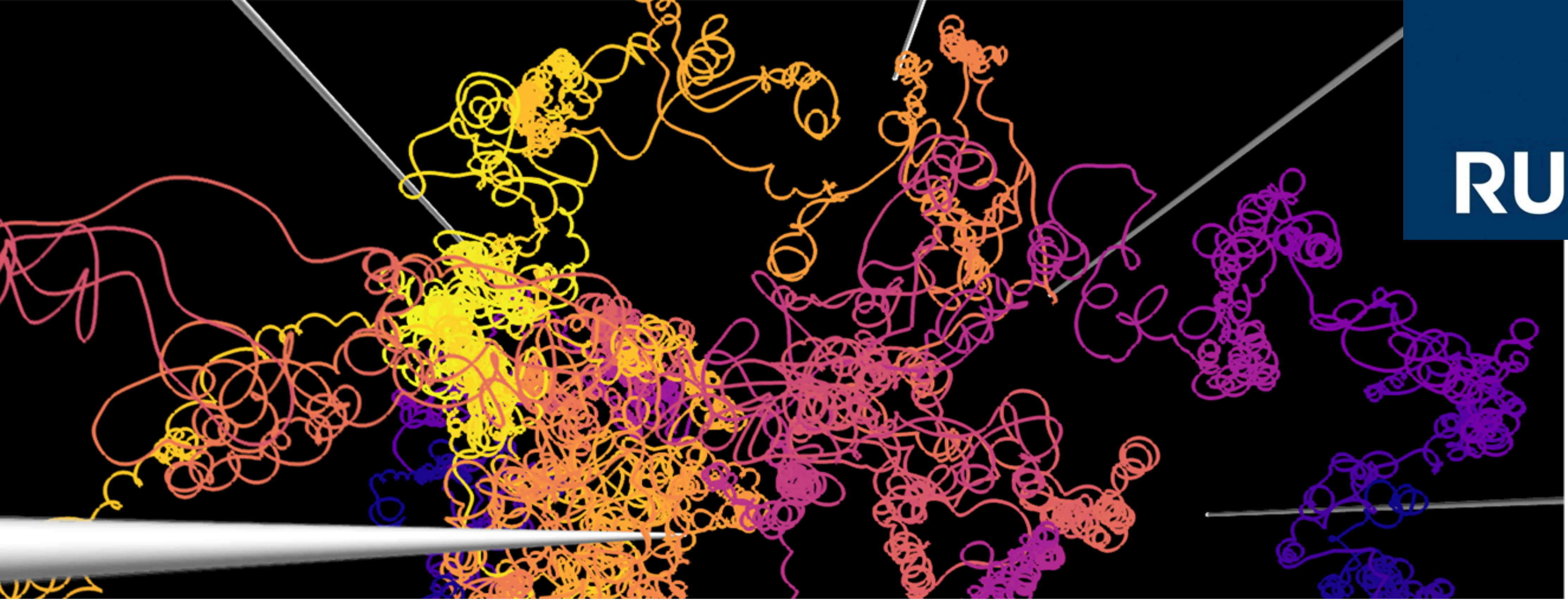

Multi-messenger modeling of Galactic cosmic-ray acceleration and transport

Ruhr University Bochum
Lukas Merten

Motivation

Observational challenges

Science Bulletin 67 (2022) 2162–2166
Contents lists available at ScienceDirect
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Article

Detection of spectral hardenings in cosmic-ray boron-to-carbon and boron-to-oxygen flux ratios with DAMPE

DAMPE Collaboration [1]

PHYSICAL REVIEW LETTERS **130,** 211002 (2023)

Properties of Cosmic-Ray Sulfur and Determination of the Composition of Primary Cosmic-Ray Carbon, Neon, Magnesium, and Sulfur: Ten-Year Results from the Alpha Magnetic Spectrometer

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, i
unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Mil
Way arrive at Earth from random directions. However, cosmic rays interact with matter near their
... during propagation, which produces high-energy neutrinos. We searched for neutrino
... techniques applied to 10 years of data from the IceCube Neutrino
... background-only hypothesis, we identified
... is consistent w

70:95 (32pp), 2024 July 20
rican Astronomical Society.
https://doi.org/10.3847/1538-4357/ad4

The Coherent Magnetic Field of the Milky Way

Michael Unger[1,2] and Glennys R. Farrar[3]
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er@kit.edu
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Received 2024 February 6; revised 202

CrossMa

RESEARCH ARTICLE

ASTROPARTICLE PHYSICS

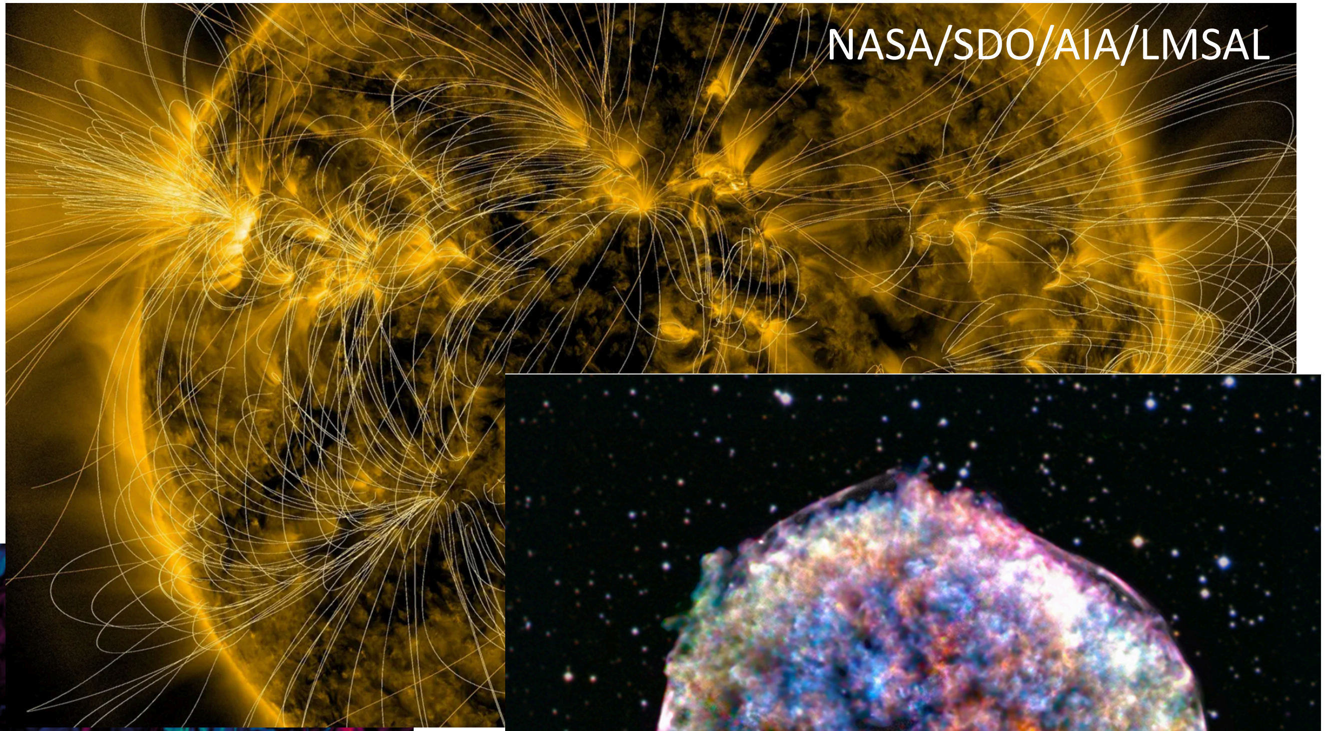
An extremely energetic cosmic ray observed by a surface detector array

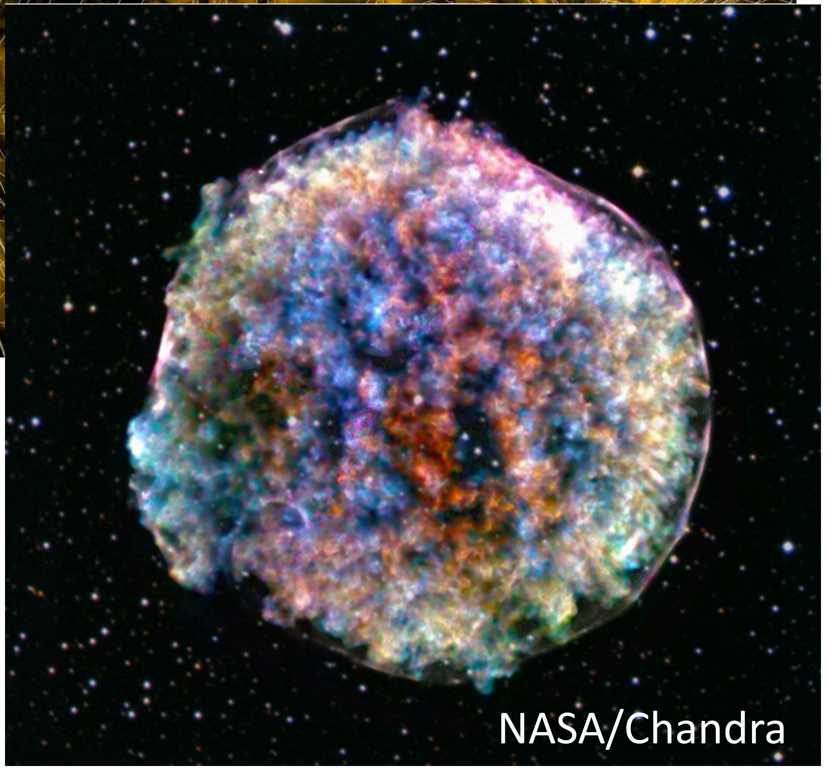
Telescope Array Collaboration*†

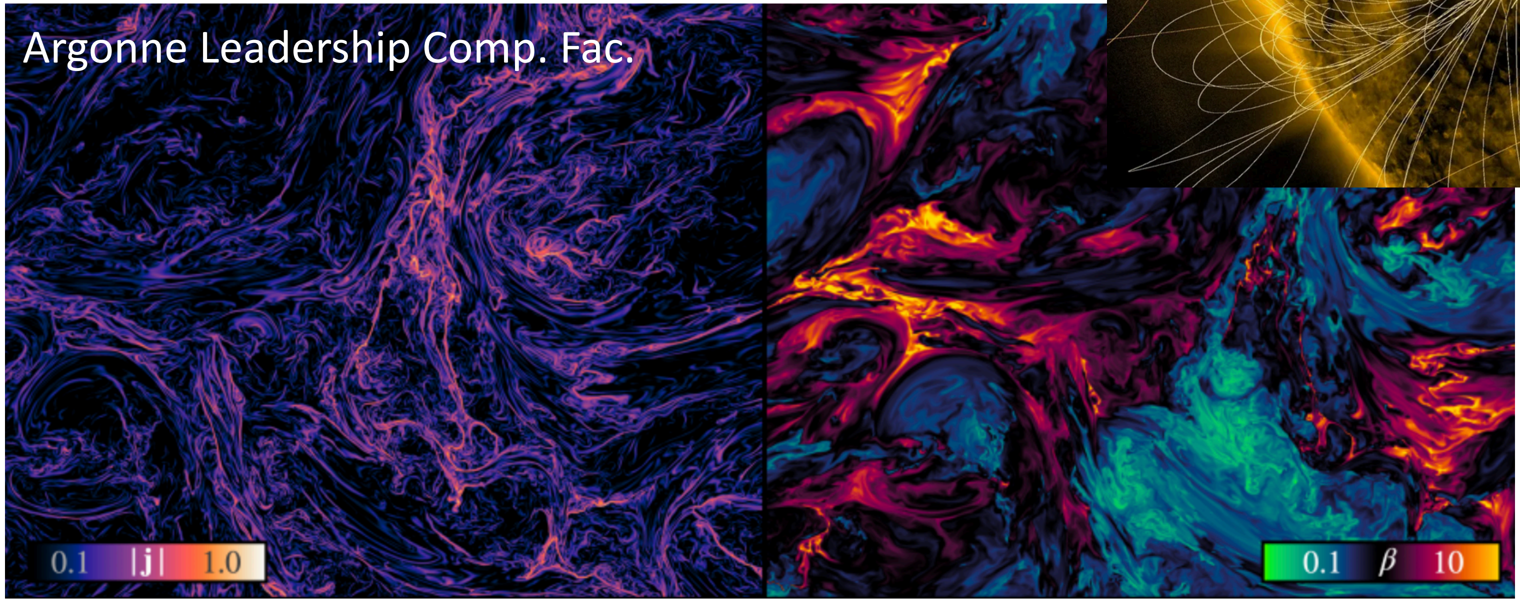
Cosmic rays are energetic charged particles from extraterrestrial sources, with the highest-energy events thought to come from extragalactic sources. Their arrival is infrequent, so detection requires instruments with large collecting areas. In this work, we report the detection of an extremely energetic particle recorded by the surface detector array of the Telescope Array experiment. We calculate the particle's energy as 244 ± 29 (stat.) $^{+51}_{-76}$ (syst.) exa–electron volts (~40 joules). Its arrival direction points back to a void in the large-scale structure of the Universe. Possible explanations include a large deflection by the foreground magnetic field, an unidentified source in the local extragalactic neighborhood, or an incomplete knowledge of particle physics.

How are Cosmic Rays accelerated?

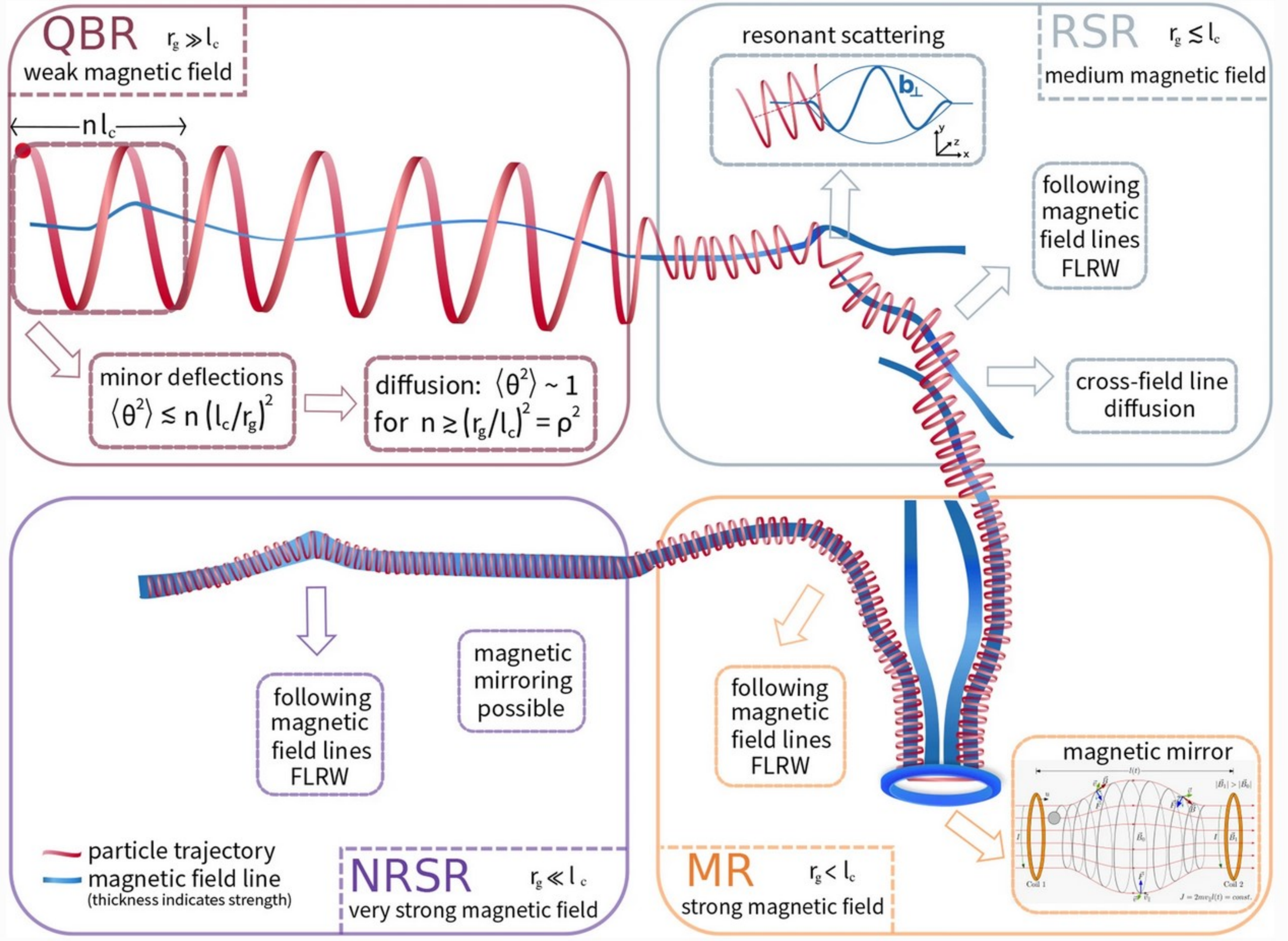
- Diffusive Shock acceleration (first order Fermi)
- Stochastic acceleration (second order Fermi)
- Magnetic Reconnection







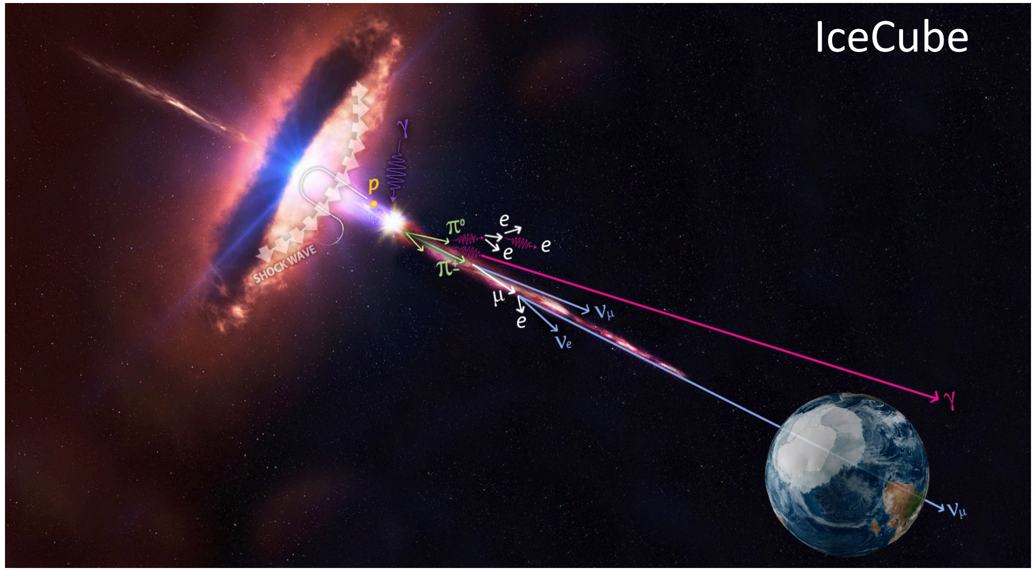
How are Cosmic Rays transported?

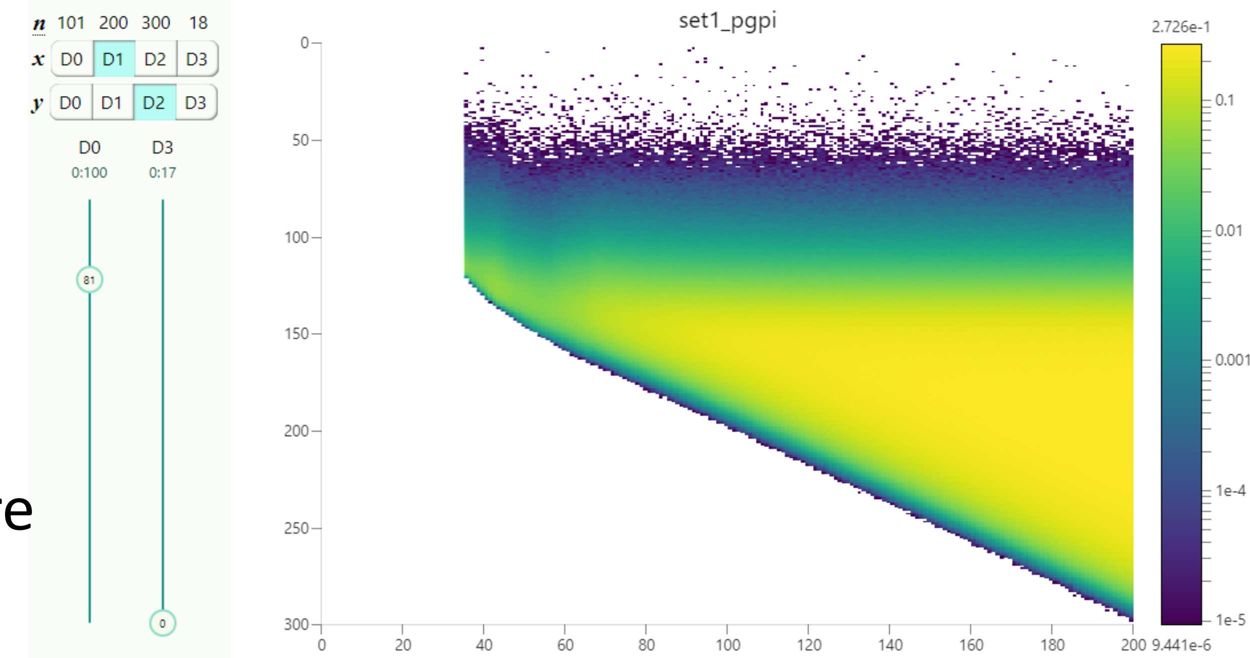


- Transport properties vary widely
- Different descriptions are needed
- Full Orbit simulations or
- Ensemble averaged descriptions

How do Cosmic Rays Interact?

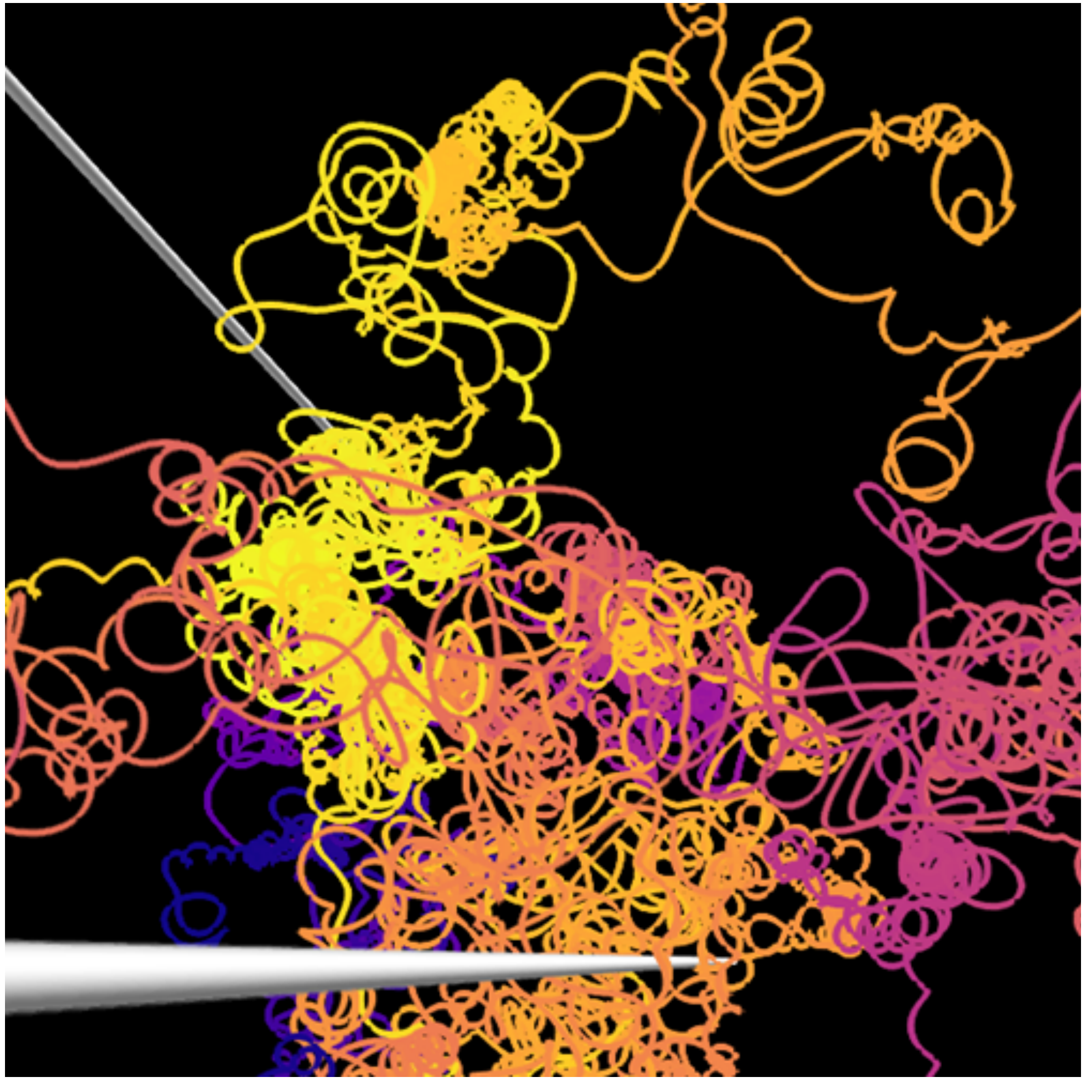
- Interaction with ambient photon and matter fields
- Feedback from cosmic rays on their environment, e.g., in sources
  - SSC, etc.
- Variety of energy losses and secondary productions
  - Harder to model
  - But gives additional channels to compare to data





CRPropa - Open Source Simulation Framework

CRPropa – Cosmic Ray Propagation Framework



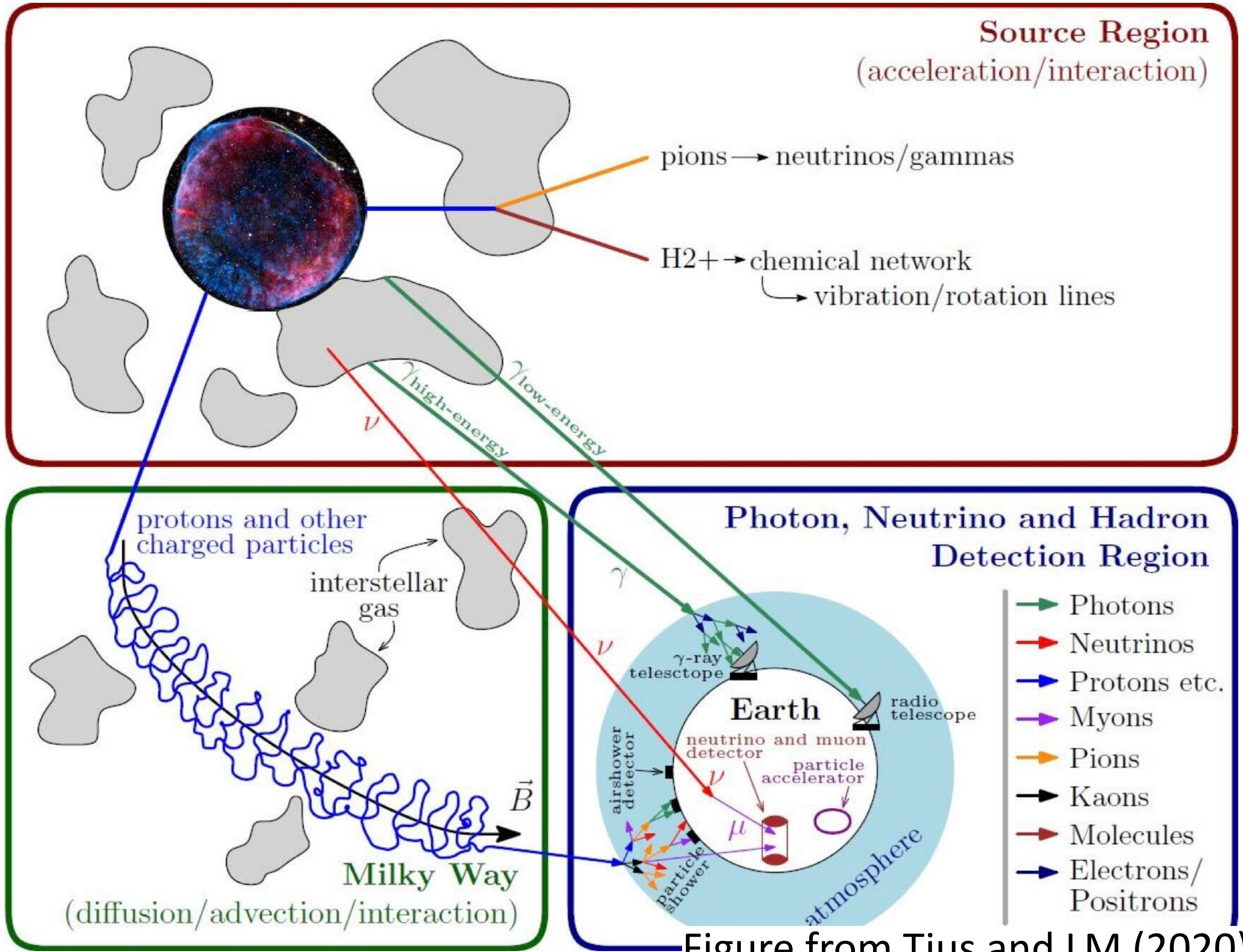


Figure from Tjus and LM (2020)

How to build a simulation?

- SimplePropagation
- PropagationCK
- PropagationBP
- DiffusionSDE

Deflection

- ElectronPairProduction
- PhotoPionProduction
- PhotoDisintegration
- NuclearDecay

Nuclei-Interacion

- EM(Double/Triple)-PairProduction
- EMInverseCompton-Scattering

EM-Interactions

- Redshift
- SynchrotronRadiation
- AdiabaticCooling

General Interactions

- MaximumTrajectory-Length
- MinimumEnergy
- CubicBoundary
- SphericalBoundary
- …

Boundaries / Threshold

- ObserverSmallSphere
- ObserverTracking
- ObserverPoint
- ObserverDetectAll
- ObserverTime-Evolution

Observer

- ShellOutput
- TextOutput
- HDF5Output
- ParticleCollector

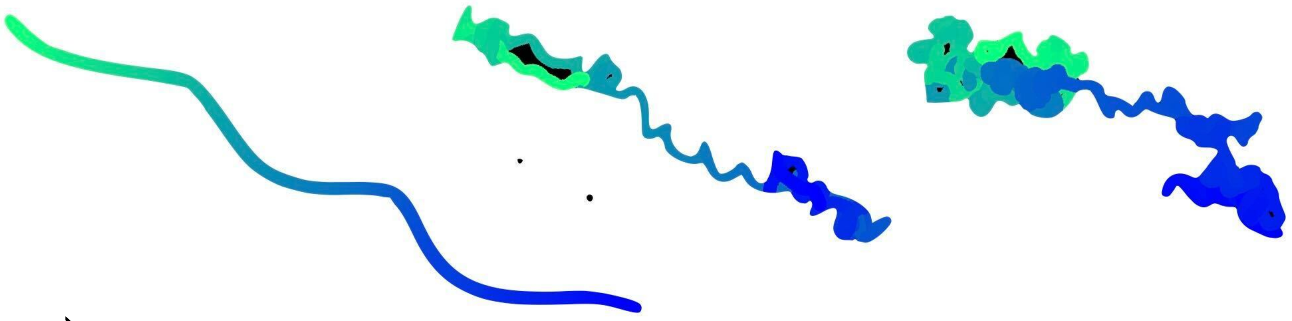
Output

- PerformanceModule

Others

Solving the Transport Equation

Transport Equations



Focused Pitch Angle Transport Equation

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) - \frac{\partial}{\partial \mu}\left(\frac{(1-\mu^2)v}{2L(s)}f\right) - \frac{\partial}{\partial s}(\mu v f) + S$$

diffusion
focusing
displacement along $\vec{B}$

Spatial Transport Equation

$$\frac{\partial f}{\partial t} = \nabla \cdot \left(\hat{\kappa}\nabla f - \mathbf{v}f\right) - \mathbf{w}\cdot\nabla f + \frac{p}{3}\nabla\cdot\mathbf{w}\frac{\partial f}{\partial p} + \frac{1}{p^2}\left(\frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial f}{\partial p}\right) - Lf + S$$

spatial diffusion
advection
adiabatic energy change
momentum diffusion
losses

Solving the Transport Equation with SDEs

Time forward Fokker Planck Equation

$$\frac{\partial f(q_1, \ldots, q_n, t)}{\partial t} = - \underbrace{\sum_{i=1}^{n} \frac{\partial}{\partial x_i} (A_i f)}_{\text{advection terms}} + \underbrace{\frac{1}{2} \sum_{i,j} \frac{\partial^2}{\partial x_i \partial x_j} \left(B_{ij} f\right)}_{\text{diffusion terms}}$$

advection terms

diffusion terms

following Itô's lemma

Corresponding stochastic differential equation

$$\mathrm{d}\mathbf{x} = \tilde{\mathbf{A}}\,\mathrm{d}t + \tilde{\hat{B}}\,\mathrm{d}\mathbf{W}_t$$

$\tilde{A}_i = A_i$ and $\tilde{\hat{B}}\tilde{\hat{B}}^{\dagger} = \frac{1}{2}(\hat{B} + \hat{B}^{t})$

LM and Aerdker subm. (2024) ArXiv:2410.01472

Fokker Planck Form

Focused Pitch Angle Transport Equation

$$\frac{\partial f(s,t)}{\partial t} = \frac{\partial}{\partial s}\left(\mu v f(s,t)\right) - \frac{\partial}{\partial \mu}\left[\left(\frac{v}{2L}(1-\mu^2) + \frac{\partial D_{\mu\mu}}{\partial \mu}\right) f\right] + \frac{1}{2}\frac{\partial^2}{\partial \mu^2}\left(2D_{\mu\mu} f\right) - \frac{\mu v}{L} f$$

Spatial Transport Equation

$$\frac{\partial f}{\partial t} = \frac{1}{2}\nabla^2(2\hat{\kappa} f) - \nabla \cdot \left[\left(\nabla \hat{\kappa} + \mathbf{v} + \mathbf{w}\right) f\right] + \frac{1}{2}\frac{\partial^2}{\partial p^2}(2Df) - \frac{\partial}{\partial p}\left[\left(\frac{\partial D}{\partial p} - \frac{2D}{p} - \frac{p}{3}\nabla \cdot \mathbf{w}\right) f\right] - \left[-\frac{2}{3}\nabla \cdot \mathbf{w} + \frac{\partial}{\partial p}\frac{2D}{p}\right] f$$

LM and Aerdker subm. (2024) ArXiv:2410.01472

What about the other terms?

$$\frac{\partial f}{\partial t} = \left[-\frac{\partial}{\partial t} A + \frac{1}{2} \frac{\partial^2}{\partial t^2} B \right] f - Cf + D$$

$$w_o = \exp(-C\mathrm{d}t) \qquad w_1 = \text{const.}$$

Usually included in CR transport equations

Transformation needs to be adapted.

Apply weights to the phase-space element

SDE Form of the

... Focused Pitch Angle Transport Equation

$$\mathrm{d}s = v\mu\,\mathrm{d}t \quad \text{and} \quad \mathrm{d}\mu = \left(\frac{v}{2L}(1-\mu^2) + \frac{\partial D_{\mu\mu}}{\partial \mu}\right)\mathrm{d}t + \sqrt{2D_{\mu\mu}}\,\mathrm{d}W_t$$

... Spatial Transport Equation

$$\mathrm{d}\mathbf{x} = \left(\nabla\hat{\kappa} + \mathbf{v} + \mathbf{w}\right)\mathrm{d}t + \sqrt{2\hat{\kappa}}\mathrm{d}\mathbf{W}_t \quad \text{and} \quad \mathrm{d}p = \left(\frac{\partial D}{\partial p} - \frac{2D}{p} - \frac{p}{3}\nabla\cdot\mathbf{w}\right)\mathrm{d}t + \sqrt{2D_{pp}}\mathrm{d}W_t$$

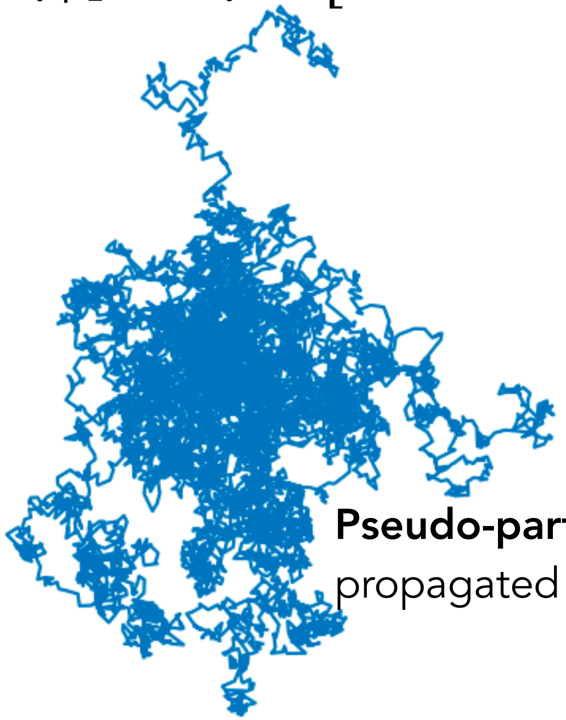
Euler-Maruyama scheme

SDE is integrated with Euler-Maruyama Scheme:

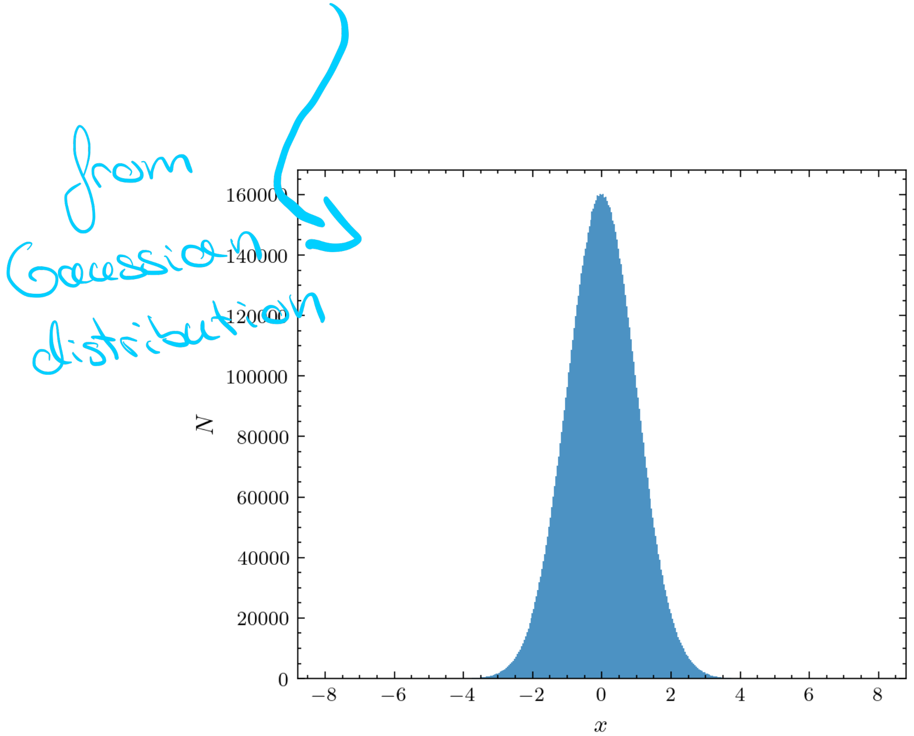
$$\hat{\kappa} = \begin{pmatrix} \kappa_{\parallel}\epsilon & 0 & 0 \\ 0 & \kappa_{\parallel}\epsilon & 0 \\ 0 & 0 & \kappa_{\parallel} \end{pmatrix}$$

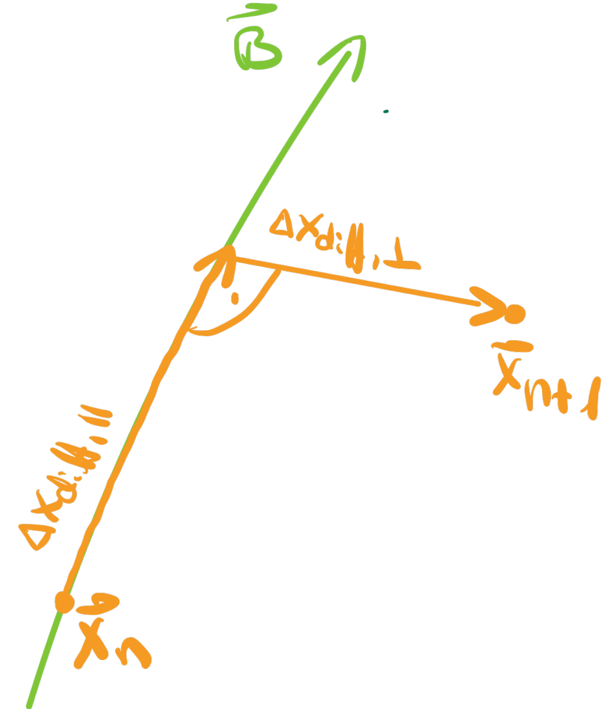
$$\mathrm{d}\mathbf{x} = \left(\nabla\hat{\kappa} + \mathbf{u}\right)\mathrm{d}t + \sqrt{2\hat{\kappa}}\,\mathrm{d}\mathbf{W}_t$$

$$\vec{x}_{t+1} = \vec{x}_t + \left[\nabla\cdot\hat{\kappa} + \vec{u}(\vec{x})\right]\Delta t + \sqrt{2\hat{\kappa}}\sqrt{\Delta t}\,\vec{\eta}_t$$



Pseudo-particles
propagated using SDEs

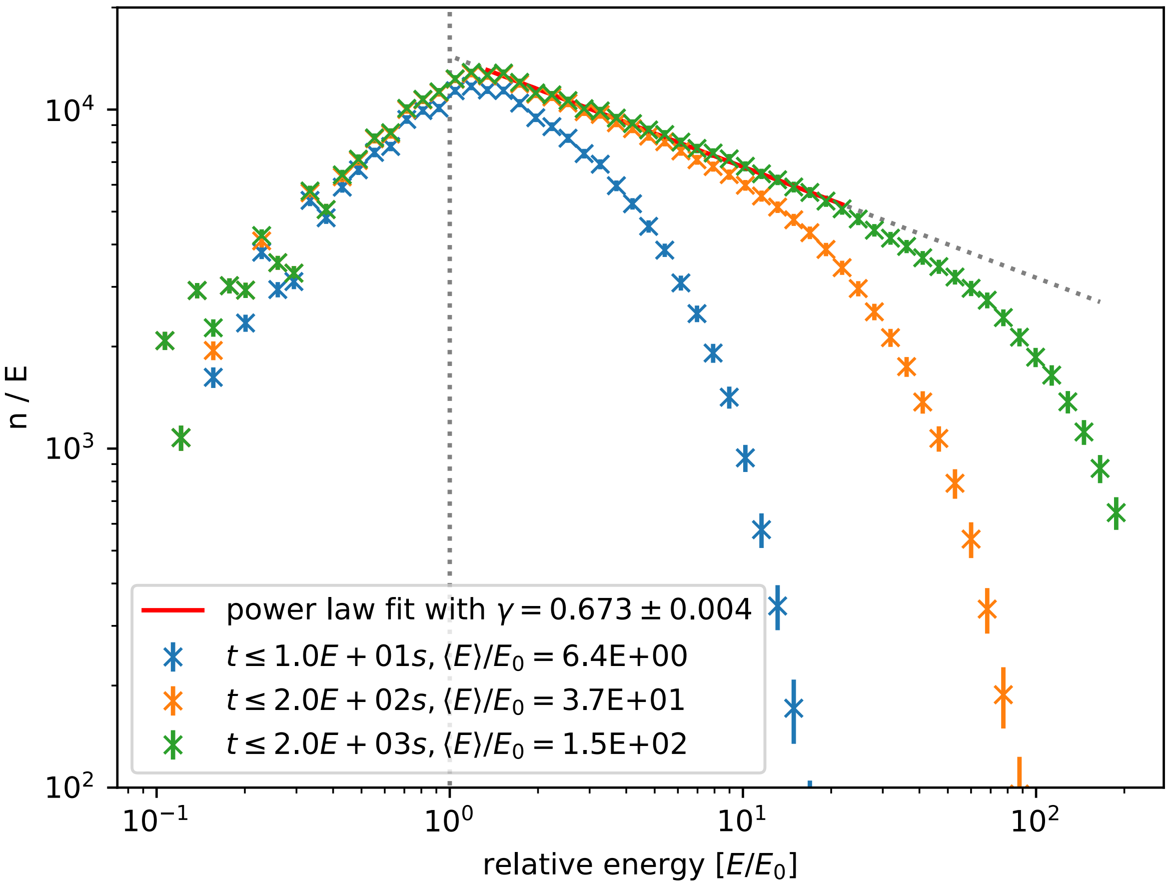




How are Cosmic Rays accelerated?

Stochastic Acceleration

Stochastic Acceleration



Stochastic Acceleration may contribute in several situations to CR energy gain, e.g., (Dogiel et al. (2018), Tautz et al. (2013), Zhang (2015))

Simple Test case:

$$0 = \frac{\partial}{\partial p}\left[p^2 D_0 p^{\alpha_p} \frac{\partial}{\partial p}\left(\frac{n}{p^2}\right)\right]$$

$$n \propto p^{1-\alpha_p}$$

Diffusive Shock Acceleration

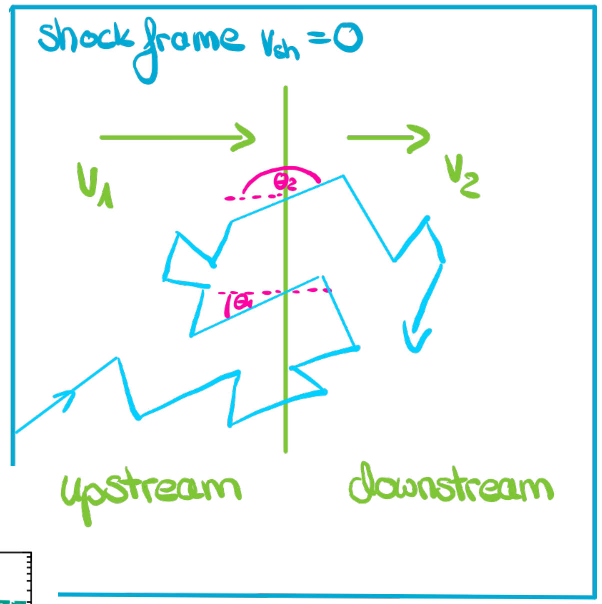
S. Aerdker, LM, et al, JCAP (2024)

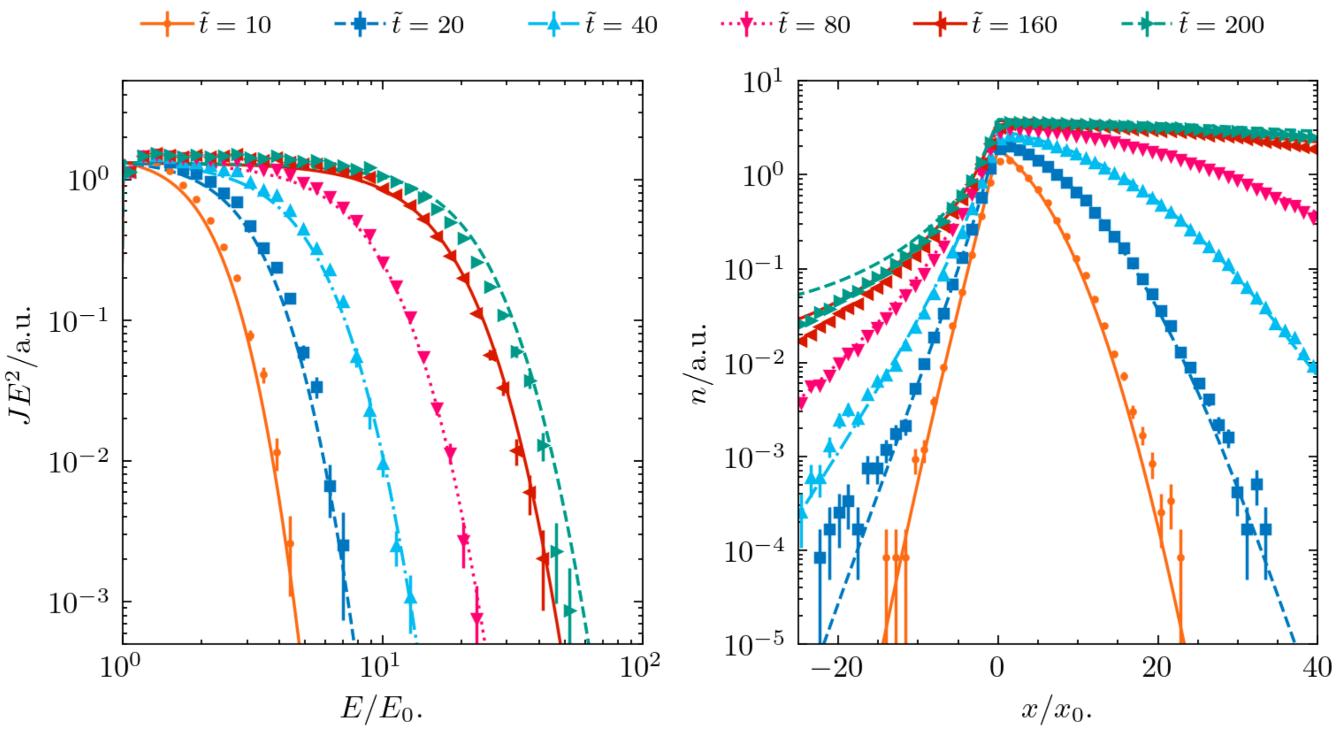
Diffusive Shock Acceleration

Interplay between diffusion, advection and adiabatic heating is responsible for energy gain at the shock:

$$\mathrm{d}\vec{x} = \left[\nabla \cdot \hat{\kappa} + \vec{u}(\vec{x})\right] \mathrm{d}t + \sqrt{2\hat{\kappa}}\, \mathrm{d}W_t$$

$$\mathrm{d}p = -\frac{p}{3} \nabla \cdot \vec{u}\, \mathrm{d}t$$

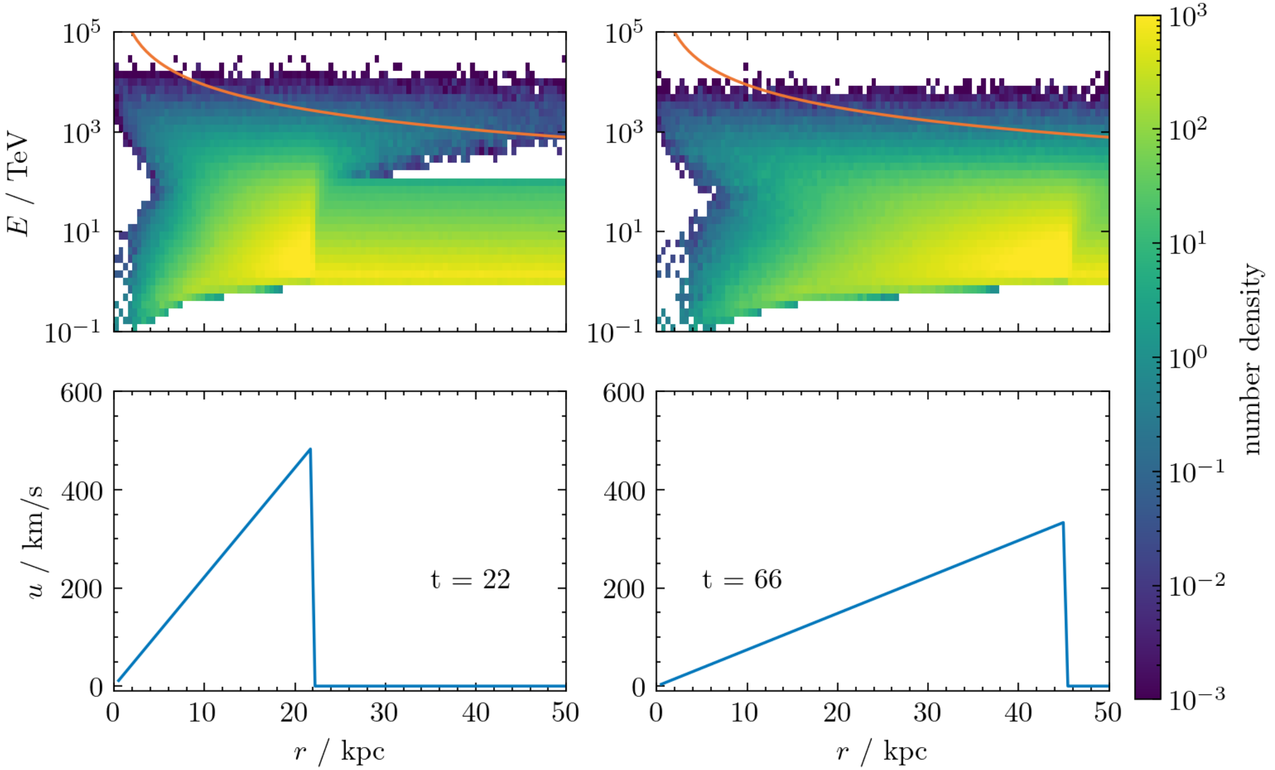




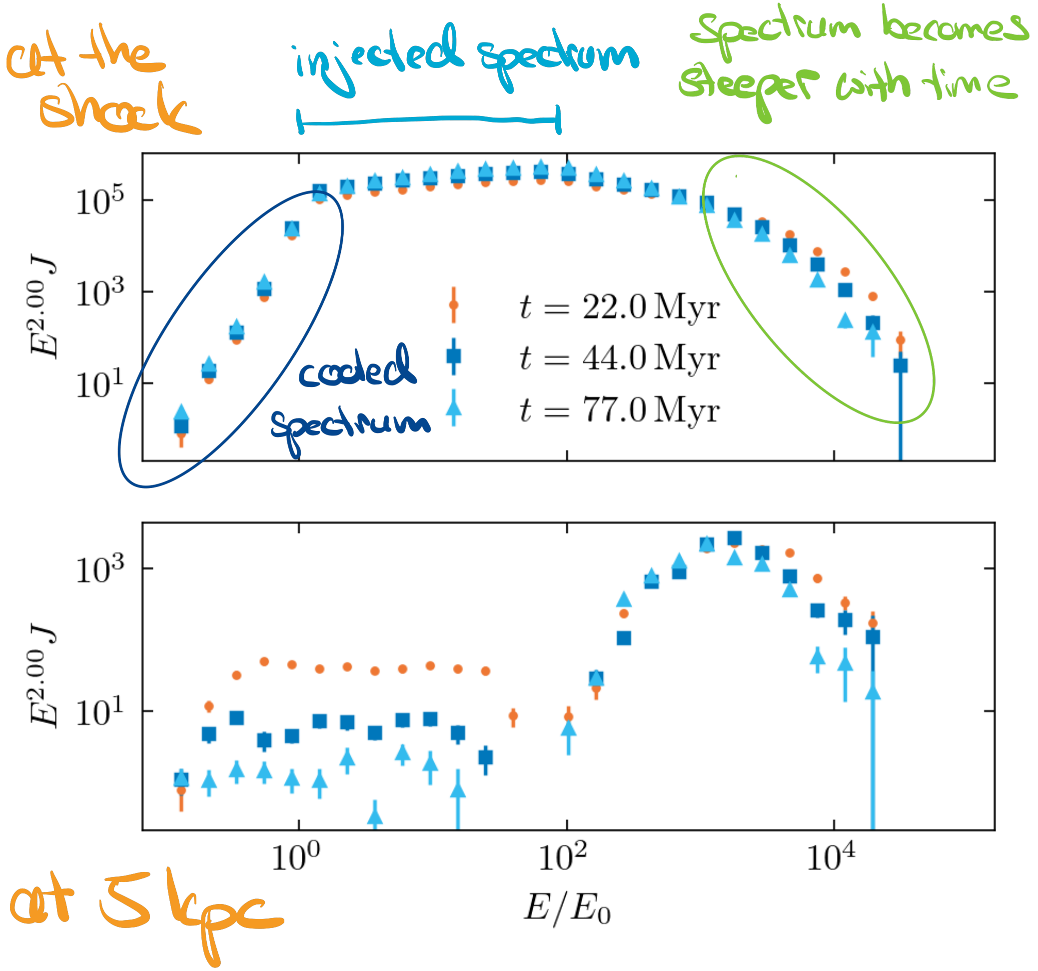
Candidate splitting module compensates loss of pseudo-particles at high energy

S.Aerdker, ..., LM, ..., in prep.

Diffusive Shock Acceleration



Time-dependent background fields, e.g. similarity solution by Isenberg, 1977



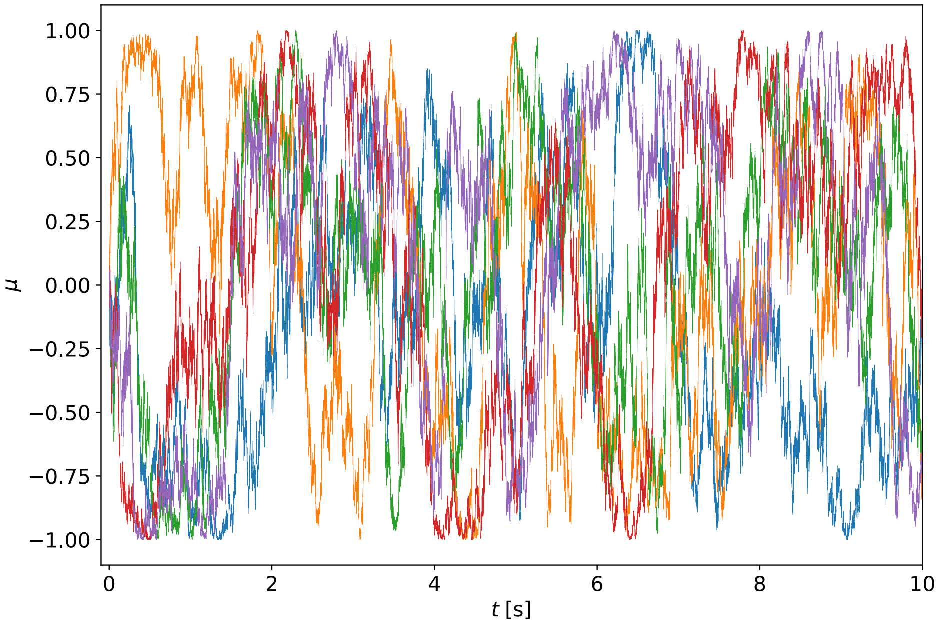
How are Cosmic Rays transported?

Focused Pitch Angle Transport

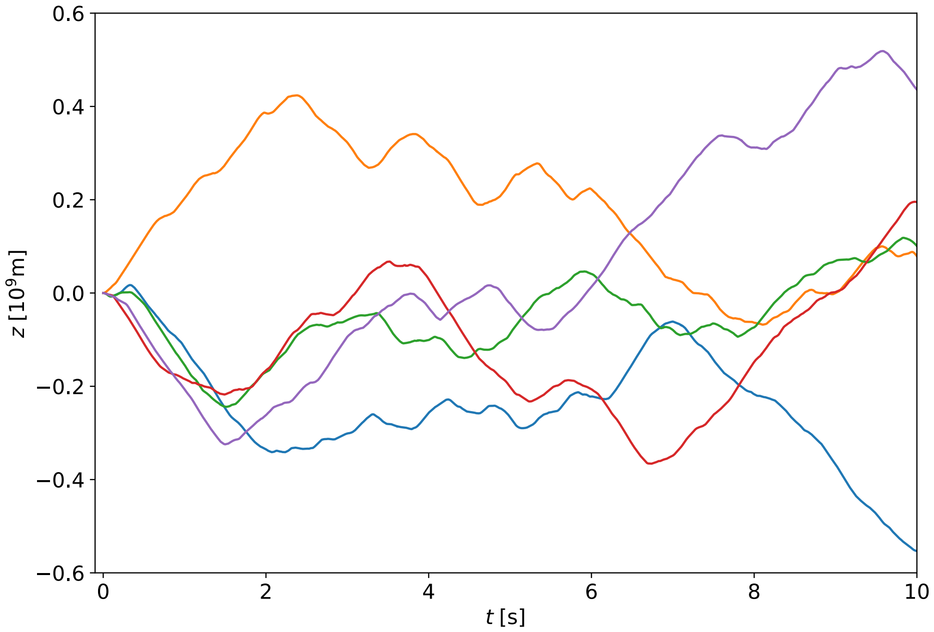
Example Trajectories

$$\mathrm{d}s = v\mu\,\mathrm{d}t \quad \text{and} \quad \mathrm{d}\mu = \left(\frac{v}{2L}(1-\mu^2) + \frac{\partial D_{\mu\mu}}{\partial \mu} \right) \mathrm{d}t + \sqrt{2D_{\mu\mu}}\,\mathrm{d}W_t$$

Pitch angle



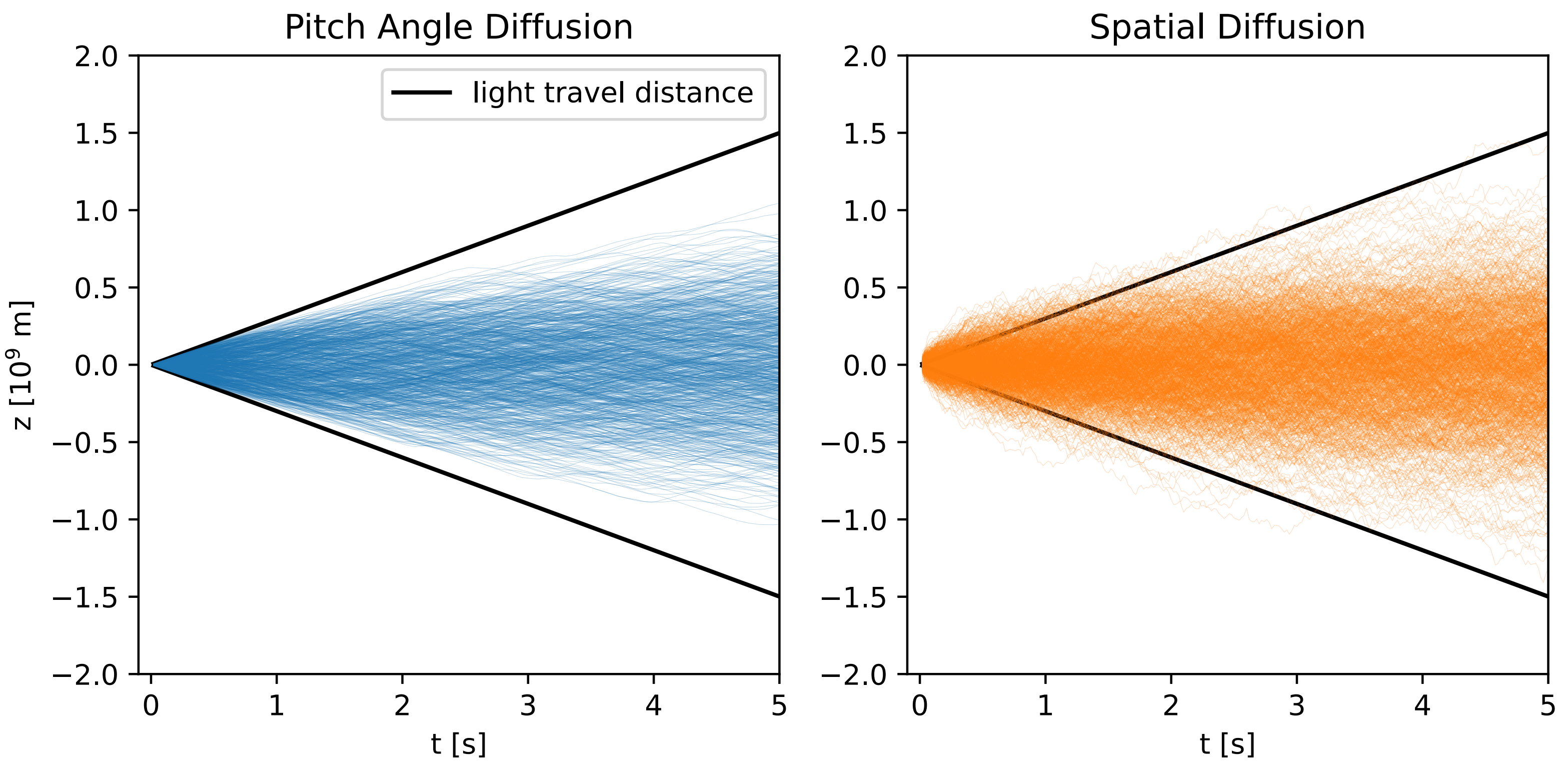
Position on field line



Regime for pitch angle is bound to $\mu \in (-1,1)$

Implemented with reflective boundaries

Example Trajectories



Same asymptotic behavior

Superluminal spreading of f for spatial diffusion

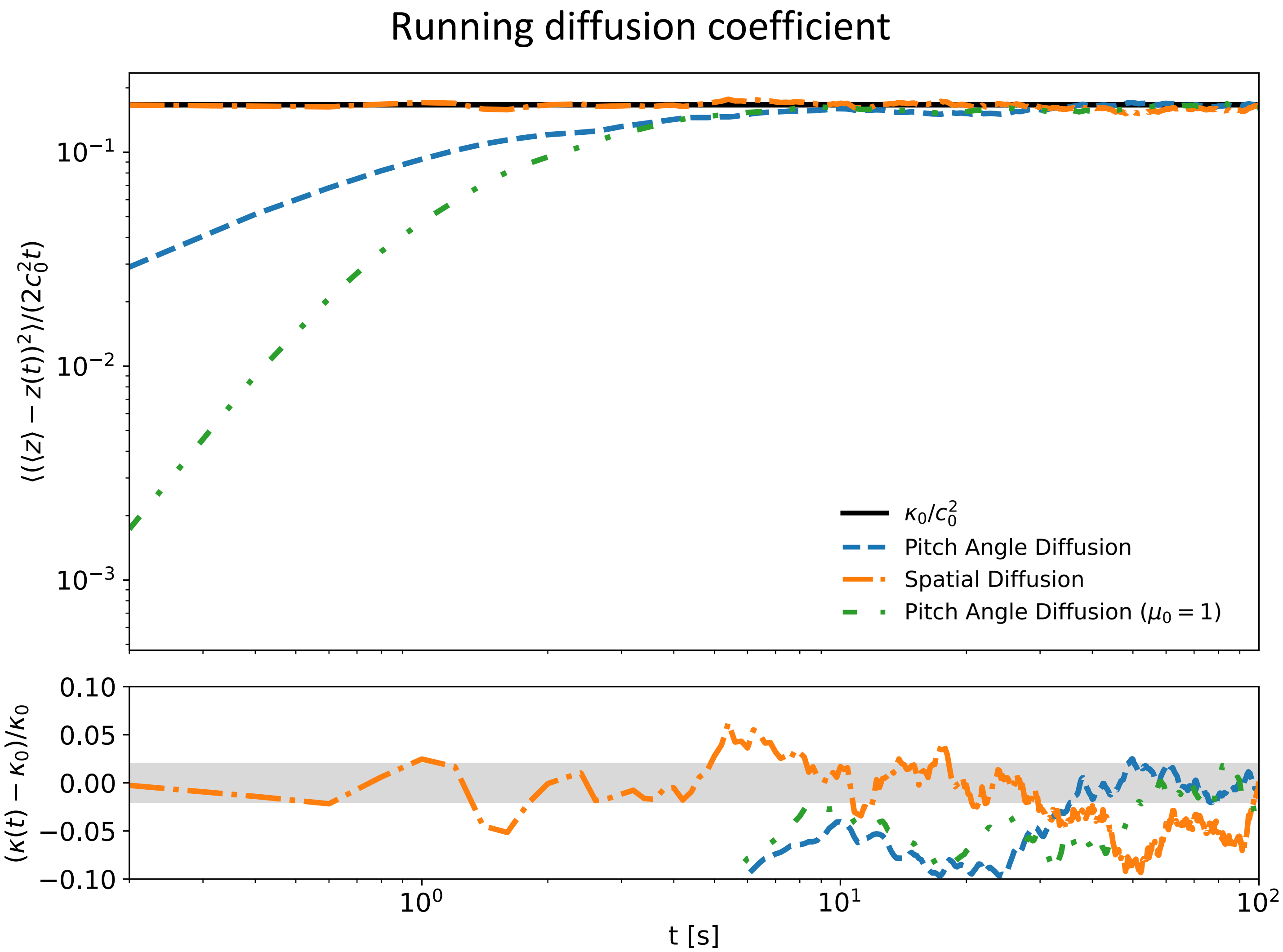
Correlated random walk for pitch angle diffusion (smoother distribution)

$$D_{\parallel} = \int_{-1}^{1} \frac{(1-\mu^2)^2}{D_{\mu\mu}} \,\mathrm{d}\mu$$

$$D_{\mu\mu} = 1 - \mu^2; v = c_0;$$

$$D_{\parallel} = c_0^2/6; h = 10^{-4}$$

First results



Without focusing the asymptotic diffusion coefficient is the same

Focusing leads to a reduced mean squared displacement

Superdiffusive phase at early times for all pitch angle diffusion models

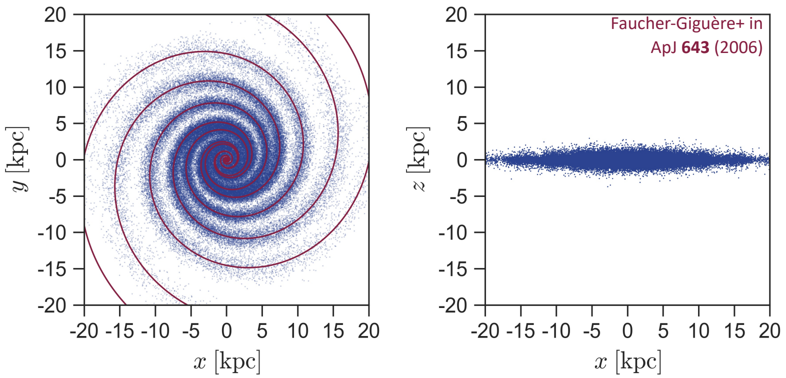
Galactic Diffusion

Source Distribution

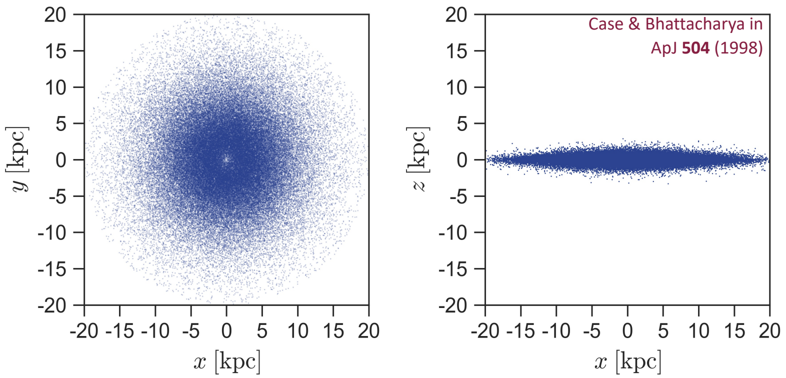
Compare different source distributions with each other

- Older simulation often assumed a homogeneous cylinder
- Likely source classes (supernova remnants, pulsar wind nebulae, etc.) have a spatial structure
- Burst injection: $S \propto \delta(t - t_0)$
- Injected energies: $E/Z = R \in \left(10 - 10^5\right)$ TV

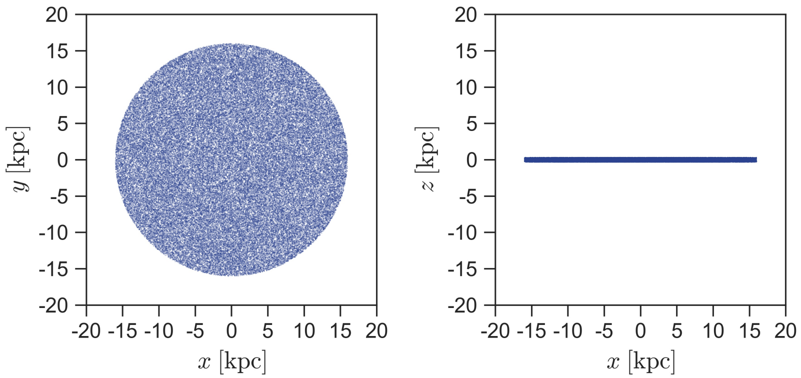
Pulsar Distribution



SNR Distribution



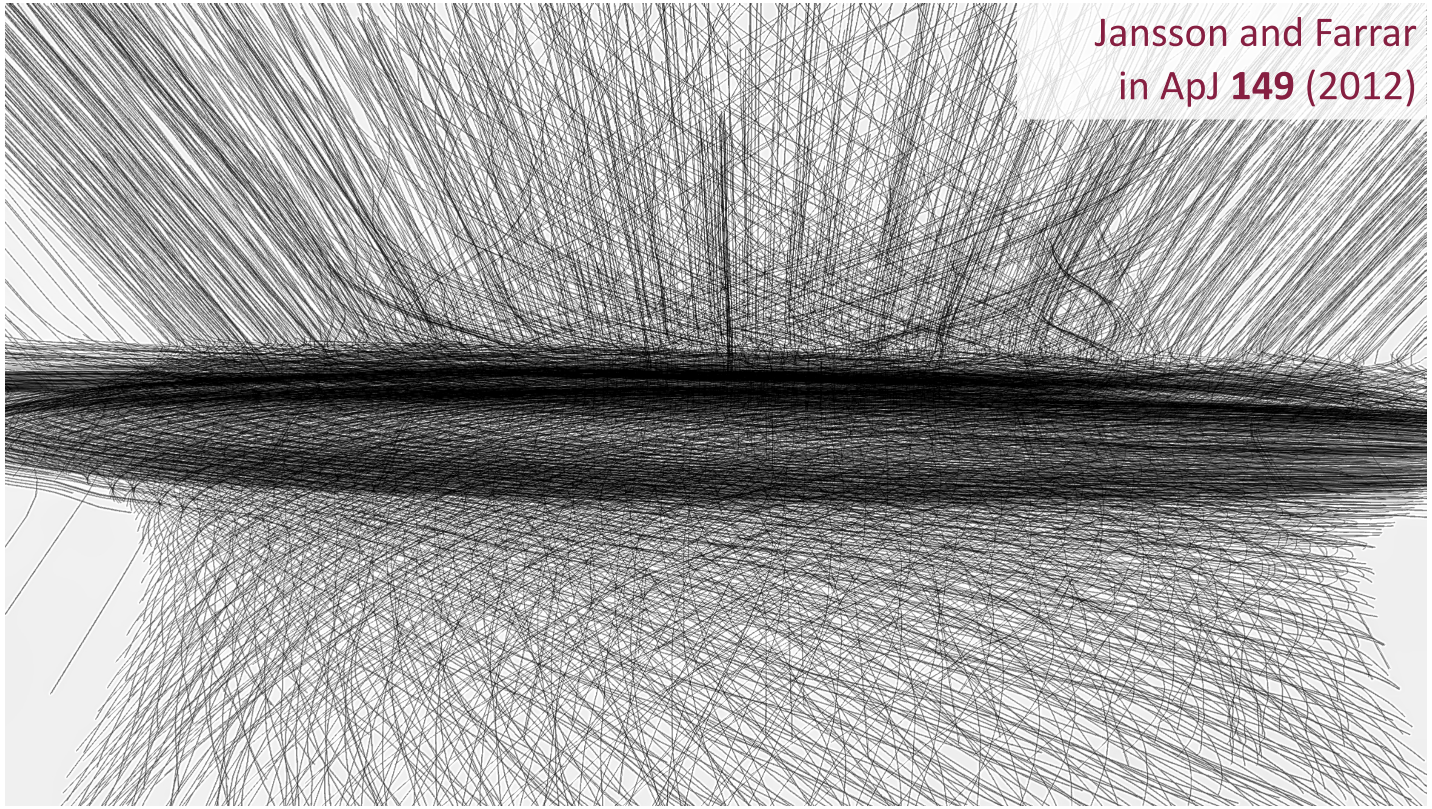
Homogeneous Cylinder



Magnetic Background Field

Model by Jansson and Farrar (2012)

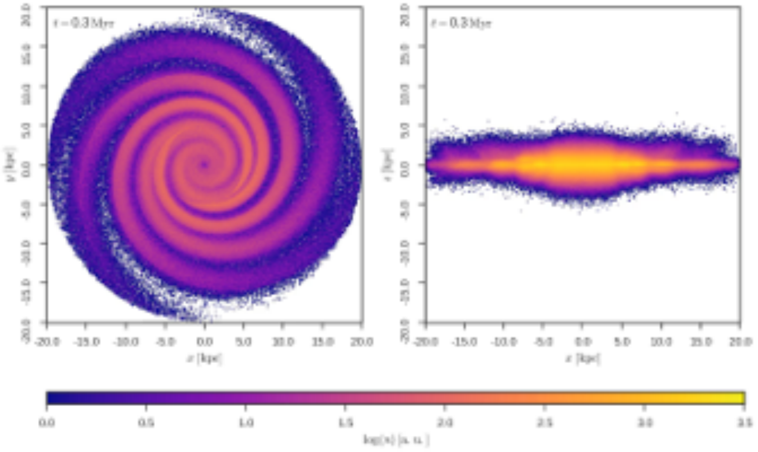
- Versatile model of the co-herent magn. field
  - Spiral arms, poloidal and toroidal components, etc.
- Available in CRPropa
- Some physics problems
  - Not cont. differentiable
  - $\nabla \boldsymbol{B} \neq 0$
  - Updated field UF23 available now



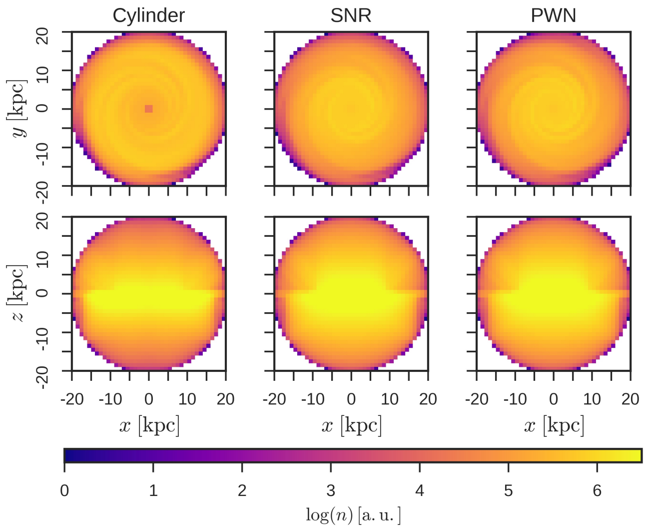
Results

- Source distribution is relevant on short timescales only.
- Magnetic field morphology plays an important role for the stationary CR distribution.
- Diffusion ratio determines the magnetic field‘s influence on CR density.
- Time scales are decreasing with increasing rigidity.

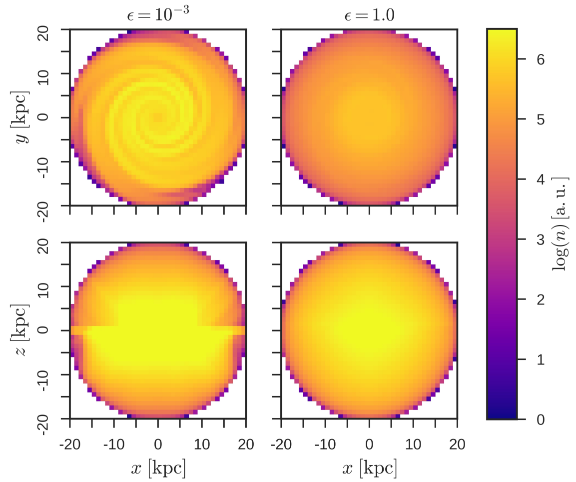
Source: PWN, $R = 10$ TV, $\epsilon = 0.01$



$R = 100$ TV, $\epsilon = 0.01$



Source: PWN, $R = 10$ TV



Escape time scale $\tau_{\mathrm{esc}} = (53 \pm 4) \cdot \epsilon^{-0.102 \pm 0.016)} \cdot \left(\frac{R}{10\,\mathrm{TeV}} \right)^{0.30 \pm 0.02}$

How do Cosmic Rays interact?

Proton proton interaction

Secondary production in CRPropa

CRPropa will include proton proton and other hadron interactions

Monte Carlo approach needs

- Total inelastic cross section (depends on primary energy)
- differential inclusive cross section (depends on primary and secondary energy)

This will allow to model

- Galactic plane neutrinos
- γ-rays from potential PeVatrons

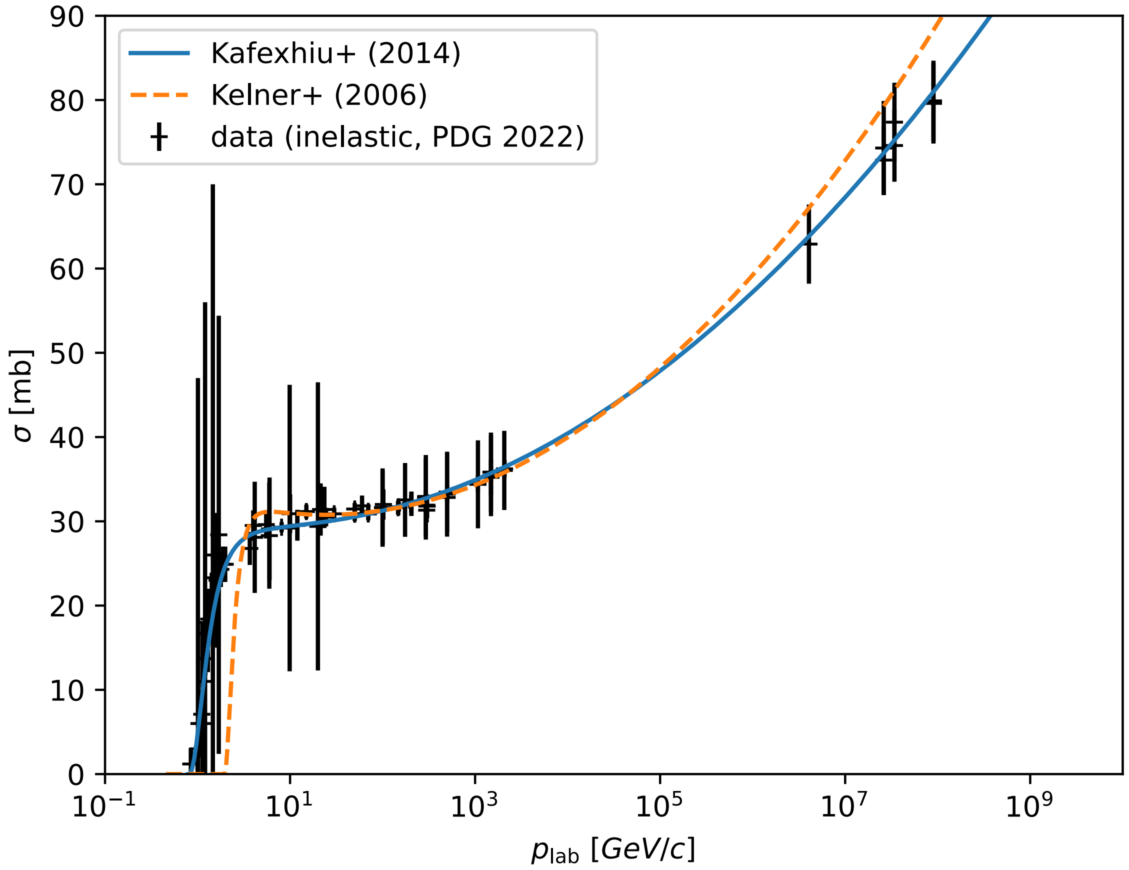


Figure by Julien Dörner

Secondary production in CRPropa

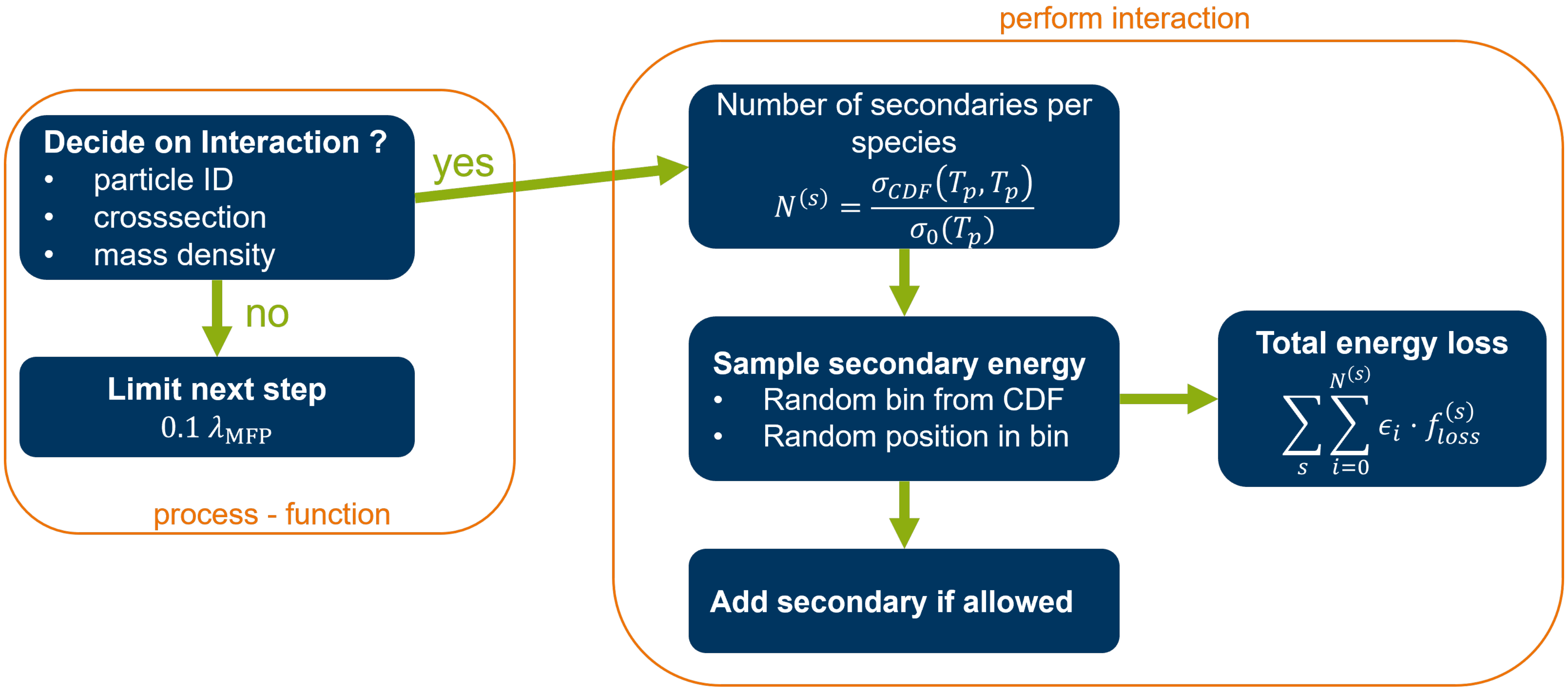
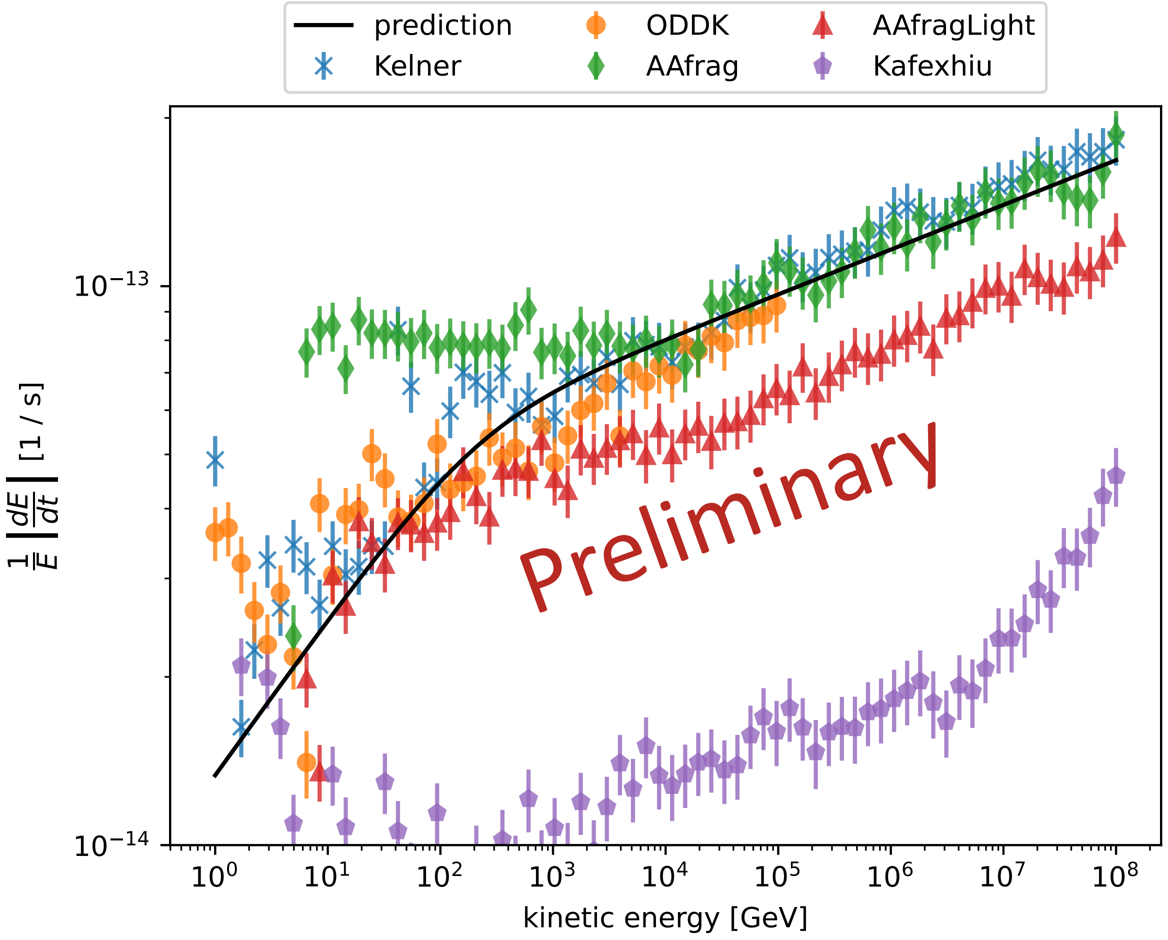


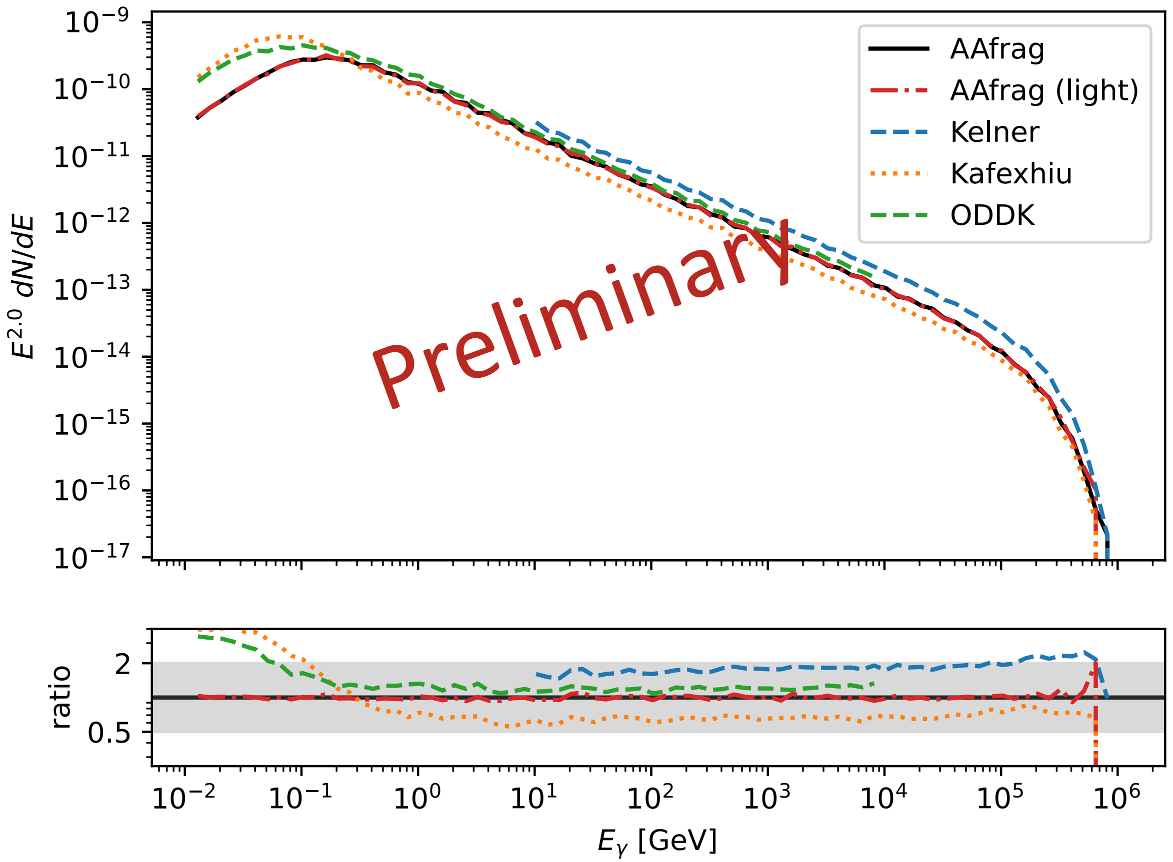
Figure by Julien Dörner

Influence on Observables

Energy loss rates



γ-ray Flux from a giant molecular cloud



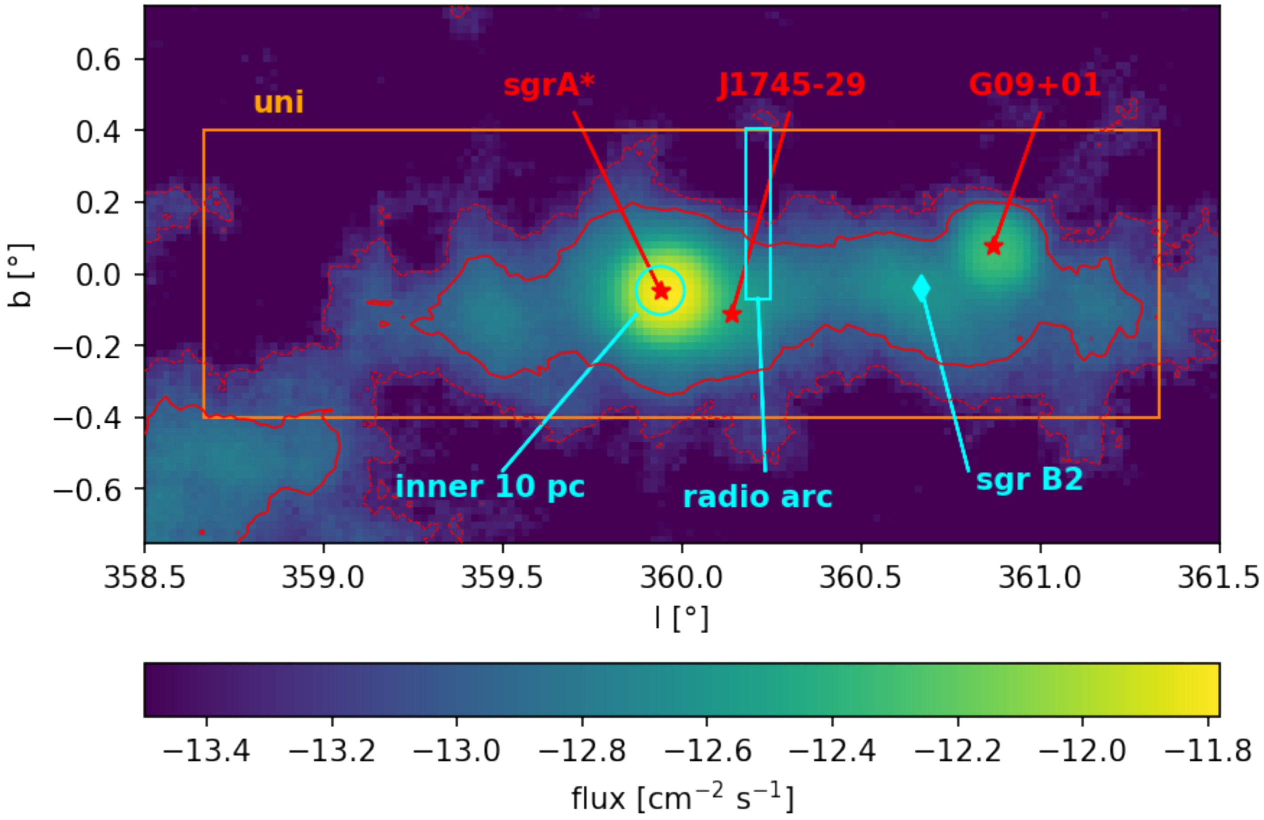
Figures by Julien Dörner

Emission from the Galactic Center

Dörner et al. ApJ (2024)

Gamma Rays from the Galactic center

Hess observation of the GC



Very high energy gamma-rays observed from the Galactic center

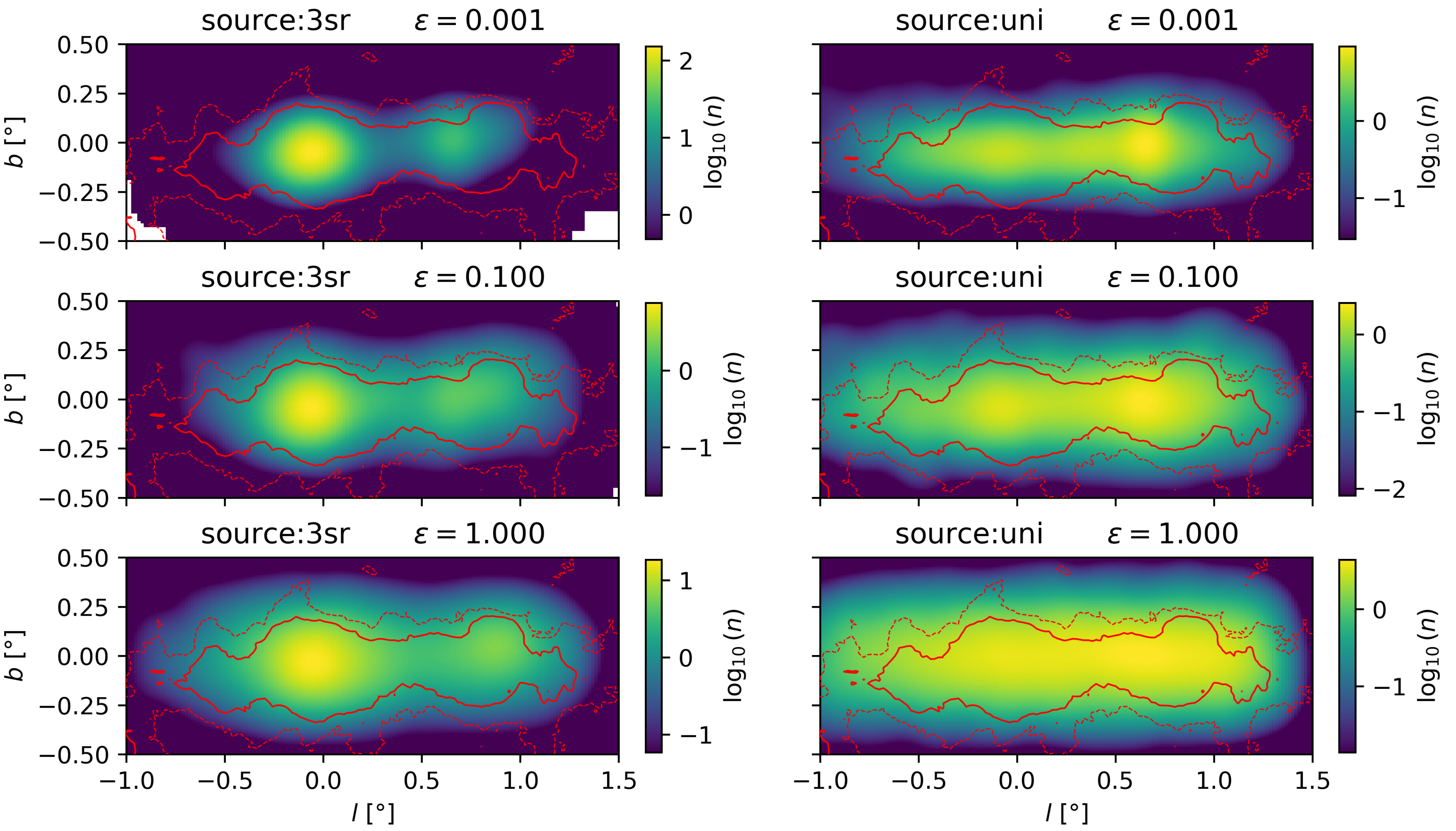
Modeling with CRPropa

- 3D magnetic field structure
- 3D approximation of the target gas densities

Questions

- Influence of the transport model?
- Relevance of source distribution?
- What is the neutrino contribution?

Gamma Rays from the Galactic center



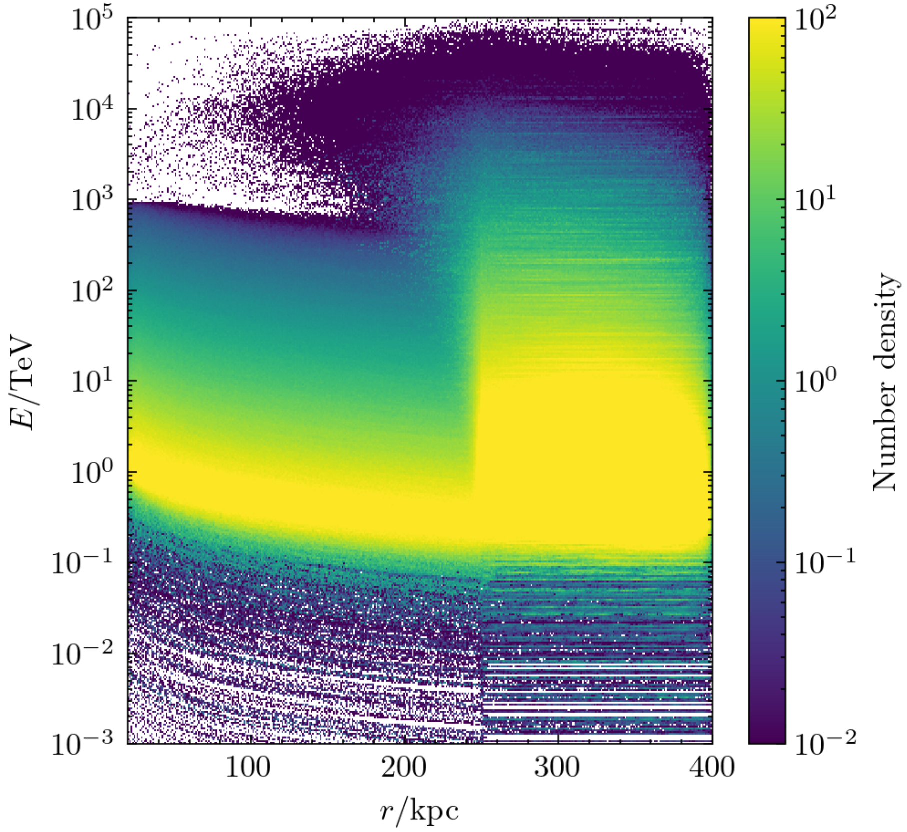
Reduced perpendicular diffusion leads to strong confinement.

Uniform source too strongly confined in Sgr B2.

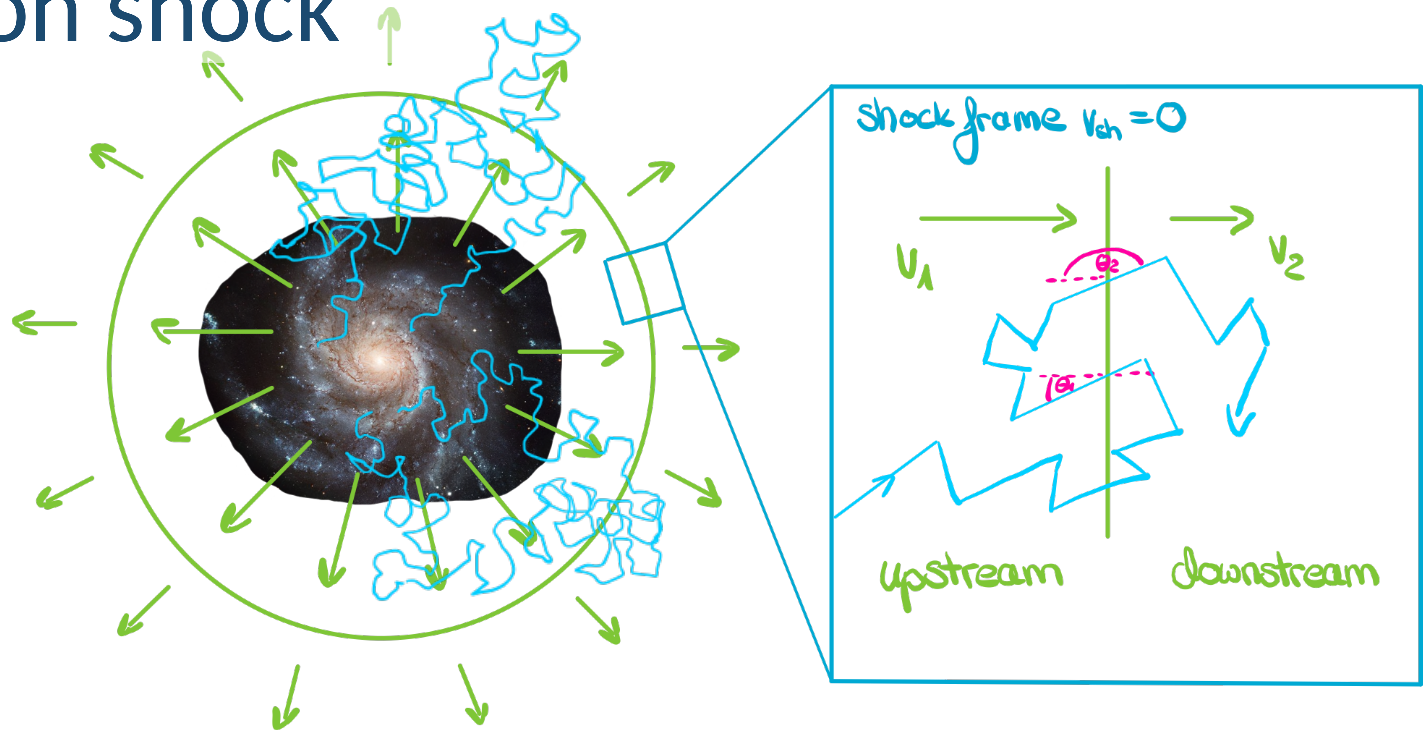
Best agreement to data for point source + isotropic diffusion

Application to Galactic Wind Termination Shock

Galactic wind termination shock



Adaptive time step for high resolution close to the shock



Assumption: Galactic Termination Shock (GTS) accelerates CRs, e.g., Bustard et al. (2017).

Question: Can these CRs propagate back into the galaxy?

GWTS - Set Up

Diffusion:

$$\kappa = 5 \times 10^{28} C_\epsilon \cdot \left(\frac{R}{4\,\mathrm{GV}}\right)^\delta \cdot \mathrm{diag}(1,\, \epsilon,\, \epsilon) \frac{\mathrm{cm}^2}{\mathrm{s}}$$

Magnetic Field:

Spherically symmetric **(model S)** and Archimedean spiral **(model A)**

Galactic Wind:

Differentiable approximation of a strong shock

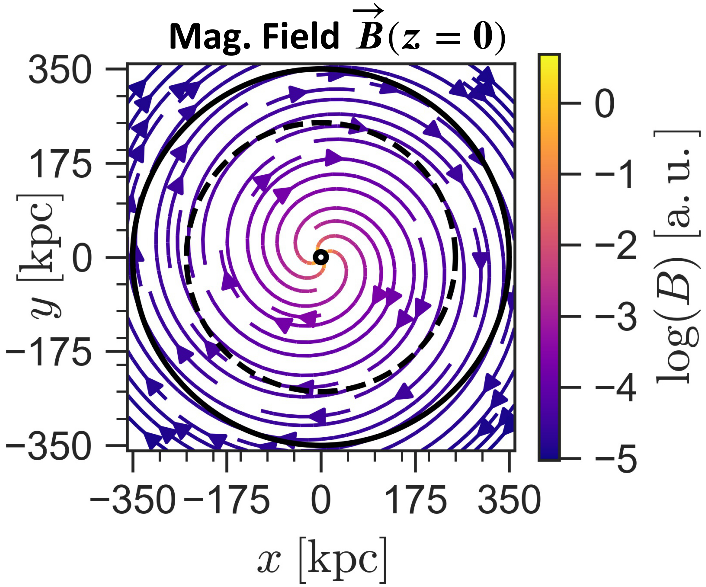
Shock:

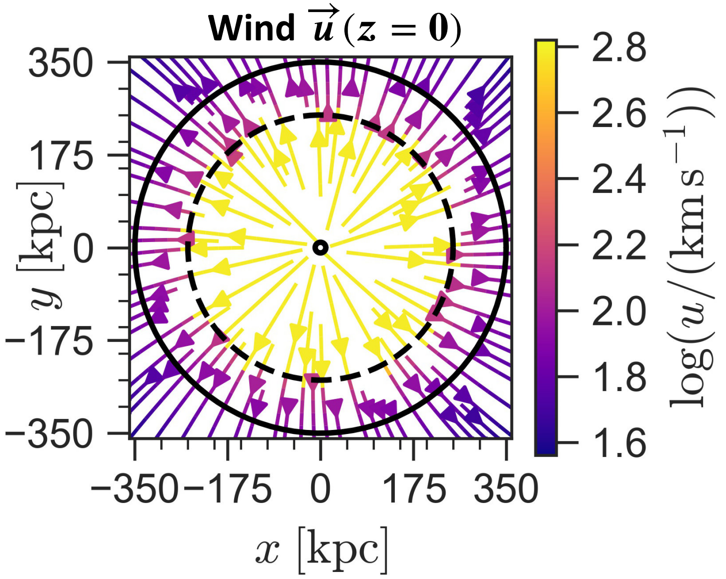
Total CR power: $L_{\mathrm{CR}} = \frac{1}{7} 10^{40} \frac{\mathrm{erg}}{\mathrm{s}}$, Init. Spectrum: $\frac{\mathrm{d}n}{\mathrm{d}E} \propto E^{-2}$

Duration: $\Delta T = 100\,\mathrm{Myr}$, Location: $r_{\mathrm{shock}} = 250\,\mathrm{kpc}$

Simulation Volume:

Free Escape Boundaries at $r_{\mathrm{obs}} = 10\,\mathrm{kpc}$ and $r_{\mathrm{b}} = 350\,\mathrm{kpc}$



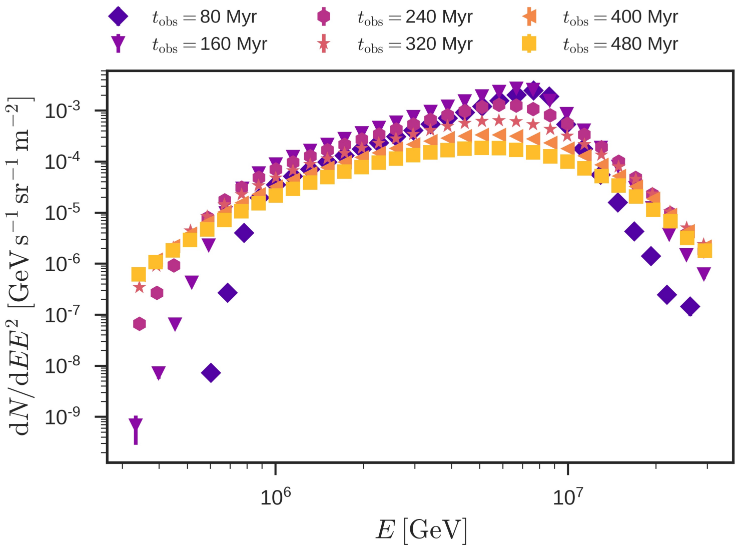


LM et al. ApJ (2018)

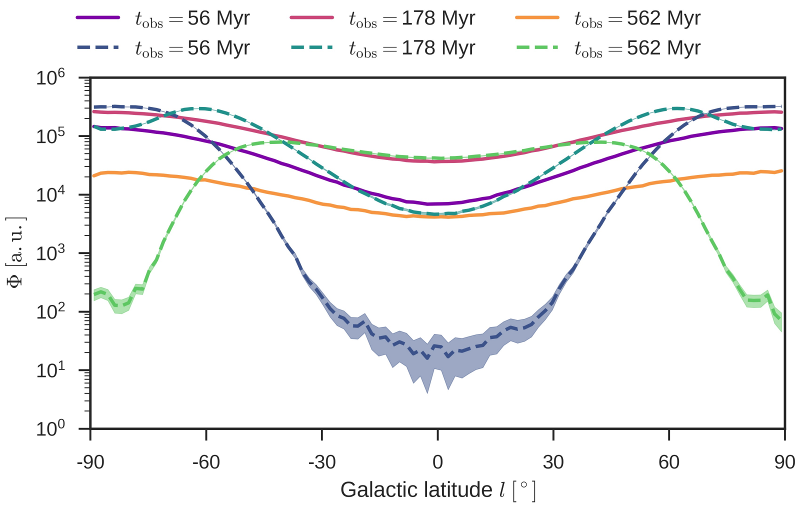
GWTS - Results

- Ensemble mainly looses energy due to adiabatic cooling
- Time scale and total luminosity depend on the diffusion index δ
- Energy spectrum is time dependent
- Perpendicular diffusion eases problematic anisotropy constrains
- Upper limit of neutrino flux is still below IceCube limits

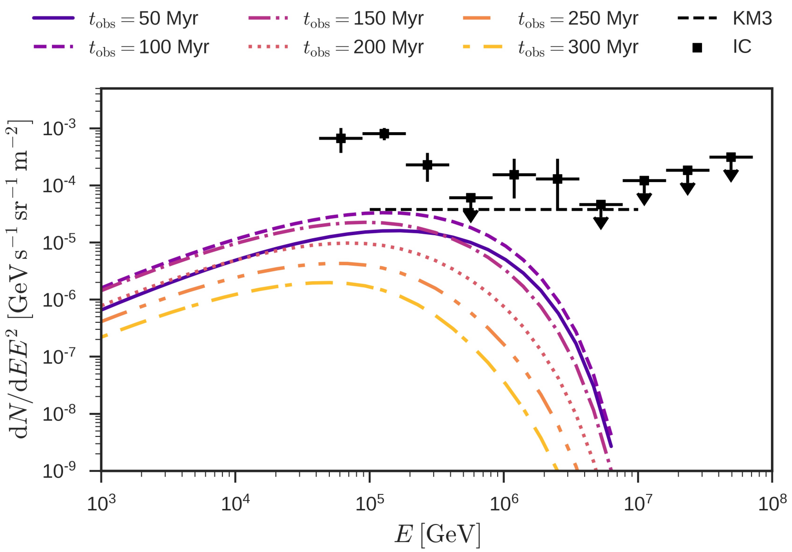
Energy Spectrum



Arrival Direction



Neutrino Flux



Summary and Outlook

Summary

- A variable toolbox to model different transport equations
- Including particle acceleration and relevant interactions
- Time-dependent background fields
- Extended to anomalous diffusion
- Comparison to full orbit simulations in same framework

- Open source & ready to use

- Applications range from UHECR to transport in the heliosphere

Advertisment

CRPropa Conference

Talks and discussion sessions on cosmic-ray transport and interaction

Focus on simulation and modeling, but not limited to CRPropa!

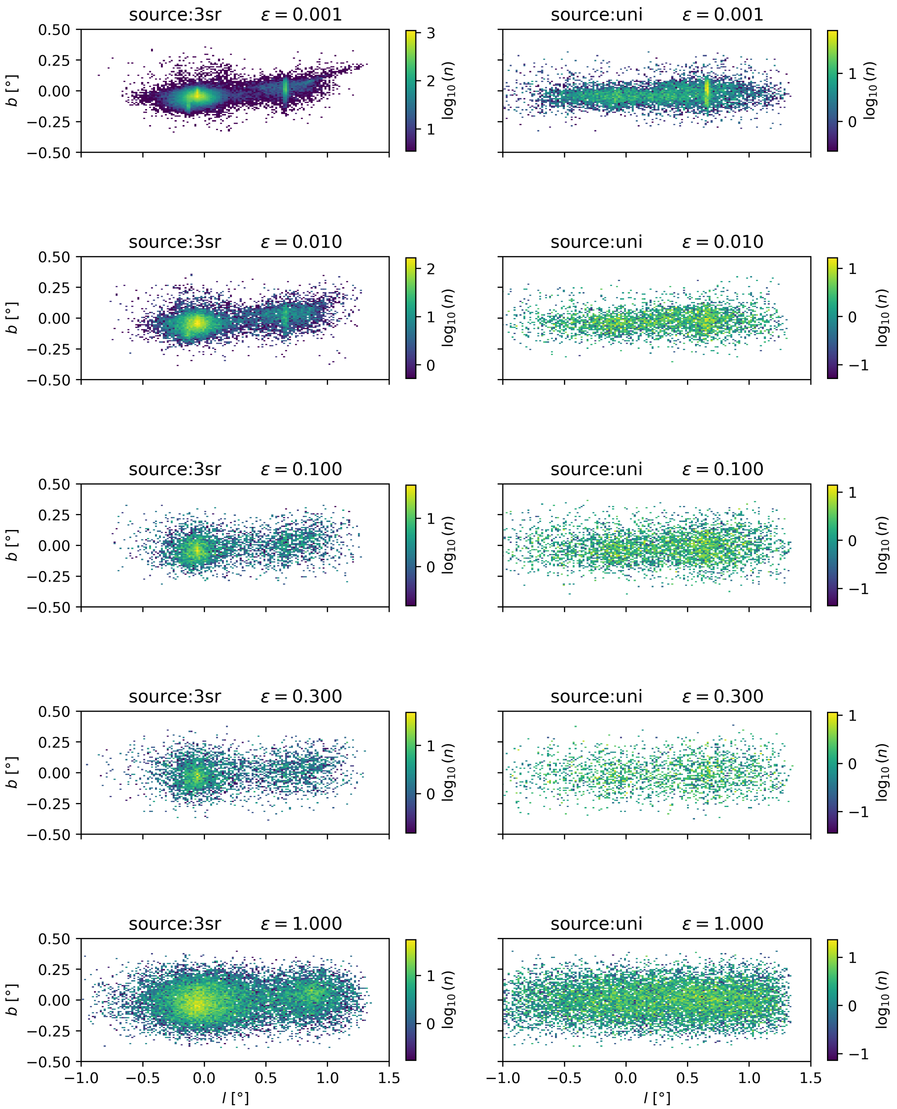
- January, 6-9 2025
- Kalifa University, Abu Dhabi, UAE
- More information
- Registration

Backup

Galactic Center

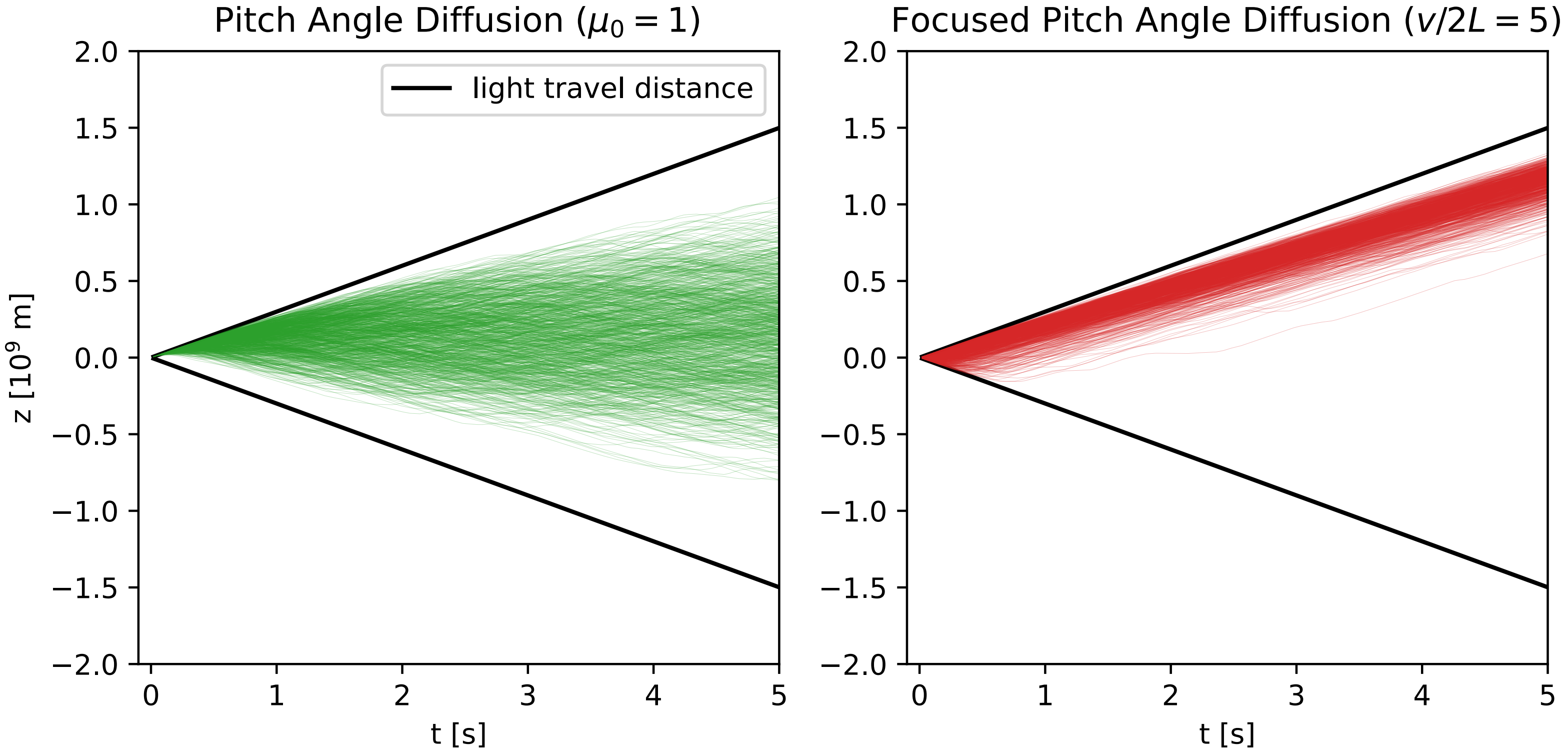
Dörner et al. ApJ (2024)

Gamma Rays from the Galactic center



Pitch Angle Diffusion

Example Trajectories



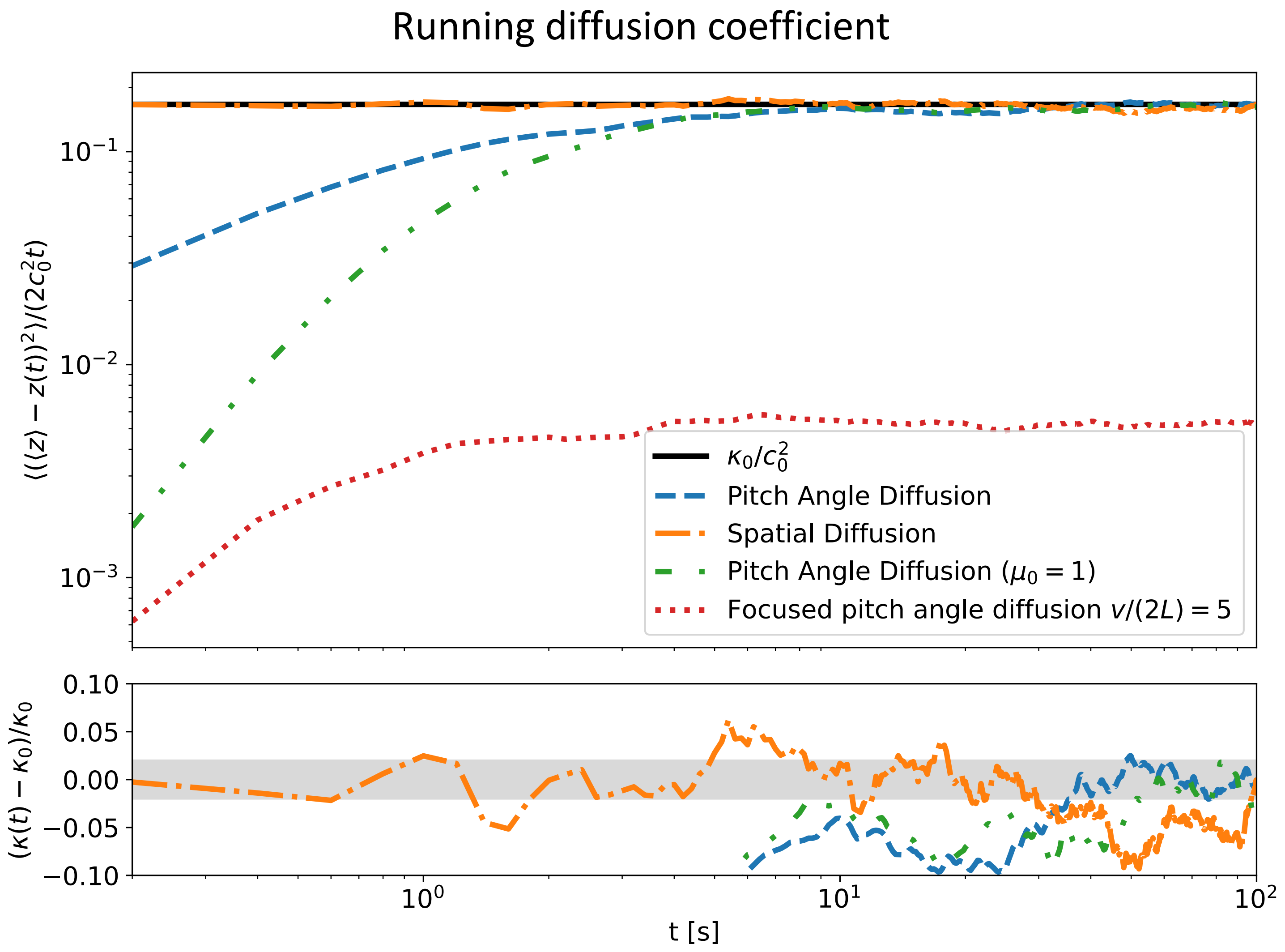
Initial distribution is quickly isotropized

Collective drift for focused transport

Reduced mean squared displacement

$$D_{\mu\mu} = 1 - \mu^2; v = c_0;$$
$$h = 10^{-4}; L = 0.1v$$

First results

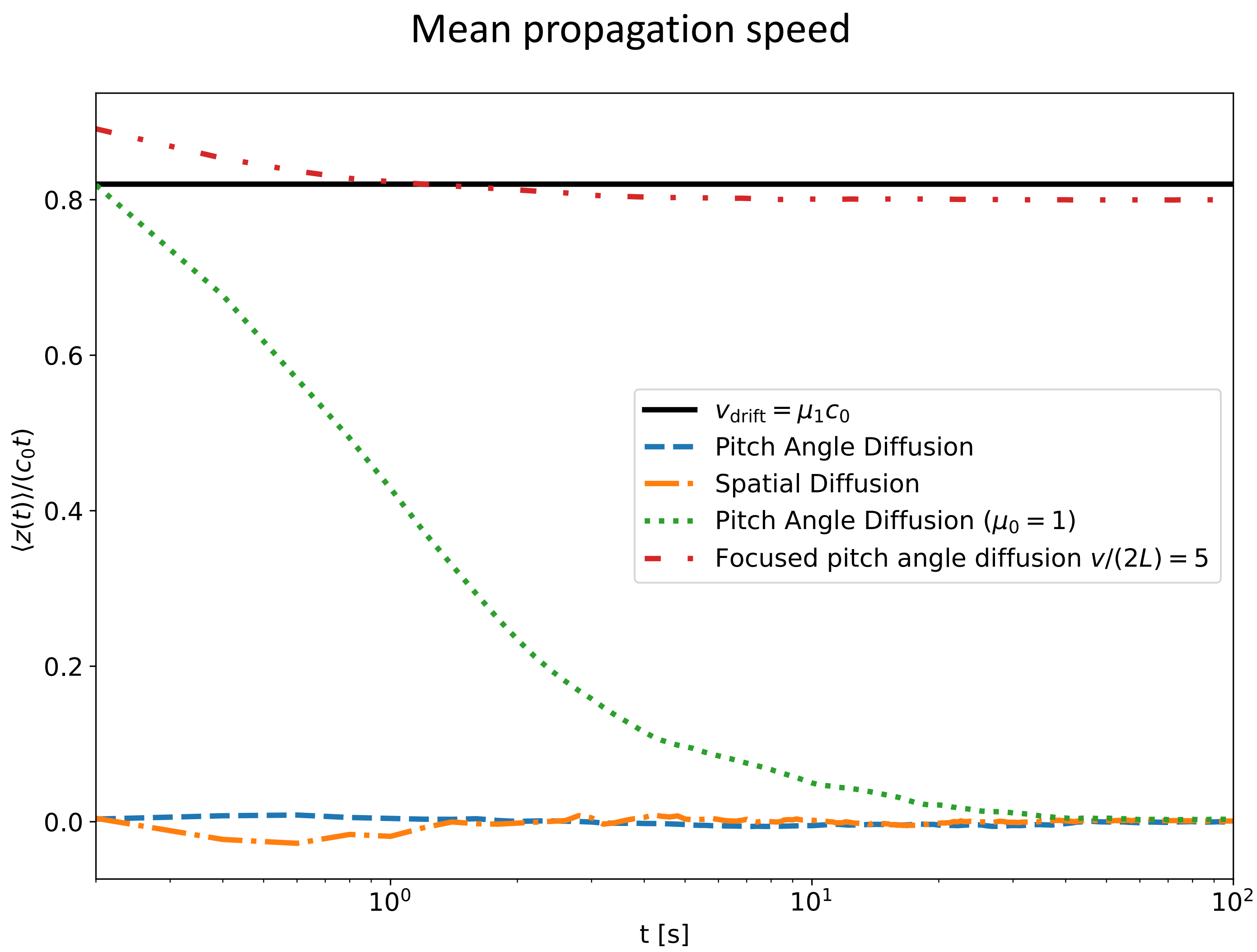


Without focusing the asymptotic diffusion coefficient is the same

Focusing leads to a reduced mean squared displacement

Superdiffusive phase at early times for all pitch angle diffusion models

First results



Focusing leads to a constant drift along the magnetic field

All other models have vanishing mean speed

Anisotropic injection leads to drift in early times

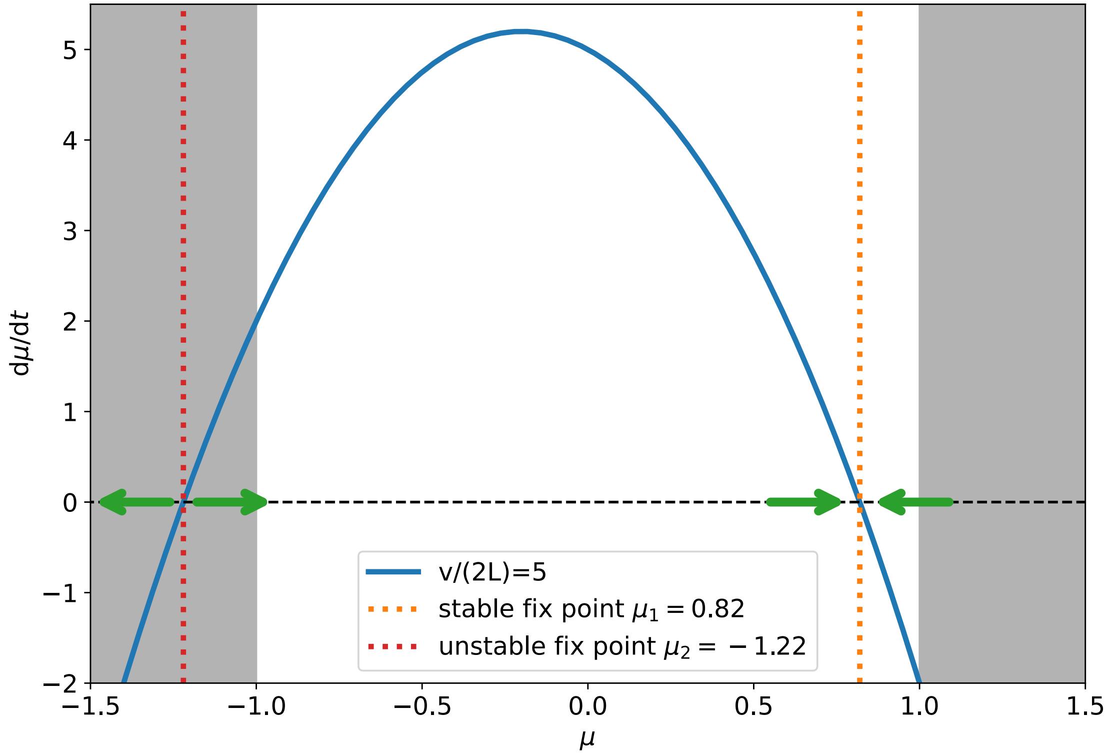
Fixed Points

$$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \frac{v}{2L}\left(1 - \mu^2\right) + \frac{\partial D_{\mu\mu}}{\partial \mu}$$

Differential Equation for the pitch angle becomes non-linear

Has several fixed points ($\mathrm{d}\mu/\mathrm{d}t = 0$)

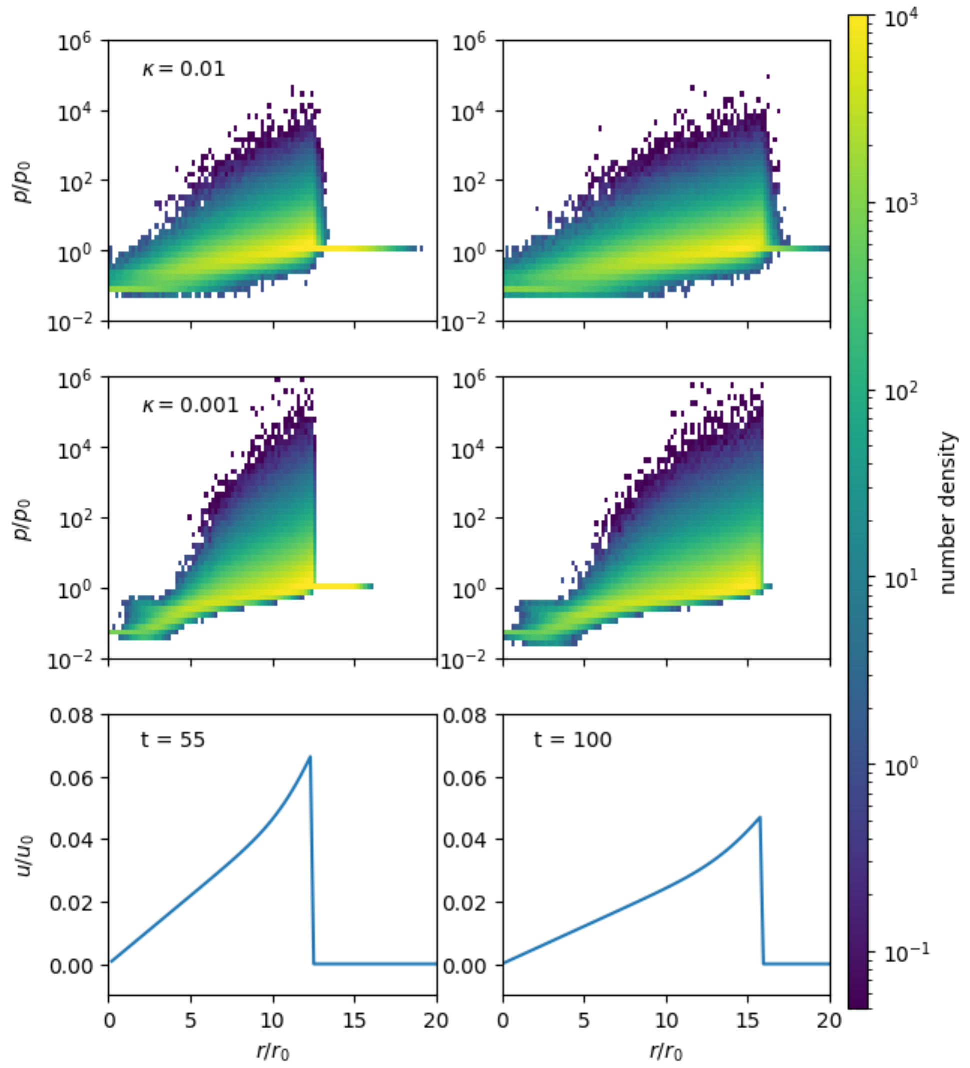
For isotropic diffusion $D_{\mu\mu} = D_0(1 - \mu^2)$ seem to dictate the drift speed



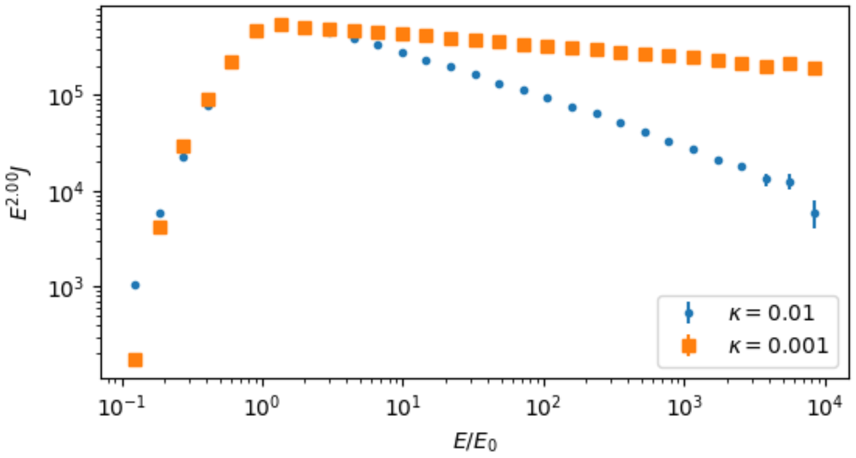
Sedov Taylor

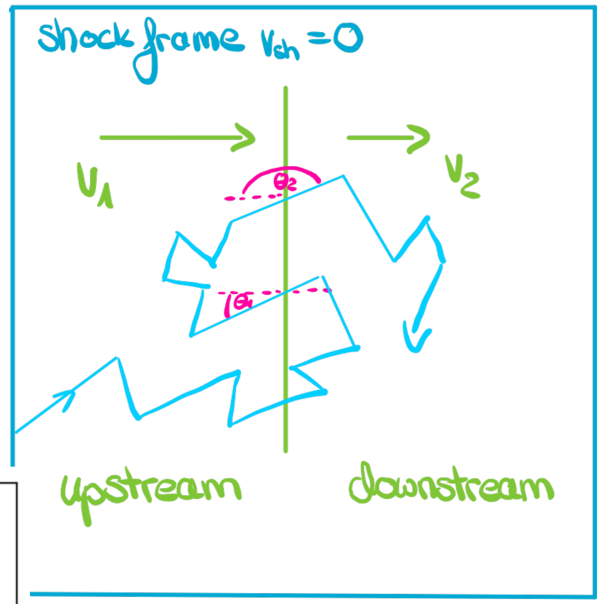
S.Aerdker, ..., LM, ..., in prep.

Diffusive Shock Acceleration



Time-dependent background fields, e.g. Sedov-Taylor similarity solution





matches estimate from Drury, 1983

$$a = 4\left[1 + (3+b)\left(\frac{\kappa_1}{Ru_1} + \frac{\kappa_2}{Ru_2}\right) + \frac{\kappa_2}{Ru_2}\right] + O(\epsilon^2)$$

where $\epsilon = \kappa/(\dot{R}R)$ and $f \propto p^{-a}R(t)^b$