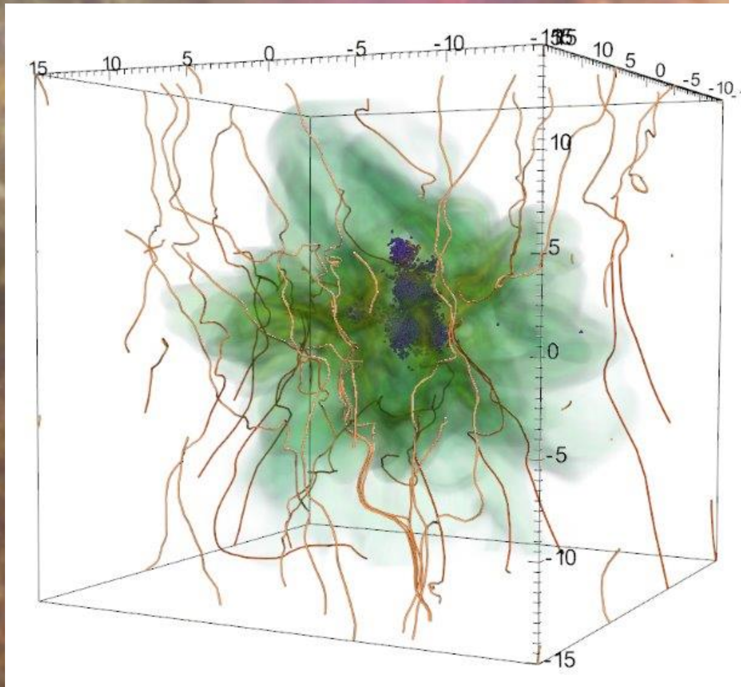
INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

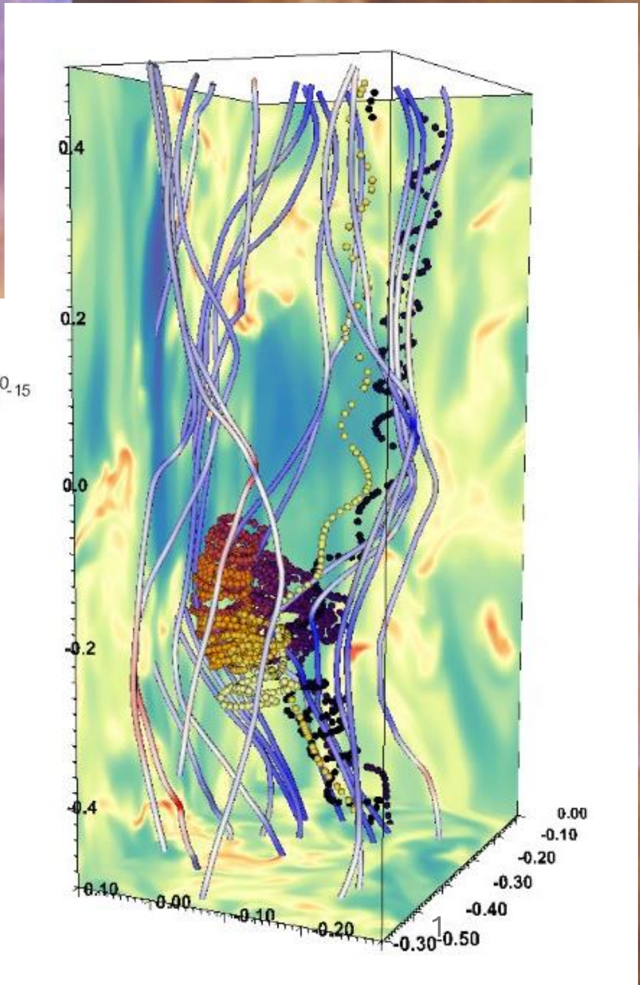
USP Universidade de São Paulo

CNPq

FAPESP FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

Probing CR Diffusion Regimes and γ-ray emission in Young Massive Stellar Clusters with 3D MHD Simulations





Lucas Barreto-Mota
Universidade de São Paulo

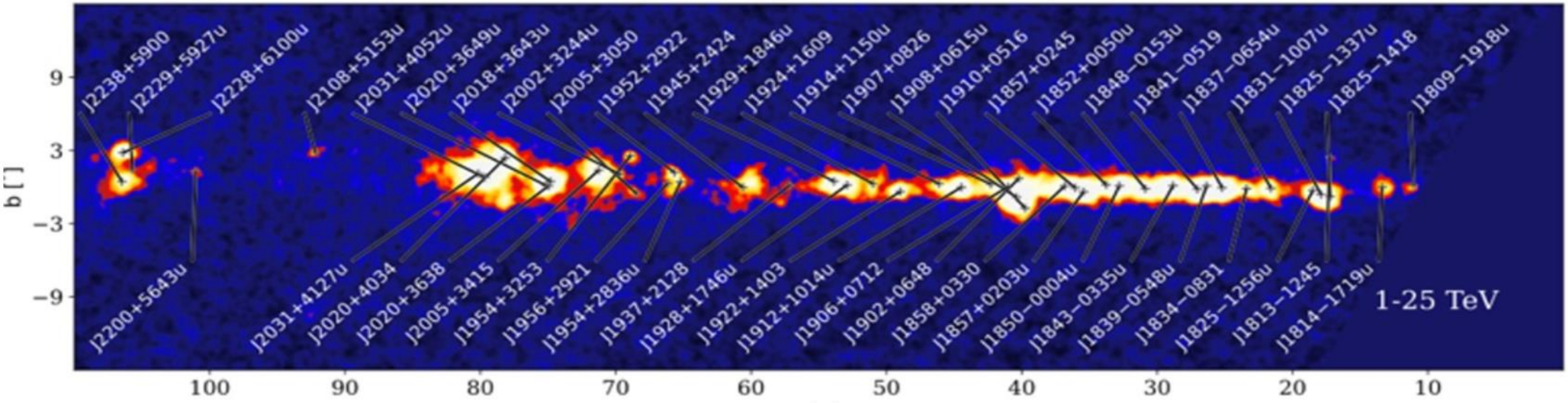
Elisabete de Gouveia Dal Pino, Gaetano di Marco,
Rafael Alves Batista, Stela Adduci Faria

Turbulence
and
very high energy (VHE)
Cosmic Rays

- Barreto-Mota; de Gouveia Dal Pino; Burkhart; Melioli; Santos-Lima; Kadowaki (2021)
- Barreto-Mota; de Gouveia Dal Pino; Xu; Lazarian (ApJ, 2025)
- Barreto-Mota; de Gouveia Dal Pino; Di Marco; Alves-Batista; Adduci Faria (in prep)

High energy emission in our Galaxy

- LHAASO observations:
  - SNRs, galactic center, pulsar wind nebulae, young stellar clusters, microquasars?



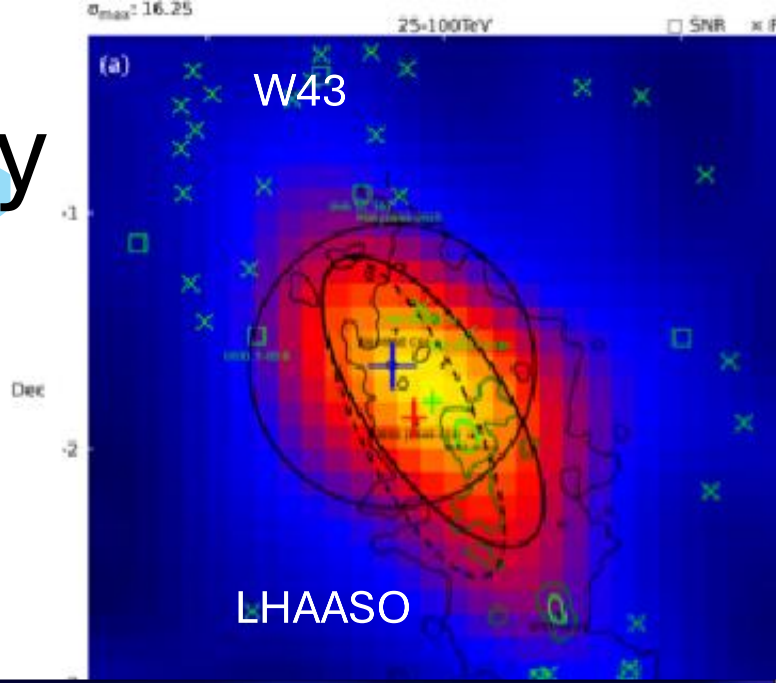
High energy emission in our Galaxy

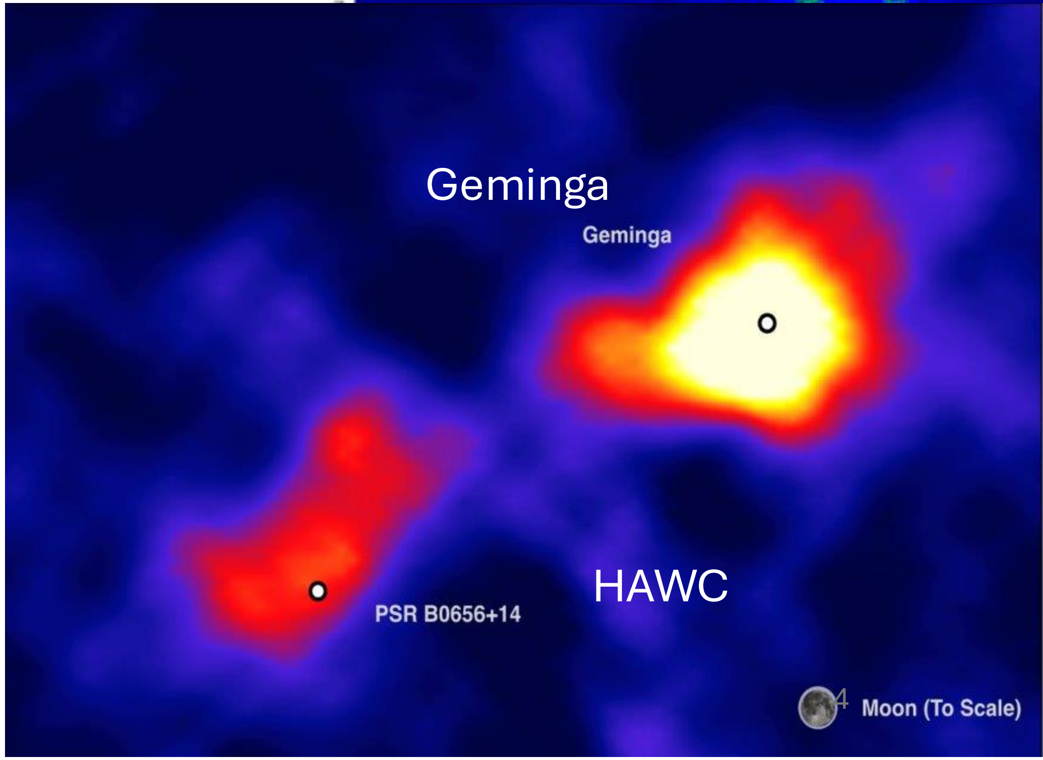
- **VHE observations of extended sources**
  - Up to ~100 TeV photons
    (Abeysekara et al. 2017; Huang et al.2018; Abeysekara et al. 2021; Cao et al. 2021; LHAASO Coll. 2025)
  - PeVatrons?

- **Observations suggest suppressed diffusion, by as much as two orders of magnitude compared to the ISM at 100 TeV**

  ~10^{28} cm^2/s or less

- Usual approach of **quasi-linear theory (QLT) cannot explain** (Shalchi, 2009)



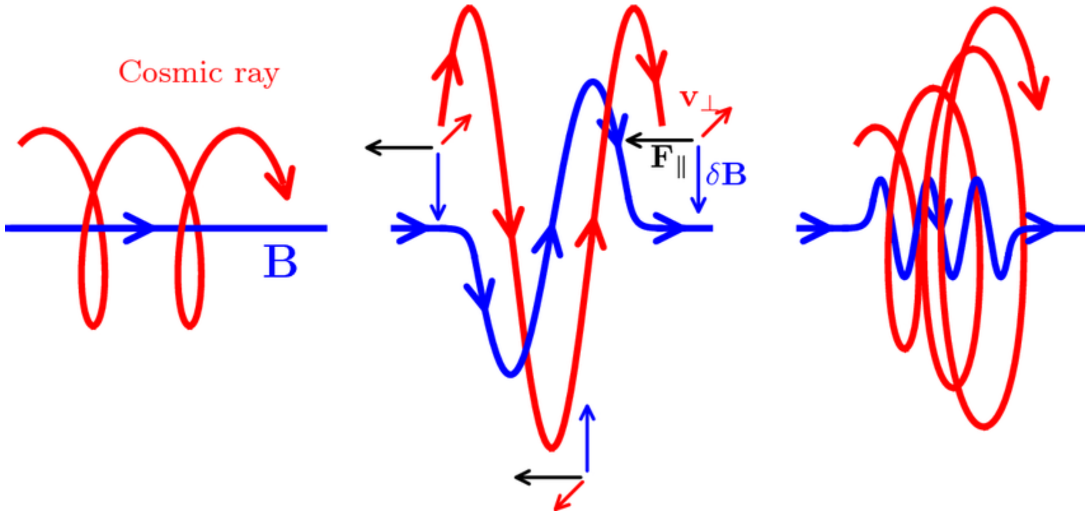


CR scattering and Quasilinear Theory (QLT)

Ruszkowski & Pfrommer (2023)

- **Resonant pitch angle scattering**

$$k_{\rm res} 2\pi R_{\rm L} \simeq \frac{(1 - \cos^2\theta_{\rm res})^{0.5}}{\cos\theta_{\rm res}}$$

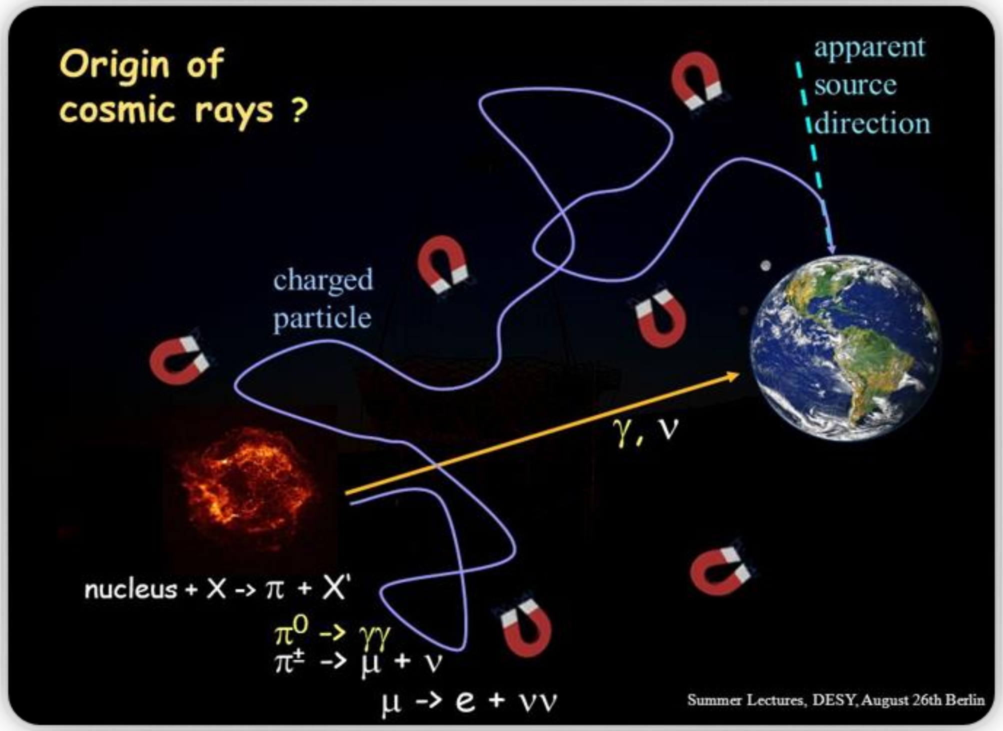


- **QLT**
  - **is comparable to a 1st order perturbation (Jokipii, 1966; Schilikeiser, 2002)**
  - **90º degree problem (particles cannot change direction)**
  - **Perpendicular diffusion and geometry problem**
    - **Predictions do not match simulations**

Shalchi (2009)

Geometry	QLT	Simulations
Slab model	$\langle(\Delta x)^2\rangle \sim t$ (Diffusion)	$\langle(\Delta x)^2\rangle \sim \sqrt{t}$ (Subdiffusion)
Composite model	$\langle(\Delta x)^2\rangle \sim t^2$ (Superdiffusion)	$\langle(\Delta x)^2\rangle \sim t$ (Diffusion)

Cosmic Ray diffusion



- **How to explain the slower diffusion?**

- **MHD Turbulence is ubiquitous:**
  - External Sources of MHD Turbulence
  - Anisotropic Diffusion
  - Relativistic Diffusion
  - Self-generated
  - Fang (2022)
- Several authors consider phenomenological approach: **HD turbulence (Kolmogorov)**
  - Does not take into account effects due to **MHD turbulence** in the system (Goldreich-Stridhar 95)

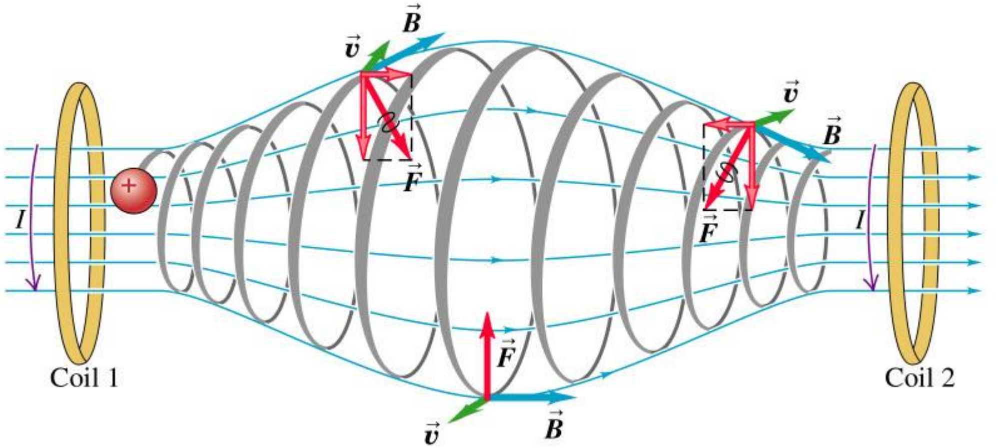
- **Mirror Diffusion**
  (Lazarian & Xu 2021; Barreto-Mota et al. 2025; Bell et al. 2025)
  - **Unavoidable in MHD turbulence!**

$$\lambda_{\parallel} \sim \frac{v_A}{\varepsilon^{1/3}} \lambda_{\perp}^{2/3}$$

Magnetic Mirrors

- **Mirrors naturally occur in MHD flows**
  (e.g. Budker 1959; Noerdlinger 1968; Kulsrud & Pearce 1969)
- If R_L is smaller than the scale of B_{mirror} in MHD turbulence:
  (1st Adiabatic Invariant)

$$\frac{p_\perp^2}{B_0} = \frac{p^2}{B_0 + \delta b}$$



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- In turbulence, particles with **$\mu<\mu_{lc}$ (loss cone for escaping particles) are subject to mirroring** (Lazarian and Xu 2021):

$$\mu = \cos(\theta)$$
$$\mu_{lc}^2 = \cos^2\theta_{lc} = \frac{\delta b}{B_0 + \delta b},$$

Superdiffusion of Magnetic Fields

- Dispersion of the magnetic field lines:

$$d\langle y^2\rangle \approx l_\perp^2 \frac{ds}{l_\parallel},$$

$$d\langle y^2\rangle \approx \langle y^2\rangle^{2/3} M_A^{4/3} L^{-1/3} ds.$$

- (Lazarian & Vishiniac 1999: // and ⊥ eddy scale)

- Extensively studied:
  - Lazarian & Yan (2014), Maiti et al. (2022), Hu et al. (2022), and Zhang and Xu (2023)

Lazarian and Xu, ApJ (2021)

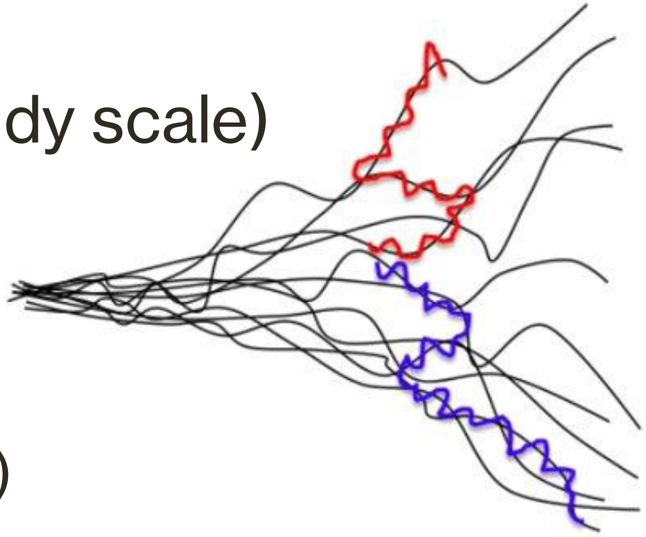


Figure 1. Because of the perpendicular superdiffusion of particles following diffusing magnetic field lines, particles that undergo bouncing move diffusively along the magnetic field. Thin lines represent magnetic field lines. Thick lines represent the trajectories of two particles whose initial separation is small.

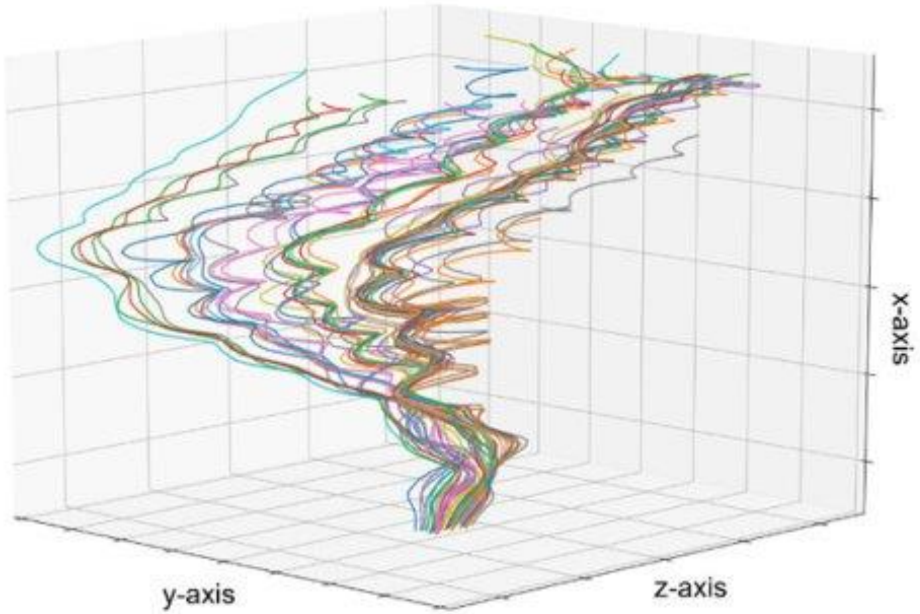
Eyink et al., Nature 497,(2013)

Superdiffusion+Mirrors = Mirror Diffusion

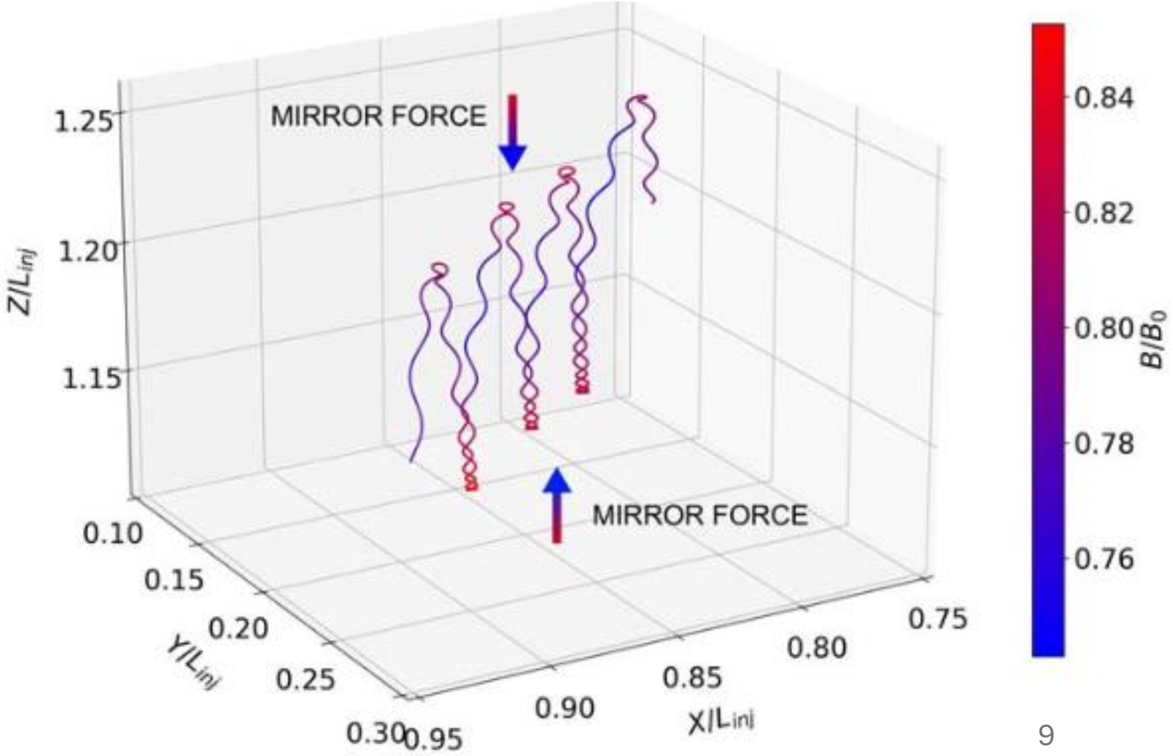
- Lazarian & Xu (2021)
- The only ingredients needed are superdiffusion and turbulence

It solves QLT problems!

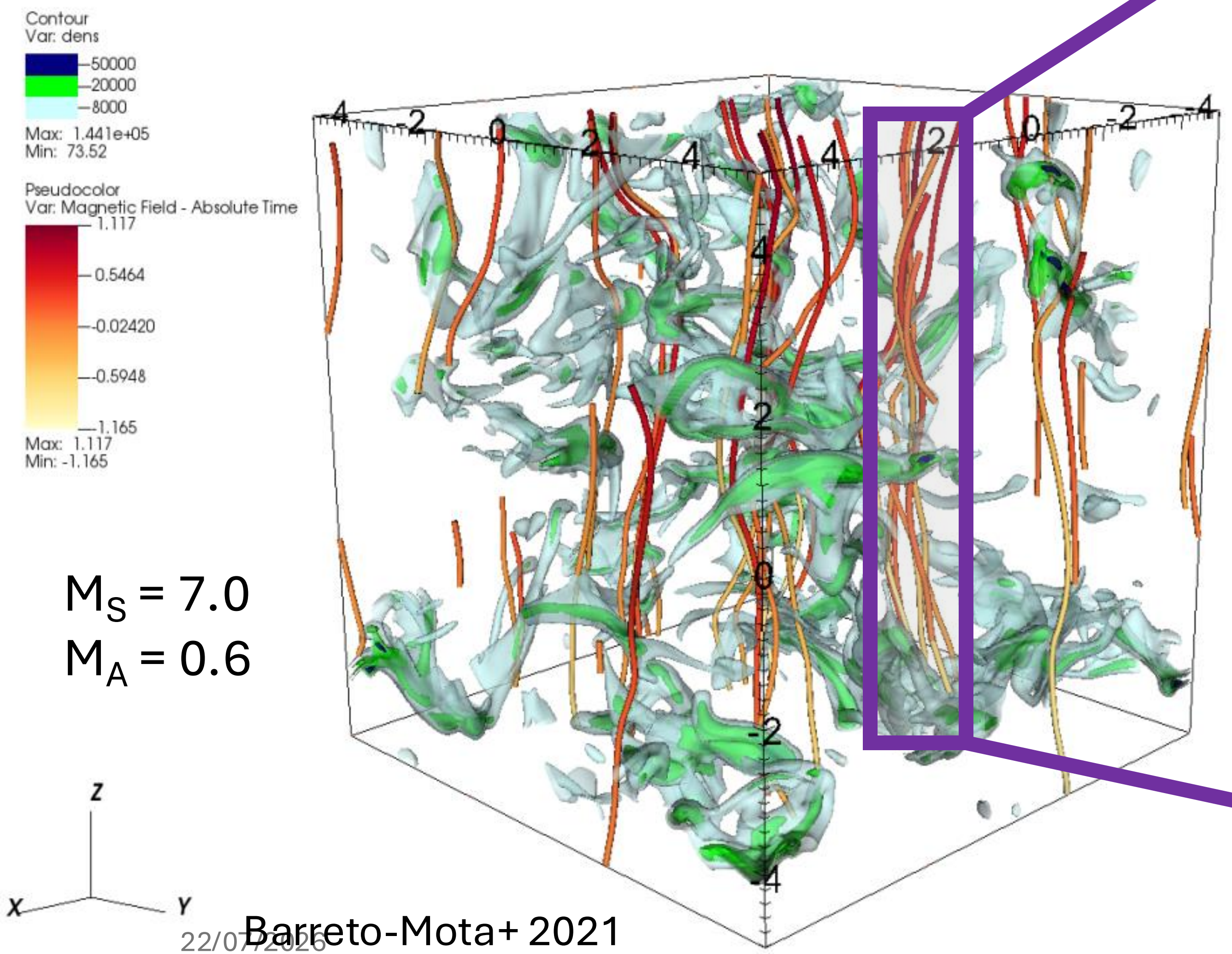
Hu et al. (2022)



Zhang & Xu (2023)

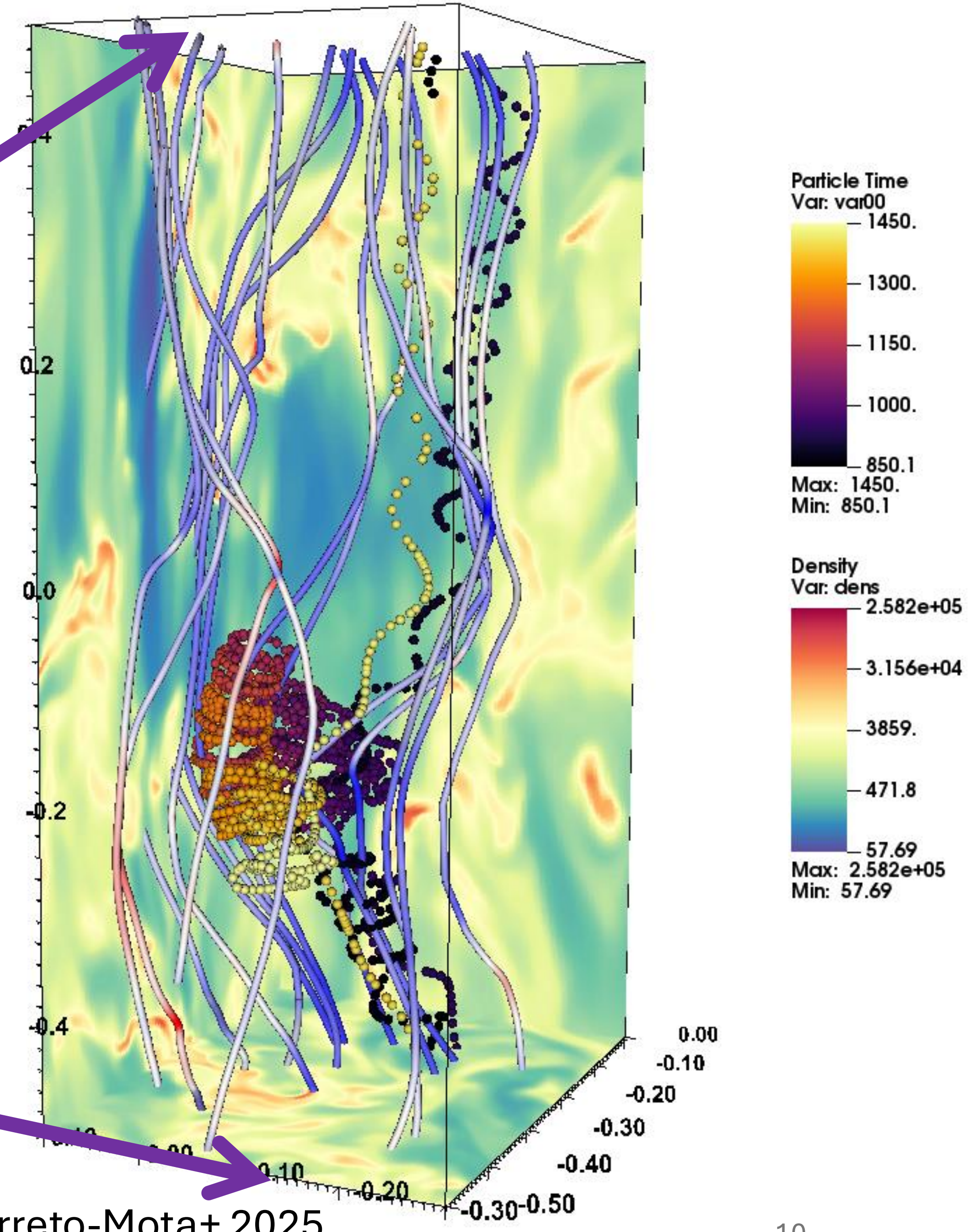


3D MHD turbulence simulations with test particles diffusion



$M_S = 7.0$
$M_A = 0.6$

Barreto-Mota+ 2021



Barreto-Mota+ 2025

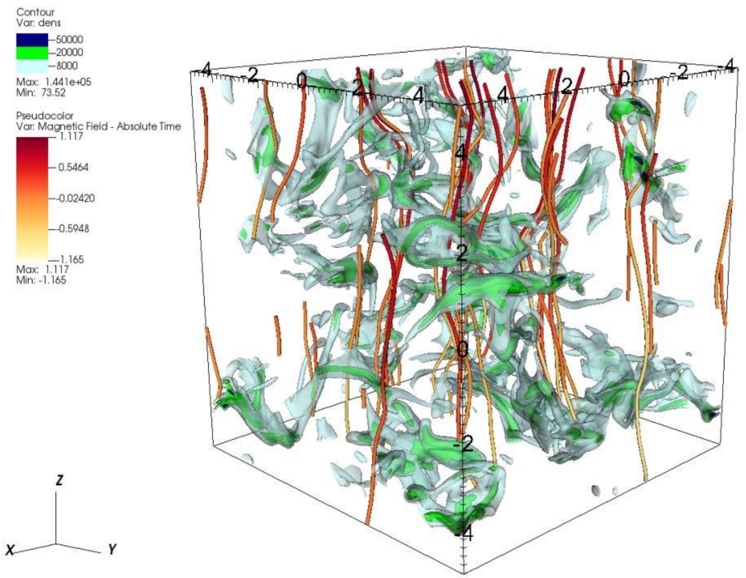
Test particle simulations
Mirror x Scattering

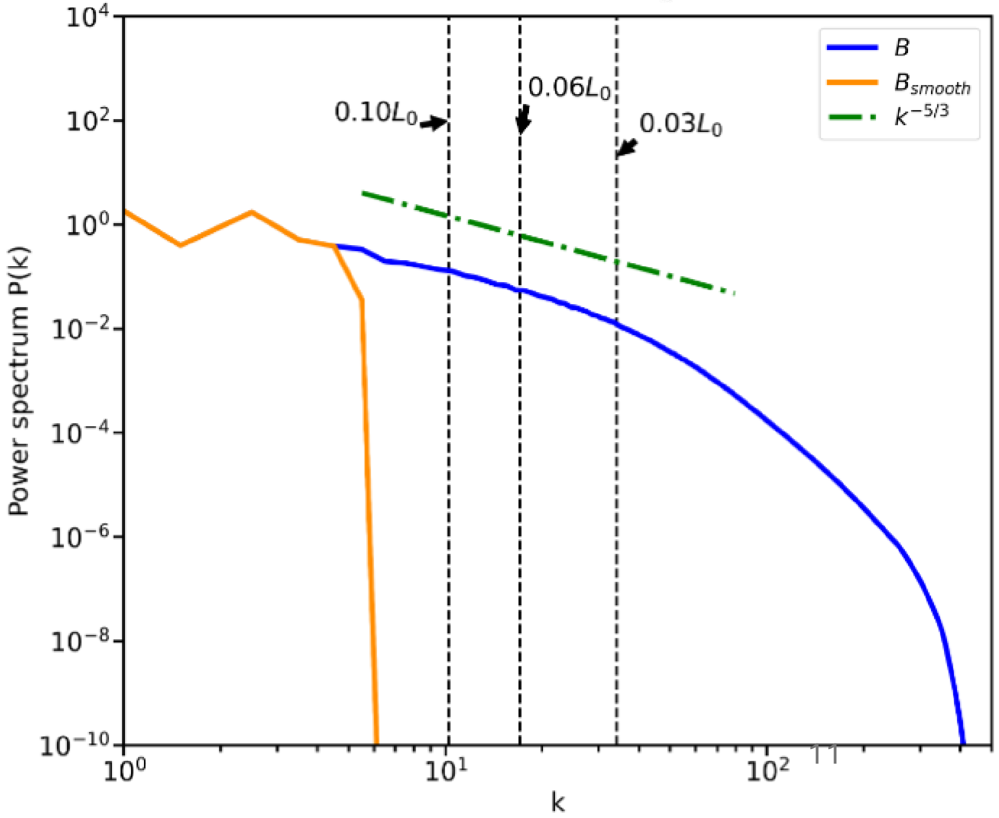
- Barreto-Mota+ 2025
- We compute the Lorentz force in each point:

$$\frac{d\mathbf{v}}{dt} = \frac{q}{\gamma mc}\mathbf{v} \times \mathbf{B}$$

- **Complete field**
  - Mirror + Scattering
- **Smoothed field**
  - Mirror only

$\mu = \cos(\theta)$	R_L/L_0
0.20	0.03
0.80	0.06
	0.10

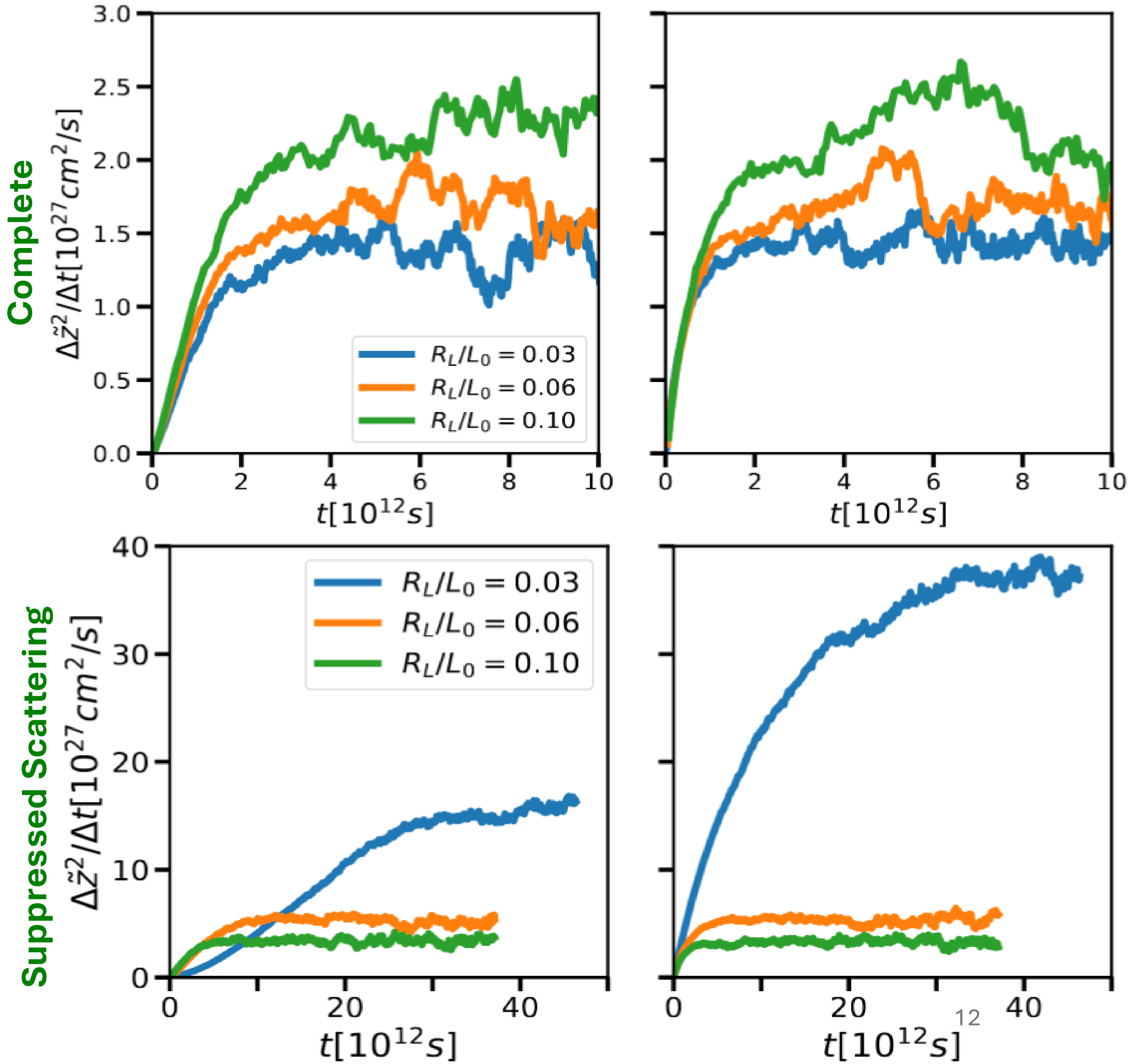




Mirror+Scattering Diffusion Modeling

- **Models scaled to a 3pc box.**
  - 3μG
  - **Region around PWN**
- **$D_{//}$ around $10^{27} cm^2/s$ (1 PeV)**
- Can be effective even with suppressed pitch-angle scattering

$$D_{\|} = \frac{<(z\text{-}z_0)^2>}{t}$$



A quick comparison to observations

- Considering different sizes

$$R_L[pc] = 1.084 \frac{(E/1PeV)}{(B/1\mu G)} \left(\frac{v_\perp}{c}\right),$$

$$\Omega[s^{-1}] \approx 9.743 \times 10^{-9} \left(\frac{1pc}{R_L}\right),$$

$$D_{\parallel,phys}[cm^2/s] = D_\parallel \cdot L_0\, c$$
$$= D_\parallel \cdot 2.776 \times 10^{29} \left(\frac{L_0}{3pc}\right)$$

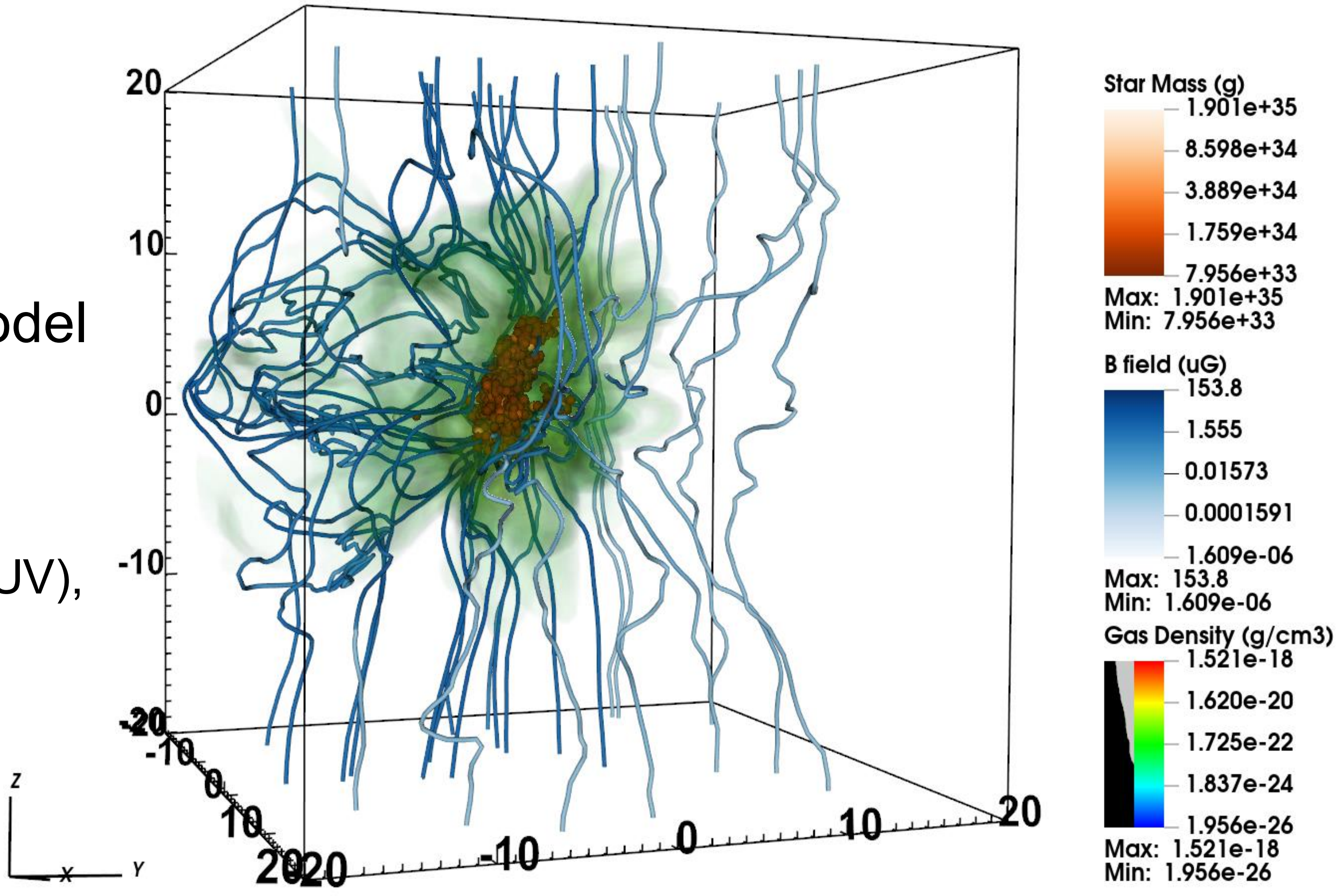
$B(\mu G)$	$L_0(pc)$	R/L_0	E(PeV)	$D_\parallel$	$D_{\parallel,phys}(cm^2/s)$
3.2	1	0.03	0.09	0.005	4.63×10^{26}
3.2	1	0.06	0.18	0.006	5.55×10^{26}
3.2	1	0.10	0.30	0.008	7.40×10^{26}
3.2	5	0.03	0.44	0.005	2.31×10^{27}
3.2	5	0.06	0.89	0.006	2.78×10^{27}
3.2	5	0.10	1.48	0.008	3.70×10^{27}
10	5	0.03	1.40	0.005	2.31×10^{27}
10	5	0.06	2.80	0.006	2.78×10^{27}
10	5	0.10	4.67	0.008	3.70×10^{27}

- Observed PWNe (Fang, 2022)

Name	Parameters of associated pulsars					100 TeV …meters	
	Gl [deg]	Gb [deg]	T [kyr]	D [kpc]	L 10^{34} [erg s^{-1}]	D_{100} [cm^2 s^{-1}]	η [%]
Geminga halo	195.13	4.27	342	0.25[a]	3.2	4.6×10^{27} [c]	5[c]
Monogem halo	201.11	8.26	111	0.288	3.8	1.5×10^{28} [d]	4[d]
LHAASO J0621+3755	175.88	10.96	208	1.6[b]	2.7	2.3×10^{27} [c]	40[c]
HESS J1831−098	21.90	−0.13	128	3.68	110	9.0×10^{27} [e]	7[e]

Applying to Young Massive Stellar Clusters

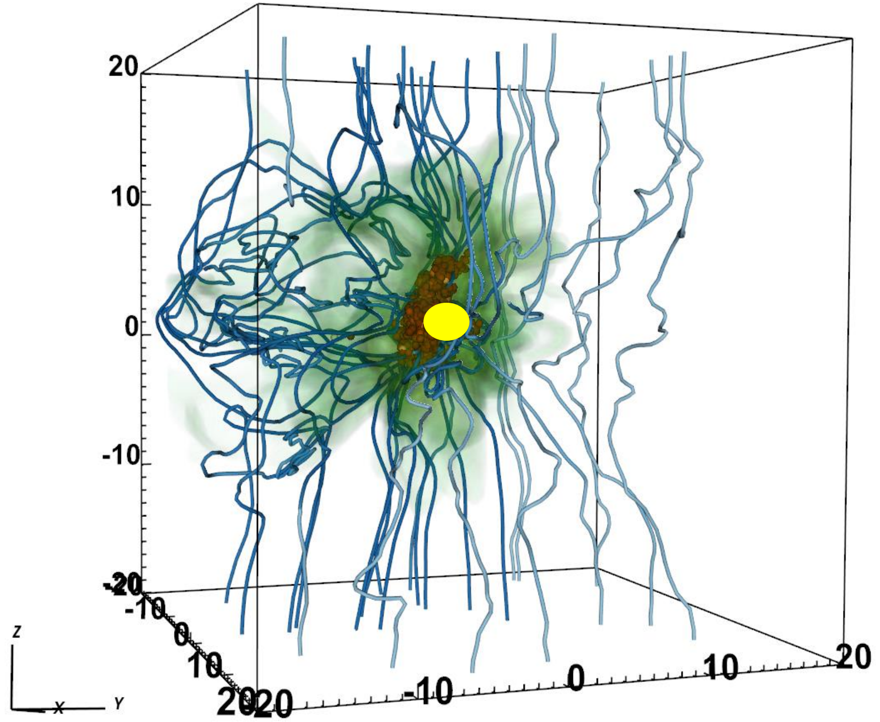
- **3D MHD simulation: background for CR cascading**
  - Polak et al. 2023
- Young massive stellar cluster model (compatible with W43 Cluster)
  - Highly super-sonic
  - <B> of a few micro Gauss
  - Includes stars, radiation feedback(UV), dust temperature



Two Scenarios for CR production in the YMSC

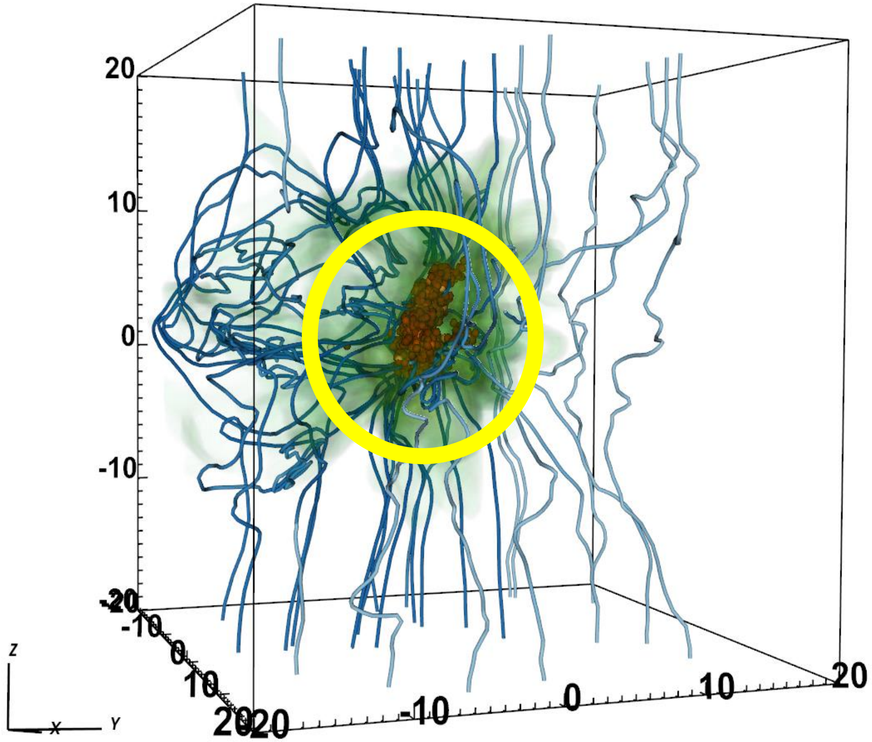
CR produced in the center:

- ➢ mimics compact source accelerator, e.g. microquasar



CR produced in a shell around Massive Stars:

- ➢ mimics SB-wind shock front accelerator



Barreto-Mota, de Gouveia Dal Pino+, (in prep)

Simulating CR diffusion with CRPropa3

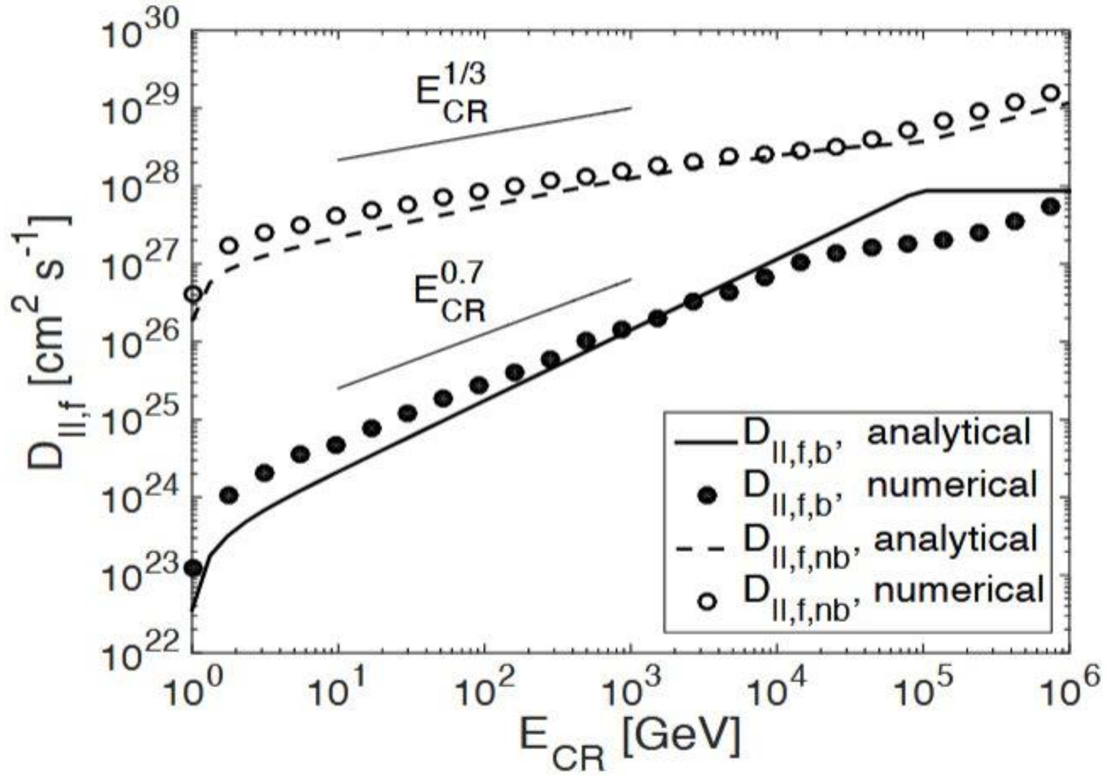
- Monte Carlo code **(CRPropa3)** (Alves-Batista et al. 2016)
- YMSCs simulations as the background (Polak et al. 2023)

We moddeled **Mirror Diffusion energy-dependence:**

$D \sim E^{1/3}$ (scattering+mirror)

$D \sim E^{0.7}$ (only mirror)

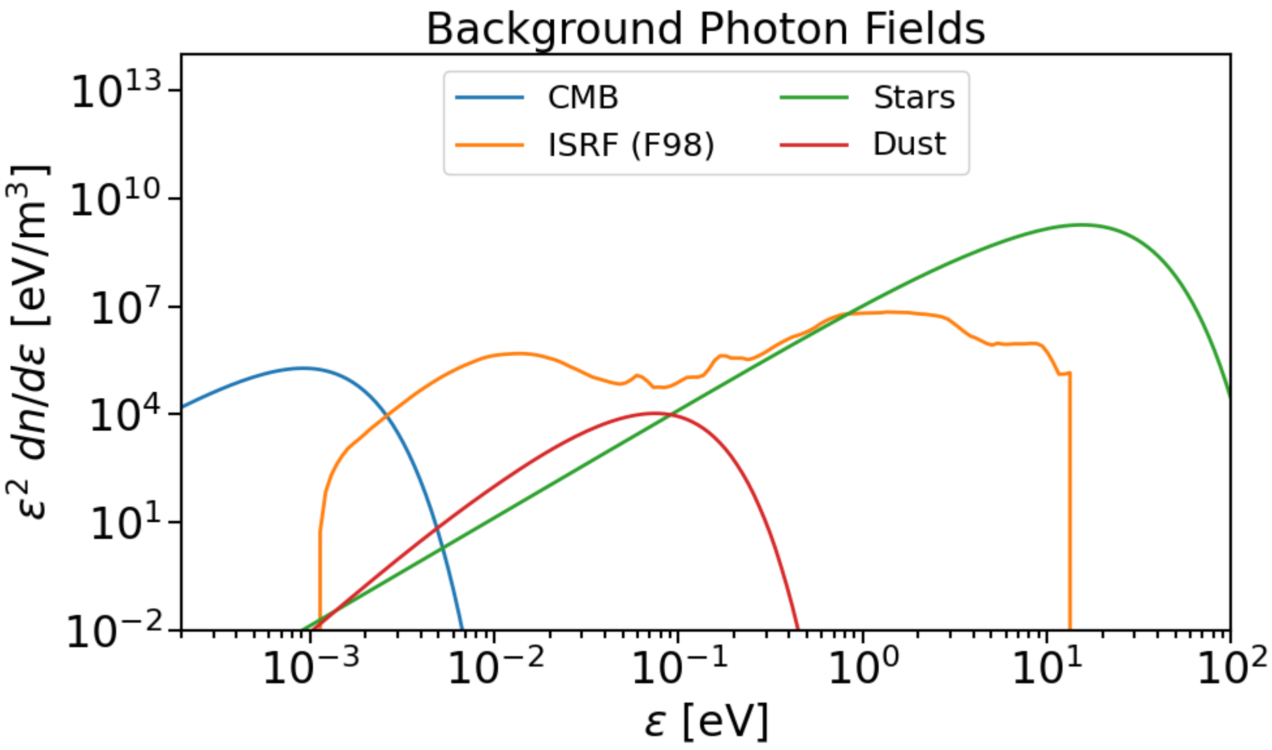
Lazarian and Xu (2021)



Target photon fields and Main interactions

We considered following **photon Fields**:

- Blackbody from the stars
- Background insterstellar radiation (ISRF)
- CMB
- Dust



Main interactions:

Proton-Proton chain

$$p + p \rightarrow p + p + \pi^{0,\pm} + X$$

$$\pi^0 \rightarrow 2\gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

Inverse Compton

$$e^\pm + \gamma_{\rm bg} \rightarrow e^\pm + \gamma$$

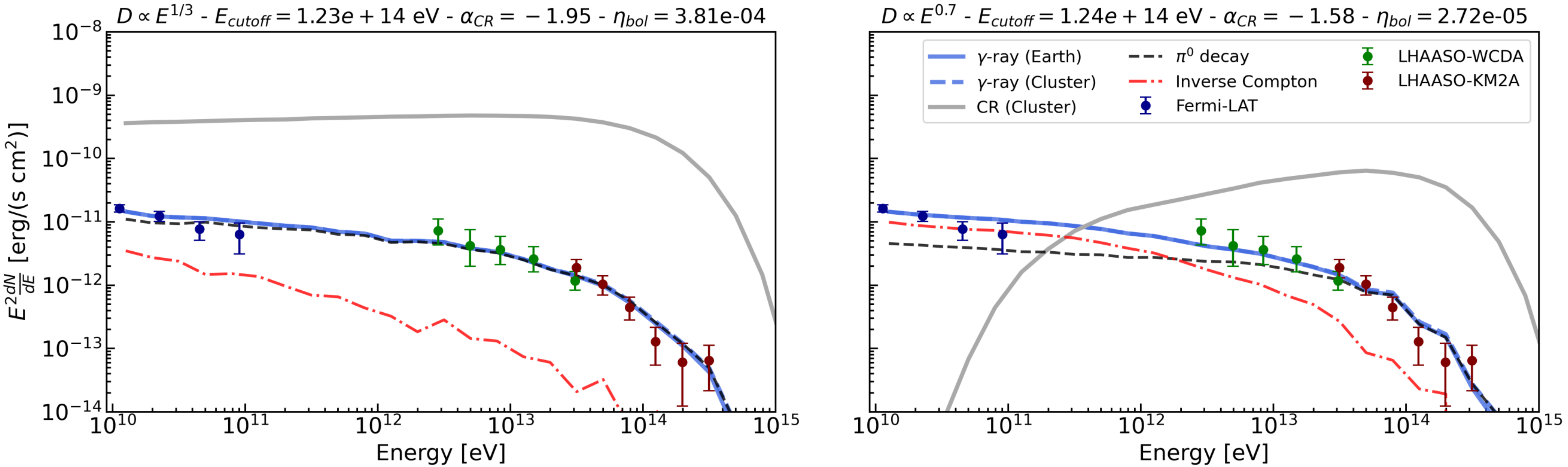
Resulting γ-ray spectrum

Barreto-Mota+ (in prep)

- Source at the center of the cluster
- Slower diffusion needs a harder injection spectra of CRs to fit observations
- Inverse Compton vs Hadronic Interactions (Dependence on the diffusion)
- $D \sim E^{1/3} + E_{inj}^{-2}$ (Fermi-like) – Most likely

W43 Observations
Cao et al. (2025)
LHAASO Collaboration

$D \sim E^{1/3}$ $E_{CR} \sim E^{-2}$ | **$D \sim E^{0.7}$ $E_{CR} \sim E^{-1.6}$**



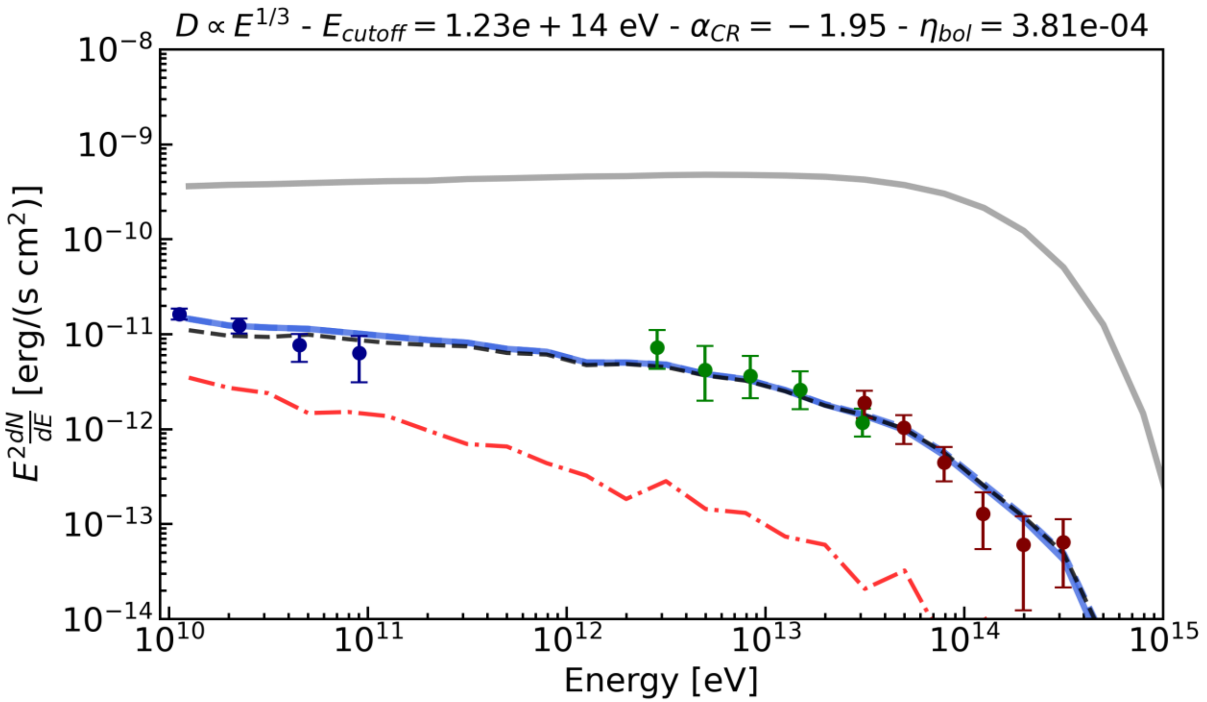
Resulting γ-ray spectrum for YMSC

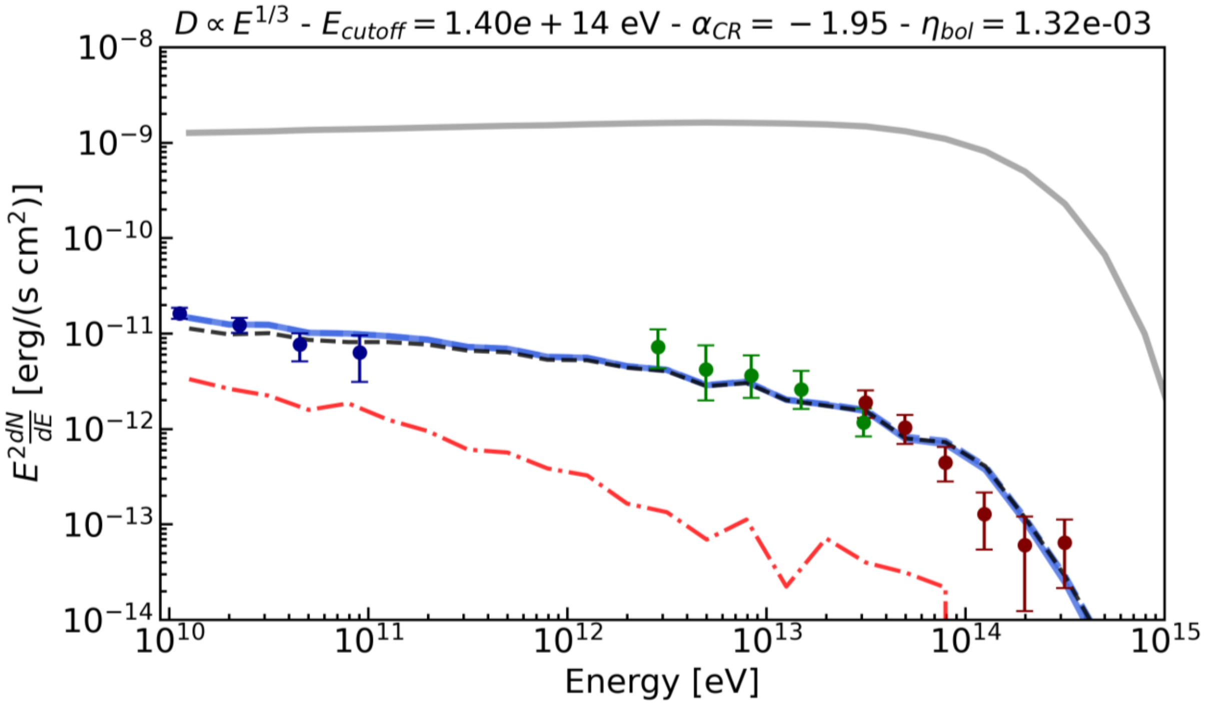
Source at the **center** of the cluster

$D \sim E^{1/3}$

$E_{CR} \sim E^{-2}$

Source at a **shell** of the cluster





Barreto-Mota, de Gouveia Dal Pino+, 2026 (in prep.)

Summary our findings and take home message

- **Mirror diffusion inhibits overall diffusion of CRs (Barreto-Mota et al 2025)**
- Present in **any MHD turbulent system!**
- **Mirror+scattering:**
  provides physical explanation for diffusion energy-dependence: D ~ $E^{1/3}$
- Can be effective even with **suppressed pitch angle scattering**
  - Even in partially ionized plasmas (Hu et al. 2025)
- Slower diffusion allows the CRs to be retained near the source
  - Important implication for **particle acceleration** (Bell et al. 2025)
- 3D Simulations of CR cascading in YMSCs:
  - **Mirror+scattering can explain the spectrum of W43 (Barreto-Mota et al.; 2026): Best solution: D~$E^{1/3}$ and CR power index ~-2 (source either at the center or at a shell of the cluster)**
- **Mirror+scattering diffusion may probably explain CR diffusion inhibition in most VHE emission systems; SNRs, GMCs, YMCS, ..**

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CTA Cherenkov Telescope Array Plus

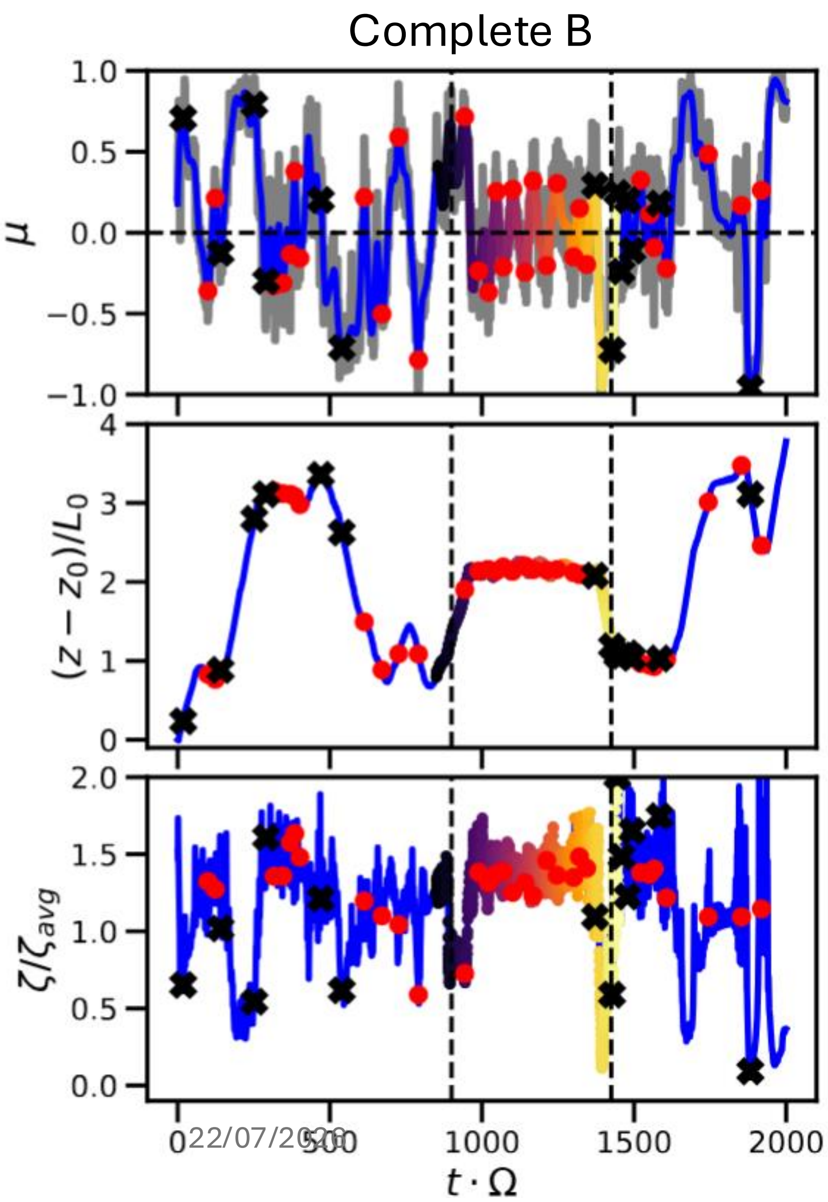
ASTRI

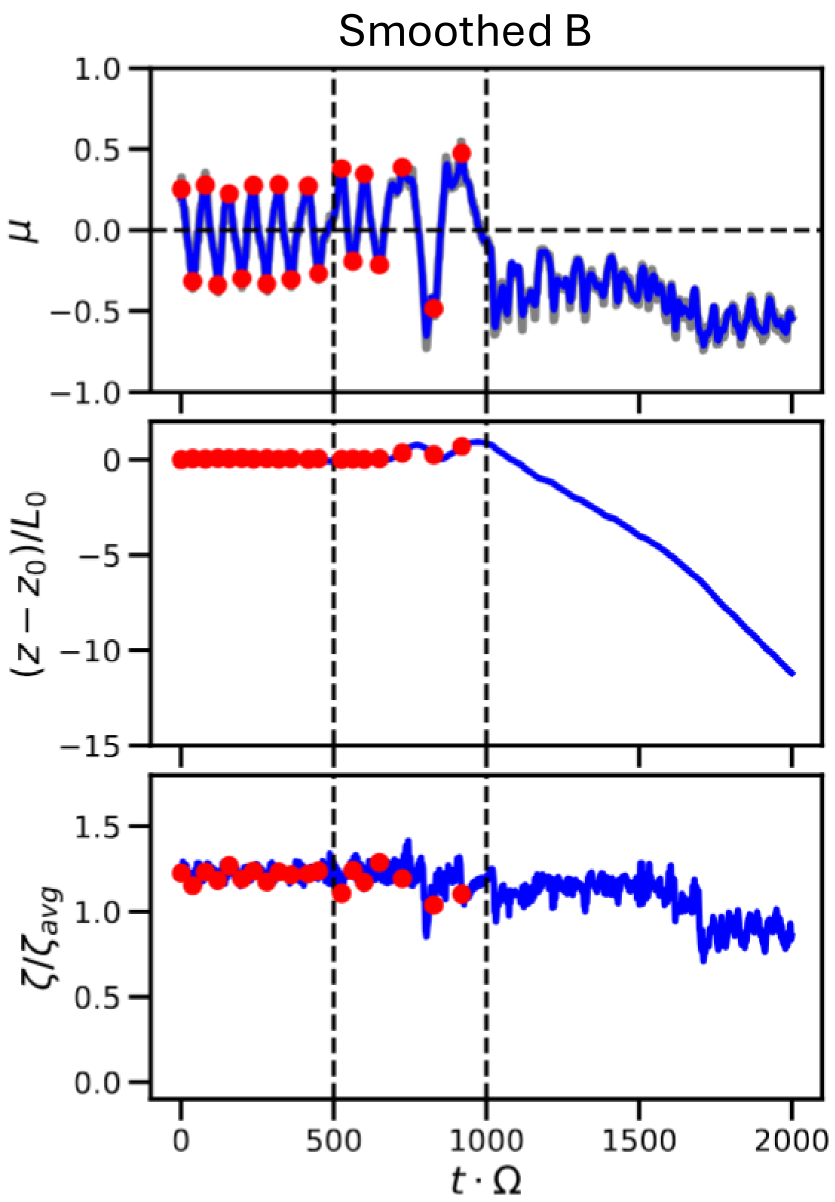
ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Thank you for your attention!

EXTRA

Particle evolution





$R_L/L_0 = 0.03, \mu_0 = 0.2$

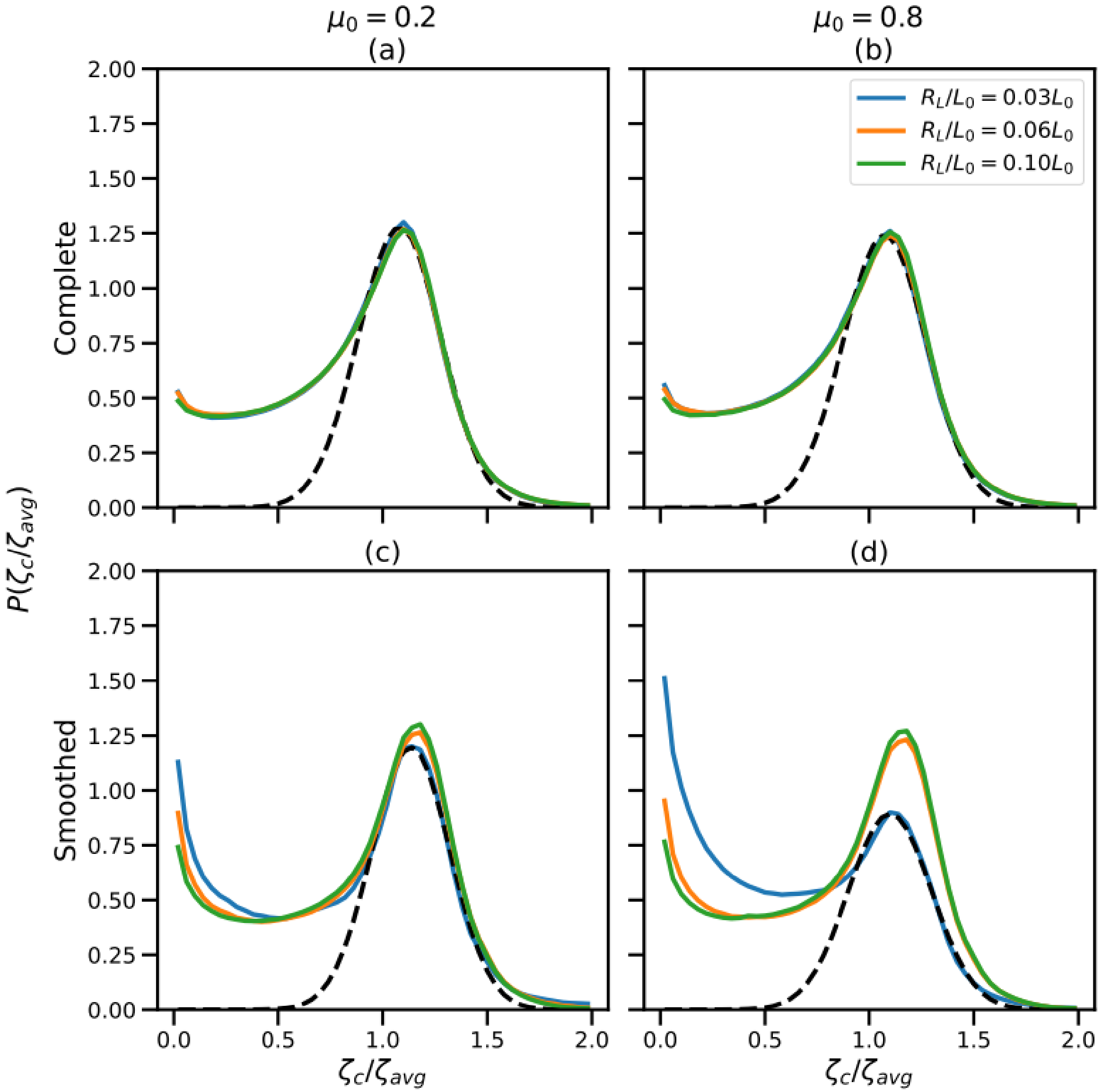
$$\mu = \cos(\theta)$$

Parallel displacement

Mirror conserves magnetic momentum:

$$\zeta(t) = \gamma m v^2 \frac{1 - \mu(t)^2}{2|\mathbf{B}(t)|},$$

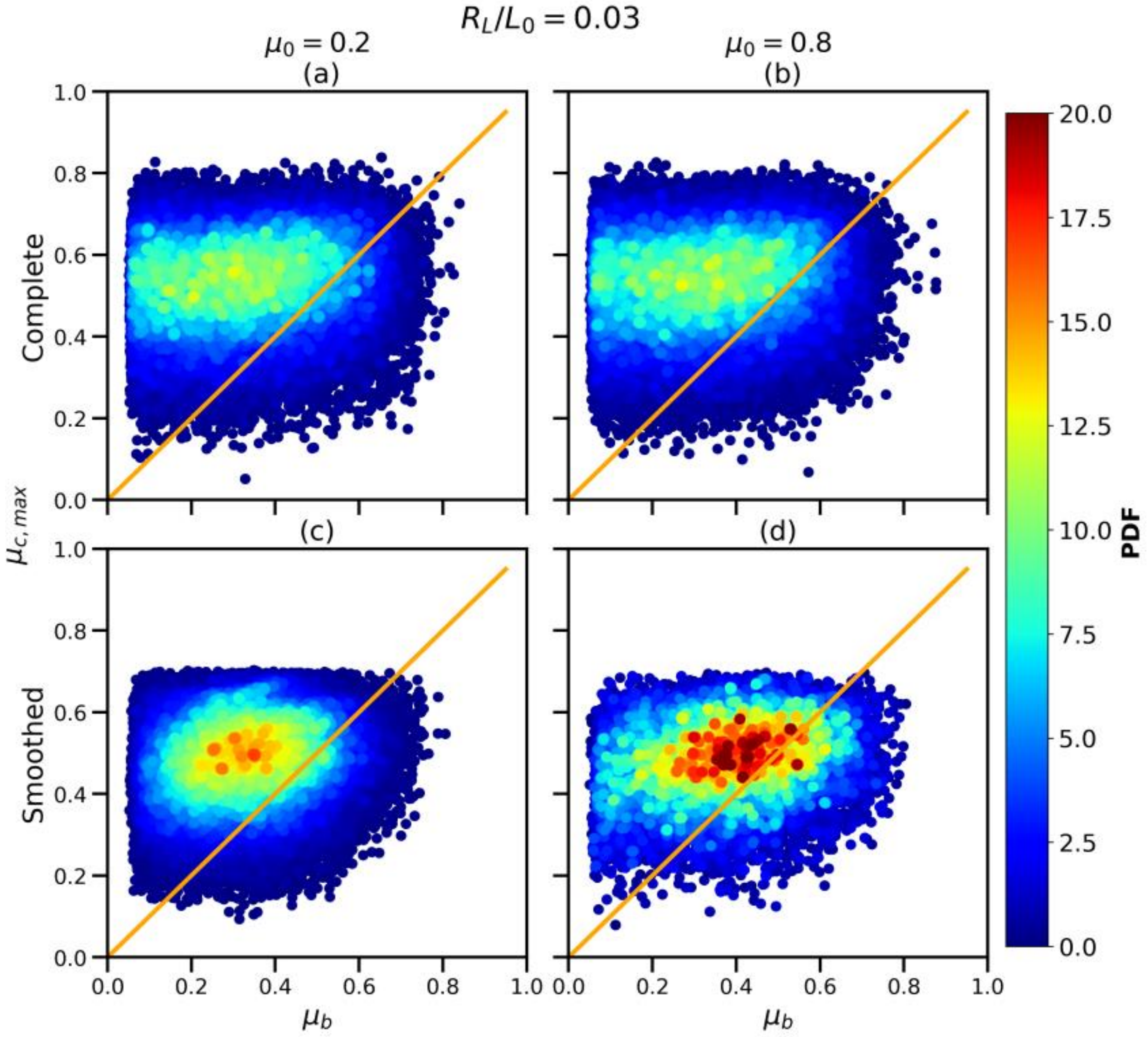
Bounce identification

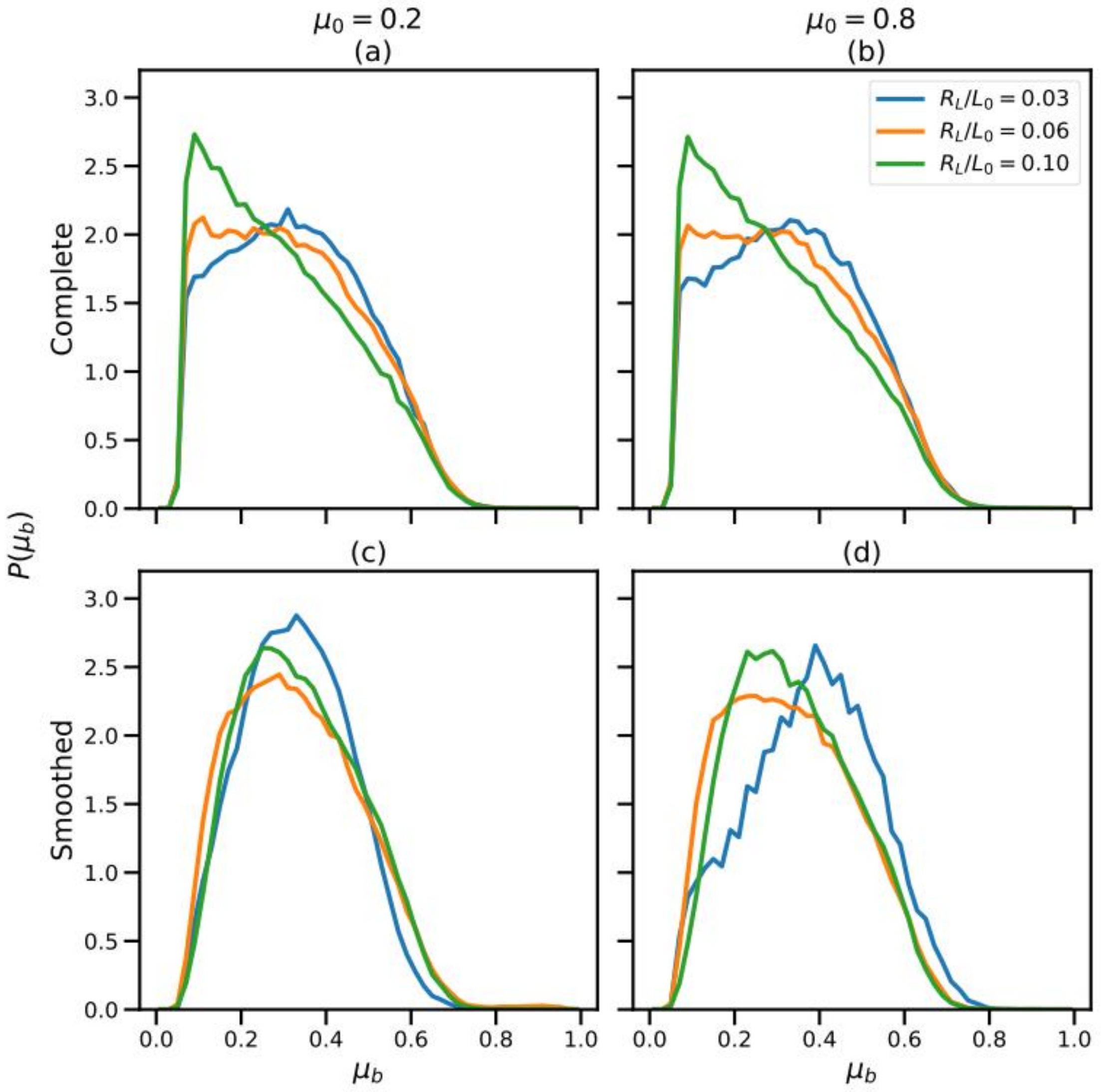


Complete	$\mu_0 = 0.2$			$\mu_0 = 0.8$		
R_L	Mirror Bounce	Total	%	Mirror Bounce	Total	%
0.03	91361	123,859	73.76	89,931	120,331	74.74
0.06	165,459	223,060	74.18	161,250	218,128	73.92
0.10	246,912	322,056	76.67	234,385	307,357	76.26

Smooth	$\mu_0 = 0.2$			$\mu_0 = 0.8$		
R_L	Mirror Bounce	Total	%	Mirror Bounce	Total	%
0.03	247,899	354,073	70.01	110,200	152,117	72.44
0.06	126,401	154,984	81.56	114,512	136,214	84.07
0.10	108,227	140,372	77.10	105,874	137,993	76.72

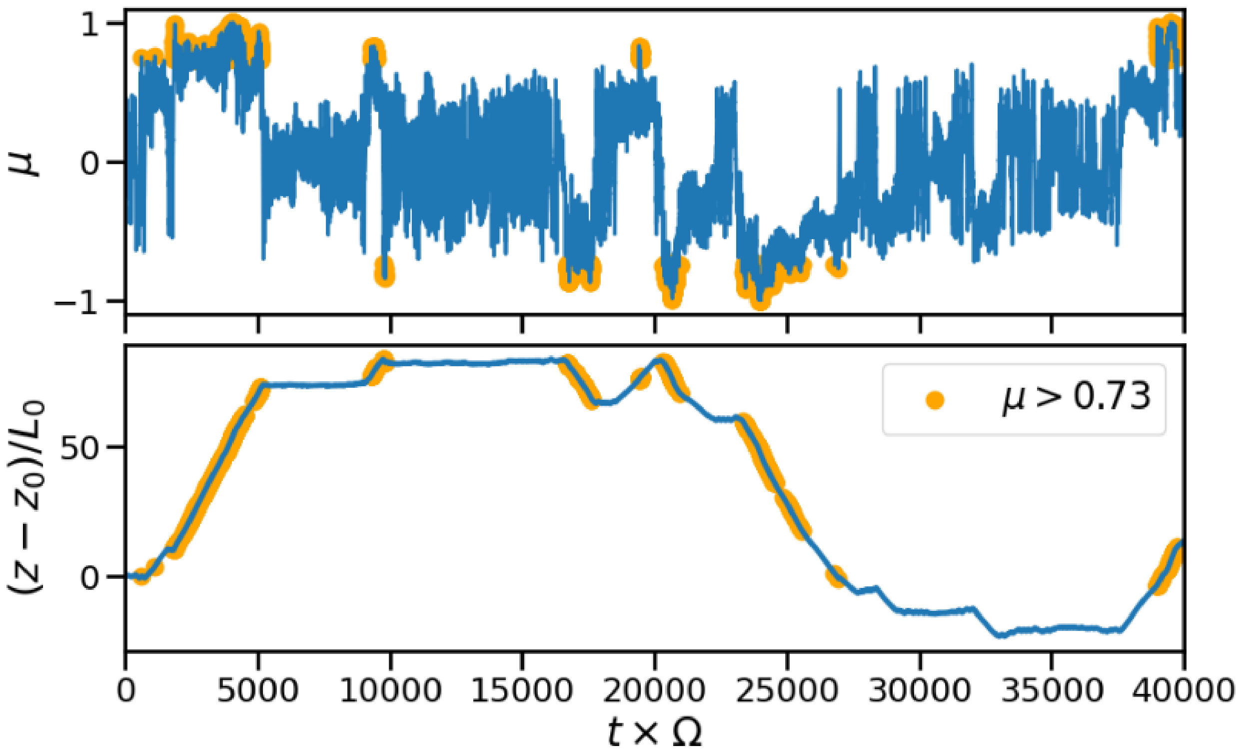
Angle distribution



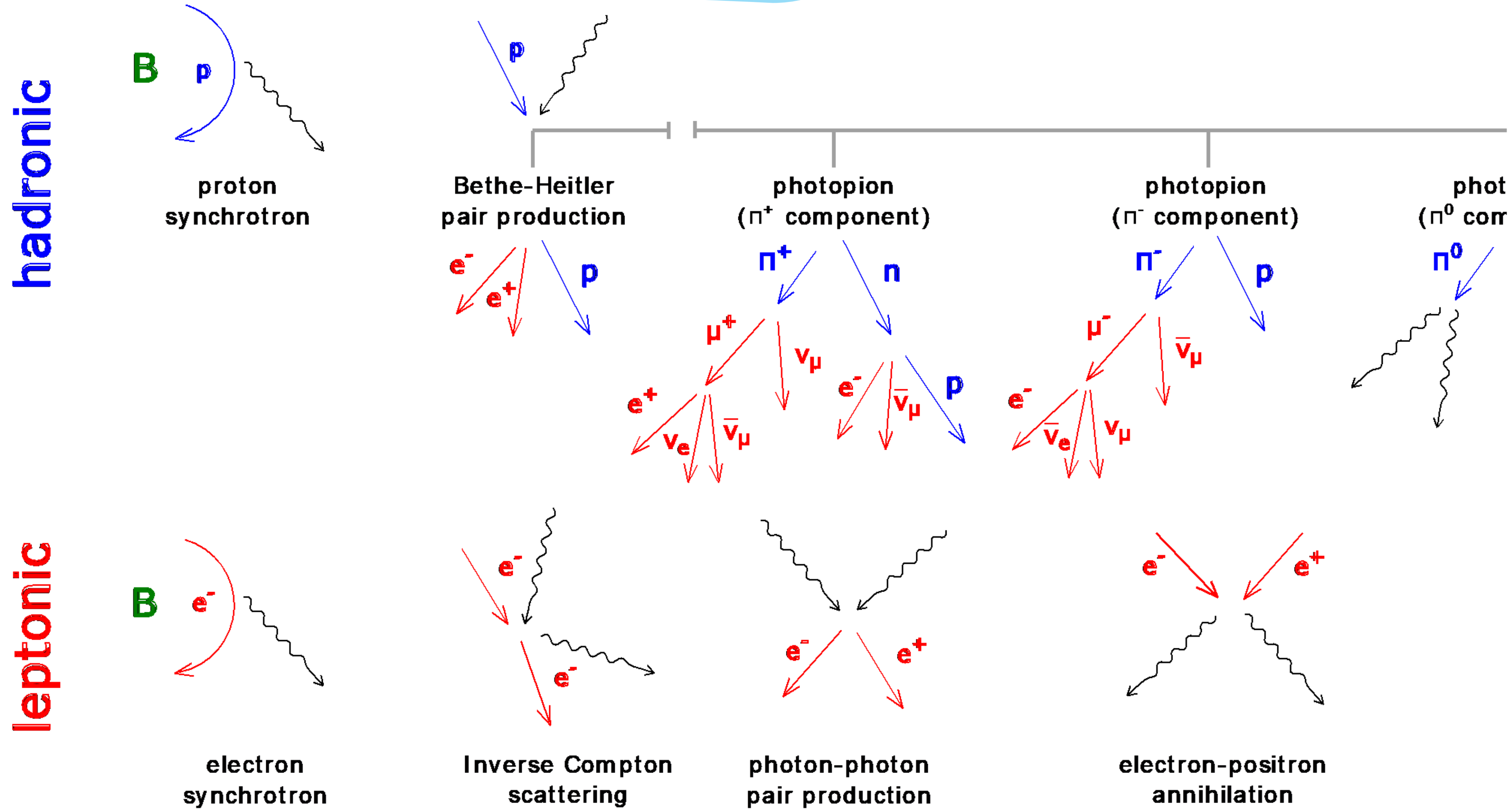


Scattering vs mirror – smoothed model

$$k_{\rm res} 2\pi R_{\rm L} \simeq \frac{(1 - \cos^2\theta_{\rm res})^{0.5}}{\cos\theta_{\rm res}},$$



Non-thermal processes



(Mastichiadis 2016)