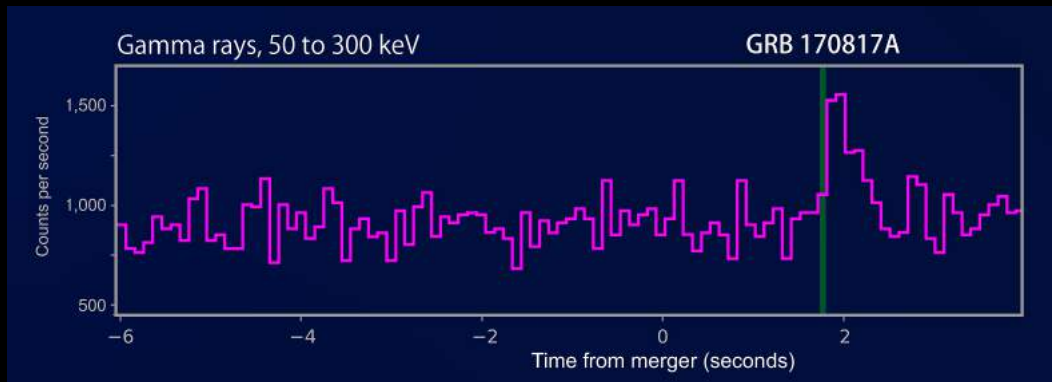
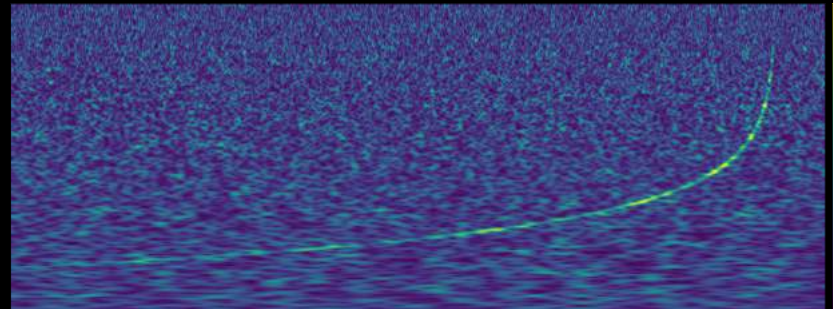

From gamma-ray bursts to gravitational waves

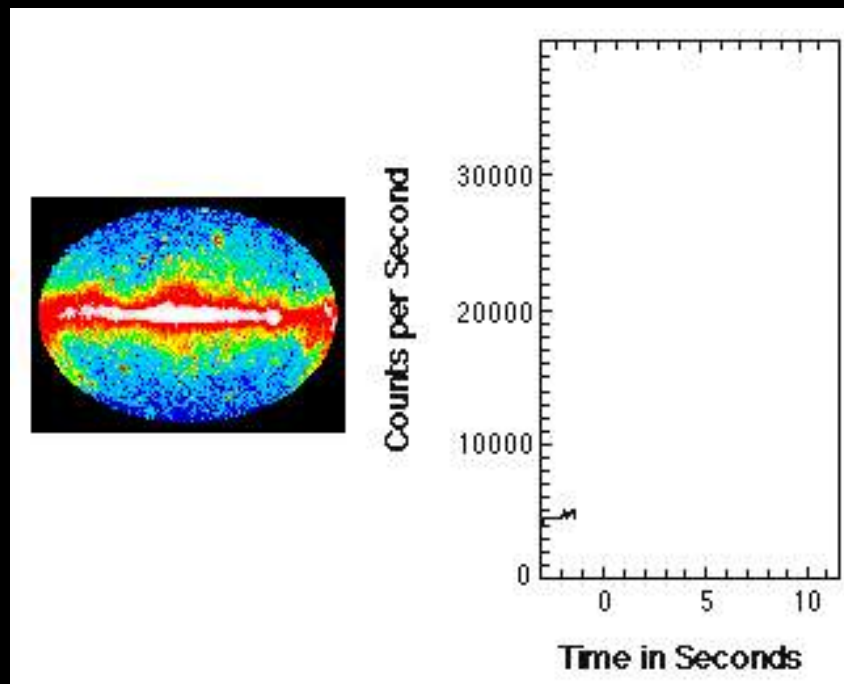
Frédéric Daigne (Institut d'Astrophysique de Paris; UPMC)



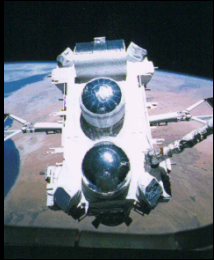
SSS17a



Gamma-ray bursts: observations and theory

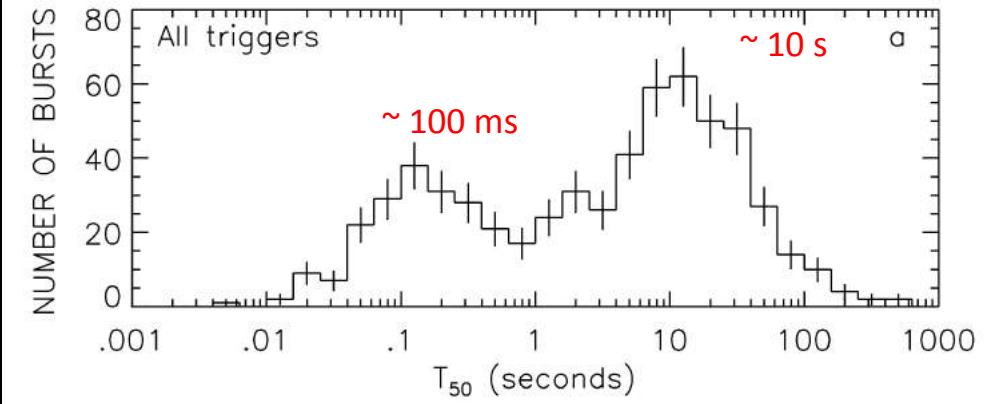


Gamma-ray bursts: prompt emission

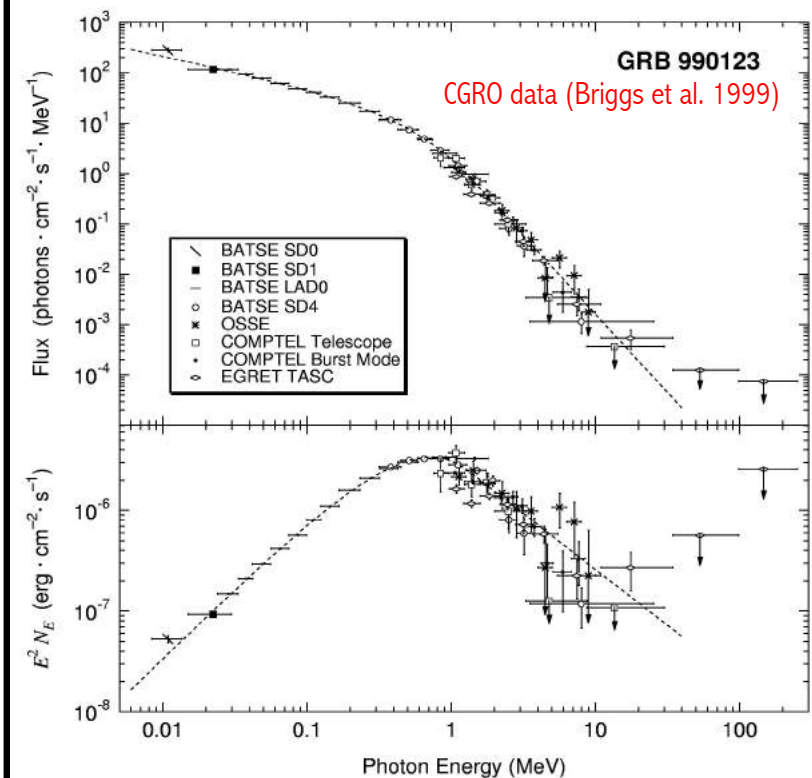
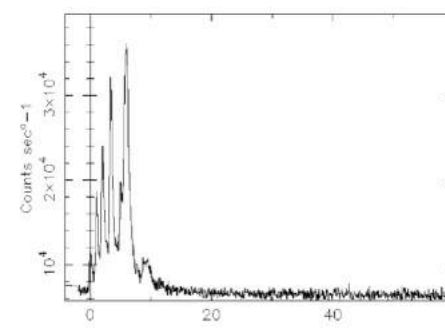
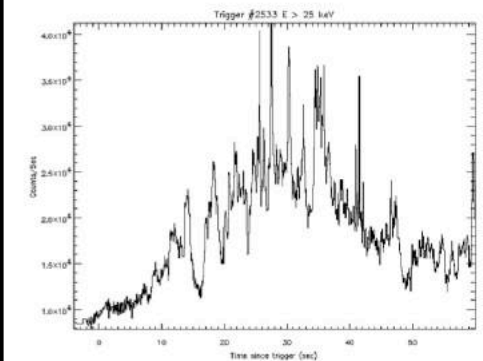
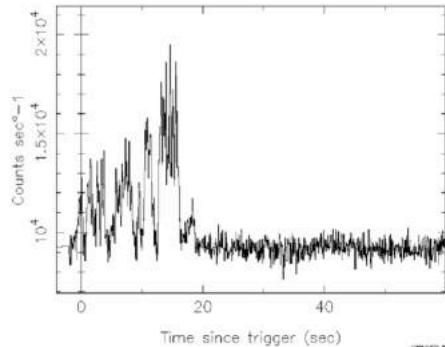
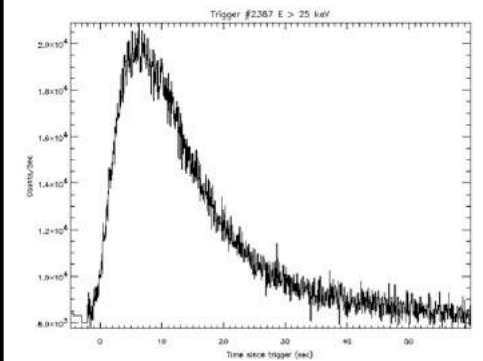


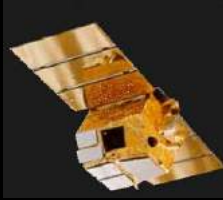
CGRO/BATSE

- Apparent rate:
~ 1 GRB / day
- Duration:
two groups
- Lightcurves : variability & diversity



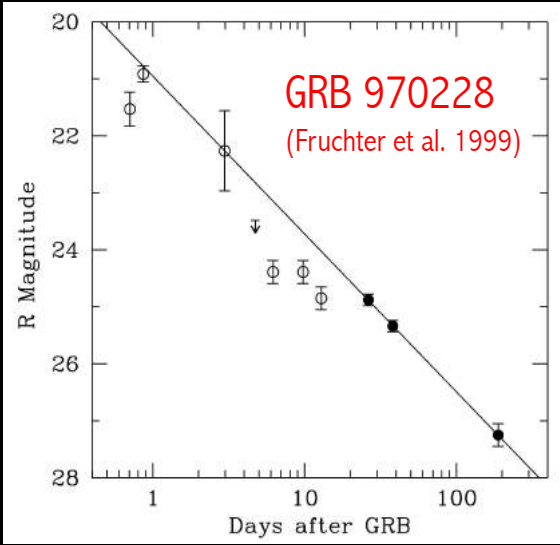
- Spectrum: non-thermal



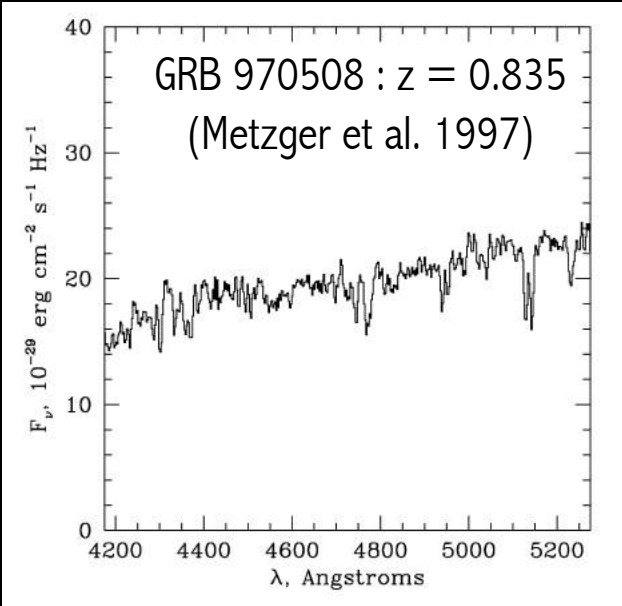


Gamma-ray bursts: afterglow

- Discovery: 1997 (X-rays: Beppo-SAX ; V: van Paradijs et al. 1997)
- Flux: power-law decay
- Non-thermal spectrum
- Spectral evolution: X-rays \rightarrow V \rightarrow radio



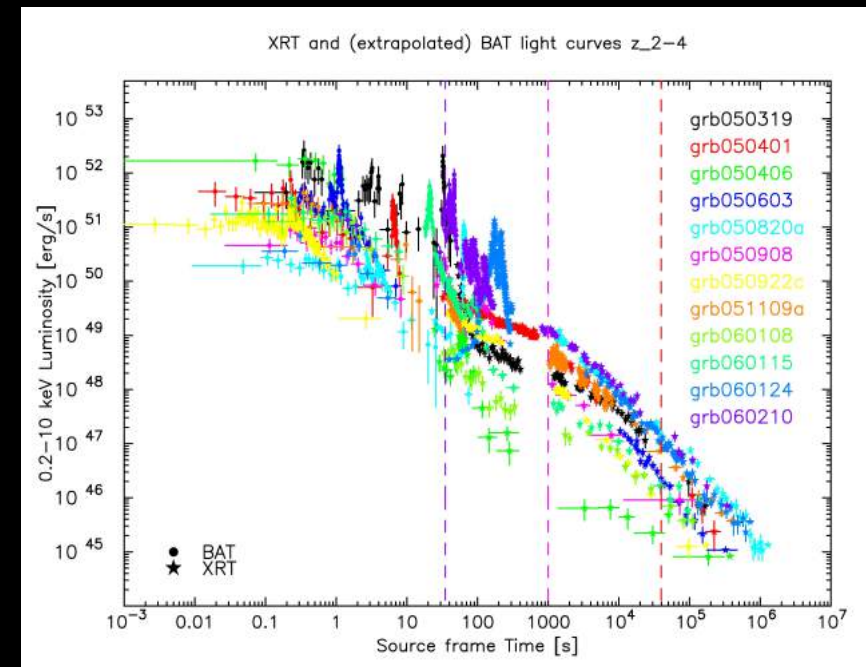
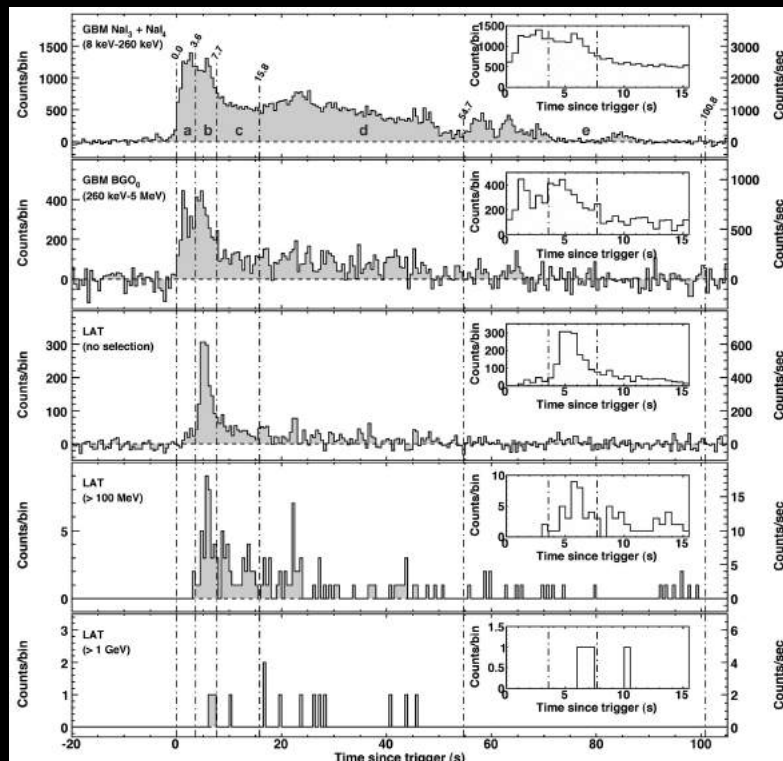
- Follow-up: redshift & host galaxy
- High redshift ($z_{\text{max,obs}} > 9$): huge luminosities!
 $E_{\text{iso},\gamma} \sim 10^{51} - 10^{54}$ erg



Swift & Fermi



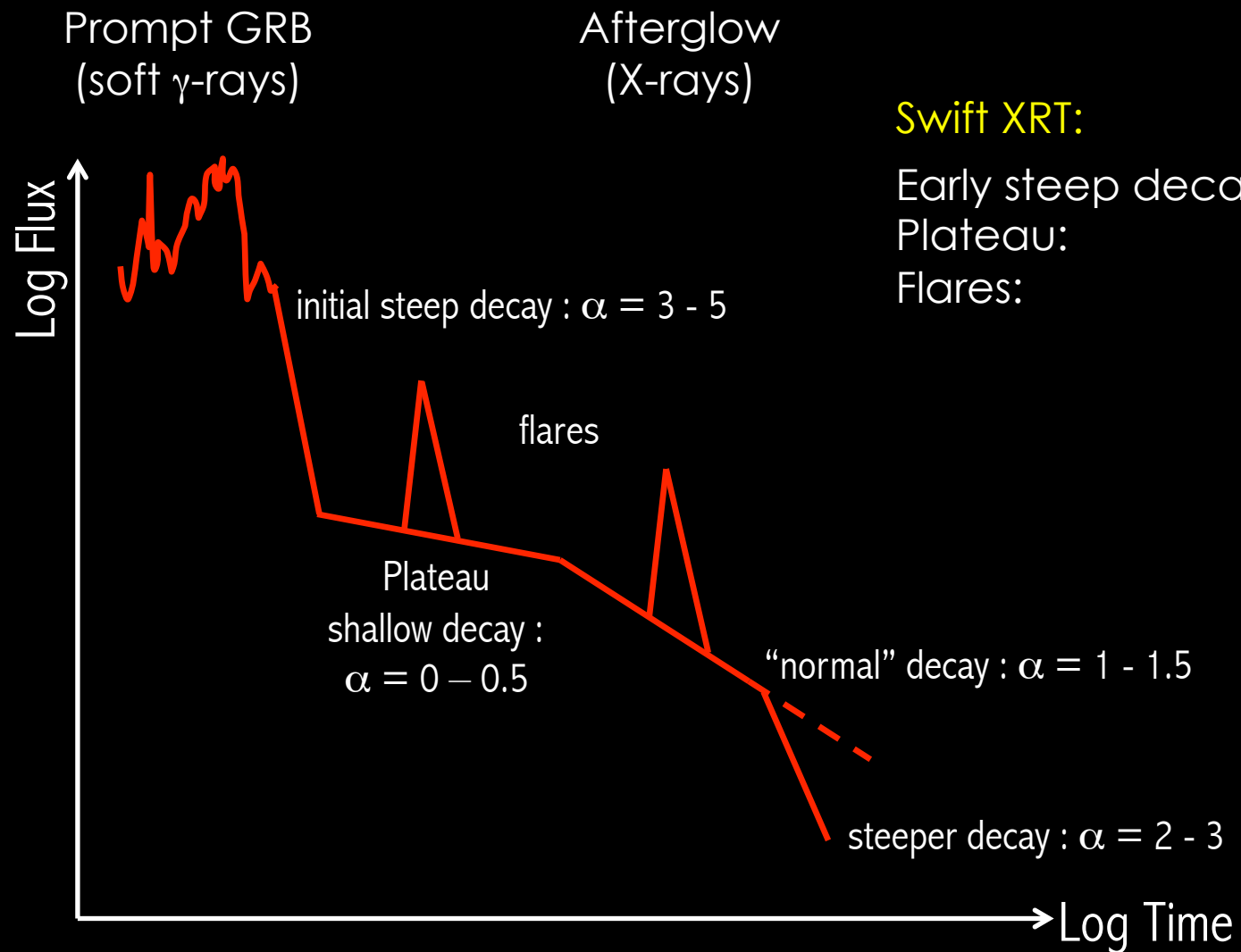
Neil Gehrels:
PI Swift
Deputy Project Scientist Fermi



Prompt emission keV \rightarrow GeV (Fermi)

X-ray afterglow (Swift)

Observed emission: light curve



Also: prompt optical, GeV

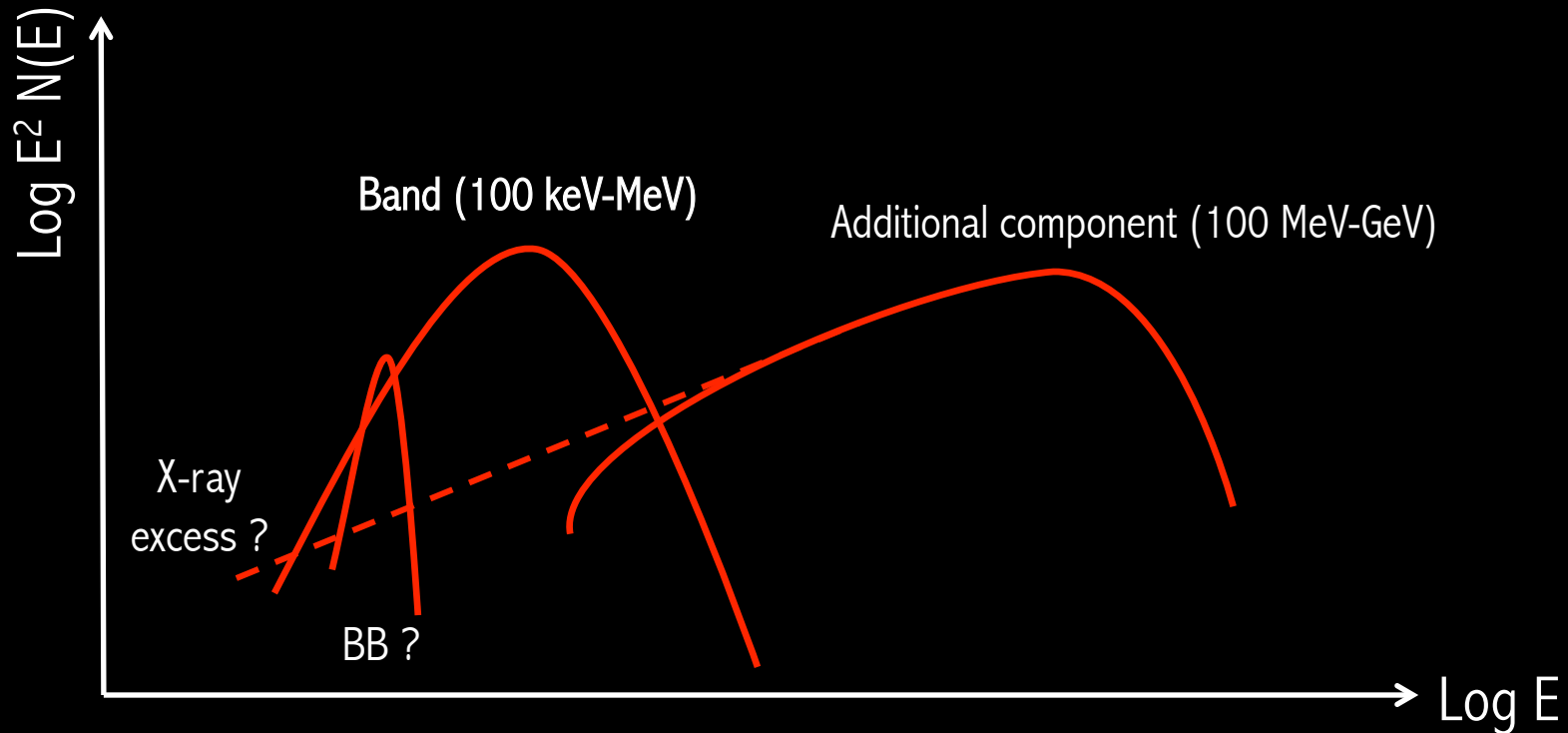
Also: optical, radio afterglow long-lasting Fermi/LAT emission

Observed emission: γ -ray spectrum

Fermi/GBM:

BB looked for in bright cases
& found in many cases

Fermi/LAT: 1st catalog
extra-component in 4/28

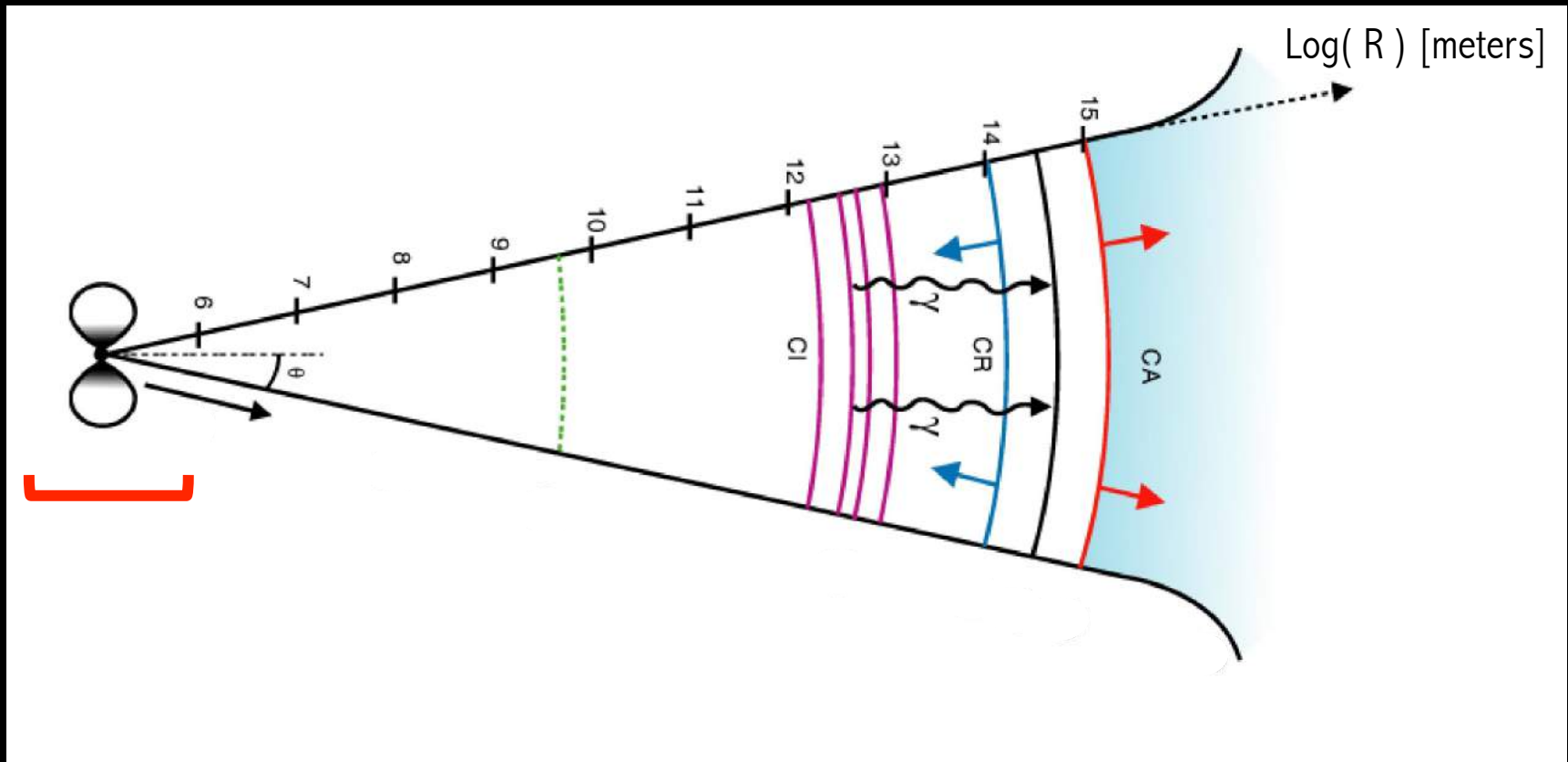


GRB Physics

- Cosmological distance: huge radiated energy ($E_{\text{iso},\gamma} \sim 10^{50}\text{-}10^{55}$ erg)
- Variability + energetics: violent formation of a stellar mass BH

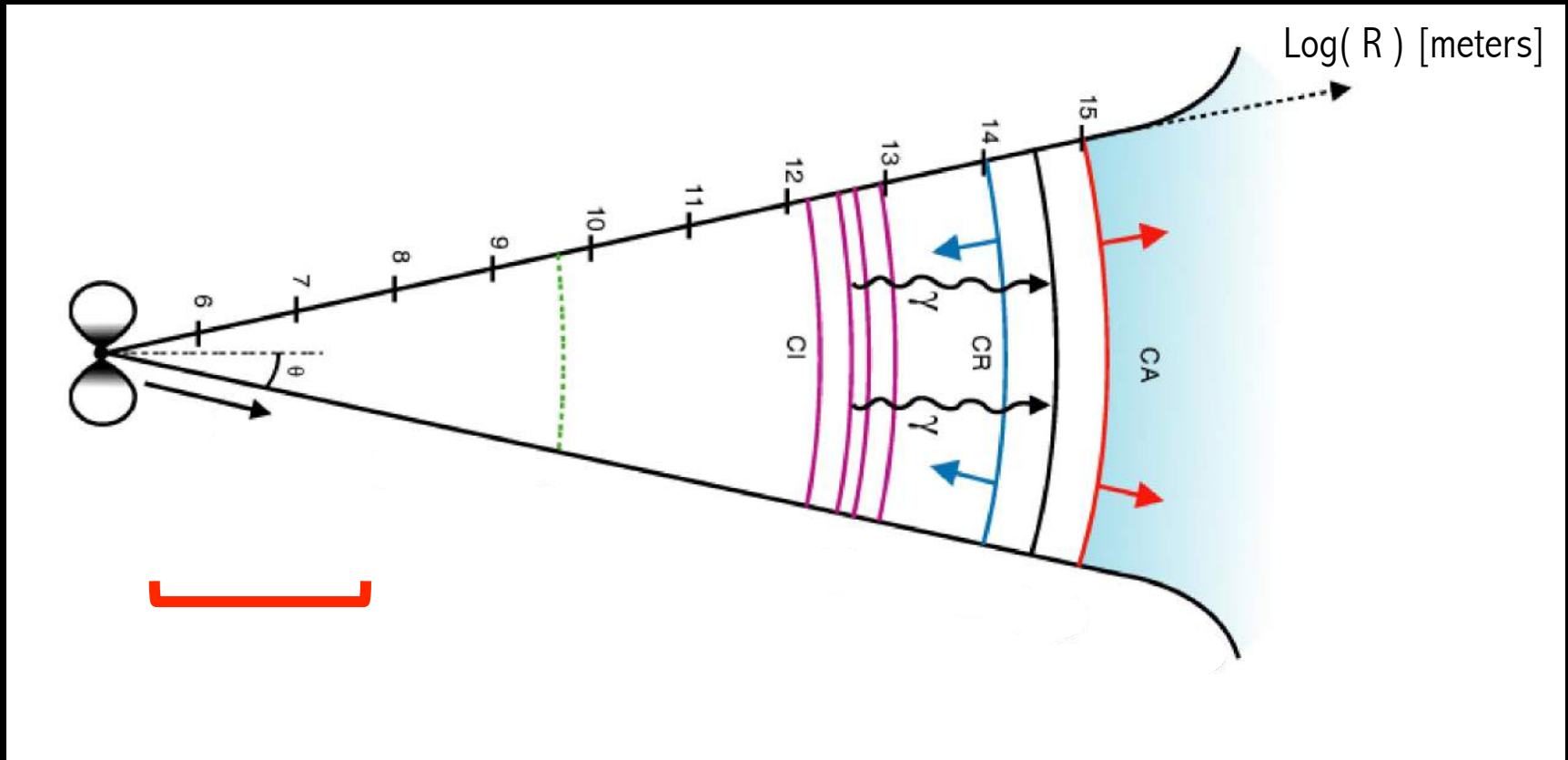
Long GRBs: collapse of a massive star

Short GRBs: NS+NS/BH merger? (link with GW)



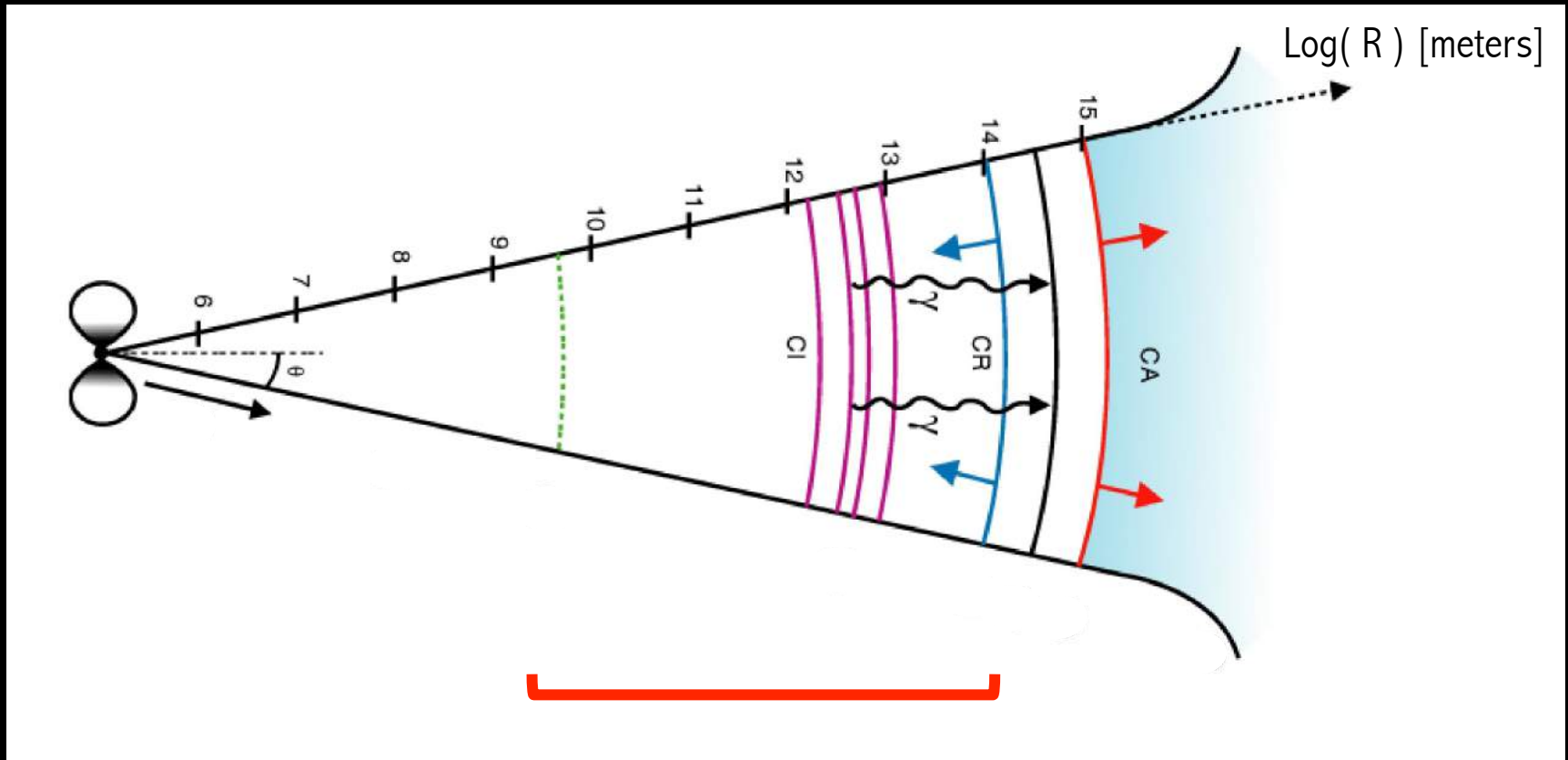
GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection



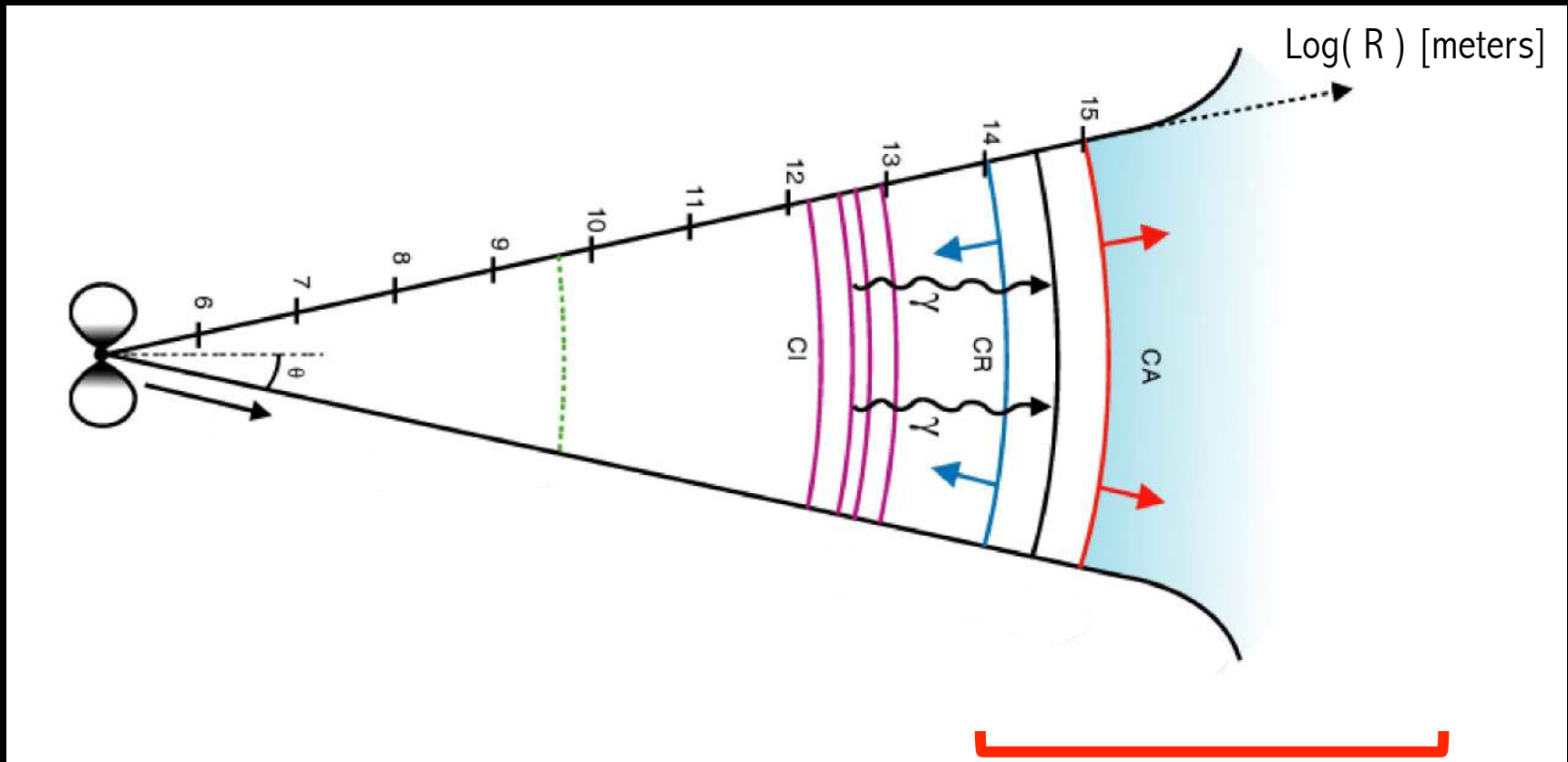
GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta



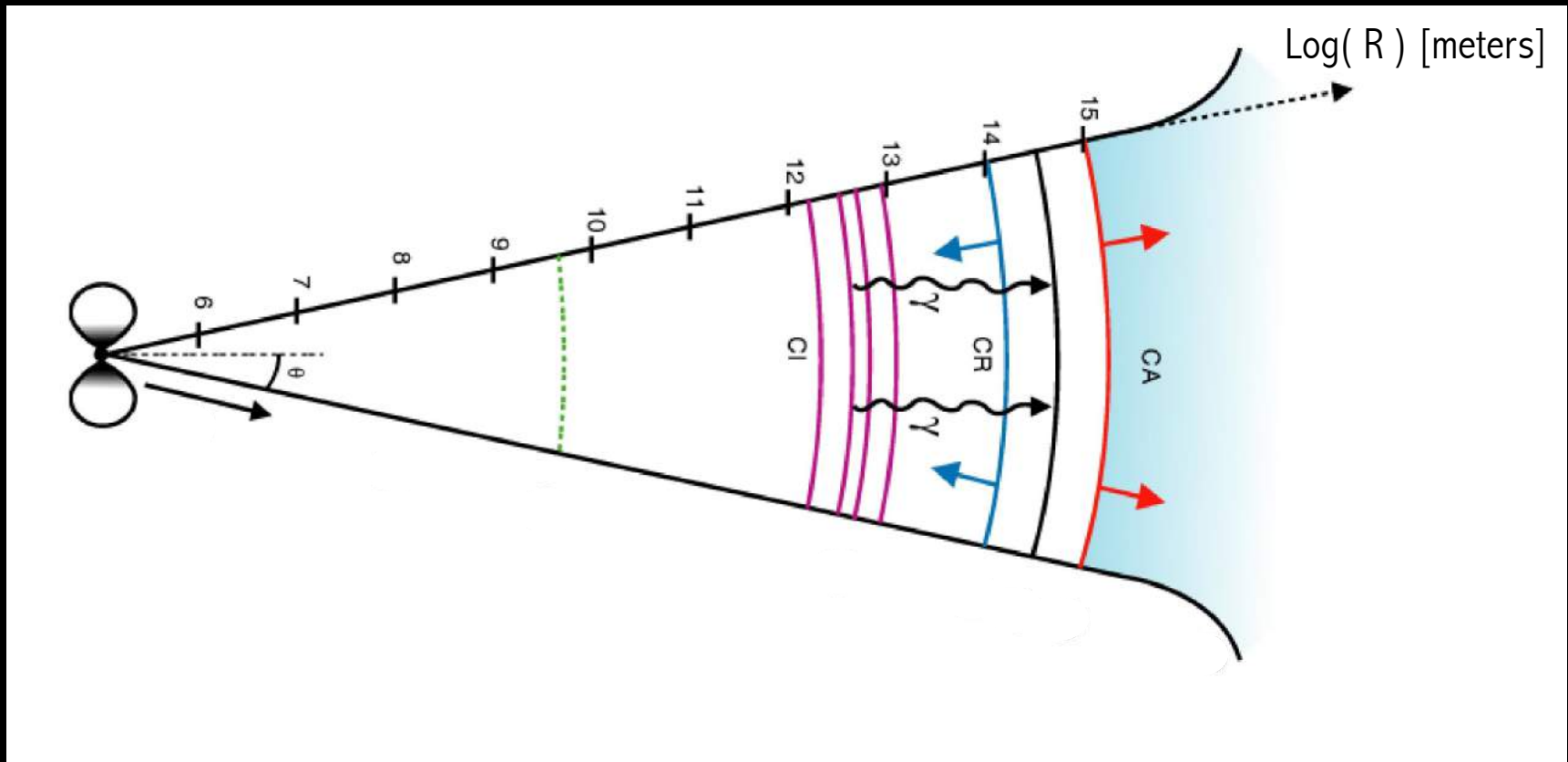
GRB Physics

- Variability + energetics + gamma-ray spectrum: relativistic ejection
- Prompt emission: internal origin in the ejecta
- Afterglow: deceleration by ambient medium



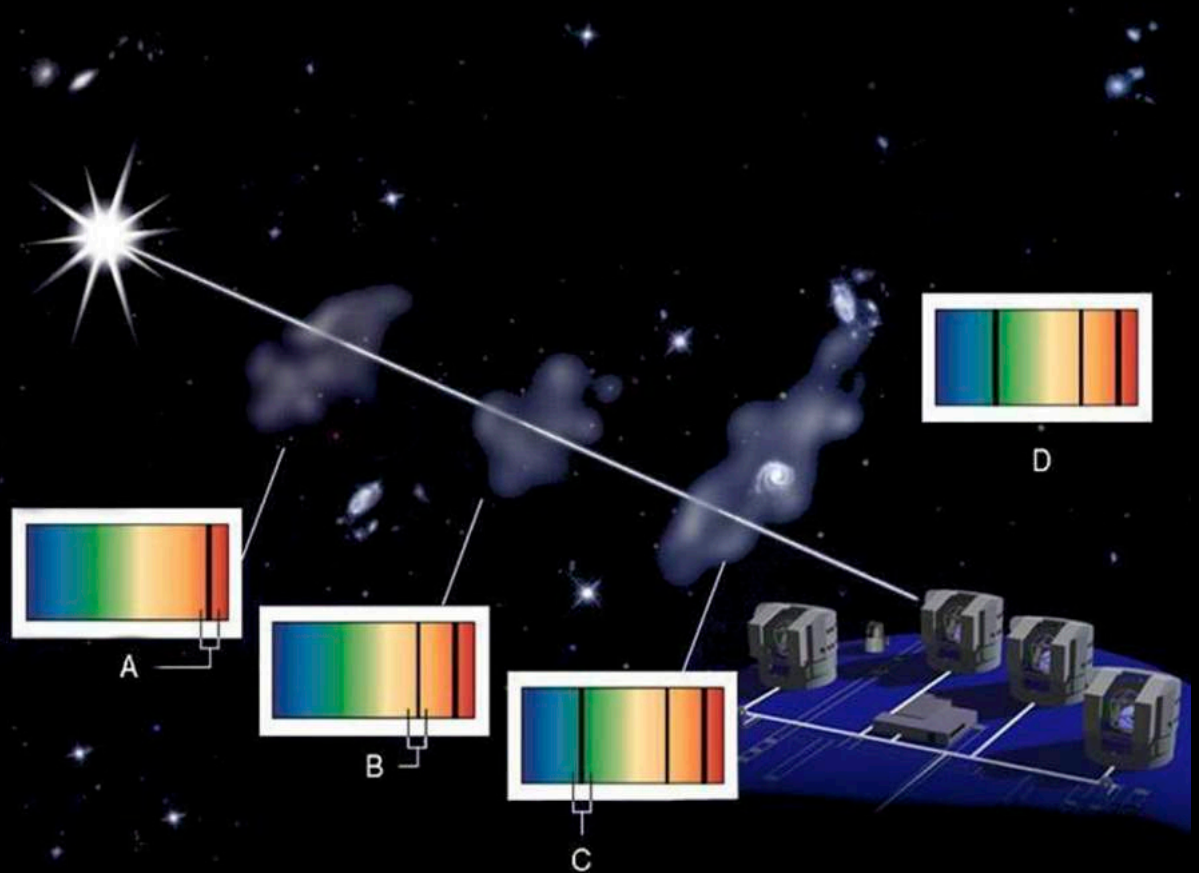
GRB Physics

- Final state of massive stars
 - Compact objects / relativistic ejecta
 - Particle acceleration / non-thermal emission
 - Non-photon emission (GW ? Neutrinos ? CRs ?)
- Etc.



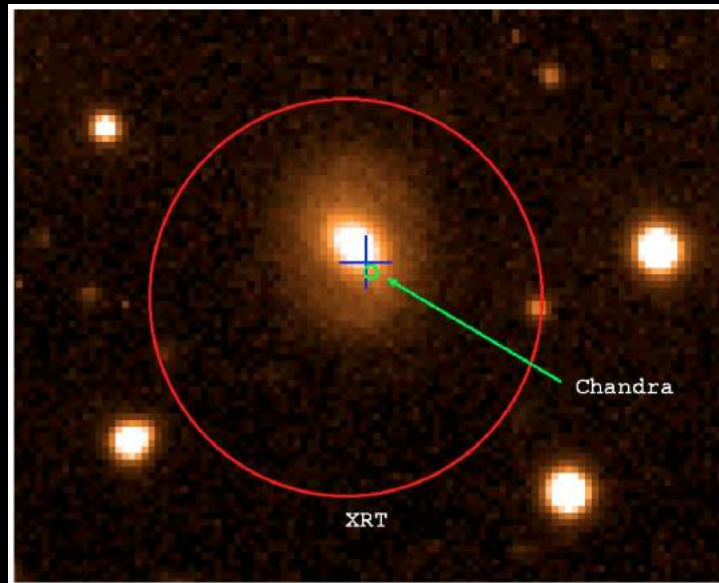
GRB as a tool for cosmology

- A sample of weak high-z galaxies (absorption & emission spectroscopy)
- Tracing the star formation rate
- Hubble diagram? Very difficult
- Absorption spectroscopy on the line of sight (ISM, IGM)
 - chemical evolution
 - reionization
 - etc.
- First stars ?



Gamma-ray bursts: progenitors

Short GRBs: NS+NS?



GRB 050724 @ VLT

Barthelmy et al. 2005

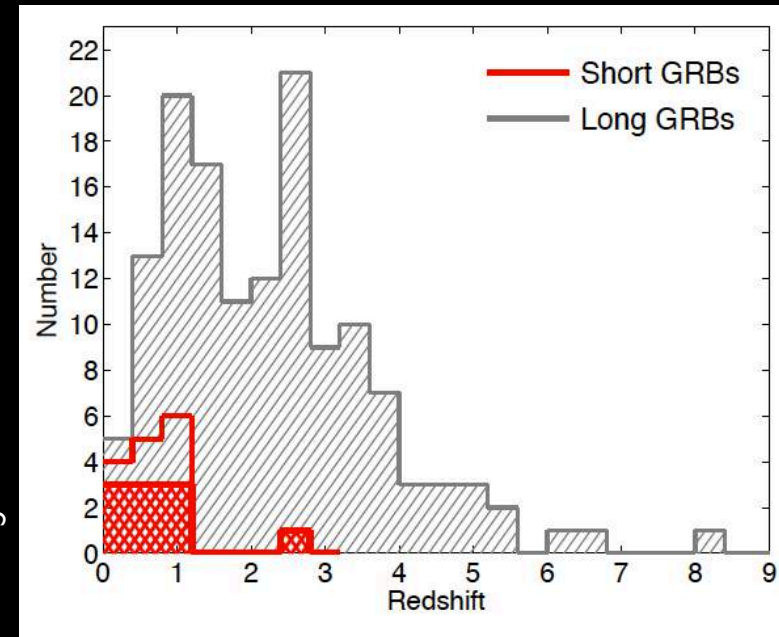
Long GRBs: gravitational collapse of a massive star
(correlation with star formation)

Short GRBs: merger scenario

- no correlation with star formation
- offsets
(see Gehrels et al. Nature 2005)
- etc.

(see review by Berger 2014)

Berger et al. 2011



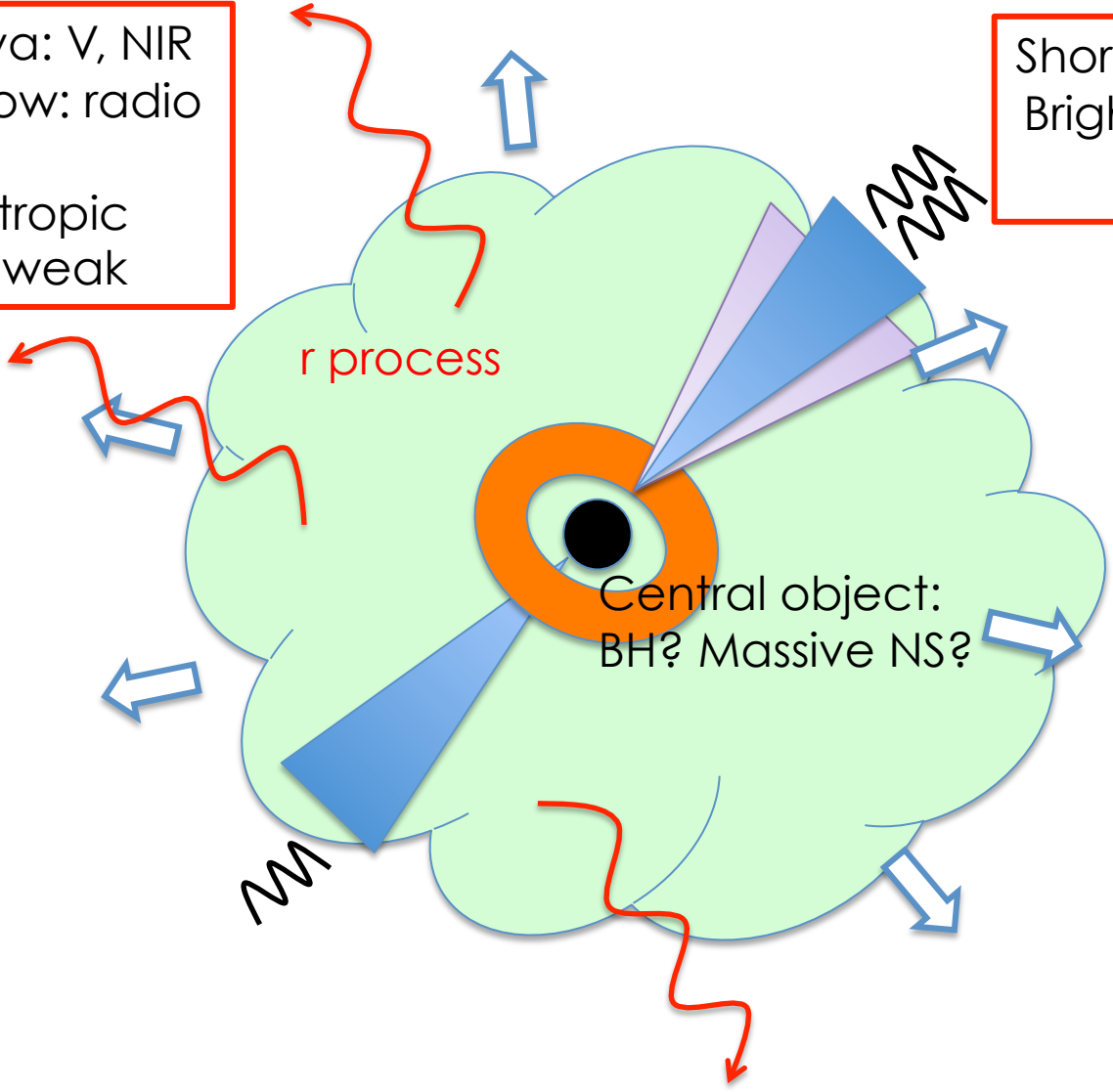
NS+NS mergers: predictions

Final state of a merger: pre-summer 2017 theory

Kilonova: V, NIR
Afterglow: radio

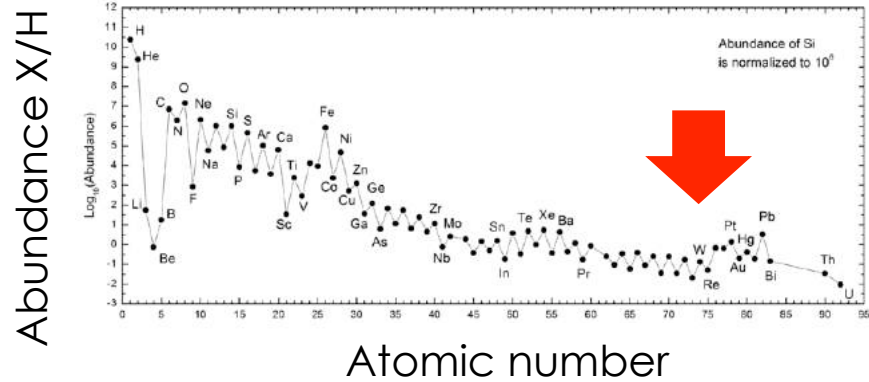
~isotropic
BUT weak

Short GRB: hard γ -rays
Bright BUT collimated
Cocoon ?

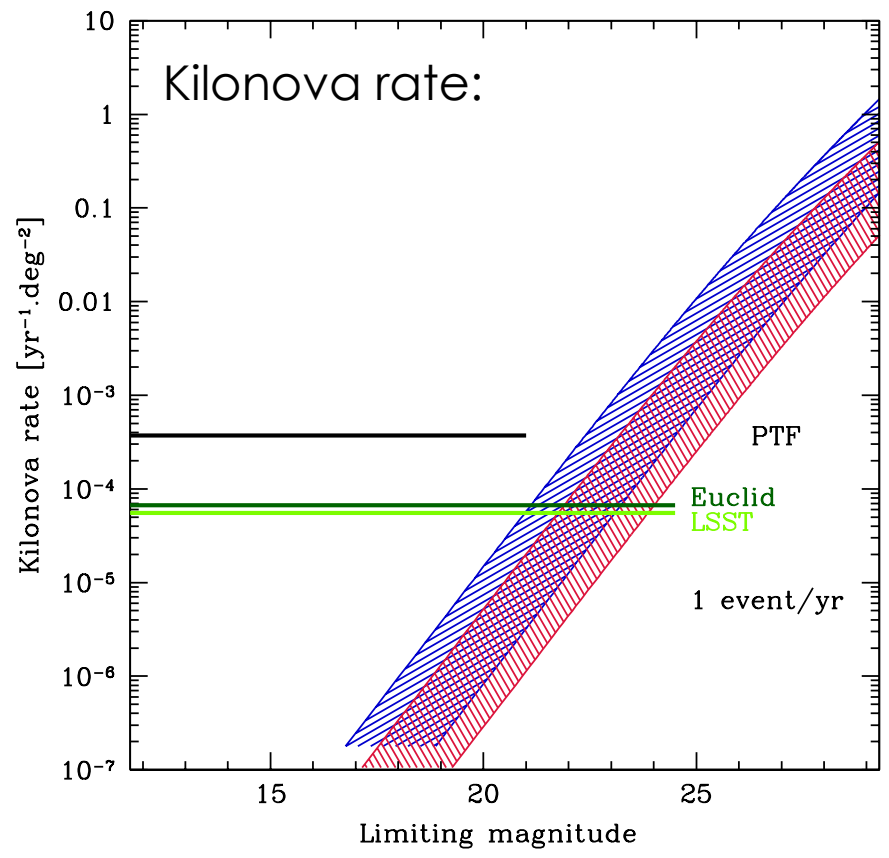
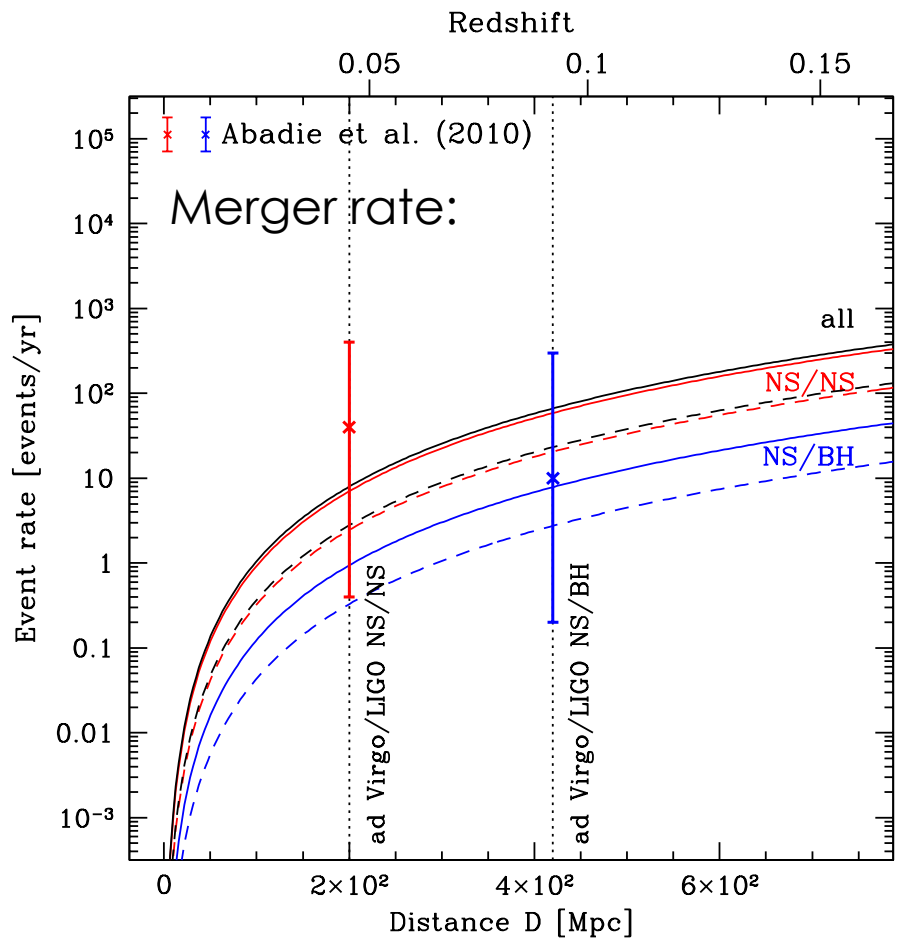


R process: constraints on the merger rate

Observations: Eu in stars, including very old (metal-poor) stars = trace evolution of r process.

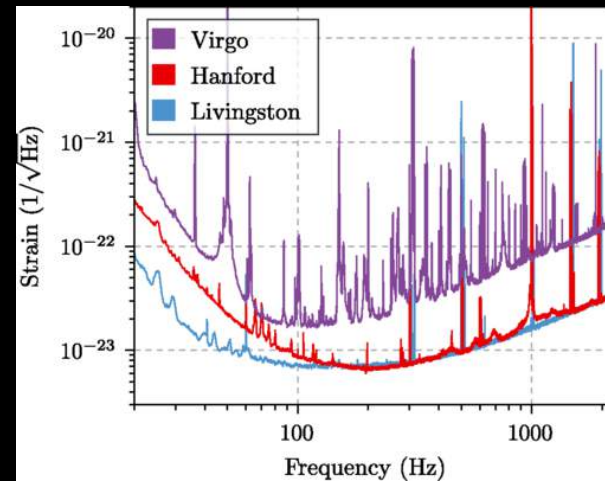


Lodders (2003)



The first multi-messenger observation of a NS+NS merger

August 17th, 2017 – Status of LIGO/Virgo

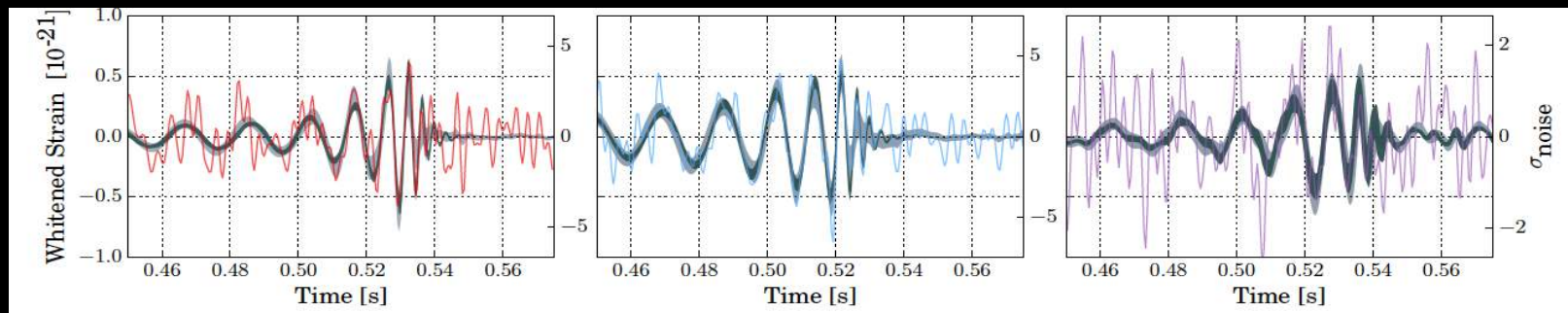


LIGO Hanford

LIGO Livingston

Virgo

Three days before: three-detector observation of GW 170814 (BH+BH)

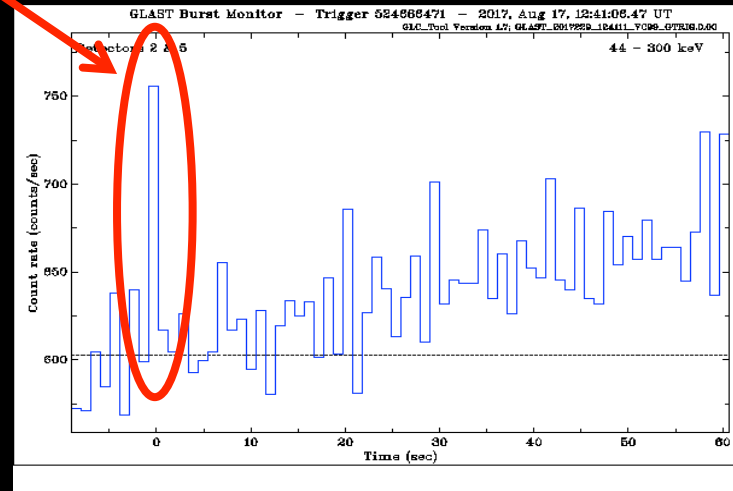


August 17th, 2017 – 12:41

Fermi/GBM



```
////////////////////////////////////  
TITLE:          GCN/FERMI NOTICE NOTICE_DATE:    Thu 17 Aug 17 12:41:20 UT  
NOTICE_TYPE:    Fermi-GBM Alert RECORD_NUM:        1  
TRIGGER_NUM:    524666471  
GRB_DATE:       17982 TJD;   229 DOY;   17/08/17  
GRB_TIME:       12066.47 SCD {12:41:06.47} UT  
TRIGGER_SIGNIF: 4.8 [sigma]  
TRIGGER_DUR:    0.256 [sec]  
E_RANGE:        3-4 [chan]   47-291 [keV]  
...  
COMMENTS:       Fermi-GBM Trigger Alert.  
COMMENTS:       This trigger occurred at longitude,latitude = 321.53,3.90 [deg].  COMMENTS:  
The LC_URL file will not be created until ~15 min after the trigger.  
////////////////////////////////////
```



GRB 170817A

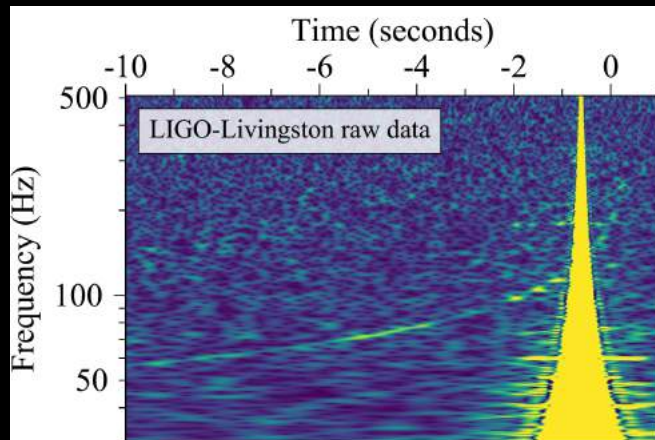
A weak short GRB...

August 17th, 2017 – 12:47

GW 170817

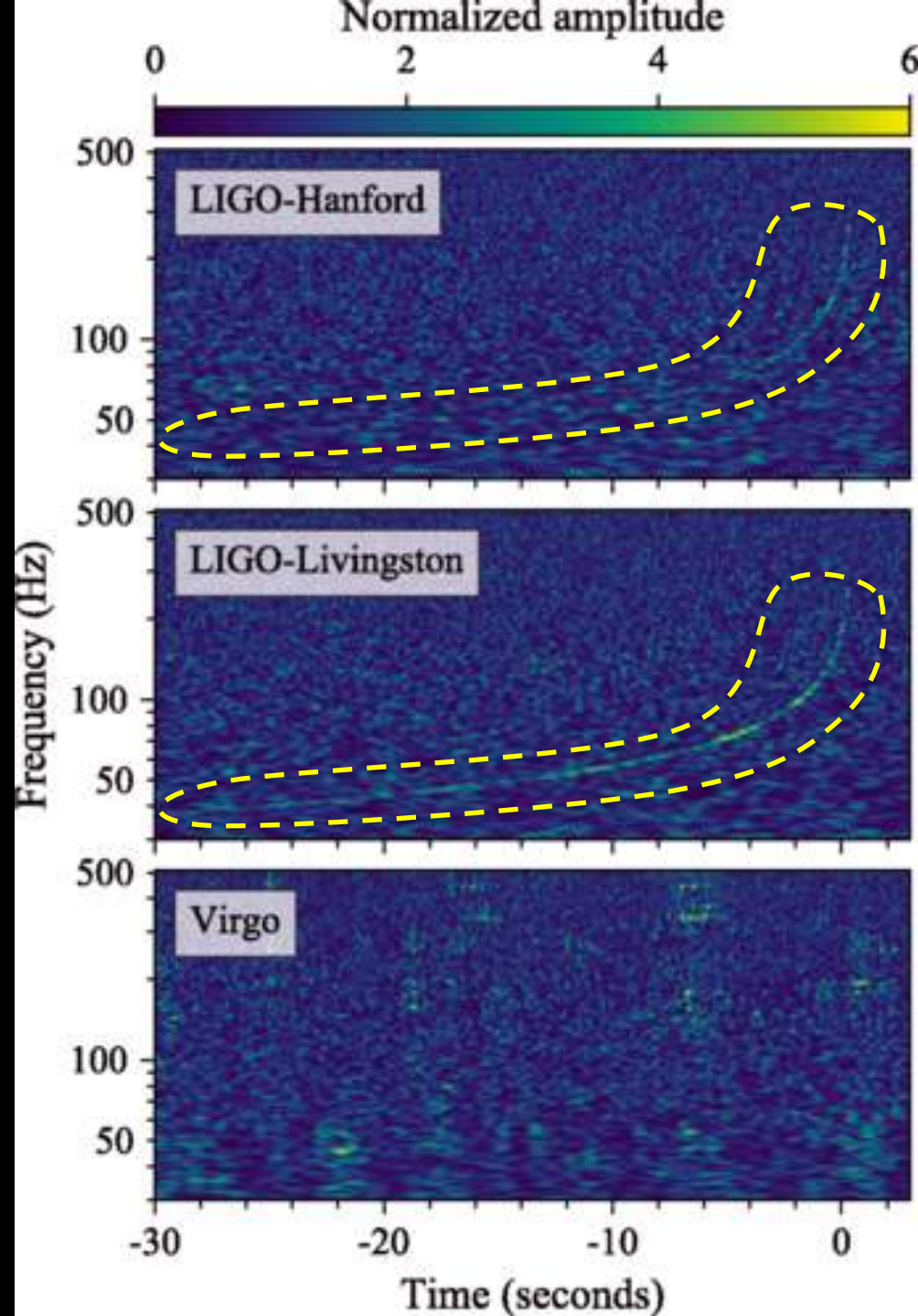
Automatic alert

- 1 detector (H1)
- + 1 detector (L1) with a glitch

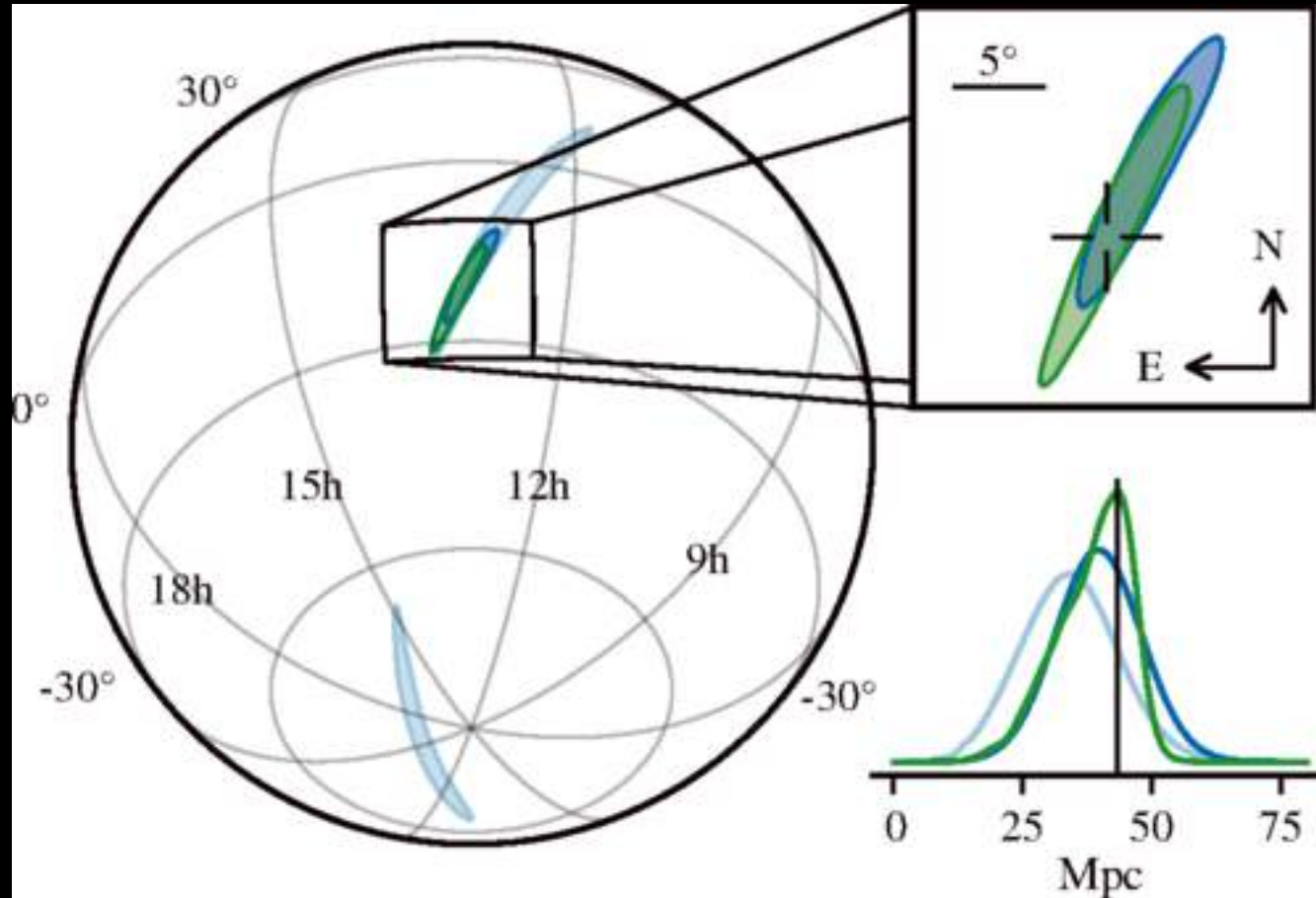


- strong signal
 - NS+NS !
 - merger 6 min ago
- i.e. ~2 s before GRB 170817A

13:21 LIGO-Virgo alert !
i.e. 40 minutes after the merger



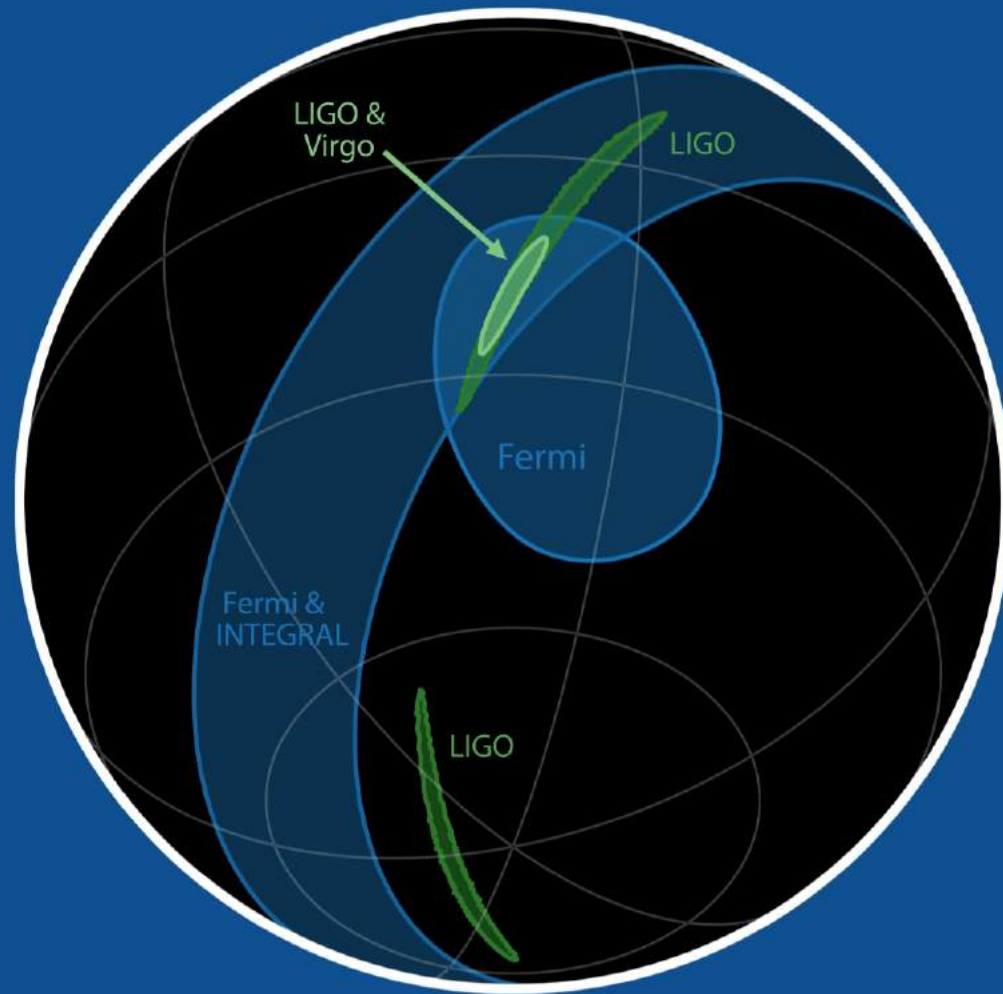
GW170817: localization



- LIGO: 190 deg^2 ; LIGO+Virgo: 30 deg^2 !
- 3D error box : distance $\sim 40 \text{ Mpc}$
- Sky map sent at 17:54, i.e. 5 hours after the merger

GW170817: localization

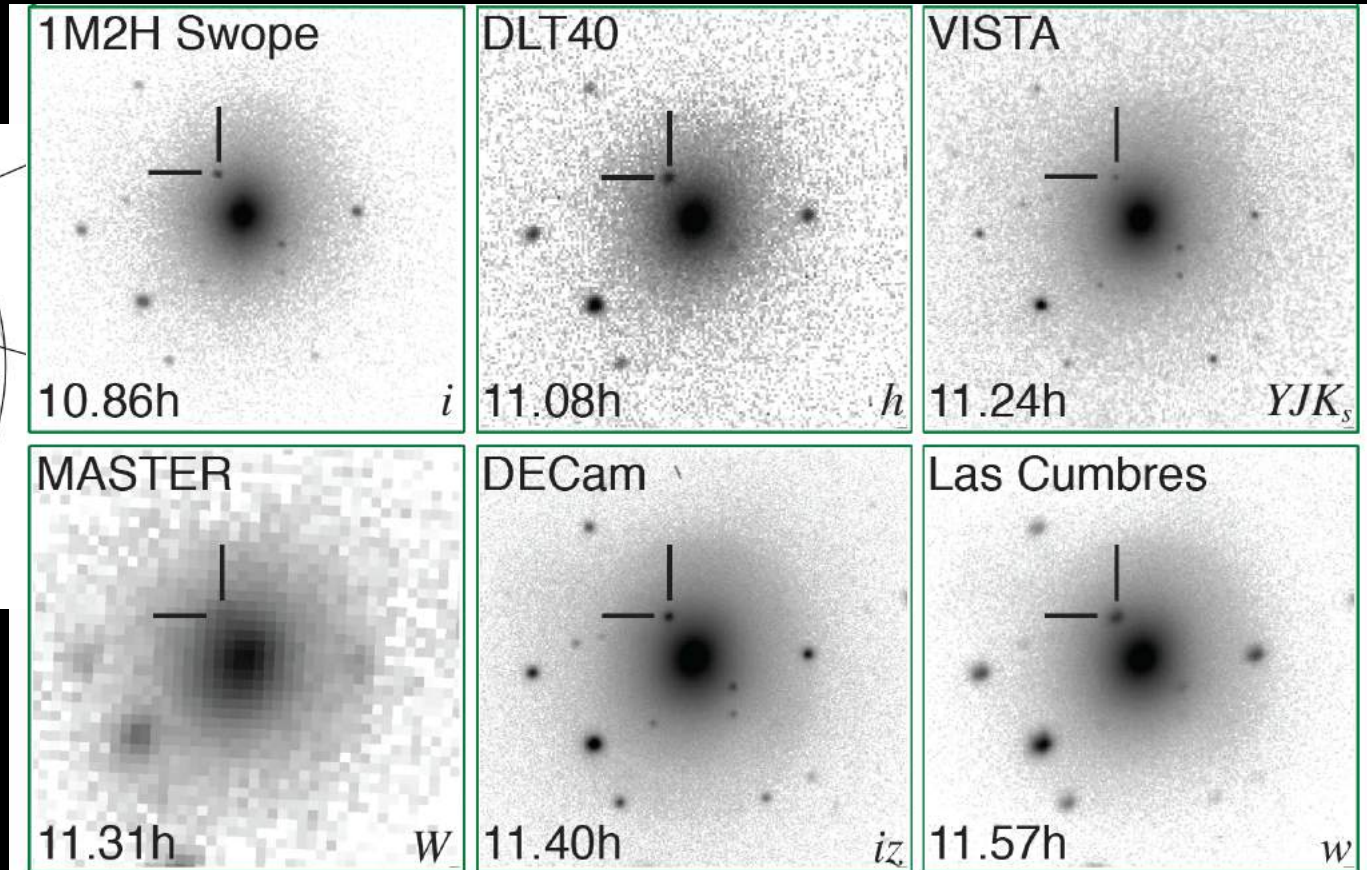
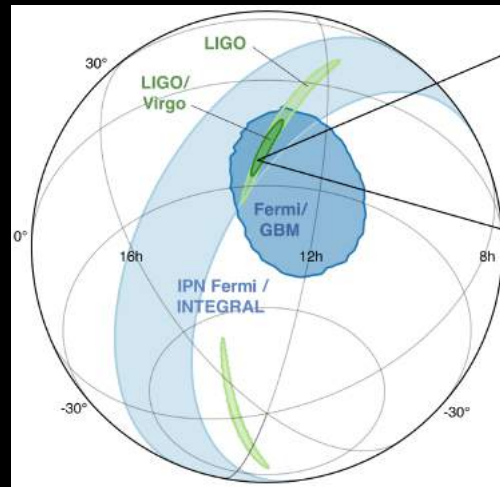
About 50 galaxies in the error box at 40 Mpc...



The search starts ~10 h after the merger (night in Chili)

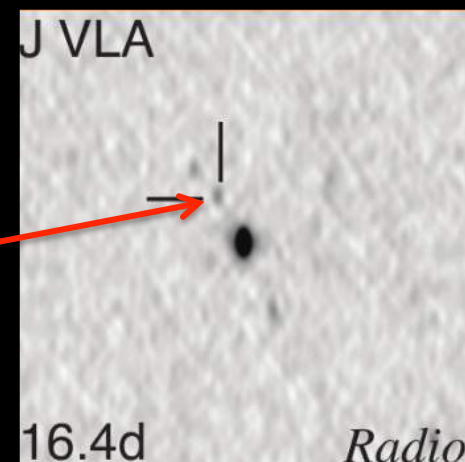
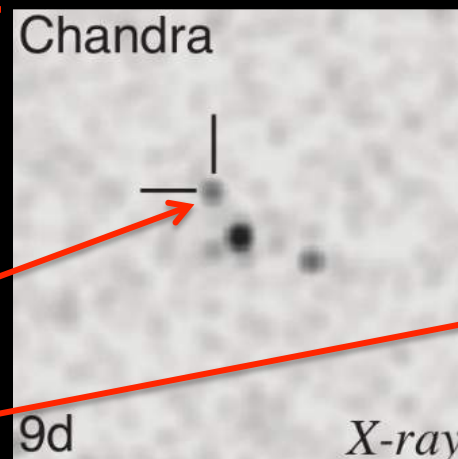
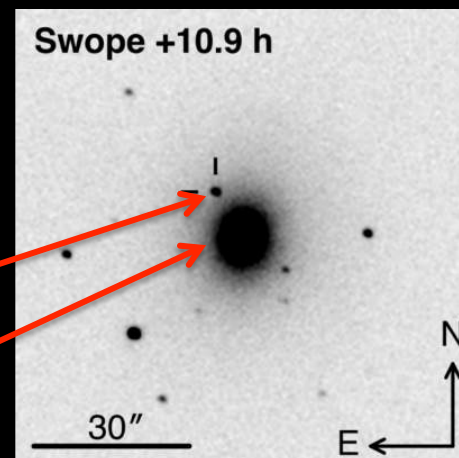
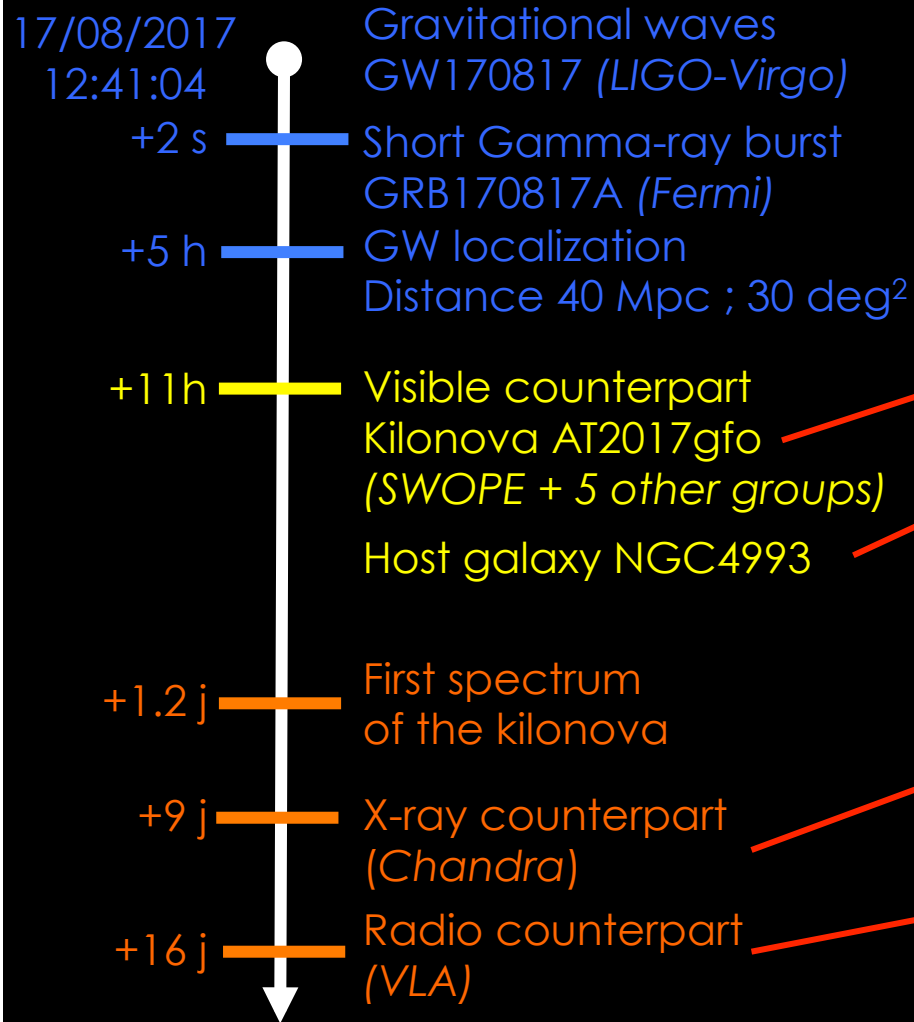
SSS17a / AT 2017gfo = KN 170817

Detection at ~merger+11h
of a new transient in NGC 4993 by SWOPE + 5 other groups

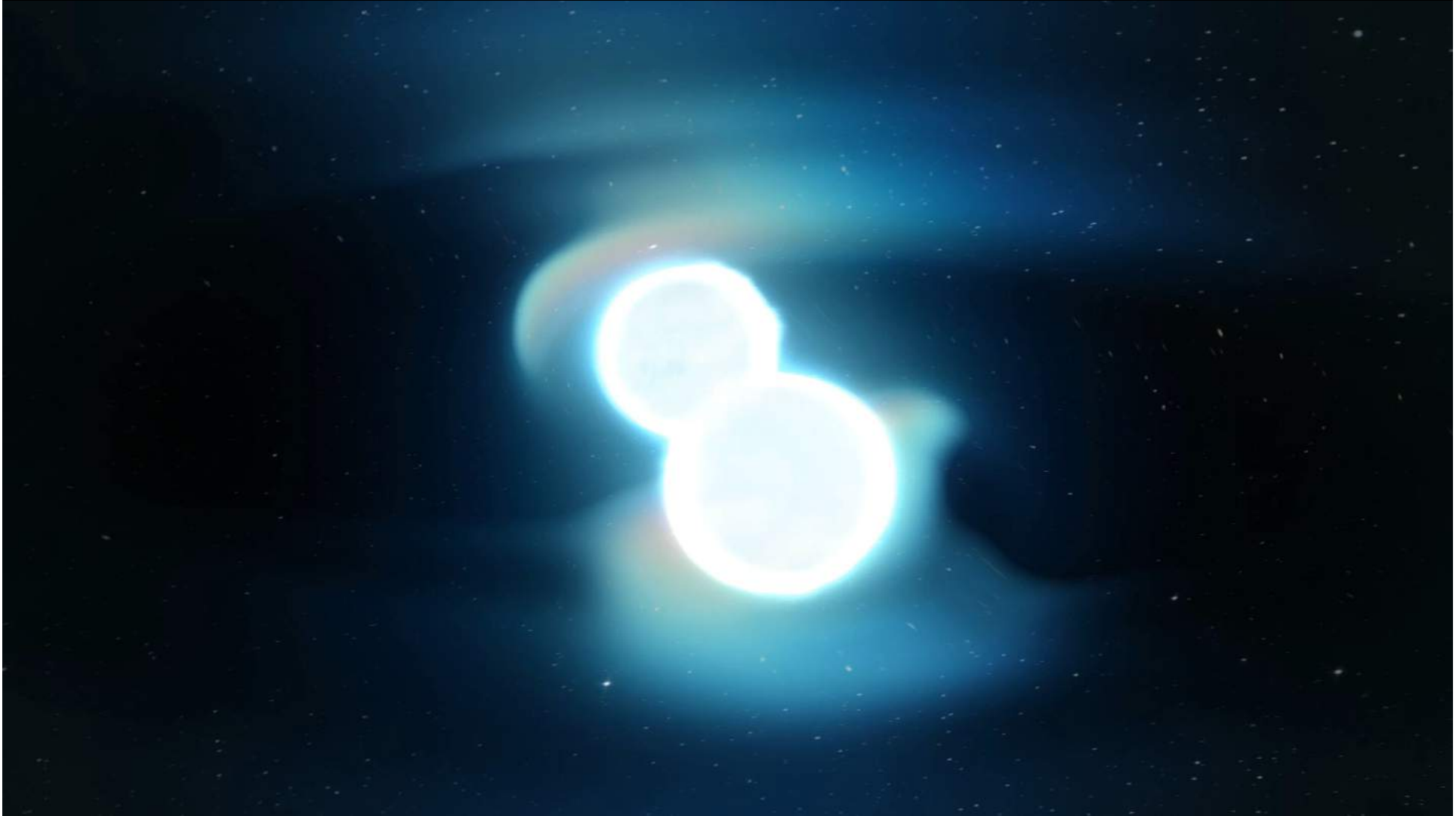


Spectro-photometric follow-up: first detection of a kilonova !

Timeline



The first multi-messenger observation of a NS+NS merger!



GW signal:



- BNS inspiral detected for ~ 100 s

- Preliminary analysis:
NS+NS, total mass = 2.7-2.8 M_{\odot}

TABLE I. Source properties for GW170817: we give ranges encompassing the 90% credible intervals for different assumptions of the waveform model to bound systematic uncertainty. The mass values are quoted in the frame of the source, accounting for uncertainty in the source redshift.

	Low-spin priors ($ \chi \leq 0.05$)	High-spin priors ($ \chi \leq 0.89$)
Primary mass m_1	1.36–1.60 M_{\odot}	1.36–2.26 M_{\odot}
Secondary mass m_2	1.17–1.36 M_{\odot}	0.86–1.36 M_{\odot}
Chirp mass \mathcal{M}	$1.188^{+0.004}_{-0.002} M_{\odot}$	$1.188^{+0.004}_{-0.002} M_{\odot}$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_{\odot}$	$2.82^{+0.47}_{-0.09} M_{\odot}$
Radiated energy E_{rad}	$> 0.025 M_{\odot} c^2$	$> 0.025 M_{\odot} c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55^{\circ}$	$\leq 56^{\circ}$
Using NGC 4993 location	$\leq 28^{\circ}$	$\leq 28^{\circ}$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4M_{\odot})$	≤ 800	≤ 1400

NS+NS

(NS+BH with a low probability)

Viewing angle

E.O.S



Kilonova

- Rapid evolution (blue → red)
- Cooling post-merger ejecta ($\sim 0.2c$)

Heating:
radioactivity of freshly synthesized heavy elements (r process)

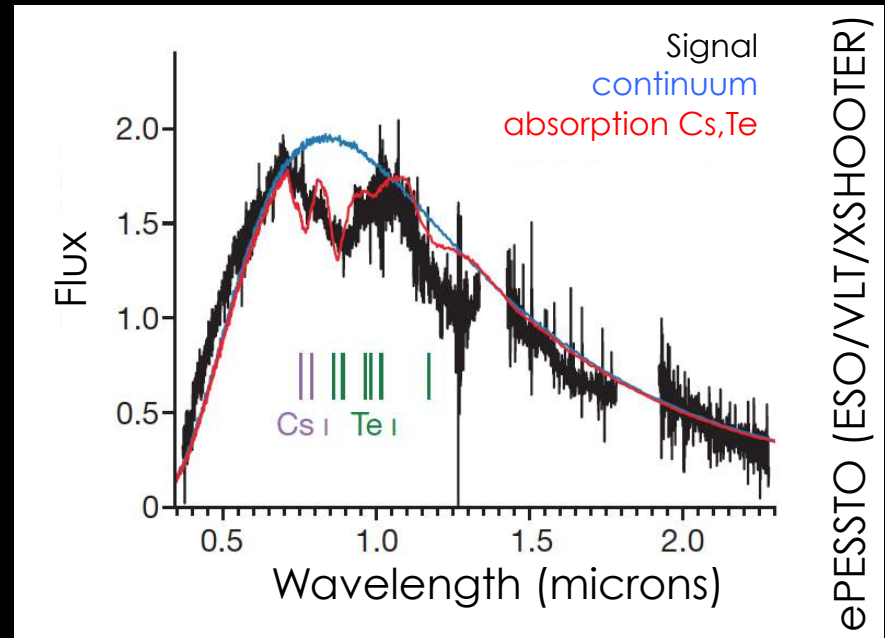
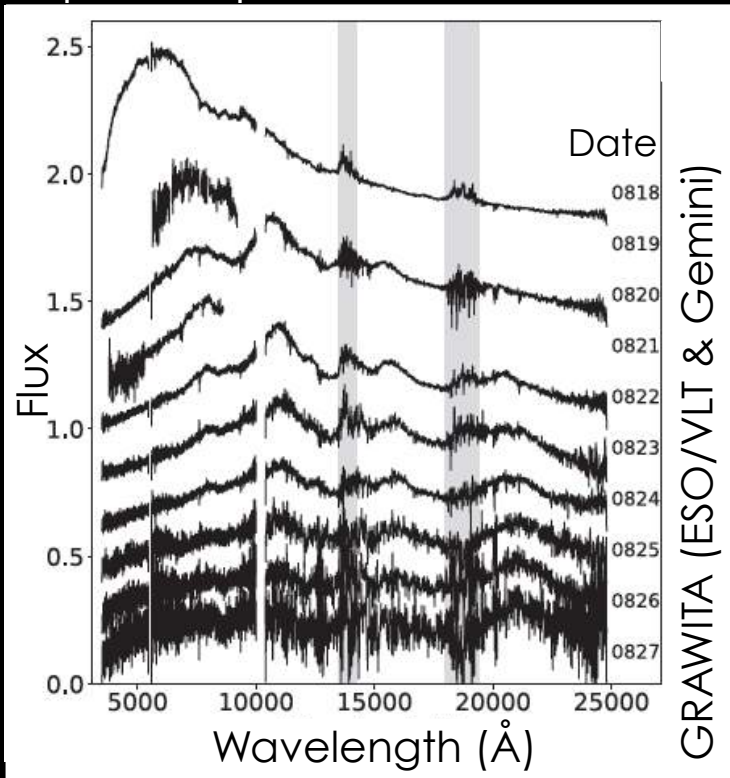
- Spectrum: absorption features associated to Cs and Te
- Spectro-photometric evolution: large opacity at late times (lanthanides)

SSS17a

August 17, 2017

August 21, 2017

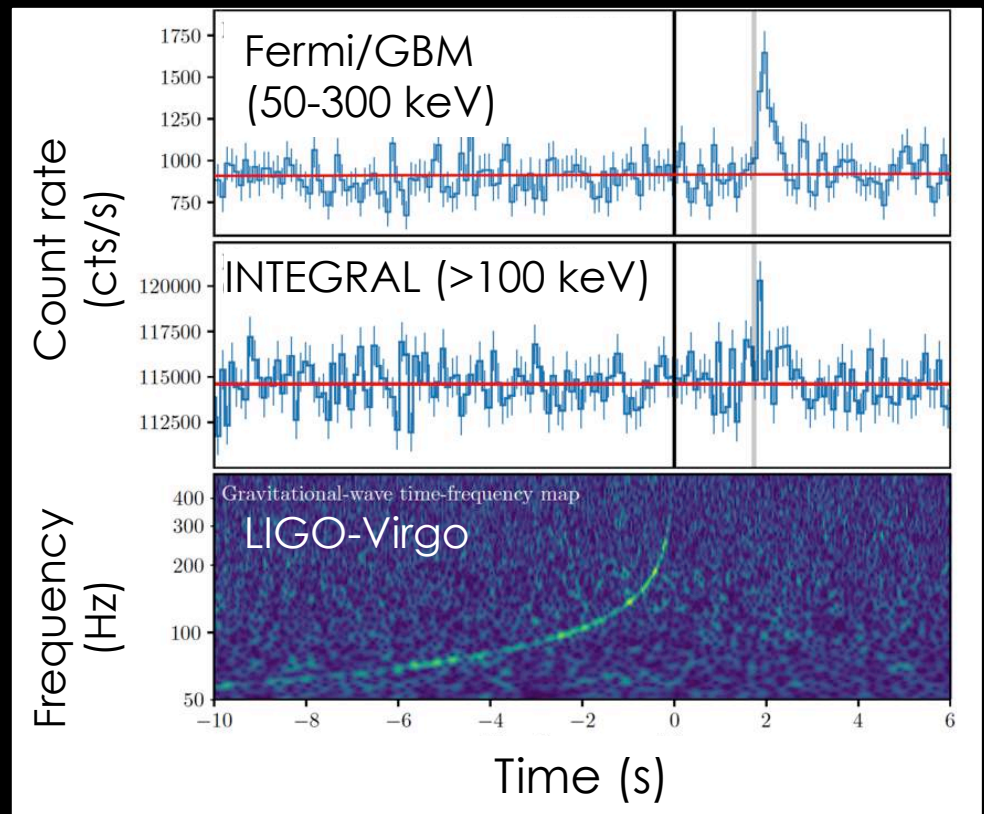
Swope & Magellan Telescopes



- Host galaxy: lenticular galaxy (gaz poor, no star formation) ; KN shows an offset
- GW+host galaxy: distance+system orientation / measure of Hubble constant

Gamma-ray burst

- At least some short GRBs are associated to NS+NS mergers!
- GW-GRB delay ~ 1.7 s
 - strong limit on GW propagation speed
 - expected intrinsic delay (merger-ejection ; jet propagation)
- Not a typical short GRB
 - Weak: 4-5 orders of magnitude
 - But emits photons above 100 keV
 - Afterglow?
- Origin of the observed emission? Geometry of the KN ejecta/relativistic ejecta?
- Connection to the classical population of short GRBs?



Conclusion

Conclusion: a new multi-messenger astronomy

- More mergers to come
- GW: future detection of the post-merger signal? Nature of the central source?
- More kilonovae? (nearby events)
- Origin of the heaviest elements: merger rate? Mass ejected? Composition?
- Geometry of the KN ejection?
- Gamma-ray burst: origin of the emission? Geometry?
(jet on/off-axis? ; cocoon? ; shock breakout? ...)
- How would GW/GRB/KN 170818 appear at different distance/orientation?
- NS+NS mergers: diversity of the electromagnetic counterpart?
- NS+BH mergers?
- Merger rate? Distribution of merger times?
- GW followup: organization / strategy / well-adapted instruments
- SVOM (2021+)