Cosmic rays in a turbulent interstellar medium: Recent progress and open questions

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Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

What are the sources of cosmic rays?

What are the sources?

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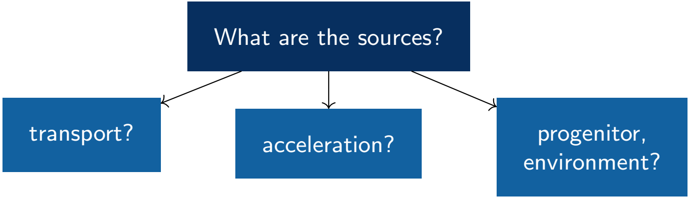

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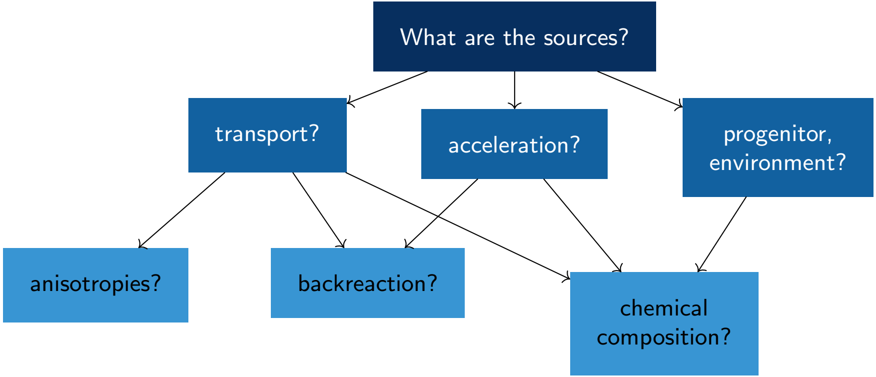

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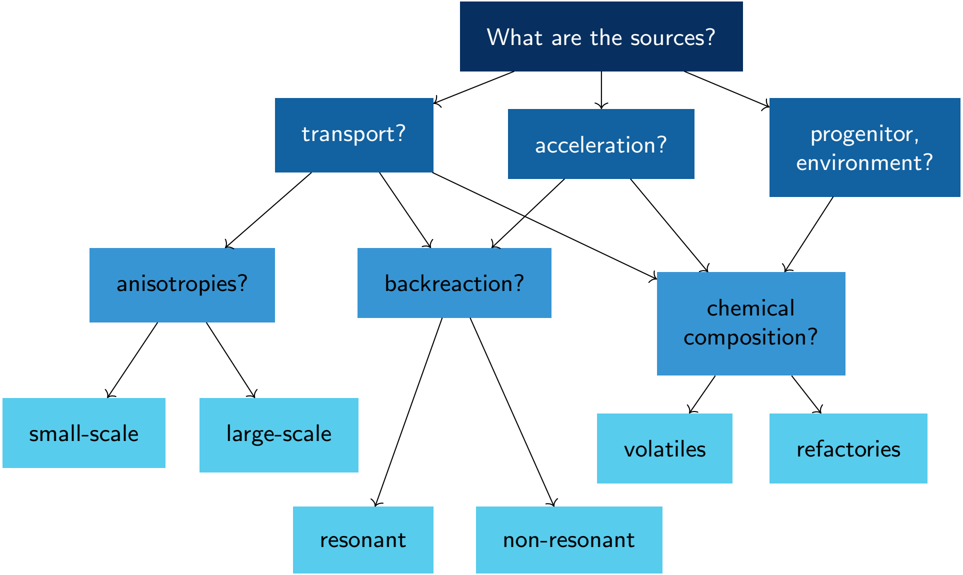
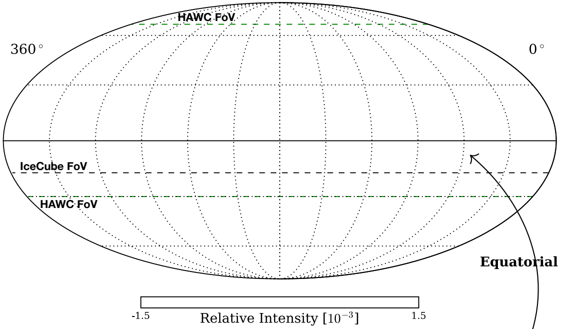


Cosmic ray dipole

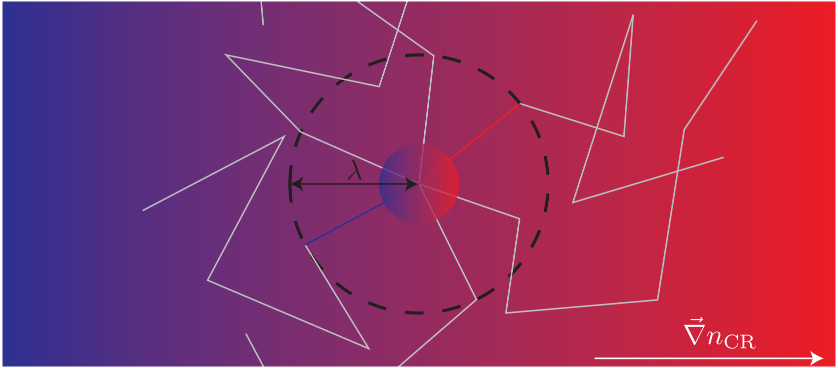
Abeysekara *et al.* (2019)



Here is the source

$$\psi(\mathbf{p}) = \psi_0(p)(1 + a\,\hat{\mathbf{a}} \cdot \hat{\mathbf{p}} + \ldots) \quad \text{with} \quad \mathbf{a} = \frac{\lambda \nabla \psi}{\psi}$$

Cosmic ray dipole



- Amplitude: $a \equiv \dfrac{\phi_{\text{max}} - \phi_{\text{min}}}{\phi_{\text{max}} + \phi_{\text{min}}} \sim \dfrac{\psi(\mathbf{r} + \lambda \hat{\mathbf{a}}) - \psi(\mathbf{r} - \lambda \hat{\mathbf{a}})}{\psi(\mathbf{r} + \lambda \hat{\mathbf{a}}) + \psi(\mathbf{r} - \lambda \hat{\mathbf{a}})} = \dfrac{\lambda |\nabla \psi|}{\psi}$
- Direction: $\hat{\mathbf{a}} \sim \nabla \psi$

Cosmic ray dipole

Mertsch & Funk (2014); also Ahlers (2016)

Assumptions

1. No coherent magnetic field
2. No deviations from average over **B**-fields

$$\psi(\mathbf{p}) = \psi_0(p)(1 + a\,\hat{\mathbf{a}}\cdot\hat{\mathbf{p}} + \ldots) \quad \text{with} \quad \mathbf{a} = \frac{\lambda \nabla \psi}{\psi}$$

Cosmic ray dipole

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Assumptions

1. ~~No coherent magnetic field~~
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$$\psi(\mathbf{p}) = \psi_0(p)(1 + a \underbrace{\hat{\mathbf{b}} \cdot \hat{\mathbf{p}}}_{\mu = \cos\theta} + \ldots) \quad \text{with} \quad a \simeq \frac{\lambda \hat{\mathbf{b}} \cdot \nabla \psi}{\psi}$$

The dipole does not point back to the source
and its amplitude is reduced by the projection.

Cosmic ray dipole

Mertsch & Funk (2014); also Ahlers (2016)

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1. ~~No coherent magnetic field~~
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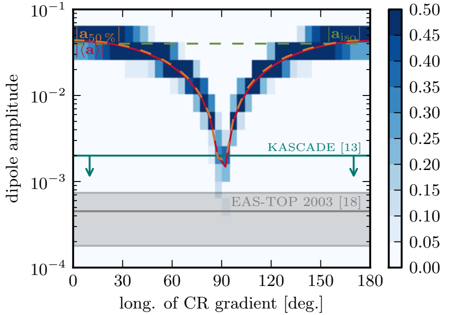
$$\langle\psi(\mathbf{p})\rangle = \psi_0(p)(1+a\,\underbrace{\hat{\mathbf{b}}\cdot\hat{\mathbf{p}}}_{\mu=\cos\theta}+\ldots) \quad \text{with} \quad a \simeq \frac{\lambda\hat{\mathbf{b}}\cdot\nabla\psi}{\psi}$$



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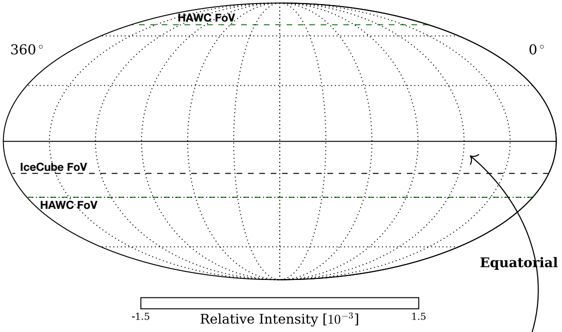
Cosmic ray dipole

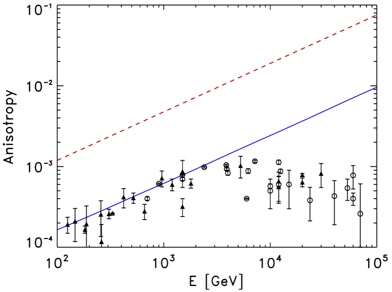


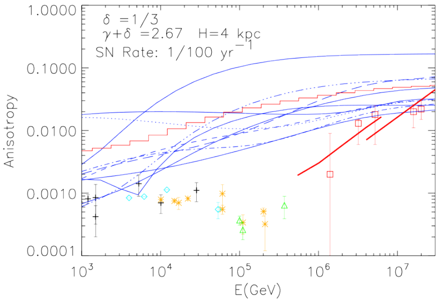
Here is the **B**-field

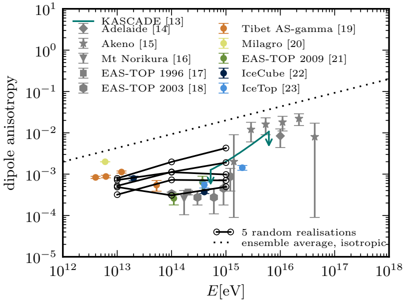
$$\langle \psi(\mathbf{p}) \rangle = \psi_0(p)(1 + a \underbrace{\hat{\mathbf{b}} \cdot \hat{\mathbf{p}}}_{\mu = \cos\theta} + \ldots) \quad \text{with} \quad a \simeq \frac{\lambda \hat{\mathbf{b}} \cdot \nabla \psi}{\psi}$$

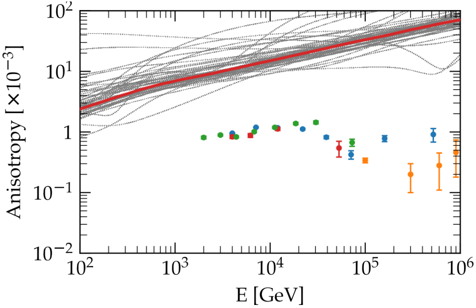
Dipole anisotropies as a constraint

Amato & Blasi (2012); Evoli *et al.* (2012); Mertsch & Funk (2014); Evoli *et al.* (2022)



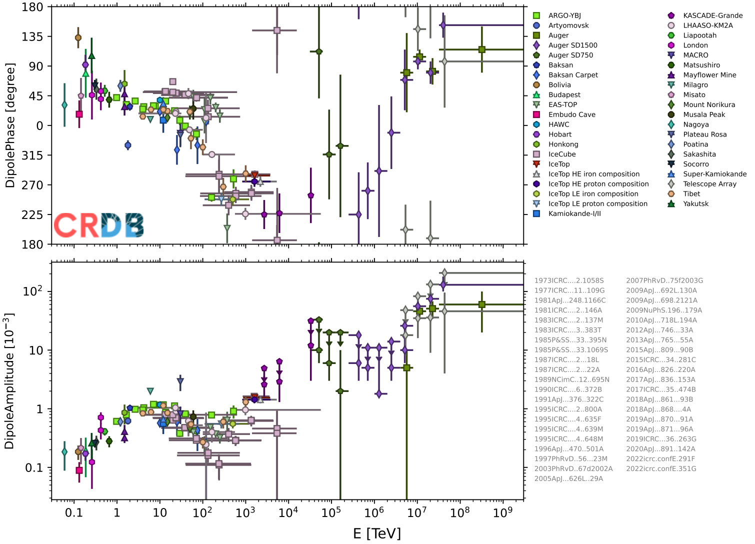






Dipole data in CRDB

with M. Ahlers, H. Dembinski, D. Maurin

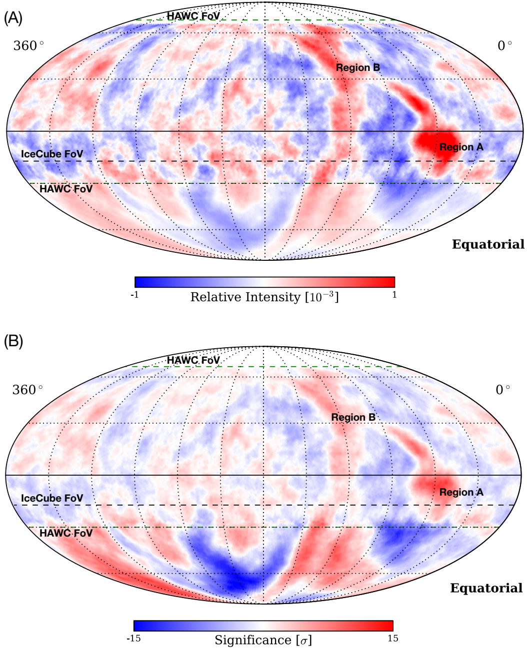


- CR database: `https://lpsc.in2p3.fr/crdb/`
- Python package crdb: `https://github.com/crdb-project`

Outline

1. Motivation
2. Small-scale anisotropies
3. Test-particle simulations
4. Suppressed diffusion
5. Conclusions

Small-scale anisotropies



- subtract off dipole and quadrupole
- smooth with 5° disk

→ small-scale features

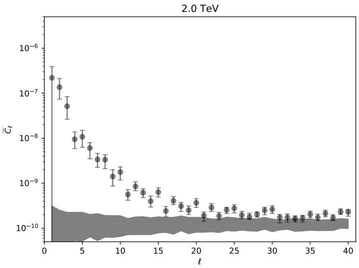
Abeysekara *et al.*, ApJ 871 (2019) 96

- Energy-dependence
- No time-dependence

Angular power spectrum

HAWC

Abeysekara *et al.*, ApJ 796 (2014) 108 Abeysekara *et al.*, ApJ 865 (2018) 57

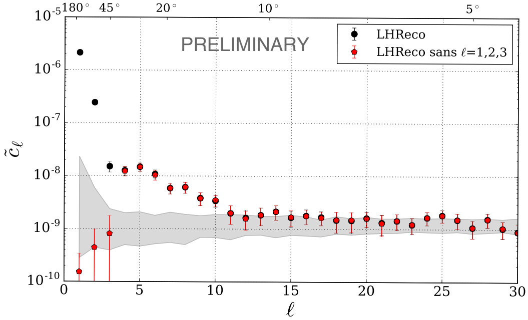


IceCube

Aartsen *et al.*, ApJ 826 (2016) 220

IceCube+HAWC

Abeysekara *et al.*, ApJ 871 (2019) 96



Diffusion approximation

Jokipii (1968)

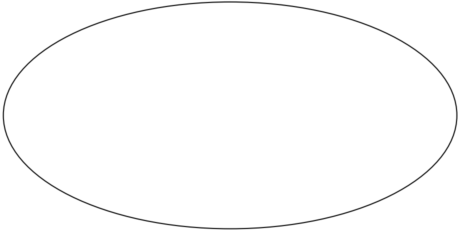
- Decompose $\langle f \rangle$ into series in pitch-angle cosine μ:

$$\langle f \rangle(p, \mu, t) = g(p, t) + h(p, \mu, t)$$

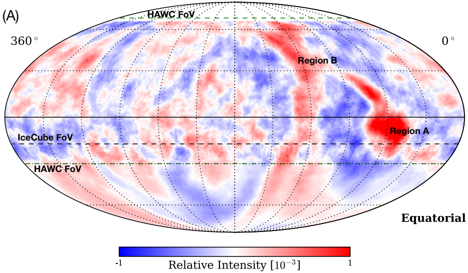
where

$$h(p, \mu, t) = -\frac{v}{2} \frac{\partial g}{\partial z} \int \mathrm{d}\mu \frac{1 - \mu^2}{D_{\mu\mu}} + \text{const.}$$

- If scattering is isotropic, $D_{\mu\mu} \propto (1 - \mu^2) \rightarrow h(\mu) \propto \mu$: dipole
- Example: Second-order quasi-linear theory Shalchi (2005)



vs



Small-scale turbulence and ensemble averaging

- In standard diffusion, compute C_ℓ from $\langle f \rangle$:

$$C_\ell^{\text{std}} = \frac{1}{4\pi} \int \mathrm{d}\hat{\mathbf{p}}_1 \int \mathrm{d}\hat{\mathbf{p}}_2 \, P_\ell(\hat{\mathbf{p}}_1 \cdot \hat{\mathbf{p}}_2) \langle f(\hat{\mathbf{p}}_1) \rangle \langle f(\hat{\mathbf{p}}_2) \rangle$$

- However, in an individual realisation of δB, $\delta f = f - \langle f \rangle \neq 0$

$$\langle C_\ell \rangle = \frac{1}{4\pi} \int \mathrm{d}\hat{\mathbf{p}}_1 \int \mathrm{d}\hat{\mathbf{p}}_2 \, P_\ell(\hat{\mathbf{p}}_1 \cdot \hat{\mathbf{p}}_2) \langle f(\hat{\mathbf{p}}_1) f(\hat{\mathbf{p}}_2) \rangle$$

- If $f(\hat{\mathbf{p}}_1)$ and $f(\hat{\mathbf{p}}_2)$ are correlated,

$$\langle f(\hat{\mathbf{p}}_1) f(\hat{\mathbf{p}}_2) \rangle \geq \langle f(\hat{\mathbf{p}}_1) \rangle \langle f(\hat{\mathbf{p}}_2) \rangle \quad \Rightarrow \quad \langle C_\ell \rangle \geq C_\ell^{\text{std}}$$

Source of the small scale anisotropies?

Giacinti & Sigl, PRL **109** (2012) 071101

Ahlers, PRL **112** (2014) 021101, Ahlers & Mertsch, ApJL 815 (2015) L2, Pohl & Rettig, *Proc. 36th ICRC* (2016) 451, López-Barquero *et al.*, ApJ 830 (2016) 19, López-Barquero *et al.* ApJ 842 (2017) 54, Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

Gradient ansatz

Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

- Vlasov equation:

$$\begin{aligned}\frac{\mathrm{d}f}{\mathrm{d}t} &= \frac{\partial f}{\partial t} + \dot{\mathbf{r}} \cdot \nabla_{\mathbf{r}} f + \frac{q\mathbf{v}}{c} \times (\langle \mathbf{B} \rangle + \delta \mathbf{B}) \cdot \nabla_{\mathbf{p}} f \\ &\simeq \frac{\partial f}{\partial t} + \underbrace{\left(c\hat{\mathbf{p}} \cdot \nabla_{\mathbf{r}} + q(\hat{\mathbf{p}} \times \langle \mathbf{B} \rangle) \cdot \nabla_{\mathbf{p}}\right)}_{\mathcal{L}} f + \underbrace{\left(q(\hat{\mathbf{p}} \times \delta \mathbf{B}) \cdot \nabla_{\mathbf{p}}\right)}_{\delta\mathcal{L}} f = 0\end{aligned}$$

- Gradient ansatz:

$$f(\mathbf{r}, \hat{\mathbf{p}}) = f_{\oplus}(\hat{\mathbf{p}}) + (\mathbf{r}_{\oplus} - \mathbf{r}) \cdot \mathbf{G}\,,$$

$\rightarrow$ Dipolar source term in the Vlasov equation:

$$\frac{\partial f_{\oplus}}{\partial t} + \underbrace{\left(q(\hat{\mathbf{p}} \times \langle \mathbf{B} \rangle) \cdot \nabla_{\mathbf{p}}\right)}_{\mathcal{L}'} f_{\oplus} + \underbrace{\left(q(\hat{\mathbf{p}} \times \delta \mathbf{B}) \cdot \nabla_{\mathbf{p}}\right)}_{\delta\mathcal{L}} f_{\oplus} = c\,\hat{\mathbf{p}} \cdot \mathbf{G}$$

Mixing matrices

Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

- Define propagator:

$$U_{t,t_0} = \mathcal{T} \exp\left[-\int_{t_0}^{t} \mathrm{d}t' \left(\mathcal{L}' + \delta\mathcal{L}(t') \right) \right]$$

- Formal solution of Vlasov equation:

$$f_\oplus(\mathbf{p}, t) = U_{t,t_0} f_\oplus(\mathbf{p}, t_0) + \int_{t_0}^{t} \mathrm{d}t' \, U_{t,t'} \, c \, \hat{\mathbf{p}} \cdot \mathbf{G}$$

$\rightarrow$ Differential equation for $\langle C_\ell \rangle$,

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}t}\langle C_\ell \rangle(t) + \left(\lim_{t_0 \to t} \frac{\delta_{\ell\ell_0} - M_{\ell\ell_0}(t, t_0)}{t - t_0} \right) \langle C_{\ell_0} \rangle(t) = \frac{8\pi}{9} K |\mathbf{G}|^2 \delta_{\ell 1}}$$

where

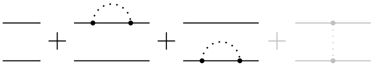
$$M_{\ell\ell_0}(t, t_0) = \frac{1}{4\pi} \int \mathrm{d}\hat{\mathbf{p}}_A \int \mathrm{d}\hat{\mathbf{p}}_B \mathrm{P}_\ell(\hat{\mathbf{p}}_A \cdot \hat{\mathbf{p}}_B) \langle U^A_{t,t_0} U^{B*}_{t,t_0} \rangle \frac{2\ell_0 + 1}{4\pi} \mathrm{P}_{\ell_0}(\hat{\mathbf{p}}_A \cdot \hat{\mathbf{p}}_B)$$

Ignoring correlations

Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

- Without "interactions":

$$\langle U^{A}_{t,t_0} U^{B*}_{t,t_0} \rangle \simeq$$



- Mixing matrix diagonal:

$$M_{\ell\ell_0}(t, t_0) \sim \delta_{\ell\ell_0}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\langle C_\ell \rangle(t) + \left(\lim_{t_0 \to t} \frac{\delta_{\ell\ell_0} - M_{\ell\ell_0}(t, t_0)}{t - t_0} \right) \langle C_{\ell_0} \rangle(t) = \frac{8\pi}{9} K |\mathbf{G}|^2 \delta_{\ell 1} \, ,$$

$\rightarrow$ Only dipolar anisotropy:

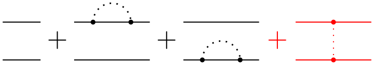
$$\langle C_\ell \rangle \propto \delta_{\ell 1} \, ,$$

With correlations

Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

- With "interactions"

$$\langle U^{A}_{t,t_0} U^{B*}_{t,t_0} \rangle \simeq$$



- Mixing matrix **not** diagonal:

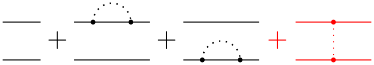
$$M_{\ell\ell_0}(t, t_0) \sim \delta_{\ell\ell_0} + \sum_{\ell_A} \kappa_{\ell_A}(t - t_0) \begin{pmatrix} \ell & \ell_A & \ell_0 \\ 0 & 0 & 0 \end{pmatrix}^2 (2\ell_0 + 1)\ell_0(\ell_0 + 1)$$

$$\frac{\mathrm{d}}{\mathrm{d}t} \langle C_\ell \rangle(t) + \left(\lim_{t_0 \to t} \frac{\delta_{\ell\ell_0} - M_{\ell\ell_0}(t, t_0)}{t - t_0} \right) \langle C_{\ell_0} \rangle(t) = \frac{8\pi}{9} K |\mathbf{G}|^2 \delta_{\ell 1} \,,$$

With correlations

Mertsch & Ahlers (2019), Kuhlen, Mertsch, Phan (2022)

- With "interactions"

$$\langle U^A_{t,t_0} U^{B*}_{t,t_0} \rangle \simeq$$ 

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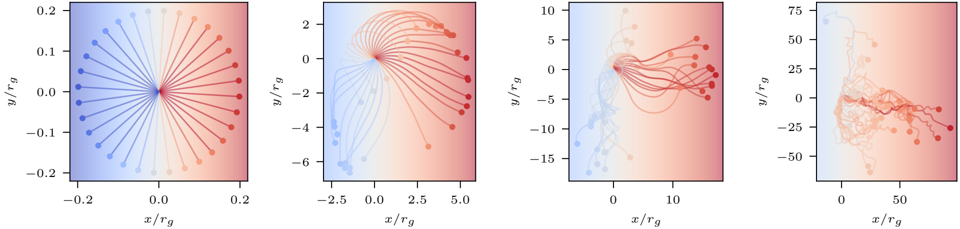
$$\frac{\mathrm{d}}{\mathrm{d}t}\langle C_\ell \rangle(t) + \left(\lim_{t_0 \to t} \frac{\delta_{\ell\ell_0} - M_{\ell\ell_0}(t, t_0)}{t - t_0} \right) \langle C_{\ell_0} \rangle(t) = \frac{8\pi}{9} K |\mathbf{G}|^2 \delta_{\ell 1} \, ,$$

$\rightarrow$ Gradient source term is mixing into higher harmonics!

Test particle simulations

Kuhlen, Mertsch, Phan (2022)

- Need to check analytical results with simulations
- Set up turbulent magnetic field on computer
- Solve the equations of motion for $\mathcal{O}(10^7)$ particles numerically

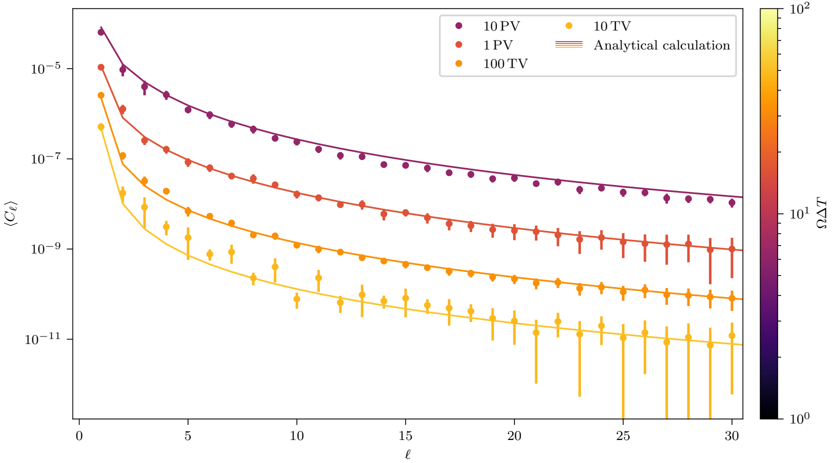


H.264 avi

- Rinse and repeat
- Compute diffusion coefficients, angular power spectra, . . .

Results

Kuhlen, Mertsch, Phan (2022)



Results

- Numerical and analytic angular power spectra become steeper for smaller energies
- Observed angular power spectra become flatter for smaller energies

Possible reasons for different scaling

- A feature in the power spectrum
- A very small outer scale
- Slab turbulence does not describe data well
- Finite energy resolution

Outline

Different scaling of $\kappa_{\|}$ and $\kappa_{\perp}$

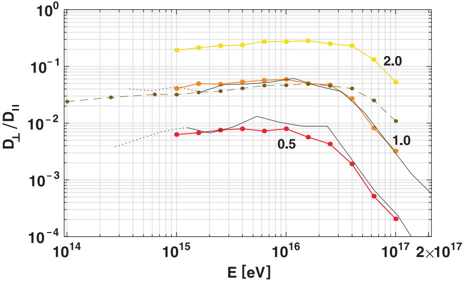
- Regular and turbulent field: $\mathbf{B}(\mathbf{r}) = \mathbf{B}_0 + \delta\mathbf{B}(\mathbf{r})$
- Isotropic turbulence (!)
- Kolmogorov power spectrum with largest turbulent scale L_c

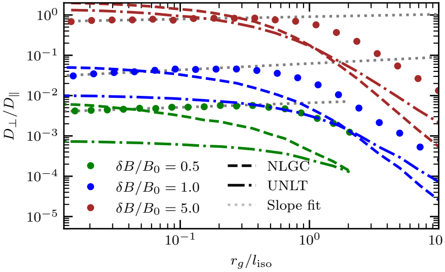
- Naive expectation:

$$\kappa_{\|} \sim \left(\frac{r_g}{L_c}\right)^{1/3} \left(\frac{\delta B^2}{B_0^2}\right)^{-1}$$

$$\kappa_{\perp} \sim \left(\frac{r_g}{L_c}\right)^{1/3} \left(\frac{\delta B^2}{B_0^2}\right)$$

DeMarco *et al.* (2007)





Dundovic *et al.* (2020)

Test particle simulations

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]; also Mertsch (2019)

1. Set up realisation of $\delta \mathbf{B}$ on computer
2. Propagate a large number of particles for long times
3. Rinse and repeat
4. Running diffusion coefficients:

$$d_{\parallel}(t) \equiv \frac{1}{2} \frac{\mathrm{d}}{\mathrm{d}t} \langle (\Delta z)^2 \rangle$$

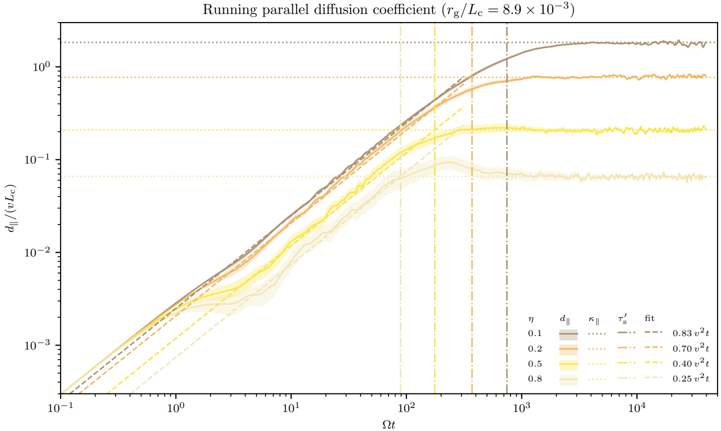
$$d_{\perp}(t) \equiv \frac{1}{2} \frac{\mathrm{d}}{\mathrm{d}t} \left(\langle (\Delta r_{\perp})^2 \rangle \right)$$

Results depend on:

- Reduced time: Ωt
- Reduced rigidity: $\frac{r_{\mathrm{g}}}{L_{\mathrm{c}}}$
- Turbulence level: $\eta = \frac{\delta B^2}{B_0^2 + \delta B^2}$

Running parallel diffusion coefficient

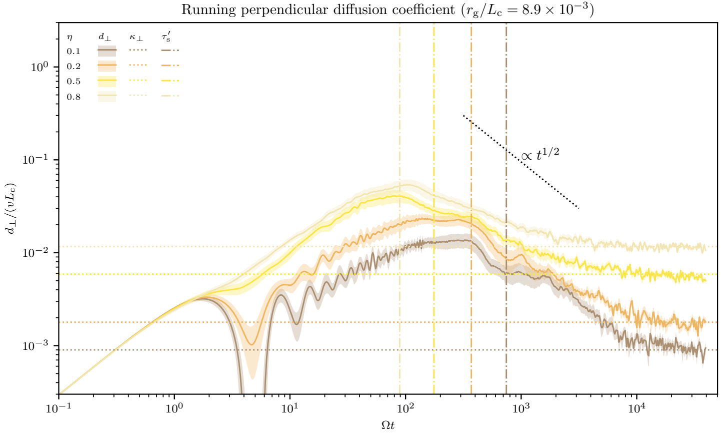
Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



- Initially ballistic: $\langle(\Delta z)^2\rangle \propto t^2$
- Ultimately diffusive: $\langle(\Delta z)^2\rangle \propto t$
- Dependence on turbulence level
- Suppression at intermediate times

Running perpendicular diffusion coefficient

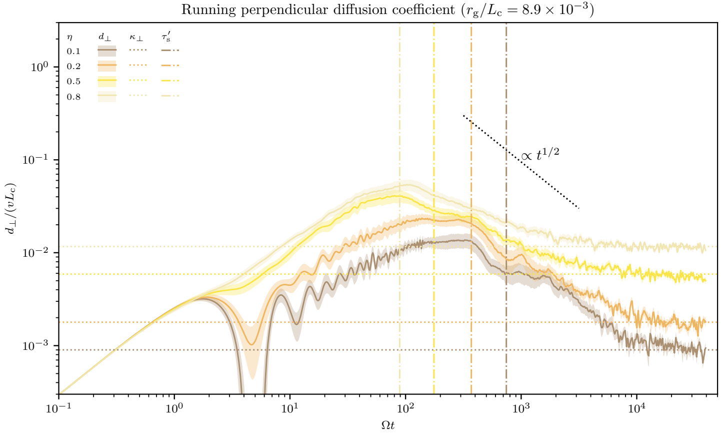
Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



- Initially ballistic: $\langle(\Delta r_\perp)^2\rangle \propto t^2$
- Ultimately diffusive: $\langle(\Delta r_\perp)^2\rangle \propto t$
- Suppression at intermediate times
- Subdiffusion: $\langle(\Delta r_\perp)^2\rangle \propto t^{0.5\ldots0.7}$

Running perpendicular diffusion coefficient

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



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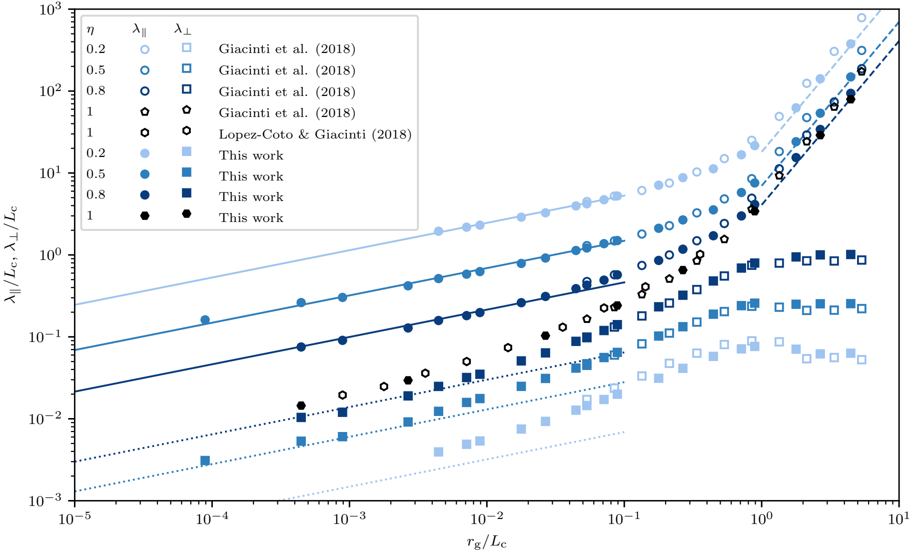
Why subdiffusion?

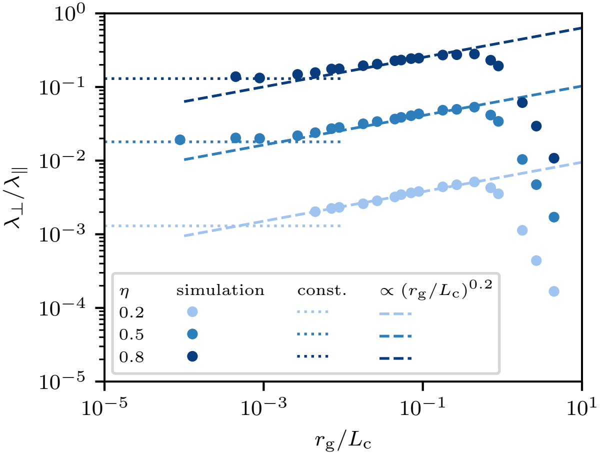
Mean-free paths

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



Ratio of mean-free paths

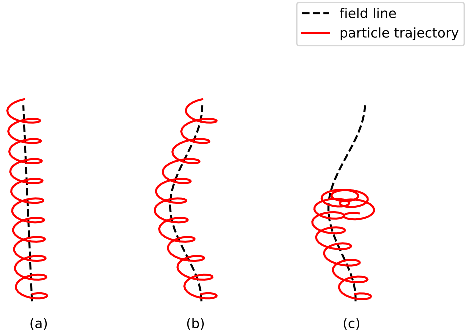
Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



$\kappa_\parallel$ and $\kappa_\perp$ scale differently at medium rigidites, but they scale the same at low rigidities

Perpendicular transport

Perpendicular transport = particle transport along field line + transport of field line



(a) Straight field line and gyration
(b) Wandering field line and gyration
(c) Wandering field line and diffusion

Field-line diffusion coefficient

$$d_{\mathrm{FL}}(z) = \frac{1}{2} \frac{\mathrm{d}\langle (\Delta r_{\perp}^{\mathrm{FL}})^2 \rangle}{\mathrm{d}z}$$

Heuristic model

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05882]

Perpendicular transport = particle transport along field line + transport of field line

1. Start from $d_{\mathrm{FL}}(z) = \frac{1}{2} \frac{\mathrm{d}\langle (\Delta r_\perp^{\mathrm{FL}})^2 \rangle}{\mathrm{d}z}$
2. Integrate: $\langle (\Delta r_\perp^{\mathrm{FL}})^2 \rangle(z) = 2 \int_0^z \mathrm{d}z' \, d_{\mathrm{FL}}(z')$
3. Assume that particles follow field lines: $\langle (\Delta r_\perp^{\mathrm{CR}})^2 \rangle(z) = \langle (\Delta r_\perp^{\mathrm{FL}})^2 \rangle(z)$
4. Subsitute into $d_\perp(t) \equiv \frac{1}{2} \frac{\mathrm{d}}{\mathrm{d}t} \left(\langle (\Delta r_\perp^{\mathrm{CR}})^2 \rangle \right) = \frac{\mathrm{d}}{\mathrm{d}t} \int_0^{z(t)} \mathrm{d}z' \, d_{\mathrm{FL}}(z')$
5. Evaluate $z(t)$ as $\sqrt{\langle z^2 \rangle(t)}$ $\Rightarrow$ $d_\perp(t) = \frac{\mathrm{d}}{\mathrm{d}t} \int_0^{\sqrt{\langle z^2 \rangle}} \mathrm{d}z' \, d_{\mathrm{FL}}(z') = \frac{d_{\mathrm{FL}}(\sqrt{\langle (\Delta z)^2 \rangle})}{\sqrt{\langle (\Delta z)^2 \rangle}} d_\parallel(t)$

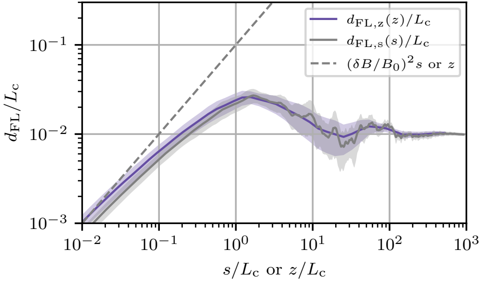
N.B.: This can also be derived from a microscopic model of particle transport.

Heuristic model

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05882]

$$d_\perp(t) = \frac{d_{\mathrm{FL}}\left(\sqrt{\langle(\Delta z)^2\rangle}\right)}{\sqrt{\langle(\Delta z)^2\rangle}} d_\parallel(t)$$

Parametrise d_{FL} and $d_\parallel$ by broken power laws

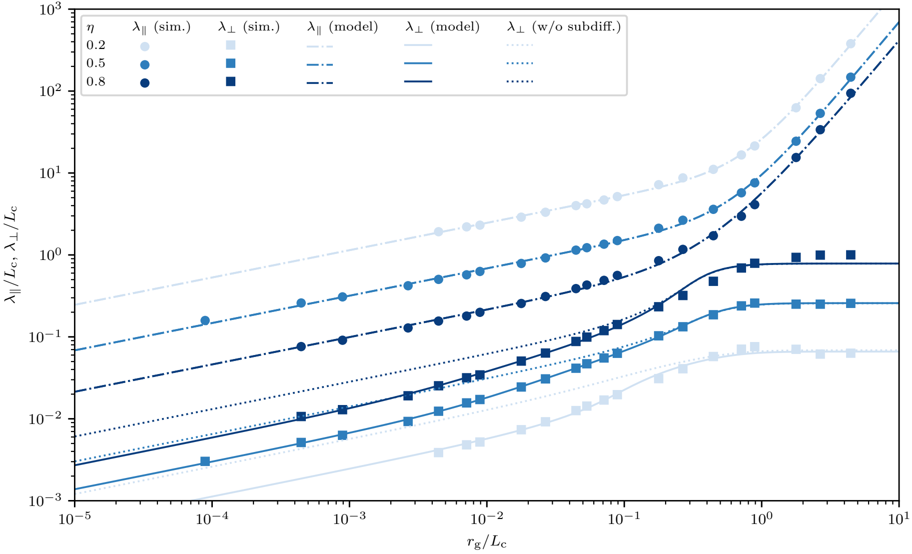


Field-line transport is subdiffusive at intermediate distances!

See also Sonsrettee *et al.* (2016)

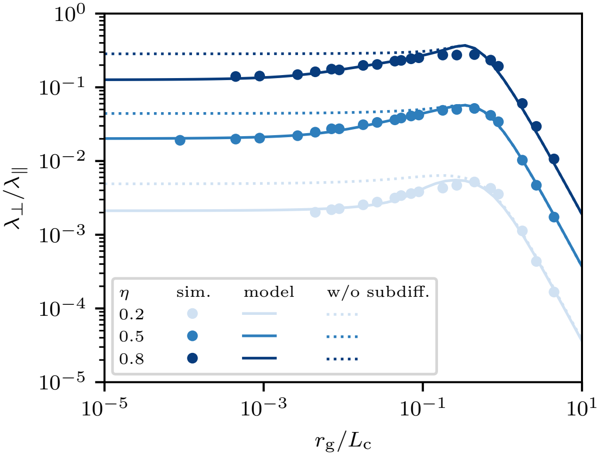
Mean-free paths

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05882]



Ratio of mean-free paths

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05882]



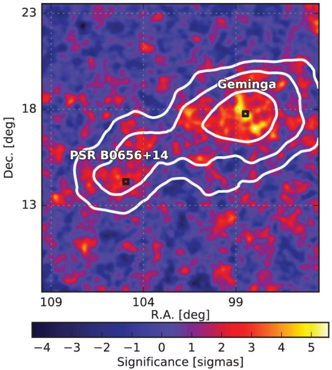
$\kappa_\parallel$ and $\kappa_\perp$ scale differently at medium rigidites,
but they scale the same at low rigidities

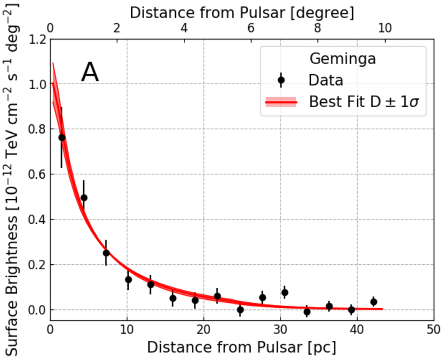
(More details → Appendix)

Outline

Gamma-ray halos

Abeysekara *et al.* (2017)





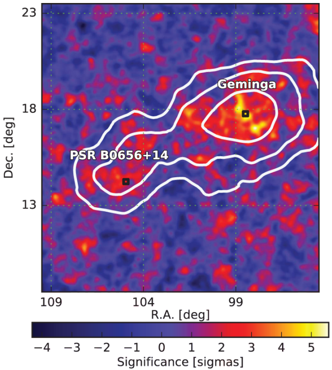
- Gamma-ray emission around two nearby pulsars
- Emission from $\mathrm{e}^{\pm}$ much more confined than expected

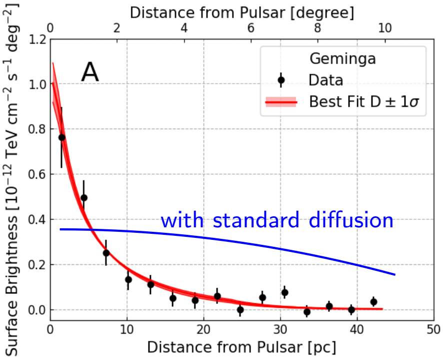
$\rightarrow$ Ambient diffusion coefficient suppressed by factor ~ 100

- Also evidence of suppressed diffusion around some supernova remnants

Gamma-ray halos

Abeysekara *et al.* (2017)





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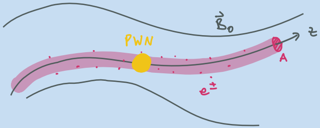
NOT the conflict

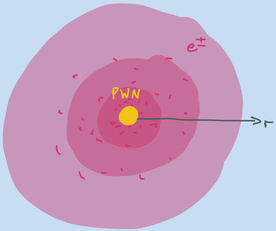
Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

1D



- Growth rate: $\Gamma_{1D} \propto \frac{\partial f}{\partial z}$
- Volume occupied: $V_{1D} \sim A \left\langle (\Delta z)^2 \right\rangle^{1/2}$

3D

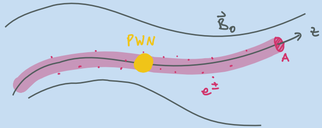


- Growth rate: $\Gamma_{3D} \propto \frac{\partial f}{\partial r}$
- Volume occupied: $V_{3D} \sim \left\langle (\Delta r)^2 \right\rangle^{3/2}$

NOT the conflict

Evoli, Linden, Morlino (2018), Linden & Mukhopadhyay (2022)

1D



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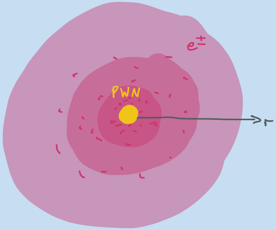


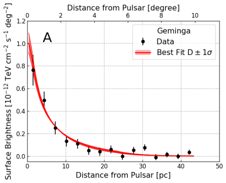
- Growth rate: $\Gamma_{3D} \propto \frac{\partial f}{\partial r}$
- Volume occupied: $V_{3D} \sim \left\langle (\Delta r)^2 \right\rangle^{3/2}$

Locally, transport is **not** isotropic

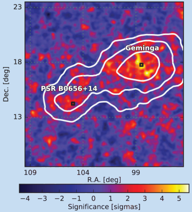
See Lopez-Coto and Giacinti (2019) though

The conflict

Profile

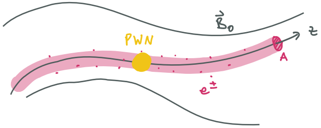


Symmetry



$\rightarrow$

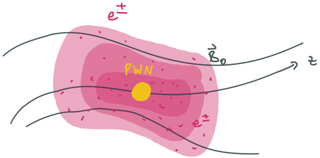
Suppression of diffusion



$$\kappa_\perp \ll \kappa_\| \quad \Leftrightarrow \quad \delta B^2 \ll B_0^2$$

$\rightarrow$

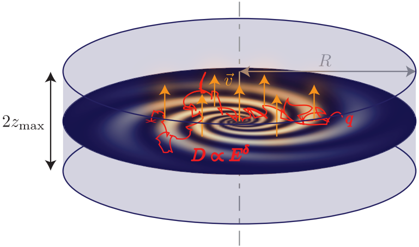
Spherical distribution



$$\kappa_\perp \sim \kappa_\| \quad \Leftrightarrow \quad \delta B^2 \gg B_0^2$$

A swiss cheese Galaxy

Jacobs, Mertsch, Phan, *in prep.*



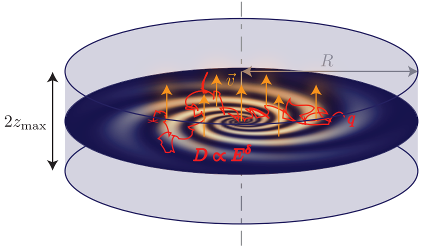
- Diffusion suppressed in bubbles around sources

$\rightarrow$ Transport of cosmic rays affected on large scales?

- Different diffusion coefficient in disk and halo: $\kappa_{\text{disk}} = \alpha\, \kappa_{\text{halo}}$

A swiss cheese Galaxy

Jacobs, Mertsch, Phan, *in prep.*



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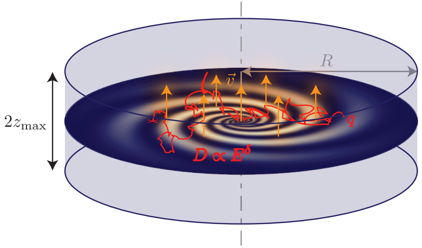

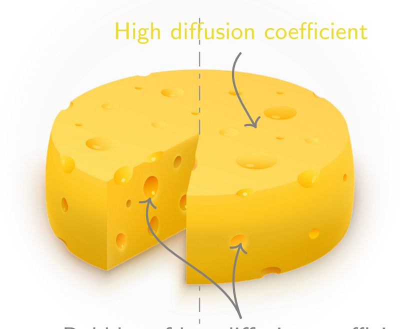

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$\rightarrow$ Transport of cosmic rays affected on large scales?

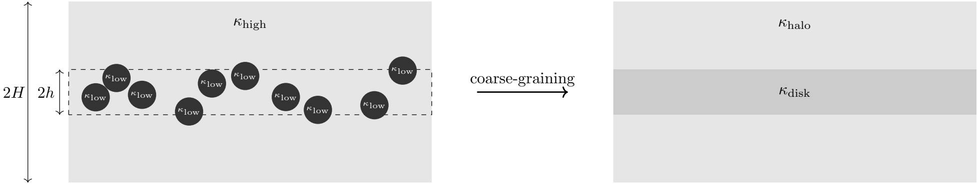
- Different diffusion coefficient in disk and halo: $\kappa_{\text{disk}} = \alpha\, \kappa_{\text{halo}}$

Coarse-graining

Jacobs, Mertsch, Phan, *in prep.*

- Filling fraction $f \lesssim$ (a few) % $\rightarrow$ negligible?
- Difficult to model numerically

$\rightarrow$ Adopt course-grainined $\kappa_{\mathsf{disk}} = \alpha \kappa_{\mathsf{high}}$ and $\kappa_{\mathsf{halo}} = \kappa_{\mathsf{high}}$

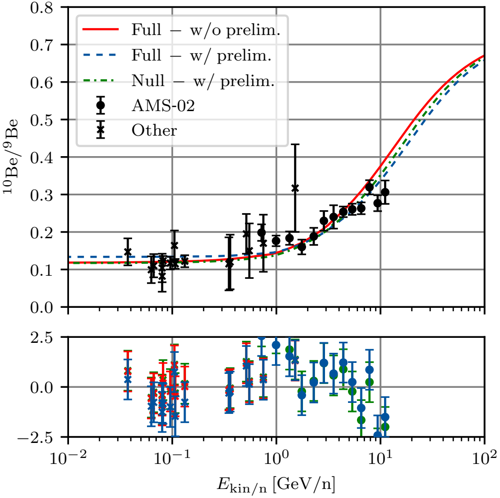


- Study impact of $\alpha < 1$ on cosmic ray observables
- The coarse-grained κ_{disk} can only depend on κ_{high}, κ_{low} and the filling fraction

$\rightarrow$ Can infer filling fraction from data?

$^{10}\mathrm{Be}/^{9}\mathrm{Be}$

Jacobs, Mertsch, Phan, *in prep.*

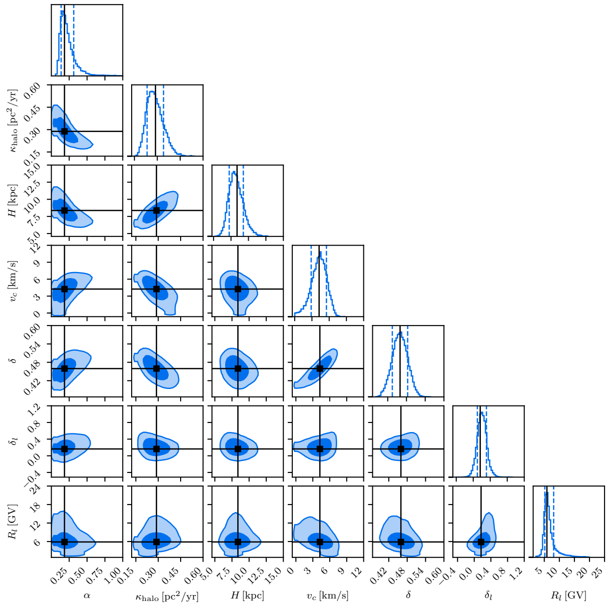


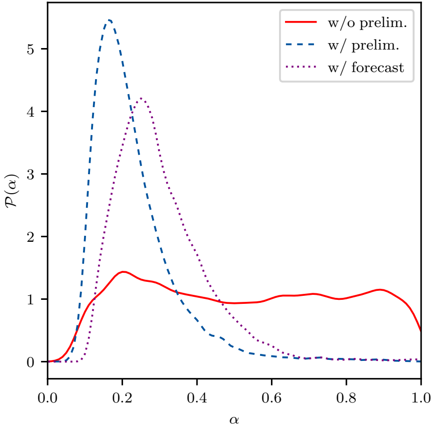
- Unstable $^{10}\mathrm{Be}$ created in disk
- At high energies: essentially stable
- At low energies: decays while diffusing

If diffusion is suppressed, $\kappa_{\text{disk}} < \kappa_{\text{halo}}$,
$^{10}\mathrm{Be}/^{9}\mathrm{Be}$ is increased at low energies

Posterior distributions

Jacobs, Mertsch, Phan, *in prep.*

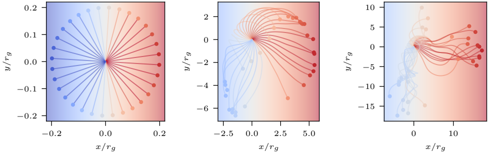




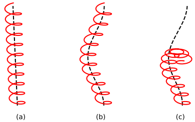
With prelim. AMS-02 data

- Best fit for $\alpha \simeq 0.2$
- $\alpha = 1$ excluded at $\sim 4\sigma$
- Implies very large filling fraction $f \sim 0.5$

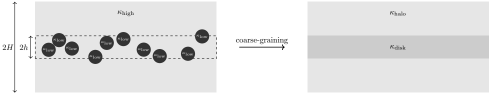
Summary



Small-scale anisotropies formed in transition from ballistic to diffusive motion



Perpendicular diffusion due to parallel diffusion and field-line subdiffusion



Evidence for suppressed diffusion from $^{10}\mathrm{Be}/^{9}\mathrm{Be}$