Multi-messenger astronomy

Labex UnivEarthS

Université de Paris

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LabEx UnivEarthS FALL SCHOOL 2021

Multi-messenger astronomy

Exploring the violent universe: the contribution of space to multi-messenger astronomy

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High-energy astrophysics

Unlike many branches of physics based on elaboration and analysis of experiments, astrophysics is a science of observation, based on the detection and study of messengers sent by celestial bodies

Messengers:

- **Electromagnetic radiations (radio to gamma rays)**
- **Particles (protons, neutrons, electrons, neutrinos, …)**
- **Gravitational waves**

Observables:

- **Direction of arrival**
- **Energy**
- **Time of arrival**
- **Flux**

} **Nature of cosmic sources: formation, evolution and physical processes at play**

High-Energy sources: *sites where extreme physical conditions prevail: intense gravity fields, very high temperatures, strong magnetic fields, …*

Outline - Lecture 1

A. Introduction to multi-messenger astronomy

1. Astrophysical objects
2. From radio to gamma-rays: multi-wavelength astronomy (emission processes and instruments)
3. Multi-messenger astronomy: cosmic rays, neutrinos, gravitational waves

Outline - Lecture 2

B. End point of massive star evolution

1. Evolution of massive stars
2. Gamma-ray bursts
3. The SVOM space mission

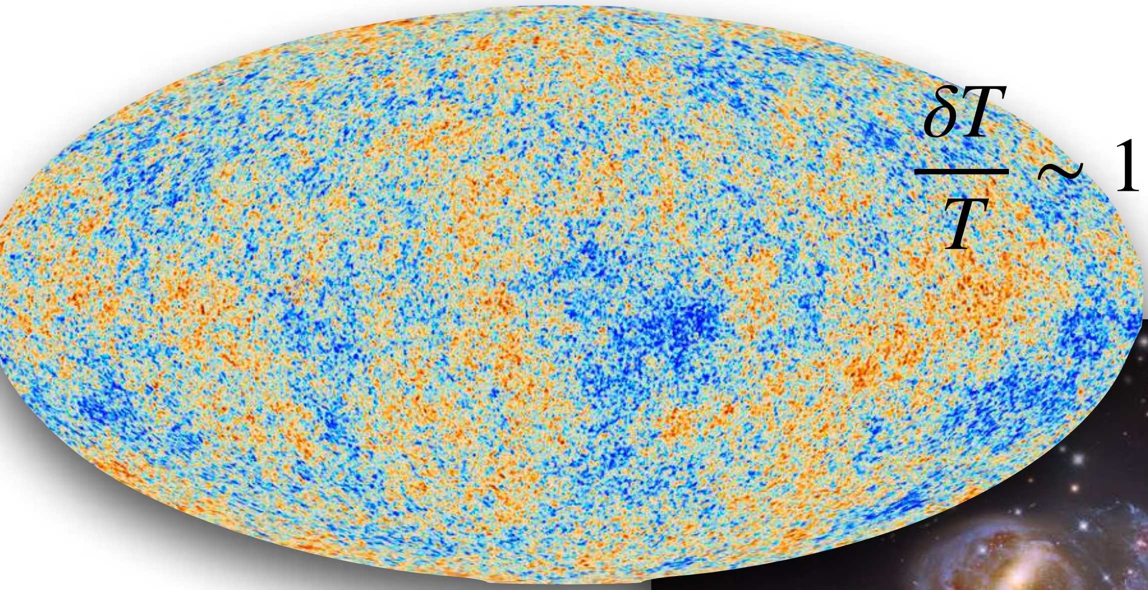
Outline - Lecture 3

C. Supermassive black holes

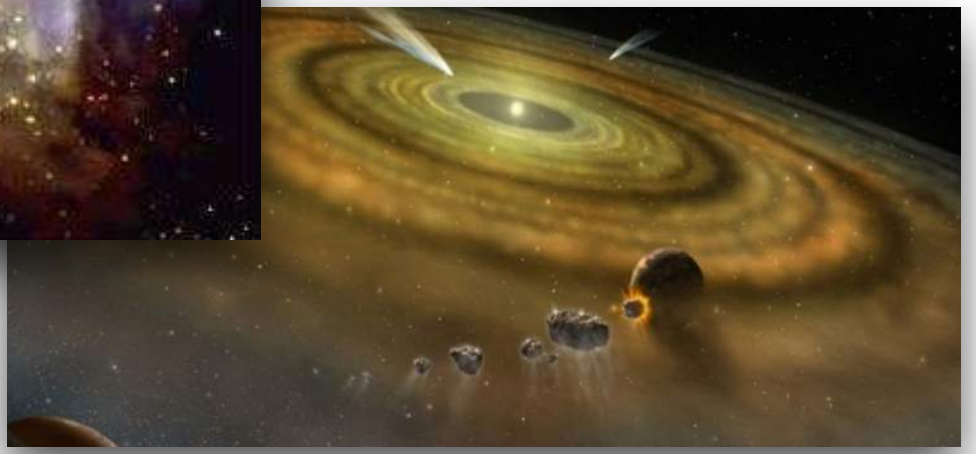
1. Supermassive black hole formation and evolution
2. Cosmic rays from Active Galactic Nuclei
3. Supermassive black hole binaries

Structuration of the Universe

High-energy objects are actors of the evolution of the Universe



$$\frac{\delta T}{T} \sim 10^{-5}$$



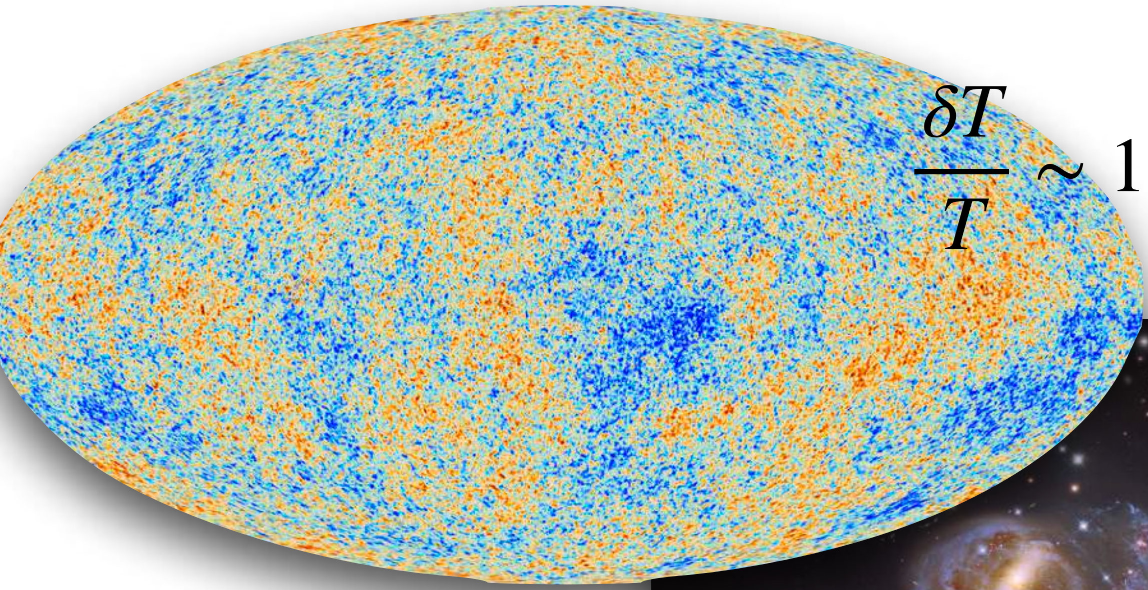
13.8 billons yr

Expansion, gravitation, cooling

Structuration of the Universe

High-energy objects are actors of the evolution of the Universe

- **Increase the disorder ⇒ prevent the Universe from evolving too fast**



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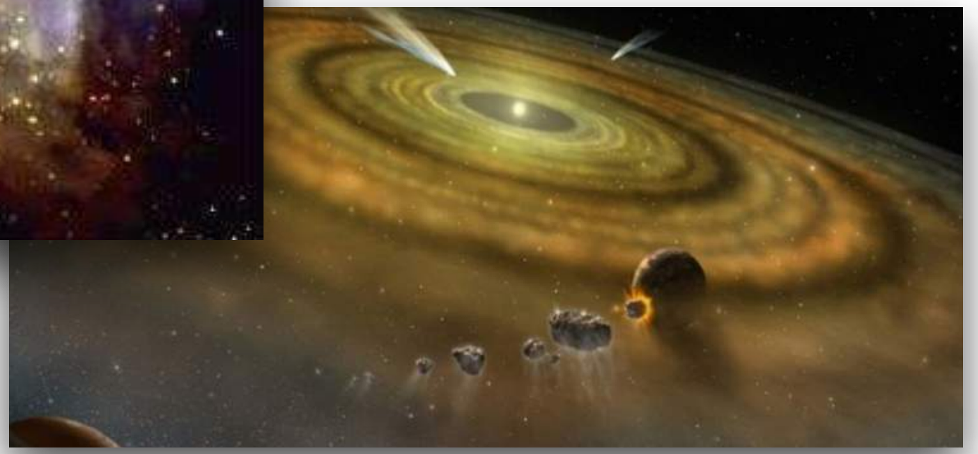

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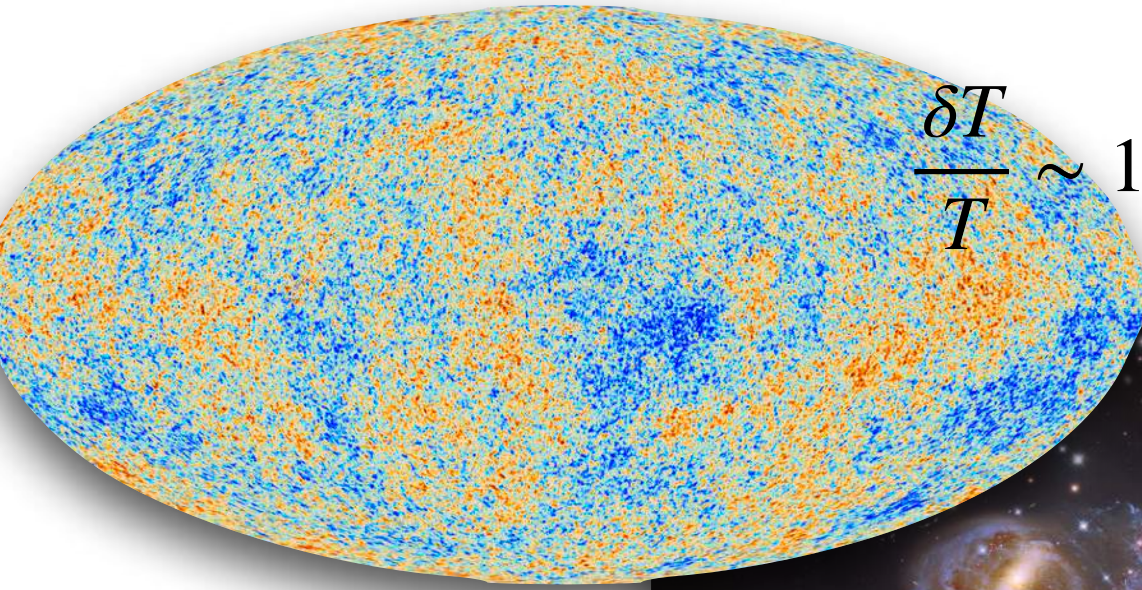

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High-energy objects are actors of the evolution of the Universe

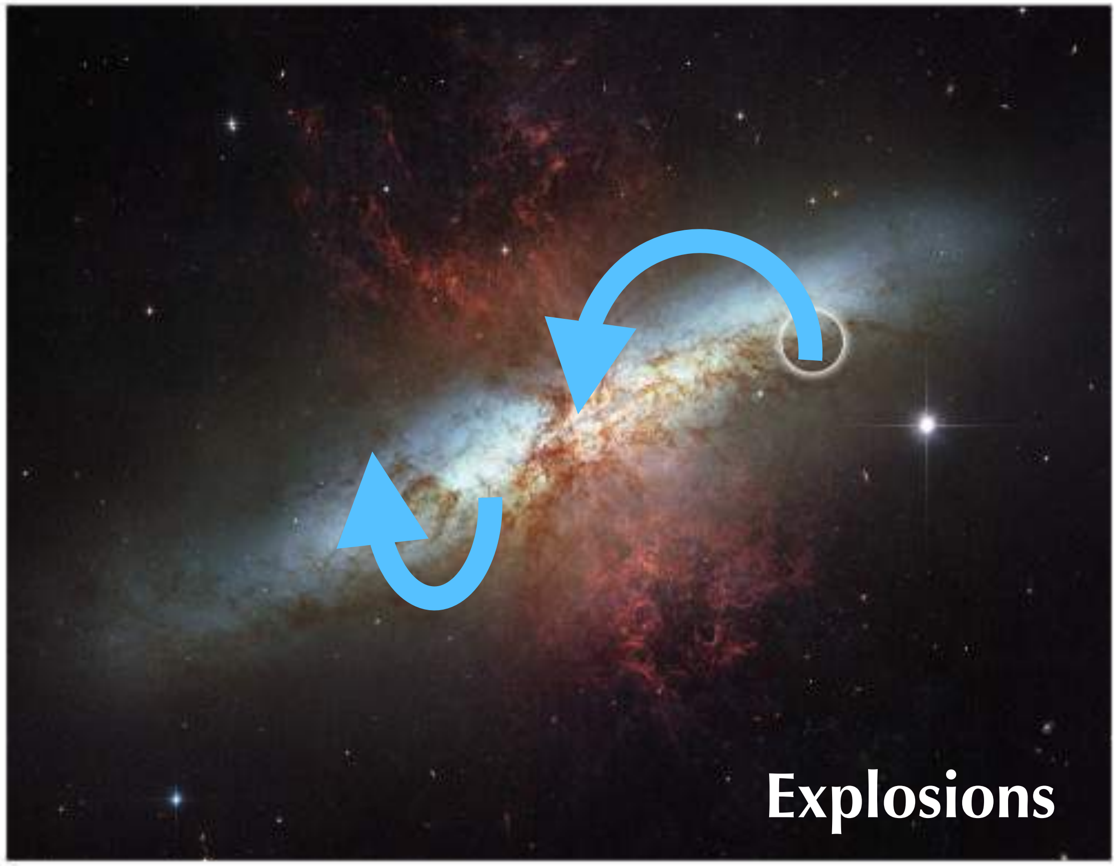
- **Increase the disorder ⇒ prevent the Universe from evolving too fast**
- **Chemical elements abundance**

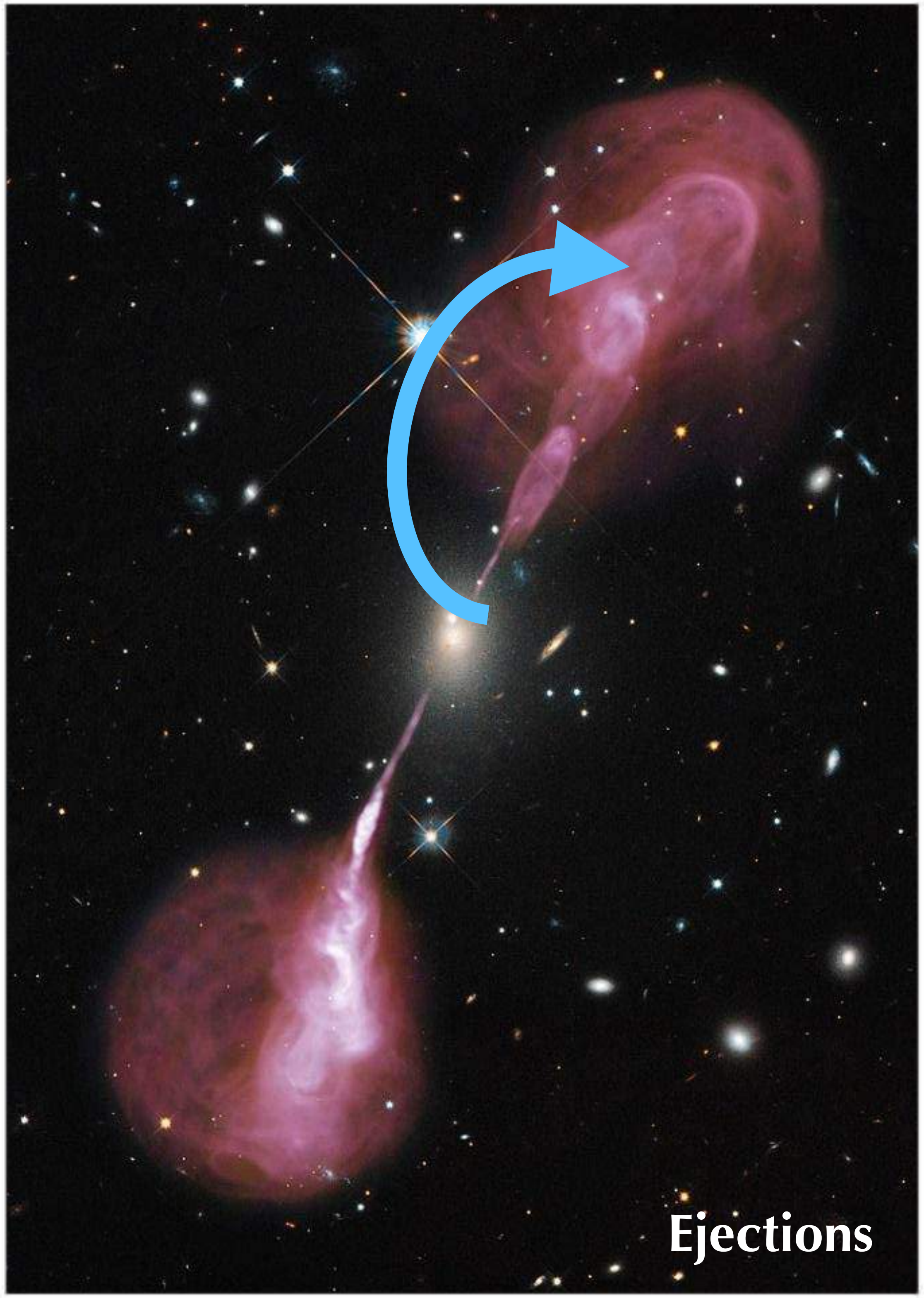
13.8 billons yr

Expansion, gravitation, cooling

High energy processes

Physical processes taking the energy at small scale and redistribute it at larger scale





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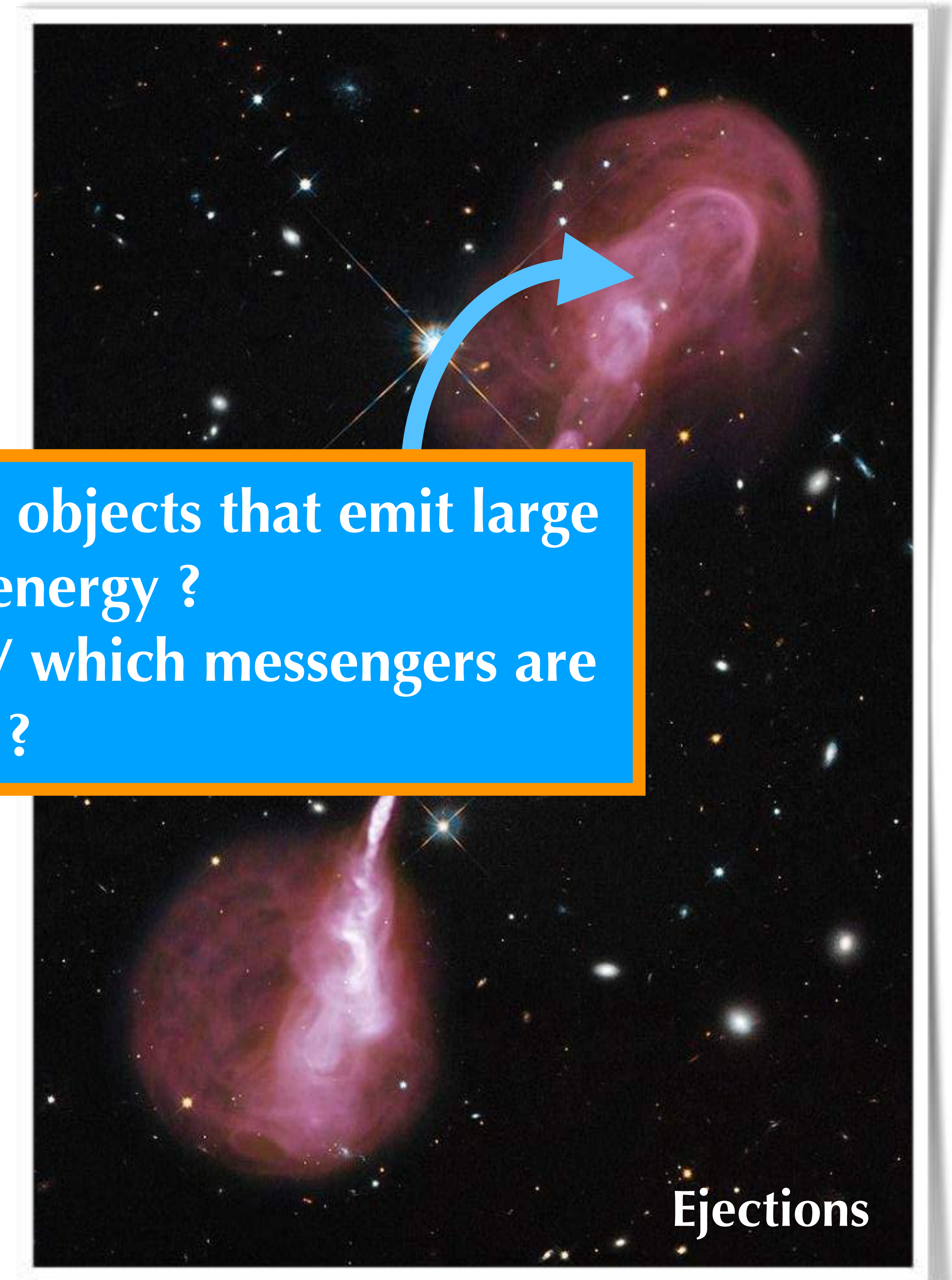

- **What are the astrophysical objects that emit large amount of energy ?**
- **How do we observe them / which messengers are used ?**

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1. **Astrophysical objects**
2. From radio to gamma-rays: multi-wavelength astronomy (emission processes and instruments)
3. Multi-messenger astronomy: cosmic rays, neutrinos, gravitational waves

Which objects ?

Compacity of an astrophysical source : $\Xi = \dfrac{GM}{Rc^2}$ (gives the intensity of gravitational field)

High mass + small radius ⇒ large Ξ

Object	Mass ($M_\odot$)		Compacity Ξ
Earth	$3\text{x}10^{-6}$		$3\text{x}10^{-10}$
Sun	1	696 000	$2\text{x}10^{-6}$
White dwarf	0.1 - 4	10 000	10^{-4} - 10^{-3}
Neutron star	1 - 3	10	0.2 - 0.4
Stellar mass black hole	> 3	$8.9(M/3M_\odot)$	1
Supermassive black hole	10^6 - 10^9	20 AU$(M/10^9M_\odot)$	1

Compact objects (Neutron star, Stellar mass black hole, Supermassive black hole)

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Gravitational energy = $-\alpha \dfrac{GM^2}{R} = -\alpha \Xi M c^2$ (with $\alpha \sim 1$)

Compact objects have large gravitational energy reservoir ⇒ can emit large amount of energy by extracting gravitational energy

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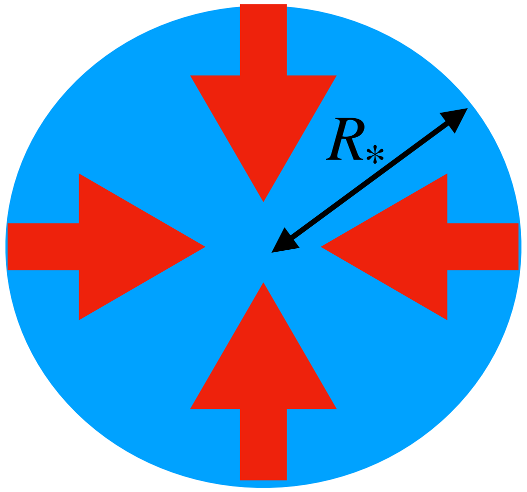
Gravitational energy can be extracted in at least 2 ways: gravitational collapse and accretion

- **Collapse**: $\Delta E_{collapse} = E_{grav}(R_*) - E_{grav}(R) \approx -E_{grav}(R) \sim \Xi M c^2$



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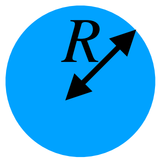

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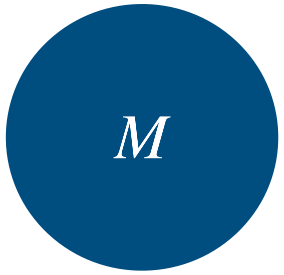

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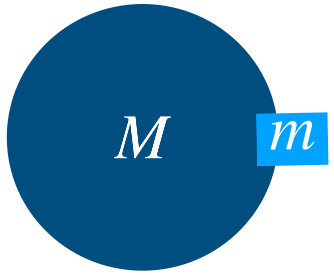

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⇒ The greater Ξ, the more gravitational energy is extracted.

⇒ High-energy phenomena related to compact objects.

Significant amount of energy compared to nuclear fusion of H ($7 \times 10^{-3}\ mc^2$).

Which objects ?

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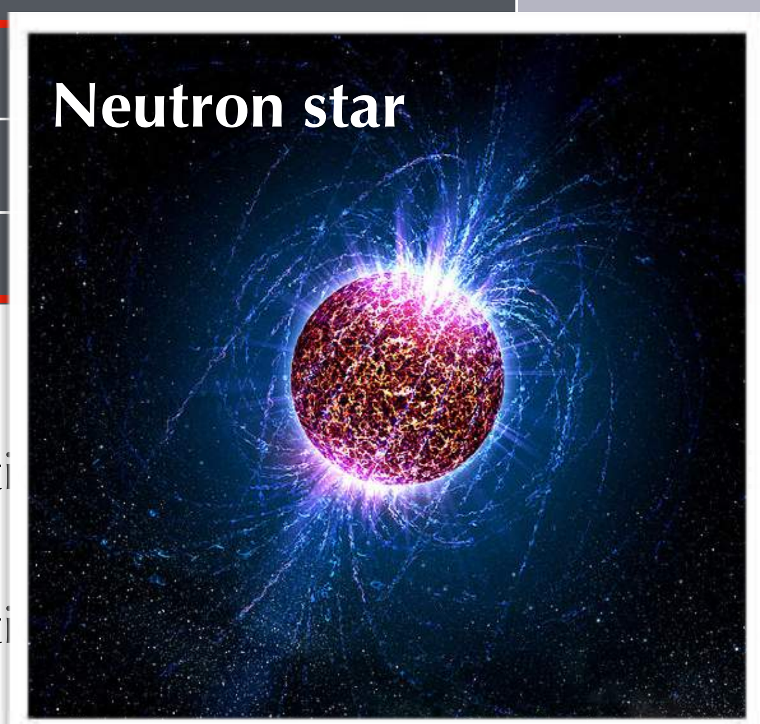
Compact objects



Gravitati

Gravitati

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End of life of massive stars (see lecture 2)

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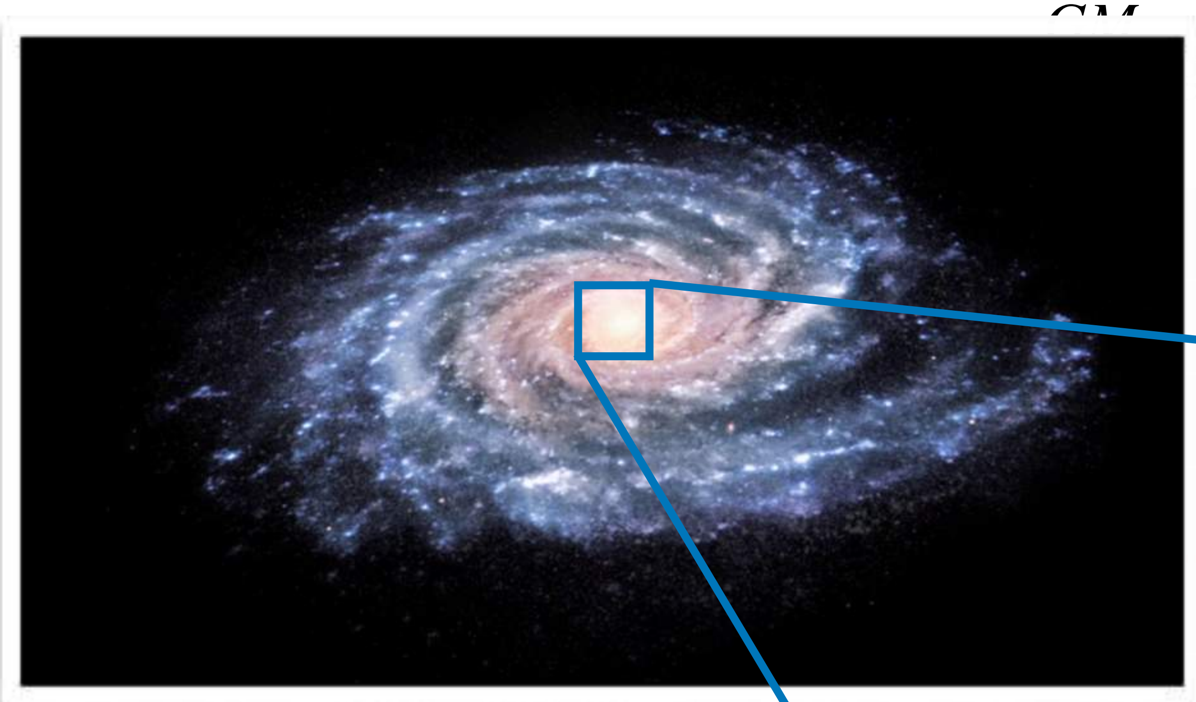
Which objects ?



… ives the intensity of gravitational field)

	Radius (km)	Compacity Ξ
	6 000	3×10^{-10}
Stellar mass black hole		
Supermassive black hole	10^{6} - 10^{9}	

Compac…

Gravitational energy $= -\alpha \frac{GM^2}{R} = -\alpha \Xi M c^2$ (with α …

Gravitational energy can be extracted in at least 2 way…

- **Collapse**: $\Delta E_{collapse} = E_{grav}(R_*) - E_{grav}(R)$ …
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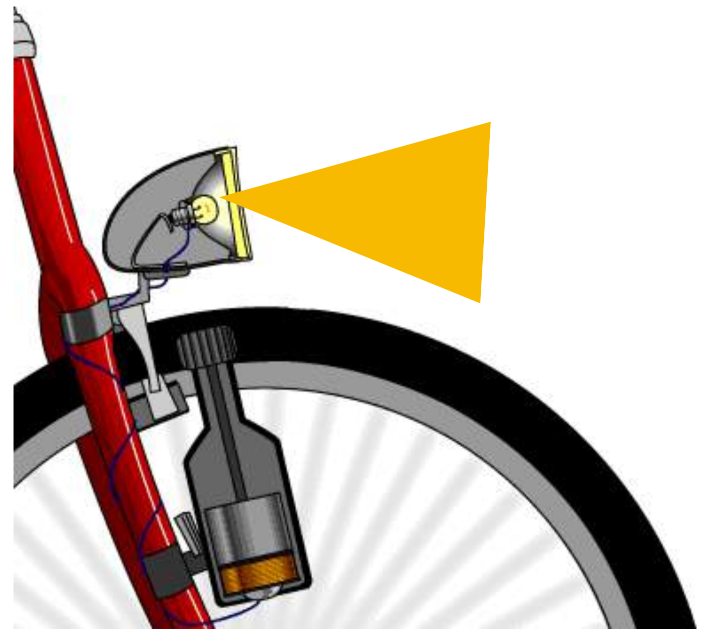
Supermassive black holes at the center of each galaxy (see lecture 3)

⇒ The greater Ξ, the more gravitational energy is extracted.
⇒ High-energy phenomena related to compact objects.
Significant amount of energy compared to nuclear fusion of H (7×10^{-3} mc^2).

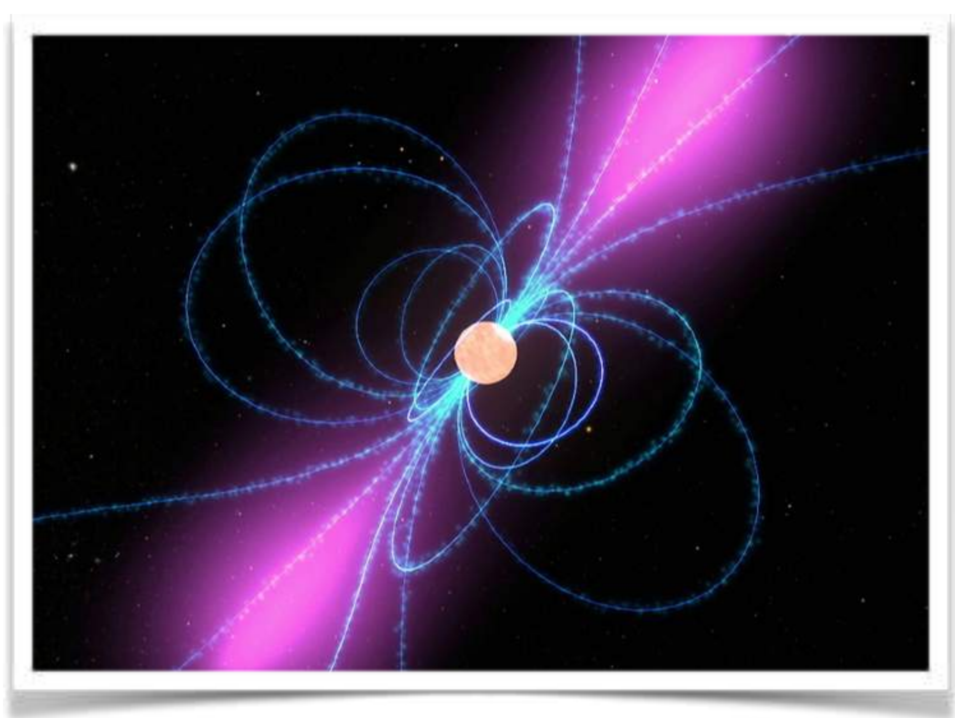
How is the energy extracted ?



Gravitation

Dynamo effect of a rotating magnet

Acceleration of charged particles on a shock wave



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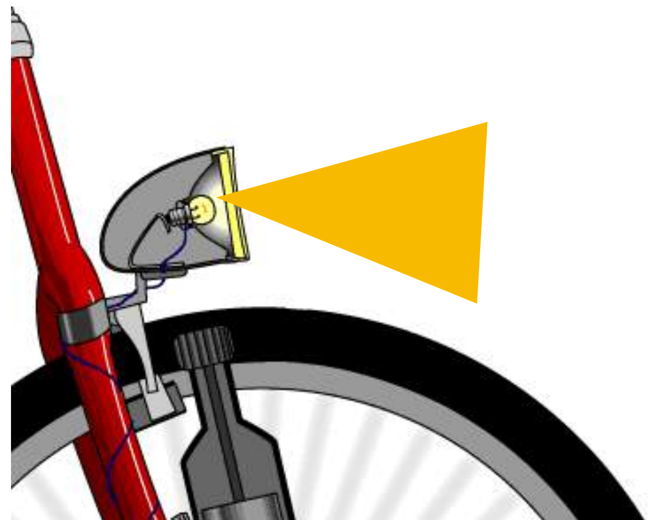

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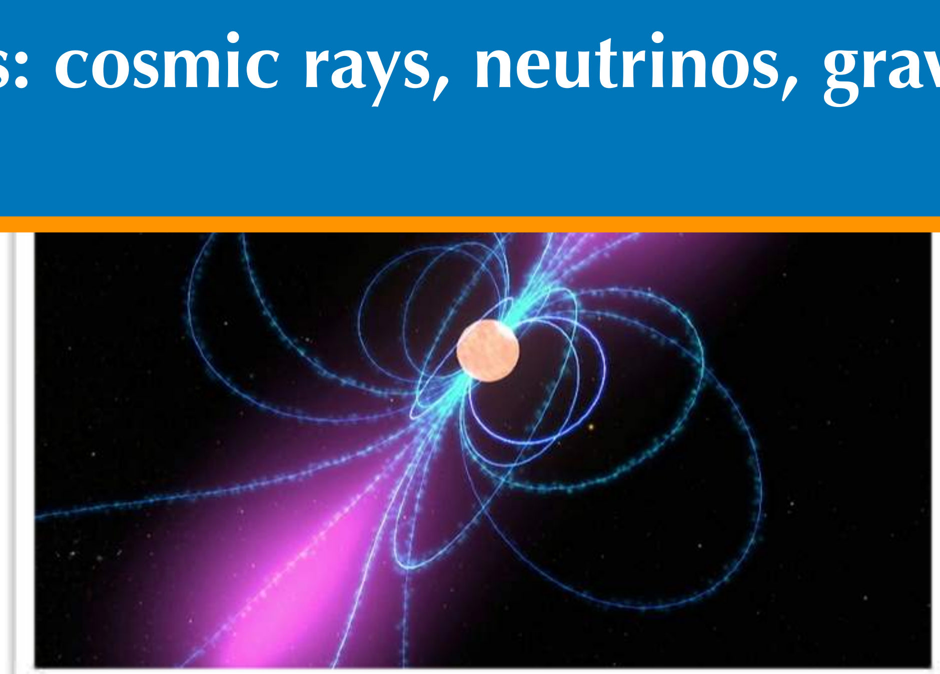
ck wave

Gravitational, rotation and shock energy released through:

- Kinetic energy
- Electromagnetic radiation
- Other messengers: cosmic rays, neutrinos, gravitational waves.



Outline - Lecture 1

A. Introduction to multi-messenger astronomy

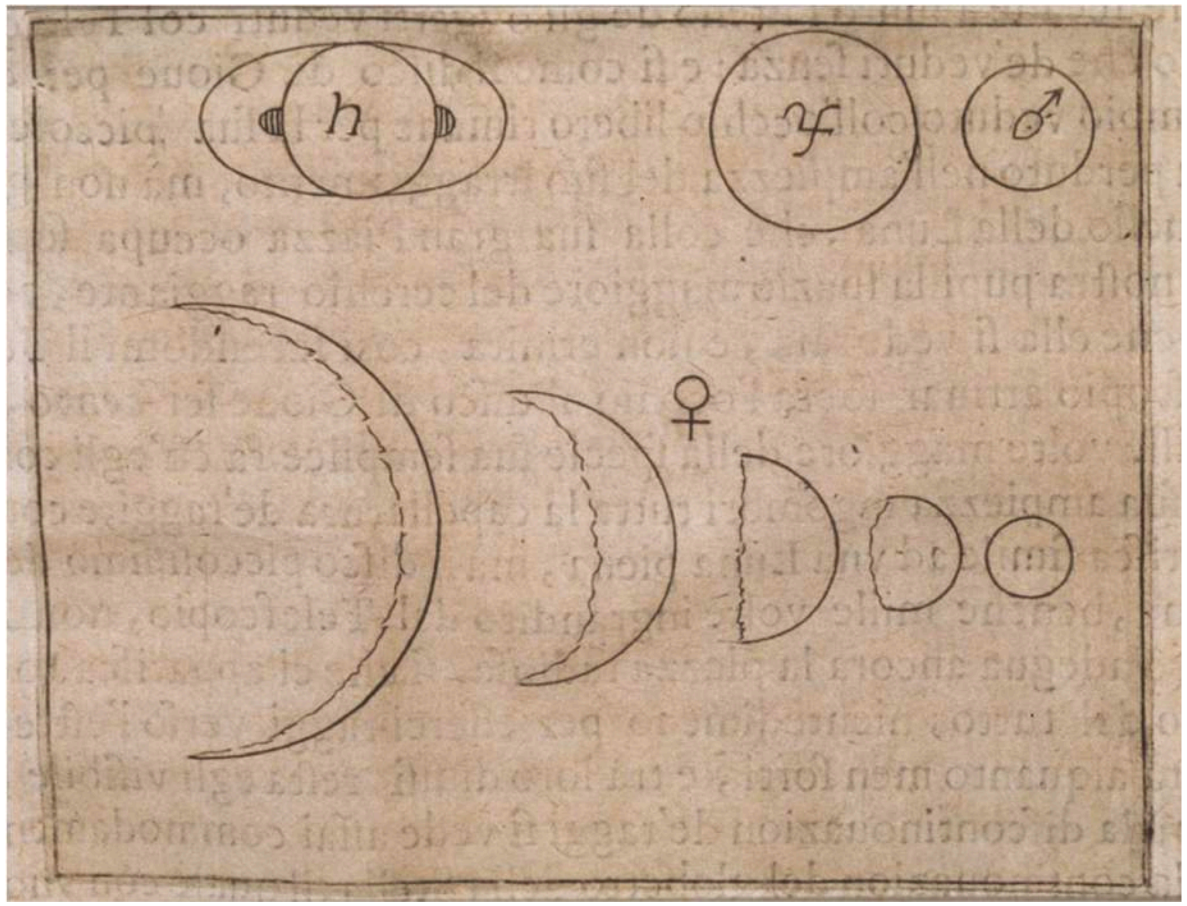
1. Astrophysical objects

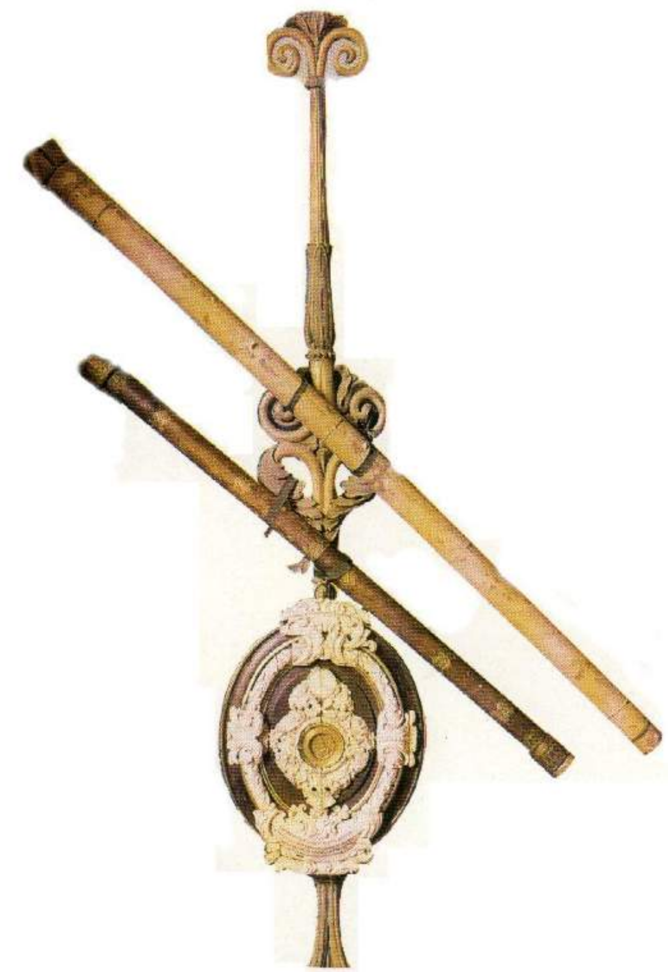
2. **From radio to gamma-rays: multi-wavelength astronomy (emission processes and instruments)**

3. Multi-messenger astronomy: cosmic rays, neutrinos, gravitational waves

Observational techniques

Progresses in observational astronomy are always strongly linked to the opening of a new window on the universe.



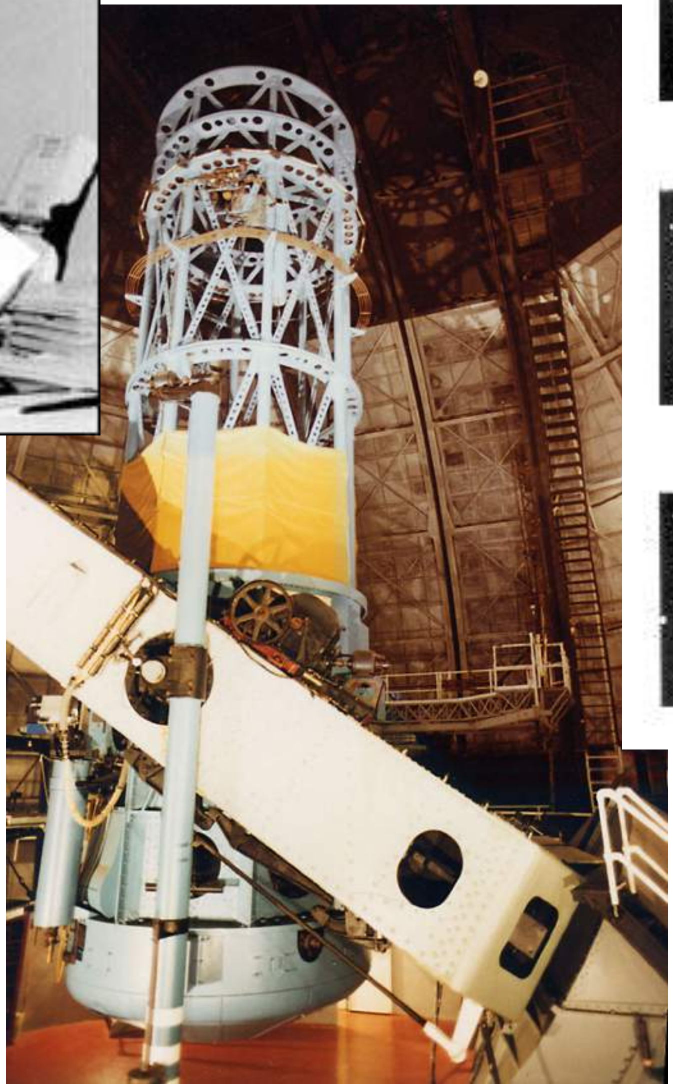


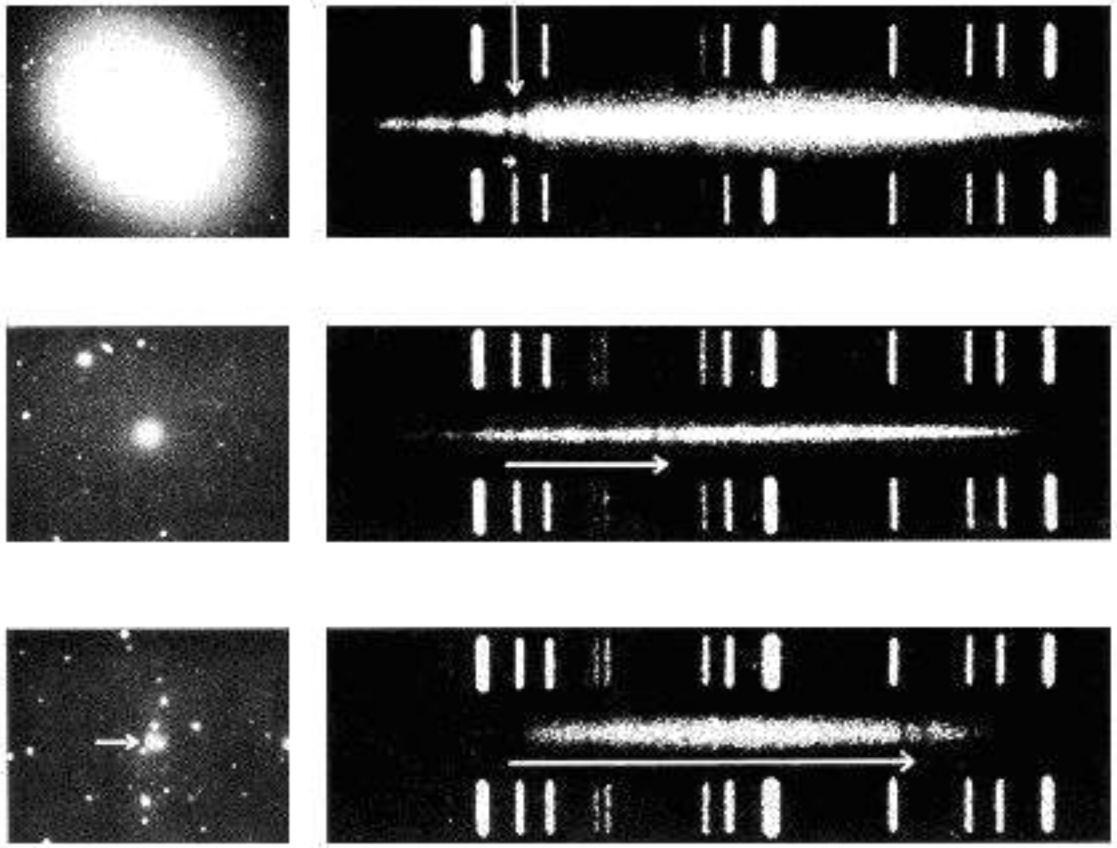
Galileo Confirmed heliocentric model

1609 **1700** **1800** **1900** **2000** **t**

Observational techniques

Hubble



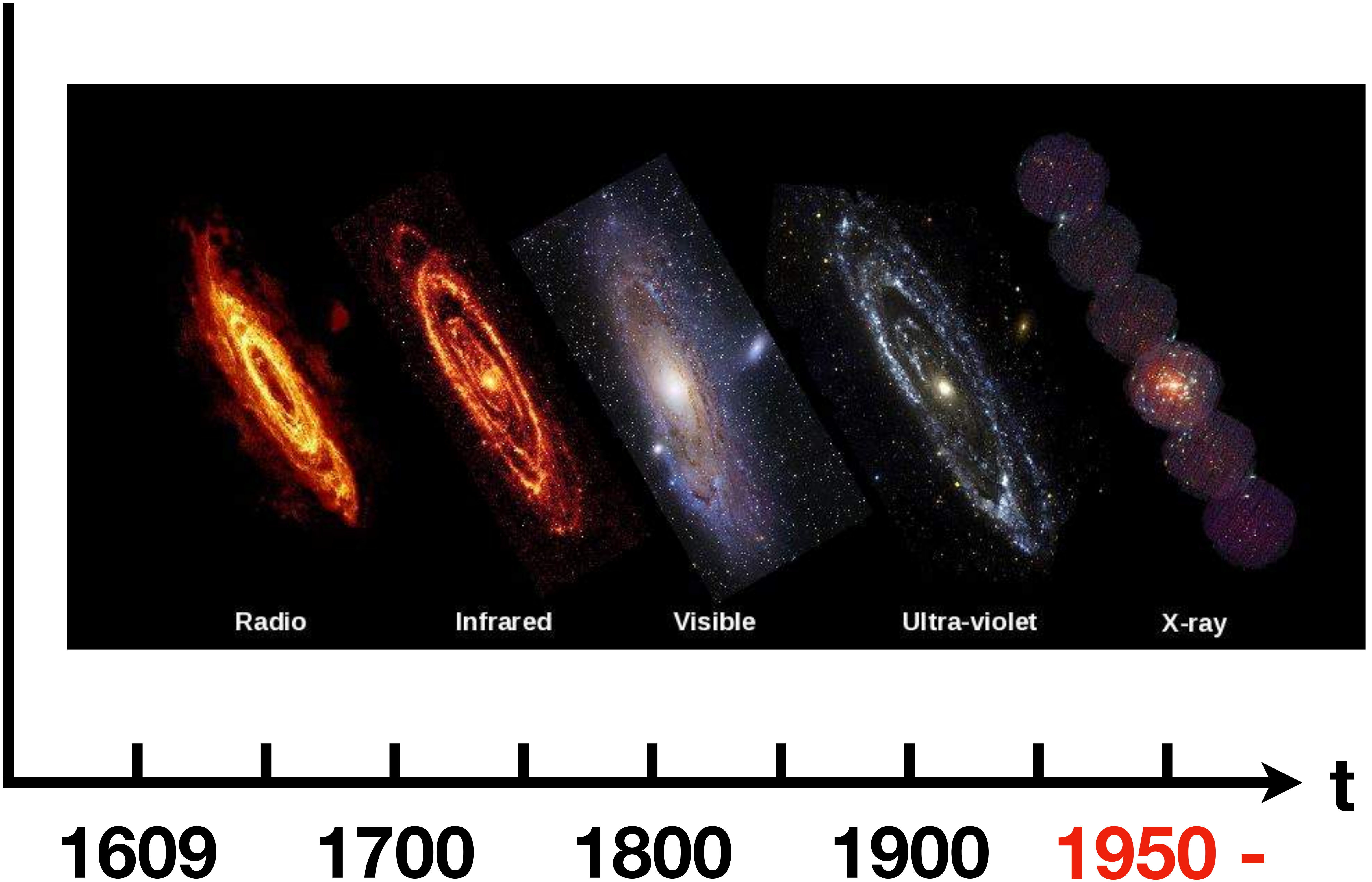


Galaxies + expansion of the Universe

t

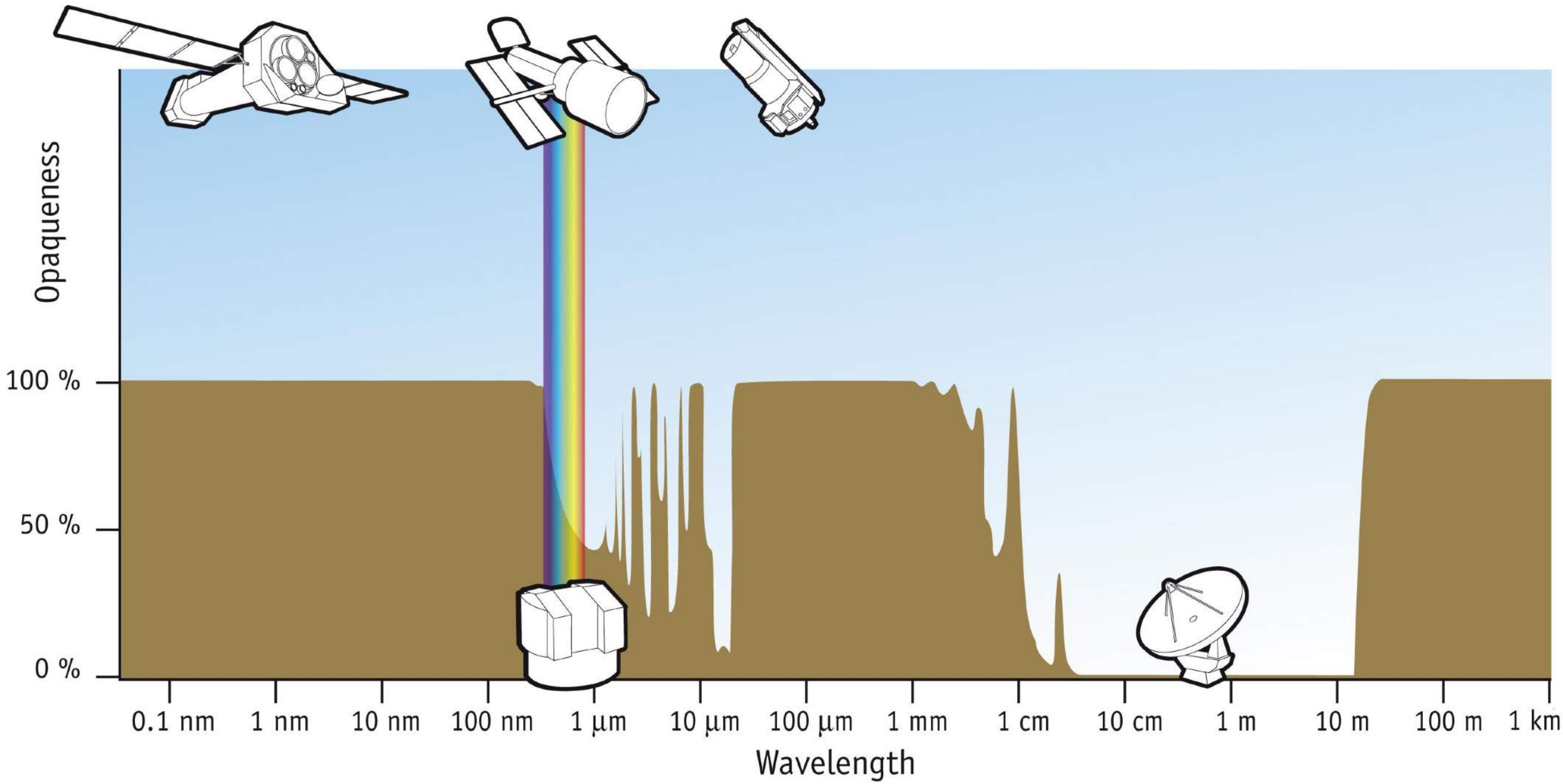
1609 1700 1800 **1929** 2000

Multi-wavelength astronomy



Multi-wavelength astronomy

Accessing new windows of the electromagnetic spectrum is quite recent and is essentially linked to our ability to go into space…



Multi-wavelength astronomy

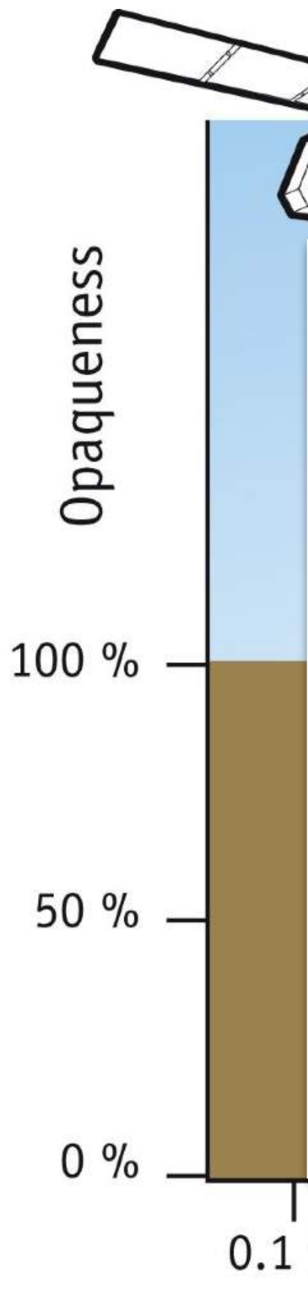
EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

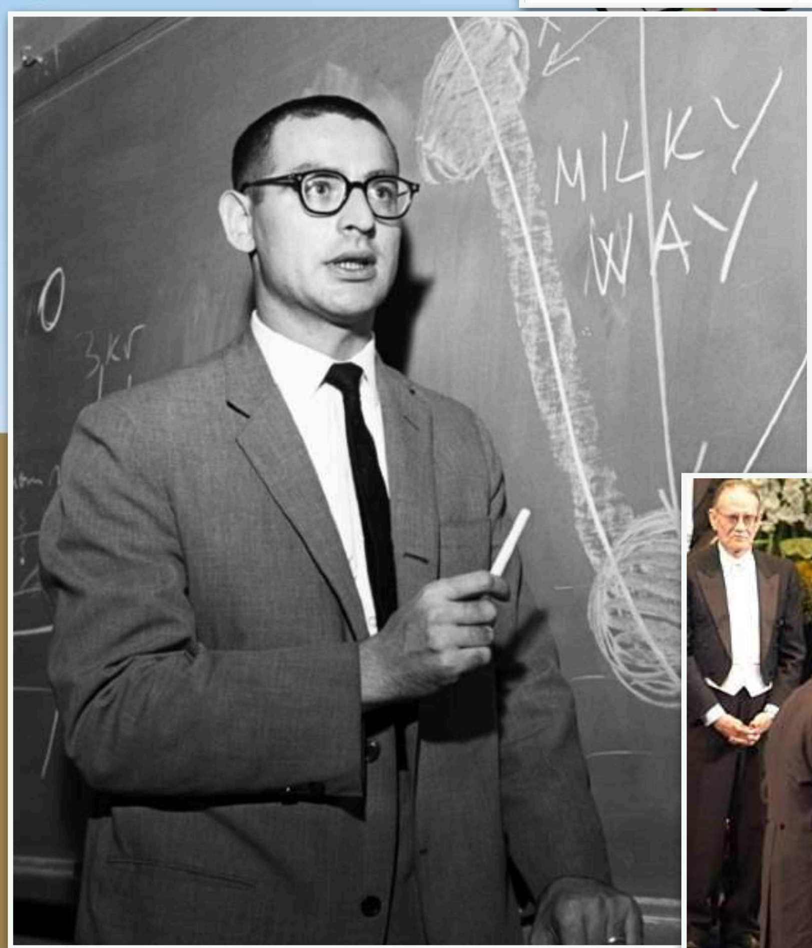
Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

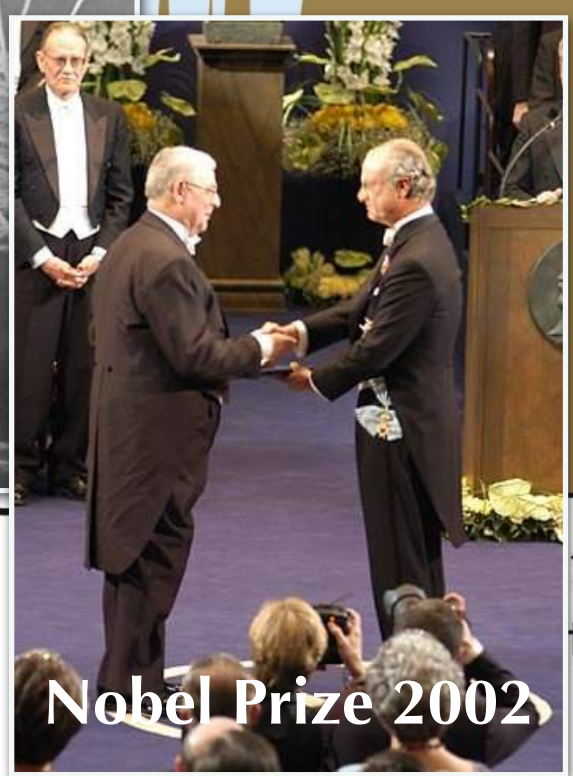
and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts

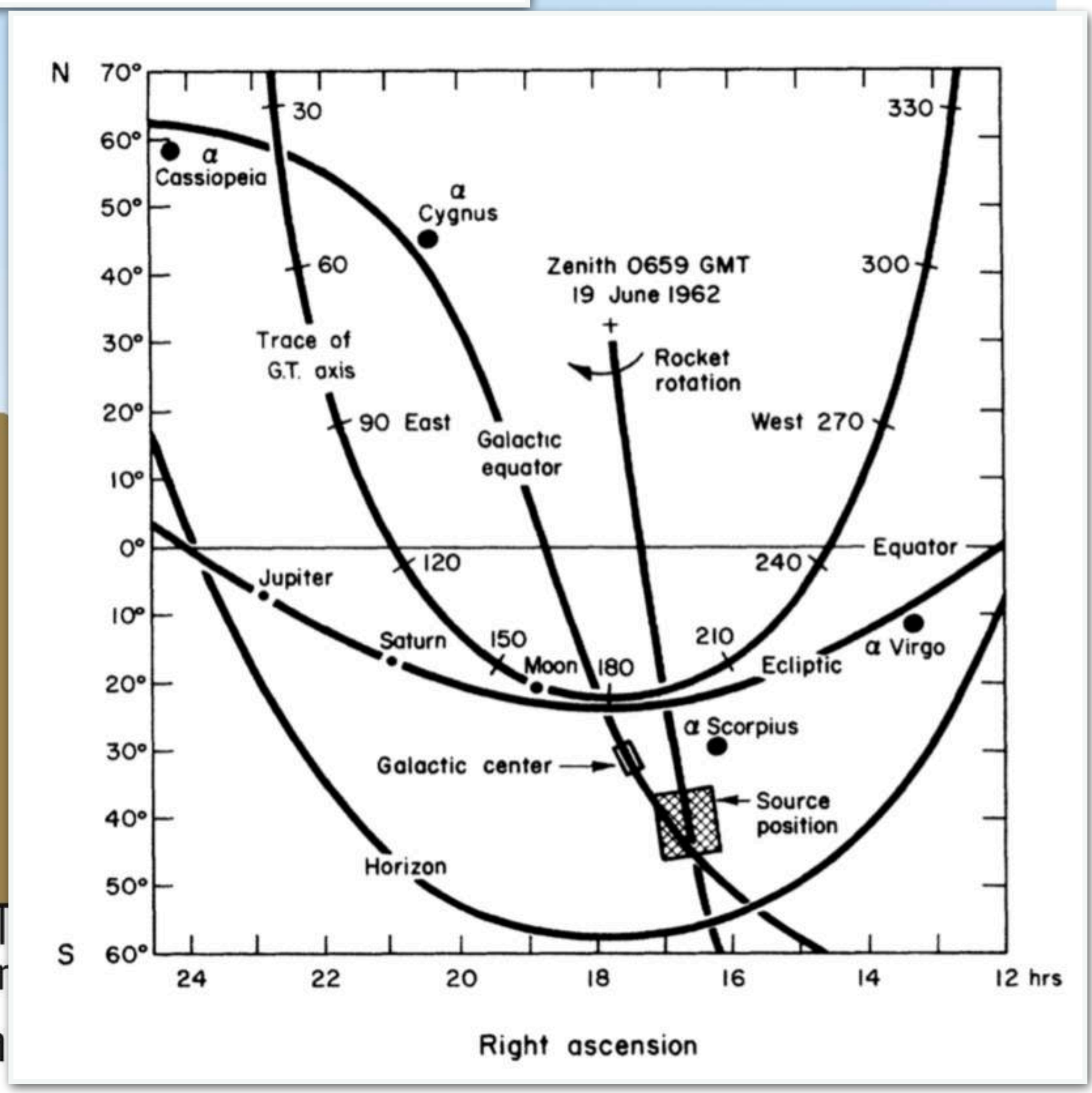
(Received October 12, 1962)







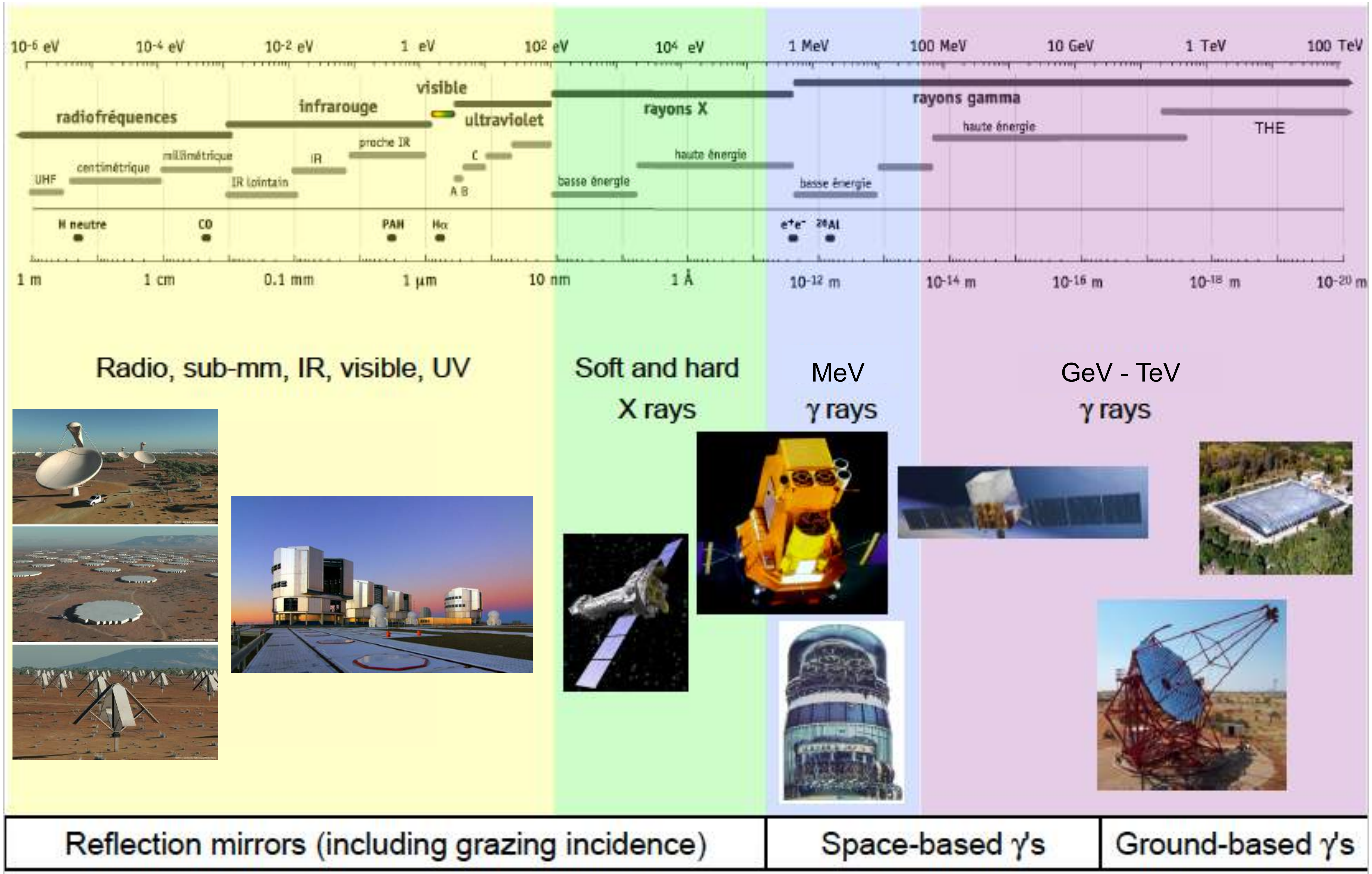
Nobel Prize 2002



59 years later

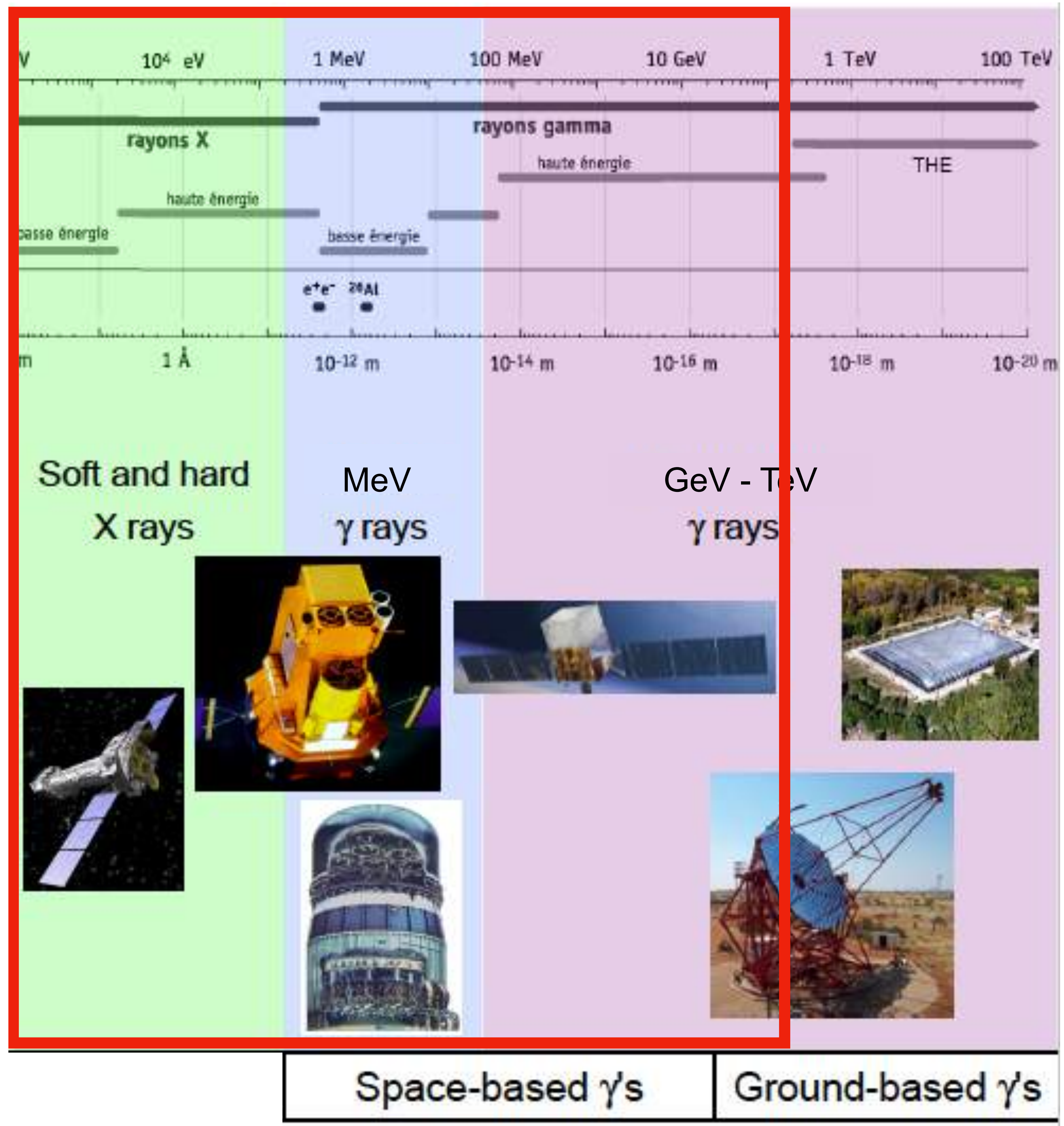
Chandra deep field South: deepest X-ray image

Multi-wavelength astronomy



Multi-wavelength astronomy

Covered in this lecture



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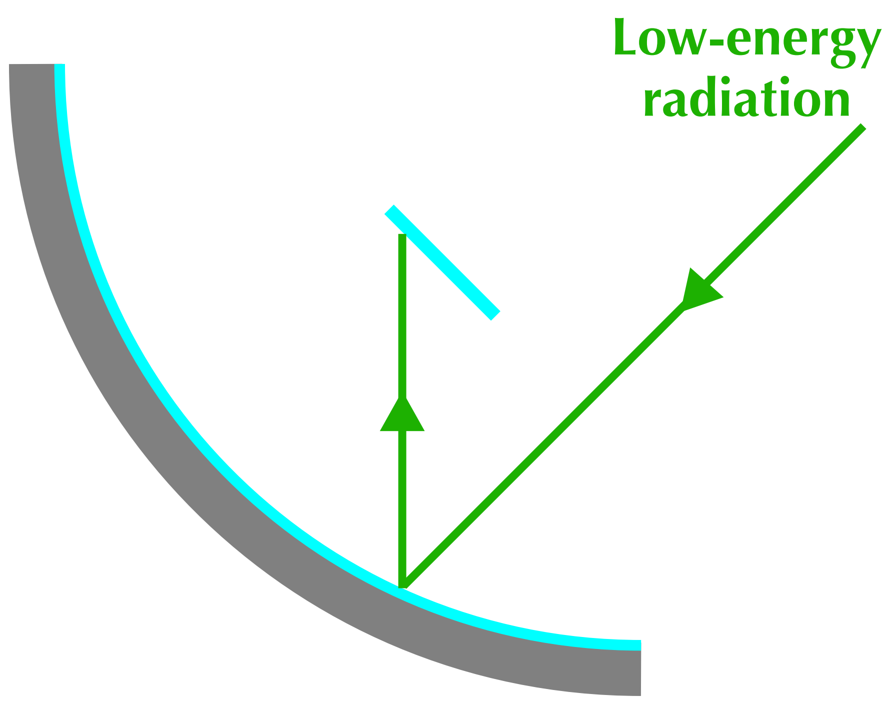

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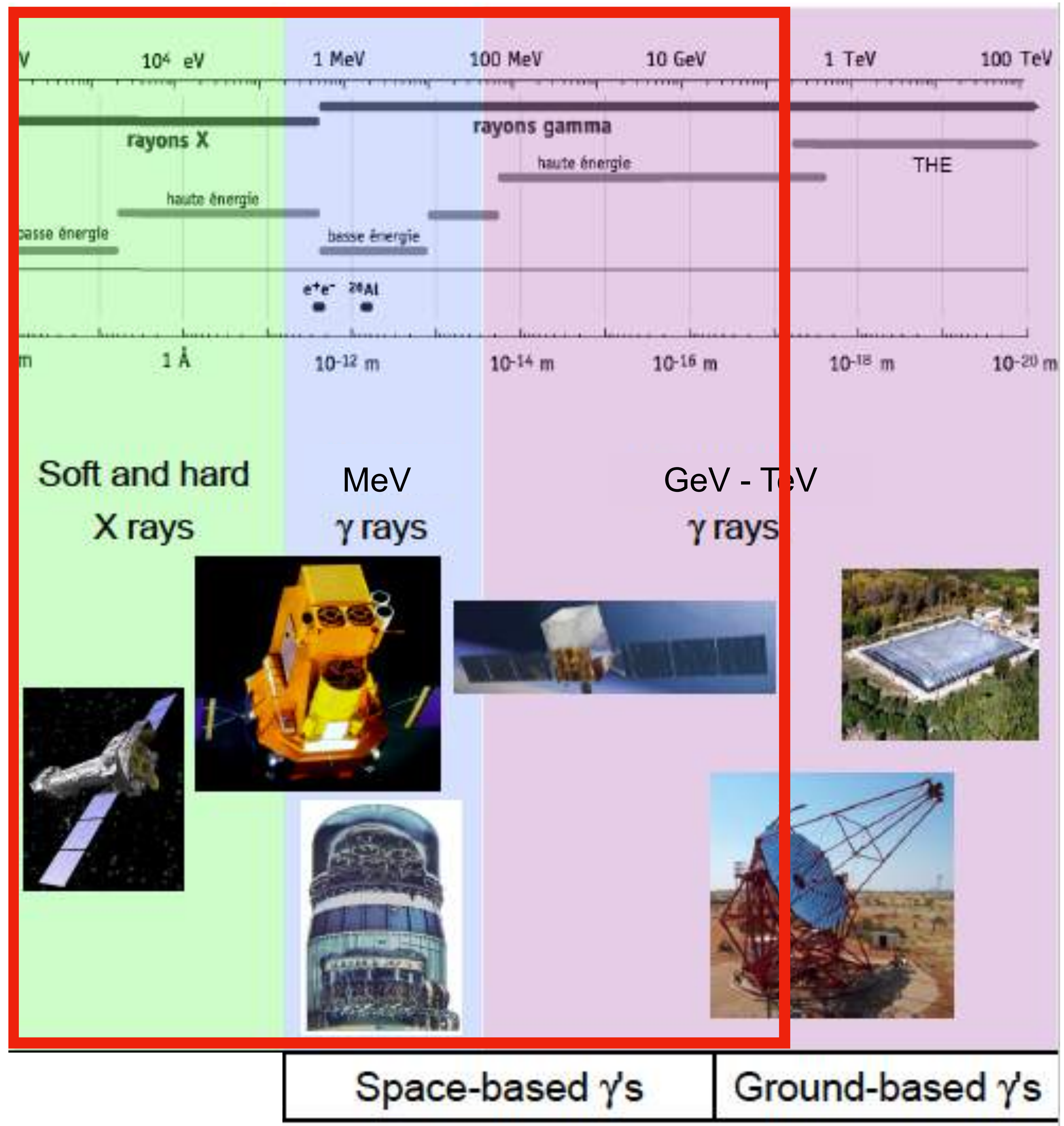

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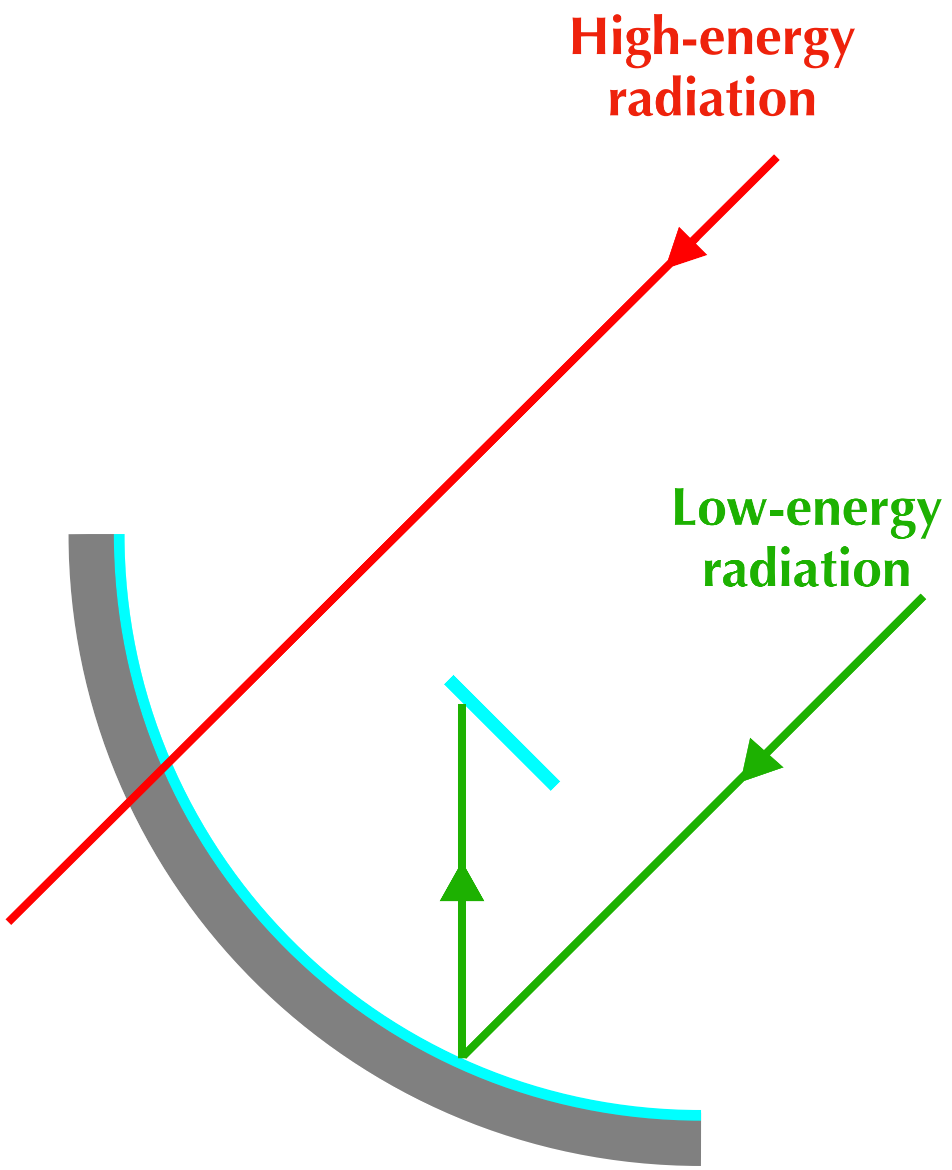
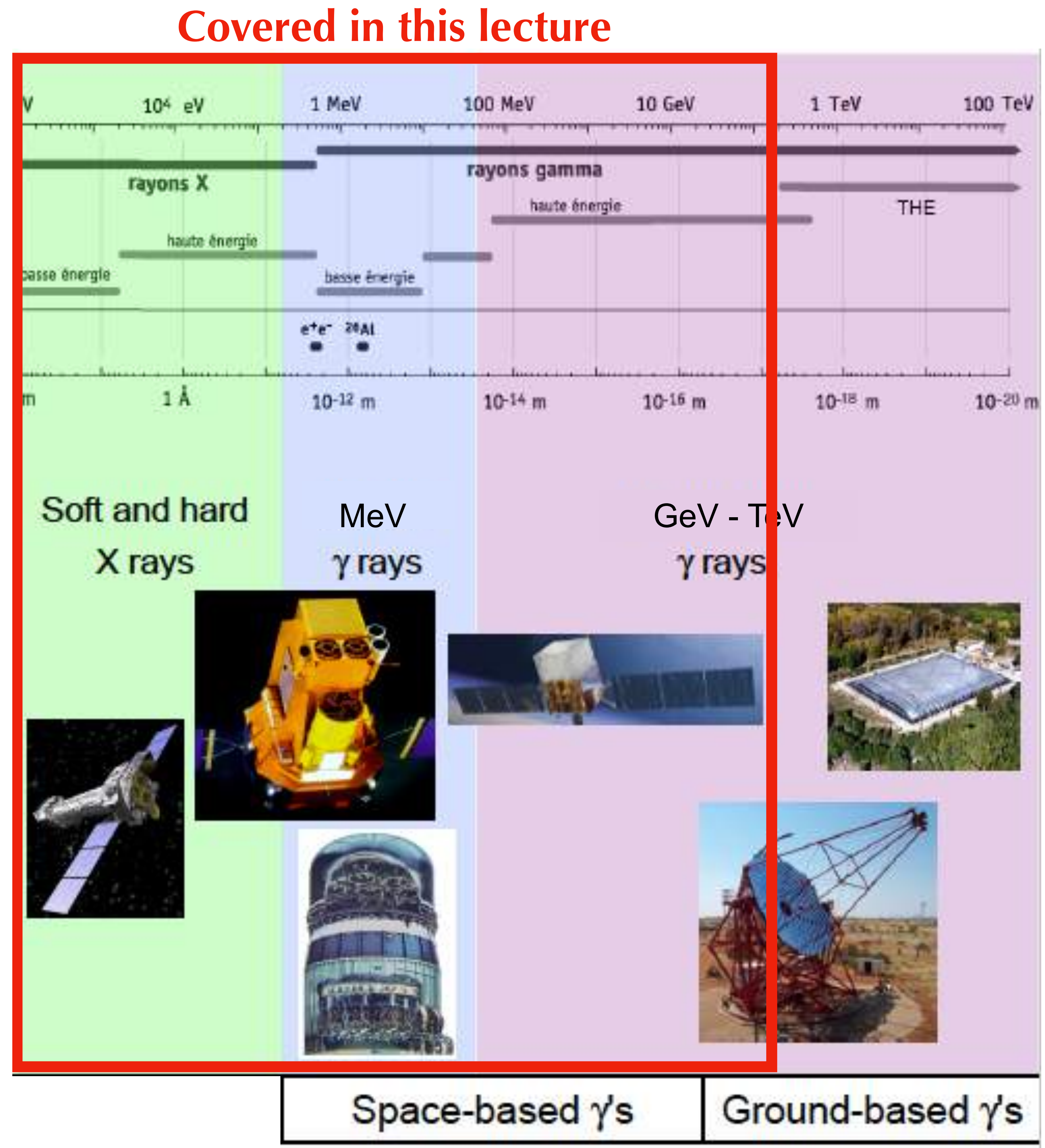
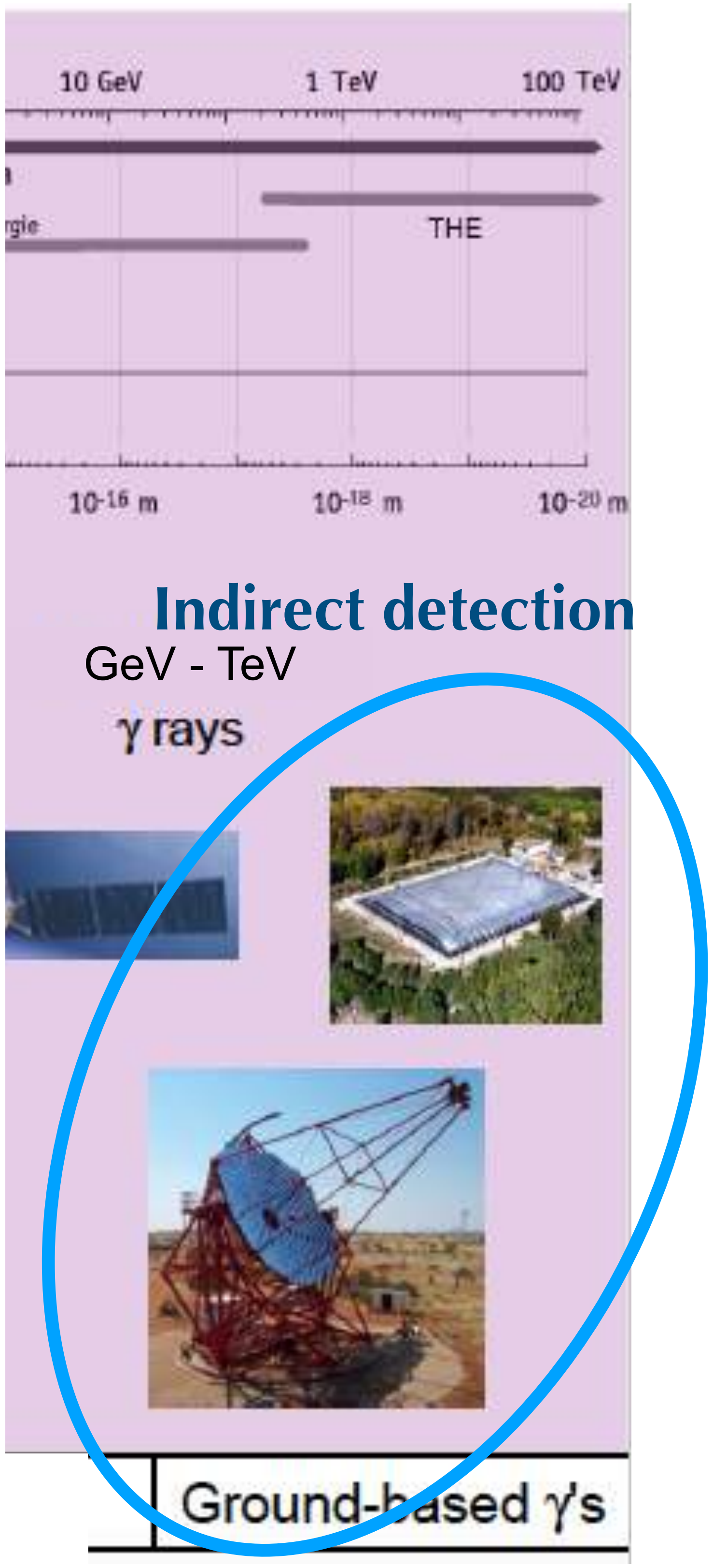




High-energy photons cannot be easily reflected or refracted ⇒ apply other techniques to focalize and detect them.

Multi-wavelength astronomy

- In gamma-ray domain: very low photon flux ⇒ requires large detection surfaces to detect enough photons.
- Space facilities cannot be used anymore.
- Direct detection impossible since high-energy particles (photons) interact with Earth atmosphere.
- Indirect observation via the detection of secondary particles produced by the interaction with the atmosphere.



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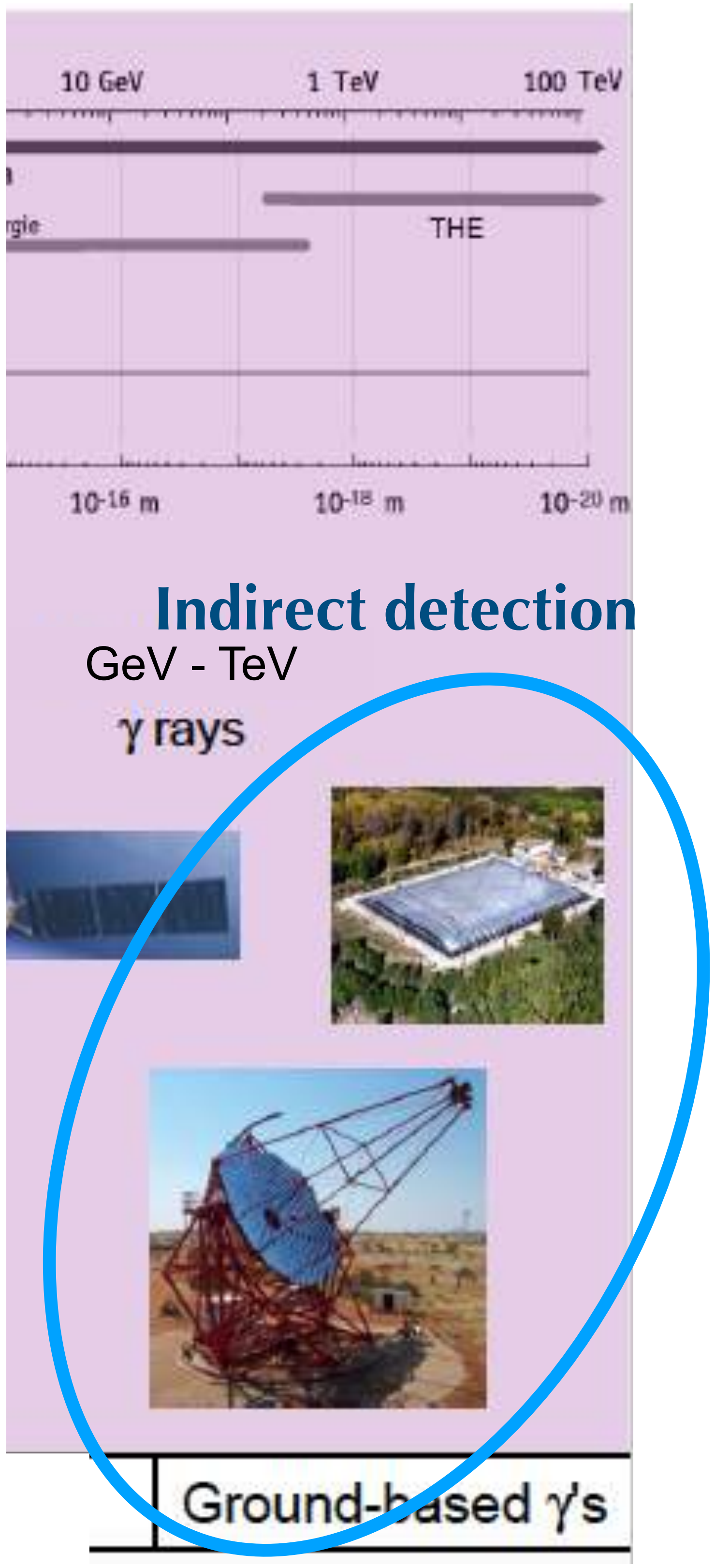

Multi-wavelength astronomy

- In gamma-ray domain: very low photon flux ⇒ requires large detection surfaces to detect enough photons.
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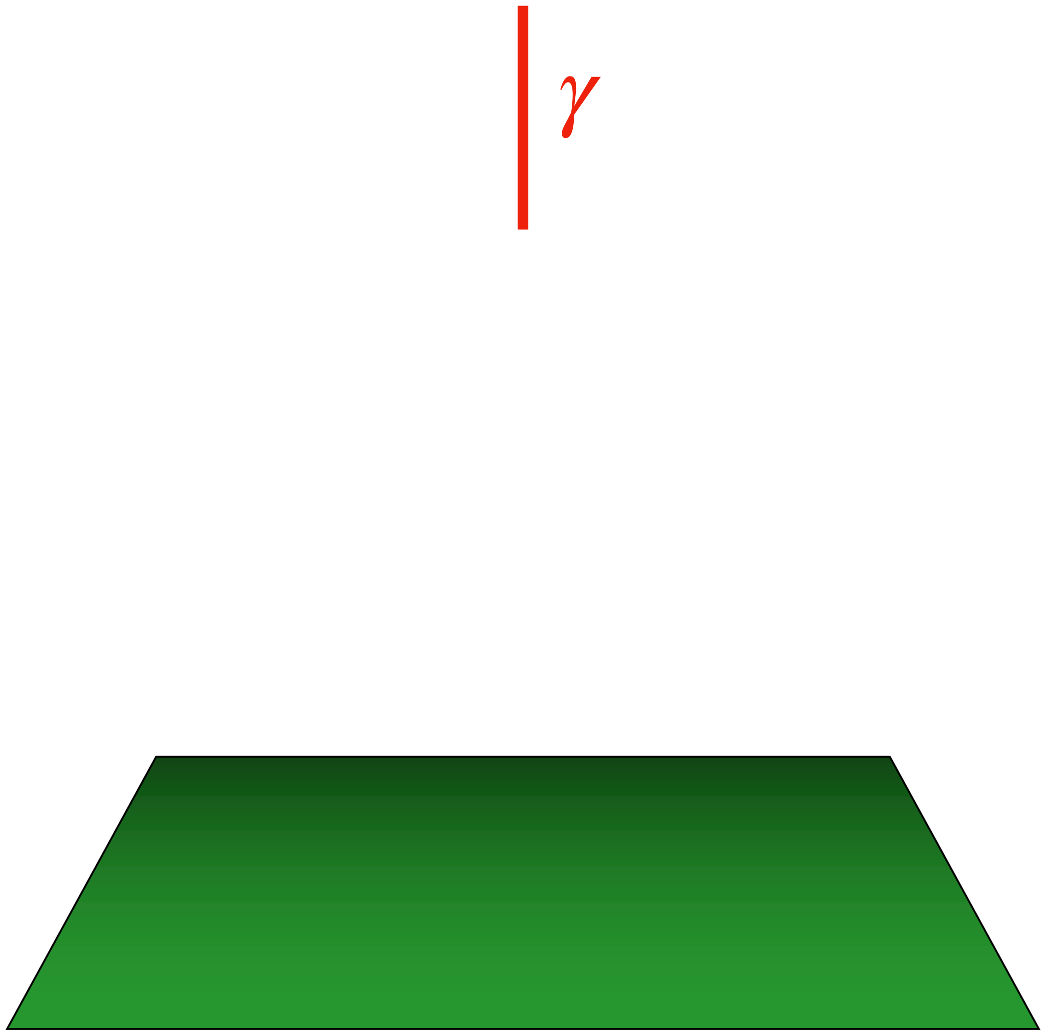

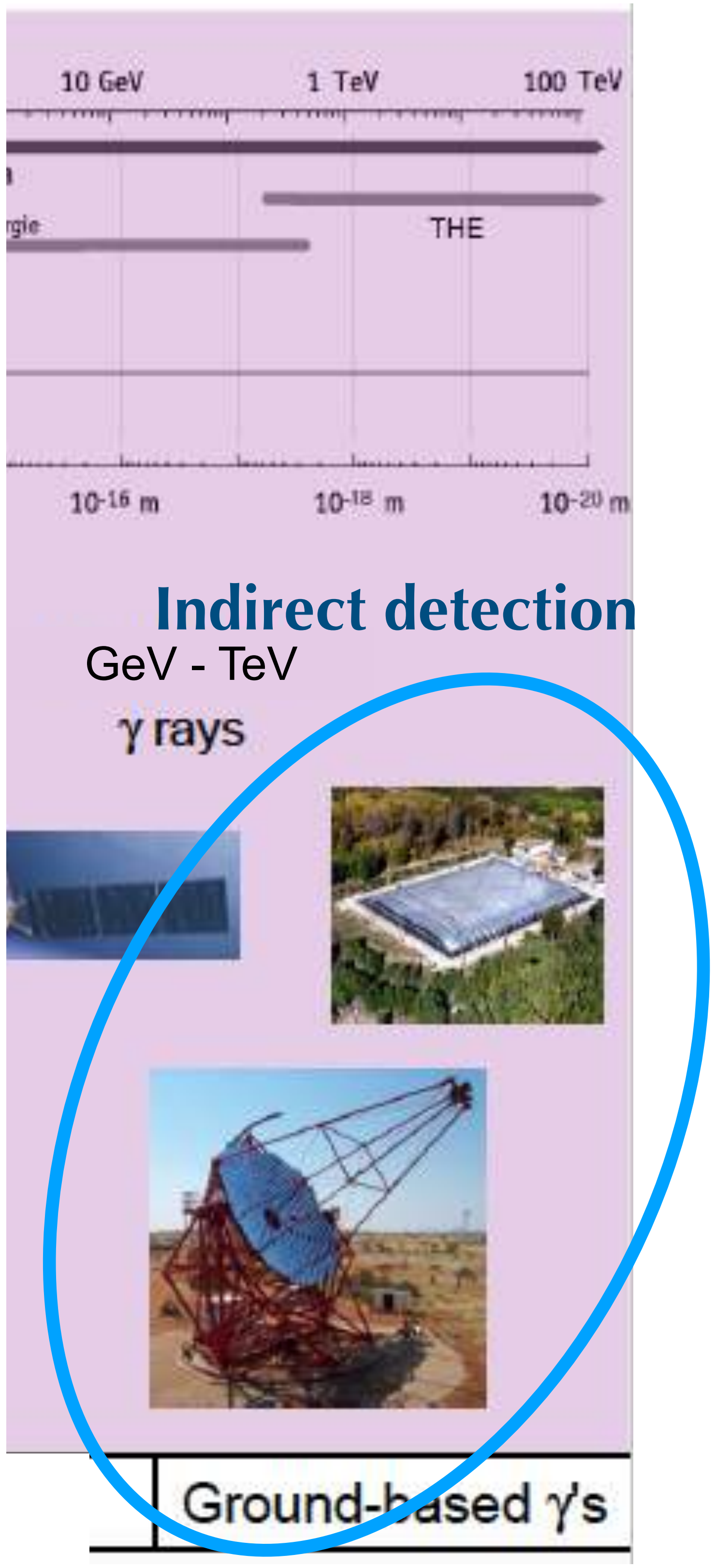

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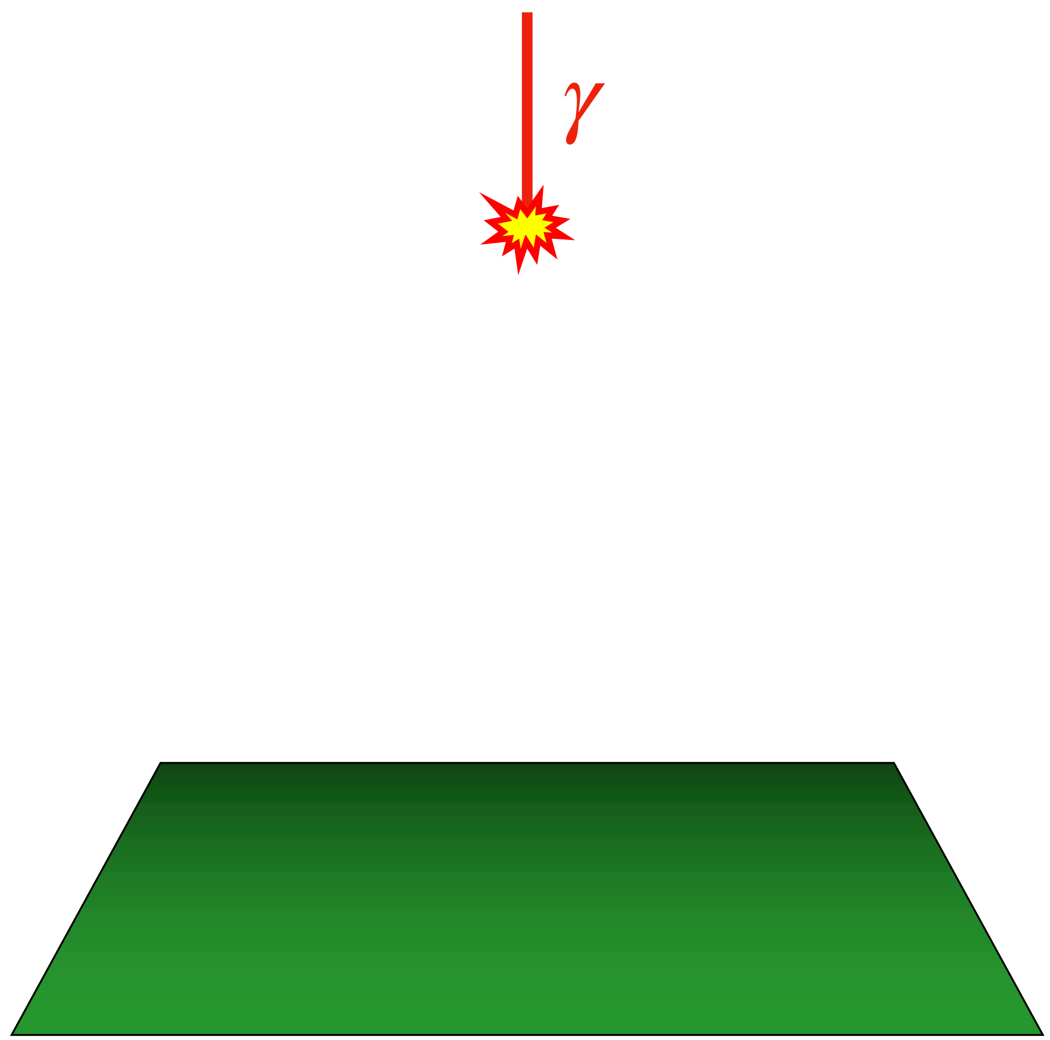

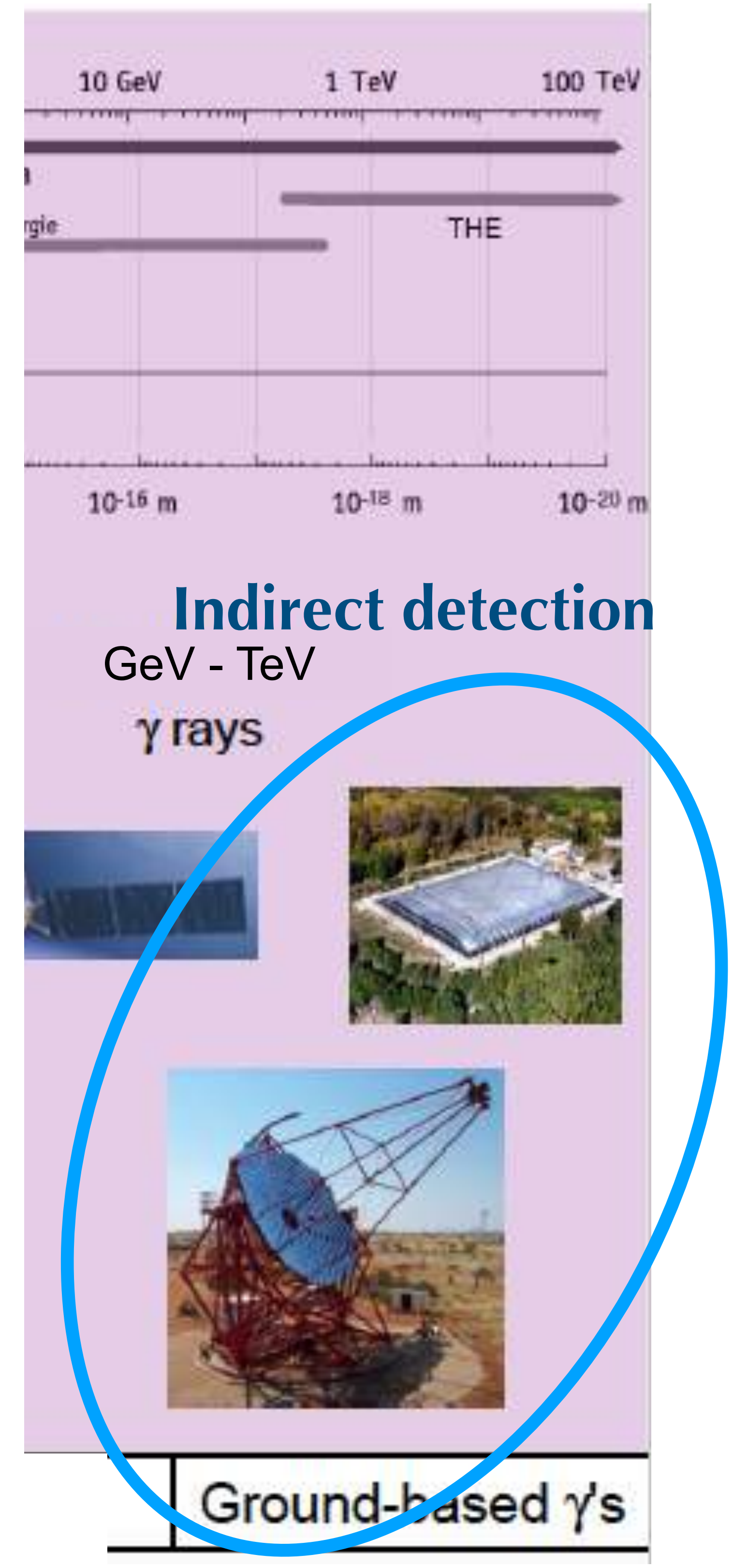

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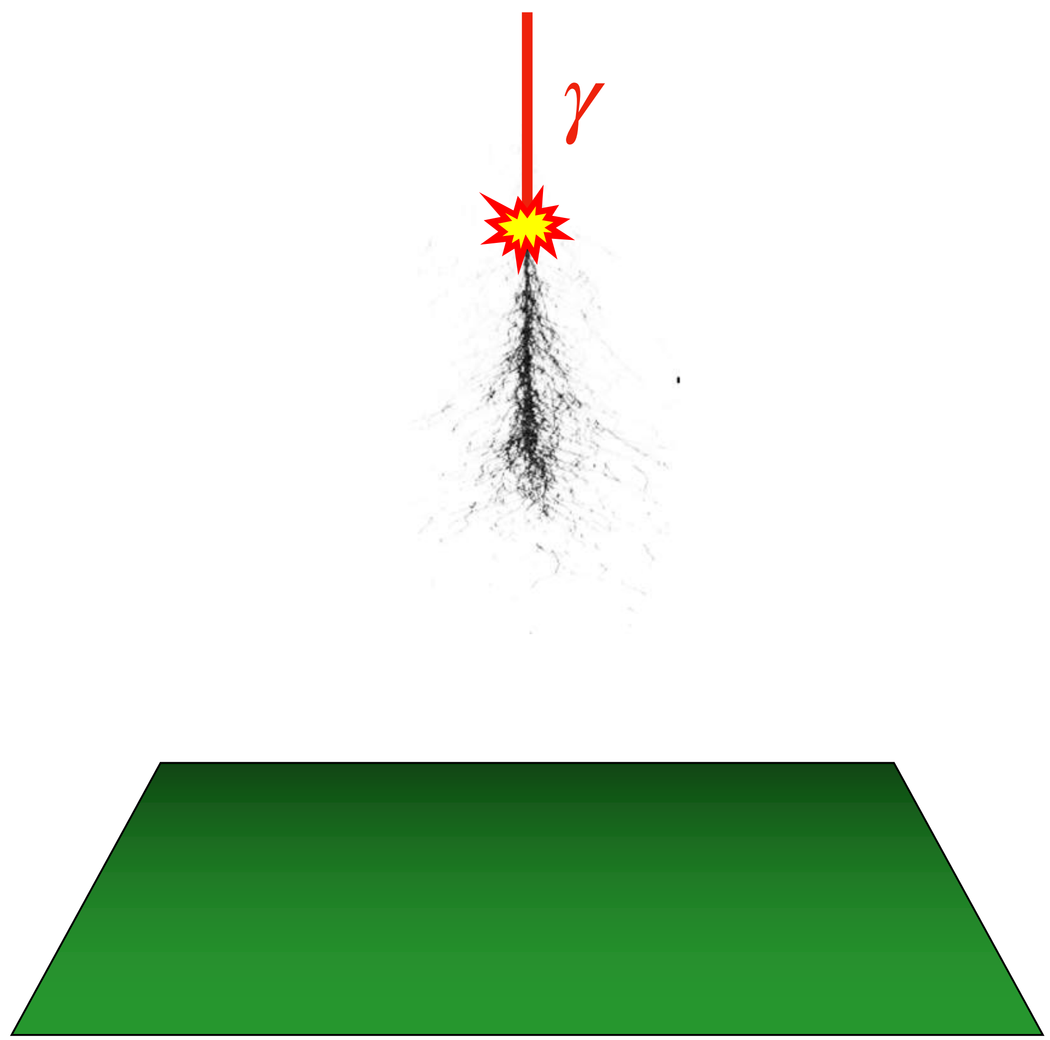

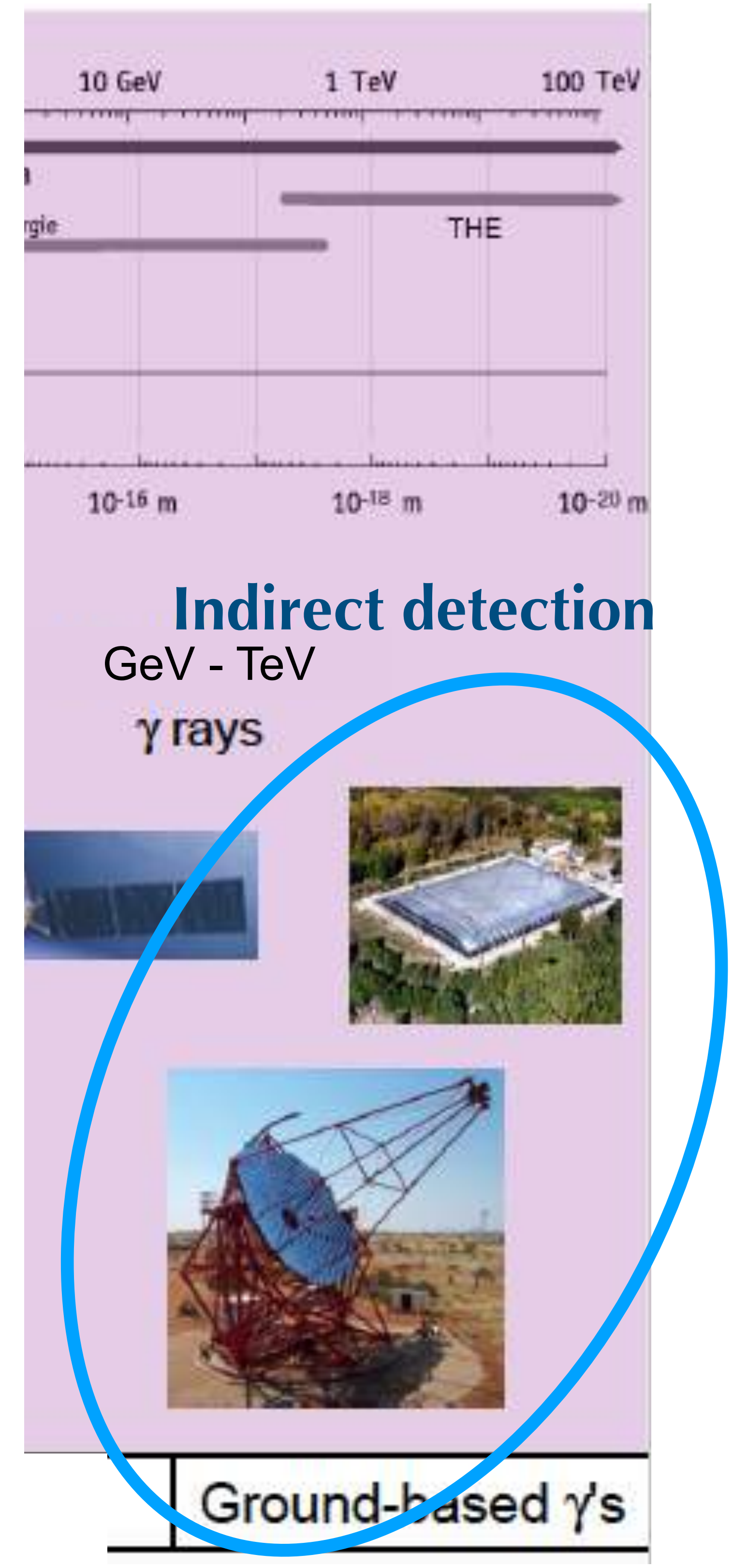

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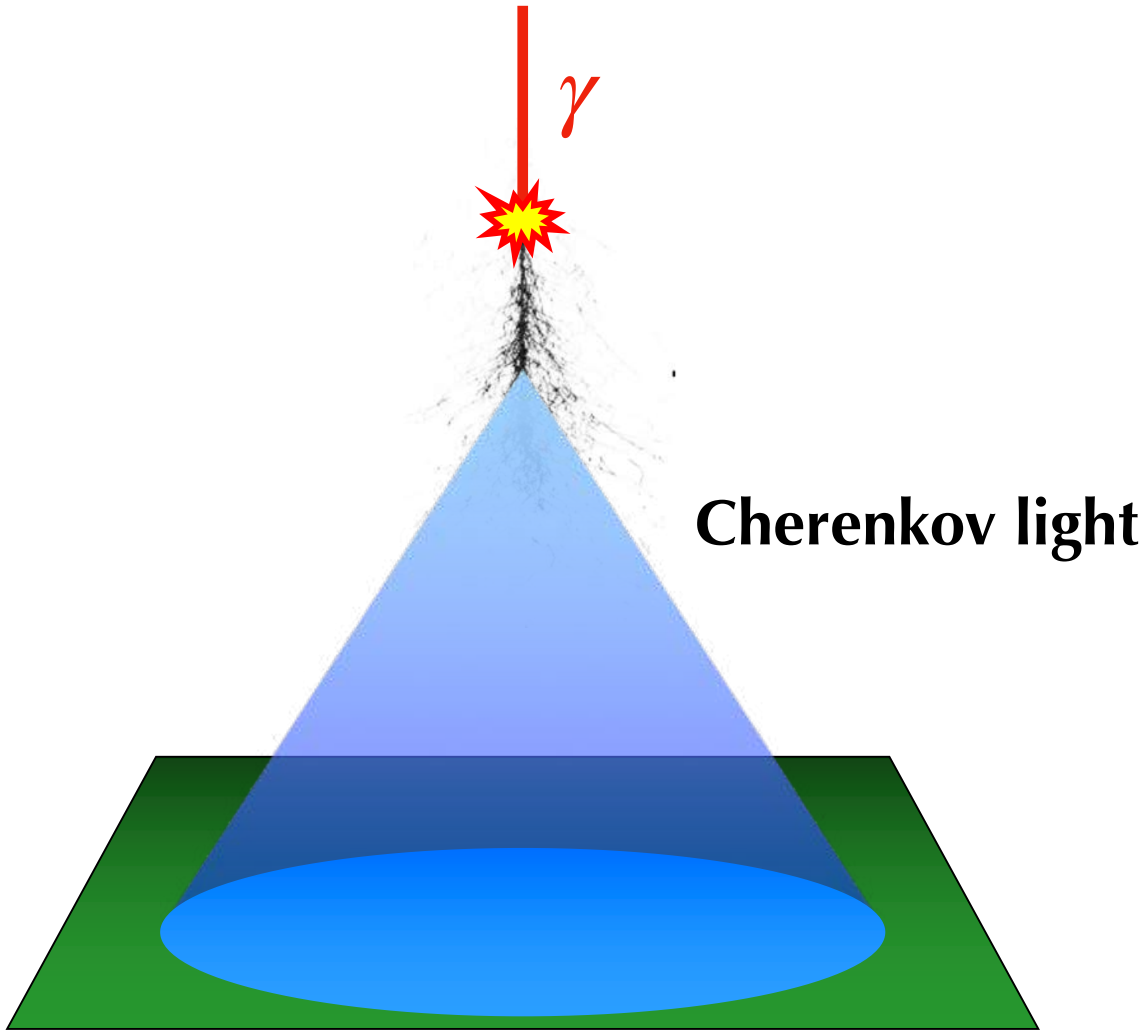

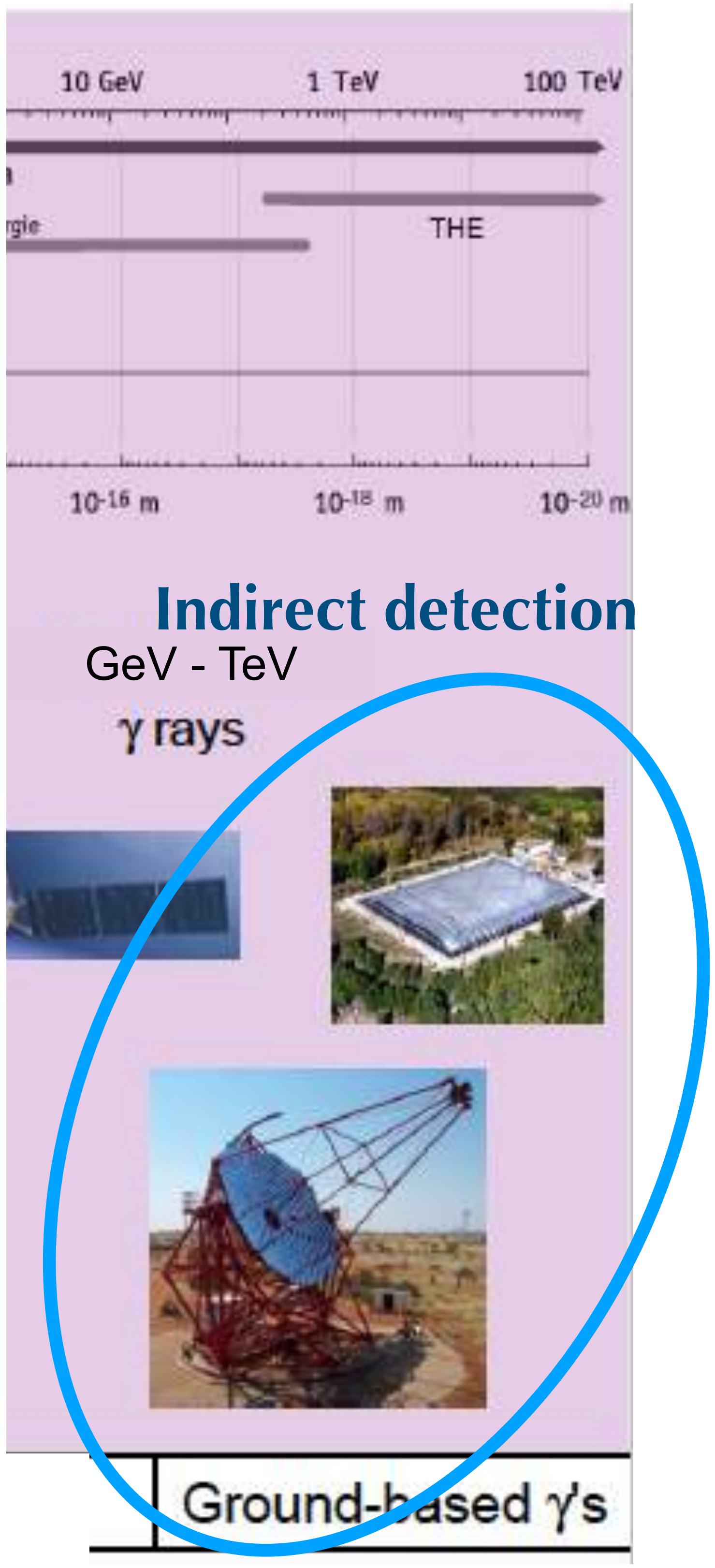

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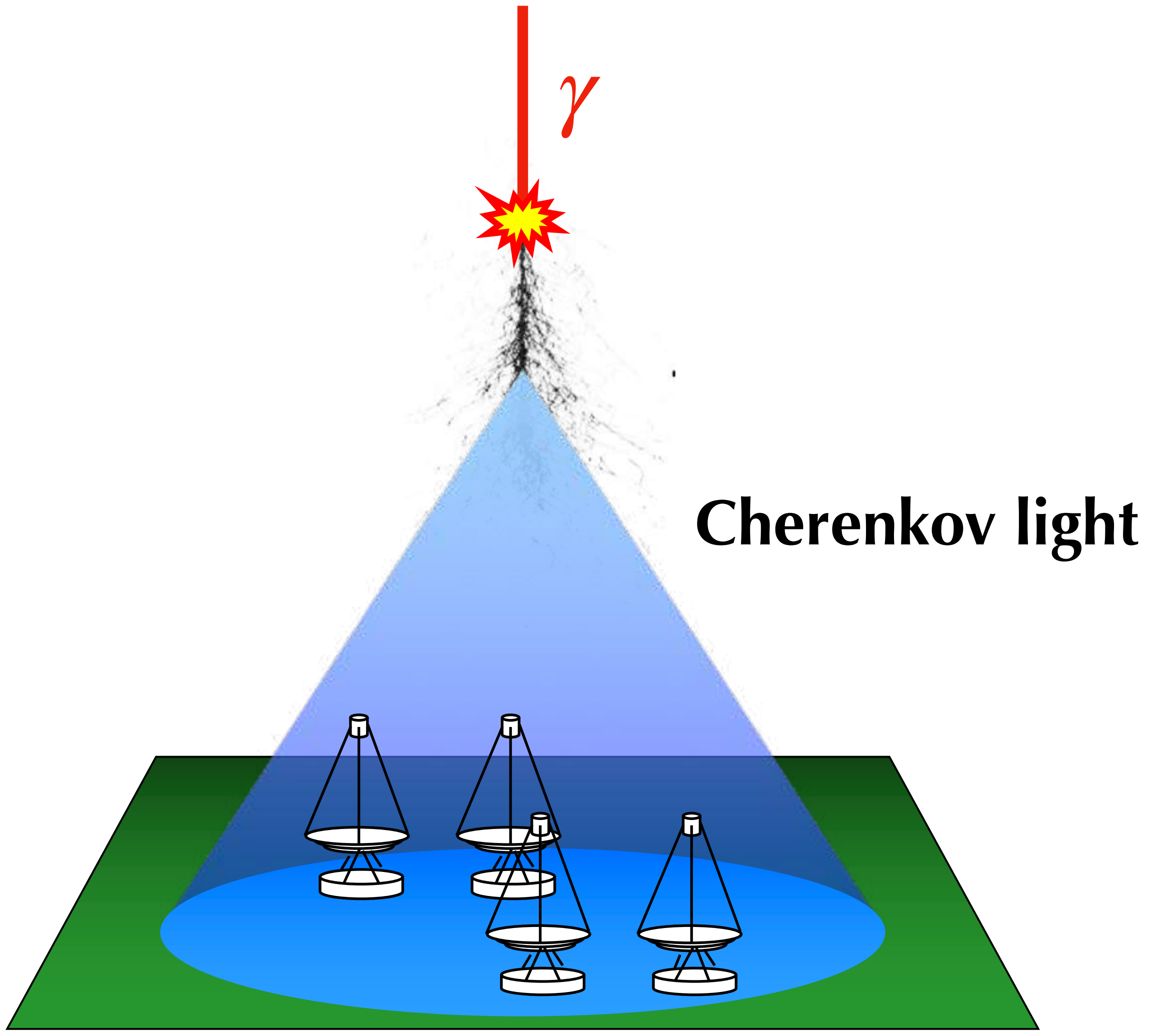
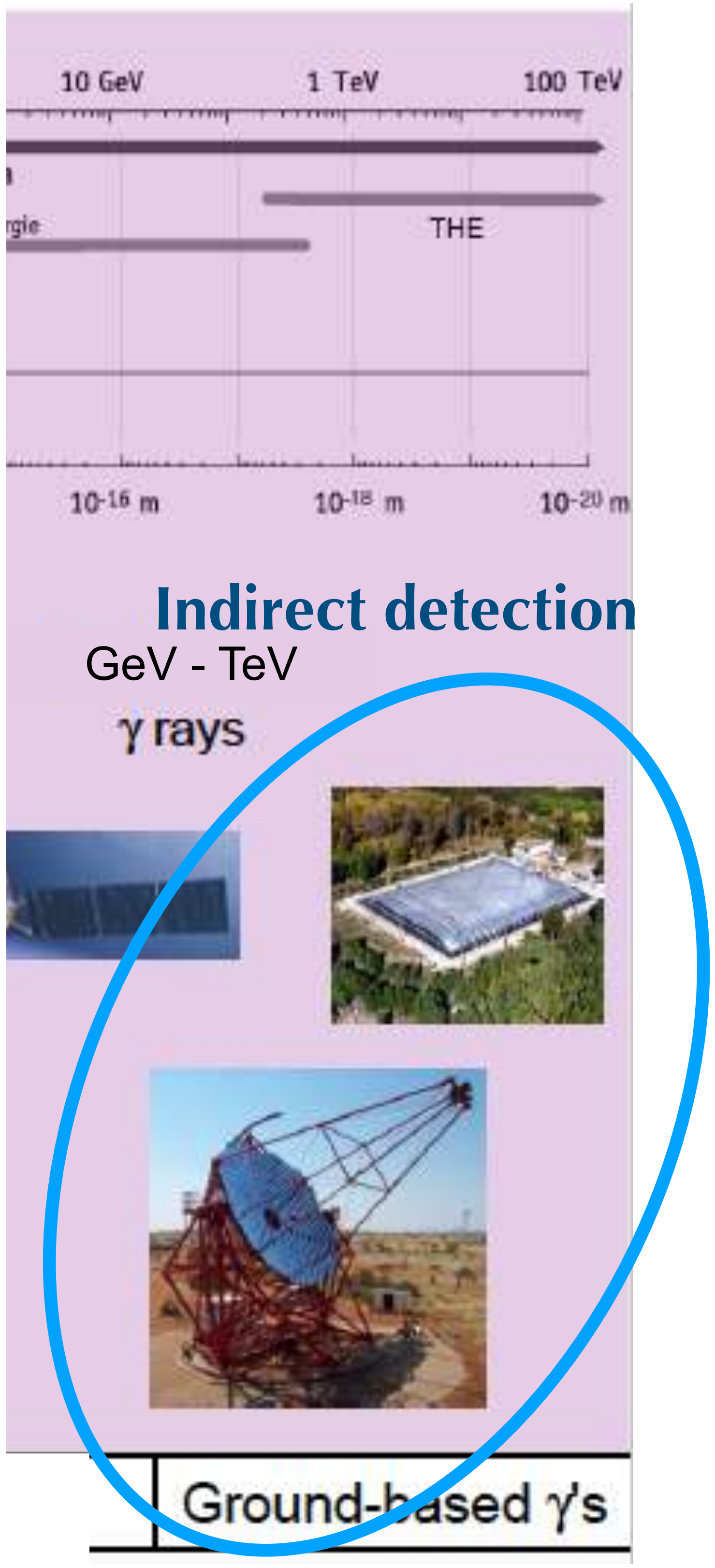


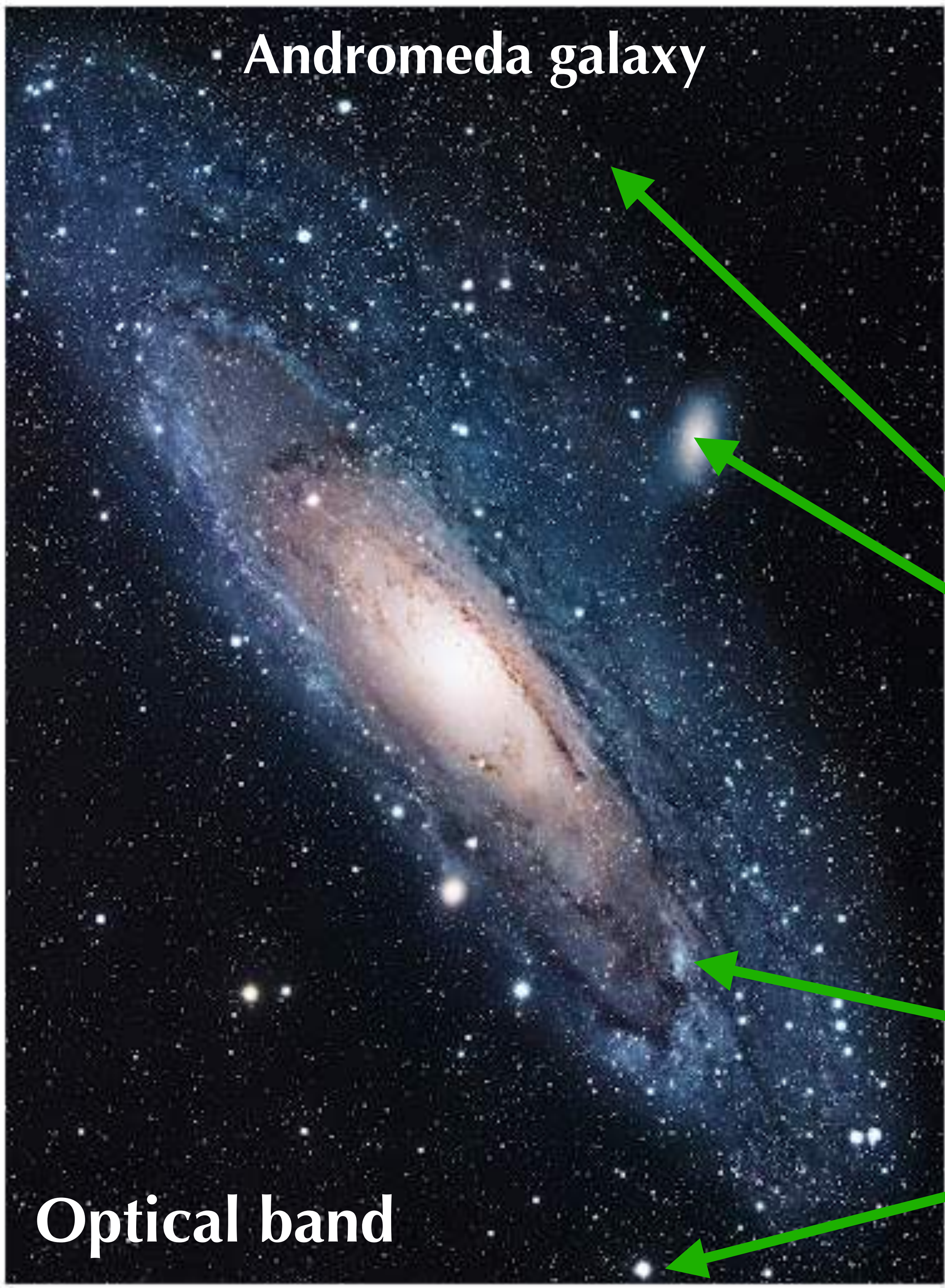


Multi-wavelength astronomy

Why do we observe the sky at different wavelengths & using different messengers ?

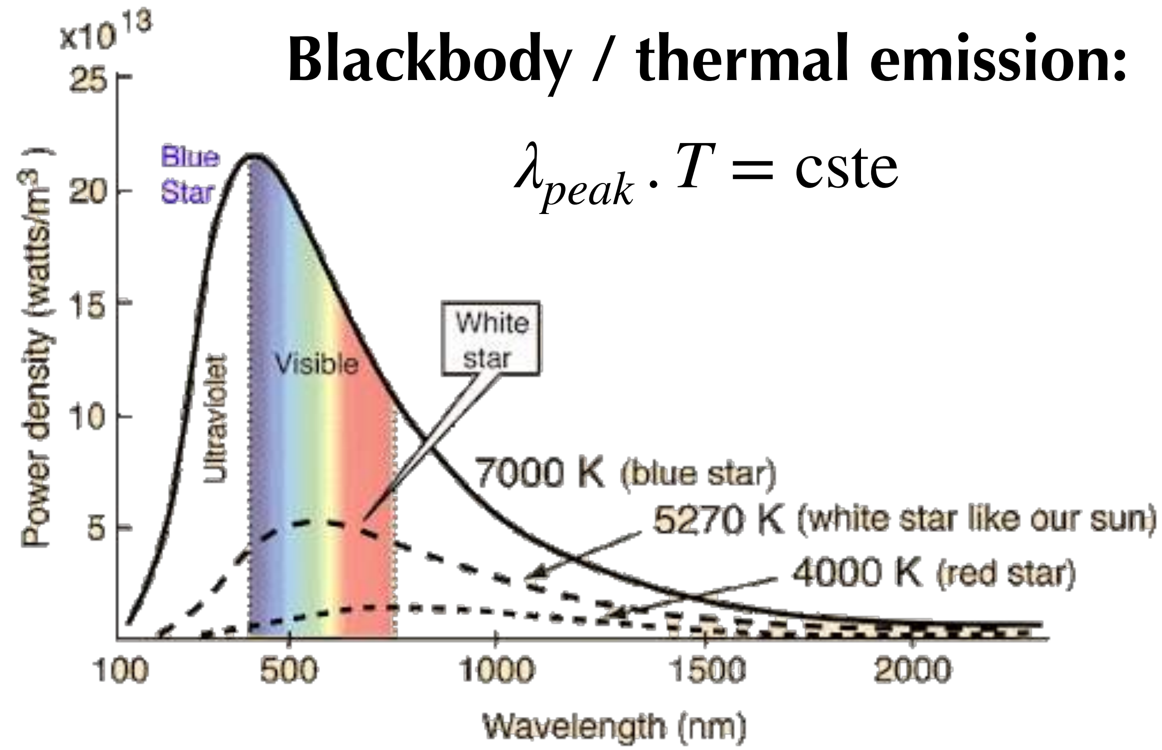
… because we don't observe the same processes at different energies !

Multi-wavelength astronomy



Blackbody / thermal emission:

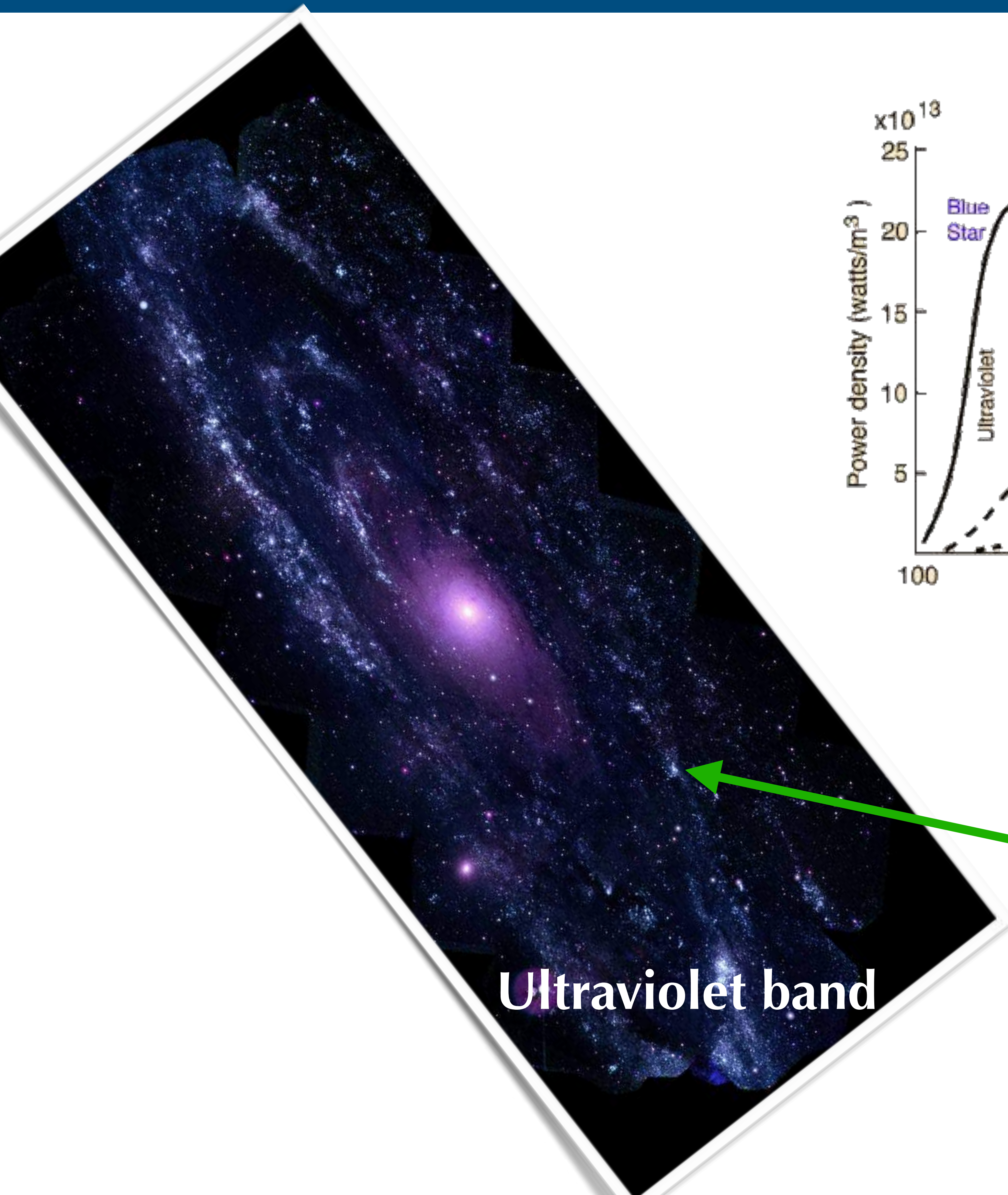
$$\lambda_{peak} \,.\, T = \text{cste}$$



Thermal emission of stars in other galaxies or galaxy clusters

Thermal emission of stars in the Milky Way or in M31

Multi-wavelength astronomy



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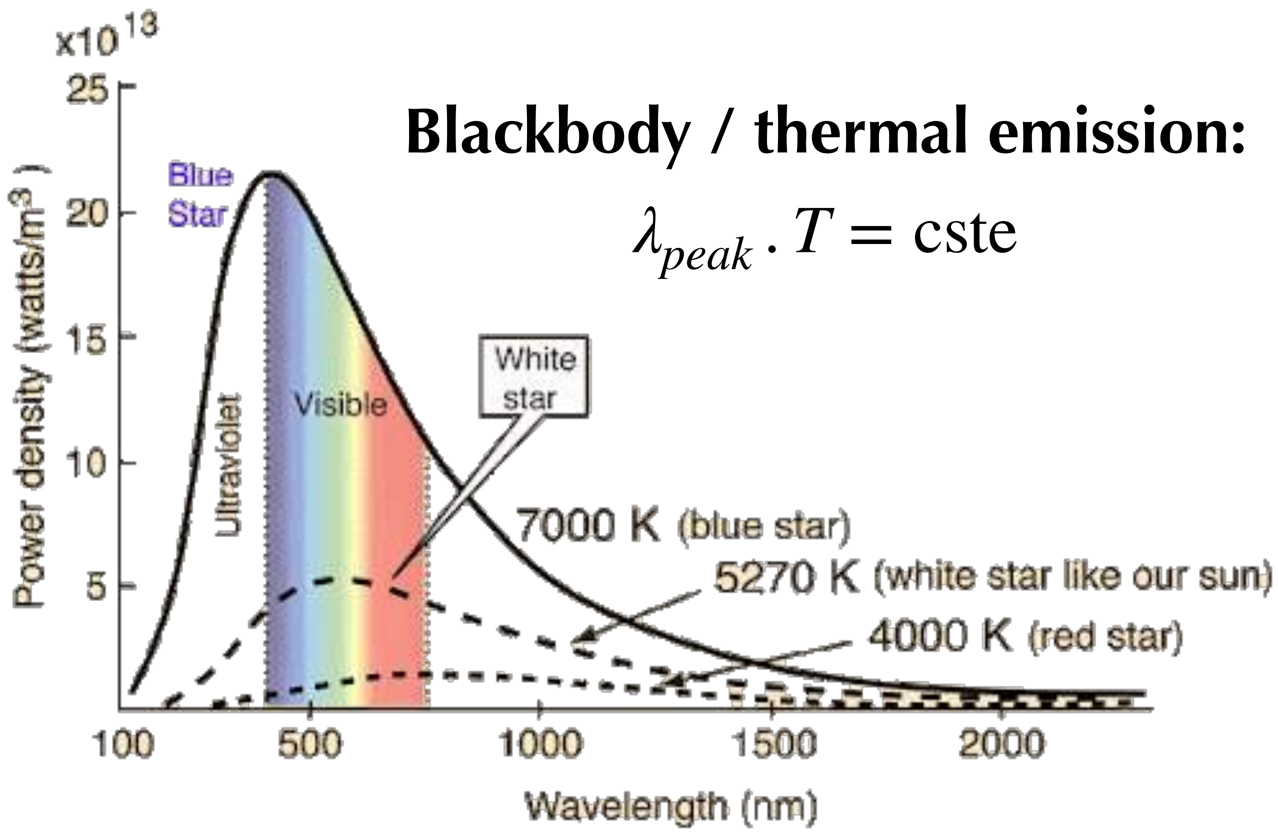
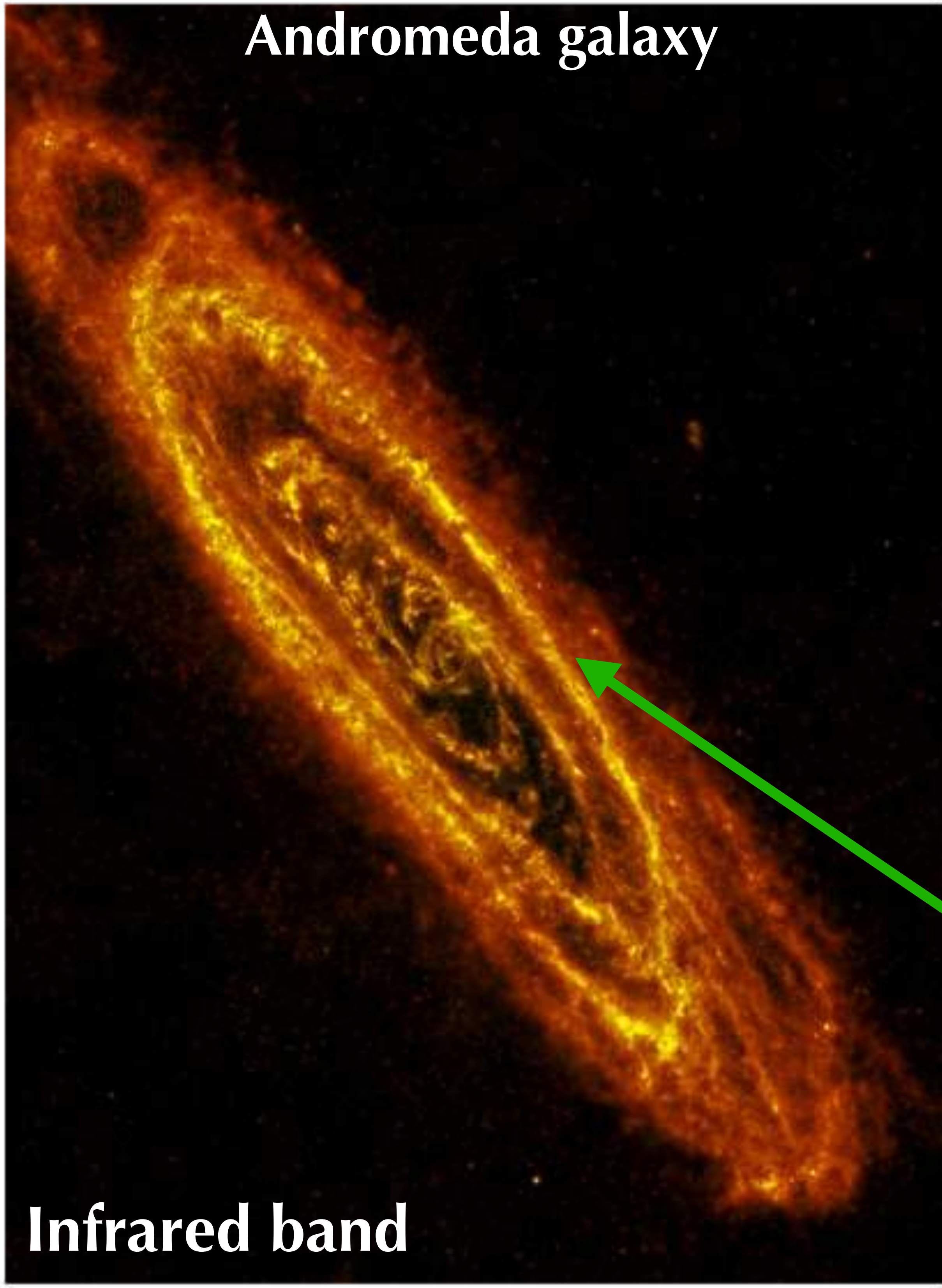
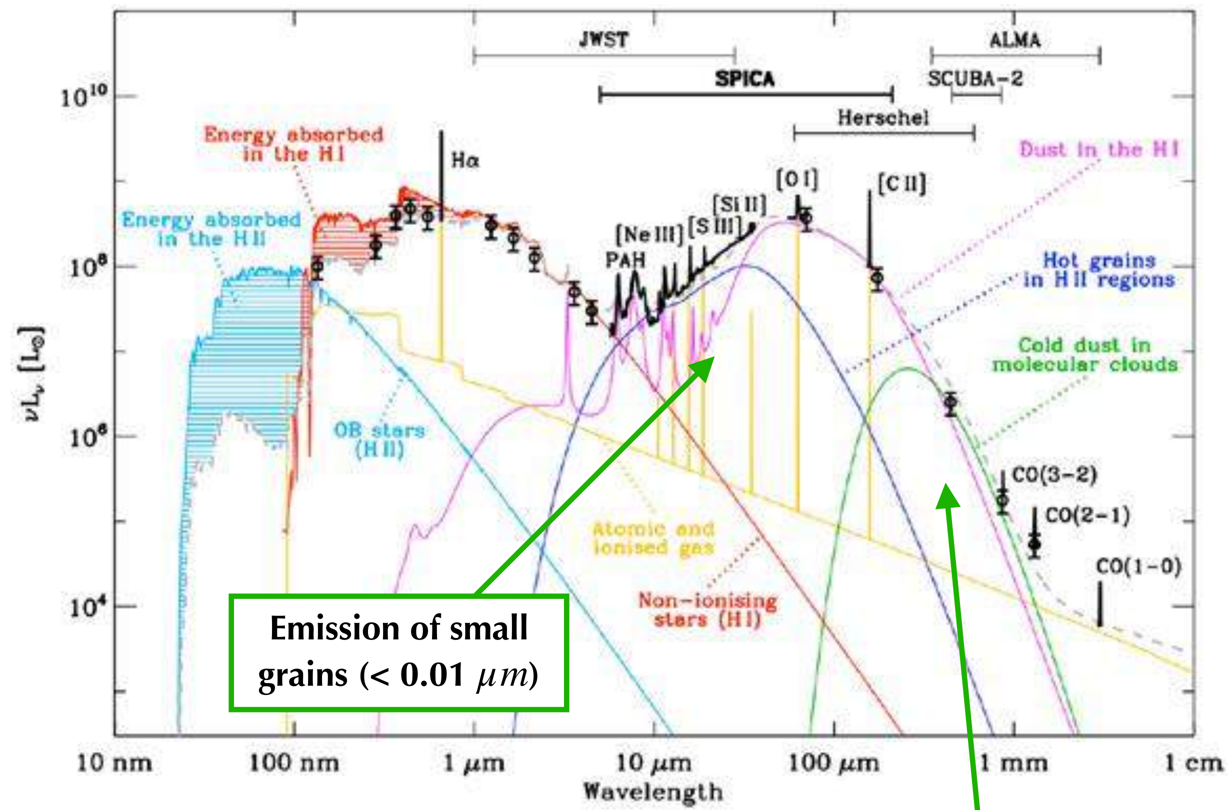


Thermal emission of massive stars in the galaxy

Multi-wavelength astronomy



Different dust composition radiate at different energies:

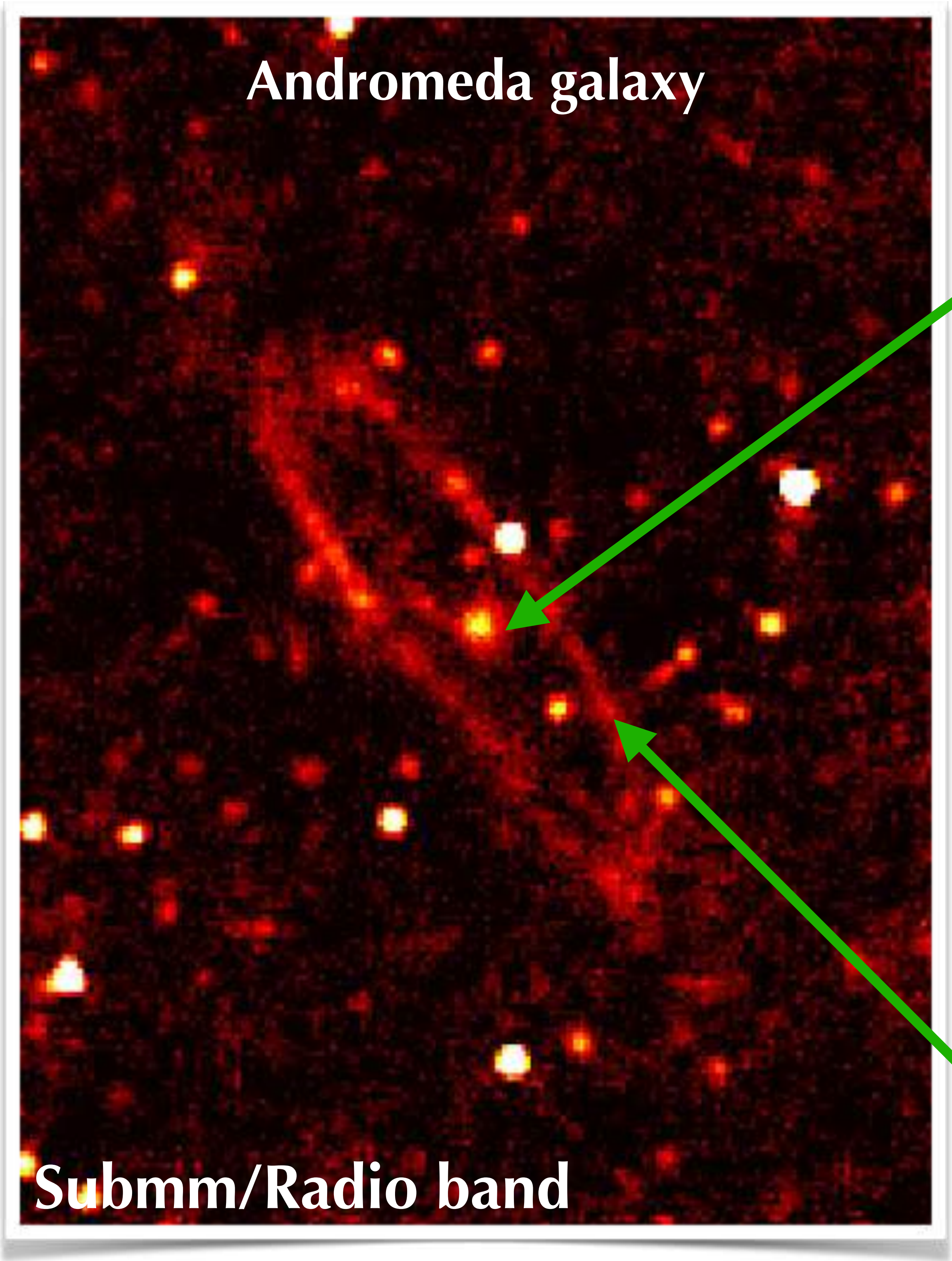


Emission of small grains (< 0.01 μm)

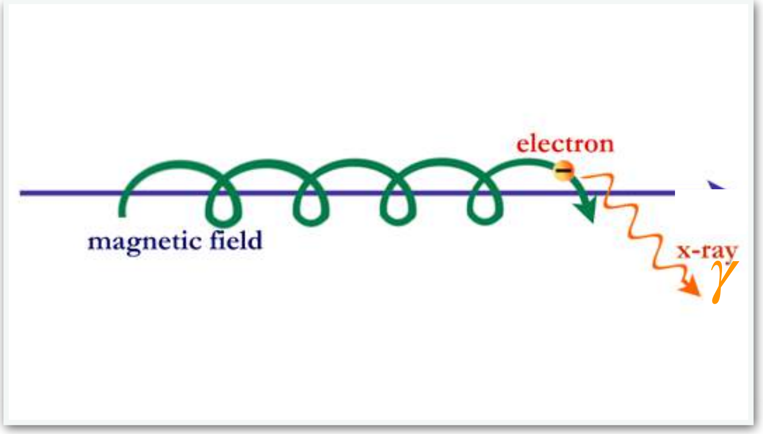
Emission of large grains (> 0.01 μm)

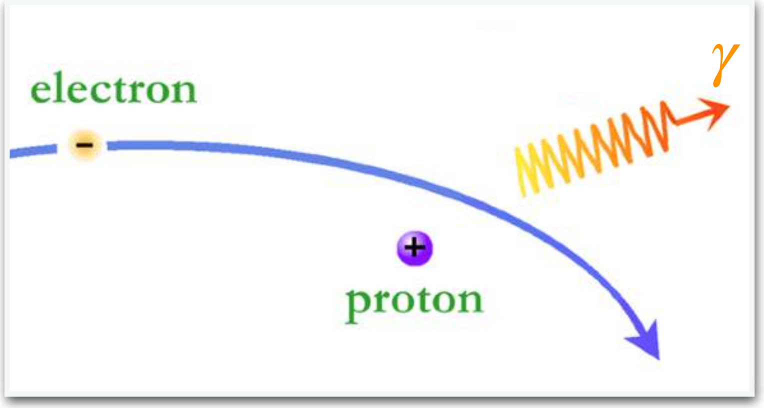
Dust in Molecular clouds: dense gas concentrations hosting star formation sites

Multi-wavelength astronomy



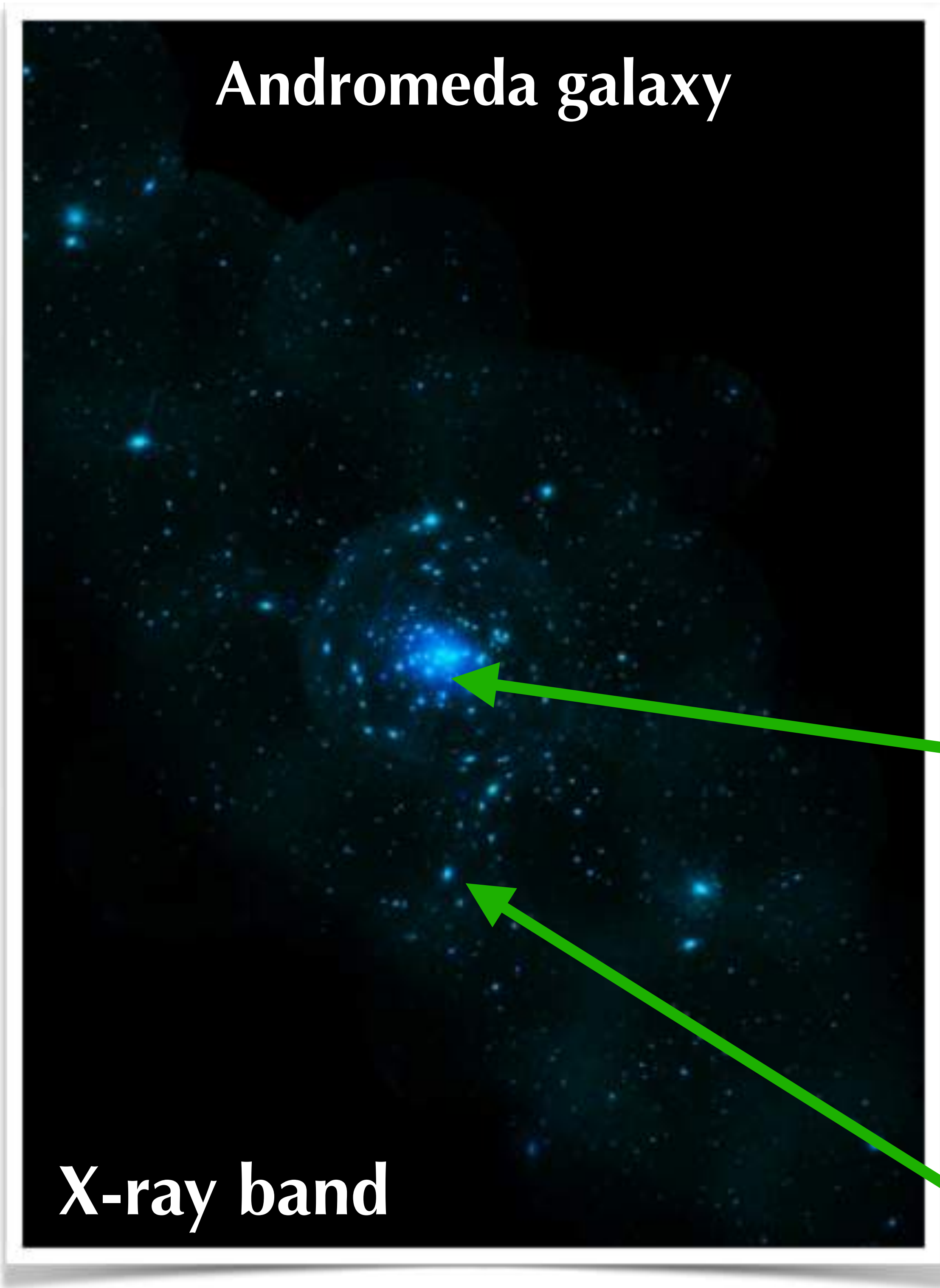
Synchrotron (non-thermal) + bremsstrahlung emission (star forming regions)

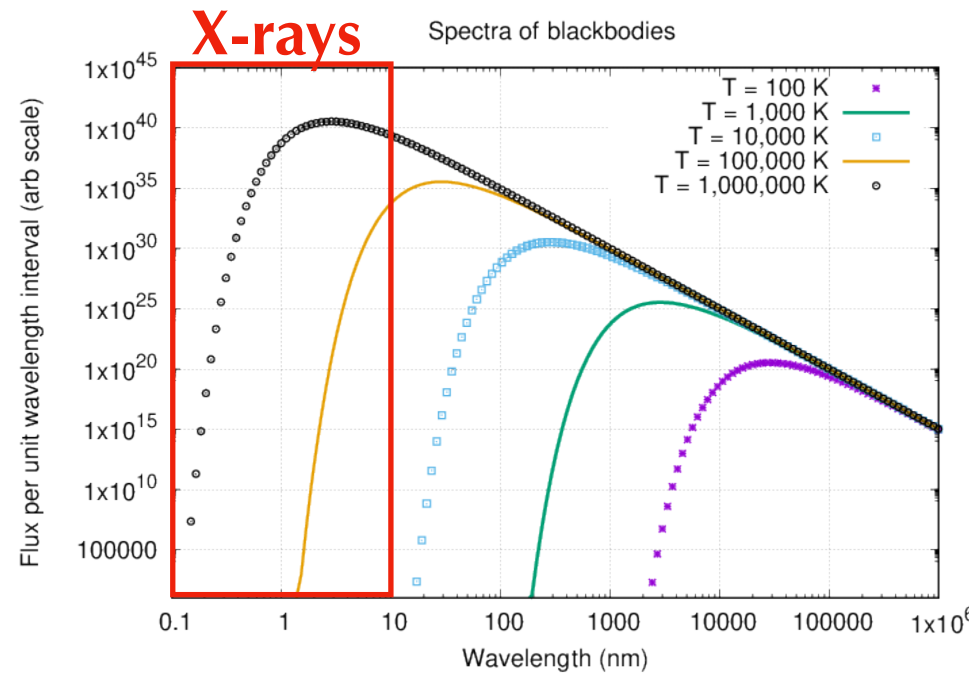




Gas in Molecular clouds: dense gas concentrations hosting star formation sites

Multi-wavelength astronomy



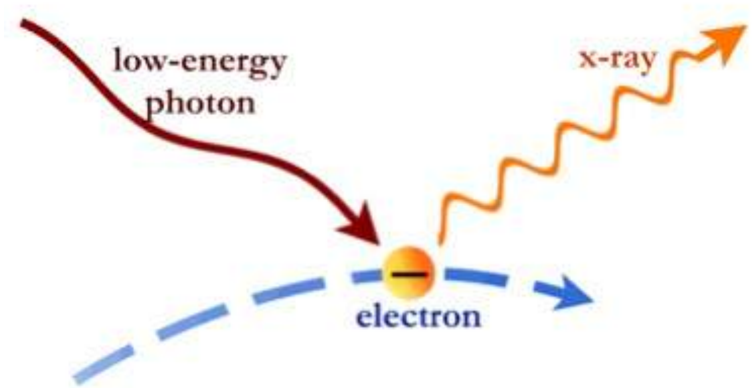


Thermal emission (blackbody + bremsstrahlung):

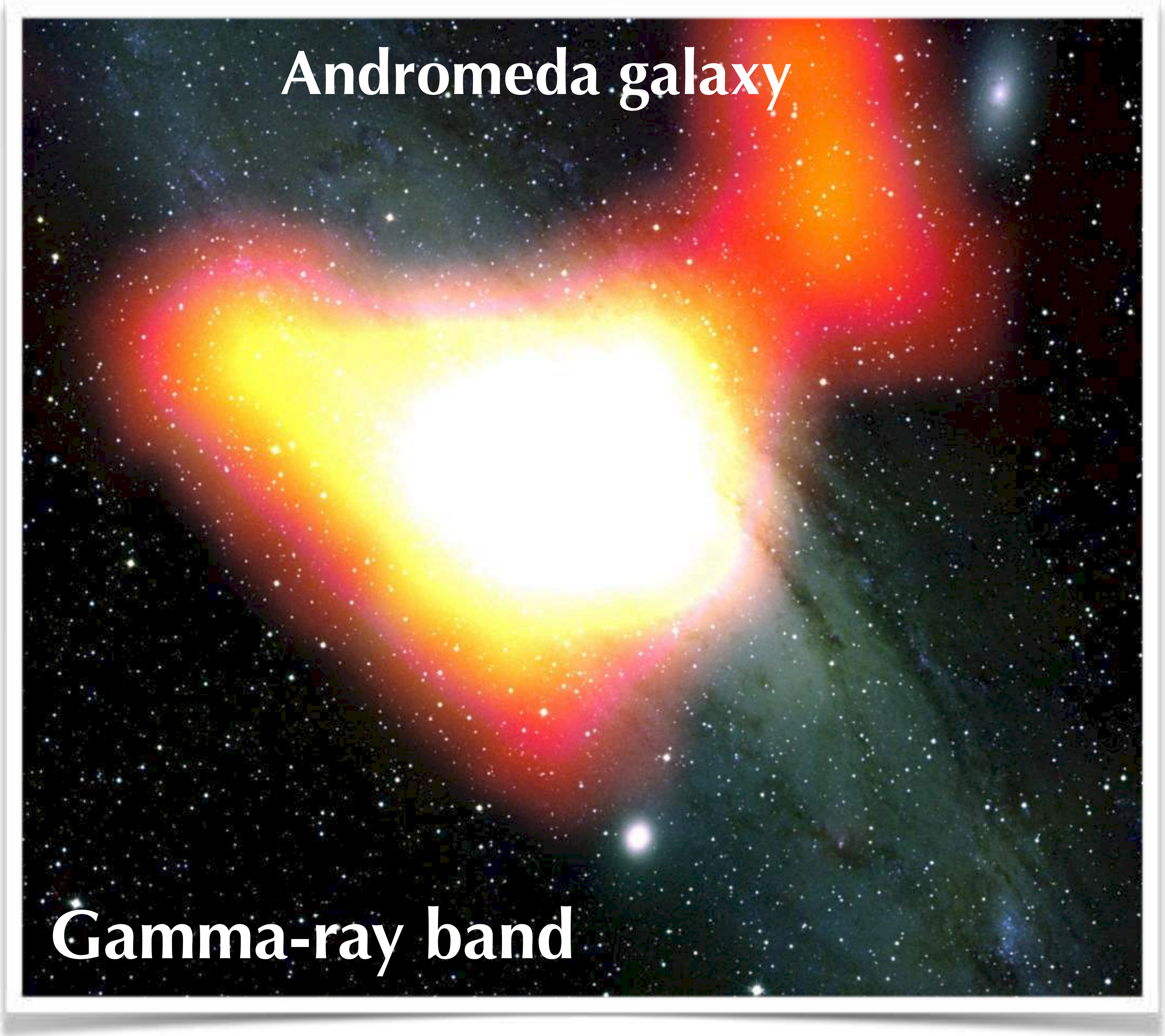
- *gas in galaxy clusters ($T \sim 10^7$ K)*
- *accretion onto compact object (potential energy converted to kinetic energy + radiation)*

Non-thermal emission:

- *synchrotron*
- *inverse Compton*



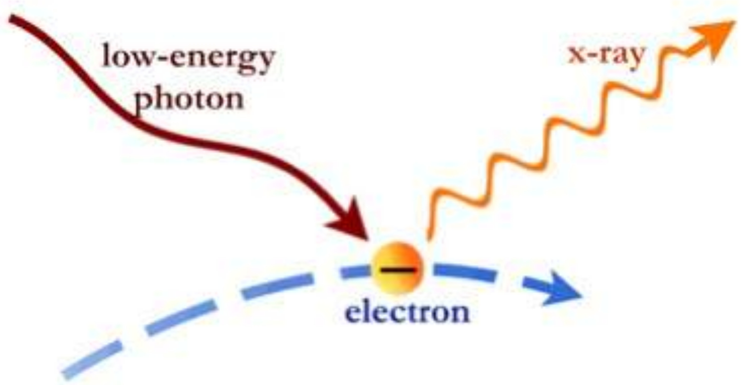
Multi-wavelength astronomy

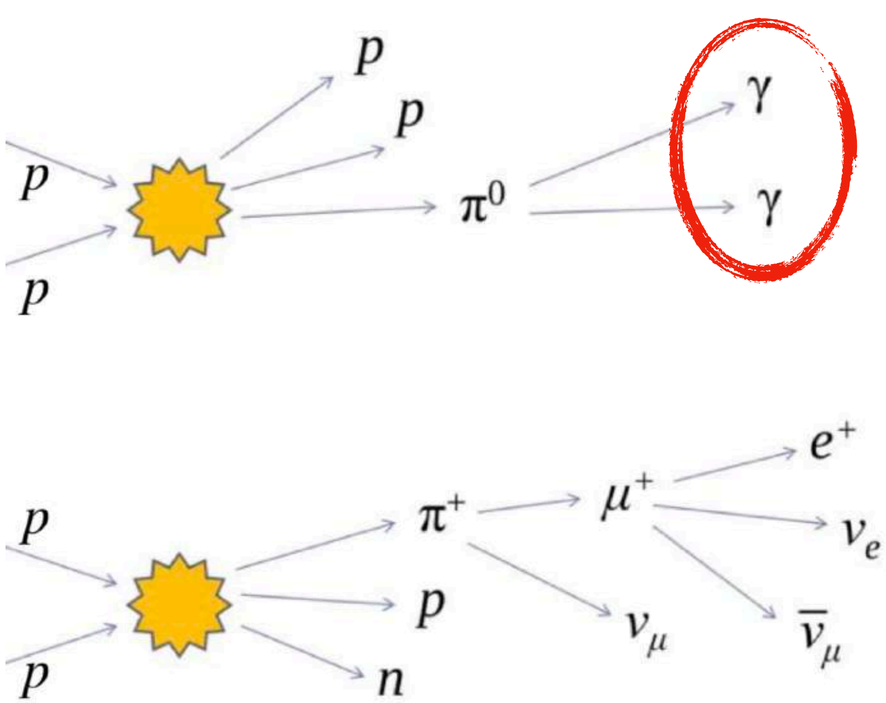


Angular resolution: ~1° (70 000 lower than in optical)

Non-thermal processes:

- *inverse Compton (leptonic origin)*
- *Interaction of high-energy protons with interstellar gas (hadronic origin)*
- *Unknown sources (dark matter) ?*



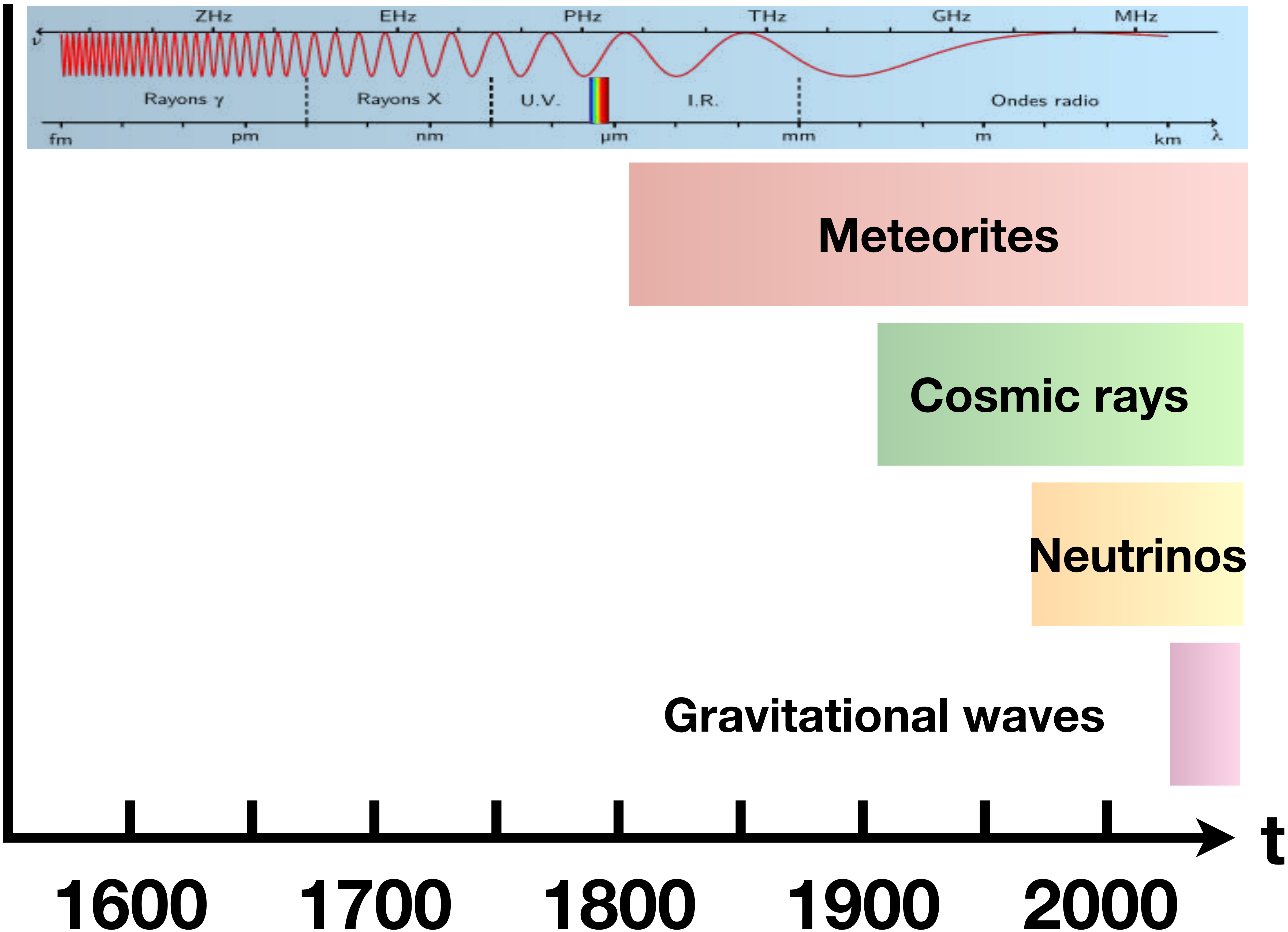


Outline - Lecture 1

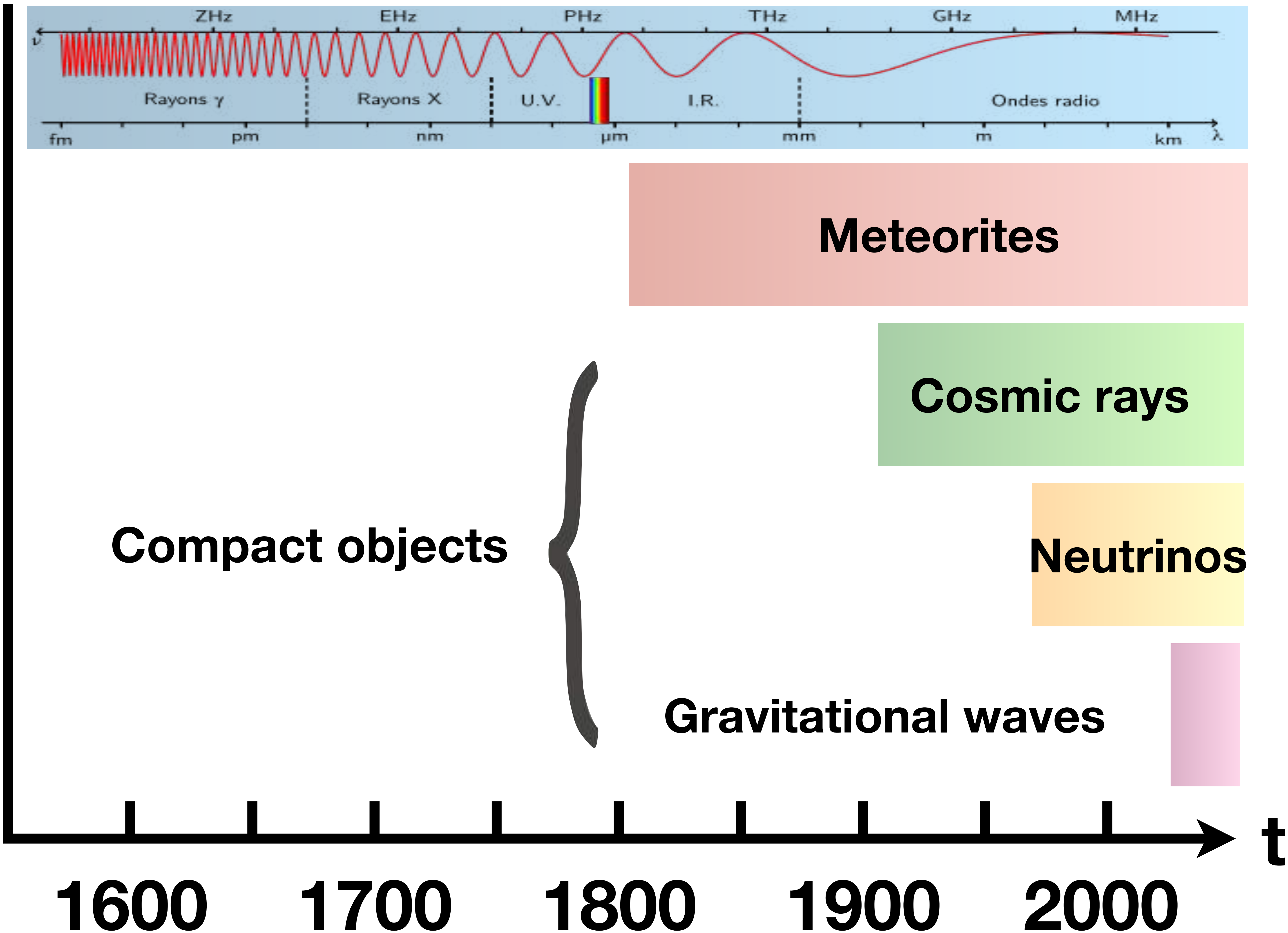
A. Introduction to multi-messenger astronomy

1. Astrophysical objects
2. From radio to gamma-rays: multi-wavelength astronomy (emission processes and instruments)
3. **Multi-messenger astronomy: cosmic rays, neutrinos, gravitational waves**

Multi-messenger astronomy



Multi-messenger astronomy

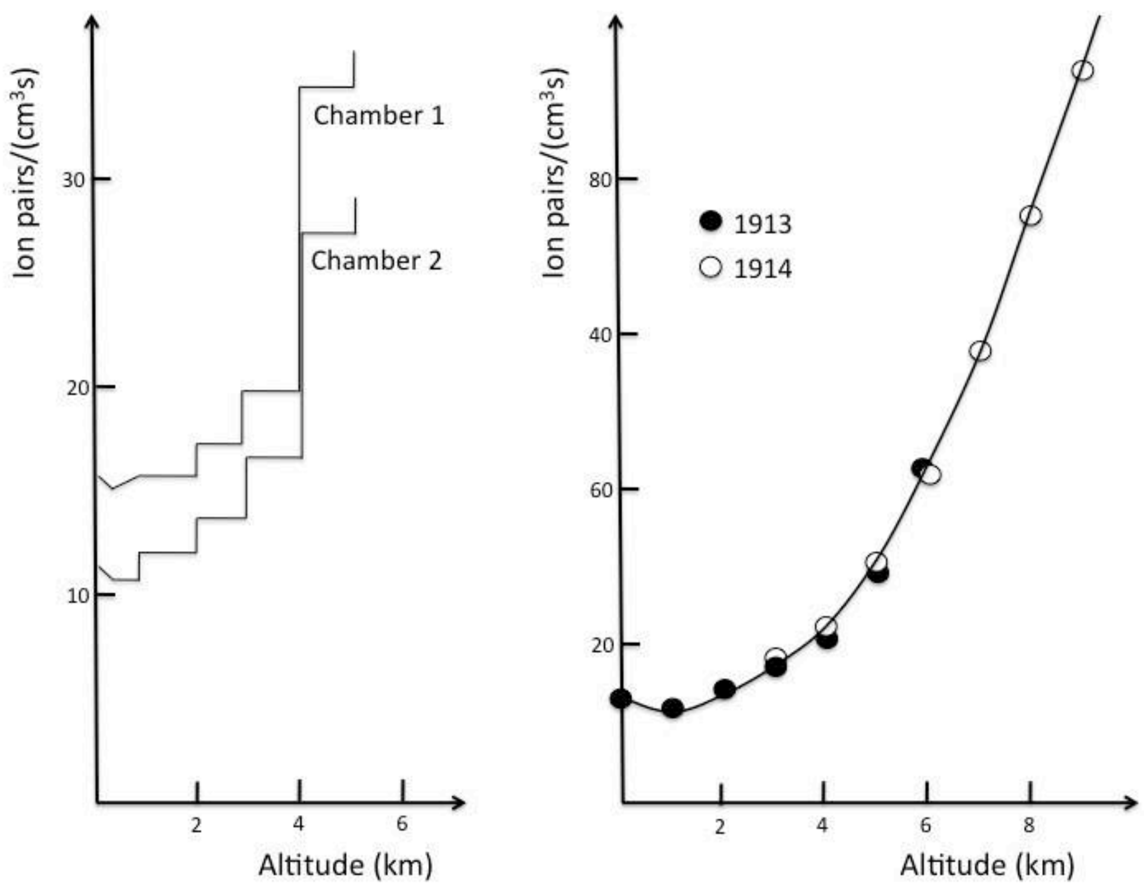


Cosmic Rays

Cosmic rays are charged particles coming from outside the atmosphere

Discovered 109 yr ago by V. Hess in 1912, through the detection of increase of the ionization rate with the altitude.

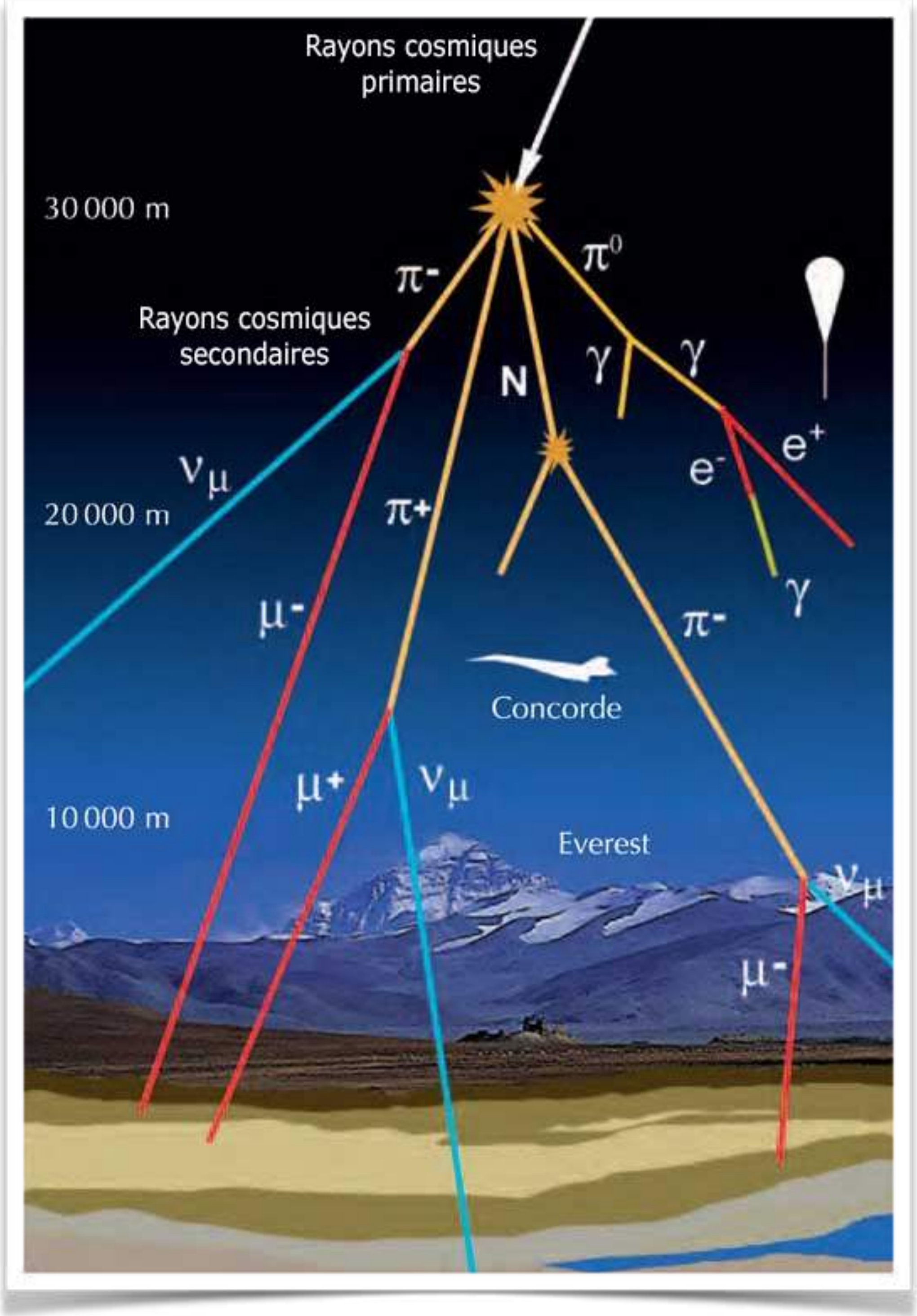
« The results of the observations seem most likely to be explained by the assumption that radiation of very high penetrating power enters from above into our atmosphere. »



Nobel Prize in Physics - 1936

Cosmic Rays

V. Hess' observations: secondary particles produced by the interaction of high-energy particles with the atmosphere.



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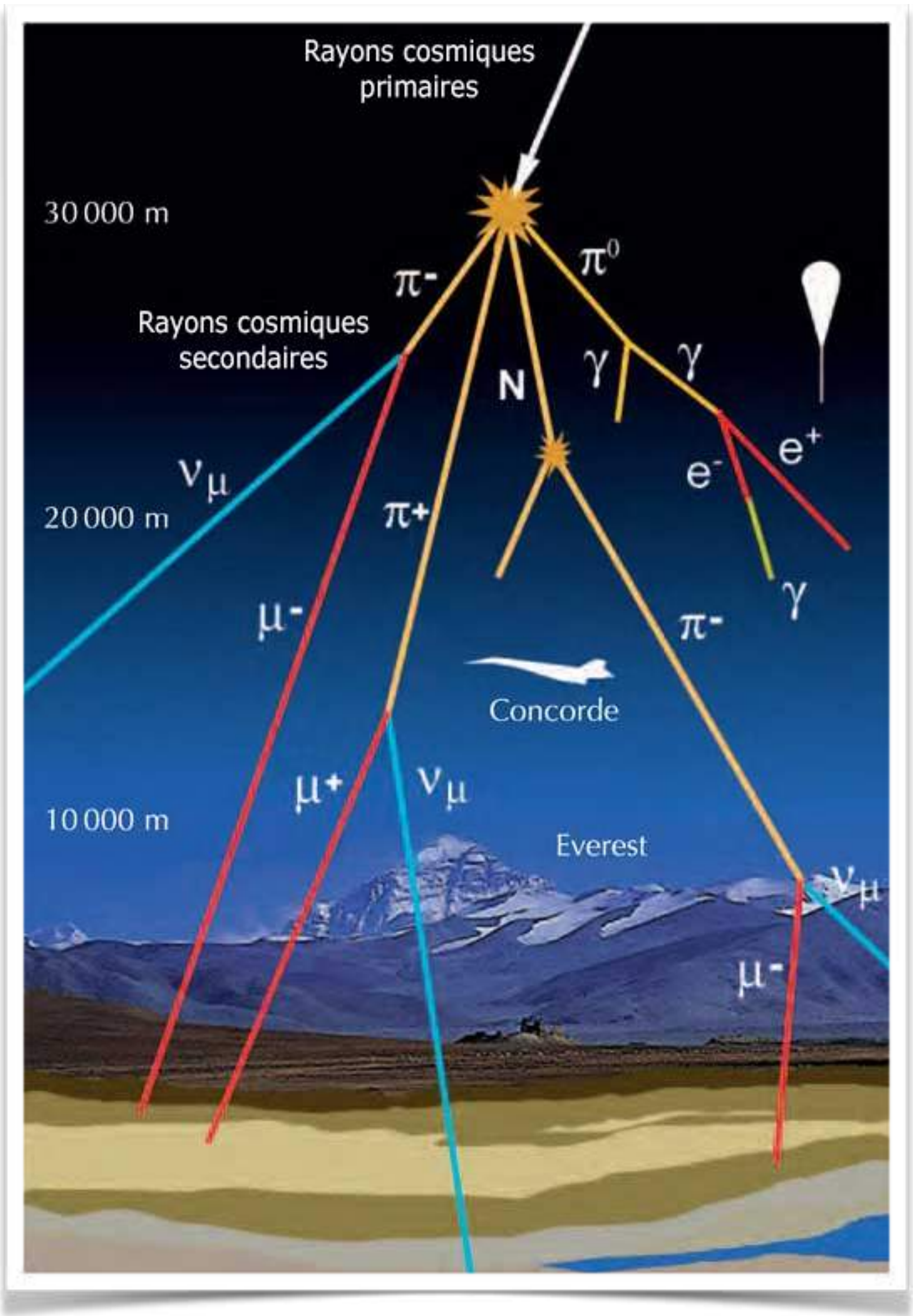
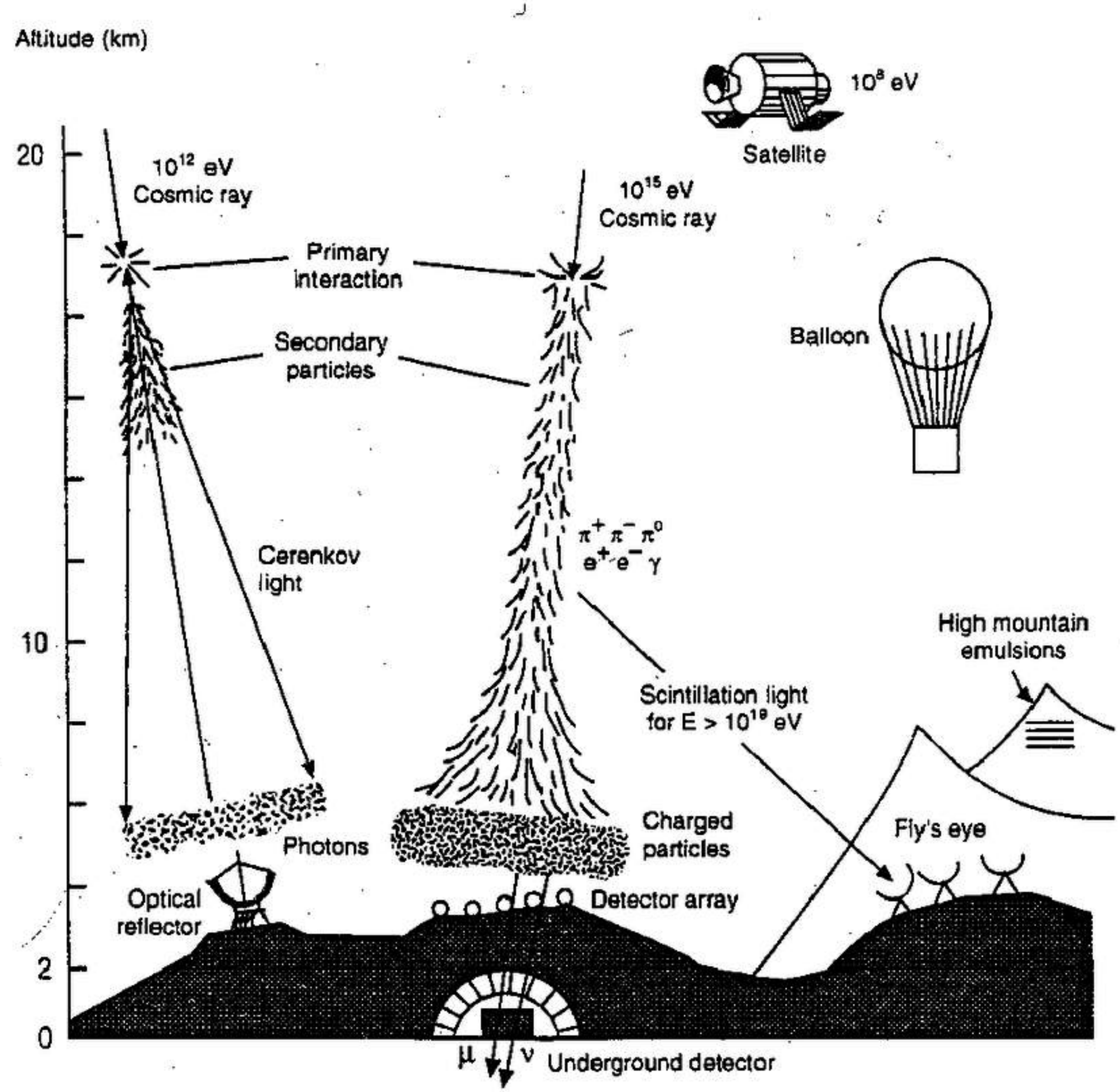


From 1950: first direct observations using satellites and stratospheric ballons.



Hadron flux:	1 particle/m^2/s	@	TeV	10^{12} eV
	1 particle/m^2/day	@	PeV	10^{15} eV
	1 particle/km^2/day	@	EeV	10^{18} eV
	1 particle/km^2/century	@		10^{20} eV

Satellites + ballons

Ground detectors (indirect detection)

Cosmic Rays

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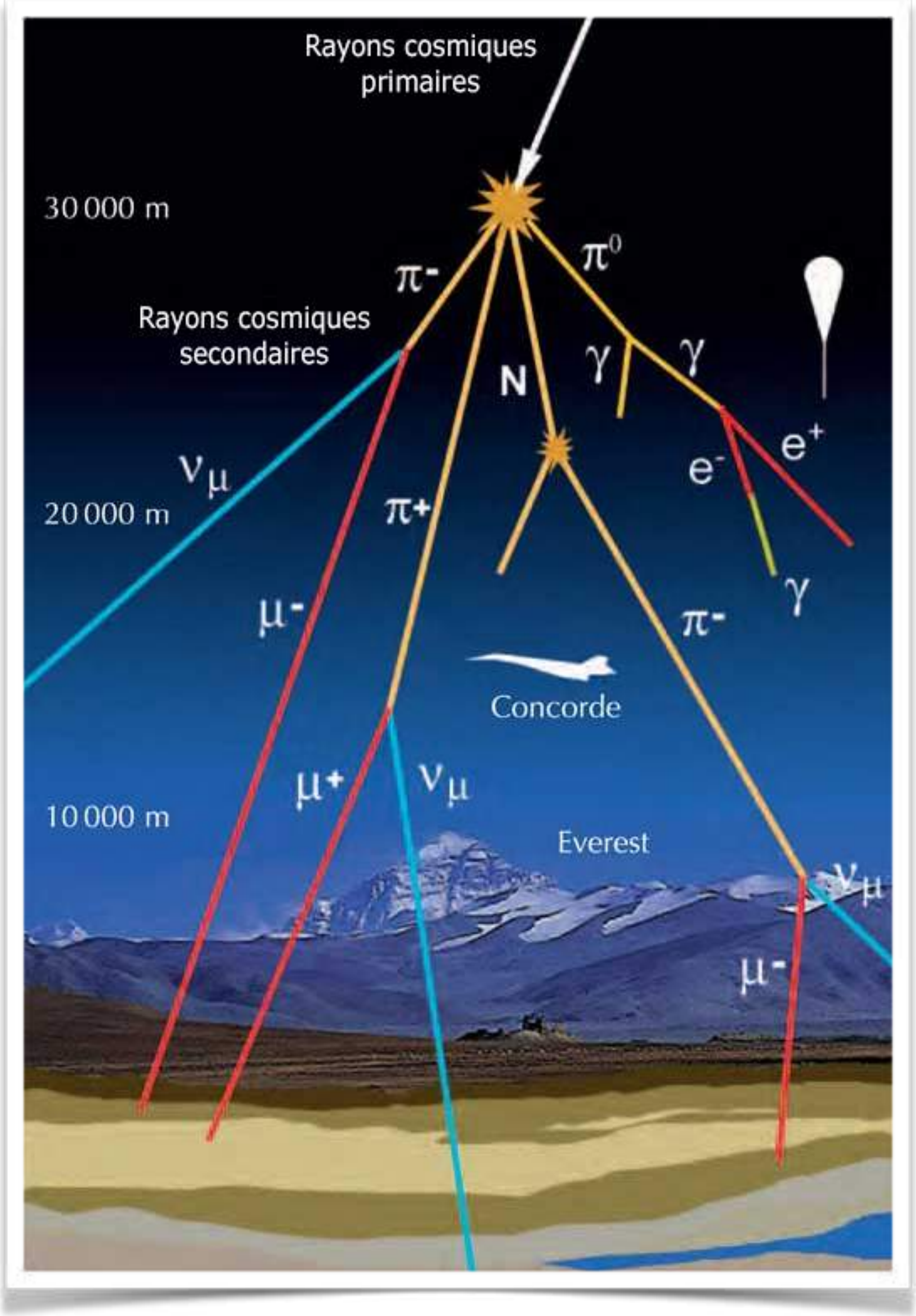

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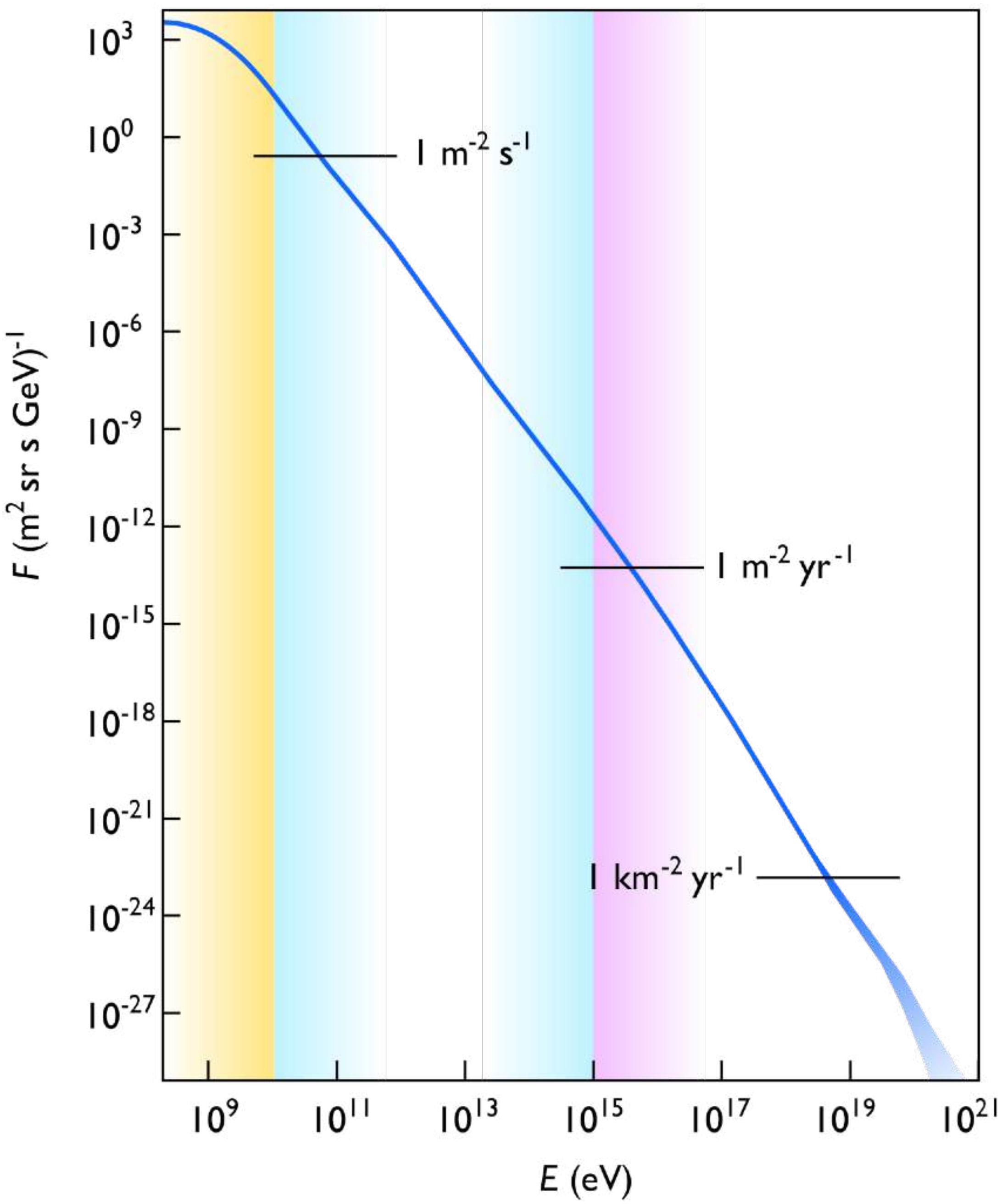
⇒ cosmic ray **composition**: 88% of protons, 9% of He nuclei, + électrons, heavier nucleons, … + **spectrum**



Nb of particles with energy $\in [E; E+dE]$, crossing a surface dS, with an observing direction $d\Omega$, in a time interval dt

Cosmic Rays

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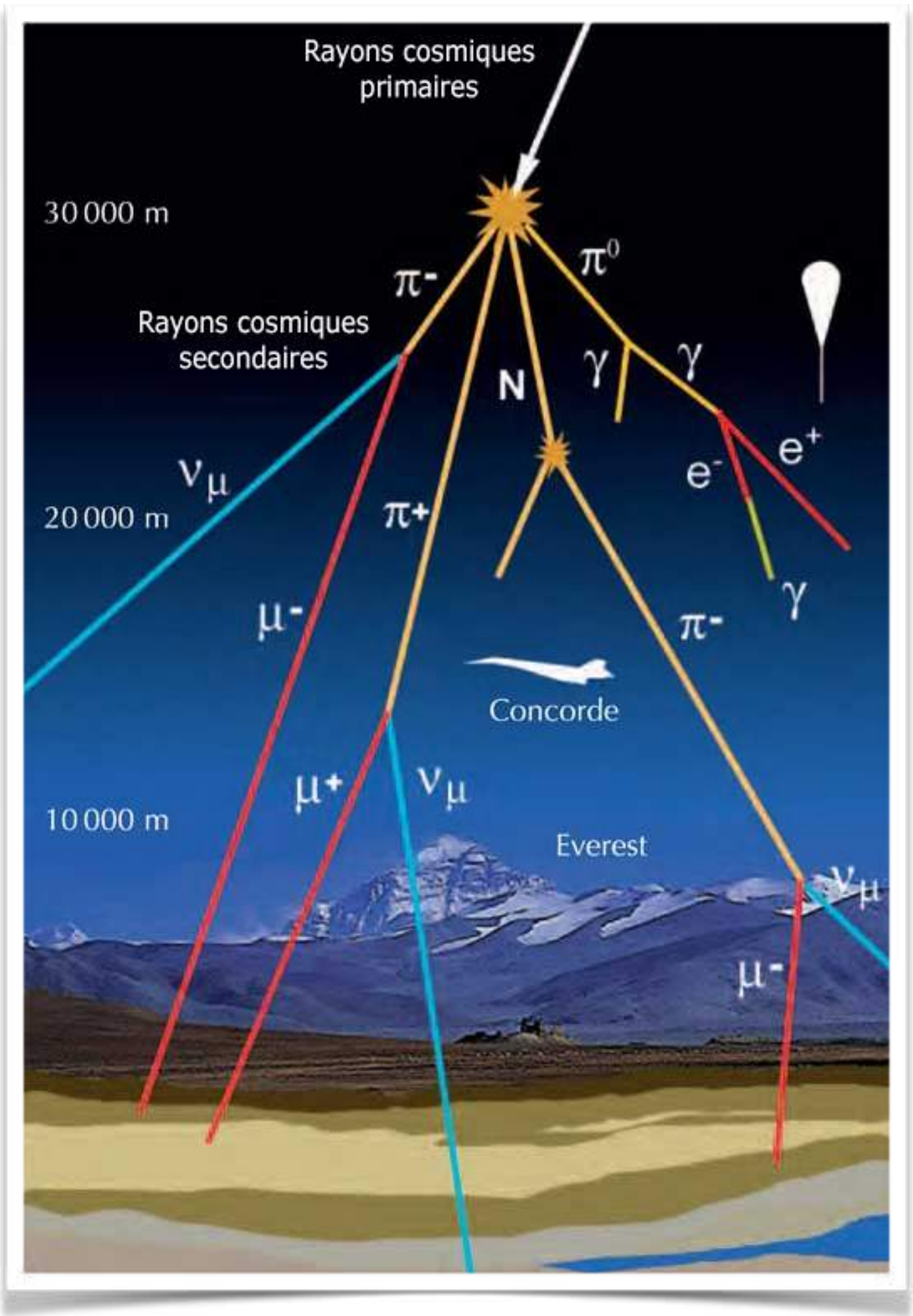

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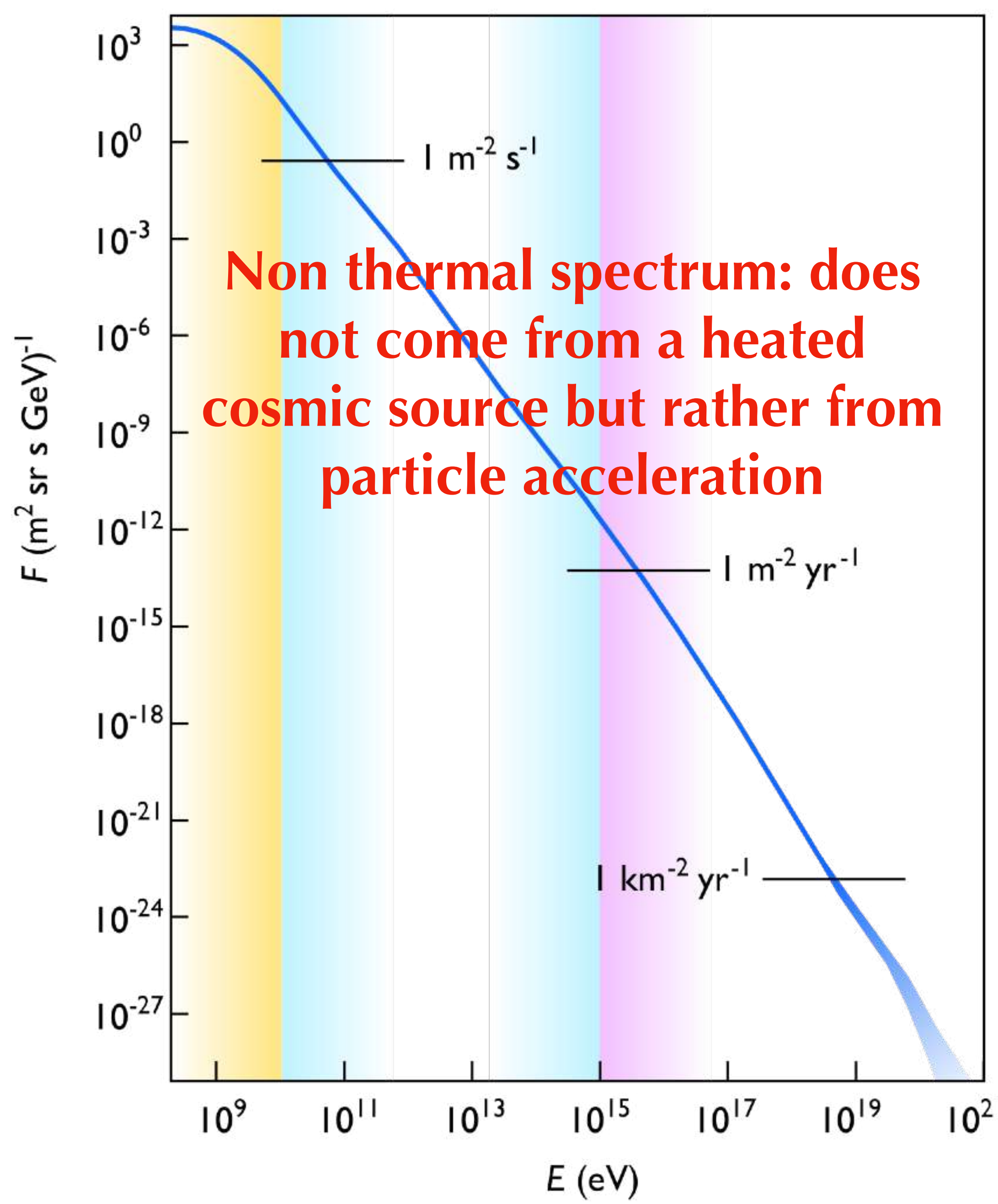

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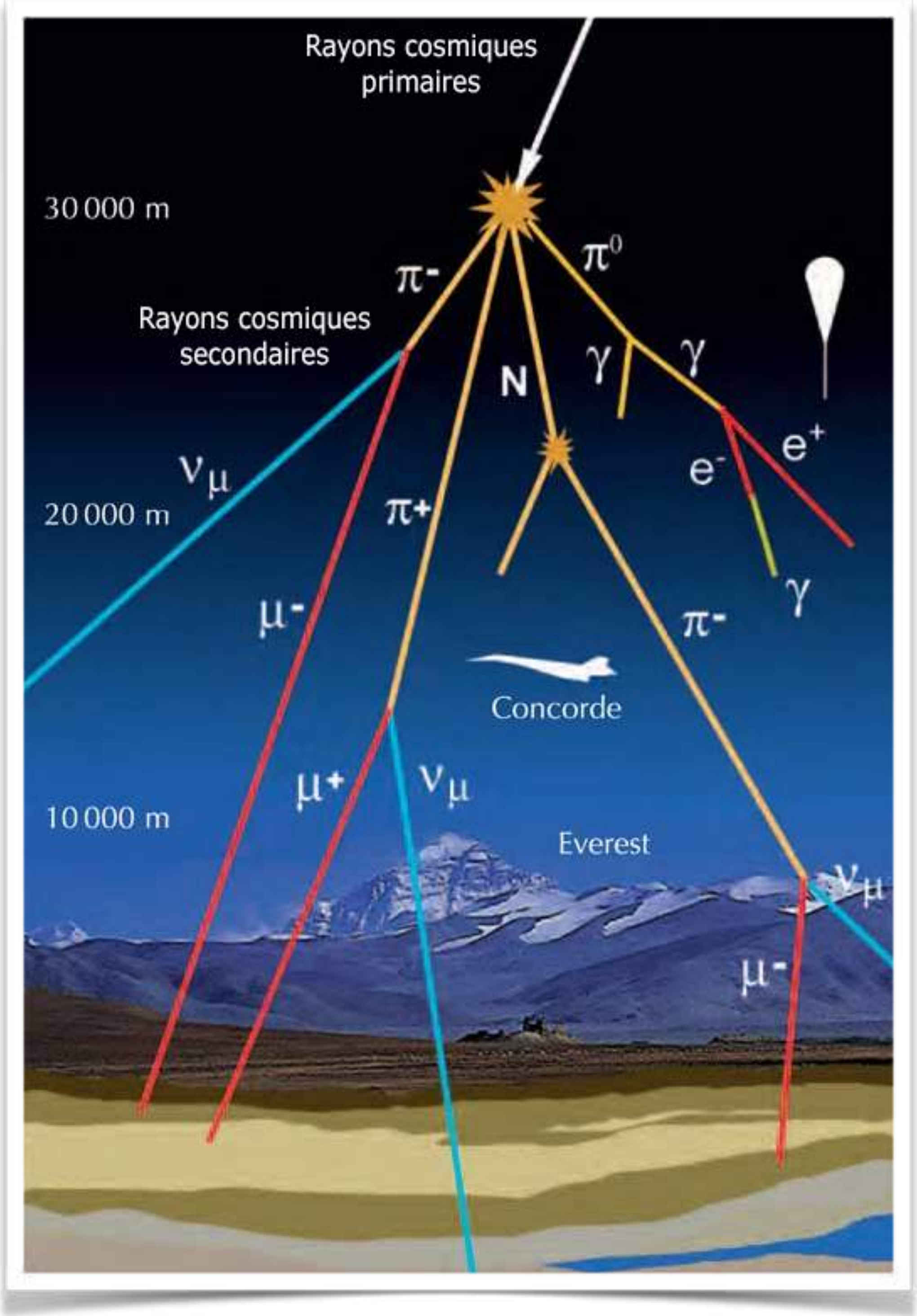

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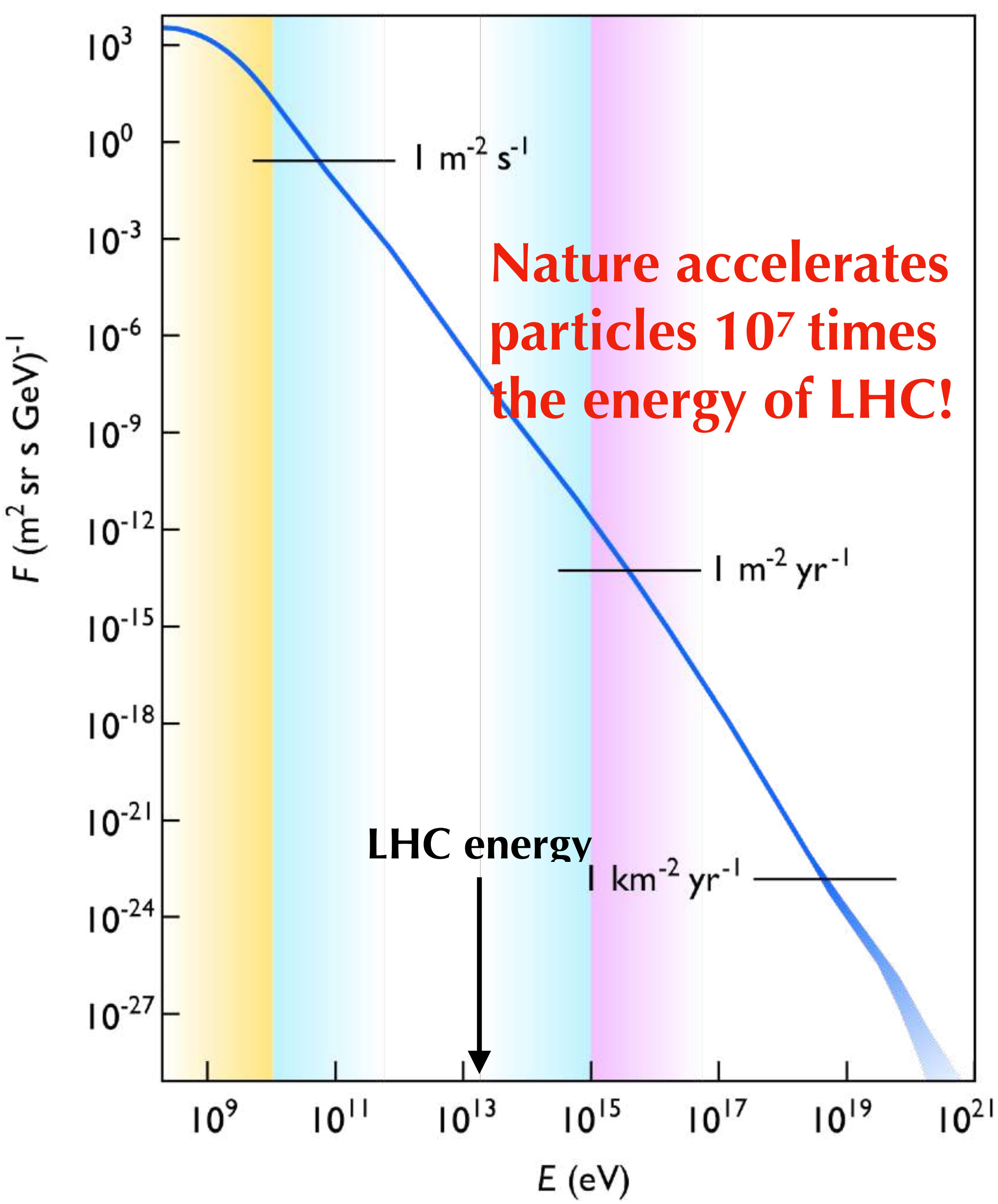

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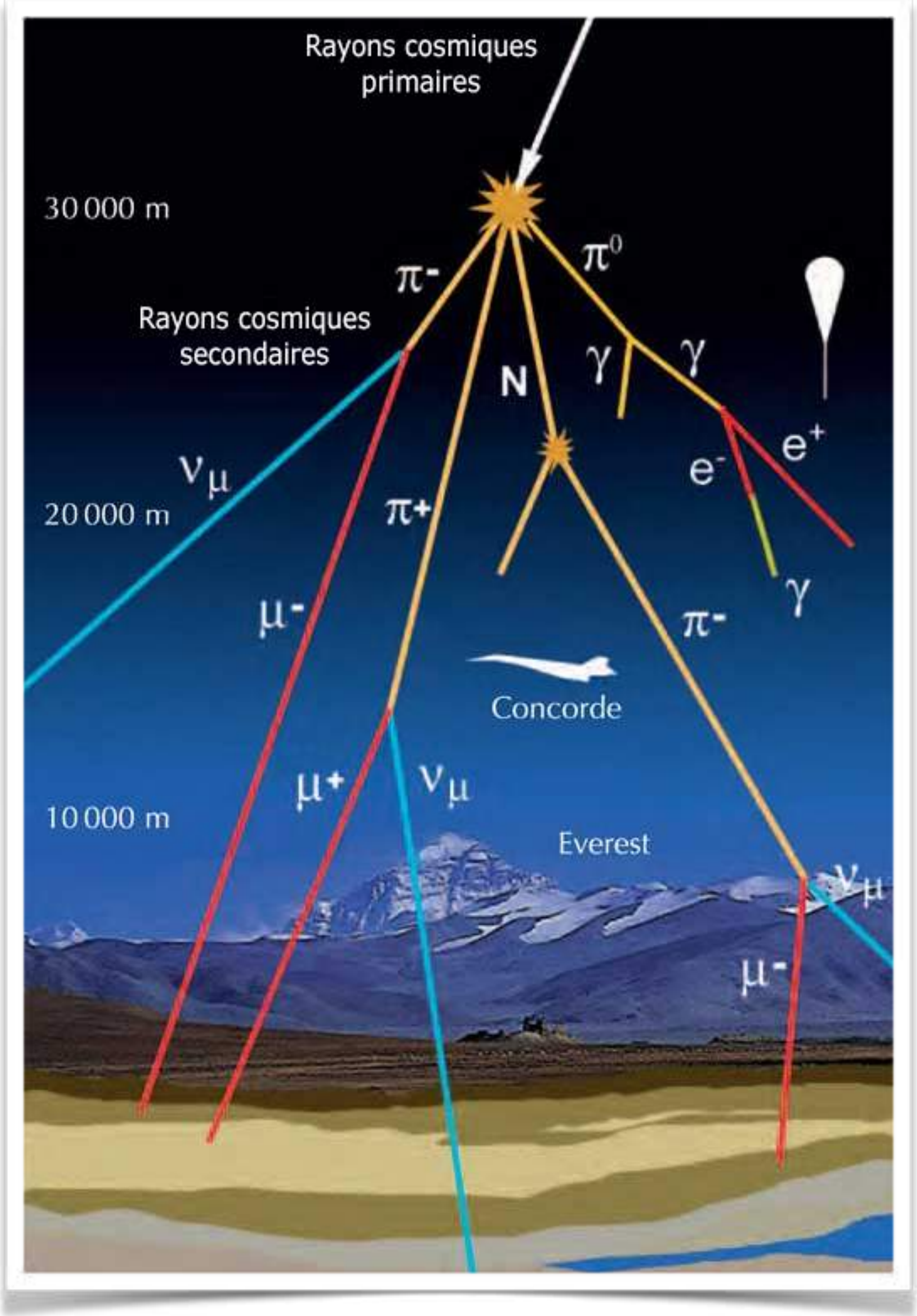

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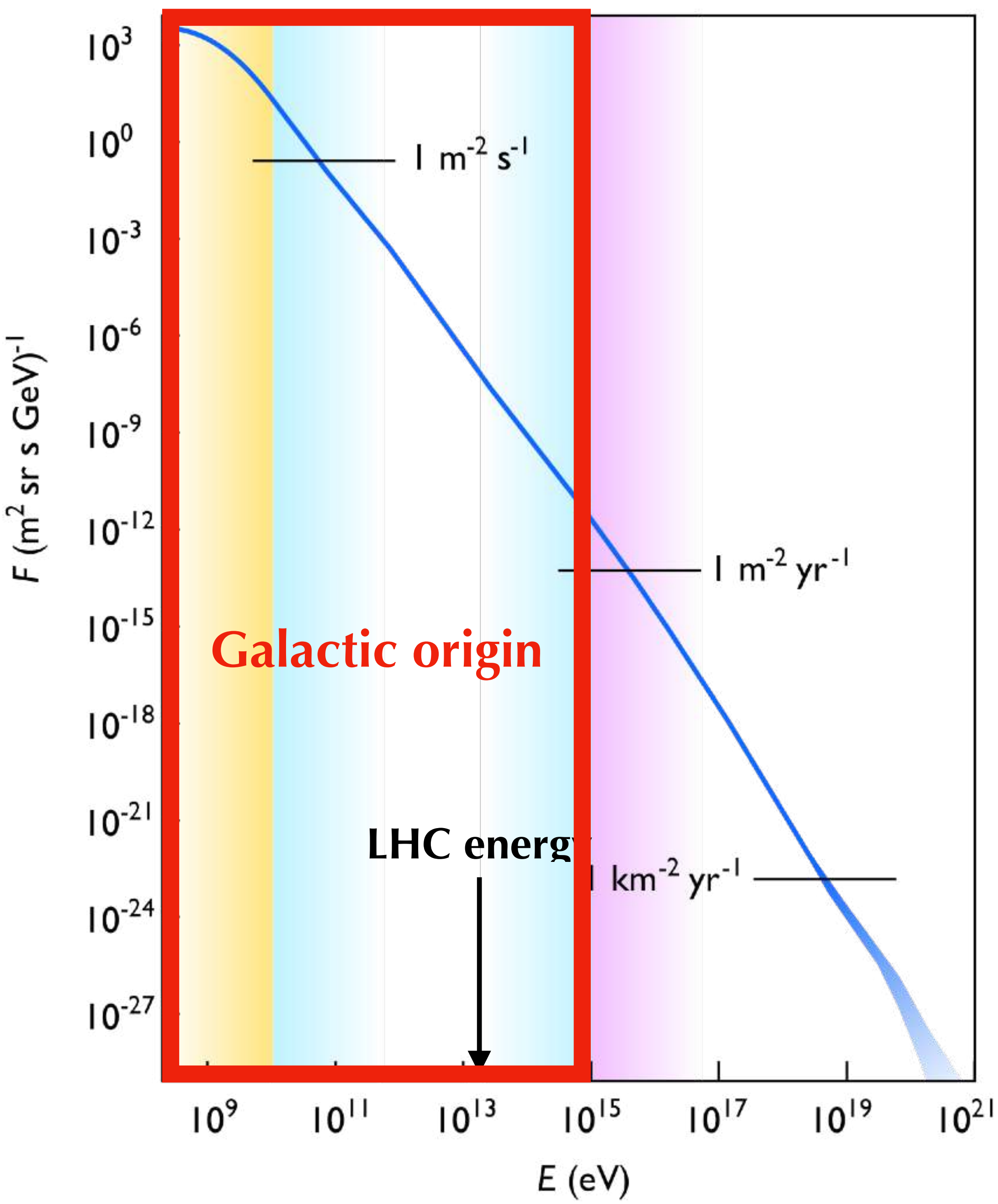

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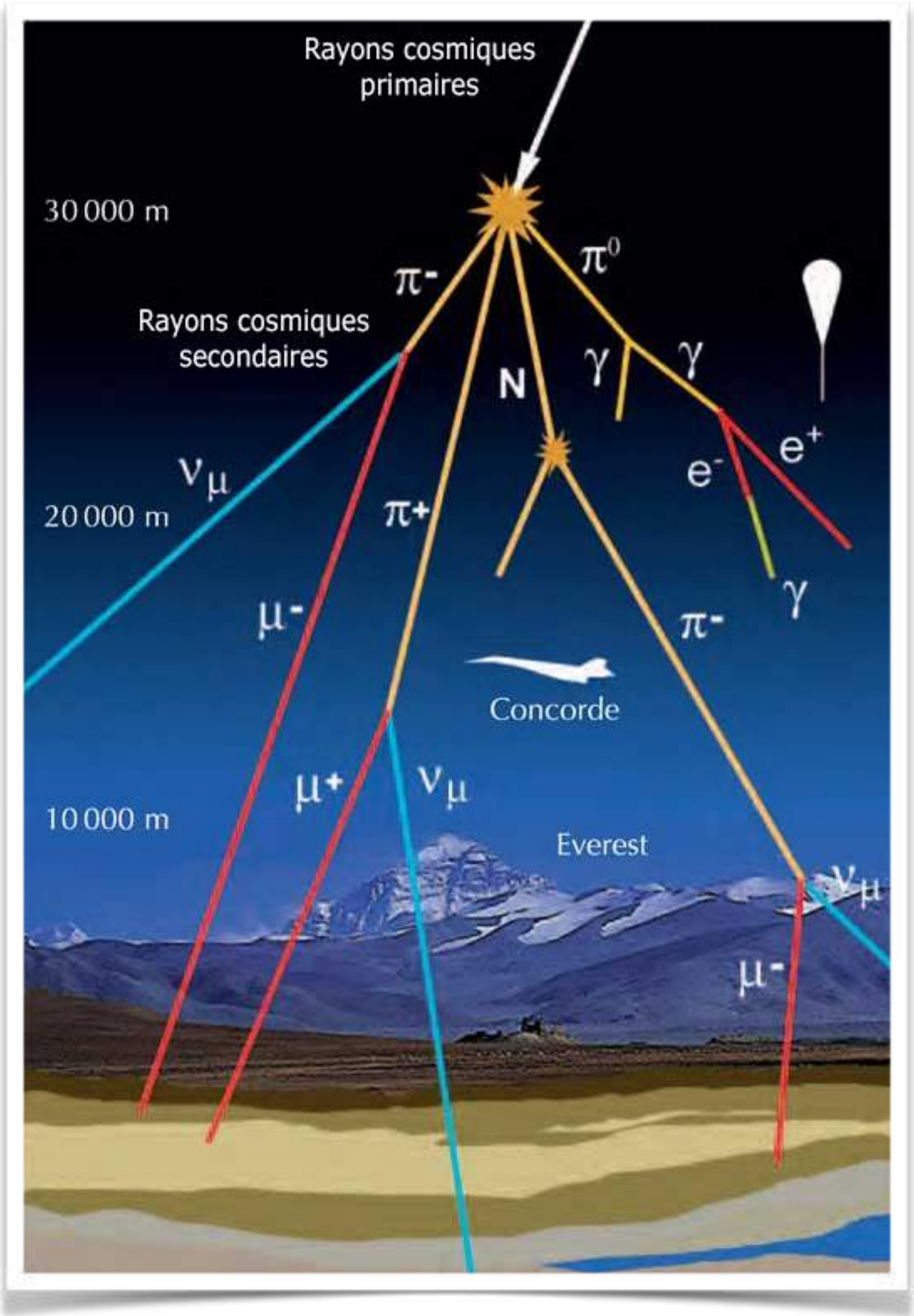

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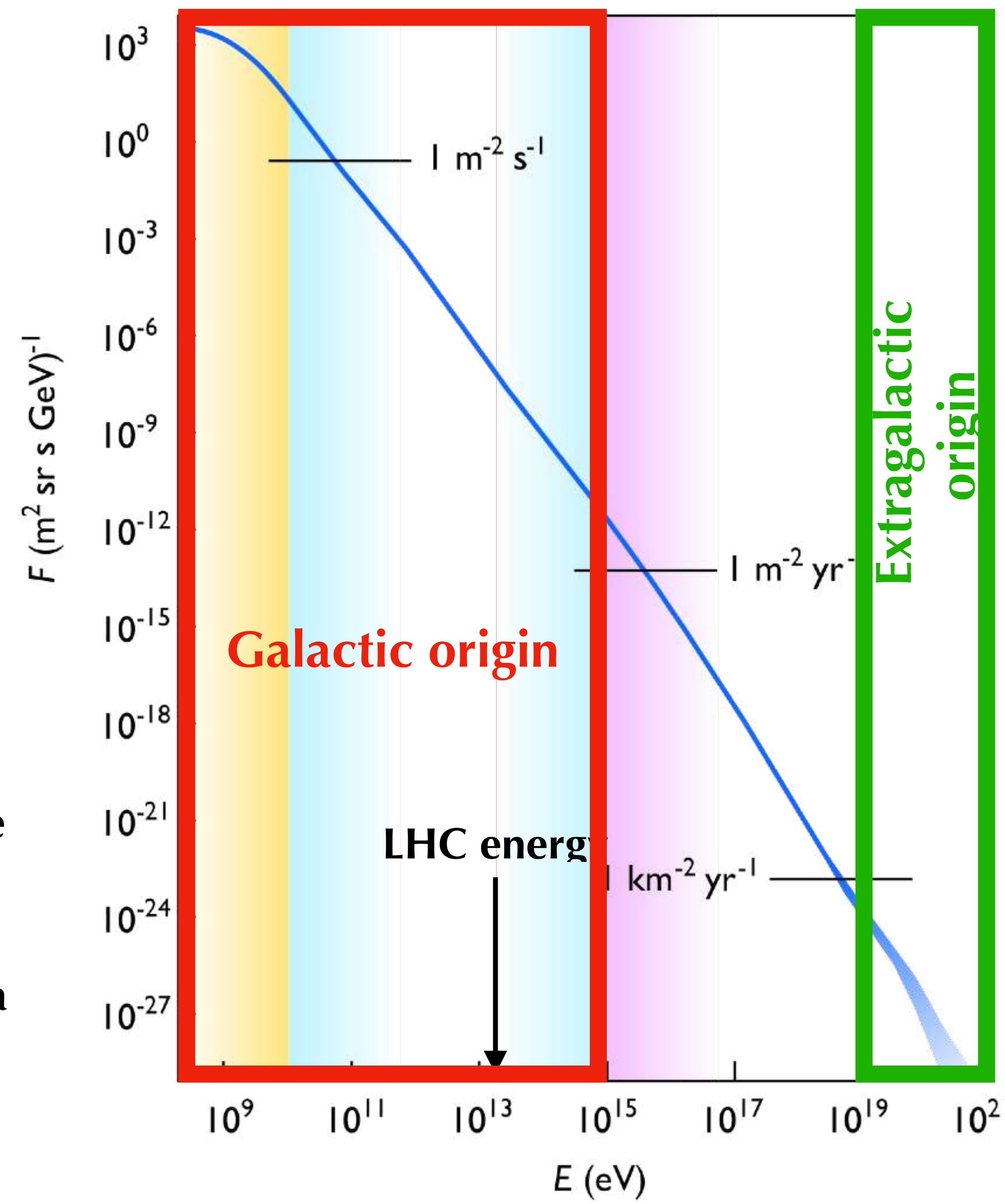

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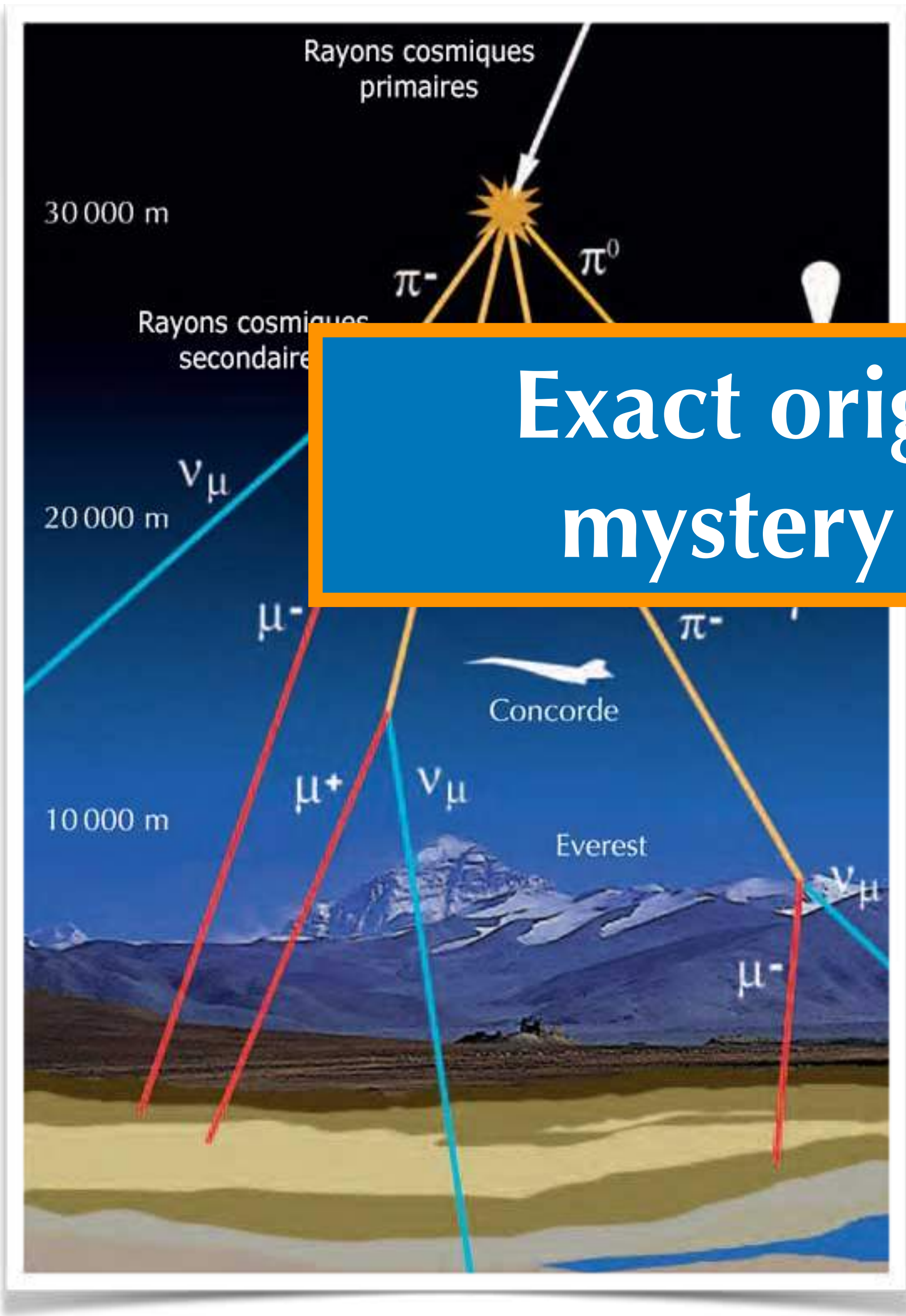

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Exact origin of cosmic rays is a mystery since one century…

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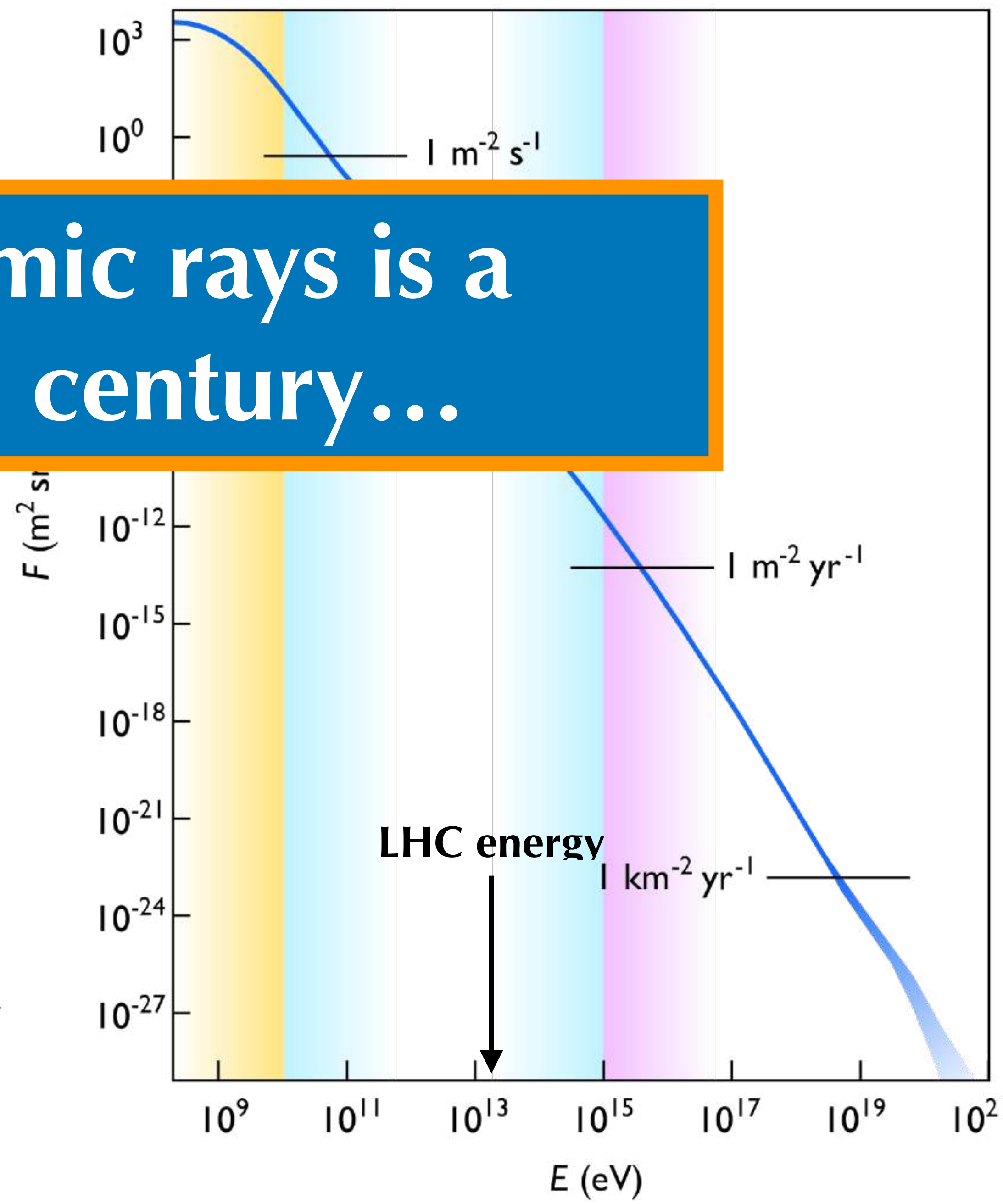


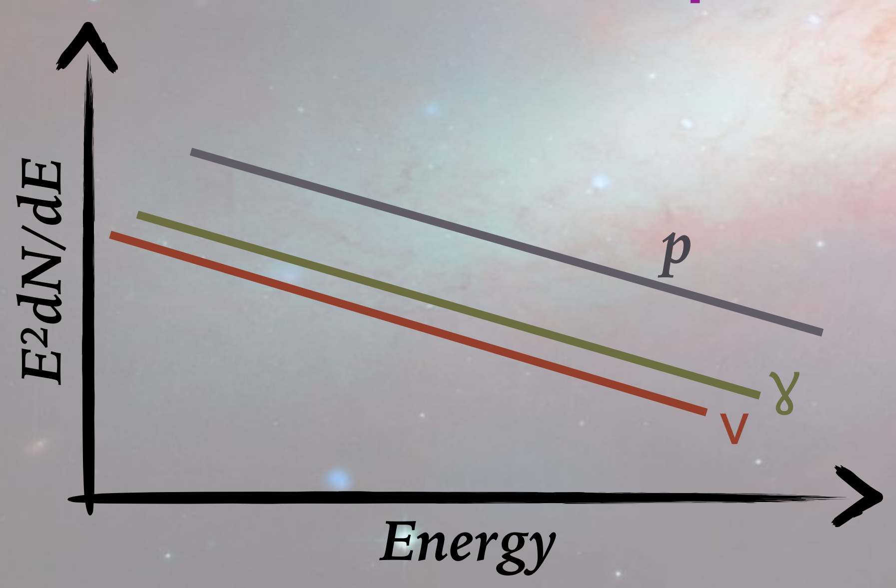
Neutrinos

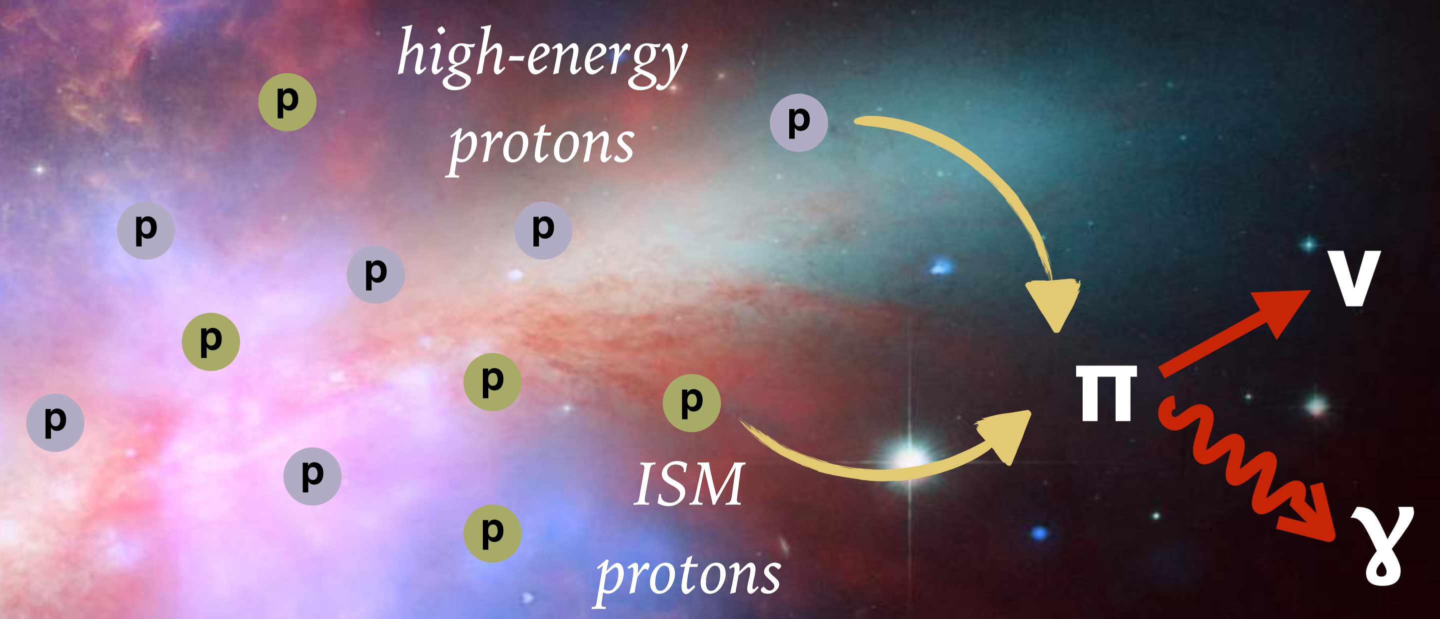
Cosmic-ray reservoirs

- *Star-forming galaxies*
- *Starburst Galaxies*
- *Galactic plane, …*

$$p + p \rightarrow p + p + \pi^0$$
$$\hookrightarrow \gamma\ \gamma$$

$$p + p \rightarrow \pi^+ + p + n$$
$$\hookrightarrow \mu\ \nu_\mu$$
$$\hookrightarrow \nu_\mu\ \nu_e\ e$$





Neutrinos

Photohadronic

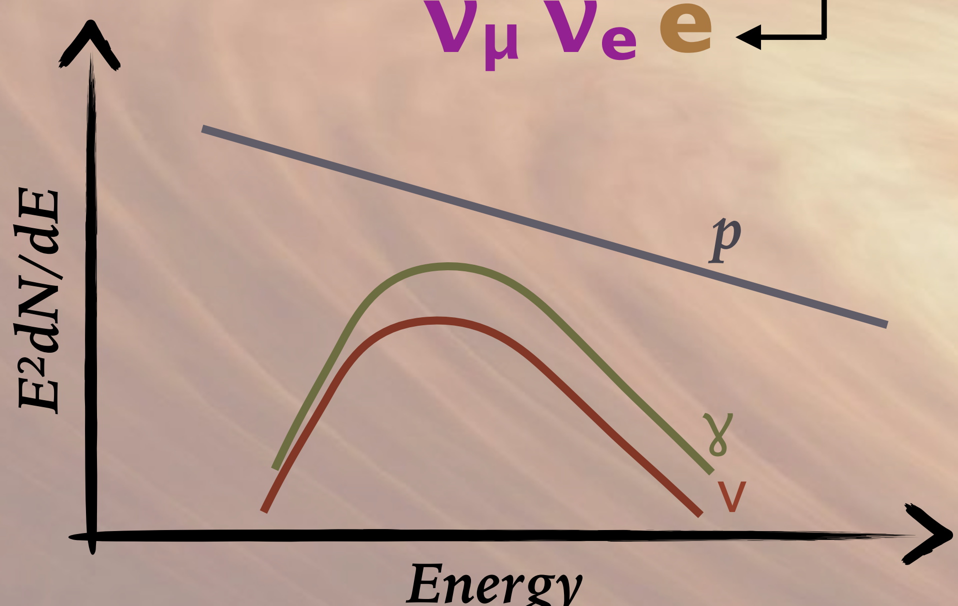
$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

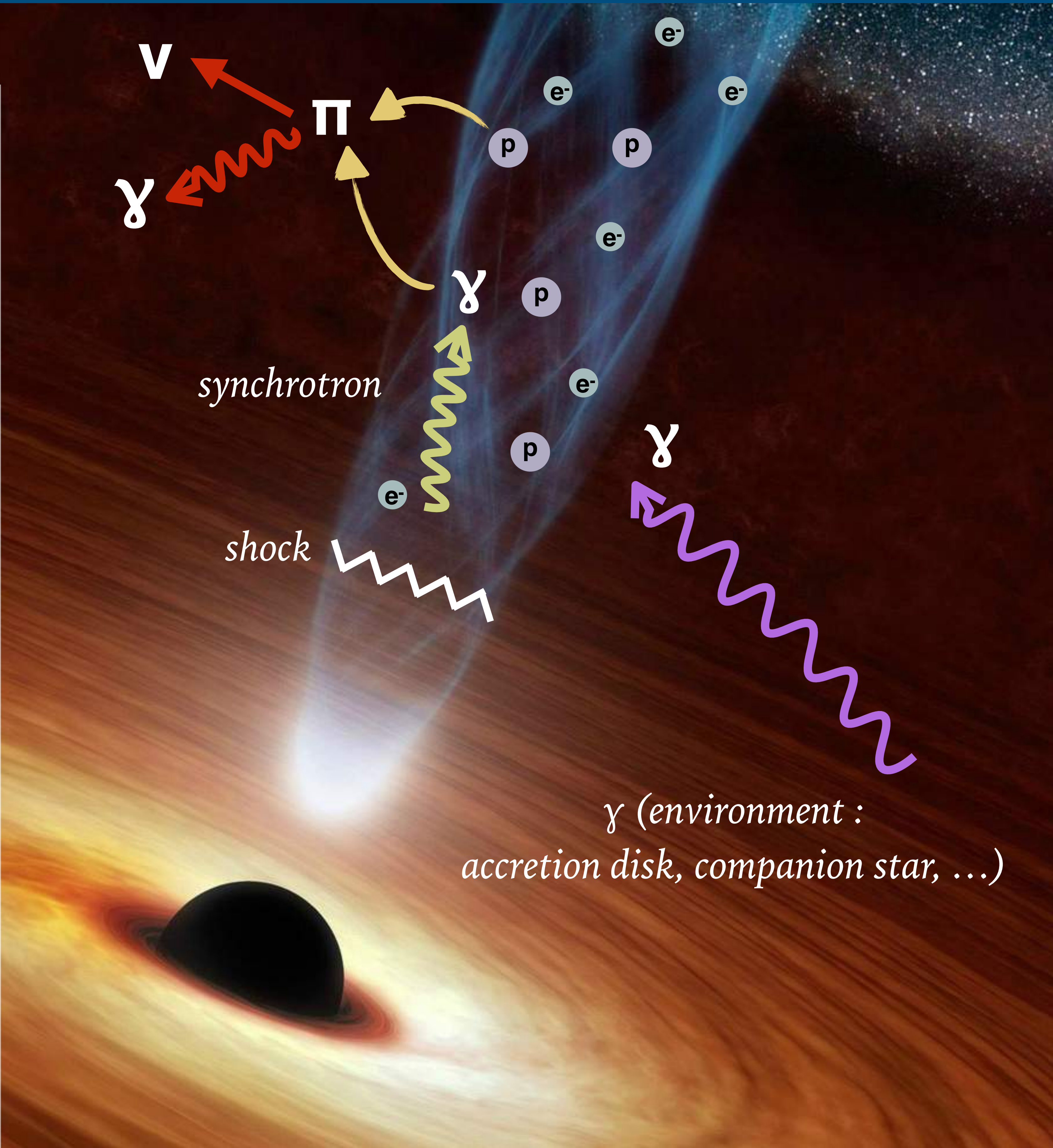
$$\hookrightarrow \gamma\ \gamma$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^+ + n$$

$$\hookrightarrow \mu\ \nu_\mu$$

$$\bar{\nu}_\mu\ \nu_e\ e$$

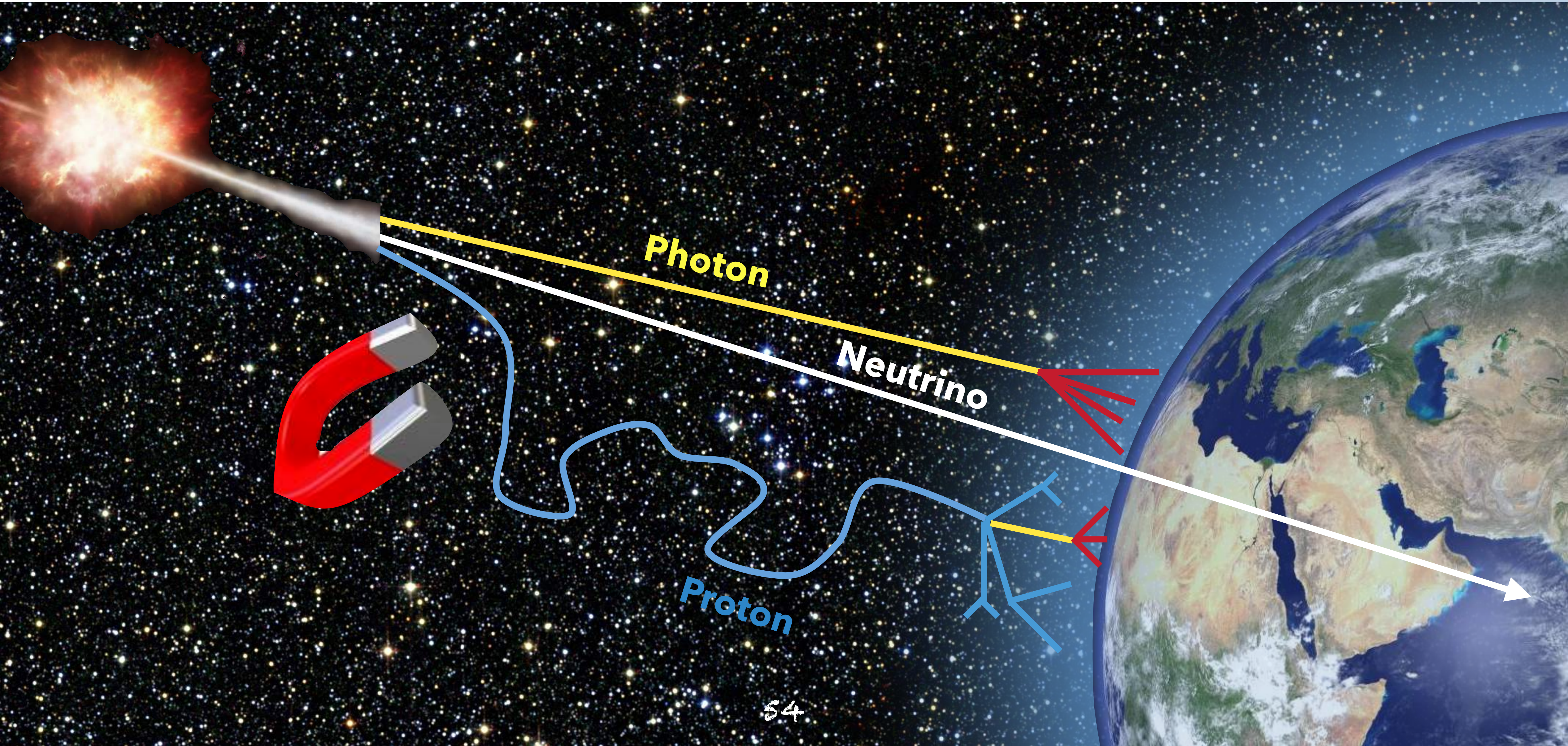




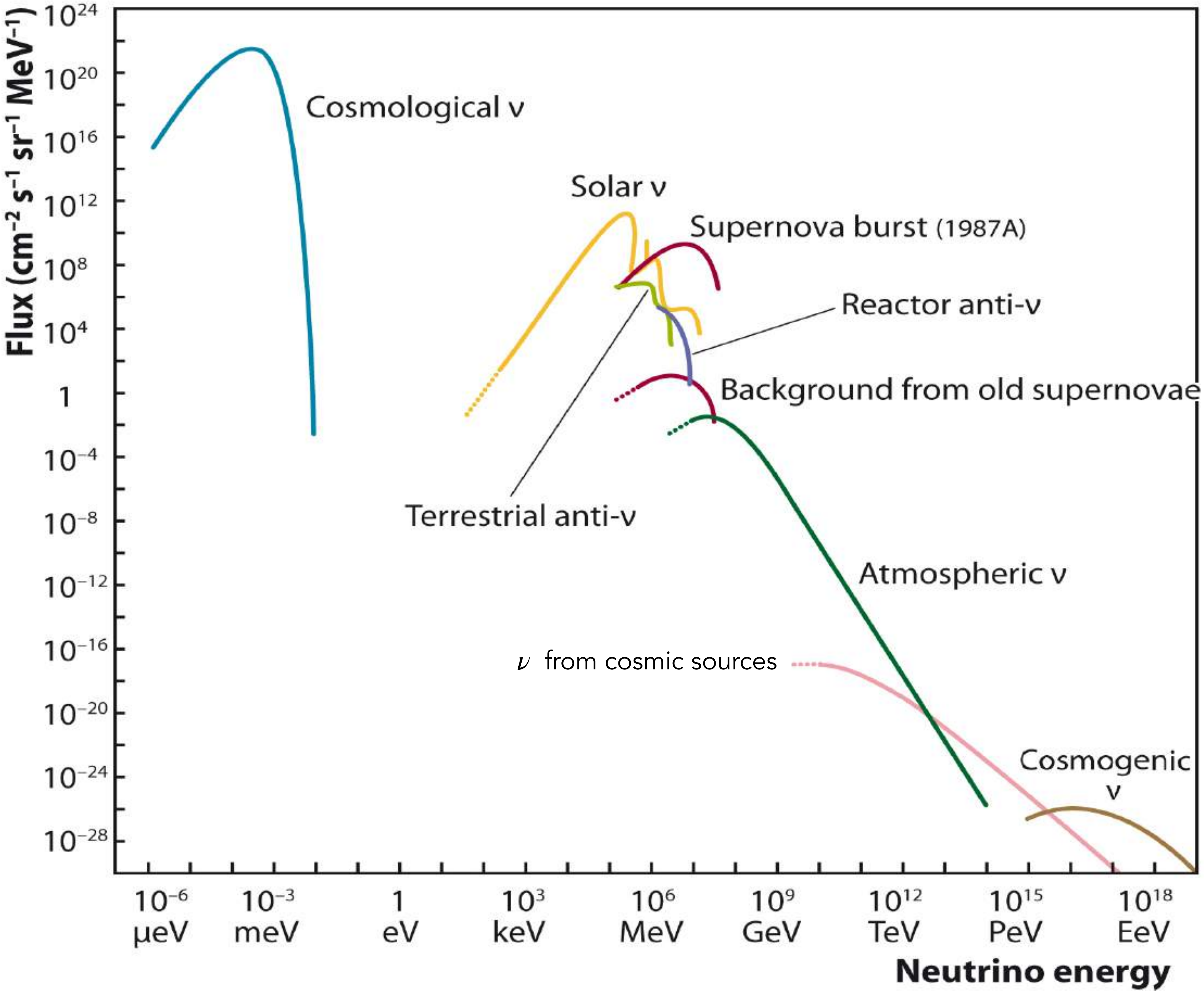
Multi-messenger astronomy

- Photons (ɣ-rays): absorbed and interact with CMB/IRB (pair production for d≳Mpc)
- Cosmic Rays: deflected by magnetic fields + GZK effect with CMB
- Neutrinos: neutral, weakly interacting particles, escape from dense mediapoint to the source

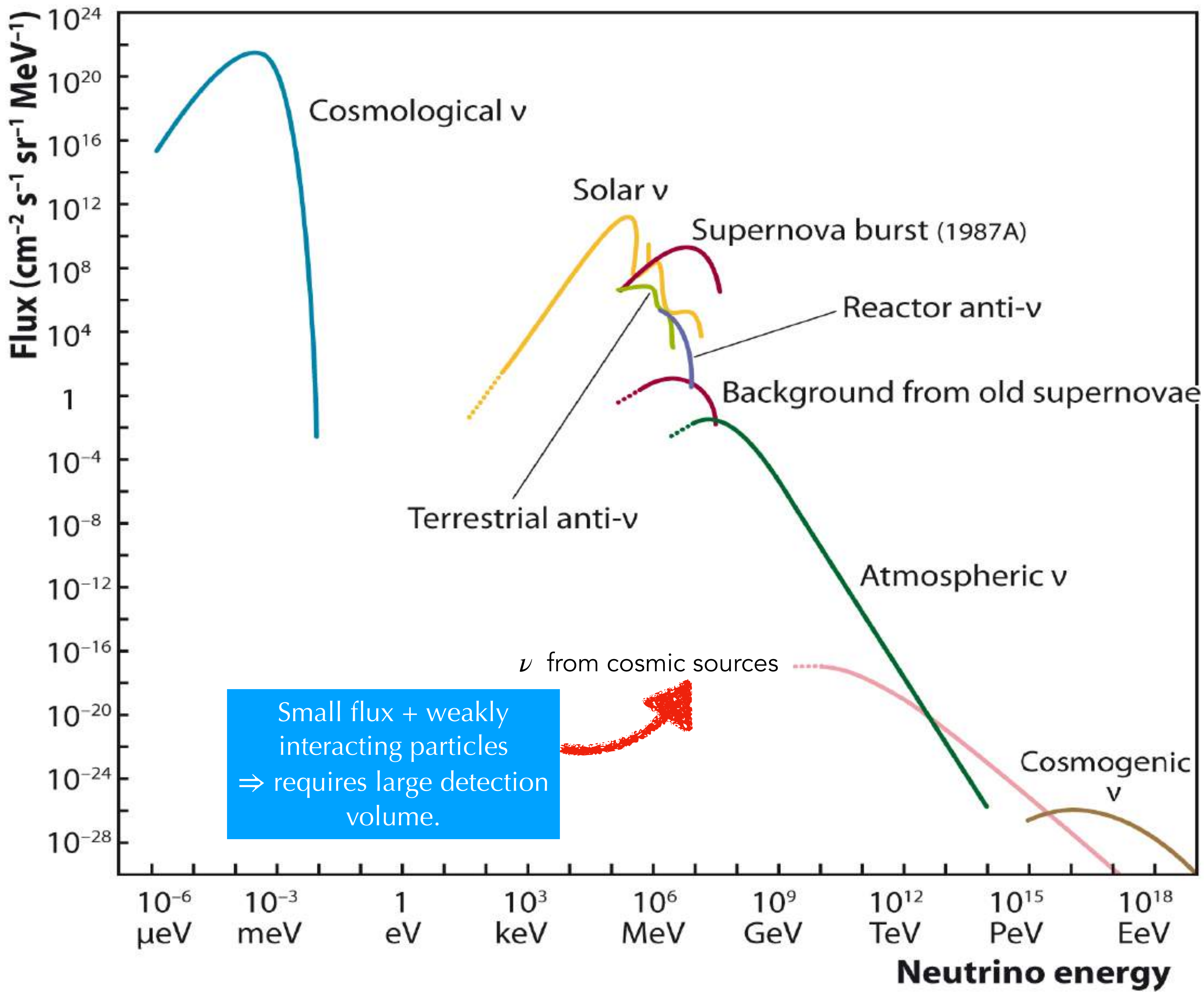
But neutrinos are rare and difficult to detect (do not undergo EM interactions, low interaction probability, huge background, indirect detection)



Neutrino spectrum

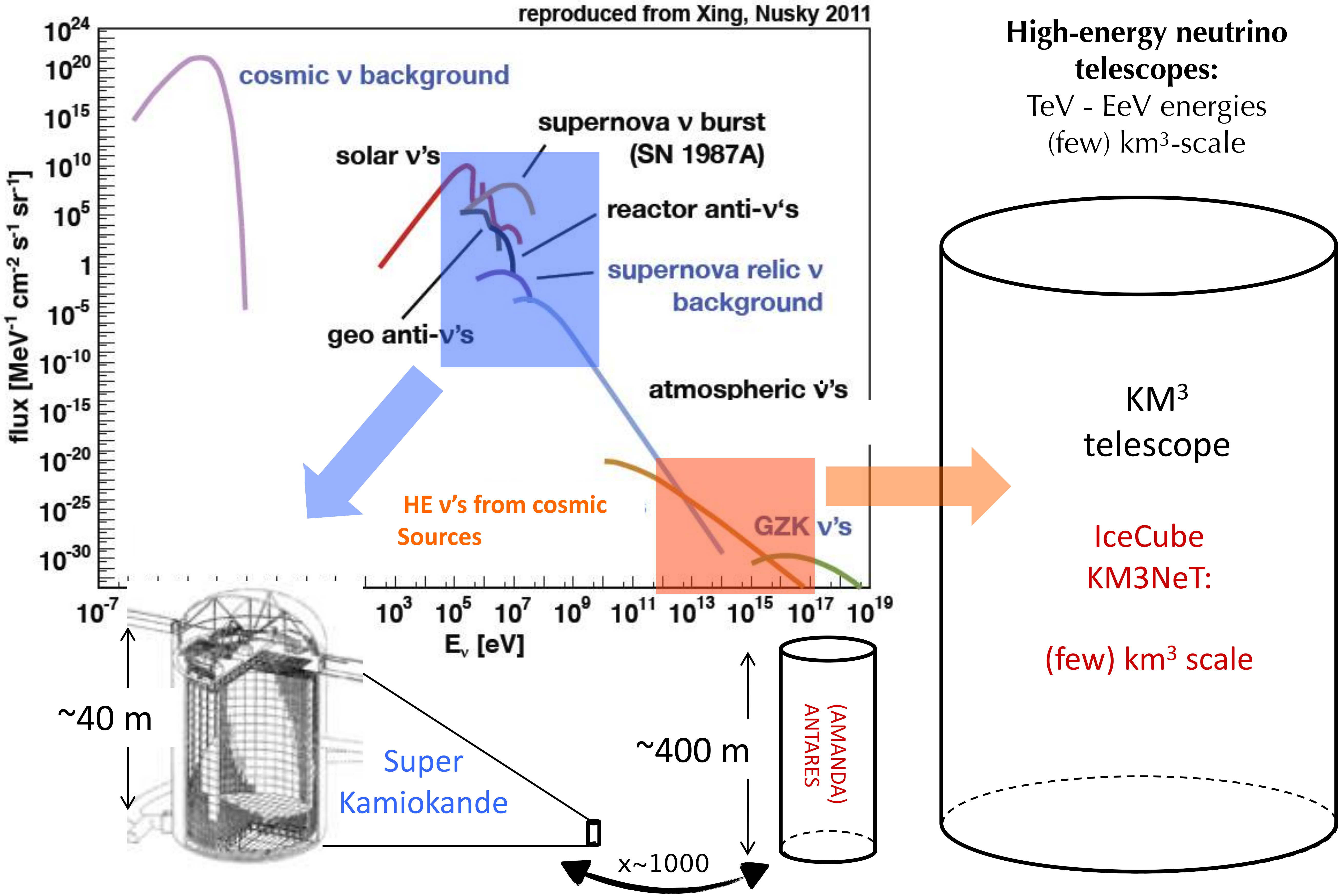


Neutrino spectrum

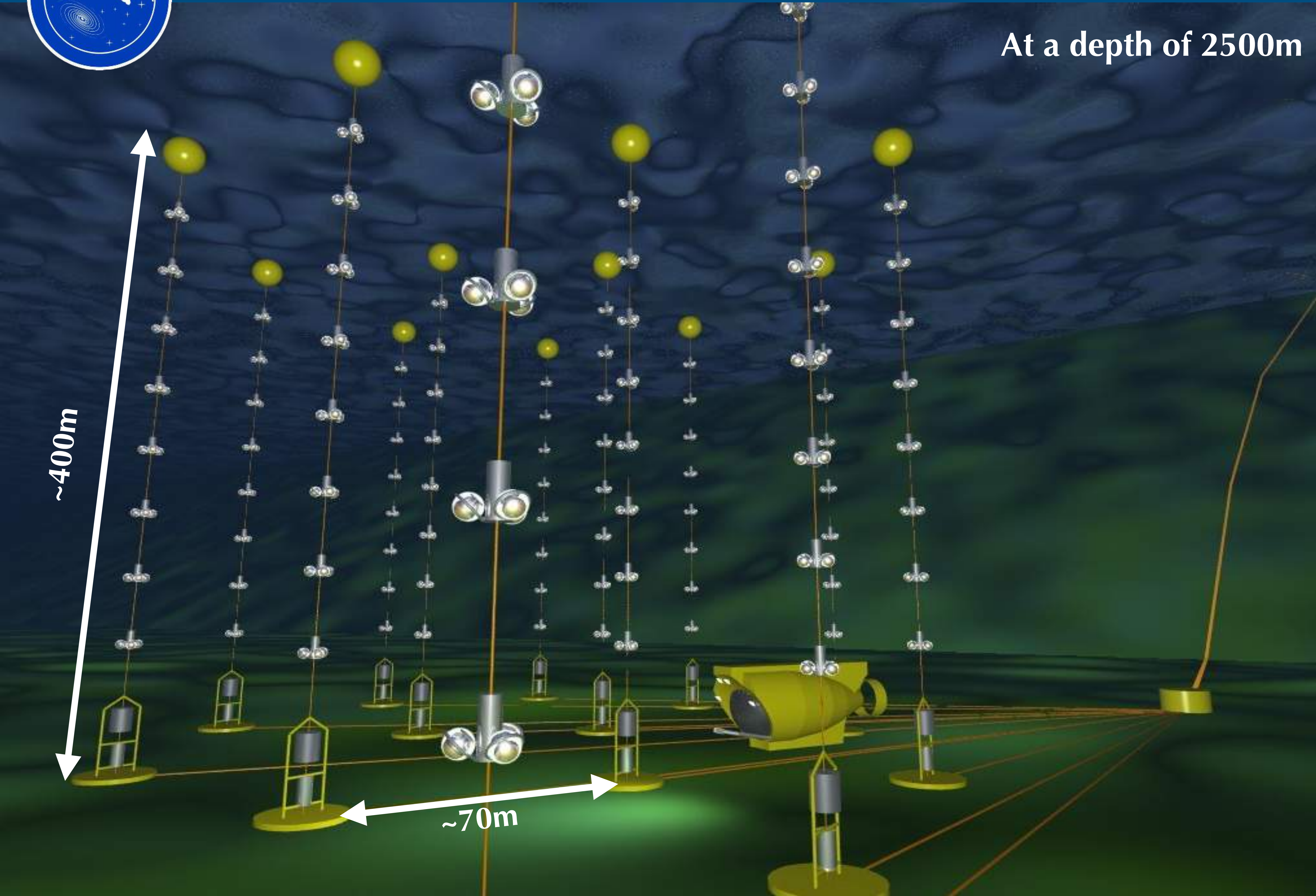


Neutrino telescopes

High-energy neutrino telescopes:
TeV - EeV energies
(few) km³-scale



Neutrino telescopes



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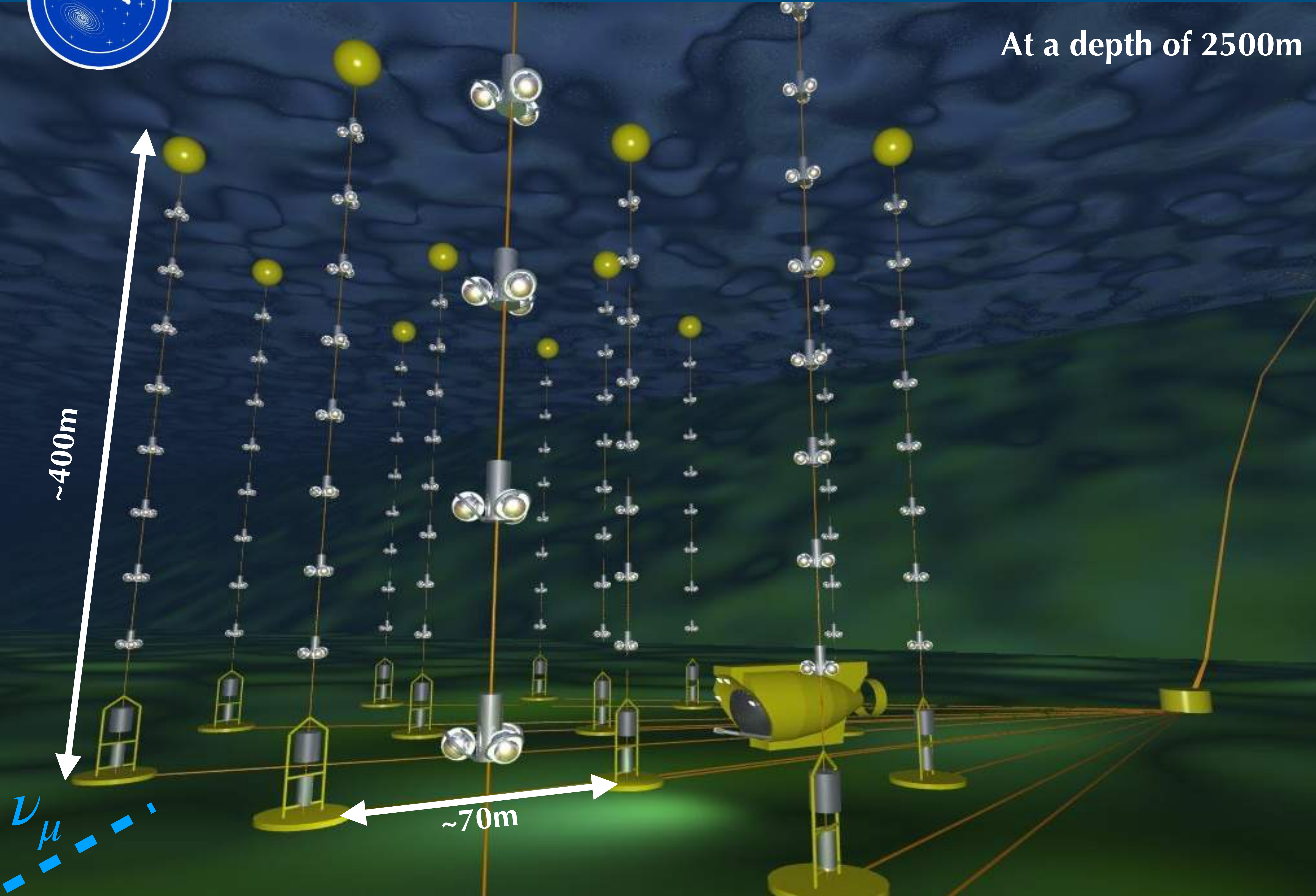

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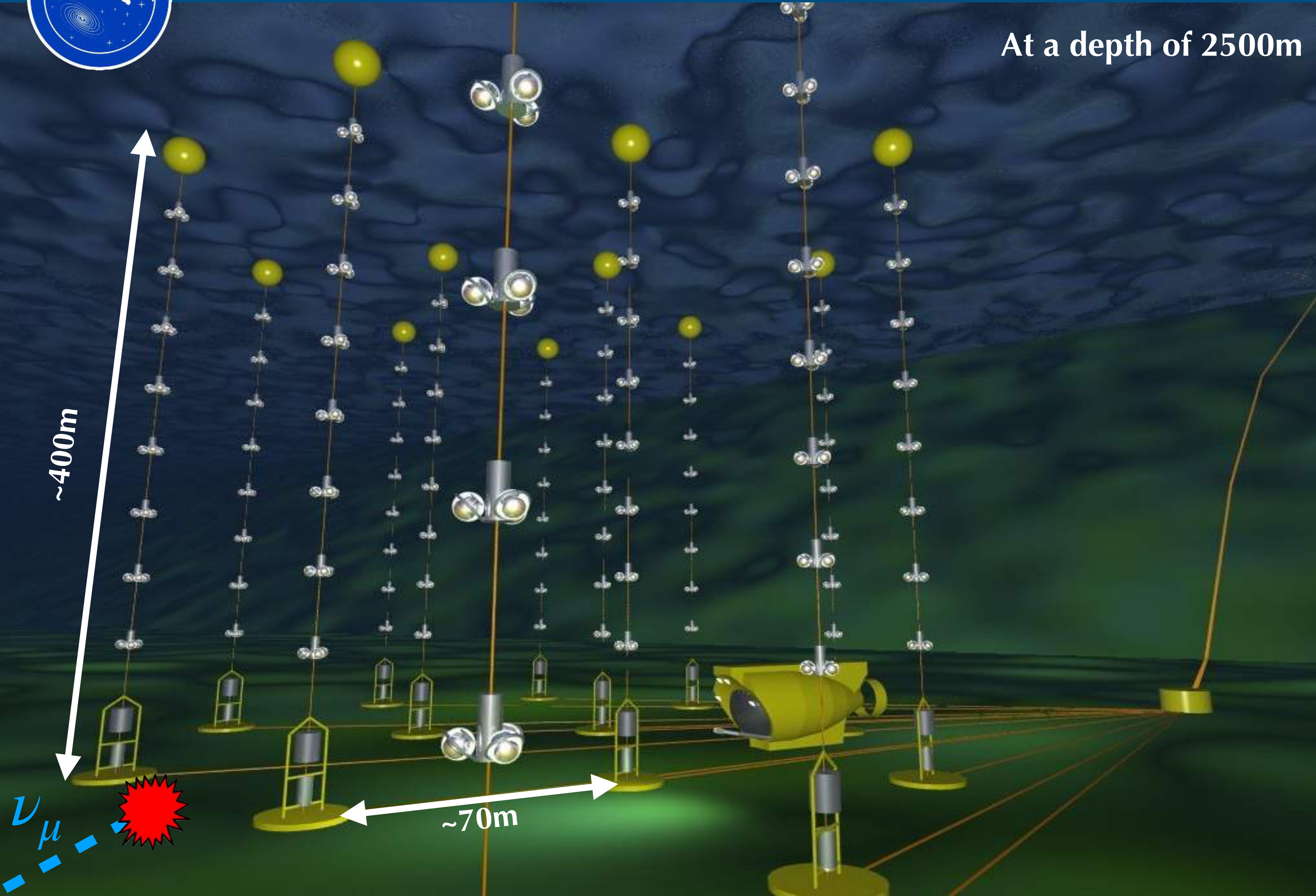

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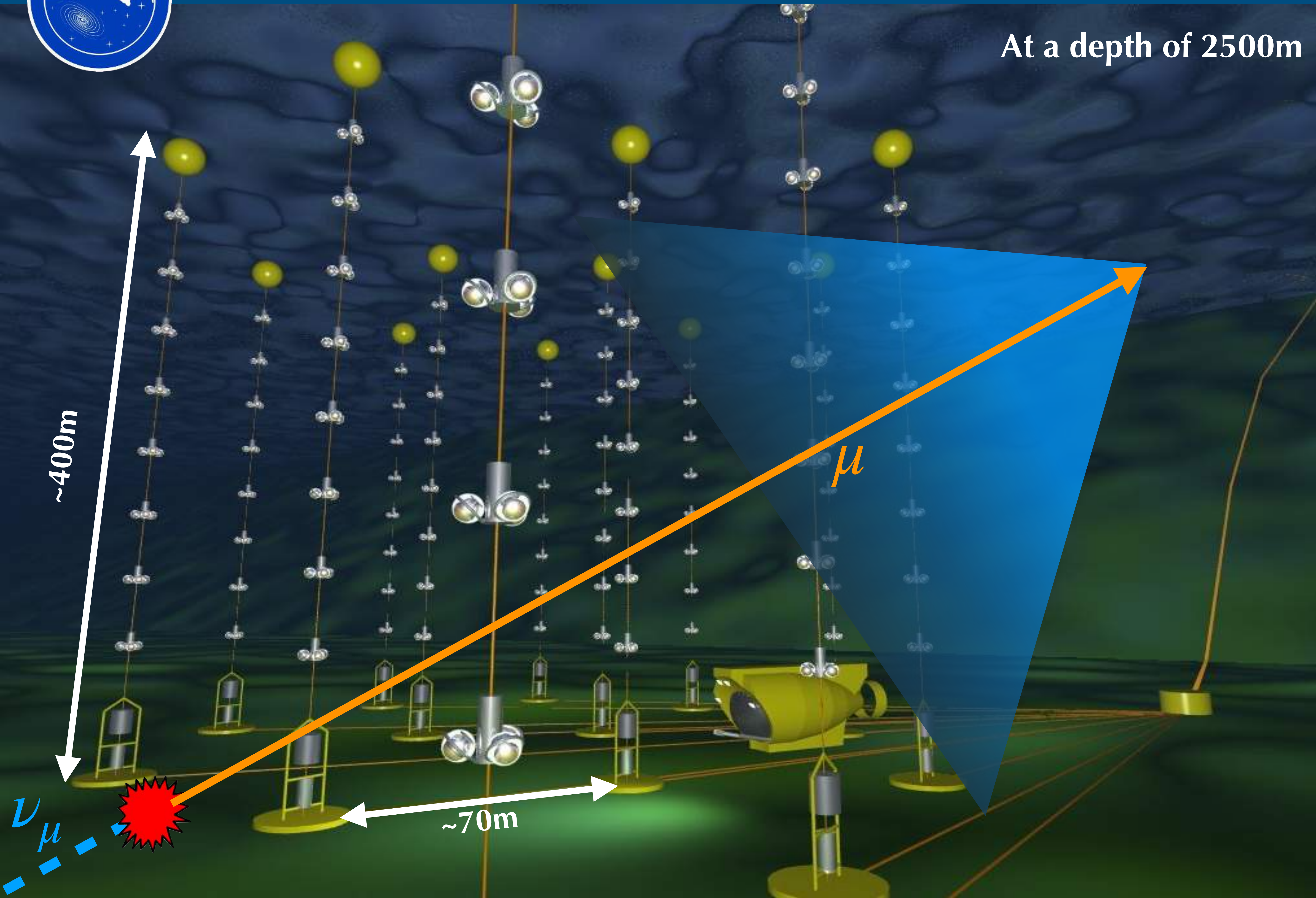
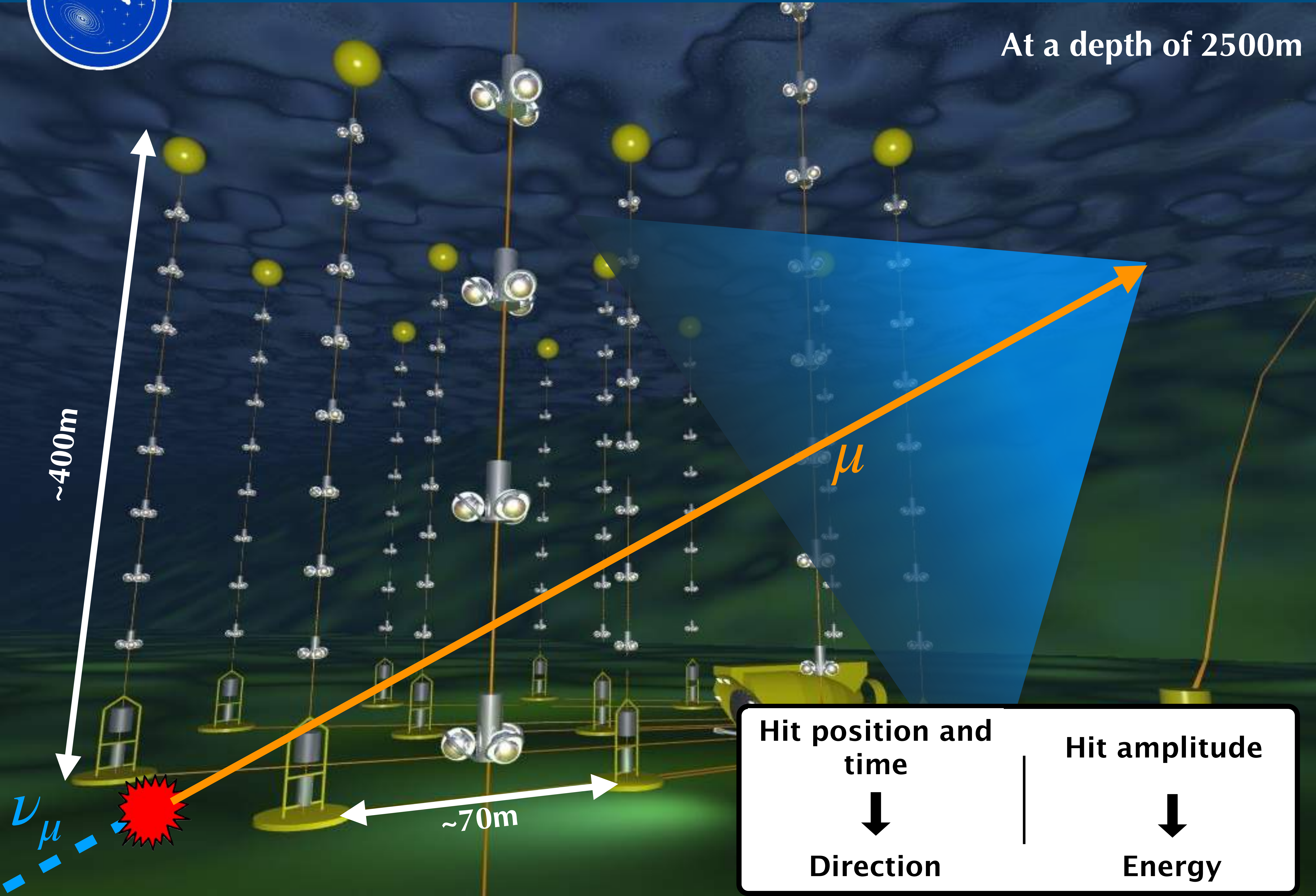


Neutrino telescopes



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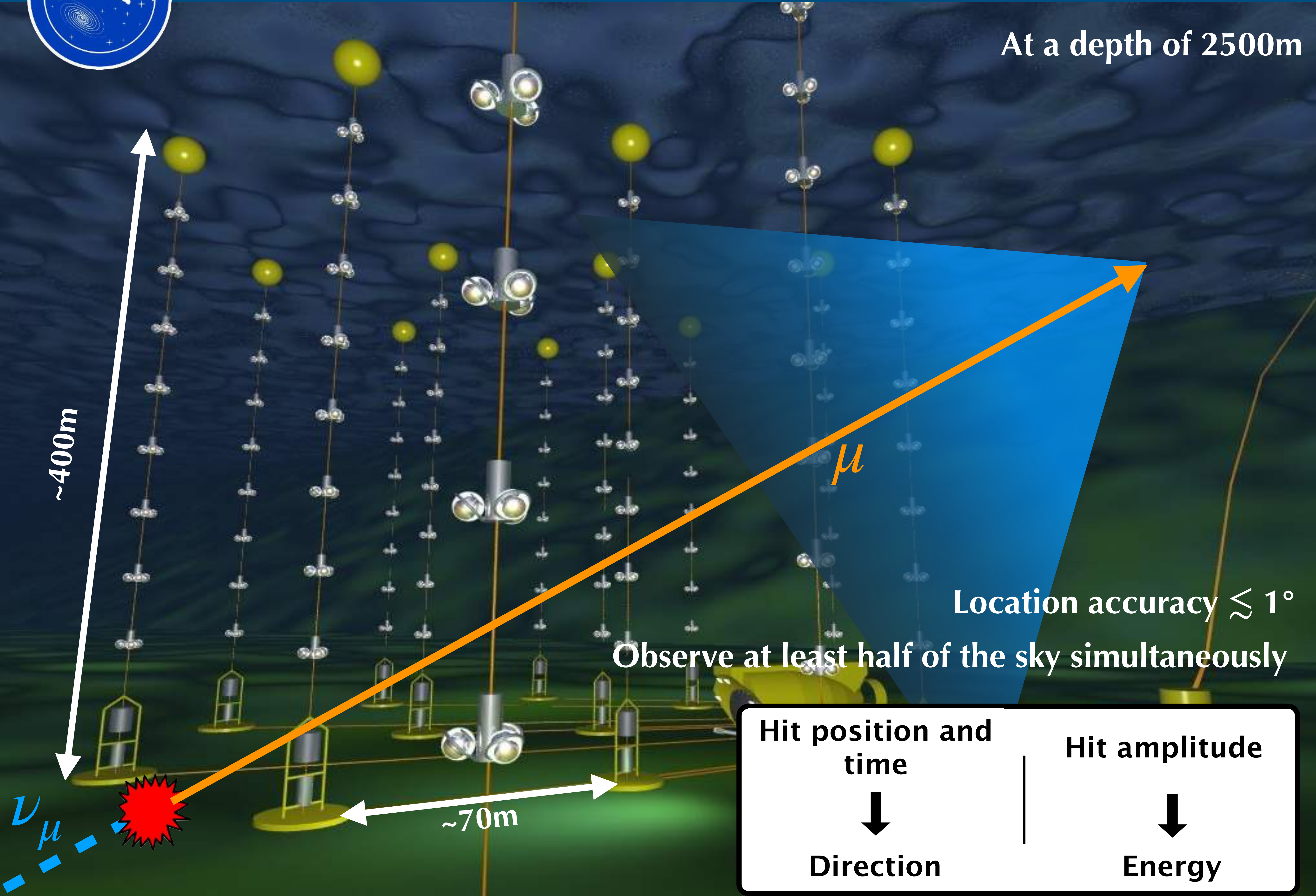

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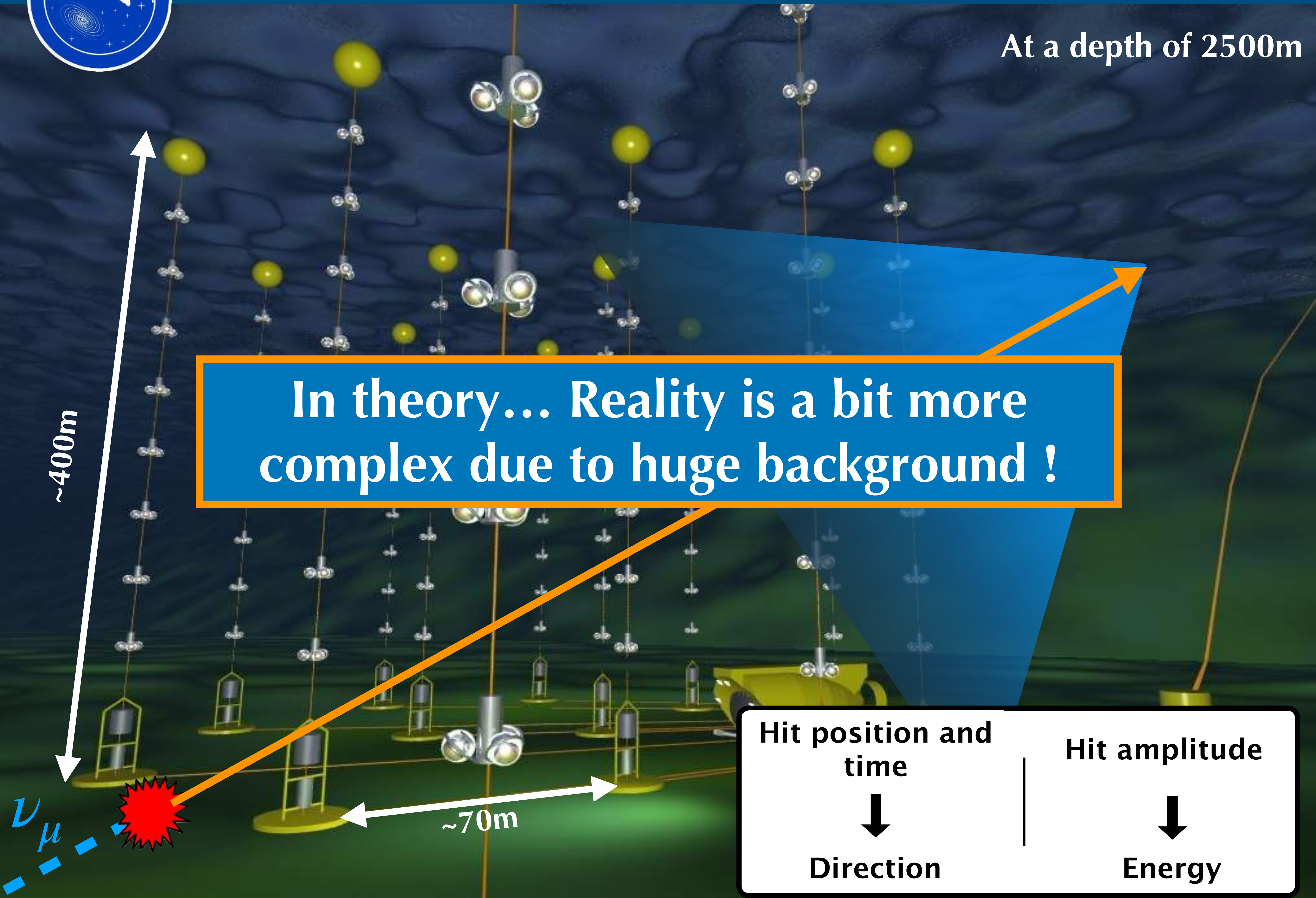
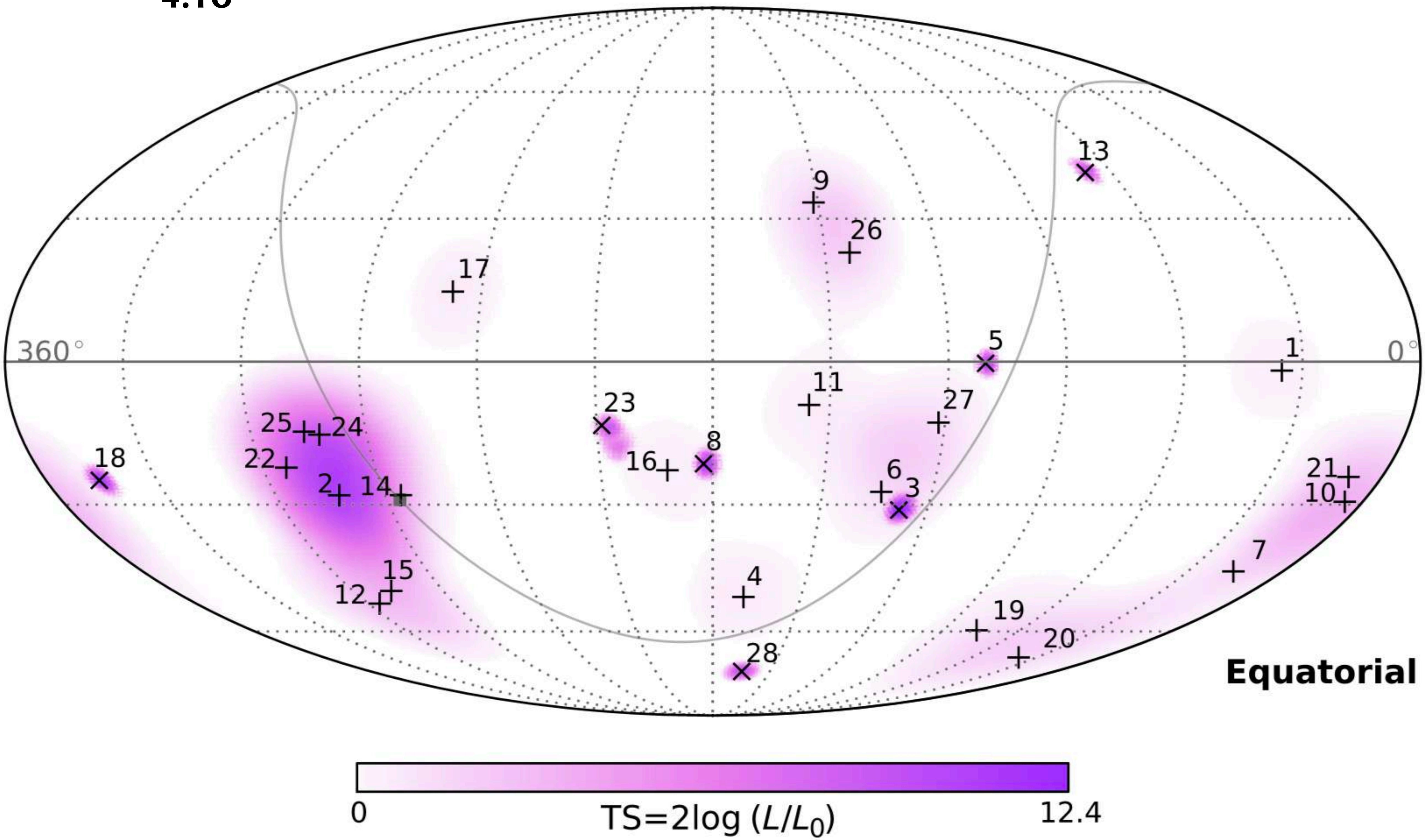


Diffuse neutrino flux (>TeV)

2-year data sample
4.1σ

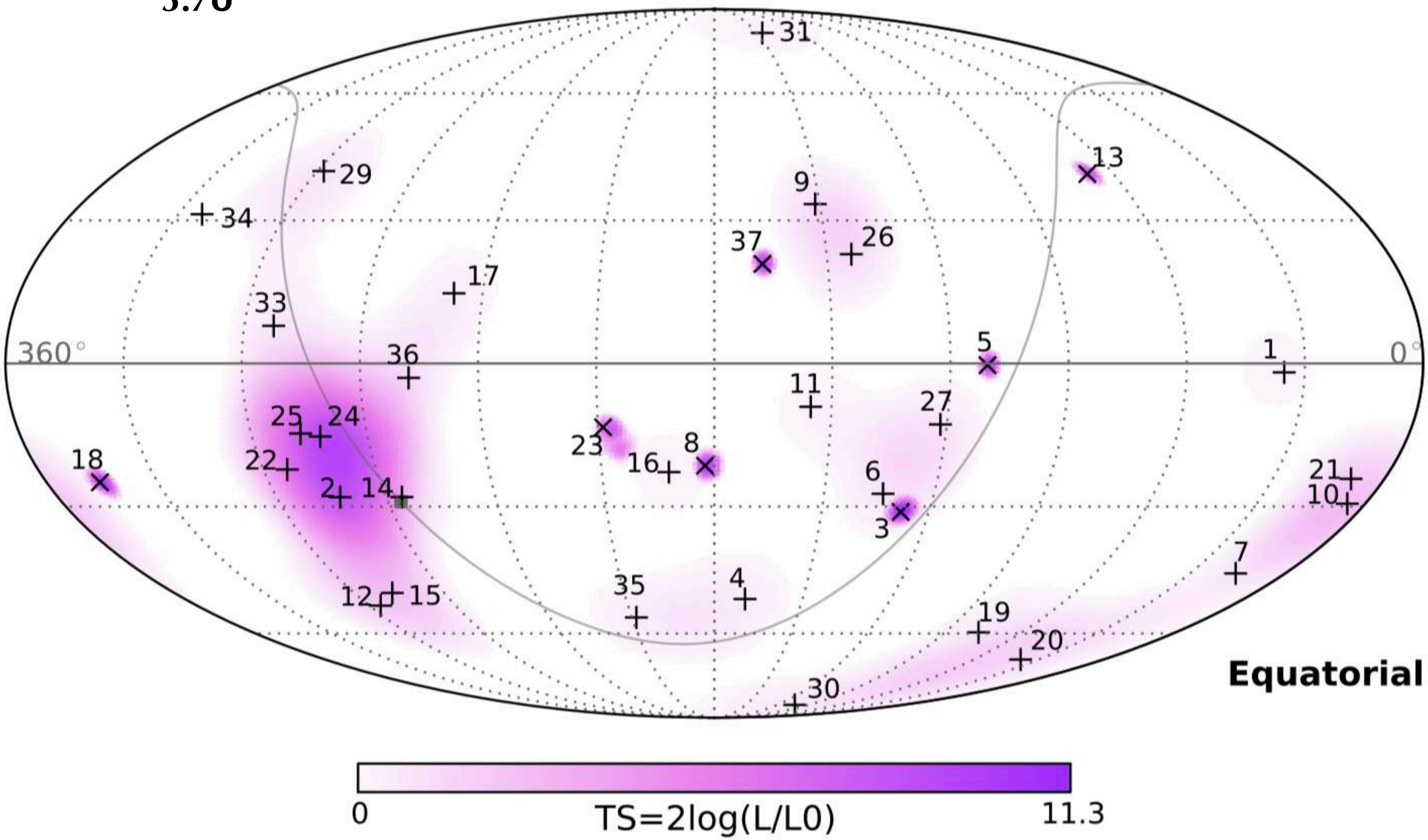
IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

3-year data sample
5.7σ

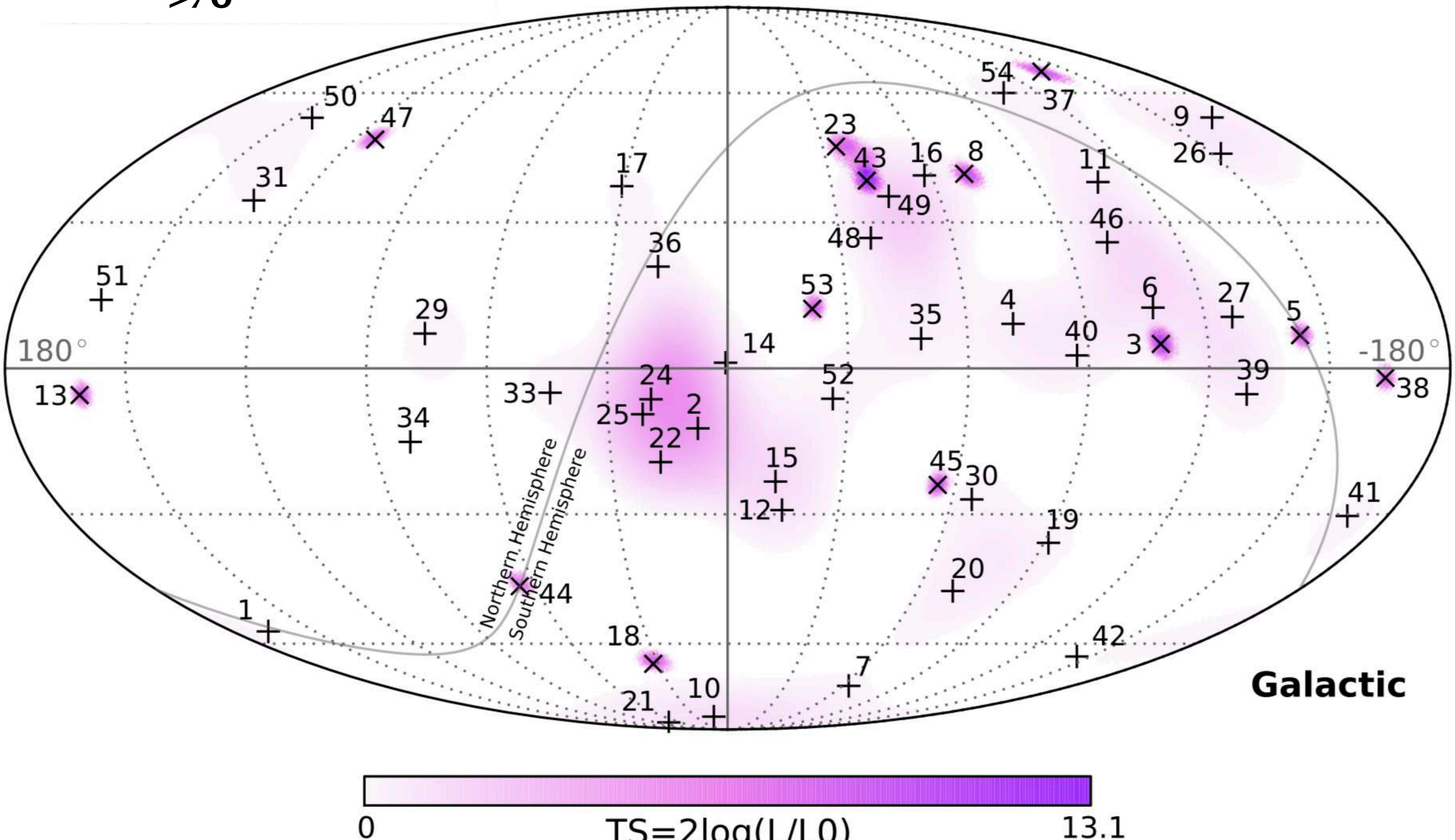
IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

4-year data sample
>7σ

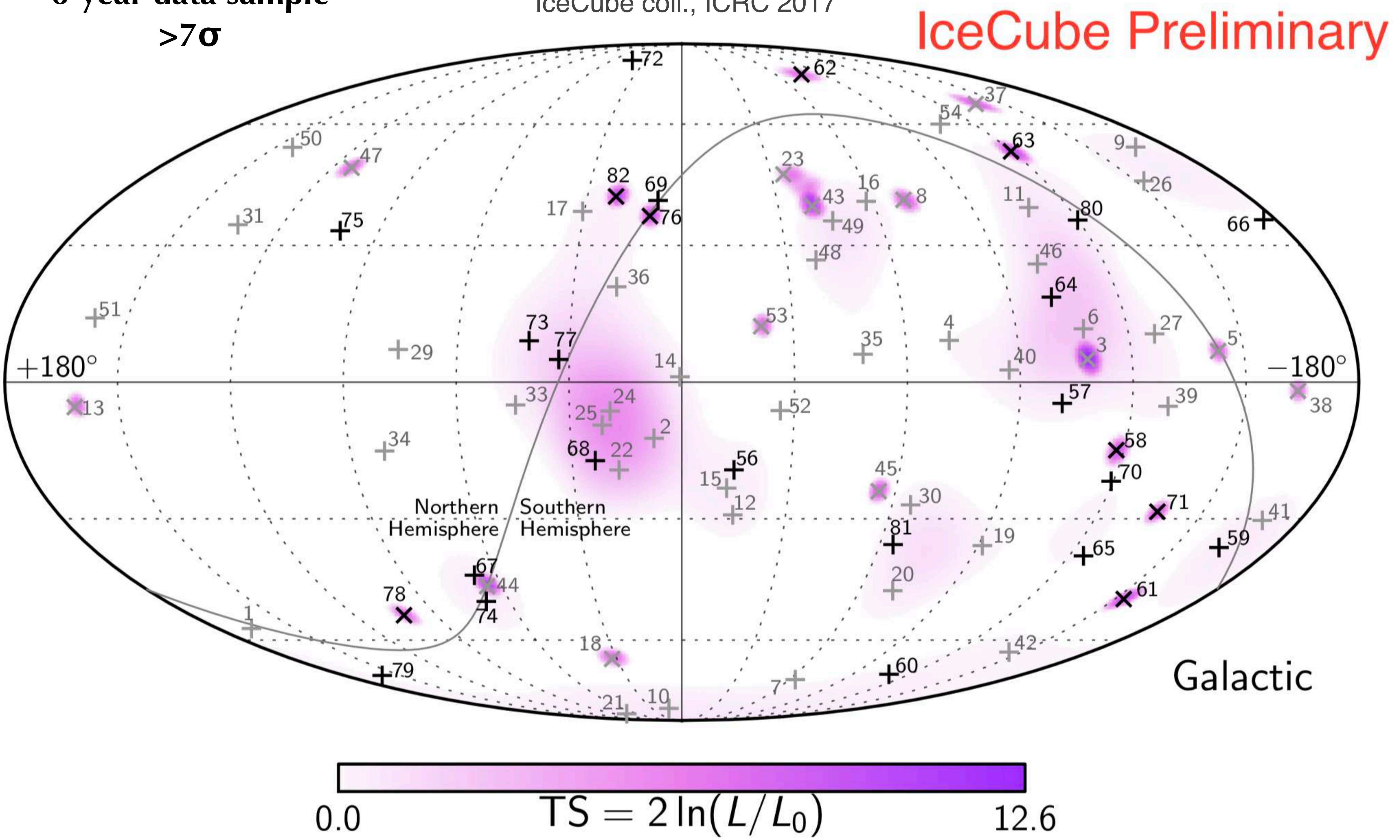
IceCube coll., ICRC 2017



Diffuse neutrino flux (>TeV)

6-year data sample
>7σ

IceCube coll., ICRC 2017



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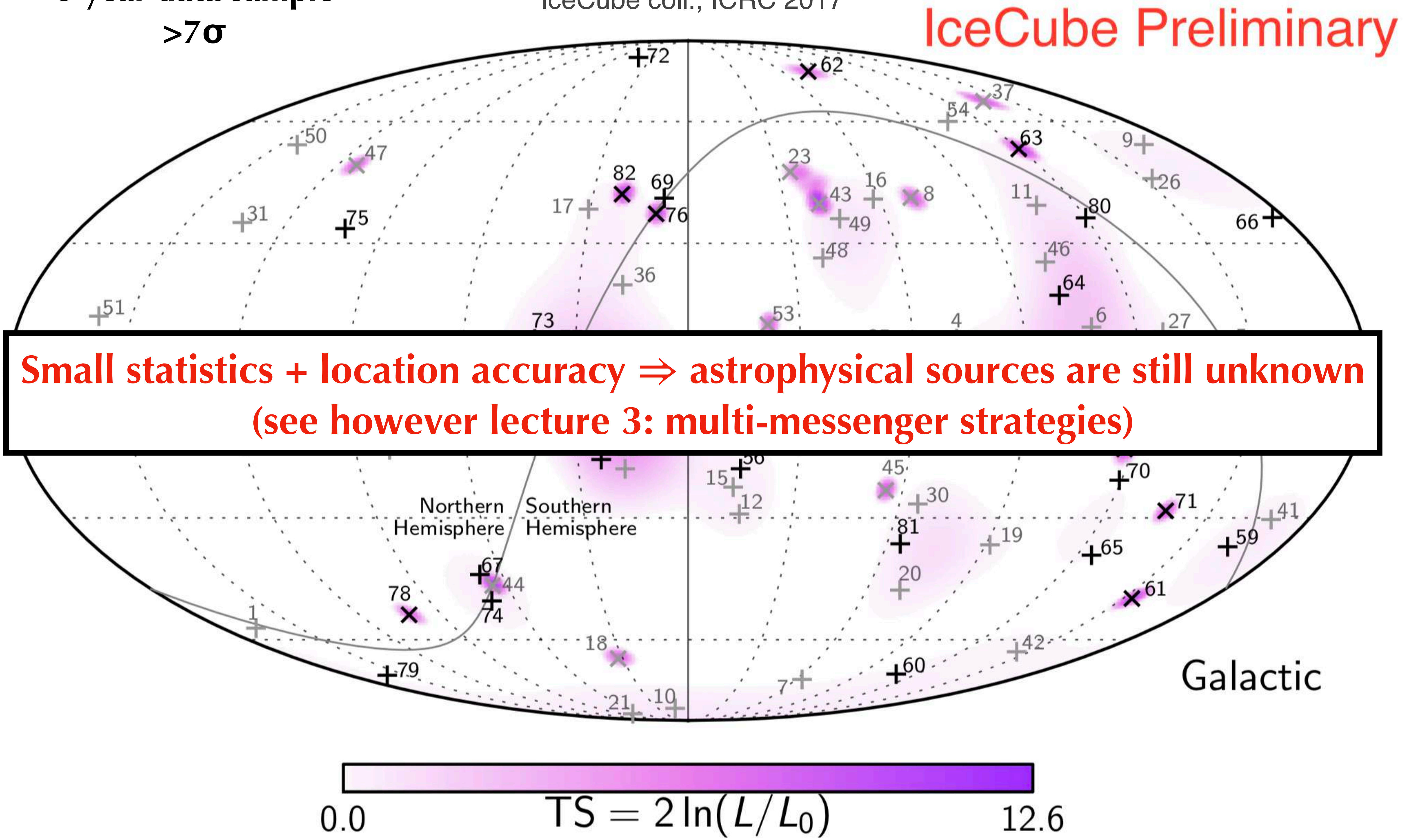
6-year data sample
>7σ

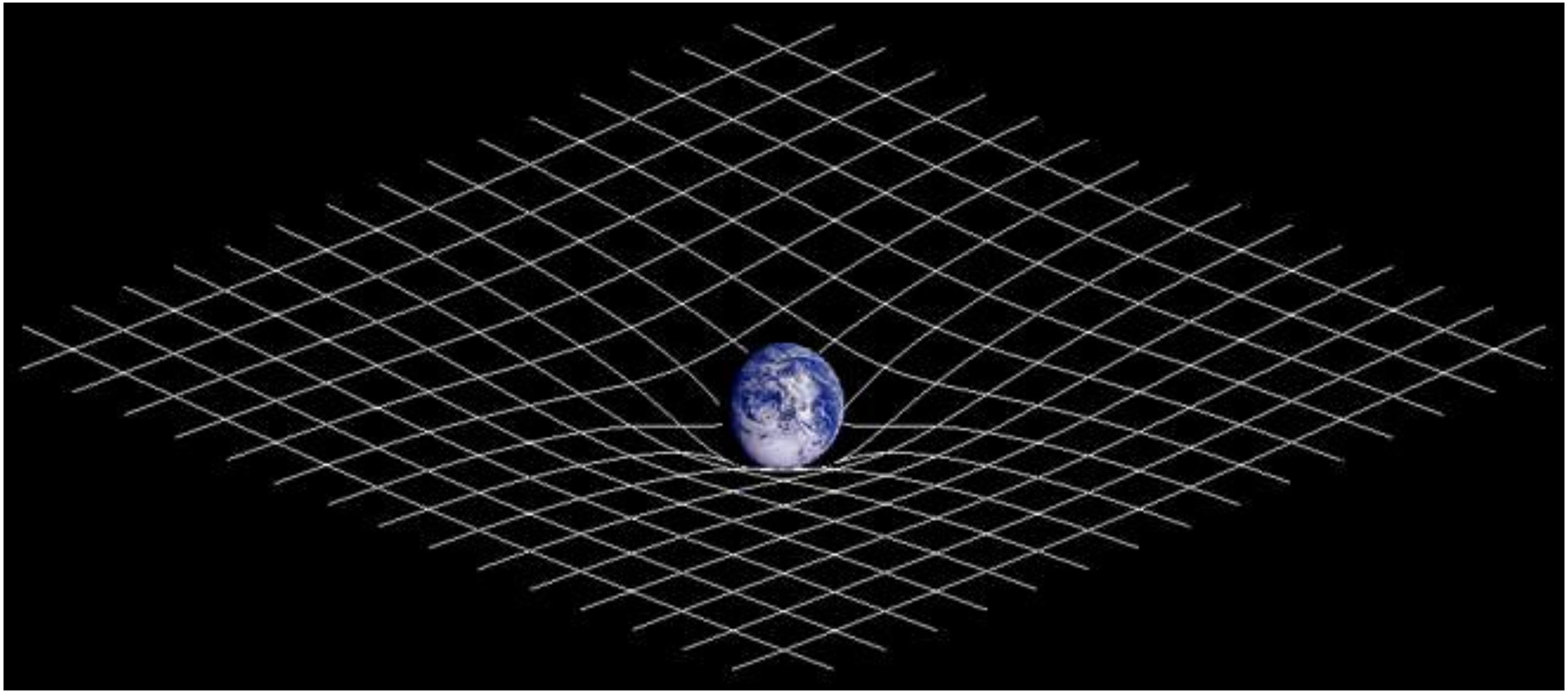
IceCube coll., ICRC 2017



Small statistics + location accuracy ⇒ astrophysical sources are still unknown
(see however lecture 3: multi-messenger strategies)

Gravitational waves

- General relativity: gravity treated as a result of curvature of spacetime caused by presence of mass.
- The more mass, the greater the curvature of space time.
- As masses move around spacetime, curvature changes to reflect the changed locations of those objects.
- In certain circumstances, accelerating objects generate changes in the curvature which propagate outwards at the speed of light: gravitational waves.



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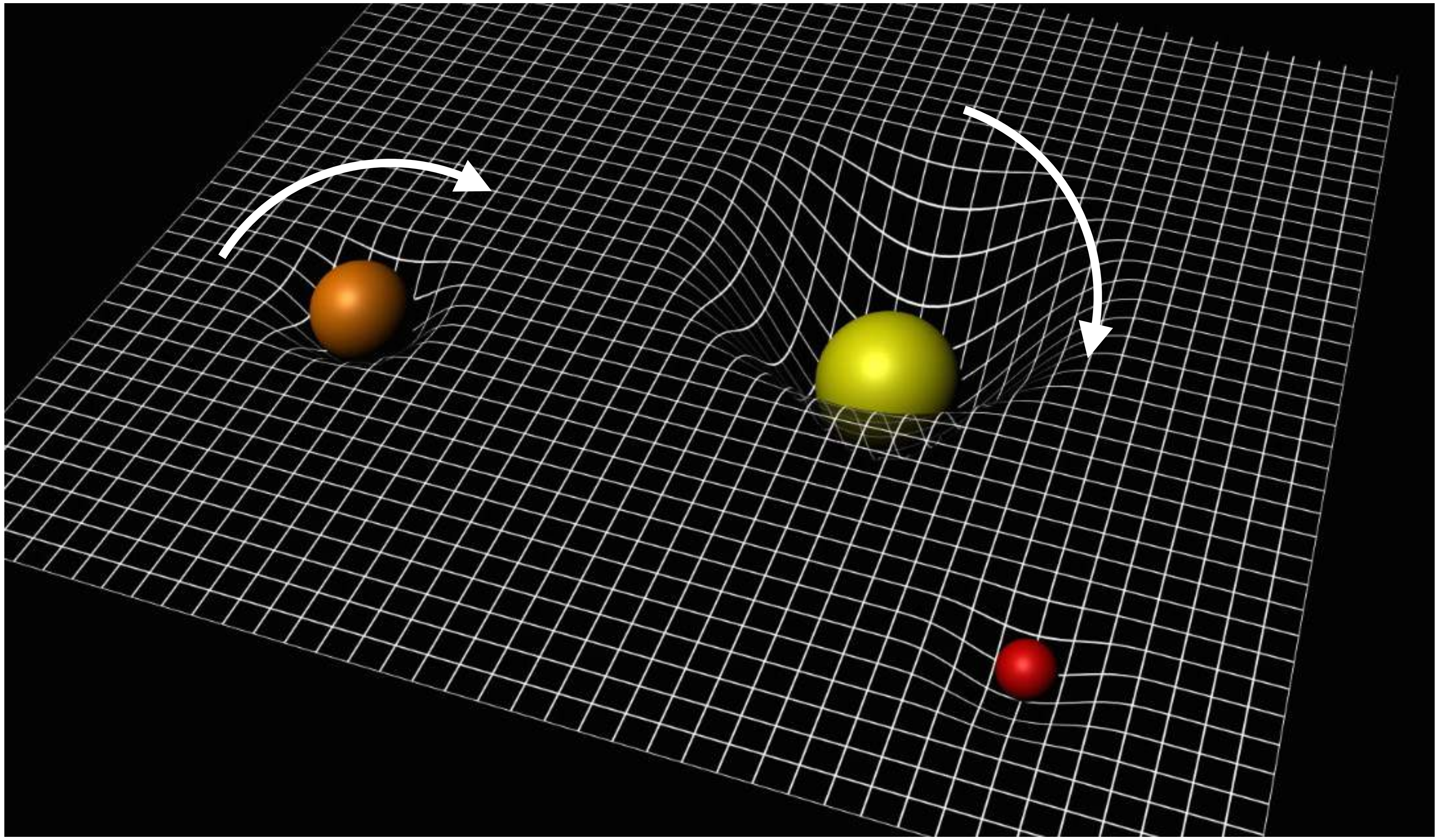
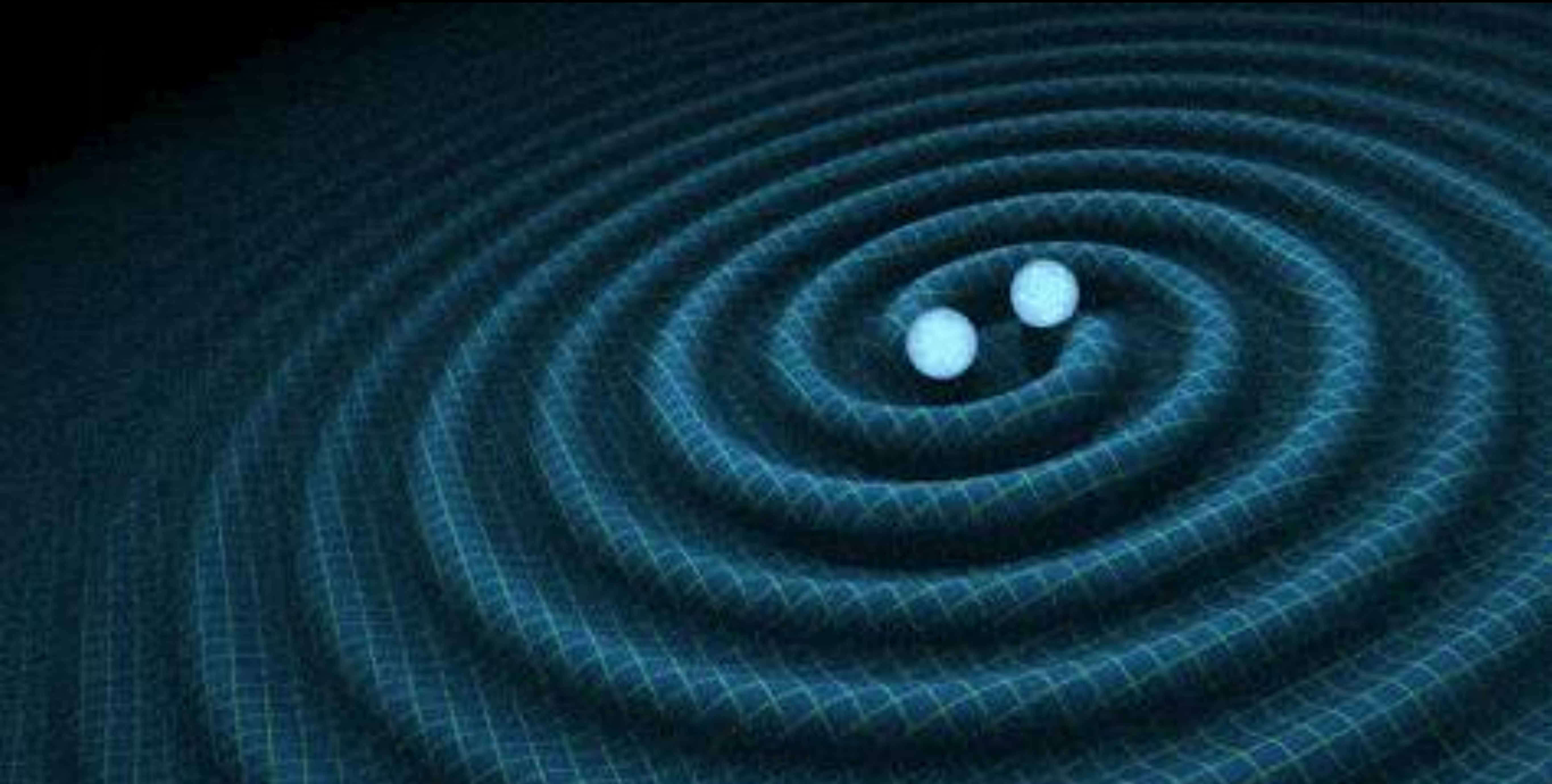
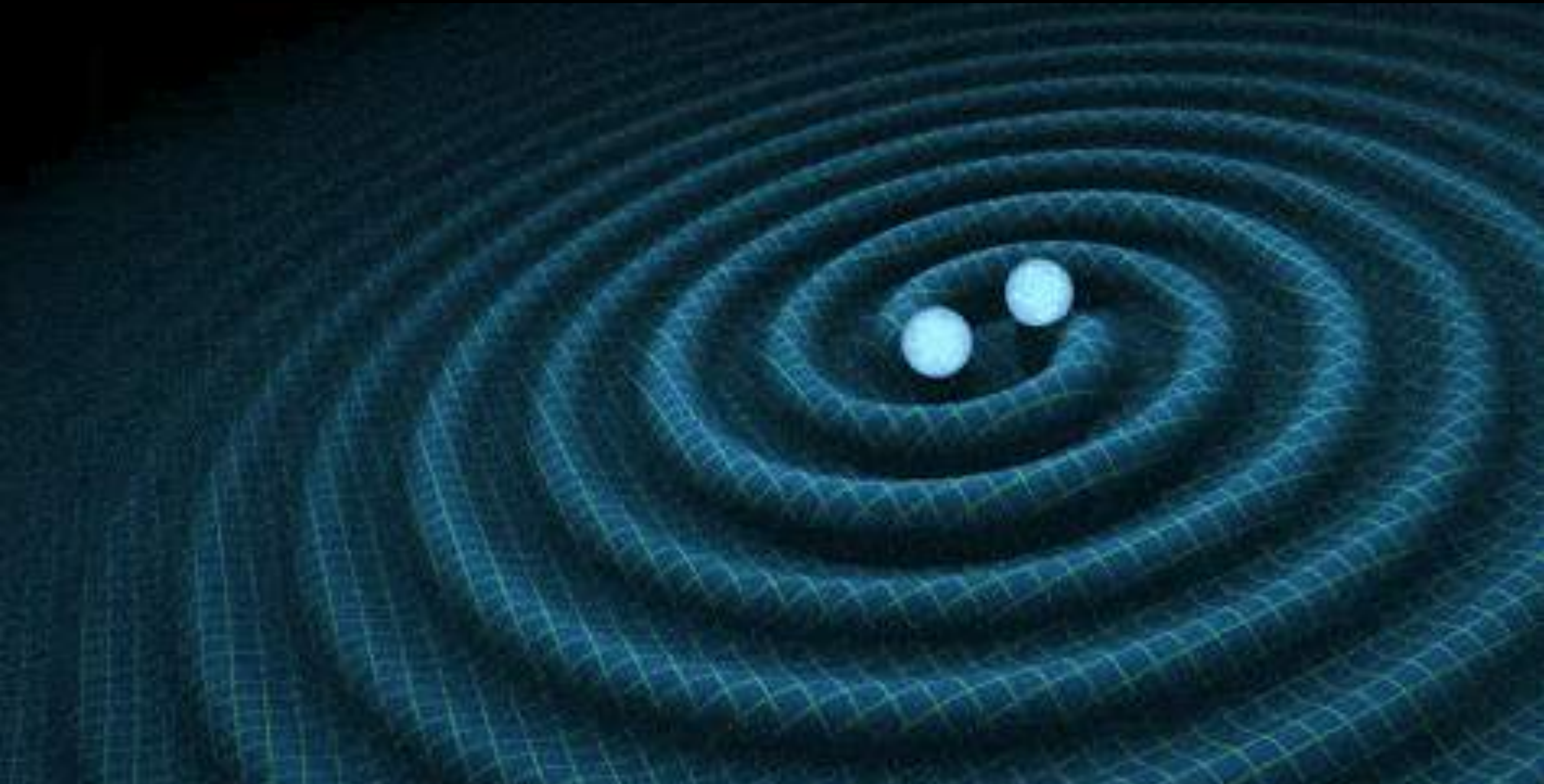


Gravitational waves



Inspiraling compact objects (black holes or neutron stars) are predicted to be a powerful source of gravitational waves due to the very large acceleration of their masses as they orbit close to each other.

Gravitational waves



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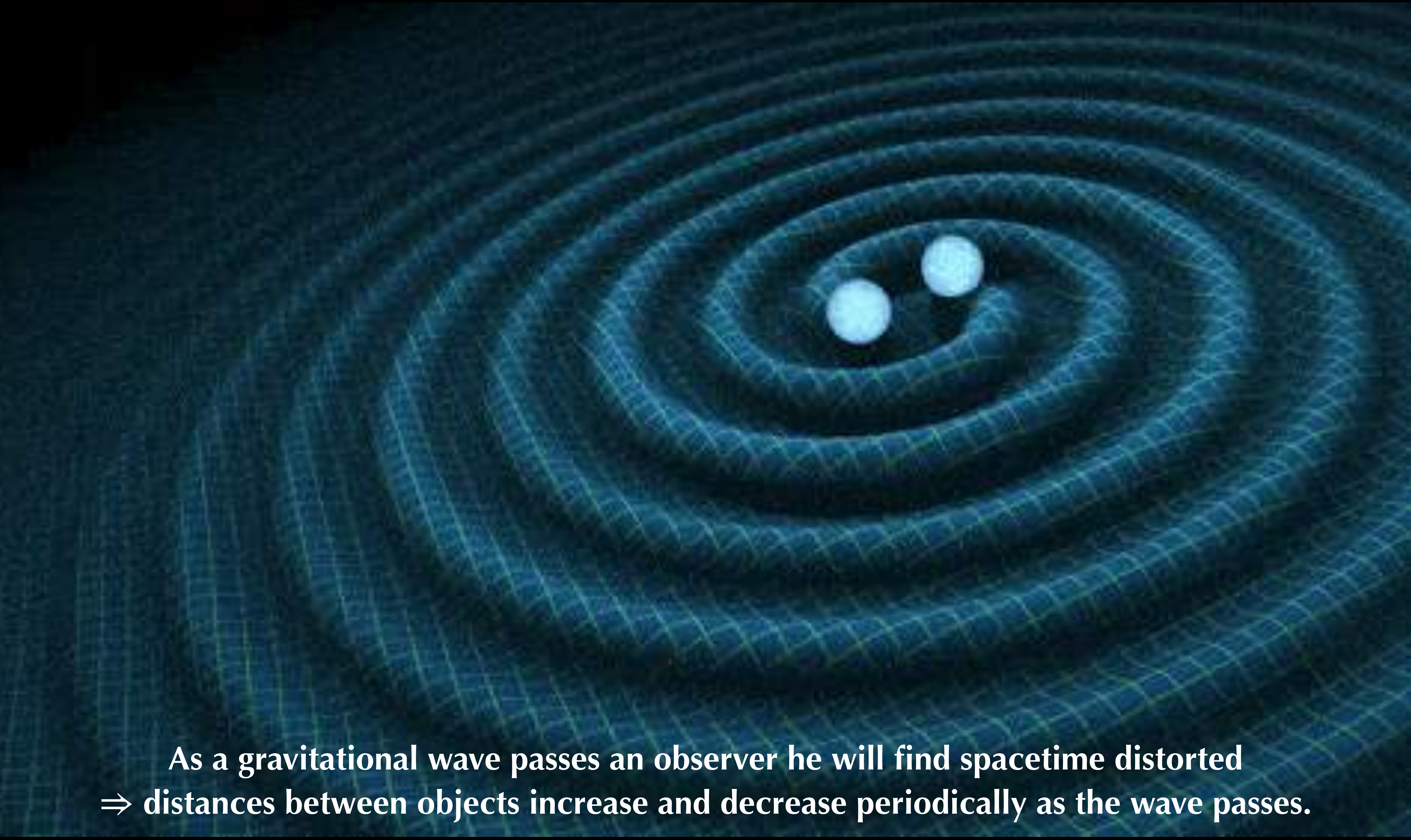
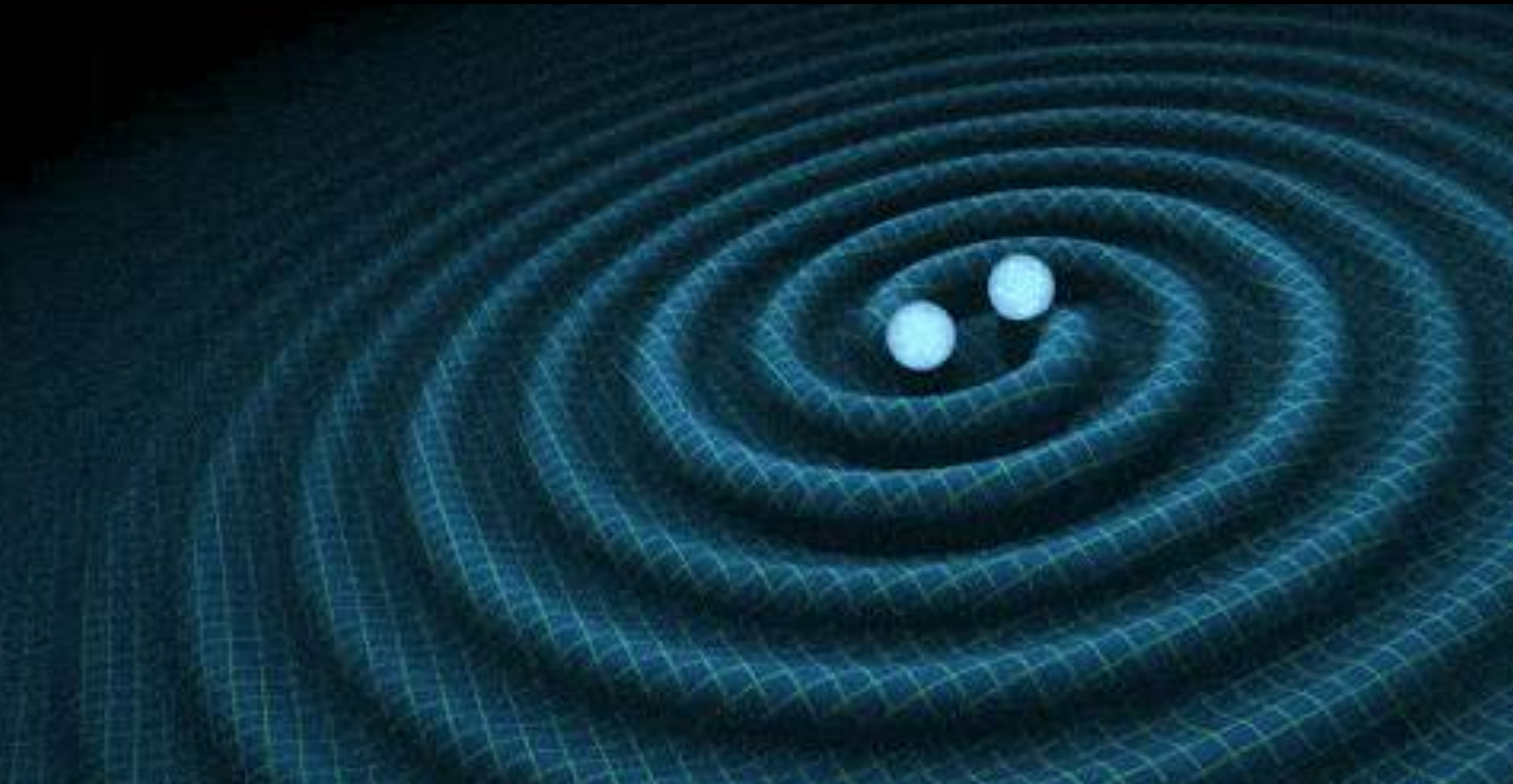


As a gravitational wave passes an observer he will find spacetime distorted
⇒ distances between objects increase and decrease periodically as the wave passes.

Gravitational waves



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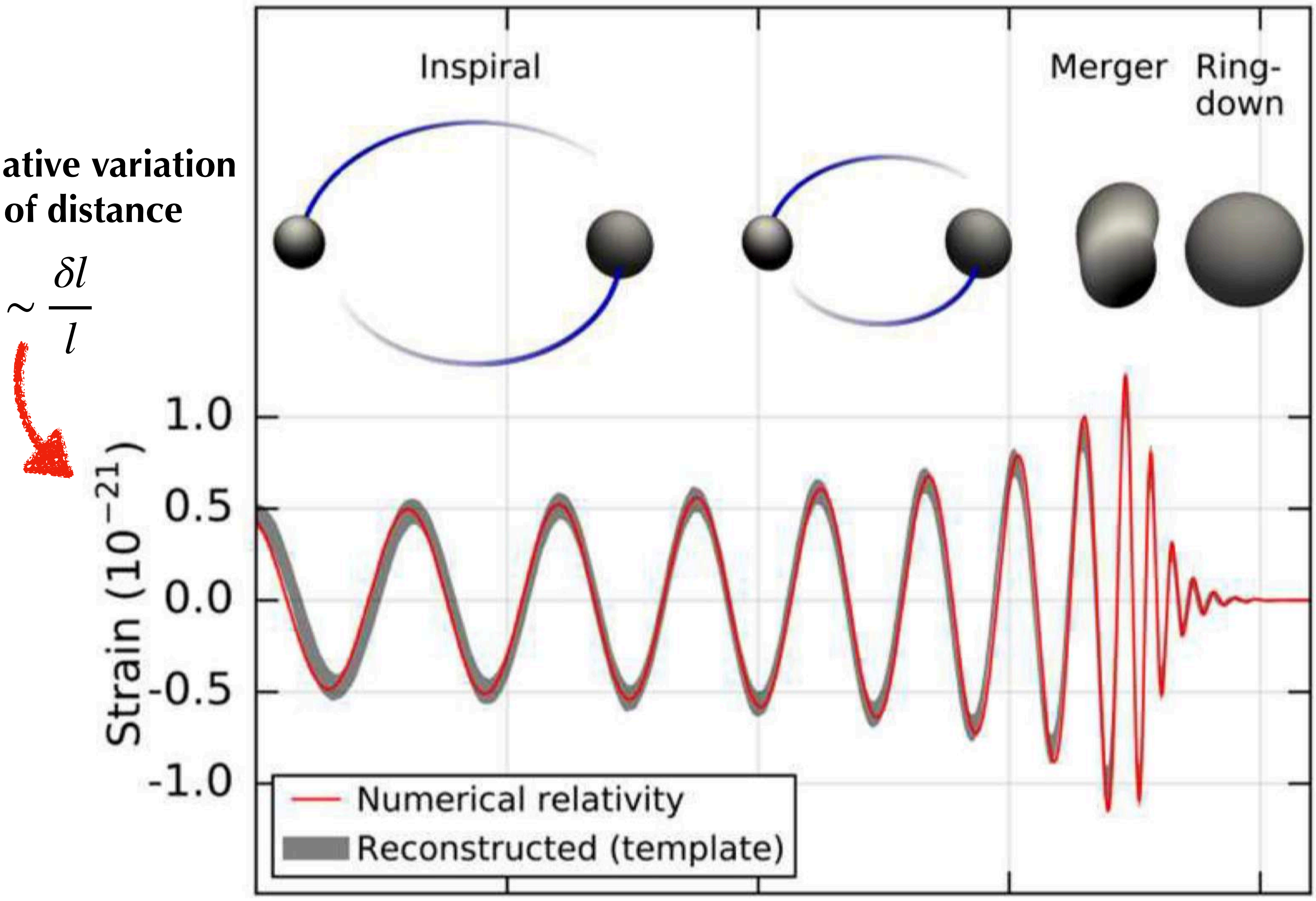
Gravitational waves

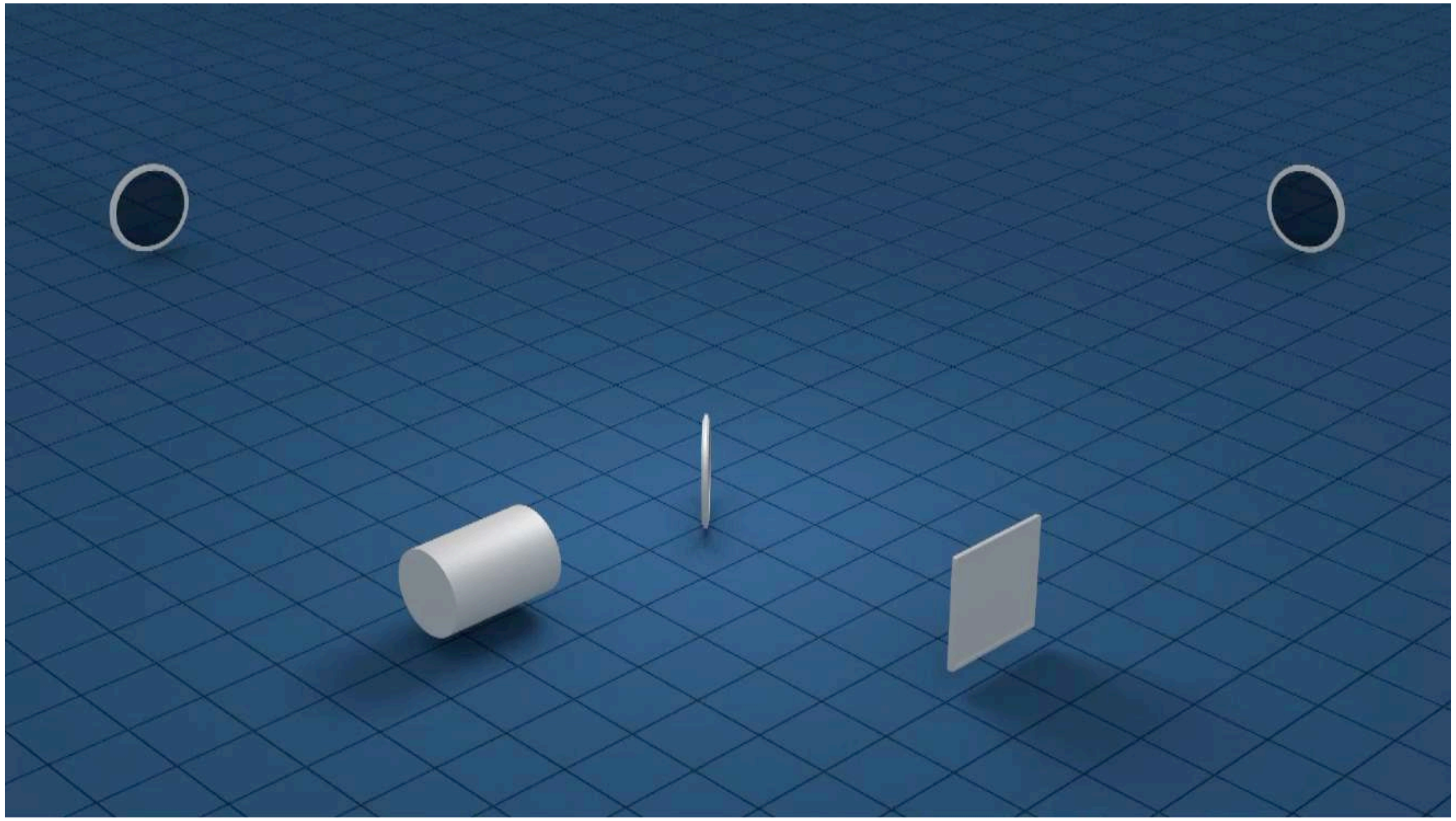
Relative variation of distance

$$\sim \frac{\delta l}{l}$$



Gravitational wave detection

Michelson interferometer



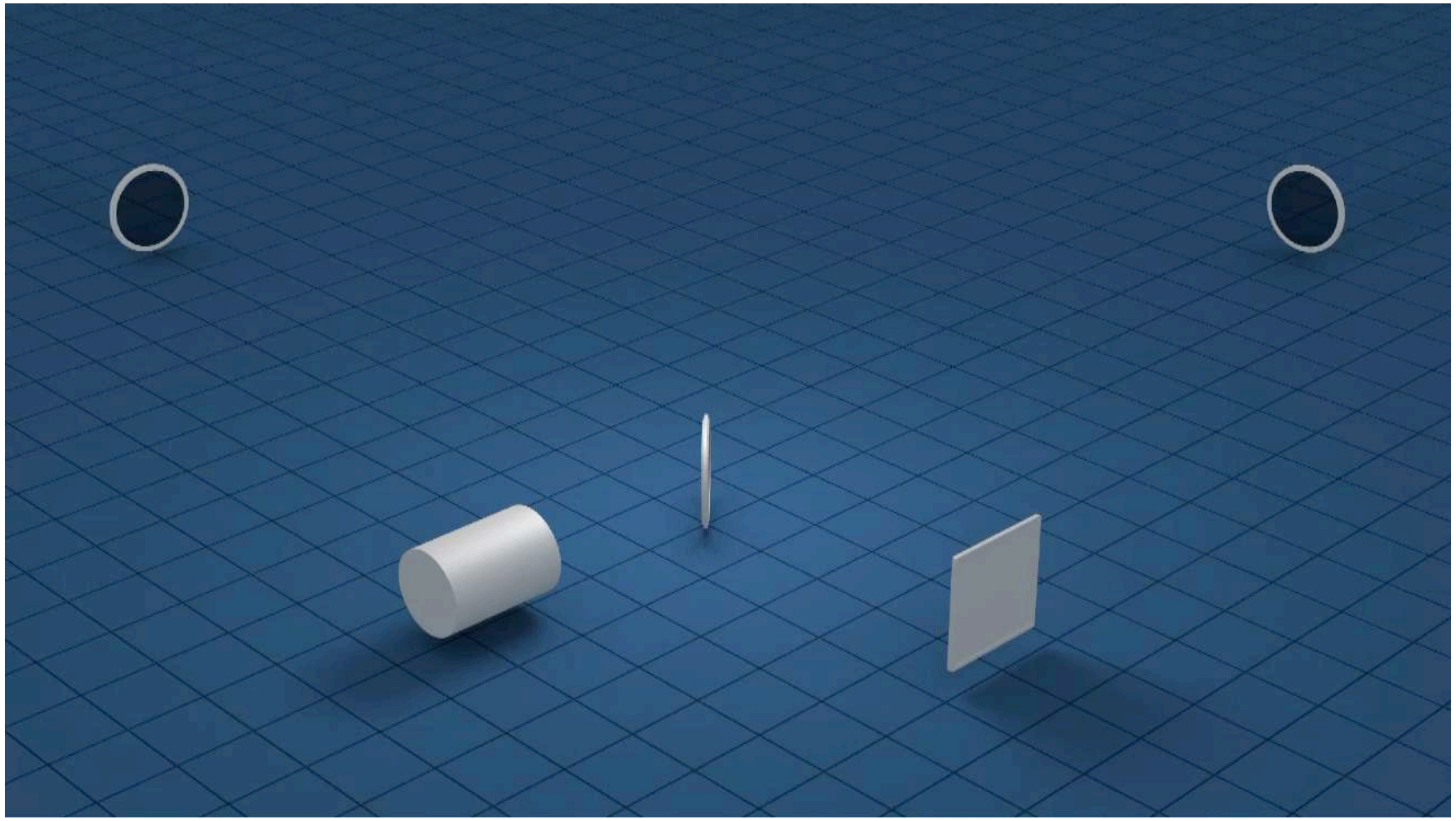
- Laser beam directed toward a beam splitter, which splits it into two separate and equal beams. Light beams then travel perpendicularly to a distant mirror. The mirrors reflect the light back to the beam splitter.

- When gravitational waves pass through this device, they cause the length of the two arms to alternately stretch and squeeze by infinitesimal amounts ($\Delta l \sim 10^{-19}\ m$).

- This produces interferences.
  - Without gravitational waves: beams kept out of phase ⇒ no light on the detector.
  - If gravitational wave detected: phase shift varies ⇒ signal flickering on the detector.

Gravitational wave detection

Michelson interferometer



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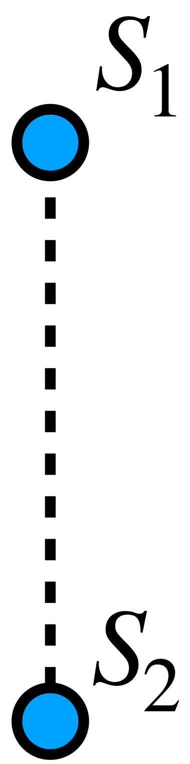
Gravitational wave detection

Source location on sky determined by triangulation of the signal over several detectors



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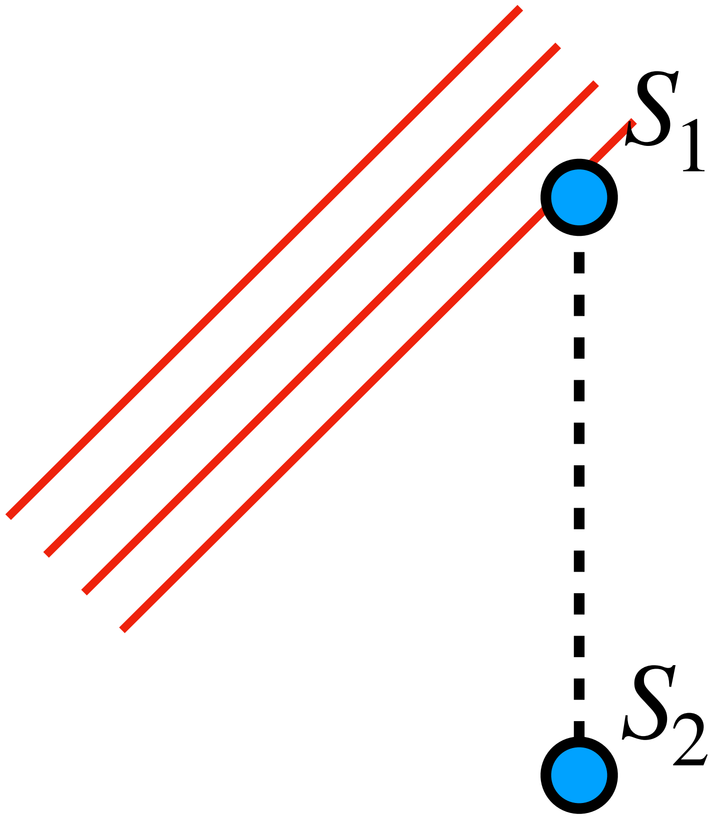

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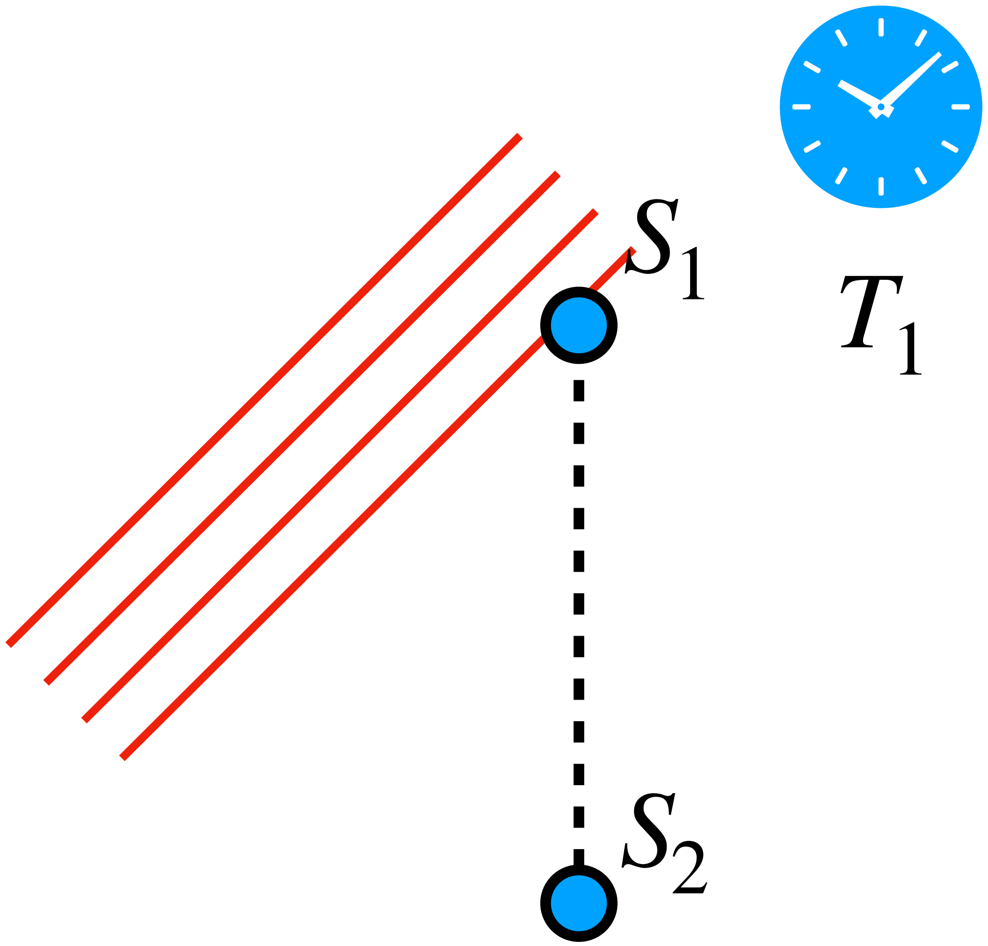

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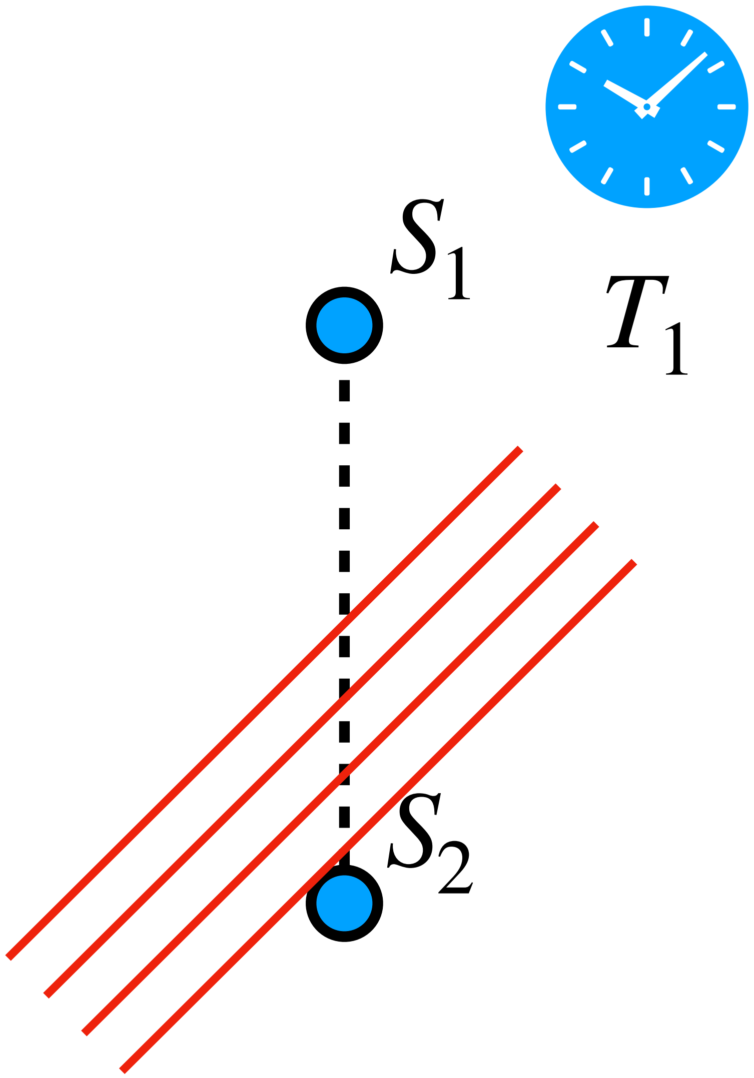

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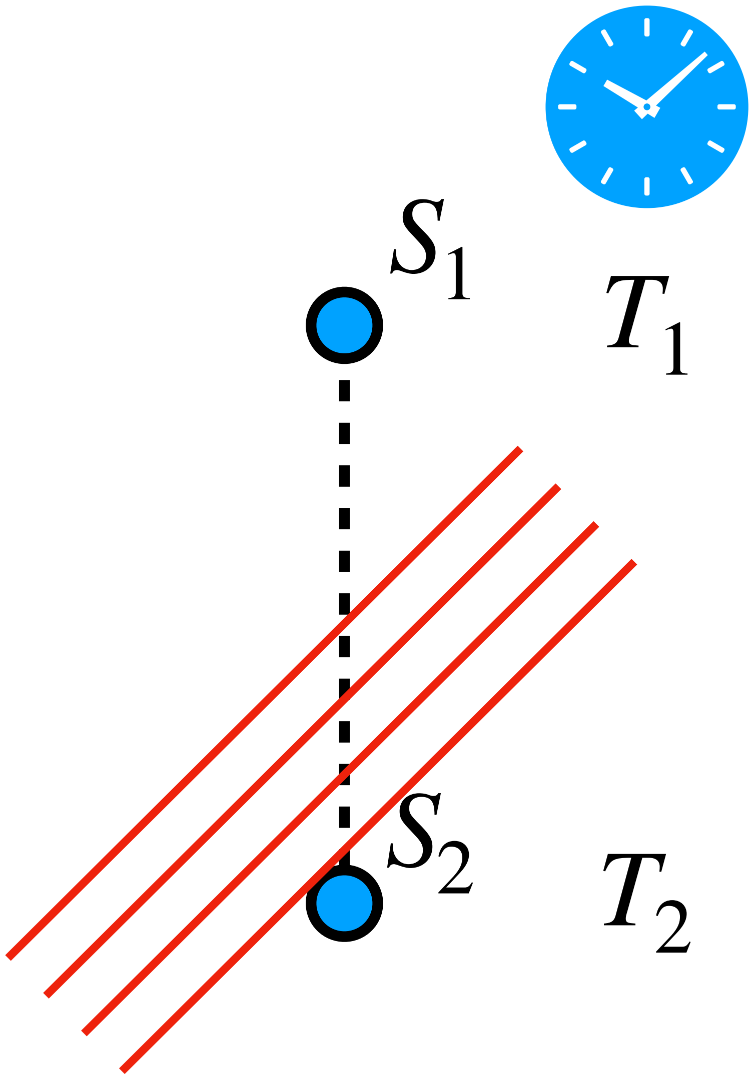

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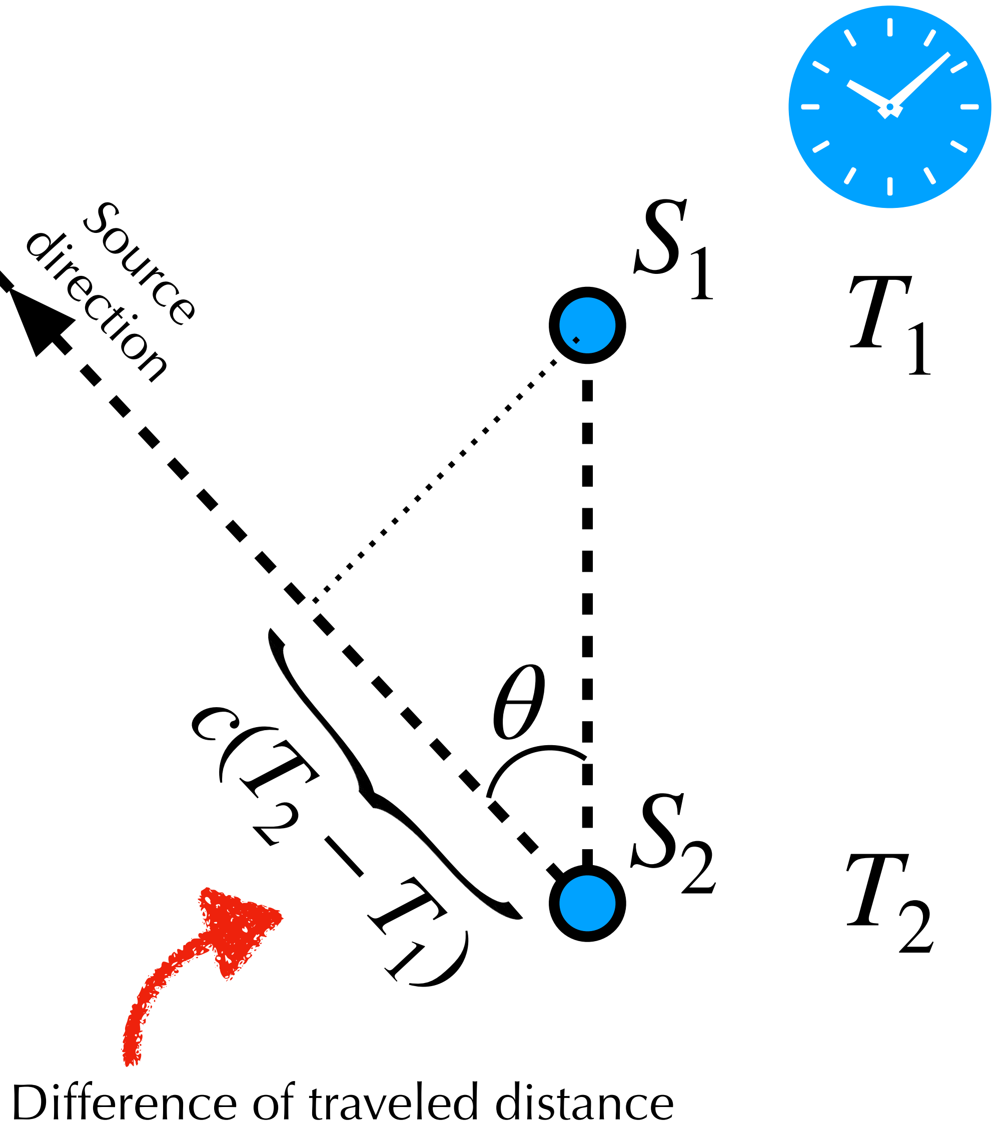

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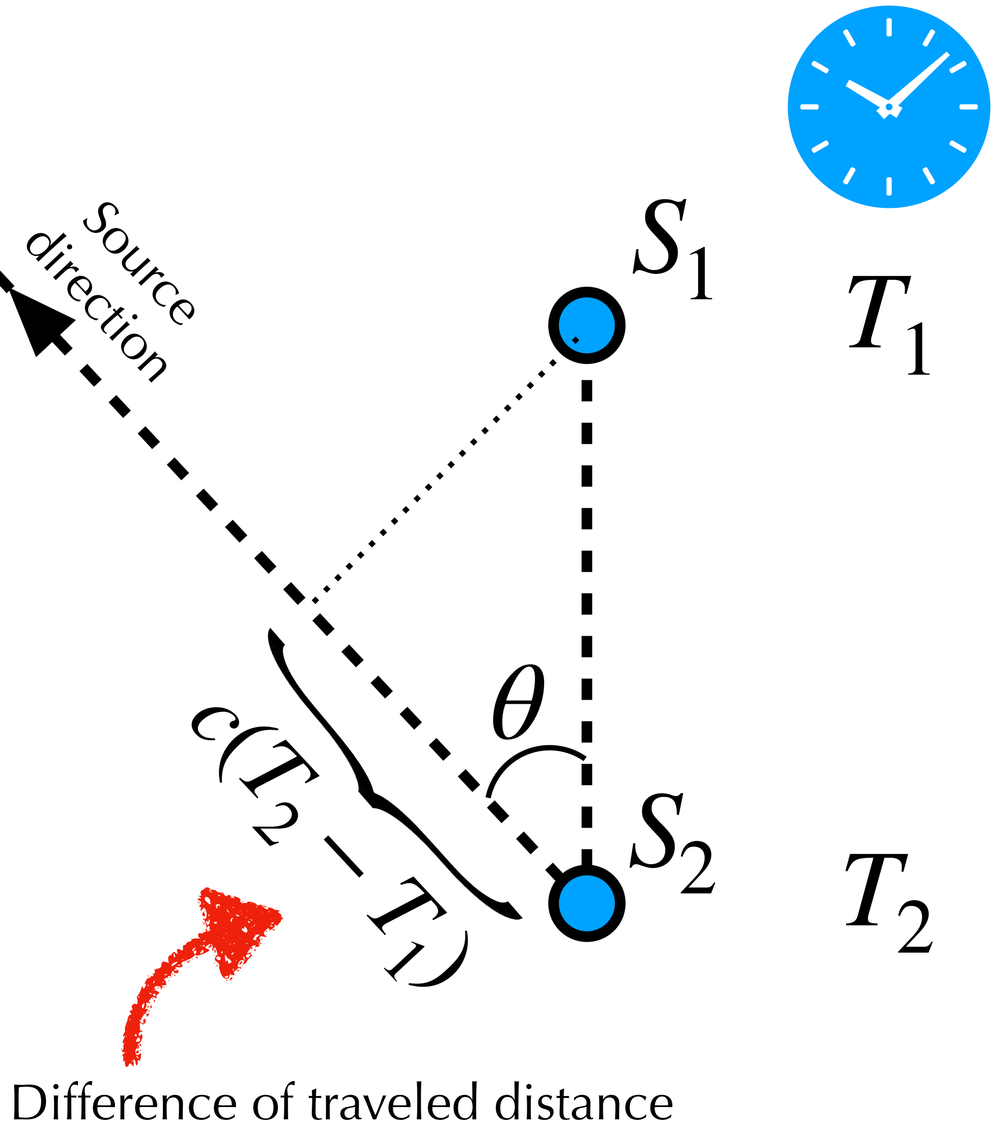

$$\Rightarrow \cos(\theta) = \frac{c(T_2 - T_1)}{S_1 S_2}$$

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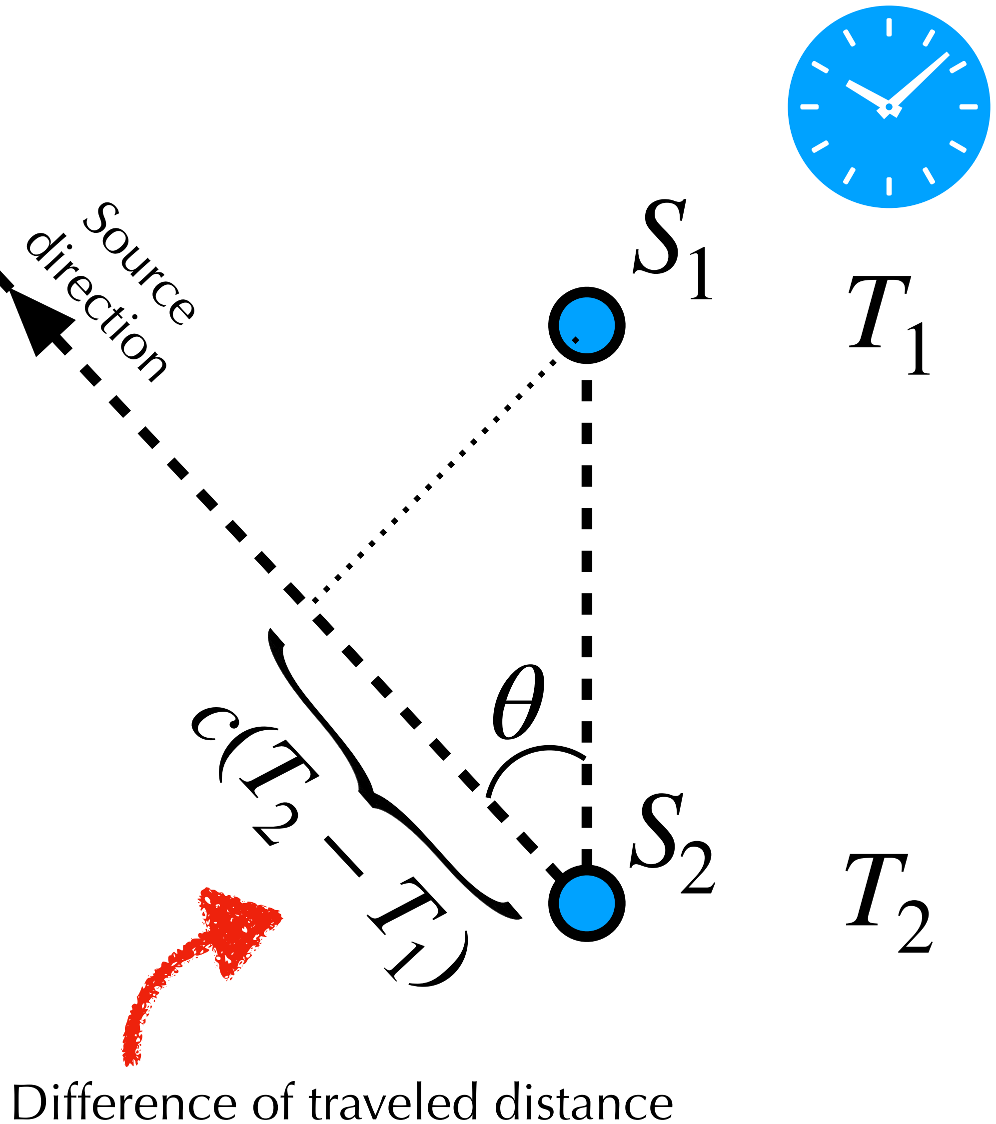

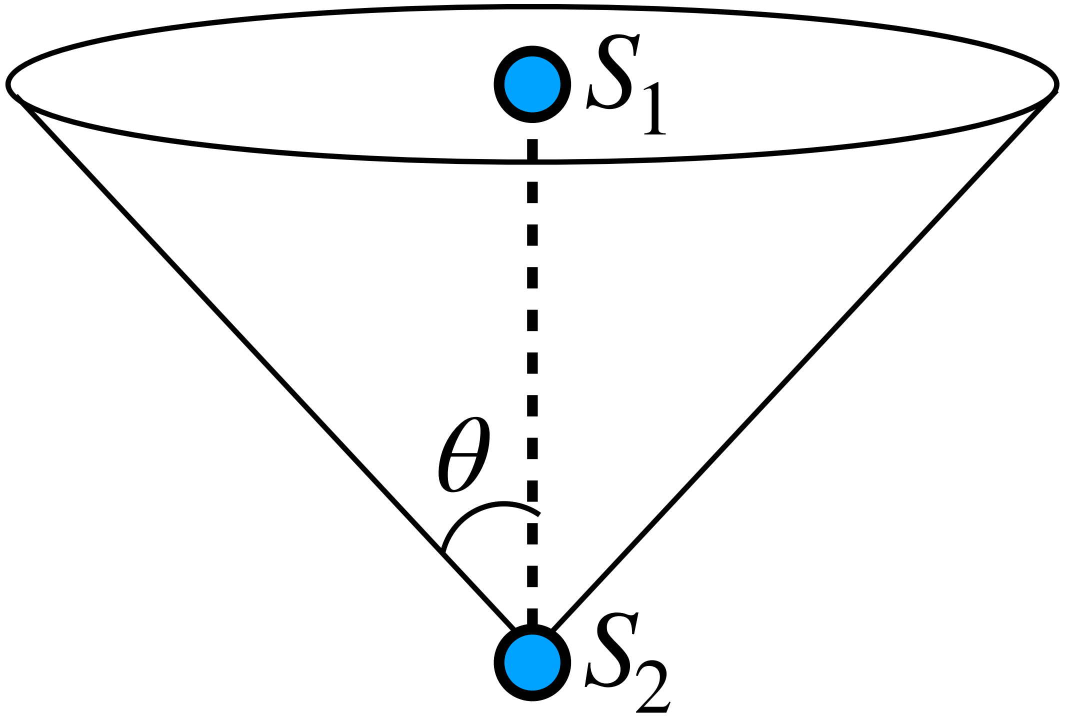

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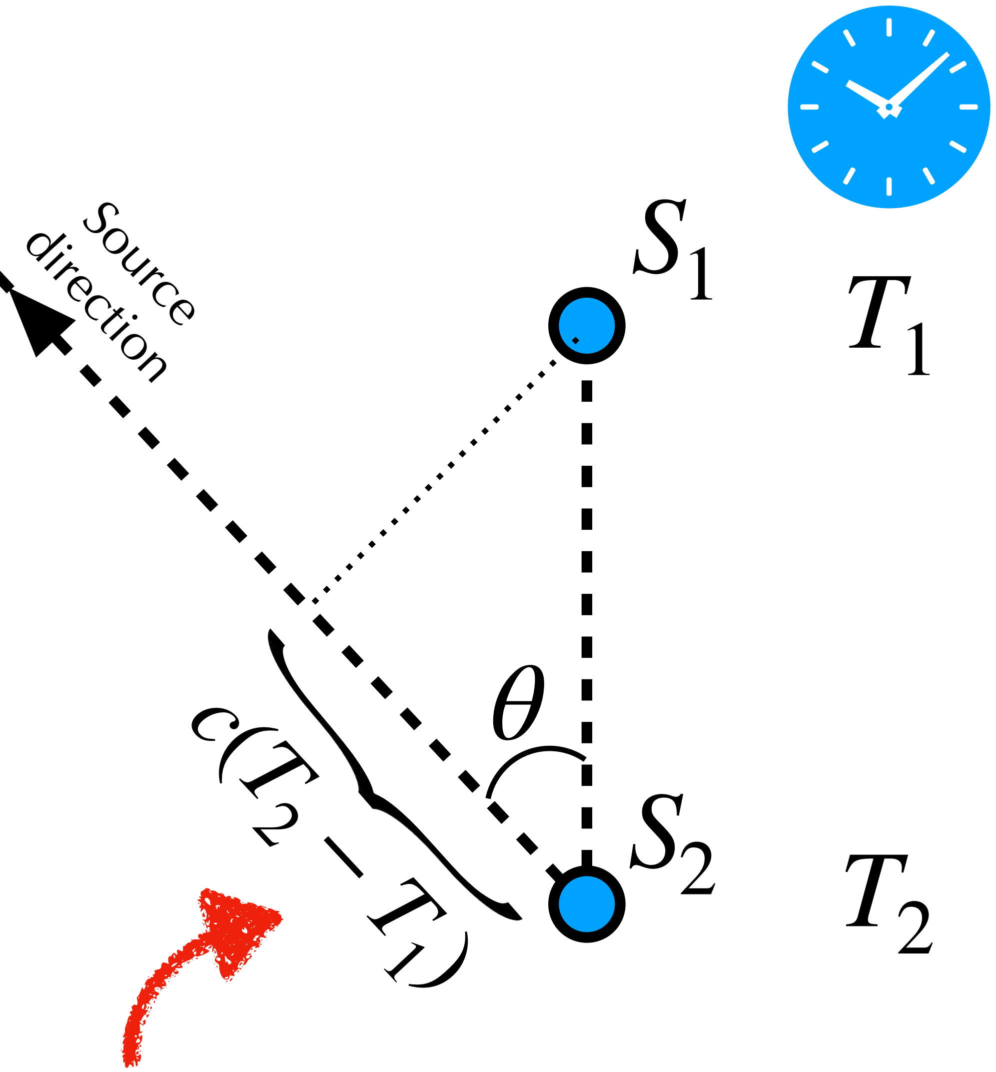
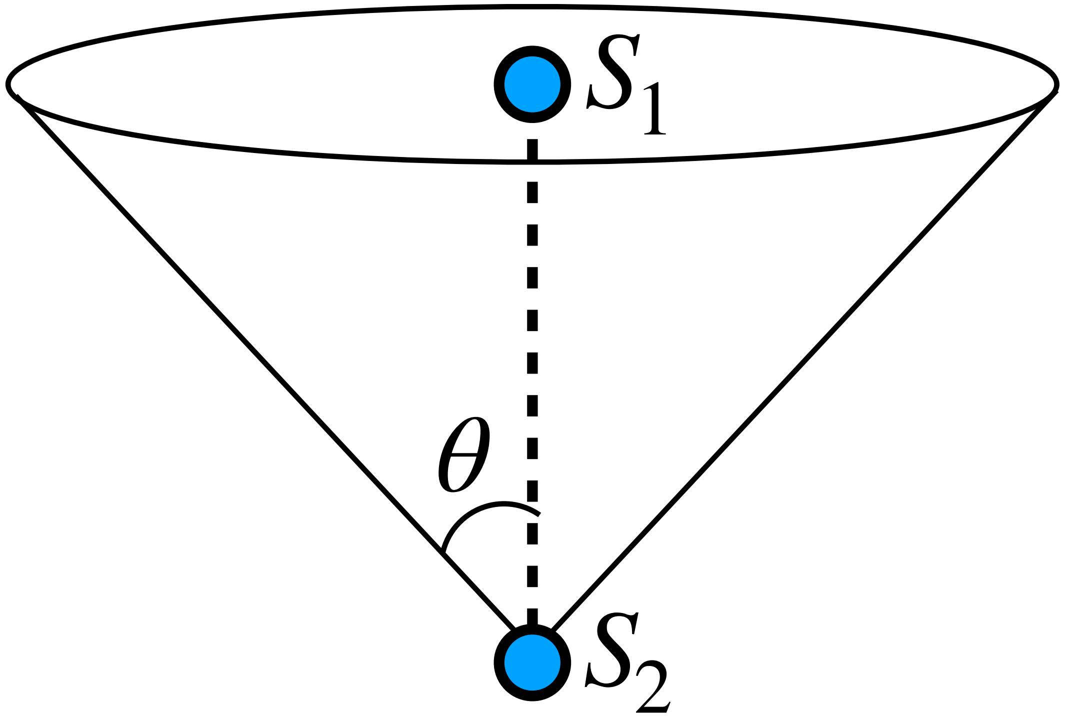


Difference of traveled distance



Two detectors ➜ locus of constant time delay forms a ring on the sky concentric about the baseline between the two sites

$$\Rightarrow \cos(\theta) = \frac{c(T_2 - T_1)}{S_1 S_2}$$

Gravitational wave detection

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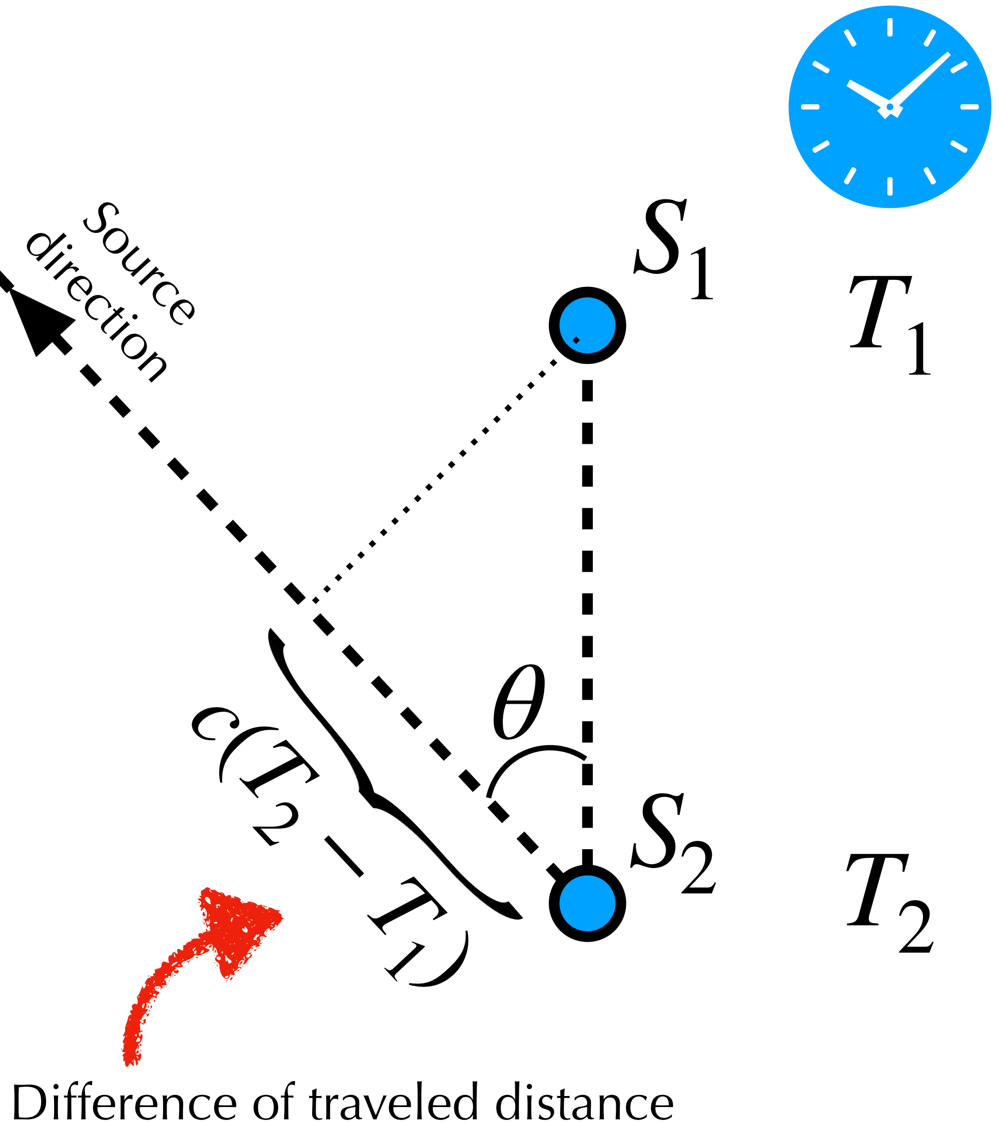

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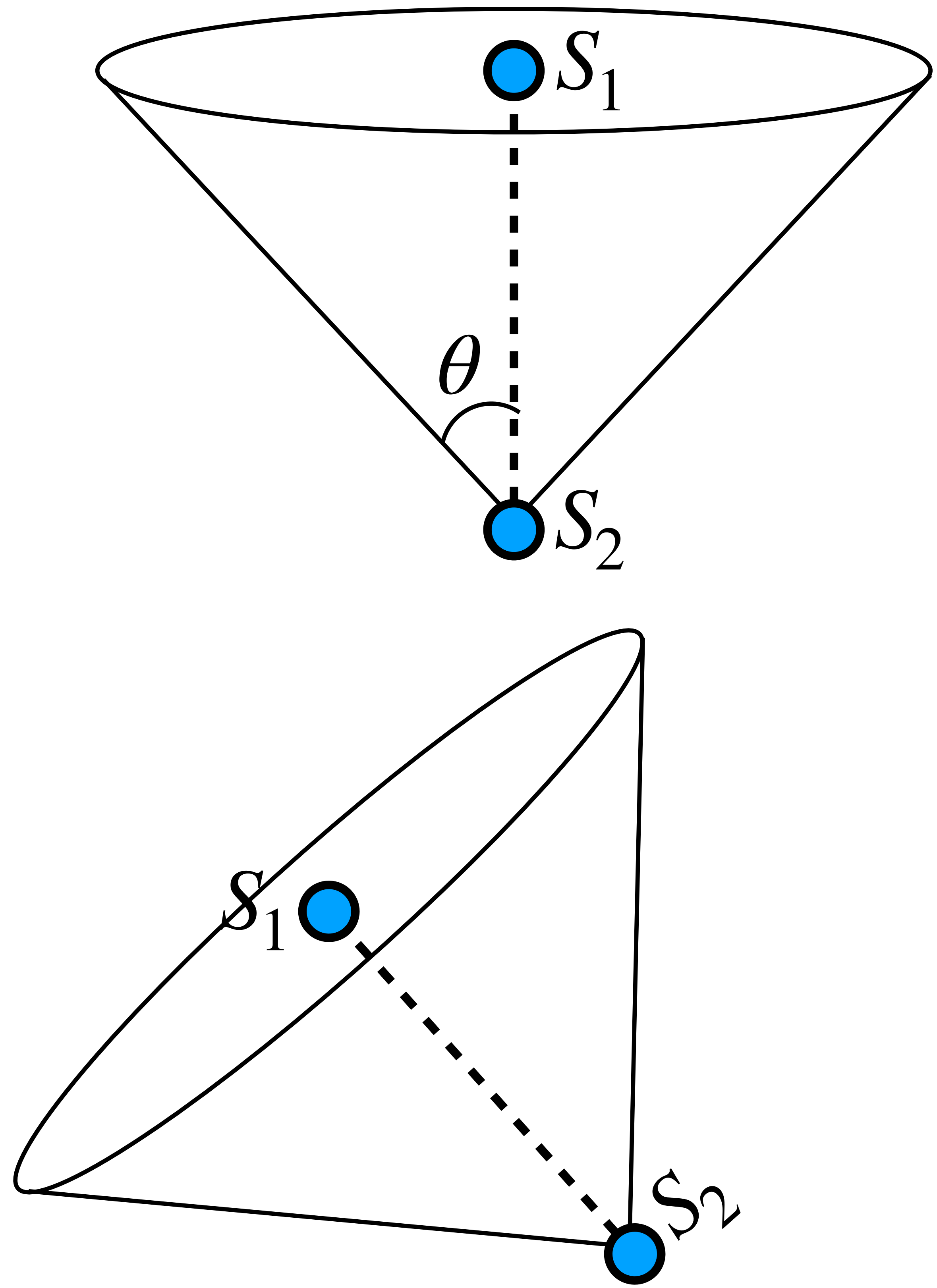

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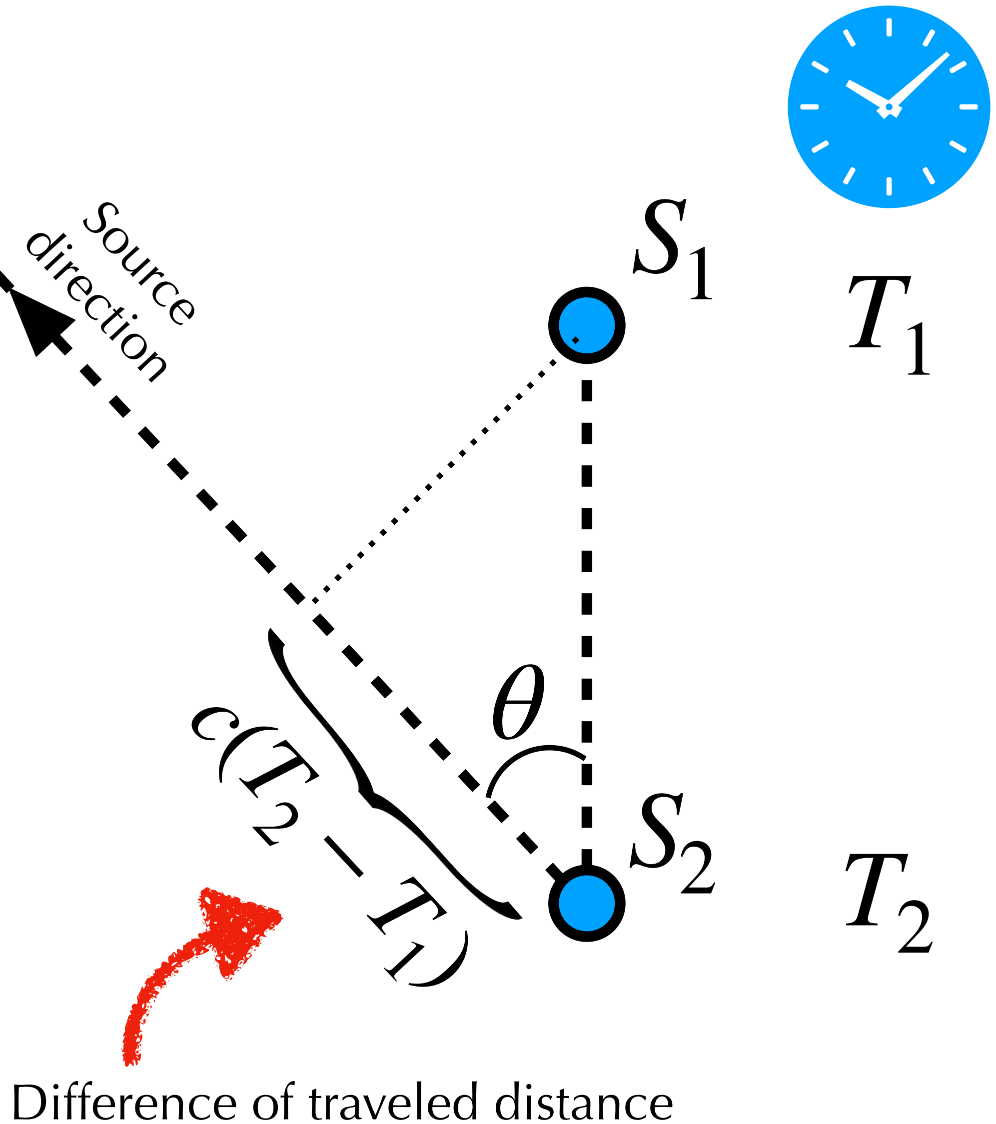

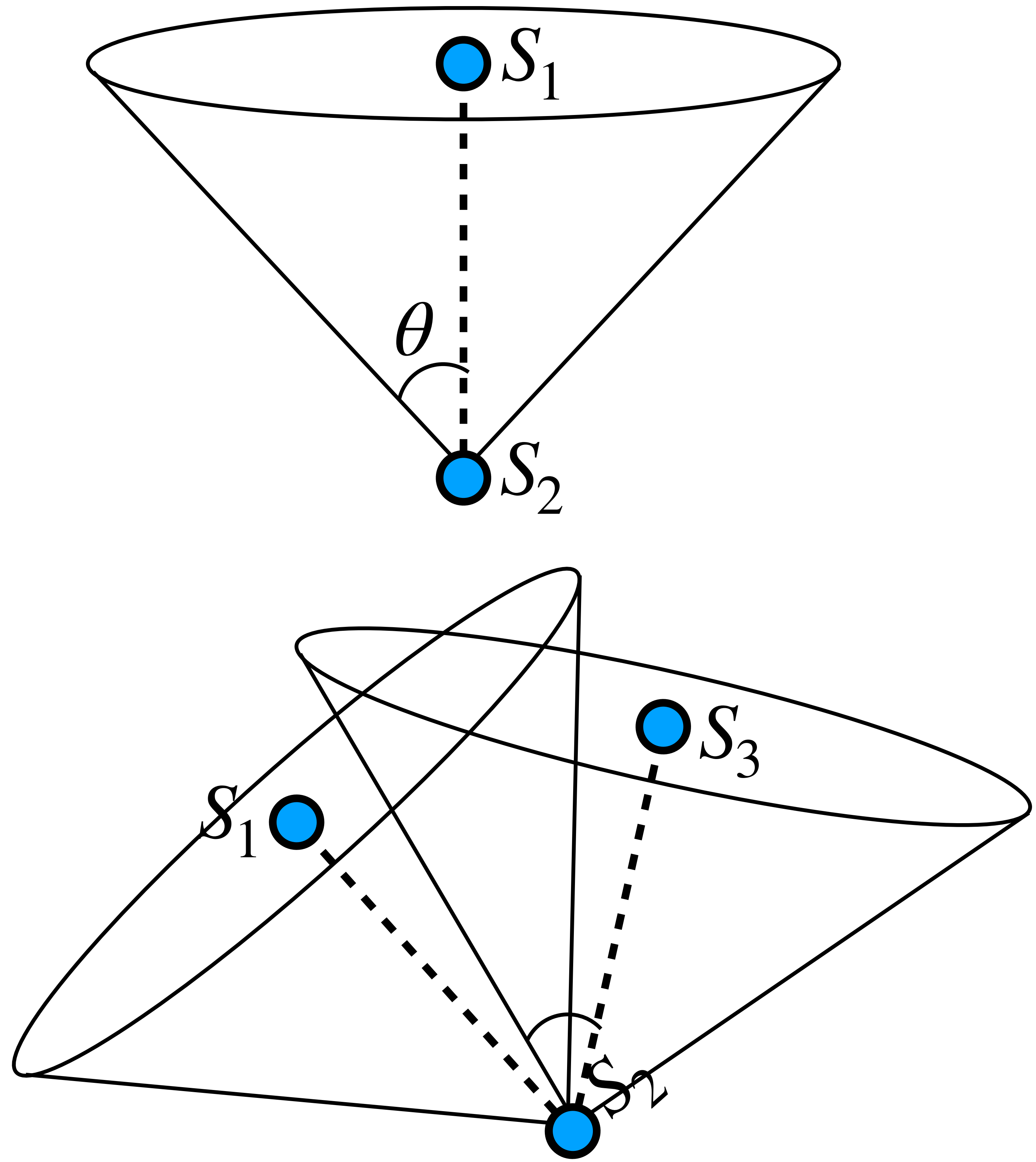

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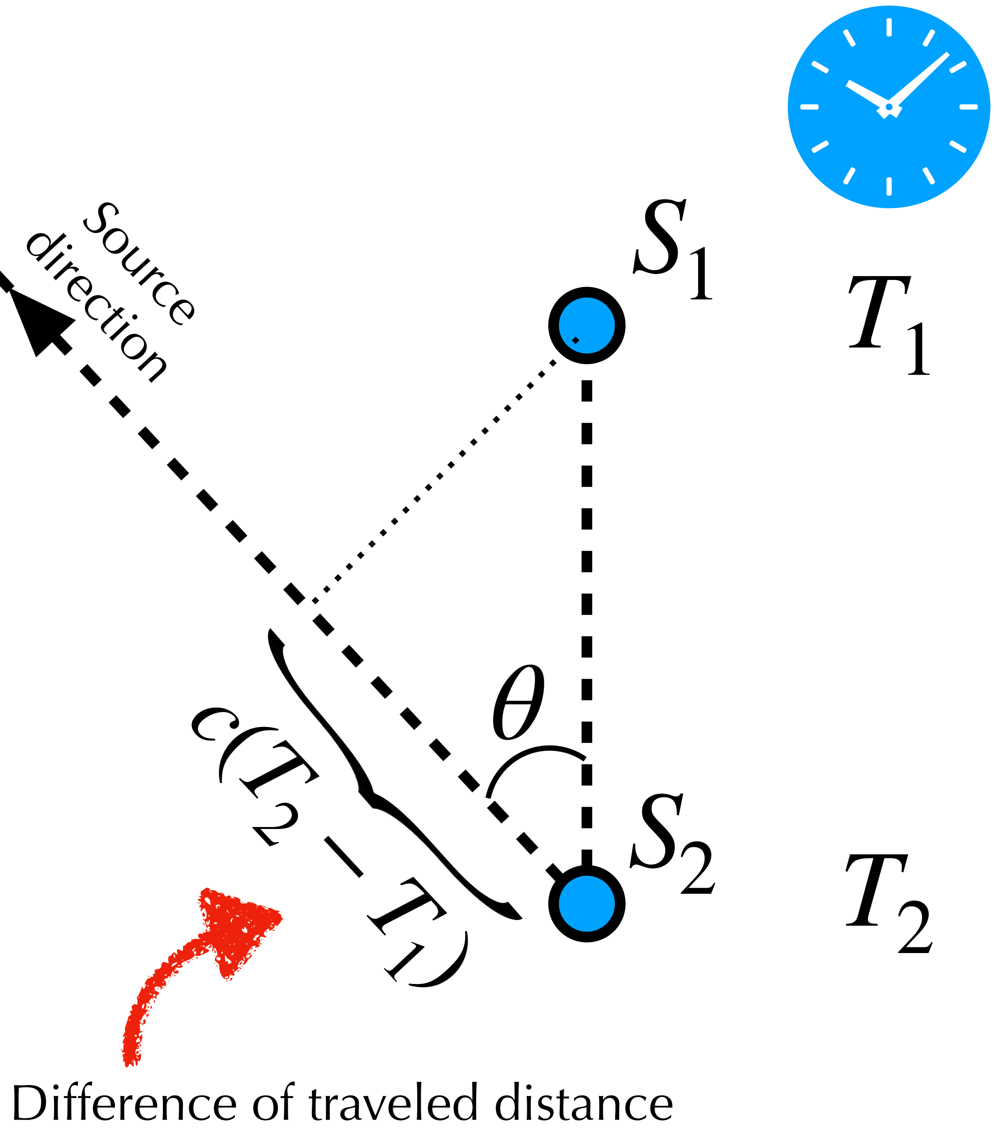

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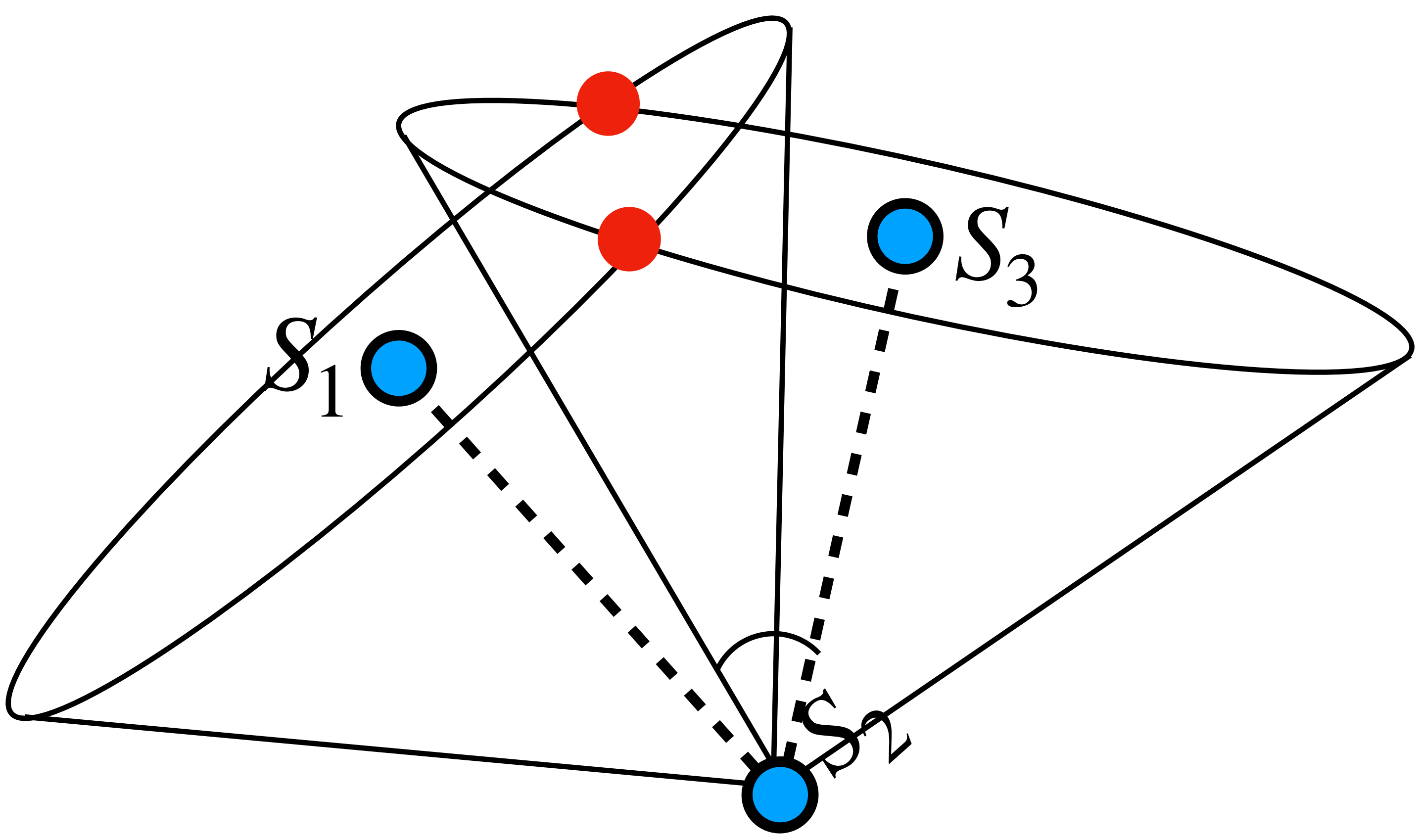
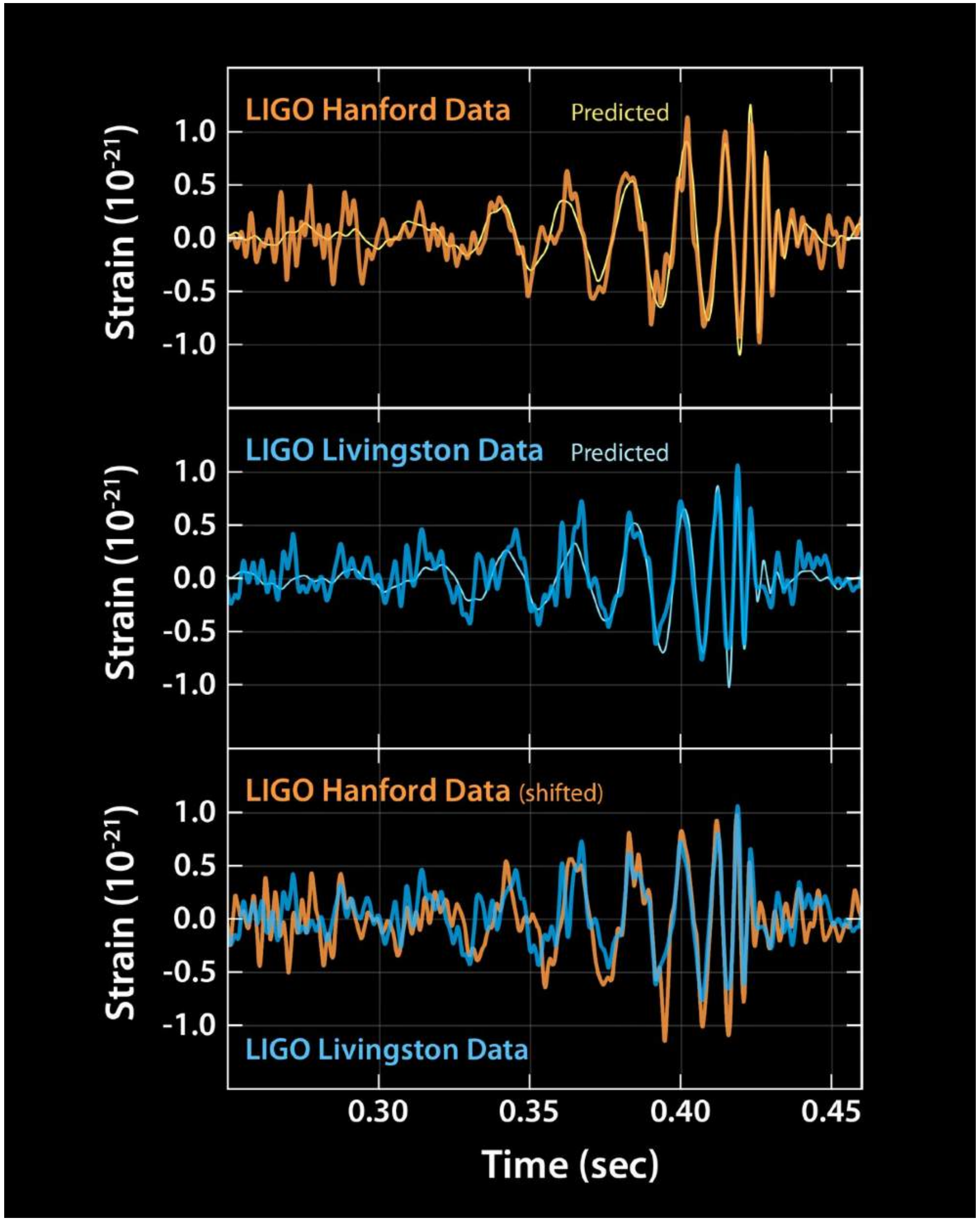
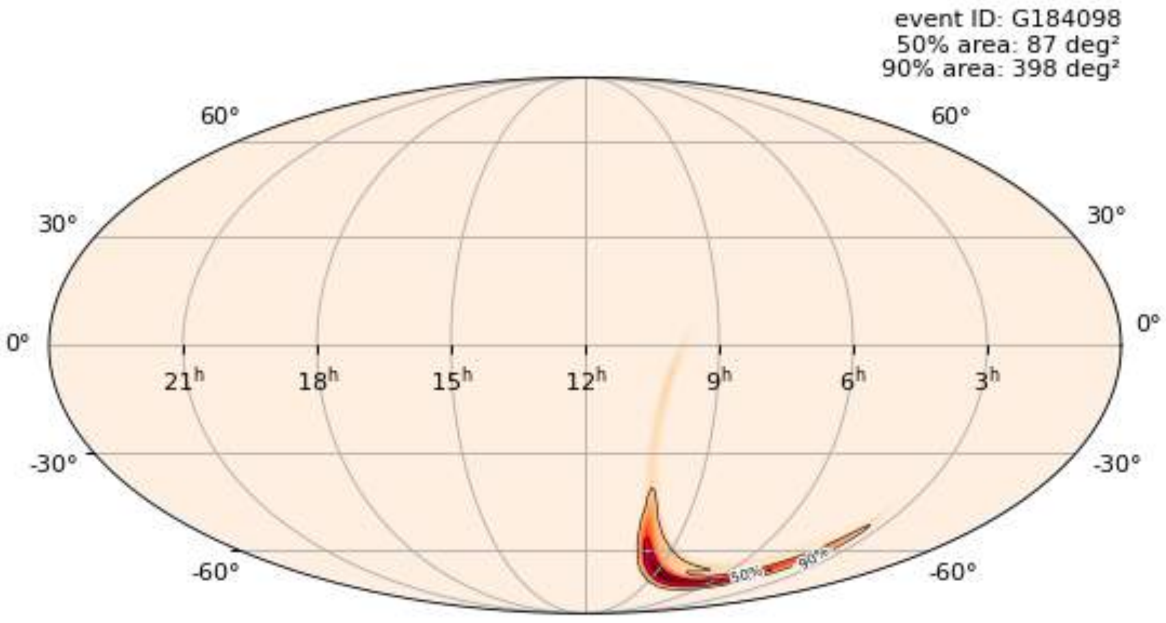
Three detectors ➜ rings intersect in **2 locations**
(including source real location)



First detection: GW150914

September 14, 2015





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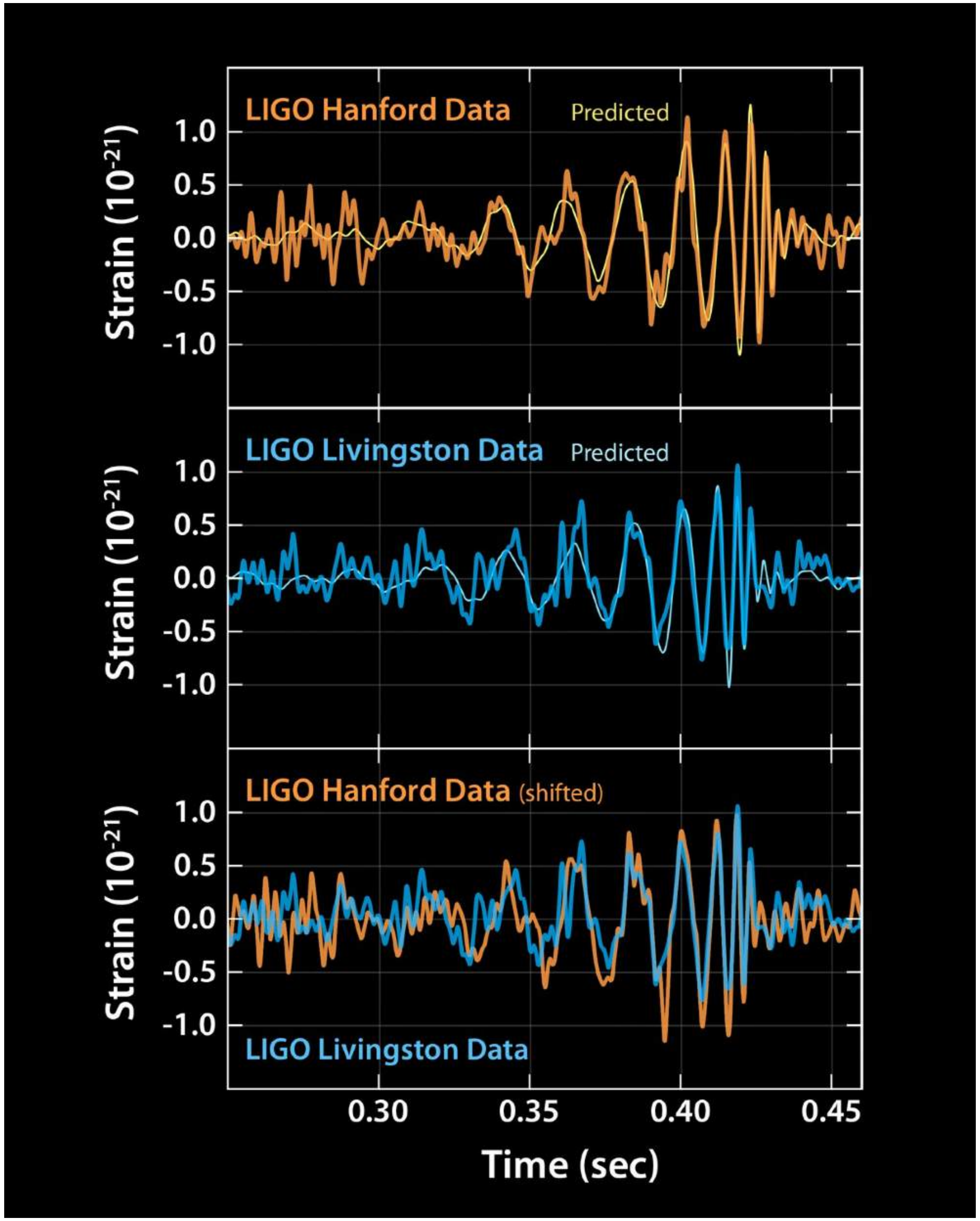
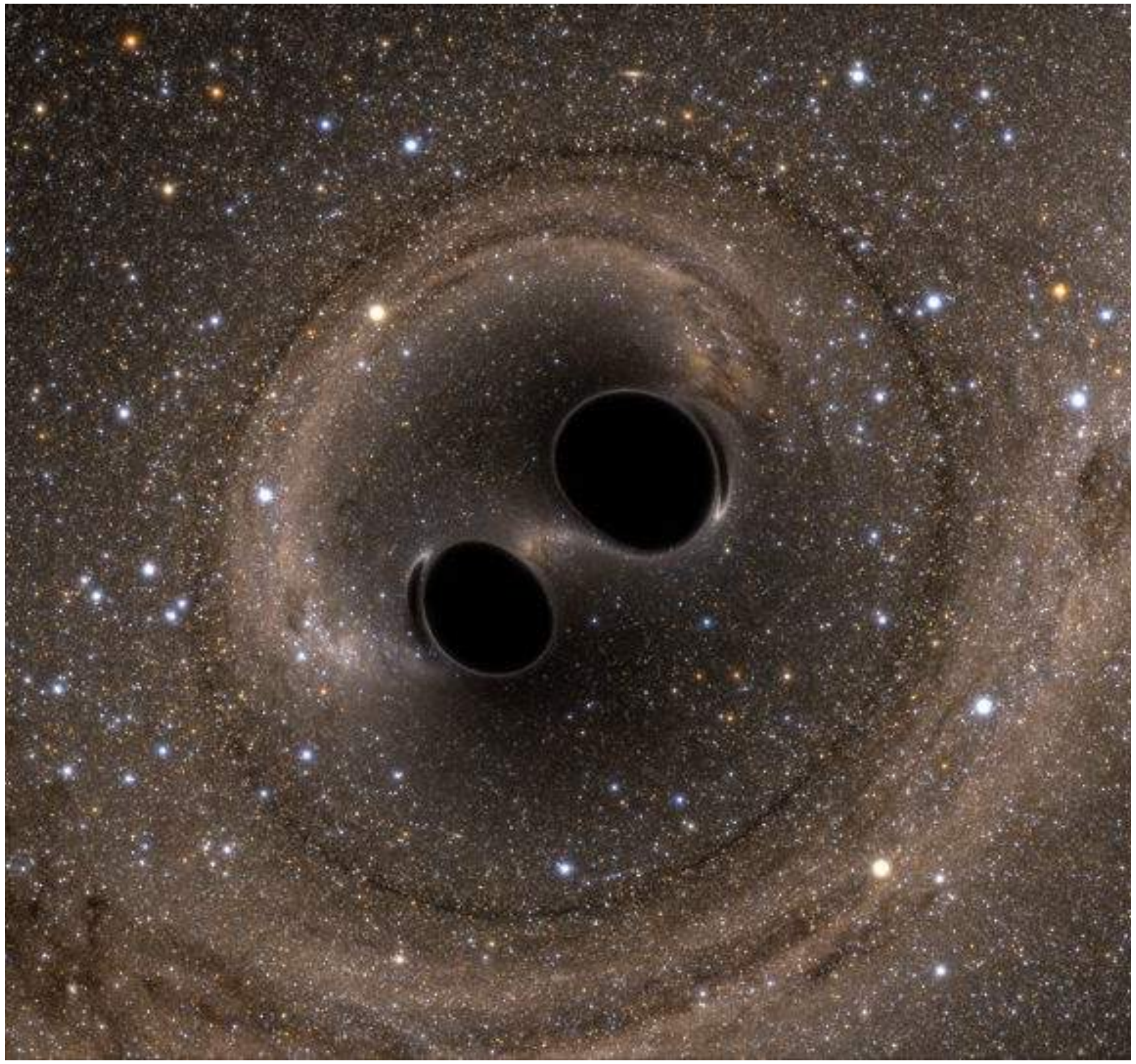


GW150914: Coalescence of two black holes of 36 and 29 $M_\odot$ respectively



No associated electromagnetic counterpart…

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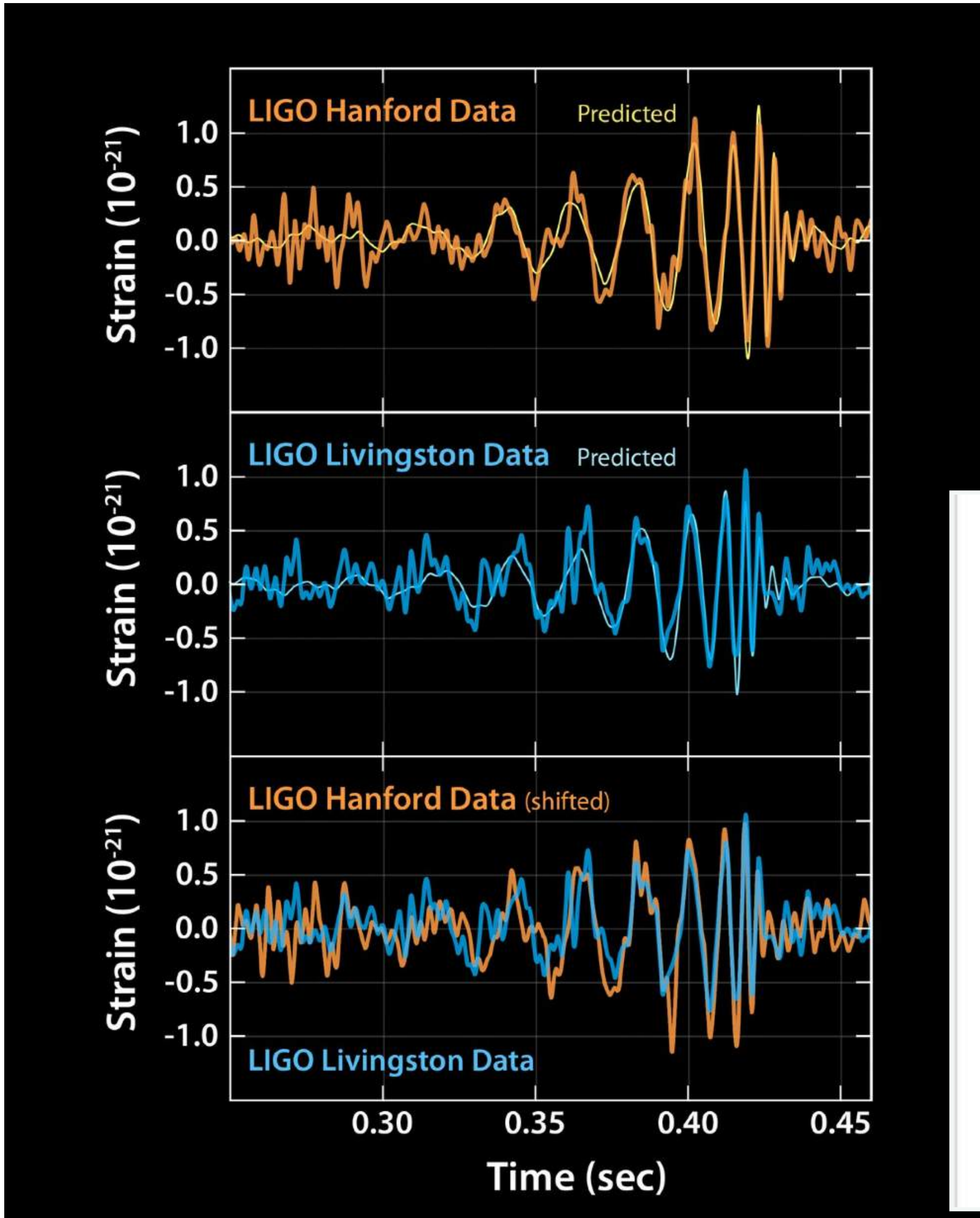

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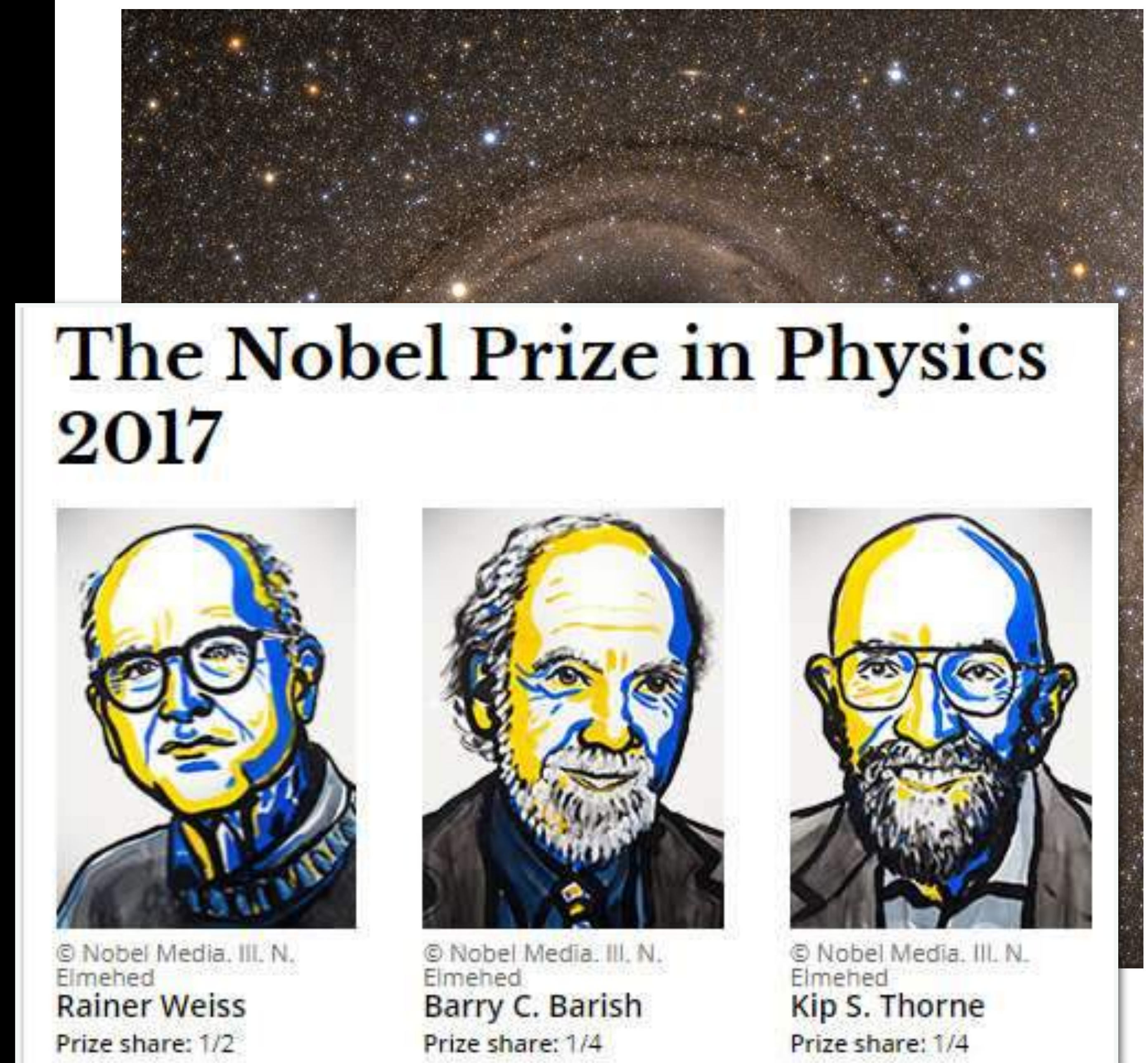
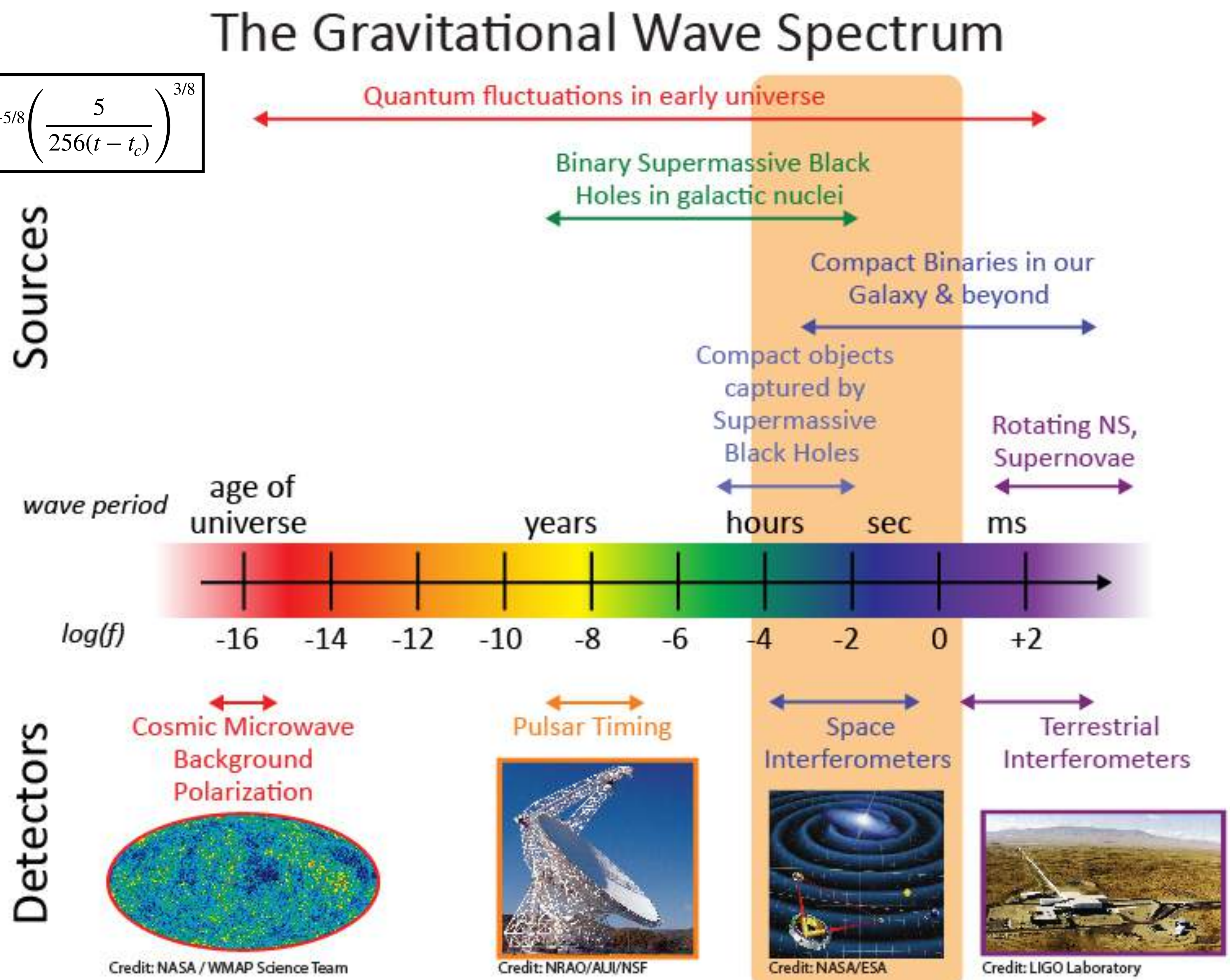


Gravitational wave spectrum

$$f_{GW} \propto (GM_c)^{-5/8}\left(\frac{5}{256(t-t_c)}\right)^{3/8}$$

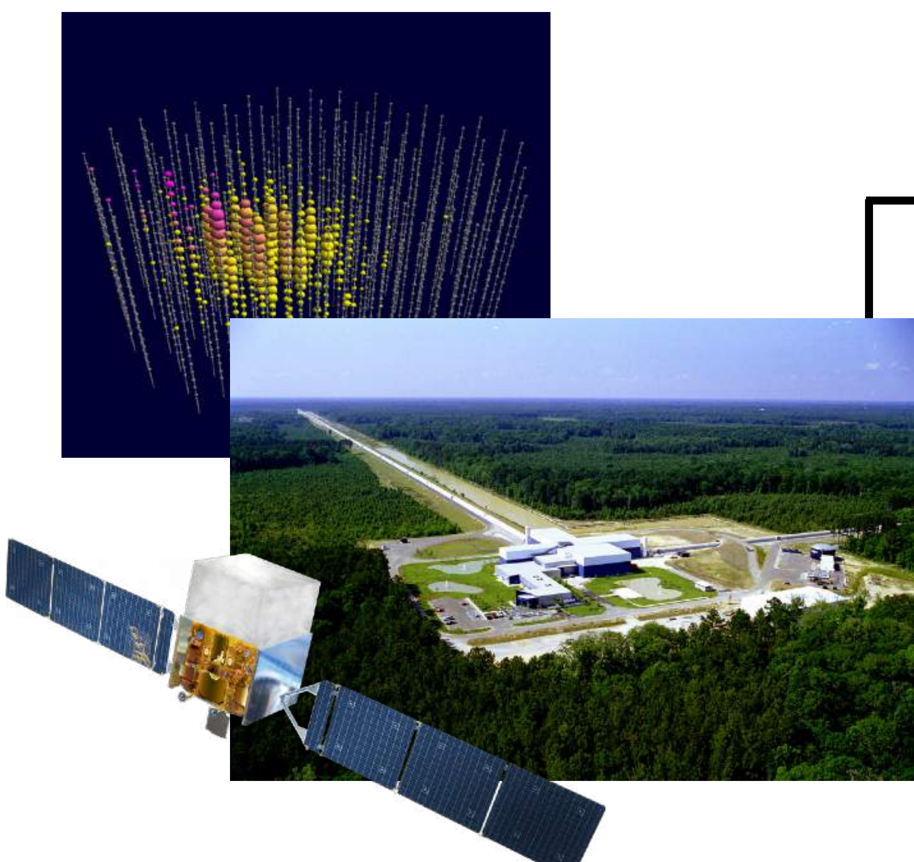


Real-time multi-messenger astronomy

Usually variable and transient sources !

Time domain astronomy:

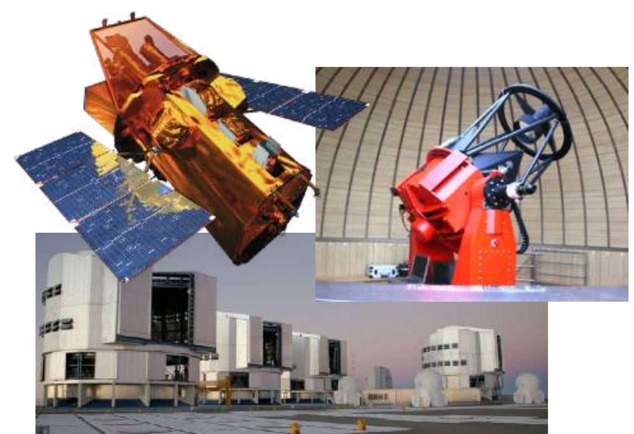
- Many science areas
- Multi-wavelength / multi-messenger
- Need dedicated wide-field instruments and fast, detailed follow-up
- Build for what we know… and what we don't know: huge discovery space !



Wide field of view instruments

Real-time analysis → **Sky localization** → **Alert triggering**

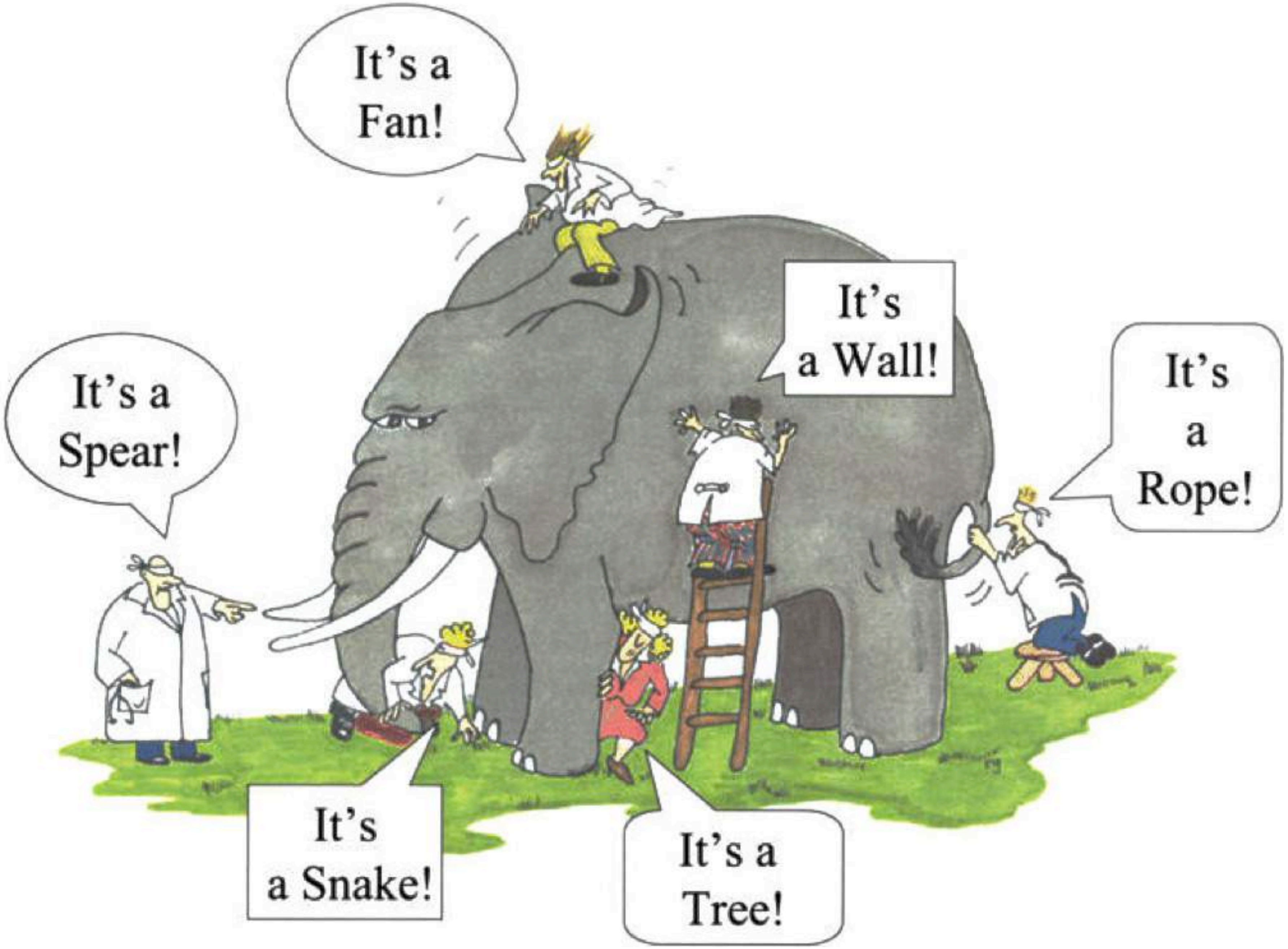
A few minutes



Conclusion

- **Main questions**: end of life of massive stars, nucleosynthesis, fundamental physics, formation and evolution of supermassive black holes

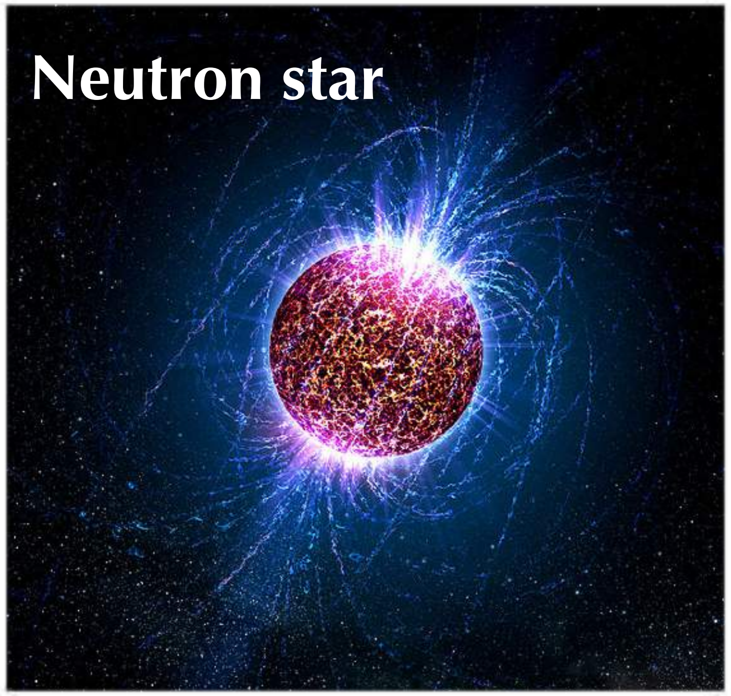
- **Multi-messenger astronomy: different tools to observe the sky**:



Outline - Lecture 2

B. End point of massive star evolution

1. Evolution of massive stars
2. Gamma-ray bursts
3. The SVOM space mission



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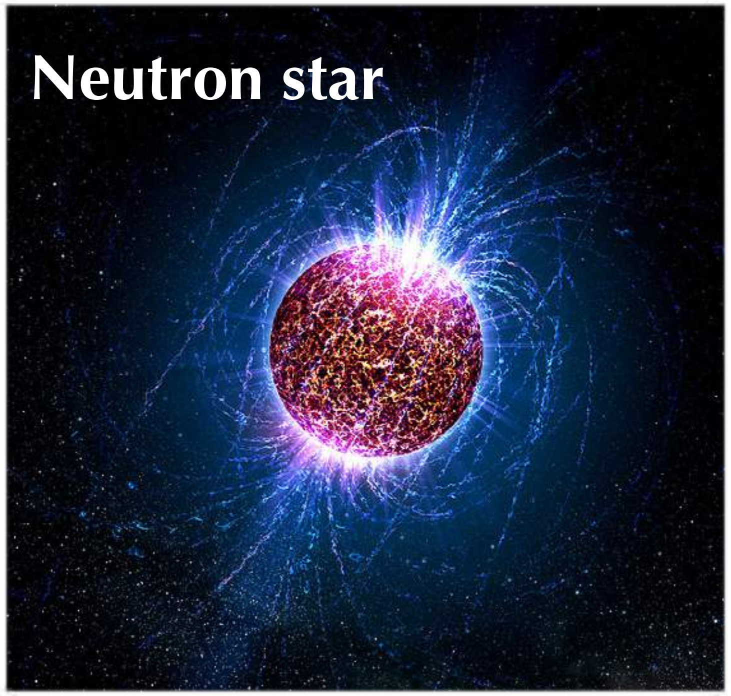
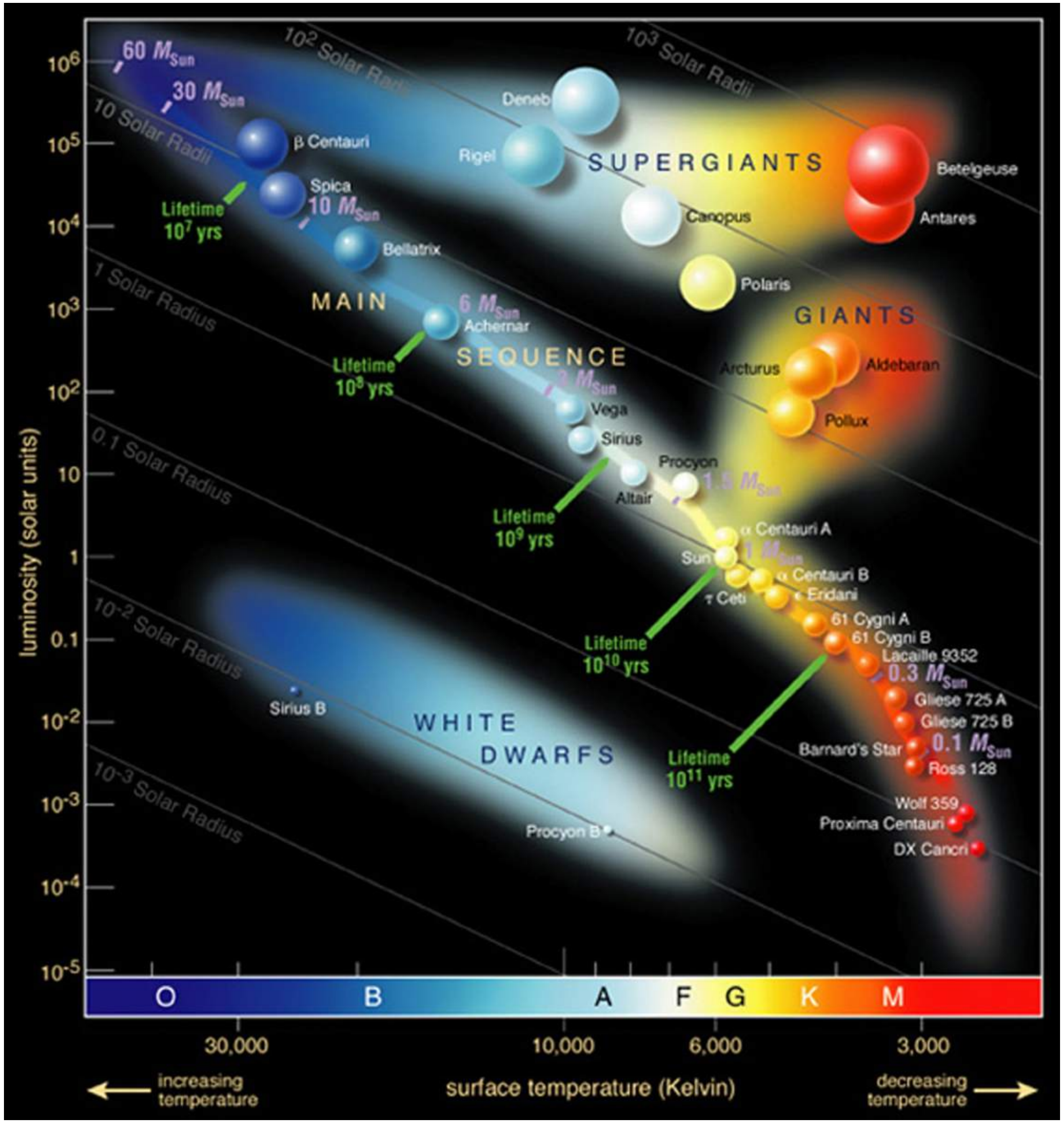


Stellar evolution

- Hertzprung-Russell diagram (1913) luminosity = f(temperature)
- Most of the stars on the main sequence
- Stars at different evolutionary stages
- Most massive stars are rare
- What is the source of energy ?

19th century: $C + O_2 \rightarrow CO_2$
releases $33\text{x}10^6$ J/kg ⇒ $t_\odot \sim 10^4$ yr
⇒ too short !



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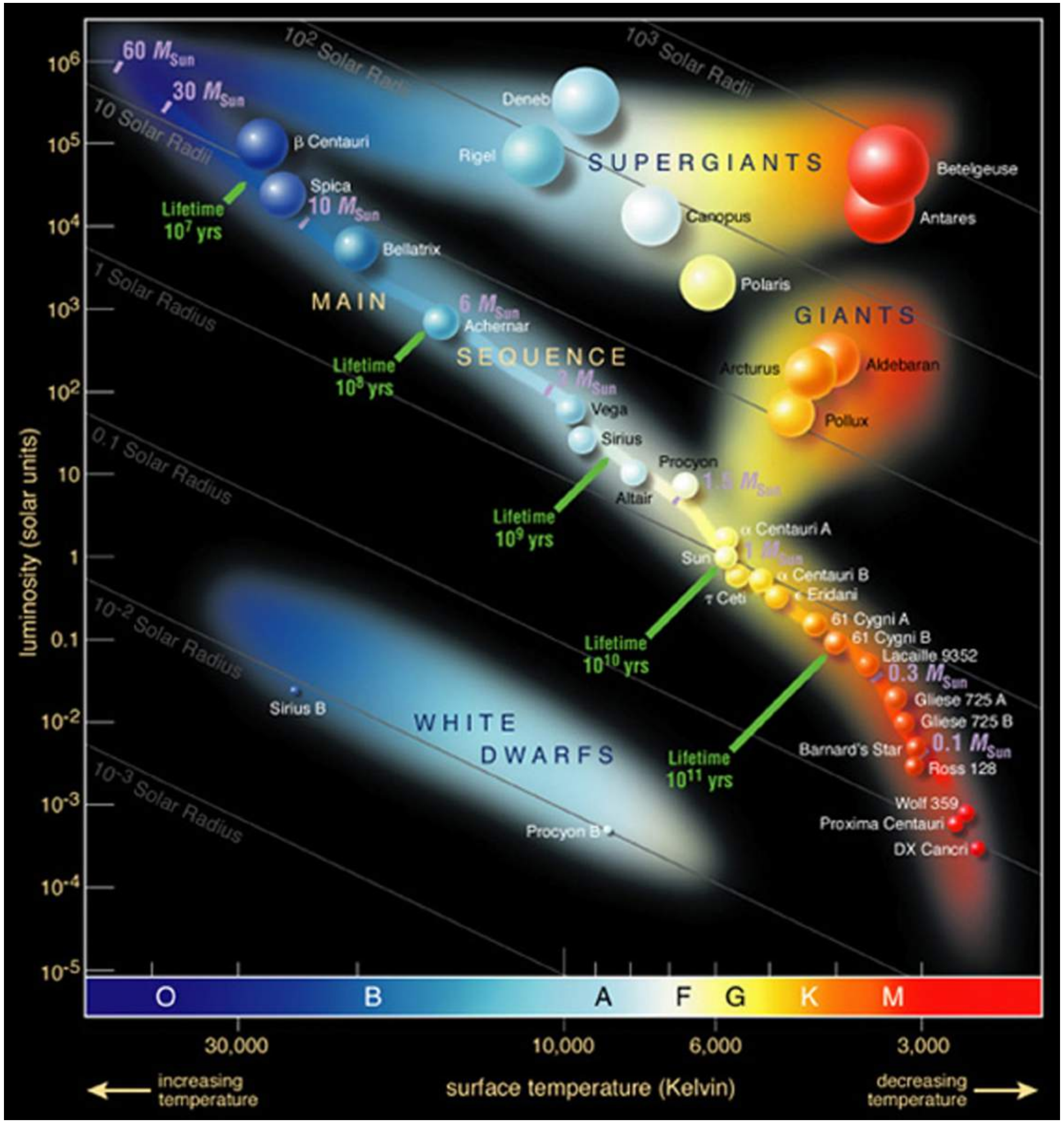
$$t_{\rm nuc} \propto \frac{Mc^2}{L} \gg t_\odot$$

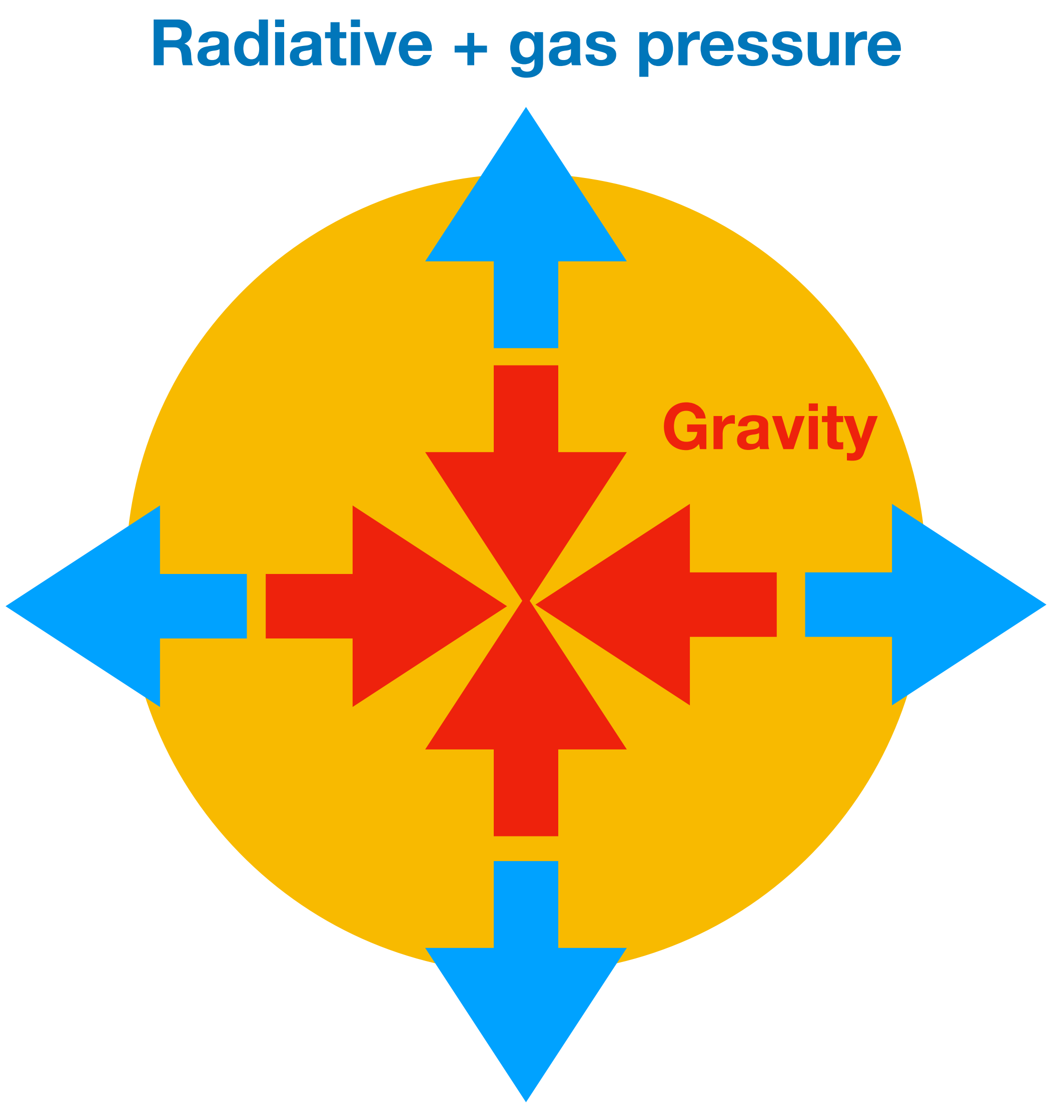
$t_{\rm nuc}$ compatible with $t_\odot$ if we assume that all mass is not converted into energy

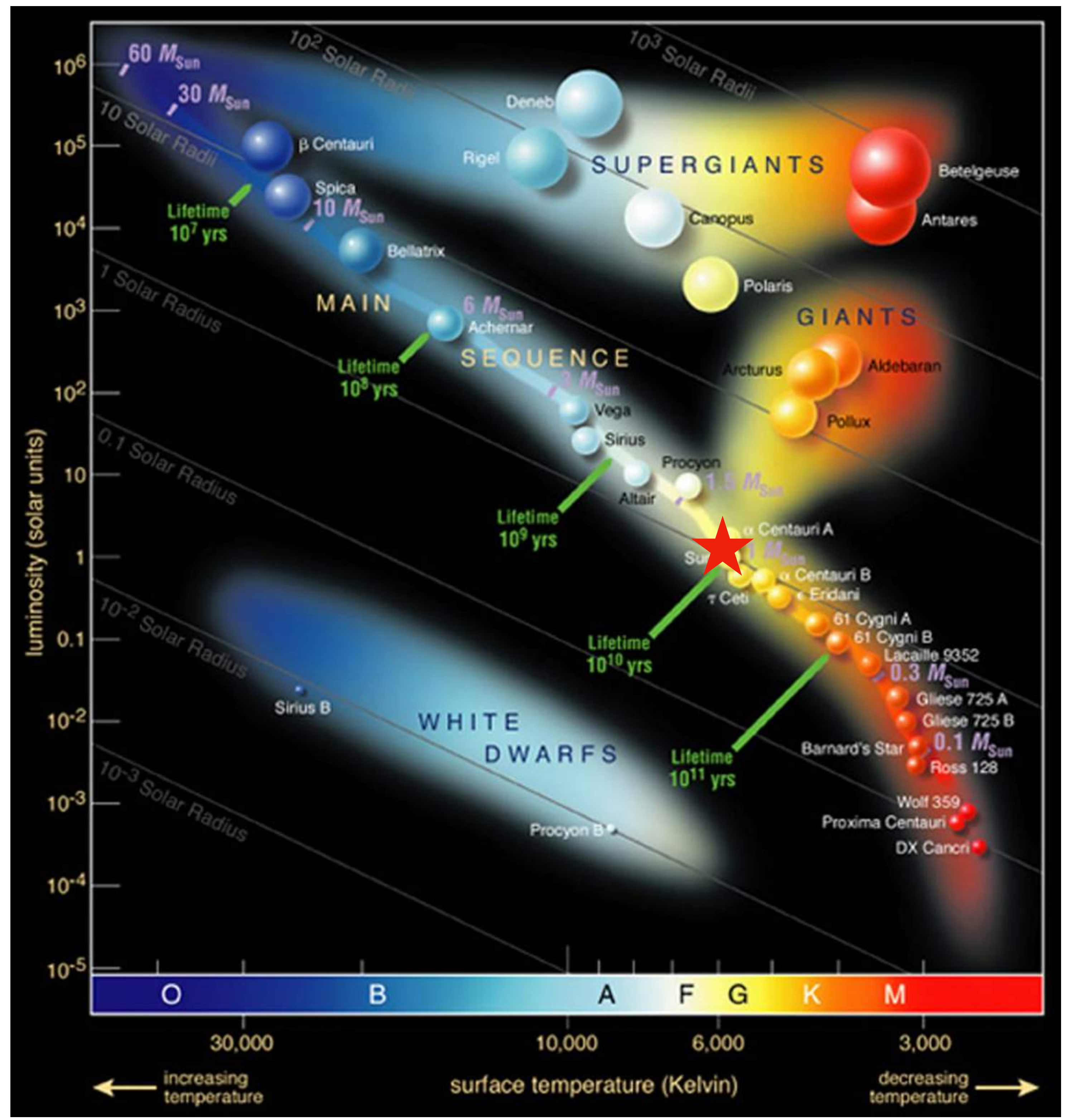


Stellar evolution

- On the main sequence: star at equilibrium (gravitation balanced by gas + radiation pressure)

- Nuclear reactions produce the radiated energy





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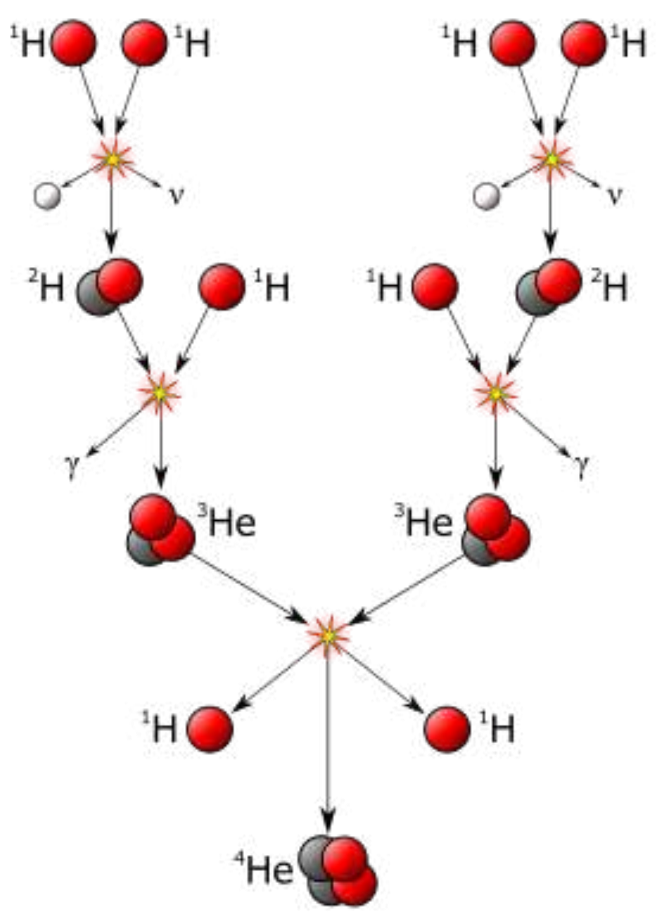
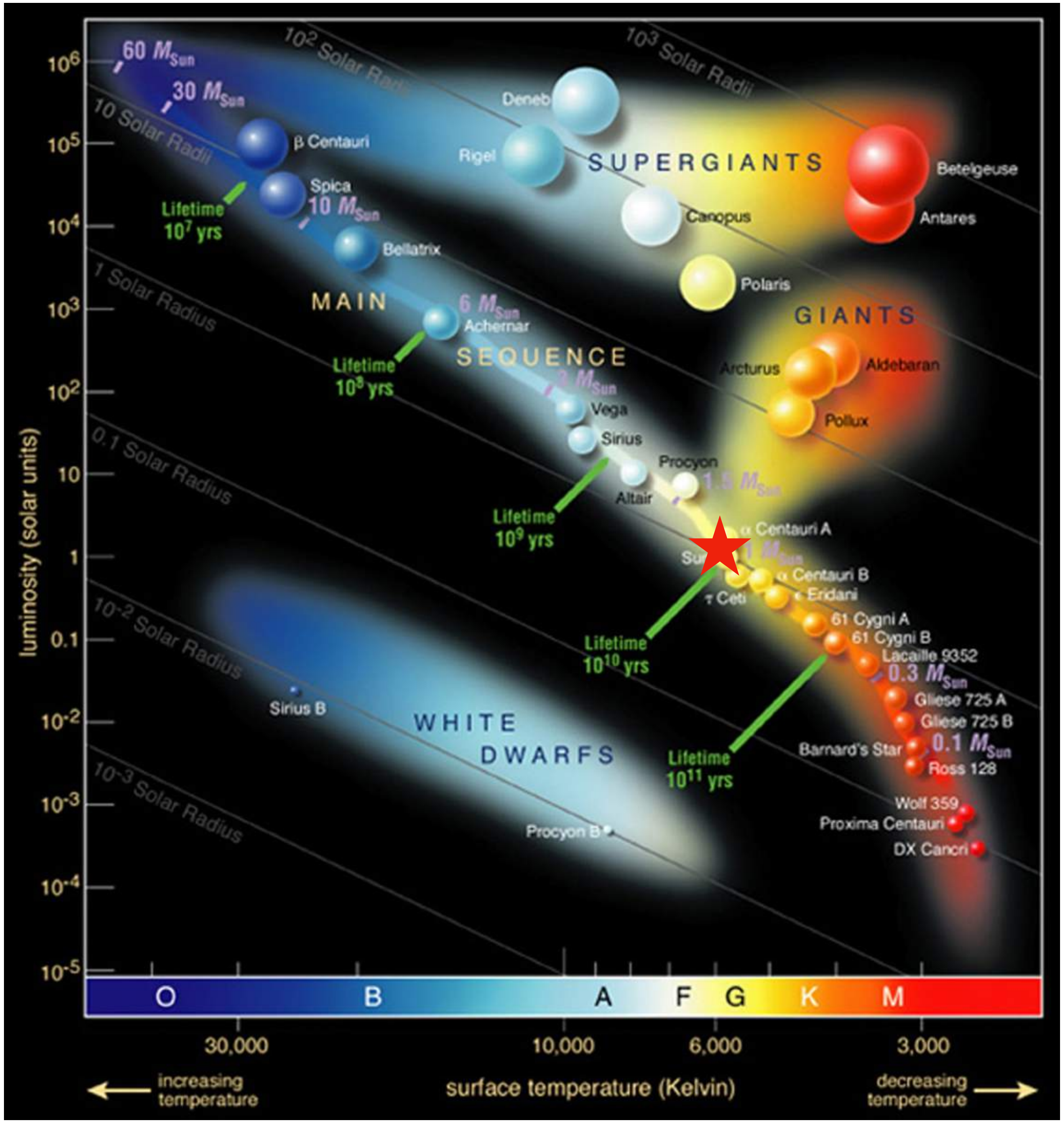
Proton-proton chain





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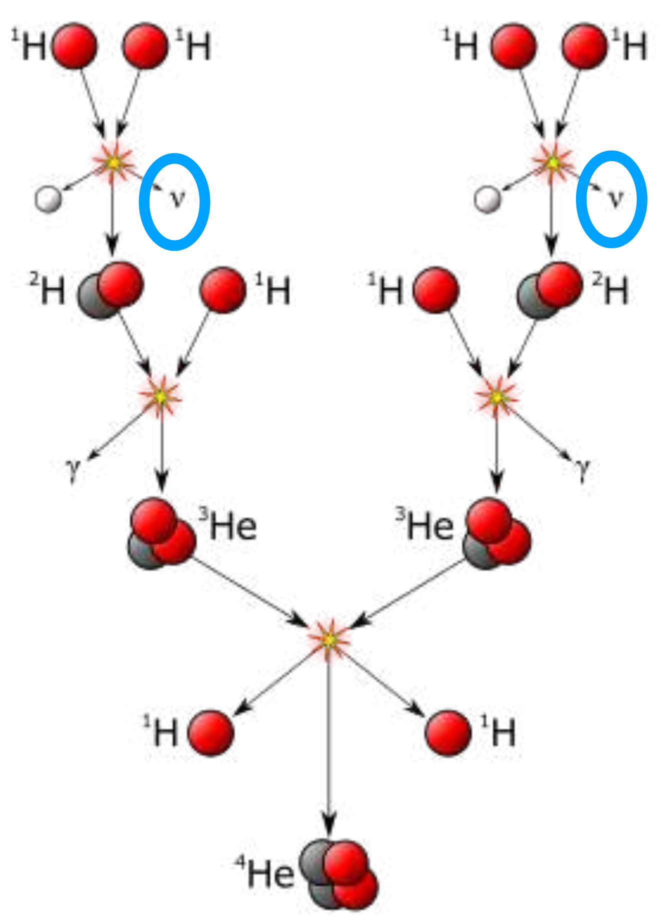
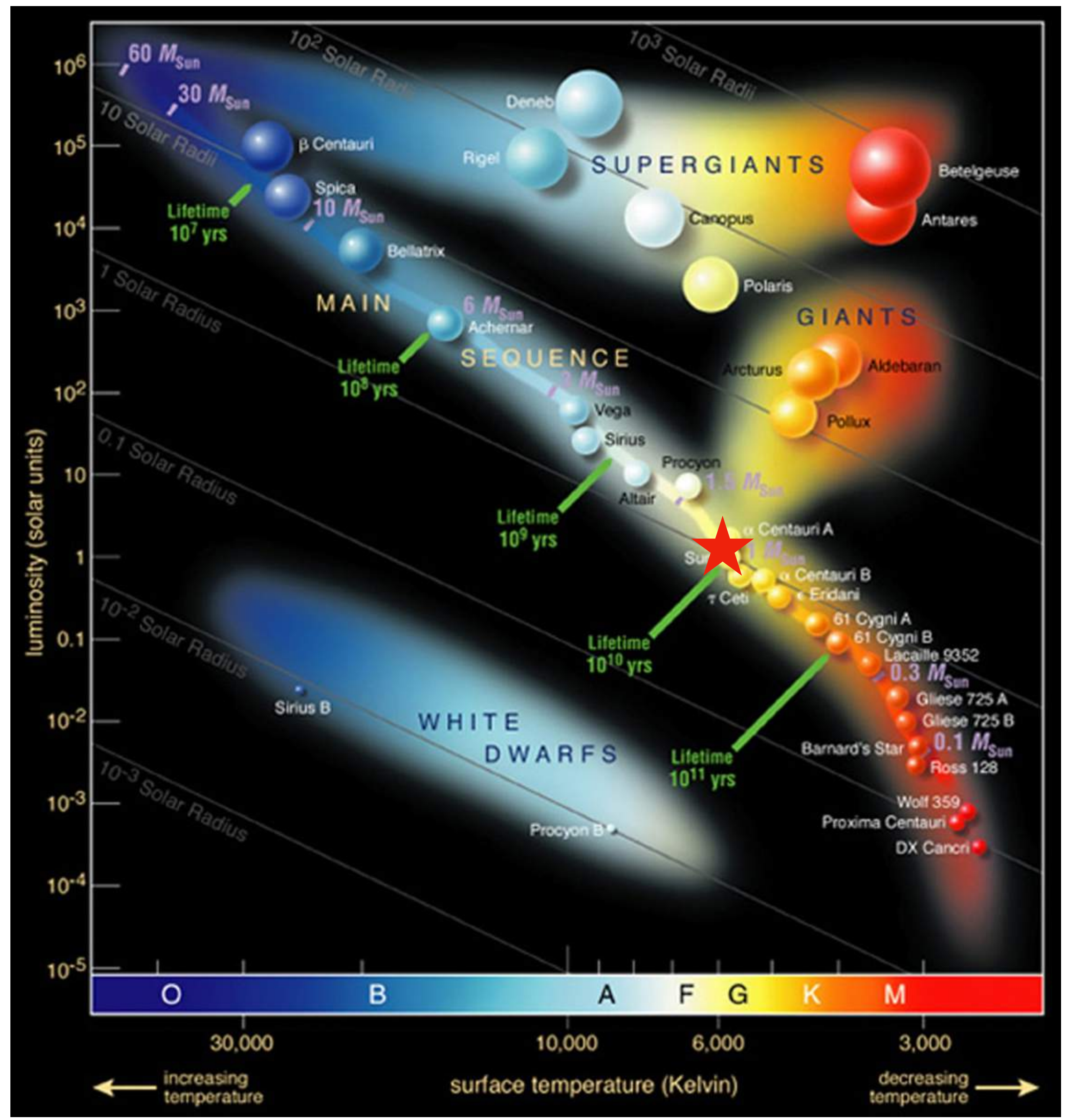


26.7 MeV released for one ^{4}He

$$F_\nu = ?$$



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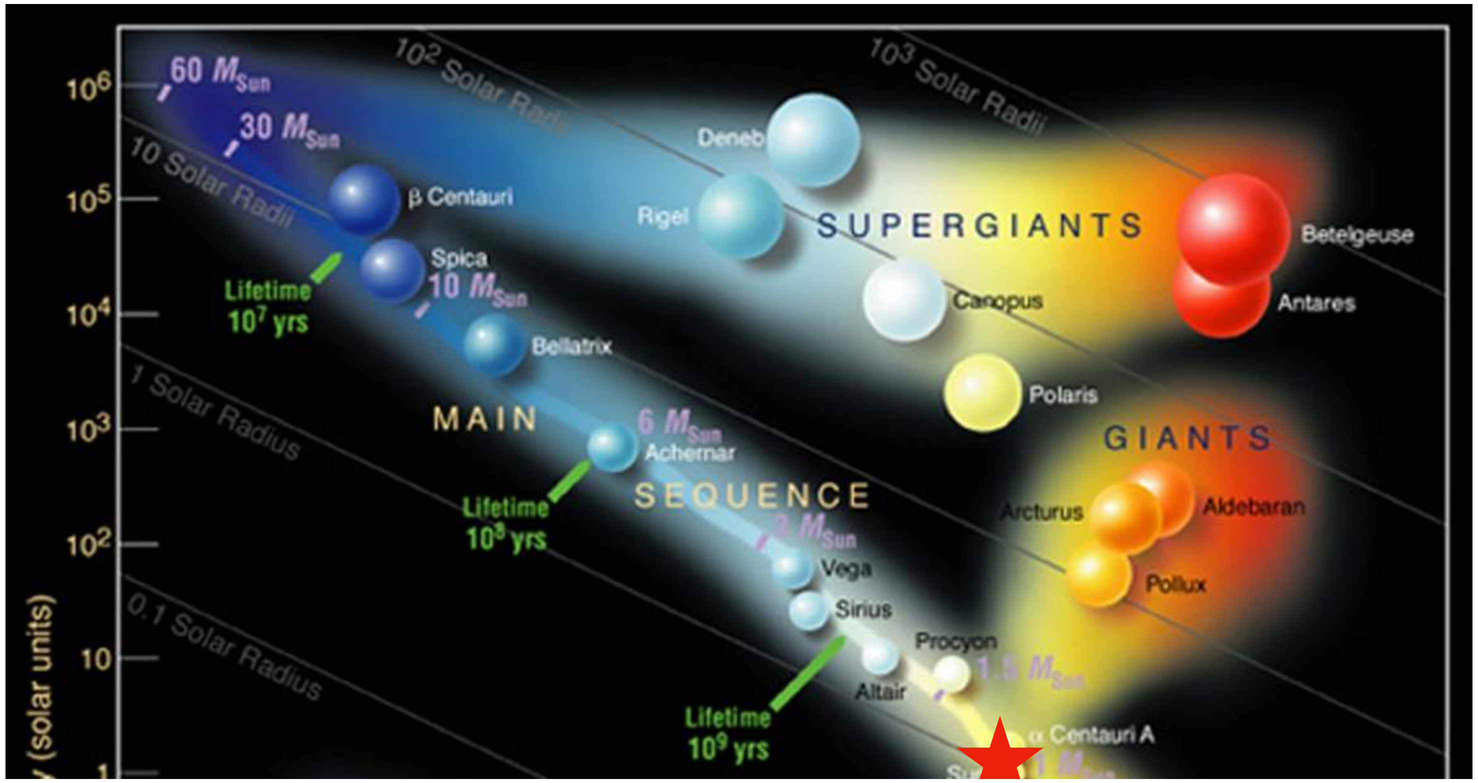

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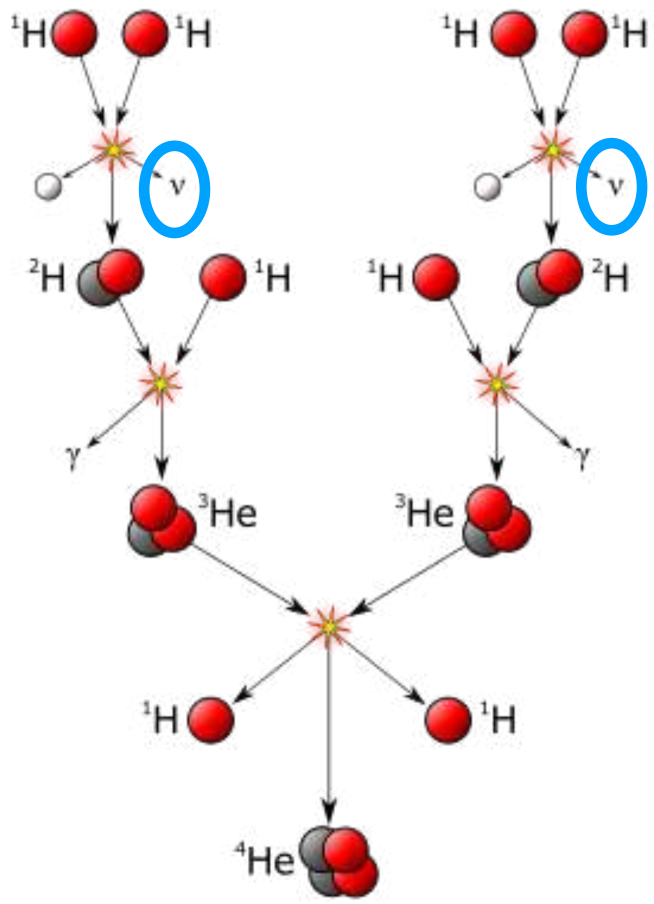

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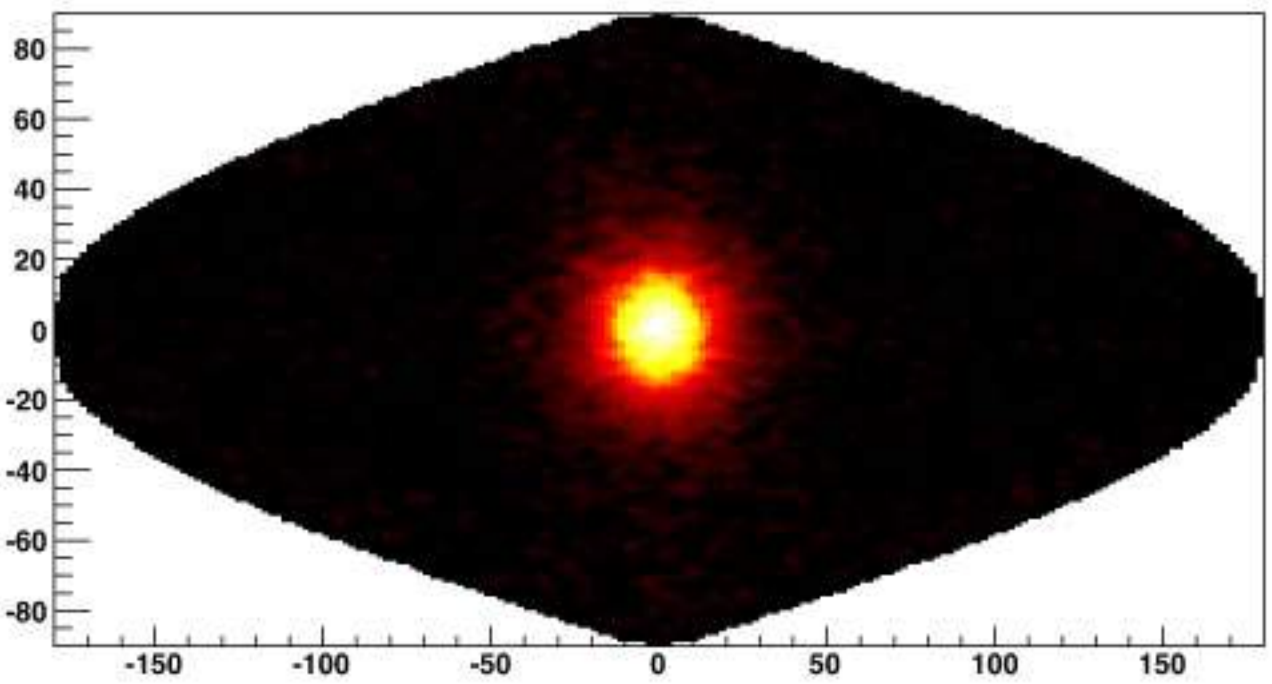

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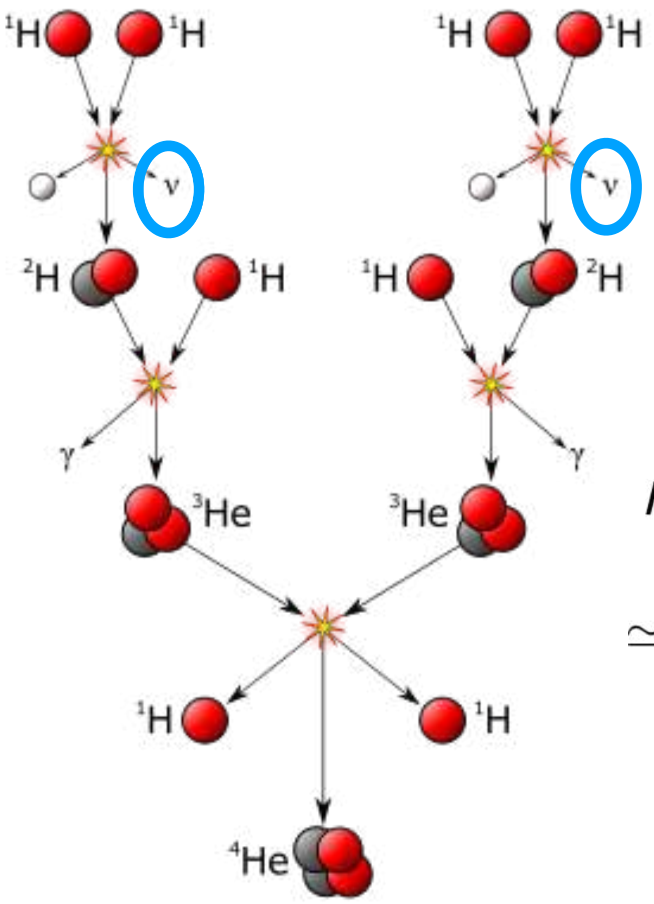
- Nuclear reactions produce the radiated energy

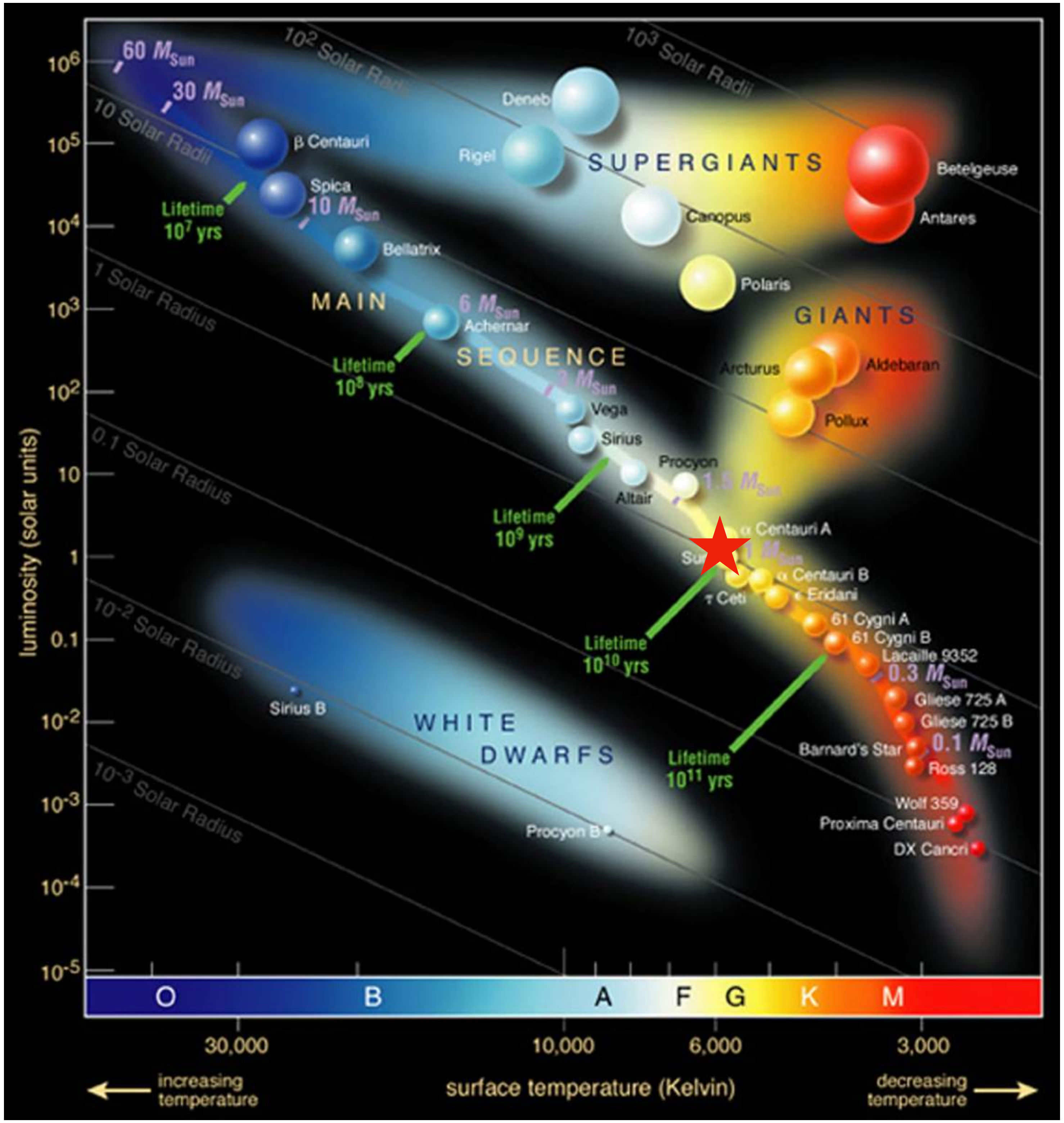
Proton-proton chain



26.7 MeV released for one ^{4}He

$$F_{\nu} \simeq 2\frac{L_\odot/26.7\text{ MeV}}{4\pi D^2}$$

$$\simeq 6.6\ 10^{10}\ \text{cm}^{-2}\ \text{s}^{-1}$$



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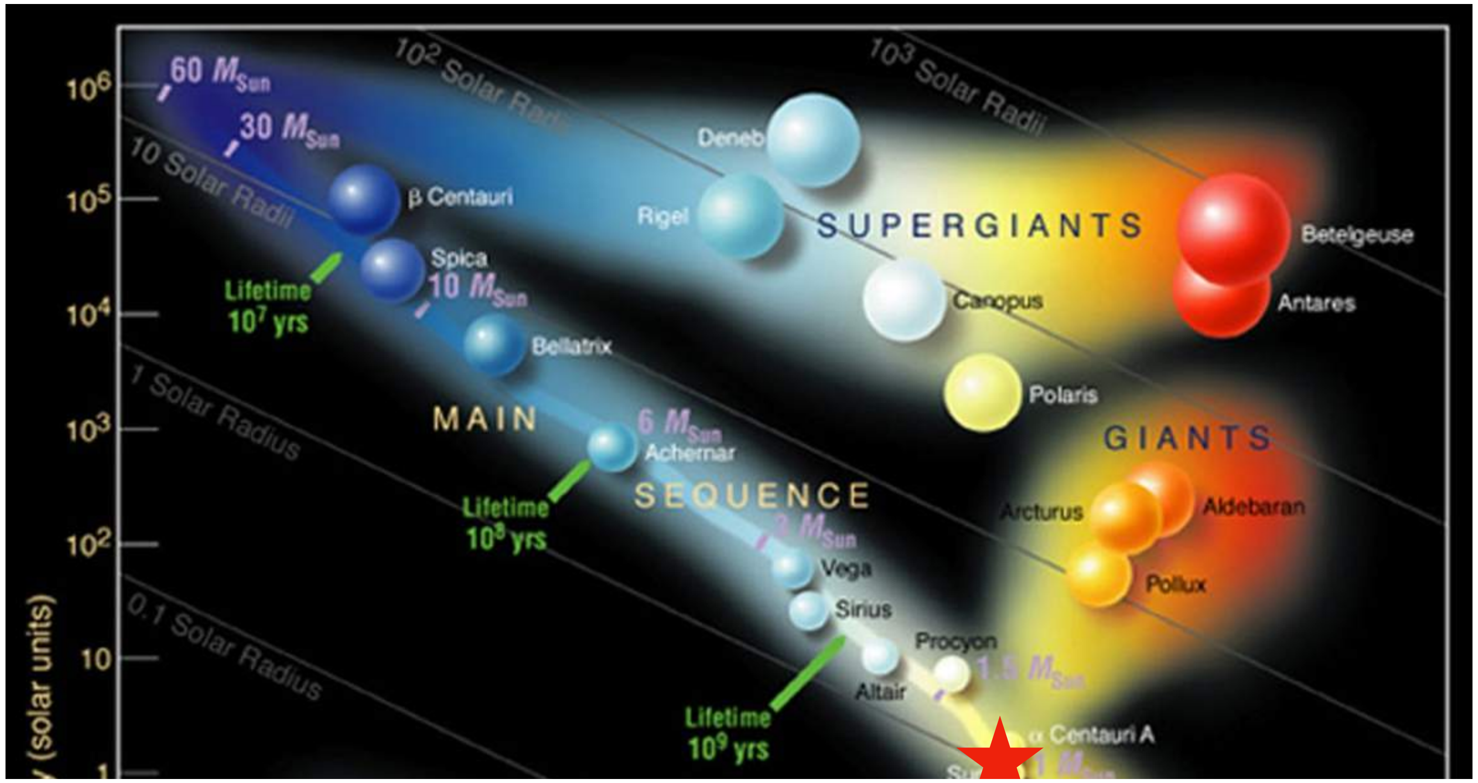

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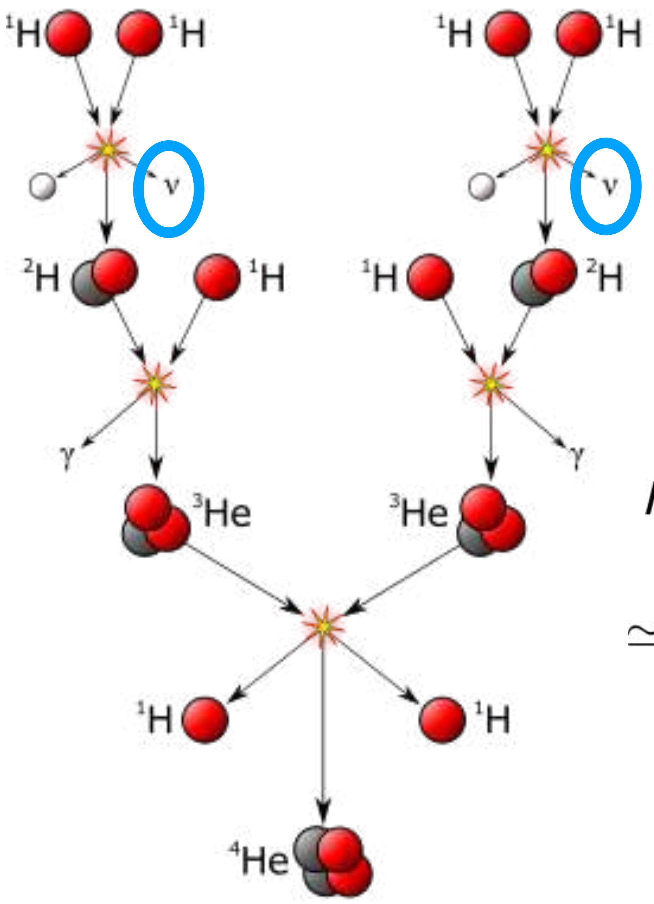

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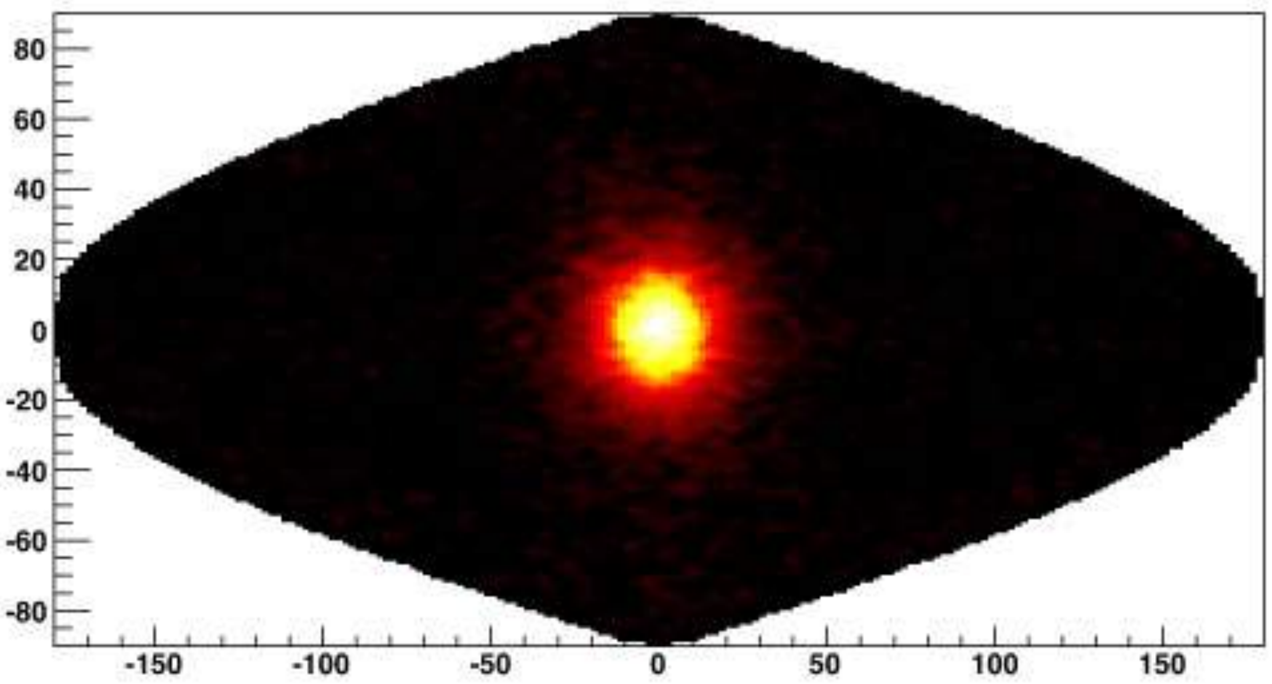

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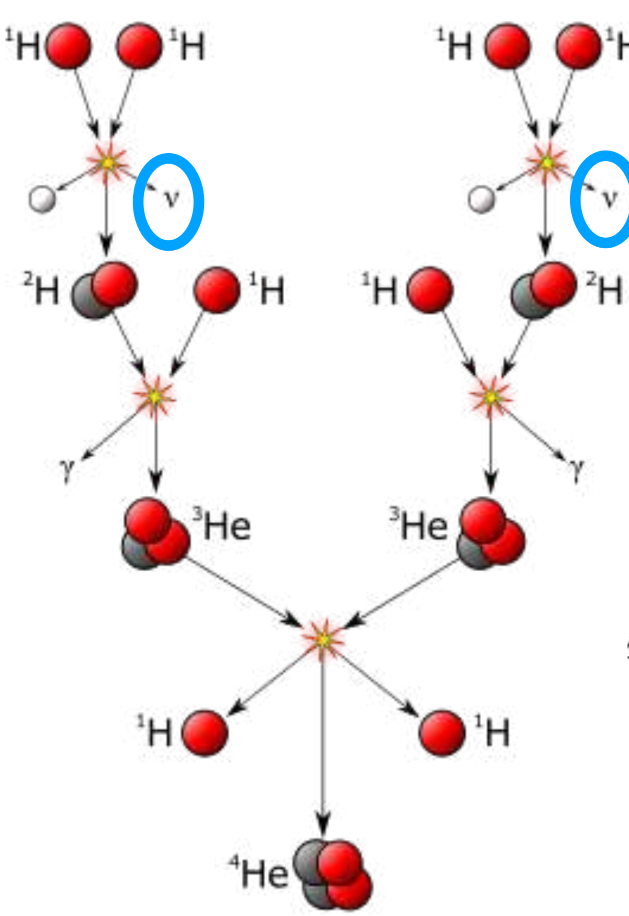

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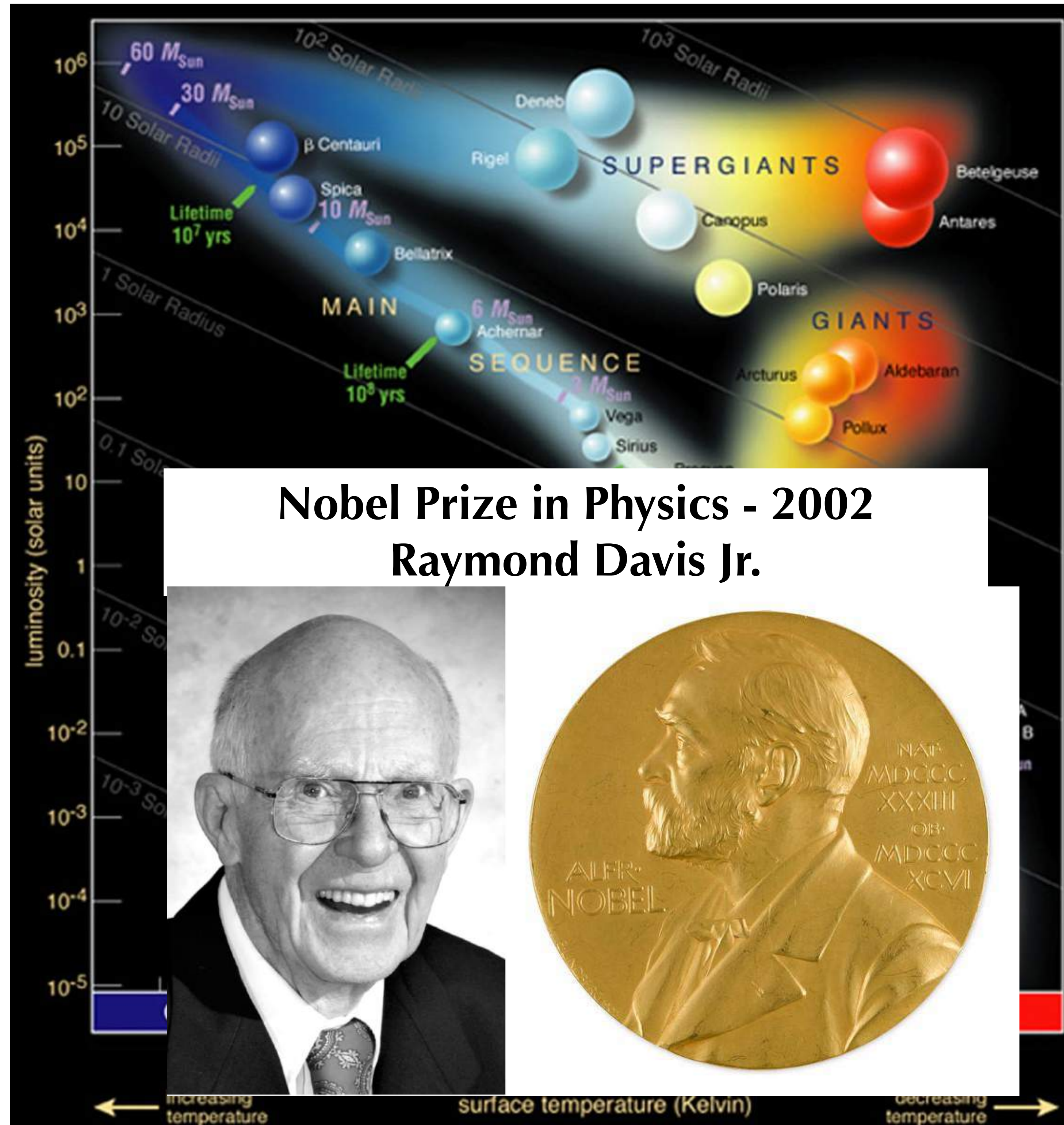

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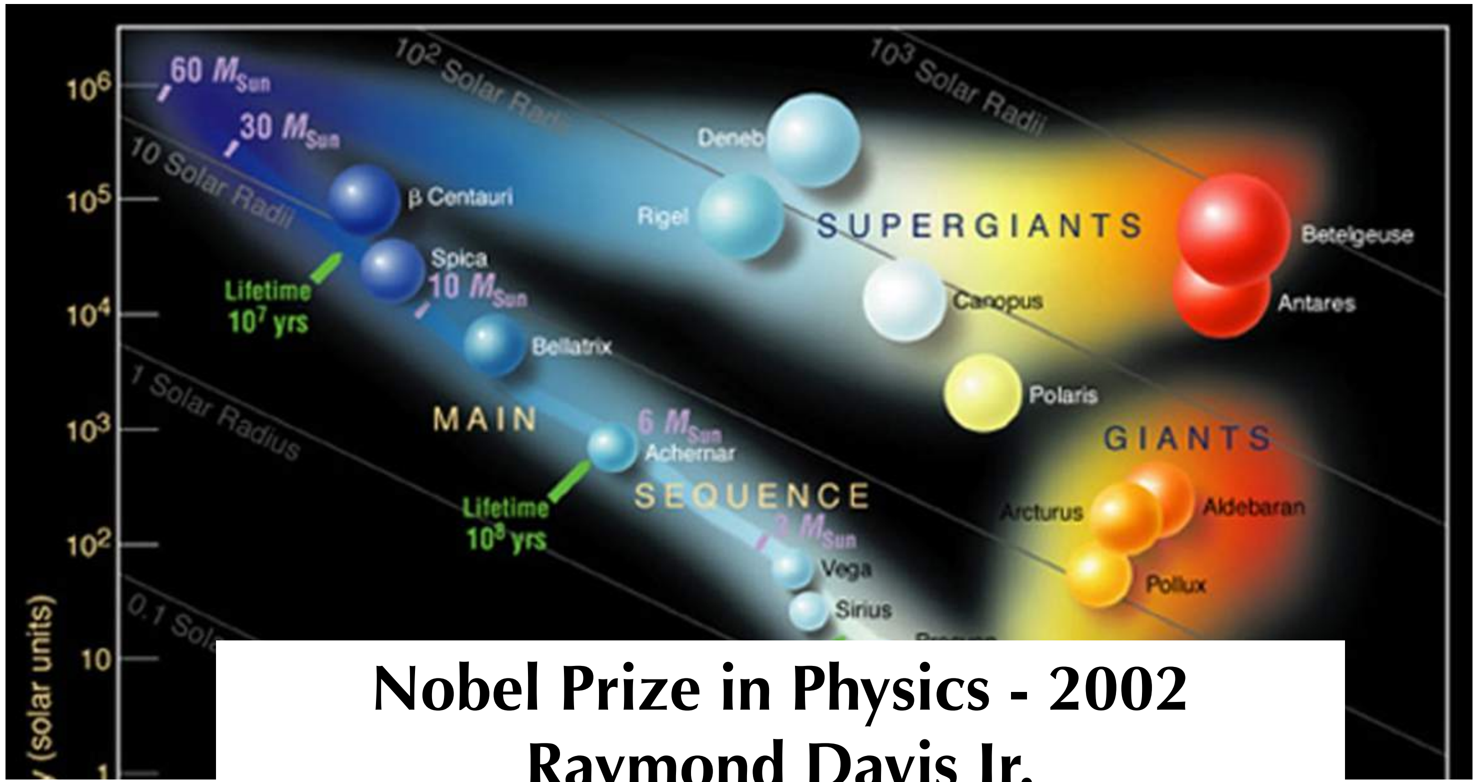

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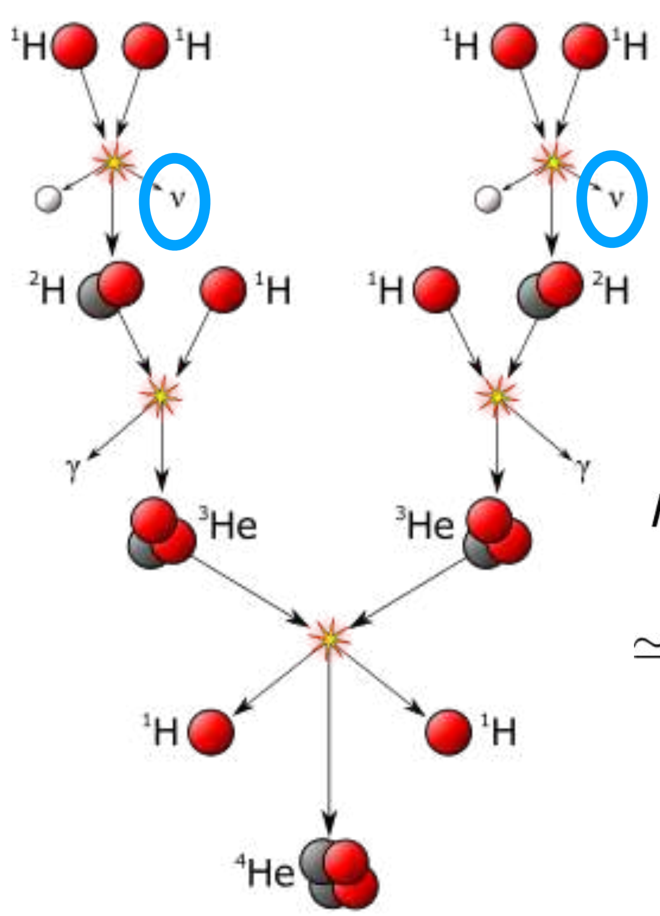

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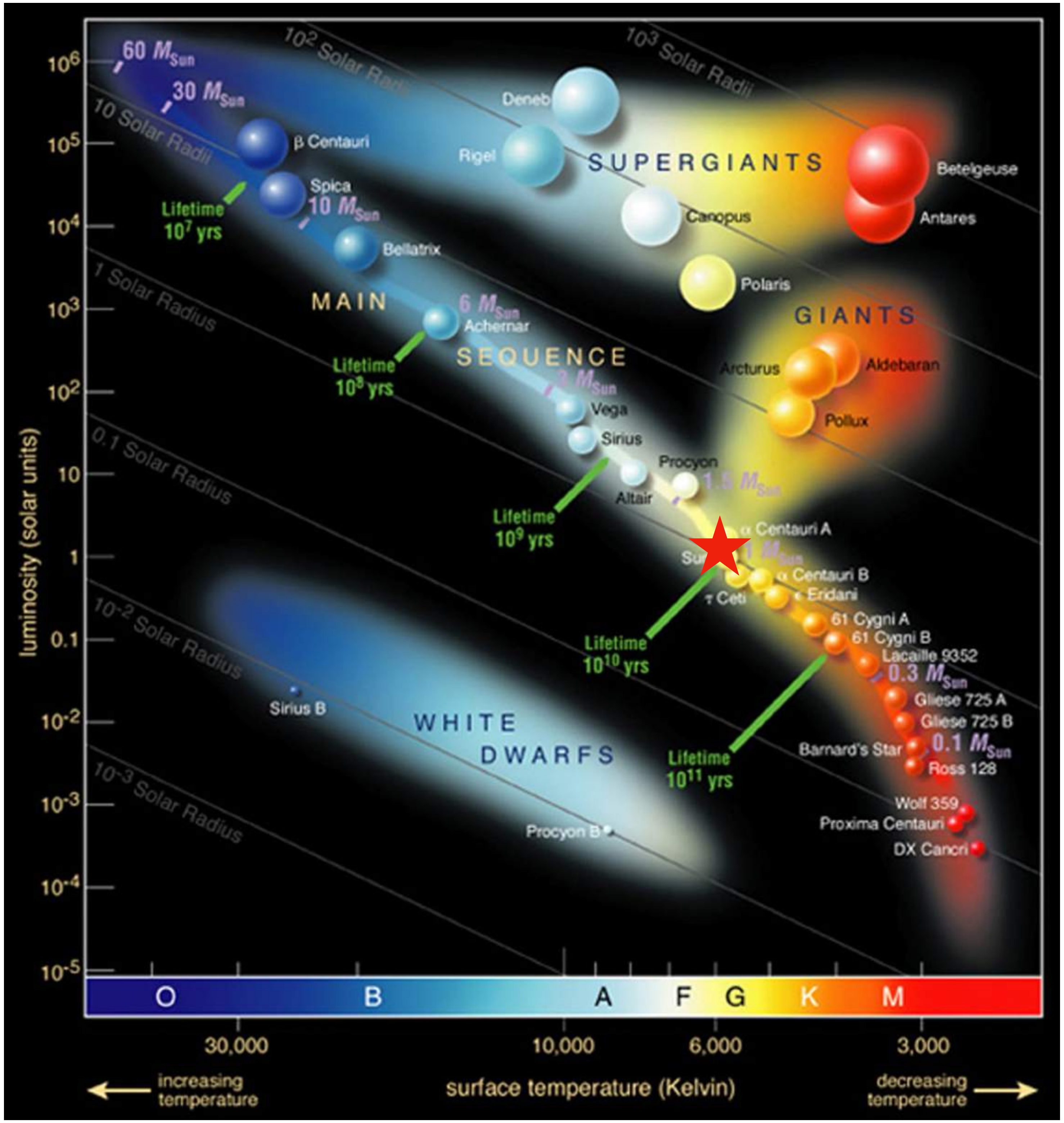
Nobel Prize in Physics - 2002
Raymond Davis Jr.

Stellar evolution

- On the main sequence: star at equilibrium (gravitation balanced by gas + radiation pressure)

- Nuclear reactions produce the radiated energy

- **When the star runs out of H, it leaves the main sequence**
- **H replaced with He in the core**
- **Core not hot enough to fuse Helium**
- **Core contraction (1 He takes less space than 4 H)**
- **Core temperature increases**



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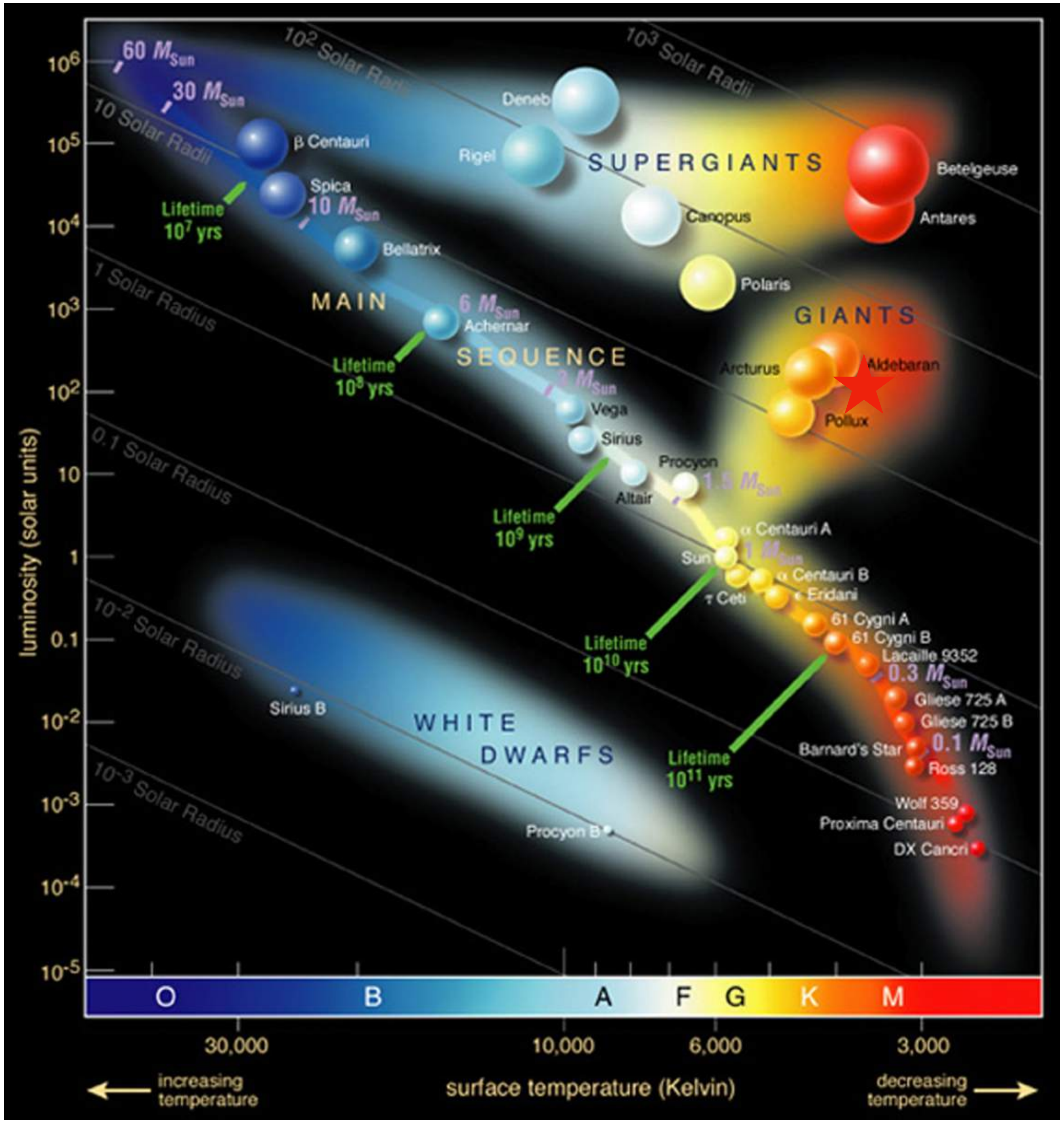

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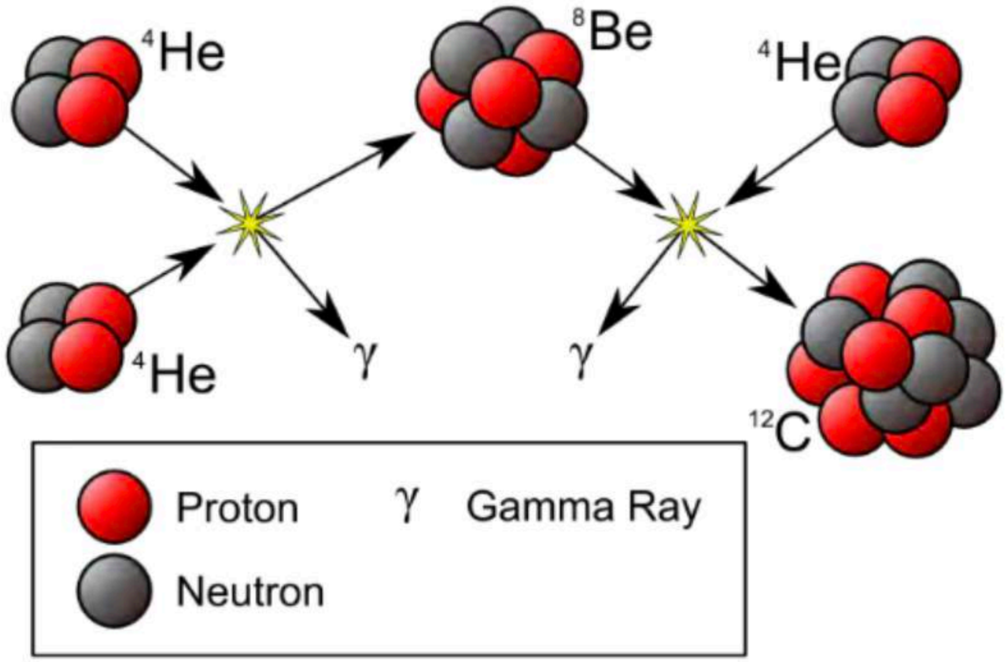
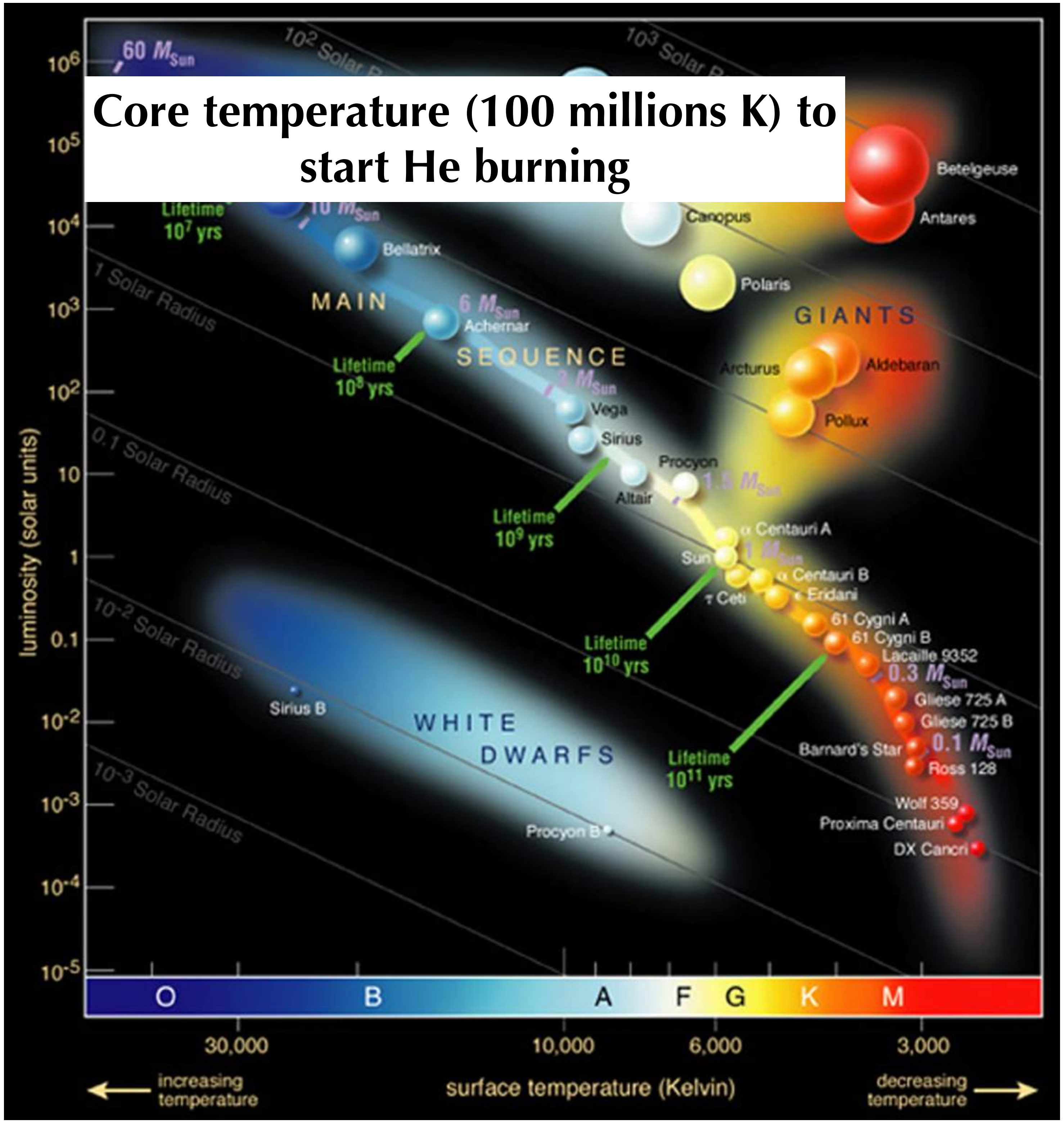
Stellar evolution

Helium burning



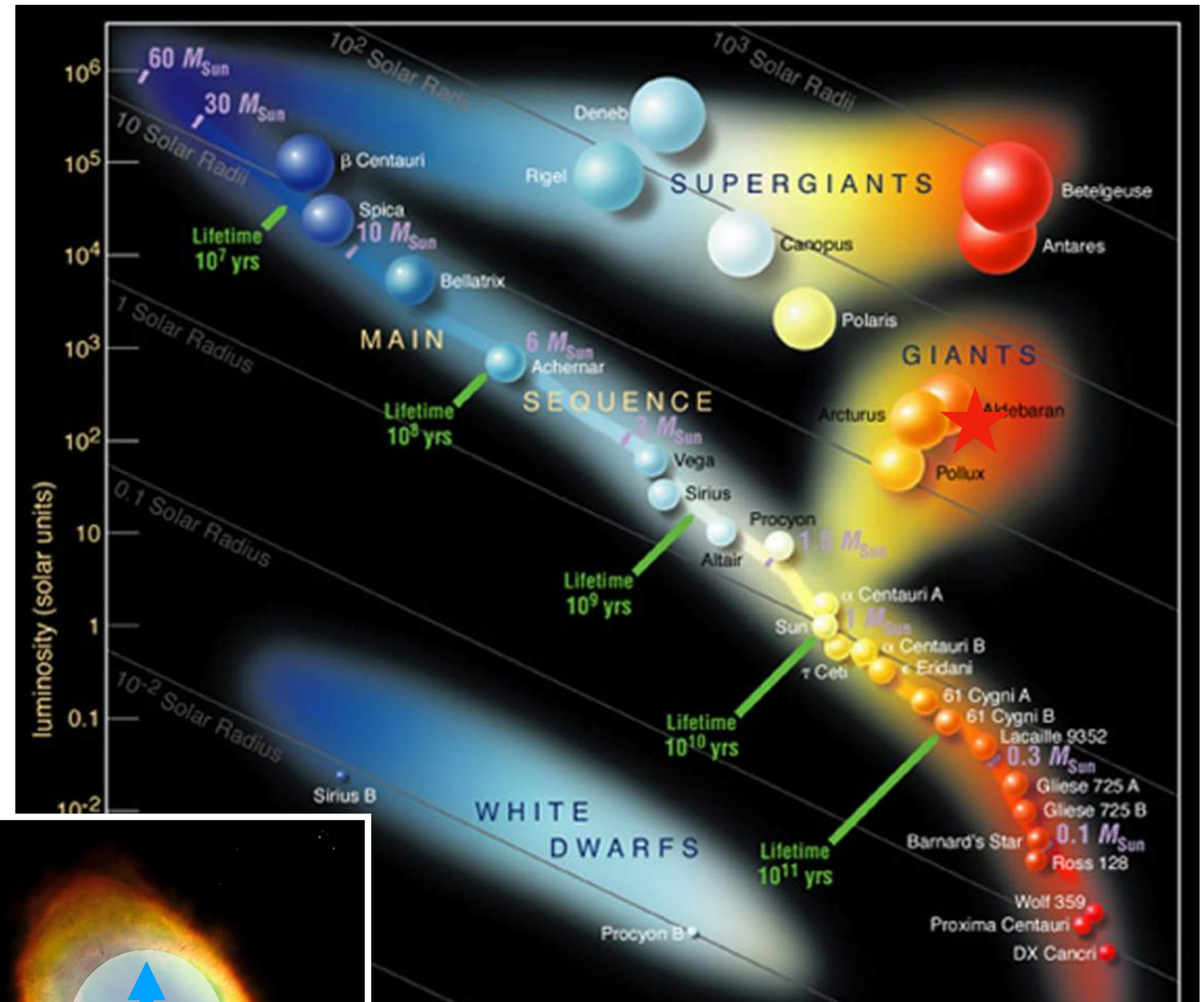
+ formation O, Ne, Mg as long as the core temperature increase

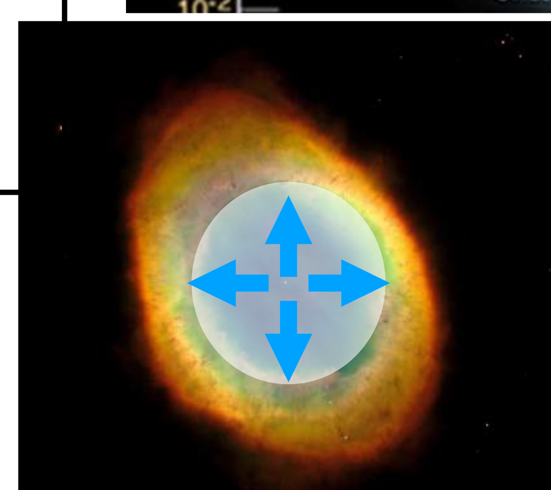


Core temperature (100 millions K) to start He burning

Stellar evolution

- After He burning → star dominated by gravity → contraction → increase of T but never enough to initiate Carbon burning.
- Carbon core continues to contract until it is supported by electron degeneracy pressure → formation of a white dwarf.
- Outer layers of the star are ejected and ionised by the white dwarf to form a planetary nebula.





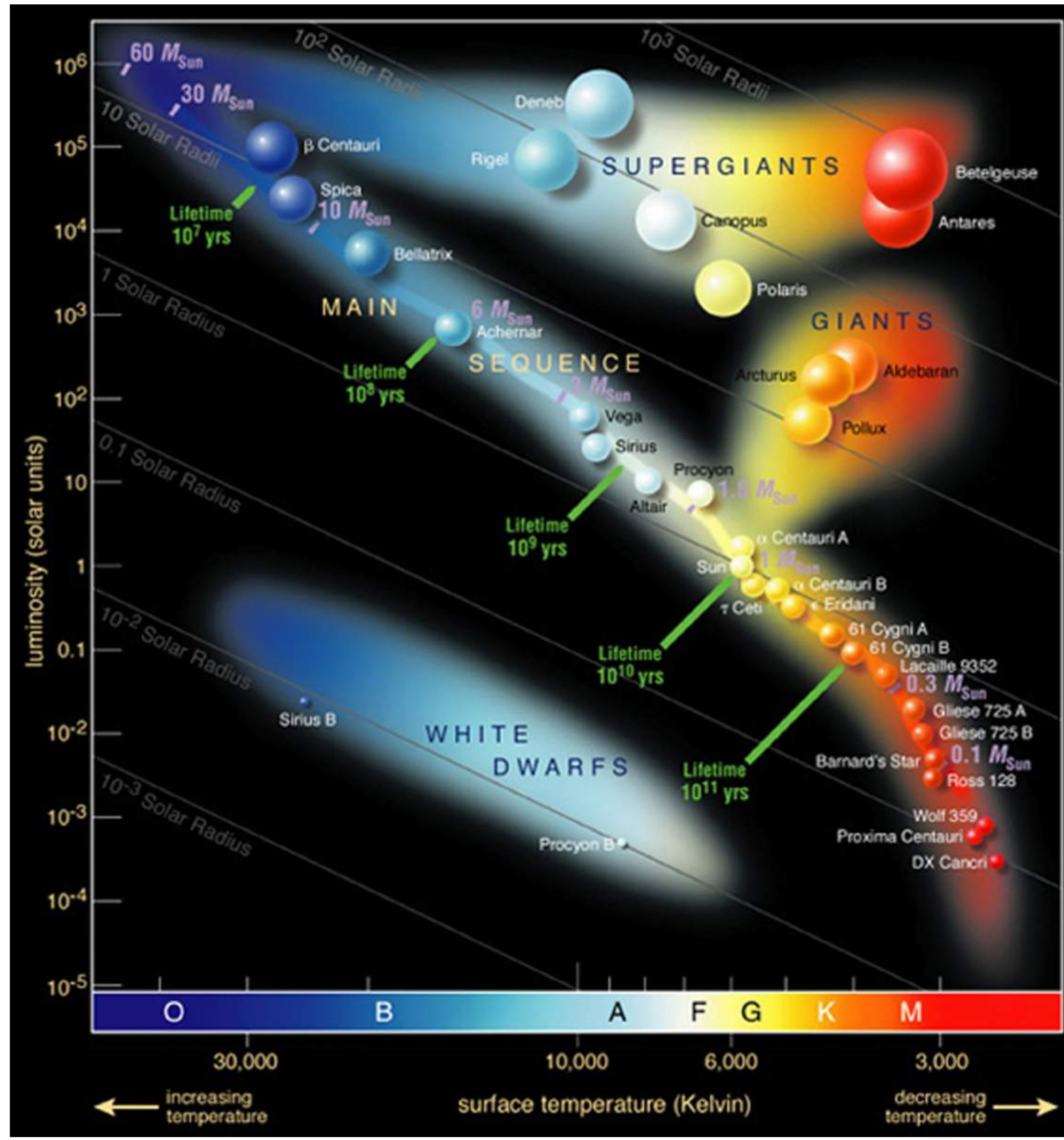
Planetary nebula

Stellar evolution

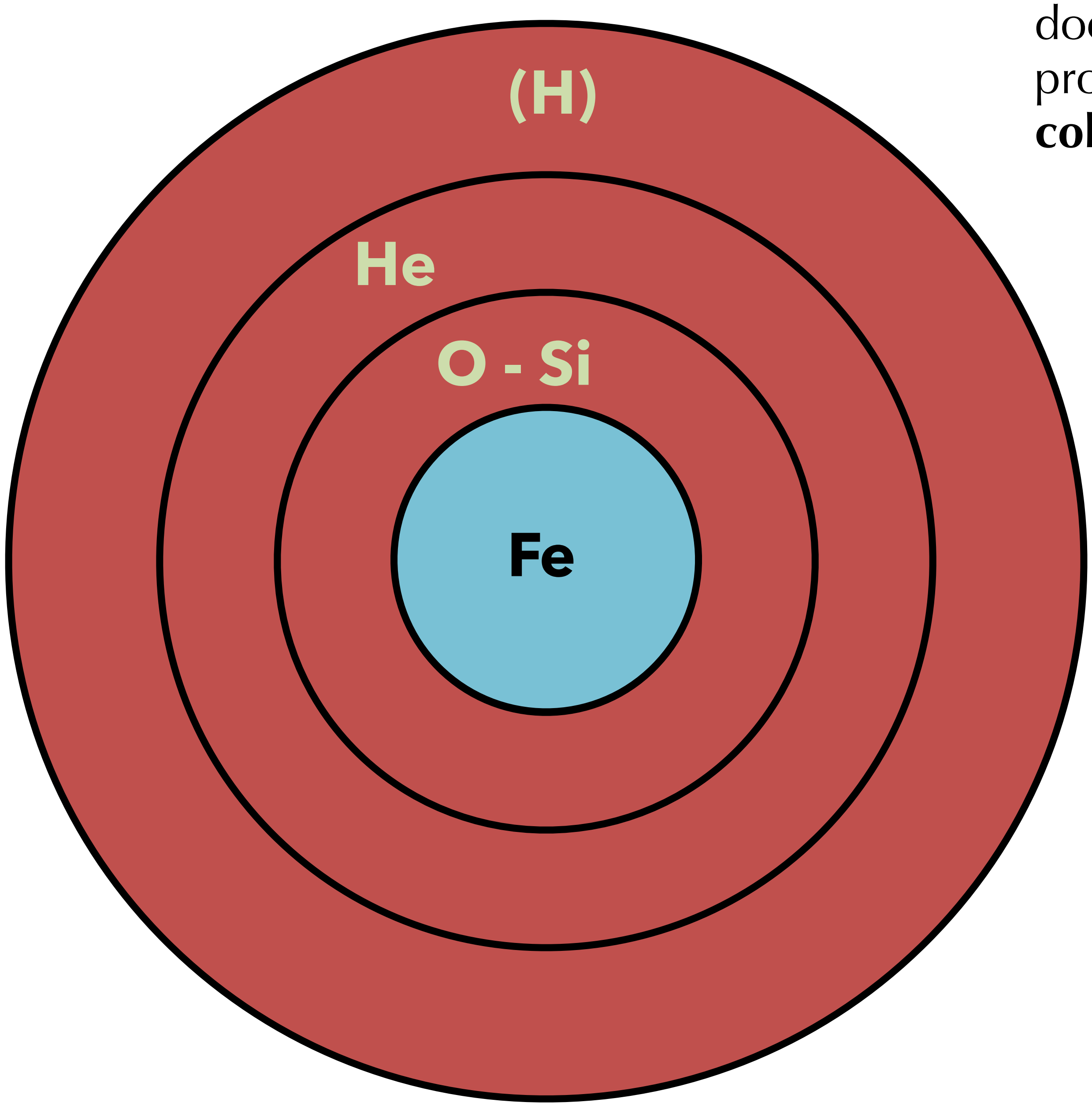
What about massive stars ?

- Contracting core will reach the temperature for carbon ignition.
- Process of core burning followed by core contraction is repeated in a series of nuclear reactions producing successively heavier elements until iron is formed in the core.

Combustible	Température	Elément formé
Hydrogène	$60\ 10^6$ K	^{4}He, ^{14}N
Hélium	$200\ 10^6$ K	^{12}C, ^{16}O
Carbone	$900\ 10^6$ K	^{24}Mg, ^{20}Ne
Oxygène	$2.3\ 10^9$ K	Isotopes de Si, S
Néon	$1.7\ 10^9$ K	^{16}O, ^{24}Mg, ^{28}Si
Silicium	$4\ 10^9$ K	^{56}Fe,…



Core-collapse supernova

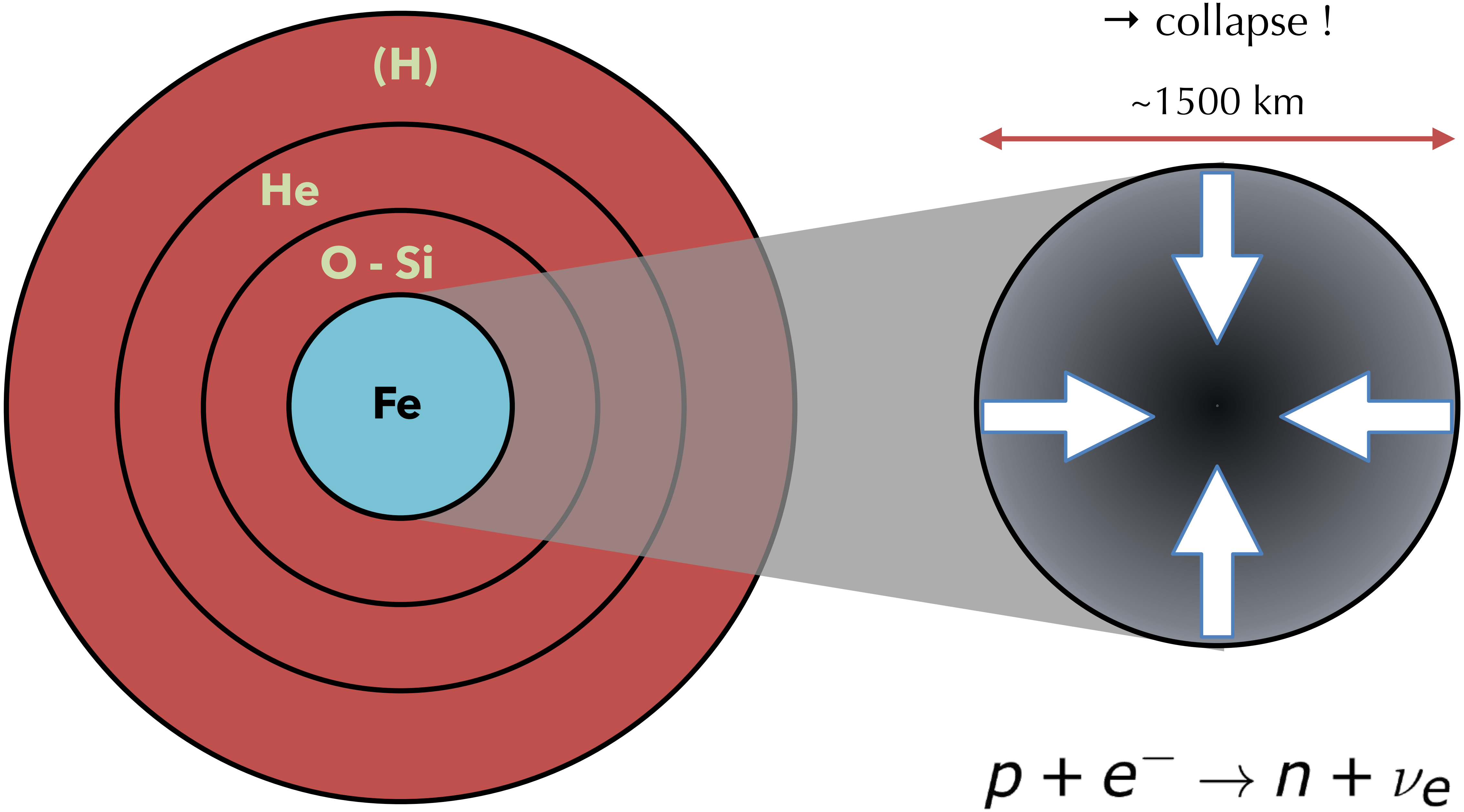


Massive star $M \gtrsim 10M_\odot$
Onion structure

Iron cannot be burned to heavier elements as this reaction does not generate energy – it requires an input of energy to proceed. The star has therefore finally run out of fuel and **collapses under its own gravity.**

Core-collapse supernova

Degenerate core. When M>1.44M⊙
→ collapse !

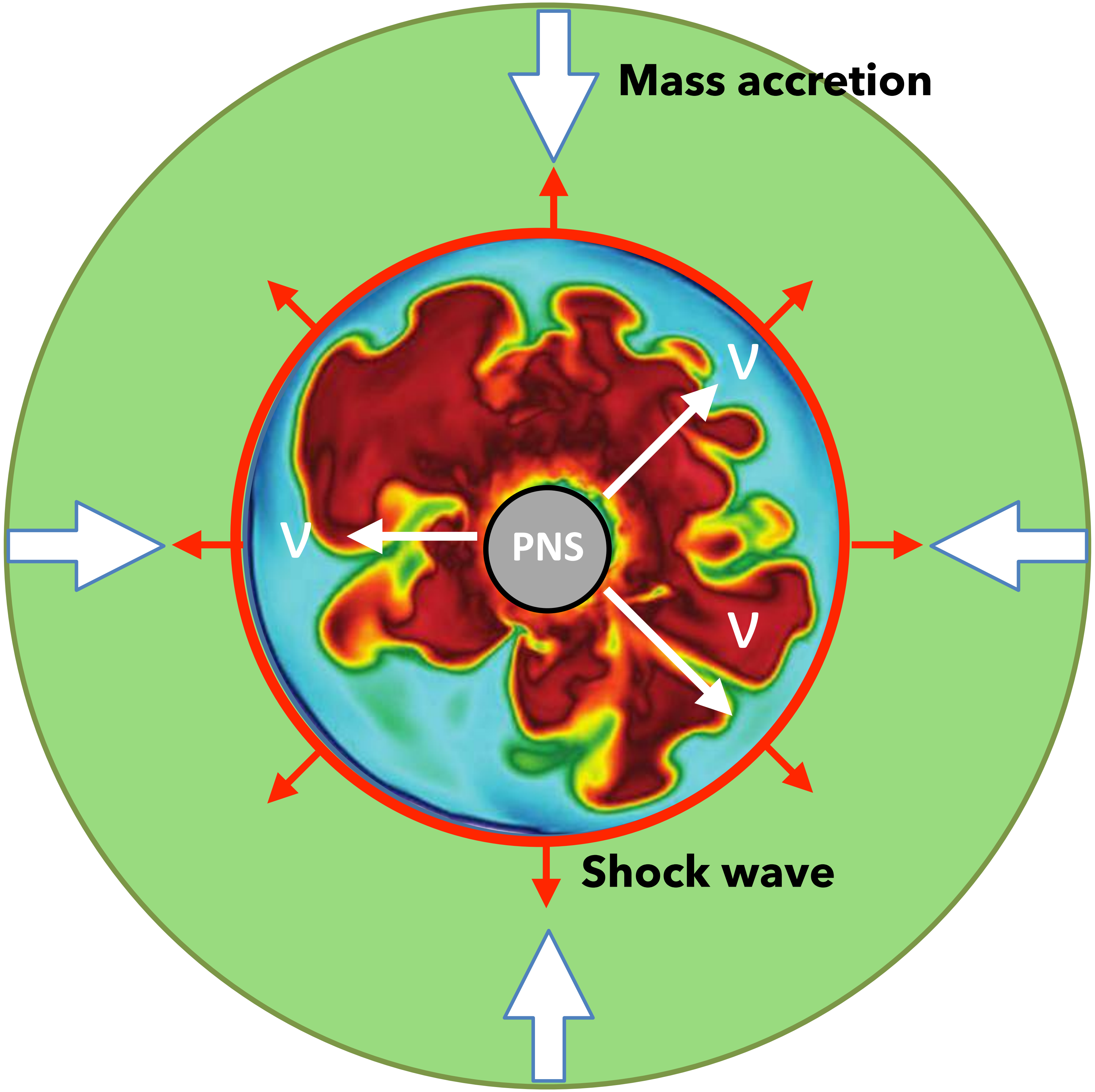


$$p + e^- \to n + \nu_e$$

Massive star M ≳ 10M⊙
Onion structure

Density such as electrons combine with protons to form electrons (+ neutrinos)

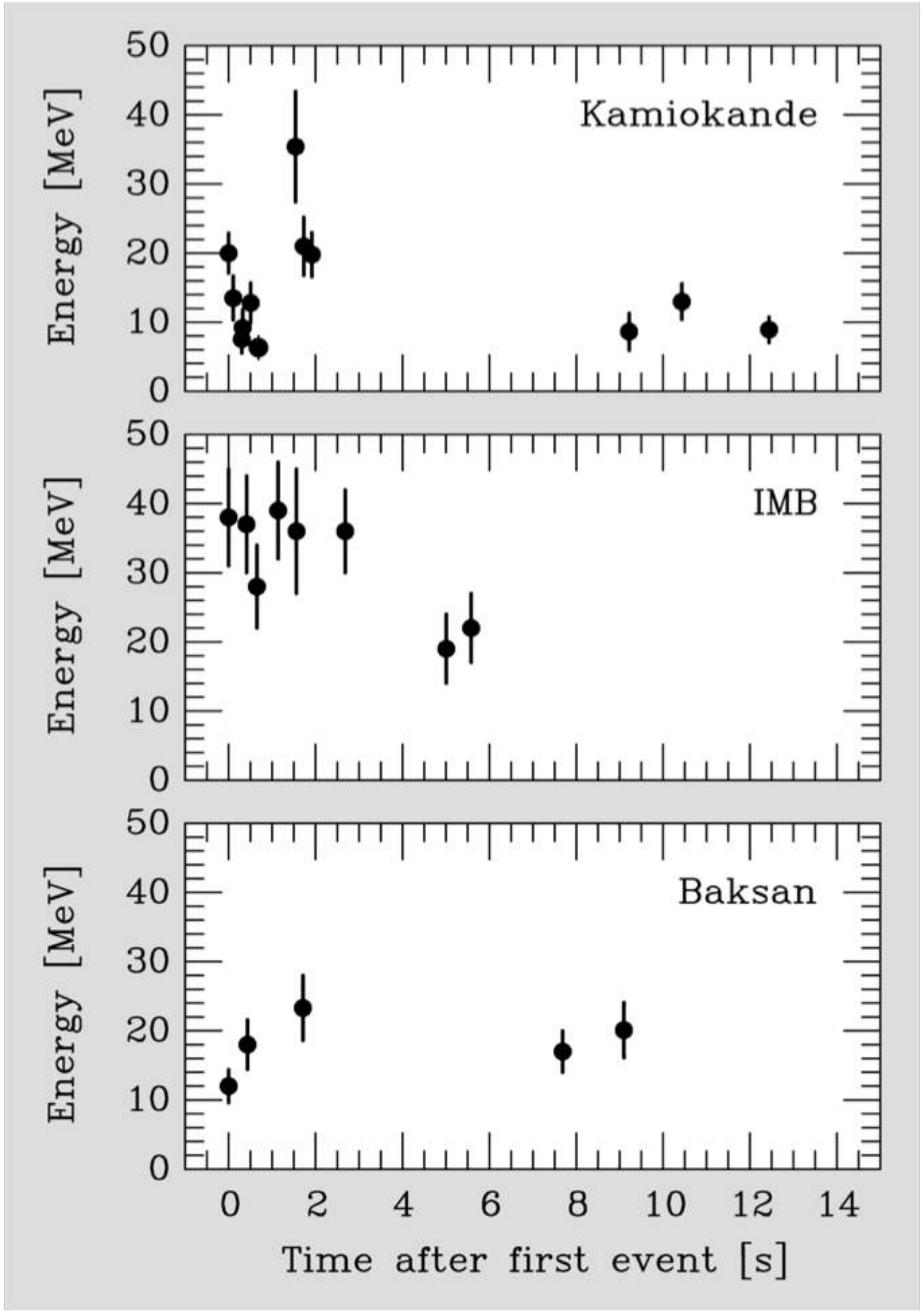
Core-collapse supernova



- After some seconds: formation of a proto-neutron star composed of degenerate neutrons: new equilibrium
- Infalling matter bounces on the core
- Shock wave forms within the iron core
- Shock wave looses kinetic energy by propagating
- Shock receives energy from neutrino heating (increased by convection and hydrodynamic instabilities)
- **10^{45} J released during the explosion (atomic bomb ~10^{13} J); ~99% released through neutrinos.**

Core-collapse supernova

- **SN1987A**: 25 neutrinos observed by 3 independant detectors (>10σ) within 13 sec.
- Confirmed the general model of core-collapse supernova explosion.
- However, determining the exact mechanism of explosion presents a great numerical and physical complexity.
- Delayed neutrino-heating mechanism emerges as key driver of supernova explosions, but many issues to address (hydrodynamic instabilities, ...).



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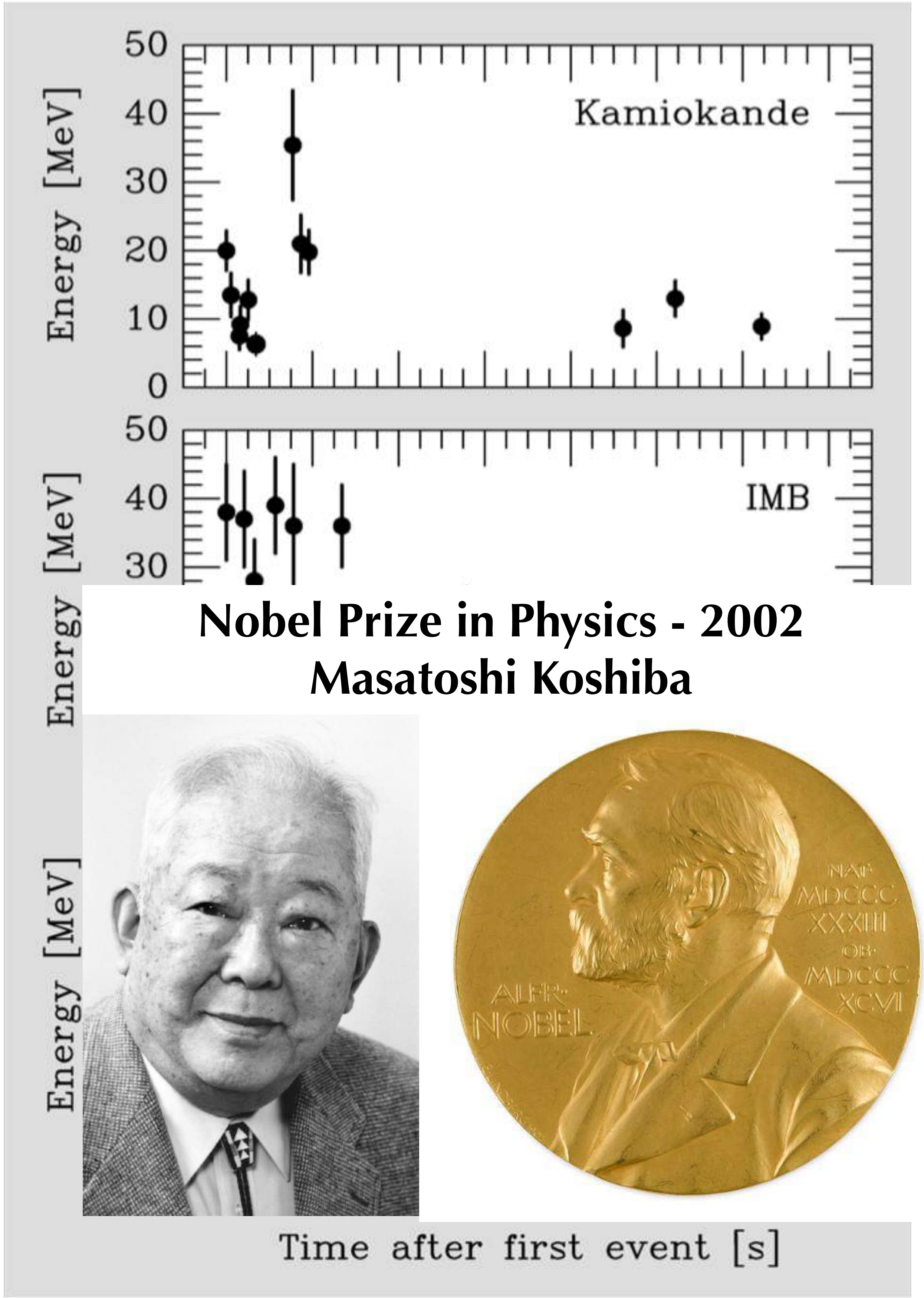
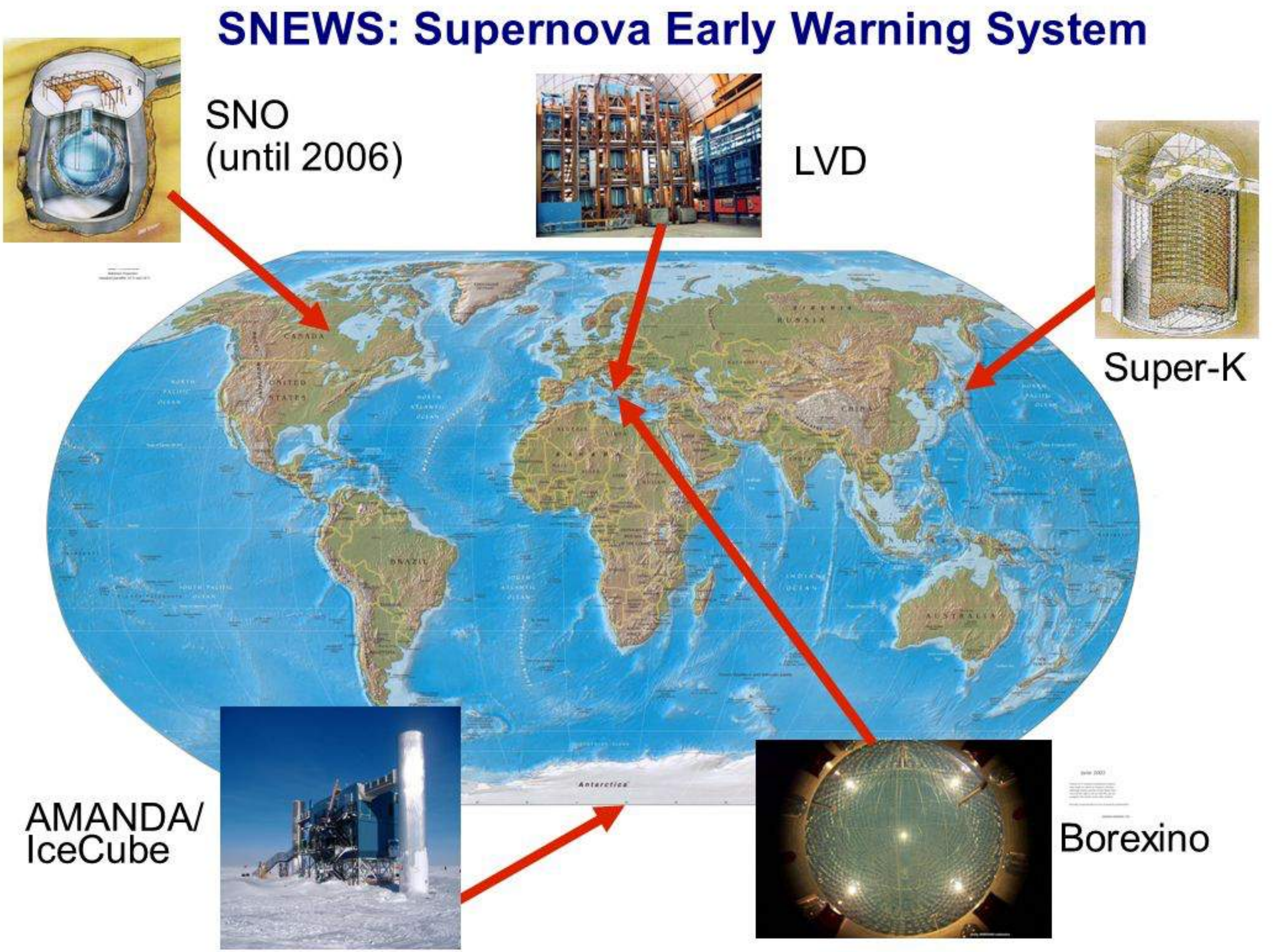


Supernova Early Warning System

Neutrinos are expected to arrive on Earth ~hours before the photons



Supernova Early Warning System

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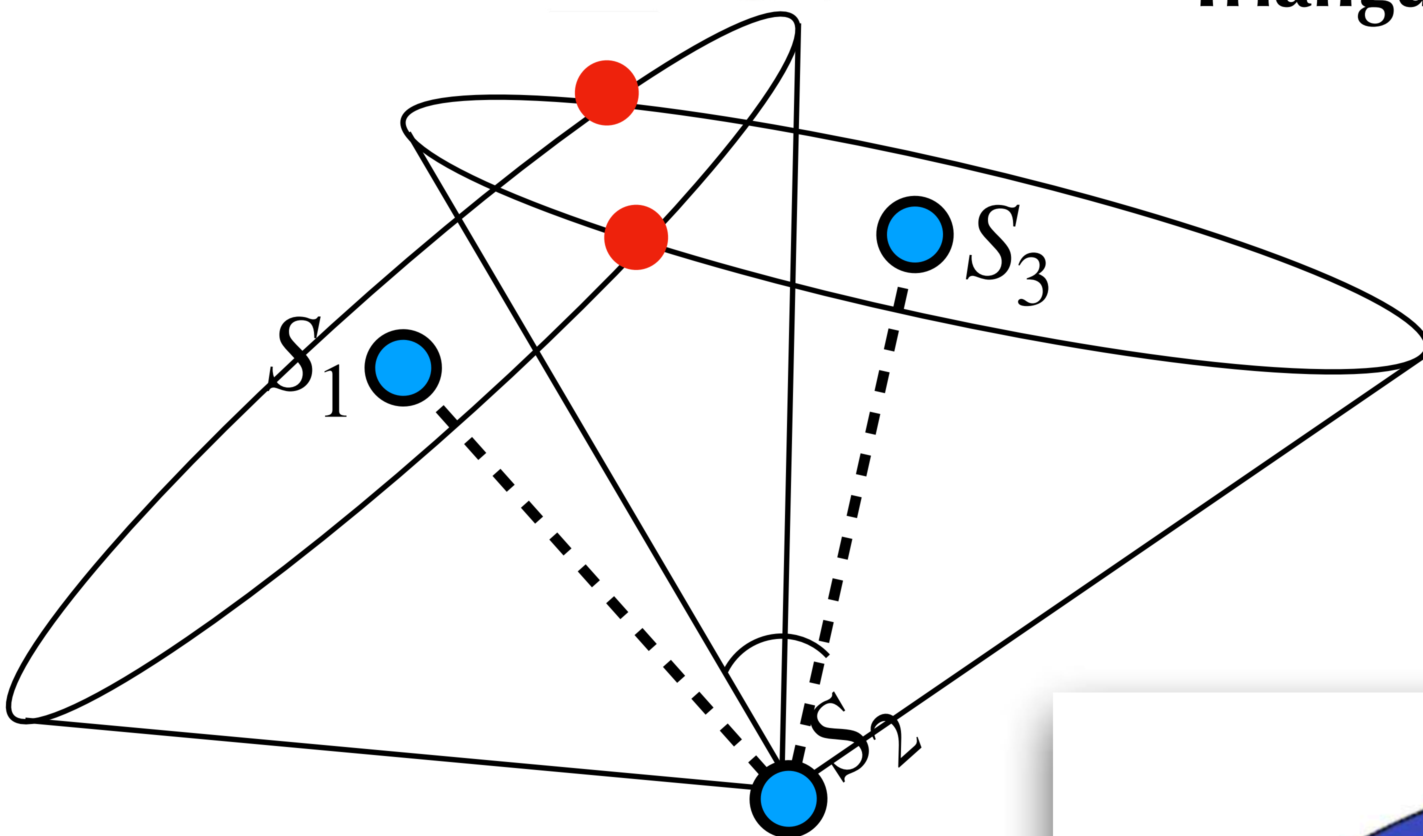
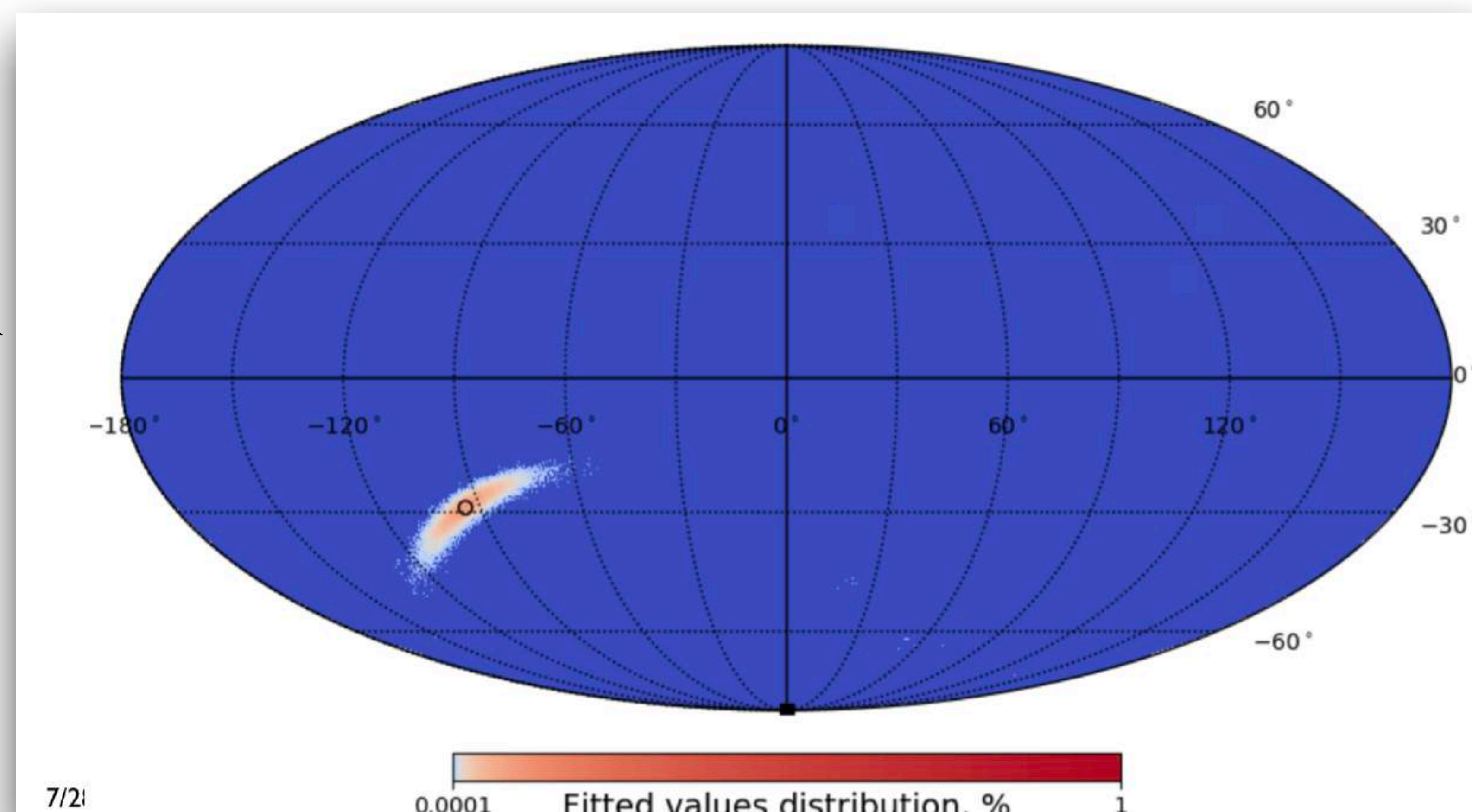
Core-collapse supernova location

Labex UnivEarthS — Université de Paris

Triangulation of multi-detector signal



Coleiro et al., 2020

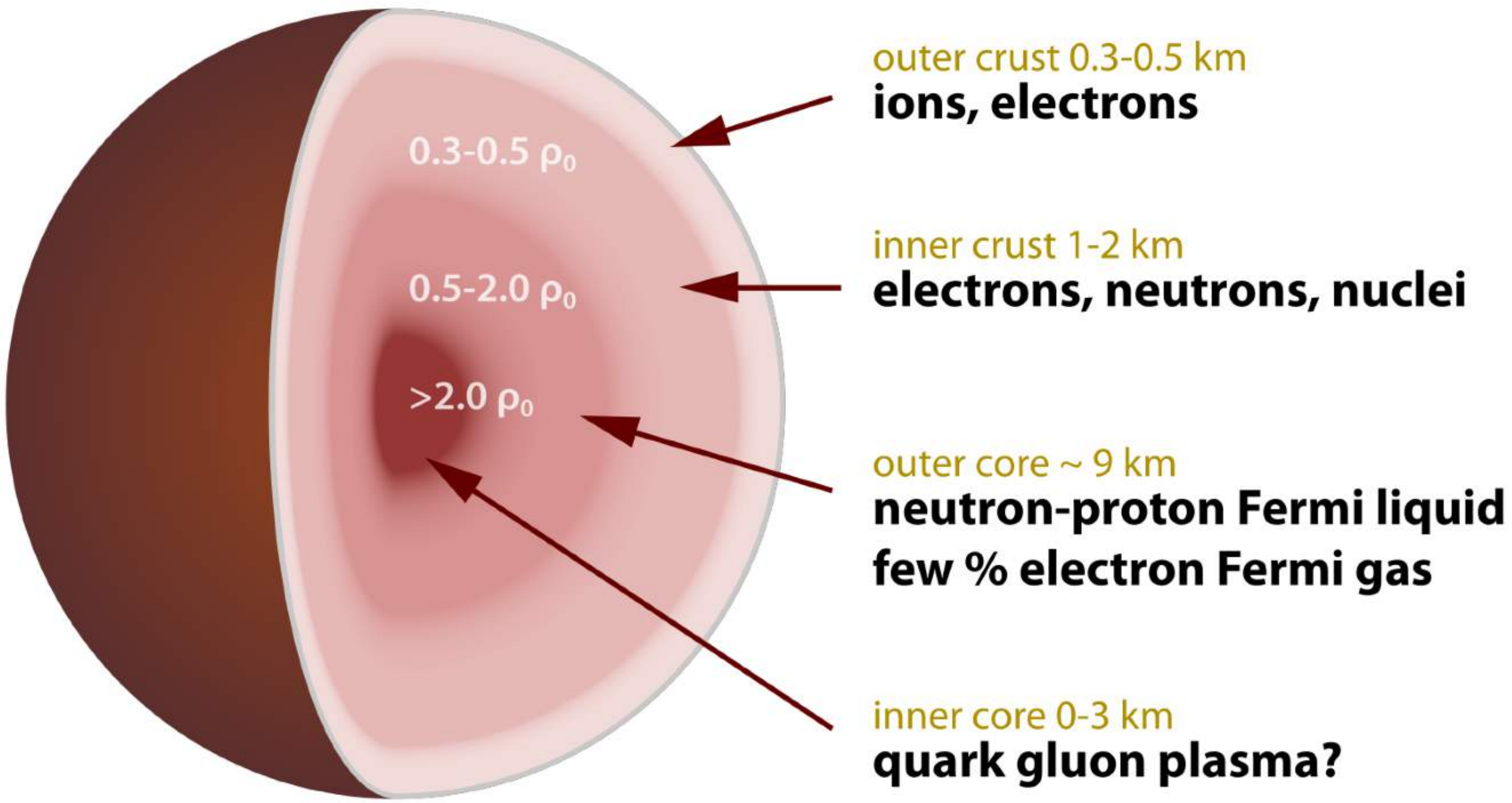


Core-collapse supernova follow-up

Labex UnivEarthS

Université de Paris

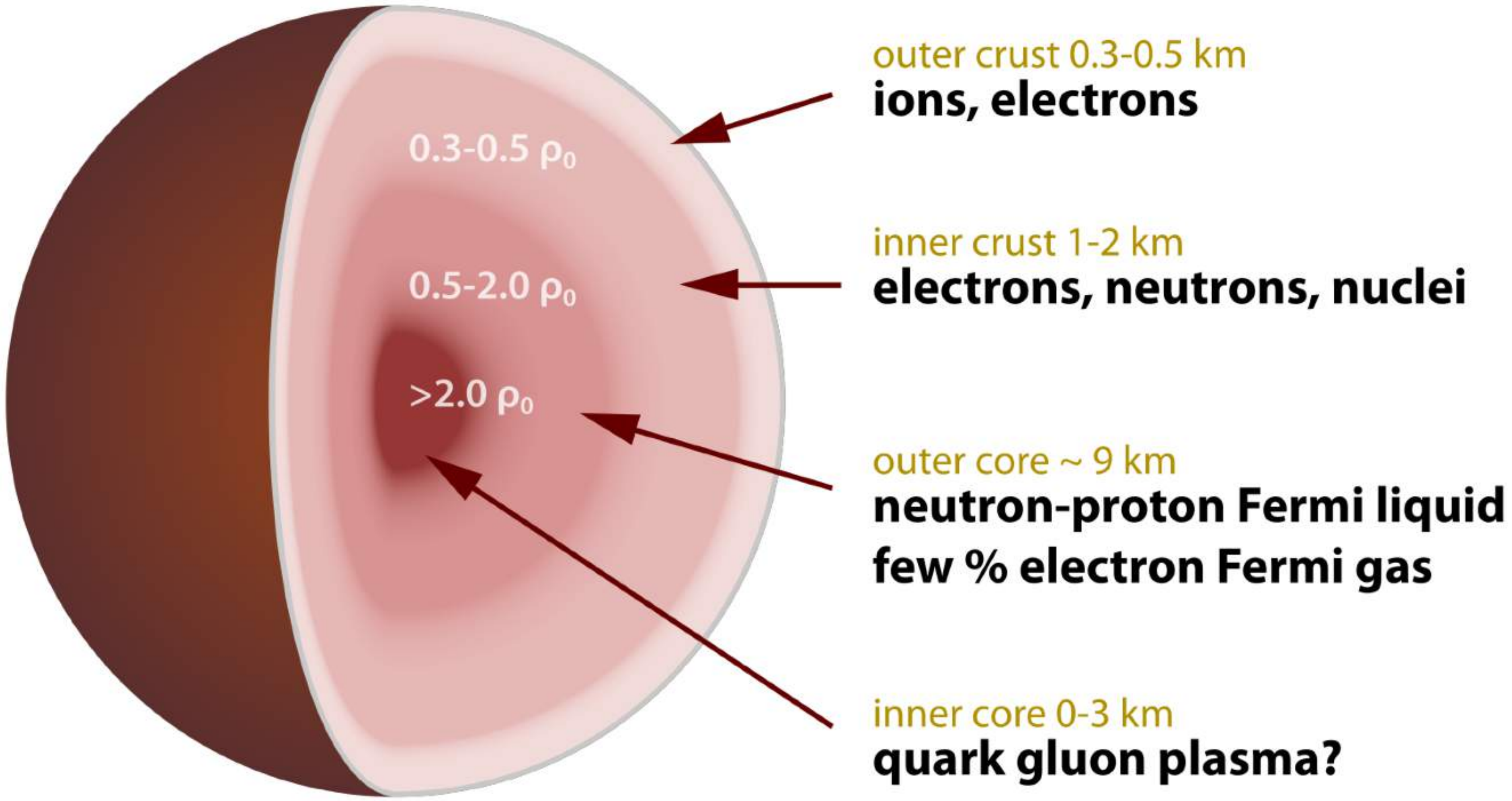
Neutron star



- Radius measurement possible by X-ray thermal emission observations or mass measurement through study of binary systems → **$M \sim 1\text{-}2 M_\odot$ and $R \sim 10$ km → $1 \text{mm}^3 \sim M_{\text{tour Eiffel}}$**

- <u>Rotation velocity:</u>

Neutron star



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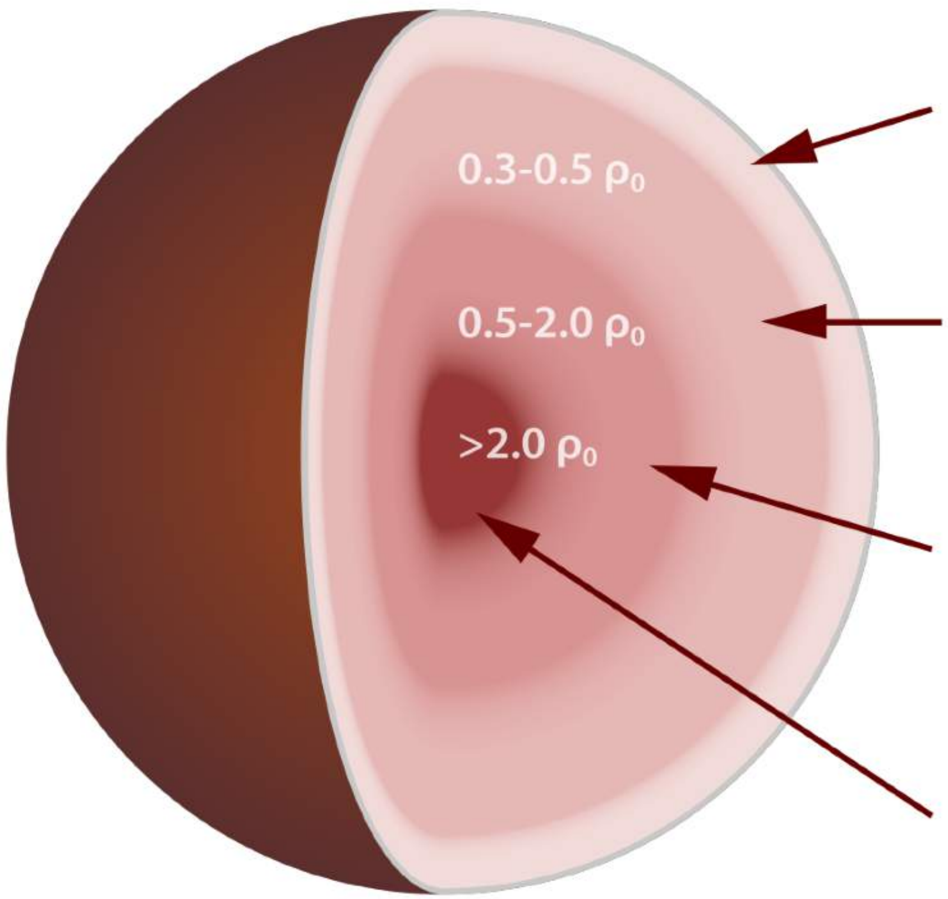
- <u>Rotation velocity:</u>

Conservation of angular momentum: $I\omega \propto MR^2\omega$. R decreases → I decreases and then ω increases.
If R_i ~700 000 km, ω_i = 1 month^{-1} and R_f = 10km → ω_f = 4.9 $10^9\,\omega_i$ → **~2 ms^{-1} !**

Neutron star



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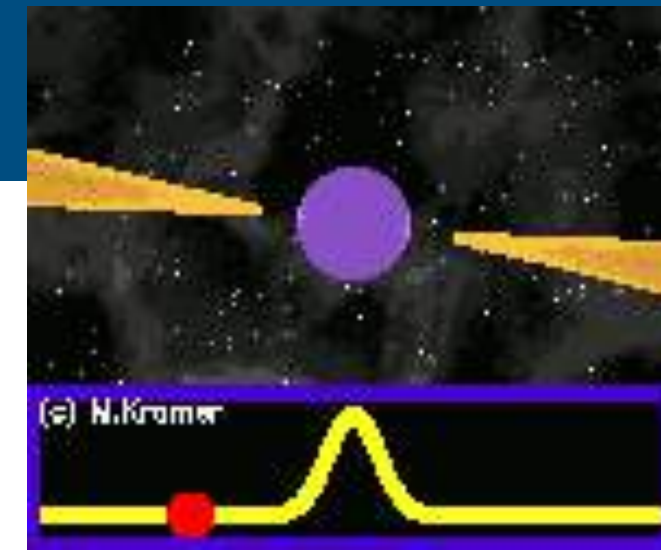
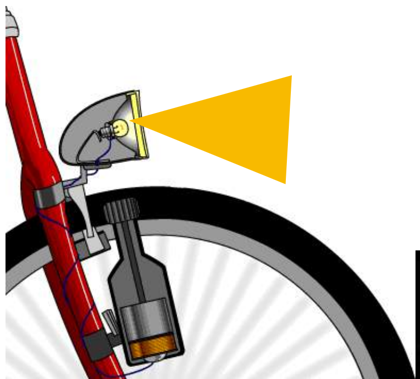
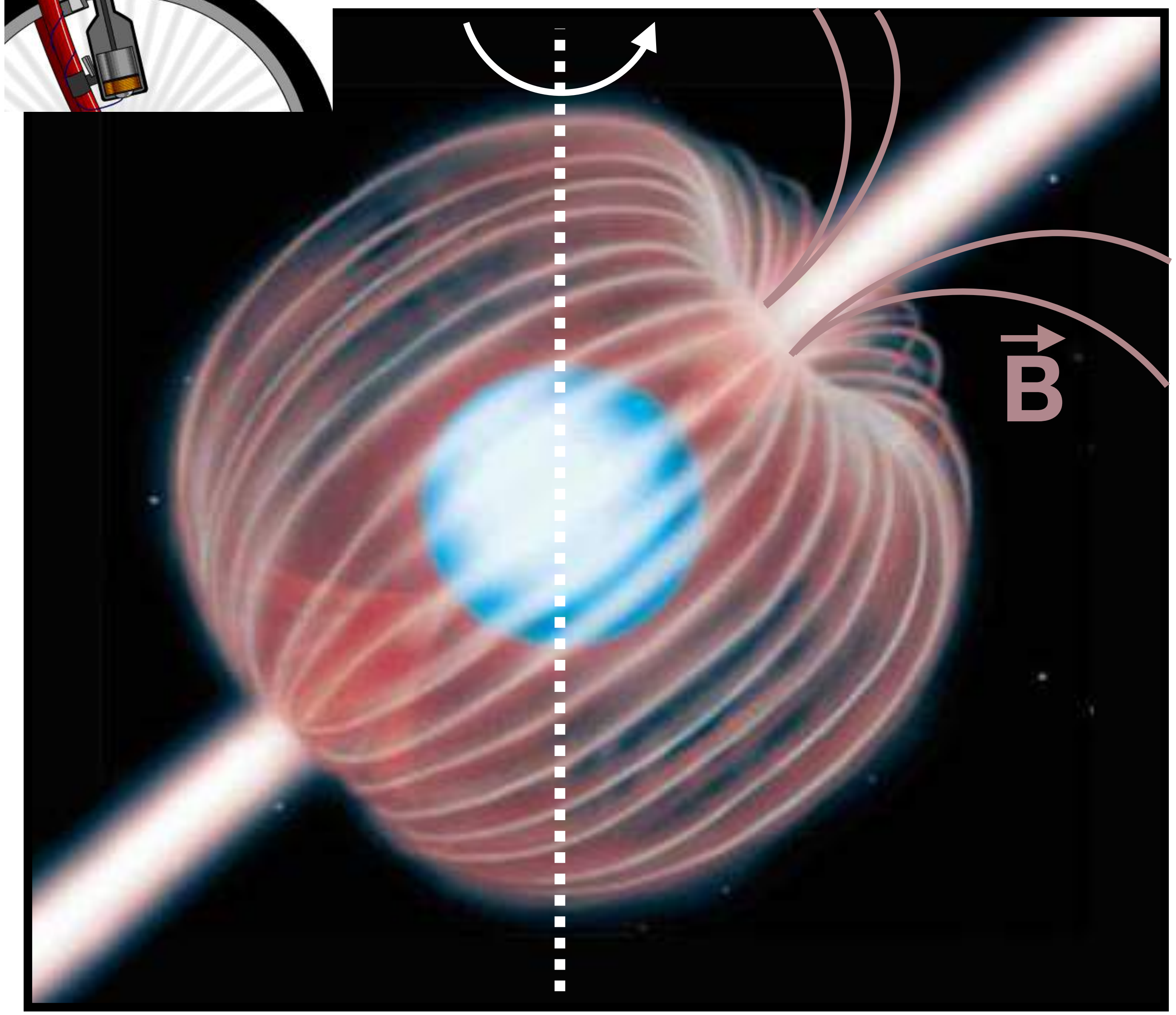
Pulsars

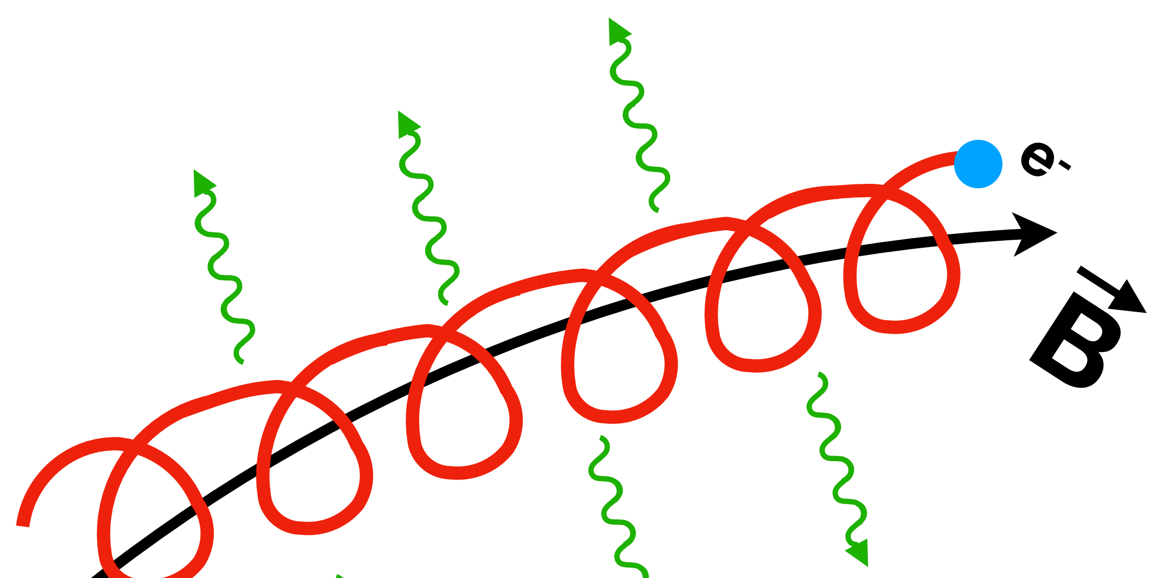


Increase of magnetic field due to magnetic flux conservation during the collapse of the progenitor star





- Pulsar = high rotation velocity + highly magnetized neutron star
- High magnetic field (~10^8 T)
- Relativistic electrons extracted from pulsar surface by electric field.
- Escaping relativistic electrons spiral around the field lines and are accelerated → synchrotron radiation escaping through the magnetic poles of the star: beam detected in radio



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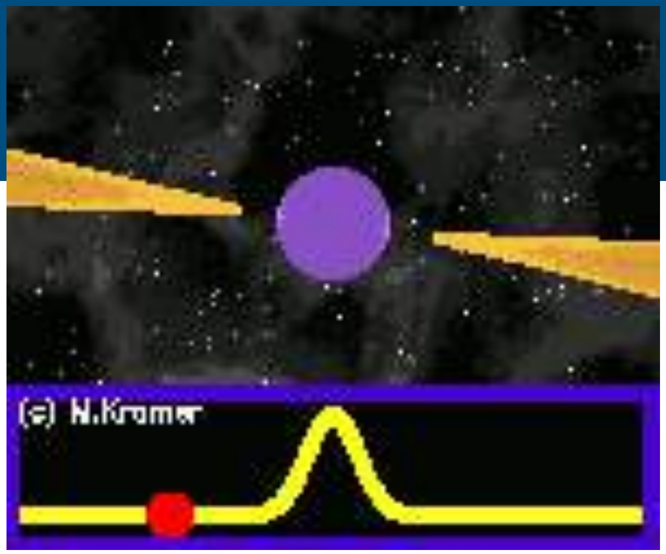

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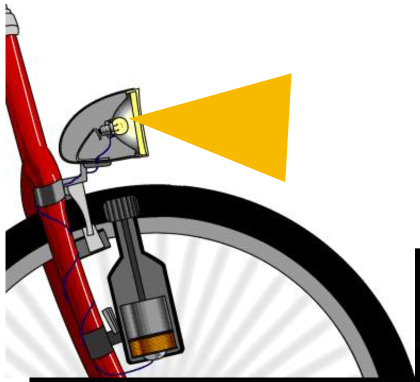

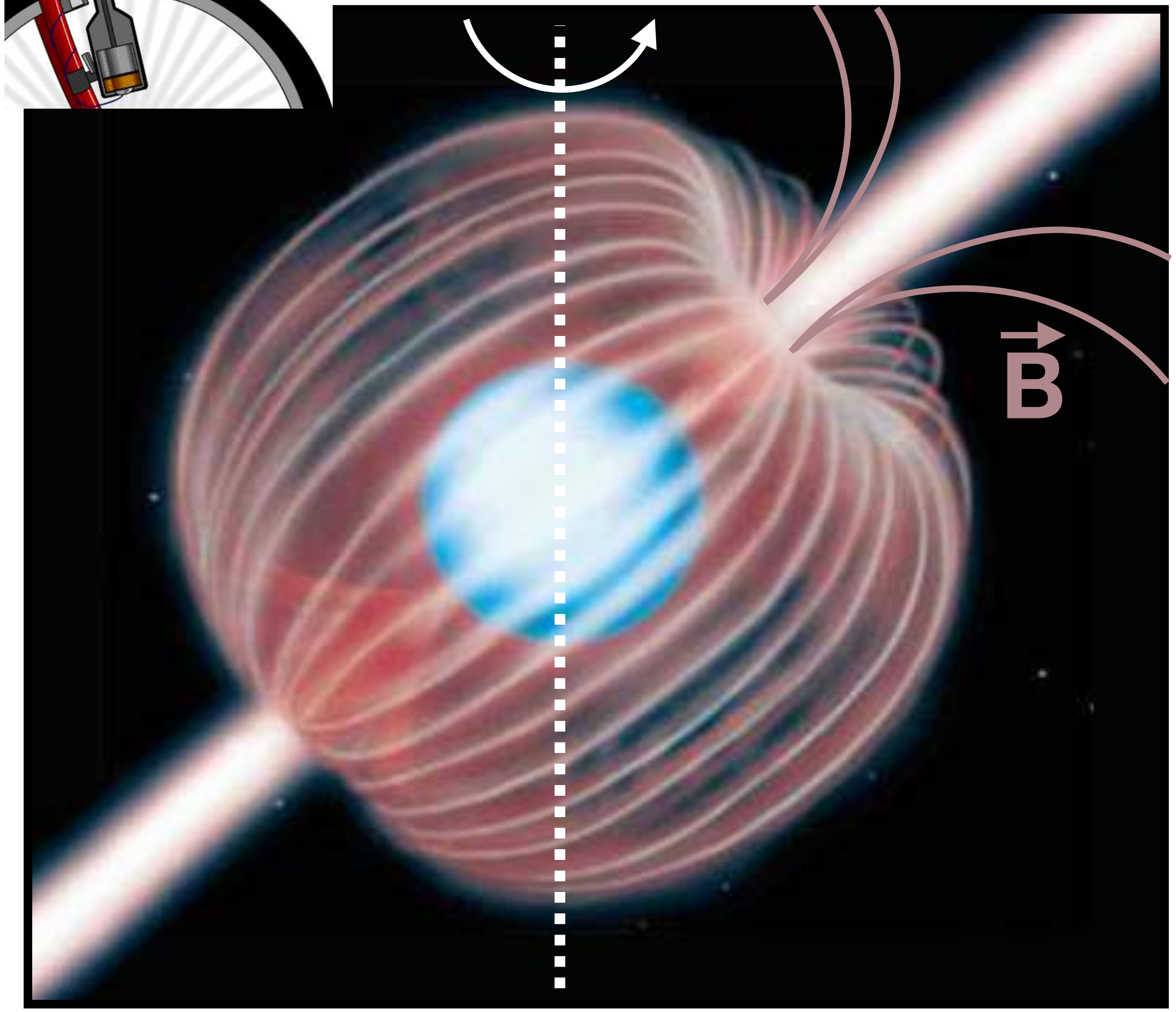

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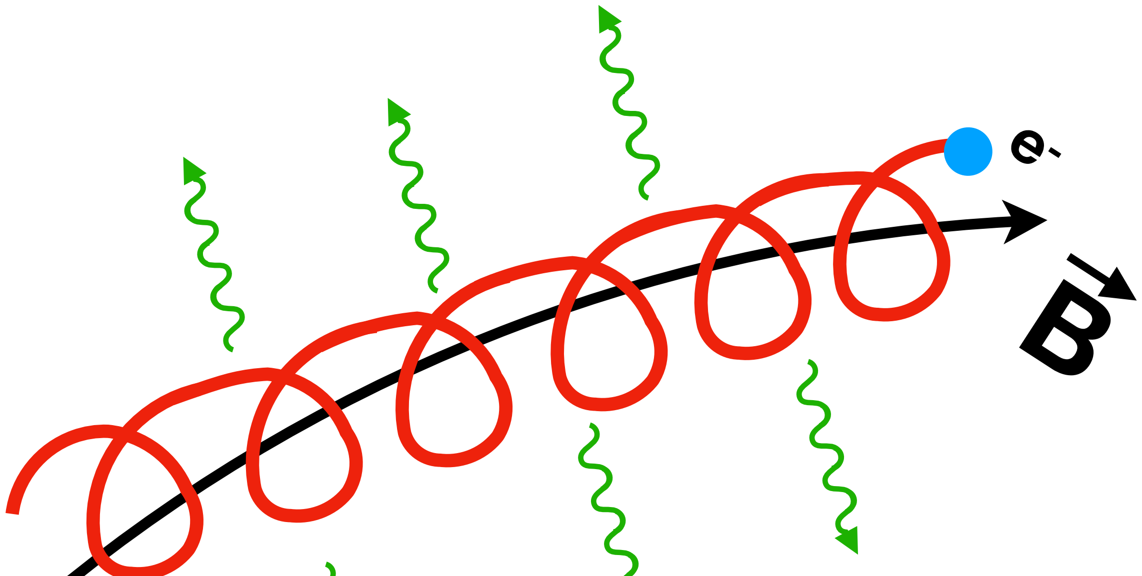

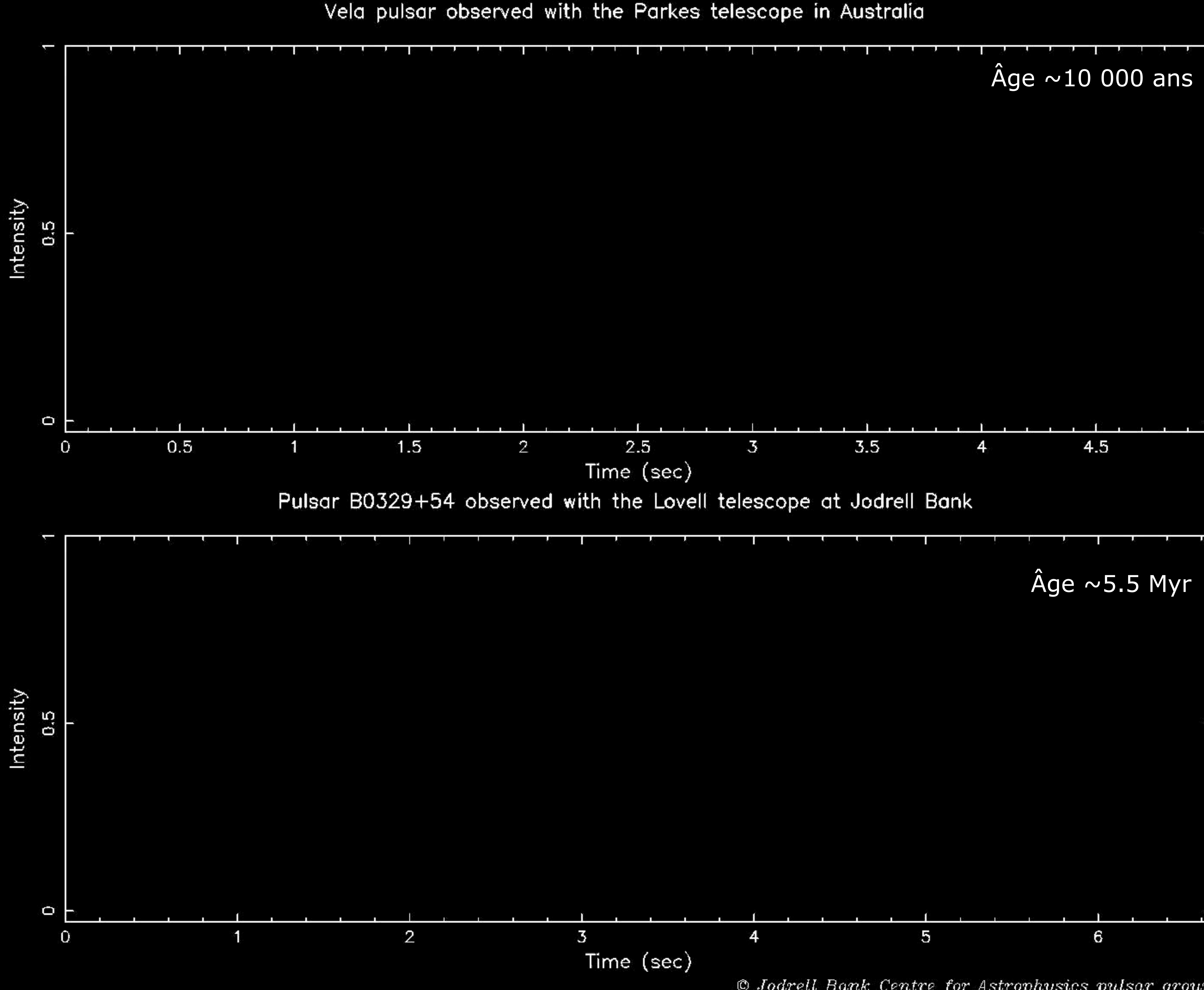
Vela pulsar observed with the Parkes telescope in Australia
Âge ~10 000 ans
Intensity
0
0.5
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)
Pulsar B0329+54 observed with the Lovell telescope at Jodrell Bank
Âge ~5.5 Myr
Intensity
0
0.5
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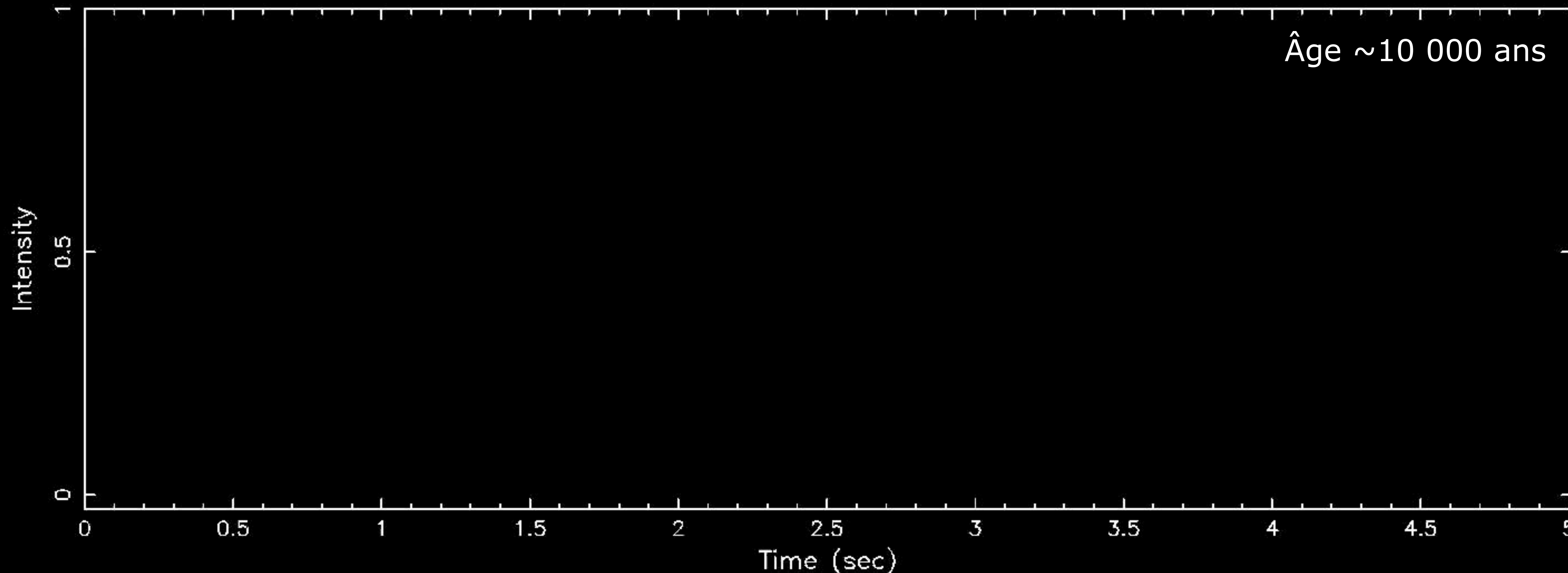
0
1
2
3
4
5
6
Time (sec)
© Jodrell Bank Centre for Astrophysics pulsar group

Vela pulsar observed with the Parkes telescope in Australia



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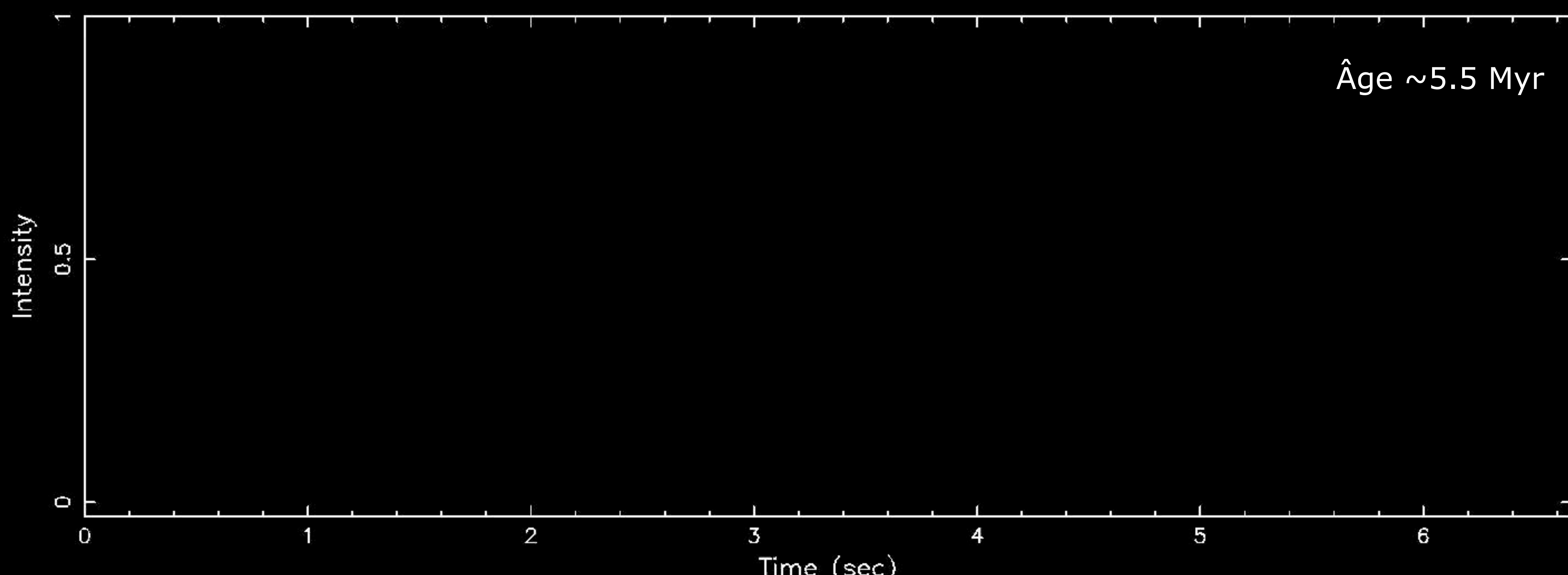

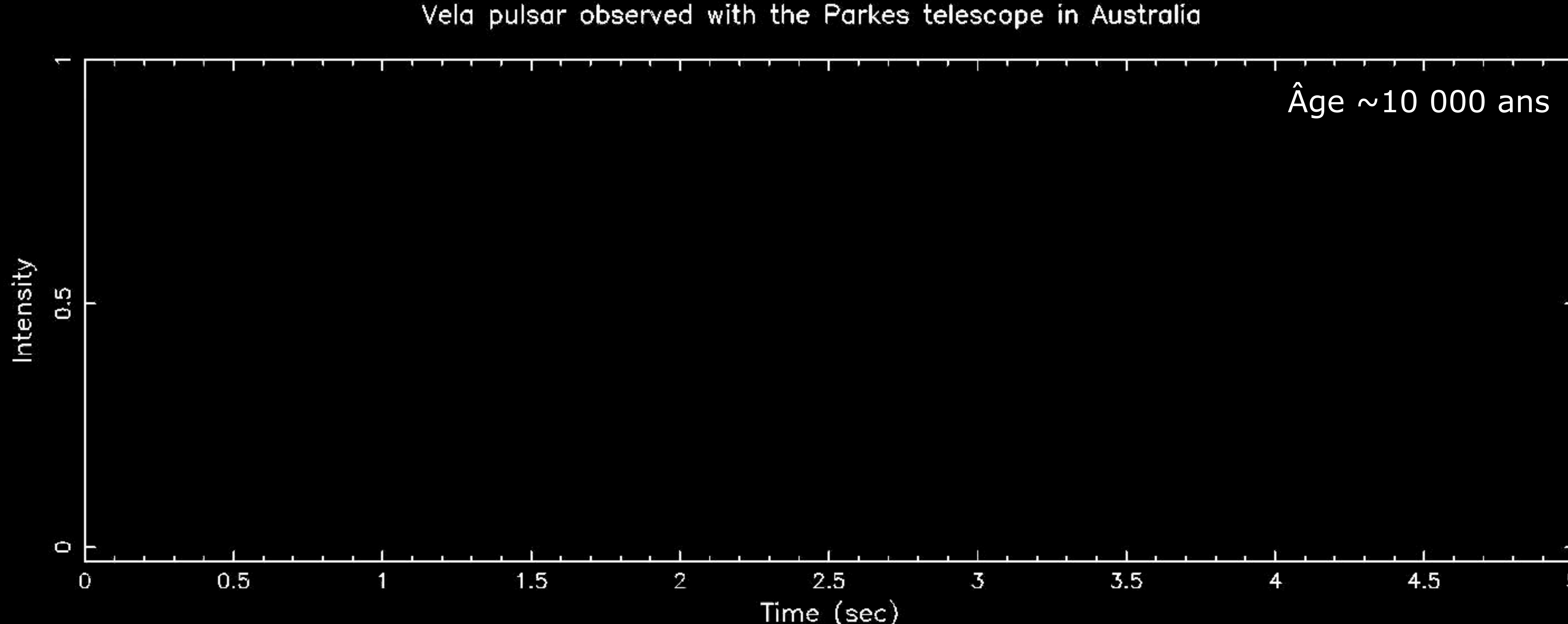
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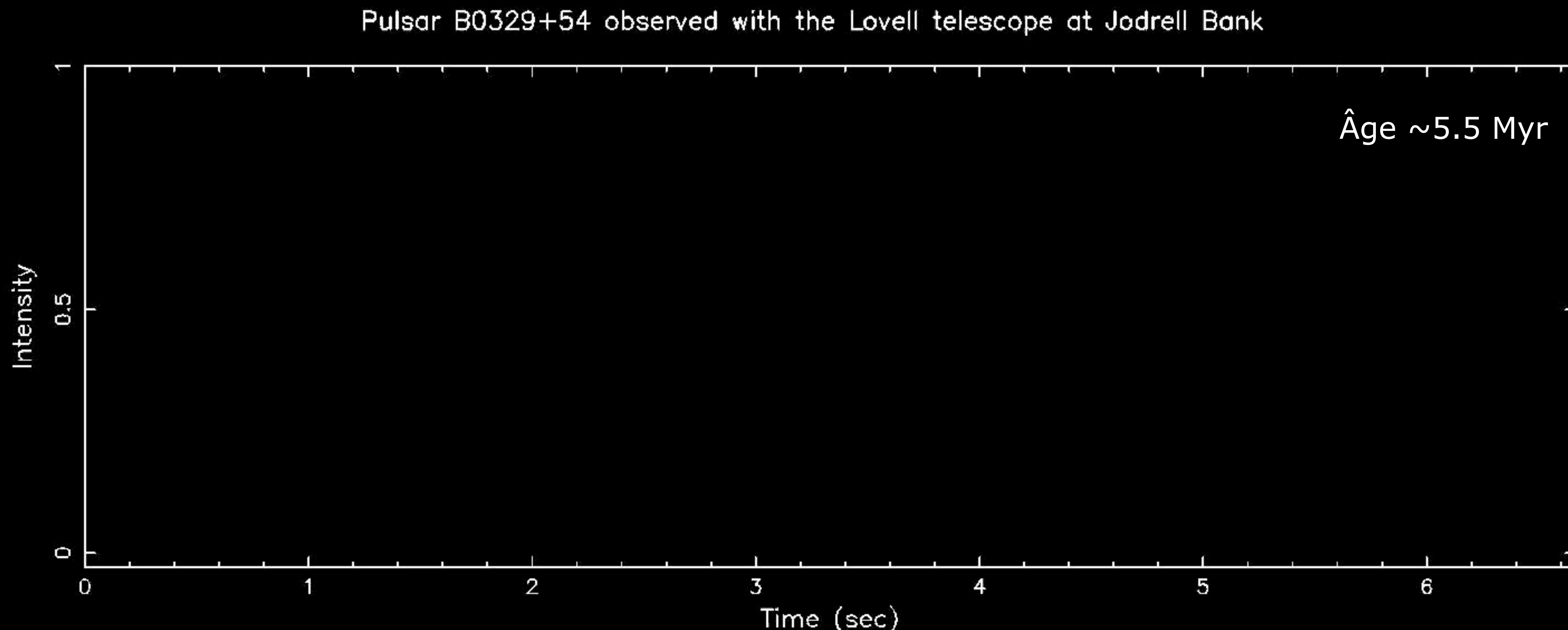
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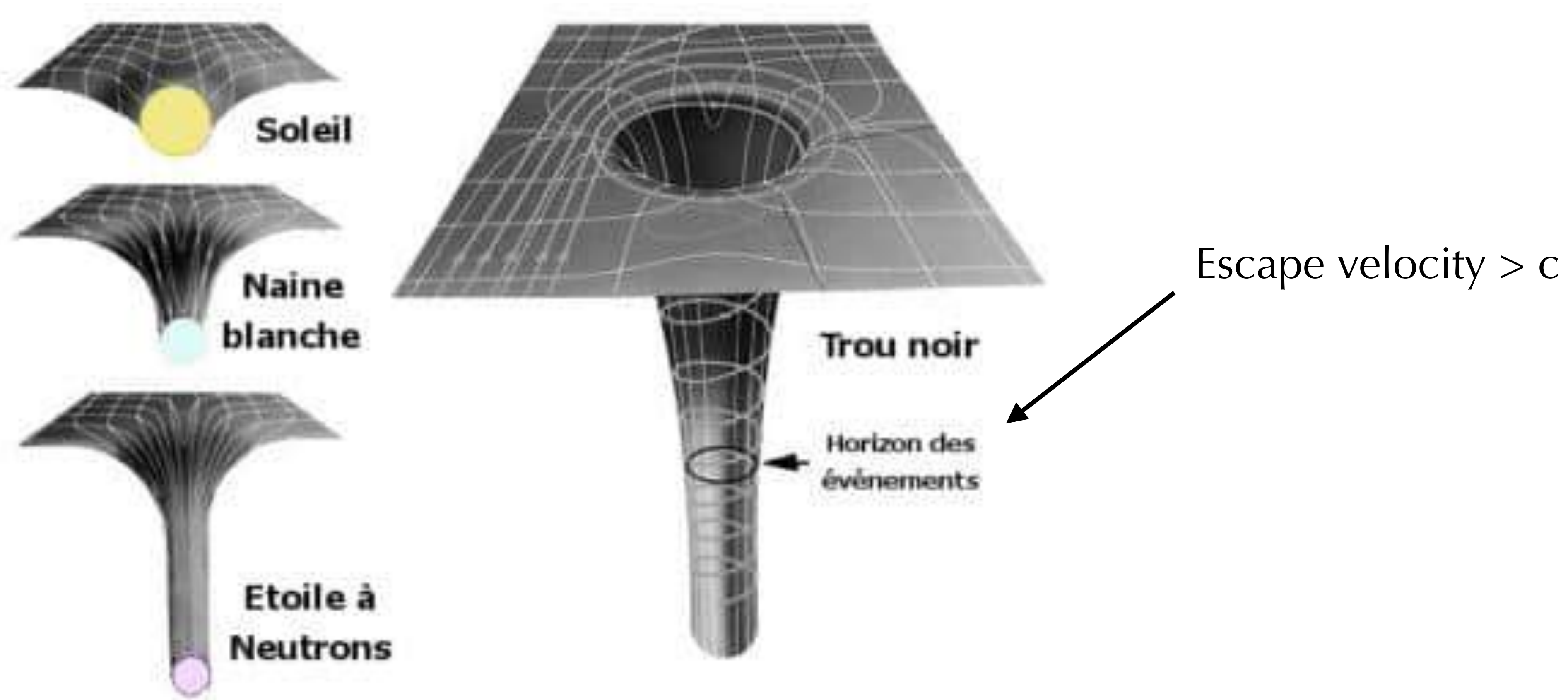
4
5
6
Time (sec)

Black holes: end of live of most massive stars

When the initial star is massive enough, the energy released during the contraction can overcome the pressure of neutron degeneracy! (occurs at densities of tens of billions of tons per cm3).

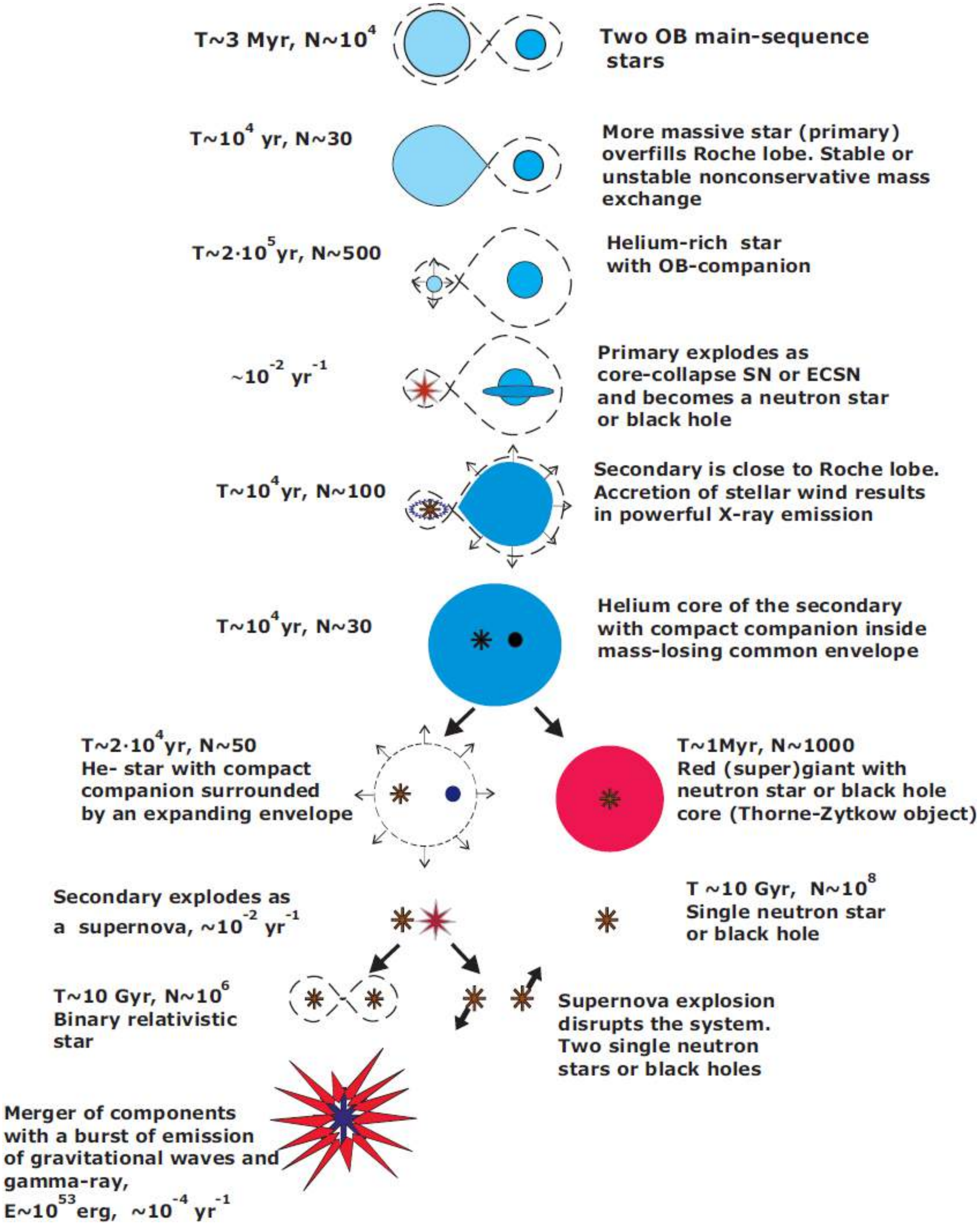
The potential well distorts space-time (general relativity) so that even photons cannot escape: **black hole**!



Binary systems

Several obstacles to get the two compact objects close to each other:

- Supernova explosions can disrupt the system;
- Common envelope phase can make the two objects merge earlier.



Outline - Lecture 2

B. End point of massive star evolution

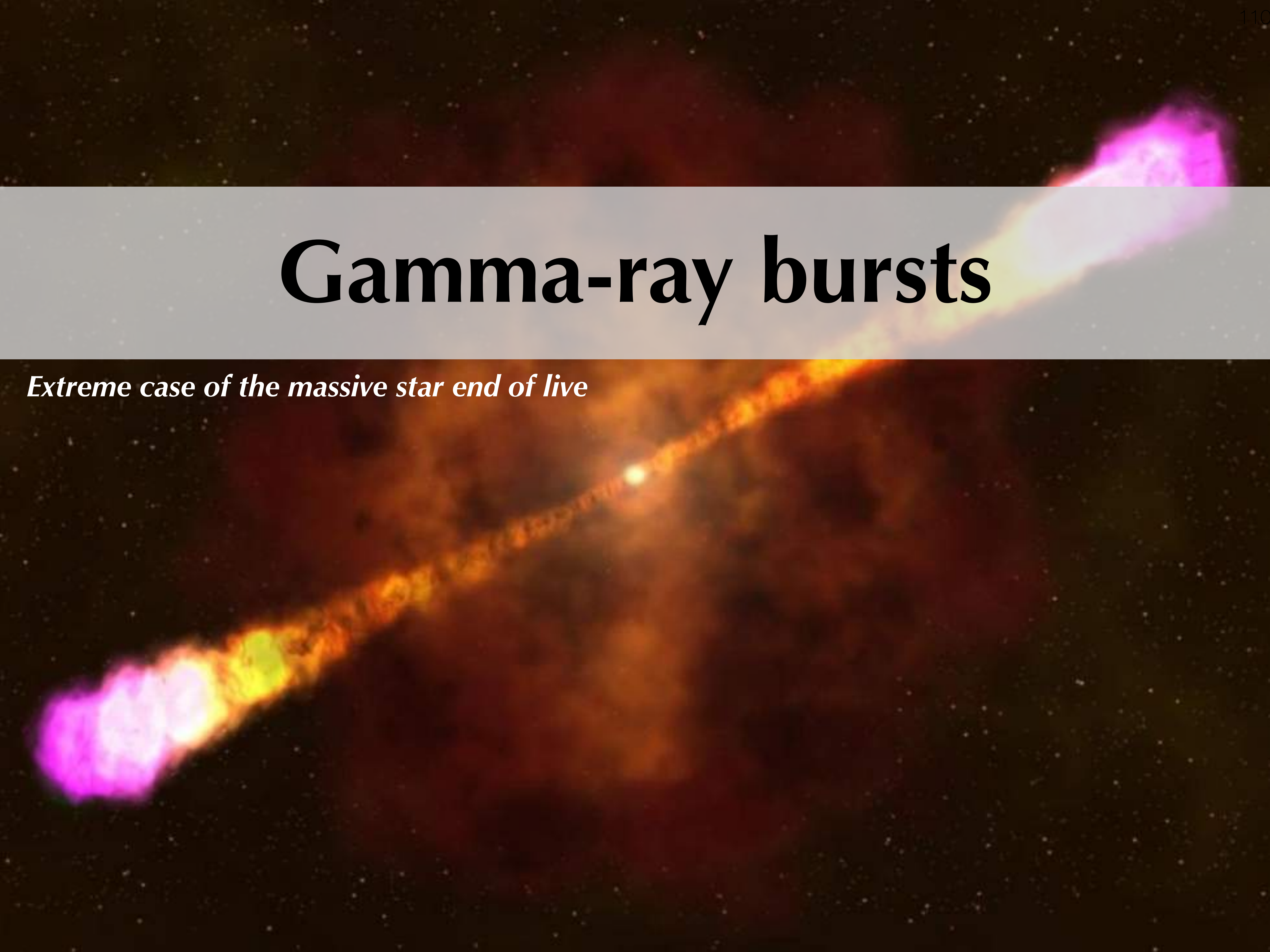
1. Evolution of massive stars

2. **Gamma-ray bursts**

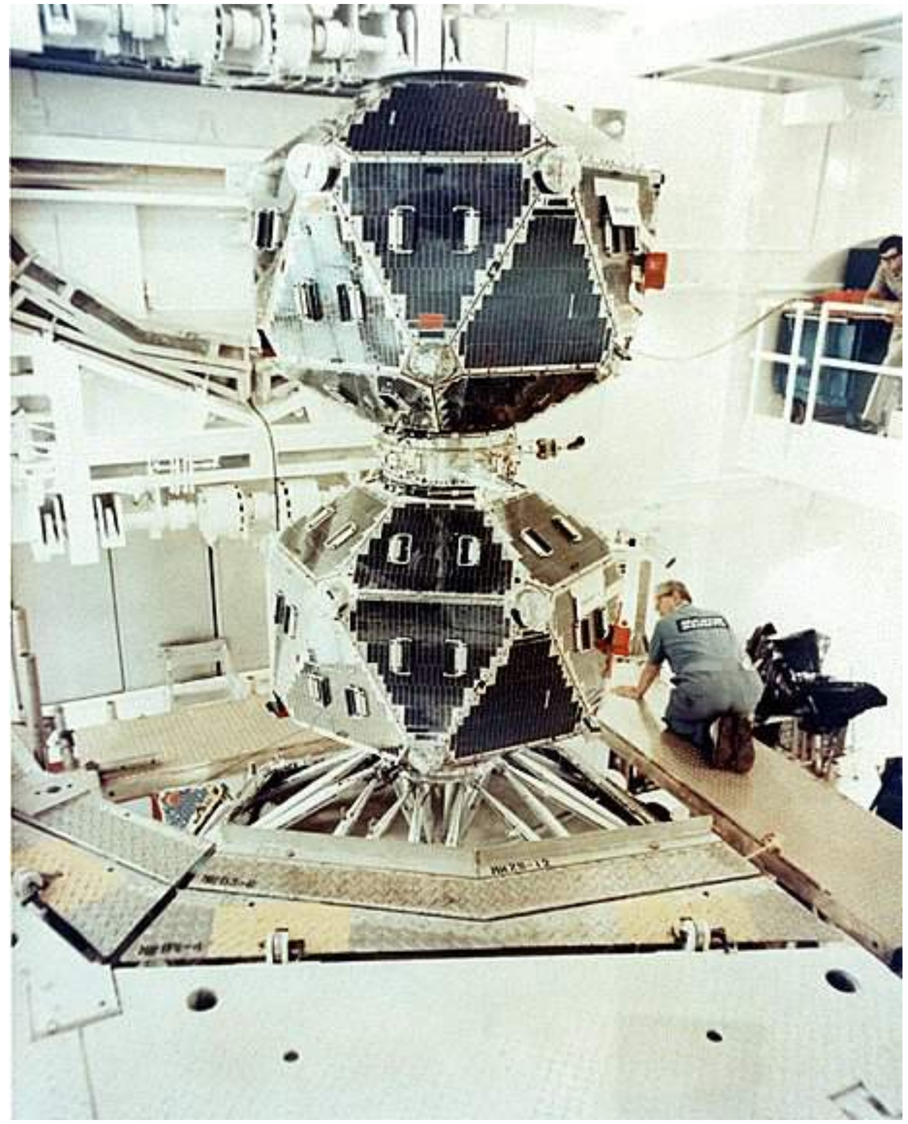
3. The SVOM space mission

Gamma-ray bursts

Extreme case of the massive star end of live



VELA satellites



Gamma-ray observations

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

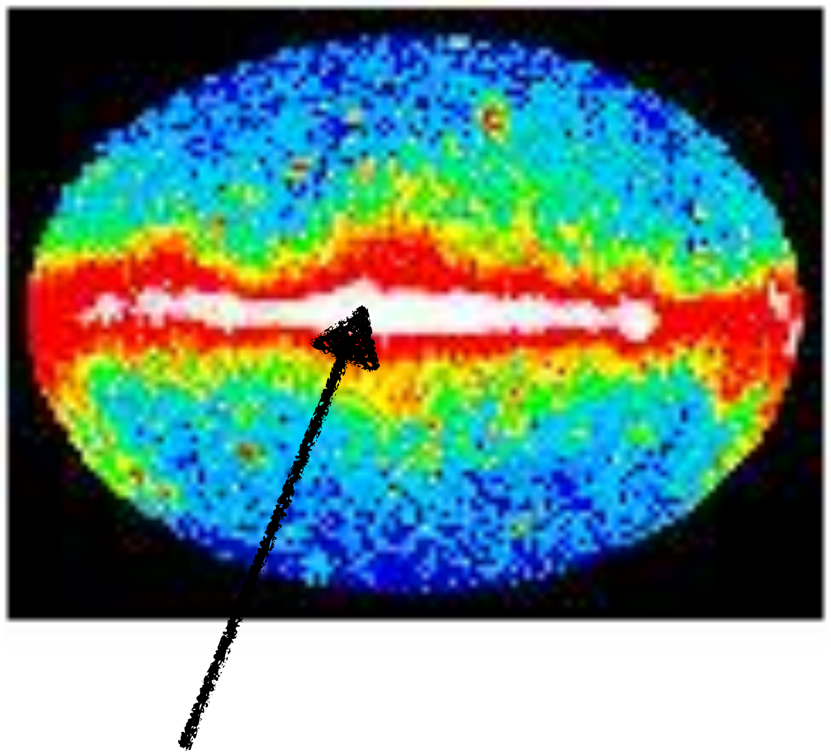
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

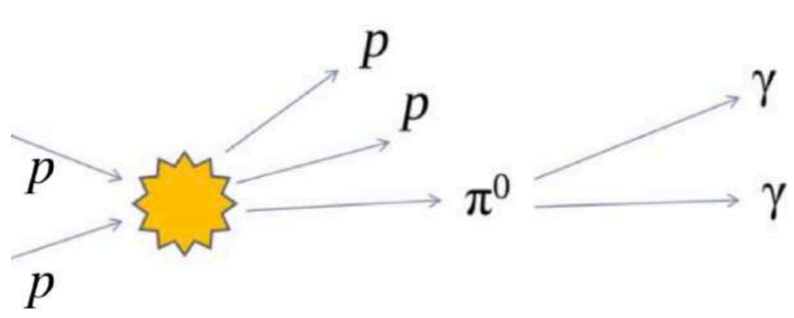
ABSTRACT

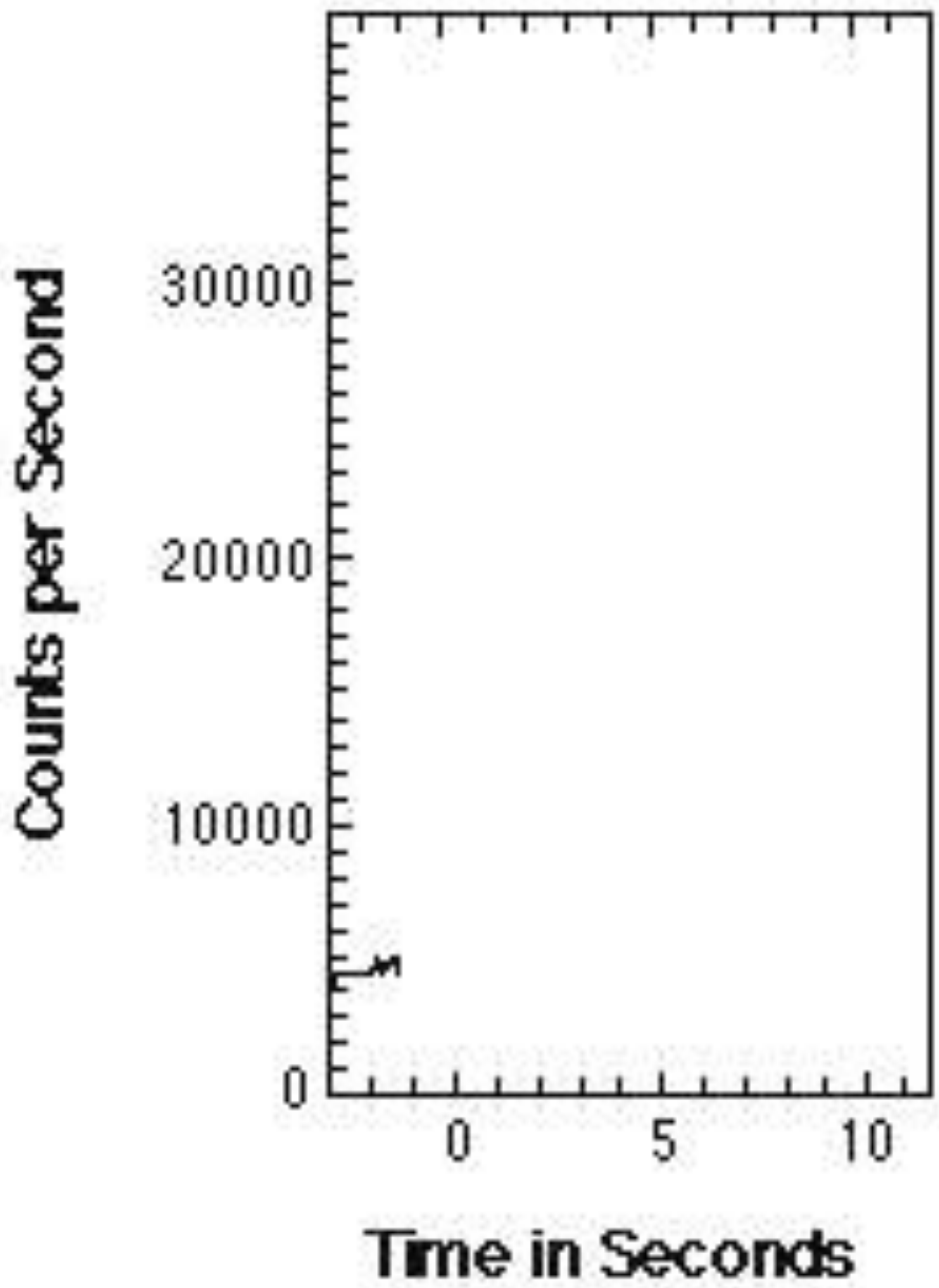
Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

What do gamma-ray burst look like ?



Galactic plane: p-p interactions





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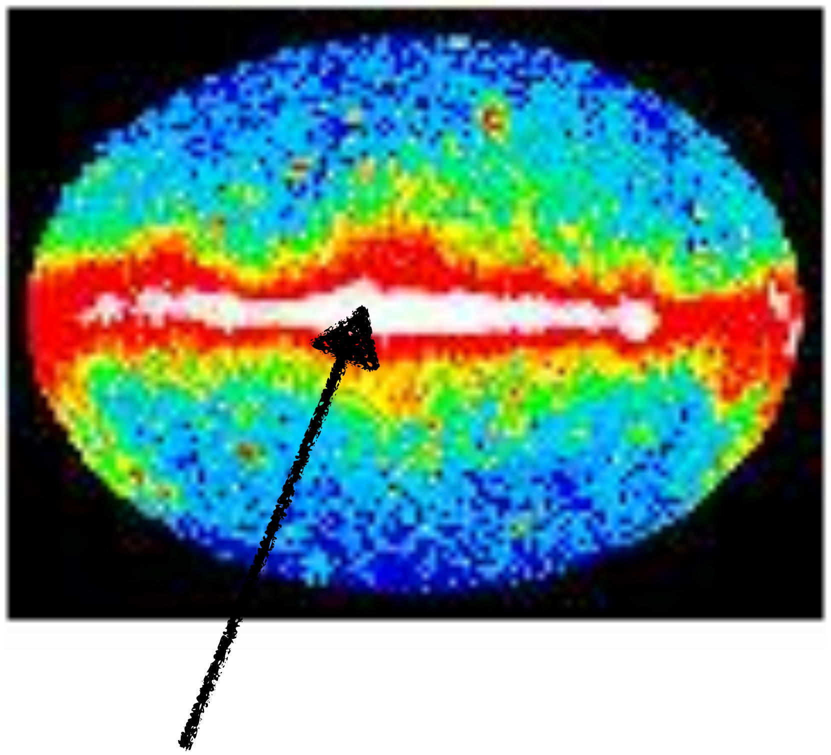

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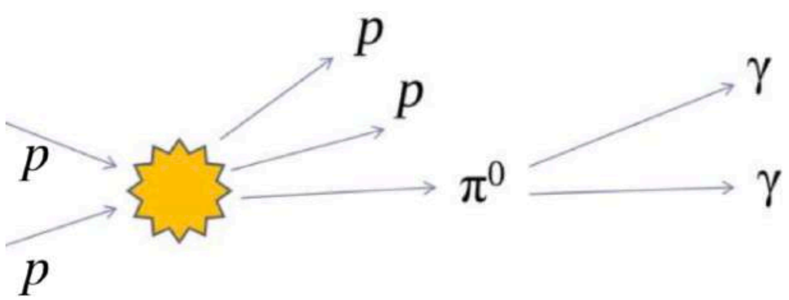
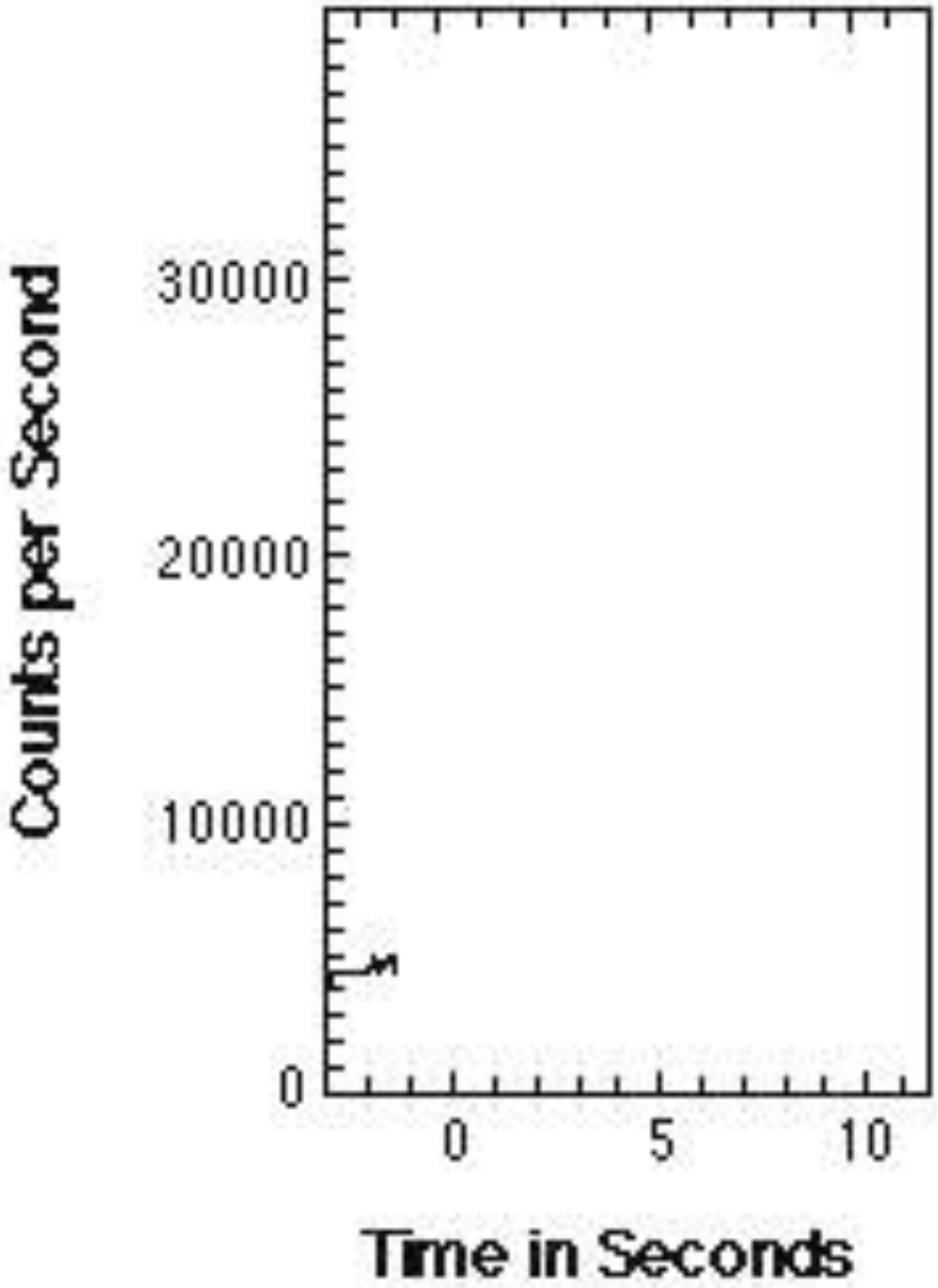
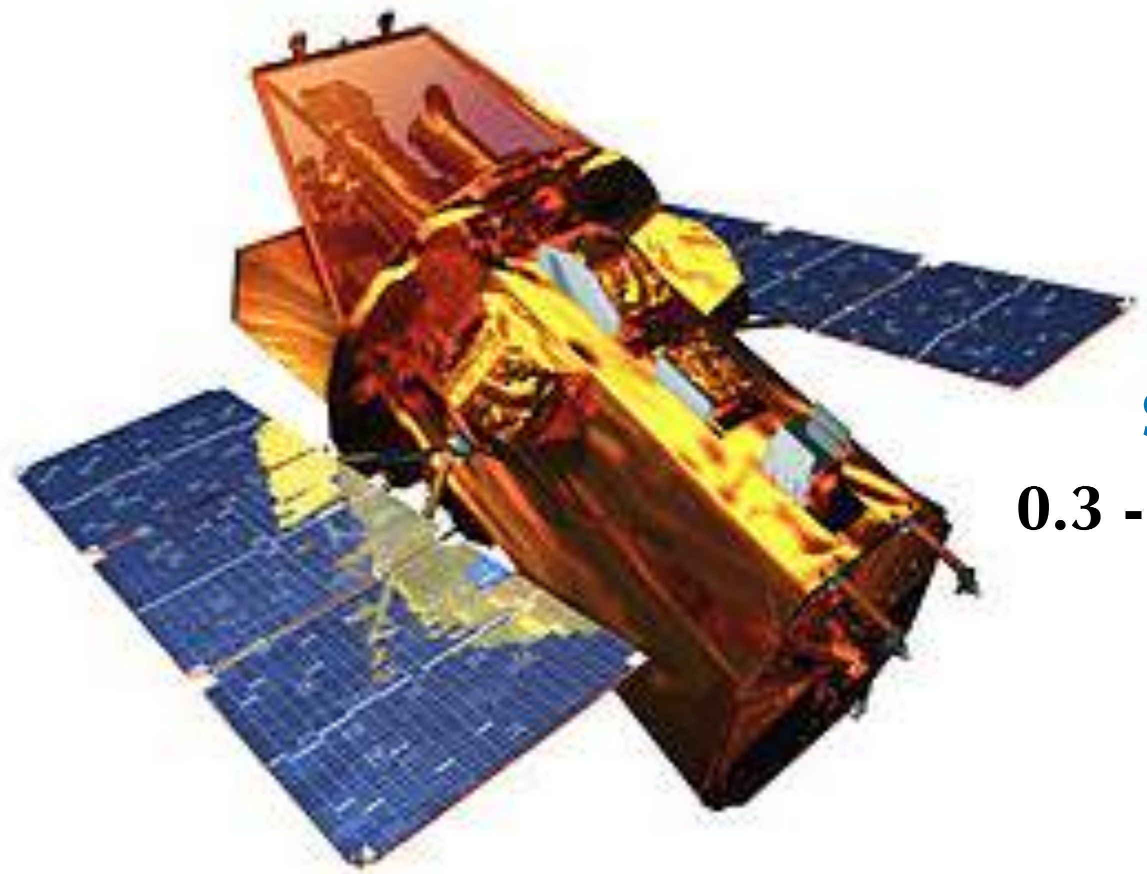


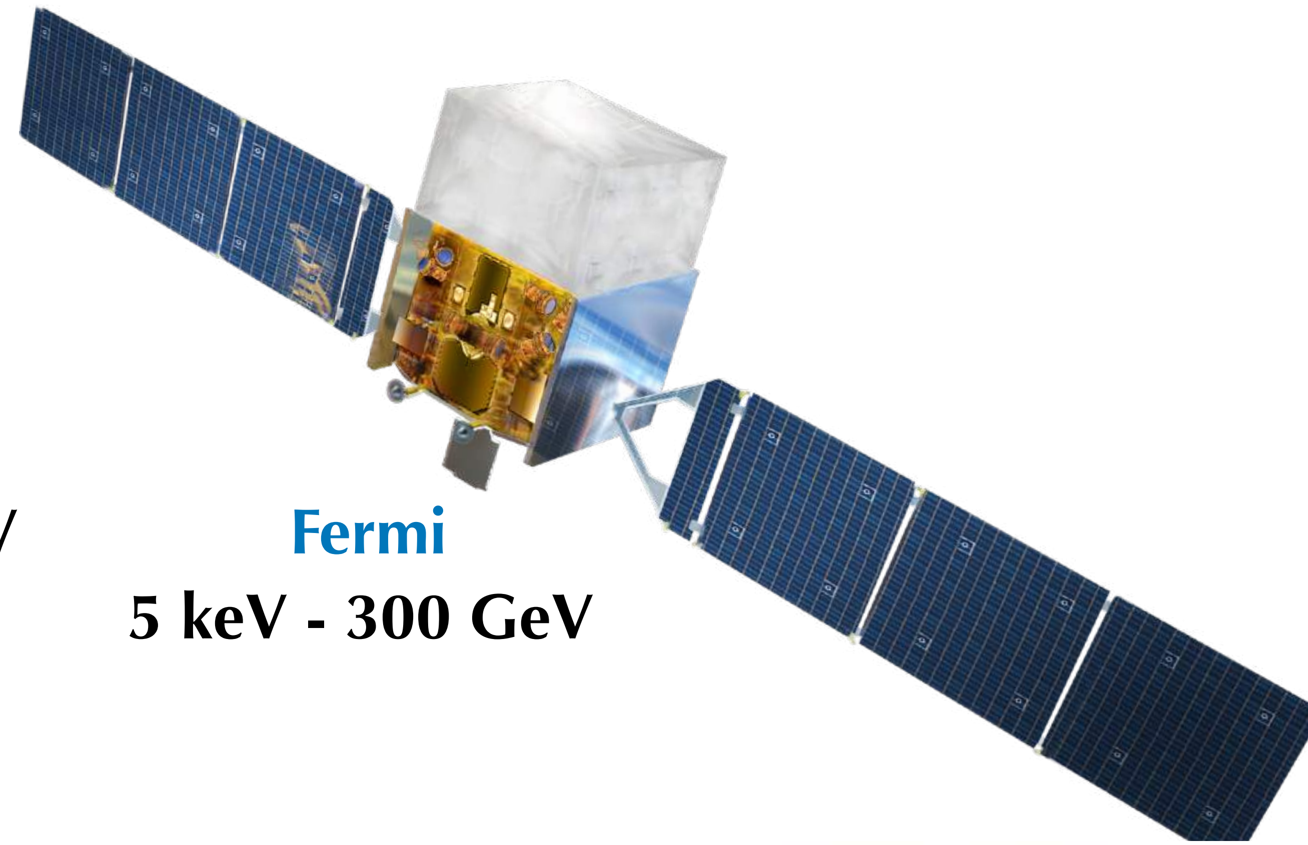


Gamma-ray bursts



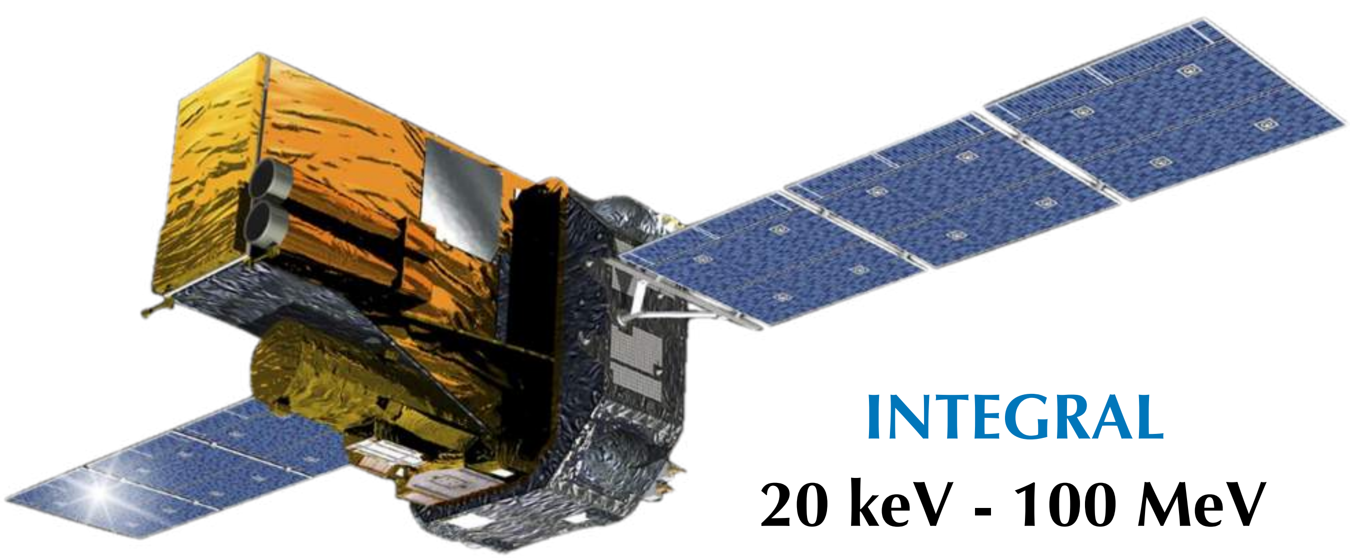
Swift

0.3 - 195 keV



Fermi

5 keV - 300 GeV



INTEGRAL

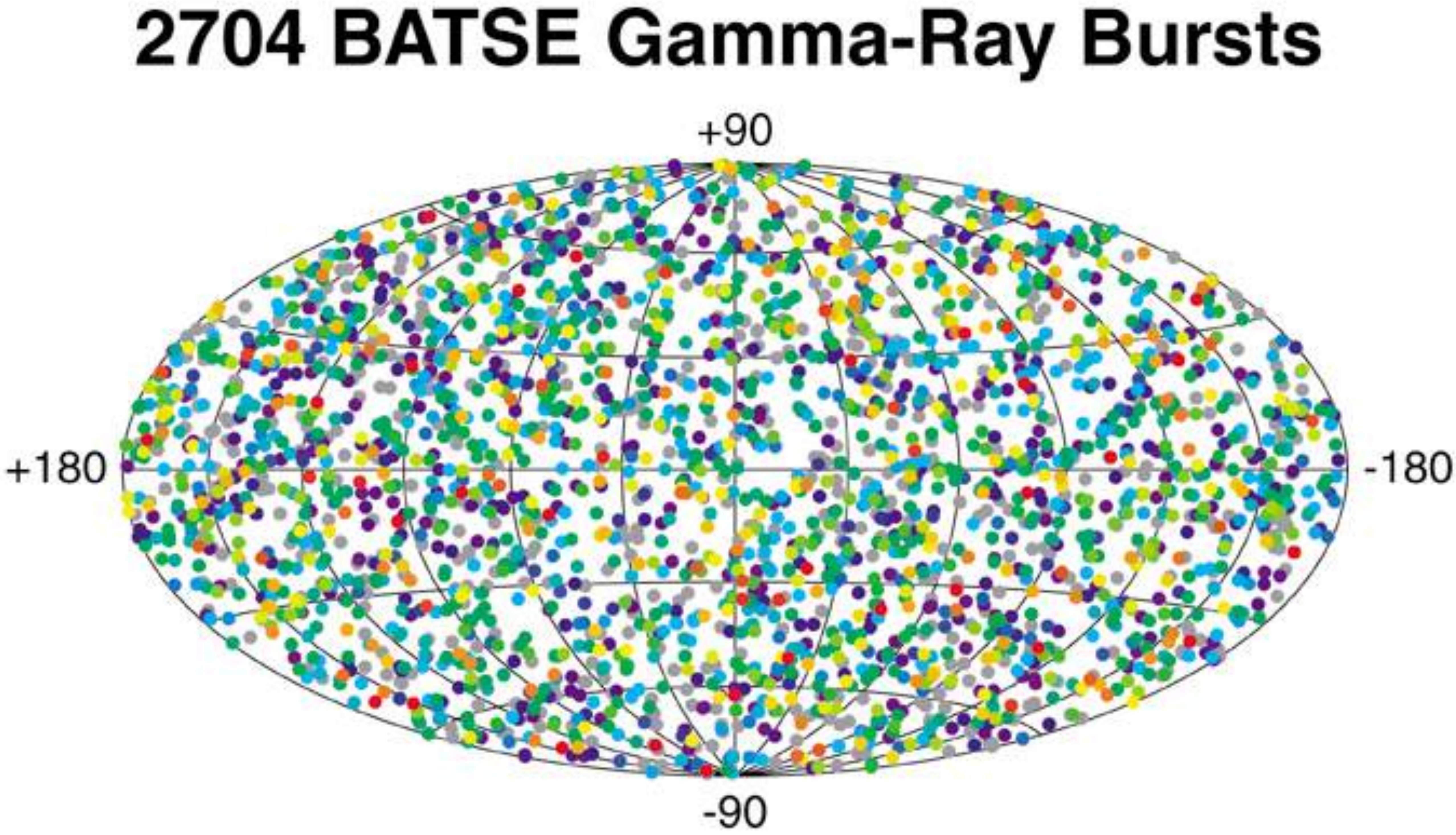
20 keV - 100 MeV

AGILE

10 keV - 50 GeV

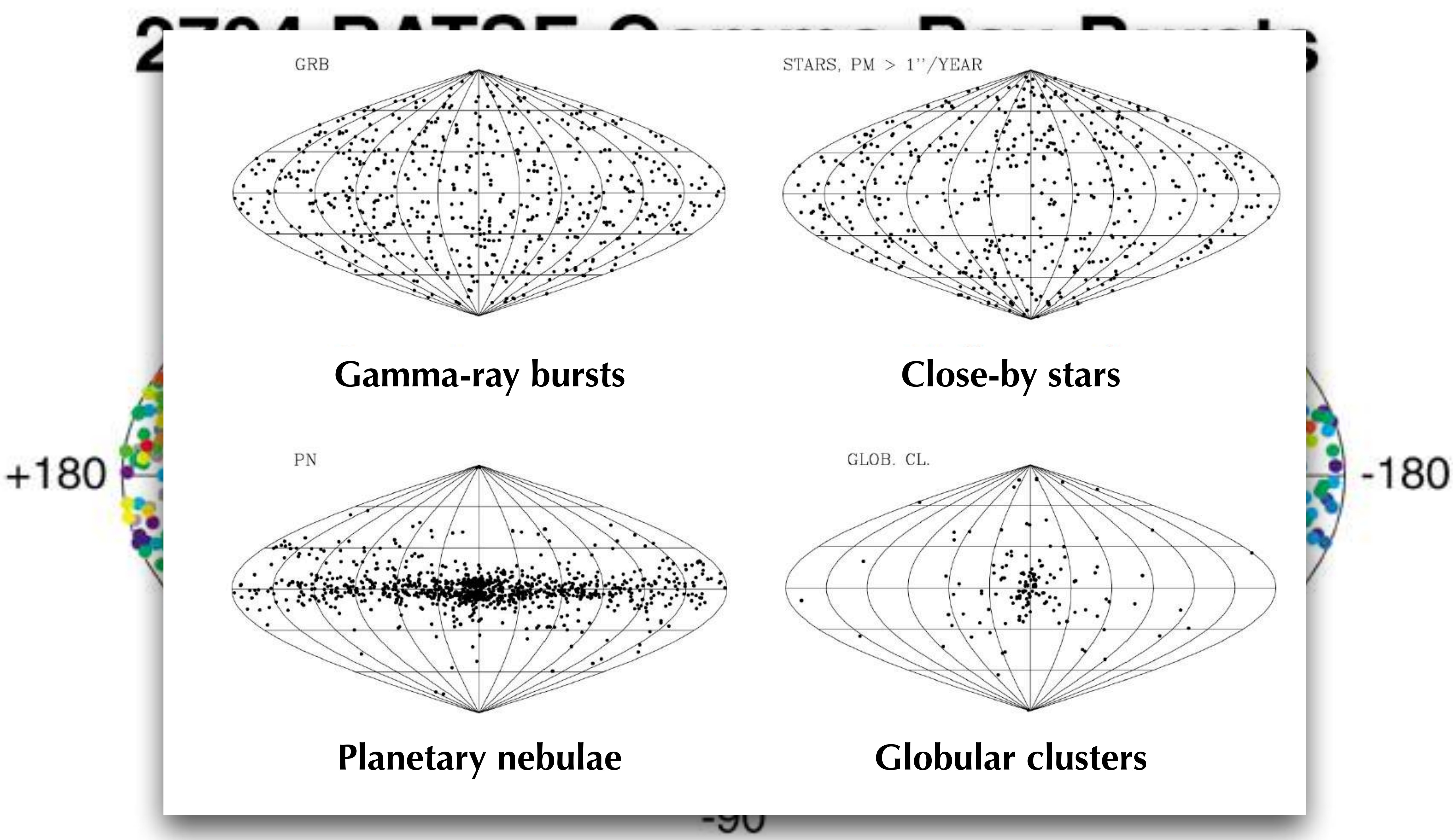
Currently ~1 GRB detected / day

Where do GRB come from ?



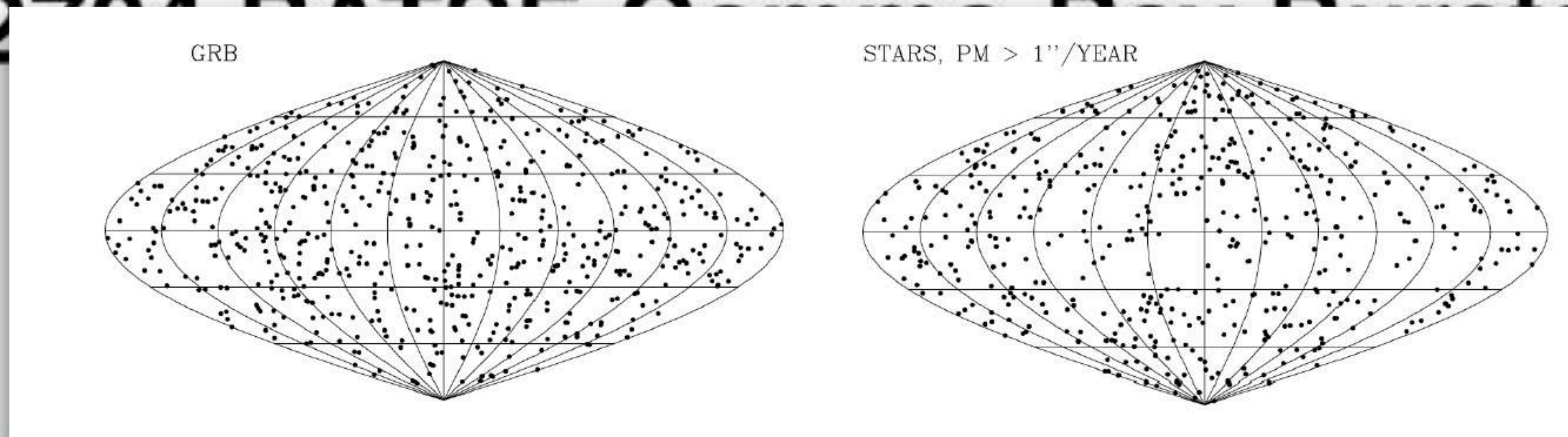
Measuring distance: a challenge in astronomy !

Where do GRB come from ?



Measuring distance: a challenge in astronomy !

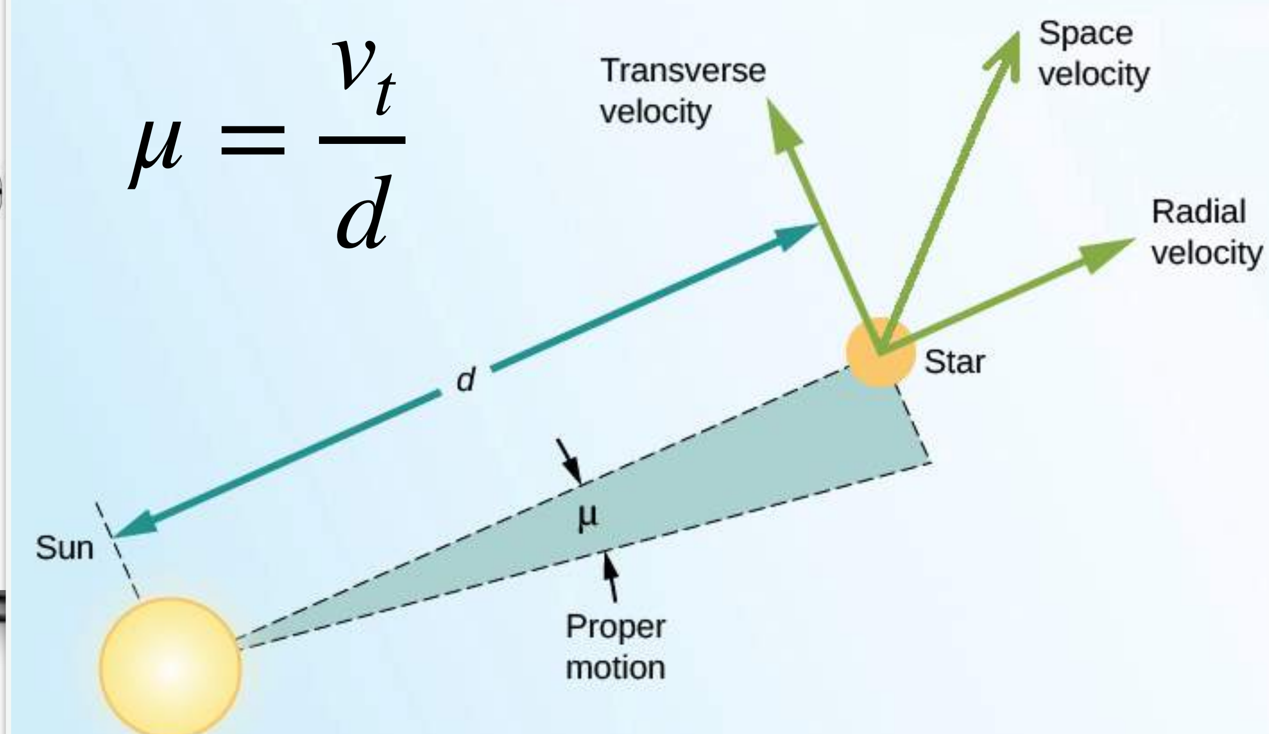
Where do GRB come from ?



Gamma-ray bursts | Close-by stars

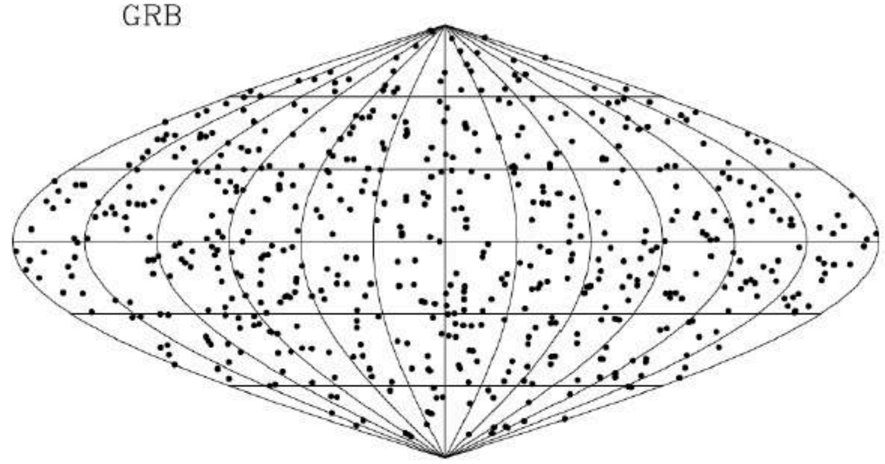
Angular displacement:

$$\mu = \frac{v_t}{d}$$

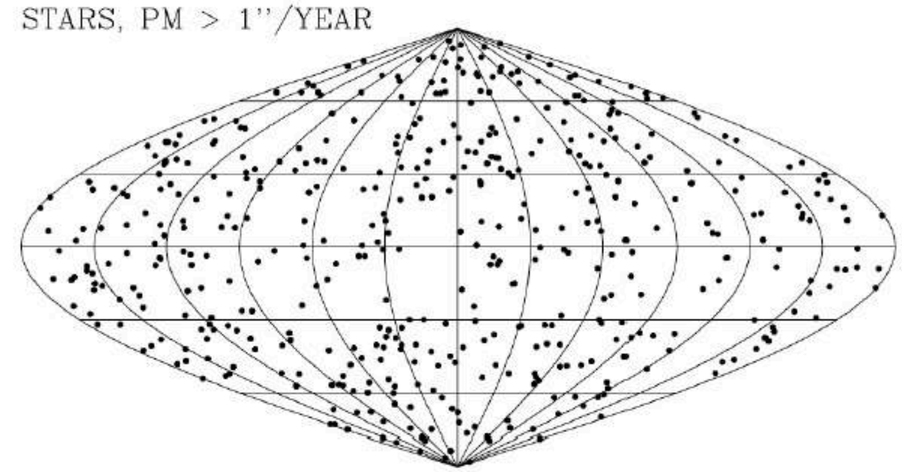


Proper Motion and Velocity of a Star

Where do GRB come from ?



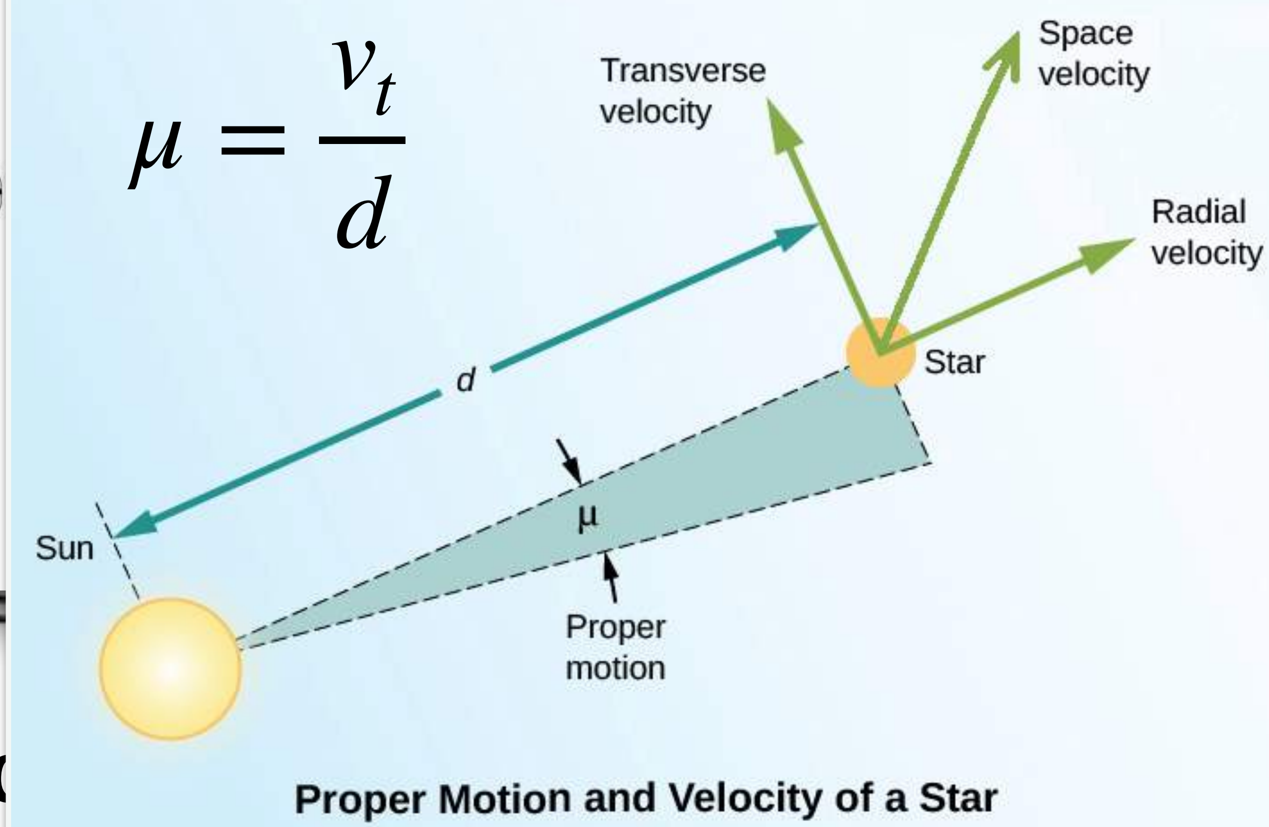
Gamma-ray bursts



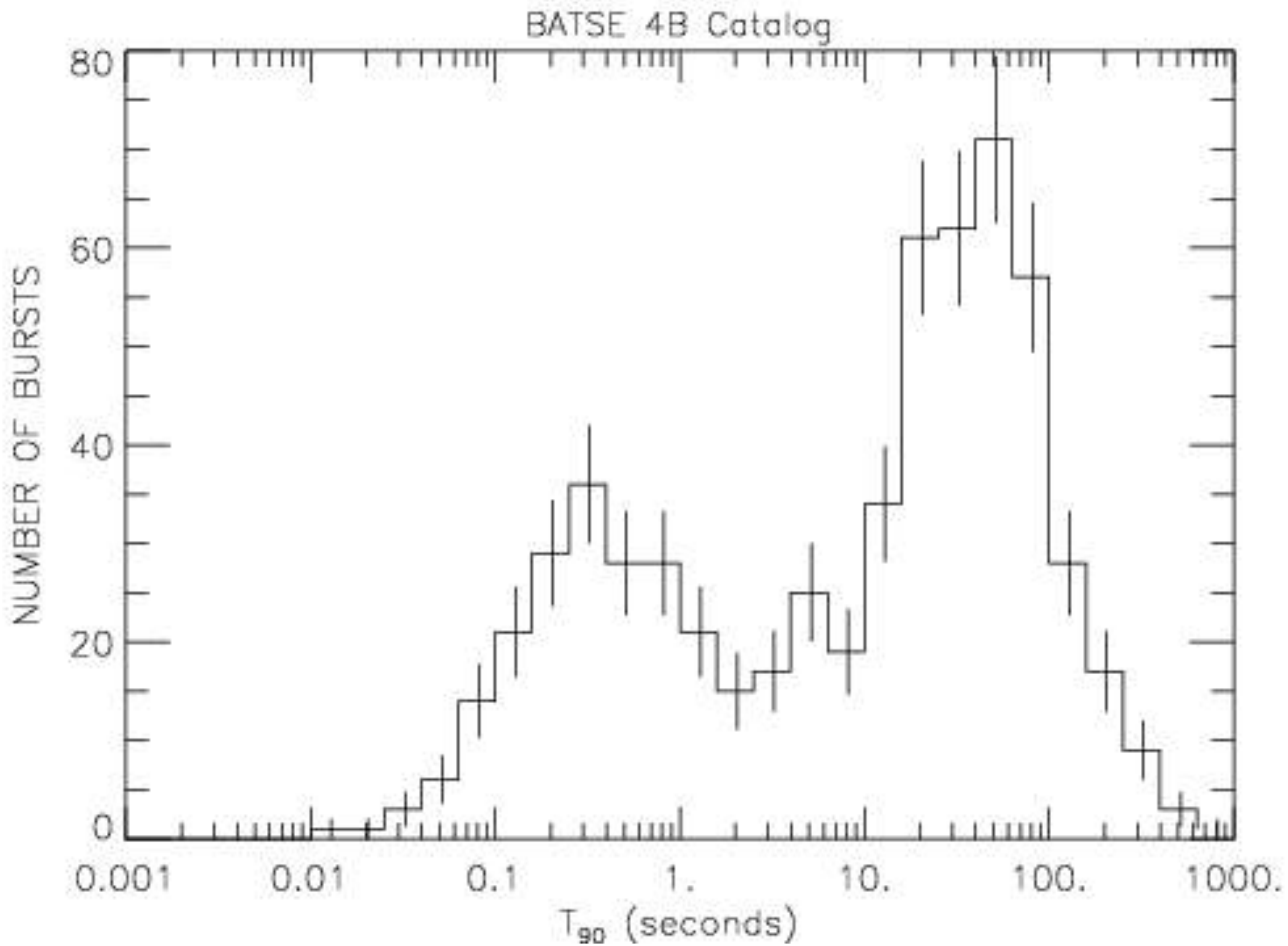
Close-by stars

Angular displacement:

$$\mu = \frac{v_t}{d}$$

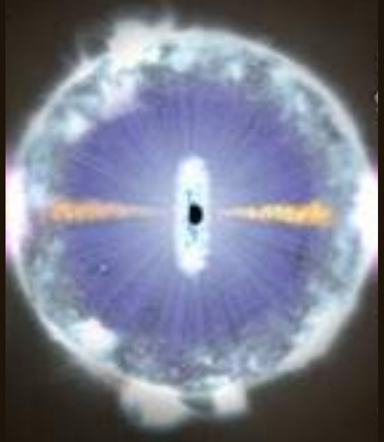


Gamma-ray bursts



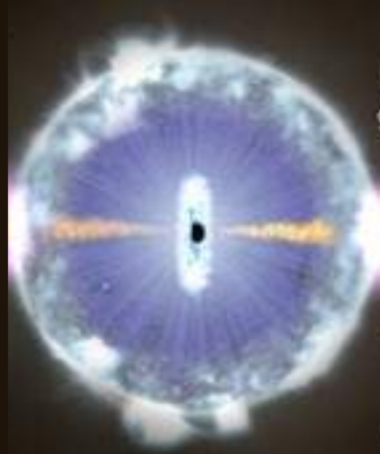
Same physics but different energy reservoir ?

A possible scenario

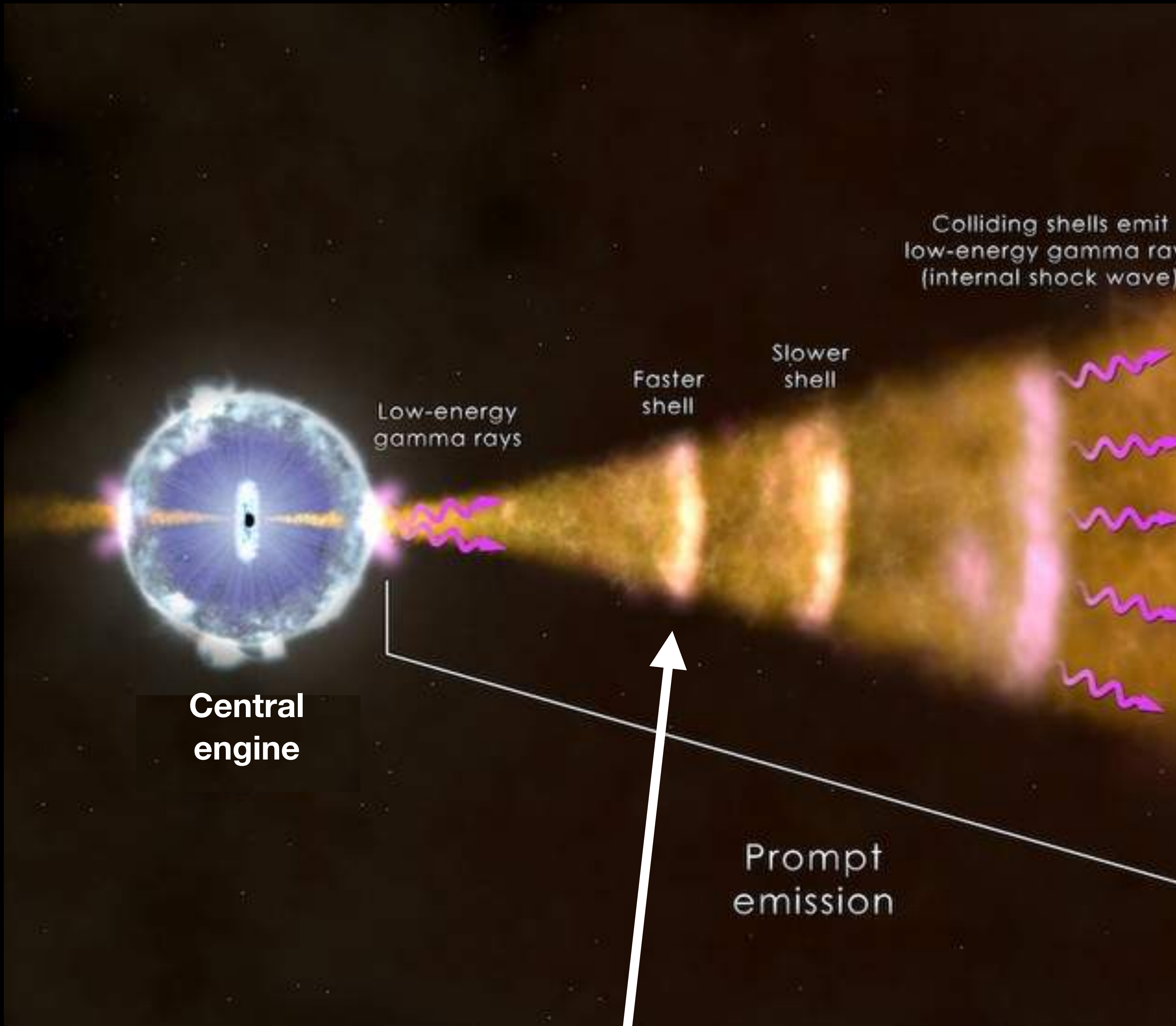


Short timescale variability ⇒ central engine of small size

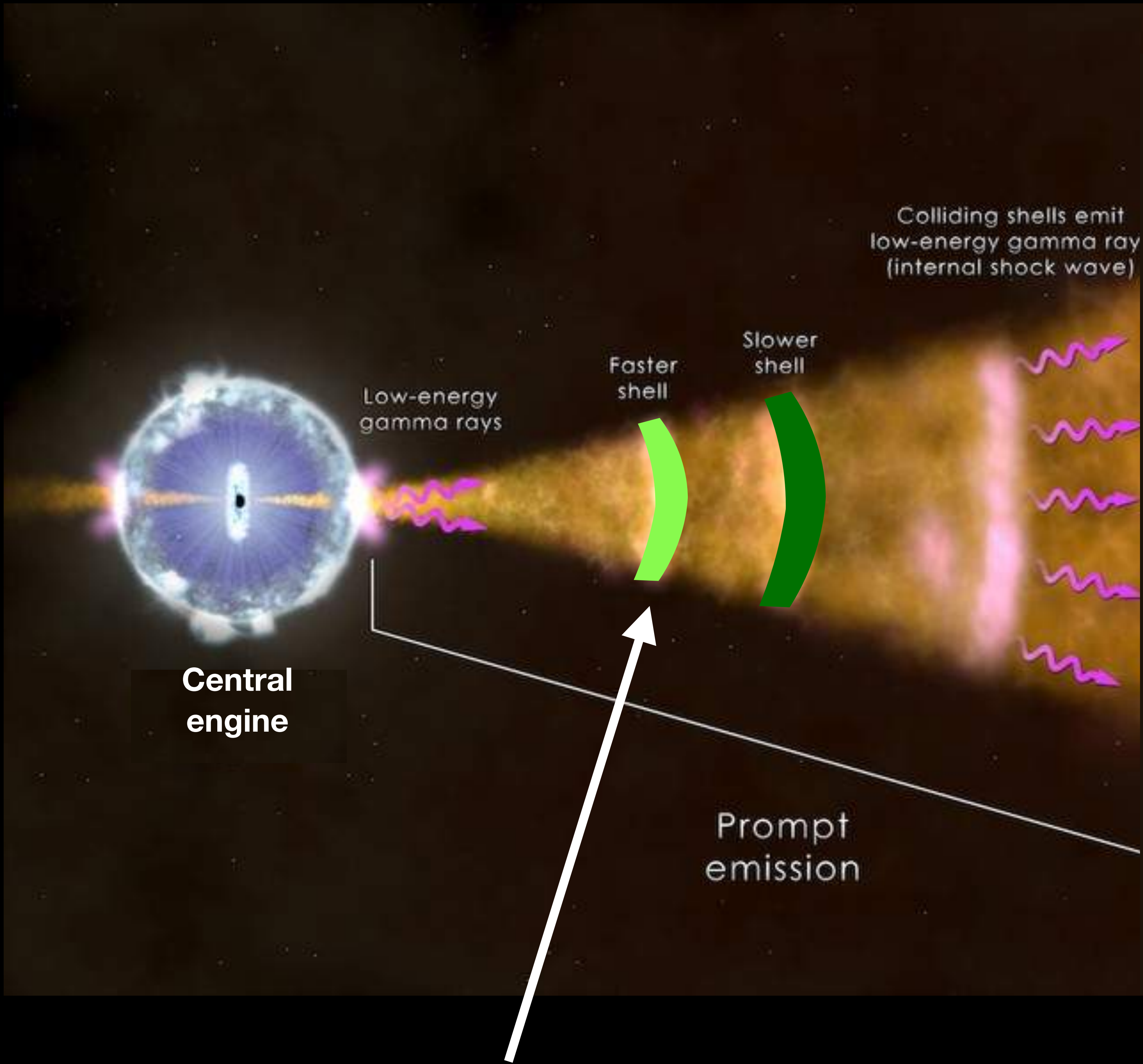
$$l \lesssim c\Delta t$$



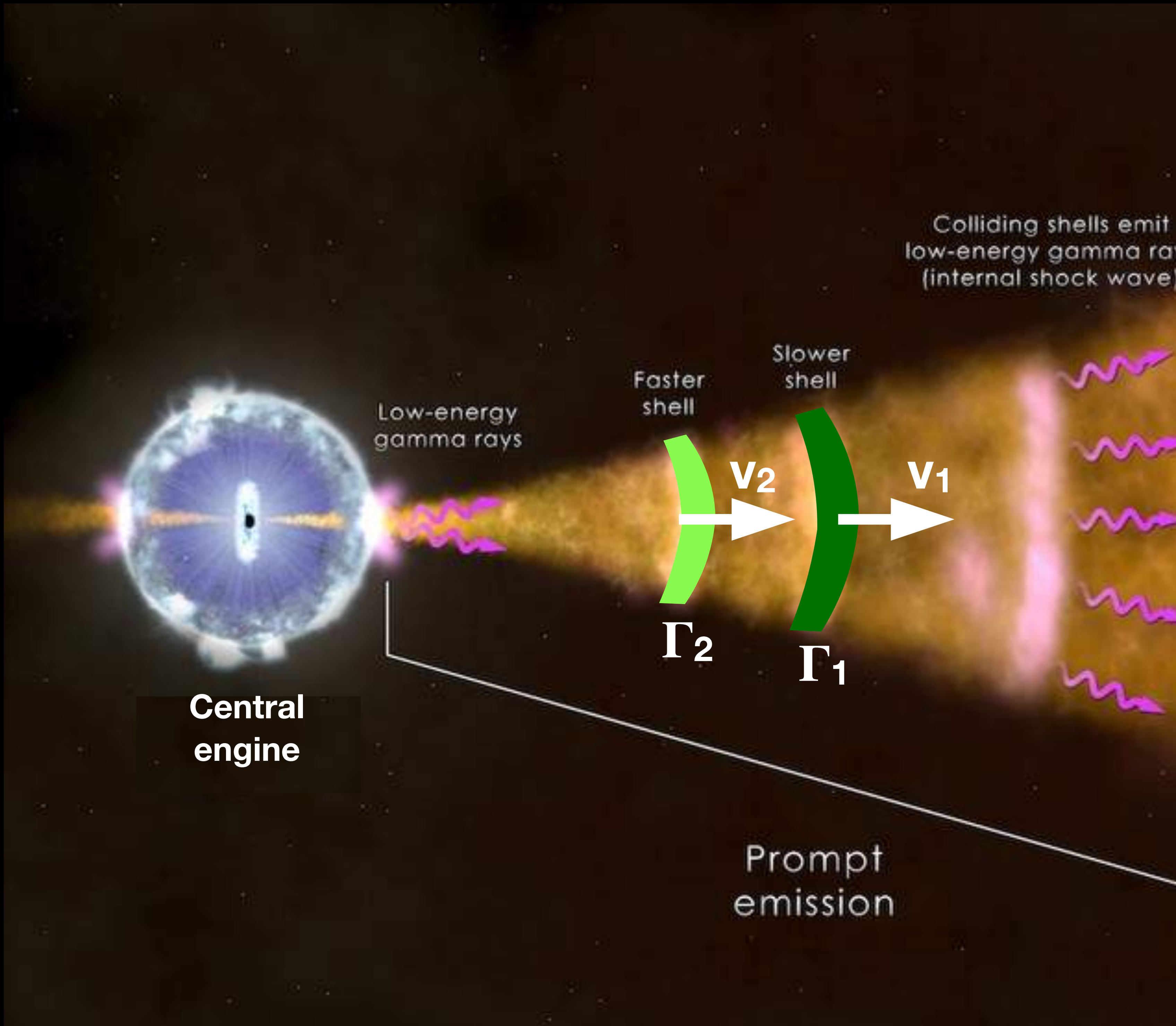
Central engine



Relativistic jet
(fraction of accreted matter).
Earth-Jupiter distance in ~40min



Shells of matter with different velocity (jet inhomogeneities and/or central engine variability)

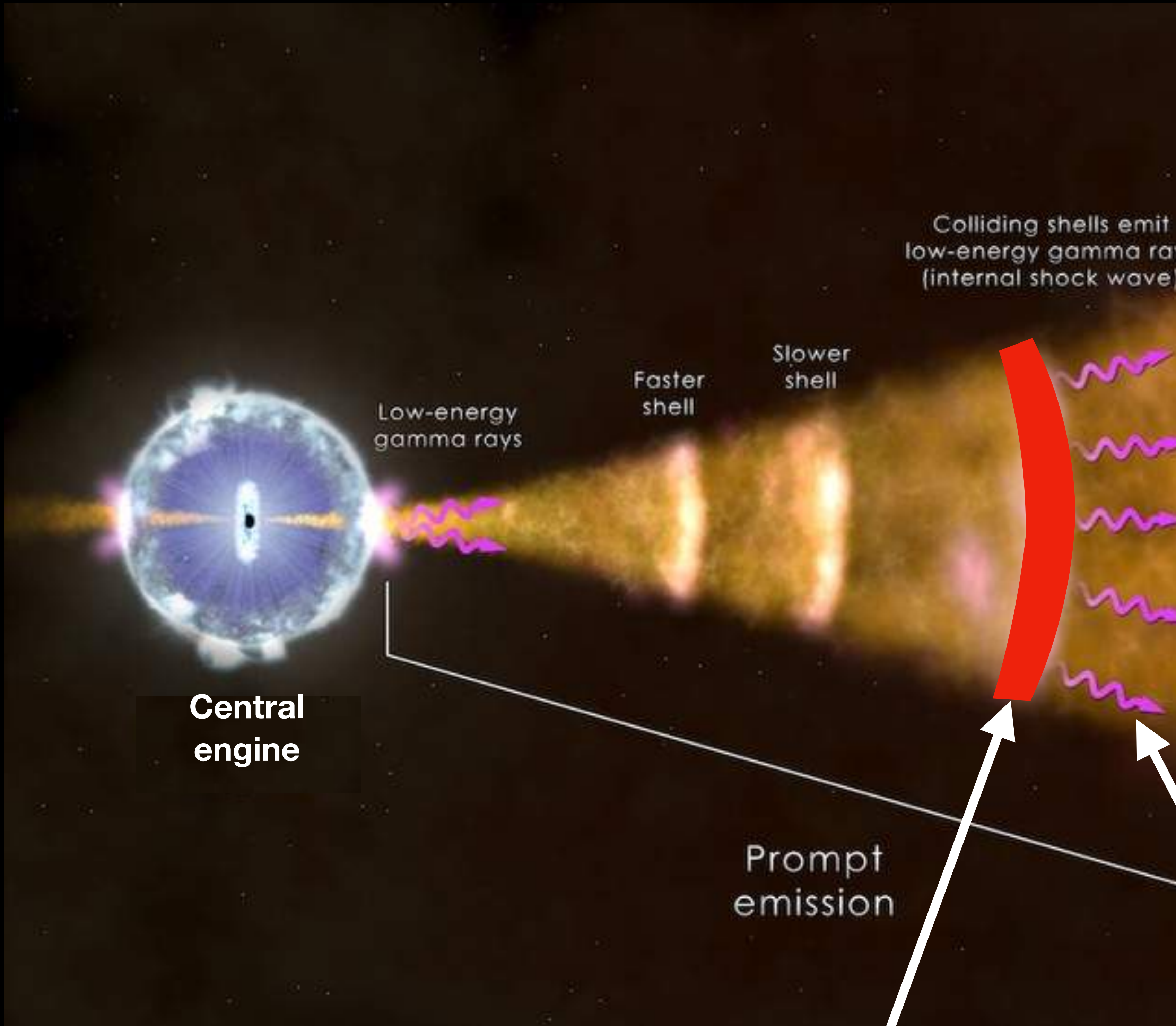


$$\beta_i = v_i/c \simeq \left(1 - \frac{1}{2\Gamma_i^2}\right)$$

$$R_{\rm choc} = \frac{\beta_1\beta_2}{\beta_2 - \beta_1} c\Delta t \simeq 2c\Delta t \frac{\Gamma_1^2\Gamma_2^2}{\Gamma_2^2 - \Gamma_1^2}$$

$$E_{\rm diss} = mc^2\left(\Gamma_1 + \Gamma_2 - 2\sqrt{\Gamma_1\Gamma_2}\right)$$

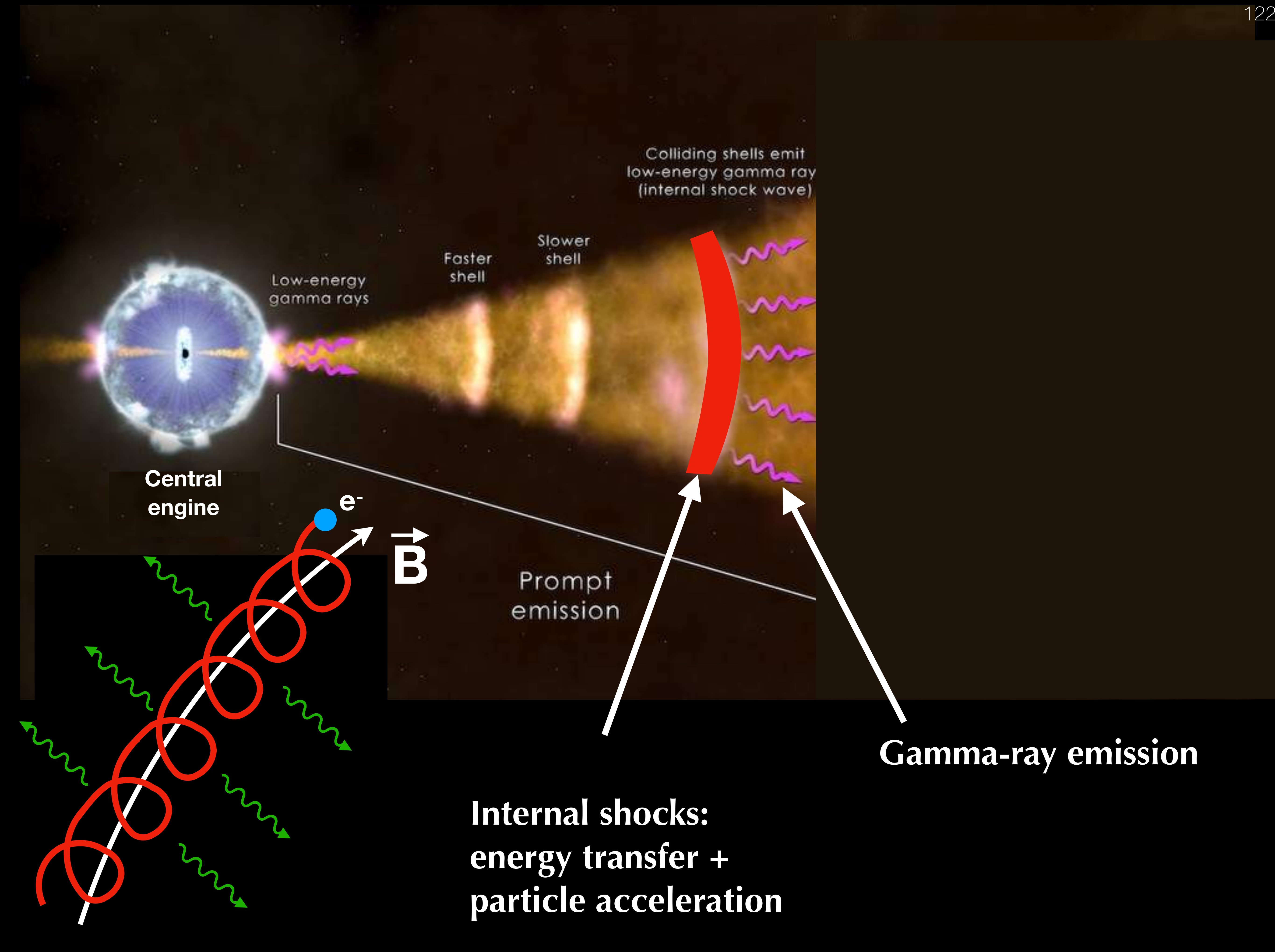
$\sim 10^{45}$ J



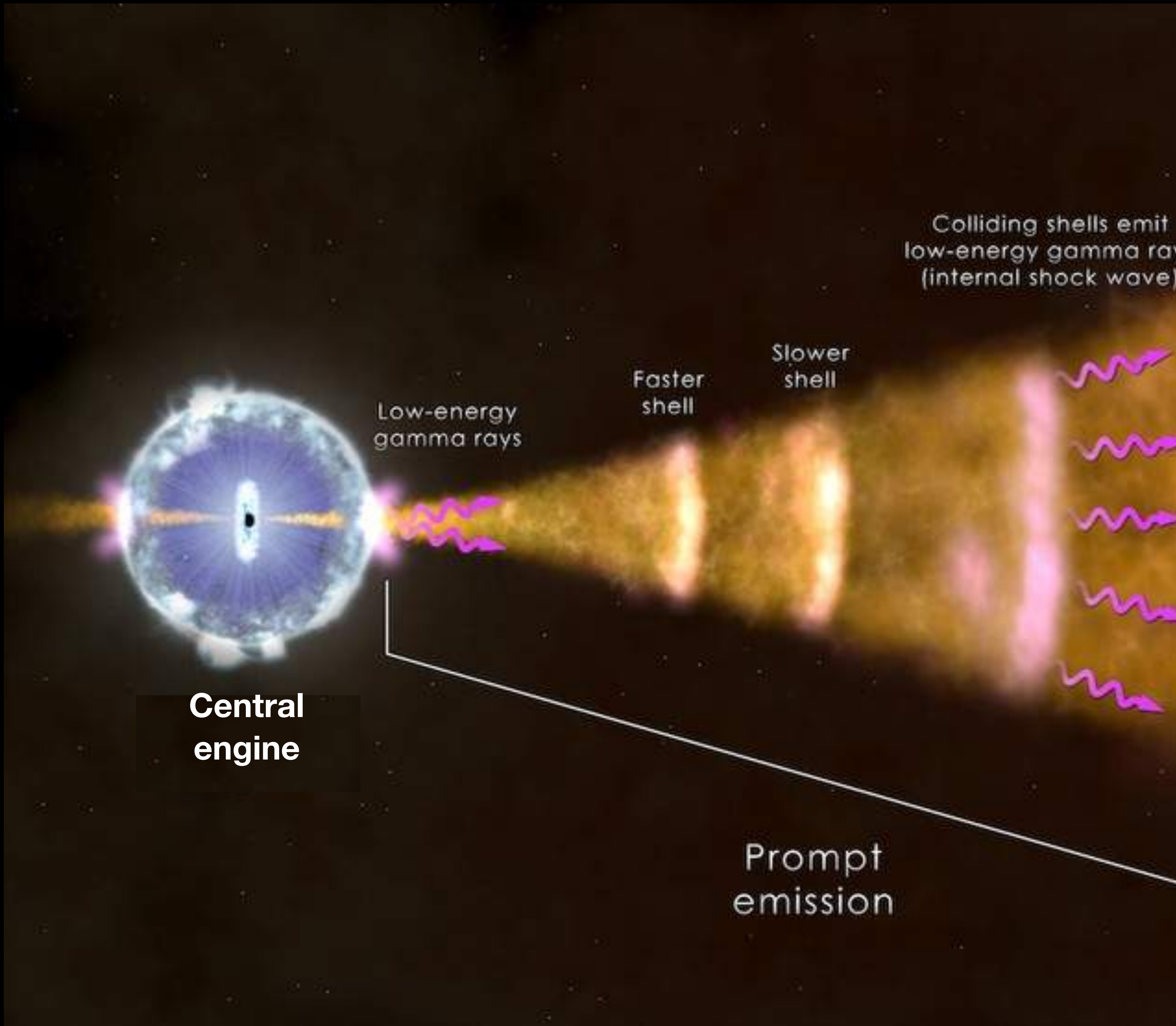
Gamma-ray emission

Internal shocks:
energy transfer

Particle acceleration



Colliding shells emit
low-energy gamma ray
(internal shock wave)
Low-energy
gamma rays
Faster
shell
Slower
shell
Central
engine
e-
B
Prompt
emission
Gamma-ray emission
Internal shocks:
energy transfer +
particle acceleration


Colliding shells emit
low-energy gamma ray
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Low-energy
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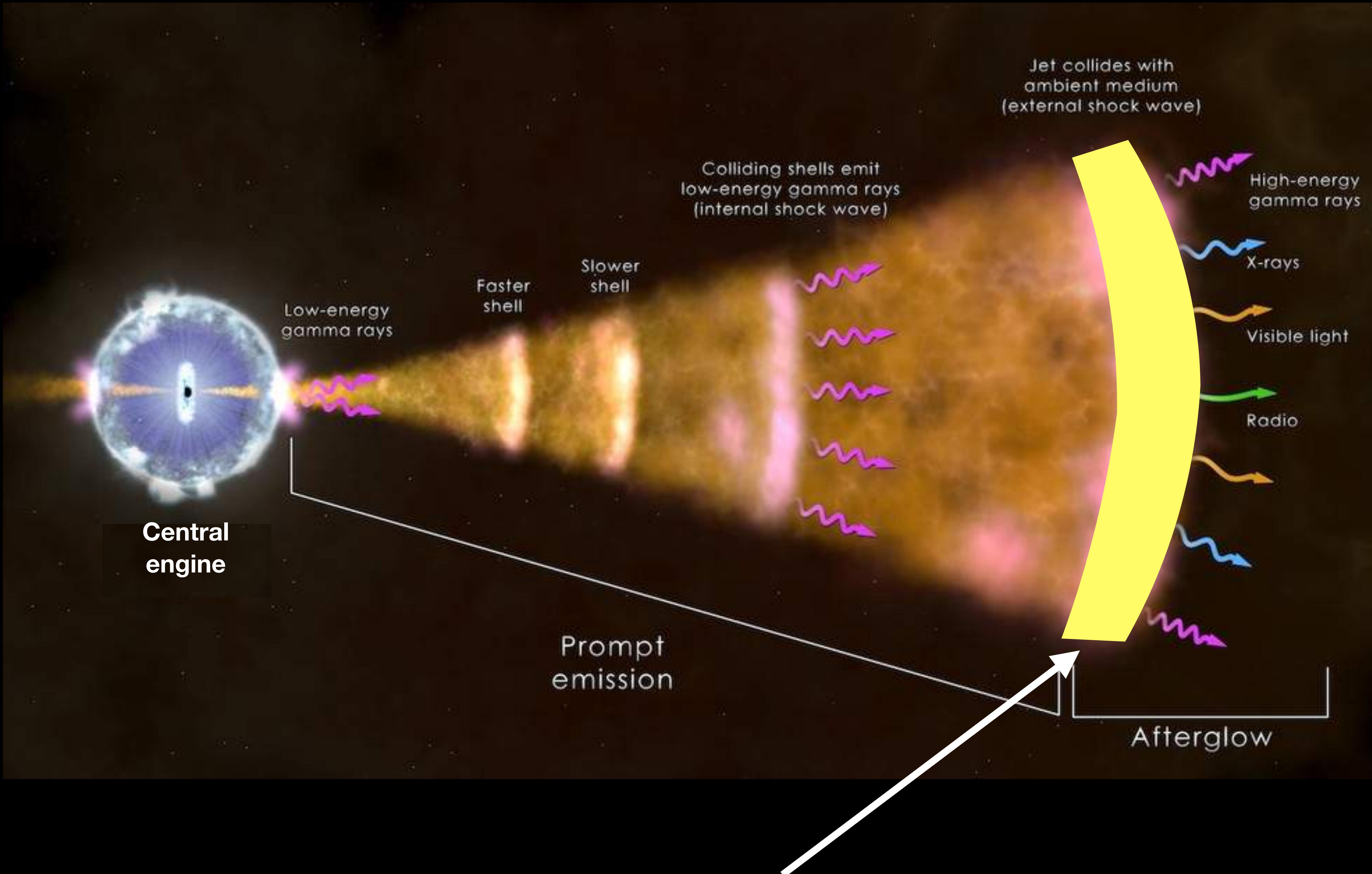
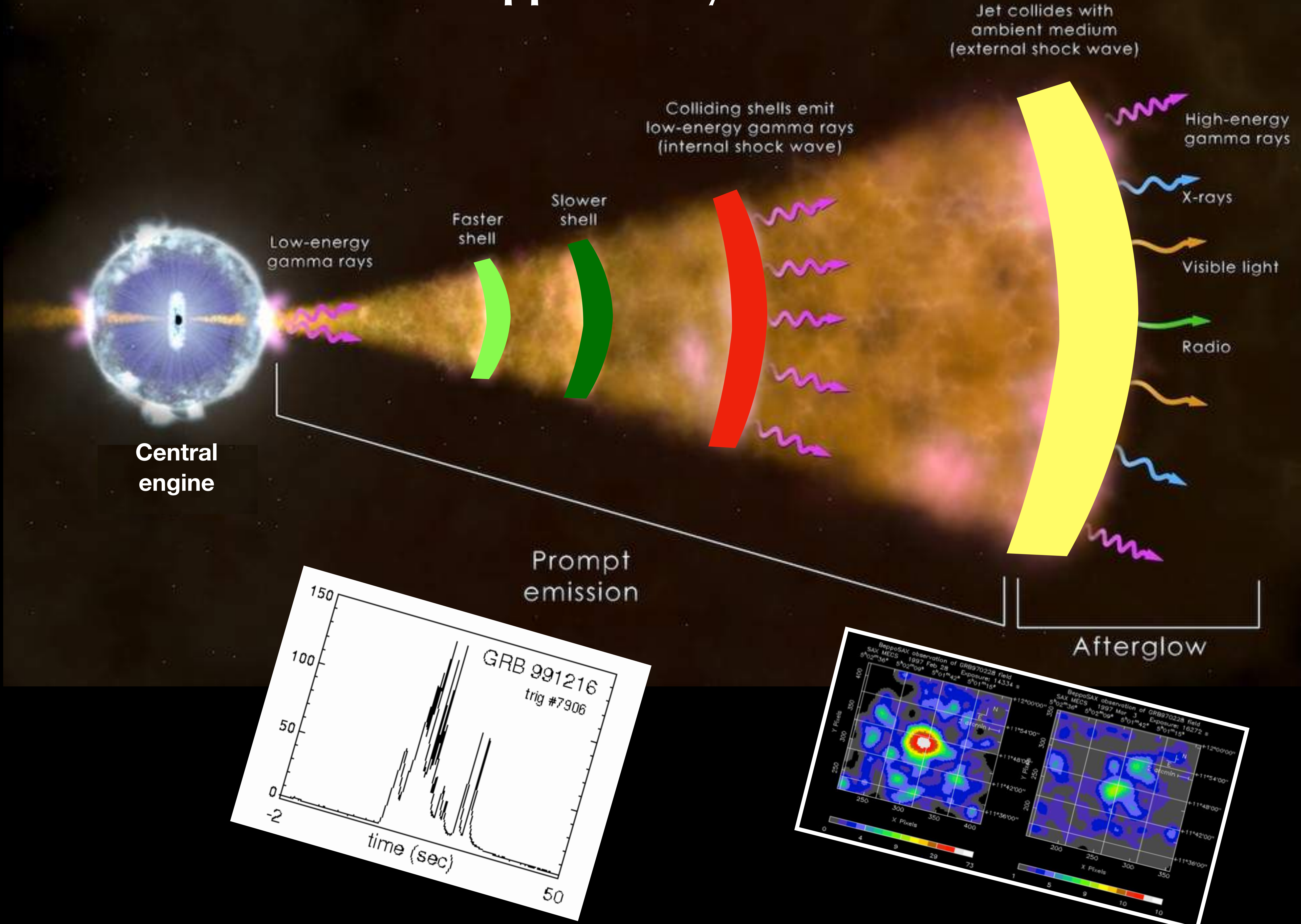


Deceleration in contact with interstellar medium

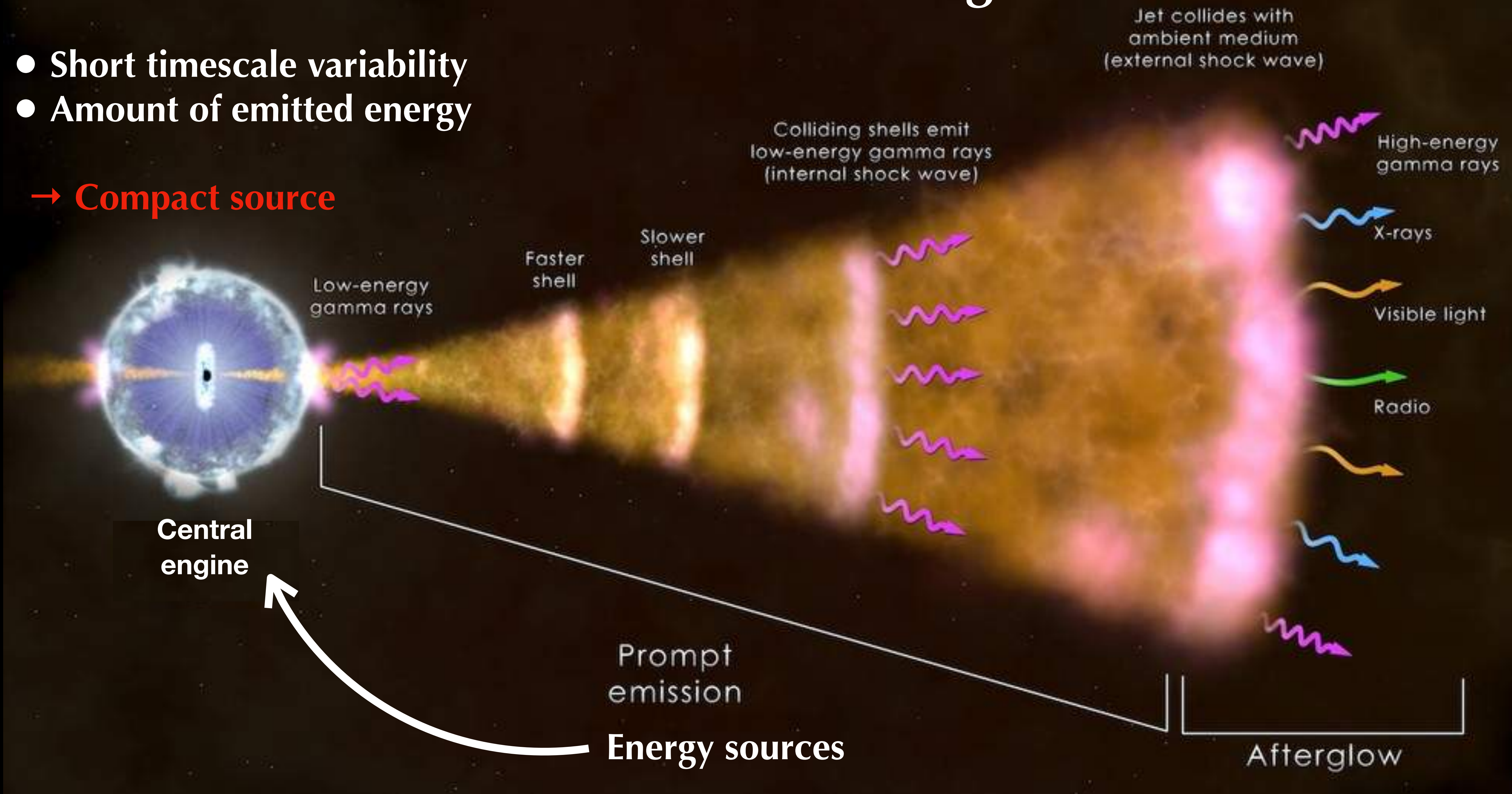
A scenario supported by observational data



What is the central engine ?

- Short timescale variability
- Amount of emitted energy

→ Compact source

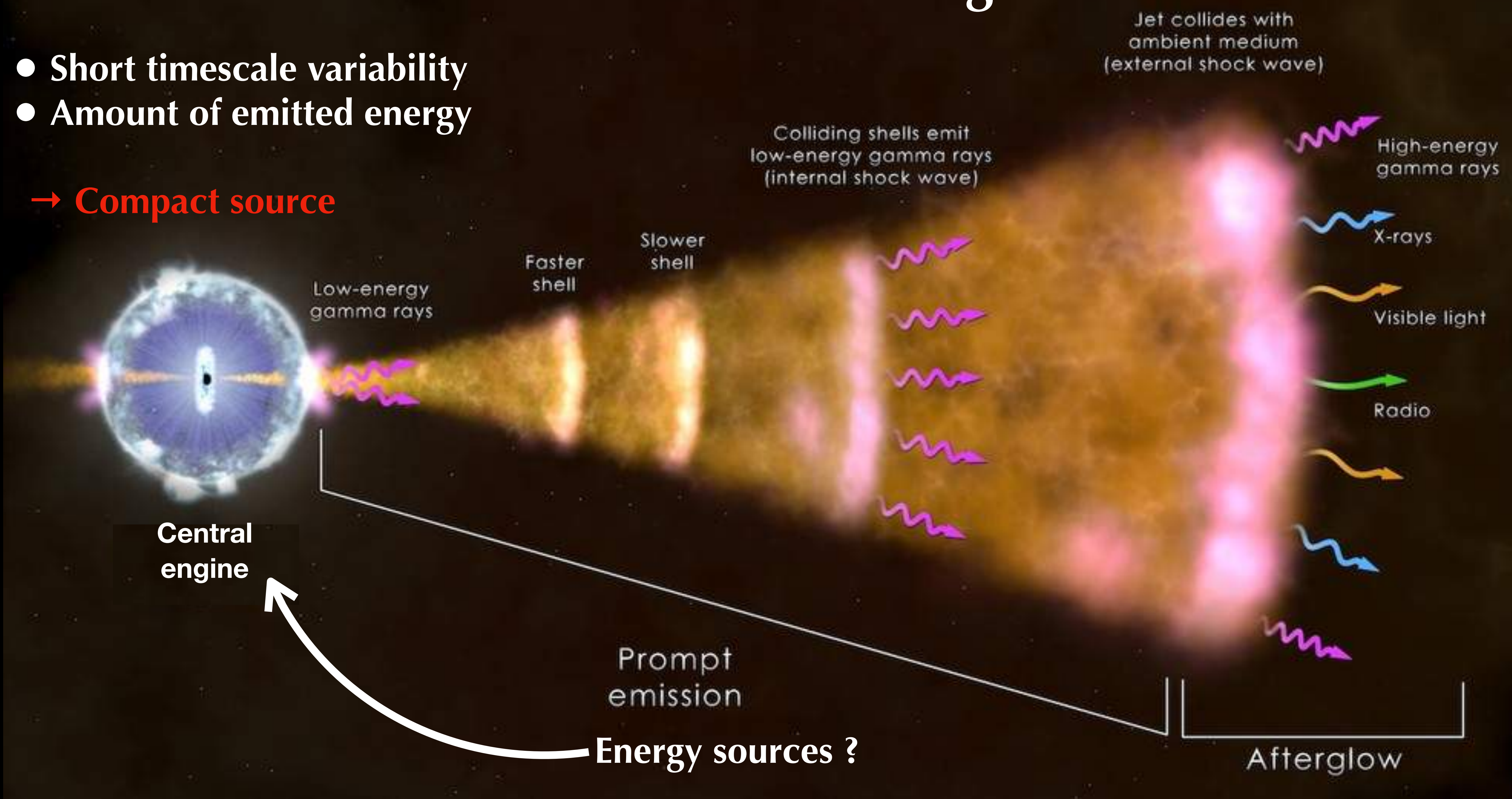


Energy sources

What is the central engine ?

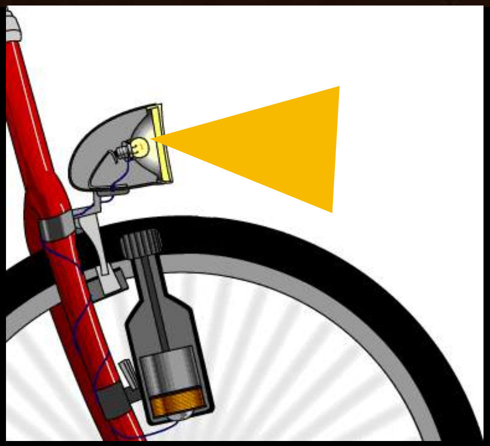
- Short timescale variability
- Amount of emitted energy

→ Compact source



Energy sources ?

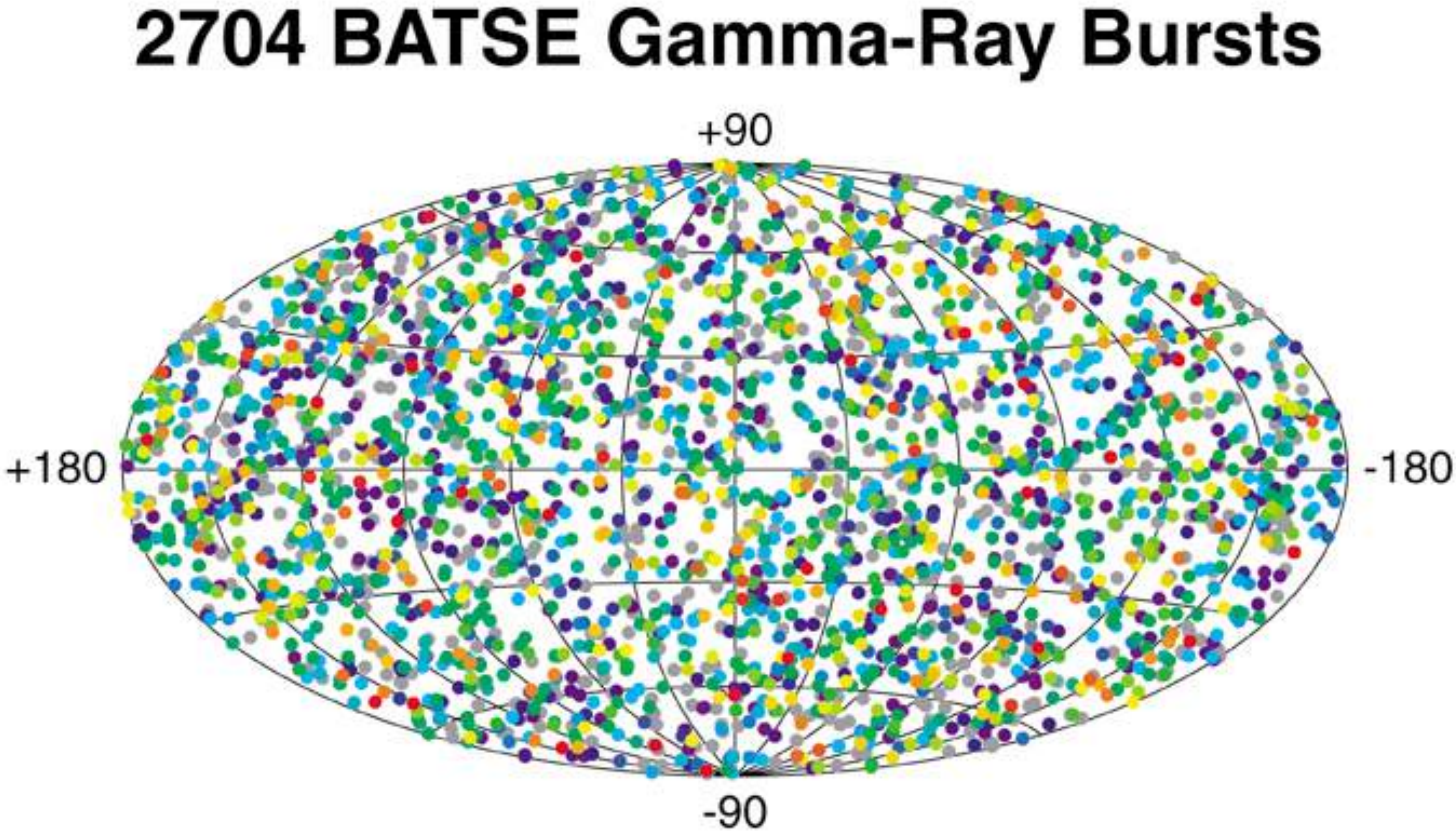
Accretion



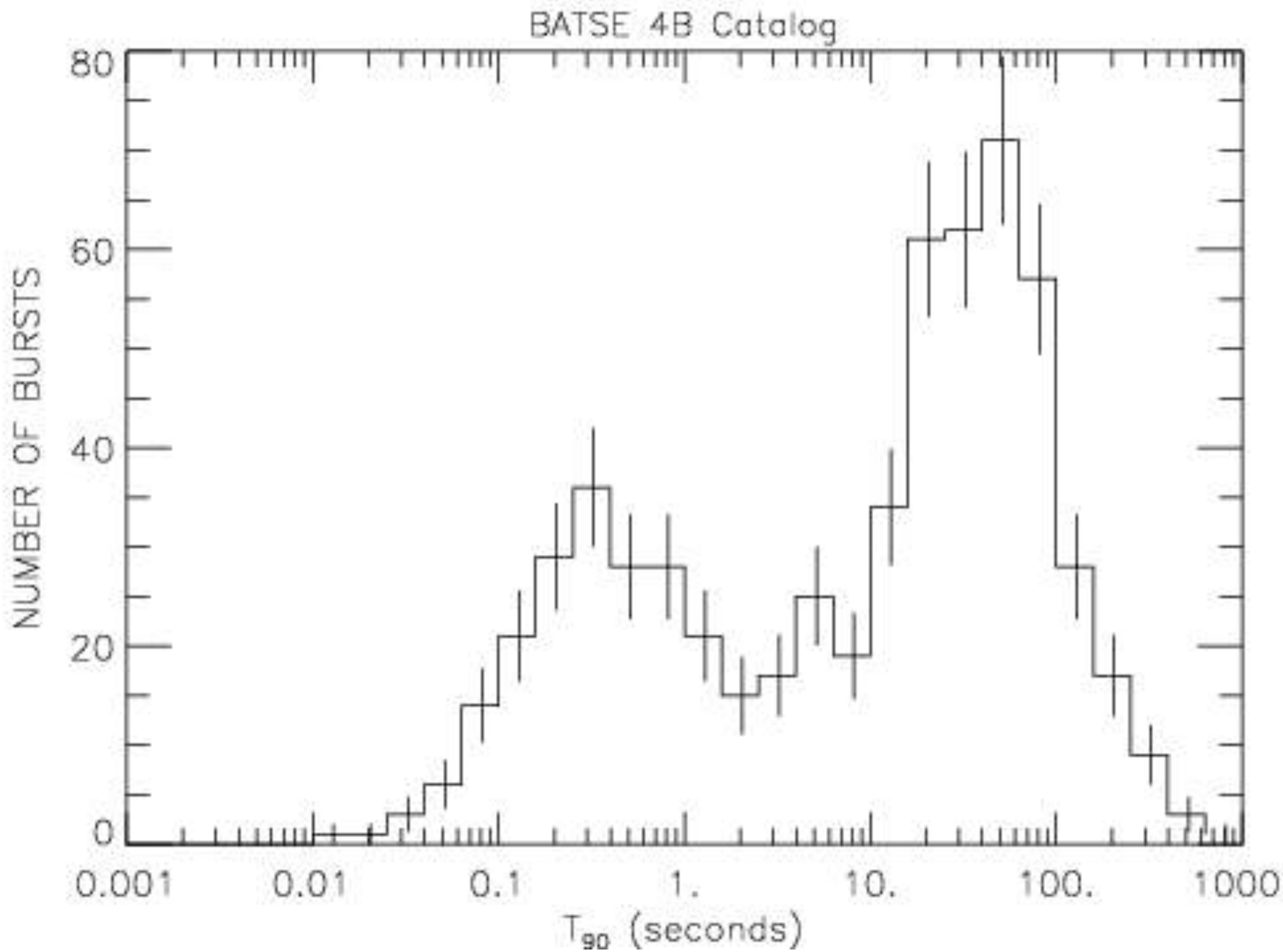
Rotation
+ magnetic field

Close to a compact object of some stellar masses

Where do GRB come from ?



Gamma-ray bursts

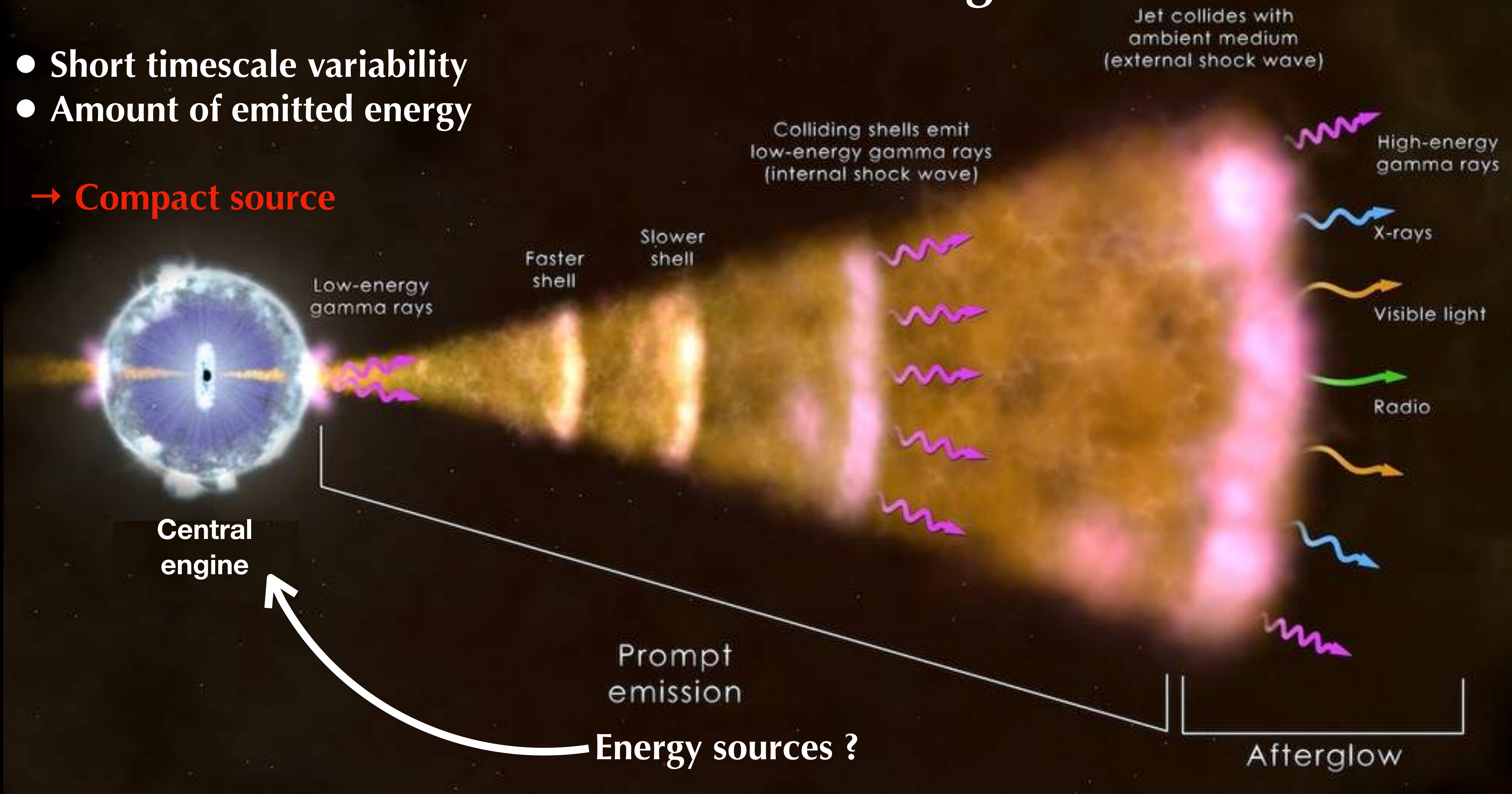


Same physics but different energy reservoir ?

What is the central engine ?

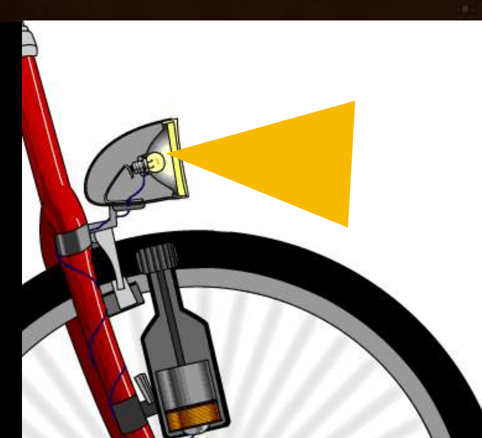
- Short timescale variability
- Amount of emitted energy

→ Compact source



Energy sources ?

Accretion

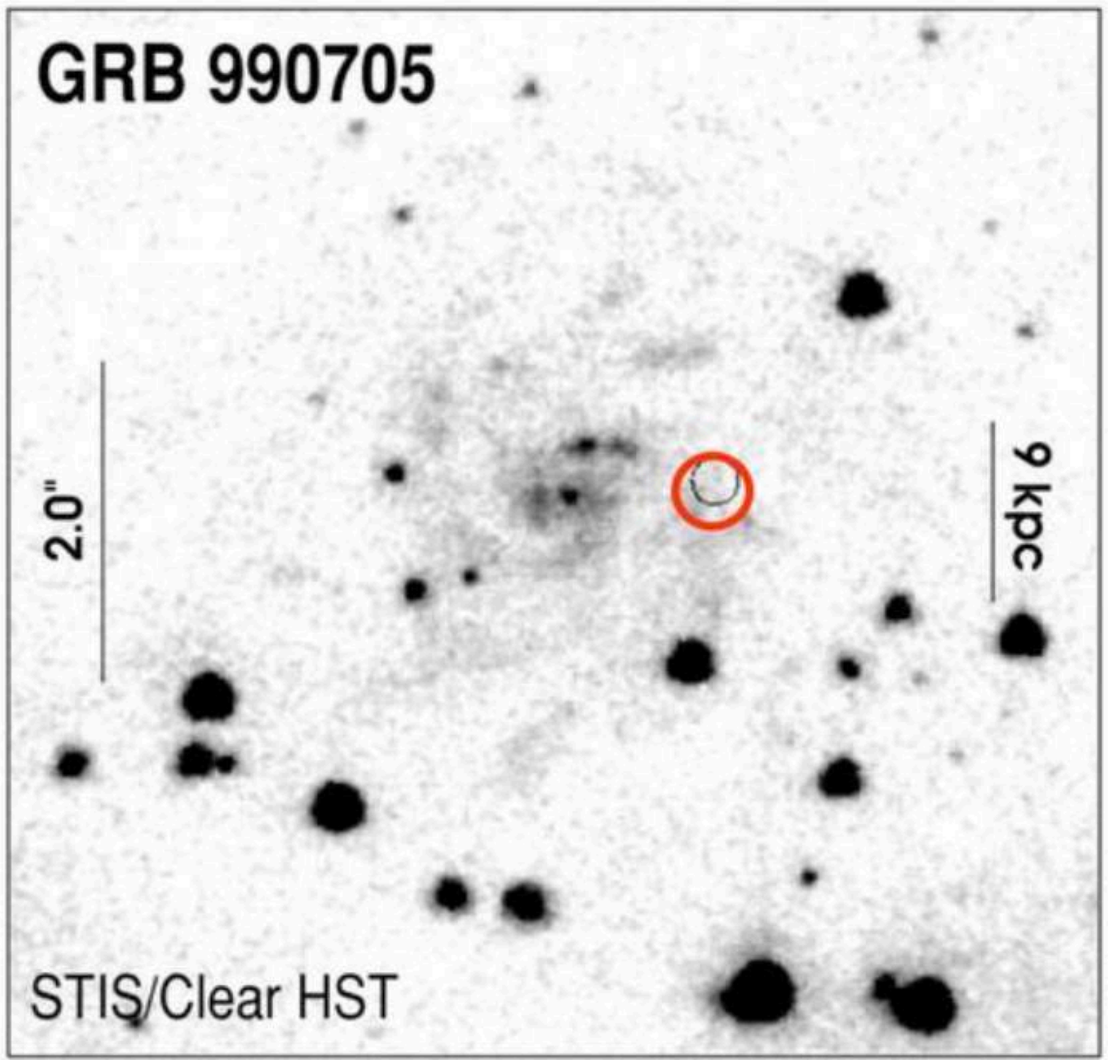


Rotation
+ magnetic field

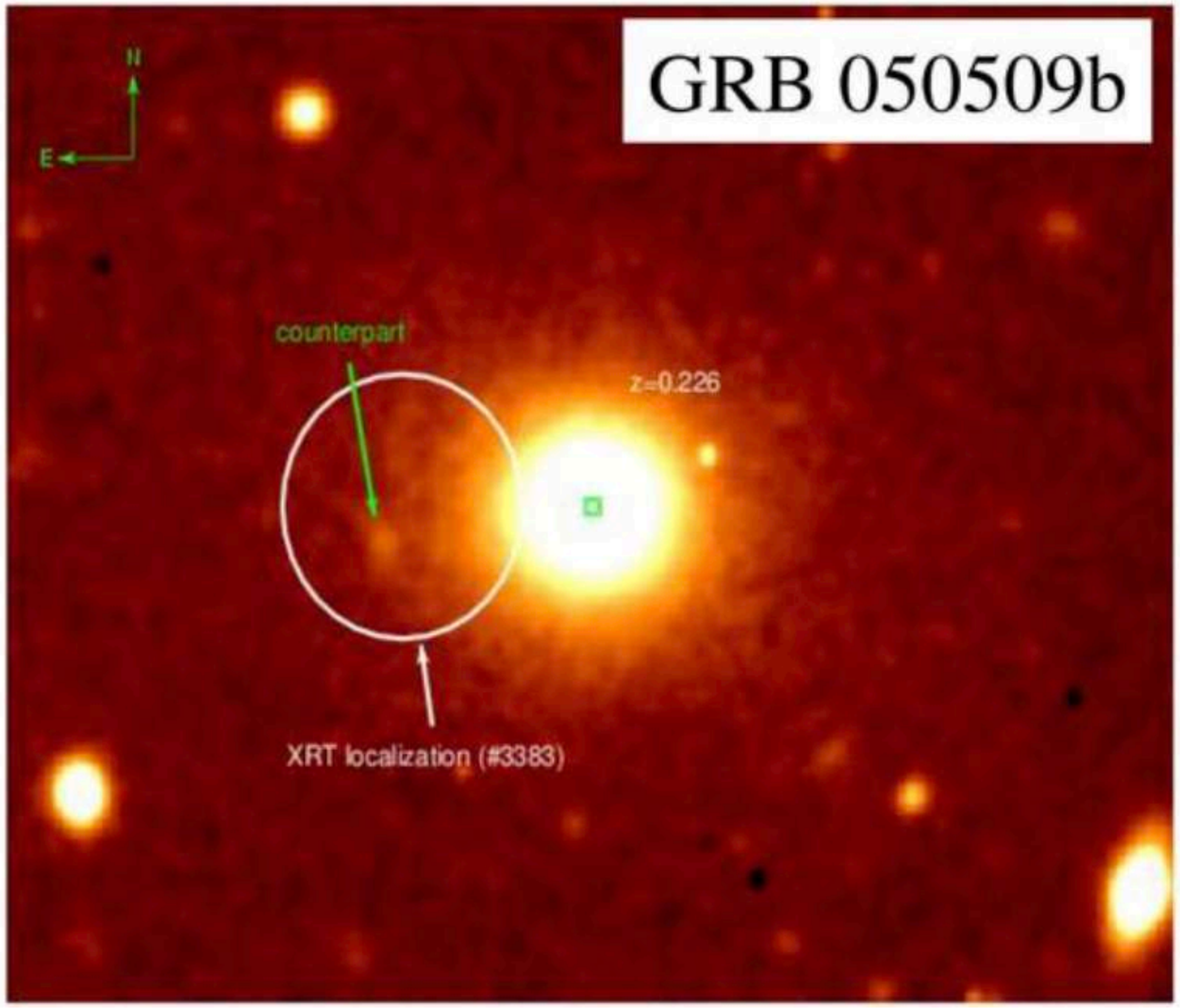
Close to a compact object of some stellar masses

Gamma-ray bursts

Further understanding GRBs requires to study their environment



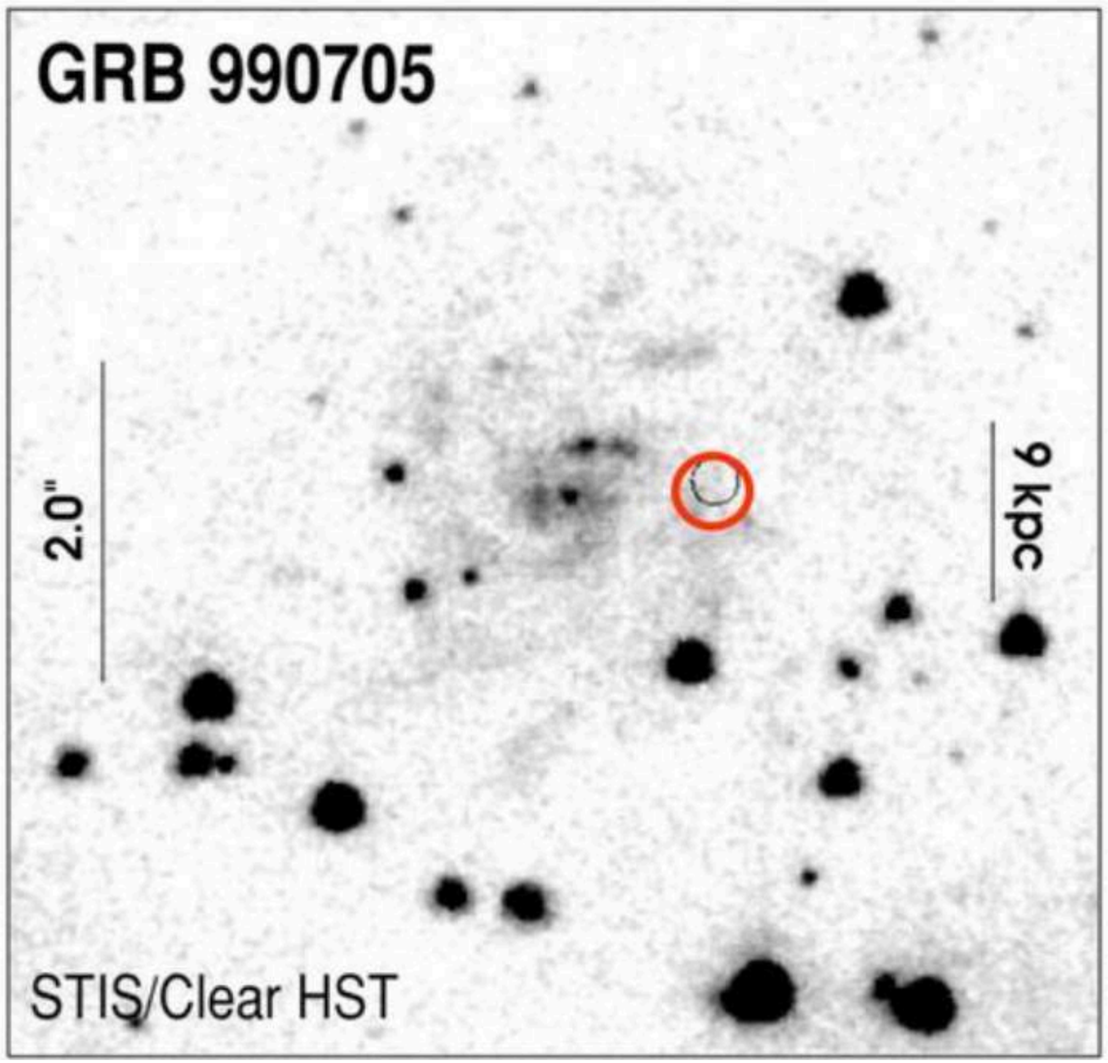
High star-forming rate



Old stellar population

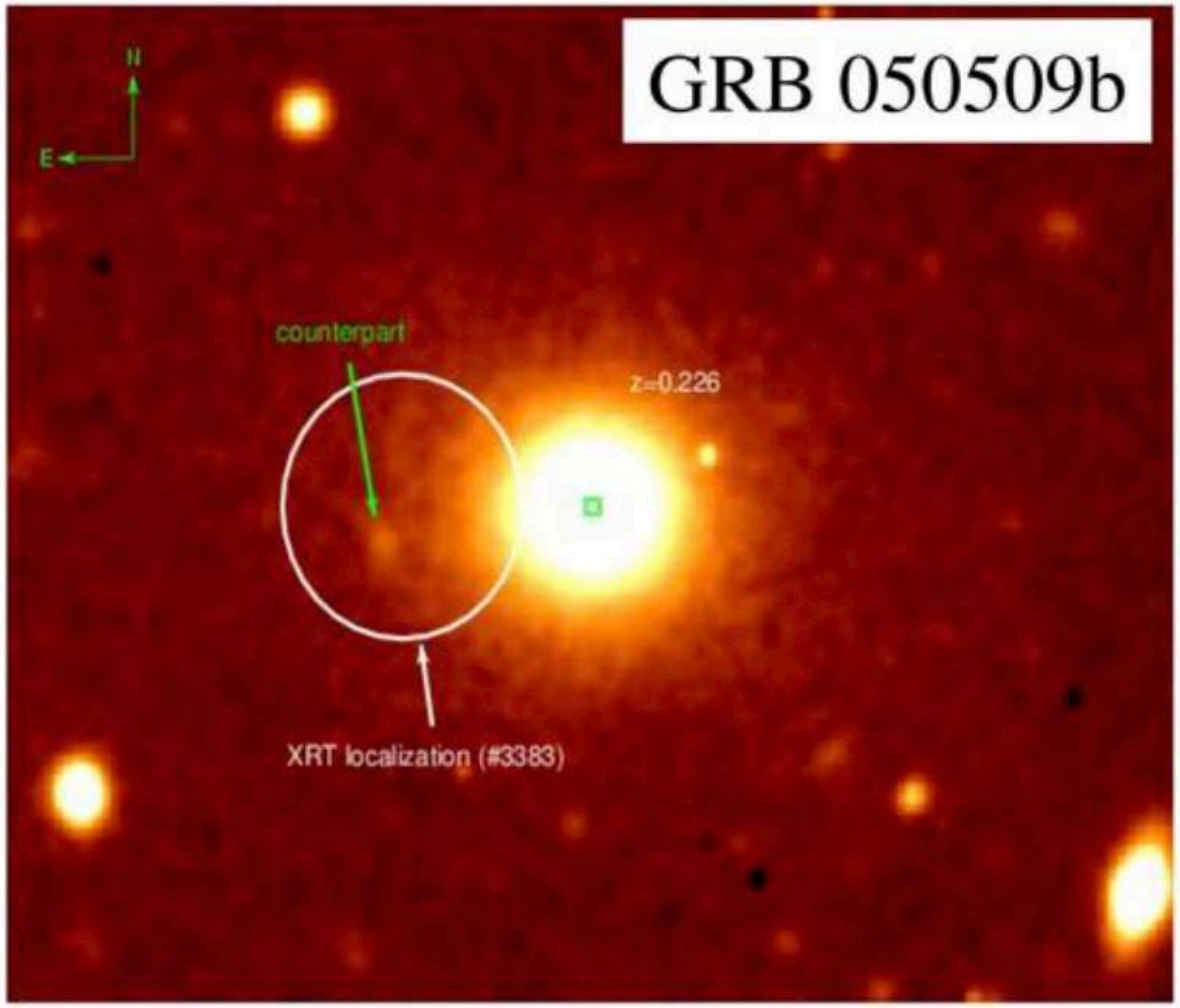
Gamma-ray bursts

Further understanding GRBs requires to study their environment



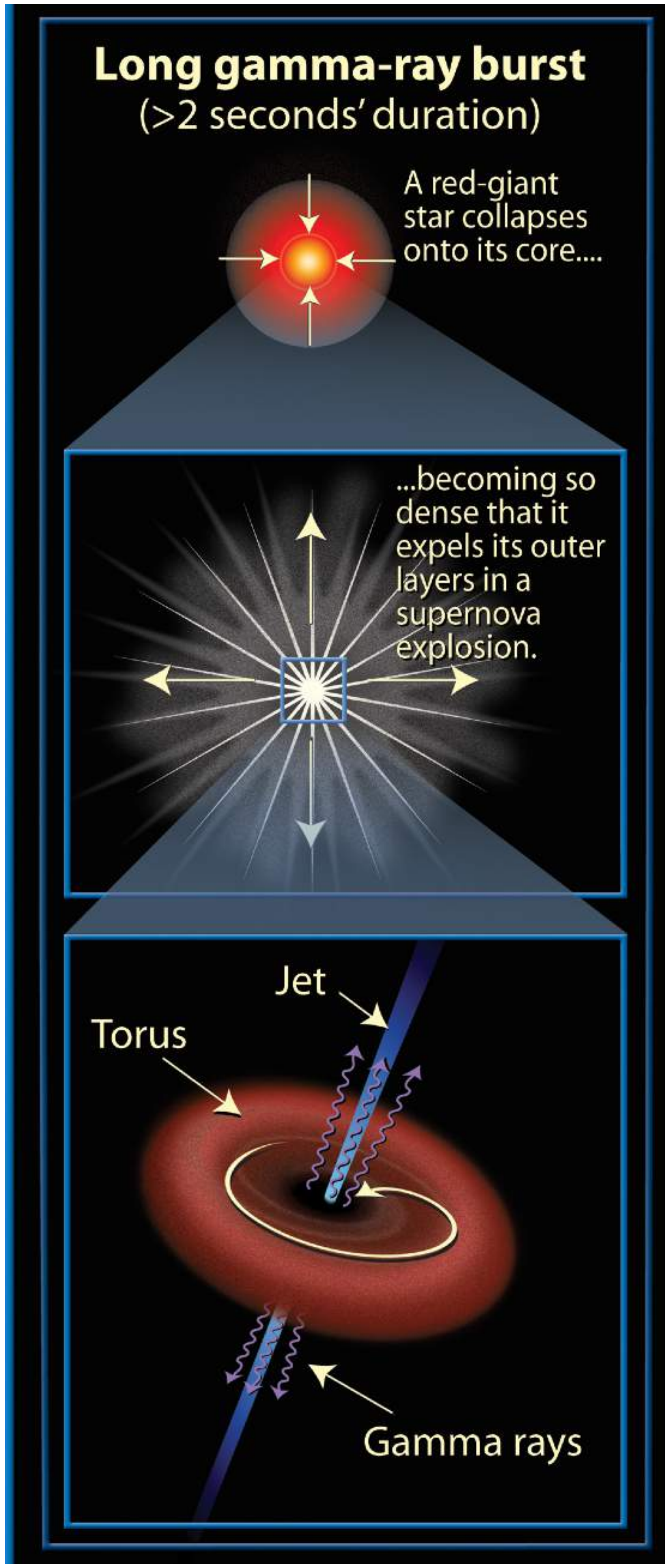
High star-forming rate

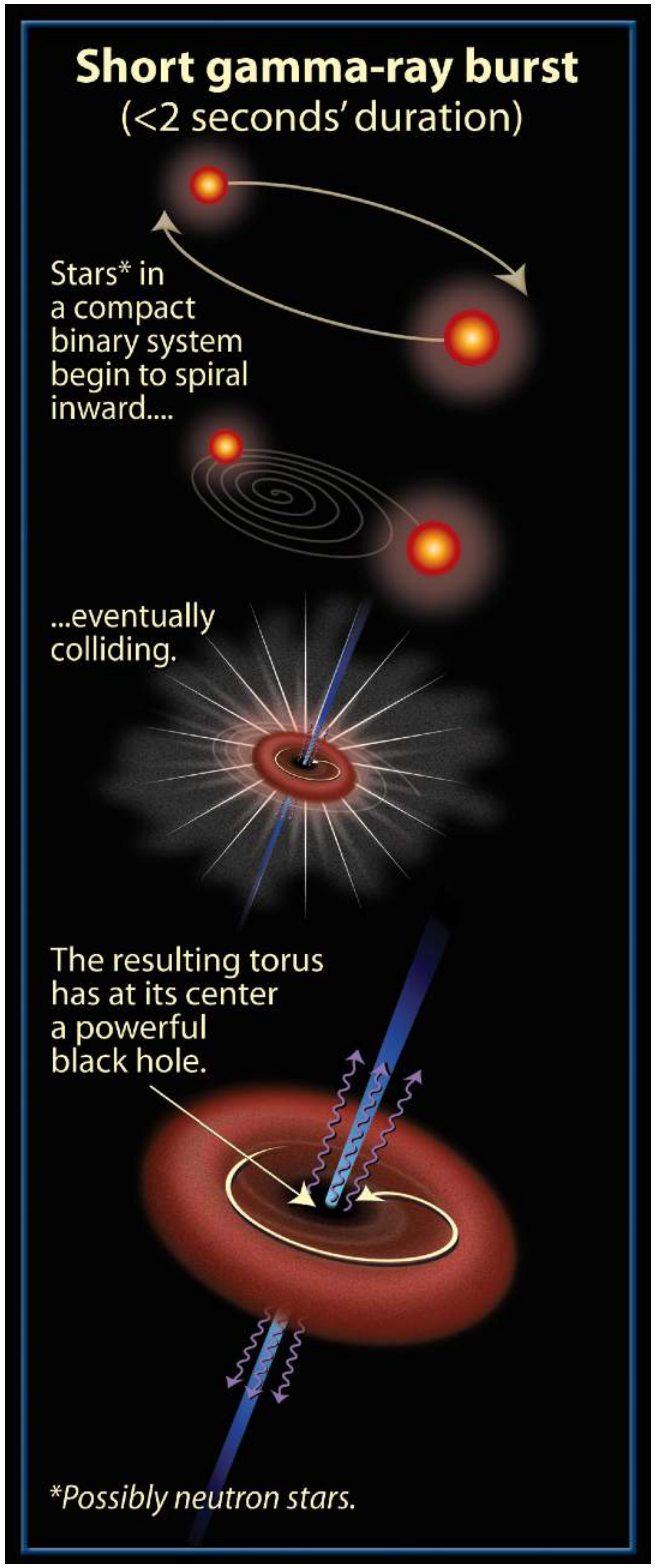
Young sources ?



Old stellar population

Old sources ?

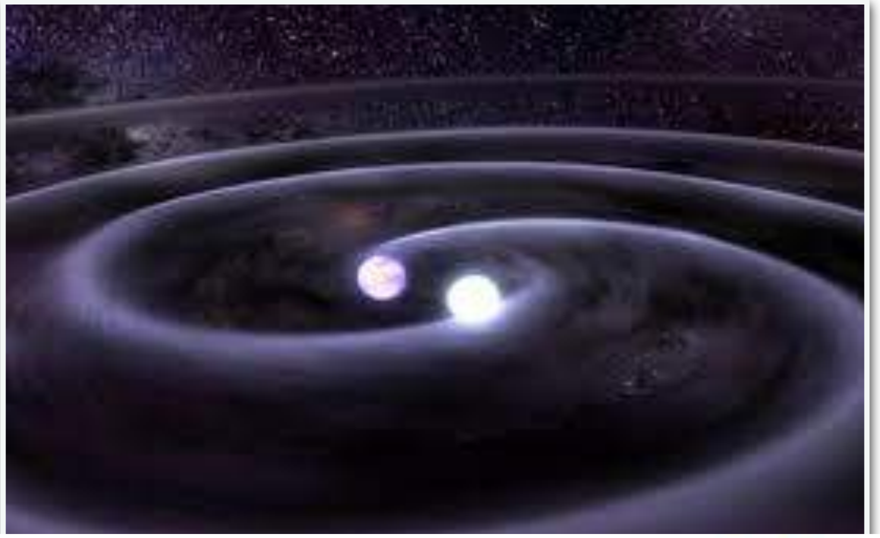


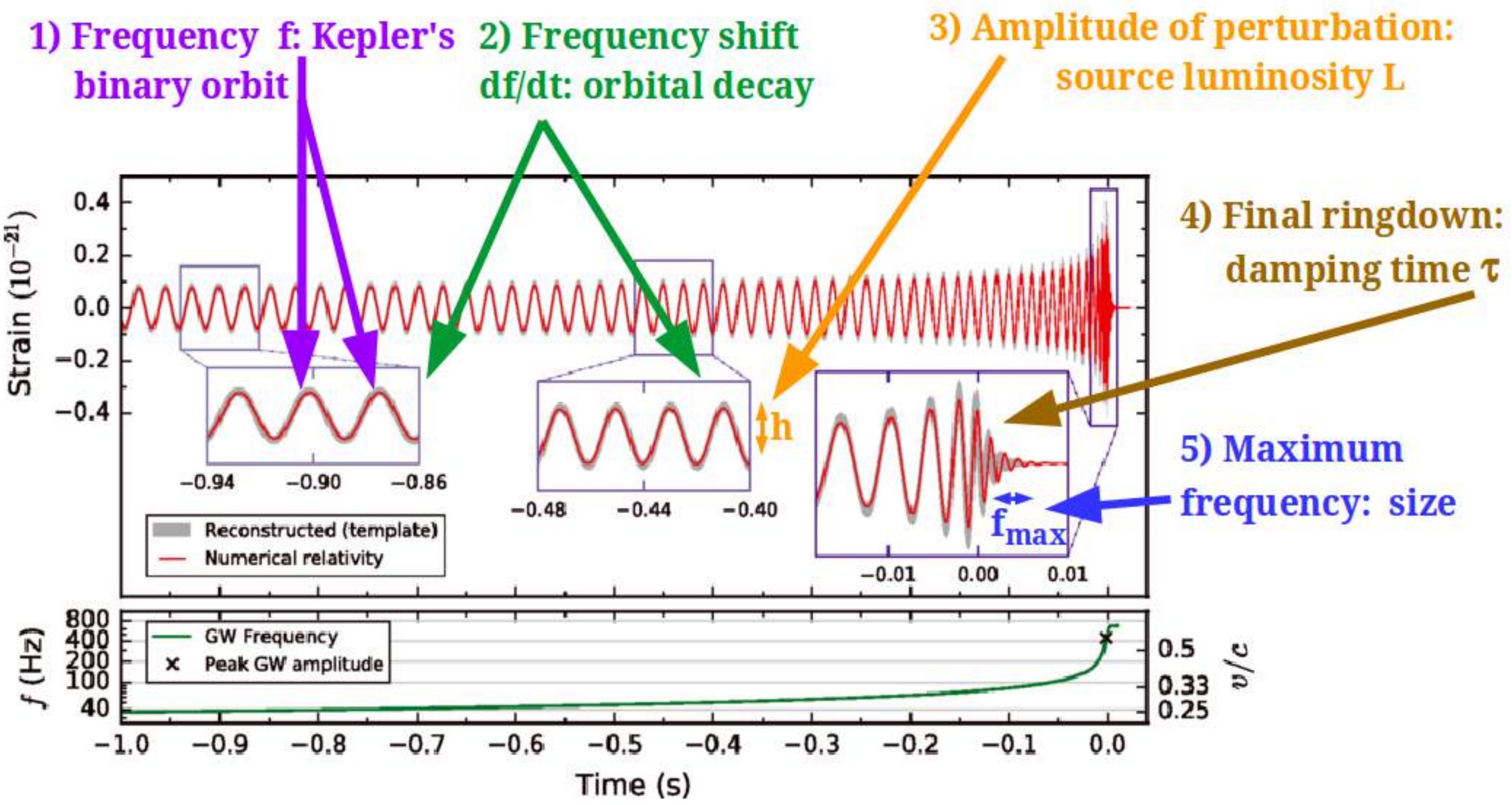


Connection long GRB / supernova (end of life of massive star) ✓

Connection short GRB / neutron star mergers ?

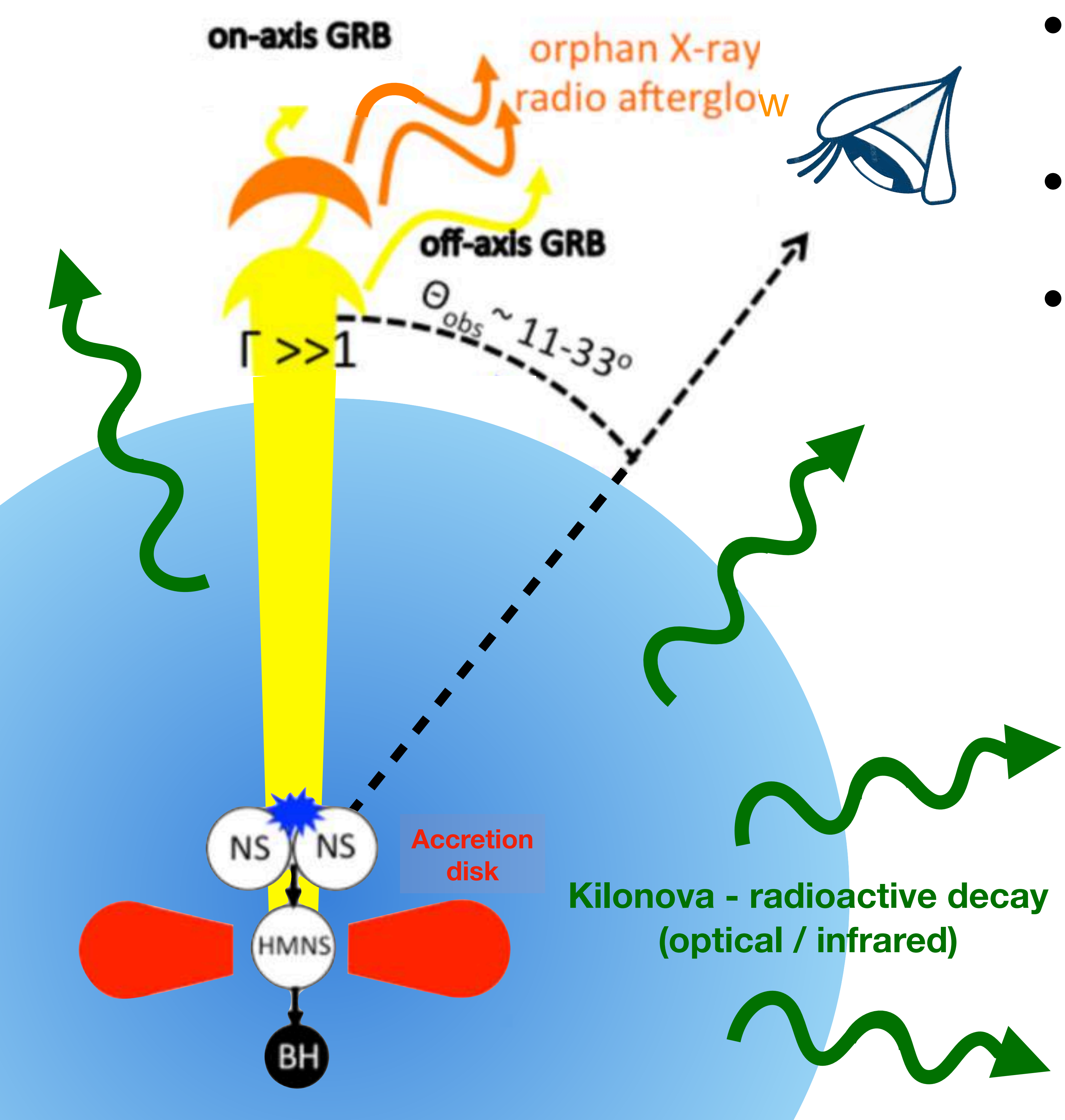
Multi-messenger emission of short GRBs



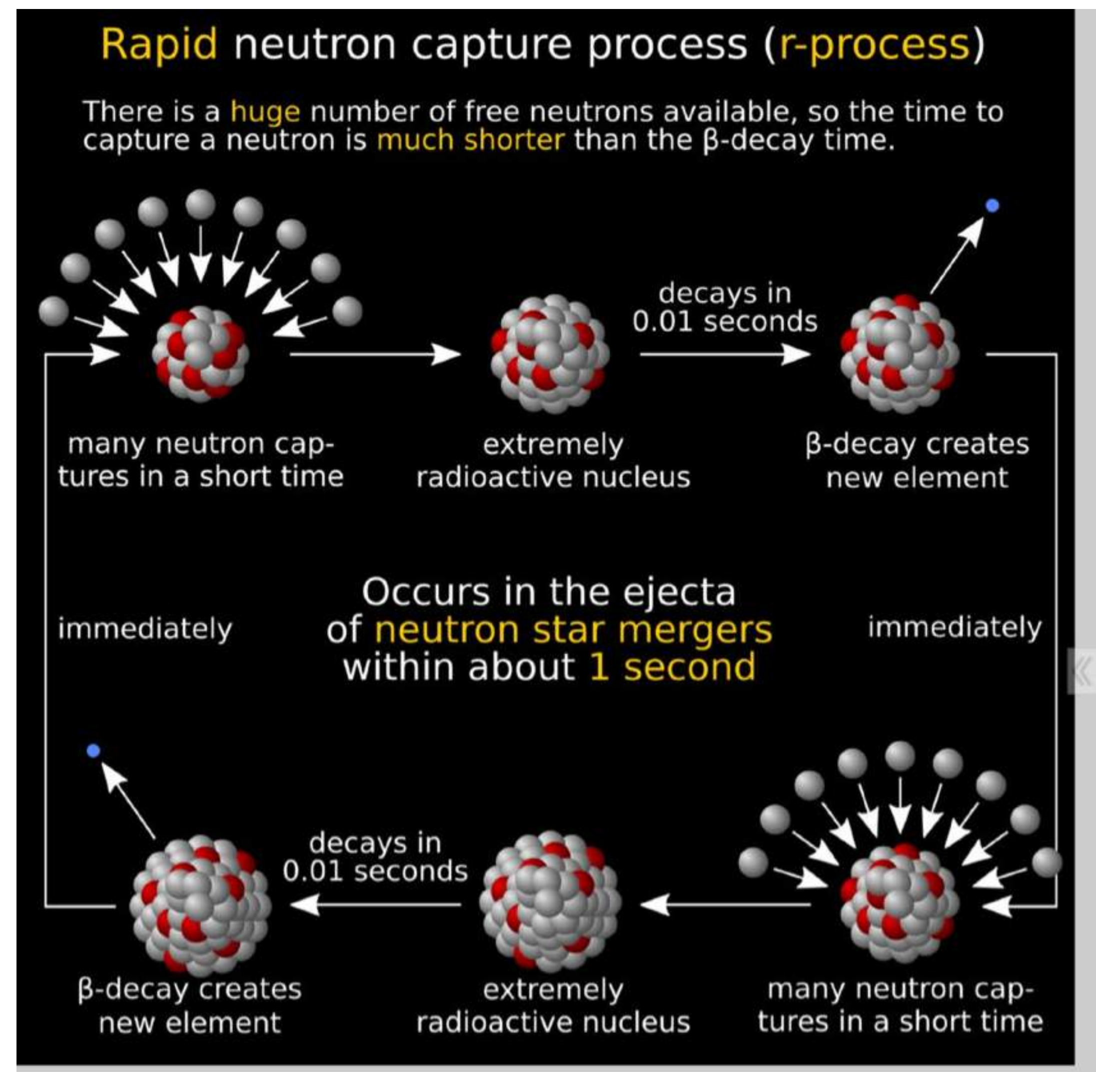


Multi-messenger emission of short GRBs

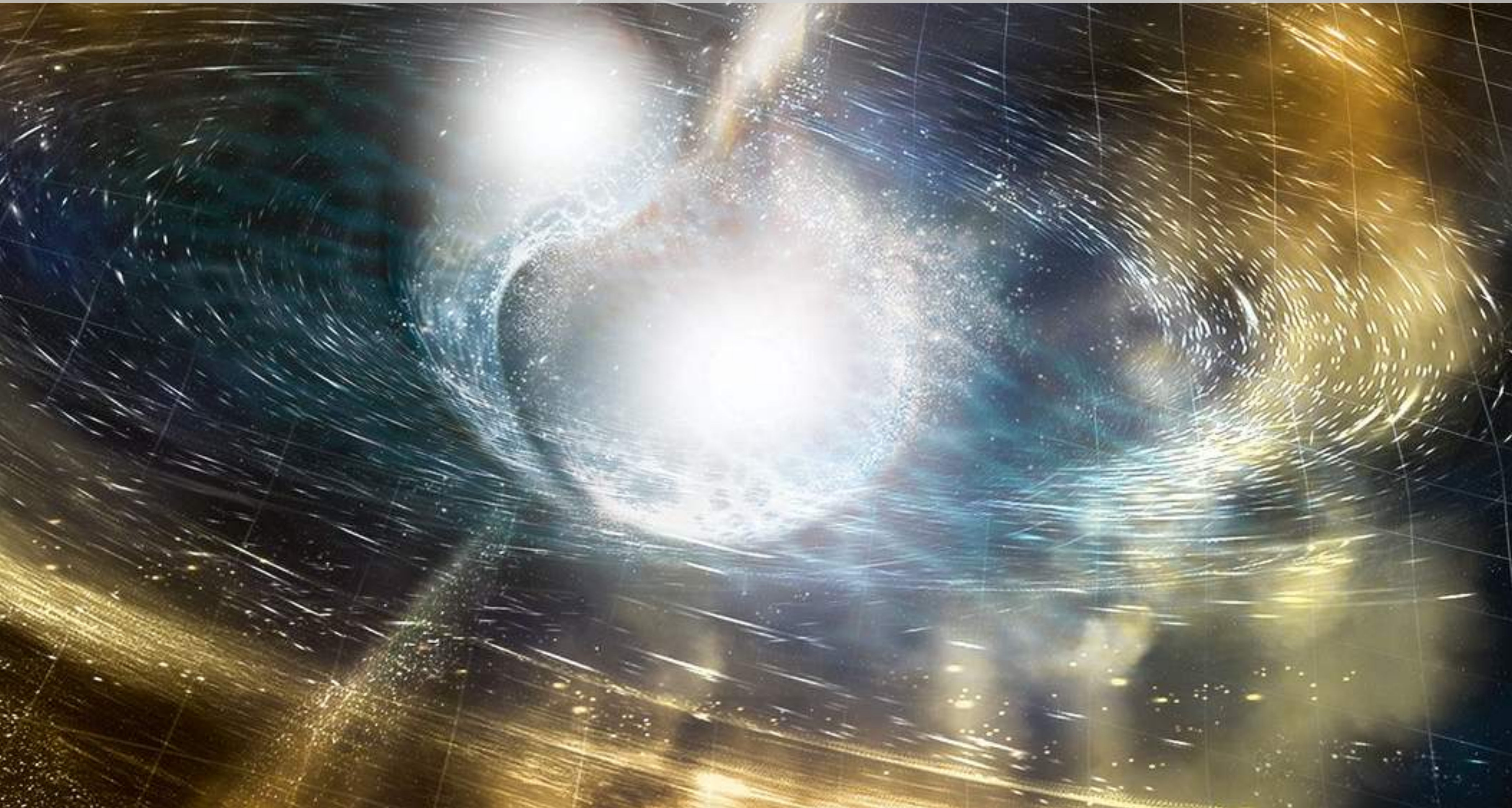
Expected electromagnetic signal (if neutron stars involved)



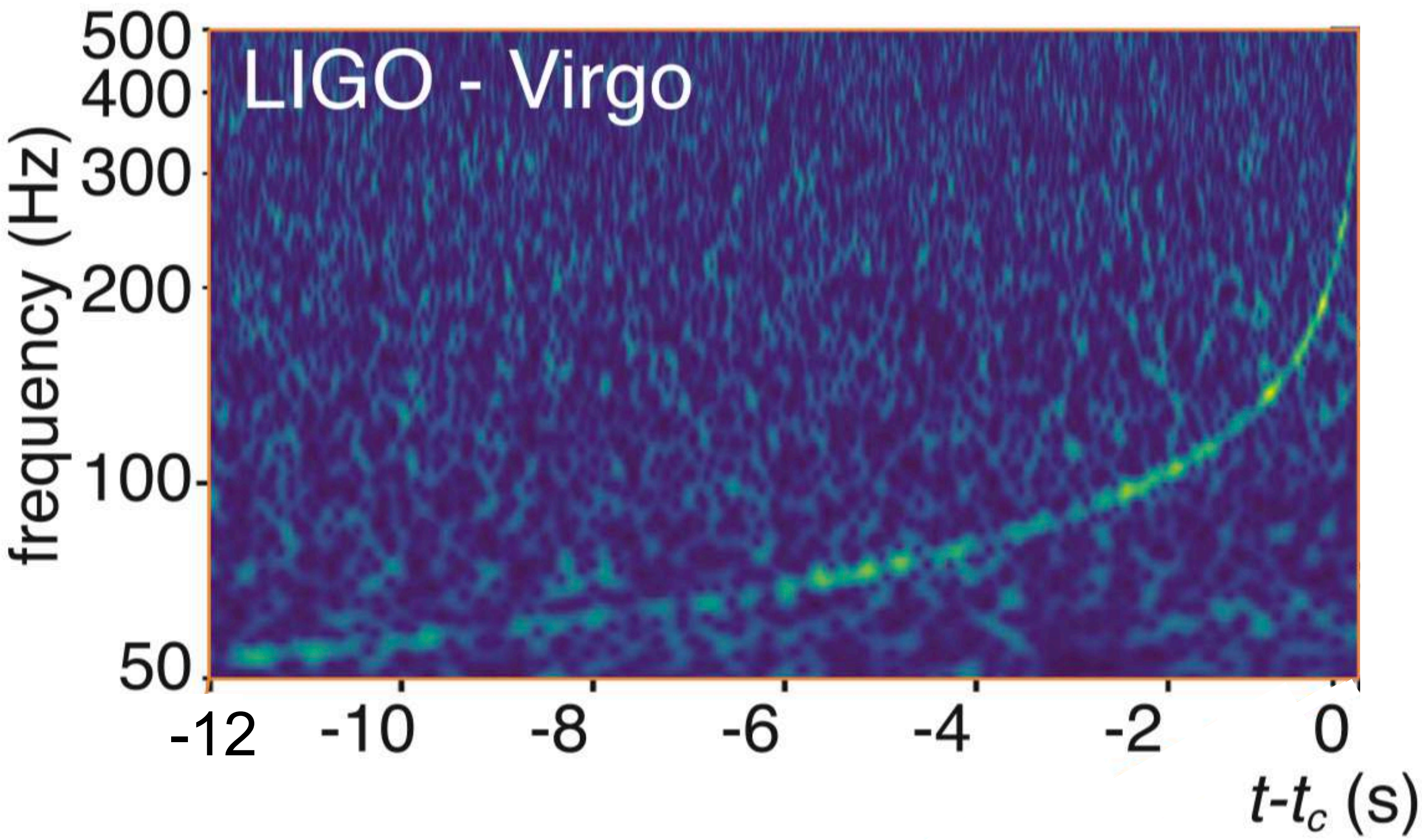
- «r-Process» expected to happen in environment with high density of free neutrons.
- Set of nuclear reactions responsible for the production of heaviest elements (> Pb).
- Succession of rapid neutron captures by one heavy nuclei.



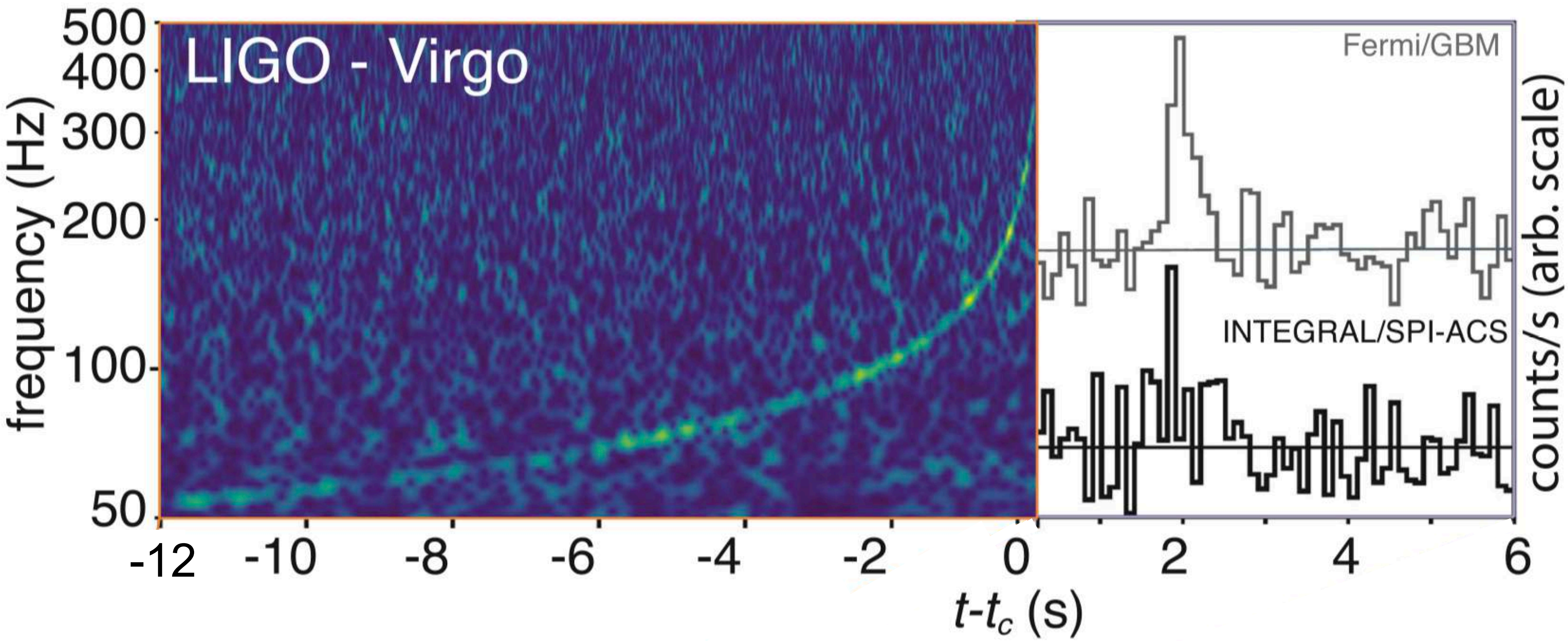
Gravitational-wave signal GW170817



August 17, 2017 at 14h41m04s …

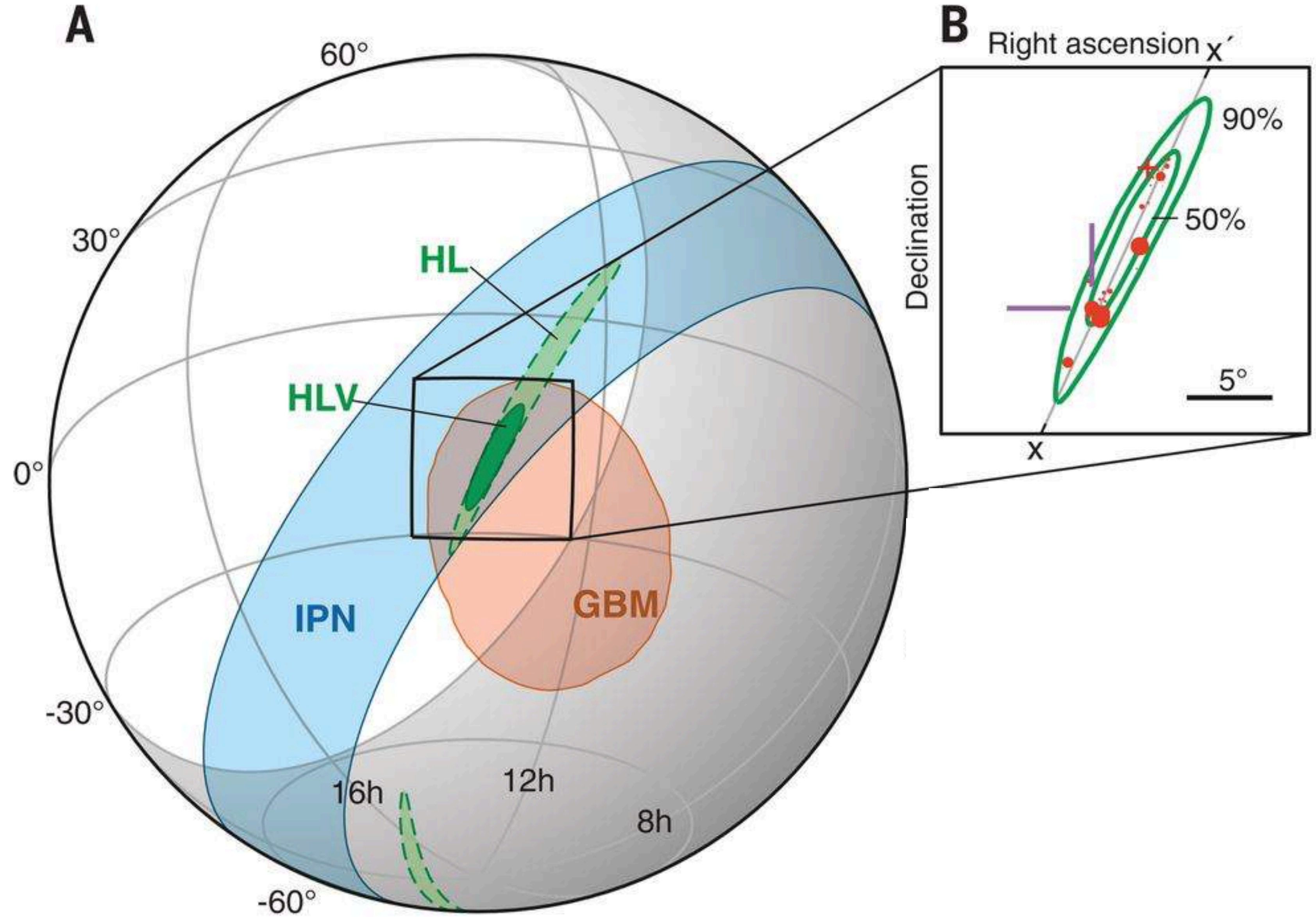


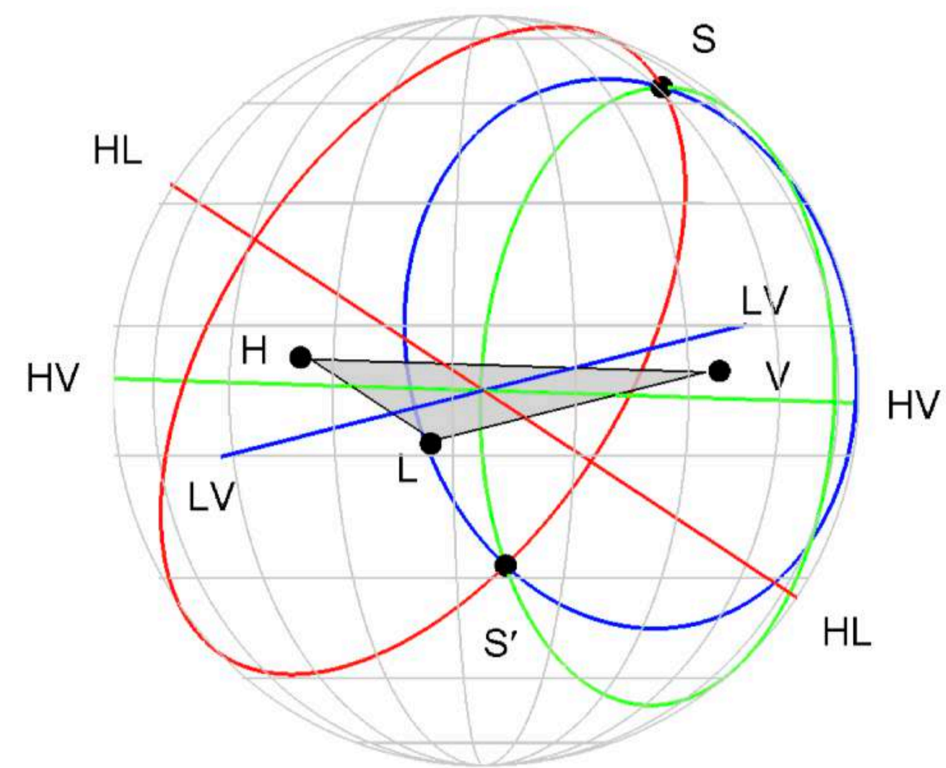
August 17, 2017 at 14h41m04s …




+2s
Short GRB
GRB 170817A


+2s
Short GRB
GRB 170817A
+5h
Location
(30°², 42 Mpc)


A
60°
30°
0°
-30°
-60°
16h
12h
8h
HL
HLV
IPN
GBM
B
Right ascension
x′
x
Declination
90%
50%
5°

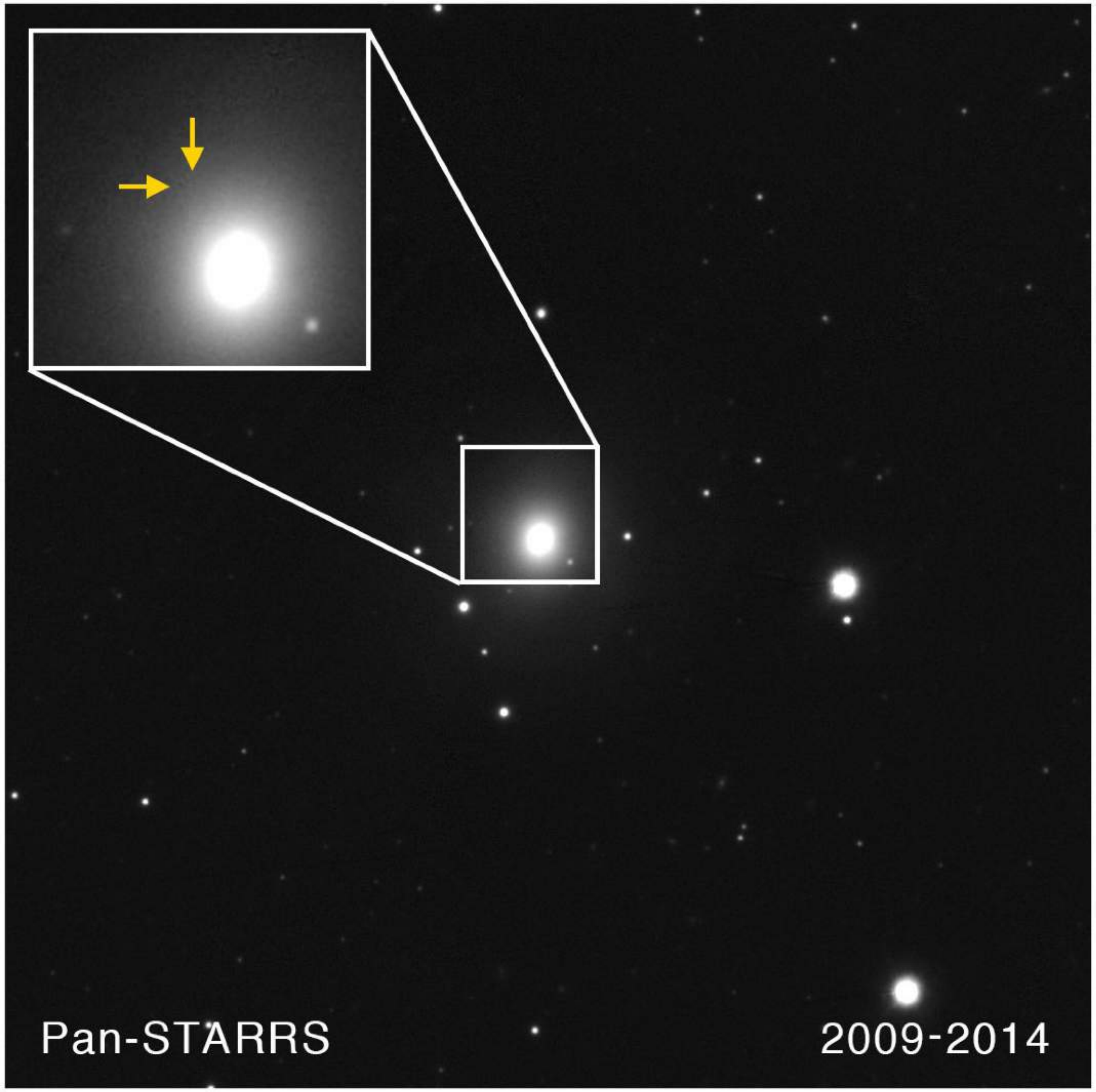

S
HL
LV
H
V
HV
HV
L
LV
S′
HL

Objective: localize the source / electromagnetic counterpart as fast as possible

+2s Short GRB
GRB 170817A

+5h Location
($30°^2$, 42 Mpc)

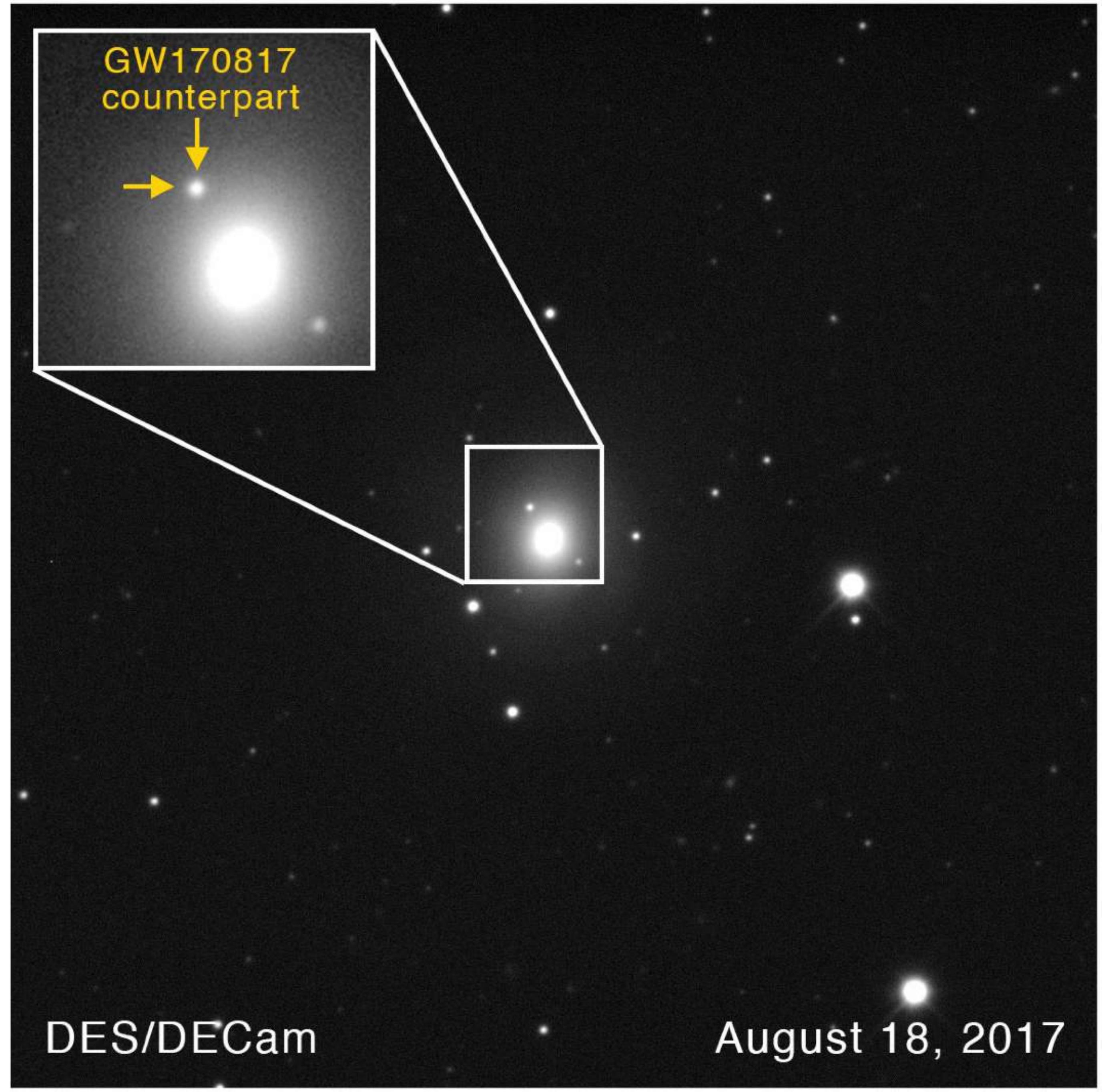
+11h Optical counterpart
AT2017gfo / NGC4993

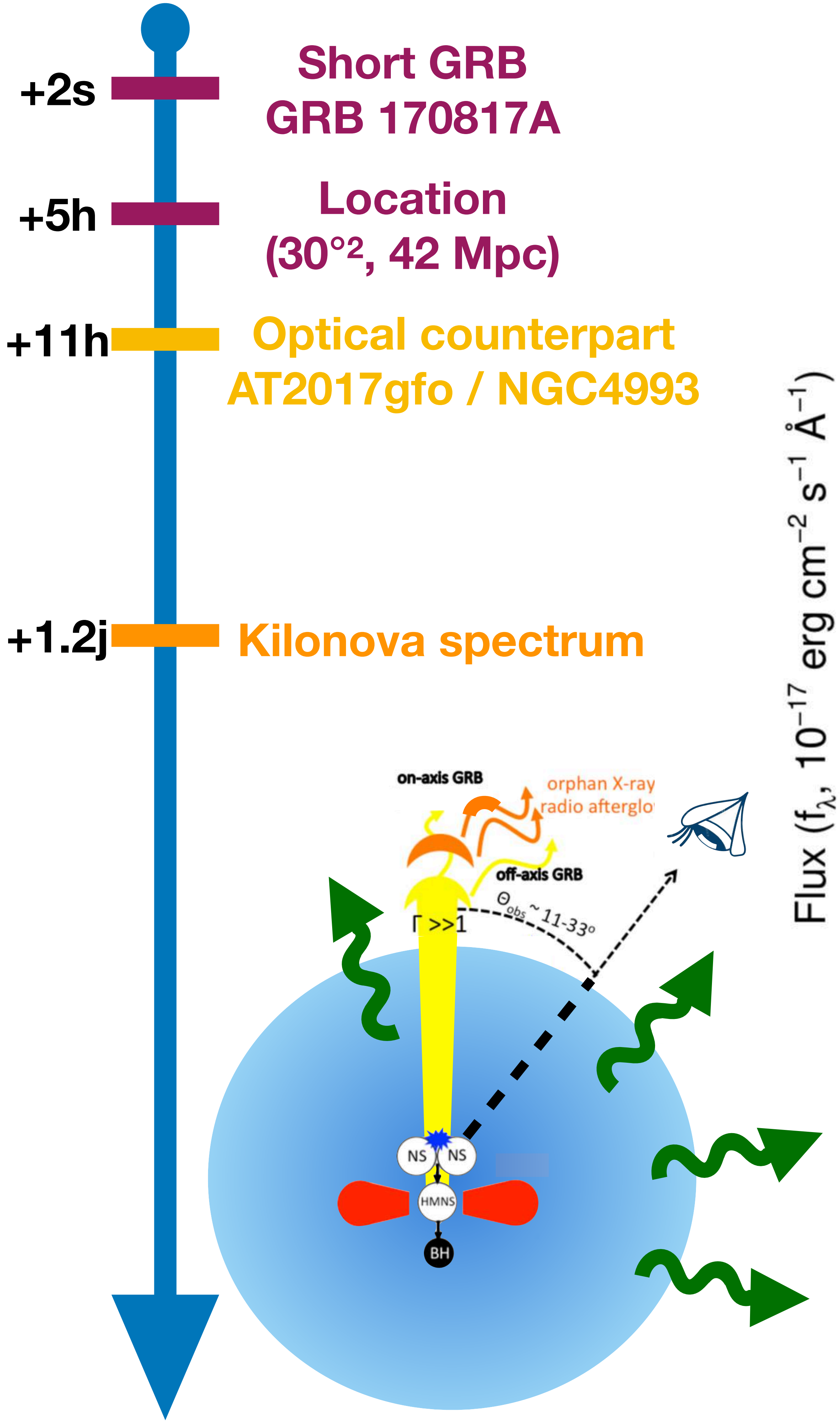


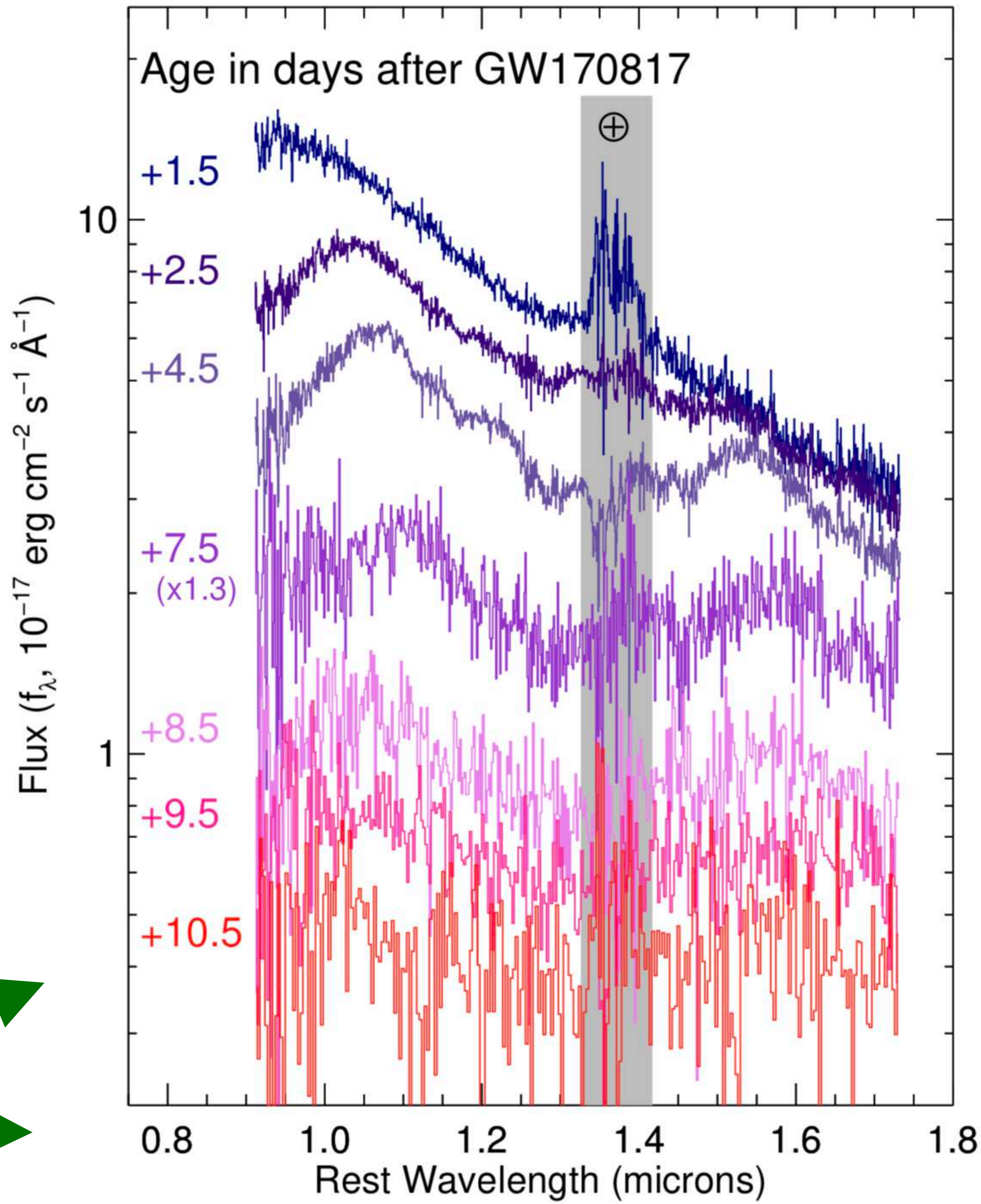
+2s — Short GRB
GRB 170817A

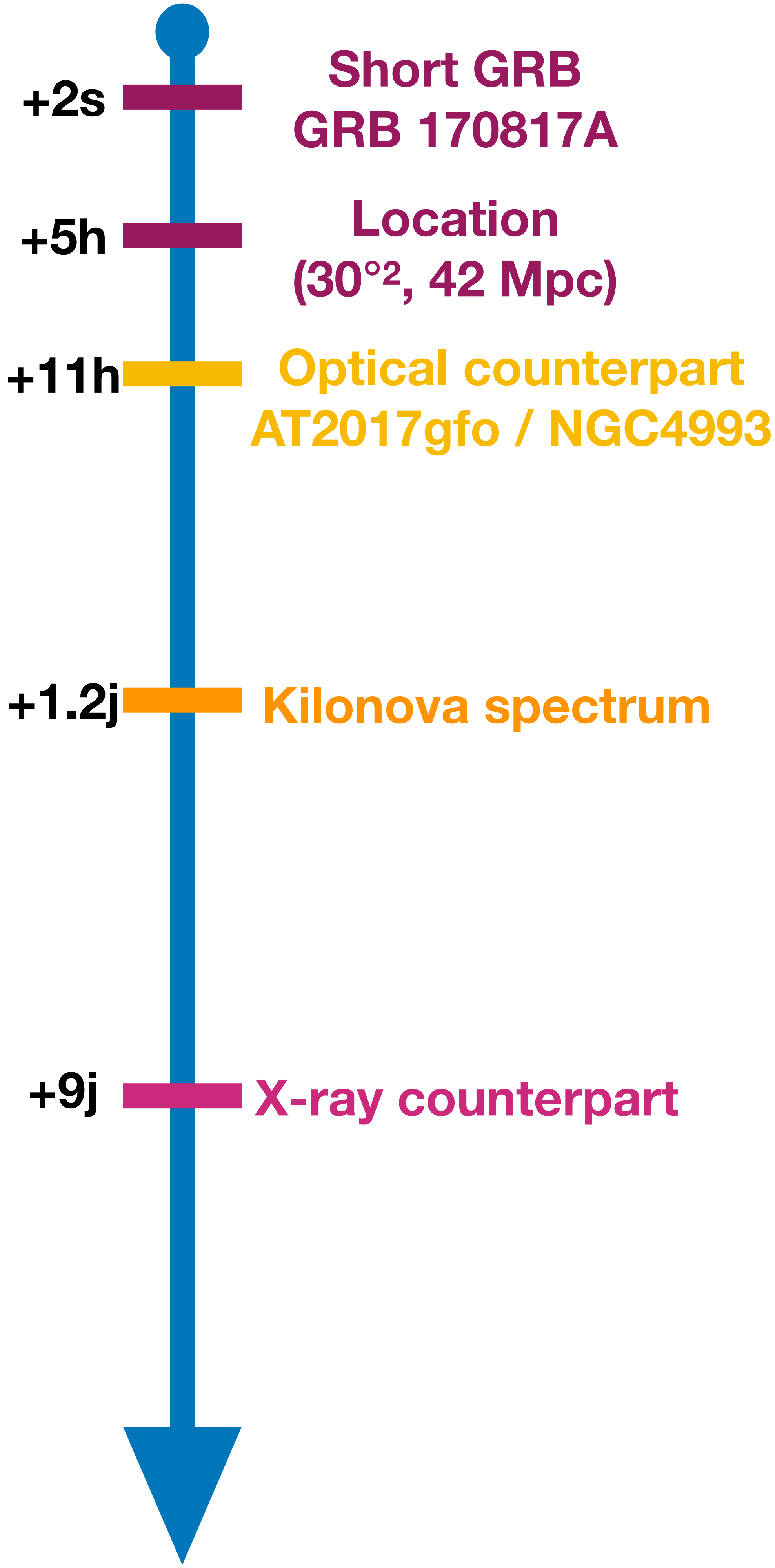
+5h — Location
(30°^{2}, 42 Mpc)

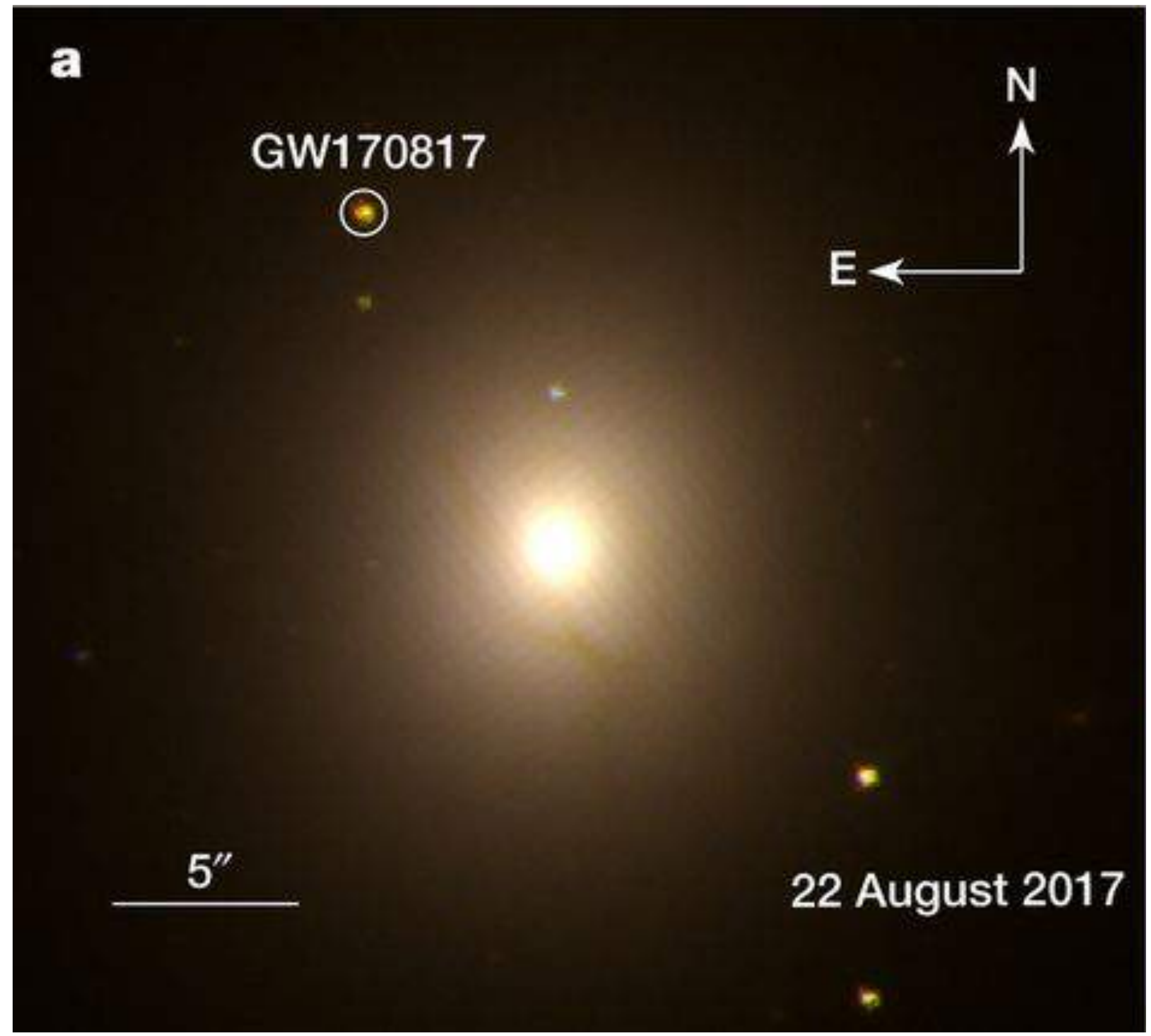
+11h — Optical counterpart
AT2017gfo / NGC4993



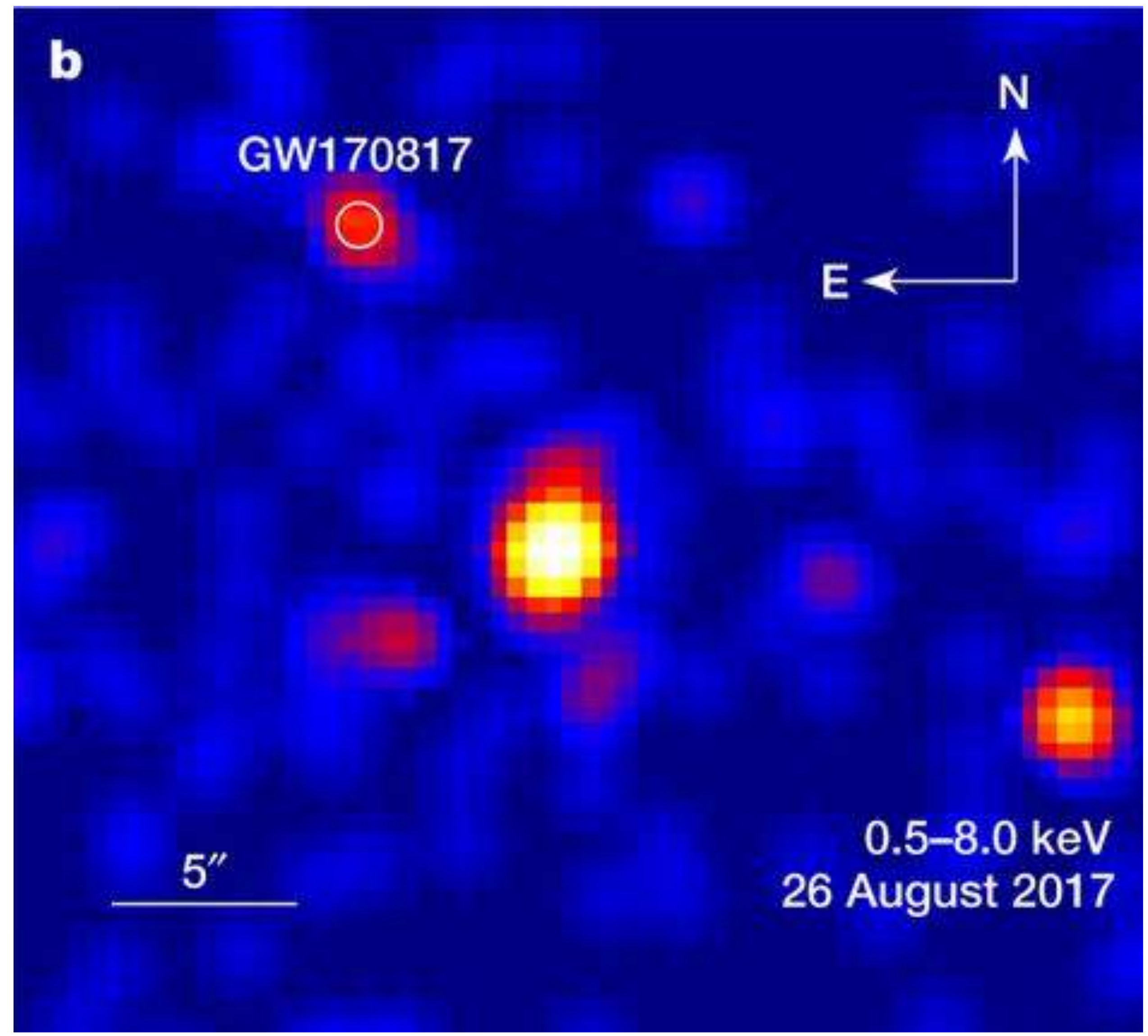

+2s
Short GRB
GRB 170817A
+5h
Location
(30°², 42 Mpc)
+11h
Optical counterpart
AT2017gfo / NGC4993
+1.2j
Kilonova spectrum
on-axis GRB
orphan X-ray
radio afterglo
off-axis GRB
Γ >>1
Θobs ~ 11-33°
NS
NS
HMNS
BH

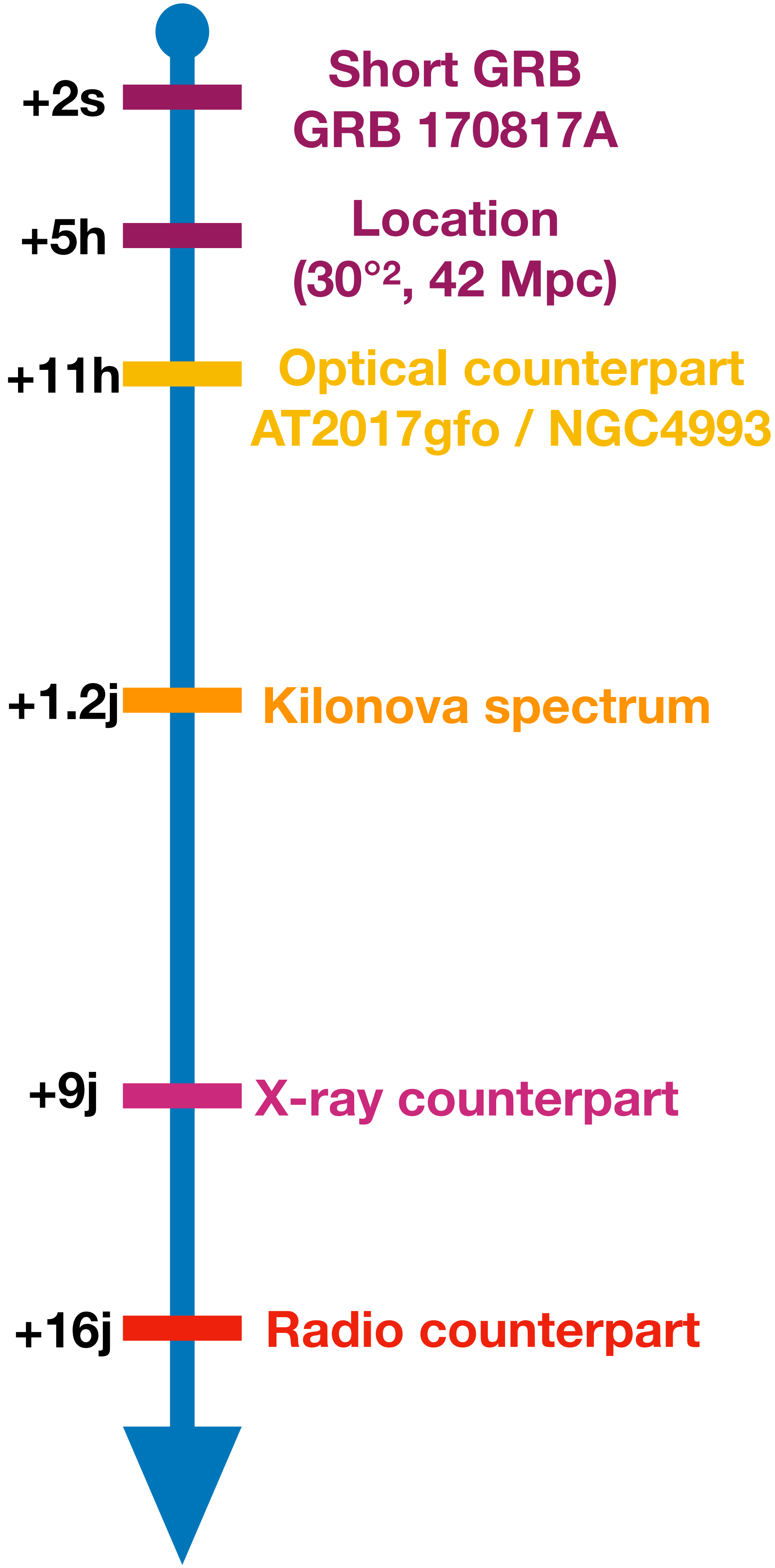

Age in days after GW170817
⊕
+1.5
+2.5
+4.5
+7.5
(x1.3)
+8.5
+9.5
+10.5
10
1
Flux (fλ, 10⁻¹⁷ erg cm⁻² s⁻¹ Å⁻¹)
0.8
1.0
1.2
1.4
1.6
1.8
Rest Wavelength (microns)

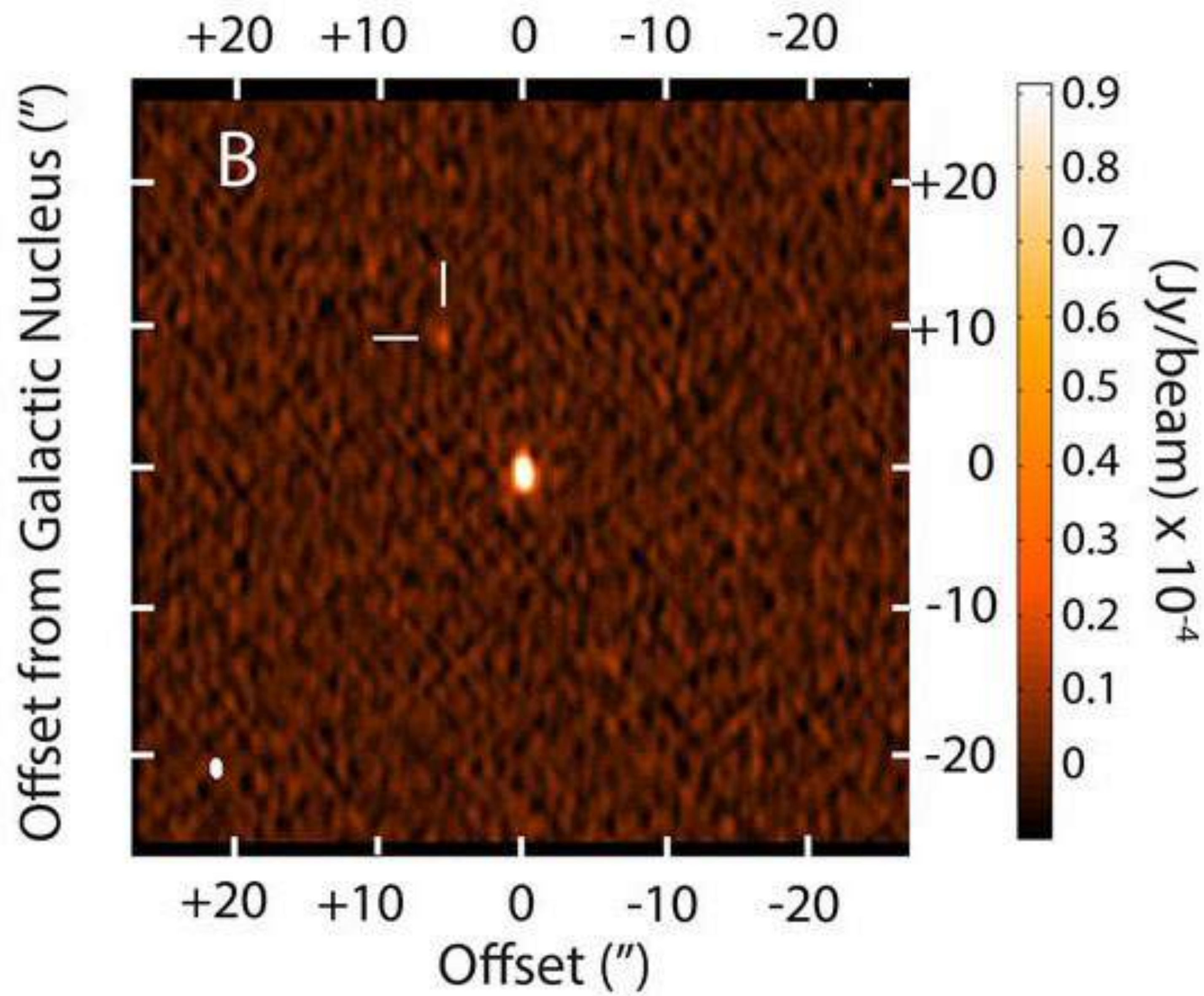

+2s
Short GRB
GRB 170817A
+5h
Location
(30°2, 42 Mpc)
+11h
Optical counterpart
AT2017gfo / NGC4993
+1.2j
Kilonova spectrum
+9j
X-ray counterpart


a
GW170817
N
E
5″
22 August 2017

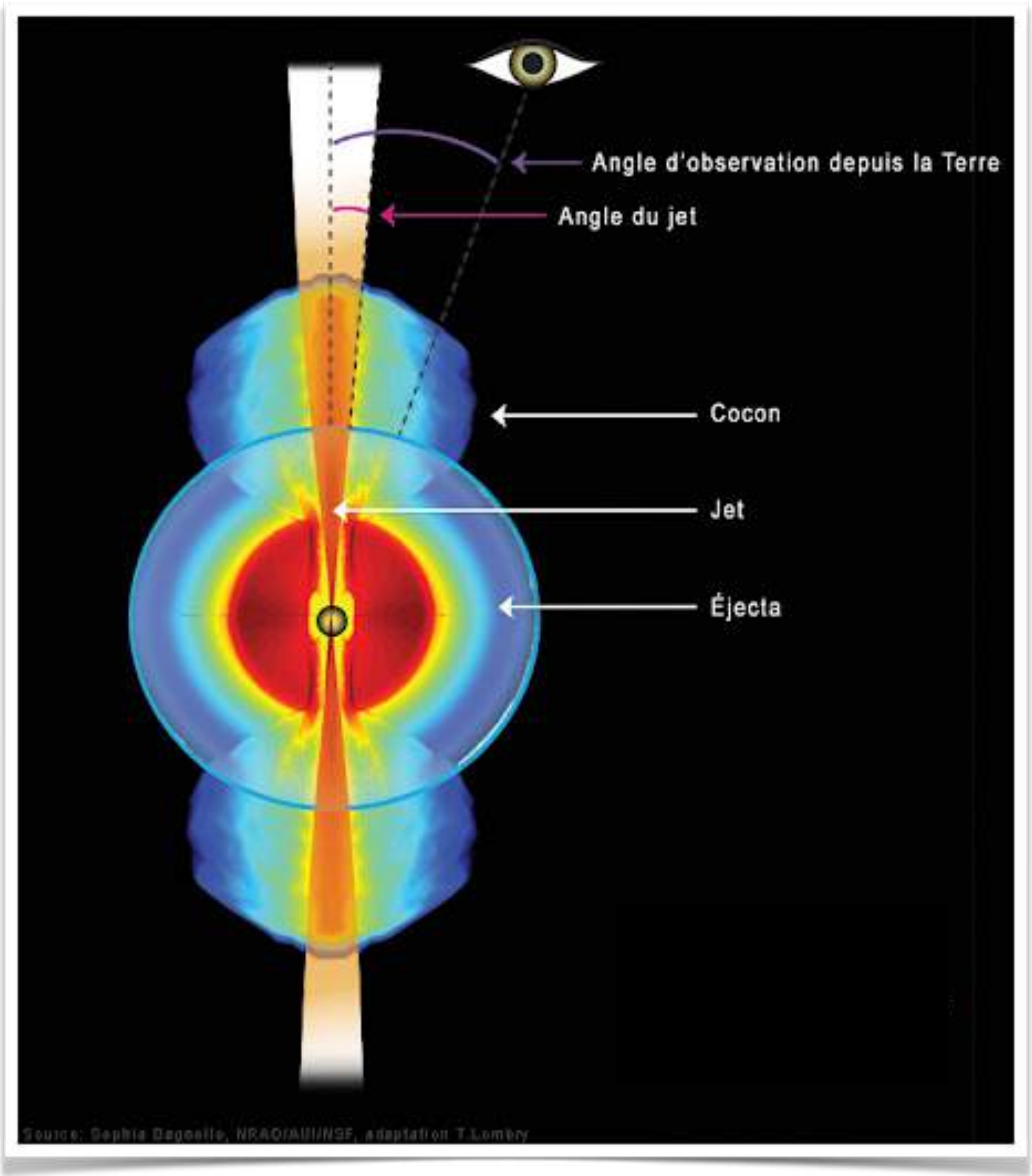
- +2s — Short GRB GRB 170817A
- +5h — Location (30°², 42 Mpc)
- +11h — Optical counterpart AT2017gfo / NGC4993
- +1.2j — Kilonova spectrum
- +9j — X-ray counterpart



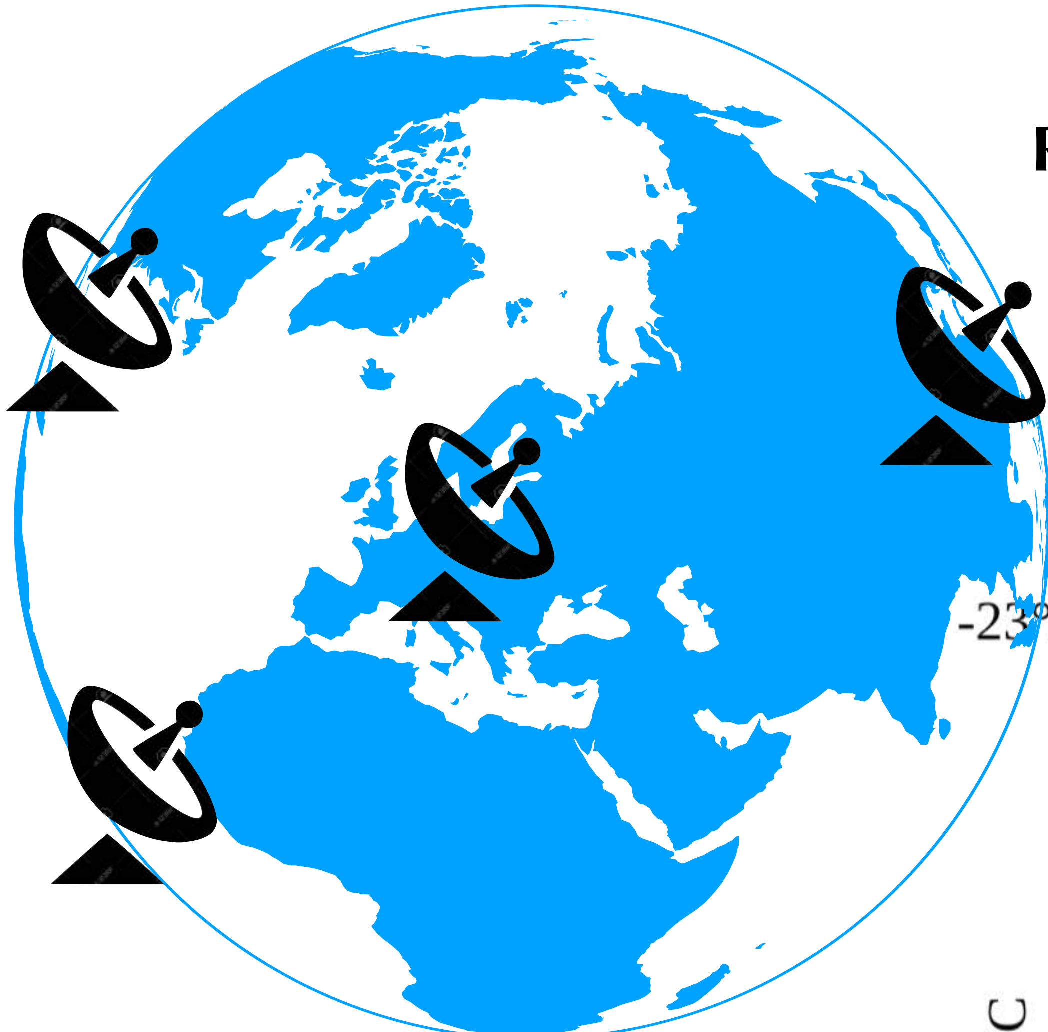

+2s
Short GRB
GRB 170817A
+5h
Location
(30°2, 42 Mpc)
+11h
Optical counterpart
AT2017gfo / NGC4993
+1.2j
Kilonova spectrum
+9j
X-ray counterpart
+16j
Radio counterpart


B
+20
+10
0
-10
-20
Offset from Galactic Nucleus (″)
Offset (″)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(Jy/beam) x 10-4

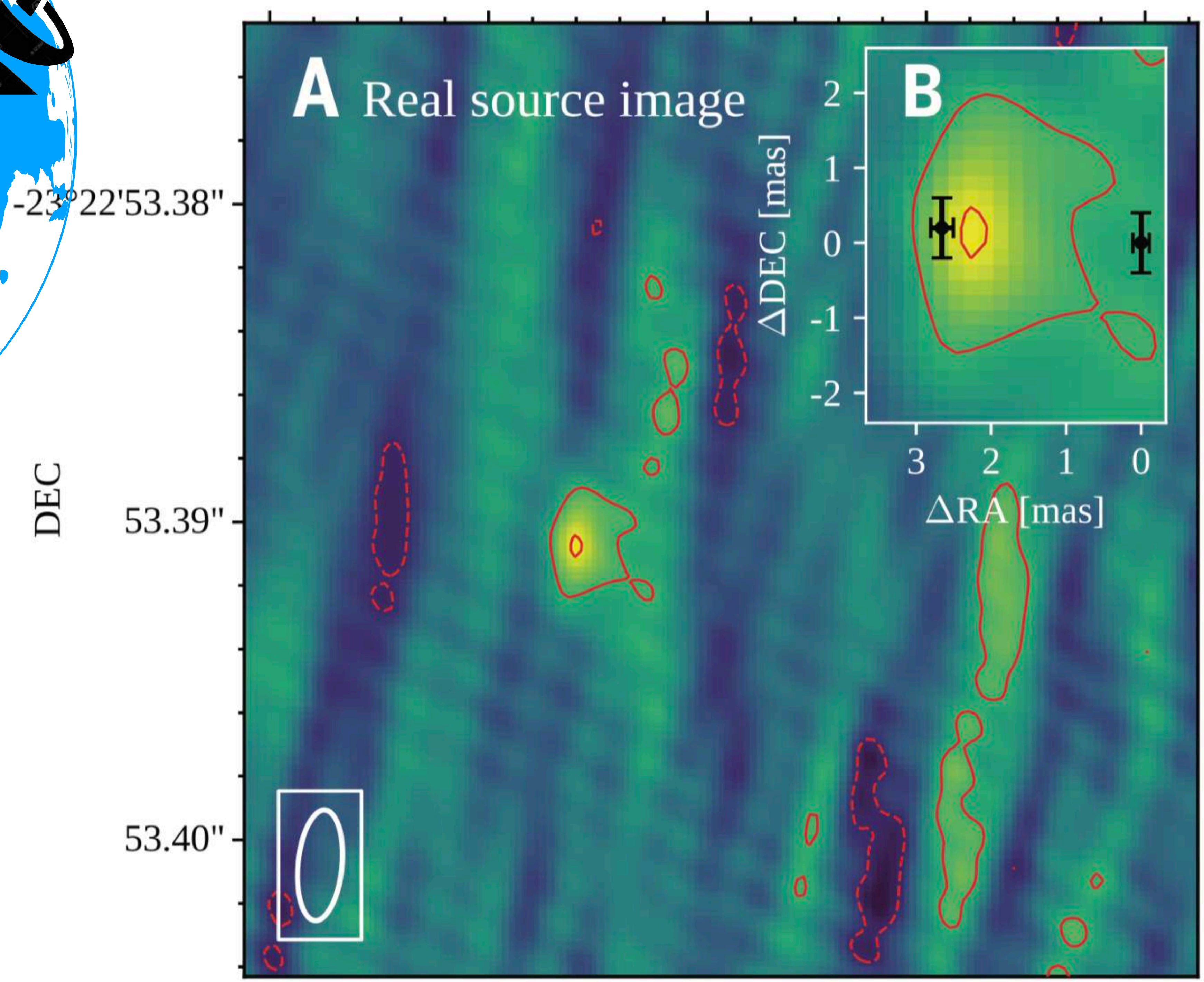
What is the ejecta geometry ?



Confirmation of the presence of a relativistic jet (February 2019)



Radio interferometry R∝1/D ~1mas



Open questions

Some open questions about GRBs and compact objects mergers:

- Neutron star/black hole or black hole/black hole merger electromagnetic emission ?
- Jet geometry in neutron star / neutron star mergers ?
- Hadronic content of relativistic jets ?
- High-redshift GRBs + diversity of long GRB (underluminous, ultra long GRBs, …)

- **Requires observations over the broad electromagnetic spectrum + multi-messenger.**

Outline - Lecture 2

B. End point of massive star evolution

1. Evolution of massive stars

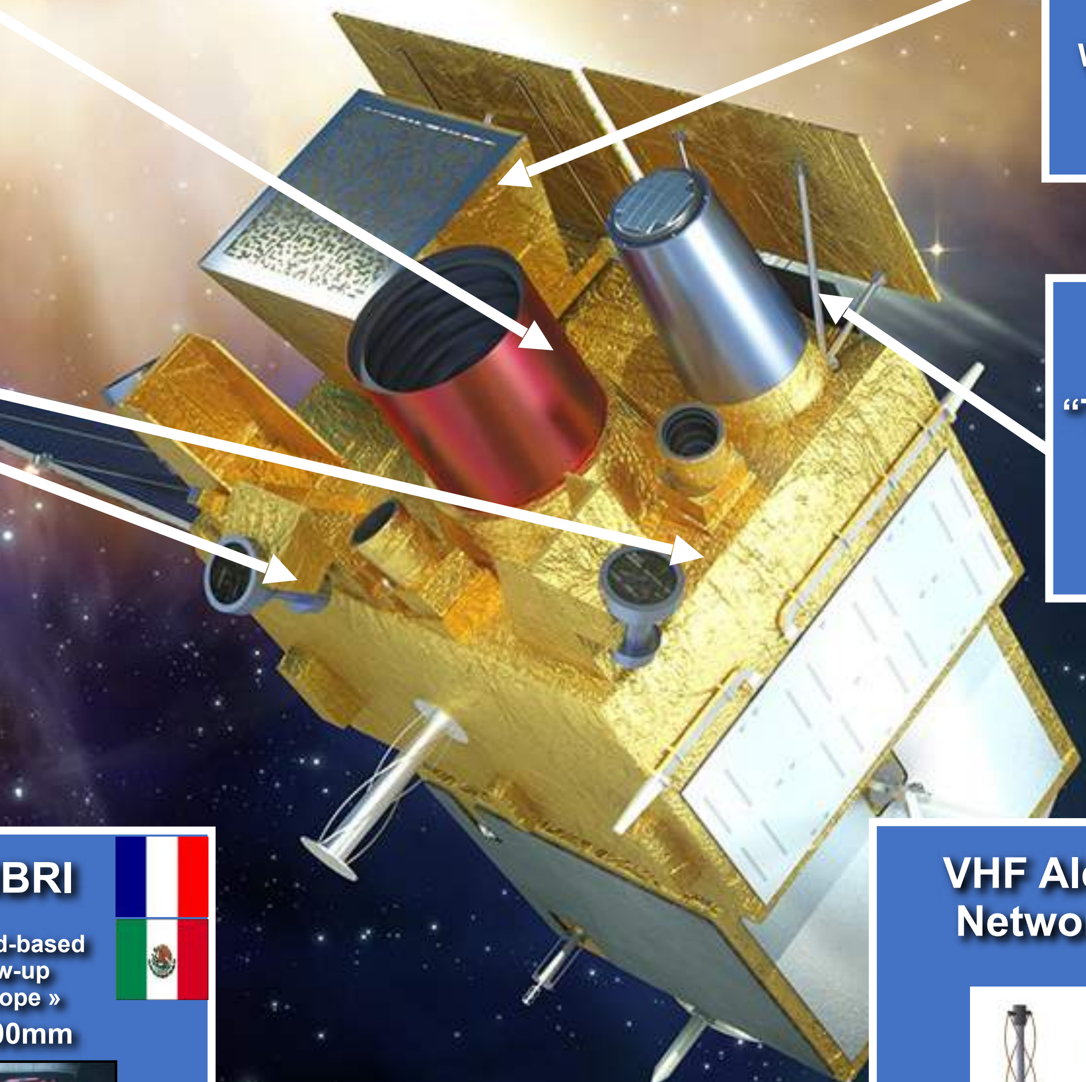
2. Gamma-ray bursts

3. **The SVOM space mission**


SVOM
Space-based multi-band astronomical Variable Objects Monitor
cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES
CNSA

SVOM

- **Launch** expected in **automn 2022 (TBC)**.
- **Circular low Earth orbit at 635 km** of altitude with an **inclination of about 29°**
- Nearly **anti-solar pointing** (so-called **« B1 » attitude law**) **to favor quick ground follow-up**
  ⇒ Earth in the field of view (**65% of duty cycle for ECLAIRs, about 50% for MXT and VT**)



VT
"The Visible Telescope"
Narrow-field visible telescope
Ritchey Chretien Φ=400mm
Localization accuracy < 1arcsec

GRM
"The Gamma-Ray burst Monitor"
X-rays and Gamma-rays detectors
15 keV – 5 MeV
Localization accuracy < 5°

LUPM*

APC*

ECLAIRs
« The trigger camera »
Wide-field X and Gamma rays telescope
Spectral range : 4 keV – 150 keV
Localization accuracy < 12arcmin

MXT
"The Micro-channel X-ray Telescope"
Narrow-field X-ray telescope
Spectral range : 0.2 keV – 10 keV
Localization accuracy < 1arcmin

IJCLab*

C-GFT
« Ground-based Follow-up Telescope »
Φ>1000mm

GWAC
« Ground Wide-Angle Cameras »
Φ=180mm

COLIBRI
« Ground-based Follow-up Telescope »
Φ>1000mm

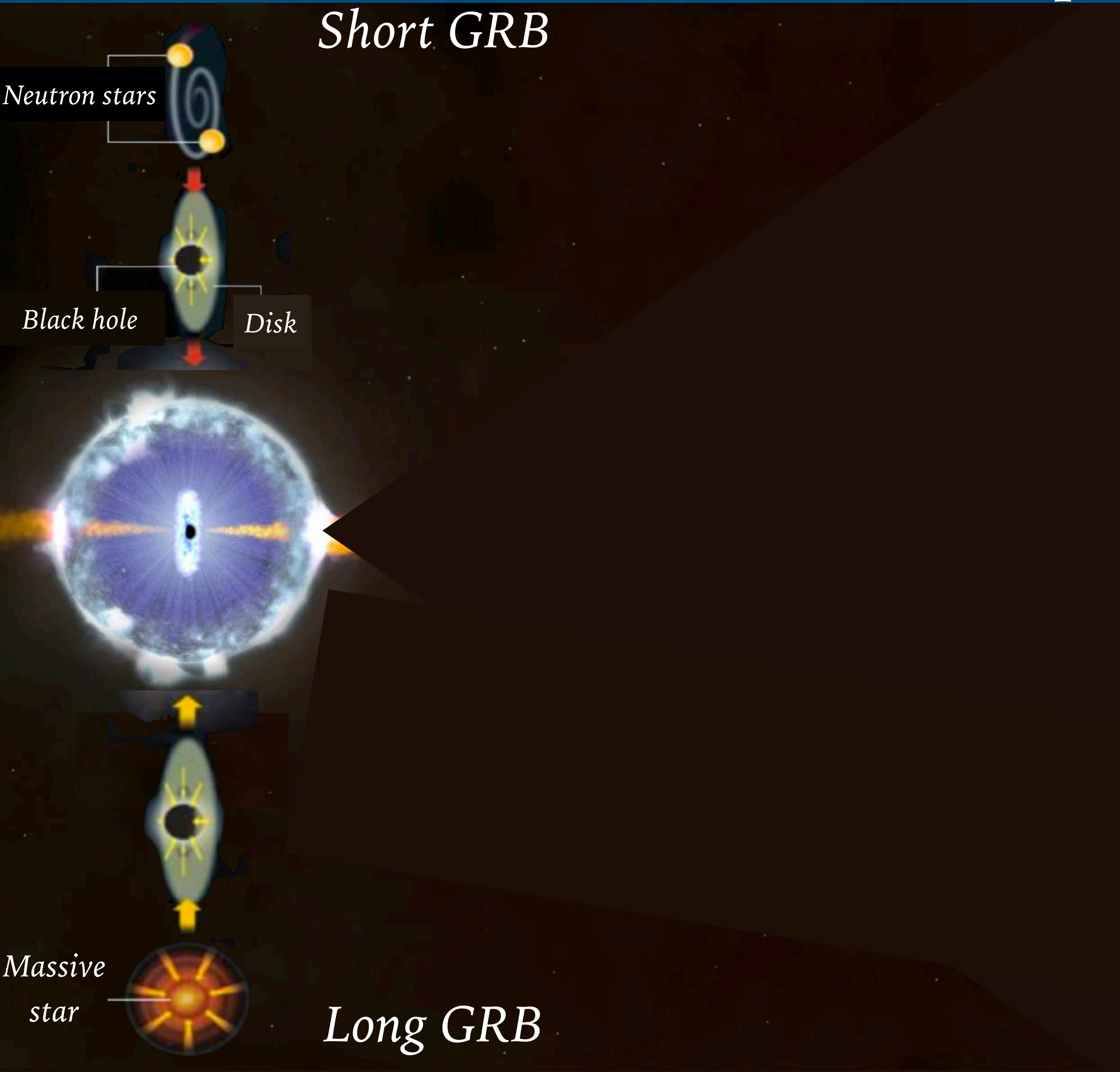
CPPM*

VHF Alert Network

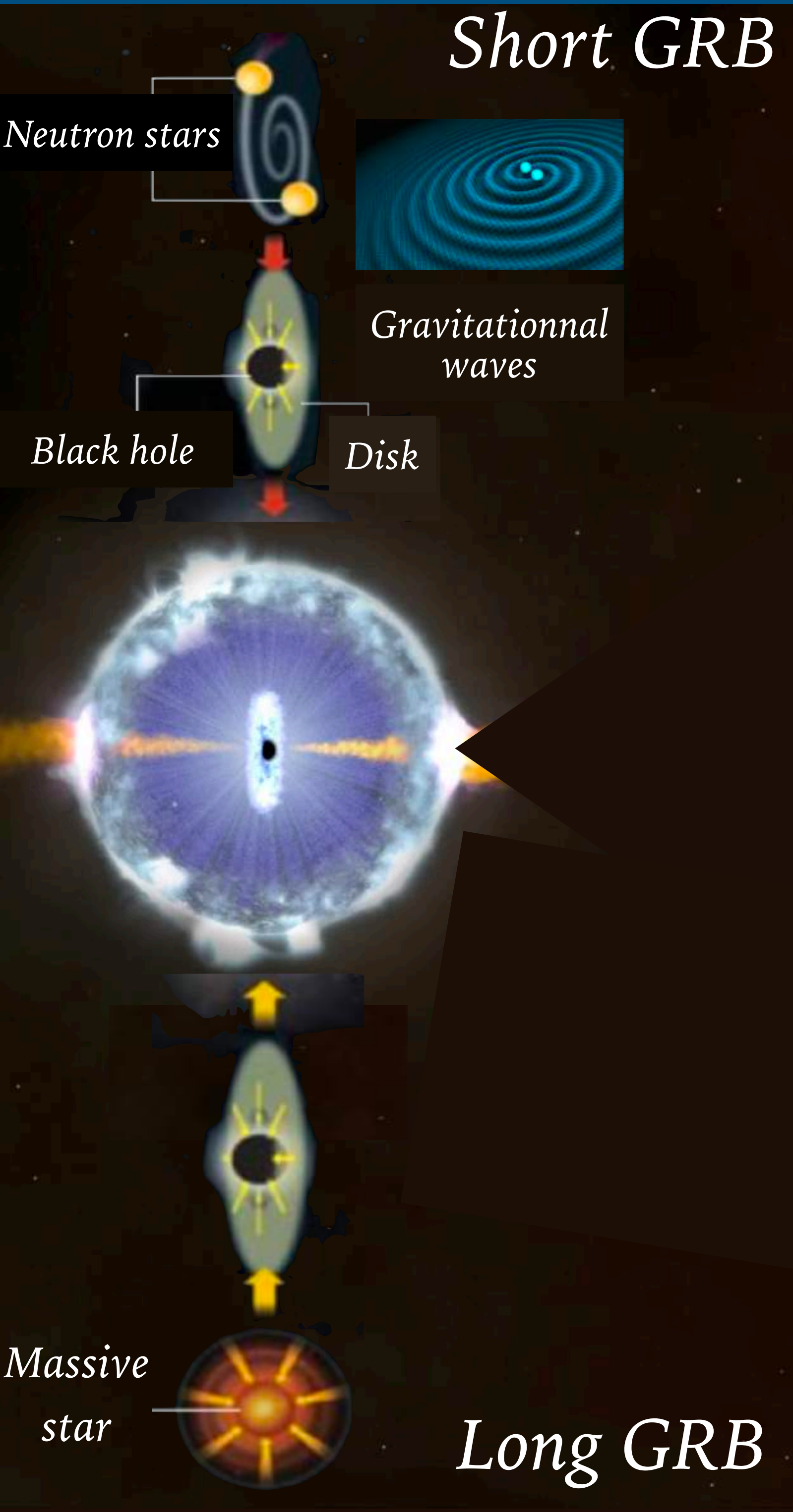
... and more !

Tracking antennas

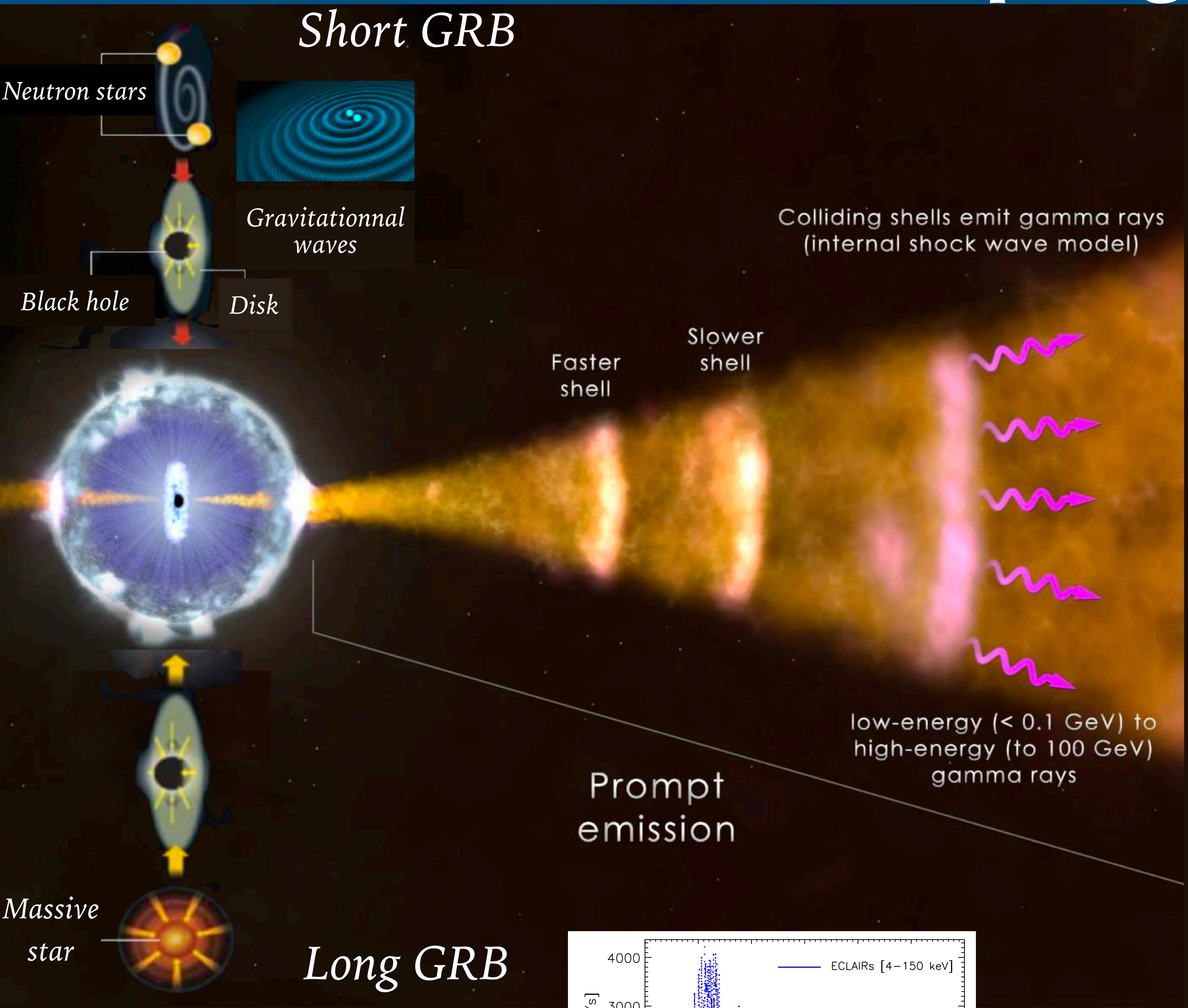
SVOM core program

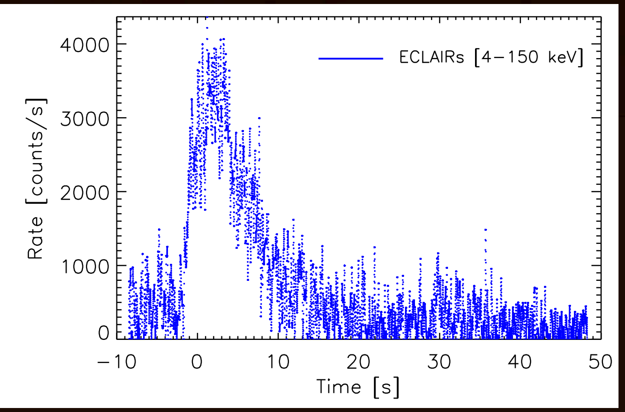


SVOM core program

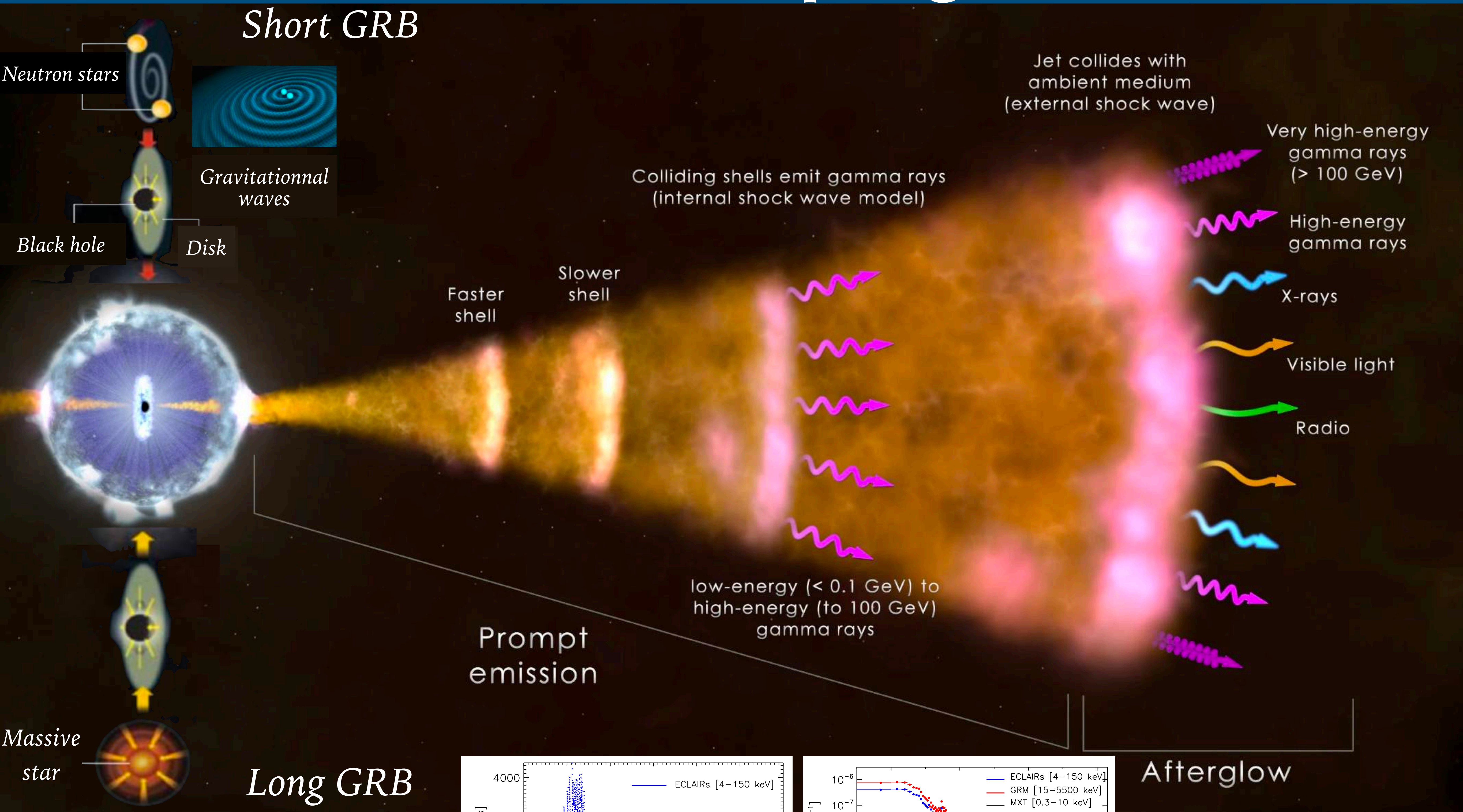


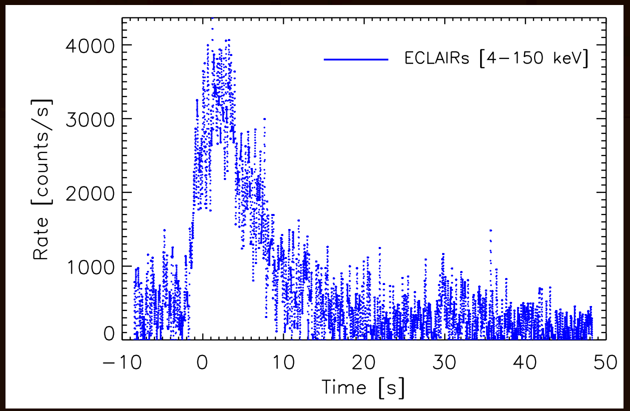
SVOM core program

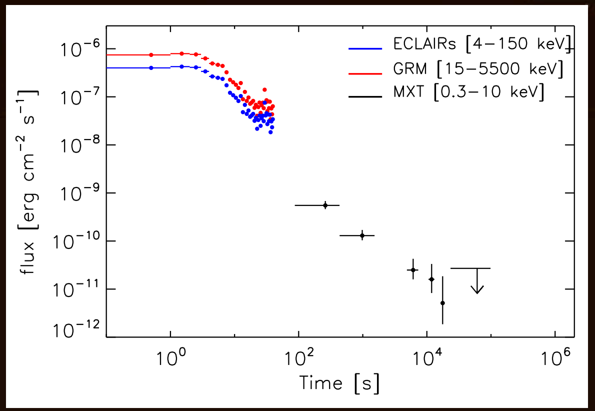




SVOM core program

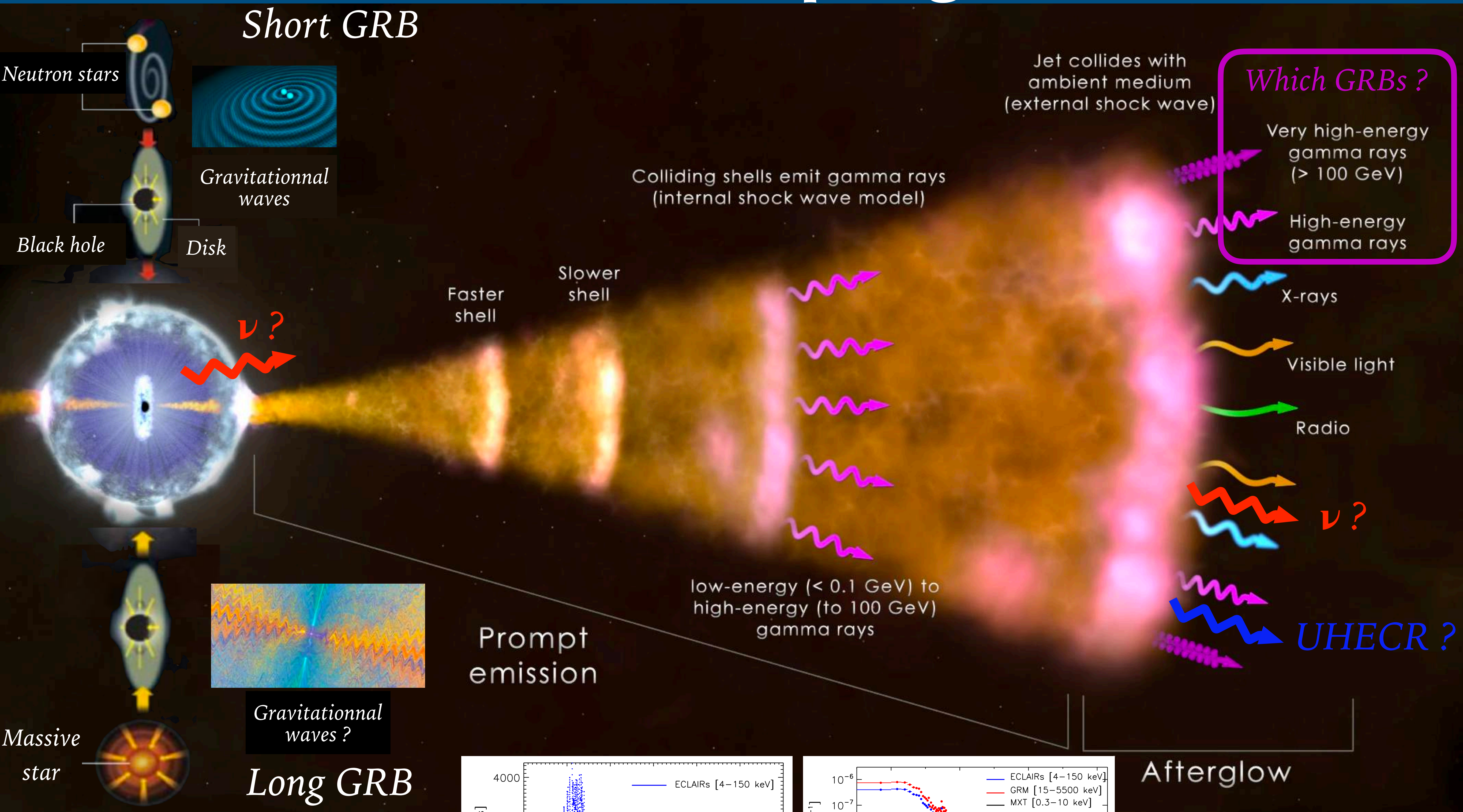


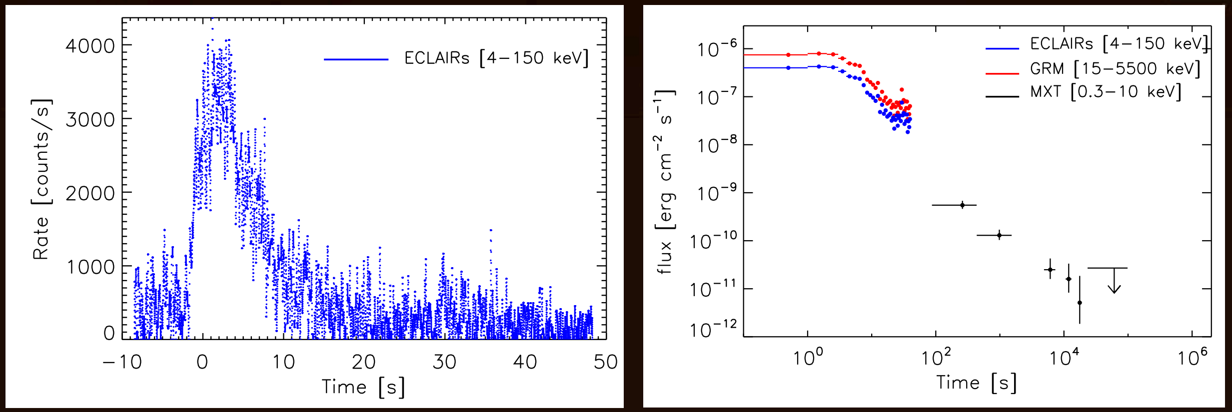




GRB091020: simulation for prompt and afterglow emissions

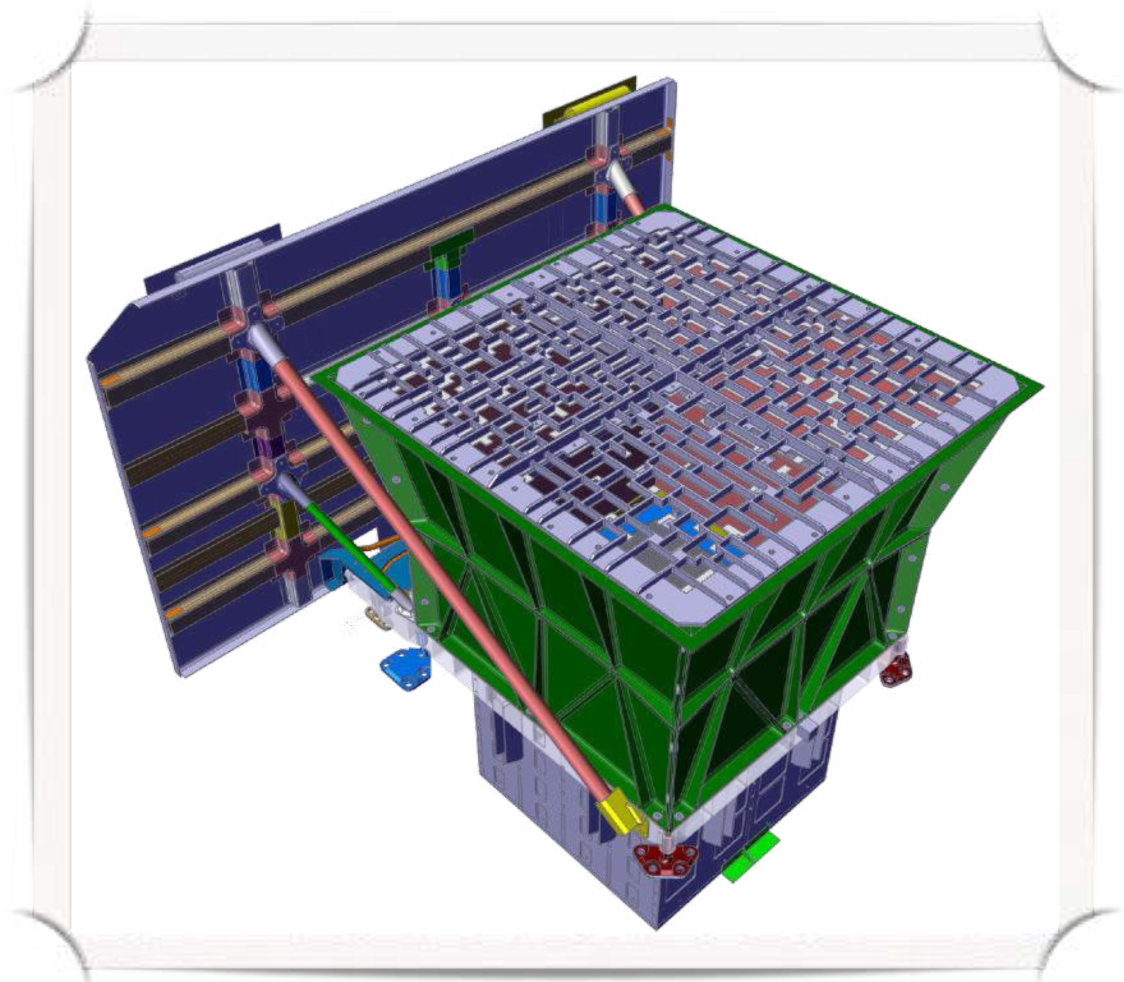
SVOM core program





GRB091020: simulation for prompt and afterglow emissions

SVOM / ECLAIRs

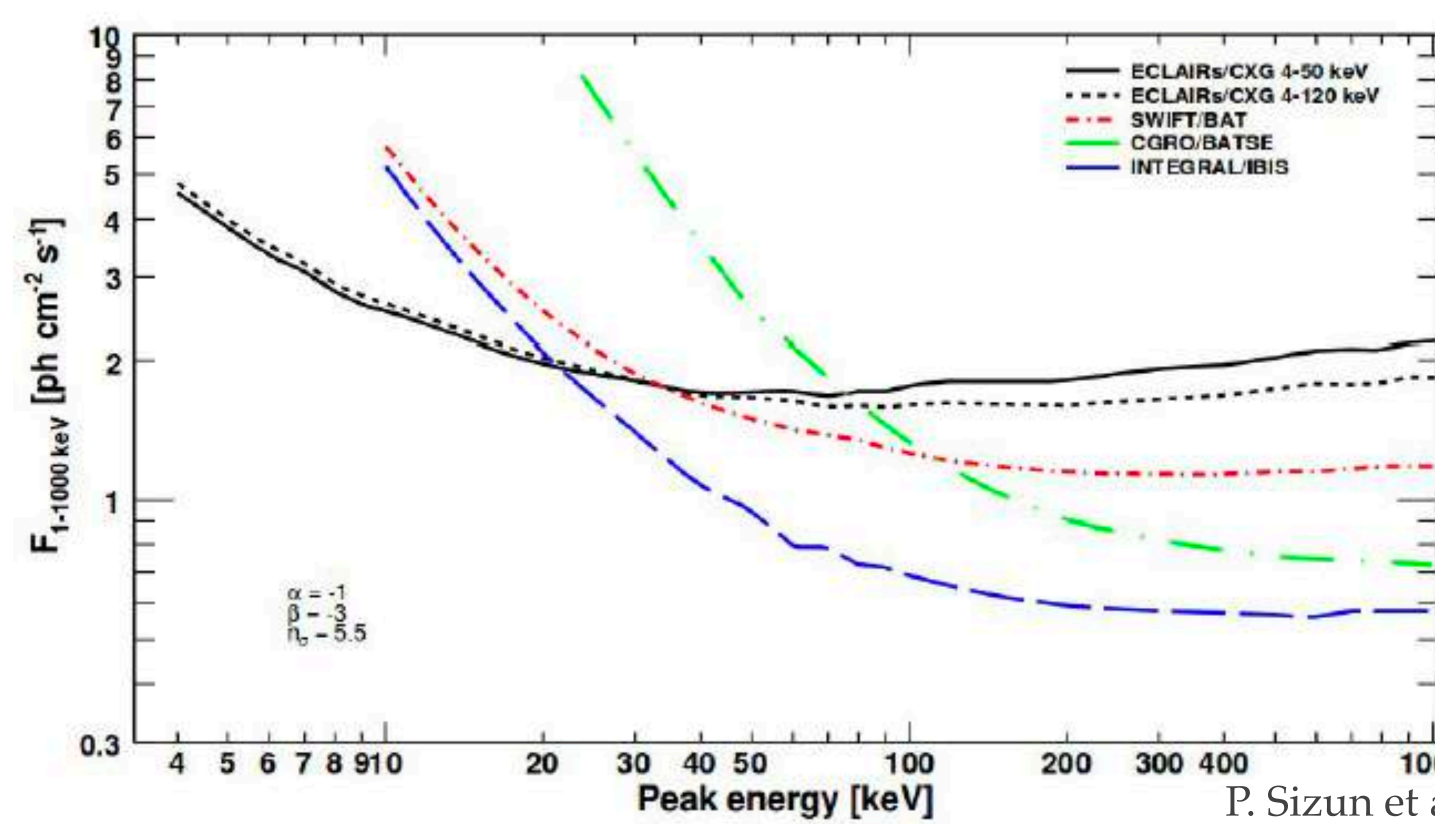


Well adapted for the detection of low-Epeak GRBs

Focalization of X rays not possible at these energies + large field of view ⇒ coded-mask imaging !

ECLAIRs (CNES, IRAP, CEA, APC)

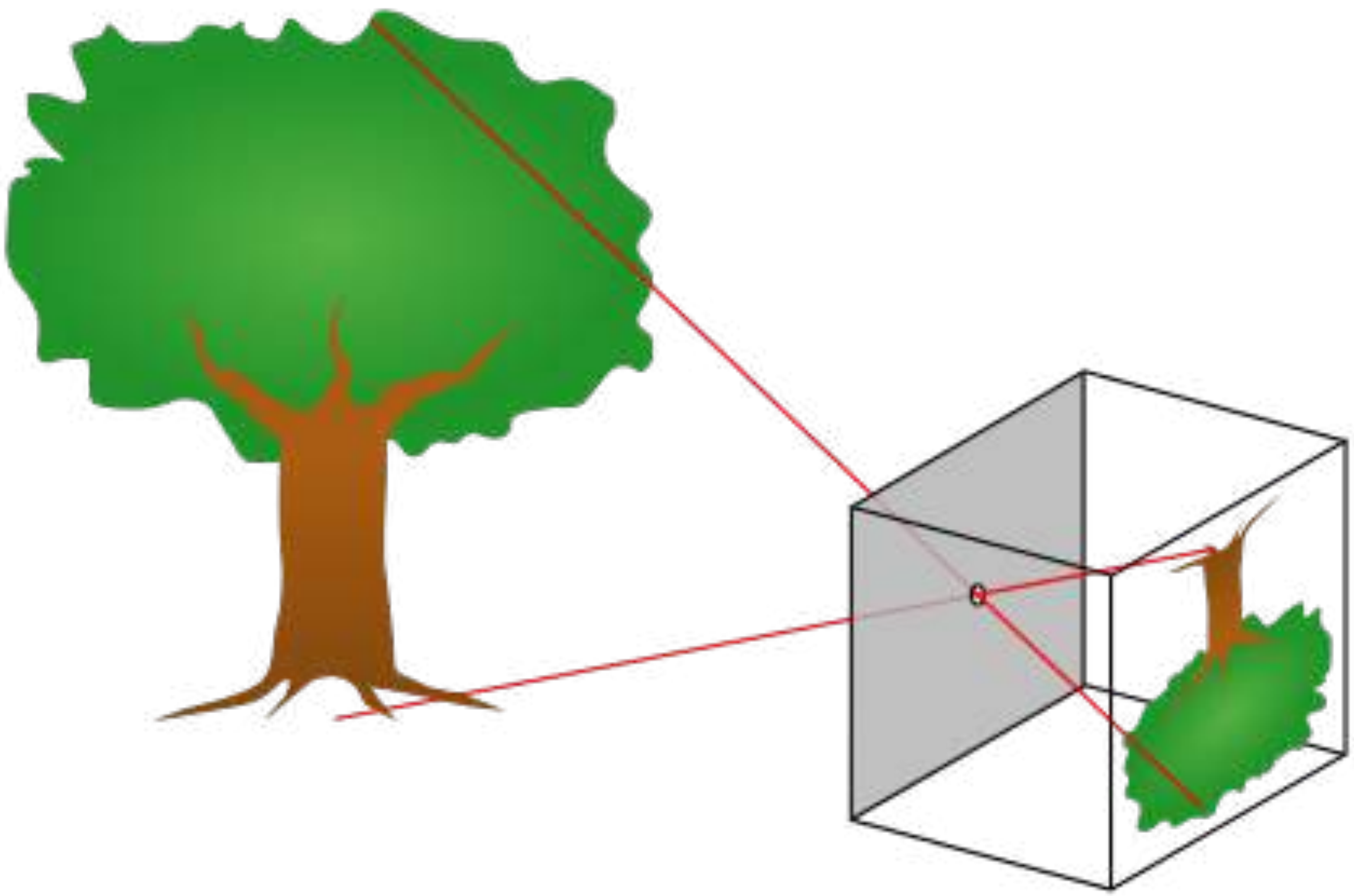
- Detection plane: **1024 cm²**
- **6400 CdTe pixels** (4x4x1 mm3)
- **FoV : 2 sr**
- **Energy range: 4-150 keV**
- **Localisation** accuracy **<12'** for 90% of the sources at detection limit
- Onboard trigger and localization: about **65 GRBs/year**



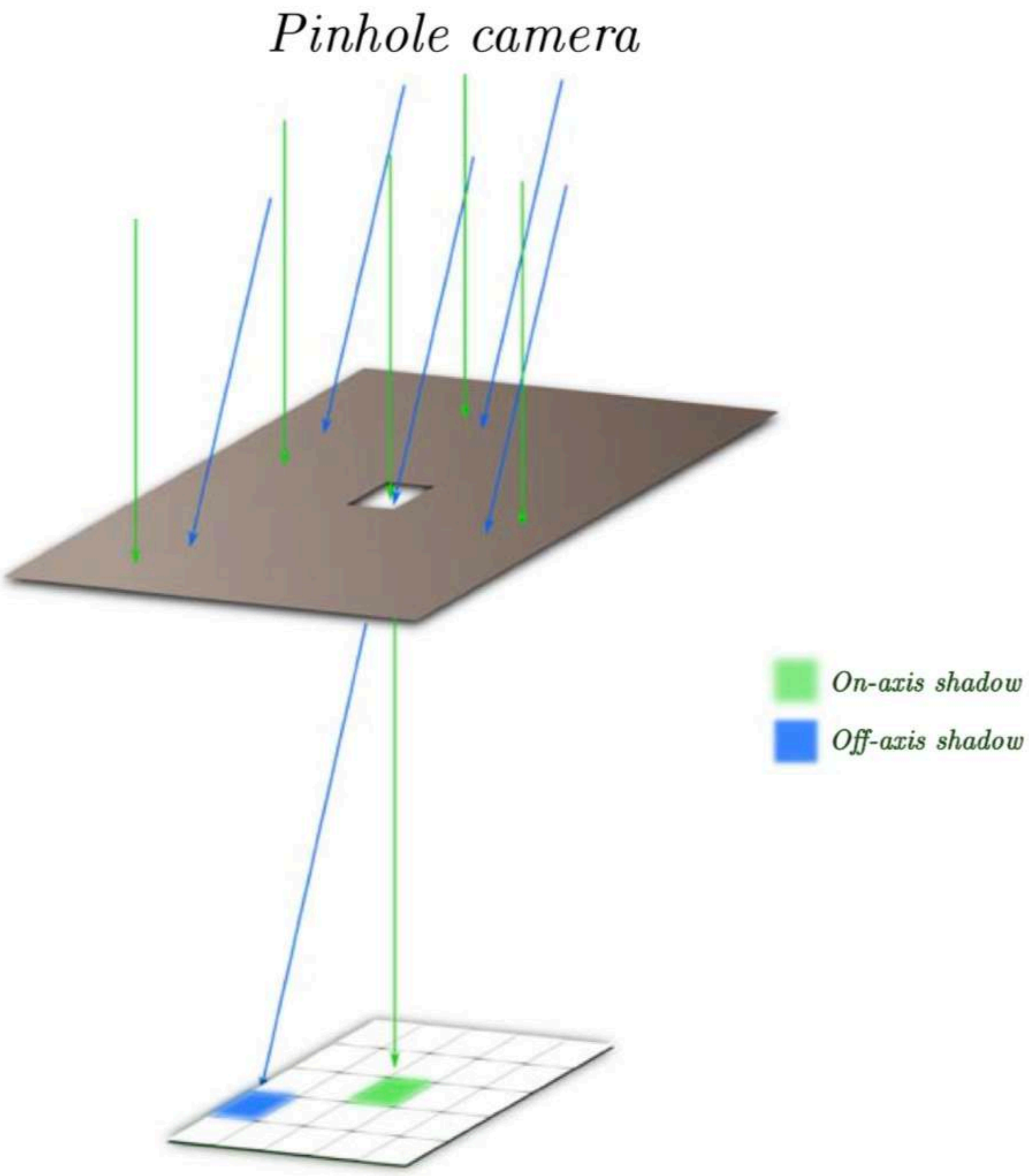
P. Sizun et al.

Pinhole camera

- Simple camera without a lens but with a tiny aperture.
- Light from a scene passes through the aperture and projects an inverted image on the opposite side of the box.

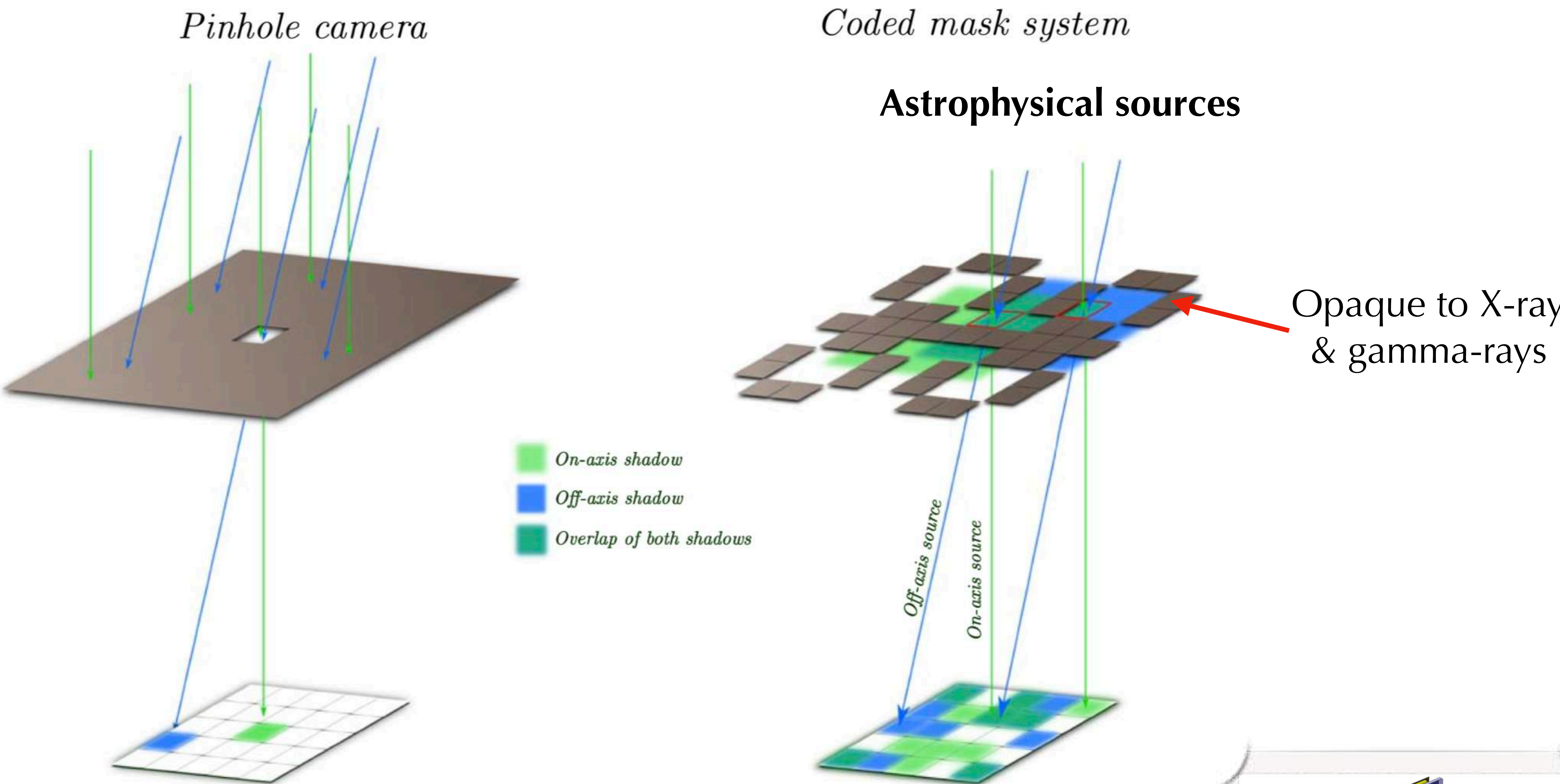


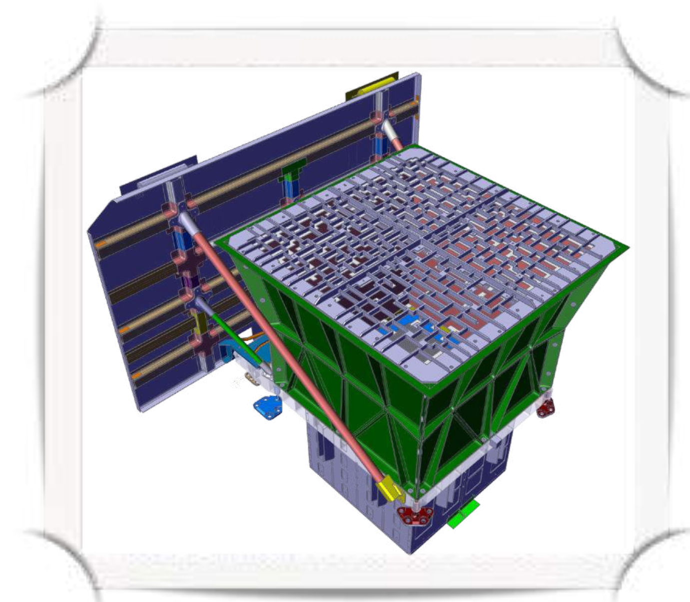
SVOM / ECLAIRs coded mask



Single hole = not sensitive enough

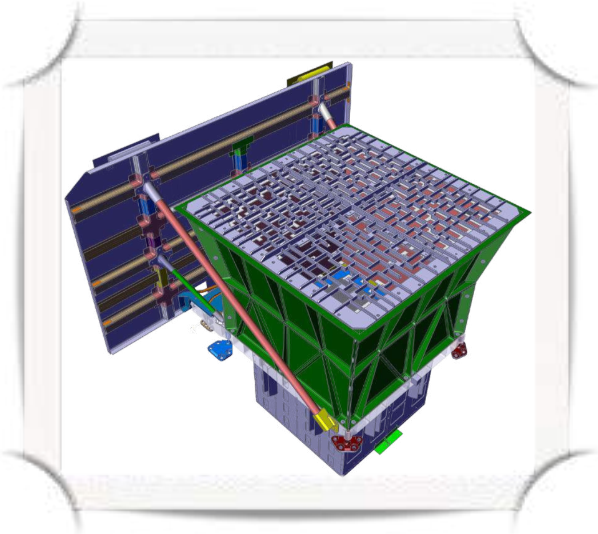
SVOM / ECLAIRs coded mask

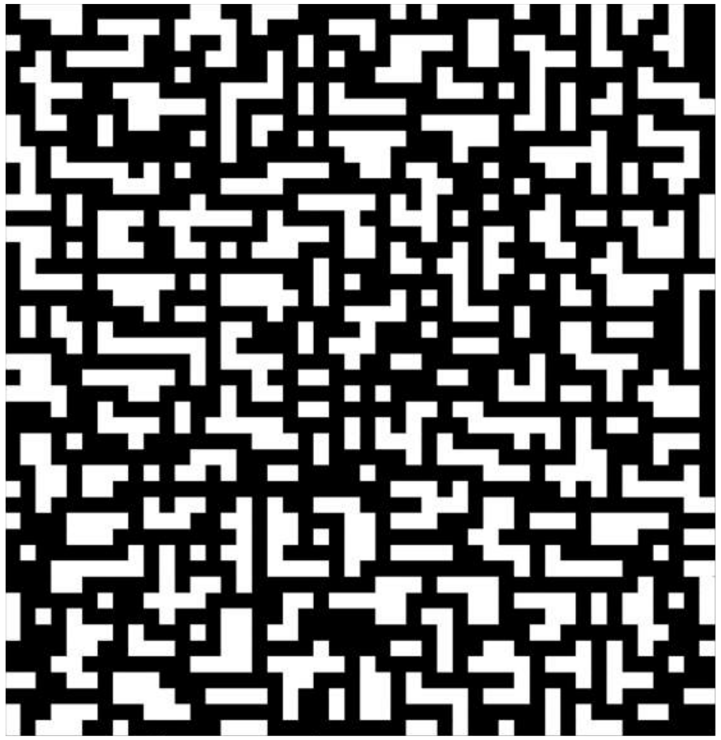




- **Coded mask between sources and detection plan.**
- **Shadow pattern of mask (opaque to X-rays) projected on the detector.**
- **One specific pattern for each source on the detector.**

SVOM / ECLAIRs coded mask





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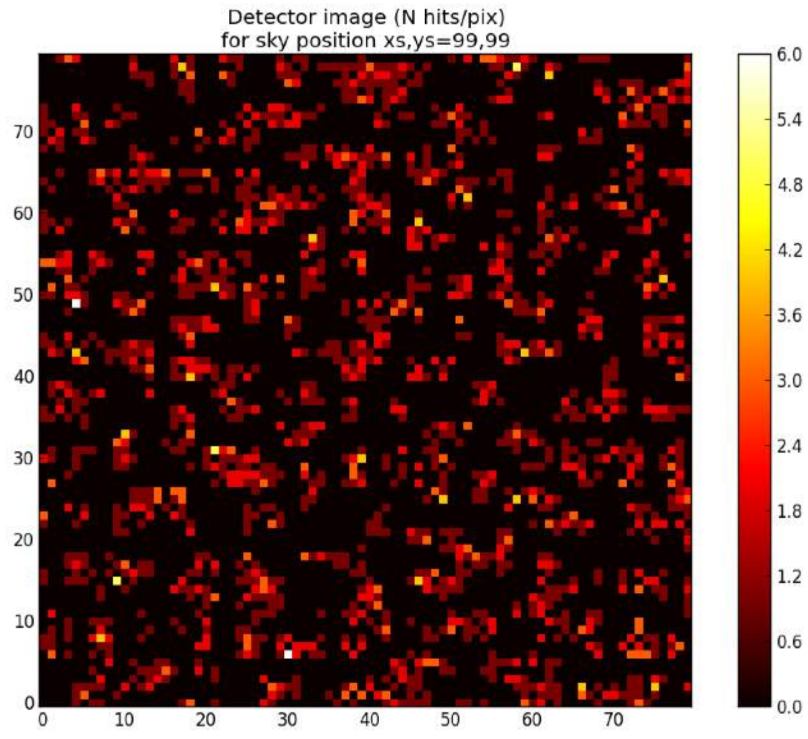
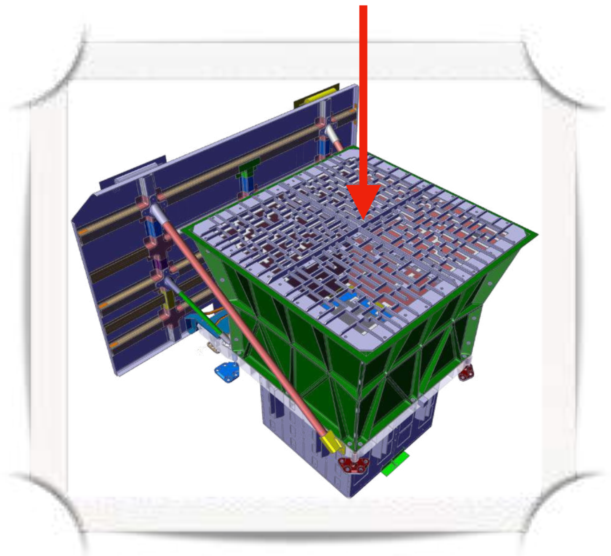
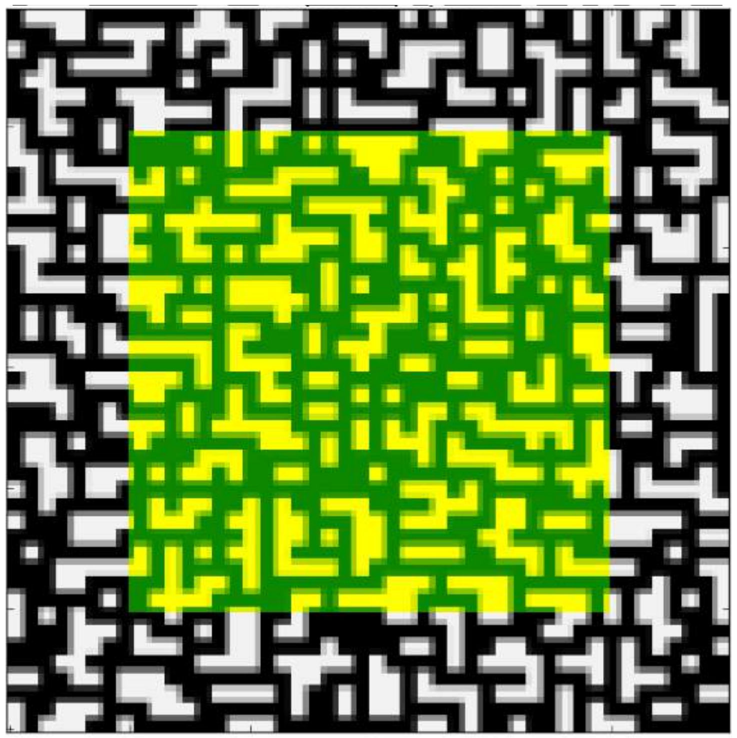
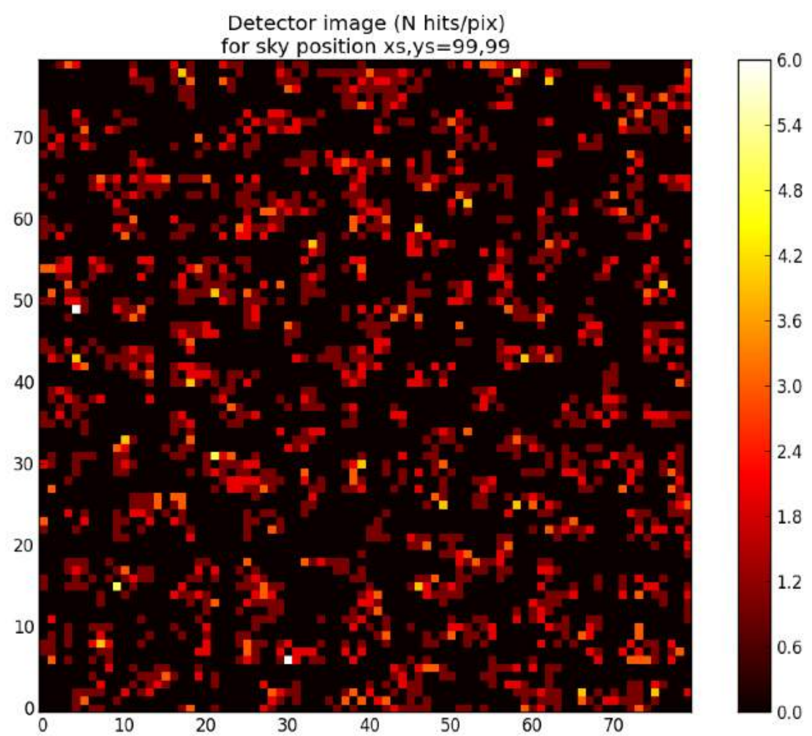
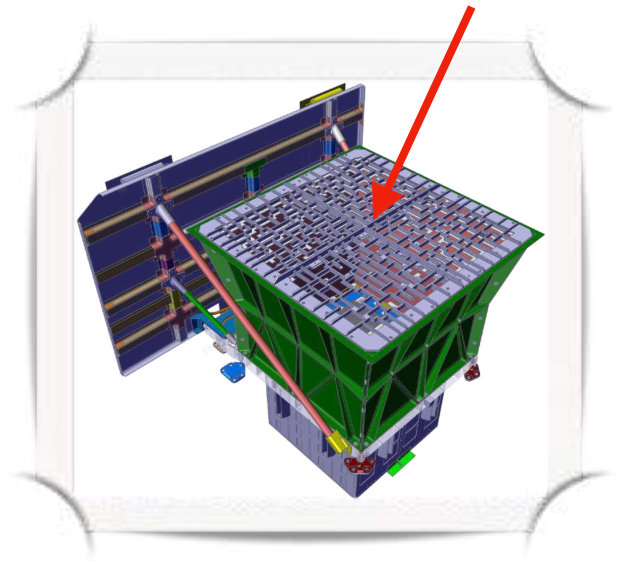


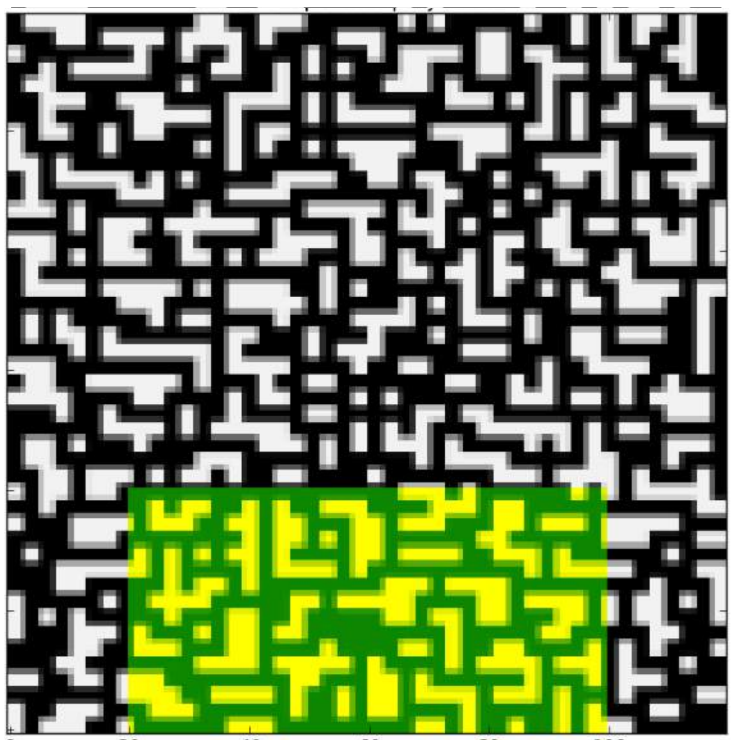


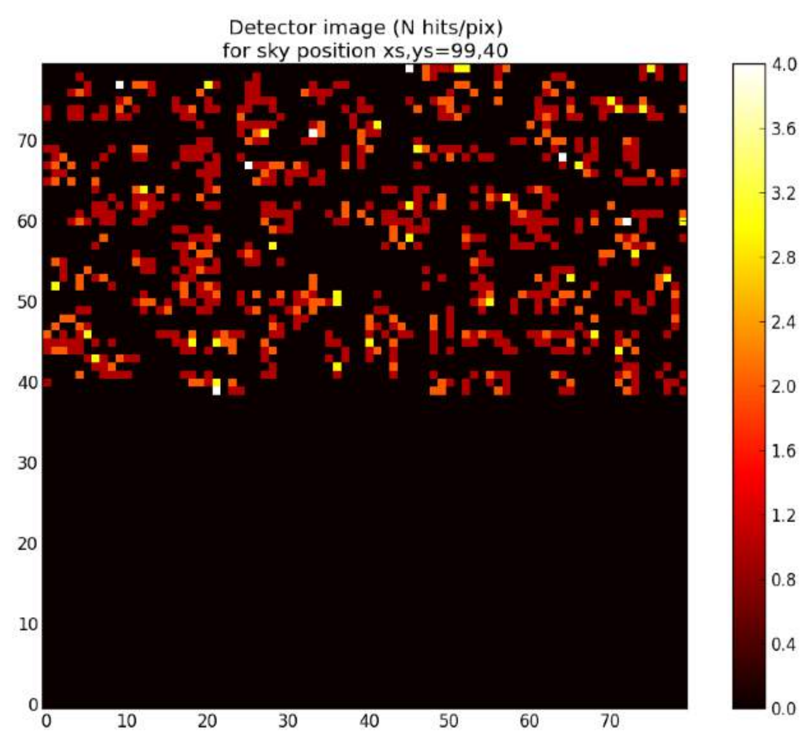


SVOM / ECLAIRs coded mask

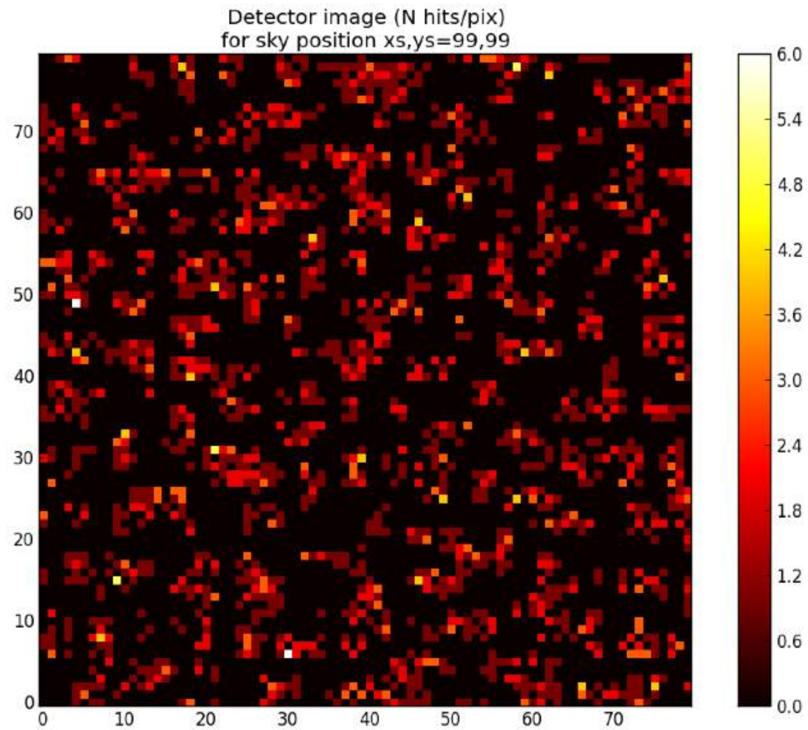


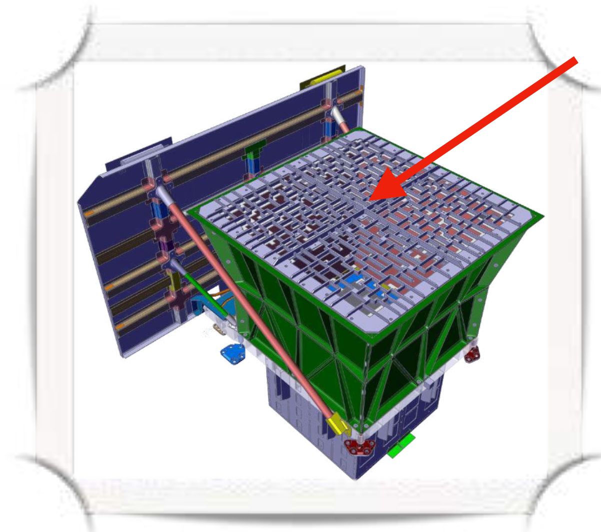


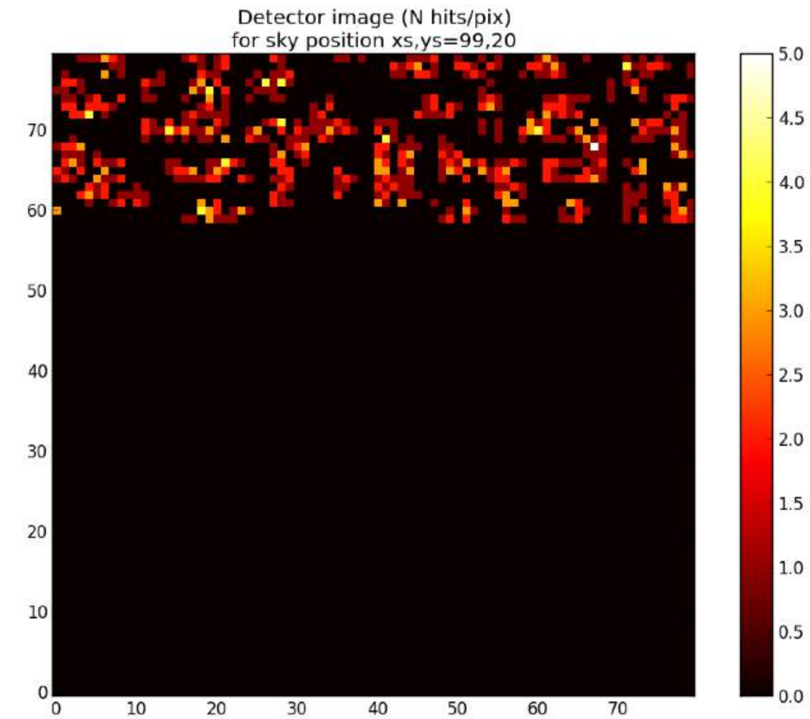


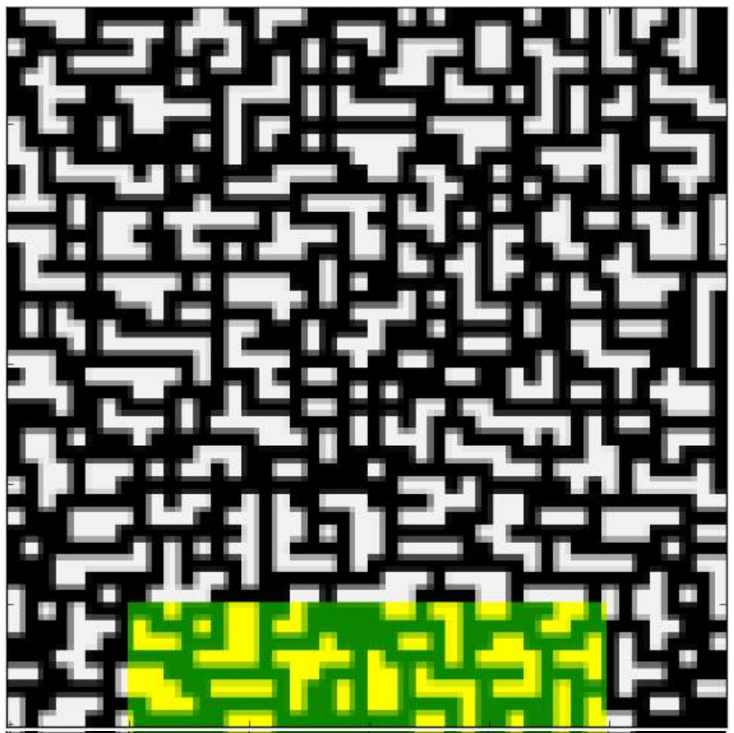


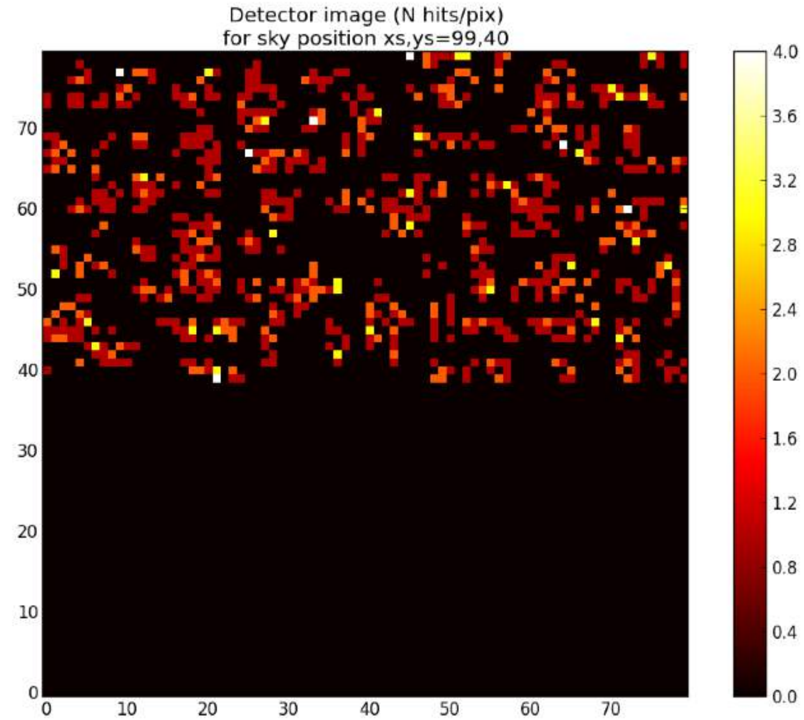
SVOM / ECLAIRs coded mask



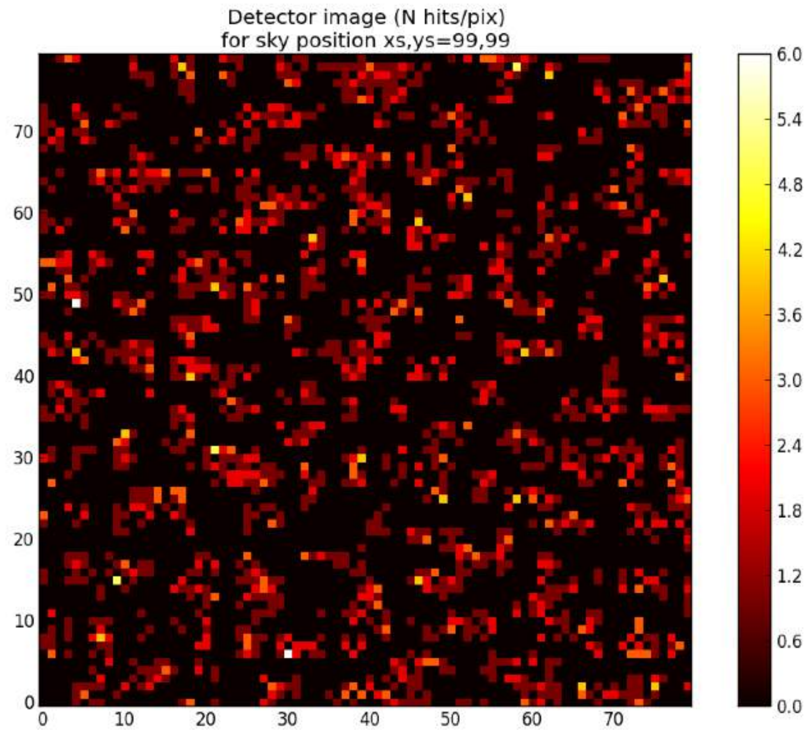


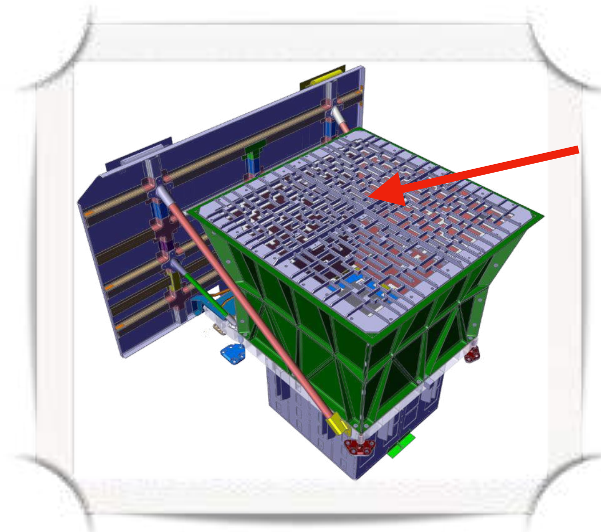


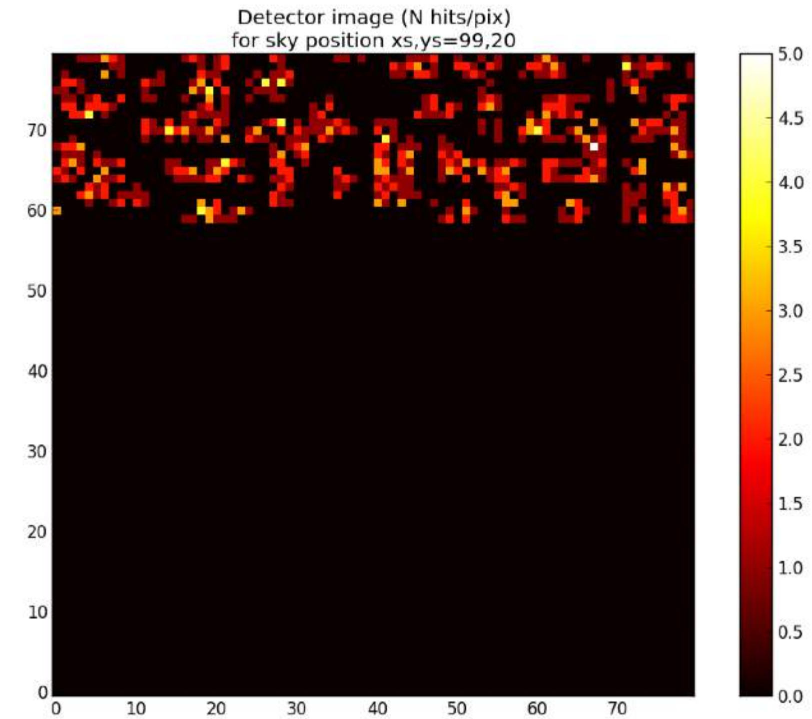


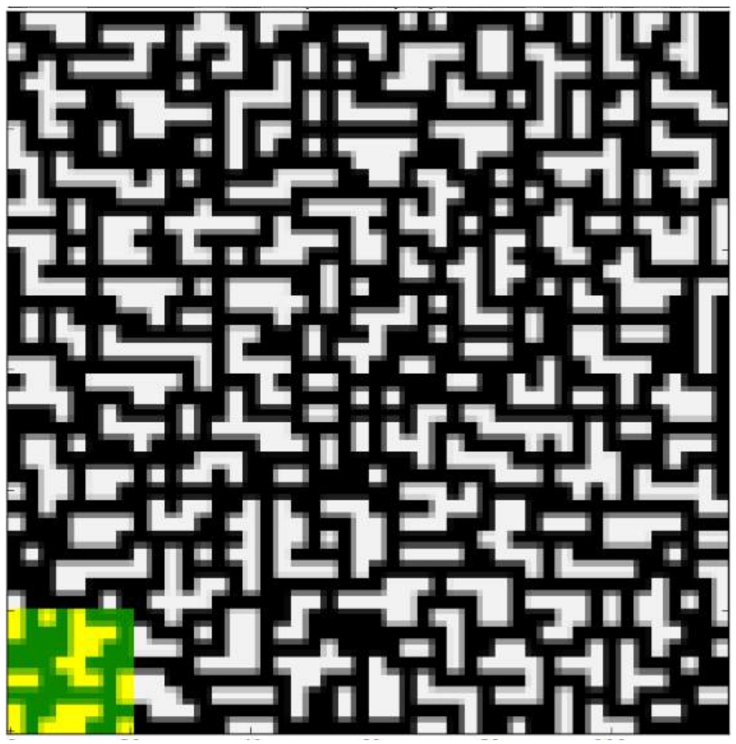


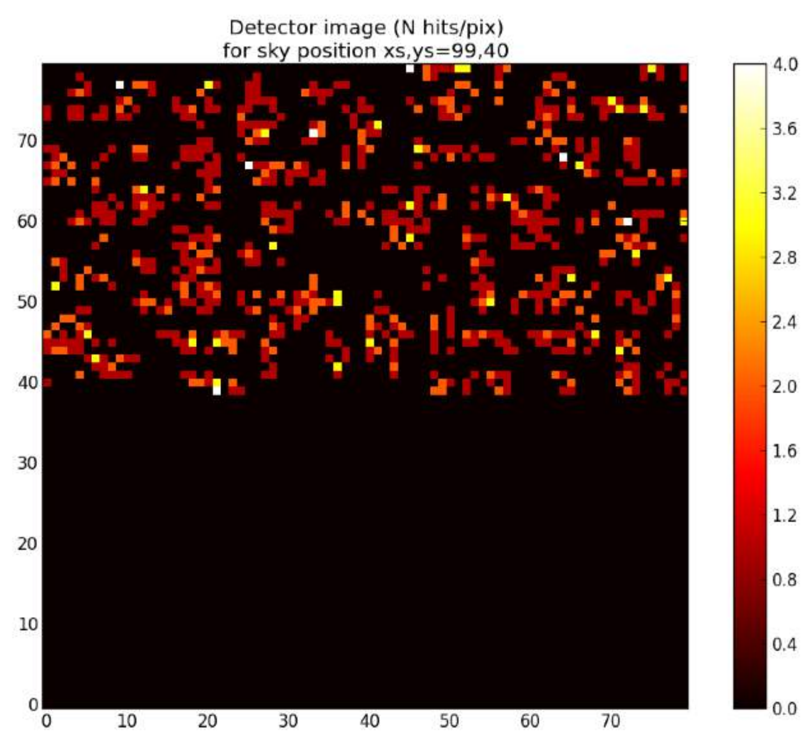
SVOM / ECLAIRs coded mask

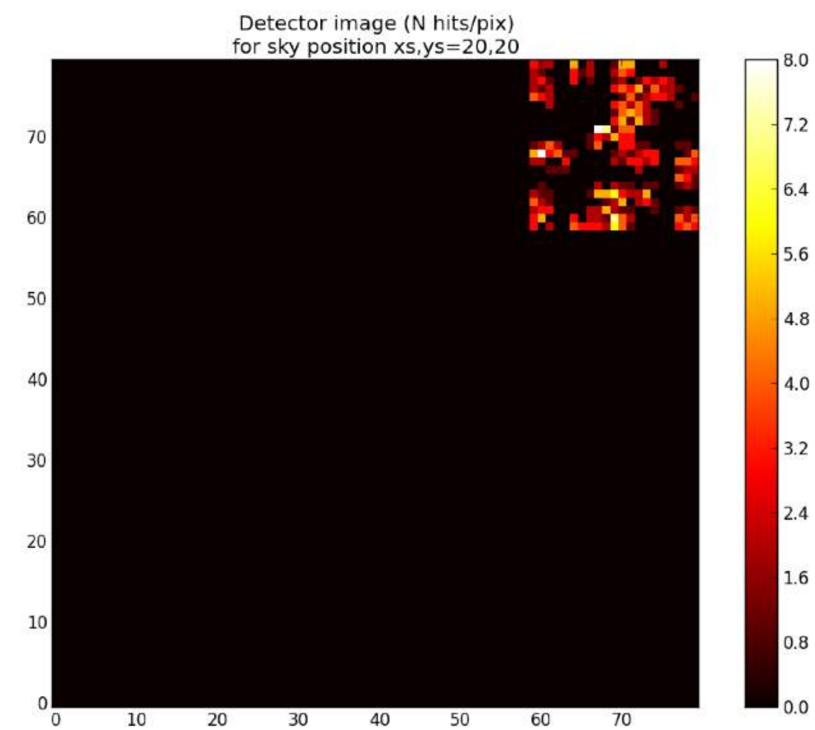






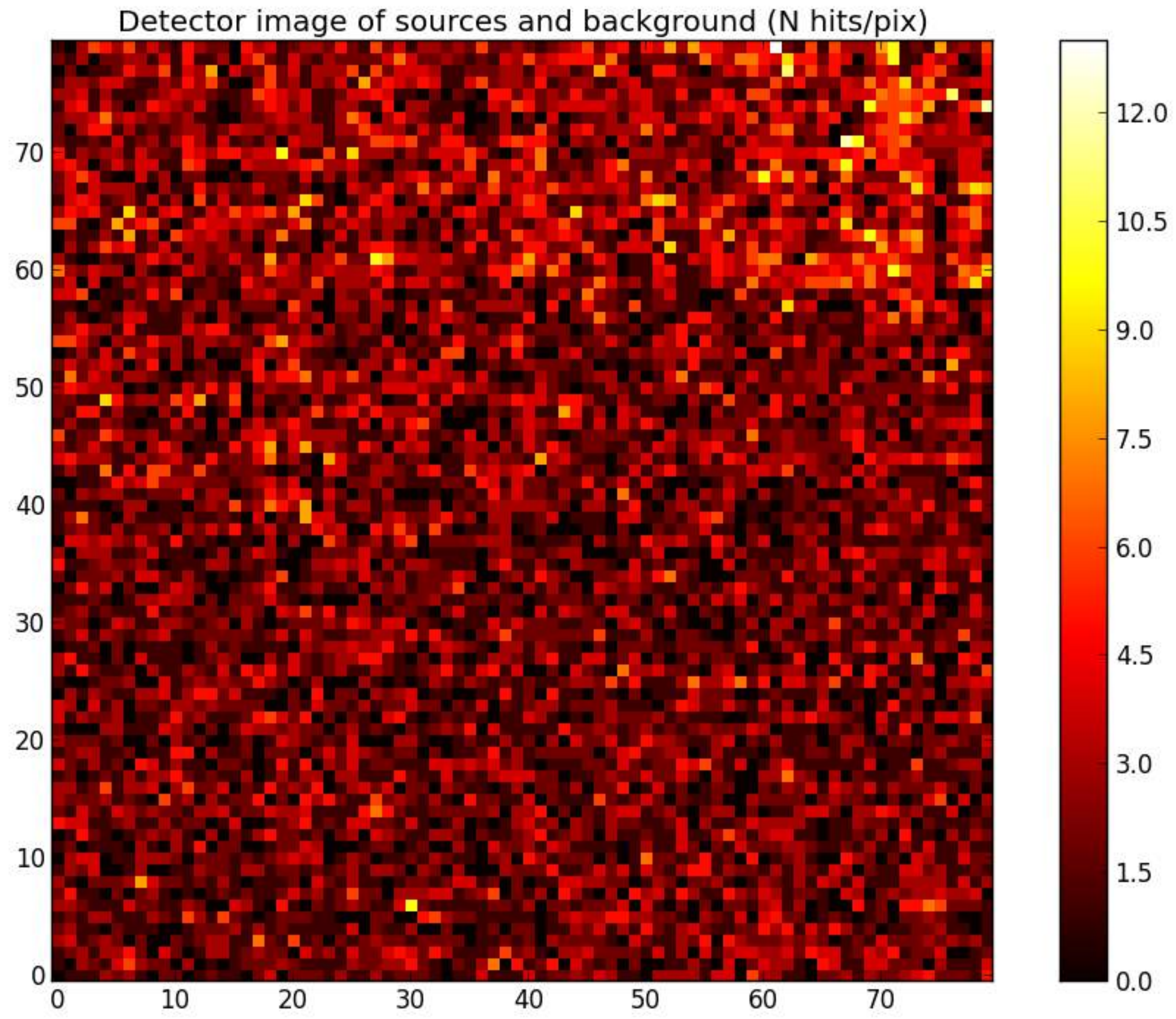






SVOM / ECLAIRs coded mask

Sum of all the sources + background detected events:



SVOM / ECLAIRs coded mask

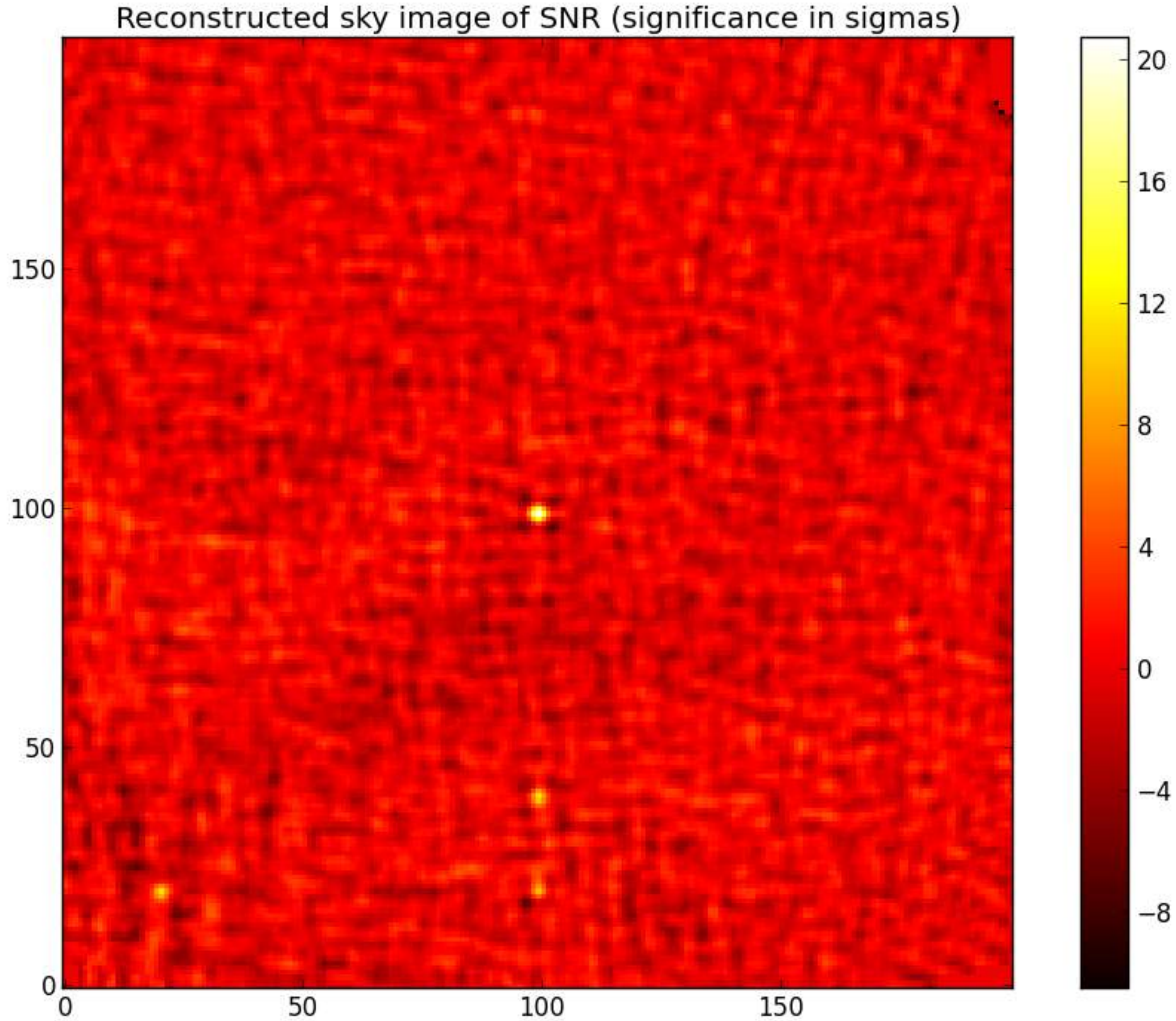
Deconvolution algorithm to reconstruct the sky image:

Signal on the detector:
$$D = S \otimes M + B$$

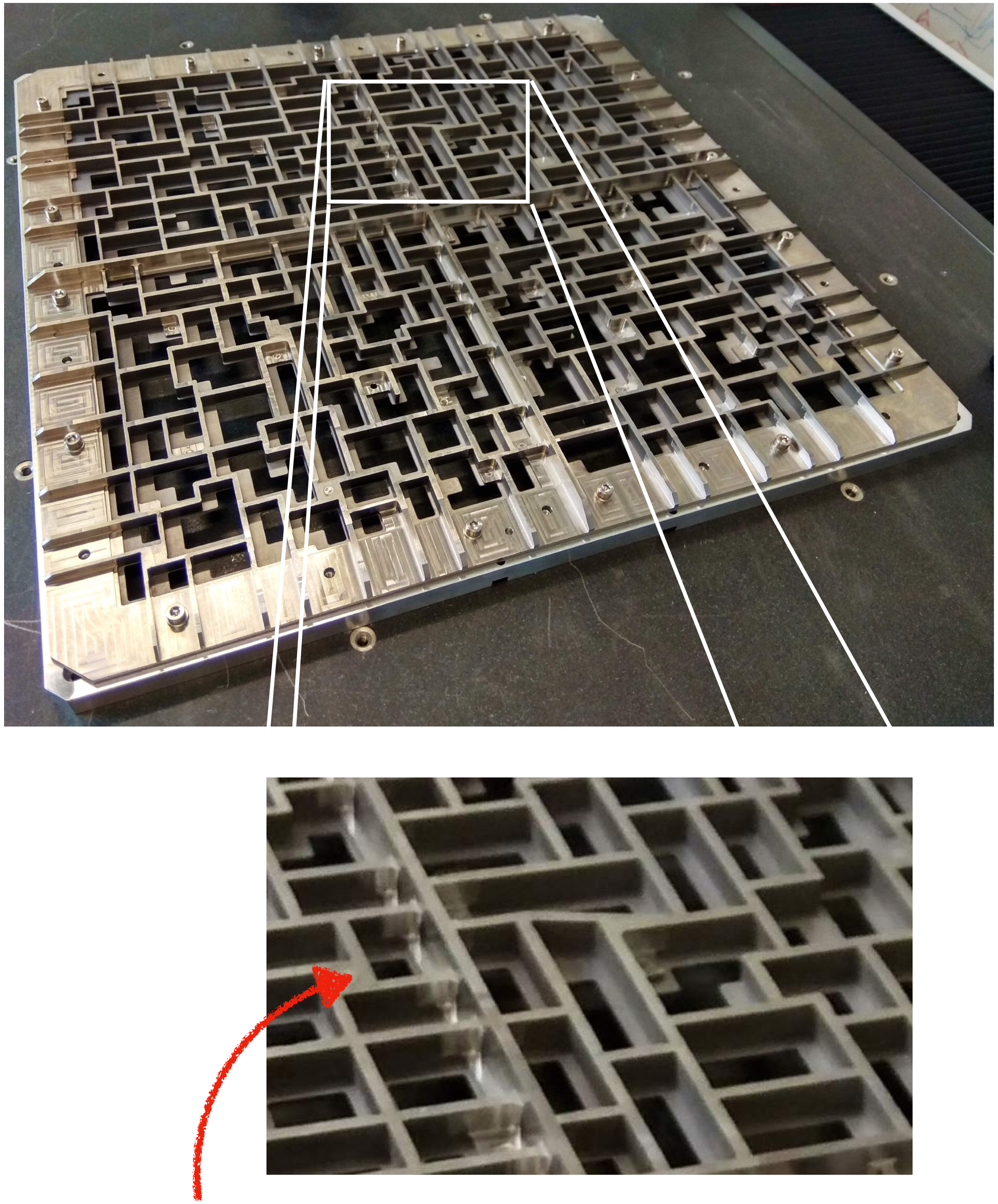
Sky image (S), Mask matrix (M), Background (B)

Sky reconstruction:
$$S' = S + B \otimes G$$

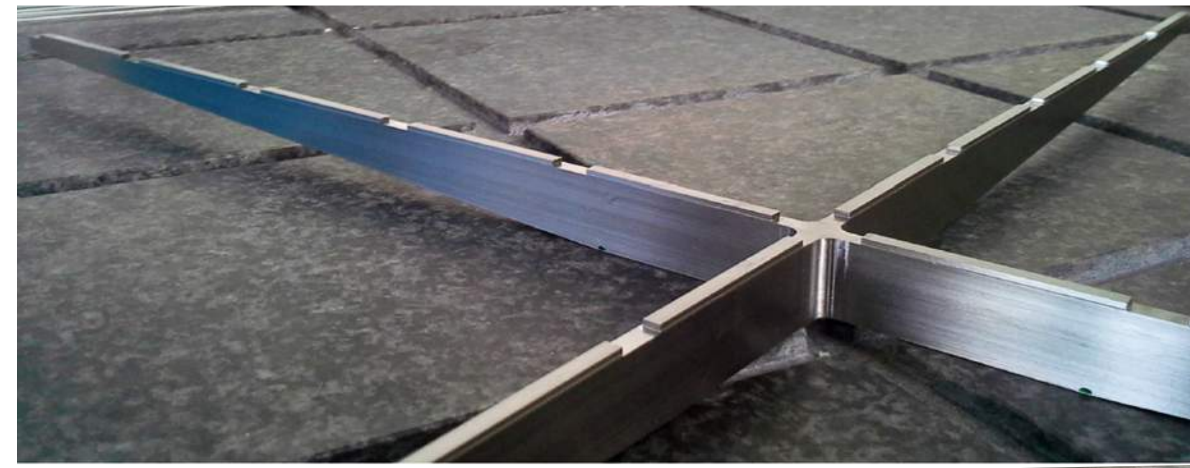
G as $M \otimes G = 1$

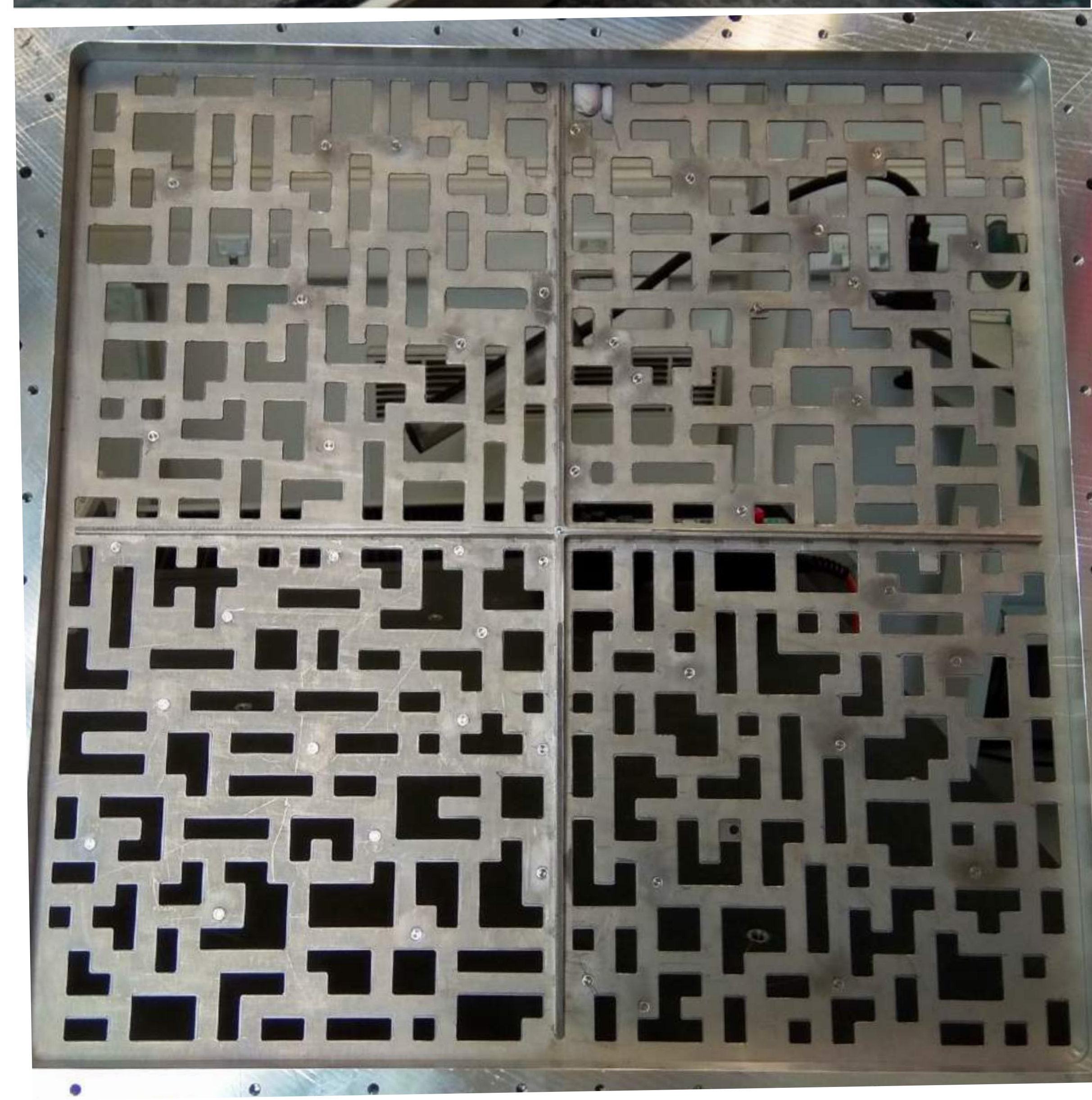


SVOM / ECLAIRs coded mask

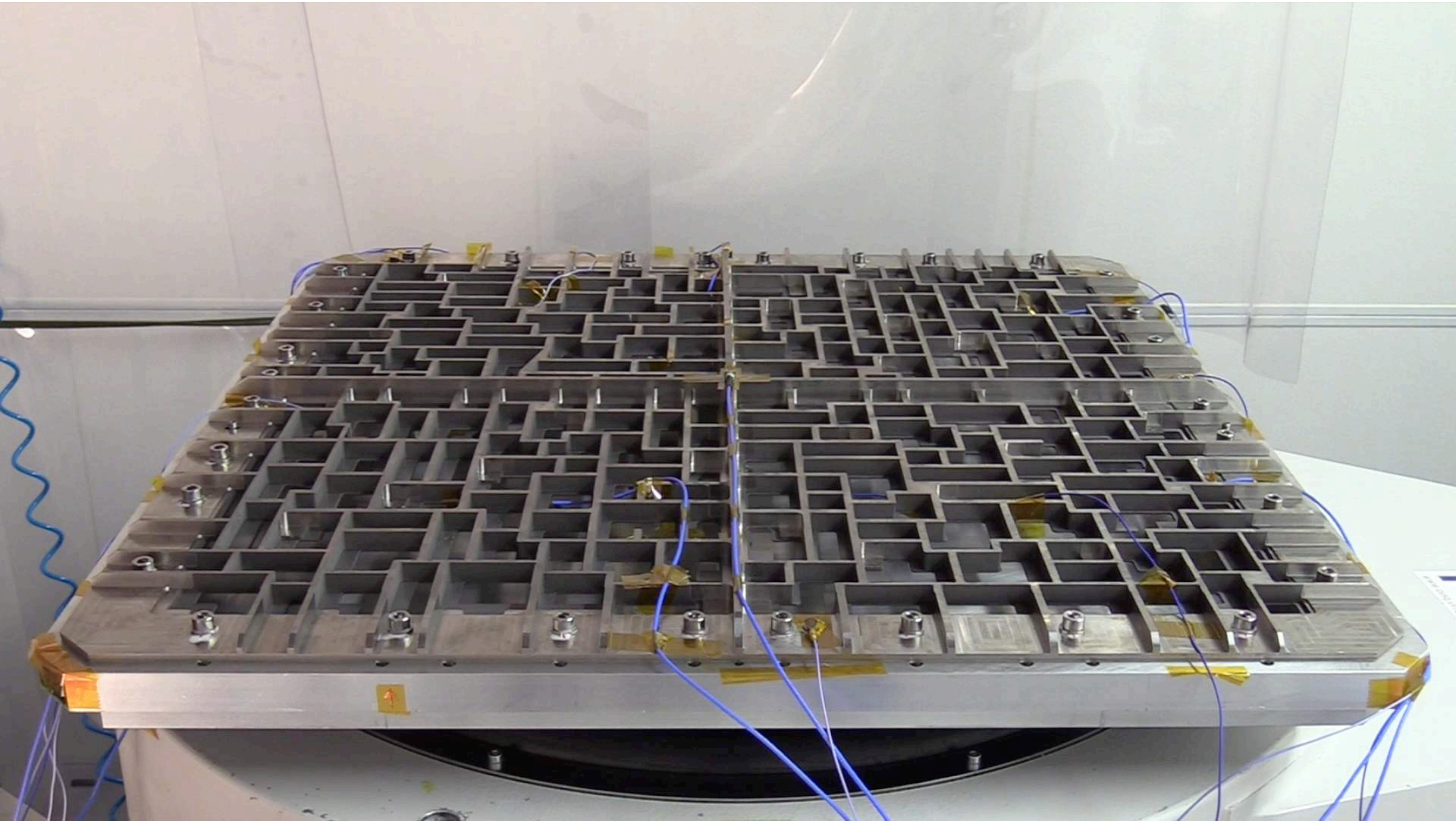


Tantalum opaque to X-ray/gamma-rays





SVOM / ECLAIRs coded mask



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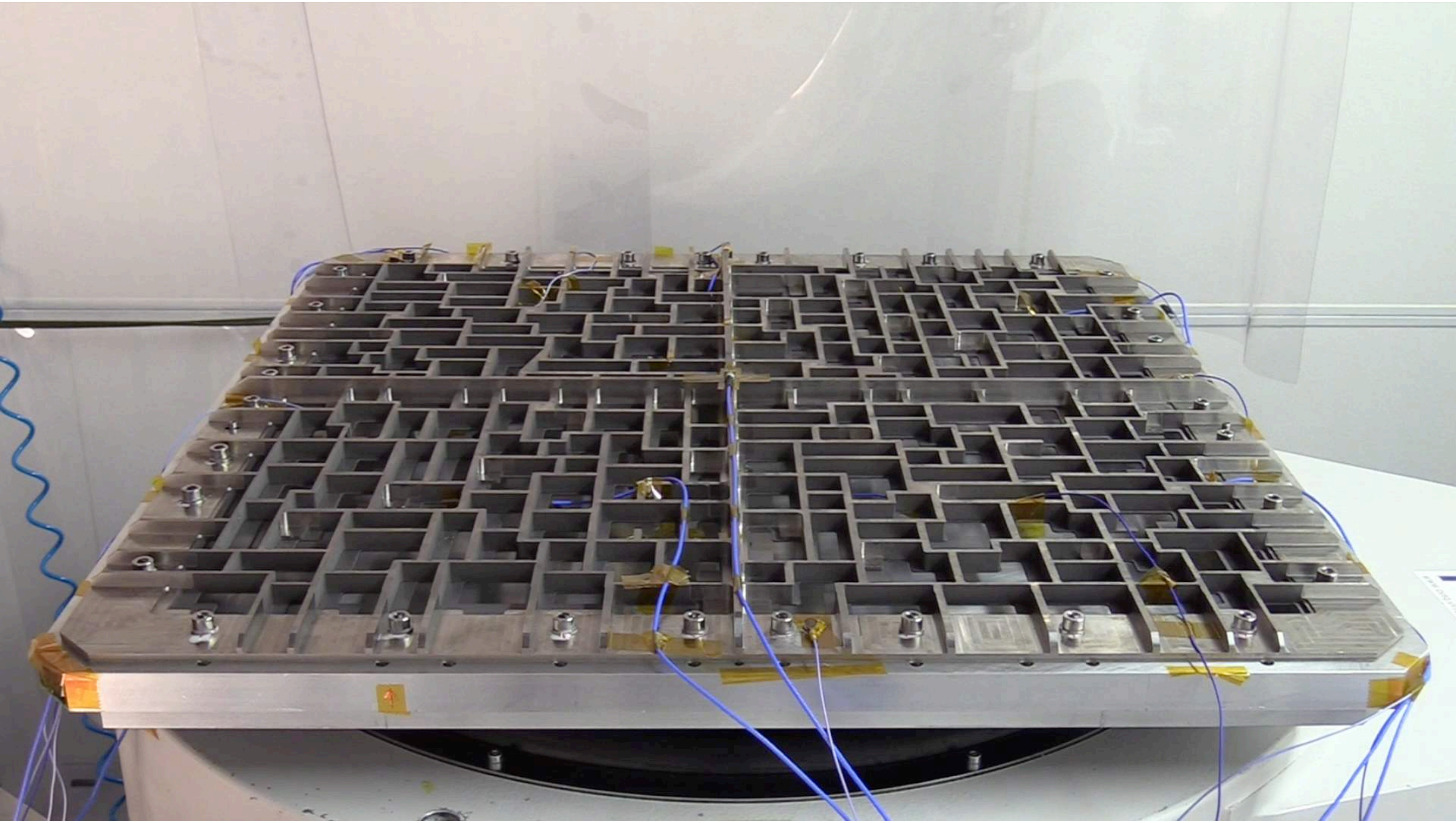
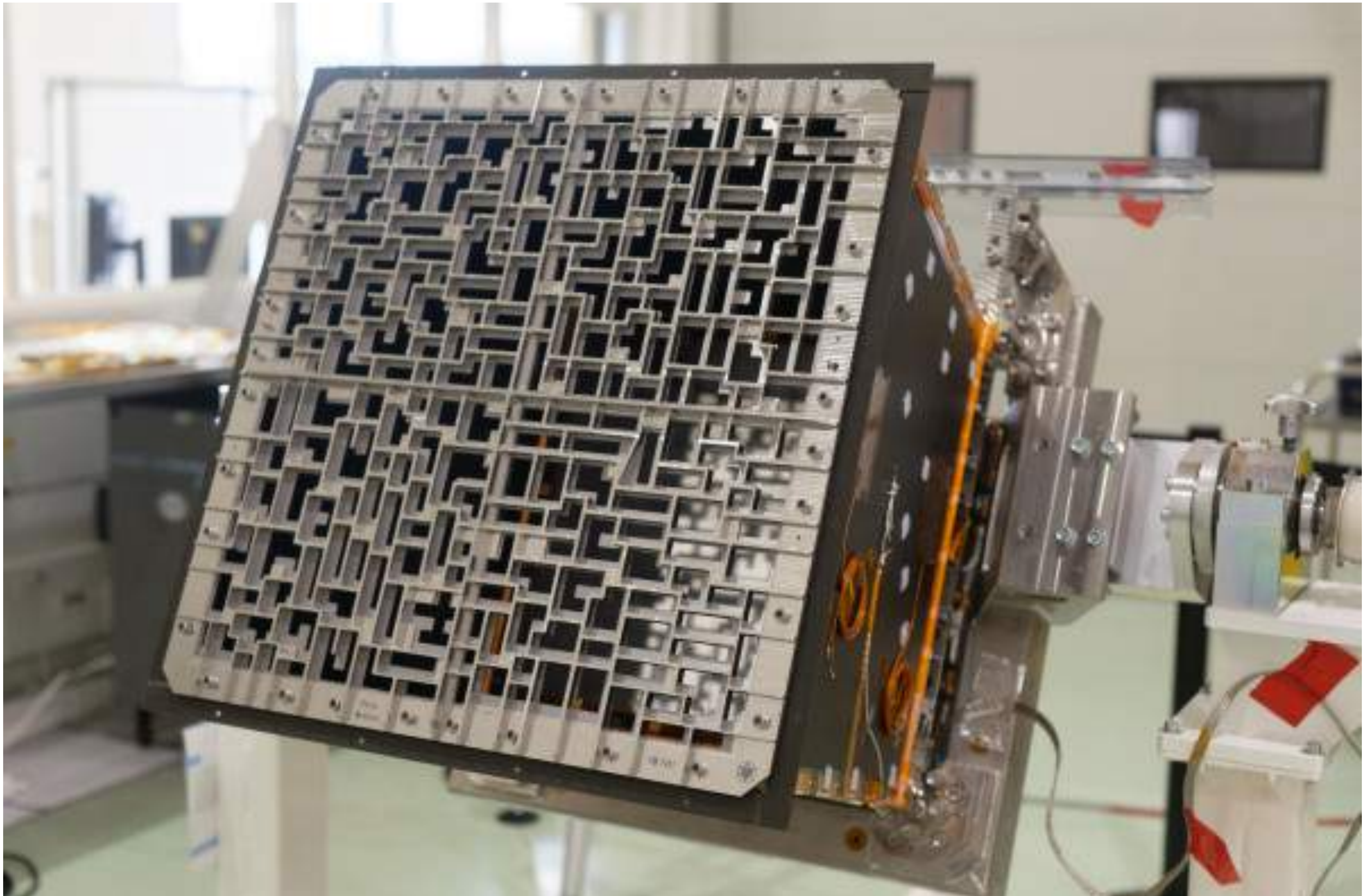


SVOM / ECLAIRs coded mask

ECLAIRs flight model integrated at CNES Toulouse (summer 2021)



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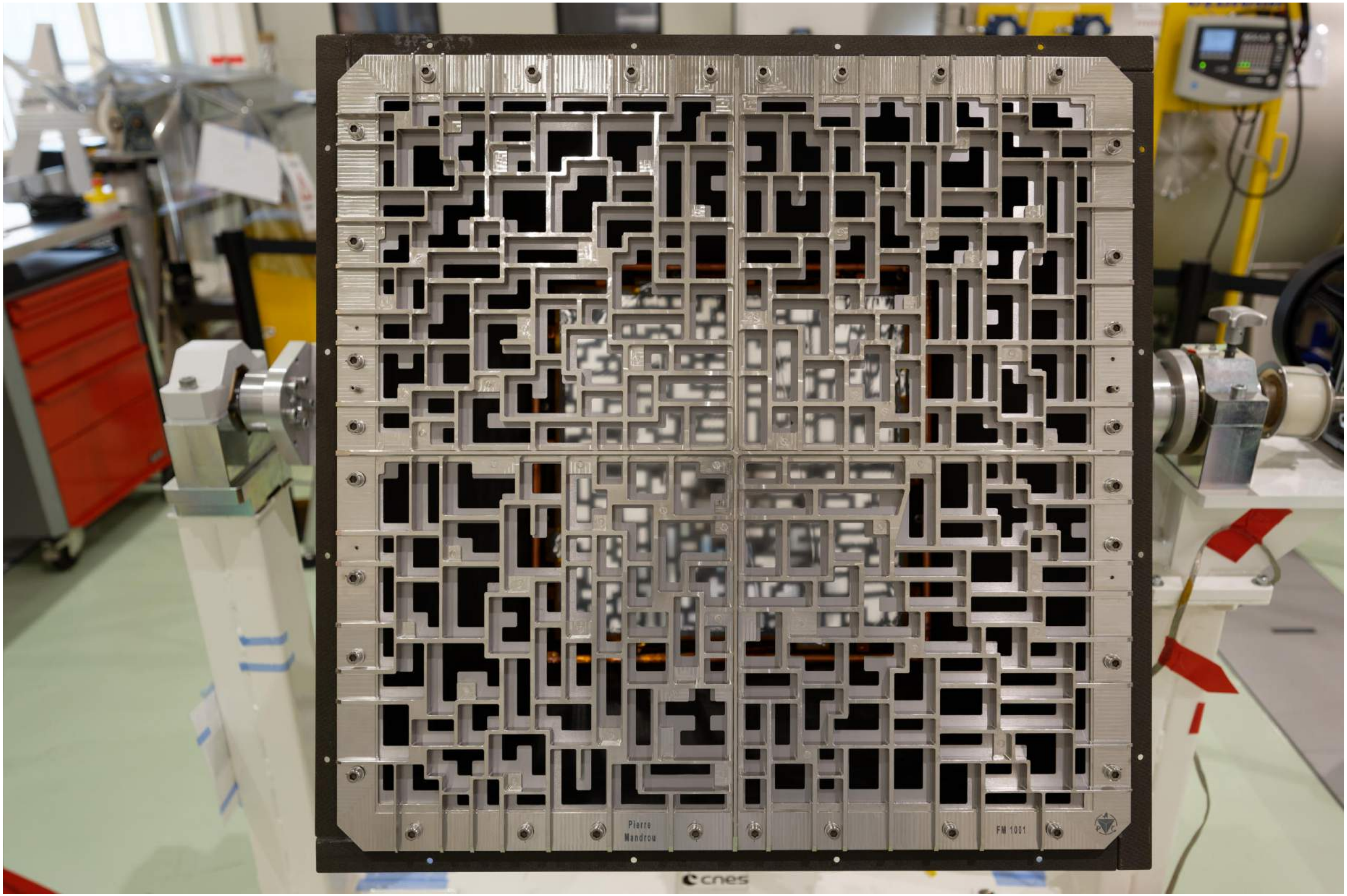

Outline - Lecture 3

C. Supermassive black holes

1. Supermassive black hole formation and evolution

2. Cosmic rays from Active Galactic Nuclei

3. Supermassive black hole binaries

Outline - Lecture 3

C. Supermassive black holes

1. Supermassive black hole formation and evolution
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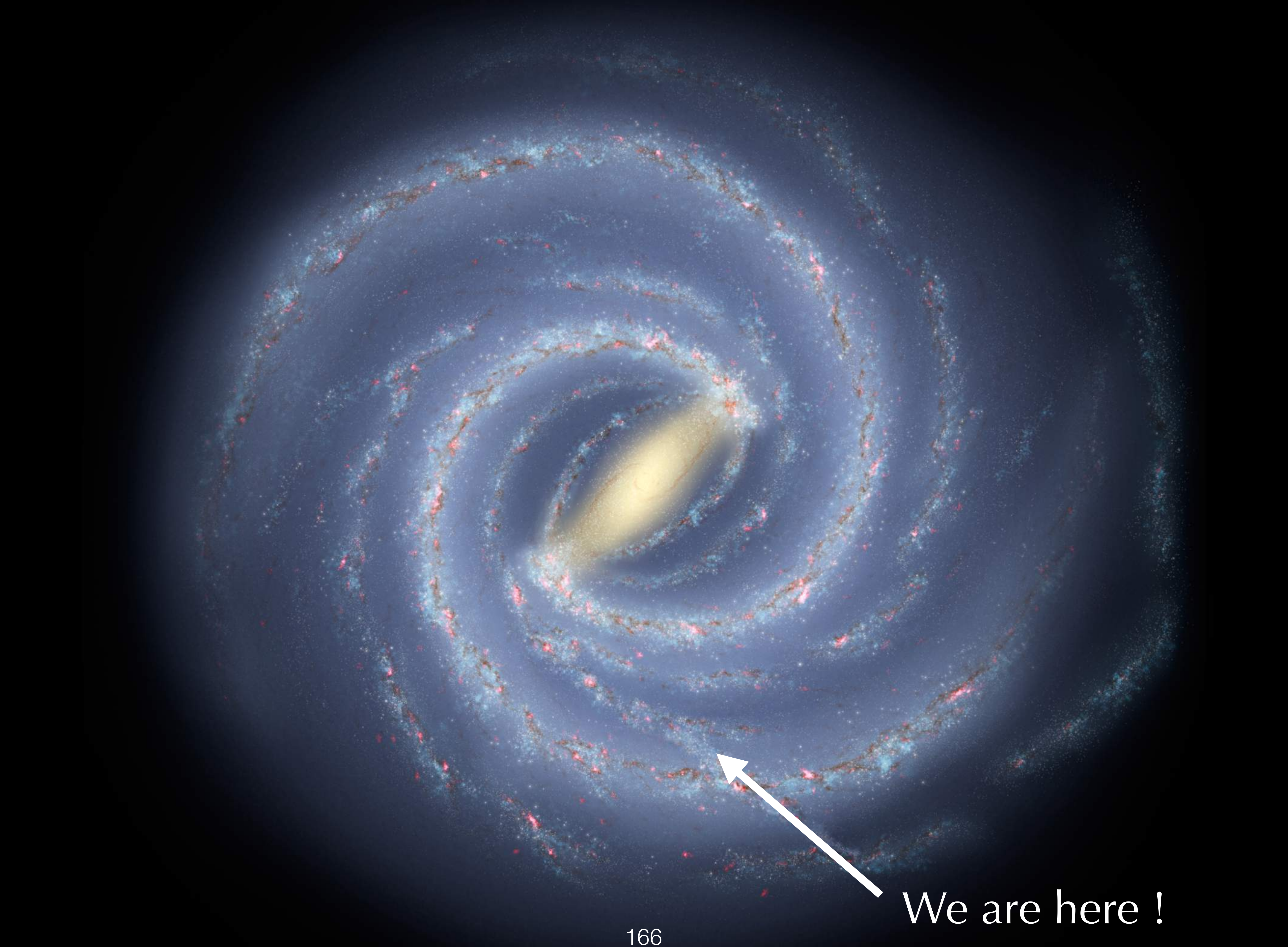
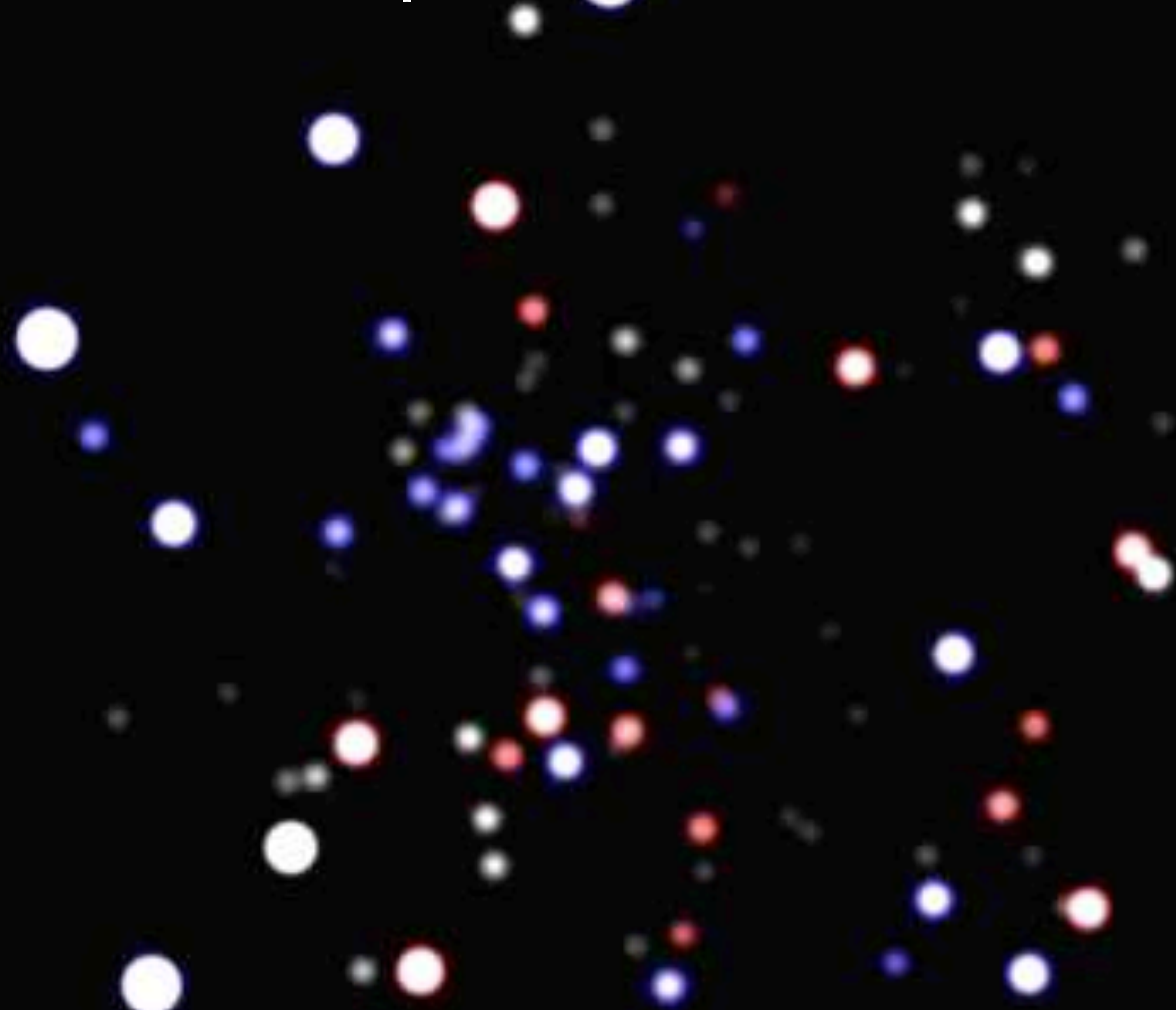
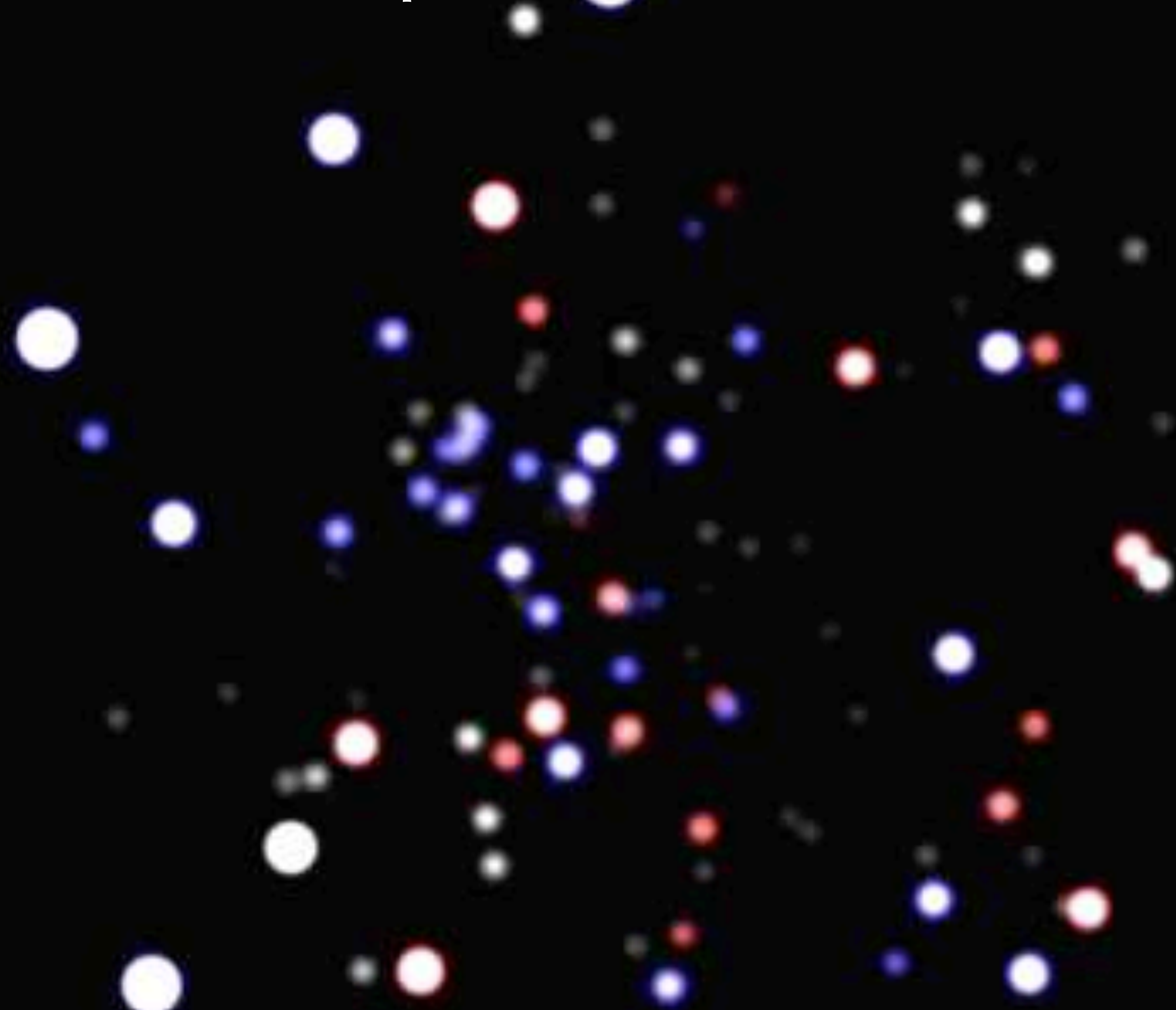

We are here !

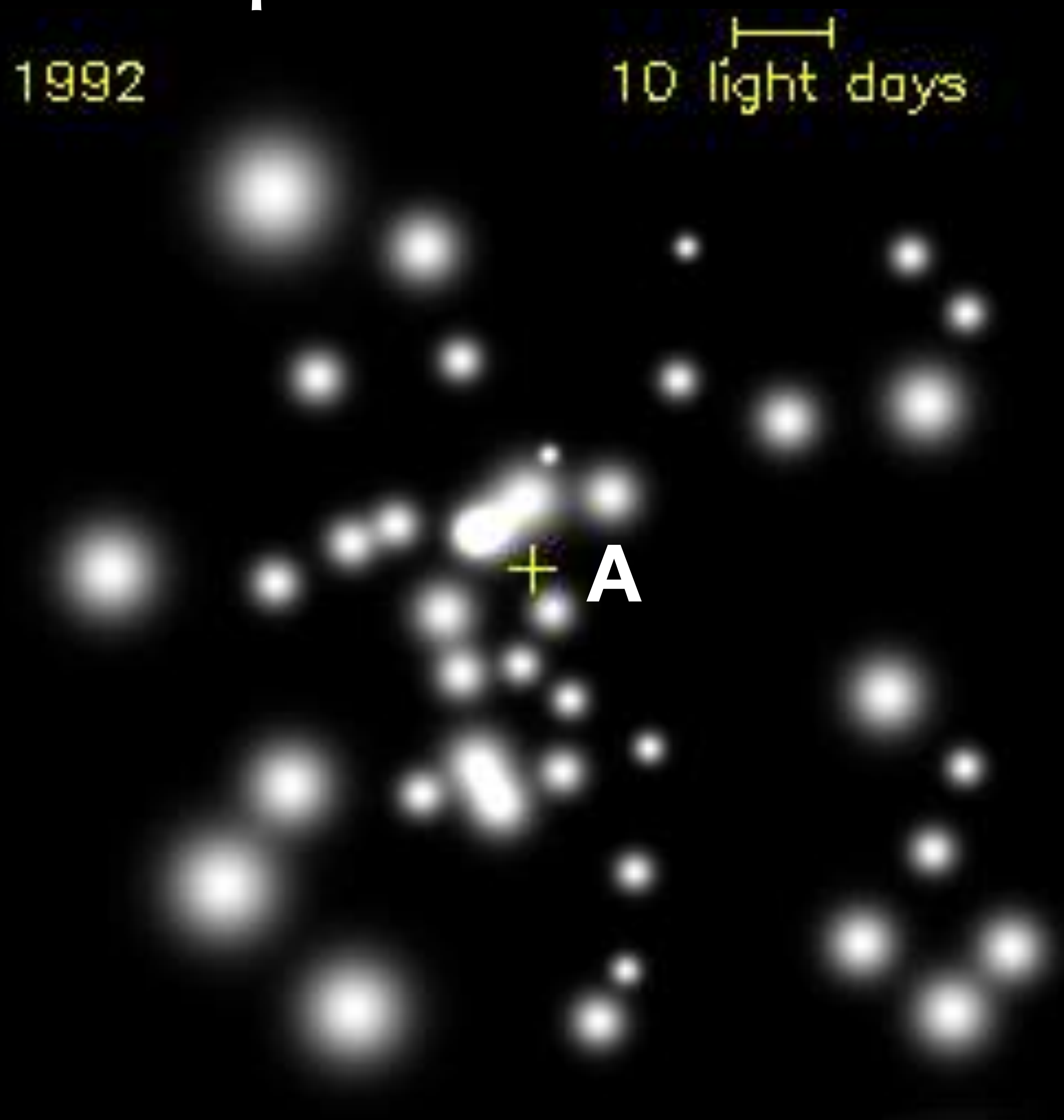
d= 2,4x10^{17} km ~ 8 kpc



d= $2{,}4 \times 10^{17}$ km ~ 8 kpc



d= 2,4x10[17] km ~ 8 kpc



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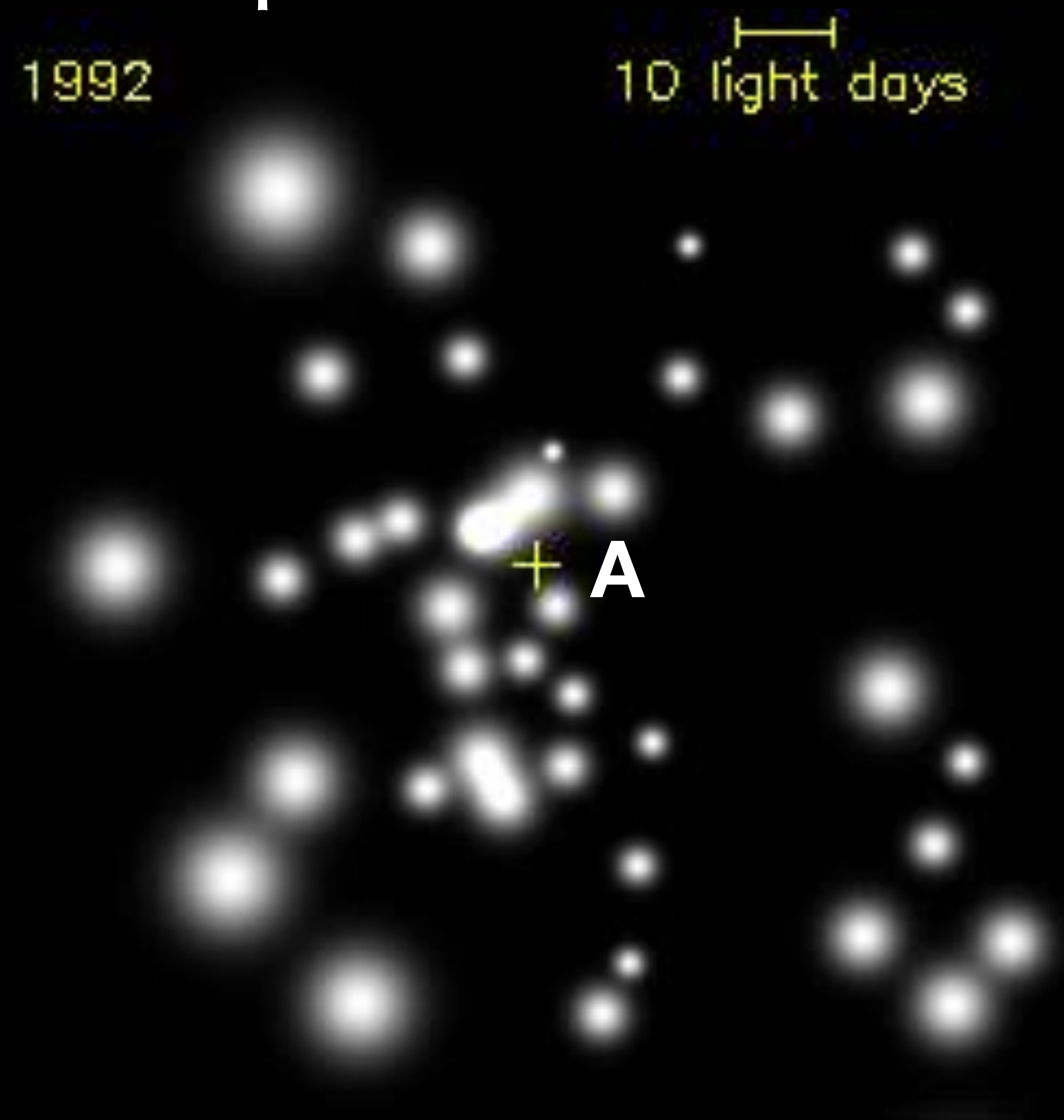
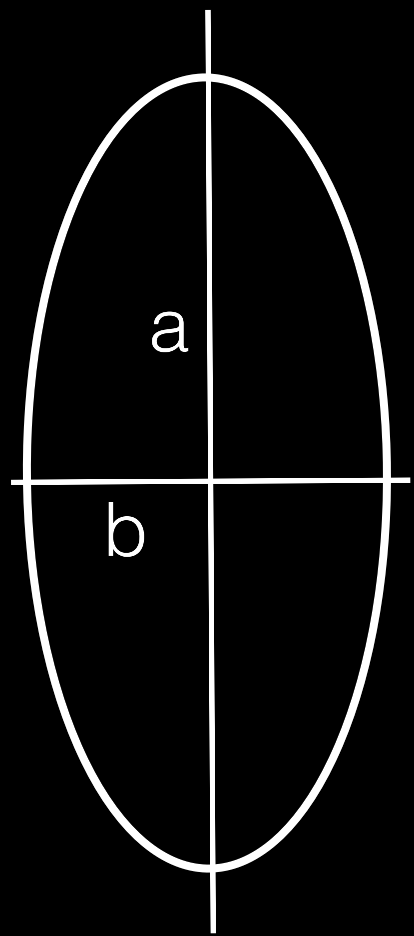
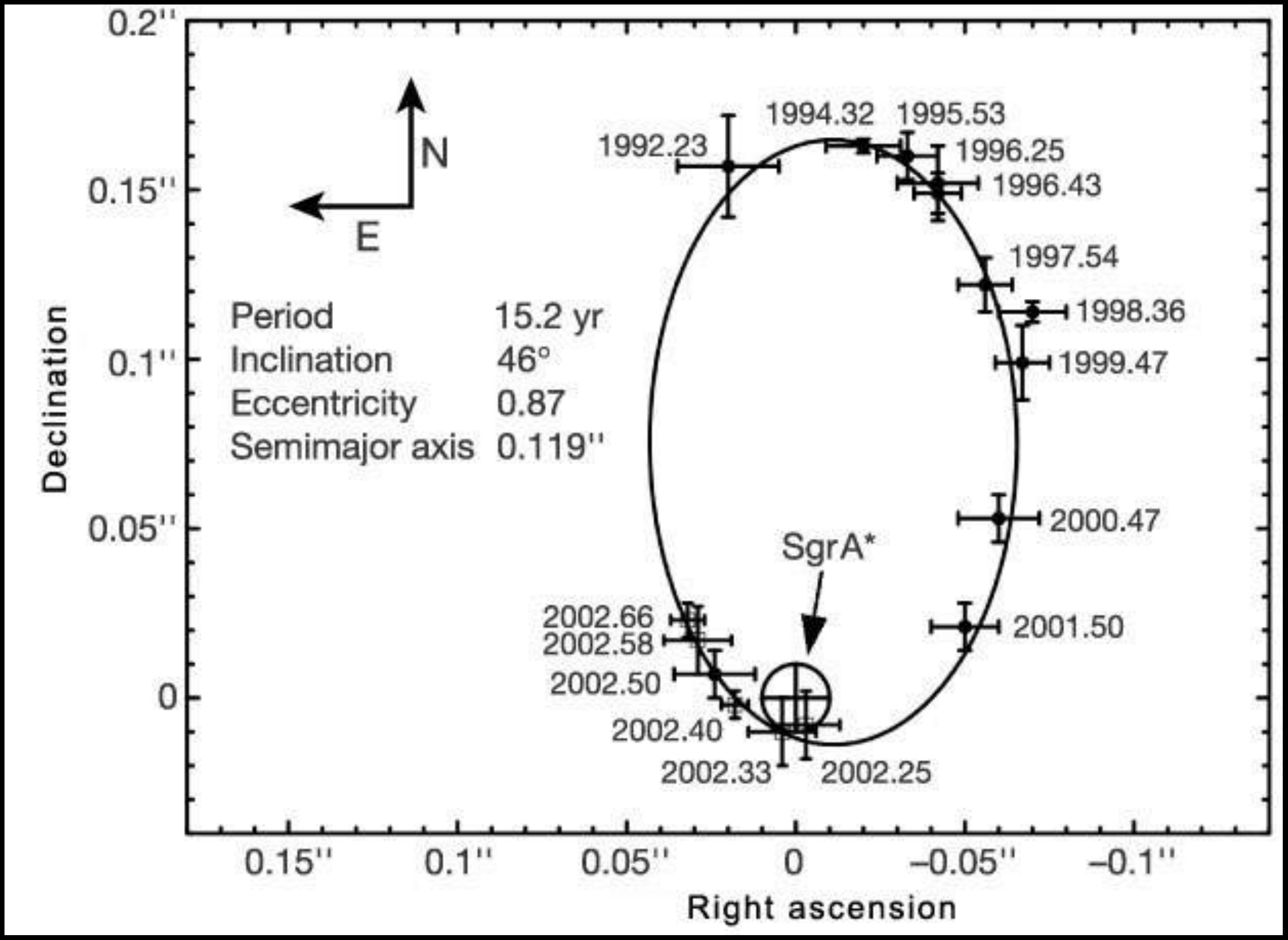
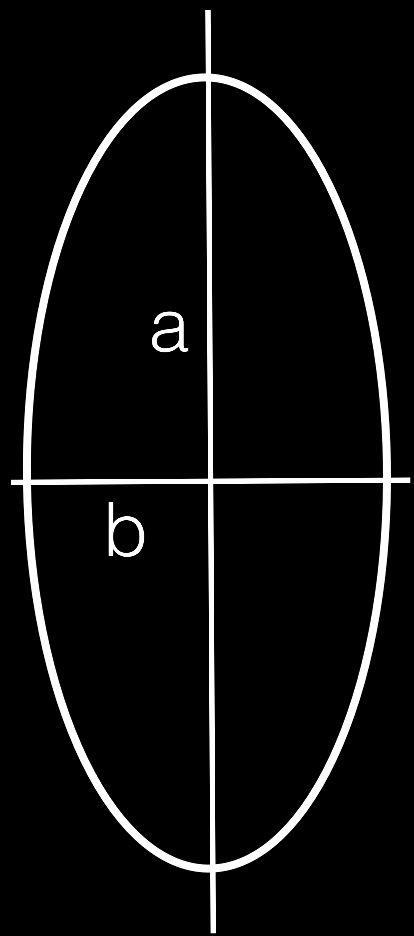




3rd Kepler law:

$$T^2 / a^3 = 4\pi^2/GM = cste$$





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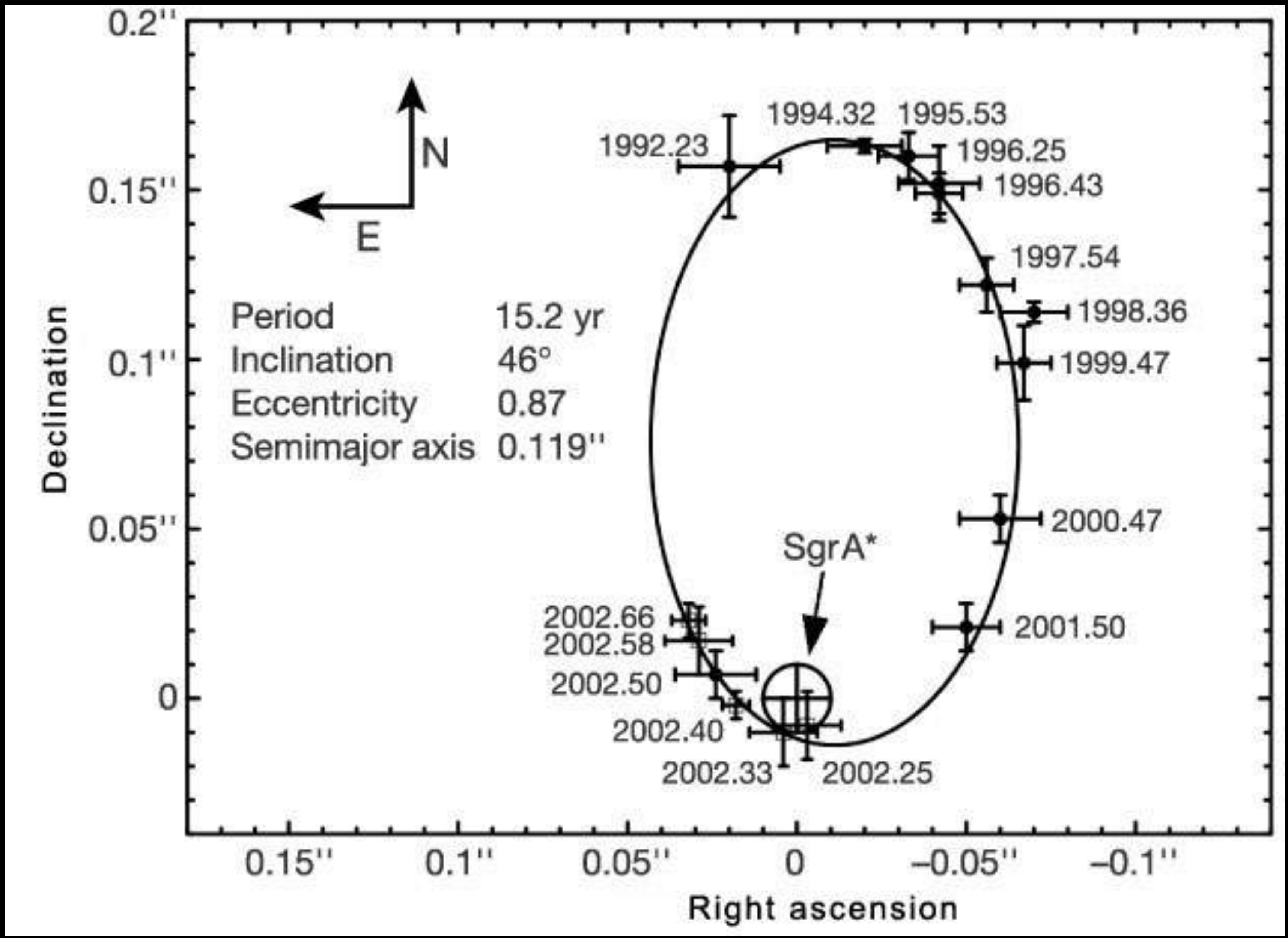
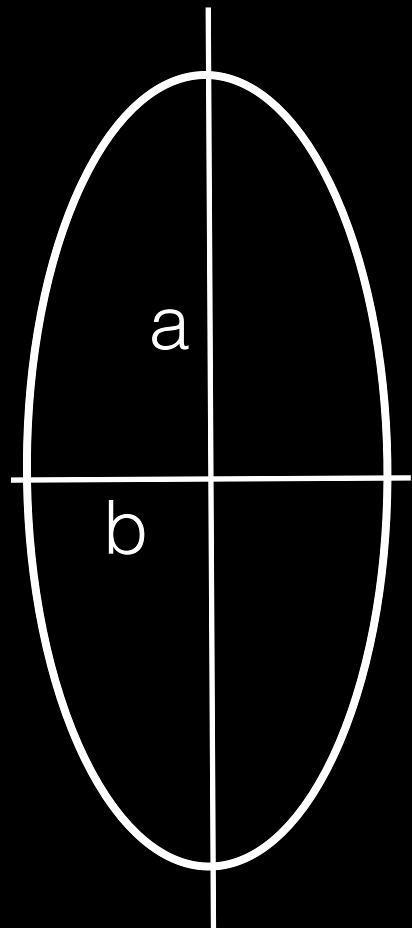
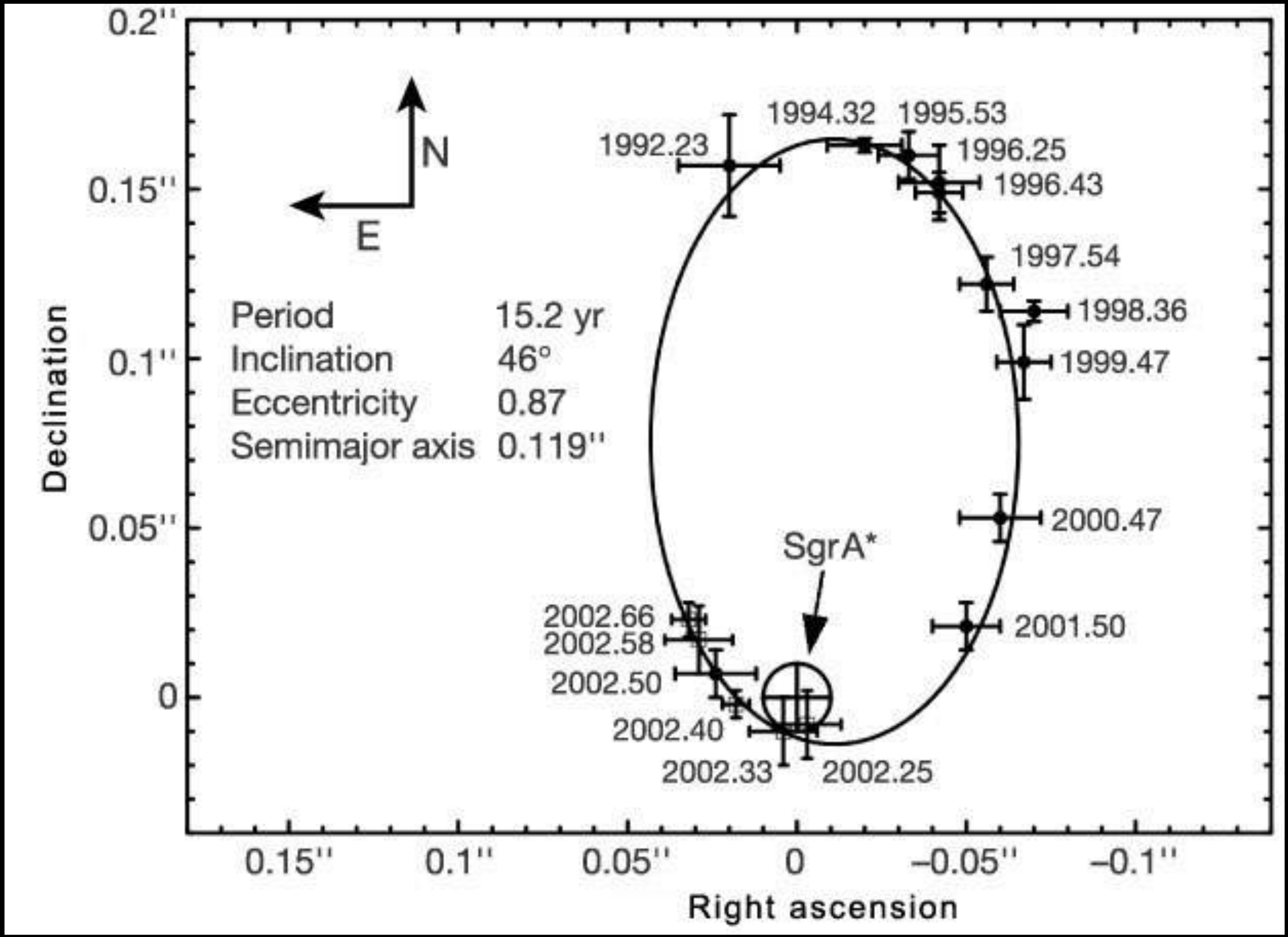
T~15 yr = 4,73 x 10^8 s





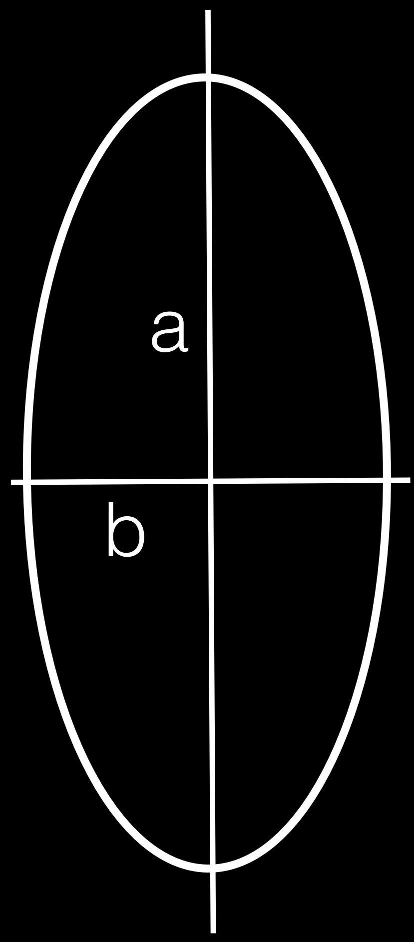
3rd Kepler law:

$T^2 / a^3 = 4\pi^2/GM = cste$



T~15 yr = 4,73 x 10^8 s

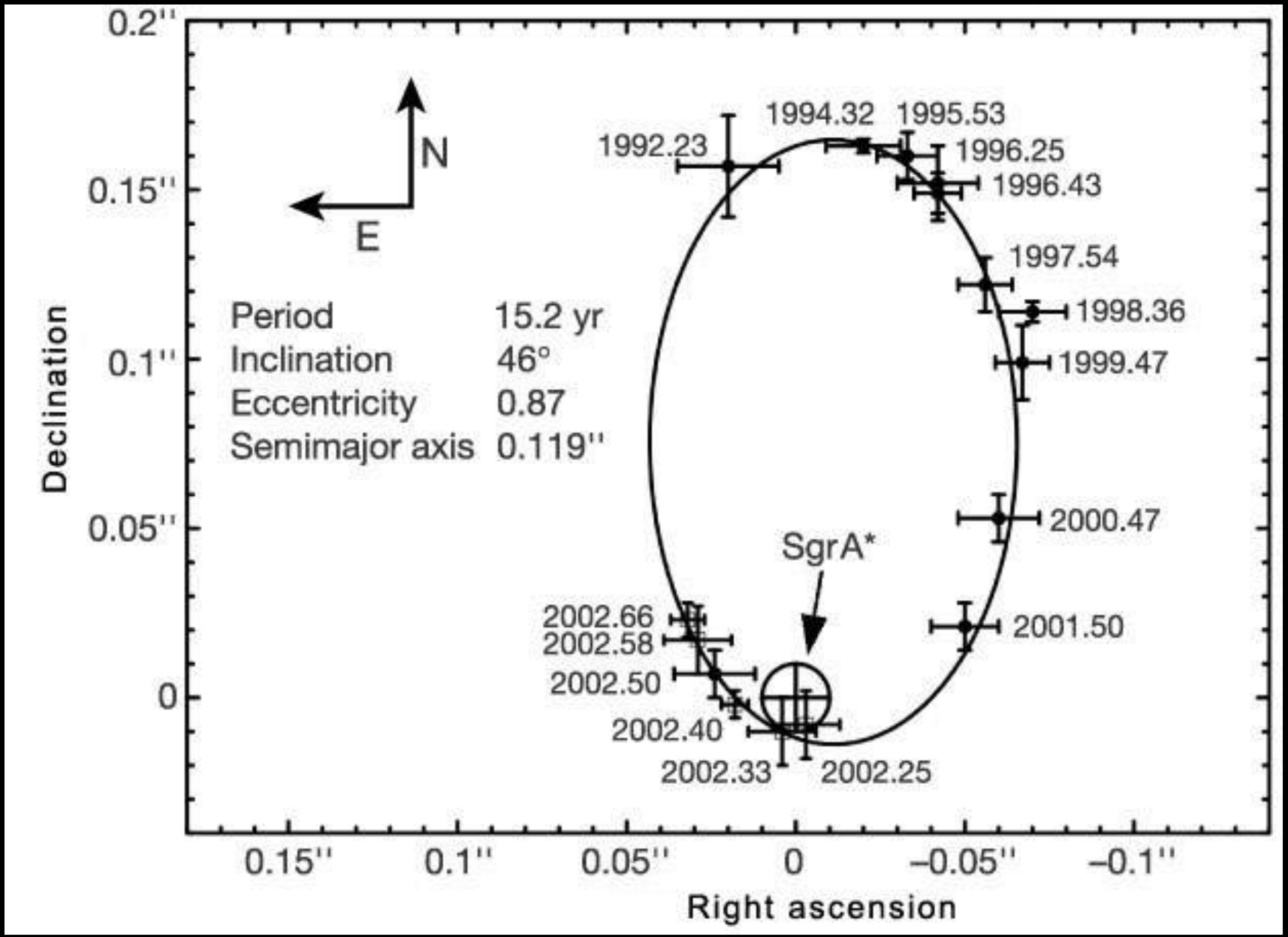
2a ~ 3 x 10^{14} m

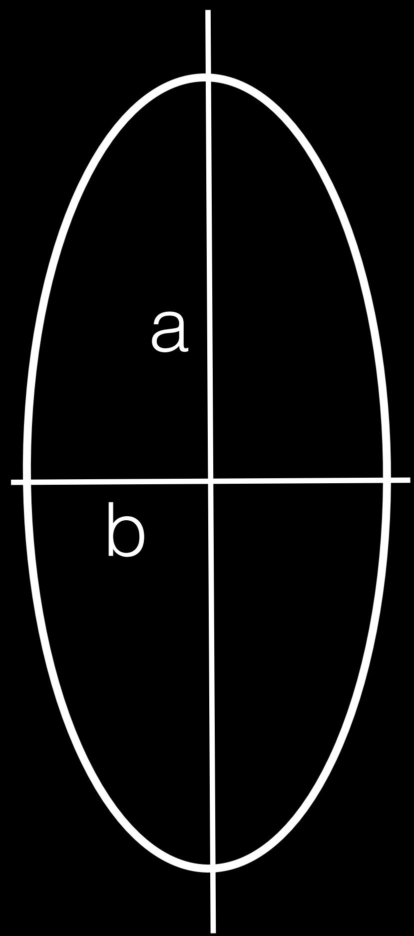


3rd Kepler law:

$$T^2 / a^3 = 4\pi^2/GM = cste$$

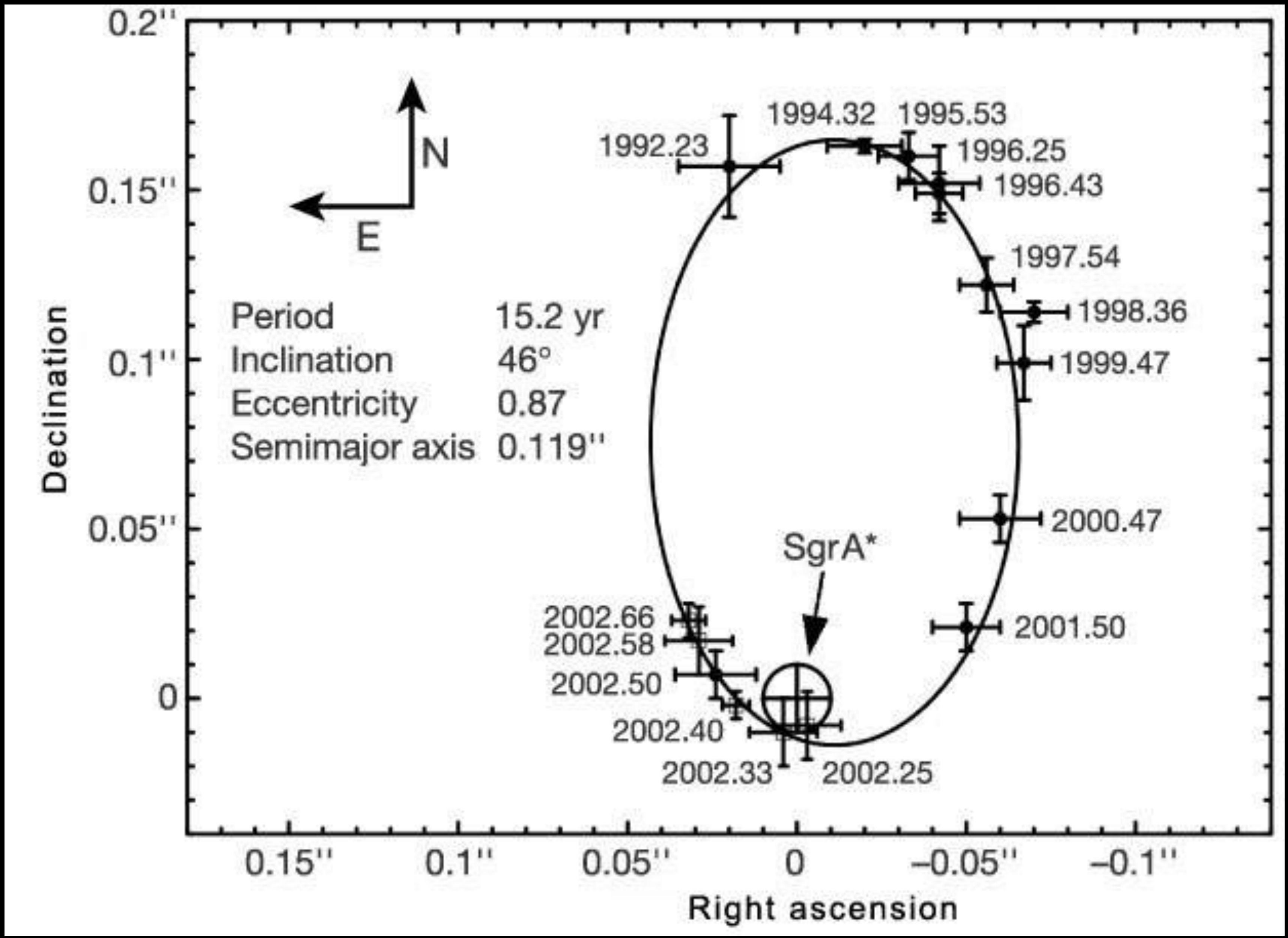
$M = 4\pi^2 \times a^3/(T^2 \times G)$
$= 3.2 \times 10^{36}$ kg





3rd Kepler law:

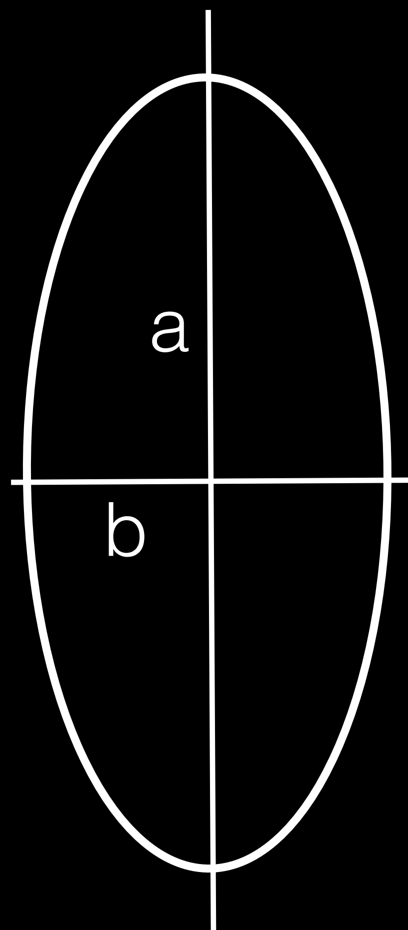
$$T^2 / a^3 = 4\pi^2/GM = \text{cste}$$



$M = 4\pi^2 \times a^3/(T^2 \times G)$
$= 3.2 \times 10^{36}$ kg

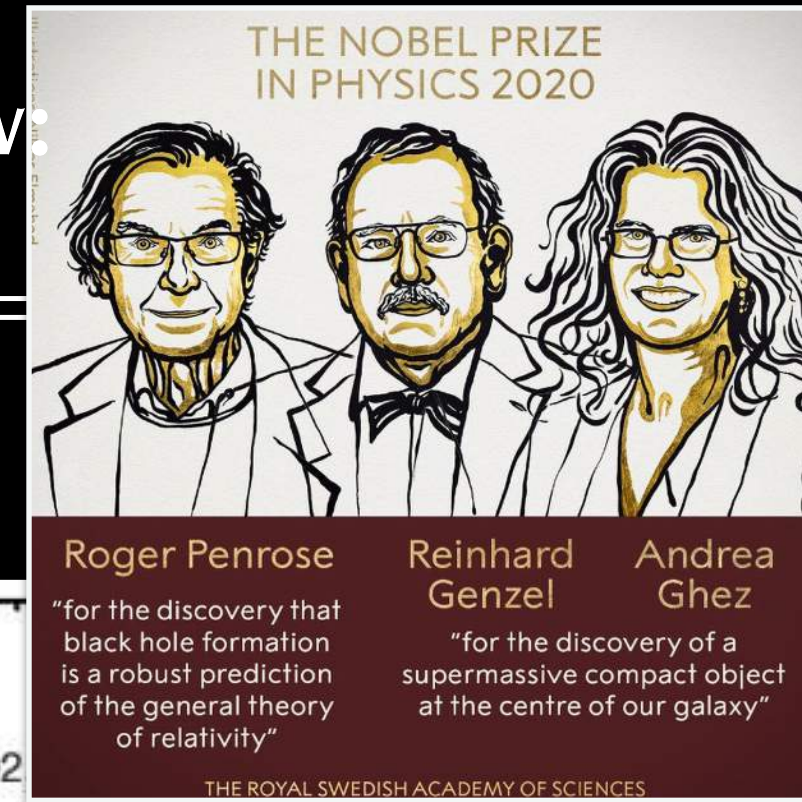
$\Downarrow$

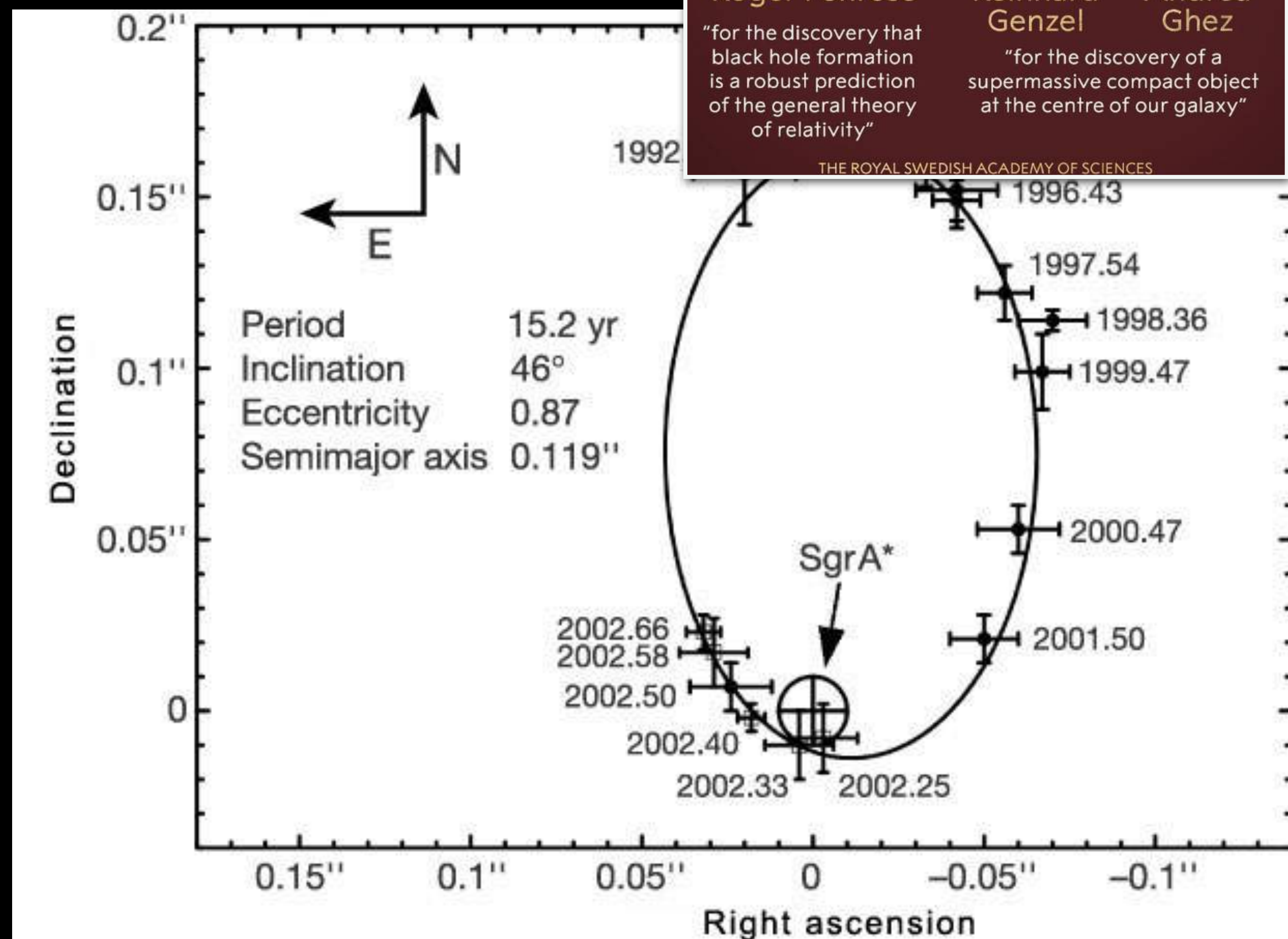
M / M_{soleil}
$= 3.2 \times 10^{36}$ kg / 2×10^{30} kg
$= 1,6 \times 10^6$



3rd Kepler law:

$$T^2 / a^3 = 4\pi^2/GM =$$





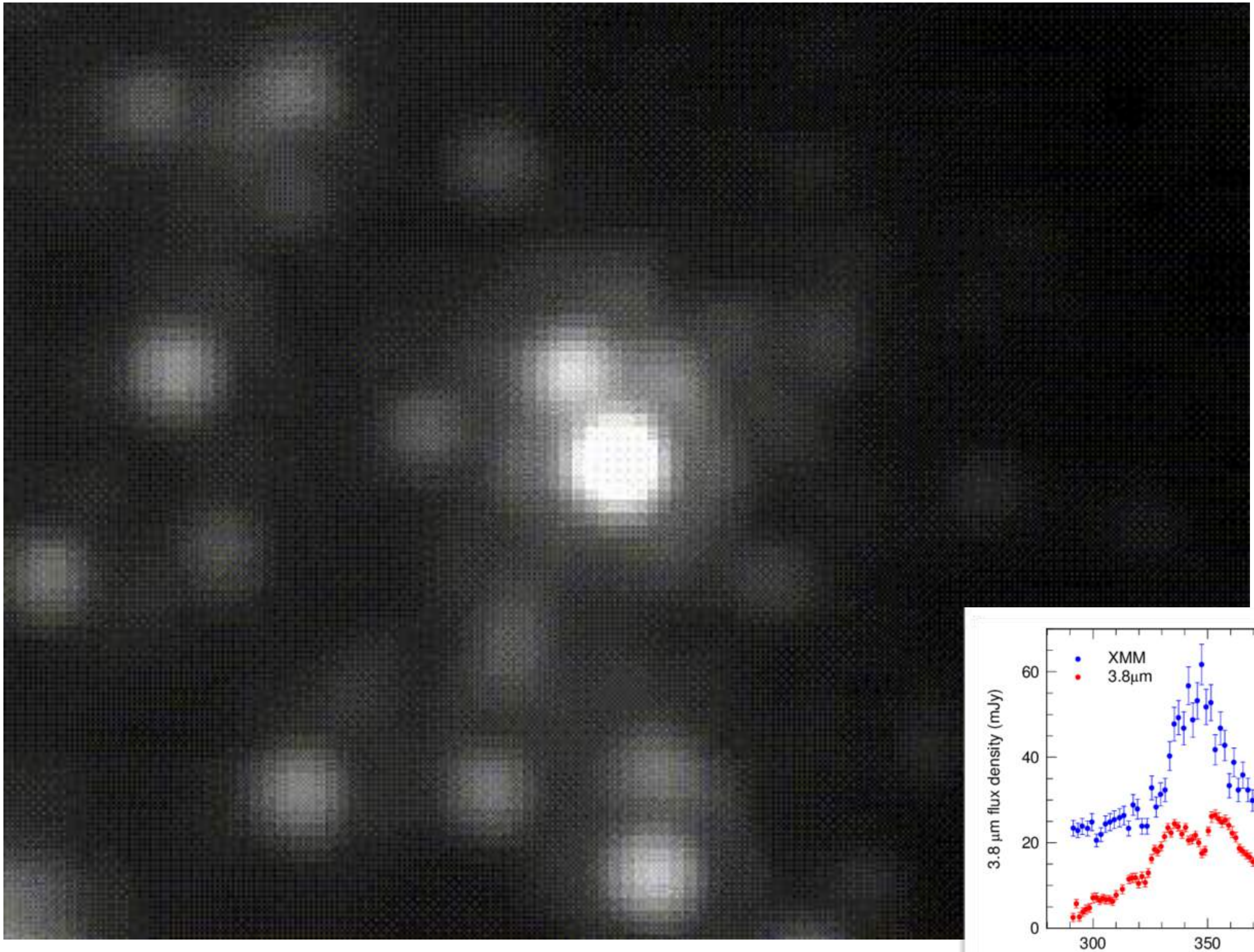
$M = 4\pi^2 \times a^3/(T^2 \times G)$
$= 3.2 \times 10^{36}$ kg

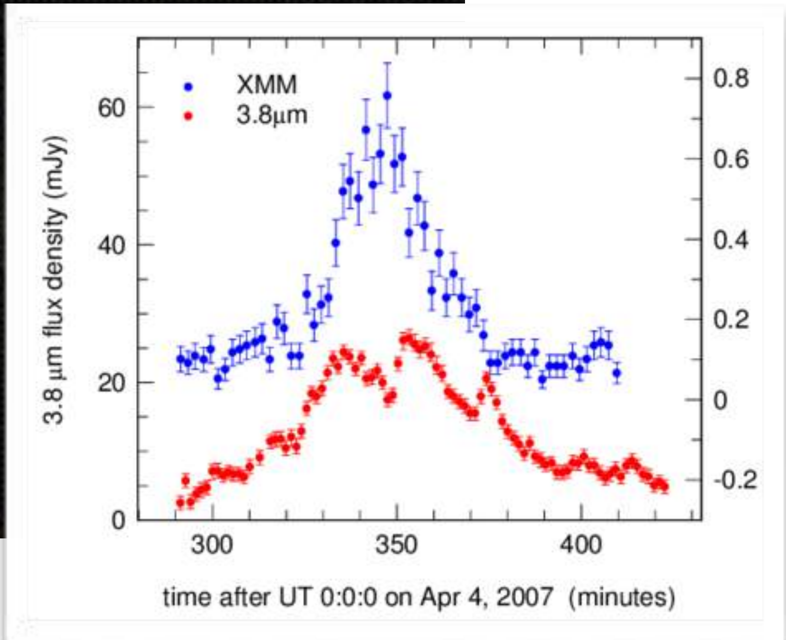
$$\Downarrow$$

M / M_{soleil}
$= 3.2 \times 10^{36}$ kg / 2×10^{30} kg
$= 1{,}6 \times 10^6$

SgrA* electromagnetic emission

Near infrared





SgrA* electromagnetic emission

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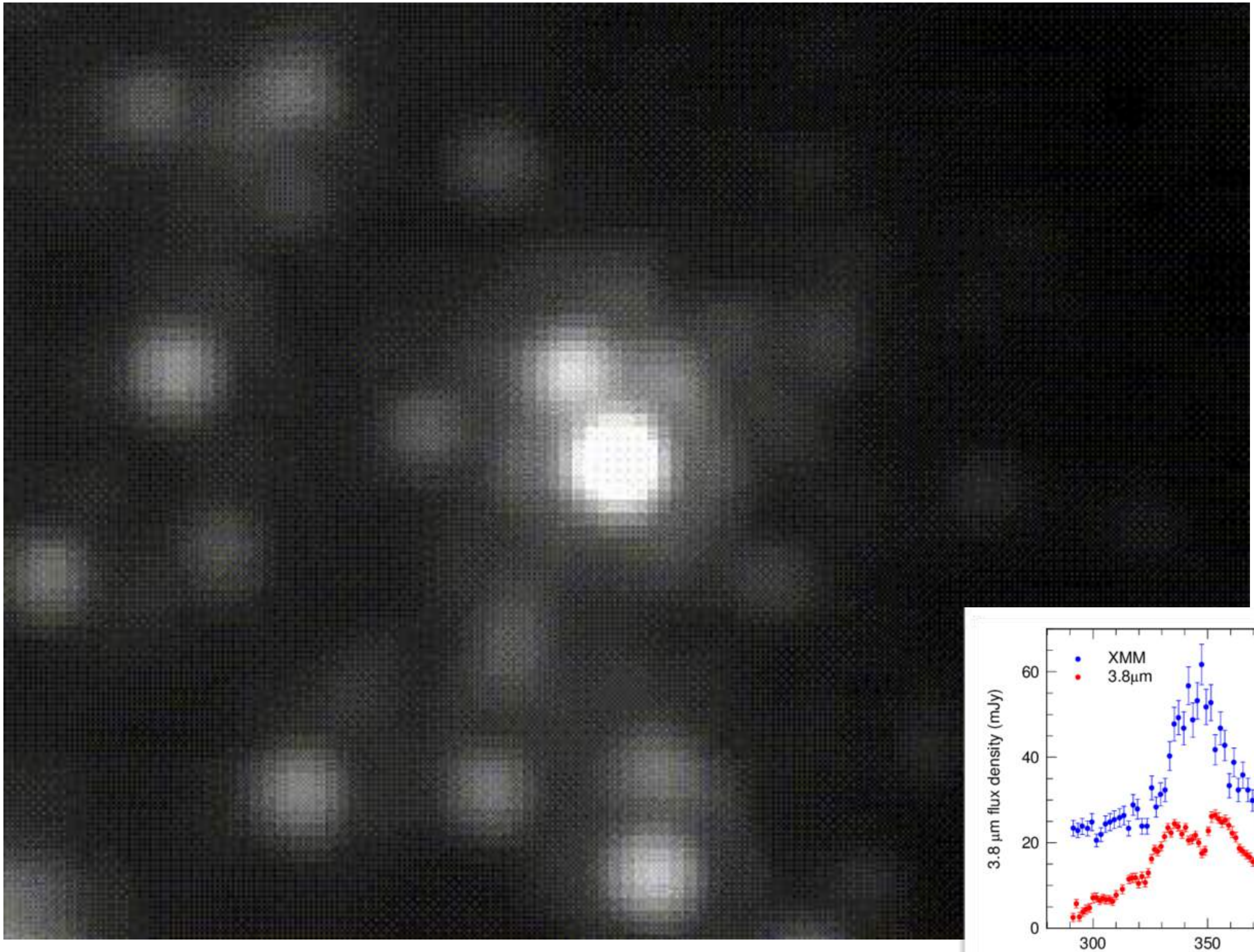
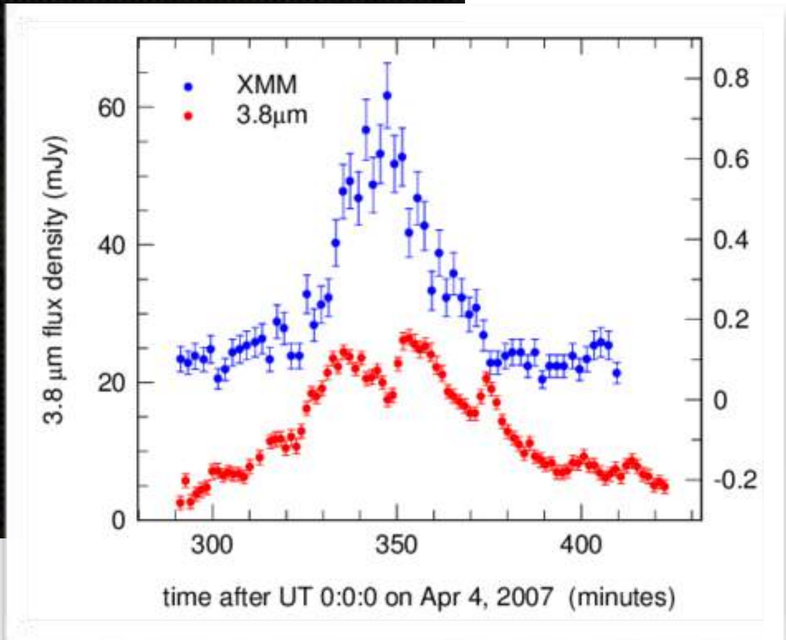
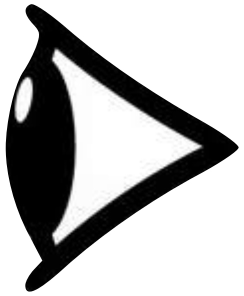




Nature of the central object

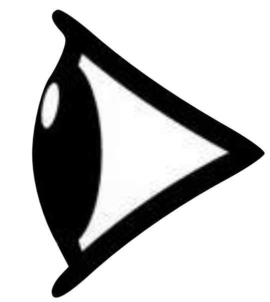
Variability timescale



Nature of the central object

Variability timescale

When light is switched on:
lampshade appears to light
up instantaneously
because it is small



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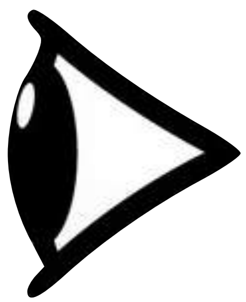

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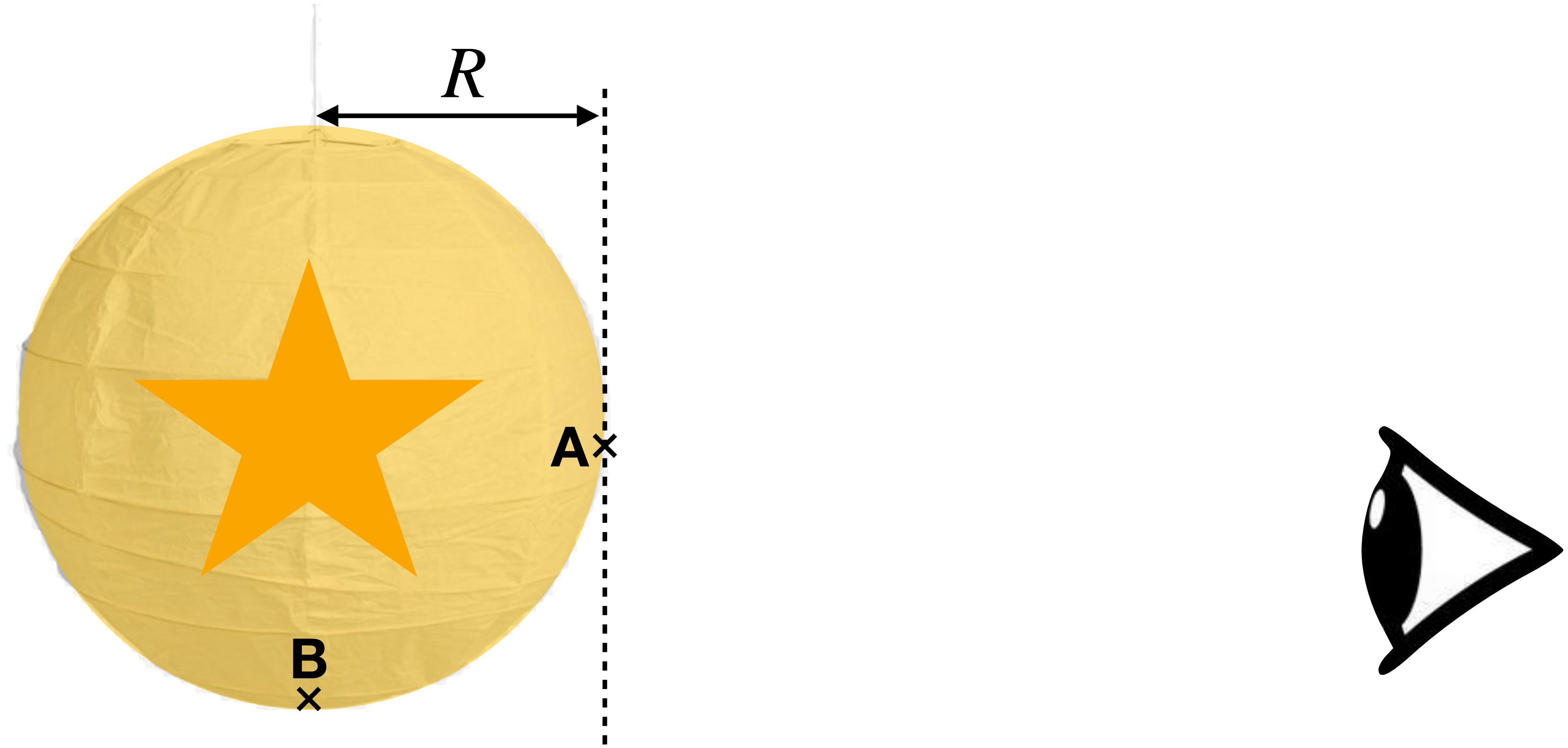

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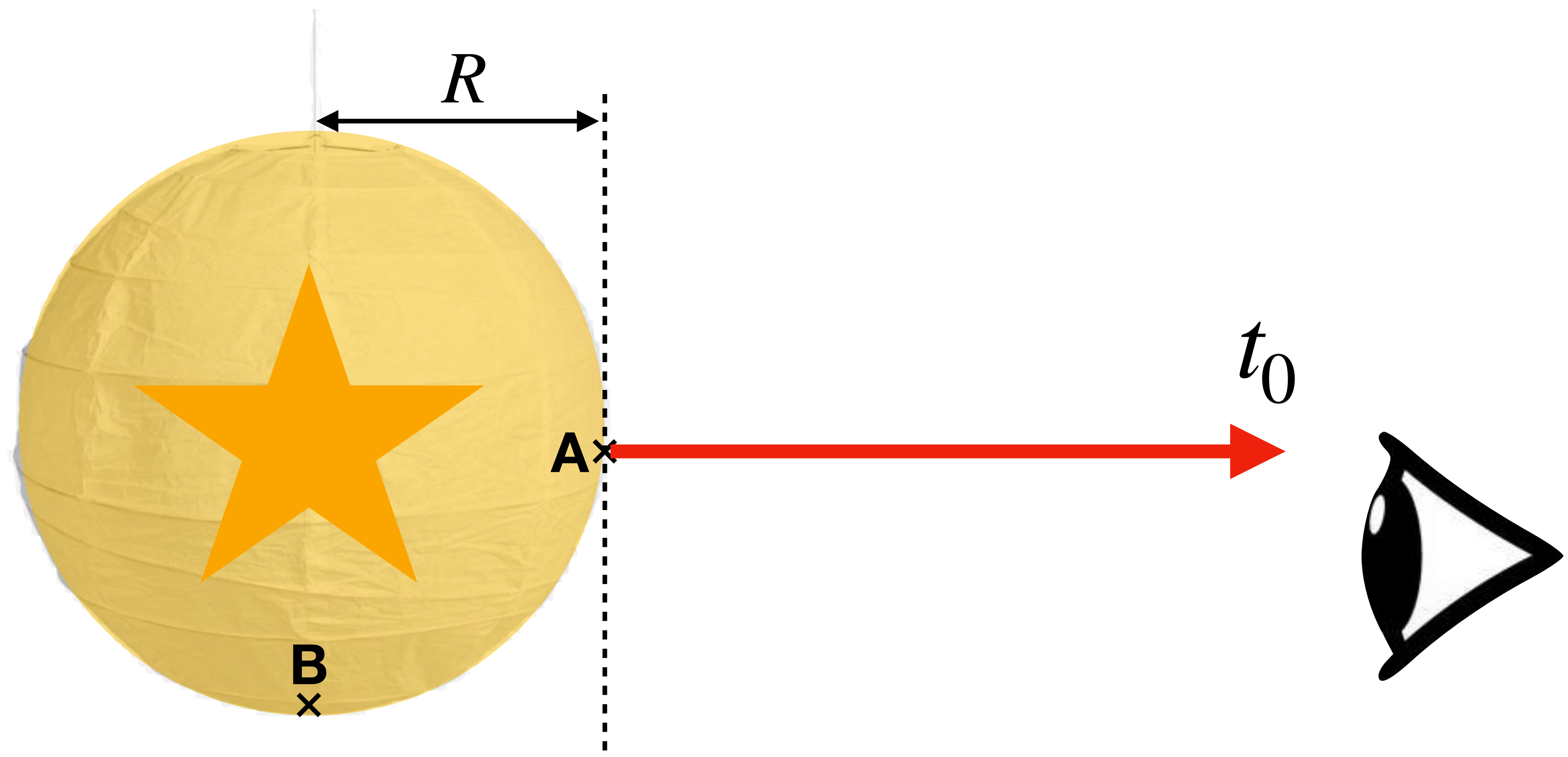
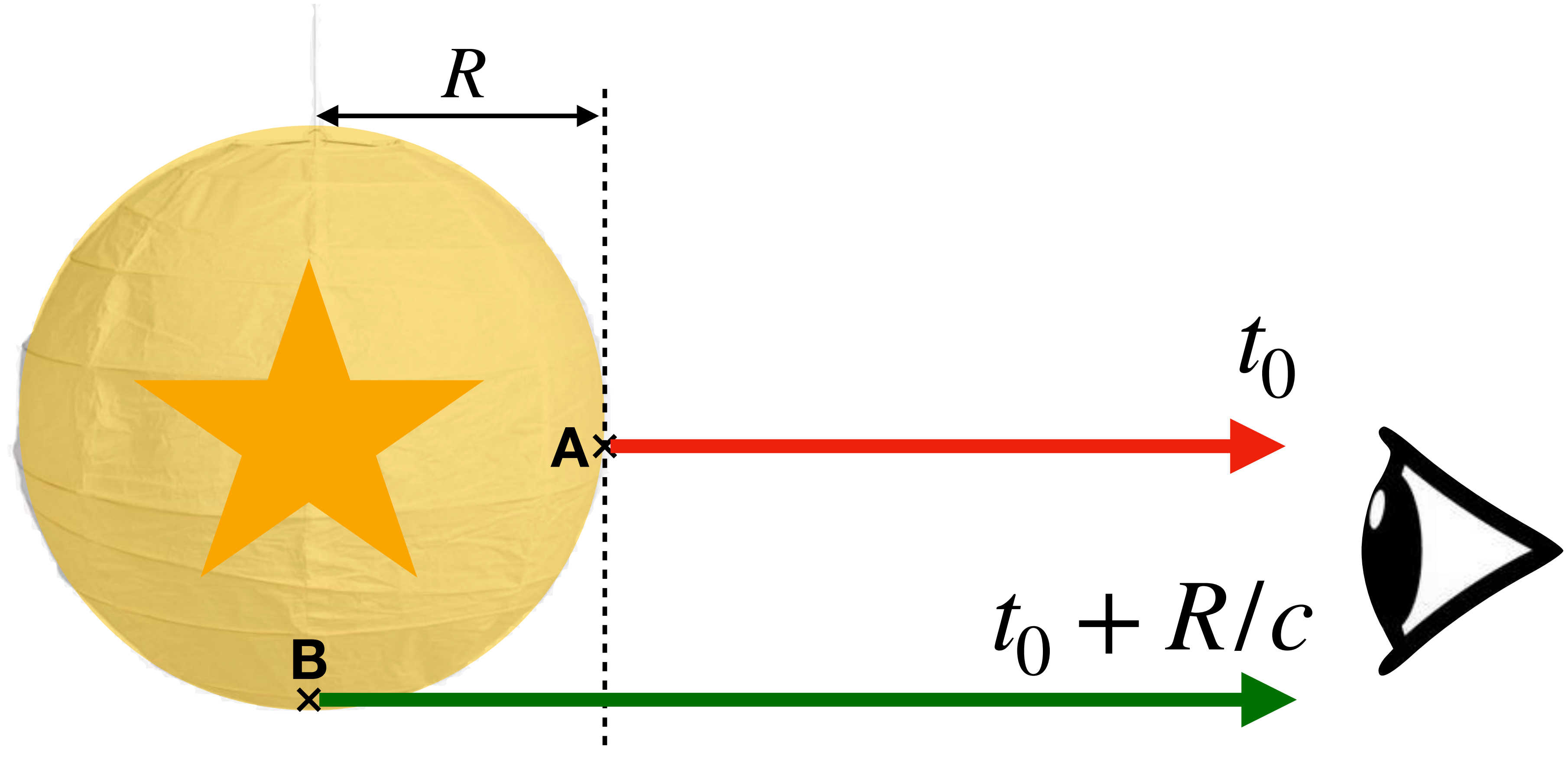


Nature of the central object

Variability timescale



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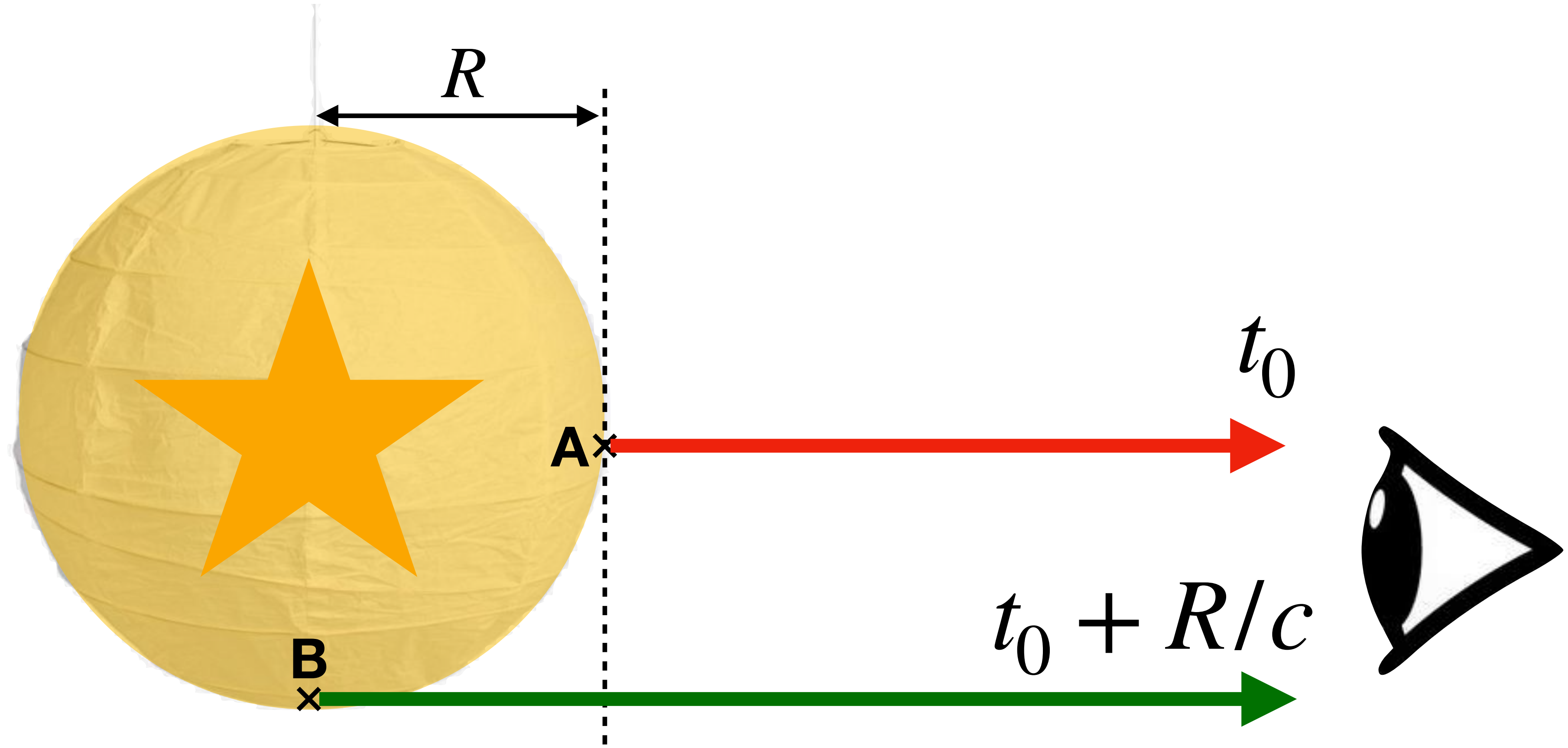
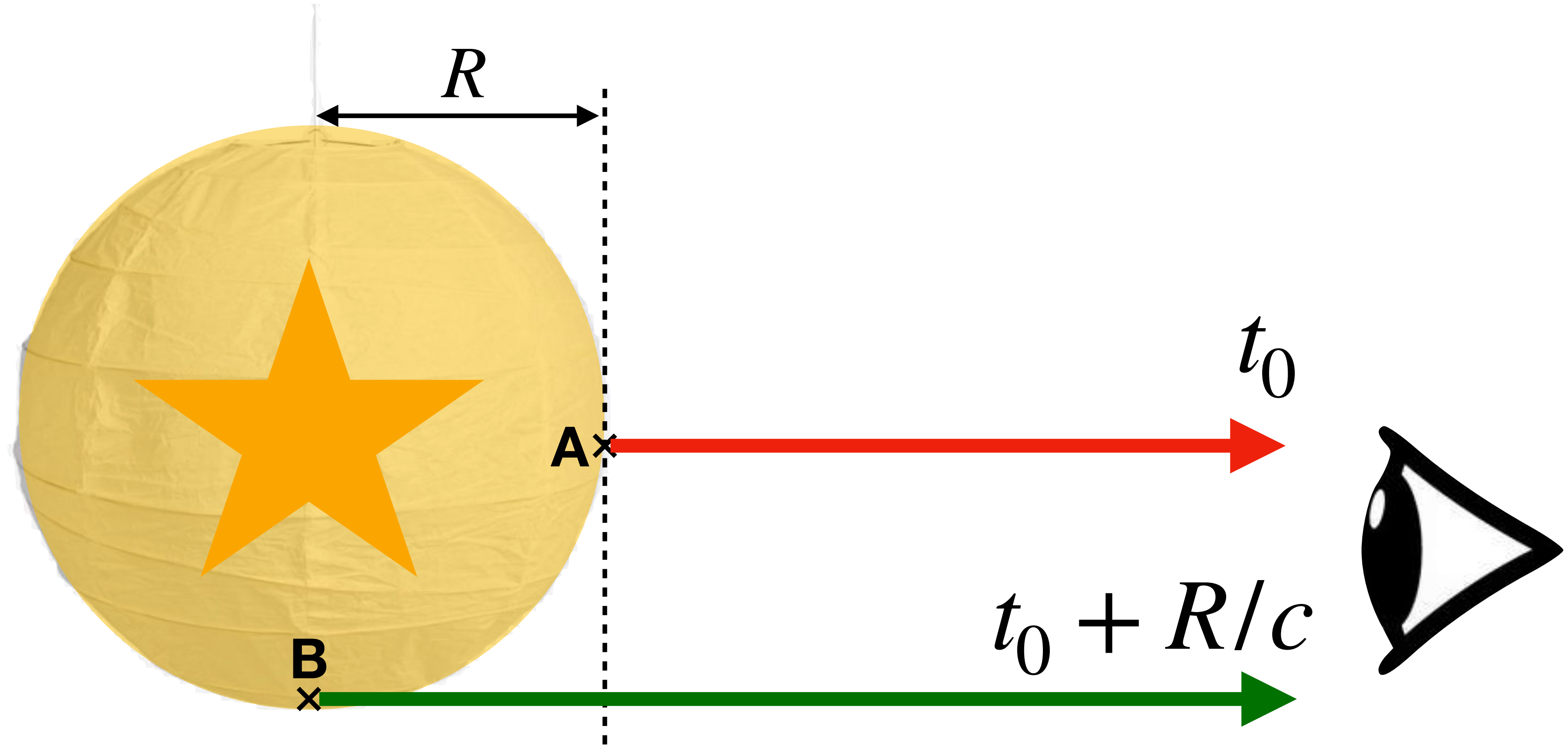


Light from B will reach the observer a time R/c later than light from A

Nature of the central object

Variability timescale

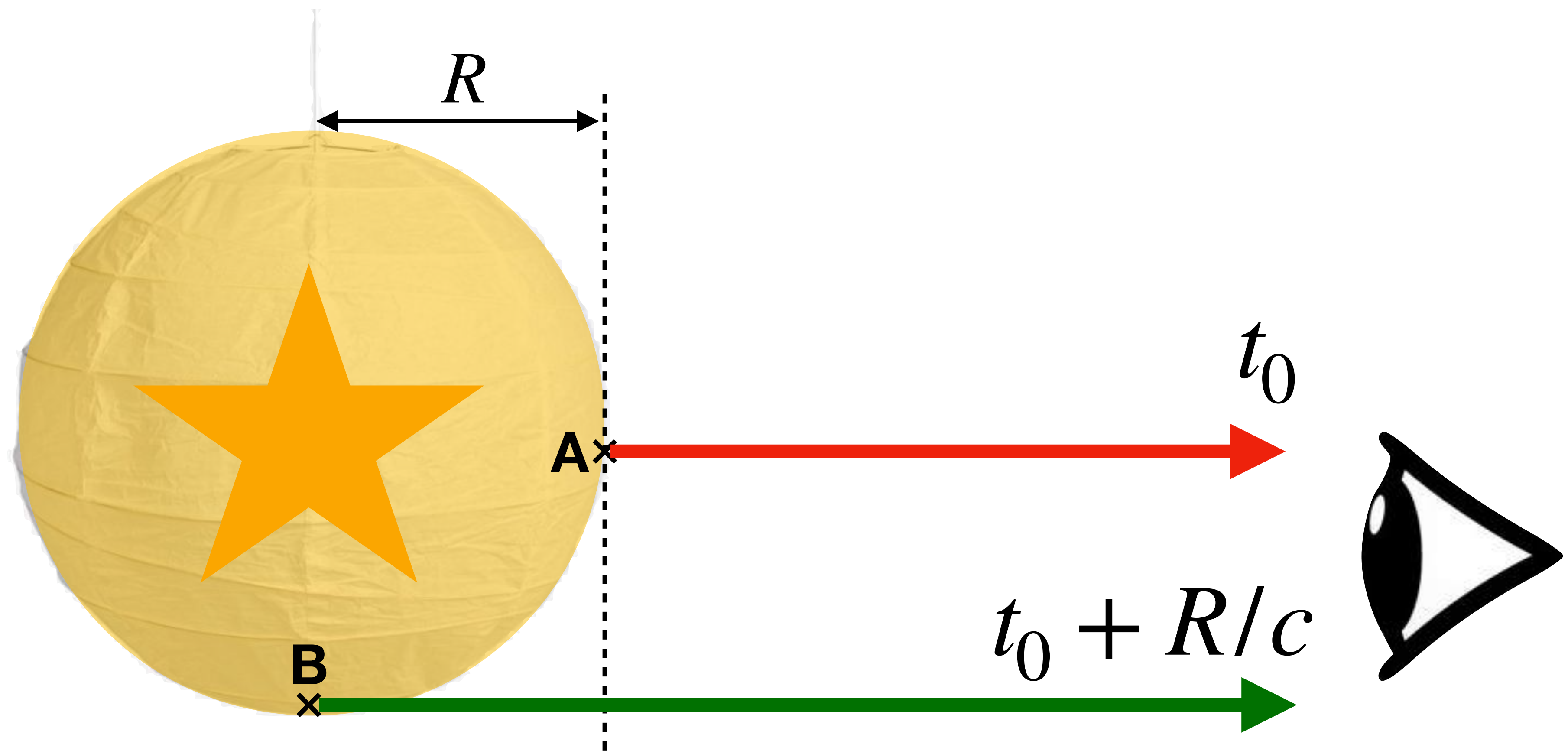


Light from B will reach the observer a time R/c later than light from A

⇒ **Fluctuations on timescales of less than *R/c* will not be observed since each flicker will take R/c to spread across the lampshade and the flickers will be smeared out and mixed together.**

Nature of the central object

Variability timescale



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⇒ Fluctuations on timescales of less than R/c will not be observed since each flicker will take R/c to spread across the lampshade and the flickers will be smeared out and mixed together.

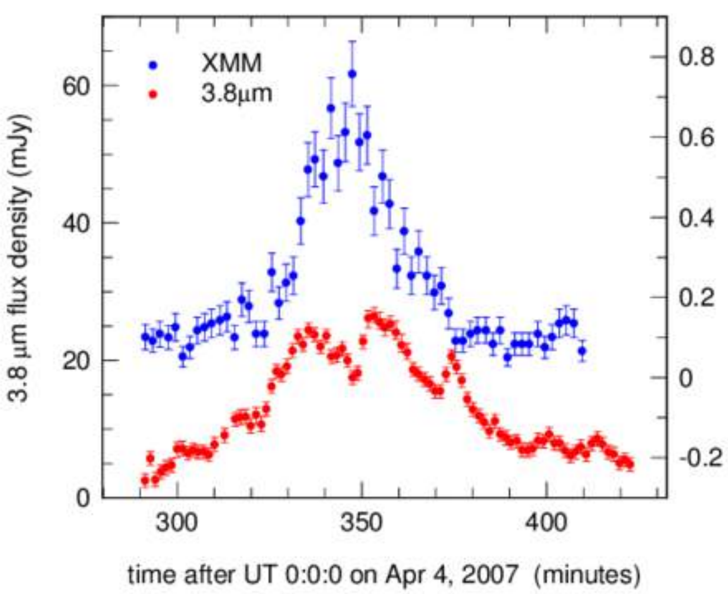
Same applies for any three-dimensional configuration where changes in brightness occur across a light-emitting surface.

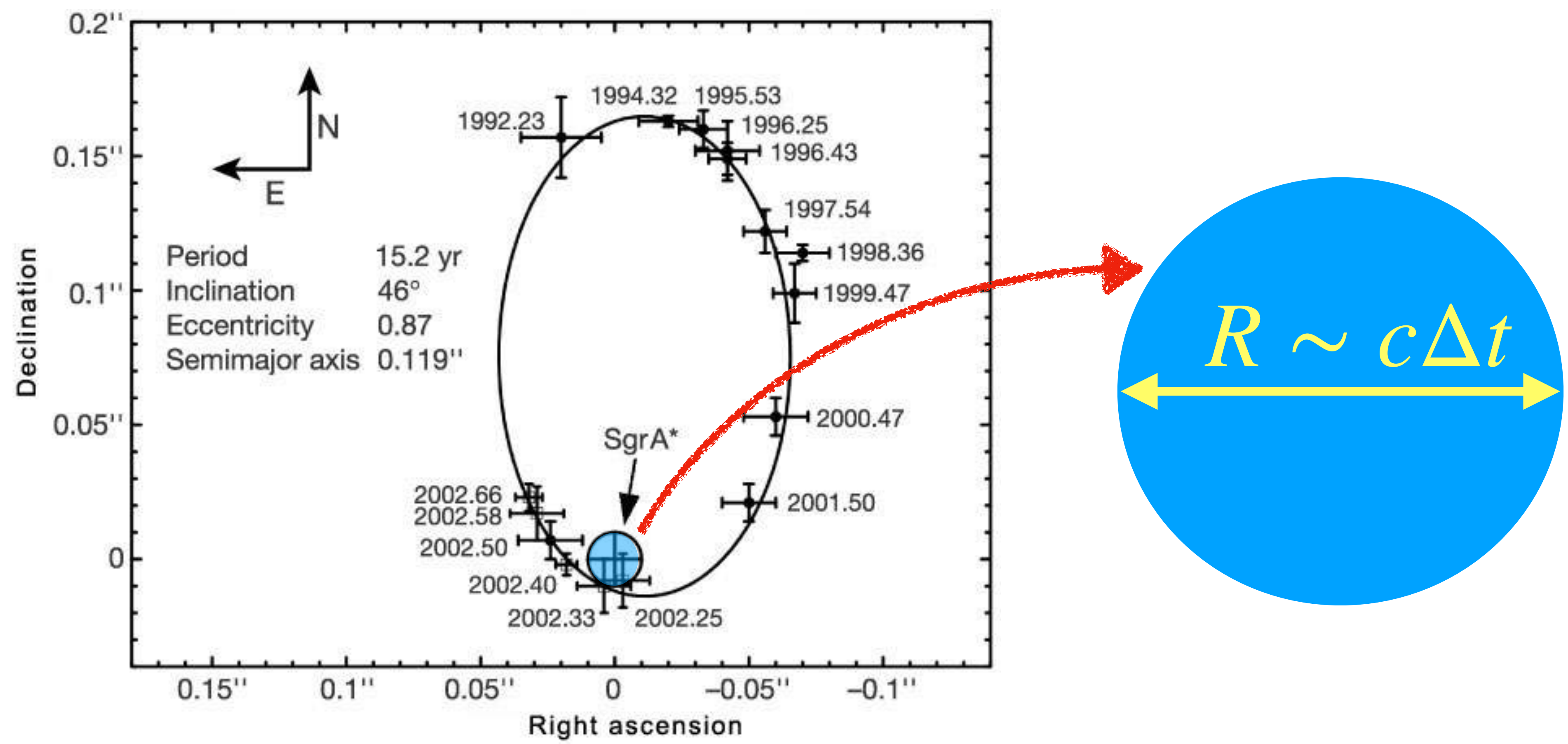
Relationship between the maximum extent (R) of any source of radiation and its timescale of variability (Δt) is usually expressed as:

$$R \sim c\Delta t$$

Nature of the central object

Variability timescale





Relationship between the maximum extent (*R*) of any source of radiation and its timescale for variability (Δt) is usually expressed as:

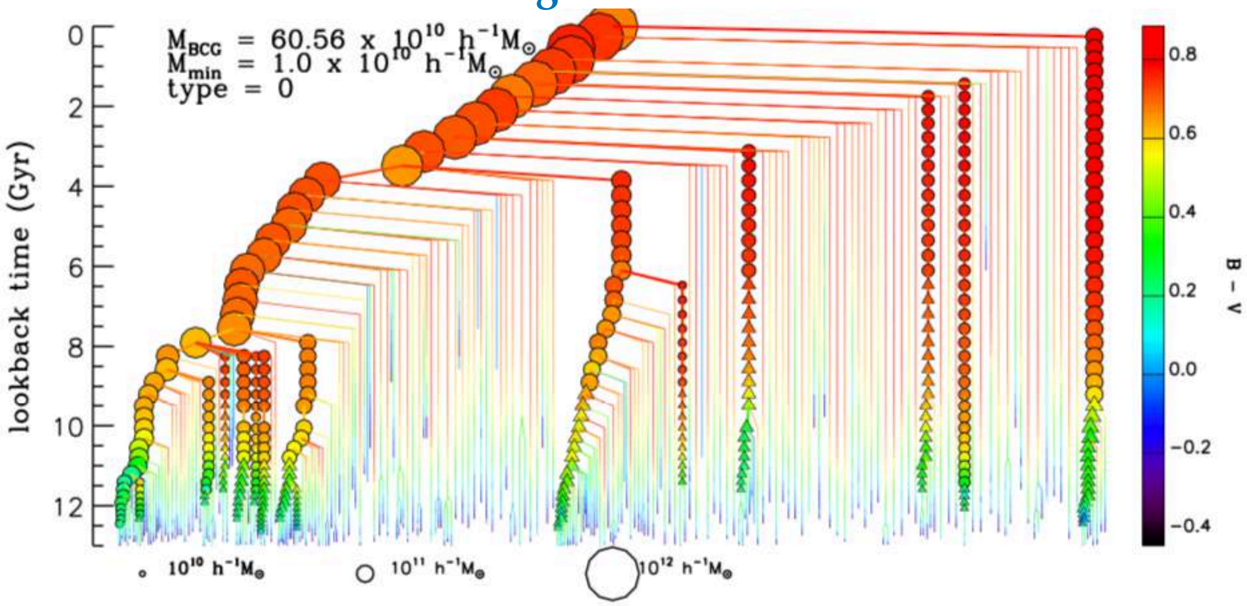
$$R \sim c\Delta t \sim 10^{12}\, m \sim 7\, AU$$

$10^6\, M_\odot$ in 7 AU ⇒ compacity Ξ compatible with a supermassive black hole

Supermassive black hole formation & evolution

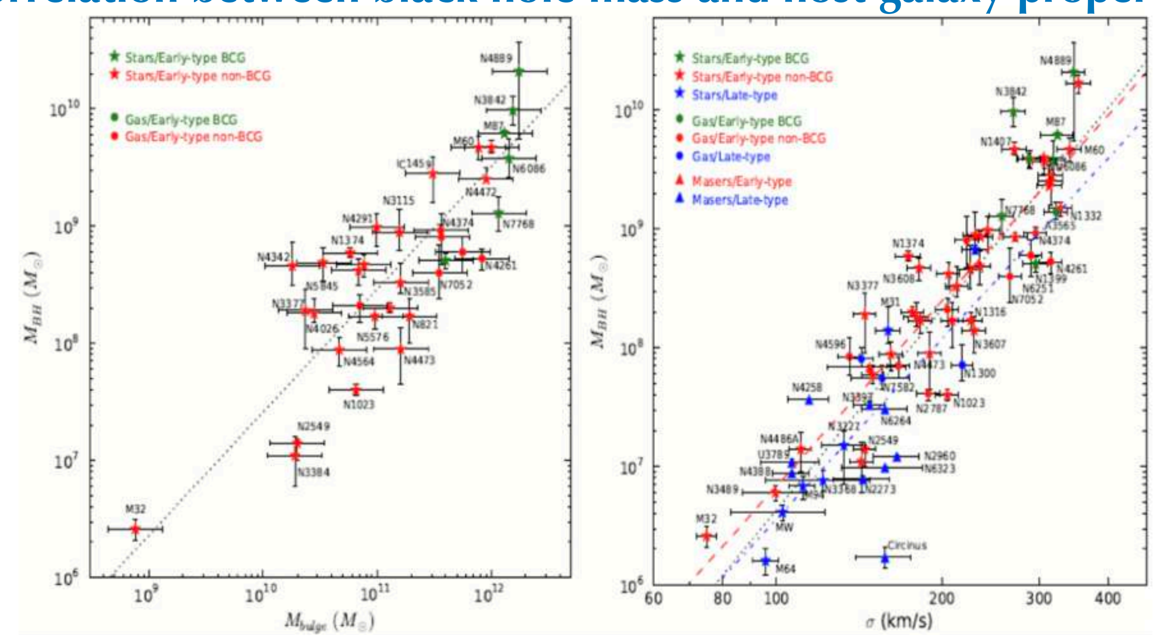
- In all cases where the inner core of a galaxy has been resolved (i.e. in nearby galaxies), a massive compact object has been found in the centre

Hierarchical formation of galaxies



+

Correlation between black hole mass and host galaxy properties



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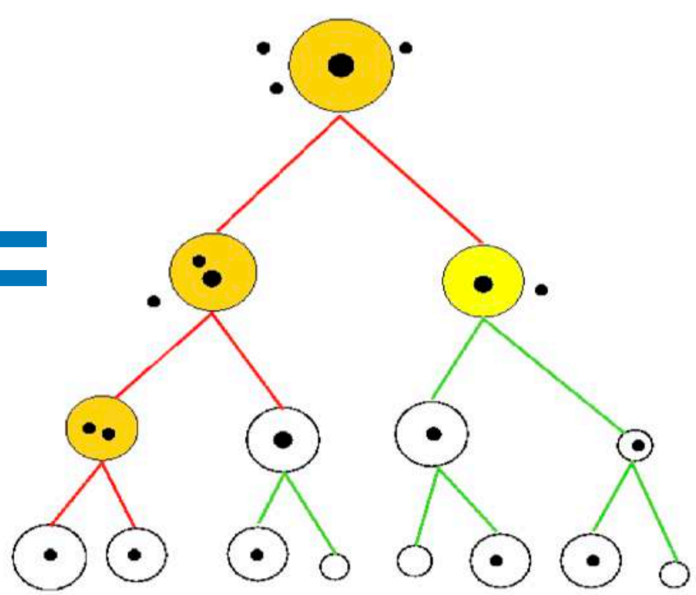

Massive black hole formation is probably hierarchical too !

- Where and when do the first MBH seeds form?
- How do they grow along the cosmic history?
- What is their role in galaxy evolution?
- What is their merger rate?
- How do they pair together and dynamically evolve?

Supermassive black hole formation & evolution

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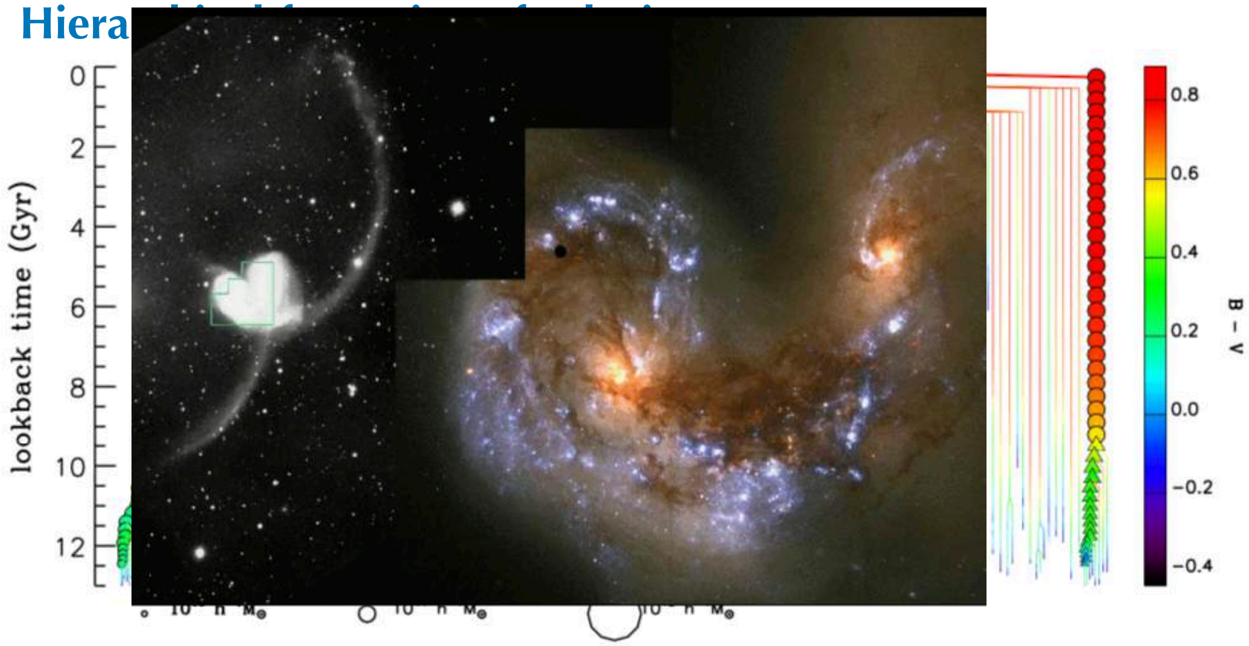

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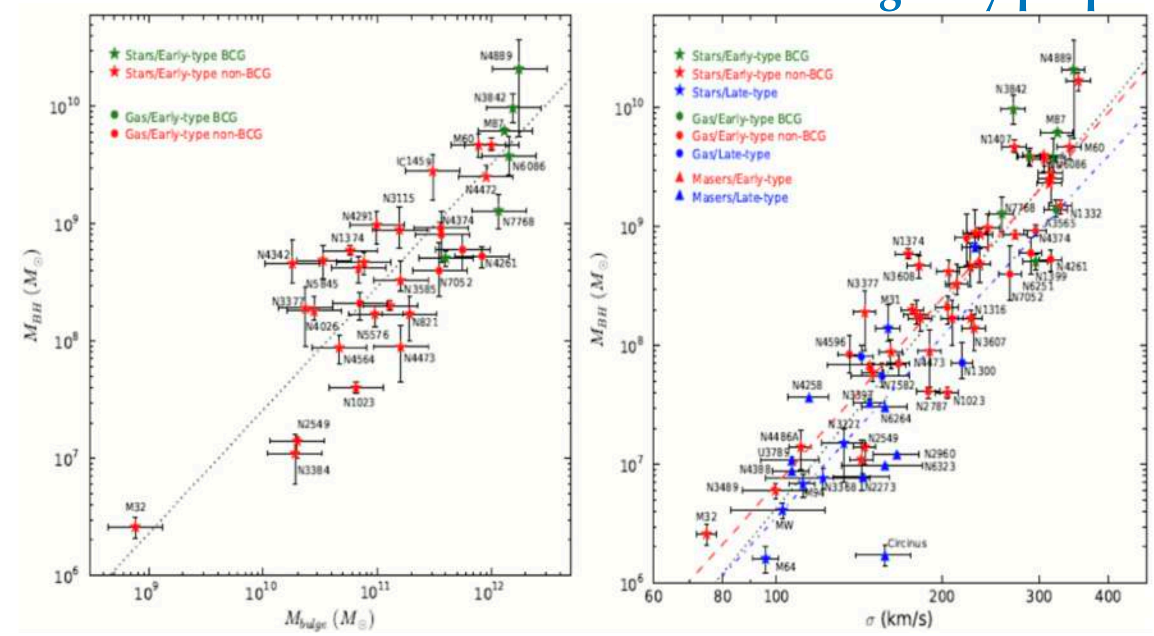

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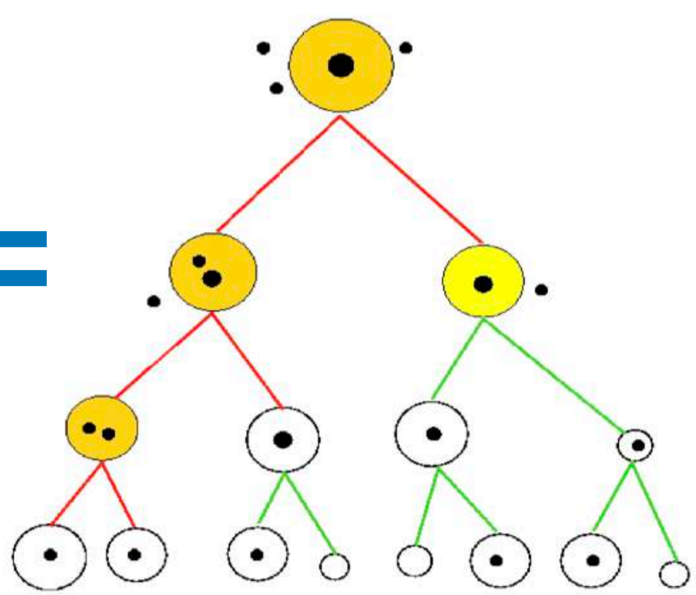

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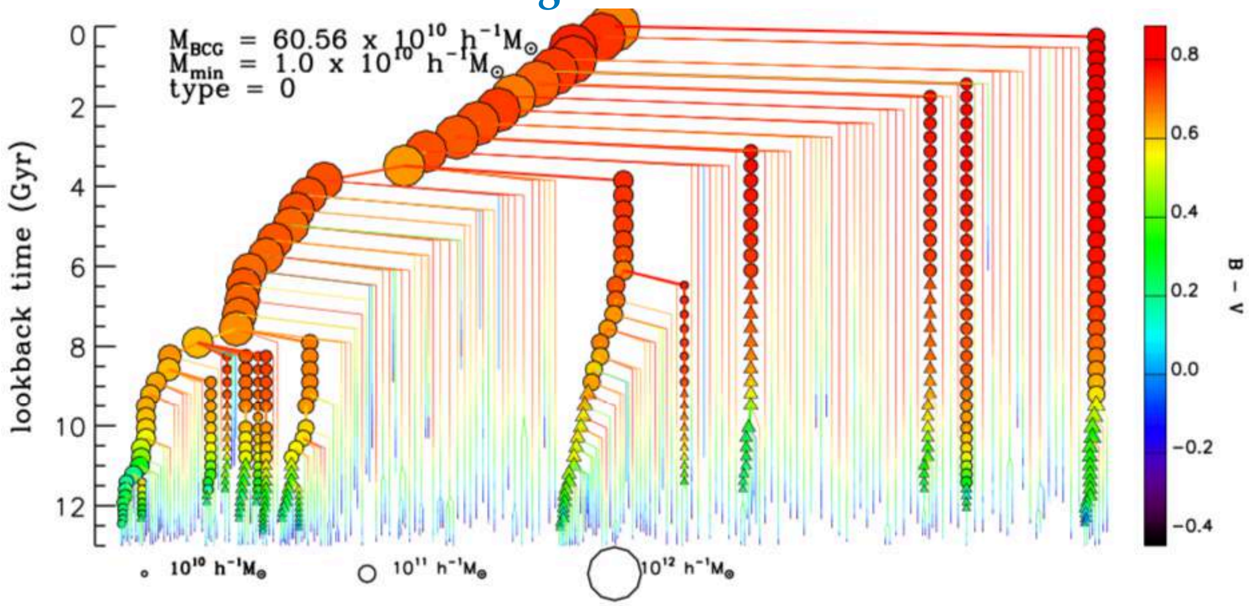

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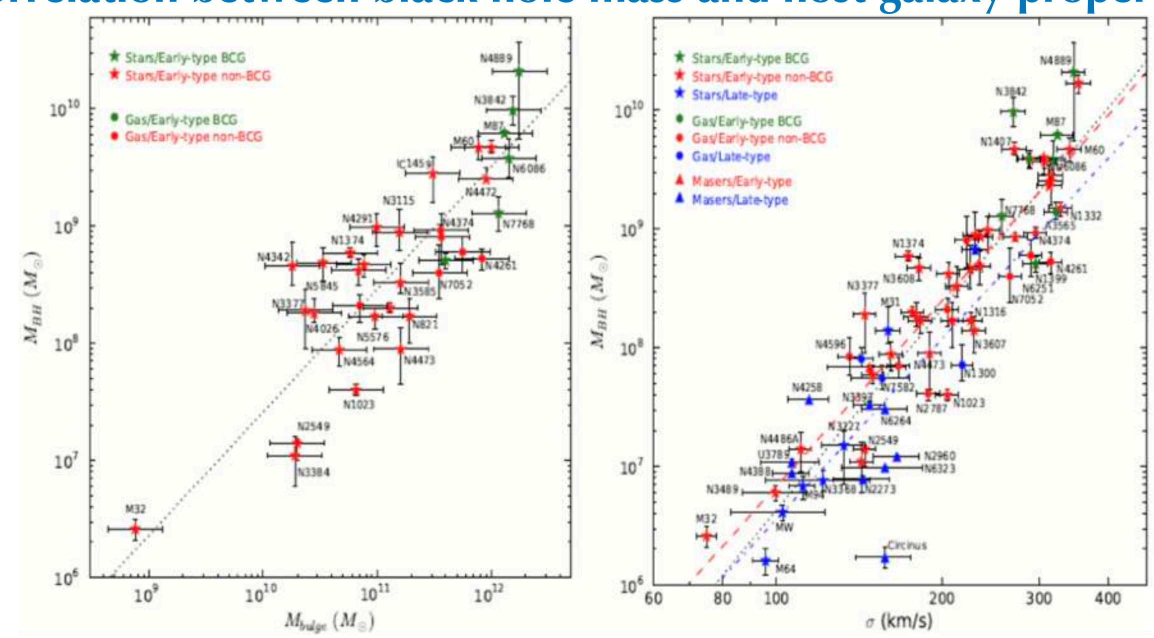

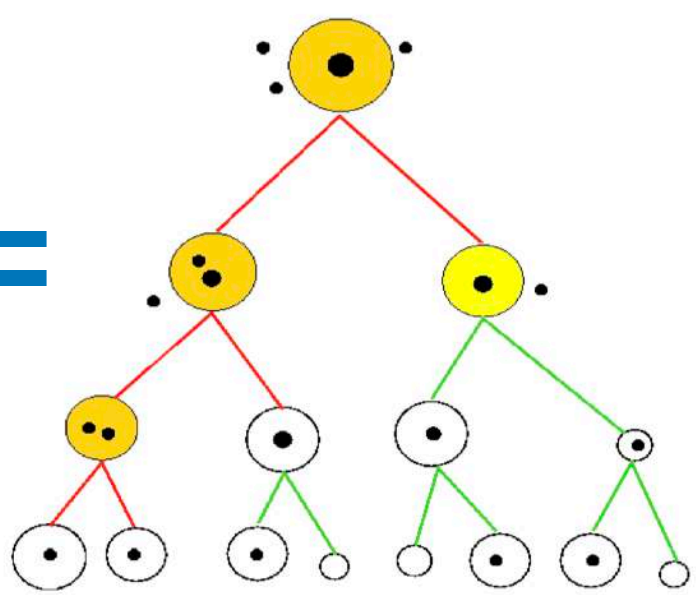

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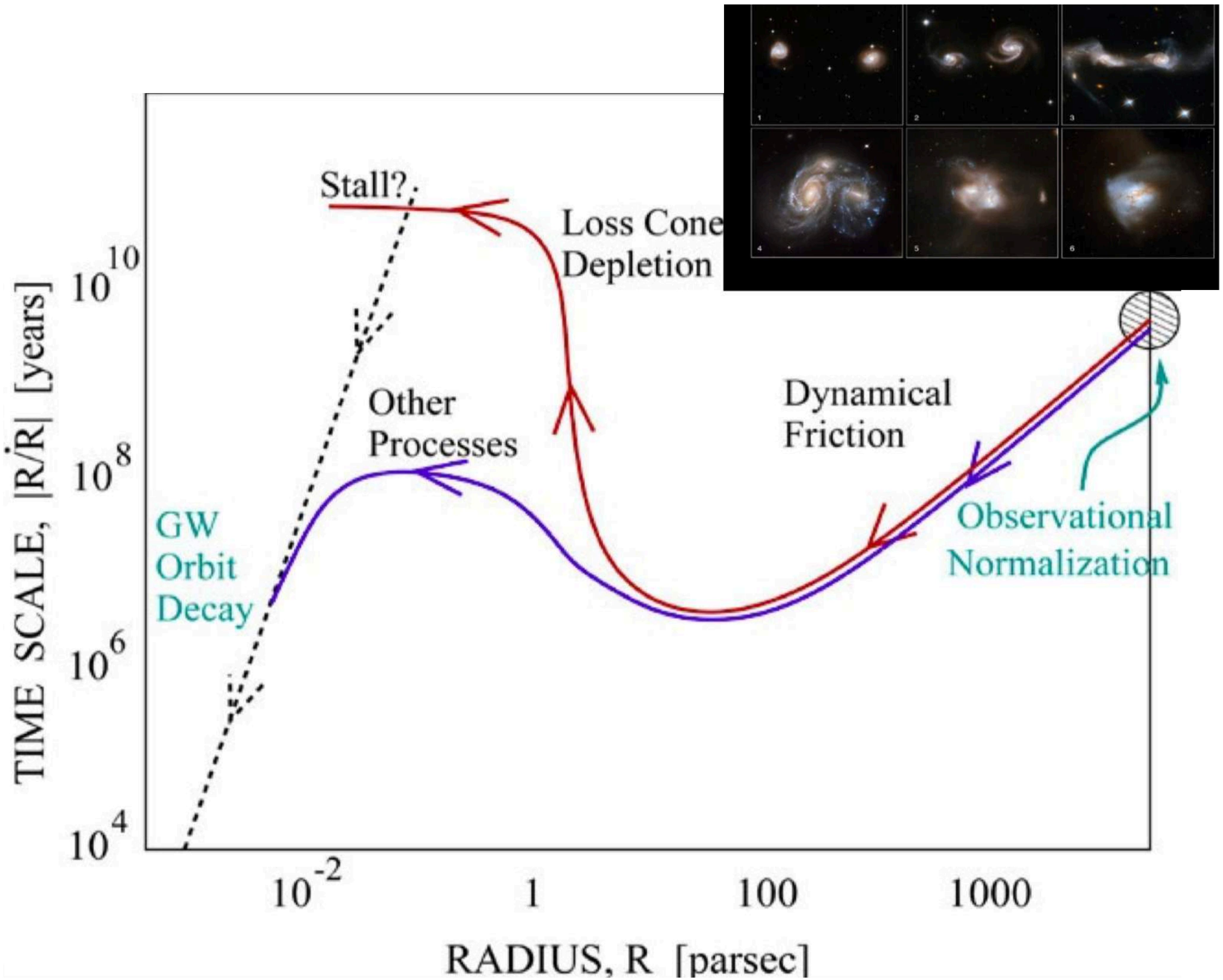
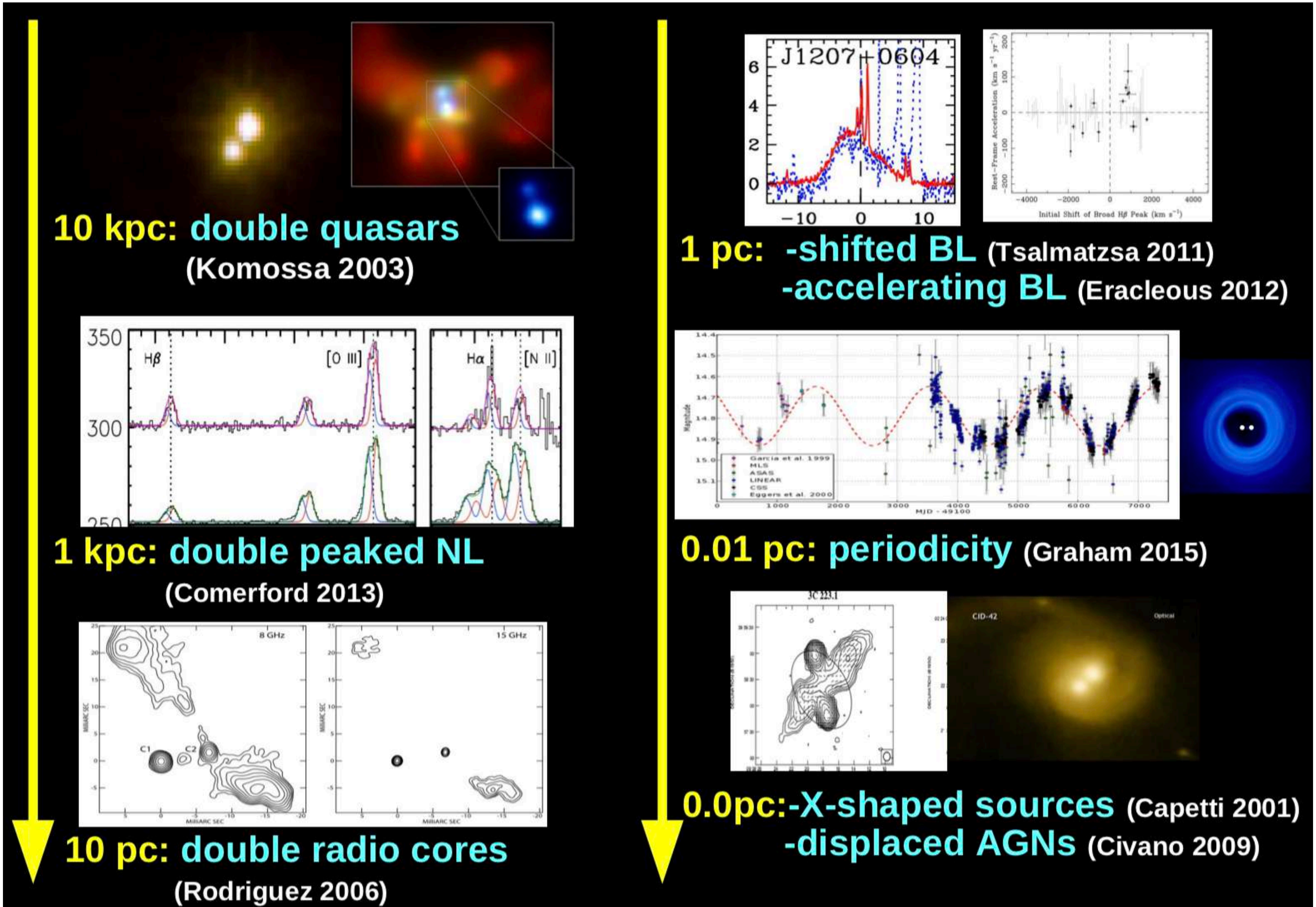


Supermassive black hole formation & evolution



Outline - Lecture 3

C. Supermassive black holes

1. Supermassive black hole formation and evolution

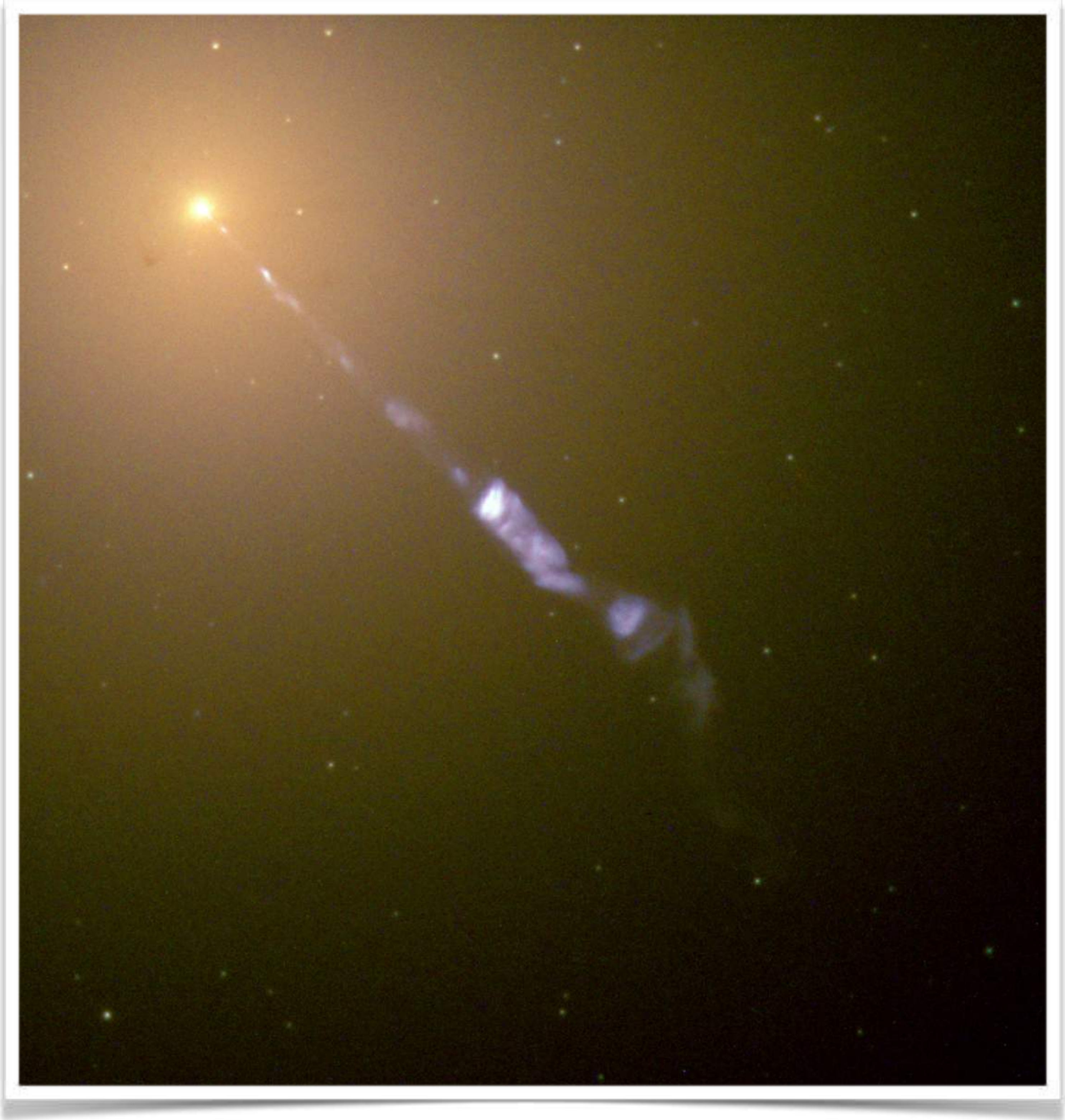
2. **Cosmic rays from Active Galactic Nuclei**

3. Supermassive black hole binaries

Active Galactic nuclei

Galaxy with (one?) very bright nuclei

- Much of the energy output of non-thermal origin ⇒ particle acceleration.
- Strong emitters of gamma/X-rays, radio and ultraviolet radiation, as well as optical radiation.
- AGN can vary in luminosity on short (hours or days) timescales ⇒ related to a supermassive black hole at the center of the galaxy.
- Origin of the high-energy emission: accretion/ejection close to the black hole.



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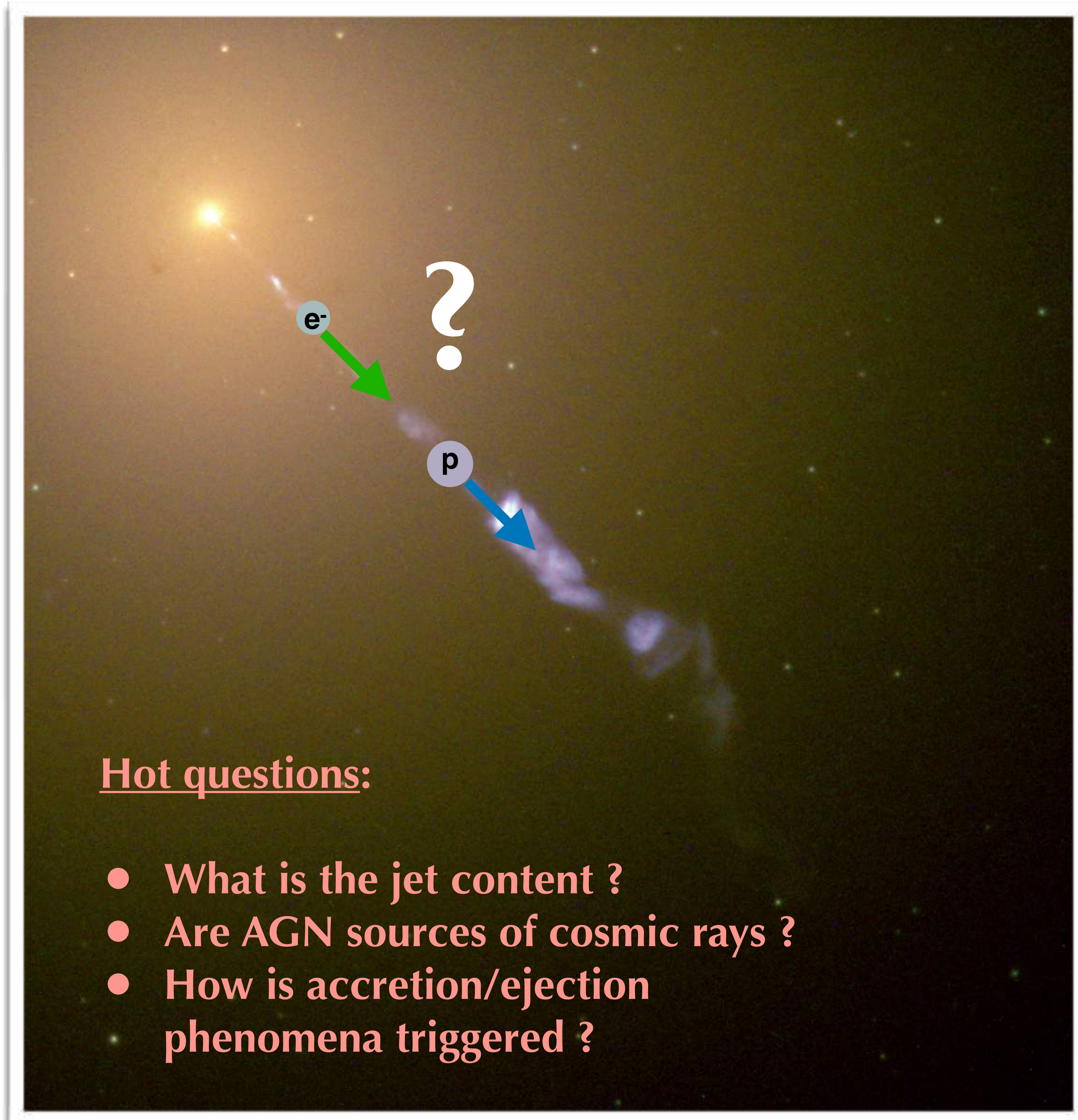

Active Galactic nuclei

Galaxy with (one?) very bright nuclei

- Muc
  the
  acce
- Stro
  radi
  well
- AGN
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  relat
  hole
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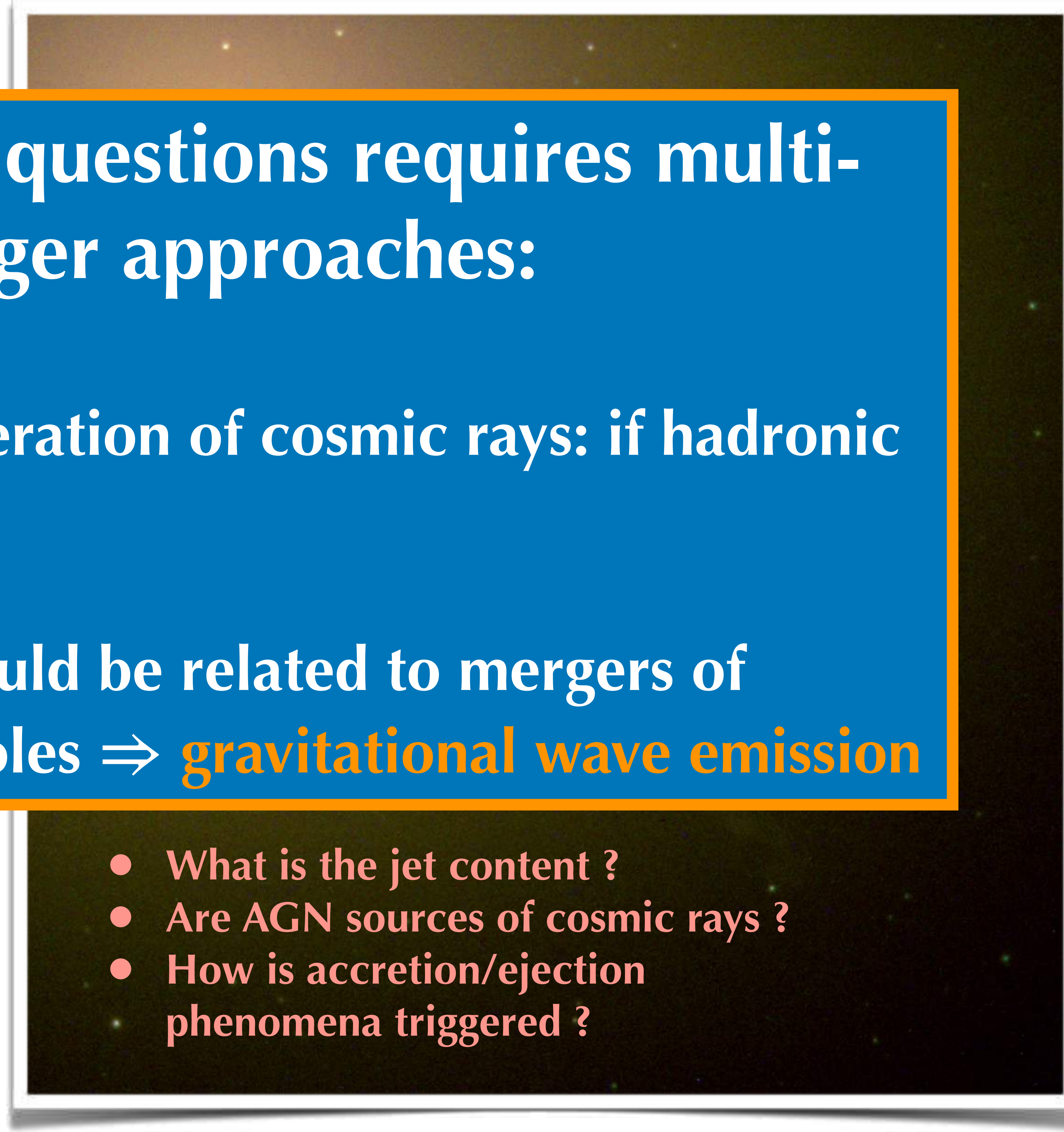
Answering these questions requires multi-messenger approaches:

- **Content of jet / acceleration of cosmic rays: if hadronic ⇒ neutrino emission**
- **Accretion/ejection could be related to mergers of supermassive black holes ⇒ gravitational wave emission**



Active Galactic nuclei

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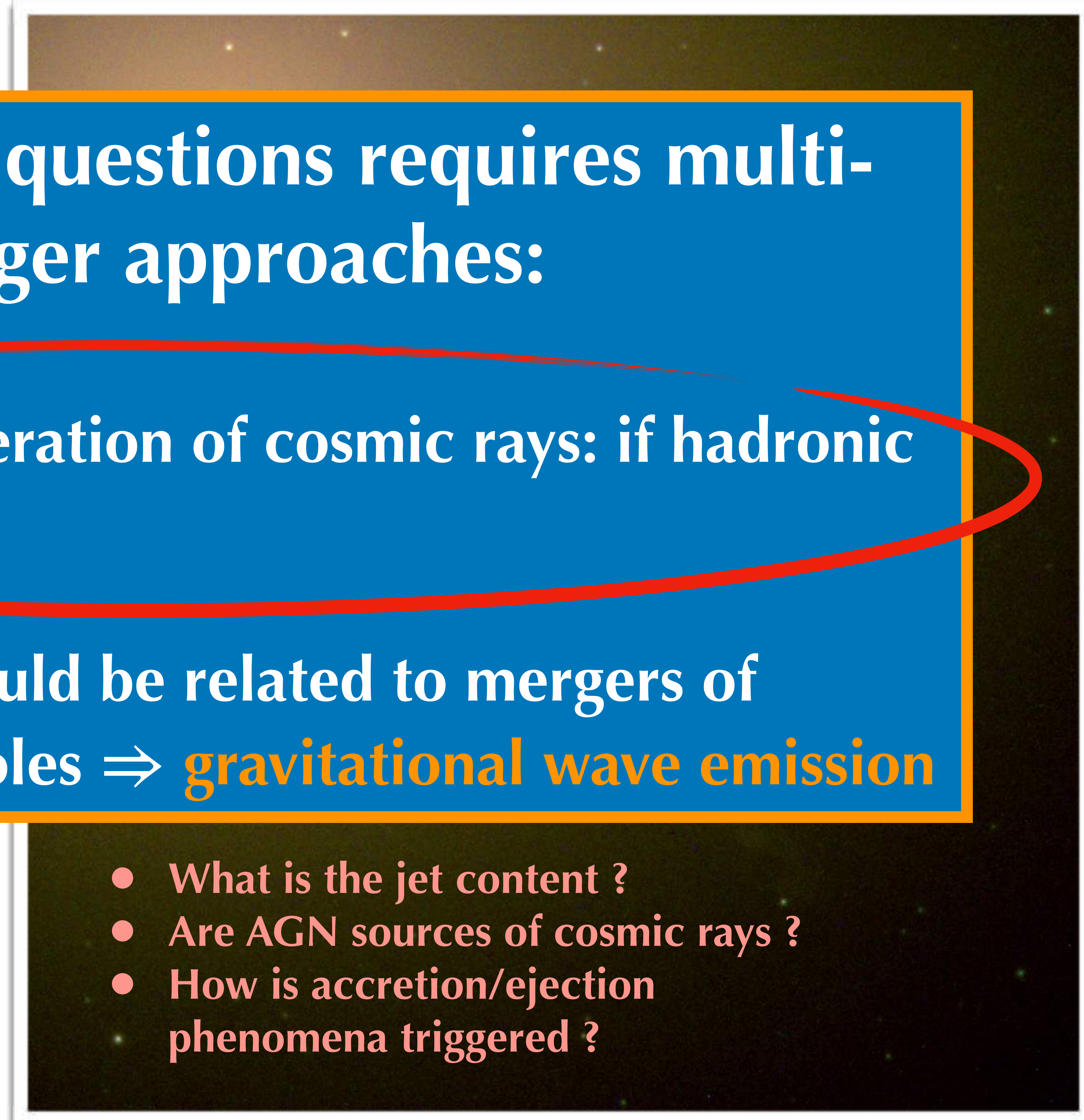
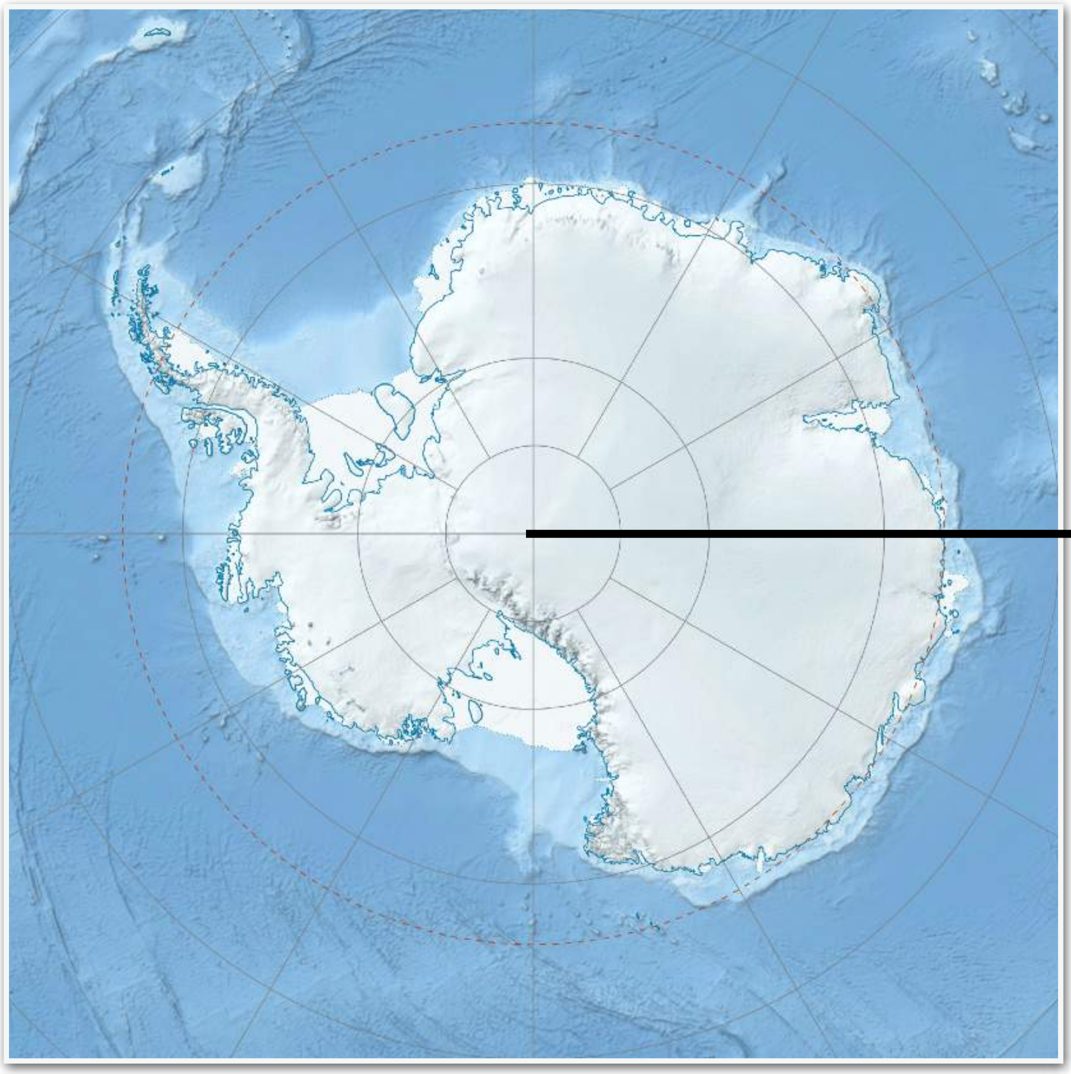
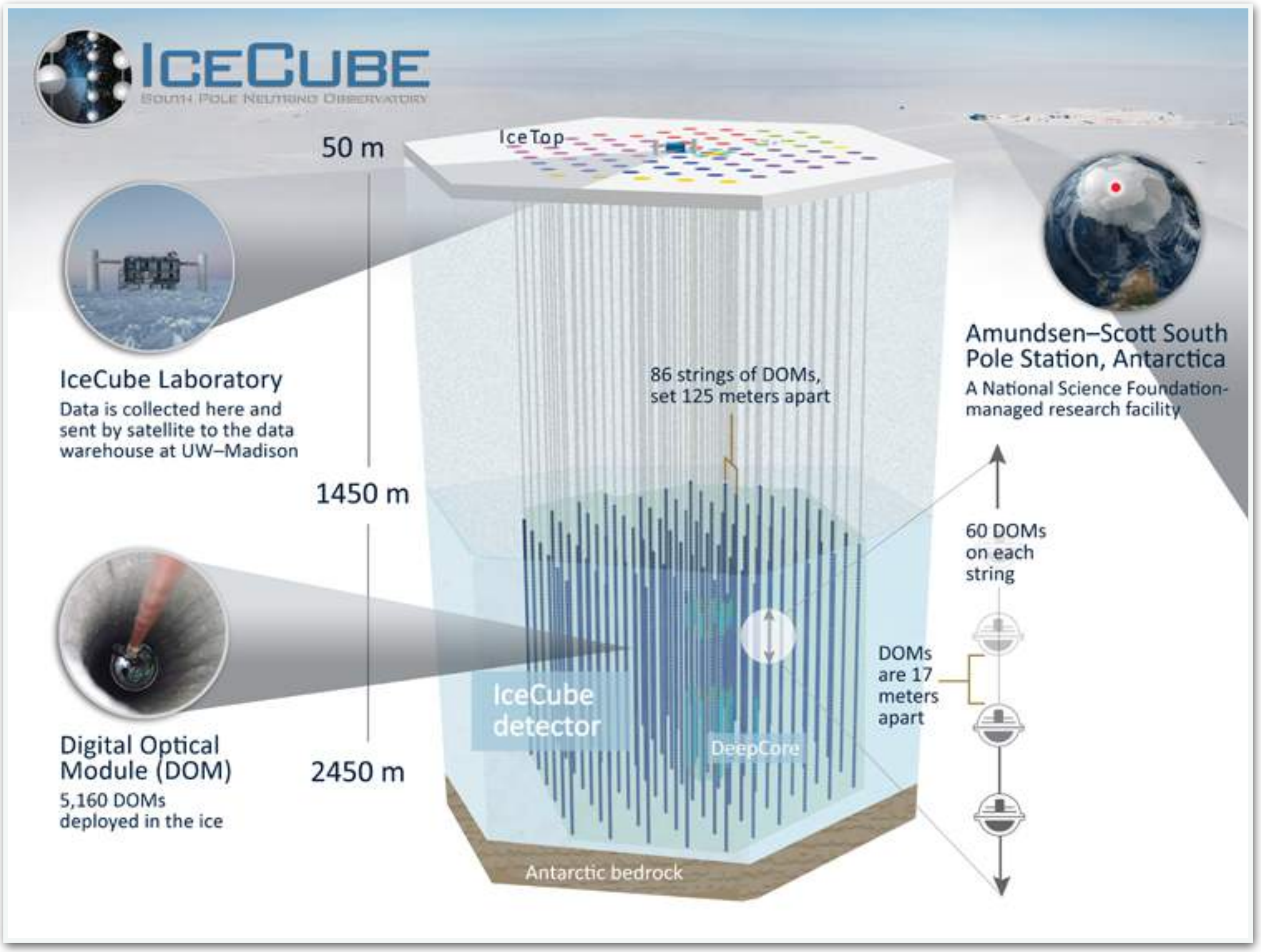


Looking for neutrinos from AGNs

Largest neutrino telescope in operation: IceCube





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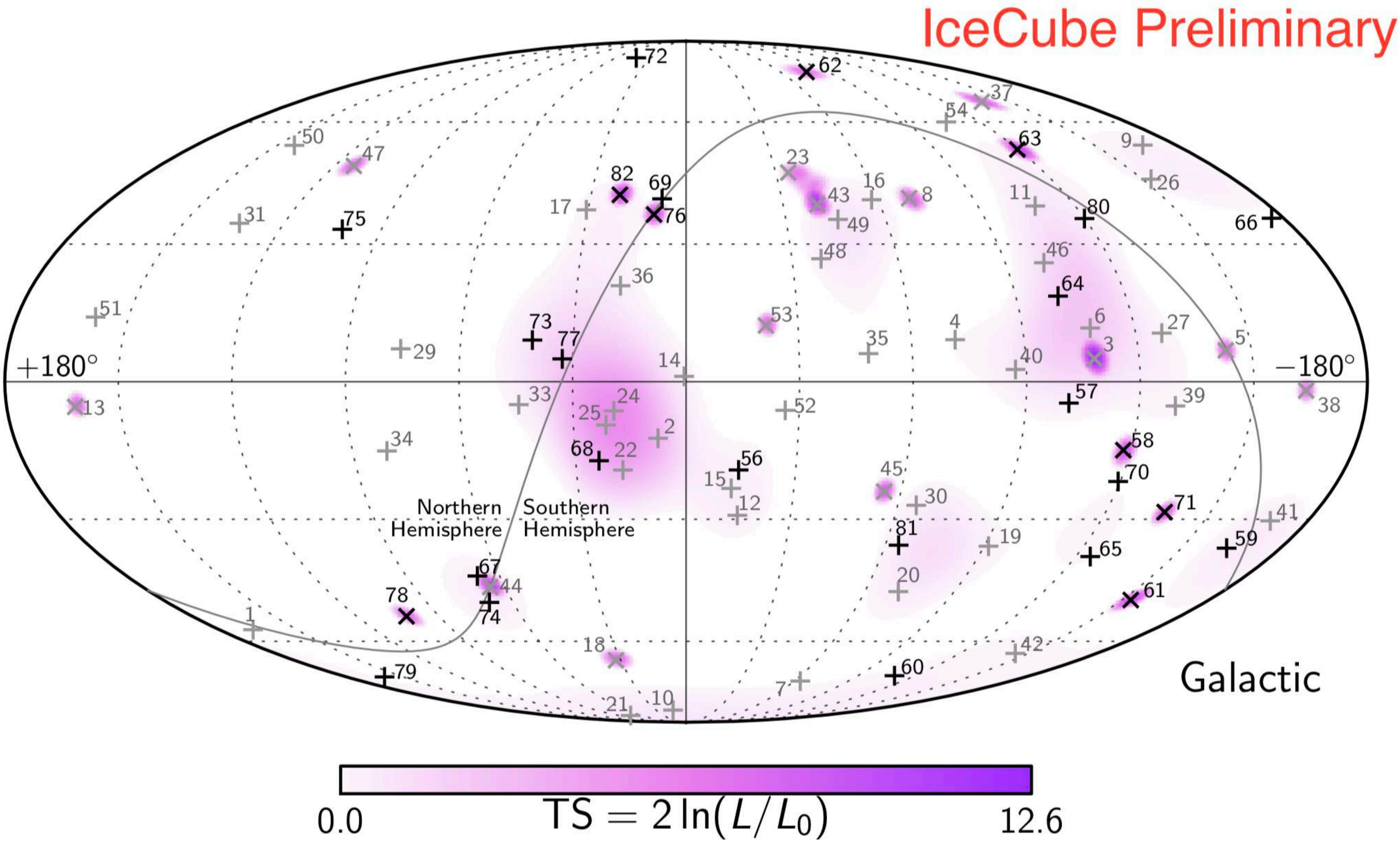
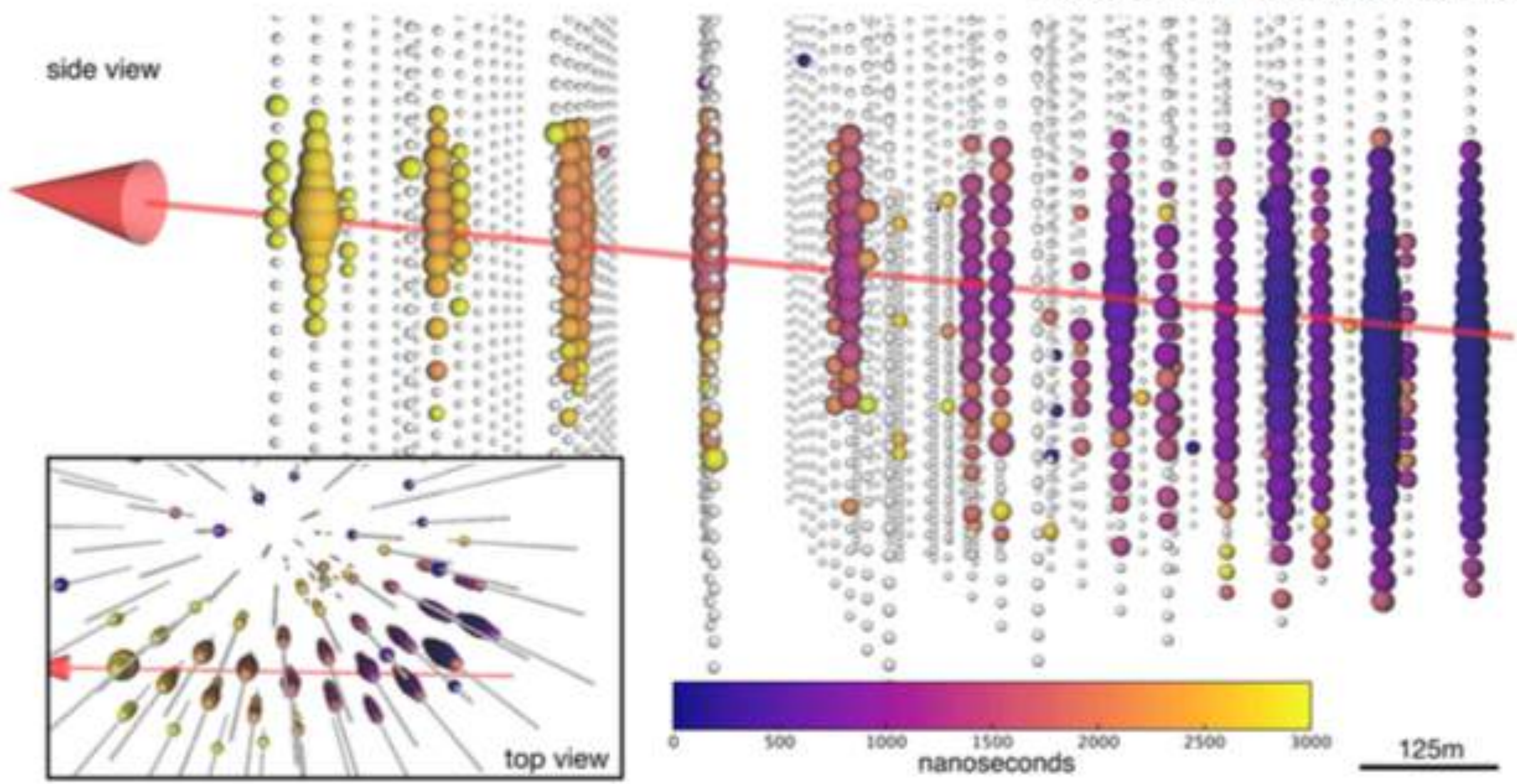


Point sources not identified yet but multi-messenger strategies can help…

IC170922A / TXS 0506+056

22 september 2017 (latency = 43 sec)
Deposited energy = 23.7 ± 2.8 TeV → 290 TeV (90% CL lower limit of 183 TeV)
Signalness = 56.5% → need of electromagnetic counterpart to confirm astro. origin.

Science 361, 6398, (2018) eaat1378



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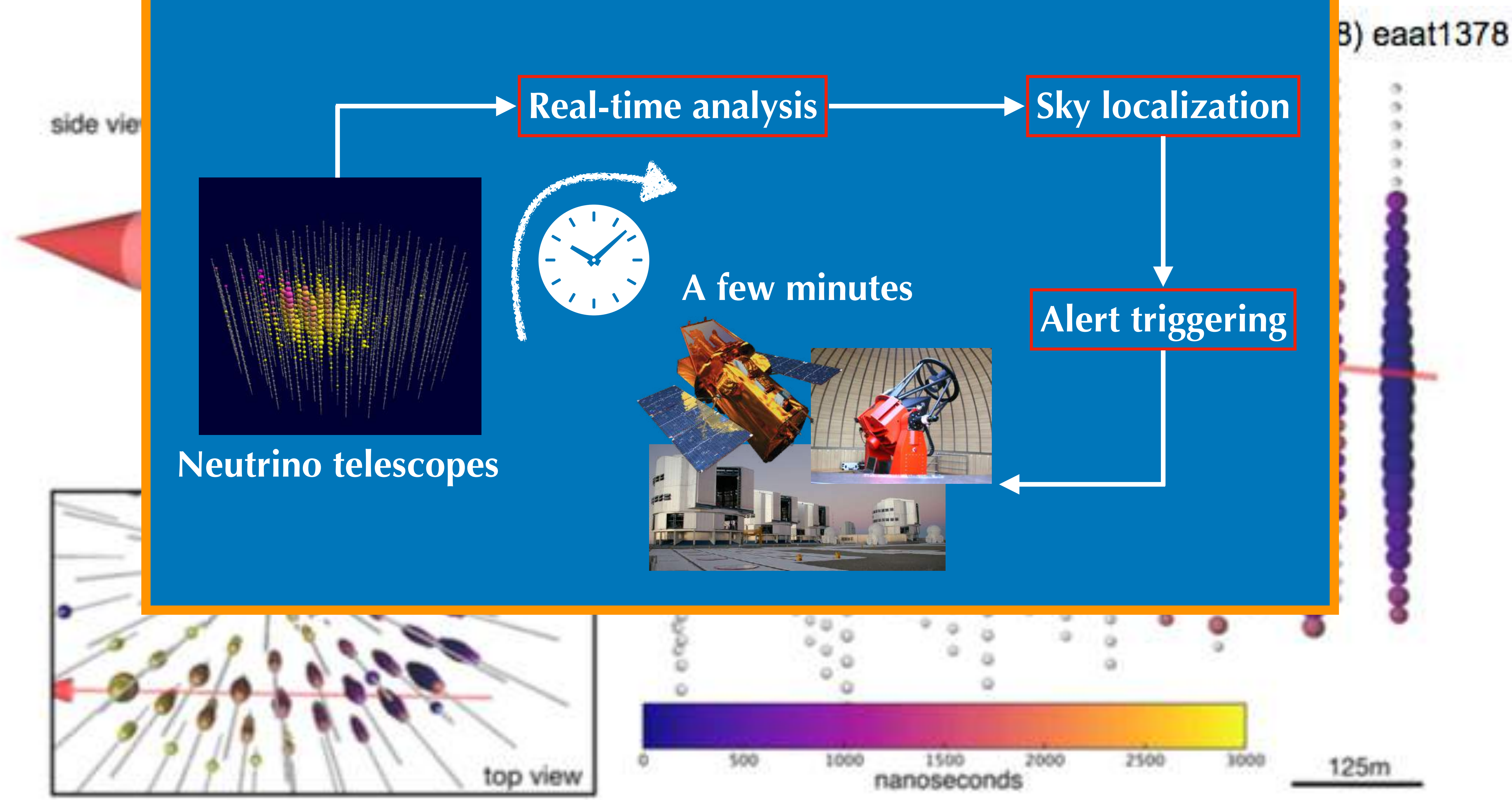
Signalne

Alert sent to astronomers to look for electromagnetic counterpart



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10802	HAWC gamma ray data prior to IceCube-170922A
10801	AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799	Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794	ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792	Further Swift-XRT observations of IceCube 170922A
10791	Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787	H.E.S.S. follow-up of IceCube-170922A
10773	Search for counterpart to IceCube-170922A with ANTARES

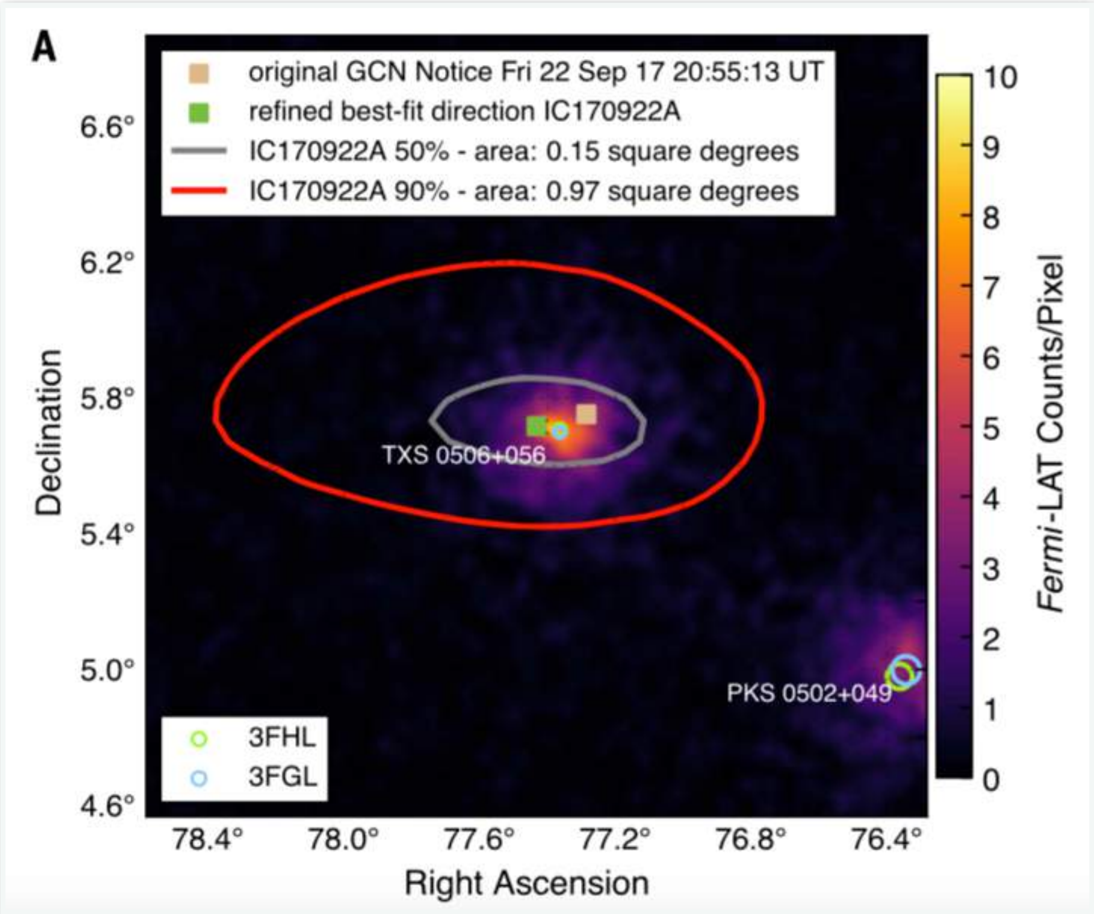
10845	Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844	Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840	VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838	MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833	VERITAS follow-up observations of IceCube neutrino event 170922A
10831	Optical photometry of TX0506+056
10830	SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817	First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

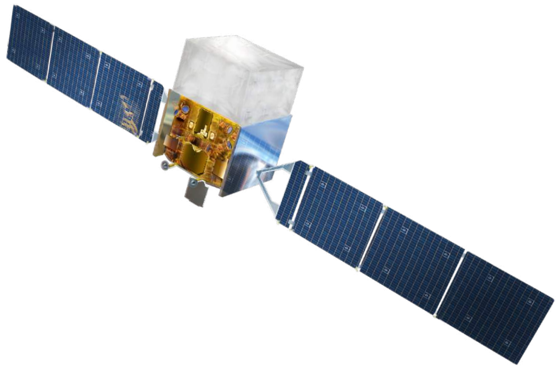
+ INTEGRAL

11489	Optical and near-infrared polarimetric observations of the IceCube-170922A counterpart candidate TXS 0506+056
11430	Optical polarimetry of TXS 0506+056 (possible counterpart of IceCube-170922A)
11419	Fermi-LAT detection of enhanced gamma-ray activity and hard spectrum of TXS 0506+056, located inside the IceCube-170922A error region

10890	Subaru/FOCAS Optical Spectroscopy for a possible IceCube-170922A counterpart TXS 0506+056
10861	VLA Radio Observations of the blazar TXS 0506+056 associated with the IceCube-170922A neutrino event

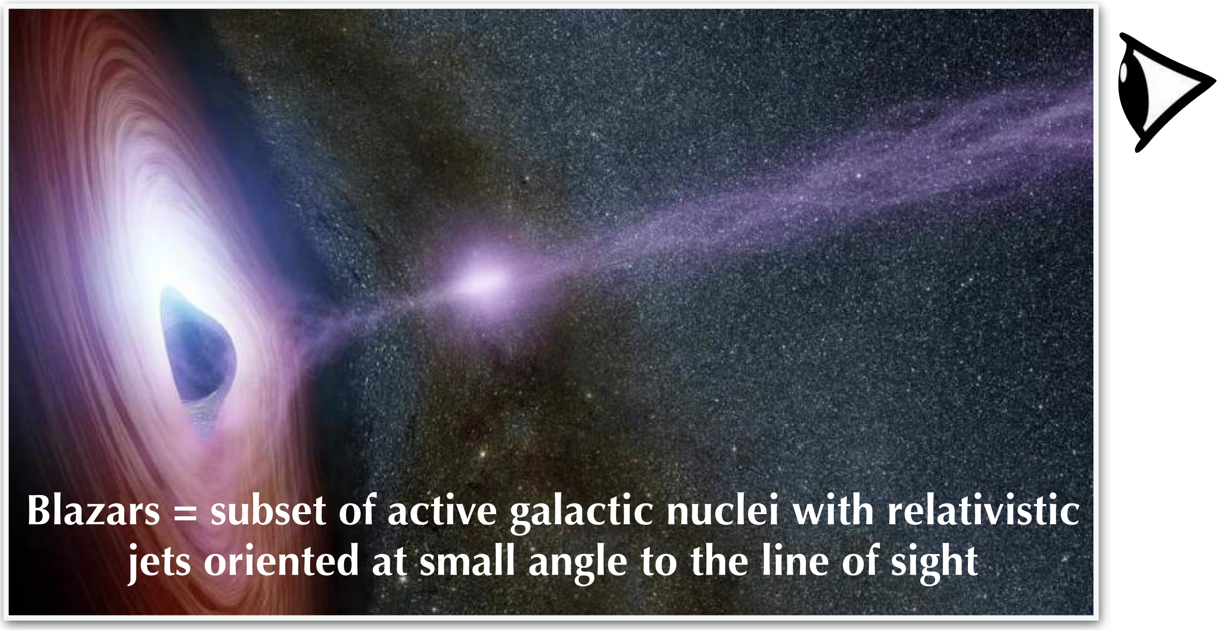
IC170922A / TXS 0506+056

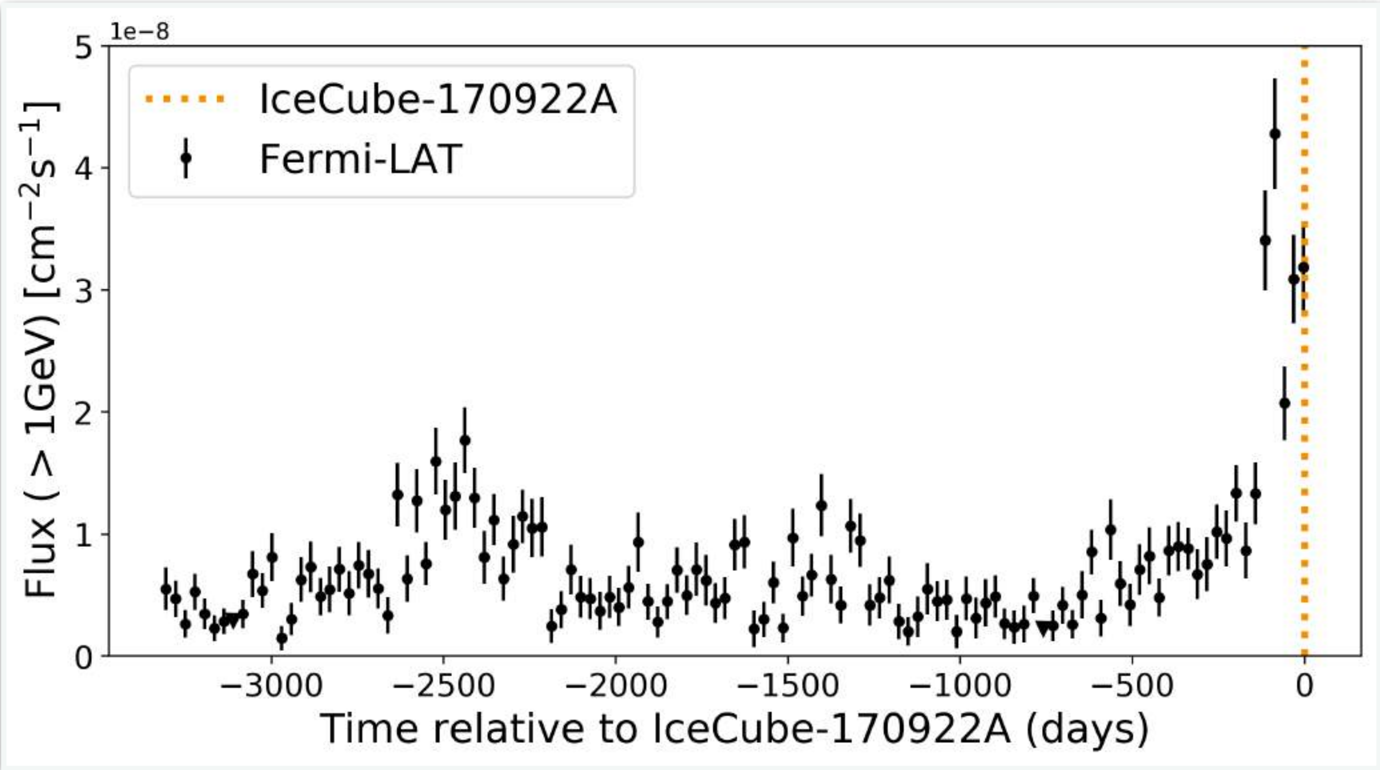




Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)



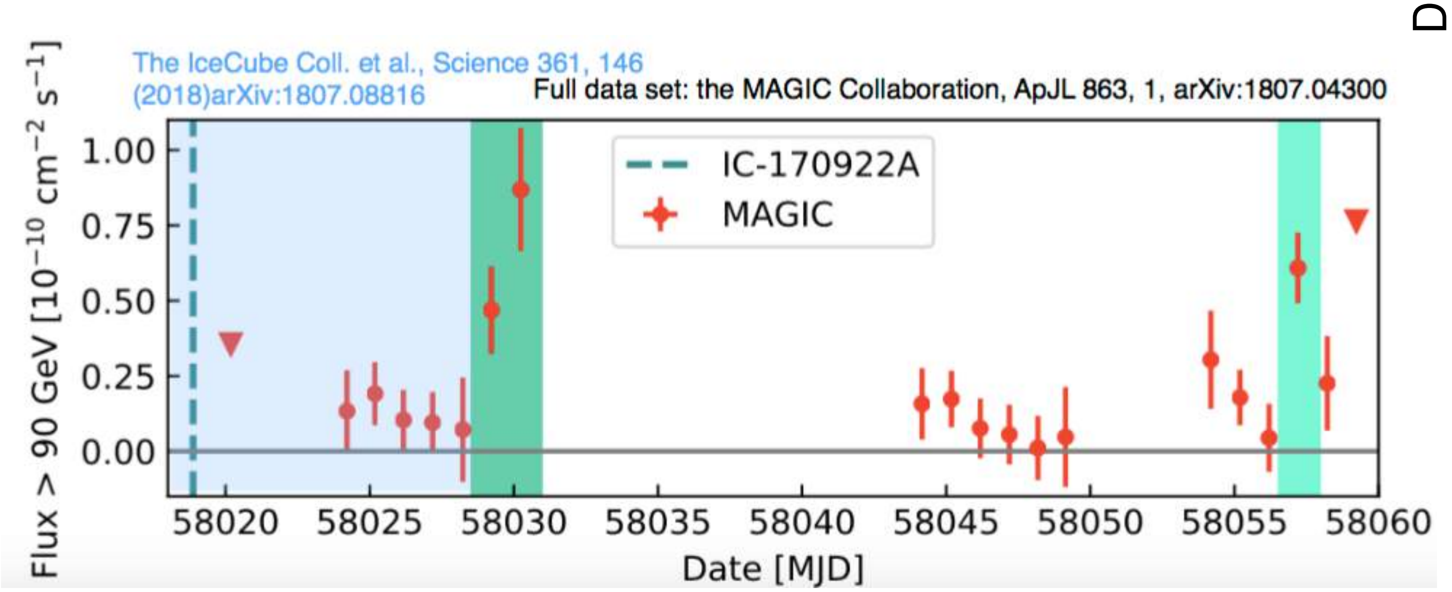


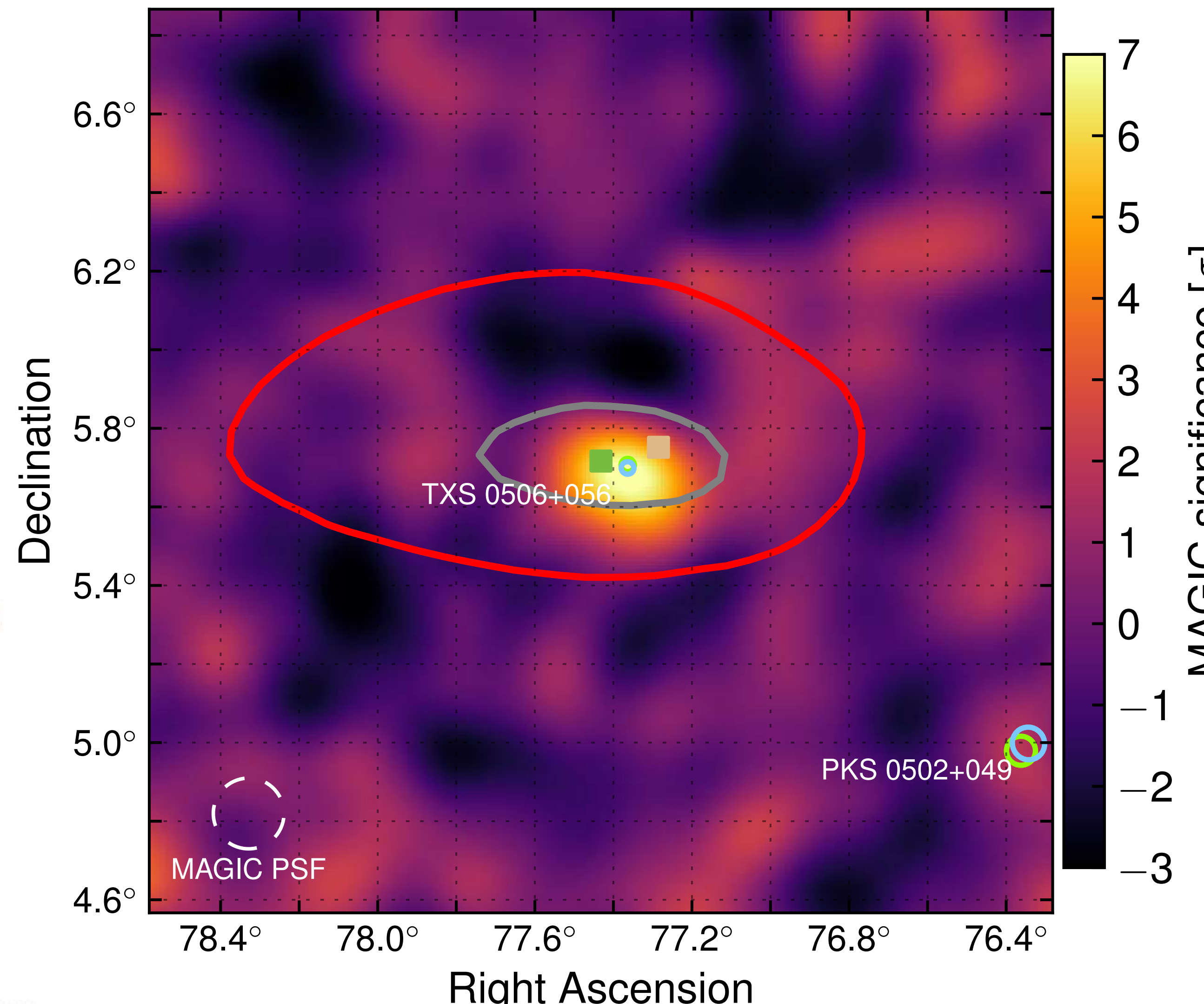
IC170922A / TXS 0506+056

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

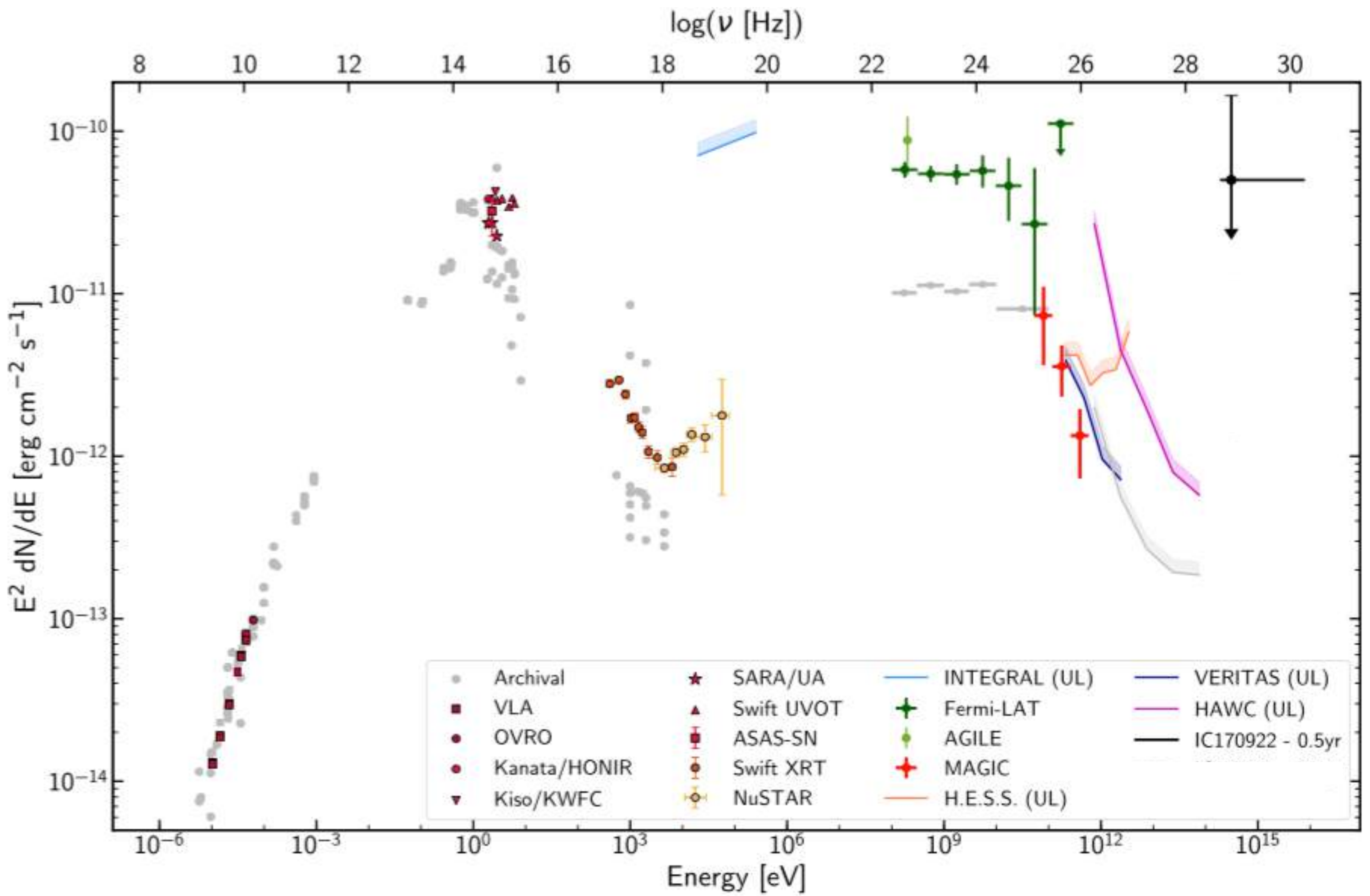
- Detection up to ~400 GeV
- Clear variability on daily timescale
- Spectral index raging from -4.0 to -3.5





Pre-trials p-value = 4.1σ. 10 public alerts + 41 archival events → post-trials p-value = 3.0σ
Significant result due to « simultaneous » detection in neutrinos and gamma-rays !

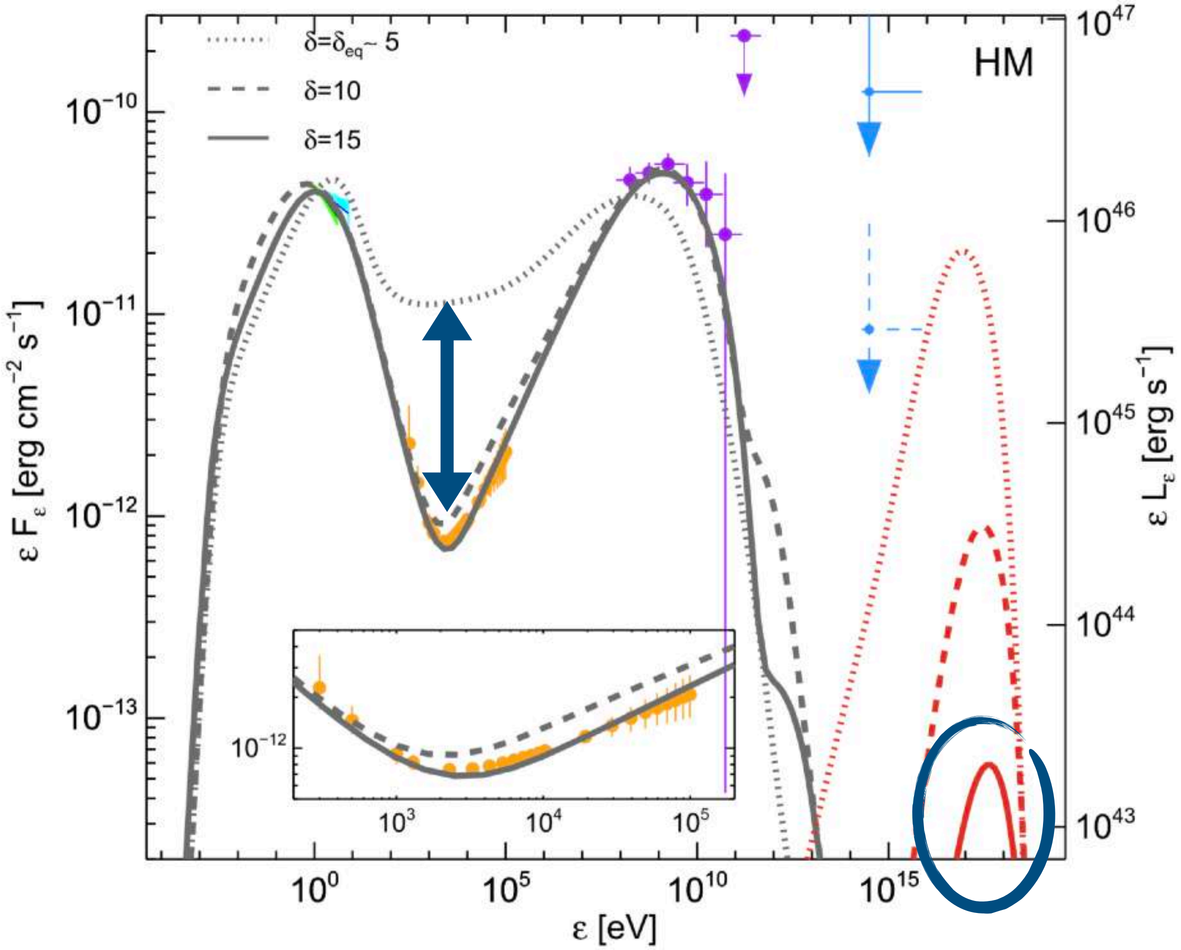
TXS 0506+056 multi-messengerr follow-up[194]



Science 361, eaat1378 (2018)

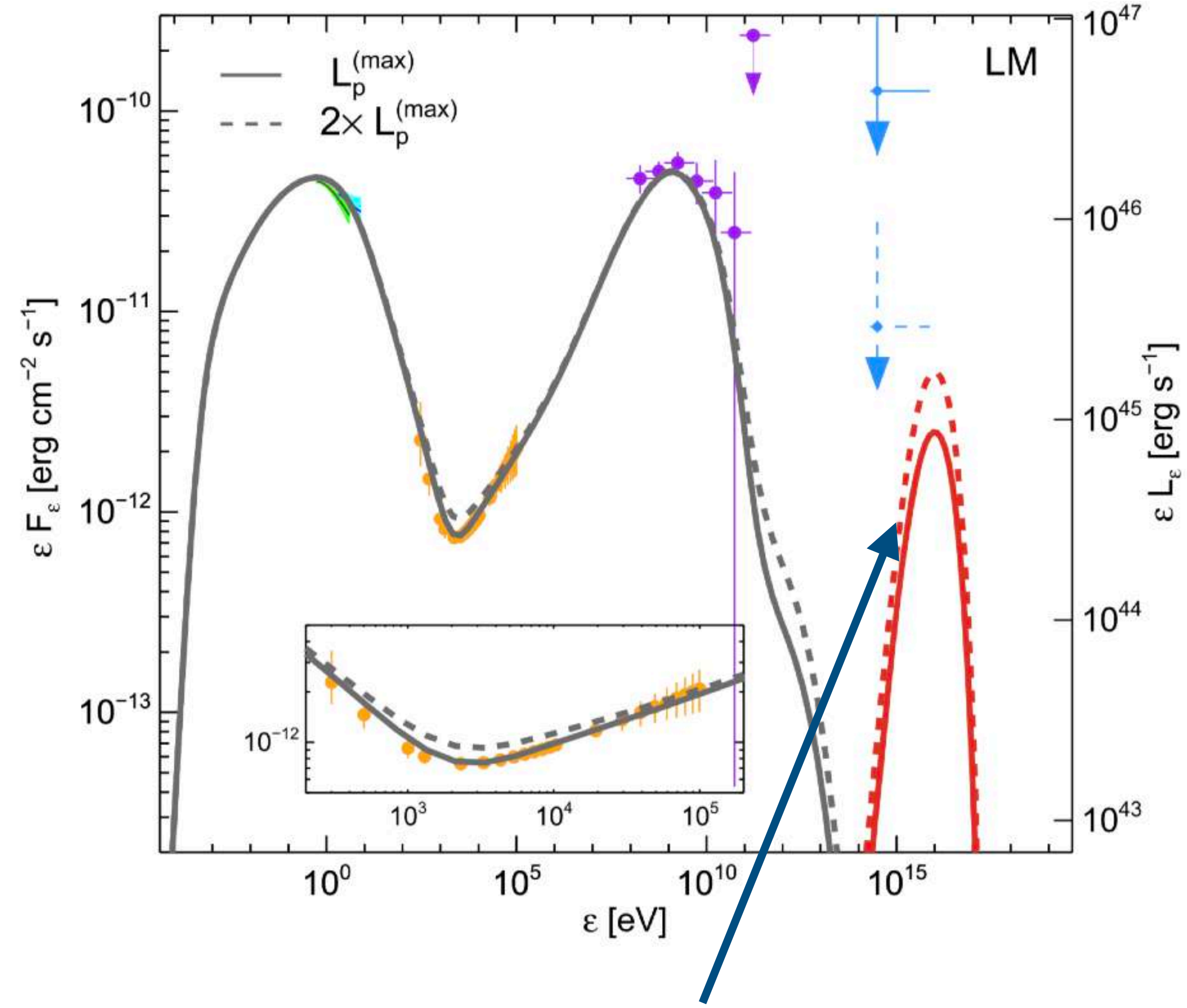
IC170922A / TXS 0506+056

Hadronic models



Keivani et al., ApJ, 864, 1, 2018
(see also Gao et al., 2018 + Murase et al. 2018 + Reimer et al. 2019)

Lepto-hadronic models

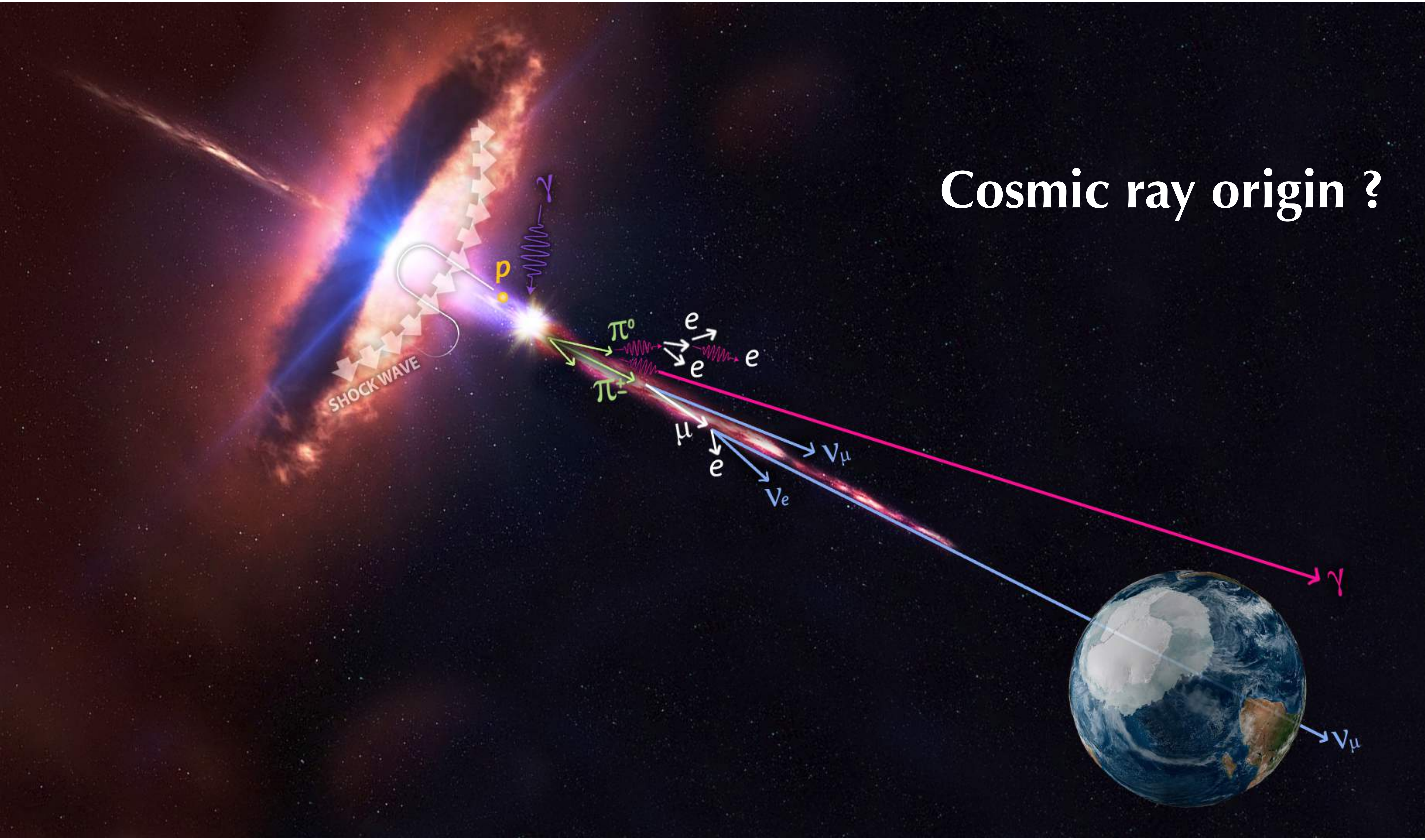


1-2% probability of observing 1 neutrino with IceCube

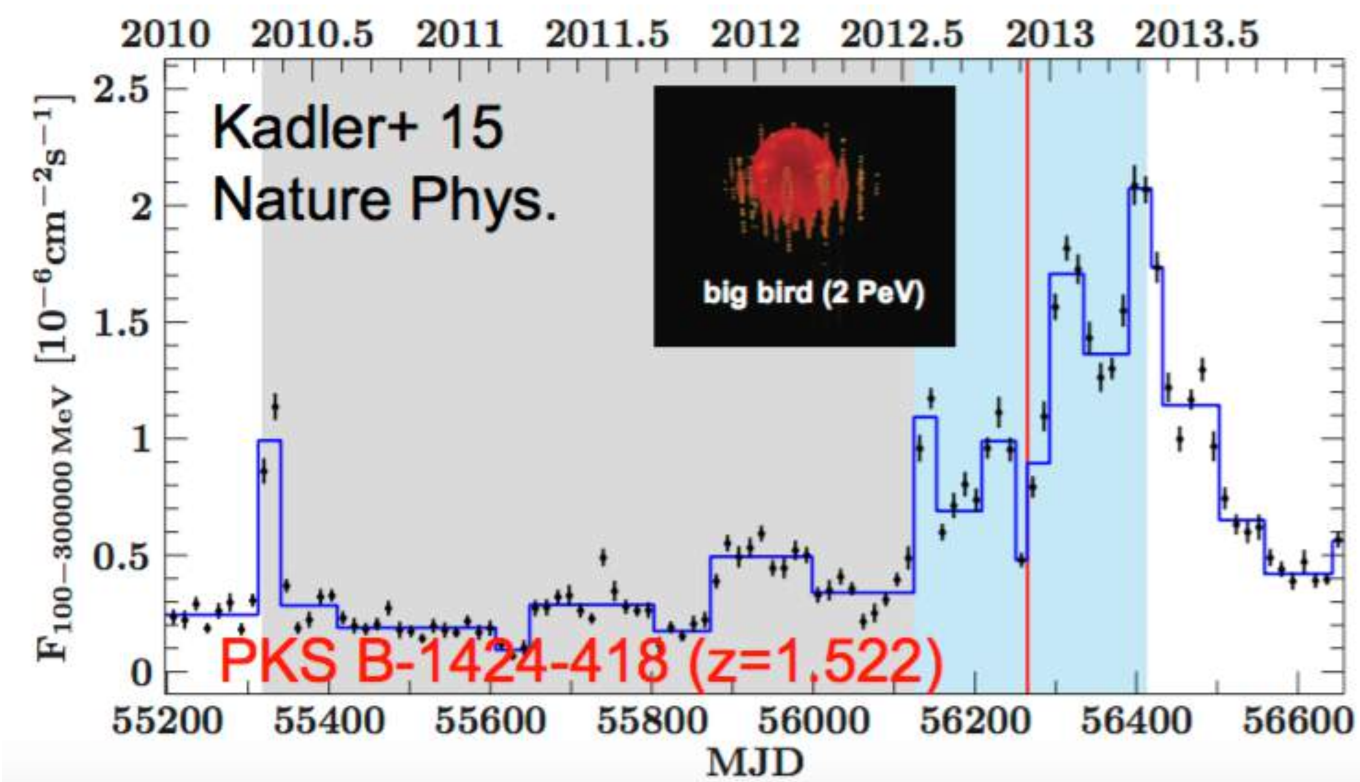
- Models with p-γ induced γ-ray emission overproduce X-rays due to emission of cascades of secondary particles (Gao et al., 2018 & Keivani et al., 2018).

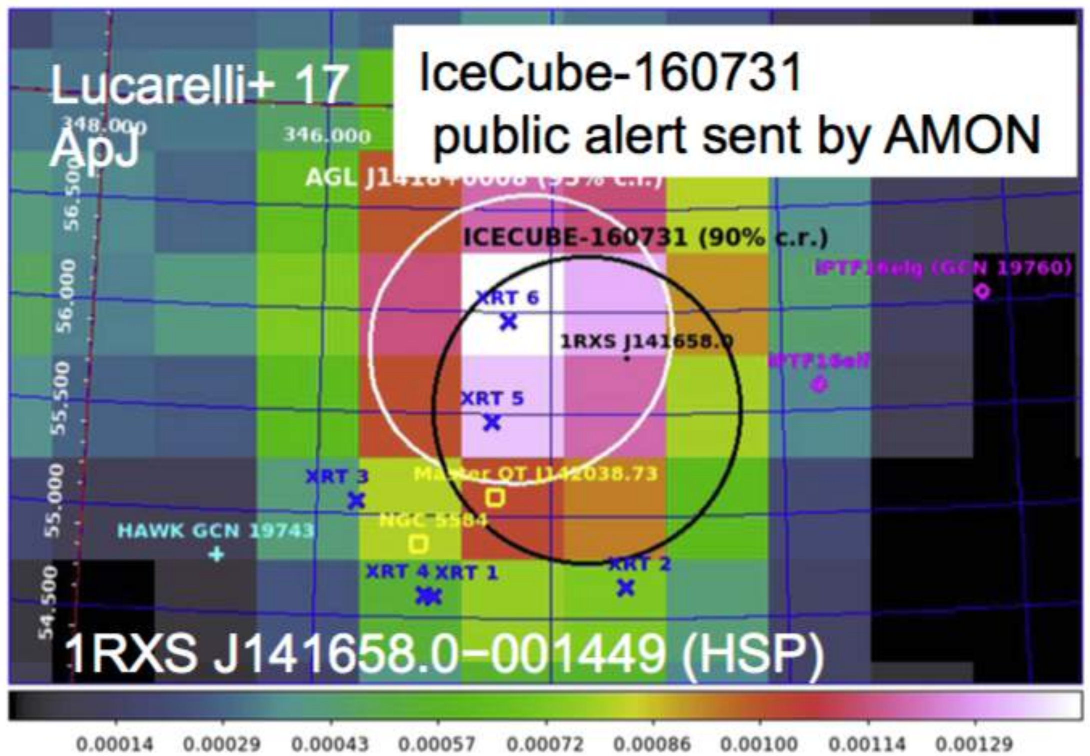
- Electromagnetic emission dominated by leptonic processes + radiatively sub-dominant hadronic component → neutrino flux: 1% probability of observing 1 neutrino over 6 months with IceCube.

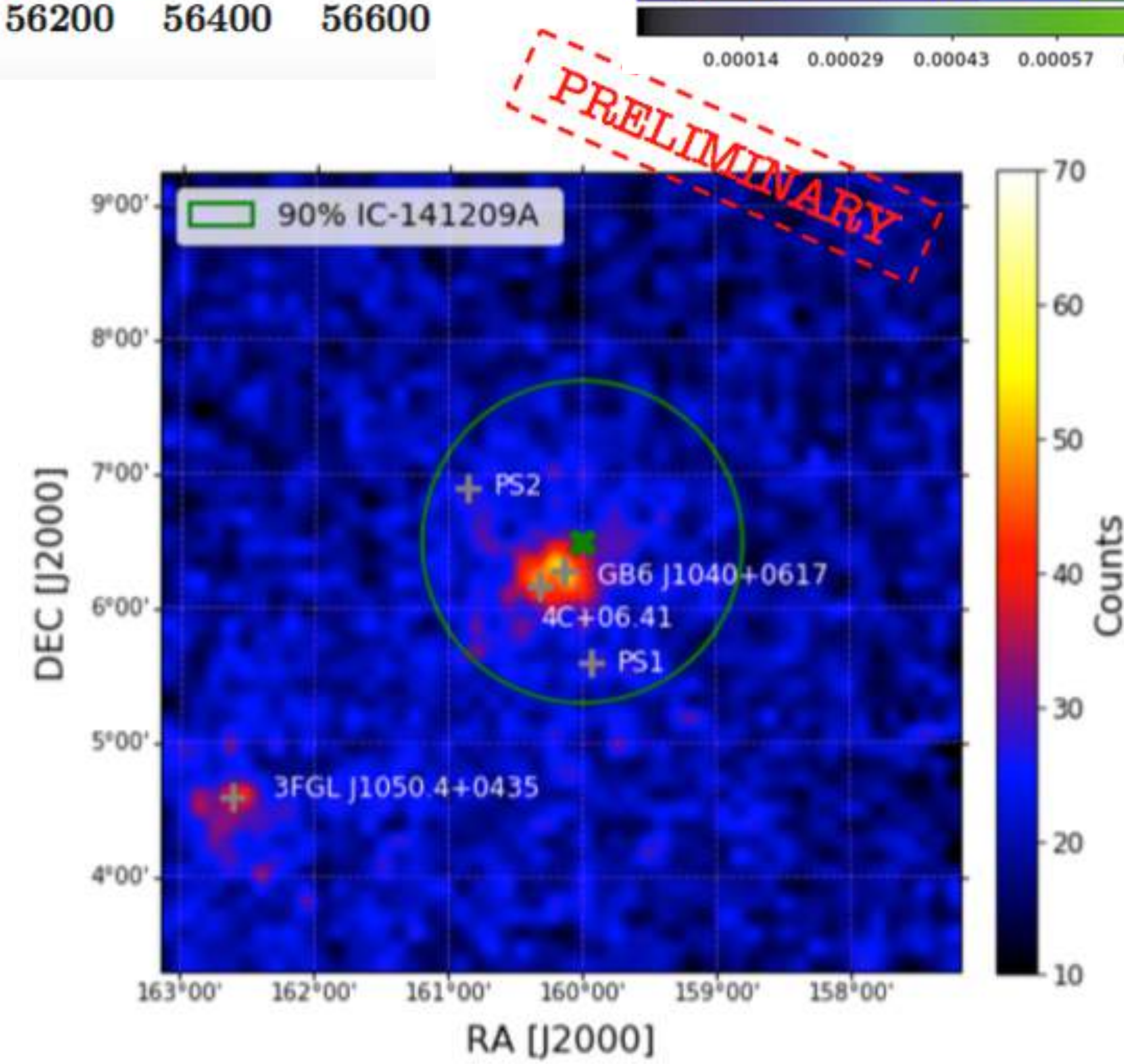
IC170922A / TXS 0506+056



Other candidates ?







IC-141209A

- MJD 57000.14
- (Ra , Dec) = (160.0°, 6.5°)
- Ang. Err. (90%) : 1.2°

GB6 J1040+0617

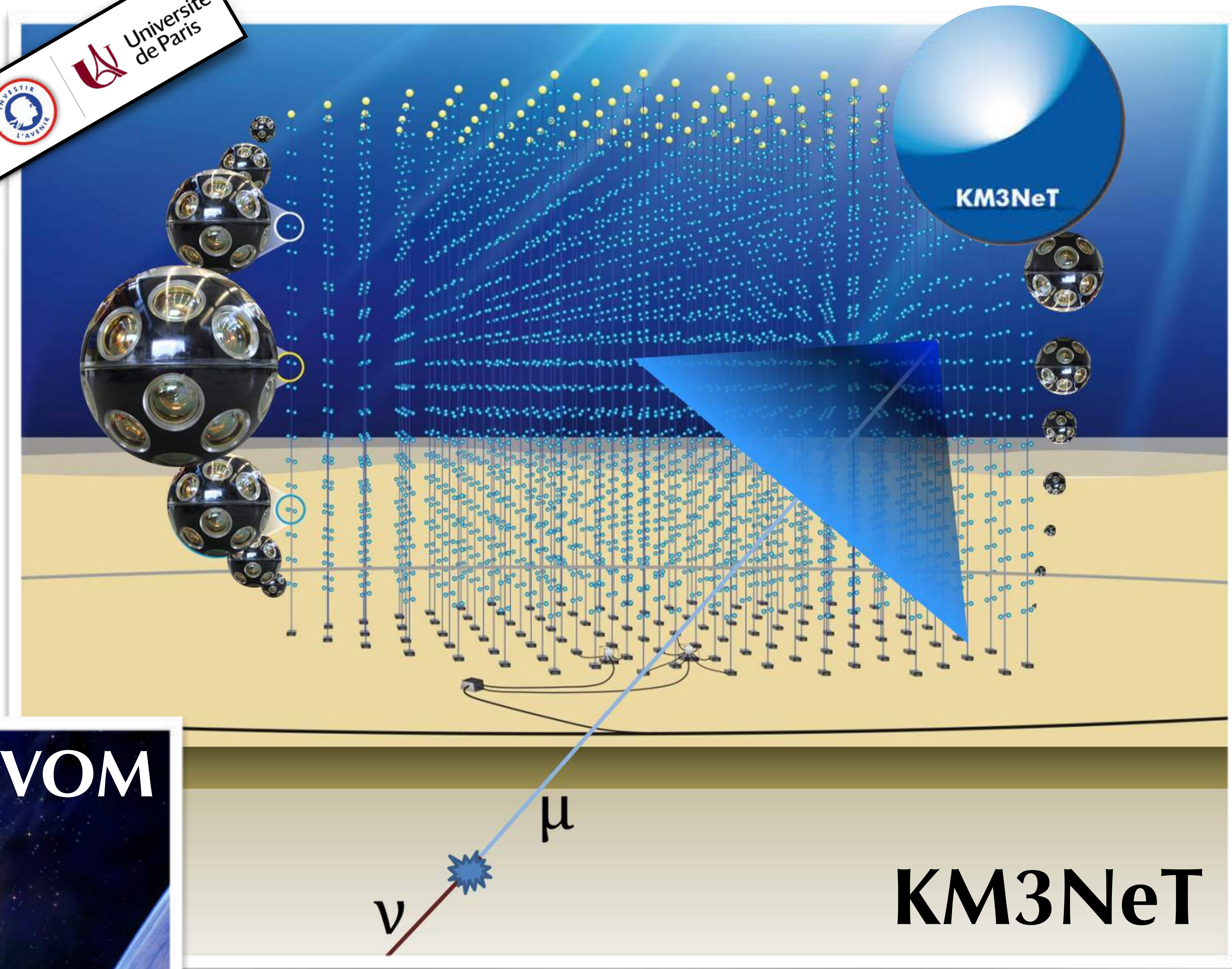
- BL Lac, LSP
- 3FGL J1040.4+0615
- z = 0.7351± 0.0045 *
- Dist. from IC-141209A: 0.27°

Stay tuned…

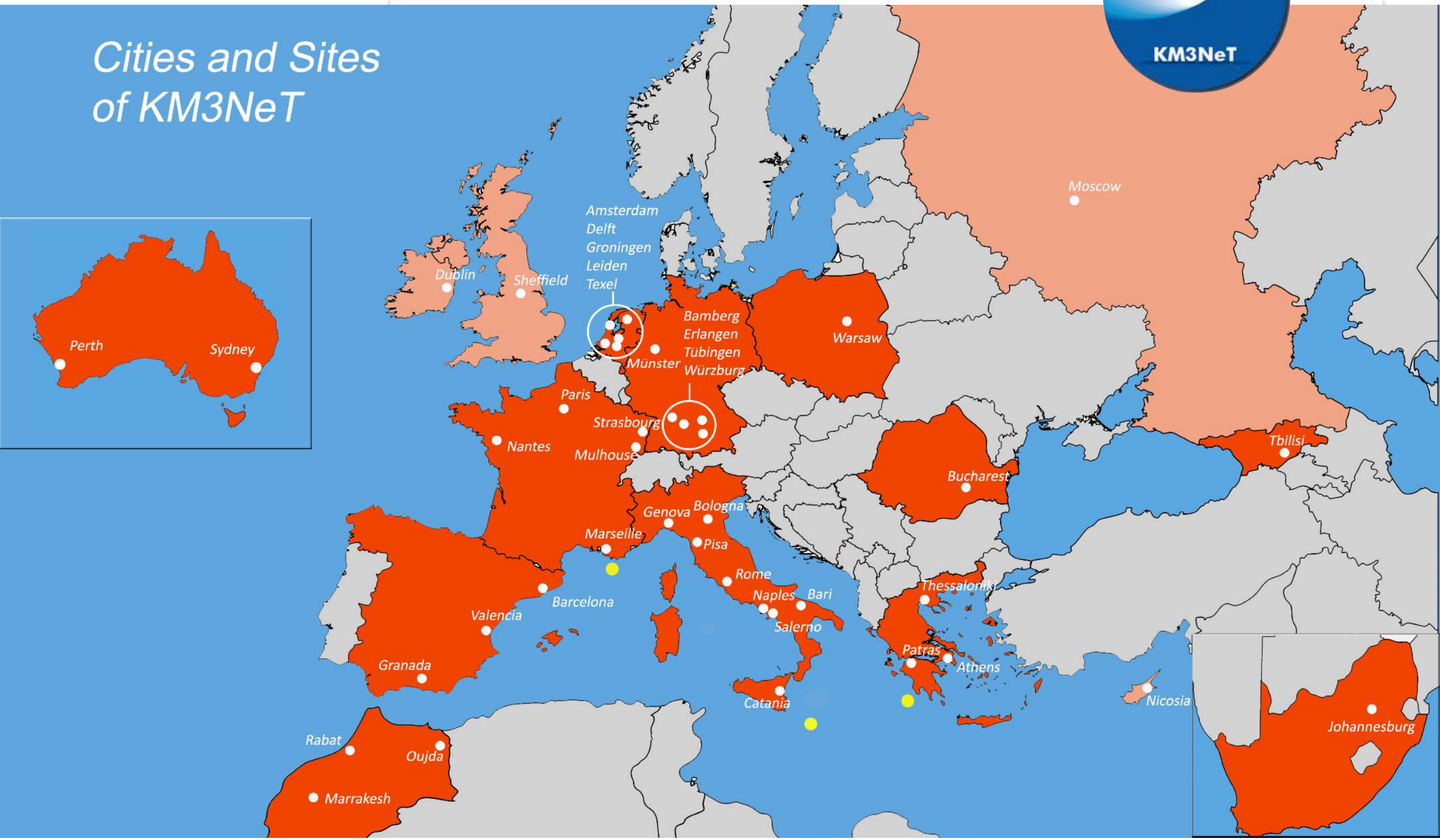
Future

Labex UnivEarthS

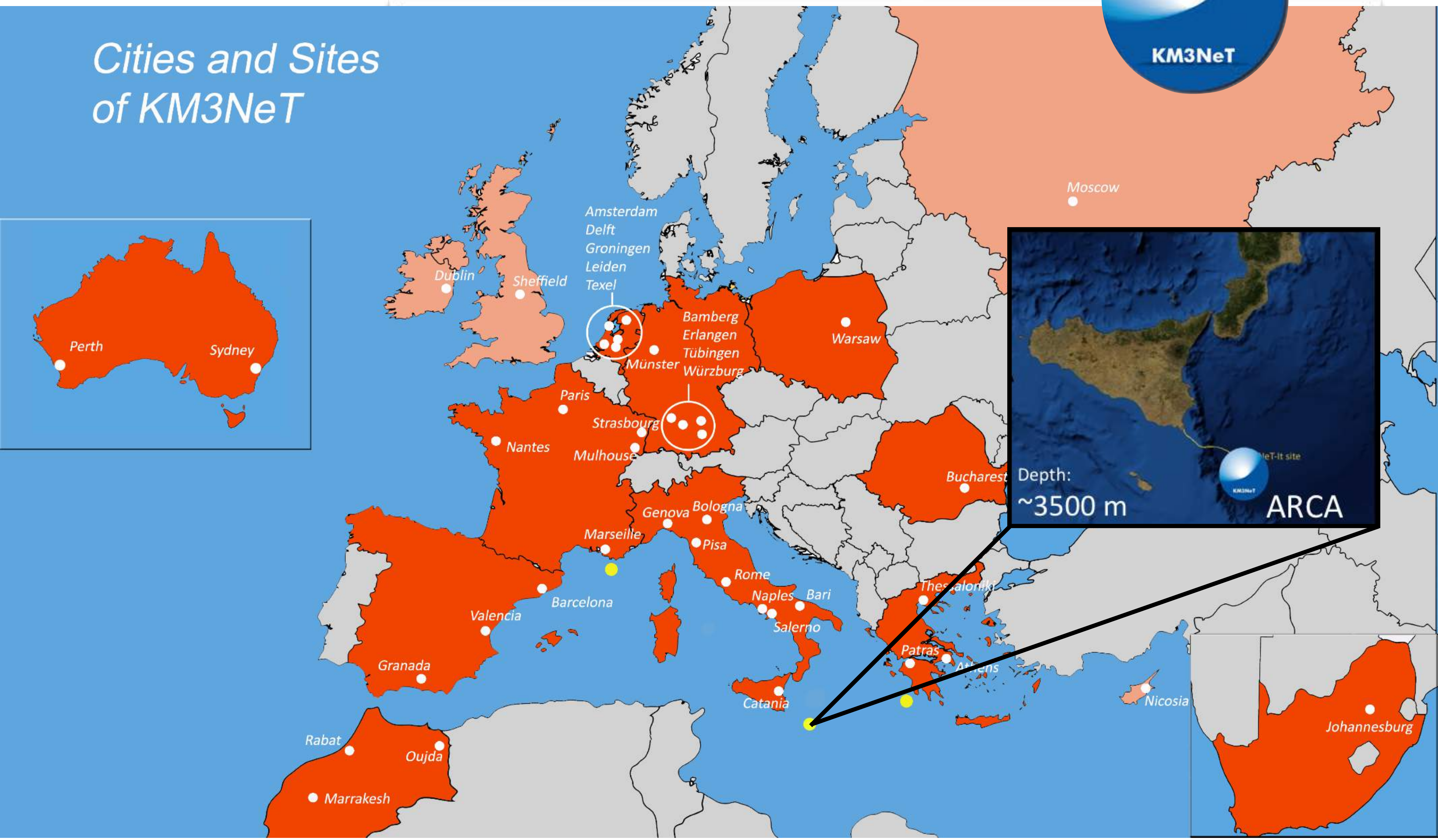
Université de Paris



Future


Cities and Sites
of KM3NeT
Perth
Sydney
Dublin
Sheffield
Amsterdam
Delft
Groningen
Leiden
Texel
Bamberg
Erlangen
Tübingen
Würzburg
Münster
Warsaw
Moscow
Paris
Strasbourg
Nantes
Mulhouse
Tbilisi
Bucharest
Genova
Bologna
Marseille
Pisa
Rome
Naples
Bari
Salerno
Barcelona
Valencia
Granada
Thessaloniki
Patras
Athens
Catania
Nicosia
Johannesburg
Rabat
Oujda
Marrakesh

Future


Cities and Sites of KM3NeT
Perth
Sydney
Dublin
Sheffield
Amsterdam
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Groningen
Leiden
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Erlangen
Tübingen
Würzburg
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Moscow
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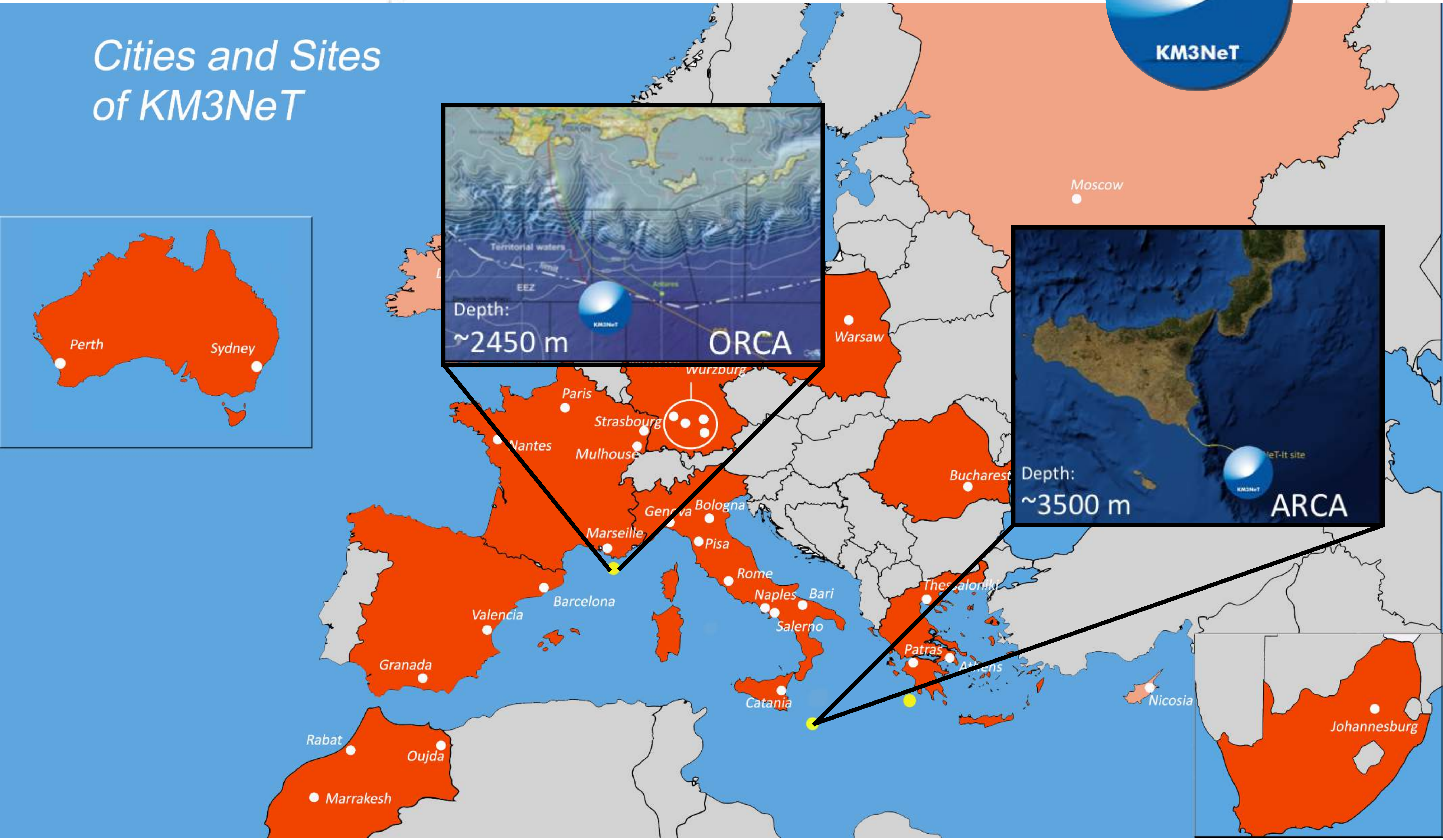
Marseille
Pisa
Rome
Naples
Bari
Salerno
Barcelona
Valencia
Granada
Patras
Catania
Nicosia
Rabat
Oujda
Marrakesh
Johannesburg
Depth:
~3500 m
ARCA

Future


Cities and Sites
of KM3NeT
Perth
Sydney
Territorial waters
EEZ
Depth:
~2450 m
ORCA
Wurzburg
Paris
Strasbourg
Nantes
Mulhouse
Warsaw
Moscow
Depth:
~3500 m
ARCA
Bucharest
Bologna
Marseille
Pisa
Rome
Naples
Bari
Salerno
Barcelona
Valencia
Granada
Patras
Catania
Nicosia
Johannesburg
Rabat
Oujda
Marrakesh

Future

Multi-messenger astronomy into space but also…under water !

Future

Multi-messenger astronomy into space but also…under water !

Outline - Lecture 3

C. Supermassive black holes

1. Supermassive black hole formation and evolution
2. Cosmic rays from Active Galactic Nuclei
3. **Supermassive black hole binaries**

Active Galactic nuclei

Galaxy with (one?) very bright nuclei

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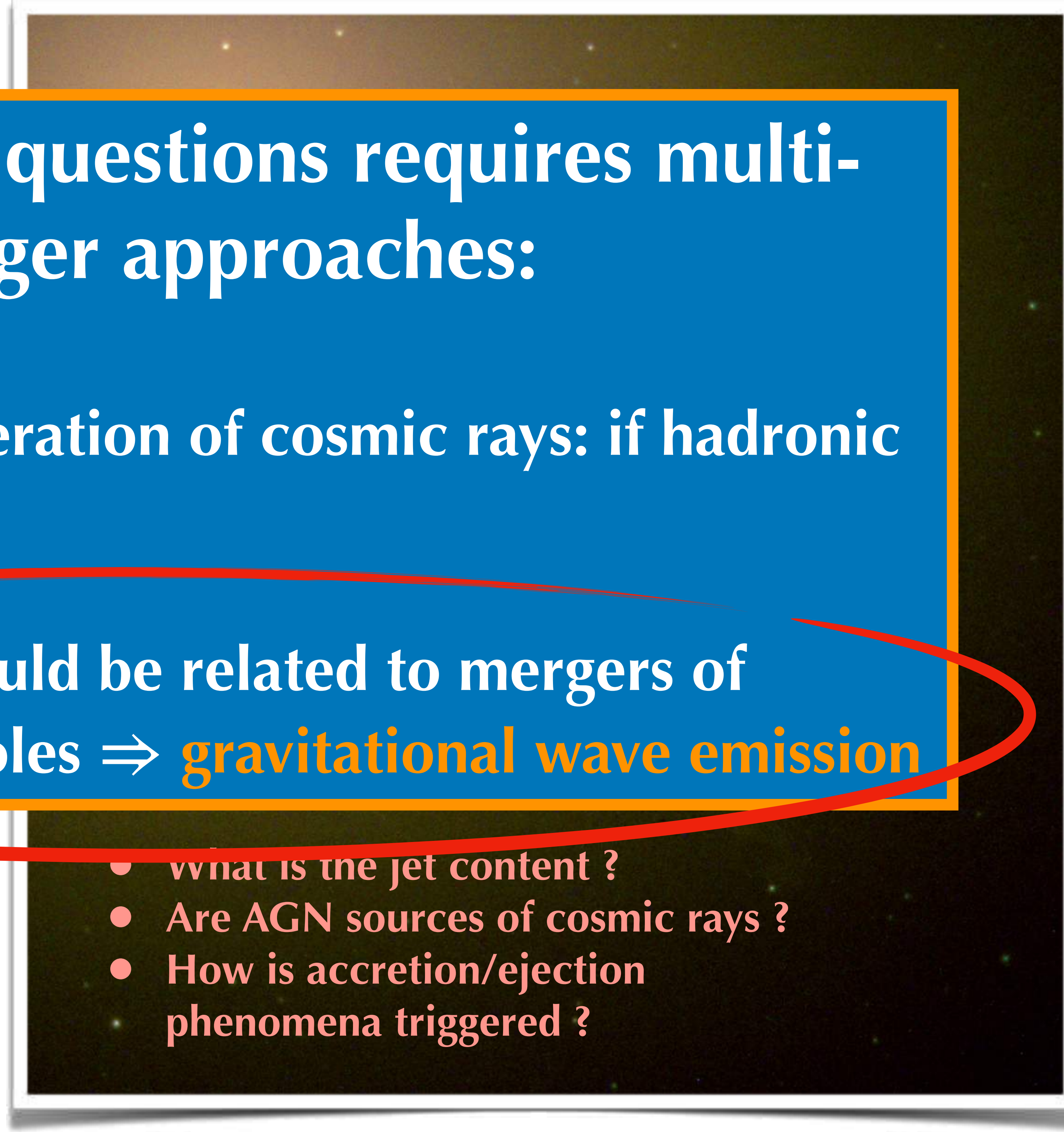
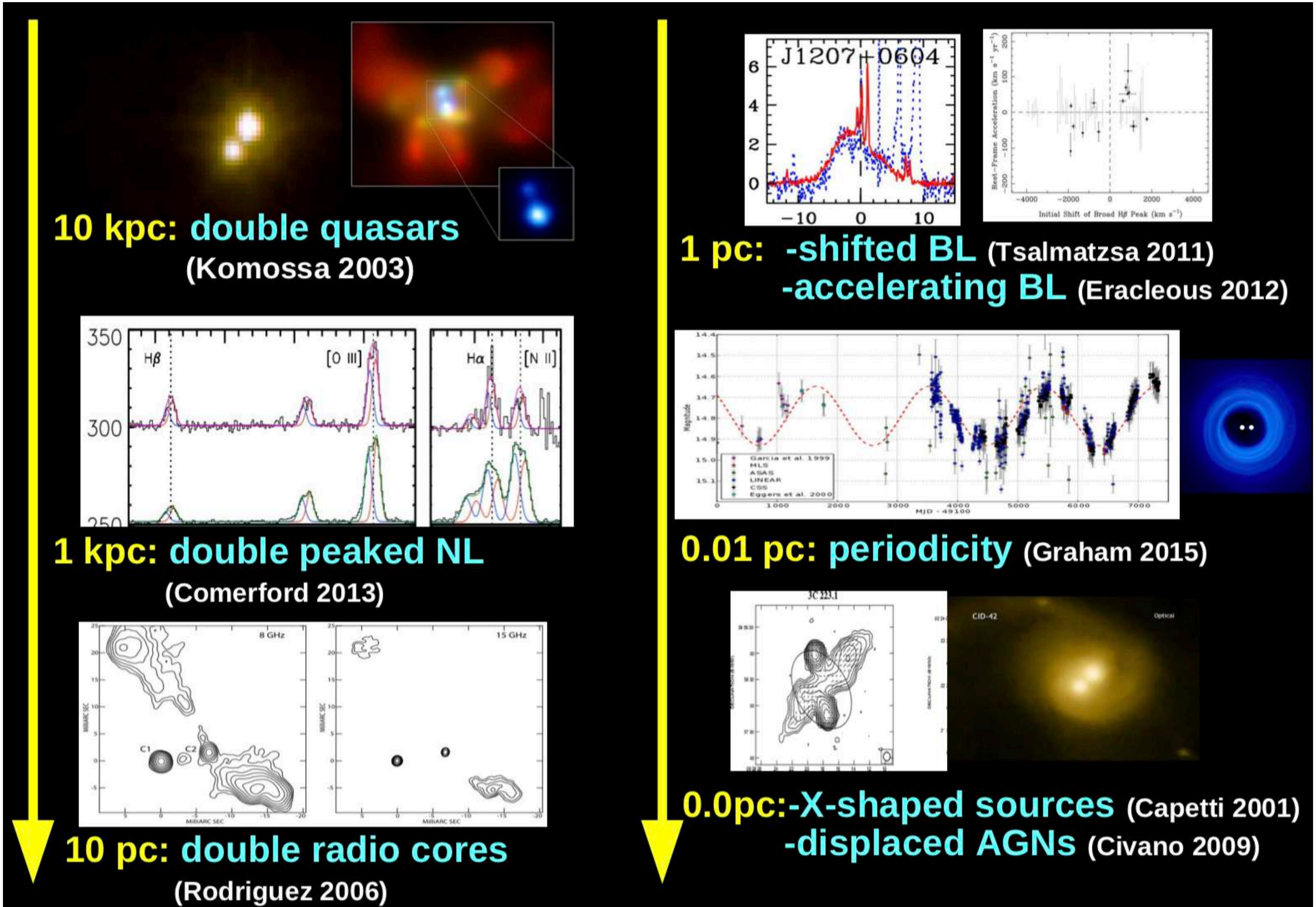
- Origin of the high-energy emission: accretion/ejection close to the black hole.



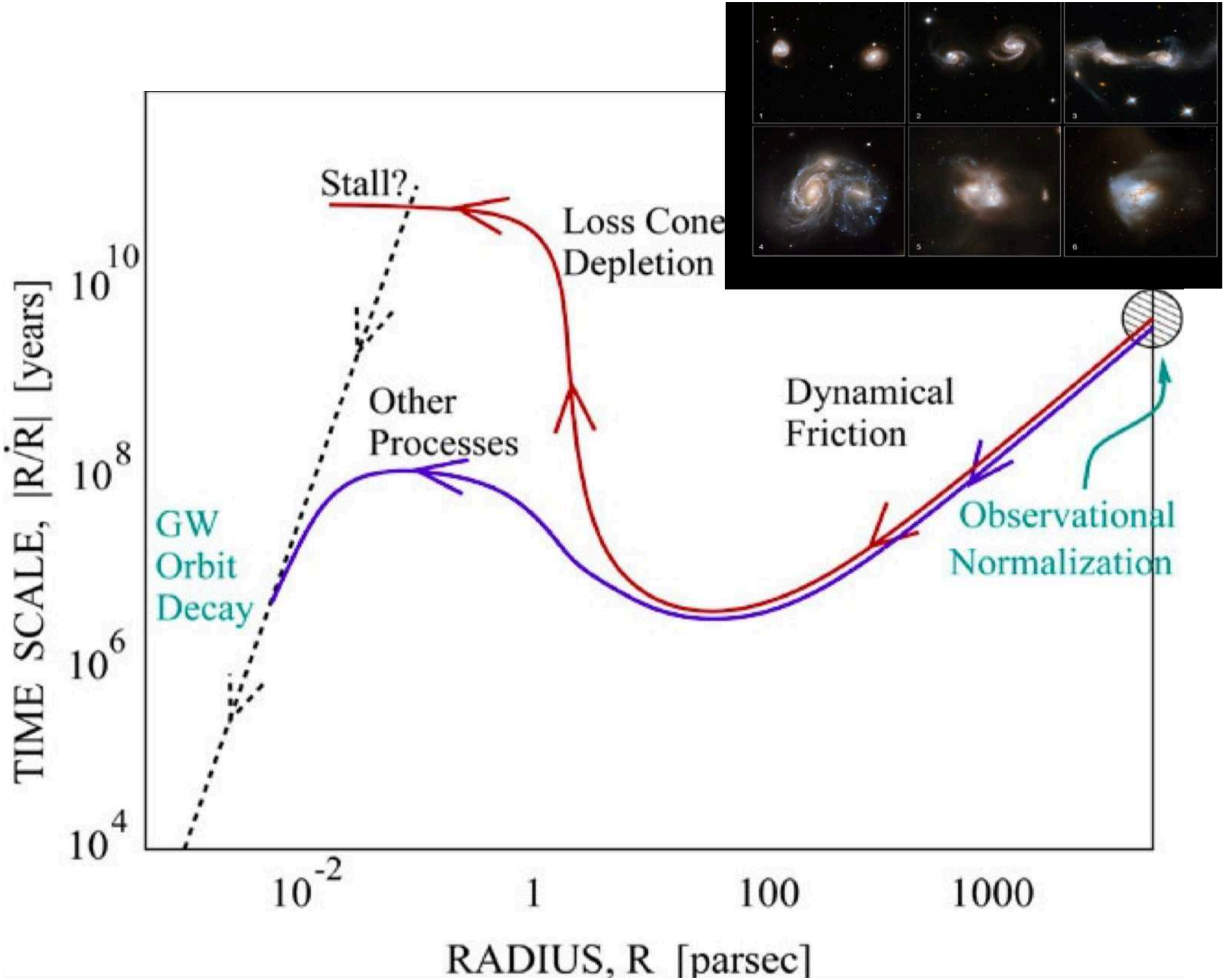
Answering these questions requires multi-messenger approaches:

- **Content of jet / acceleration of cosmic rays: if hadronic ⇒ neutrino emission**
- **Accretion/ejection could be related to mergers of supermassive black holes ⇒ gravitational wave emission**

Supermassive black hole formation & evolution

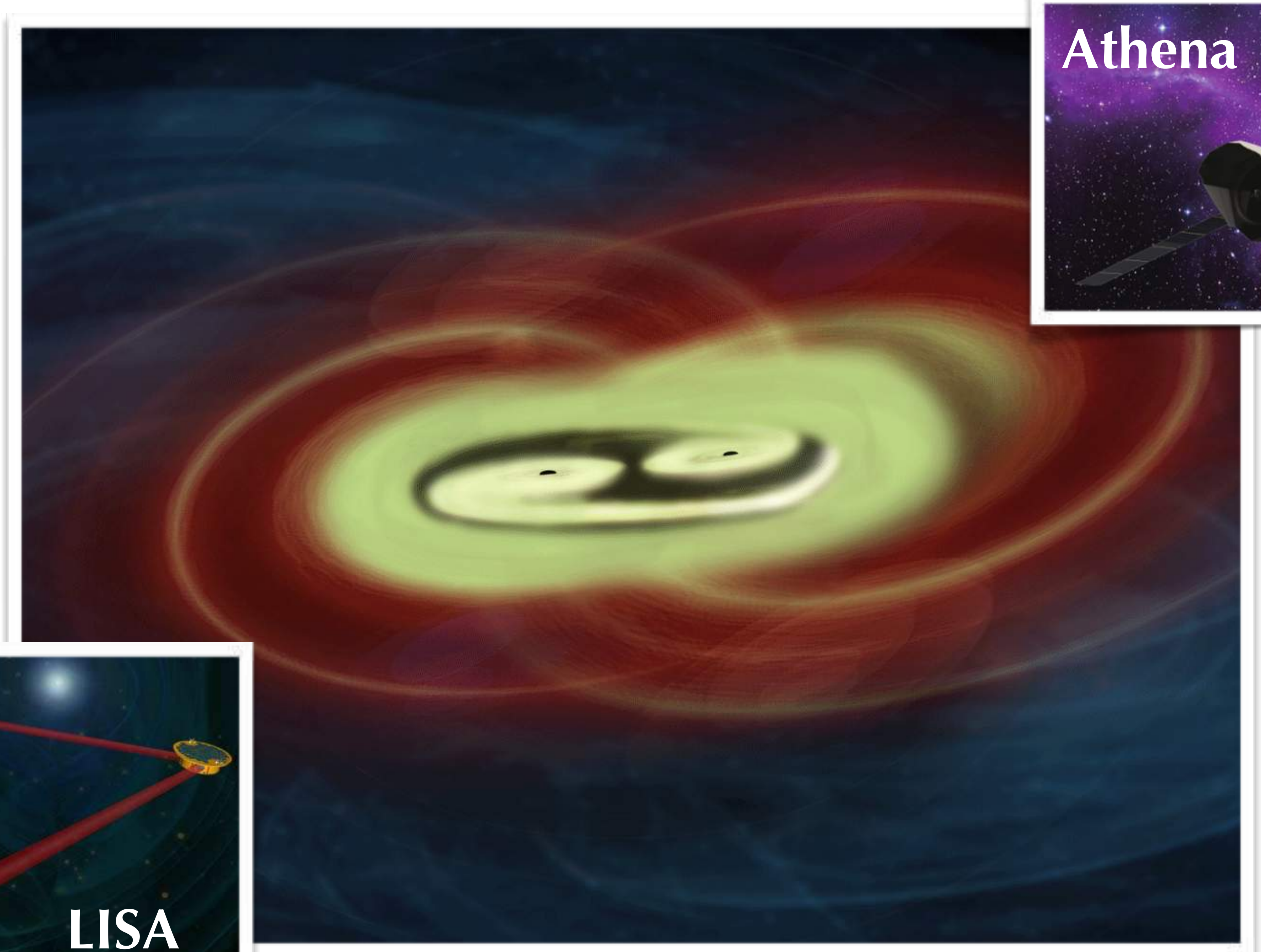


Supermassive black hole formation & evolution



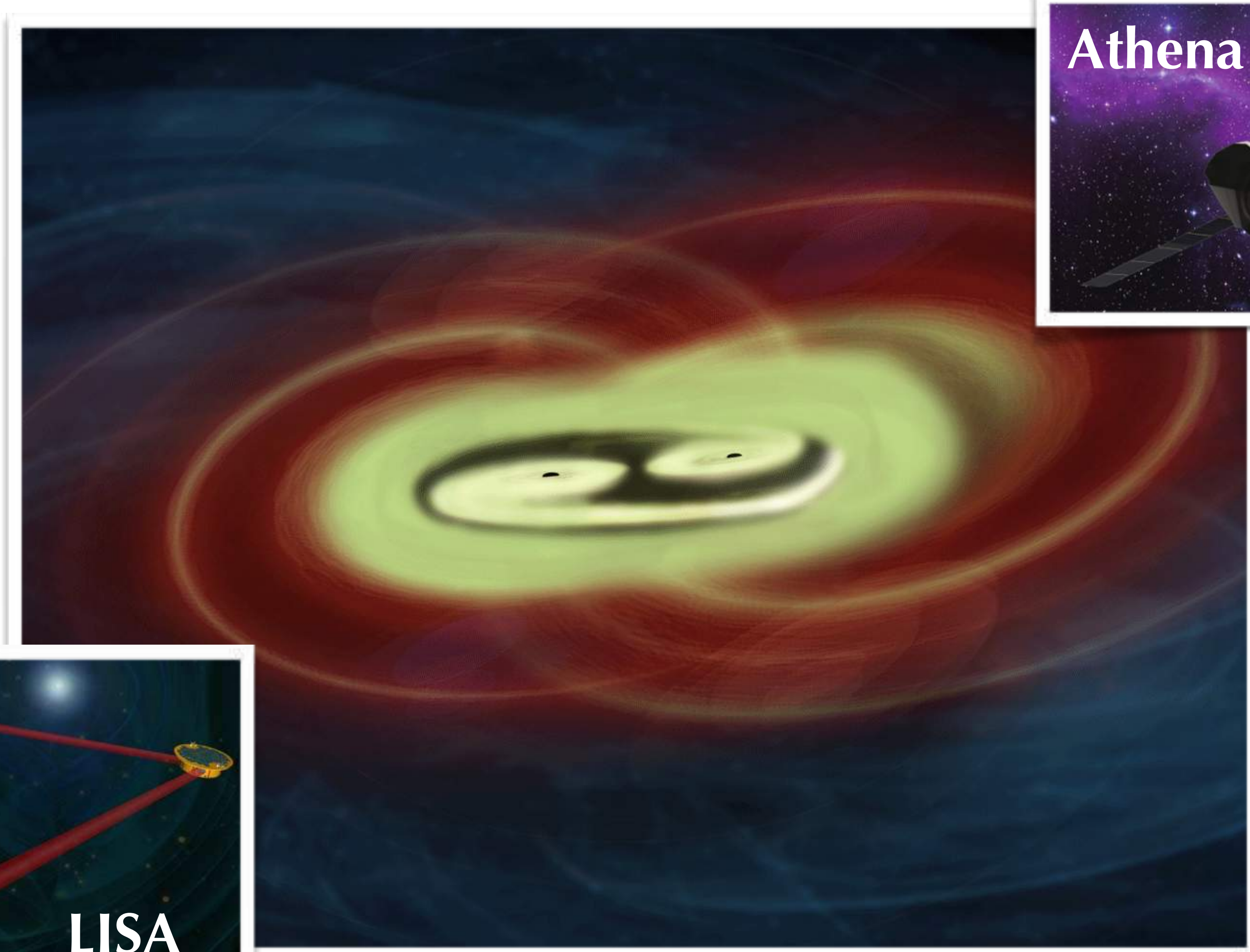
Multi-messenger signal ?

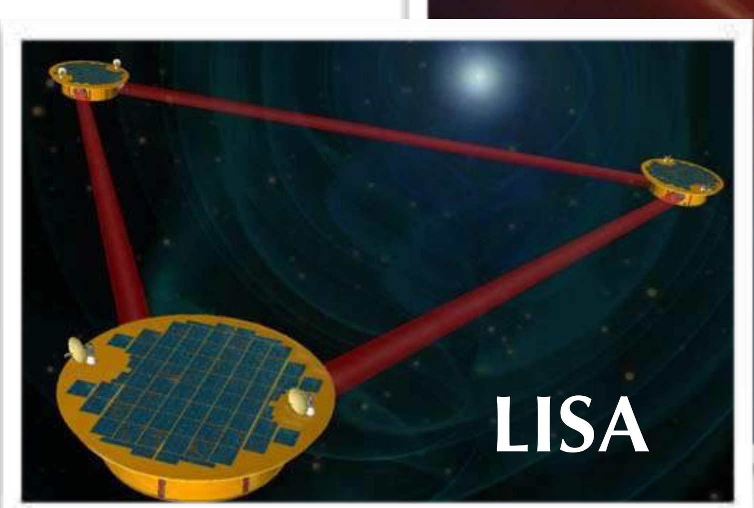
Which multi-messenger signal when two supermassive black holes merge ?



Multi-messenger signal ?

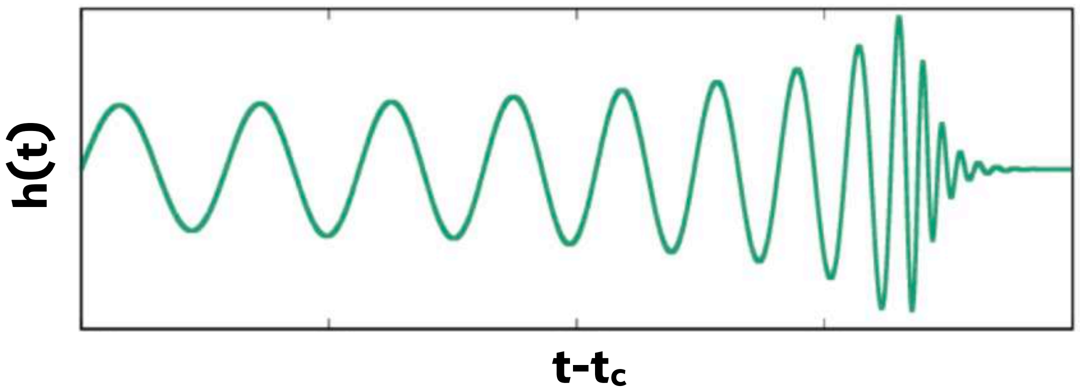
Which multi-messenger signal when two supermassive black holes merge ?





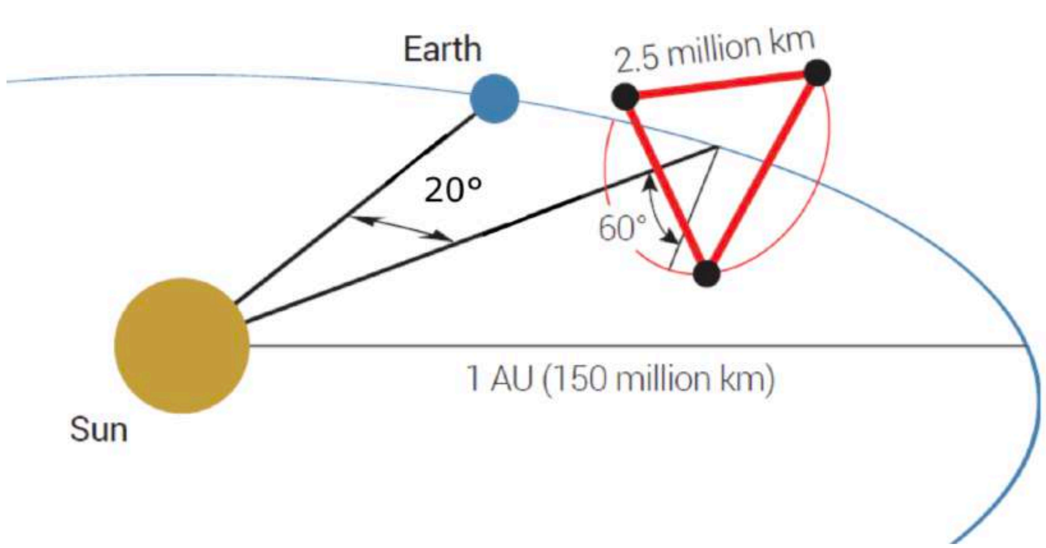
Gravitational-wave signal & LISA

Signal waveform:

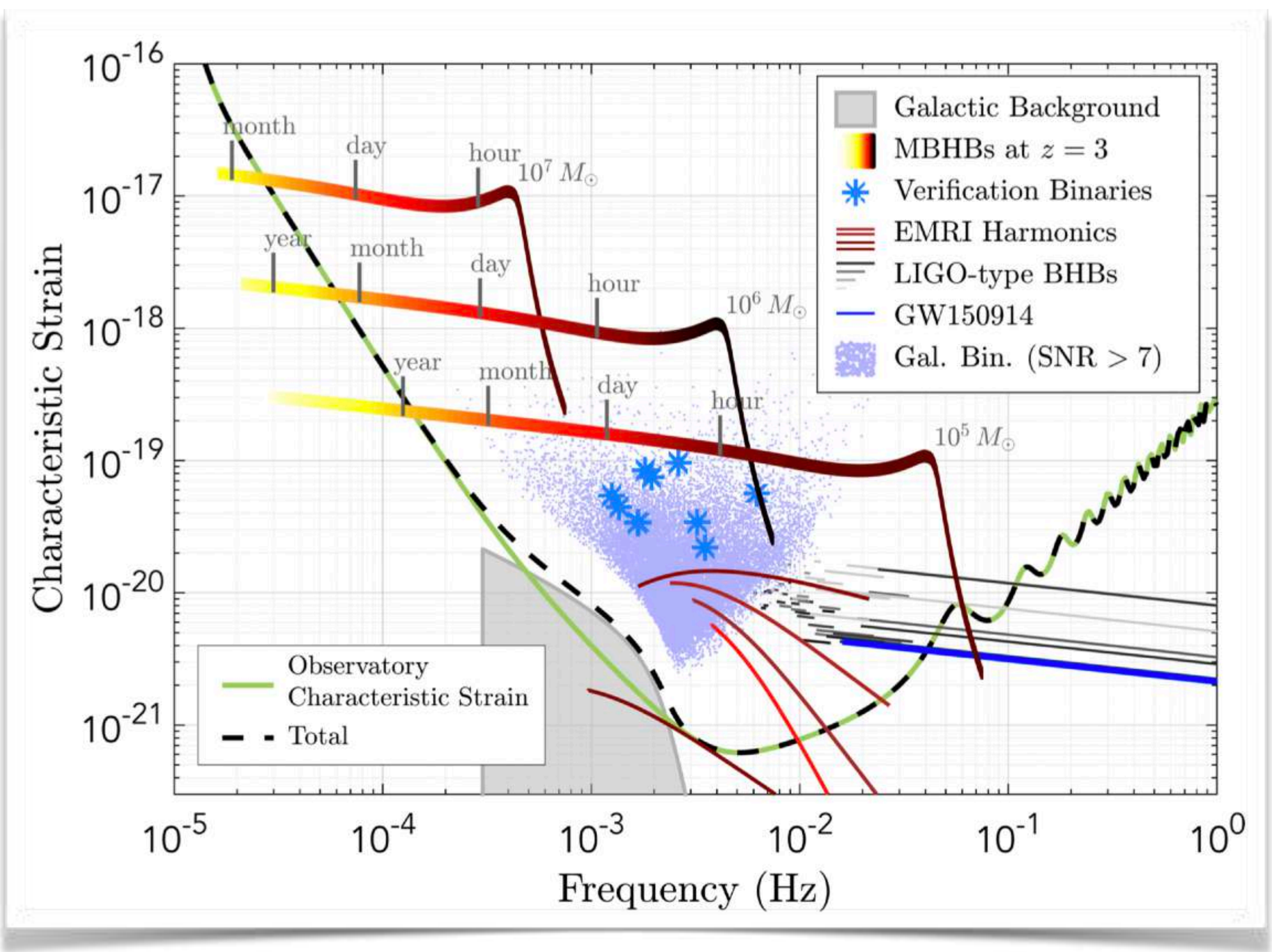


$$f_{GW} \propto (GM_c)^{-5/8} \left(\frac{5}{256(t - t_c)} \right)^{3/8}$$

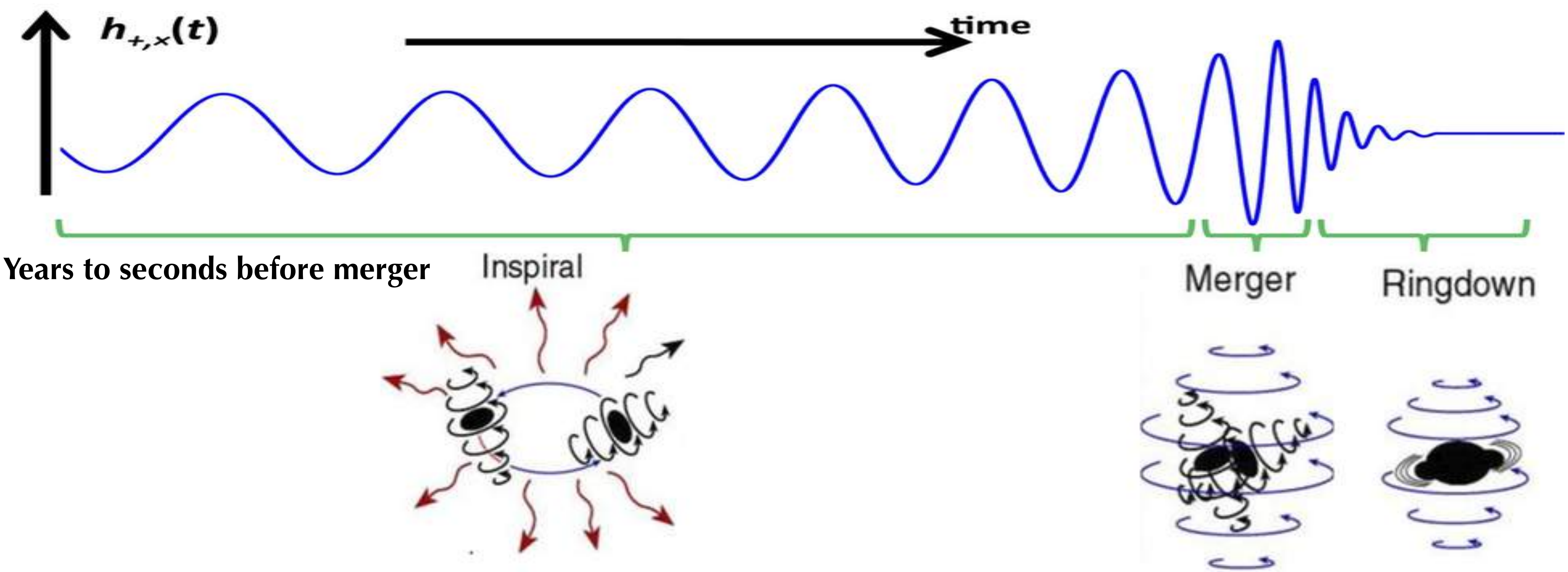
⇒~mHz for SMBH binaries

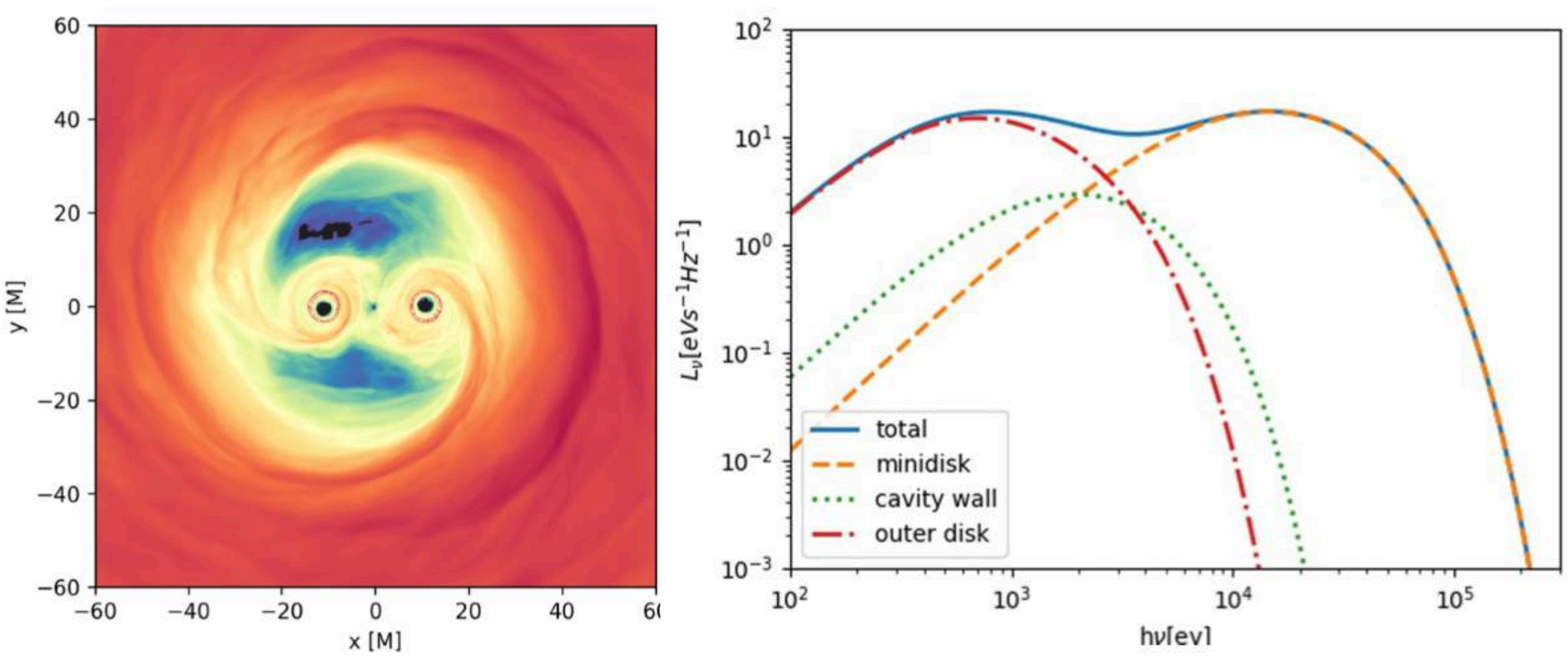


- **Laser Interferometer Space Antenna (launch in ~2034)**
- 3 spacecrafts on heliocentric orbits and distant from 2.5 millions kilometers
- Goal: detect relative distance changes of 10^{-21}: few picometers
- All-sky monitor to detect low frequency gravitational waves.

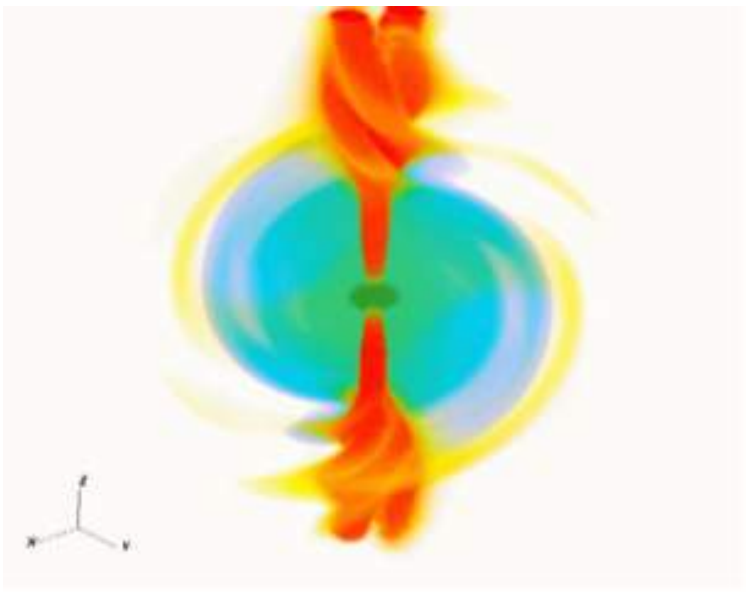


Electromagnetic counterparts ?



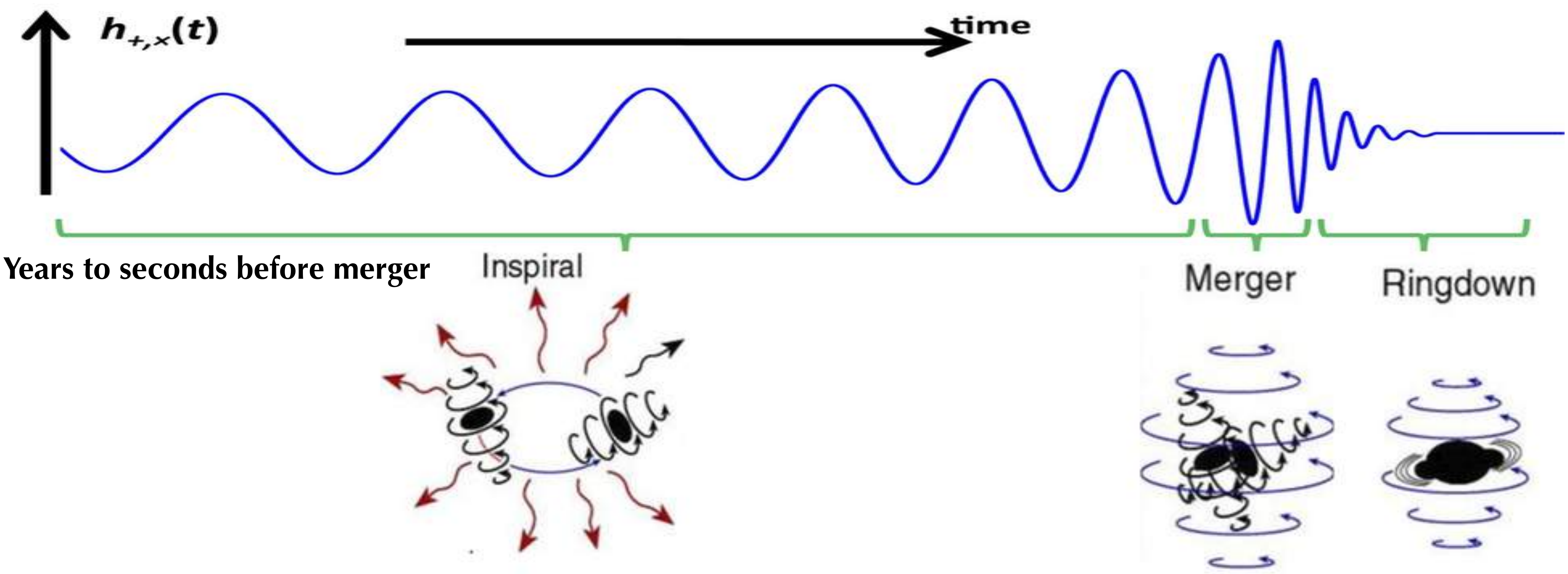


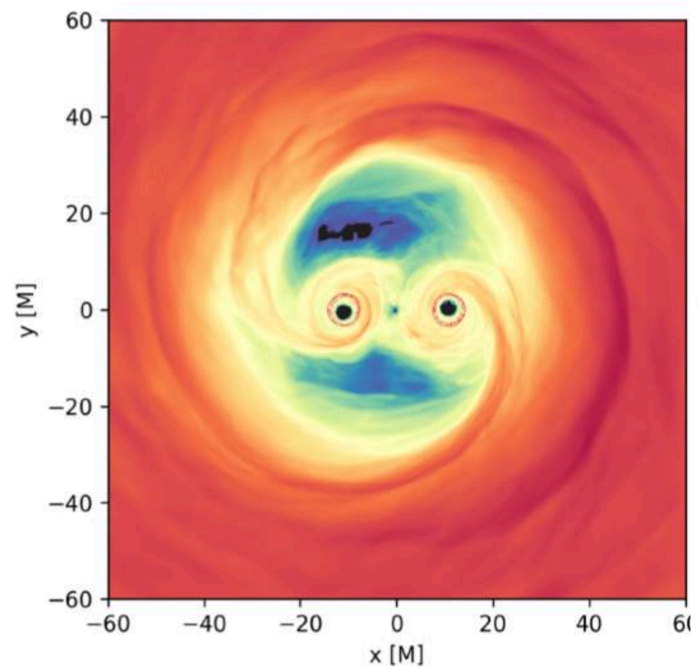
d'Ascoli et al., 2018

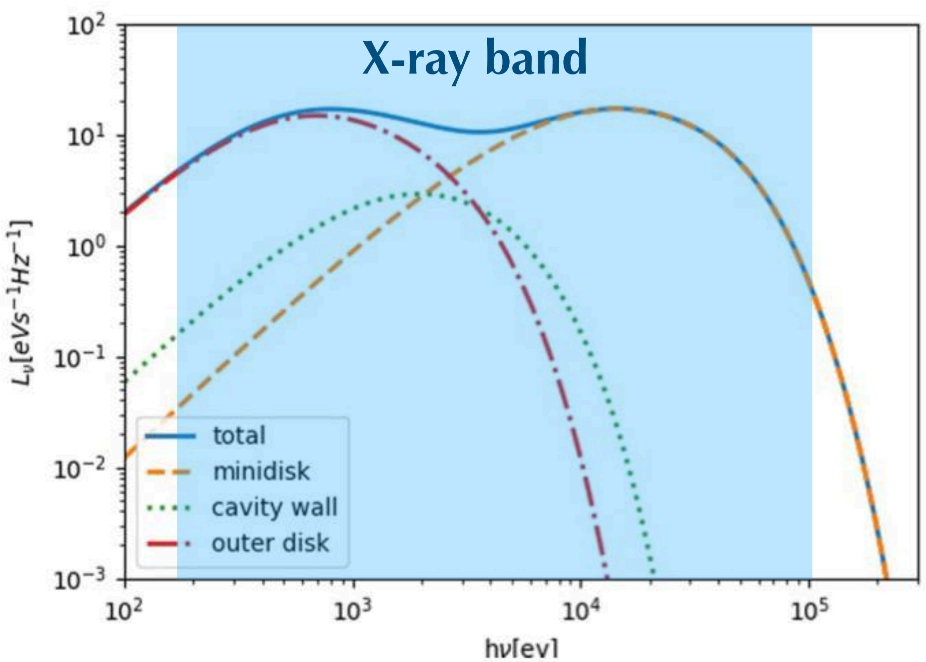


Palenzuela et al., 2010

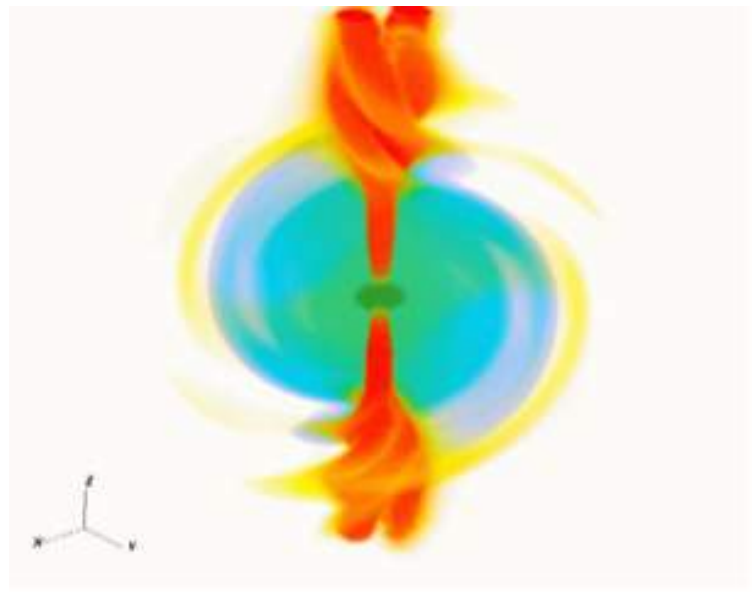
Electromagnetic counterparts ?





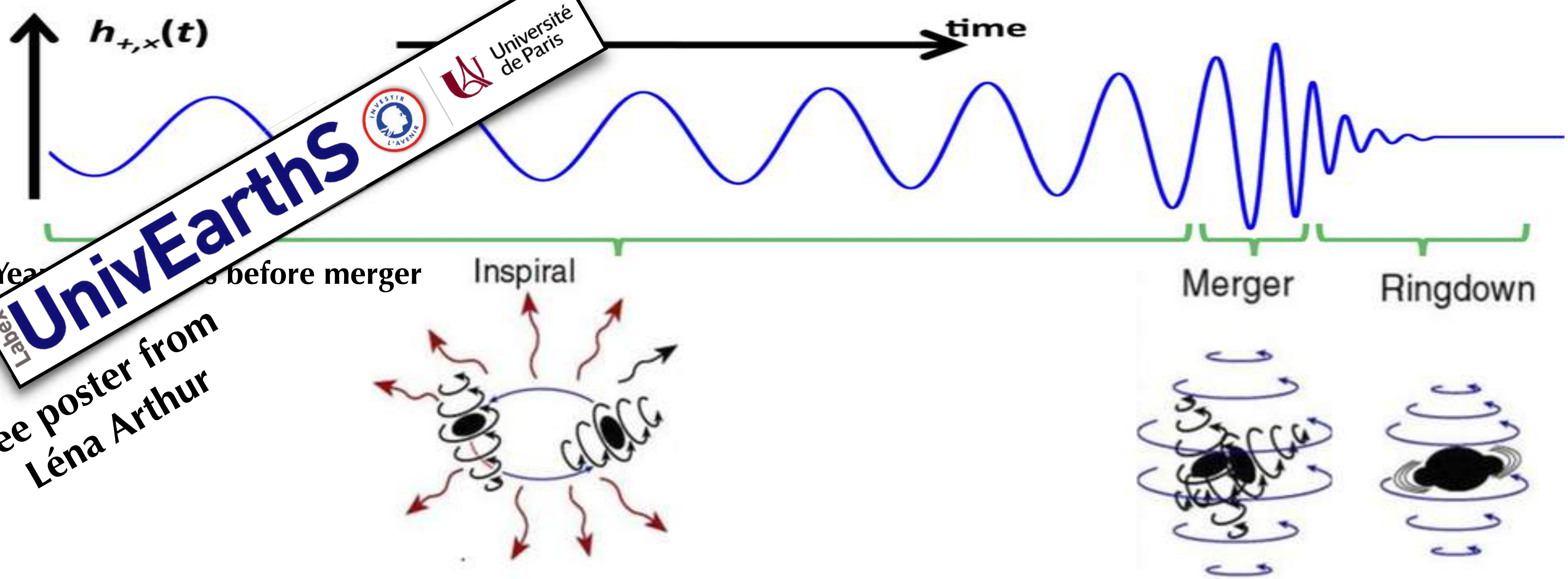


d'Ascoli et al., 2018

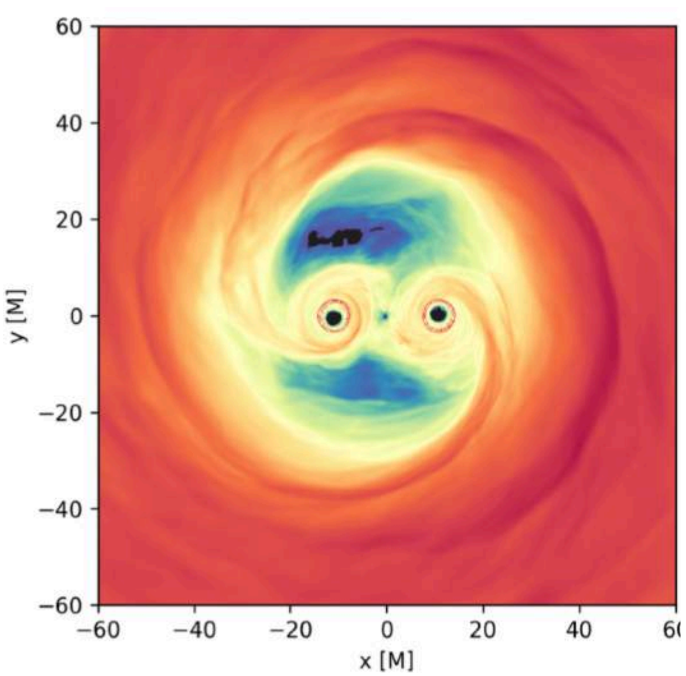


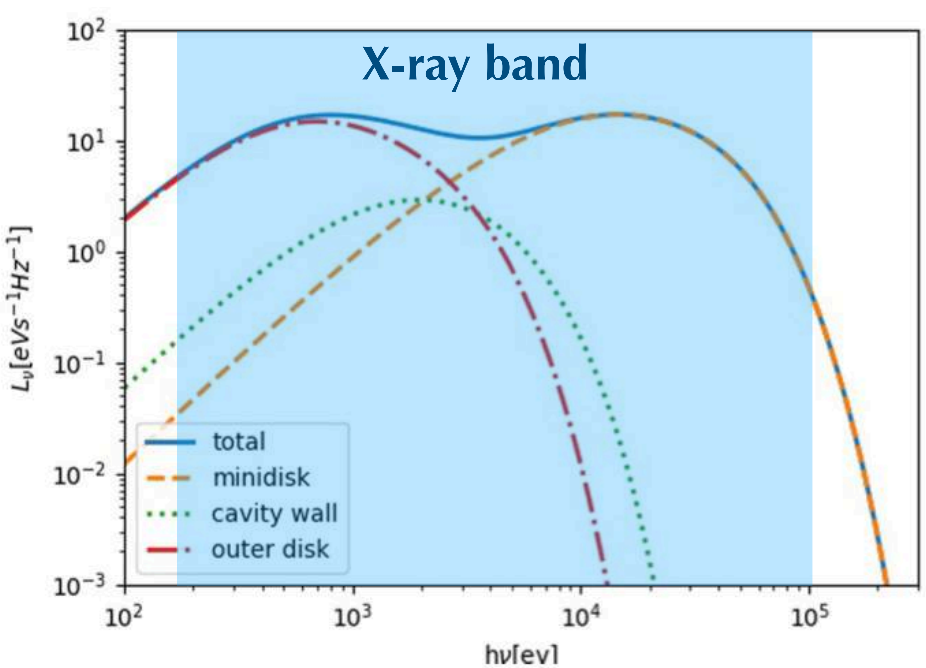
Palenzuela et al., 2010

Electromagnetic counterparts ?

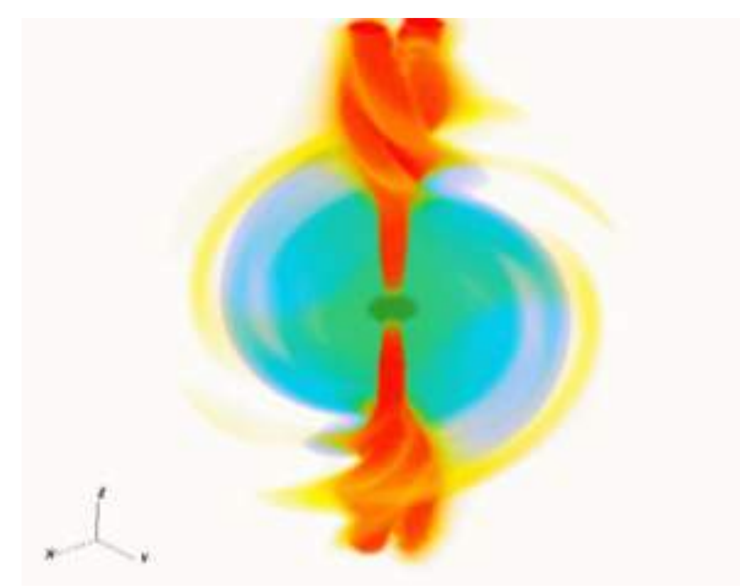


See poster from Léna Arthur





d'Ascoli et al., 2018

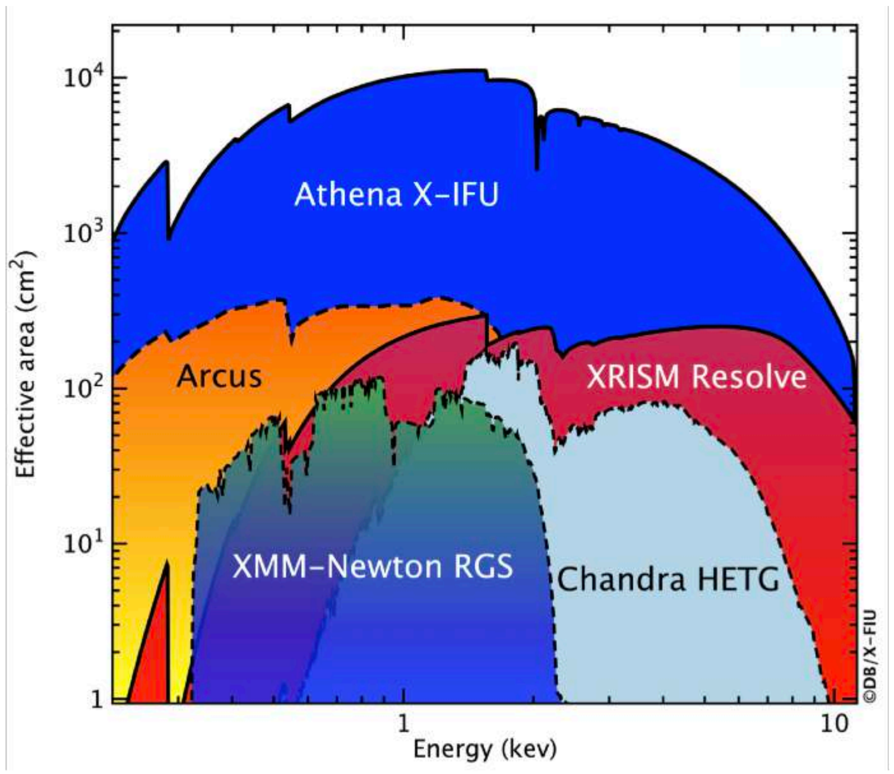


Palenzuela et al., 2010

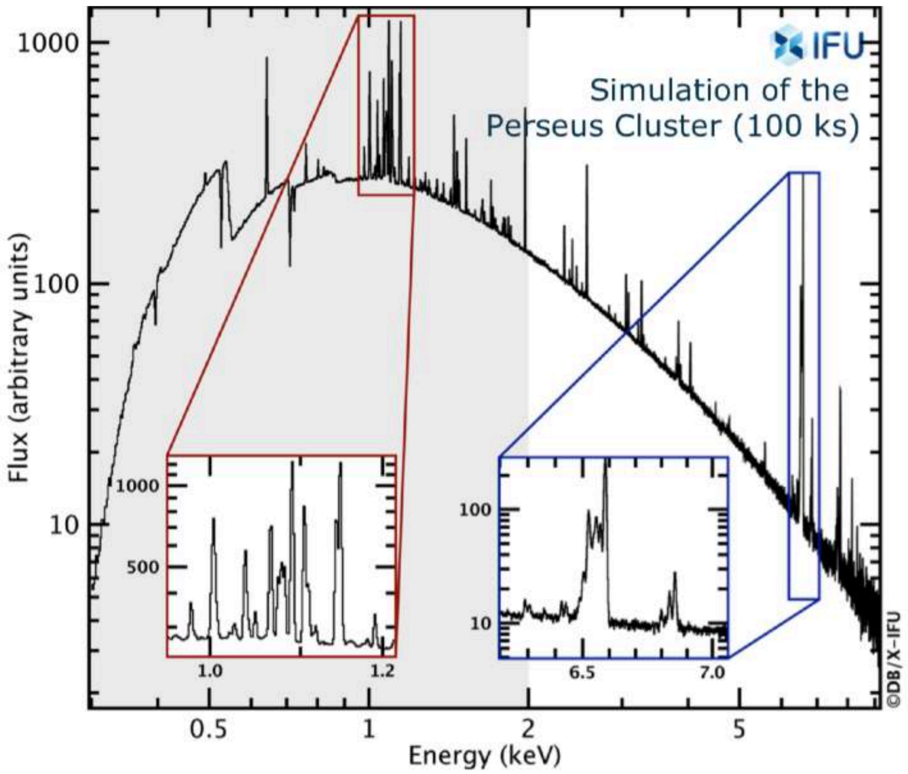
The Athena satellite

- Soft X-ray satellite (ESA with NASA + JAXA participation) to be launched in ~2030.
- Three innovative elements:

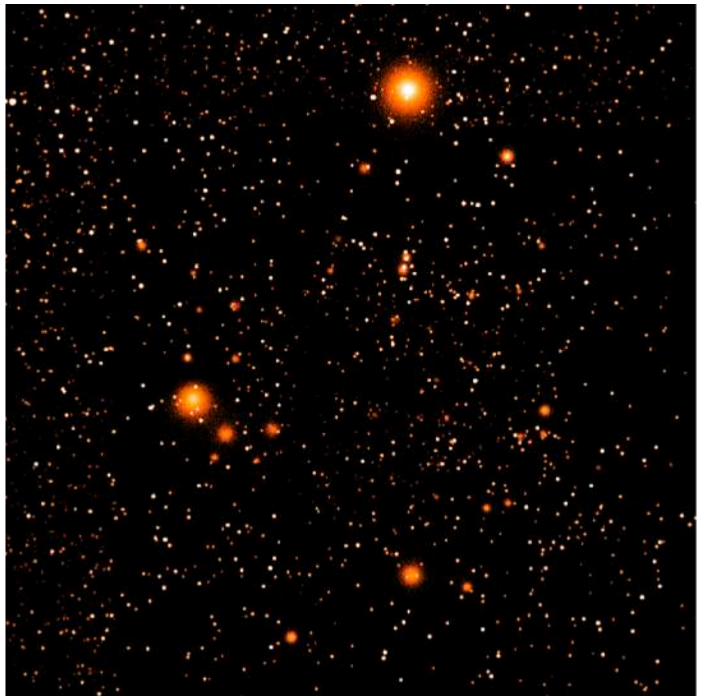
The largest X-ray mirror for astronomy ever studied



Unprecedented X-ray spectroscopic capabilities



The fastest X-ray sky survey machine



The Athena satellite

- Soft X-ray s
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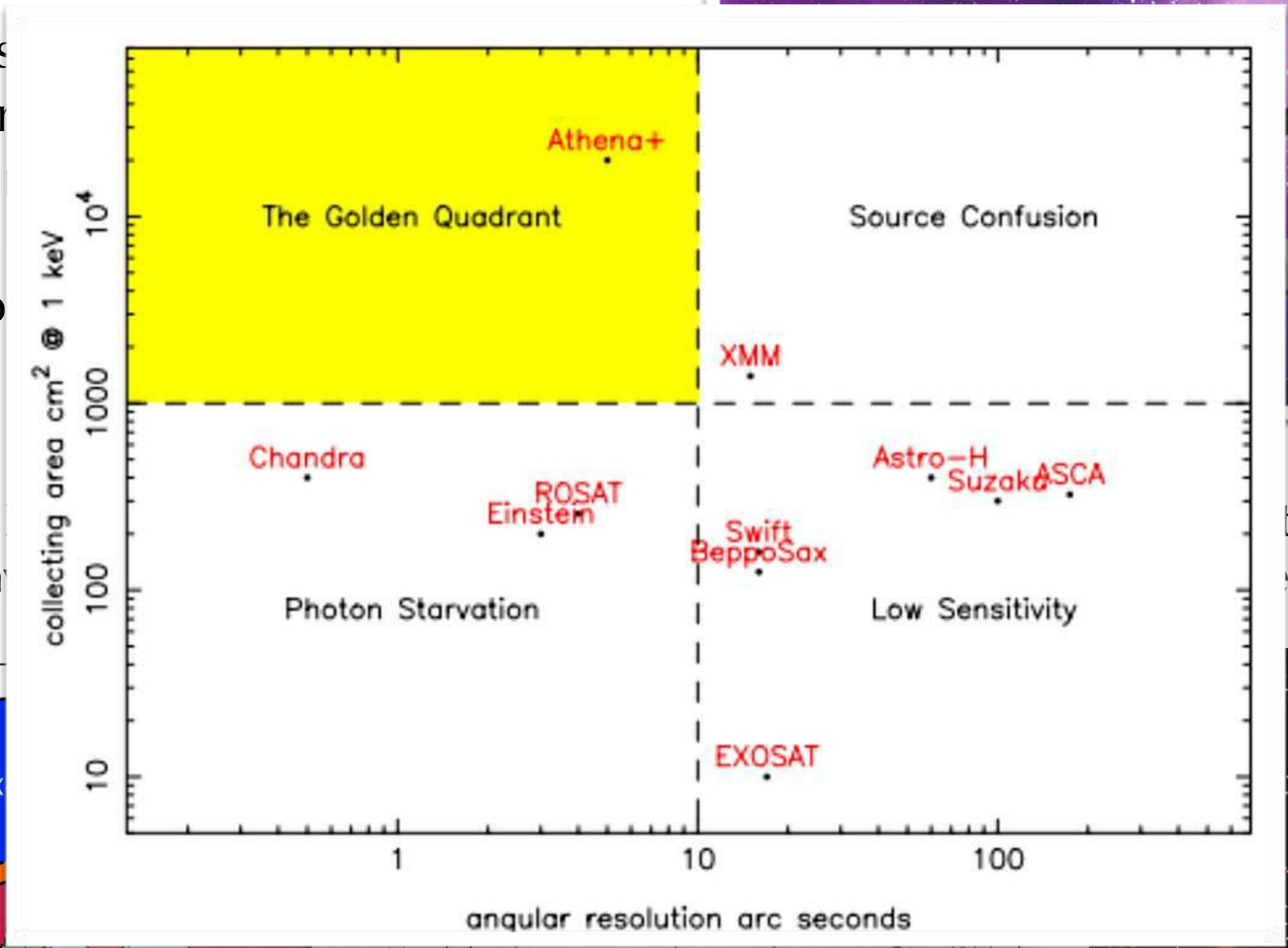

The largest
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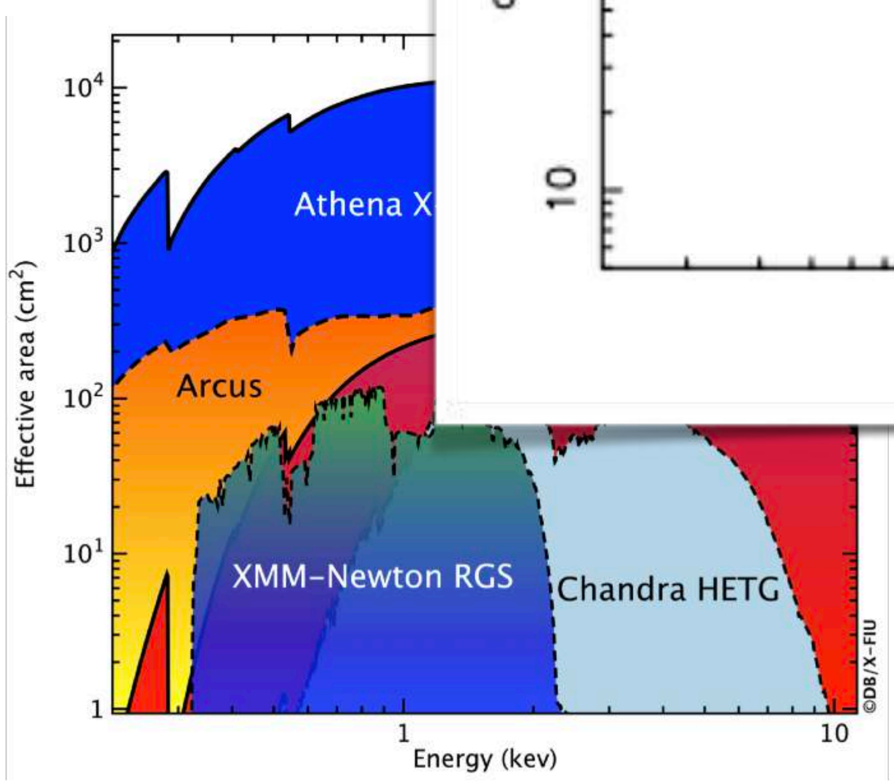
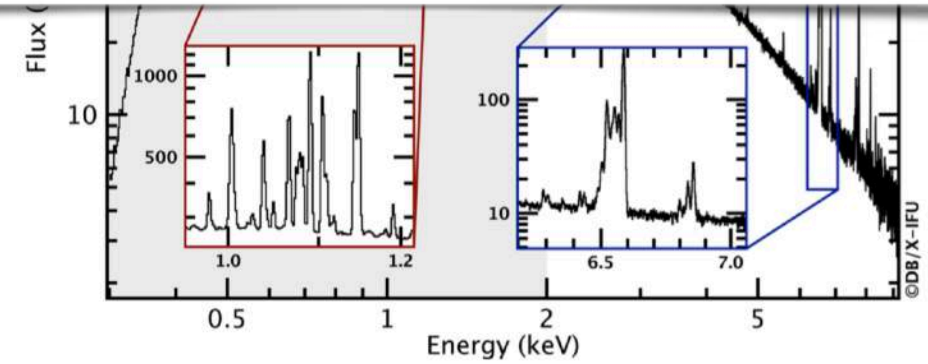
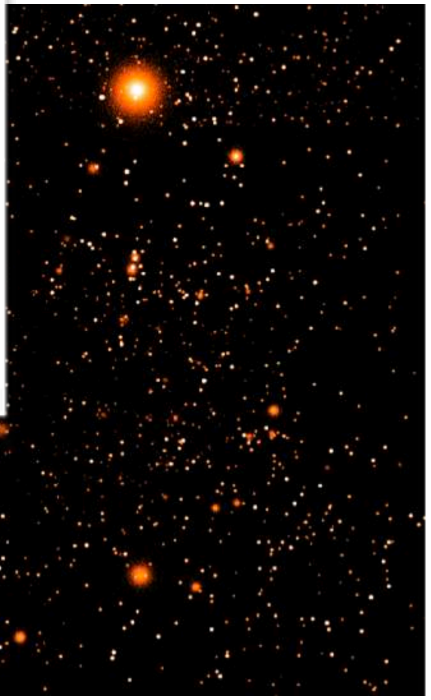
y machine



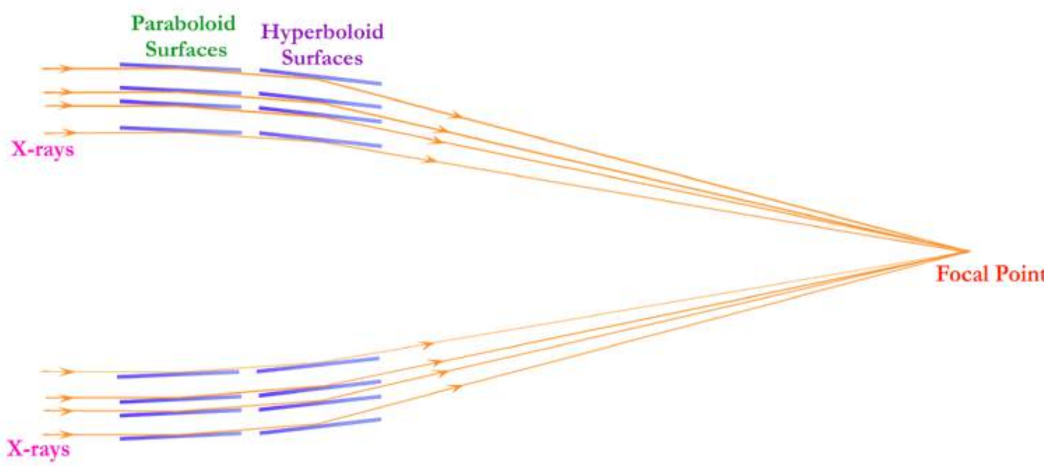


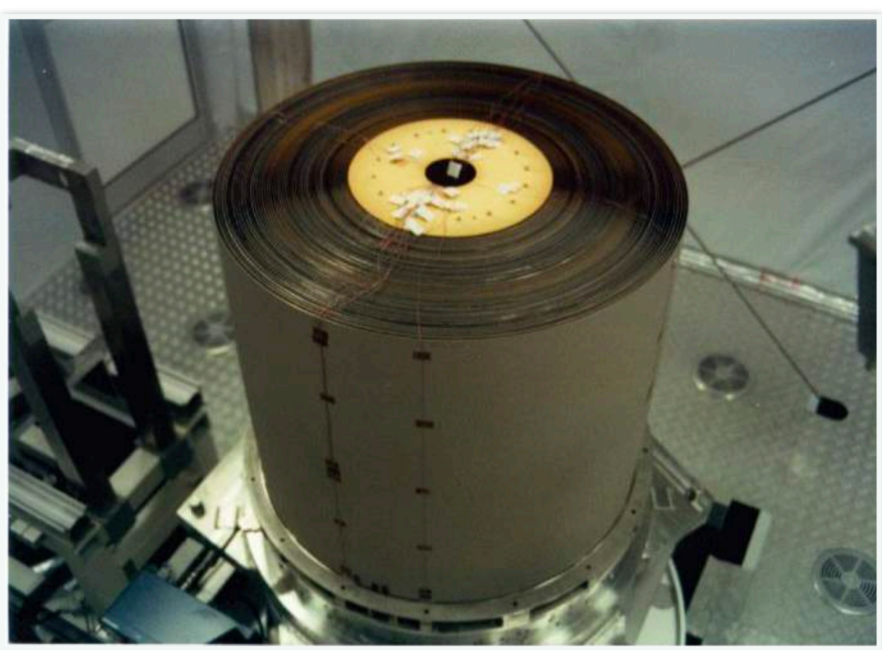


The Athena satellite

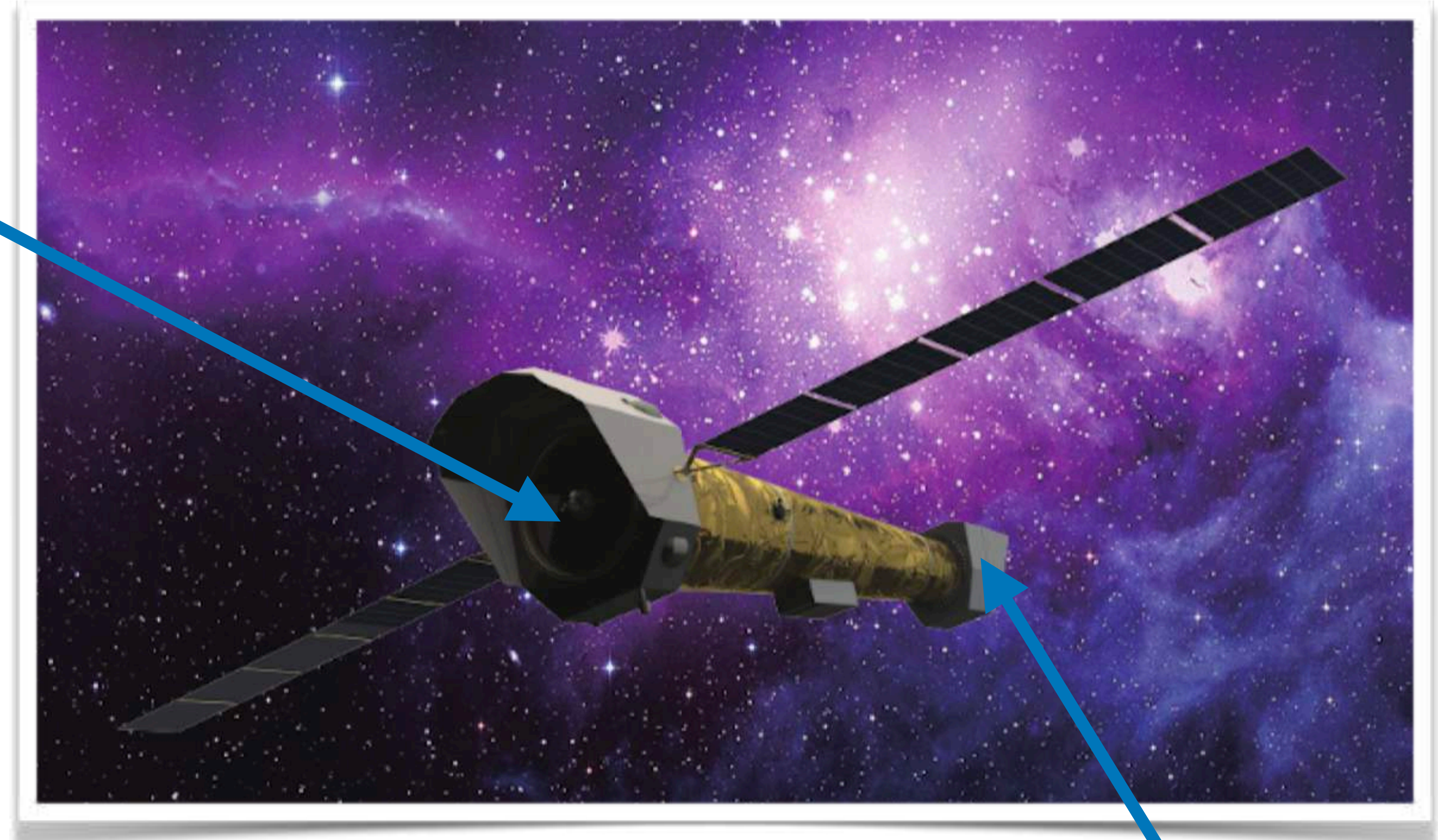
- **Grazing incidence optics**

  X-rays do not reflect off mirrors the same way that visible light does

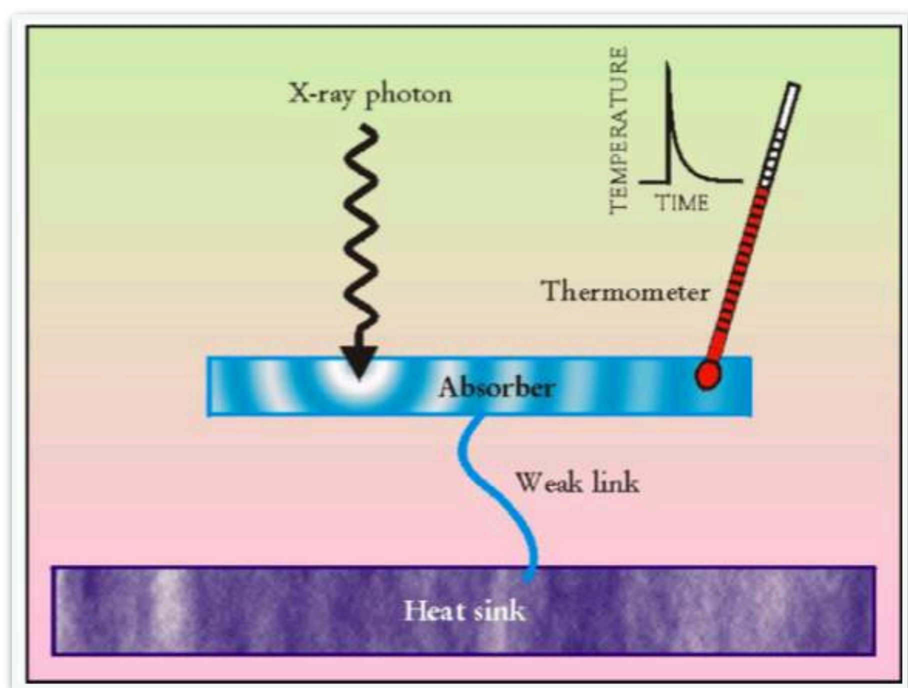




Effective area (=sensitivity) can be increased by nesting mirrors one inside the other.



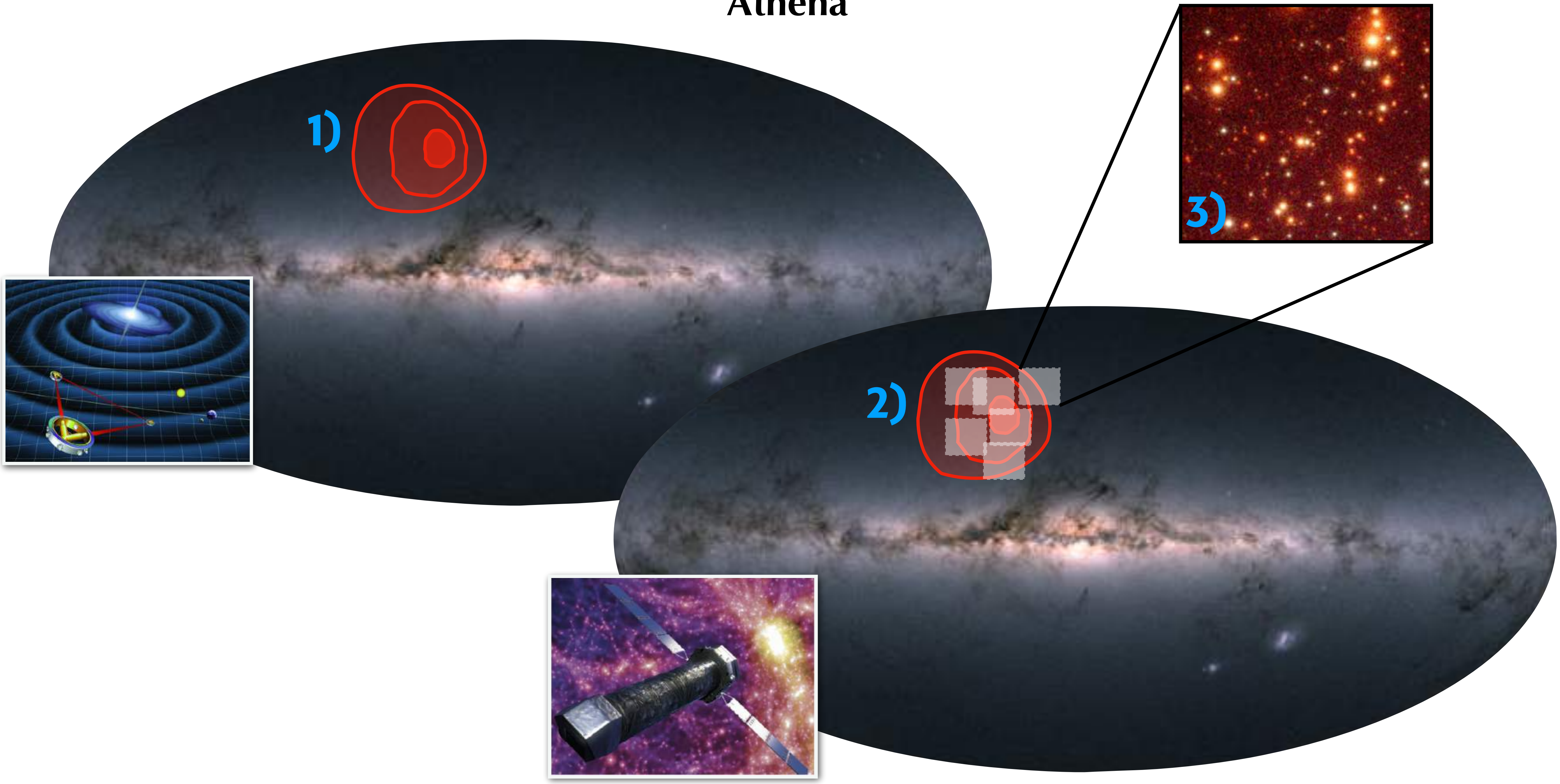
- **Detector = micro-calorimeter**



Micro-calorimeters operated at cryogenic temperatures measure the energy of an incoming photon via conversion to heat ⇒ very good energy resolution.

Athena & LISA flying together

Objective: Detect the electromagnetic counterpart to a supermassive black hole merger with Athena



Questions to be answered:

- Where to look ?
- How to optimize the observational strategies ?

Labex UnivEarthS — Université de Paris

See poster from Jonathon Baird