How fast do GeV-TeV cosmic rays travel?

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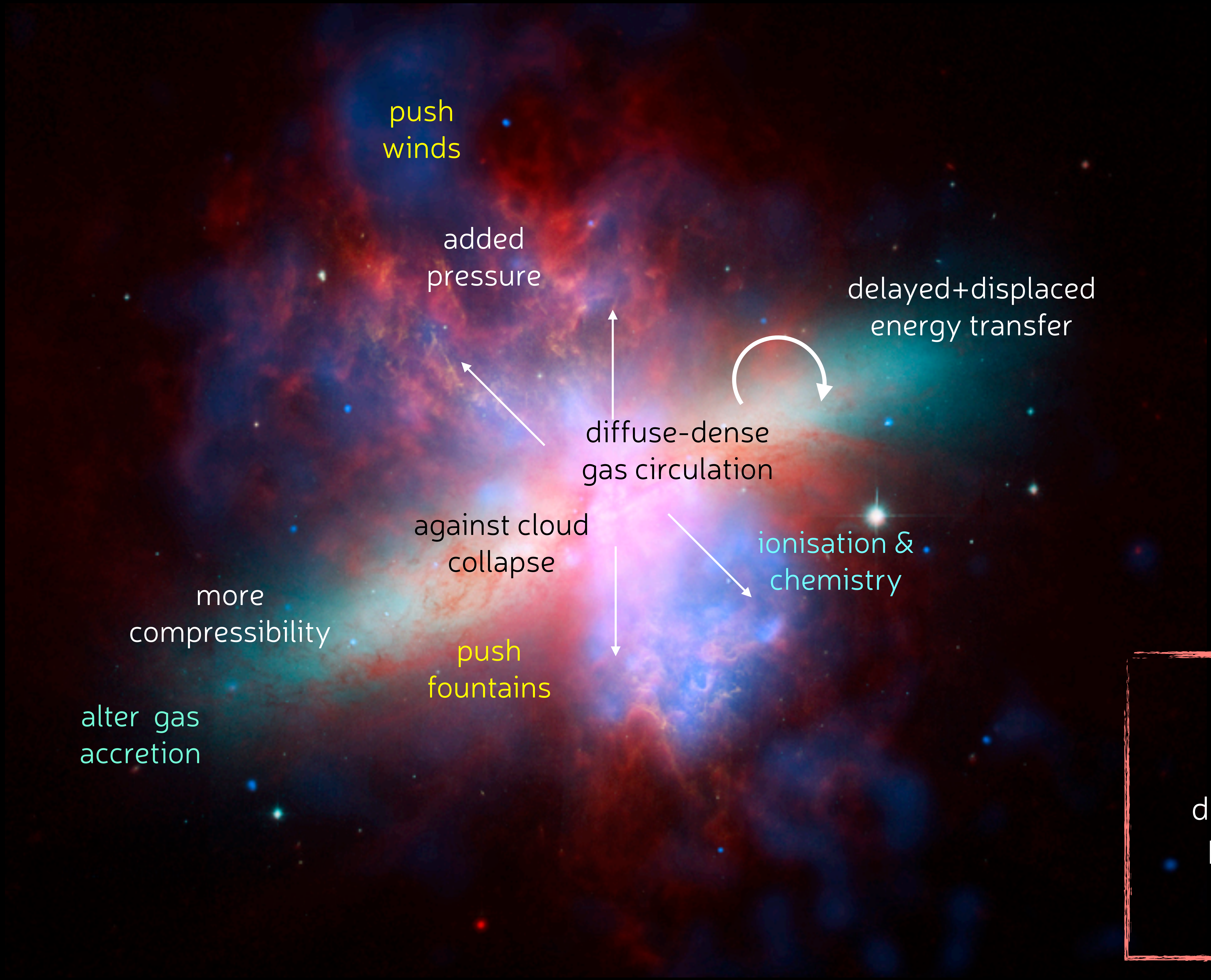
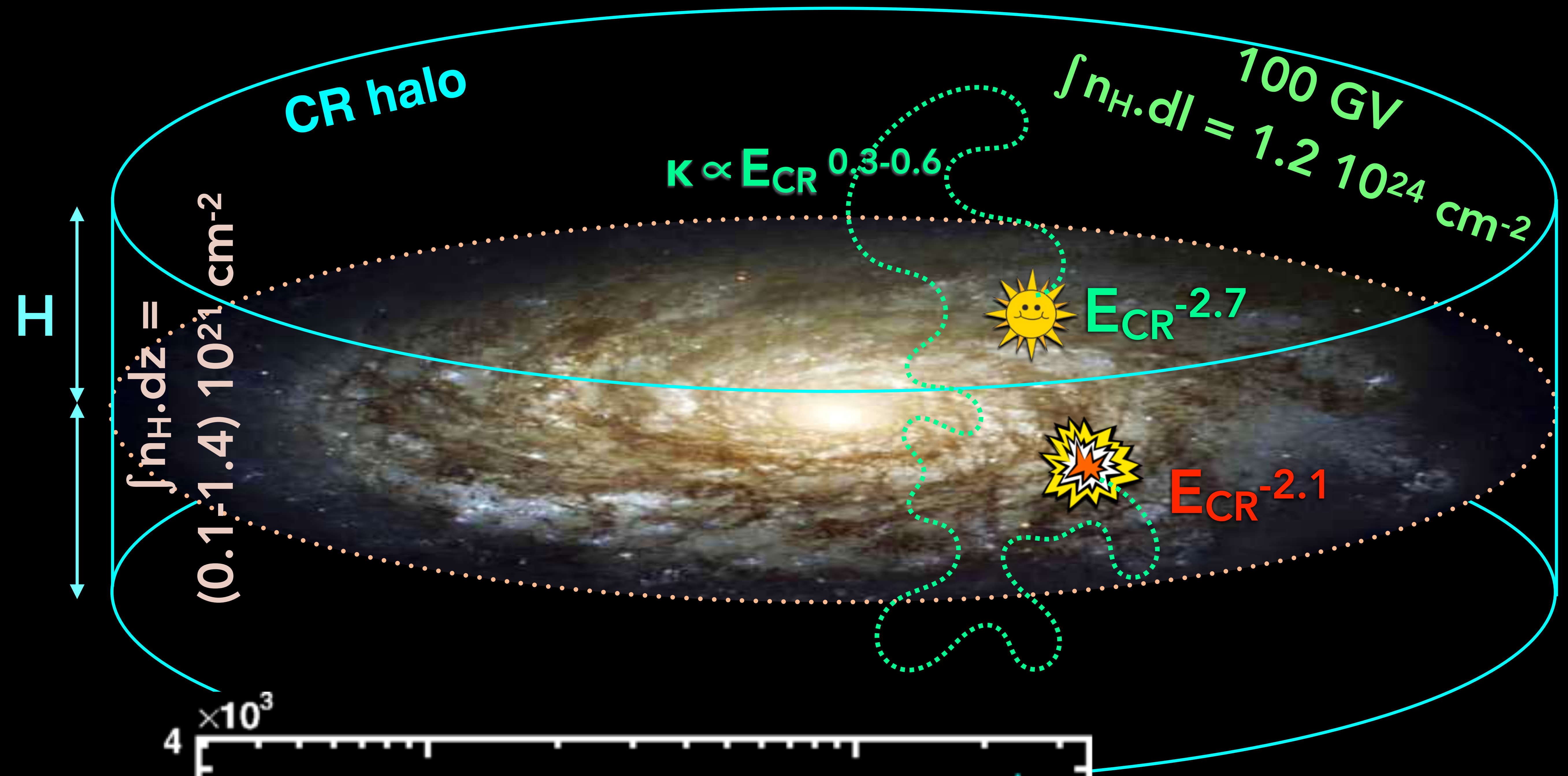
cosmic-ray feedback on galaxy evolution

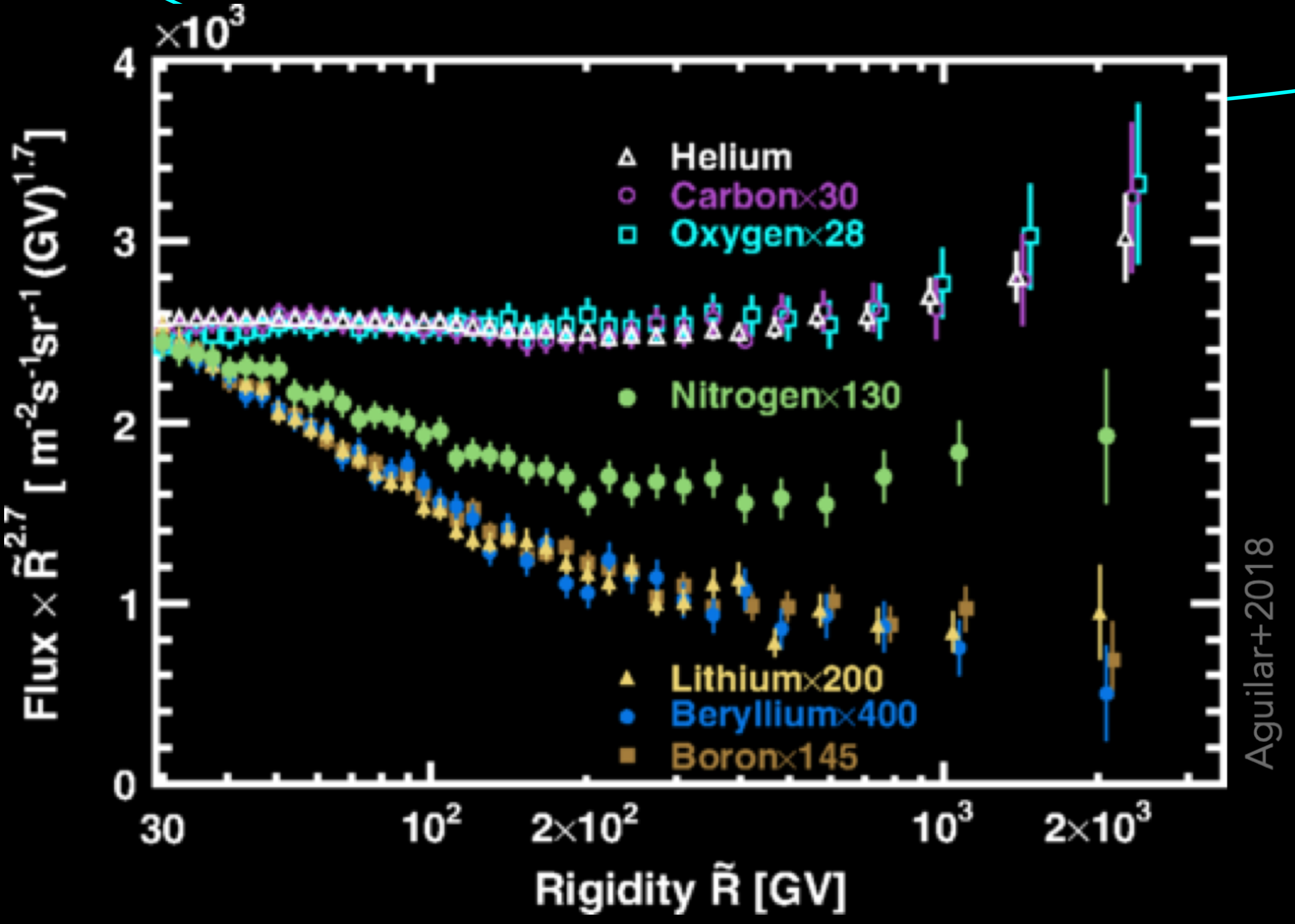


self or interstellar confinement?
diffusion coeff $\kappa(E)$?
how uneven $\kappa(E)$?
halo extent?

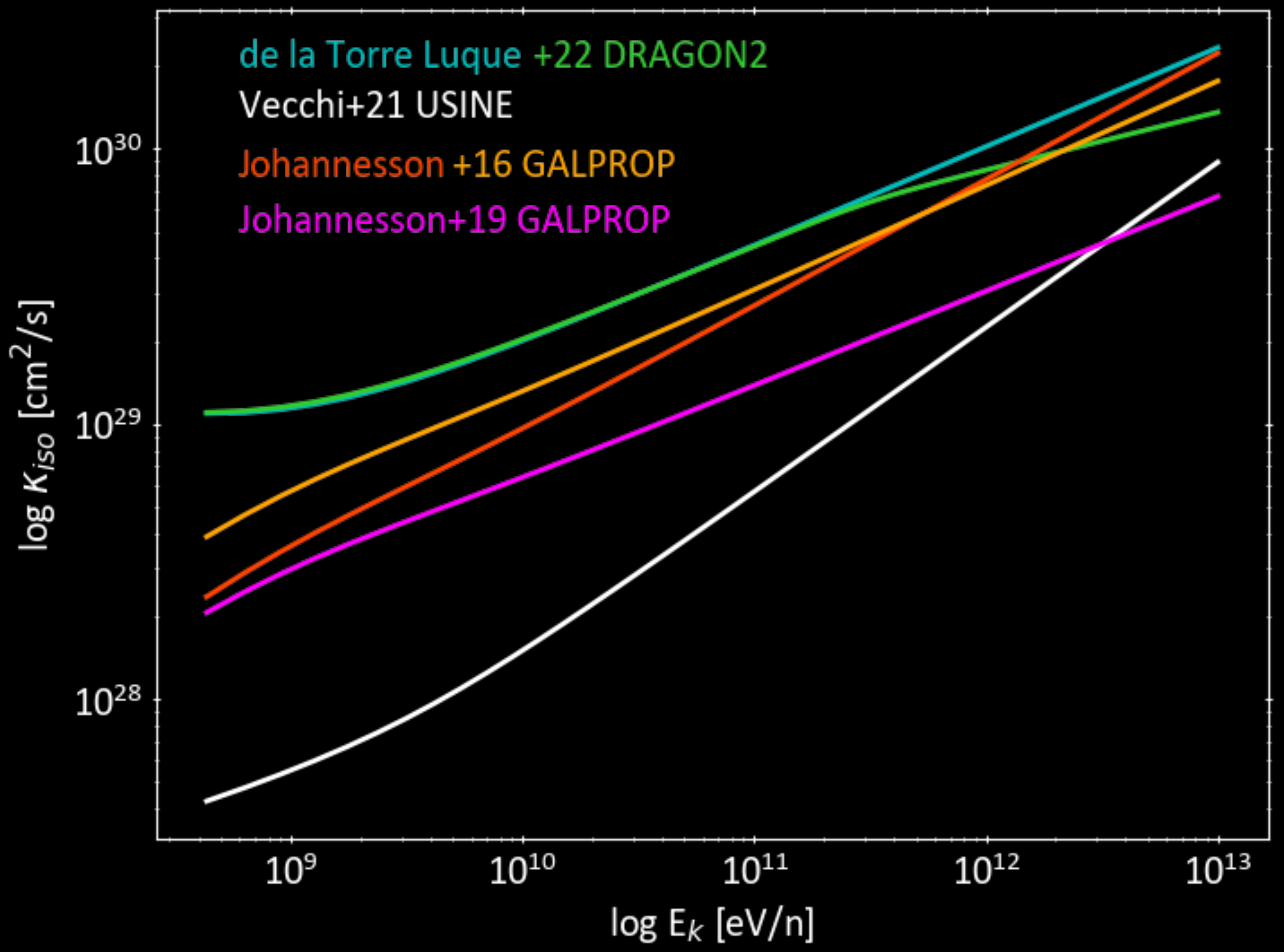
local diffusion inference



κ(GeV/n) ≈ 10^{28-29} cm^2/s,
different $\frac{n_2}{n_1}(E)$ trends,
different cross-sections,
inelastic collisions,
advection, reacceleration…



$$\Rightarrow \frac{n_2(E)}{n_1(E)} \propto \kappa(E)^{-1}$$



how uneven is diffusion?

- diffusion on self-excited or ISM-cascade Alfven waves

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

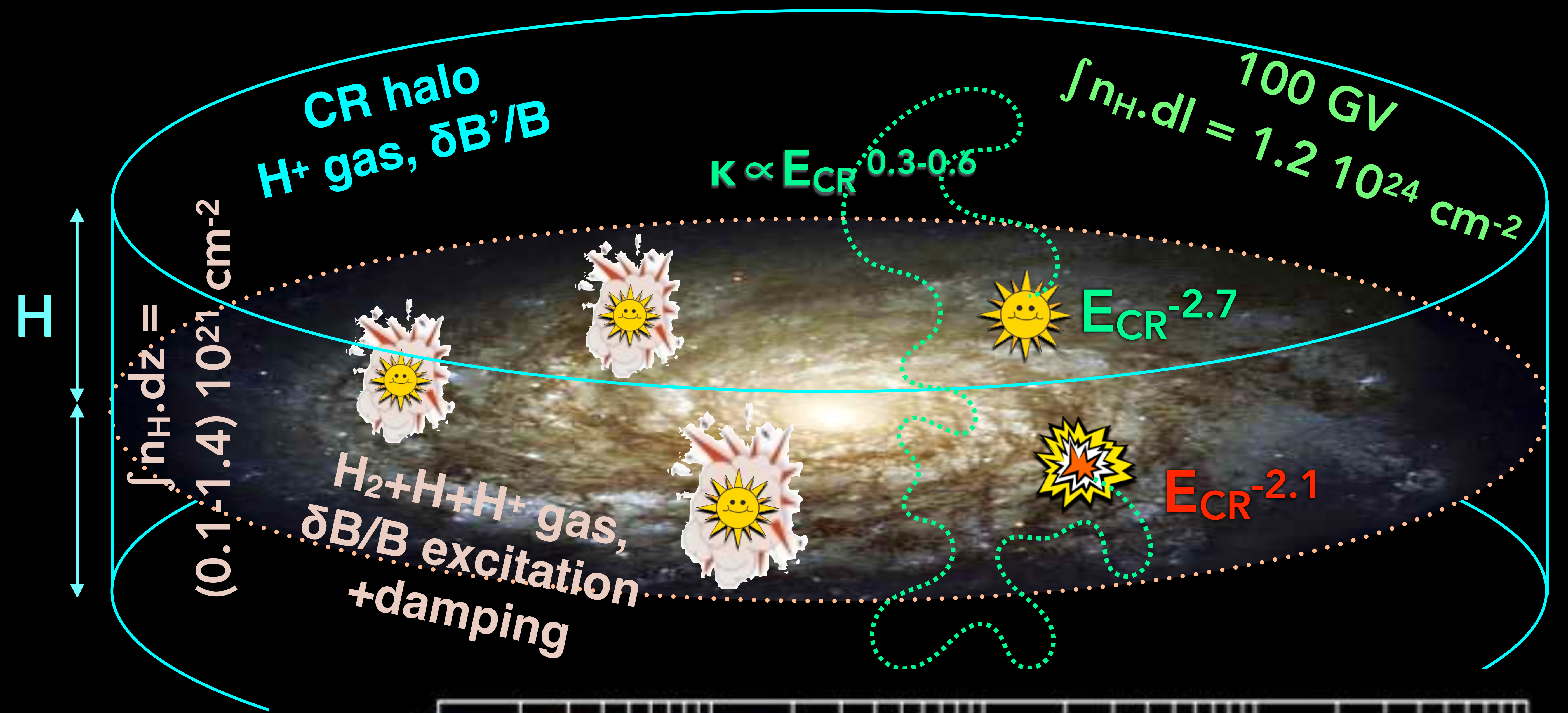
$$R_{gyr} = 0.08\ \text{au or } 0.4\ \mu\text{pc} \left(\frac{R}{1\,GV}\right)\left(\frac{B}{5\,\mu G}\right)^{-1}$$

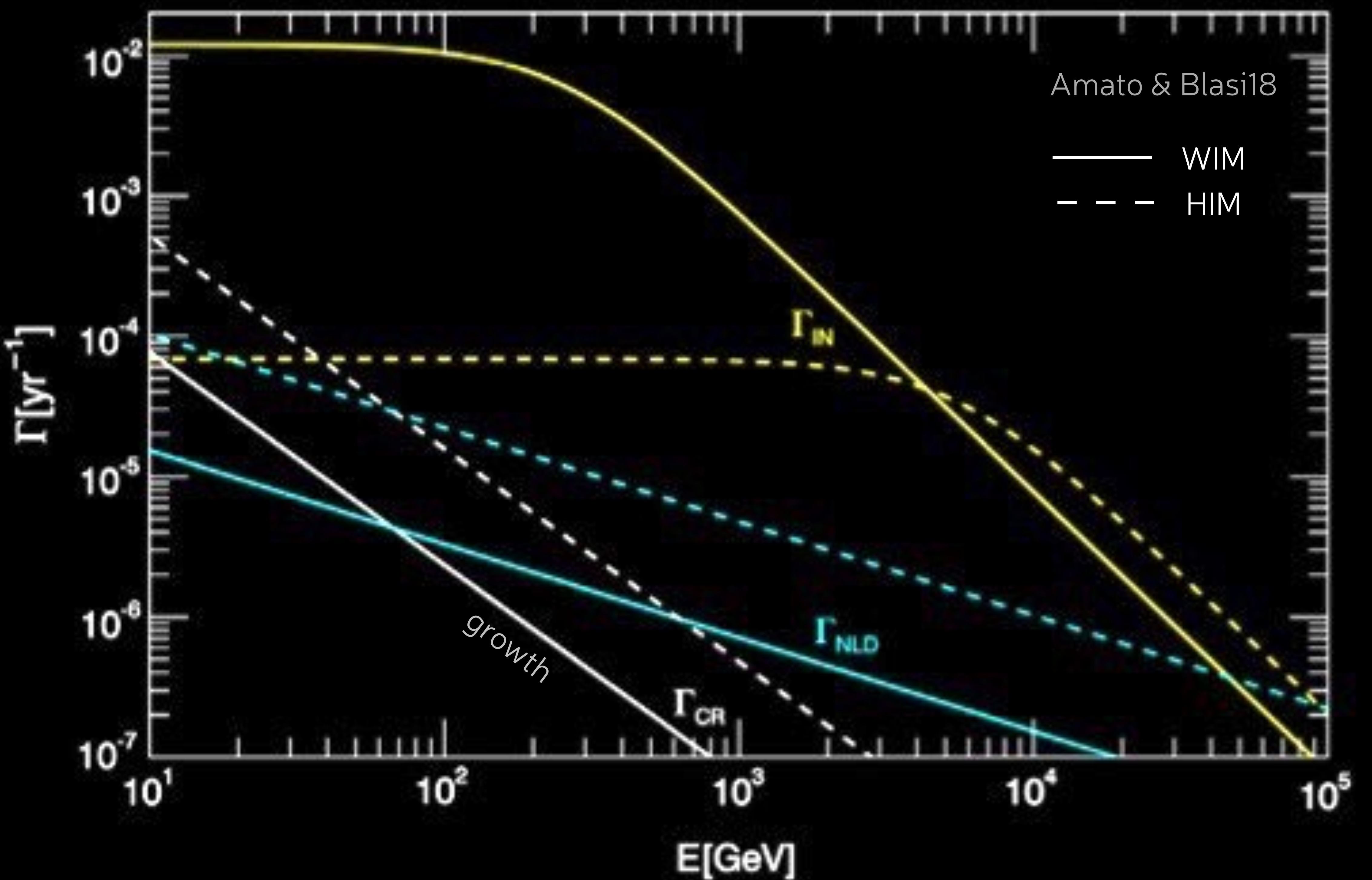
- halo HIM
  - non-linear Landau damping (ion resonance with beat waves between Alfven wave couples) Xu & Lazarian 22
  - $v_{stream} \approx v_A$ Lee & Völk 73, Kulsrud 78
  - $\kappa(E) \propto E^{0.7}$ Blasi+12

- WIM 1.8 kpc-thick layer
  - turbulent damping (interactions between self-excited waves & ISM waves)
  - $\kappa \propto \kappa_0(M_A)\,(E/E_0)^{1.1}$ Xu & Lazarian 22

- neutral gas
  - ion-neutral damping
  - $v_{stream} \sim 30\, v_{A,ion} \gg v_A$
  - diffusion via B line random wandering ?

  if $M_A > 1$: $\kappa \propto L_{inj}\, M_A^{-3}\, E^{1.6}$

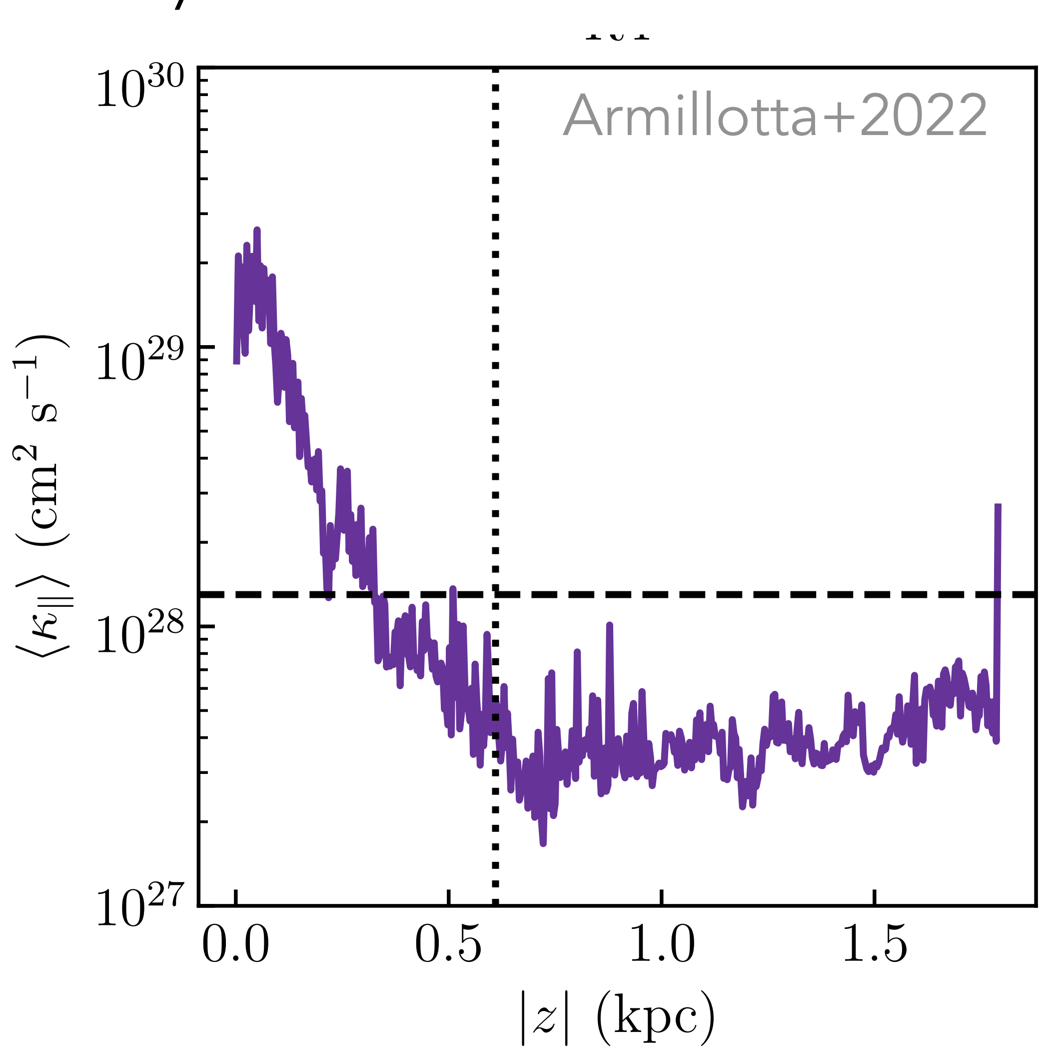


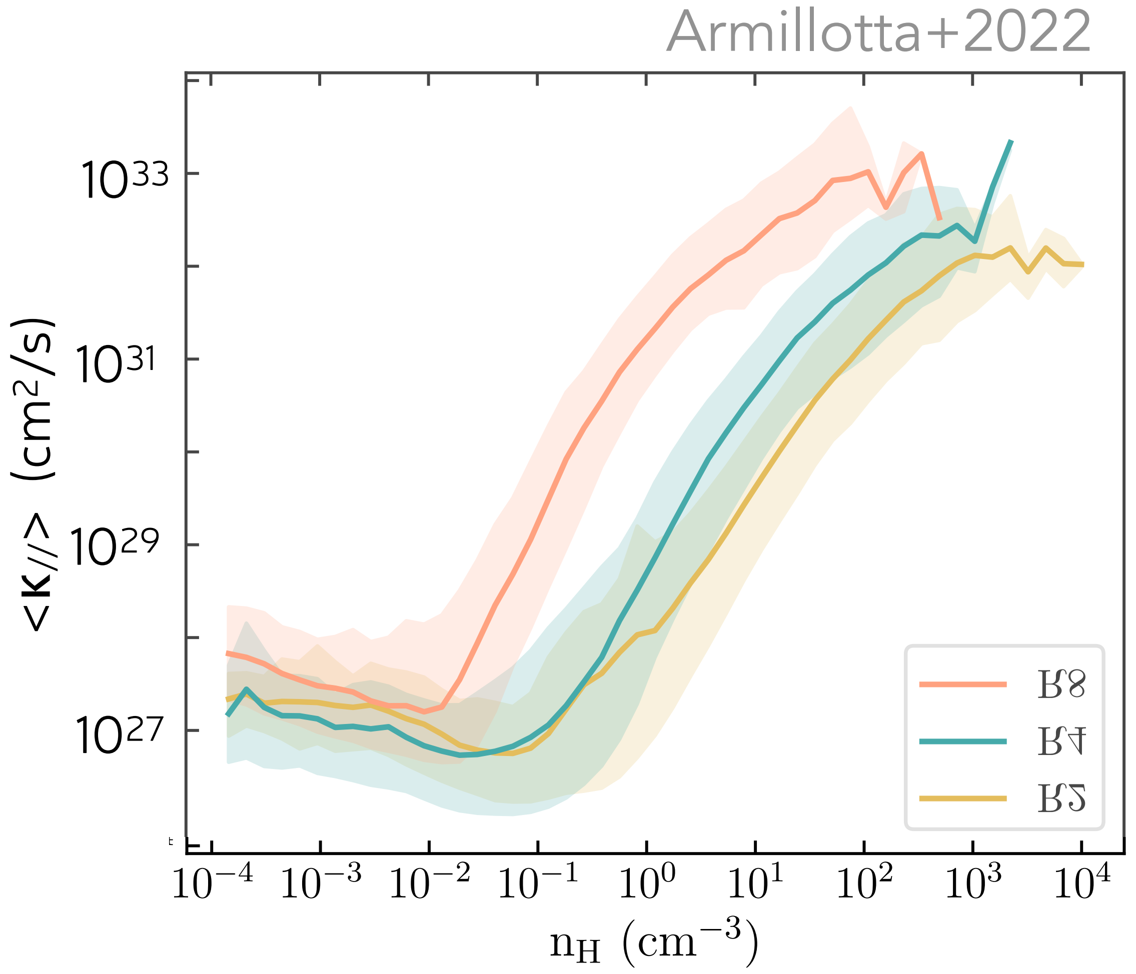


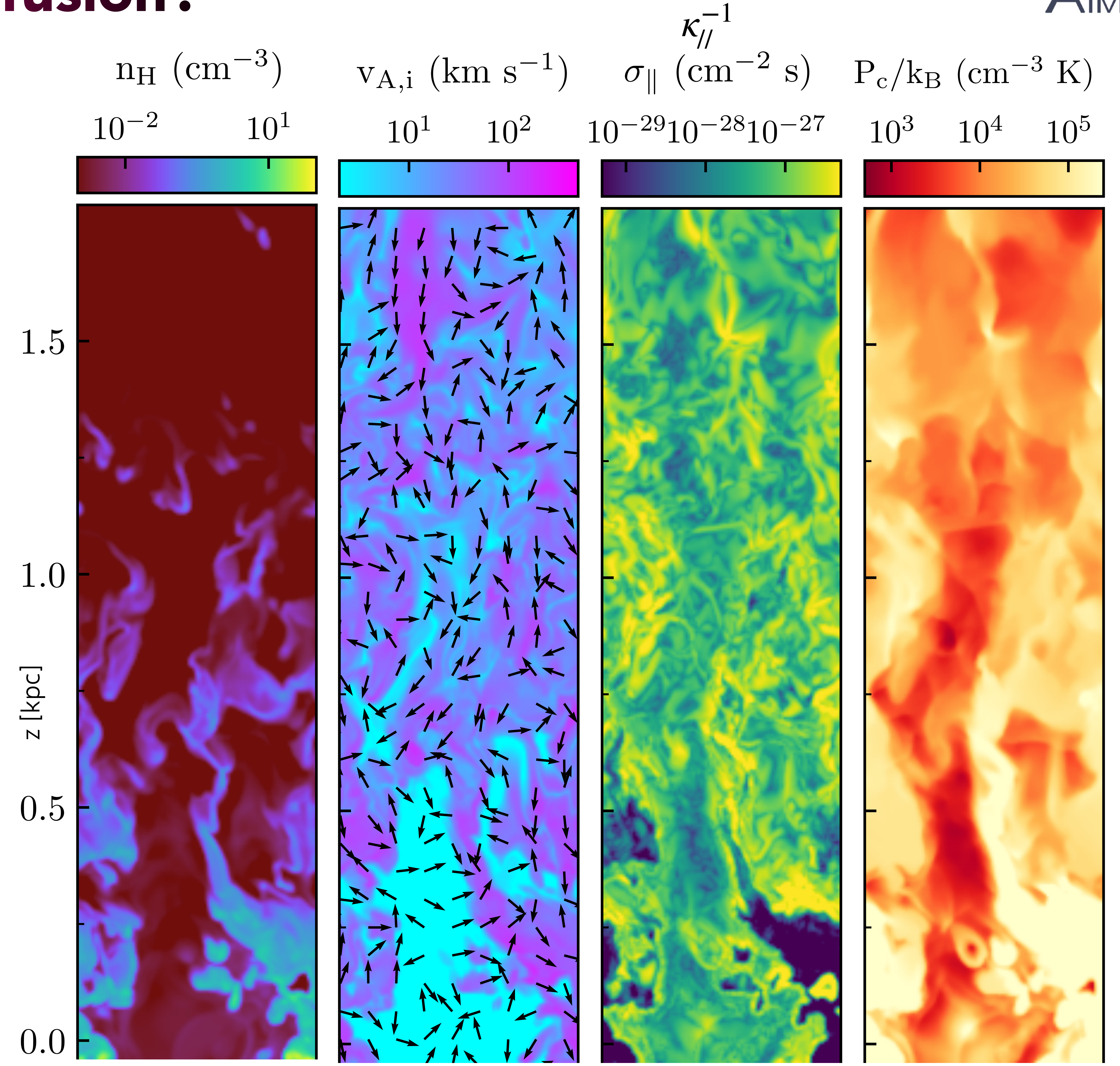
environmental changes in κ(E) value & slope, with M_A & ionisation rate. self-confinement < 100 GeV?

how uneven is diffusion?

- variations by 50 to 1000 ...

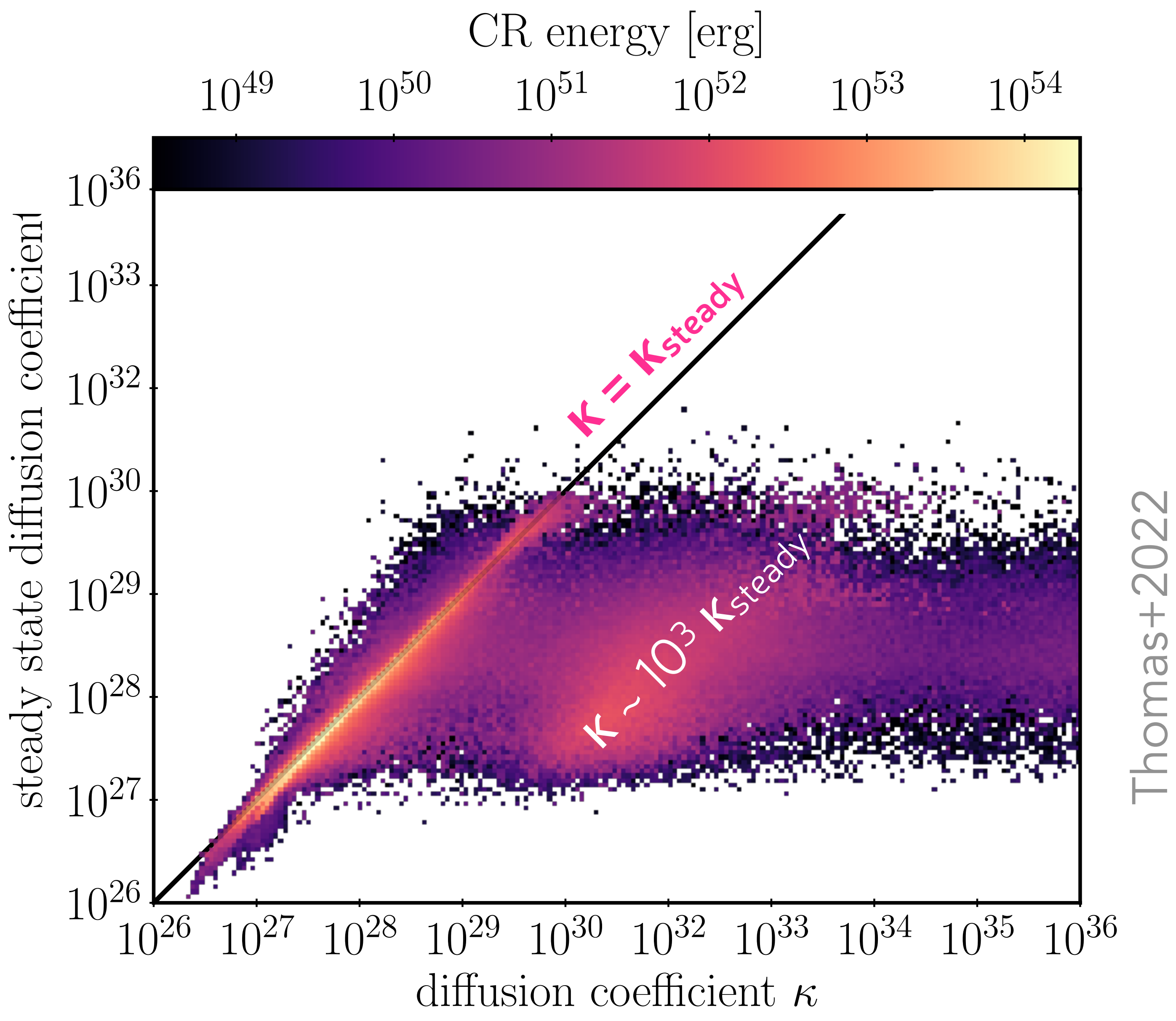


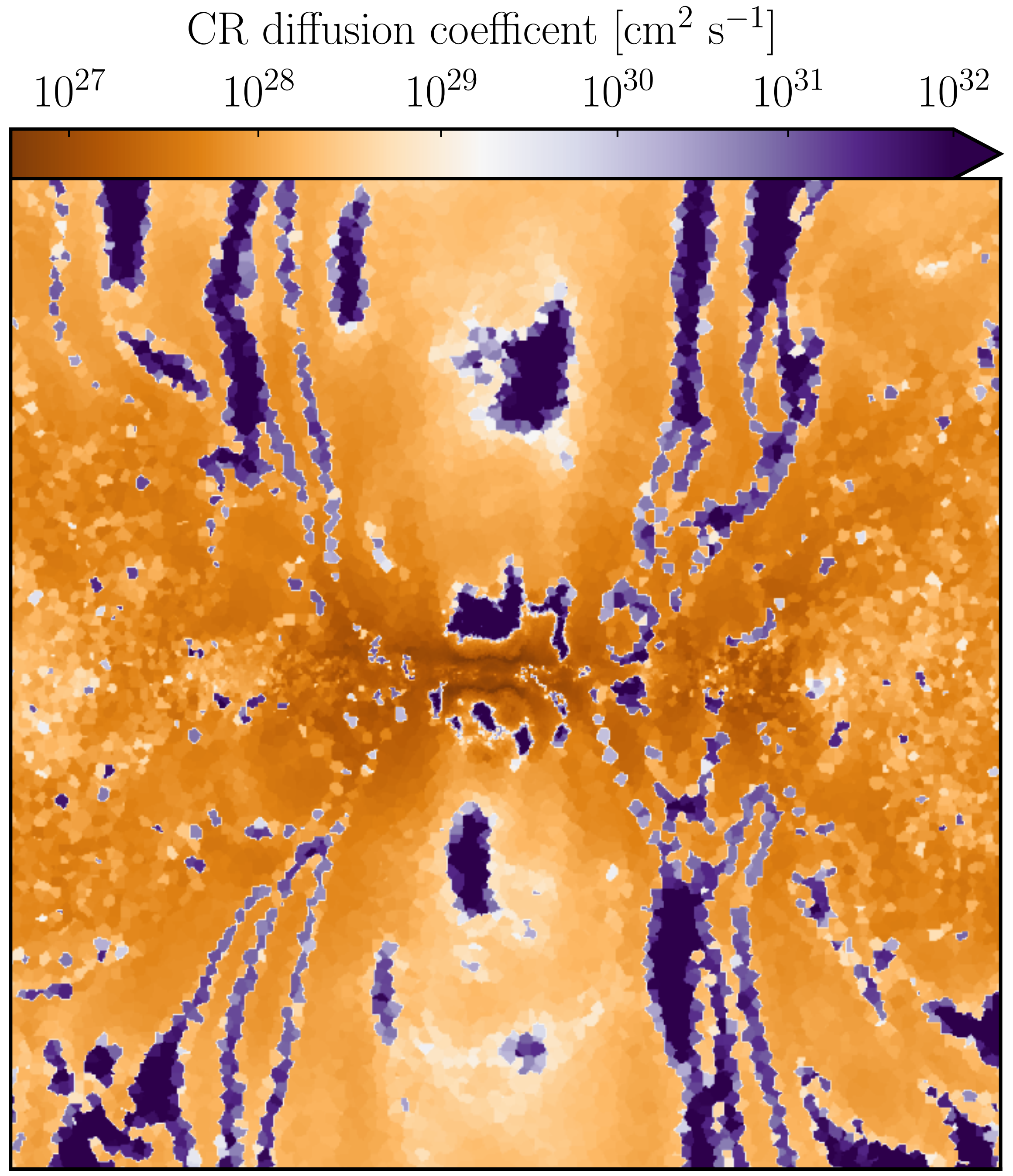




Armillotta+2022

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



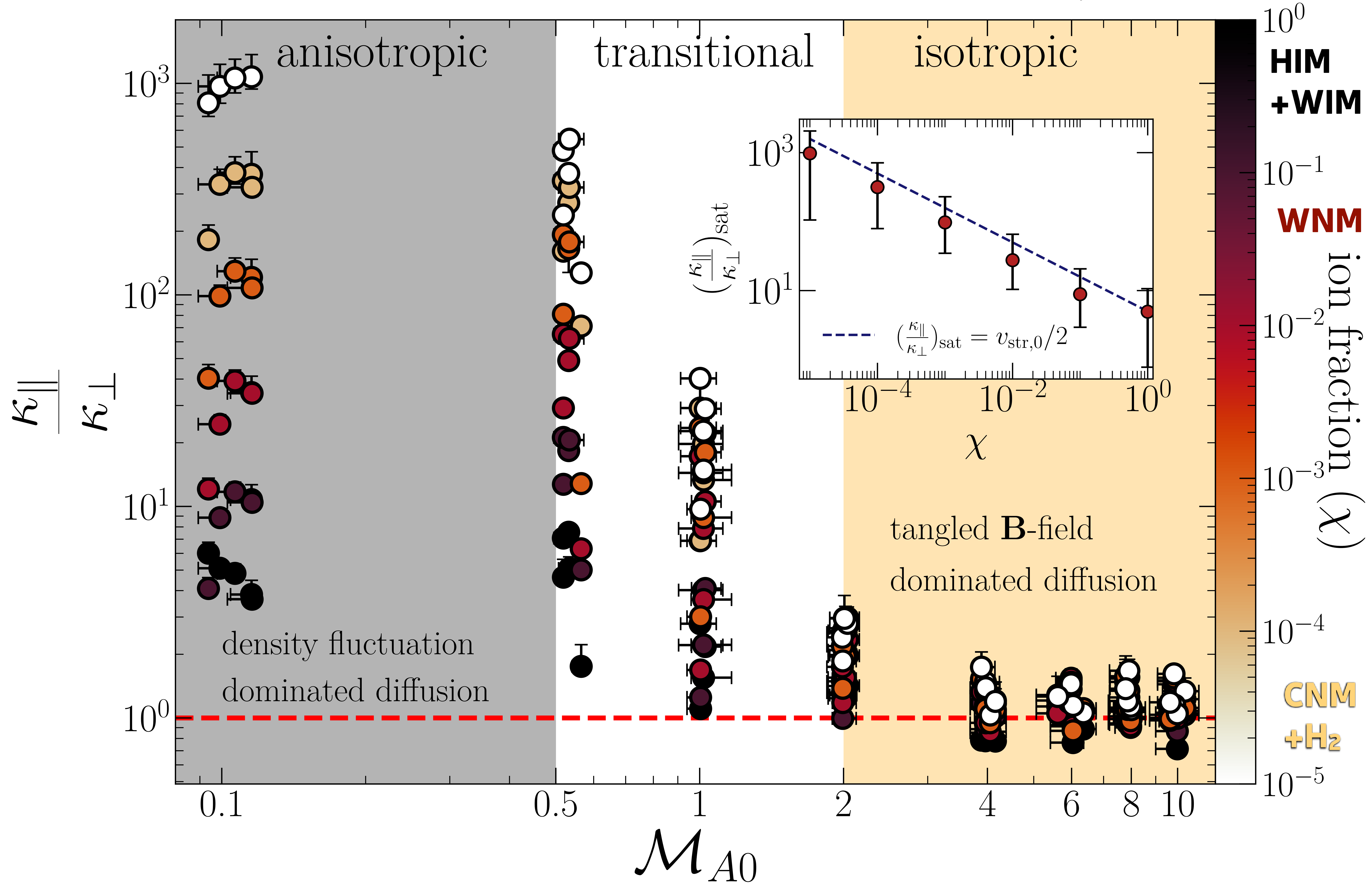


Thomas+2022

how anisotropic is diffusion?

- CR transport $\frac{\partial f}{\partial t} = \vec{\nabla} \cdot \left[\left(\vec{u}_{gas} + v_{A,ion} \frac{\vec{B}}{|\vec{B}|} \right) f \right]$ in MHD turbulence, assuming strong coupling with Alfvén waves

Sampson+2022

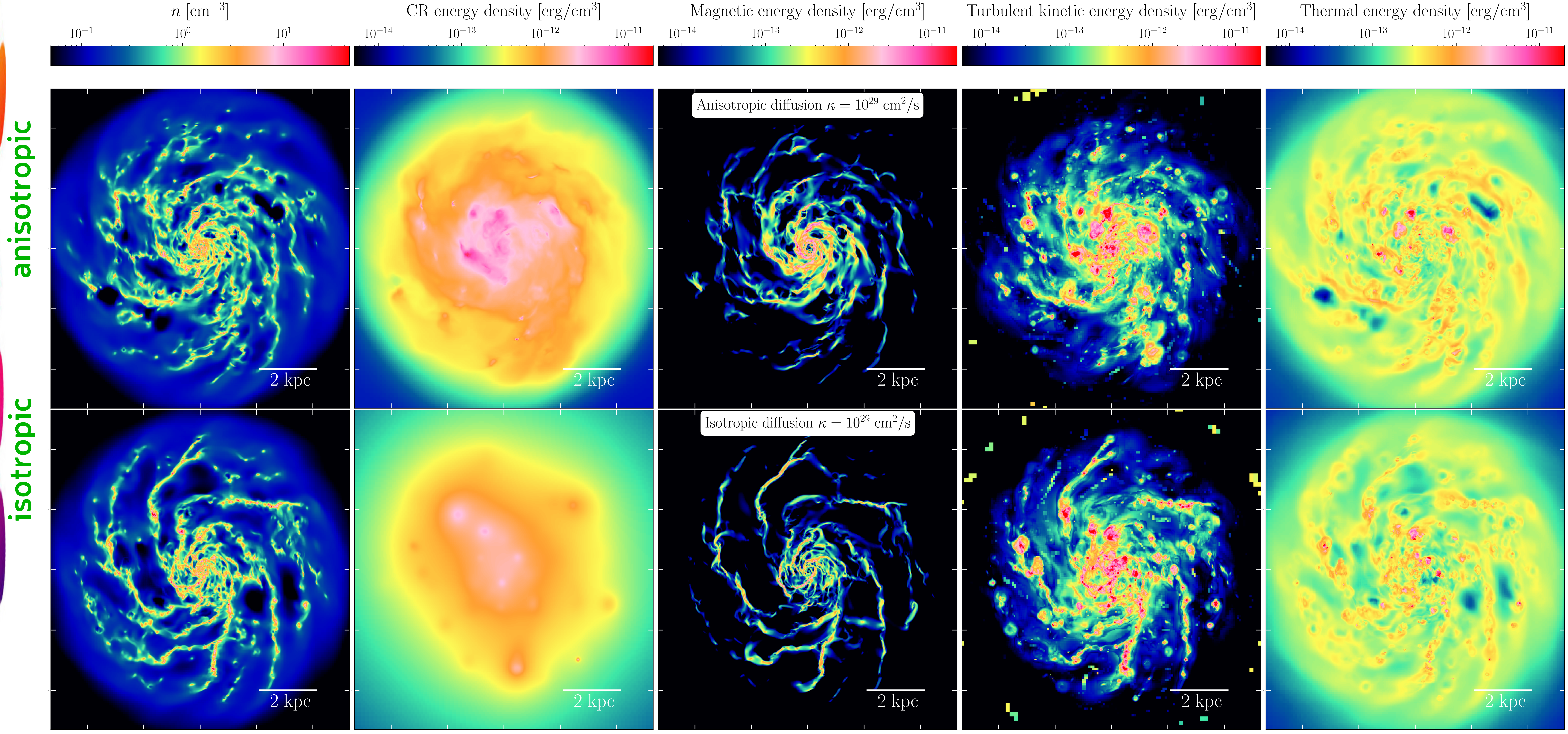


gas-rich dwarf galaxies

Nunez-Castineyra+2022

- 10^{11} M⊙ total mass, forming 1 M⊙ /yr of stars
- multiphasic gas down to 9-pc resolution, ideal MHD with RAMSES

10^{29} cm²/s



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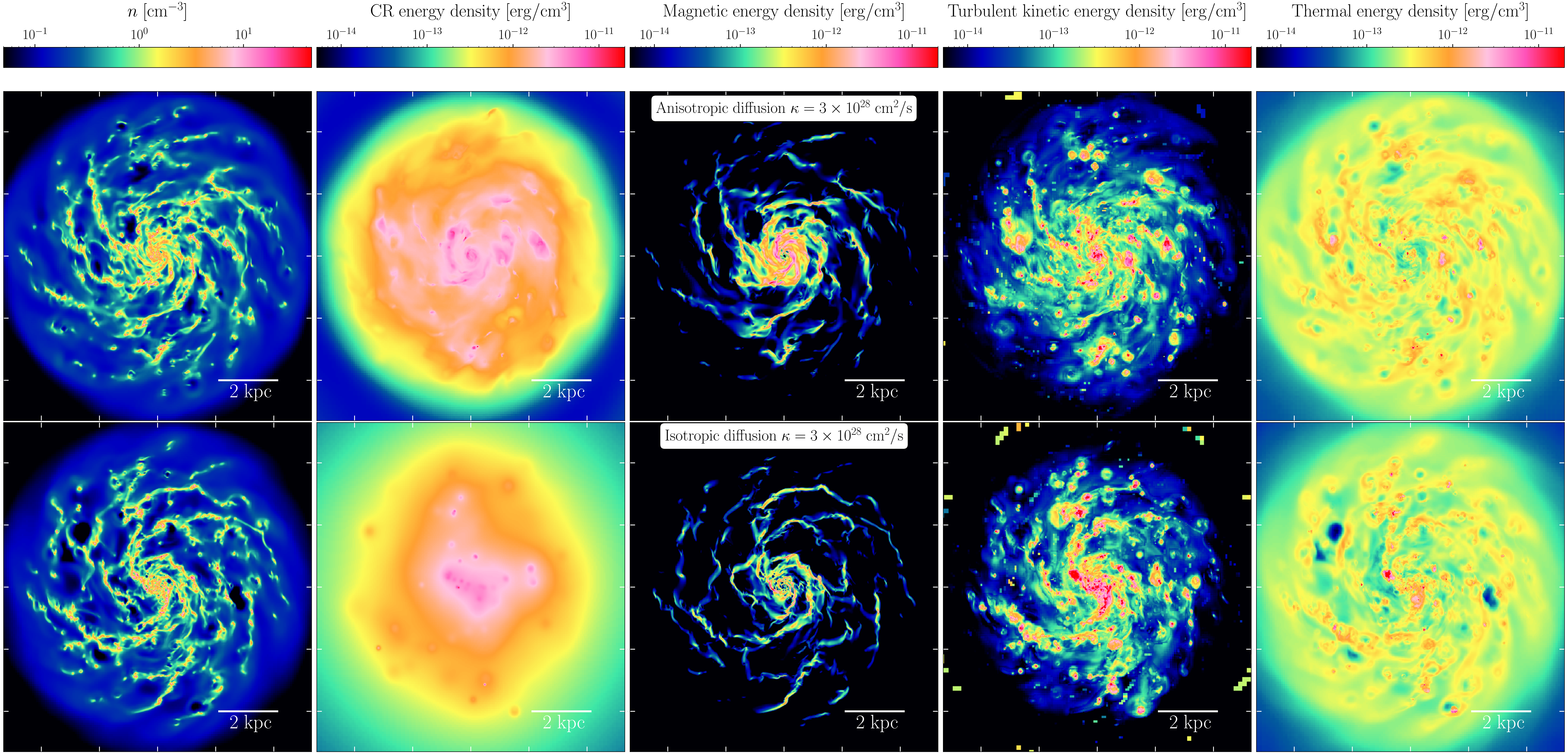
3 10^{28} cm²/s 10^{29} cm²/s

anisotropic

isotropic



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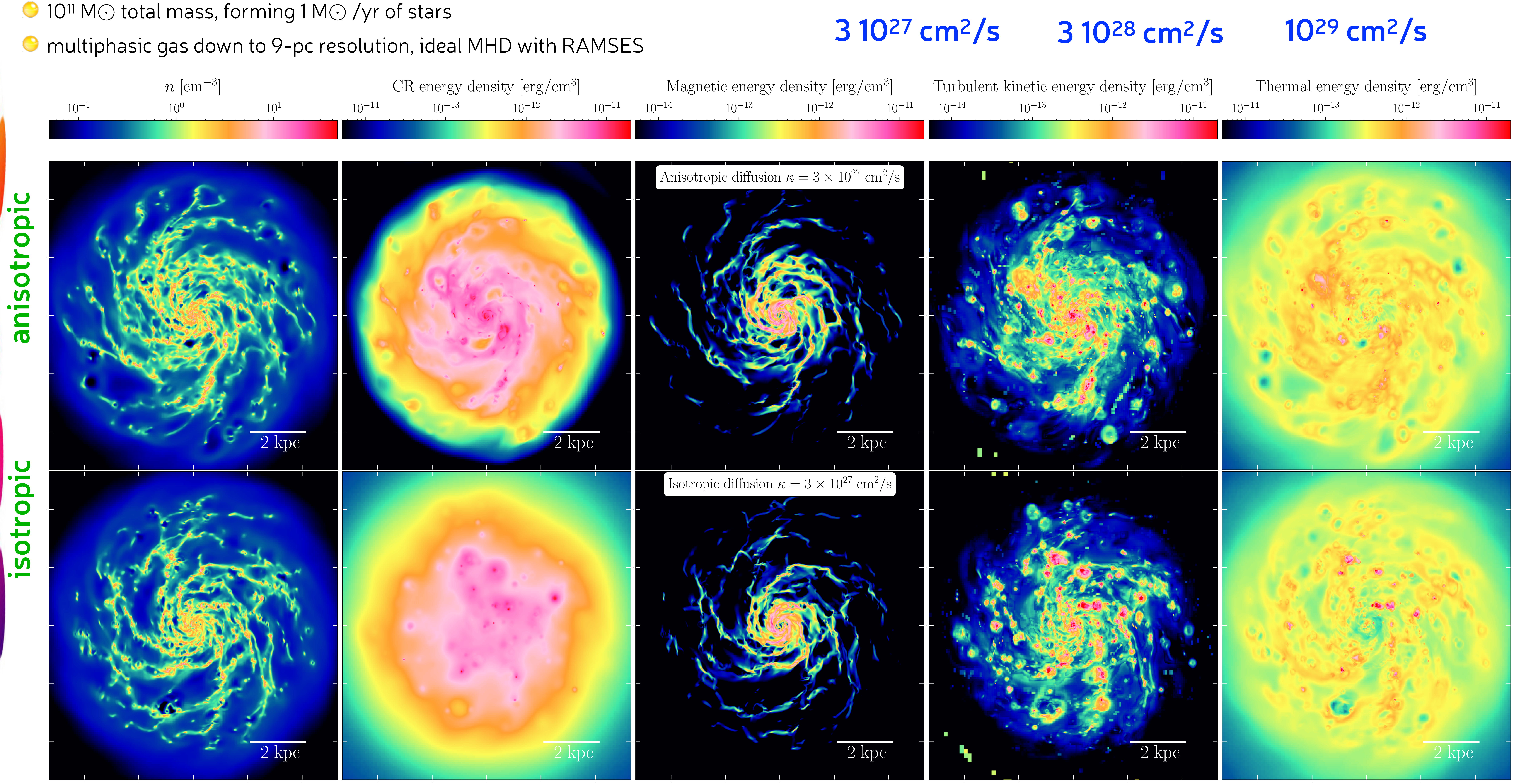

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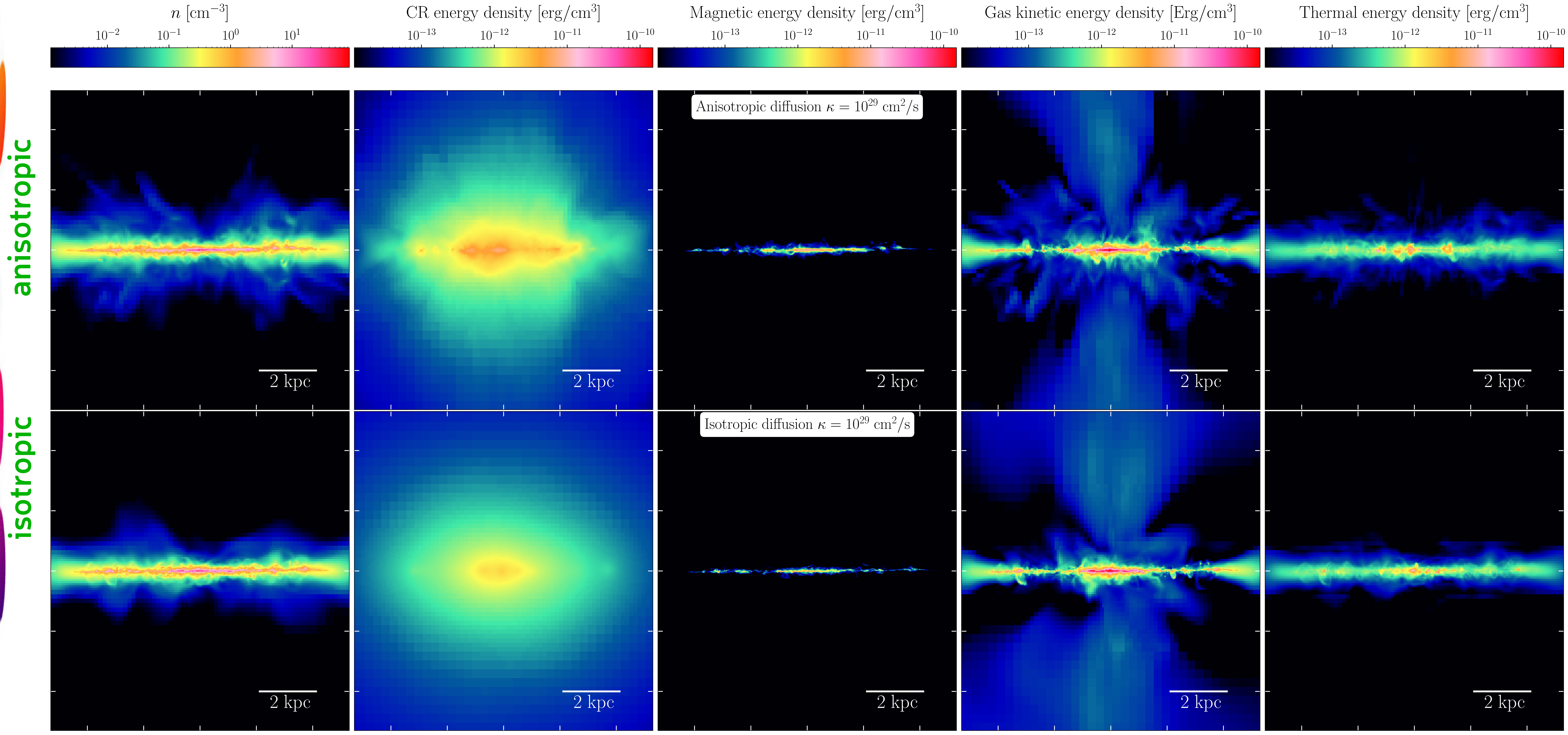

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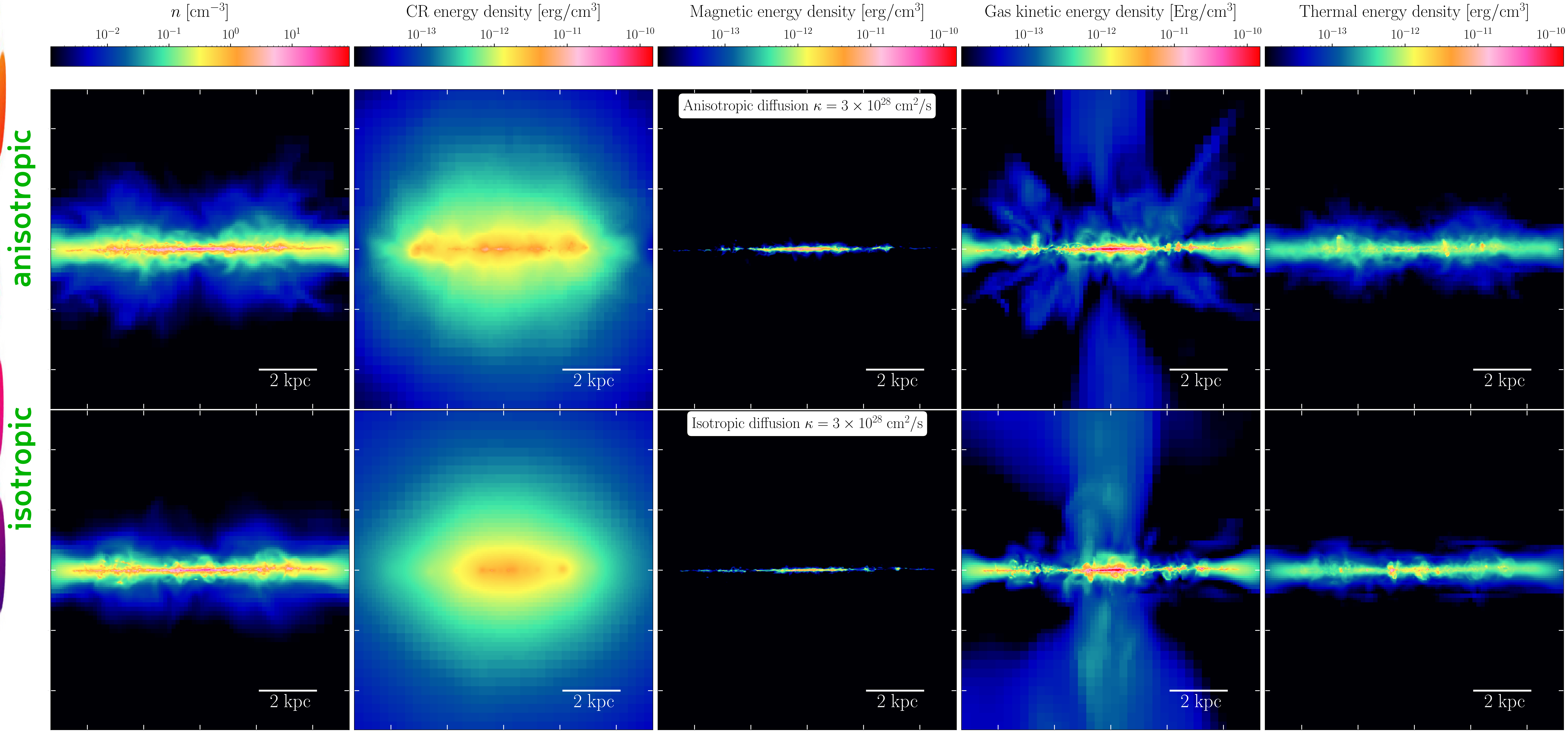
$3\ 10^{28}$ cm²/s $\quad$ 10^{29} cm²/s



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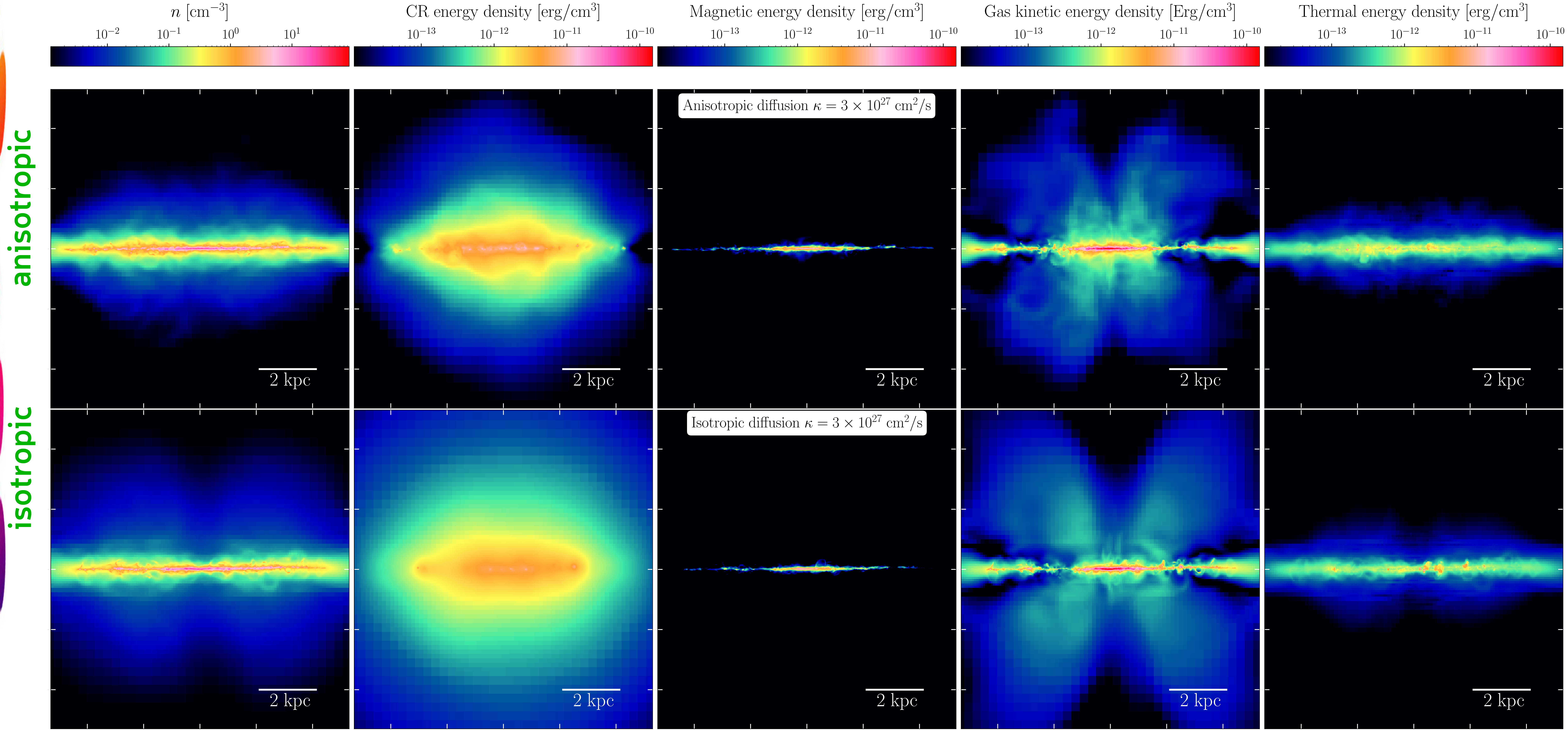
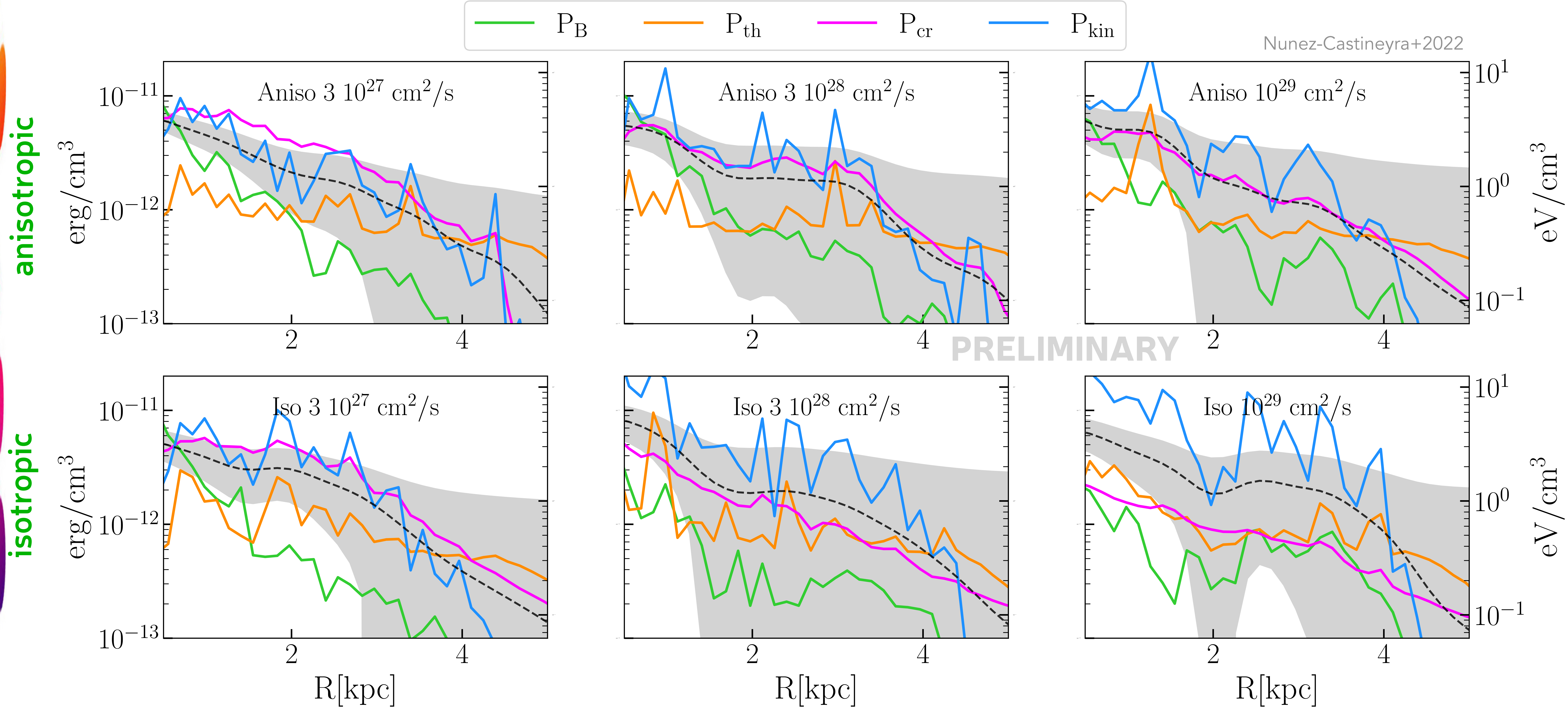
3 10^{27} cm²/s   3 10^{28} cm²/s 10^{29} cm²/s



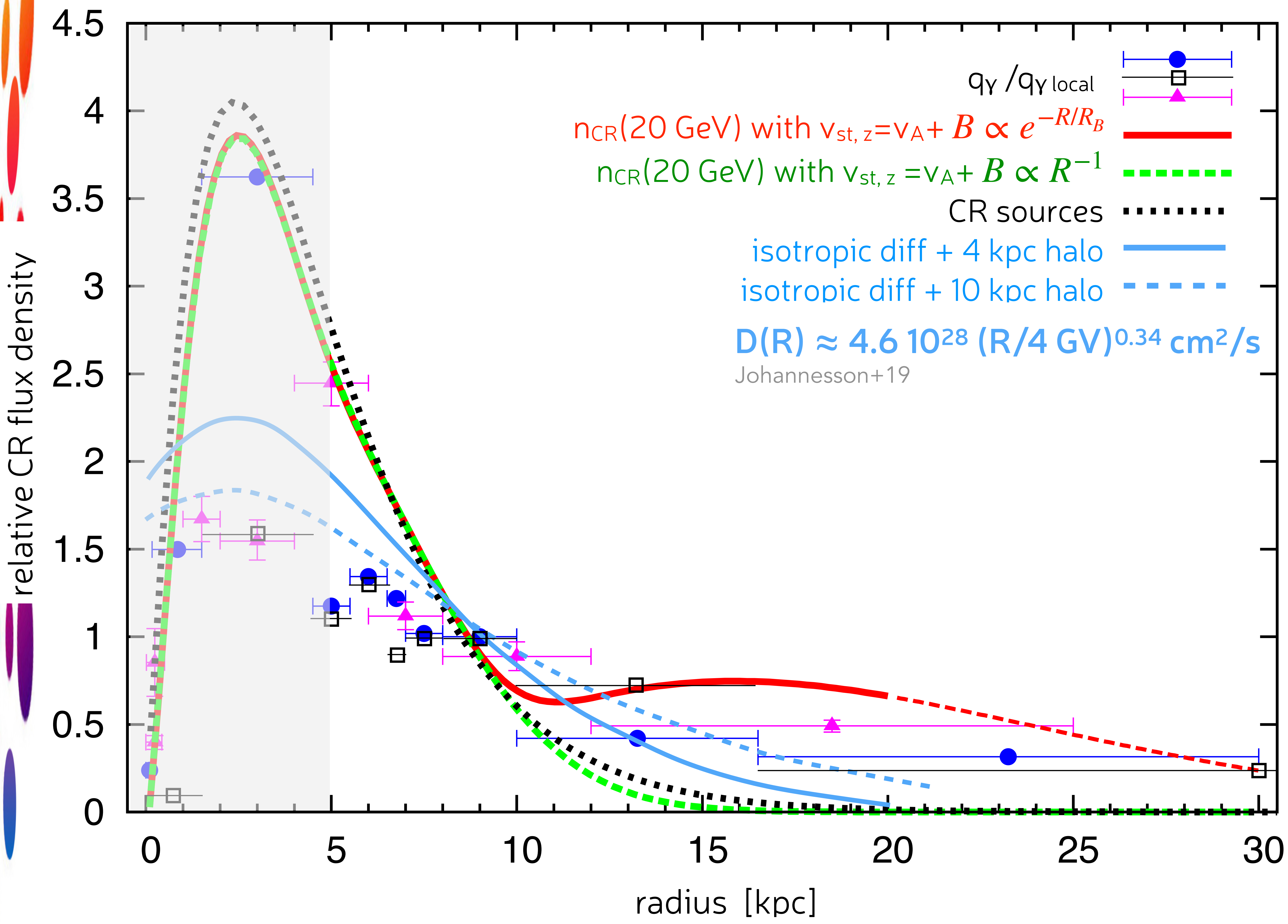
radial pressure gradients

- global radial CR gradients steeper than in the Milky Way, but only slightly sensitive to κ value or degree of anisotropy (shallower if isotropic)
- magnetic field still growing in the simulations

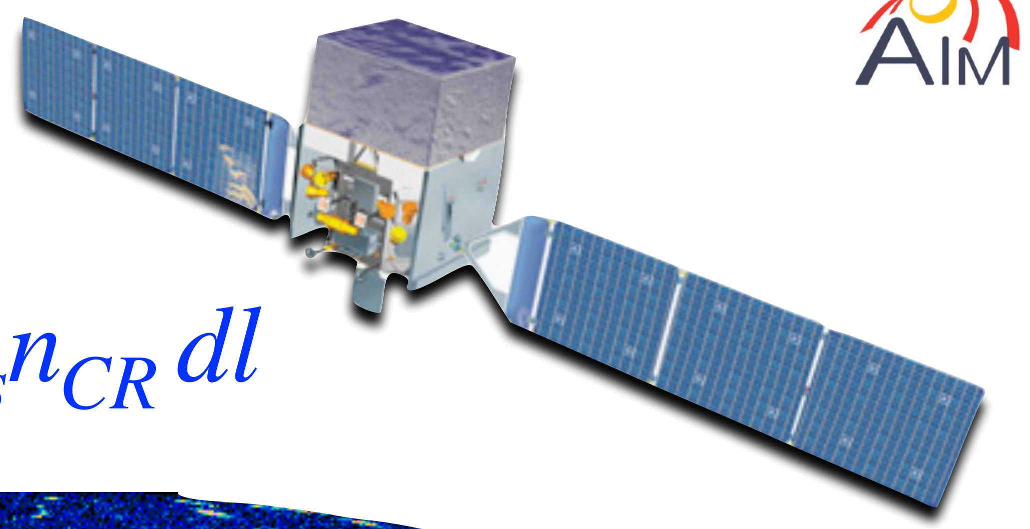


cosmic-ray radial gradient

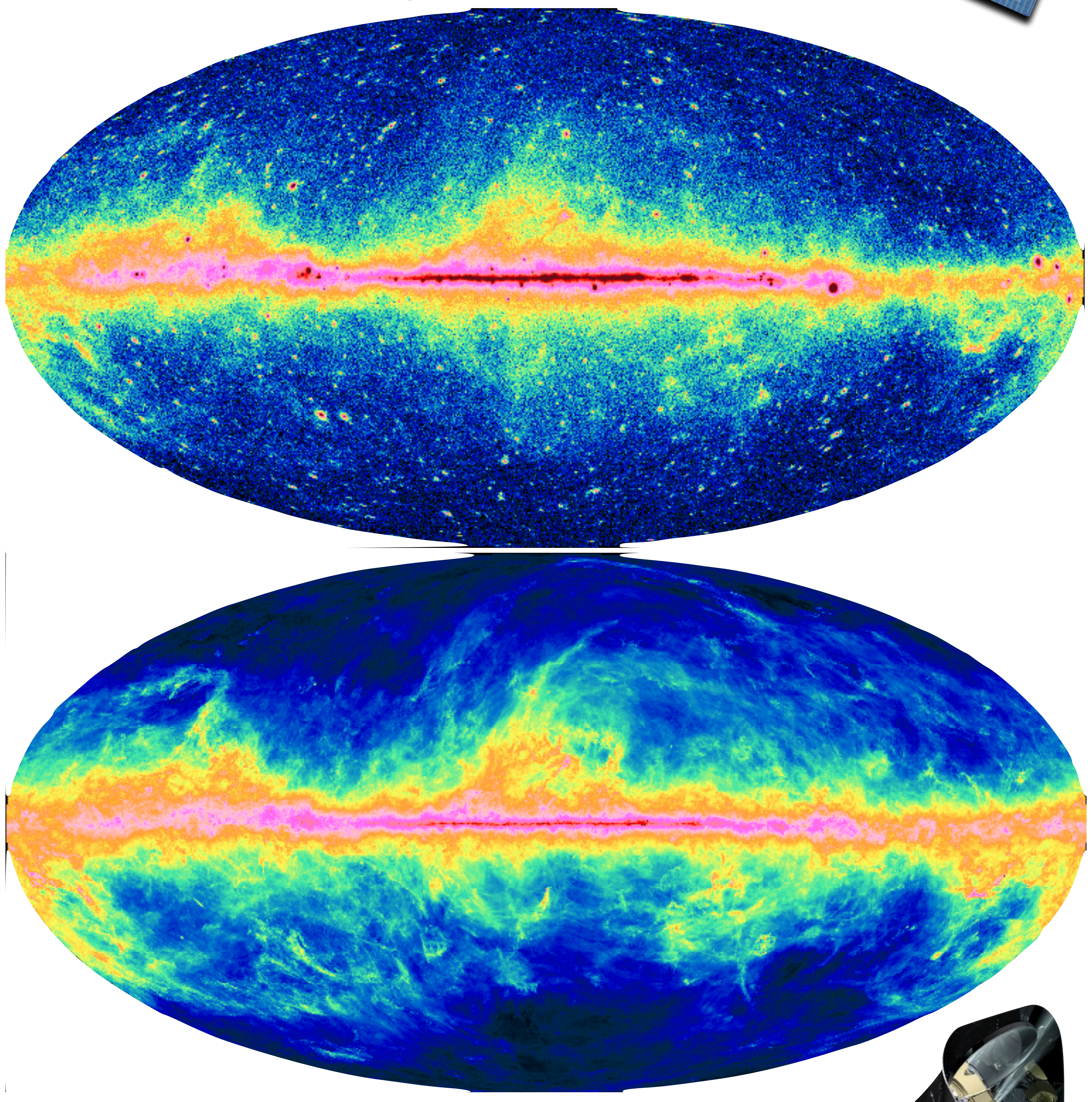
- few-GeV to TeV CR nuclei flux: Galactic profile at variance with transport models
  - importance of B_0 and Alfvenic Mach number M_A
  - increased $\delta B/B$ in spiral arms => smaller $D_{//}$ and larger $D_{\perp}$? large amount of dark gas?
-



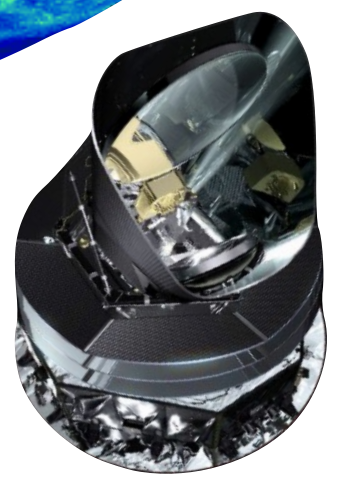
Acero+16, Yang+16, Pothast+18, Recchia+16, Tibaldo+13



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

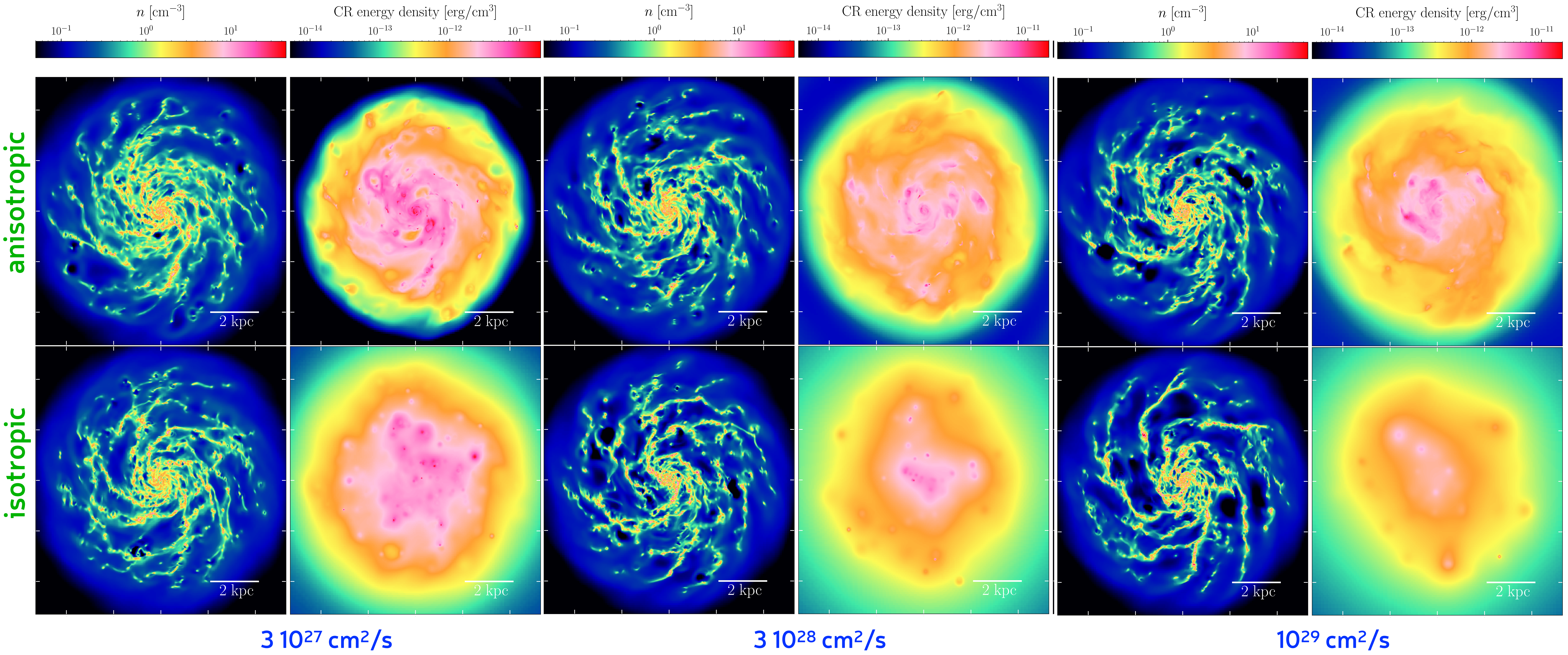


$$\int n_{gas} \frac{M_d}{M_{gas}} \kappa_0 \left(\frac{\nu}{\nu_0}\right)^{\beta} B_\nu(T_d)\, dl$$



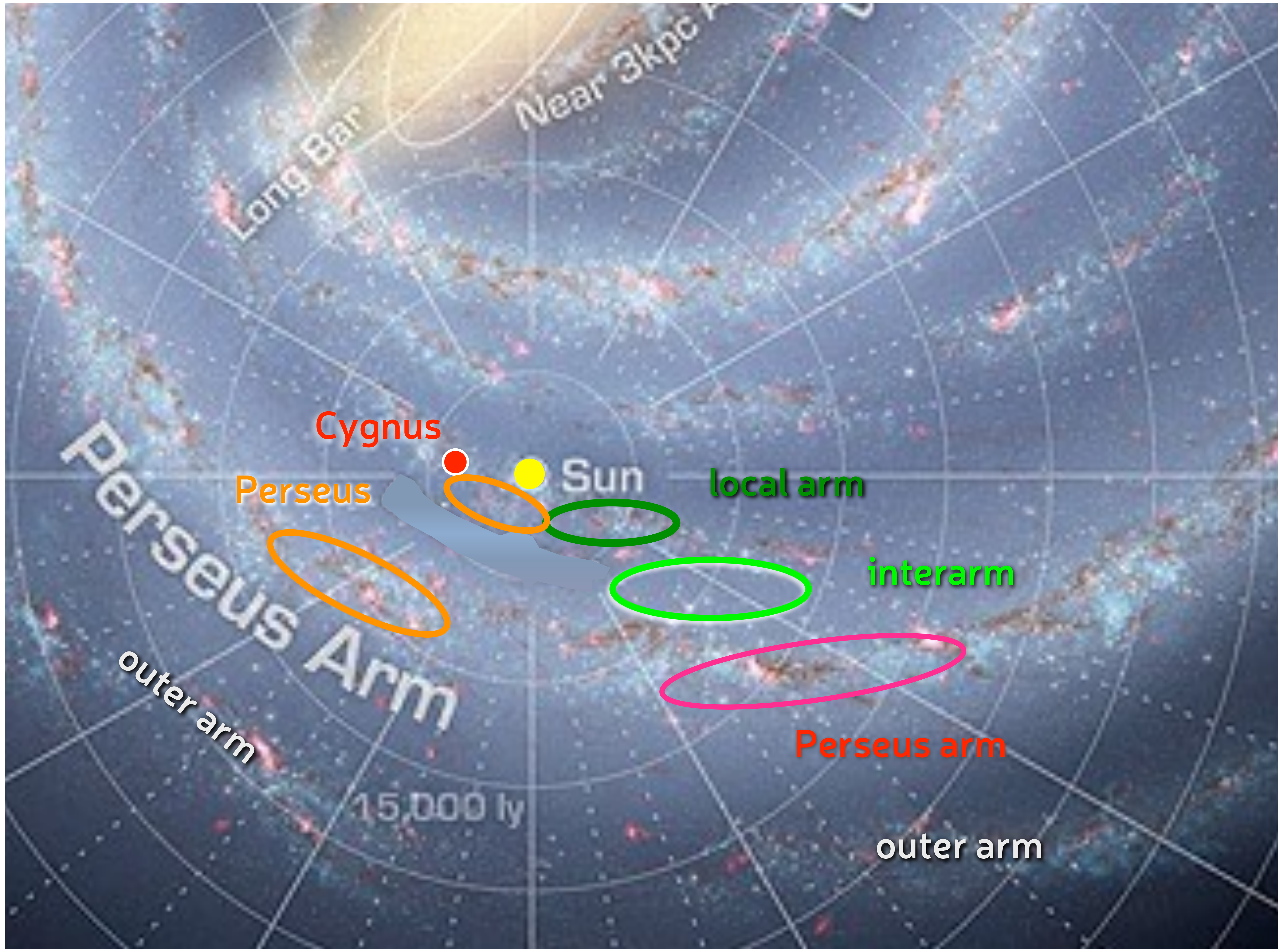
spiral arm contrast

- fewer gas spurs if κ increases, even fewer if isotropic diffusion
- more elongated/blobby CR spurs if anisotropic/isotropic, along star formation activity

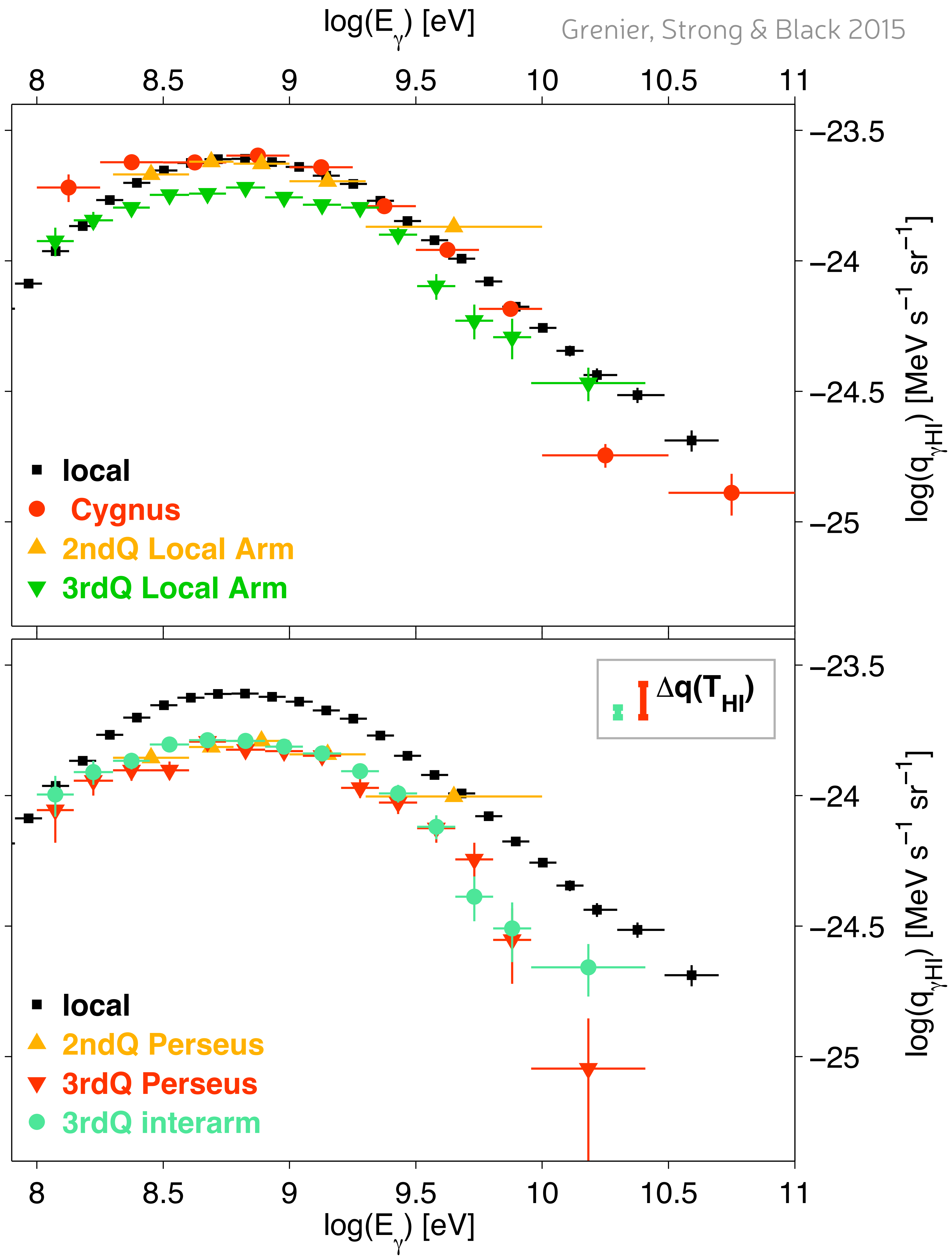


no clear contrast with SFR

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

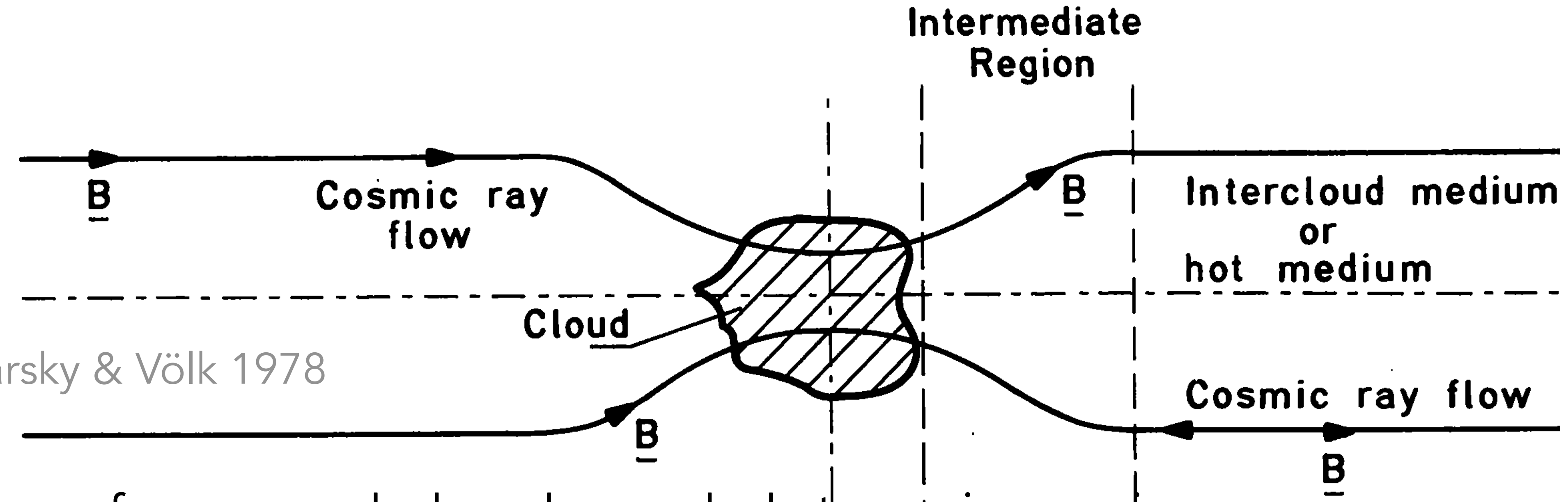


Grenier, Strong & Black 2015



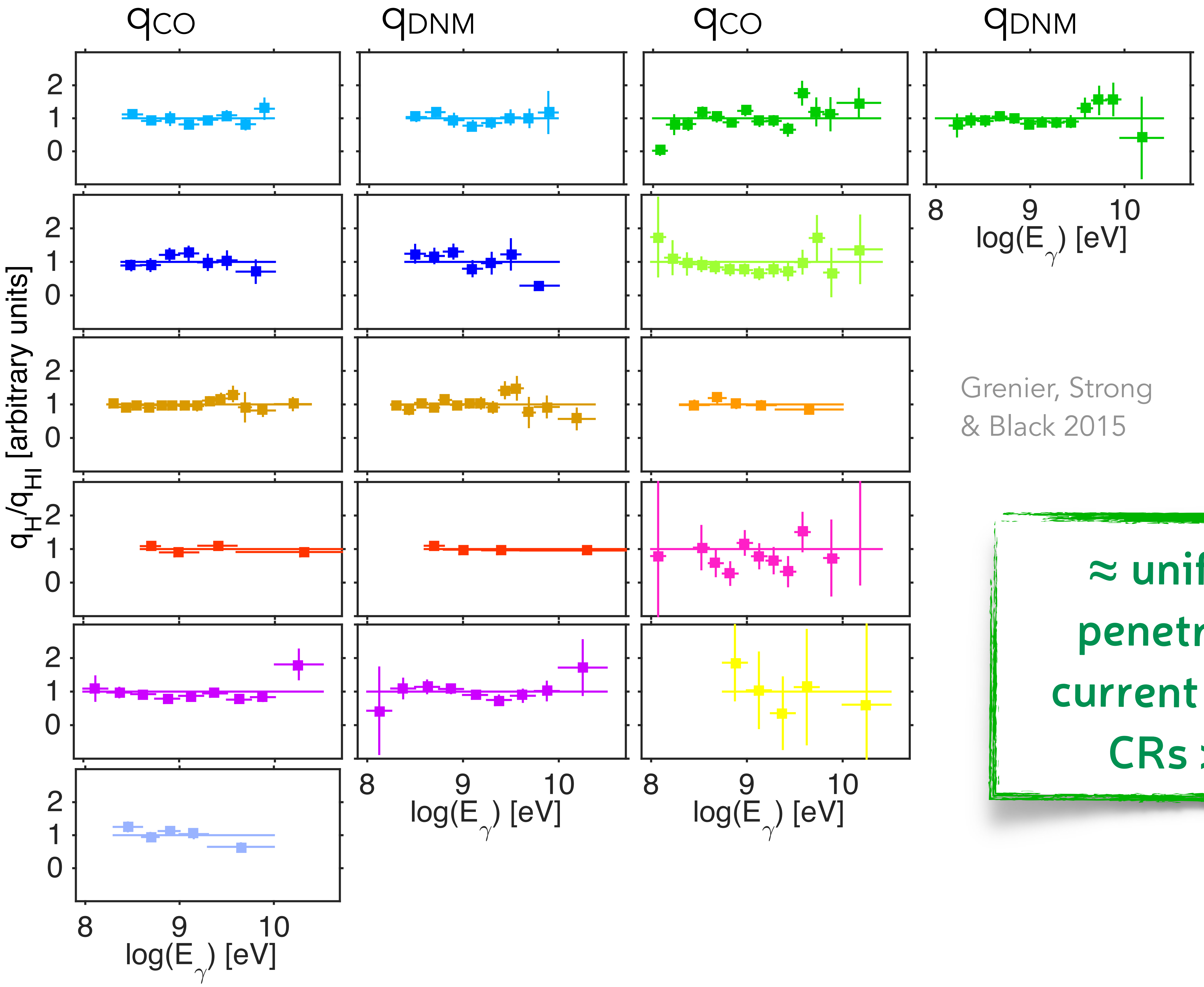
penetration of few-GeV-TeV cosmic rays inside clouds

- mirroring CR depression vs. increased scattering by self-generated waves
  - CR loss < factor 2 to 5



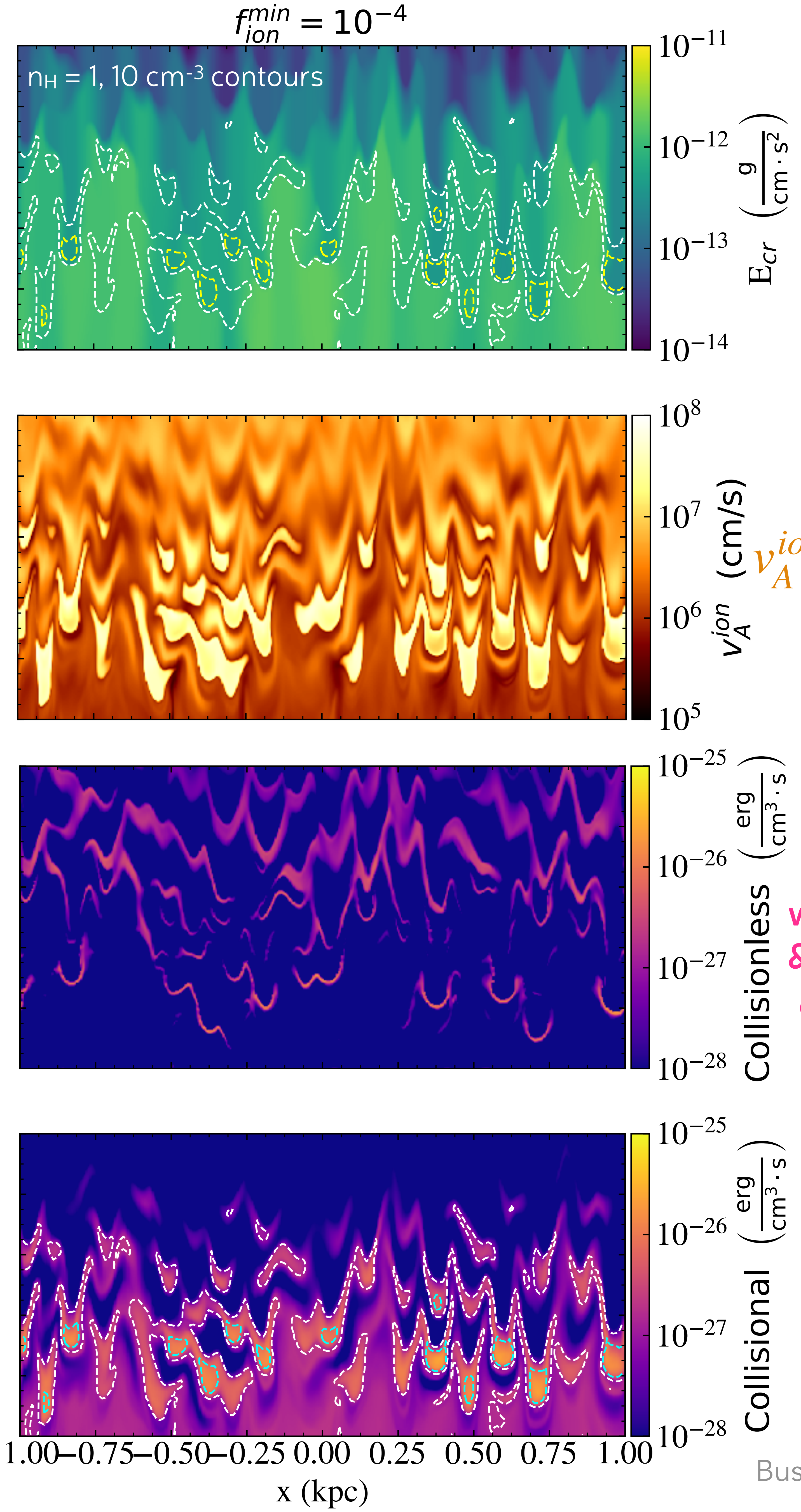
Cesarsky & Völk 1978

- multiphase ISM = "obstacle course of gas-coupled vs decoupled streaming regimes, further complicated by hadronic and Coulomb collisions with ambient gas"
- 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



CR flux shadows at 1 GeV

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

wave excitation & damping $\propto v_A^{ion} \cdot \nabla P_{CR}$

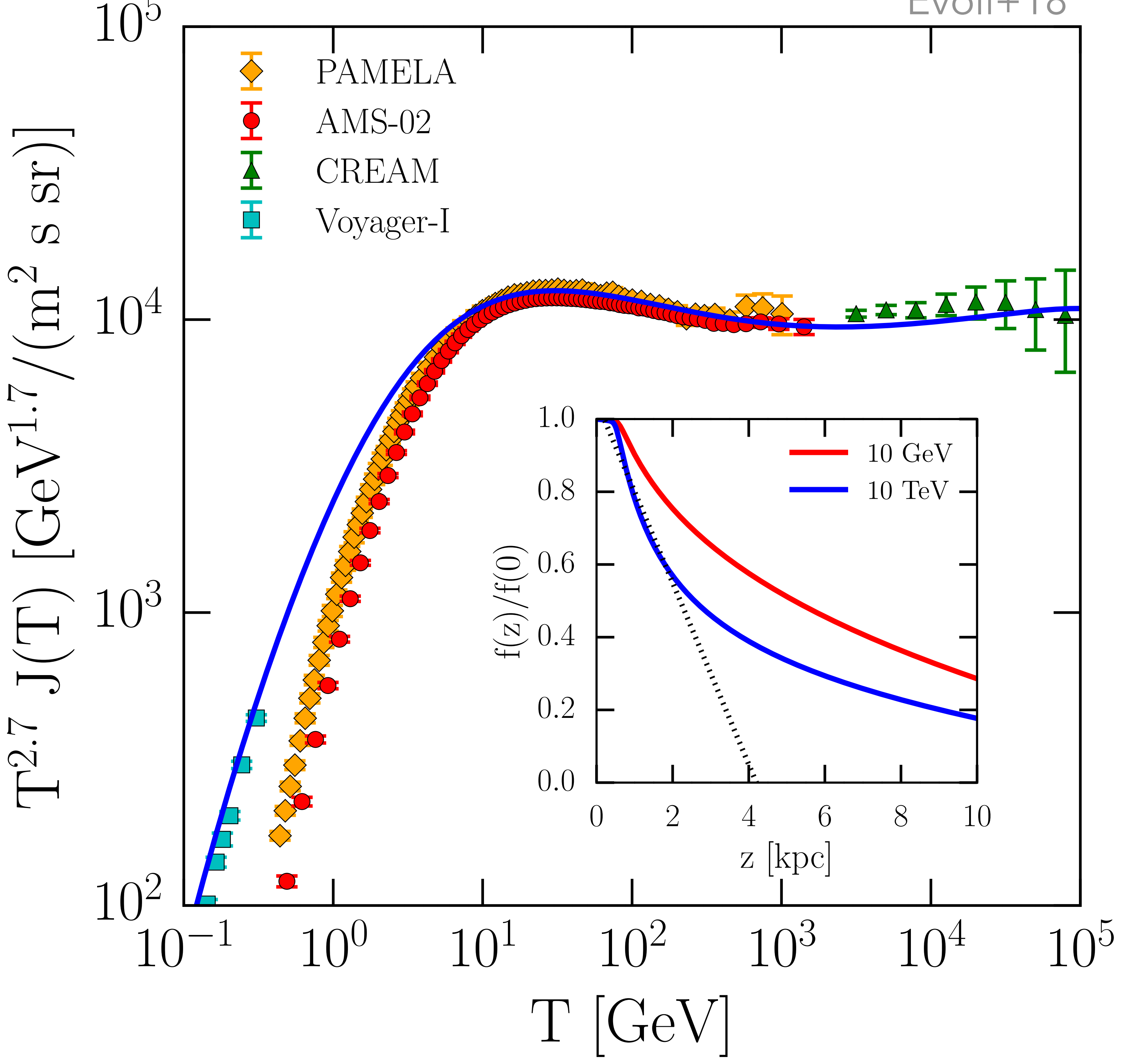
pp+Coulomb losses $\propto e_{CR}\, n_{gas}$

Bustard & Zweibel 2021

cosmic-ray vertical gradient

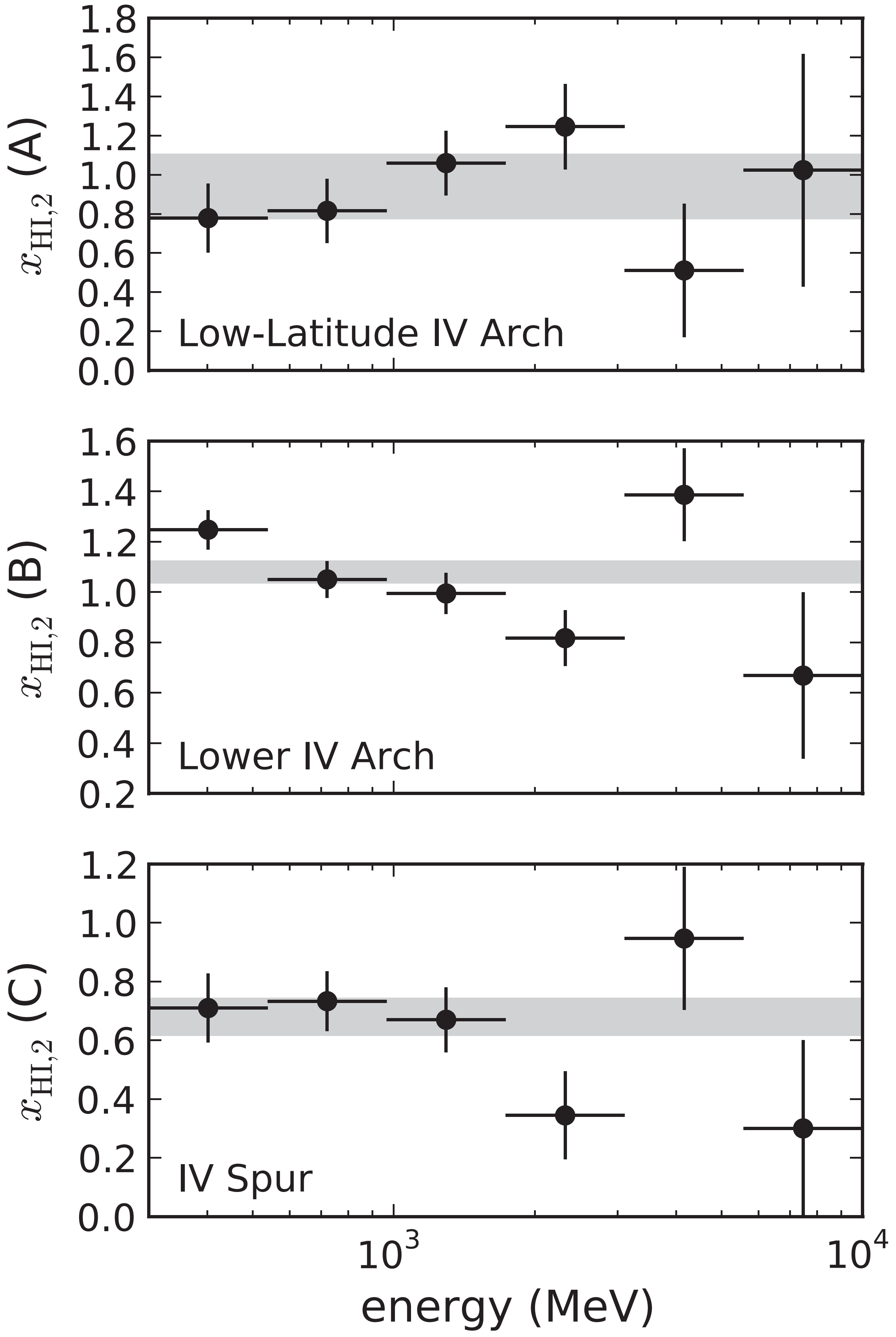
- γ-ray measurements of the local CR flux with height
  - 1D curve advection+diffusion : H = 4.5 ± 0.2 kpc Joubaud+20
- AMS-02 2nd/1ary spectra Weinrich+20
  - USINE modelling with advection+reaccel+diffusion or pure diffusion H = 5 $^{+3}_{-2}$ kpc
  - DRAGON modelling H = 7.5 $^{+1.13}_{-0.95}$ kpc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

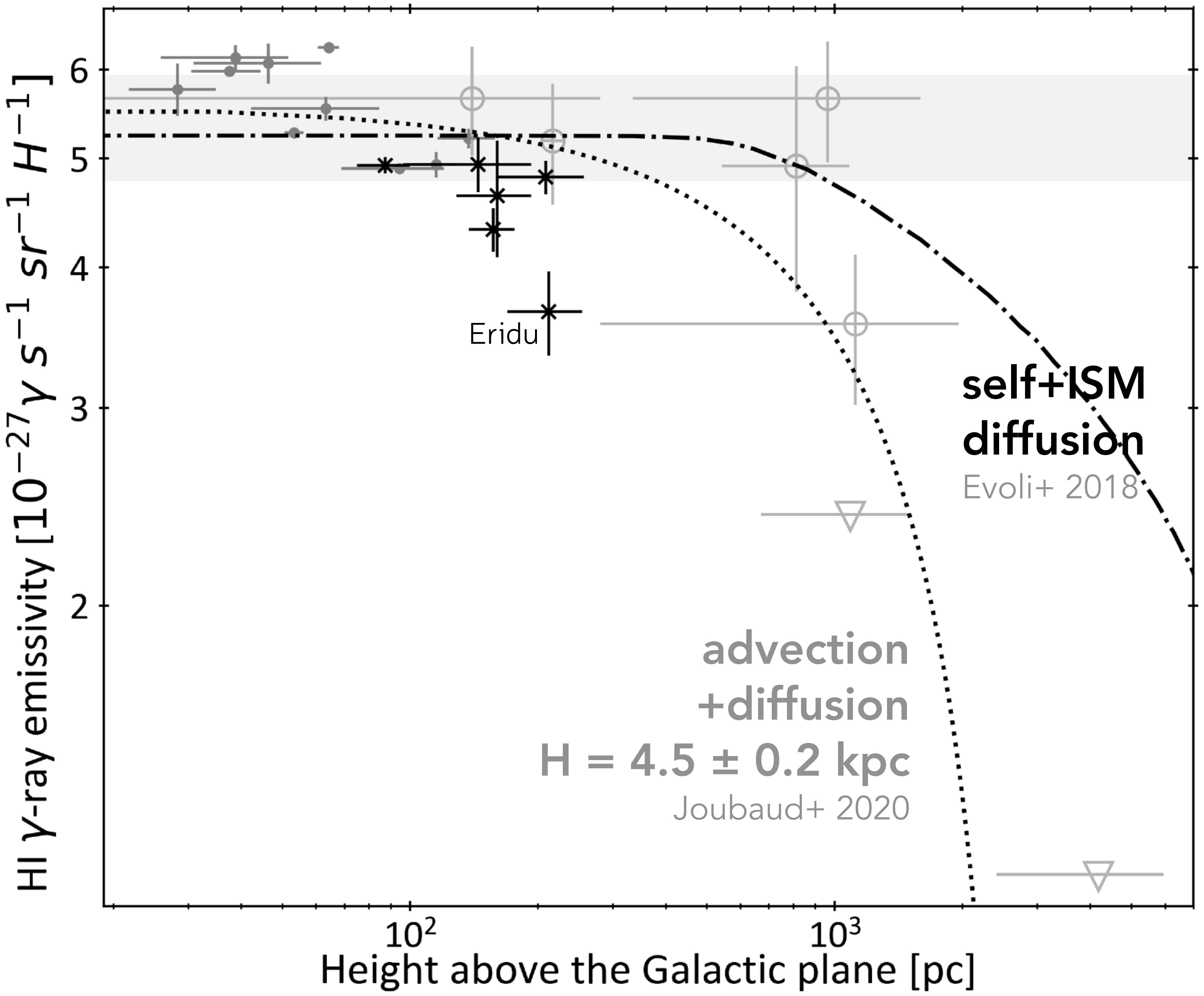
Evoli+18



self-diffusion up to 2 kpc ⟷ ISM-diffusion at z ≳ 2 kpc

Tibaldo+15





important assessment for vertical gas outflows in galaxy evolution

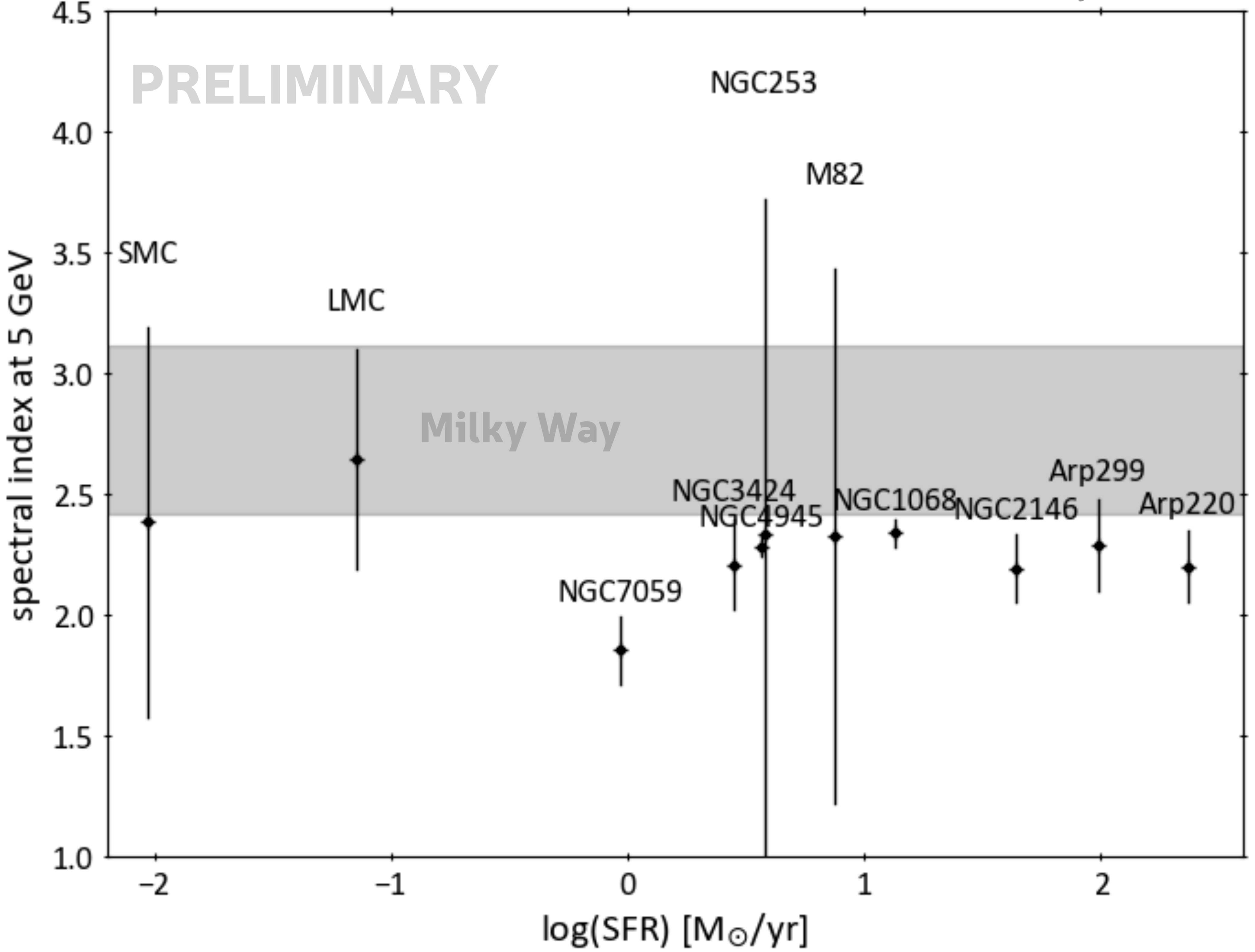
above a reasonably quiet disc : ok

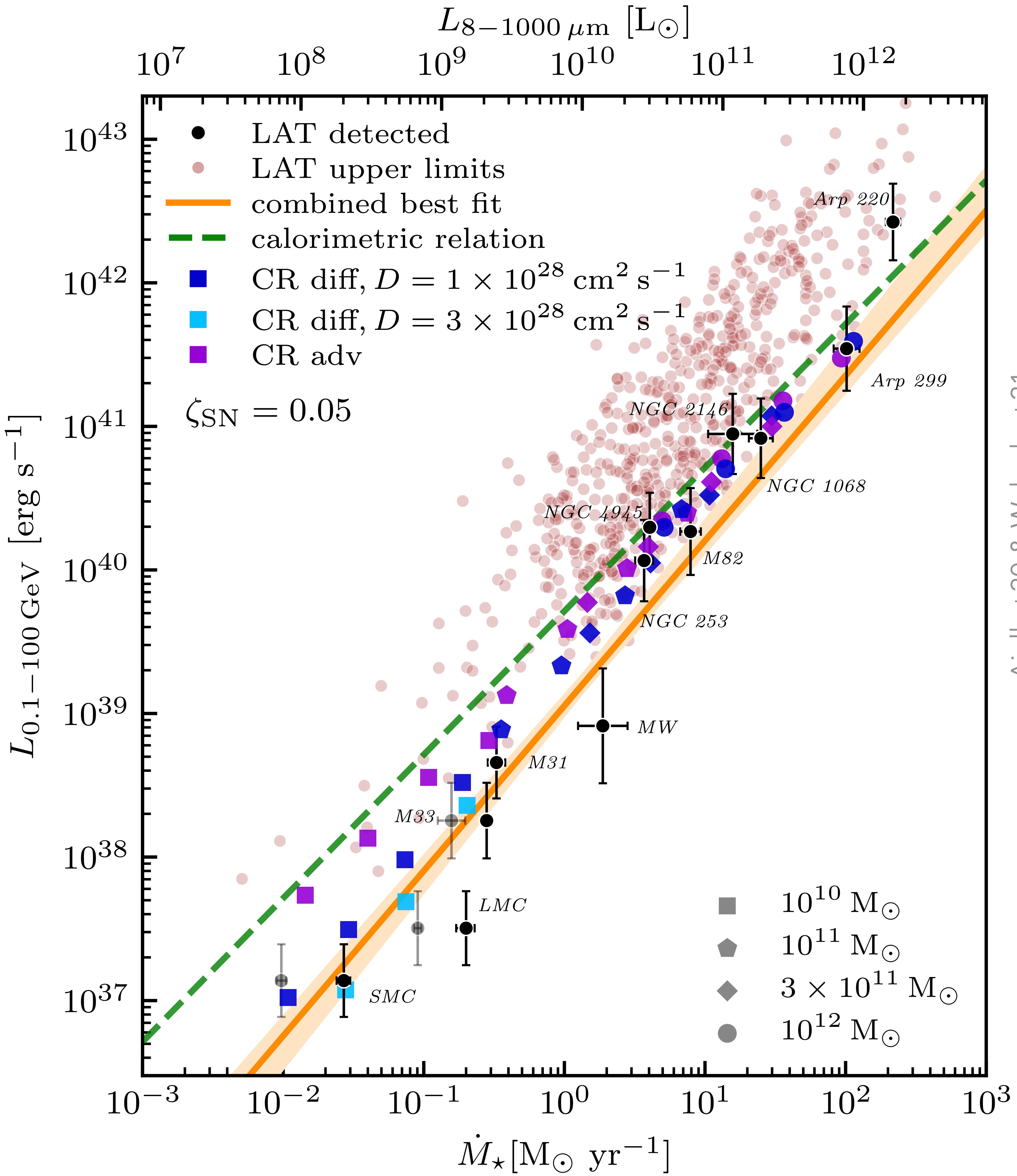
wind in the central regions : extreme challenge

cosmic-ray calorimeters

- CR activity scales with star-formation activity traced by the FIR luminosity
- calorimetric limit: $\tau_{residence} \approx \tau_{pp}$
  - starburst galaxies = good calorimeters
  - Milky Way = leaking calorimeter
- harder starburst galaxies but no spectral change over 2 decades in SFR

Nunez-Castineyra+2022

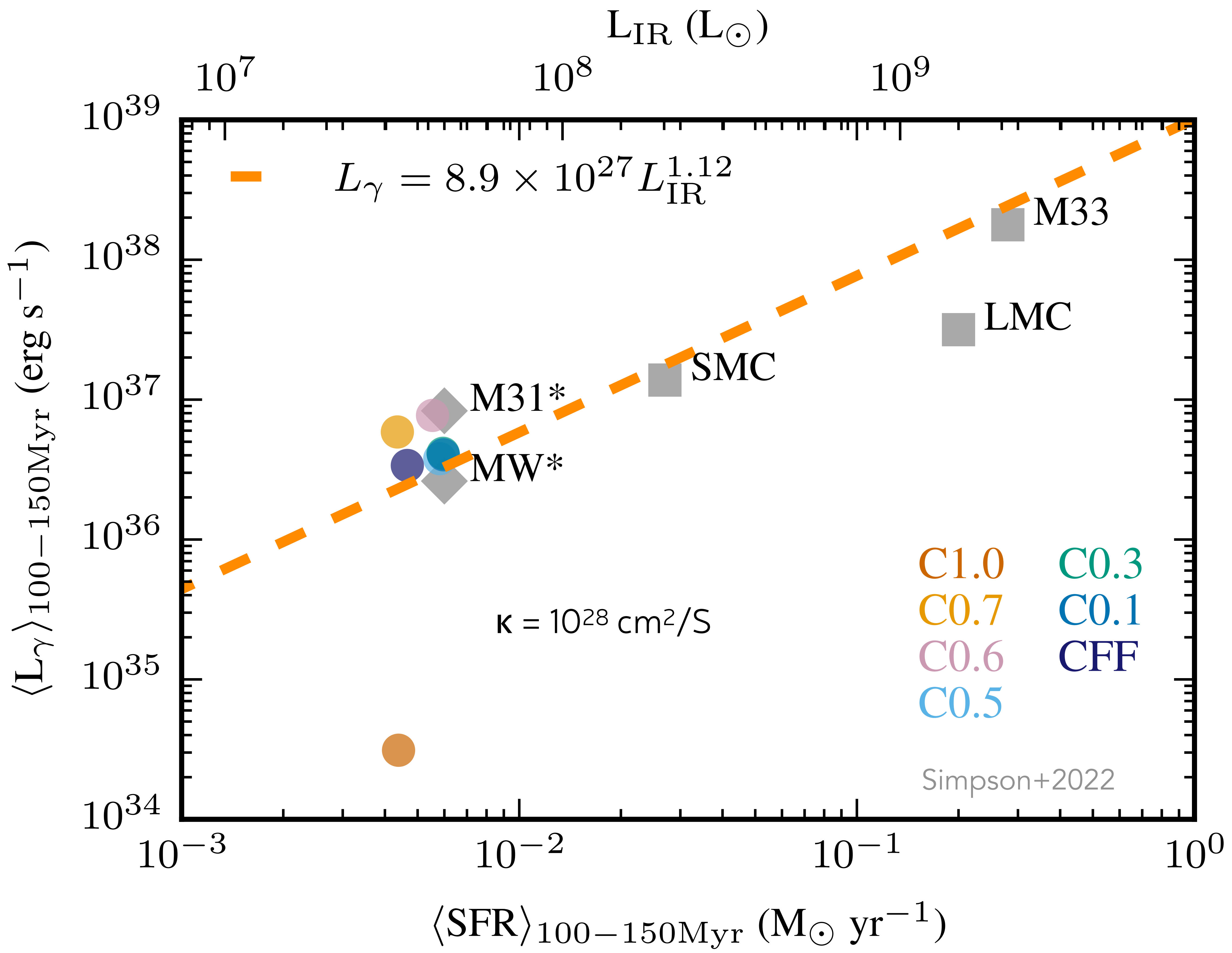


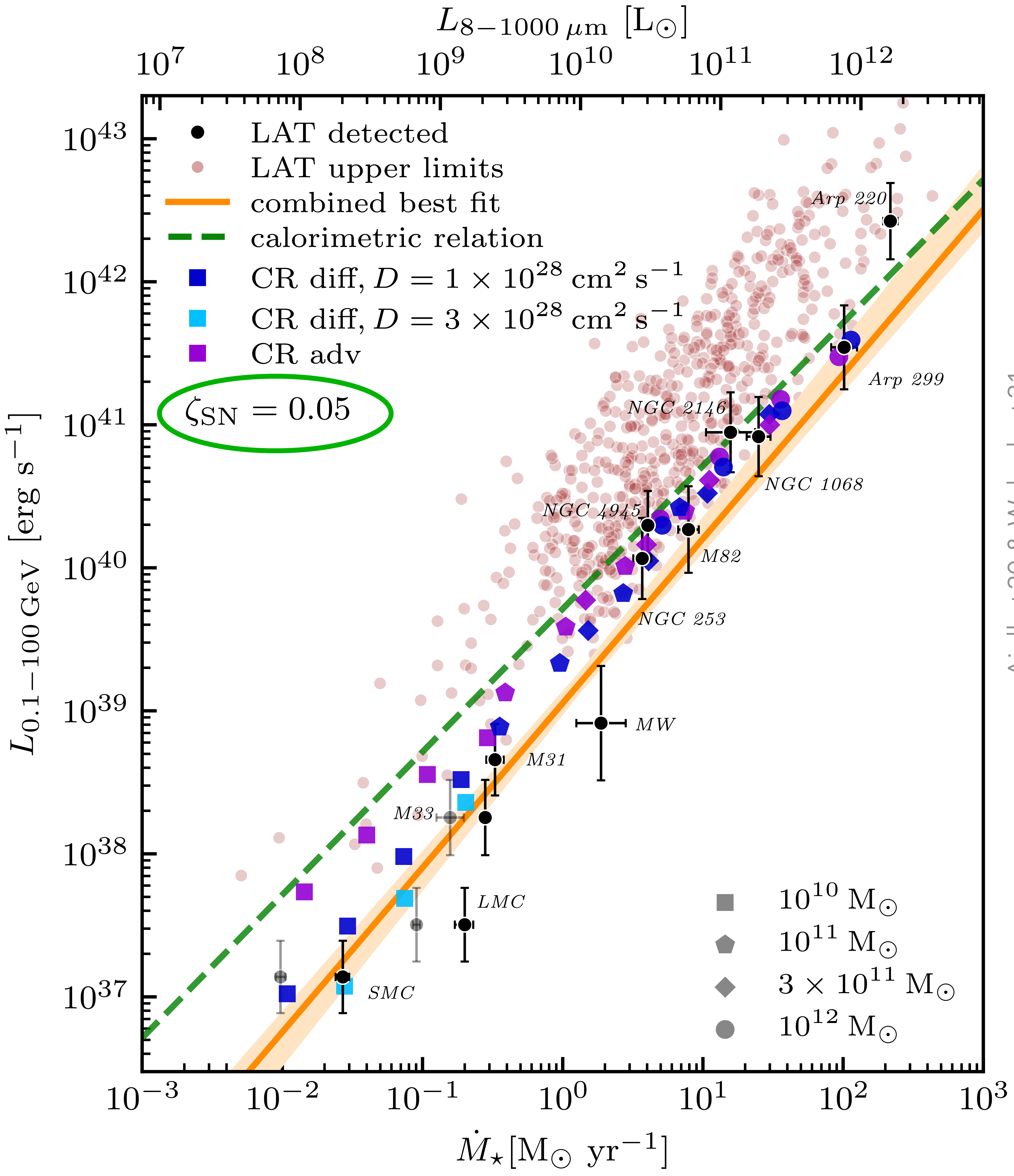


Ajello+20 & Wehrahn+21

cosmic-ray calorimeters

- CR activity scales with star-formation activity traced by the FIR luminosity
- calorimetric limit: $\tau_{residence} \approx \tau_{pp}$
  - starburst galaxies = good calorimeters
  - Milky Way = leaking calorimeter
- small dependence on SN feedback

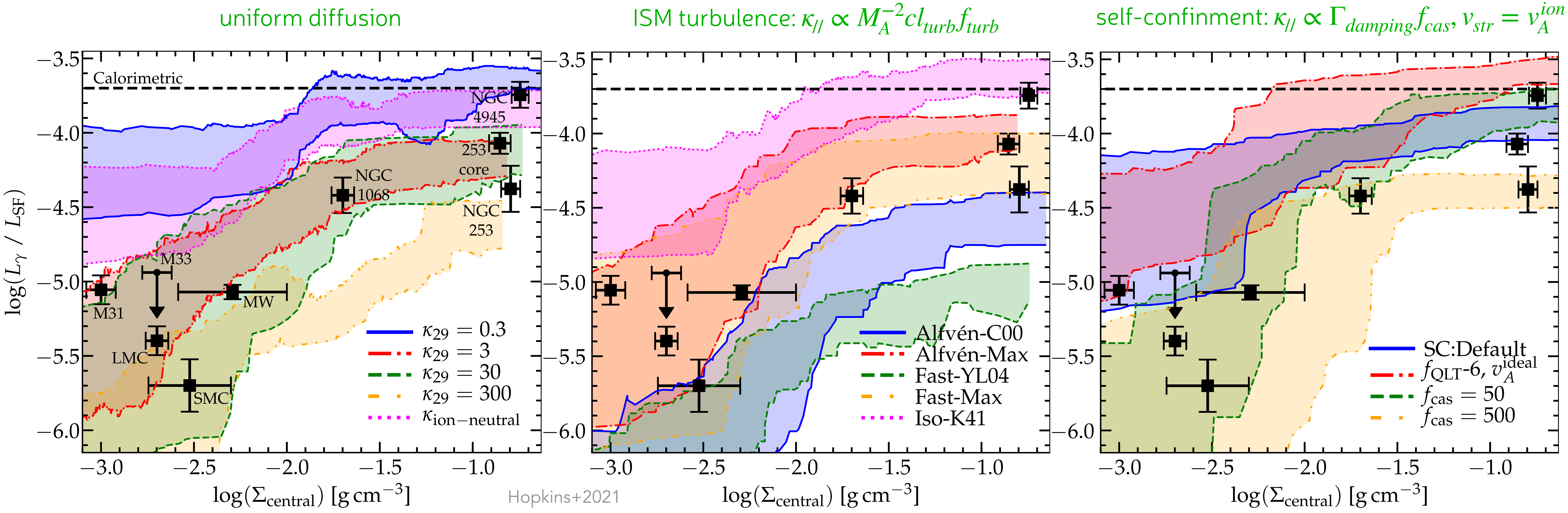




Ajello+20 & Wehrahn+21

diffusion impact on Lγ-SFR relation?

- need for much faster diffusion than estimated in the Milky Way or

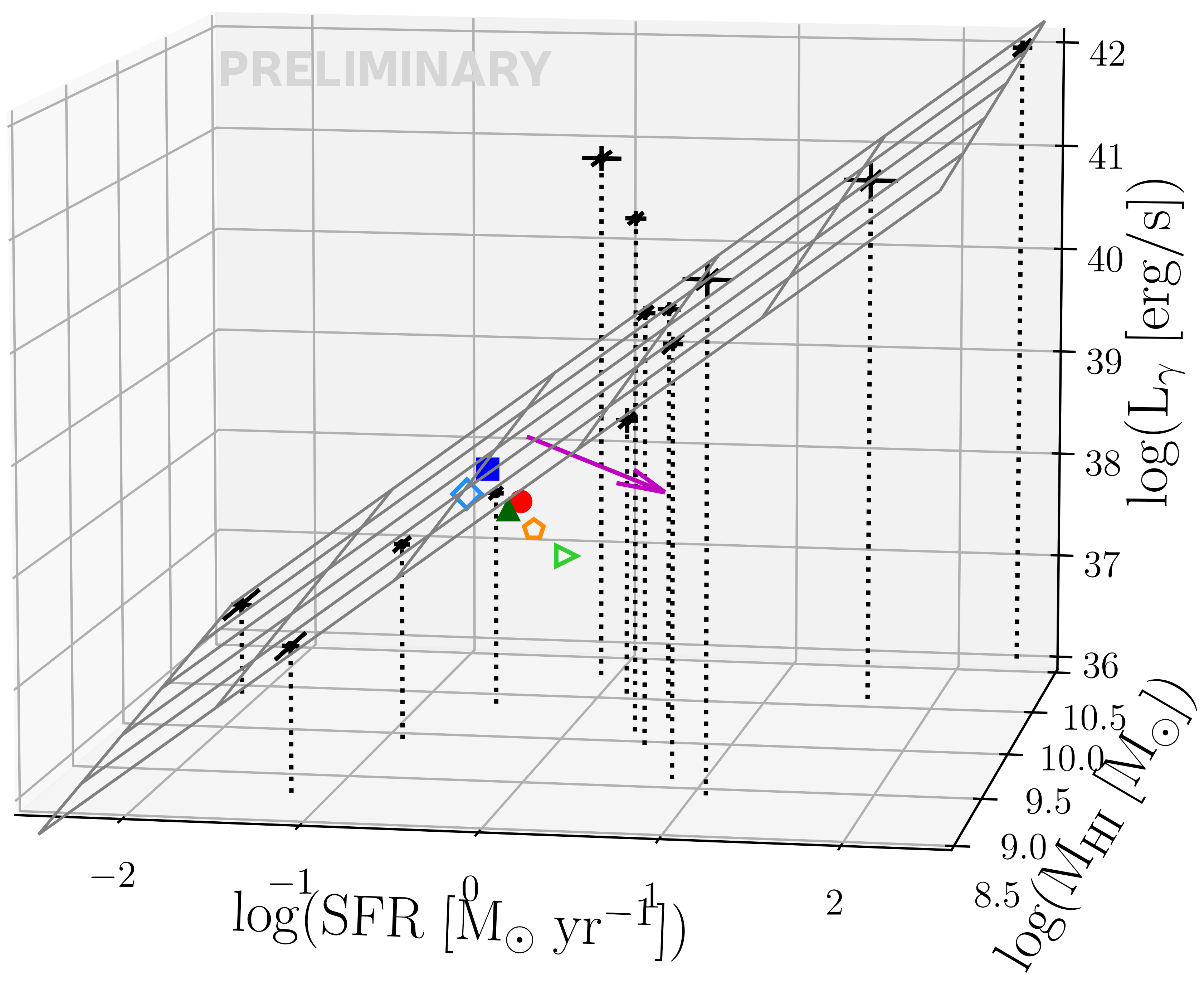


Hopkins+2021

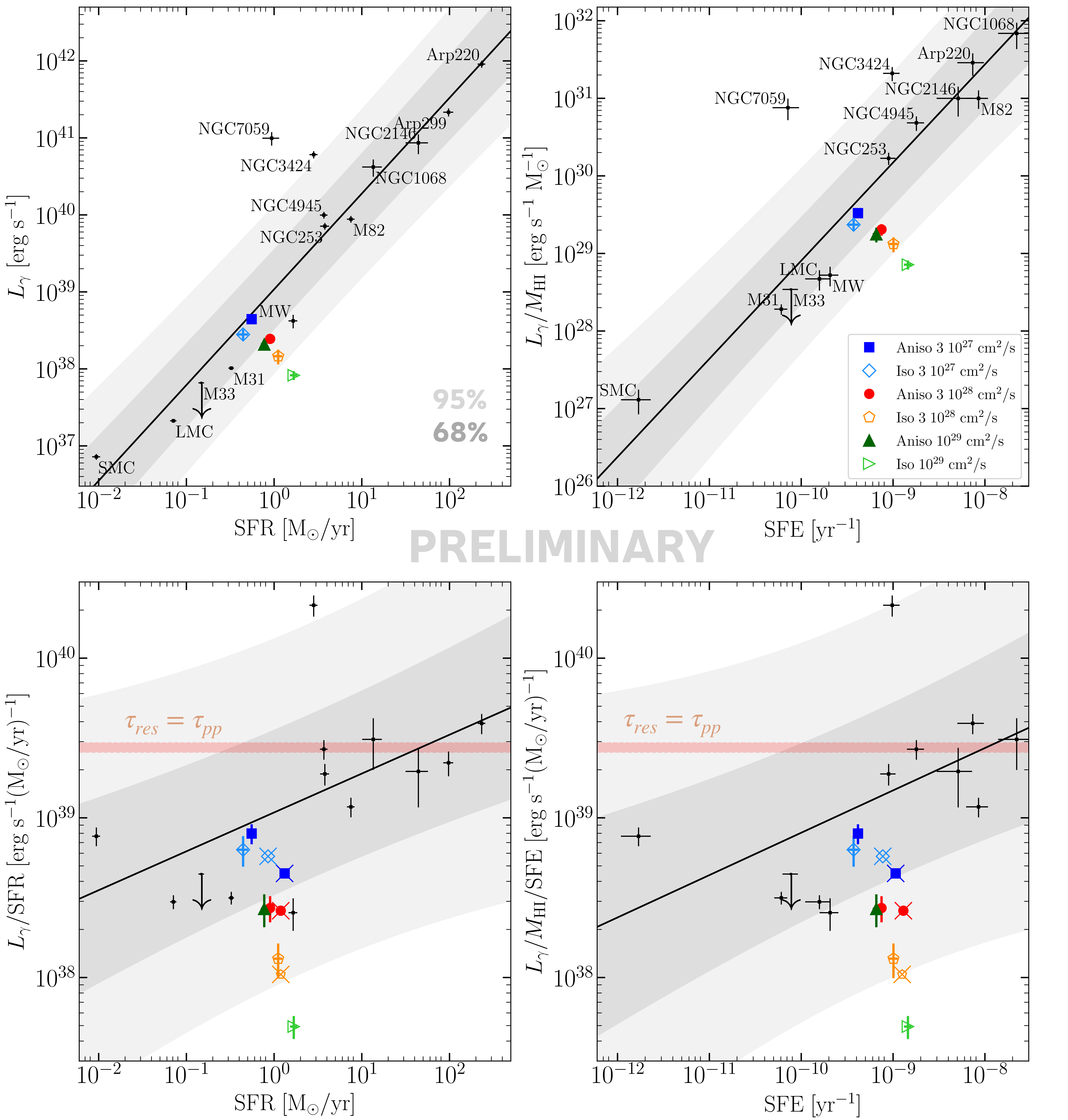
no need to speed up cosmic rays

- diffusion impact on γ-ray luminosity ⊥ observation plane
- anisotropic $10^{27.5-29}$ or isotropic < 3 10^{28} cm²/s ok
- unlikely association for NGC 7059 in 4FGL

Nunez-Castineyra+2022

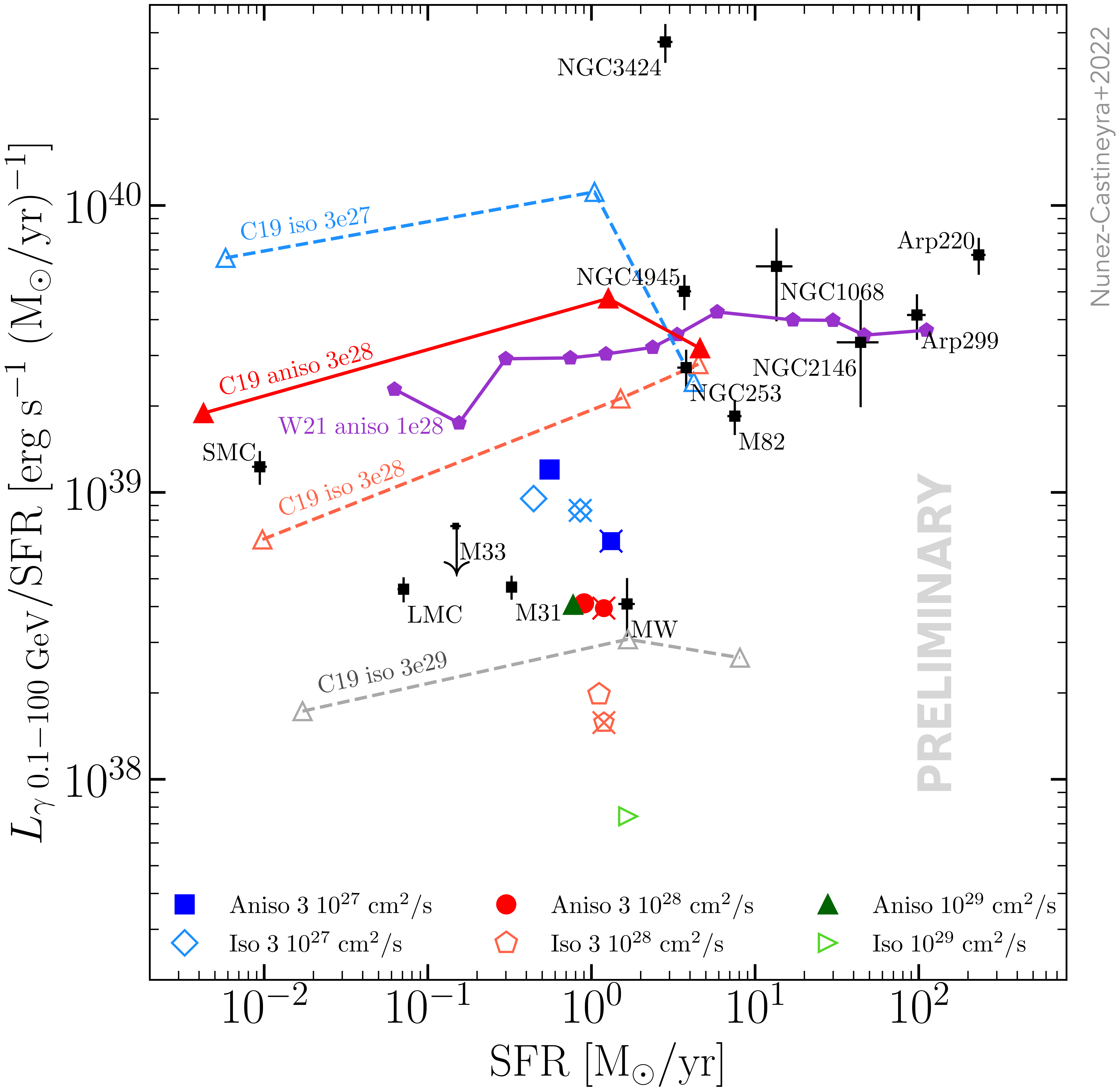


0.5 - 50 GeV



???

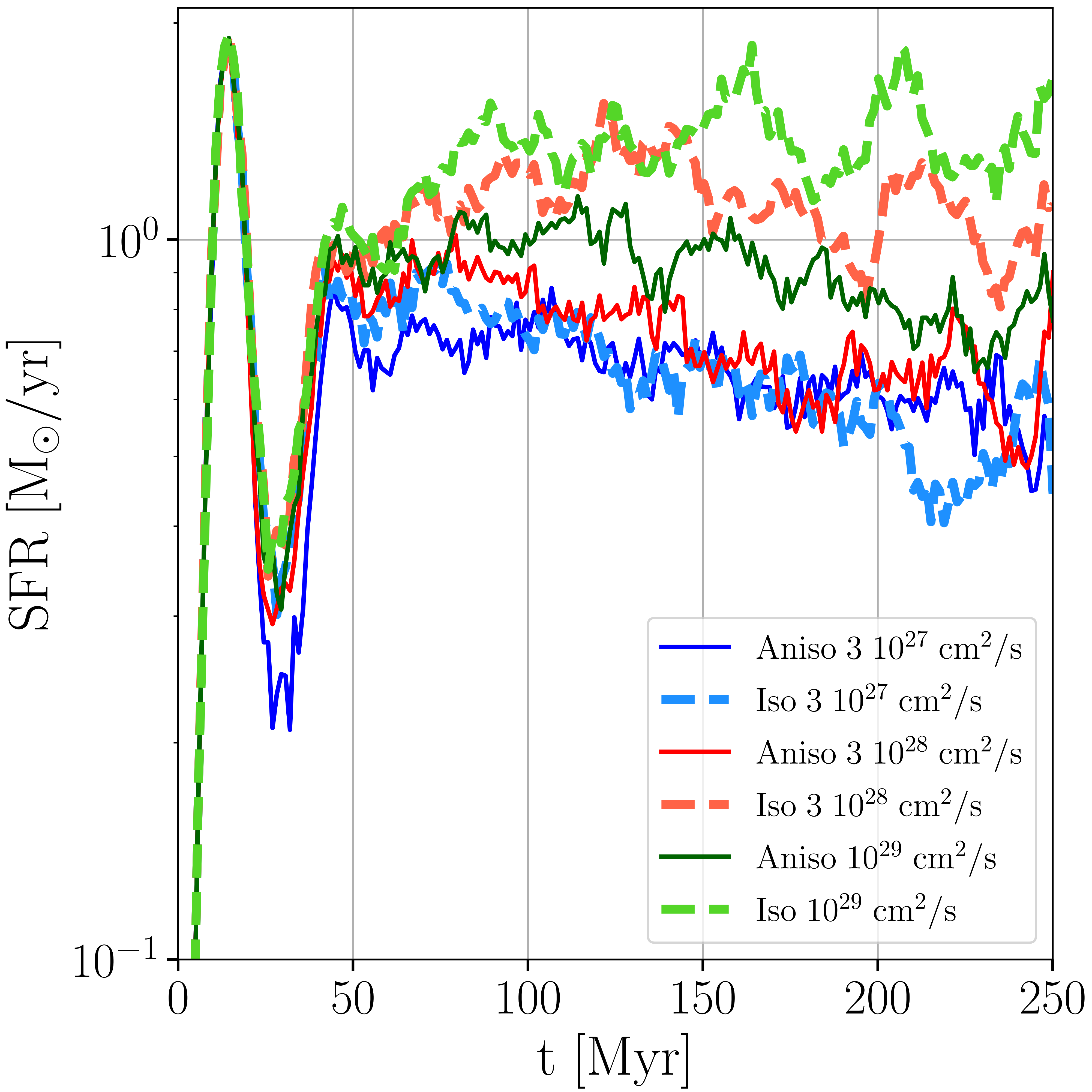
- all $E_{inj,CR}$ / E_{SN} = 10% per SN

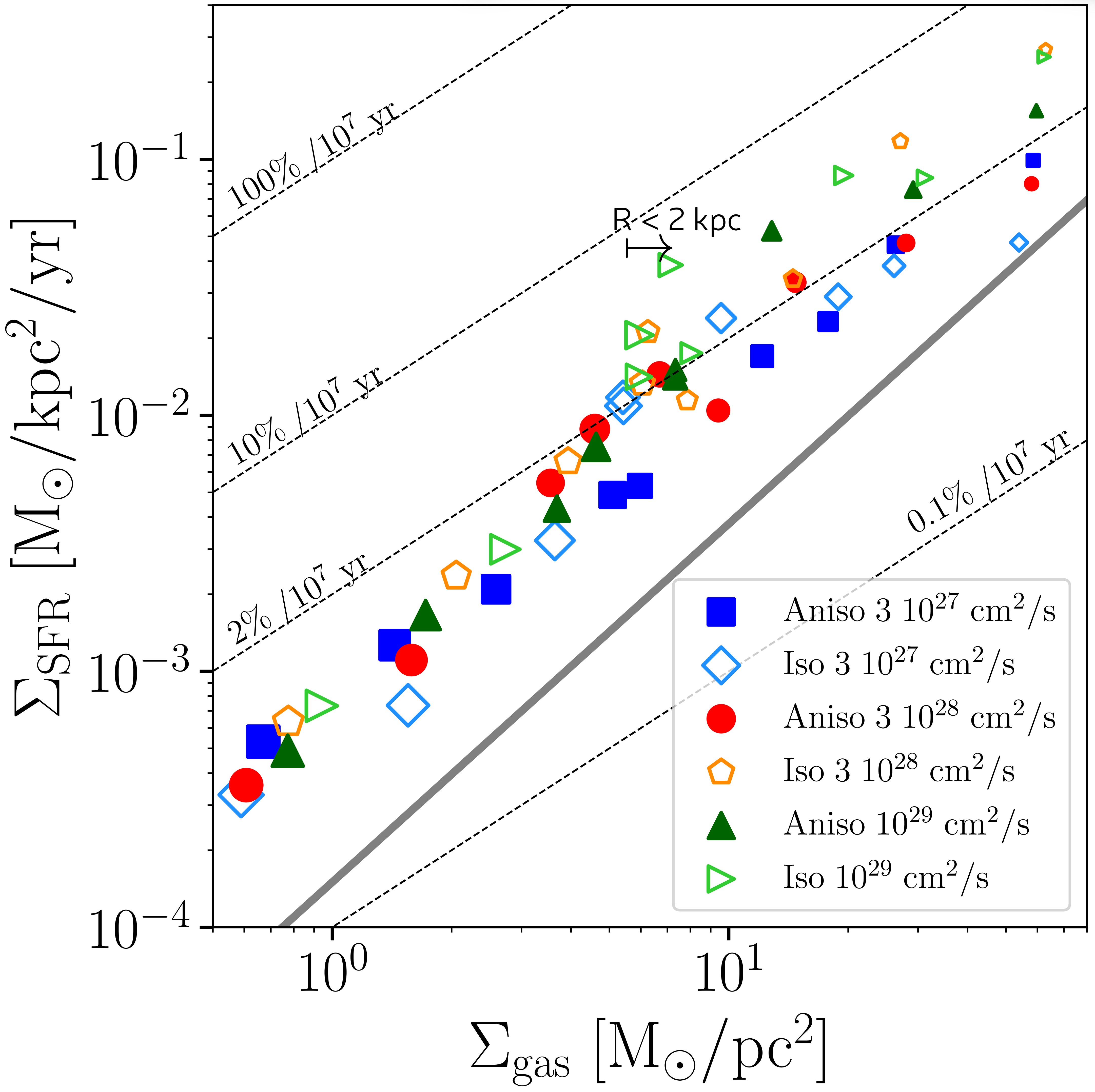


cosmic-ray suppression of star formation

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

suppressed SFR if slow/ anisotropic CR diffusion





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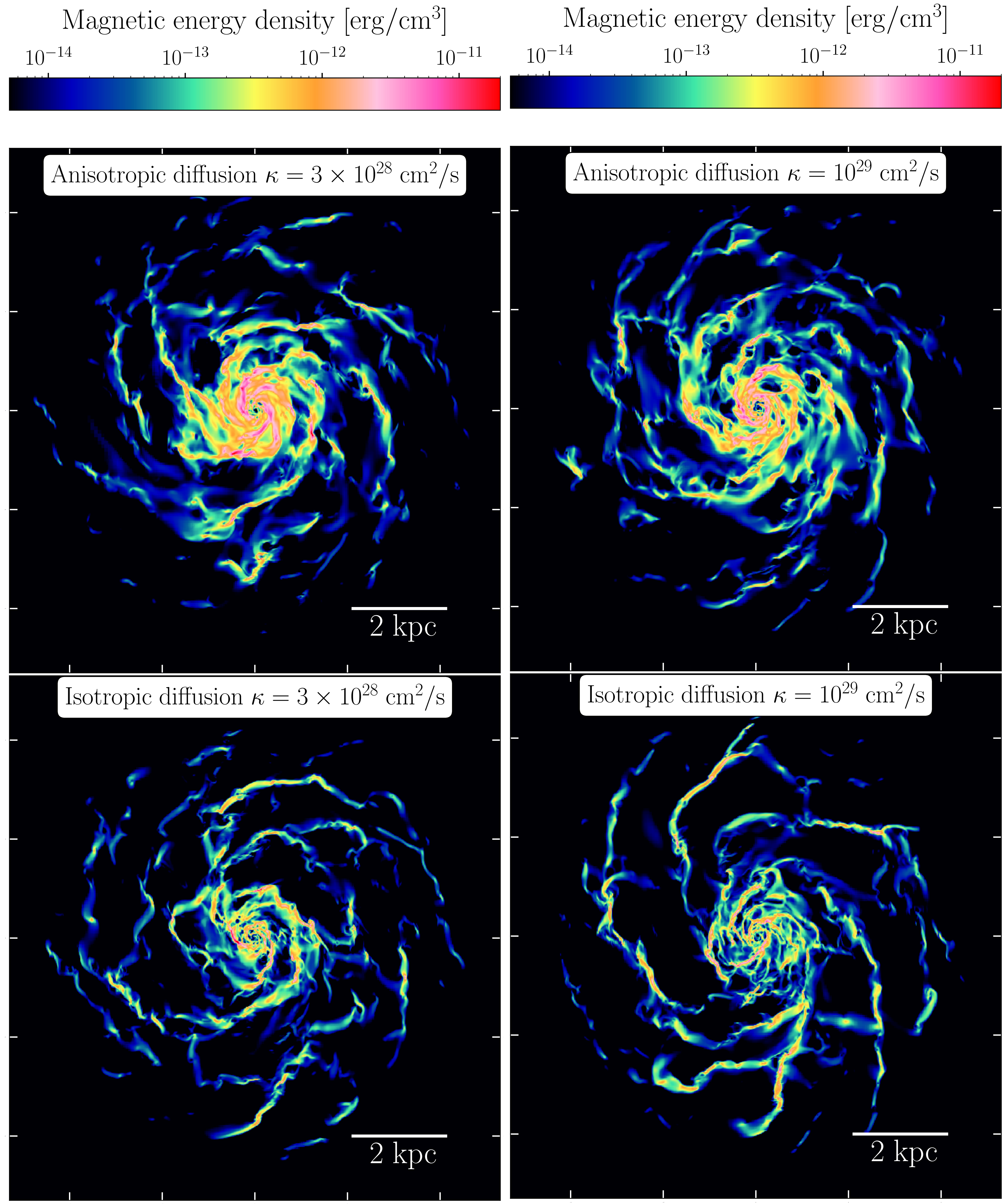
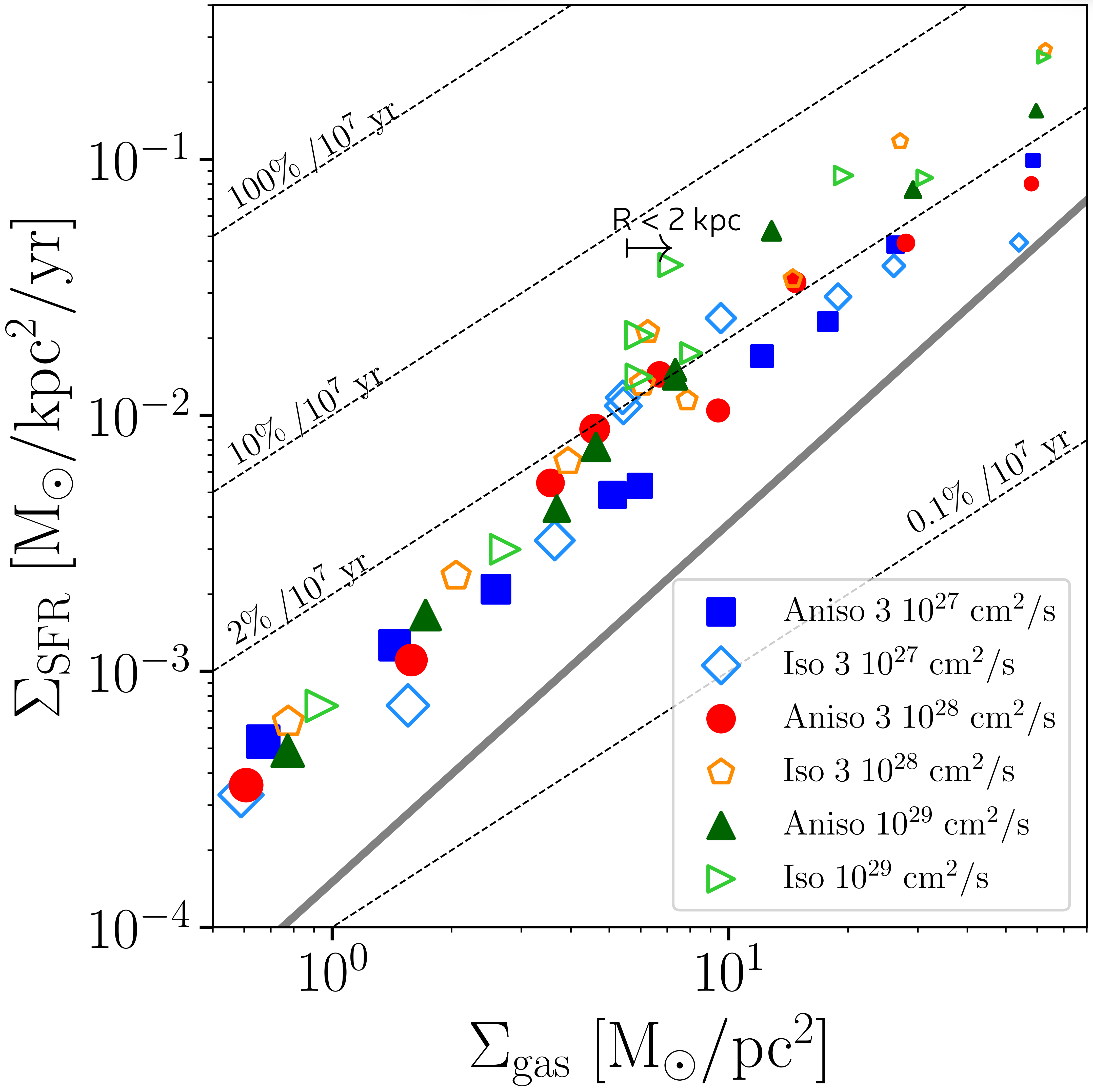
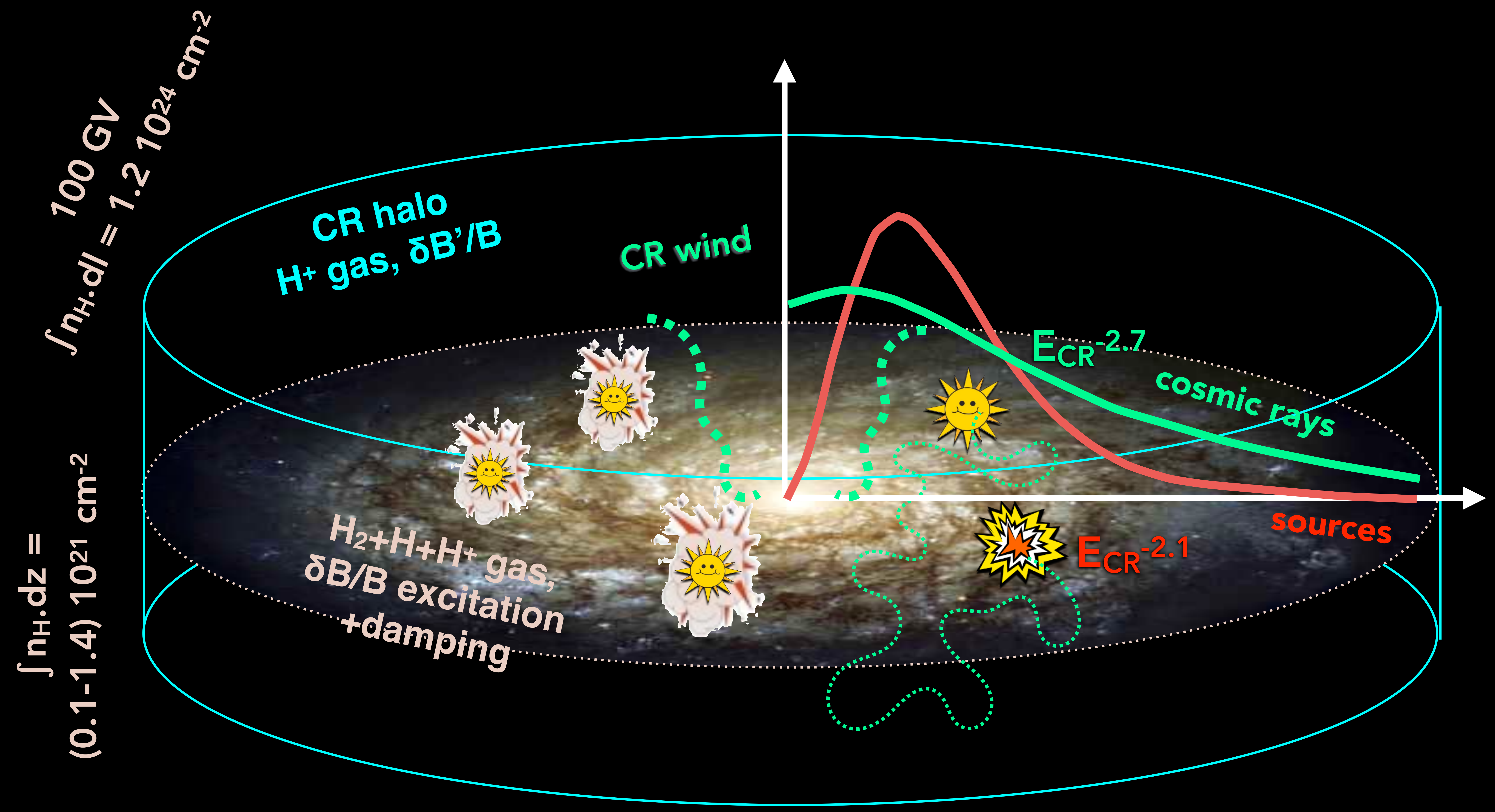




how fast do GeV-TeV cosmic rays travel?



$D \propto E_{CR}^{\,0.3\text{-}0.6}$ (B/C) to $E_{CR}^{\,0.34\text{-}0.36}$ (Galprop)

SNR envt escape?
superbubble escape?

level of superbubble/SNR
re-acceleration?
diffusive ISM re-accel?

self-generated
or ISM-induced
confinement?
where? D(E)? D(SFR)?

level of flux & spectral
variations across
spiral arms & B valleys?
hidden grammage?

Gal. wind impact?
local Chimney impact?