Propagation in the Galactic magnetic field

Flux predictions for Galactic and extragalactic cosmic rays

Alex Kääpä

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Galactic magnetic field (GMF)

see also: PoS(ICRC2021)004

GMF model: JF12 (ApJ 757 14x) with three components:

- Large-scale regular
- Large-scale random (striated)
- (Small-scale) random

GMF has **three regions** of differing **field strength**:

- **Galactic plane (GP): ~ 1 – 10 μG**
- Halo: ~ 0.1 – 1 μG
- Edge of Galaxy: 10 – 100 nG

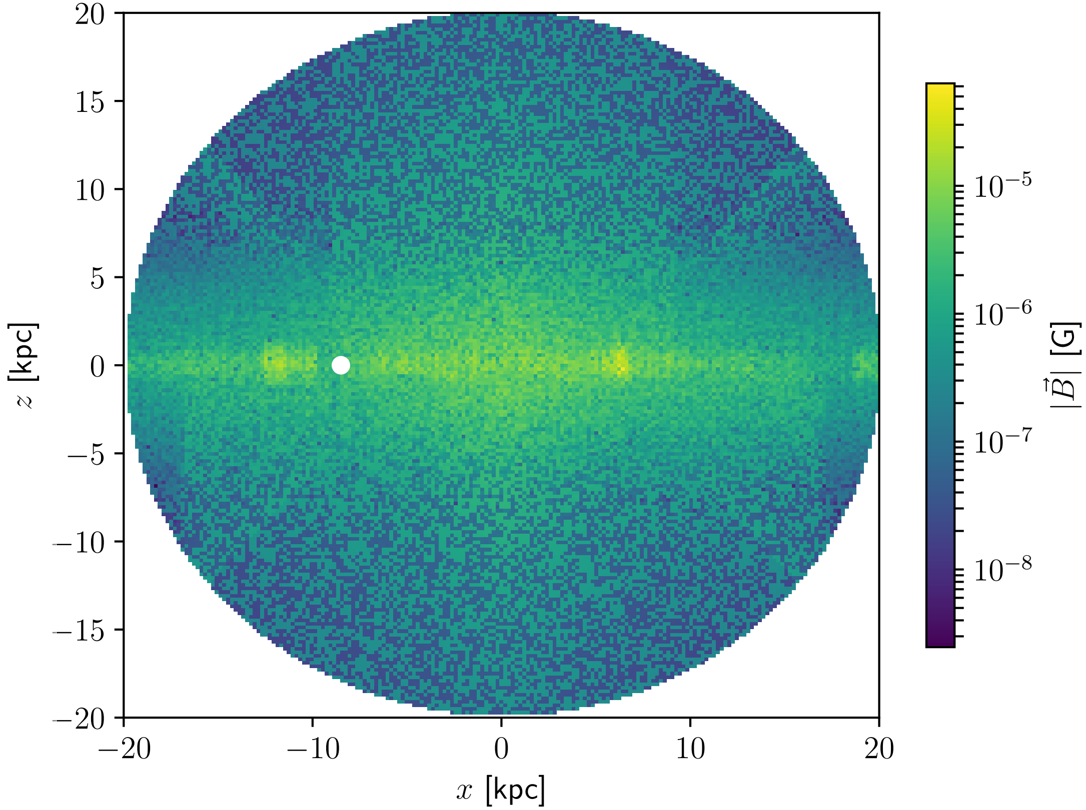
Gyroradius r_g:

$$r_g[\mathrm{pc}] \approx 11 \cdot \frac{R\,[\mathrm{PV}] \cdot v_\perp/c}{B\,[\mu\mathrm{G}]}, \quad R = E/Ze$$

Transition region = **change in propagation regimes**

- **diffusive** → **ballistic** propagation

x-z projection of JF12 field



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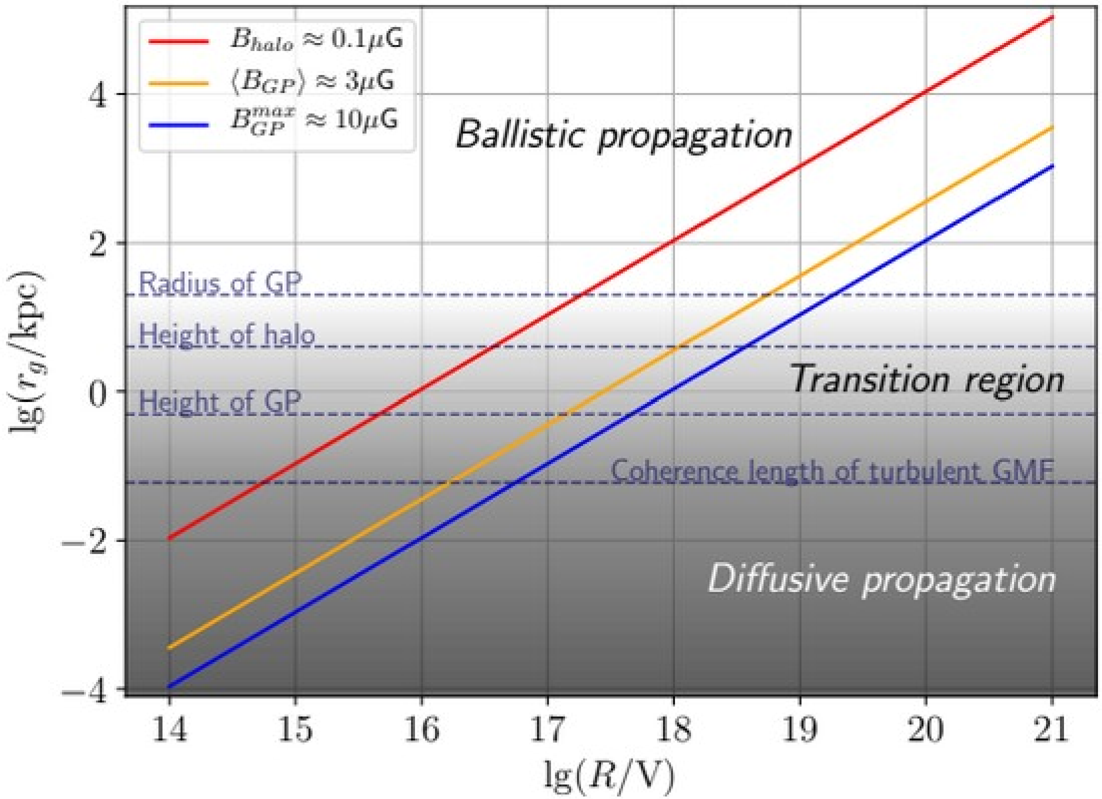
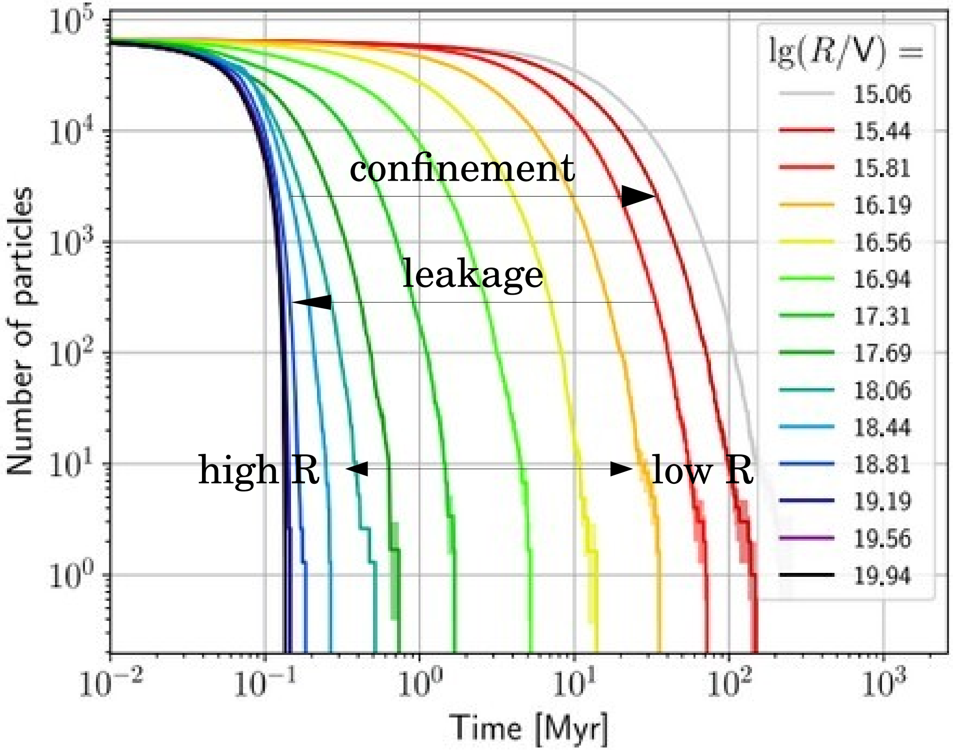
Change of gyroradius with rigidity plus typical length scales of Galaxy



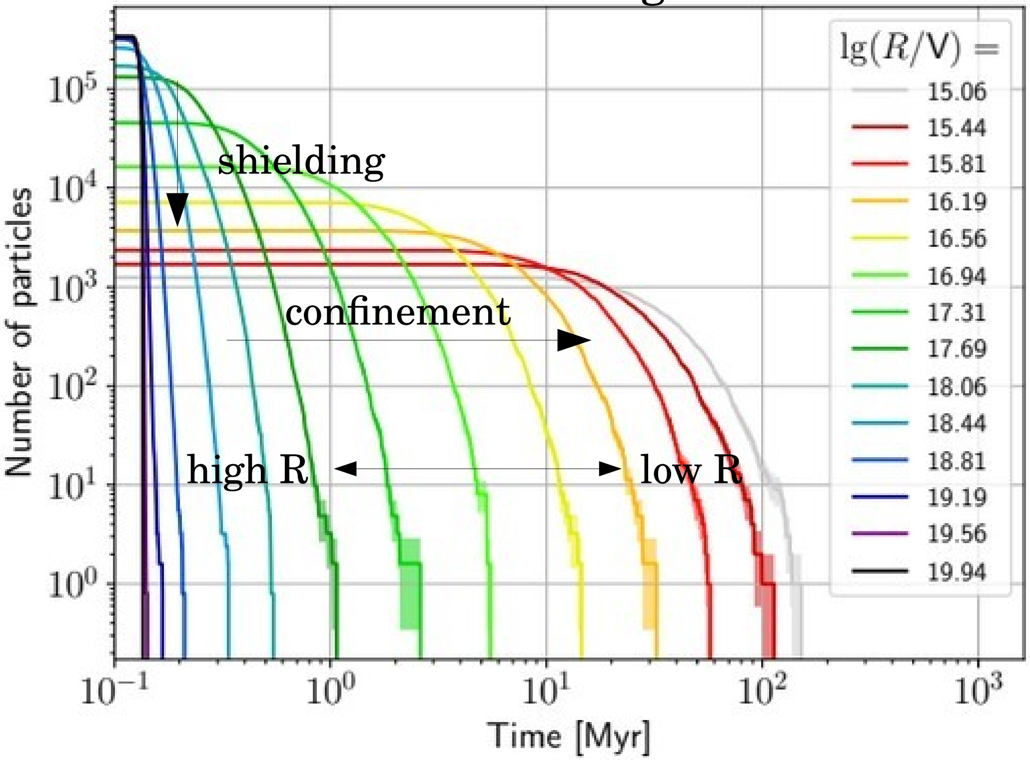
Simulation studies: Galactic residence time

see also: PoS(ICRC2021)004

GCRs



EGCRs reaching the GP

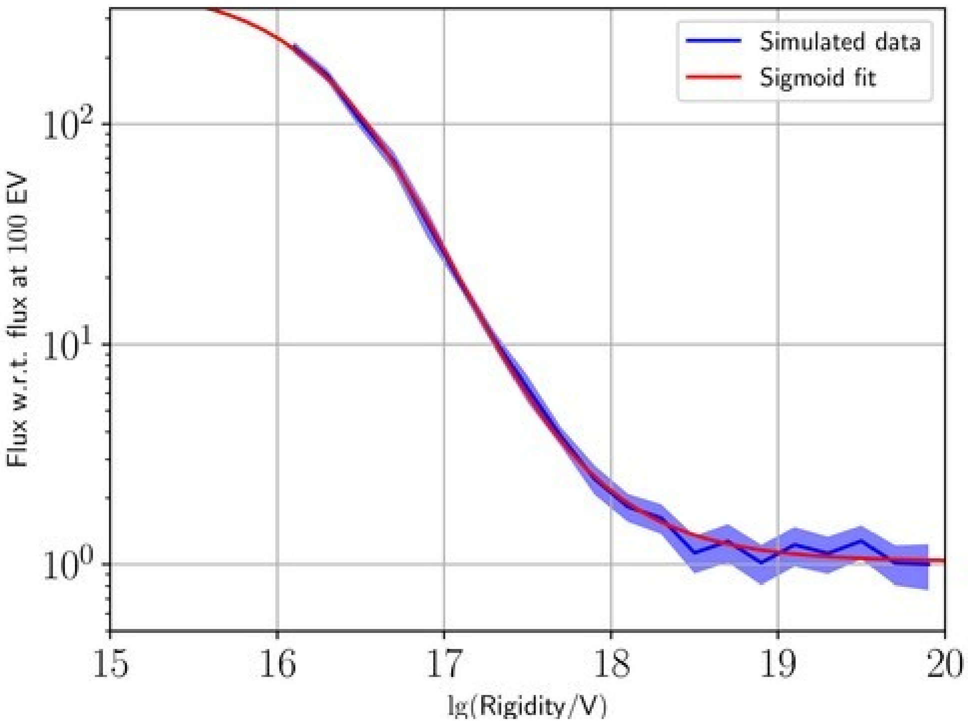


- GCRs **leak out of Galaxy** with increasing rigidity
- EGCRs are **shielded, rest confined in GP → counteracting effects**; both effects decrease with increasing rigidity
- NOTE: Lowest-rigidity particles have residence times **up to 100 Myr.**

Effect on observables: GCRs – Flux suppression

see also: PoS(ICRC2021)004

Rigidity spectrum (sigmoid fit)

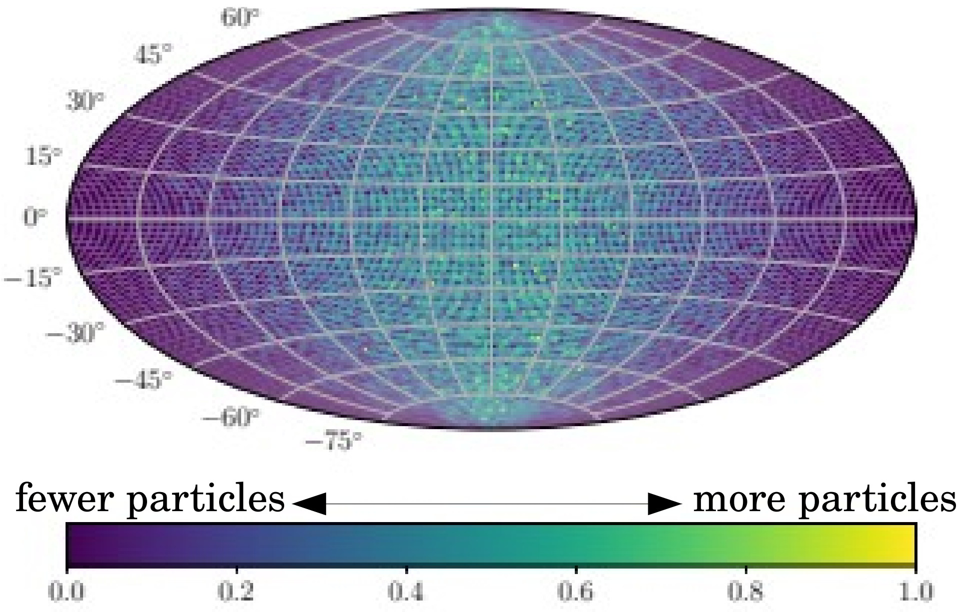


Increasing leakage → **flux reduction**

Effect on observables: Anisotropic EGCRs – Galactic lensing

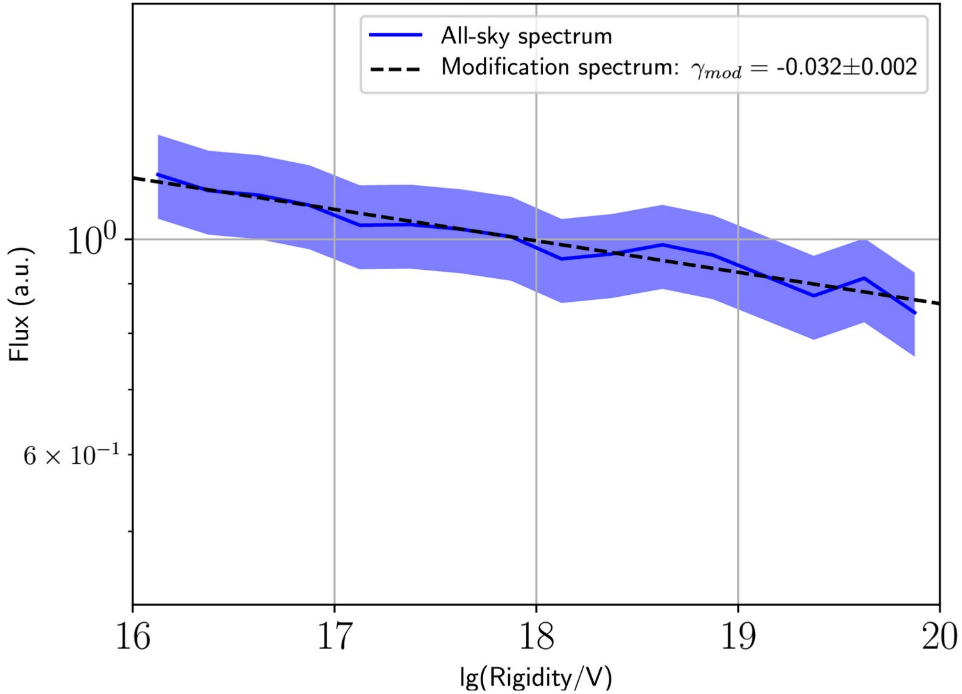
see also: PoS(ICRC2021)004

Injected flux



Injection direction distribution:
Pure dipole

Flux at Earth



Rigidity spectrum at Earth →
possible flux modification

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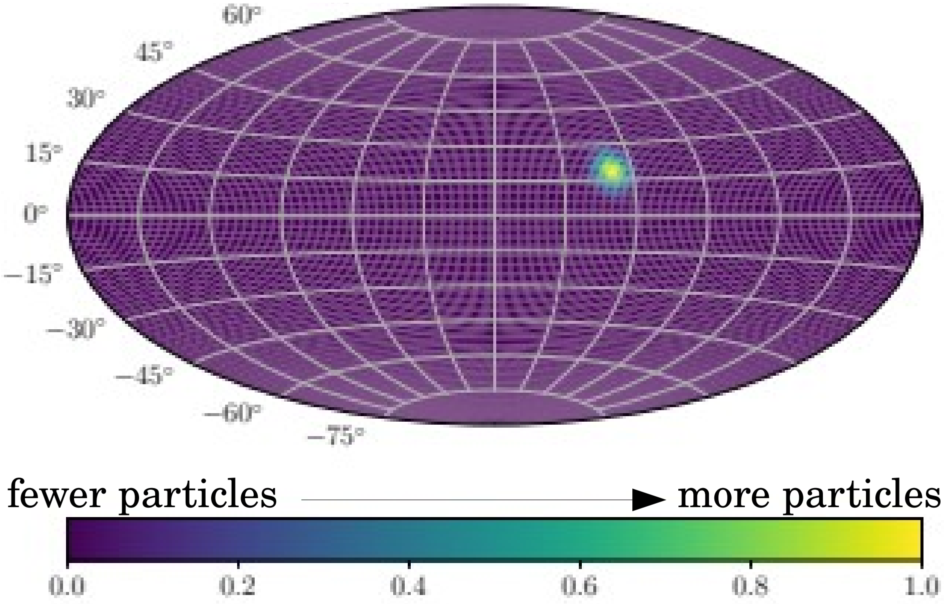

Injection direction distribution:
Pure single-point source (Cen A)

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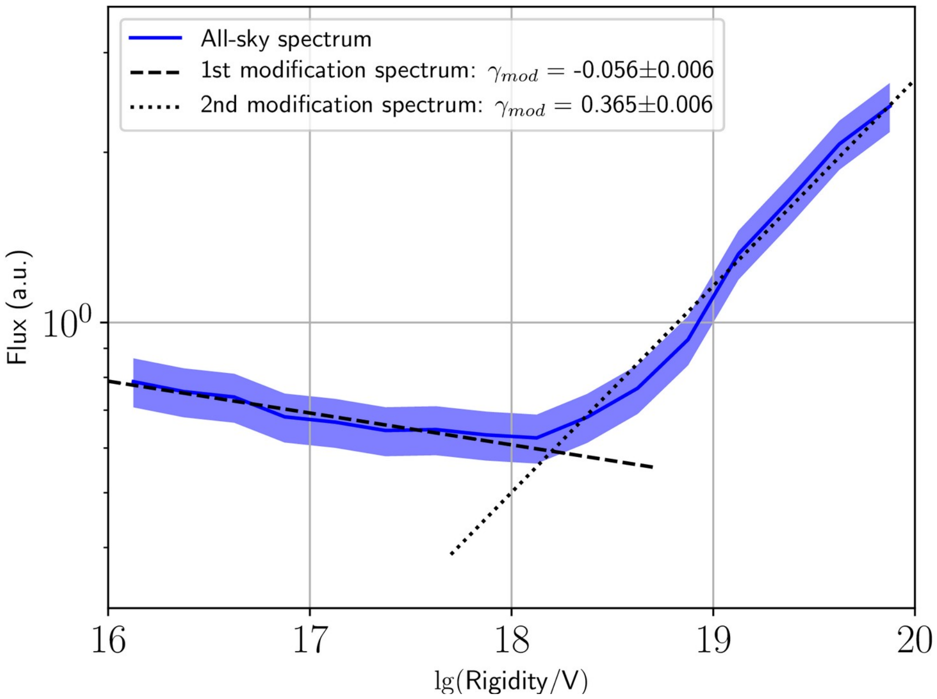

Rigidity spectrum at Earth →
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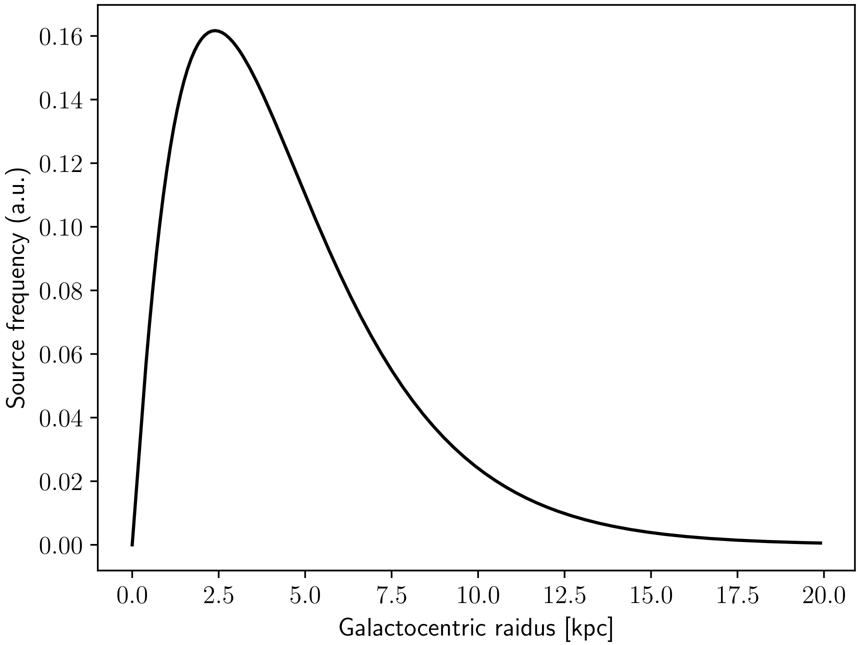
Goal: Flux prediction

Adapt simulated rigidity spectra:

- GCRs:
  - employ **realistic source distribution**
  - include **maximum rigidity cut-off** of Galactic sources
- EGCRs:
  - apply Galactic lens to realistic injection direction distribution
    - **point sources from "Auger Starbust"** paper: APJ.Lett. 853 (2018) 2, L29
    - rigidity- and distance-dependent **smearing**

Galactocentric distribution of SNRs



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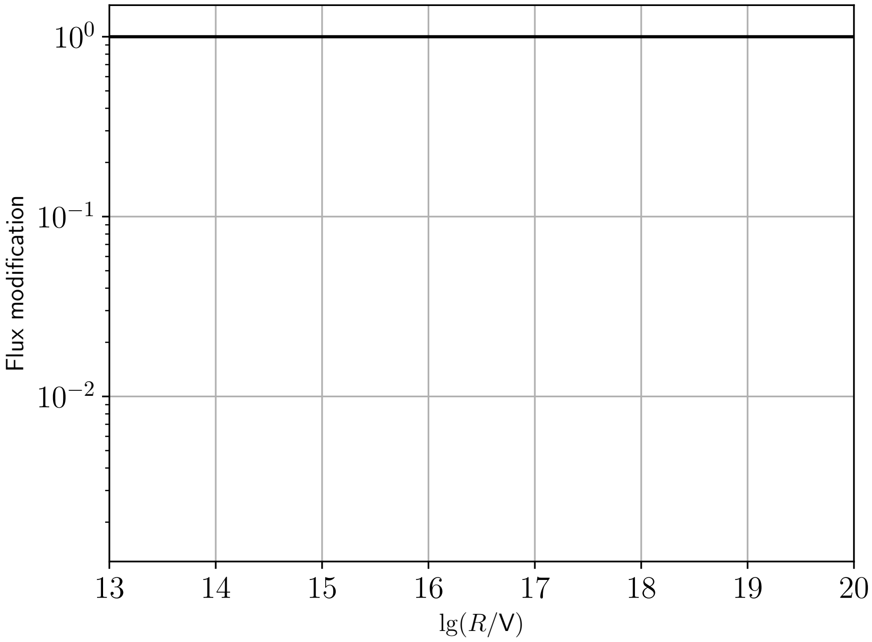

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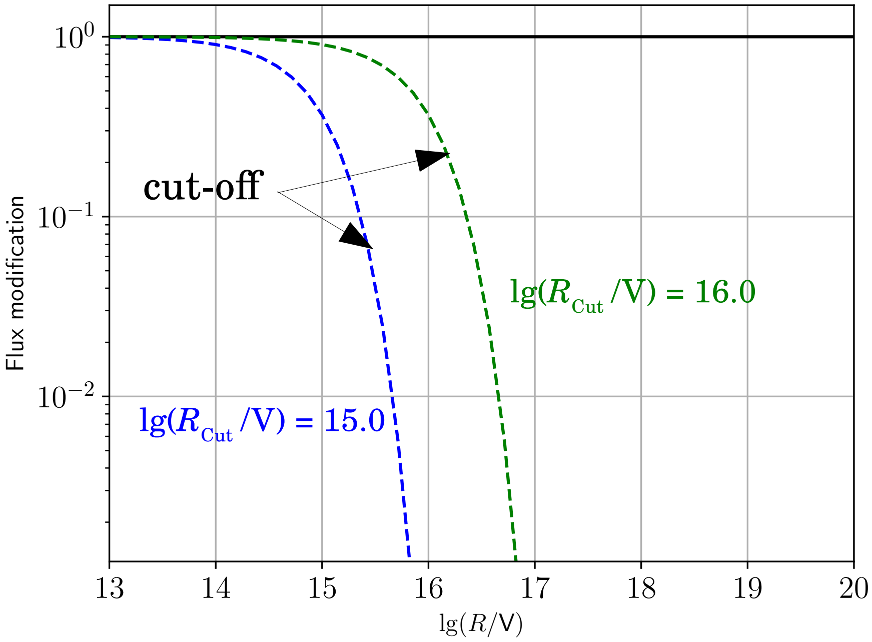

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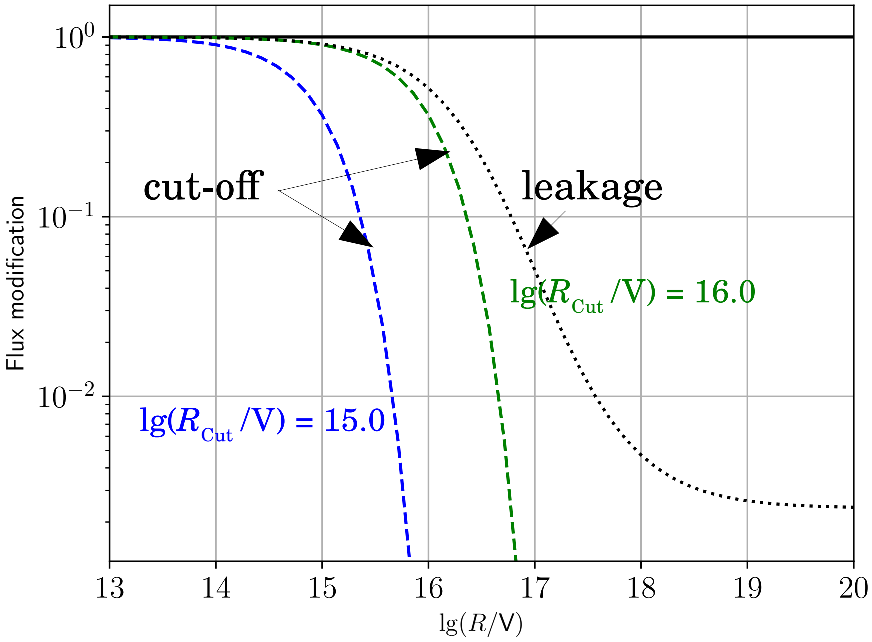

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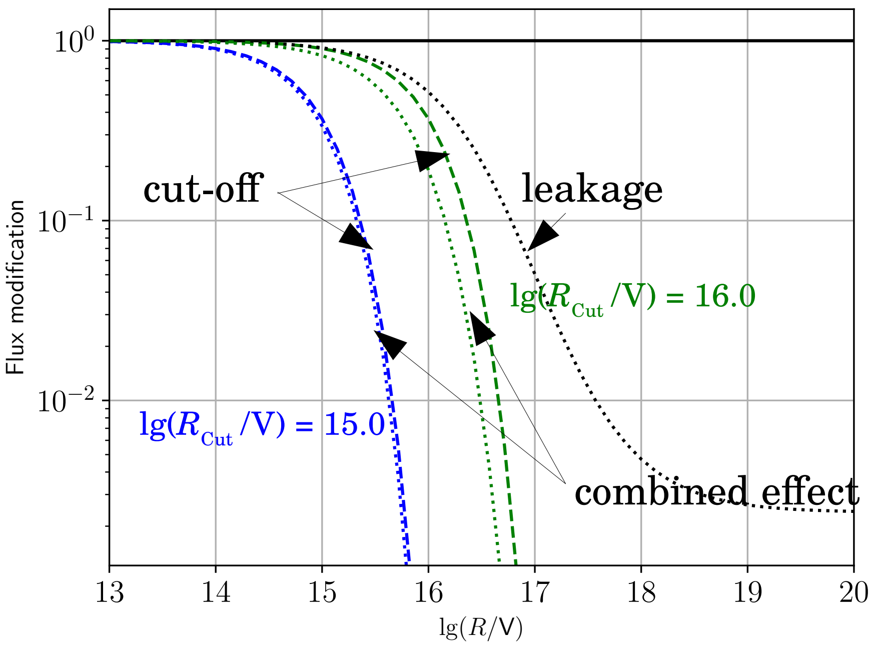

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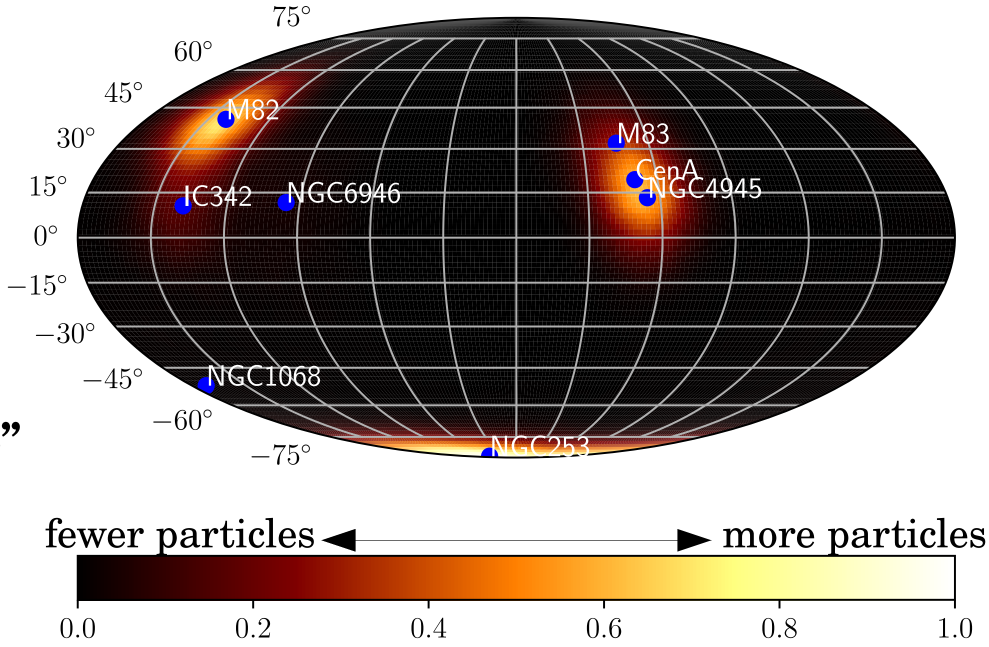

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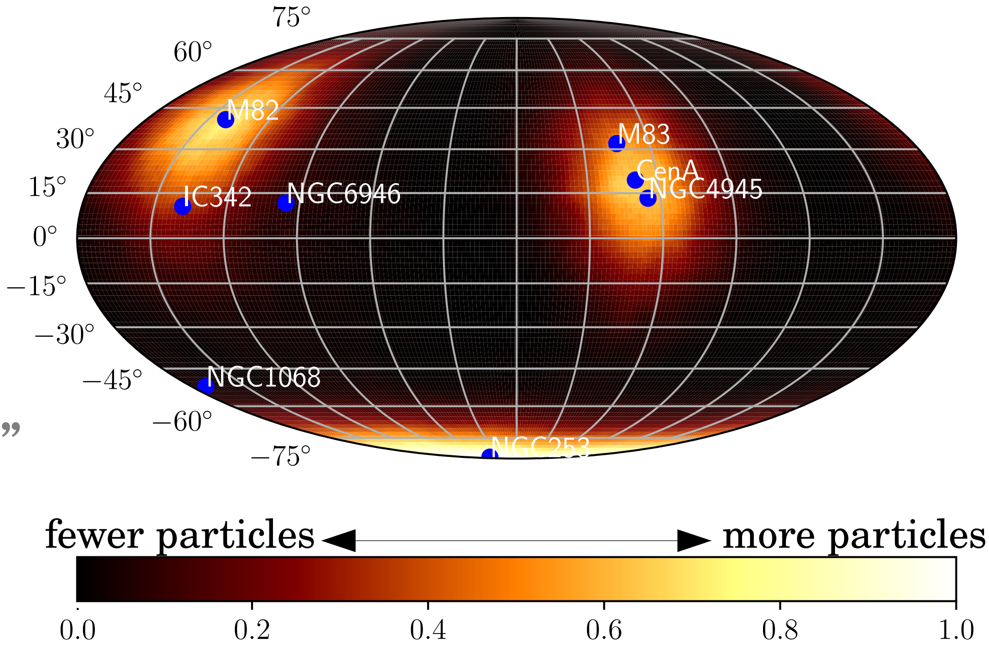

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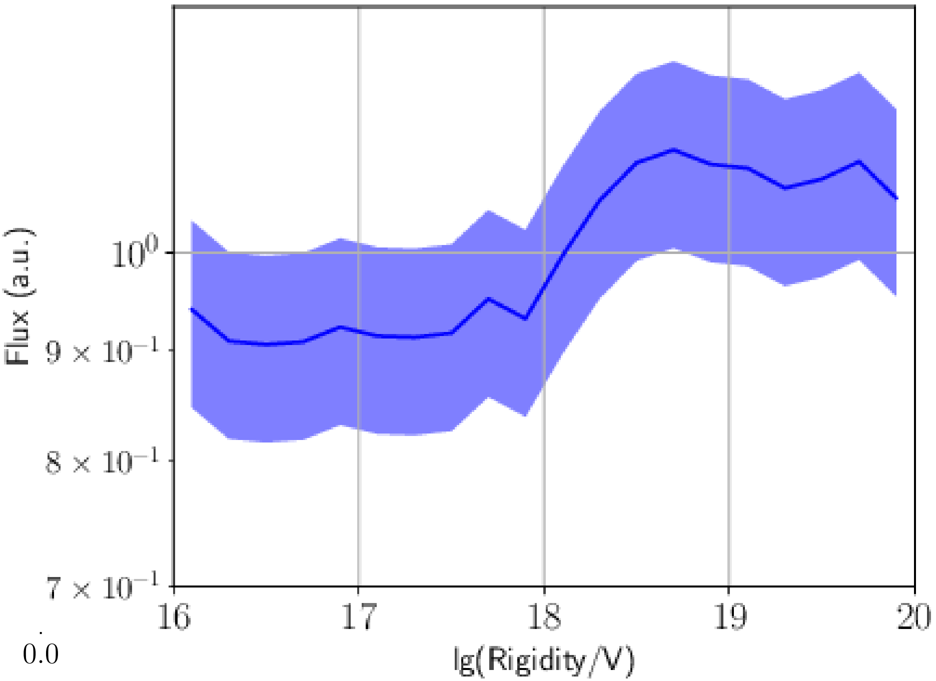
Rigidity spectrum of lensed EGCRs flux



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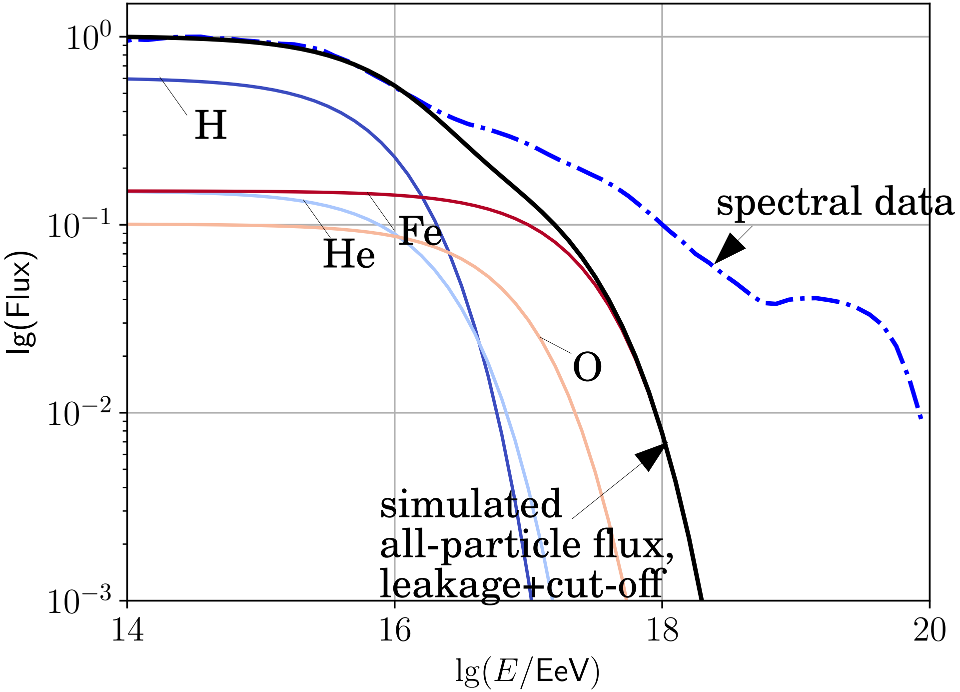
Create all-particle spectra:

- Scale rigidity spectra to **different nuclei**
  → **energy spectra**
- Find **suitable injection spectra:**
  - 4-component composition: H, He, O, Fe
  - **GCR** component to energies around **“knee”**
  - **EGCR** component to **post-“ankle”** energies

  → **all-particle spectra** that **reproduce data**

Energy spectrum of GCRs with leakage and cutoff ($\lg(R_{\mathrm{Cut}}/\mathrm{V}) = 16.5$)



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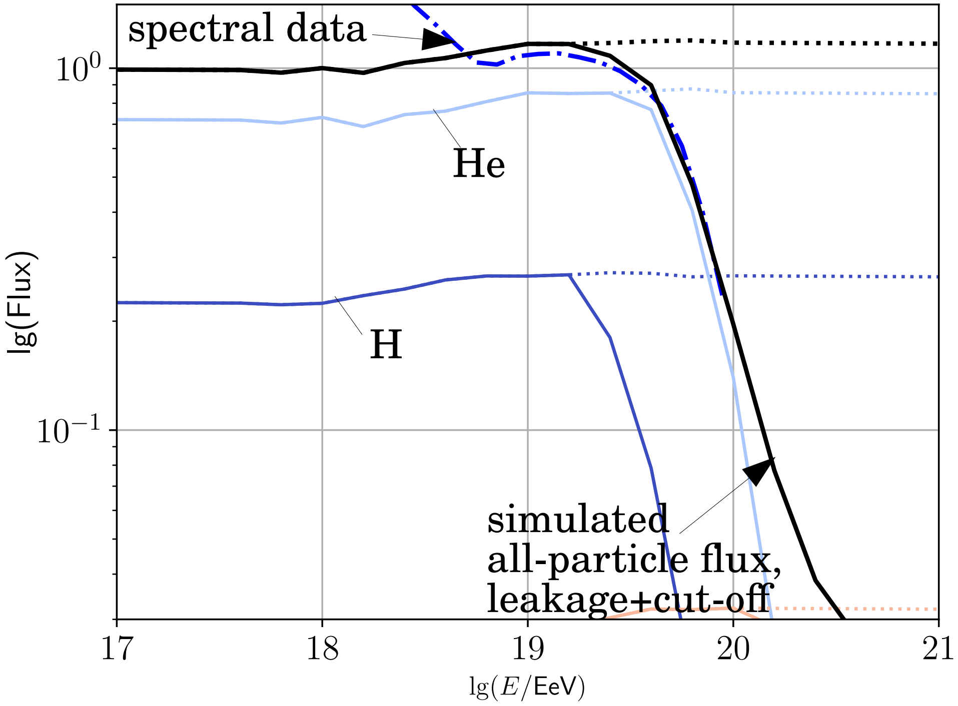
Energy spectrum of EGCRs with spectral break and cutoff (lg(R_{Cut} /V) = 19.25)



Alex Kääpä alex.kaeaepae@rub.de

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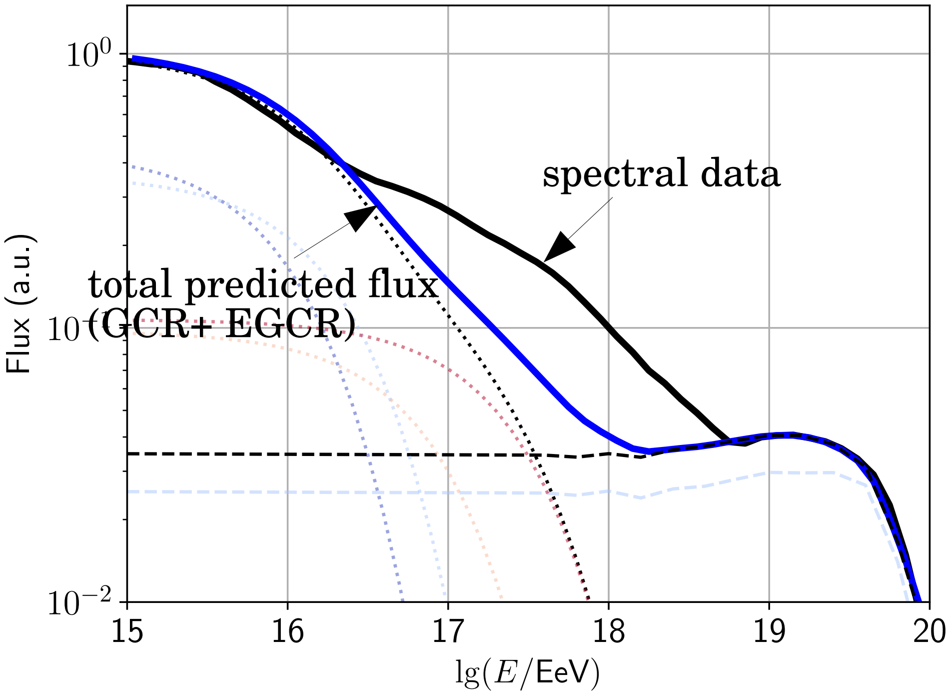
Total combined energy spectrum



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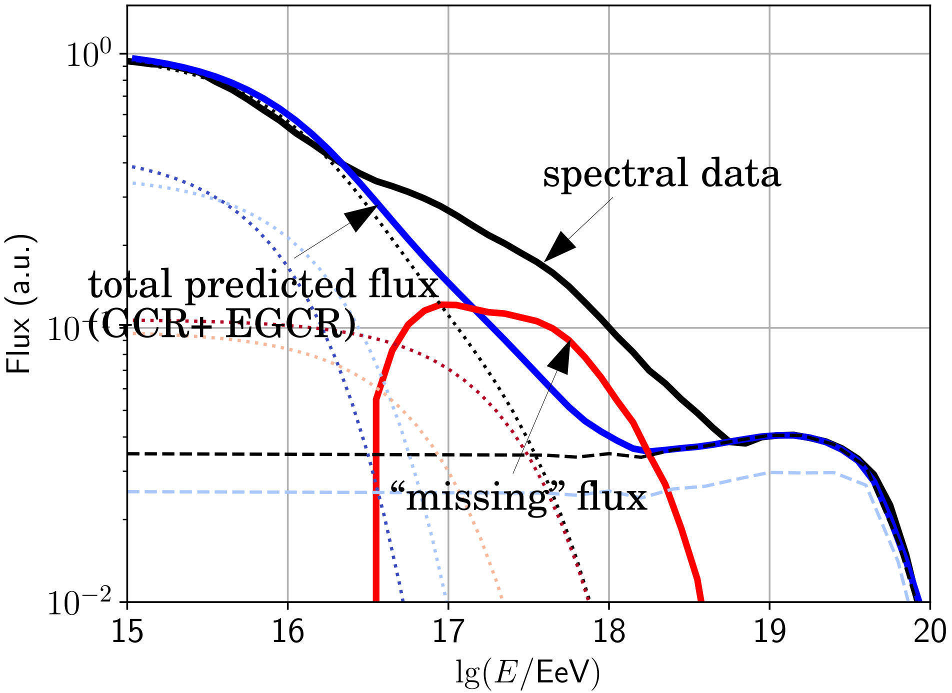


Summary

Propagation effects in the GMF need to be considered in the transition region!

- GCRs: **flux suppression** towards higher rigidities due to **leakage from Galaxy**
- EGCRs: **flux modifications** depending on **nature & direction of injected anisotropy**

Incorporate propagation effects into the total flux

- GCRs: **leakage** leads to **earlier onset of suppression**; degree dependent on R_{Cut}
- EGCRs: **injected flux from SBG/AGN** leads to **spectral break**

Total energy spectrum: flux predictions **cannot account for flux** in transition region

Outlook

- **comparison** with **composition & anisotropy data**

Alex Kääpä alex.kaeaepae@rub.de

Thank you for your attention!

Cosmic ray energy spectrum

Broken power-law with three 'main' features:

- **'knee'**: softening at ~$10^{15.4}$ eV
- **'ankle'**: hardening at ~$10^{18.7}$ eV
- high-energy cut-off beyond ~$10^{19.6}$ eV

Further more subtle features:

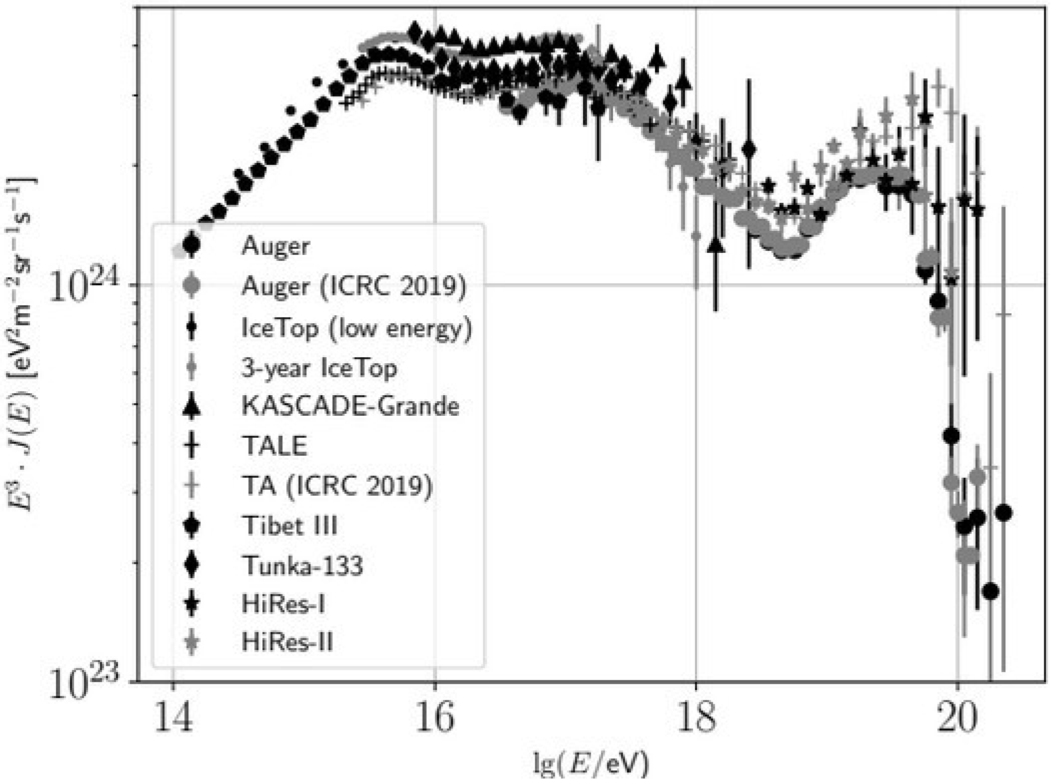
- 'low-energy ankle' at ~$10^{16.7}$ eV
- **'2nd knee':** softening at ~$10^{17.(0...4)}$ eV
- 'toe': softening at ~$10^{19.1}$ eV

Galactic cosmic rays (**GCR**s) for diffusive shock acceleration (DSA) in supernova remnants (SNR) dominate **below 'knee'** energies.

Extragalactic cosmic rays (**EGCR**s) dominate at energies **above 'ankle'**.

Transition region (= 'shin') **unexplained**:

- unaccounted for flux



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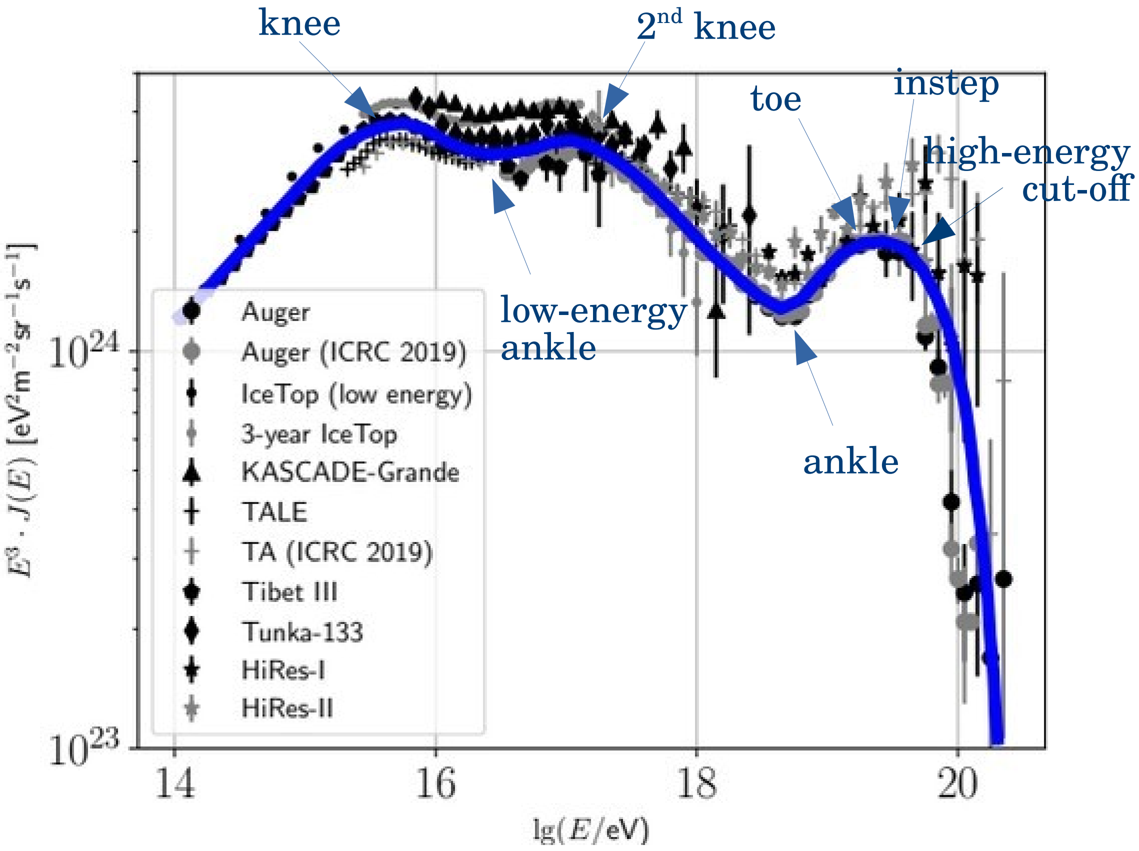

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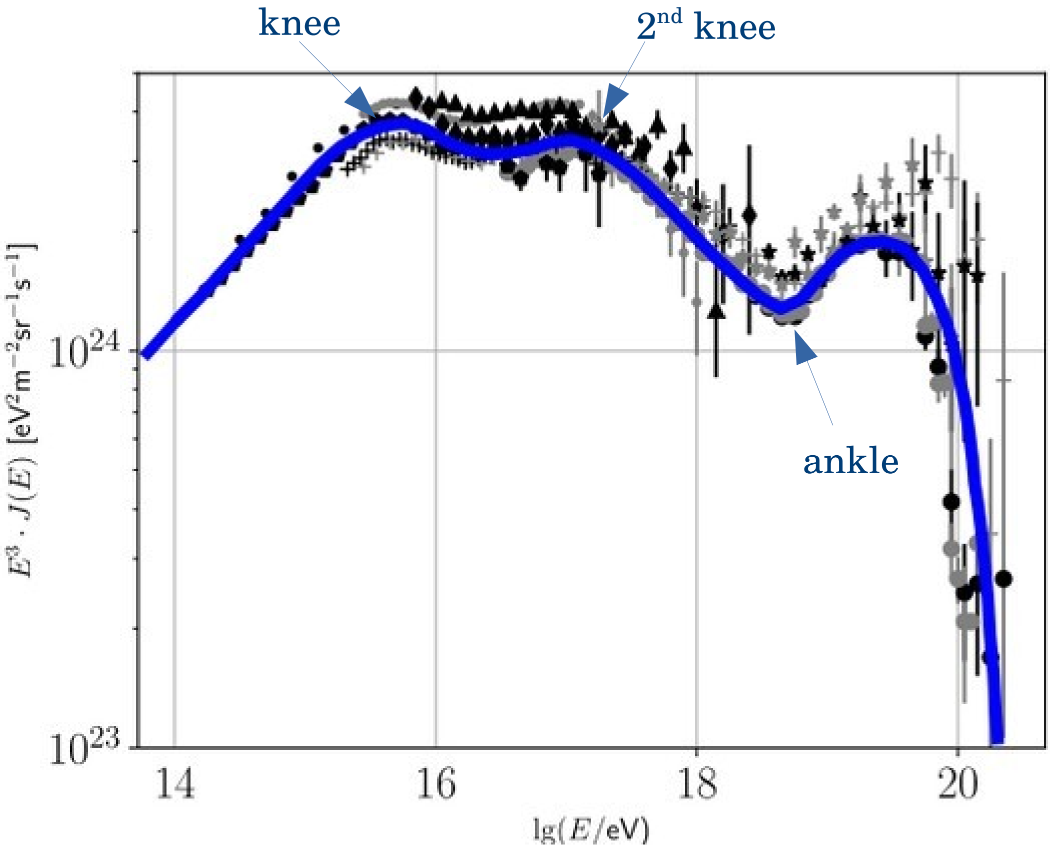

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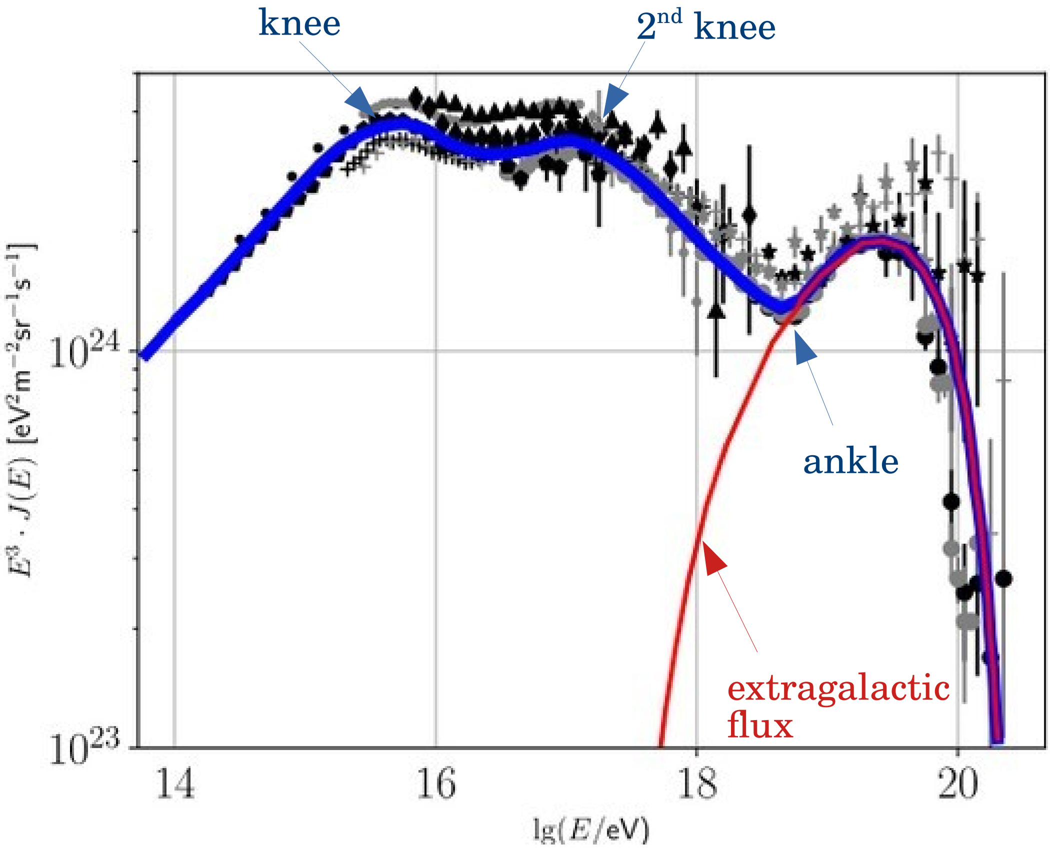
knee

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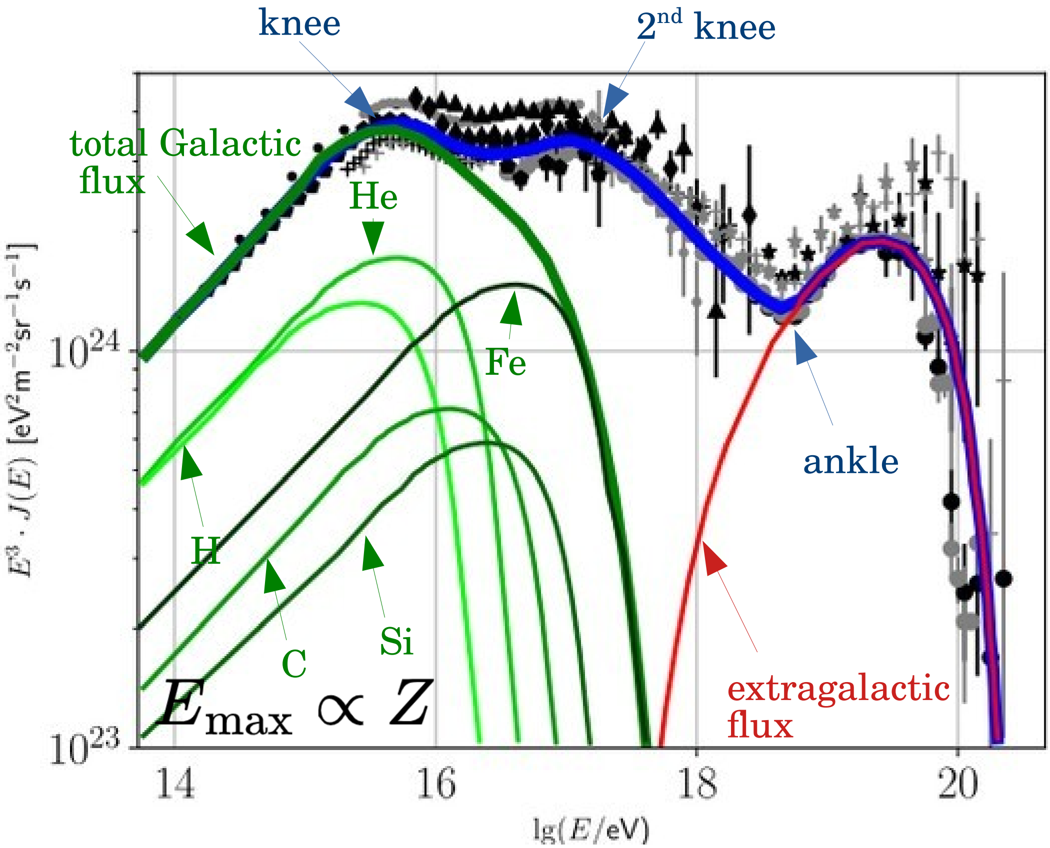


Cosmic ray composition

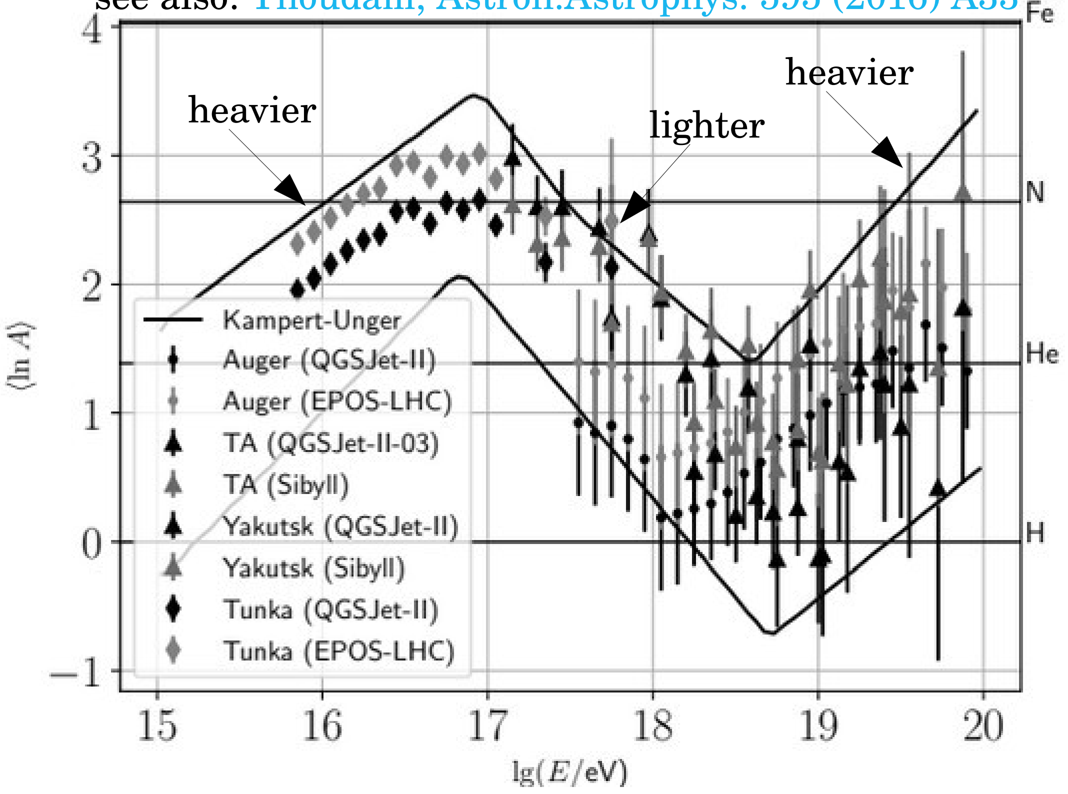
Composition highly energy-dependent:

- heavier beyond the ‘knee’
- maximum **before** ‘2nd knee’
- minimum just before ‘ankle’
- **increasing mean mass at** high-energy **cut-off**

Increasing mean mass
→ **rigidity-dependent** change in:

- source properties (**maximum acceleration energy**)
- **propagation regimes** in magnetic fields

see also: Thoudam, Astron.Astrophys. 595 (2016) A33



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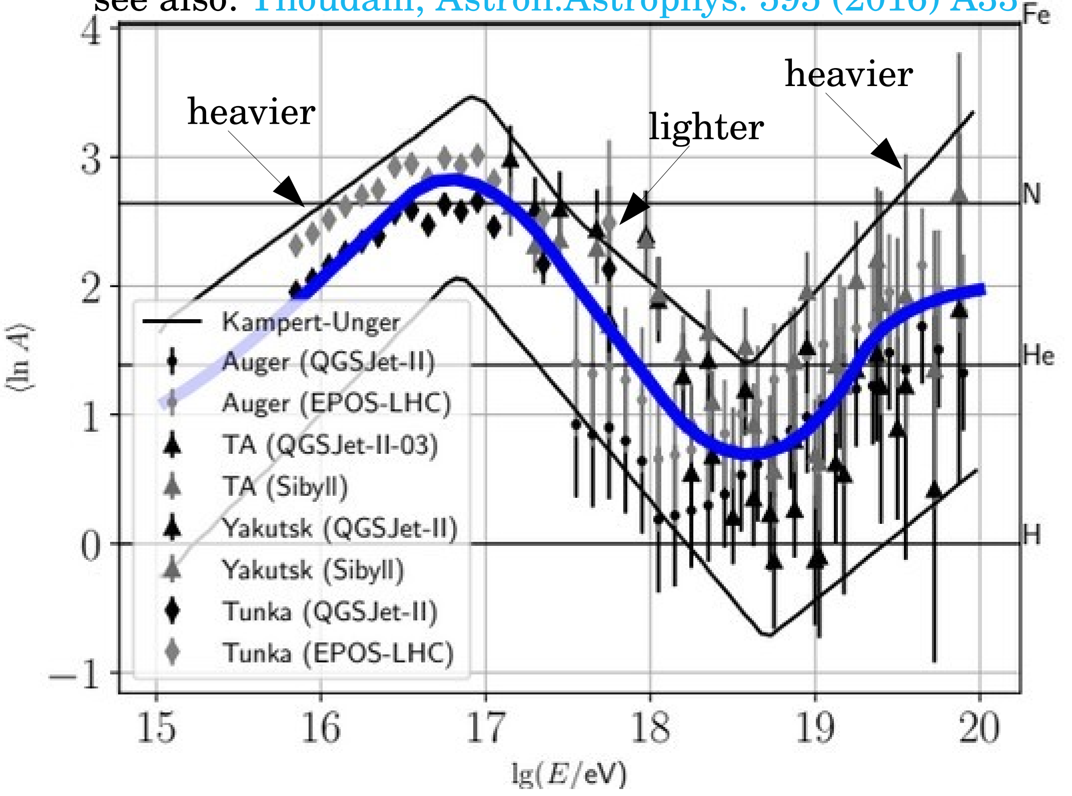


Anisotropies

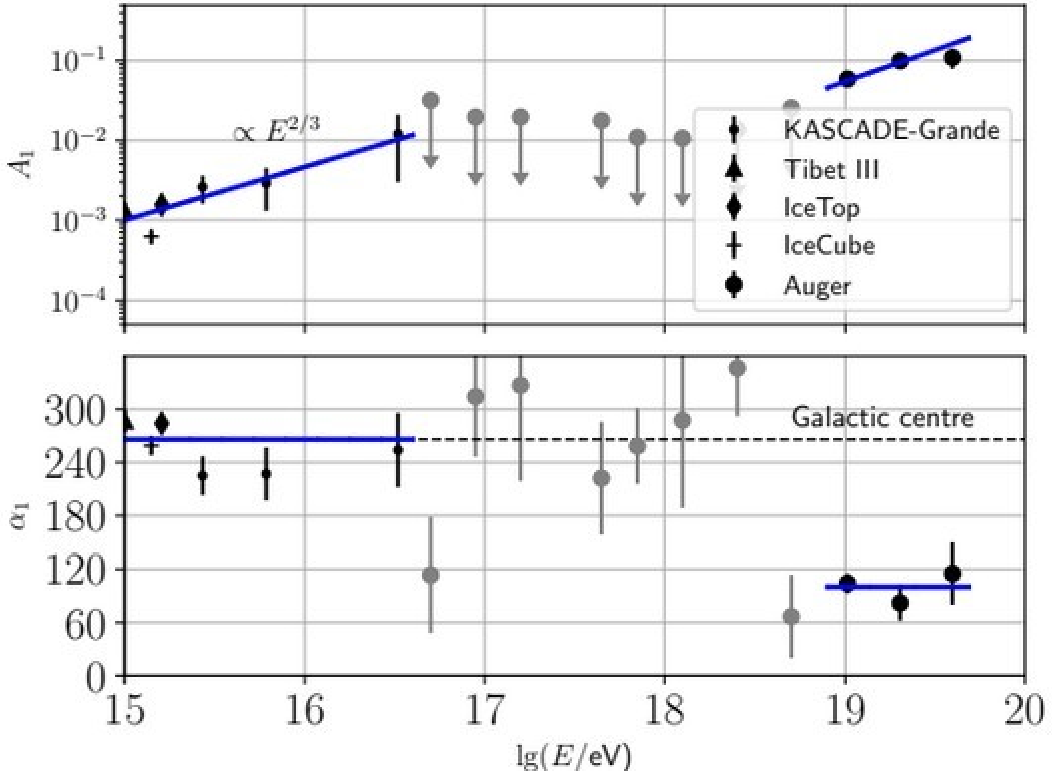
Dipole anisotropy:

- amplitude increases with energy
- **no significant dipole** between ~$10^{16.5}$ eV – 10^{19} eV
- **phase roughly constant** in both energy ranges but **shifts away from Galactic centre** (GC) for highest energies
  → **extragalactic** origin likely

Small-scale anisotropies:

- amplitude and direction indicate strength of **diffusion** vs. **advection**: correlation with **source direction** ⇔ **strength of Galactic wind**

see also: Becker-Tjus, Physics Reports 872 (2020) pp.1-98



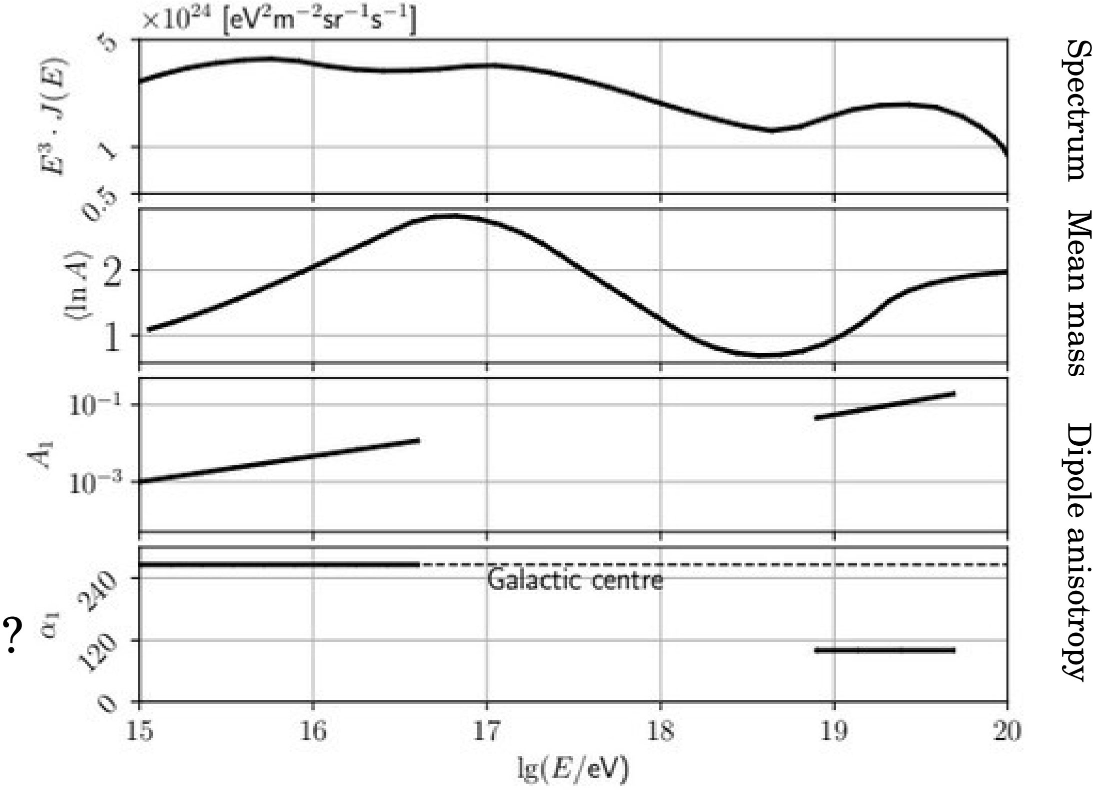
“All” data in one look

Composition:

- What **explains ‘2nd knee’** if maximum mean mass is reached well before?
- Why does the composition become **lighter up to the ‘ankle’**?

Spectrum:

- How could **GCRs** be accelerated up to energies **beyond the ‘knee’**?
- What **constraints** are there on **low-energy** contribution of **EGCRs**?
- **How are observables affected by the propagation in the Galactic magnetic field (GMF)?**



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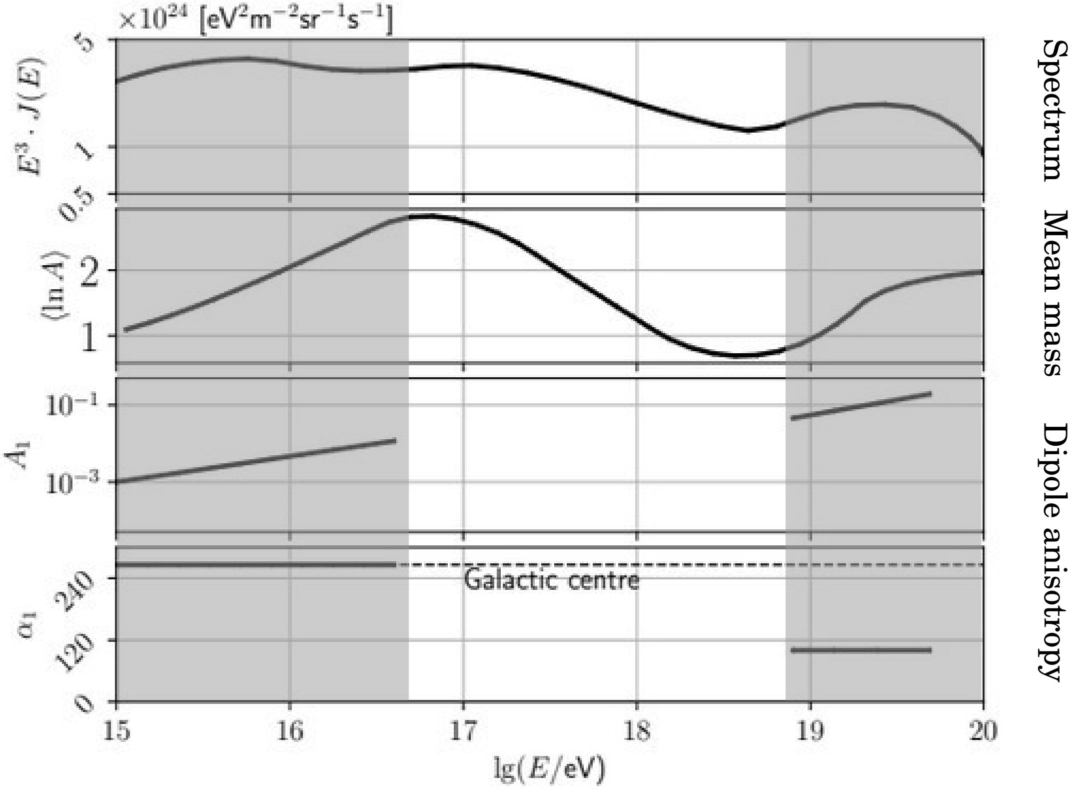


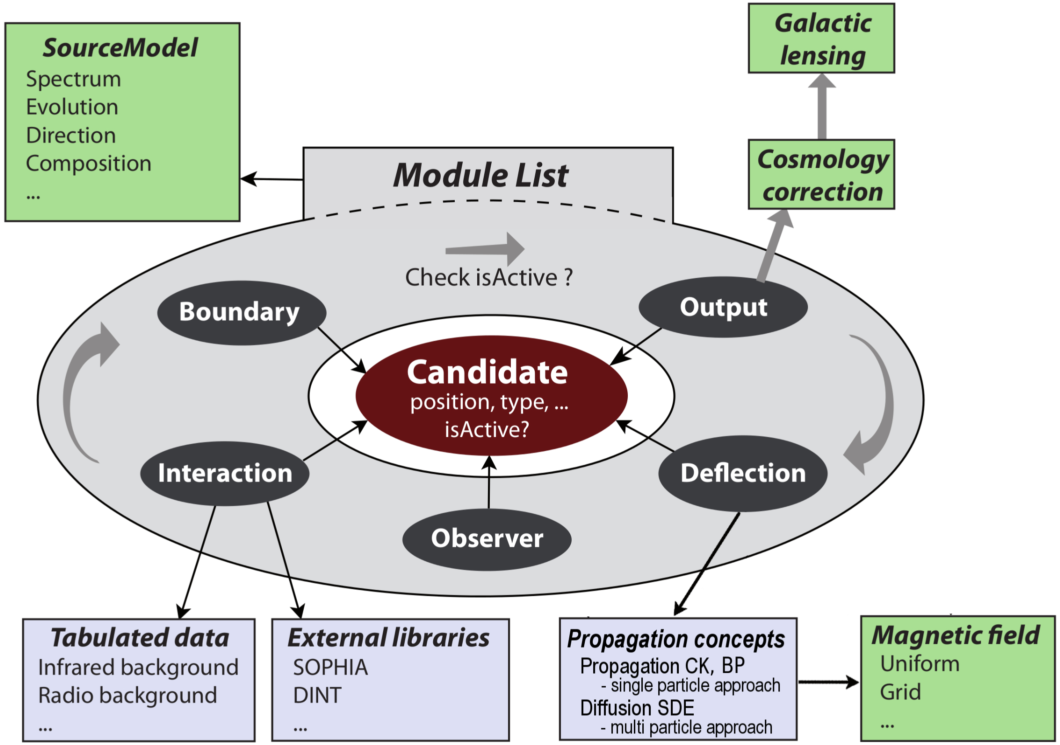
Simulation software, computational challenges and requirements

Simulation software: CRPropa 3

CRPropa 3: Monte-Carlo based software for simulation of CR propagation:

- Modular structure:
  - Modules modify properties of candidate at each step of simulation
  - Source, interaction, deflection, observer, boundary, output
- Contain all atomic nuclei,photonuclear interactions, **magnetic field models, propagation algorithms,** …

Modular structure of CRPropa 3



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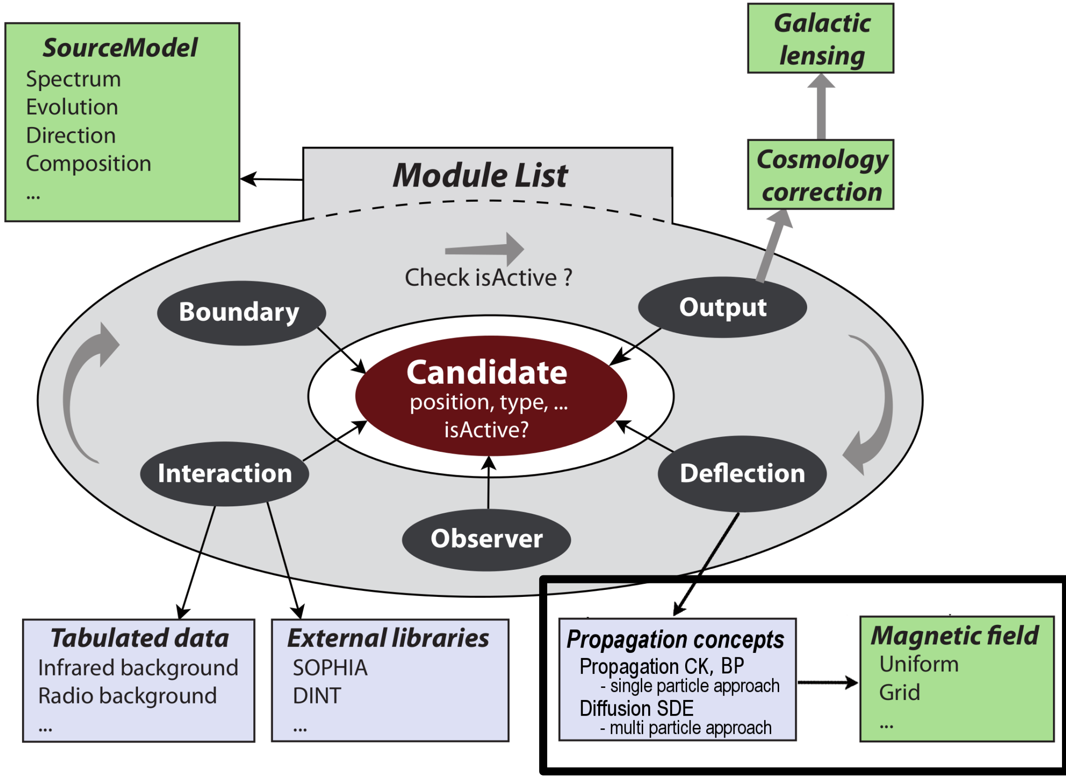
Modular structure of CRPropa 3



Ballistic propagation

Solve equation of motion:

$$\ddot{\vec{r}} = \frac{q}{E/c^2}\left(\vec{v} \times \vec{B}\right)$$

- tracking of single particles (microscopic view)
- best suited when r_g is large
- applicable for arbitrary fields

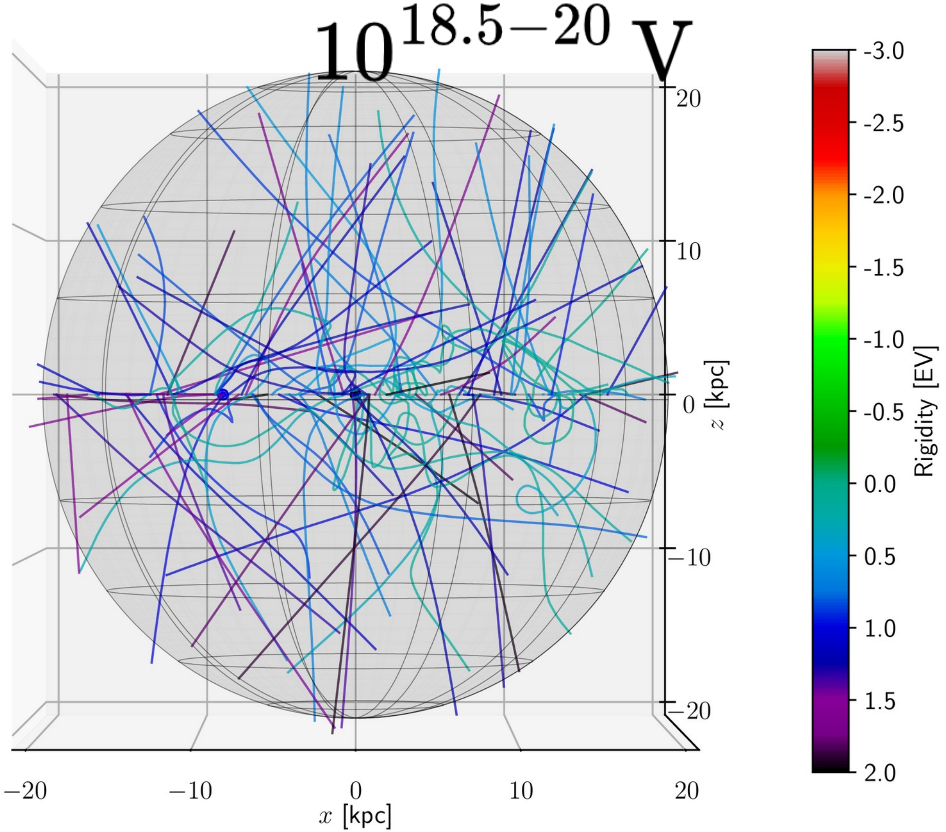
  → more fundamental and precise*
- particle trajectories are tracked

  → possibility of anisotropy studies
- Implemented in CRPropa via Cash-Karp and Boris-Push

BUT:

- below $\approx 10^{17}$ V, computation times start to diverge
- *: precision dependent on grid size

Trajectories of ballistically propagating GCRs



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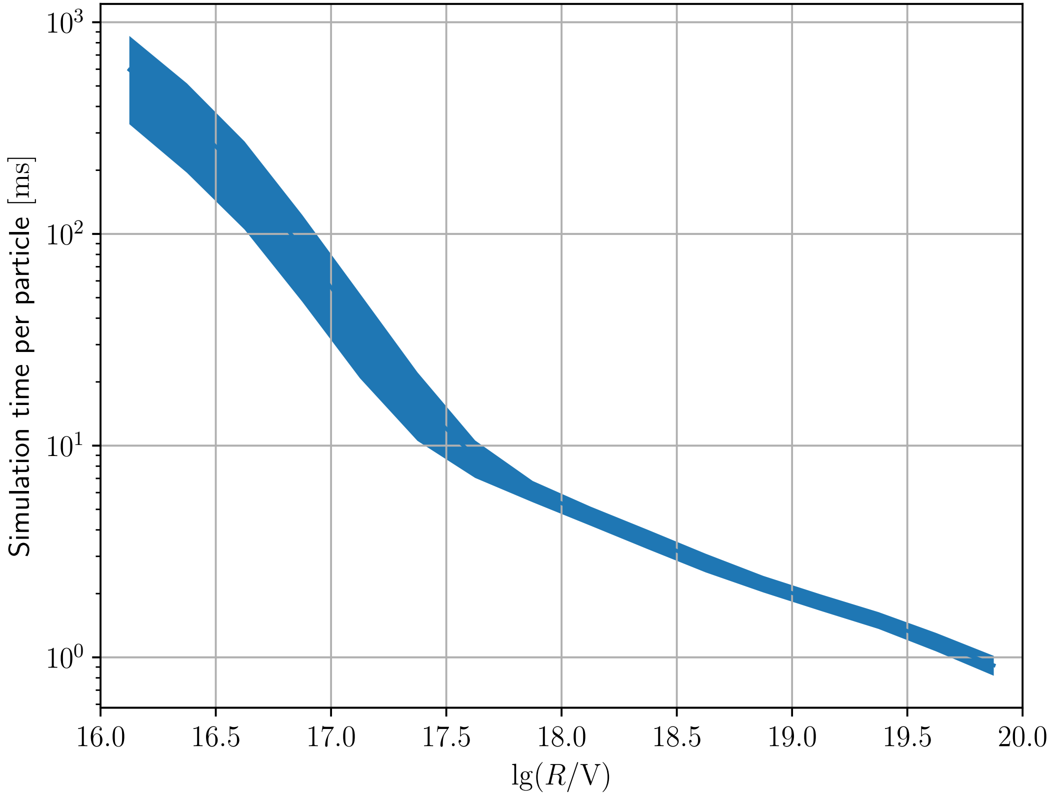
Change of computation time per particle with rigidity for propagation in GMF



Diffusive propagation

Solve transport equation:

$$\frac{\partial n}{\partial t} = \nabla \cdot \left(D \nabla n - \vec{u} n \right) - \frac{n}{\tau_f} - \frac{n}{\tau_d} + Q$$
$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{n}{p^2} - \left(\dot{p} - \frac{p}{3} \nabla \cdot \vec{u} \right) n \right)$$

multi-particle approach:

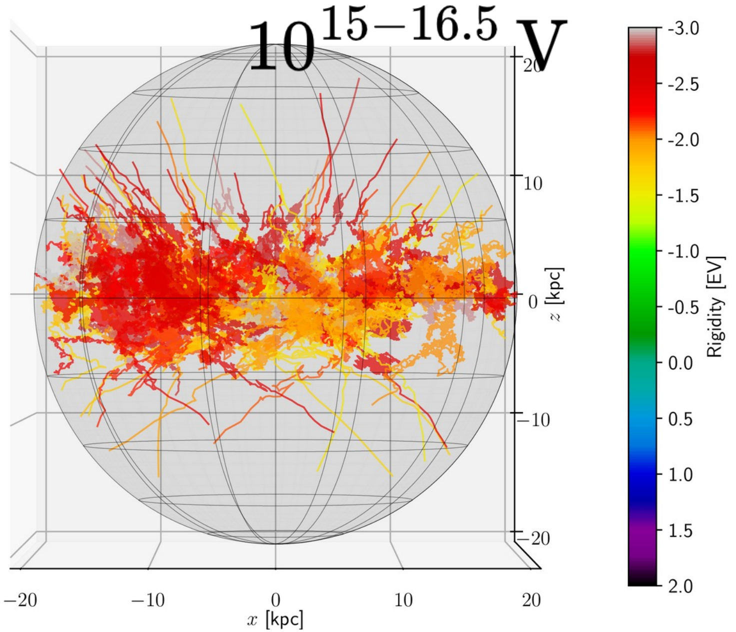
  - change of momentum density (macroscopic view)

- best suited when r_g is small & turbulent B-field component dominant
- generally shorter computation times

NOTE:

- CRPropa 3 has implement diffusive propagation module via SDEs (JCAP 06 (2017) 046)
- For a full description of the transition region both propagation methods must be applied

Trajectories of diffusively propagating GCRs



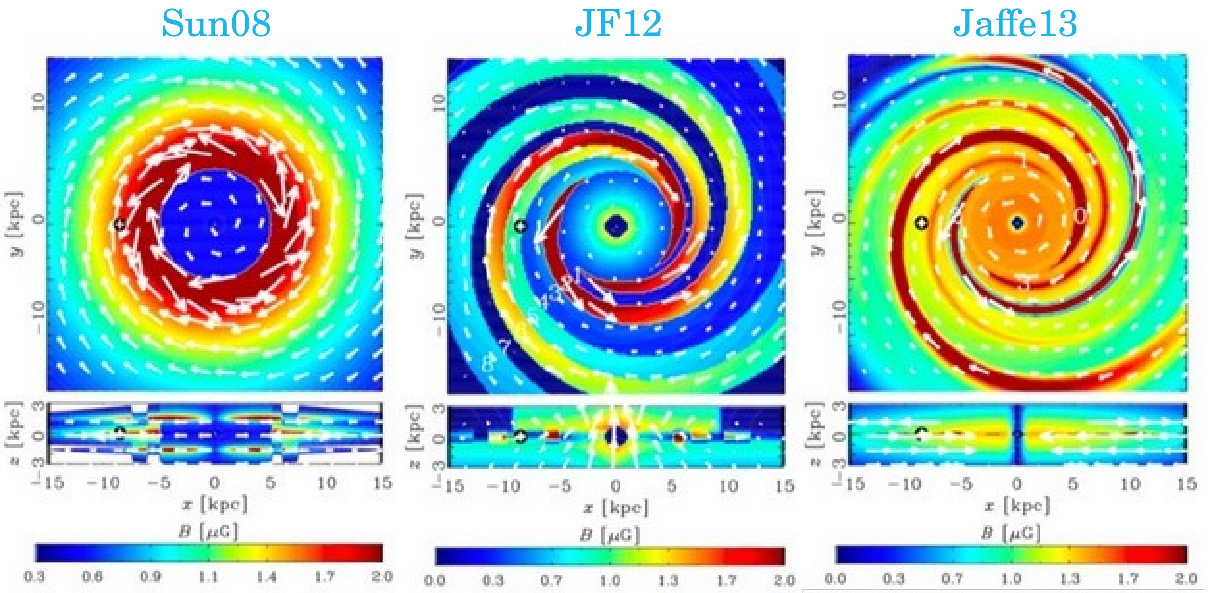
Major challenge: GMF model

GMF not well known:

- field strength inferred indirectly via observables:
  - Faraday rotation (for $B_\parallel$)
  - synchrotron emission (for $B_\perp$)
  - thermal dust emission/ polarised starlight (for $B_\perp$)

  → uncertainty in quantities, contamination from other sources of radiation
- ad hoc assumptions necessary (simplifications):
  - morphological features
  - field components (regular, turbulent etc.)

x-y and x-z projections of coherent field for various GMF models



Sun08 JF12 Jaffe13

Procedure: Ballistic propagation with CRPropa3

Forward tracking:

- particle tracked **from source to observer**
- highly **inefficient** (1:10^{28} for observer the size of Earth)
  → increase observer size, BUT: this introduces **artefacts**!

Only propagation effects (i.e. only deflections/no interactions):

- propagation of **one nuclear species: proton**
  → results can be scaled to all nuclei (important for composition)

Galactic magnetic field model:

- **JF12** (including regular, random and striated components)
  → edge of Galaxy defined as volume within which GMF is defined (20 kpc sphere around Galactic centre)

Source properties:

- $\boldsymbol{R}^{-1}$ injection spectrum, lg(R/V) = **16.0 – 20.0** (lg(R_{Fe}(@knee)/V) = 15.4 - lg(26) = 14 !)

Alex Kääpä alex.kaeaepae@rub.de

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Sources and observers

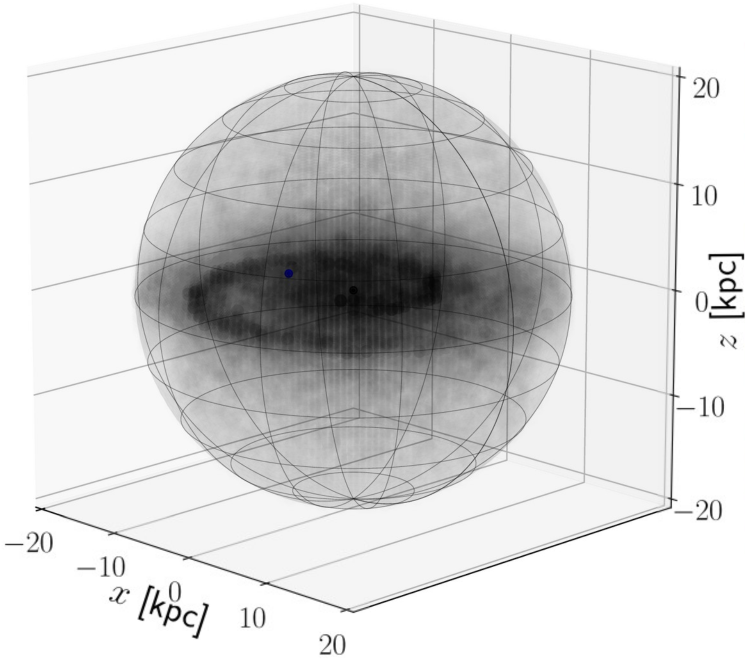
Sources:

- GCRs:
  - **homogeneously distributed in GP**
  - isotropic injection direction distribution
- EGCRs:
  - **isotropic injection:** Lambertian injection direction distribution from Galactic shell

Observers:

- ‘**Galactic plane**’: **cylinder** of 100 pc height around Galactic centre with variable radius
- ‘**Earth**’: **observer sphere** at Earth’s position in Galactic coordinates (-8.5 kpc, 0, 0)

Galactic volume with GMF



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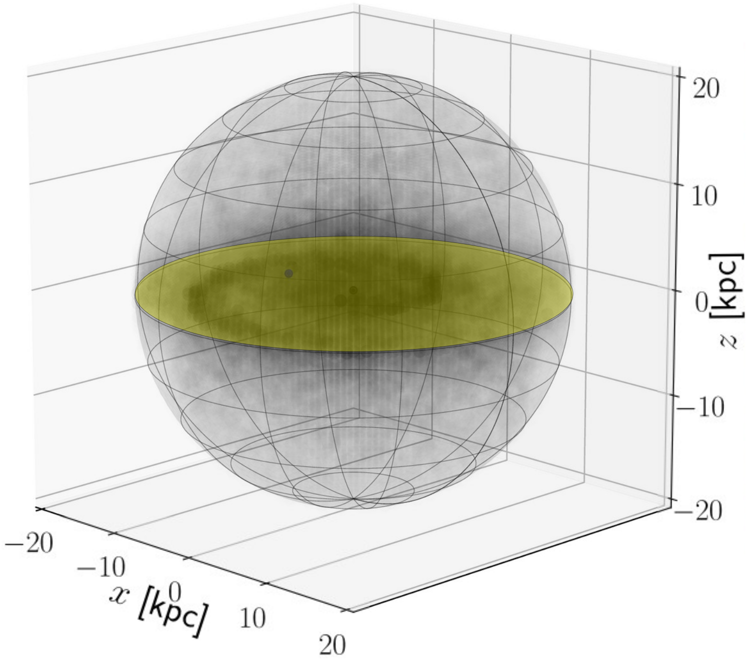
GCR source distribution



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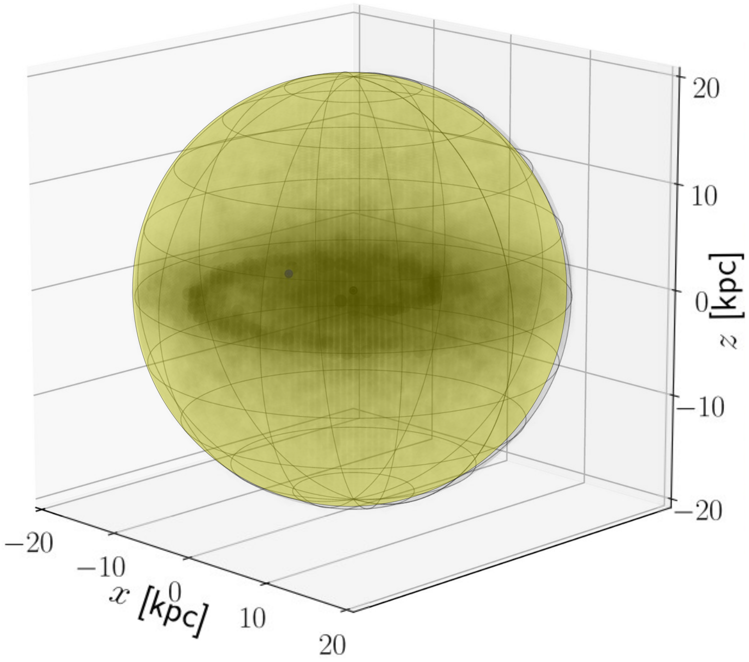
EGCR source distribution



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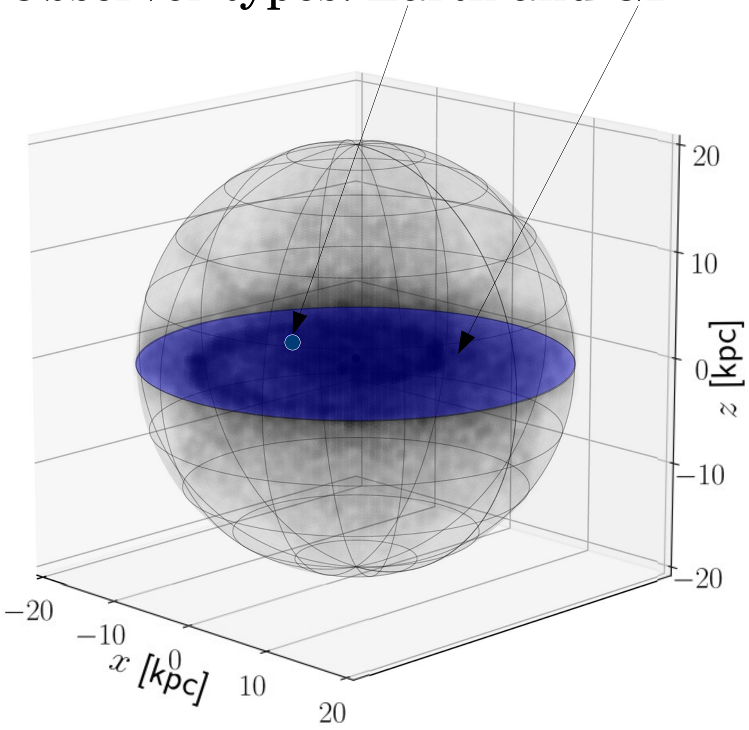
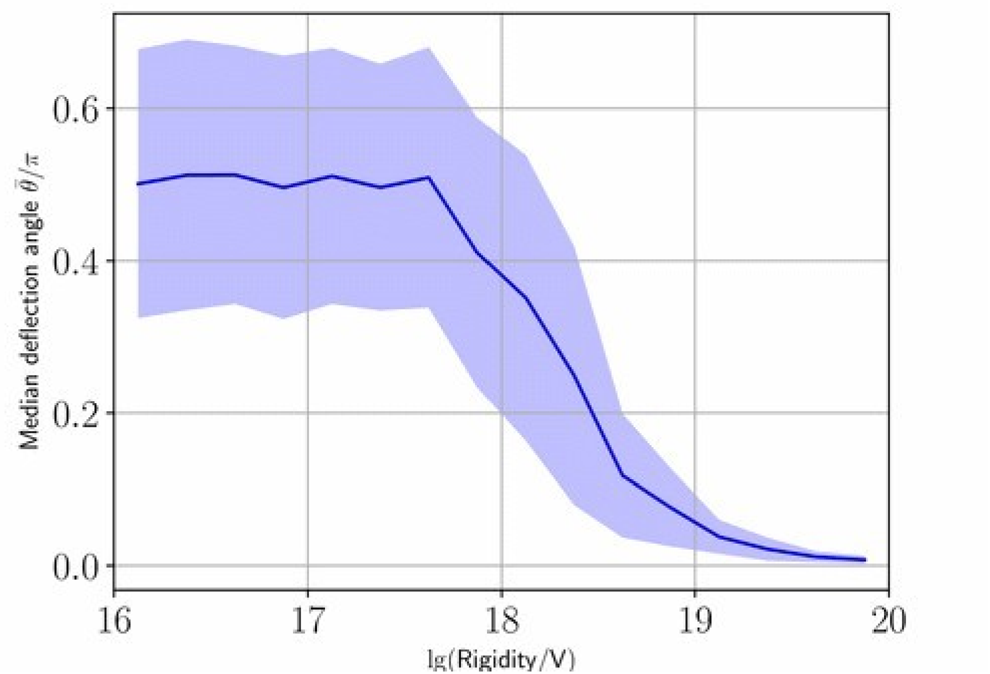
Observer types: Earth and GP



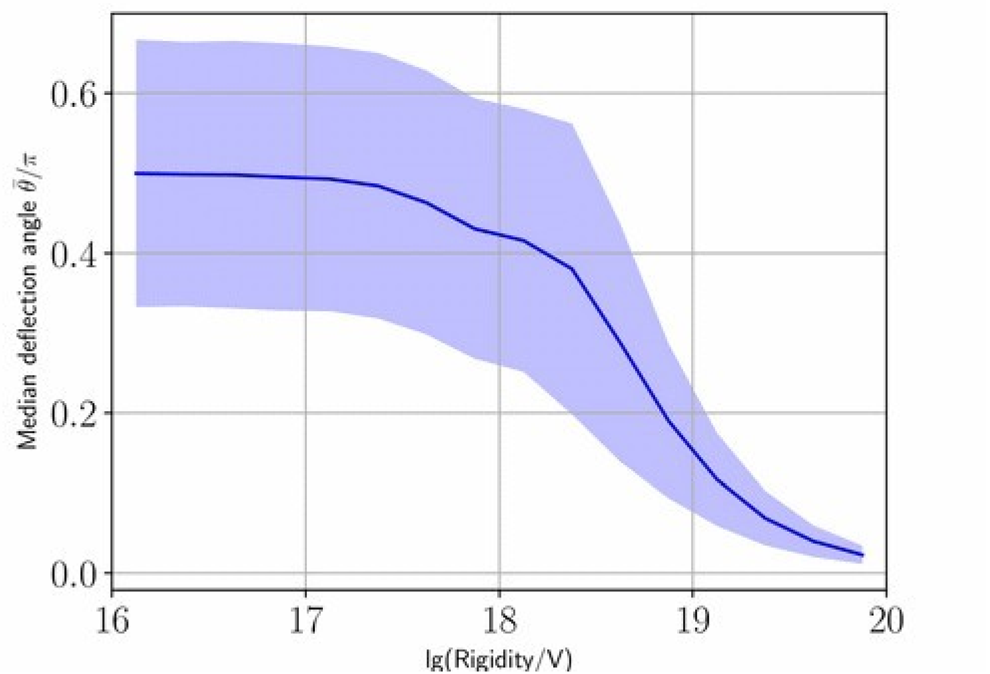
Propagation effects in the GMF

Change in propagation regimes: Deflection angle

GCRs forward tracked to Earth



EGCRs backtracked from Earth



$\theta = \pi/2$ for $\lg(R/\mathrm{V}) \leq 18$ → **diffusive** propagation
(see also: Erdman, Astropart.Phys. 85 (2016) 54-64)

Change in propagation regimes: Deflection angle

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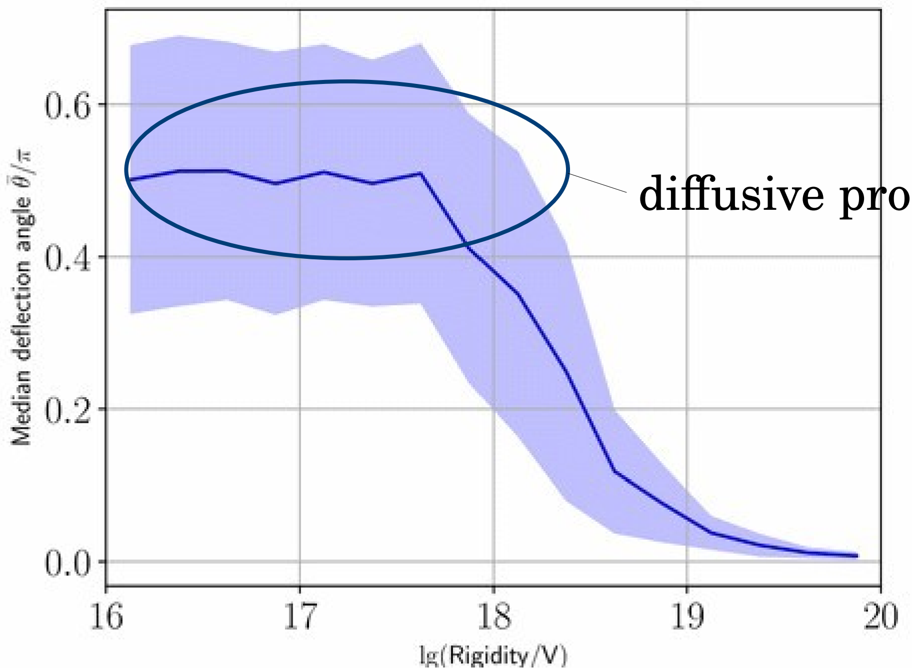
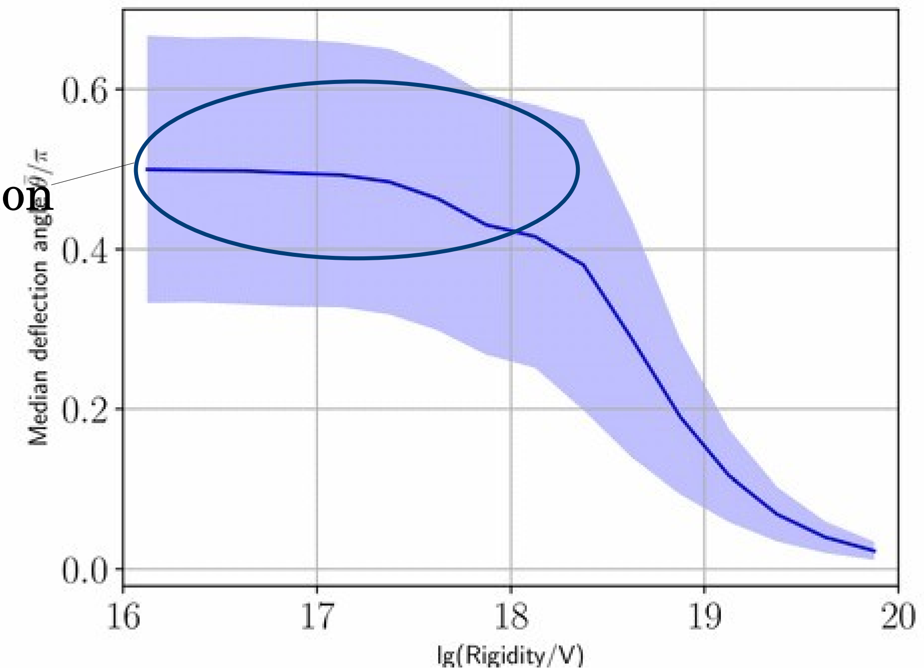


diffusive propagation

EGCRs backtracked from Earth



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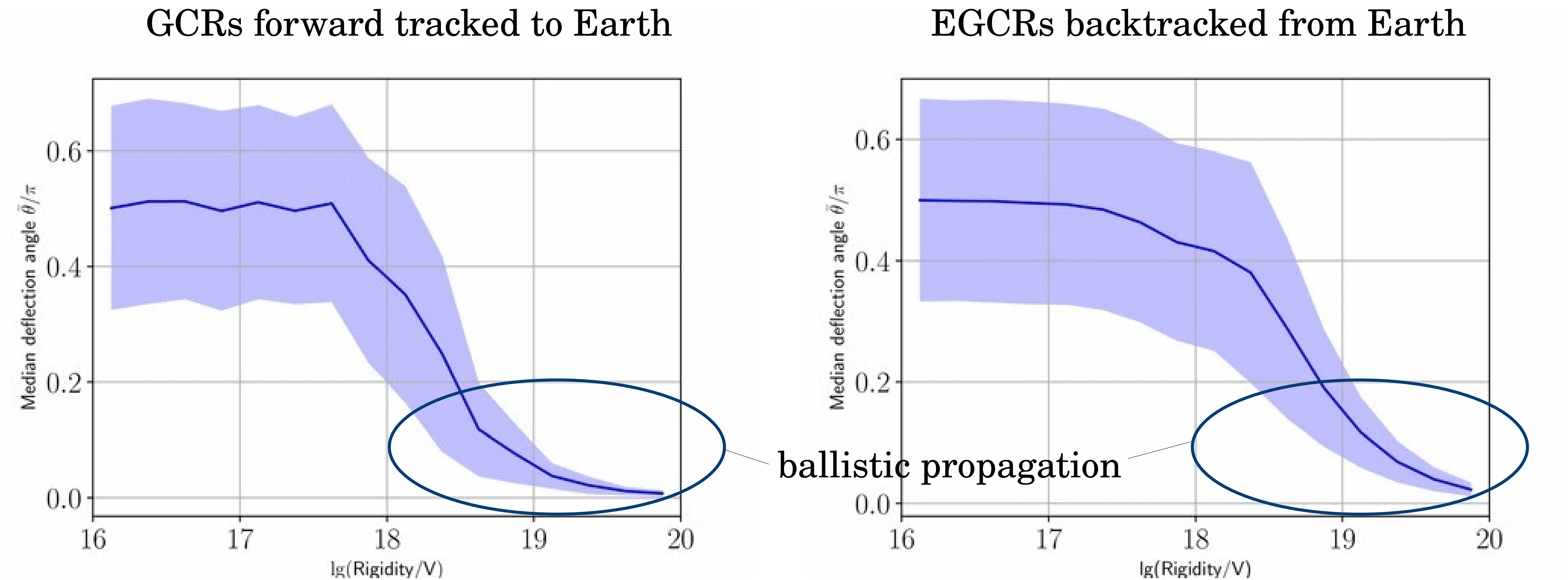

GCRs forward tracked to Earth

EGCRs backtracked from Earth

ballistic propagation

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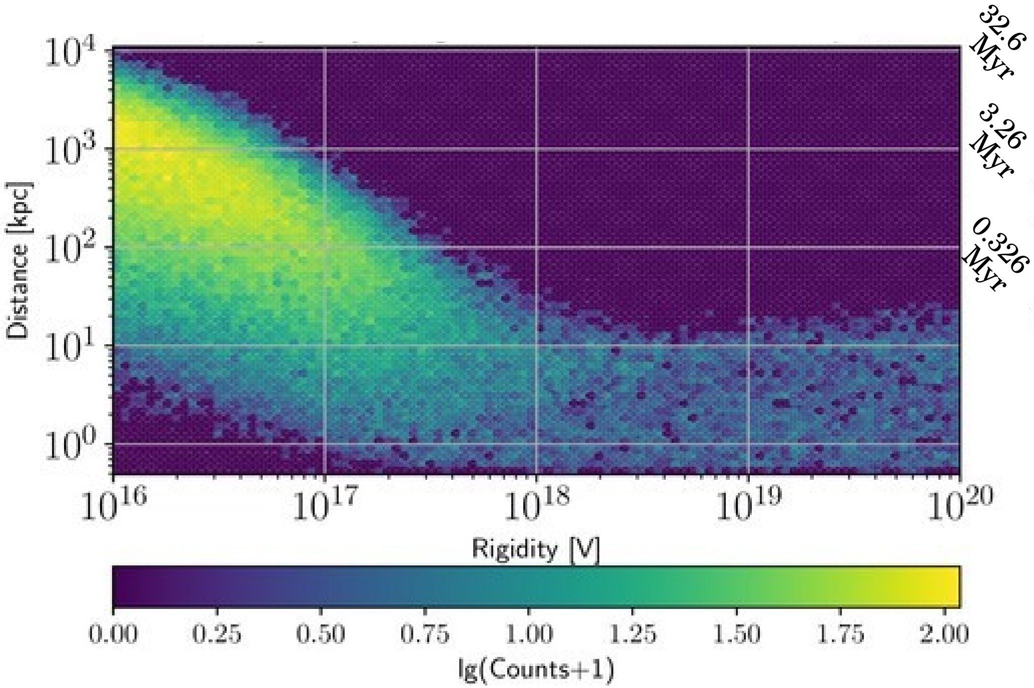
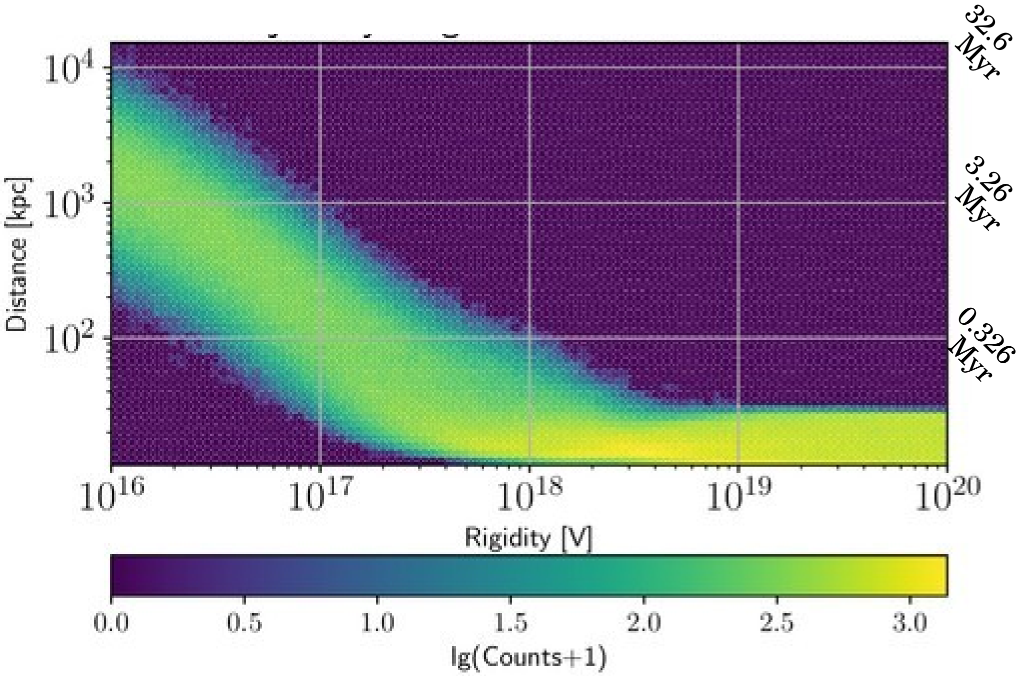
Change in propagation regimes: Propagation time

GCRs forward tracked to Earth



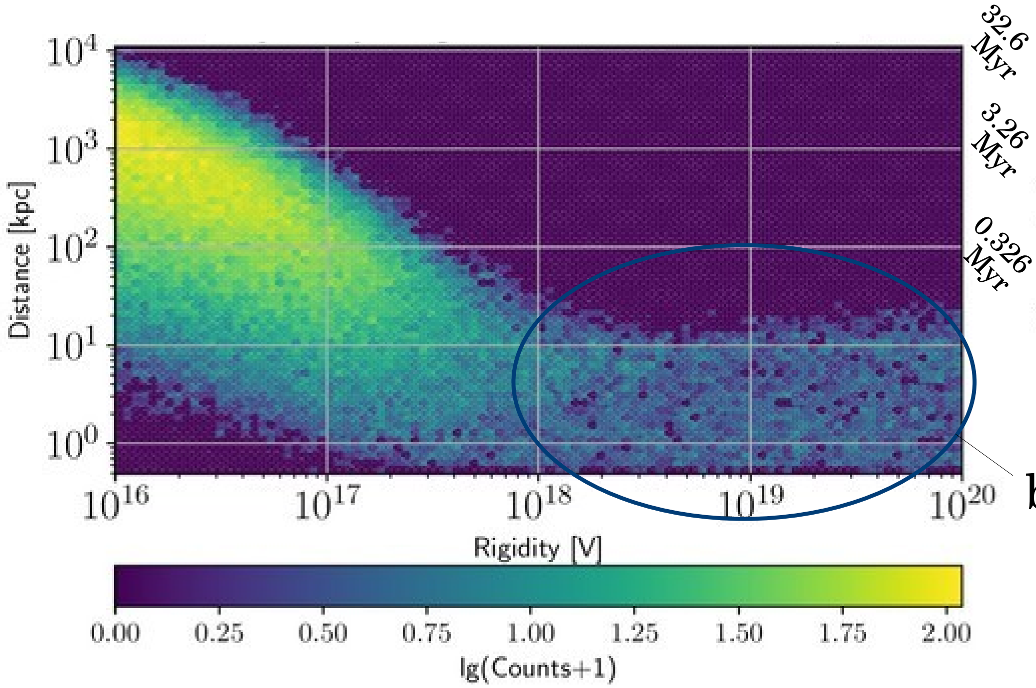
EGCRs backtracked from Earth



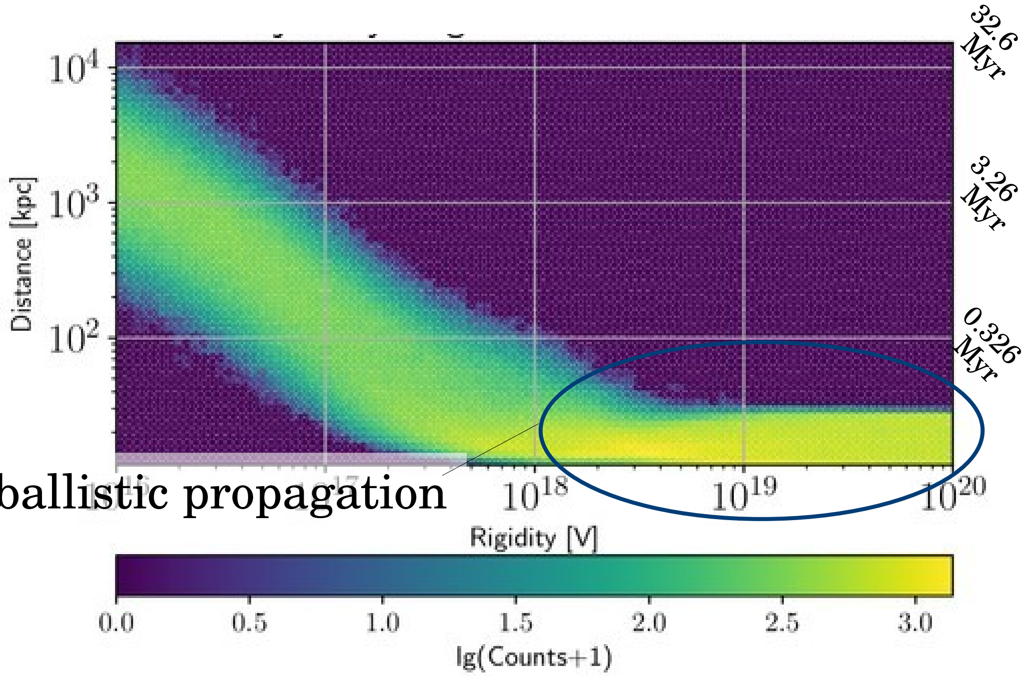
Propagation time increases below rigidities of a few EV.

Change in propagation regimes: Propagation time

GCRs forward tracked to Earth



EGCRs backtracked from Earth



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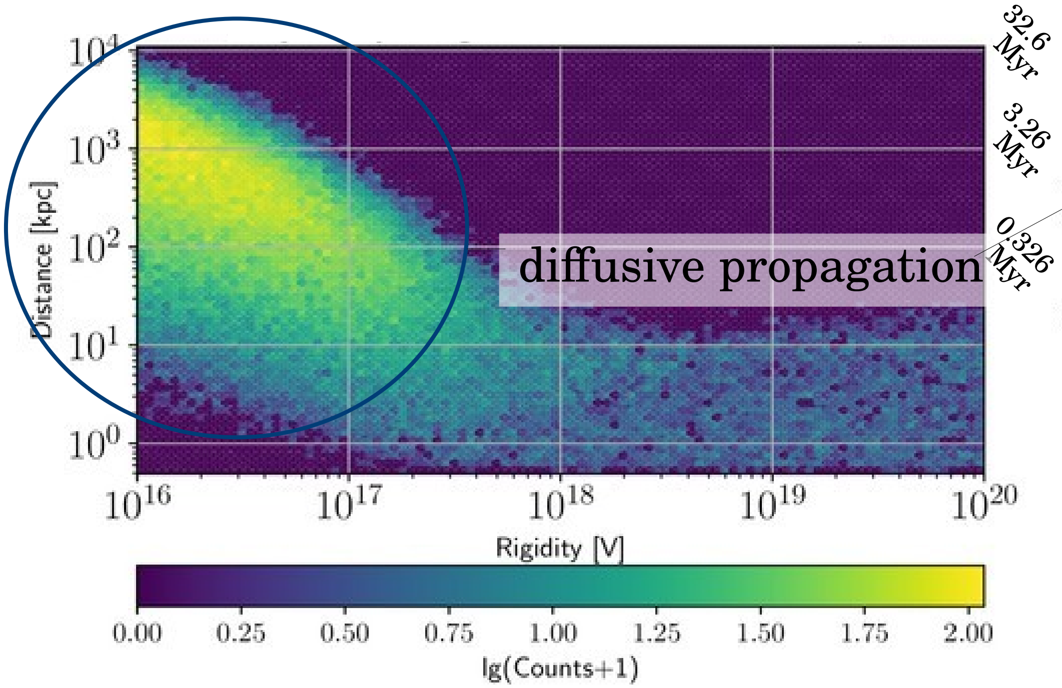

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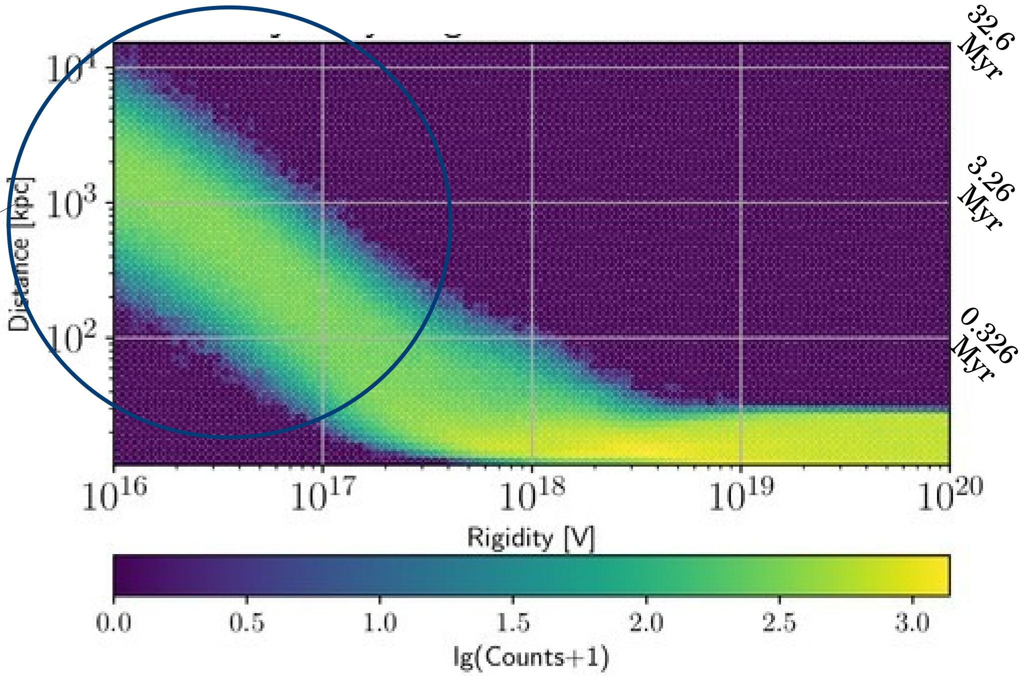

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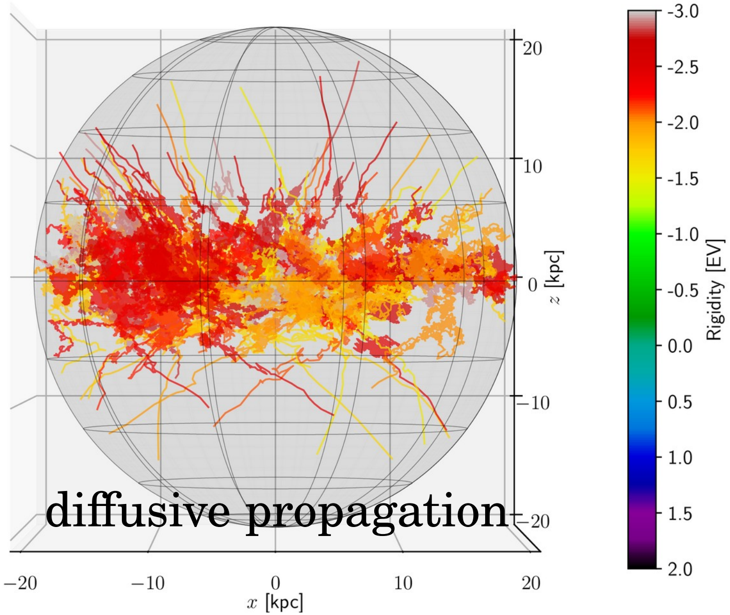
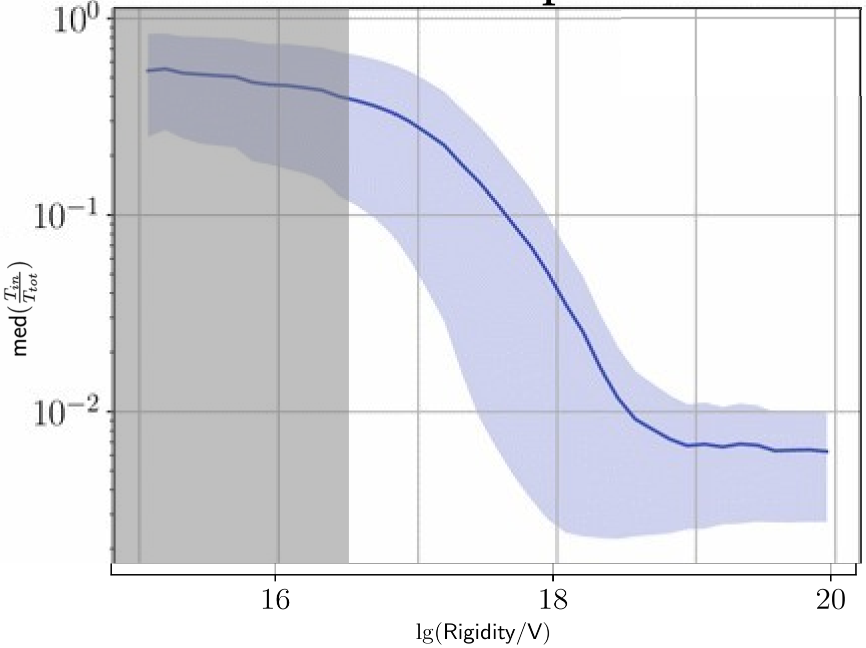
Propagation effects: GCRs – Confinement in GP

Galactic trajectories ($\lg(R/\mathrm{V}) = 15 - 16.5$)



Relative time spent in GP

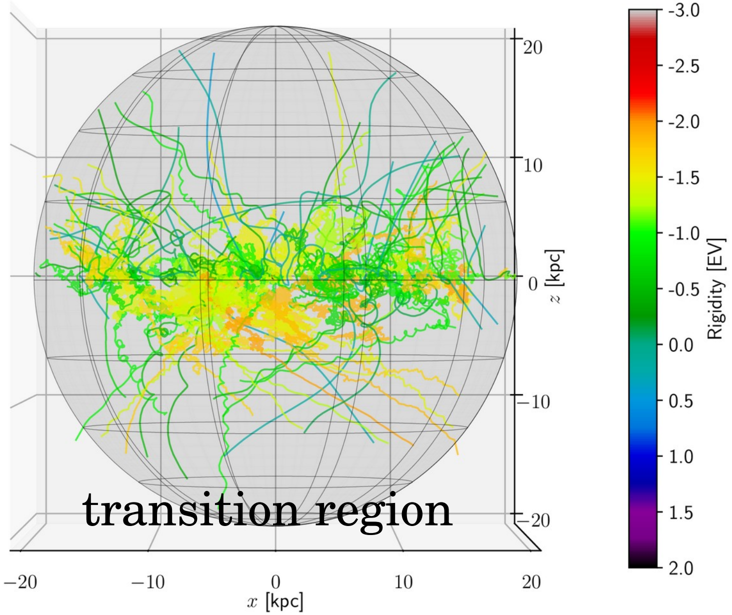


Decreasing confinement in GP **with rigidity.**

Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: GCRs – Confinement in GP

Galactic trajectories (lg(R/V) = 16 – 18.5)



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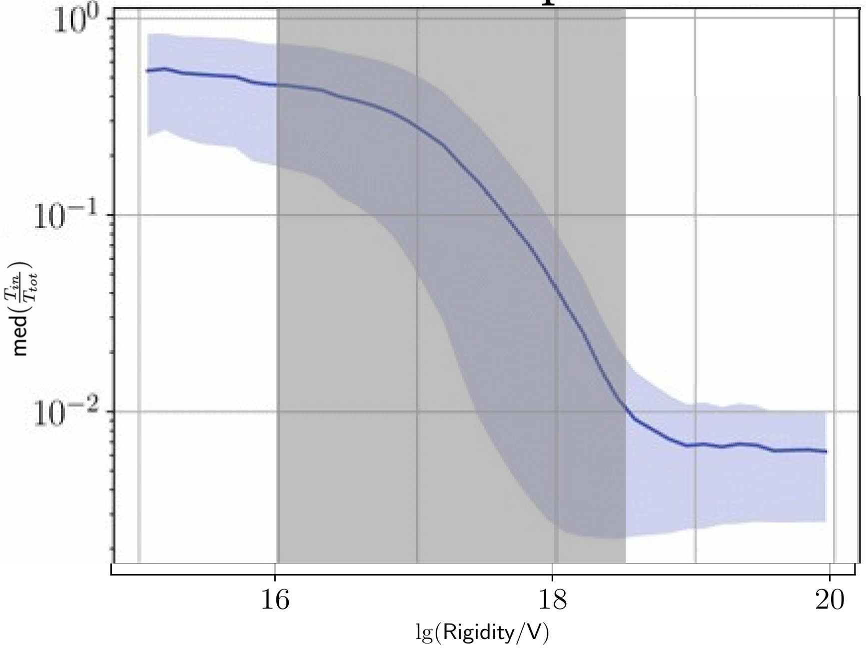

Decreasing confinement in GP **with rigidity.**

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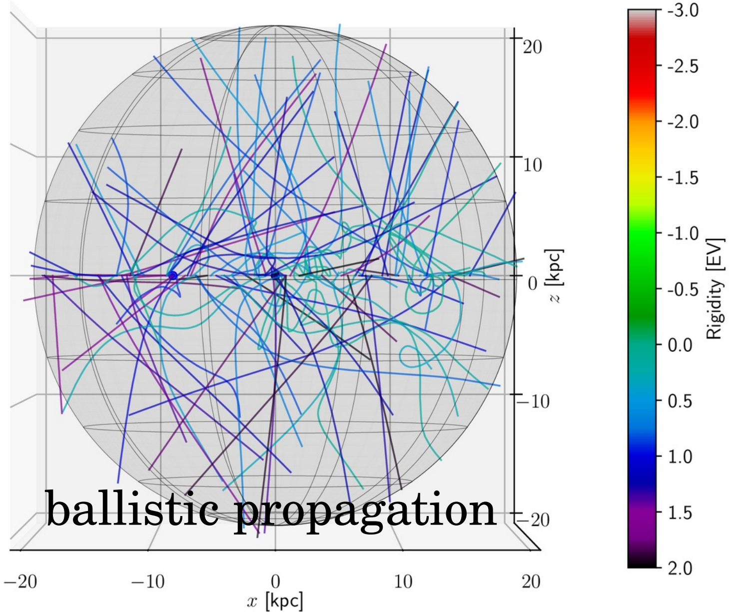
Propagation effects: GCRs – Confinement in GP

Galactic trajectories ($\lg(R/\mathrm{V}) = 18 - 20$)



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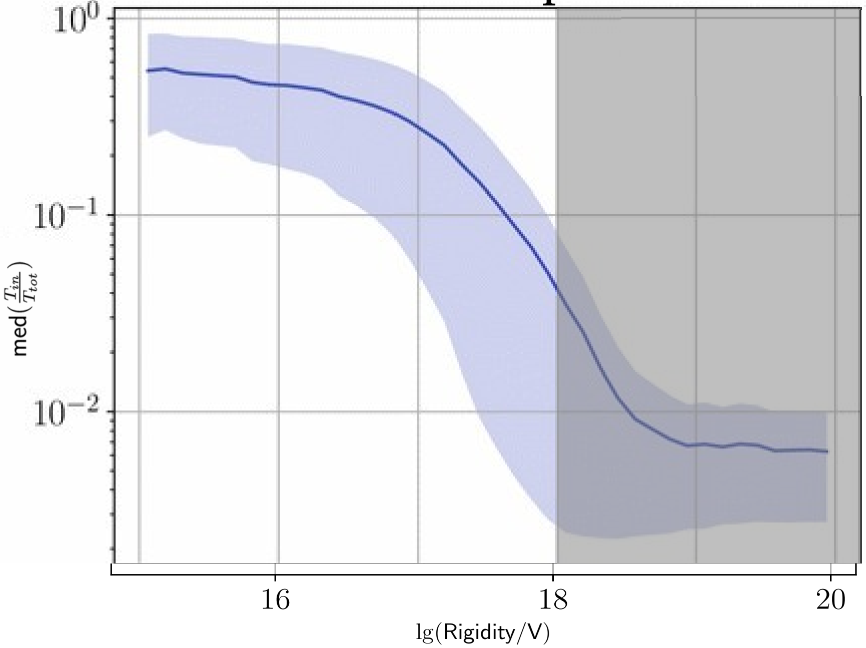

Decreasing confinement in GP **with rigidity.**

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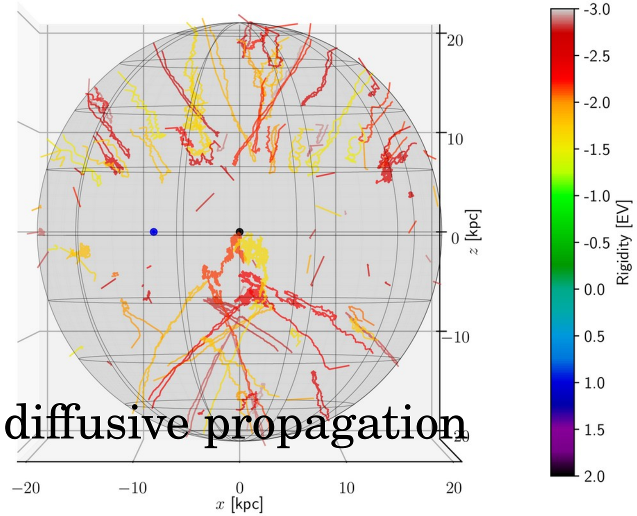
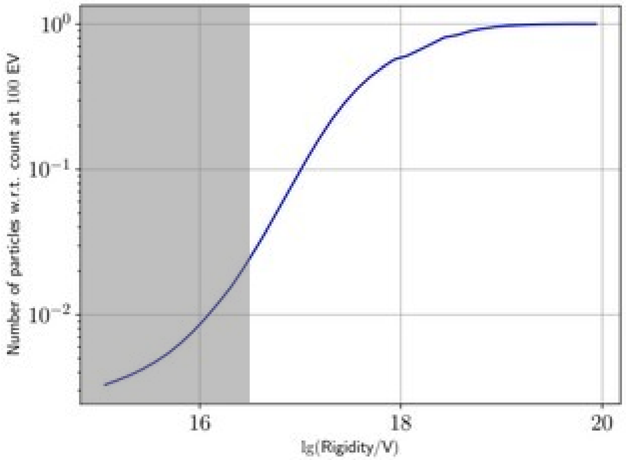
Propagation effects: EGCRs – Shielding from vs. confinement in GP

Galactic trajectories
($\lg(R/\mathrm{V})$ = 15 – 16.5)



diffusive propagation

CR count reaching GP



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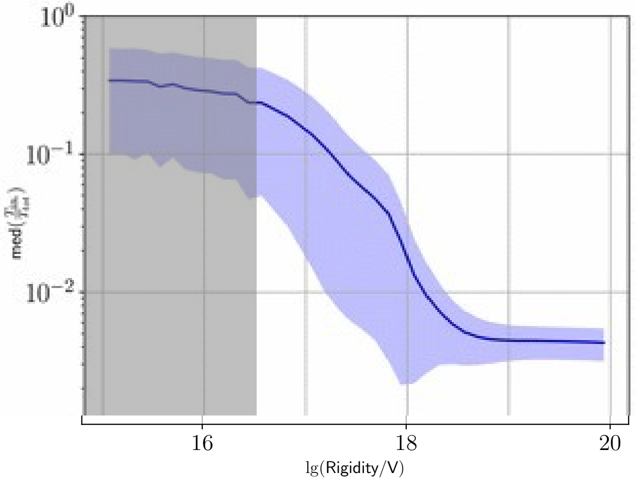


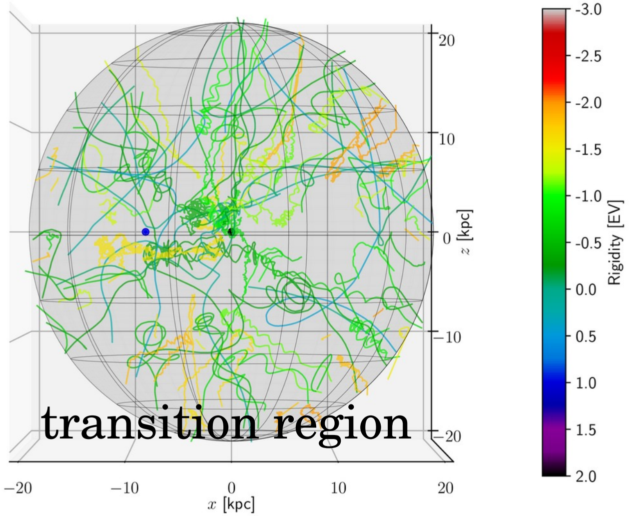
Decreasing shielding from and confinement in GP with rigidity.

CR count decreases for smaller rigidities; **inflection point at a few EV.**

Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: EGCRs – Shielding from vs. confinement in GP

Galactic trajectories
($\lg(R/\mathrm{V}) = 16 – 18.5$)



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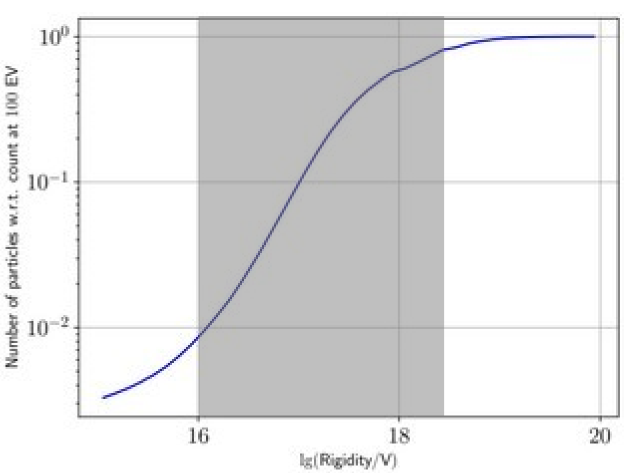
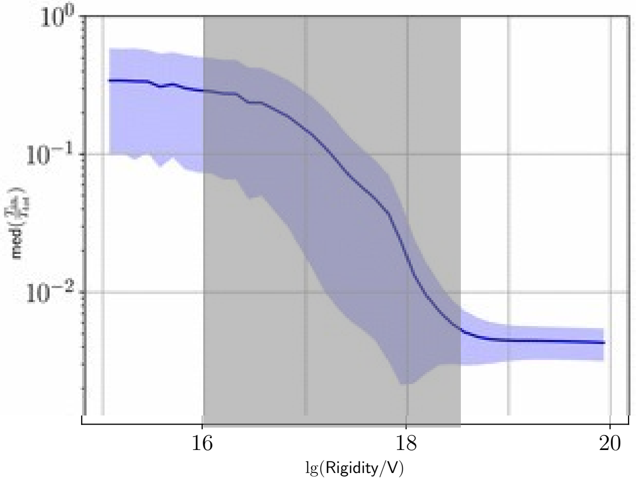


Relative time spent in GP



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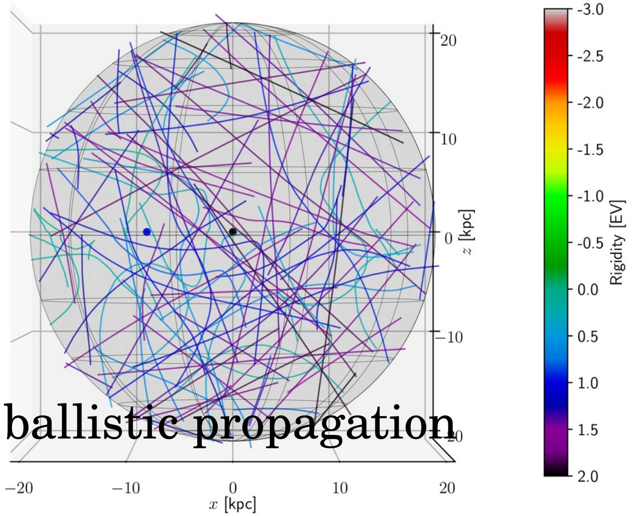
(lg(R/V) = 18 – 20)



ballistic propagation

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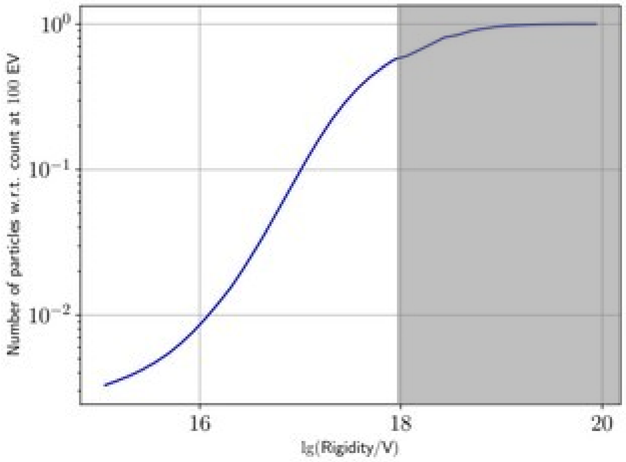

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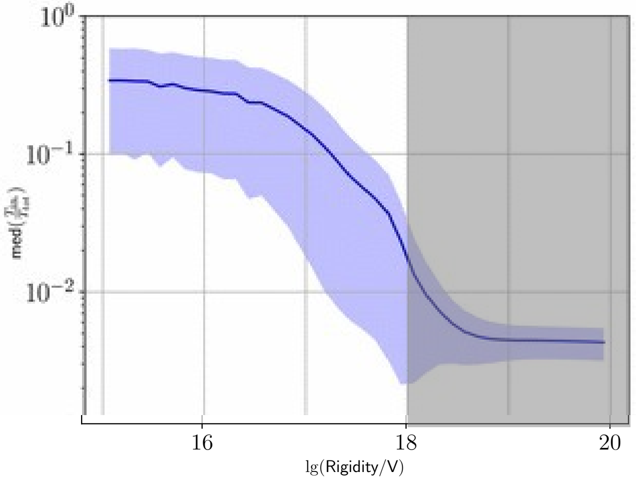

Decreasing shielding from and confinement in GP with rigidity.

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Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

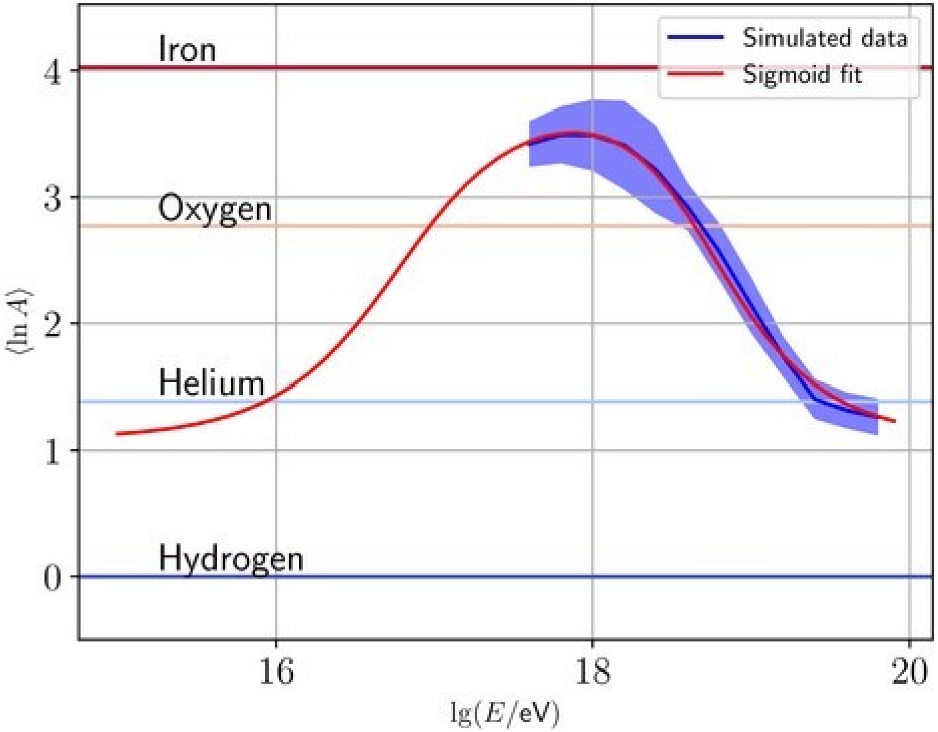
Effect on observables: GCRs – Heavier composition

Decreasing confinement
→ **flux reduction**

Mixed composition
→ **heavier towards 'ankle'**

Arrival direction distribution:
correlation with GP direction
above 0.1 EV

Mean logarithm of mass number (sigmoid fit)



NOTE: Only propagation effects in GMF!

Effect on observables: GCRs – Correlation with source direction (GP)

Decreasing confinement
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Mixed composition
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Arrival direction distribution:
correlation with GP direction
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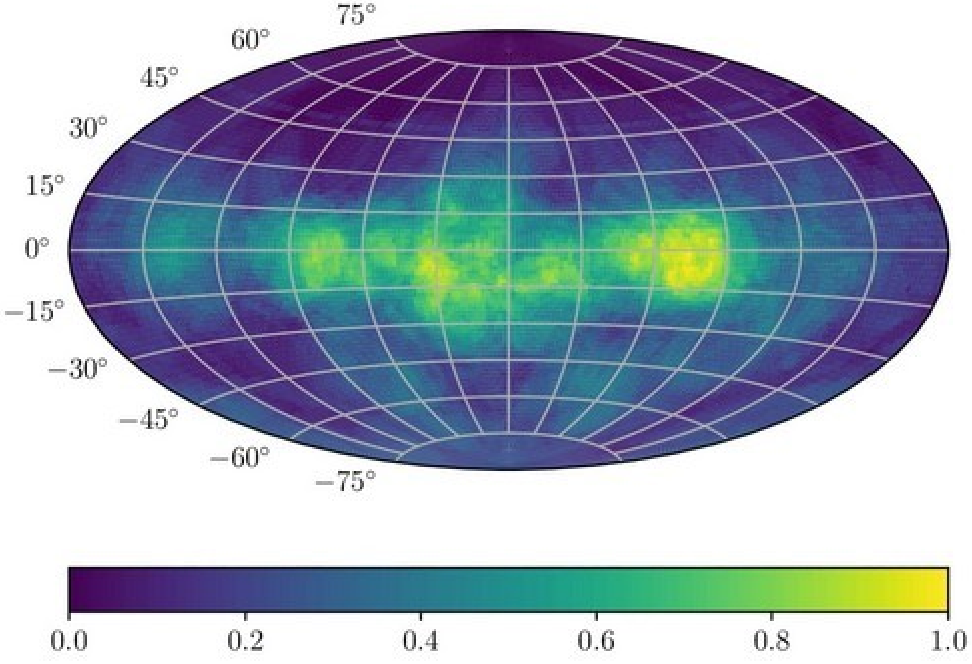
Arrival direction distribution above 0.1 EV



Effect on observables: Isotropic EGCRs – Flux conservation

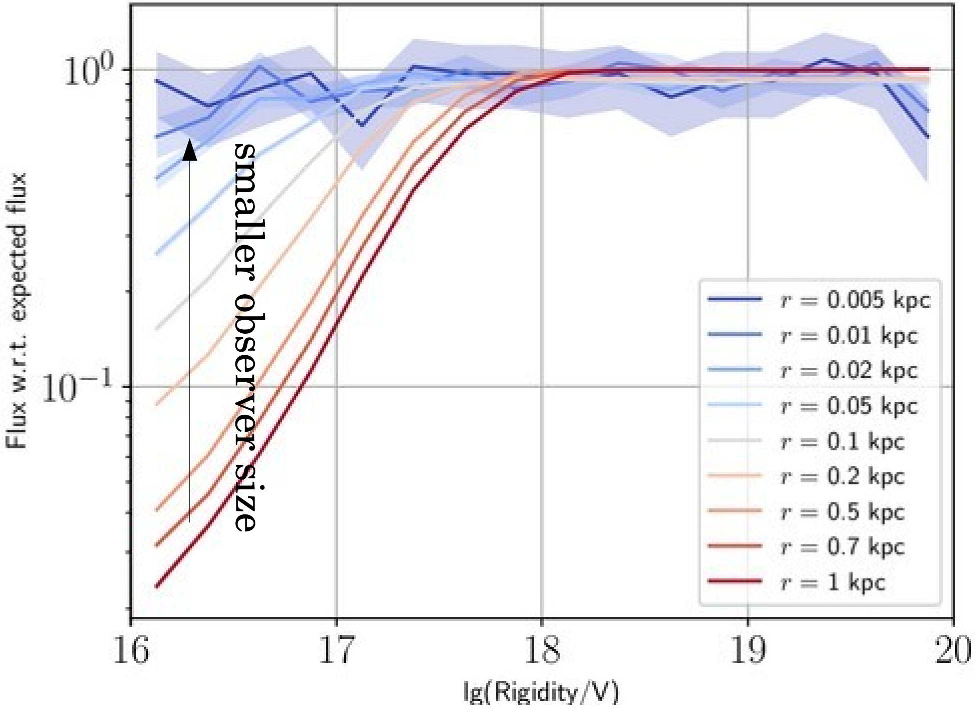
Apparent flux suppression for large observer sphere sizes; effect vanishes as $r \to 0$.

Increased confinement in GP compensates increased shielding:

→ **flux conservation**

Isotropic arrival direction

Rigidity spectrum



Effect on observables: Isotropic EGCRs – Isotropic arrival direction

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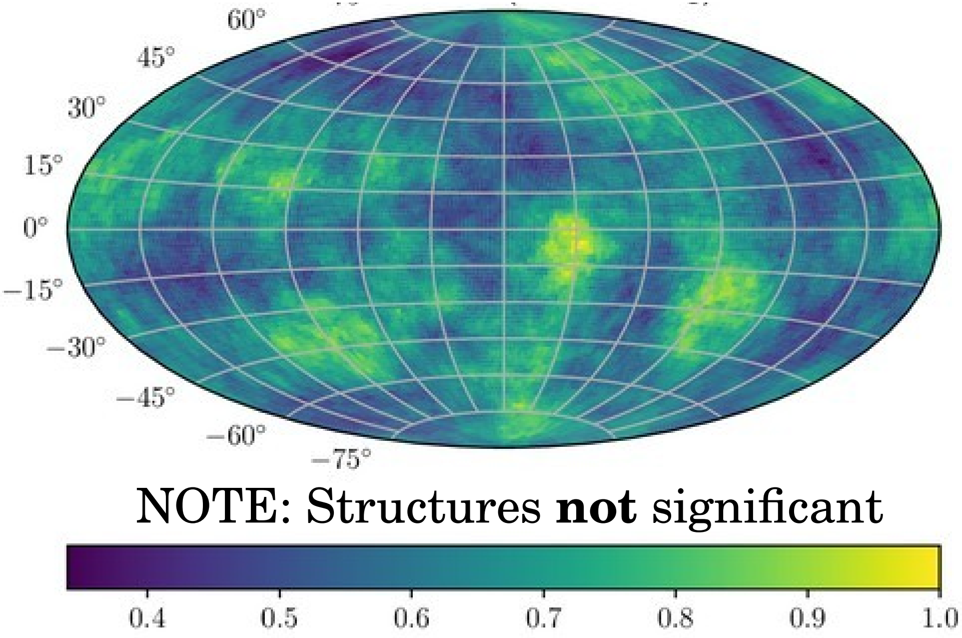
Isotropic arrival direction

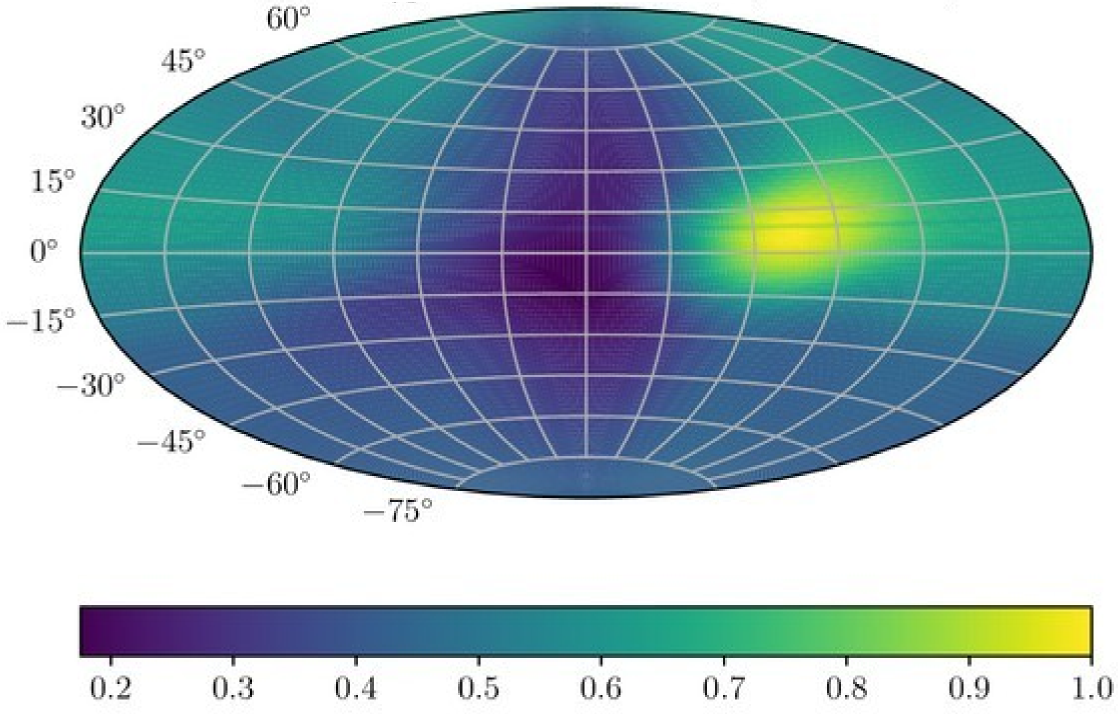
Arrival direction distribution



NOTE: Structures **not** significant

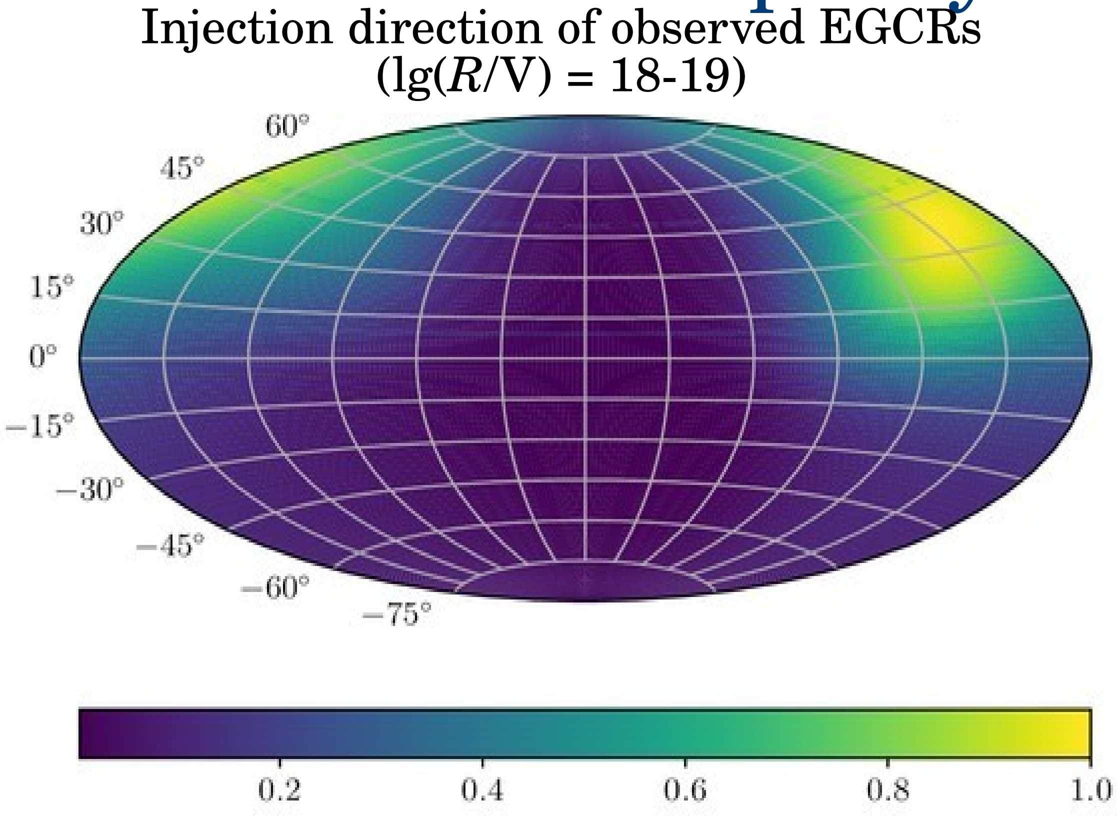
Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy

Injection direction of observed EGCRs
(lg(R/V) = 19-20)



- Regions of enhanced/suppressed transparency **shift with rigidity**

Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy



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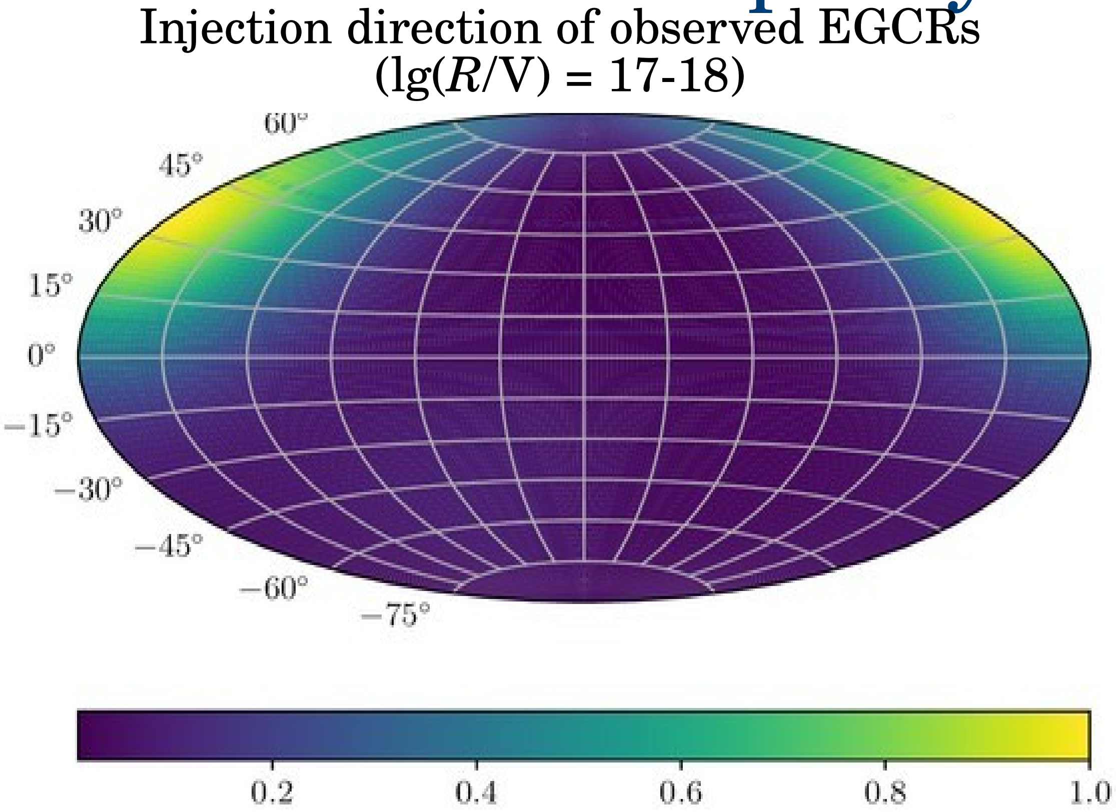
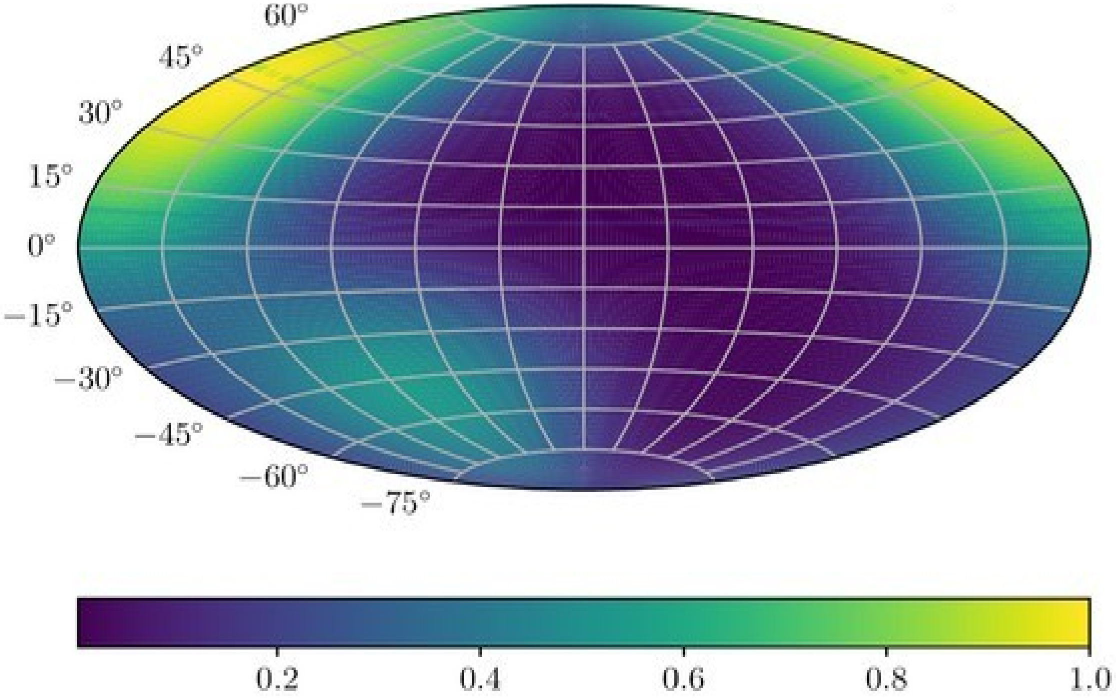


- Regions of enhanced/suppressed transparency **shift with rigidity**

Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy

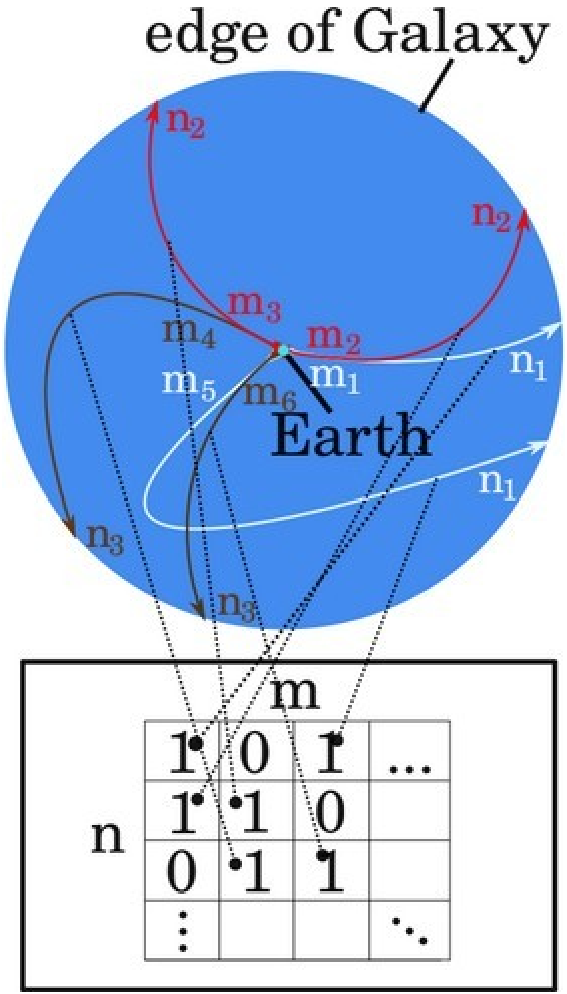
Injection direction of observed EGCRs
($\lg(R/\mathrm{V})$ = 16-17)



- Regions of enhanced/suppressed transparency **shift with rigidity**

Effect on observables: Anisotropic EGCRs – Galactic lensing

see also: Astropart.Phys. 85 (2016) 54-64 for lensing scheme &
Eichmann, JCAP04(2020)047 for parallel work



Propagation in GMF can be quantified via lens

- distance of EG source to observer >> size of Galaxy

  → only injection **direction** relevant

Procedure:

1. **track** ***N*** **particles** between Earth and edge of Galaxy and **store injection direction** at edge and **arrival direction** at Earth
2. **discretise solid angle** range and **assign numbers** *n* and *m* to corresponding **injection and arrival directions**

Alex Kääpä alex.kaeaepae@rub.de

Effect on observables: Anisotropic EGCRs – Galactic lensing

see also: Astropart.Phys. 85 (2016) 54-64 for lensing scheme &
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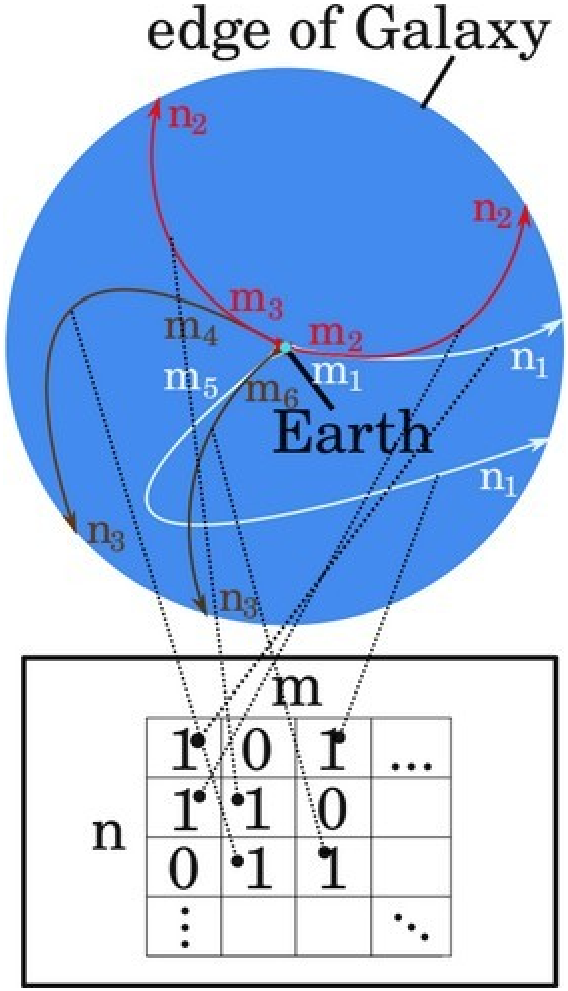


3 count occurrence *o* of each injection/arrival direction **pair** (n,m)

- spans matrix L ($l_{nm} = o$)
- L signifies **distribution of arrival directions** m at the observer point for each **injection direction** n

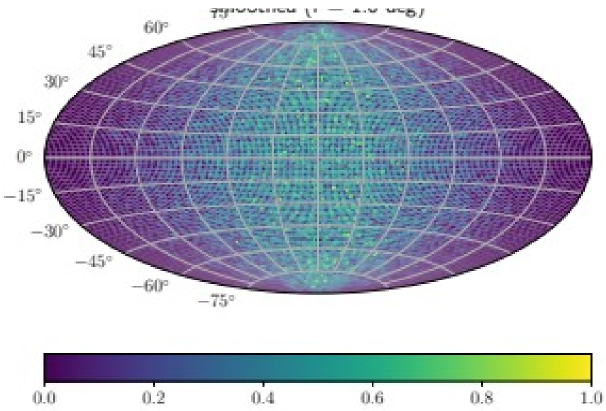
4 matrix weighted by its 1-norm (= number of simulated particles N) **defines lens**

→ calculate arrival direction distribution for any injection direction distribution:

$$\vec{A} = \vec{I} \cdot \mathcal{L}$$

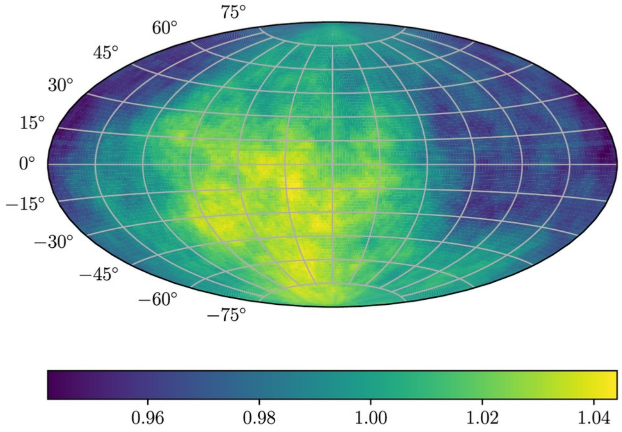
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



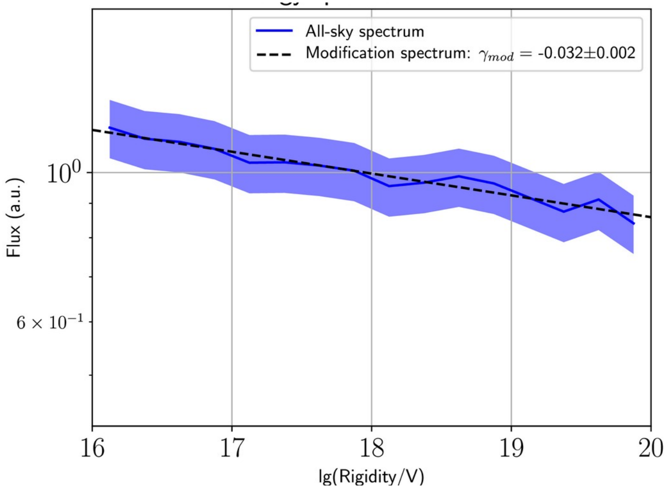
Injection direction distribution:
Pure dipole

Flux at Earth



- **surviving dipole** in arrival direction distribution **above 1 EV**
- **strong isotropisation** by GMF at lower energies
- dipole amplitude **< 10% !**

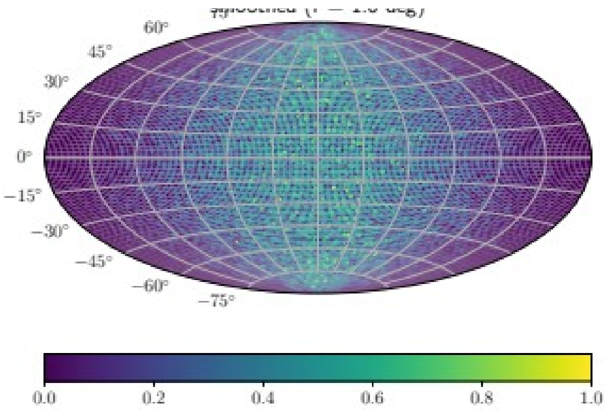
Flux at Earth



Rigidity spectrum at Earth → **possible flux modification**

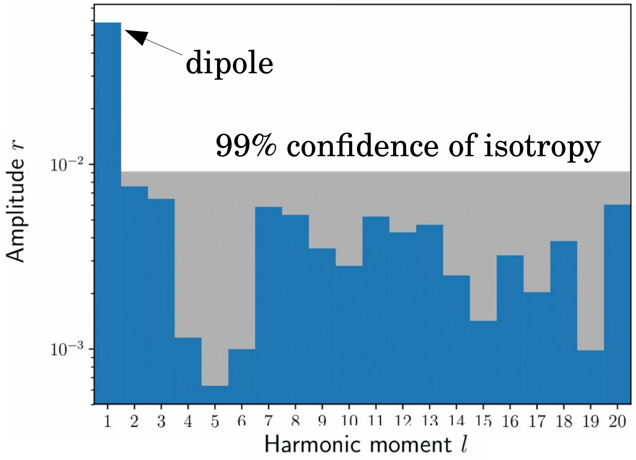
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



Injection direction distribution: **Pure dipole**

Distribution of moments above 1 EV



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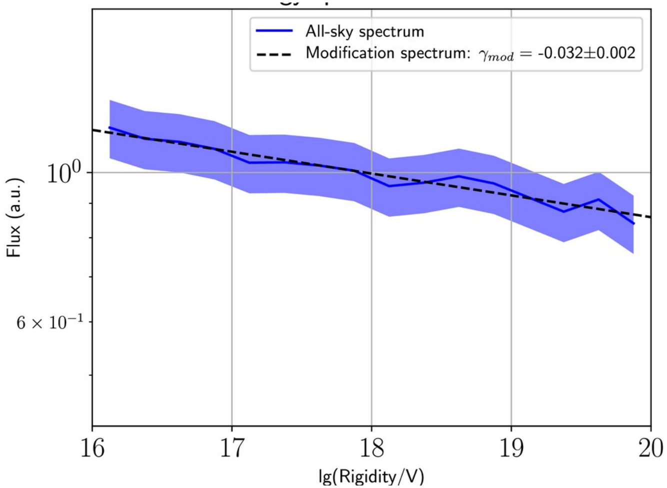
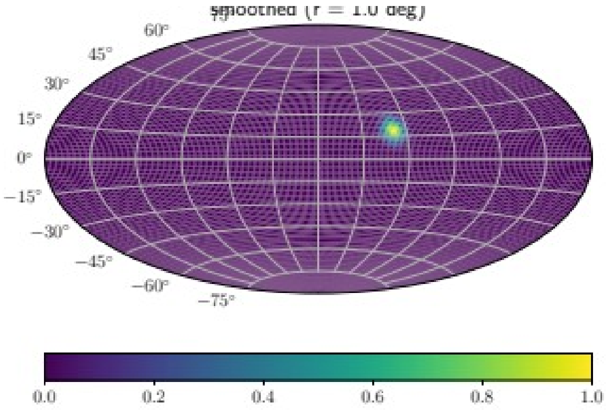


Rigidity spectrum at Earth → **possible flux modification**

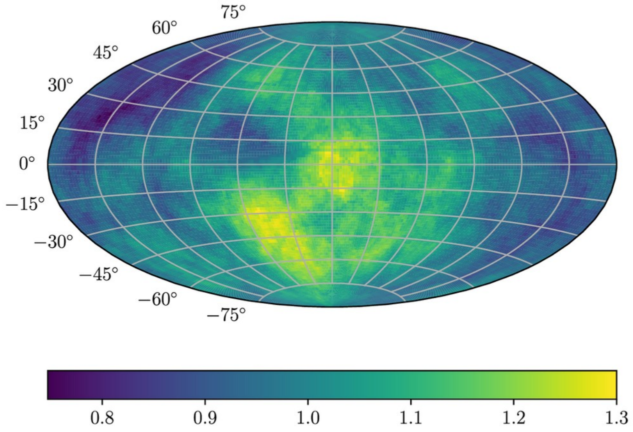
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



Injection direction distribution: **Pure single-point source** (Cen A)

Flux at Earth



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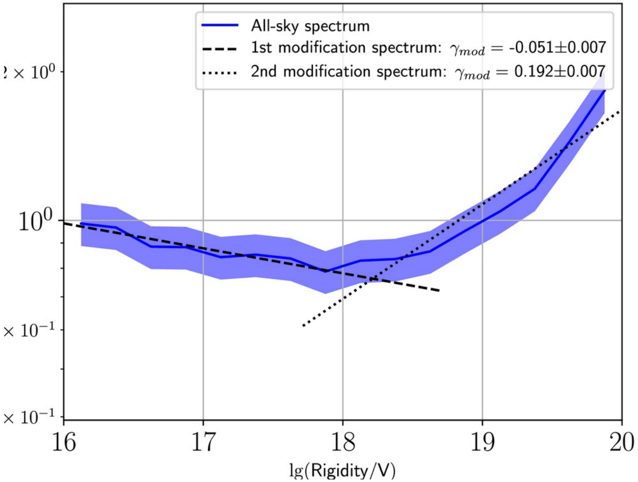
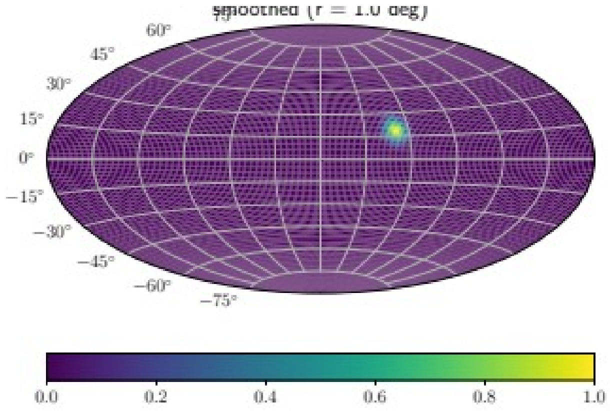


Rigidity spectrum at Earth → **possible flux modification**

Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



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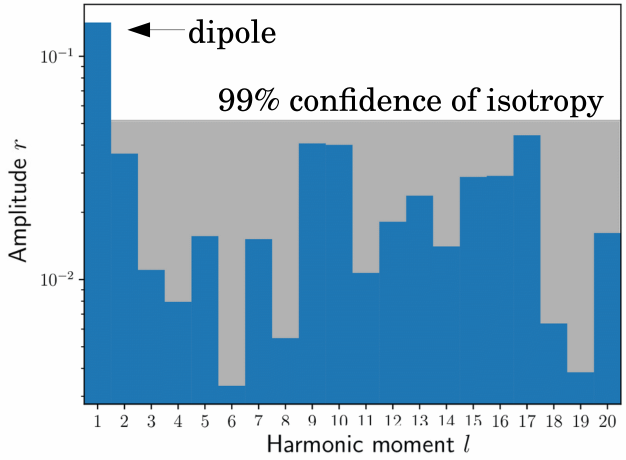

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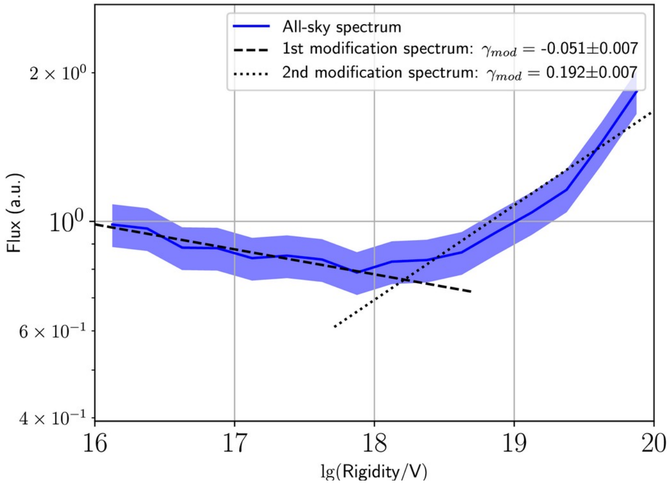
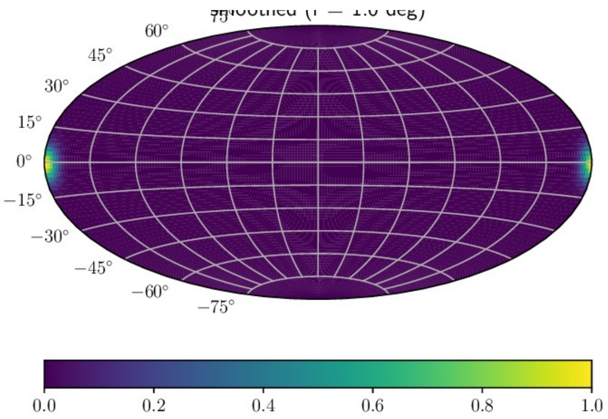


Rigidity spectrum at Earth → **possible flux modification**

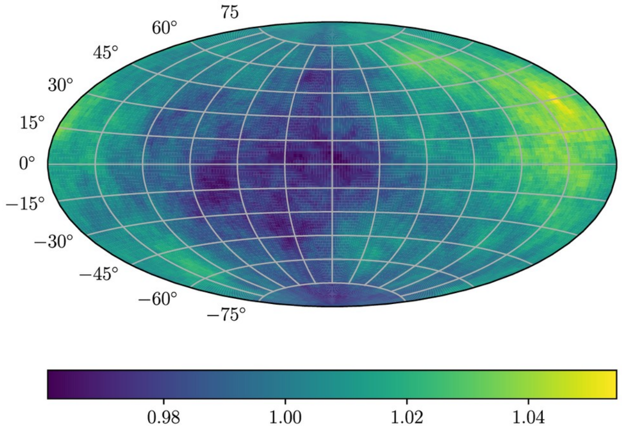
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



Injection direction distribution: **Pure single-point source** (Galactic anti-centre)

Flux at Earth



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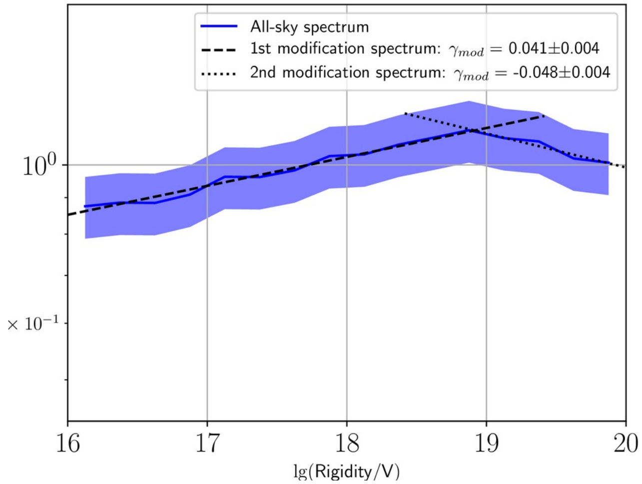
Flux at Earth

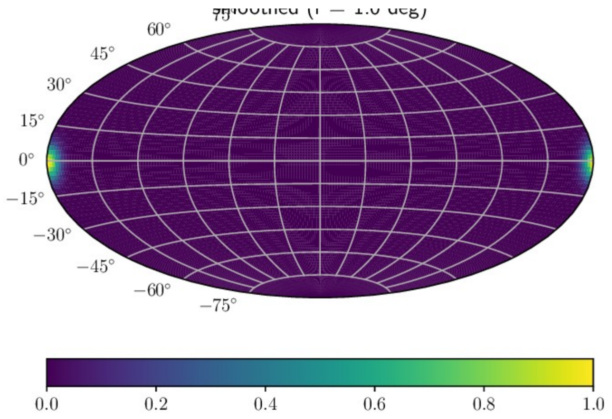


Rigidity spectrum at Earth → **possible flux modification**

Alex Kääpä alex.kaeaepae@rub.de Transition from GCRs to EGCRs

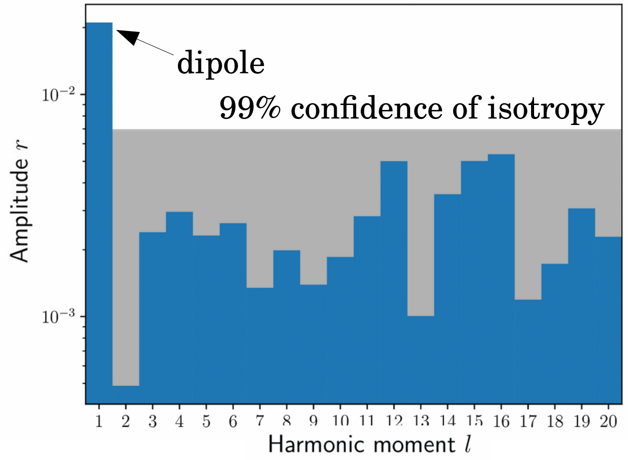
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



Injection direction distribution: **Pure single-point source** (Galactic anti-centre)

Distribution of moments above 1 EV



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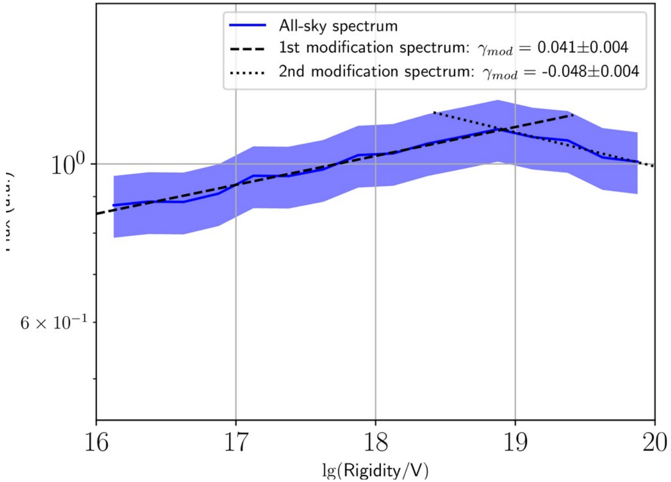
Flux at Earth

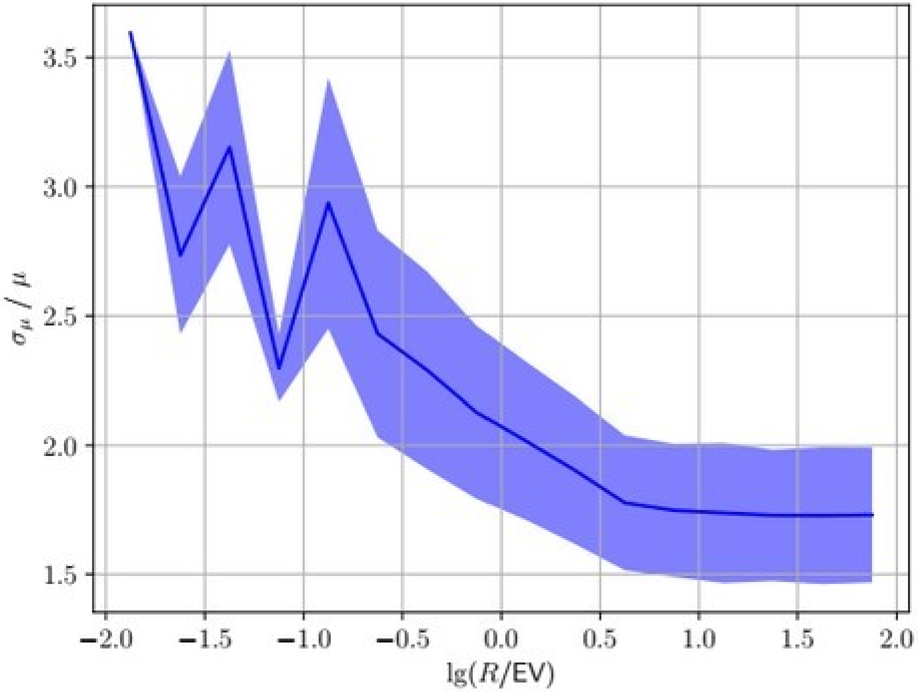


Rigidity spectrum at Earth → **possible flux modification**

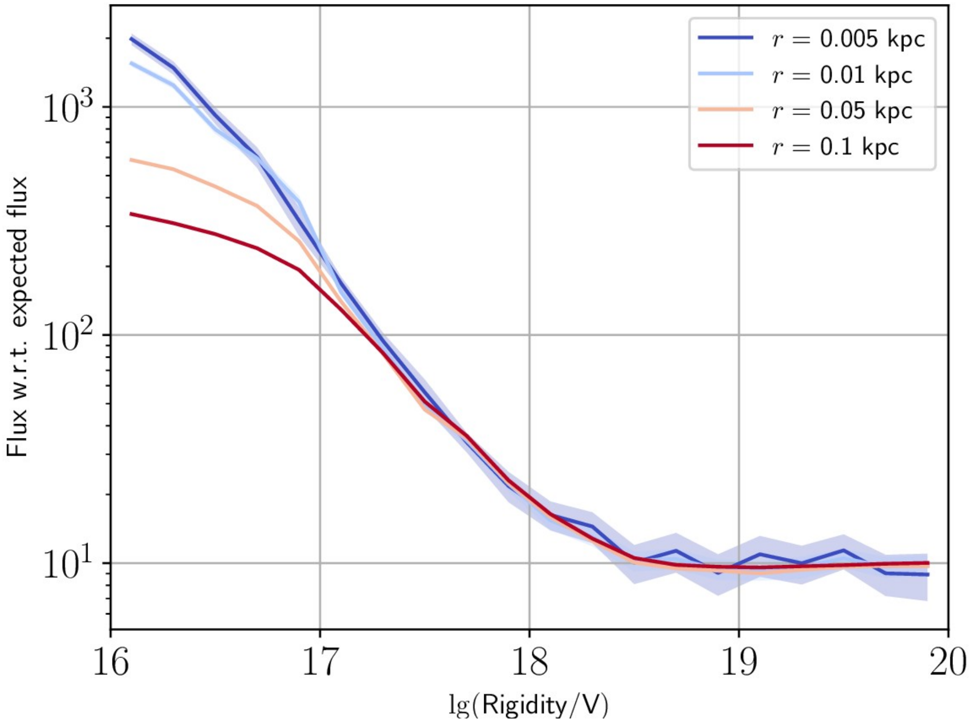
Liouville's Theorem

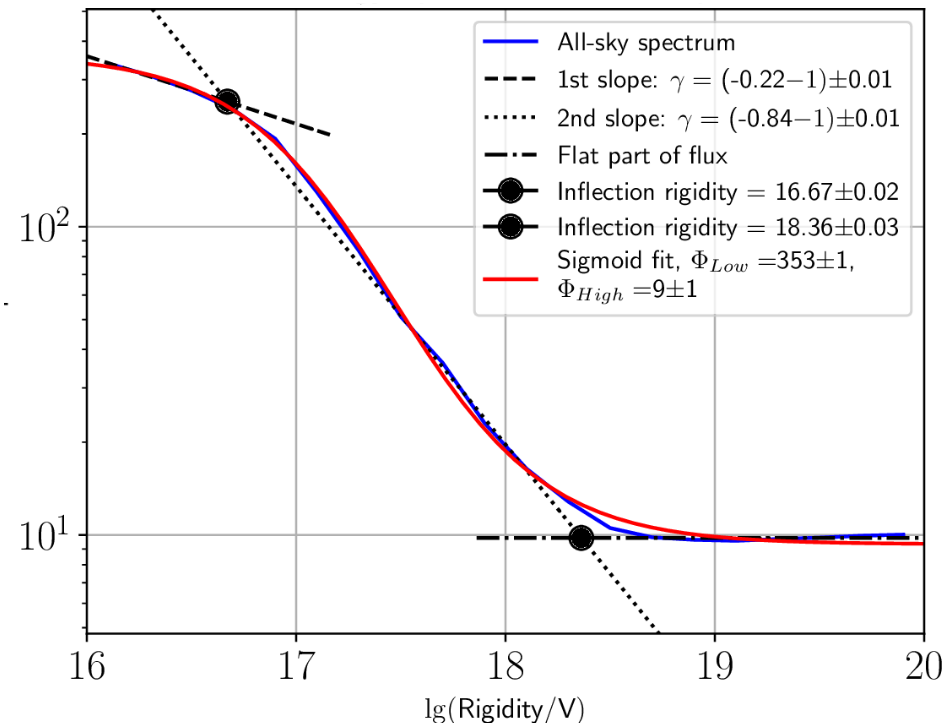
- Objection to flux modification of EGCRs: **Liouville's Theorem**
  - If **phase space density is conserved, so is flux**
  - BUT: If Liouville holds, then **other quantities are conserved, i.a. first adiabtic invariant**
    ~ classical magnetic moment (APJ 842:54, APJ 830:19):

$$\boxed{\mu = \frac{e}{2\,m\pi\,c} \cdot I = \text{const.} \Rightarrow r_\mu = \frac{\sigma_\mu}{\langle\mu\rangle} \text{ small}}$$



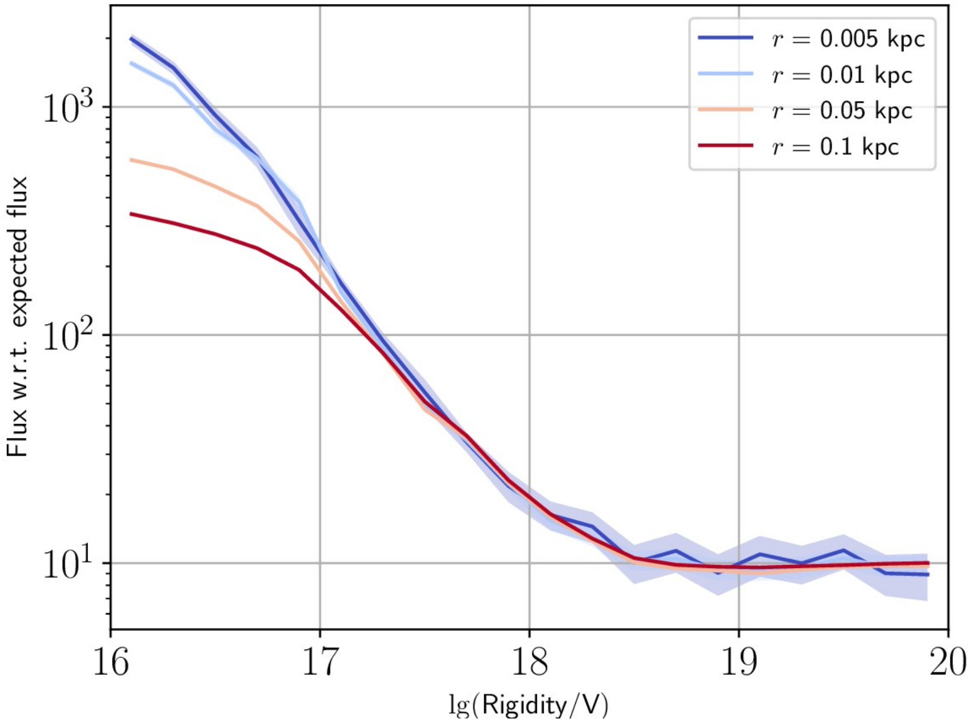
GCRs – Sigmoid fit to flux

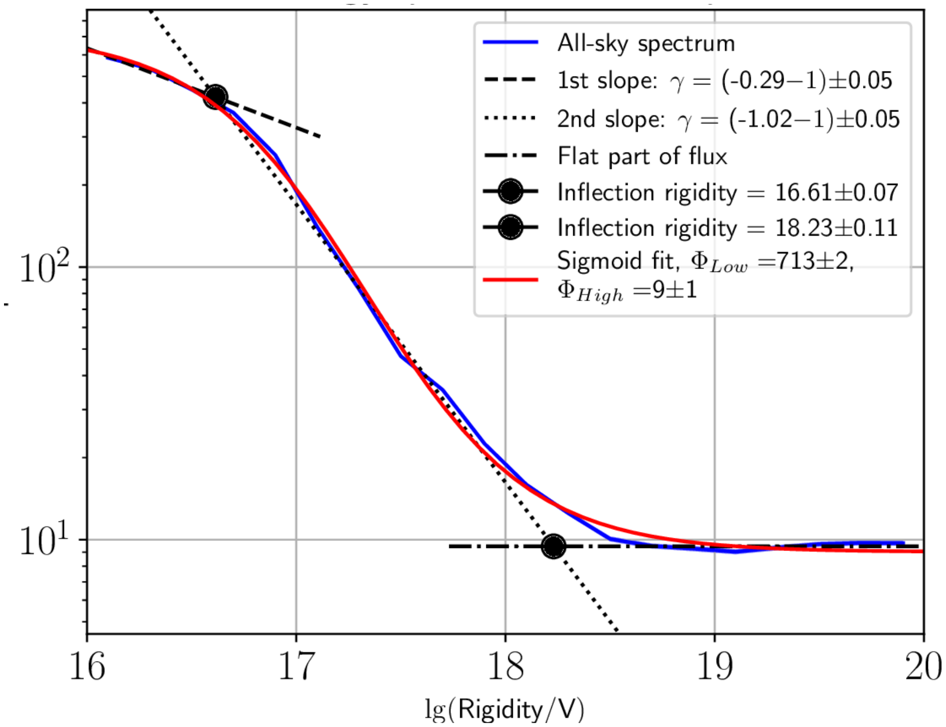




- Flux enhancement towards lower rigidities appears to flatten out → sigmoid fit
- Advantage: wider overlapping energy range of mixed compositions

GCRs – Sigmoid fit to flux





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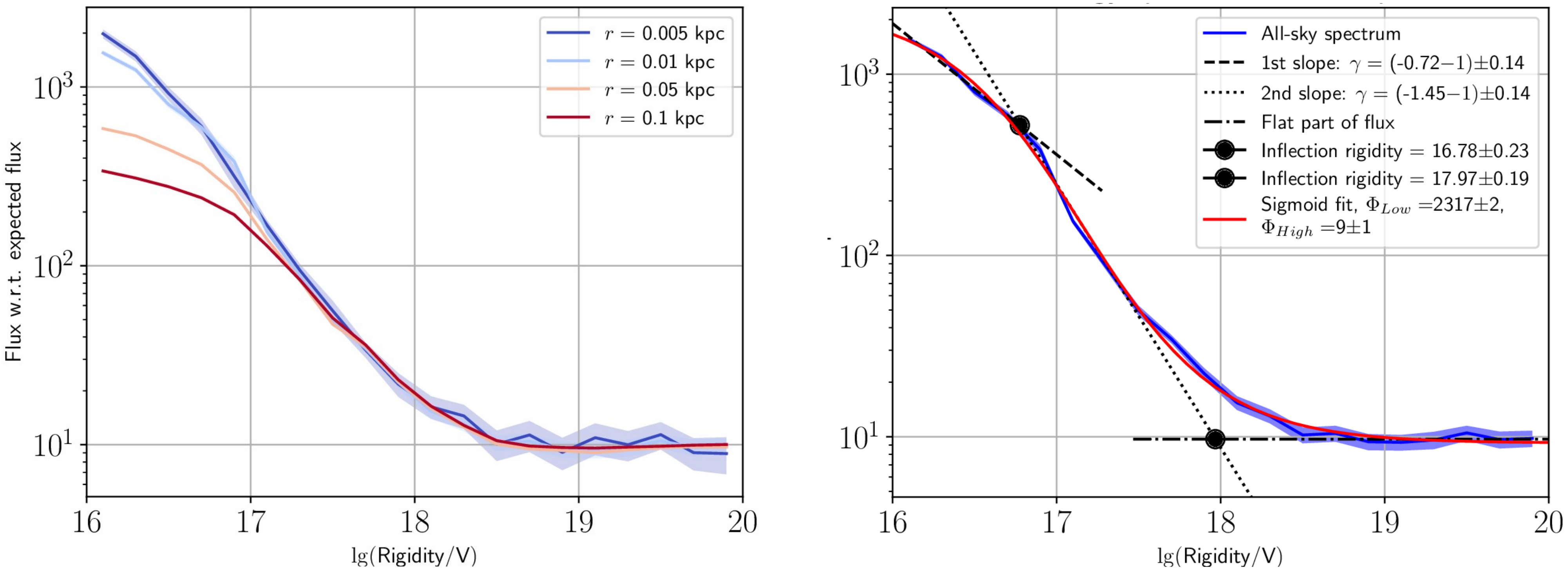
GCRs – Sigmoid fit to flux



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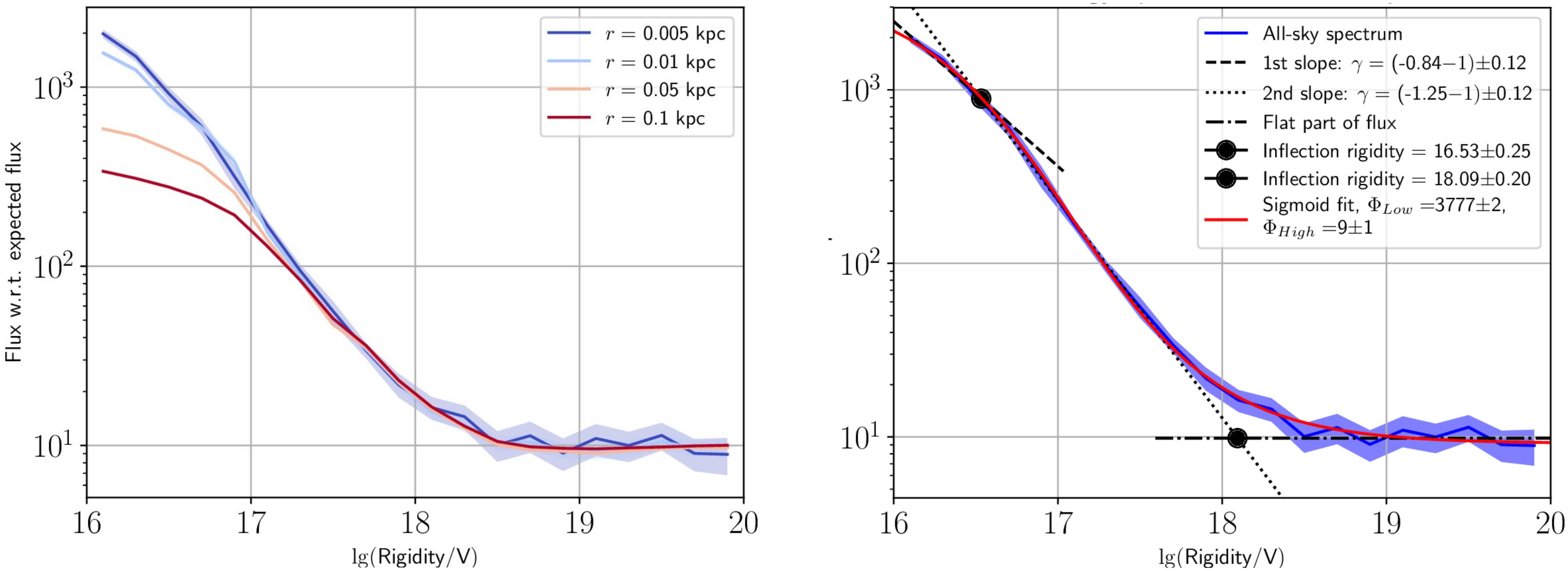
GCRs – Sigmoid fit to flux



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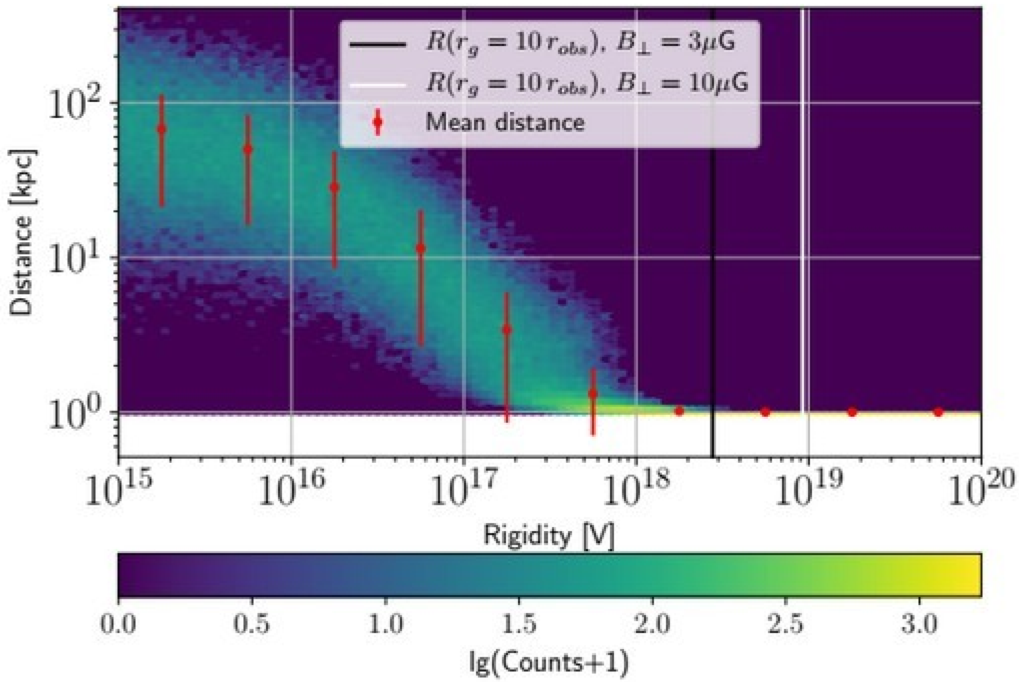
On the modification of EGCR energy spectrum

- **Propagation time** and **fraction of space traversed** increases to **compensate shielding**



On the modification of EGCR energy spectrum

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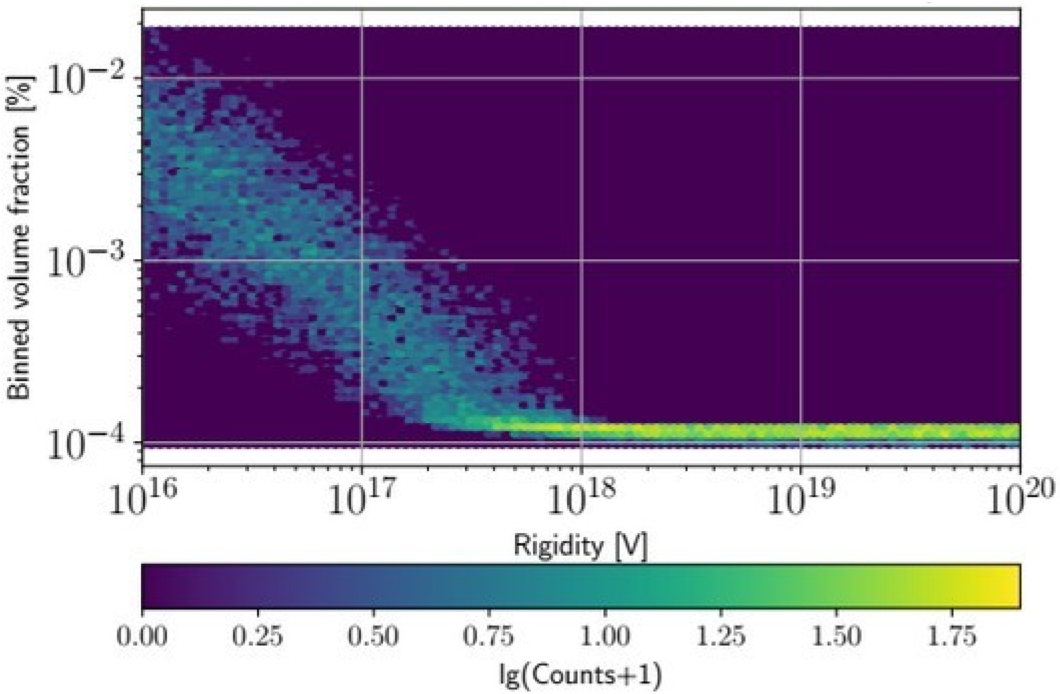


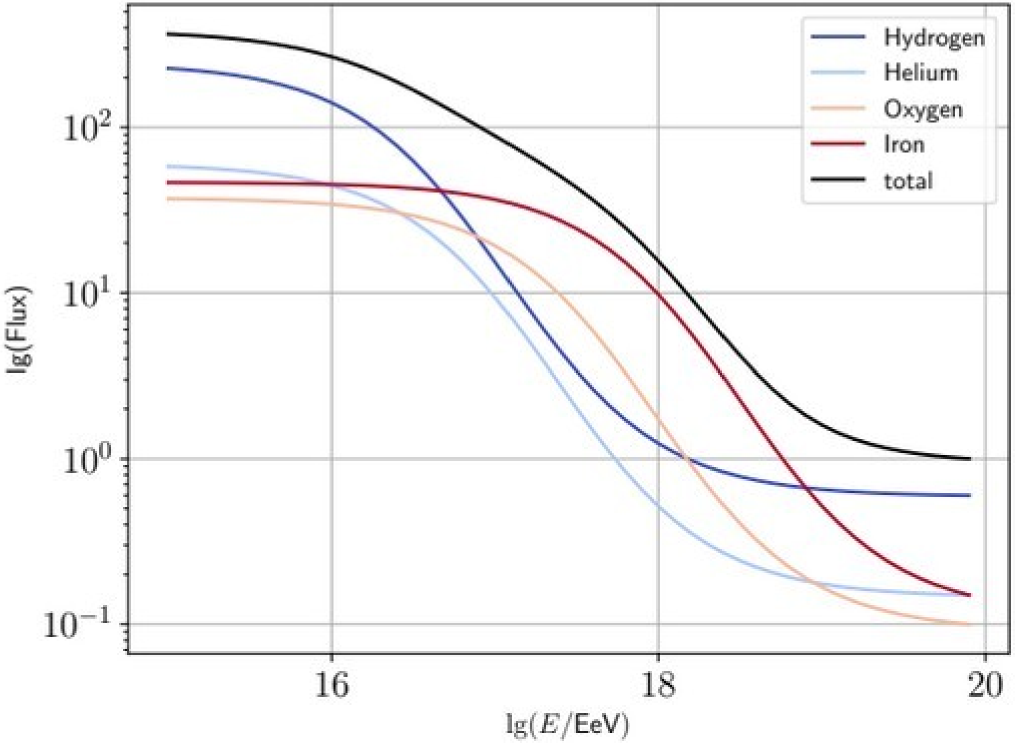
Effect on observables: GCRs – Flux suppression

Decreasing confinement
→ **flux reduction**

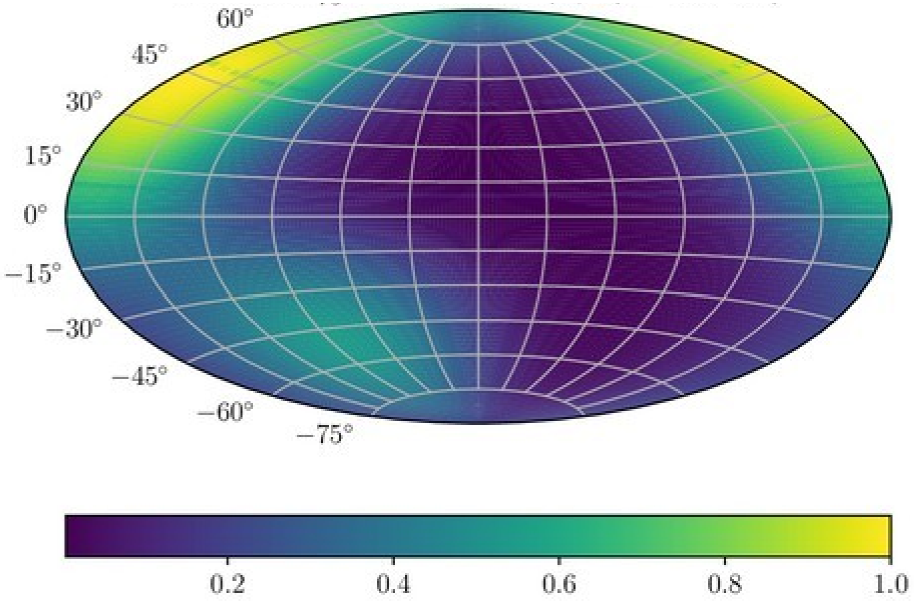
Mixed composition
→ **heavier towards 'ankle'**

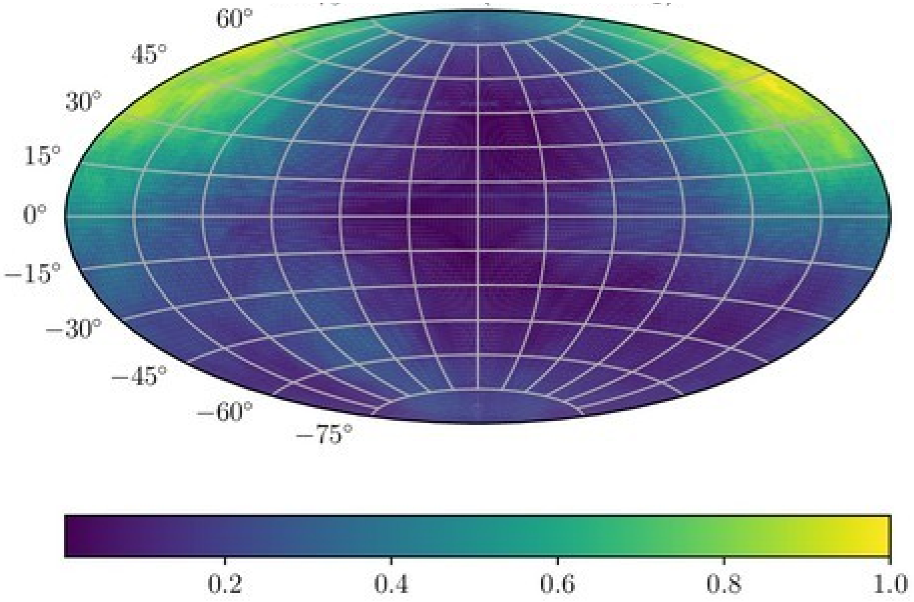
Arrival direction distribution:
correlation with GP direction
above 0.1 EV

All-particle energy spectrum (sigmoid fit)



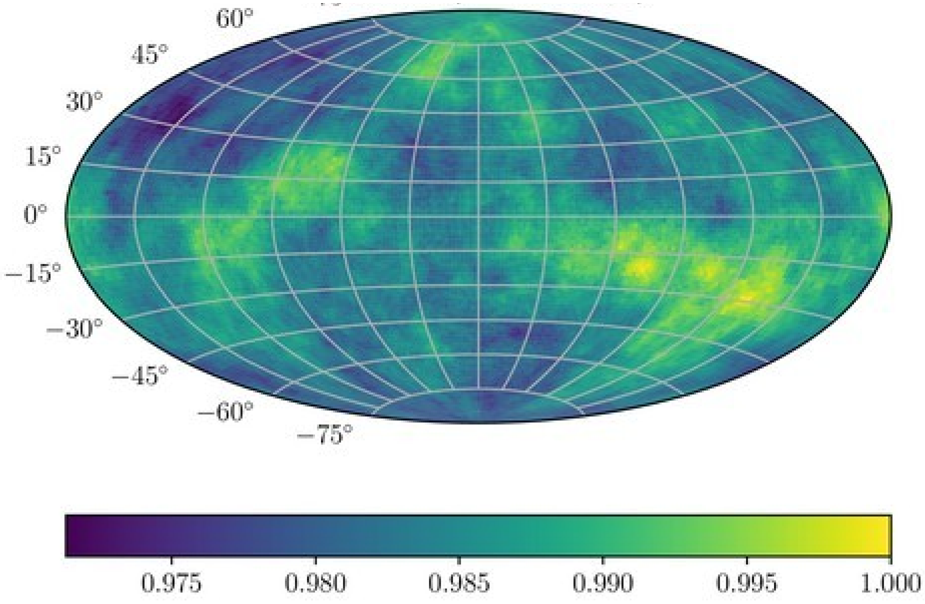
Galactic lensing – time reversibility


Injection direction of observed EGCRs backtracking

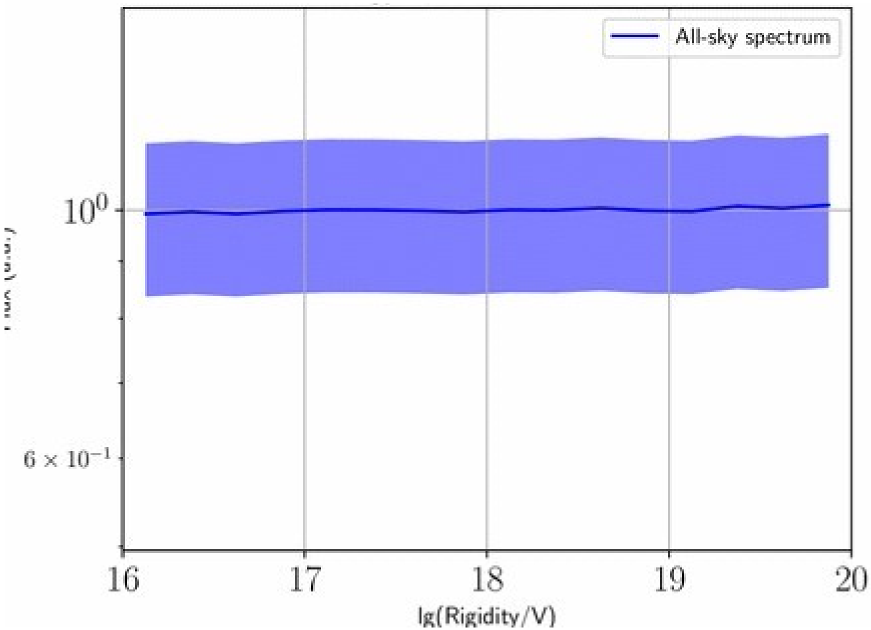

Injection direction of observed EGCRs forward tracking

Injection direction distributions of backtracked and forward tracked protons match

Galactic lensing – testing lens



Arrival direction of lensed isotropic injection distribution



Spectrum of lensed isotropic injection distribution

Lensed arrival direction distribution and spectrum of isotropic injection distribution is as expected.