Towards a new theory of Cosmic Ray Transport

NGC 3079 (Chandra)

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Outline

- CRs and CR transport in galaxies: the standard paradigm
- Theoretical and observational challenges and the need for a new theory
- A possible new class of models

Cosmic Ray Basics

Cosmic Rays = Relativistic particles that pervade in galaxies, clusters …

Mostly protons

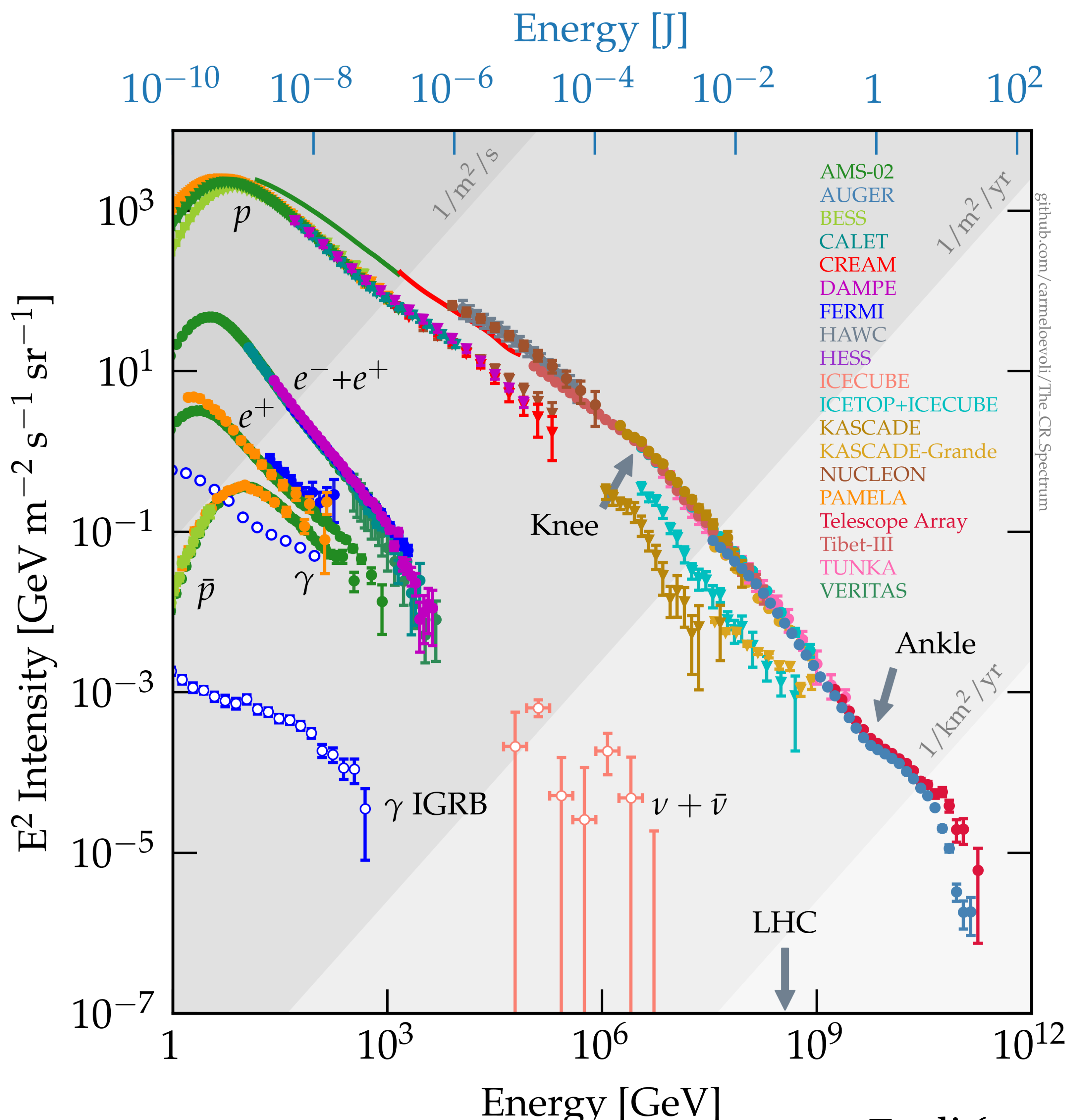
Power law spectrum over wide range of energies

$$\frac{dn_{CR}}{dE} \sim E^{-2.7}$$

Most of the energy in the GeV particles

Milky Way: $U_{CR} \sim U_{th} \sim U_B$

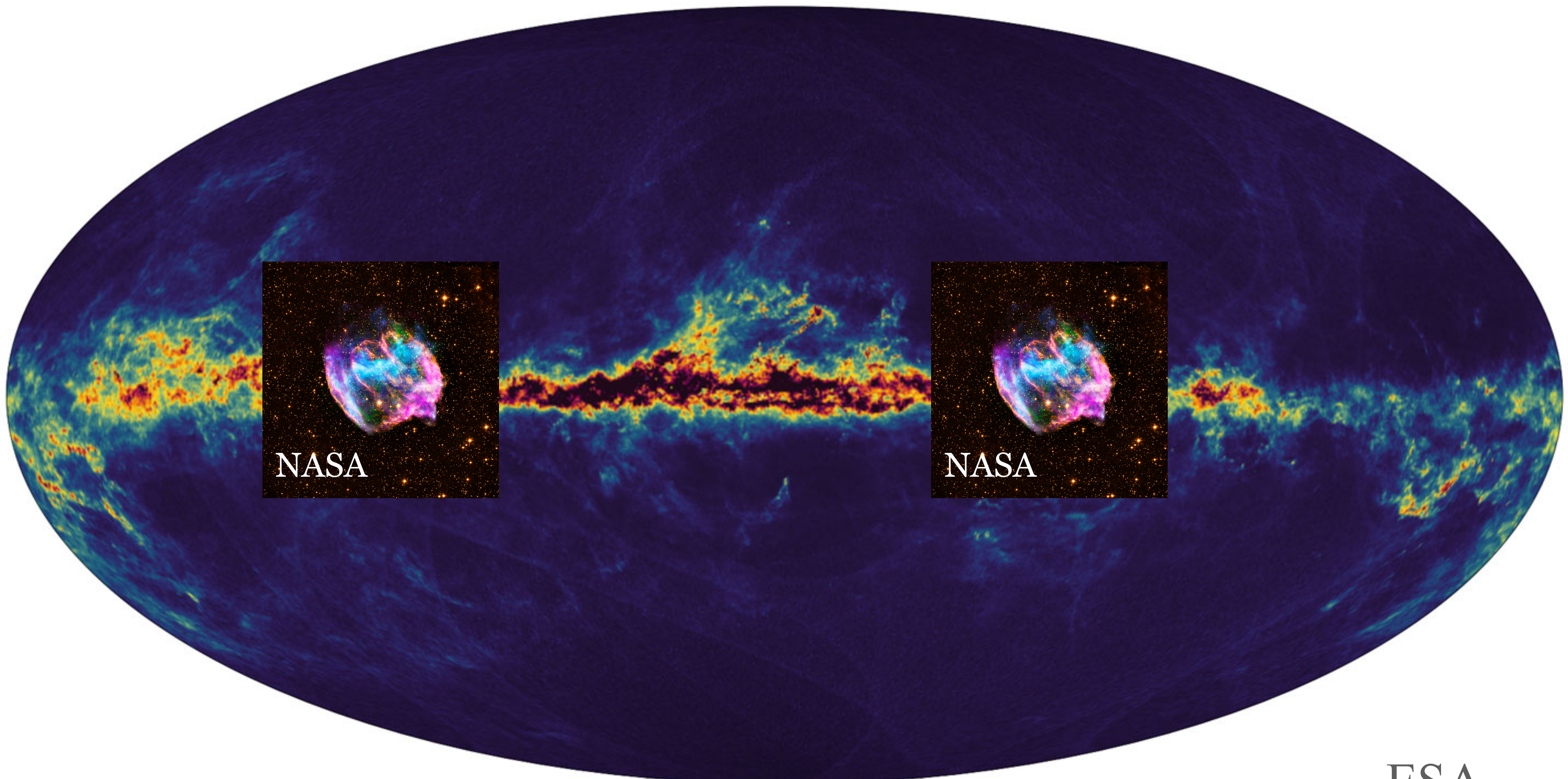
$\Rightarrow$ Galaxy Evolution



Evoli (2021)

Interpretation of observations

Based on CR spectra, abundance ratios, gamma ray observations, etc...



ESA

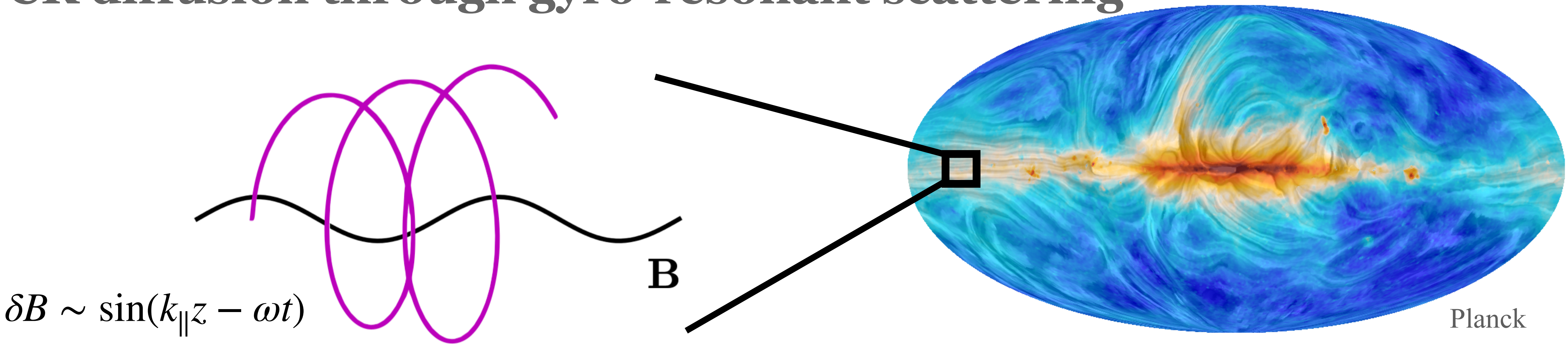
CRs accelerated by SNe : $f(E) \sim E^{-\gamma_{\text{inj}}}, \quad \gamma_{\text{inj}} \epsilon \, [2, 2.2]$

CRs escape time : $\tau_{\text{esc}} \propto E^{-\delta}, \quad \delta \sim 0.5$

Steady state spectrum in MW : $f(E) \sim E^{-2.7}$

Standard paradigm of long confinement

CR diffusion through gyro-resonant scattering



$$k_{\parallel} v_{\parallel} - \omega = n\Omega \qquad n = 0, \pm 1, \pm 2, \ldots$$

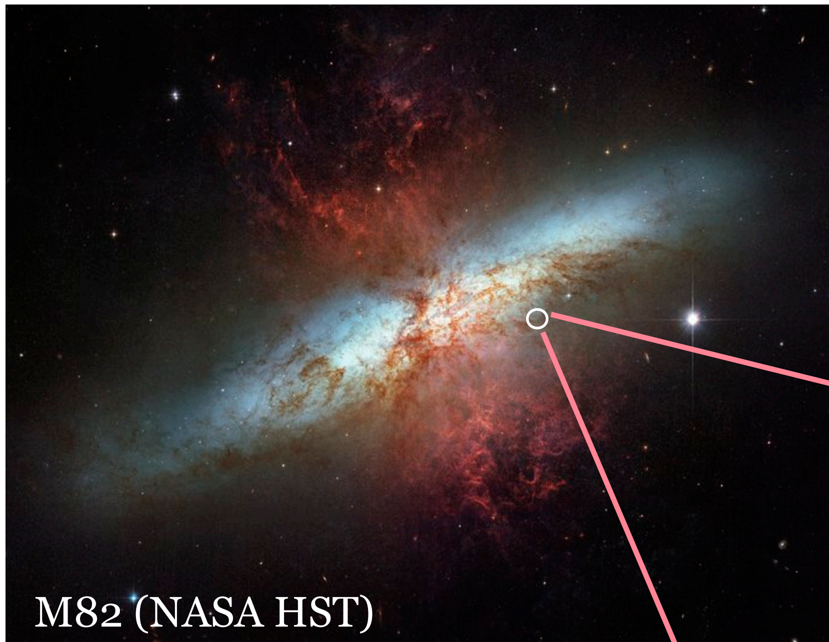
Cyclotron Resonance:

$$k_{\parallel} v_{\parallel} \approx \Omega \;\Rightarrow \lambda \sim \rho_L \qquad \Rightarrow \qquad \nu \sim \Omega(\delta B/B)^2$$

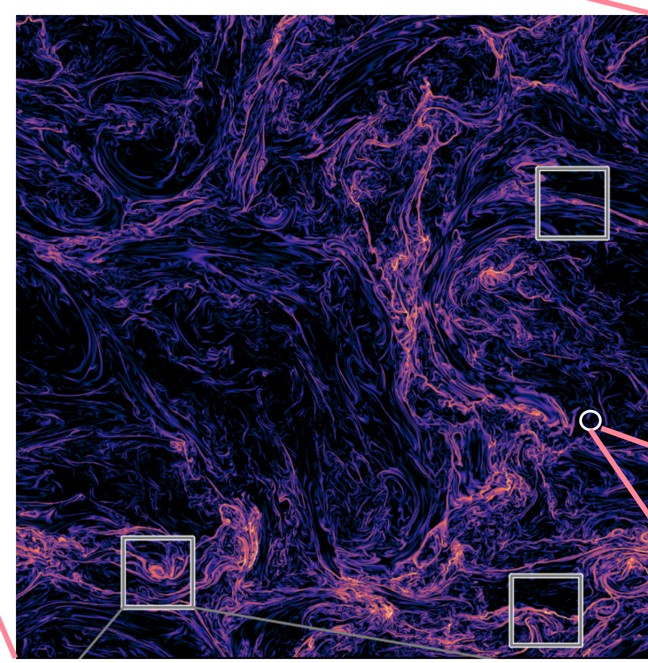
Resonant pitch-angle scattering by volume-filling small-amplitude magnetic fluctuations

A note about scales

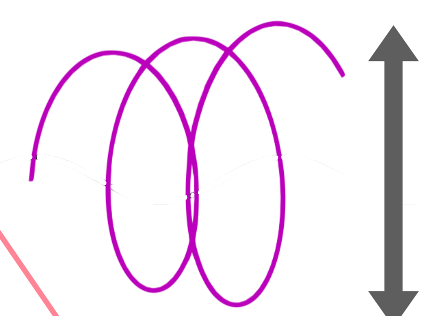
$1 \text{ pc} \approx 3$ light years



~ 10 kpc



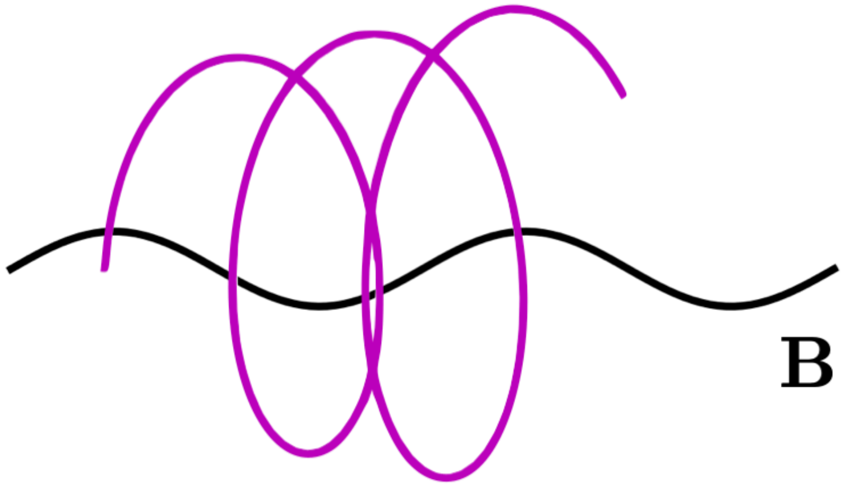
~ 100 pc



1 AU $\sim 10^{-6}$ pc

GeV CR

Standard paradigm of long confinement



$\delta B \sim \sin(k_{\parallel} z - \omega t)$

$$\nu \sim \Omega \left[\frac{\delta B(k \sim r_L^{-1})}{B} \right]^2$$

For isotropic Kraichnan-type cascade:

$$\delta B(k) \sim k^{-1/4} \quad \Rightarrow \quad \nu \propto r_L^{-1/2}$$

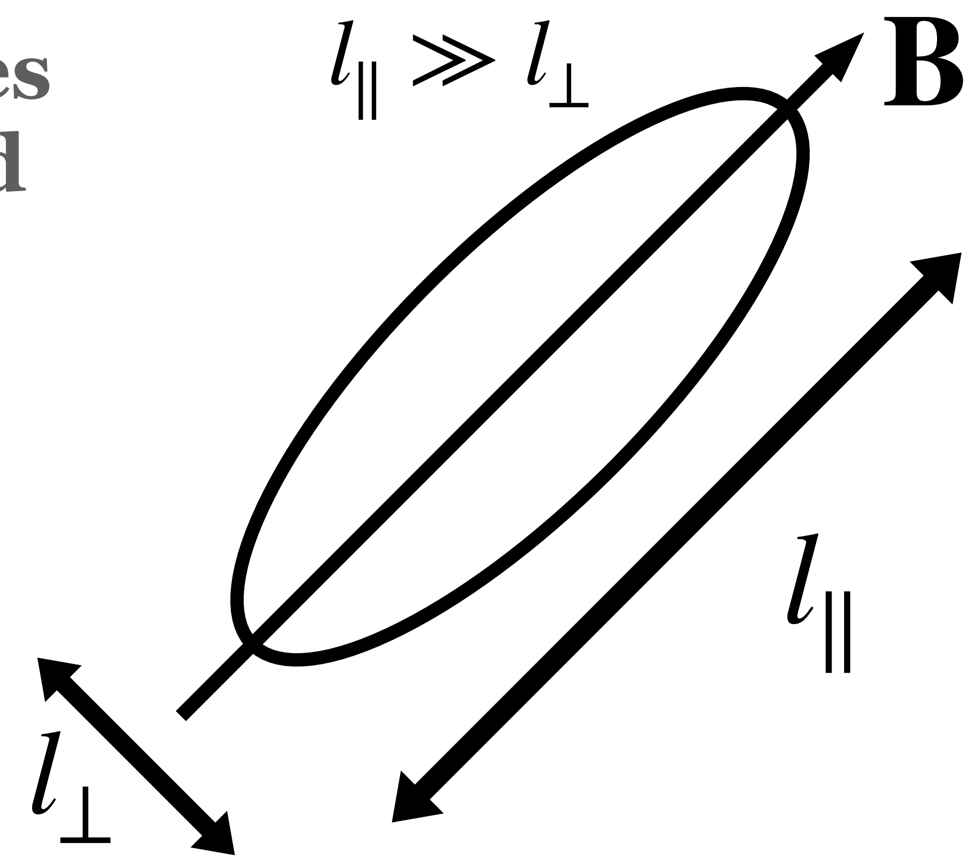
Successful at reproducing observations

Commonly used model in the CR literature*

***often in combination with additional source of waves on small scales from the CR streaming instability**

MHD Turbulence not isotropic

In incompressible MHD, turbulent eddies are highly elongated along magnetic field



Eddy shape set by “Critical Balance”:

$$\frac{l_{\|}}{v_A} \sim \frac{l_{\perp}}{\delta u(l_{\perp})} \quad \Rightarrow \quad \frac{l_{\|}}{l_{\perp}} \sim \frac{v_A}{\delta u(l_{\perp})} \gg 1$$

CR scattering suppressed (Chandran 2000)

Compressible MHD Turbulence

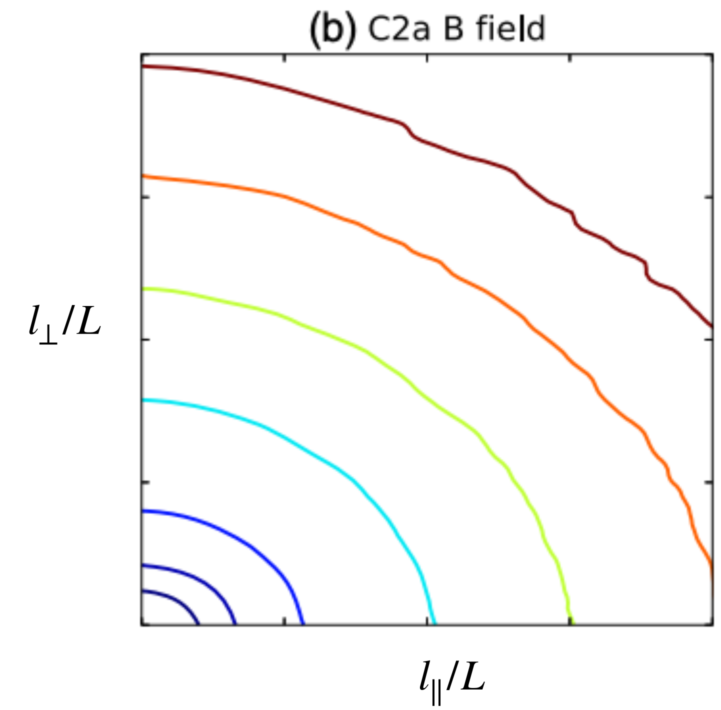
Cascade of fast modes proposed by Yan & Lazarian (2004) as alternative for CR scattering

1. Plausibly isotropic (Cho & Lazarian 2003)

2. If weak turbulence cascade

$$\tau_{\mathrm{casc}}^{-1}(k, \delta \mathrm{v}) \sim \frac{k \delta \mathrm{v}^2}{\mathrm{v}_{\mathrm{ph}}} \quad \Rightarrow \quad P(k) \sim k^{-3/2}$$

Kraichnan-like power spectrum (Zakharov & Sagdeev 1970)



Makwana & Yan 2020

$$\kappa \sim l_{\mathrm{mfp}} \propto E^{0.5} \sim \text{observations}$$

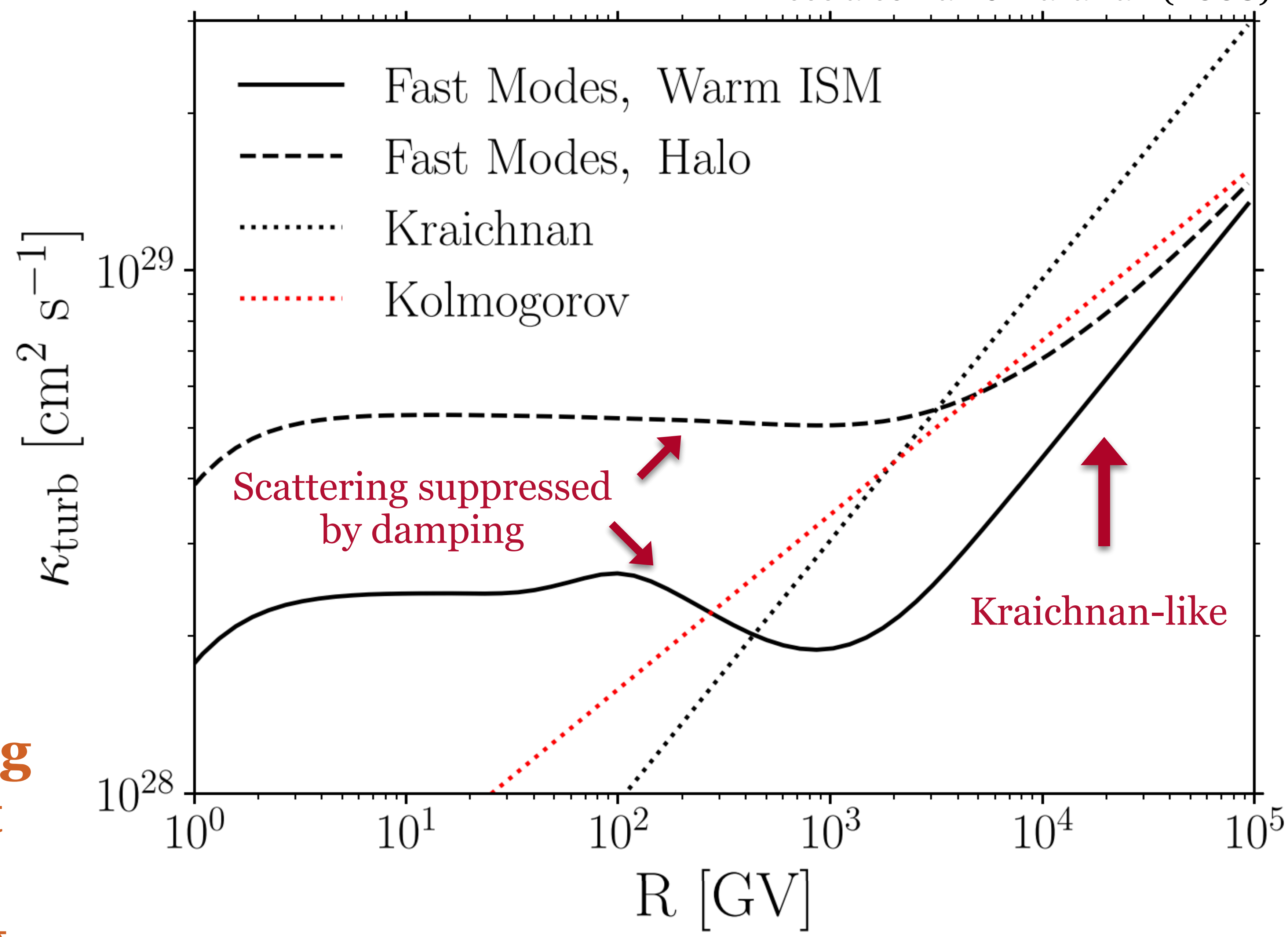
Leading theory for CR scattering in turbulence over the past two decades

Fast-mode damping

Fast modes strongly damped by non-ideal MHD effects (neutrals, **low collisionality**)

Kempski & Quataert (2022),
see also Yan & Lazarian (2008)

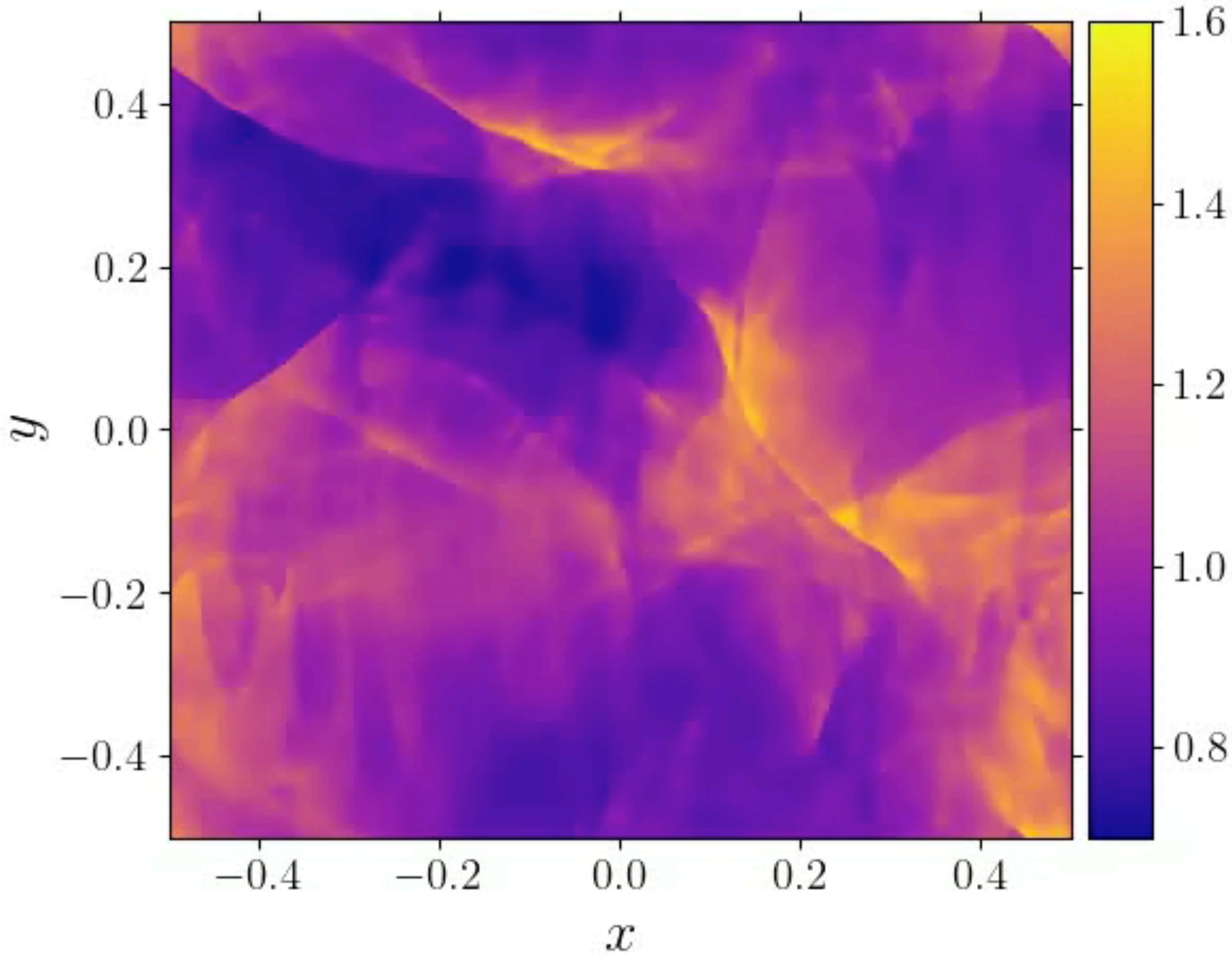
Dilute, hot plasmas occupy most of the galactic volume

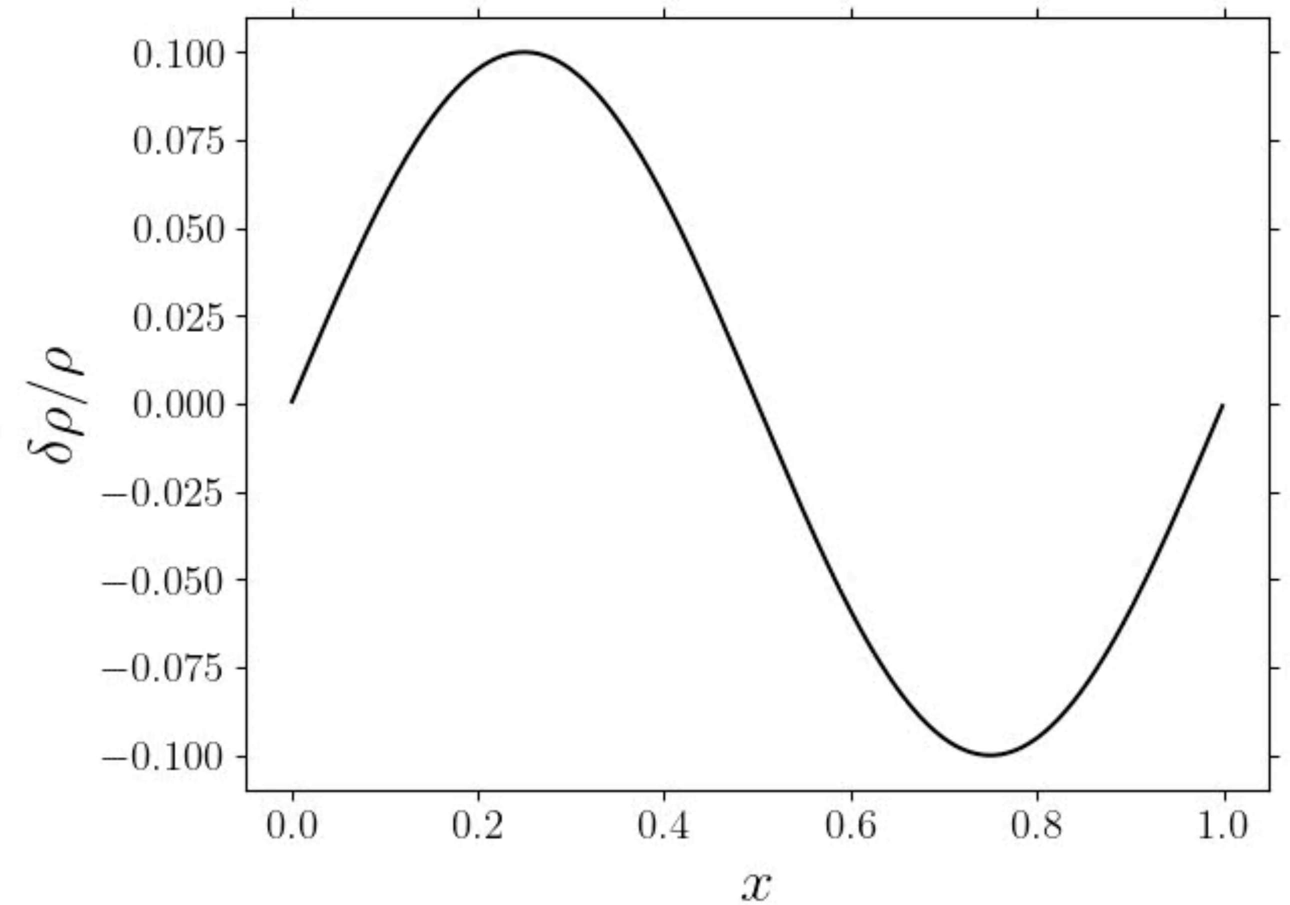


As a result, reproducing observables using fast modes involves very significant fine-tuning

Kempski & Quataert (2022)

Does fast-mode turbulence exist?





Driving generates weak shocks, not a cascade!

$$\tau_{\rm steep}^{-1} \sim k\delta{\rm v}$$

$$\frac{\tau_{\rm steep}^{-1}}{\tau_{\rm casc}^{-1}} \sim \frac{k\delta{\rm v}}{k\delta{\rm v}^2/{\rm v}_{\rm ph}} \sim \frac{{\rm v}_{\rm ph}}{\delta{\rm v}} \gg 1$$

Suppresses fast-mode cascade & CR scattering

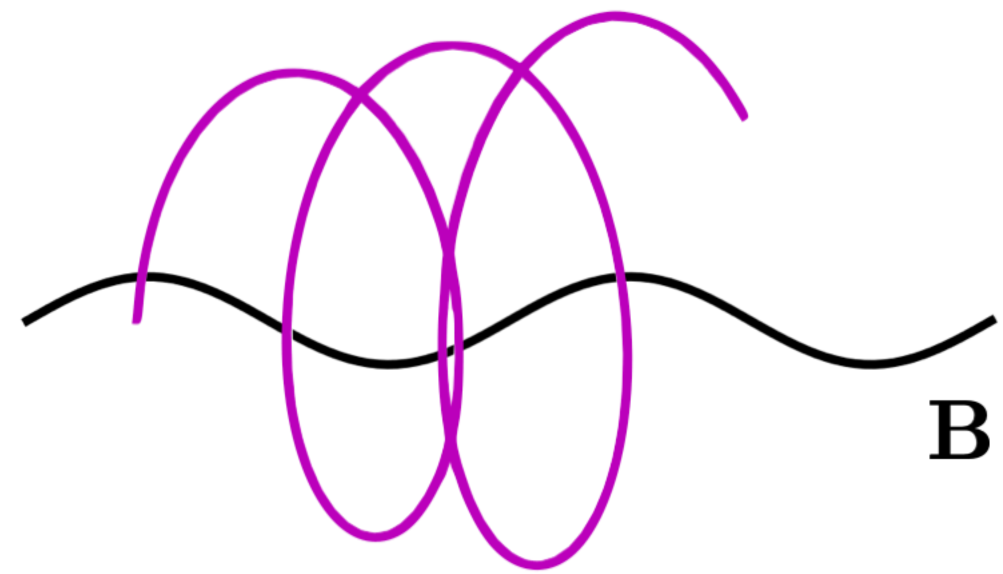
Kempski & Quataert (2022)

Existing models of CR transport face severe observational and theoretical challenges

Do we need a new theory of CR transport in turbulence?

Standard paradigm of CR transport

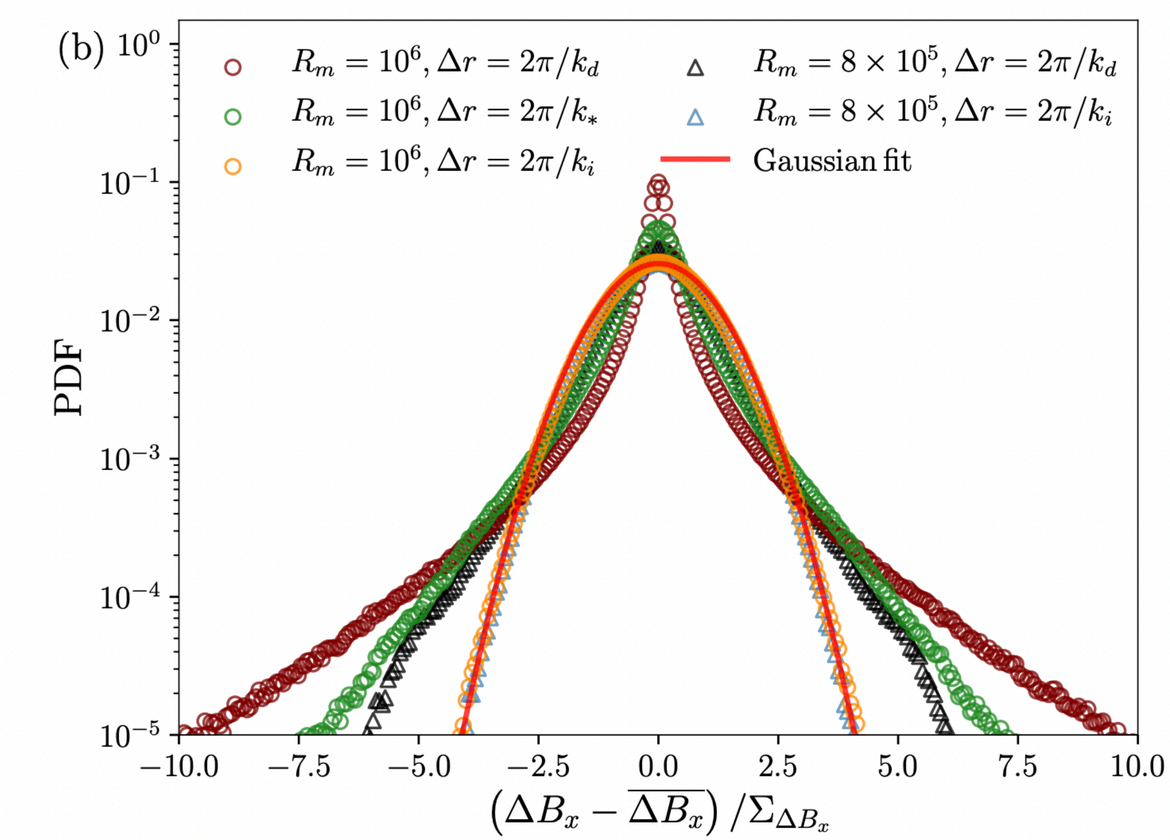
Small-angle scattering by volume-filling small-amplitude magnetic fluctuations



Key assumptions of standard calculation:

1. Assume quasi-linear theory
2. Assume gaussian fluctuations and random phases

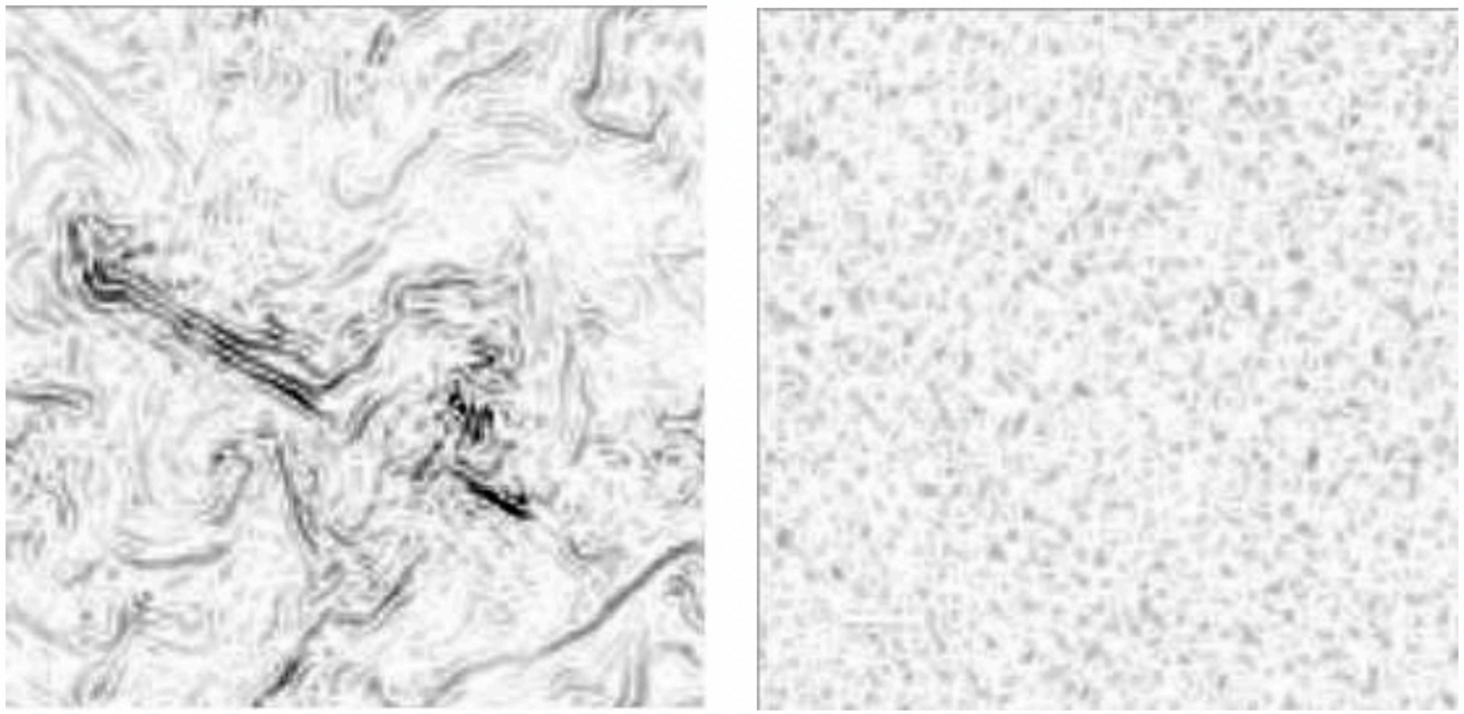
Particle transport fully determined by turbulence power spectrum, no intermittency effects



Dong et al. (2018)

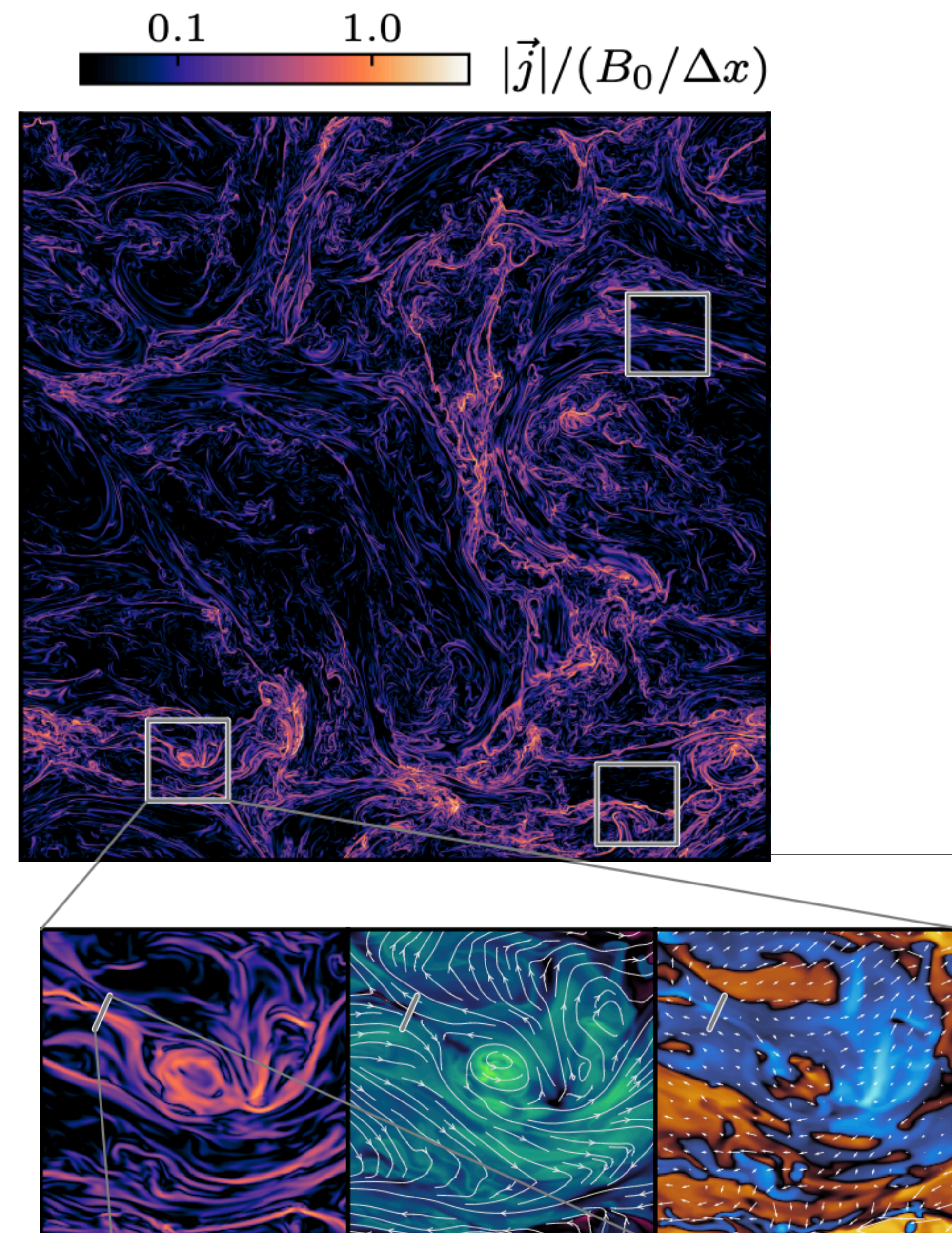
How important is intermittency?

Turbulent Field **Randomized Phases**



Maron & Goldreich (2001)

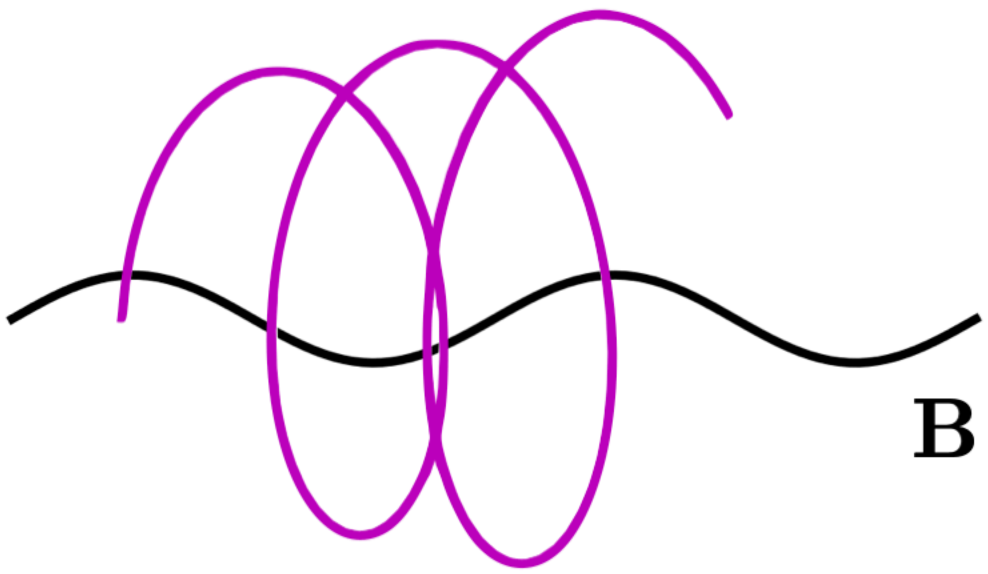
Fielding et al. (2022)



Field reversals on all scales?

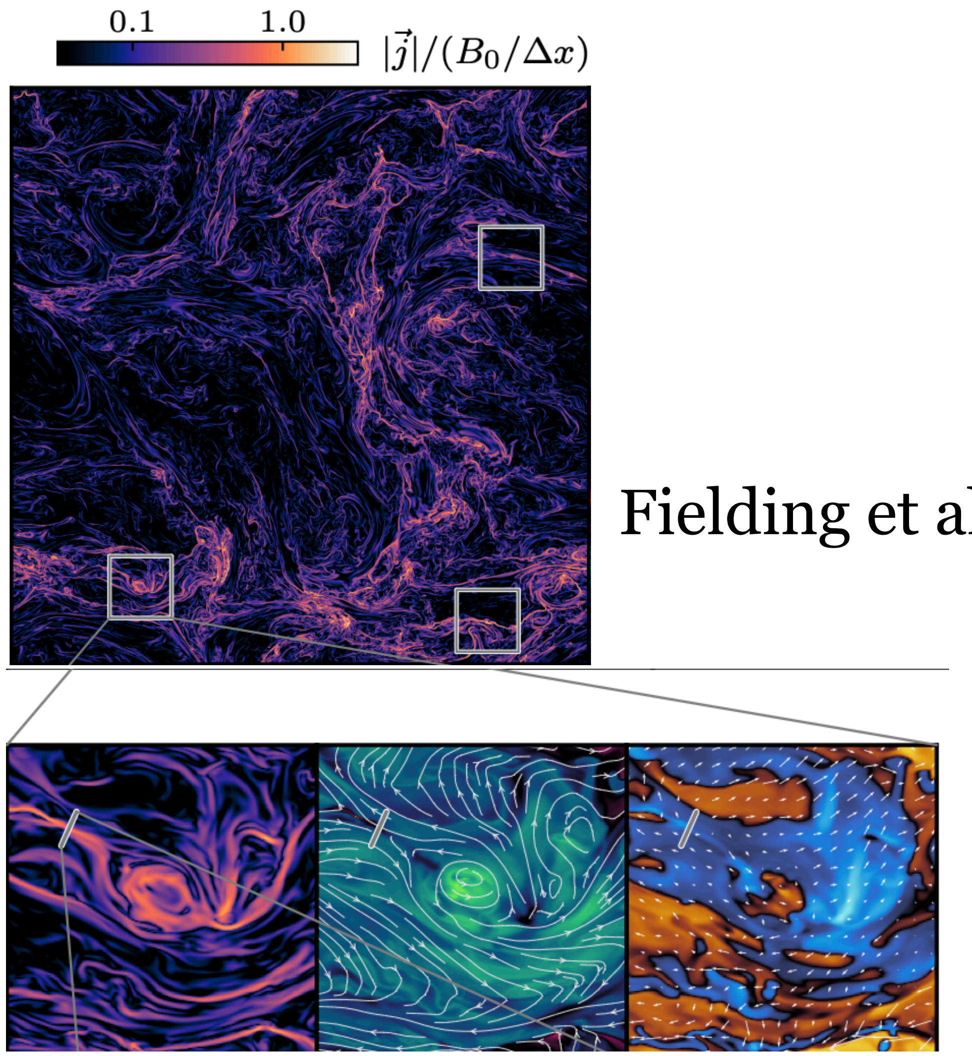
Standard paradigm of CR transport

Small-angle scattering by volume-filling small-amplitude magnetic fluctuations



Possible new transport model

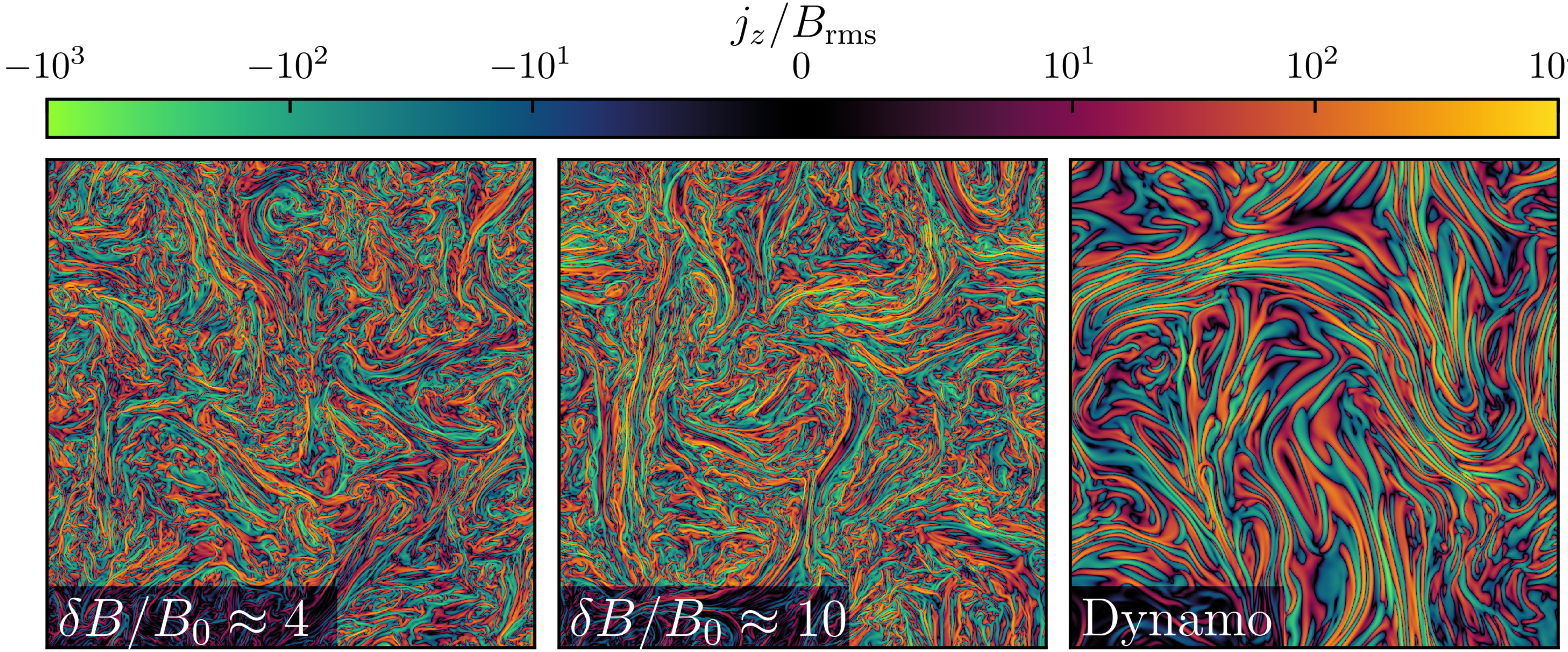
Is CR transport mediated by rare reversals in the B-field direction?



Fielding et al. (2022)

Testing the intermittent scattering hypothesis

Test particle simulations of CR transport in the presence of **frequent field reversals** in regime **without strong guide field**



Galishnikova et al. (2022)

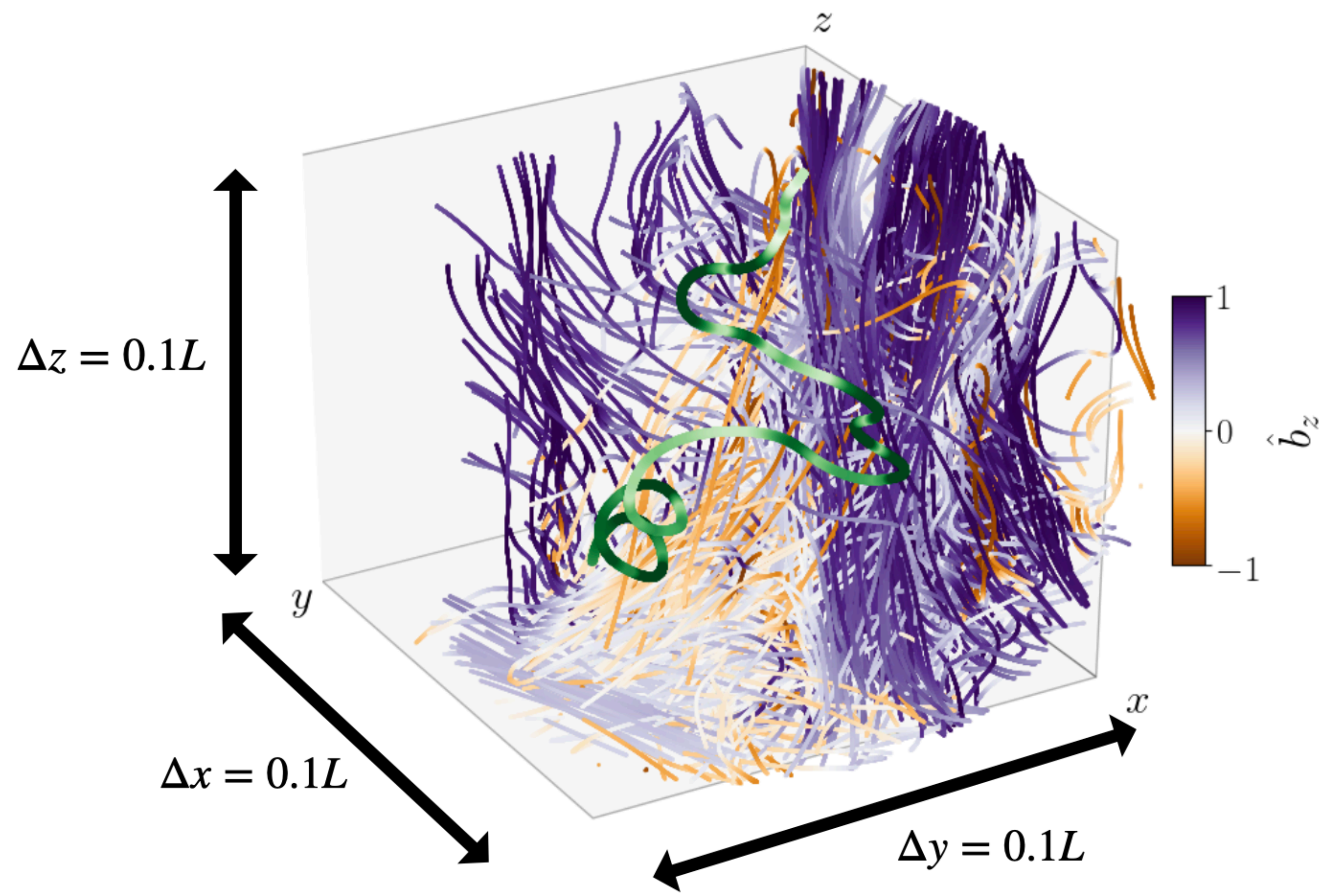
$$\mathbf{j} = \nabla \times \mathbf{B}$$

Dynamo: Re~20, Pm=500

Kempski et al. (2023), arXiv:2304.12335

Particle transport

Particle transport very different from strong guide field limit, as particles interact with frequent field reversals



Quantifying transport using pitch-angle diffusion not appropriate

Kempski et al. (2023), arXiv:2304.12335

Turbulent Leaky Box

Inject particles in turbulent box at fixed time intervals (uniformly and space and time)

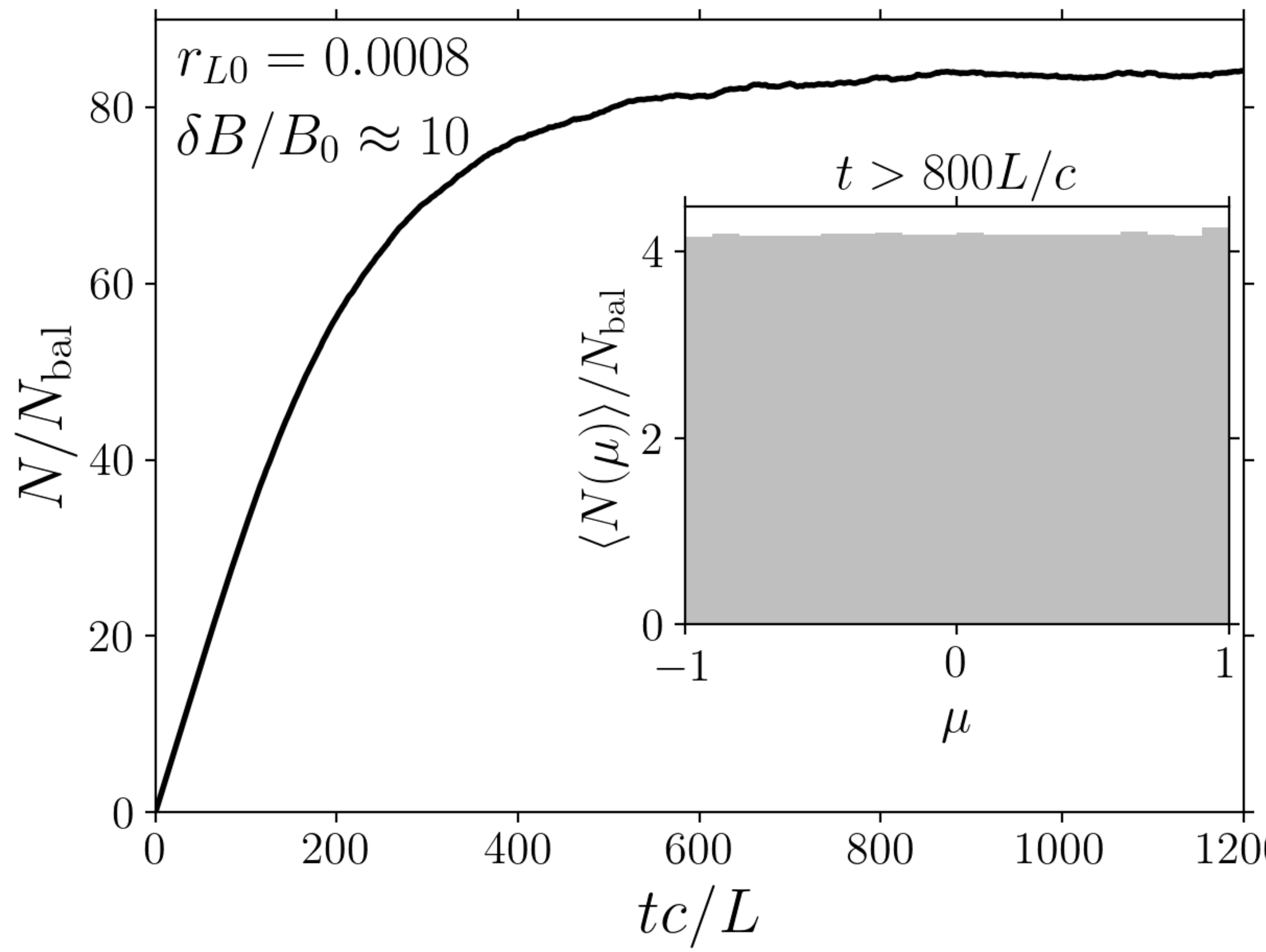
Particle "escapes" when:

$$\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} > H$$

If diffusive transport:

$$\langle N \rangle \sim \frac{H^2}{\kappa_{\rm eff}} \propto \nu_{\rm eff}$$

Measures net transport due to scattering, trapping in magnetic mirrors and field line tangling



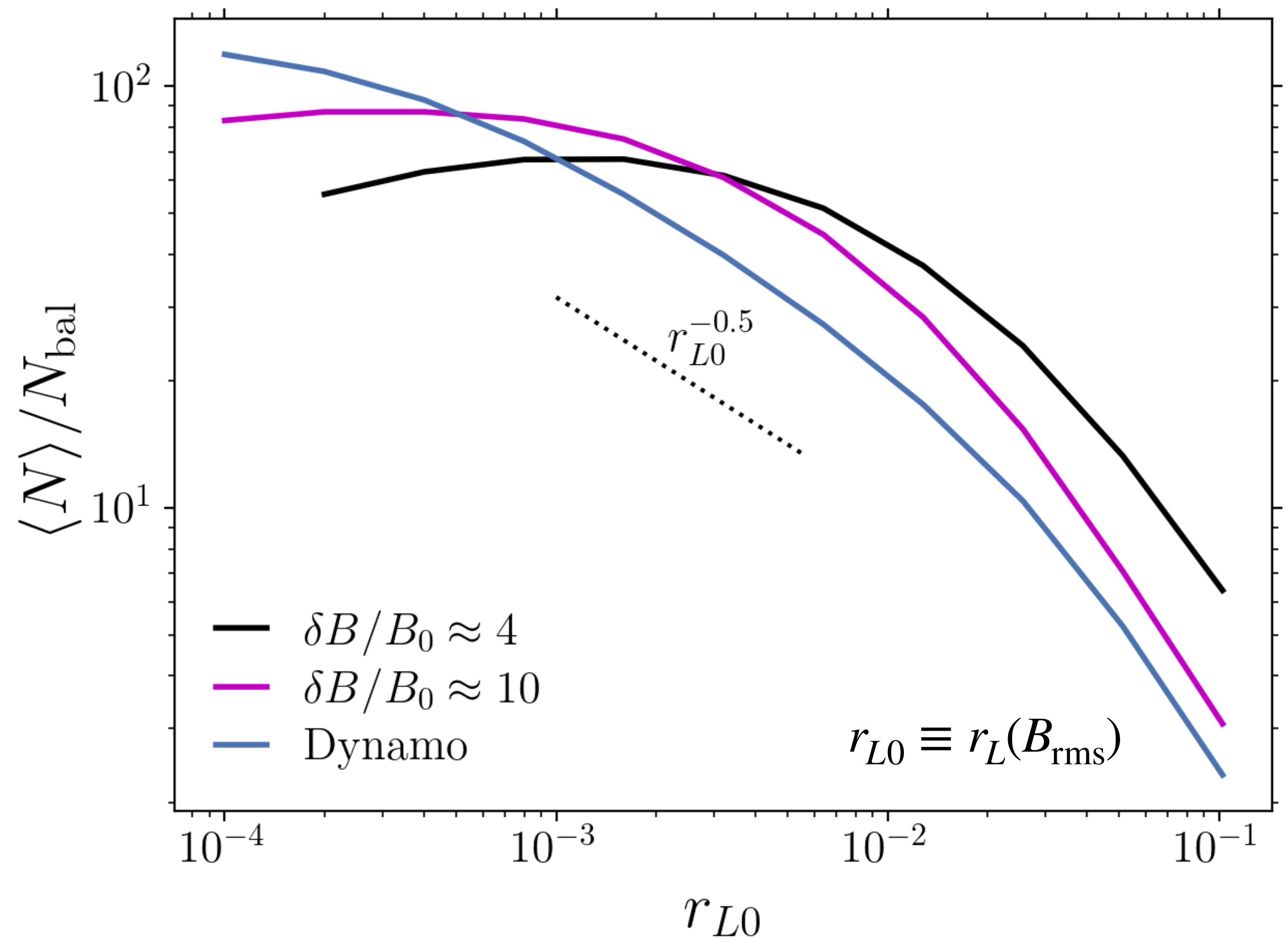
$$N_{\rm bal} \equiv \frac{QH}{c}$$

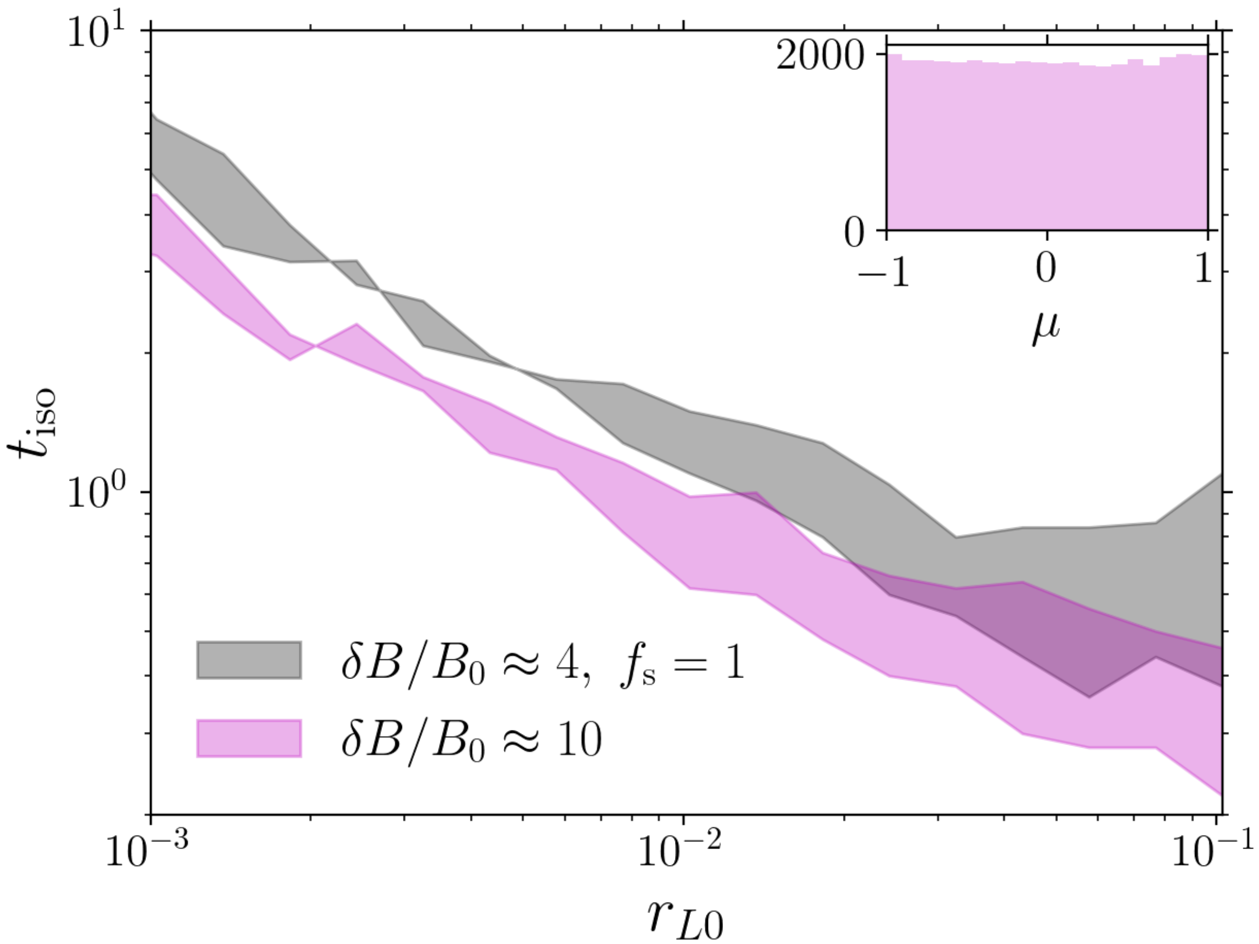
Kempski et al. (2023), arXiv:2304.12335

Leaky Box Results

Low-energy particles better confined than high-energy particles, as in the Milky Way

Dynamo scaling remarkably consistent with observations





Despite slower pitch angle isotropization!

Physics of transport very different from standard idea that spatial diffusion is due to pitch-angle diffusion

Kempski et al. (2023), arXiv:2304.12335

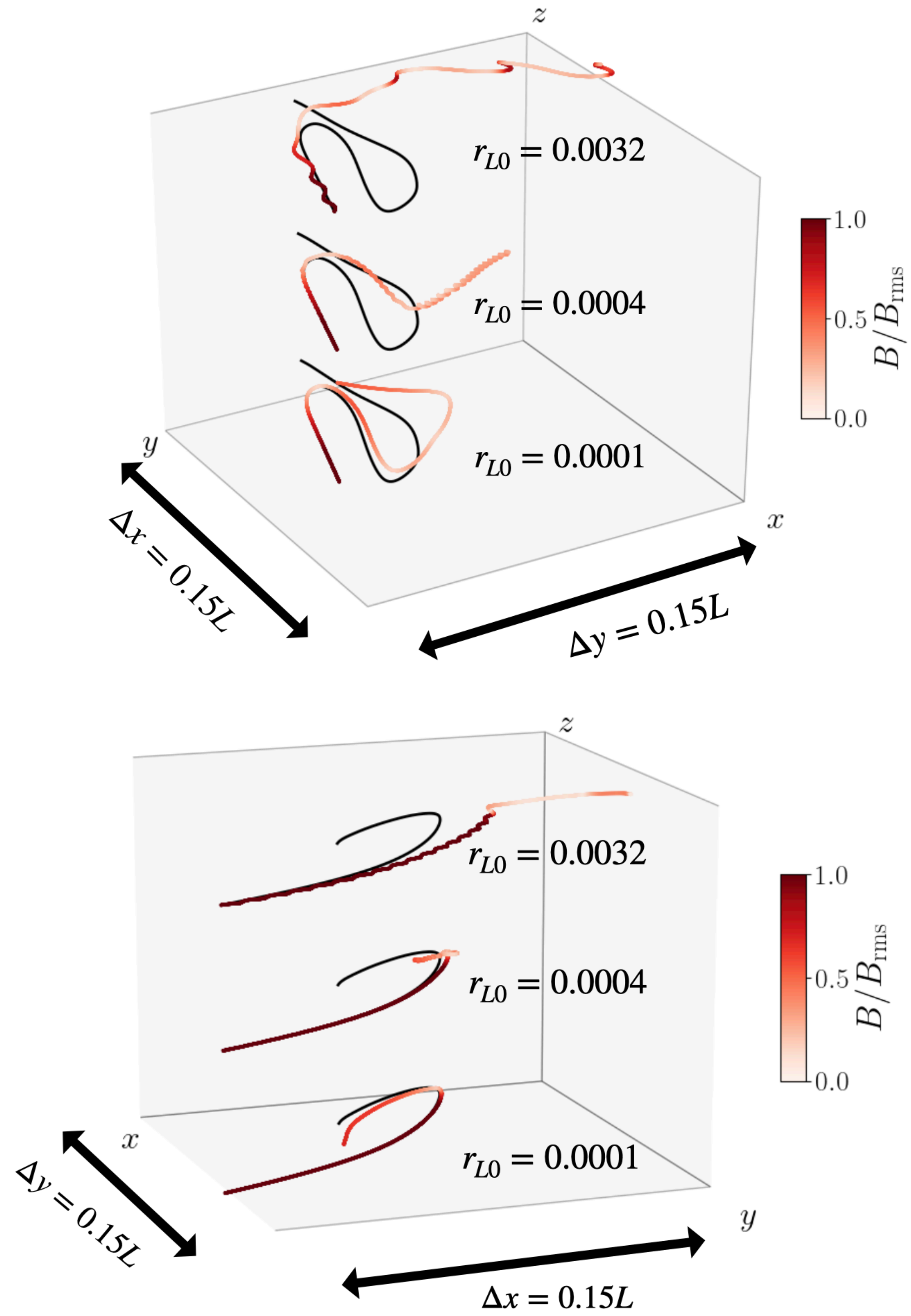
Particle Trajectories

Re~20, Pm=500 Dynamo

Energy-dependent ability to follow reversing magnetic field lines

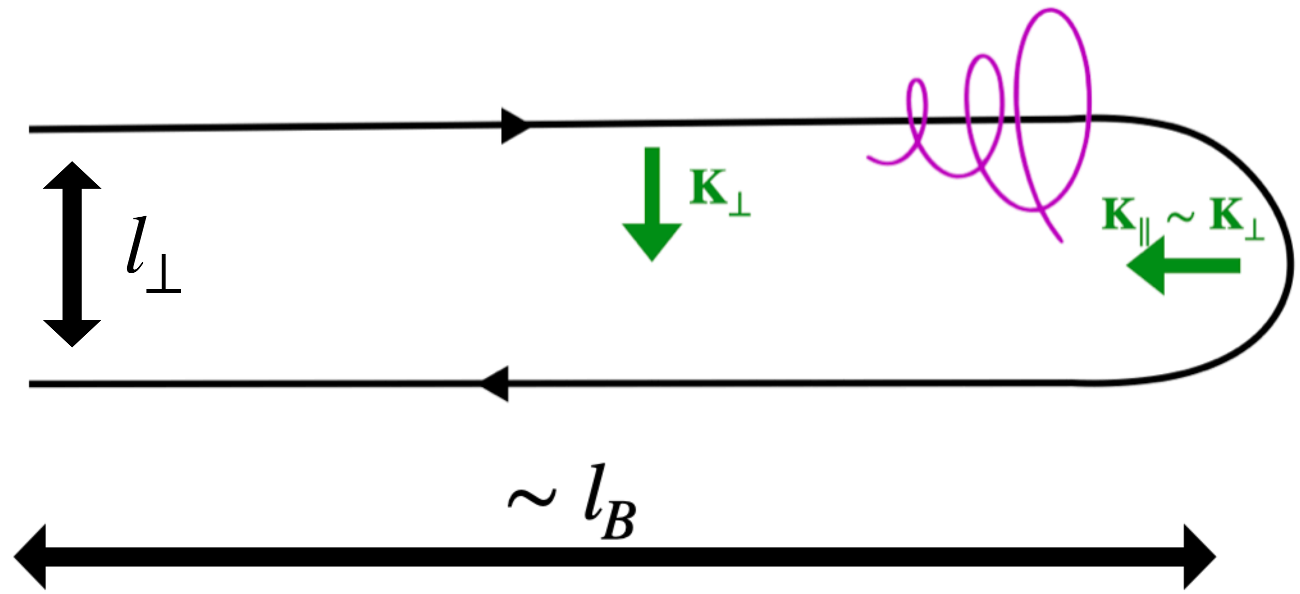
Pitch-angle scattering in regions of “resonant curvature”

Effective “scattering” if adiabatically following reversing field line



Kempski et al. (2023), arXiv:2304.12335

Particle transport in magnetic folds



$$K_\parallel = |\hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}}|$$

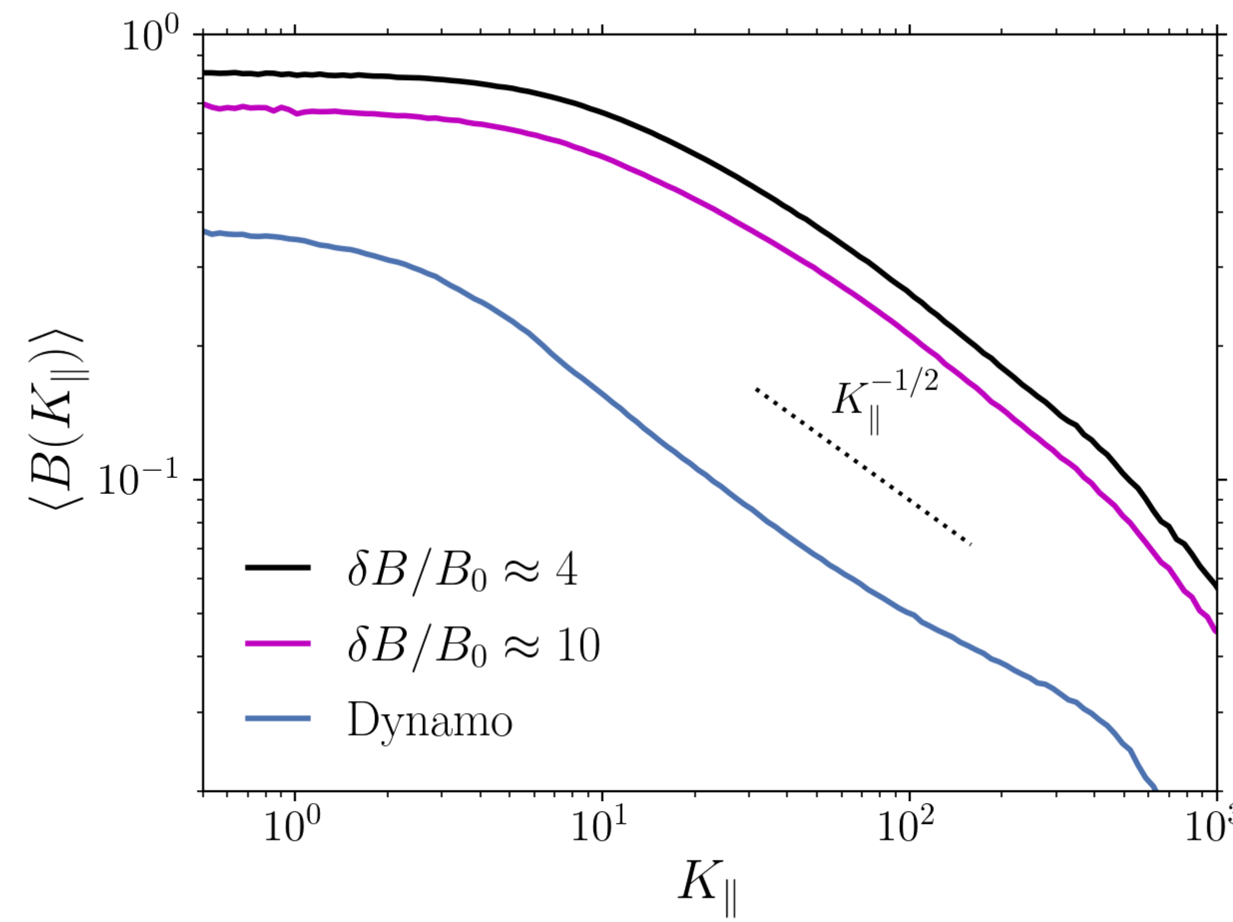
$$K_\perp = \hat{\mathbf{b}} \times \hat{\mathbf{b}} \times \nabla \ln B$$

$$K_\perp = l_\perp^{-1}$$

$$B(K_\parallel) \propto K_\parallel^{-0.5}$$

Fields bend on scales comparable to their perpendicular reversal scale

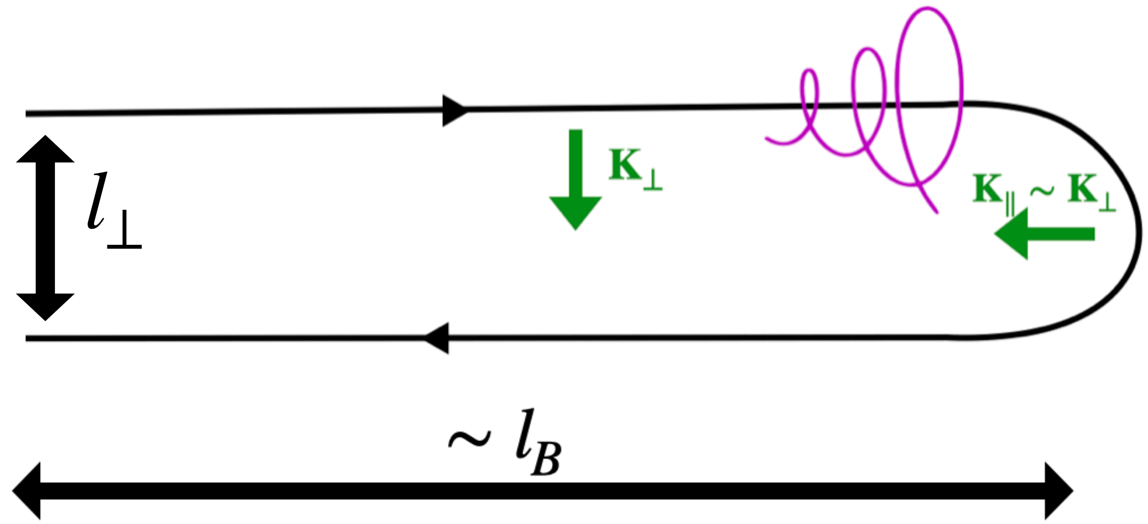
Magnetic field drops as a particle approaches regions of high curvature, and its gyro-orbit expands



Kempski et al. (2023), arXiv:2304.12335

Scattering in magnetic folds

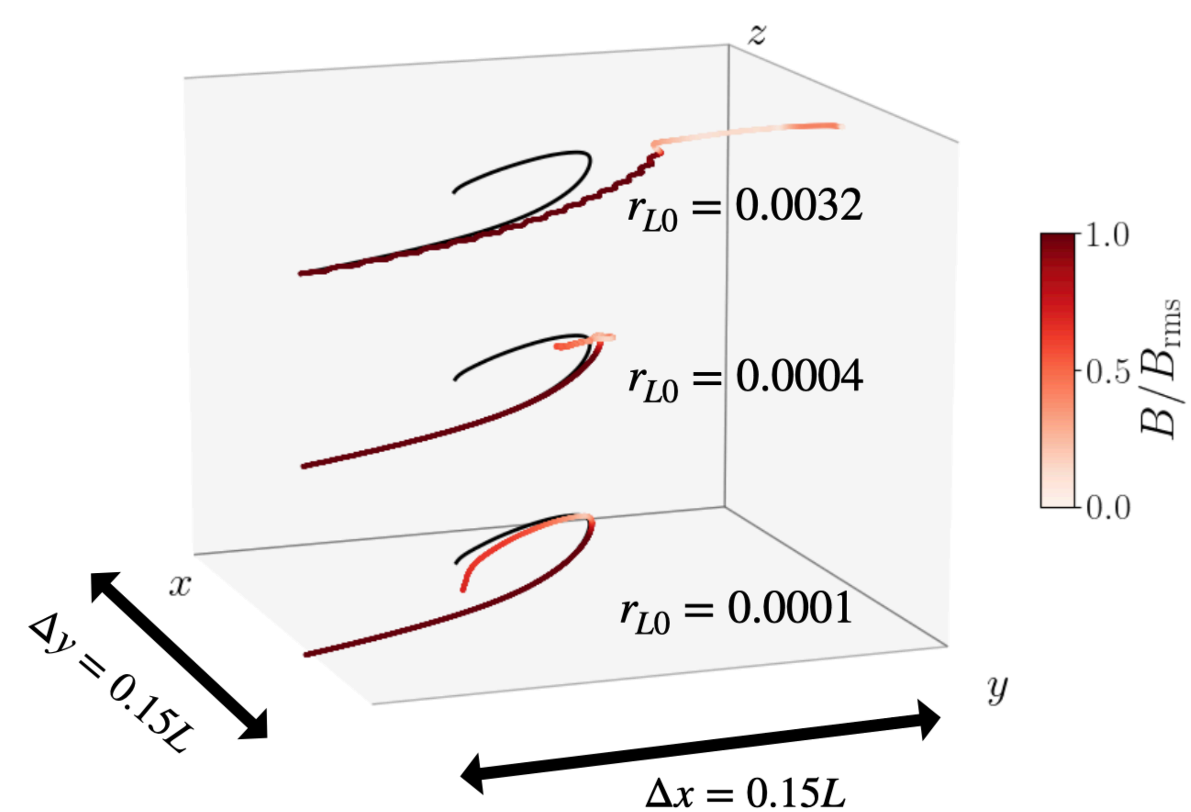
Particle scattered if gyro-radius is small compared to perpendicular fold width



$r_L \gg l_\perp \;\Rightarrow$ Random “kicks”, unaffected by fold

Scattering by “resonant curvature”

$$l_\perp \sim r_L(B_{\text{bend}})$$



“Scattering” by adiabatically following a reversing field line

$$l_\perp \gg r_L(B_{\text{bend}})$$

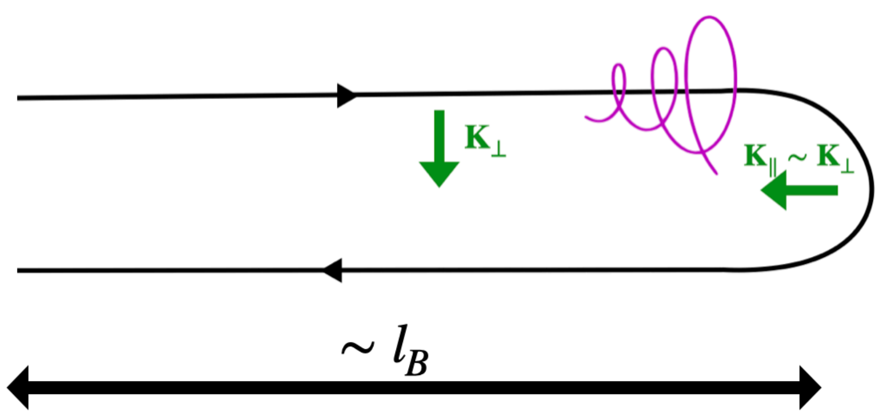
Folds come in variety of sizes:

$$\nu(r_{L0}) \sim \frac{c}{l_B} P[l_\perp \gtrsim r_L(B_{\text{bend}})]$$

Scattering in Folds

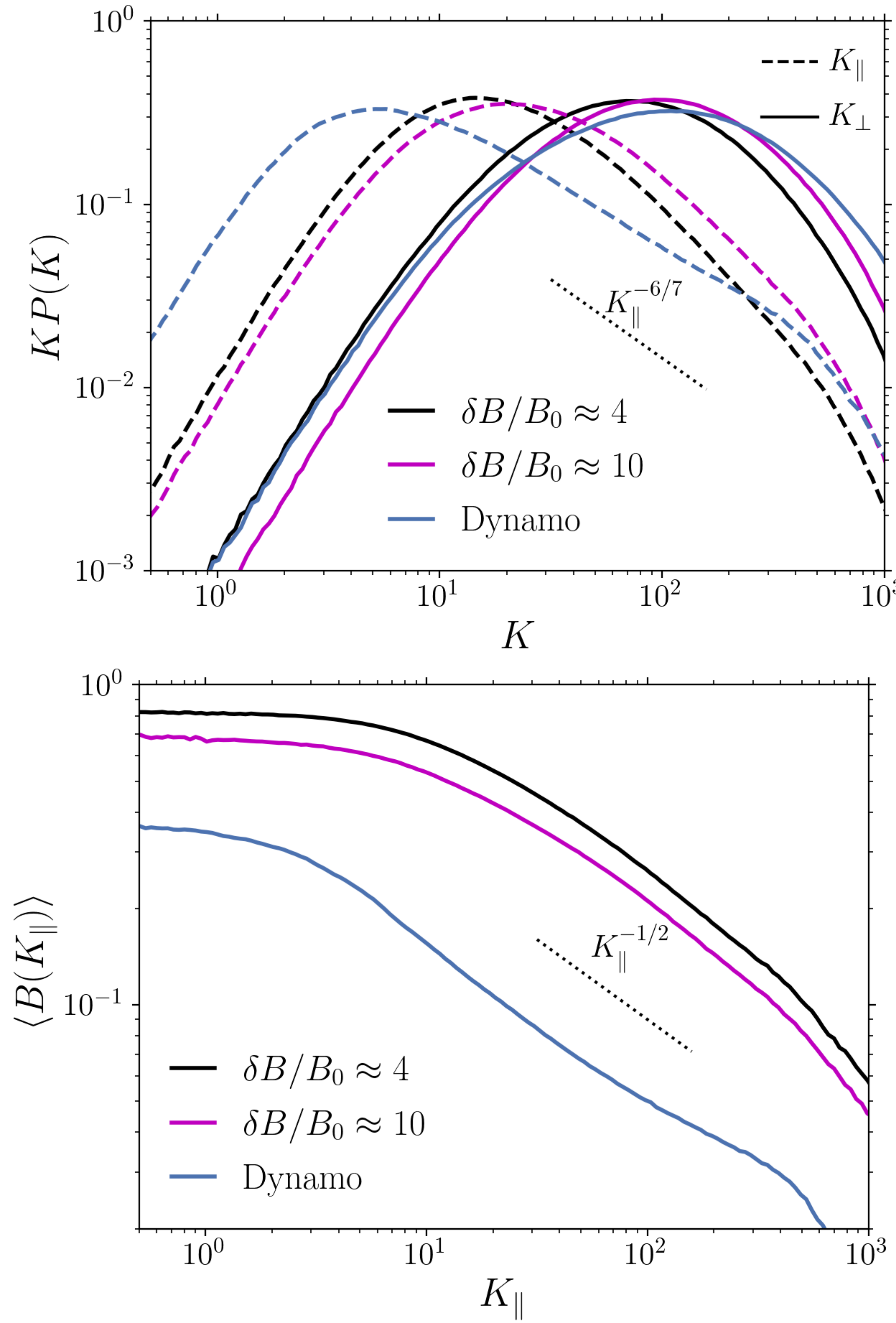
More concretely:

$$K_\parallel = \hat{\mathbf{b}} \cdot \nabla \hat{\mathbf{b}} \qquad K_\perp = \hat{\mathbf{b}} \times \hat{\mathbf{b}} \times \nabla \ln B$$



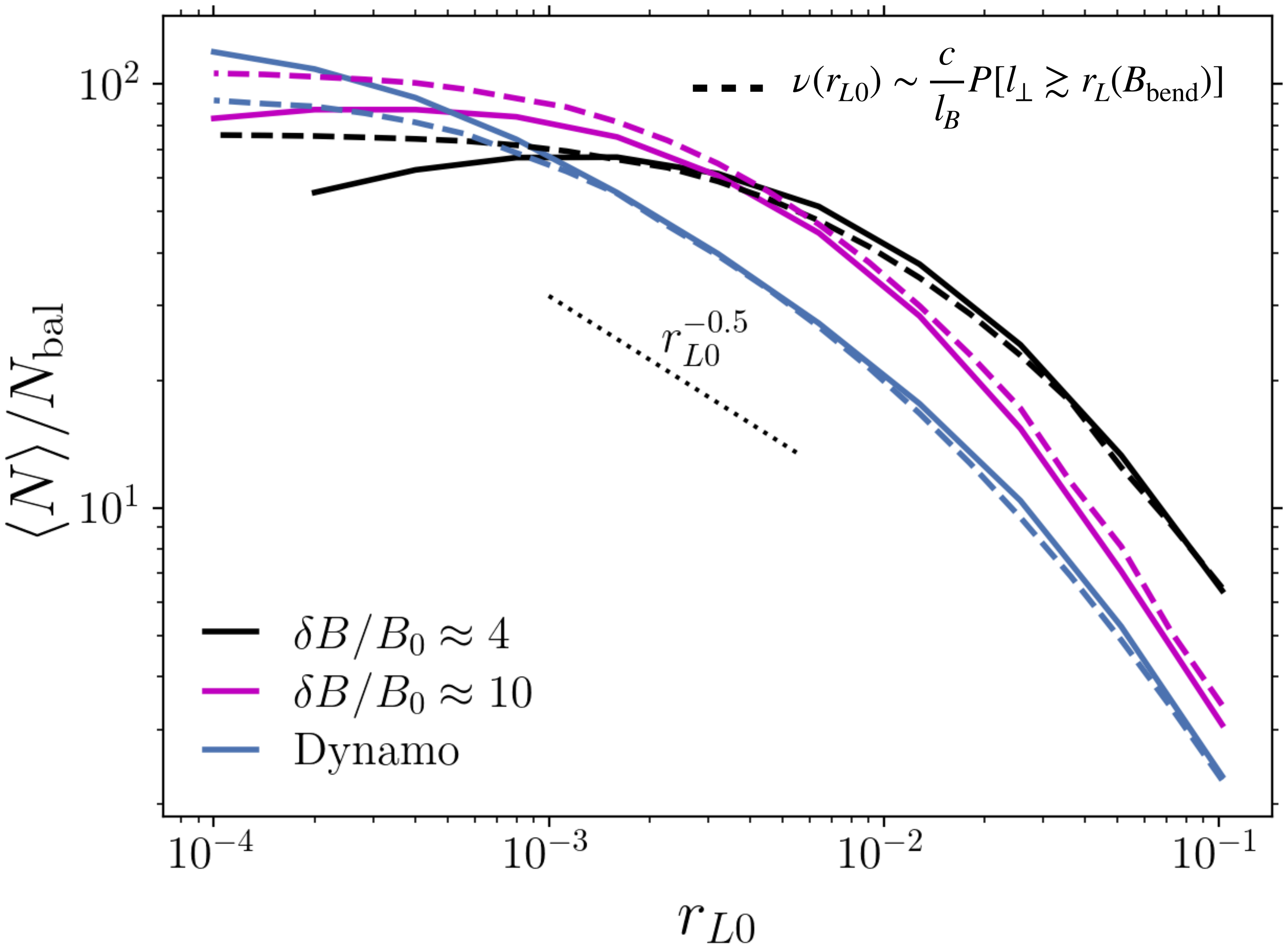
$$\nu(r_{L0}) \sim \frac{c}{l_B} \int^{K_{\max}} P(K_\perp) dK_\perp$$

$$K_{\max} r_{L0} \sim \frac{\langle B(K_\parallel = K_{\max}) \rangle}{B_{\rm rms}} \qquad l_B = \int K_\parallel^{-1} P(K_\parallel) dK_\parallel$$



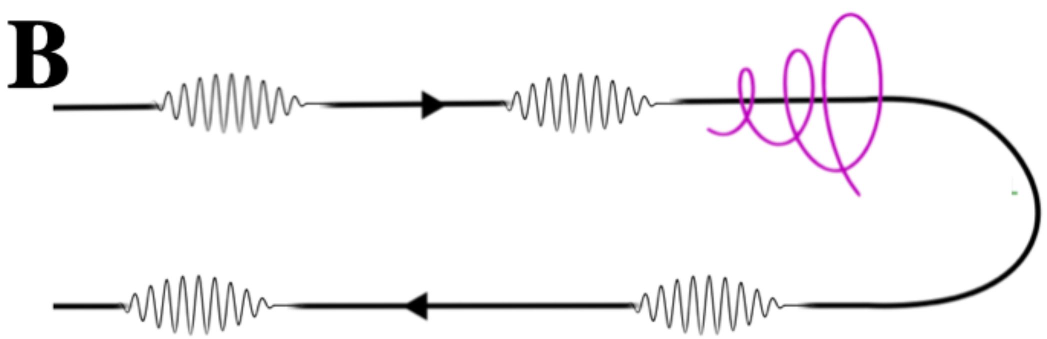
Kempski et al. (2023), arXiv:2304.12335

Model vs Leaky Box



Overall good agreement between the model and leaky box results

CR transport mediated by rare reversals in the B-field direction?



Appears consistent with results from large-amplitude turbulence

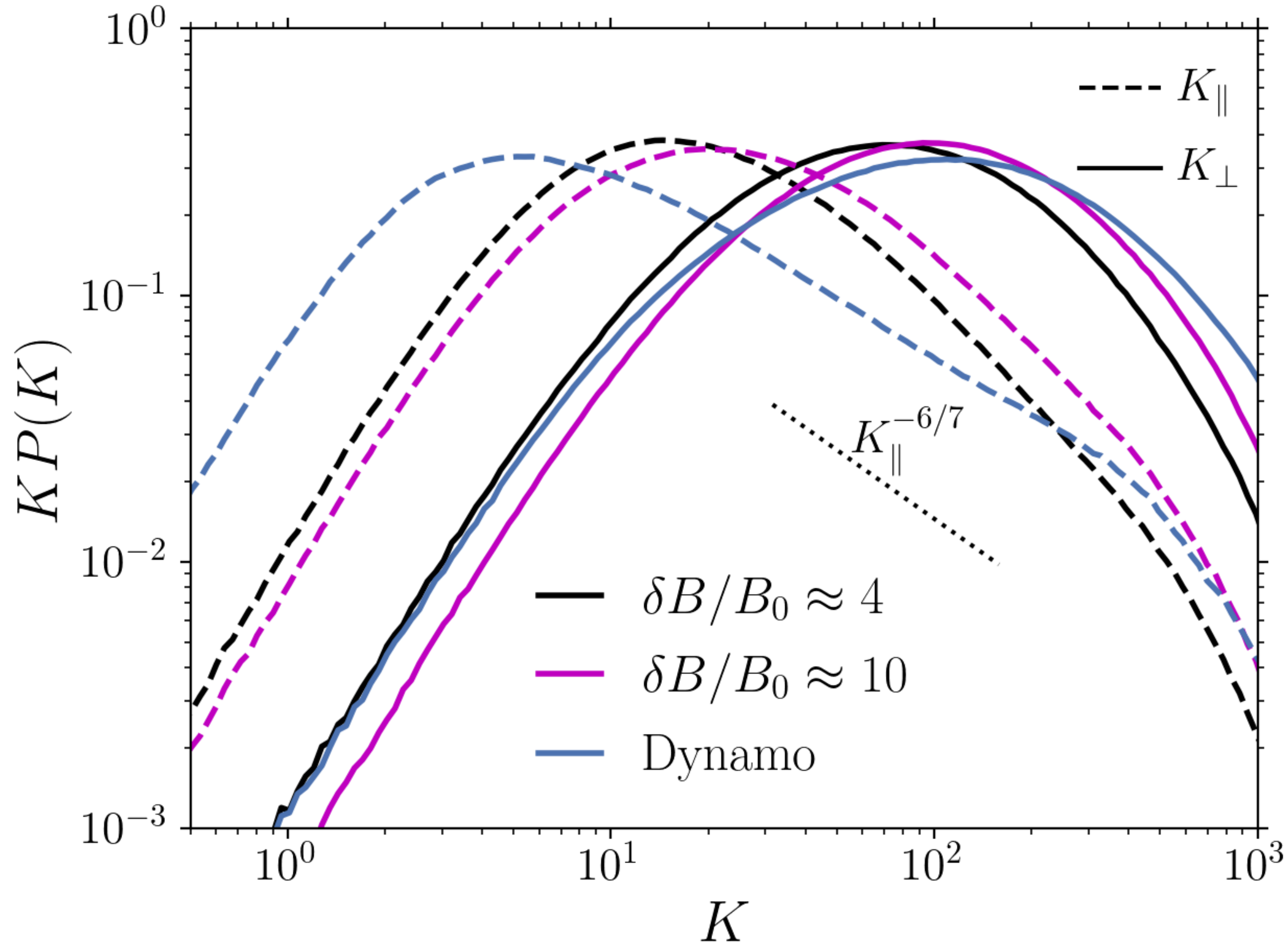
Kempski et al. (2023), arXiv:2304.12335

Questions: Energy dependence vs observations?

$$\nu(r_{L0}) \sim \frac{c}{l_B} \int^{K_{\max}} P(K_\perp) dK_\perp$$

Observations require:

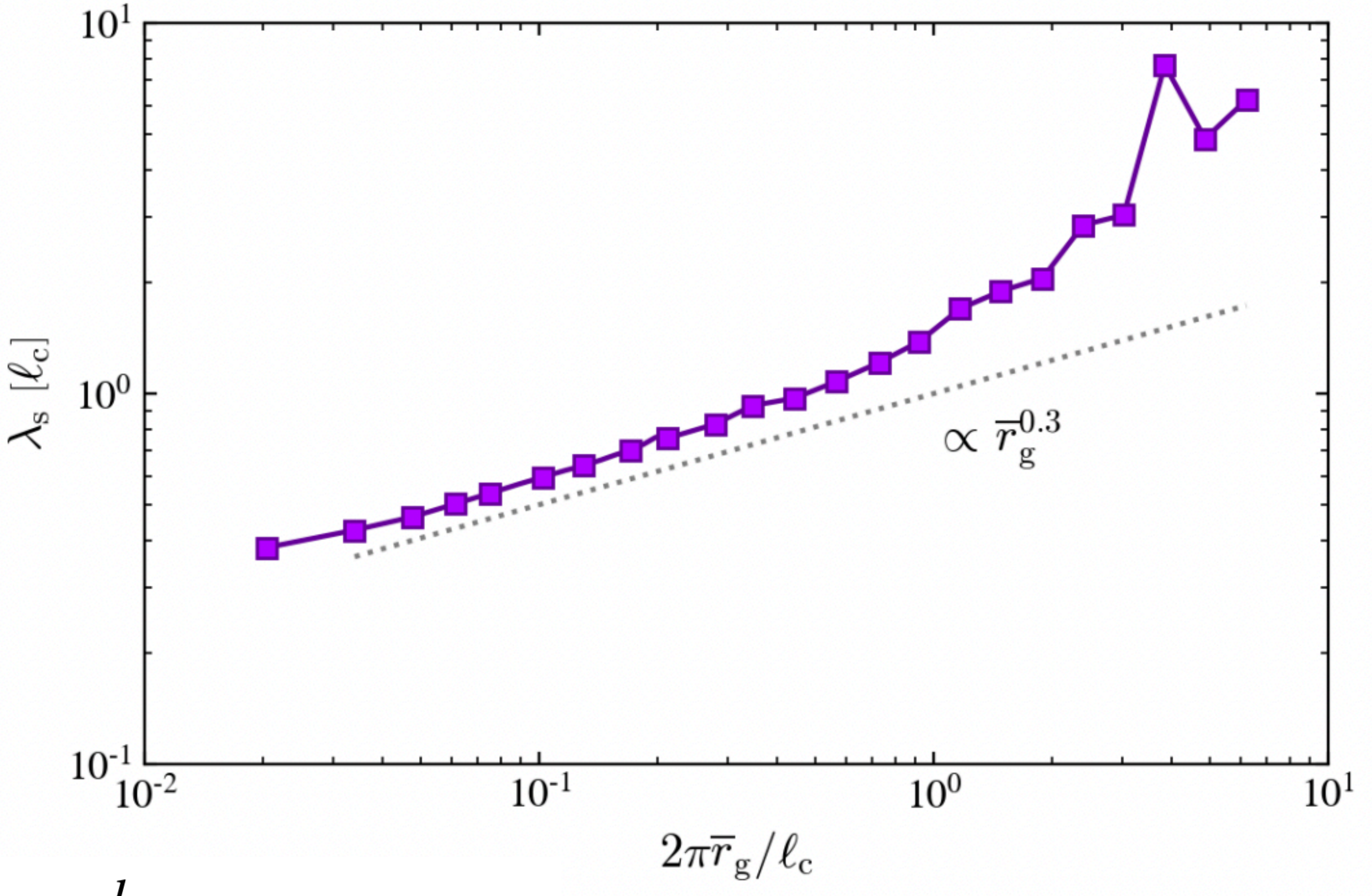
$$\nu(r_{L0}) \propto r_{L0}^{-0.5} \iff K_\perp P(K_\perp) \sim K_\perp^{3/4}$$



Kempski et al. (2023), arXiv:2304.12335

Scattering by large curvature in turbulence with significant guide field?

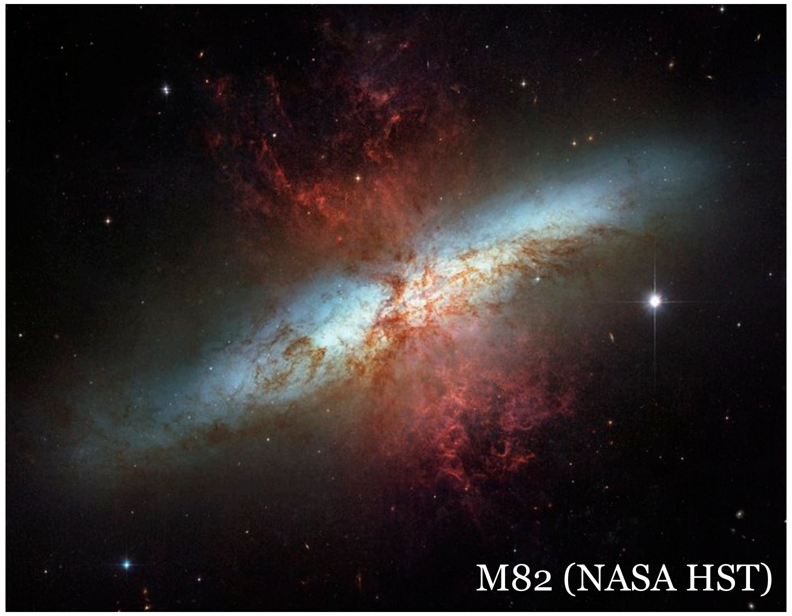
Based on PDFs of curvature calculated using coarse-grained MHD fields, Lemoine (2023) predict



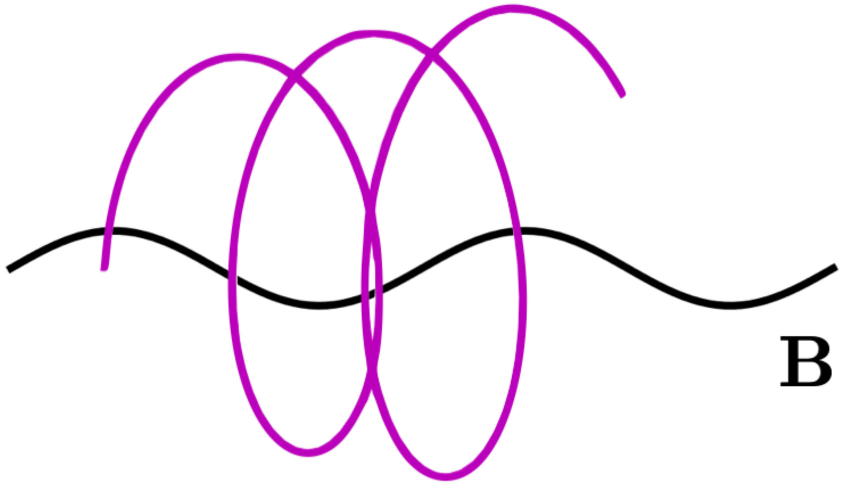
$$\lambda_{\rm s} \equiv \frac{l}{\int_1^{+\infty} {\rm d}x\, \mathsf{p}_{\hat{\kappa}_l l}(x)} \qquad \left(l \sim \overline{r}_{\rm g}\right)$$

Lemoine (2023), arXiv:2304.03023

Summary


M82 (NASA HST)

Existing CR transport models in turbulence that use QLT face theoretical and observational inconsistencies



Possible remedy: scattering by rare but intense magnetic structures, e.g. field reversals