CR Bounce Diffusion in Highly Turbulent and Magnetized Environments

Lucas Barreto-Mota[1], Elisabete de Gouveia Dal Pino[1], Syao Xu[2], Alex Lazarian[3]

1 Instituto de Astronomia, Universidade de São Paulo

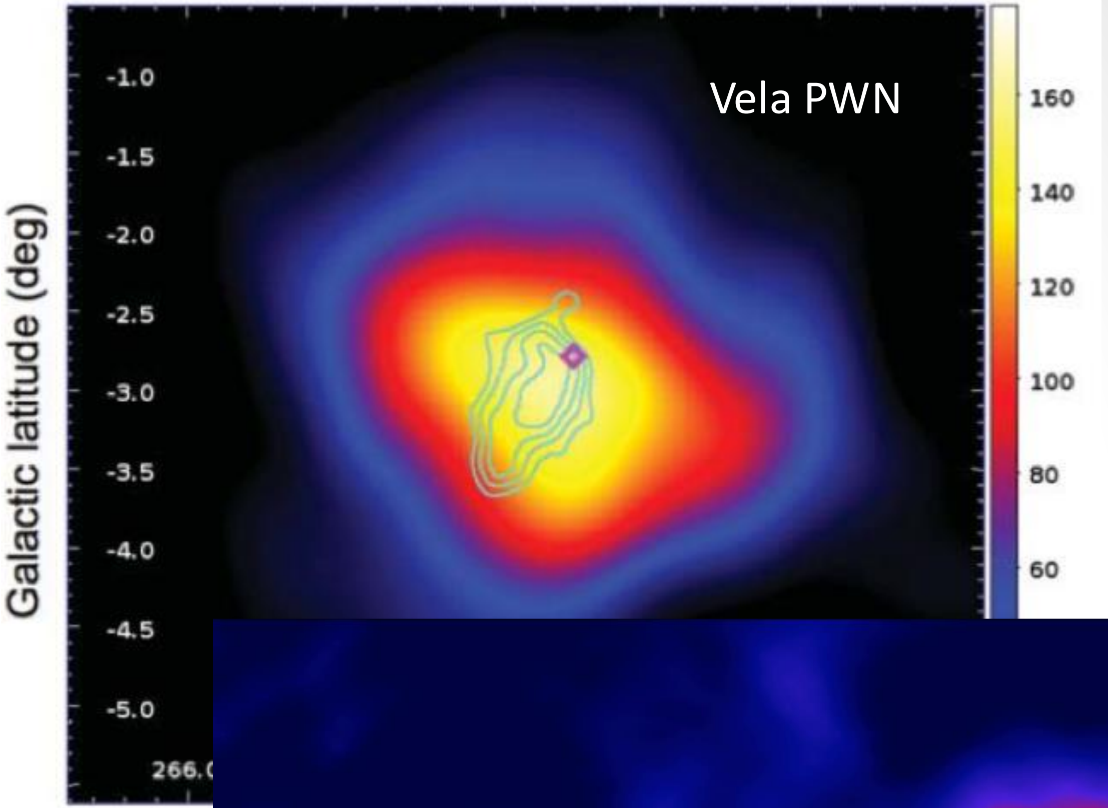
2 University of Florida

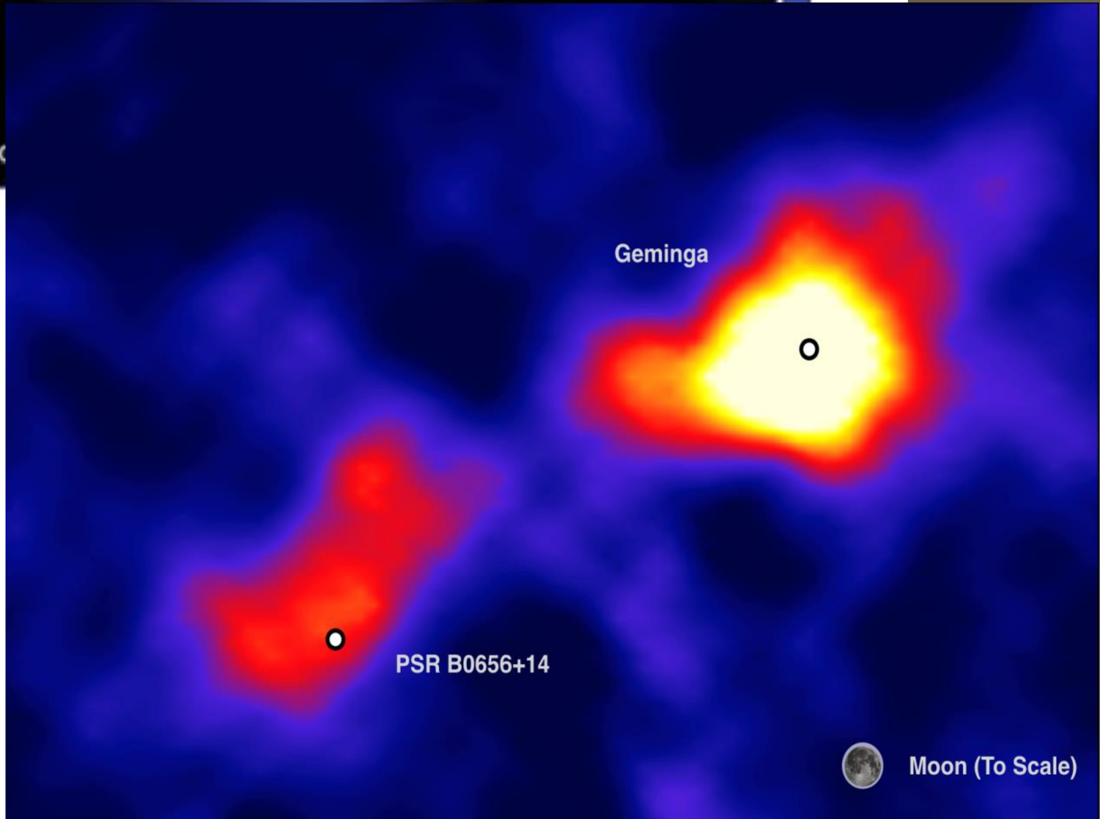
3 Department of Astronomy, University of Wisconsin

ArXiv link

TeV Observations

- VHE emission from extended sources.
  - Up to TeV photons
    (Abeysekara et al. 2017; Huang et al. 2018;
    Abeysekara et al. 2021; Cao et al. 2021)
  - PeVatrons?
- Observations suggest diffusion coefficients up to two orders of magnitude less than typical values for the ISM.
  - $\sim 10^{28}\ cm^2/s$ or less.
- Usual approach of quasi-linear theory (QLT) cannot explain (Jokipii, 1966; Schlickeiser, 2002)





The Fermi-LAT 0.3 - 1 GeV TS map for the Vela PWN
(Grondin et al. 2013https://dx.doi.org/doi:10.1088/0004-637X/774/2/110)

Sky map of TeV emission from Geminga and its neighbor PSR B0656+14
(Abeysekare et al., 2017. https://doi.org/10.1126/science.aan4880)

Quasilinear Theory (QLT) and its problems

- Quasilinear Theory (QLT) can be used to simplify the problem. (Jokipii, 1966; Schlickeiser, 2002)
  - Comparable to a 1st order pertubation

$$x_i(t), v_i(t) \quad \overset{\text{QLT}}{\Longrightarrow} \quad x_{i,0}(t), v_{i,0}(t).$$

- QLT problems:
  - 90^o problem
    - $\lambda_{||}$ does not converge
  - Perpendicular diffusion and the geometry problem
    - Prediction does not match simulations

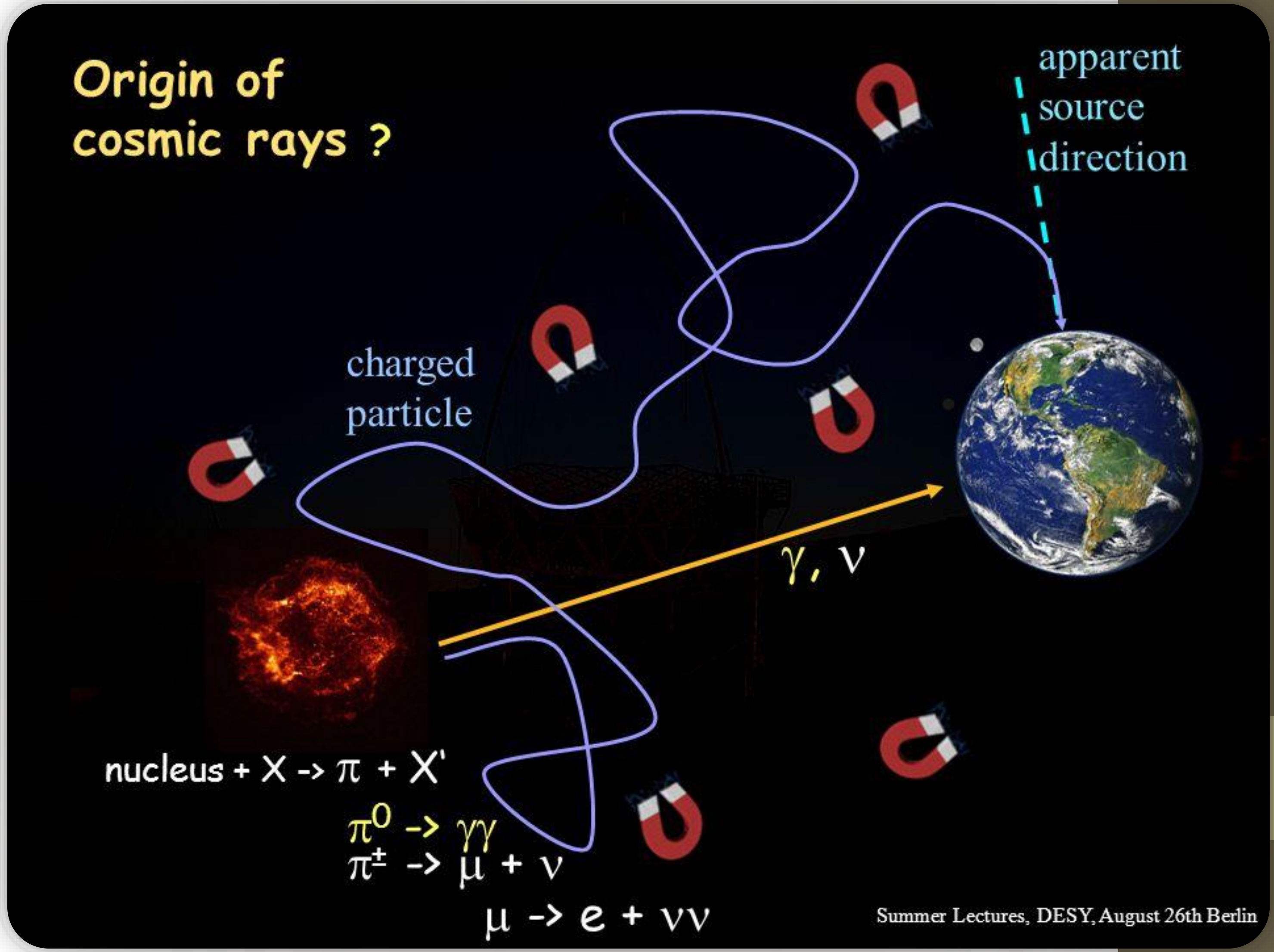
$$D_{\mu\mu} = D_{\mu\mu}^{\text{slab}} + D_{\mu\mu}^{\text{2D}},$$
$$D_{\perp} = D_{\perp}^{\text{slab}} + D_{\perp}^{\text{2D}}.$$

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)

Shalchi (2009)

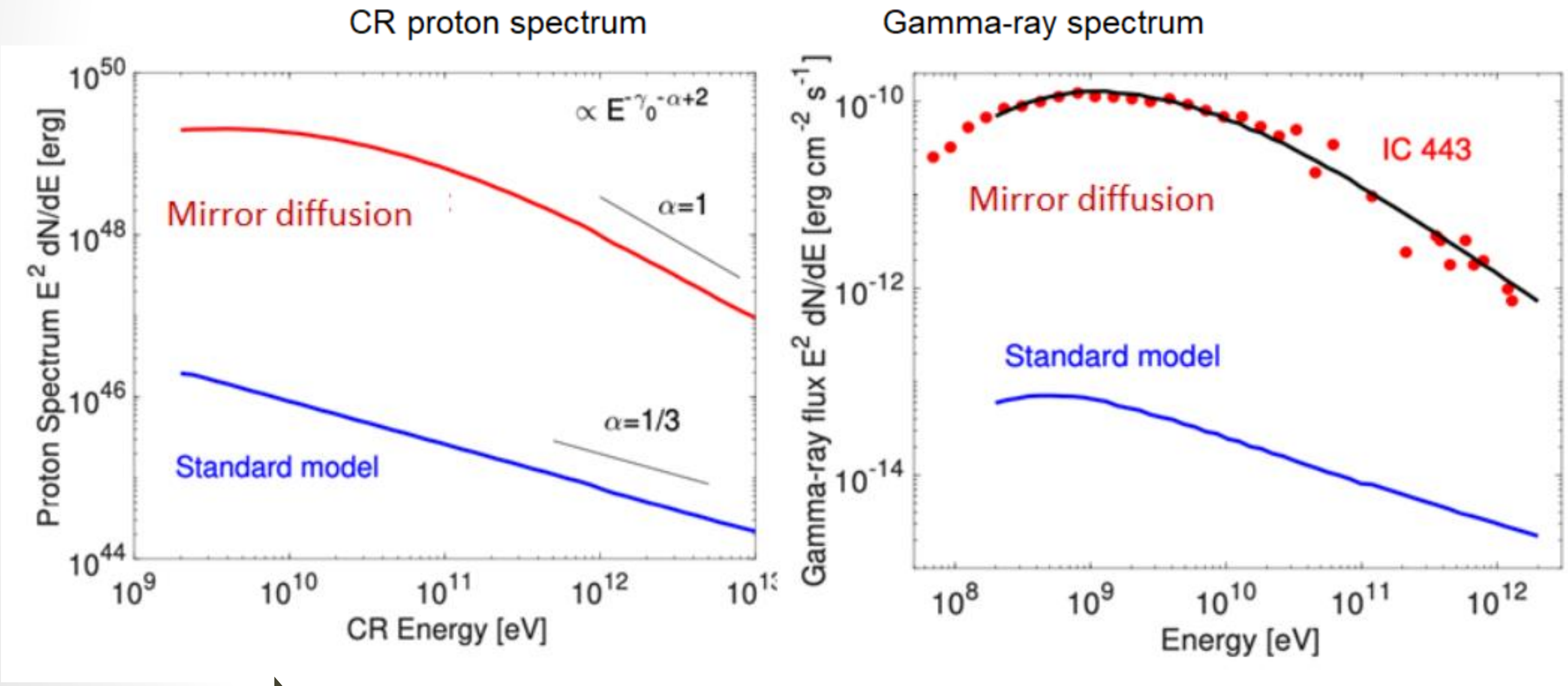
Cosmic Ray Diffusion

- How to explain the slower diffusion? (Fang, 2022)
  - Self-generated MHD Turbulence
  - External Sources of MHD Turbulence
  - Anisotropic Diffusion
  - Relativistic Diffusion
- In this work we test a new mechanism: Mirror Diffusion (Lazarian & Xu 2021)



SNRs and Molecular Clouds

- Supressed CR spectrum.
- Xu (2021)
  - Average diffusion coeficient is not enough



IC 443 - Fermi GeV gamma-ray (magenta), optical wavelengths (yellow), and infrared data from NASA's WISE (blue (3.4 microns), cyan (4.6 microns), green (12 microns) and red (22 microns)).

NASA/DOE/Fermi LAT Collaboration, NOAO/AURA/NSF, JPL-Caltech/UCLA

Mirror diffusion can help to explain the spectrum! But how does it work?

ISM is Turbulent

- Observations indicate a single **power law** for the turbulence cascade.
    - From Interstelar Medium fluctuations to the sub-parsec scales around stars.

- Points towards a universal origin for the turbulence in the Galaxy (supernova remnants, spiral arms).

- The cascading of energy in the presence of magnetic fields: (Goldreich & Sridhar, 1995; Lazarian & Vishiniac, 1999)

$$E(k) \propto \varepsilon^{2/3} k^{-5/3} \qquad \lambda_{\parallel} \sim \frac{v_A}{\varepsilon^{1/3}} \lambda_{\perp}^{2/3}$$

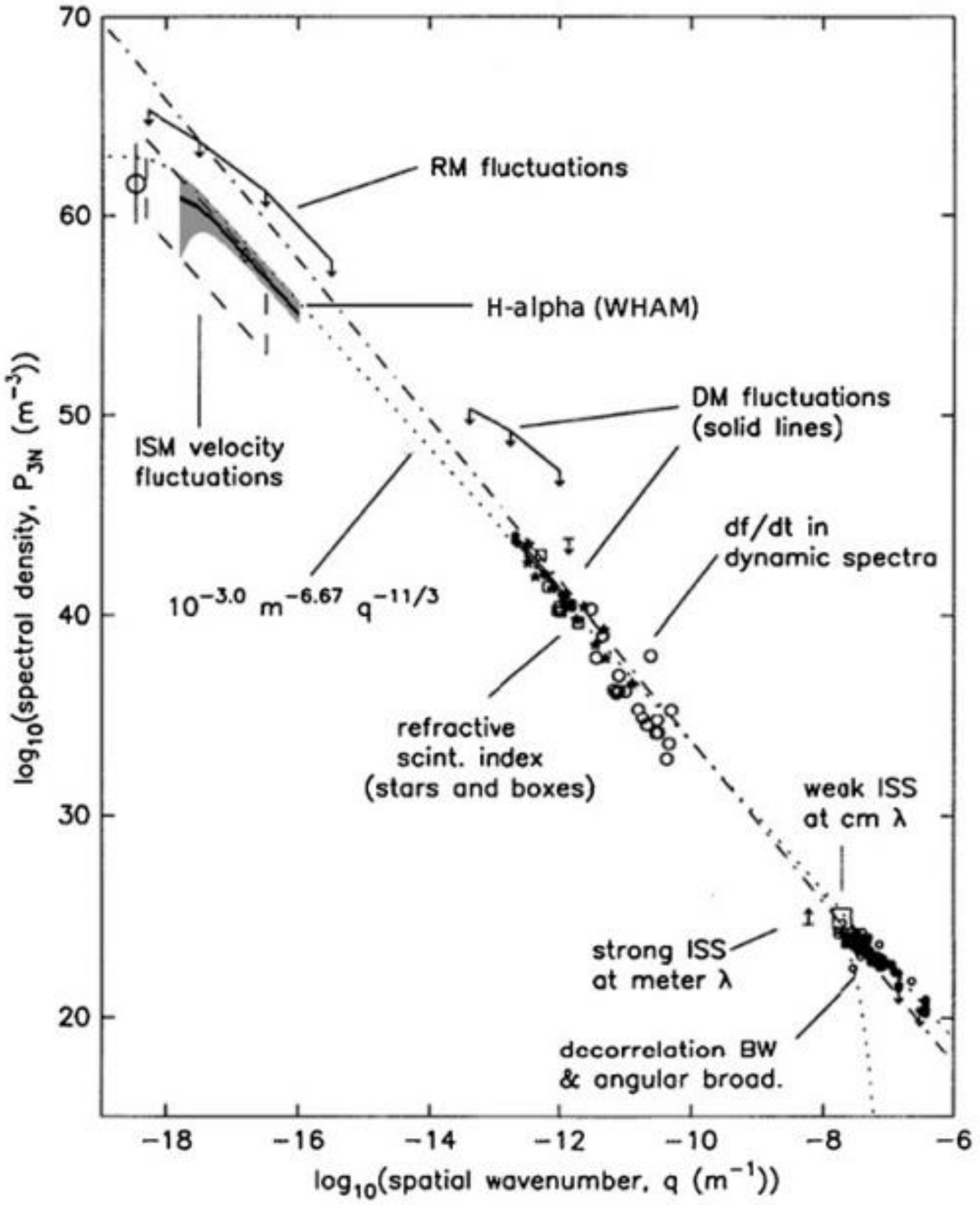


Fig -WHAM estimation for electron density overplotted on the figure of the Big Power Law in the sky figure from Armstrong et al. (1995). The range of statistical errors is marked with gray color. Spectrum of the turbulence in the ISM from Chepurnov and Lazarian (2010).

Superdiffusion of magnetic field lines

- 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 (2021)

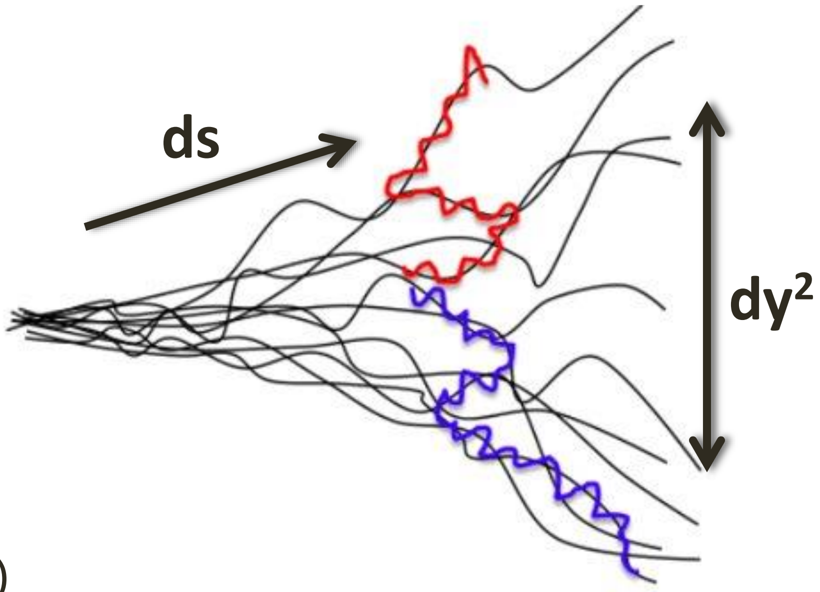


Figure 1. Because of the perpendicular superdiffusion of particles following diffusing magnetic field lines, particles that undergo bouncing move diffusively along the magnetic field. Thin lines represent magnetic field lines. Thick lines represent the trajectories of two particles whose initial separation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

Eyink et al. (2011)

Nonlinear Diffusion - Mirrors

- Mirrors are well known in plasma physics
  (e.g. Budker 1959; Noerdlinger 1968; Kulsrud & Pearce 1969)

- If R_L is smaller than the scale of B_{mirror}:
  (1st Adiabatic Invariant)

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

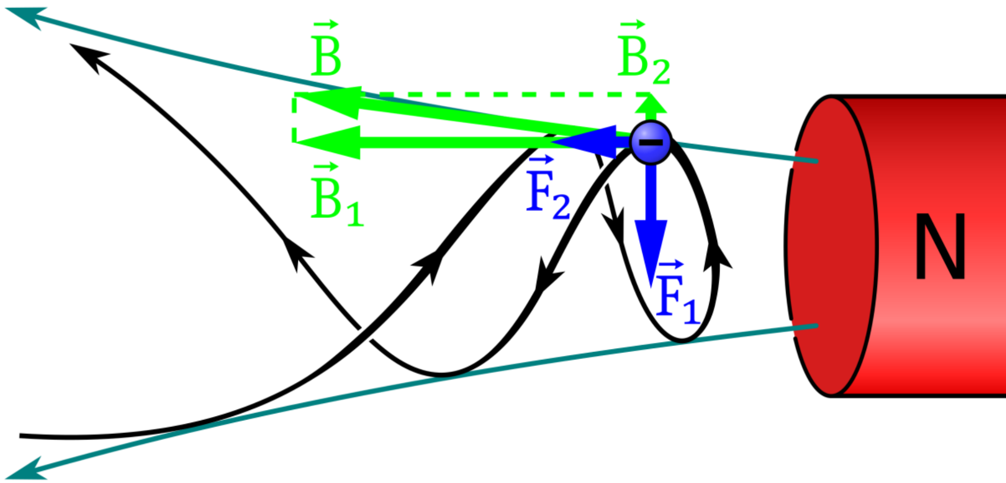


Image from
https://commons.wikimedia.org/wiki/File:Magnetic-mirror.svg

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

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

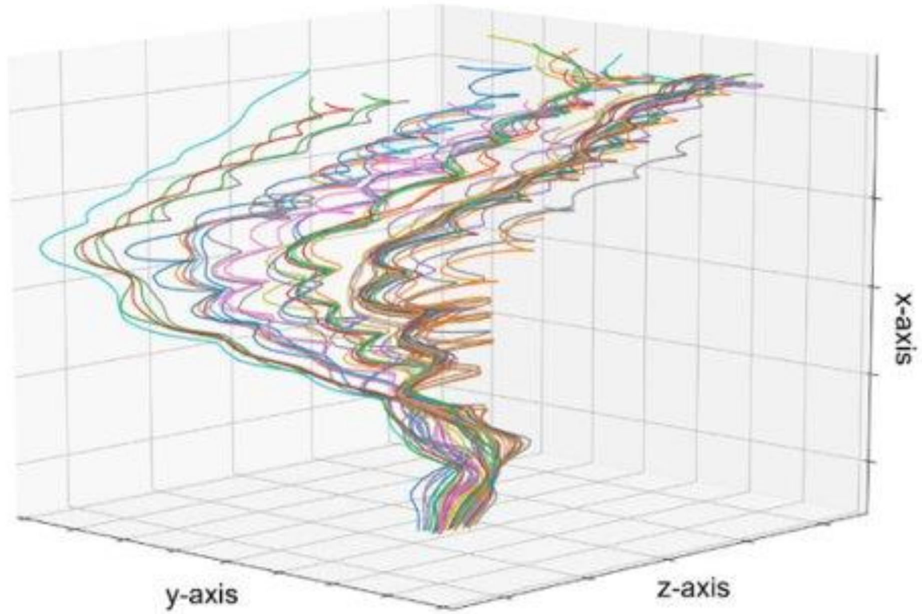
$$\mu_{lc}^2 = \cos^2\theta_{lc} = \frac{\delta b}{B_0 + \delta b},$$

Superdiffusion+Mirrors=Mirror Diffusion

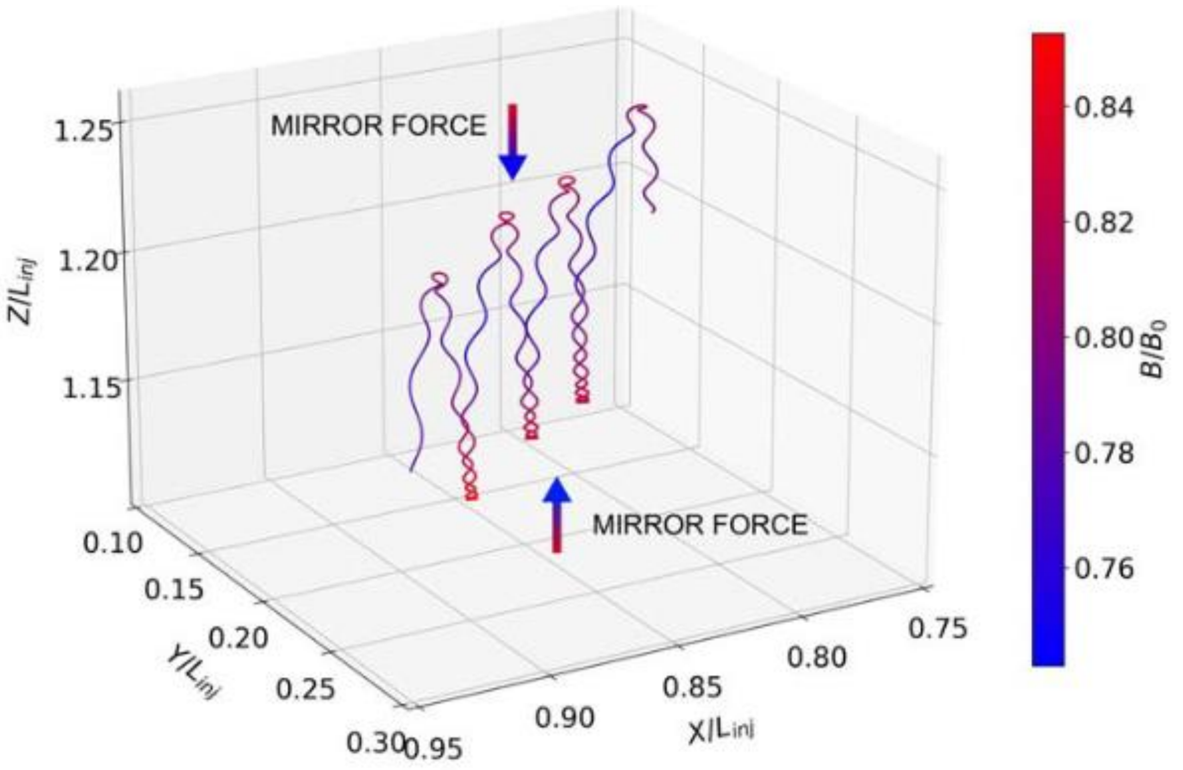
- Lazarian & Xu (2021).
- The only ingriedients needed are superdiffusion and mirrors.

It solves the QLT problems!

Hu et al. (2022)

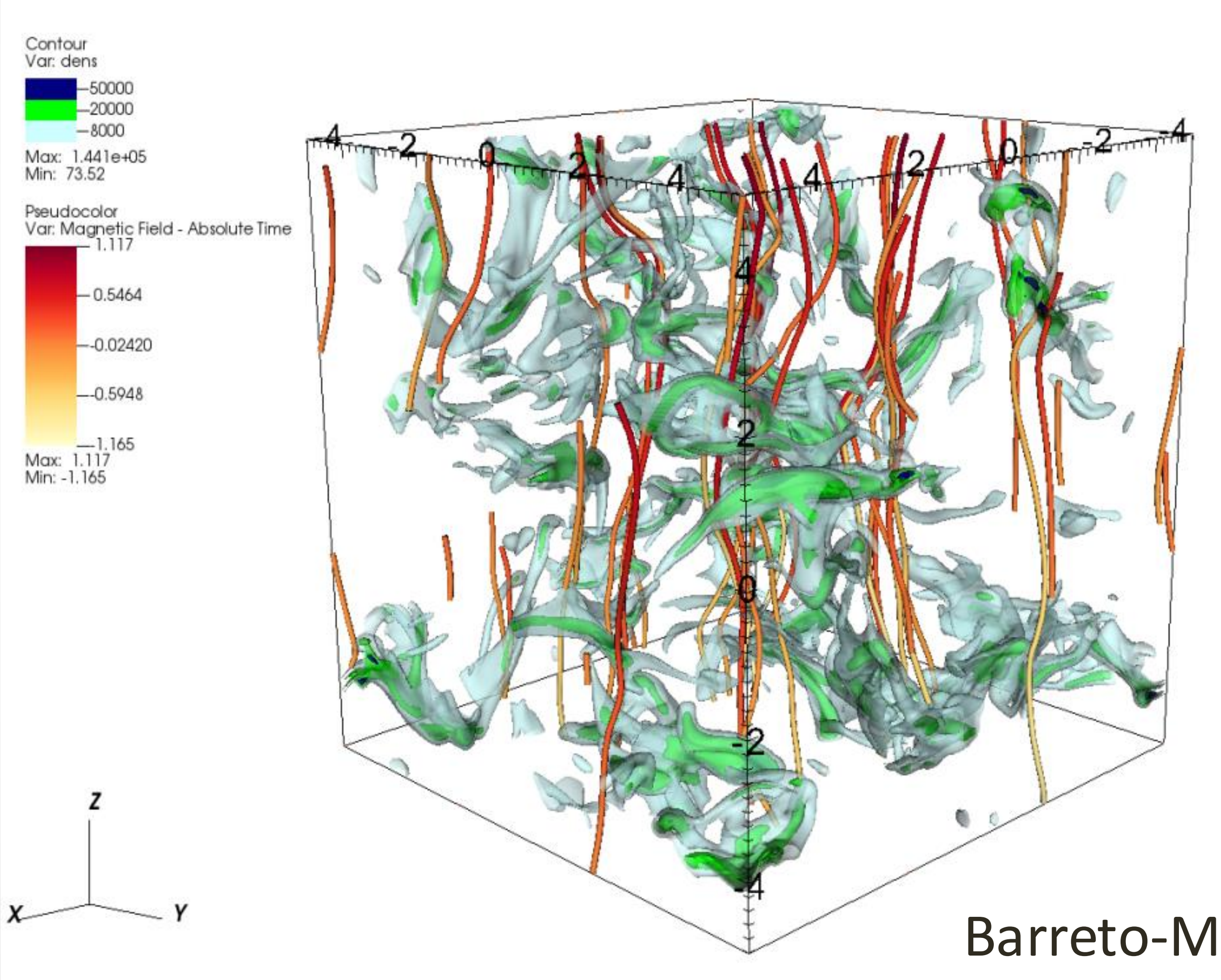


Zhang & Xu (2023)



SIMULATIONS TO TEST MIRROR DIFFUSION

Background MHD turbulent model of Molecular Cloud



- Gravitational collapse in magnetized, turbulent Molecular Clouds.
- Supersonic, sub-Alfvénic turbulence.

Barreto-Mota et al. 2021

Inject Test Particle Simulations

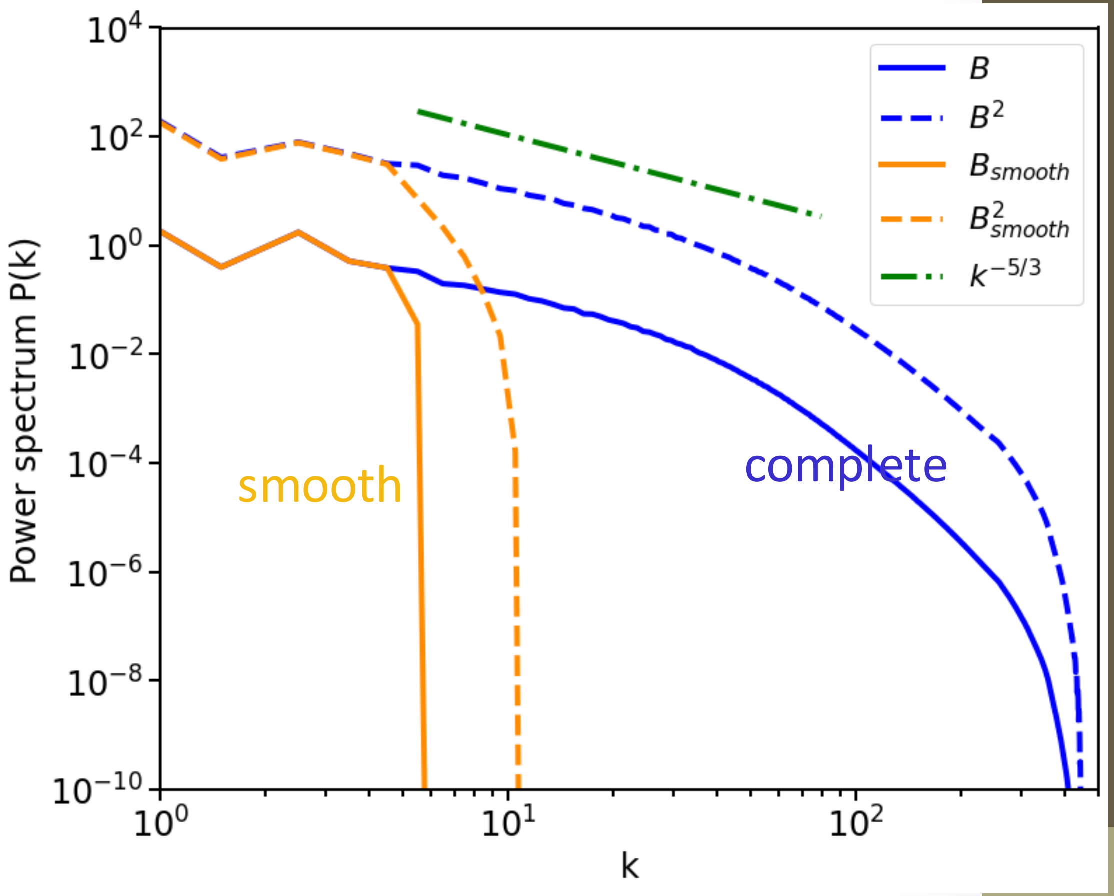
- We compute the Lorentz force in each point:

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

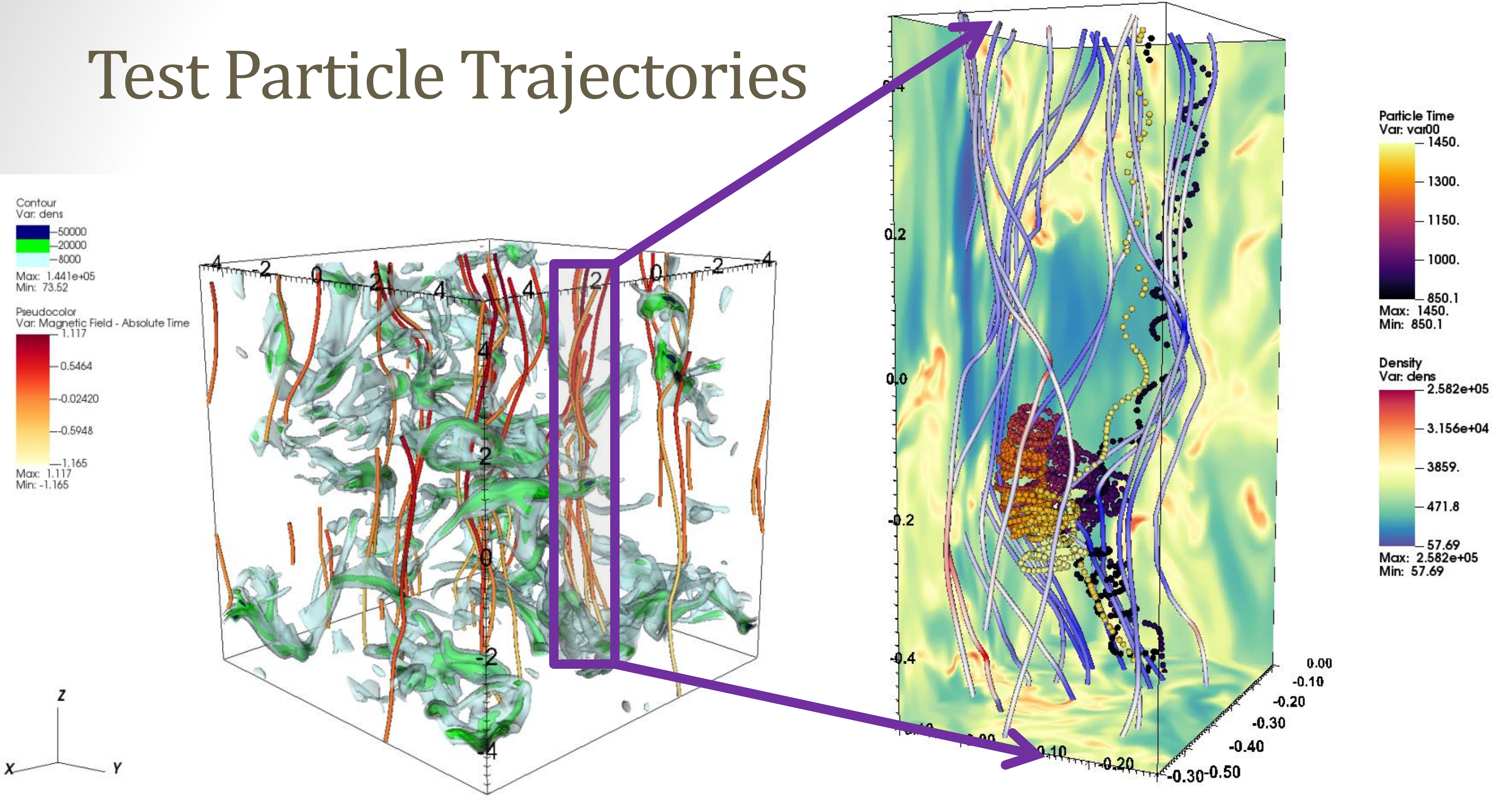
- Initial conditions:
  - Larmor radius
  - Pitch angle

R_L/L_0	$\mu_0 = \cos(\theta_0)$
0.03	0.20
0.06	0.80
0.10	

- Background magnetic field:
  - **Complete turbulent field distribution**
  - **Smoothed field**
    (small scale structures are removed,
    to reduce scattering diffusion)
    - $K_{smooth} = 5$

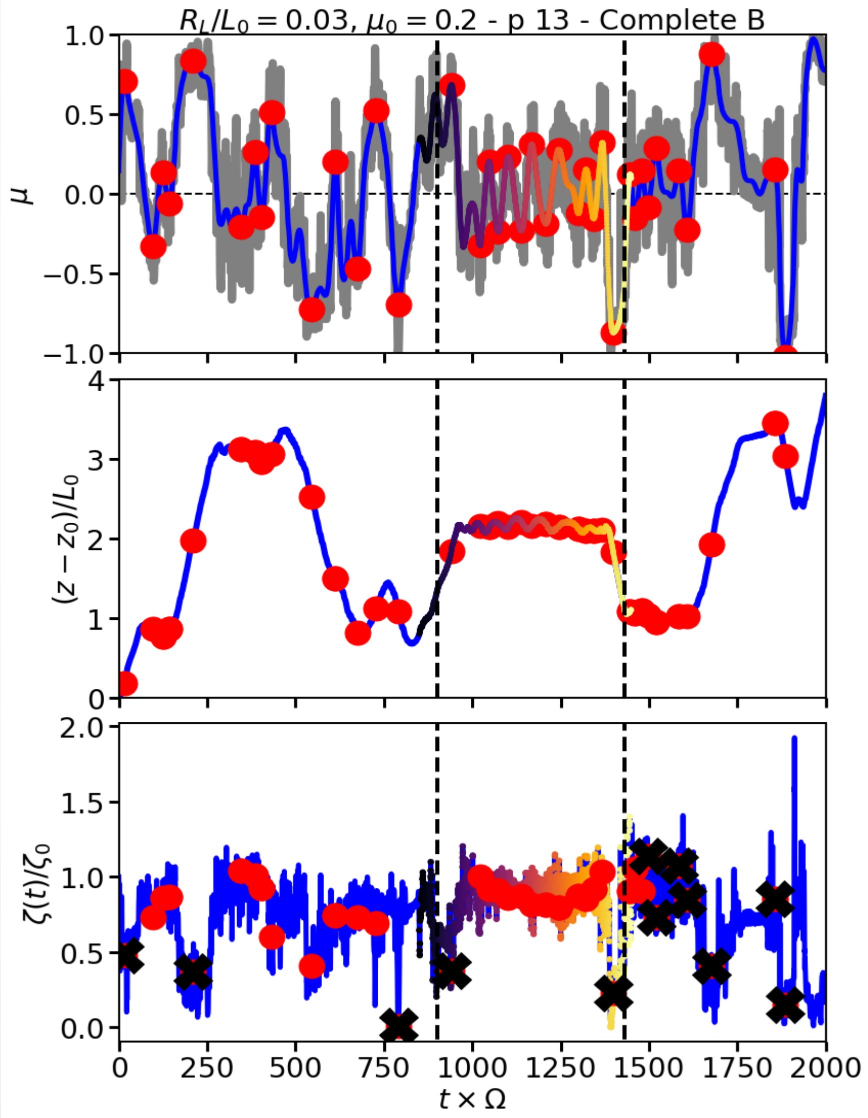


Test Particle Trajectories

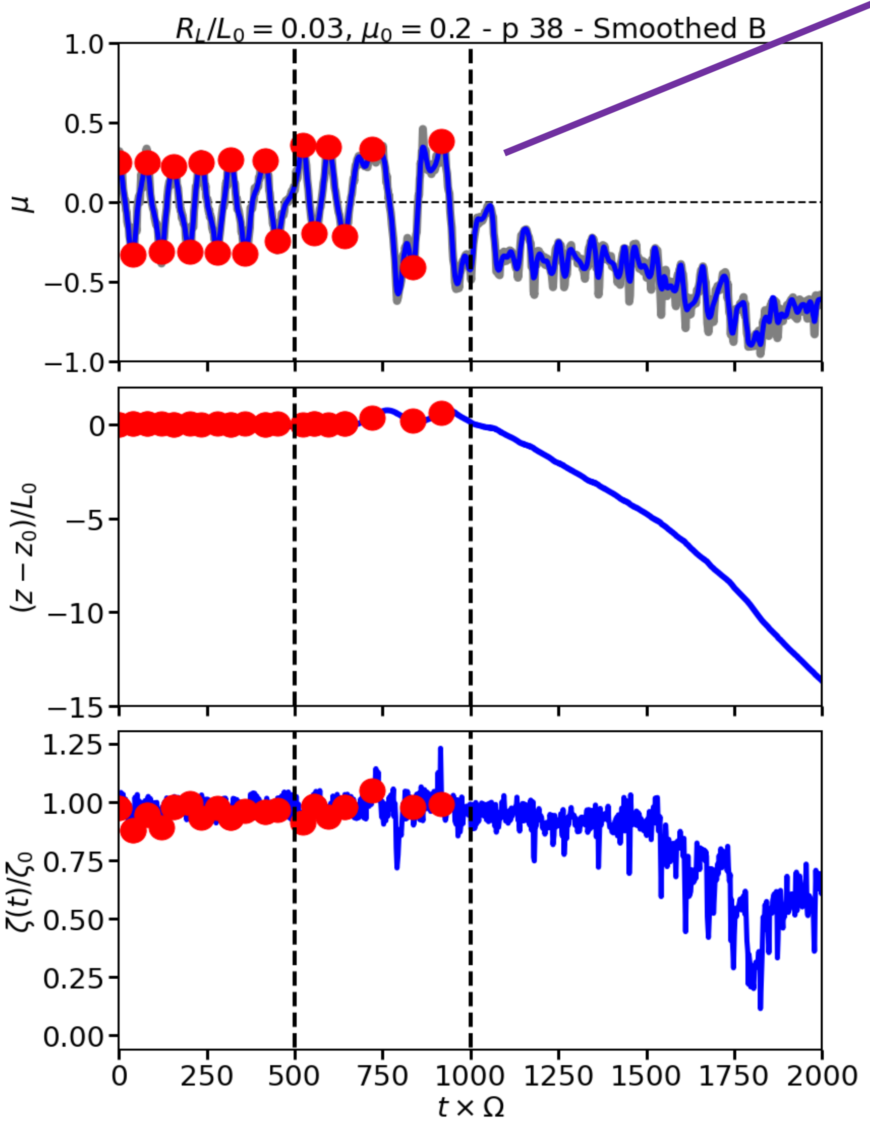


Identifying bounces

COMPLETE



SMOOTHED FIELDS



μ_b

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

Parallel displacement

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

Bounce μ distribution and Critical μ_c

- Bounces: $\mu < \mu_c$.

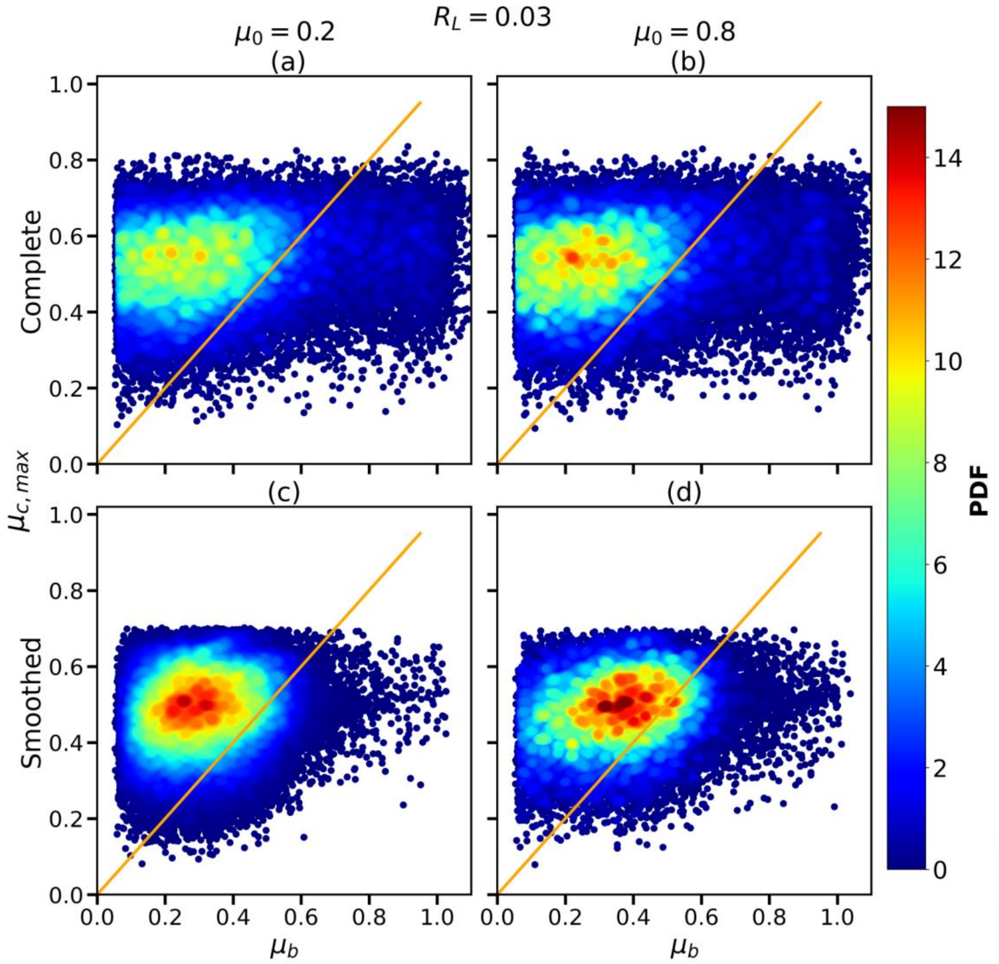
$$\mu_{c,\max} = \sqrt{\frac{\delta B_f}{B_0 + \delta B_f}}.$$

- Only events with nearly constant ζ / ζ_0.

- Most events follow Lazarian & Xu (2021).

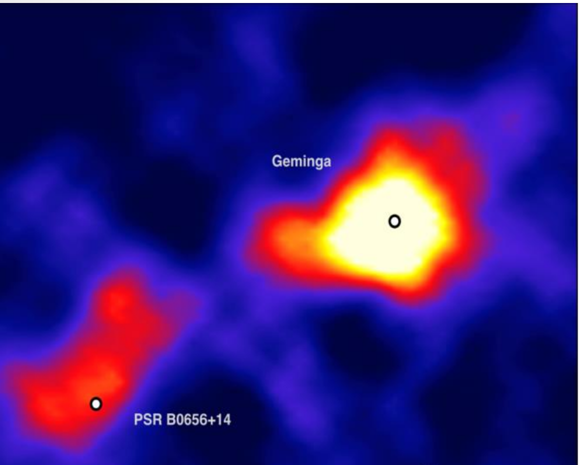
Complete

Smoothed

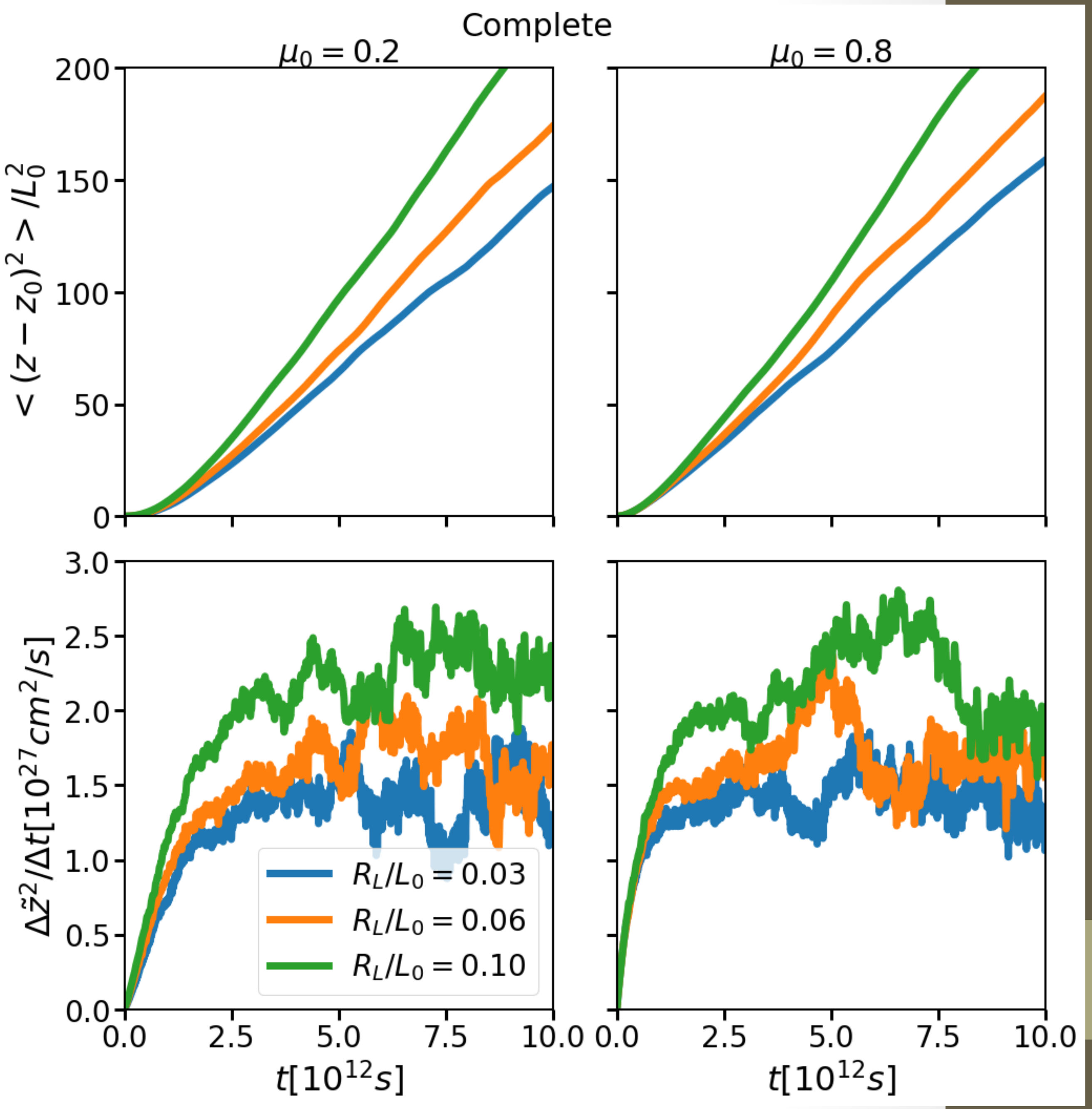


Parallel diffusion
Complete

- **Models scaled to a 3pc box.**
  - 3μG
  - **Region around PWN**
- Time to reach diffusion changes
- **$D_{//}$ around 10^{27} cm^2/s**



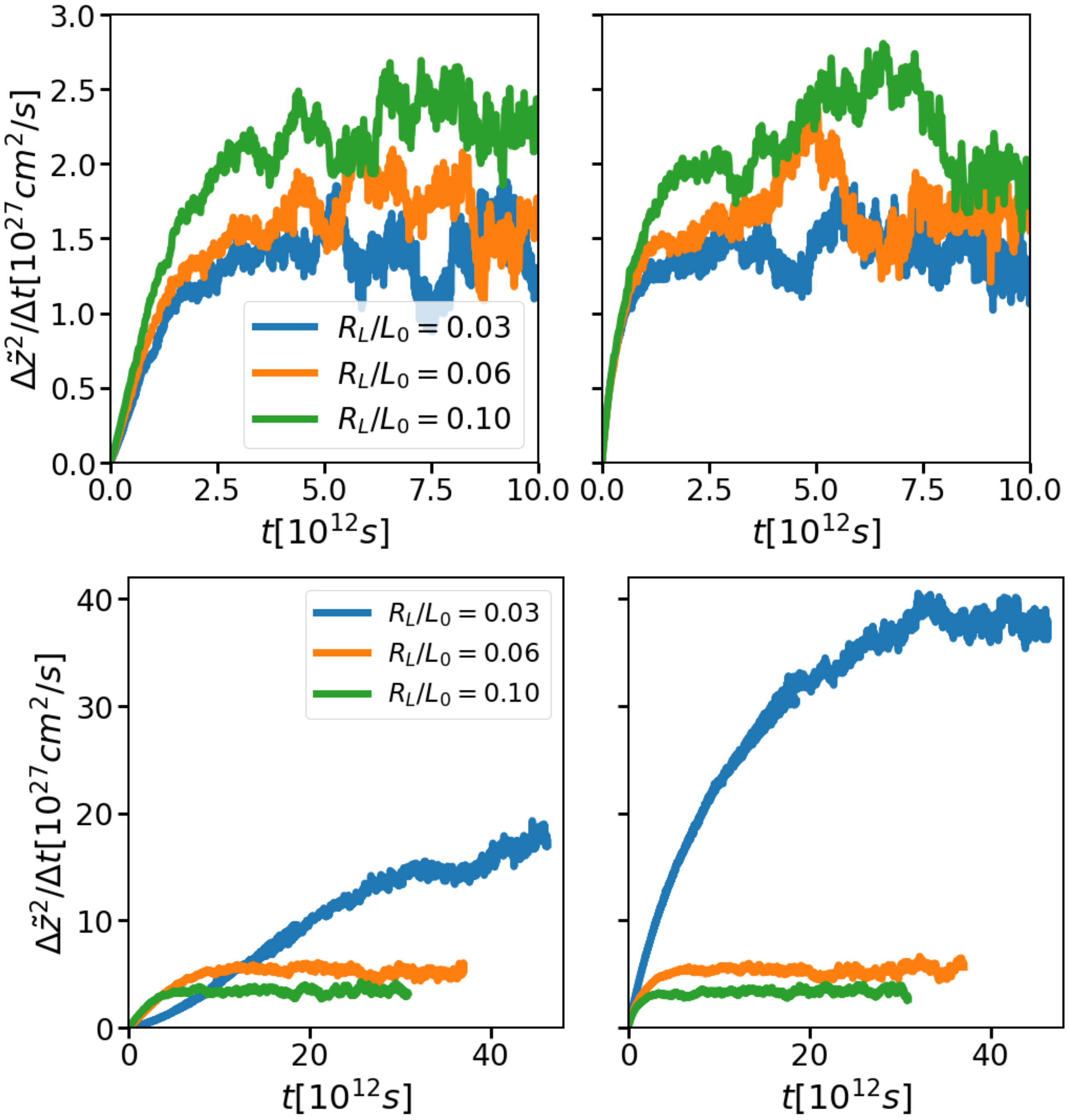
$$D_{\parallel} = \frac{<(z\text{-}z_0)^2>}{t}$$



Parallel diffusion
Smoothed

- Smoothed models.
  - Reduced scattering
  - Less small mirror structures
- Larger R_L still affected by scattering.
  - R_L > dissipation scale
- D is higher, but still smaller than ISM.

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



Applying our simulations to real systems

$B(\mu G)$	$L_0(pc)$	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}

- Considering different sizes

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

- Observed PWNe (Fang, 2022)

Source	**D_{100} [$cm^2 s^{-1}$]**
Gemiga halo	4.6×10^{27}
Monogem halo	1.5×10^{28}
LHAASO J0621+3755	2.3×10^{27}
HESS J1831-098	9.0×10^{27}

Applying our simulations to real systems

- Considering different sizes

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

$B(\mu G)$	$L_0(pc)$	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)

Source	**D_{100} [cm^2s^{-1}]**
Gemiga halo	4.6×10^{27}
Monogem halo	1.5×10^{28}
LHAASO J0621+3755	2.3×10^{27}
HESS J1831-098	9.0×10^{27}

Conclusions

- **Mirror diffusion allows for a slower diffusion of CRs.**
  - CRs do not stay trapped due to superdiffusion of the B lines.
  - Derived coefficients are compatible with observations.

- **Initial pitch angle is only important if scattering is suppressed**.
  - More pronounced for lower energy CR.
  - Diffusion near the source could depend on μ.

- **Important effects on CR propagation, acceleration and in the production of non-thermal radiation**, particularly at very high energies (TeV gamma-rays).

- **Can help to solve current puzzles related to the origin of gamma-ray emission, especially in TeV halos** (e.g., Abeysekara et al. 2017; Huang et al. 2018; Abeysekara et al. 2021; Cao et al. 2021).

Conclusions

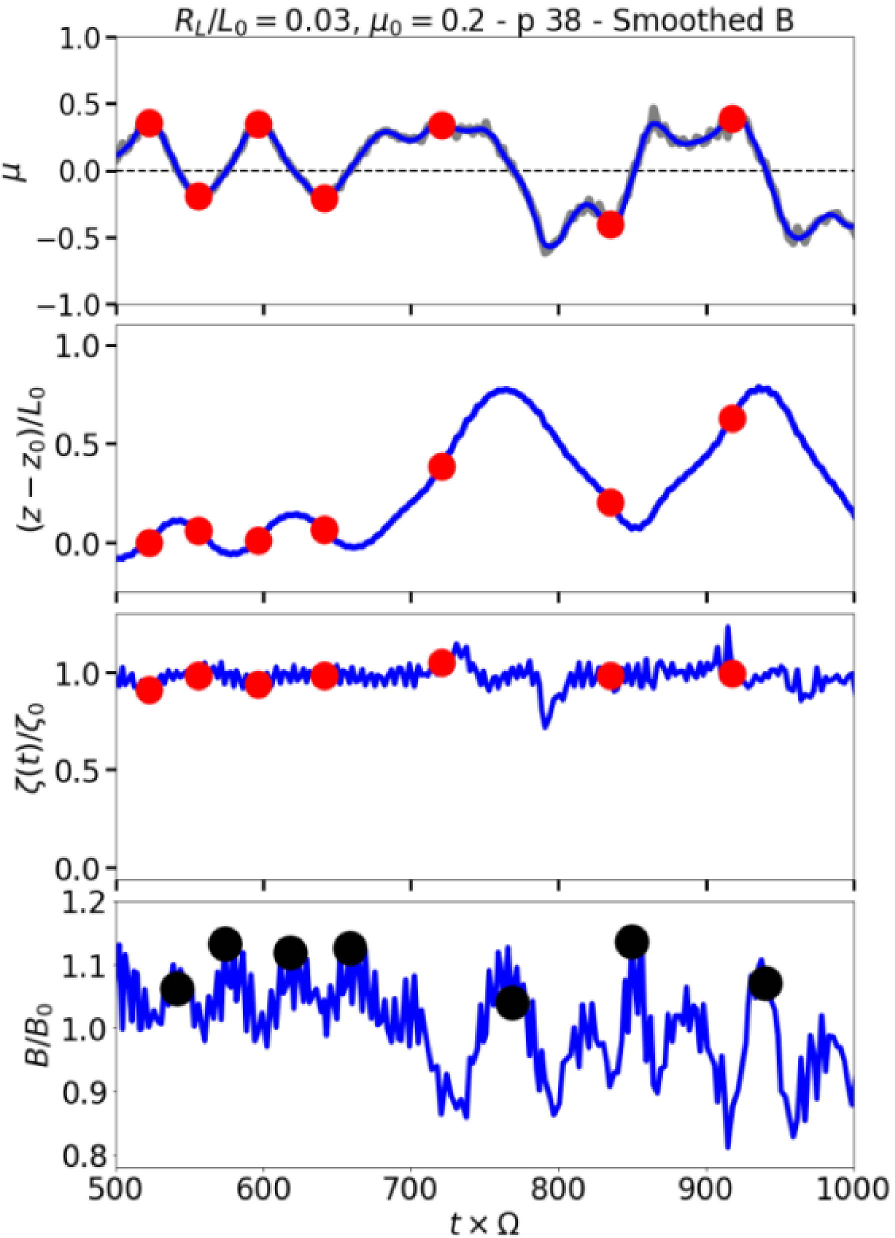
- **Mirror diffusion allows for a slower diffusion of CRs.**
  - CRs do not stay trapped due to superdiffusion of the B lines.
  - Derived coefficients are compatible with observations.
- **Initial pitch angle is only important if scattering is suppressed**.
  - More pronounced for lower energy CR.
  - Diffusion near the source could depend on μ.
- **Important effects on CR propagation, acceleration and in the production of non-thermal radiation**, particularly at very high energies (TeV gamma-rays).
- **Can help to solve current puzzles related to the origin of gamma-ray emission, especially in TeV halos** (e.g., Abeysekara et al. 2017; Huang et al. 2018; Abeysekara et al. 2021; Cao et al. 2021).

Thank you!

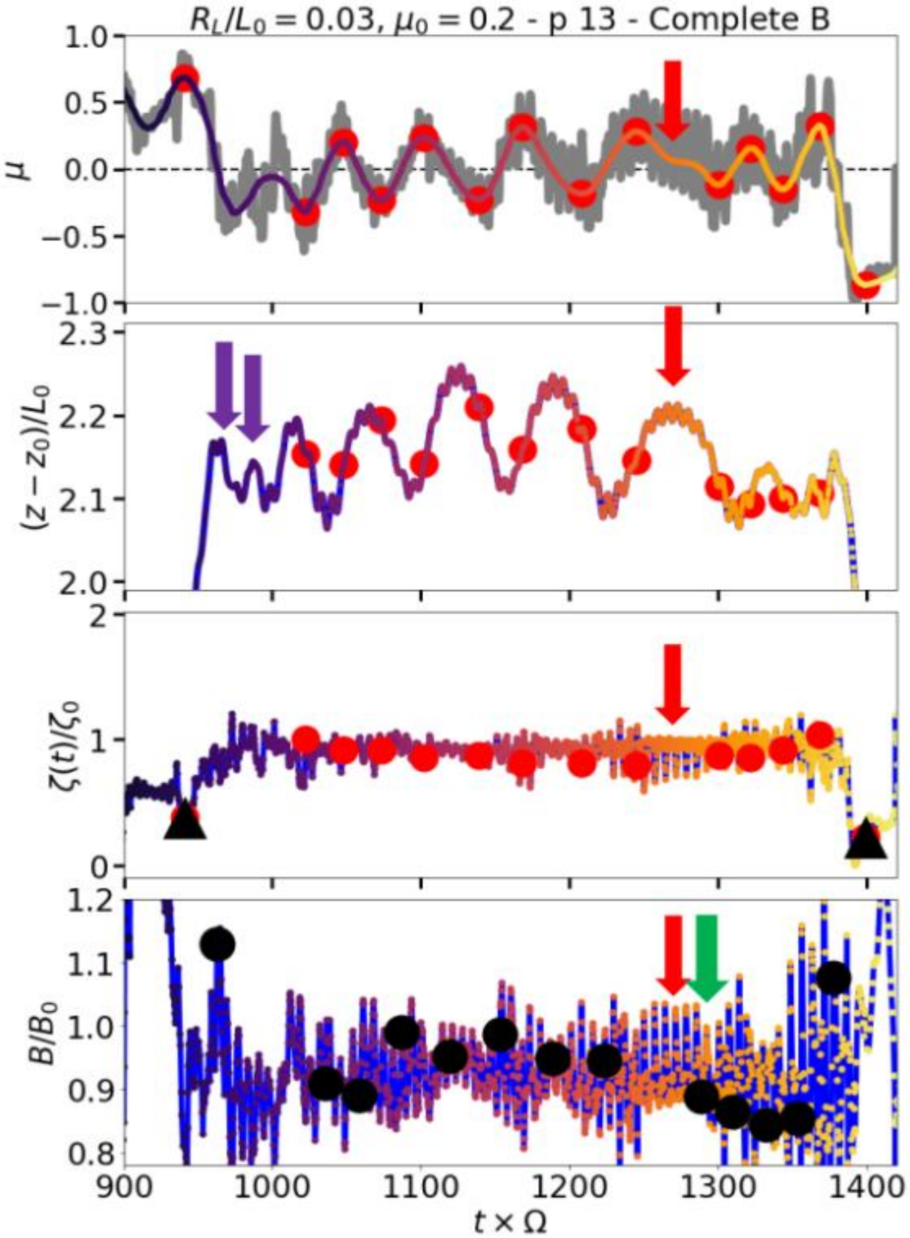
EXTRA SLIDES

R_L < dissipation scale

"No" scattering



R_L > dissipation scale



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

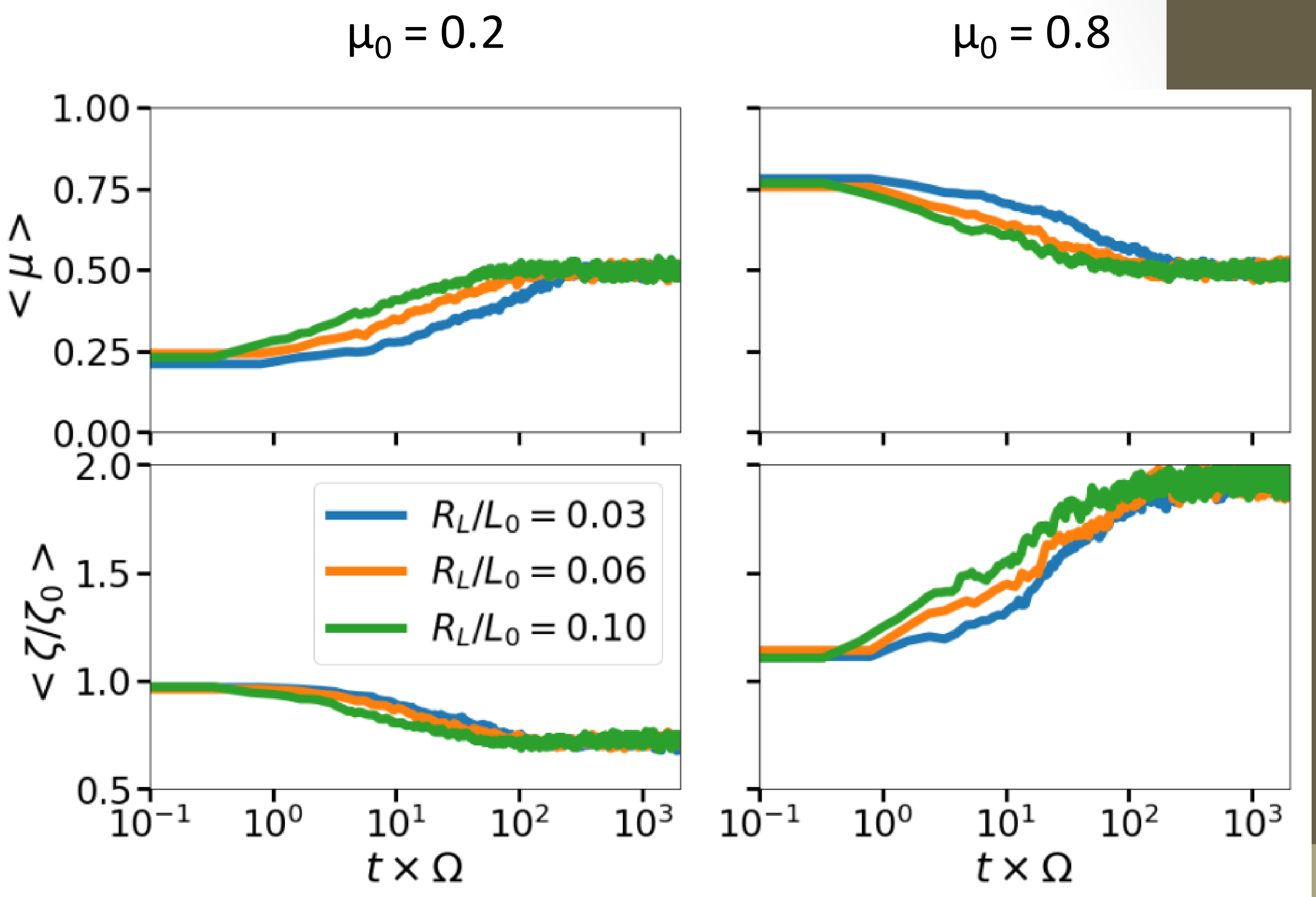
Parallel displacement

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

B/B_0

Parallel diffusion Complete

- All models reach a diffusive regime by the saturation.



Applying our simulations to real systems

- 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					Derived parameters	
	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	$4.6 \times 10^{27\ c}$	5^c
Monogem halo	201.11	8.26	111	0.288	3.8	$1.5 \times 10^{28\ d}$	4^d
LHAASO J0621+3755	175.88	10.96	208	1.6^b	2.7	$2.3 \times 10^{27\ c}$	40^c
HESS J1831−098	21.90	−0.13	128	3.68	110	$9.0 \times 10^{27\ e}$	7^e

Bounce μ distribution and Critical μ_c

- Bounces: $\mu < \mu_c$

$$\mu_{c,\max} = \sqrt{\frac{\delta B_f}{B_0 + \delta B_f}}.$$

Complete

Smoothed