Stochastic modelling of cosmic ray sources sped up

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Cosmic ray sources

Long-standing questions

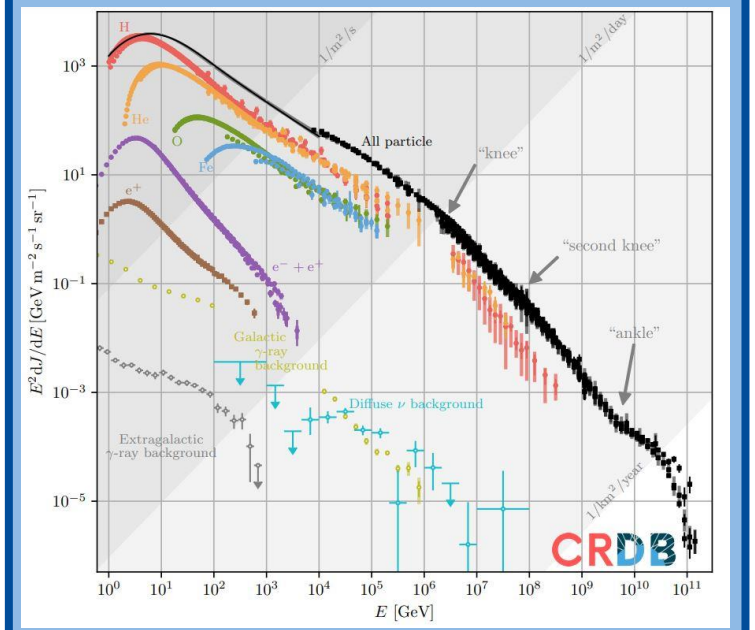
What are the sources of cosmic rays?

How can galactic cosmic rays reach **PeV** energies?

How do cosmic rays **escape** their sources?

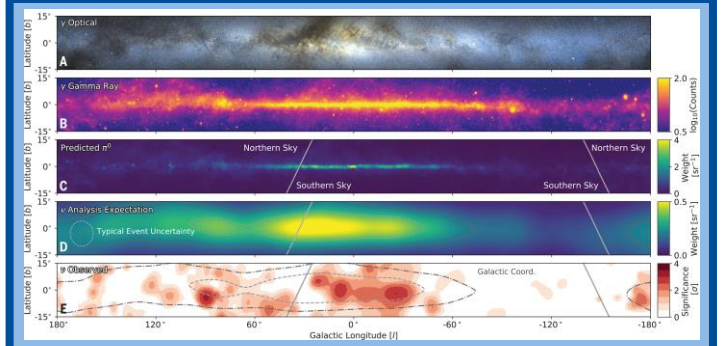
?

Cosmic Ray Spectrum



[CRDB – 2023]

Diffuse emissions



[IceCube – 2023]

Source stochasticity

What are the sources? → Supernova paradigm

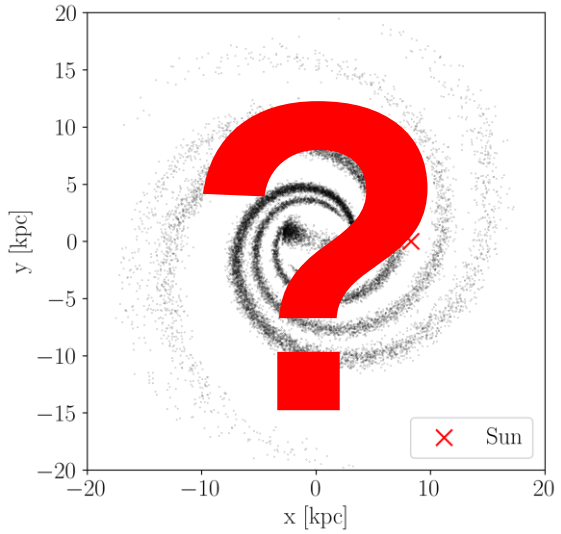
Where are the sources? → Very limited knowledge

How do we deal with our limited knowledge?

Smooth source distribution **vs.** **Discrete sources**

- good, if many sources contribute

- Monte Carlo approach
- necessary, if few sources contribute



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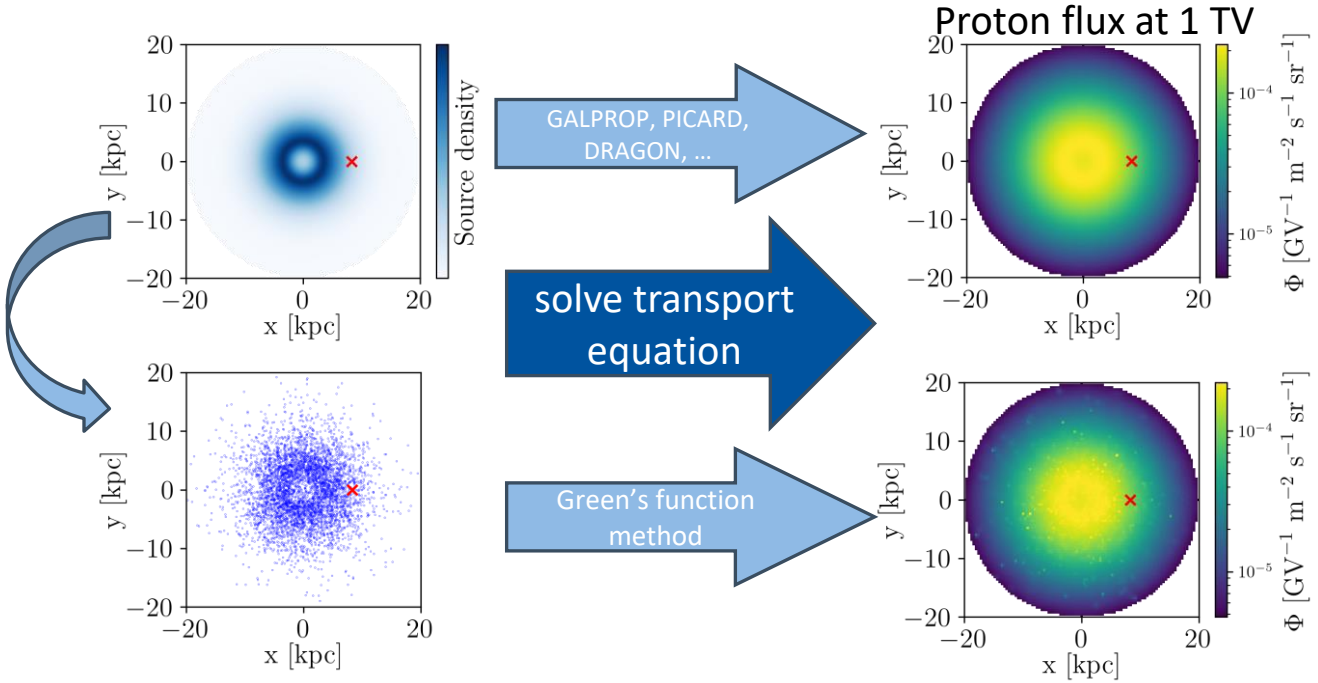


Examples for stochasticity studies:

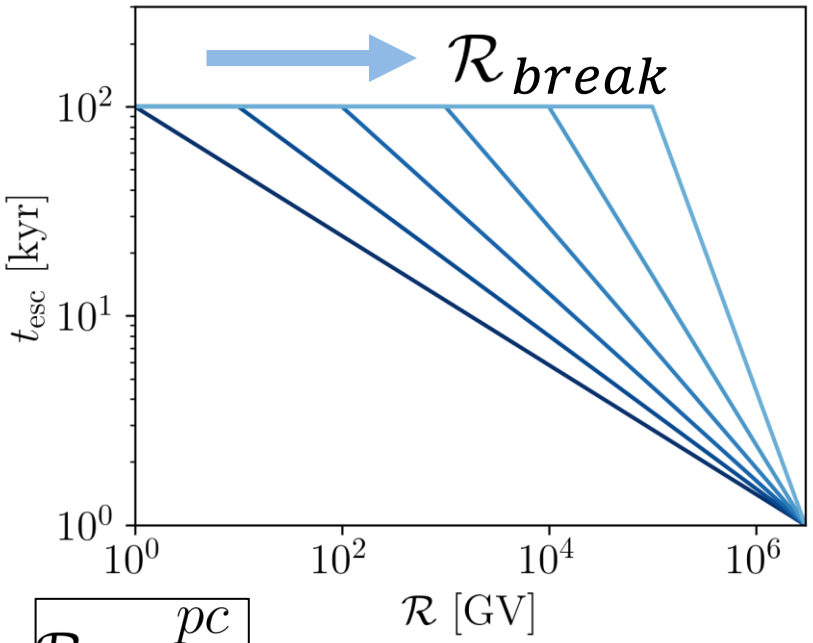
- High energy electrons
  e.g. [Mertsch'18]
- Low energy cosmic rays
  e.g. [Phan'23]
- High energy protons
  e.g. [Genolini'17]

Source modelling

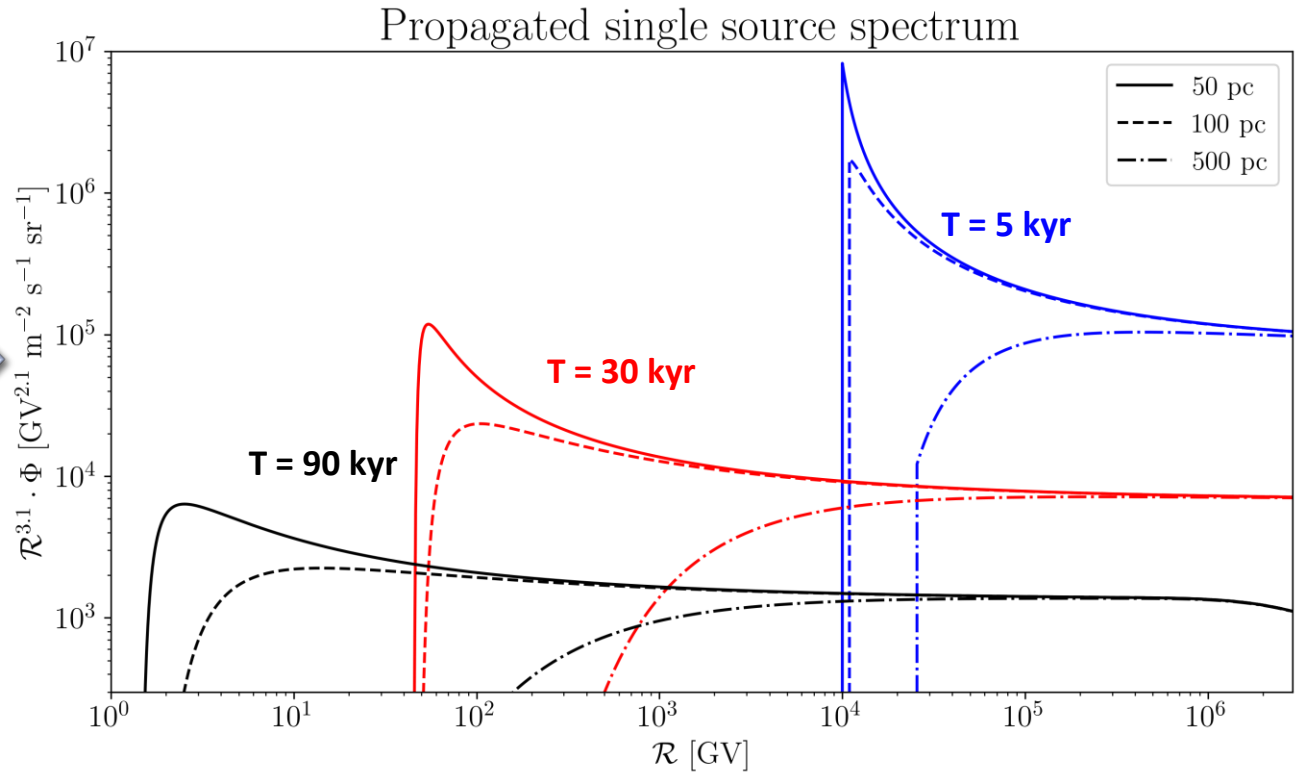
Solve cosmic ray transport equation for point source (Green's function)

$$\mathcal{L}\left[G\right]\left(t,\mathbf{x},\mathcal{R};t_i,\mathbf{x}_i\right)=\delta\left(t-t_i\right)\delta\left(\mathbf{x}-\mathbf{x}_i\right)Q\left(\mathcal{R}\right)$$ + boundary condition

Time-dependent escape



$$\mathcal{R}=\frac{pc}{Ze}$$



Source modelling

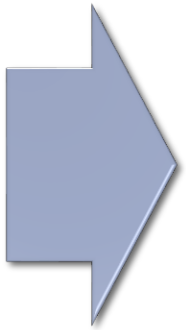
Add contributions from sources with randomly drawn positions $\mathbf{x}_i$ and ages t_i

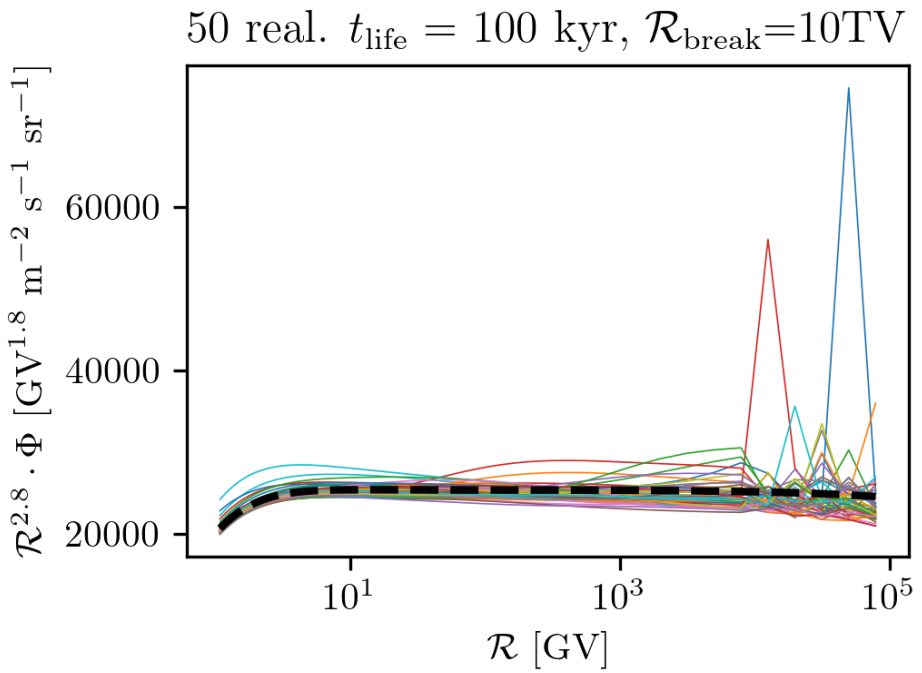
- flux at position $\mathbf{x_0}$ and time t_0 is calculated as sum over all source contributions:

$$\Phi = \sum_{i=1}^{N} G\left(t_0, \mathbf{x}_0, \mathcal{R}; t_i, \mathbf{x}_i\right)$$

each contribution calculated **the same way**

contributions can be calculated in **parallel**



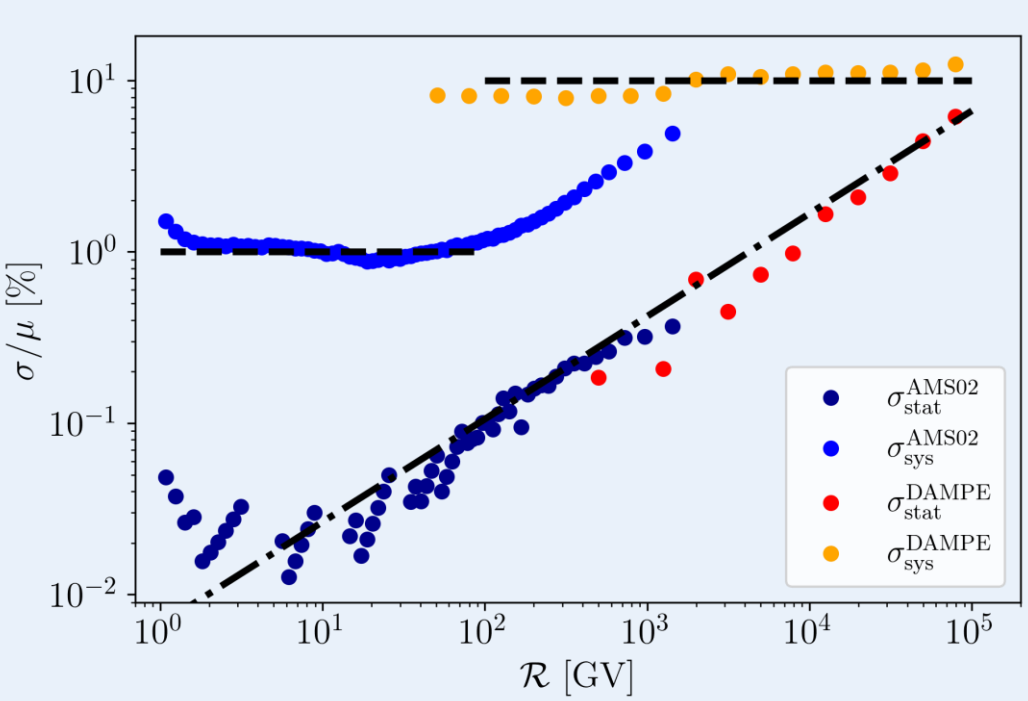


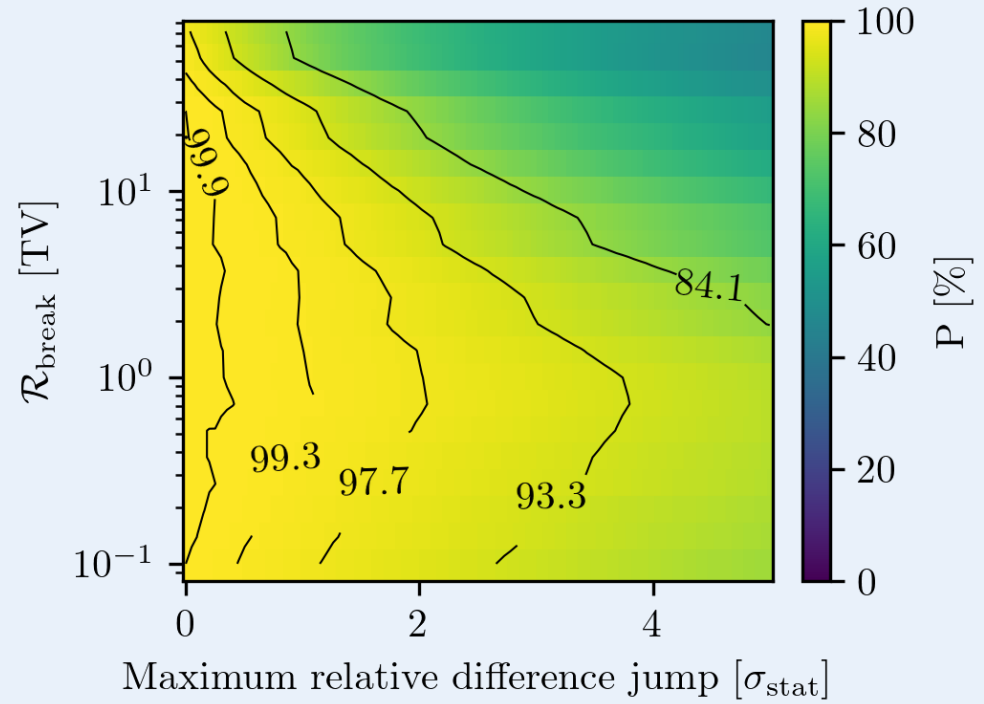
Young sources, that are not fully evolved, contribute with pronounced jump-like features!

➢ **Would we detect those if this was the correct escape model?**

Results of stochastic modelling

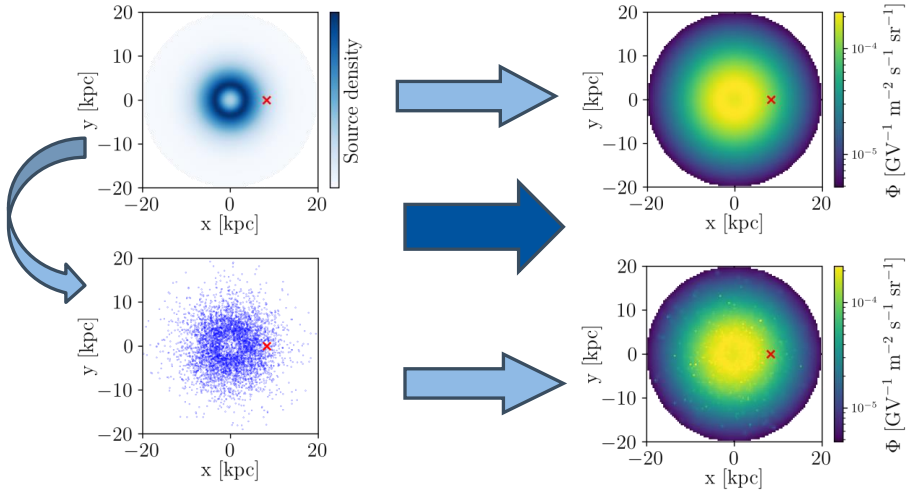
Could jumps due to time-dependent escape be detected?

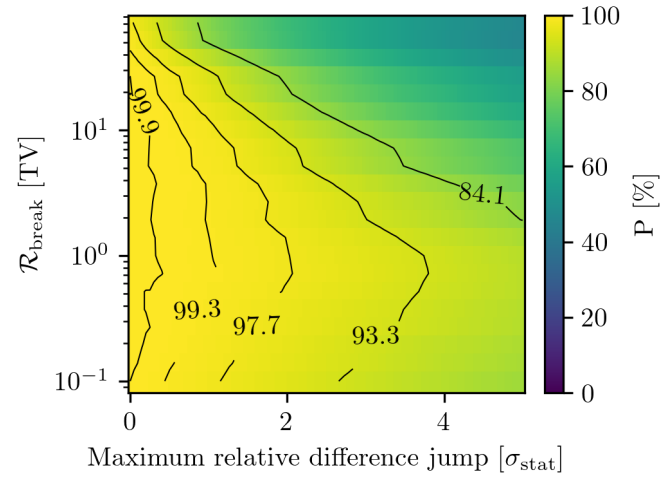




Summary and Outlook

1. **Individual sources** must be considered for the realistic modelling.
2. **Computations** can potentially be **accelerated using GPUs.**
3. **Local measurements** can be used to **constrain source properties.**
4. **Stochasticity** in galactic diffuse emissions can be **quantified.**





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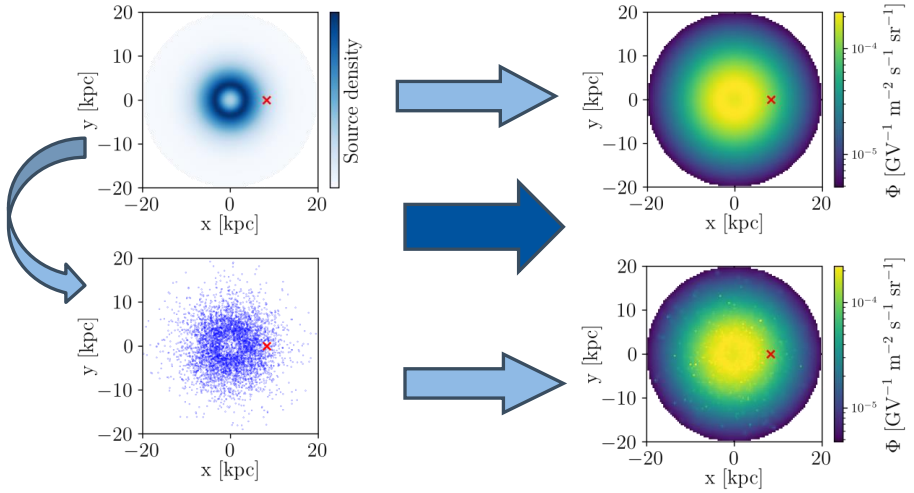

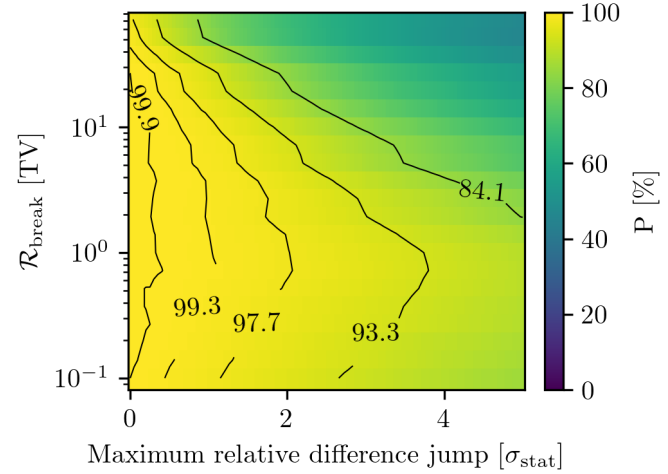

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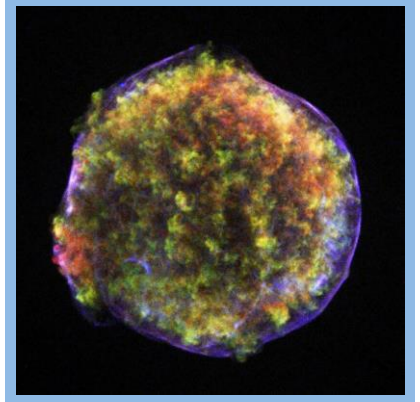
Thank you!

Questions?

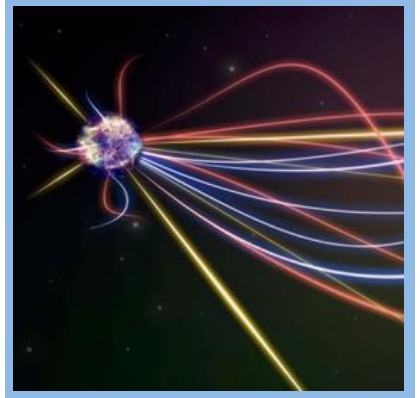
Backup

Modelling of cosmic rays

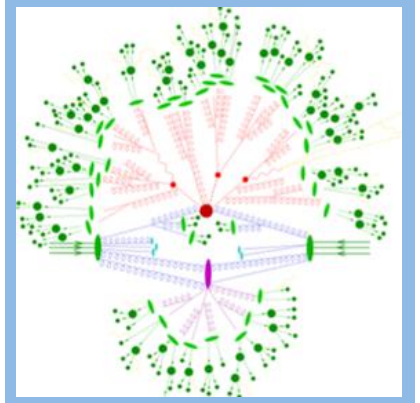
Source properties



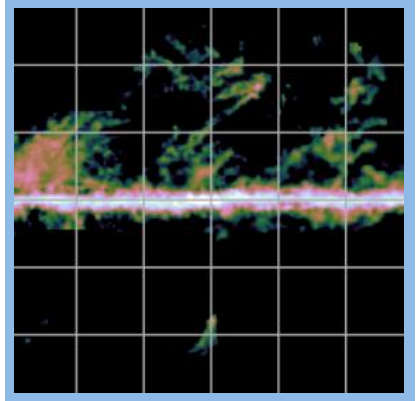
Cosmic ray transport



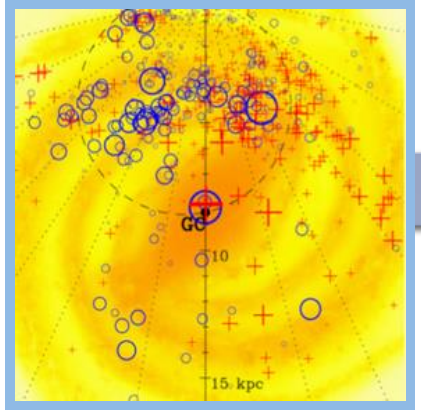
Cross-sections

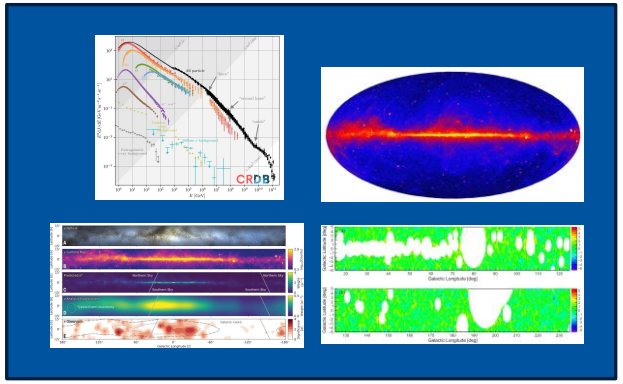


Gas maps



Source distribution





Others

Magnetic fields
Re-acceleration
Solar modulation
...

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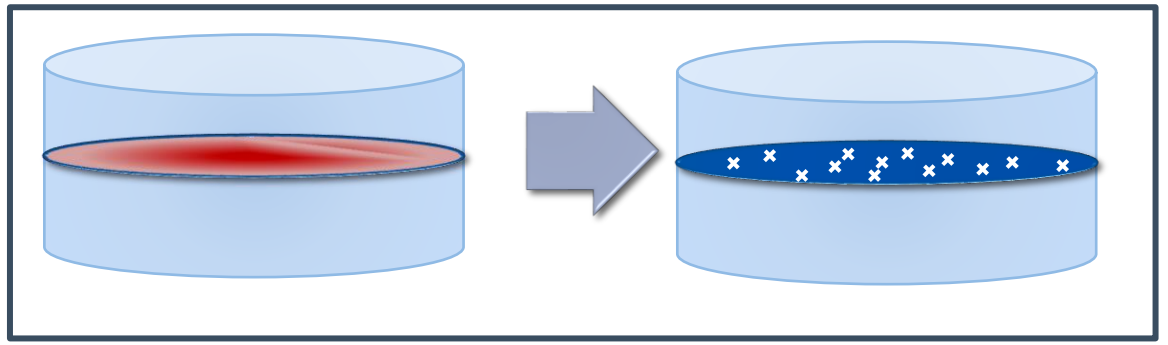
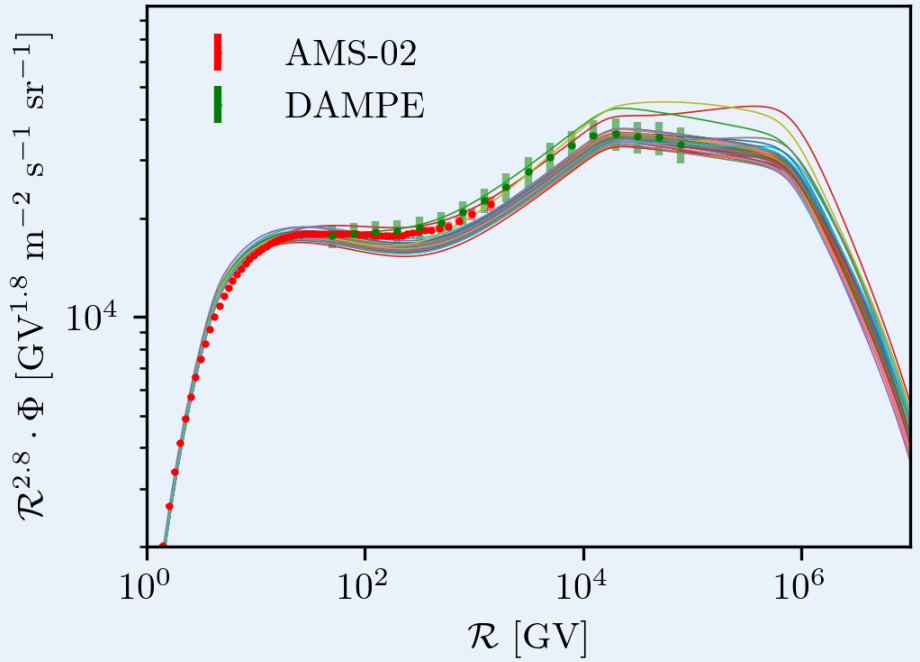


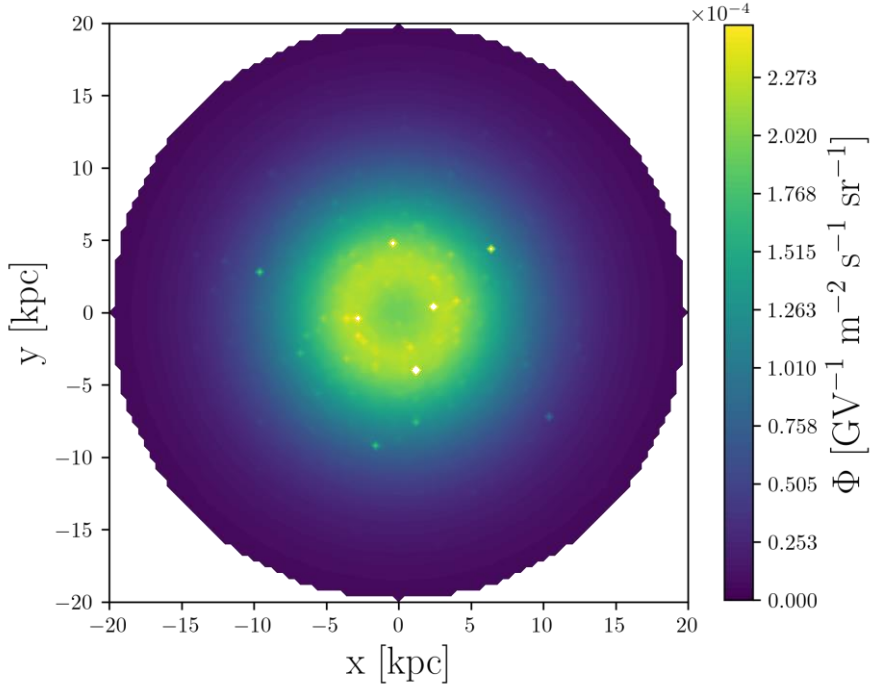
Results for the stochastic proton spectrum

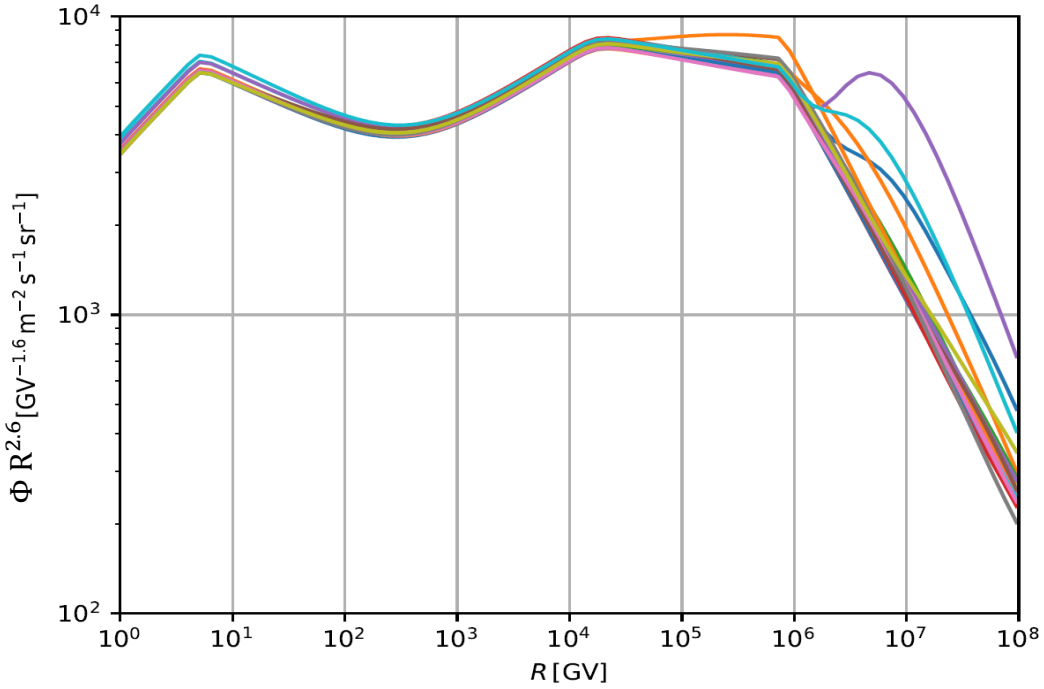


Fluctuations are larger at higher rigidities relevant for galactic diffuse γ and ν at 100 TeV.

Stochastic proton spectrum

Proton flux Φ at 1 TV





The average is consistent with the corresponding smooth model, but fluctuations occur.

Fluctuations are larger at higher energies/rigidities.

Features in PV protons are relevant for galactic diffuse $\boldsymbol{\gamma}$ and $\boldsymbol{\nu}$ at 100 TeV.