# Cosmic ray theory (III)

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31 July 2026

Institute for Theoretical Particle Physics and Cosmology
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# Outline

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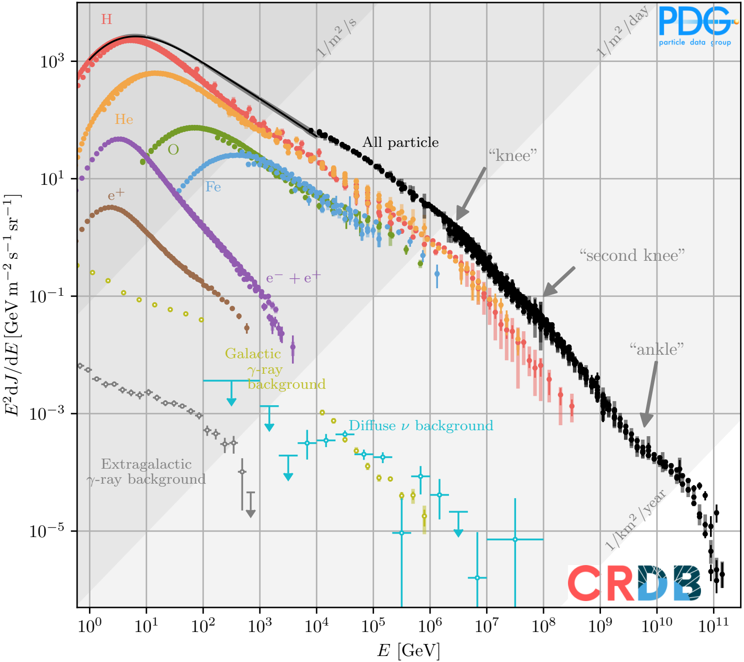
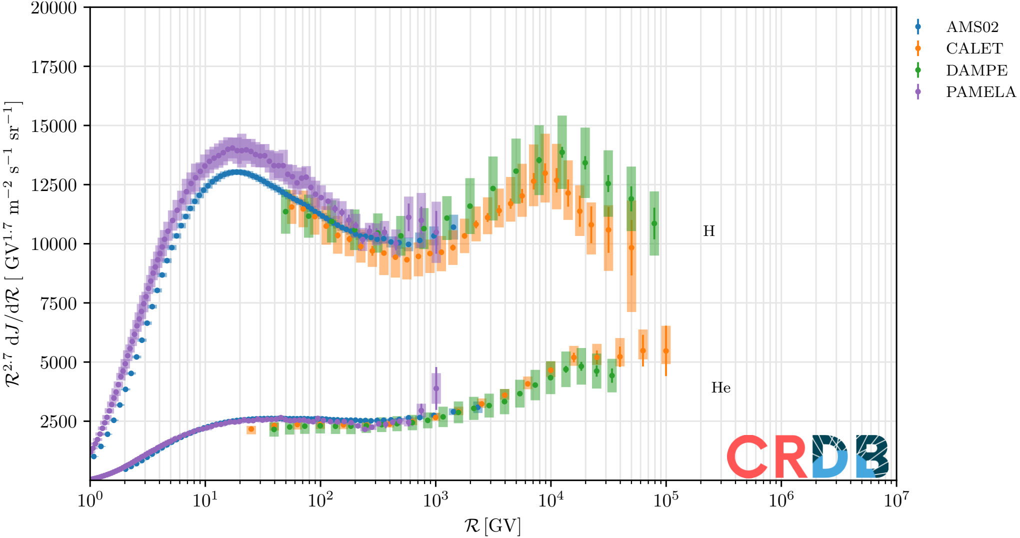
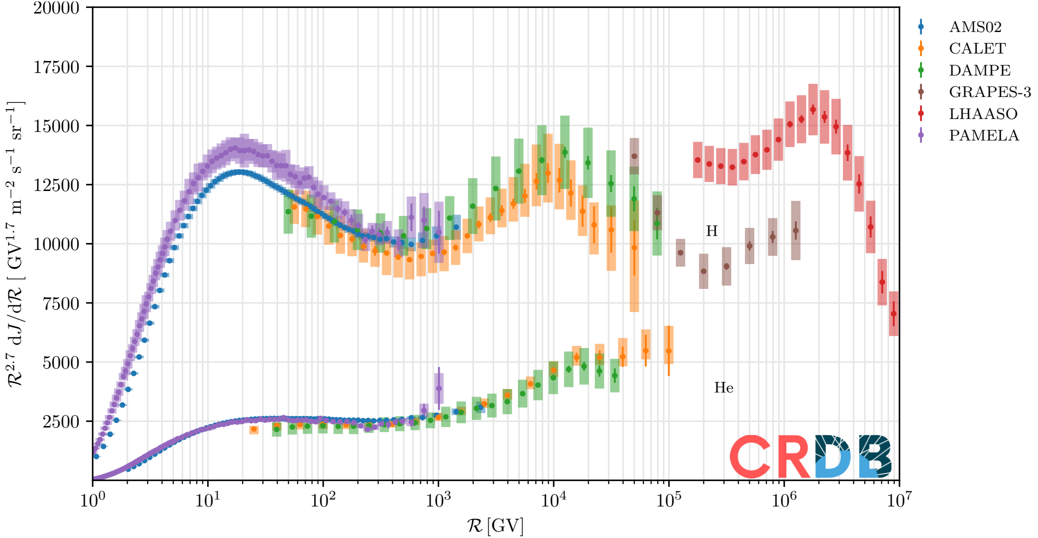
# The cosmic ray spectrum

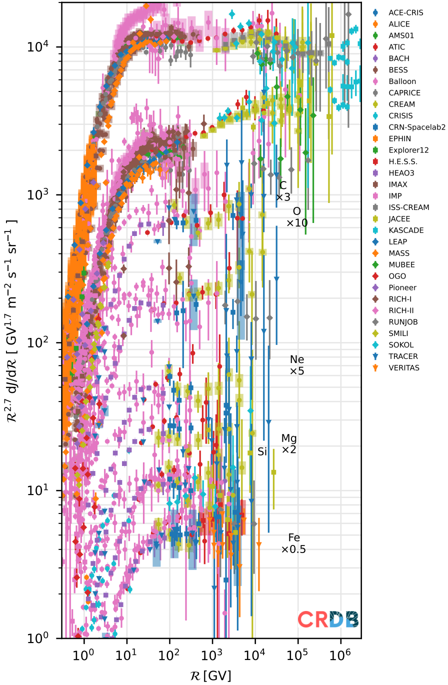


# The proton and helium spectra

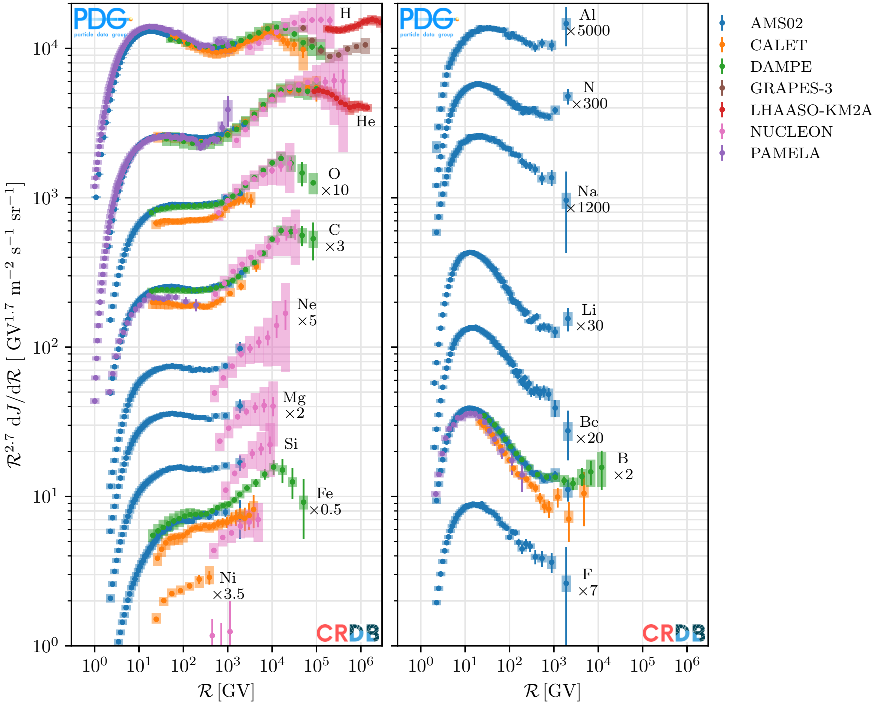


# The proton and helium spectra

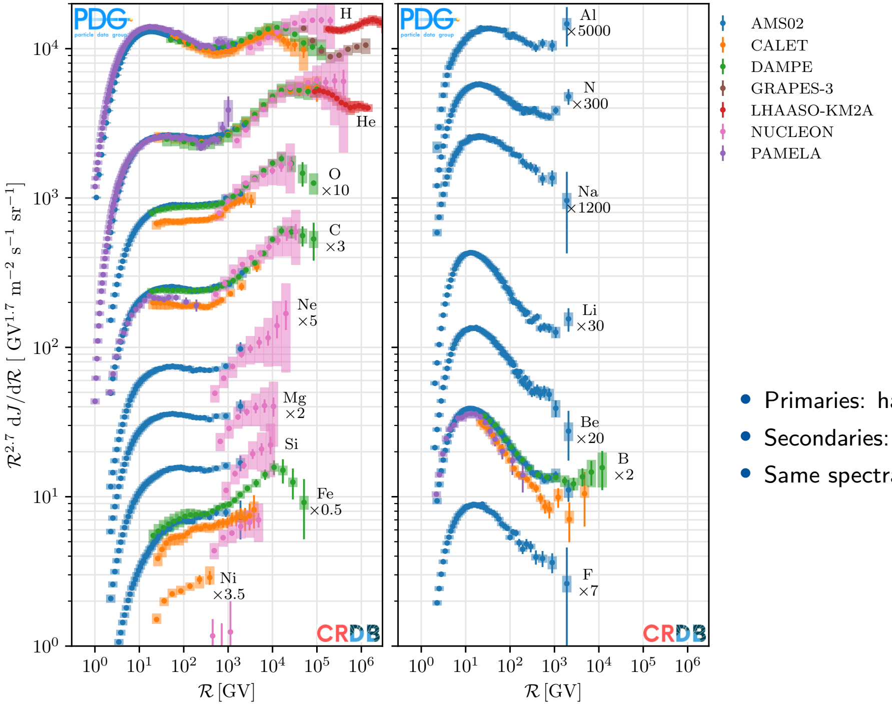




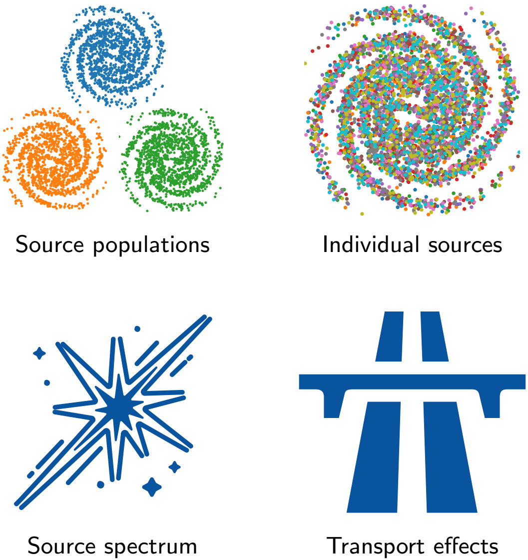
C ×3
O ×10
Ne ×5
Mg ×2
Si
Fe ×0.5
CRDB
$\mathcal{R}^{2.7}$ dJ/d$\mathcal{R}$ [ GV$^{1.7}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ ]
$\mathcal{R}$ [GV]
ACE-CRIS
ALICE
AMS01
ATIC
BACH
BESS
Balloon
CAPRICE
CREAM
CRISIS
CRN-Spacelab2
EPHIN
Explorer12
H.E.S.S.
HEAO3
IMAX
IMP
ISS-CREAM
JACEE
KASCADE
LEAP
MASS
MUBEE
OGO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

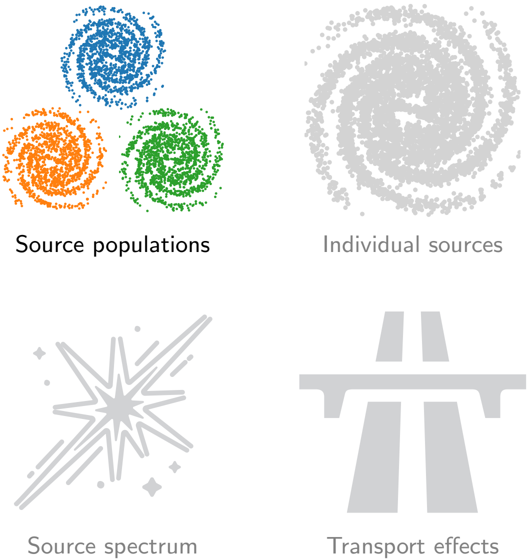


$\mathcal{R}^{2.7}\ \mathrm{d}J/\mathrm{d}\mathcal{R}\ [\ \mathrm{GV}^{1.7}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}]$
$\mathcal{R}$ [GV]
H
He
O ×10
C ×3
Ne ×5
Mg ×2
Si
Fe ×0.5
Ni ×3.5
Al ×5000
N ×300
Na ×1200
Li ×30
Be ×20
B ×2
F ×7
AMS02
CALET
DAMPE
GRAPES-3
LHAASO-KM2A
NUCLEON
PAMELA




- Primaries: harder spectra
- Secondaries: softer spectra
- Same spectral breaks


Source populations
Individual sources
Source spectrum
Transport effects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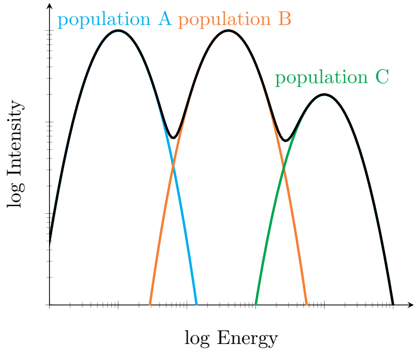
# Population of sources

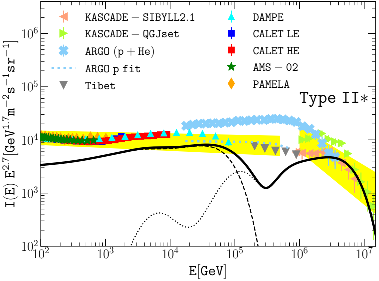



- Different populations of sources
- Hard spectra, different cut-off energies

→ Bumps and dips

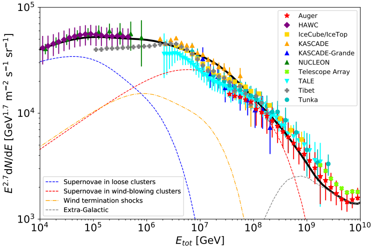
- Supernova remnants

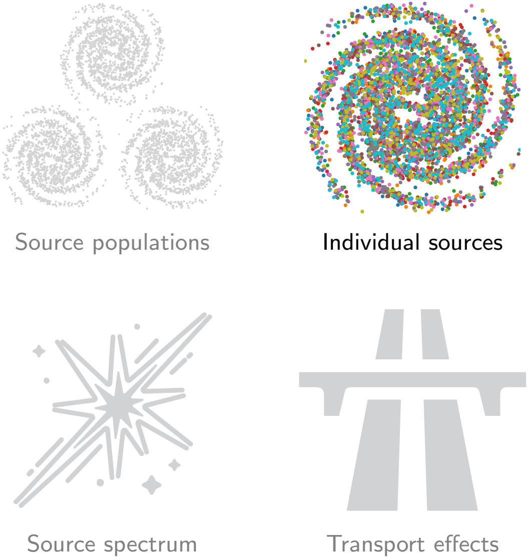
  e.g. Zirakashvili & Ptuskin (2015), Cristofari, Blasi, Amato (2020)




- *Isolated* supernova remnants + star clusters

  e.g. Reville & Vieu (2020),

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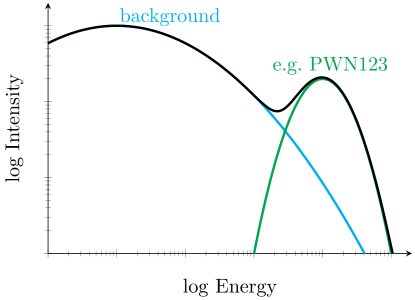
# Individual sources

Erlykin and Wolfendale (2012), Kachelrieß *et al.* (2018), Fornieri *et al.* (2020) and many more




- Background from bulk of sources
- One (or a few) individual source(s)

$\rightarrow$ Bumps and dips

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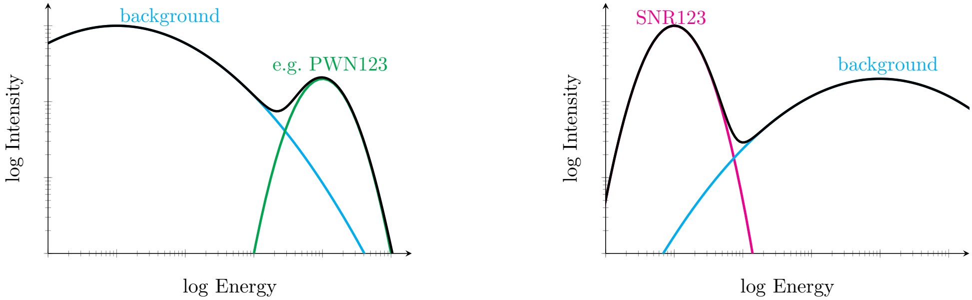


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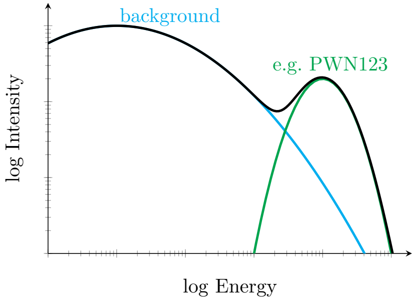


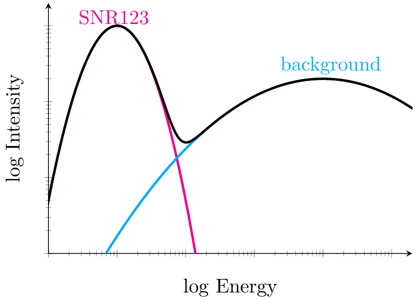


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- One (or a few) individual source(s)

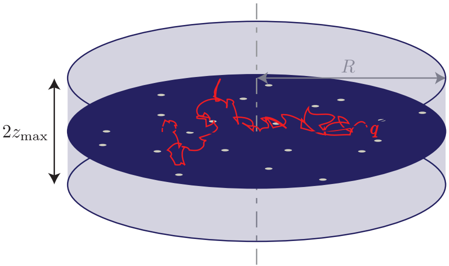
→ Bumps and dips

**Supernova remnant paradigm**

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

Génolini *et al.* (2017)

# The number of sources contributing to CR flux decreases with energy




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

With typical parameters (for details → Appendix):

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

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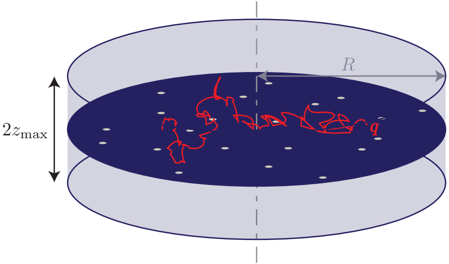


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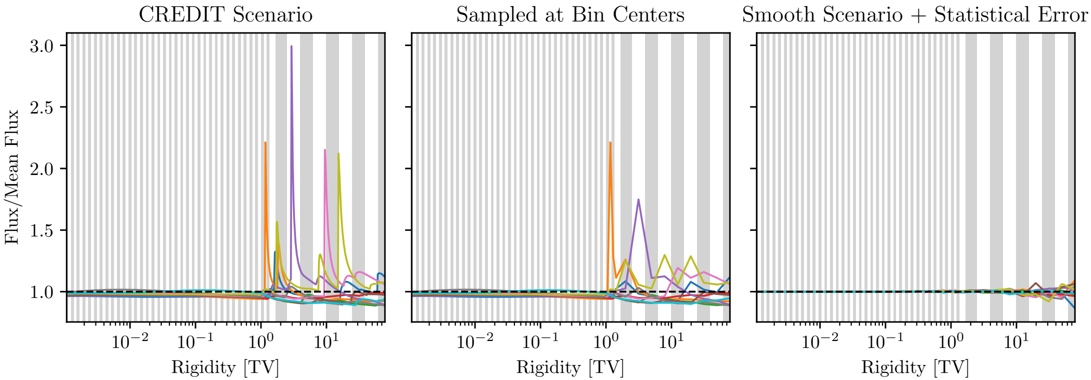
Need to run Monte Carlo simulations
instead of cherry-picking catalogues!

# Statistical errors are much smaller than CREDIT features

Stall, Loo, Mertsch (2025)

**B**-field amplification + time-dependent escape → prominent features



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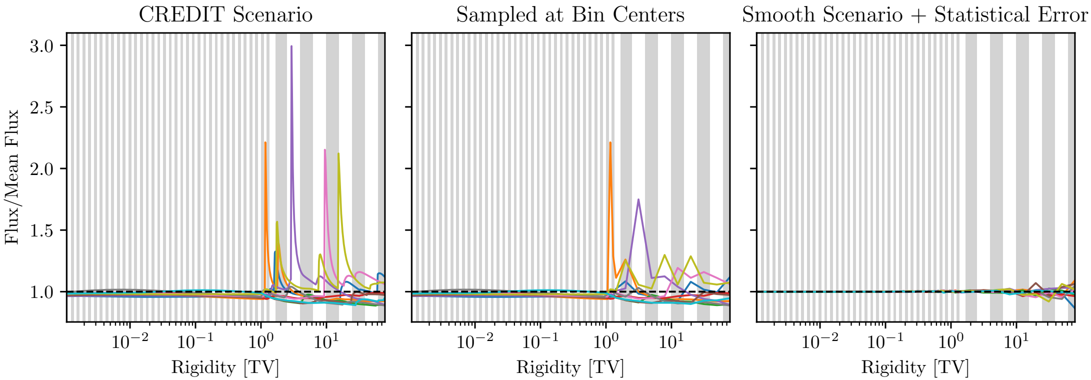
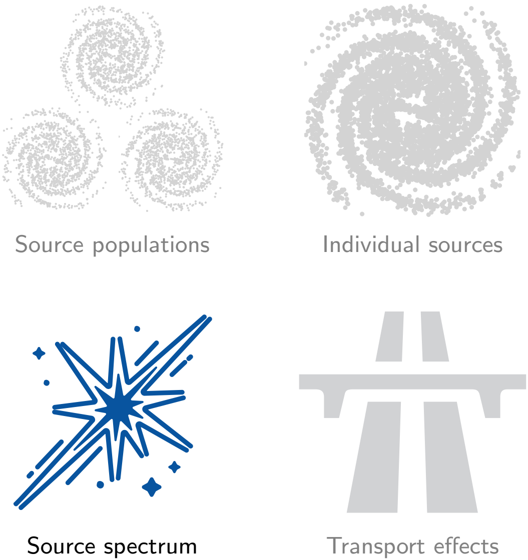



## What can we learn?

- Test of field-amplification models
- Supernova paradigm


Source populations
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Source populations



Individual sources

Source spectrum



Transport effects

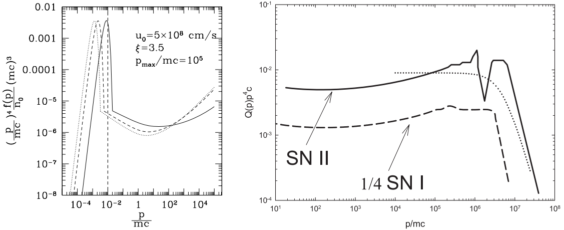
# Feature in source spectrum

**Reminder: Solution (without advection or decay)**

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

# Example: concavity of non-linear diffusive shock acceleration

Blasi, Gabici, Vannoni (2005)   Ptuskin & Zirakashvili (2005)



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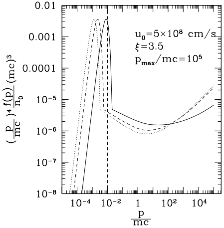


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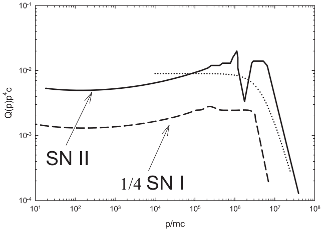


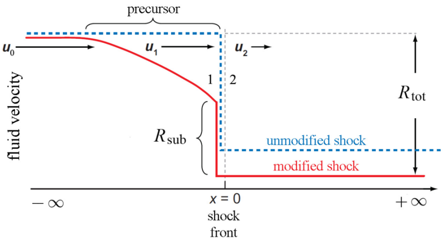


- Spectral index $\gamma$ depends on compression ratio $r$: $\gamma \sim \dfrac{3r}{r-1}$
- Low energy particles: stay close to shock $\rightarrow$ experience only subshock $\rightarrow$ soft spectrum
- High energy particles: travel further $\rightarrow$ experience full shock $\rightarrow$ hard spectrum

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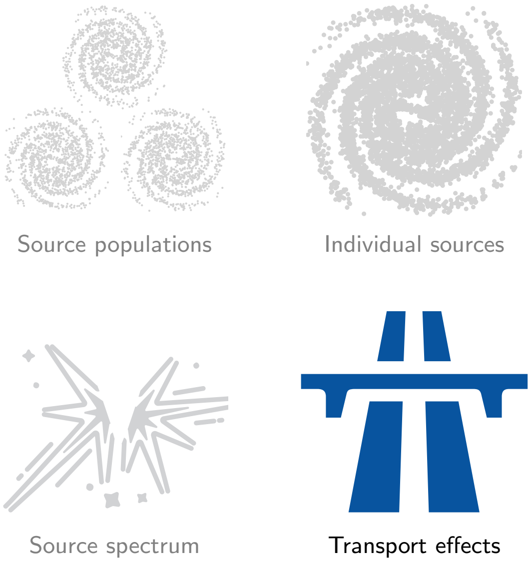
**Potential issue**

- $\mathcal{R}_{\text{feature}}$ depends on environmental parameters
- Scatter in environmental parameters; time-dependencies

$\rightarrow$ Feature washed out in superposition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# Feature in diffusion coefficient

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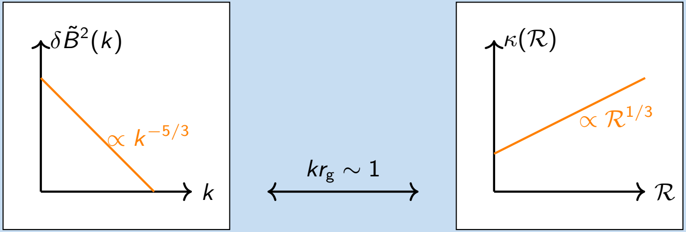
**Resonant interactions**



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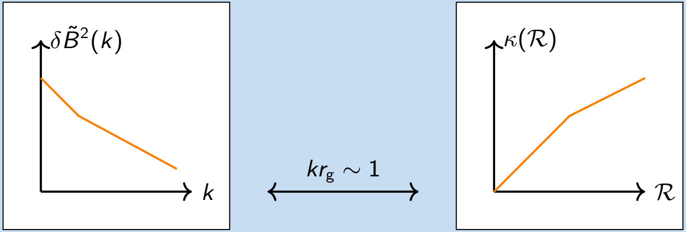
**Resonant interactions**

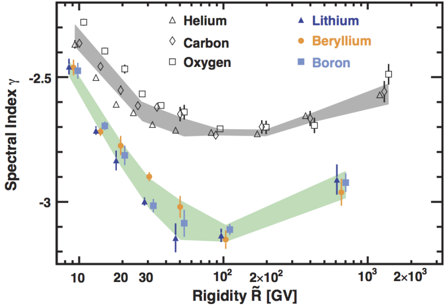


# Source or transport?

- 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)



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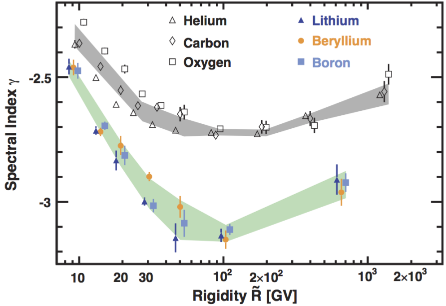


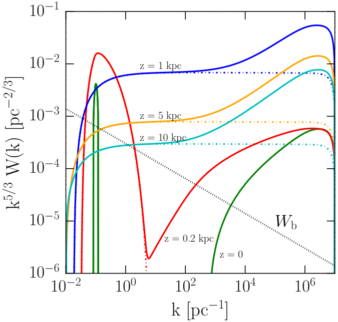

**What can we learn?**

The break is in the diffusion coefficient!

# Streaming instability and large-scale transport

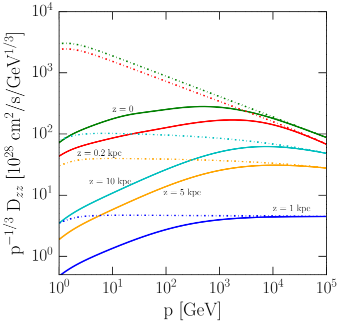
Evoli *et al.*, PRD **99** (2019) 103023

### Turbulence power spectrum




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

### Diffusion coefficient



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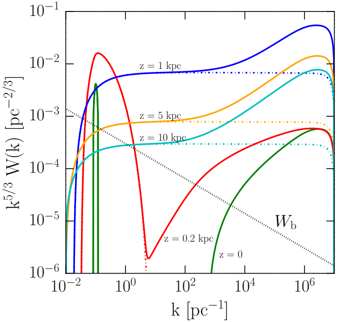
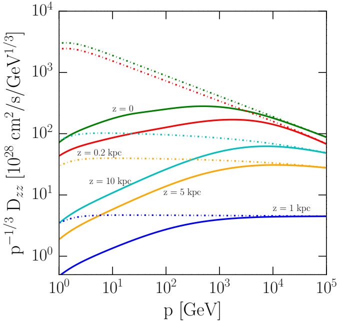



$$\xrightarrow{\left(\frac{k}{10^6\,\mathrm{pc}^{-1}}\right) \sim \left(\frac{p}{\mathrm{GeV}}\right)^{-1}}$$

Diffusion coefficient




### What can we learn?

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

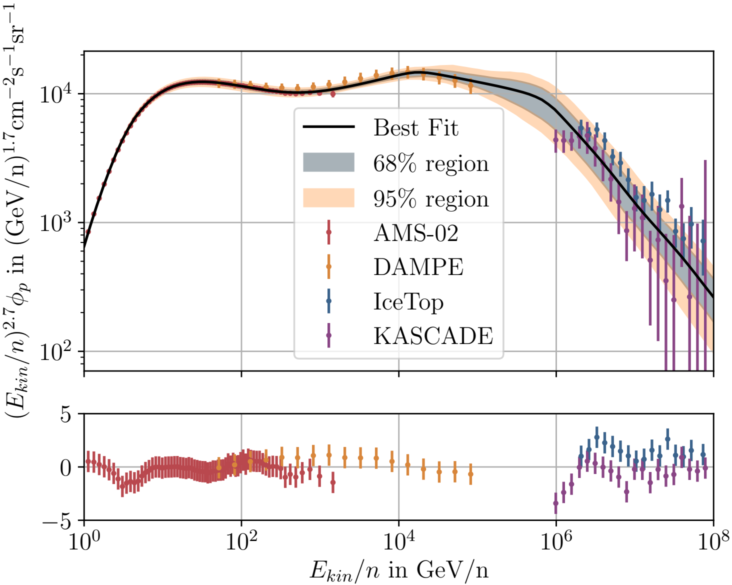
$\to$ Turbulence generated by $\begin{cases} \text{supernovae} & \text{for } k \lesssim k_{\mathrm{br}} \\ \text{cosmic rays} & \text{for } k \gtrsim k_{\mathrm{br}} \end{cases}$

$\to$ Important consequences for galaxy formation and evolution

# Anatomy of a diffusion coefficient

Schwefer, Mertsch, Wiebusch (2022)

Proton



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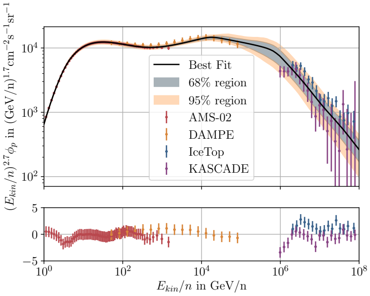
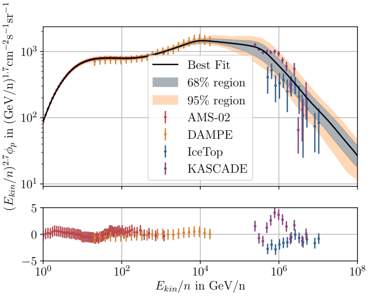
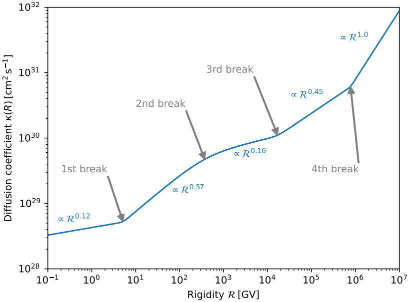


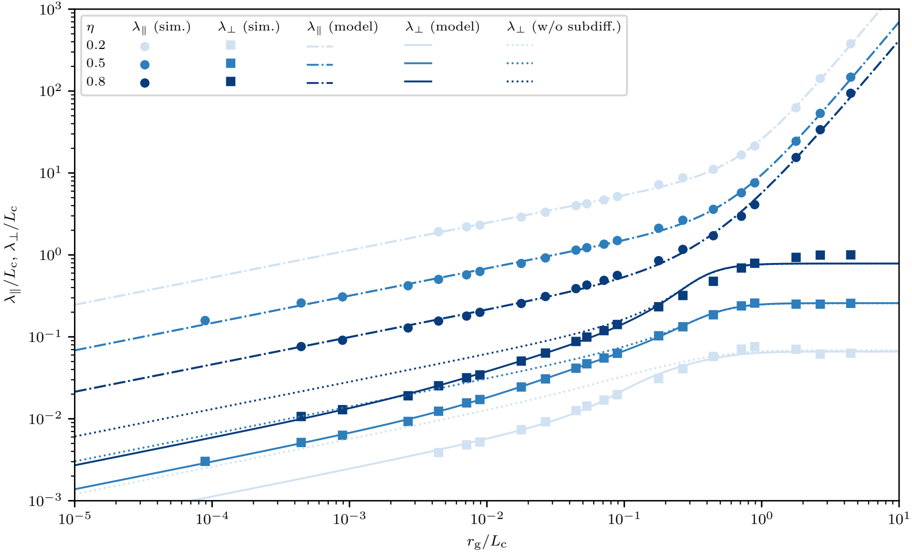

Helium



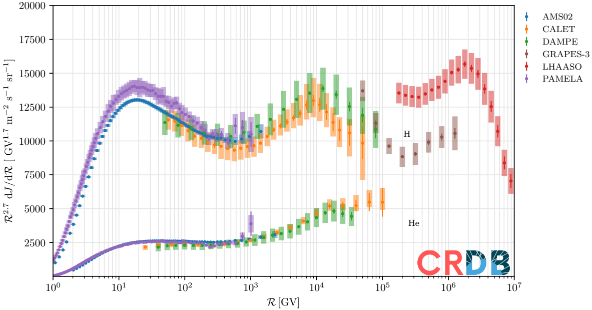

- 1. Break: Hardening of spectra at low energies due to stochasticity effect Phan *et al.* (2021) (for details $\rightarrow$ Appendix):
- 2. Break: Transition from self-generated to external turbulence Blasi, Amato, Serpico (2012)
- 3. Break: ?!
- 4. Break: Transition from resonant to small-angle scattering

# Mean-free paths

Kuhlen, Mertsch, Phan (2025)



# Non-universality




- Spectral breaks at $\sim$ same rigidities ☺
- Spectral indices shifted by $\sim 0.1$ ☹

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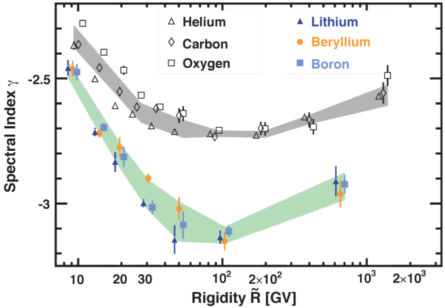


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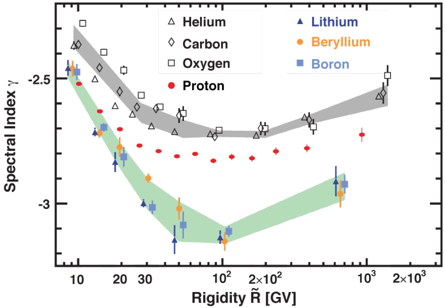


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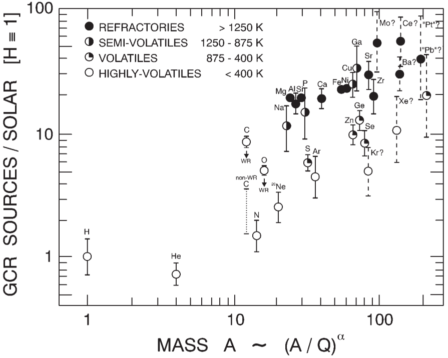
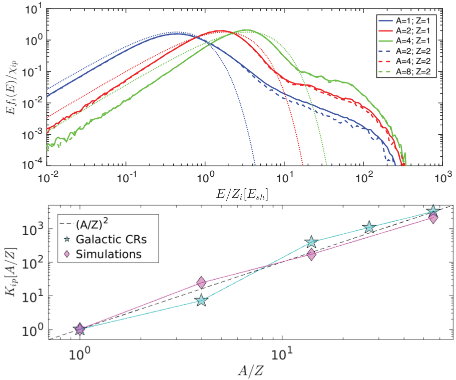
# Species-dependence in DSA?

Meyer, Drury, Ellison (1997)




Caprioli, Yi, Spitkovsky (2017)




Source abundances ∼ solar, but with mass-dependent trend

Injection into DSA depends on $A/Z$, but spectral shapes are the same

# Environmental effect

Ohira & Ioka (2010)

1. $p_{\mathrm{max}}$ decreases with time or $R_{\mathrm{sh}}$:

$$p_{\mathrm{max}}(R_{\mathrm{sh}}) \propto R_{\mathrm{sh}}^{-\alpha}, \quad \text{e.g.} \quad p_{\mathrm{max}} = Z p_{\mathrm{knee}} \left( \frac{R_{\mathrm{sh}}}{R_{\mathrm{Sedov}}} \right)^{-\alpha}; \quad \text{e.g.} \quad \alpha = 6.5$$

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Inverse function: $p_{\mathrm{max}}^{-1}(p) \propto p^{-1/\alpha}$

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Ohira & Ioka (2010)

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4. $s$, $\alpha$ depend on environment, $\beta$ can depend on species

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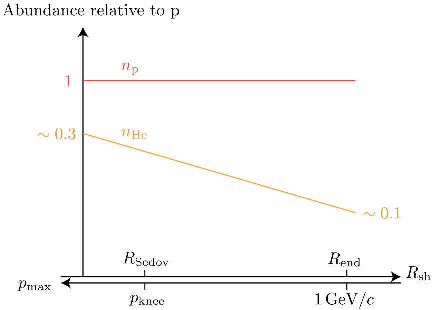

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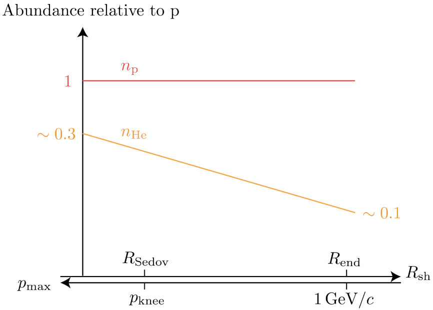


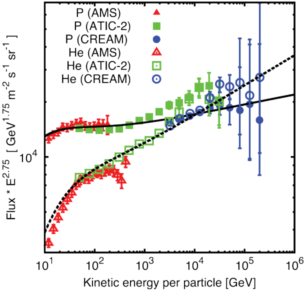

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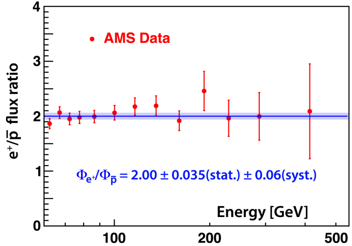

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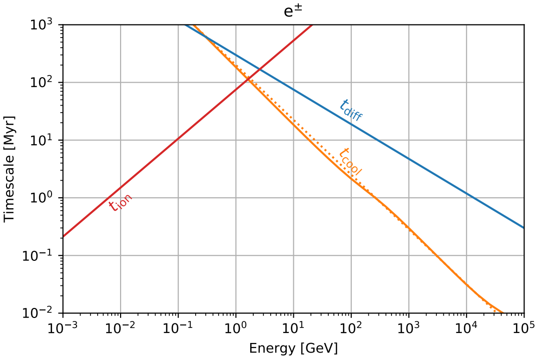
Time scales:

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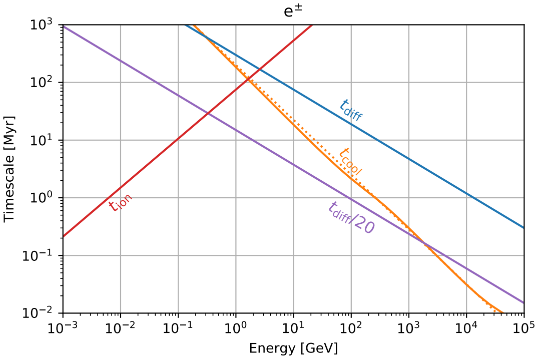


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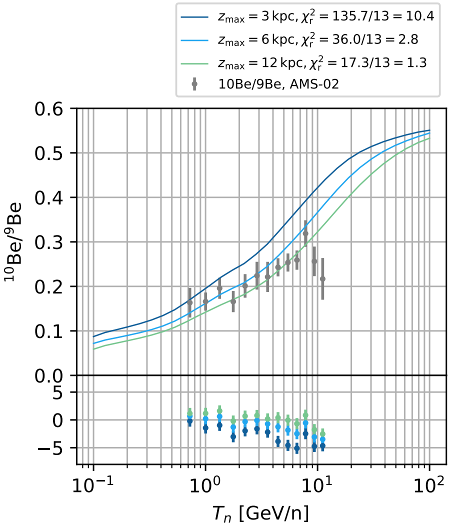


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- Transition escape $\rightarrow$ cooling leads to spectral break
- If $t_{\mathrm{diff}}(1\mathrm{GeV}) \sim t_{\mathrm{cool}}(1\mathrm{GeV}) \rightarrow$ hidden due to other transport processes
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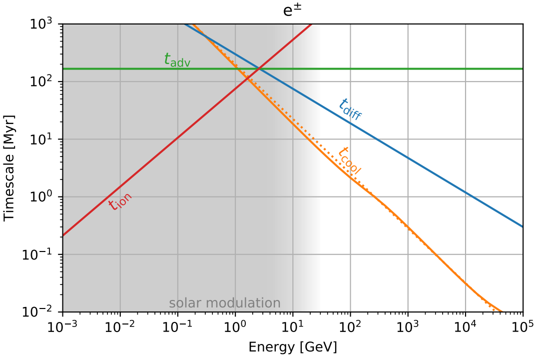


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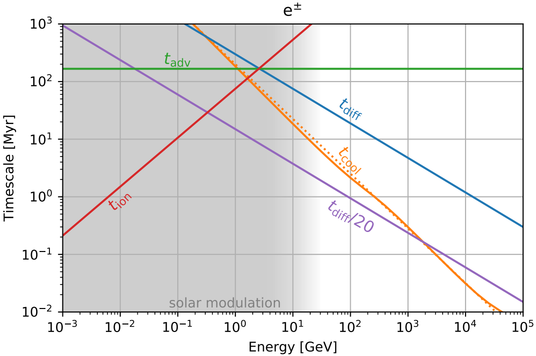


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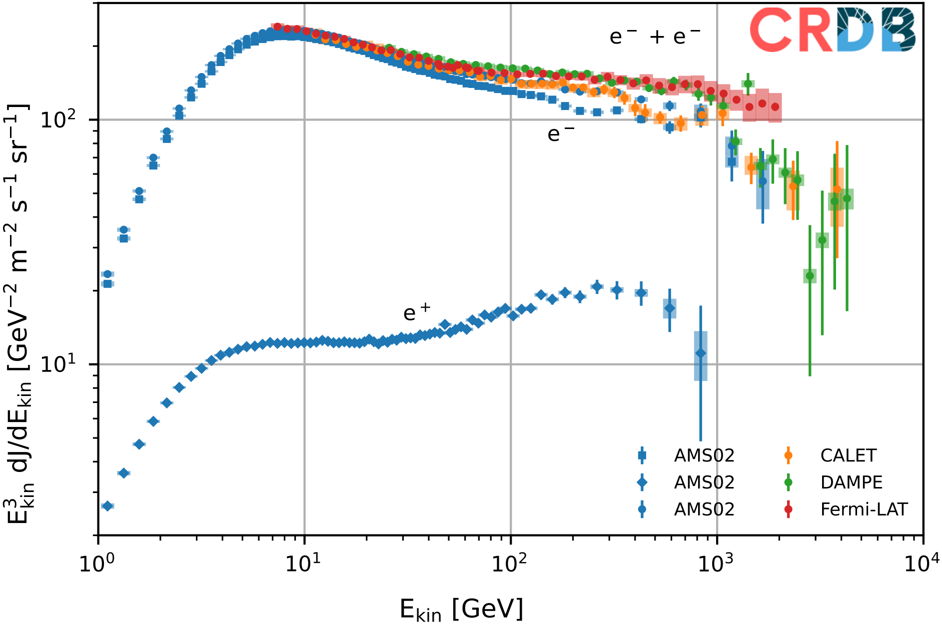

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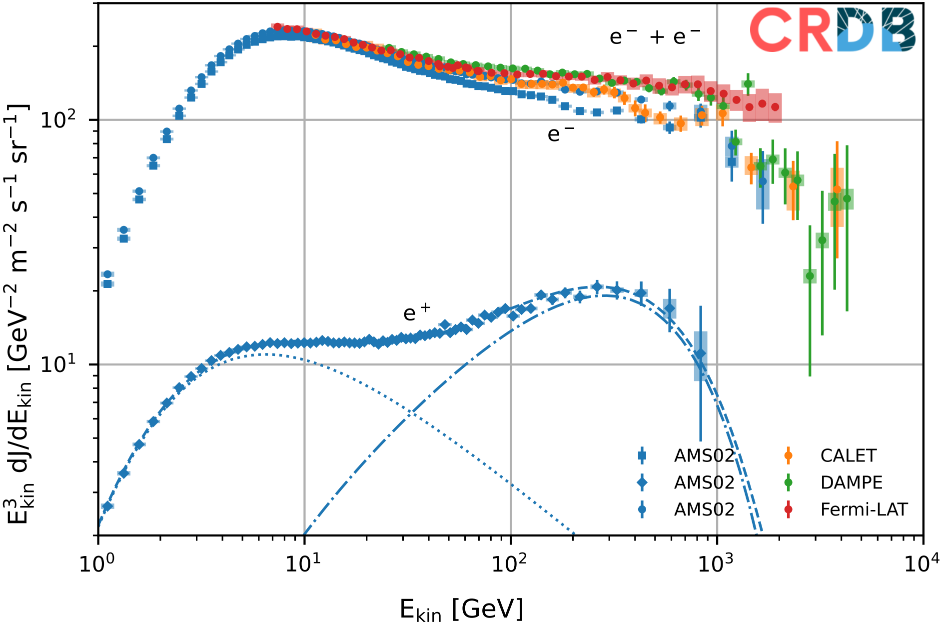

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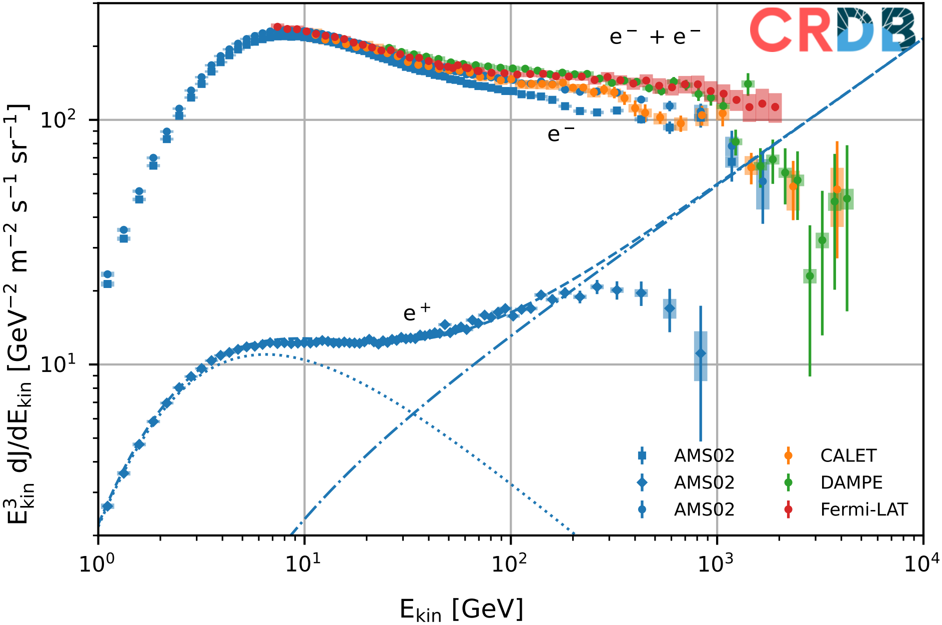

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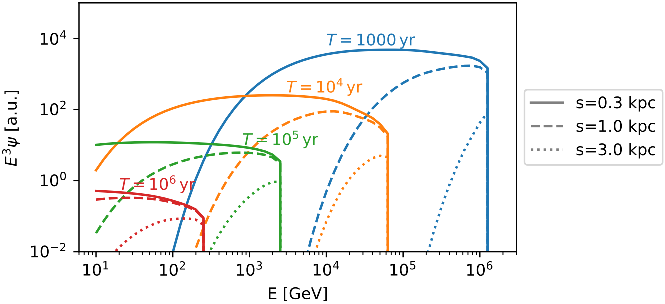


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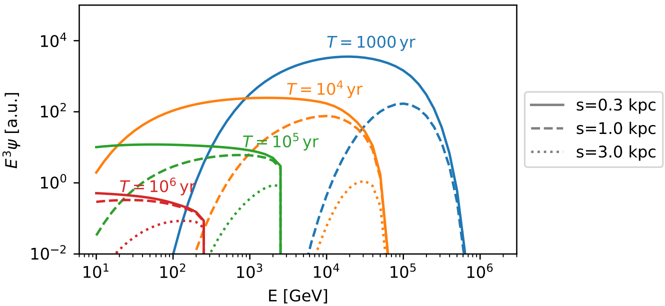


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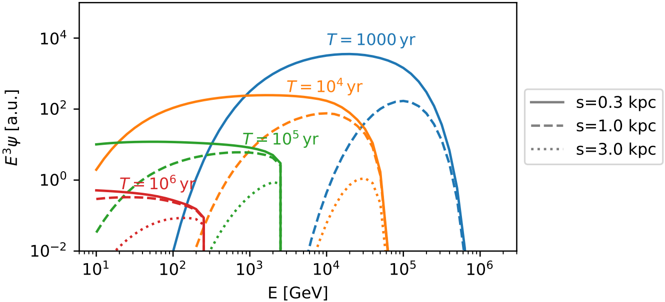


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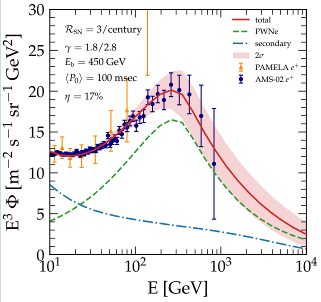
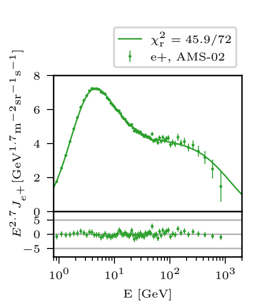
## Pulsars

e.g. Evoli *et al.* (2020)




## Other astro sources

e.g. Mertsch, Sarkar, Vittino (2020)



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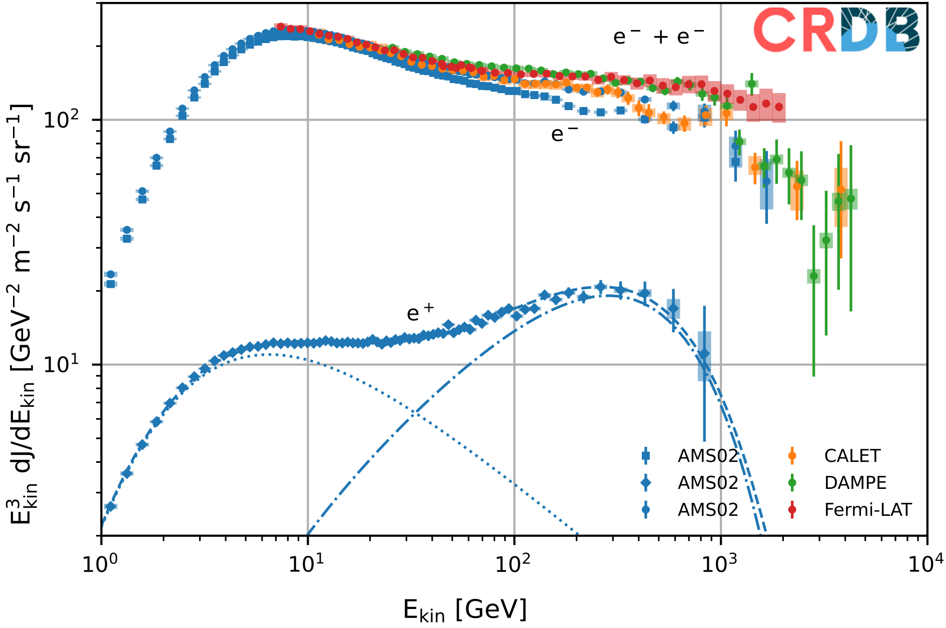

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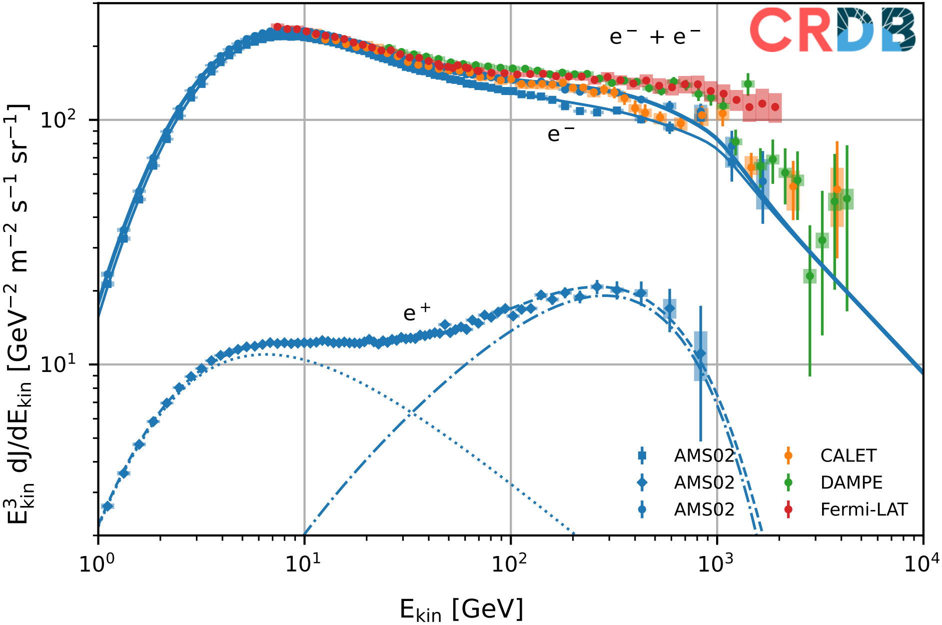
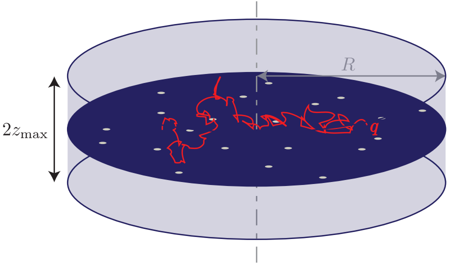


# The number of sources contributing to CR flux decreases with sharply energy




- Residence time: $t_{\mathrm{cool}} = \frac{E}{\dot{E}}$
- Diffusion distance: $R = \sqrt{2\kappa t_{\mathrm{cool}}}$
- Source density: $\sigma = \frac{\nu t_{\mathrm{cool}}}{\pi R_{\mathrm{disk}}^2}$
- Source number: $N_{\mathrm{src}} = \sigma \pi R^2 = \nu t_{\mathrm{cool}} \frac{2\kappa t_{\mathrm{cool}}}{R_{\mathrm{disk}}^2}$

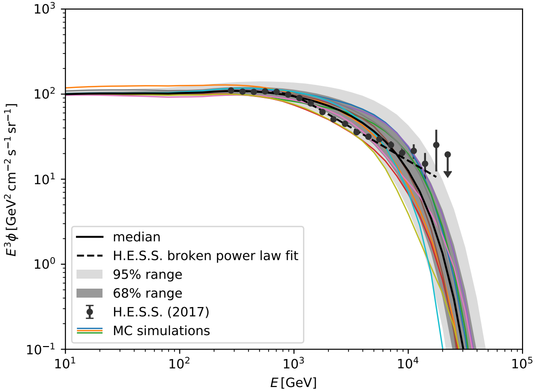
With typical parameters (for details → Appendix):

$$\mathcal{R} = 10\,\mathrm{GV}\,, \quad 10\,\mathrm{TV}\,, \quad 10\,\mathrm{PV}$$
$$N_{\mathrm{src}} \simeq 2 \times 10^4\,, \quad 1\,, \quad 10^{-4}$$

# Spectral shape and source rate

Mertsch (2018)

## Canonical supernova rate




Statistically disfavoured

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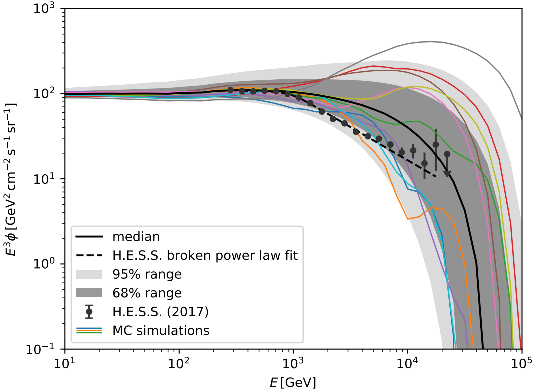


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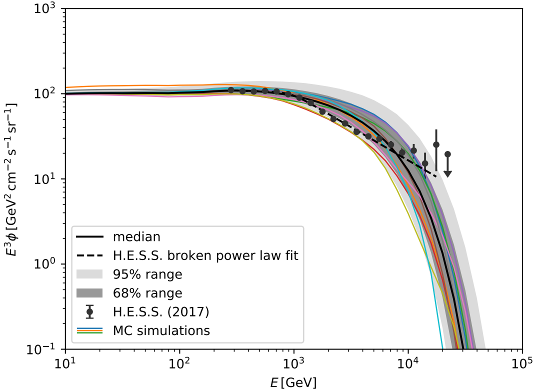


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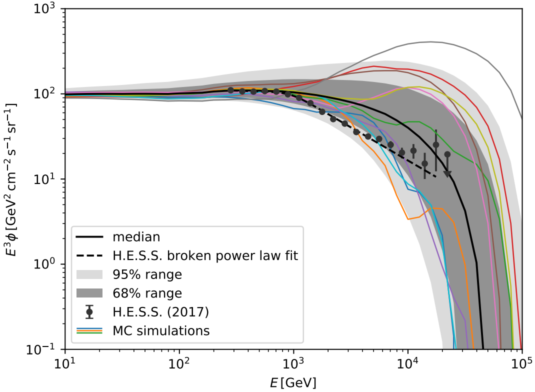


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**What can we learn?**

The TeV break indicates lower source rate, e.g. super bubbles

Any questions?

# Outline

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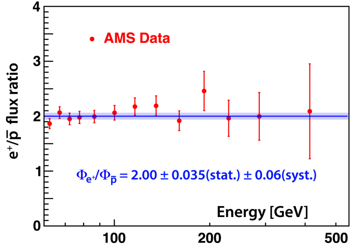

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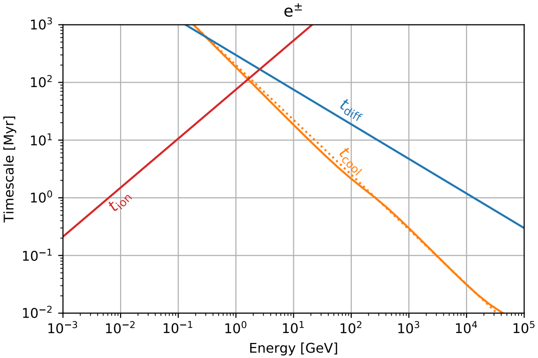


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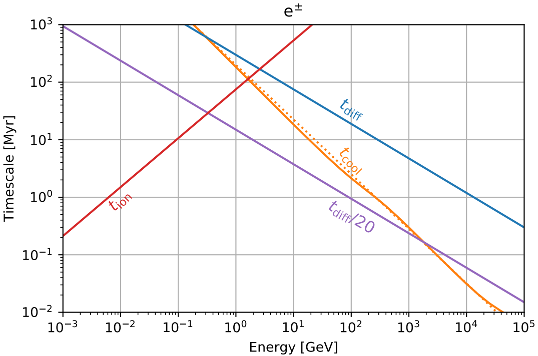


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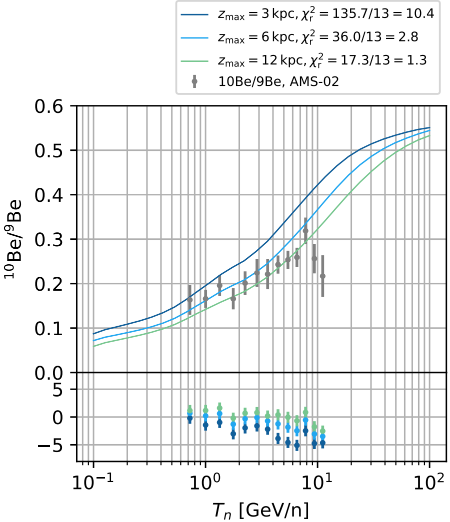


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