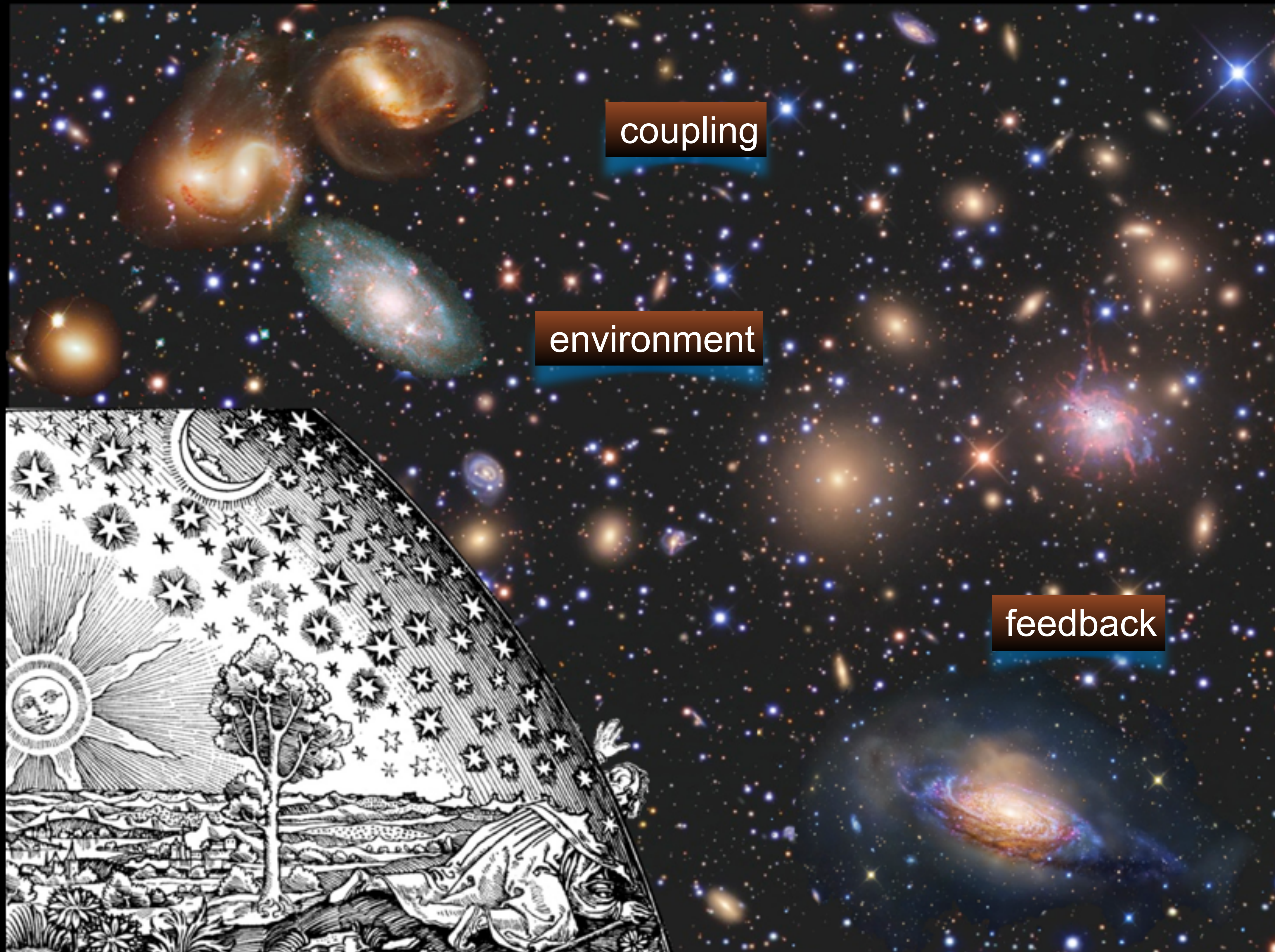
The local whirlpool: gas, stars, bubbles & feedback

Isabelle Grenier

AIM, Université Paris Diderot & CEA Saclay

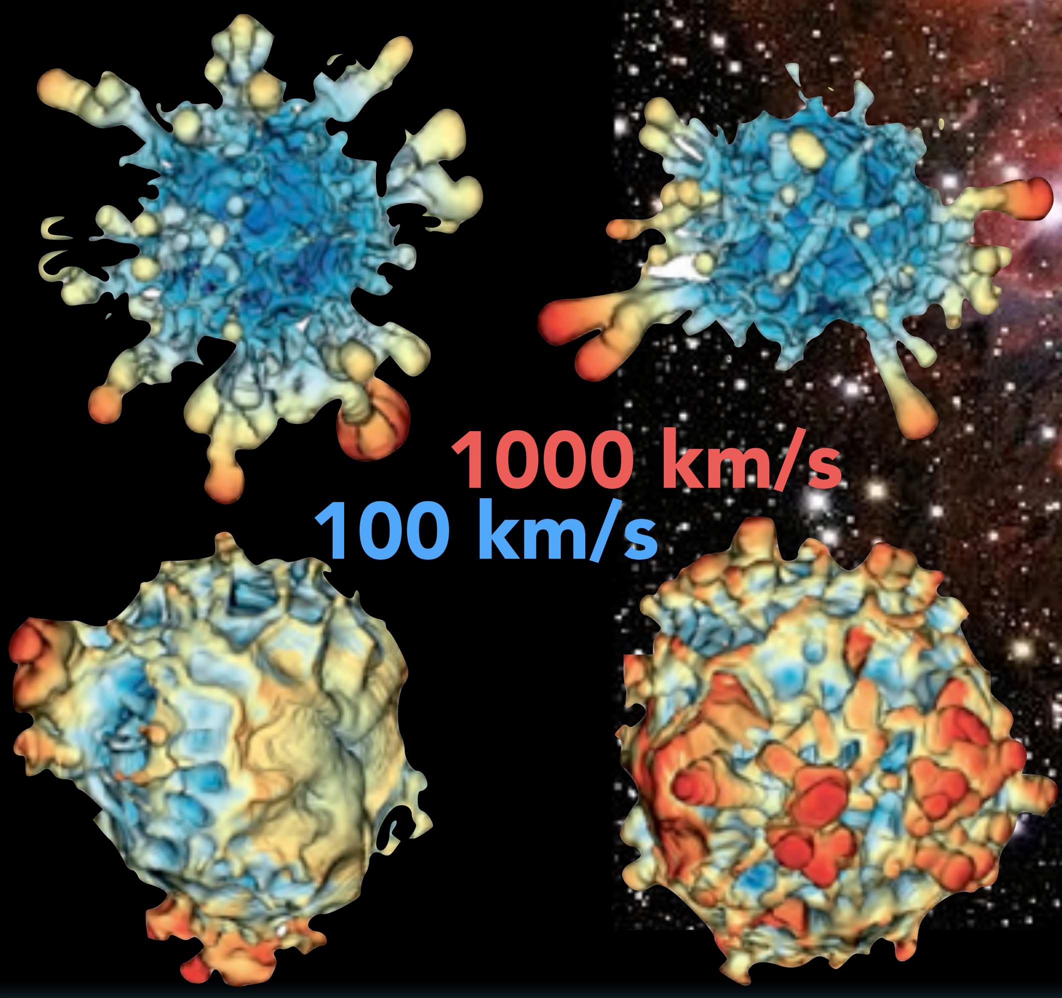
from steady state to evolution

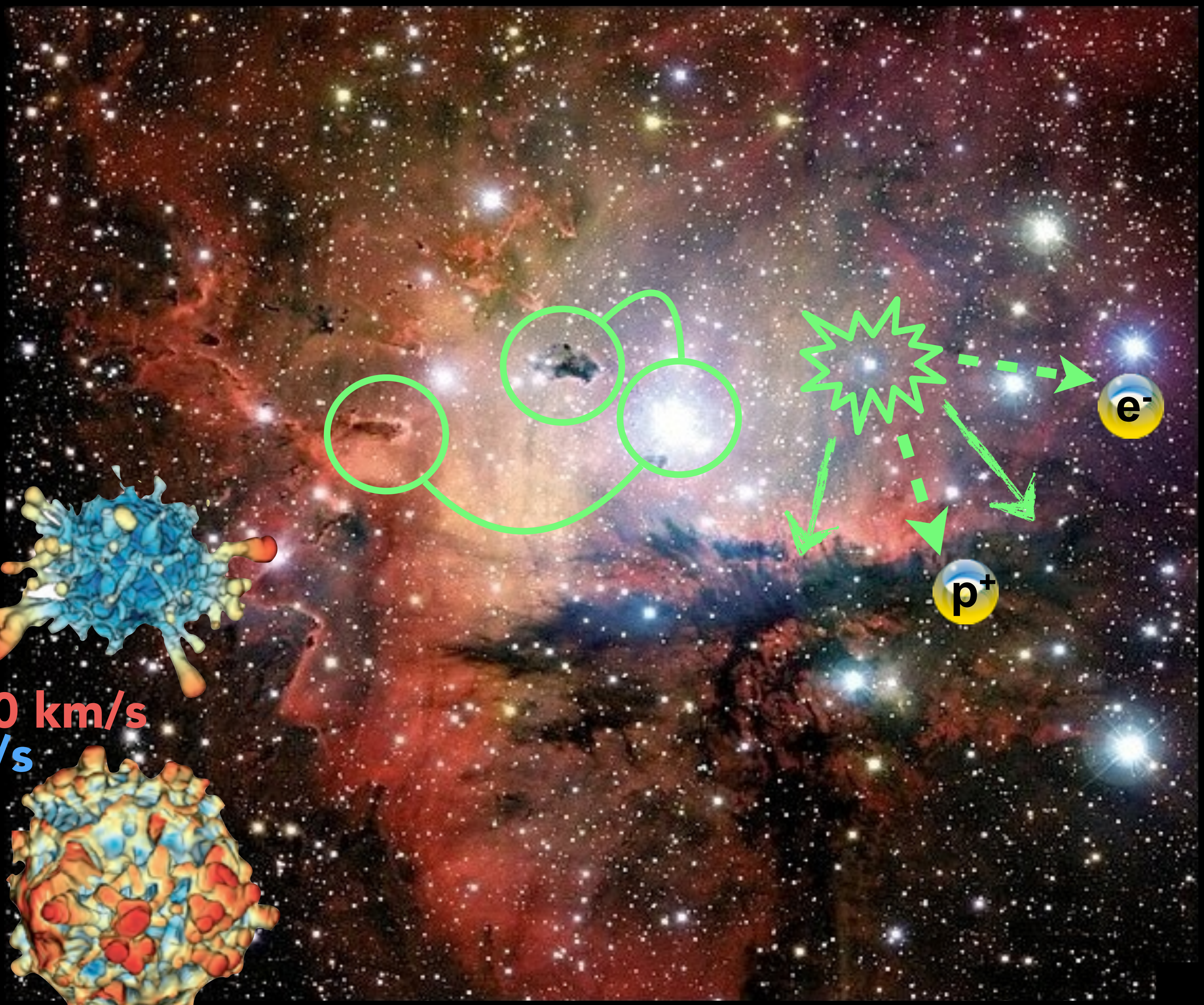


from calm to turmoil

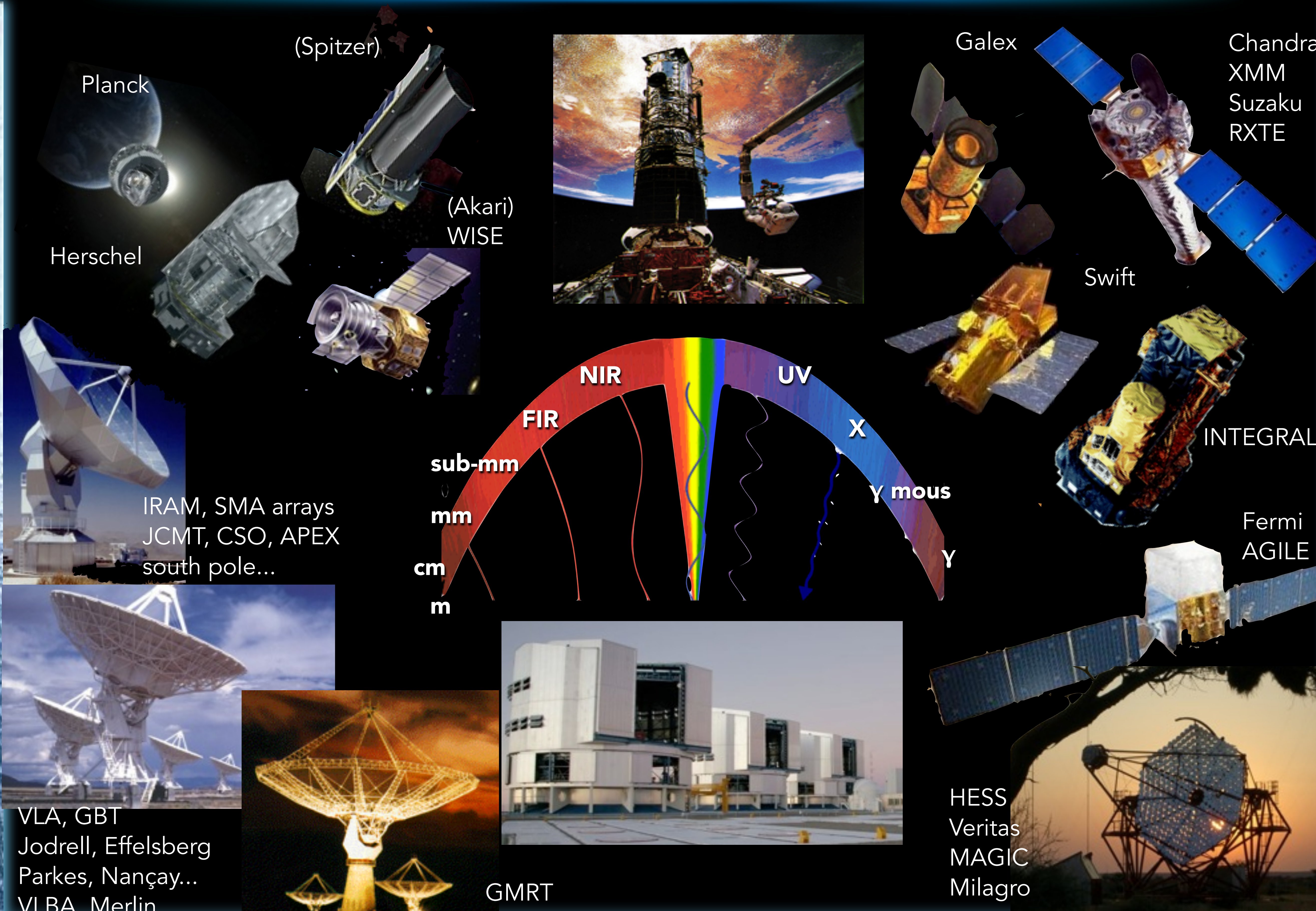
interstellar medium - high energy events

- real feedback: radiation, supersonic turbulence, pressure vs. heating, ionization, chemistry
- tracing feedback





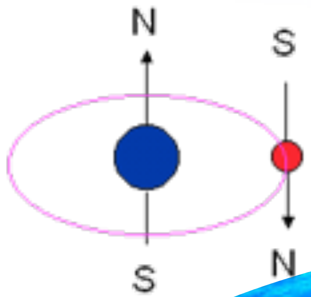
tool kit


Planck
(Spitzer)
Herschel
(Akari)
WISE
Galex
Chandra
XMM
Suzaku
RXTE
Swift
INTEGRAL
Fermi
AGILE
NIR
FIR
sub-mm
mm
cm
m
UV
X
γ mous
γ
IRAM, SMA arrays
JCMT, CSO, APEX
south pole...
VLA, GBT
Jodrell, Effelsberg
Parkes, Nançay...
VLBA, Merlin
GMRT
HESS
Veritas
MAGIC
Milagro

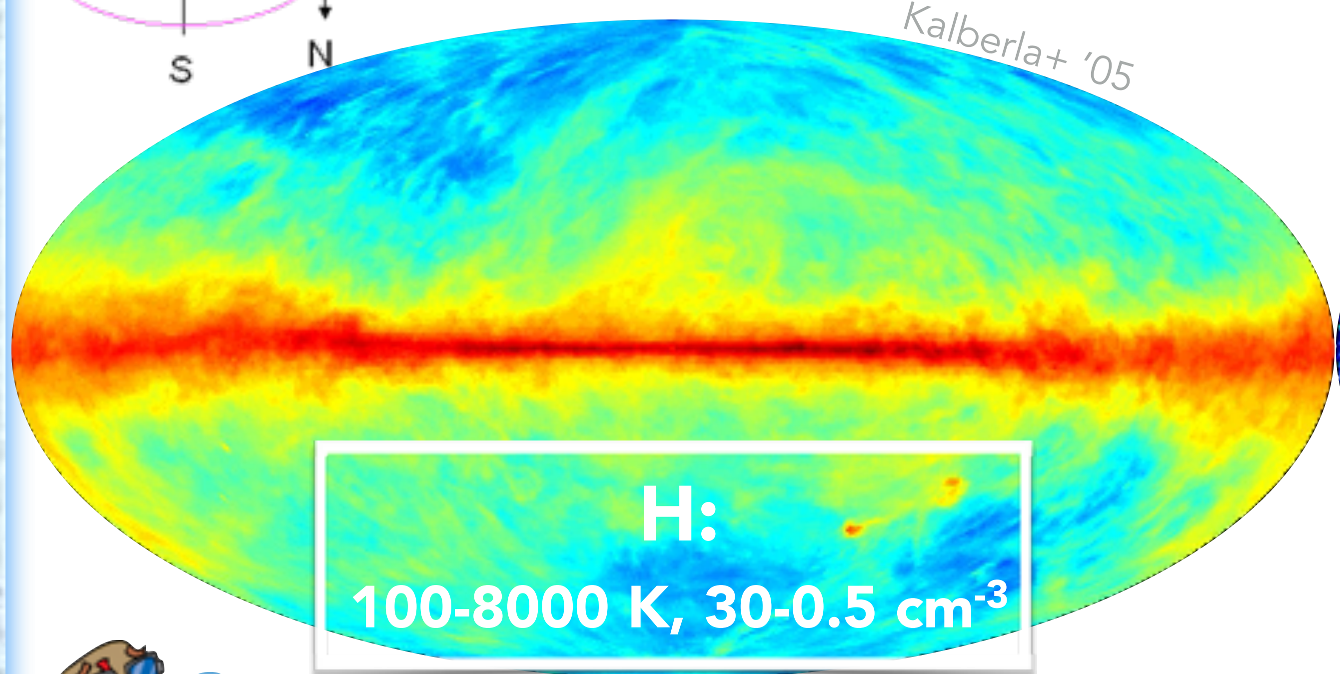
the quiet interstellar medium

gas reserves

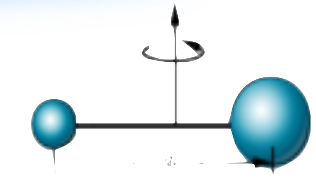
Univ
EarthS

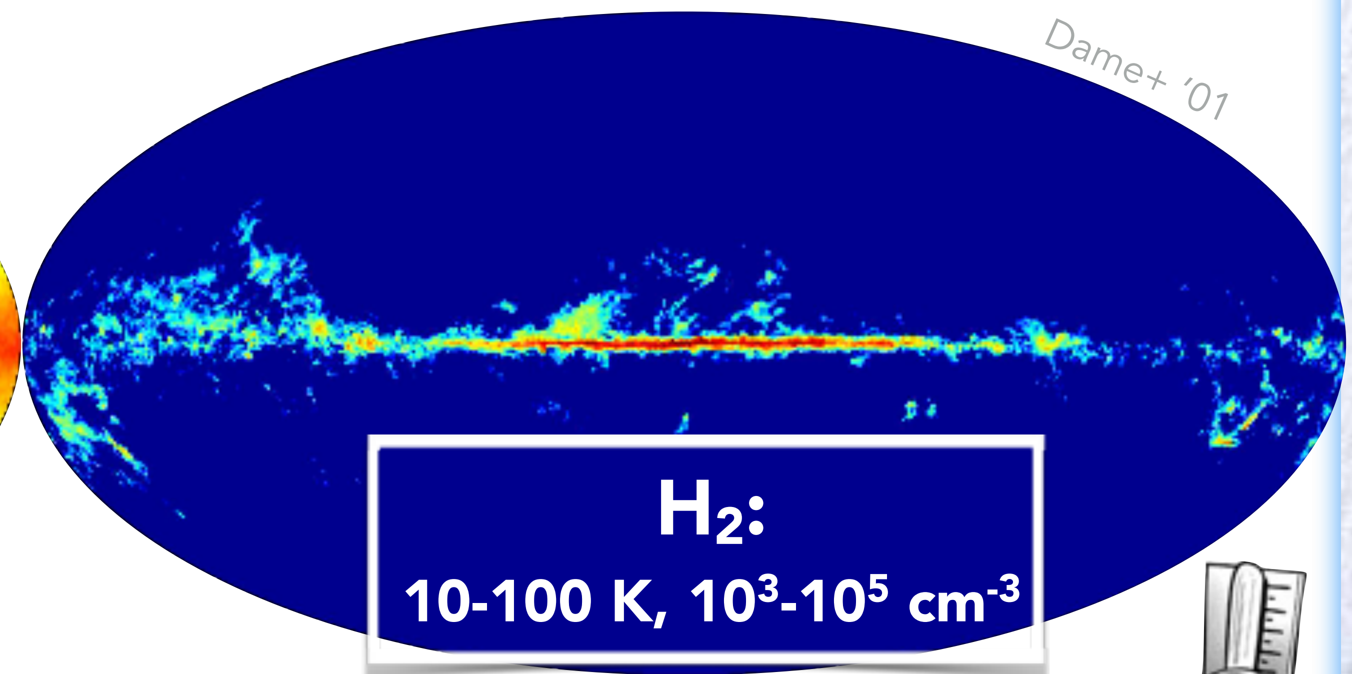


HI line 21 cm



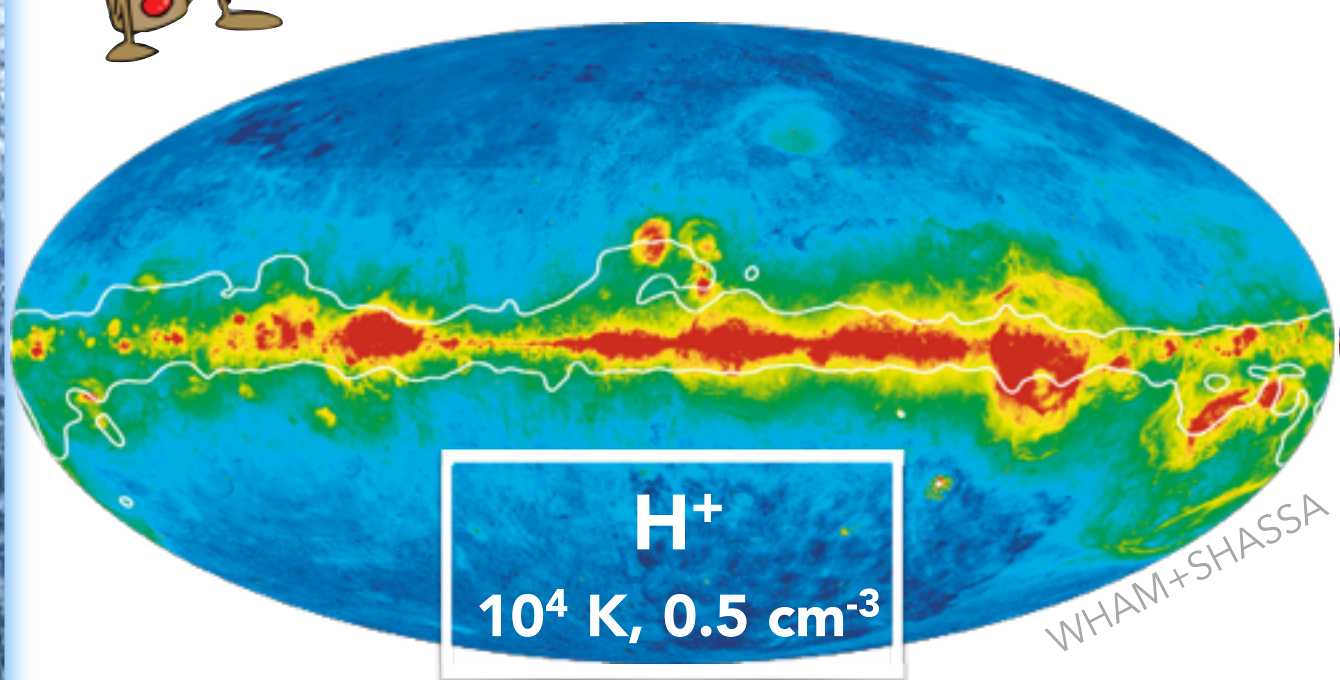
CO line 115 GHz

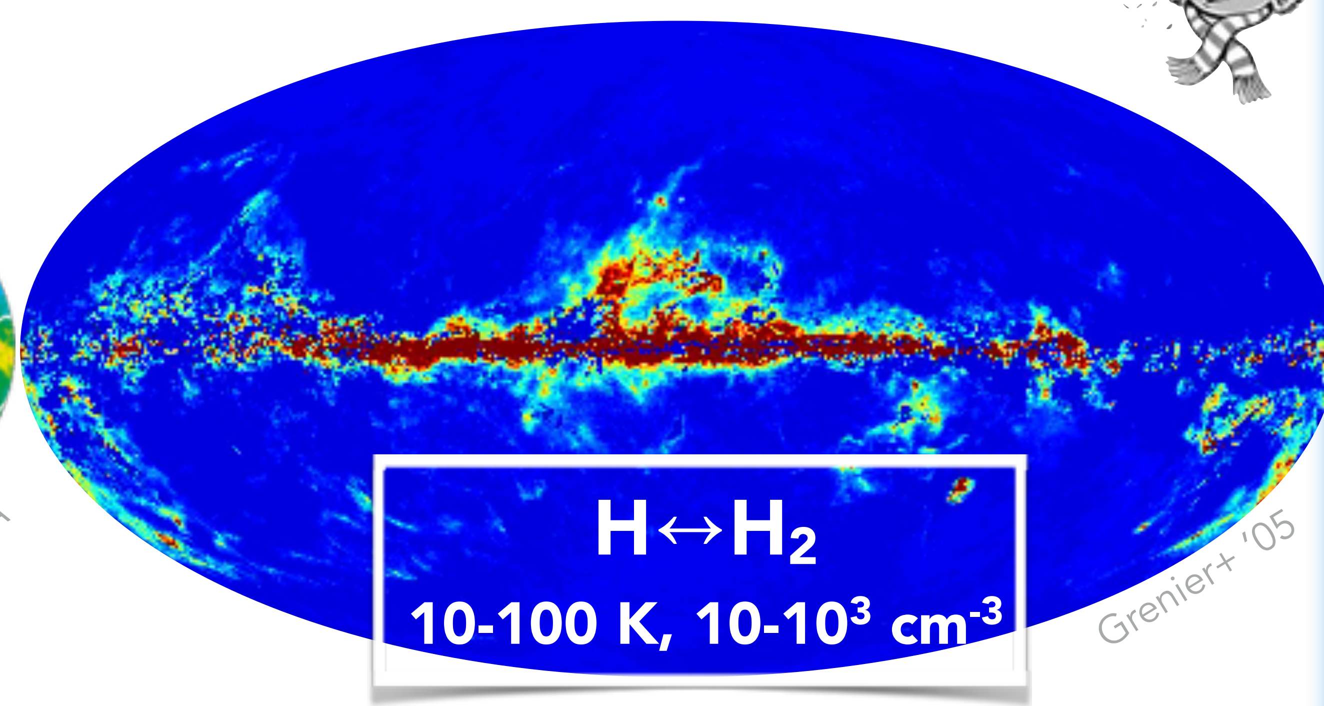




Hα line 0.66 μm

dark neutral medium

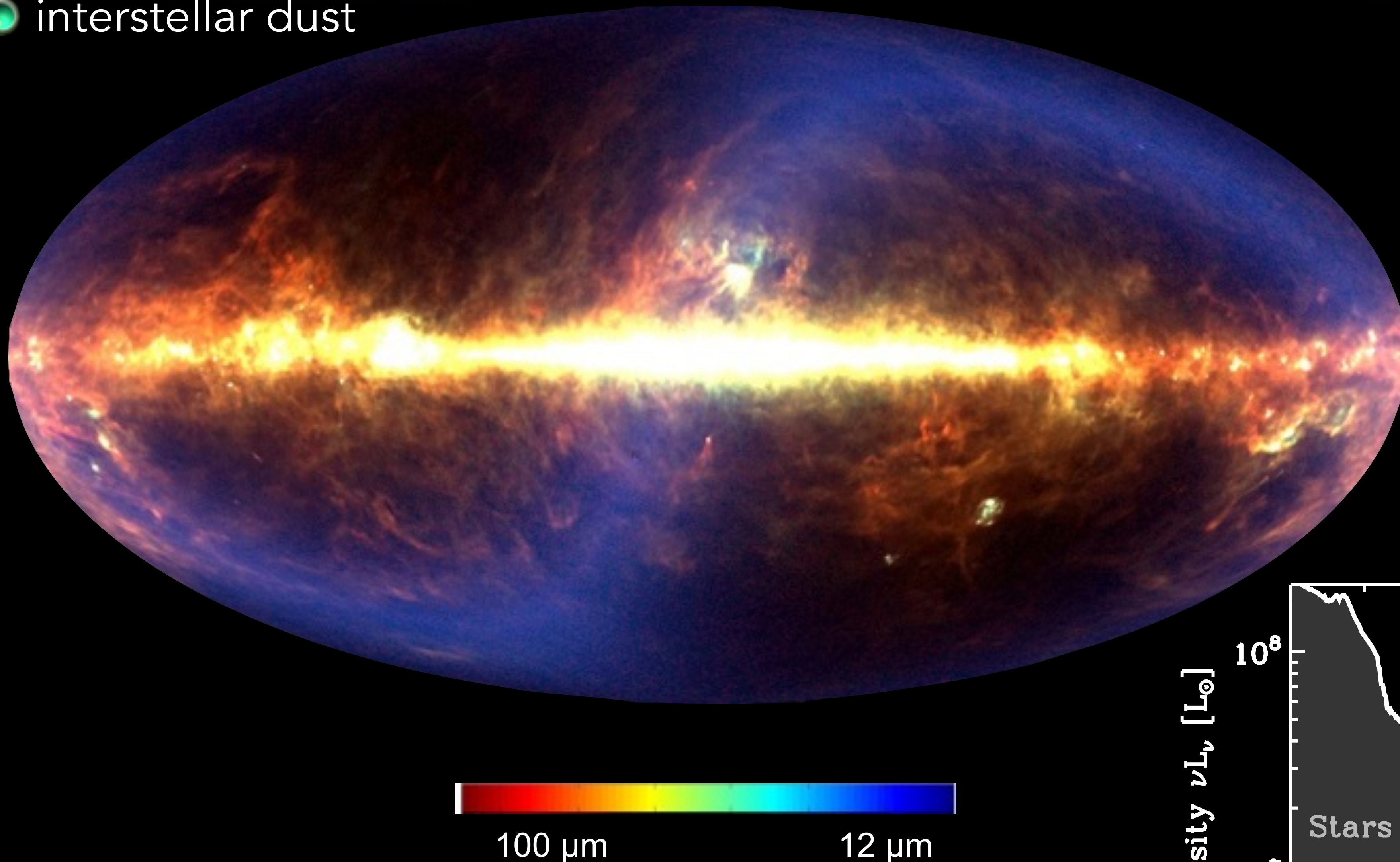


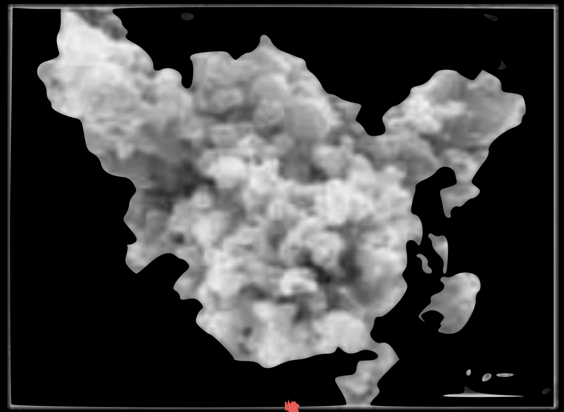


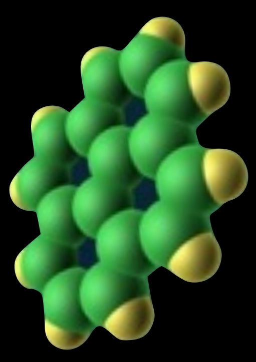
$$H^+ + e^- \rightarrow H$$

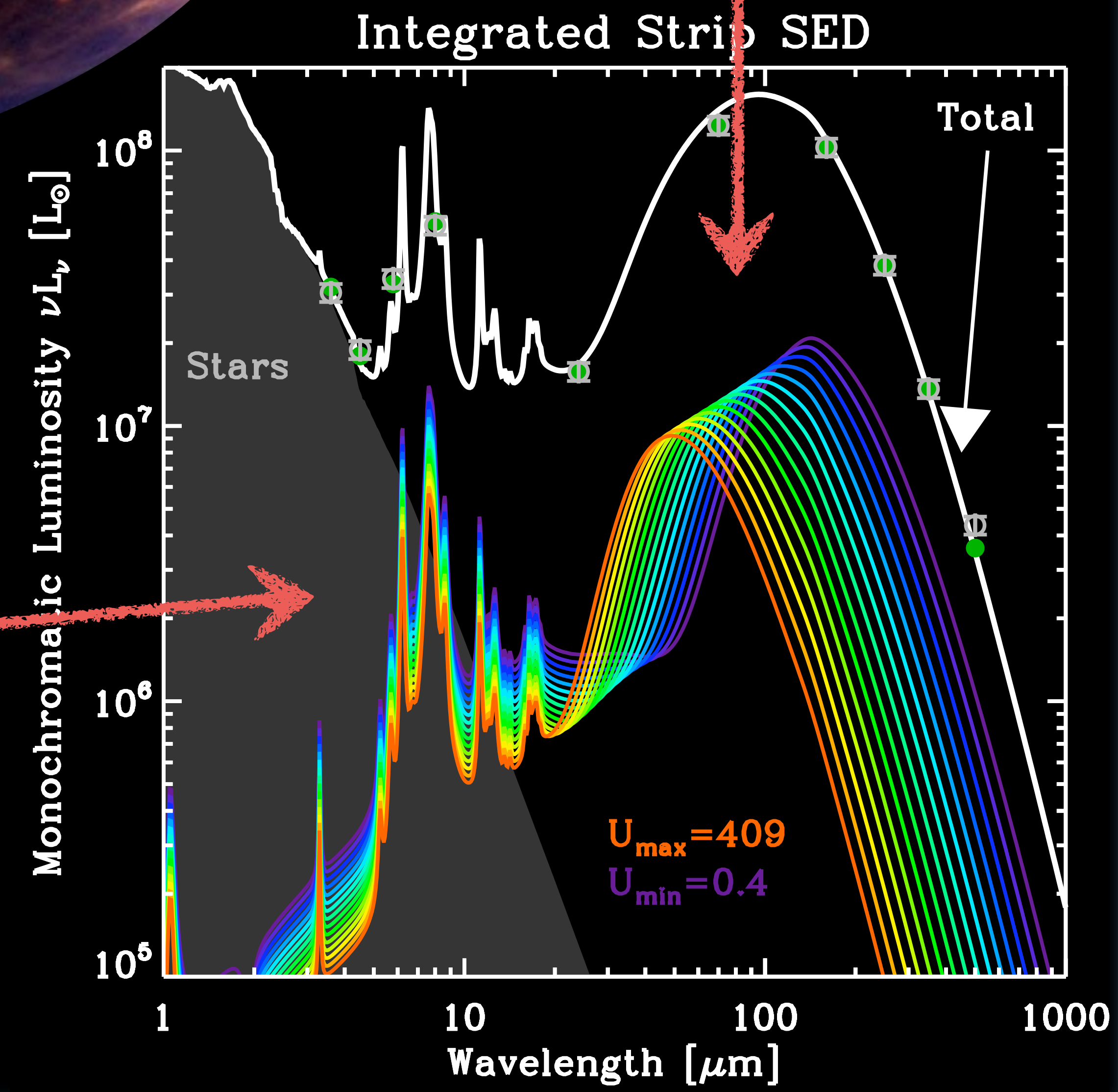
indirect gas tracers

- interstellar dust









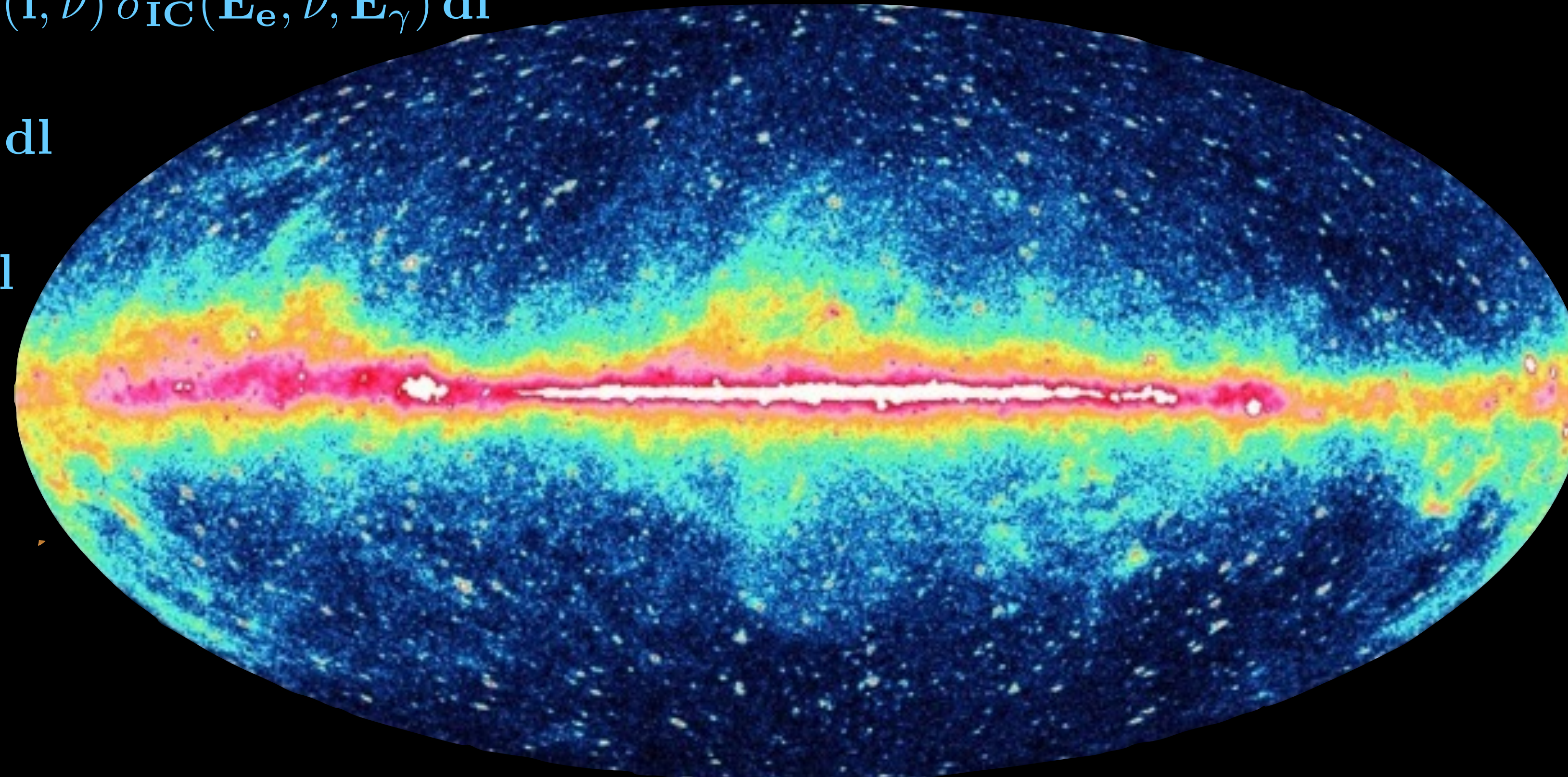
- IRAS, Herschel, WMAP, Planck, Sofia, Alma…

indirect gas tracers

$$\mathbf{I_{\gamma ISM}(l, b, E_\gamma) = \int_{l.o.s.} n_e(l, E_e)\, n_{ISRF}(l, \nu)\, \sigma_{IC}(E_e, \nu, E_\gamma)\, dl}$$

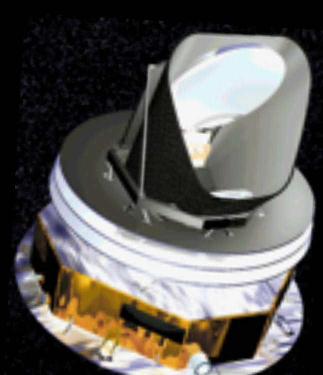
$$\mathbf{+ \int_{l.o.s.} n_e(l, E_e)\, n_{gas}(l)\, \sigma_{brem}(E_e, E_\gamma)\, dl}$$

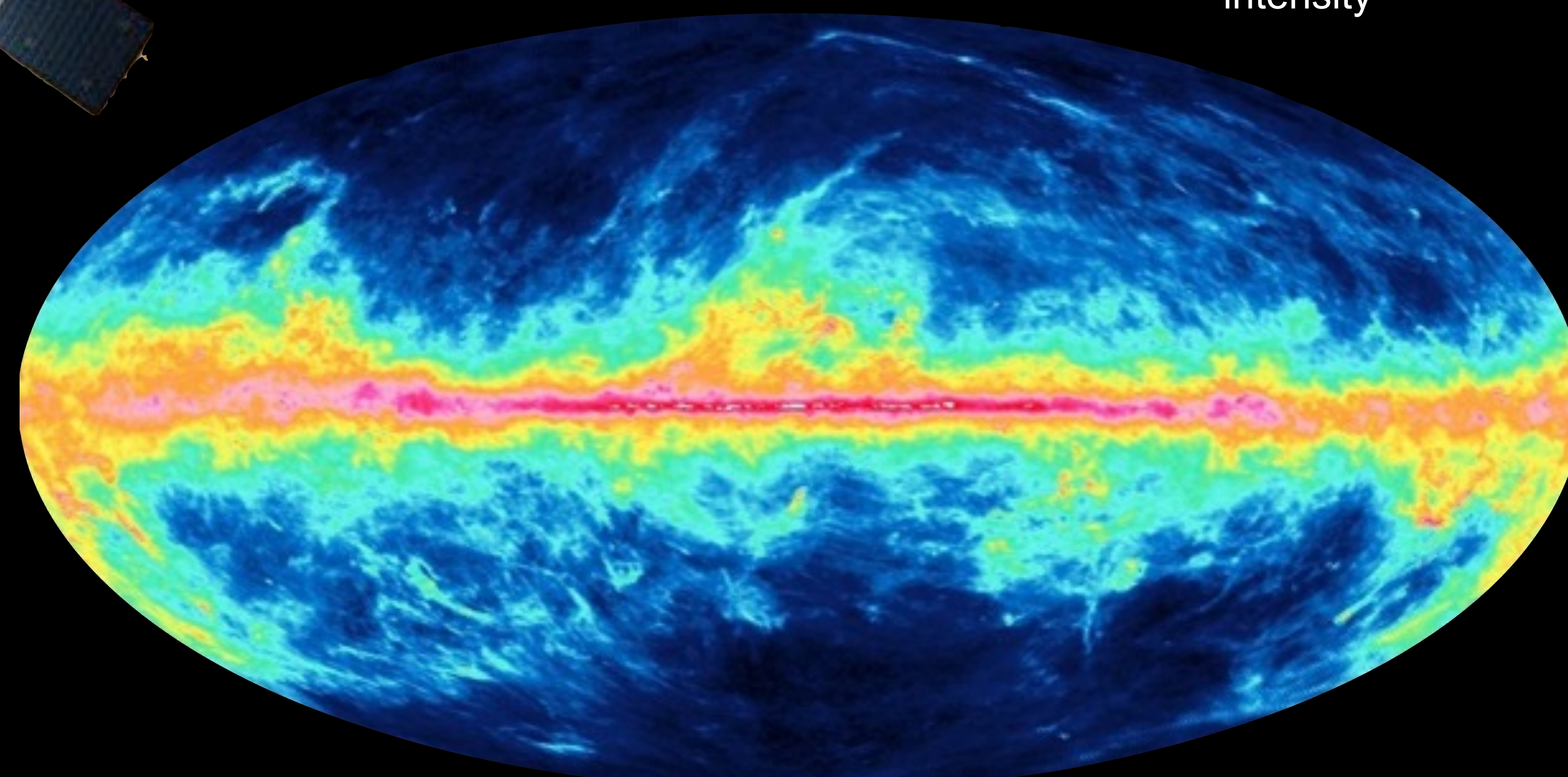
$$\mathbf{+ \int_{l.o.s.} n_A(l, E_A)\, n_{gas}(l)\, \sigma_\pi(E_A, E_\gamma)\, dl}$$



- cosmic rays
  Fermi

- dust
  Planck

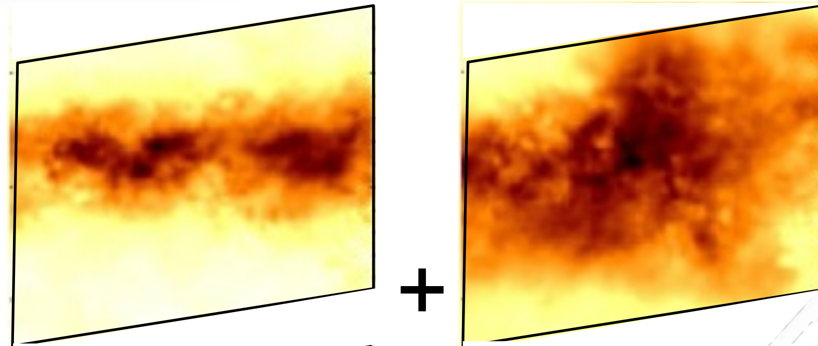




γ-ray and dust modelling

- CRays in HI: N(HI)

$$\frac{dN_{CR}}{dV}$$

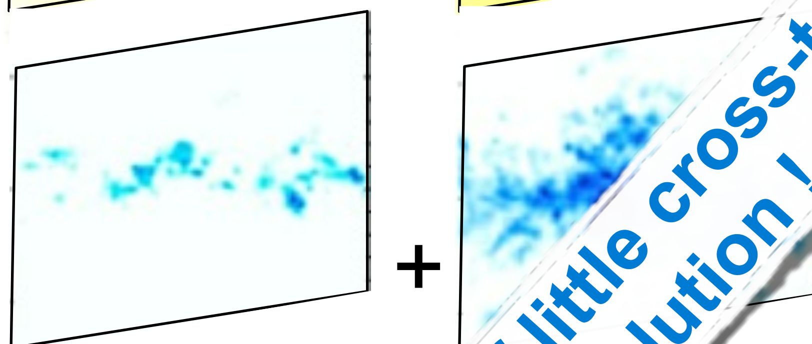


dust in HI

$$\frac{\tau_{dust}}{NH}$$

- CRays in H_2:

$$X_{CO} = \frac{N(H_2)}{W(CO)}$$

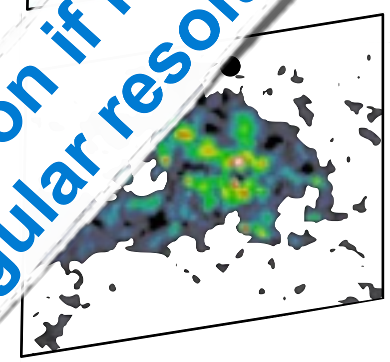


dust in H_2

$$X_{CO} = \frac{N(H_2)}{W(CO)}$$

- CRays in dark neutral gas:

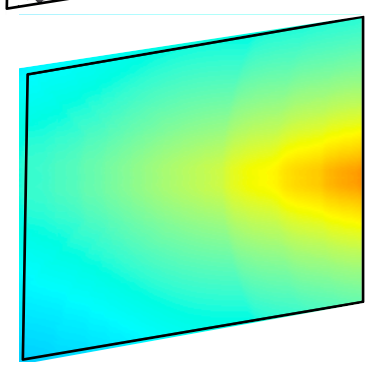
$$I_\gamma - a\,N(HI) - b\,W(CO)$$



dust in dark gas

$$\tau_{dust} - a'\,N(HI) - b'\,W(CO)$$

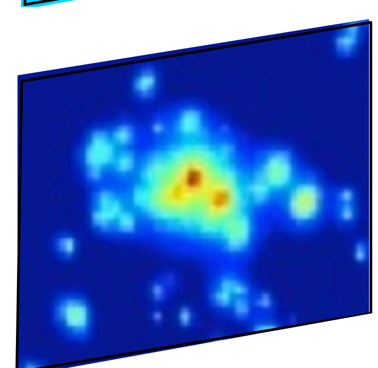
- Galactic inverse Compton



ISRF + CMB

- γ-ray source

+ constant ?

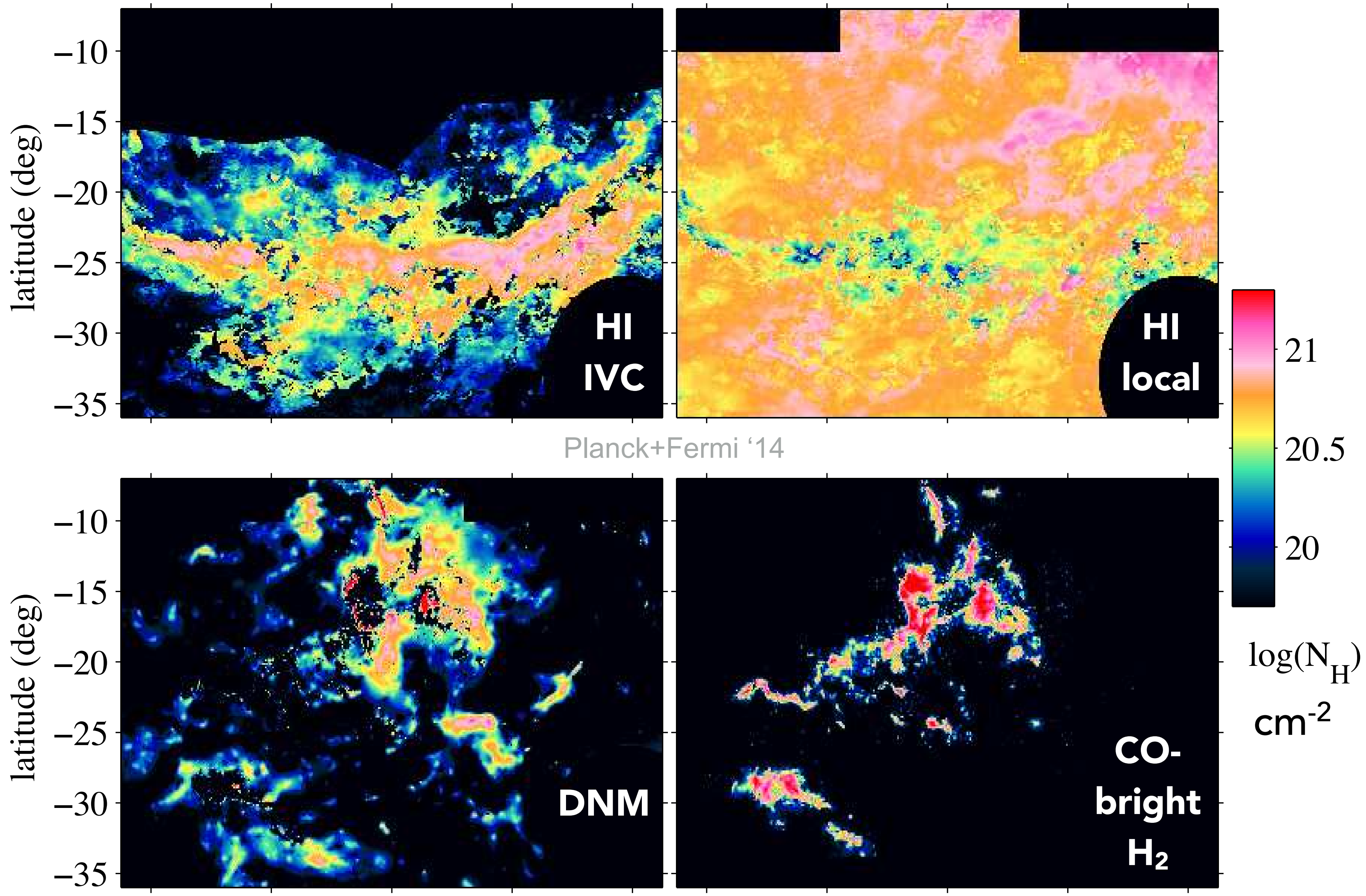


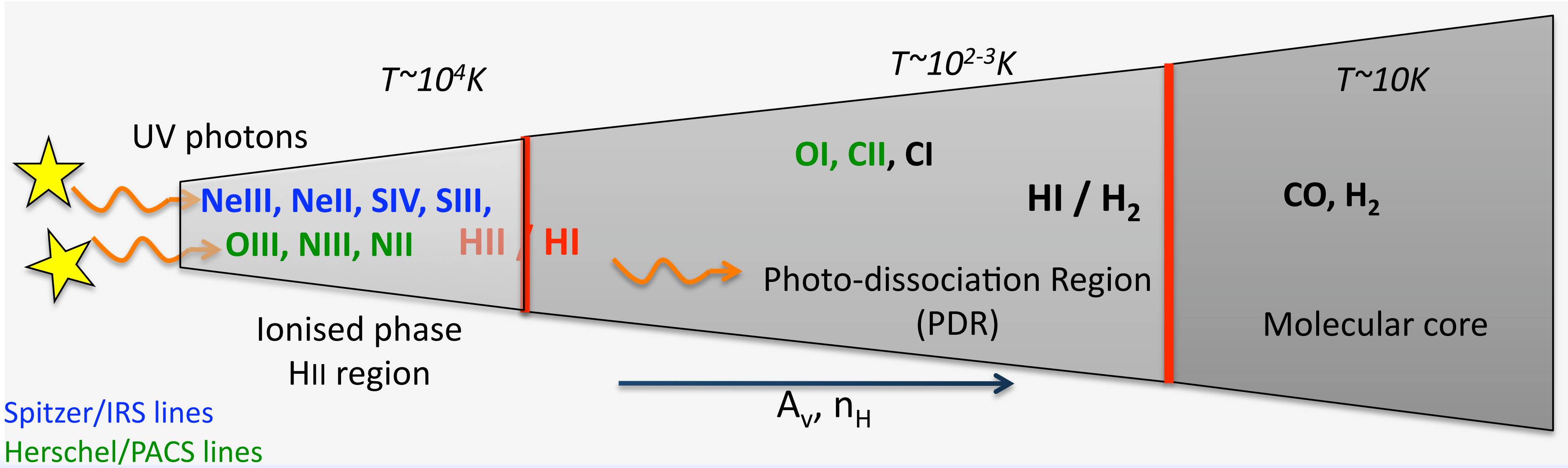
IR sources

component separation if little cross-talk
⇒ good angular resolution !

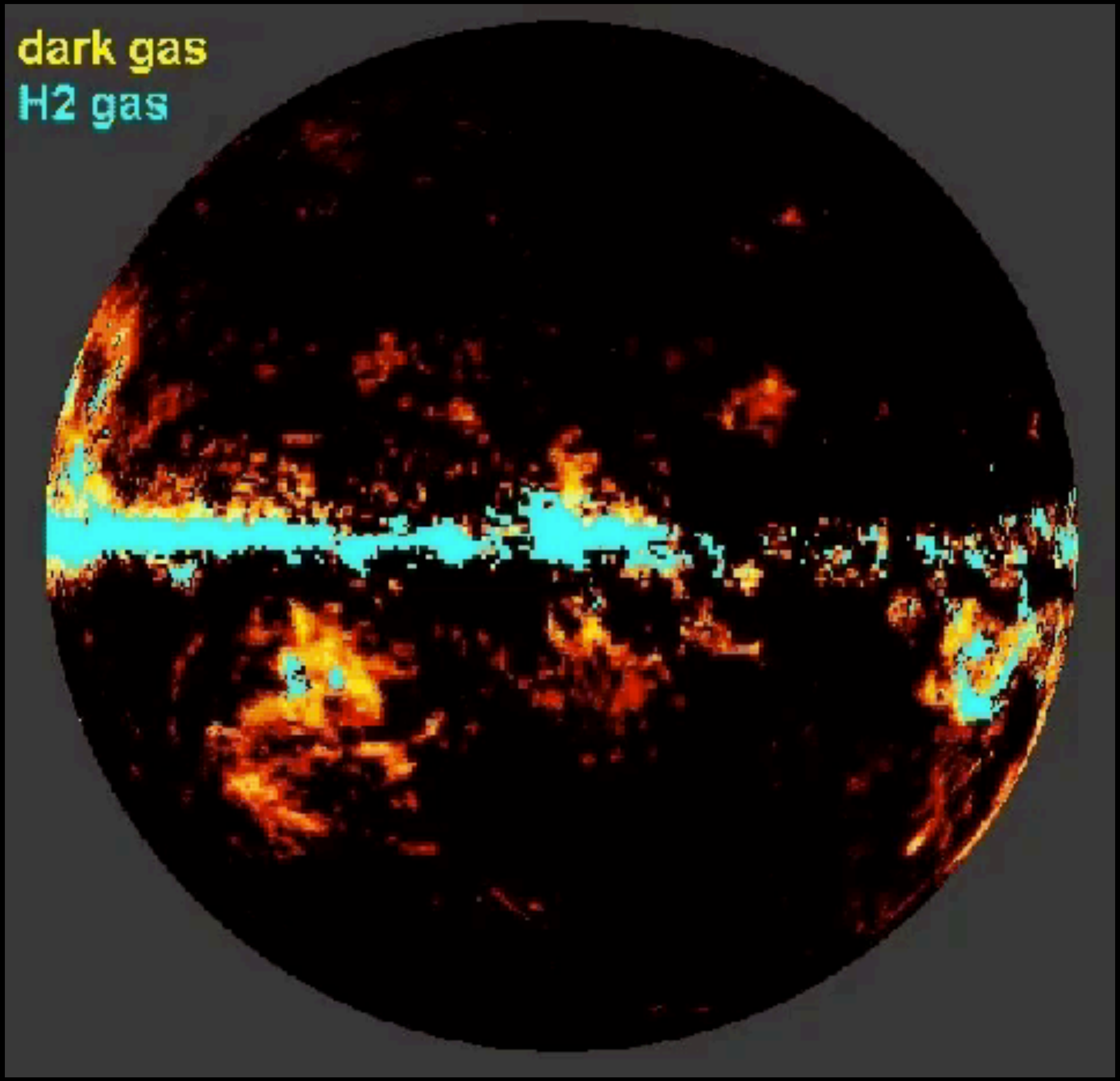
something missing?

- $M_{DNM} \approx M(\text{local thin HI}) / 5 \approx M(\text{CO-bright } H_2) * 2$





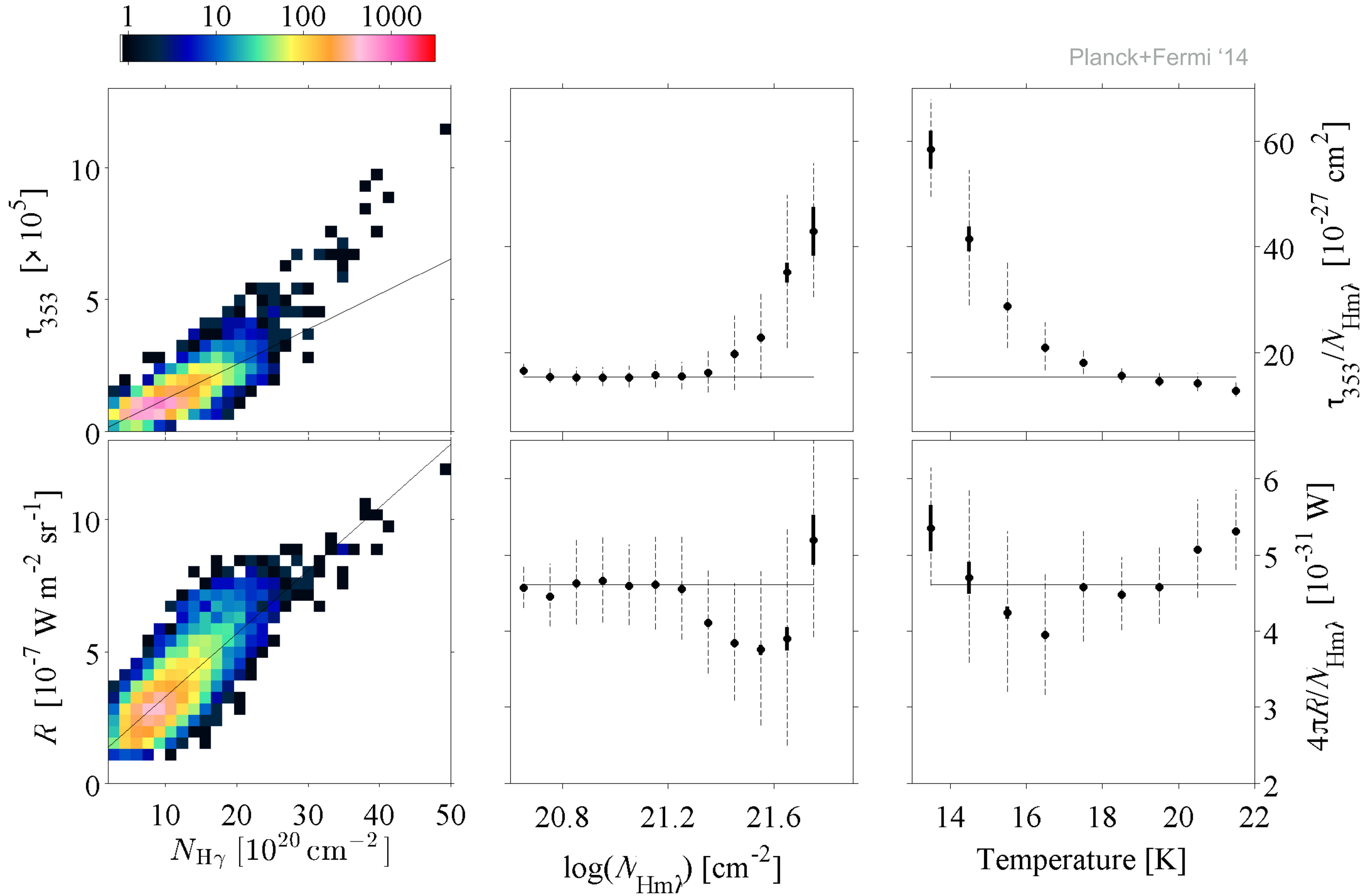
dark neutral medium



Grenier+ '05

bad surprise

- non-linear tracers!

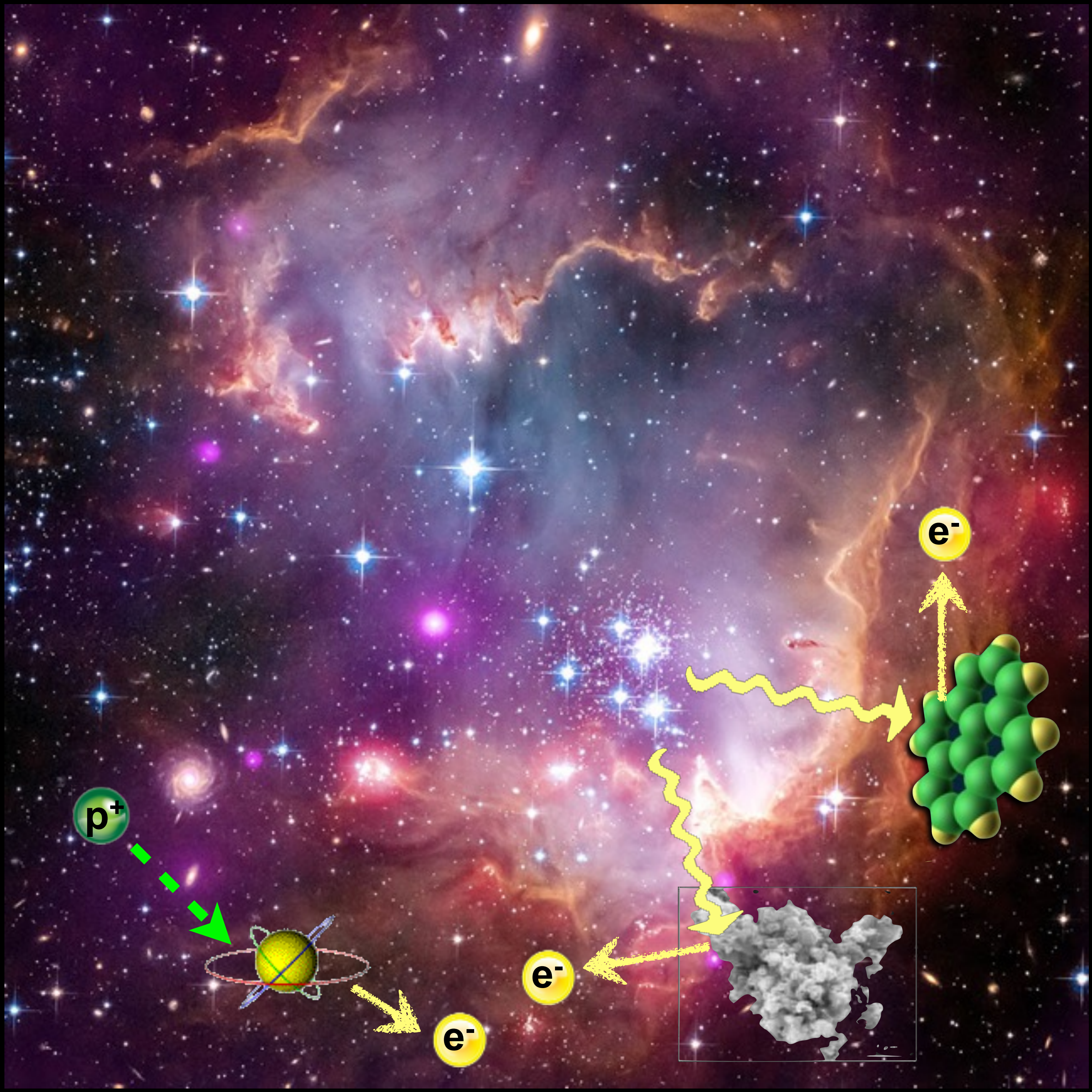


the active interstellar medium: thermodynamical & dynamical feedback

gas heating

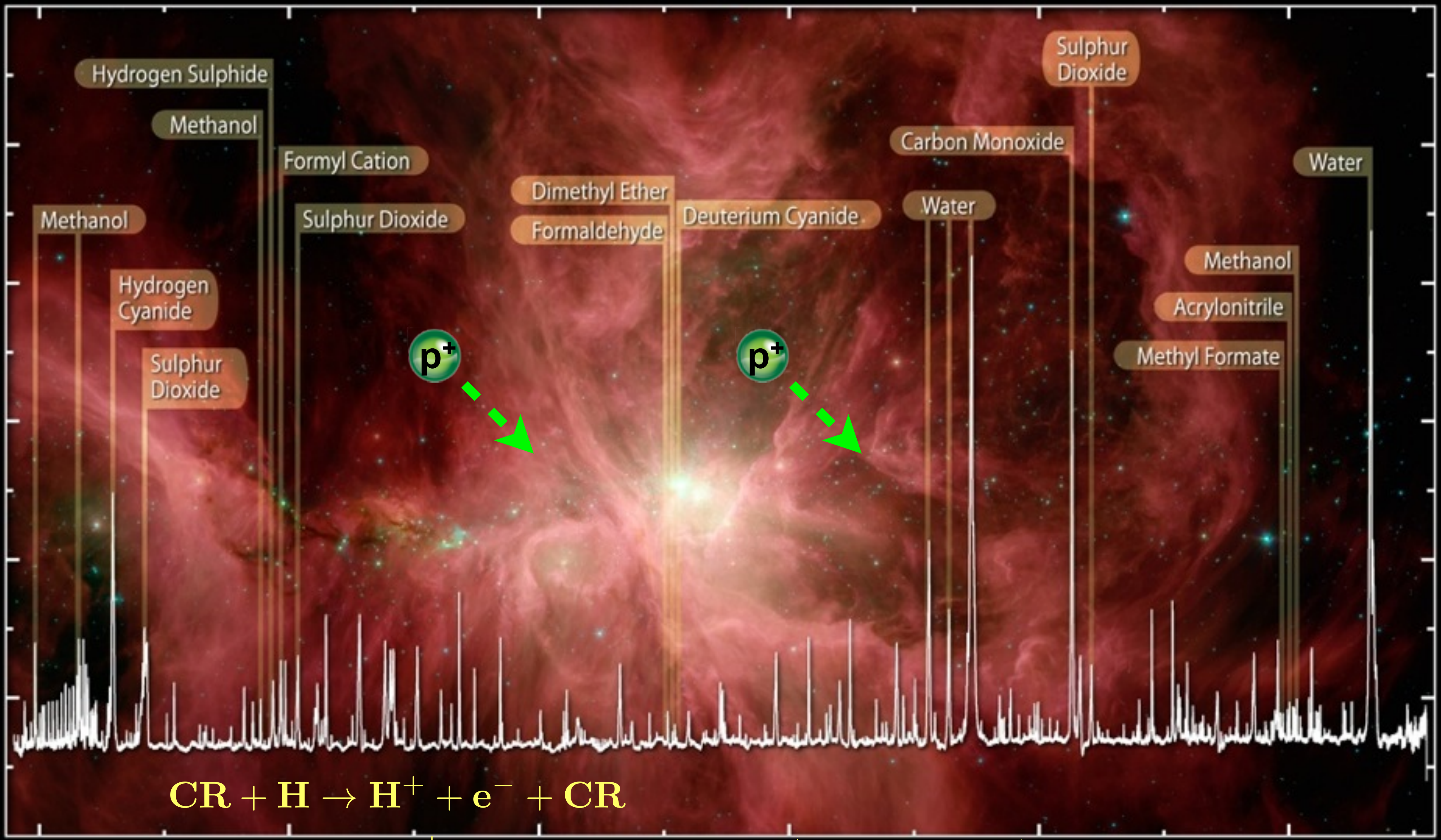
- stellar feedback:
  on cold to warm medium
  UV radiation => heating by
  photoelectric effect

- high-energy feedback:
  on cold H_2 medium
  (no UV penetration):
  cosmic rays => heating



coolants

- H_2 gas: CO > H_2O > O_2 (chemical feedback)
- HI gas: C+, C, O, Si+
- H^+ gas: recombination lines
- hot gas: free-free



$$\mathrm{CR + H \rightarrow H^+ + e^- + CR}$$

$$\mathrm{CR + H_2 \rightarrow H_2^+ + e^- + CR}$$

$$\mathrm{H_2^+ + H_2 \rightarrow H_3^+ + H}$$

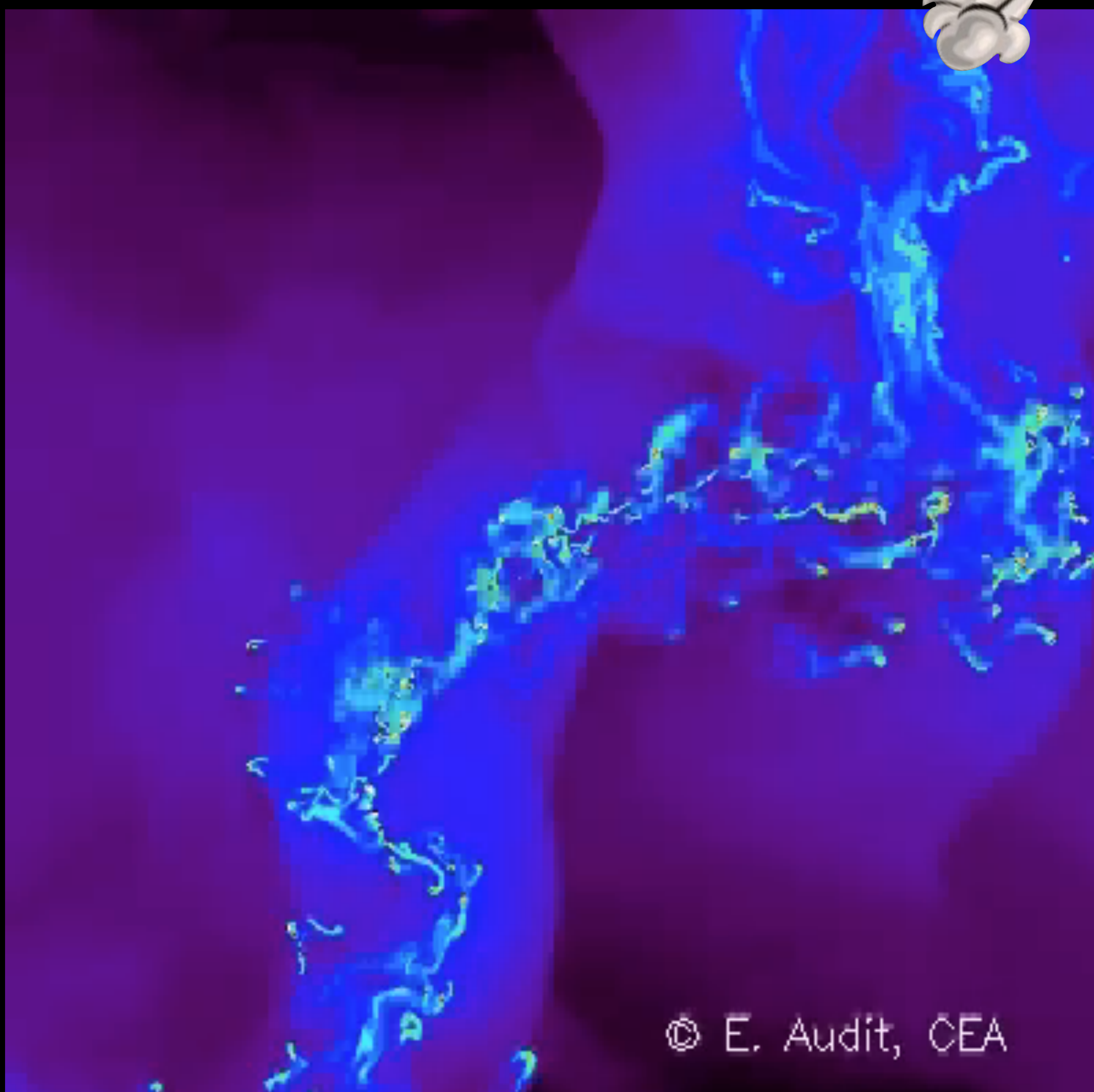
$$\mathrm{H_3^+ + C \rightarrow CH^+ + H_2 \rightarrow C_xH_y \ldots}$$

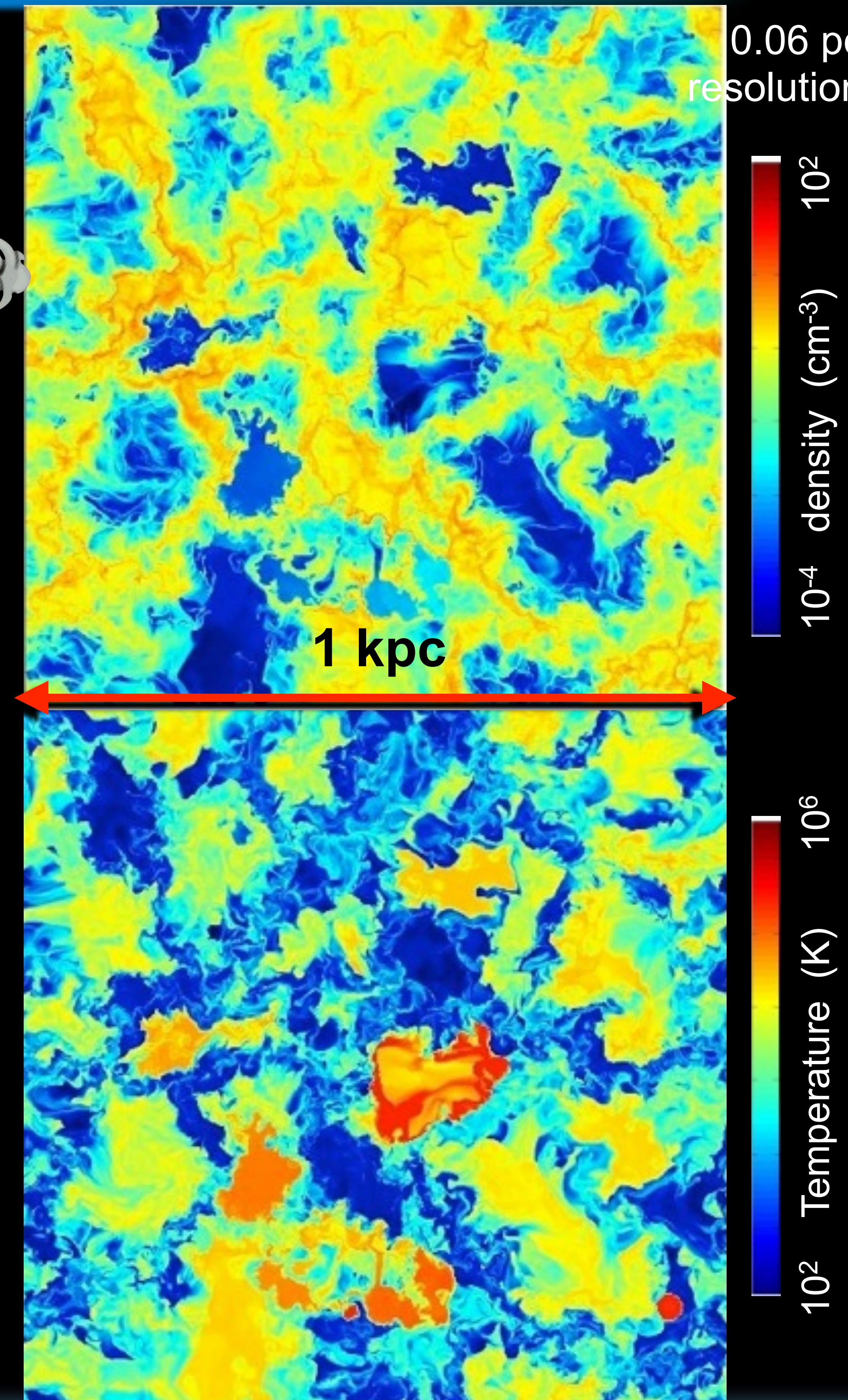
$$\mathrm{H_3^+ + O \rightarrow OH^+ + H_2 \rightarrow CO,\ H_2O \ldots}$$

mechanical feedback

- stellar feedback: radiation/ionization pressure, winds, supernovae
- turbulence: energy transfer from large scales (supersonic) to thermal dissipation

global pressure ≈ equilibrium





collapse: Jeans mass

- virial equilibrium

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{v}.\vec{\nabla}$$ dérivée Lagrangienne qui "suit" l'élément fluide

$$\frac{1}{2}\frac{D^2 I}{Dt^2} = 2E_{cin\ macro} + E_{pot} - \iint\left(p_{th} + \frac{B^2}{2\mu_0}\right)\vec{r}.d\vec{S} + \iint \frac{1}{\mu_0}(\vec{B}.\vec{r})\vec{B}.d\vec{S} + \iiint\left(3p_{th} + \frac{B^2}{2\mu_0}\right)dV$$

p_{th} and p_B work — B tension — internal energy

$E_{cin\ macro}$ since $E_{cin\ micro}$ already in thermal energy

- spherical cloud, no B

$$E_{cin} = \frac{3}{2}\frac{M}{m}kT \text{ or } E_{cin} = \frac{1}{2}M\sigma_v^2 \qquad E_{pot} = -\frac{3}{5}\frac{GM^2}{R}$$

collapse if 2 $E_{cin} \leq E_{pot}$ =>

$$M \geq \left(\frac{5kT}{G}\right)^{3/2}\left(\frac{4\pi}{3}n\right)^{-1/2}(\mu m_H)^{-2} \qquad R \geq \left(\frac{15kT}{4\pi G}\right)^{1/2}(\mu m_H)^{-1} n^{-1/2}$$

$$M \geq \left(\frac{5}{3G}\right)^{3/2}\left(\frac{4\pi}{3}n\mu m_H\right)^{-1/2}\sigma_v^3 \qquad R \geq \left(\frac{5}{4\pi G}\right)^{1/2}(n\mu m_H)^{-1/2}\sigma_v$$

cold HI (30 cm^{-3}, 80 K, μ = 1.4) M ≥ 6200 M⊙, R ≥ 11 pc: no collapse

cold H_2 (10^3 cm^{-3}, 15 K, μ = 2.8) M ≥ 22 M⊙, R ≥ 0.4 pc or

cold H_2 (10^3 cm^{-3}, 1 km/s, μ = 2.8) M ≥ 440 M⊙, R ≥ 1.1 pc: collapse too easy (p_B)

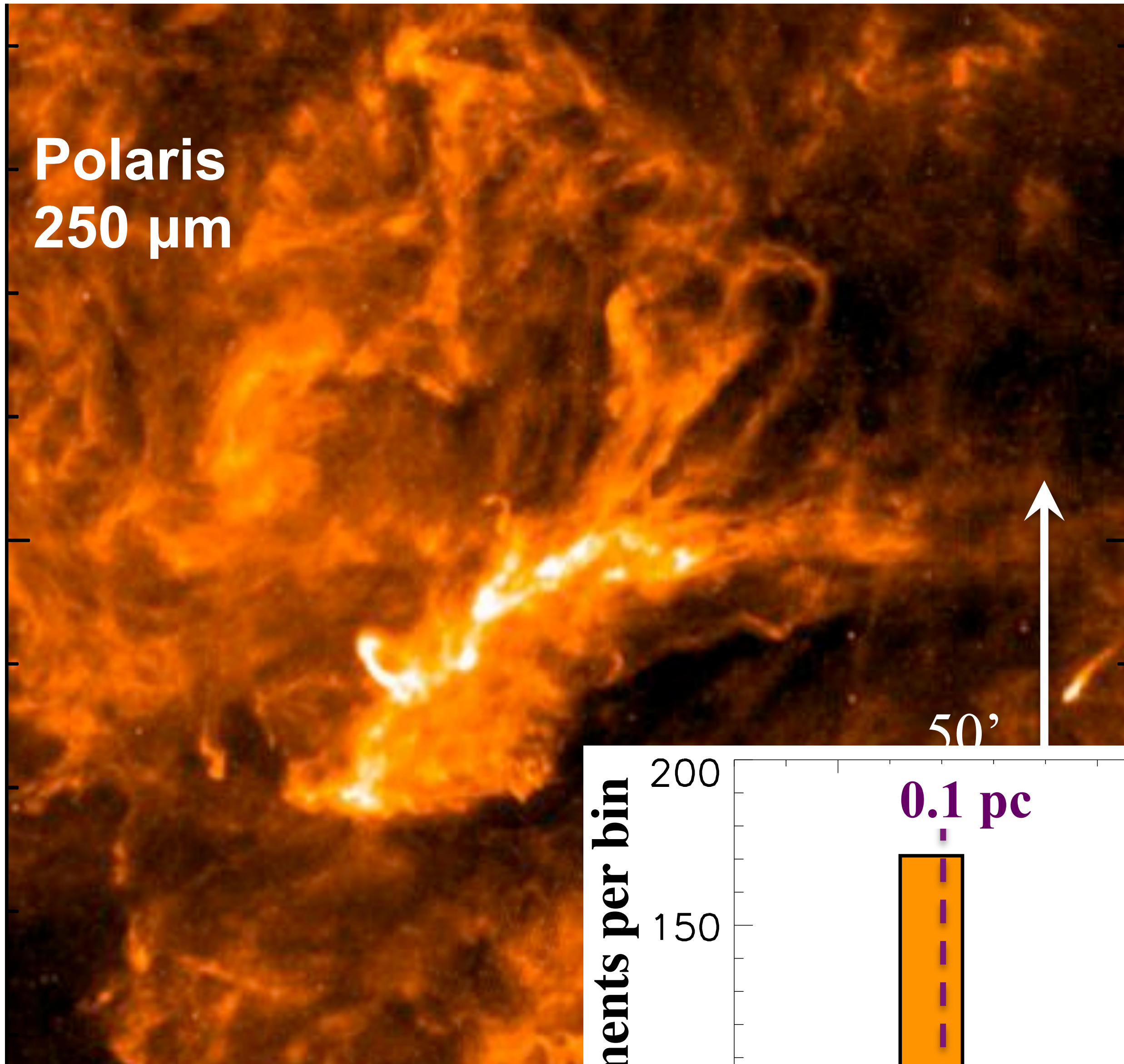
- the answer: filaments !

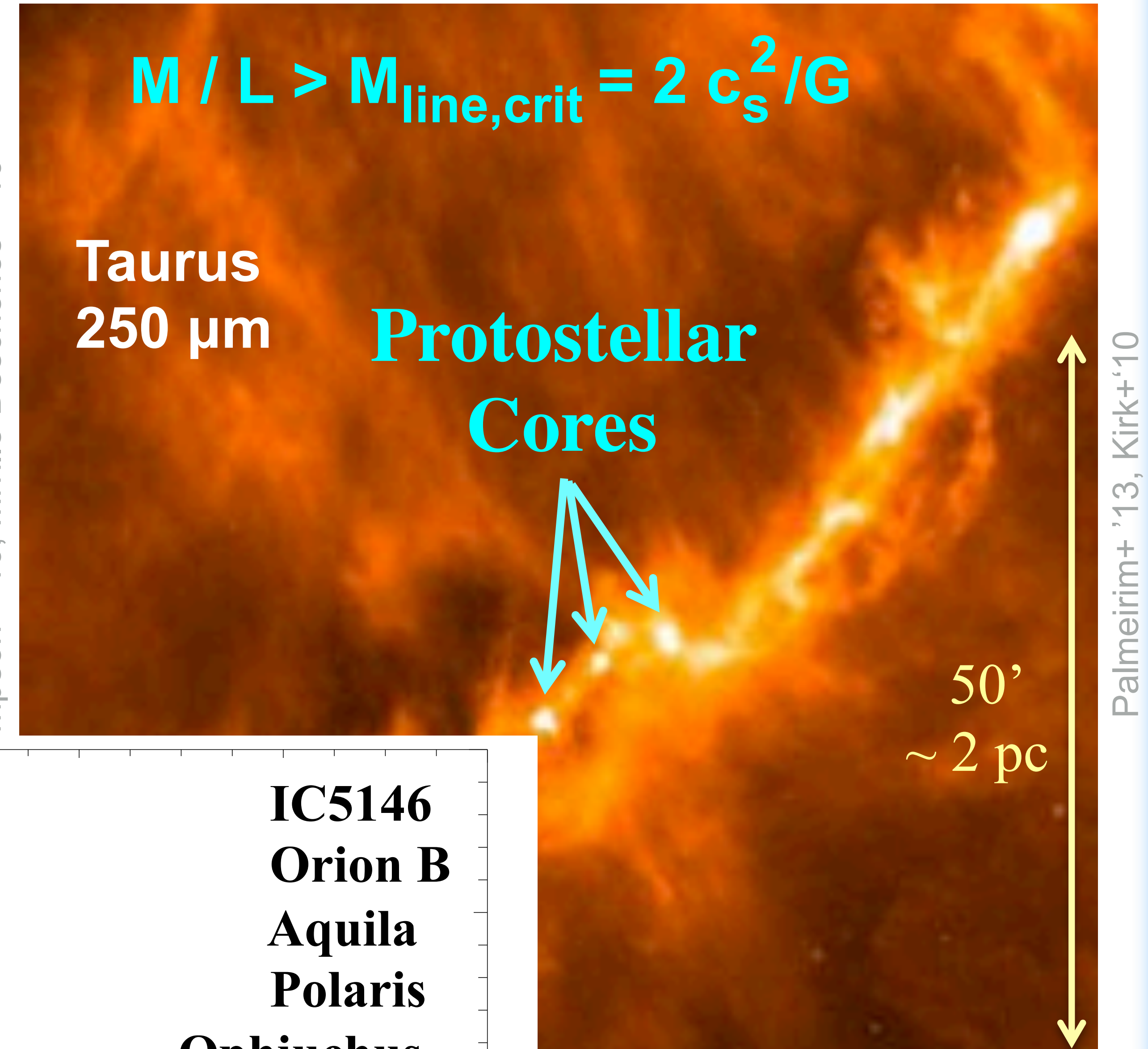
Orion

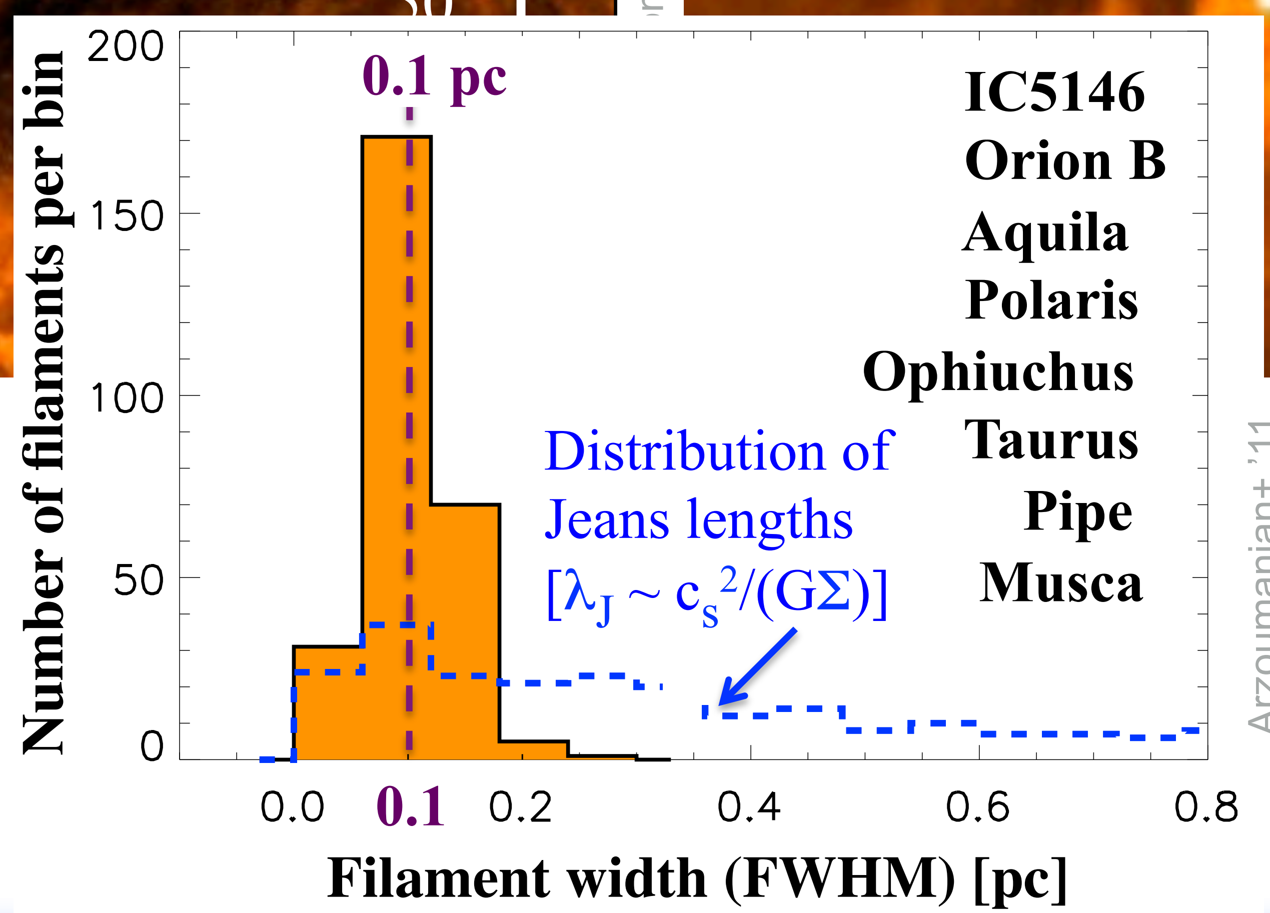
the local cosmic web !

Univ
EarthS

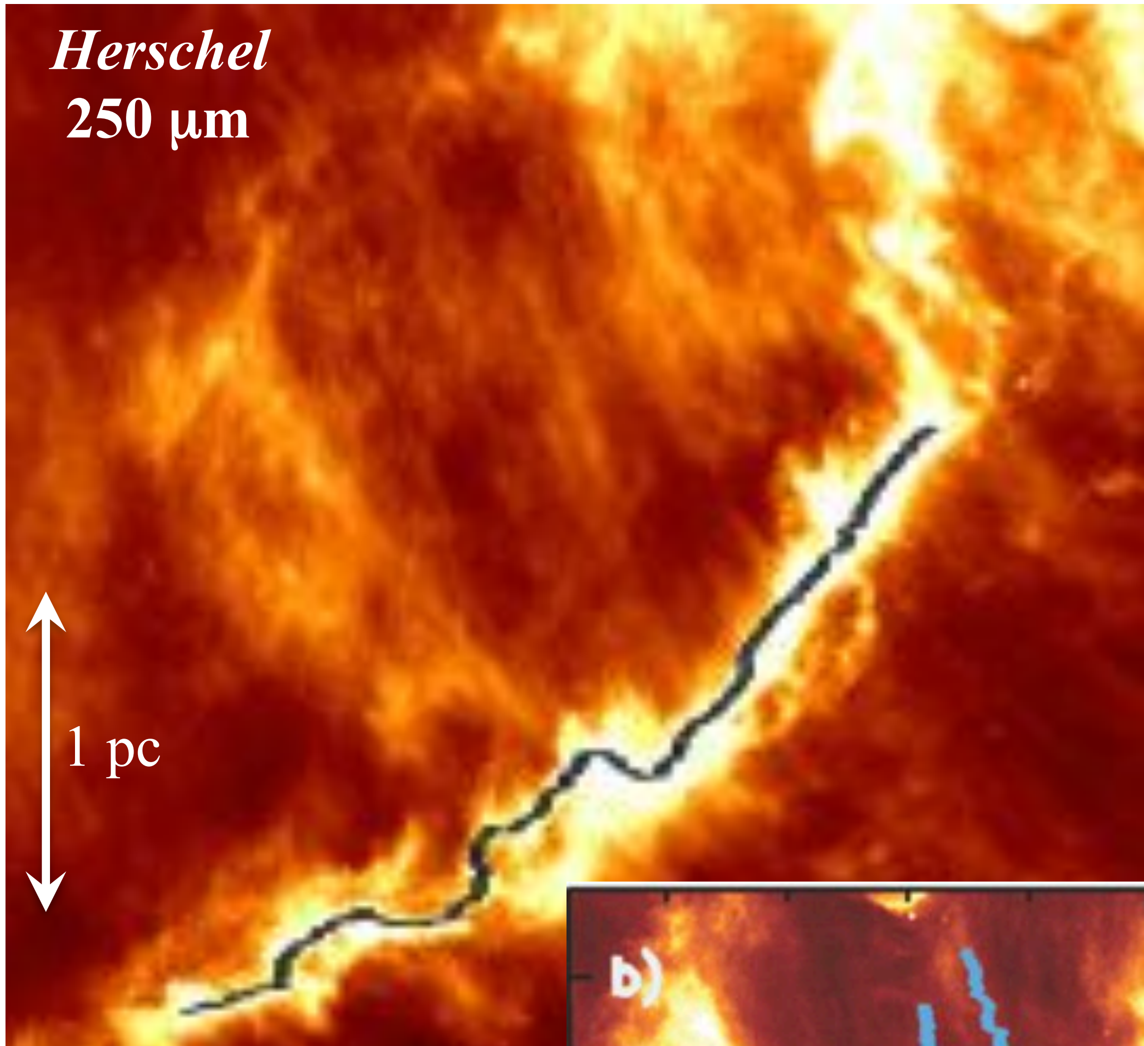
- dissipation of large scale MHD in filaments
- gravity fragments dense filaments

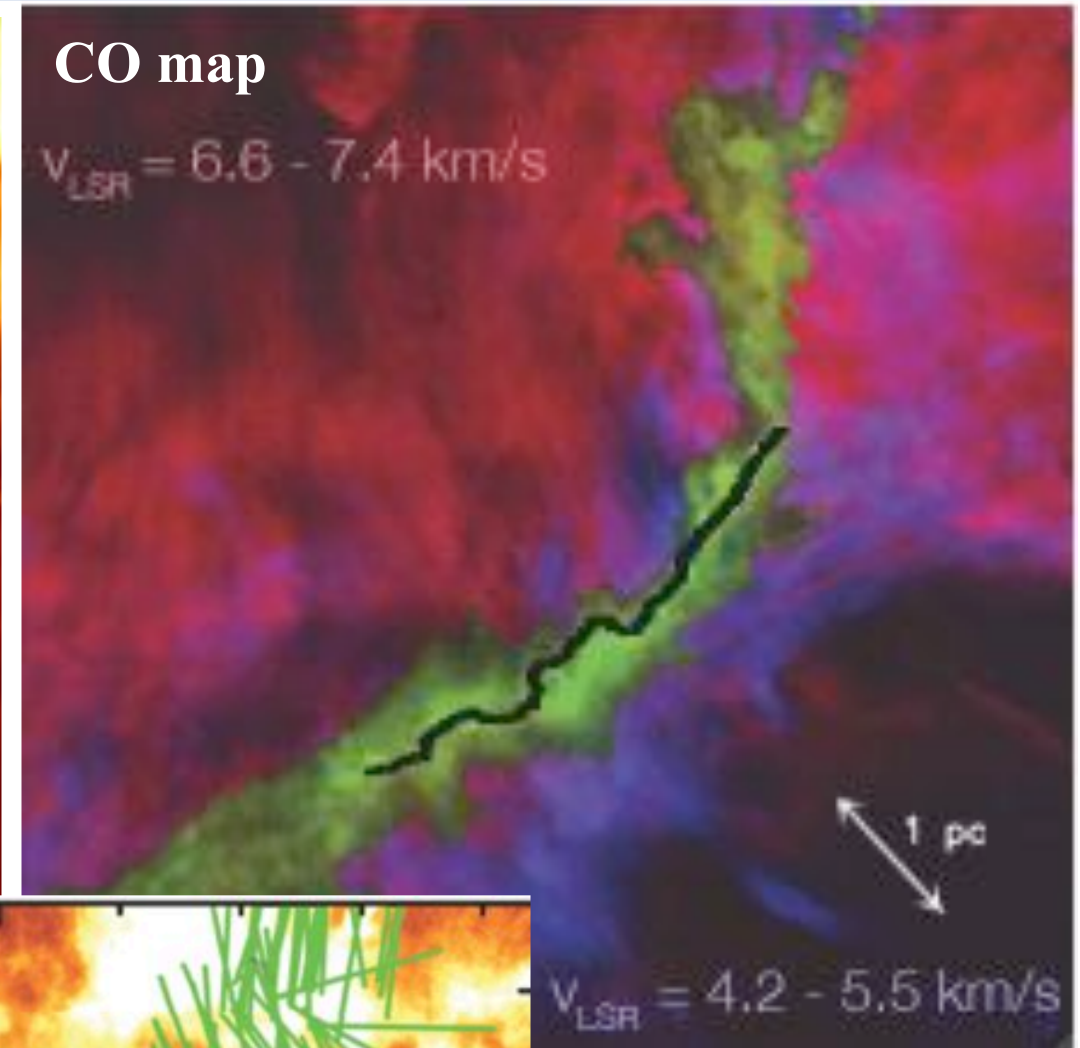




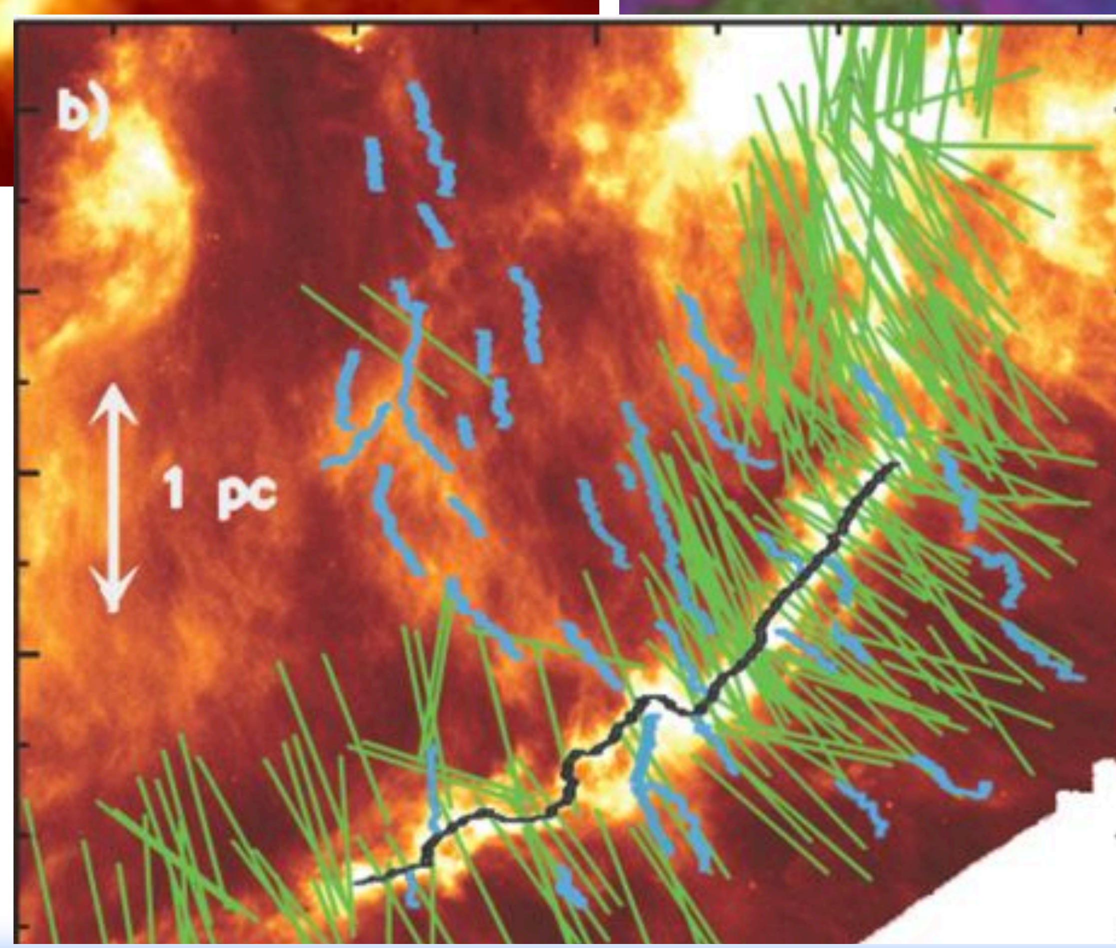


accreting filaments





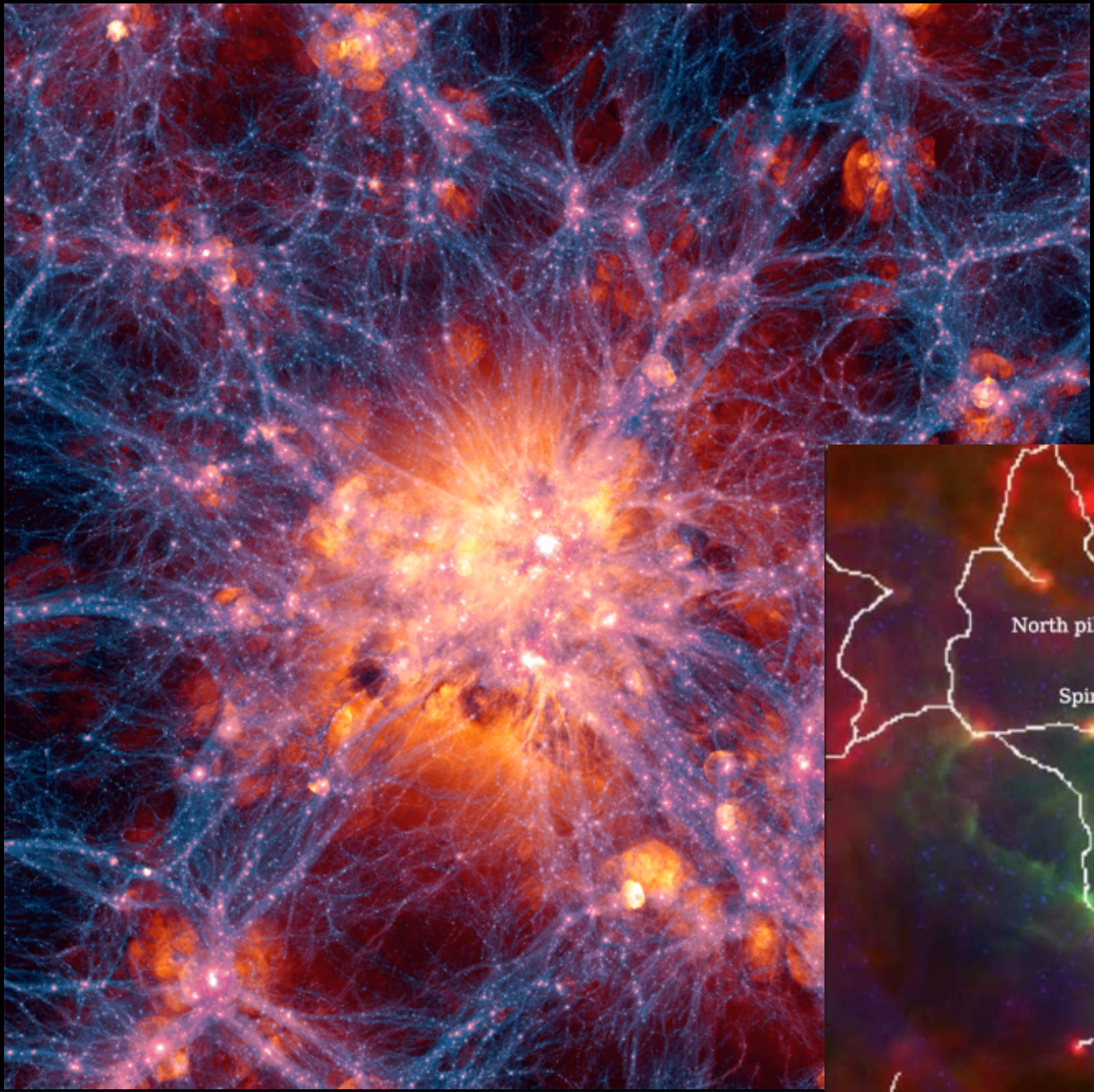
Palmeirim+ '13

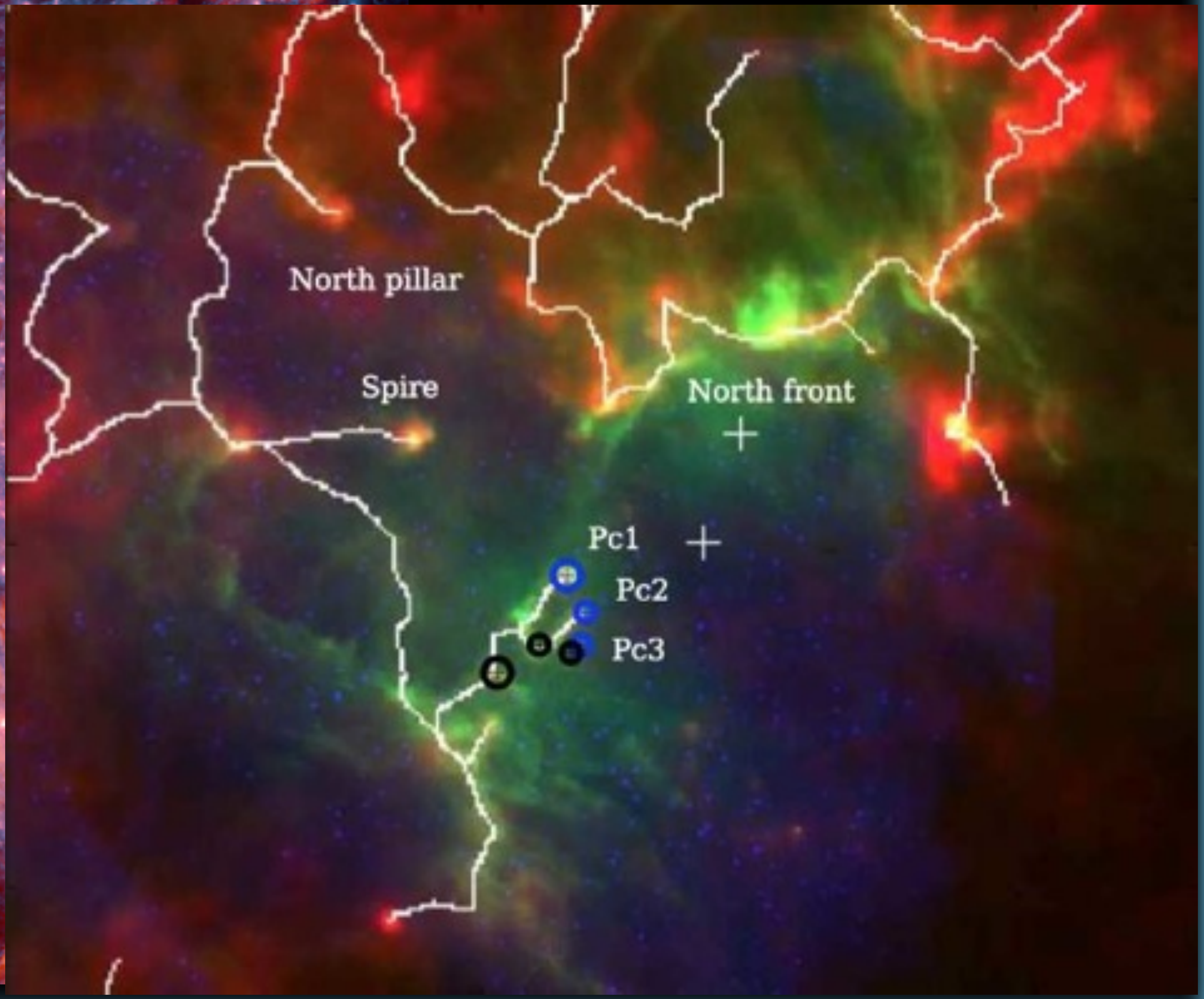


- evidence for accretion:
- striations and polarization

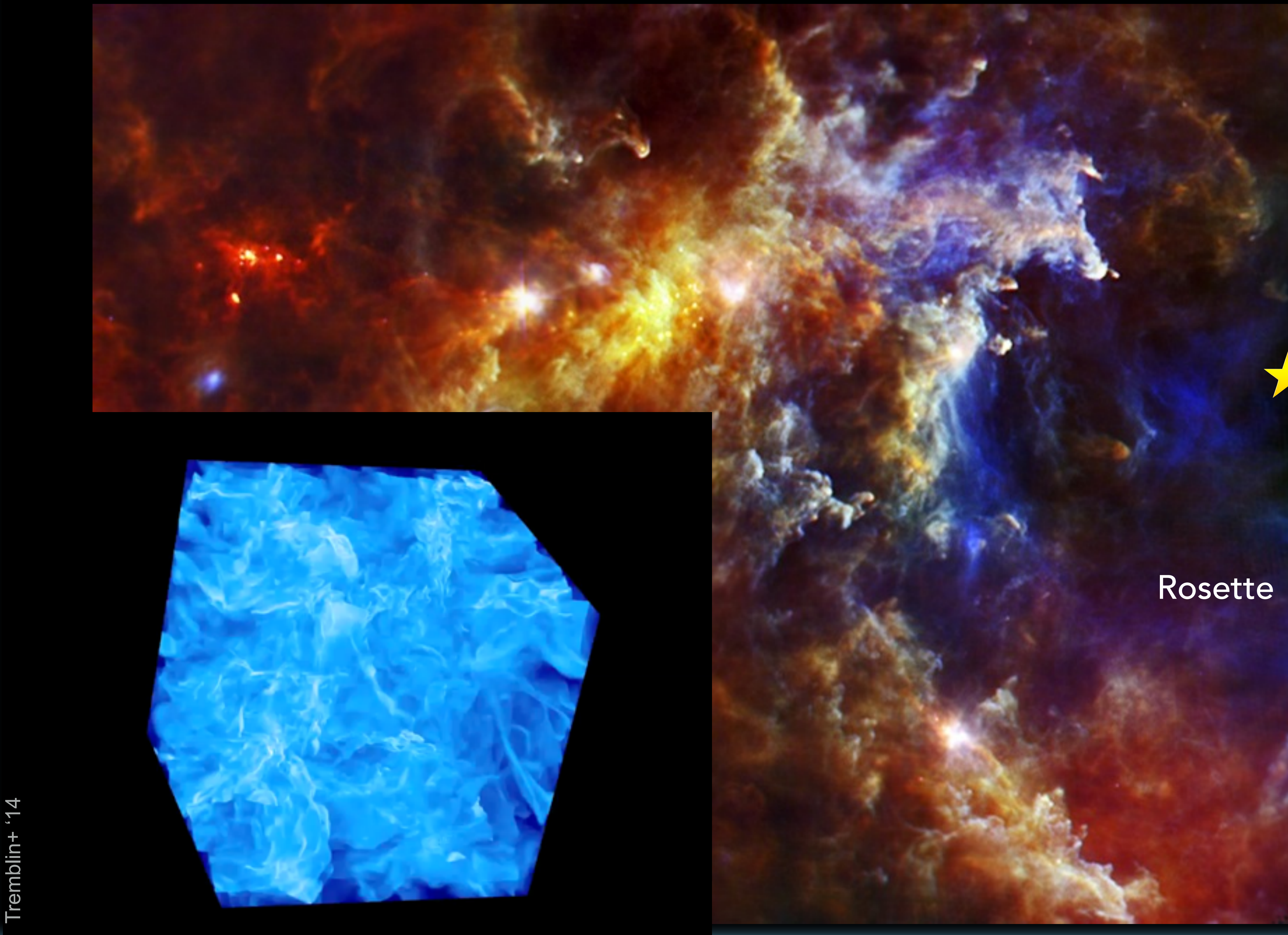
- ex: Taurus:
  M = 54 M☉/pc,
  $\dot{M}$ = 25-50 M☉/pc/ Myr

cosmic web





interstellar sculpture



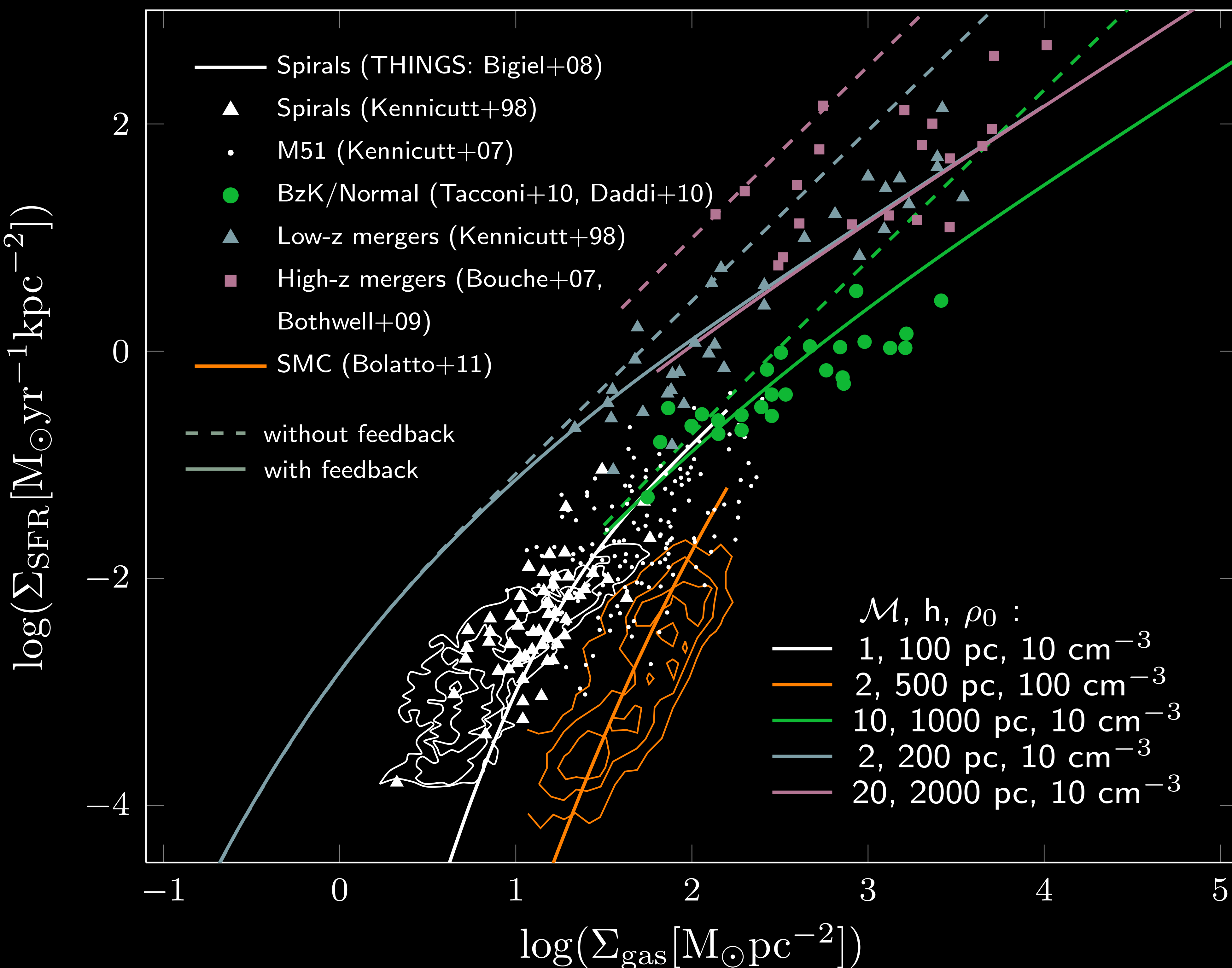
Tremblin+ '14

mold & sculpt

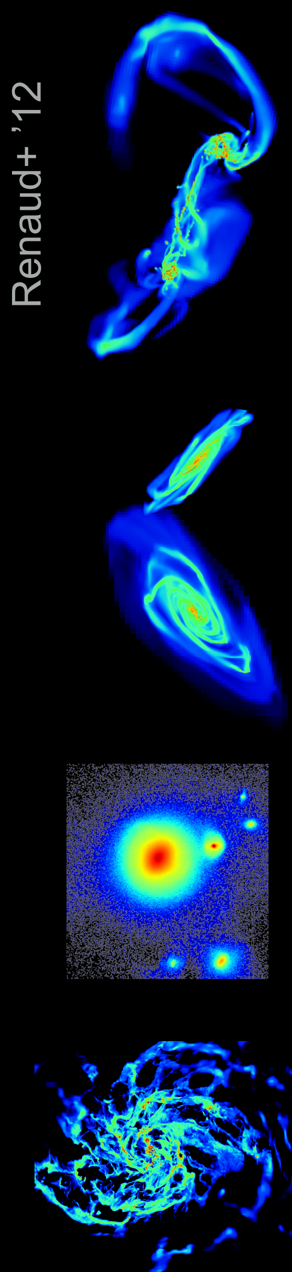
supersonic turbulence & star formation

Univ EarthS

- parameters: Mach nb, size, gas density
- impact of feedback

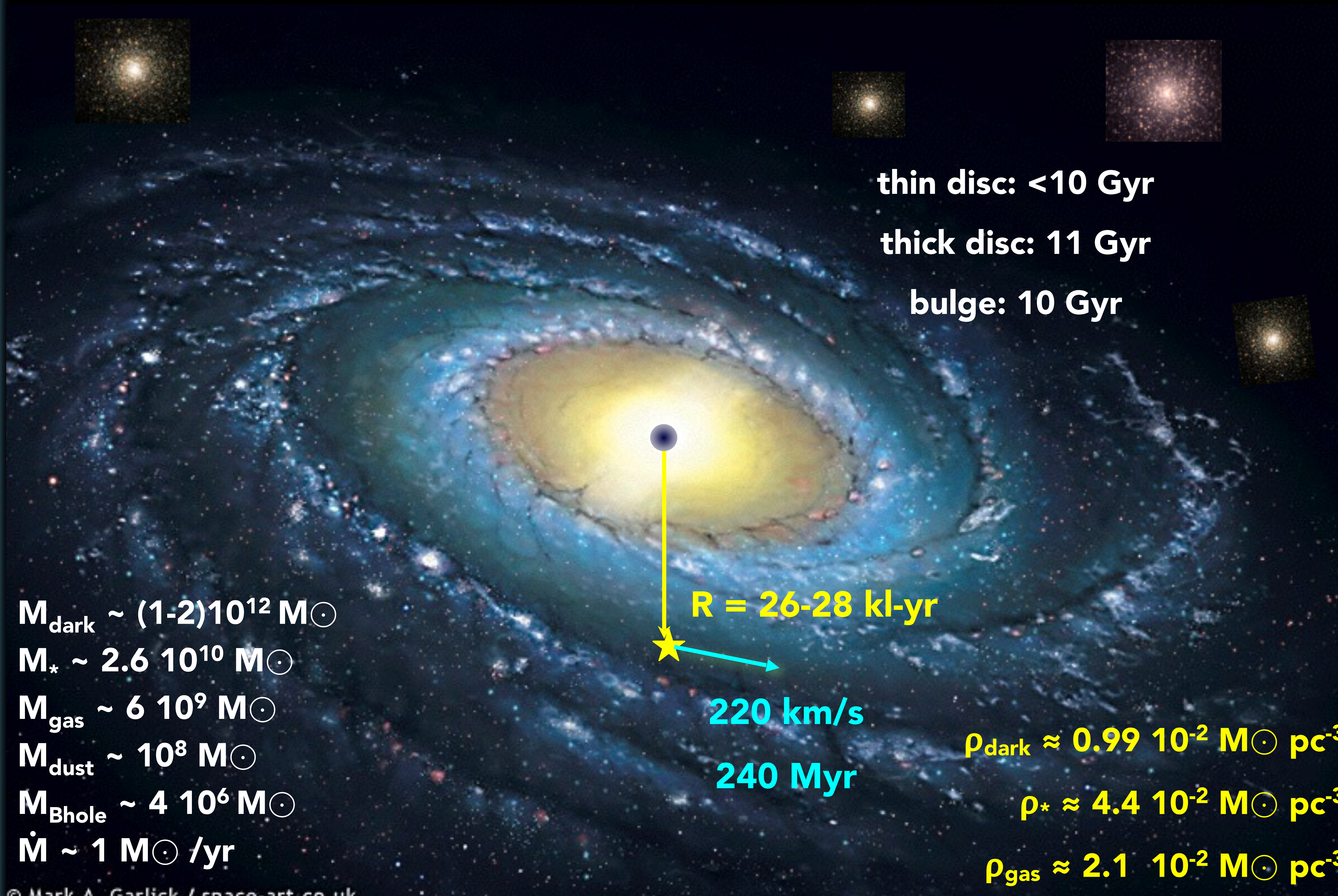


Renaud+ '12



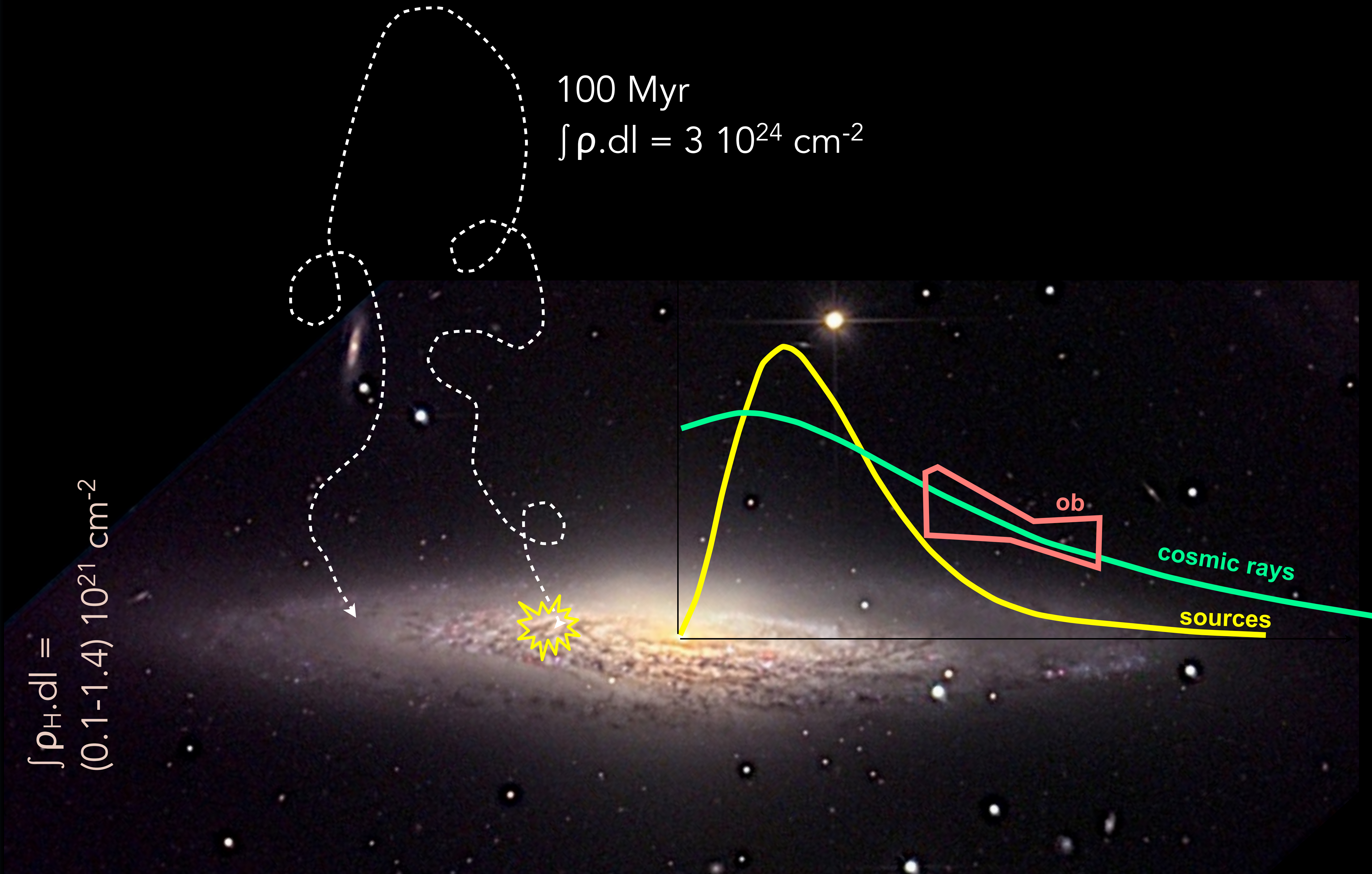
the bubbling interstellar medium

the Milky Way

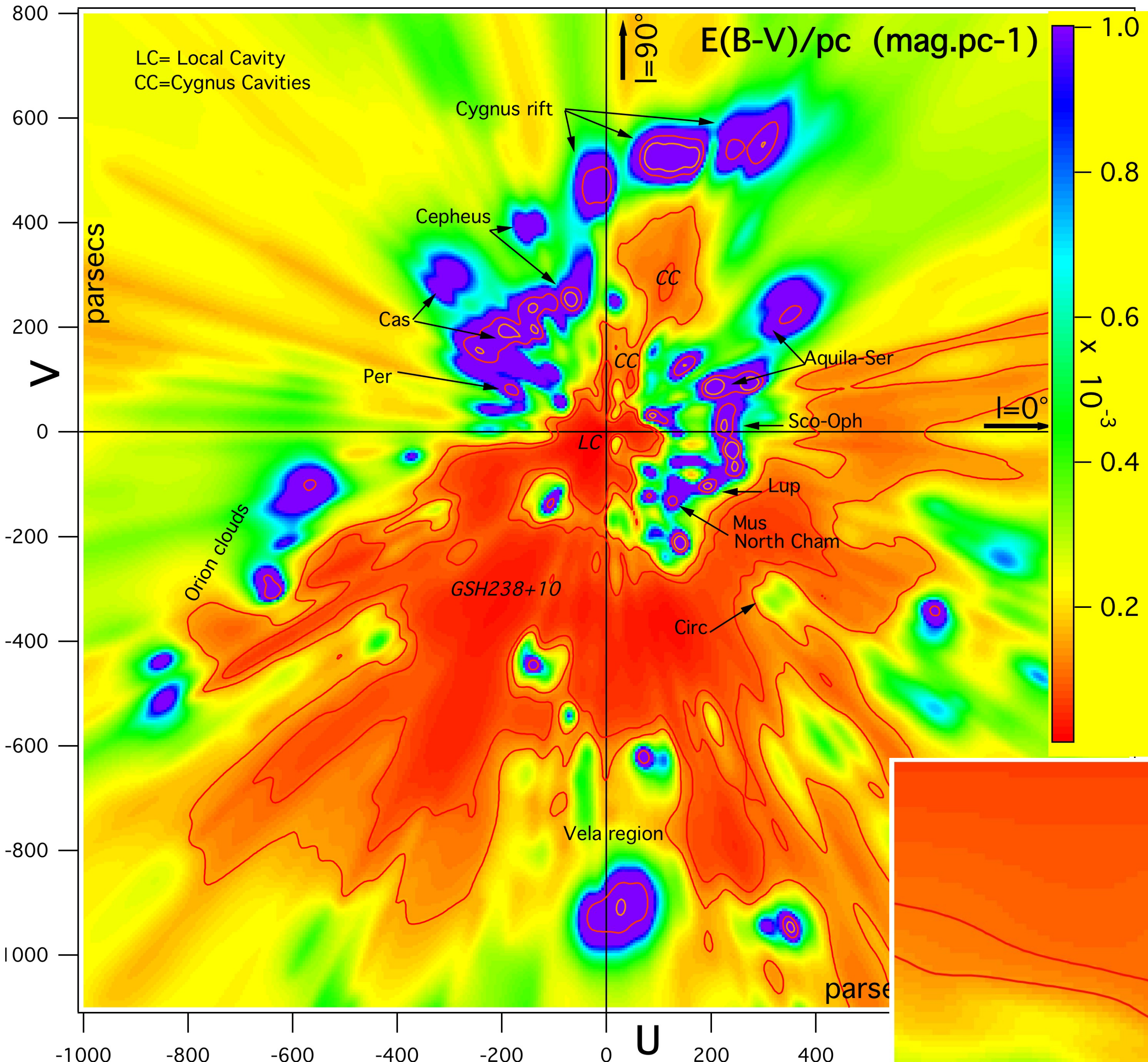


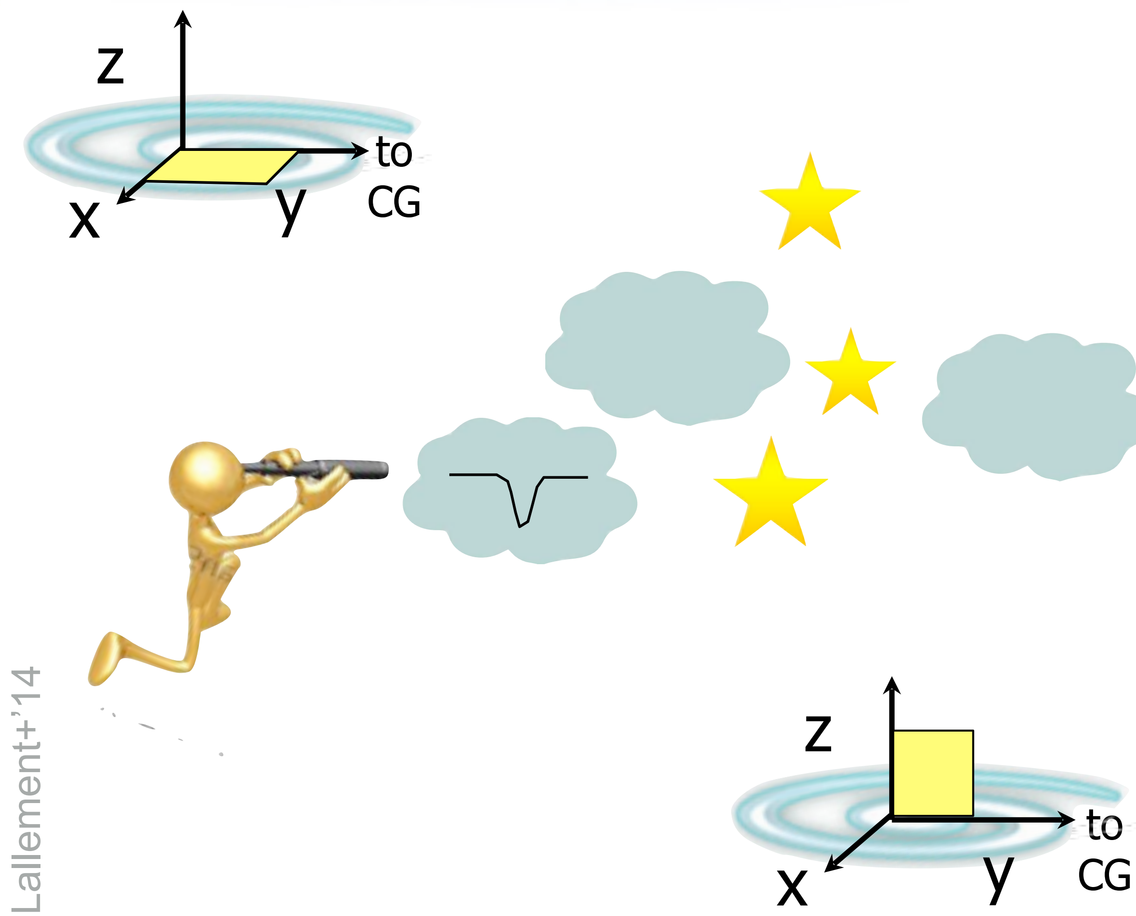
© Mark A. Garlick / space-art.co.uk

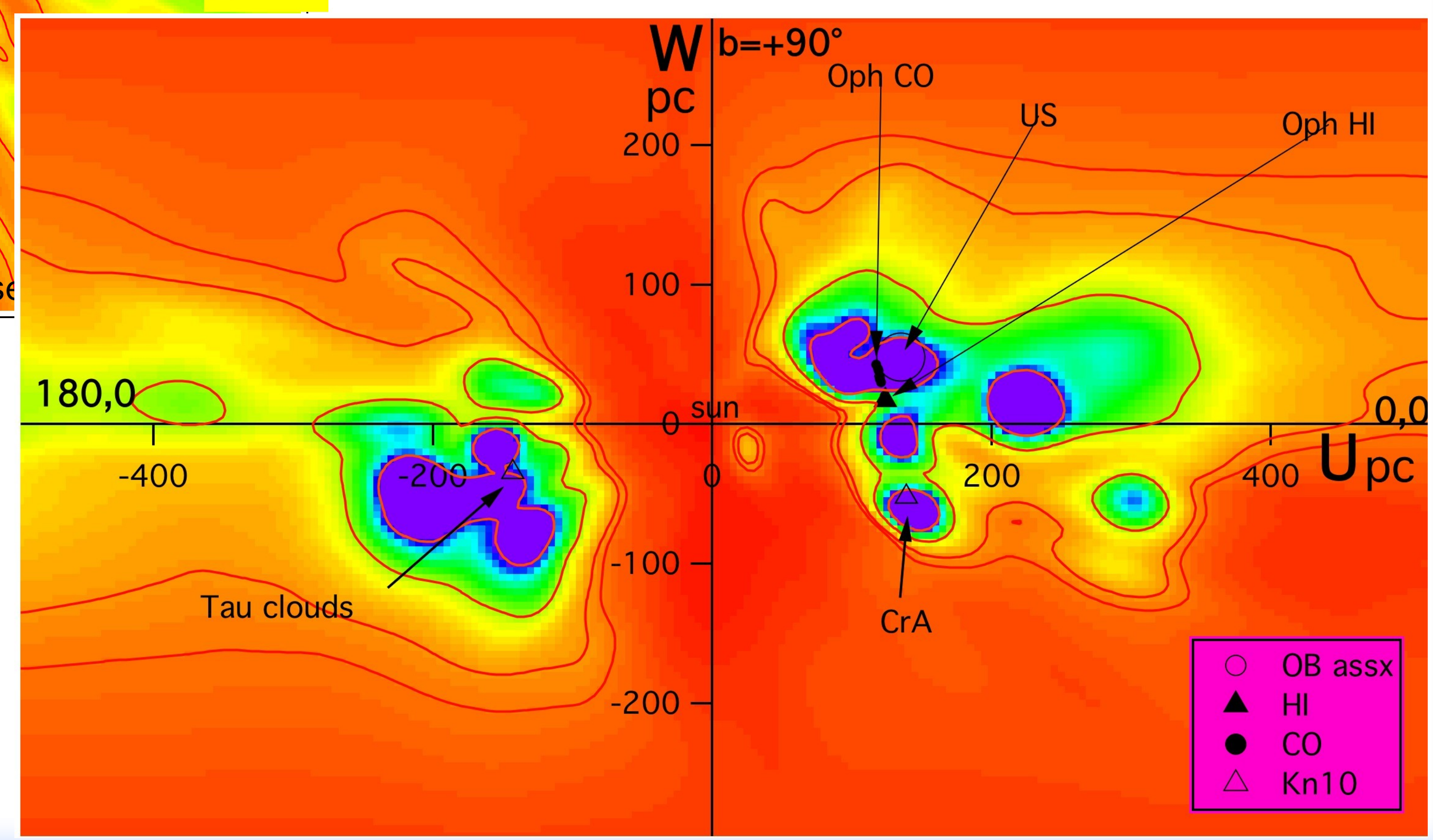
cosmic-ray rain



the local whirlpool





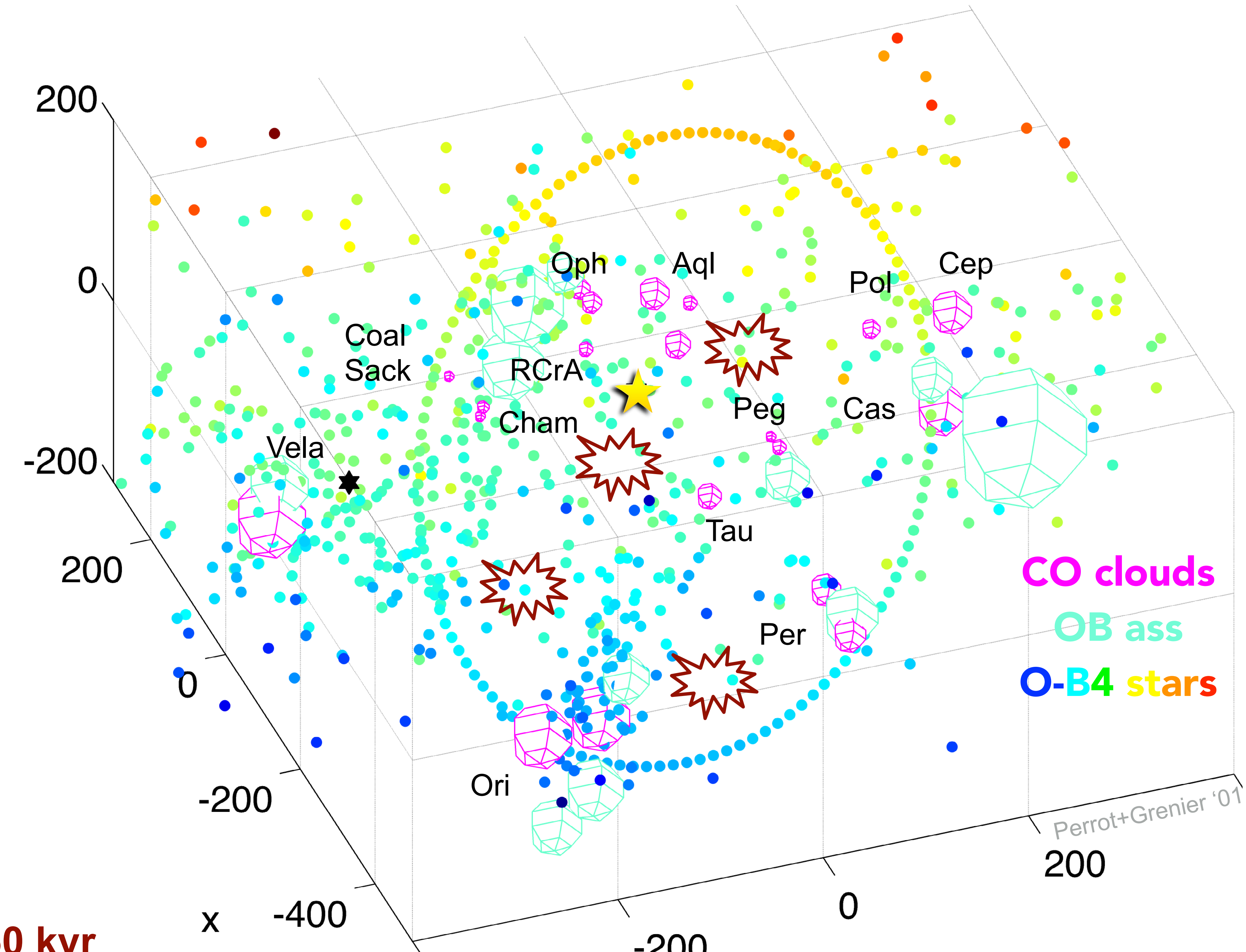


- inversion of thousands of absorption lines

the local jacuzzi

- 1200 x 750 l-yr, inclination ≈ 17°
- dynamical age
  ≈ 26 Myr
  stellar age
  ≈ 60 Myr
- origin ?
  (10 supernovae ?
  1 γ-ray burst ?
  cloud impact ?)
- supernova nest:
  1 supernova
  per 40 kyr
  (3-4 times the
  Galactic rate)

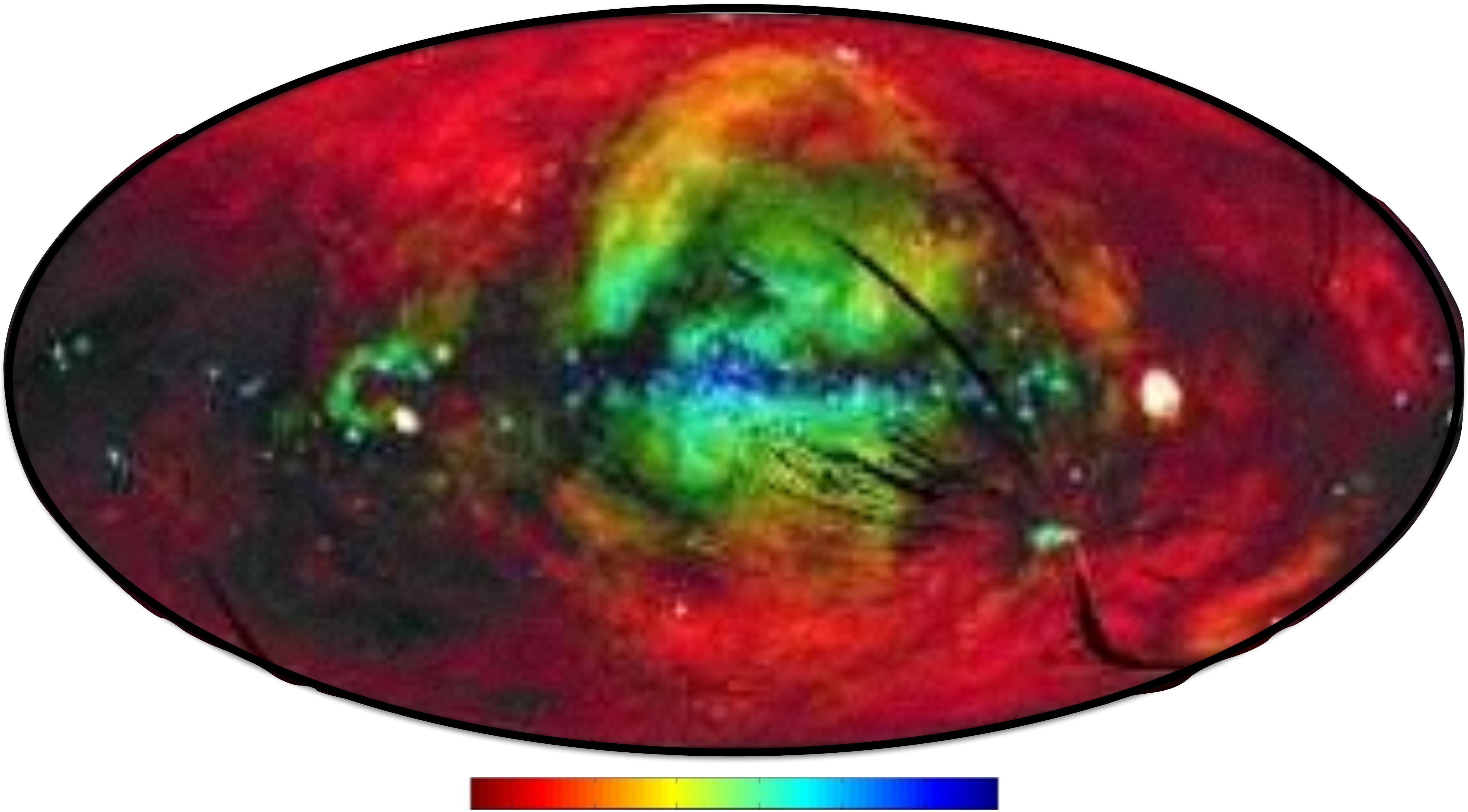
Grenier '00

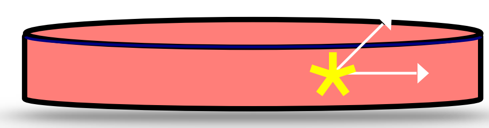


pôles: ^{10}Be 33 & 60 kyr

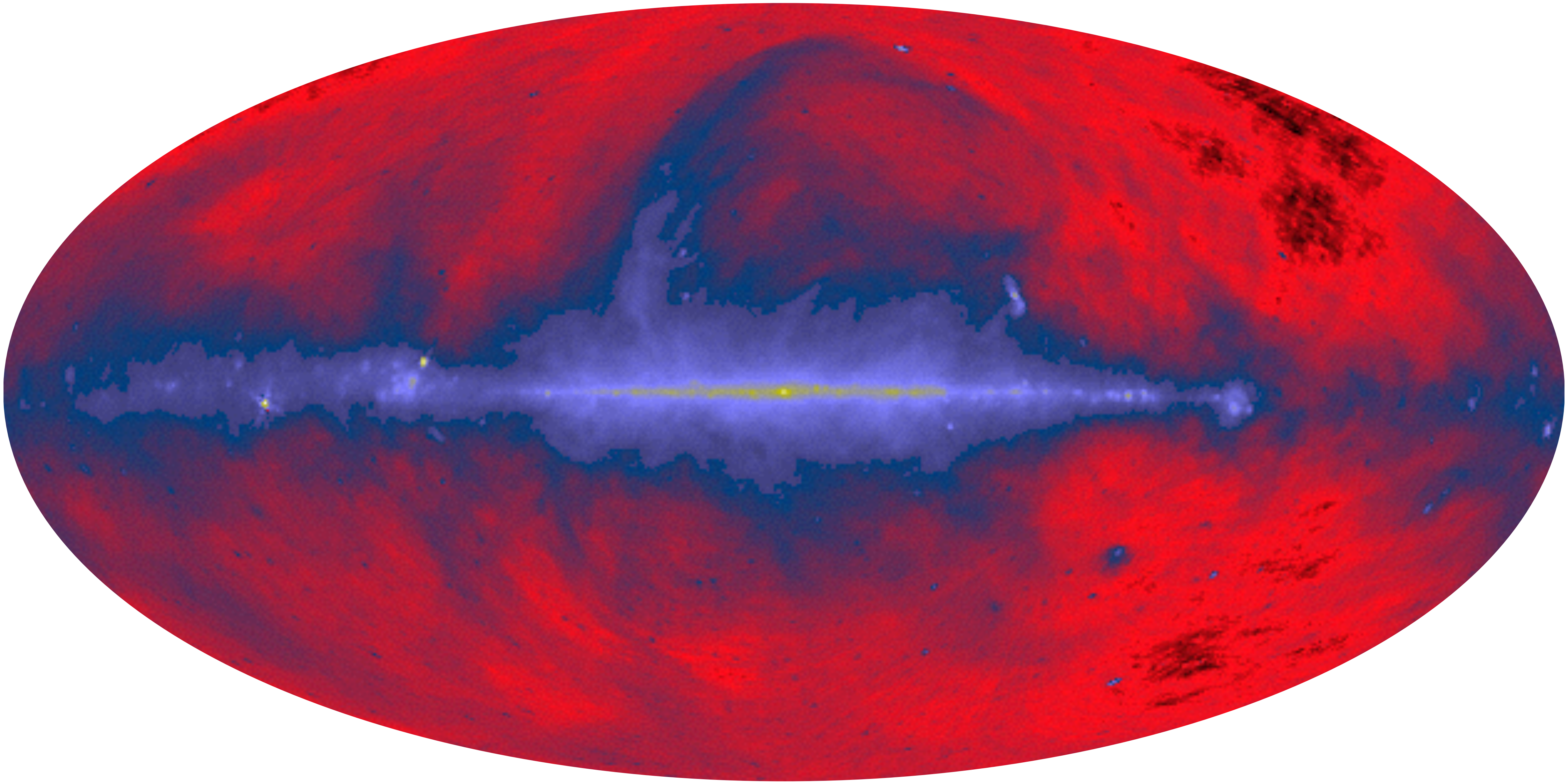
mer: ^{60}Fe 5 Myr 90 l-yr

the hot local bubble





local radio bubbles



Voyager crossing the heliopause?

Univ
EarthS

- increase of 10-300 MeV GCRs

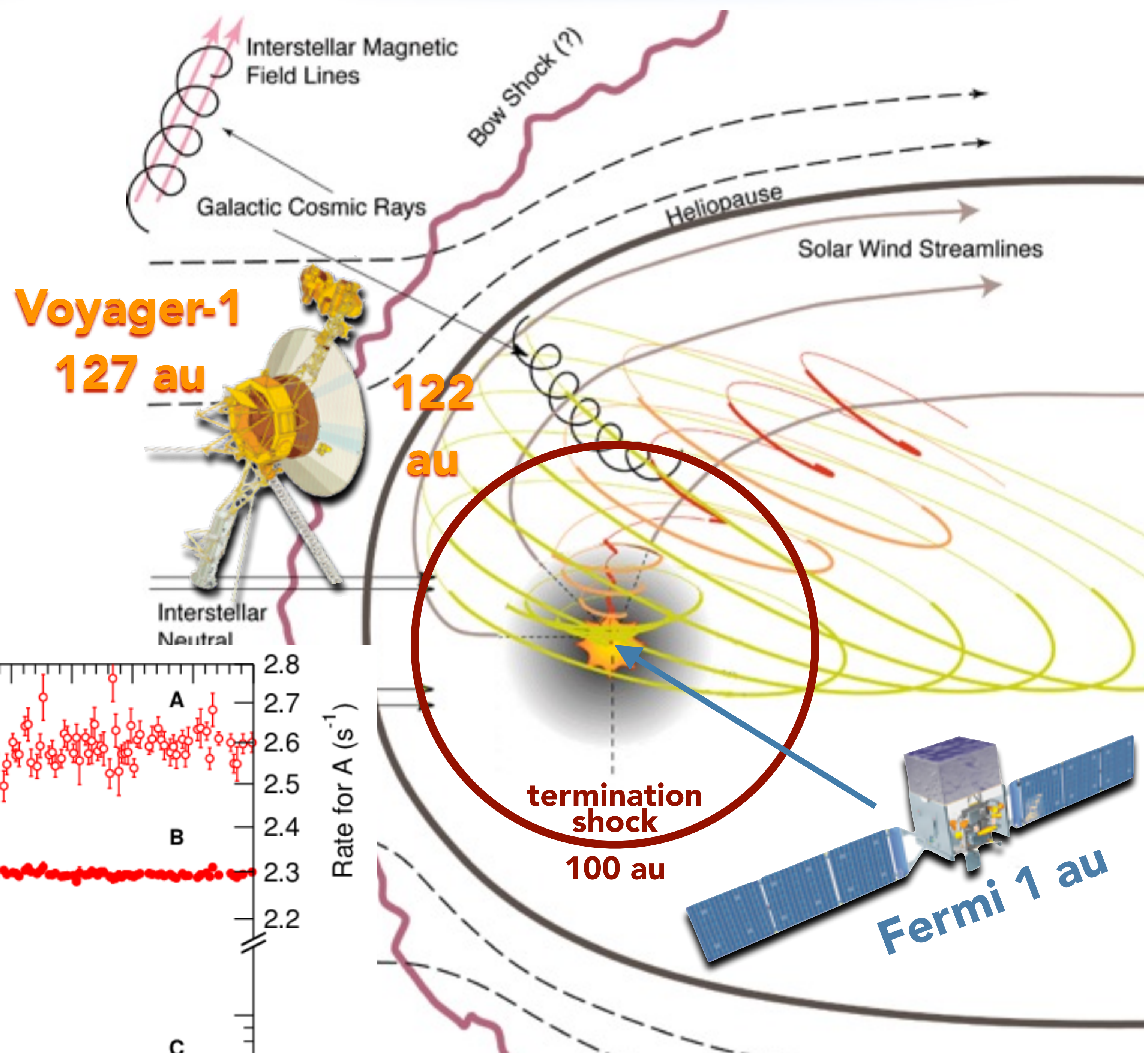
  Stone+ 2013, Decker+2013

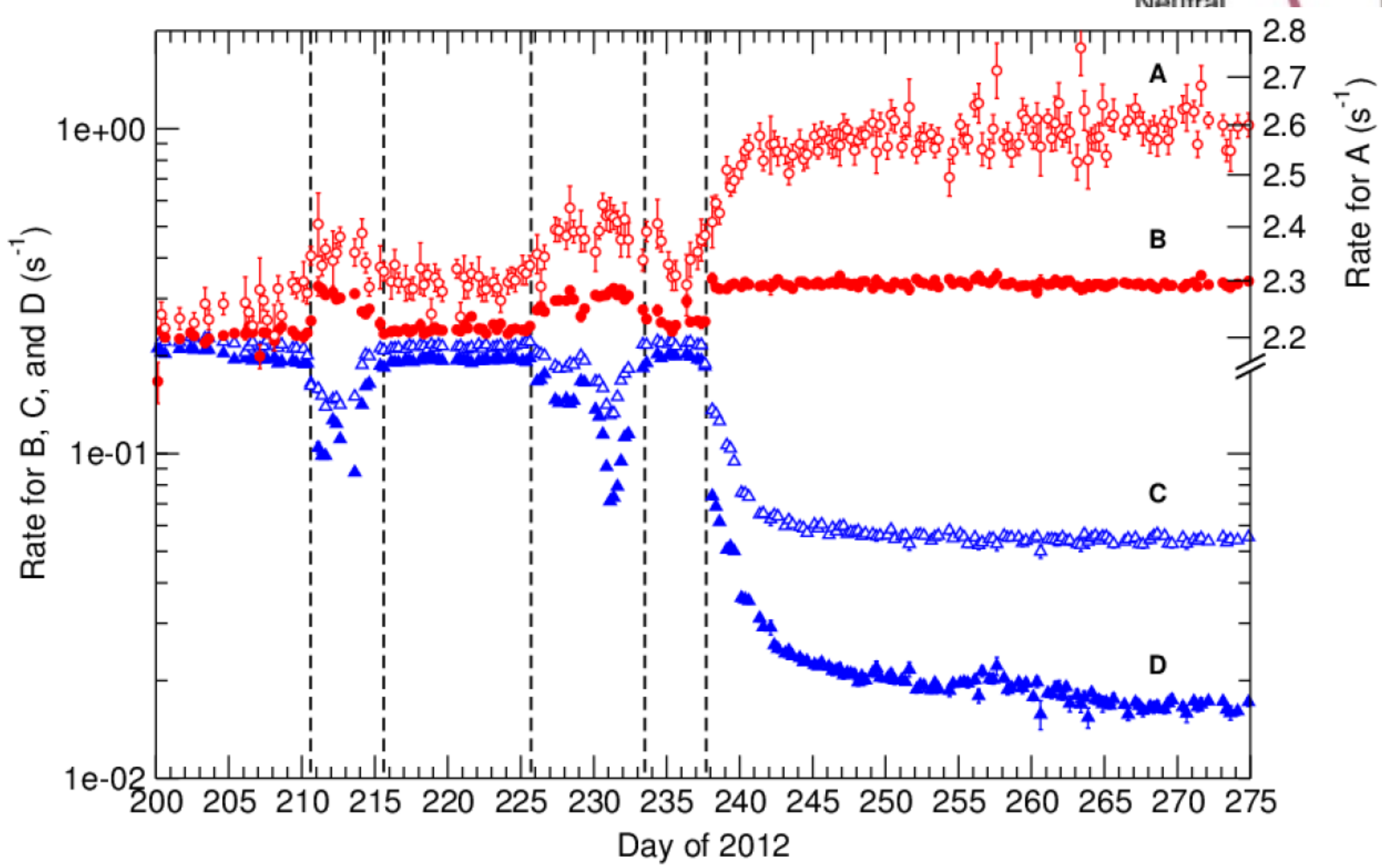
- decrease of heliospheric particles

  Krimigis+ 2013

- plasma oscillations triggered by a solar wind stream => measure of the ambiant electron density: n(e) = 0.04-0.08 cm^{-3} » n(e) solar wind ≈ expected interstellar value

  Gurnett+ 2014





from inside	from outside
ACR p^+ 7-60 MeV	CR p^+ > 70 MeV
TSPs 0.5-30 MeV	CR e^- 7-100 MeV

uniform bath of cosmic rays

- local cosmic-ray measurements