'TeVPA', Sydney, 2019

Cosmic ray feedback in star-formation and implications for gamma-ray emission from starbursts

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Describing these works:

- *'Cosmic ray transport in starburst galaxies';*
  Krumholz, Crocker, Xu, Lazarian, Robertson & Bedwell (2019), *in submission,* MNRAS (1911.09774)
- *'Cosmic Ray Feedback Bounds the Star Formation Efficiency of Spiral Galaxies';*
  Crocker, Krumholz, Thompson, et al. (2020); *in preparation*

Two Claims

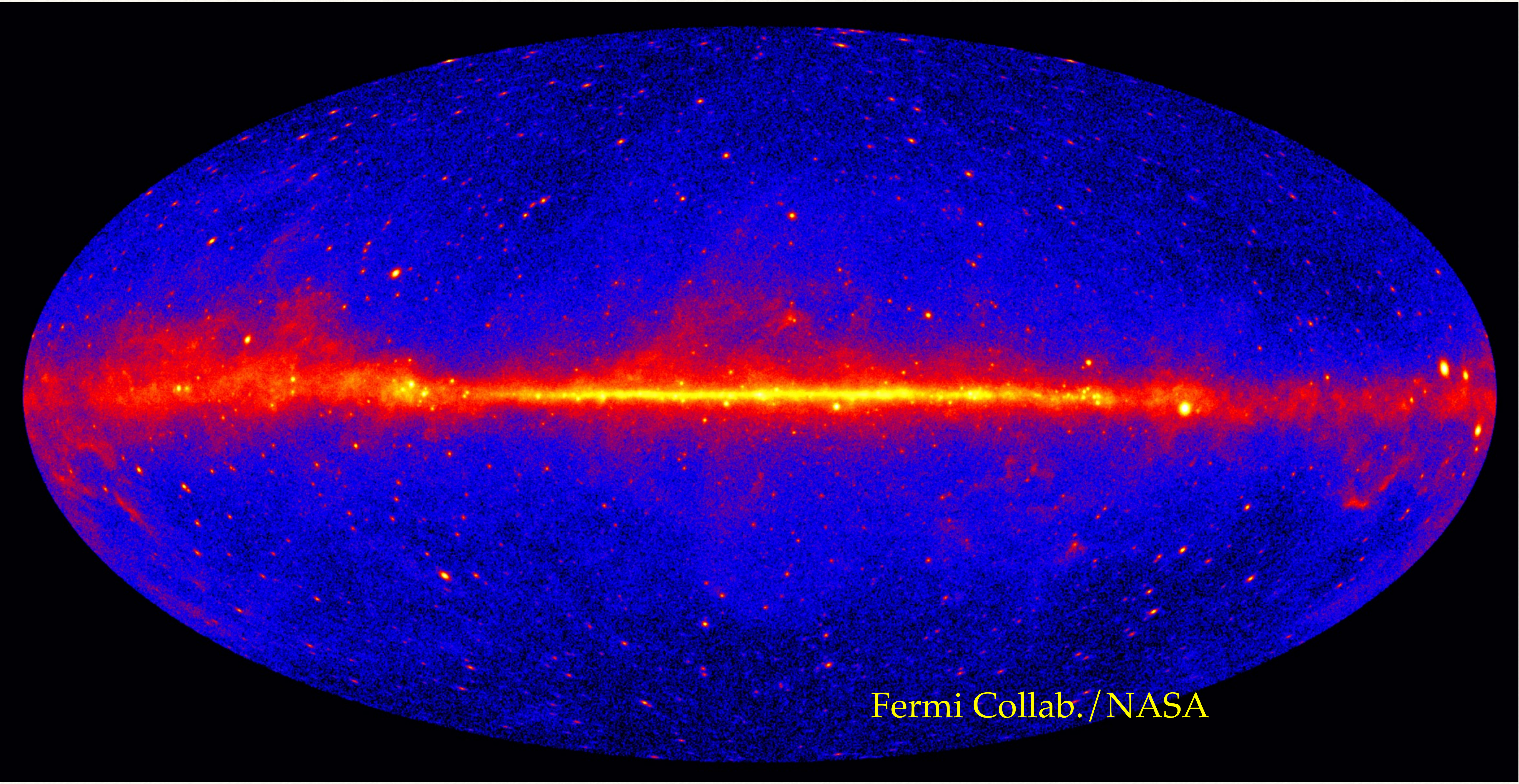
A correct understanding of cosmic ray transport in (relatively) dense, partially ionised (but largely neutral) gas allows us to

1. *Make sense of the observed gamma-ray spectra of some nearby starbursts and the empirically-demanded CR loss timescales*

2. *Make sense of the fact that there is an empirical upper limit to the star formation of 'normal' galaxies*

Cosmic Rays

- Cosmic rays can be measured locally and their presence throughout the Galactic disk can be inferred from its gamma-ray emission


Fermi Collab. / NASA

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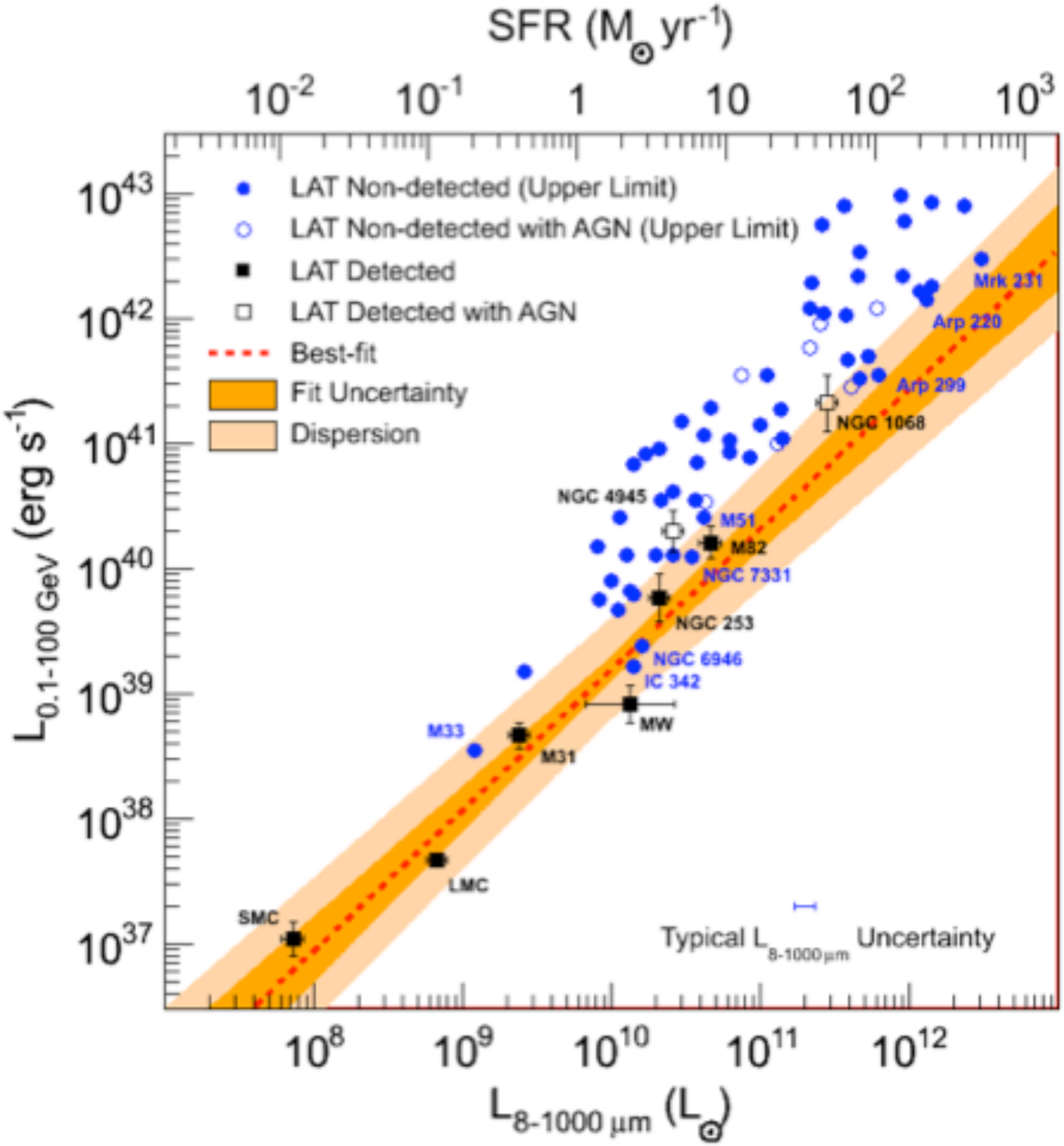
- Similarly, we know from gamma-ray observations that there are diffuse cosmic ray populations suffusing the disks of external, star-forming galaxies (local group, nearby starbursts)



Martin, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).

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- As CRs scatter on B field they exchange momentum with the B field
- $\Rightarrow$ they exert an effective pressure to the gas into which the B field is "frozen in"

CRs are dynamically important in galaxies:

- (hadronic gamma-ray emission ⇒) suffuse the dense gas
- inferred to dominate heating and ionisation of H_2

  ⇒ maintain temp of H_2 and ensure it is coupled to magnetic fields

  ⇒ affect star formation
- in the Milky Way, they provide energy density/pressure equivalent to other ISM phases (Boulares & Cox 1990)

  ⇒ help to support the scale height of the gaseous disk
- help launch galactic outflows (Ipavich 1975, Breitchwerdt +)

Cosmic Rays in the Milky Way (classical picture)

- CR transport in Gal disk ~ random walk
- CRs effectively diffuse with scattering length: λ_{CR} **~ pc**
- $\lambda_{CR} \gg r_g$

$$r_g = \frac{\gamma m c v \sin\alpha}{eB} \approx \frac{E_{CR} \sin\alpha}{eB} \sim 10^{-6}\ E_{CR,0}\ B_0^{-1}\ \mathrm{pc},$$

- At a heuristic level, λ_{CR} can be derived from quasi-linear theory in a picture where there is a ~Kolmogorov turbulence cascade from the ~100 pc turbulence injection scale down to the gyroradius scale
- CRs spend most of their time in ionised ISM, with ~kpc scale height

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CR Transport in 'Neutral' Gas

- The mid-planes of starbursts are dominated by cold, neutral gas, neutral gas filling factor → 100%
- ⇒ The ISM processes determining CR transport in starbursts are different to those operating AT LARGE in galaxies like the Milky Way.
- However, even for the MW, close to midplane, filling factor of `neutral' gas approaches 50%

CR Transport in ‘Neutral’ Gas

- Low ionisation fractions in this medium ⇒ damping of turbulence by ion-neutral drag. This fundamentally changes the nature of CR transport (Kulsrud & Pearce 1969, Lazarian 2016, Xu & Lazarian 2016,2017,2018).
- In particular, GeV CRs can***not*** scatter off the strong, large-scale turbulence found in starbursts, because efficient ion-neutral damping prevents such turbulence from cascading down to their ~10^{-6} pc gyroradius scale

Why does ion-neutral damping kill the turbulence cascade?

- The neutral gas is, in reality ionised at some level,

  $\chi \sim 10^{-5}$ - 10^{-2} (by mass)

- For given ISM parameters, 3 different frequencies that must be compared:
  - frequency of a particular MHD wave: ν
  - ion-neutral collision frequency: ν_{in}
  - neutral-ion collision frequency: ν_{ni}
  - $\nu_{ni} = \chi\, \nu_{in}$

3 regimes

- $\nu \ll \nu_{ni} < \nu_{in}$, ***coupled:*** many collisions will occur per oscillation, forcing the ions and neutrals to move together, thus act as a **single magnetised fluid** supporting the usual family of MHD waves.

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- $\nu_{ni} < \nu < \nu_{in},$ ***damping:***
  - ions attempt to oscillate in response to perturbations in the magnetic field, but still collide with the surrounding neutrals. Thus, the ion-neutral collisions prevent the ions from oscillating freely.
  - neutrals, decoupled from ions due to their infrequent collisions with ions, cannot move with the Alfven waves.
  - the ion-neutral collisions will convert organised Alfven wave motions in the weakly coupled ions and neutrals into microscopic random motions, dissipating them into heat.

Implication

- The turbulence cascade in the ions cuts off at a damping scale

$$L_{\mathrm{damp,A}} = \frac{\pi}{\sqrt{2L}}\left(\frac{u_{\mathrm{LA}}}{\gamma_{\mathrm{d}}\chi\rho}\right)^{3/2}\min\left(1, \mathcal{M}_{\mathrm{A}}^{1/2}\right)$$

$$\approx \frac{0.0011}{L_2^{1/2}}\left(\frac{u_{\mathrm{LA,1}}}{n_{\mathrm{H,3}}\chi_{-4}}\right)^{3/2}\min\left(1, \mathcal{M}_{\mathrm{A}}^{1/2}\right)\ \mathrm{pc}$$

- ..much bigger than the GeV gyroradius

$$r_{\mathrm{g}} = \frac{\gamma mcv\sin\alpha}{eB} \approx \frac{E_{\mathrm{CR}}\sin\alpha}{eB} \sim 10^{-6}\ E_{\mathrm{CR},0}\ B_0^{-1}\ \mathrm{pc},$$

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Alfven Mach number

M_A ~ 2

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Implication

- Thus, GeV CRs can***not*** scatter off the strong, large-scale turbulence found in starbursts, because efficient ion-neutral damping prevents such turbulence from cascading down to their $\sim 10^{-6}$ pc gyroradius scale
- Instead, GeV CRs stream along field lines at a rate determined by the **competition between streaming instability and ion-neutral damping**, leading to transport via a process of **field line random walk**
- This results in an effective diffusion coefficient that is nearly energy-independent for ~GeV-TeV CRs

- The damping rate in the decoupled regime is (Kulsrud & Pearce 1969):

$$\omega_{\rm d} = \frac{\nu_{\rm in}}{2},$$

- the growth rate of the streaming instability is:

$$\Gamma_{\rm CR} = \frac{eB}{mc}\frac{n_{\rm CR}(>\gamma)}{n_{\rm i}}\left(\frac{V_{\rm st}}{V_{\rm Ai}} - 1\right),$$

- balance growth against damping (i.e., set $\Gamma_{CR} = \omega_d$):

$$\frac{V_{\rm st}}{V_{\rm Ai}} - 1 = 2.3 \times 10^{-3} \frac{E_{\rm CR,0}^{p-1} n_{\rm H,3}^{3/2} \chi_{-4} \mathcal{M}_{\rm A}}{C_3 u_{\rm LA,1}},$$

- unless the CR energy density in starbursts is small (comparable to that in the Milky Way $C_3 \sim 10^{-3}$), the streaming velocity will be very close to V_{Ai}, the ***ion*** Alfven speed:

$$V_{\rm st} \approx V_{\rm Ai} \approx 1000 \frac{u_{\rm LA,1}}{\chi_{-4}^{1/2} \mathcal{M}_{\rm A}} \ \mathrm{km\ s^{-1}}.$$

- Can now estimate the effective macroscopic diffusion coefficient (Yan & Lazarian 2008)
- No source of turbulence on the CR gyroscale other than that excited by the streaming instability
- ⇒ no mechanism to scatter CRs perpendicular to field lines.
- ⇒ diffusion relative to the macroscopic mean magnetic field direction is solely due to **field line random walk** (**FLRW**)
- The diffusion rate due to this process is determined by the coherence length of the field, which is related to the injection length of the turbulence by (Yan & Lazarian (2008):

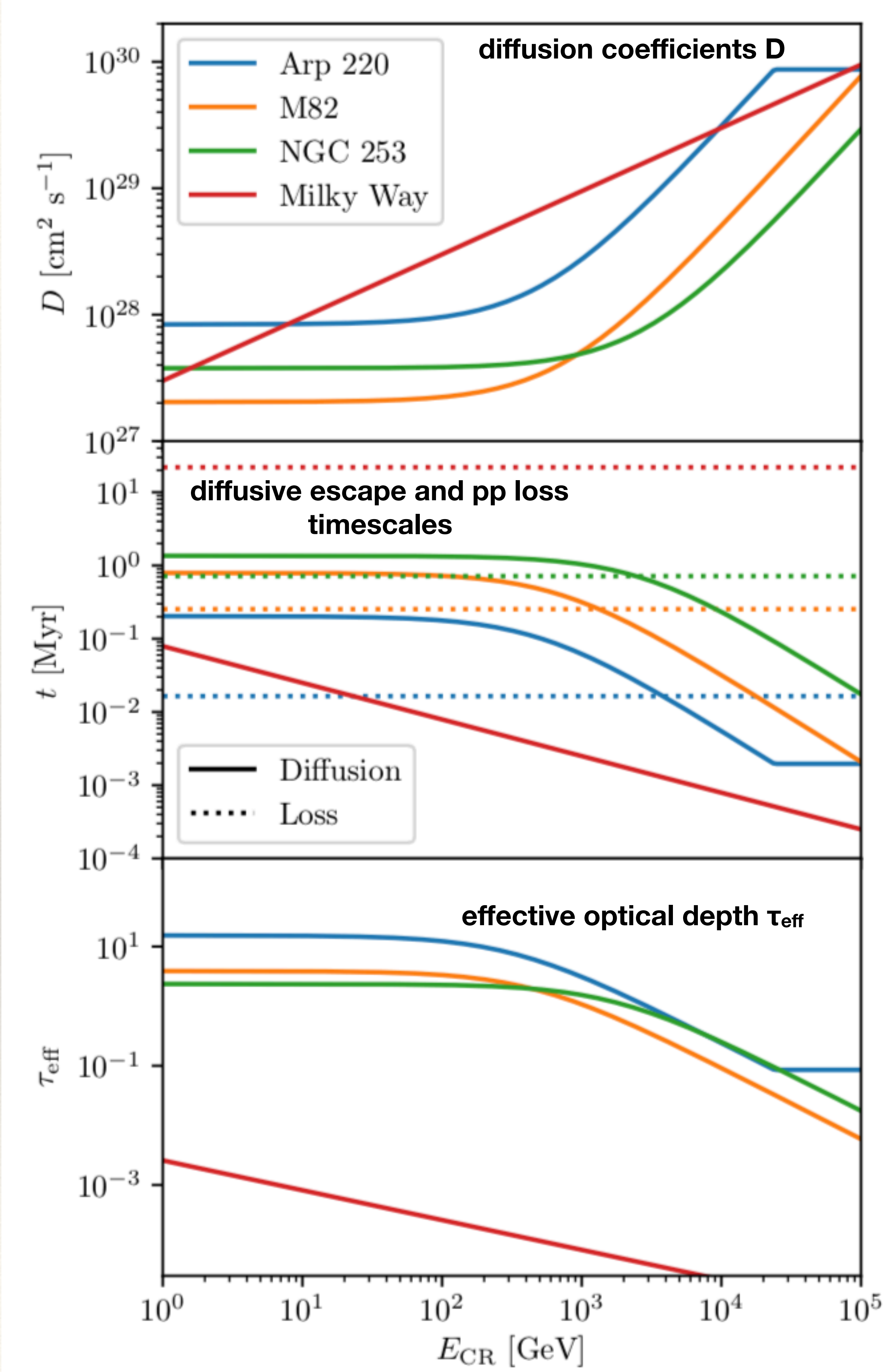
$$L_{\mathrm{A}} \approx L \min\left(1, \mathcal{M}_{\mathrm{A}}^{-3}\right).$$

- The corresponding diffusion coefficient for CRs in the direction parallel to the large-scale field is:

$$
\begin{aligned}
D_{\|} &\approx V_{\rm st} L_{\rm A} \\
&\approx 3.1 \times 10^{28} \frac{u_{\rm LA,1} L_2}{\sqrt{\chi_{-4}}} \min\left(\mathcal{M}_{\rm A}^{-1}, \mathcal{M}_{\rm A}^{-4}\right) \ {\rm cm}^2\ {\rm s}^{-1},
\end{aligned}
$$

- If $M_A > 1$ as expected, then the perturbations in the field are not preferentially aligned with the large-scale mean field, and thus the diffusion coefficient perpendicular to the large-scale field is the same as that parallel to it, $D_{\perp} \approx D_{\|}$, and thus there is a single diffusion coefficient D in all directions.
- Note D is energy independent AND similar in magnitude to Galactic value @ ~10 GeV

Application I: Starburst Gamma-Ray Spectra



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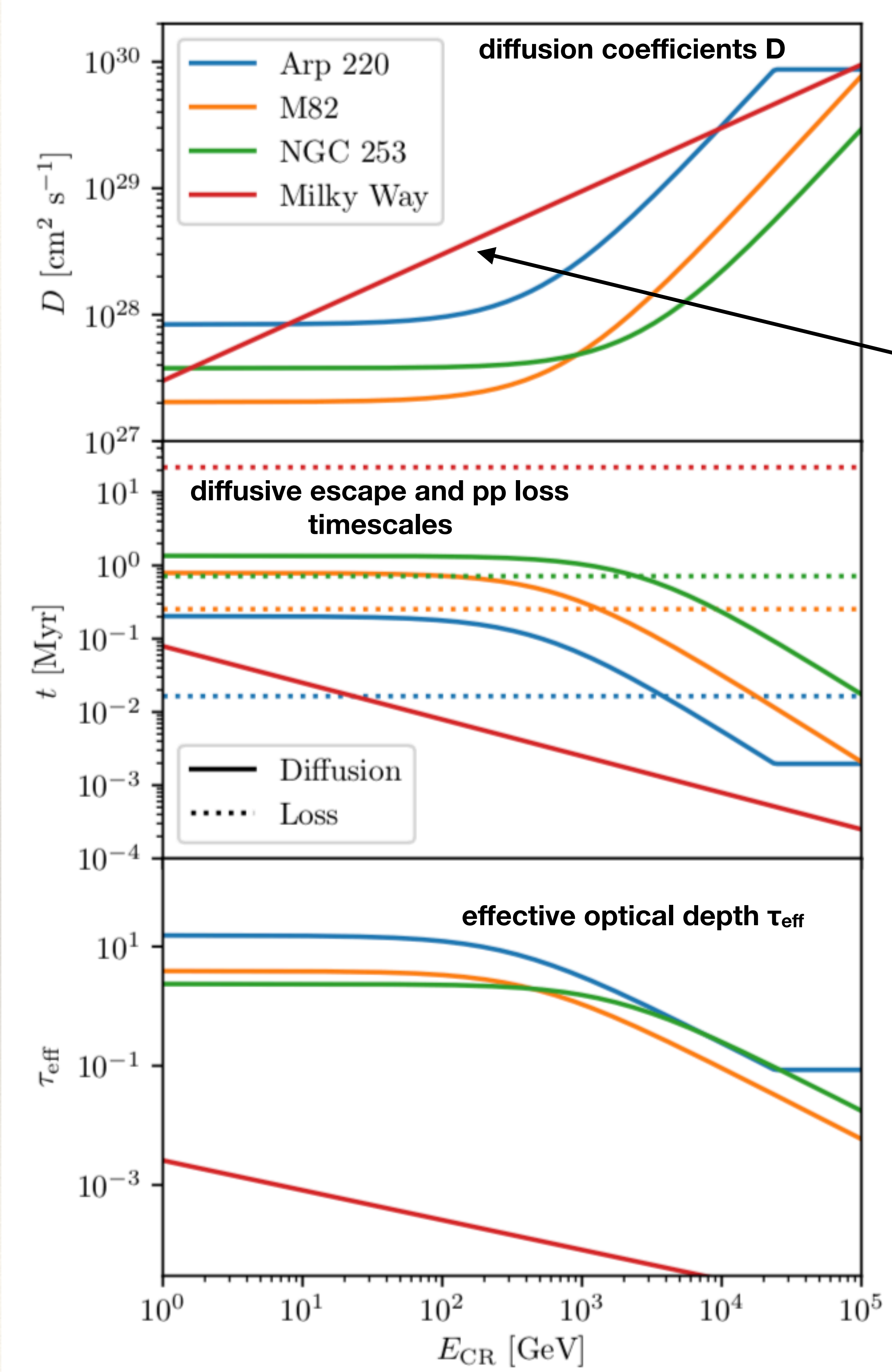

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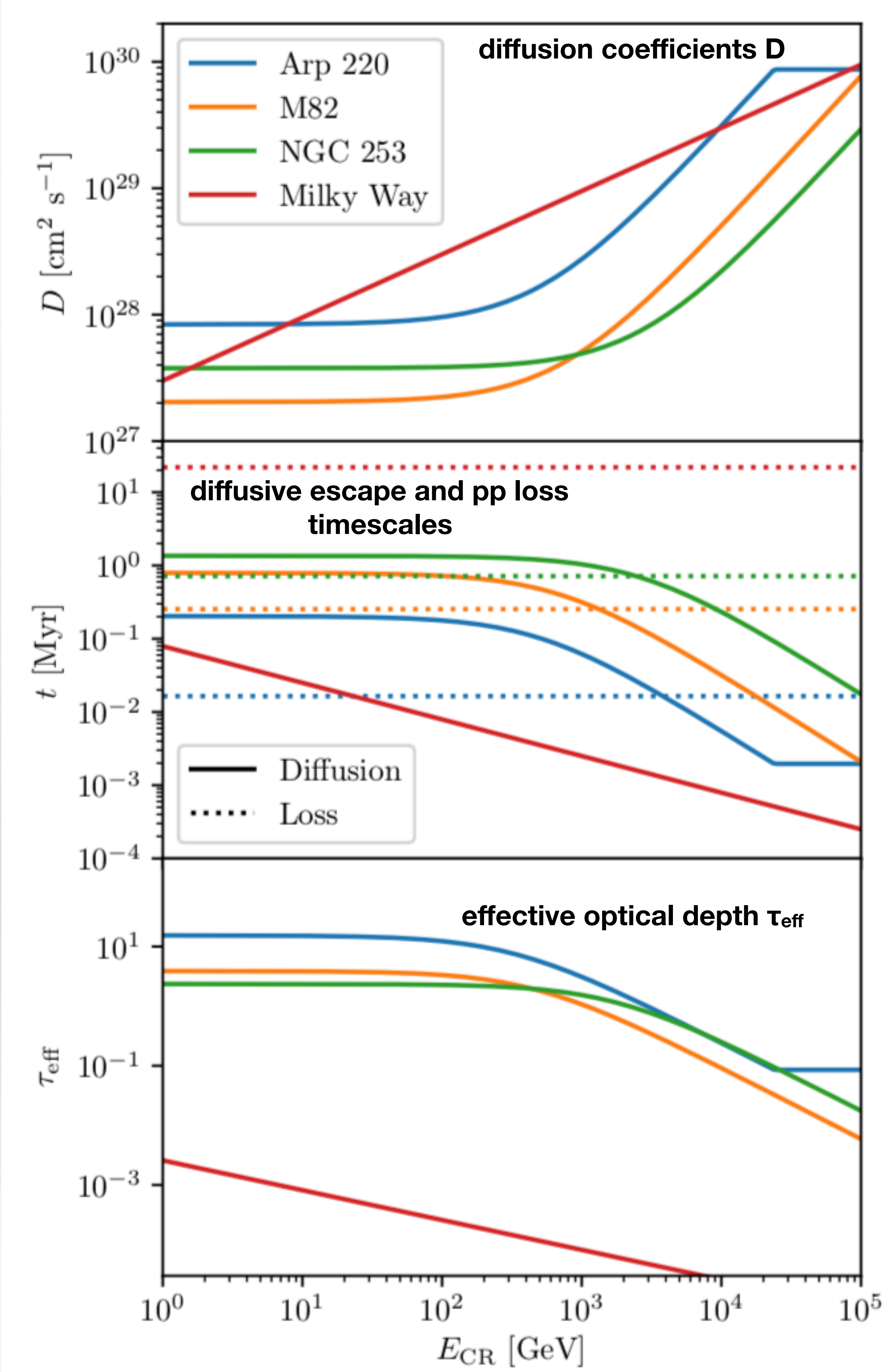
$$D_{MW} \approx 3 \times 10^{27} E_{CR,0}^{1/2} \text{ cm}^2 \text{ s}^{-1}$$



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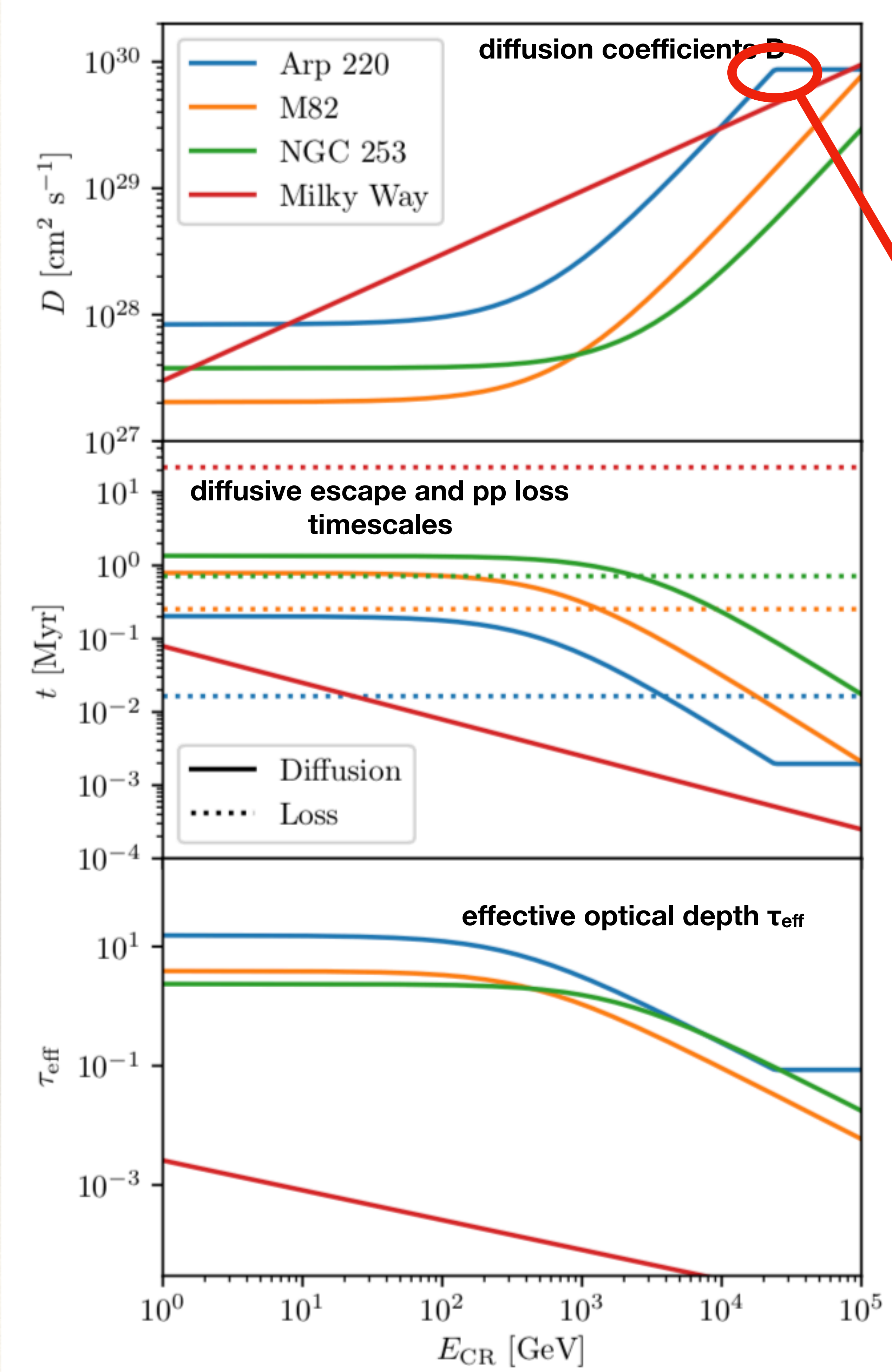

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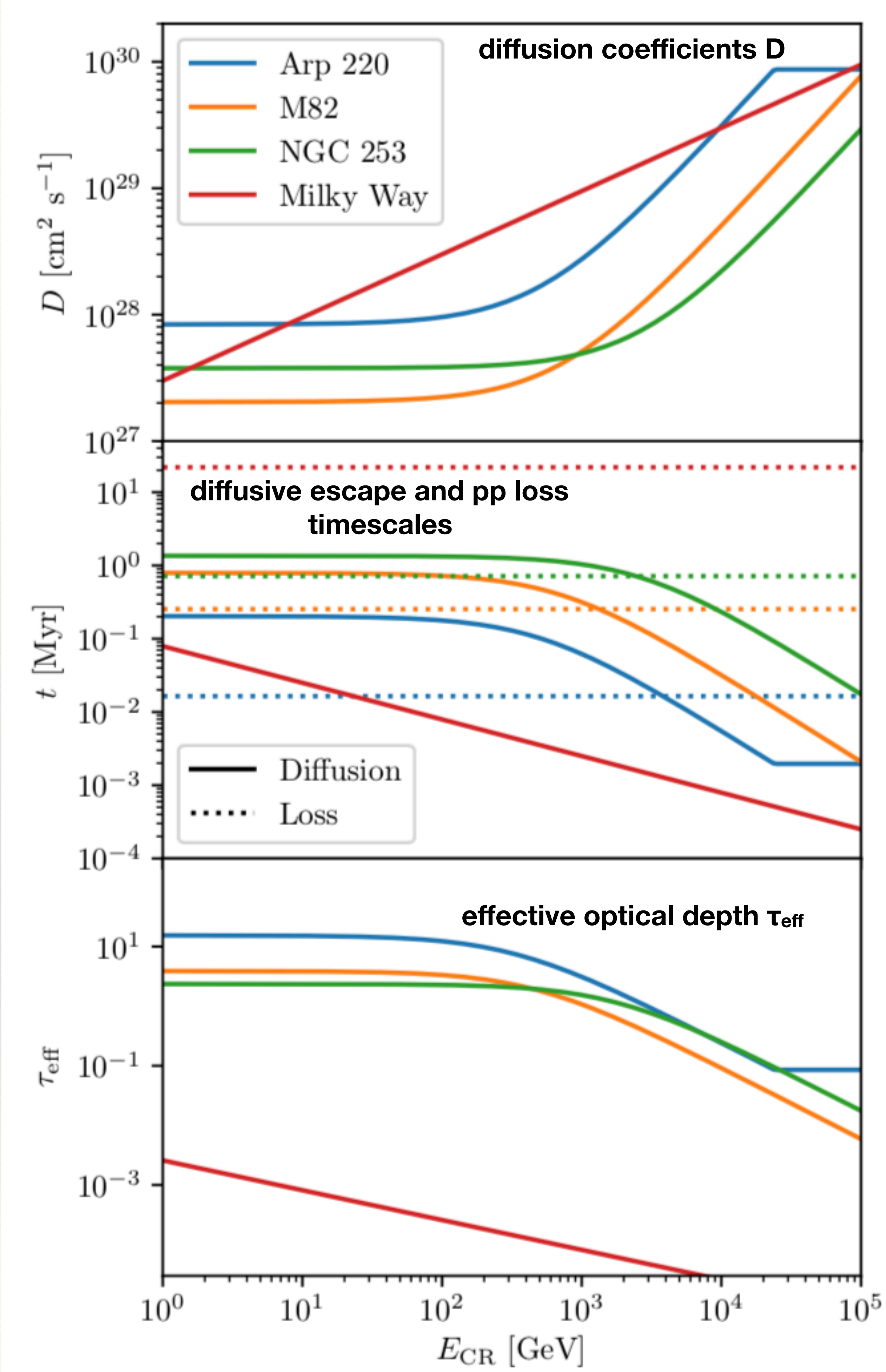
CR streaming speed approaches c



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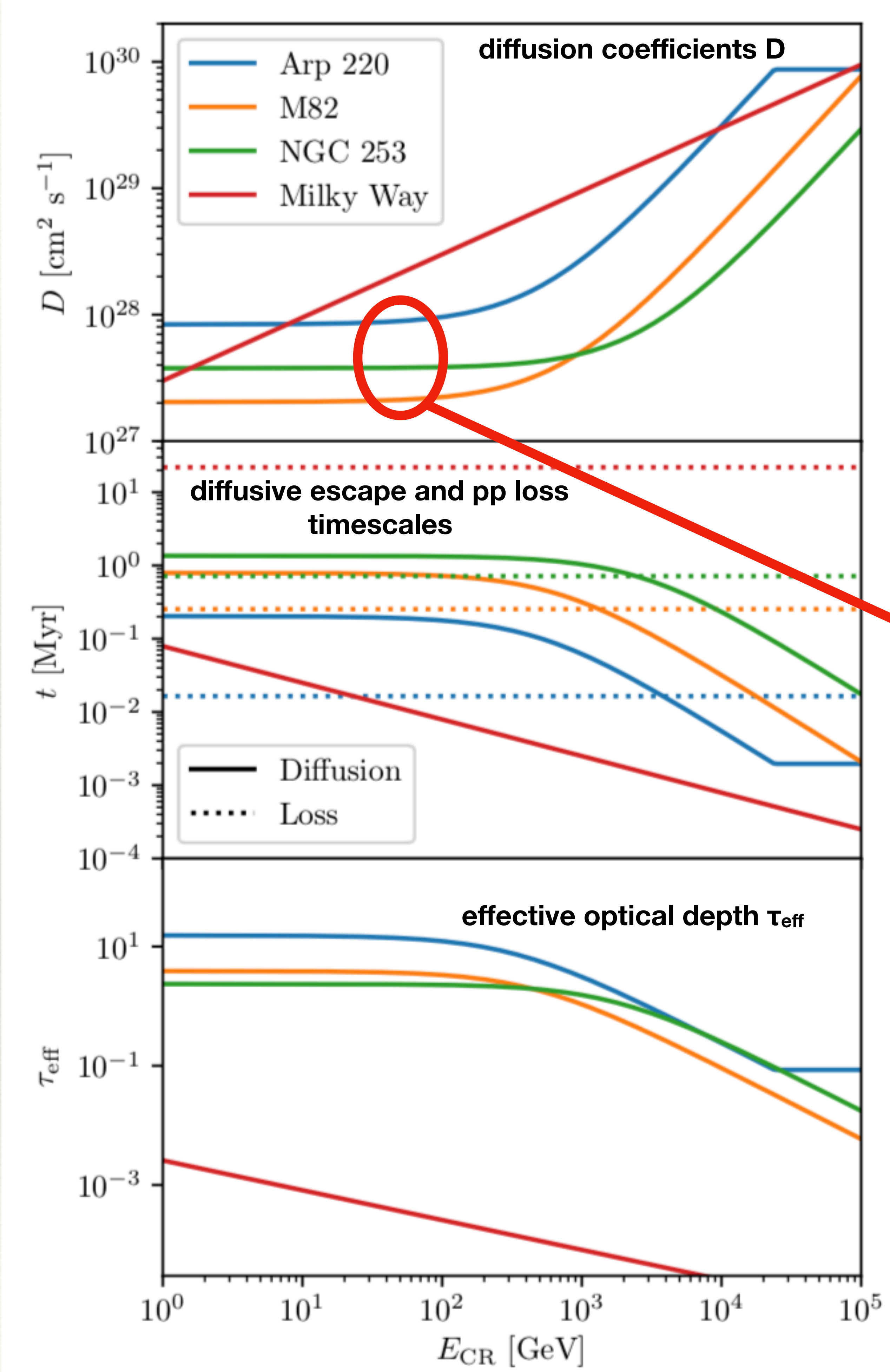

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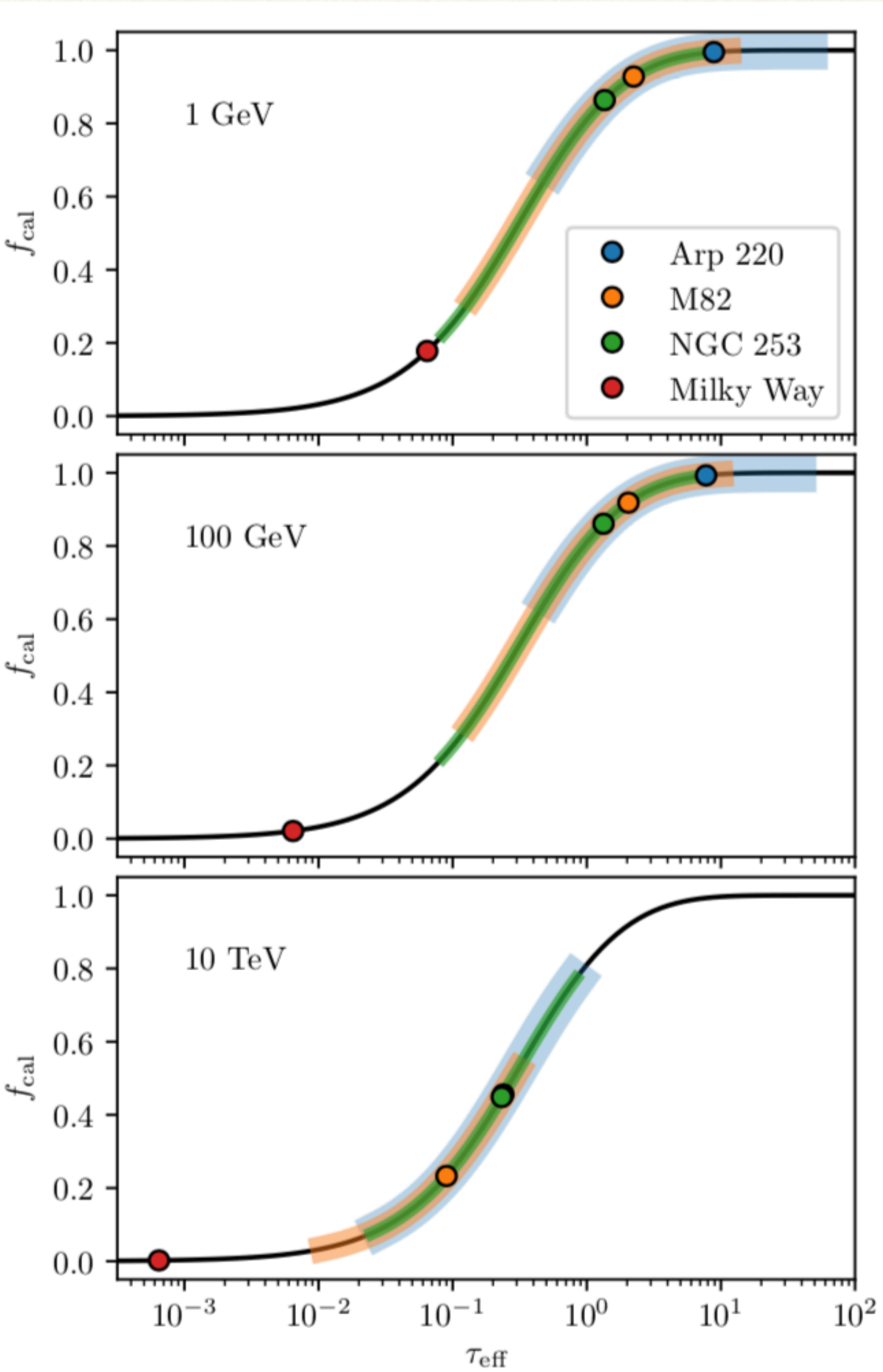
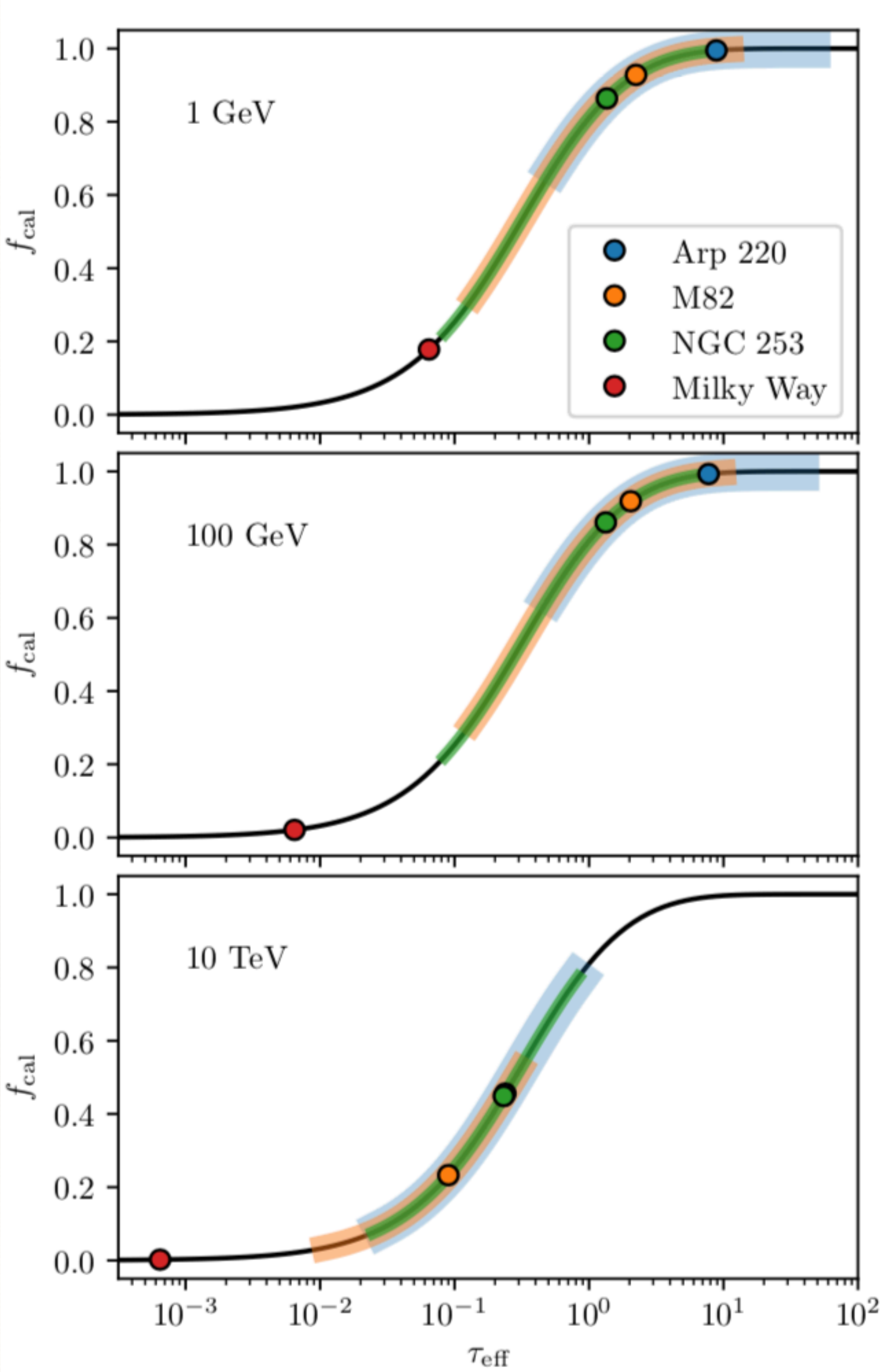
Note energy-independent D here;

Other models invoke energy-independent wind advection here at v_{wind} ~ 500 km/s, but the molecular gas in SBs is NOT advected at this speed



Calorimetric fraction f_{cal} as a function of effective optical depth τ_{eff}



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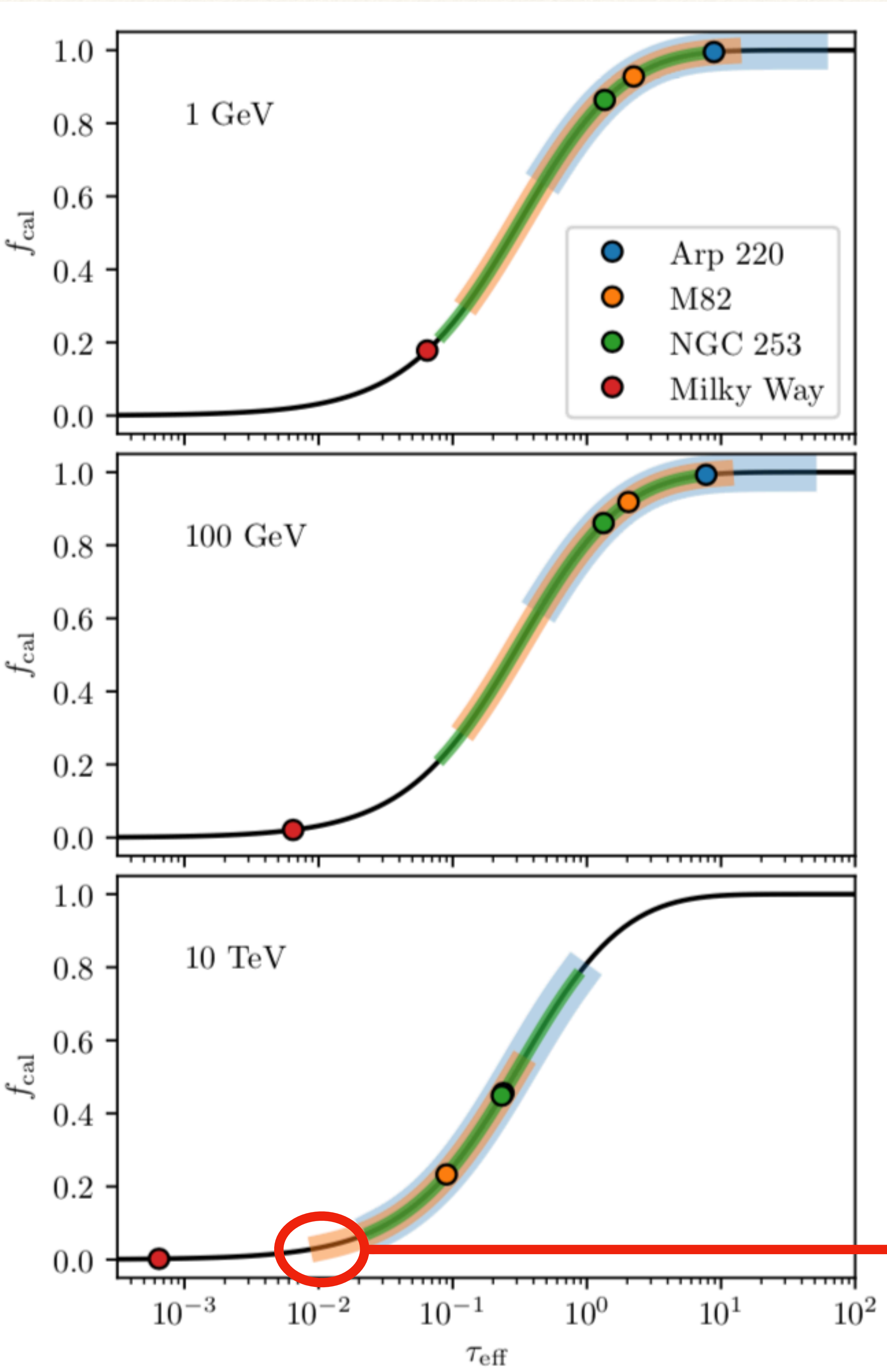

$M_A = 1$

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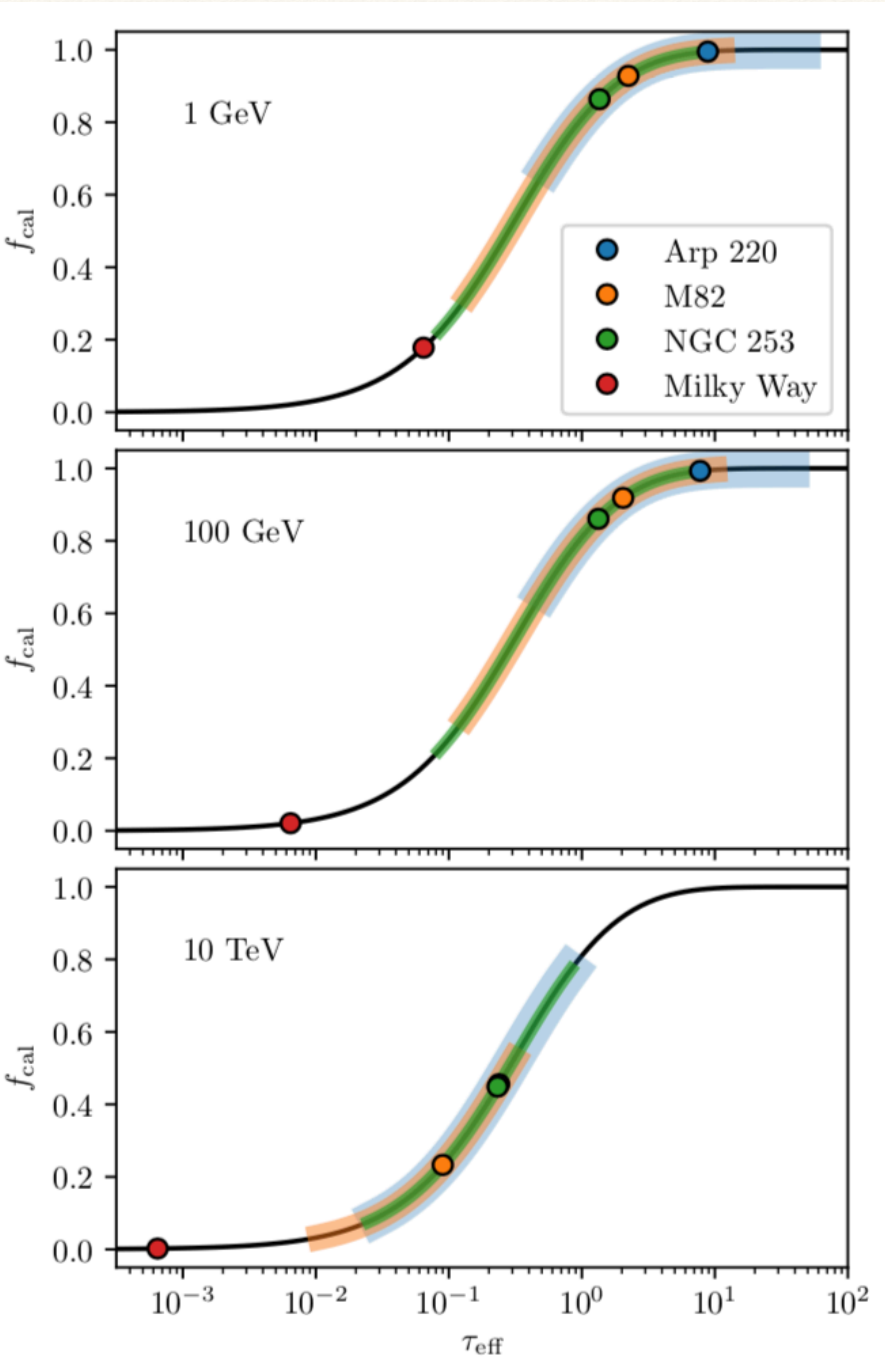

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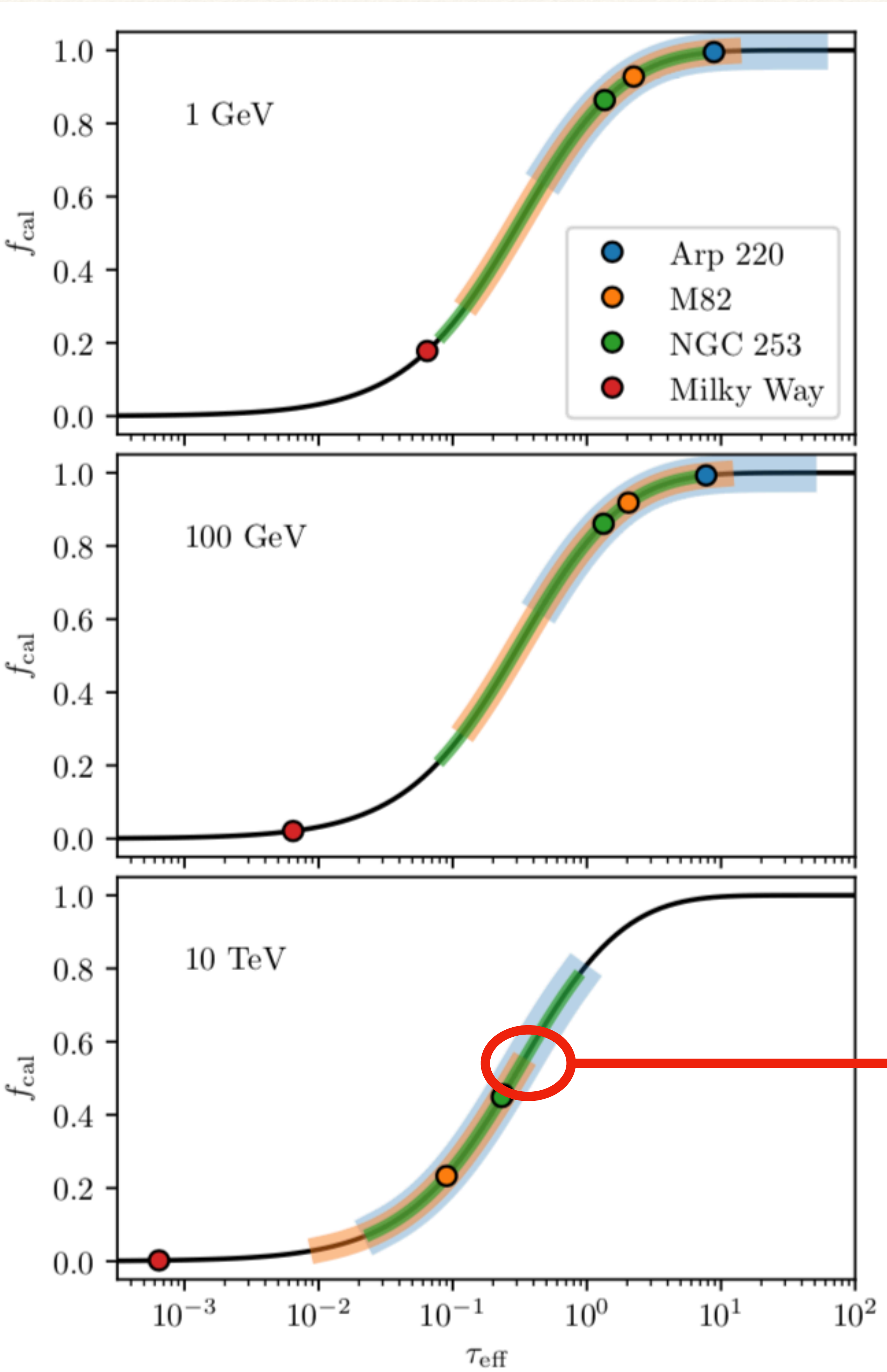
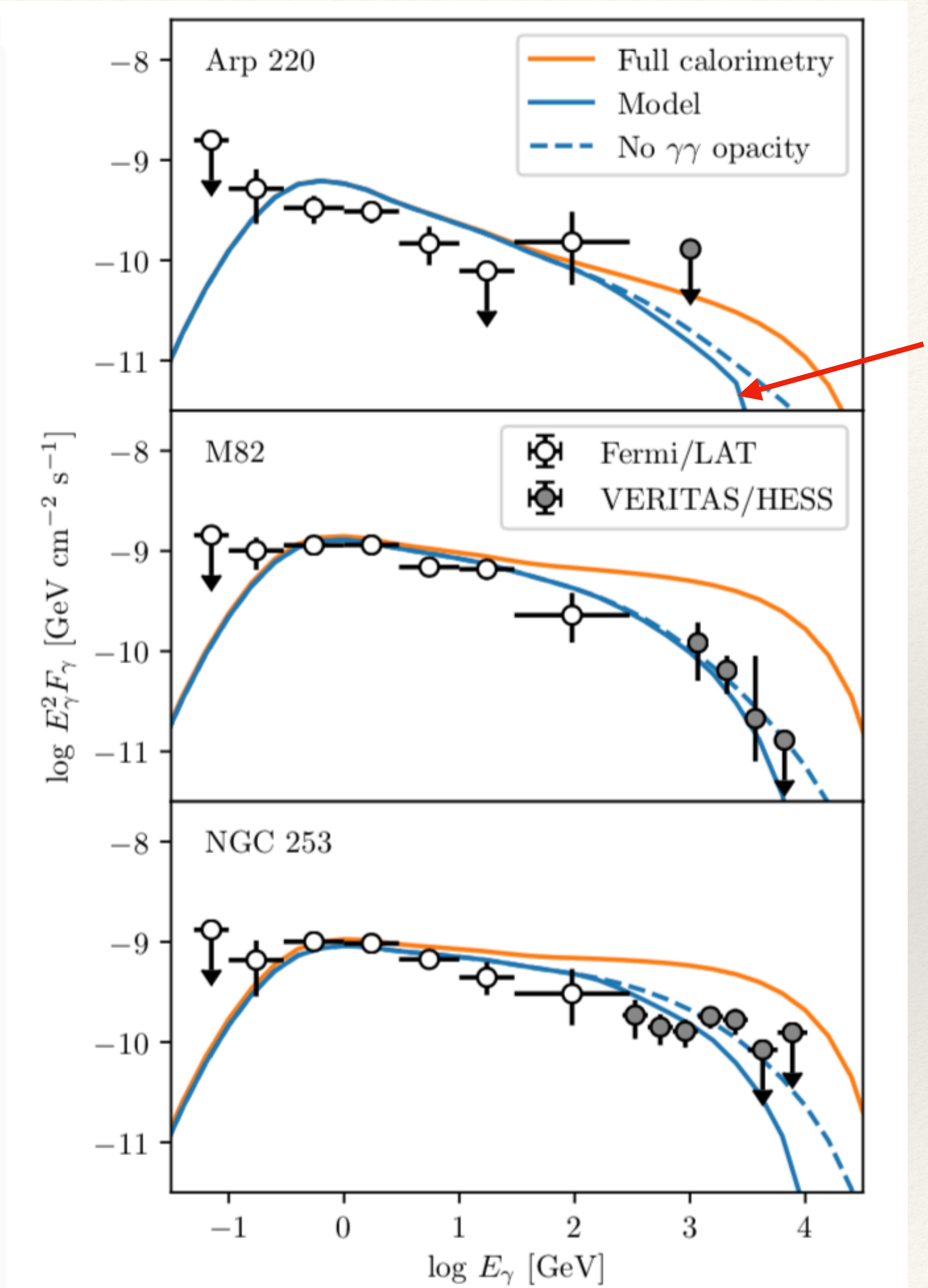


Calorimetric fraction f_{cal} as a function of effective optical depth τ_{eff}

M_A = 3

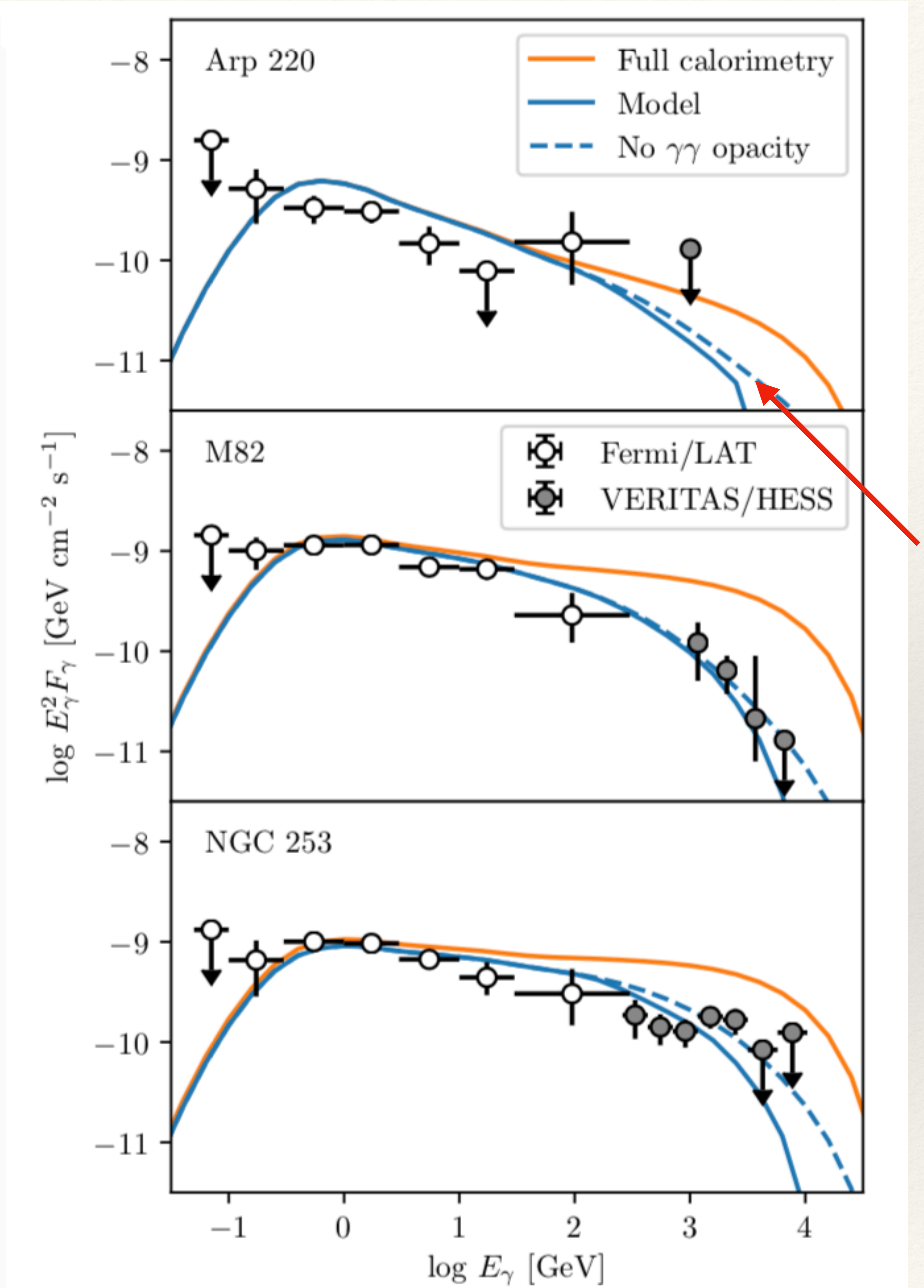


Spectra of NGC 253, M82, and Arp 220

Solid blue lines: standard model

dashed blue lines: predictions if we ignore the effects of $\gamma\gamma$ opacity

orange lines: spectra expected for perfect calorimetry independent of CR energy.



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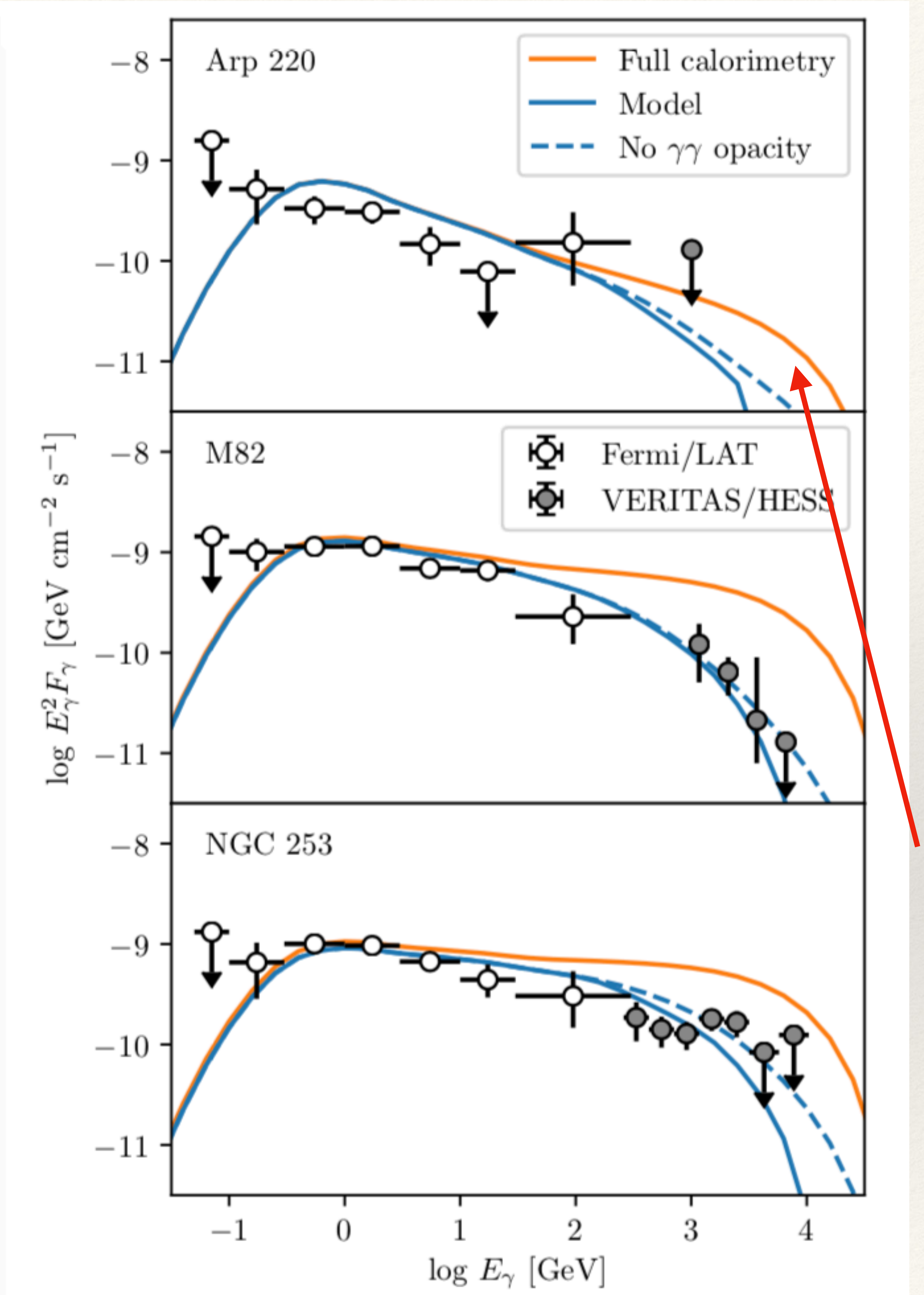

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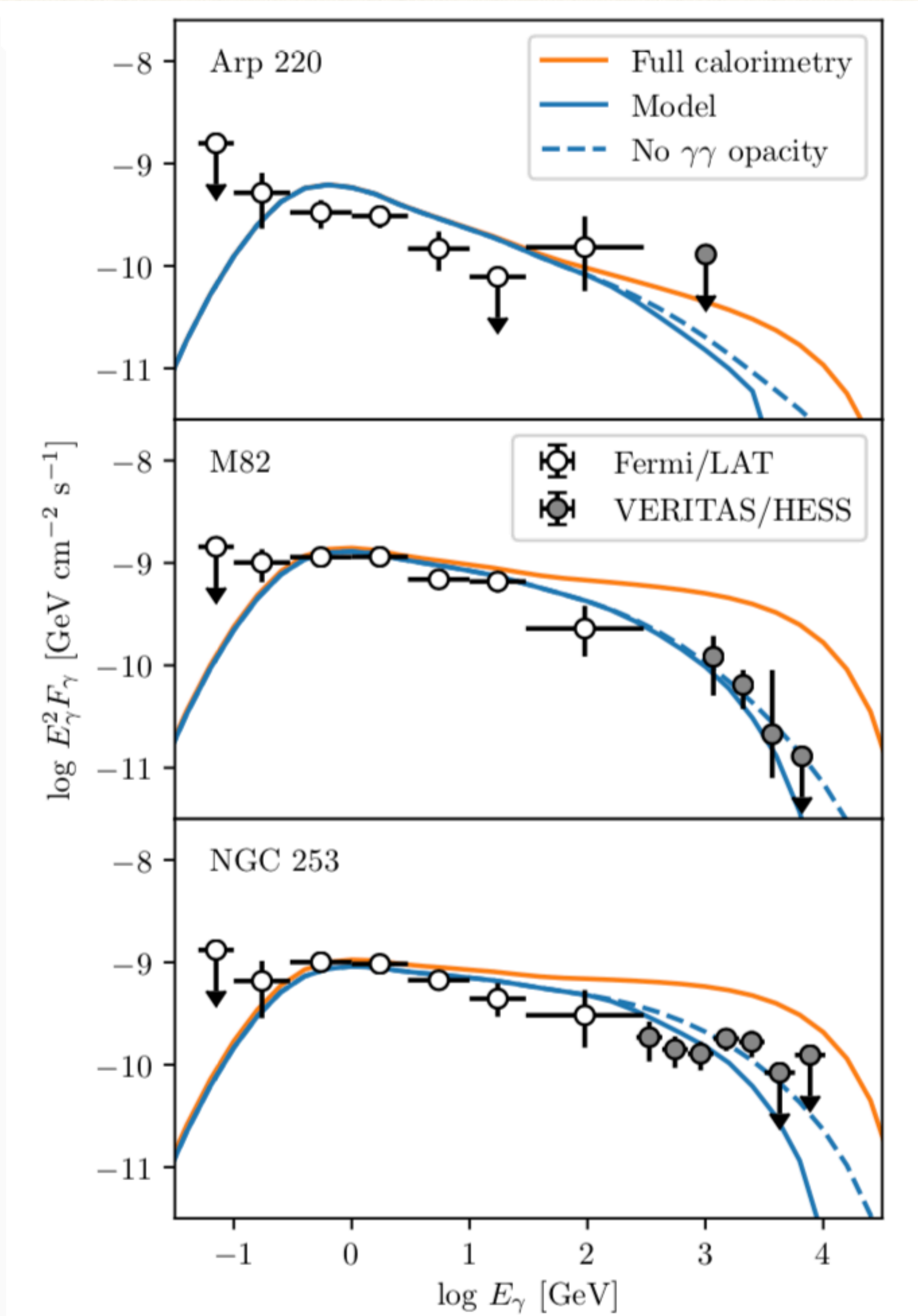

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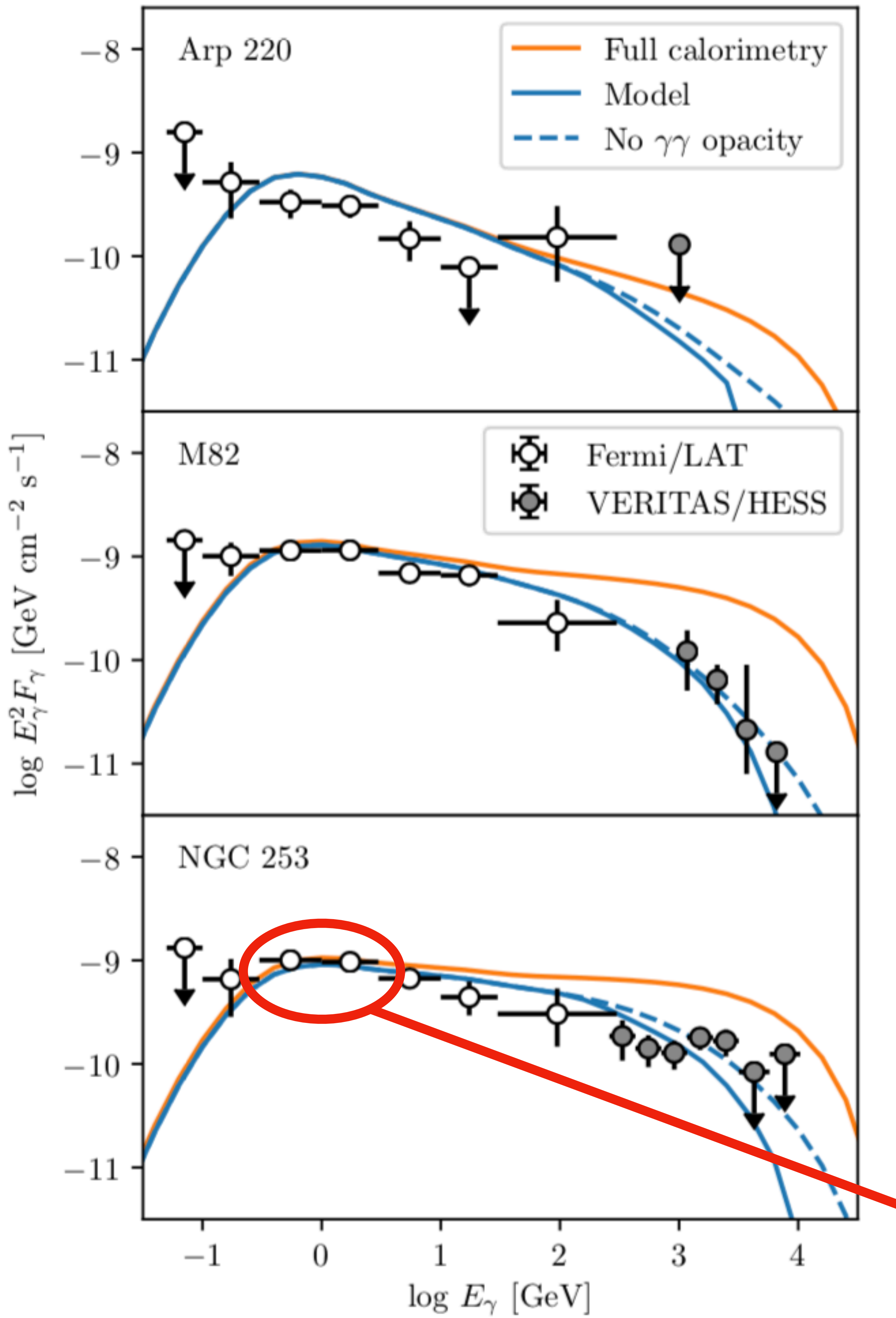

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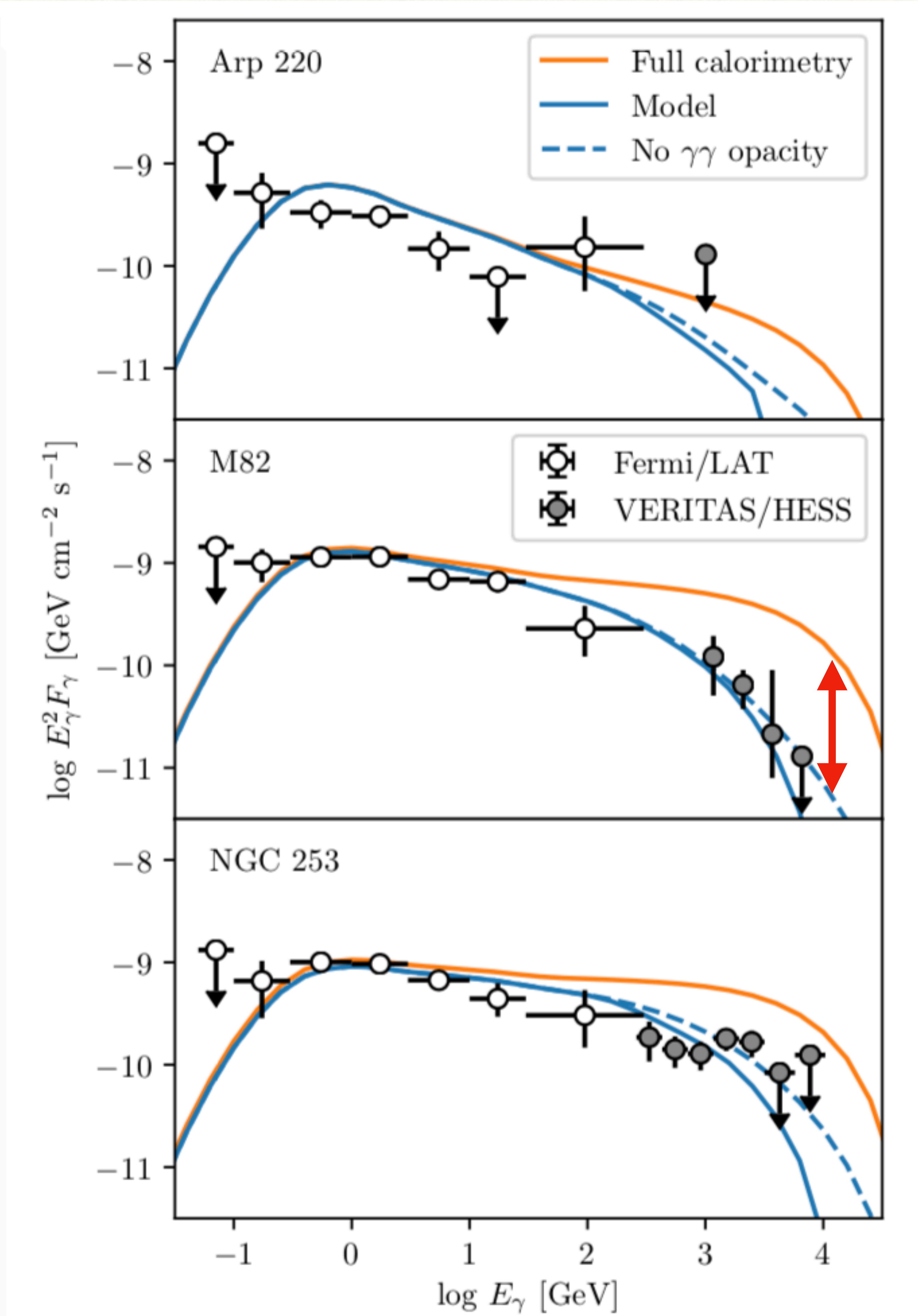
Spectral index from *Fermi* ~GeV data



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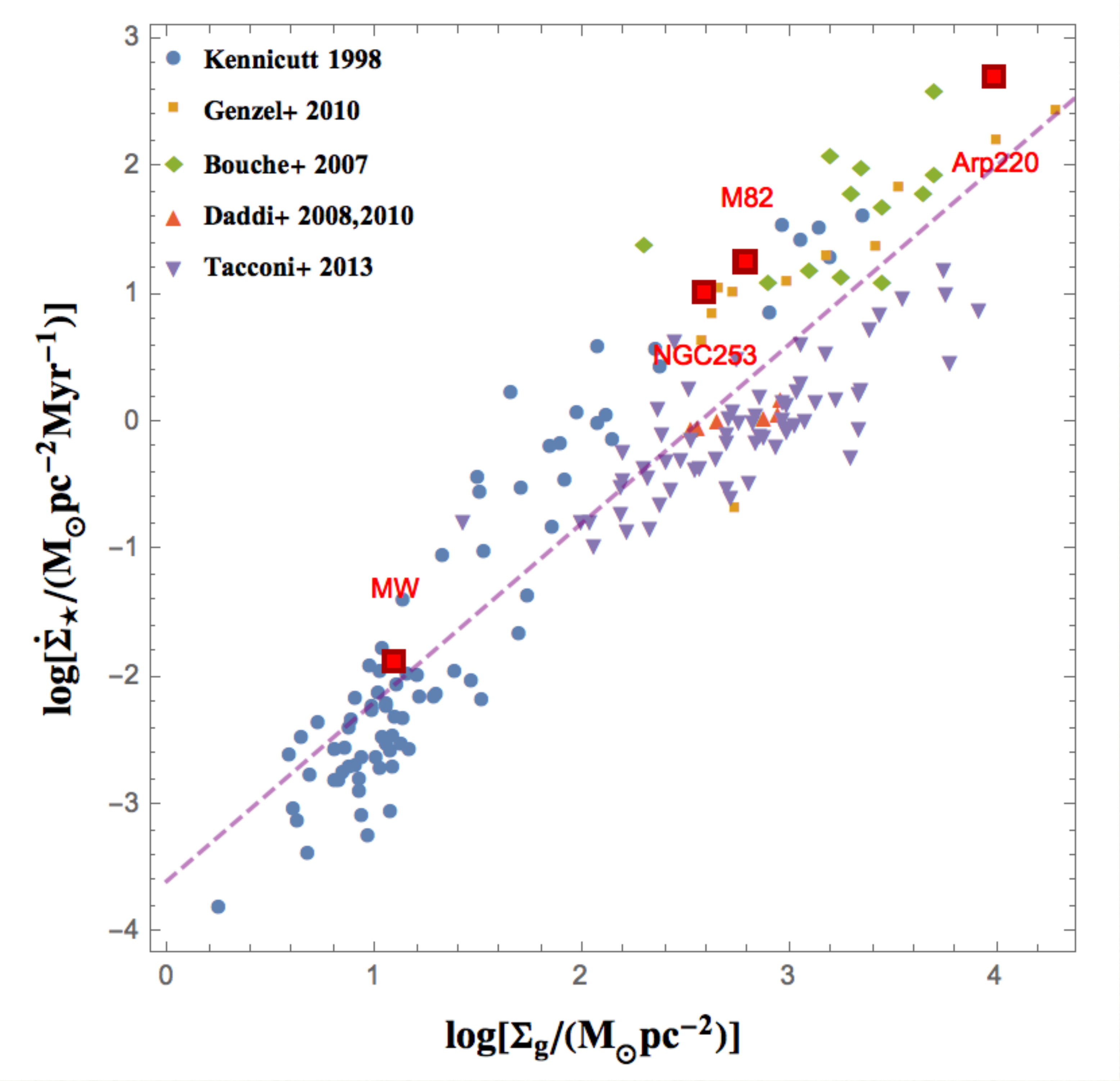
Application II: Cosmic Ray Feedback in 'Normal' Galaxies

Star-forming Galaxies; Kennicutt-Schmidt Plane



Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4\tau_s{}^2\left(\frac{ds}{d\xi}\right)^{\beta} p_c - \tau_{\rm path}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

$$\frac{dp_c}{d\xi} + \xi_{\rm turb}\frac{d^2 s}{d\xi^2} = -\left(1 - f_{\rm gas}\right)\frac{ds}{d\xi} - f_{\rm gas}\, s\,\frac{ds}{d\xi}$$

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Transport/loss equation

$$\frac{dp_c}{d\xi} + \xi_{\text{turb}}\frac{d^2 s}{d\xi^2} = -\left(1 - f_{\text{gas}}\right)\frac{ds}{d\xi} - f_{\text{gas}}s\frac{ds}{d\xi},$$

Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4\tau_s{}^2\left(\frac{ds}{d\xi}\right)^{\beta}p_c - \tau_{\mathrm{path}}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

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Hydrostatic balance

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Transport/loss equation

diffusive transport

$$\frac{dp_c}{d\xi} + \xi_{\rm turb}\frac{d^2 s}{d\xi^2} = -\left(1 - f_{\rm gas}\right)\frac{ds}{d\xi} - f_{\rm gas}s\frac{ds}{d\xi}$$

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Transport/loss equation

diffusive transport

Fermi-II

$$\frac{dp_c}{d\xi} + \xi_{\rm turb}\frac{d^2 s}{d\xi^2} = -\left(1 - f_{\rm gas}\right)\frac{ds}{d\xi} - f_{\rm gas}s\frac{ds}{d\xi}$$

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Transport/loss equation

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hadronic losses

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Hydrostatic balance

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Transport/loss equation

diffusive transport **Fermi-II** **hadronic losses** **streaming losses**

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Transport/loss equation

diffusive transport | **Fermi-II** | **hadronic losses** | **streaming losses**

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Hydrostatic balance

CR pressure gradient

Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4\tau \left(\frac{ds}{d\xi}\right)^{\beta} p_c - \tau_{\rm path}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

Transport/loss equation

diffusive transport — **Fermi-II** — **hadronic losses** — **streaming losses**

$$\frac{dp_c}{d\xi} + \xi_{\rm turb}\frac{d^2s}{d\xi^2} = -\left(1 - f_{\rm gas}\right)\frac{ds}{d\xi} - f_{\rm gas}\, s\,\frac{ds}{d\xi}$$

Hydrostatic balance

CR pressure gradient — **turbulent pressure gradient**

Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4\tau \ldots \left(\frac{ds}{d\xi}\right)^{\beta} p_c - \tau_{\rm path}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

Transport/loss equation

diffusive transport | **Fermi-II** | **hadronic losses** | **streaming losses**

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Hydrostatic balance

CR pressure gradient | **turbulent pressure gradient** | **stellar gravity**

Coupled ODEs:

$$\frac{d}{d\xi}\left[-\left(\frac{ds}{d\xi}\right)^{-\beta}\frac{dp_c}{d\xi}\right] = 4\tau \cdots \left(\frac{ds}{d\xi}\right)^{\beta} p_c - \tau_{\text{path}}\frac{ds}{d\xi}p_c + \tau_s\frac{dp_c}{d\xi}$$

Transport/loss equation

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Hydrostatic balance

CR pressure gradient | **turbulent pressure gradient** | **stellar gravity** | **gas self gravity**

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Hydrostatic balance

CR pressure gradient | **turbulent pressure gradient** | **stellar gravity** | **gas self gravity**

+ 4 BCs

Coupled ODEs:

$$\tau_s \equiv \left(\frac{z_*}{\lambda_{c,*}}\right)$$

height of atmosphere

mfp to scattering

optical depth to scattering

$$\tau_{\rm path} \equiv \frac{\tau_s \tau_{\rm pp}}{\beta_{A,i}}$$

rectilinear optical depth

ion Alfven speed

optical depth to absorption over path

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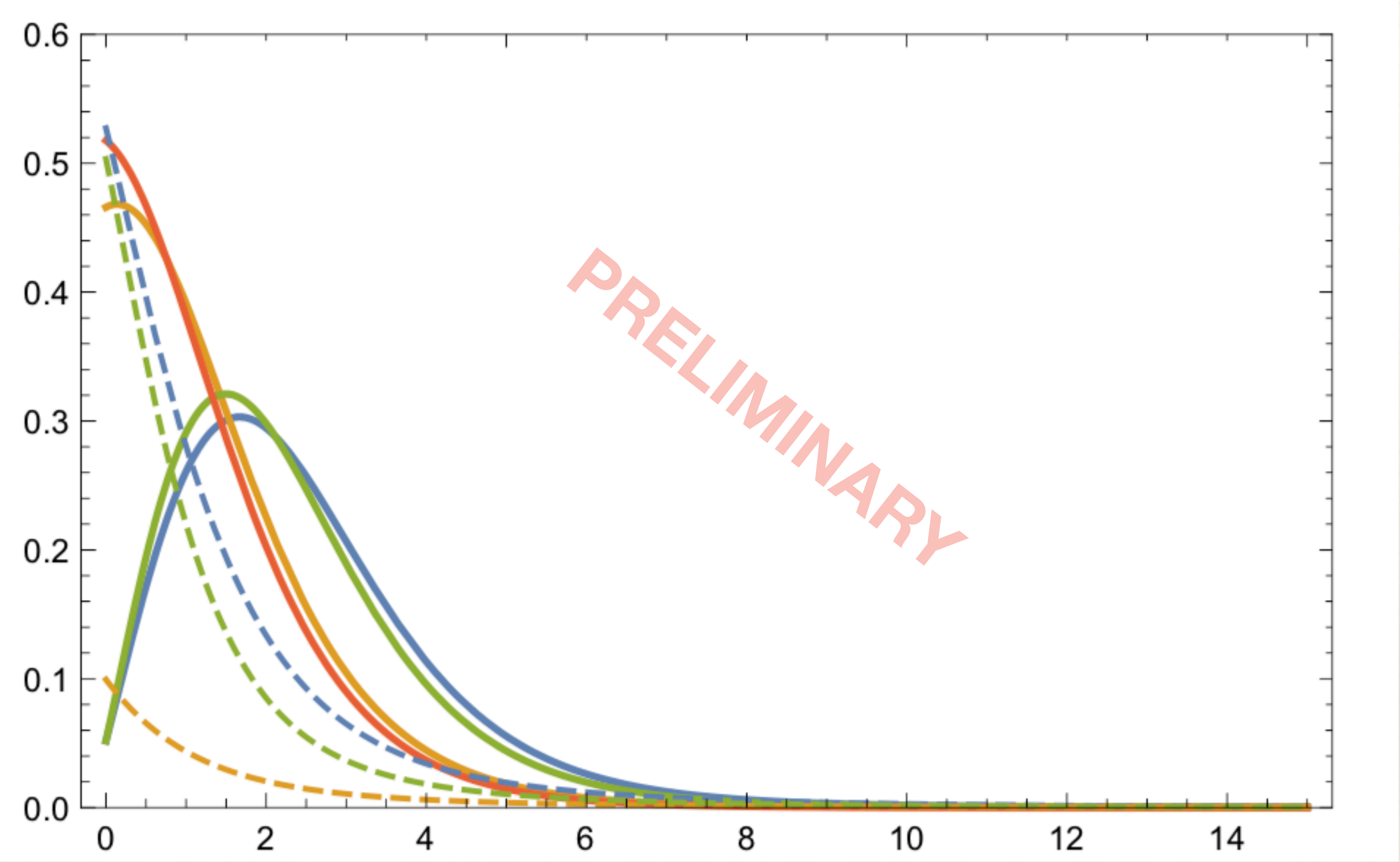
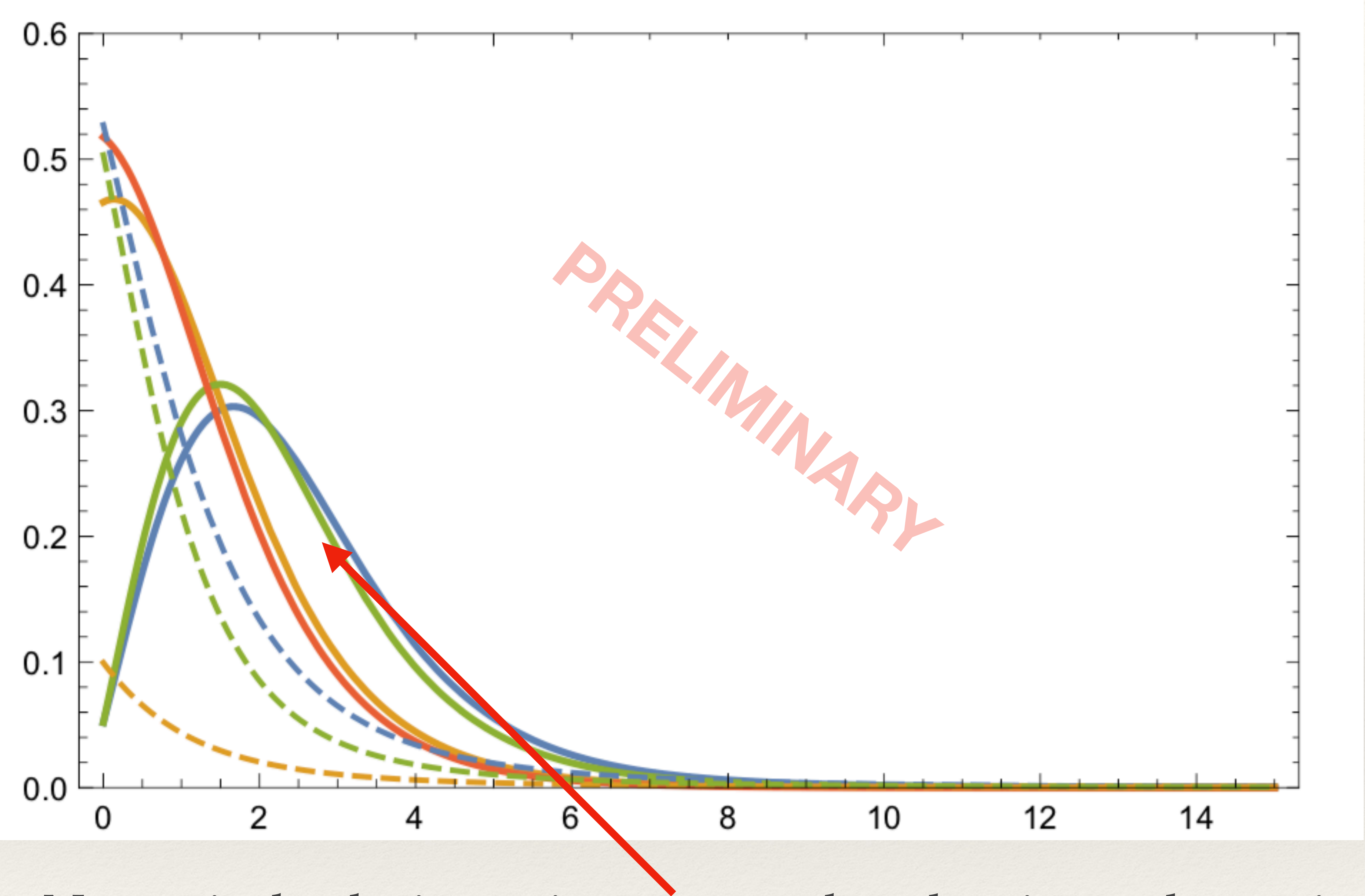


Numerical solutions give gas number density and cosmic ray pressure profiles



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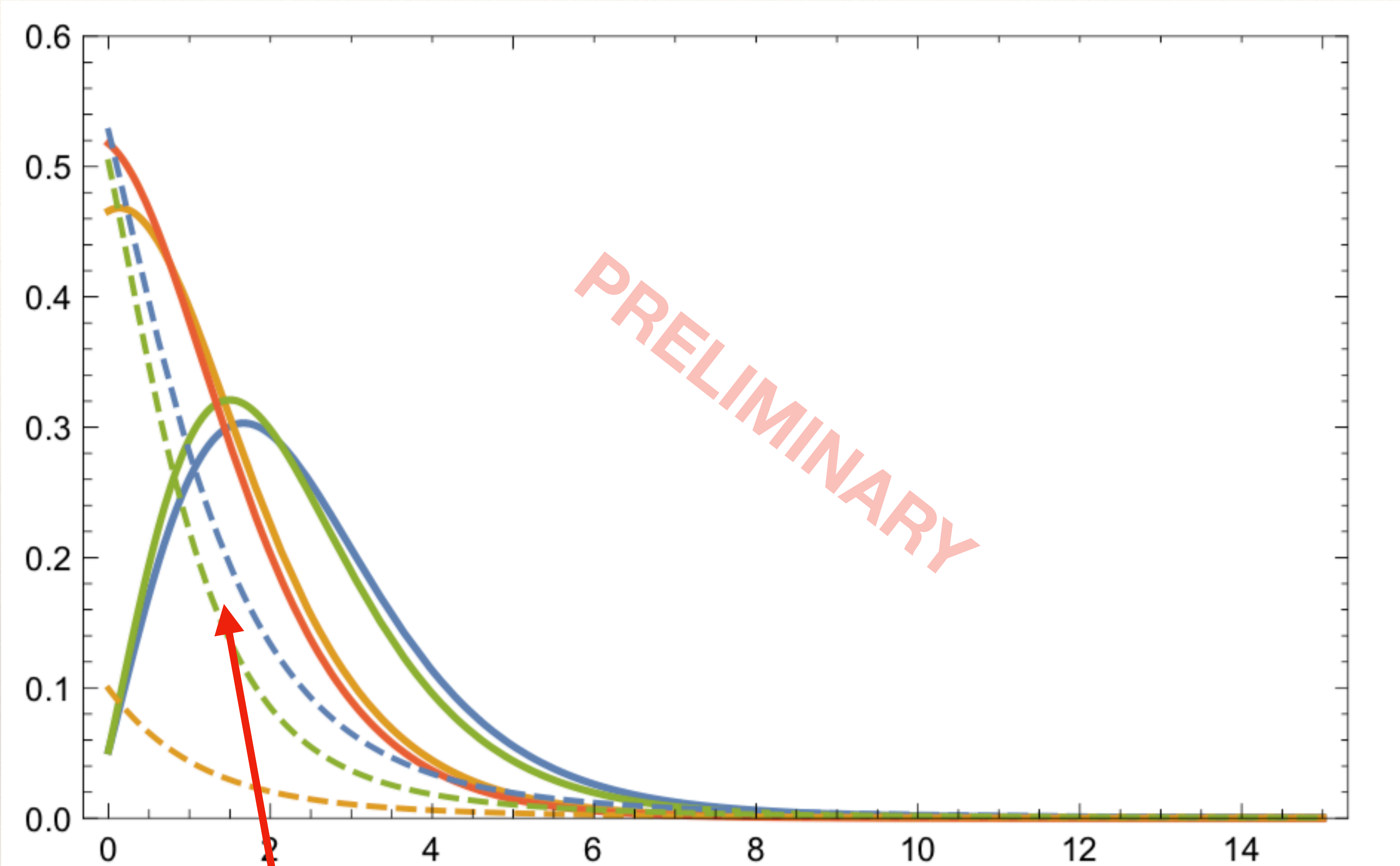

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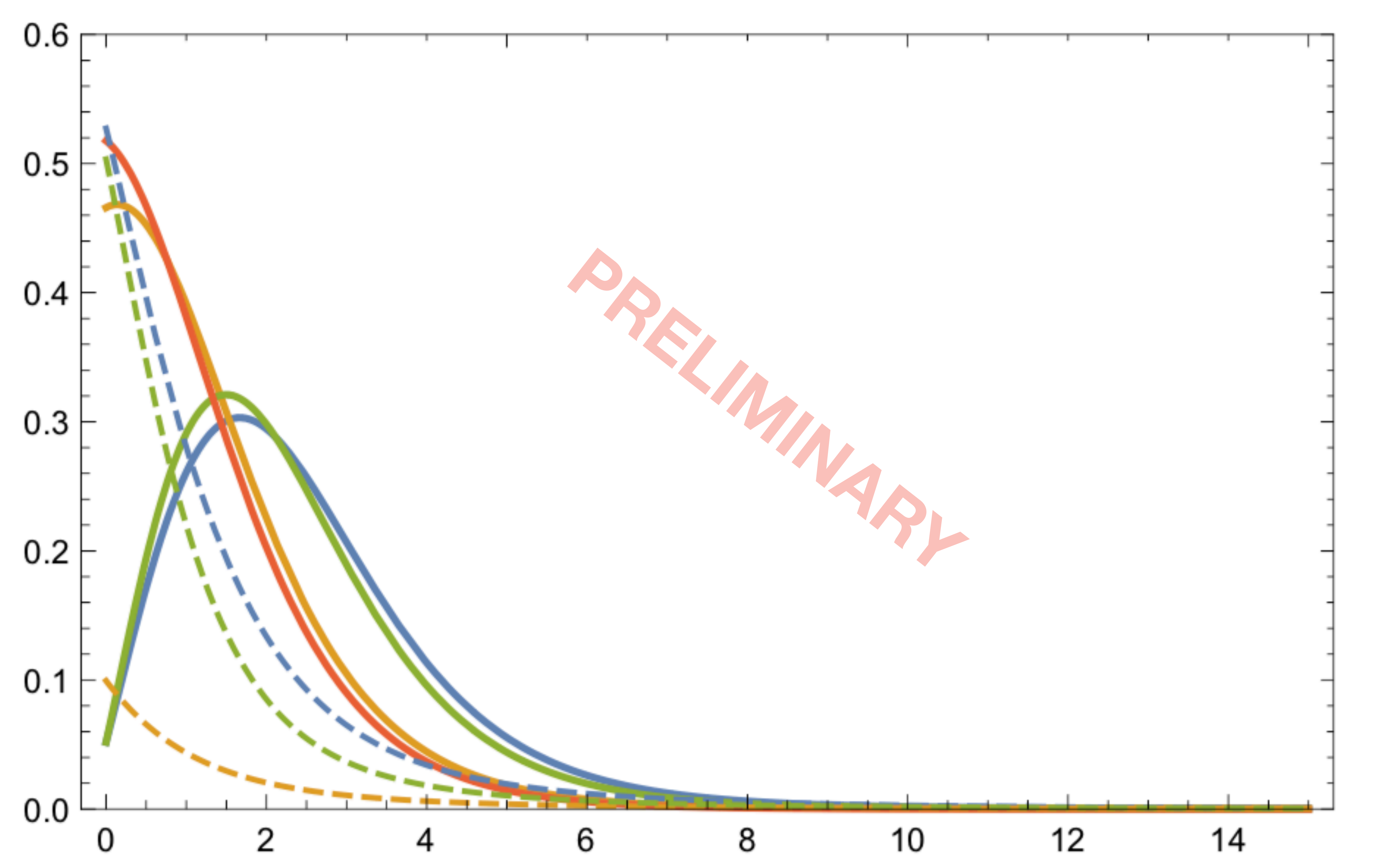

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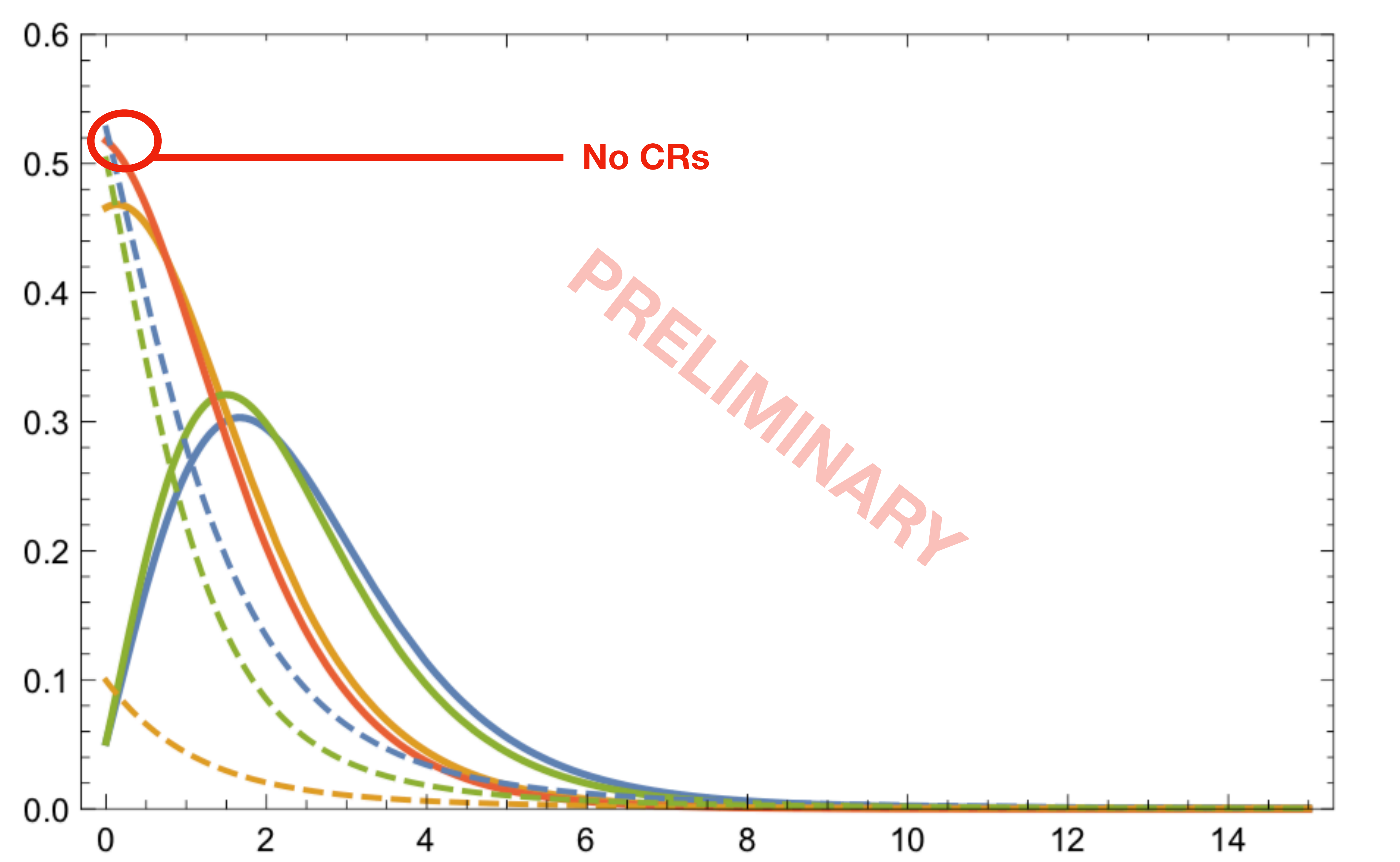

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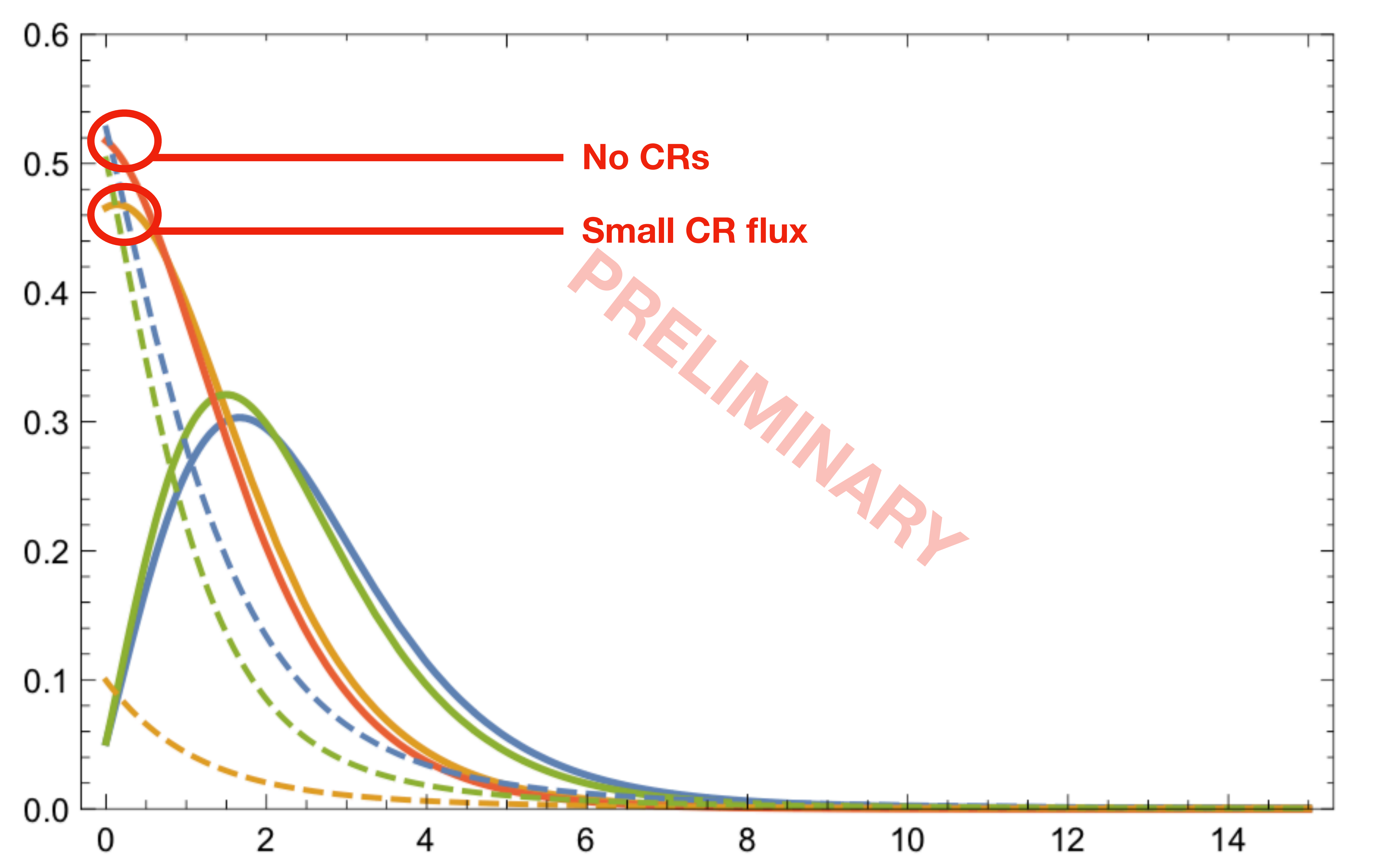

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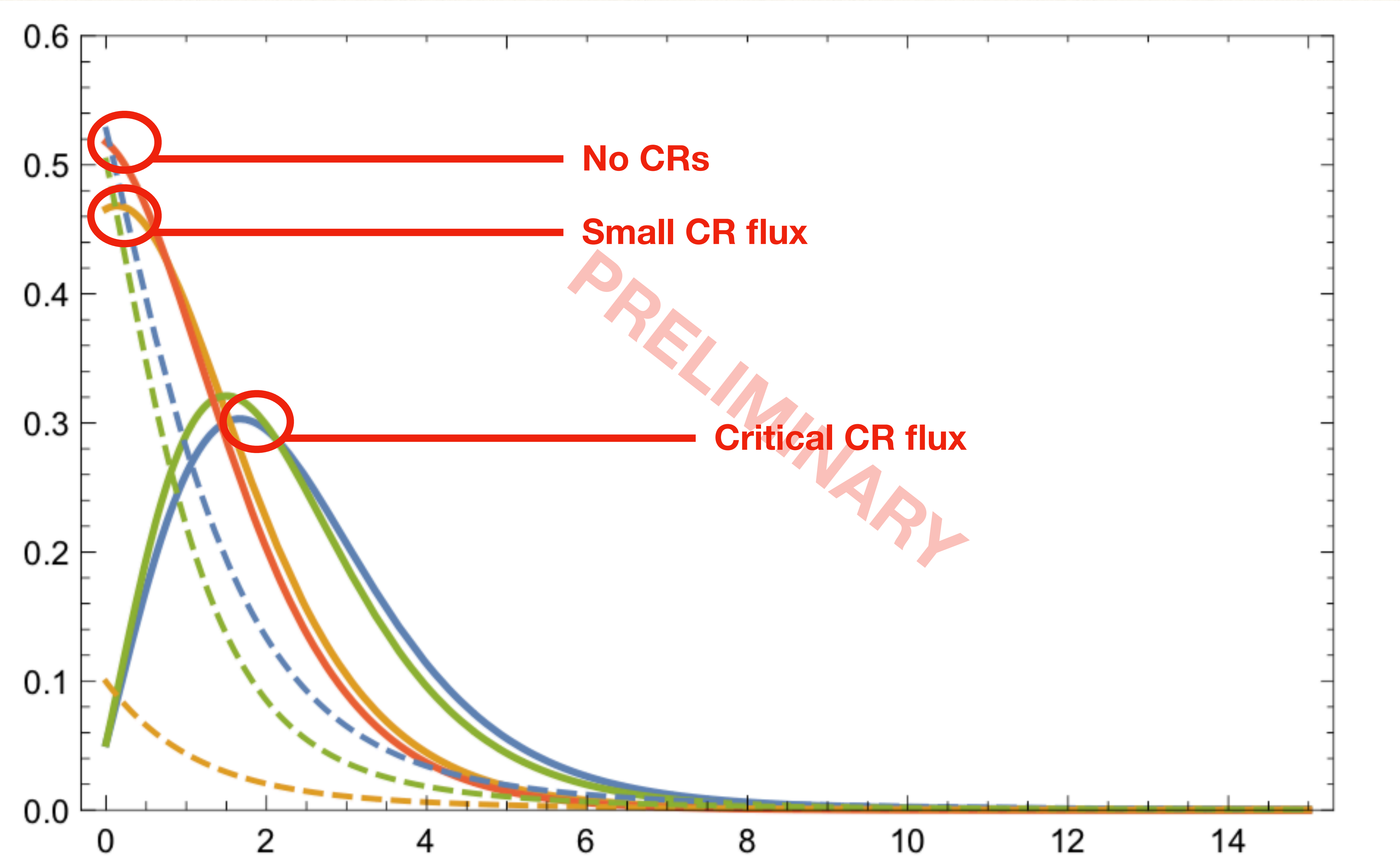

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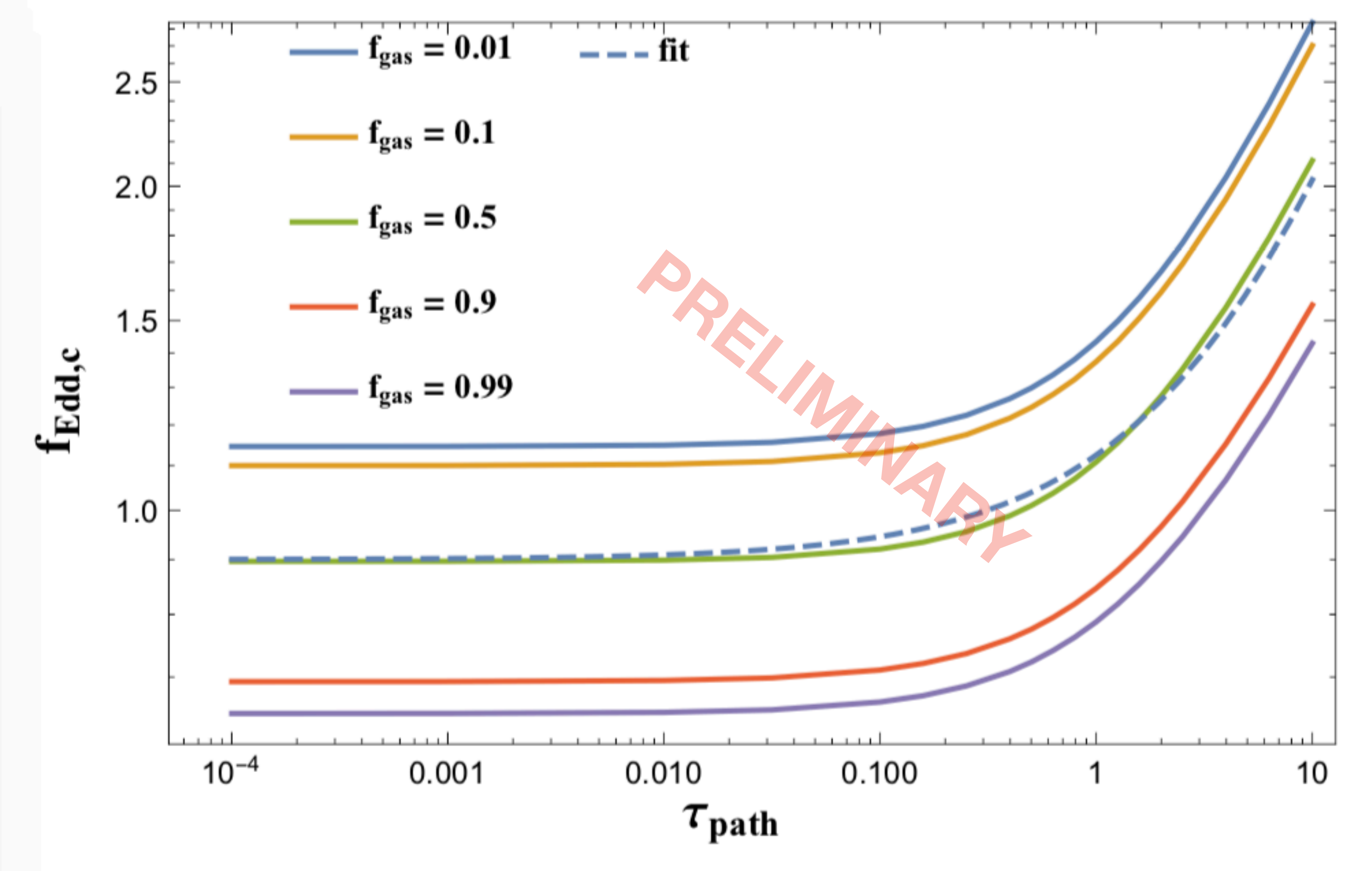
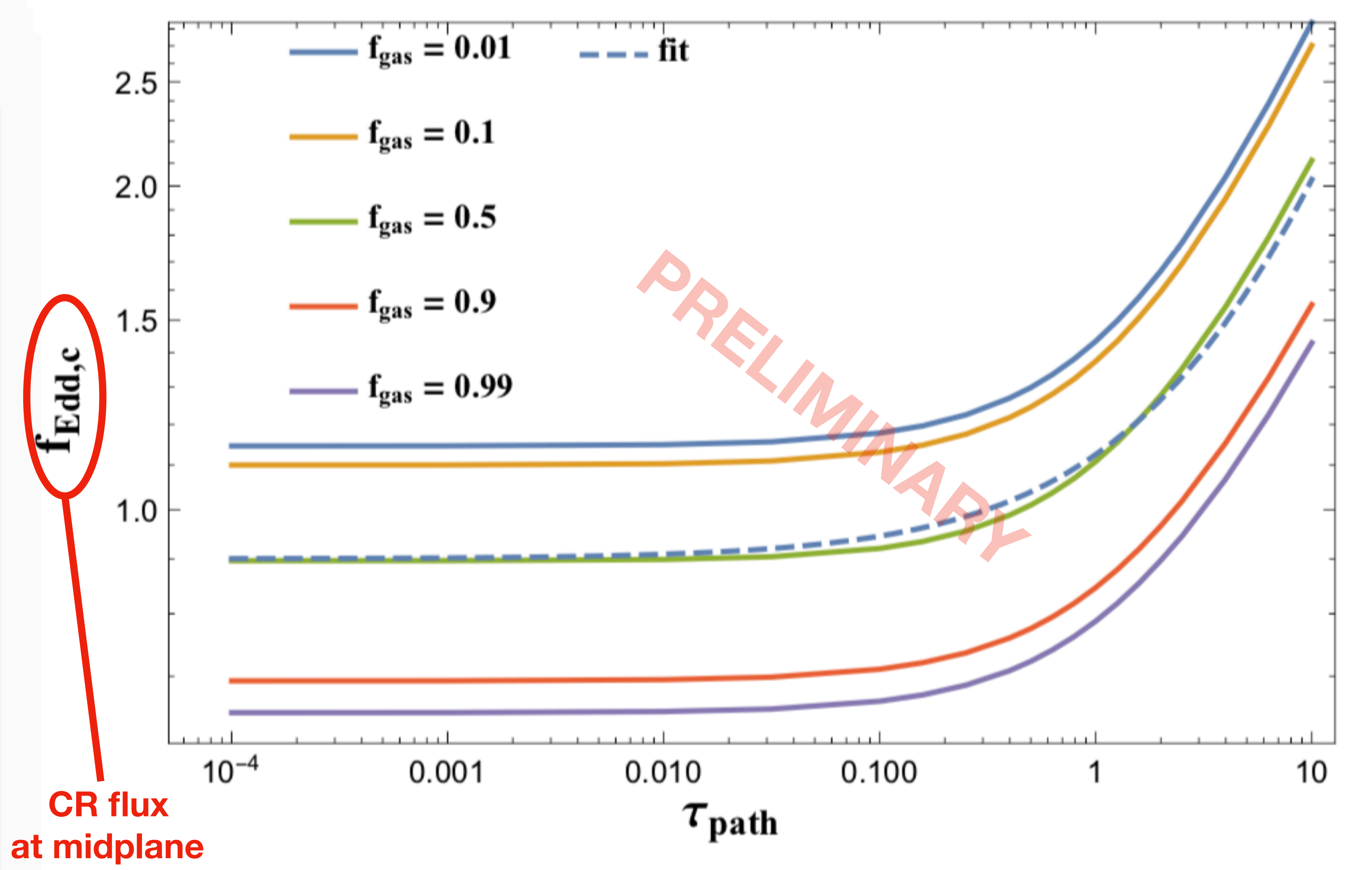


Cosmic ray critical cosmic ray flux as a function of τ_{path} at fixed $\tau_s = 1$ and $\beta = 1/4$



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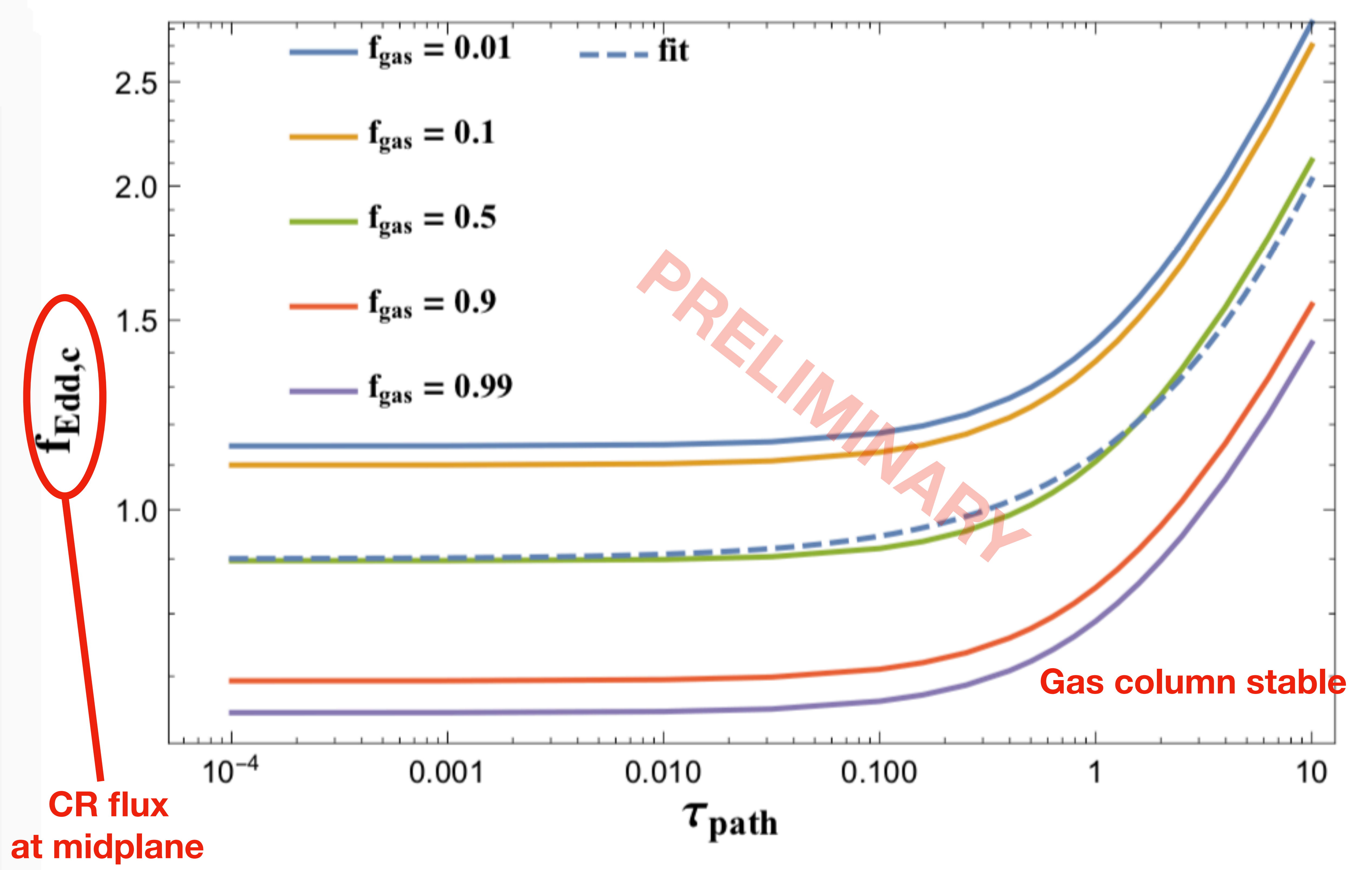

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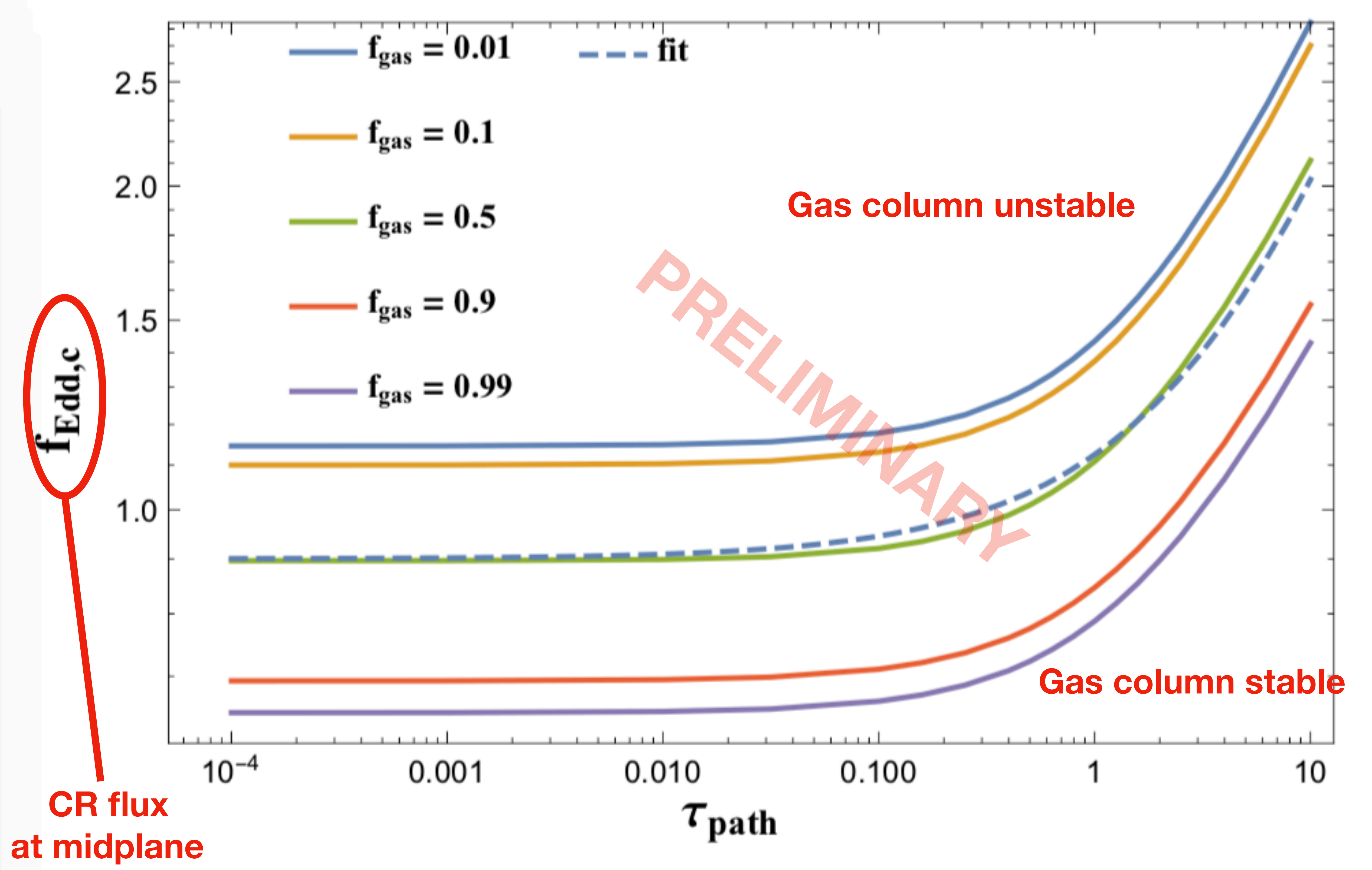
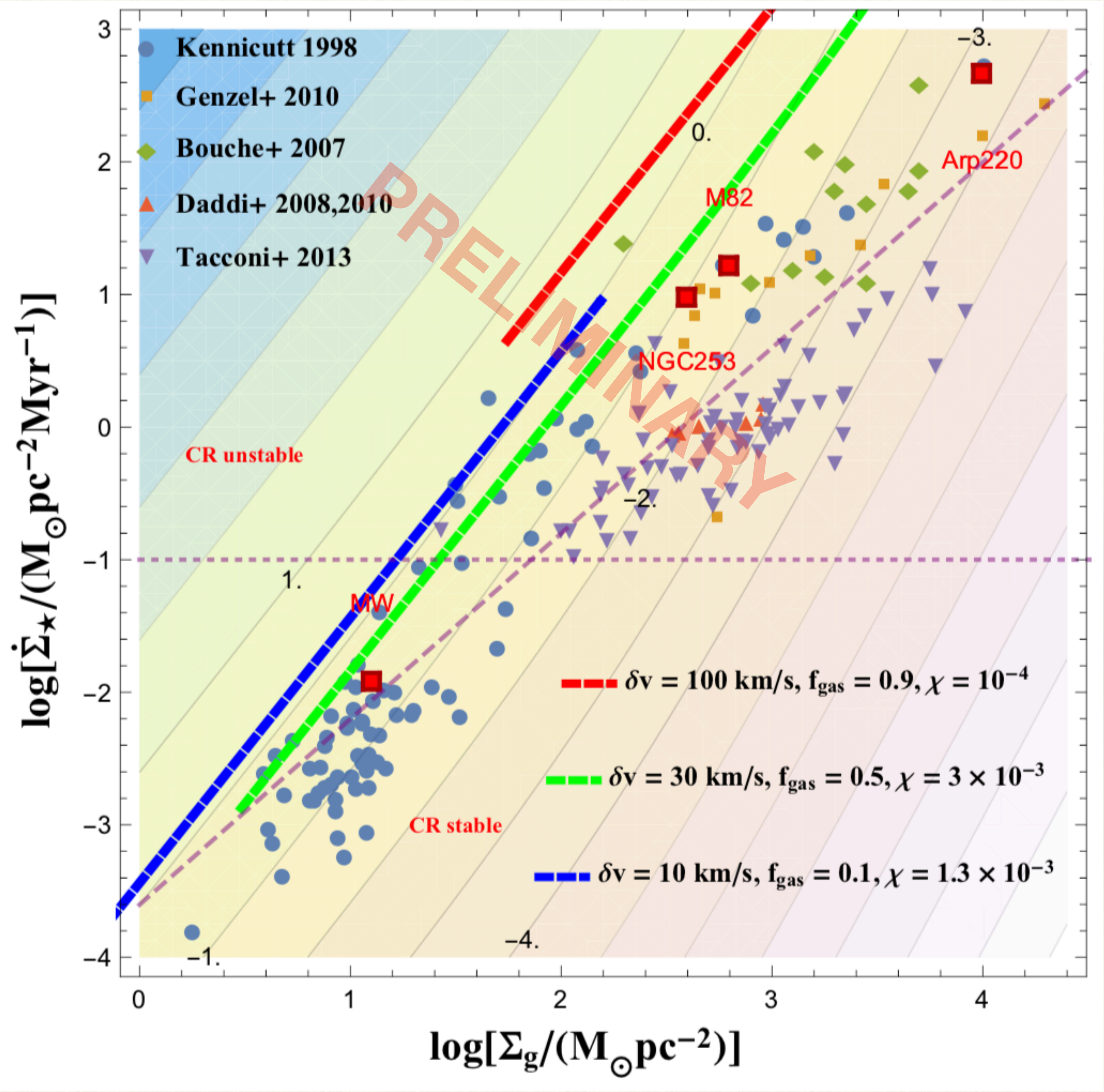


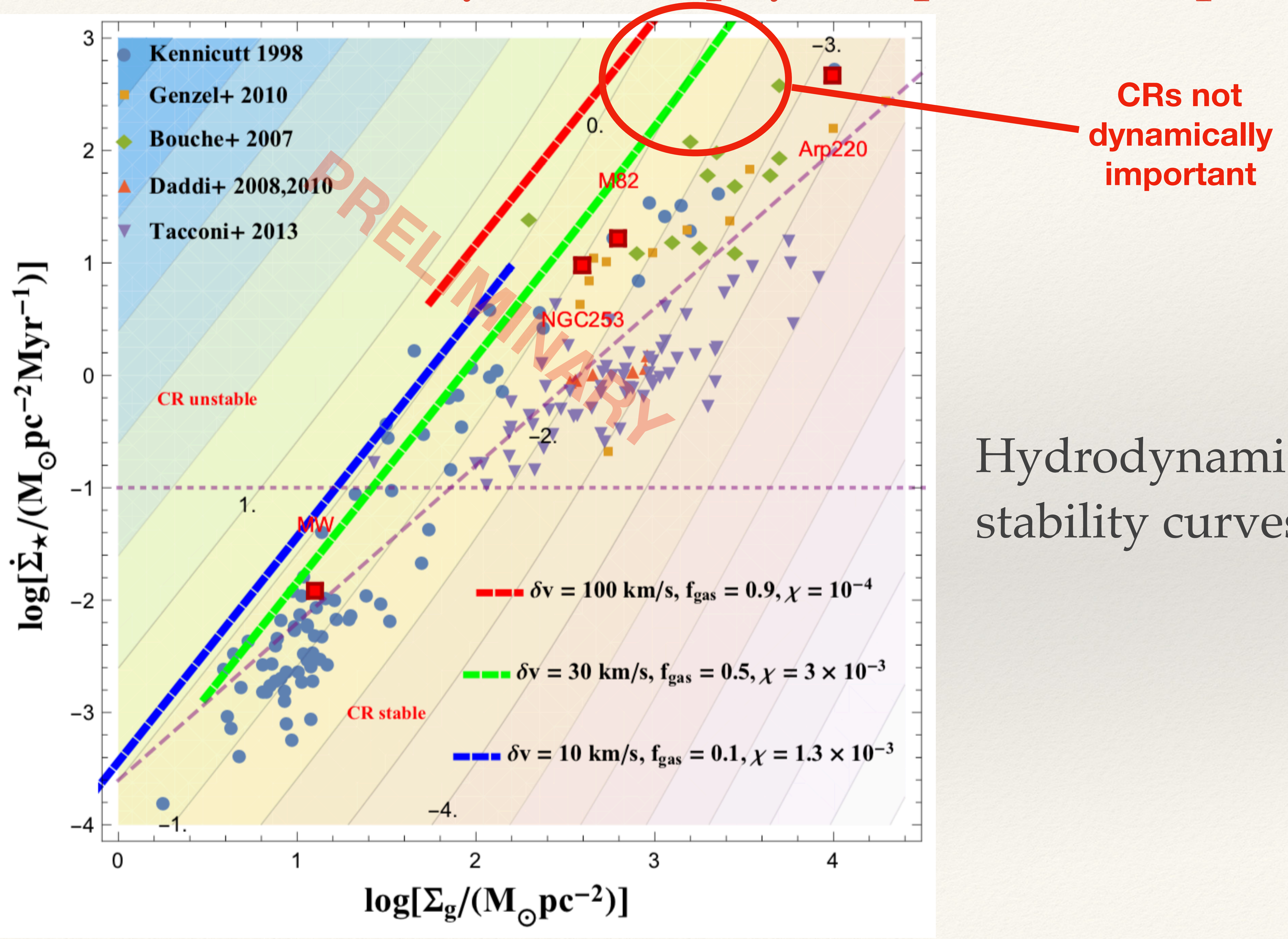
Cosmic ray critical cosmic ray flux as a function of τ_{path} at fixed $\tau_s = 1$ and $\beta = 1/4$

Translate stability curve to physical parameter space:



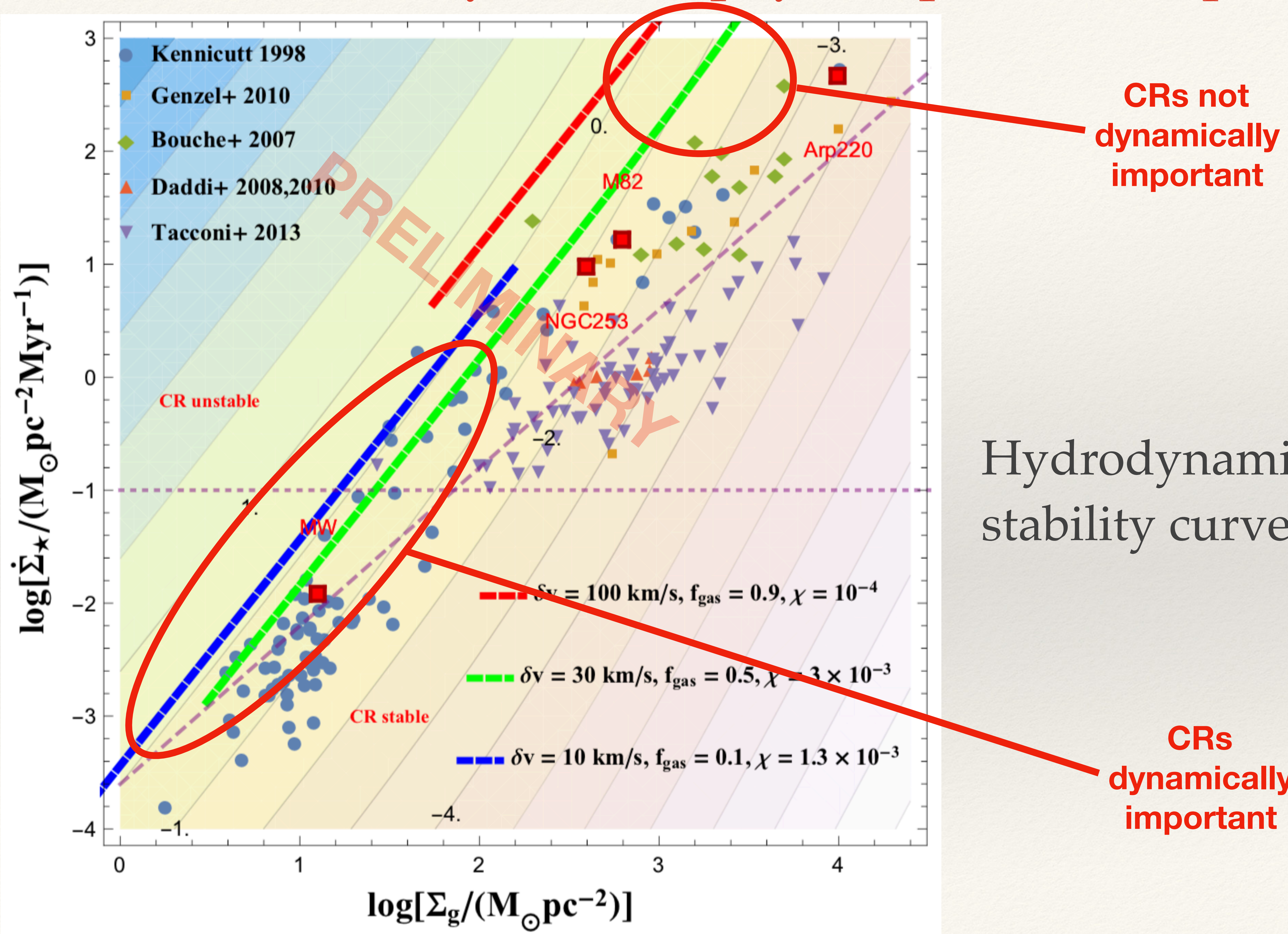
Hydrodynamic stability curves

Translate stability curve to physical parameter space:



Hydrodynamic stability curves

Translate stability curve to physical parameter space:



Hydrodynamic stability curves

Summary

Part I:

- In the dense, star-forming ISM phase, cosmic ray transport is described by field line random walk at the **ion** Alfven speed v_{Ai}
- Implies energy-independent diffusion for GeV-TeV CRs in starbursts

Part II:

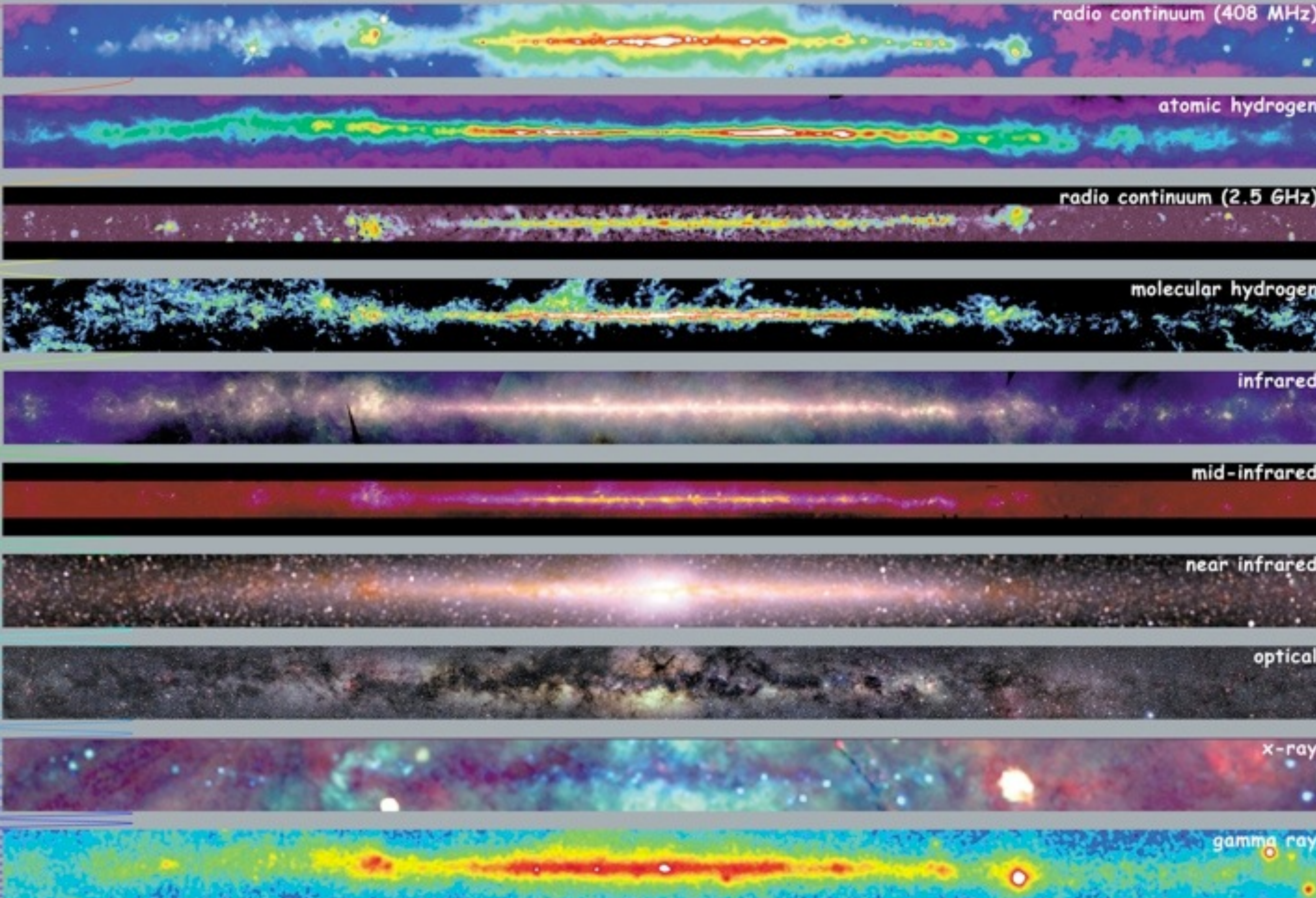
- The CR flux due to star formation can become so large that it precludes a hydrostatic equilibrium
- For 'normal' star-forming galaxies ($\Sigma_{gas} < 10^{2.5}\, M_\odot / pc^2$), CR feedback bounds the star formation rate surface density

Extra slides

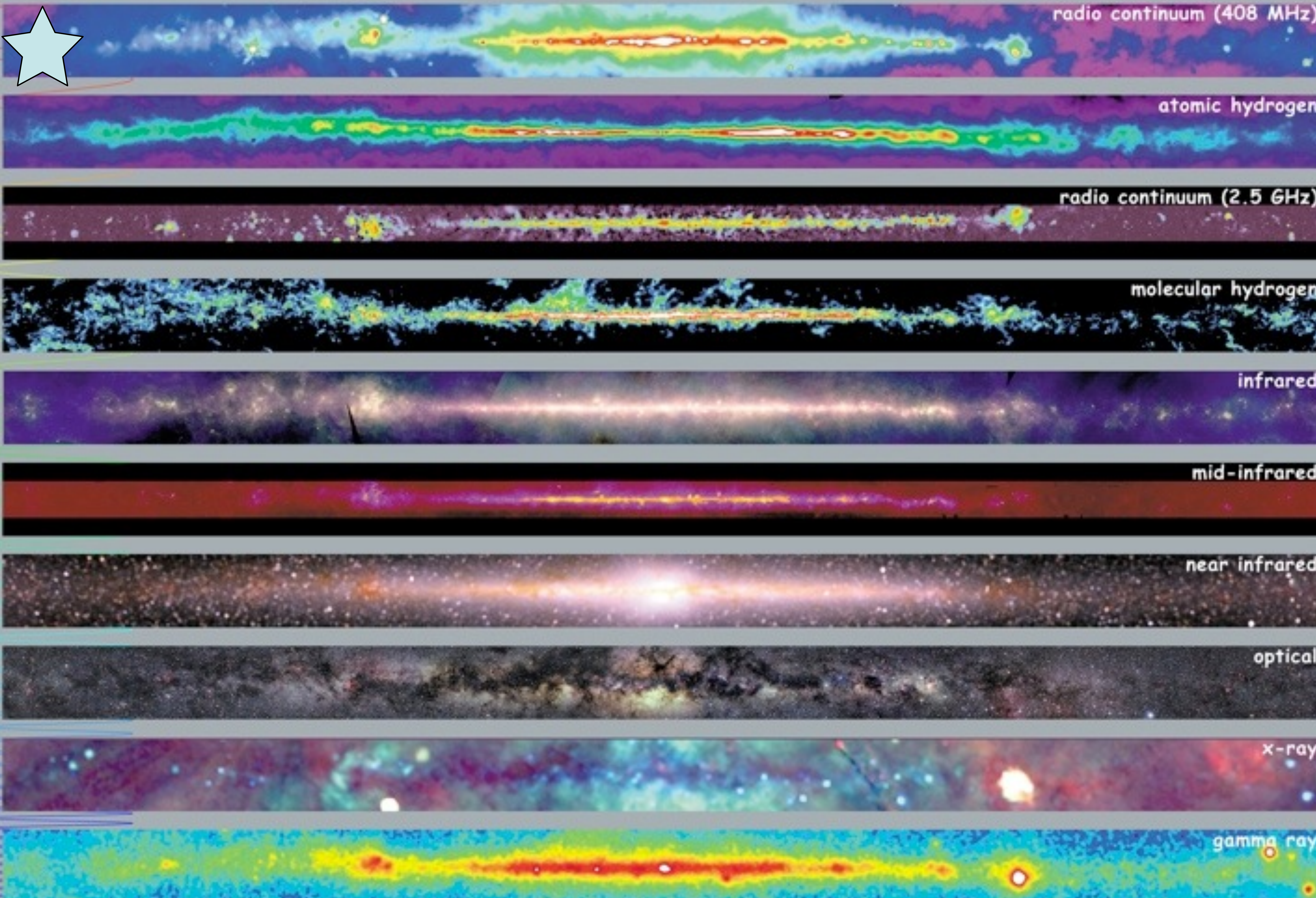
- Why are starbursts mostly calorimetric?
  - The degree of calorimetry is mostly controlled by the parameter τ_{eff} which can be written as:

$$\tau_{\mathrm{eff}} \approx \chi_{-4}^{1/2} \mathcal{M}_{\mathrm{A},2}^{4} Q_{\mathrm{gas},2}^{-1} \frac{20.2\ \mathrm{Myr}}{t_{\mathrm{orb}}},$$

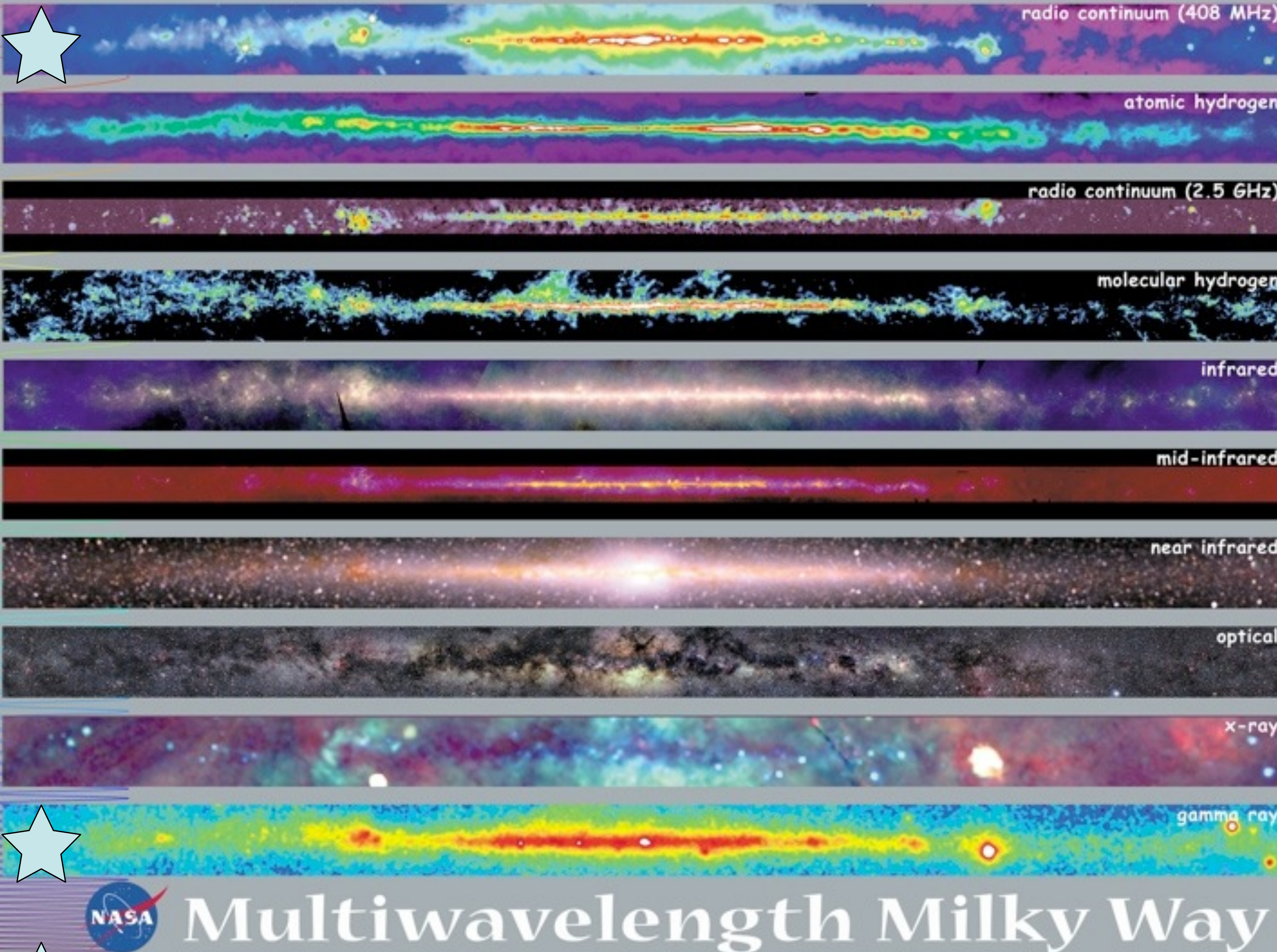
- non-starburst galaxies: orbital periods $\gg$ 20 Myr $\Rightarrow$ transparent to CRs
- starbursts: orbital periods $\ll$ 20 Myr $\Rightarrow$ calorimetric

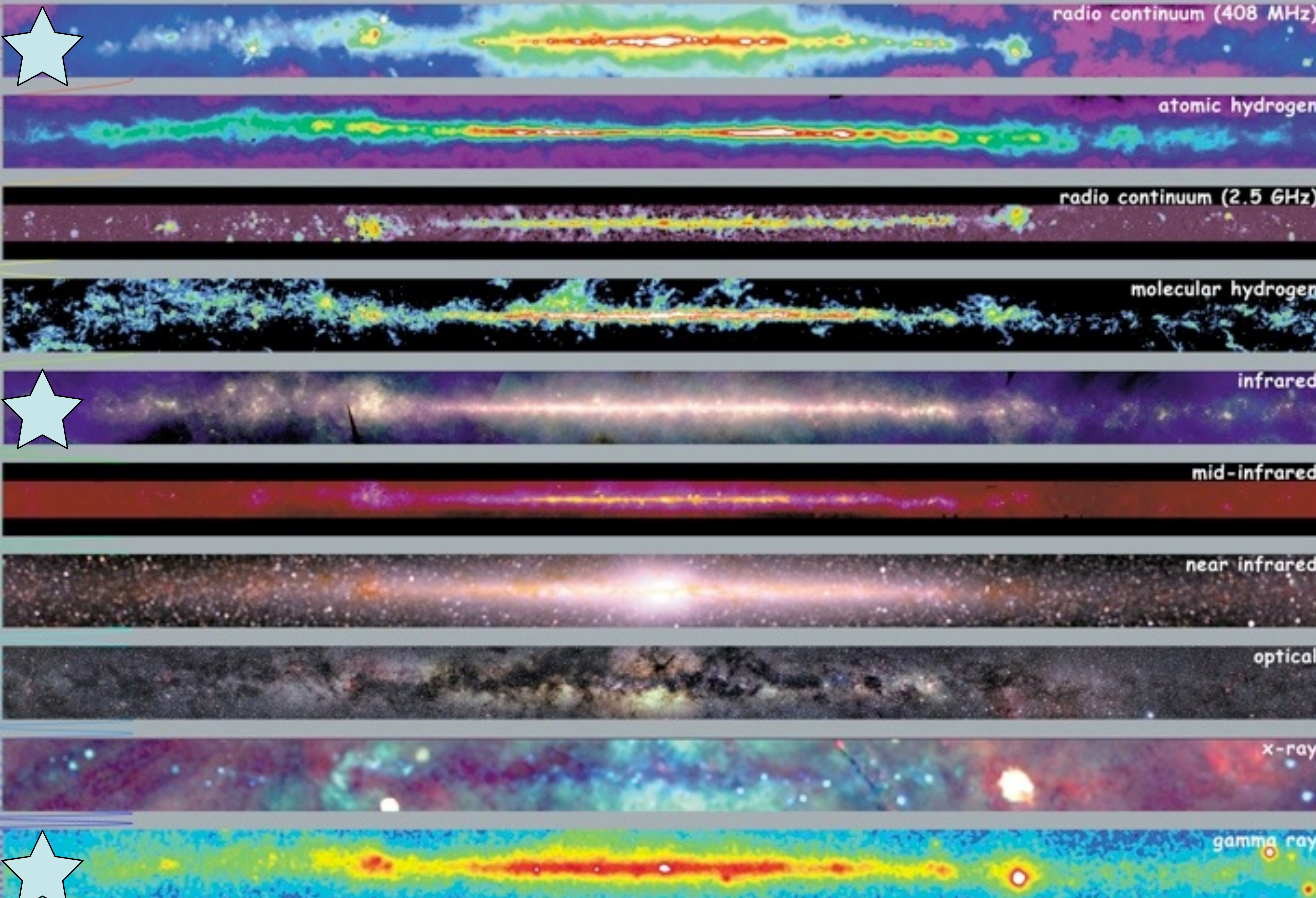


Multiwavelength Milky Way



Multiwavelength Milky Way


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
NASA
Multiwavelength Milky Way



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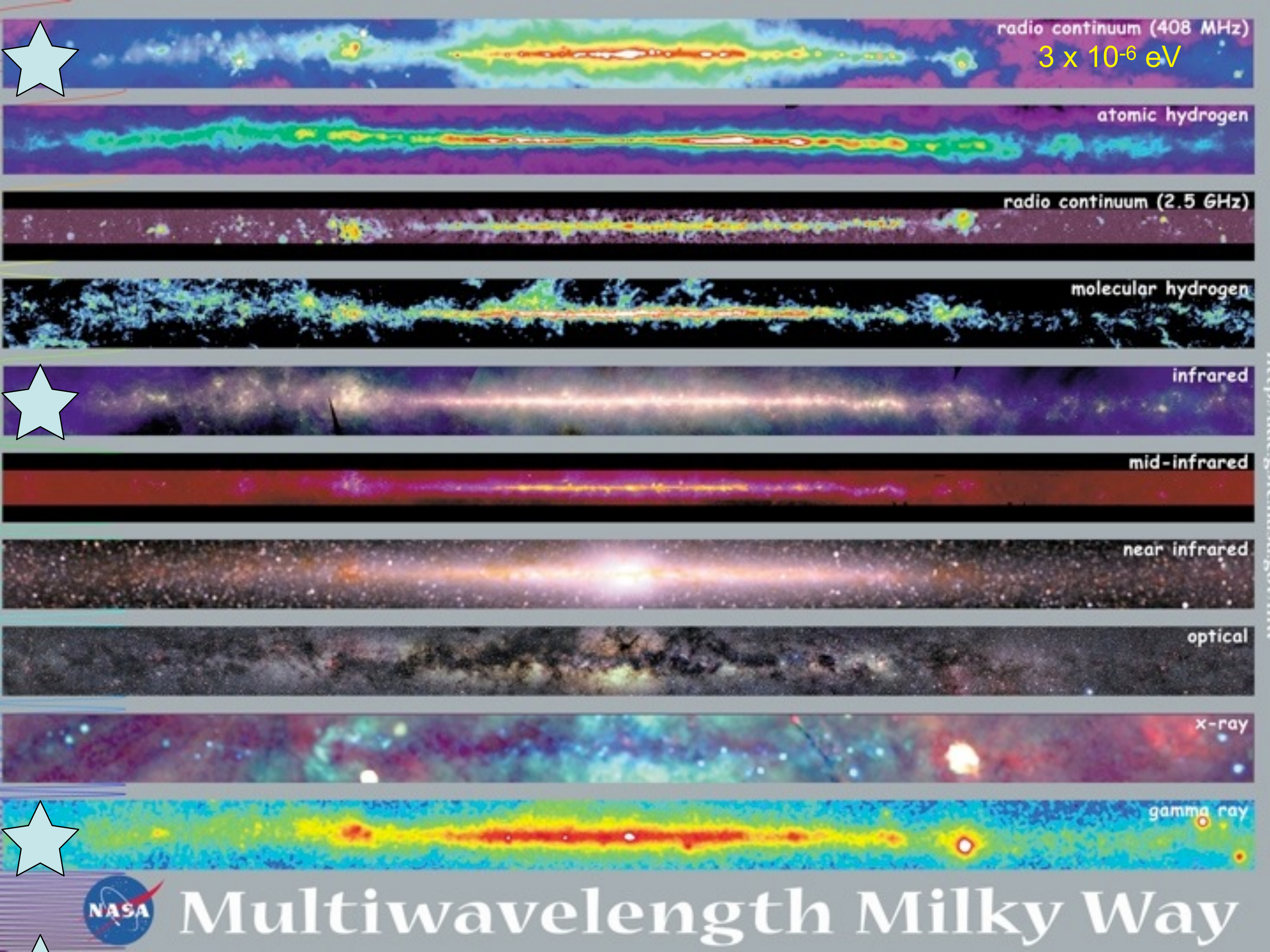
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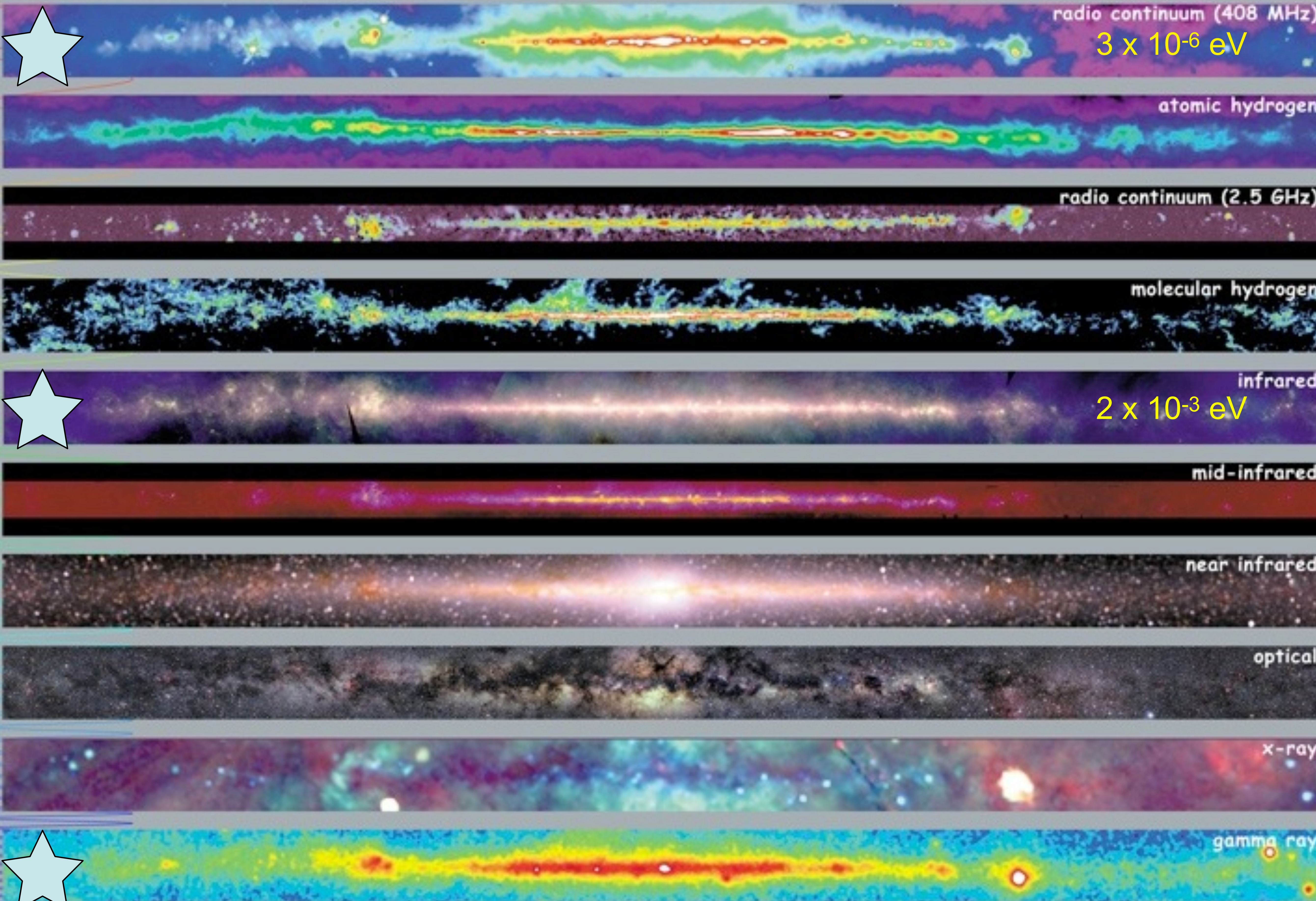
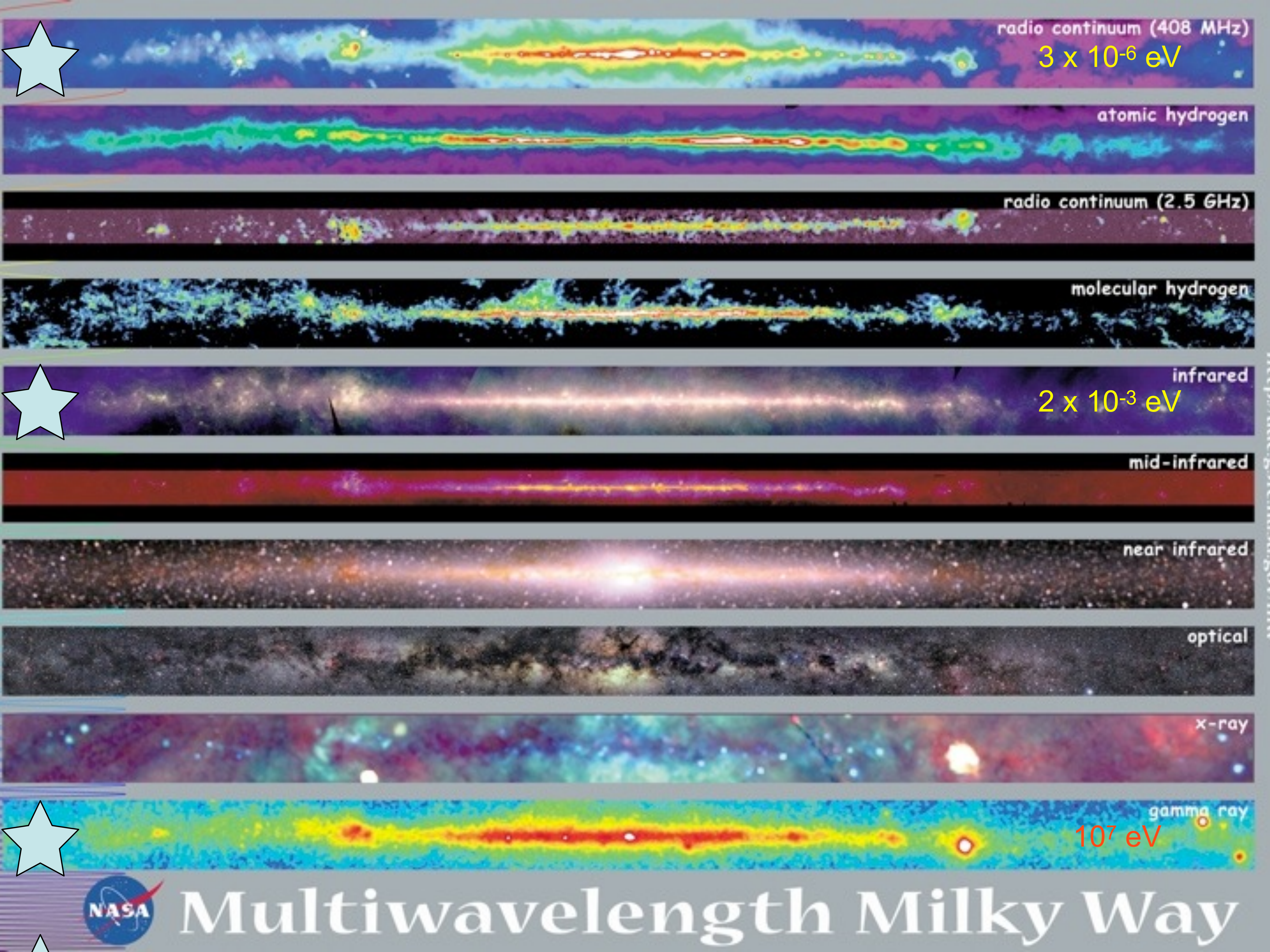


Multiwavelength Milky Way



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2 x 10-3 eV
mid-infrared
near infrared
optical
x-ray
gamma ray
107 eV
NASA
Multiwavelength Milky Way

- consider Alfv′enic modes; since they carry most of the energy of the MHD cascade and, in fact, slow modes are passively mixed by Alfv′enic turbulence and follow the same cascade
- damping scale depends on whether the Alfv′en Mach number of the turbulence at its injection scale,

  $M_A = u_{LA}/V_A$,

  …is larger or smaller than unity;

where

u_{LA}: turbulent velocity of Alfv′enic modes at the injection scale L

- In the decoupled regime, the rate at which CRs are able to stream is set implicitly by the condition that, at their streaming speed, the rate at which they drive Alfven waves via the streaming instability balances the rate at which those waves dissipate due to ion-neutral damping
- attractor: if the CRs stream at less than this speed, damping will sap the Alfv´en waves, which in turn will reduce CR scattering and allow them to stream faster; conversely, if the CRs are travelling at above the speed that satisfies this condition, the amplitude of the Alfv´en waves they produce will grow, scattering them more effectively and reducing their streaming speed.
- Thus we must balance growth against damping.

Implication

- We can define a critical CR energy $E_{CR,scat}$ below which CRs will not be effectively scattered by turbulence injected at a large scale.

$$E_{\rm CR,scat} \approx 27 \frac{u_{\rm LA,1}^{5/2}}{L_2^{1/2} \chi_{-4}^{3/2} n_{\rm H,3}} \frac{\min\left(\mathcal{M}_{\rm A}^{-1}, \mathcal{M}_{\rm A}^{-1/2}\right)}{\sin\alpha} \text{ TeV}.$$

Cosmic Rays:

- Can make sense of the analogue of an "Eddington limit" in CRs (Socrates et al. 2008)
- Momentum flux imparted by CRs, **dot{P}$_{CR}$,** can be significantly enhanced because of the large effective optical depth they experience
- dot{P}$_{CR}$ ~ τ_{CR} L_{CR} ; τ_{CR} : cosmic ray optical depth
- $\tau_{CR} \sim R/\lambda_{CR} \sim 1000$ pc/1 pc ~ 10^3 ;

[λ_{CR} : N.B. CR mean free path $\lambda_{CR} \gg r_{gyro}$]

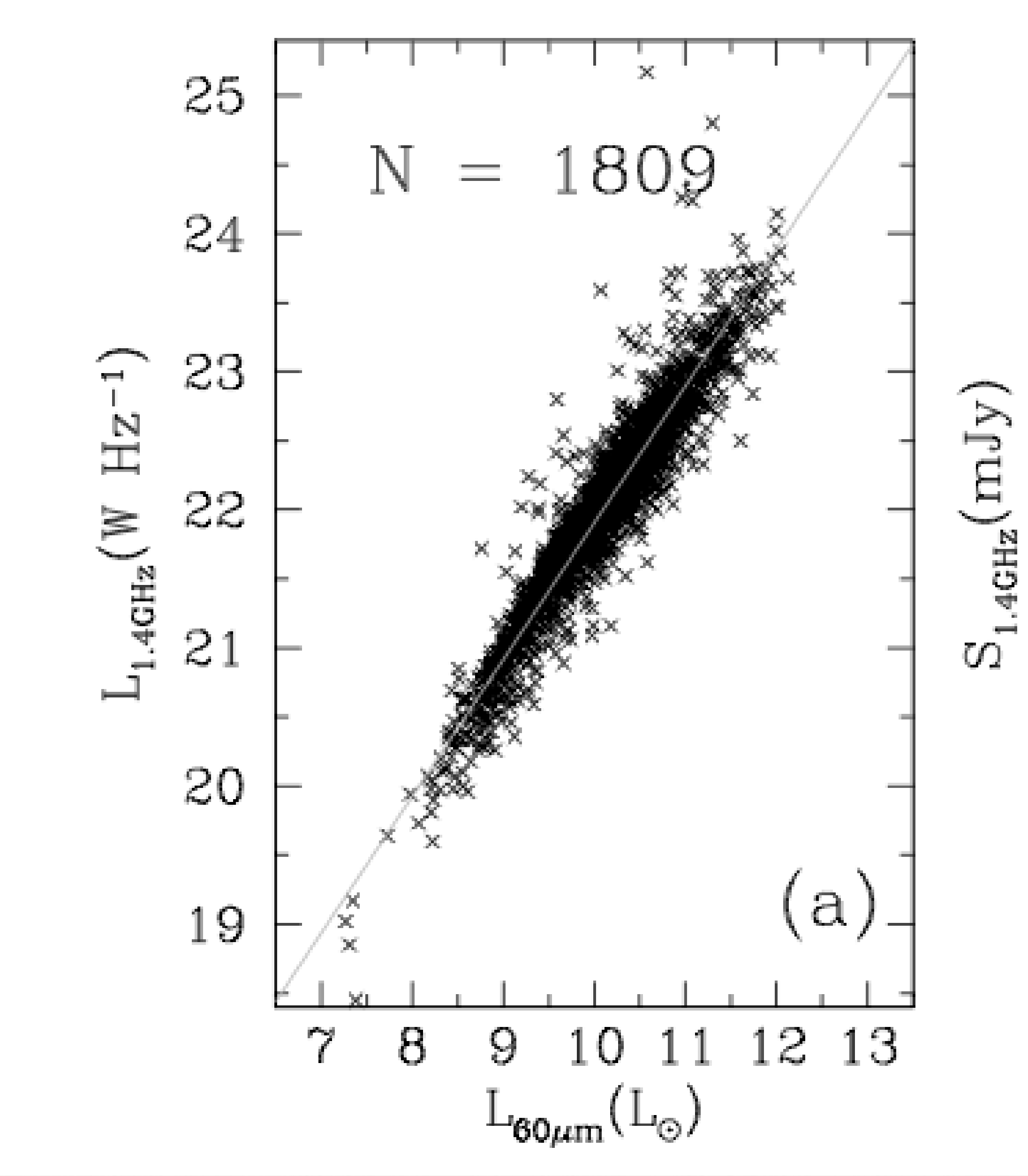
⇒ dot{P}$_{CR}$ ~ 10^3 x 10^{-3} L_{light} ~ L_{light}

Cosmic Rays:

- CRs effectively behave as a relativistic fluid with adiabatic index $\gamma = 4/3$
- adiabatic losses are smaller than for non-rel fluid in an expanding outflow

  $\Rightarrow$ CRs become progressively more important the more a wind expands

‘Far Infrared-Radio Continuum Correlation’



Yun et al. 2001 ApJ 554, 803 fig 5

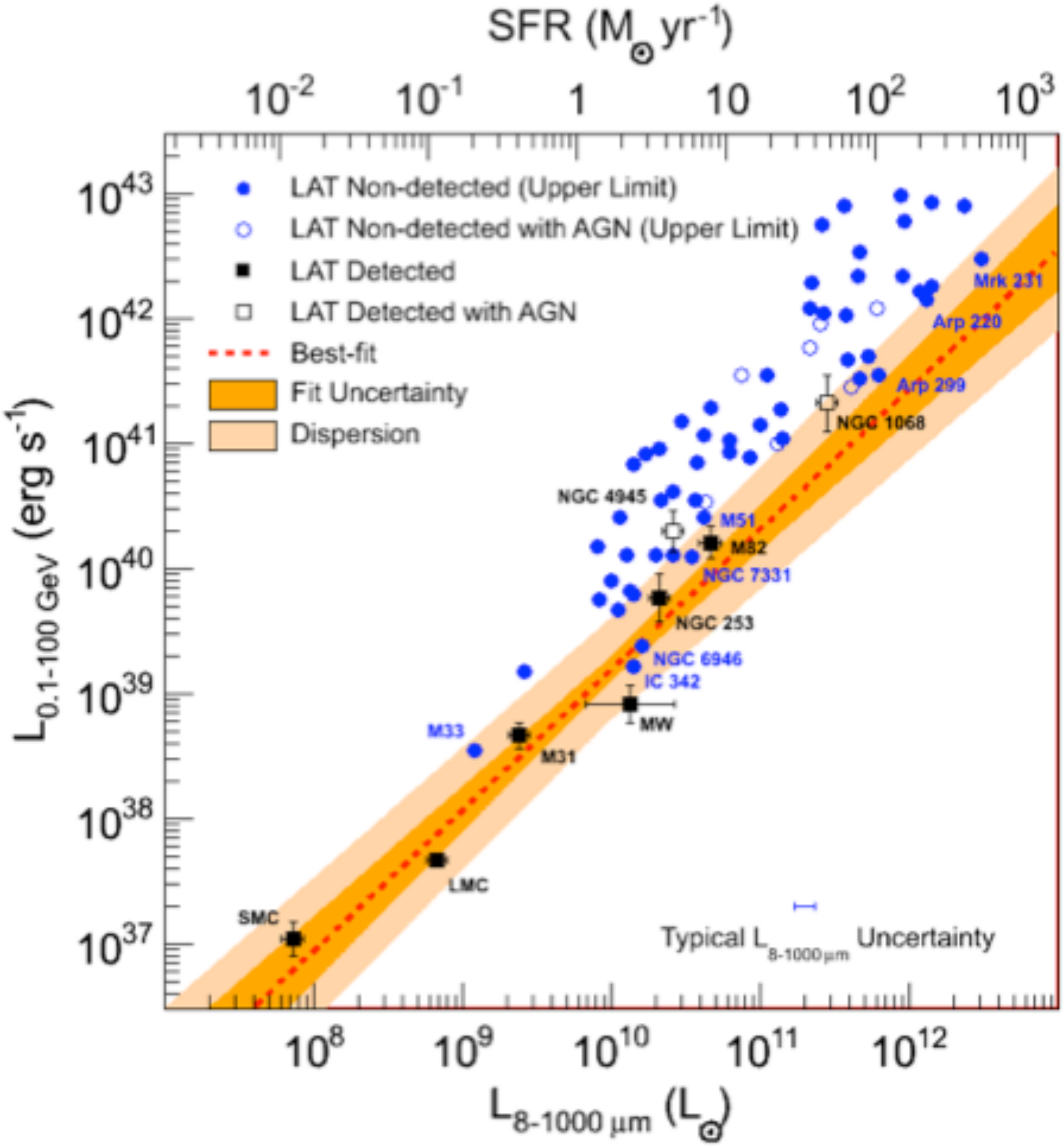
Sidebar: origin of FIR-RC?

- correlation between FRC and RC ultimately tied back to massive star formation (Voelk 1989)
- massive stars → UV → (dust) → IR
- massive stars → supernovae → SNRs → acceleration of CR e′s → (B field) → synchrotron

FIR-γ-ray Correlation?

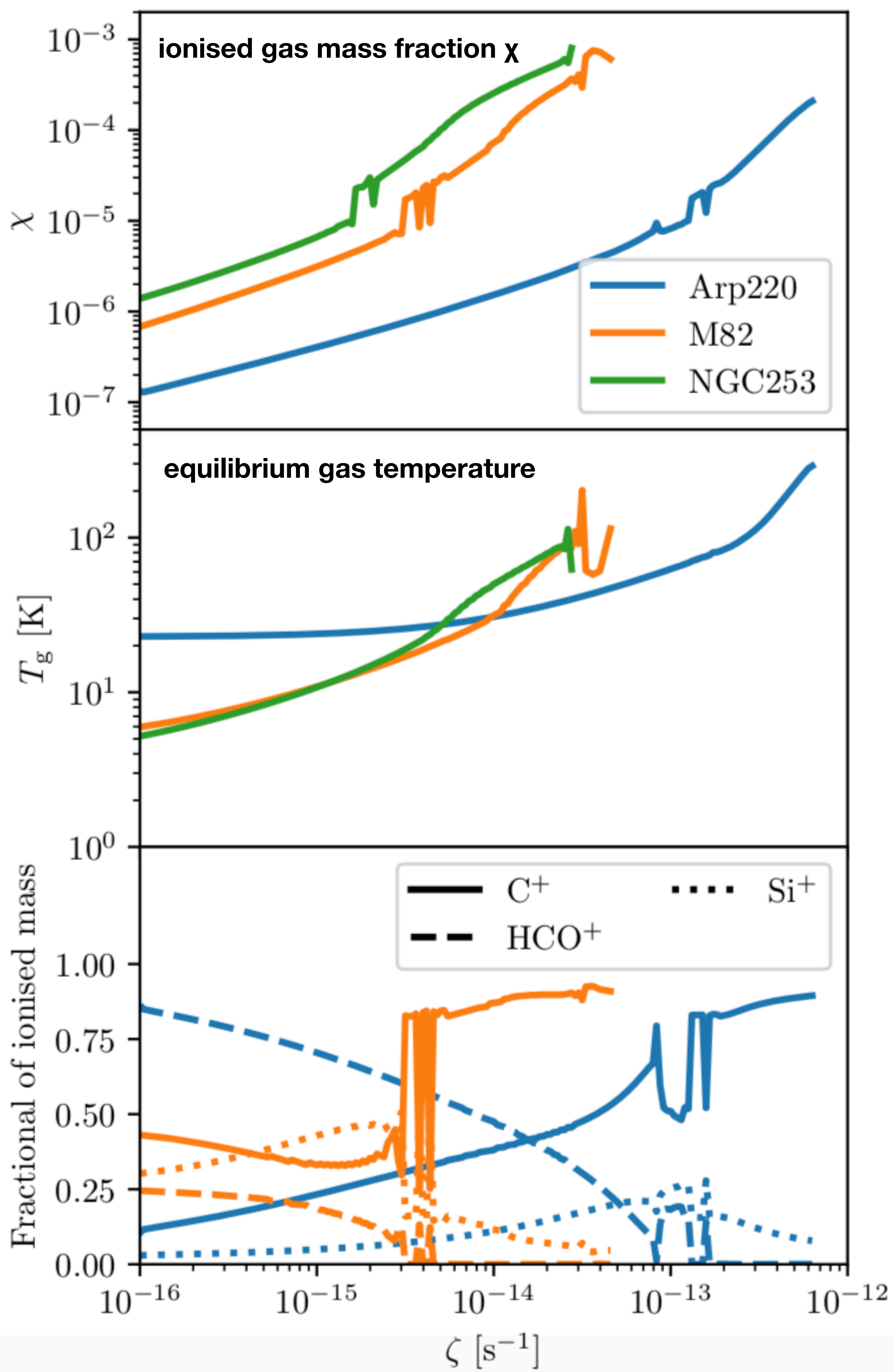
- SNR accelerate CR p's (and heavier ions)
- there should exist a global scaling b/w FIR and gamma-ray emission from region (Thompson et al. 2007):

$$L_{GeV} \sim 10^{-5}\ L_{TIR}\ \text{(assuming } 10^{50} \text{ erg per SN in CRs)}$$



Martin, *Fermi collab*

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



Chemical and thermal equilibria for the ISM in Arp 220, M82, and NGC 253 as a function of primary cosmic ray ionisation rate ζ (using DESPOTIC).

Cosmic Rays:
What are they good for?

- Because CRs are charged, they respond to ISM magnetic fields

  ⇒ we cannot do CR astronomy (except maybe at highest energies)

- Scatter most strongly on magnetic field inhomogeneities of same scale as their *gyro radius*

  ⇒ CRs execute a random walk through turbulent ISM magnetic field structure

Cosmic Rays:

- Energetic match to power available from SNe
- $L_{CR} \sim 10^{-3}\ L_{light}$
- Q: why energy density in different ISM components ~the same?:

  $u_{CR} \sim u_{ISRF} \sim u_{turb} \sim u_{therm} \sim 1$ eV cm^{-3}

- A: because long CR escape/energy loss times, >10^7 years
- $u_{CR} \sim L_{CR}\ t/V_{CR}$
- $t_{CR} \sim Min[t_{esc},t_{loss}]$
- $t_{esc} \sim 0.1\ t_{loss}$ in MW
- $L_{CR} \sim SFR/(100\ M_{Sun}/CCSN) \times 0.1$

  $\sim 3 \times 10^{40}$ erg/s

Cosmic Rays:

- $V_{CR} \sim 2\,Pi\,2\,kpc\,(8\,kpc)^2 \sim 2\,10^{67}\,cm^3$
- $u_{CR} \sim L_{CR}\,t / V_{CR}$

  $\sim 3\,10^{40}\,erg/s\;\;3\,10^7\,year/(2\,10^{67}\,cm^3)$

  $\sim 1.5\,eV\,cm^{-3}$