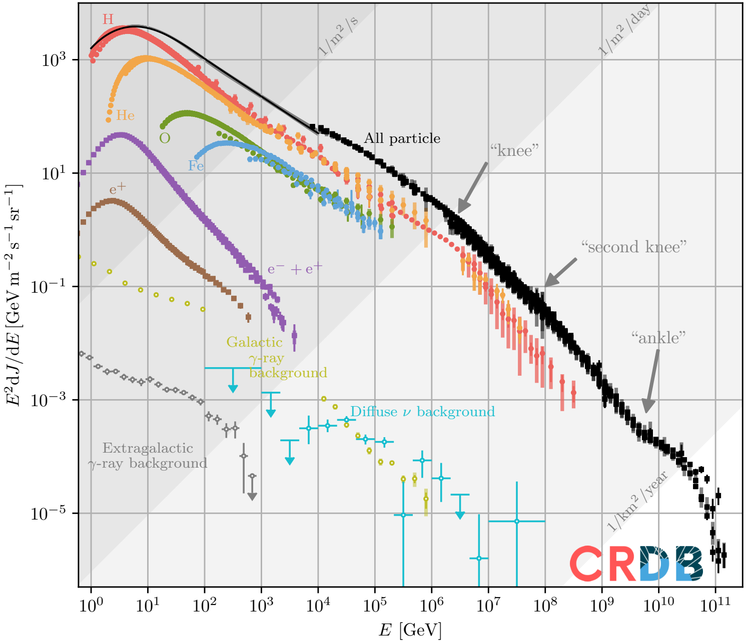
Galactic cosmic rays: an interstellar laboratory

Philipp Mertsch

GSSI colloquium, L'Aquila
11 March 2026

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

The cosmic ray spectrum



Intensity $\mathrm{d}J/\mathrm{d}E$

$$\frac{\mathrm{d}J}{\mathrm{d}E} \equiv \frac{(\#\text{particles})}{\Delta t\ \Delta A\ \Delta\Omega\ \Delta E}$$

- $\sim$ 12 orders of magnitude in energy
- $\sim$ power law $\mathrm{d}J/\mathrm{d}E \propto E^{-3}$ with some features

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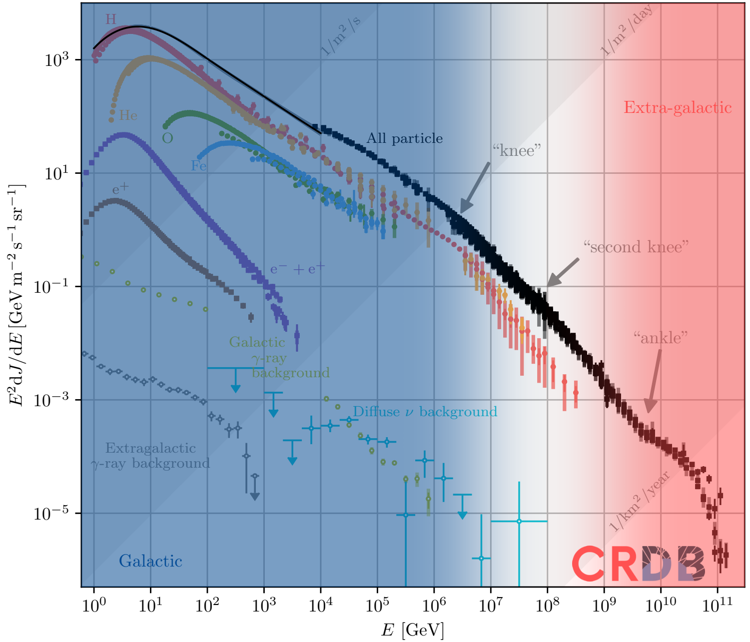

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Why are cosmic rays interesting?

Cosmic ray origin

- What are the sources of cosmic rays?
- Century-old problem!
- Astrophysical interest

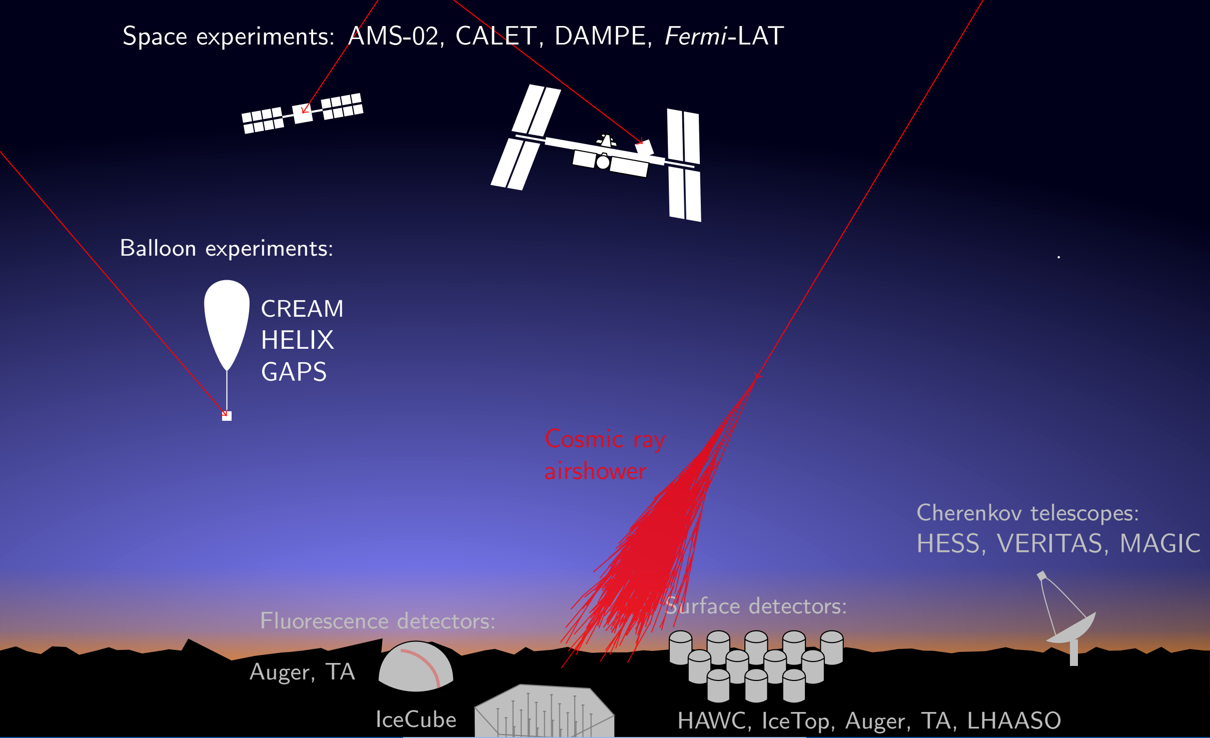
Ingredient

Cosmic rays ...

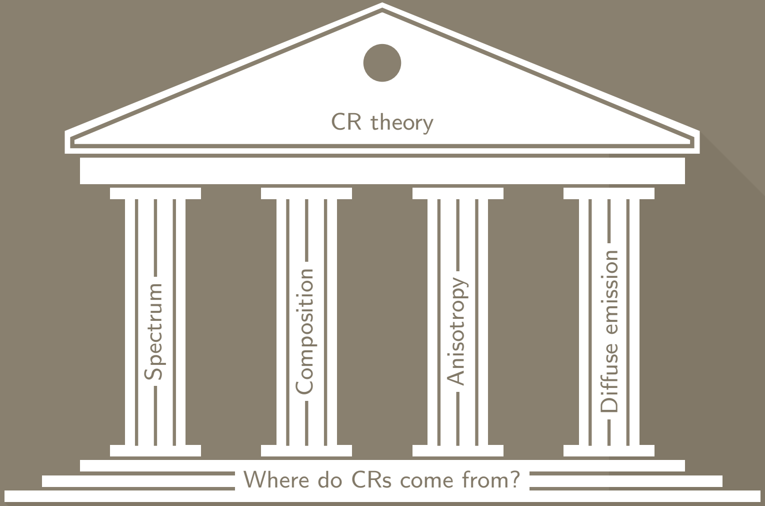
- produce diffuse emission
- ionise and heat
- provide gravitational support
- drive winds
- generate turbulence

Exotic probe

- Indirect searches of dark matter
- Dark matter cools cosmic rays, cosmic rays scatter dark matter
  Bringmann *et al.* (2019), Ng *et al.* (2019)
- Primordial anti-matter?

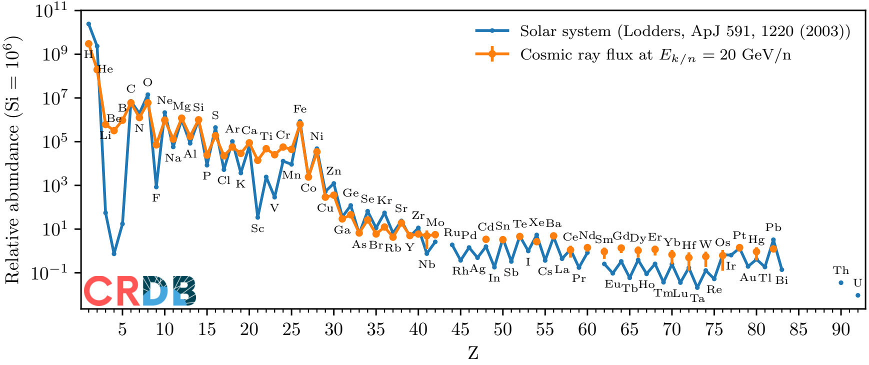


Space experiments: AMS-02, CALET, DAMPE, *Fermi*-LAT
Balloon experiments:
CREAM
HELIX
GAPS
Cosmic ray
airshower
Cherenkov telescopes:
HESS, VERITAS, MAGIC
Fluorescence detectors:
Auger, TA
Surface detectors:
IceCube
HAWC, IceTop, Auger, TA, LHAASO


CR theory
Spectrum
Composition
Anisotropy
Diffuse emission
Where do CRs come from?

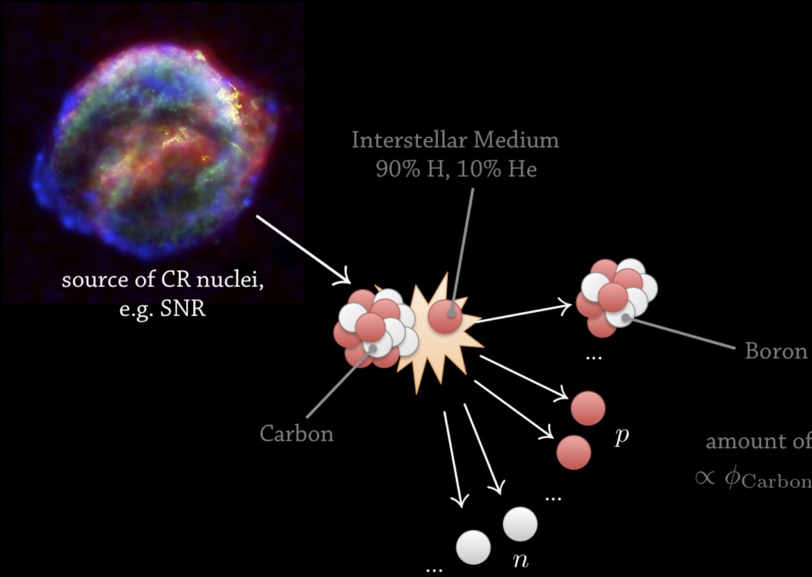
Composition

- Some species have same abundances in CRs and in solar system → primaries
- Other species are overabundant with respect to solar abundances:



→ Must have been produced during the transport → secondaries

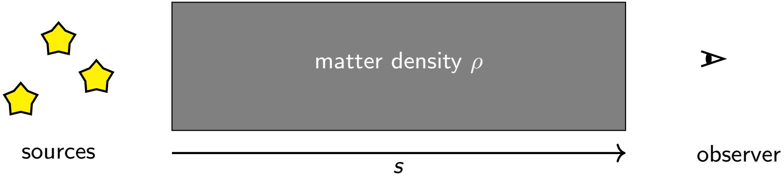
Secondaries from spallation



amount of Boron

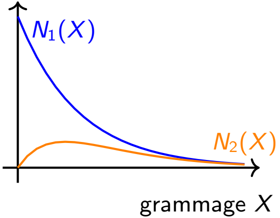
$\propto \phi_{\text{Carbon}}\, \sigma_{\text{spall}}\, n_{\text{gas}}$

Slab model



- Define CR grammage: $X \equiv \int \mathrm{d}s' \, \rho(s') = s\bar{\rho}$
- Consider number of primary and secondary CRs, N_1 and N_2:

$$\frac{\mathrm{d}N_1}{\mathrm{d}X} = -\frac{N_1}{\lambda_1}$$
$$\frac{\mathrm{d}N_2}{\mathrm{d}X} = -\frac{N_2}{\lambda_2} + \mathrm{BR}_{1\to 2}\frac{N_1}{\lambda_1}$$



with $1/\lambda_{1,2} = \sigma_{1,2}/m$ the specific cross-section

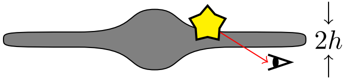
- Observations: $N_2/N_1 \simeq 0.3 \quad \to \quad X \simeq 7.2\,\mathrm{g\,cm^{-2}}$

Grammage

- Where does the grammage come from?
- If CRs traverse the Galactic disk, every crossing contributes

$$\Delta X \sim h m_{\mathrm{N}} n_{\mathrm{gas}} \simeq (100\,\mathrm{pc})(1.7 \times 10^{-24}\,\mathrm{g})(1\,\mathrm{cm}^{-3}) \simeq 5 \times 10^{-4}\,\mathrm{g\,cm}^{-2}$$

- $(1\,\mathrm{pc} \simeq 3.1 \times 10^{18}\,\mathrm{cm})$



CRs must cross the disk many times, e.g. through **diffusion**

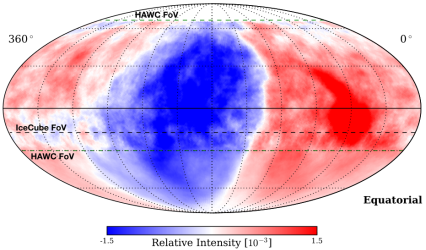
- Residence time in disk:

$$t_{\mathrm{esc}} = \frac{s}{v} = \frac{X}{v\,\bar{\rho}} = \frac{X}{v\,m_N\,\bar{n}_{\mathrm{gas}}} \simeq 3 \times 10^{6}\,\mathrm{yr}$$

for $n_{\mathrm{gas}} = 1\,\mathrm{cm}^{-3}$

Anisotropy (I)

- Angular distribution of CRs is very isotropic
- E.g., the dipole anisotropy $$a \equiv \frac{\phi_{\mathrm{max}} - \phi_{\mathrm{min}}}{\phi_{\mathrm{max}} + \phi_{\mathrm{min}}}$$



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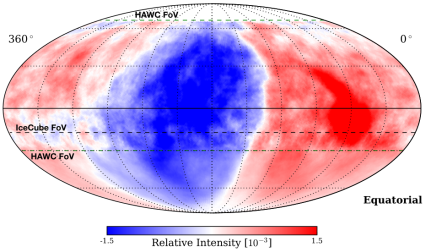
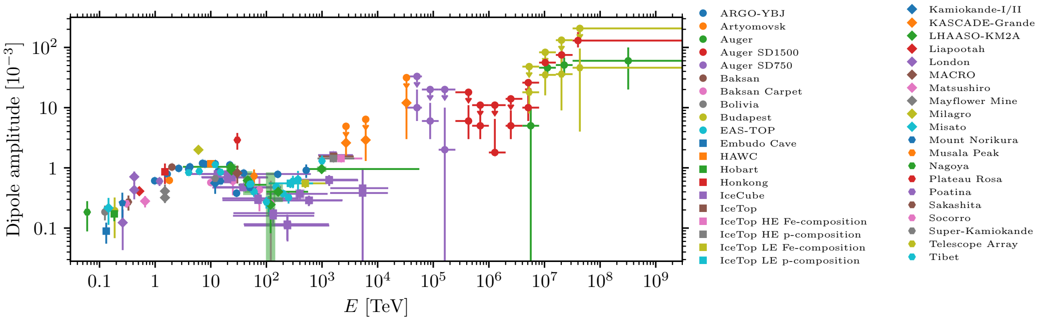
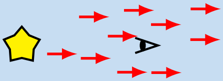




Anisotropy (II)

Between a few GeV and a PeV: $a = \mathcal{O}(10^{-4} \ldots 10^{-3})$



- Sources are discrete
- If CRs were travelling balistically, would expect $\mathcal{O}(1)$ anisotropy
- See, e.g., electro-magnetic radiation

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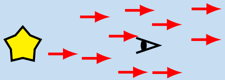

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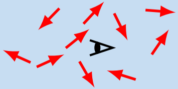

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→ Need to isotropise CRs

- (Coulomb) collisions with interstellar matter too infrequent

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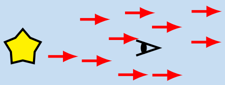

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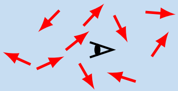

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- (Coulomb) collisions with interstellar matter too infrequent

- Scattering of charged particles with turbulent magnetic field isotropises particle directions

→ Particles perform a random walk in space:

$$\langle (\Delta r)^2 \rangle \propto \Delta t$$

- The constant of proportionality is called the **diffusion coefficient** κ

Mathematical description

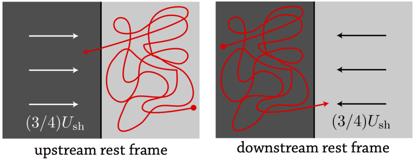
Ginzburg & Syrovatskii (1964)

Transport equation

$$\frac{\partial \psi_j}{\partial t} - \boldsymbol{\nabla} \cdot (\kappa \cdot \boldsymbol{\nabla} \psi_j - \boldsymbol{u} \psi_j) + \frac{\partial}{\partial p} \left(\frac{p}{3} (\boldsymbol{\nabla} \cdot \boldsymbol{u}) \psi_j \right) = q_j$$

↓

Application to blast wave:



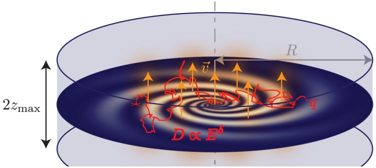
Shock acceleration

Source spectrum: $q(\mathcal{R}) \propto \mathcal{R}^{-2.4\ldots-1.9}$

Axford, Leer, Skadron (1977); Krymskii (1977); Bell (1978); Blandford, Ostriker (1978)

↓

Application to galactic halo:



Diffusive escape

Observed spectrum: $\psi(\mathcal{R}) \propto \frac{q(\mathcal{R})}{\kappa(\mathcal{R})}$ e.g. $\frac{\mathcal{R}^{-2.2}}{\mathcal{R}^{0.6}} \propto \mathcal{R}^{-2.8}$

Outline

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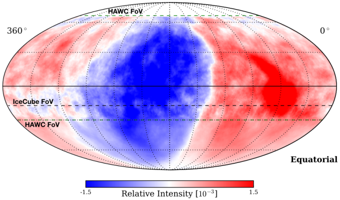
Supernova remnants have long been considered the sources of cosmic rays

1. Observations
2. Energetics
3. Shock acceleartion

Lopez and Fesene (2018)

We do not know individual sources of *local* cosmic rays

Anisotropies:



Problem: cosmic rays diffuse

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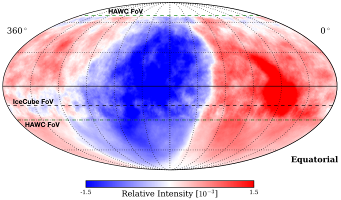

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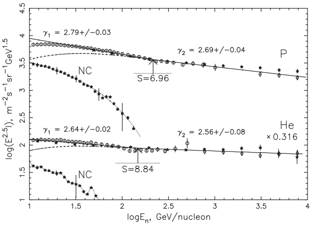
Spectrum:

Erlykin and Wolfendale (2012)



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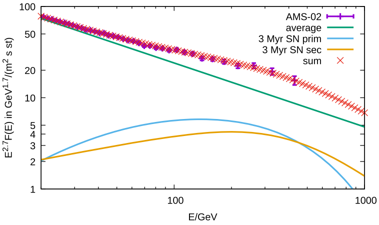

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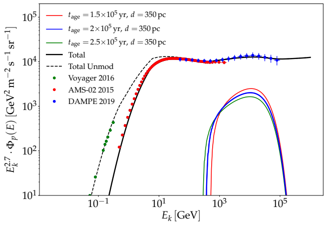

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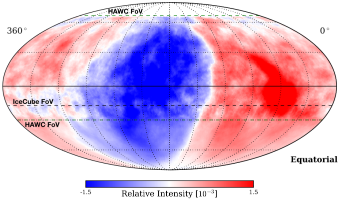

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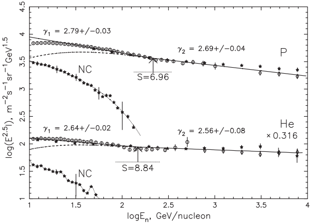

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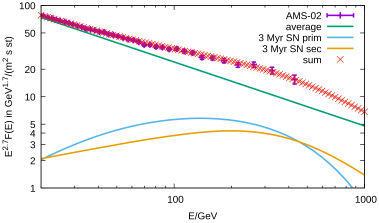

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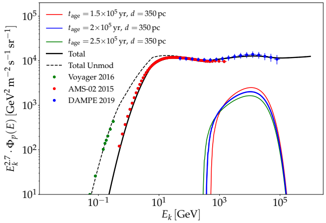
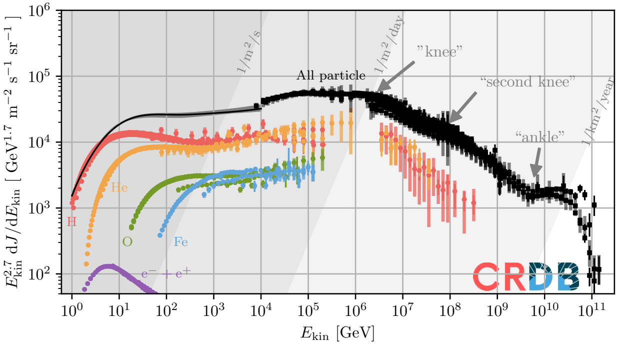


Supernova remnant paradigm

1 000 - 100 000 "active" supernova remnants in the Galaxy

Génolini *et al.* (2017)

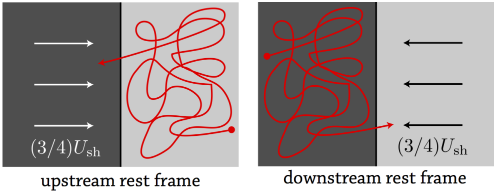
Galactic sources should accelerate to $E_{\rm knee}$, probably via shock acceleration



- $E_{\rm knee} \simeq 3\,$PeV: either maximum energy of source or change in transport regime

→ $E_{\rm max} \gtrsim 3\,$PeV for protons

Axford, Leer, Skadron (1977); Krymskii (1977); Bell (1978); Blandford, Ostriker (1978)



Small energy gain ΔE, little particle loss ΔN per cycle

$$\left. \begin{array}{l} \dfrac{\Delta E}{E} \propto \dfrac{U_{\rm sh}}{c} \\[2ex] \dfrac{\Delta N}{N} \propto \dfrac{U_{\rm sh}}{c} \end{array} \right\} \Rightarrow \frac{{\rm d}N}{{\rm d}E} \propto E^{-2}$$

We do not understand how supernova remnants accelerate to E_{knee}

What is E_{max}?

- Equate age with acceleration time: $t_{\text{age}} = t_{\text{acc}} = 8 \frac{\kappa}{U_{\text{sh}}^2}$ ← Diffusion coefficient
- Assume Bohm diffusion: $\kappa = \frac{c \ell_{\text{mfp}}}{3} = \frac{c r_g}{3} = \frac{c}{3} \frac{E_{\text{max}}}{qB}$ (Gyro radius → r_g)
- Hillas-like relation: $\Rightarrow E_{\text{max}} \simeq \frac{U_{\text{sh}}^2}{c} q B t_{\text{age}}$ or $\frac{U_{\text{sh}}}{c} q B R$

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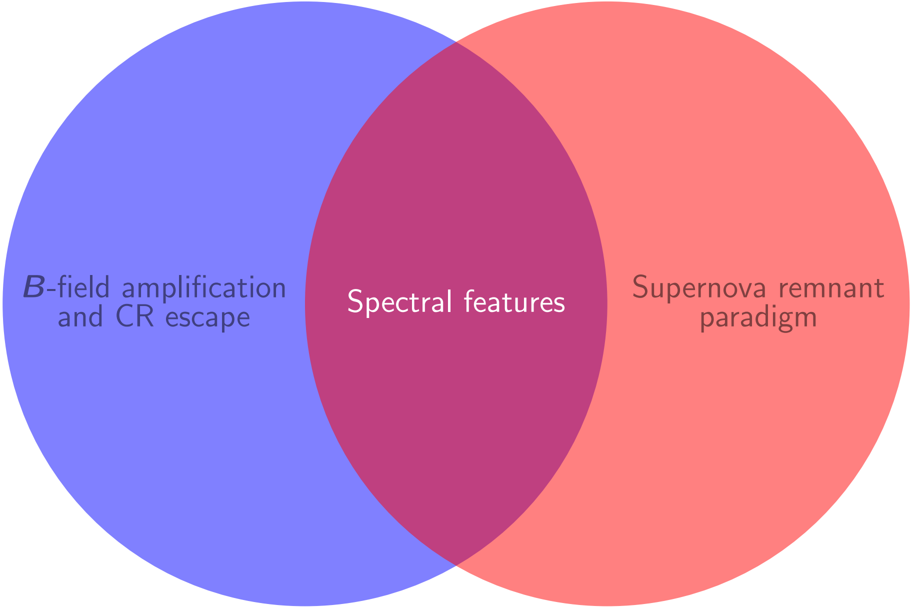
- With typical values: $U_{\text{sh}} = 10^4 \, \text{km} \, \text{s}^{-1}$, $B = 1 \, \mu\text{G}$, $t_{\text{age}} = 10^3 \, \text{yr}$

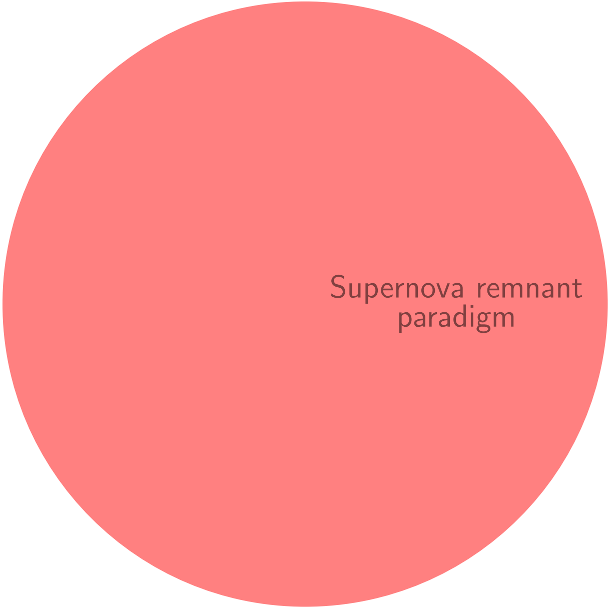
$$\Rightarrow E_{\max,b} \simeq 100 \, \text{TeV} \ll E_{\text{knee}}$$

Lagage and Cesarsky (1983)

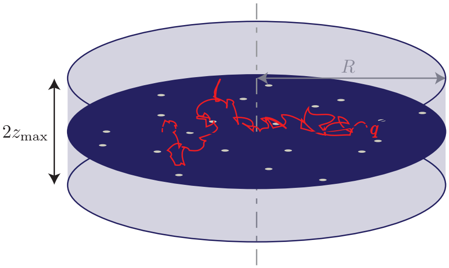
1. Choosing larger t_{age} does not help: $U_{\text{sh}} \propto t_{\text{age}}^{-3/5}$, so $E_{\max}$ decreases with time
2. Need to amplify $\boldsymbol{B}$-field to $B \simeq 100 \, \mu\text{G}$

Combining standard ingredients, we predict novel spectral features




Supernova remnant
paradigm

The number of sources contributing to CR flux decreases with energy



- Residence time: $t_{\text{esc}} = \frac{z_{\text{max}}^2}{2\kappa}$
- Diffusion distance: $R = \sqrt{2\kappa t_{\text{esc}}} = z_{\text{max}}$
- Source density: $\sigma = \frac{\nu t_{\text{esc}}}{\pi R_{\text{disk}}^2}$
- Source number: $N_{\text{src}} = \sigma \pi R^2 = \nu t_{\text{esc}} \frac{z_{\text{max}}^2}{R_{\text{disk}}^2}$

With typical parameters (for details → Appendix):

$$\mathcal{R} = 10\,\text{GV}\,, \quad 10\,\text{TV}\,, \quad 10\,\text{PV}$$
$$N_{\text{src}} \simeq 2 \times 10^5\,, \; 2000\,, \quad 40$$

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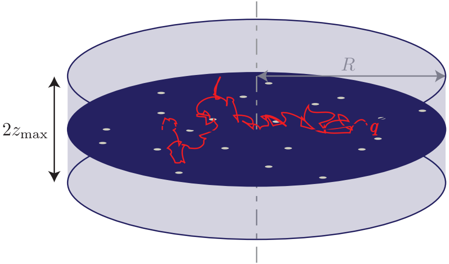

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Need to run Monte Carlo simulations
instead of cherry-picking catalogues!

Source density is oftentimes considered smooth, while it really is discrete

Transport equation

$$\frac{\partial \psi}{\partial t} - \boldsymbol{\nabla} \cdot \kappa \cdot \boldsymbol{\nabla} \psi + \ldots = q$$

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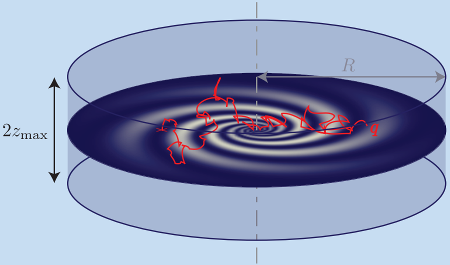
Smoth source density



$$q = q(\boldsymbol{r}, t, E) = \nu \, \rho(\boldsymbol{r}) \, Q(E)$$

SN rate

smooth function

spectrum

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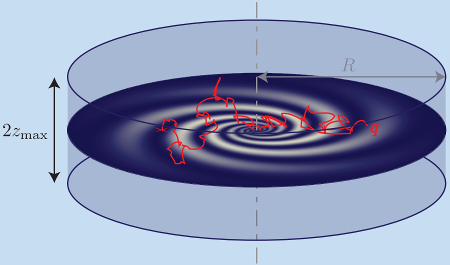

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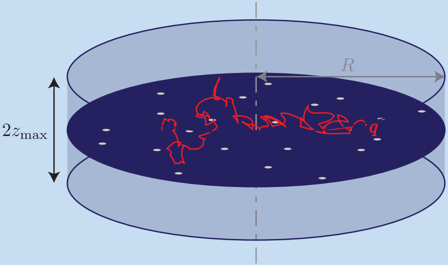
Discrete sources



$$q = q(\boldsymbol{r}, t, E) = \sum_i \delta^{(3)}(\boldsymbol{r} - \boldsymbol{r}_i)\delta(t - t_i)Q(E)$$

$\boldsymbol{r}_i$ drawn from $\rho(\boldsymbol{r})$ and t_i from uniform distribution

Source density is oftentimes considered smooth, while it really is discrete

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$$\frac{\partial G}{\partial t} - \nabla \cdot \kappa \cdot \nabla G + \ldots = \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i)Q(E)$$

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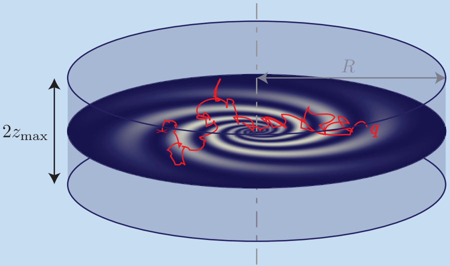

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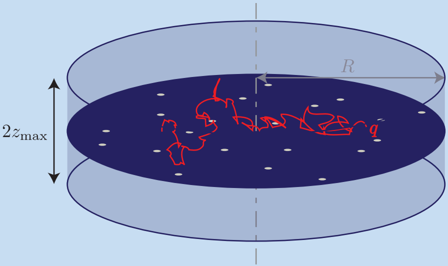

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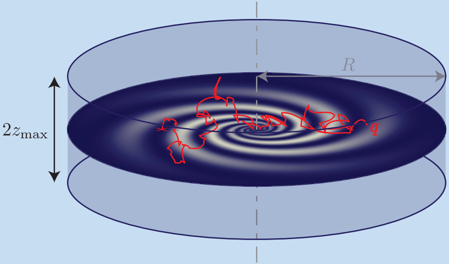

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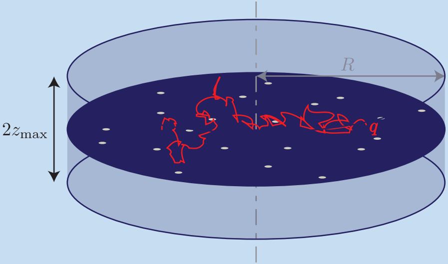
$$\psi(\mathbf{r}, t, E) = \int \mathrm{d}^3\mathbf{r}'\mathrm{d}t'\, \nu\, \rho(\mathbf{r}')\, G(\mathbf{r} - \mathbf{r}', t - t', E)$$

Discrete sources



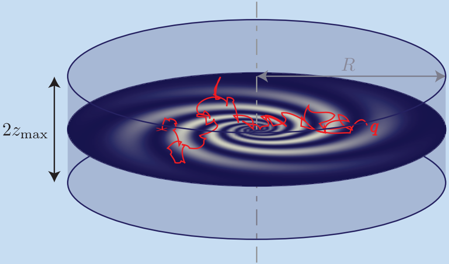
$$q = q(\mathbf{r}, t, E) = \sum_i \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i)Q(E)$$

Source density is oftentimes considered smooth, while it really is discrete

Transport equation

$$\frac{\partial G}{\partial t} - \boldsymbol{\nabla} \cdot \kappa \cdot \boldsymbol{\nabla} G + \ldots = \delta^{(3)}(\mathbf{r} - \mathbf{r}_i)\delta(t - t_i)Q(E)$$

Smoth source density



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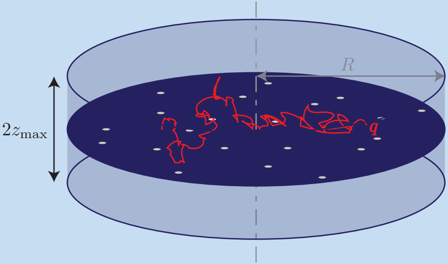

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Stochastic nature of sources implies fluctuations in spectrum

- Solution: $$\psi(\boldsymbol{r}, t, p) = \sum_i G(\boldsymbol{r} - \boldsymbol{r}_i, t - t_i, E)$$
- $\boldsymbol{r}_i$, t_i are random variables $\Rightarrow$ $\psi(\boldsymbol{r}, t, p)$ is random variable
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Can we use $\psi - \langle \psi \rangle$ to find sources?

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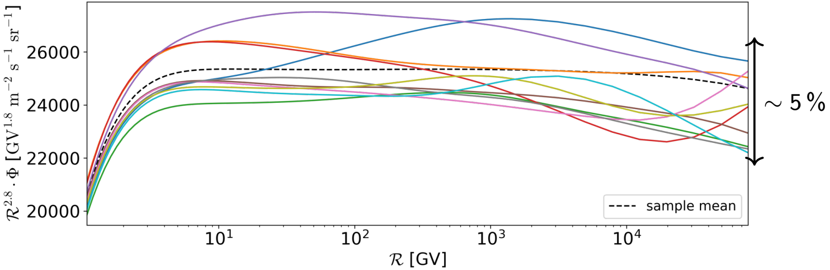
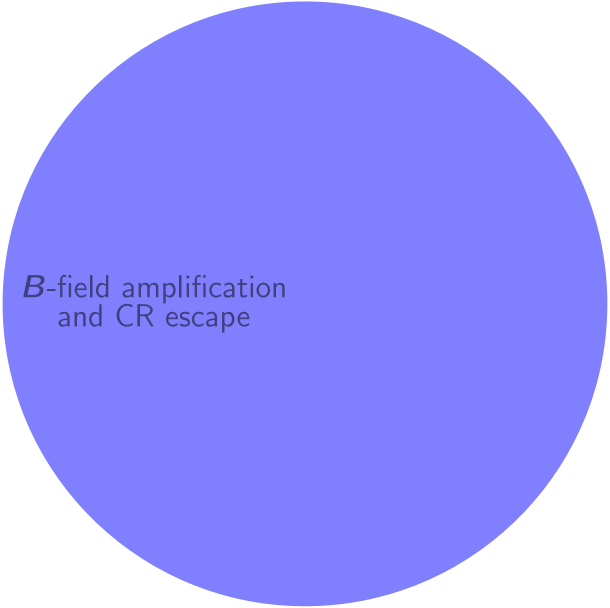
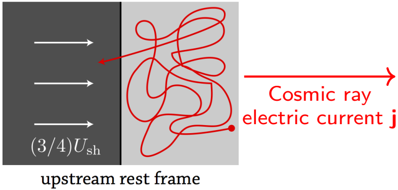



B-field amplification
and CR escape

The Bell instability can amplify B-fields

Bell (2004)



- If B-field too weak, particles escape

$\rightarrow$ Electric current $\boldsymbol{j}$

- Waves modes unstable in the presence of current $\boldsymbol{j}$

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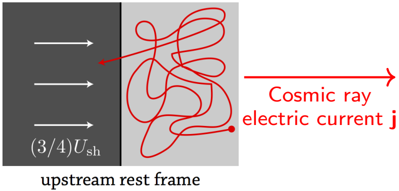

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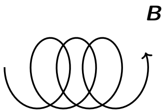

- CRs with gyroradius r_g tied to field lines

→ Instability saturates once $\lambda \sim r_g$

- $\boldsymbol{B}$-field density satisfies $\varepsilon_B \sim \frac{U_{sh}}{c} \varepsilon_{CR}$

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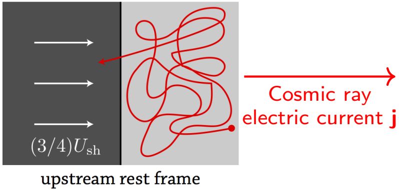

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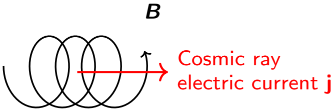

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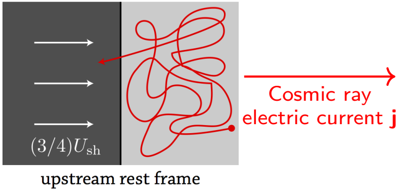

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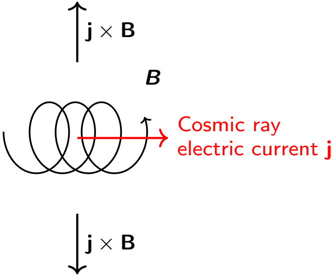

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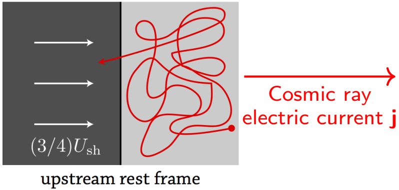

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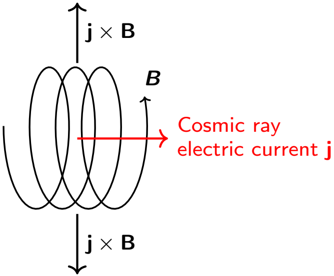

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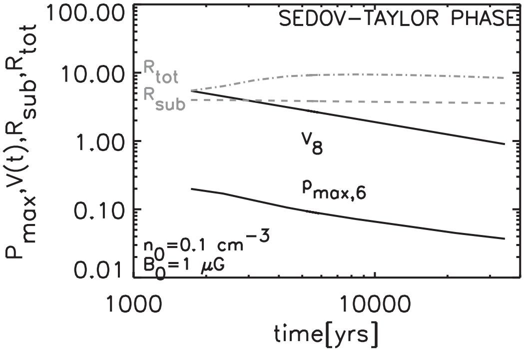
The highest CR energies can be achieved at start of Sedov-Taylor phase

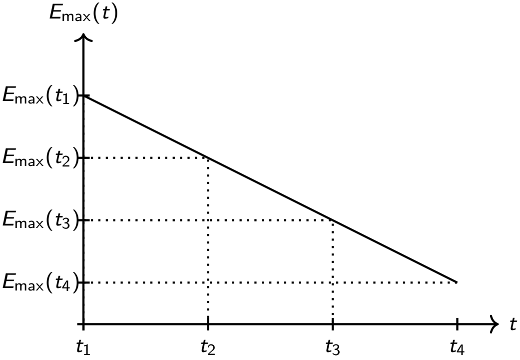
- Shock speed $U_{\rm sh}$ enters into growth rate γ through escape current j
- Saturation field $B \propto U_{\rm sh}^{3/2}$
- $U_{\rm sh} \propto t_{\rm age}^{-3/5}$

$\rightarrow$ $E_{\rm max} \propto U_{\rm sh}^2 B t_{\rm age} \propto t_{\rm age}^{-11/10}$

Caprioli, Blasi, Amato (2009)



Time-dependence of B-field amplification determines CR escape



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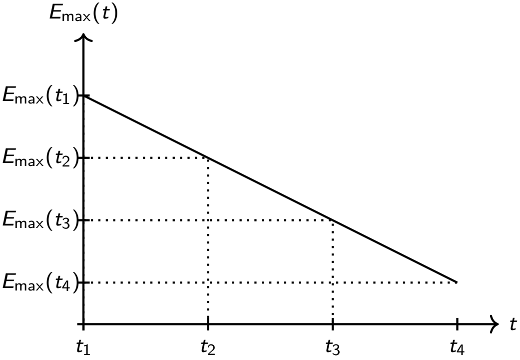

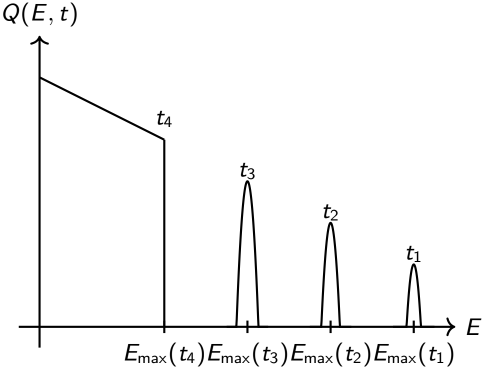

also Gabici, Aharonian, Casanova (2009); Caprioli, Blasi, Amato (2010); Blasi and Amato (2012); Thoudam and Hörandel (2012)

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- At any one time t, particles of energy $E_{max}(t)$ escape
- Ultimately, all particles with $E < E_{max,b}$ escape

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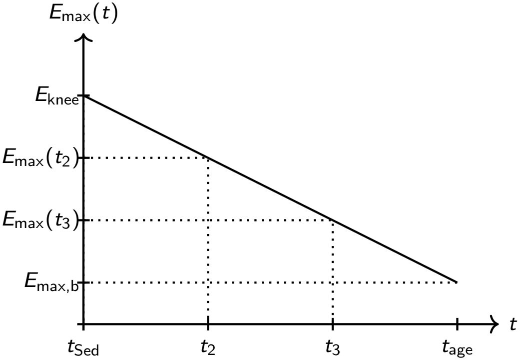

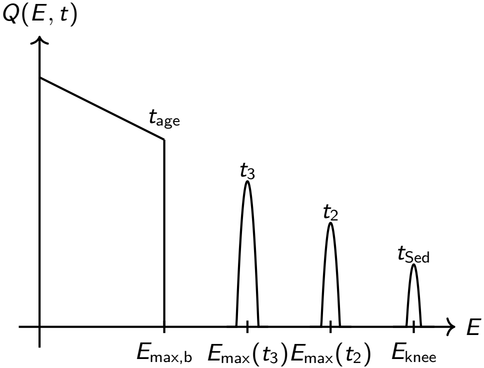

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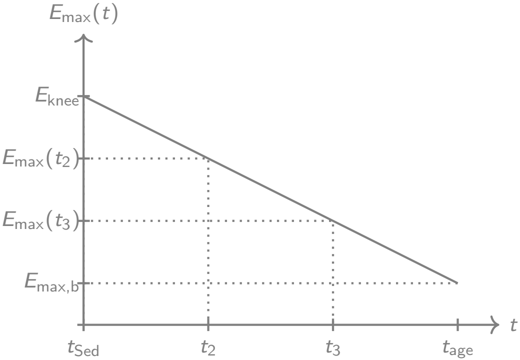

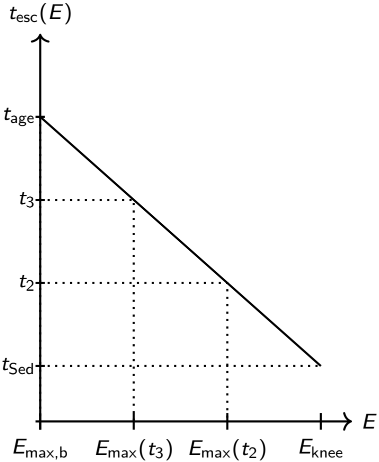

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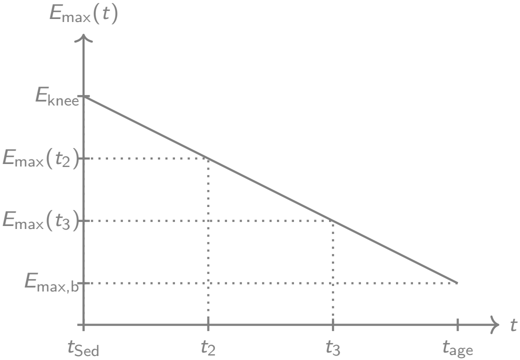
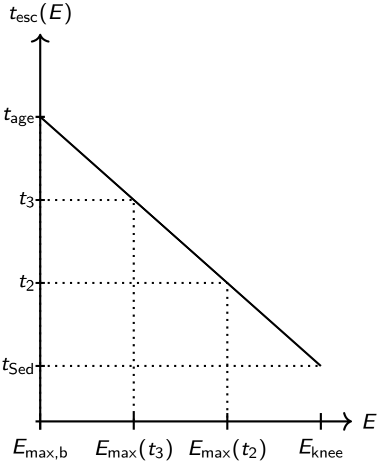
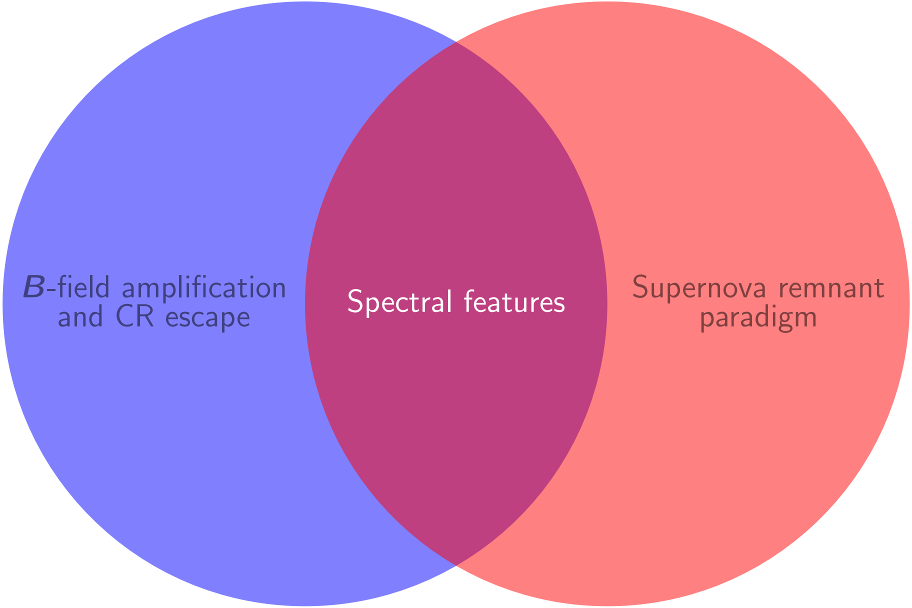


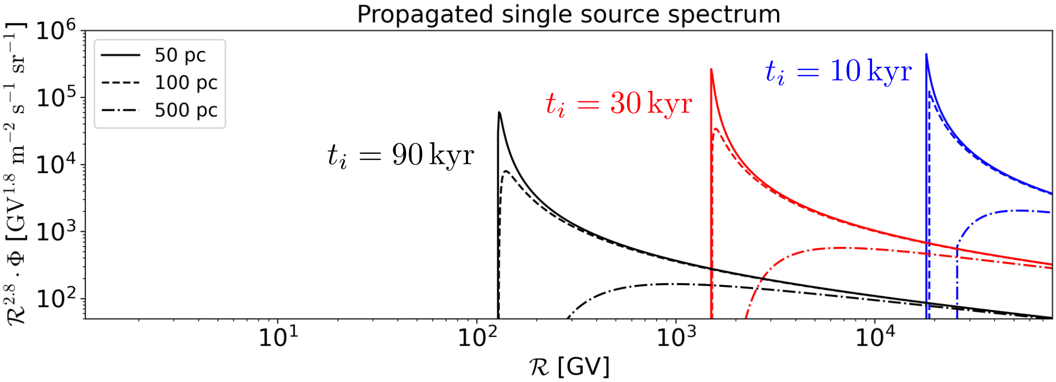


Cosmic-**R**ay **E**nergy-**D**ependent **I**njection **T**ime
(CREDIT) scenario


B-field amplification and CR escape
Spectral features
Supernova remnant paradigm

The Green's function has narrow spectral features

$$\frac{\partial G}{\partial t} - \boldsymbol{\nabla} \cdot \kappa \cdot \boldsymbol{\nabla} G = \delta^{(3)}(\boldsymbol{r} - \boldsymbol{r}_i)\delta(t - t_i - t_{\mathrm{esc}}(E))Q(E)$$



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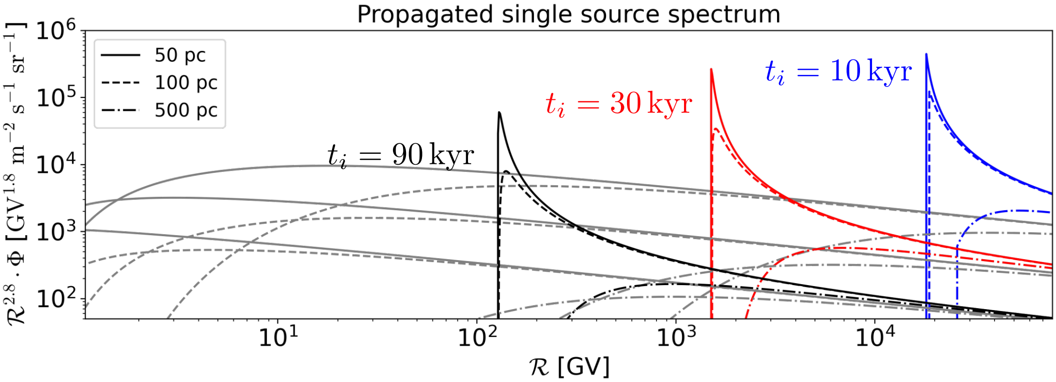

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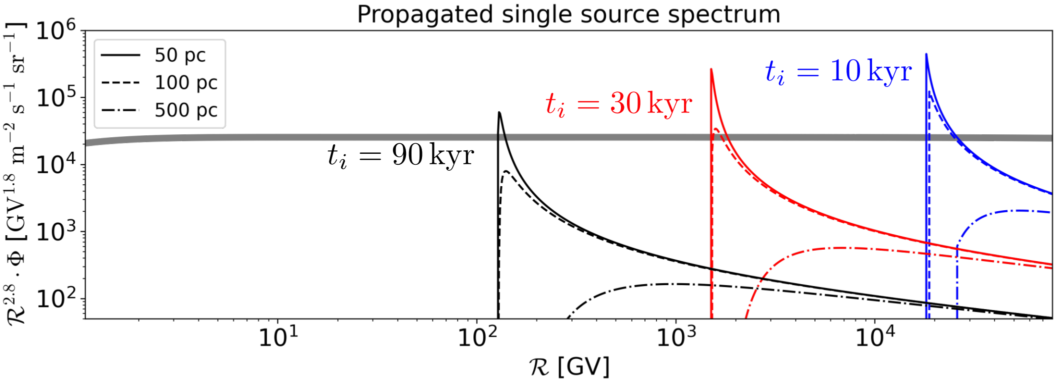
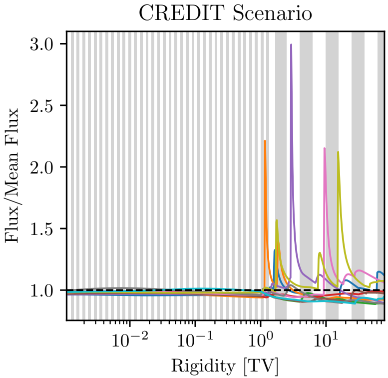


CREDIT scenario predicts dramatic spectral features

Stall, Loo, Mertsch (2025)



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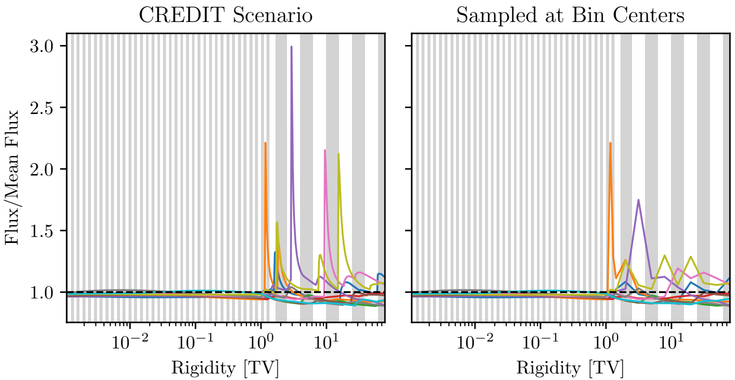
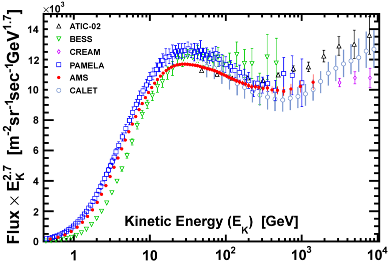
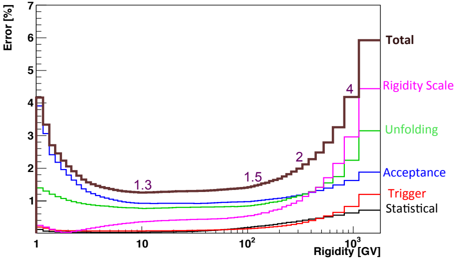


Modern proton data offer unprecedented accuracy

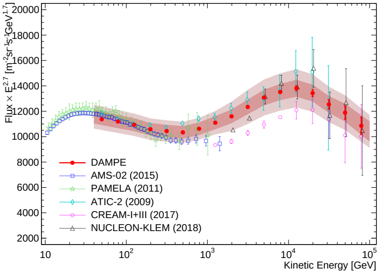
V. Choutko (2015), An *et al.* (2019), Aguilar *et al.* (2020),

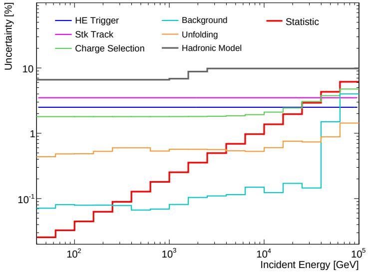
AMS-02





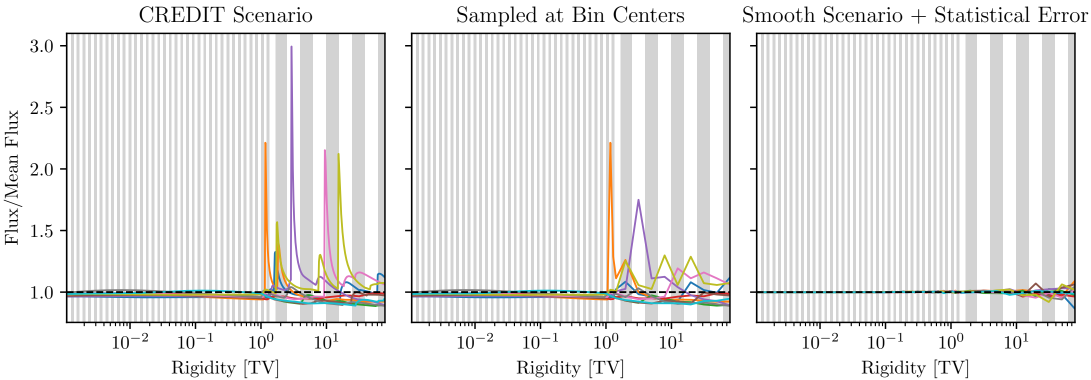
DAMPE





Statistical errors are much smaller than CREDIT features

Stall, Loo, Mertsch (2025)



We can confidently discriminate between the different scenarios

Stall, Loo, Mertsch (2025)

Can discriminate features
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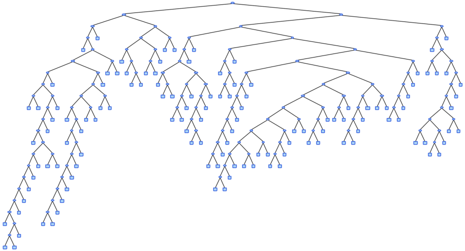
$\rightarrow$ Classical machine learning task



Decision tree

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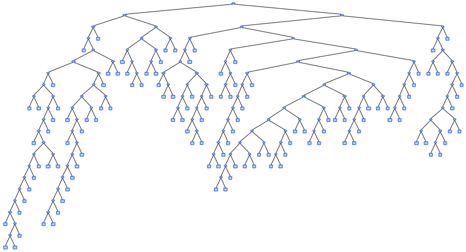

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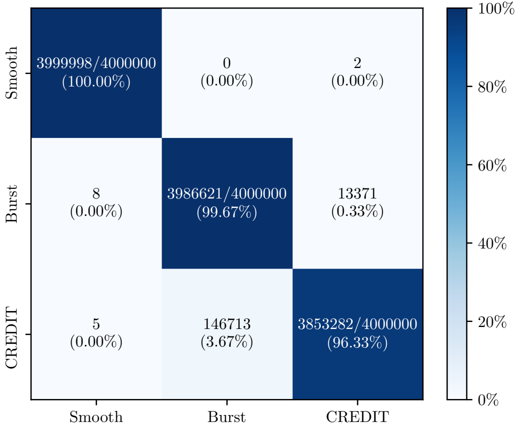
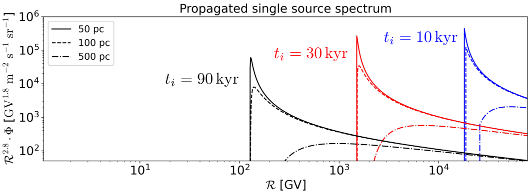


The results are going to be interesting either way

Classifier finds . . .

1. CREDIT scenario

$\rightarrow$ Investigate sources



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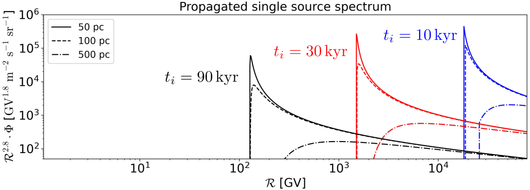
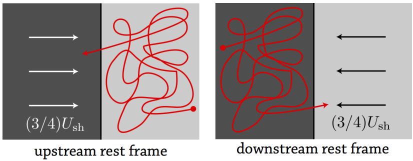


2. Burst-like scenario ($E_{\mathrm{max,b}} \rightarrow \infty$)

$\rightarrow$ Constraints on acceleration models



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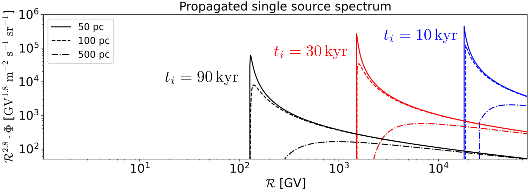

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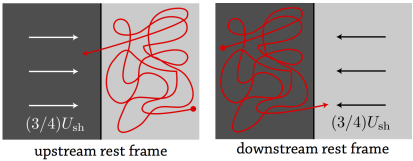
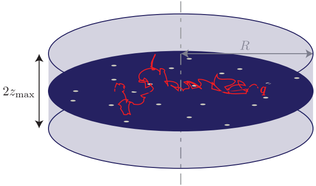


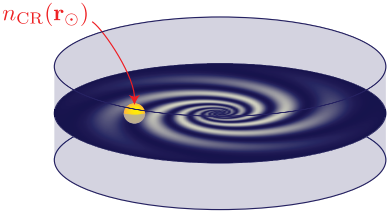
3. Smooth scenario
   → Trouble for supernova remnant paradigm



Outline

Local fluxes vs diffuse emission

Local fluxes



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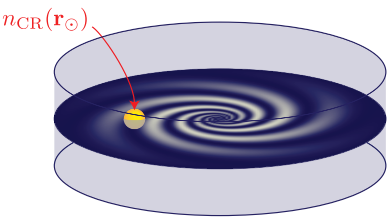
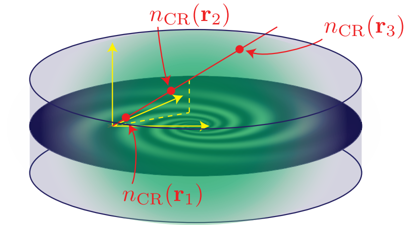


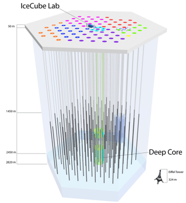
Diffuse emission



Recently measured at $\sim$ PeV

Tibet ASγ+MD

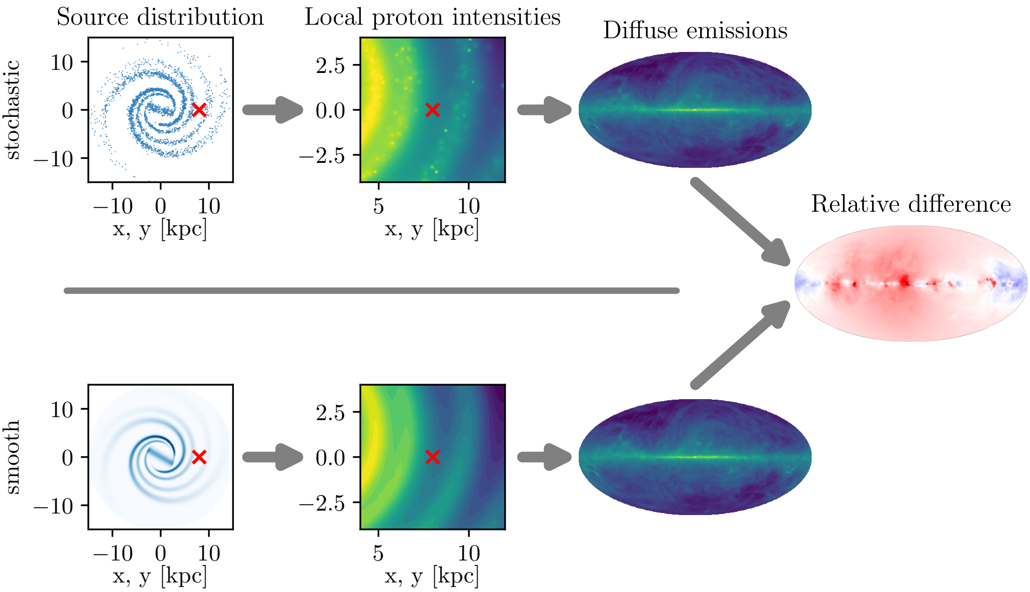
LHAASO



IceCube

Stochastic diffuse emission

Mertsch & Stall (2025)



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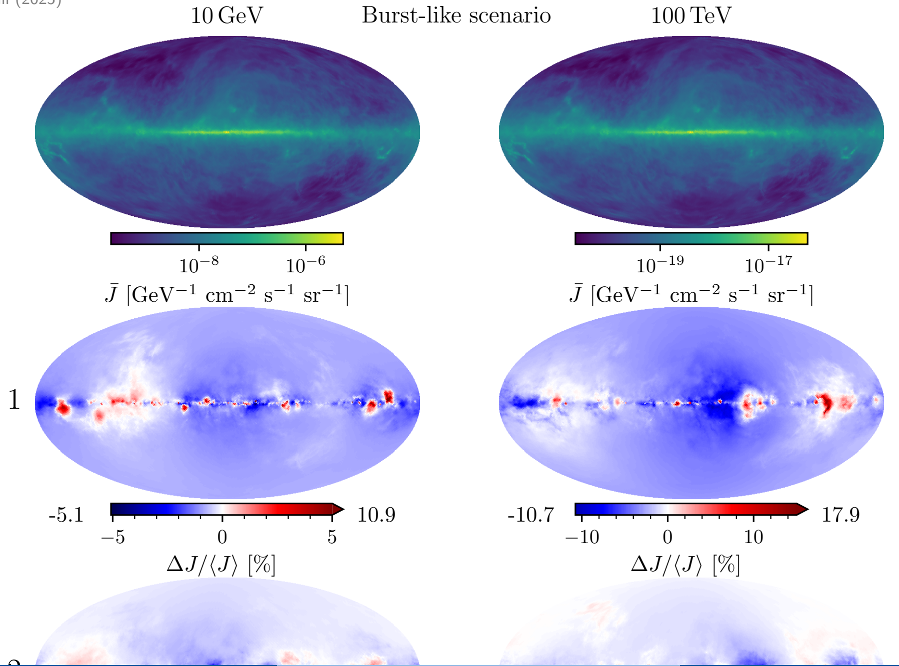

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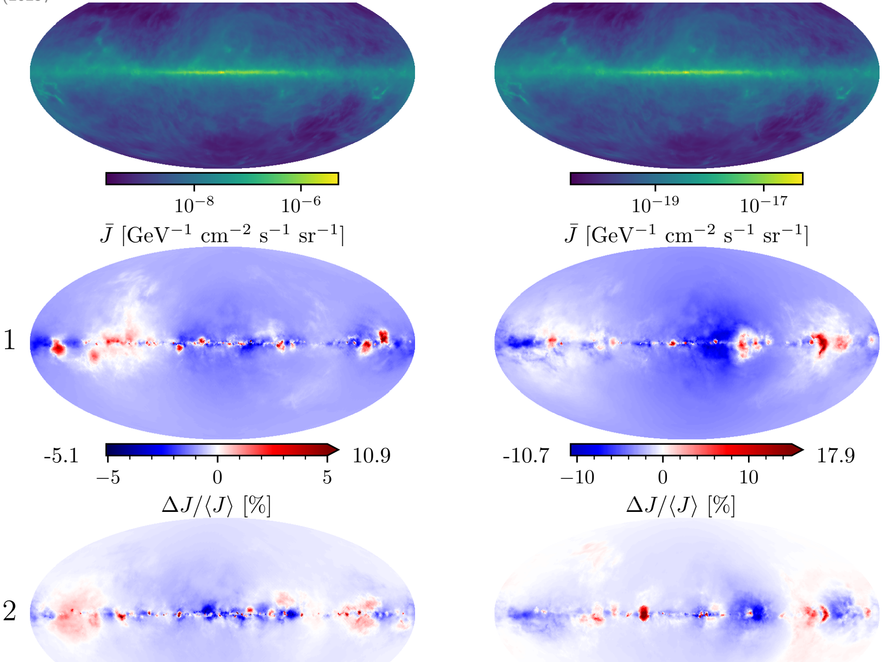

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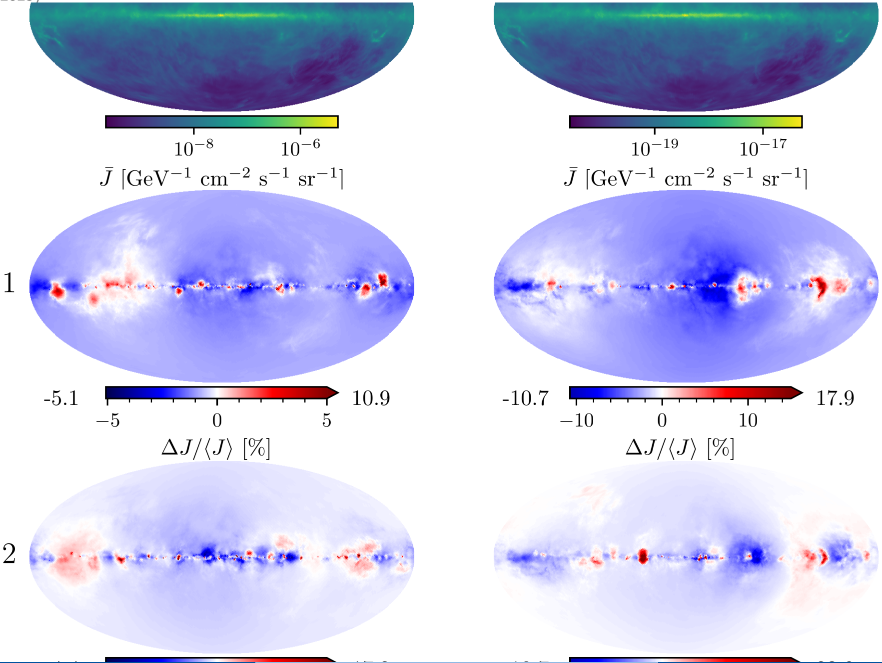

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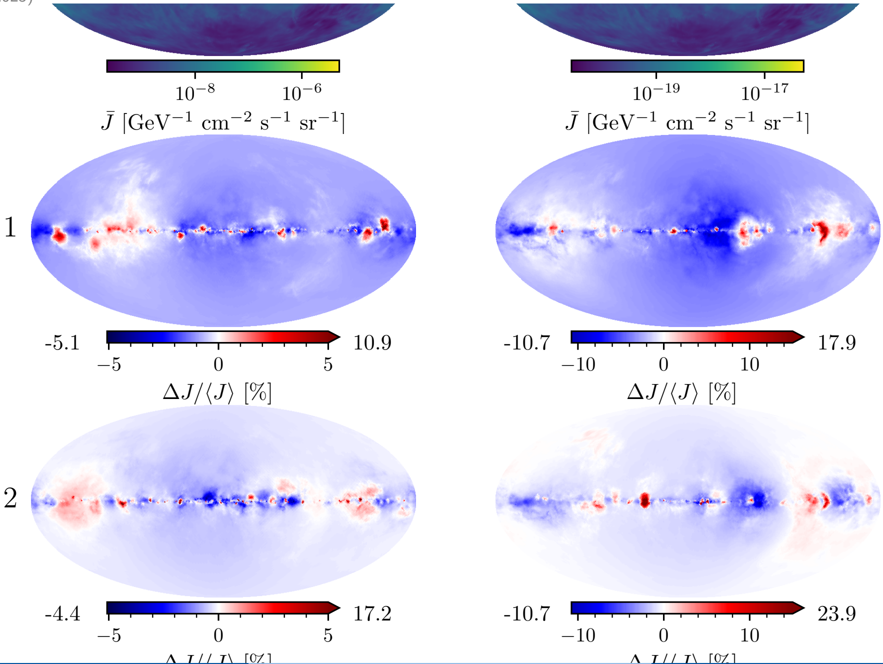
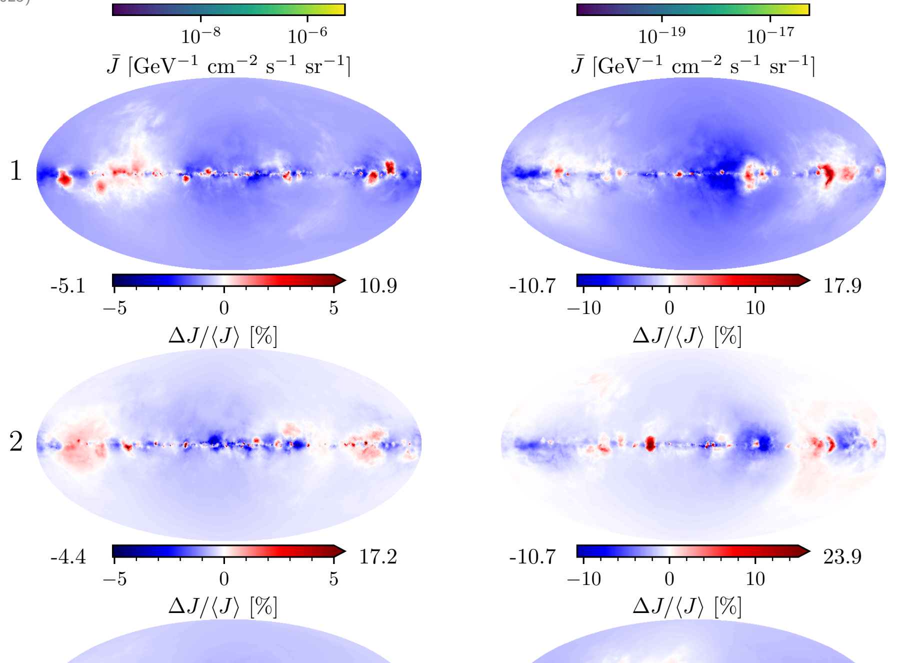


Stochastic diffuse emission

Mertsch & Stall (2025)



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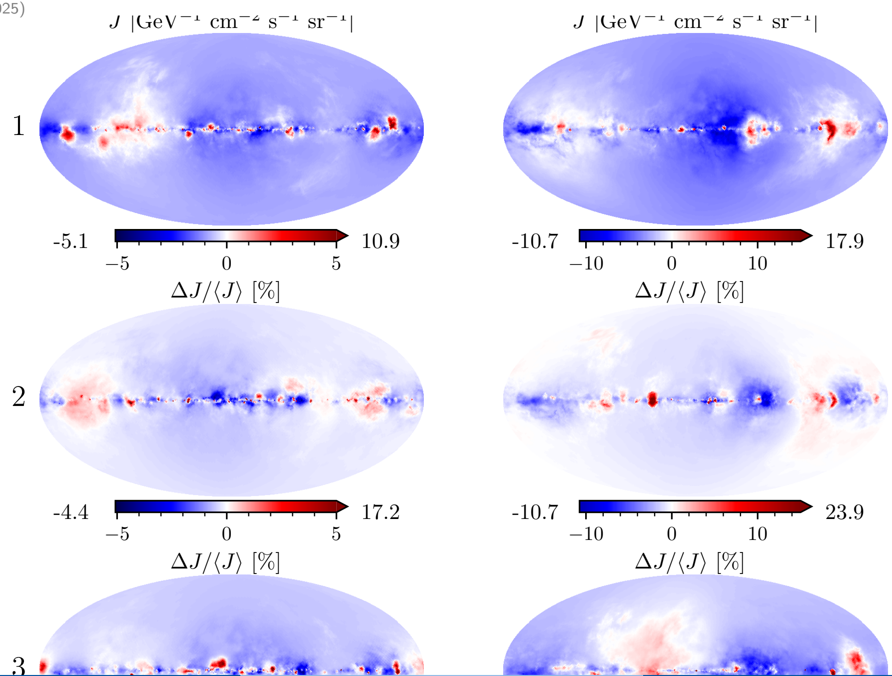

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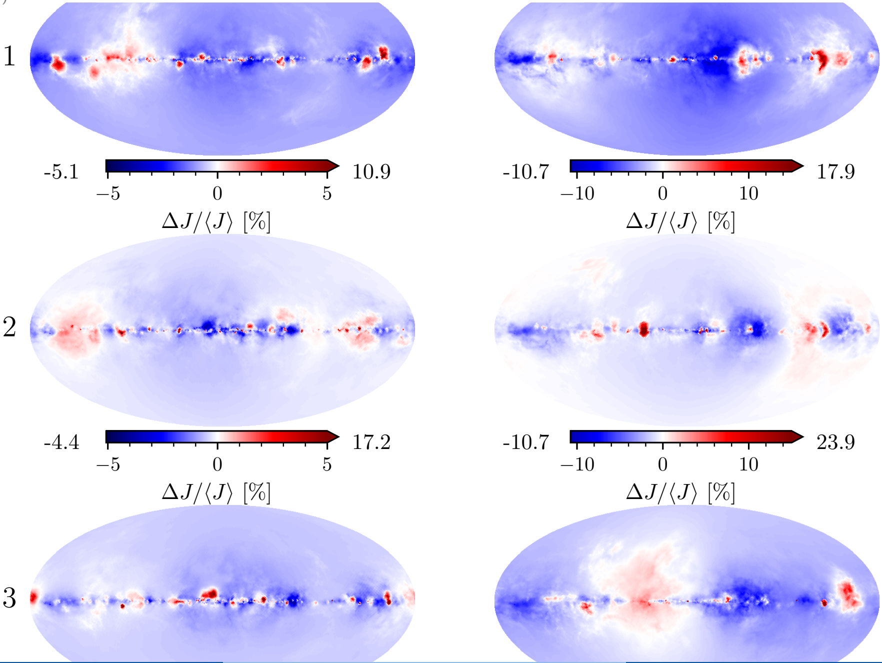

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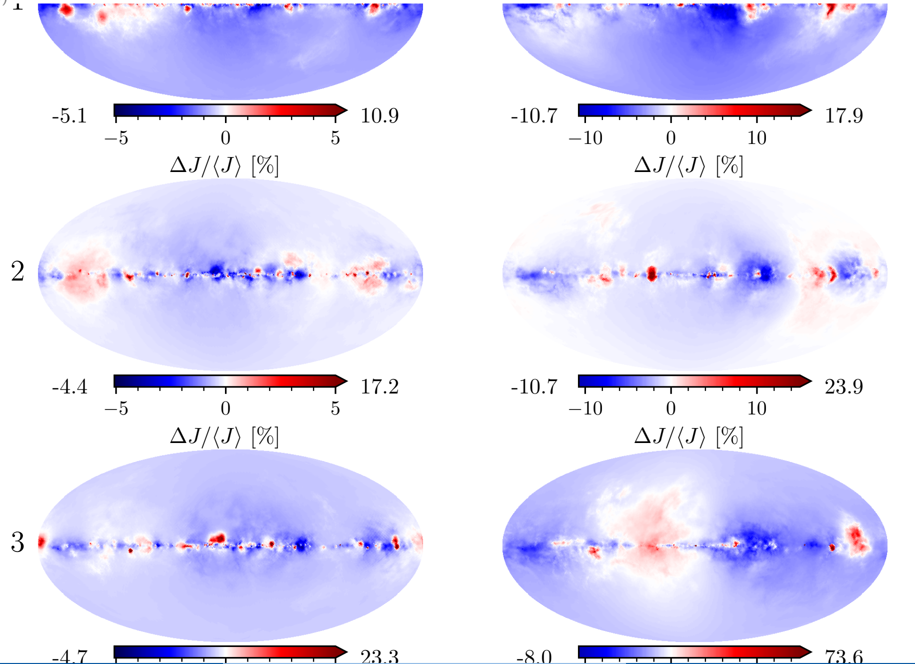

Stochastic diffuse emission

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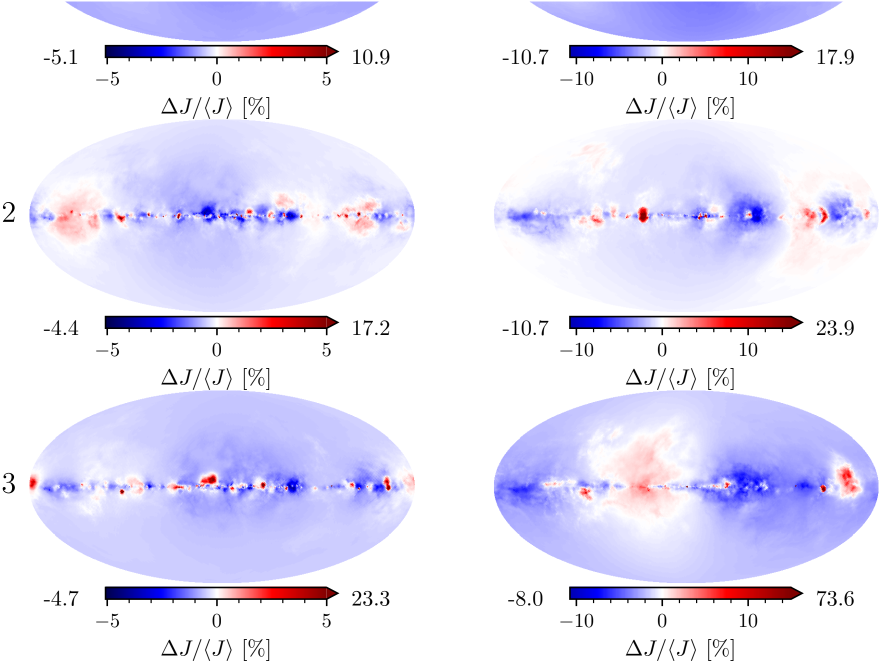
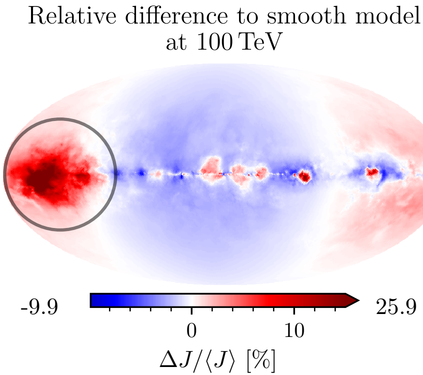
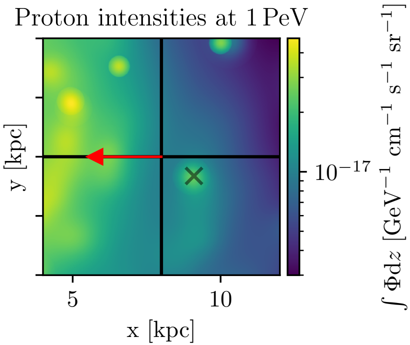


Sources manifest as deviations from the smooth model

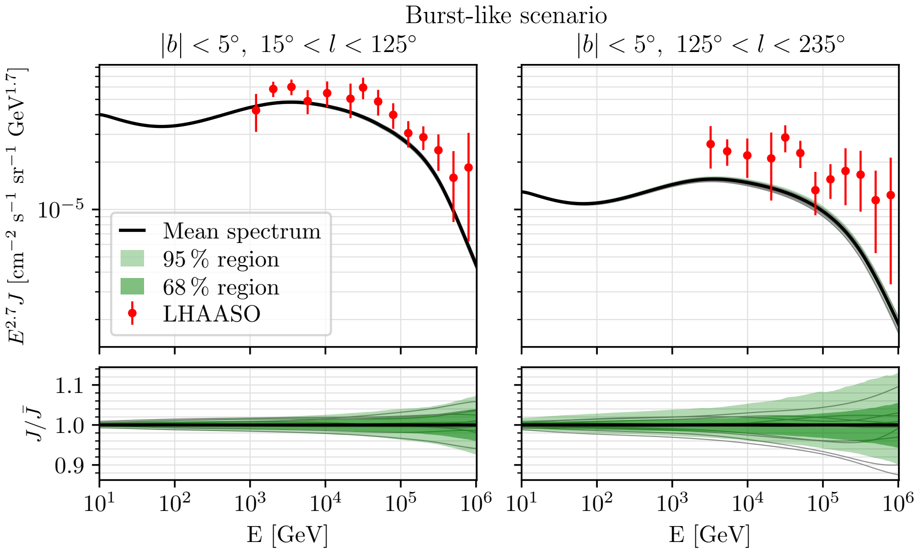
Mertsch & Stall (2025)





Deviations from the ensemble average can be sizeable

Mertsch & Stall (2025)



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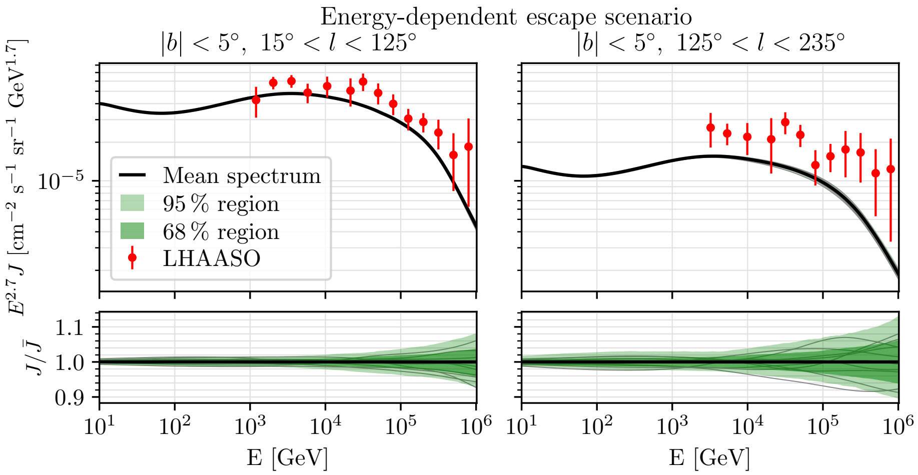

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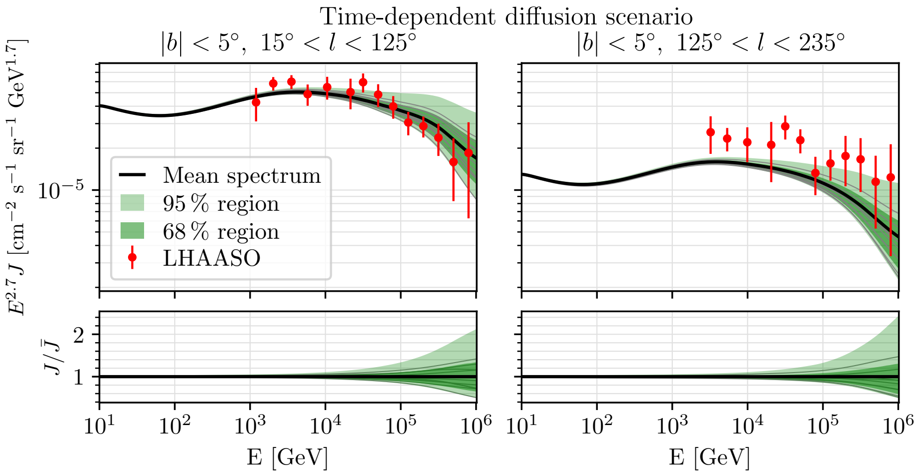
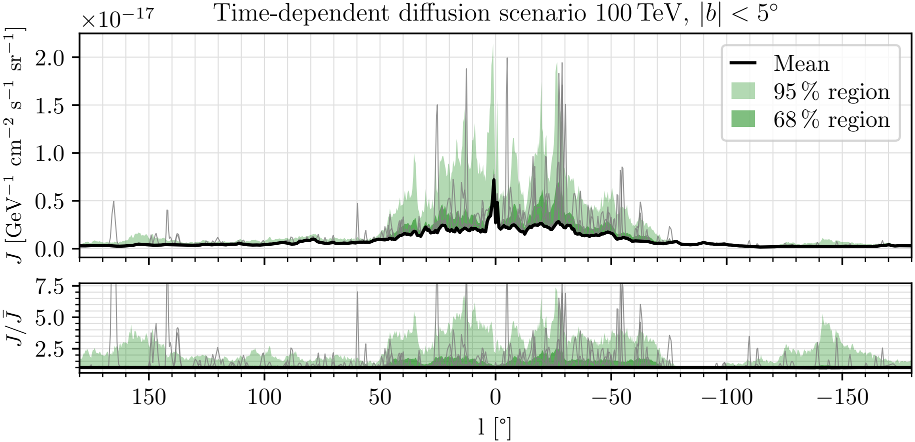


Along the galactic plane, intensity can be enhanced by factors of a few

Mertsch & Stall (2025)



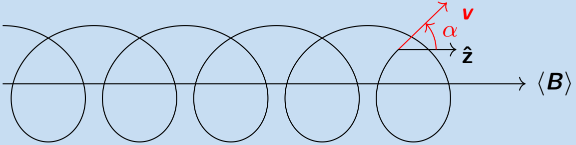
Outline

Parallel transport

- Magnetic field: $\langle \boldsymbol{B} \rangle + \delta \boldsymbol{B} \quad \rightarrow \quad$ phase-space density: $\langle f \rangle + \delta f$

$$\Rightarrow \frac{\partial \langle f \rangle}{\partial t} + \boldsymbol{v} \cdot \nabla_{\boldsymbol{r}} \langle f \rangle = \int_0^t \mathrm{d}t \left\langle (\boldsymbol{v} \times \delta \boldsymbol{B}) \cdot \nabla_{\boldsymbol{p}} \Big[(\boldsymbol{v} \times \delta \boldsymbol{B}) \cdot \nabla_{\boldsymbol{p}} \langle f \rangle \Big]_{\boldsymbol{r}(t')} \right\rangle$$

Unperturbed trajectory $\boldsymbol{r}(t)$ characterised by pitch-angle cosine $\mu \equiv \cos \alpha$

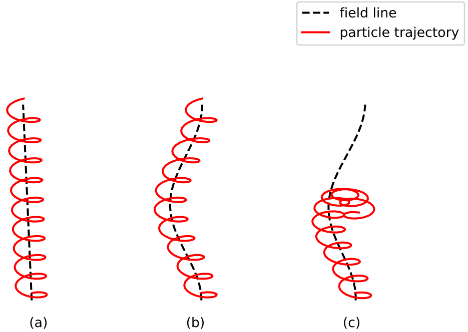


$\Rightarrow$ Pitch-angle scattering $\dfrac{\partial \langle f \rangle}{\partial t} + v\mu \dfrac{\partial \langle f \rangle}{\partial z} = \dfrac{\partial}{\partial \mu} D_{\mu\mu} \dfrac{\partial \langle f \rangle}{\partial \mu}$ with $D_{\mu\mu} \sim \left(\dfrac{\delta B^2}{B_0^2} \right)^{-1} \left(\dfrac{r_g}{L_c} \right)^{q-2} \Omega_g$

$\Rightarrow$ For isotropic phase-space density $\bar{f}$: $\dfrac{\partial \bar{f}}{\partial t} - \dfrac{\partial}{\partial z} \kappa_{\parallel} \dfrac{\partial \bar{f}}{\partial z} = 0$ with $\kappa_{\parallel} = \displaystyle\int_{-1}^{1} \mathrm{d}\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}}$

Perpendicular transport

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

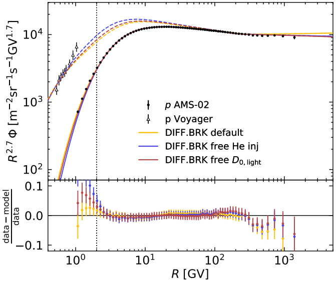


(a) Straight field line and gyration
(b) Wandering field line and gyration
(c) Wandering field line and diffusion

Particle “jumps” field lines upon scattering

How to model particle diffusion

Korsmeier & Cuoco (2021)

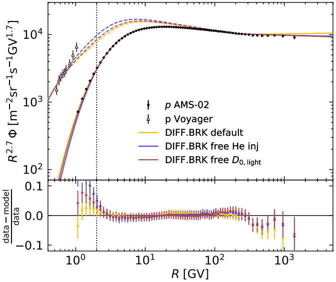


Phenomenological models

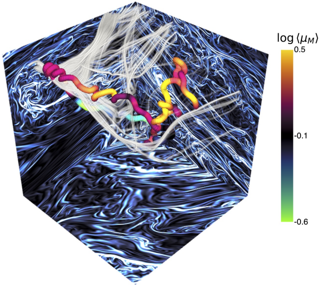
- Parametric form for $\kappa(\mathcal{R})$
- Fit to CR data ☺
- Connection to microphysics? ☹

How to model particle diffusion

Korsmeier & Cuoco (2021)



Kempski *et al.* (2025)



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MHD models

- $\kappa(\mathcal{R})$ computed from microphysics
- First principles ☺
- Do not fit data ☹

How to model particle diffusion

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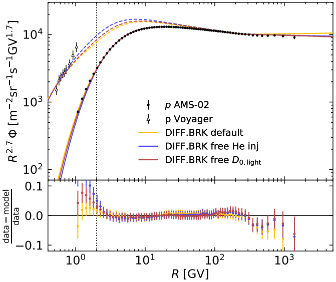
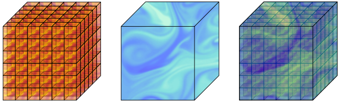


PM (2019)



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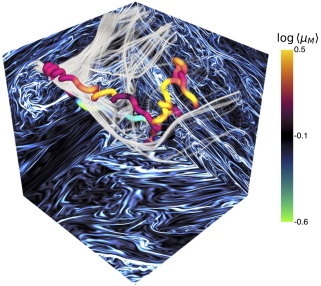

Phenomenological models

- Parametric form for $\kappa(\mathcal{R})$
- Fit to CR data ☺
- Connection to microphysics? ☹

Synthetic turbulence models

- Parametric form for $\kappa(\mathcal{R})$
- Dynamical range ☺
- Realistic? ☹

MHD models

- $\kappa(\mathcal{R})$ computed from microphysics
- First principles ☺
- Do not fit data ☹

Test particle simulations

Kuhlen, Mertsch, Phan (2025); also Mertsch (2019)

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

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

Results depend on:

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

Polarisation

MHD equations:

$$\partial_t \rho + \nabla \cdot (\rho \boldsymbol{V}) = 0$$

$$\rho \left(\partial_t + \boldsymbol{V} \cdot \nabla \right) \boldsymbol{V} = -\nabla P + \frac{1}{4\pi} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B}$$

$$\partial_t \boldsymbol{B} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B})$$

$$\frac{\mathrm{d}}{\mathrm{d}t} \left(\frac{P}{\rho^\gamma} \right) = 0$$

Alfvén modes

- Incompressible: $\delta\rho, \delta P = 0$
- Restoring force: magnetic tension
- $\delta \boldsymbol{B} \perp \boldsymbol{B}_0, \boldsymbol{k}$

Magnetosonic modes

- Compressible: $\delta\rho, \delta P \neq 0$
- Restoring force: gas + magnetic pressure
- $\delta \boldsymbol{B} \perp \boldsymbol{k}$, but with components $\parallel \boldsymbol{B}_0$

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$$\delta \boldsymbol{B}(\boldsymbol{r}) = \sum_i A_i \boldsymbol{\xi}_i \cos \left[k_i \hat{\mathbf{k}}_i \cdot \boldsymbol{r} + \beta_i \right]$$

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Isotropic modes

- Equal mixture of Alfvén and magnetosonic

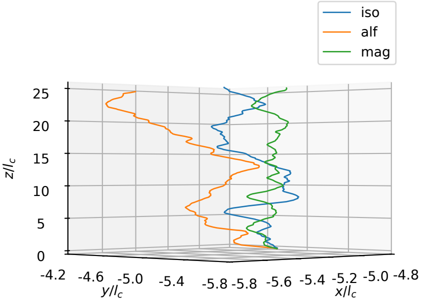
$\rightarrow$ Same power in all directions

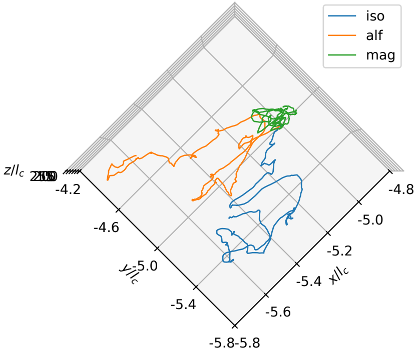
Field lines

Bouchet *et al.* (*in prep.*)

Integrate field line equation:

$$\frac{\mathrm{d}\boldsymbol{r}(s)}{\mathrm{d}s} = \frac{\boldsymbol{B}_0 + \delta\boldsymbol{B}(\boldsymbol{r}(s))}{|\boldsymbol{B}_0 + \delta\boldsymbol{B}(\boldsymbol{r}(s))|}$$





Much less variation in perpendicular direction for magnetosonic than for Alfvénic

Field line diffusion

- Running field-line diffusion coefficient

$$\mathcal{D}_{\perp}(s) = \frac{1}{4}\frac{\mathrm{d}}{\mathrm{d}s}\left\langle (x(s) - x_0)^2 + (y(s) - y_0)^2 \right\rangle$$

- Asymptotic field-line diffusion coefficient

$$\mathcal{K}_{\perp}(s) = \lim_{s \to \infty} \mathcal{D}_{\perp}(s)$$

Field line diffusion

- Running field-line diffusion coefficient

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- Asymptotic field-line diffusion coefficient

$$\mathcal{K}_\perp(s) = \lim_{s\to\infty} \mathcal{D}_\perp(s)$$

Alternative parametrisation

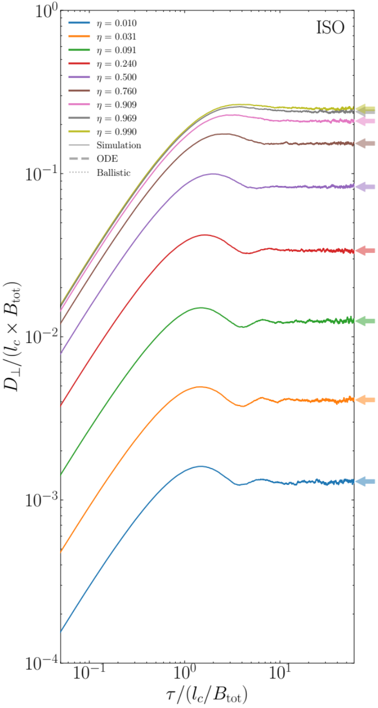
Sonsrettee *et al.* (2019)

- Reparametrise $s \to \tau$: $\mathrm{d}\tau \equiv \frac{\mathrm{d}s}{|\boldsymbol{B}|} \to \frac{\mathrm{d}\boldsymbol{r}(s)}{\mathrm{d}\tau} = \boldsymbol{B}_0 + \delta\boldsymbol{B}(\boldsymbol{r}(s))$
- Running field-line diffusion coefficient

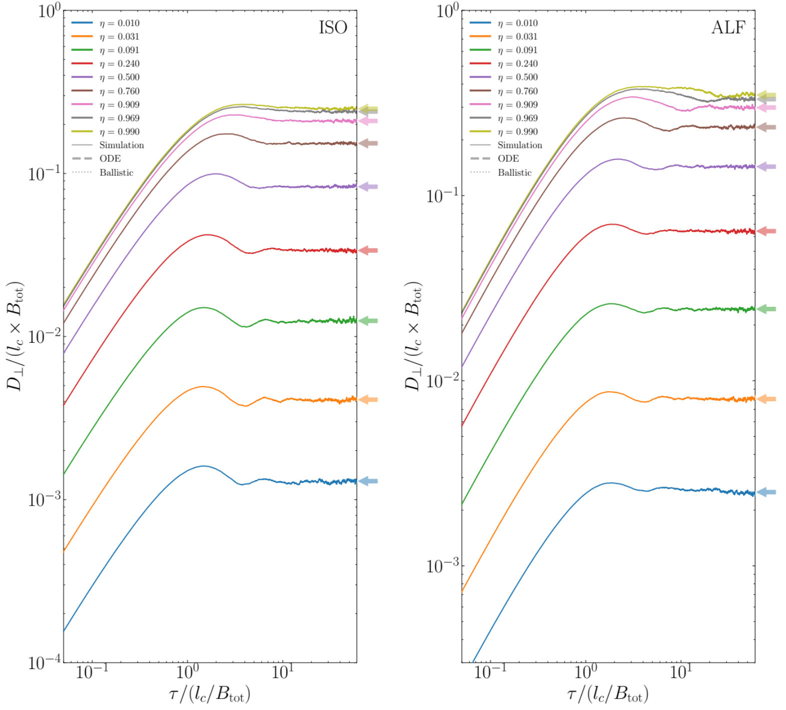
$$D_\perp(\tau) = \frac{1}{4}\frac{\mathrm{d}}{\mathrm{d}\tau}\left\langle (x(\tau) - x_0)^2 + (y(\tau) - y_0)^2 \right\rangle$$

- Asymptotic field-line diffusion coefficient

$$K_\perp = \lim_{\tau\to\infty} D_\perp(s)$$



ISO
$\eta = 0.010$
$\eta = 0.031$
$\eta = 0.091$
$\eta = 0.240$
$\eta = 0.500$
$\eta = 0.760$
$\eta = 0.909$
$\eta = 0.969$
$\eta = 0.990$
Simulation
ODE
Ballistic
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$D_\perp/(l_c \times B_{\mathrm{tot}})$
10^{-1}
10^0
10^1
$\tau/(l_c/B_{\mathrm{tot}})$



ISO
ALF
$\eta = 0.010$
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$\eta = 0.760$
$\eta = 0.909$
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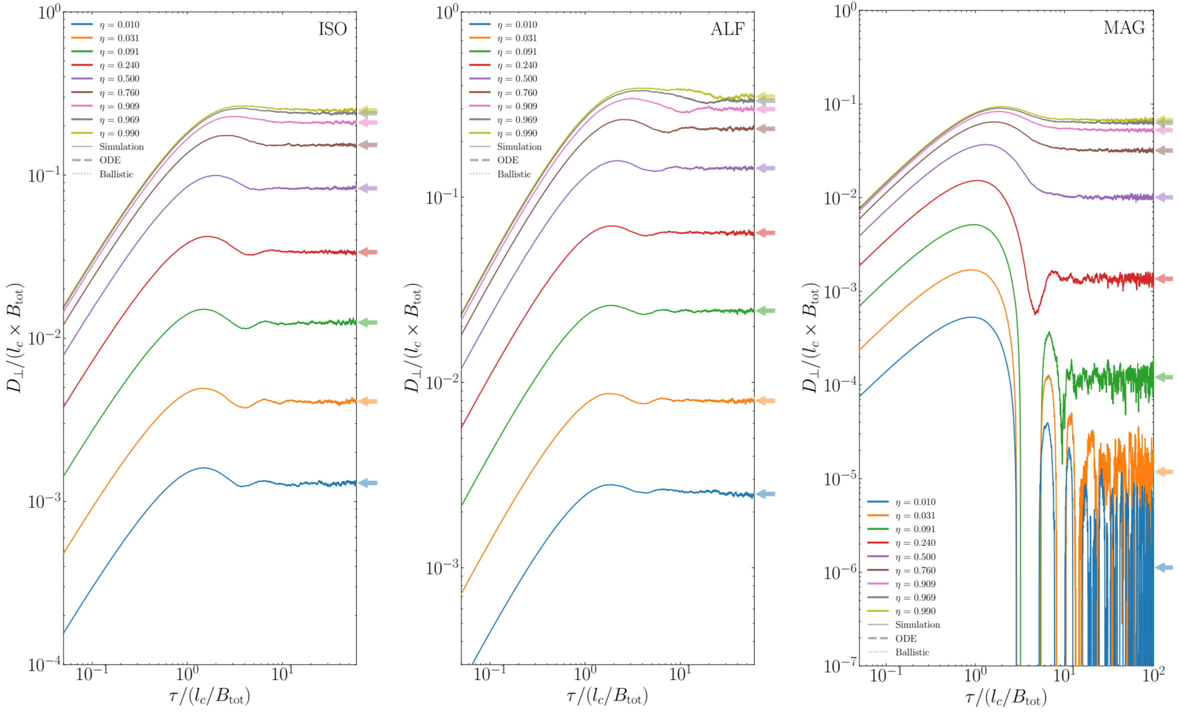
Simulation
ODE
Ballistic
$D_\perp/(l_c \times B_{\rm tot})$
$\tau/(l_c/B_{\rm tot})$



ISO
ALF
MAG
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Simulation
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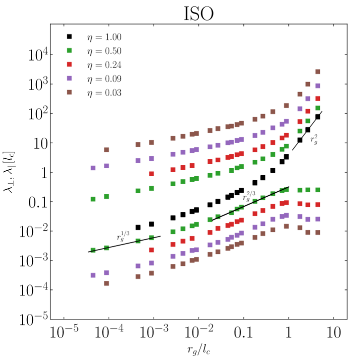
$D_\perp/(l_c \times B_{\mathrm{tot}})$
$\tau/(l_c/B_{\mathrm{tot}})$

Perpendicular particle transport

Bouchet *et al.* (*in prep.*)

Turbulence level:
$\eta = \delta B^2 / (B_0^2 + \delta B^2)$



- $10^{-3} \ll r_g / l_c \ll 1$: extended transition
- $r_g \ll 10^{-3}$: $\lambda_\perp \propto (r_g / l_c)^{1/3}$

  Dundovic *et al.* (2020),

  Kuhlen, Phan, Mertsch (2025)

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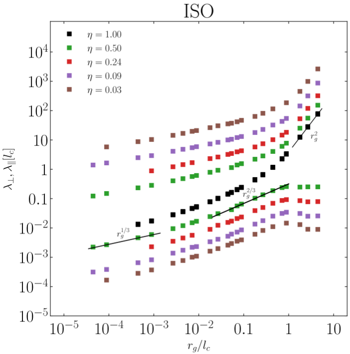

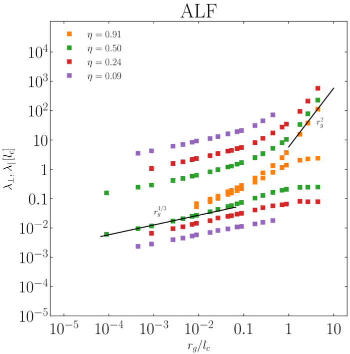

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  Kuhlen, Phan, Mertsch (2025)

- $10^{-3} \ll r_g / l_c \ll 1$:
  no extended transition

Perpendicular particle transport

Bouchet *et al.* (*in prep.*)

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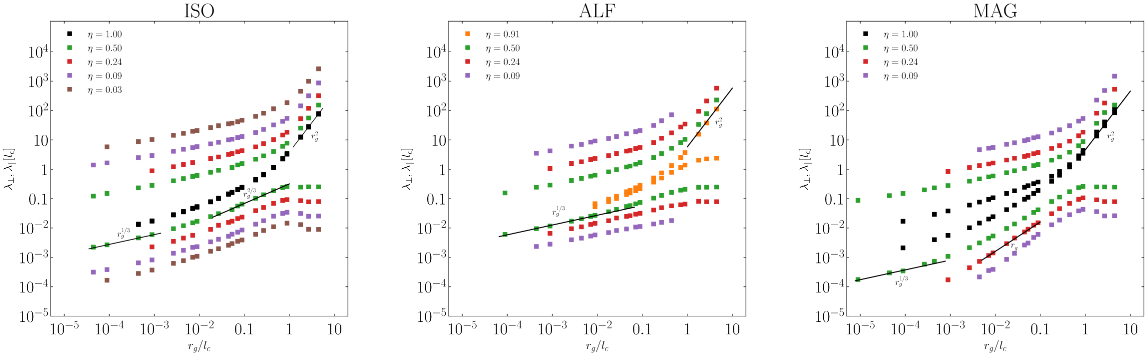

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  Dundovic *et al.* (2020),

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- $10^{-3} \ll r_g / l_c \ll 1$:
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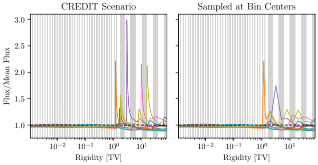
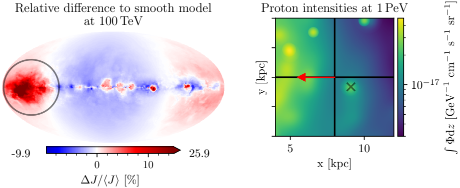
Outline

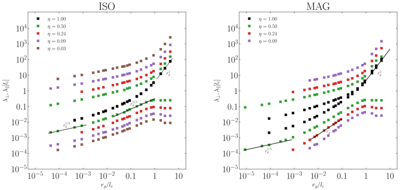
Summary



Shock acceleration and supernova paradigm $\rightarrow$ stark spectral features



Fluctuations in local CR density $\rightarrow$ effect on diffuse γ-ray maps



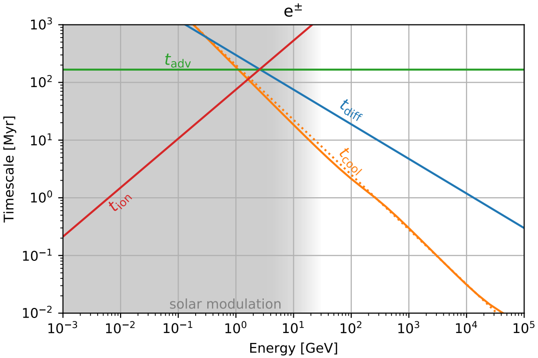
Non-standard transport of magnetic field lines and particles in polarised synthetic turbulence

Outline

6 Backup

Time scales

Time scales:



- $t_{\mathrm{diff}} = \frac{z_{\mathrm{max}}^2}{2\kappa}$ with $z_{\mathrm{max}} = 5\,\mathrm{kpc}$, $\kappa(10\,\mathrm{GV}) = 5 \times 10^{28} \mathrm{cm}^2\,\mathrm{s}^{-1}$
- t_{cool}: KN cross-section with $\rho = \{0.26, 0.6, 0.6, 0.1\}\,\mathrm{eV\,cm}^{-3}$ for CMB, IR, opt, UV; $3\,\mu\mathrm{G}$ B-field
- t_{ion}: $n_{\mathrm{H}} = 0.5\,\mathrm{cm}^{-3}$ (WIM) and $n_{\mathrm{H}} = 0.5\,\mathrm{cm}^{-3}$ (WNM) and 100 pc wide gas disk

In a diffusion model with $E^{-\Gamma}$ sources in disk:

- $\phi(E) \propto E^{-\Gamma-\delta}$ if diffusion dominated
- $\phi(E) \propto E^{-\Gamma-(\delta+1)/2}$ if cooling dominated