News on theoretical aspects of cosmic ray physics

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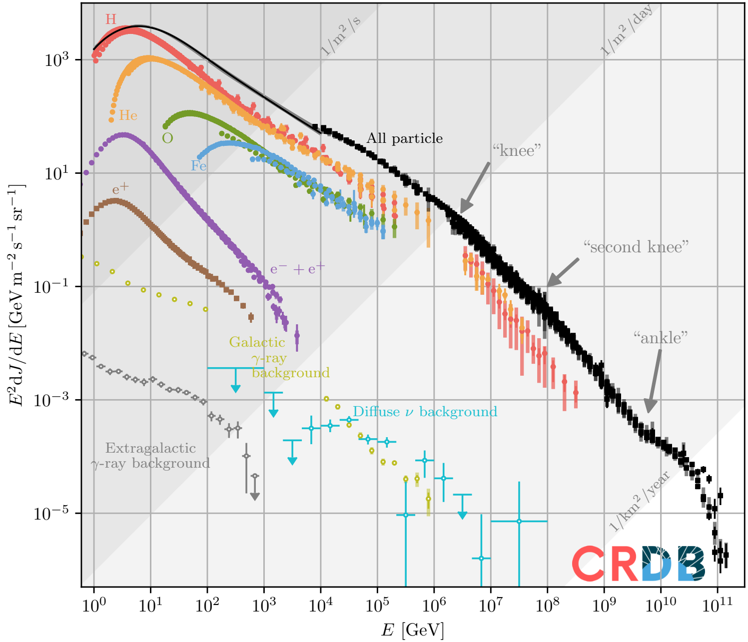
The cosmic ray spectrum



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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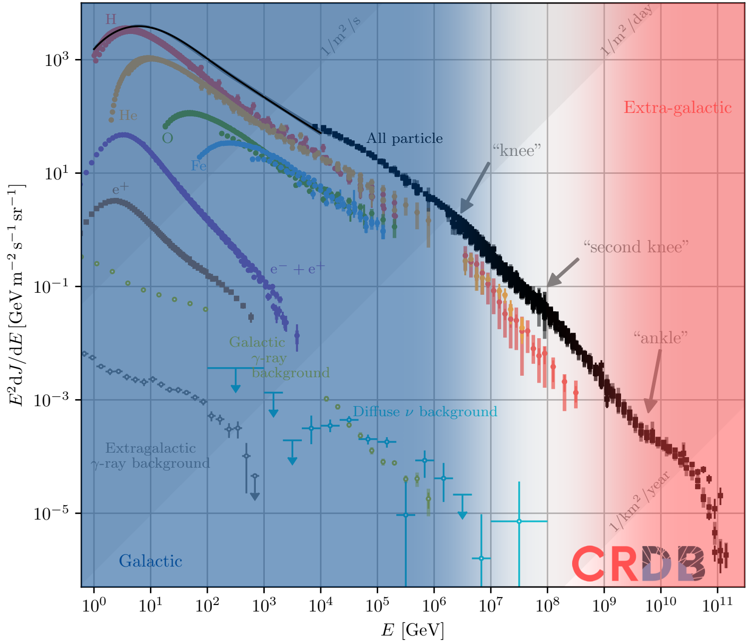

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Why are cosmic rays interesting?

Cosmic ray origin

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

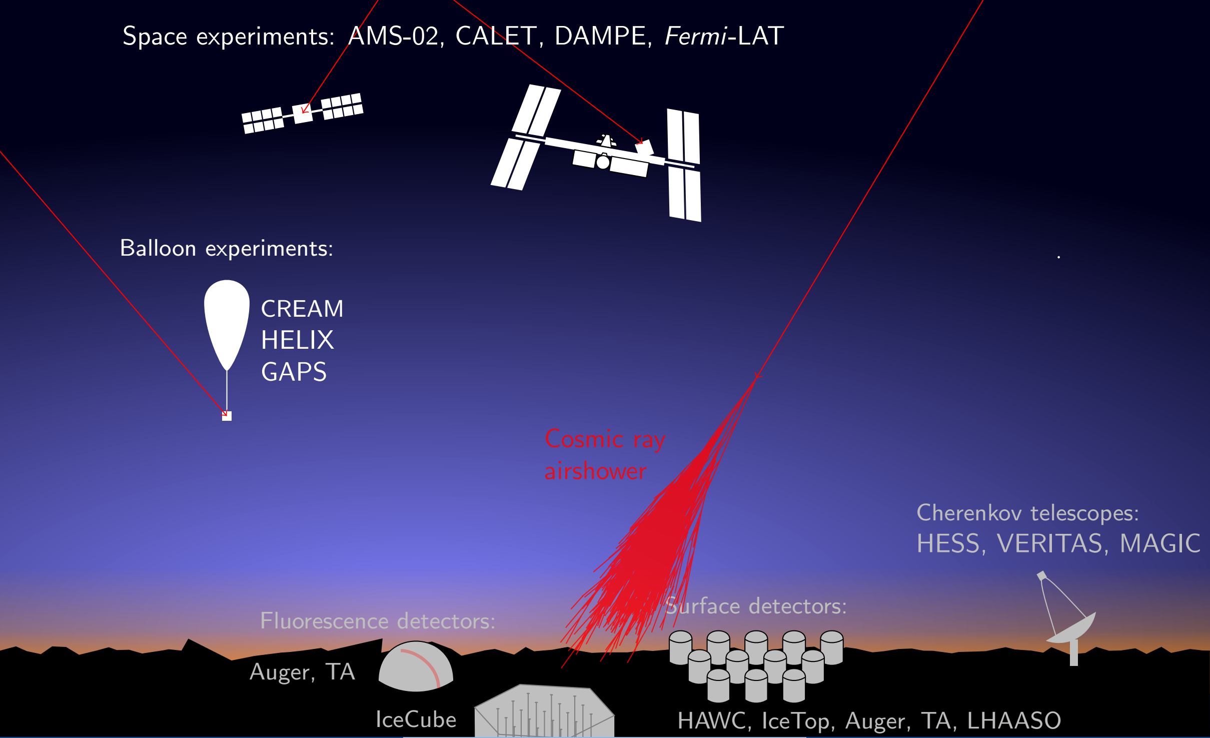
Ingredient

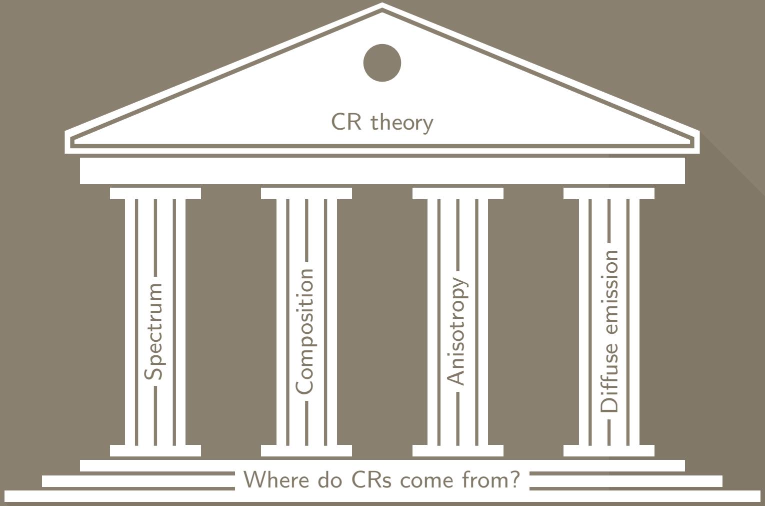
Cosmic rays . . .

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

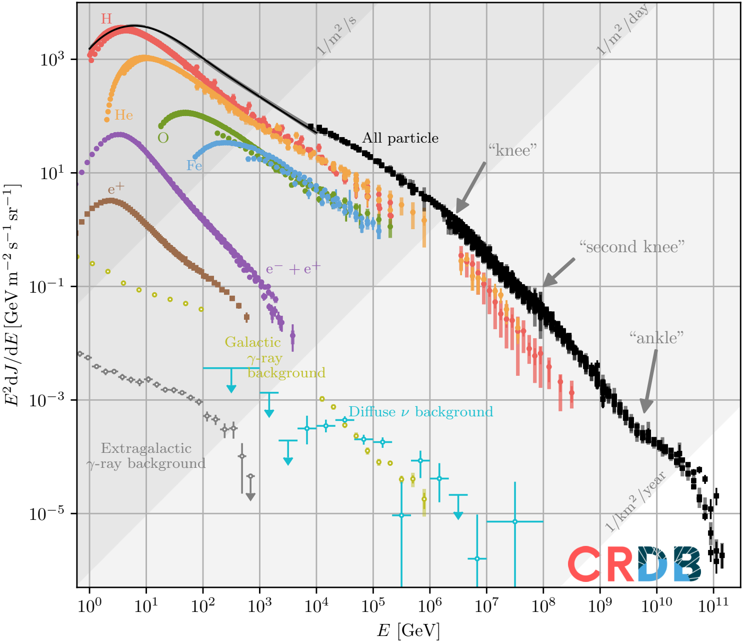
Exotic probe

- 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?

The cosmic ray spectrum



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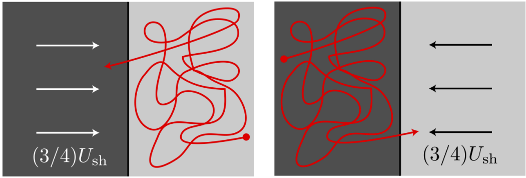
A gambling analogy

- Amount p; probability of not having lost N
- Chance of losing q: $N_{i+1} = N_i(1-q)$
- Fractional gain g: $p_{i+1} = p_i(1+g)$
- Probability of having more than p_n: $N(> p_n)$

$$\left.\begin{aligned} \ln N(> p_n)/N_0 &= \ln(1-q)^n \simeq -nq \\ \ln p_n/p_0 &= \ln(1+g)^n \simeq ng \end{aligned}\right\} \Rightarrow N(> p_n) = N_0 \left(\frac{p_n}{p_0}\right)^{-q/g} = \int_{p_0}^{p_n} \mathrm{d}p \, \frac{\mathrm{d}N}{\mathrm{d}p}$$

$$\frac{\mathrm{d}N}{\mathrm{d}p} \propto \left(\frac{p}{p_0}\right)^{-(1+q/g)}$$



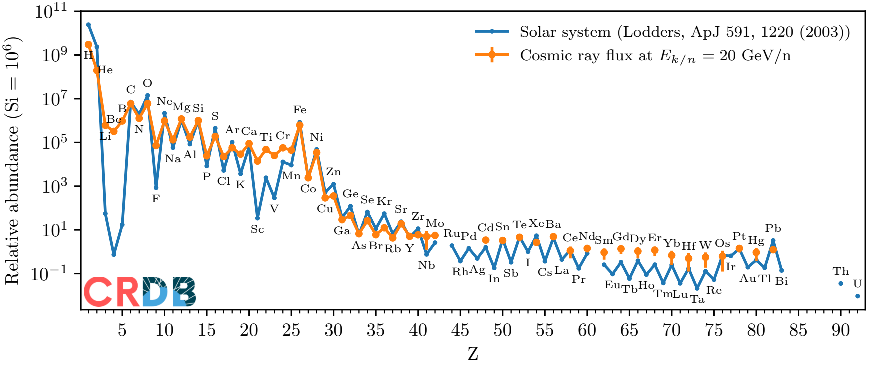
upstream rest frame   downstream rest frame

Diffusive shock acceleration

- Prob. of escape: $q = \frac{U_{\mathrm{sh}}}{v}$
- fractional gain: $g = \frac{\Delta p}{p} = \frac{U_{\mathrm{sh}}}{v}$
- spectrum: $\frac{\mathrm{d}N}{\mathrm{d}p} \propto p^{-2}$

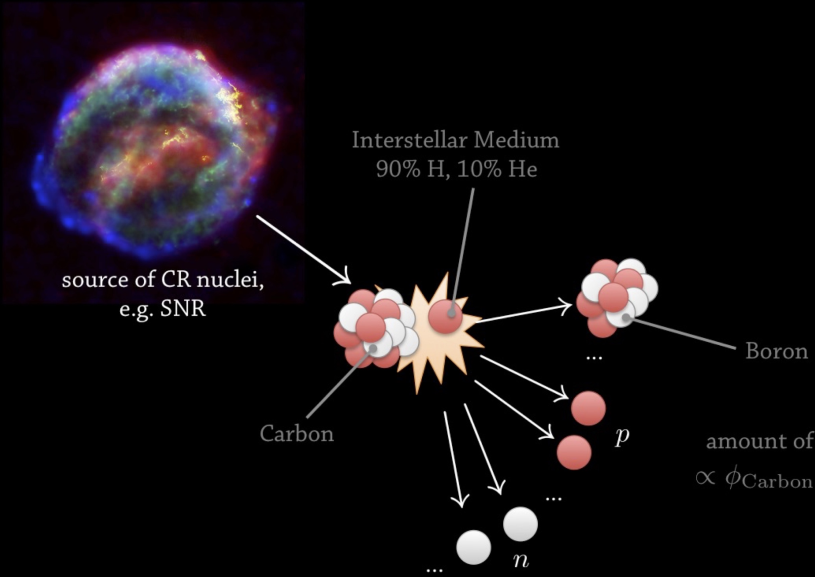
Composition

- 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

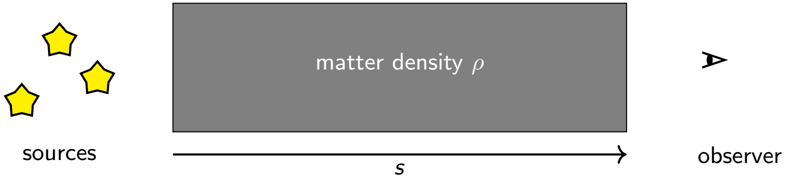
Secondaries from spallation



amount of Boron

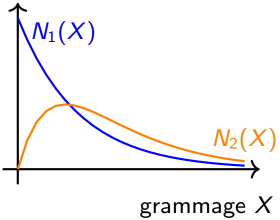
$\propto \phi_{\text{Carbon}}\, \sigma_{\text{spall}}\, n_{\text{gas}}$

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**

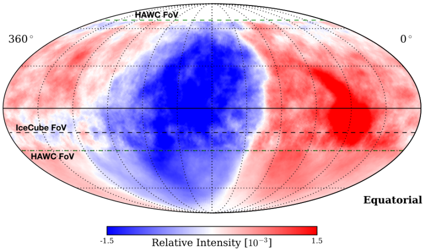
- Residence time in disk:

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

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

Anisotropy (I)

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



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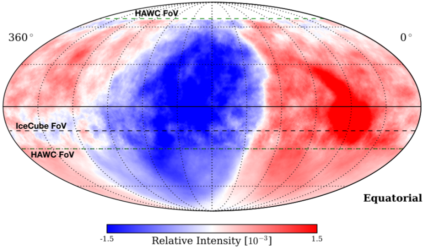
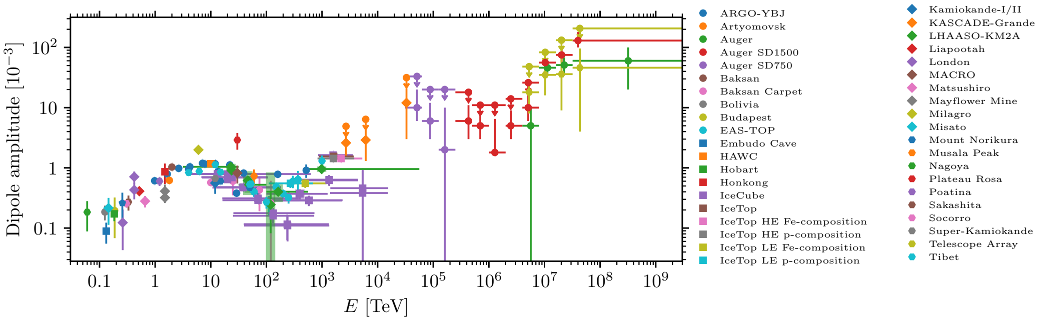
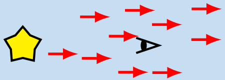




Anisotropy (II)

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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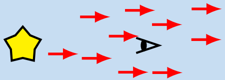

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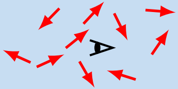

- But CRs arrive very isotropically

$\rightarrow$ Need to isotropise CRs

- (Coulomb) collisions with interstellar matter too infrequent

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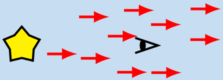

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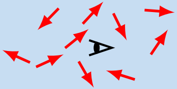

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$\rightarrow$ Need to isotropise CRs

- (Coulomb) collisions with interstellar matter too infrequent

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

$\rightarrow$ 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

What are the sources of (galactic) CRs?

- Already Baade & Zwicky suggested supernovae (SNe)
- SN liberates much of gravitational energy of star, typically 10^{51} erg
- ($1\,\mathrm{erg} = 10^{-7}\,\mathrm{J} \simeq 624\,\mathrm{GeV}$)

- However, particles accelerated in SN event suffer from adiabatic losses

The case for supernova remnants

Ginzburg & Syrovatskii

1. Presence of strong shocks
2. Observation of PeV particles
3. Energetics:

$$
\begin{aligned}
&\text{CR energy density:} & \varepsilon &= 0.3\,\mathrm{eV\,cm^{-3}} \simeq 5\times 10^{-13}\,\mathrm{erg\,cm^{-3}} \\
&\text{Volume of CR halo:} & V &= \pi(10\,\mathrm{kpc})^2(3\,\mathrm{kpc}) \simeq 3\times 10^{67}\,\mathrm{cm^3} \\
&\text{Total CR energy:} & \varepsilon V &= 10^{55}\,\mathrm{erg} \\
&\text{Residence time:} & t_{\mathrm{res}} &= 10^7\,\mathrm{yr} \\
&\text{Power needed:} & \varepsilon V/t_{\mathrm{res}} &= 10^{48}\,\mathrm{erg\,yr^{-1}} \\
&\text{Galactic supernova rate:} & R &= 0.03\,\mathrm{yr^{-1}} \\
&\text{Contribution from one supernova:} & \varepsilon V/(R t_{\mathrm{res}}) &= 3\times 10^{49}\,\mathrm{erg}
\end{aligned}
$$

“What is accelerating to $E_{\rm knee} \sim 3 \times 10^{15}$ eV ?”

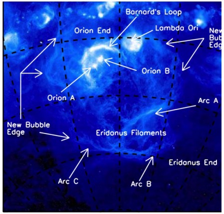
Supernova remnants

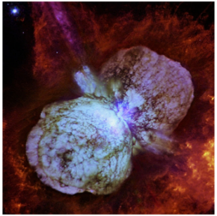
- $E_{\rm max} \lesssim 10^{13...14}$ eV for $B \sim B_{\rm ISM}$
  Lagage & Cesarsky (1983)
- Amplify magnetic fields, non-resonant instability
  Bell (2004)
- Saturation?

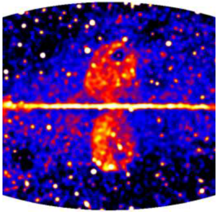
$\rightarrow$ Particle-in-cell simulations

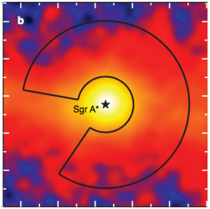
Other sources

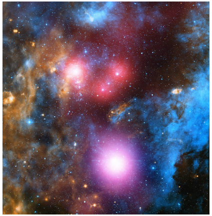
- Superbubbles
- Supernovae before shock breakout
- Colliding wind binaries
- Pulsar wind nebulae
- The Fermi bubbles
- The Galactic centre
- Massive star clusters











The transport equation

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j)$$

spatial diffusion and advection

$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right)$$

momentum diffusion

$$+ \frac{\partial}{\partial p} \left(- \frac{\mathrm{d}p}{\mathrm{d}t} \psi_j + \frac{p}{3} \left(\nabla \cdot \mathbf{U} \right) \psi_j \right)$$

momentum change incl. adiabatic

$$- v n_{\mathrm{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j}$$

spallation and decay

$$+ v n_{\mathrm{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$

spallation and decay

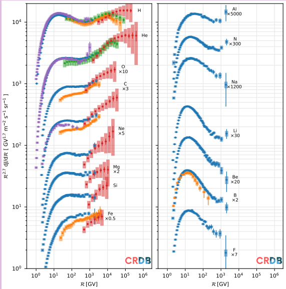
$$+ S_j$$

primary sources

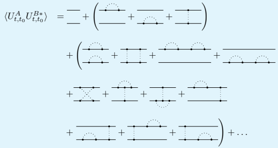
Open questions

Introduction

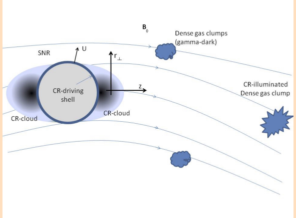
A tale of breaks



Anisotropies



Self-confinement



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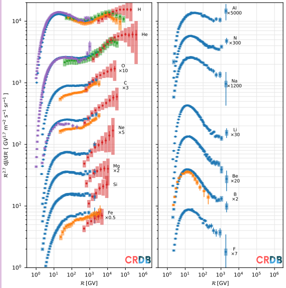

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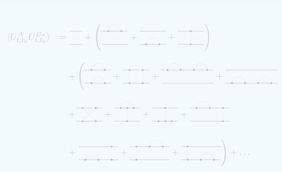


Self-confinement

Rigidity

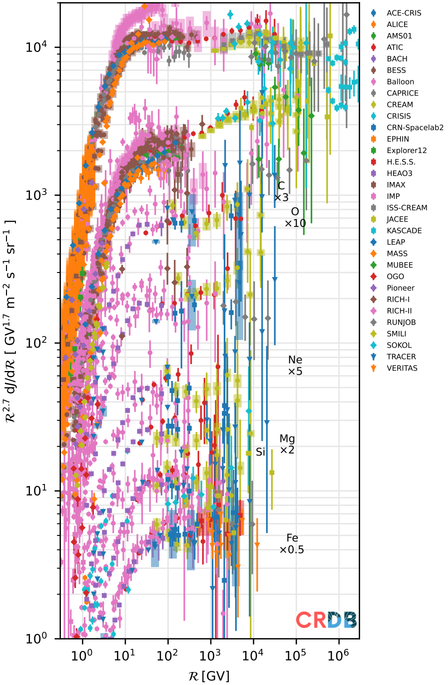
- Charged particles subject to Lorentz force:

$$
\begin{aligned}
\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} &= \frac{Ze}{c}(\mathbf{v} \times \mathbf{B}) \\
\Leftrightarrow m\gamma v \frac{\mathrm{d}\hat{\mathbf{v}}}{\mathrm{d}t} &= \frac{Ze}{c} vB(\hat{\mathbf{v}} \times \hat{\mathbf{B}}) \\
\Leftrightarrow \frac{1}{B} \underbrace{\frac{pc}{Ze}}_{\equiv R} \frac{\mathrm{d}\hat{\mathbf{v}}}{\mathrm{d}s} &= \hat{\mathbf{v}} \times \hat{\mathbf{B}} \quad \text{with } s = vt
\end{aligned}
$$

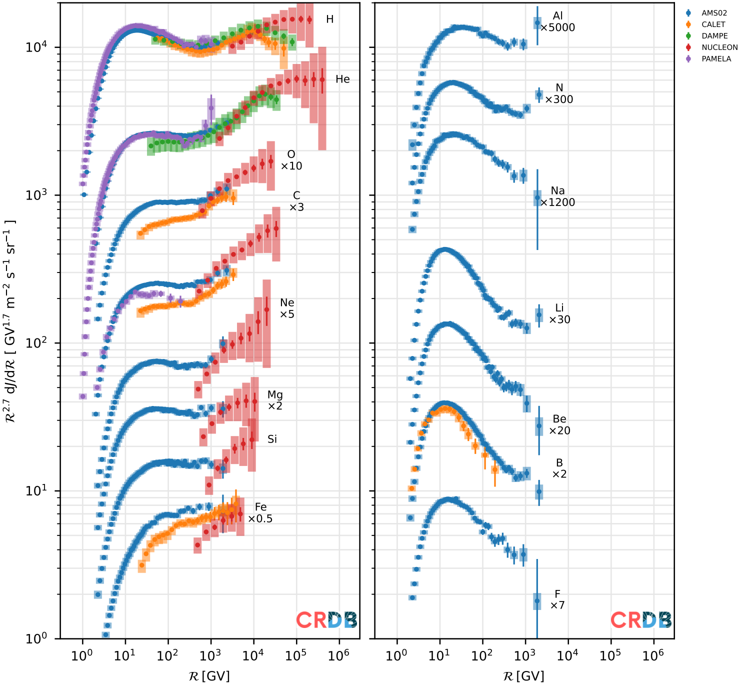
- Here, $R = \frac{pc}{Ze}$ is called the rigidity and $s = vt$ is the path length
- For relativistic nuclei, rigidity $= 2 \times$ (energy per nucleon):

$$
eR = \frac{pc}{Z} \simeq \frac{E}{Z} = \frac{A}{Z}\frac{E}{A} \simeq 2\frac{E}{A}
$$

Particle spectra should look the same in rigidity or energy per nucleon



$\mathcal{R}^{2.7}$ dJ/d$\mathcal{R}$ [GV$^{1.7}$ m^{-2} s^{-1} sr^{-1}]
$\mathcal{R}$ [GV]
C ×3
O ×10
Ne ×5
Mg ×2
Si
Fe ×0.5
CRDB
ACE-CRIS
ALICE
AMS01
ATIC
BACH
BESS
Balloon
CAPRICE
CREAM
CRISIS
CRN-Spacelab2
EPHIN
Explorer12
H.E.S.S.
HEAO3
IMAX
IMP
ISS-CREAM
JACEE
KASCADE
LEAP
MASS
MUBEE
OGO
Pioneer
RICH-I
RICH-II
RUNJOB
SMILI
SOKOL
TRACER
VERITAS



Spectral universality,
but $\sim$ two groups

Simplified 1D model

- 1D approximation; homogeneous diffusion, advection

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

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- Steady-state

- Infinitely thin disk of half-height h

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

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Solution (without advection or decay)

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

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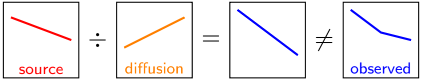
- Broken power law: $\kappa(\mathcal{R}) = \kappa_0 \beta \left(\frac{\mathcal{R}}{\mathcal{R}_{12}} \right)^{-\delta_1} \prod_{i=1}^{4} \left(1 + \left(\frac{\mathcal{R}}{\mathcal{R}_{i(i+1)}} \right)^{1/s} \right)^{-s(\delta_{i+1} - \delta_i)}$

Discrepant hardening

Standard picture: $\frac{\mathrm{d}J(p)}{\mathrm{d}p} \sim \frac{Q(p)}{\kappa(p)}$



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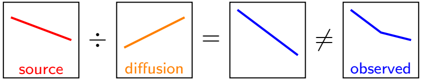
Standard picture: $\frac{\mathrm{d}J(p)}{\mathrm{d}p} \sim \frac{Q(p)}{\kappa(p)}$



Source effect

- Break in source spectrum
  Stanev, Biermann and Gaisser (1993)
  Parizot (2004)
  Ptuskin, Zirakashvili and Seo (2013)

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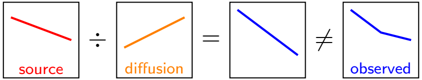


Source effect

- Break in source spectrum
  Stanev, Biermann and Gaisser (1993)
  Parizot (2004)
  Ptuskin, Zirakashvili and Seo (2013)

Transport effect

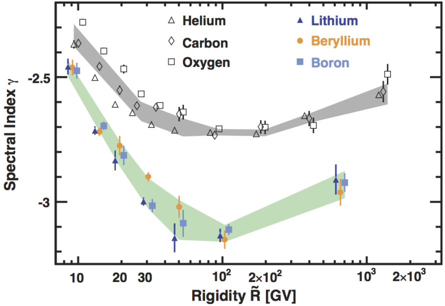
- Break in diffusion coefficient
  Blasi, Amato & Serpico, PRL 109 (2012) 061101
  Tomassetti, ApJL 752 (2012) 13

Source or transport?

- Can be distinguished by secondaries Vladimirov *et al.* (2012)
- break in source spectrum: break in secondaries similar

- break in diffusion coefficient: break in secondaries $\sim 2\times$ as strong

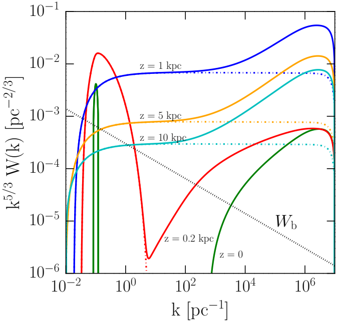
Aguilar *et al.* (2019)



Streaming instability and large-scale transport

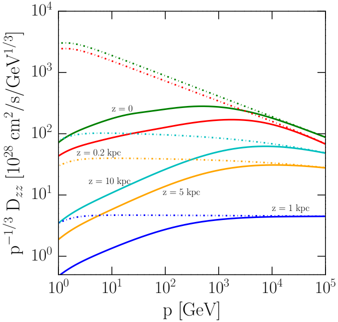
Evoli *et al.*, PRD **99** (2019) 103023

Turbulence power spectrum



$$\left(\frac{k}{10^6\,\mathrm{pc}^{-1}}\right) \sim \left(\frac{p}{\mathrm{GeV}}\right)^{-1}$$

Diffusion coefficient

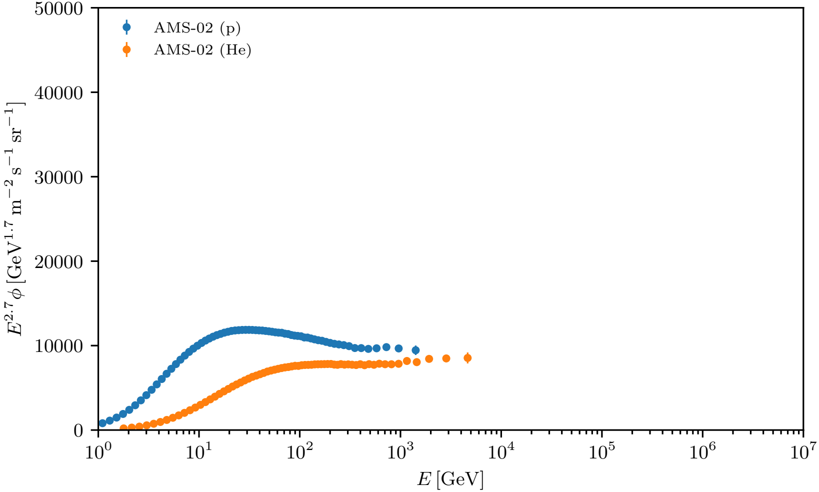


- The power spectrum of magnetised turbulence has a break at $k_{\mathrm{br}} \simeq 3000\,\mathrm{pc}^{-1}$

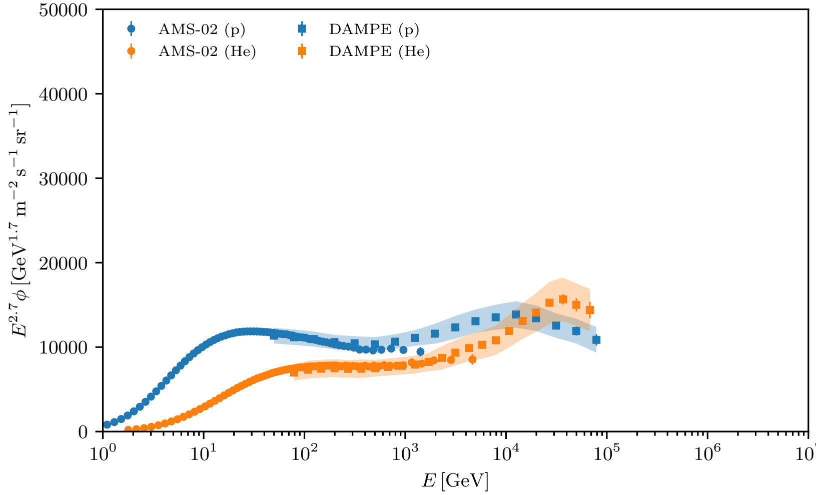
$\rightarrow$ Turbulence generated by $\begin{cases} \text{supernovae} & \text{for } k \lesssim k_{\mathrm{br}} \\ \text{cosmic rays} & \text{for } k \gtrsim k_{\mathrm{br}} \end{cases}$

$\rightarrow$ Important consequences for galaxy formation and evolution

Nuclear spectra



Nuclear spectra



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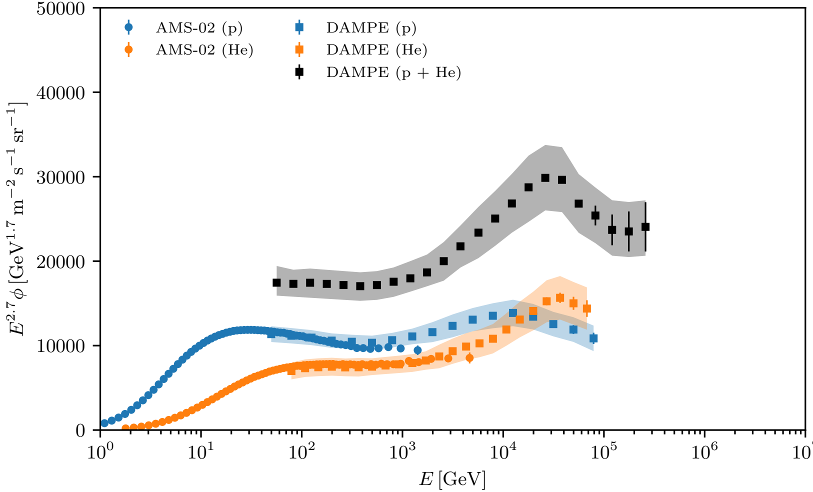

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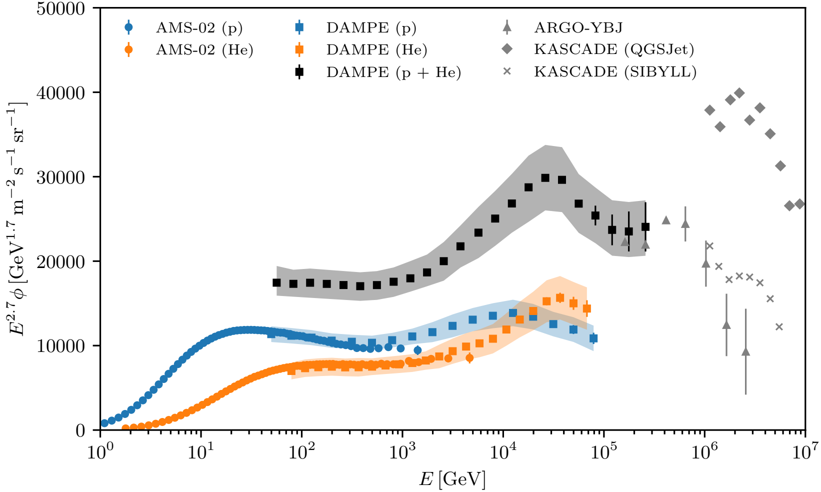

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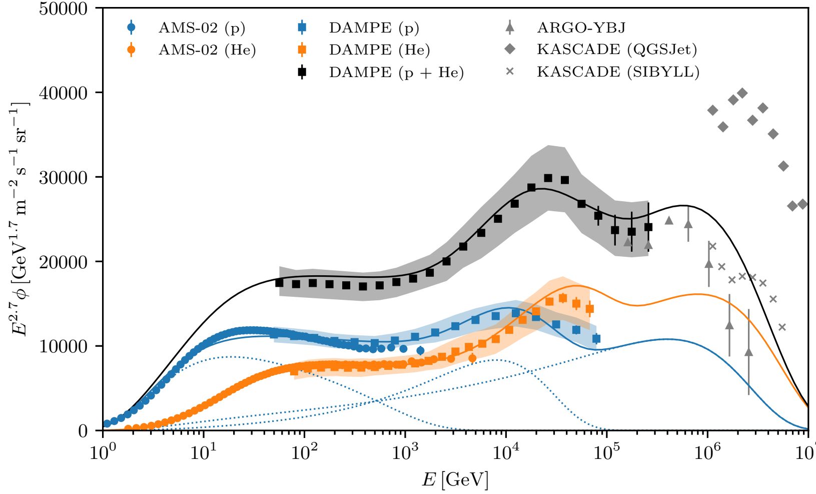
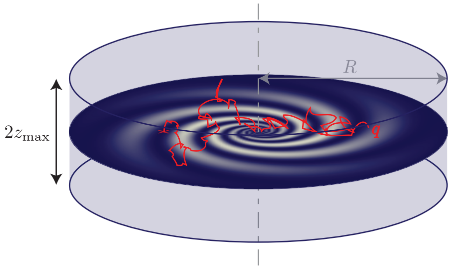


Spectral features in nuclei

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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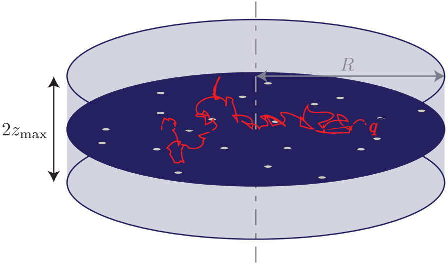

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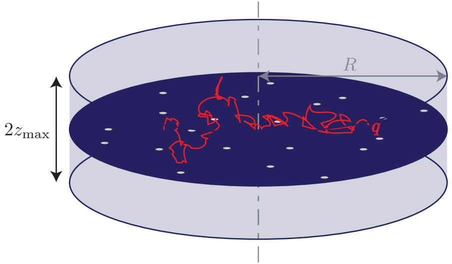

Spectral breaks as evidence for nearby sources

- Young source $\rightarrow$ hard spectrum at Earth
- If the $\mathcal{R}_{\rm max}$ 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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- Residence time: $$t_{\mathrm{esc}} = \frac{z_{\mathrm{max}}^2}{2\kappa}$$
- Diffusion distance: $$R = \sqrt{2\kappa t_{\mathrm{esc}}} = z_{\mathrm{max}}$$
- Source density: $$\sigma = \frac{\mathcal{R}_{\mathrm{SN}}\, t_{\mathrm{esc}}}{\pi R_{\mathrm{disk}}^2}$$
- Source number: $$N_{\mathrm{src}} = \sigma \pi R^2 = \mathcal{R}_{\mathrm{SN}}\, t_{\mathrm{esc}} \frac{z_{\mathrm{max}}^2}{R_{\mathrm{disk}}^2}$$

With typical parameters (for details $\to$ Appendix):

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

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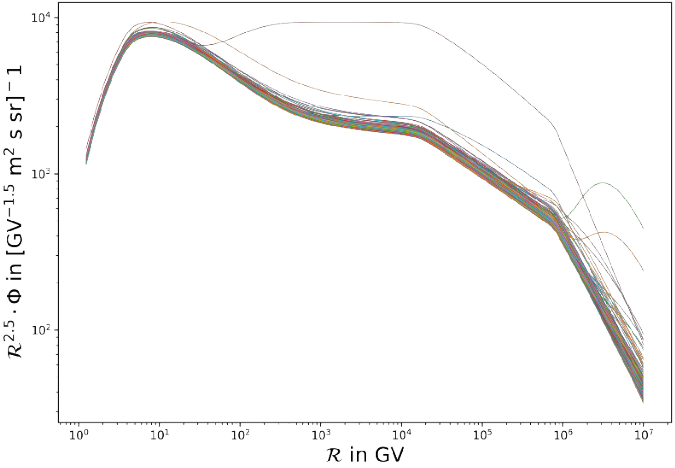
A Monte Carlo exercise

Mertsch & Stall, *in prep.*



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

$$\mathcal{R}_{\mathrm{SN}} = 3 \times 10^4\,\mathrm{Myr}$$

- Acceleration efficiency of $\sim 10\,\%$

$\rightarrow$ Nearby sources can lead to features

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

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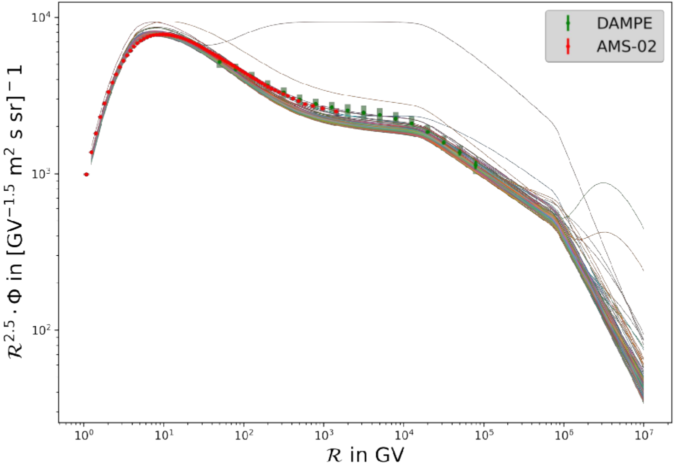

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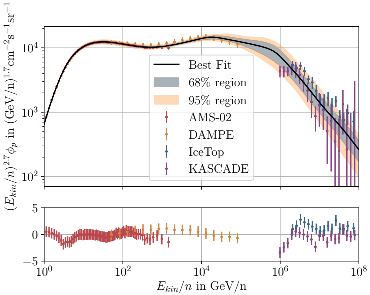
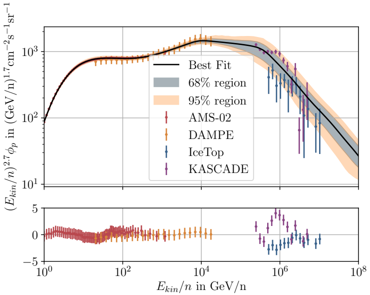
Anatomy of a diffusion coefficient

Schwefer, Mertsch, Wiebusch, ApJ **949** (2023) 16

Proton



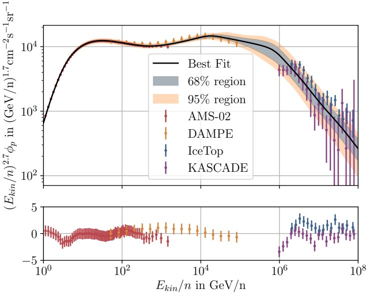


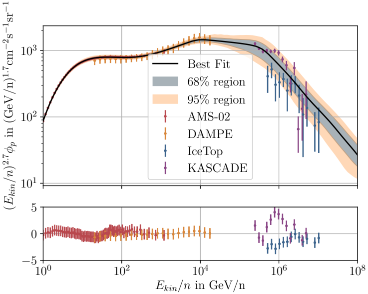
Helium

Anatomy of a diffusion coefficient

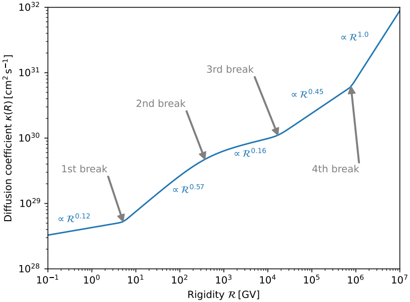
Schwefer, Mertsch, Wiebusch, ApJ **949** (2023) 16

Proton





Helium



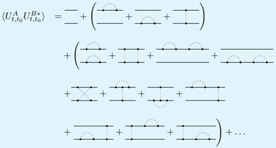
- 1. Break: Hardening of spectra at low energies due to stochasticity effect Phan *et al.* PRL **127** (2021) 141101 (for details → Appendix):
- 2. Break: Transition from self-generated to external turbulence
  Blasi, Amato, Serpico PRL **109** (2012) 061101
- 3. Break: ?!
- 4. Break: Transition from resonant to small-angle scattering

Open questions

Introduction

A tale of breaks

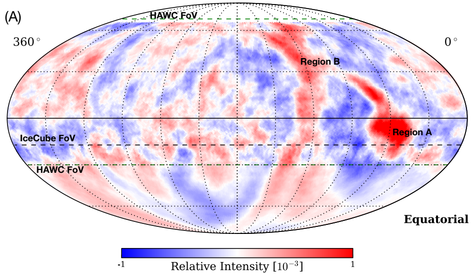
Anisotropies

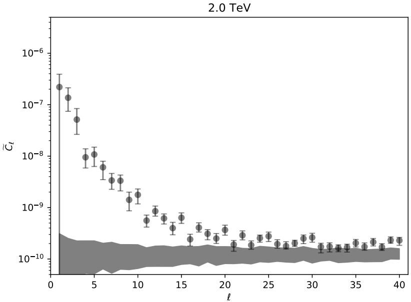


Self-confinement

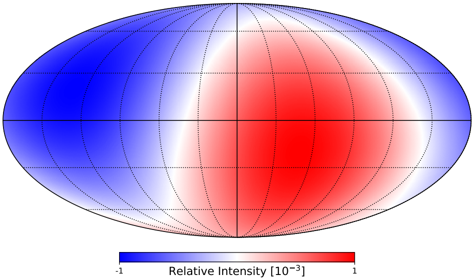
Small-scale anisotropies

Abeysekara *et al.*, ApJ 796 (2014) 108 Aartsen *et al.*, ApJ 826 (2016) 220; Abeysekara *et al.*, ApJ 865 (2018) 57; Abeysekara *et al.*, ApJ 871 (2019) 96





Diffusion models predict only large-scale anisotropy



Vlasov equation

Frisch (1968), Pelletier (1977)

- Liouville equation:

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \dot{\mathbf{r}} \cdot \nabla_{\mathbf{r}} f + \dot{\mathbf{p}} \cdot \nabla_{\mathbf{p}} f = 0$$

- Lorentz force:

$$\dot{\mathbf{p}} = \frac{q}{c} \mathbf{v} \times \left(\langle \mathbf{B} \rangle + \delta \mathbf{B} \right)$$

deterministic $\gg$ stochastic

- Vlasov equation:

$$\frac{\partial f}{\partial t} + \dot{\mathbf{r}} \cdot \nabla_{\mathbf{r}} f + \frac{q}{c} \mathbf{v} \times \left(\langle \mathbf{B} \rangle + \delta \mathbf{B} \right) \cdot \nabla_{\mathbf{p}} f = 0$$

- Ignoring the gradient:

$$\frac{\partial f_{\oplus}}{\partial t} + \underbrace{\left(\frac{q}{c} (\mathbf{v} \times \langle \mathbf{B} \rangle) \cdot \nabla_{\mathbf{p}} \right)}_{\mathcal{L}_0} f_{\oplus} + \underbrace{\left(\frac{q}{c} (\mathbf{v} \times \delta \mathbf{B}) \cdot \nabla_{\mathbf{p}} \right)}_{\delta \mathcal{L}} f_{\oplus} = 0$$

QM analogy

- Liouville's theorem:

$$\partial_t f + \mathcal{L}_0 f(t) = -\delta\mathcal{L}(t) f(t) \qquad \imath\hbar\partial_t|\psi(t)\rangle - H_0|\psi(t)\rangle = -H_1(t)|\psi(t)\rangle$$

- Formally solved as

$$f(\mathbf{r}, \mathbf{p}, t) = U_{t,t_0} f(\mathbf{r}, \mathbf{p}, t_0) \qquad |\psi(t)\rangle = U(t, t_0)|\psi(t_0)\rangle$$

- With time evolution operator:

$$U_{t,t_0} = \mathcal{T}\exp\left[-\int_{t_0}^{t} \mathrm{d}t' \left(\mathcal{L}_0 + \delta\mathcal{L}(t')\right)\right] = U^{(0)}_{t,t_0}\mathcal{T}\exp\left[-\int_{t_0}^{t} \mathrm{d}t' \underbrace{\left(U^{(0)}_{t',t_0}\right)^{-1} \delta\mathcal{L}(t') U^{(0)}_{t',t_0}}_{\sim\text{interaction picture Hamiltonian}}\right]$$

and free propagator:

$$U^{(0)}_{t,t_0} = \exp\left[-\mathcal{L}_0(t - t_0)\right] \qquad U^{(0)}(t, t_0) = \exp\left[-\imath H_0(t - t_0)/\hbar\right]$$

Perturbative expansion

Frisch (1968), Pelletier (1977)

- Series expansion:

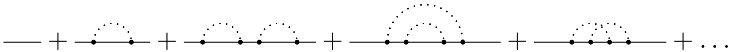
$$U_{t,t_0} = U^{(0)}_{t,t_0} + \sum_{n\geq 1} (-1)^n \int_{t_0}^{t} \mathrm{d}t_n \int_{t_0}^{t_n} \mathrm{d}t_{n-1} \ldots \int_{t_0}^{t_2} \mathrm{d}t_1 \, U^{(0)}_{t,t_n} \delta\mathcal{L}(t_n) U^{(0)}_{t_n,t_{n-1}} \delta\mathcal{L}(t_{n-1}) \ldots \delta\mathcal{L}(t_1) U^{(0)}_{t_1,t_0}$$

- But can only make predictions for ensemble-averaged quantities, e.g. $\langle U^{(0)}_{t,t_0} \rangle$

$\rightarrow$ Correlation functions, e.g. $\langle \delta\mathcal{L}(t_2)\delta\mathcal{L}(t_1)\rangle \quad \rightarrow \quad \langle \delta\mathbf{B}(t_2)\delta\mathbf{B}(t_1)\rangle$

- Diagrammatic representation:

$\langle U_{t,t_0} \rangle \quad =$

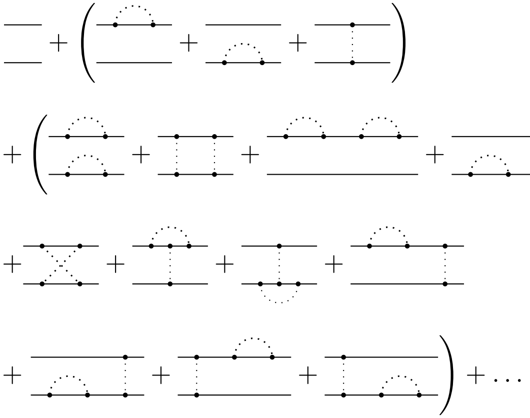


Double propagator

Mertsch & Ahlers (2019)

For $\langle f(\hat{\mathbf{p}}_1) f(\hat{\mathbf{p}}_2) \rangle$ we need correlated evolution of two particles:

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

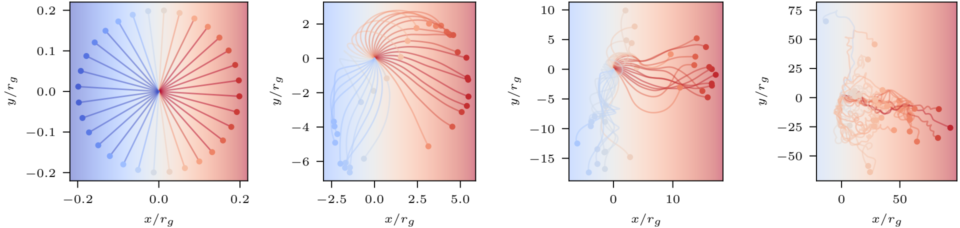


Formulate differential equation of $\langle C_\ell(t) \rangle$ and solve for steady-state

Test particle simulations

Kuhlen, Mertsch, Phan (2022)

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

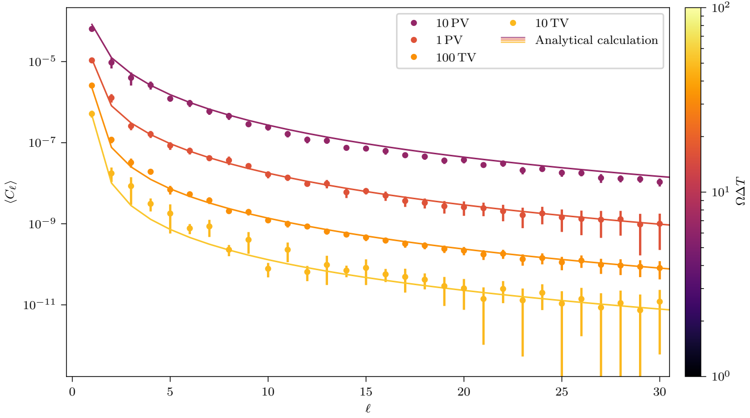


- Rinse and repeat
- Compute diffusion coefficients, angular power spectra, . . .

H.264 avi

Results

Kuhlen, Mertsch, Phan (2022)



When applying to observational data:

- Independent measurement of scattering time
- Constraints on details of magnetised turbulence

Open questions

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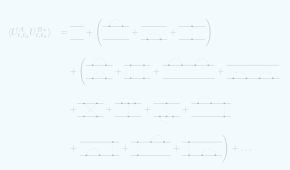
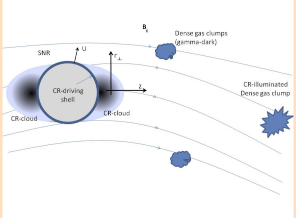
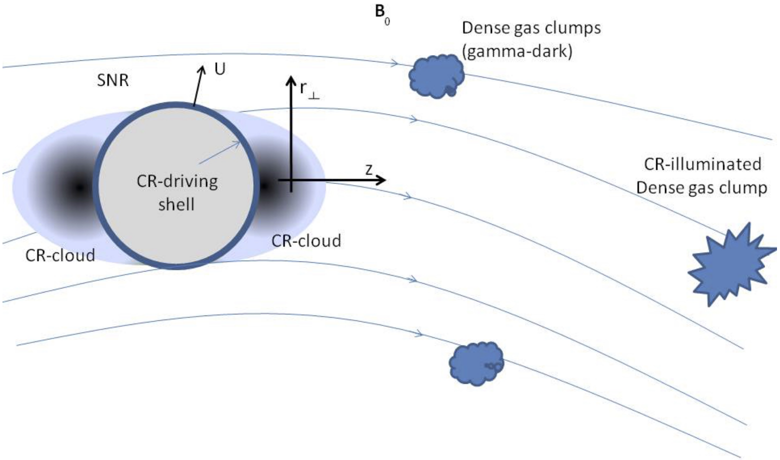


Self-confinement



The cosmic ray cloud

Malkov *et al.* (2013)



Non-linear transport

$$\frac{\partial \psi_{\mathrm{CR}}}{\partial t} + v_{\mathrm{A}} \frac{\partial \psi_{\mathrm{CR}}}{\partial z} = \frac{\partial}{\partial z}\left(D_{zz} \frac{\partial \psi_{\mathrm{CR}}}{\partial z} \right)$$

$$D_{zz} \sim \left. \frac{D_{\mathrm{B}}}{k W(k)} \right|_{k=1/r_g}$$

- CR density ψ_{CR}
- Diffusion coefficient D_{zz}
- Bohm diffusion coefficient D_{B}
- Magnetic turbulence spectrum $W(k)$

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$$\Gamma_{\mathrm{CR}} = -\frac{v_{\mathrm{A}}}{kW} p^2 \frac{\partial \psi_{\mathrm{CR}}}{\partial z}$$

$$\frac{\partial W}{\partial t} + v_{\mathrm{A}} \frac{\partial W}{\partial z} + = \left(\Gamma_{\mathrm{CR}}(z,k) - \Gamma_{\mathrm{d}}\right) W$$

- CR density ψ_{CR}
- Diffusion coefficient D_{zz}
- Bohm diffusion coefficient D_{B}
- Magnetic turbulence spectrum $W(k)$
- Growth rate Γ_{CR}
- Damping rate Γ_{d}

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Around supernova remnants:

Nava & Gabici (2013), D'Angelo *et al.* (2016, 2018), Nava *et al.* (2019), Brahimi *et al.* (2020), Brose *et al.* (2021), Schroer *et al.* (2021), Recchia *et al.* (2022), Jacobs, Mertsch, Phan (2022)

Around pulsar wind nebulae:

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

On Galaxy scales:

Amato, Blasi, Serpico (2012), Evoli *et al.* (2019)

Non-linear transport

$$\frac{\partial \psi_{\mathrm{CR}}}{\partial t} + v_{\mathrm{A}} \frac{\partial \psi_{\mathrm{CR}}}{\partial z} = \frac{\partial}{\partial z}\left(D_{zz} \frac{\partial \psi_{\mathrm{CR}}}{\partial z} \right) - \frac{\partial}{\partial p}\left(\dot{p} \psi_{\mathrm{CR}} \right)$$

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$$\Gamma_{\mathrm{CR}} = - \frac{v_{\mathrm{A}}}{kW} p^2 \frac{\partial \psi_{\mathrm{CR}}}{\partial z}$$

$$\frac{\partial W}{\partial t} + v_{\mathrm{A}} \frac{\partial W}{\partial z} + \frac{\partial}{\partial k}\left(D_{kk} \frac{\partial W}{\partial k} \right) = \left(\Gamma_{\mathrm{CR}}(z, k) - \Gamma_{\mathrm{d}} \right) W$$

- CR density ψ_{CR}
- Diffusion coefficient D_{zz}
- Bohm diffusion coefficient D_{B}
- Magnetic turbulence spectrum $W(k)$
- Growth rate Γ_{CR}
- Damping rate Γ_{d}
- Momentum loss rate $\dot{p}$
- Momentum diffusion coefficient D_{zz}

Around supernova remnants:

Nava & Gabici (2013), D'Angelo *et al.* (2016, 2018), Nava *et al.* (2019), Brahimi *et al.* (2020), Brose *et al.* (2021), Schroer *et al.* (2021), Recchia *et al.* (2022), Jacobs, Mertsch, Phan (2022)

Around pulsar wind nebulae:

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

On Galaxy scales:

Amato, Blasi, Serpico (2012), Evoli *et al.* (2019)

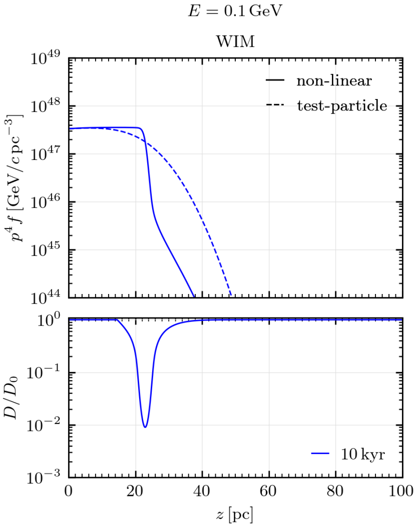
Spatial dependence

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

- At $t = 0$: top hat profile
- Flux tube extends to 100 pc

Results

- Test-particle solution approximately gaussian
- Longer confinement in non-linear simulation:
  - Suppression of diffusion by up to $\mathcal{O}(100)$
  - Lasts up to 1 Myr



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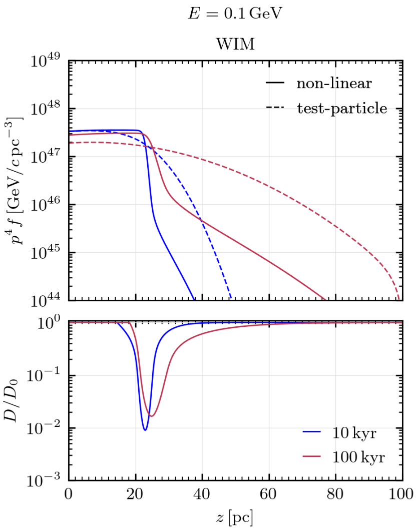

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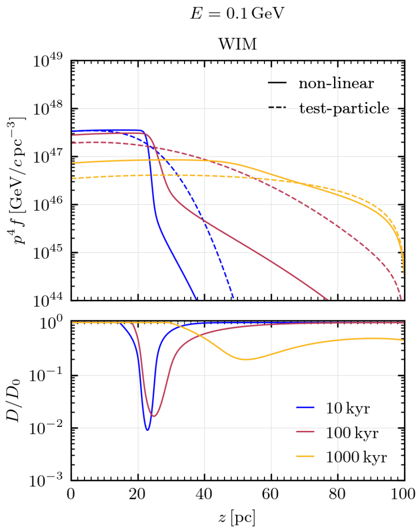
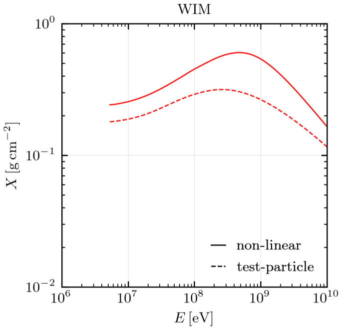


Grammage

H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

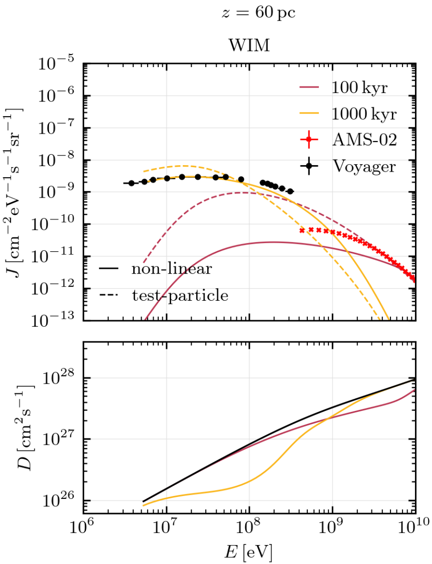


- Reminder grammage: $X \equiv \int \mathrm{d}s\, \rho(s) = s_{\mathrm{max}} \bar{\rho}$
- Usually, near-source grammage ignored
- Increased by factor 2 to 3 due to non-linear transport

$\rightarrow$ Cannot be ignored anymore

Spectral dependence

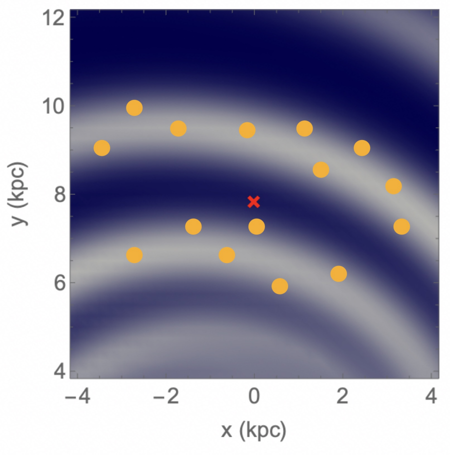
H. Jacobs, P. Mertsch, M. Phan, JCAP 05 (2022) 05, 024 [arXiv:2112.09708]

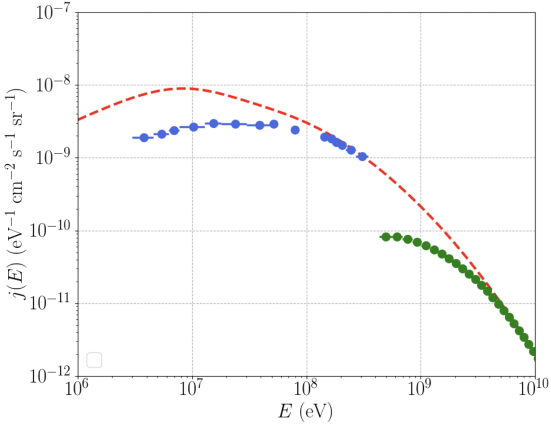


- Self-confinement affects spectral shape
- Compare with Voyager and AMS-02 data
- Can *in principle* reproduce data with:
  - one 100 kyr-old source at ~ 60 pc distance
  - one 1000 kyr-old source at ~ 60 pc distance

$\rightarrow$ Fine-tuning?!

Importance of nearby sources





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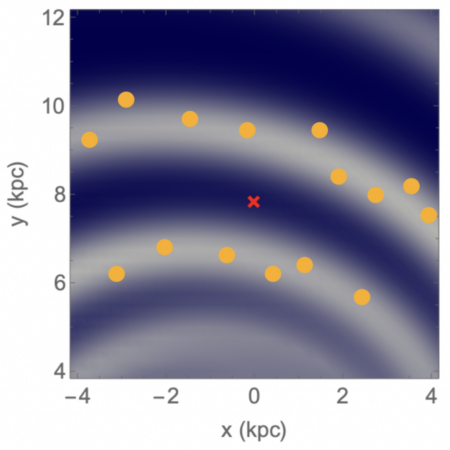

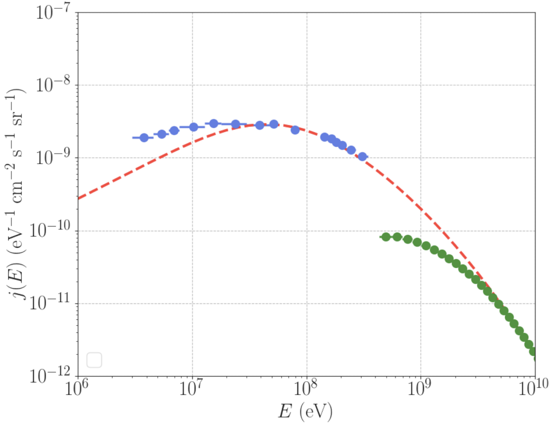

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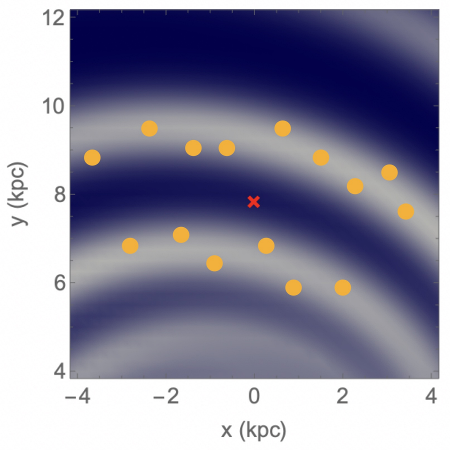

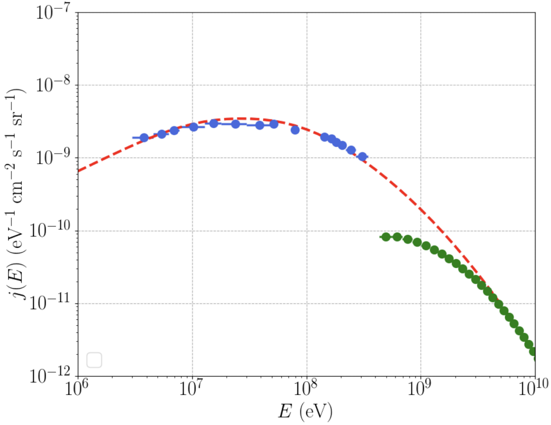

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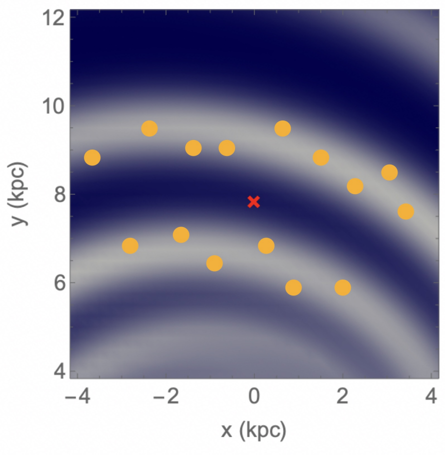
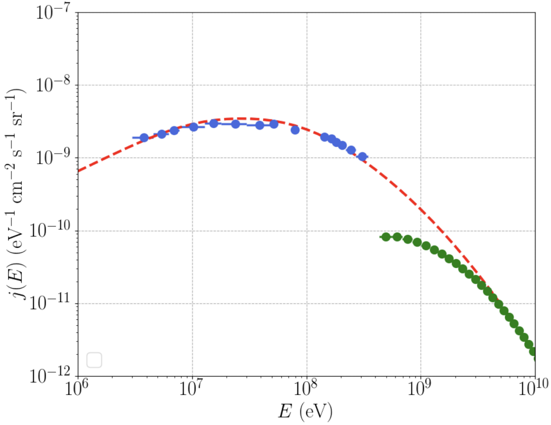




Cosmic ray flux is a stochastic quantity

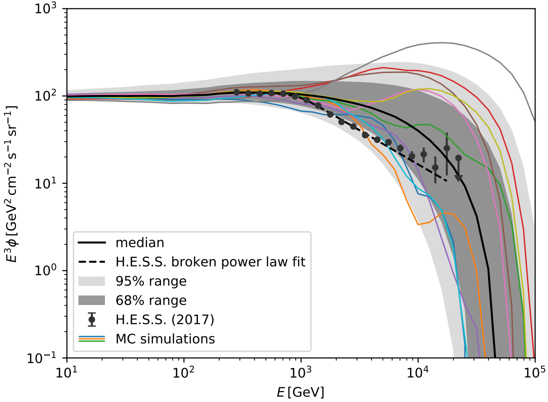
Electrons and positrons at high energies

- Sensitivity to source distances and ages

$\rightarrow$ Need to consider when comparing to data

$\rightarrow$ Great potential for identifying sources

Mertsch (2018)



Monte Carlo study

1. Draw random distances $\{d_i\}$ and ages $\{t_i\}$
2. Add contributions from $i = 1, \ldots N_{\mathrm{src}}$ sources in *one realisation* of the Galaxy
3. Repeat for *different realisations* of the Galaxy

Density estimation task

N. Frediani, M. Krämer, K. Nippel, P. Mertsch

- Have discrete samples of flux vector $\{\phi_1, \phi_2, \ldots \phi_N\}$
- Want multivariate distribution $p(\phi_1, \phi_2, \ldots \phi_N)$

$\rightarrow$ Density estimation task

Sklar's theorem Sklar (1959)

$$p(\phi_1, \phi_2, \ldots \phi_N) = p(\phi_1) p(\phi_2 | \phi_1) \ldots p(\phi_N | \phi_1, \ldots \phi_{N-1})$$

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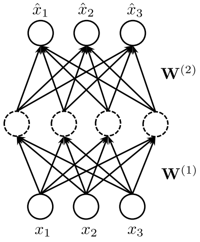

Dense NN

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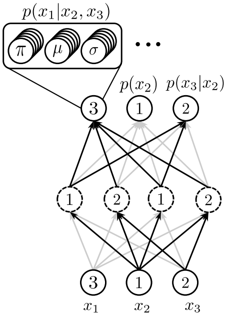

MADE

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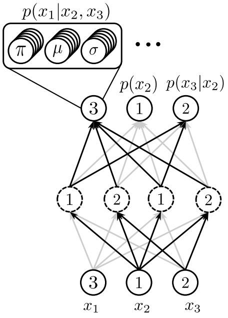

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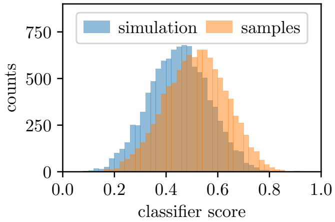
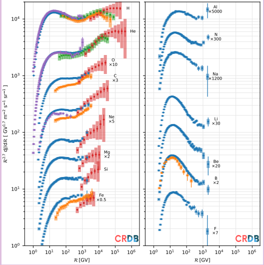


Summary

Introduction

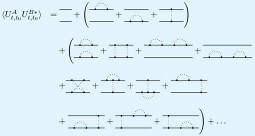
Dynamics of cosmic rays described by transport equation

A tale of breaks



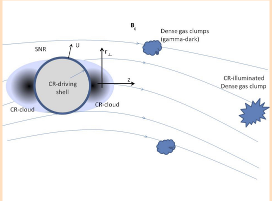
Spectral breaks
$\rightarrow$ properties of magnetised turbulence

Anisotropies



Small-scale anisotropies due to local turbulence

Near-source transport



Non-linear transport around sources

- Improving ingredients for the transport equation

$\rightarrow$ Progress towards:
  - Origin of cosmic rays
  - Impact in galaxy evolution
  - Exotic physics