Fermi Gamma-ray Space Telescope

AIM

Cosmic Rays, interstellar voyagers

Isabelle Grenier
Université Paris Cité & AIM CEA Saclay

Université Paris Cité

how do
cosmic rays travel?

how do they
disperse?

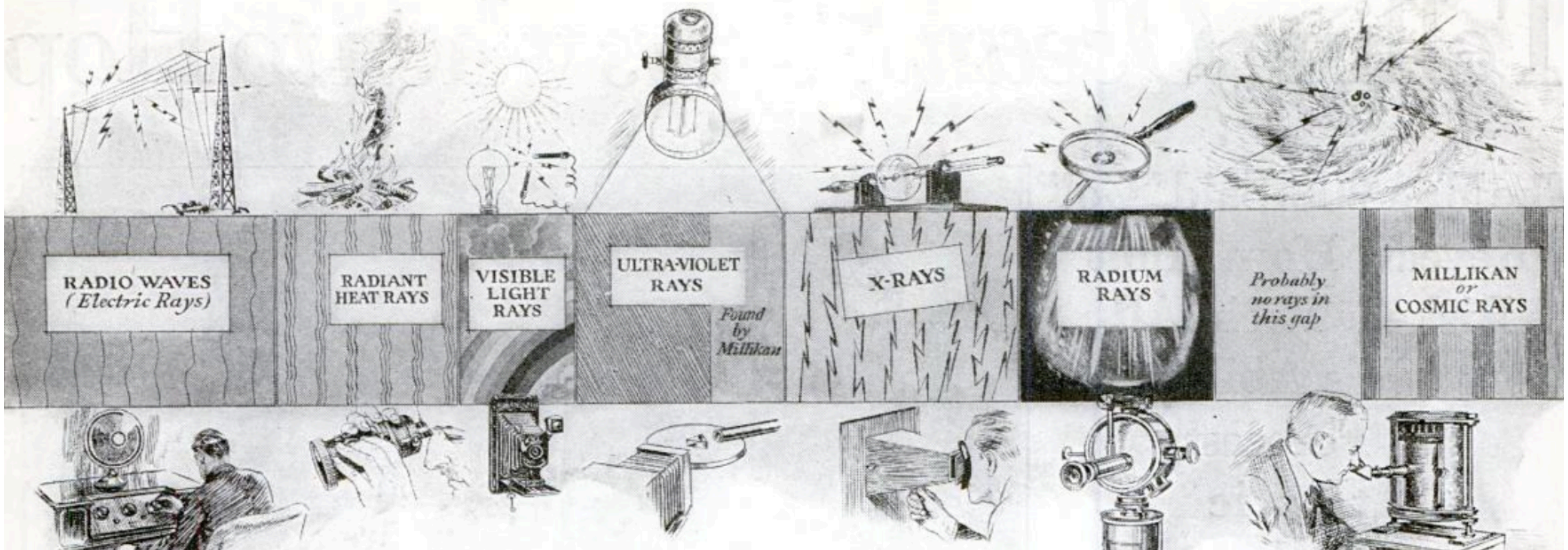
how fast
do they travel?

Popular Science MONTHLY
FOUNDED 1872
FIFTY SEVENTH YEAR
JULY, 1928 SUMNER BLOSSOM *Editor* VOL. 113, NO. 1

Super-Rays Reveal Secret of Creation

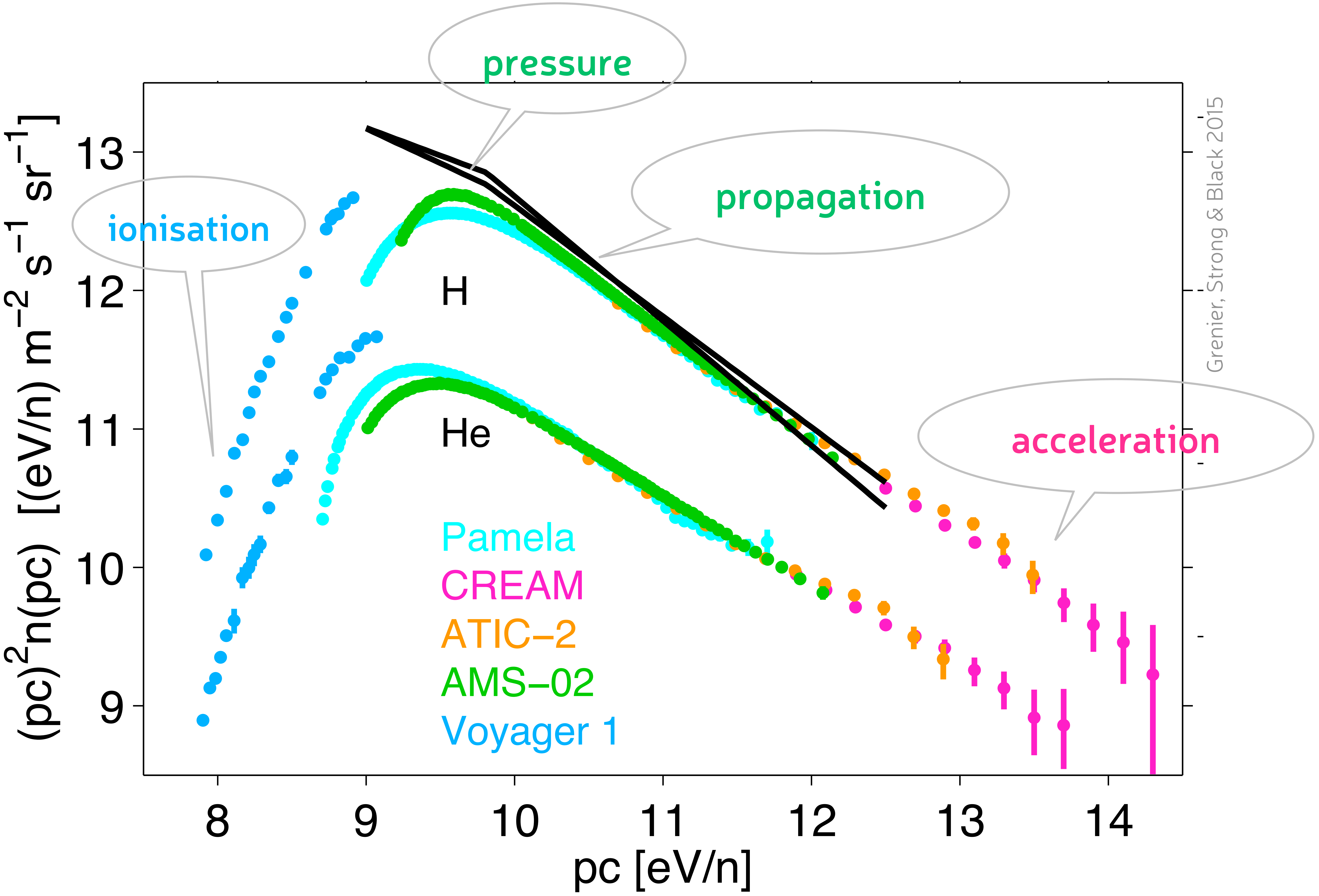
wicked facts
& beautiful models

super rays
to reveal gas



Millikan & Cameron 1928: the creation of atoms in a single act,
not in stars, but in interstellar space, $\Delta m\, c^2$ radiated as cosmic rays

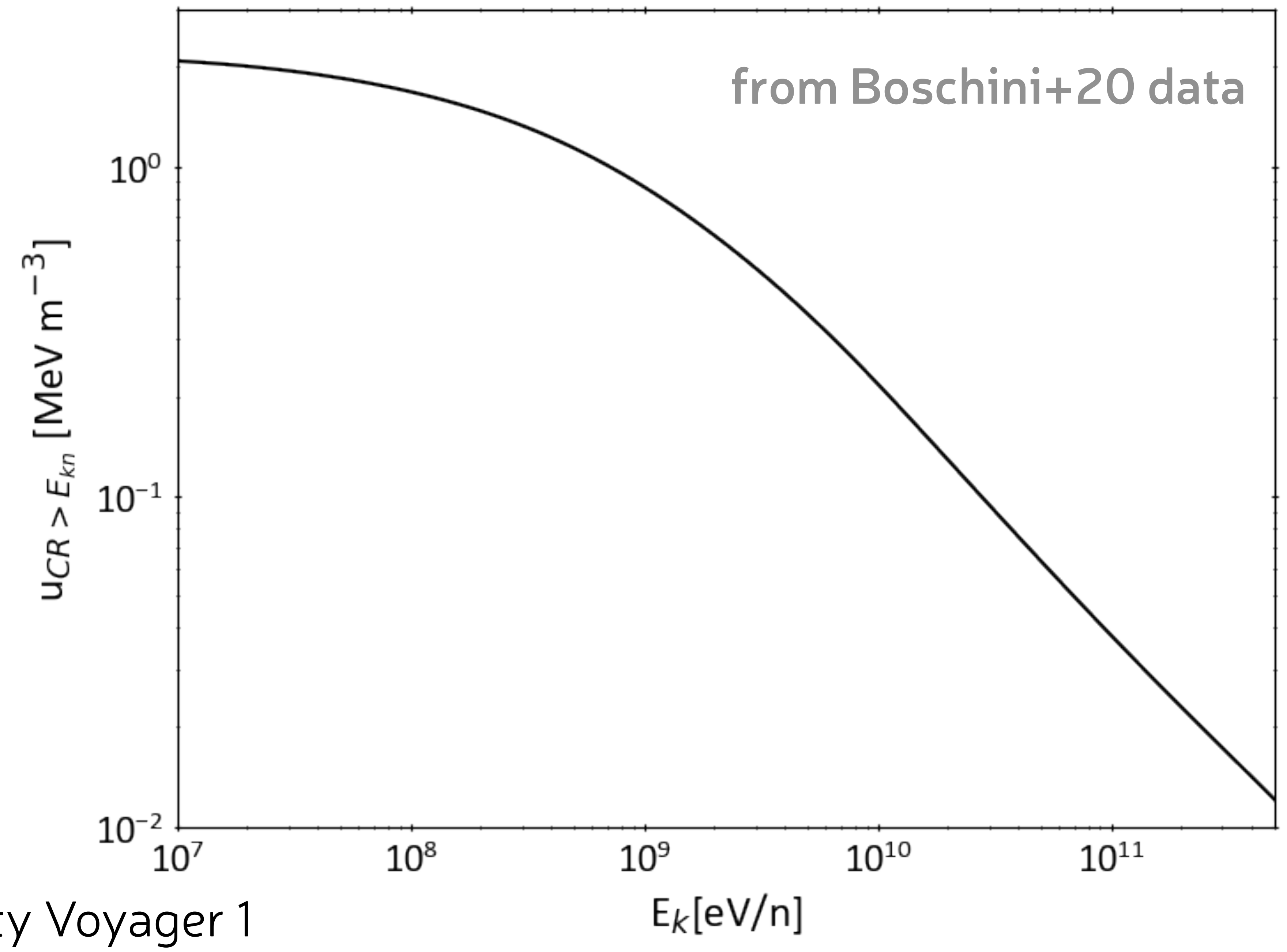
which energy for what?

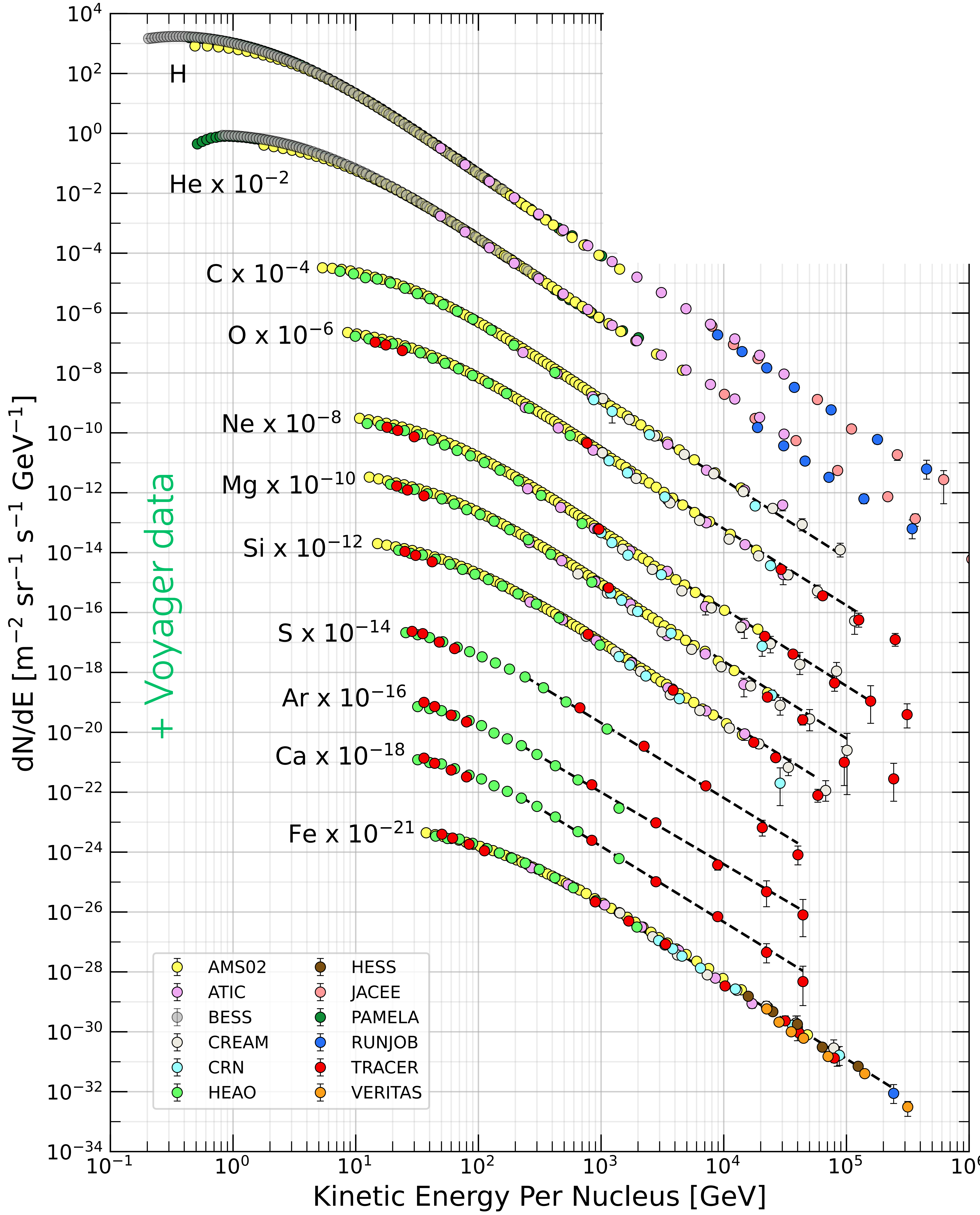


local cosmic-ray energy density

- Voyager 1 nuclei+e > 3 MeV/n : u_{CR} = 0.83 - 1.02 MeV m^3 Cummings+2016
- heliosphere demodulated spectra $u_{CR} \approx$ 2 MeV m^3

local energy equipartition



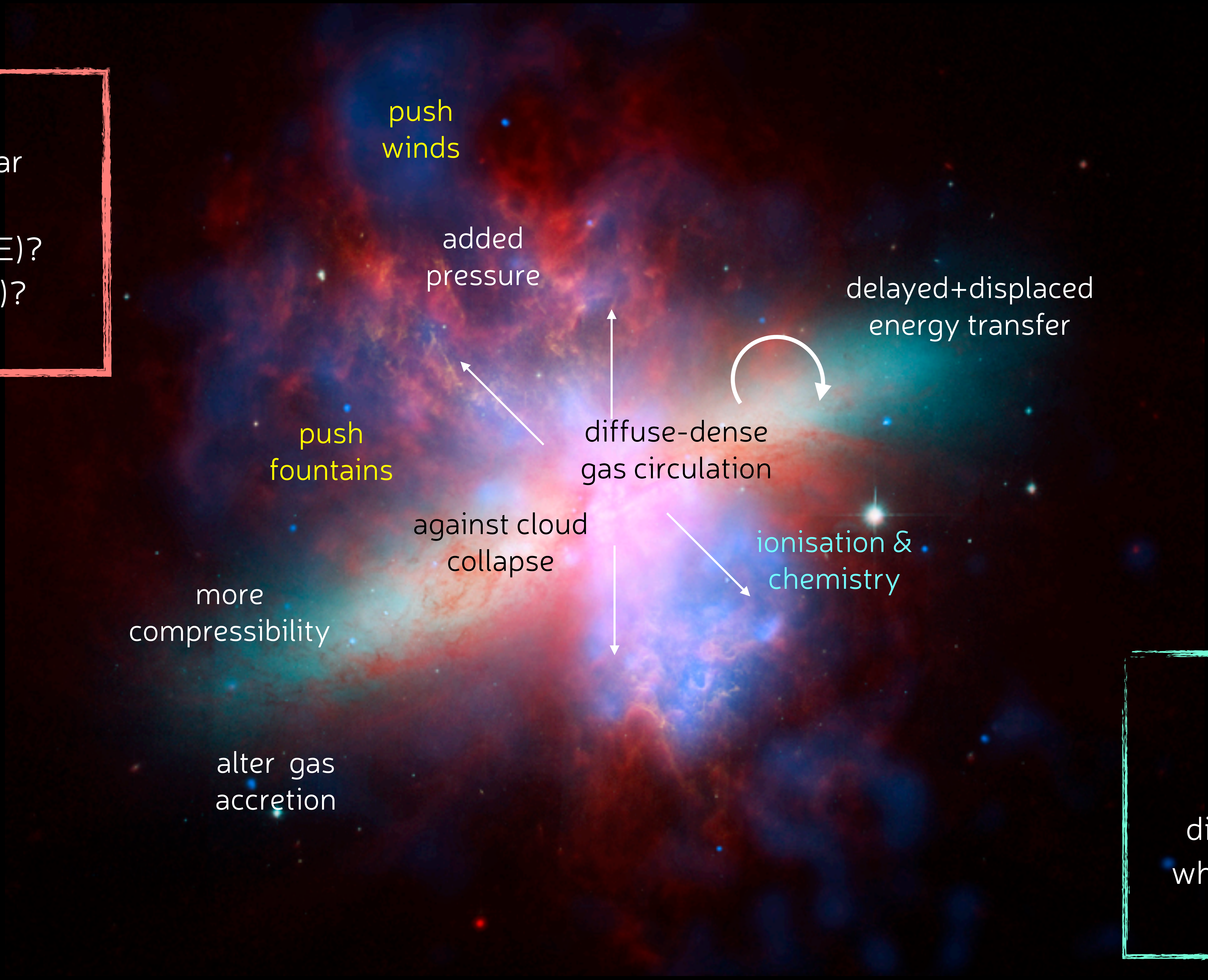


- local magnetic-field energy density Voyager 1
  - B_{tot} = (0.56 ± 0.01) nT $\Rightarrow B^2/2\mu_0$ = 0.78 ± 0.03 MeV m^3
- local gas pressure $\frac{p}{k} = \frac{N}{V} T = 10^{3.58 \pm 0.175}$ K cm^{-3} Jenkins & Tripp 2011
  - so u_{th} = $0.49^{+0.24}_{-0.16}$ MeV m^{-3}
- turbulent kinetic energy densities Hard & Kalberla 2007
  - CNM: $\frac{1}{2}\rho\sigma_v^2 = 0.6\,\mathrm{MeV\,m^{-3}} \left(\frac{n_{HI}}{30\,\mathrm{cm^{-3}}}\right) \left(\frac{\sigma_{v\,HI}}{1.7 \pm 0.3\,\mathrm{km/s}}\right)^2$
  - LNM: $\frac{1}{2}\rho\sigma_v^2 = 0.5\,\mathrm{MeV\,m^{-3}} \left(\frac{n_{HI}}{3\,\mathrm{cm^{-3}}}\right) \left(\frac{\sigma_{v\,HI}}{5.0 \pm 0.2\,\mathrm{km/s}}\right)^2$
  - WNM: $\frac{1}{2}\rho\sigma_v^2 = 0.4\,\mathrm{MeV\,m^{-3}} \left(\frac{n_{HI}}{0.5\,\mathrm{cm^{-3}}}\right) \left(\frac{\sigma_{v\,HI}}{10.3 \pm 0.3\,\mathrm{km/s}}\right)^2$

cosmic-ray feedback on galaxy evolution

$\gtrsim$ GeV CRays
self or interstellar confinement?
diffusion coeff κ(E)?
how uneven κ(E)?
halo extent?

> 100 TeV CRay
acceleration?
sources?



< 100 MeV CRays
sources?
diffusion properties?
why strong variations?

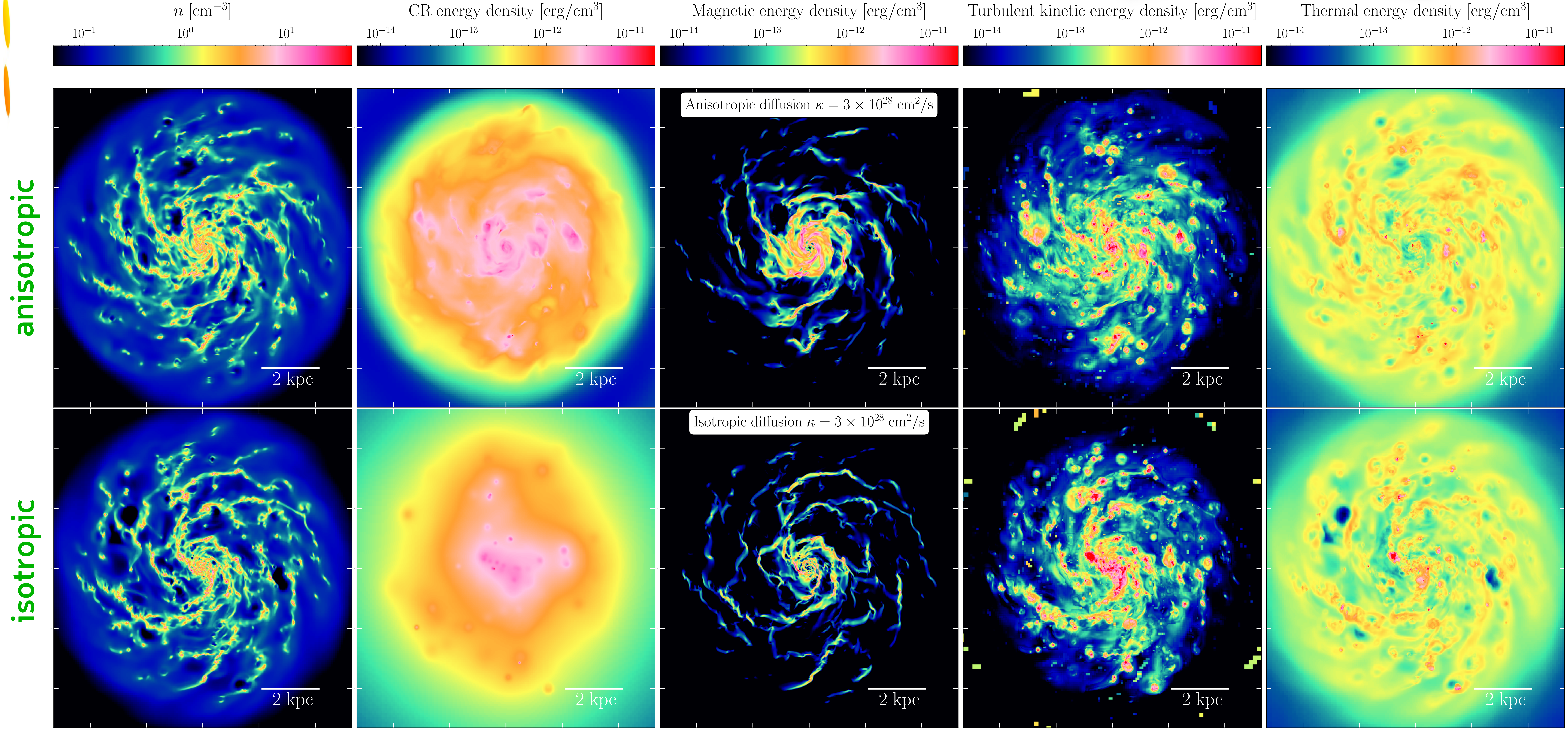
GeV CRays
as gas tracers

gas-rich dwarf galaxies

- $M_{tot} = 10^{11}$ M⊙, $M_b = 10^9$ M⊙ , SFR ~ 1 M⊙ /yr, starting from smooth gas & smooth B
- multiphasic gas down to 9-pc resolution, ideal MHD with RAMSES

$3\ 10^{28}$ m²/s

u_{turb} & u_{CR} > u_{therm} & u_B
on 100- 200 pc scales



Nunez-Castineyra+2022

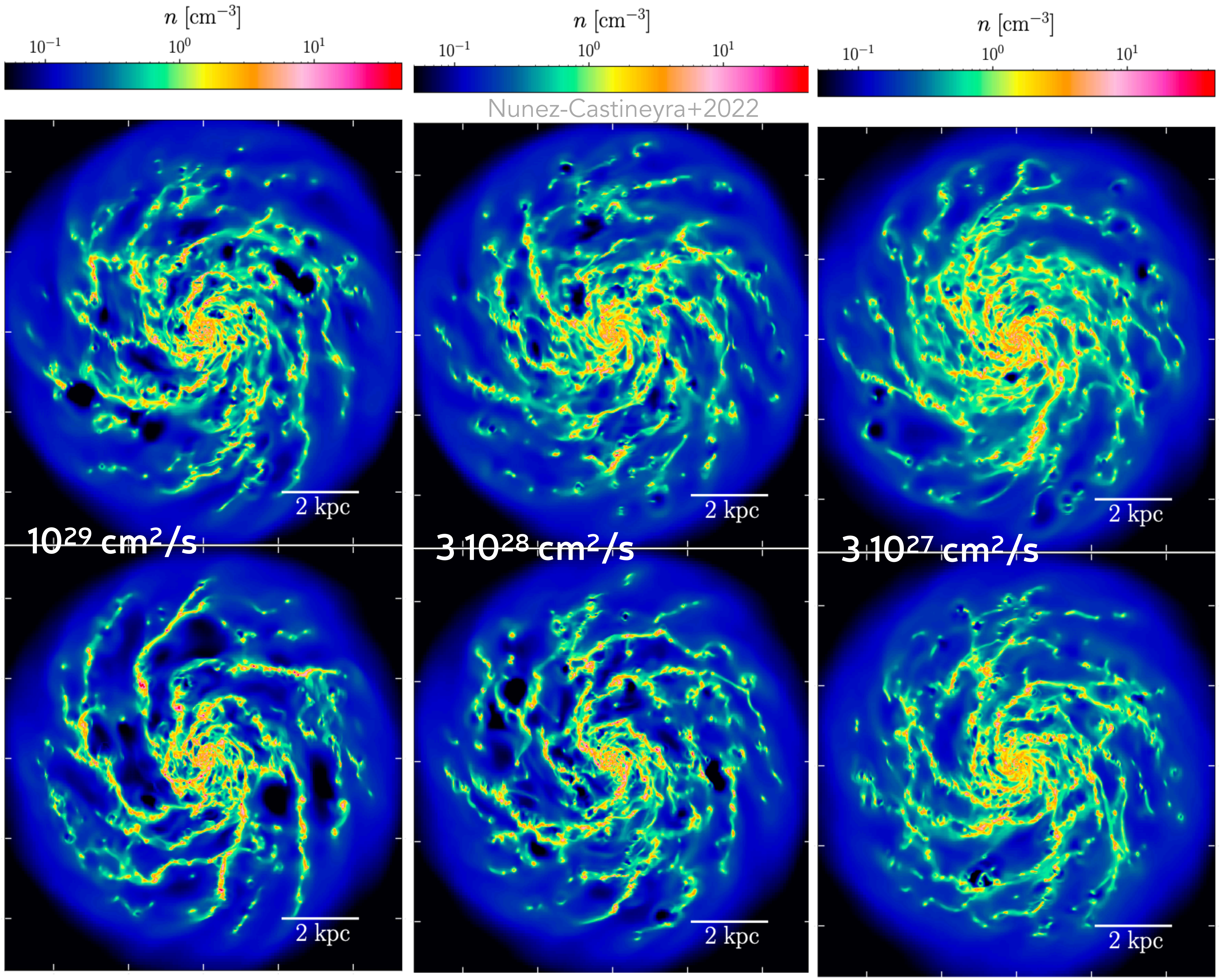
gas & star-formation response to cosmic rays

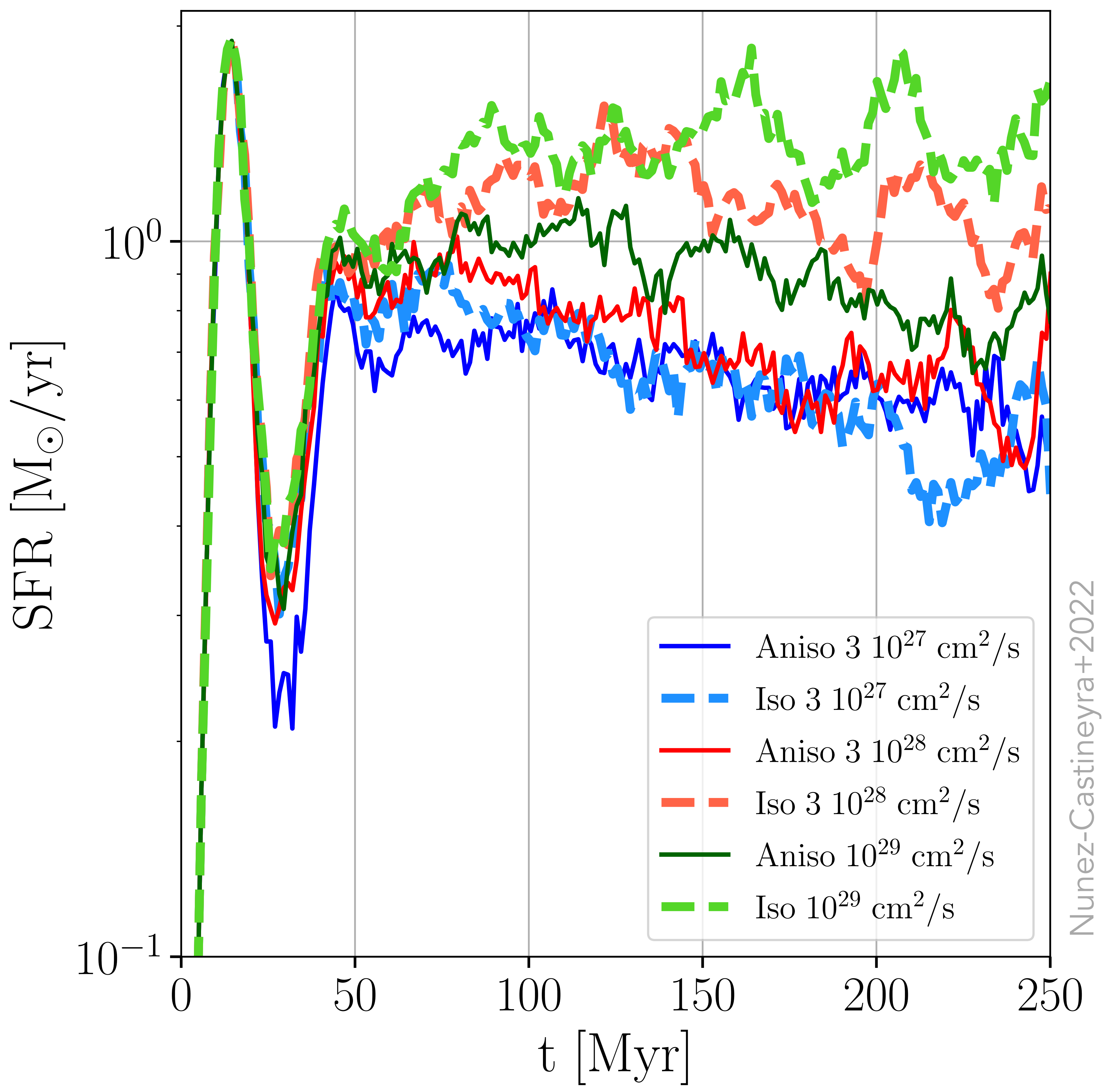
- R > 2 kpc : increased P_{CR} pressure => SFR suppressed by < 50%
- R < 2 kpc : increased P_{CR} and <B>x3.5 where $e_{CR} \gtrsim$ 1-2 eV/cm³ => SFR suppressed by 2.5
- not SN-induced turbulence, but role of increased fountains? gal. wind?

smoother gas & suppressed SFR
if slow/anisotropic CR diffusion

anisotropic

isotropic





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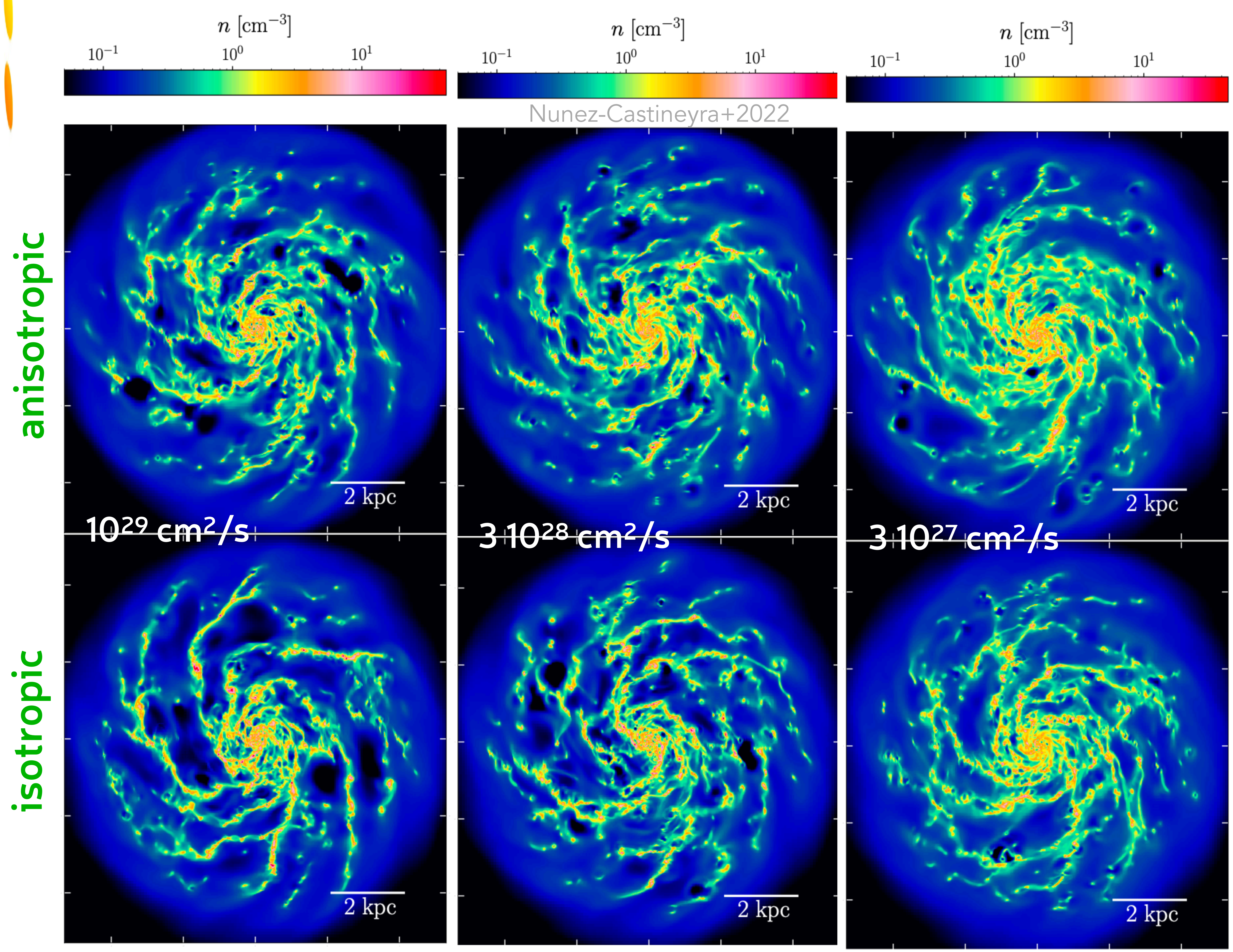
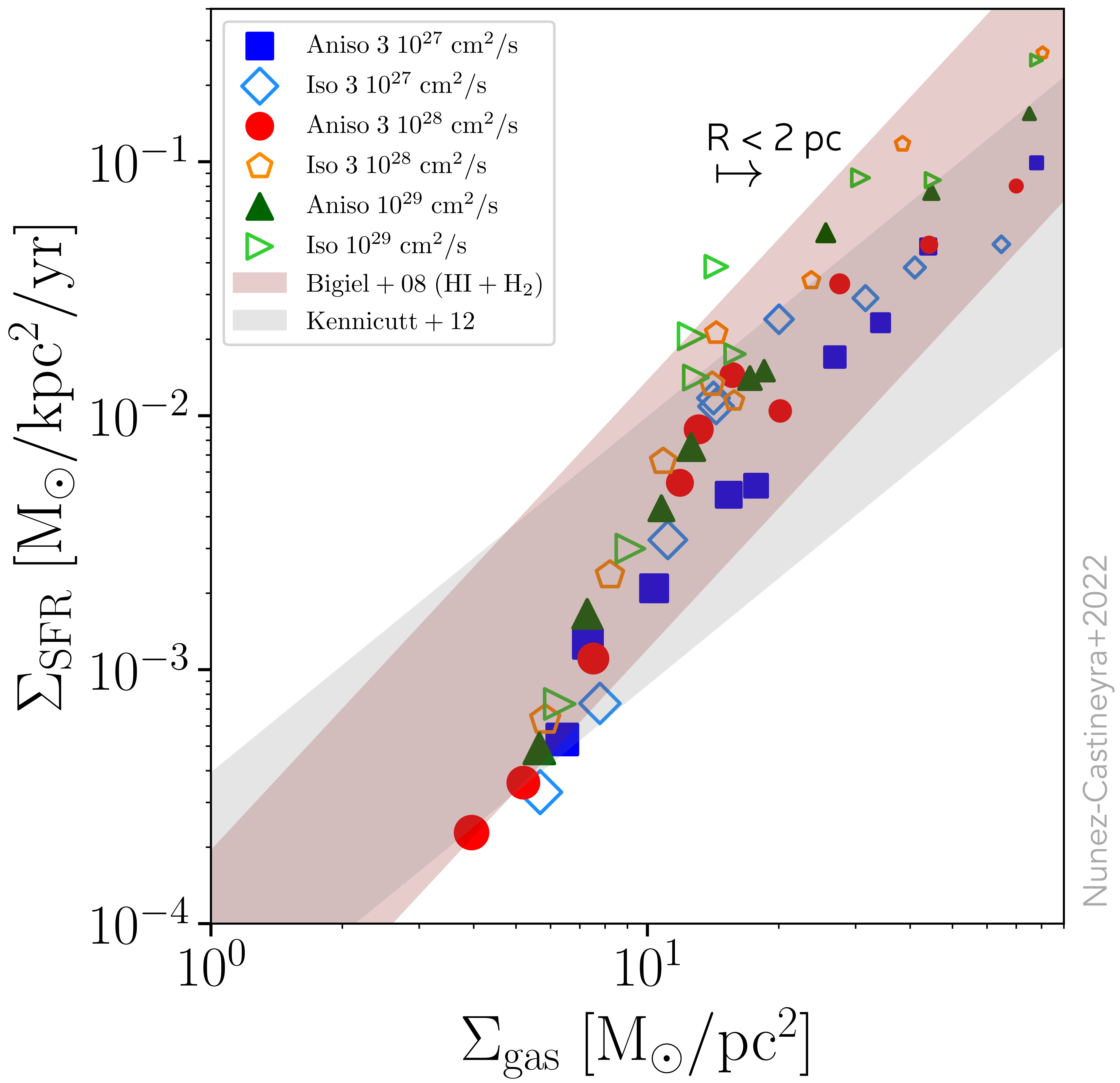
- not SN-induced turbulence, but role of increased fountains? gal. wind?

smoother gas & suppressed SFR if slow/anisotropic CR diffusion

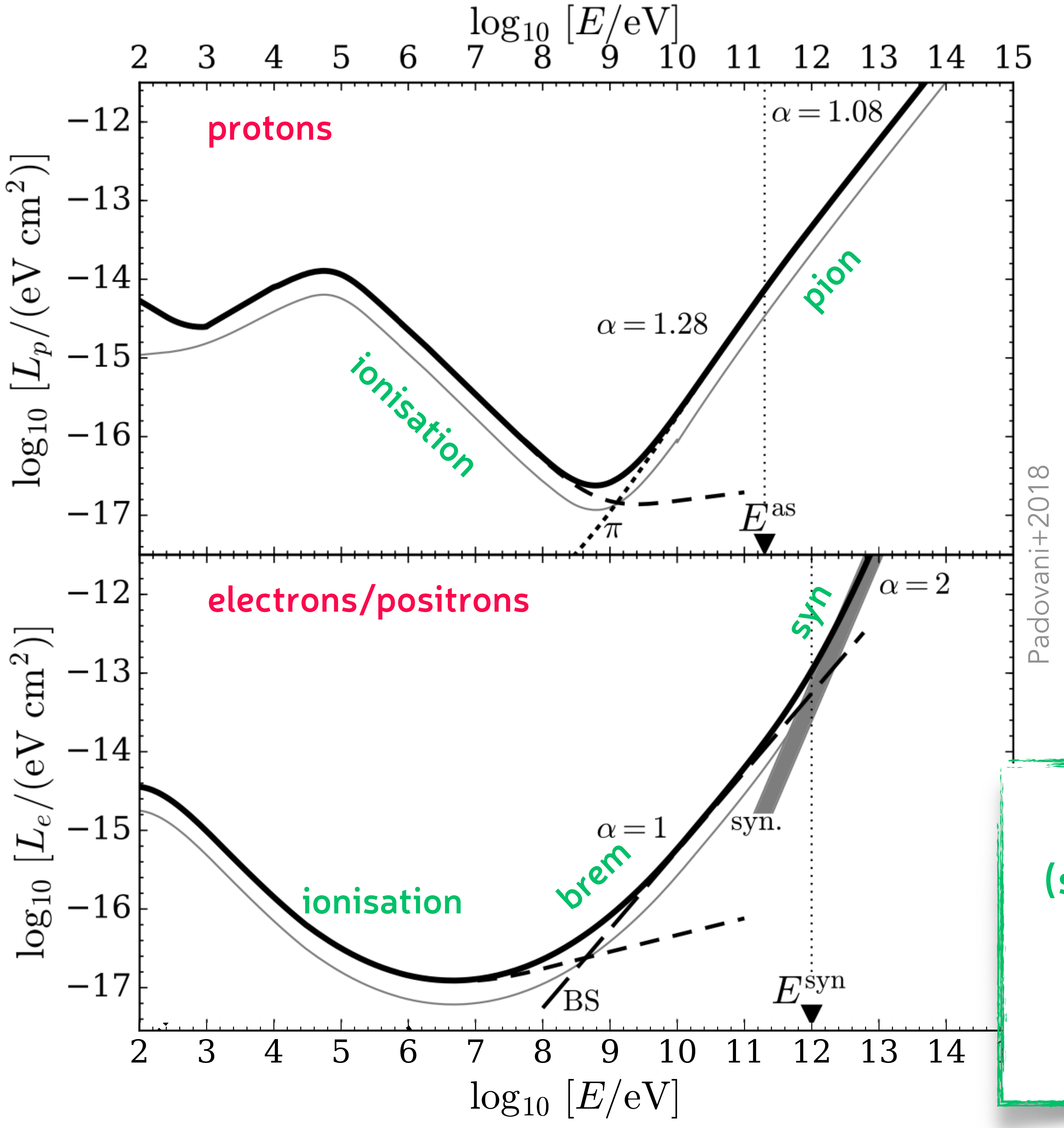




low-energy, ionising cosmic rays

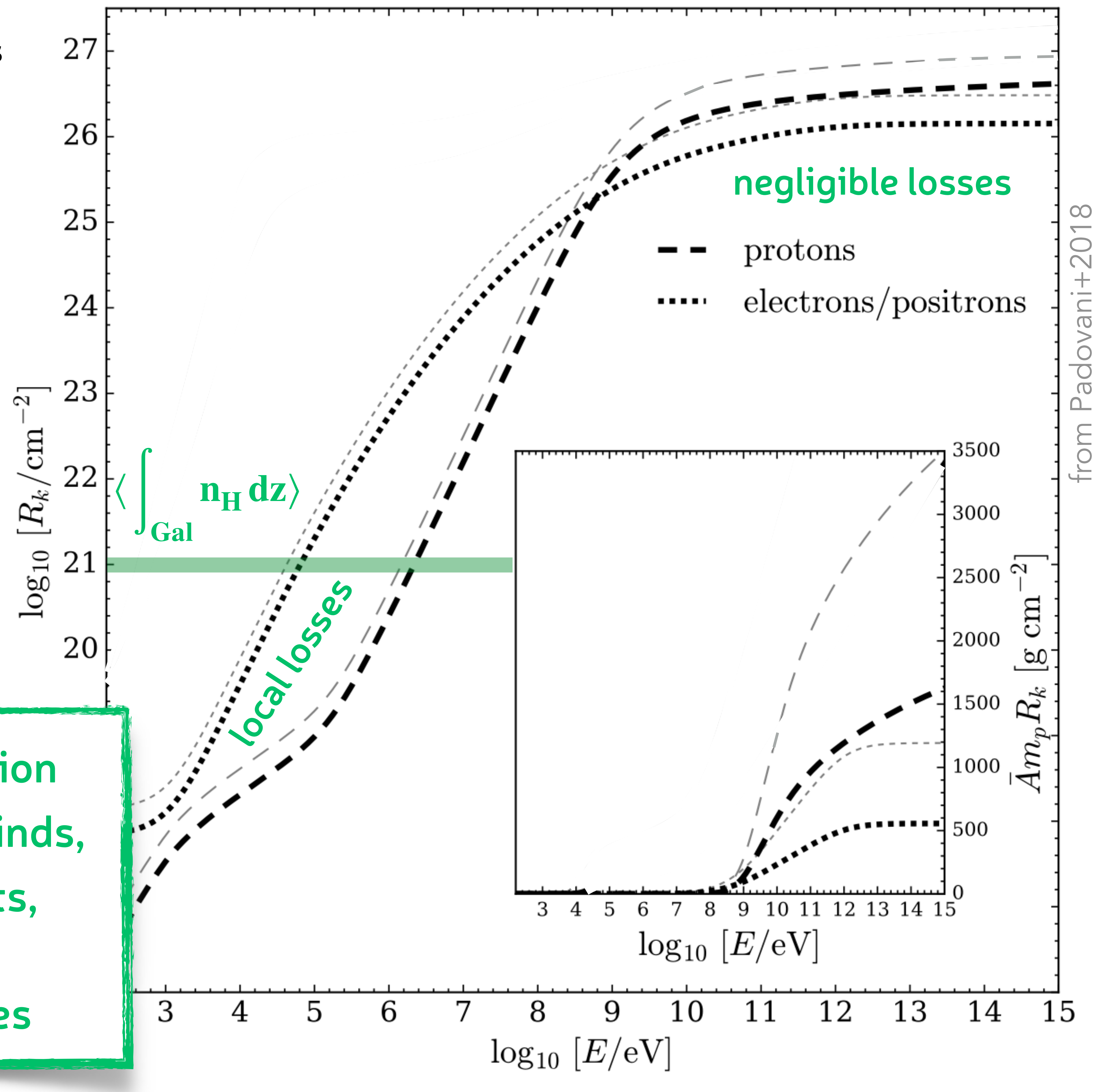
cosmic-ray losses

- loss functions
  - continuous loss $L(E) = \int_0^{\Delta E_{max}} E' \frac{d\sigma(E,E')}{dE'} dE'$
  - catastrophic loss $L(E) \sim E\sigma(E)$
- range functions $\int_s n_{ISM}\, ds = R_k(E_{initial}) - R_k(E_{final})$



in molecular gas (thick curves)

in atomic gas (thin curves)



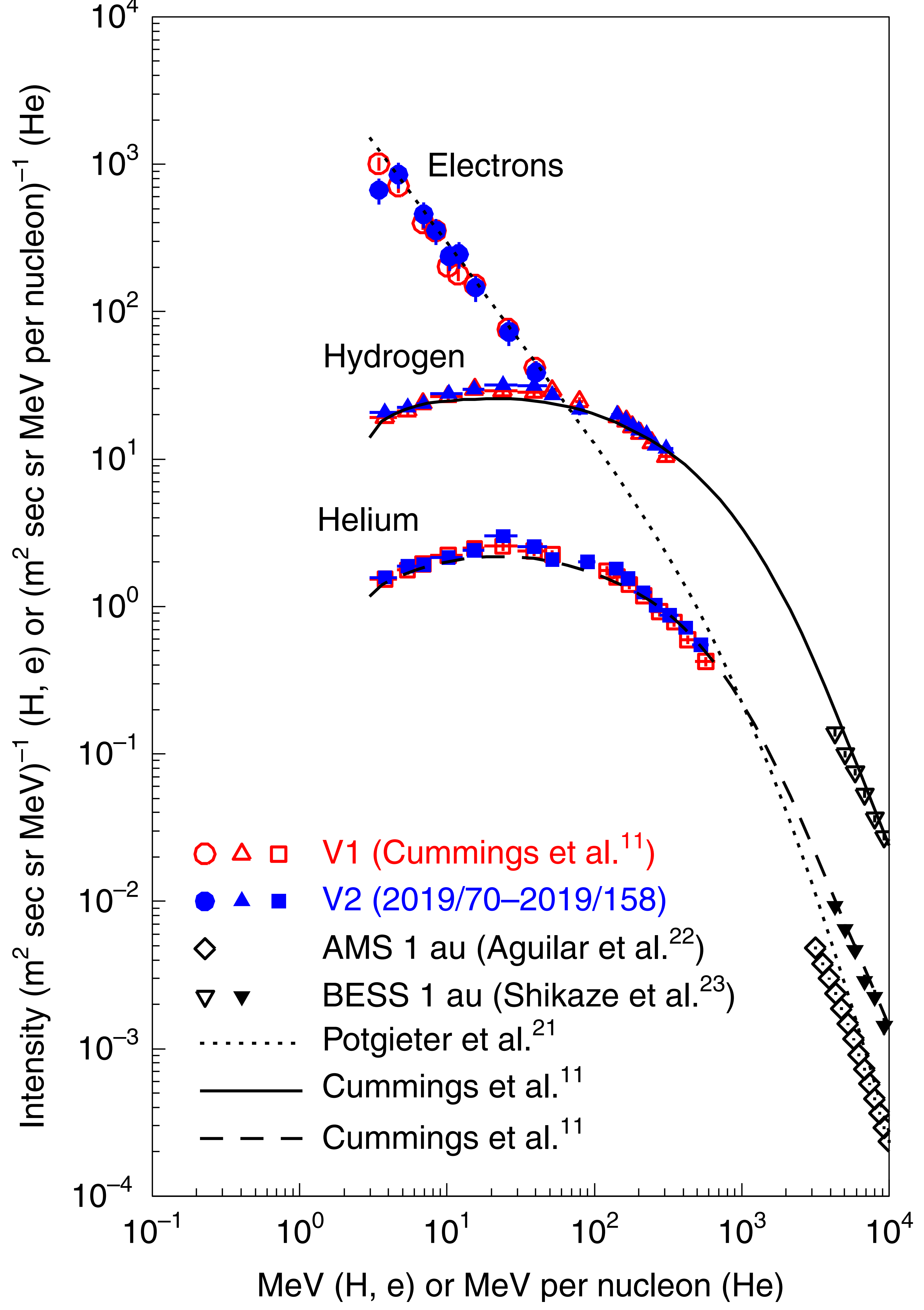
local production (star flares+winds, protostar jets, shocks…)

& local losses

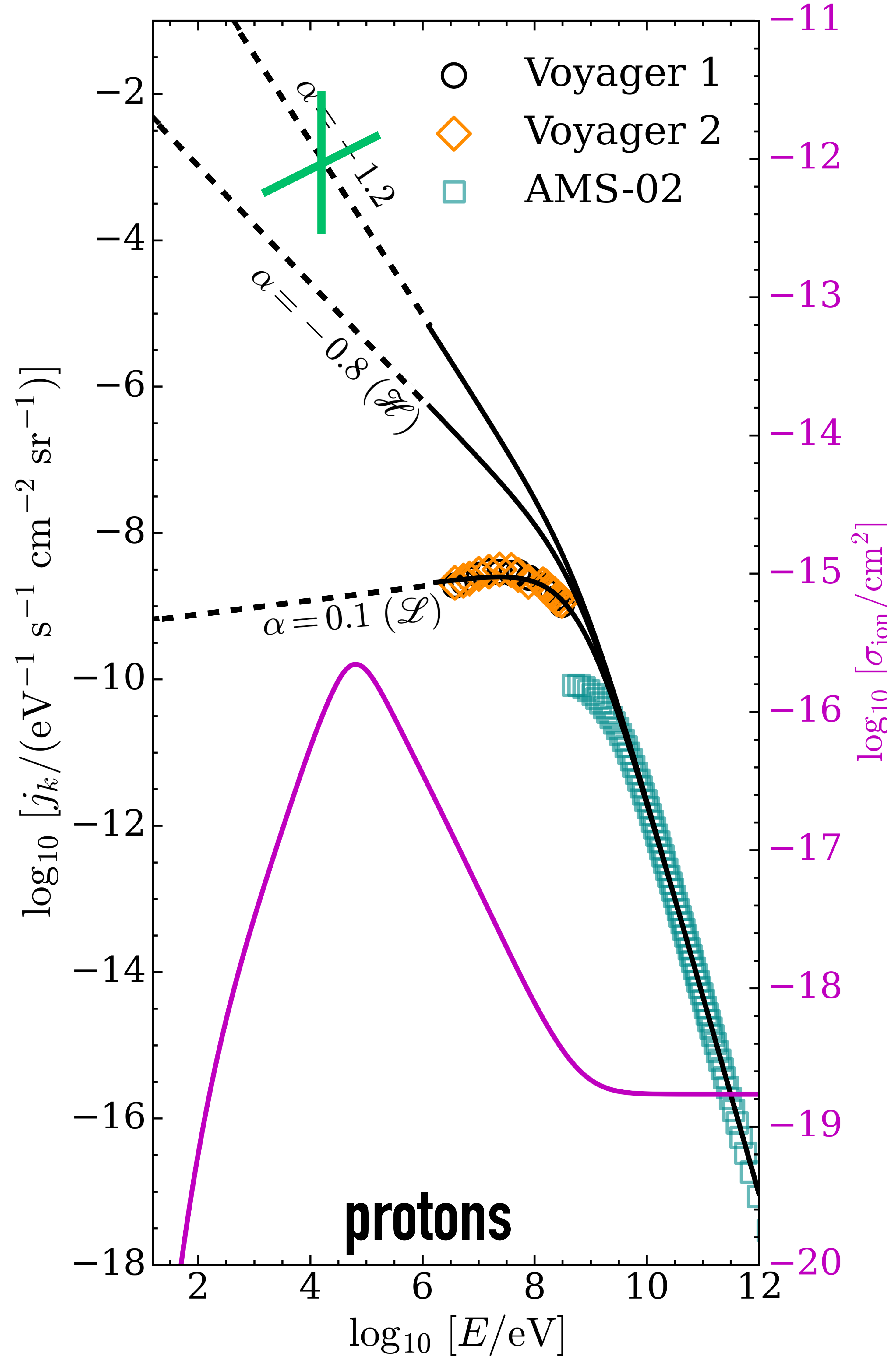
low-energy cosmic-ray gradients

- from Voyager CR data : $\zeta_{CR}^{H} = (1.51 - 1.64) \times 10^{-17}\,\mathrm{s}^{-1}$ Cummings+2016 $\zeta_{CR}^{H} \approx 0.65\zeta_{CR}^{H_2}$

Stone+2019

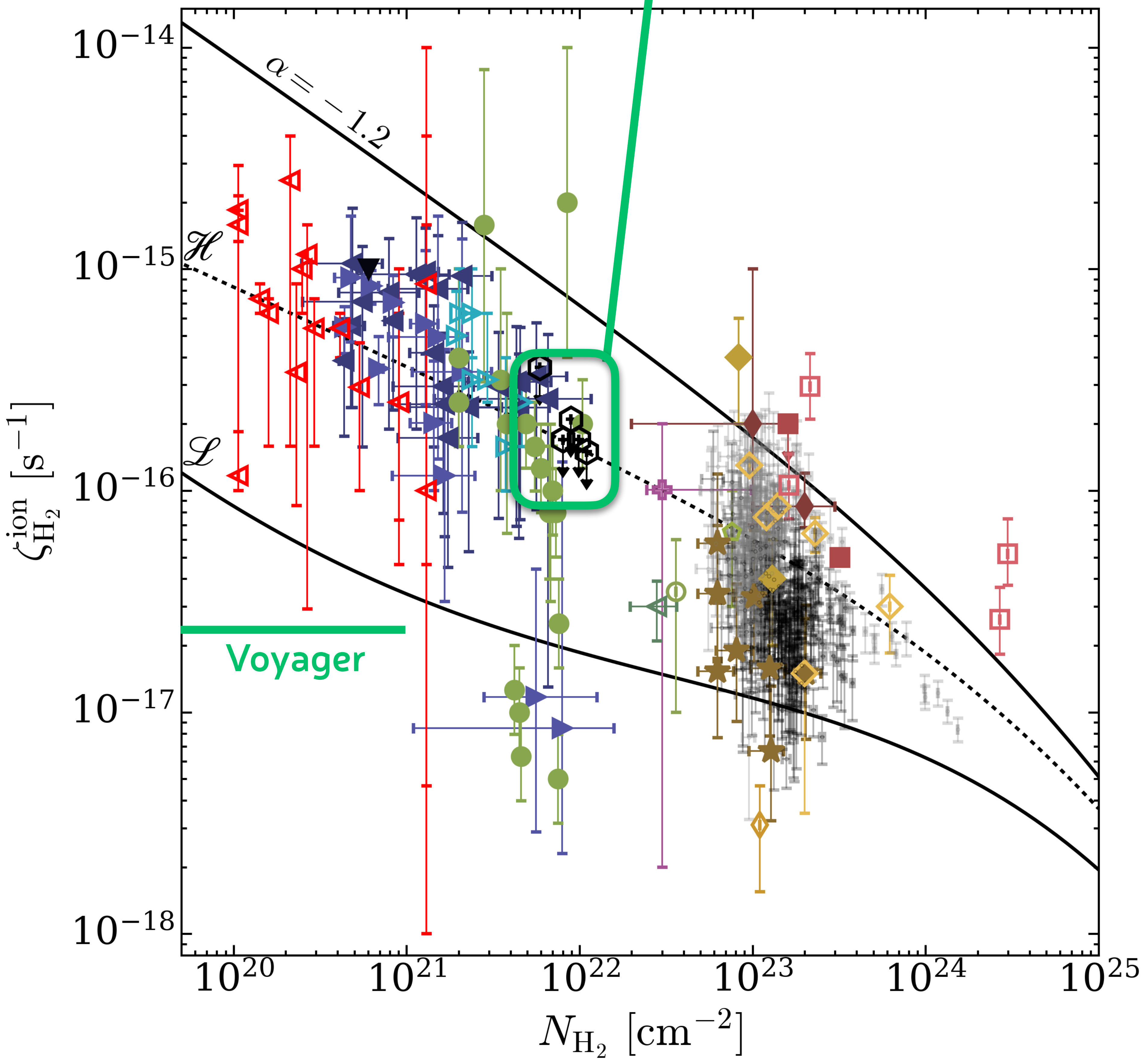


Padovani+2022.

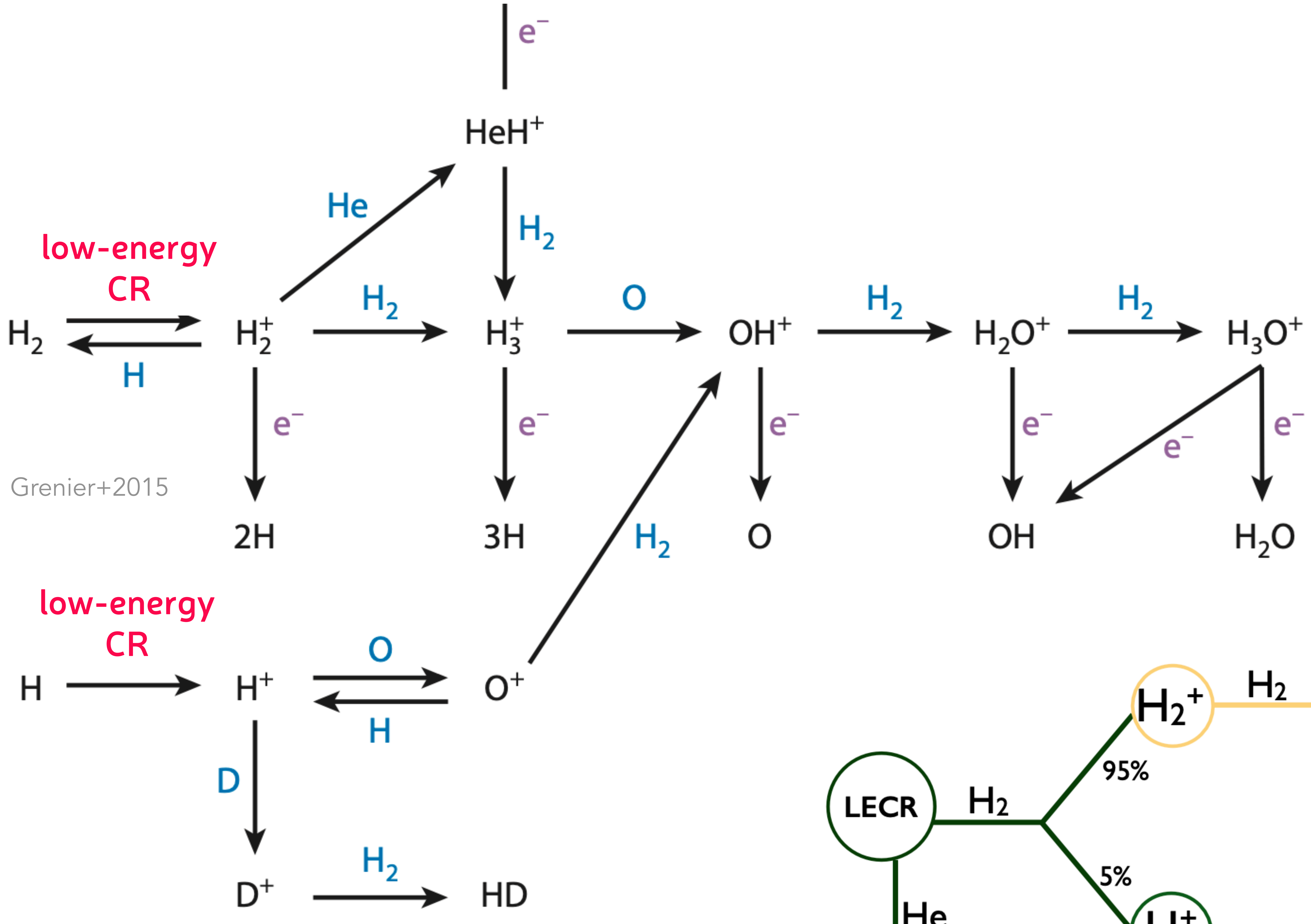


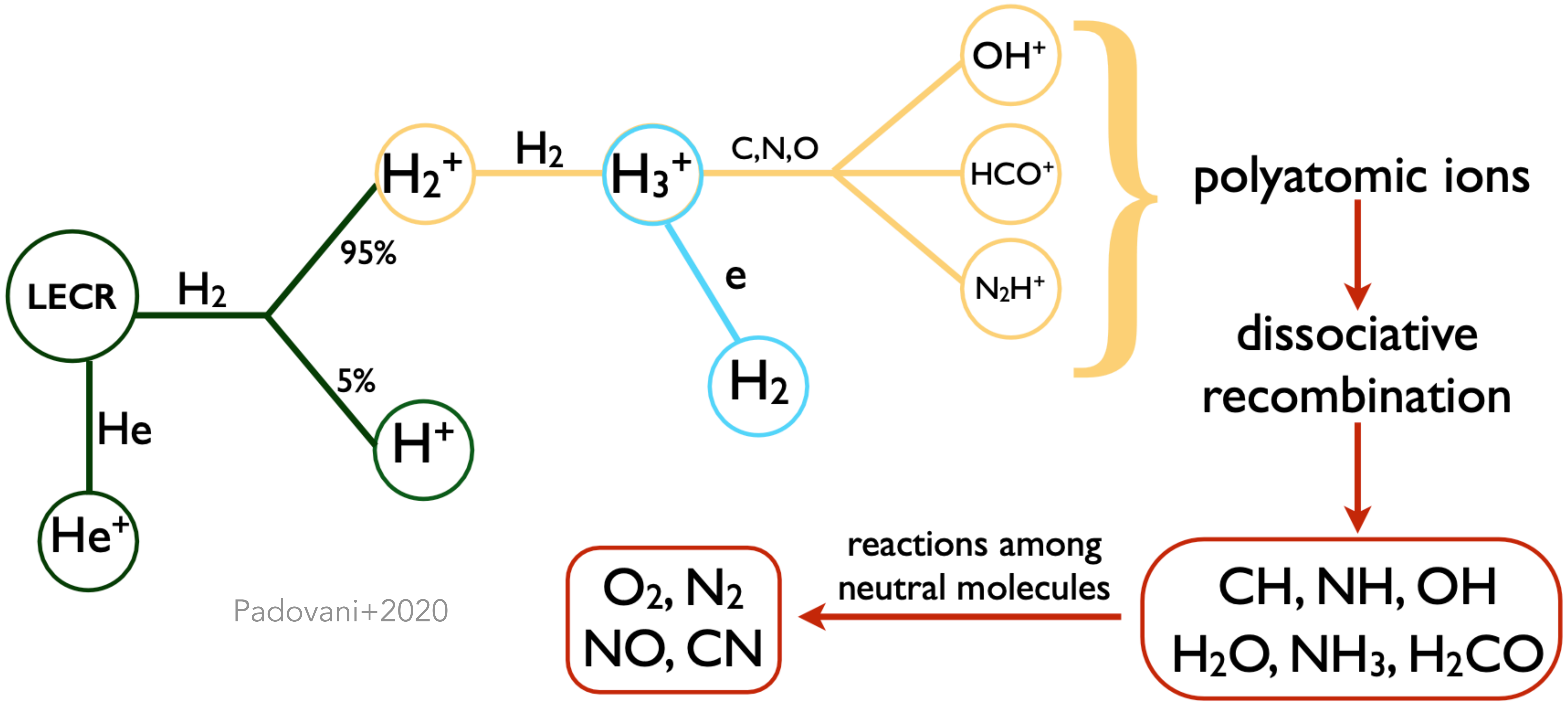
Bialy+2022
CR-excited H_2 lines
JWST ζ upper limits

Padovani+2023



cosmic-ray induced interstellar chemistry

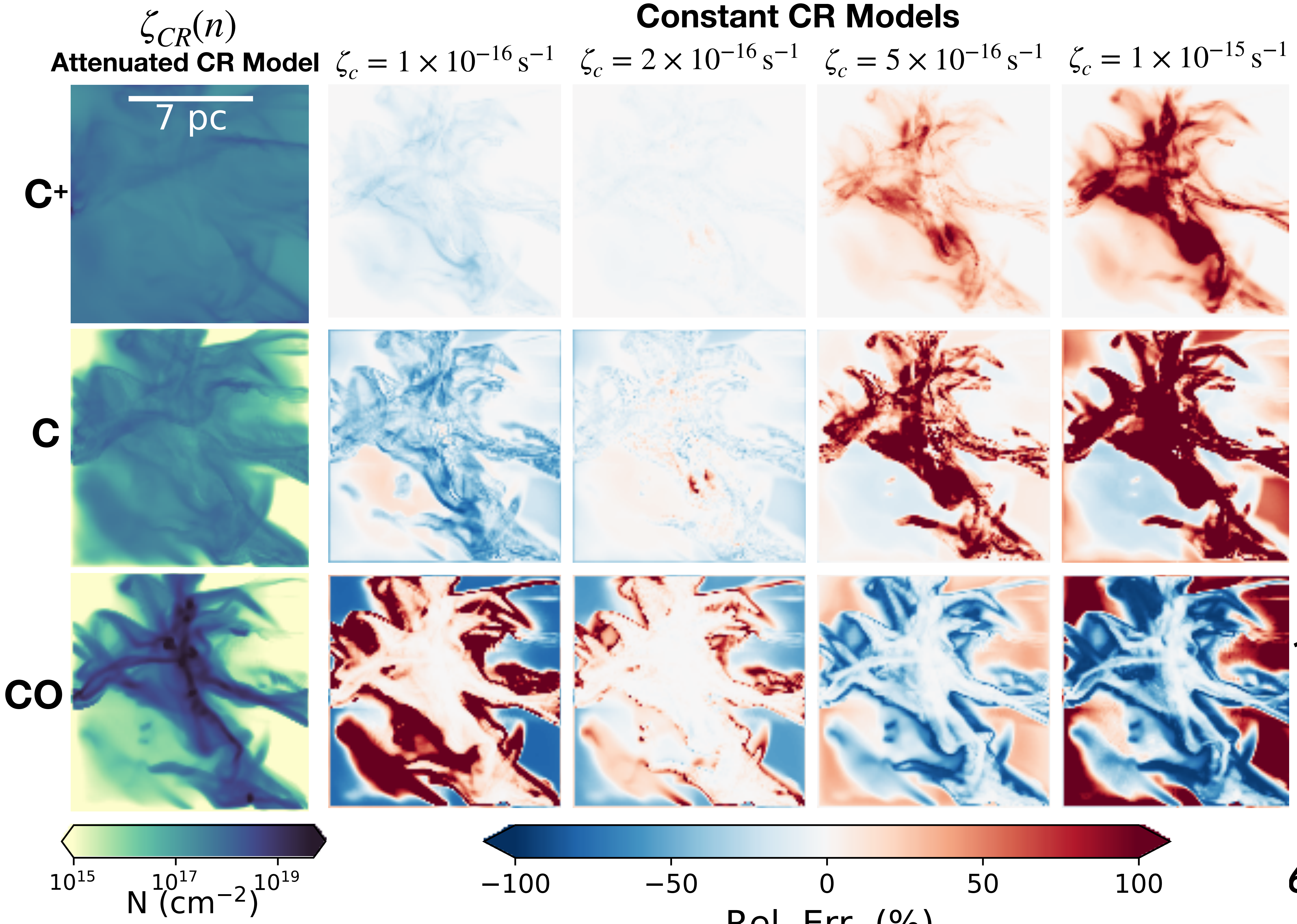




- hydrolysis of HCN oligomers => amino acids

low-energy cosmic-ray induced interstellar chemistry

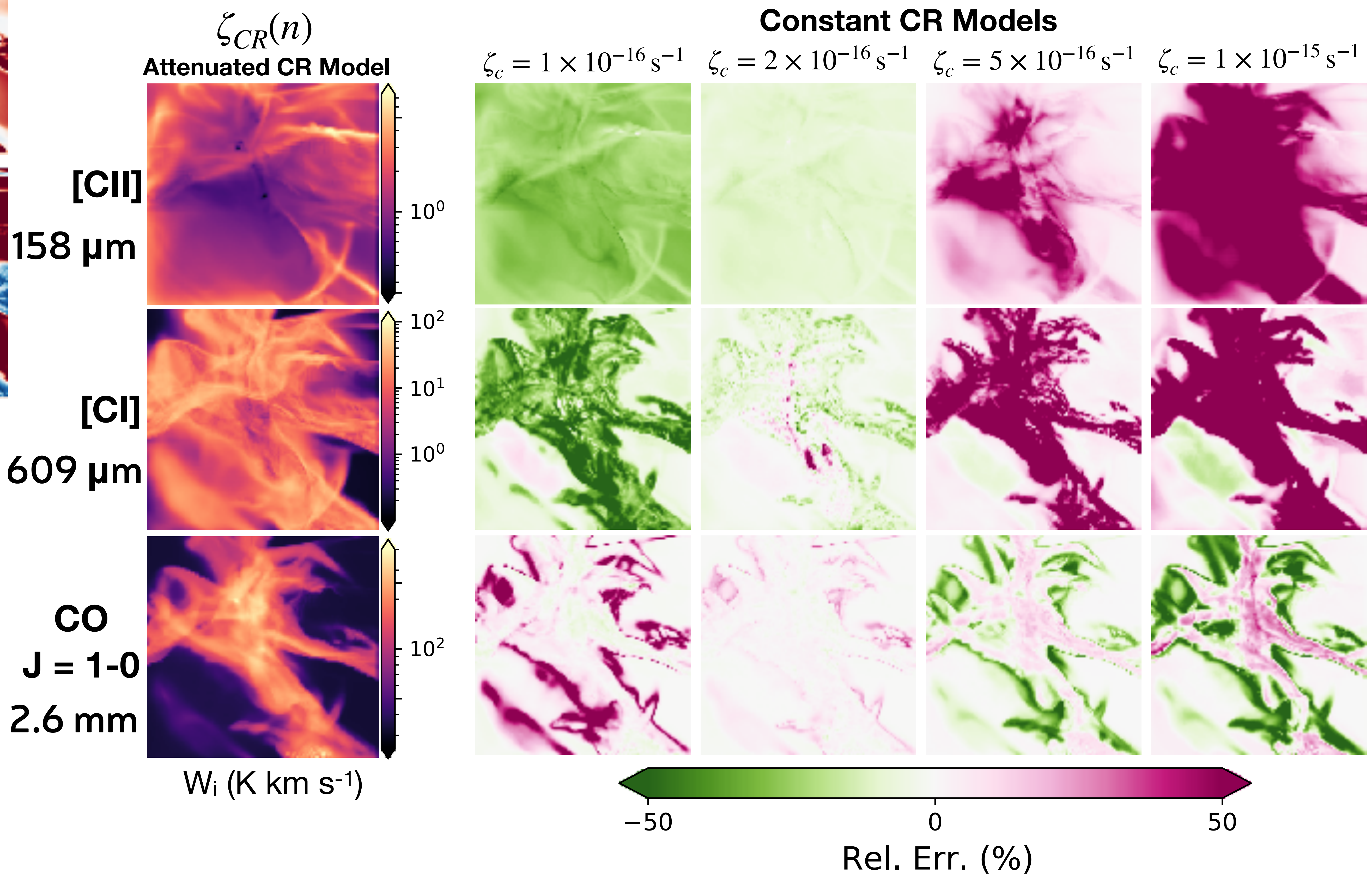
- variations in column densities through the cloud



Gaches+2022

significant impact of ζ_{CR} on
CII (158 µm), CI (609 µm), and CO (J=1-0)
cooling intensities in a cloud

- variations in cooling line intensities

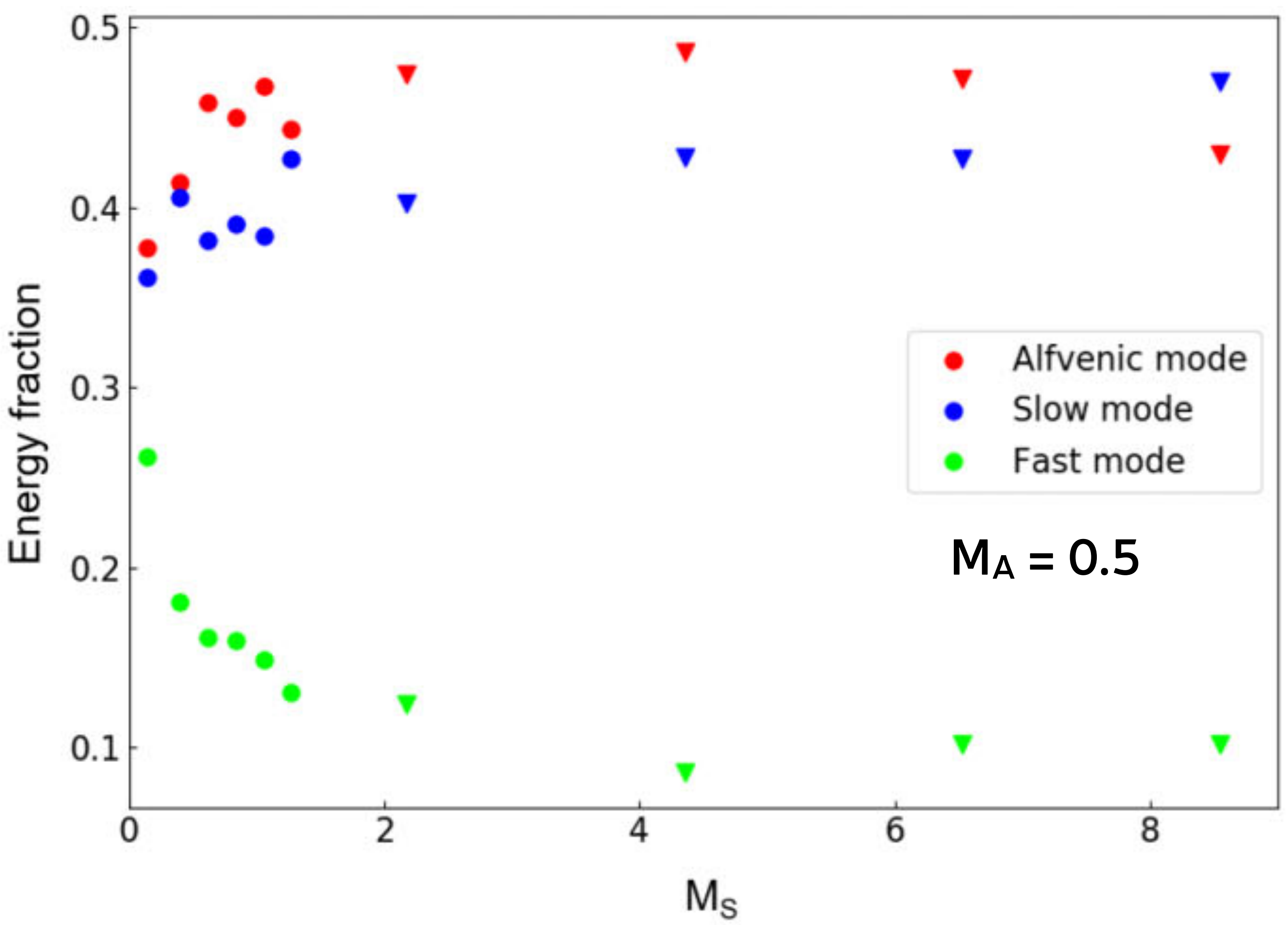


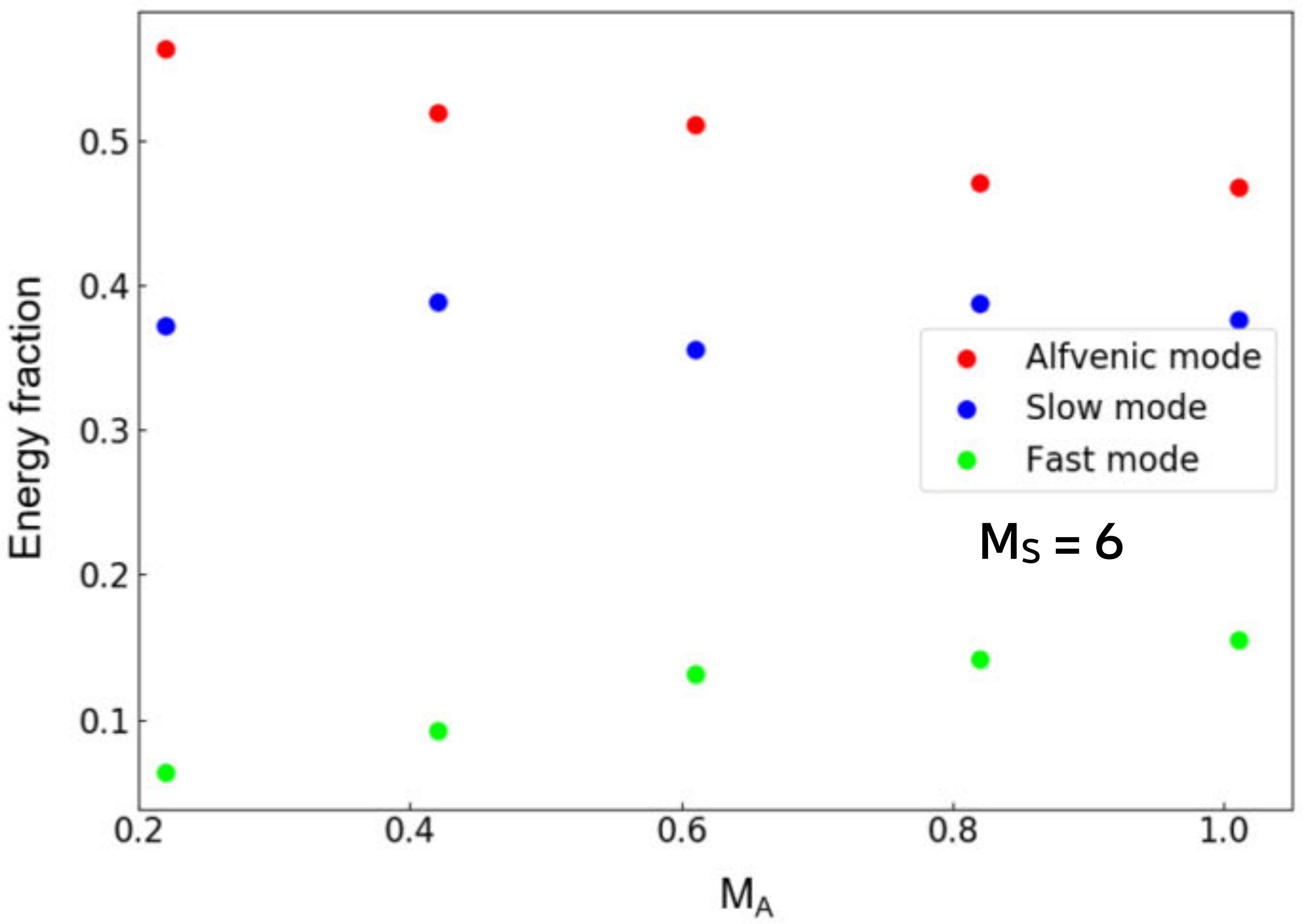
How do GeV cosmic rays travel?

3 fundamental modes of MHD turbulence

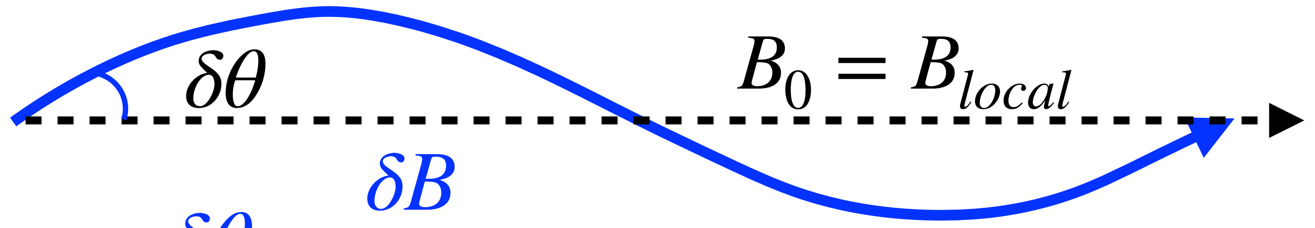
- energy fraction as a function of the sonic and Alfvénic Mach numbers

Hu+ 2022





- Alfvén transverse wave driven by magnetic tension propagating along B at v_A.

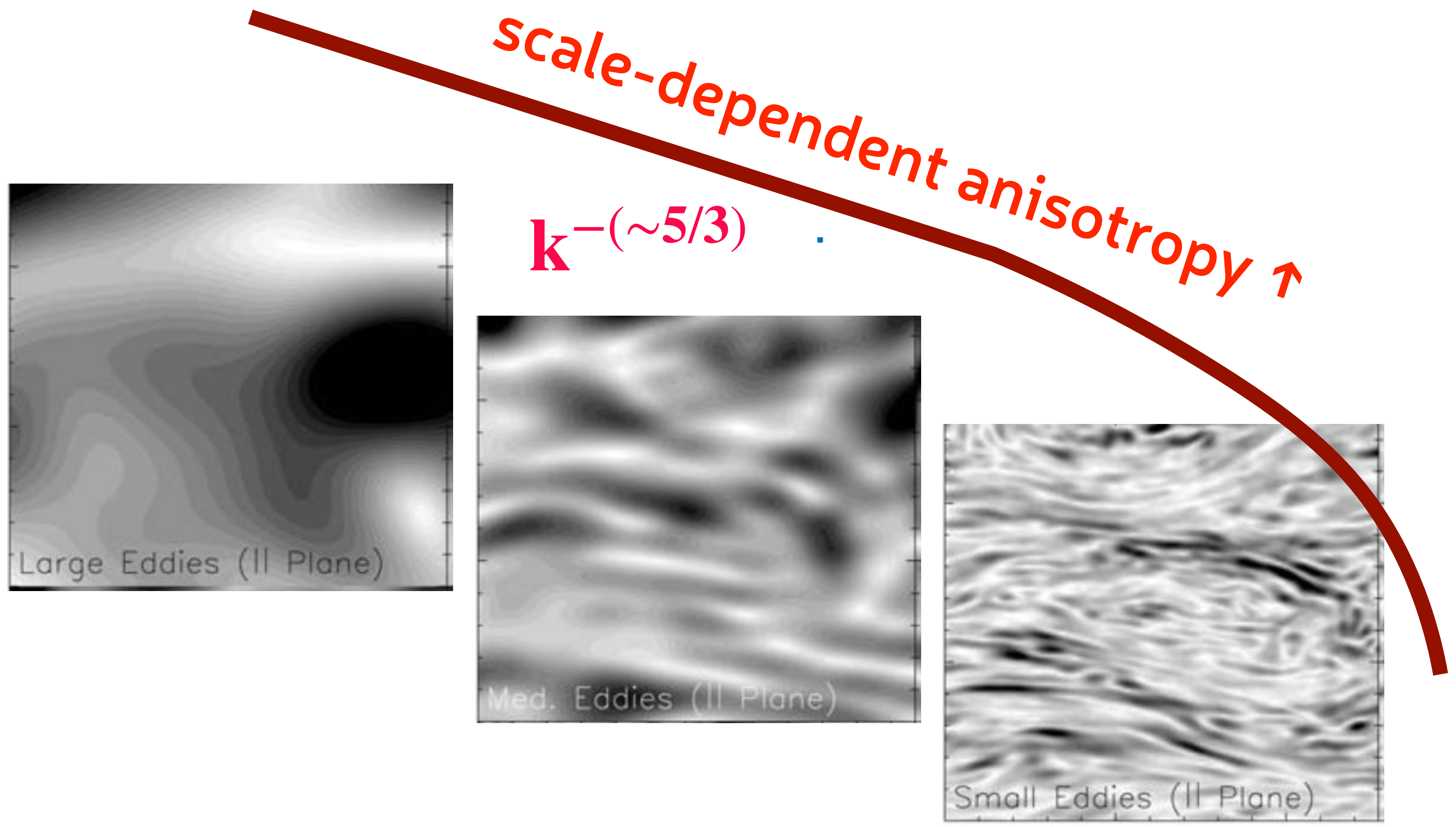


$$\delta\theta \sim \frac{\delta B}{B_0}$$

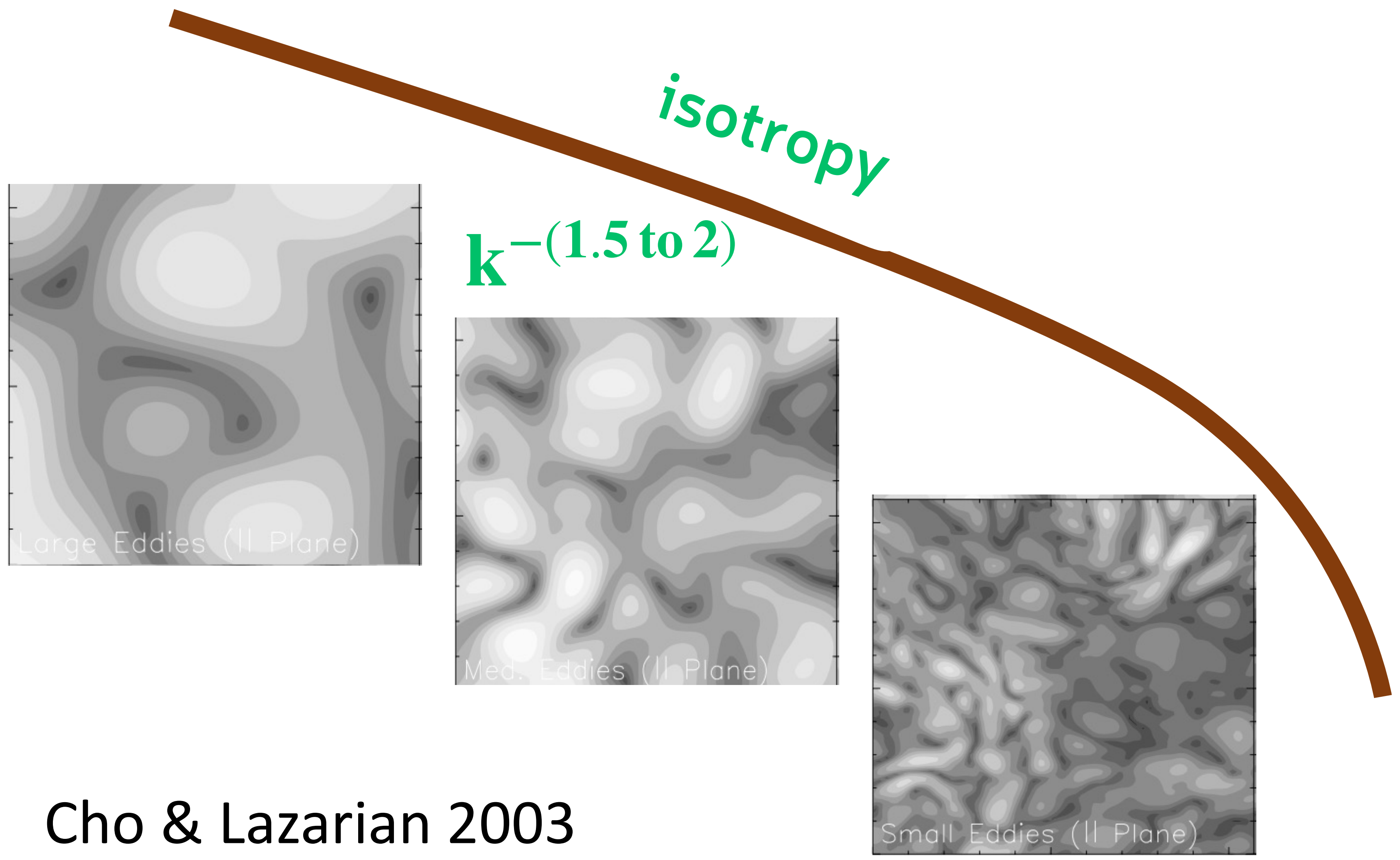
$$\frac{\omega}{k} = v_A = \frac{B}{\sqrt{\mu_0 \rho_{ion}}}$$

- cascading and anisotropy of the slow mode imposed by Alfvén modes

Alfvén modes



Fast modes



Cho & Lazarian 2003
Hu et al. 2024

cosmic-ray transport modes

- gyro pulsation : $\Omega_{gyr} = \dfrac{|q|B_0}{\gamma mc}$
- Larmor gyroradius $R_{gyr} = \dfrac{p_\perp}{|q|B} = \dfrac{v_\perp}{\Omega_{gyr}}$

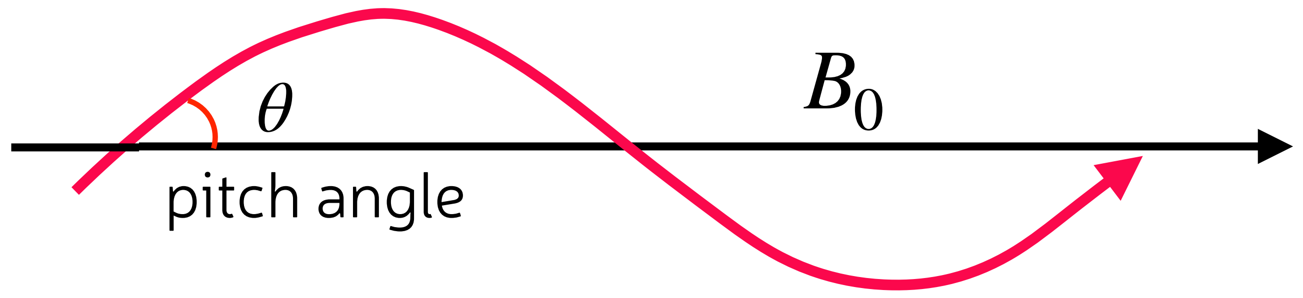
$$\mathbf{R_{gyr} = 1\,.\,2\,10^{-6}}\ \text{pc}\ \left(\frac{\mathbf{B}}{\mathbf{1\,nT}}\right)^{-1}\left(\frac{\mathbf{E_{kin}}}{\mathbf{10\,GeV}}\right)$$

$$\mathbf{R_{gyr} = 0\,.\,25}\ \text{au}\ \left(\frac{\mathbf{B}}{\mathbf{1\,nT}}\right)^{-1}\left(\frac{\mathbf{E_{kin}}}{\mathbf{10\,GeV}}\right)$$

- magnetic moment $\mu_B = \dfrac{p_\perp^2}{2B}$

(conserved if adiabatic conditions B ~ constant within R_{gyr} and T_{gyr})

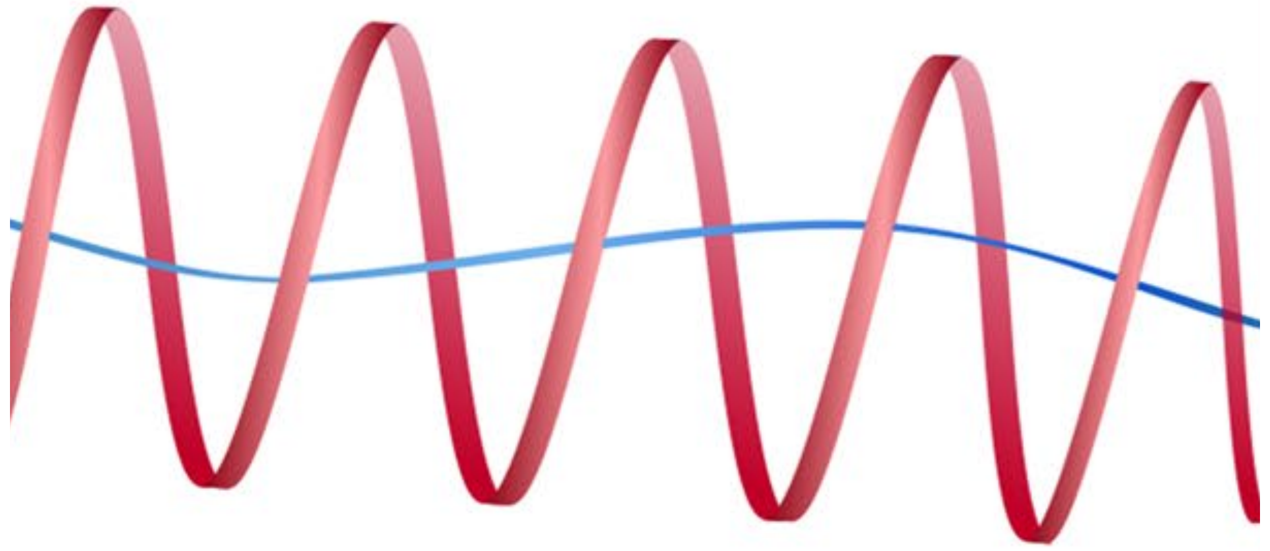
- pitch angle



$$\mu = \cos\theta_{\mathbf{pitch}} = \frac{\vec{\mathbf{p}}\cdot\vec{\mathbf{B}}}{\mathbf{pB}} = \frac{\mathbf{v_\parallel}}{\mathbf{v}}$$

$$\mathbf{v_\perp = v\sqrt{1-\mu^2}}$$

weak B or large E

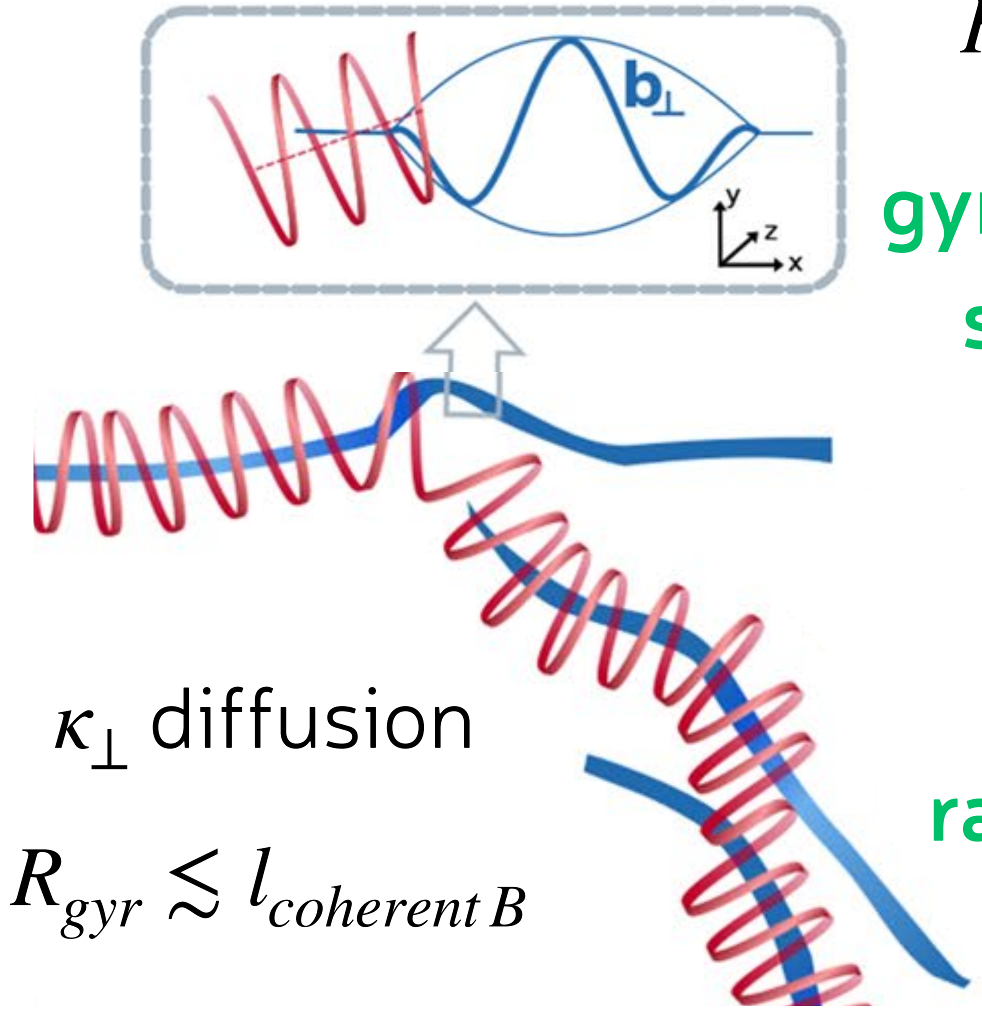


quasi-ballistic $R_{gyr} \gg l_{coherent\,B}$

$\kappa_\parallel$ diffusion

$R_{gyr} \lesssim \lambda_B$

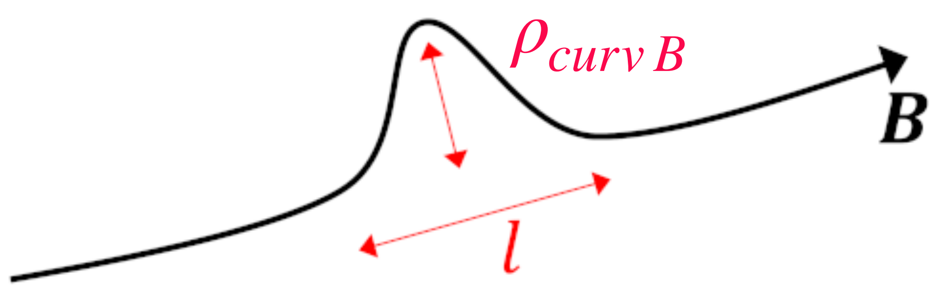
gyro-resonant scattering



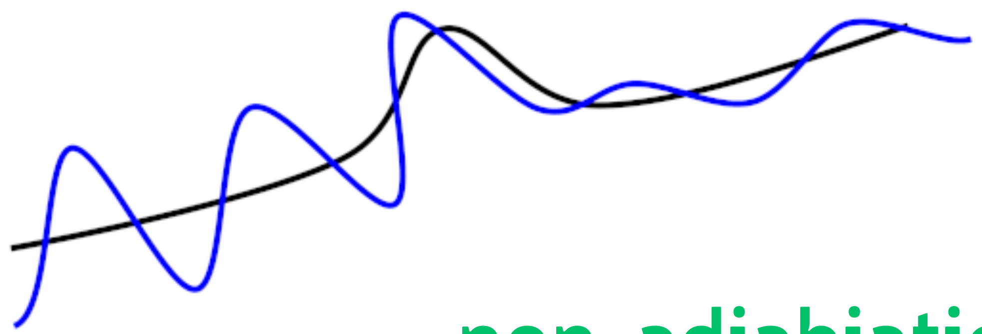
$\kappa_\perp$ diffusion

$R_{gyr} \lesssim l_{coherent\,B}$

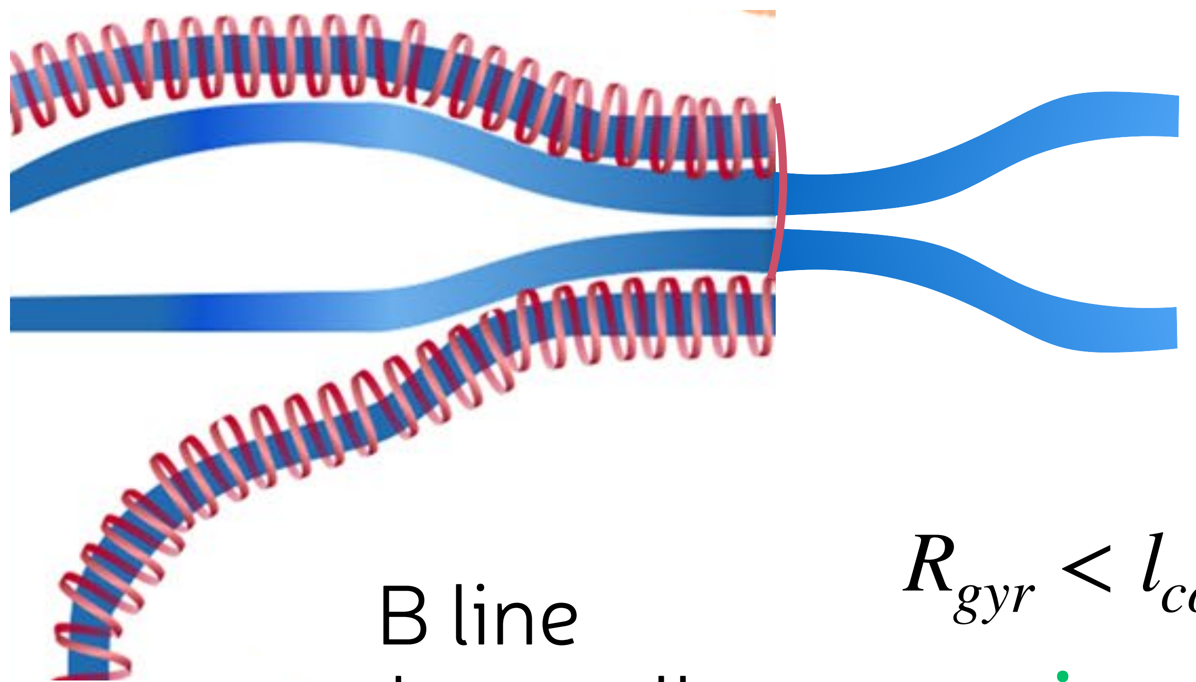
B line random walk



$R_{gyr} \approx \rho_{curv\,B}$



non-adiabatic kicks in kinks



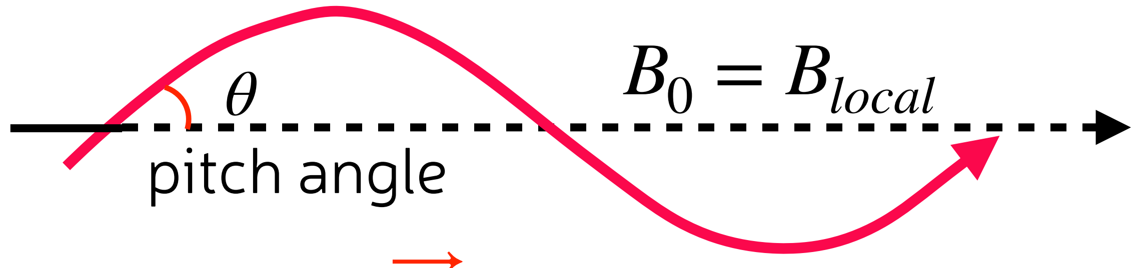
B line random walk

$R_{gyr} < l_{coherent\,B}$

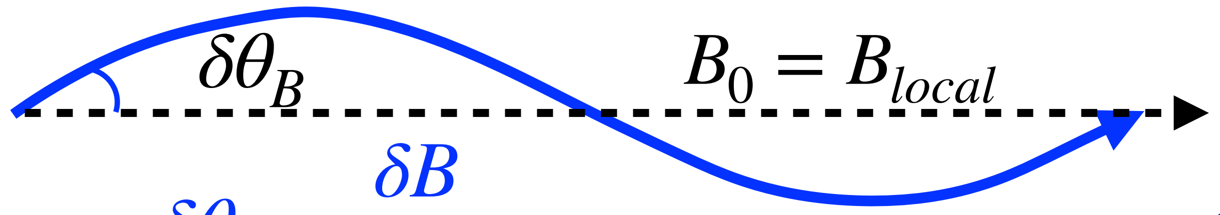
mirroring

strong B or low E

gyro-resonant pitch-angle diffusion



$$\mu = \cos\theta_{pitch} = \frac{\vec{p}\cdot\vec{B}}{pB} = \frac{v_\parallel}{v} \qquad v_\perp = v\sqrt{1-\mu^2}$$



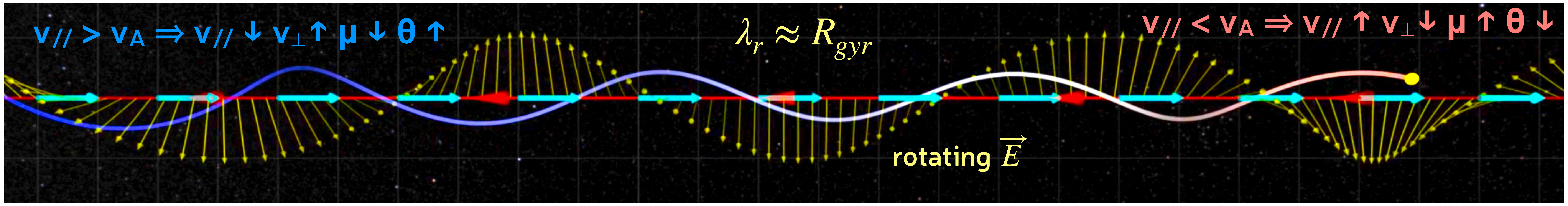
$$\delta\theta_B \sim \frac{\delta B}{B_0} \qquad v_A^2 = \frac{B^2}{\mu_0\,\rho_{ion}}$$

- **gyro-resonant scattering** on all MHD waves, in particular Alfvén waves,
  - mediated by the Lorentz force
  - gyro-resonance when the Doppler-shifted rotation rate ω_r of a circularly polarised wave is a multiple of the CR gyro frequency.

$$\mathbf{k_\parallel v_\parallel} - \omega_\mathbf{r} = \pm\,\mathbf{n}\,\mathbf{\Omega_{gyr}}$$

=> interaction with the rotating $\vec{E}$ of the Doppler-shifted wave rotating in the same direction and at the same frequency as the CR rotation in its rest frame.

  - n = 1 for Alfvén waves propagating // B₀ $\quad \omega_r = kv_A \quad$ hence $\quad k_\parallel(v_\parallel - v_A) = \pm\,\Omega_{gyr}$

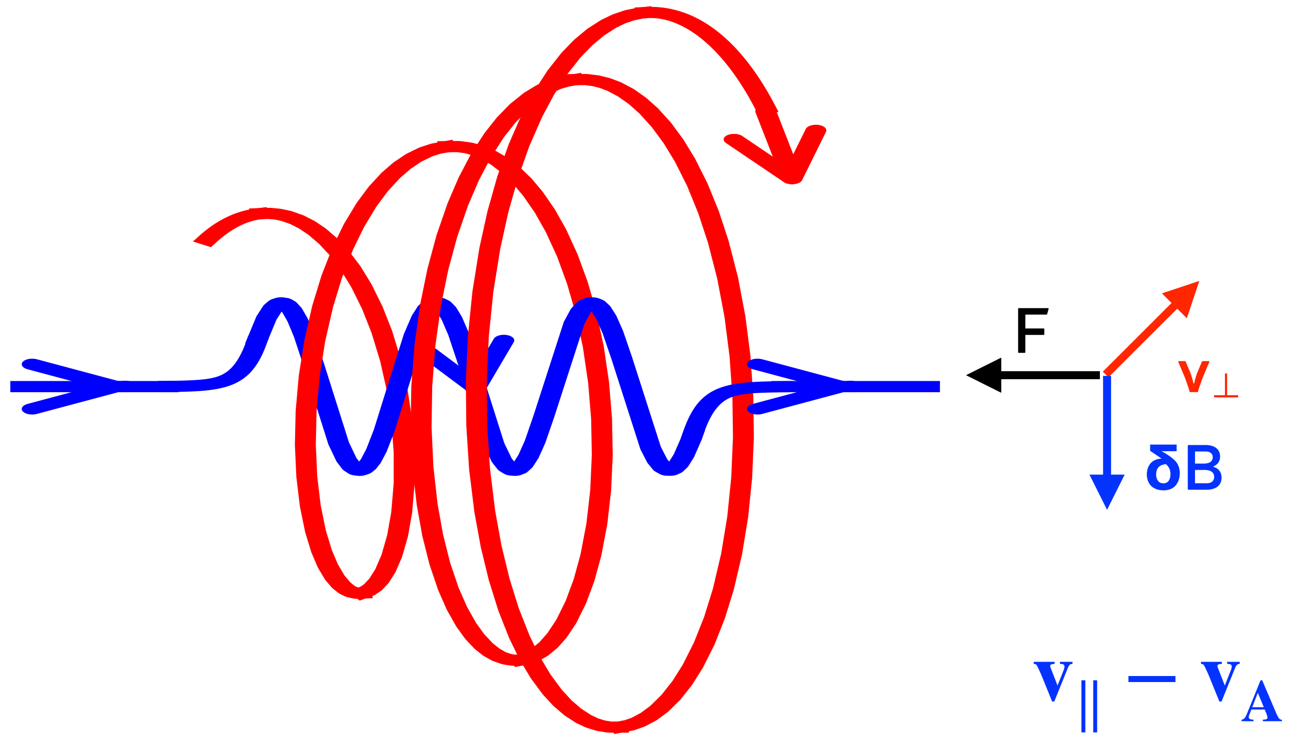


  - implying a random "walk" in $\mu = \dfrac{v_\parallel}{v}$

described by diffusion with scattering deviation $|\delta\theta| \sim \delta\theta_\mathbf{B} \sim \delta\mathbf{B}/\mathbf{B}$

and scattering frequency

$$\nu_{sc} \approx \frac{\langle \delta\theta^2 \rangle}{\delta t} \sim \nu_{gyr}\left(\frac{\delta B}{B_0}\right)^2$$



no $\vec{E}$ in the wave frame
$$\Rightarrow (\mathbf{v_\parallel} - \mathbf{v_A})^2 + \mathbf{v_\perp^2} = \mathbf{cte}$$
$$\mathbf{v_\parallel} - \mathbf{v_A} \downarrow\ \Rightarrow \mathbf{v_\perp} \uparrow\ \Rightarrow \theta_\mathbf{pitch} \uparrow\ \Rightarrow \mu \downarrow$$
and vice versa

  - diffusion mean free path

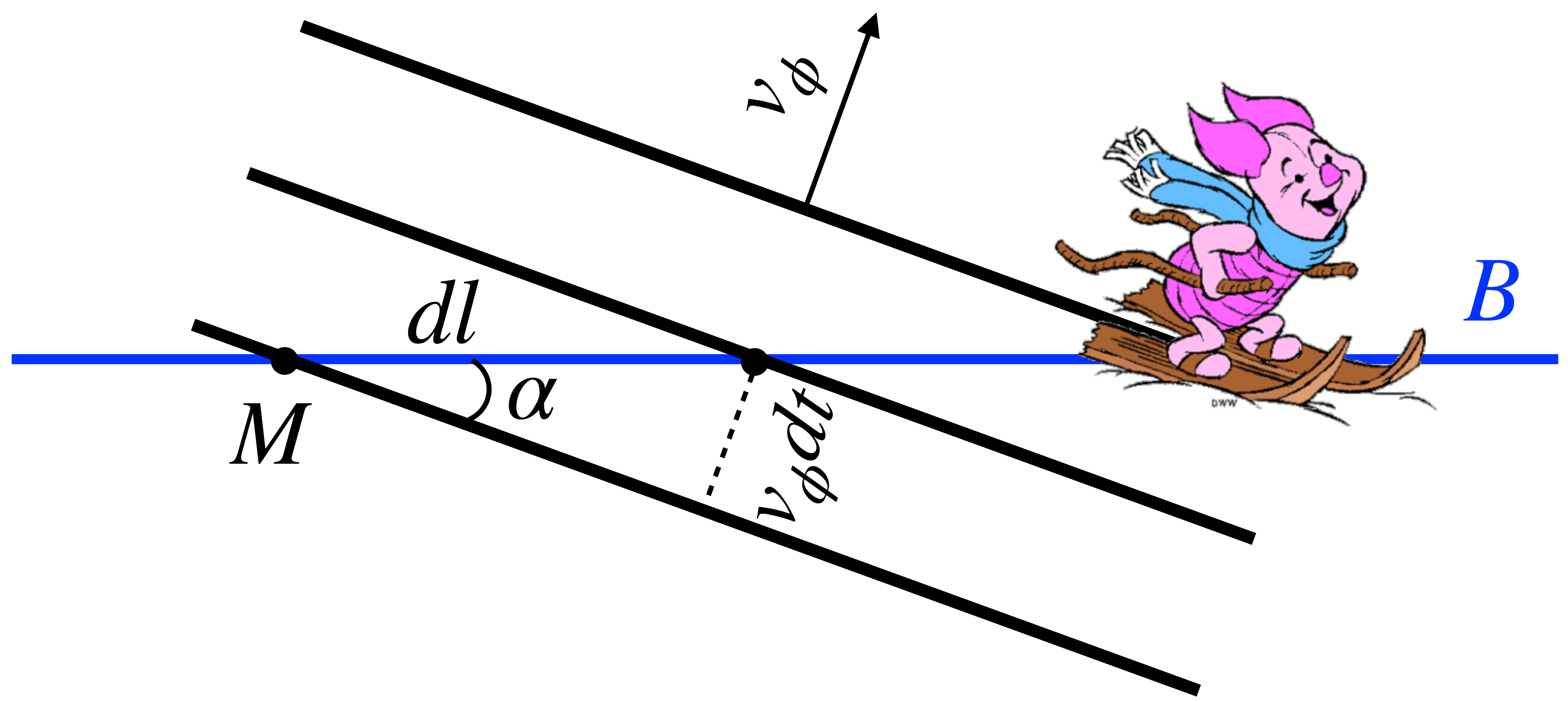
$$\lambda_{sc} = \frac{\beta c}{\nu_{sc}} \propto R_{gyr}\left(\frac{B_0}{\delta B}\right)^2$$

  - diffusion coefficient

$$\kappa_\parallel = \frac{1}{3}\lambda_{sc}\beta c = \frac{1}{3}\frac{\beta^2 c^2}{\nu_{sc}} \propto R_{gyr}\left(\frac{B_0}{\delta B}\right)^2 \qquad \kappa_\parallel = \int_{-1}^{+1}\frac{v^2(1-\mu^2)}{4\nu_{sc}}\,d\mu$$

transit-time damping (TTD) = transit-time surfing

- surfing the wavefront of oblique compressible fast and slow wave modes
  - v_ϕ =phase velocity of the compression wave.
  - intersection point M between the wavefront and the mean local B moves at speed $v_M = \frac{dl}{dt} = \frac{v_\phi}{\sin\alpha}$
  - surf if CR moves at $v_\| = v_M$
    - ✦ small range of small α given the large $v_\|$ of CRs



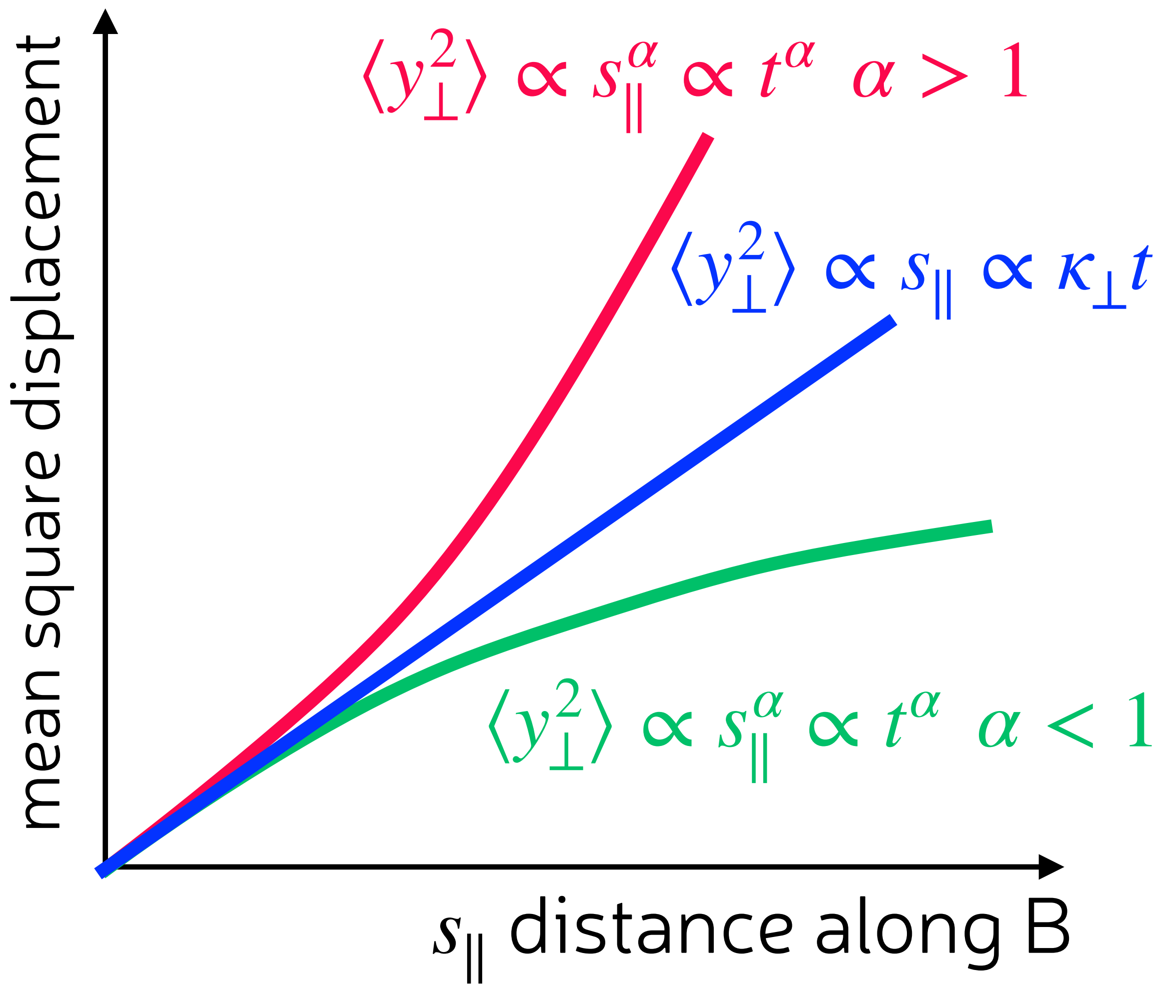
- n = 0 mode
  - transit time for the CR to cross the wave: $n = 0 \;\Rightarrow\; k_\| v_\| = \omega_r \;\Rightarrow\; \tau = \frac{\lambda_\|}{v_\|} = \frac{2\pi}{k_\| v_\|} = \frac{2\pi}{\omega_r} = T$ equal to the wave period T
  - CR gains/looses $p_\|$ from the wave $\vec{E}$ field
  - stochastic gain because head-on interactions between CR and wave are more frequent than head-tail interactions (2nd order Fermi acceleration)
  - hence wave damping

Schlickeiser 2002
Lazarian, Xu, Hu 2023

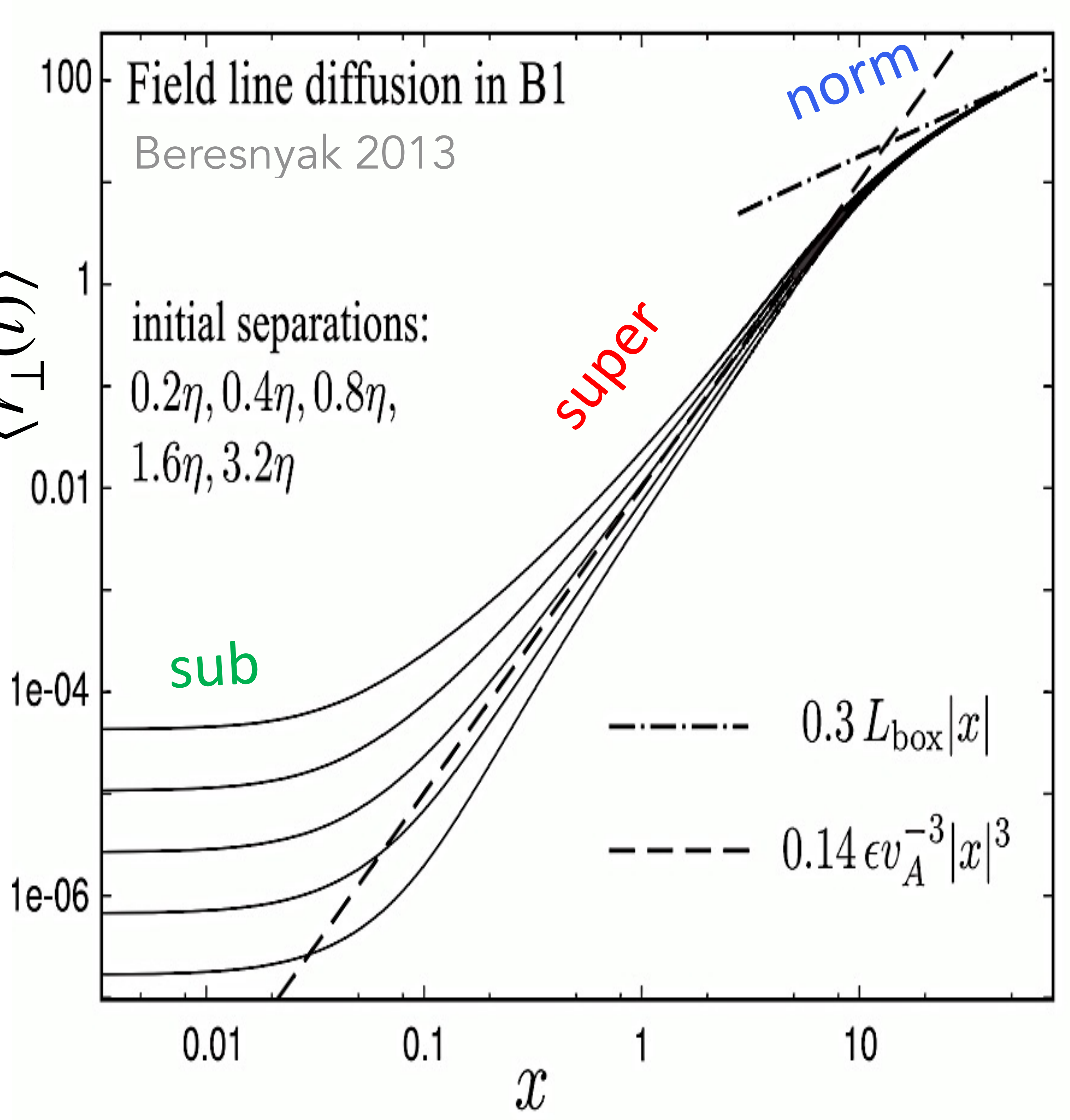
- **no specific resonant scale : turbulence over all scales $l > R_{gyr}$ contributes to scattering.**
  - TTD unable to scatter CRs at small pitch angles
  - => TTD contributes to scattering, but **only if another process has distributed CRs to $\theta \gtrsim 60^\circ$**

perpendicular diffusion in external MHD turbulence

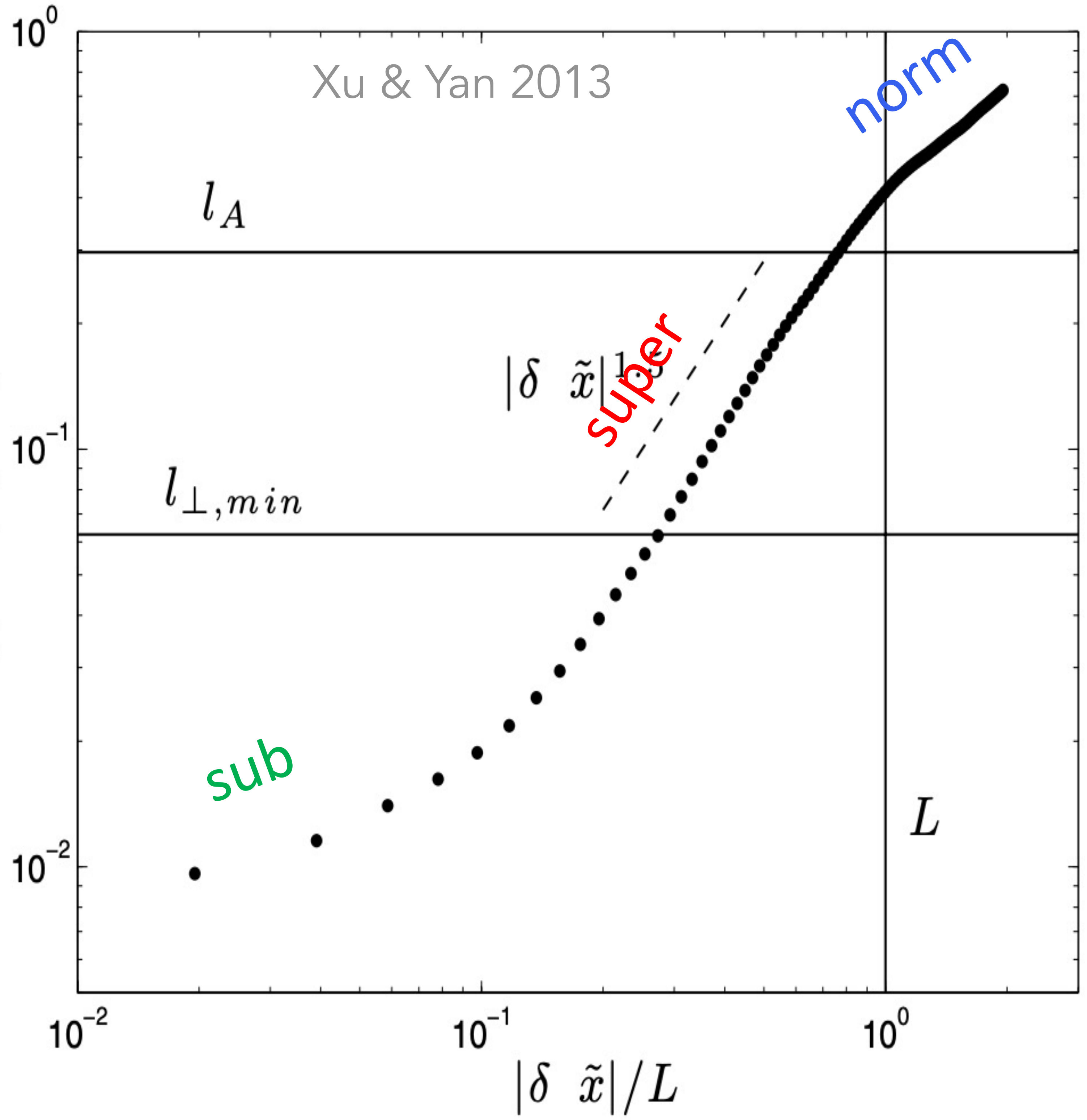
- maximum $\kappa_\perp = R_{gyr}c \approx 10^{21}$ cm²/s from pitch-angle scattering => **perpendicular diffusion due to B line diffusion**
- B line perpendicular diffusion
  - normal diffusion at large scales (for $s > l_A = L_{inj}M_A^{-3}$ for $M_A > 1$ and $s > L_{inj}$ for $M_A < 1$)
  - super diffusion in the turbulence inertial range

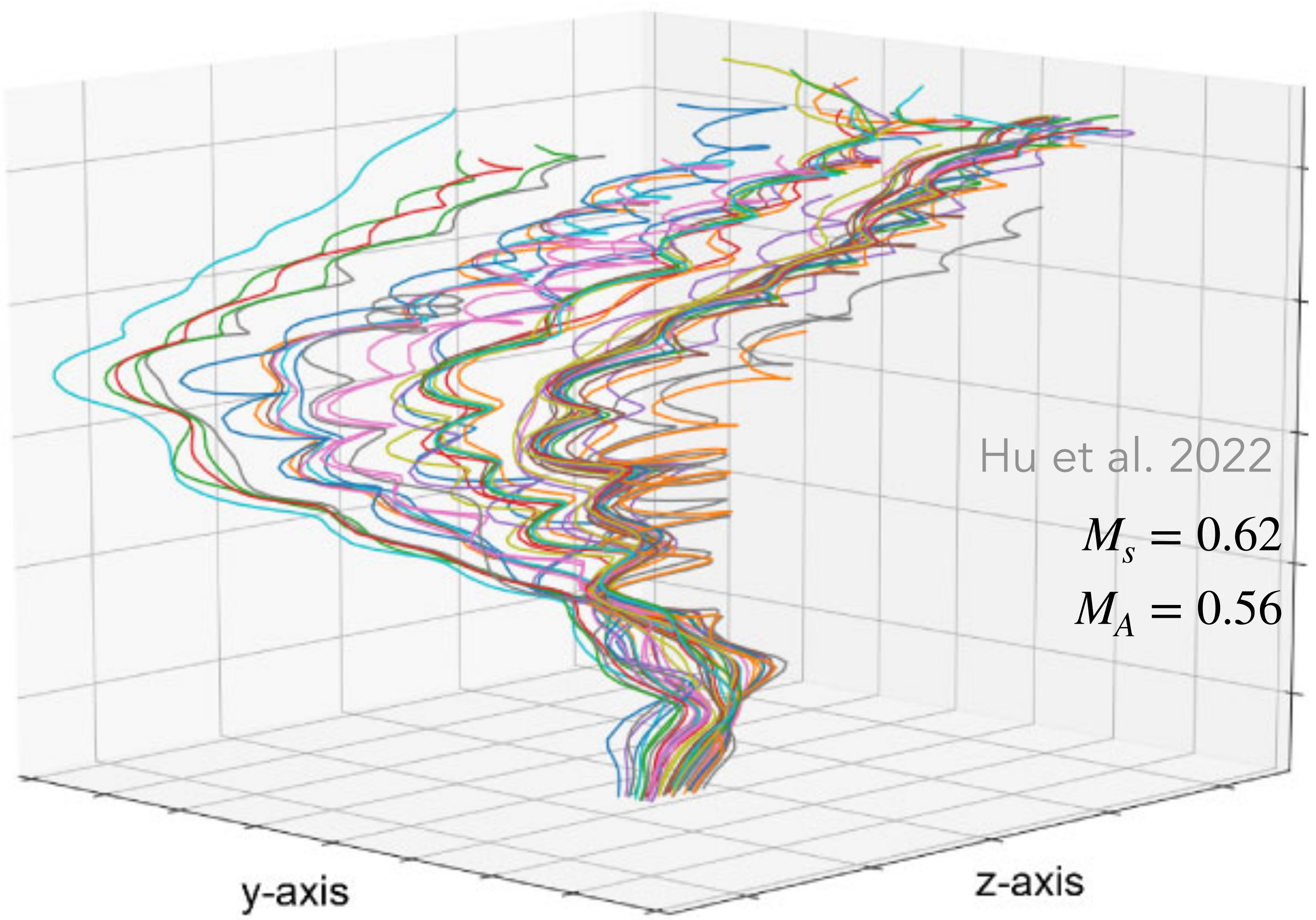


magnetic fields



CR particles



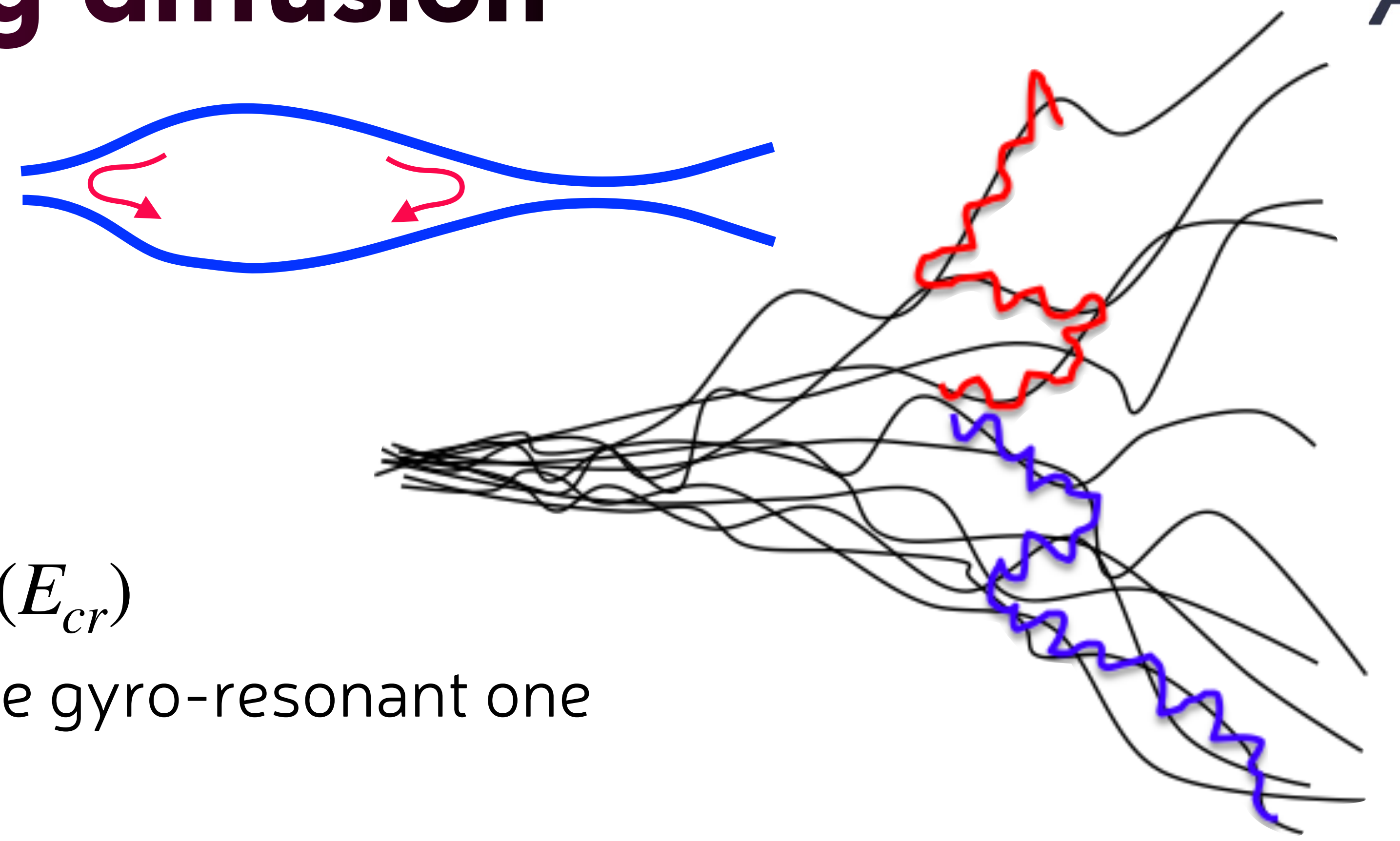


- if CR scattering mean free path along B $\lambda_\parallel < L_{inj}$ (as for GeV-TeV CRs in the ISM) : $\langle y_{cr\perp}^2 \rangle \propto t^{3/2}$
- if $\lambda_\parallel > L_{inj}$: $\langle y_{cr\perp}^2 \rangle \propto t^3$
- $\kappa_\perp \propto M_A^4$

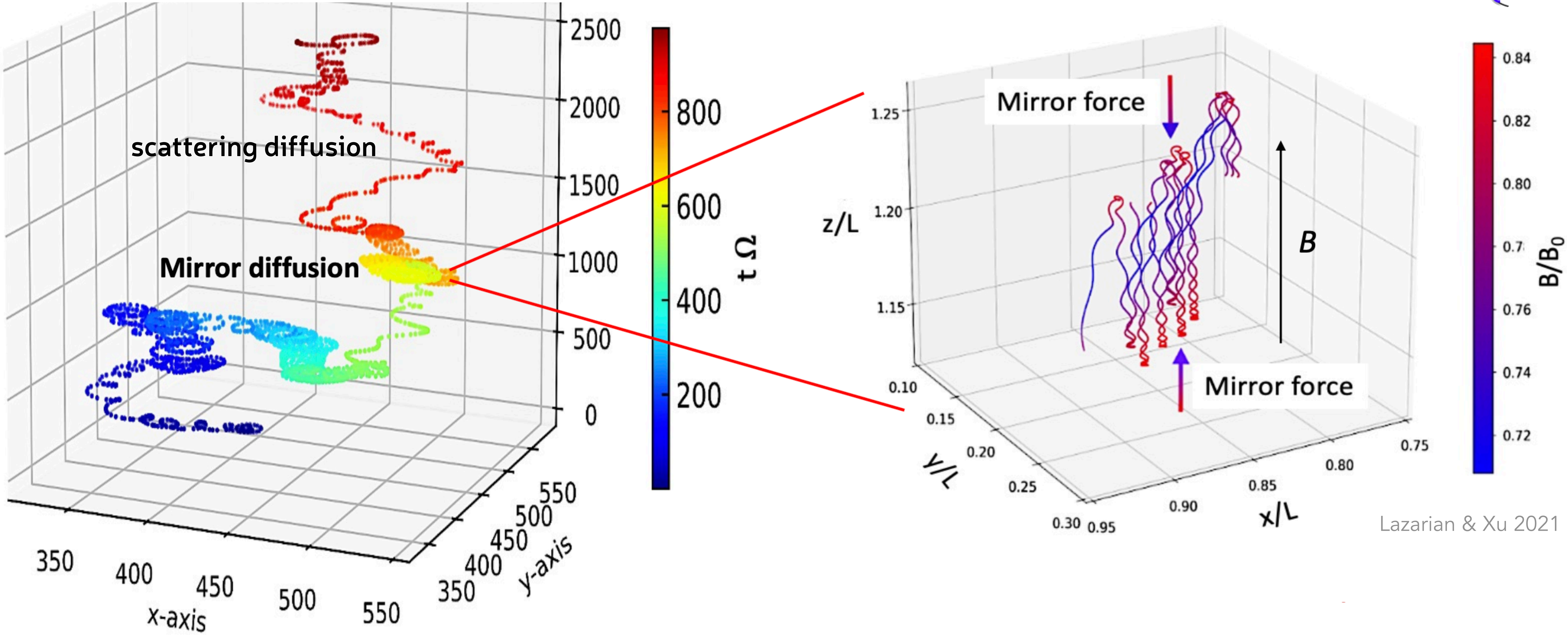
$\kappa_\perp$ diffusion largely due to B line wandering

fast gyro-resonant diffusion vs. slow mirroring diffusion

- small net μ change if CR remains along the same line bundle
- but super-diffusion of B lines during the CR propagation => CRs follow ≠ B lines after bouncing back



- **loss cone => reflected CRs only for large pitch angles** $\sin^2\theta > \frac{B}{B+\delta B} \Rightarrow \mu < \mu_{crit}(B) \Rightarrow \mu < \mu_{crit}(E_{CR})$
  - gyro-resonant scattering at low pitch angles populates the large-pitch angle domain for mirror diffusion : $\mu_{crit}(E_{cr})$
- mirror scattering for only small fraction of the CR population => the average $\kappa_{||}$ of the CR population close to the gyro-resonant one

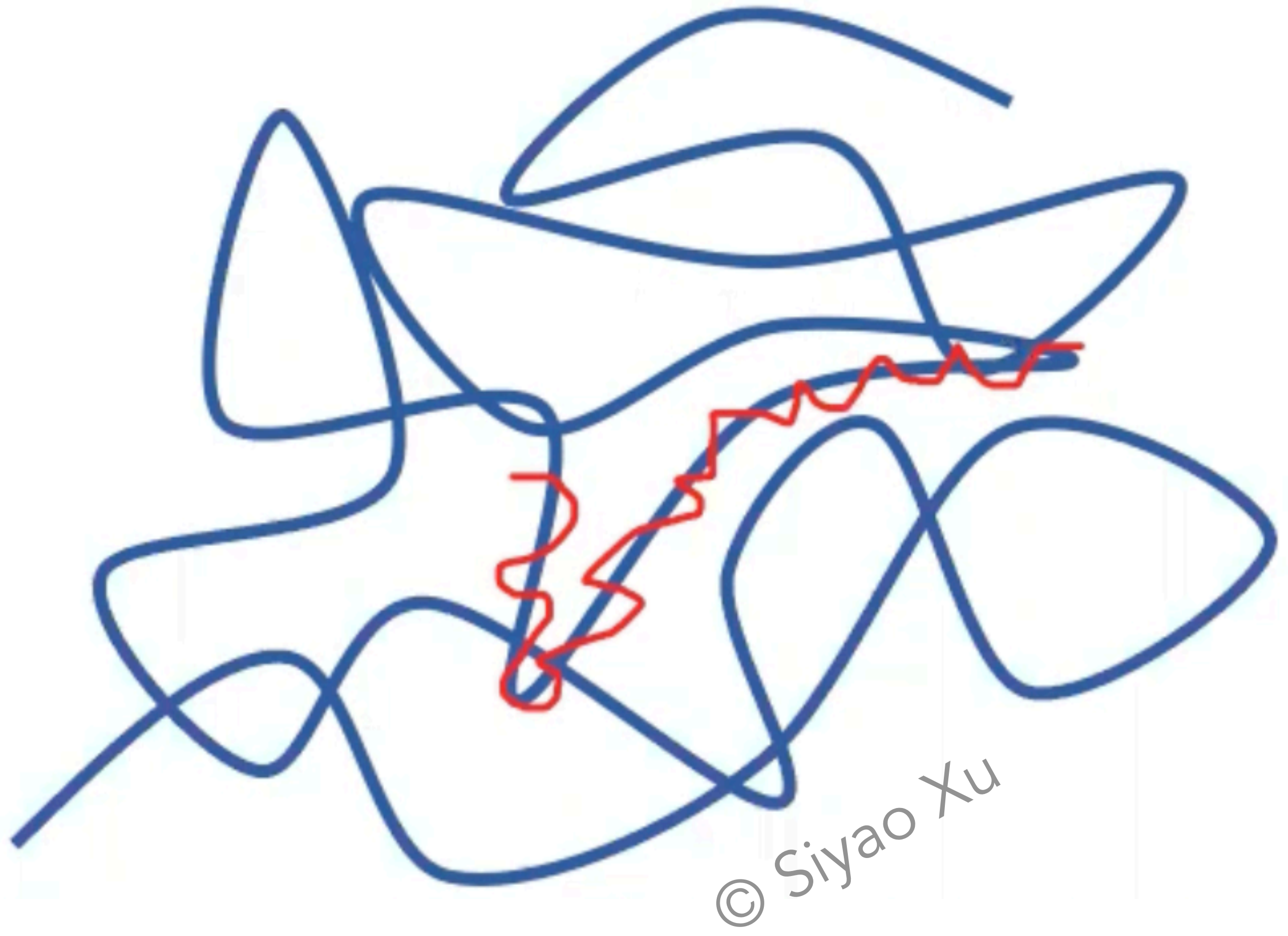


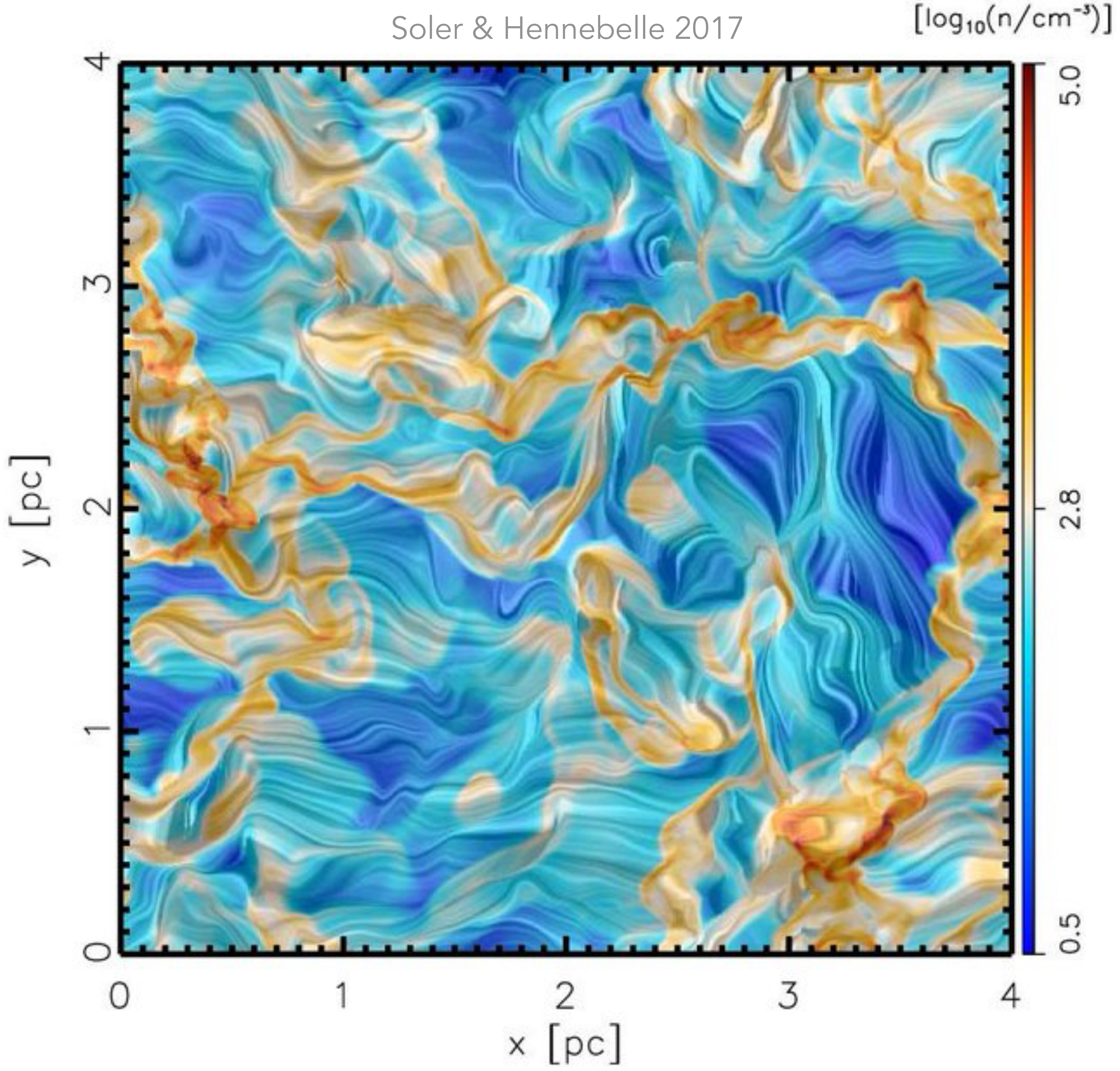
Lazarian & Xu 2021

CR diffusion in tangled magnetic fields

- in super-Alfvénic turbulence, gas turbulent motions drag B lines in complex twists

$$M_A^2 = \frac{\frac{1}{2}\rho_H \delta v_{H,rms}^2}{B^2/(2\mu_0)} = \frac{e_{kin,turb}}{e_B}$$





- **free gyration** around B lines induces an effective diffusion in space
  - mean free path = coherence length of B

    $l_{mfp} = l_A = L_{inj} M_A^{-3}$
  - slows down CRs **in addition to** the gyro-resonant scattering

- important in
  - low-B environments
  - molecular clouds
  - starburst environments

Krumholz+ 2020
Sampson+ 2022

which waves
scatter CRs ?

damping of MHD waves

- Landau damping because the wave $\vec{E}$ field tends to synchronise the ions
  - more accelerated than decelerated ions => wave damping

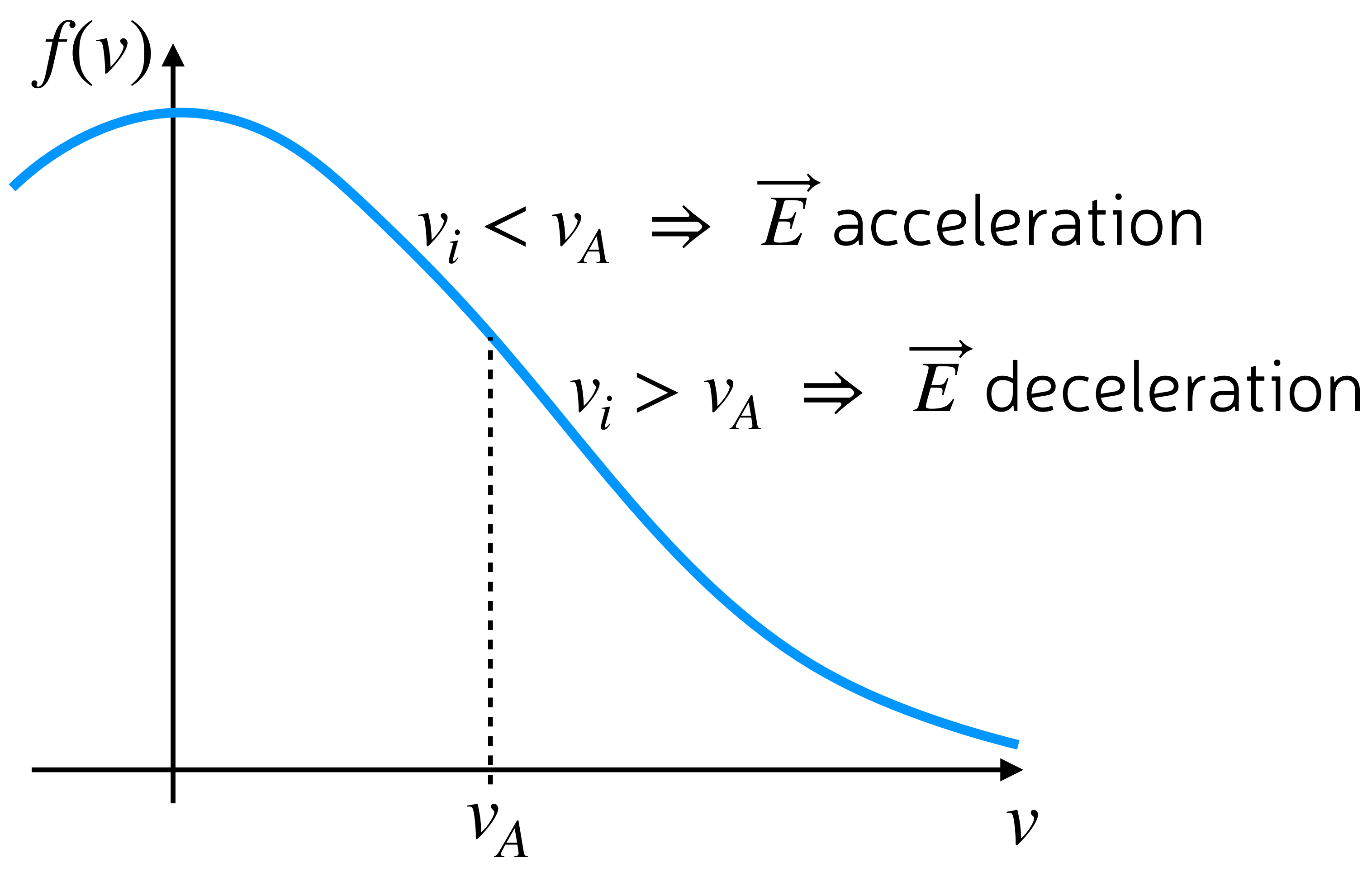
Landau 1946

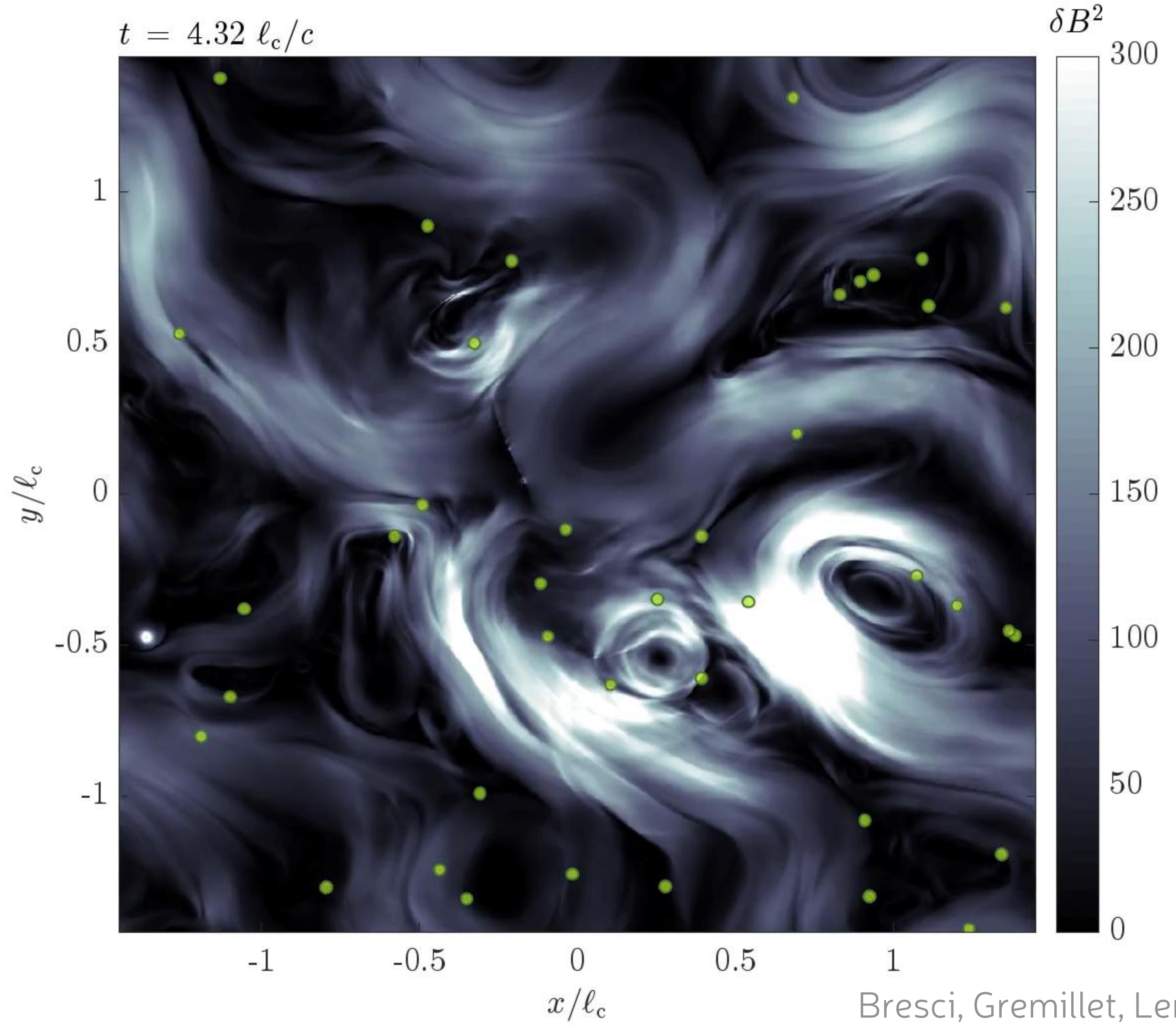
- non-linear Landau damping by ions in the beat wave formed by 2 almost-co-propagating waves
  - mirror force acceleration for $v_i \approx v_{beat}$

- turbulent damping : shearing of two counter-propagating MHD eddies
  - efficient if crossing time ≈ turnover time
  - induces the energy cascade to smaller scale
  - depends on M_A and scale

Goldreich & Sridhar 1995

- ion-neutral damping
  - ion-neutral momentum transfer in collisions, but also neutral viscosity
  - dominant in neutral gas phases (WNM, CNM, DNM, H_2)



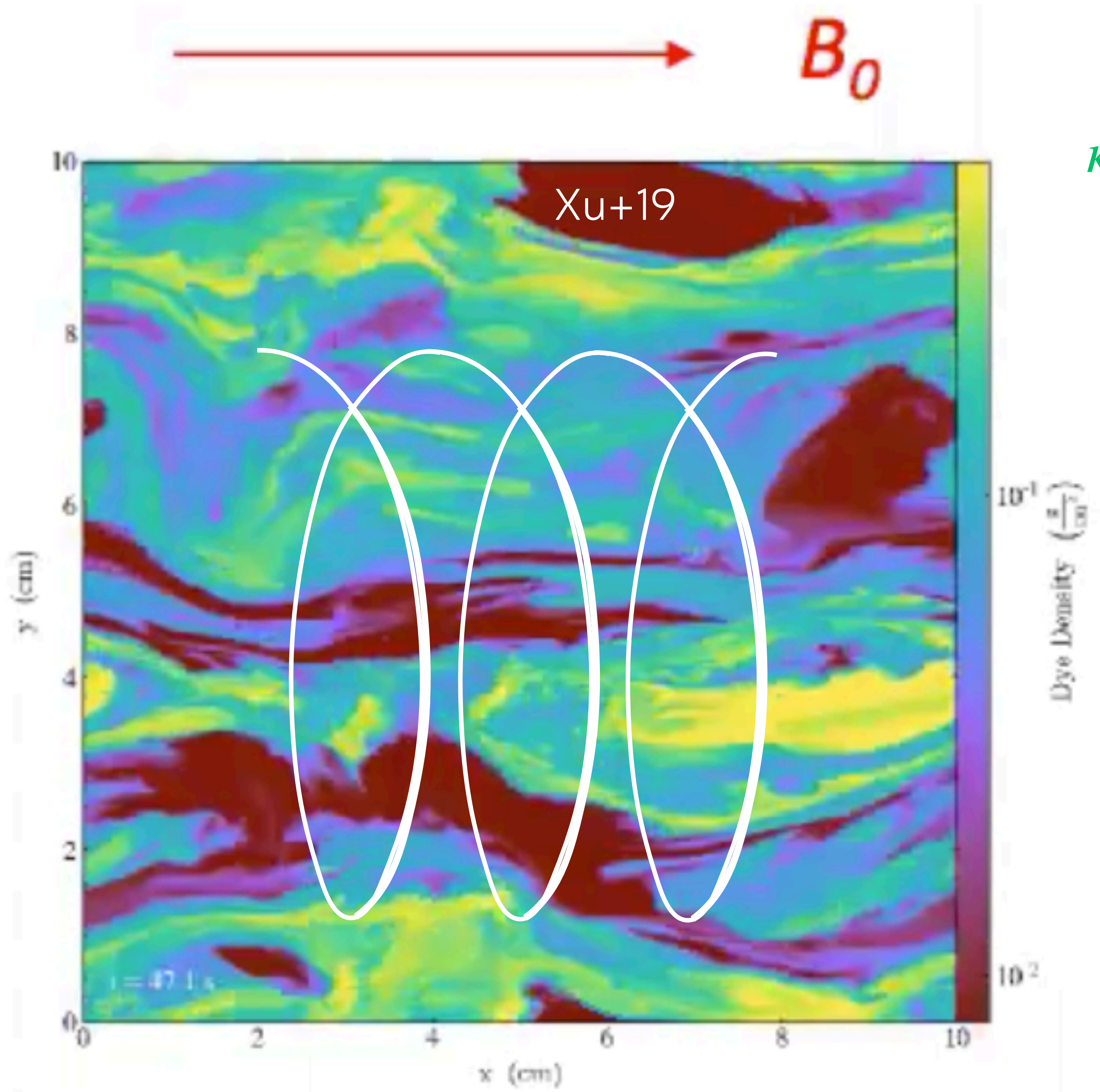


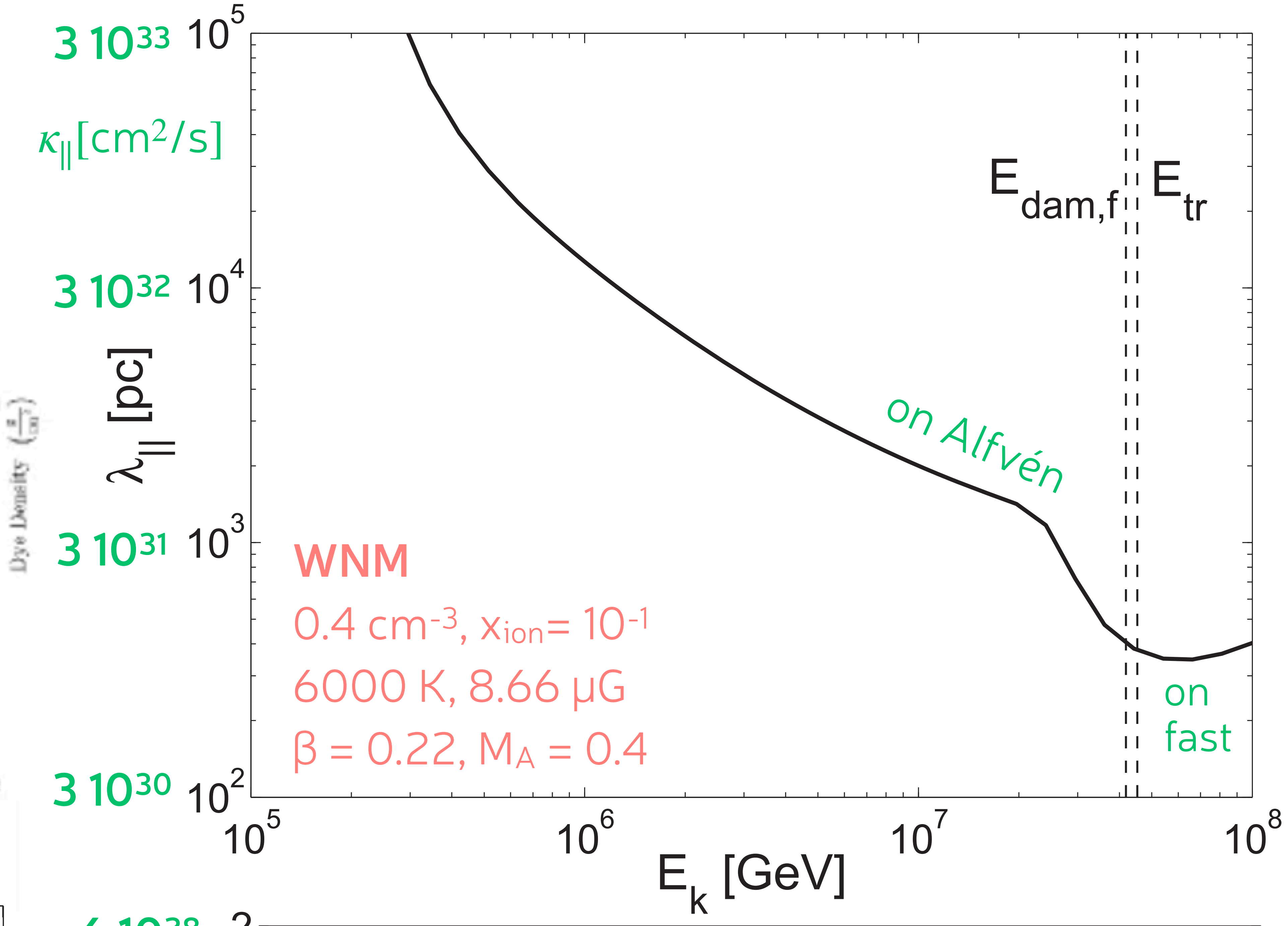
Bresci, Gremillet, Lemoine

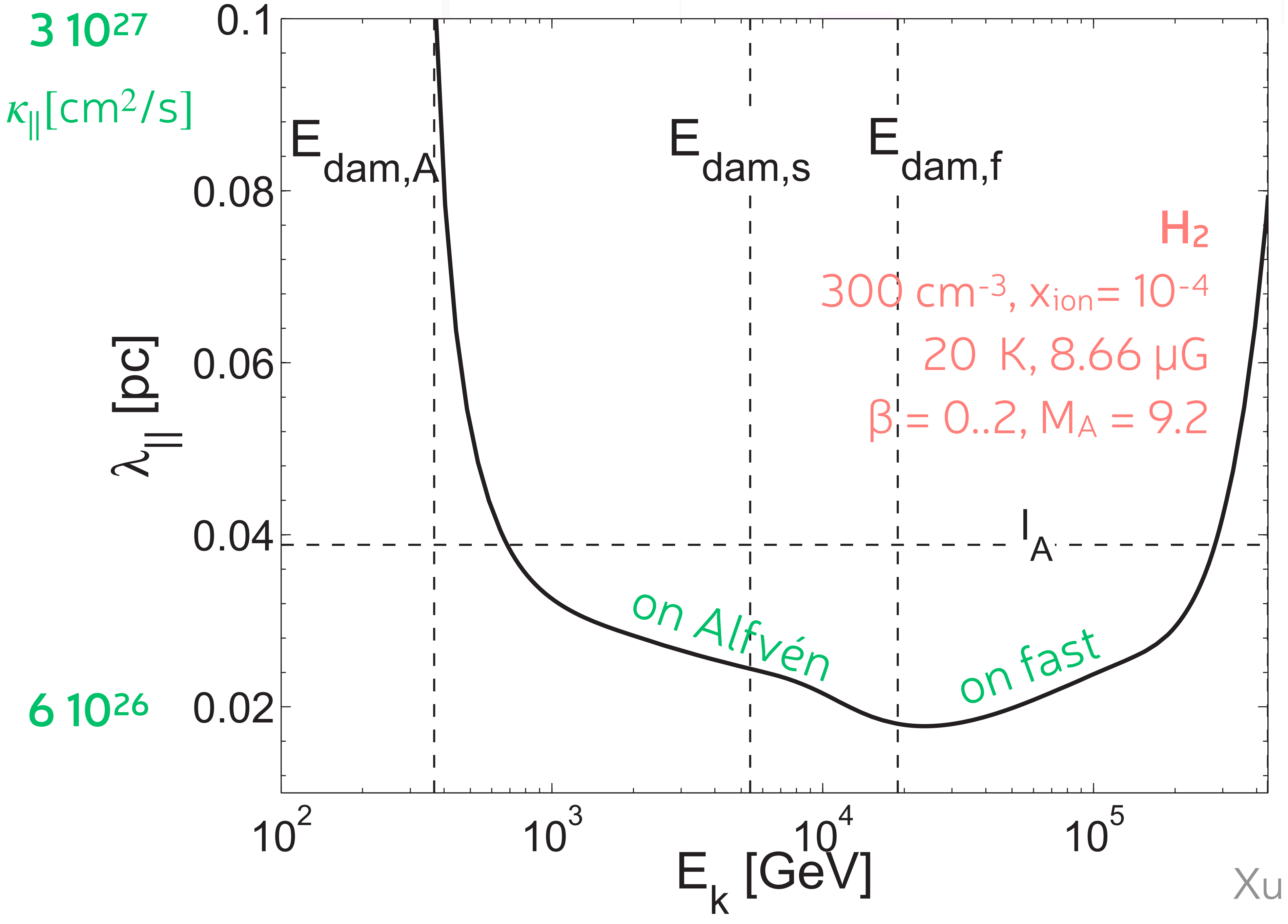
scattering on pre-existing MHD turbulence

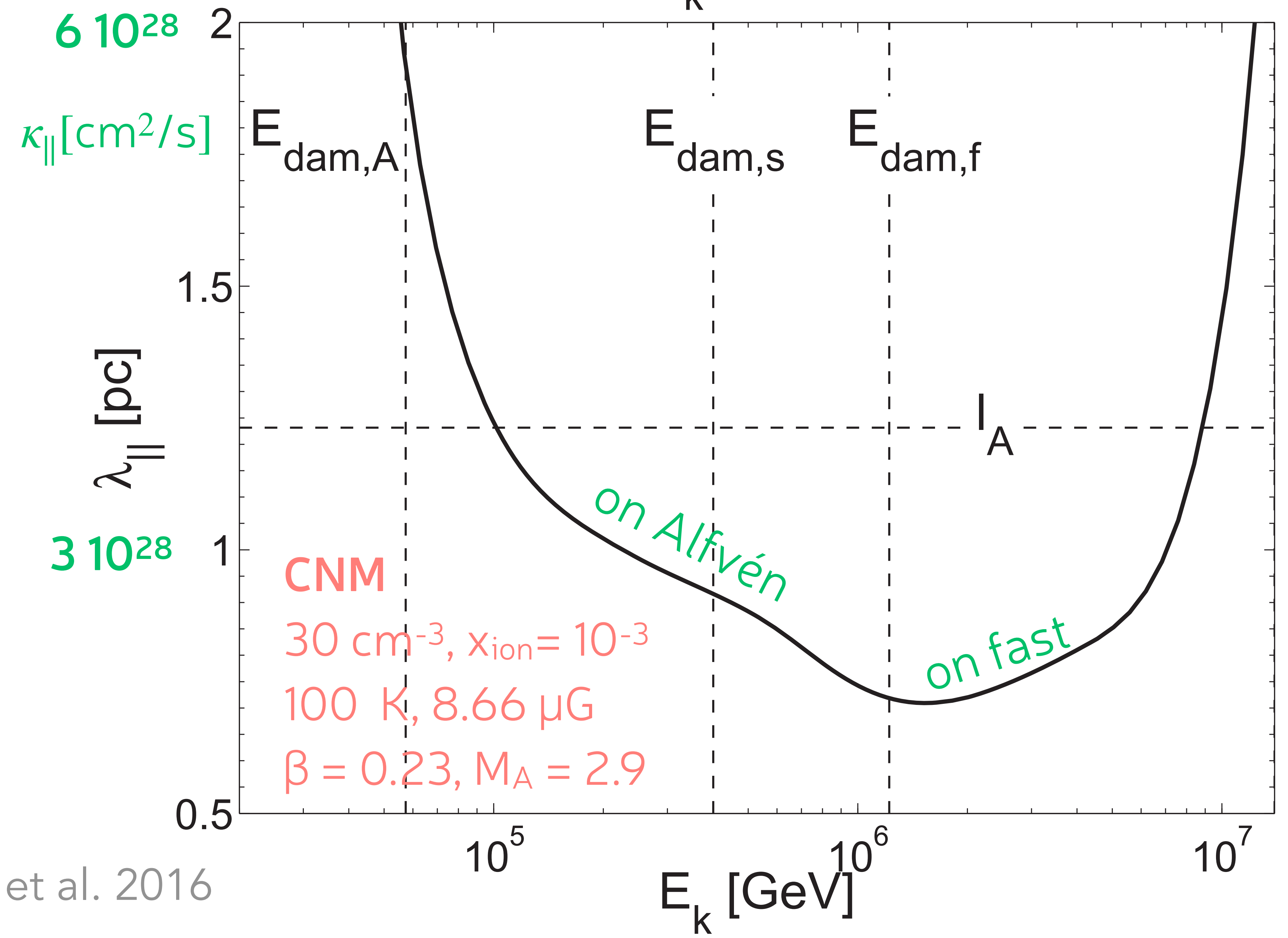
- **inefficient scattering on anisotropic Alfvén modes**
- small scattering efficiency preserved at small scales from the isotropic fast modes (but ⩽ 20% of MHD turbulence energy, if not damped)
  - small role of slow modes
- ion-neutral damping for scales such that $E_k < E_{\rm dam}$
  - ✦ Alfvén modes $E_{\rm dam,A}$
  - ✦ slow modes $E_{\rm dam,s}$
  - ✦ fast modes $E_{\rm dam,f}$
- very fast diffusion in the WNM for all Galactic CRs
- slow diffusion in H_2 > TeV
  - 2nd-order Fermi (re)acceleration

inefficient scattering for CRs < 10 TeV outside the Galactic halo









Xu et al. 2016

scattering on self-excited waves

$\Omega_0 = \Omega_{class} = \gamma \Omega_{gyr}$

- gyro-resonance:: $k_\| v_\| - \omega_r \approx k_\| v_\| = \Omega_{gyr}$
- co-propagating wave excited by the **streaming instability**
  - if **locally anisotropic CR distribution** : $\Gamma_{grow} > 0$ if $\dfrac{\partial f}{\partial \mu} > 0$
  - excited by the **number density of all CR** with rigidity > B/k

$$\Gamma_{grow}(k) = \frac{\pi^2}{2} \frac{q^2 v_A}{ck} \int \frac{v(1-\mu^2)}{cp} \left[\delta(\mu + \frac{m\Omega_0}{kp}) + \delta(\mu - \frac{m\Omega_0}{kp}) \right] \frac{\partial f}{\partial \mu} p^2 \, dp \, d\mu \, d\phi$$

resonance condition
for 2 circular polarisations

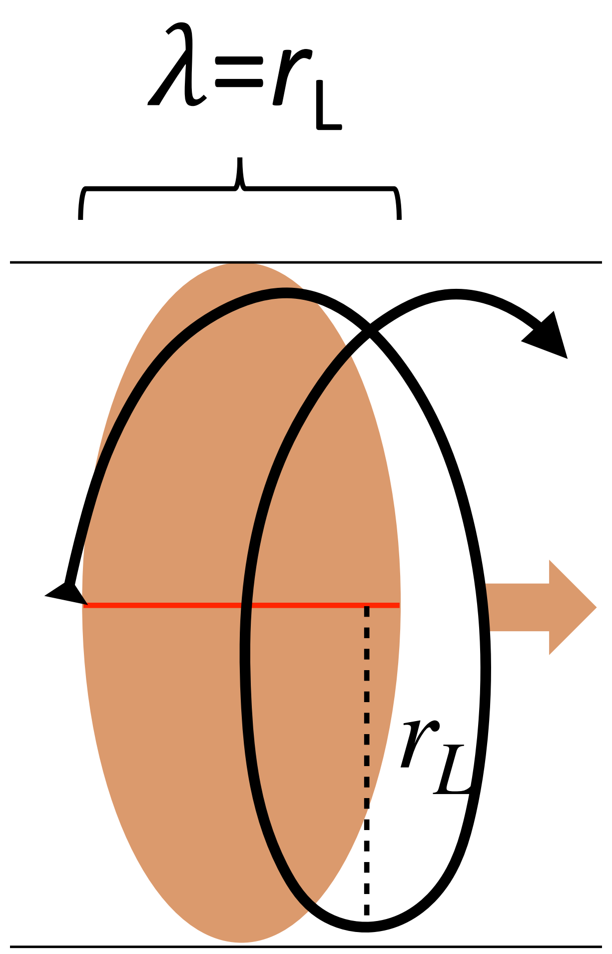
Kulsrud & Pearce 1969
Kulsrud & Cesarsky 1971

- relation between CR anisotropy and spatial density gradient
  - if $f(p) = f_0(p) + \mu f_1(p) + \frac{1}{2}\mu^2 f_2(p)$ (small anisotropy)
  - relation $\dfrac{\partial f_1}{\partial \mu} = -\dfrac{v}{\nu_{sc}} \dfrac{\partial f_0}{\partial s}$ Zweibel 2013

- efficient pitch-angle scattering because $\lambda \sim R_{gyr}$
  - if strong coupling => CR isotropisation in the Alfvén wave frame => **advection at v_A down CR pressure gradients**

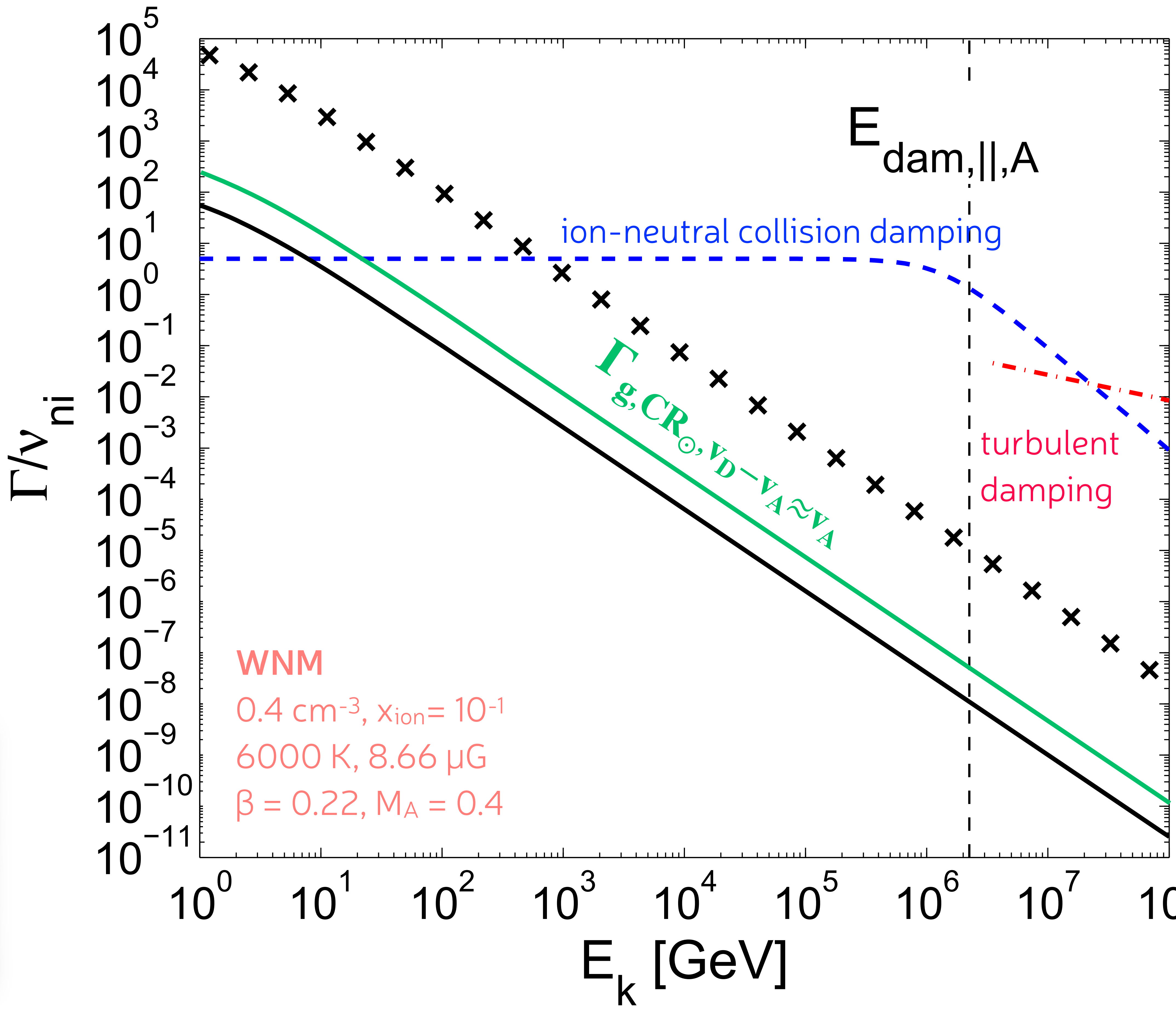
$$\mathbf{v_{st}} \rightarrow -\frac{\vec{\mathbf{B}} \cdot \vec{\nabla} \mathbf{p_{CR}}}{|\vec{\mathbf{B}} \cdot \vec{\nabla} \mathbf{p_{CR}}|} \mathbf{v_A^{ion}}$$

  - if moderate coupling : faster diffusion (larger $\kappa_\|$)



- no 2nd-order Fermi (re)acceleration
- CRs exert a force on the gas $-\nabla_\| \mathbf{P_{CR}}$
- CRs heat the gas $\mathbf{rate} \propto \mathbf{v_A^{ion}} \cdot \nabla_\| \mathbf{P_{CR}}$

≈ efficient scattering for CRs ≲ 100 GeV in the weakly ionised gas



Xu et al. 2016

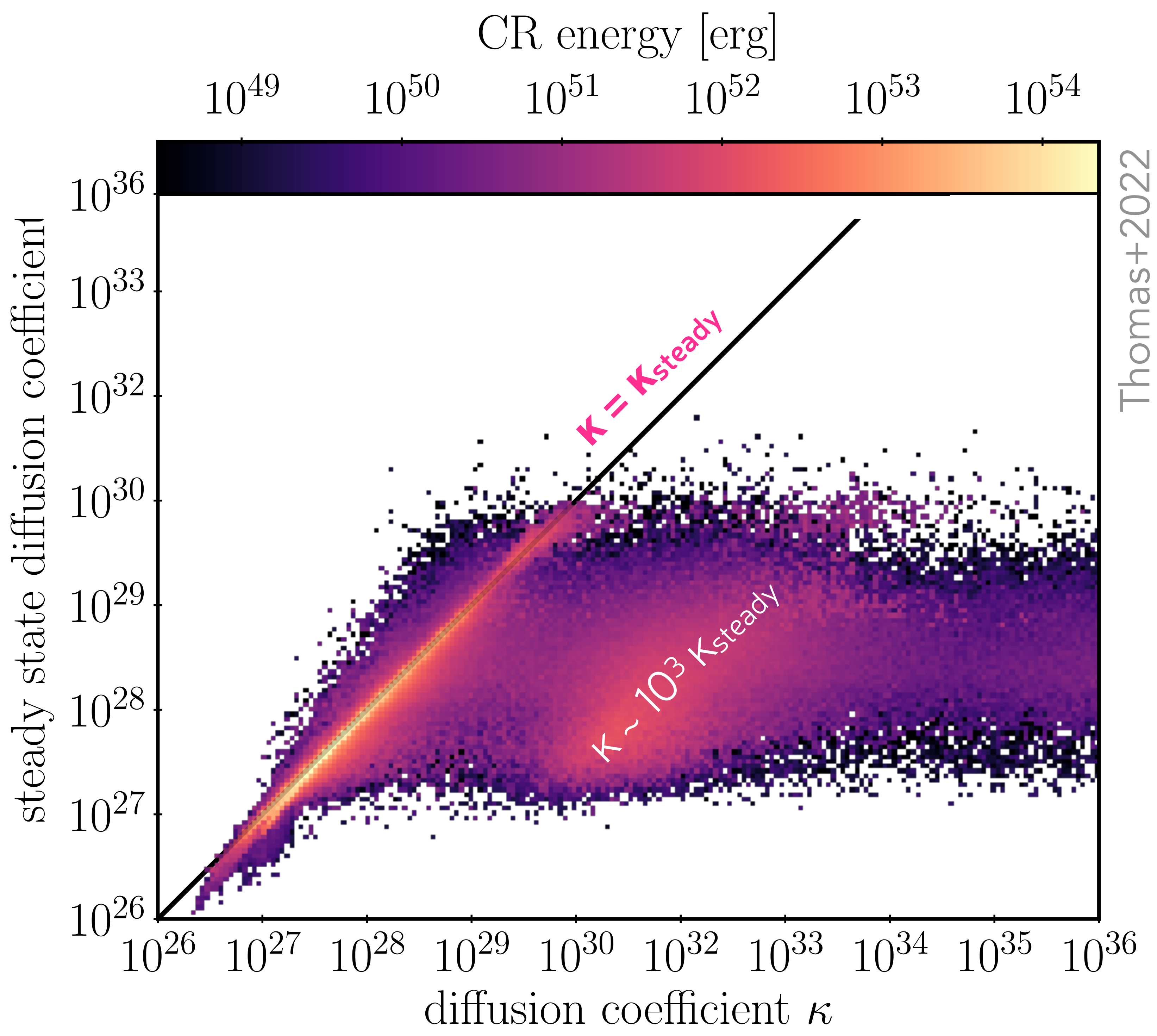
how fast do
cosmic rays travel ?

how fast, uneven, anisotropic is diffusion?

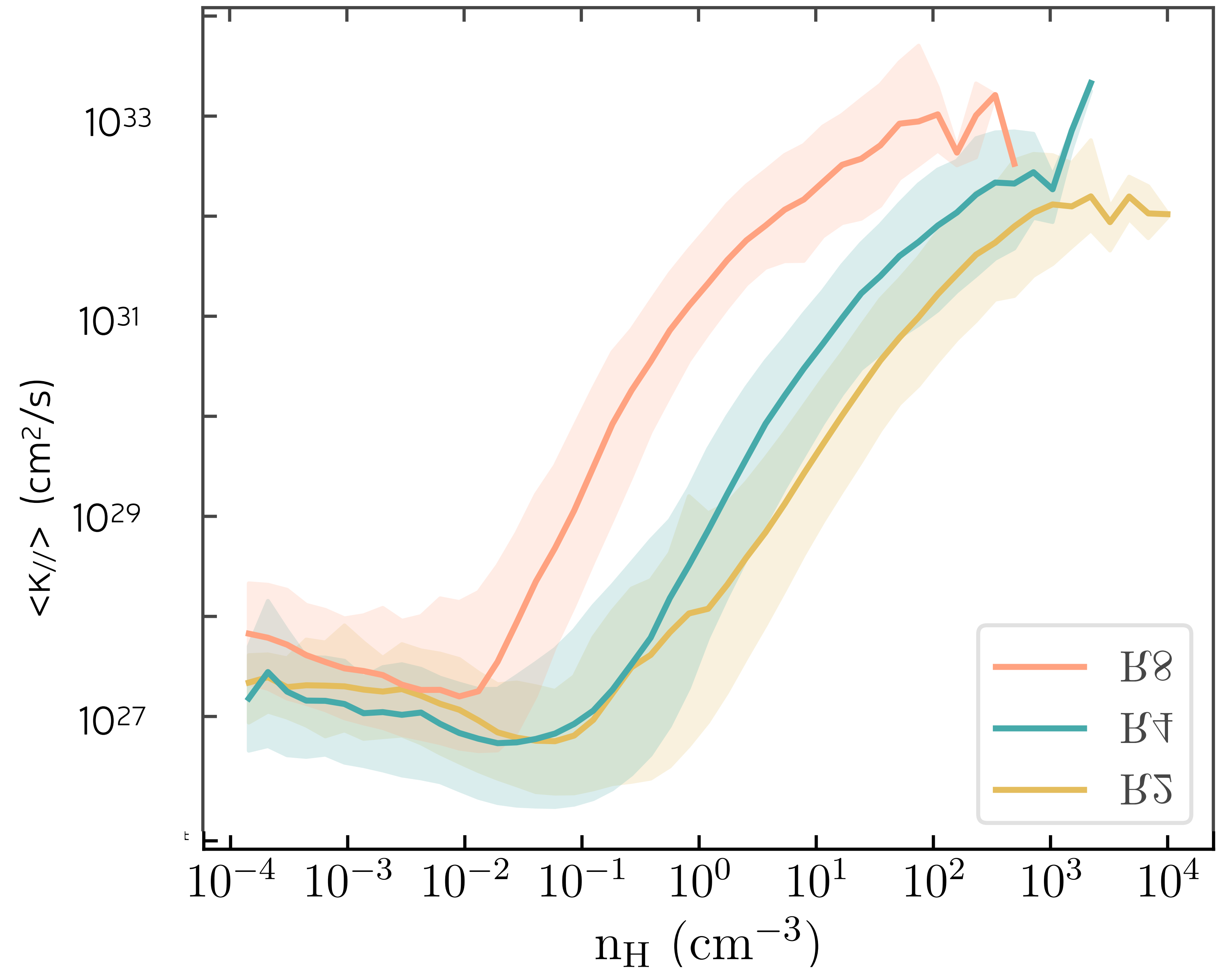
- **if self-streaming transport**

- 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

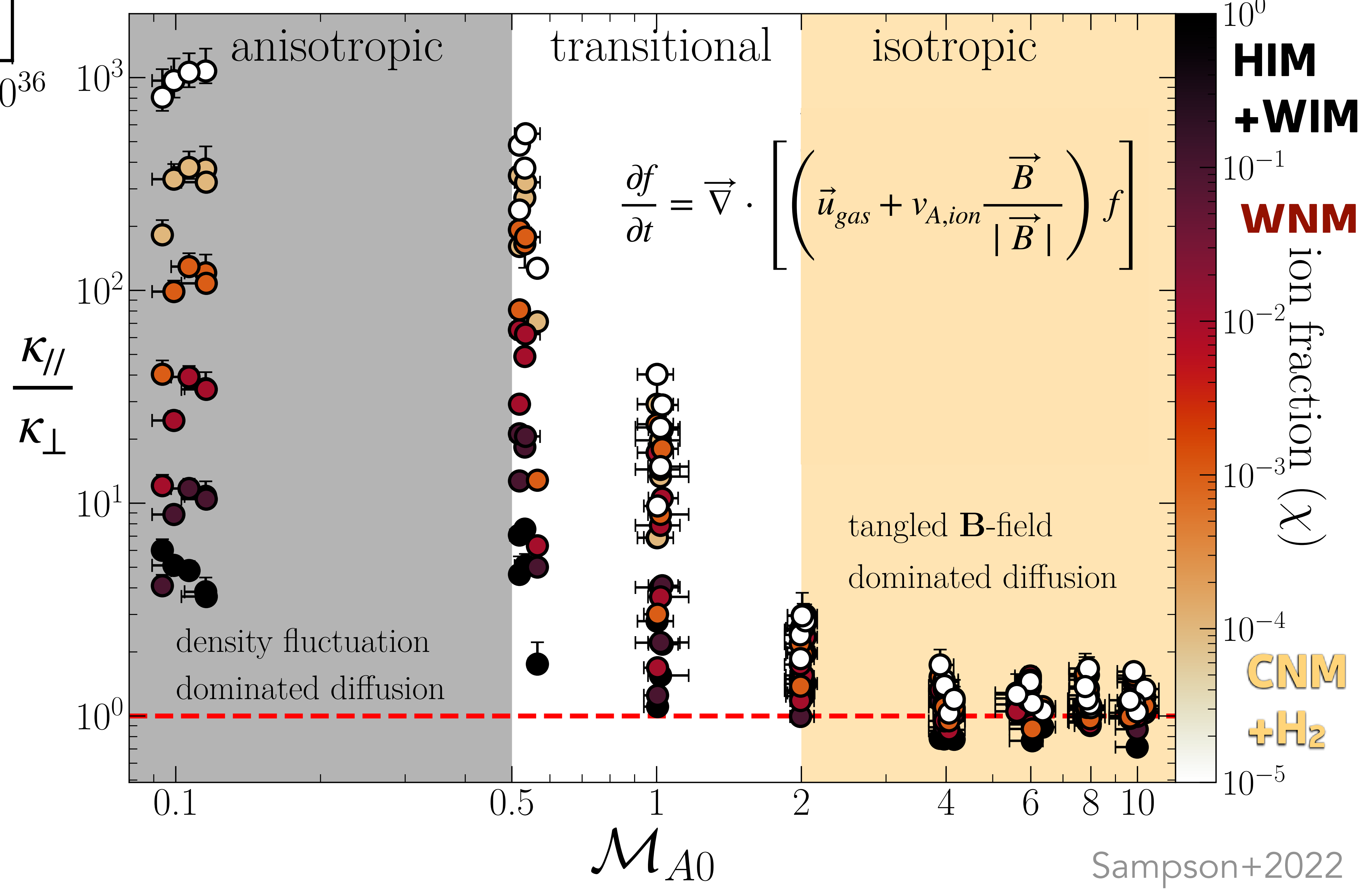


Thomas+2022



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

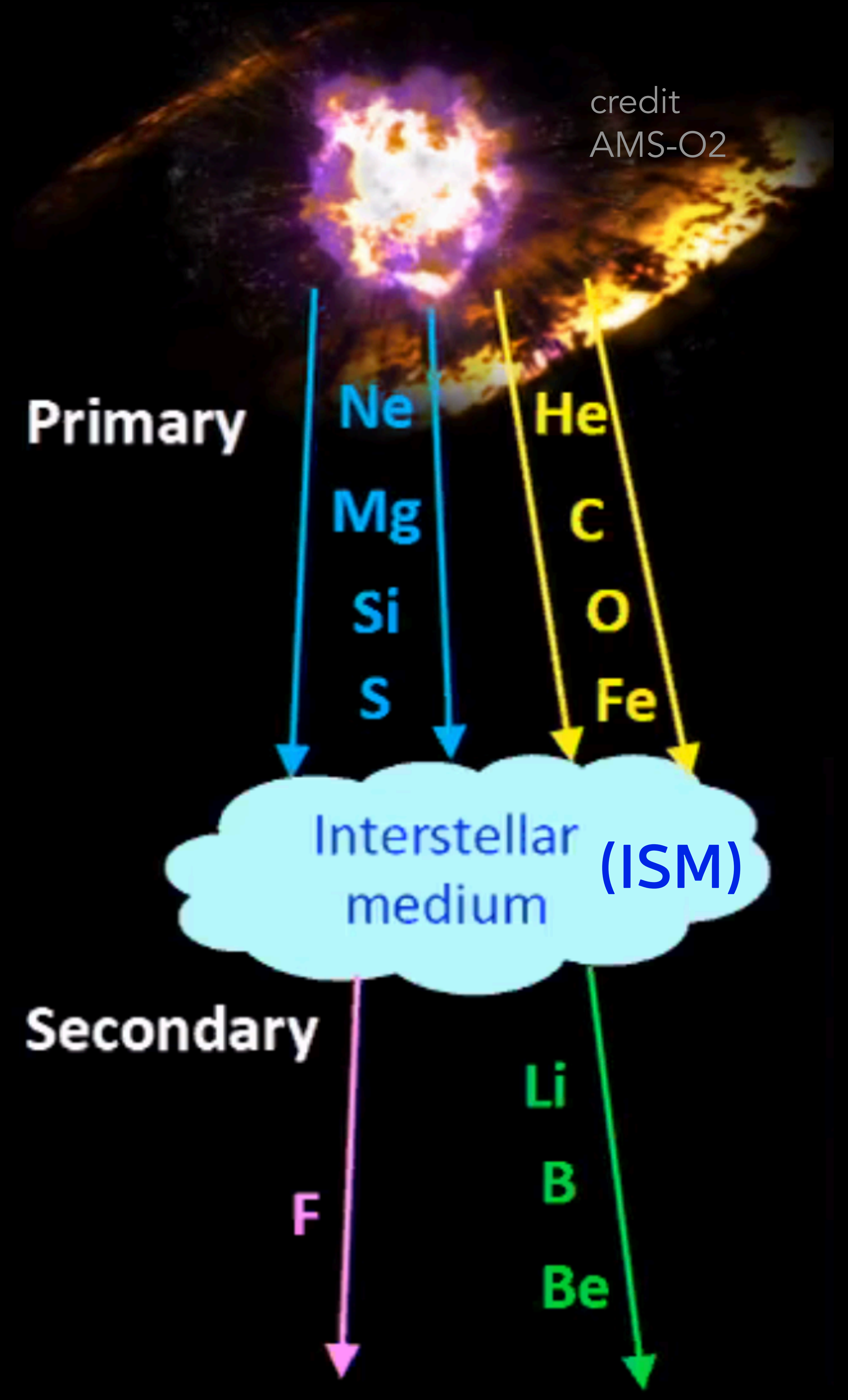


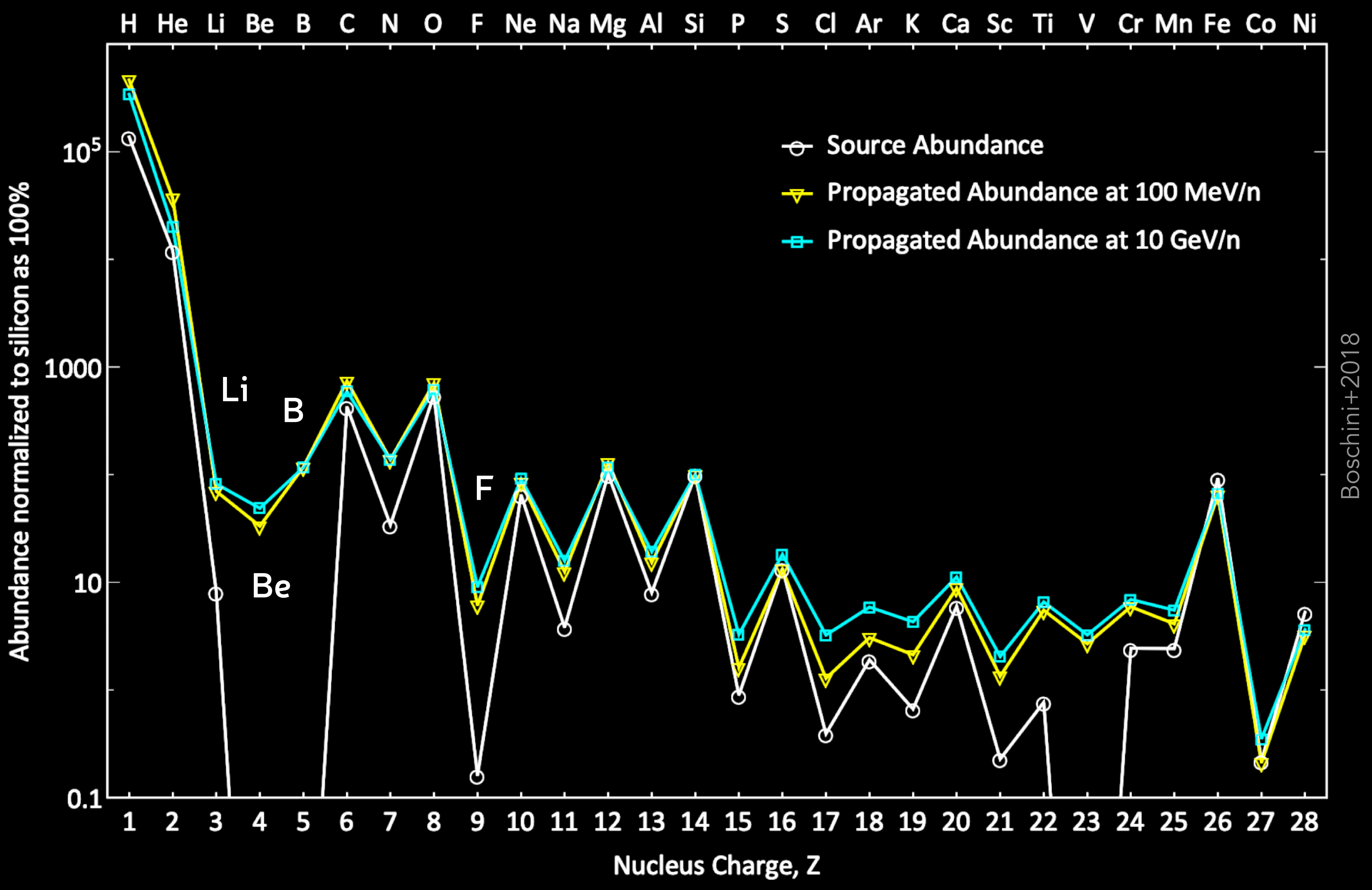
Sampson+2022

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

cosmic-ray composition vs. solar abundances

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





cosmic-ray composition vs. solar abundances

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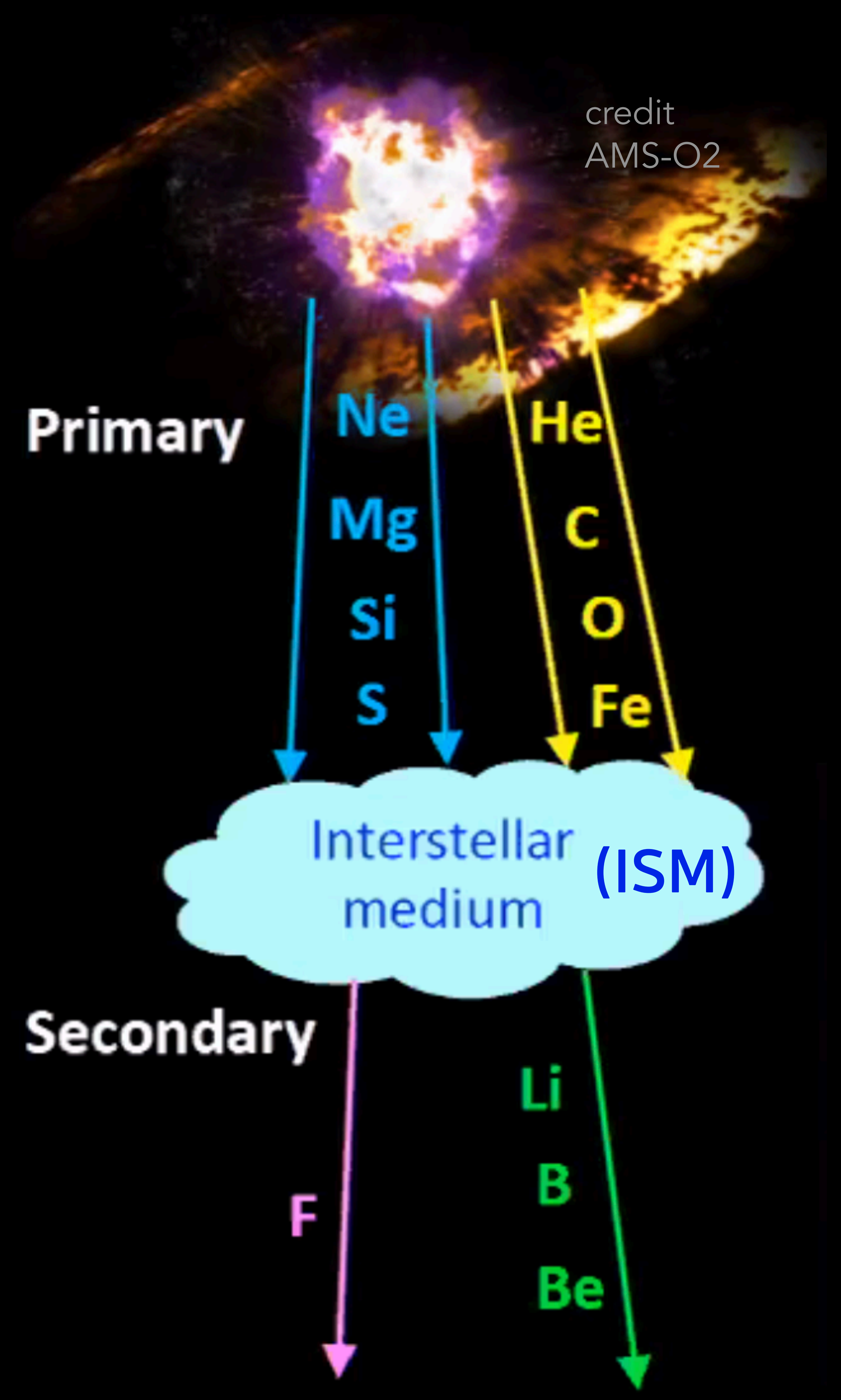
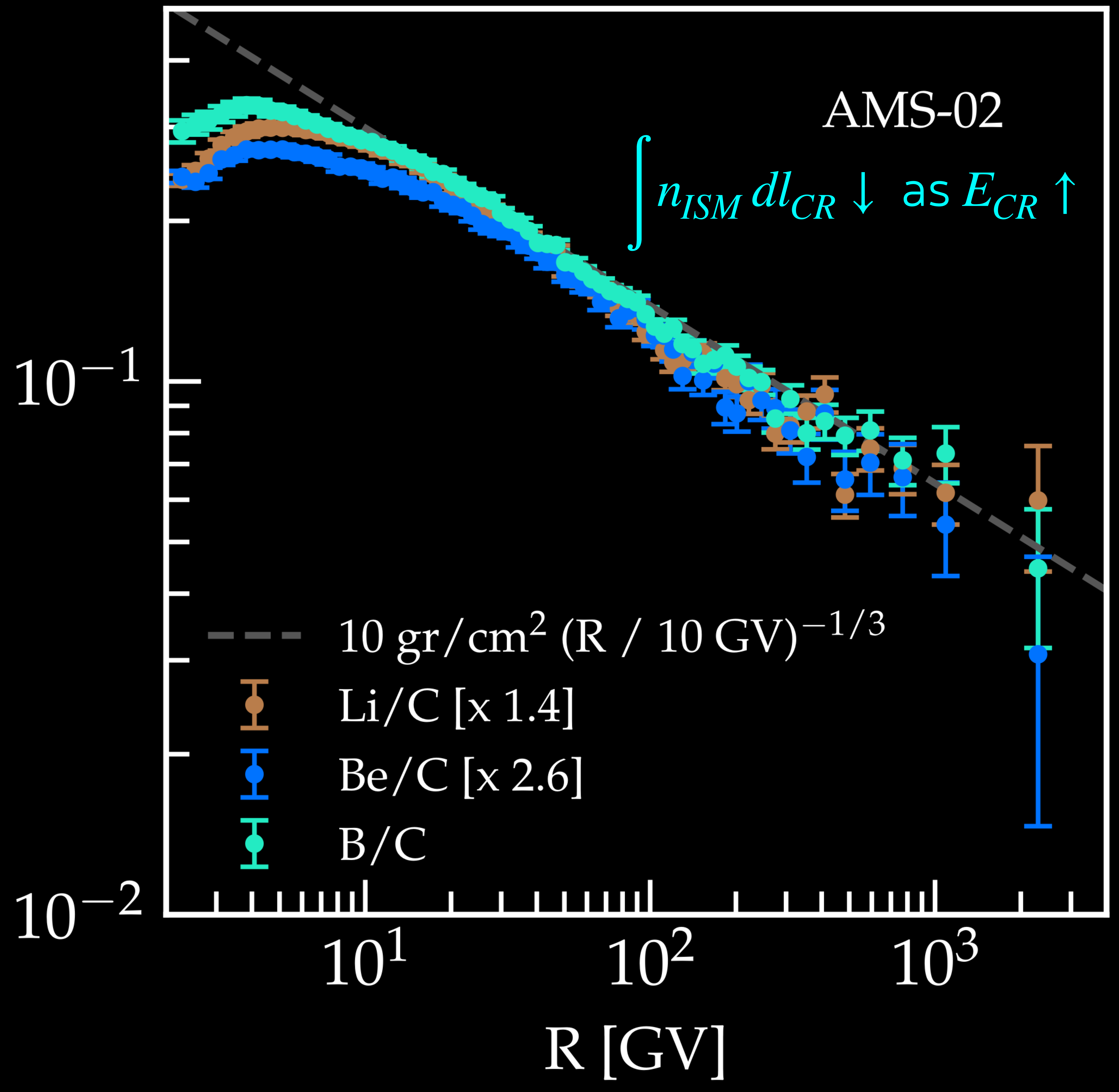
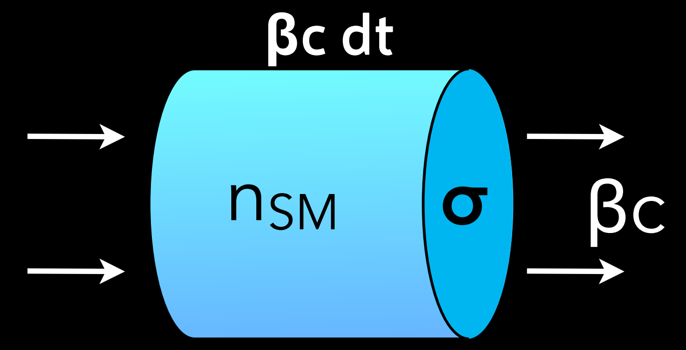




simplest leaky box model

- steady state between source input and loss + escape

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



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

- ISM grammage crossed before escape: $X(p) = n_{ISM}\,\beta(p) c\, T_{esc}(p)$
- spallation reactions in the ISM
  - secondary source input

$$Q_2 = \frac{dM_2}{dt} = n_{ISM}\sigma_{1\to2}\,\beta c\, M_1$$

  - secondary spallation losses

$$T_{sp2} = (n_{ISM}\sigma_{2\to3}\,\beta c)^{-1}$$

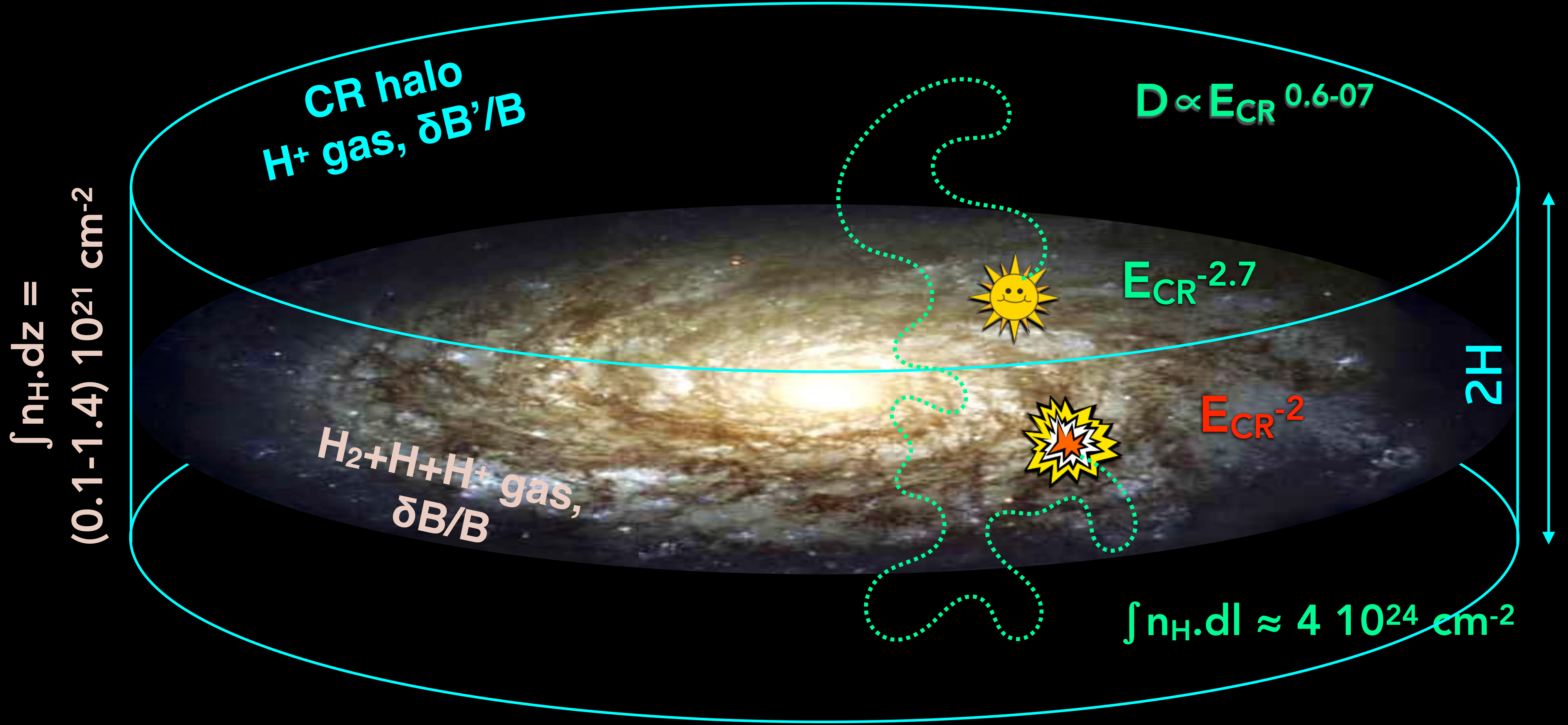
  - steady state $\Rightarrow M_2\left[T_{sp2}^{-1} + T_{esc}^{-1}\right] = M_2\left[n_{ISM}\sigma_{2\to3}\beta c + T_{esc}^{-1}(p)\right] = Q_2 = n_{ISM}\sigma_{1\to2}\,\beta c\, M_1$

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

- 2dary/1ary ratio $\dfrac{M_2(p)}{M_1(p)} = \dfrac{\sigma_{1\to2}}{\sigma_{2\to3} + X^{-1}(p)}$

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

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

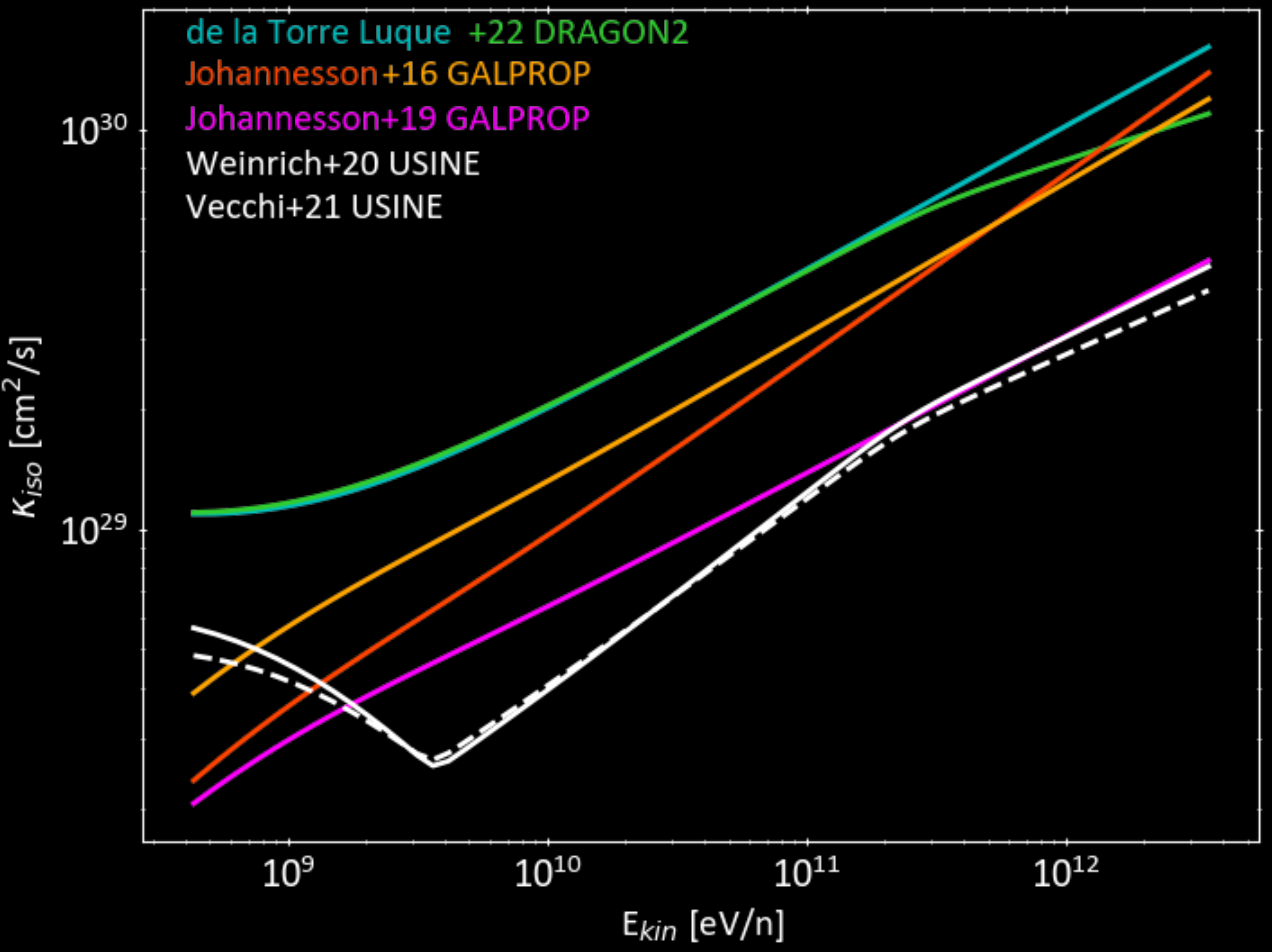


  - $X \approx 10$ g/cm^2 or $N_H \approx 4\ 10^{24}$ cm^{-2}
  - radioactive secondaries : CR clocks
  - $T_{esc} \approx 10$-20 Myr

1D - 2D - 3D diffusion codes

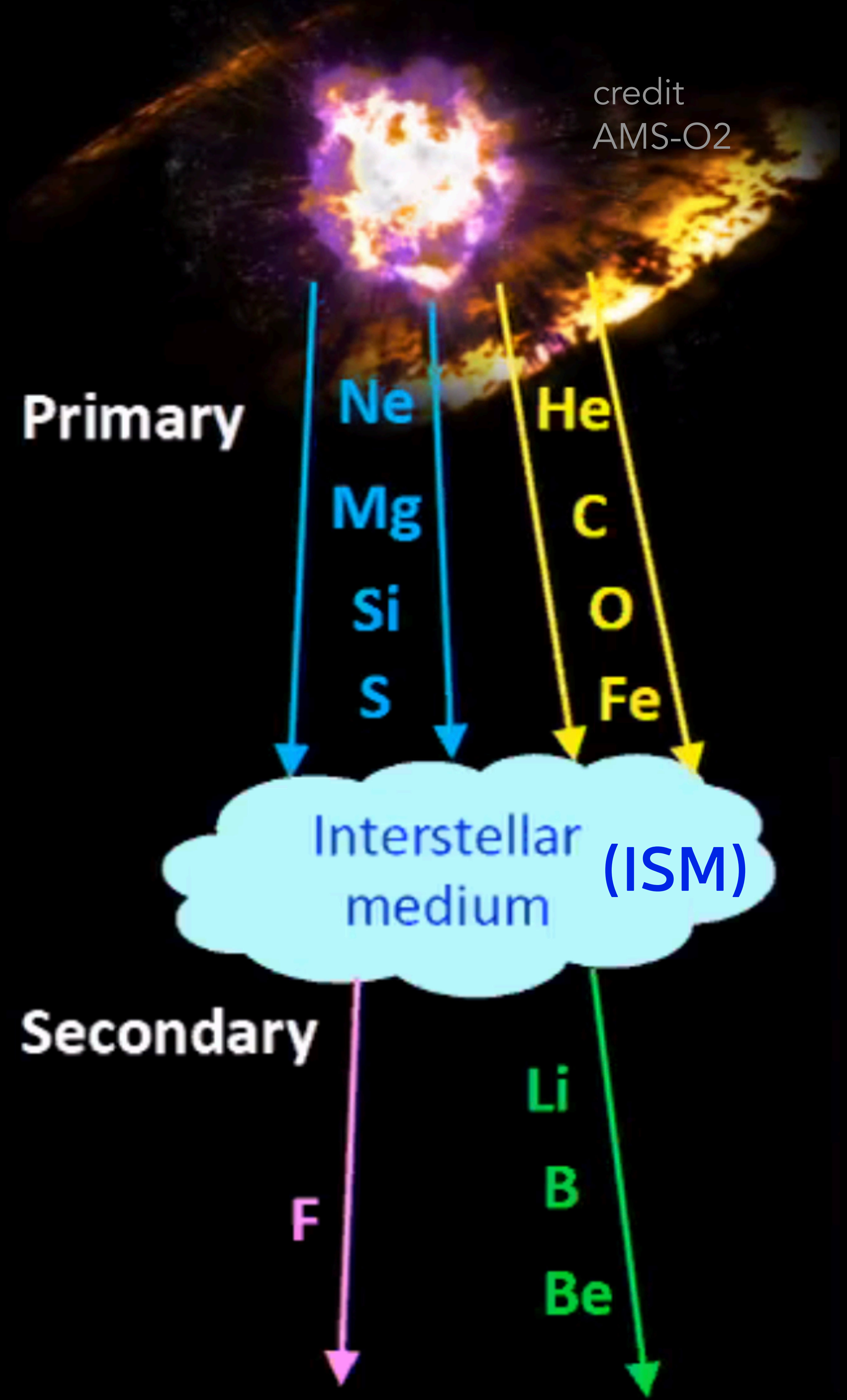
- mean uniform diffusion coefficient in the Milky Way

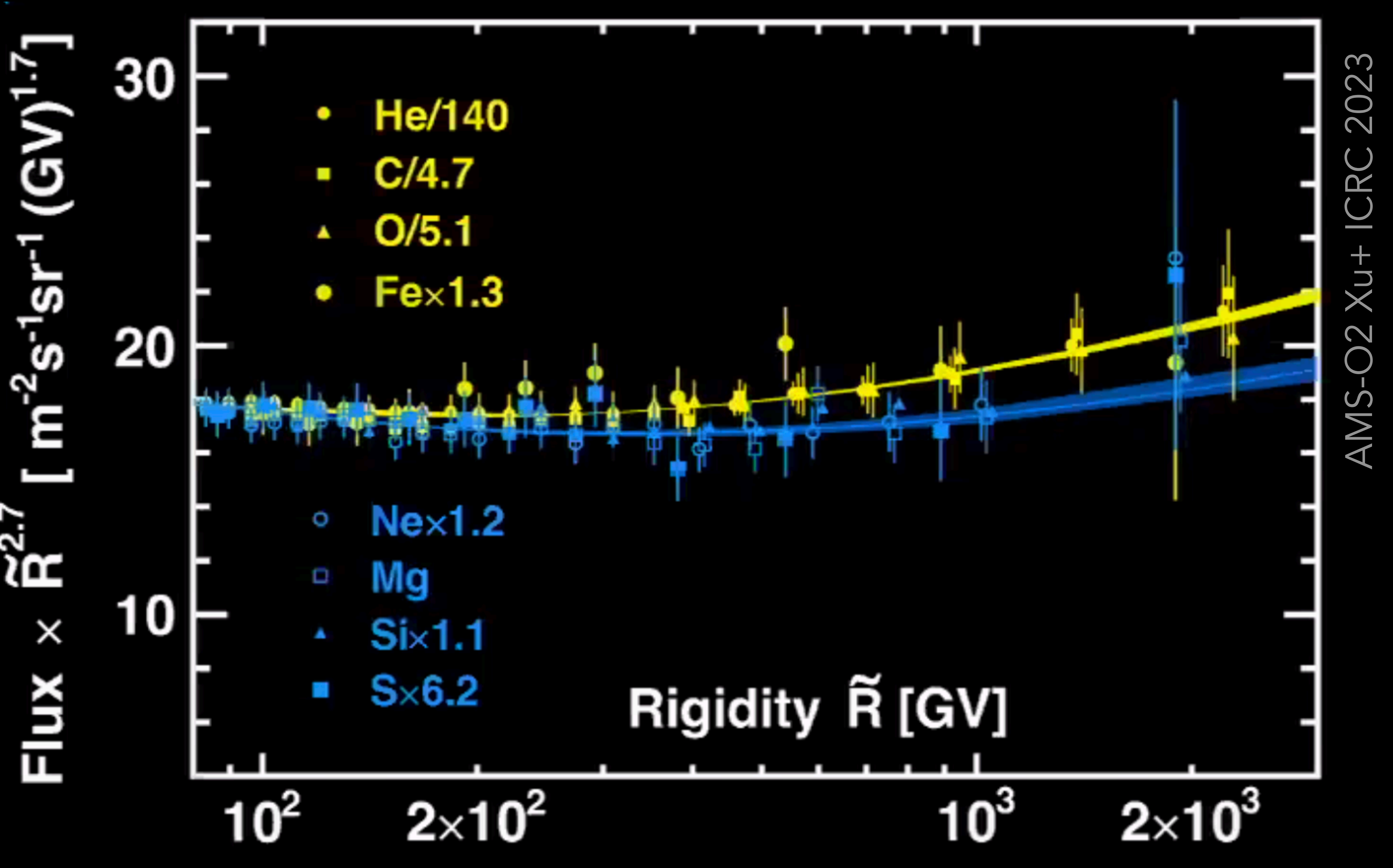
$$\kappa(GeV/n) \approx 10^{28-29}\ \text{cm}^2/s, \quad l_{scat} \approx 3\kappa/c \sim 1\ \text{pc}$$

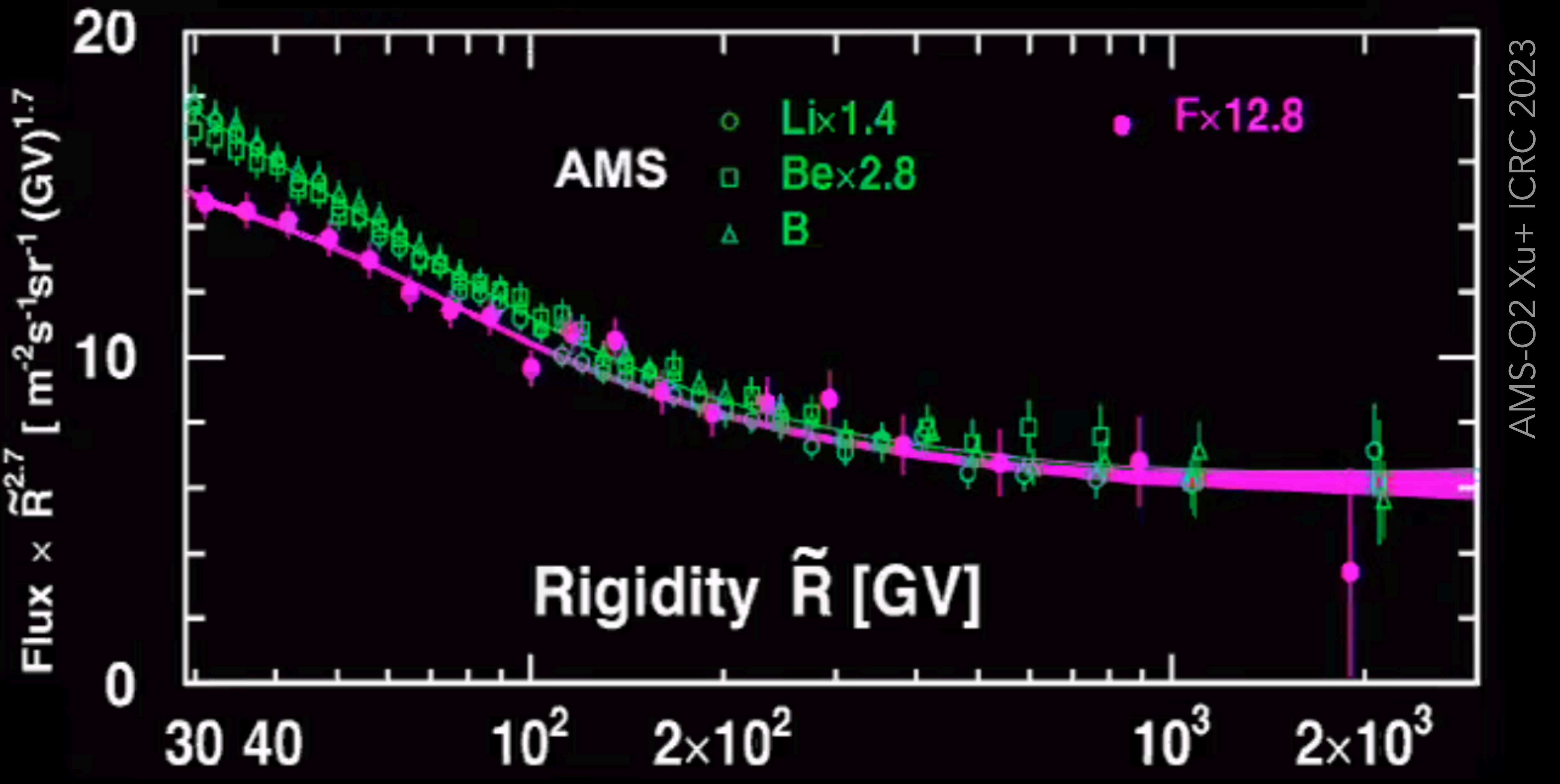


cosmic-ray composition vs. solar abundances

- but 2 classes of CR primaries, with secondary contamination







- but 2 classes of secondaries

total cosmic-ray power

- total power ⩾ GeV
  - from spallation residence time Δt_{cr} and grammage $X_{cr} \sim \rho_{ISM}\, c\, \Delta t_{cr}$

Dogiel+2002

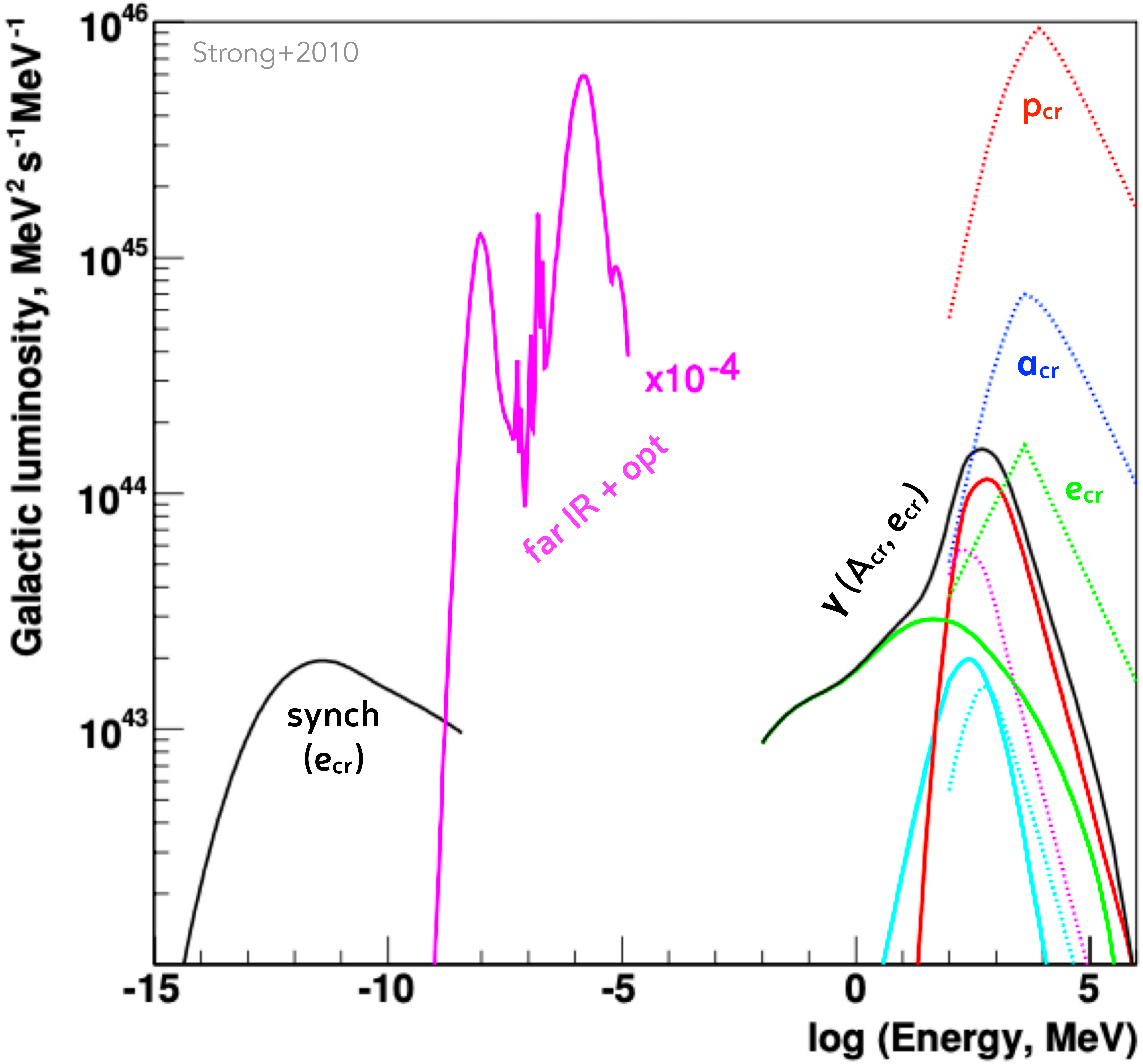
$$P_{cr} \sim \frac{E_{CR}}{\Delta t_{cr}} = \frac{u_{cr} V_{gal}}{\Delta t_{cr}} = \frac{u_{cr} V_{gal} \rho_{ISM}\, c}{X_{cr}} = \frac{u_{cr}\, c\, M_{ISM,gal}}{X_{cr}}$$

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

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

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

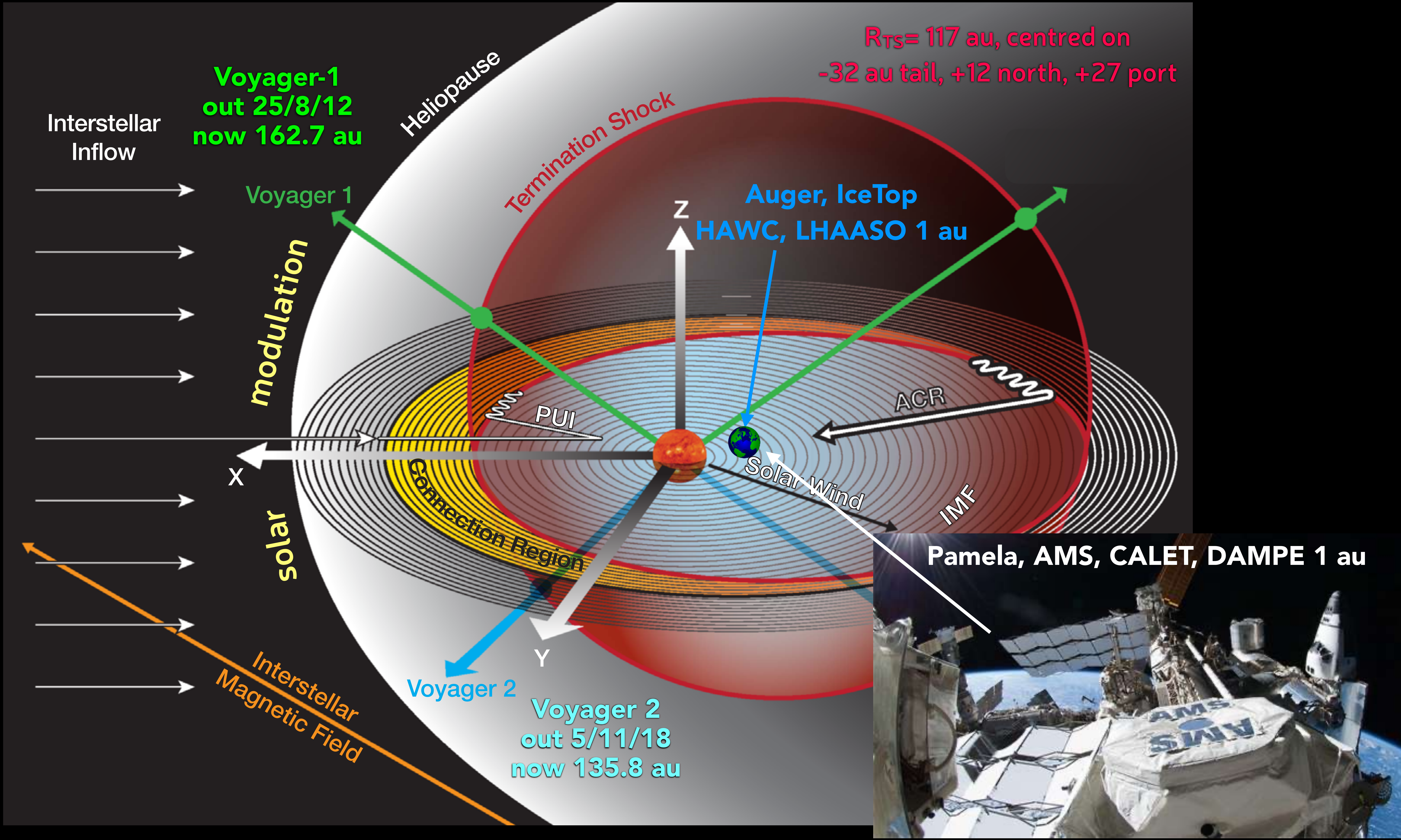
10% of the total power of supernova explosions in the Milky Way



wicked data

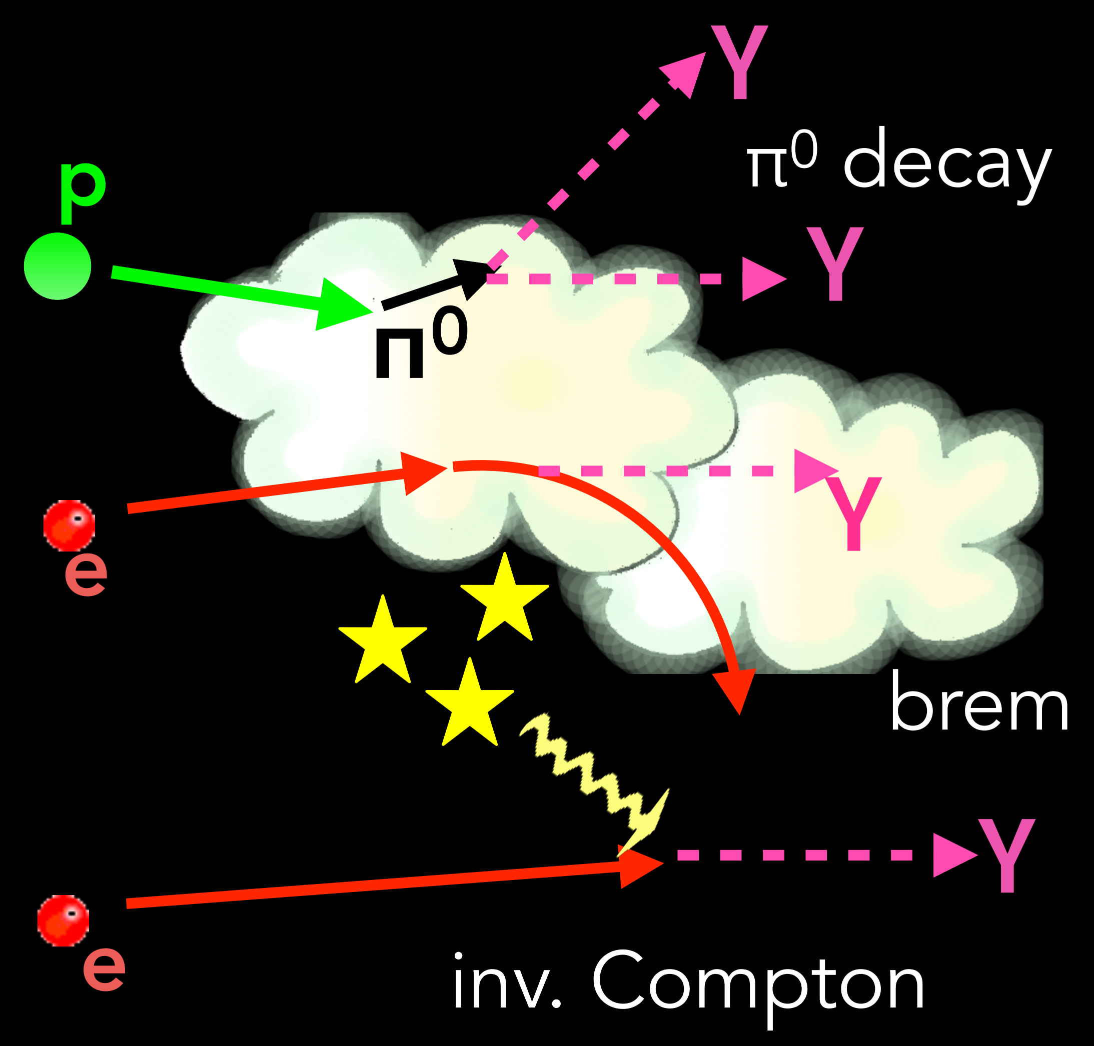
outer-space collection

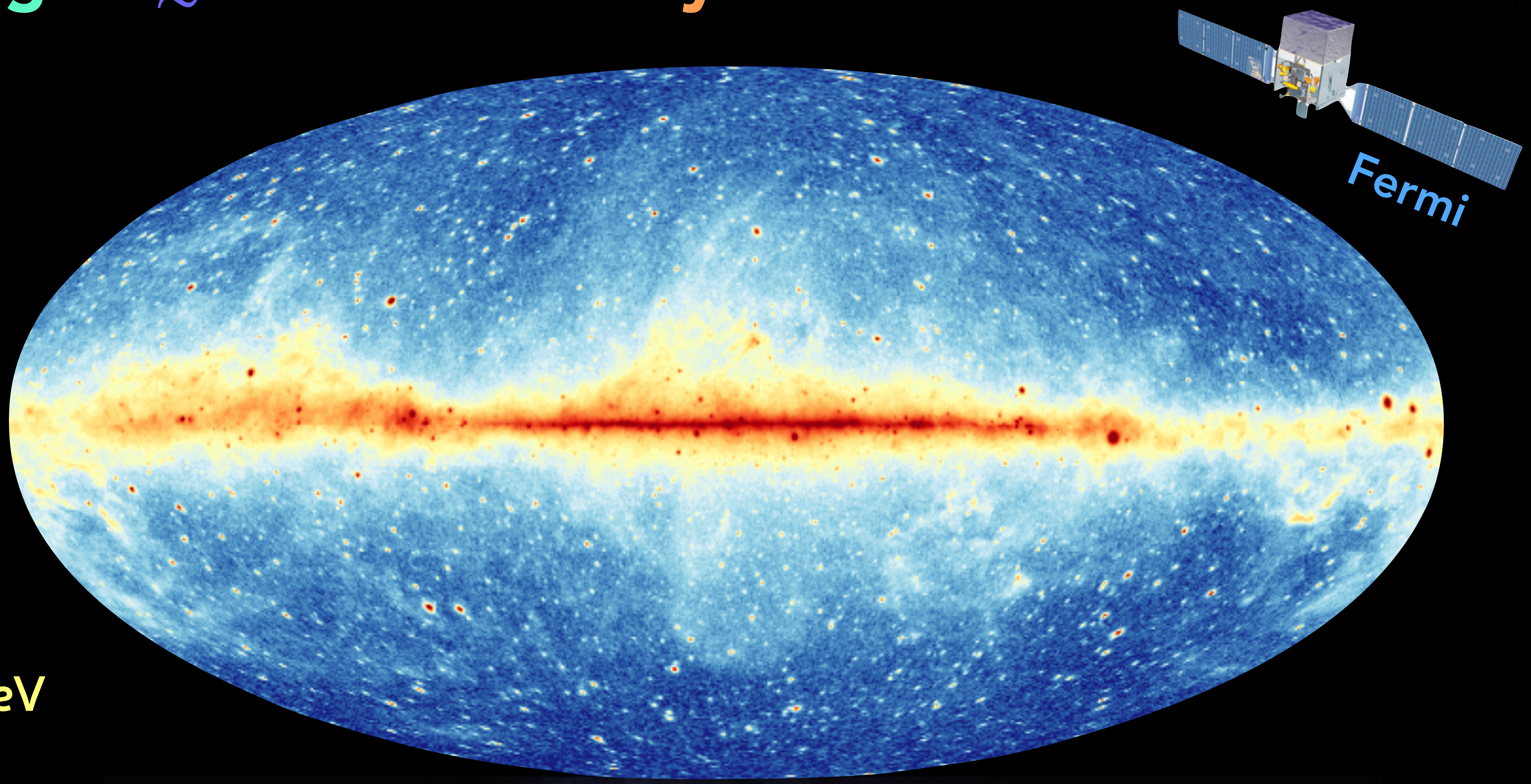
McComas+ 2019



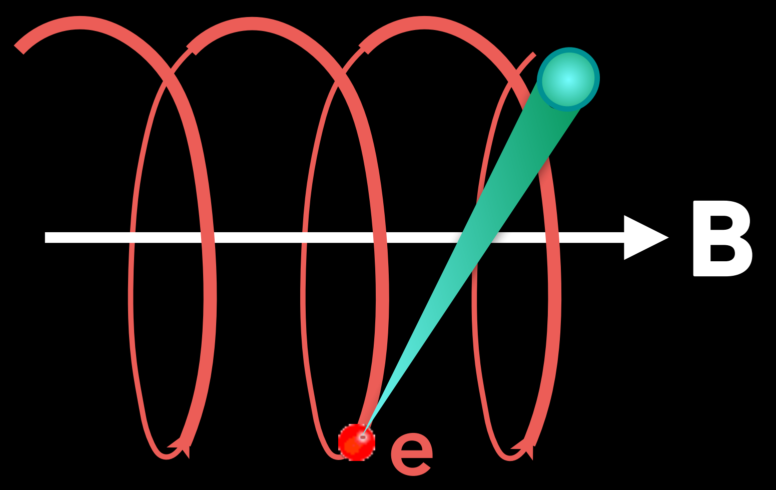
remote sensing of ≳ GeV cosmic rays

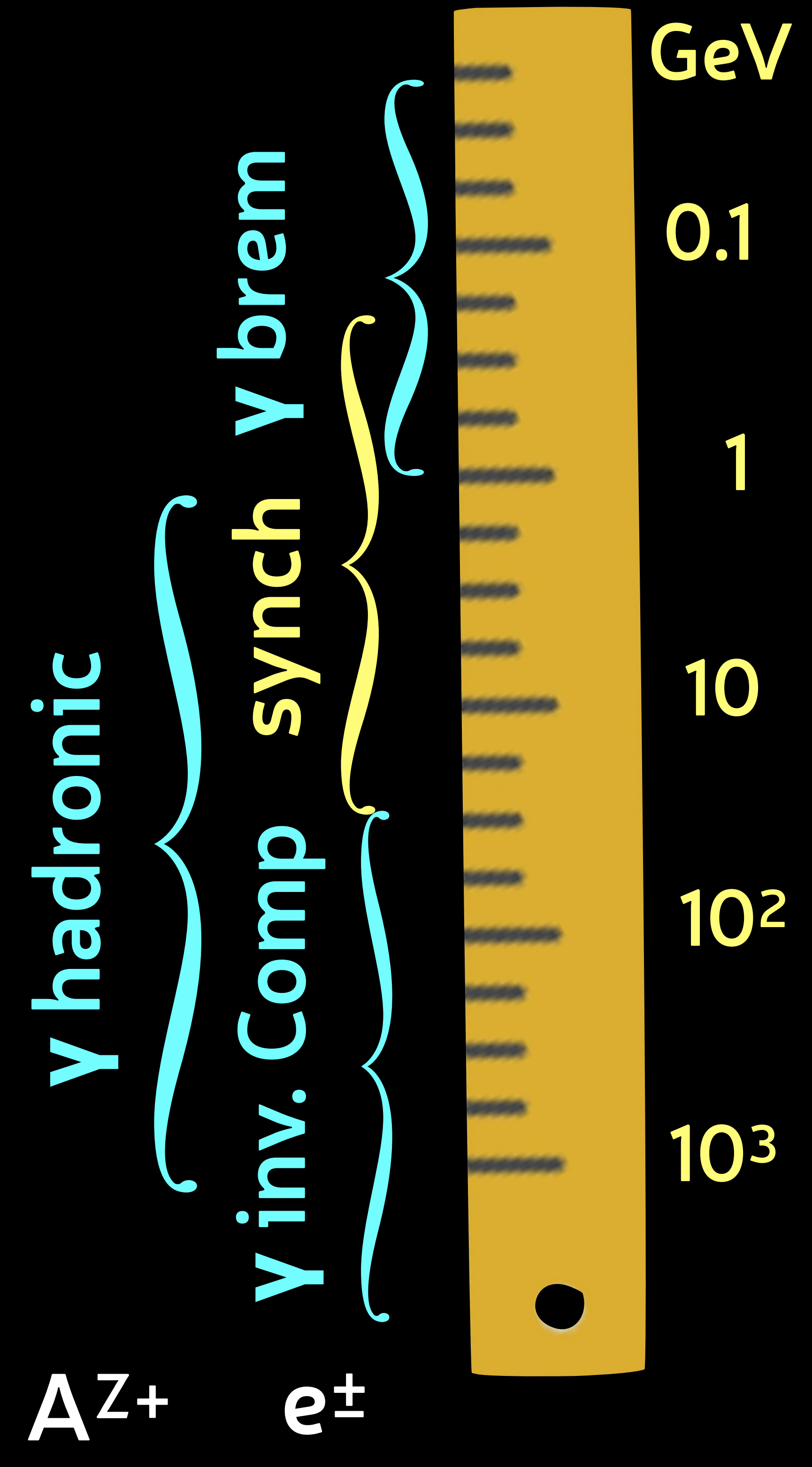
- A^{Z+} + $e^{\pm}$ probed in γ rays
  - Fermi LAT > GeV





- $e^{\pm}$ probed by radio synchrotron
  - 30 haloes piled-up by Chan-ges



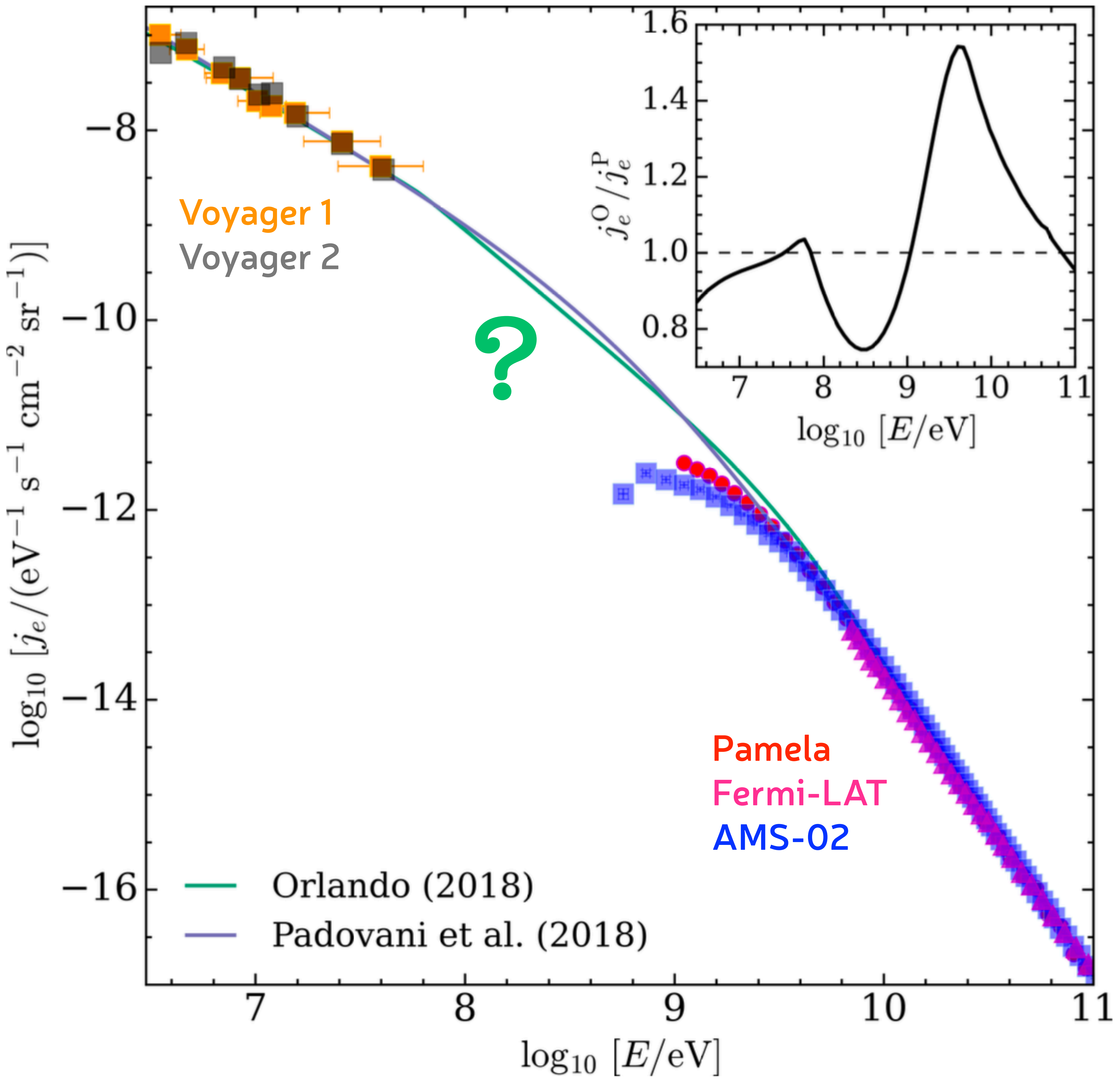


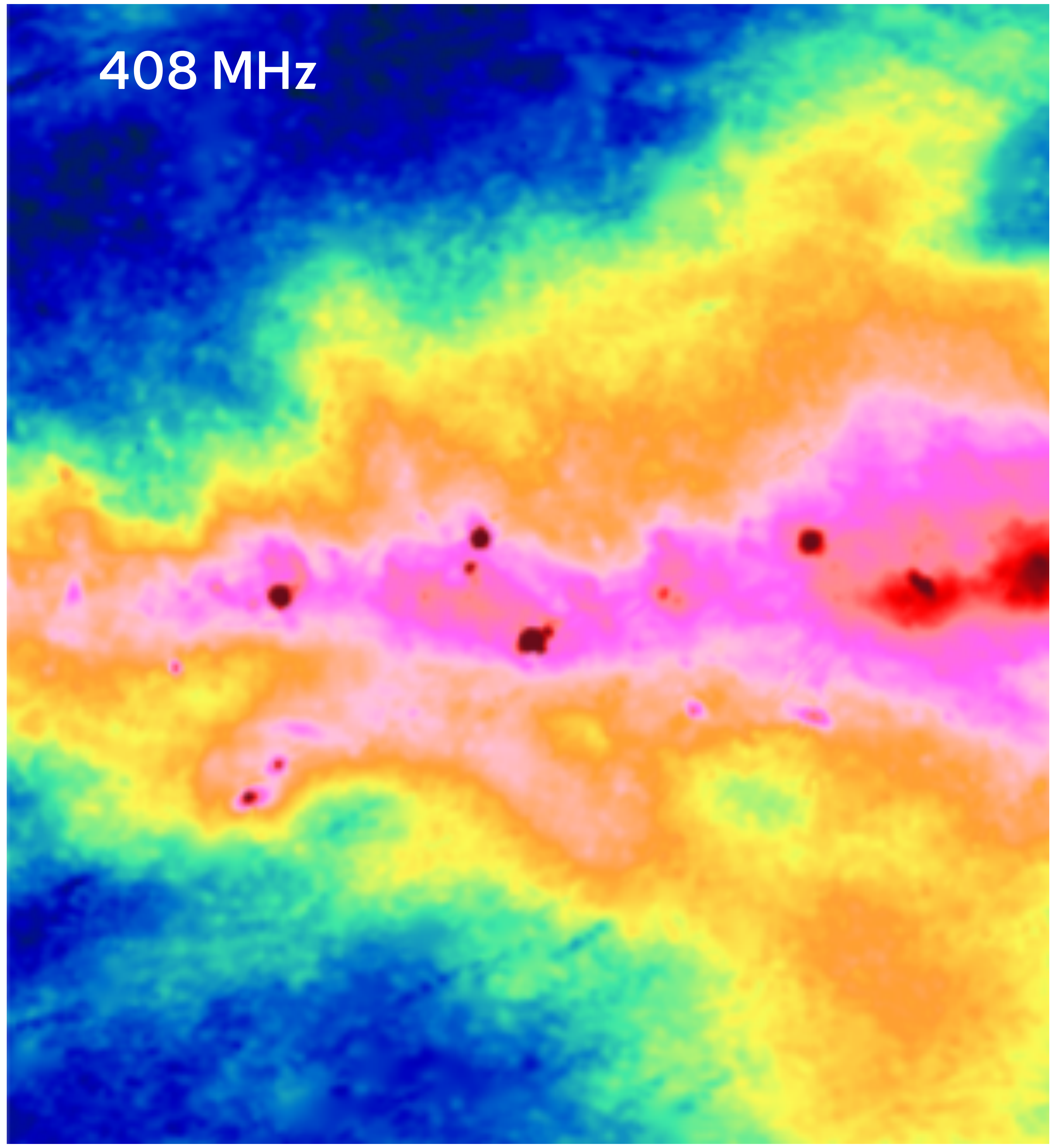
radio tracing difficulties

- $B_{ISM} \approx 2$ - 20 μG, ν_{radio} = 0.1-10 GHz => 0.1 ⩽ E_e ⩽ 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

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

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





radio tracing problem

- collapse of "elongated" clouds along B with $h_{\parallel} > R_{\perp}$ 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 ?