

Theory: Diffuse flux of photons

Philipp Mertsch

with Georg Schwefer, Anton Stall, Christopher Wiebusch

14th CosPa Meeting

27 October 2025

Outline

- ① Diffuse emission: Introduction
- ② Diffuse emission: The CRINGE model
- ③ Alternatives
 - Unresolved sources
 - Stochasticity
- ④ Sources
- ⑤ Conclusions

Outline

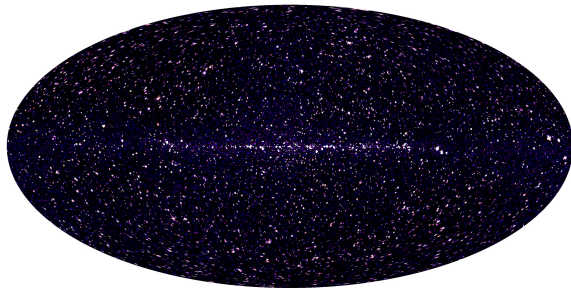
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What are we looking for?

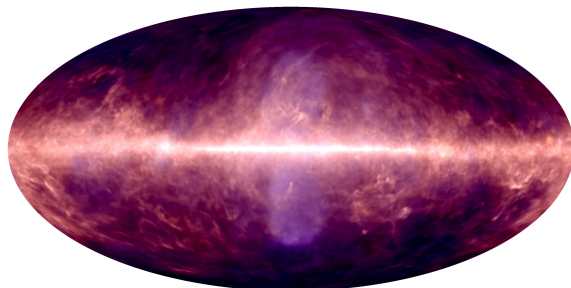
At GeV energies

Platz *et al.* (2022)

Sources



Diffuse emission

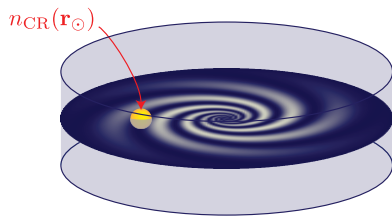


- Simple: point-like, e.g. power law spectrum
 - Source of cosmic rays
- Long-standing issue

- Diffusion, gas, ... it's complicated!
 - Interstellar medium
- Mere details ...

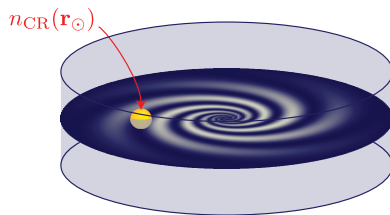
Local fluxes vs diffuse emission

Local fluxes

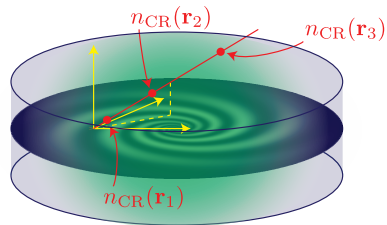


Local fluxes vs diffuse emission

Local fluxes



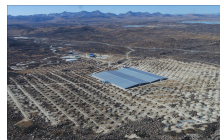
Diffuse emission



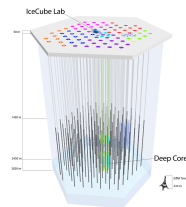
Recently measured at $\sim \text{PeV}$



Tibet AS γ +MD

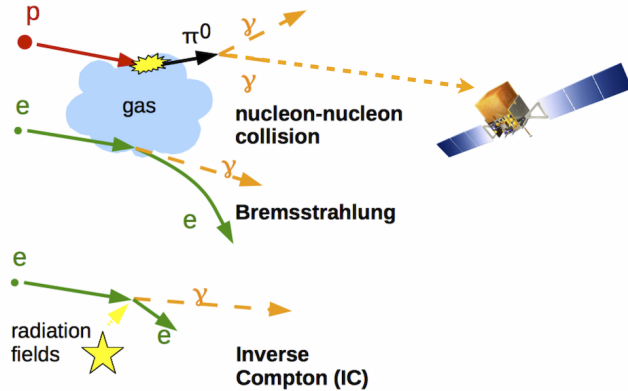


LHAASO

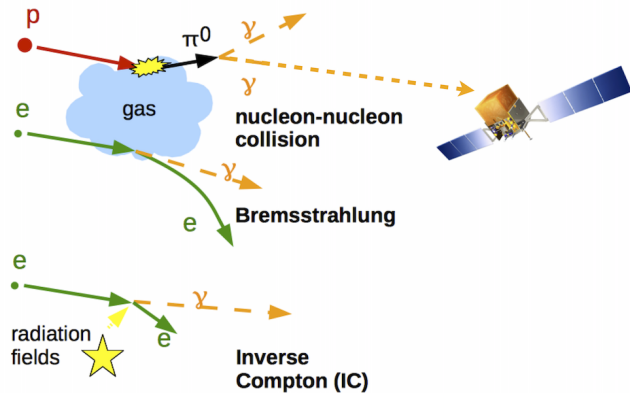


IceCube

Cosmic rays produce diffuse emission

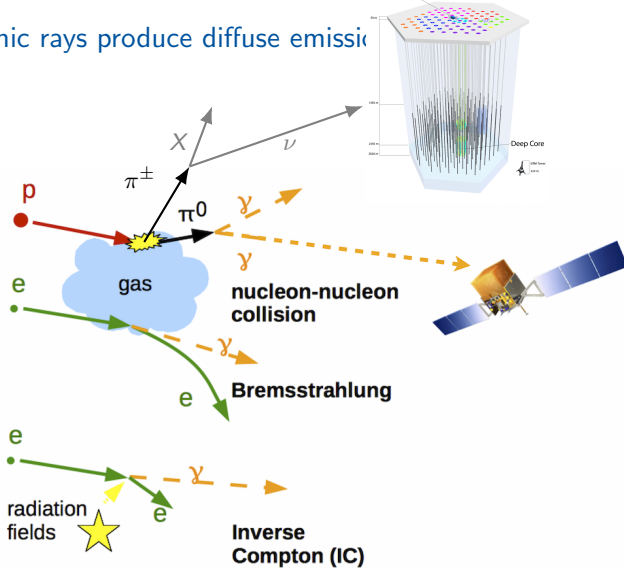


Cosmic rays produce diffuse emission



For given source:
hadronic or leptonic?

Cosmic rays produce diffuse emission



For given source:
hadronic or leptonic?

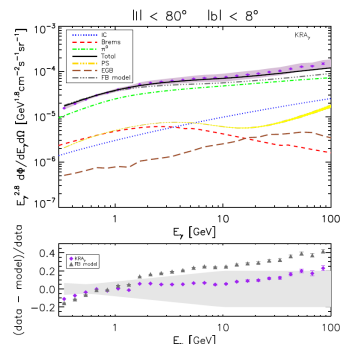
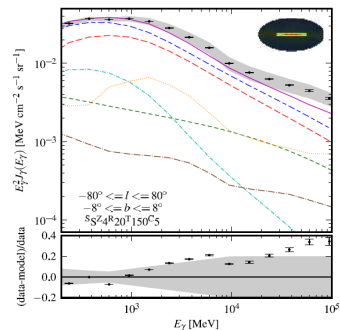
Previous attempts

Fermi- π^0 model *Ackermann et al. (2012)*

- Assumes homogeneous diffusion
- Fit to cosmic ray data of ~ 2010
- Residuals in inner galaxy

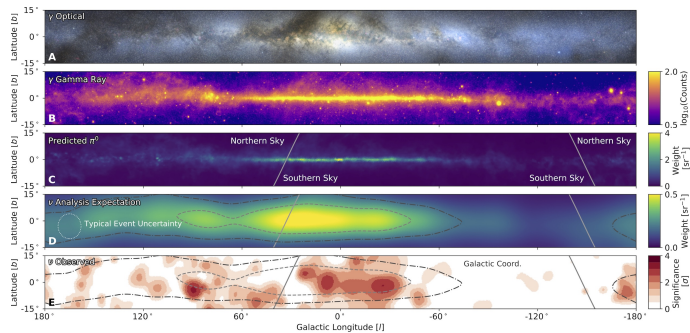
KRA γ model *Gaggero et al. (2015)*

- Tuned to reduce the residuals in inner galaxy
 - Spatially dependent diffusion coefficient
- Harder spectra towards the Galactic centre



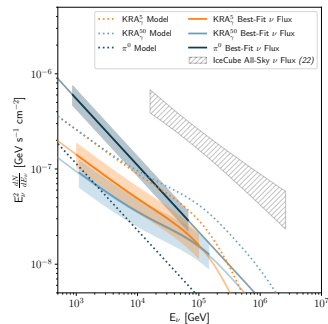
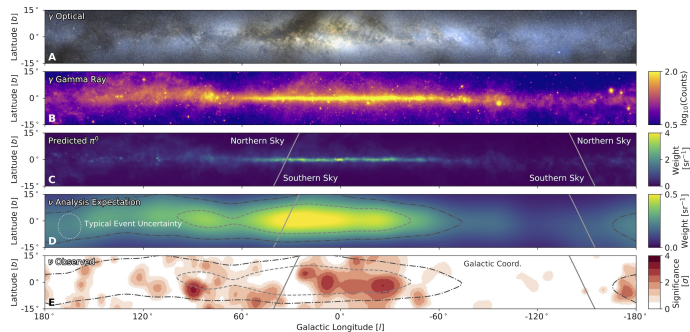
High-energy neutrinos from the Galactic plane

IceCube Collaboration (2023)



High-energy neutrinos from the Galactic plane

IceCube Collaboration (2023)



But normalisation
differs from models?!

Why study diffuse emission?



Check generic prediction



Can discriminate
hadronic/leptonic



Test supernova paradigm

Credit: Noun Project; Olena Panasovska; Victoruler; Zahrotus sa'idah

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- Built on cosmic ray model fit to AMS-02, DAMPE, KASCADE and IceTop data
- Uncertainties propagated into diffuse fluxes
- Additional uncertainties: source distribution, gas densities, cross-section

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CrossMark

Diffuse Emission of Galactic High-energy Neutrinos from a Global Fit of Cosmic Rays

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Abstract

In the standard picture of Galactic cosmic rays, a diffuse flux of high-energy gamma rays and neutrinos is produced from inelastic collisions of cosmic-ray nuclei with the interstellar gas. The neutrino flux is a guaranteed signal for high-energy neutrino observatories such as IceCube but has not been found yet. Experimental searches for this flux constitute an important test of the standard picture of Galactic cosmic rays. Both observation and nonobservation would allow important implications for the physics of cosmic-ray acceleration and transport. We present CRINGE, a new model of Galactic diffuse high-energy gamma rays and neutrinos, fitted to recent cosmic-ray data from AMS-02, DAMPE, IceTop, as well as KASCADE. We quantify the uncertainties for the predicted emission from the cosmic-ray model but also from the choice of source distribution, gas maps, and cross sections. We consider the possibility of a contribution from unresolved sources. Our model predictions exhibit significant deviations from older models. Our fiducial model is available at <https://doi.org/10.5281/zenodo.7859442>.

Unified Astronomy Thesaurus concepts: Gamma-ray astronomy (628); Neutrino astronomy (1100); Diffuse radiation (383); Galactic cosmic rays (567)

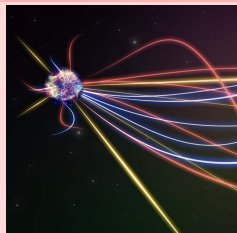
1. Introduction

Unlike the multicomponent fluxes of photons, the flux of

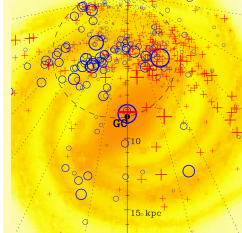
Known unknowns

Schwefer, Mertsch, Wiebusch (2022)

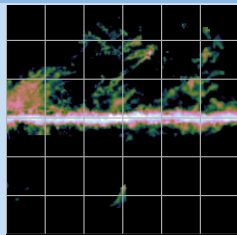
Cosmic ray model



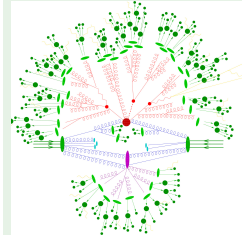
Source distribution



Gas map



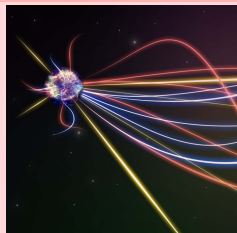
Cross-sections



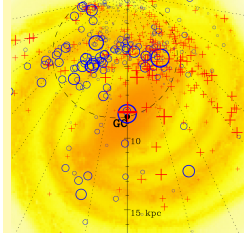
Known unknowns

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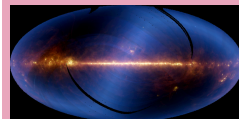
Cosmic ray model



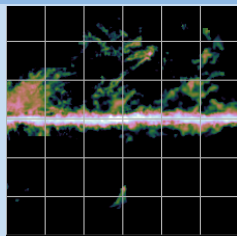
Source distribution



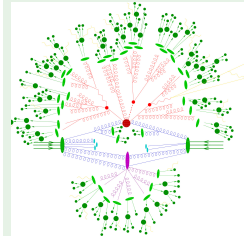
Photon backgrounds



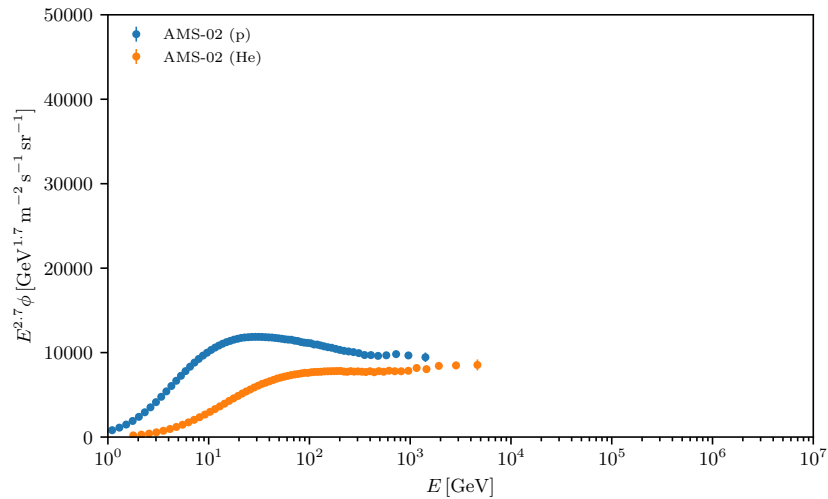
Gas map



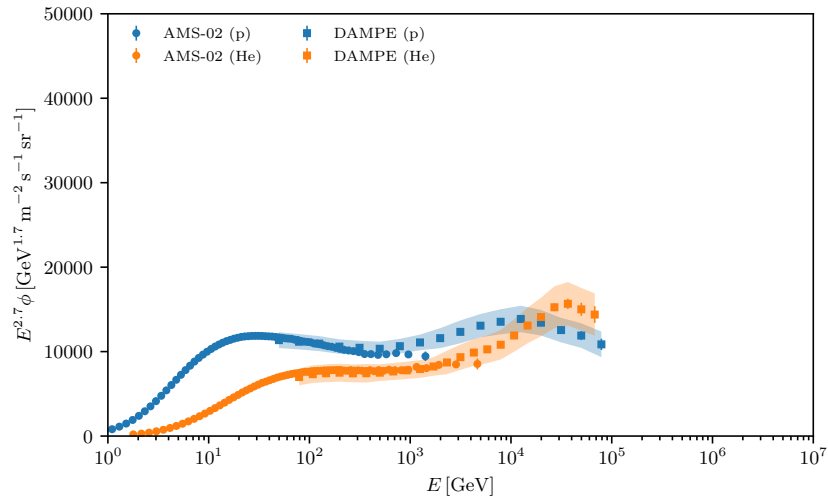
Cross-sections



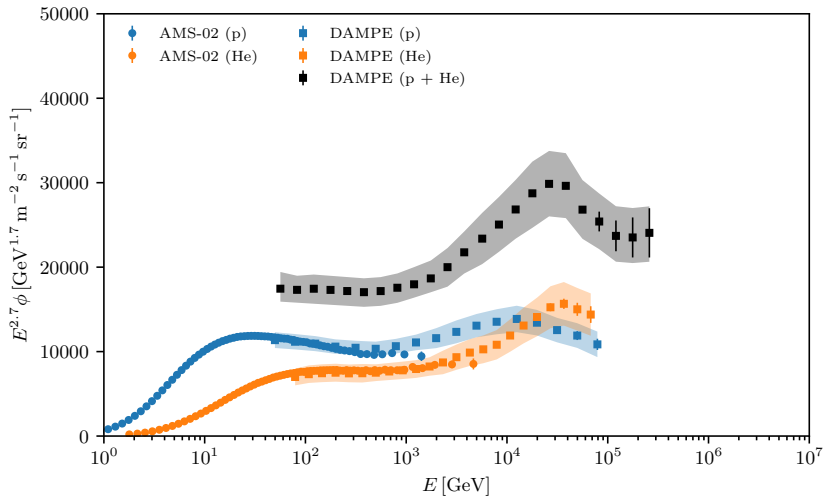
Nuclear spectra



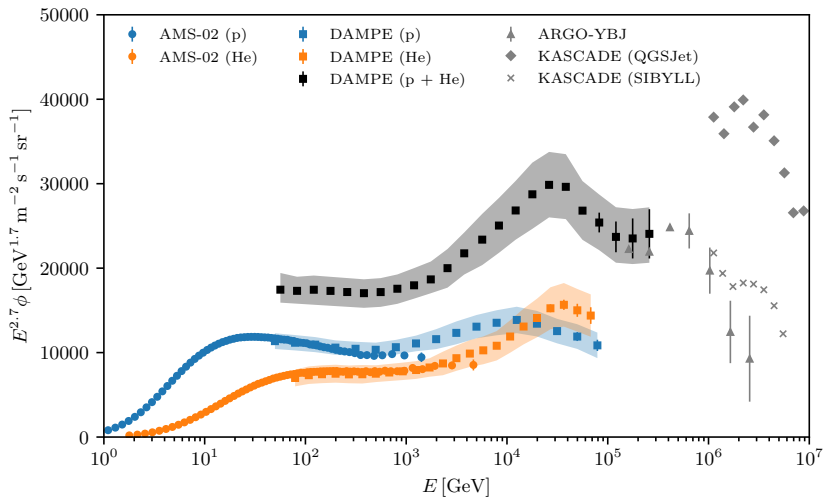
Nuclear spectra



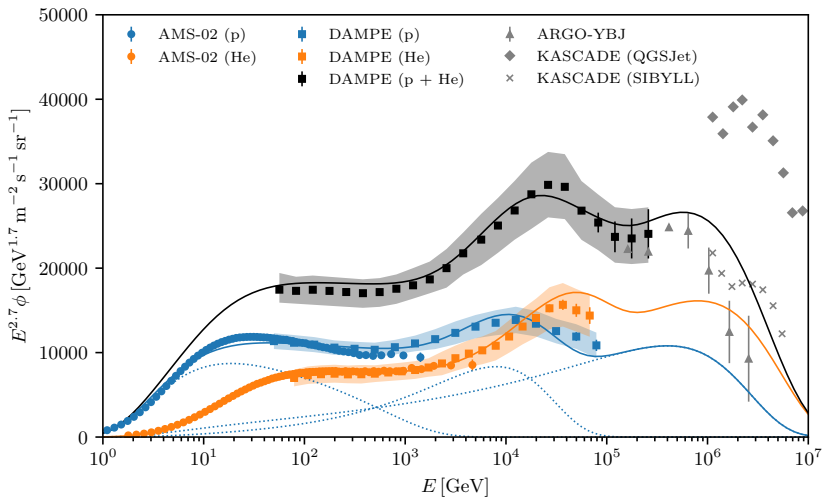
Nuclear spectra



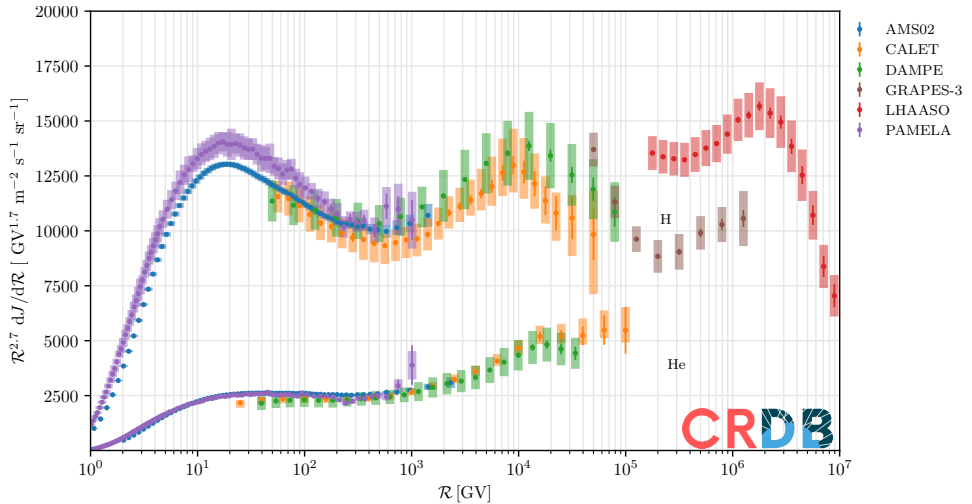
Nuclear spectra



Nuclear spectra



Nuclear spectra



The cosmic-ray transport equation

$$\begin{aligned}\frac{\partial \psi_j}{\partial t} = & \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j) && \text{spatial diffusion and advection} \\ & + \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right) && \text{momentum diffusion} \\ & + \frac{\partial}{\partial p} \left(-\frac{dp}{dt} \psi_j + \frac{p}{3} (\nabla \cdot \mathbf{U}) \psi_j \right) && \text{momentum change incl. adiabatic} \\ & - v n_{\text{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j} && \text{spallation and decay} \\ & + v n_{\text{gas}} \sum_{k>j} \sigma_{k \rightarrow j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \rightarrow j}} && \text{spallation and decay} \\ & + S_j && \text{primary sources}\end{aligned}$$

Idealised setup

- Isotropy
- Gaussianity
- ...

The cosmic-ray transport equation

$$\begin{aligned}
 \frac{\partial \psi_j}{\partial t} = & \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j) && \text{spatial diffusion and advection} \\
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 & + S_j && \text{primary sources}
 \end{aligned}$$

Idealised setup

- Isotropy
- Gaussianity
- ...

Frequent assumptions

- Symmetry
- Ignorable dimensions
- Smooth source distribution

→ Numerical solution needed

In reality

- No exact symmetries
- 3D
- Point-like sources

Large number of free parameters

- Unknown parameters:

- Source spectrum: $\gamma^{\text{p}}, \gamma^{\text{He}}, \gamma^{\text{C}}; N_{\text{He}}, N_{\text{C}}; (e^{\pm} \text{ parameters})$
 - Gal. transport: $\kappa_0; \delta_1 \dots \delta_5; \mathcal{R}_{12} \dots \mathcal{R}_{45}; s_{12} \dots s_{45}$
 - Solar modulation: $\phi_{\text{p}}, \phi_{e^+}, \phi_{e^-}, \phi_{\text{nuc}}$
 - Energy scale uncert.: $\alpha_{\text{AMS-02}}, \alpha_{\text{DAMPE}}, \alpha_{\text{IceTop}}, \alpha_{\text{KASCADE}}$
- } $\mathcal{O}(30)$

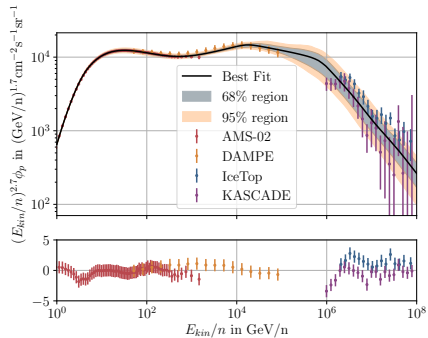
→ Need to efficiently scan parameter space

- Used affine-invariant MC sampler **emcee** Foreman-Mackey *et al.* (2012)

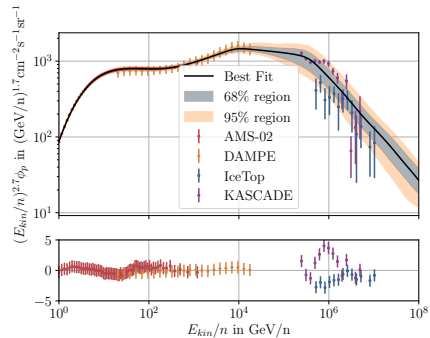
Cosmic ray results

Schwefer, Mertsch, Wiebusch (2022)

Protons



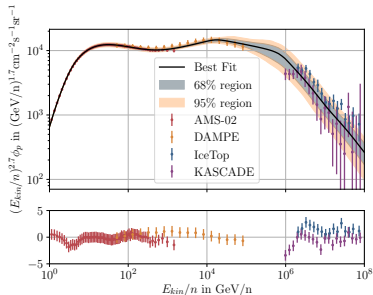
Helium



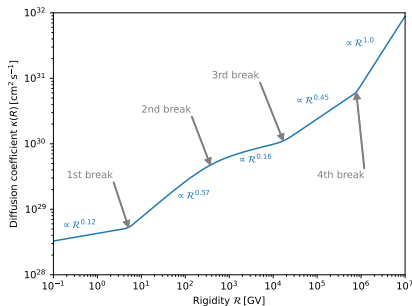
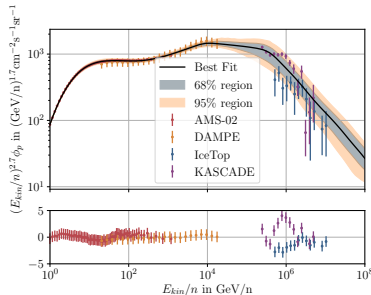
Anatomy of a diffusion coefficient

Schwefer, Mertsch, Wiebusch (2022)

Proton



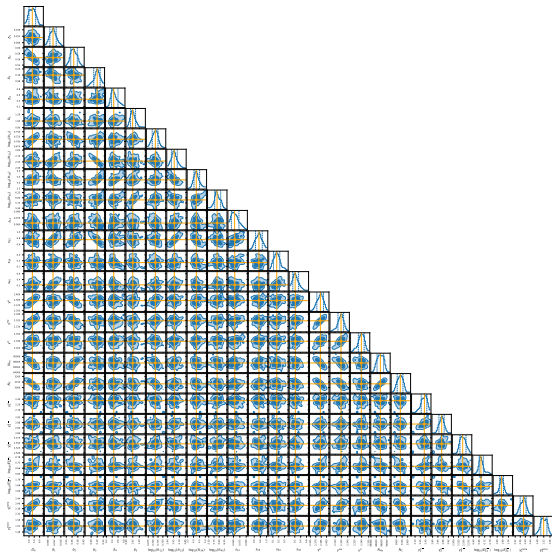
Helium



- 1. Break: Hardening of spectra at low energies due to stochasticity effect *Phan et al. (2021)*
- 2. Break: Transition from self-generated to external turbulence *Blasi, Amato, Serpico (2012)*
- 3. Break: ?!
- 4. Break: Transition from resonant to small-angle scattering

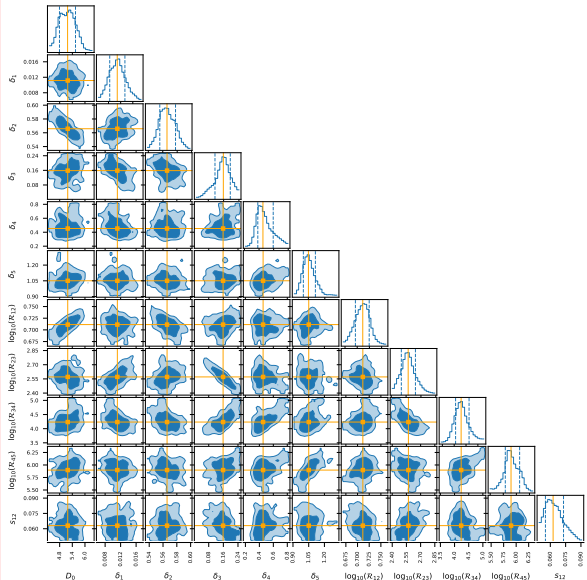
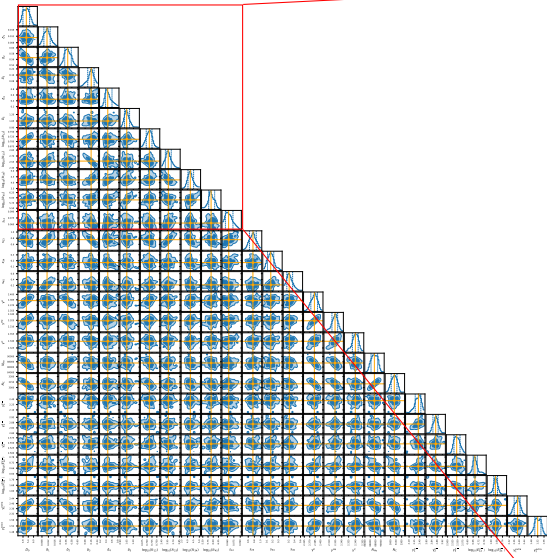
Challenges

Schwefer, Mertsch, Wiebusch (2022)



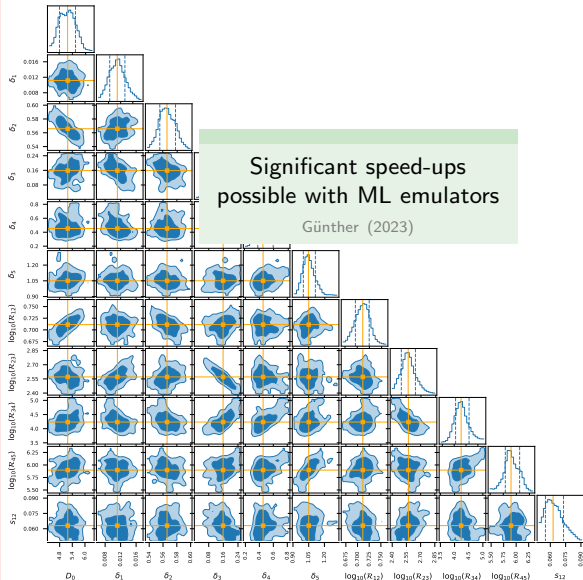
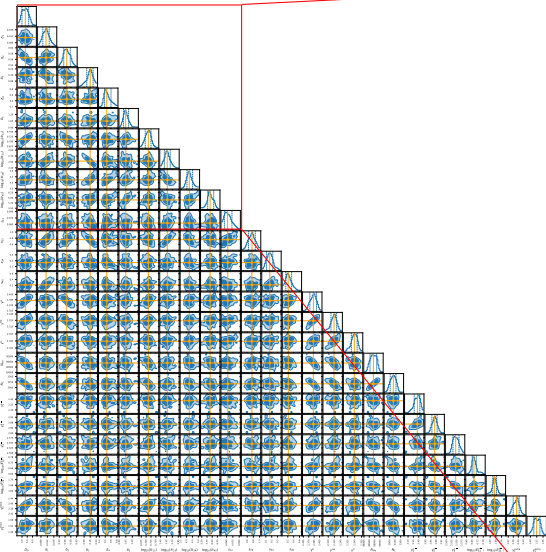
Challenges

Schwefer, Mertsch, Wiebusch (2022)



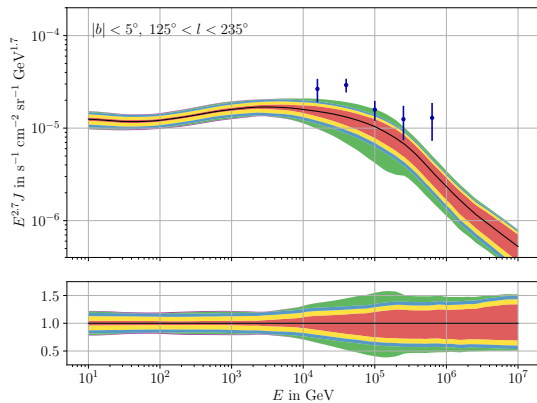
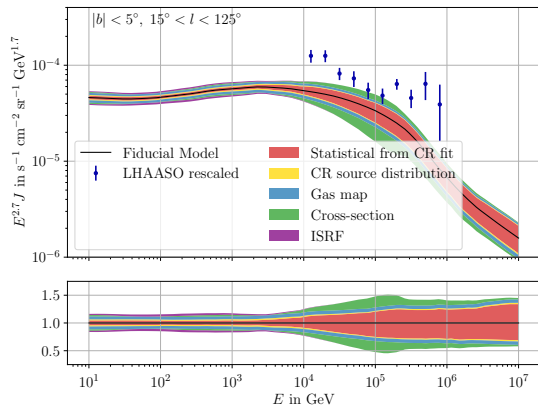
Challenges

Schwefer, Mertsch, Wiebusch (2022)



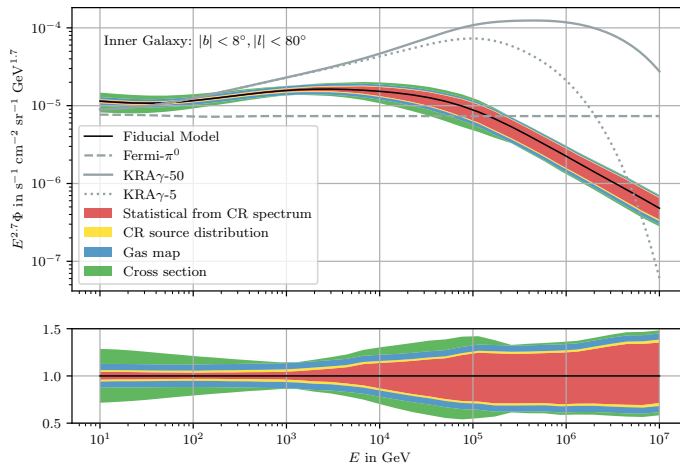
Results

Schwefer, Mertsch, Wiebusch (2023)



ν results (inner Galaxy)

Schwefer, Mertsch, Wiebusch (2022)

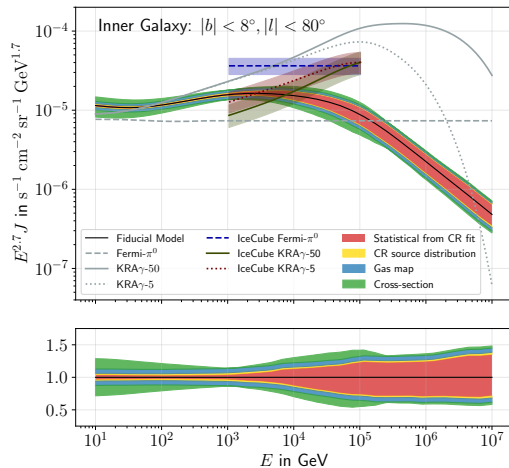


- Close to $E^{-2.7}$ for $E \lesssim 30 \text{ TeV}$
- Uncertainty up to 50 %, mostly from CR model
- Harder than Fermi- π^0 , softer than KRA γ

Results

Schwefer, Mertsch, Wiebusch (2023)

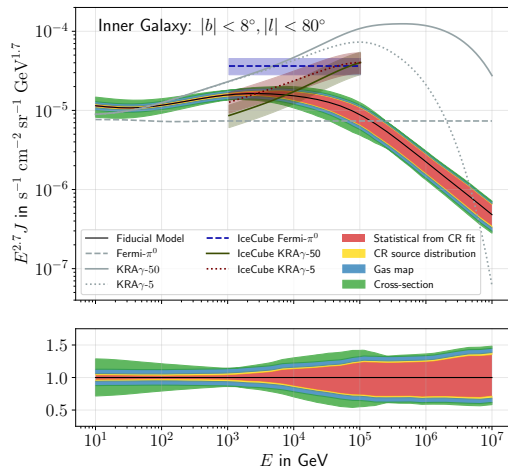
Neutrinos



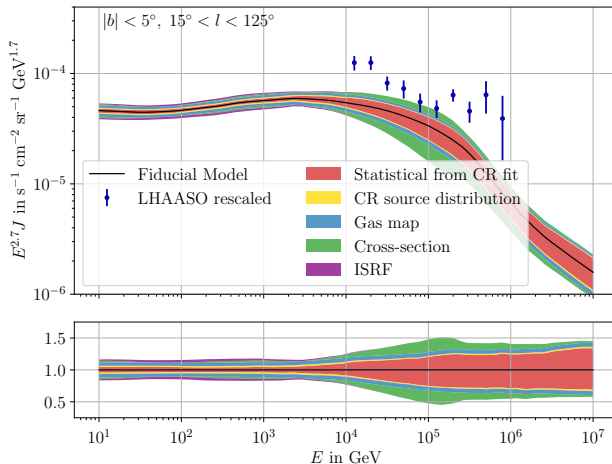
Results

Schwefer, Mertsch, Wiebusch (2023)

Neutrinos



Gamma-rays



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Strongly anchor in local CR data

- 1 Unresolved sources



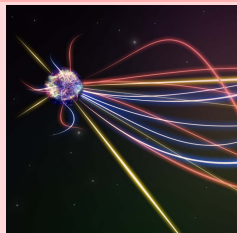
Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient
- 3 Advection
- 4 Stochasticity

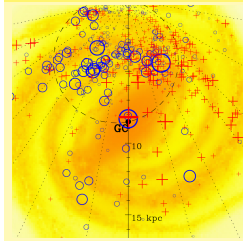
Known unknowns

Schwefer, Mertsch, Wiebusch (2022)

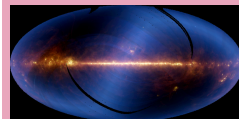
Cosmic ray model



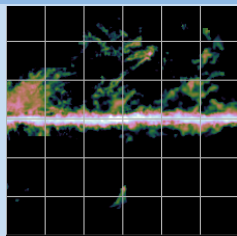
Source distribution



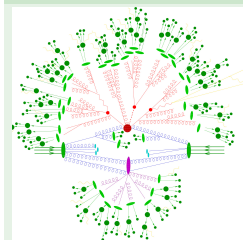
Photon backgrounds



Gas map



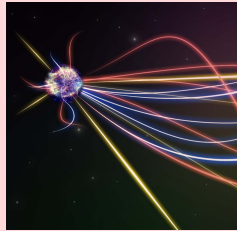
Cross-sections



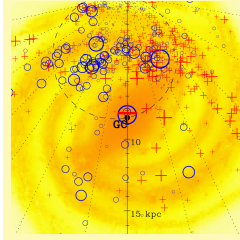
Known unknowns

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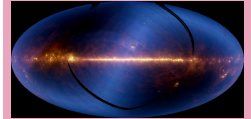
Cosmic ray model



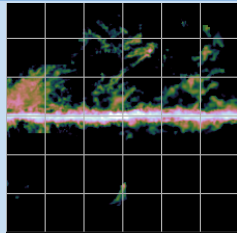
Source distribution



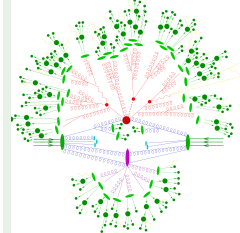
Photon backgrounds



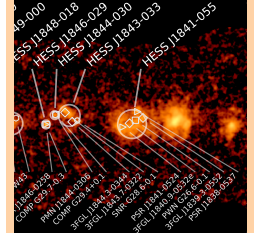
Gas map



Cross-sections



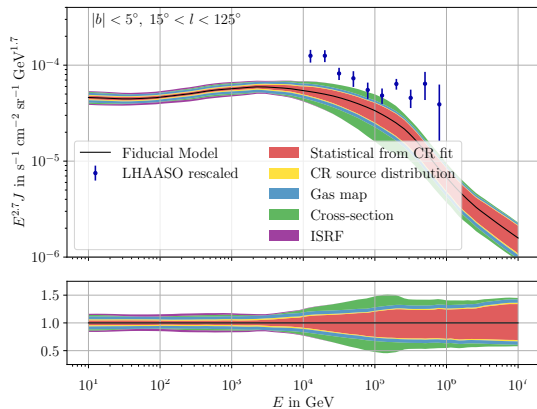
Unresolved sources



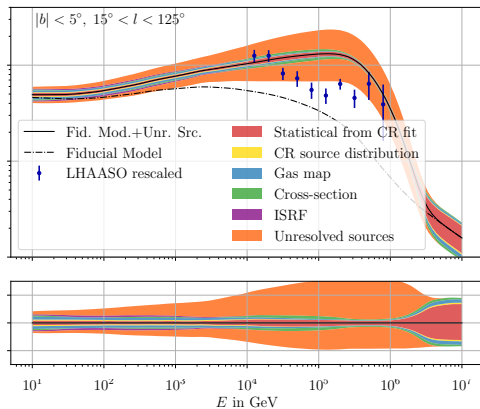
γ results (post LHAASO publication)

Schwefer, Mertsch, Wiebusch (2023)

Without unresolved sources



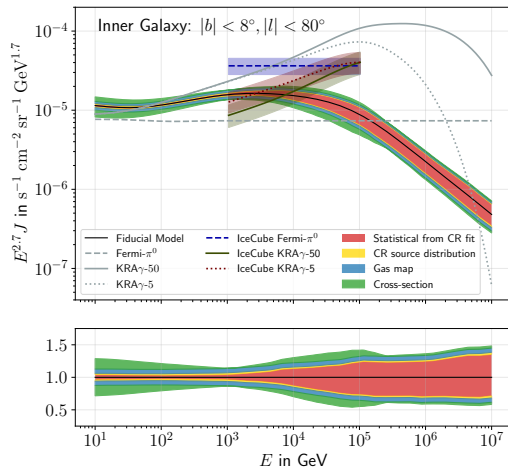
With unresolved sources



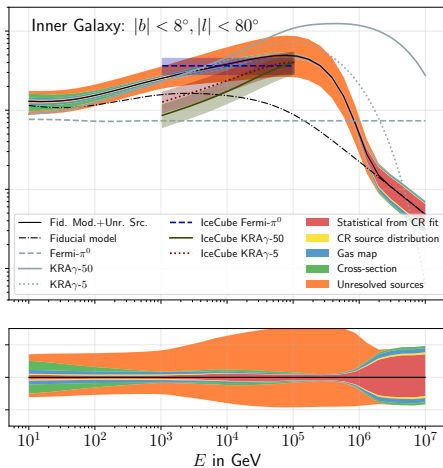
ν results (post IceCube publication)

Schwefer, Mertsch, Wiebusch (2023)

Without unresolved sources



With unresolved sources





Strongly anchor in local CR data

- 1 Unresolved sources 😊



Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient
- 3 Advection
- 4 Stochasticity

Alternatives



Strongly anchor in local CR data

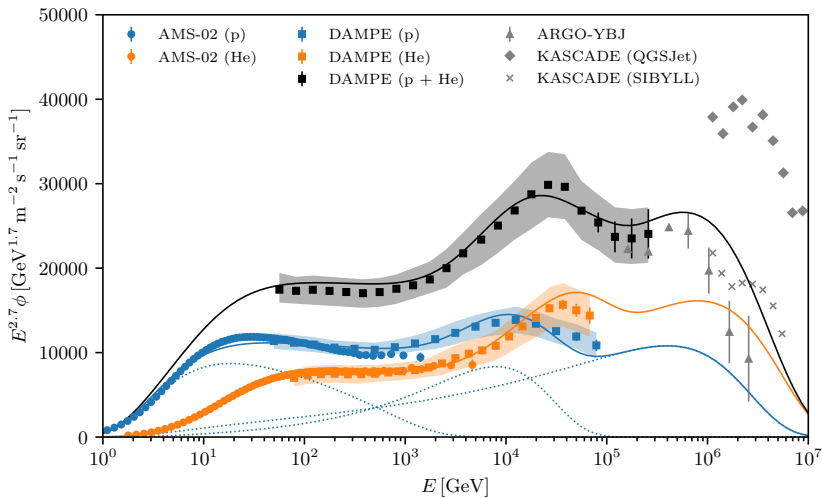
- 1 Unresolved sources 😊



Allow for variation from local CR data

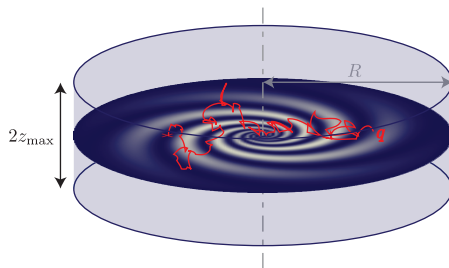
- 2 Spatially varying diffusion coefficient 😞
- 3 Advection 😞
- 4 Stochasticity

Nuclear spectra



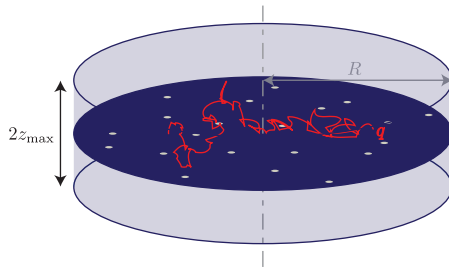
Spectral features in nuclei

Bernard *et al.* (2012); Wei *et al.* (2014); Savchenko *et al.* (2015); Genolini *et al.* (2017); Bouyahiaoui *et al.* (2018); Evoli *et al.* (2022)



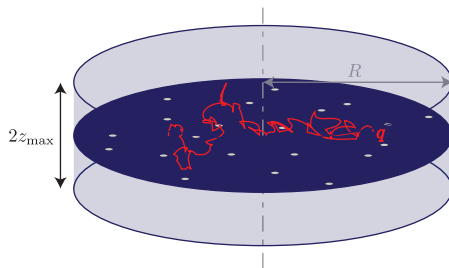
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Spectral breaks as evidence for nearby sources

- Young source $\rightarrow$ hard spectrum at Earth
- If the $\mathcal{R}_{\max}$ is limited, can lead to bump
- Rationale: tune parameters (distance, age, cut-off) to match observations

Spectral breaks **not** due to nearby sources

- Individual sources can lead to features
- What is likelihood for such a configuration?
- Rationale: Run MC simulations to quantify this

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With typical parameters (for details → [Appendix](#)):

$$\mathcal{R} = 10 \text{ GV}, \quad 10 \text{ TV}, \quad 10 \text{ PV}$$
$$N_{\text{src}} \simeq 2 \times 10^4, \quad 200, \quad 4$$

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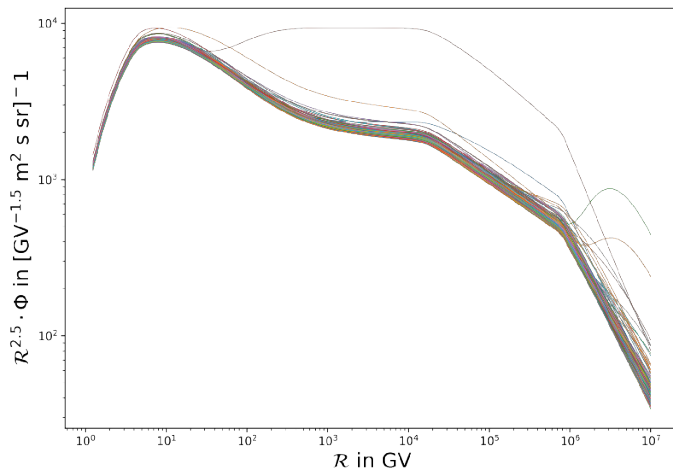
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A Monte Carlo exercise

Mertsch & Stall (2025)



- 50 realisation of the Galaxy
- Homogeneous distribution of sources in disk
- Canonical SN rate:

$$\mathcal{R}_{\text{SN}} = 3 \times 10^4 \text{ Myr}^{-1}$$

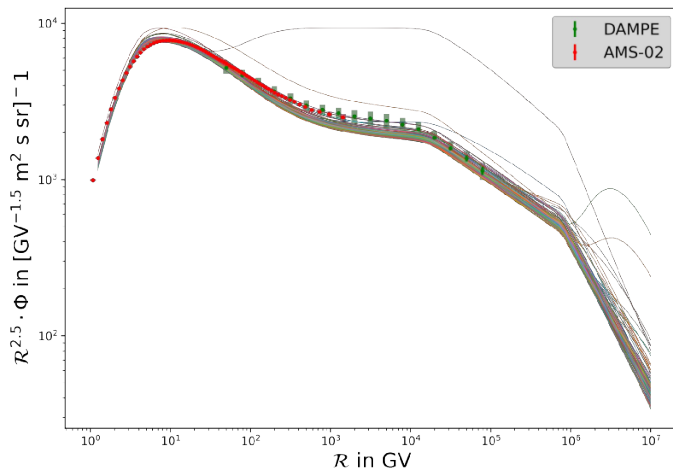
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Major features below $\sim 10^6$ GV
from diffusion coefficient

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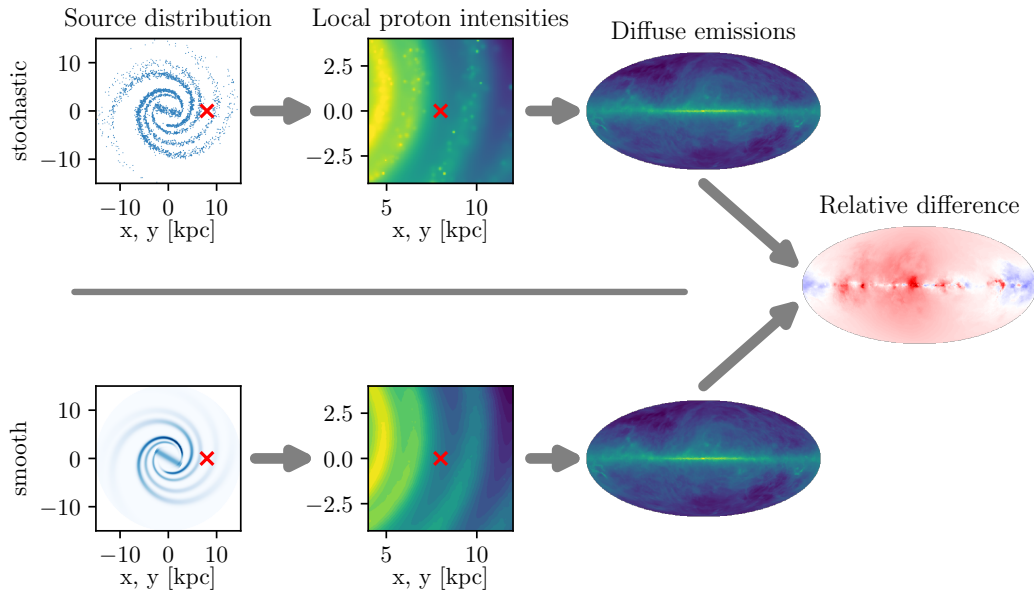
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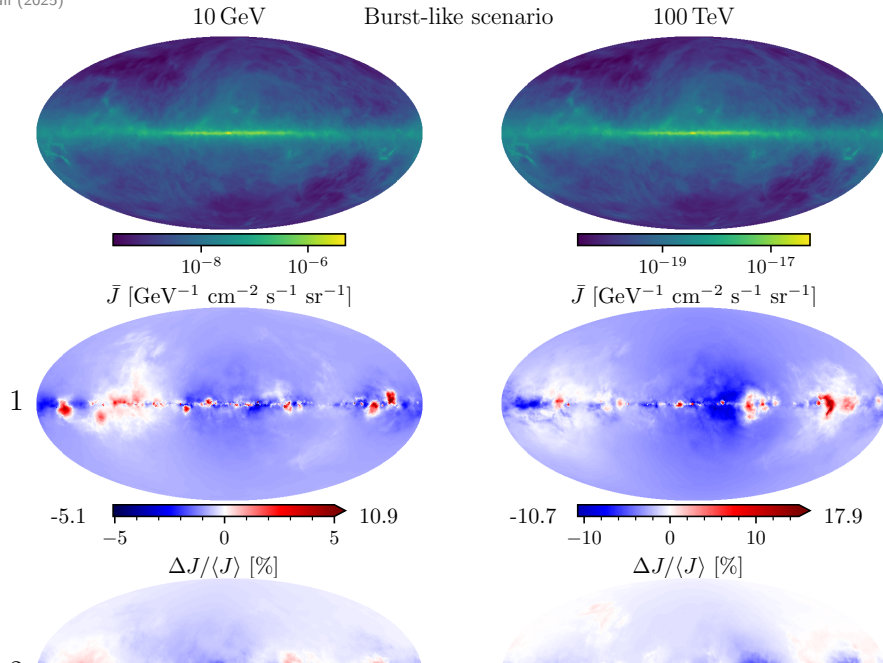
Stochastic diffuse emission

Mertsch & Stall (2025)



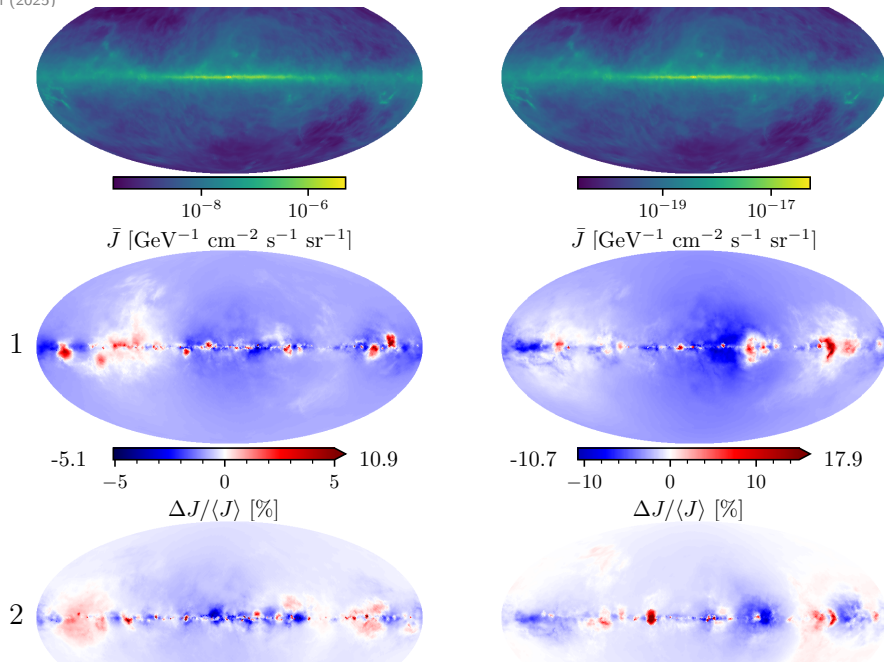
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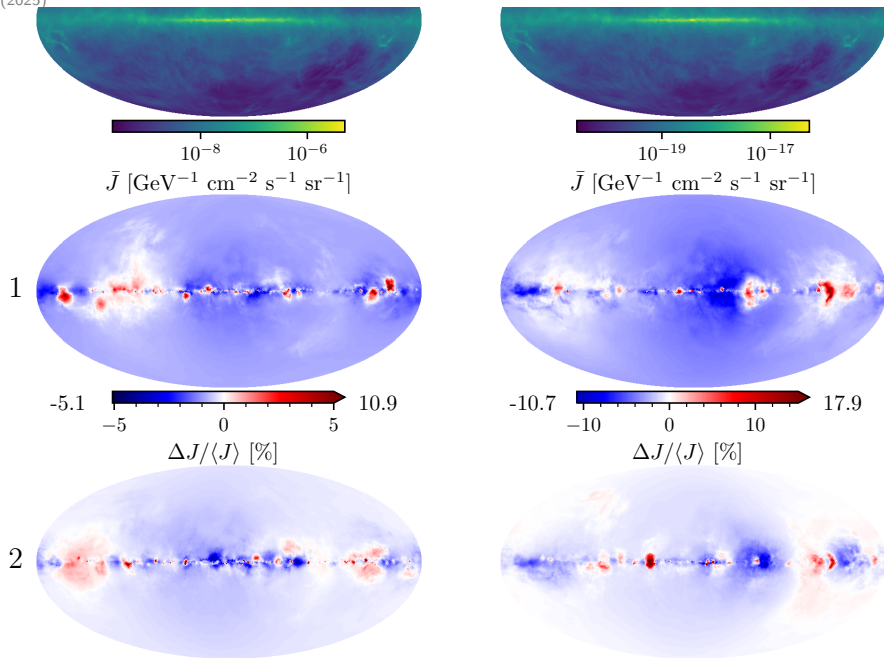
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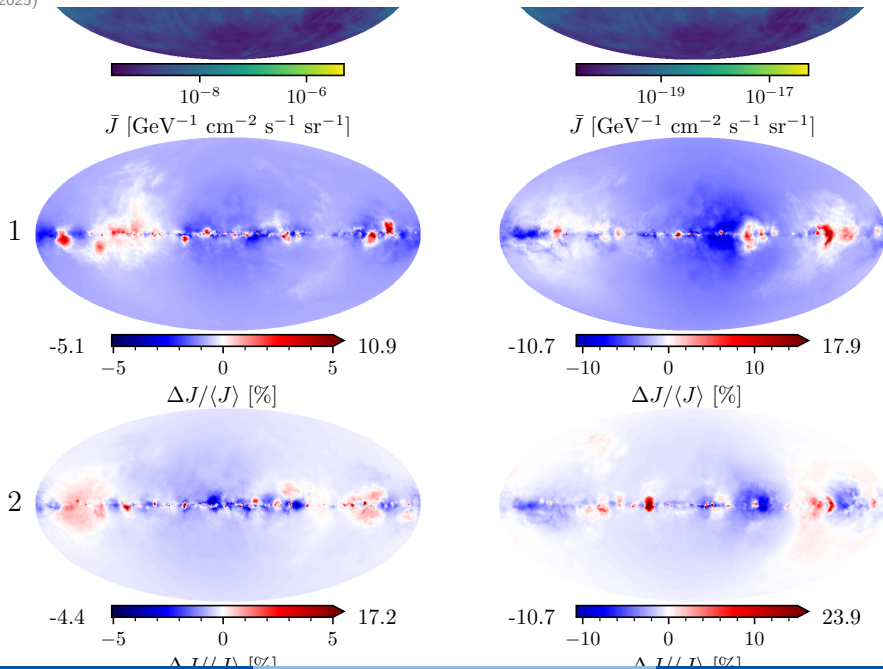
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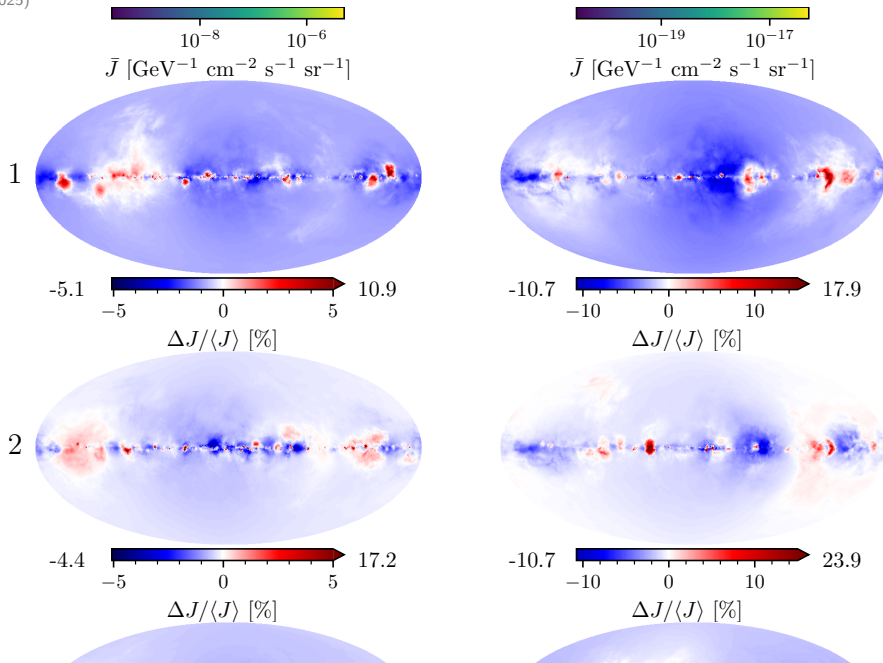
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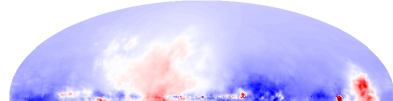
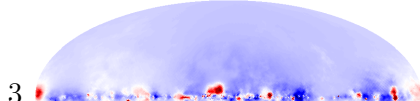
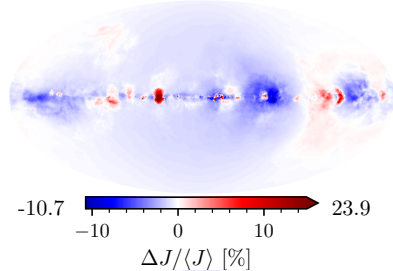
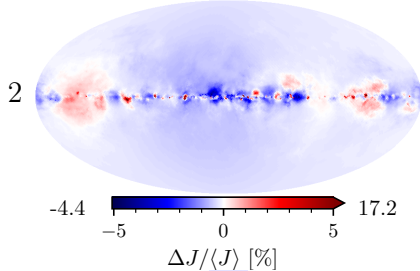
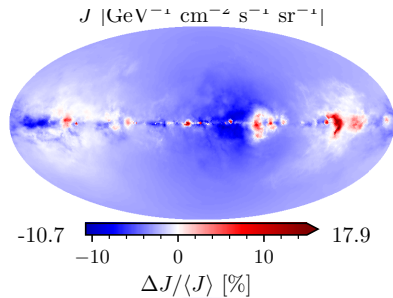
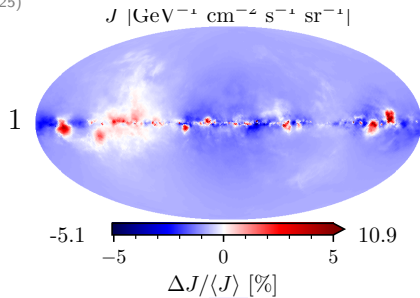
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Mertsch & Stall (2025)



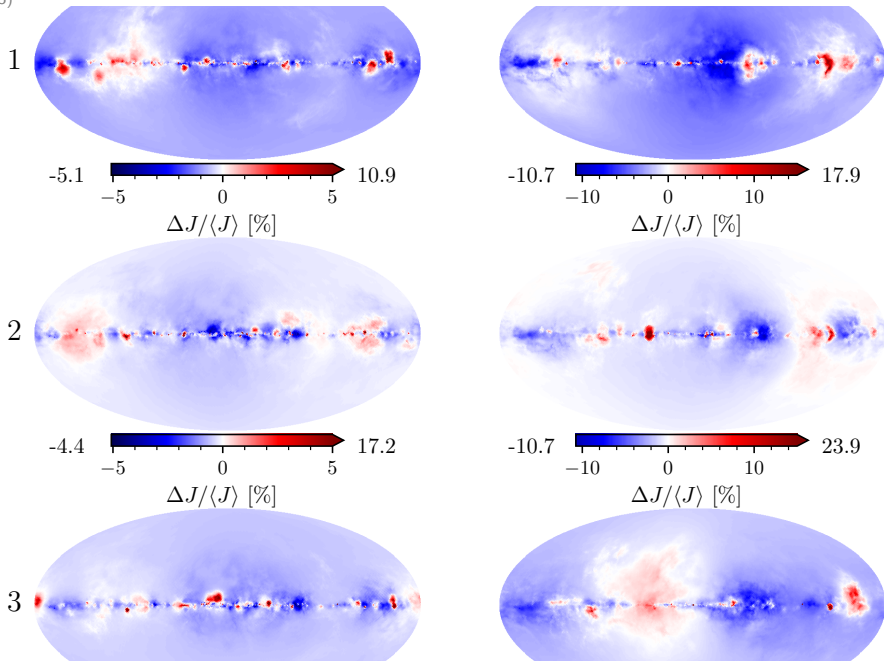
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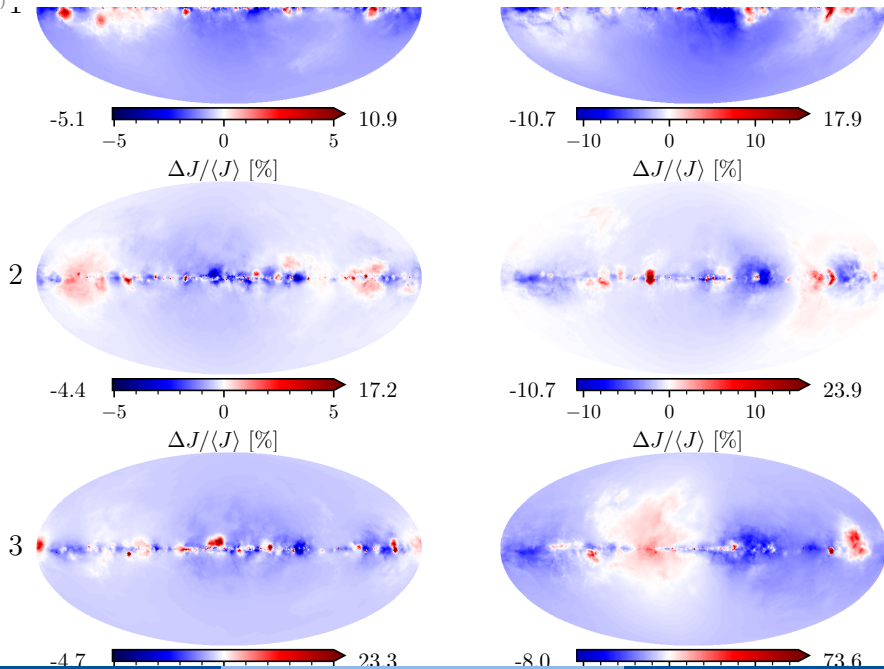
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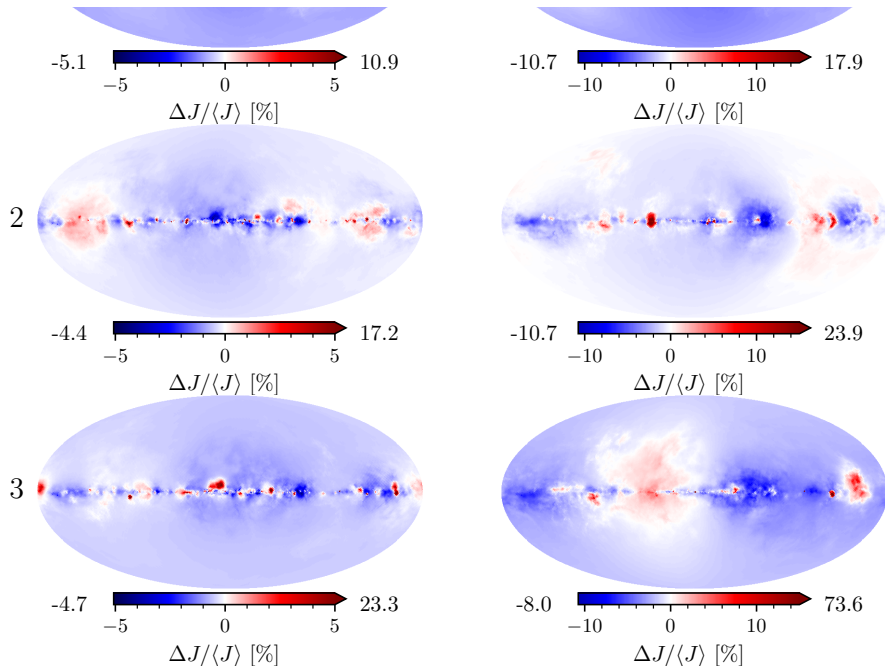
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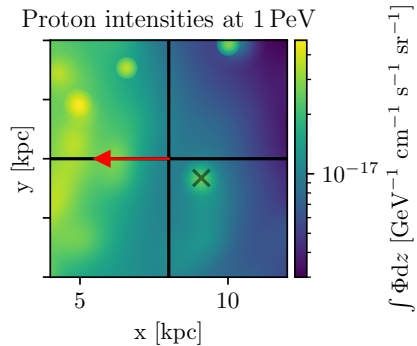
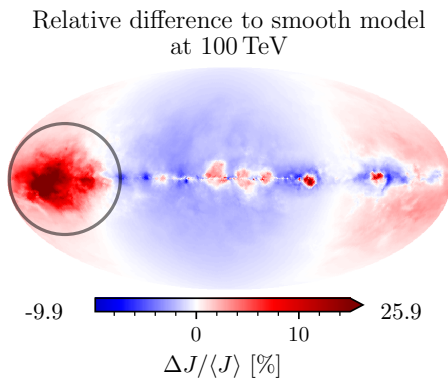
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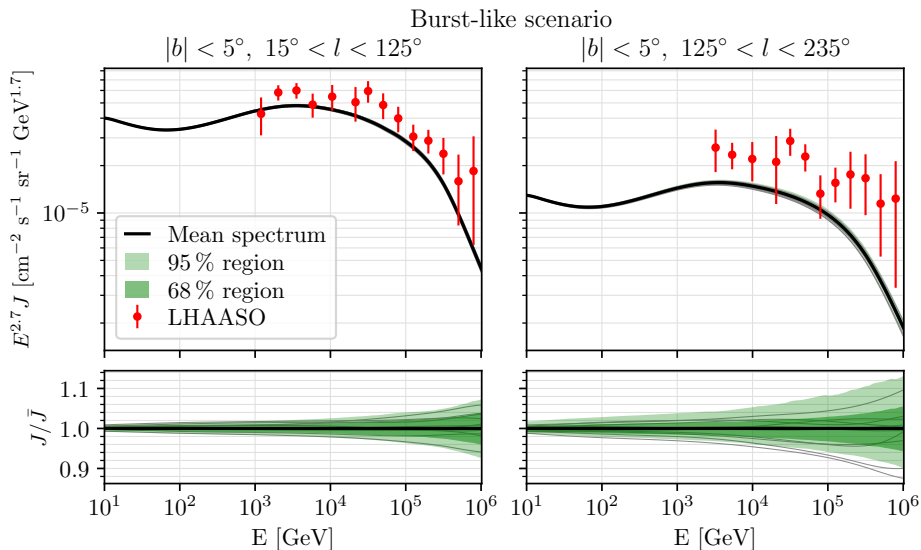
Sources manifest as deviations from the smooth model

Mertsch & Stall (2025)



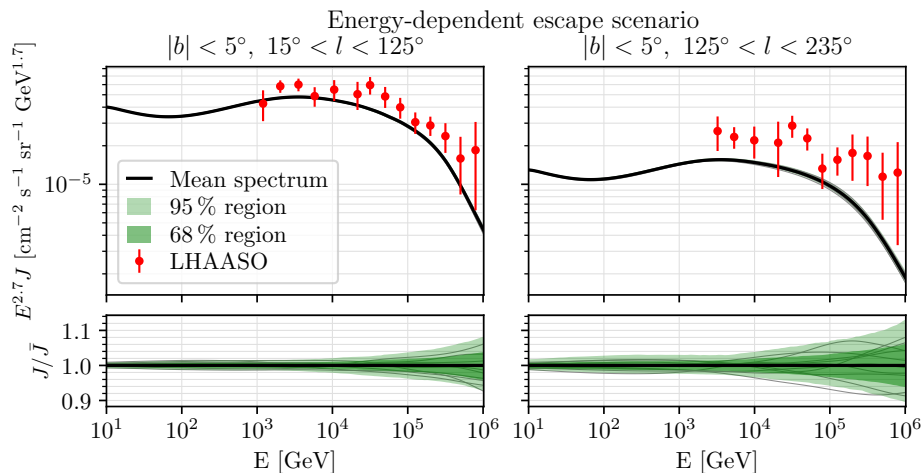
Deviations from the ensemble average can be sizeable

Mertsch & Stall (2025)



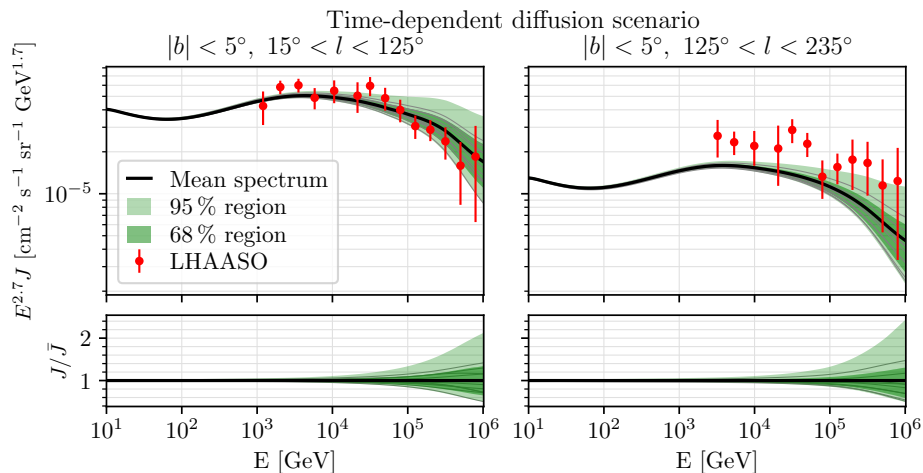
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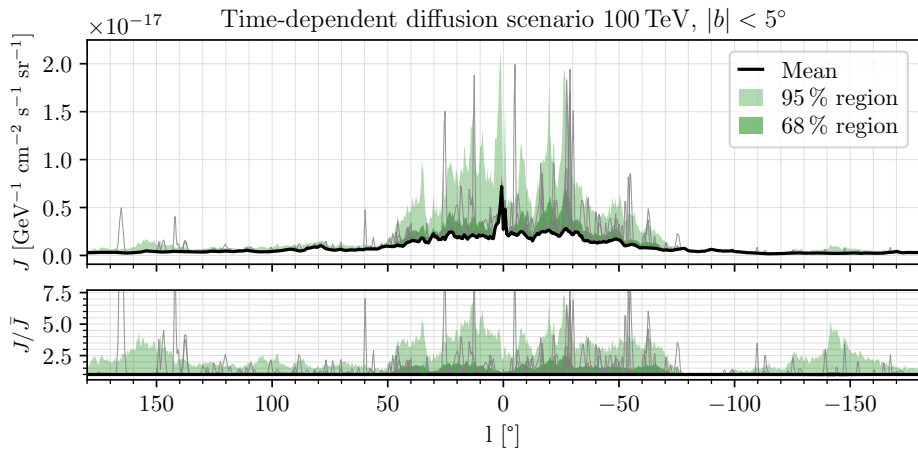
Deviations from the ensemble average can be sizeable

Mertsch & Stall (2025)



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

Mertsch & Stall (2025)





Strongly anchor in local CR data

- 1 Unresolved sources 😊



Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient 😞
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Outline

- ① Diffuse emission: Introduction
- ② Diffuse emission: The CRINGE model
- ③ Alternatives
 - Unresolved sources
 - Stochasticity
- ④ Sources
- ⑤ Conclusions

10th COSPA meeting: Cosmic Rays

Friday 4 Oct 2019, 09:30 → 17:00 Europa-Brussels

Solvay room, 5th floor NO (JULB)

Juan Antonio Aguilar-Sánchez (Universidad Libre de Bruxelles (ULB)), Ioana Codina Maris (ULB),
Simona Tosscano (Université Libre de Bruxelles (ULB))

Registration

Participants

Participants: Alessio Porcell, Arkya Sagha, Athina Misi, Axi Bhattacharya, Bob Ozyen, Daniela Mockler, Erik Ruckstuhl, Enrique Herrera Sanchez, Feras Halimeh, Giovanni Rossi, Krishna Kumar Anand

09:30 ~ 09:40 **Welcome**
Speaker: Jean-René Cadoret (LJMU) @ 10m Solvay room, 5th floor NO

09:40 ~ 10:30 **Indirect measurements of cosmic rays**
Speaker: Olivier Deligny (CERN) @ 10m Solvay room, 5th floor NO

10:30 ~ 11:00 **Cosmic ray origin and transport**
Speaker: Philipp Mertsch (RWTH Aachen) @ 10m Solvay room, 5th floor NO

11:30 Coffee break

Mertsch (2019)

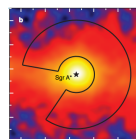
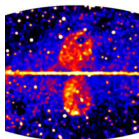
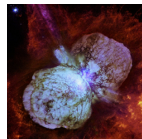
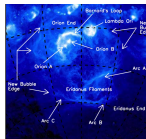
"What is accelerating to $E_{\text{knee}} \sim 3 \times 10^{15} \text{ eV}$?"

Supernova remnants

- $E_{\text{max}} \lesssim 10^{13...14} \text{ eV}$ for $B \sim B_{\text{ISM}}$
Lagage & Cesarsky (1983)
 - Amplify magnetic fields, non-resonant instability Bell (2004)
 - Saturation?
- Particle-in-cell simulations

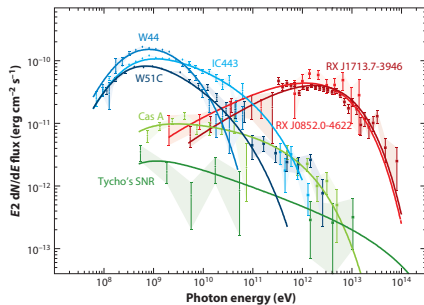
Other sources

- Superbubbles
- Supernovae before shock breakout
- Colliding wind binaries
- Pulsar wind nebulae
- the Fermi bubbles
- the Galactic centre



LHAASO disfavors supernova remnants as PeVatrons

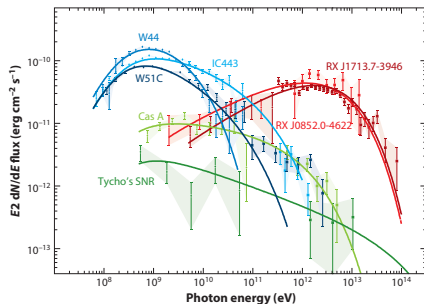
Funk et al. (2015)



- LHAASO Galactic plane survey
- Majority of sources: pulsars/pulsar wind nebulae
- Supernova remnants have very soft spectra

LHAASO disfavors supernova remnants as PeVatrons

Funk et al. (2015)

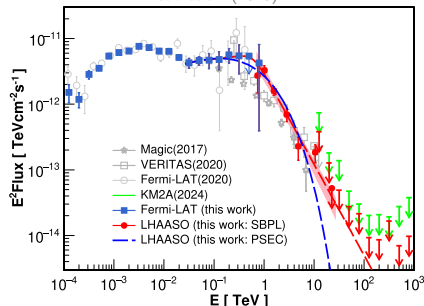


Cas A

- Very bright in radio
- 350 yr
- Possibly a PeVatron?

- LHAASO Galactic plane survey
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Cao et al. (2025)



Star cluster winds could be sources of $\simeq$ PeV cosmic rays

Adjusted from Peron (2025)



Young massive star clusters (YMSCs)

- Energetics:

$$\sum_{\text{gal. YMSCs}} P \approx \sum_{\text{gal. SNRs}} P$$

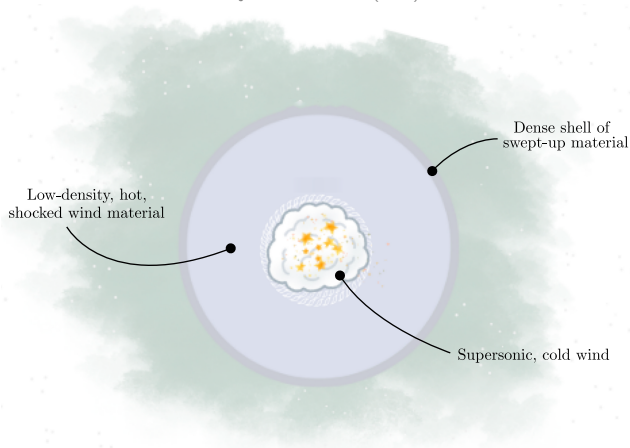
- Interaction of multiple stellar winds

→ turbulence

→ shock acceleration, stochastic acceleration

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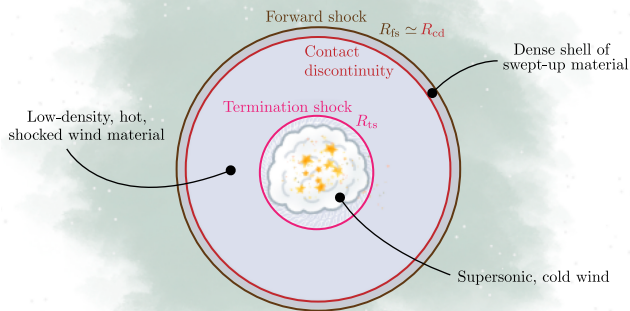
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E_{max} for YMSCs can reach PeV energies

- Estimate E_{max} by equating diffusion length with size of system:

$$\frac{\kappa}{U_{\text{sh}}} \simeq R_{\text{ts}}$$

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$$\text{Kolmogorov : } E_{\max} \simeq 1.2 \left(\frac{\eta_B}{0.1} \right)^{\frac{1}{2}} \left(\frac{\dot{M}}{10^{-4} M_{\odot} \text{ yr}^{-1}} \right)^{-\frac{3}{4}} \left(\frac{L_w}{10^{39} \text{ erg s}^{-1}} \right)^{\frac{37}{20}} \left(\frac{\rho_0}{20 m_p \text{ cm}^{-3}} \right)^{-\frac{3}{5}} \left(\frac{t_{\text{age}}}{3 \text{ Myr}} \right)^{\frac{4}{5}} \left(\frac{L_{\text{inj}}}{2 \text{ pc}} \right)^{-2} \text{ PeV},$$

$$\text{Kraichnan : } E_{\max} \simeq 2.84 \left(\frac{\eta_B}{0.1} \right)^{\frac{1}{2}} \left(\frac{\dot{M}}{10^{-4} M_{\odot} \text{ yr}^{-1}} \right)^{-\frac{5}{10}} \left(\frac{L_w}{10^{39} \text{ erg s}^{-1}} \right)^{\frac{13}{10}} \left(\frac{\rho_0}{20 m_p \text{ cm}^{-3}} \right)^{-\frac{3}{10}} \left(\frac{t_{\text{age}}}{3 \text{ Myr}} \right)^{\frac{2}{5}} \left(\frac{L_{\text{inj}}}{2 \text{ pc}} \right)^{-1} \text{ PeV},$$

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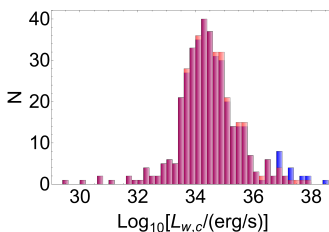
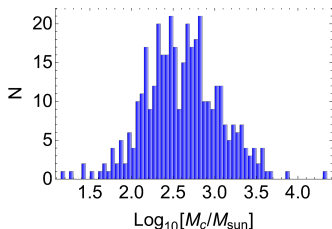
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Celli et al. (2024)

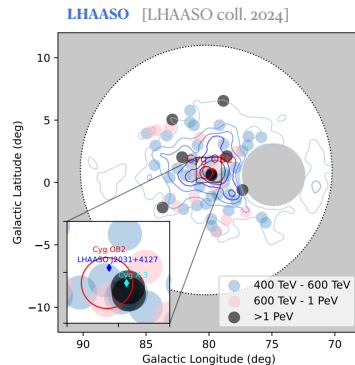
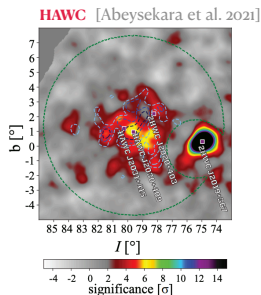
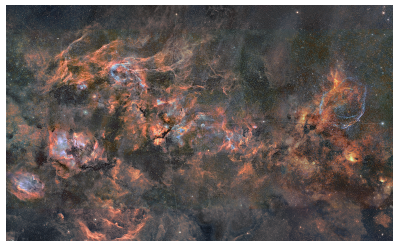
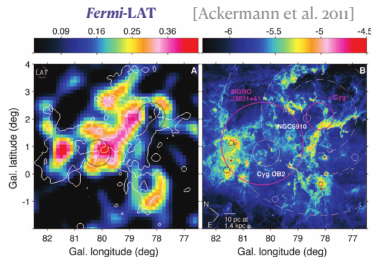
YMSCs as gamma-ray sources I

Peron (2025)

How many do we know?

Cygnus Region

- Complex Star forming region: OB associations (OB2, but also OB1...9), PSRs, SNRs, background MQs (Cyg X-3)
- Hadronic emission up to PeV!

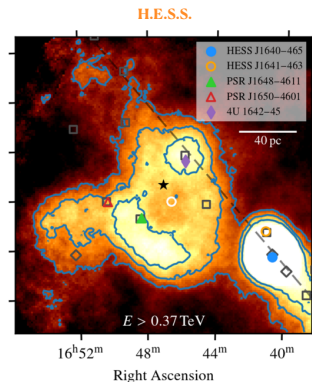


Giada Peron - ICRC 2025 - 18/07/2025

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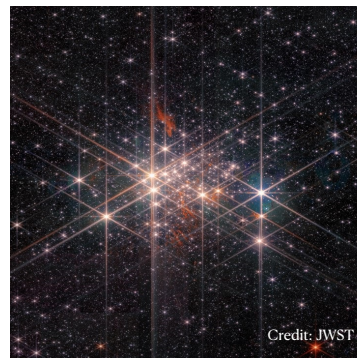
How many do we know?

Westerlund 1



[Aharonian et al. 2022]

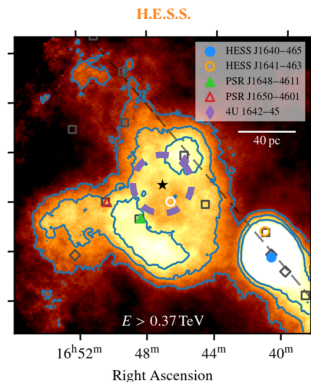
- Most powerful SC in the Galaxy
- ~ 4-5 Myr old
- Contains ~20 WRs !
- No dense surrounding gas
- Emission predominantly *leptonic* [Härer et al. 2023]



YMSCs as gamma-ray sources II

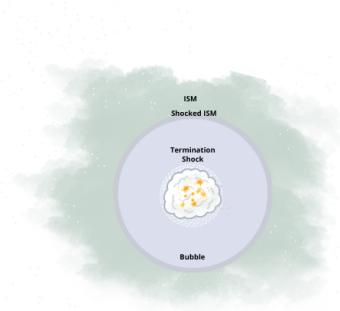
Peron (2025)

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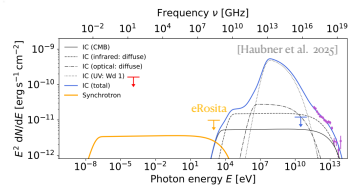
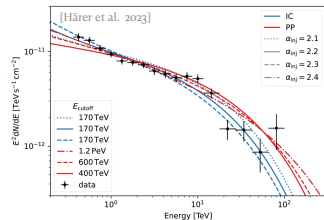
[Aharonian et al. 2022]

Westerlund 1



Accelerated electrons at the edge
of the TS interacting with high
radiation field of the cluster

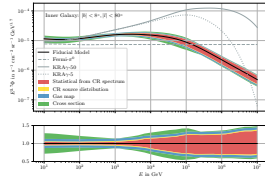
[Härer et al. 2023]



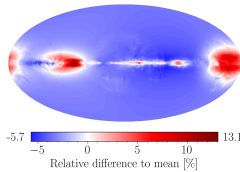
Outline

- ① Diffuse emission: Introduction
- ② Diffuse emission: The CRINGE model
- ③ Alternatives
 - Unresolved sources
 - Stochasticity
- ④ Sources
- ⑤ Conclusions

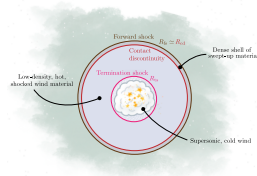
Summary



Modelling of high-energy diffuse emission
→ room for improvement



Stochastic sources
→ probabilistic predictions



Star cluster winds as new source
of cosmic rays and gamma-rays

Outline

⑥ Diffuse emission: Introduction

⑦ Alternatives

- Spatially varying diffusion coefficient
- Advection

⑧ CREDIT

Simplified 1D model

- 1D approximation; homogeneous diffusion, advection

$$\frac{\partial \psi_j}{\partial t} - \kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(v n_{\text{gas}}(z) \sigma_j + \frac{1}{\tau_j} \right) \psi_j = q_j(z) + \sum_{j < k} \left(v n_{\text{gas}}(z) \sigma_{k \rightarrow j} + \frac{1}{\tau_{k \rightarrow j}} \right) \psi_k$$

Simplified 1D model

- 1D approximation; homogeneous diffusion, advection

$$\frac{\partial \psi_j}{\partial t} - \kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(\underbrace{v n_{\text{gas}}(z) \sigma_j}_{\text{in}} + \frac{1}{\tau_j} \right) \psi_j = \underbrace{q_j(z)}_{\text{source}} + \sum_{j < k} \left(\underbrace{v n_{\text{gas}}(z) \sigma_{k \rightarrow j}}_{\text{out}} + \frac{1}{\tau_{k \rightarrow j}} \right) \psi_k$$

- Steady-state

• Infinitely thin disk of half-height h

$$-\kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(2 \underbrace{h \delta(z) n_{\text{gas}}(0)}_{\text{in}} v \sigma_j + \frac{1}{\tau_j} \right) \psi_j = \underbrace{2 h \delta(z) q_j(0)}_{\text{source}} + \sum_{j < k} \left(2 \underbrace{h \delta(z) n_{\text{gas}}(0)}_{\text{out}} v \sigma_{k \rightarrow j} + \frac{1}{\tau_{k \rightarrow j}} \right) \psi_k$$

Simplified 1D model

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Solution (without advection or decay)

$$\psi_j(0, \mathcal{R}) = \frac{h \left(\underbrace{q_j(0, \mathcal{R})}_{\text{source}} + \sum_{k > j} v n_{\text{gas}}(0) \sigma_{k \rightarrow j} \psi_k \right)}{\left(h v n_{\text{gas}}(0) \sigma_j + \frac{\kappa(\mathcal{R})}{z_{\text{max}}} \right)}$$

Outline

⑥ Diffuse emission: Introduction

⑦ Alternatives

- Spatially varying diffusion coefficient
- Advection

⑧ CREDIT

Alternatives



Strongly anchor in local CR data

- 1 Unresolved sources 😊

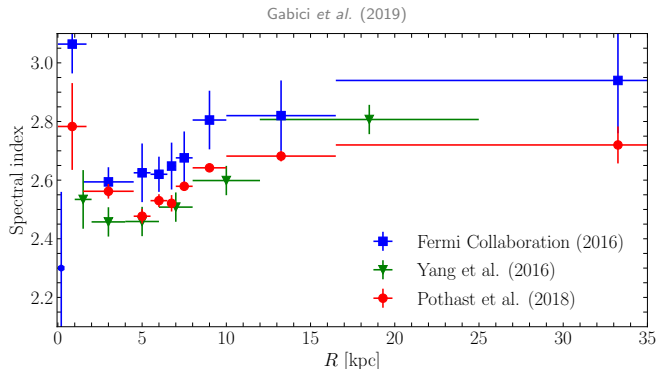


Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient
- 3 Advection
- 4 Stochasticity

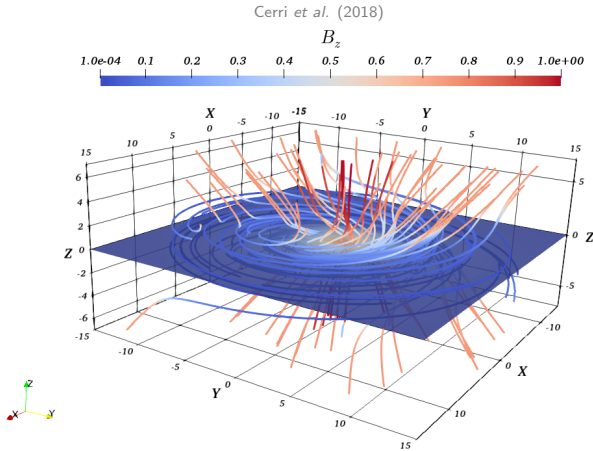
Spectral hardening

- Diffuse intensity:
$$J(l, b, E) = \frac{1}{4\pi} \int_0^\infty ds \underbrace{\sum_{m,n} \int_E^\infty dE' \frac{d\sigma_{m,n}}{dE}(E', E) J_m(\mathbf{r}, E') n_{\text{gas},n}(\mathbf{r})}_{\varepsilon(E, \mathbf{r})} \Big|_{\mathbf{r}=\mathbf{r}(l,b,s)}$$
- Assume axisymmetry: $\varepsilon(E, r) \propto E^{-\gamma(r)}$



- Realised if $\kappa(E, r) \propto E^{\delta(r)}$ and if $\delta(r)$ decreases with r
- E.g., $q(E) \propto E^{-\gamma_{\text{src}}} = E^{-2.2}$; locally: $\delta = 0.6 \Rightarrow \gamma \simeq \gamma_{\text{src}} + \delta = 2.8$;
in Galactic centre: $\delta = 0.2 \Rightarrow \gamma = 2.4$

Spectral hardening



Inner galaxy

- B-field mostly **vertical**

$$\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial z} \kappa_{\parallel} \frac{\partial \psi}{\partial z} \simeq \dots$$

- Spectrum determined by $\kappa_{\parallel}$

Locally

- B-field mostly **parallel** to plane

$$\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial z} \kappa_{\perp} \frac{\partial \psi}{\partial z} \simeq \dots$$

- Spectrum determined by $\kappa_{\perp}$

Could work if $\delta_{\parallel} < \delta_{\perp}$

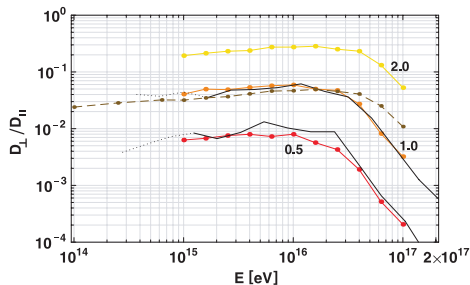
Different scaling of $\kappa_{\parallel}$ and $\kappa_{\perp}$

- 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

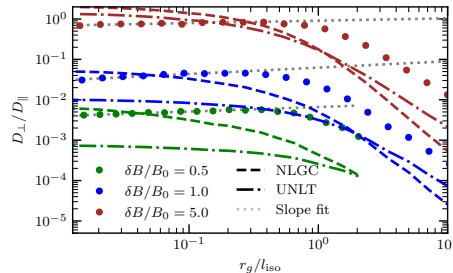
- Naive expectation:

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

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



DeMarco *et al.*
(2007)



Dundovic *et al.*
(2020)

Test particle simulations

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



Results depend on:

- 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:

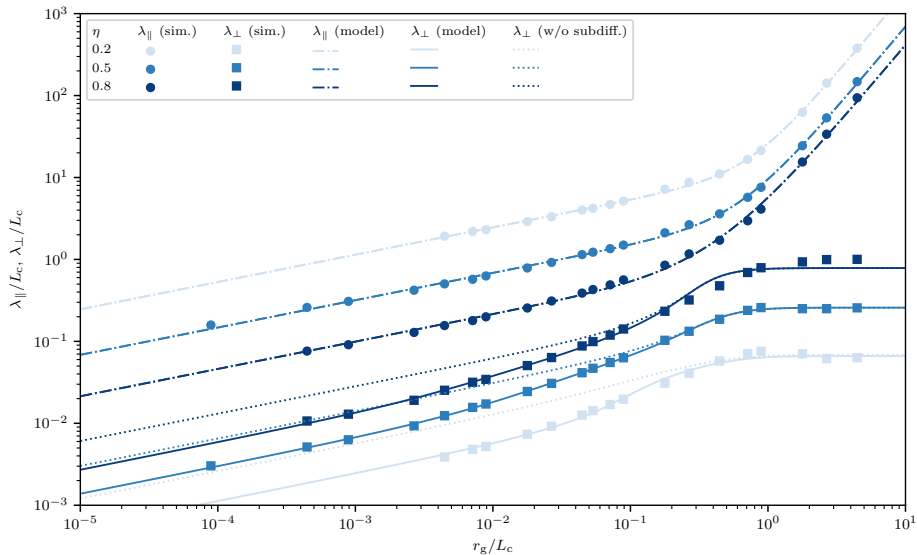
$$d_{\parallel}(t) \equiv \frac{1}{2} \frac{d}{dt} \langle (\Delta z)^2 \rangle$$

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

- Reduced time: Ωt
- Reduced rigidity: $\frac{r_g}{L_c}$
- Turbulence level: $\eta = \frac{\delta B^2}{B_0^2 + \delta B^2}$

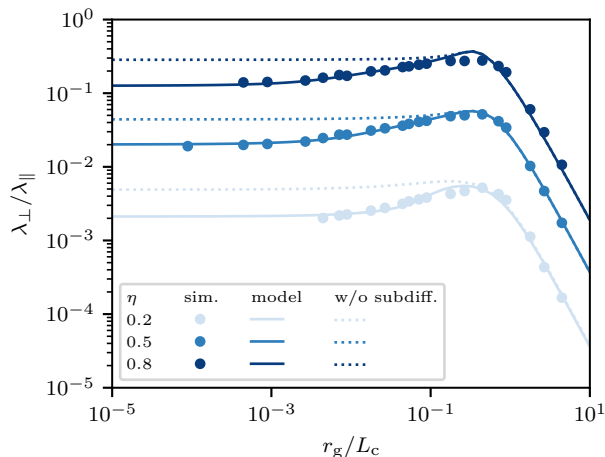
Mean-free paths

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



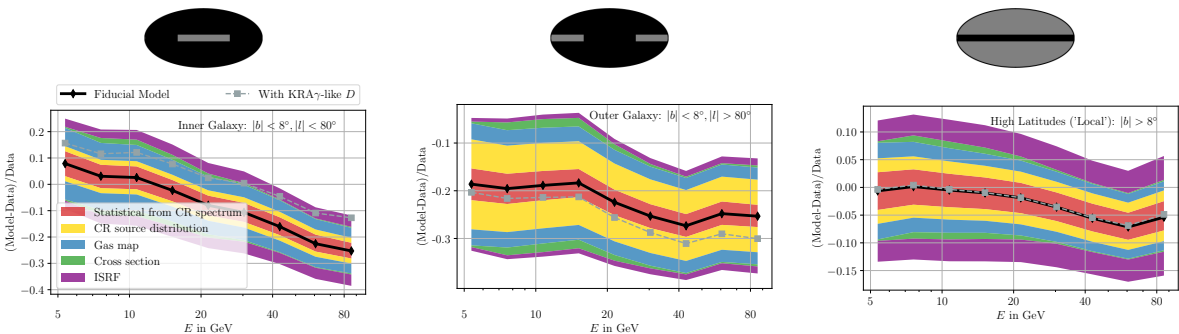
Ratio of mean-free paths

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



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

(More details → [Appendix](#))



Alternatives



Strongly anchor in local CR data

- 1 Unresolved sources 😊



Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient
- 3 Advection
- 4 Stochasticity



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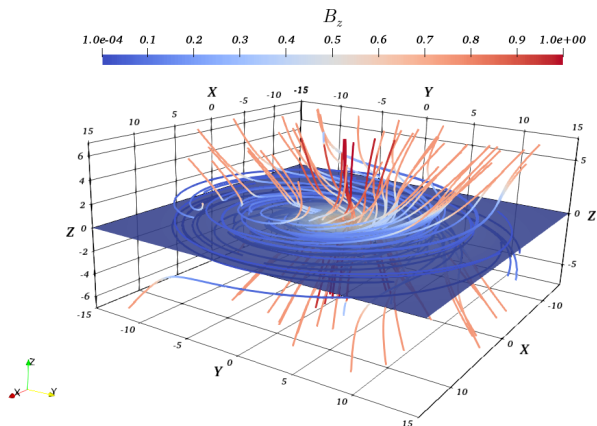


Allow for variation from local CR data

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Advection in Galactic Centre

Cerri et al. (2018)



Inner galaxy

- B-field mostly **vertical**

$$\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial z} \kappa_{\parallel} \frac{\partial \psi}{\partial z} \simeq \dots$$

- Spectrum determined by $\kappa_{\parallel}$

Locally

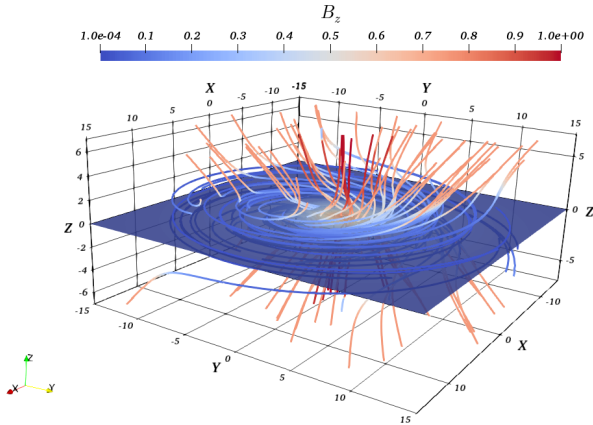
- B-field mostly **parallel** to plane

$$\frac{\partial \psi}{\partial t} - \frac{\partial}{\partial z} \kappa_{\perp} \frac{\partial \psi}{\partial z} \simeq \dots$$

- Spectrum determined by $\kappa_{\perp}$

Advection in Galactic Centre

Cerri et al. (2018)



Inner galaxy

- Strong galactic wind

$$\frac{\partial \psi}{\partial t} - U(z) \frac{\partial \psi}{\partial z} \simeq \dots$$

- Escape rate independent of energy

Locally

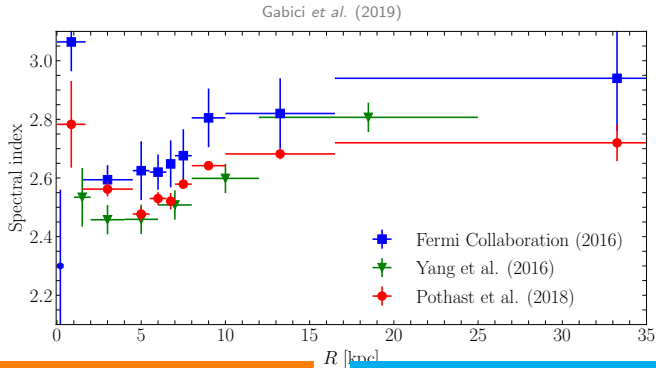
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Spectral hardening (through advection)

- Diffuse intensity:
$$J(l, b, E) = \frac{1}{4\pi} \int_0^\infty ds \underbrace{\sum_{m,n} \int_E^\infty dE' \frac{d\sigma_{m,n}}{dE}(E', E) J_m(\mathbf{r}, E') n_{\text{gas},n}(\mathbf{r})}_{\varepsilon(E, \mathbf{r})} \Big|_{\mathbf{r}=\mathbf{r}(l,b,s)}$$
- Assume axisymmetry: $\varepsilon(E, r) \propto E^{-\gamma(r)}$



Galactic Centre

$$q(E) \propto E^{-\gamma_{\text{src}}} = E^{-2.2} \text{ and } U = \text{const.}$$

$$\Rightarrow \psi(E) \propto \frac{q(E)}{U} \propto E^{-\gamma_{\text{src}}} = E^{-2.2}$$

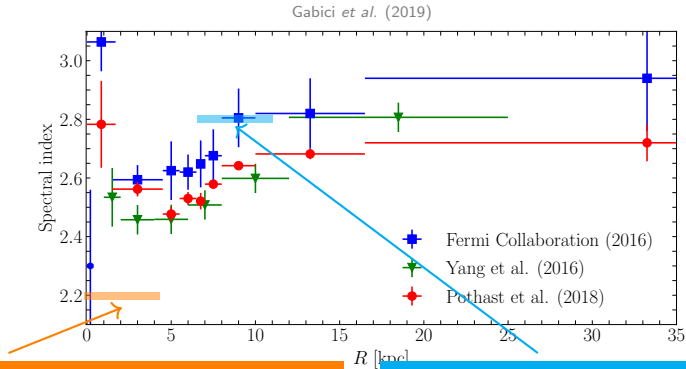
Locally

$$q(E) \propto E^{-\gamma_{\text{src}}} = E^{-2.2} \text{ and } \kappa \propto E^{\delta=0.6}$$

$$\Rightarrow \psi(E) \propto \frac{q(E)}{\kappa(E)} \propto E^{-\gamma_{\text{src}}-\delta} = E^{-2.8}$$

Spectral hardening (through advection)

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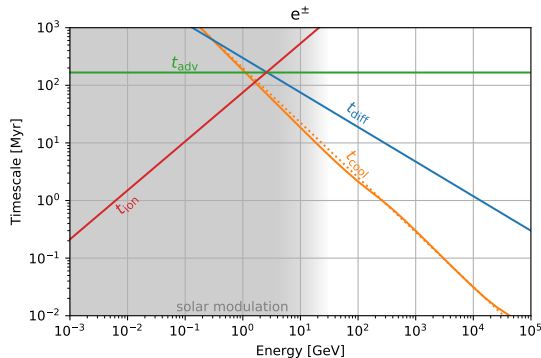
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Time scales

Time scales:



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



Strongly anchor in local CR data

- 1 Unresolved sources 😊



Allow for variation from local CR data

- 2 Spatially varying diffusion coefficient 😞
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Outline

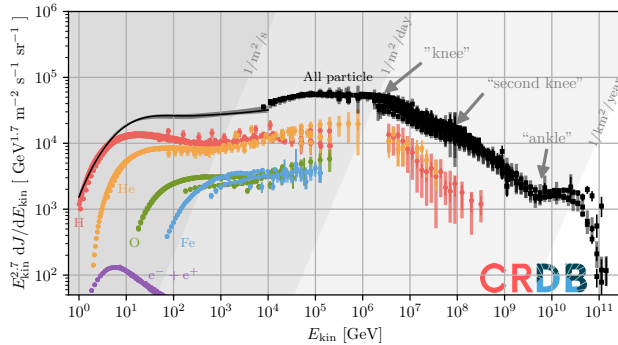
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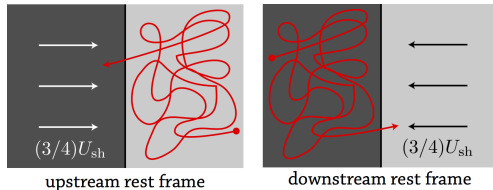
Galactic sources should accelerate to E_{knee} , probably via shock acceleration



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

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

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



Small energy gain ΔE , little particle loss ΔN per cycle

$$\left. \begin{aligned} \frac{\Delta E}{E} &\propto \frac{U_{\text{sh}}}{c} \\ \frac{\Delta N}{N} &\propto \frac{U_{\text{sh}}}{c} \end{aligned} \right\} \Rightarrow \frac{dN}{dE} \propto E^{-2}$$

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

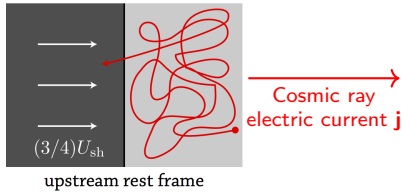
$$\Rightarrow E_{\text{max,b}} \simeq 100 \text{ TeV} \ll E_{\text{knee}}$$

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 **B**-field to $B \simeq 100 \mu\text{G}$

The Bell instability can amplify B-fields

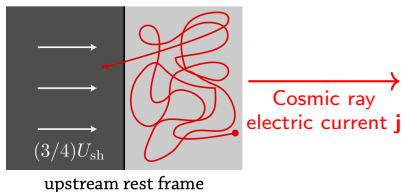
Bell (2004)



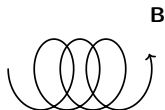
- If B -field too weak, particles escape
- Electric current $\mathbf{j}$
- Waves modes unstable in the presence of current $\mathbf{j}$

The Bell instability can amplify B-fields

Bell (2004)



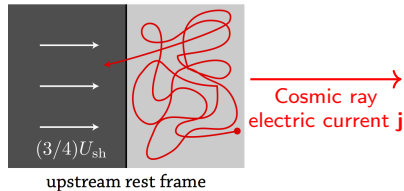
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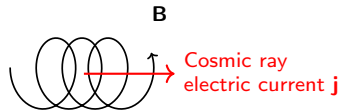
- CRs with gyroradius r_g tied to field lines
- Instability saturates once $\lambda \sim r_g$
- B -field density satisfies $\varepsilon_B \sim \frac{U_{sh}}{c} \varepsilon_{CR}$

The Bell instability can amplify B-fields

Bell (2004)



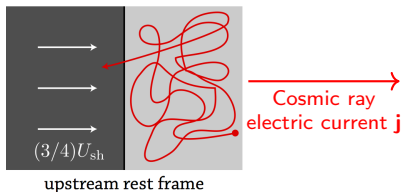
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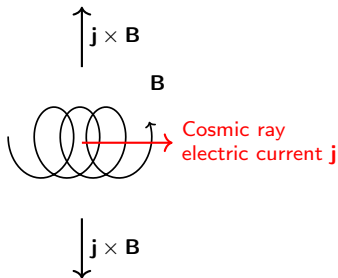
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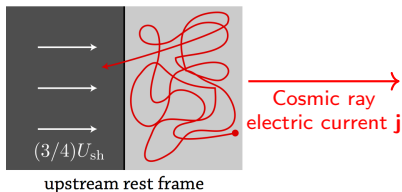
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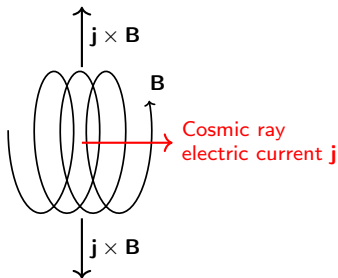
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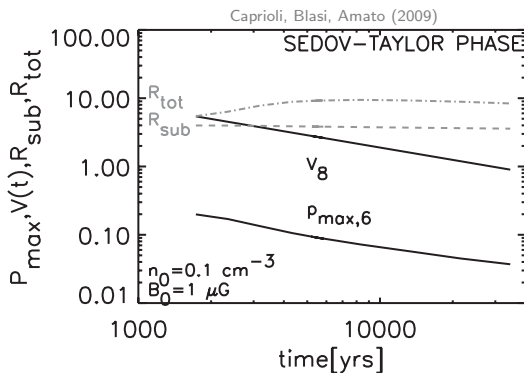
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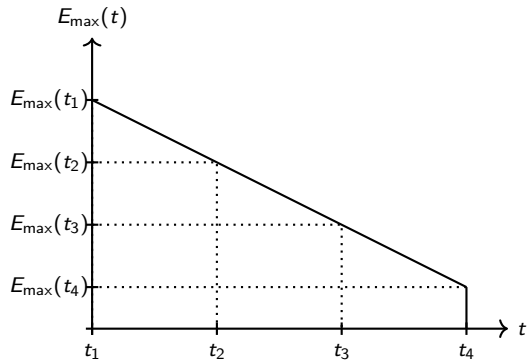
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The highest CR energies can be achieved at start of Sedov-Taylor phase

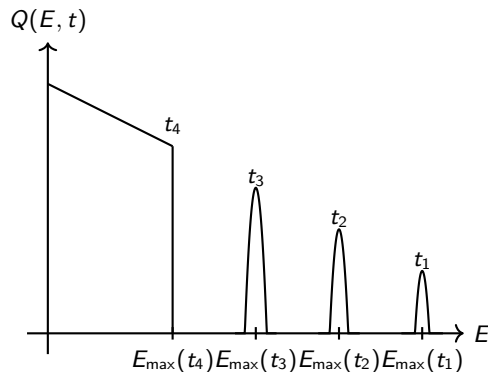
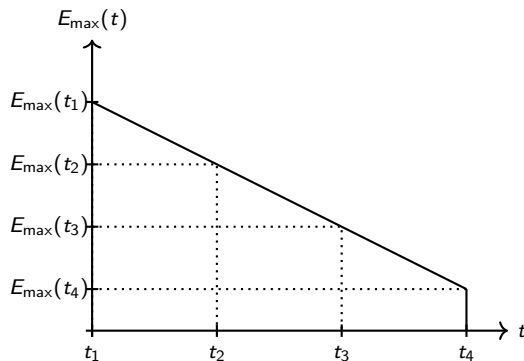
- Shock speed U_{sh} enters into growth rate γ through escape current j
 - Saturation field $B \propto U_{\text{sh}}^{3/2}$
 - $U_{\text{sh}} \propto t_{\text{age}}^{-3/5}$
- $E_{\text{max}} \propto U_{\text{sh}}^2 B t_{\text{age}} \propto t_{\text{age}}^{-11/10}$



Time-dependence of B-field amplification determines CR escape



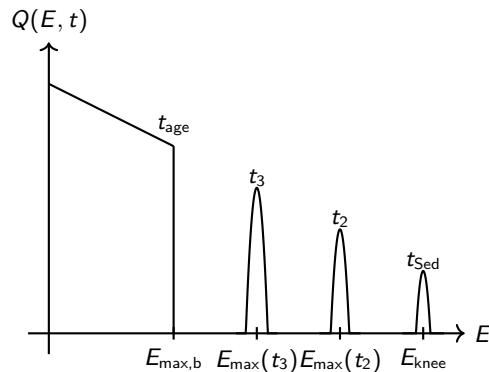
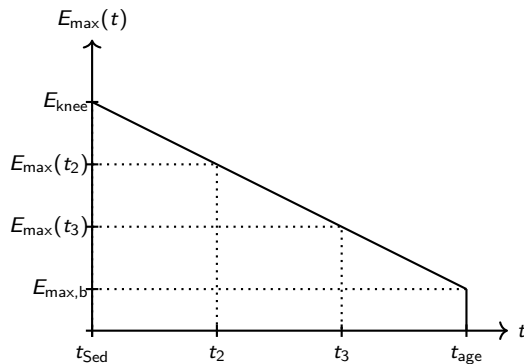
Time-dependence of B-field amplification determines CR escape



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

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

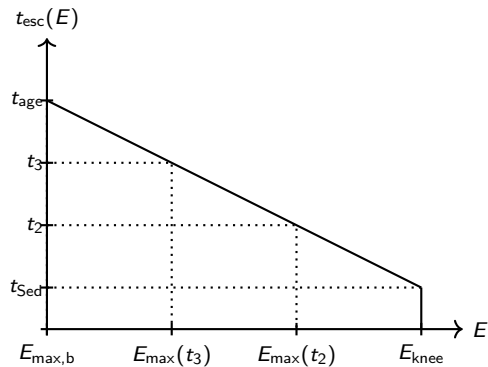
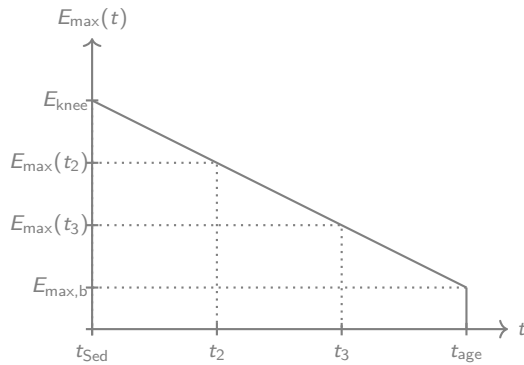
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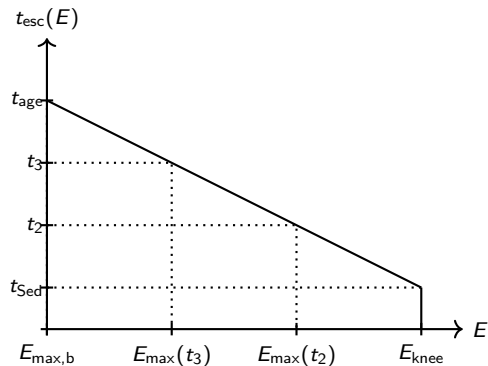
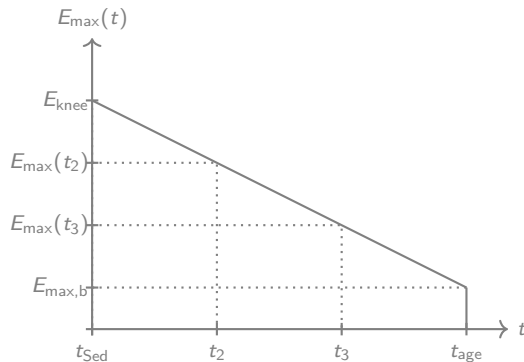
also Gabici, Aharonian, Casanova (2009); Caprioli, Blasi, Amato (2010);
Blasi and Amato (2012); Thoudam and Hörandel (2012)

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

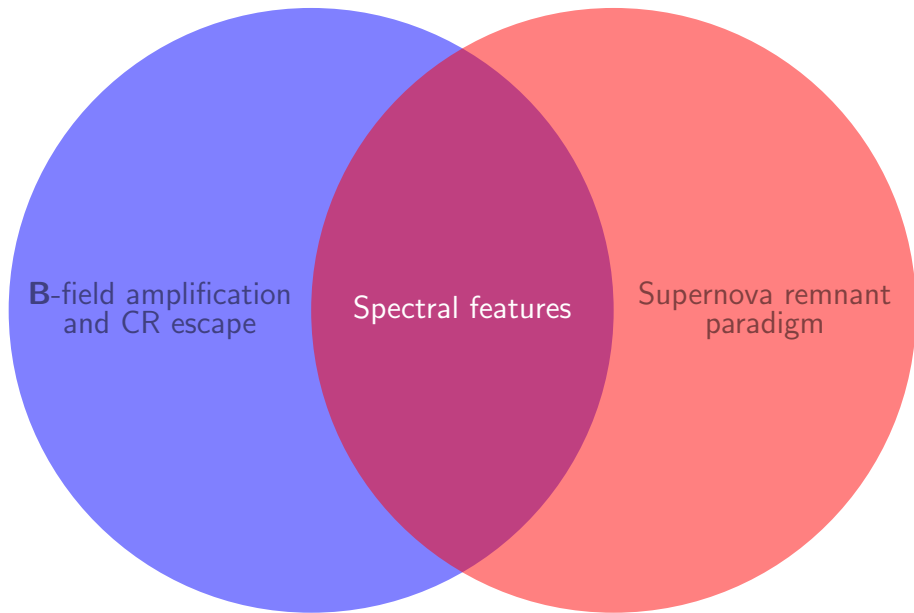
Time-dependence of B-field amplification determines CR escape



Time-dependence of B-field amplification determines CR escape

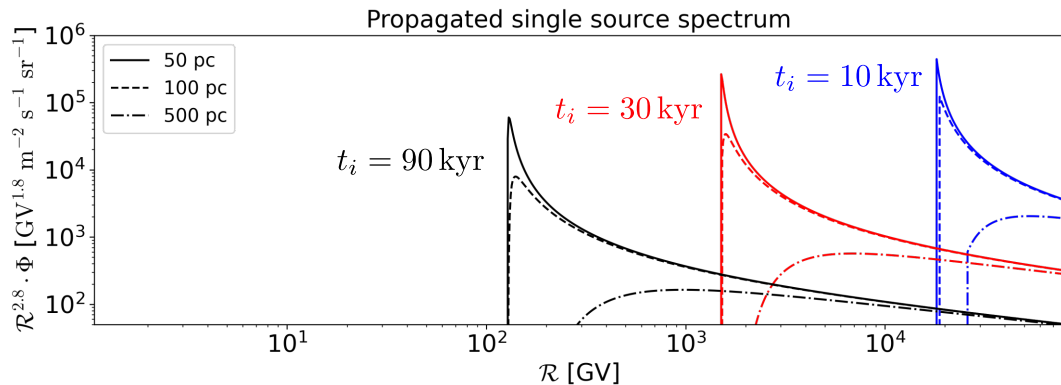


**Cosmic-Ray Energy-Dependent Injection Time
(CREDIT) scenario**



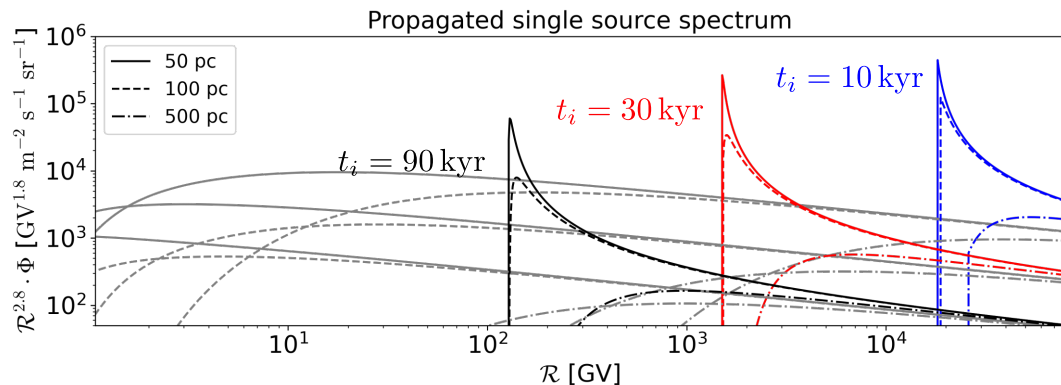
The Green's function has narrow spectral features

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



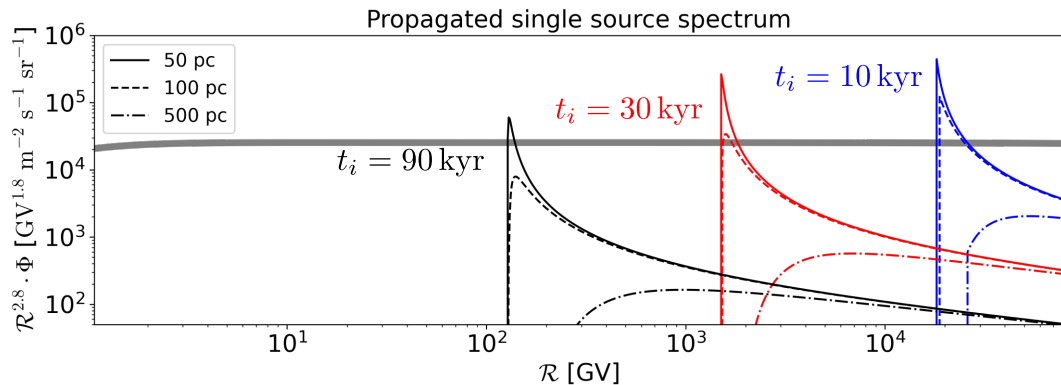
The Green's function has narrow spectral features

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



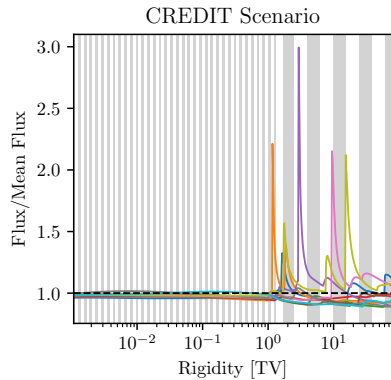
The Green's function has narrow spectral features

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



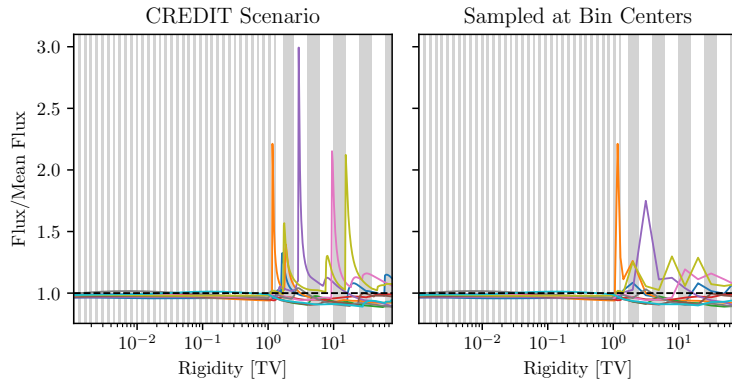
CREDIT scenario predicts dramatic spectral features

Stall, Loo, Mertsch, arXiv:2409.11012



CREDIT scenario predicts dramatic spectral features

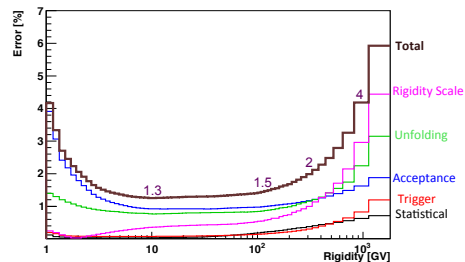
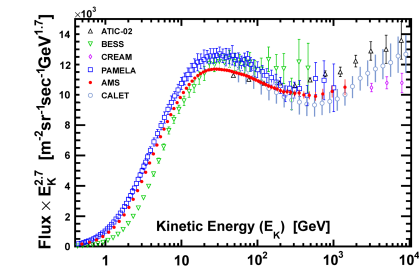
Stall, Loo, Mertsch, arXiv:2409.11012



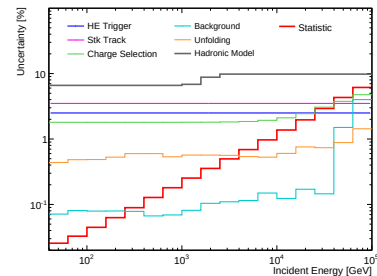
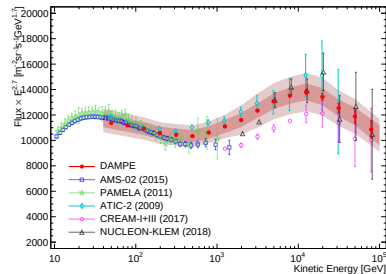
Modern proton data offer unprecedented accuracy

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, arXiv:2409.11012

