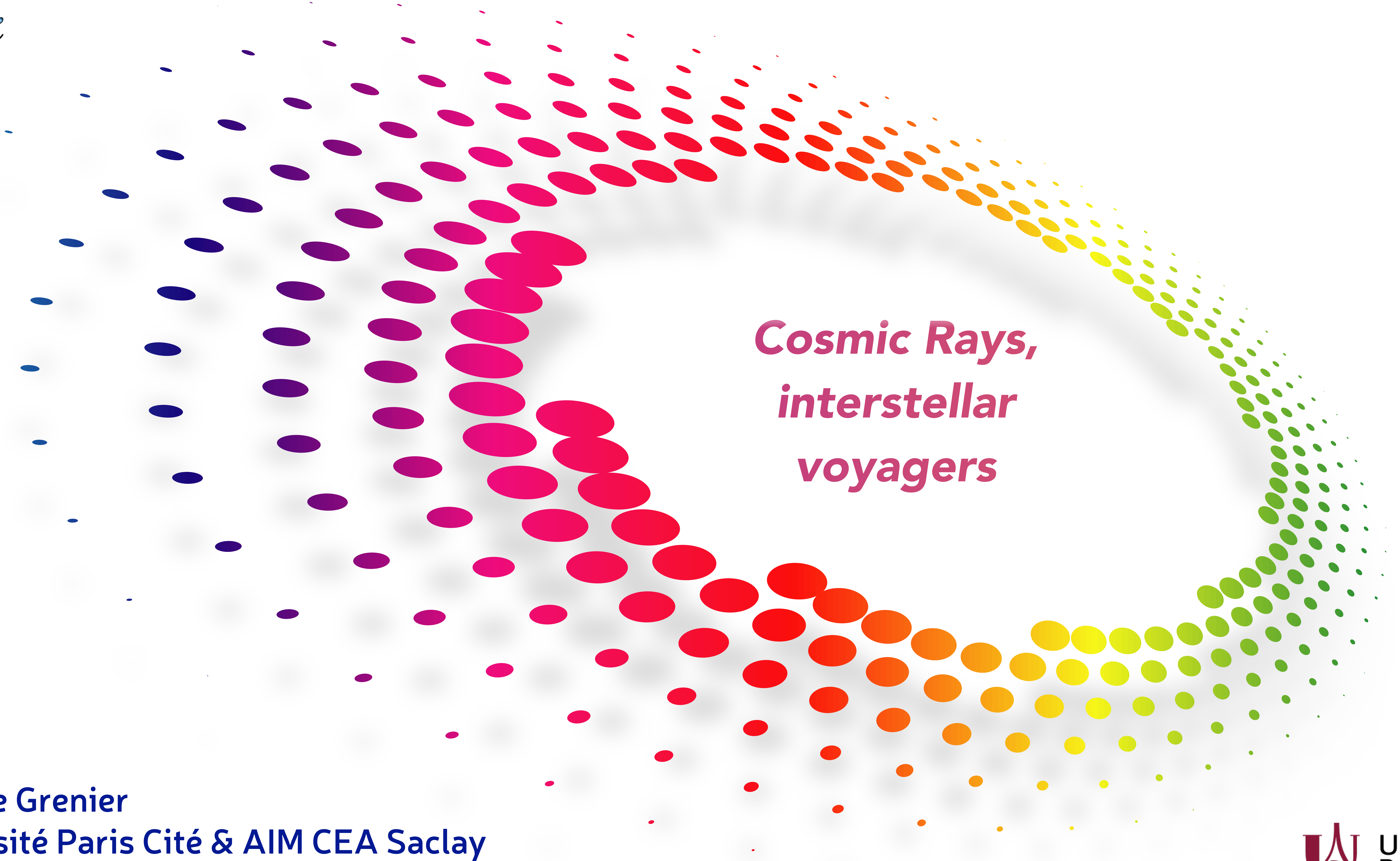


Cosmic Rays, interstellar voyagers

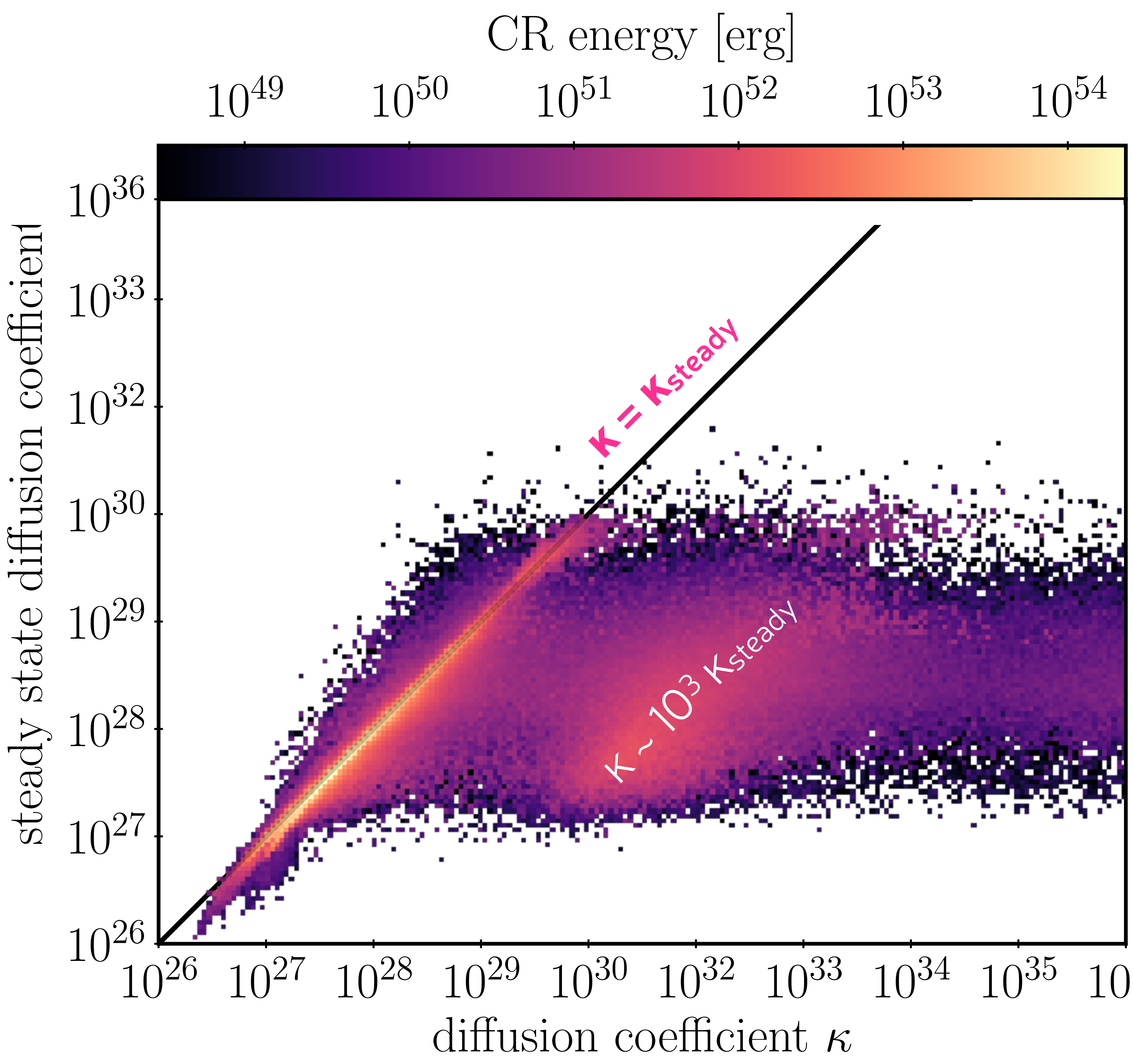
Isabelle Grenier
Université Paris Cité & AIM CEA Saclay

how fast, uneven, anisotropic is diffusion?

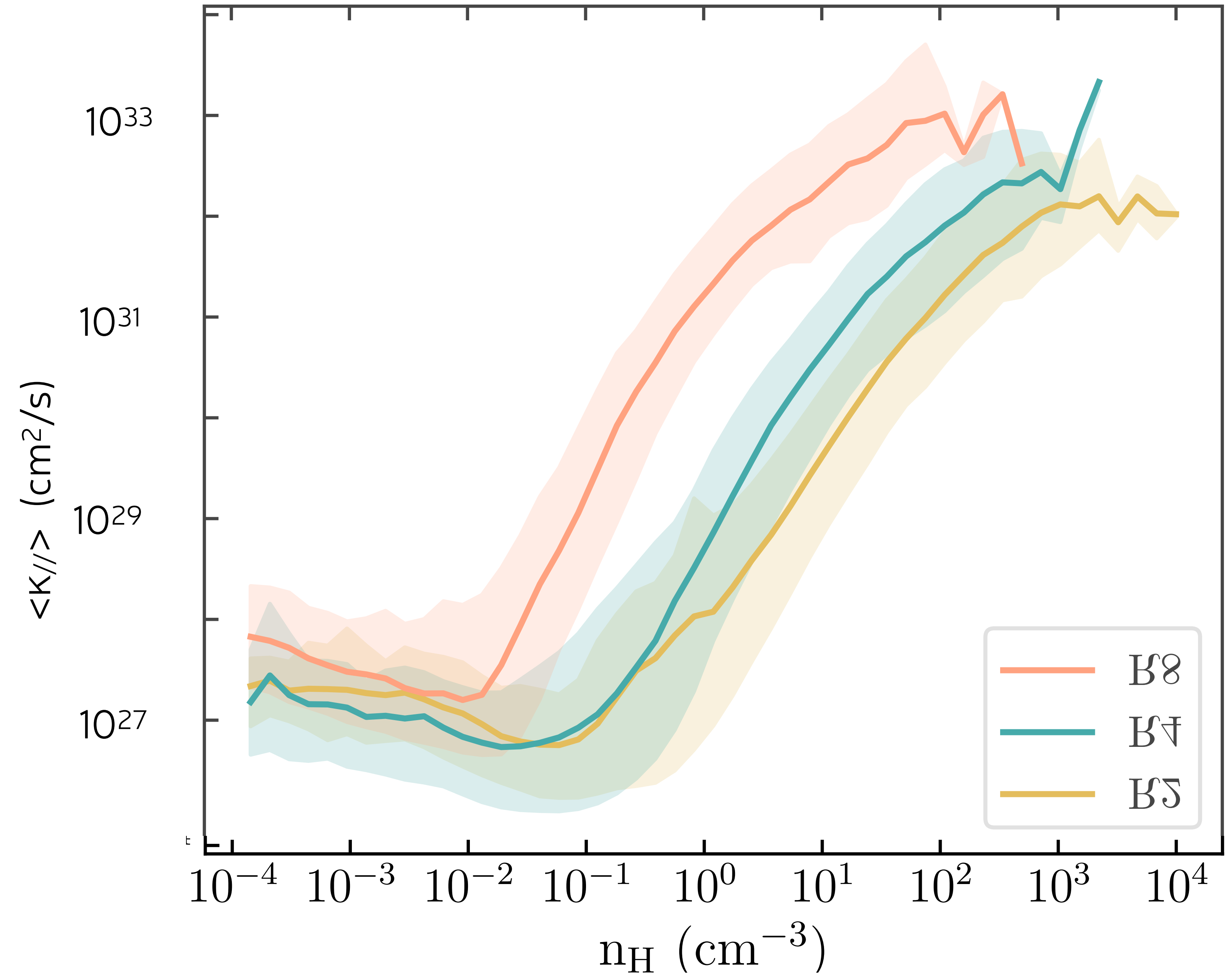
- **if self-streaming transport**

- steady-state approximation often holds
  - + Alfven-wave dark regions where $\vec{B} \perp \vec{\nabla} P_{CR}$

- $\kappa_{||}$ variations by 50 to 1000 in multi-phase ISM

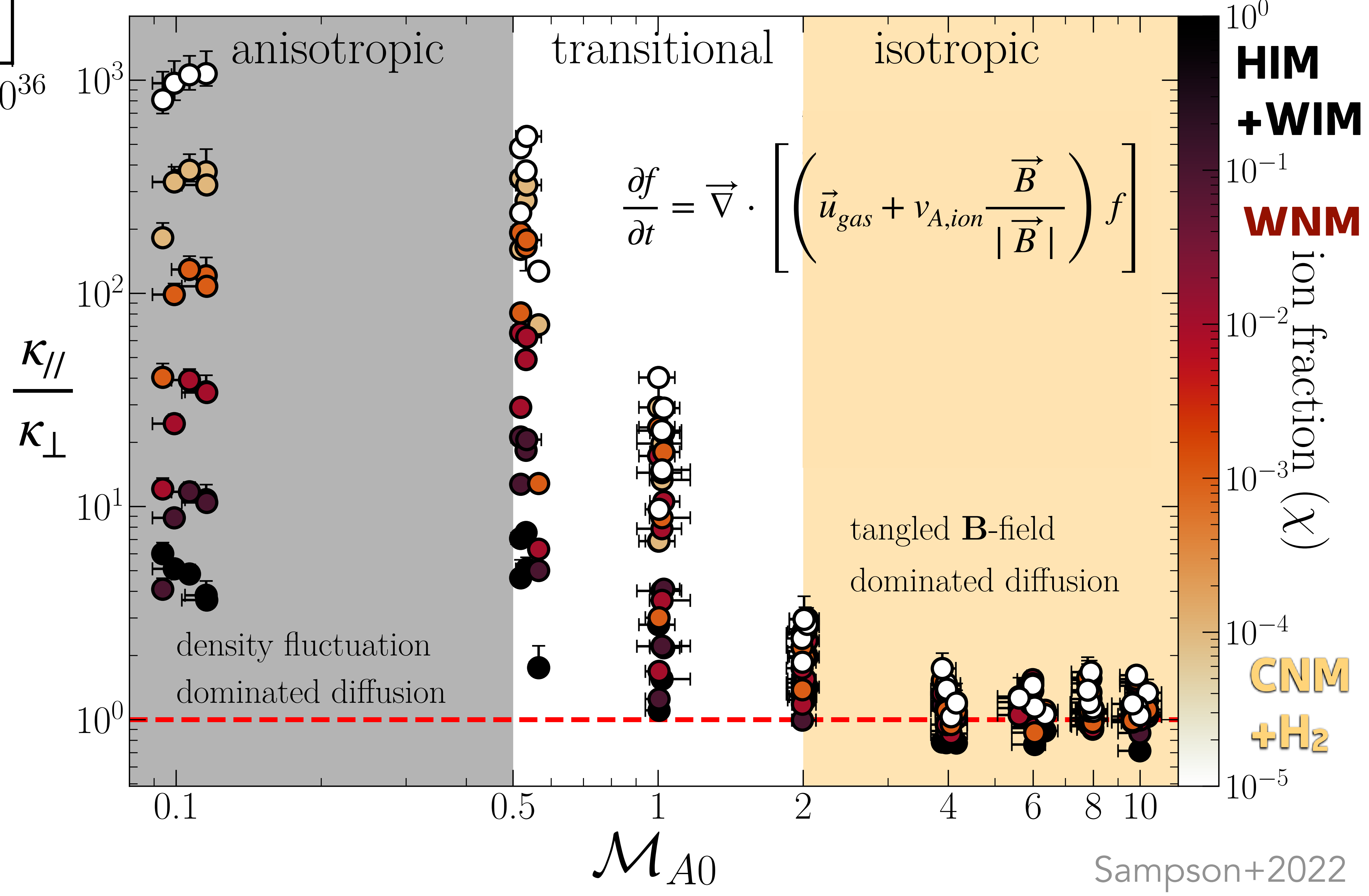


Thomas+2022



Armillotta+2022

- if self-streaming CR transport with waves and CRs fully coupled
  - diffusion anisotropy varies with M_A and ionisation fraction
  - super-diffusion perpendicular to B, but also often along B

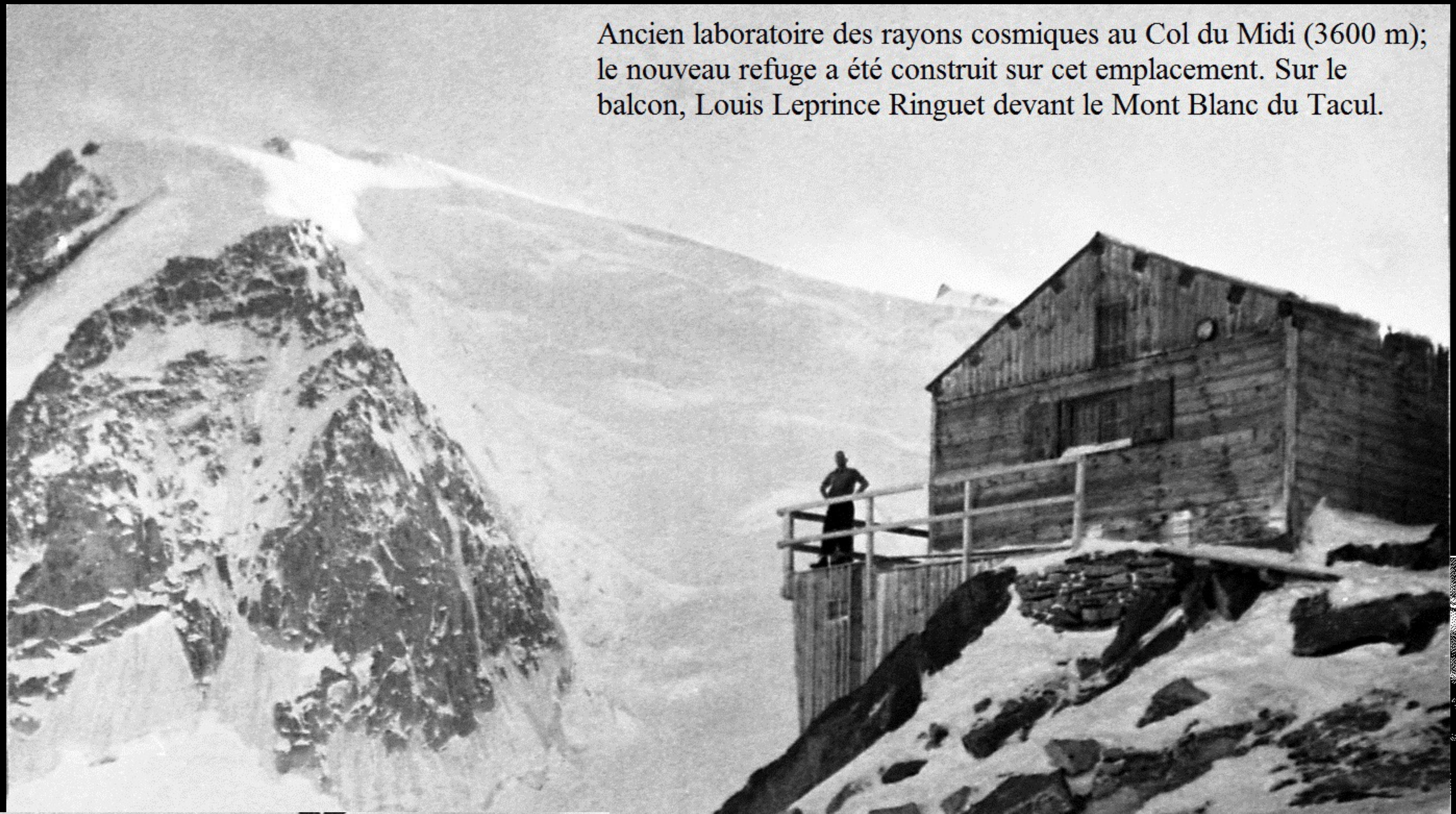


Sampson+2022

highly uneven & (an)isotropic
IF self-excited scattering

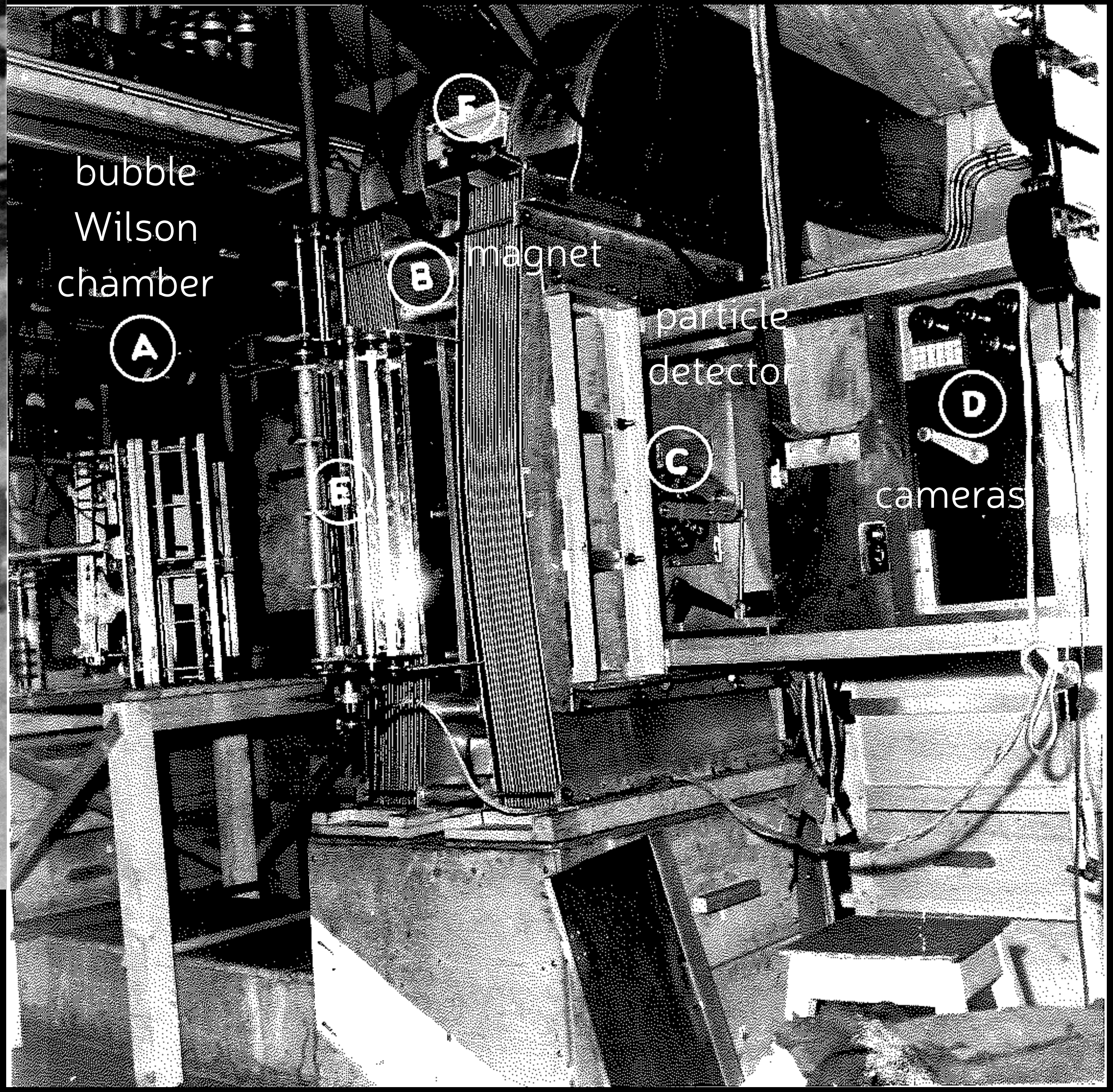
Col du Midi cosmic-ray lab (1943-1955)

- Louis Leprince-Ringuet



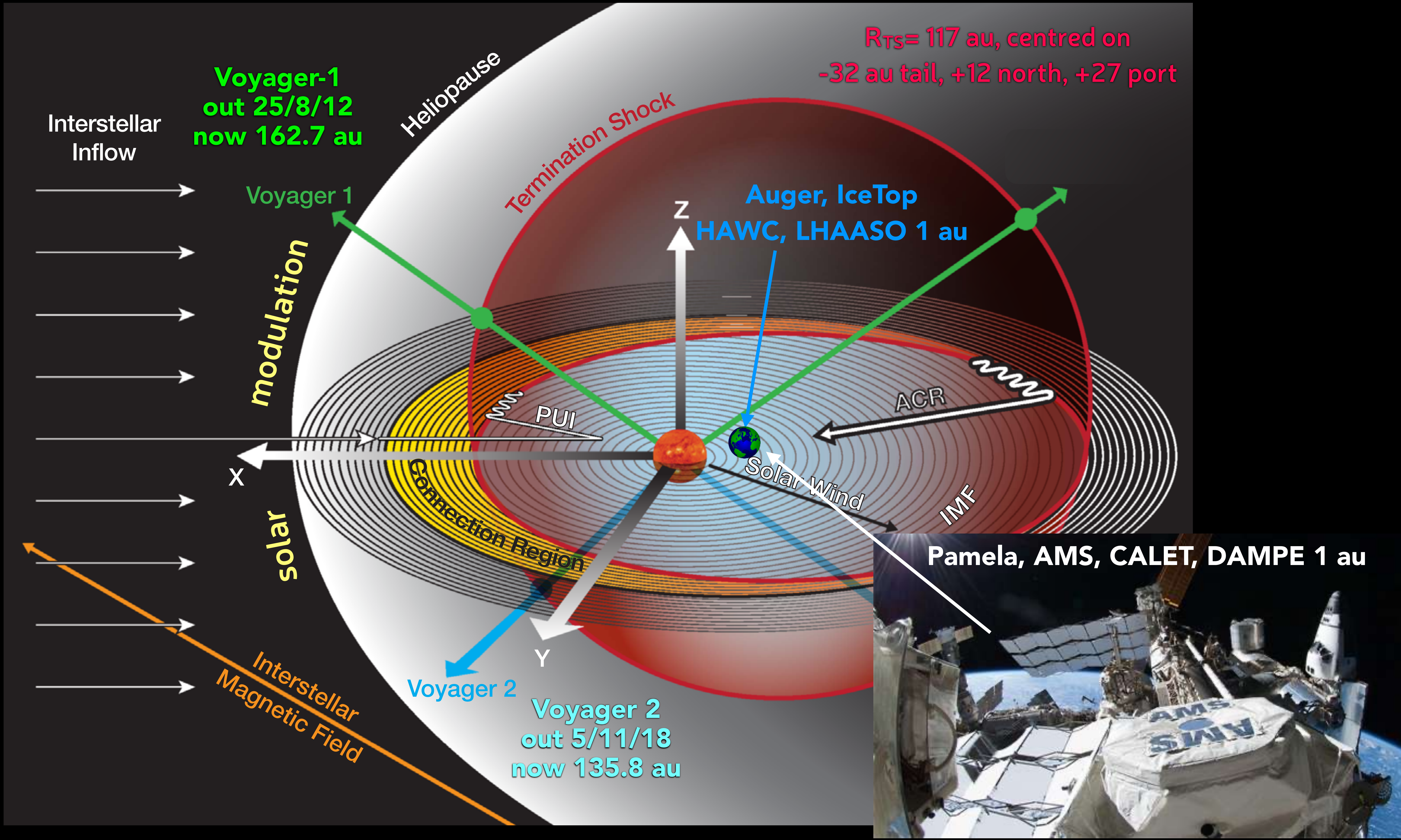
Ancien laboratoire des rayons cosmiques au Col du Midi (3600 m); le nouveau refuge a été construit sur cet emplacement. Sur le balcon, Louis Leprince Ringuet devant le Mont Blanc du Tacul.

Câble de transport aérien entre le laboratoire et le terminus de la benne de service du Col du Midi



outer-space collection

McComas+ 2019



R_{TS}= 117 au, centred on -32 au tail, +12 north, +27 port

Voyager-1
out 25/8/12
now 162.7 au

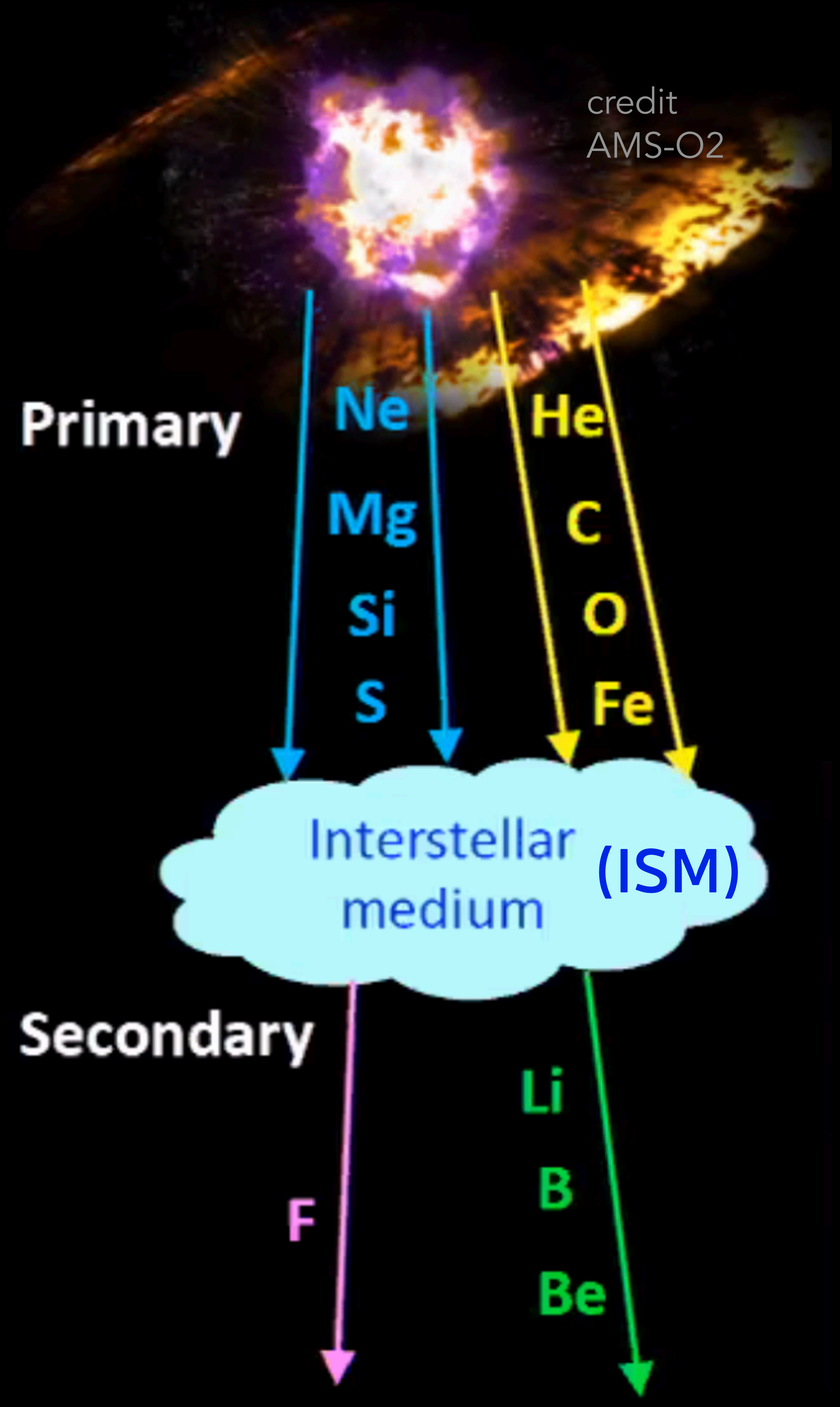
Voyager 2
out 5/11/18
now 135.8 au

Auger, IceTop
HAWC, LHAASO 1 au

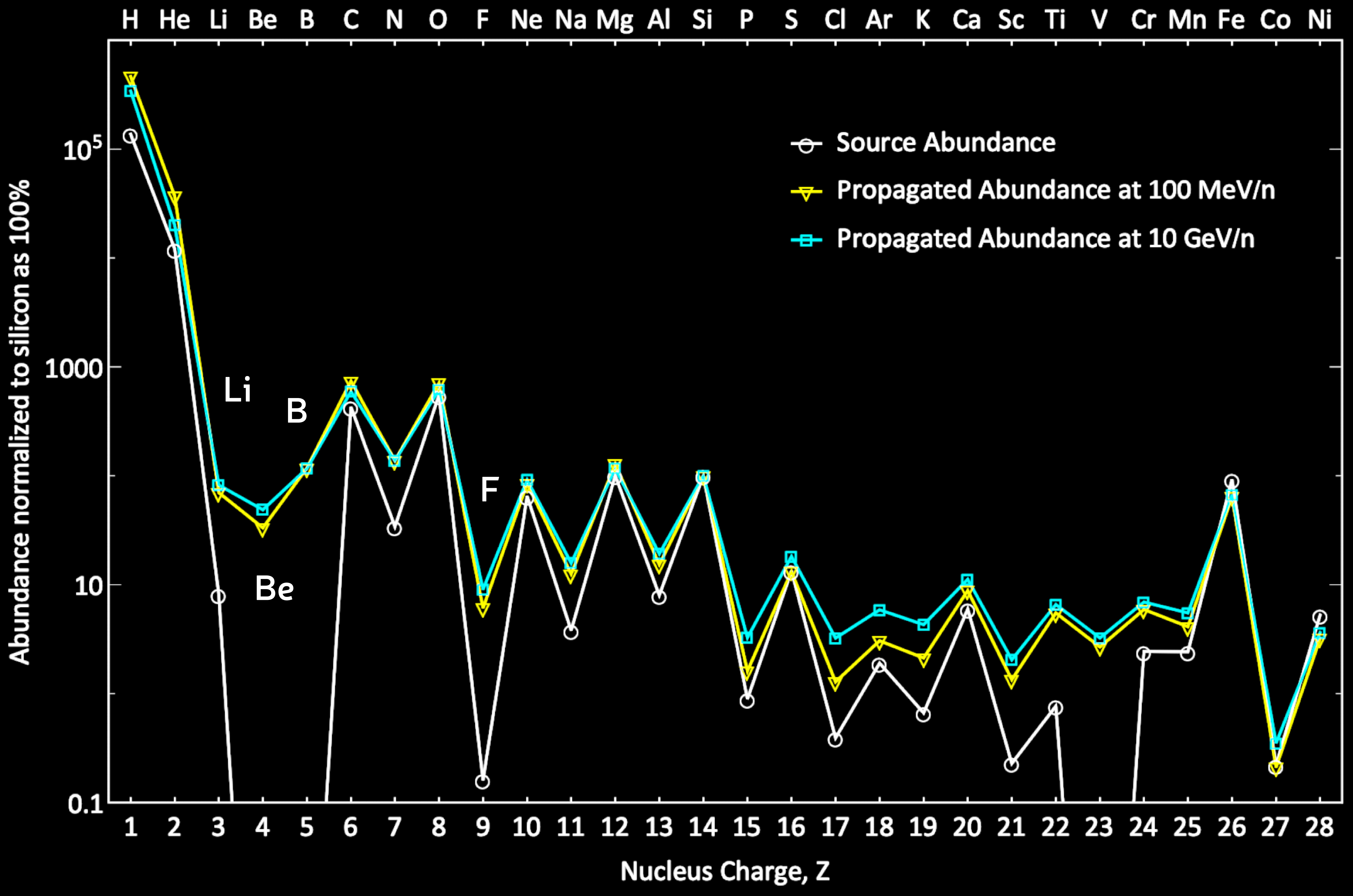
Pamela, AMS, CALET, DAMPE 1 au

cosmic-ray composition vs. solar abundances

- 99% nuclei (~ 89% protons, ~ 10% He, ~ 1% heavier nuclei) + 1% electrons
- spallation reaction products in the interstellar medium



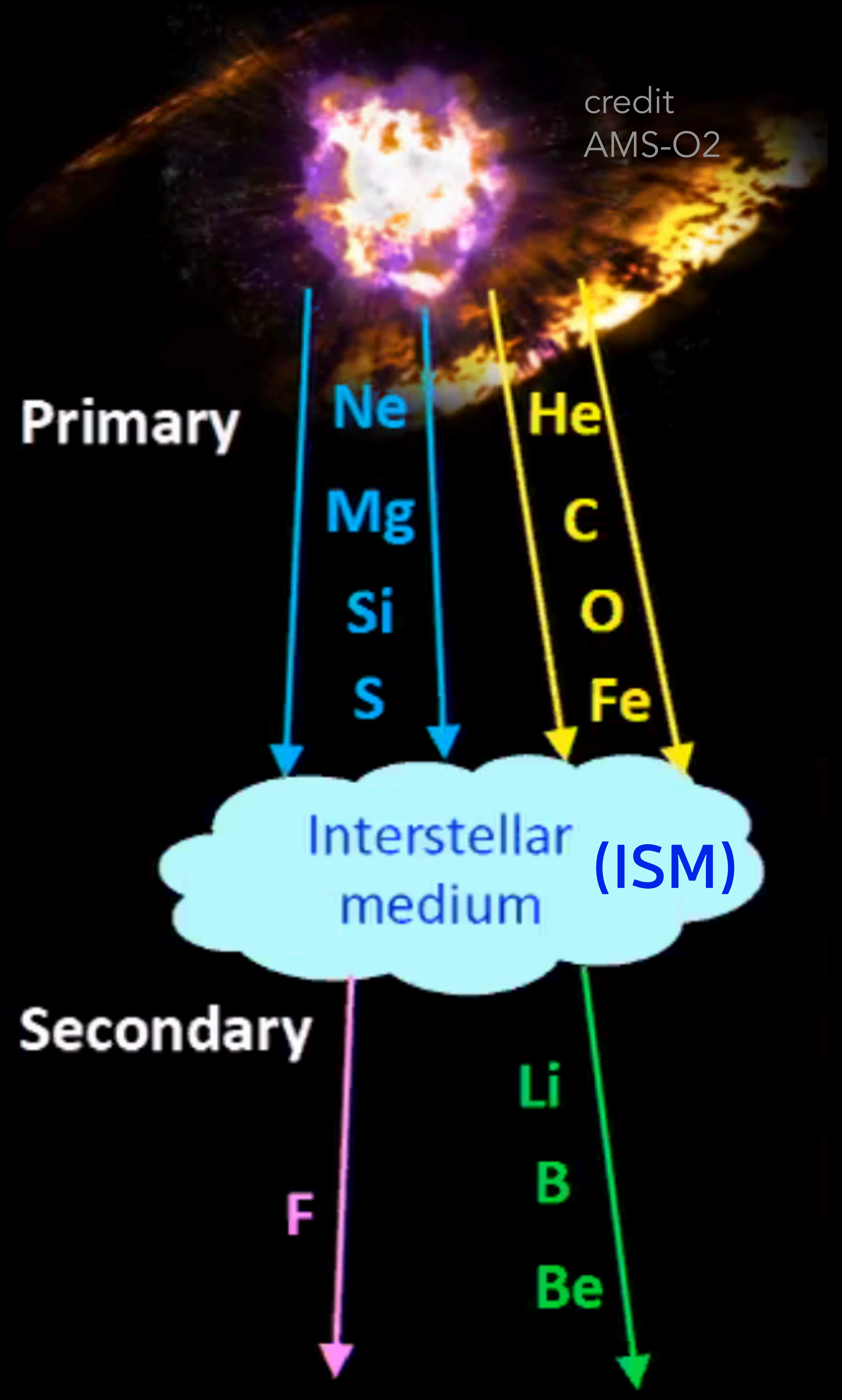
credit AMS-O2

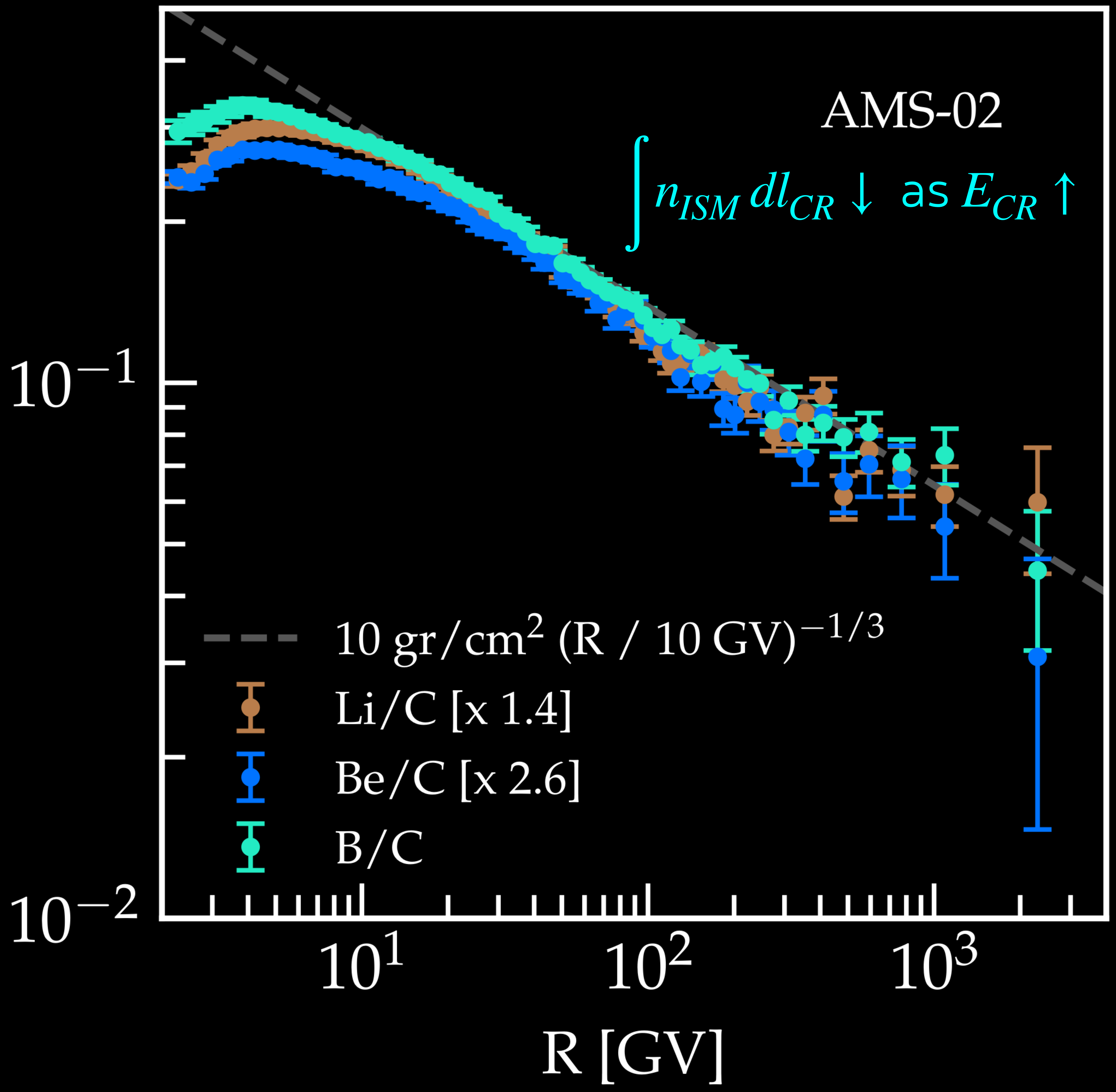


Boschini+2018

cosmic-ray composition vs. solar abundances

- 99% nuclei (~ 89% protons, ~ 10% He, ~ 1% heavier nuclei) + 1% electrons
- spallation reaction & products in the interstellar medium

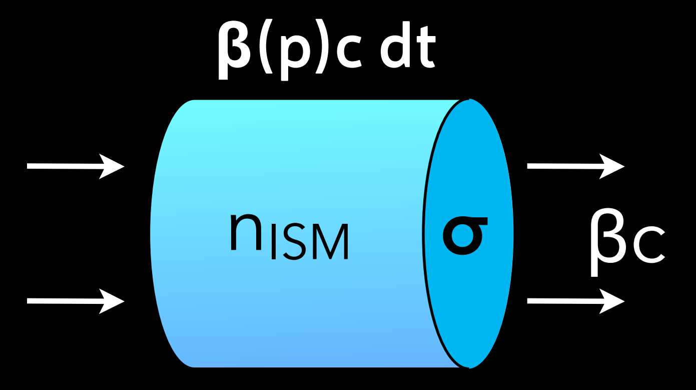




simplest leaky box model

- steady state between source input and loss + escape

$$\frac{M_a(p)}{T_{sp}(p)} + \frac{M_a(p)}{T_{esc}(p)} = Q_a(p)$$



$$n_{ISM}\sigma\,\beta(p)c dt = 1$$

- spallation reactions in the ISM
  - secondary source input

$$Q_2 = \frac{dM_2}{dt} = n_{ISM}\sigma_{1\to 2}\,\beta c\,M_1$$

  - secondary spallation losses

$$T_{sp2} = (n_{ISM}\sigma_{2\to 3}\,\beta c)^{-1}$$

  - steady state $\Rightarrow M_2\left[T_{sp2}^{-1} + T_{esc}^{-1}\right] = M_2\left[n_{ISM}\sigma_{2\to 3}\beta c + T_{esc}^{-1}(p)\right] = Q_2 = n_{ISM}\sigma_{1\to 2}\,\beta c\,M_1$

- ISM grammage crossed before escape: $x(p) = n_{ISM}\,\beta(p)c\,T_{esc}(p)$

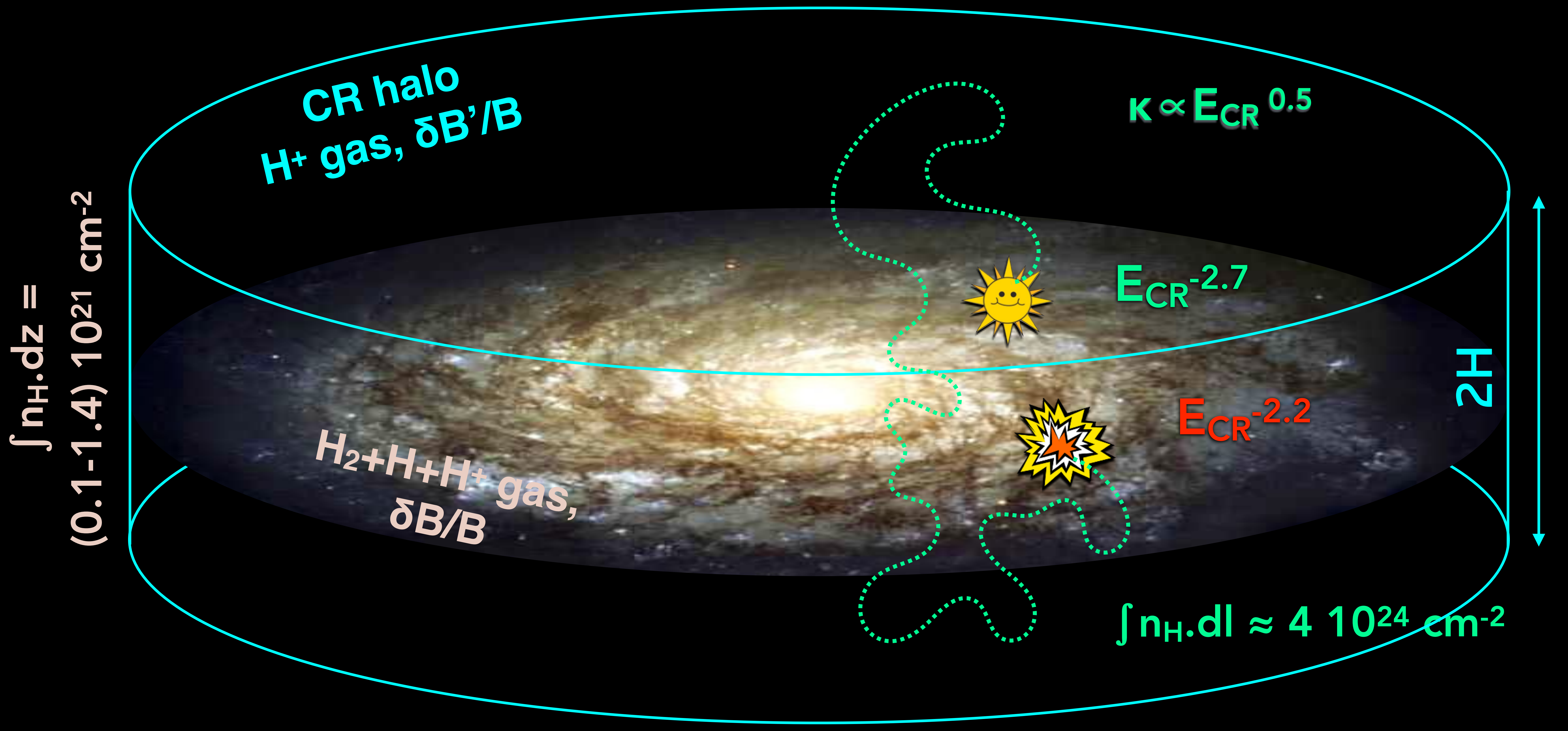
$$\frac{H^2}{\kappa(p)} = T_{esc}(E) \propto \kappa(p)^{-1}$$

- 2dary/1ary ratio

$$\frac{M_2(p)}{M_1(p)} = \frac{\sigma_{1\to 2}}{\sigma_{2\to 3} + x^{-1}(p)}$$

$$\frac{M_2}{M_1} \to x(p) \propto T_{esc}(p) \propto \kappa^{-1}(p)$$

$$\frac{M_2}{M_1} \propto p^{-\delta} \Rightarrow \kappa(p) \propto p^{\delta}$$

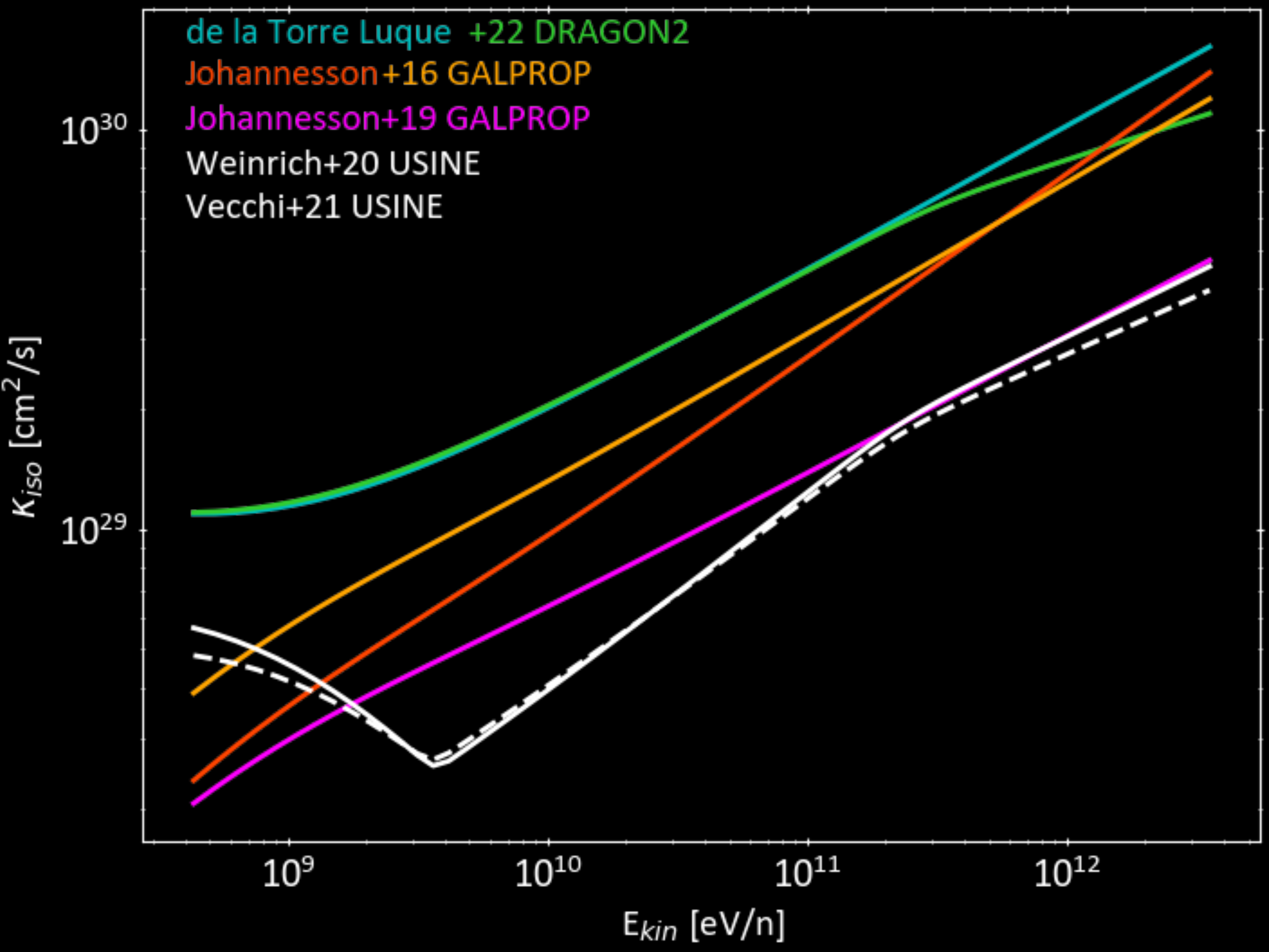


  - $X \approx 10$ g/cm^2 or $N_H \approx 4\ 10^{24}$ cm^{-2}
  - radioactive secondaries : CR clocks
  - $T_{esc} \approx$ 10-20 Myr

1D - 2D - 3D diffusion codes

- mean uniform diffusion coefficient in the Milky Way

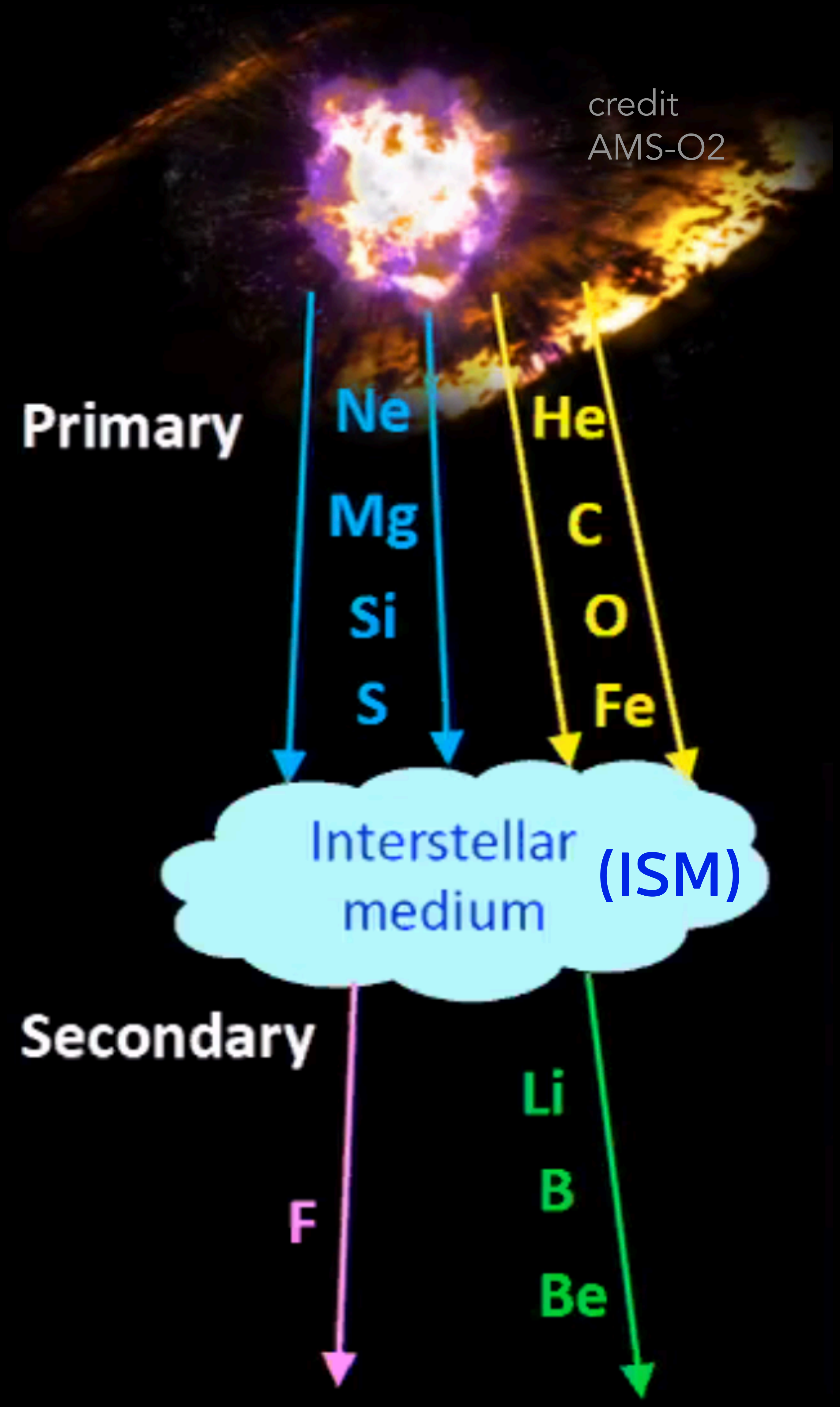
$$\kappa(GeV/n) \approx 10^{28-29}\ \mathrm{cm}^2/s, \quad l_{scat} \approx 3\kappa/c \sim 1\ \mathrm{pc}$$

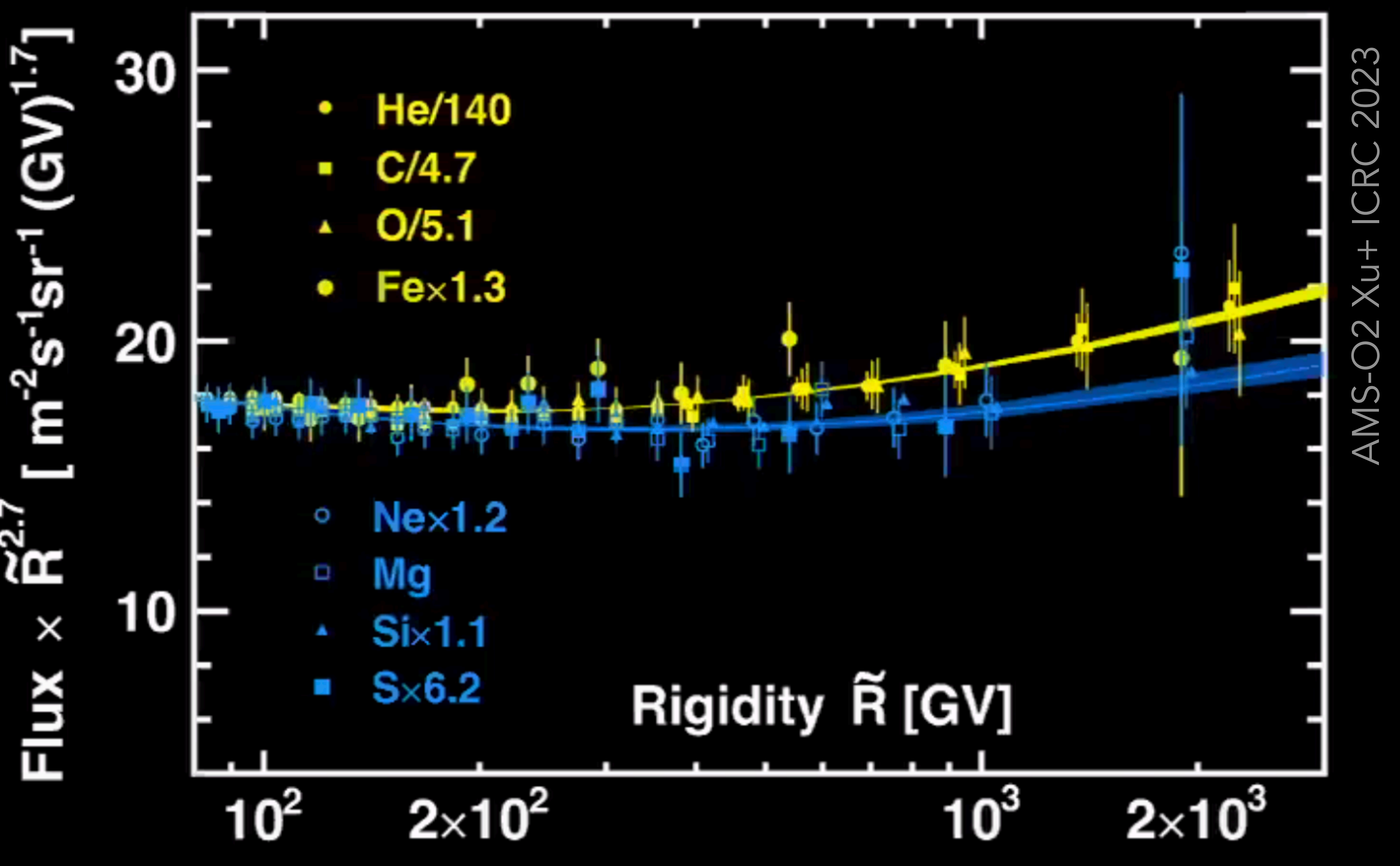


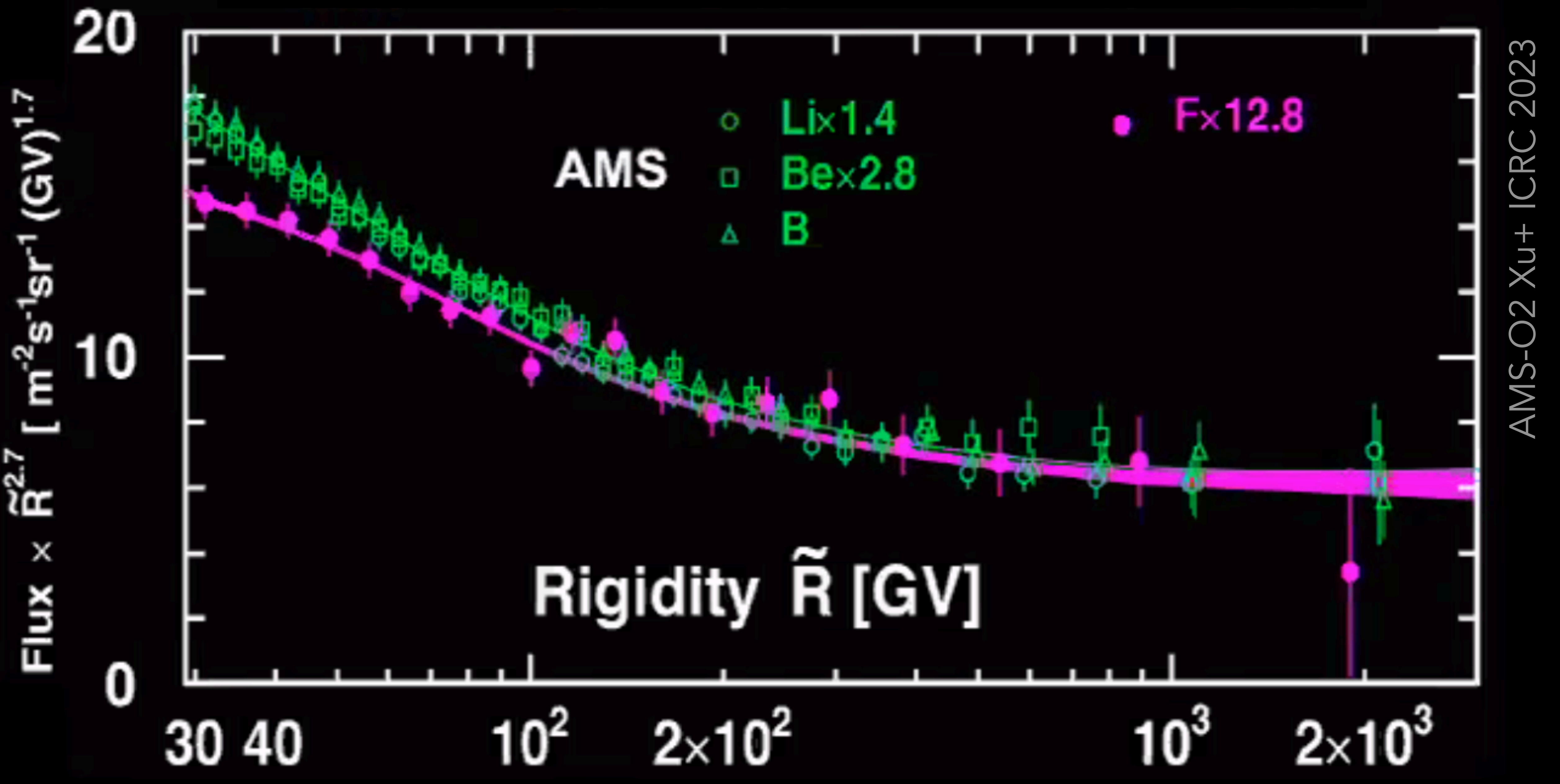
🤔

cosmic-ray composition vs. solar abundances

- but 2 classes of CR primaries, with secondary contamination







- but 2 classes of secondaries

cosmic-ray power

- total power ⩾ GeV
  - from spallation residence time $\Delta t_{res} = T_{esc}$
  - grammage $X_{cr} \sim \rho_{ISM}\, c\, \Delta t_{cr}$

$$P_{cr} \sim \frac{E_{CR}}{\Delta t_{cr}} = \frac{u_{cr} V_{gal}}{\Delta t_{cr}} = \frac{u_{cr} V_{gal} \rho_{ISM}\, c}{X_{cr}} = \frac{u_{cr}\, c\, M_{ISM,gal}}{X_{cr}}$$

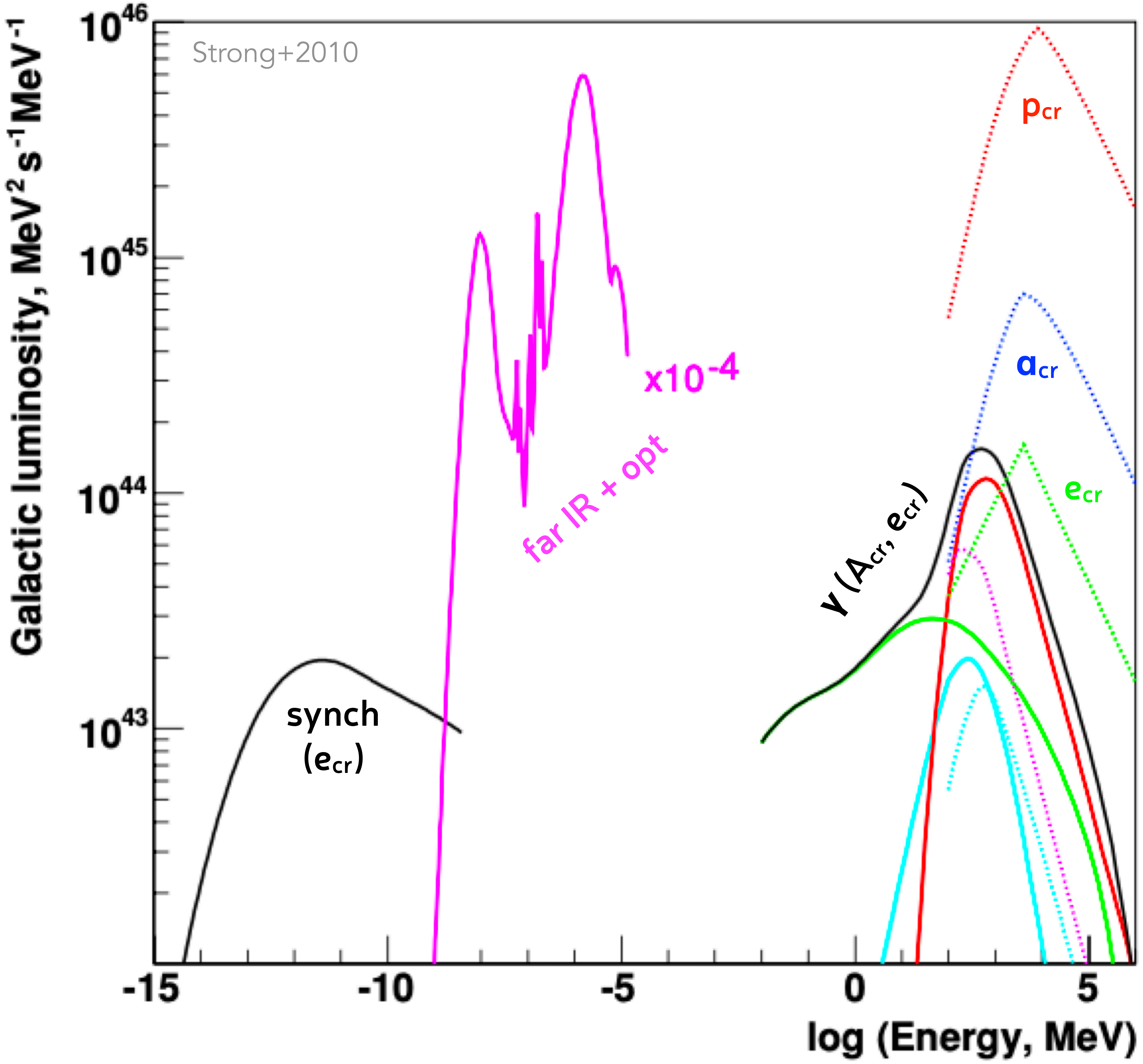
  - $M_{ISM} = 10^{10}\ M_\odot \approx 2\ 10^{40}$ kg, $X_{cr} \approx 10^2$ kg/m^2

$$\boxed{P_{cr} \approx 10^{34}\ \mathrm{W}}$$

Dogiel+2002

  - total Milky Way CR power from GALPROP diffusion model = (0.7 - 0.8) 10^{34} W

10% of the total power of supernova explosions in the Milky Way

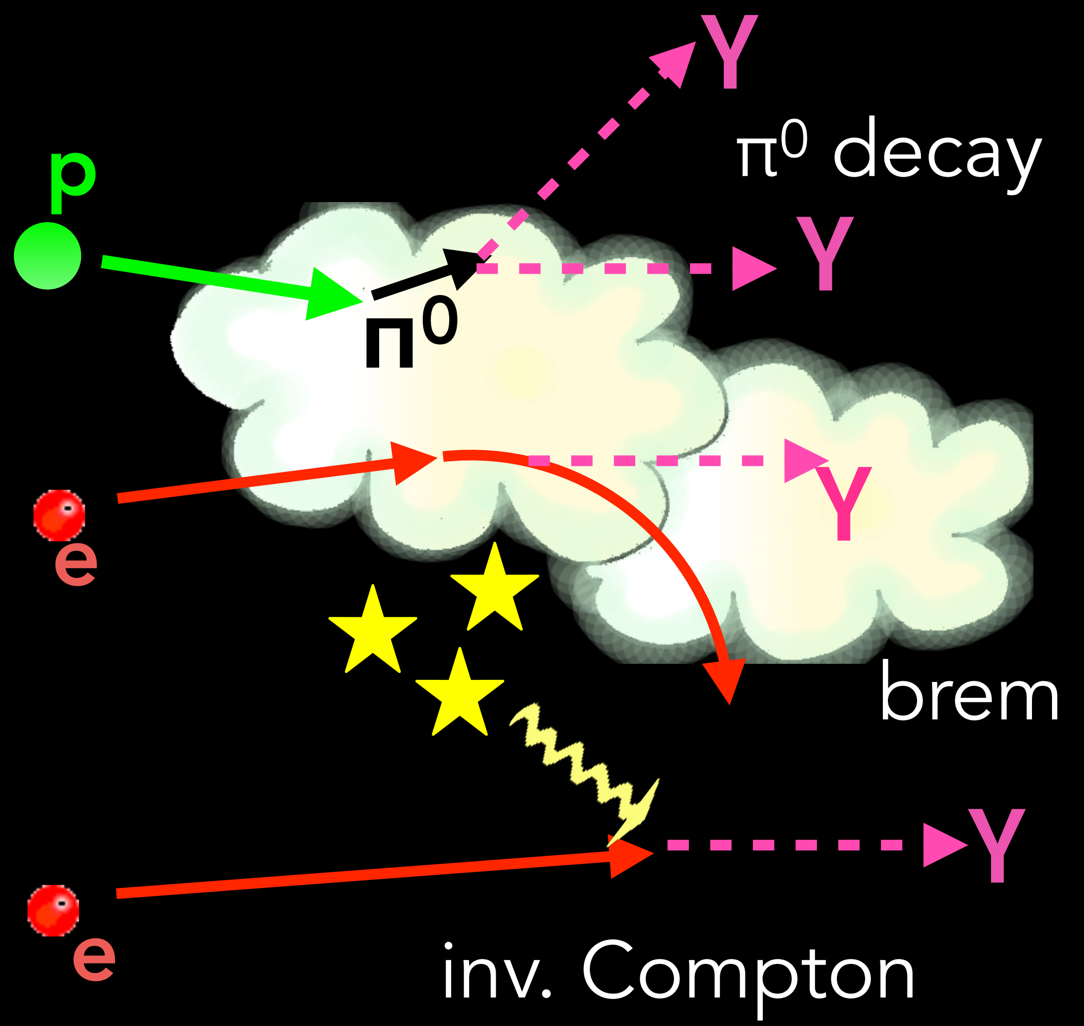


Strong+2010

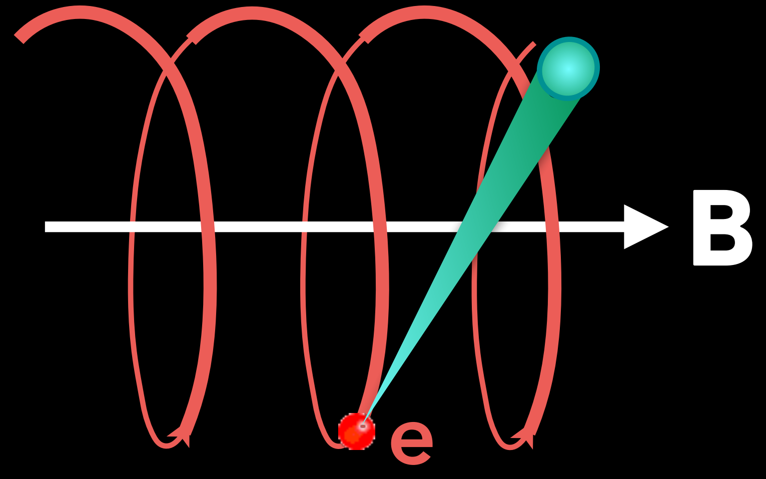
remote
observations

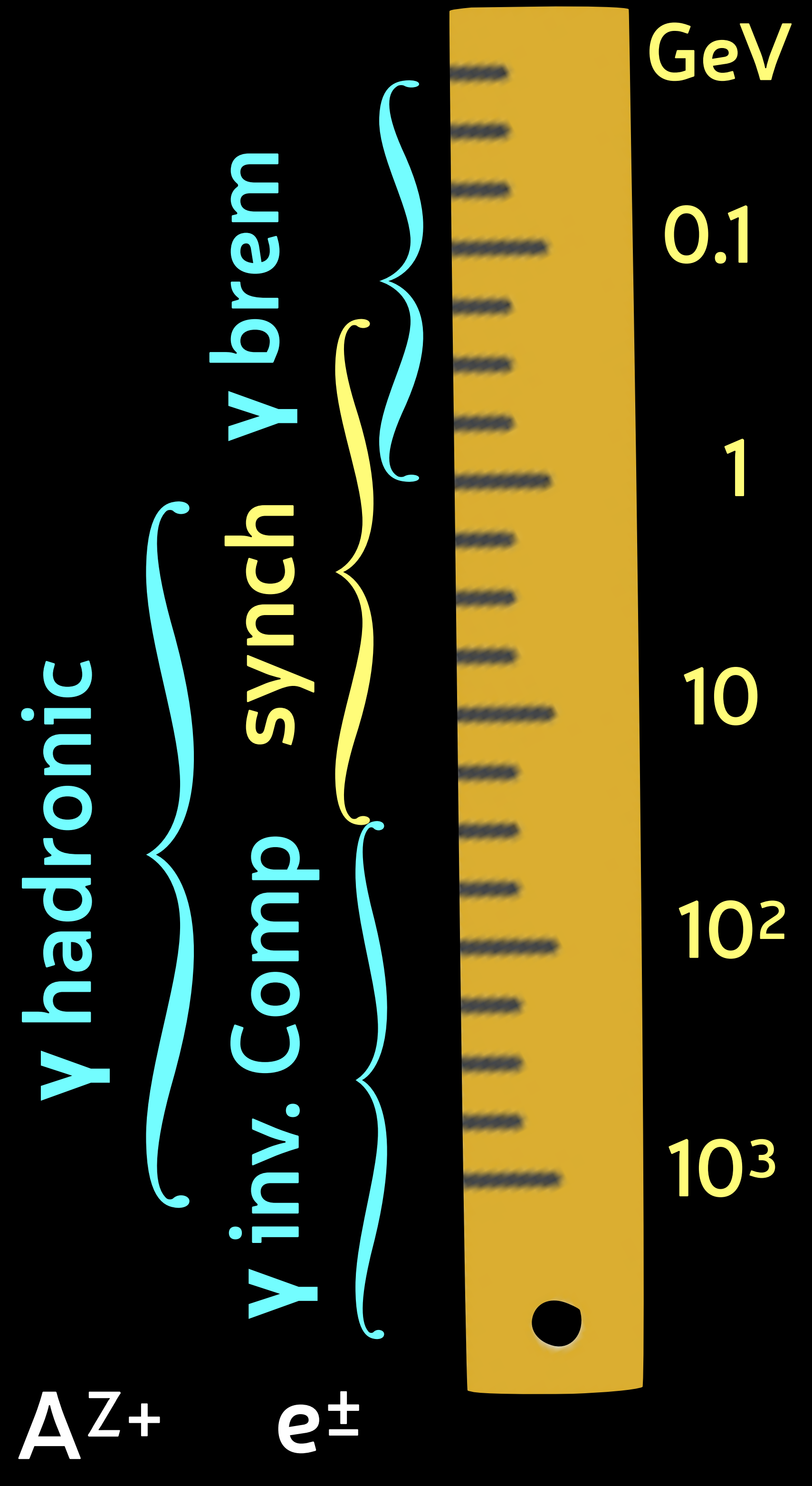
remote sensing of ≳ GeV cosmic rays

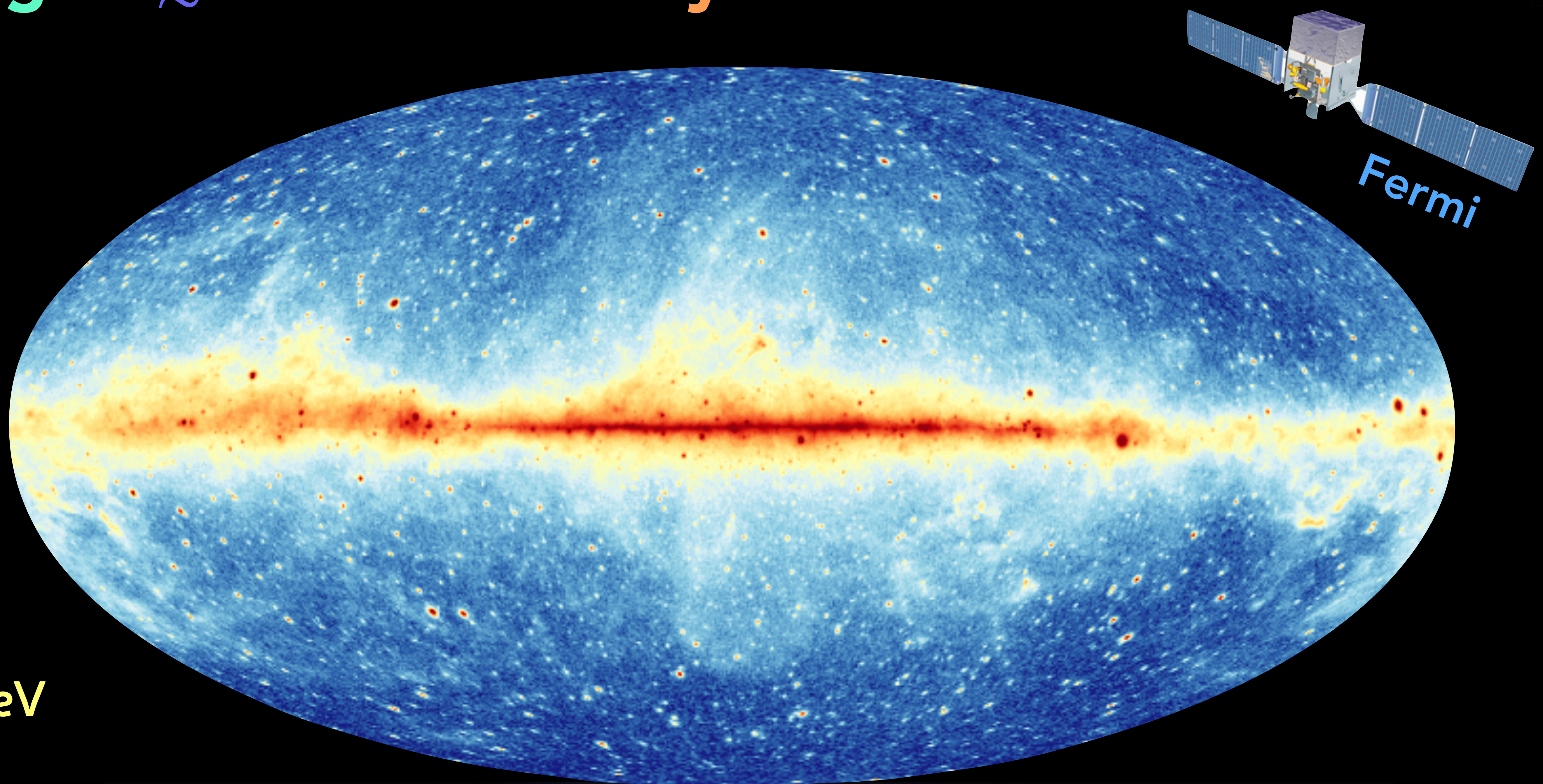
- A^{Z+} + $e^{\pm}$ probed in γ rays
  - Fermi LAT > GeV



- e± probed by radio synchrotron
  - 30 haloes piled-up by Chan-ges







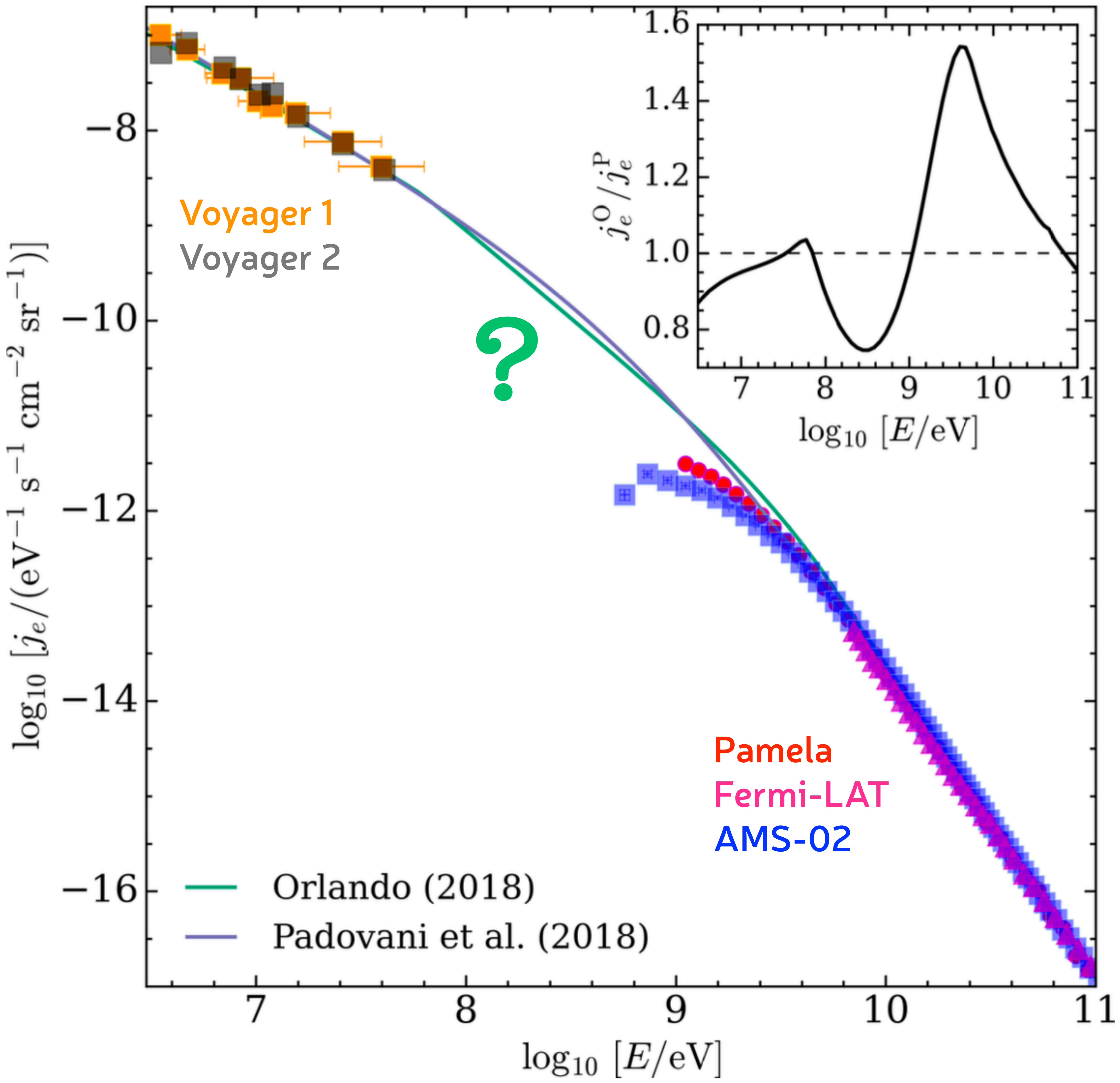
Wiegert+ 2015 AJ 150 81

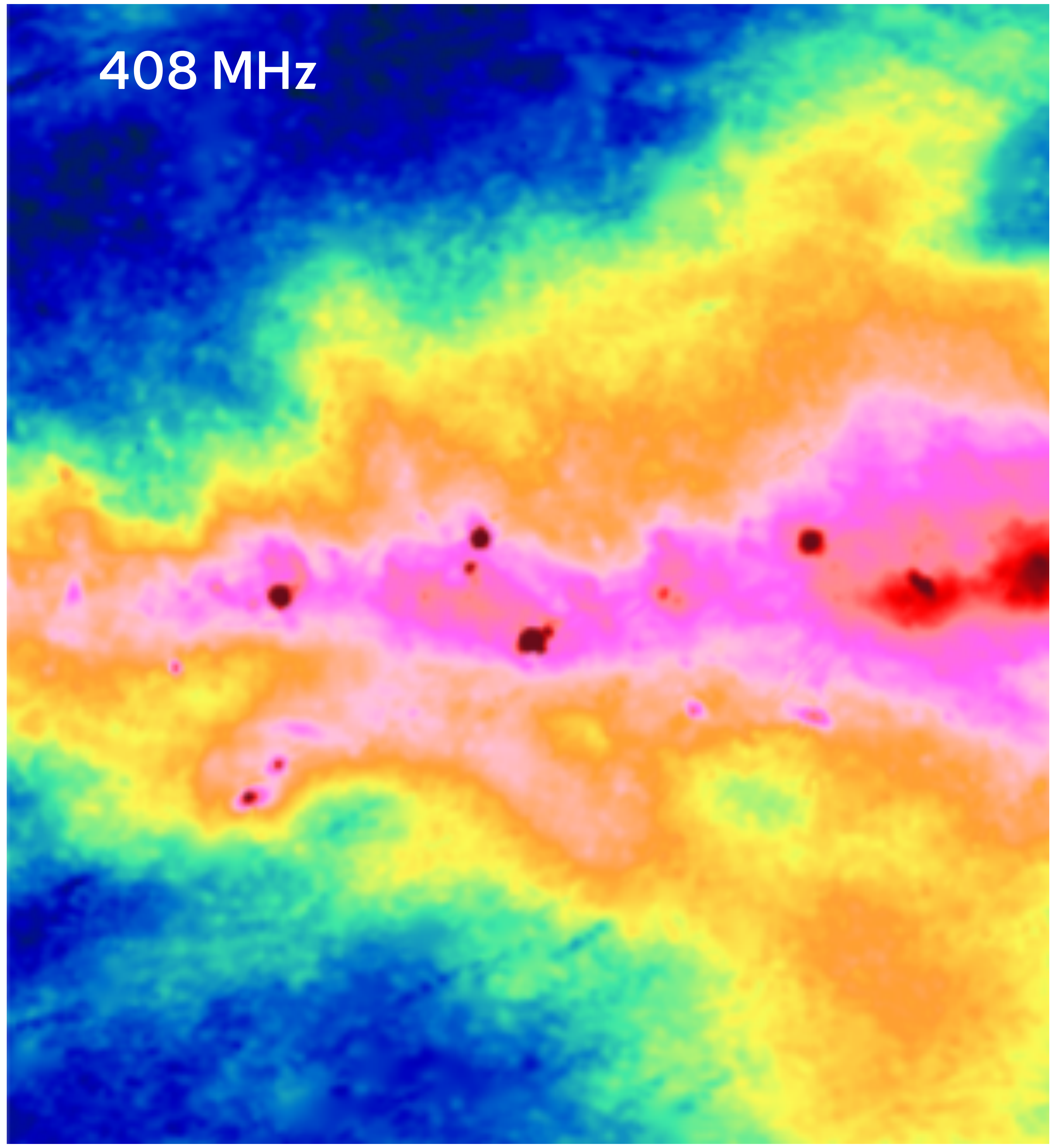
radio tracing difficulties

- $B_{ISM} \approx 2$ - 20 μG, ν_{radio} = 0.1-10 GHz => $0.1 \leqslant E_e \leqslant 50$ GeV in the unknown spectral range where significant change in slope
- $B_\perp$ variations along the line of sight and in the telescope beam

$$\text{if } n(E_e) = \kappa \left(\frac{E_e}{E_0}\right)^{-p}$$

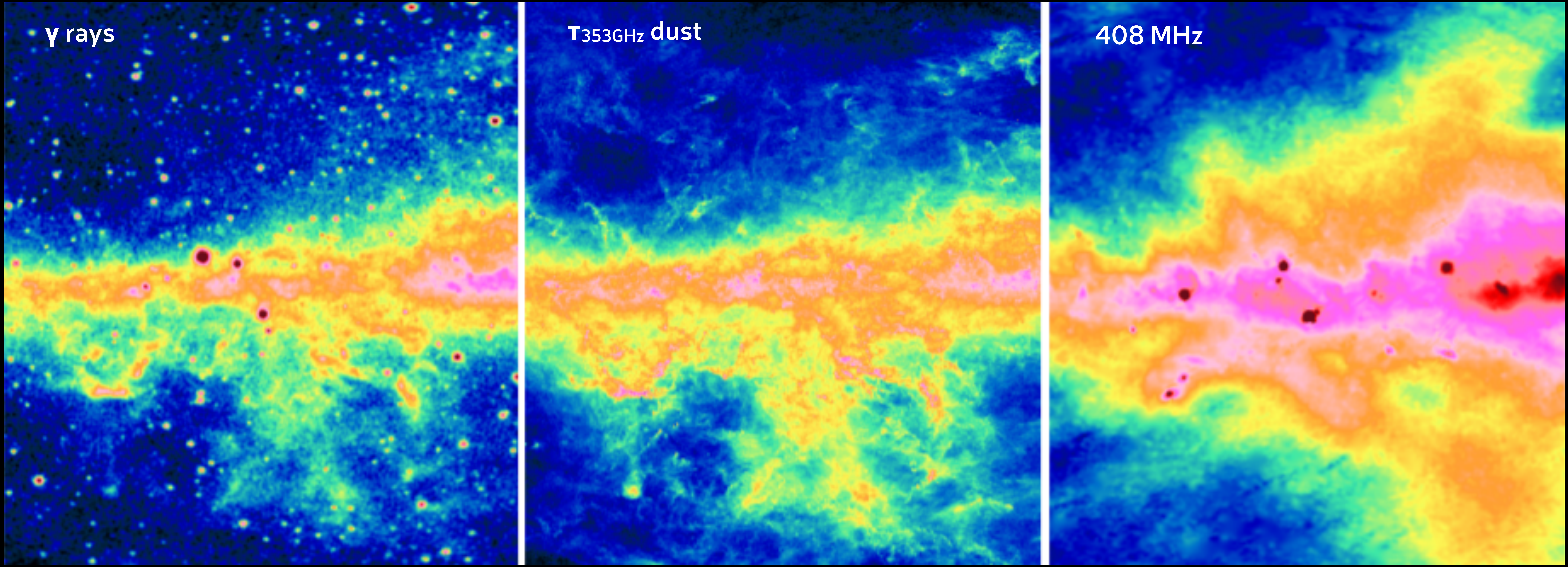
$$S_\nu \propto \int \kappa B^{\frac{1+p}{2}} \nu^{\frac{1-p}{2}} dl$$





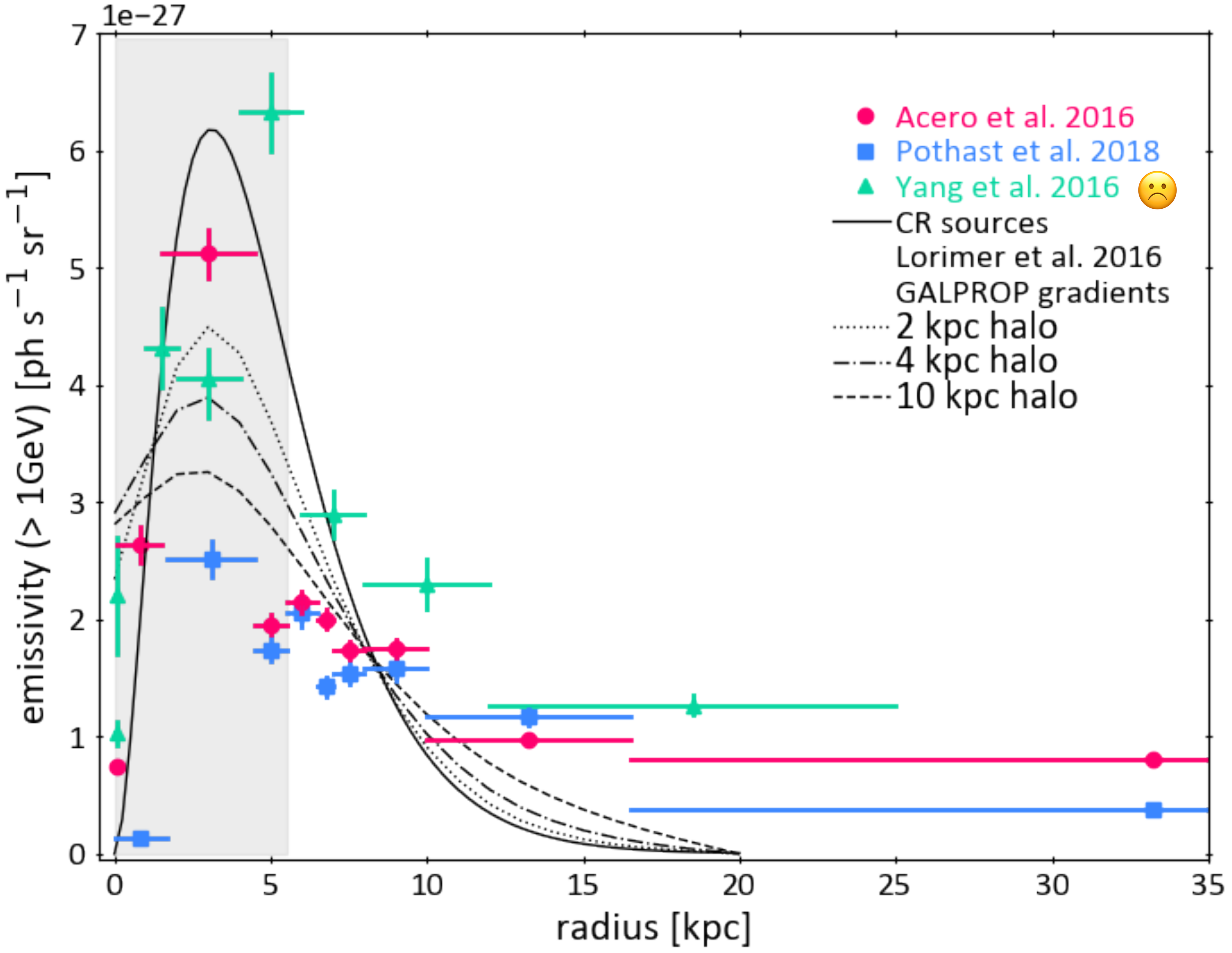
long-lived radio tracing problem

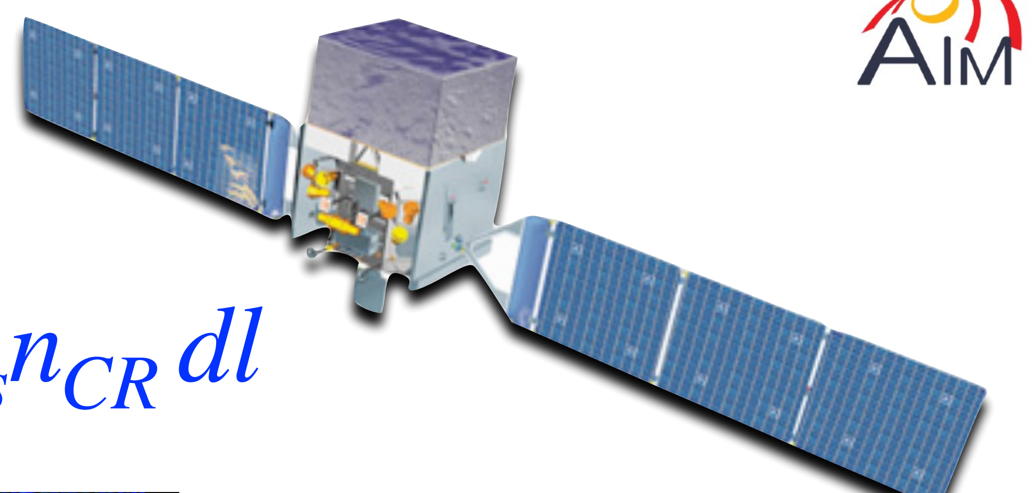
- collapse of “elongated” clouds along B with $h_{\|} > R_{\perp}$ and mass $M \propto \rho R^2 h$
  - virial equilibrium $c_s^2 \propto \Phi_g \propto \rho h^2$ and magnetic flux : $BR^2 = cte \Rightarrow B \propto c_s \rho^{1/2}$
  - equipartition between magnetic and kinetic (thermal+turbulent) energy densities : $\frac{B^2}{2\mu_0} \propto \rho \sigma_v^2 \Rightarrow B \propto \sigma_v \rho^{1/2}$
- why don’t we see the dense clouds in synchrotron emission ?



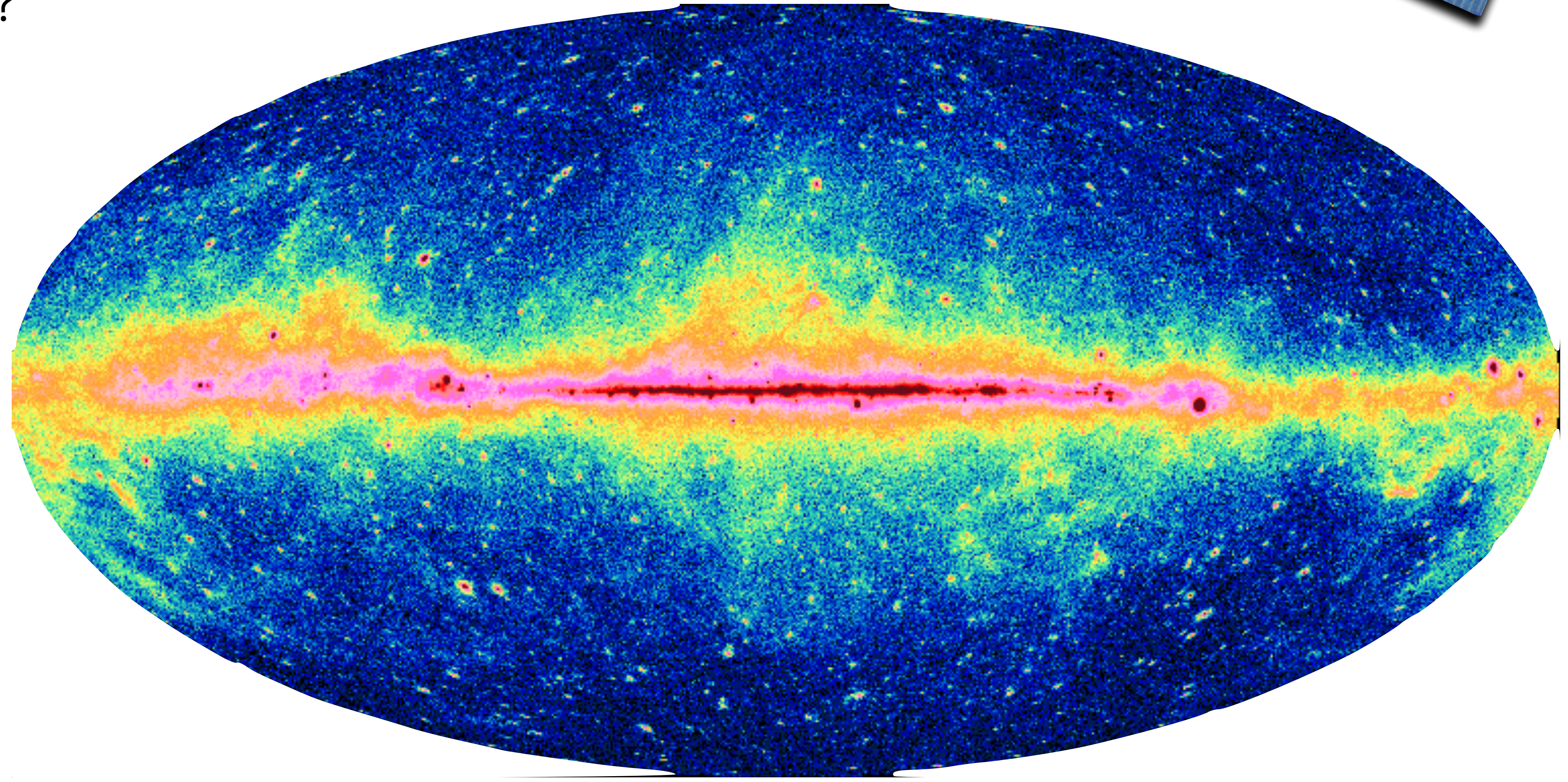
long-lived cosmic-ray radial gradient problem

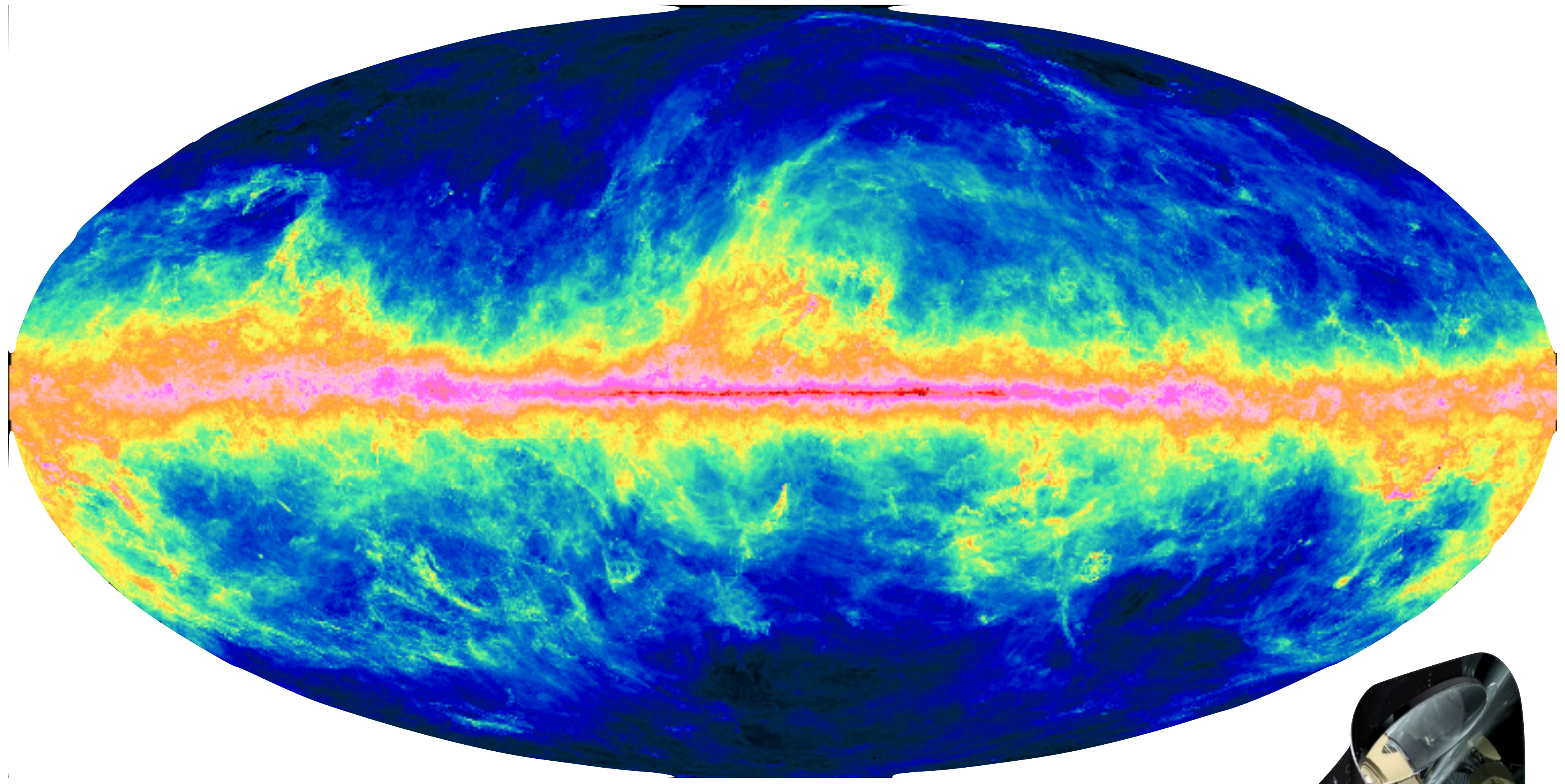
- few-GeV to TeV CR nuclei flux:
  - Galactic profile at variance with transport models
  - firm inference from the comparison between the dust & γ-ray skymaps
  - increased δB/B in spiral arms => smaller $\kappa_{//}$ and larger $\kappa_{\perp}$? large amount of outer-disc dark gas?



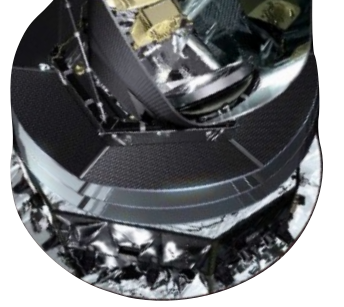


$$\int n_{gas} n_{CR}\, dl$$



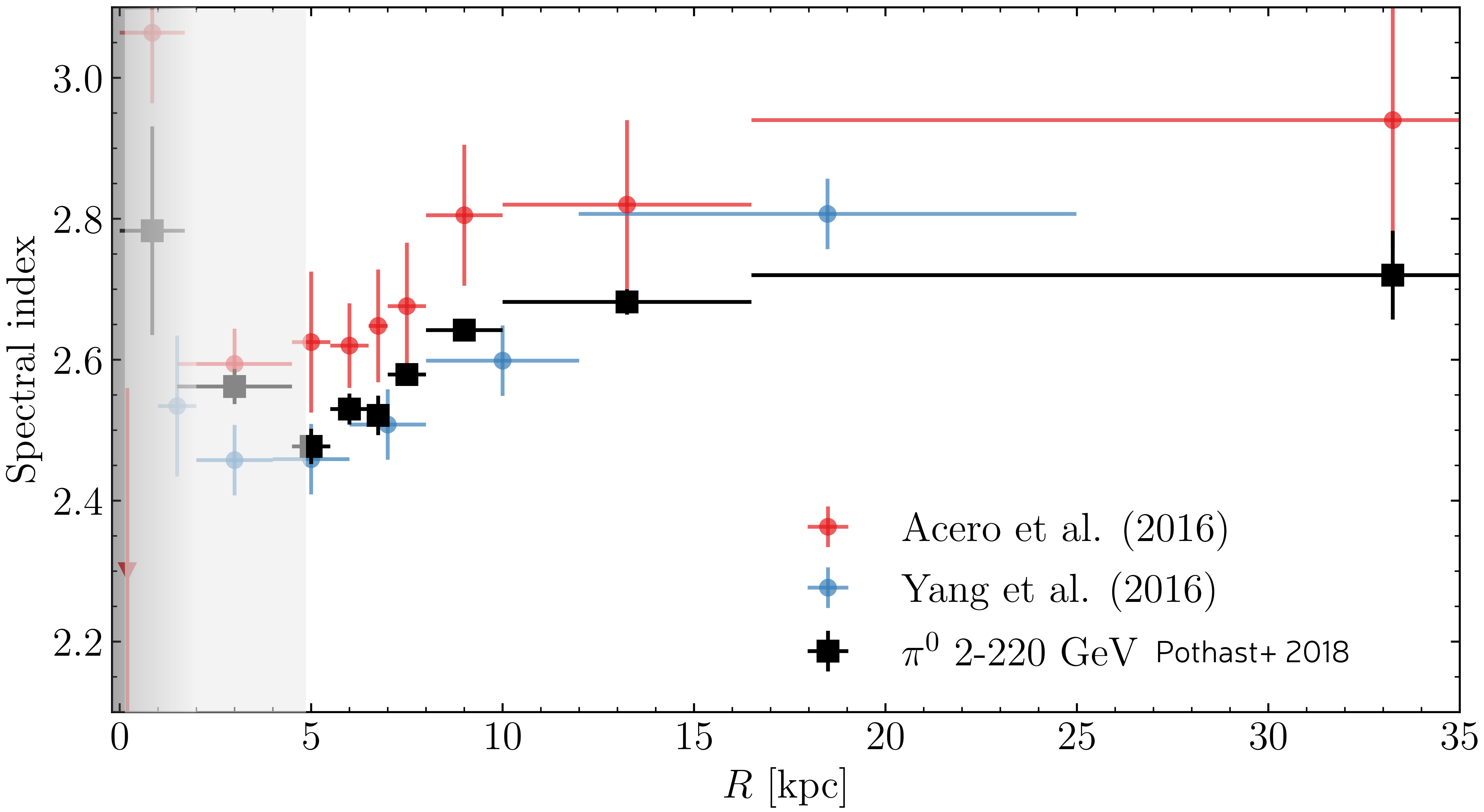


$$\int n_{gas} \frac{M_d}{M_{gas}} \kappa_0 \left(\frac{\nu}{\nu_0}\right)^{\beta} B_\nu(T_d)\, dl$$

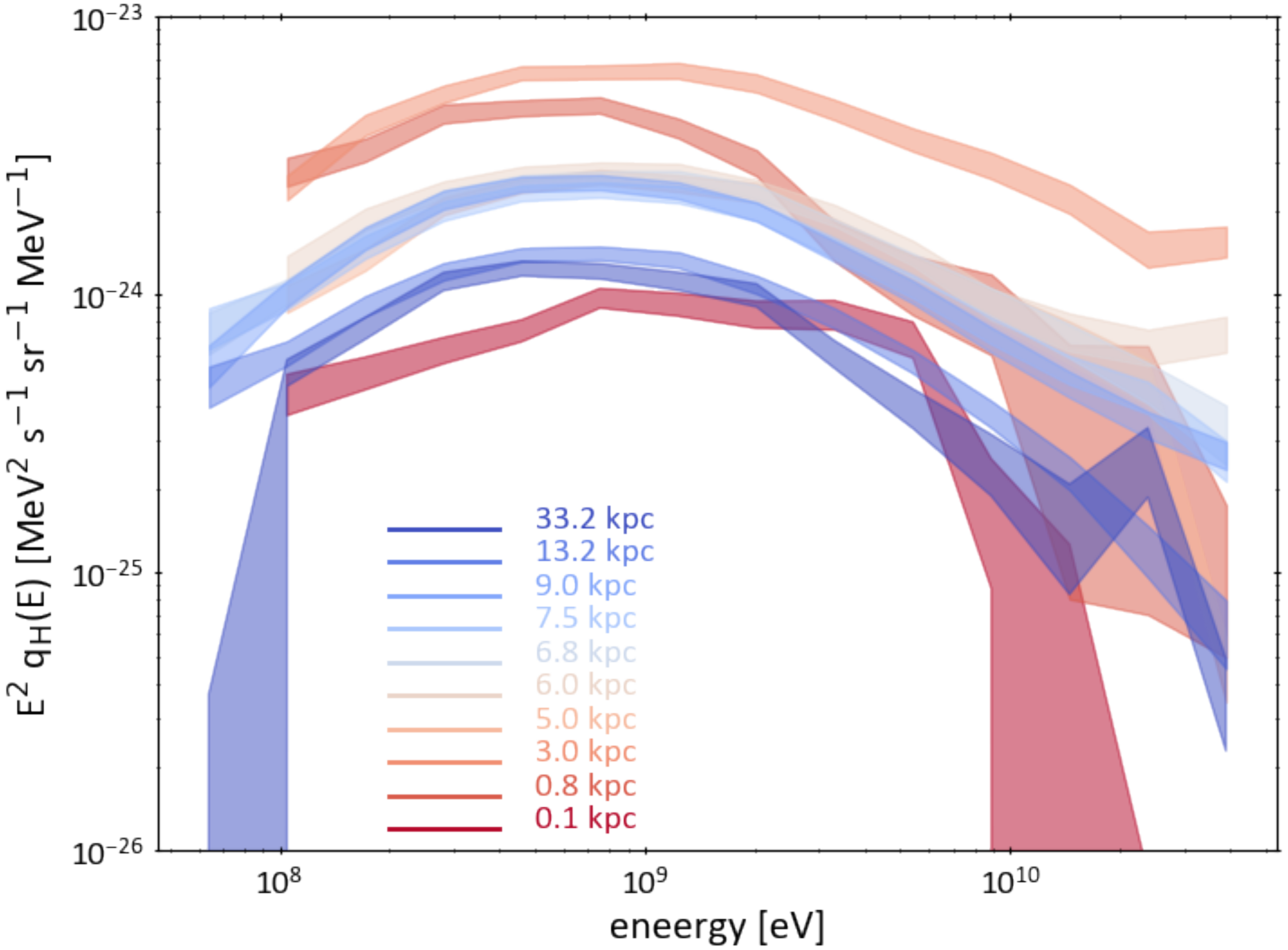


cosmic-ray spectral gradient ?

- slight hardening in the inner Galaxy ?
  - source contamination? target gas closer to CR sources?
  - more advection (wind) less diffusion, D(R, B(R)) variations?
  - diffuse emission modelling too smooth?



Acero+2016



don't bet yet on CR hardening in the molecular ring

cosmic-ray vertical gradient

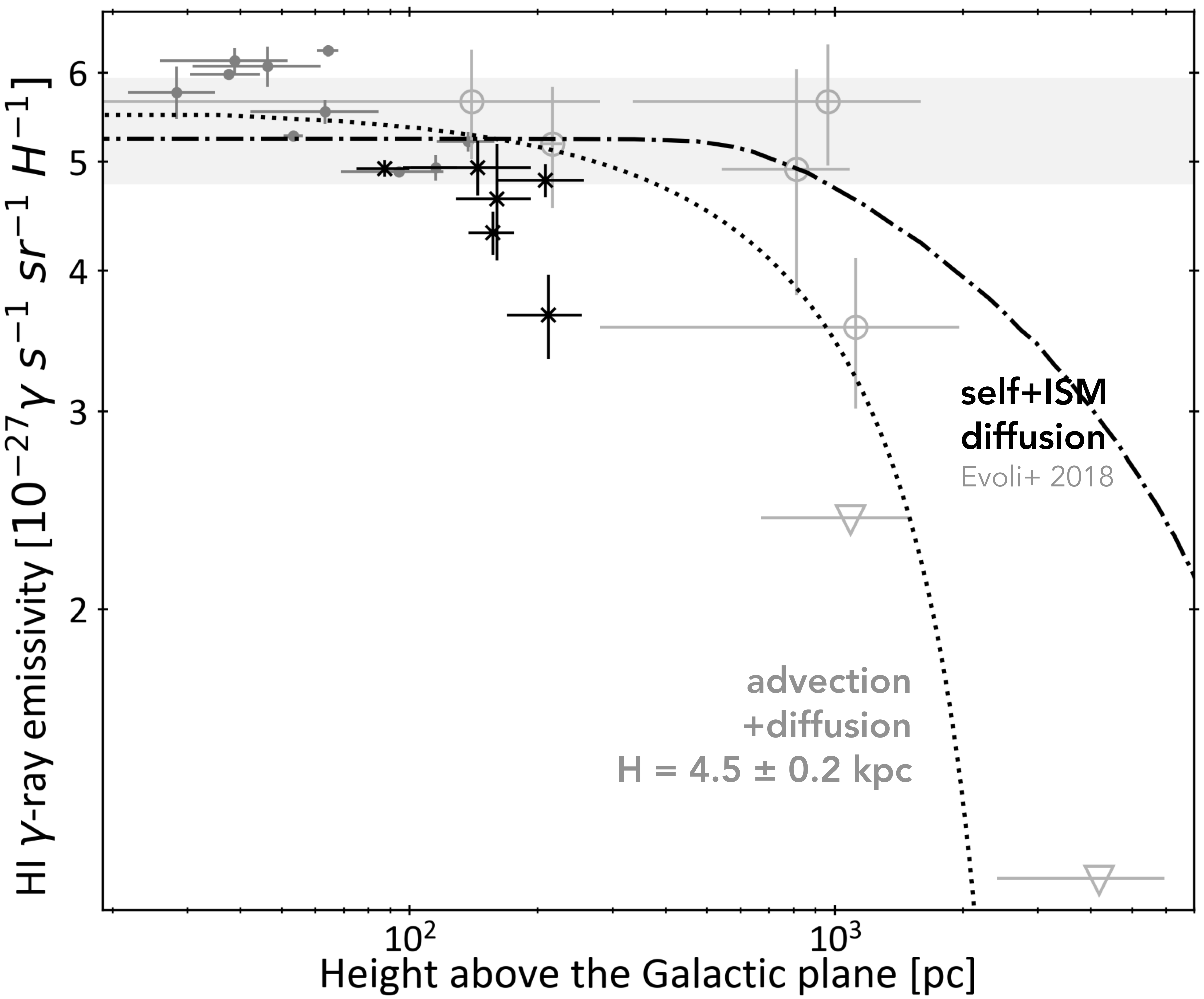
- γ-ray measurements of the local CR flux with height
  - 1D curve advection+diffusion : H = 4.5 ± 0.2 kpc Joubaud+20
- AMS-02 2nd/1ary spectra
  - USINE modelling with advection+reaccel+diffusion or pure diffusion H = 5 $^{+3}_{-2}$ kpc Weinrich+20
  - DRAGON modelling H = 7.5 $^{+1.13}_{-0.95}$ kpc de la Torre Luque+22
- transport changes with height above the Galactic disc?

important assessment for vertical gas outflows in galaxy evolution

above a reasonably quiet disc : hopefully

wind in the central regions : extreme challenge

Joubaud+20



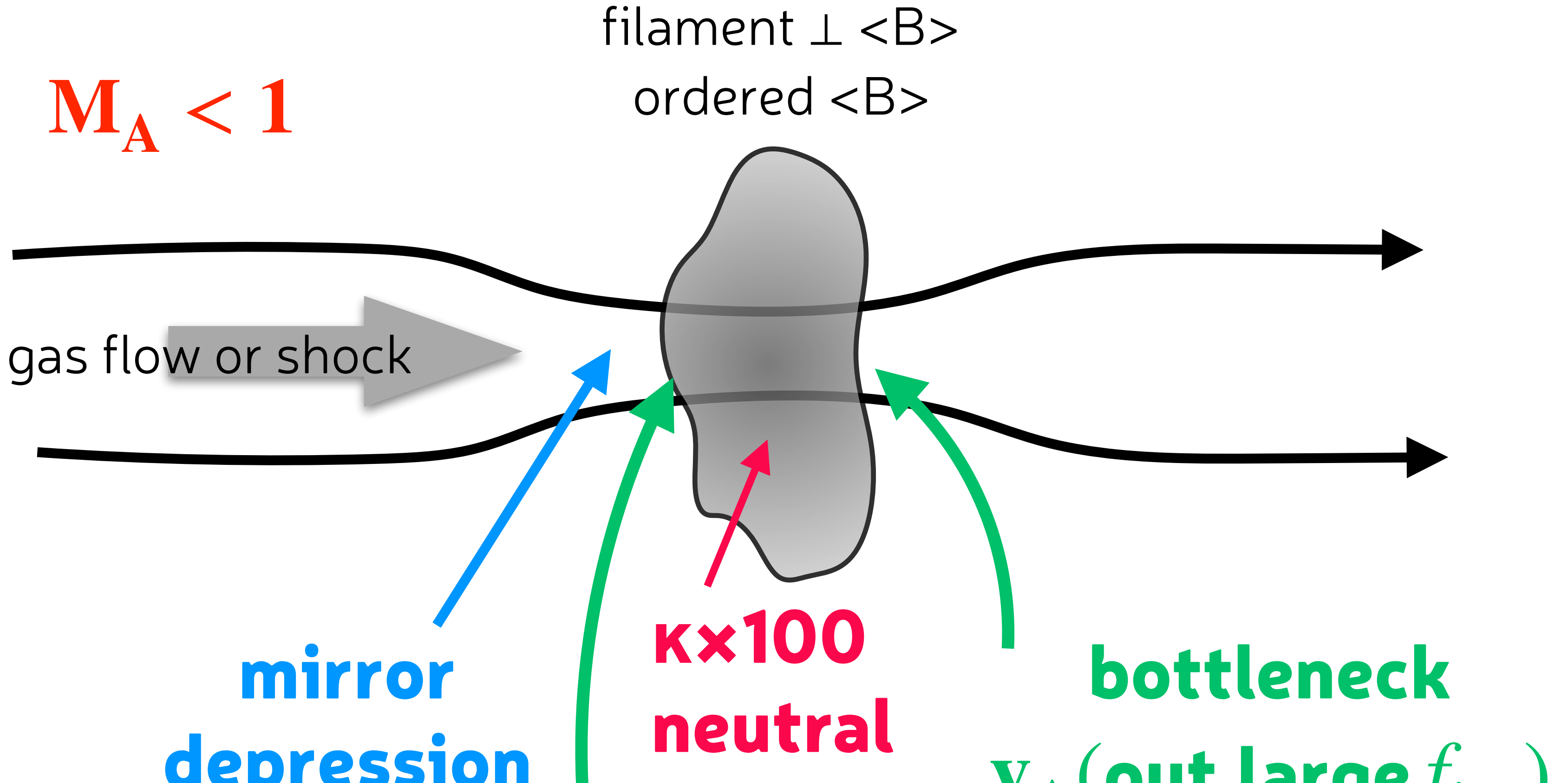
CR obstacle course in clouds

$\boxed{\beta = P_{th}/P_B = 3}$

- gas filament alignment // B lines in diffuse HI
- B turns to ⊥ or mess in dense gas

Planck 2016 XXXV

- obstacle course
  if self-excited diffusion



$M_A < 1$

filament ⊥ <B>
ordered <B>

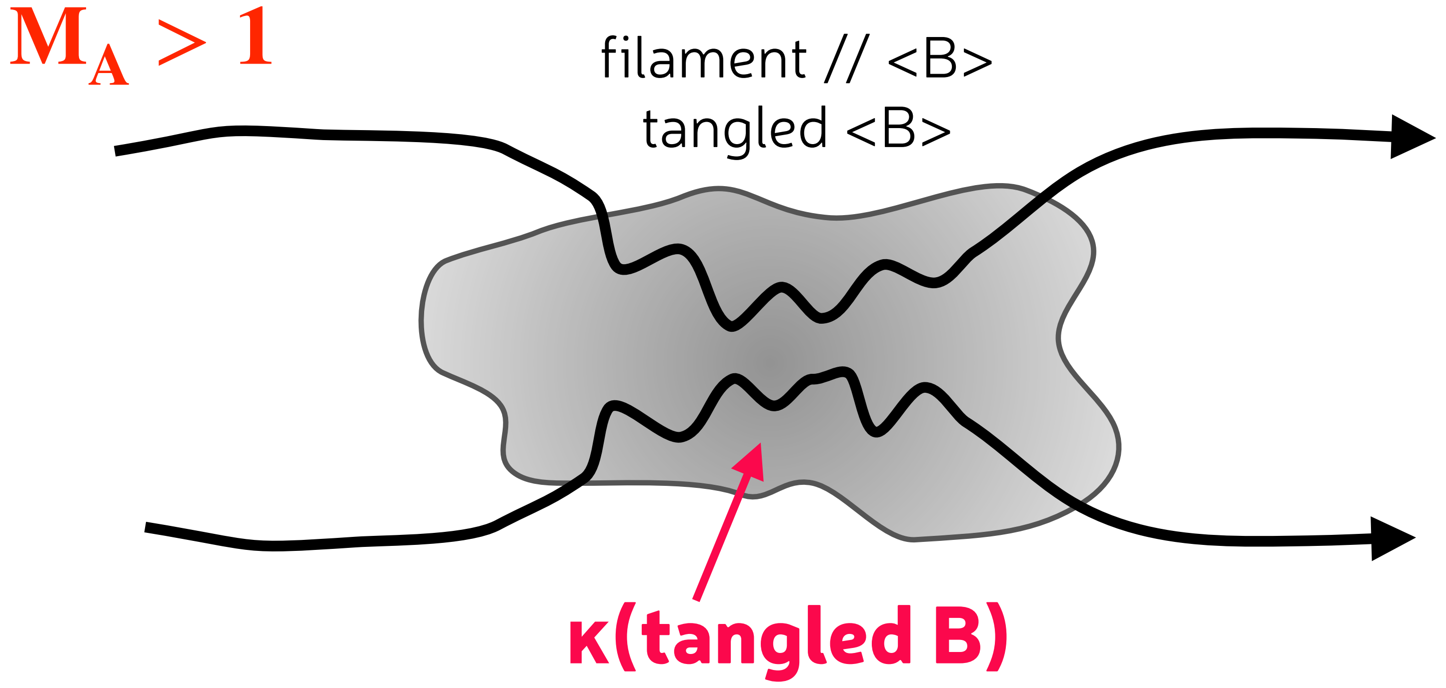
gas flow or shock

mirror depression

κ×100 neutral damping

bottleneck
$v_A(\text{out,large } f_{ion}) < v_A(\text{in, low } f_{ion})$

bottleneck
$v_A \downarrow$ as $\rho \uparrow \uparrow$ $x_{ion} \downarrow$



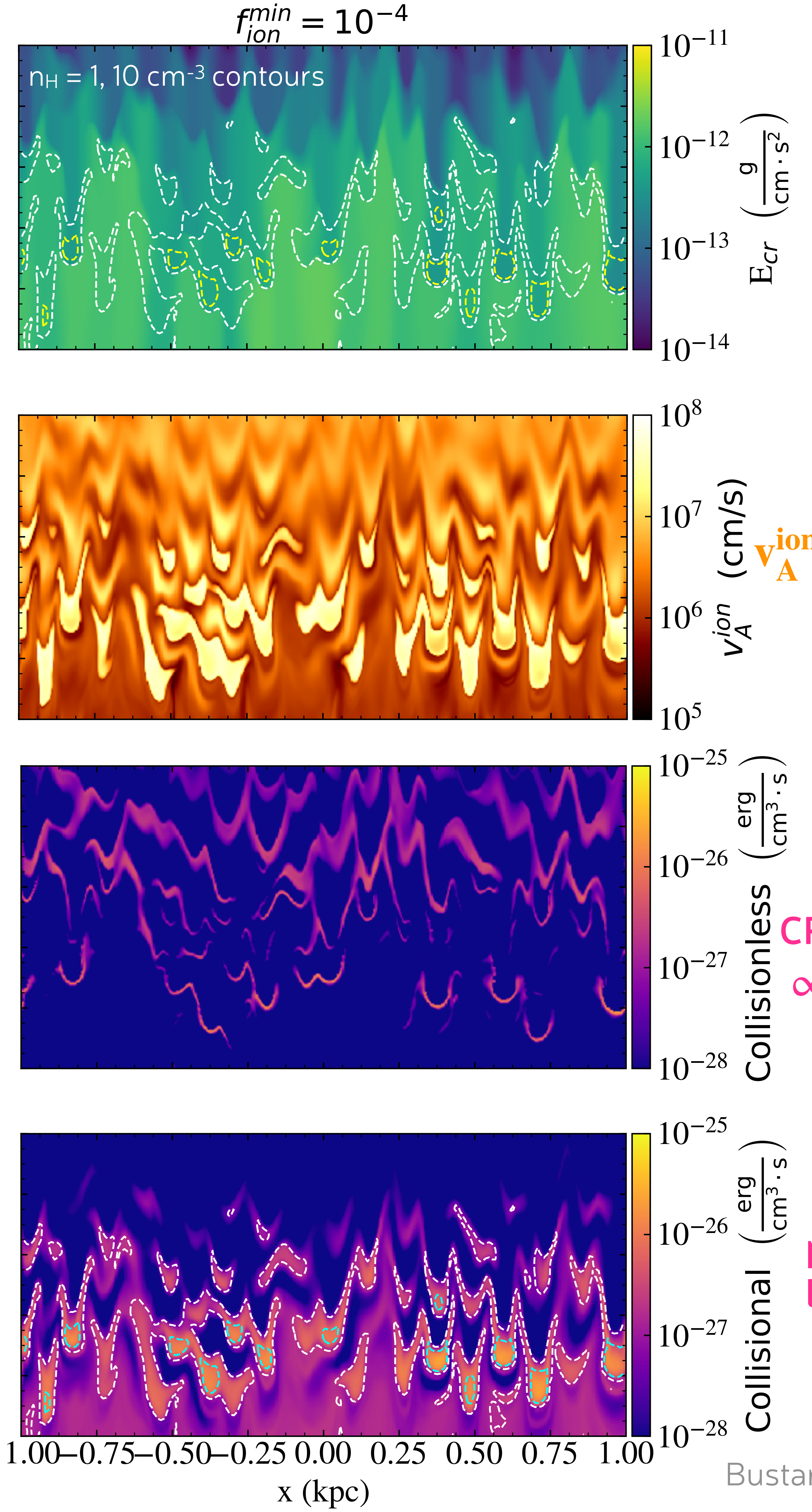
$M_A > 1$

filament // <B>
tangled <B>

κ(tangled B)

- **1 GeV CR shadows**
  - CR loss < factor 2 to 5
  - large <B>-dependent factors
  - if plasma $\beta = P_{th}/P_B \gg 1$ B lines are draped around the dense clouds and most CRs follow the inter-cloud "escape" ways
- energy-dependent shadows/enhancements
  - should **vanish above several GeV in energy**

Cesarsky & Völk 1978.
Skilling & Strong 1976
Schlickeiser et al. 2016
Bustard & Zweibel 2021



CR flux shadows at 1 GeV

$$v_A^{ion} = \frac{B}{\sqrt{4\pi\rho_{ion}}}$$

add dust charges !

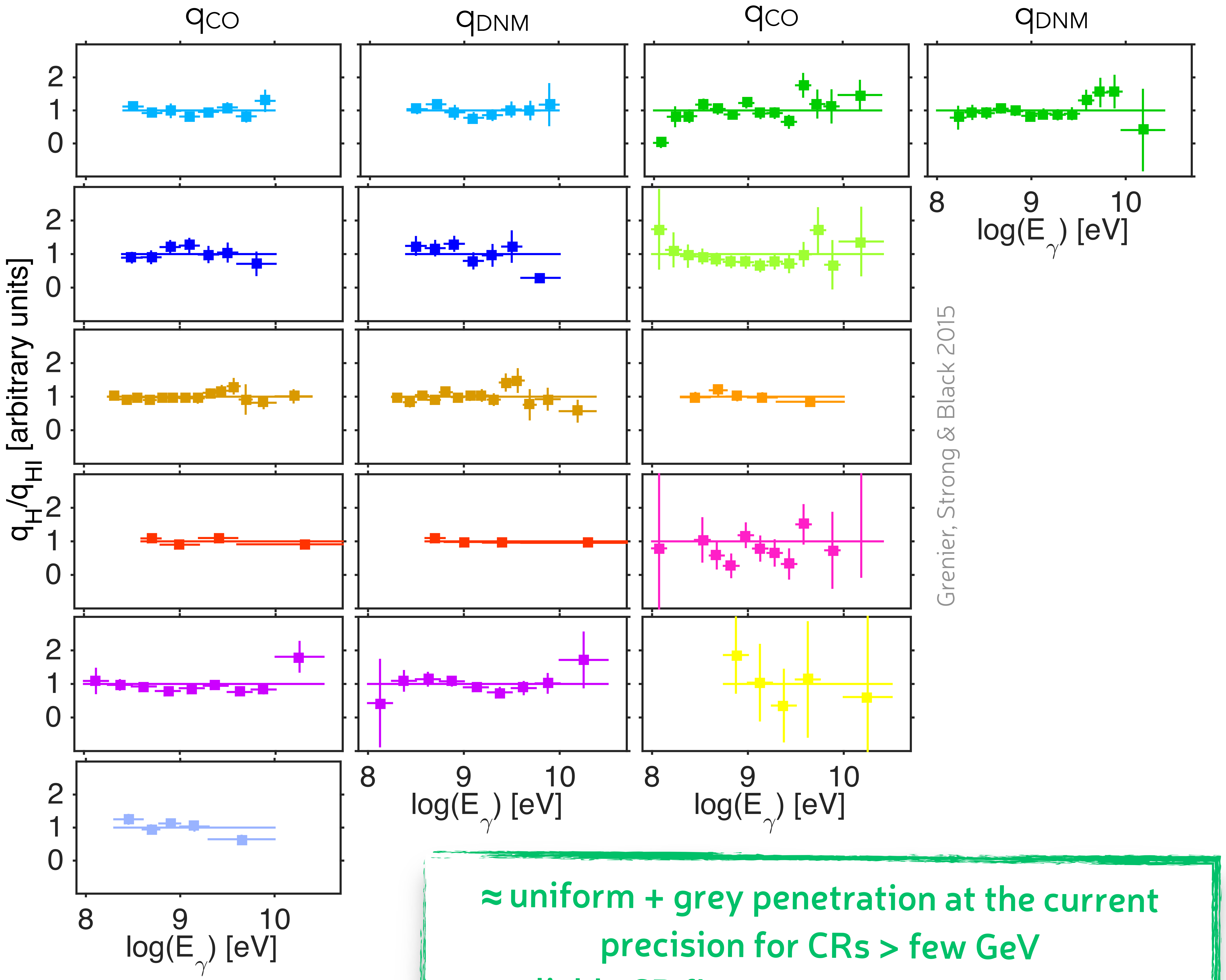
CR loss to waves
$\propto v_A^{ion} \cdot \nabla_{\parallel} P_{CR}$

pp+Coulomb losses
$\propto e_{CR}\, n_{gas}$

Bustard & Zweibel 2021

penetration of few-GeV-TeV cosmic rays inside clouds

- obs: no spectral deviations seen across the HI, DNM, and H_2 gas phases down to pc scale

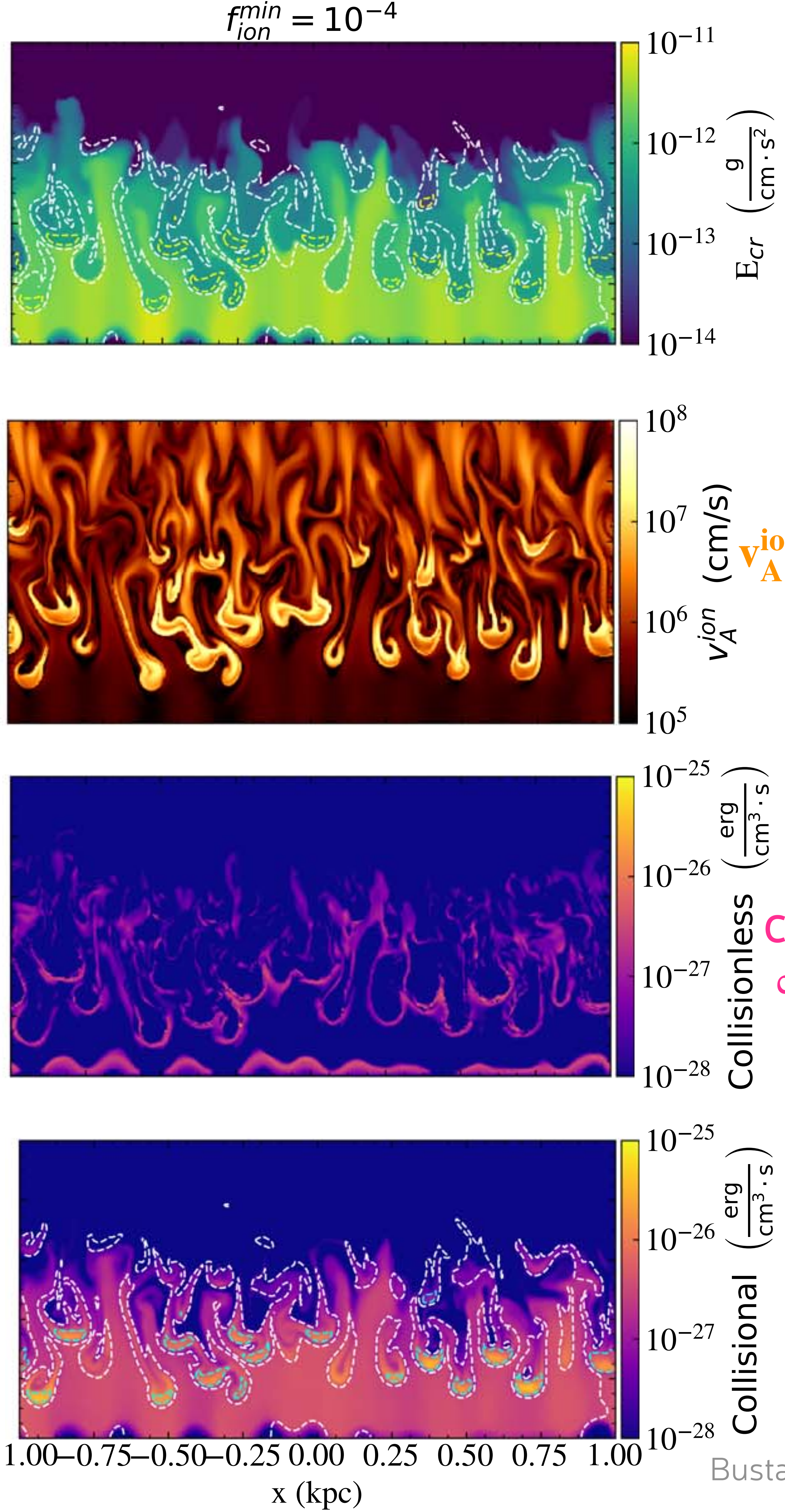


Grenier, Strong & Black 2015

≈ uniform + grey penetration at the current precision for CRs > few GeV

=> reliable CR flux measurements in the HI gas

$\beta = P_{th}/P_B = 75$



CR flux shadows at 1 GeV

$$v_A^{ion} = \frac{B}{\sqrt{4\pi\rho_{ion}}}$$

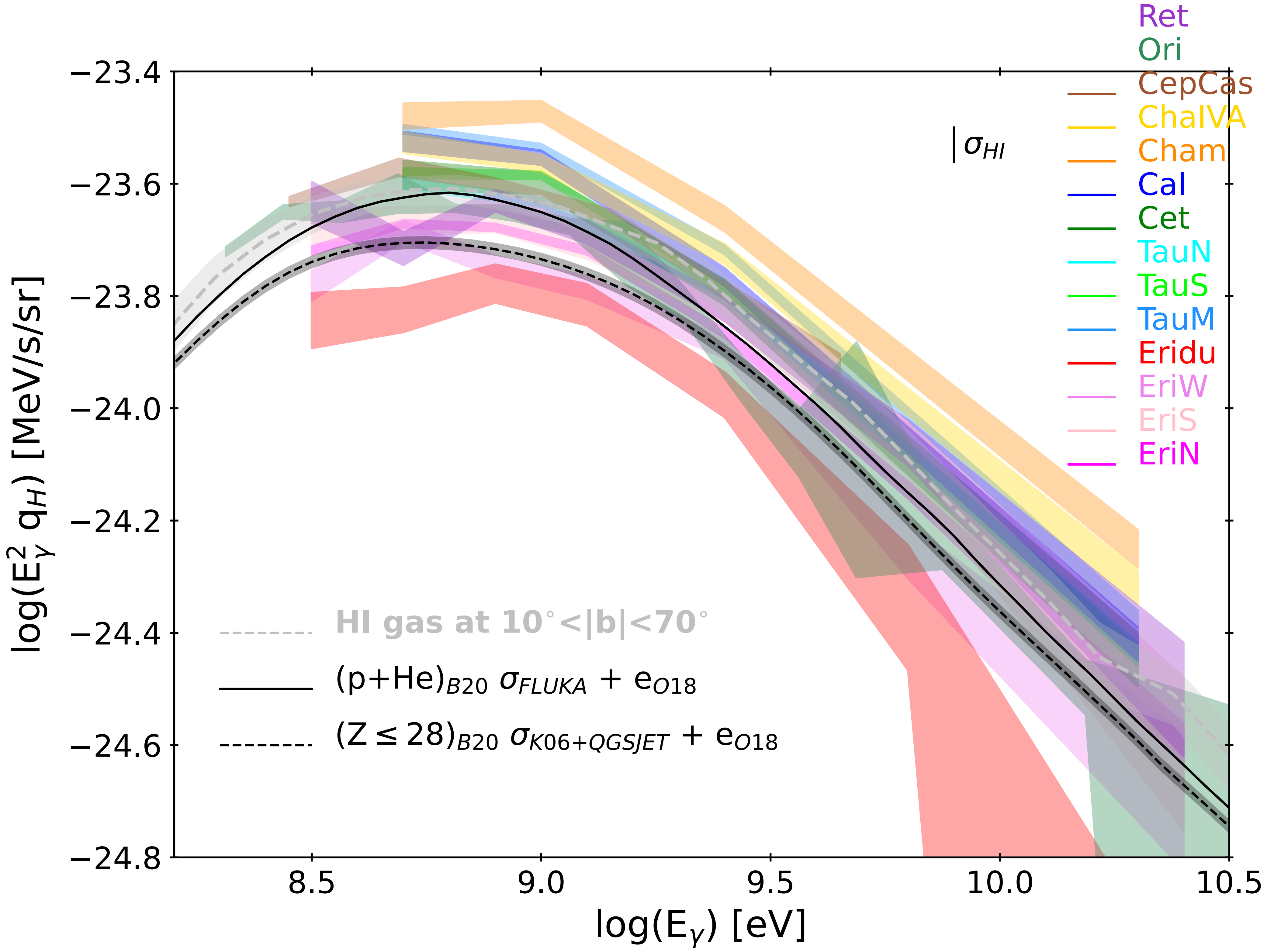
add dust charges !

CR loss to waves $\propto v_A^{ion} \cdot \nabla_{\parallel} P_{CR}$

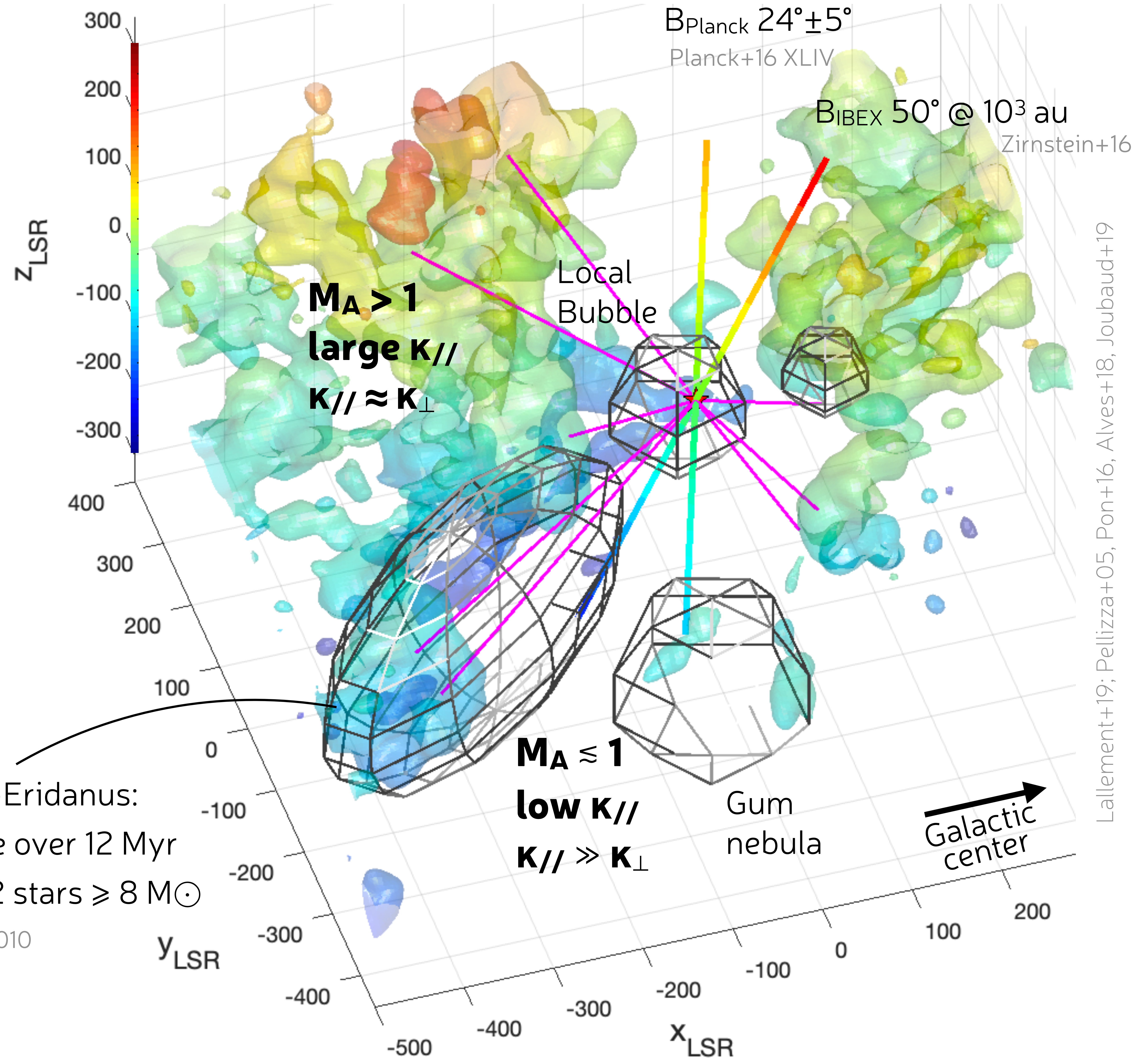
pp+Coulomb losses $\propto e_{CR}\, n_{gas}$

Bustard & Zweibel 2021

cosmic-ray uniformity in the Local Valley



CR flux in the local ISM
= near the heliosphere?
why only small differences in flux?
why no change in spectrum?



B_{Planck} 24°±5°
Planck+16 XLIV

B_{IBEX} 50° @ 10^3 au
Zirnstein+16

$M_A > 1$
large $\kappa_{//}$
$\kappa_{//} \approx \kappa_\perp$

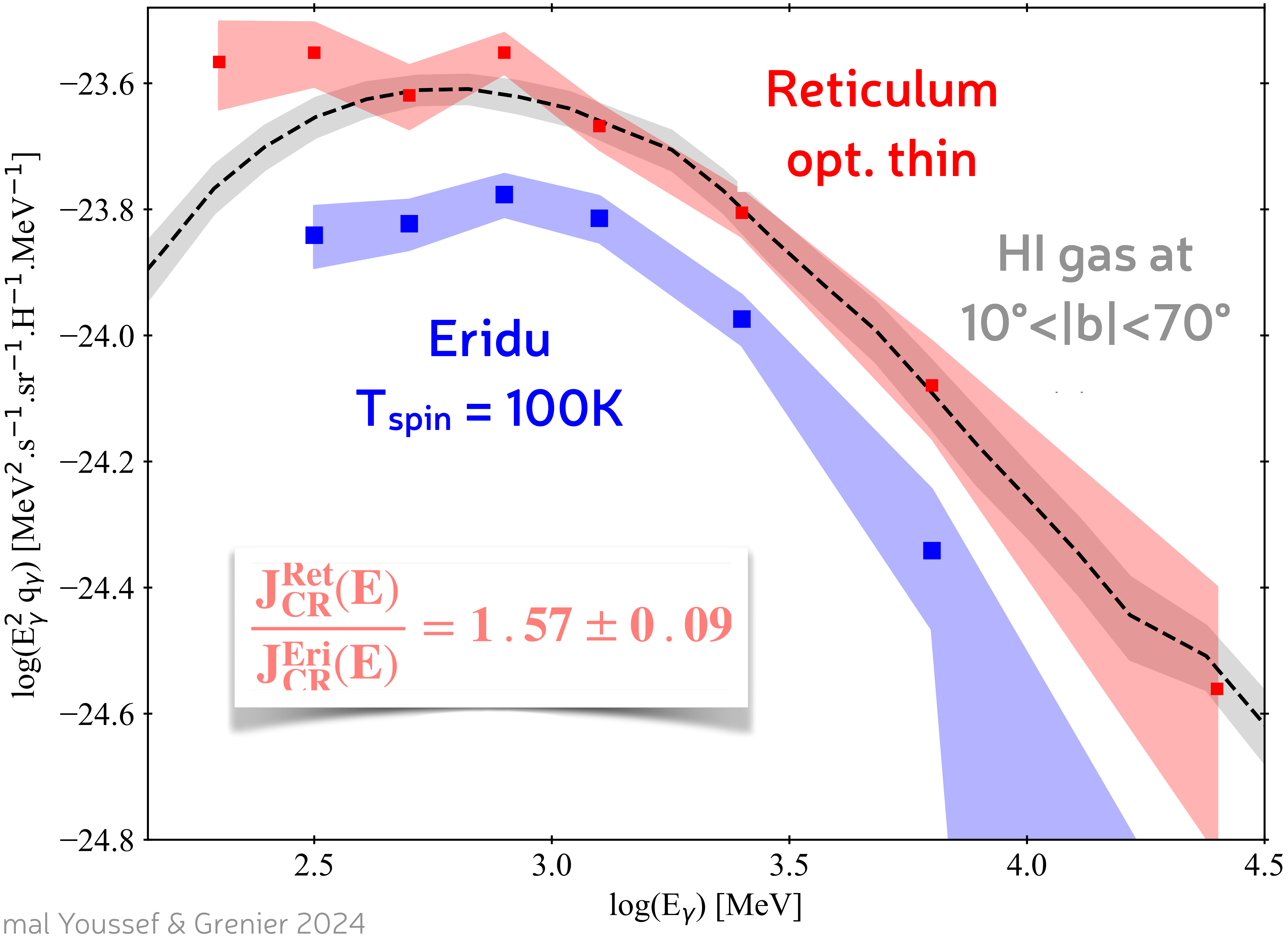
$M_A \lesssim 1$
low $\kappa_{//}$
$\kappa_{//} \gg \kappa_\perp$

Orion-Eridanus:
10 SNe over 12 Myr
still 62 stars ⩾ 8 M☉
Voss+ 2010

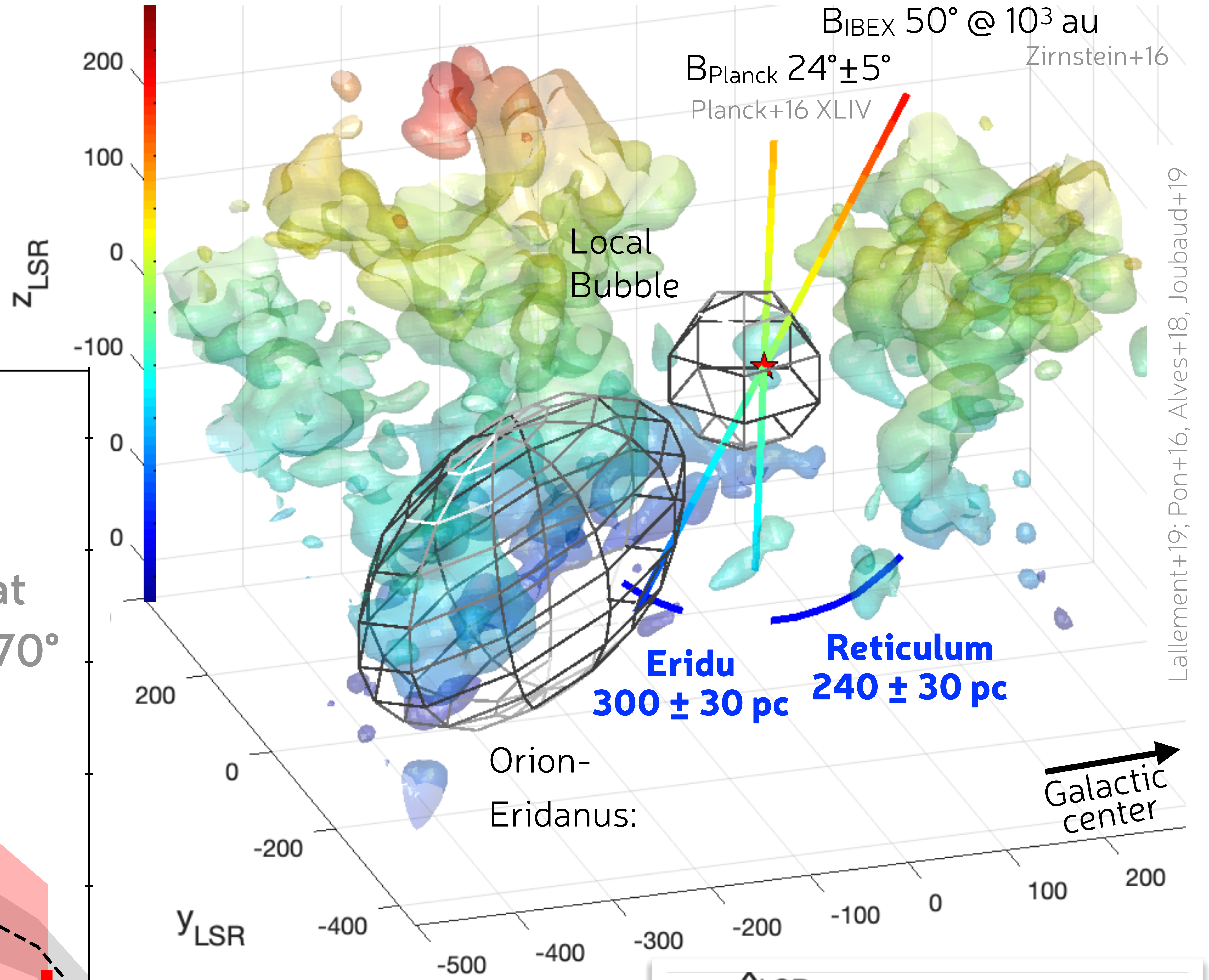
Lallement+19, Pellizza+05, Pon+16, Alves+18, Joubaud+19

a local cosmic-ray puzzle

- γ-ray emissivity from CR interactions **per gas nucleon** in Reticulum consistent with the local average over a few 100 pc



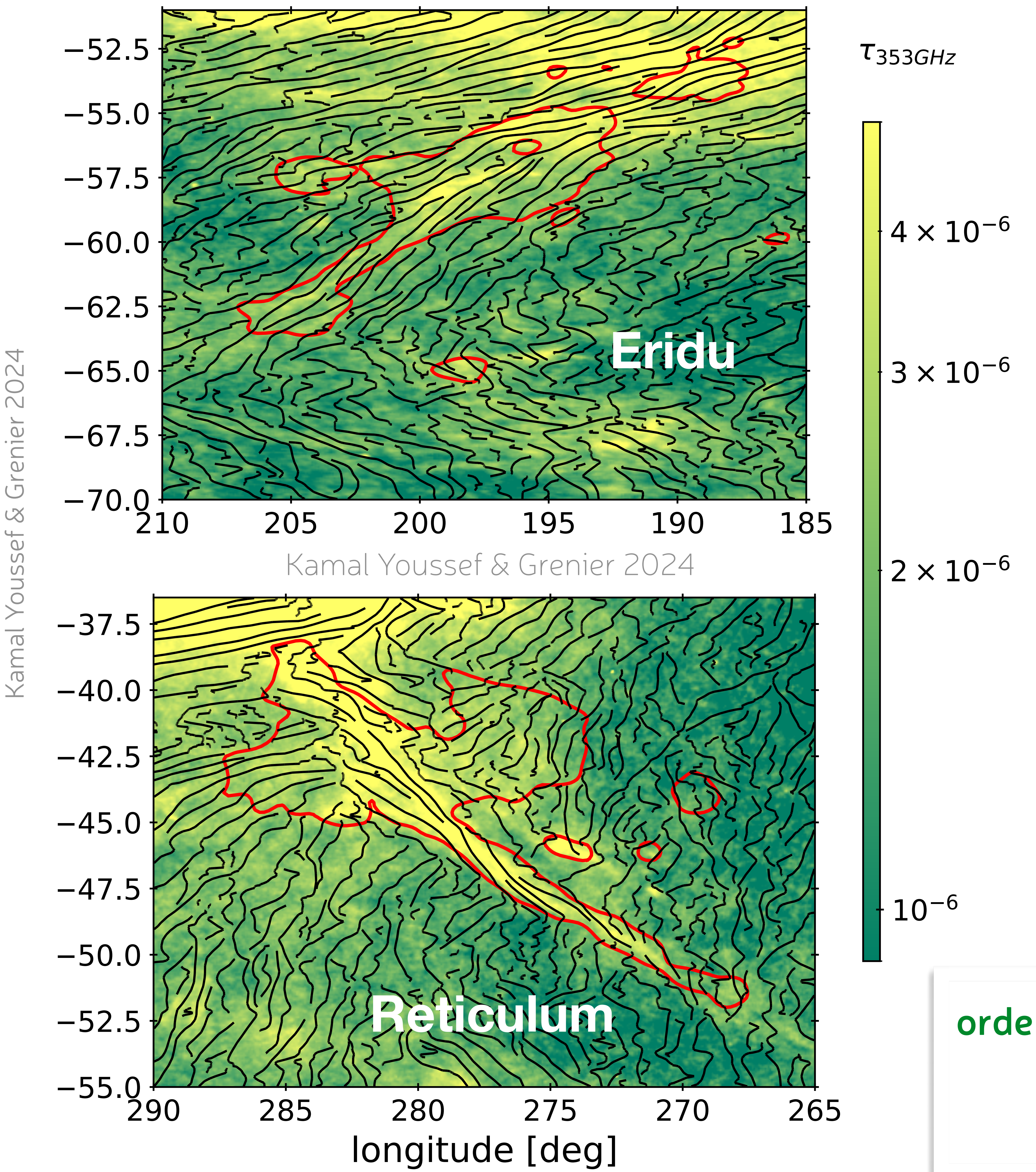
Kamal Youssef & Grenier 2024



Lallement+19; Pon+16, Alves+18, Joubaud+19

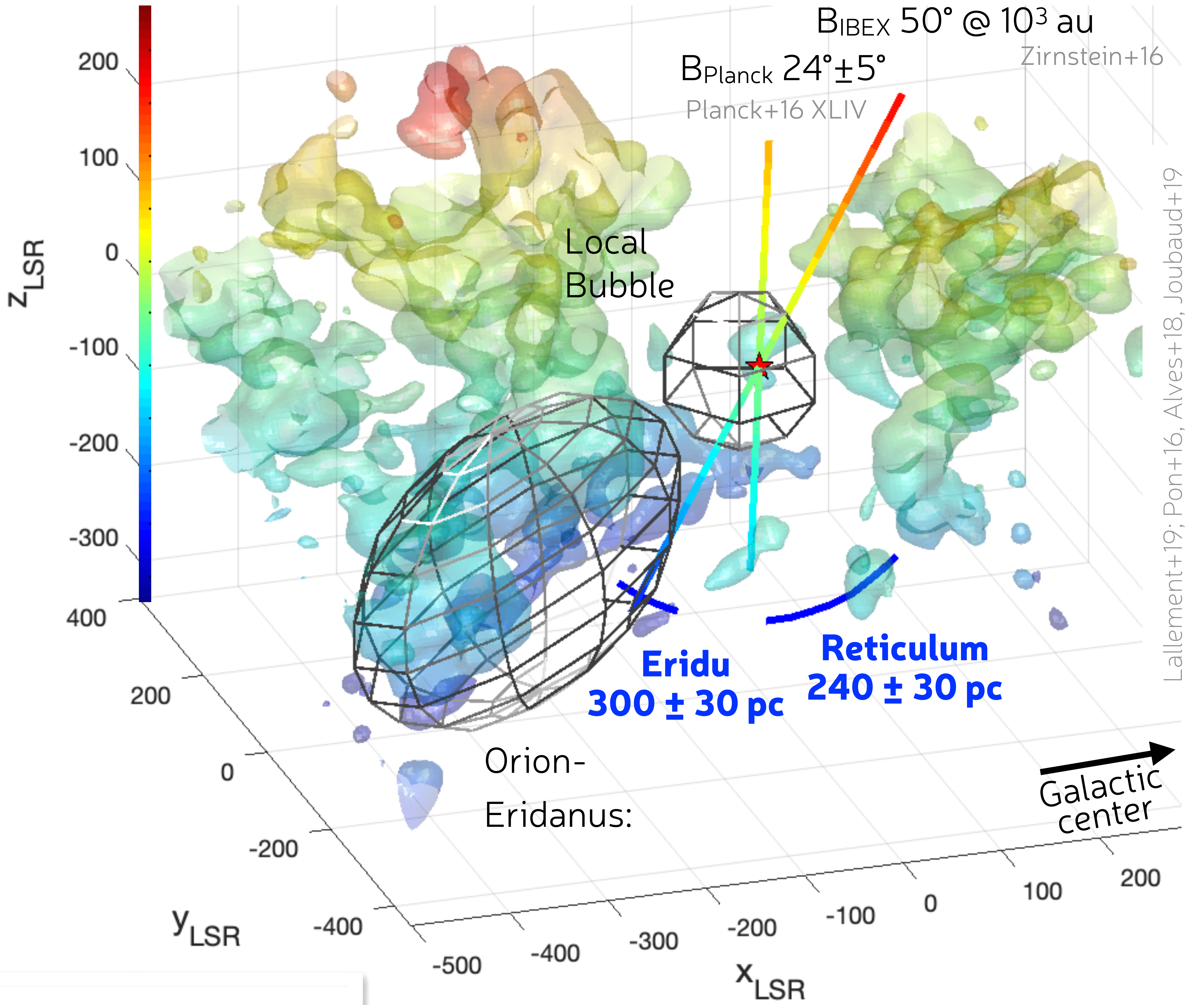
extending
across the Local Valley
along B tubes
quasi perpendicular to B_{LIMF}

two comparable HI filaments



Kamal Youssef & Grenier 2024

Kamal Youssef & Grenier 2024



Lallement+19; Pon+16, Alves+18, Joubaud+19

ordered ($\delta\psi \lesssim 10° - 15°$)

$B_{sky} \approx$ 1 - 4 μG

in both clouds

two comparable HI filaments

- on 1 pc scale

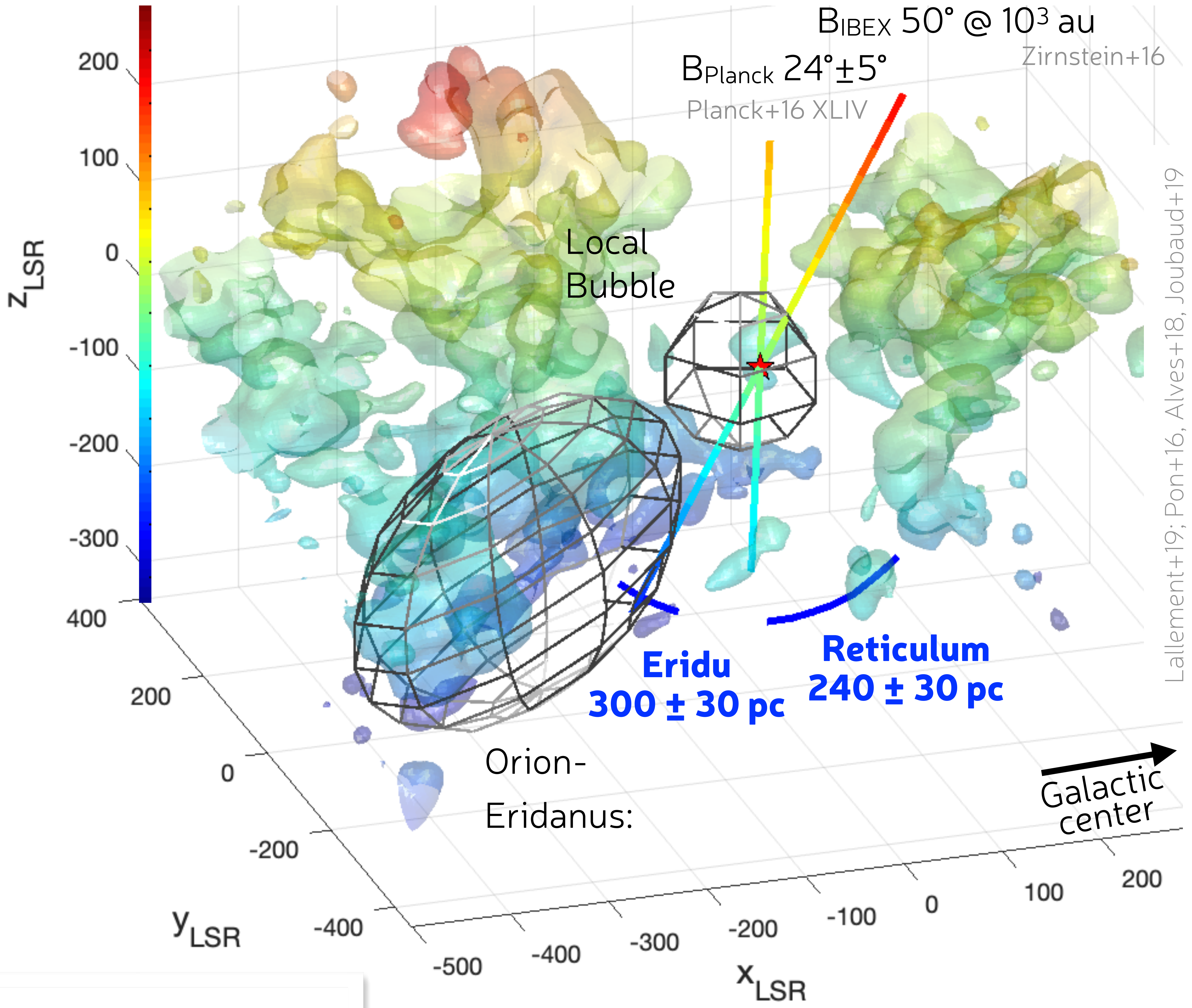
Eridu
WNM + LNM
Reticulum
WNM + CNM + DNM

similar
pressure balance
$p_{therm}/p_B \approx 0.3 - 3$
in both clouds

$\delta v_{Eri} \approx 2\, \delta v_{Ret}$
but same trans-sonic
turbulence along
the core of both clouds

same $\kappa_{//}$ of few 10^{28} cm^2/s
in both clouds if self-streaming
little change from edge to core

Kamal Youssef & Grenier 2024

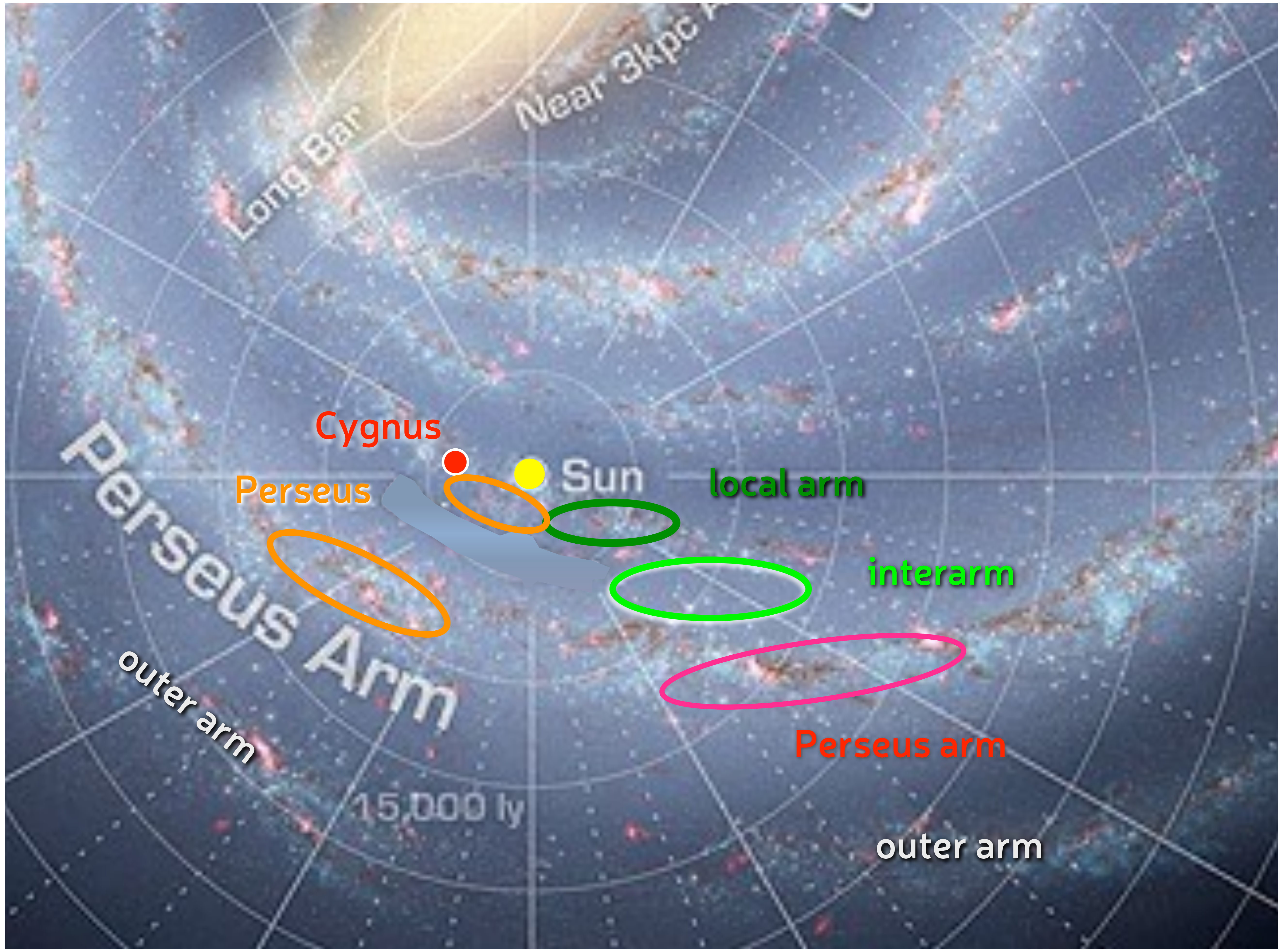


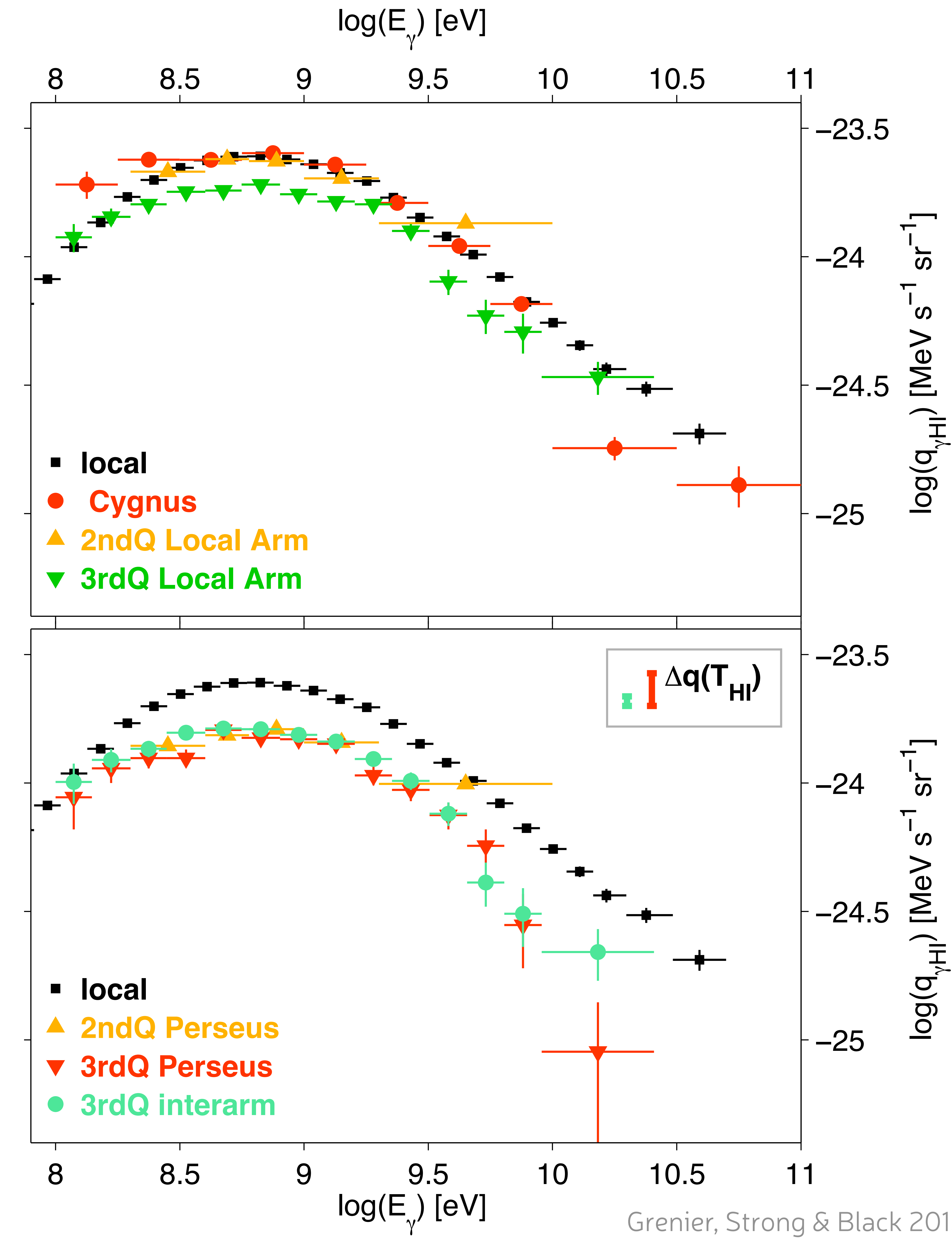
Lallement+19; Pon+16, Alves+18, Joubaud+19

ordered ($\delta\psi \lesssim 10° - 15°$)
$B_{sky} \approx 1 - 4\ \mu G$
in both clouds

no clear contrast with star formation activity

- super-Alfvénic arm (tangled B, isotropic κ) vs interarm sub-Alfvénic (stiff B, anisotropic κ)
- more supernova sources
  - yet same average spectrum …





Grenier, Strong & Black 2015

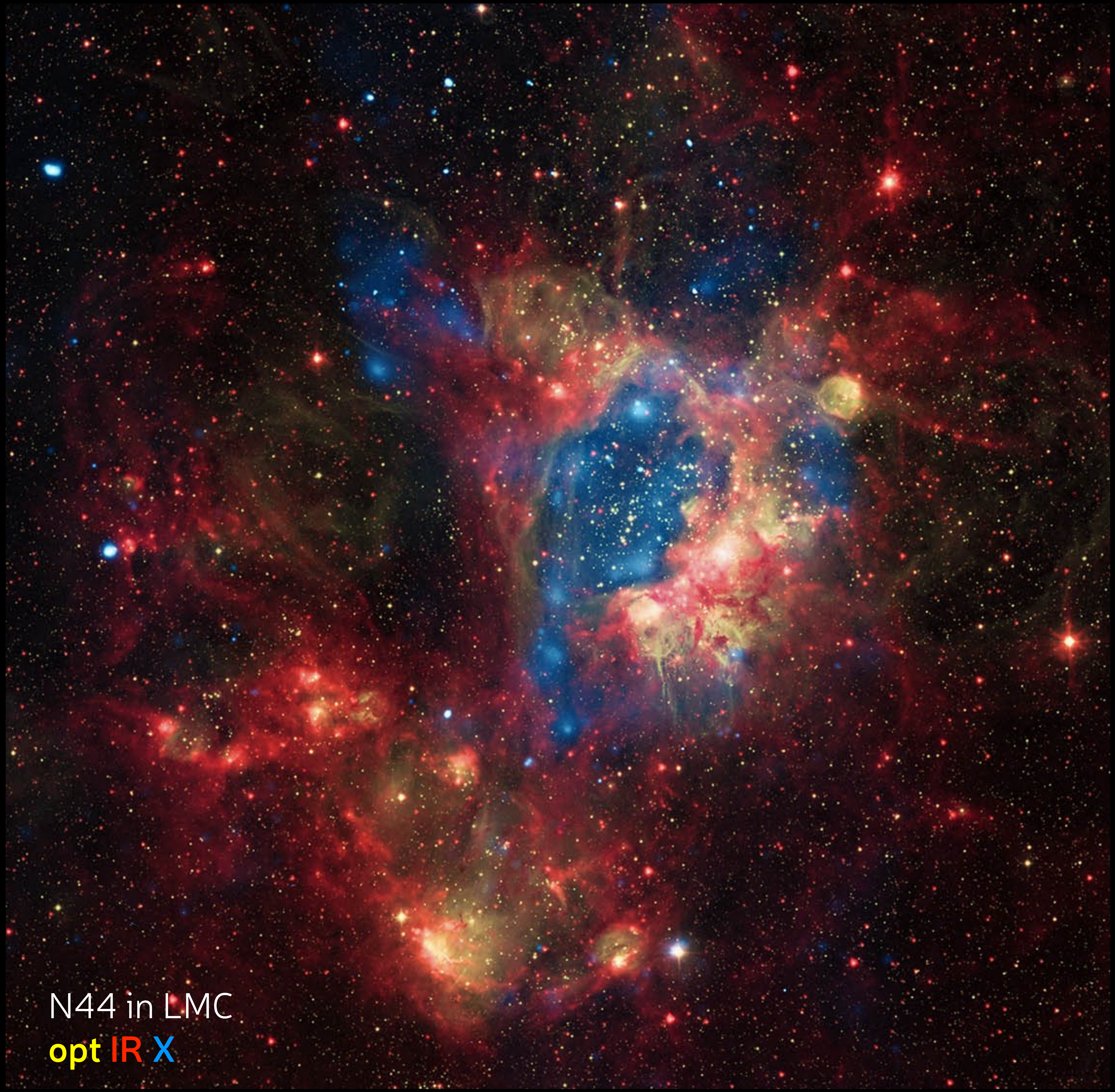
bubbling cosmic-ray nurseries

- Fermi I acceleration by a series (in space & time) of SN shock waves
- Fermi II re-acceleration by stellar winds and reflected shocks
- expansion losses & radiative losses

- CR composition =>

19^{+11}_{-6} % of accelerated nuclei from OB+SN ejecta
+ 81 % accelerated from ISM gas

Murphy+2016



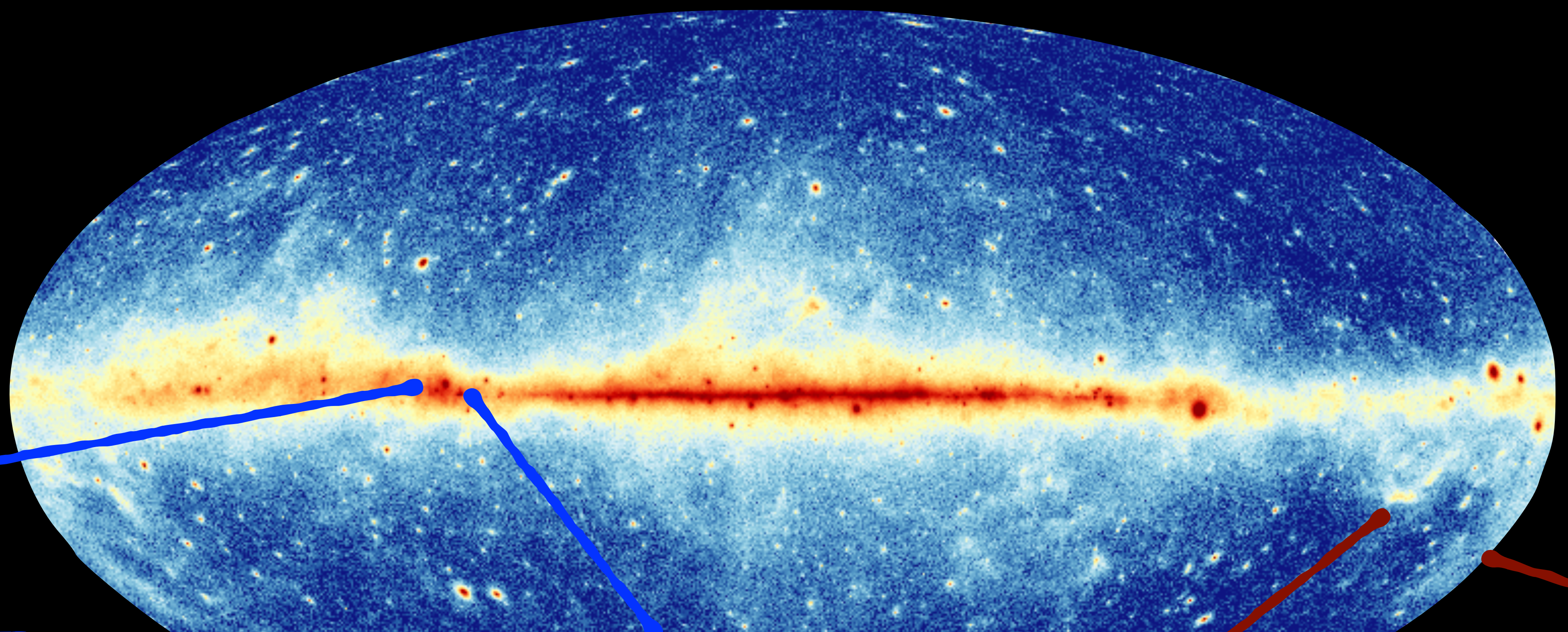
N44 in LMC
opt IR X

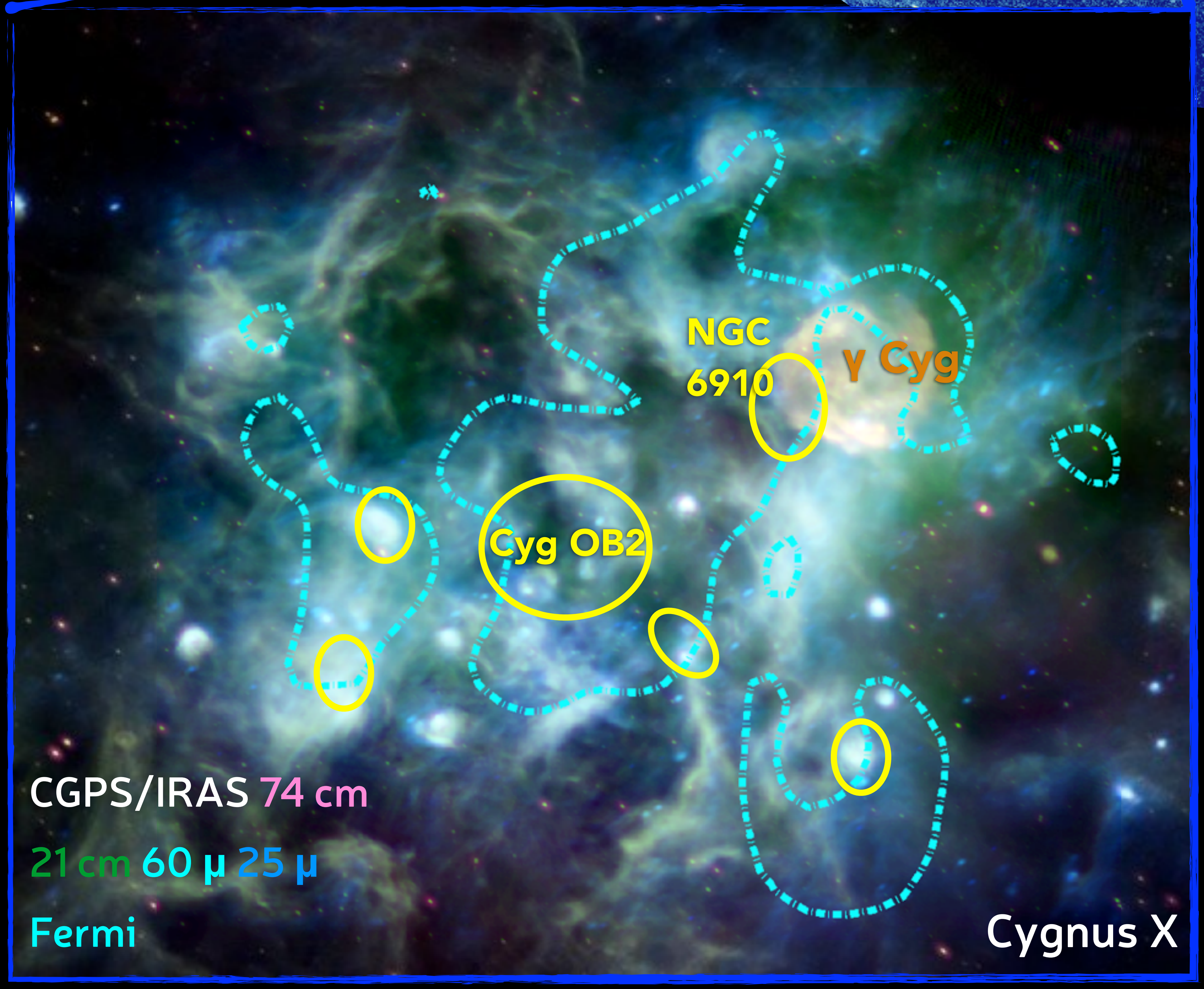
Enrico Fermi and Frank Capra 1957: A strange case of cosmic rays

two cases of bubbling cosmic-ray nurseries

- resolved in γ rays

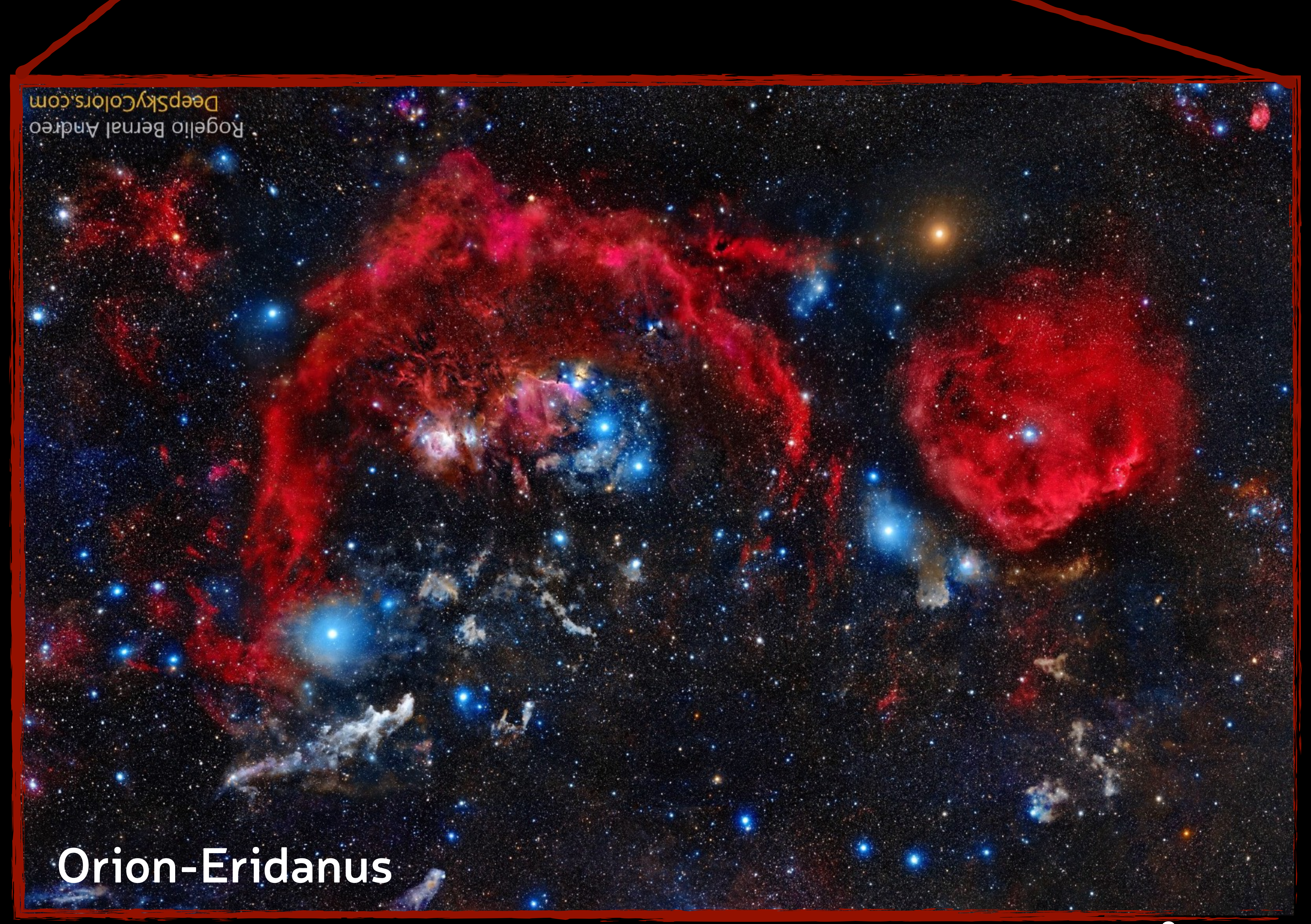
	OB stars	SN/Myr	R [pc]
Cyg X	143	6	50
Eridanus	62 +48	1	100





Ackermann+ 2011

hard γ rays, $E_{CR}^{-2.4}$ κ(E)≈ $\kappa_{ISM}/100$?



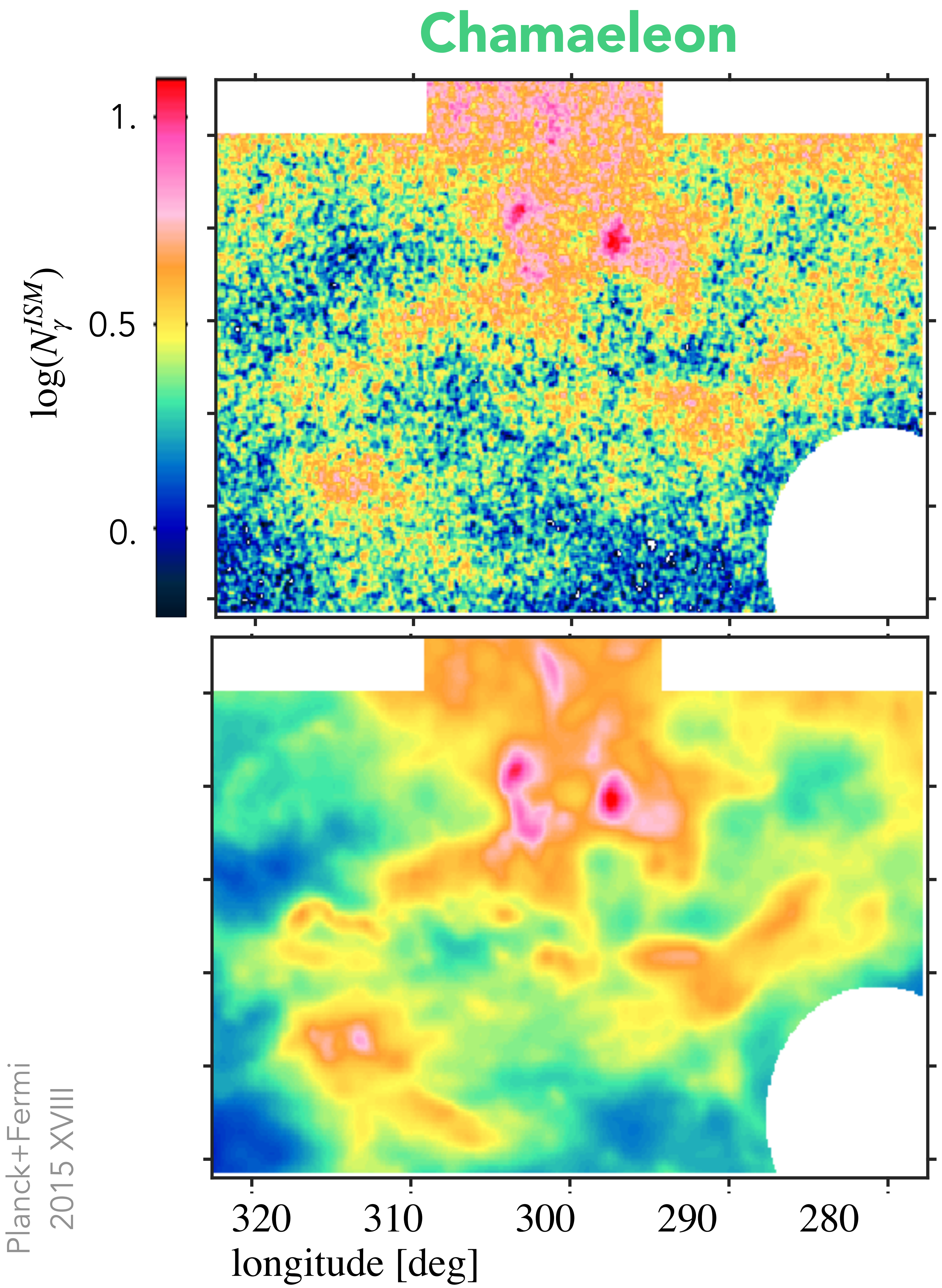
Joubaud+ 2020

no hard γ rays, $E_{CR}^{-2.7}$ $\Rightarrow \delta B_k^2 \propto k^{-5/3}$ or $\delta B_k^2 \propto k^{-3/2}$ & $\dfrac{\delta B_k^2}{B^2} < 30\%$

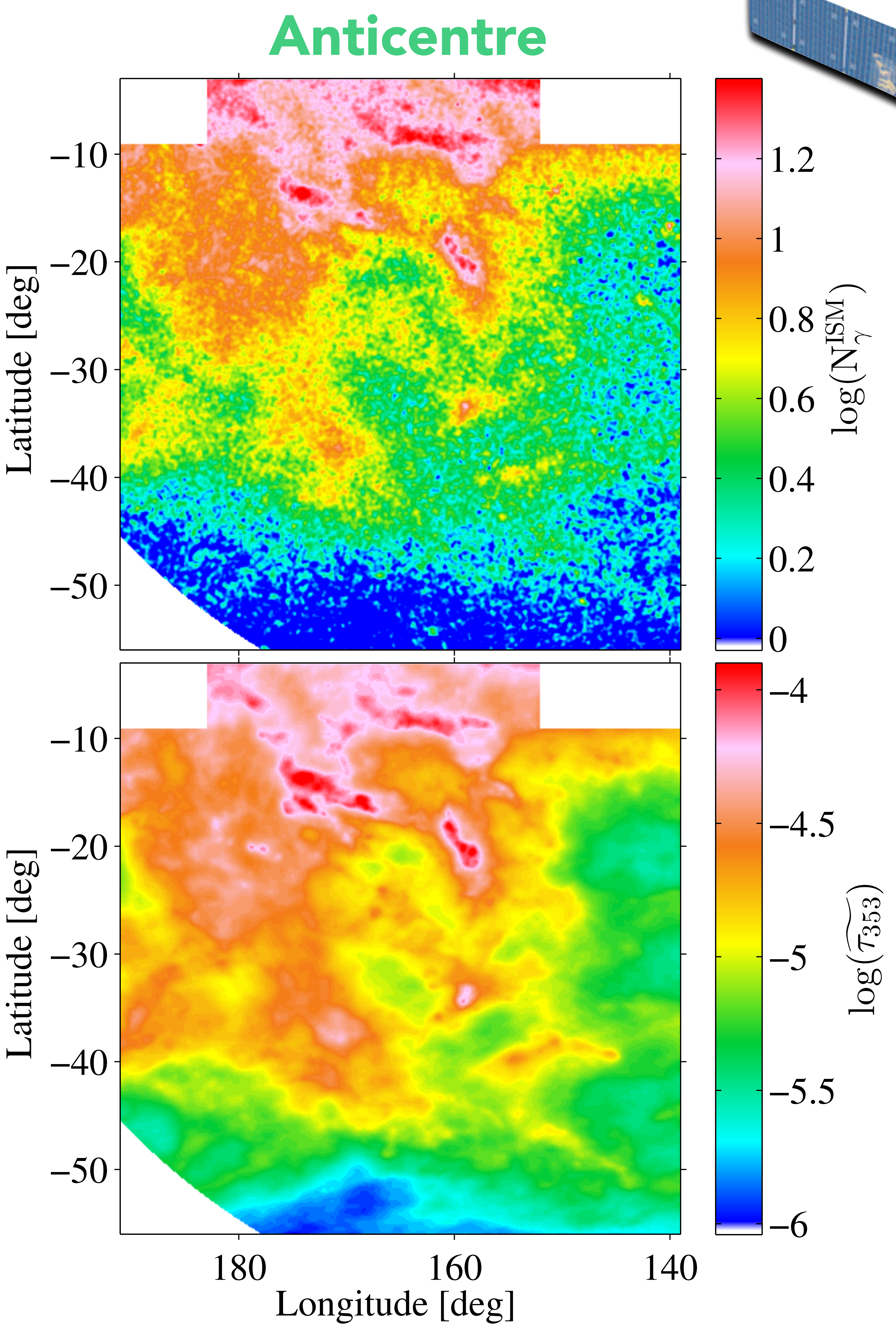
super rays
to weigh interstellar gas

coupling total gas tracers

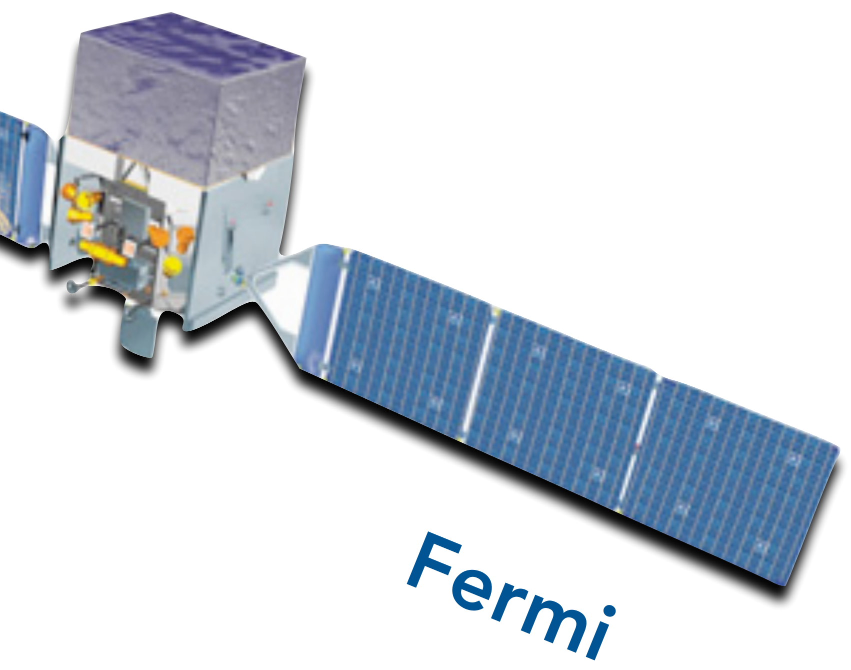
- γ rays if uniform CR flux (> few GeV) across the HI and H_2 phases of a given cloud complex ✓
- dust if uniform dust emission opacity τ_{353}/N_H ✗

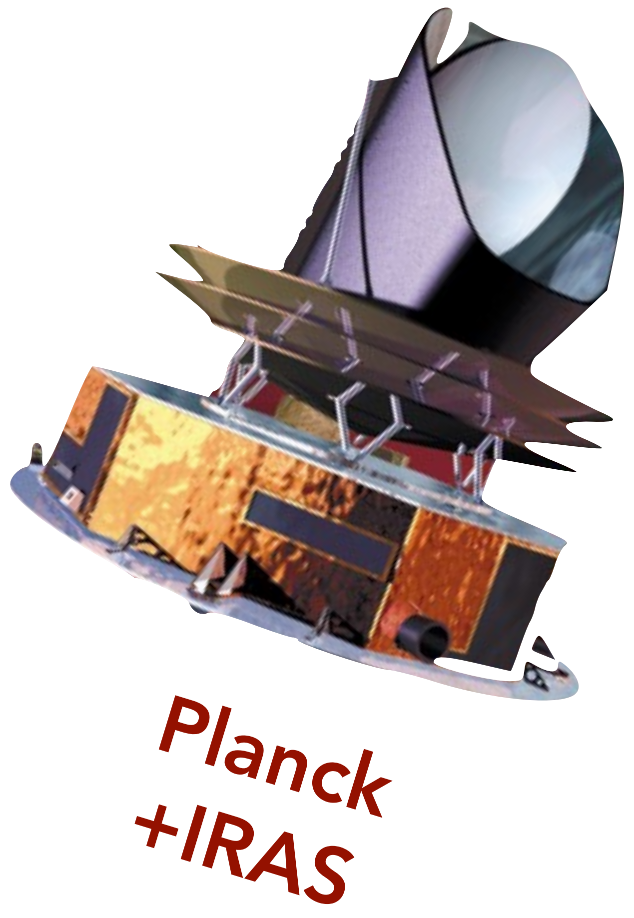

Chamaeleon

Planck+Fermi 2015 XVIII


Anticentre

Remy+ 2017



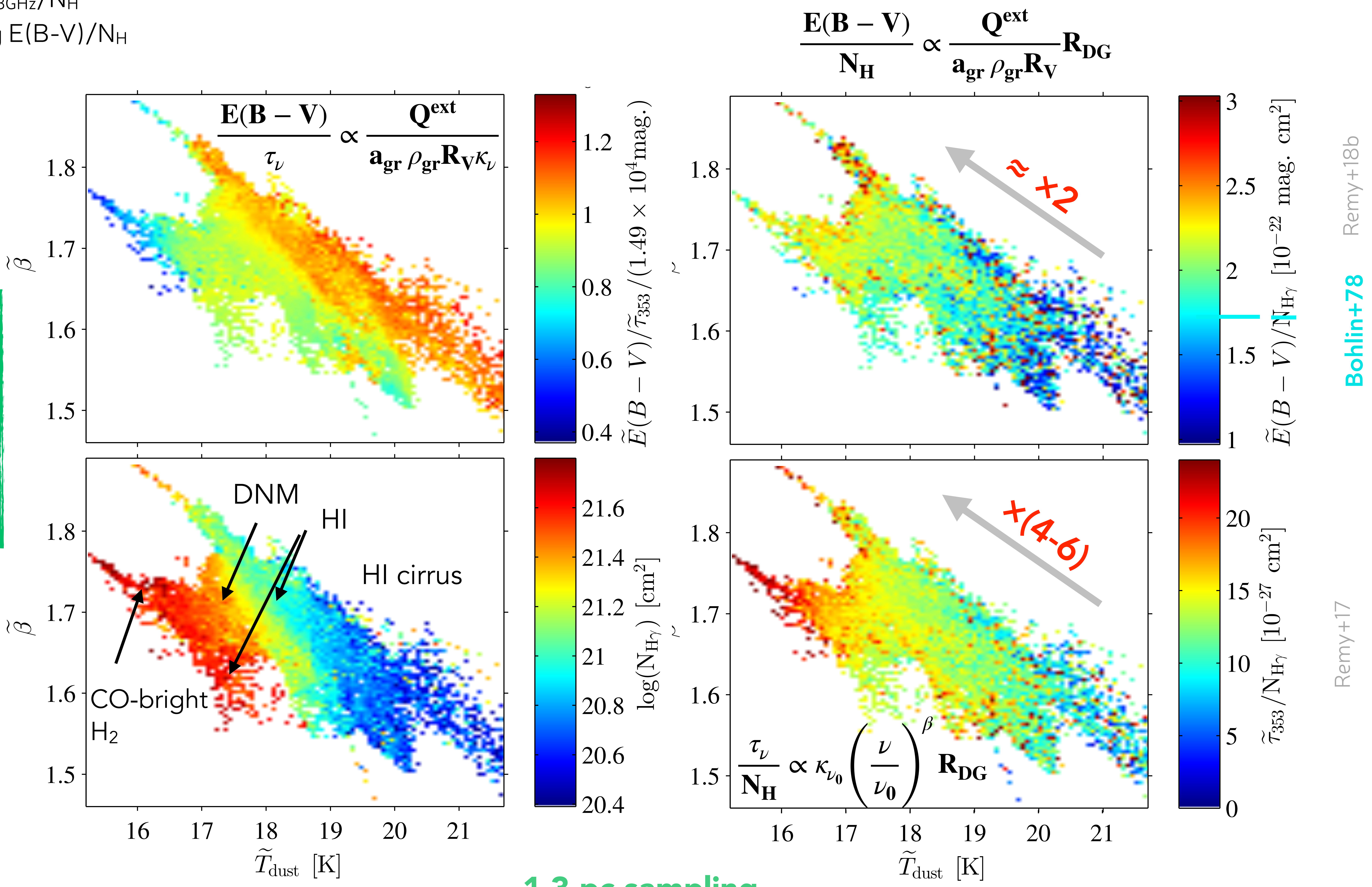


dust grain evolution

- changes in dust properties per gas nucleon
  - large increase in emission opacity τ_{353GHz}/N_H
  - modest increase in specific reddening $E(B-V)/N_H$

dust = non-linear, environment-dependent gas tracer

linear gas tracing if N_H < few 10^{21} cm^{-2}



$$\frac{\mathbf{E(B-V)}}{\mathbf{N_H}} \propto \frac{\mathbf{Q^{ext}}}{\mathbf{a_{gr}\,\rho_{gr} R_V}} \mathbf{R_{DG}}$$

$$\frac{\mathbf{E(B-V)}}{\tau_\nu} \propto \frac{\mathbf{Q^{ext}}}{\mathbf{a_{gr}\,\rho_{gr} R_V}\kappa_\nu}$$

$$\frac{\tau_\nu}{\mathbf{N_H}} \propto \kappa_{\nu_0}\left(\frac{\nu}{\nu_0}\right)^\beta \mathbf{R_{DG}}$$

1-3 pc sampling

- R_{DG} = dust-to-gas mass ratio
- κ = emission cross section
- Q_{ext} = extinction efficiency
- $R_V = \frac{A_V}{E(B-V)}$
- a_{gr} = grain radius
- ρ_{gr} = grain mass density

γ-ray versus dust of X_{CO} estimates

- X_{CO} CO to H_2 conversion ratio

$$X_{CO} = \frac{N(H_2)}{W(CO)} = \frac{N(H_2)}{\int I_{^{12}CO(J=1\rightarrow0)}(v)\,dv}$$

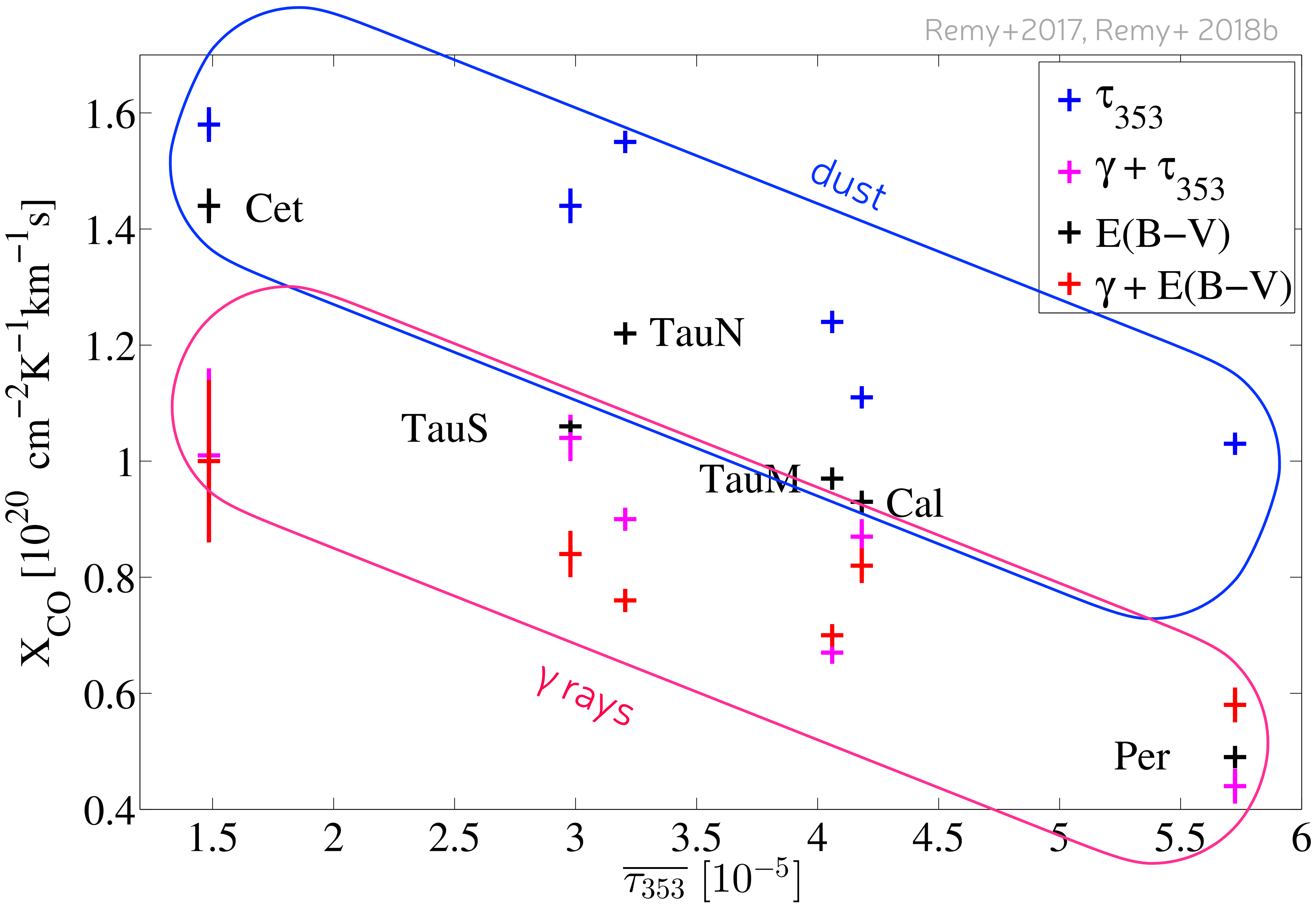
- measurement assumption in **one given** cloud
  = same CR flux or same dust/gas in the HI and CO phases

$$X_{CO}^{\gamma} = \frac{q_{\gamma}^{CO}}{2q_{\gamma}^{HI}} \qquad X_{CO}^{dust} = \frac{(N_{dust}/N_H)^{CO}}{2(N_{dust}/N_H)^{HI}}$$

- systematic bias in X_{CO}^{dust} due to dust grain evolution

$$X_{CO}^{\tau_{353GHz}} > X_{CO}^{E(B-V)} \gtrsim X_{CO}^{\gamma}$$

local ISM cloud average
$X_{CO} \approx 10^{20}$ cm^{-2} (K km/s)$^{-1}$

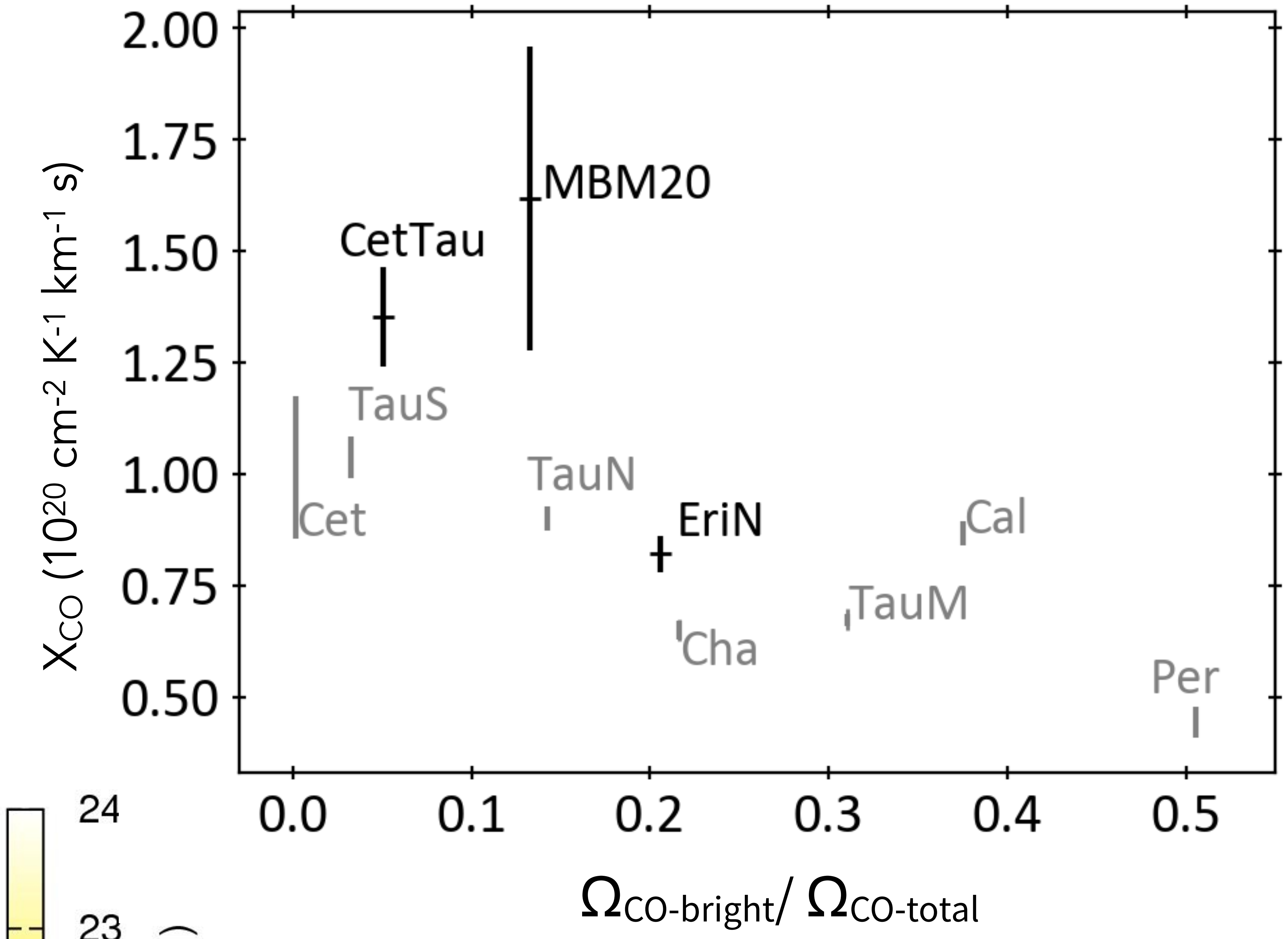

Remy+2017, Remy+ 2018b

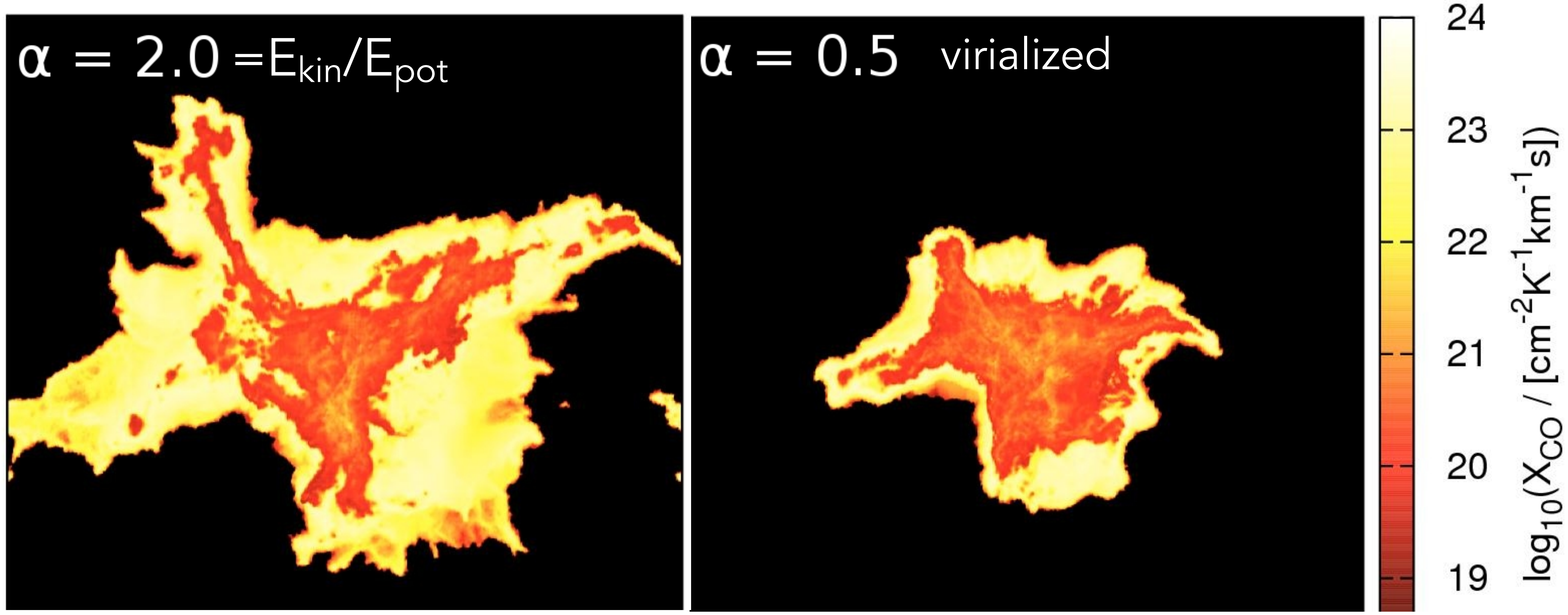
X_{CO} versus cloud state

Remy+ 2017
Joubaud+20

- decrease in average X_{CO} per cloud from diffuse to compact CO clouds
  - ok with latest simulations Gong+18
- X_{CO}(kpc) ≈ 2 X_{CO}(pc) ≈ 1.9 10^{20} cm^{-2} (K km/s)$^{-1}$ Grenier+15

average X_{CO}:
cloud-state &
scale dependent factor



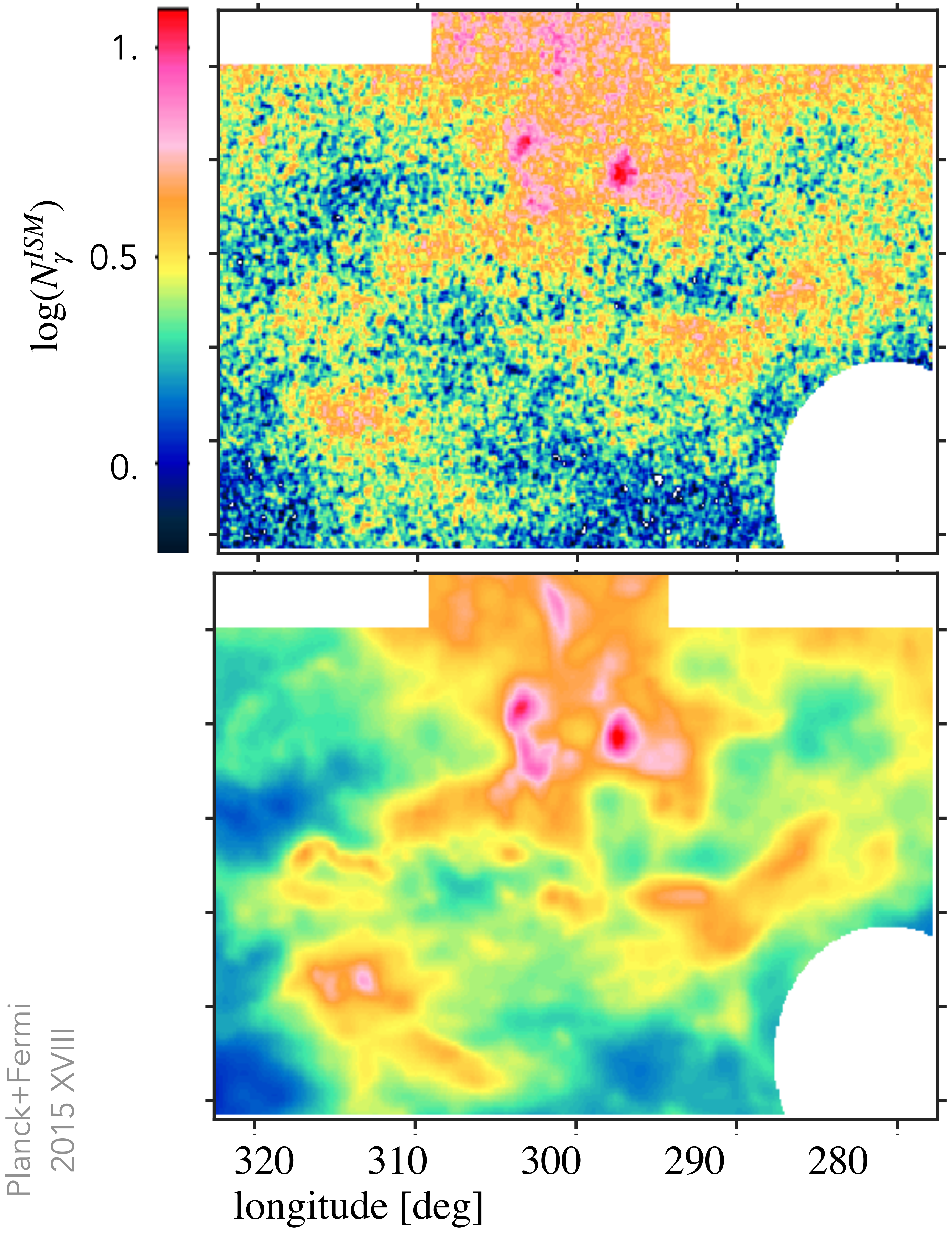


Bertram+ 2016

coupling total gas tracers

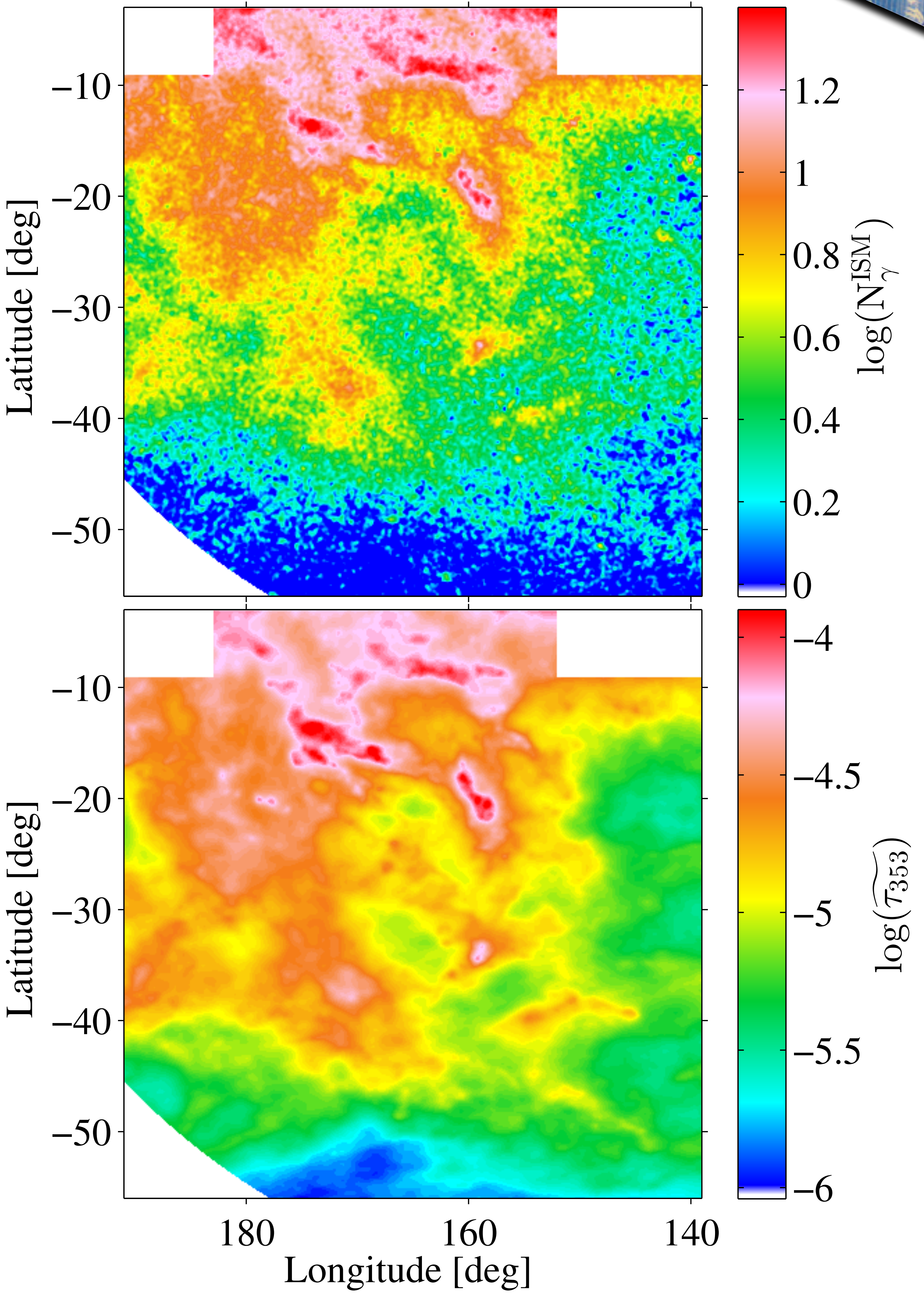
- γ rays if uniform CR flux (> few GeV) across the HI and H_2 phases of a given cloud complex ✓
- dust if uniform dust emission opacity τ_{353}/N_H ✗

Chamaeleon

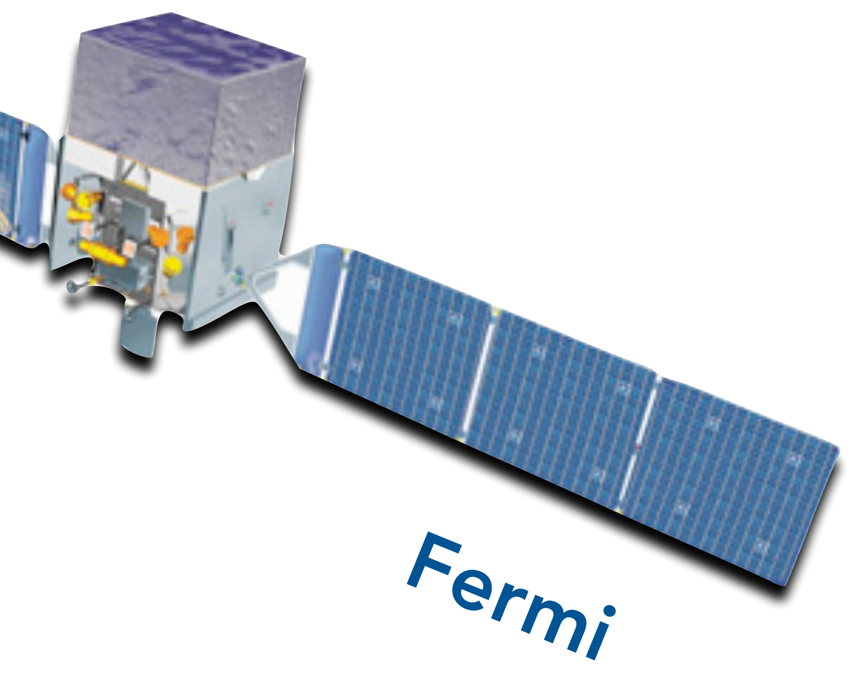


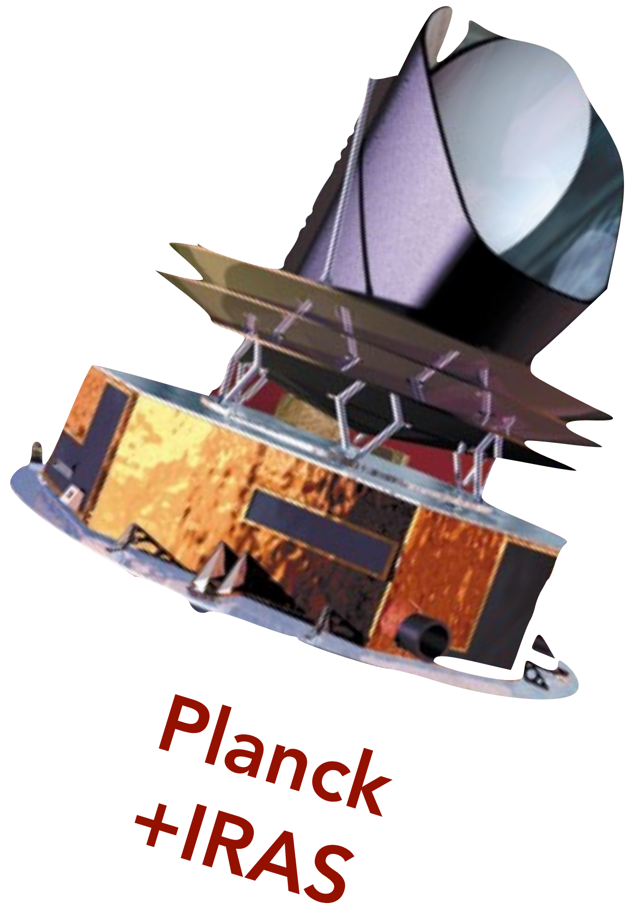
Planck+Fermi 2015 XVIII

Anticentre



Remy+ 2017





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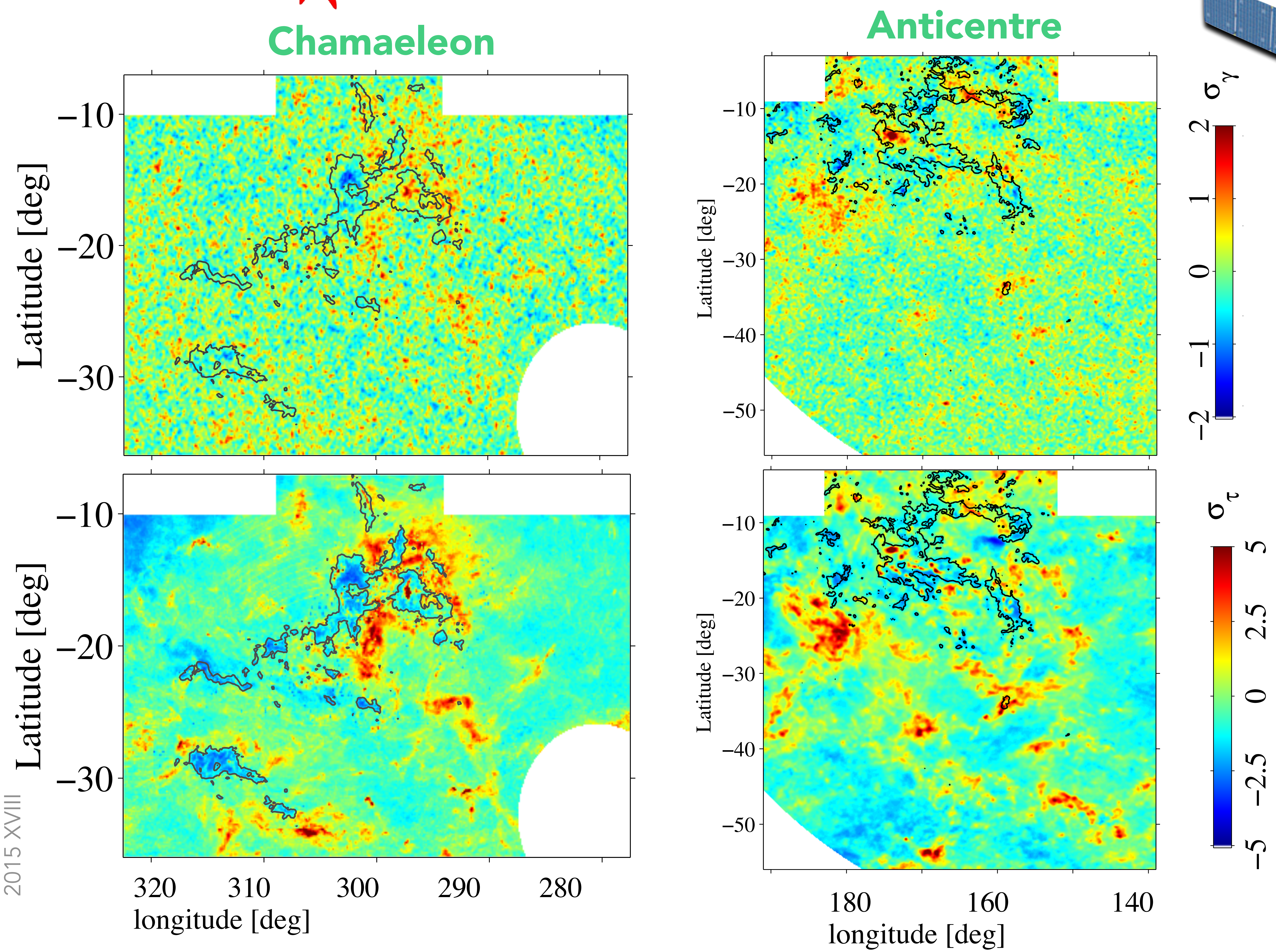

Planck+Fermi 2015 XVIII

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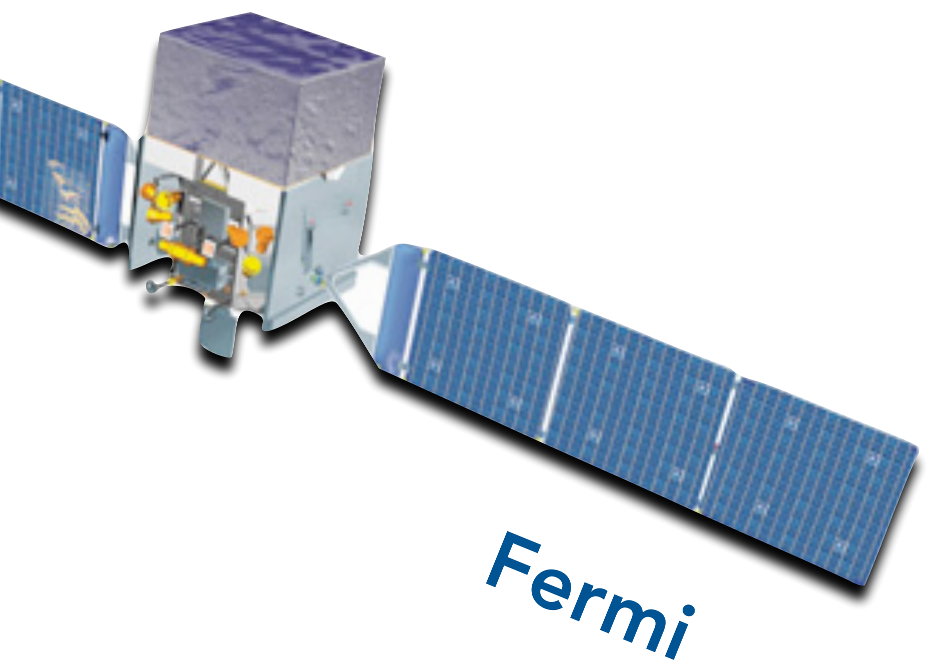

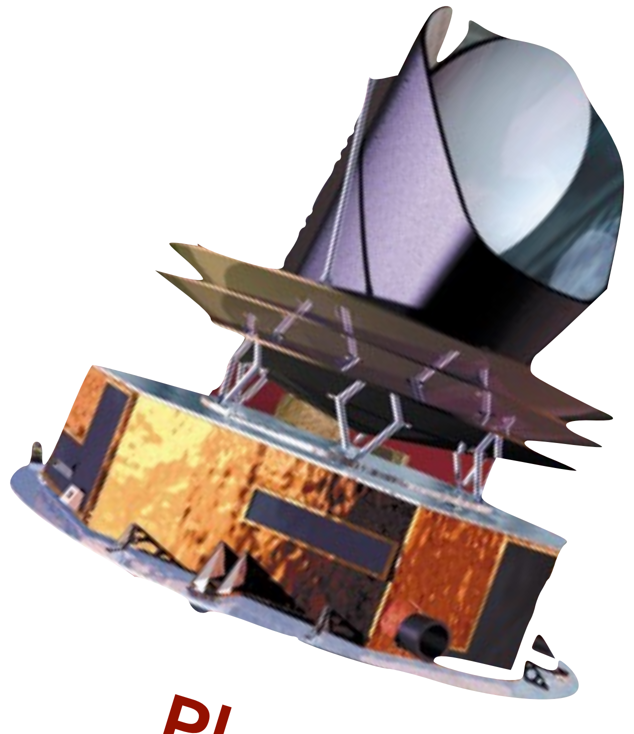

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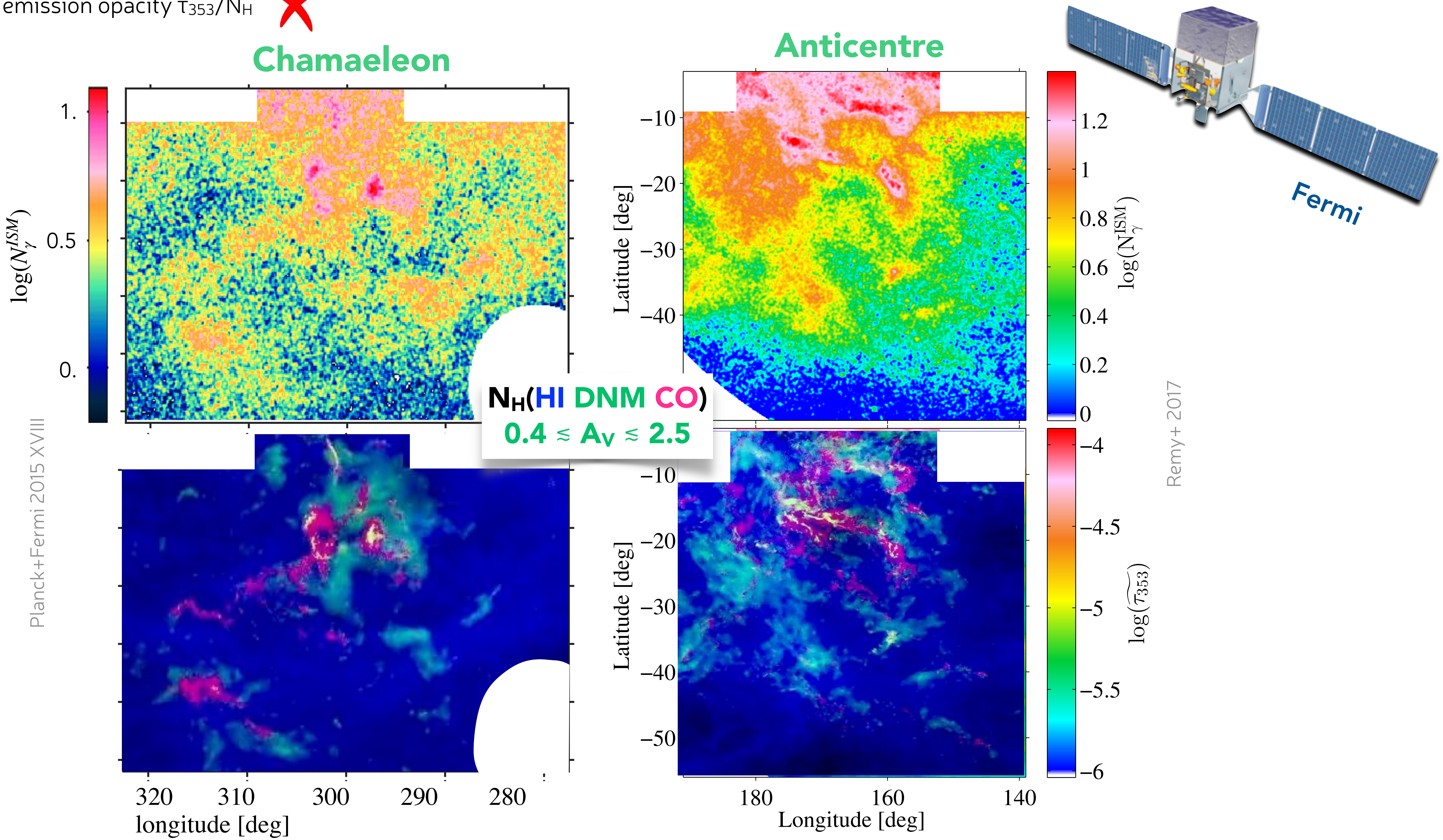
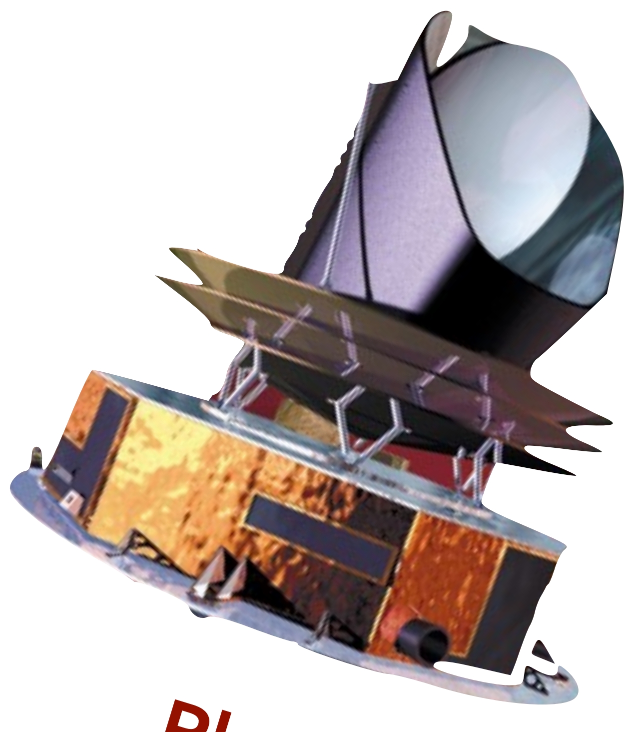


N_H(HI DNM CO)
$0.4 \lesssim A_V \lesssim 2.5$

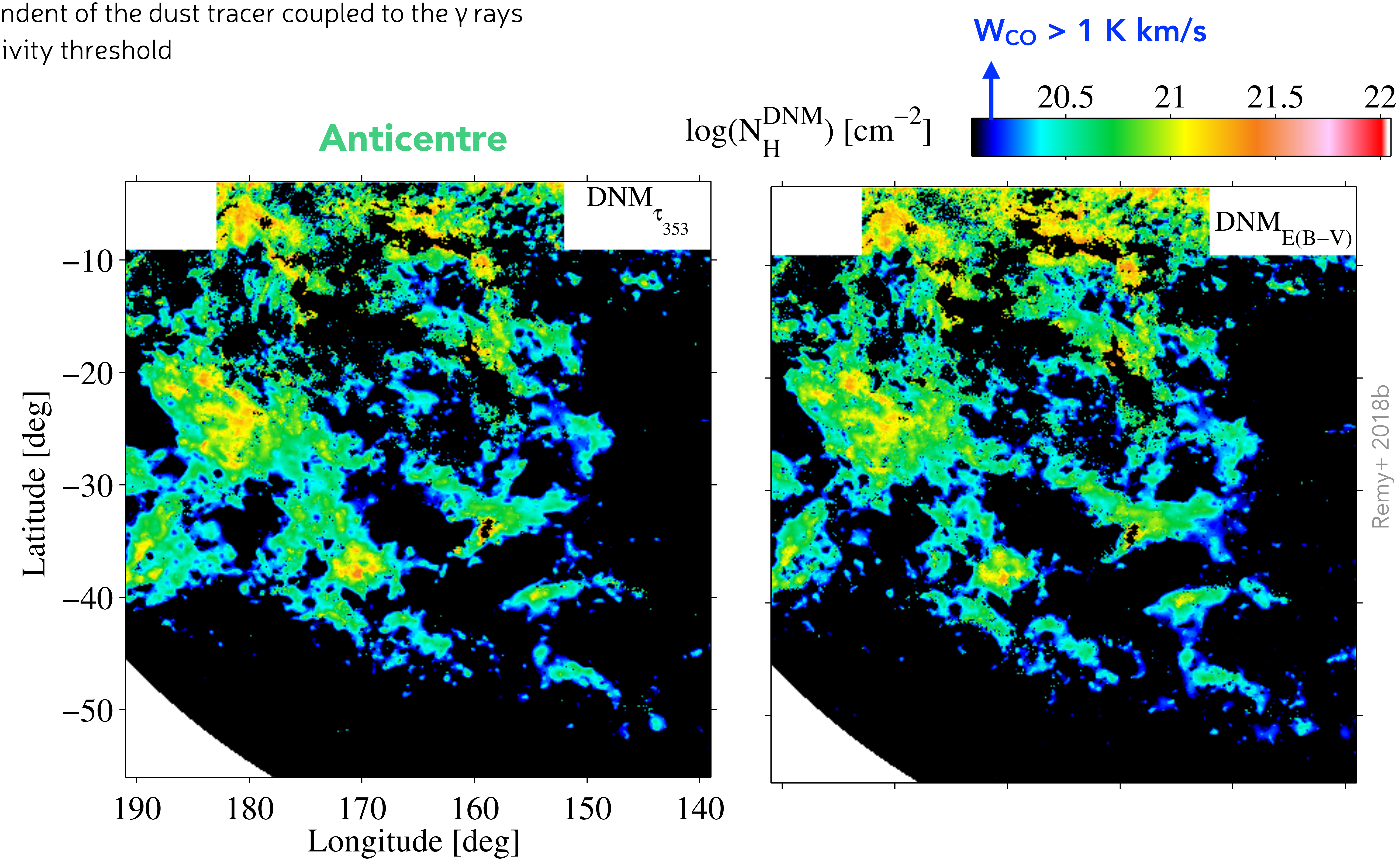
Planck+Fermi 2015 XVIII

Remy+ 2017



dark neutral medium

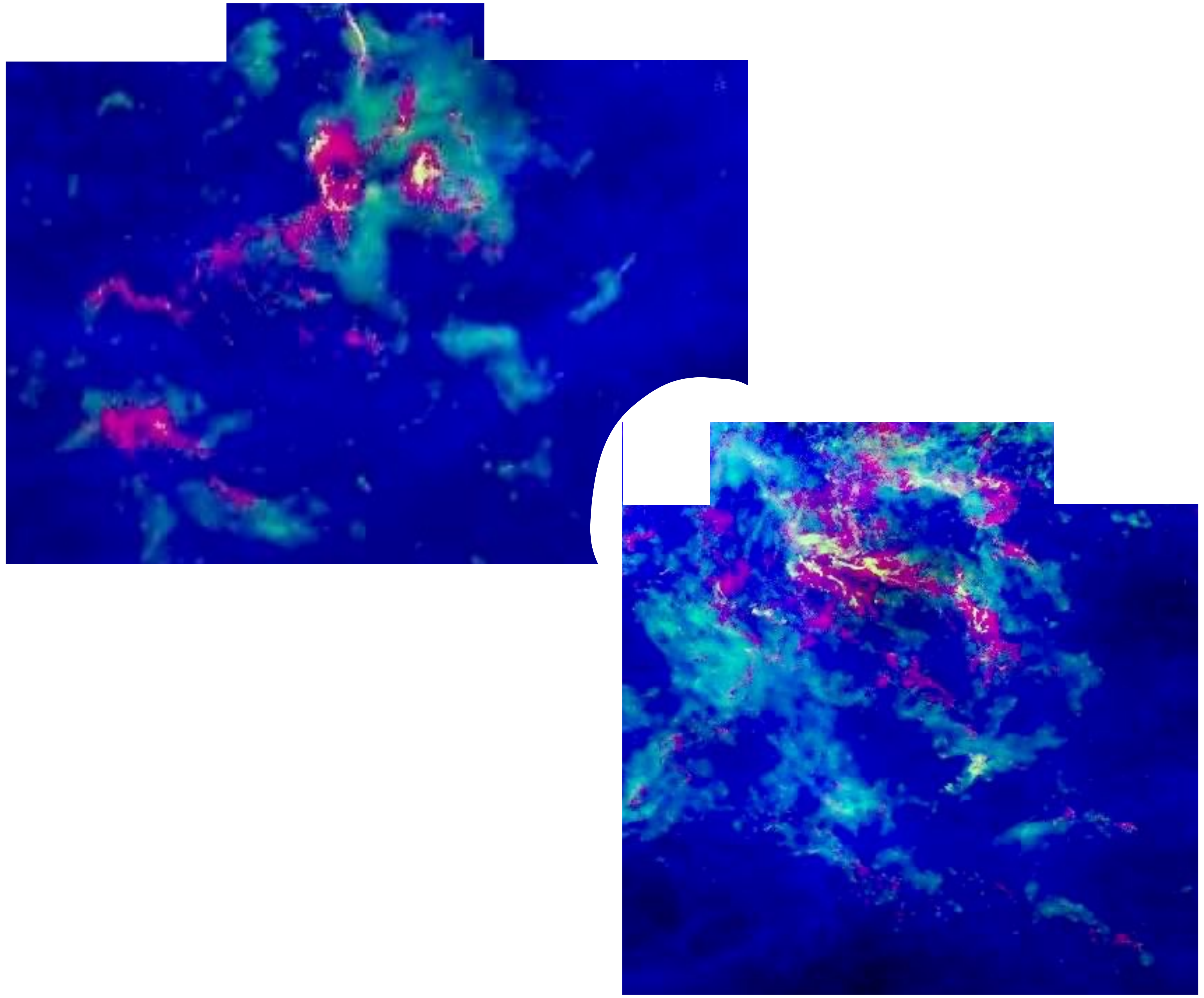
- N_H^{DNM} rather independent of the dust tracer coupled to the γ rays
- not due to CO sensitivity threshold

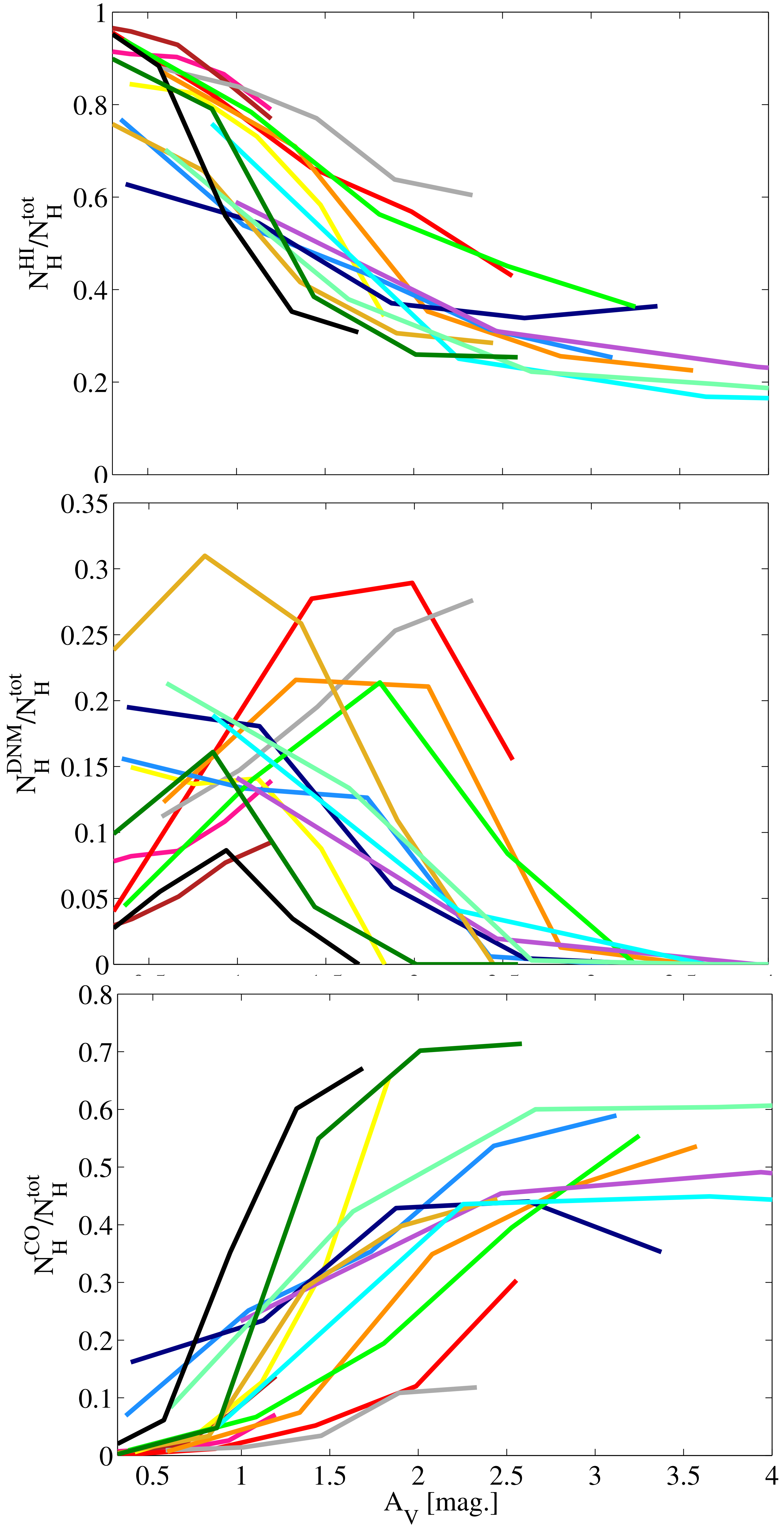


- CO in absorption $4\,10^{13} \lesssim N(CO) \lesssim 1.2\,10^{15}\,\mathrm{cm}^{-2}$ $\Rightarrow 0.04 \lesssim W(CO) \lesssim 1.2\,\mathrm{K\,km/s}$ Liszt+ 2019

dark HI-H_2 transition.....

- at pc scale in nearby clouds:
  - HI to DNM transition at $N_H = (8.0 \pm 0.6)\ 10^{20}$ H/cm^2
    or $A_V = 0.4 \pm 0.03$ mag
  - DNM spans the CO-dark H_2 range in A_V
  - DNM fractions < 30% because N_H^{tot} includes the extended WNM HI envelopes



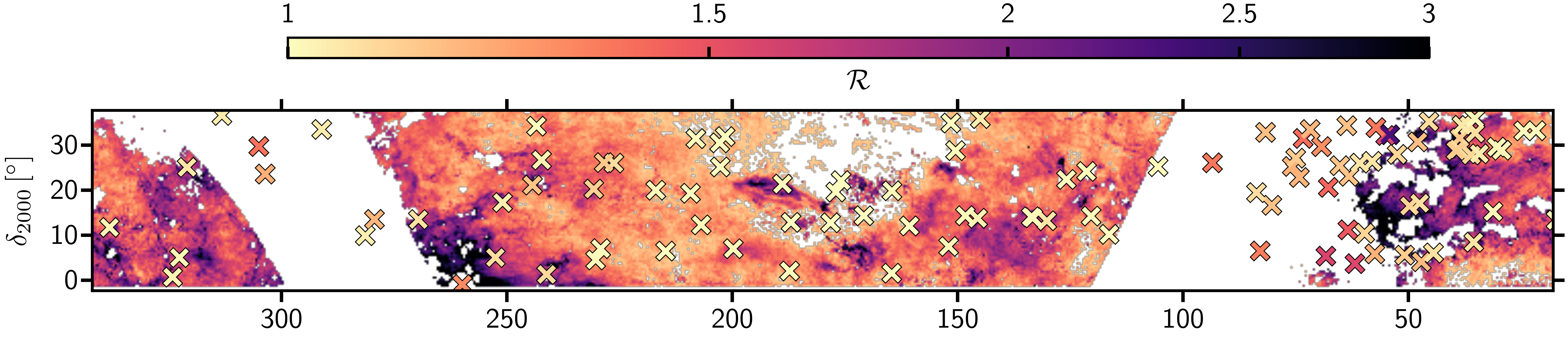


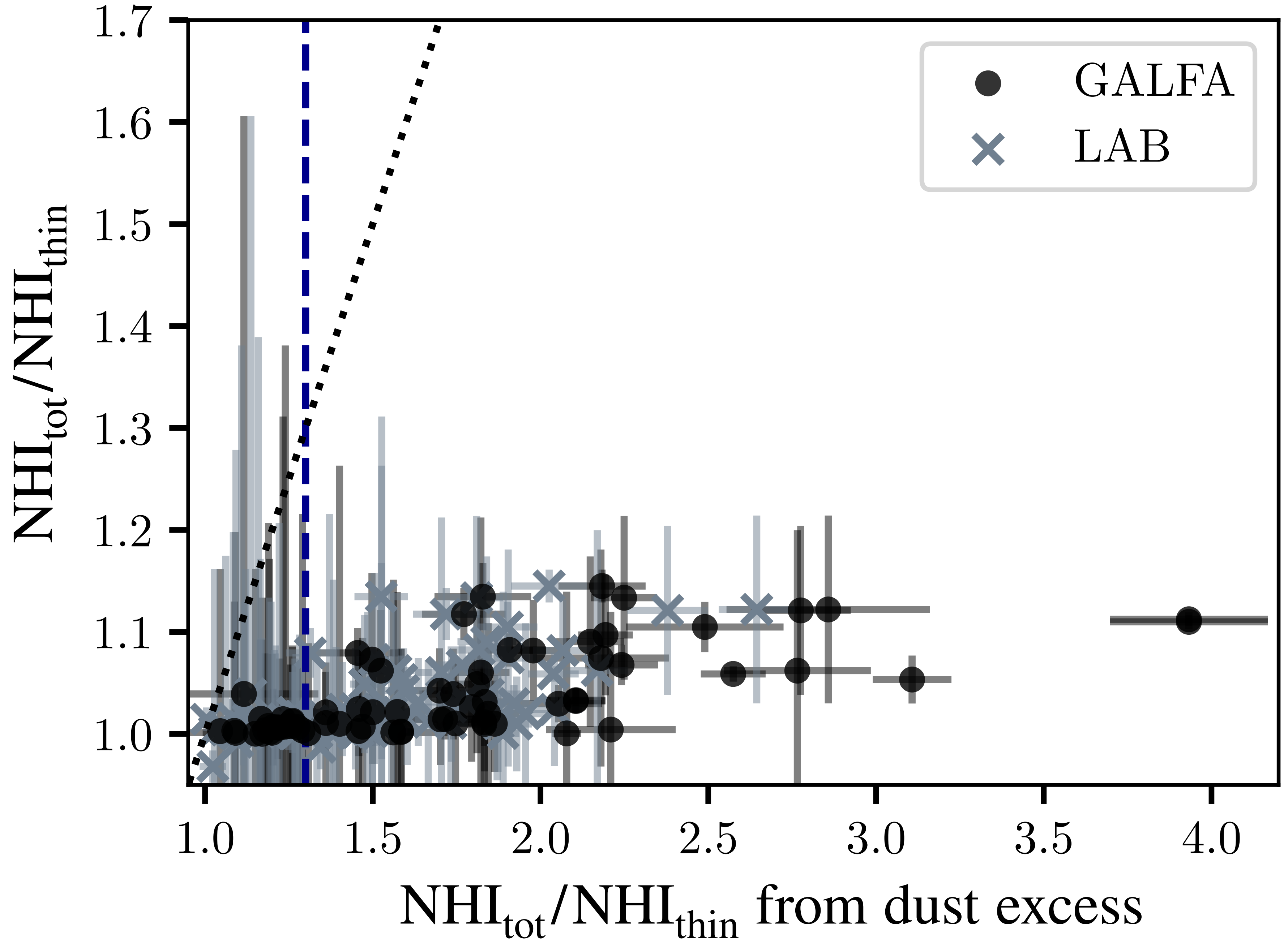
Remy+ 2018b

Anticentre+Chamaeleon

not purely thick HI

- dust excesses cannot be explained by opt-thick CNM HI column densities => dust evolution
  - small contribution from thick HI
  - unrealistic pressures if thick HI blobs





Murray+ 2018

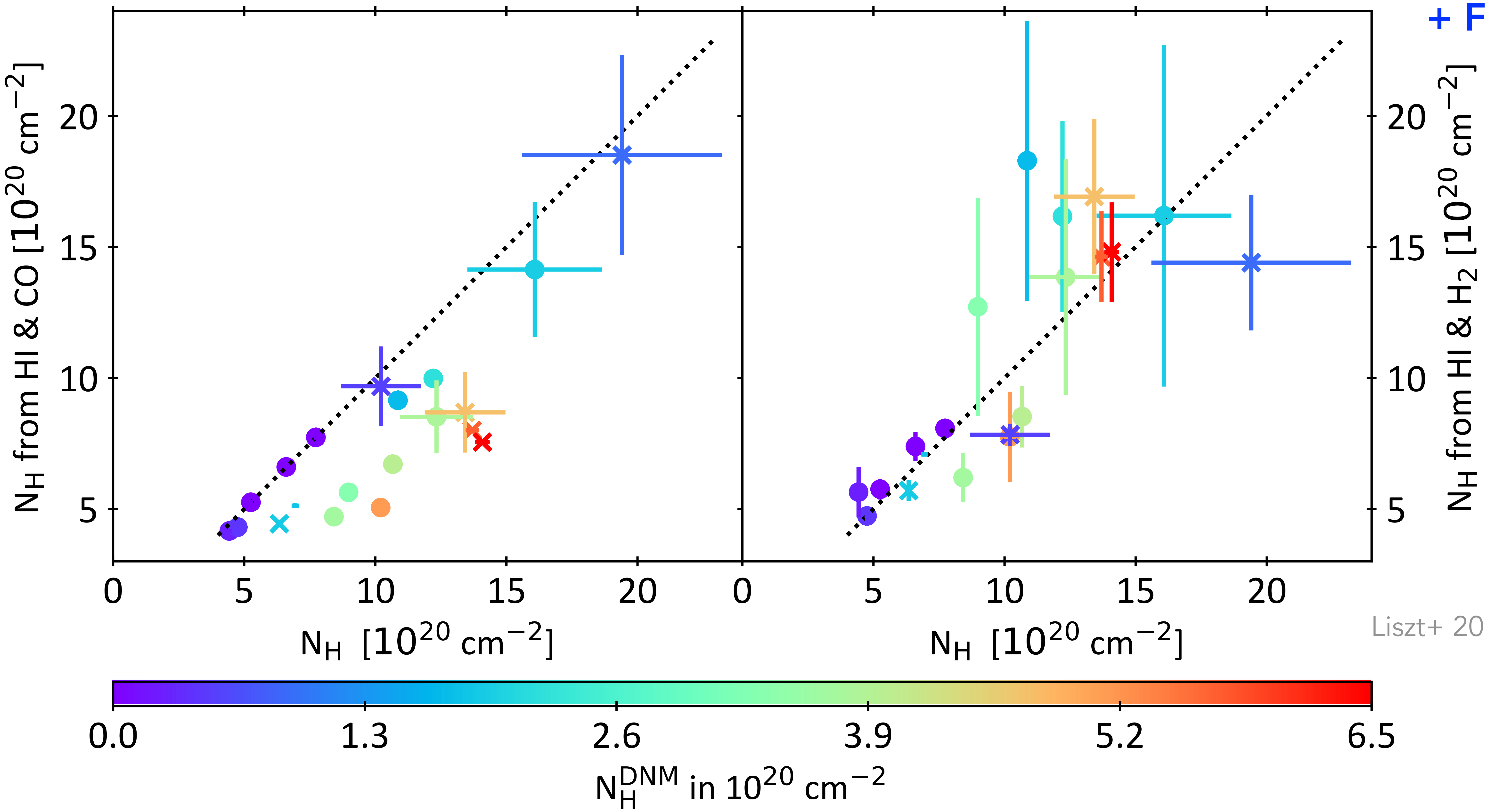
diffuse H_2 around the Chamaeleon

- very faint CO

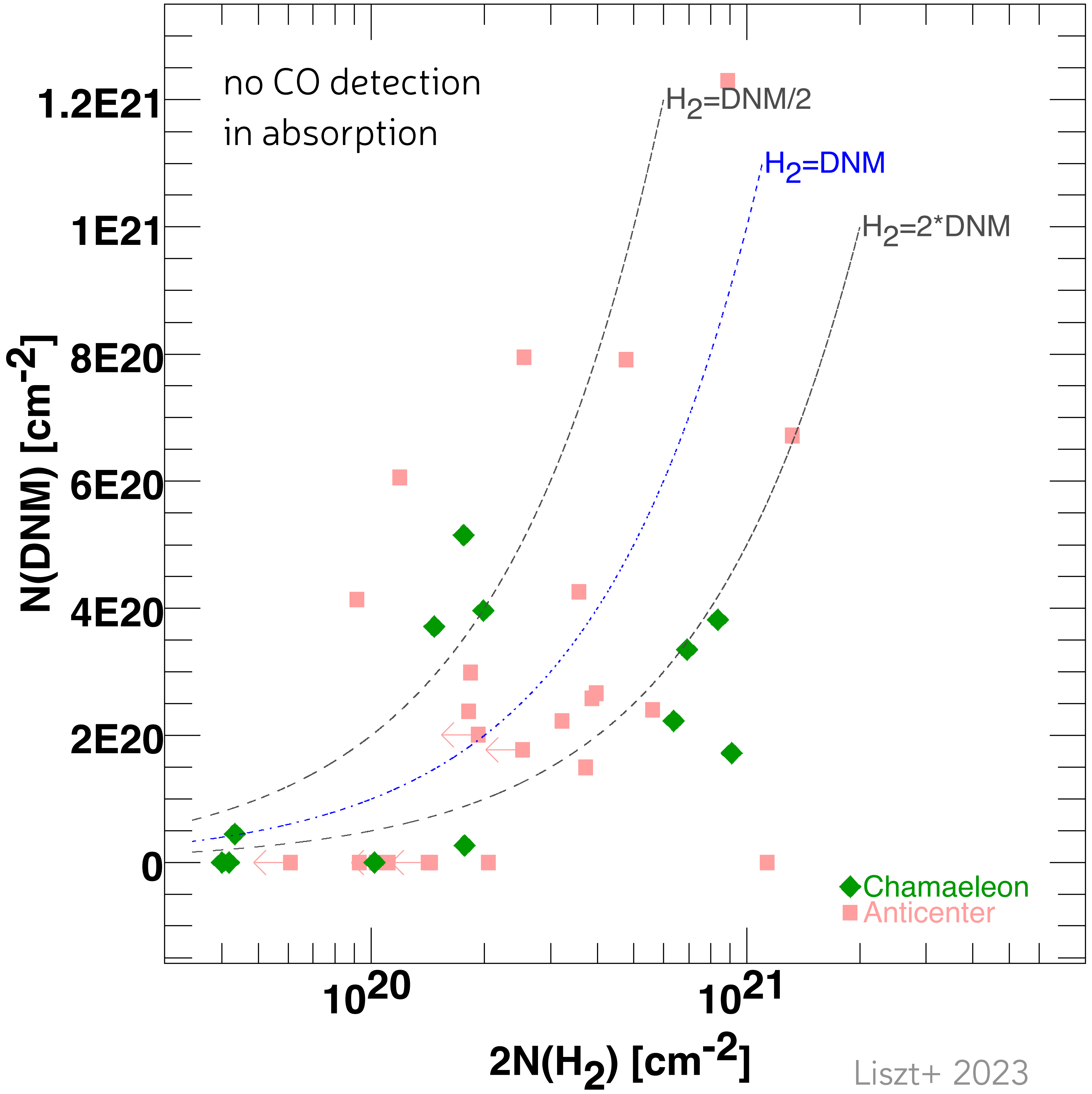
$$4\,10^{13} \lesssim N(CO) \lesssim 1.2\,10^{15}\,\mathrm{cm}^{-2} \quad \Rightarrow 0.04 \lesssim W(CO) \lesssim 1.2\,\mathrm{K\,km/s}$$

- diffuse H_2 accounts for the whole DNM gas along most sightlines
  - no reservoir of dark H_2 undetected

$N(HCO^+)/N(H_2) = 3\ 10^{-9}$
+ FUSE



Liszt+ 2019



Liszt+ 2023

- challenges:
  - find more mm-bright background sources
  - join absorption observations in HI and molecules (=> radio+mm bright sources)

DNM fractions with cloud state

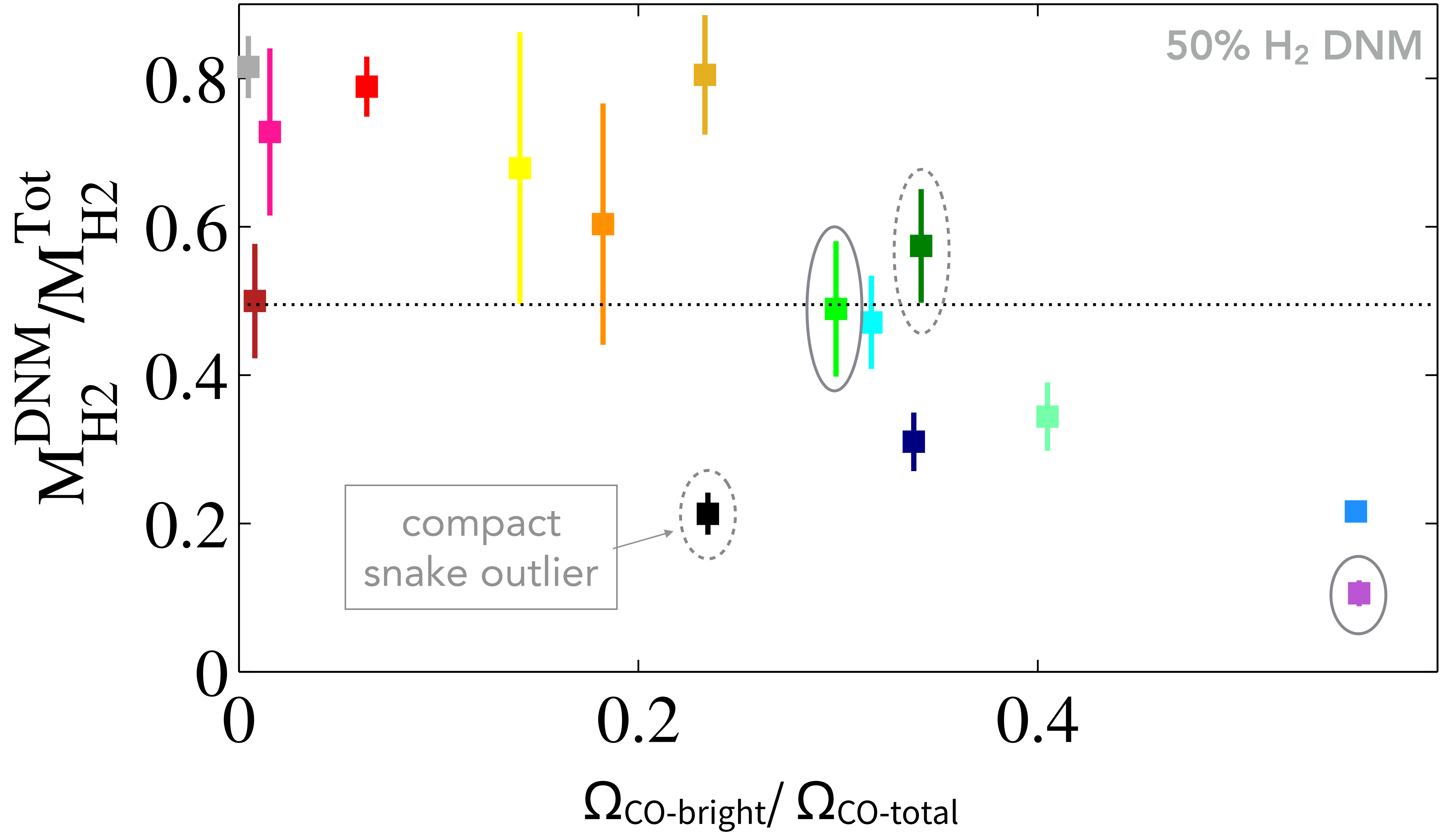
- more abundant DNM in tenuous CO clouds
- M(CO-dark H_2) > M(CO-bright H_2) for clouds with peak W_{CO} < 15-20 K km/s
- large fractions wrt predictions
  - $<f_{DG}>_{Wolfire+2010}$ = 0.25-0.33, $<f_{DG}>_{Levrier+2012}$ = 0.32-0.36
  - $<f_{DG}>_{Gong+2018}$ = 0.26-0.79, decreasing with A_V(CO)

- theory: little dependence on cloud mass or ISRF
  - yet environmental differences in the same cloud complex

DNM mass fraction variations due to UV screening/porosity ?
time evolution? E_{grav}?

2 10² - 2 10⁴ M⊙ in CO

Remy+ 2018b



further reading

- low-energy cosmic rays : Padovani et al. 2020, Space Science Reviews 216:29, arXiv:2002.10282, Impact of Low-Energy Cosmic Rays on Star Formation
- cosmic ray physics : Zweibel 2013 Physics of Plasmas, **20**, 055501 , The microphysics and macrophysics of cosmic rays
- GeV cosmic rays and the ISM : Grenier, Black and Strong 2015, Annual Review of Astronomy & Astrophysics, 3, 199–246, the nine lives of cosmic rays in galaxies, https://www.annualreviews.org/doi/10.1146/annurev-astro-082214-122457
- cosmic-ray transport and feedback on galaxy evolution : Ruszkowski & Pfrömmer 2023 eprint arXiv:2306.03141, Cosmic ray feedback in galaxies and galaxy clusters
- the origin of Galactic cosmic rays : Gabici et al. 2019, International Journal of Modern Physics D, Volume 28, Issue 15, arXiv:1903.11584v1, The origin of Galactic cosmic rays: challenges to the standard paradigm
- cosmic rays in super bubbles : Bykov, A et al. 2020, High-Energy Particles and Radiation in Star-Forming Regions, Space Science Reviews, Volume 216, Issue 3, article id.42, arXiv:2003.11534