Galactic propagation of GCRs and EGCRs in the shin region with CRPropa

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CRPropa Workshop on Astroparticle Propagation
Instituto de Física Teórica UAM-CSIC, Madrid
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Outline of lecture

1) The transition region in data
   - Spectrum, composition and dipole anisotropy
   - Open questions → role of GMF
2) Computational challenges and requirements
   - Ballistic vs. diffusive propagation
   - Galactic magnetic field modelling
3) Combating the transition region: Propagation in the Galactic magnetic field
   - Propagation effects in the GMF
   - Effect on observables (flux, composition and arrival direction)
4) Summary

The transition region in data

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:

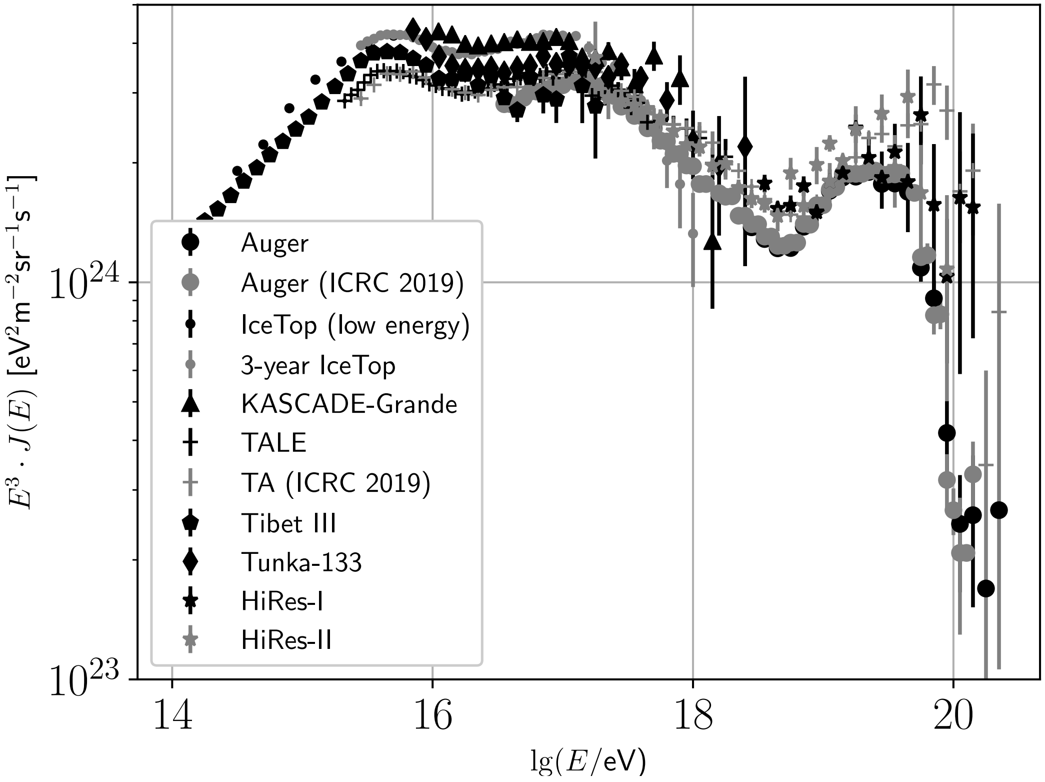
- hardening at ~$10^{16.7}$ eV
- **'2nd knee':** softening at ~$10^{17.(0...4)}$ eV
- 'toe': softening at ~$10^{19.1}$ eV

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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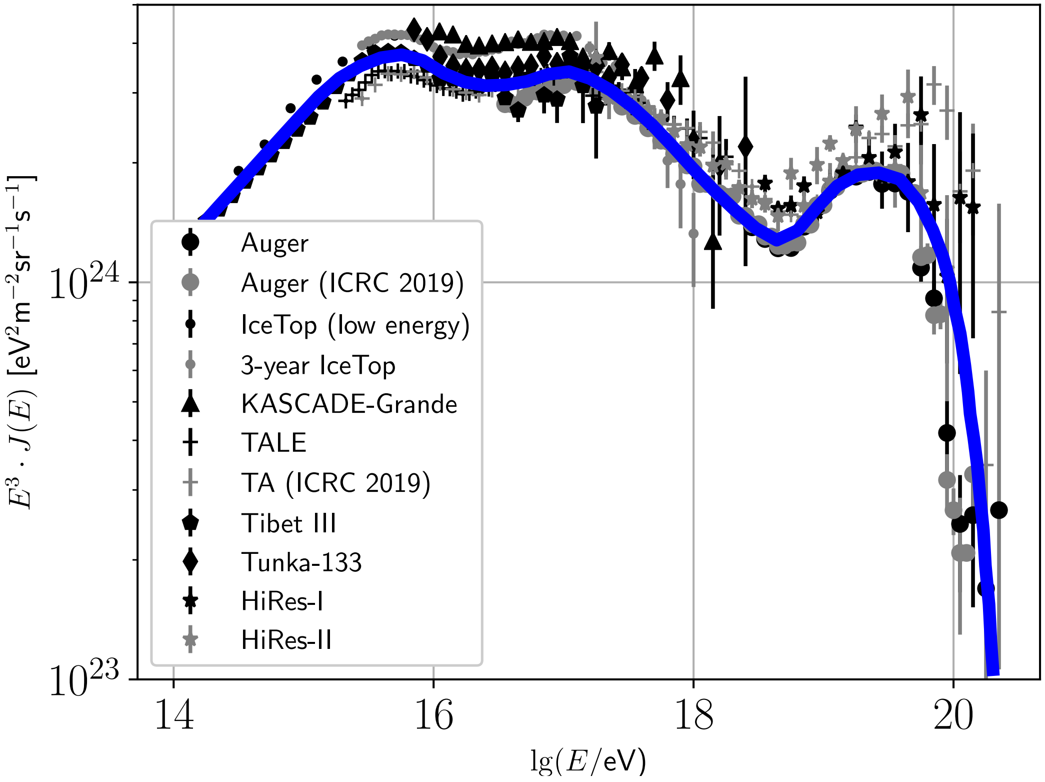

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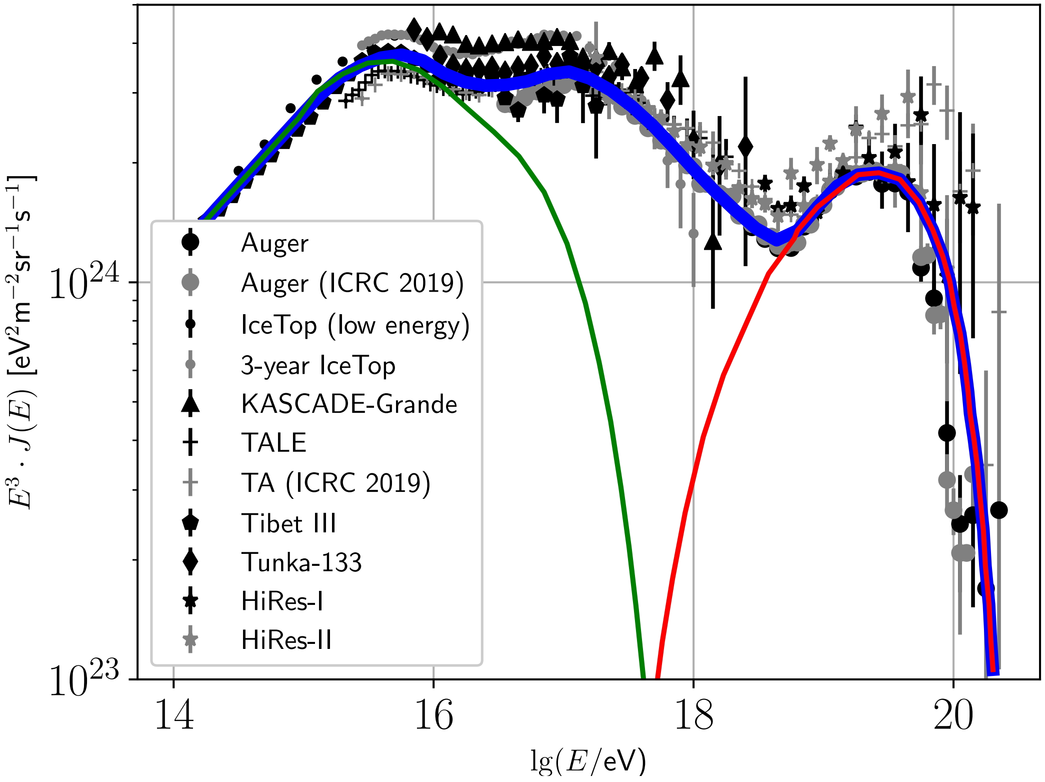

Cosmic ray composition

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

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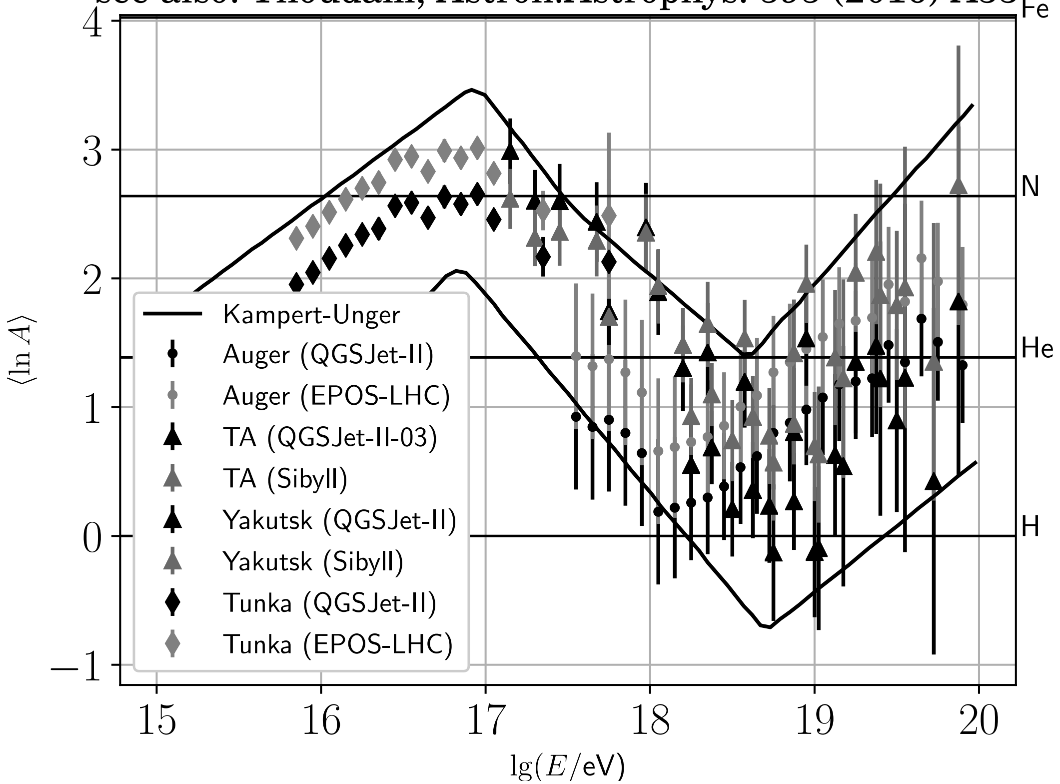

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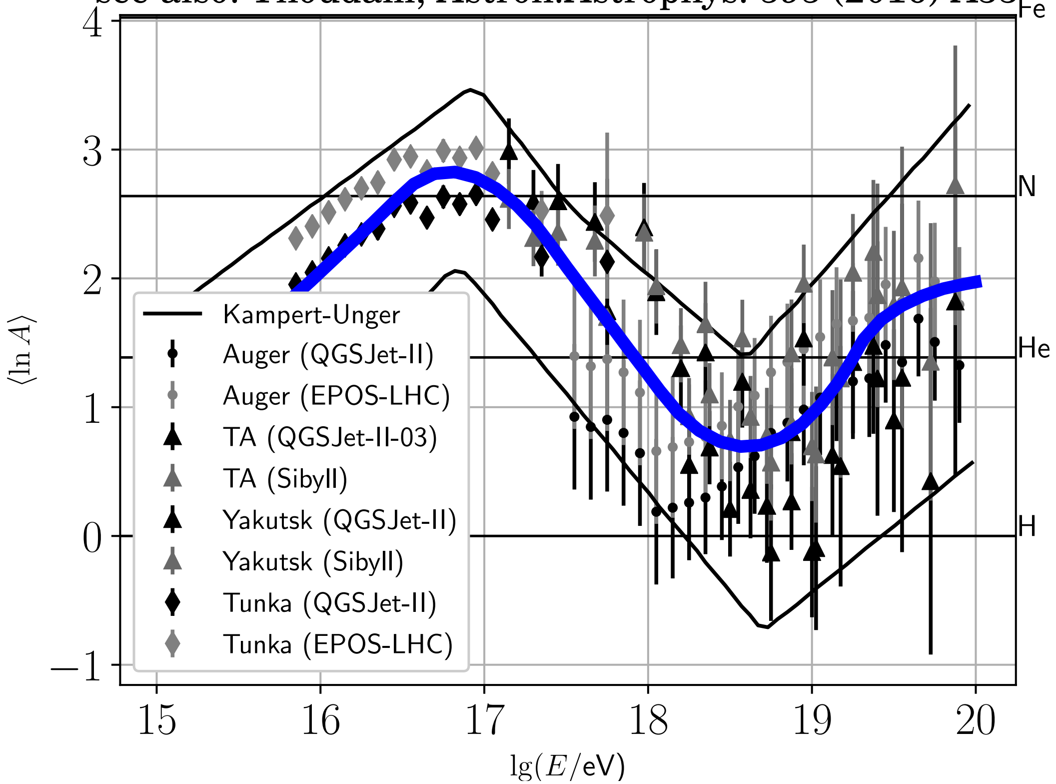


Cosmic ray anisotropy (dipole)

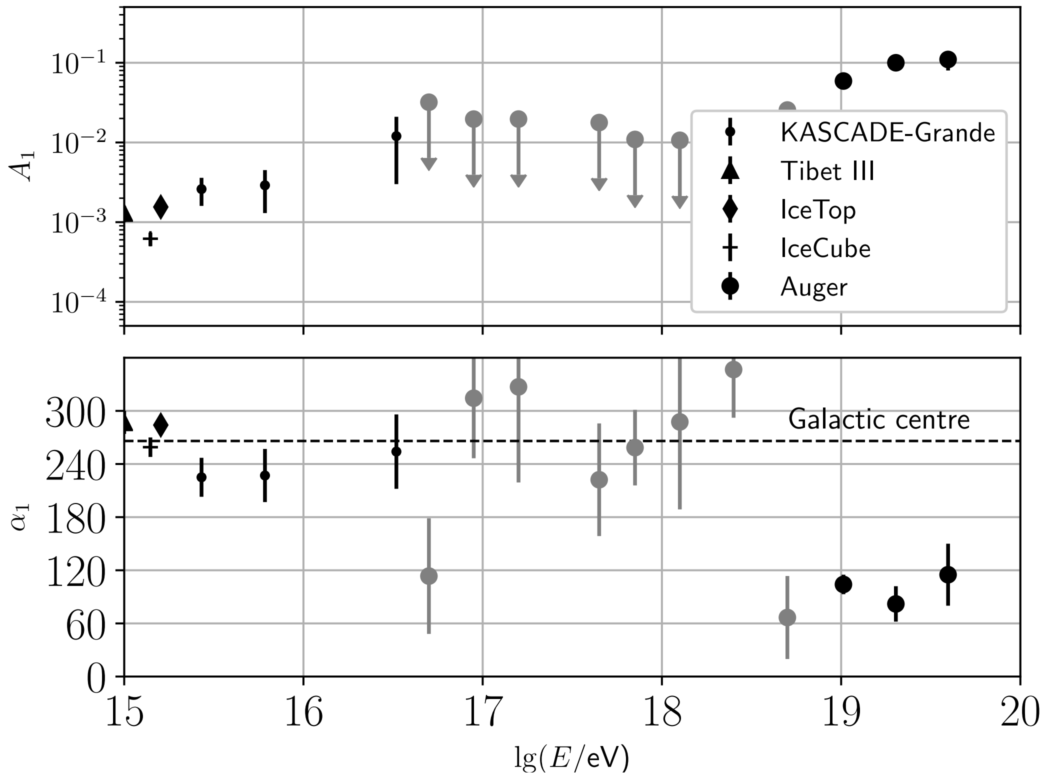
Dipole anisotropy:

- 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



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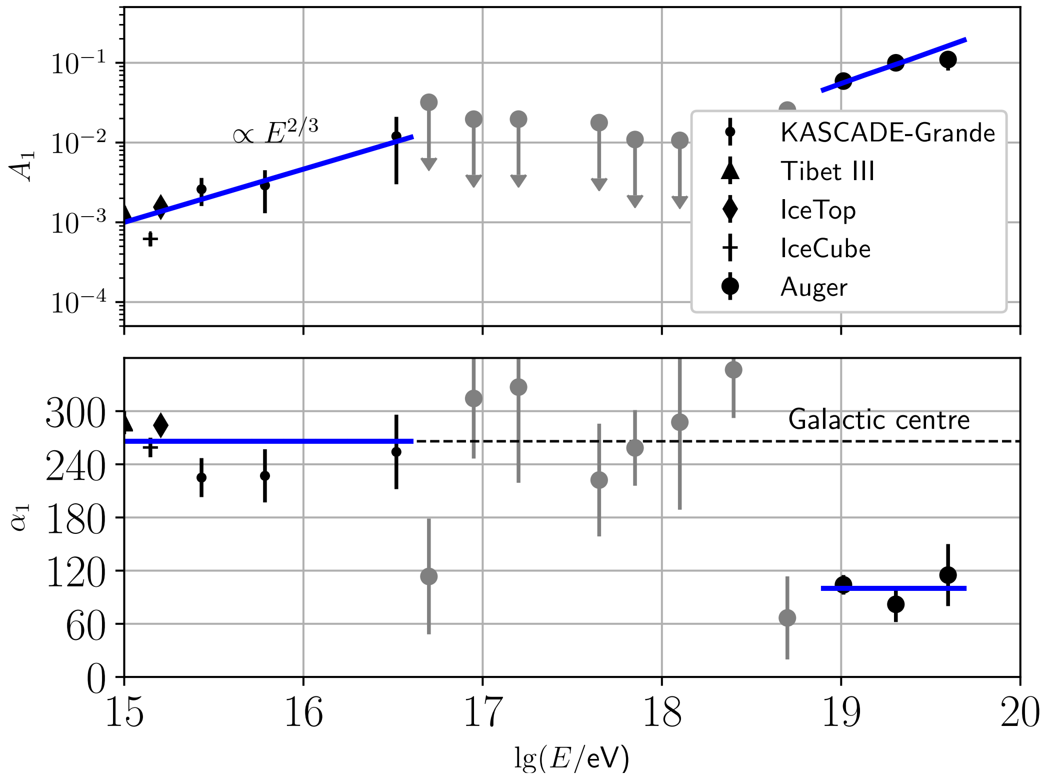


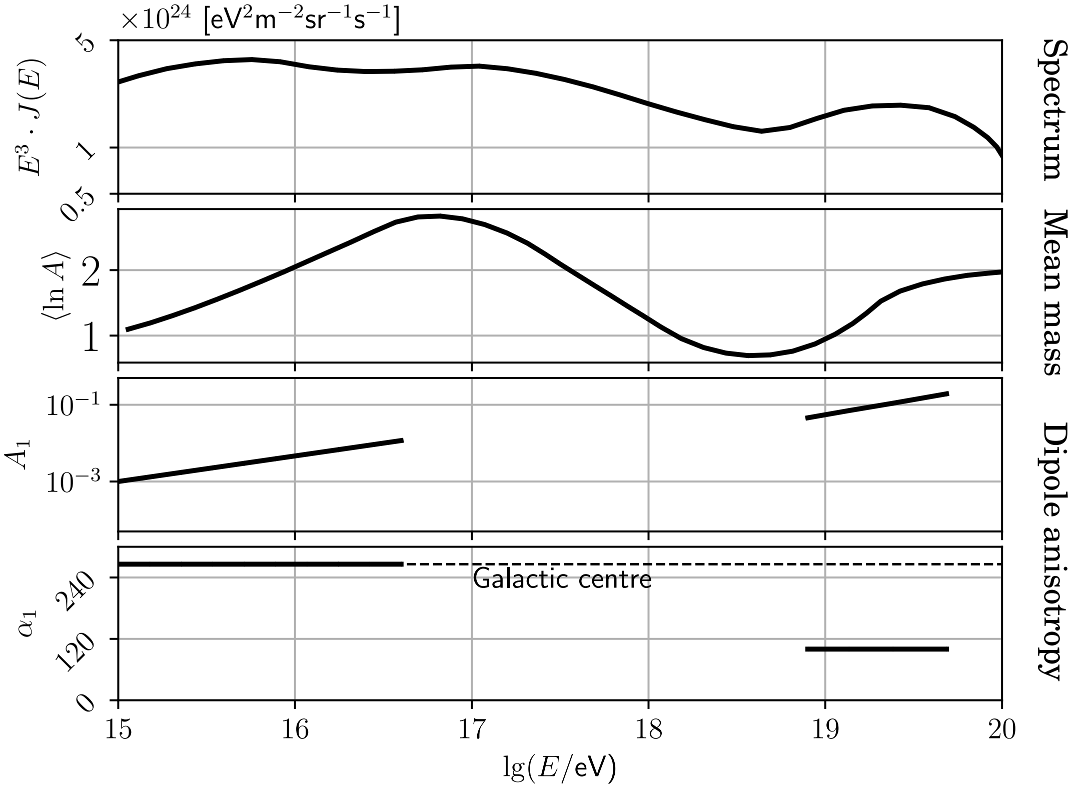
“All” data in one look

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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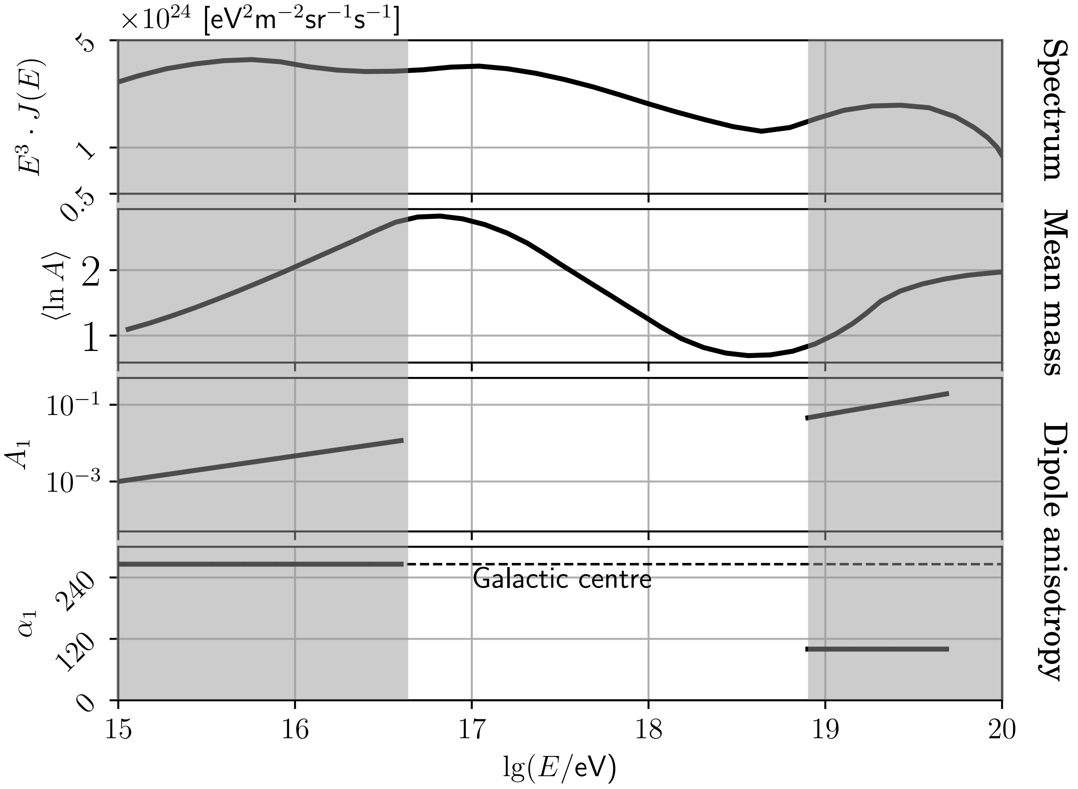


Galactic magnetic field (GMF)

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

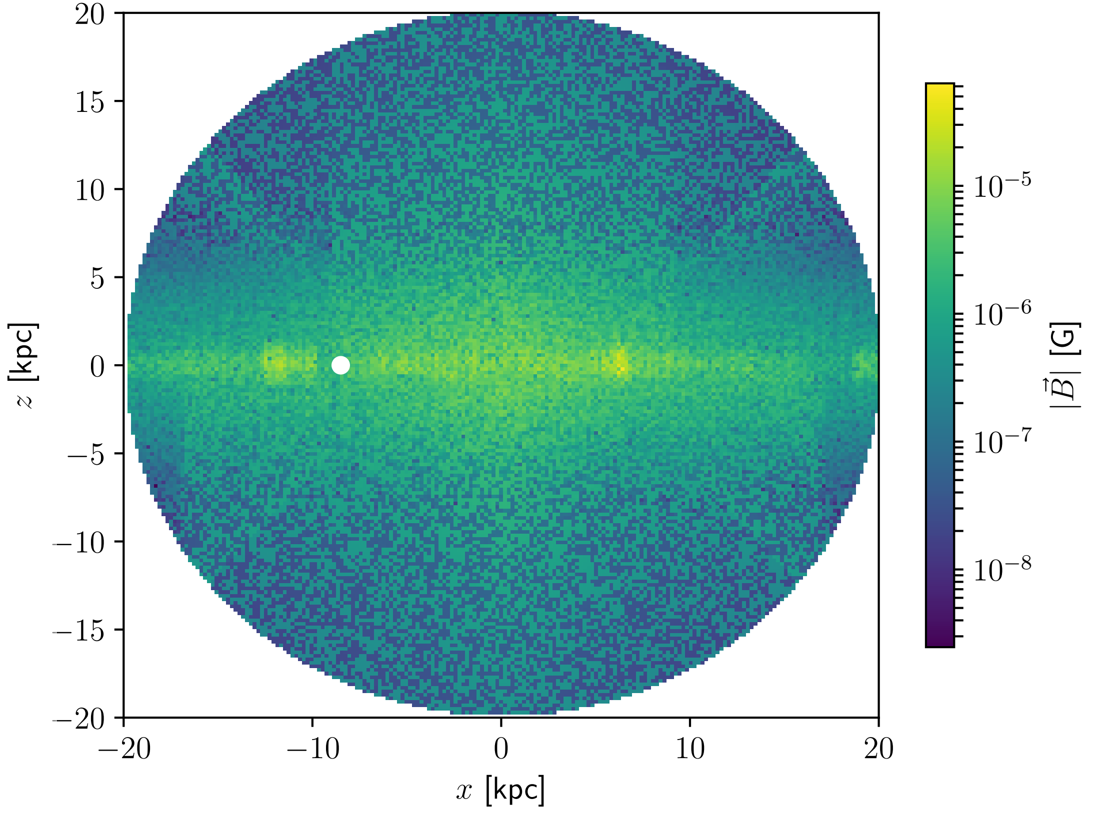
Gyroradius r_g:

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

Transition region = **change in propagation regimes**

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

x-z projection of JF12 field



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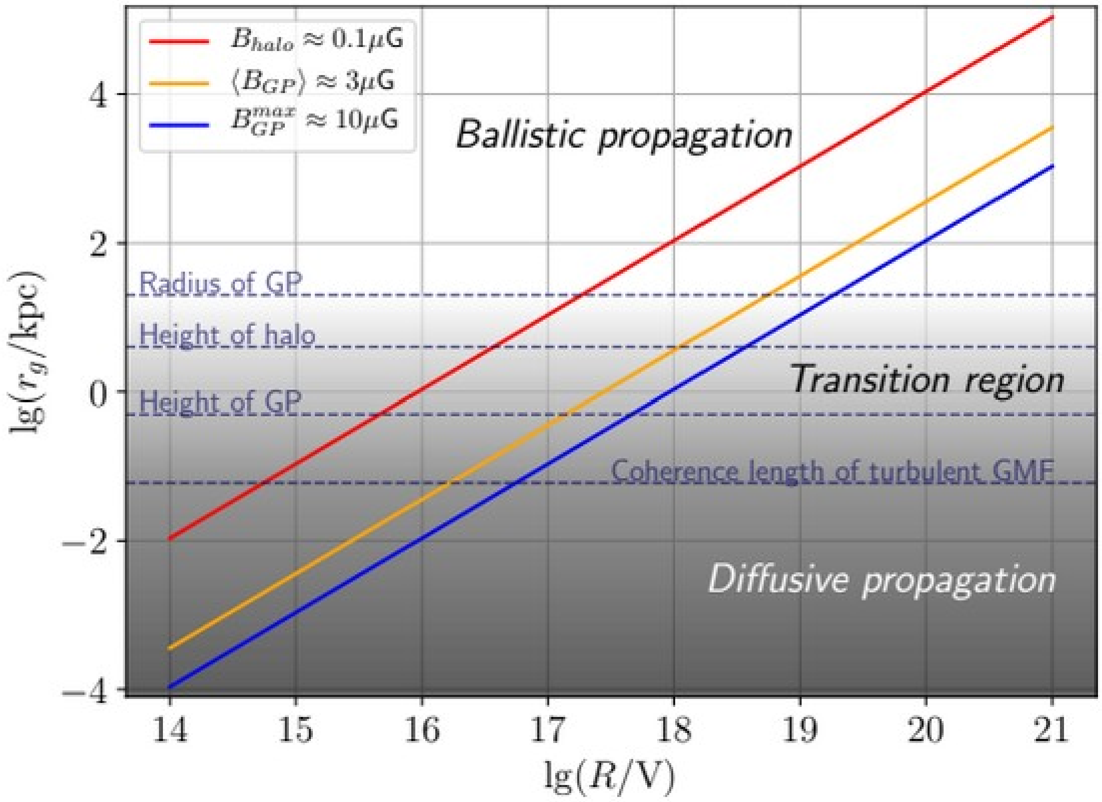
Change of gyroradius with rigidity plus typical length scales of Galaxy



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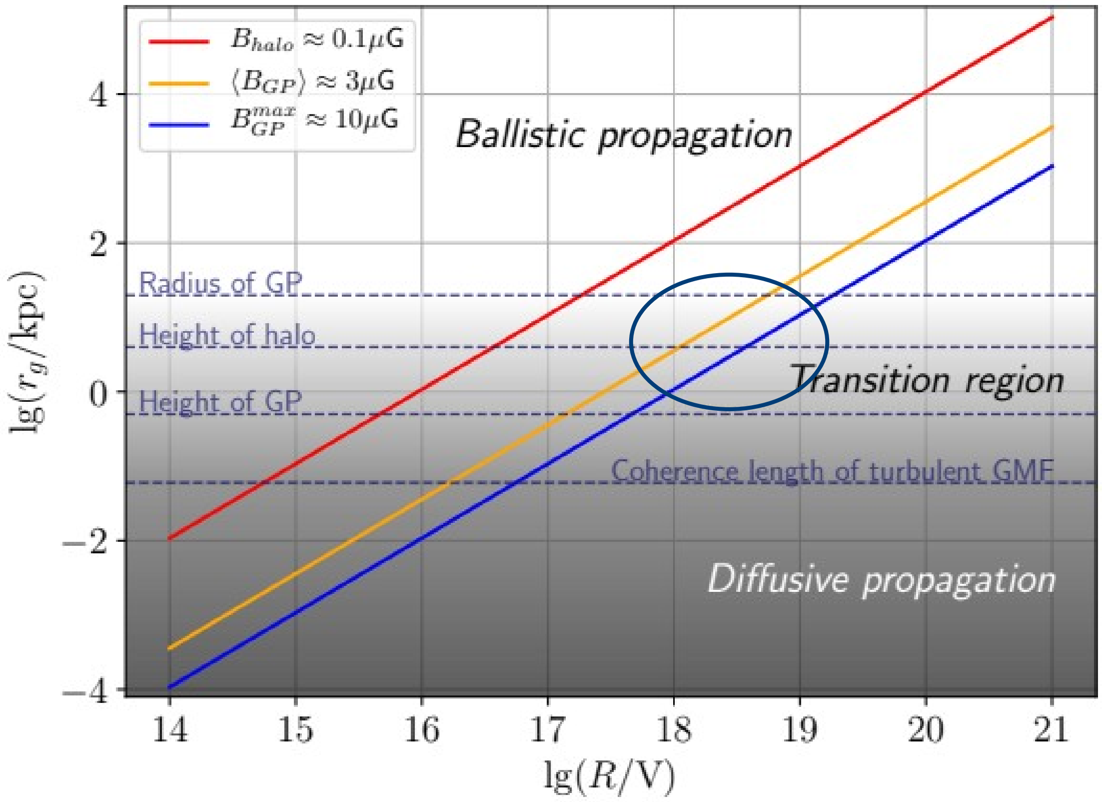


Computational challenges and requirements

Ballistic propagation

Solve **equation of motion (EoM)**:

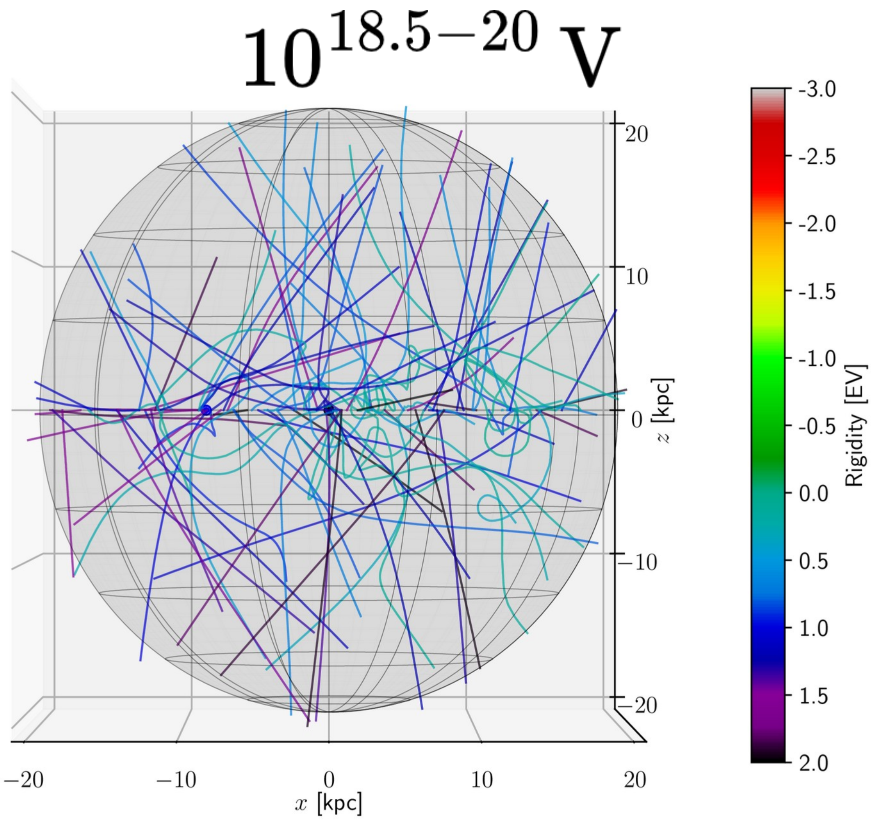
$$\ddot{\vec{r}} = \frac{q}{E/c^2} \left(\vec{v} \times \vec{B}\right)$$

- tracking of **single particles** (microscopic view)
- best suited for **large r_g**
- applicable for arbitrary fields
  → **more fundamental and precise***
- particle trajectories are tracked
  → possibility of anisotropy studies

BUT:

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

Trajectories of ballistically propagating GCRs



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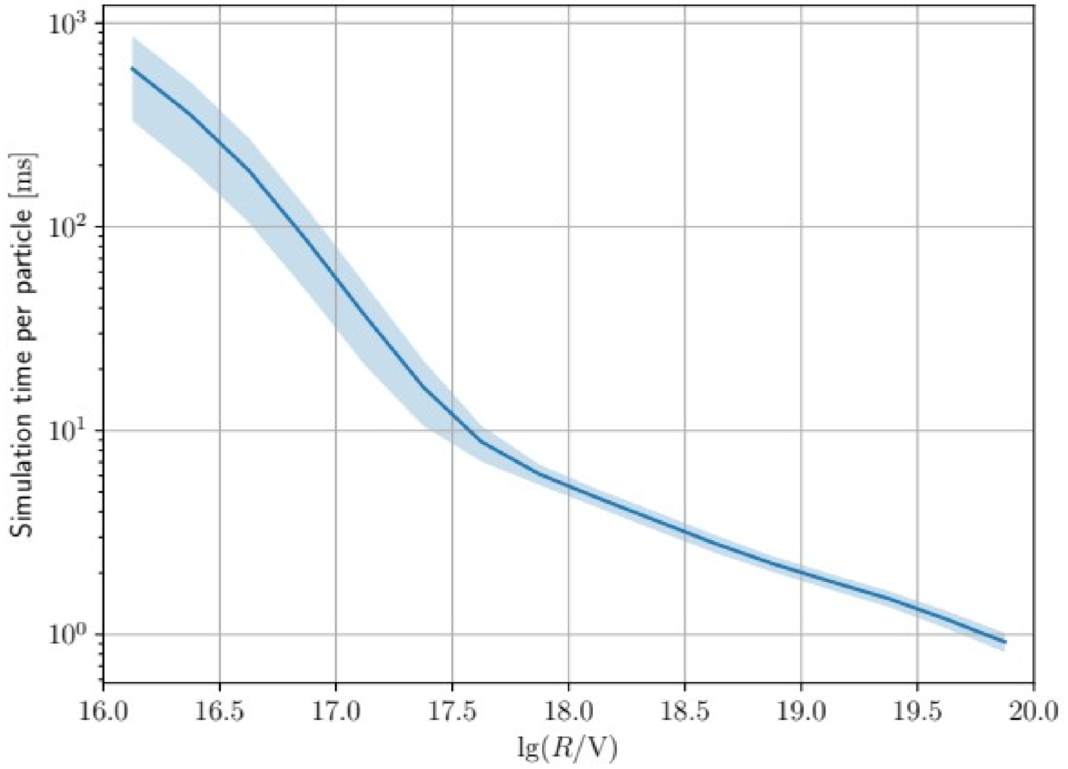
Change of computation time per particle with rigidity for propagation in GMF



Diffusive propagation

Solve **transport equation (TE):**

$$\frac{\partial n_l}{\partial t} = \sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left[\left(D_{jk}\cdot\frac{\partial}{\partial x_k}\right) n_l\right] - \frac{\partial}{\partial x_j}\left[u_j \cdot n_l\right] + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{n_l}{p^2}\right)\right]$$
$$- \frac{\partial}{\partial p}\left[\dot{p}\, n_l - \frac{p}{3}\left(\nabla\cdot\vec{u}\right)\cdot n_l\right] + \sum_{j>l}\frac{v_l}{c}\, n_0 \int dp'\sigma_{j\to l}(p,p')\, n_j(p') - \frac{n_l}{\tau} + Q_l(p)$$

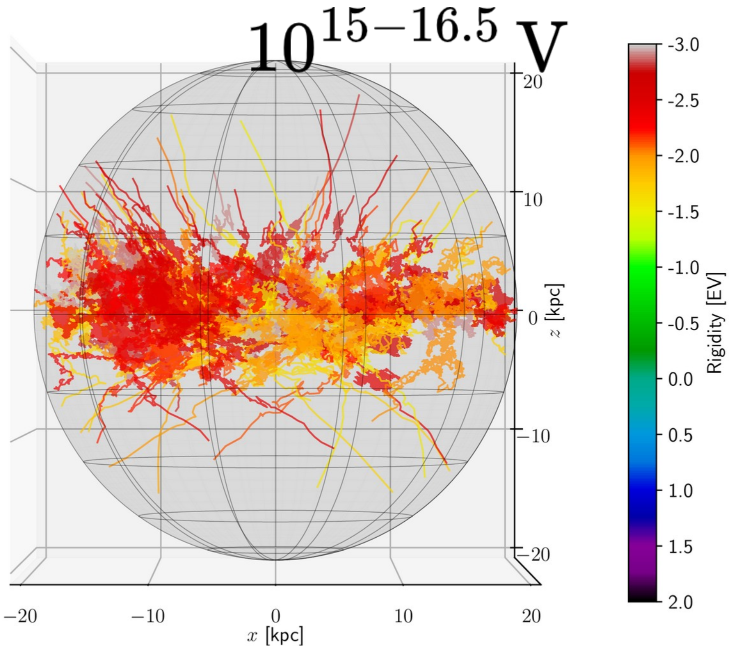
- **multi-particle** approach:
  - change of momentum density (macroscopic view)
- best suited for **small** r_g & **dominant turbulent** B-field component

  → resonant scattering regime is reached for EoM approach
- generally **shorter** computation times
- For large r_g increasingly inaccurate

NOTE:

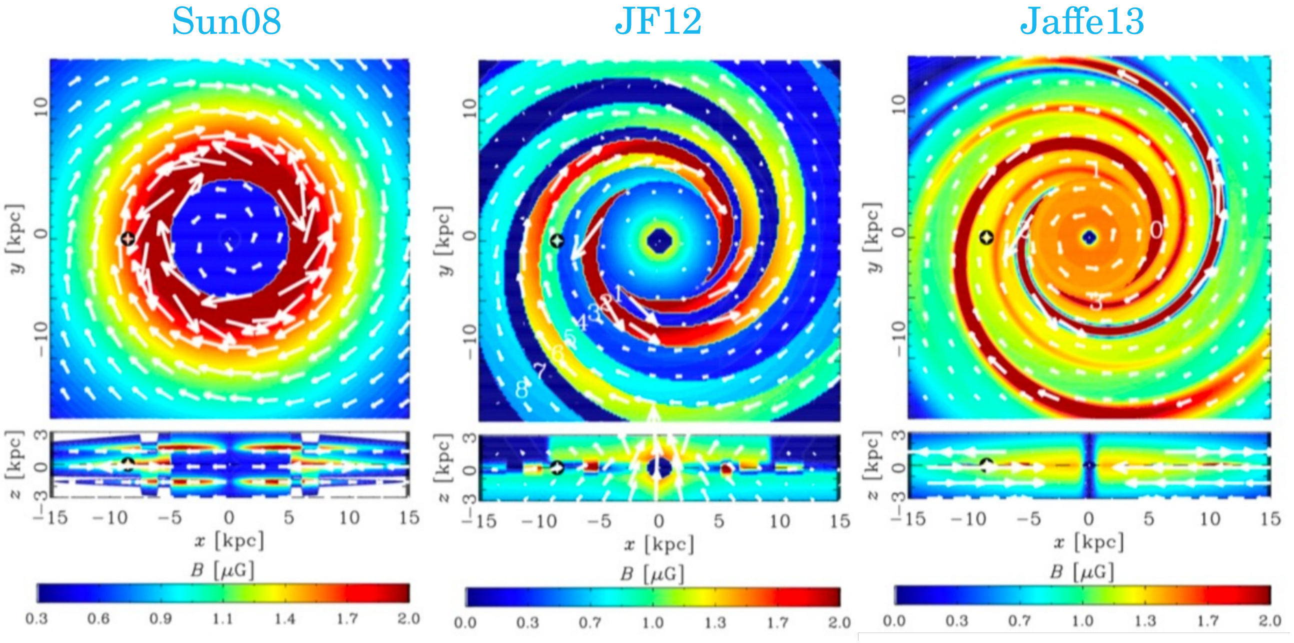
- diffusive propagation module via SDEs is **implemented in CRPropa 3** (JCAP 06 (2017) 046)
- For a **full description** of the transition region **both EoM & TE approaches** must be applied

Trajectories of diffusively propagating GCRs



Major challenge: GMF model

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



GMF not well known:

- field strength **inferred indirectly via observables** with large uncertainties & contamination
- **ad hoc assumptions** necessary (simplifications): morphological features (spiral arms, halo field), field components (regular, turbulent etc.)

→ many GMF models exist

Combating the transition region: Propagation in the GMF

Procedure: Ballistic propagation with CRPropa3

Forward tracking:

- Cash-Karp algorithm: minimal step size $d_{min} < 0.1\ r_g$
  - Boris-Push recommended!
- particle tracked **from source to observer**:
  - highly **inefficient** (1:10^{28} for observer the size of Earth)

  → increase observer size, BUT: this introduces **artefacts**! → observer size ~ r_g

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 are Galactic centre)

Source properties:

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Sources and observers

Sources:

- GCRs:
  - **homogeneously distributed in GP**
  - isotropic injection direction distribution
- EGCRs:
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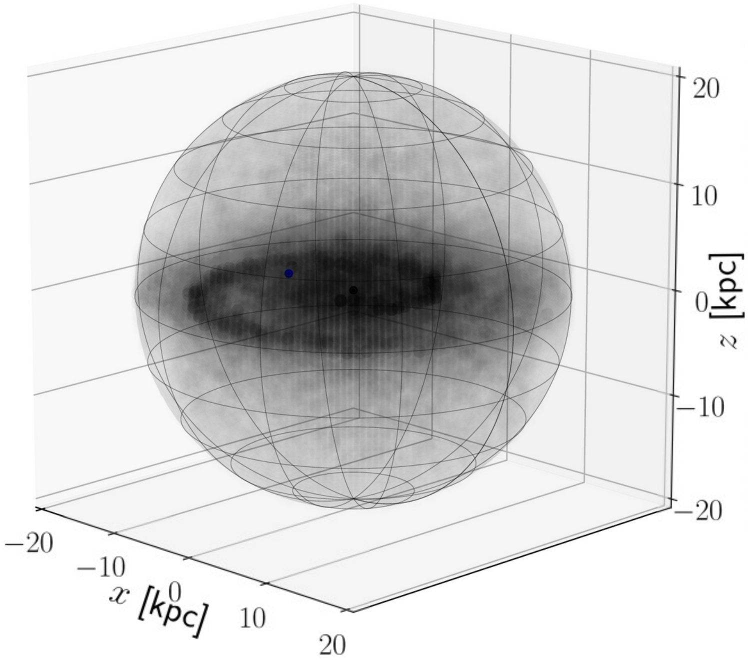
Observers:

- '**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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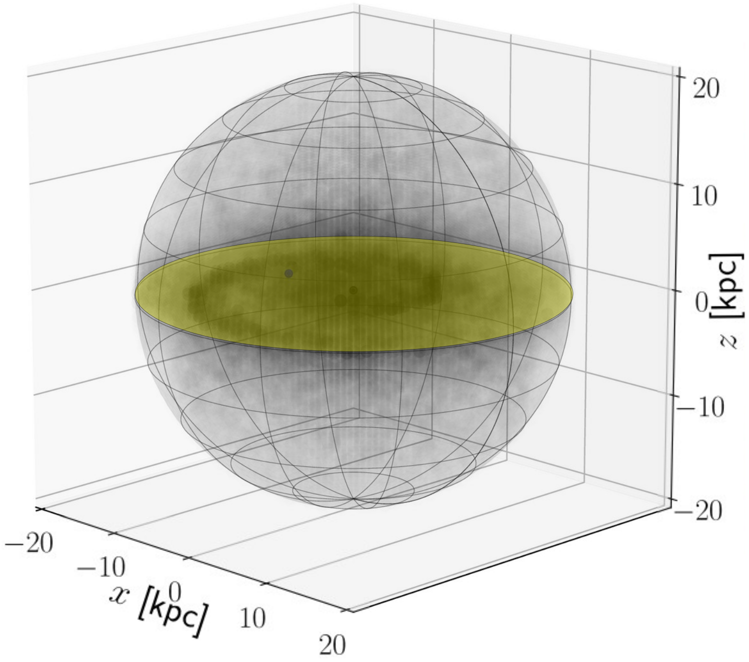
GCR source distribution



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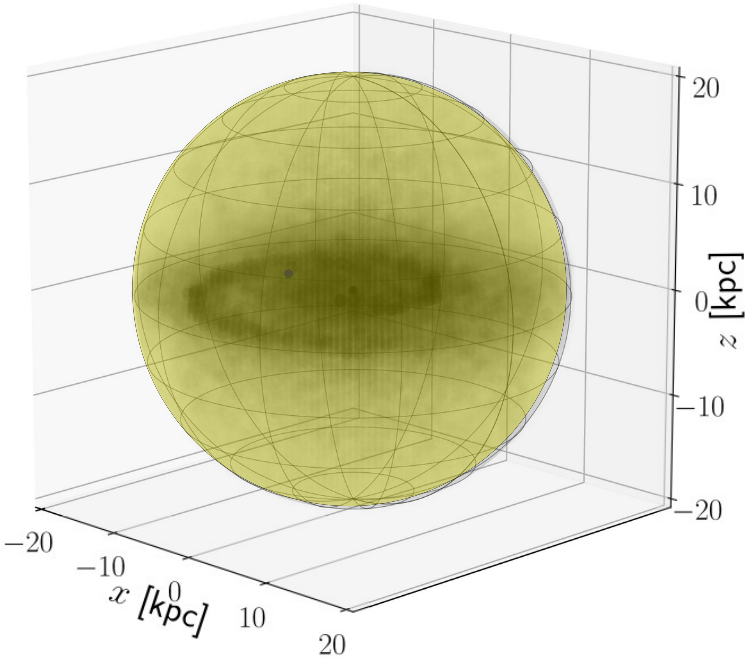

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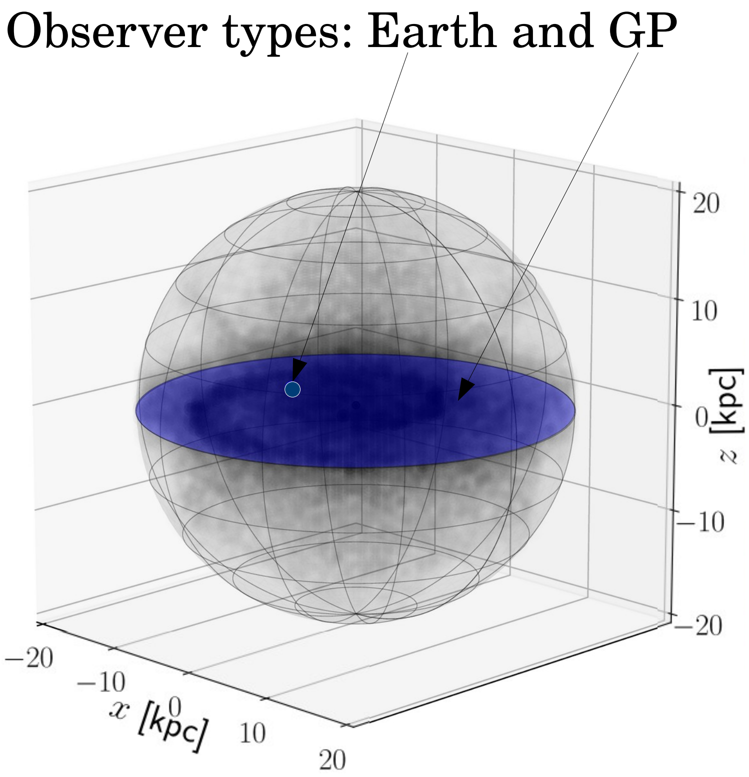
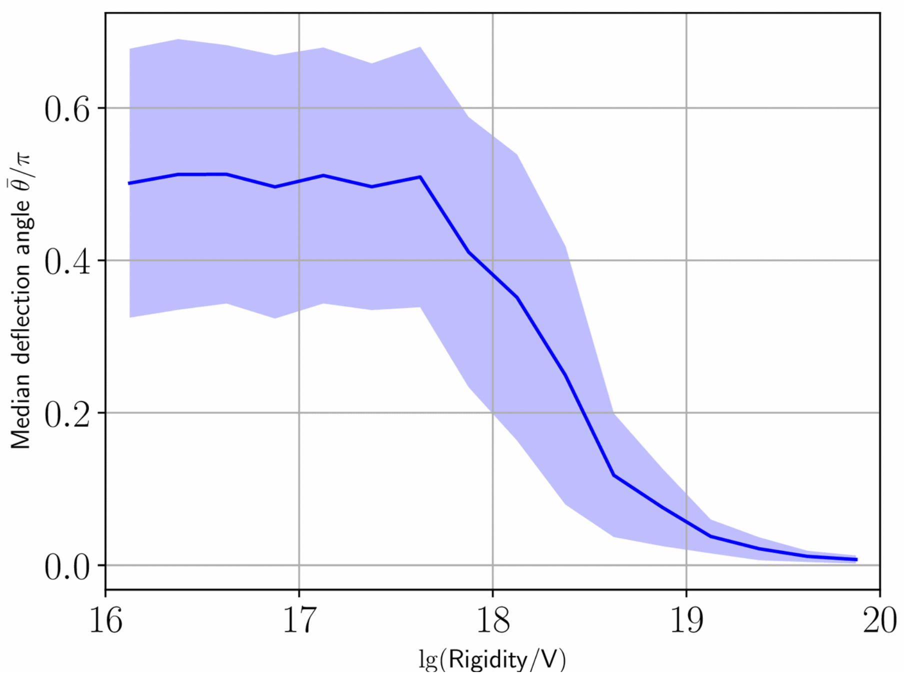
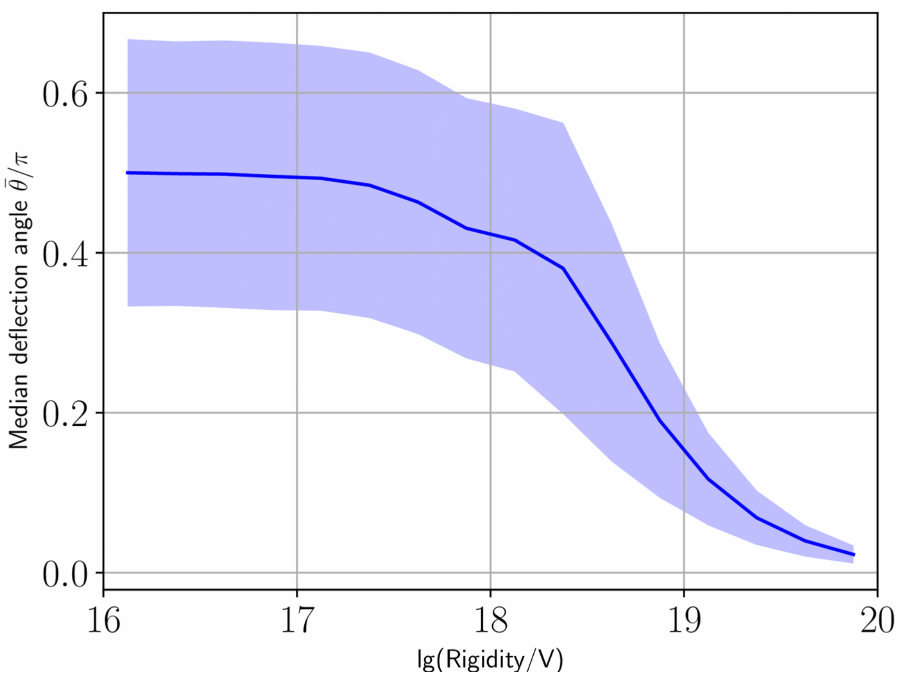


Change of propagation regimes: Deflection angle

GCRs forward tracked to Earth



EGCRs backtracked from Earth



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(see also: Erdman, Astropart.Phys. 85 (2016) 54-64)

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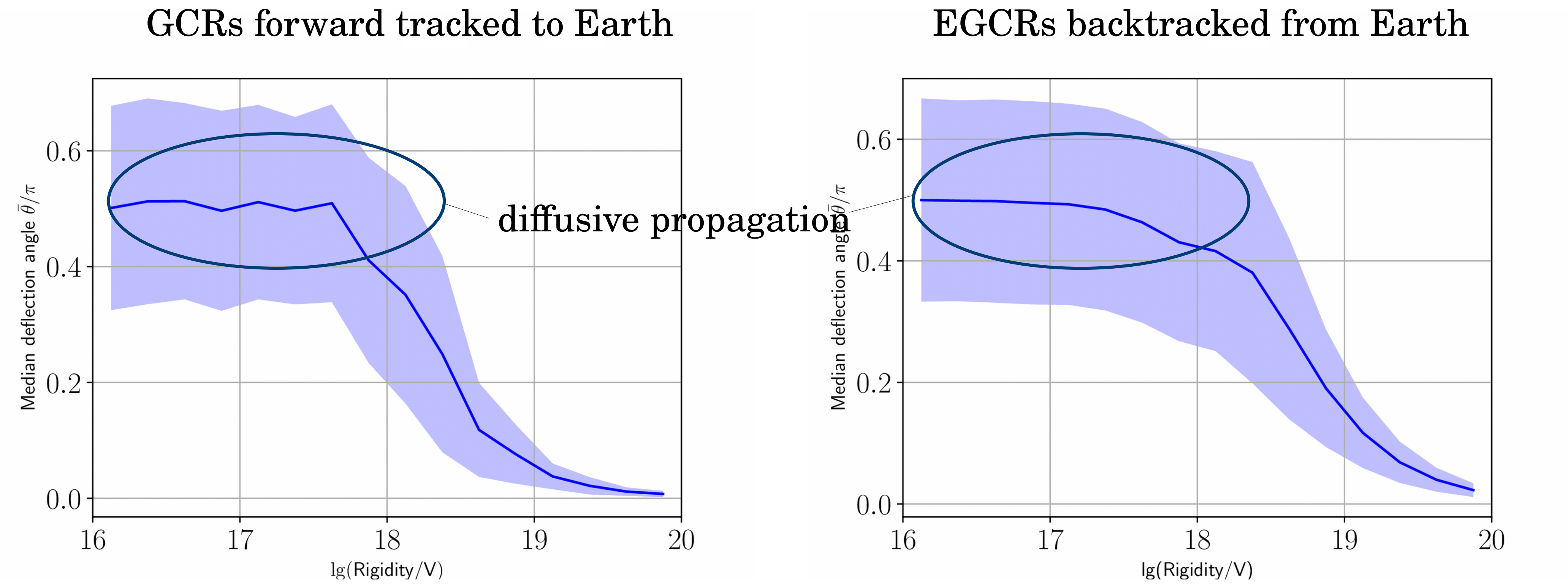

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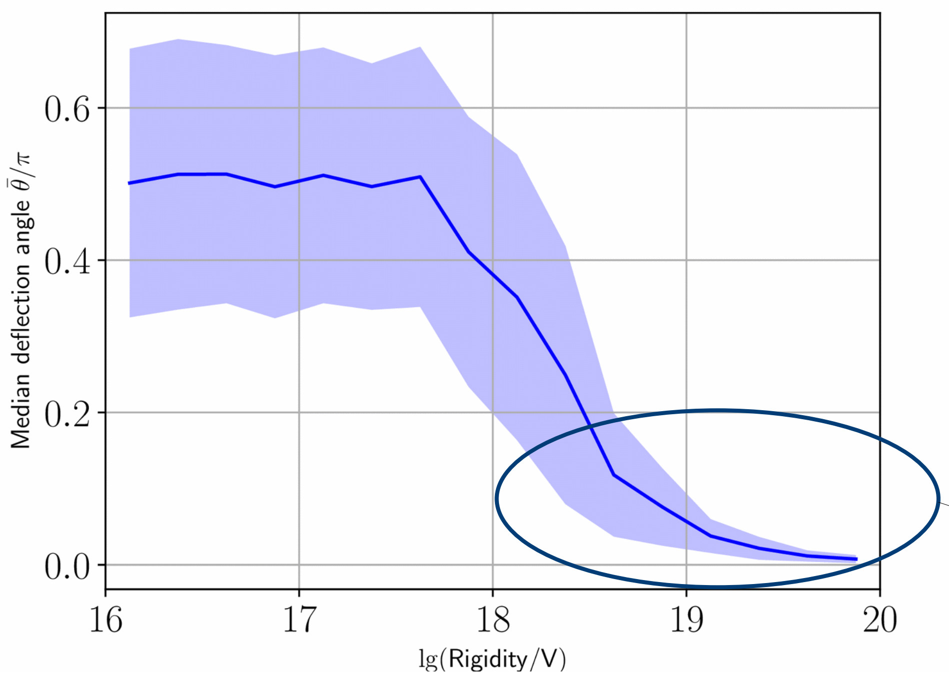

ballistic propagation

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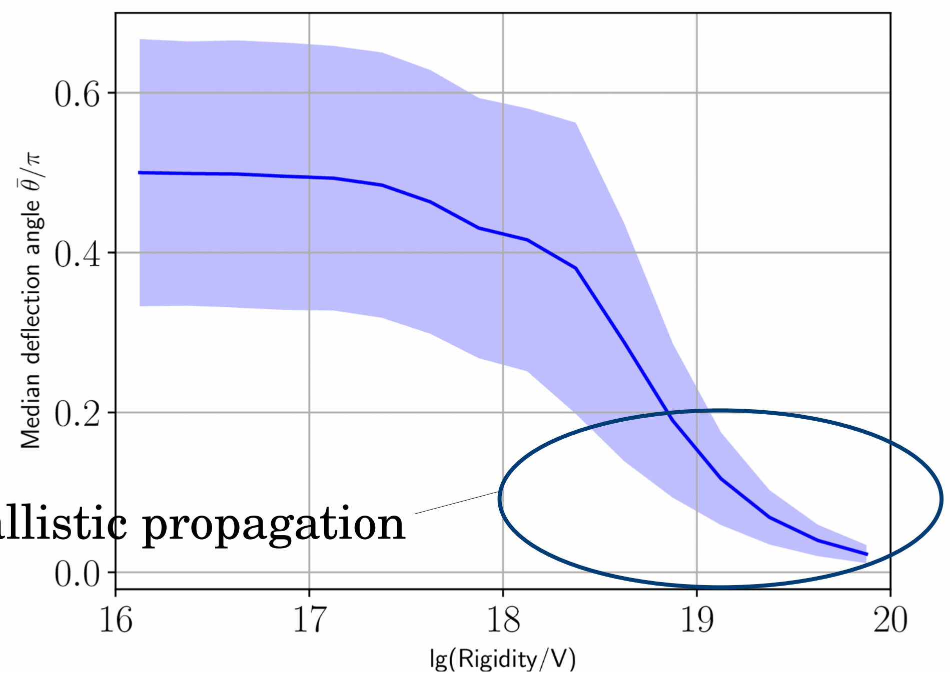

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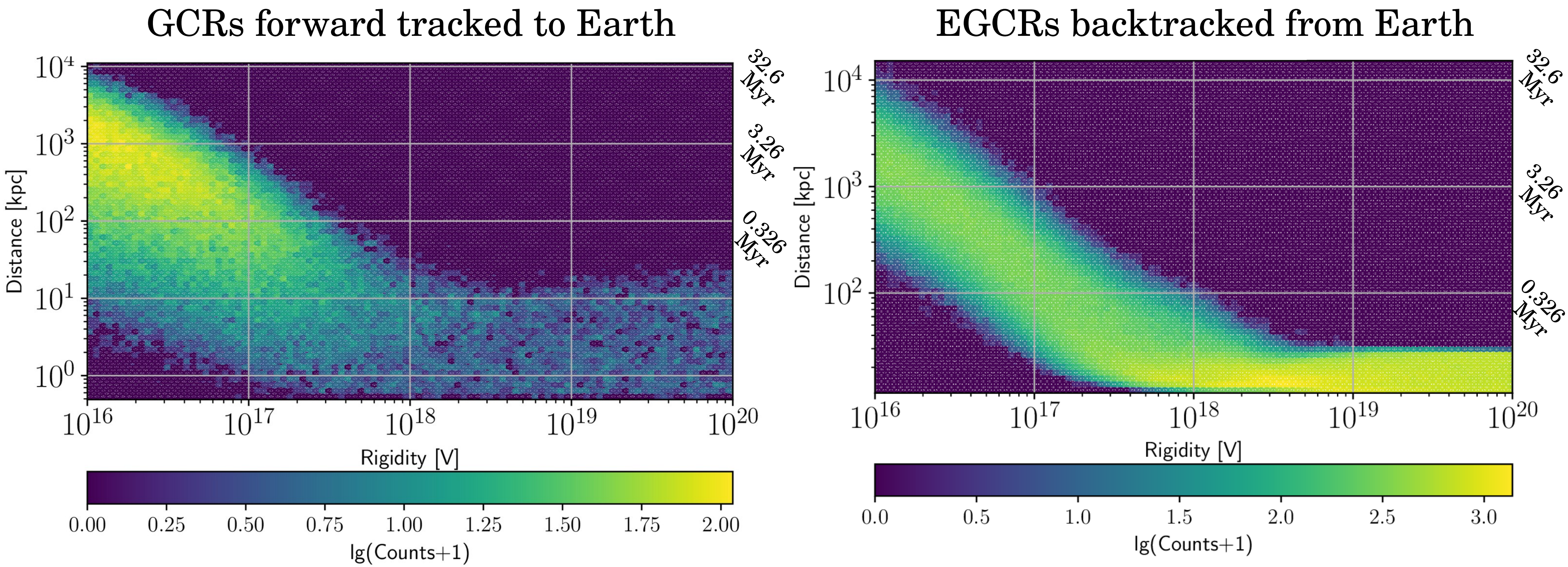

Propagation time increases below rigidities of a few EV.

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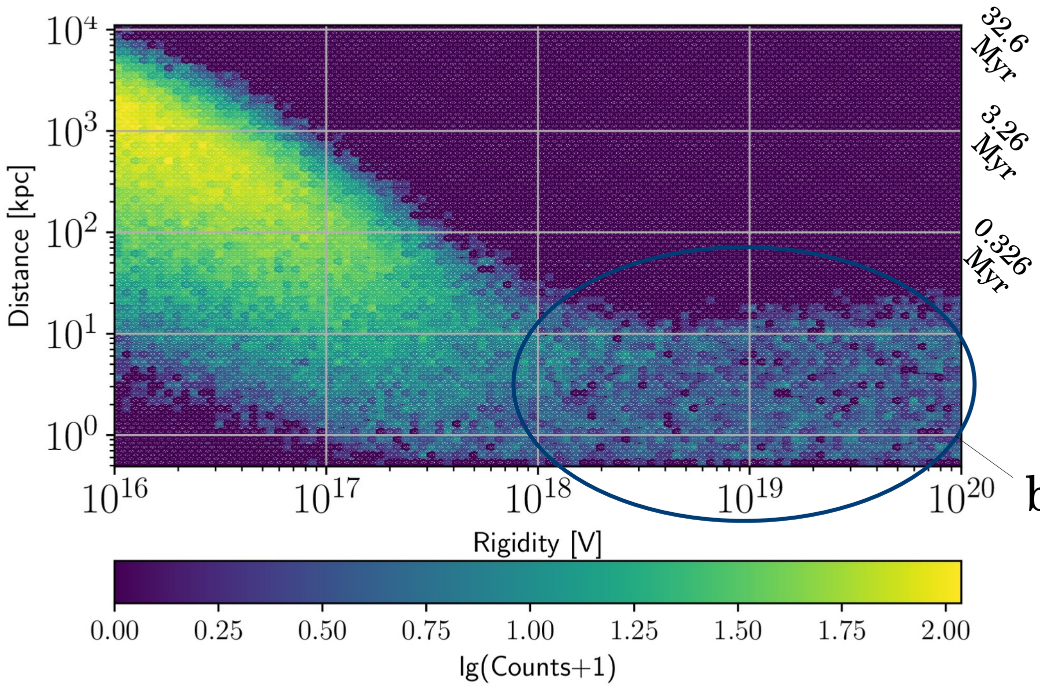

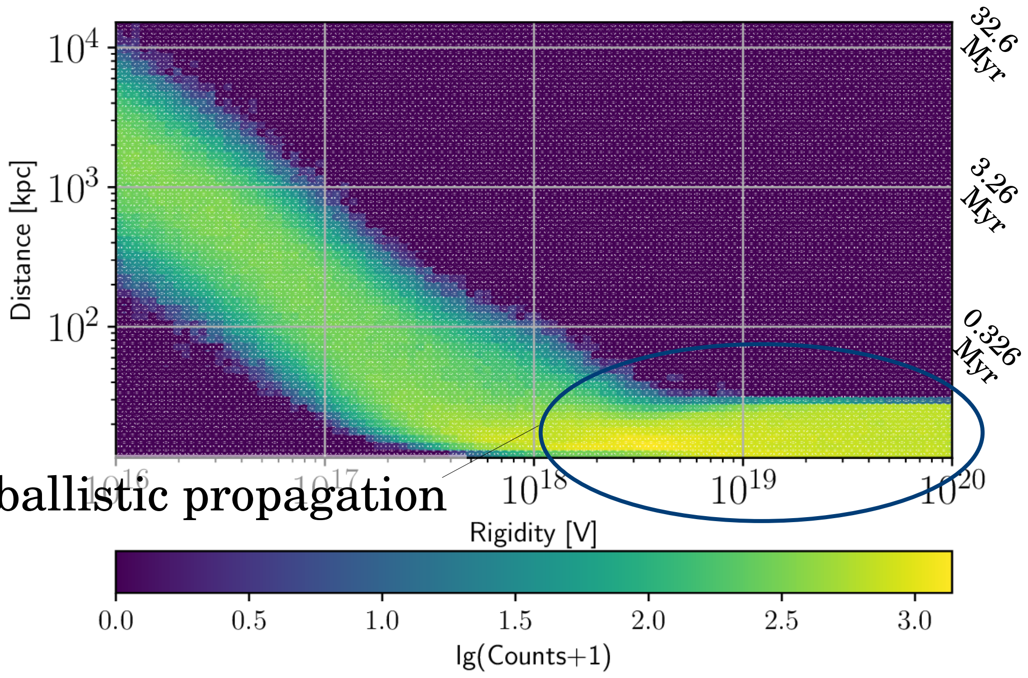

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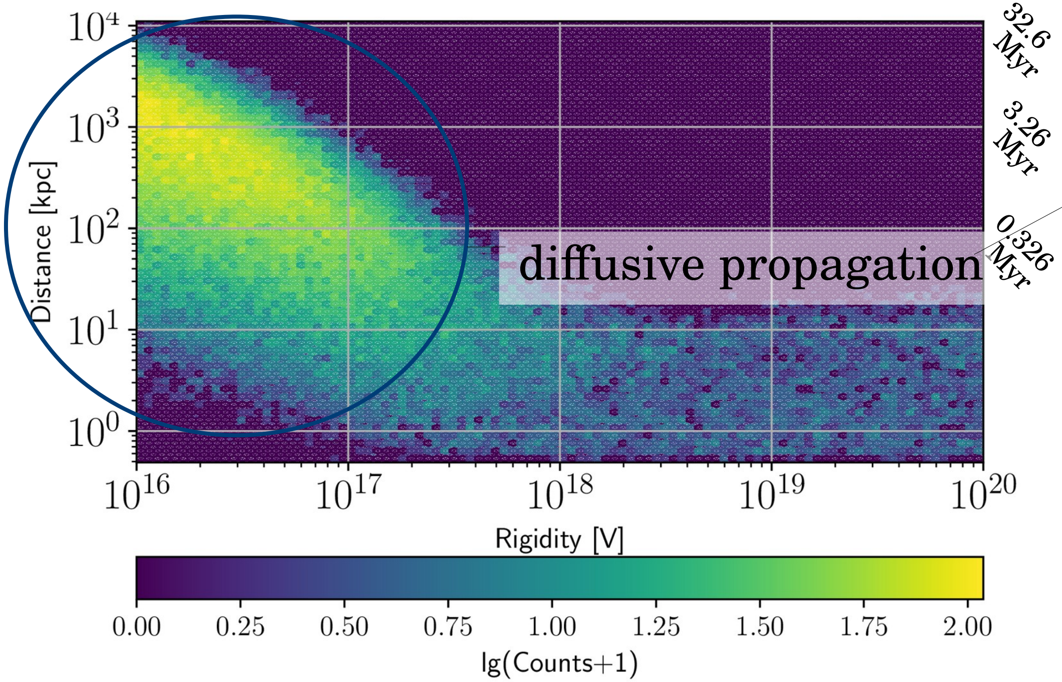

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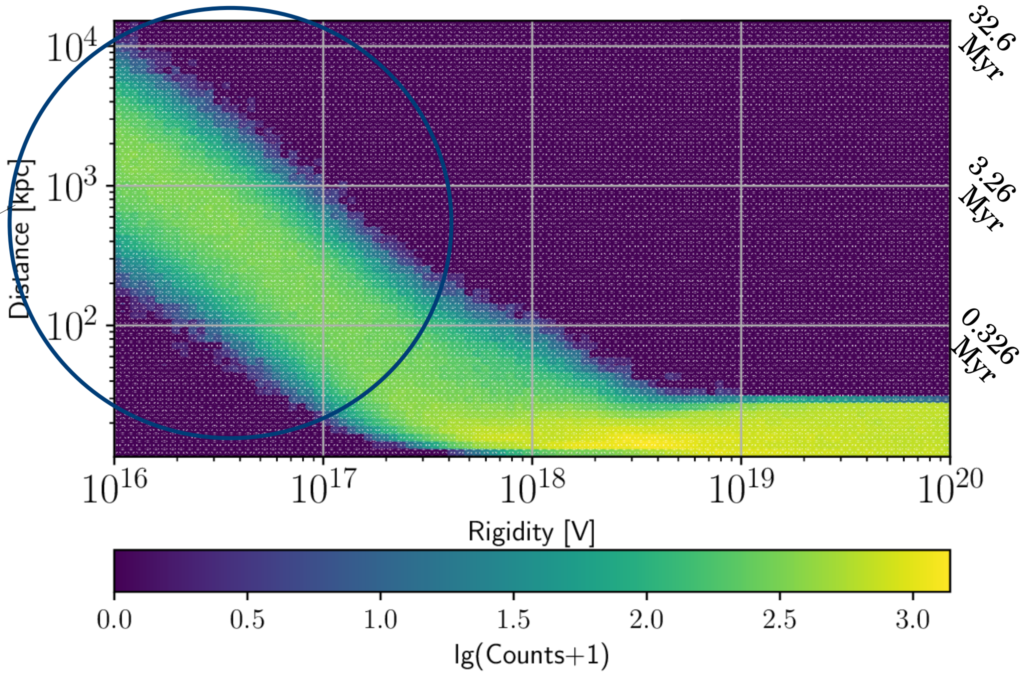
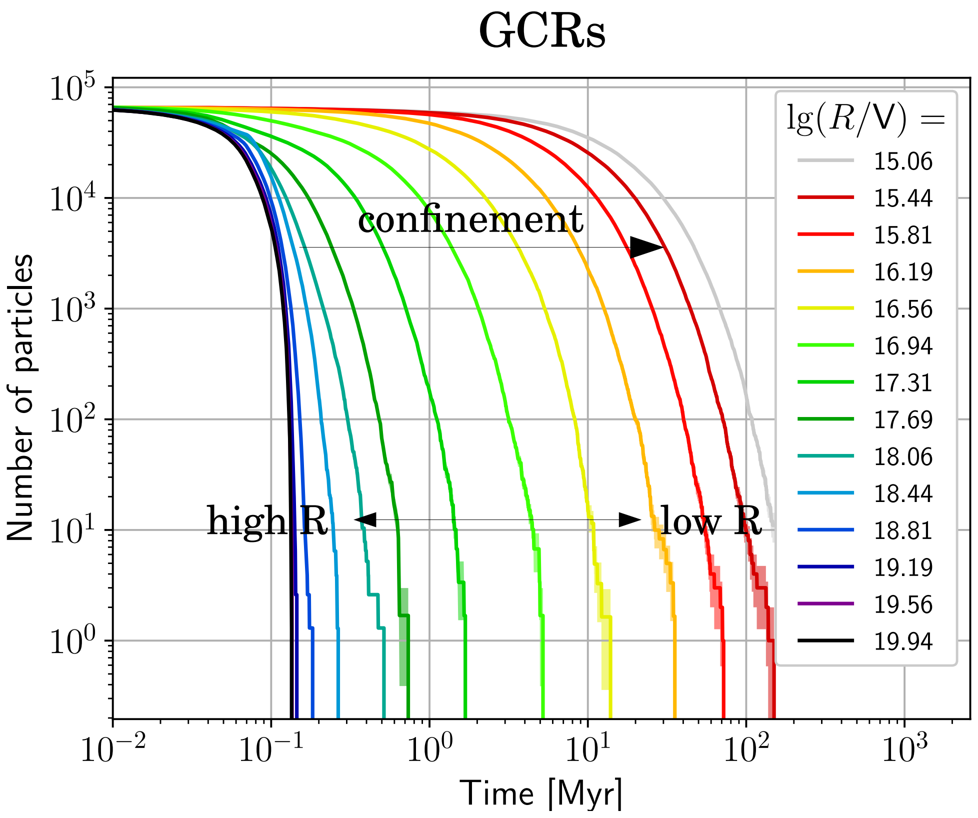
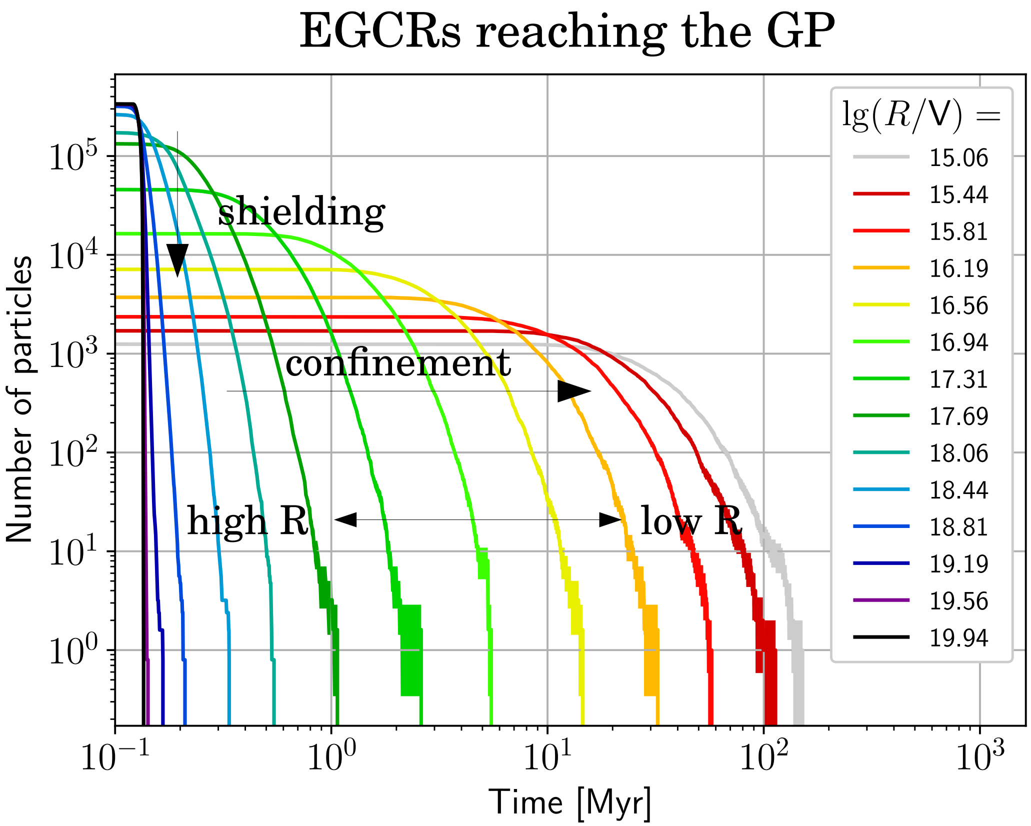


Propagation time increases below rigidities of a few 1 EV.

Propagation effects: Galactic residence time

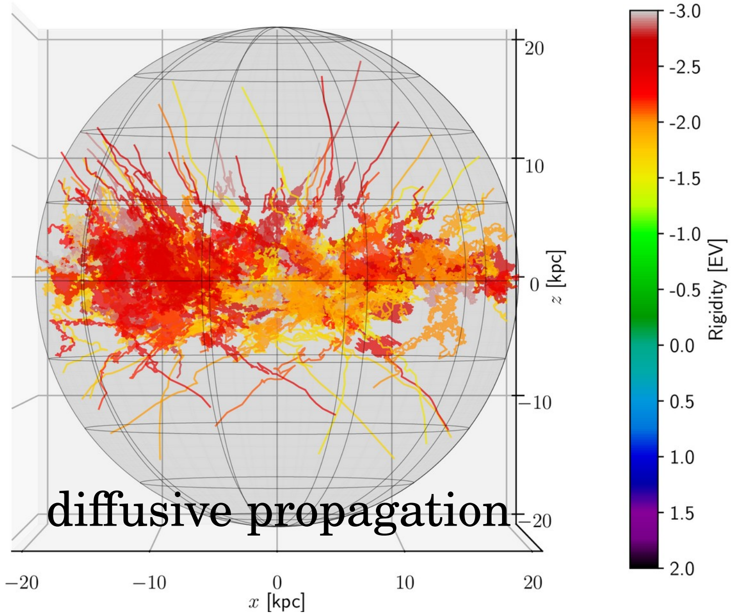




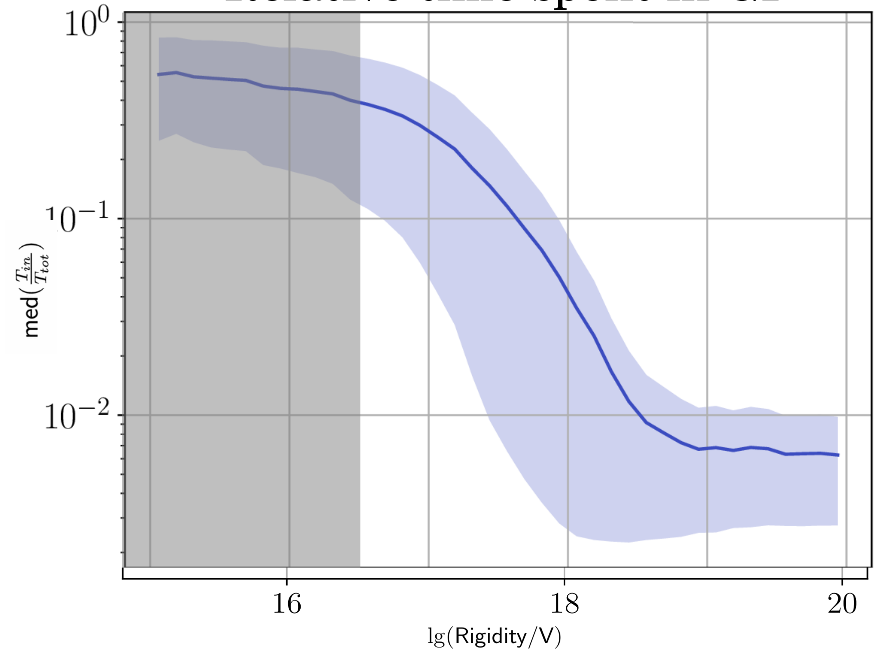
NOTE: Lowest-rigidity particles have residence times up to 100 Myr.

Propagation effects: GCRs – Confinement in GP

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



Relative time spent in GP

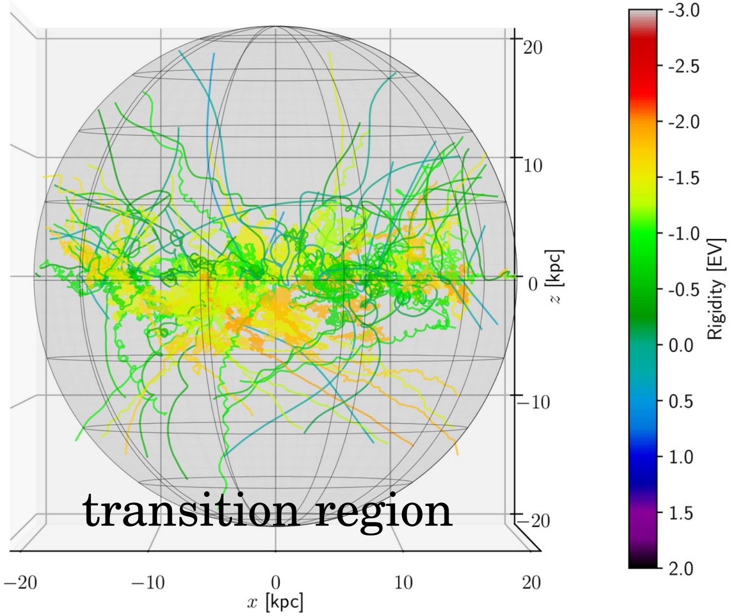


Decreasing confinement in GP **with rigidity.**

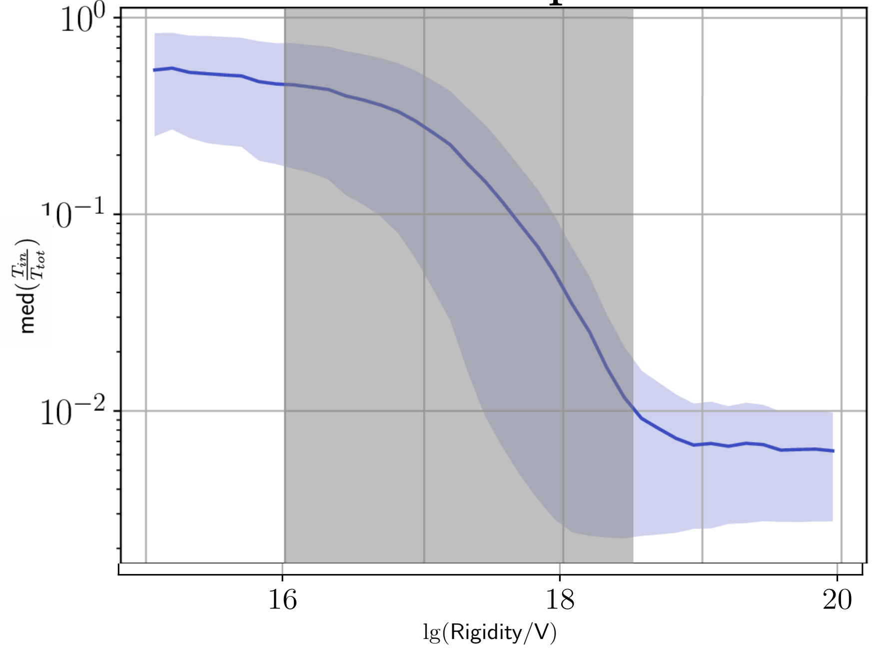
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: GCRs – Confinement in GP

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



Relative time spent in GP

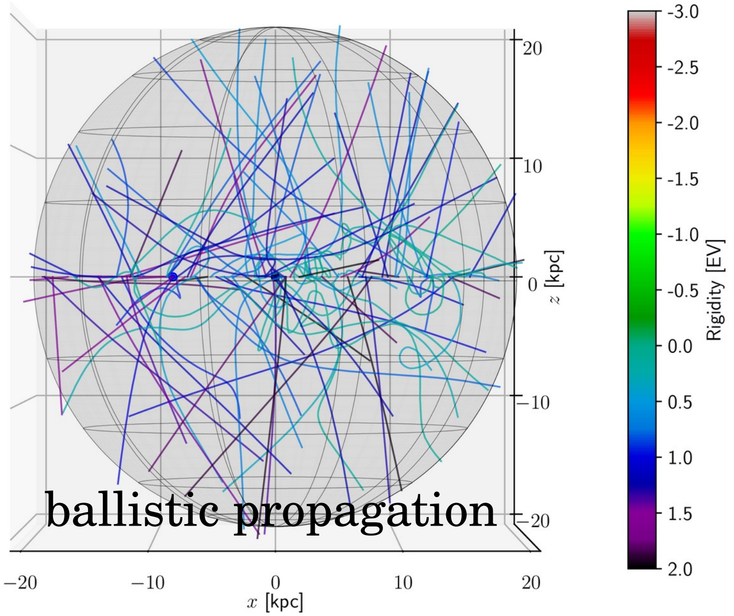


Decreasing confinement in GP **with rigidity.**

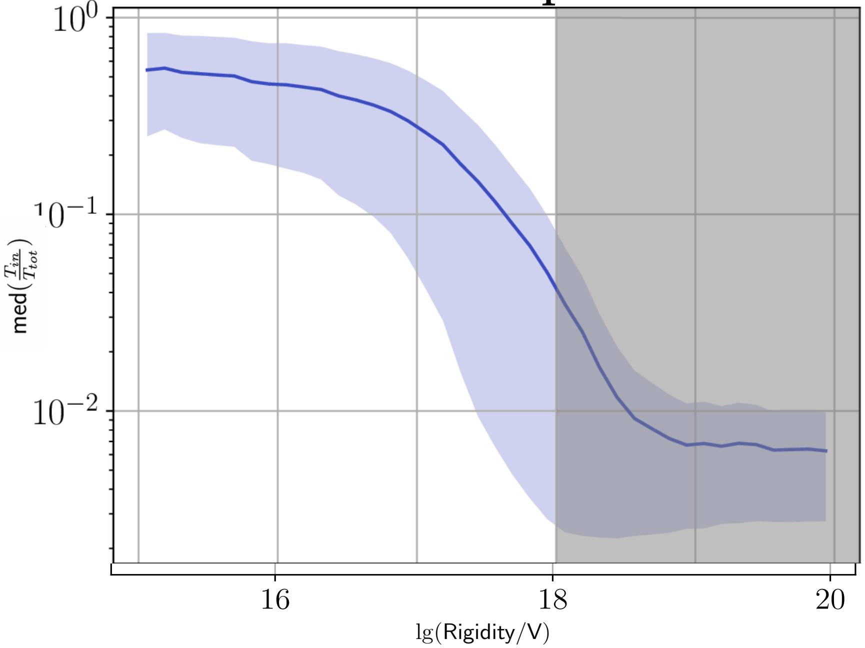
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: GCRs – Confinement in GP

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



Relative time spent in GP



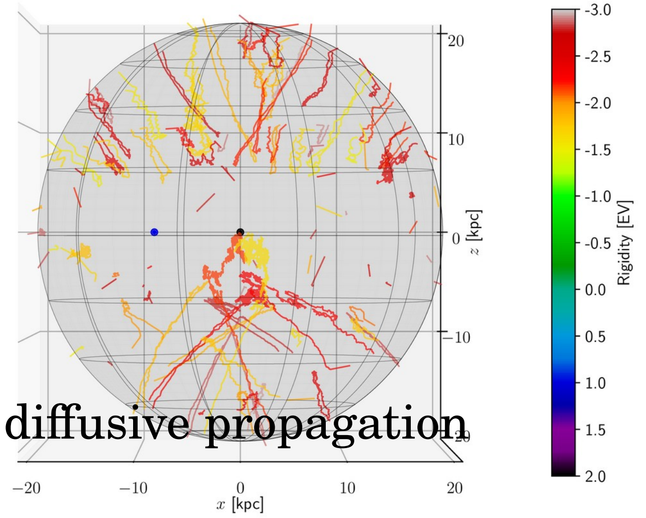
Decreasing confinement in GP **with rigidity.**

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

Alex Kääpä a.kaeaepae@uni-wuppertal.de

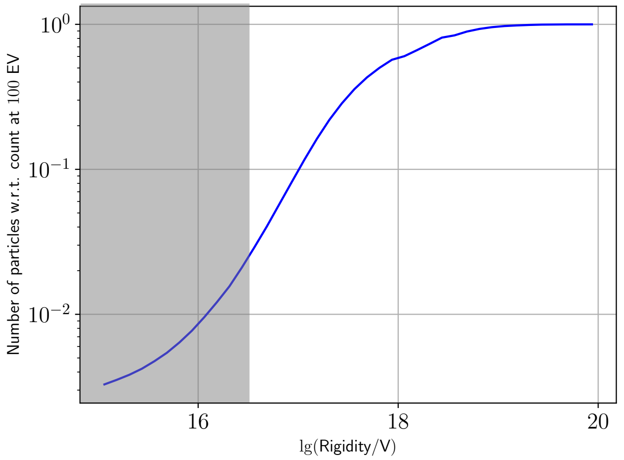
Propagation effects: EGCRs – Shielding from vs. confinement in GP

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



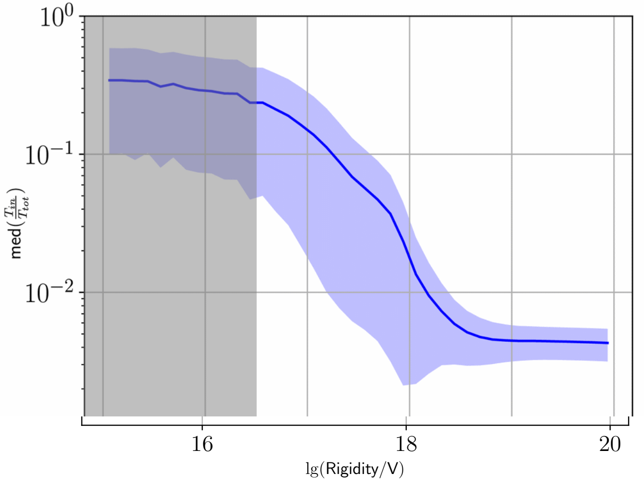
Decreasing shielding from and confinement in GP with rigidity.

CR count reaching GP



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

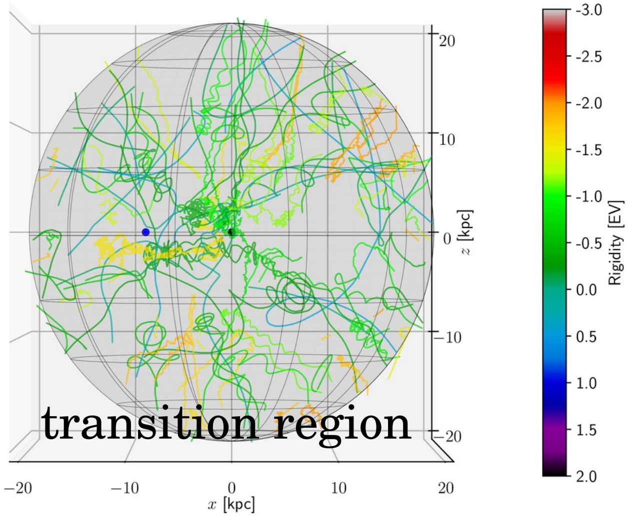
Relative time spent in GP



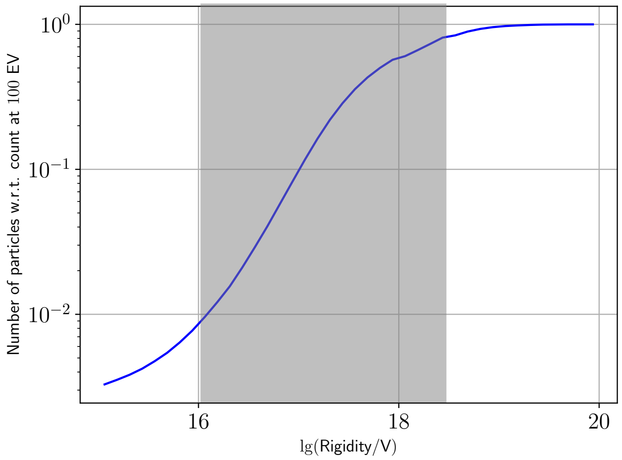
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

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

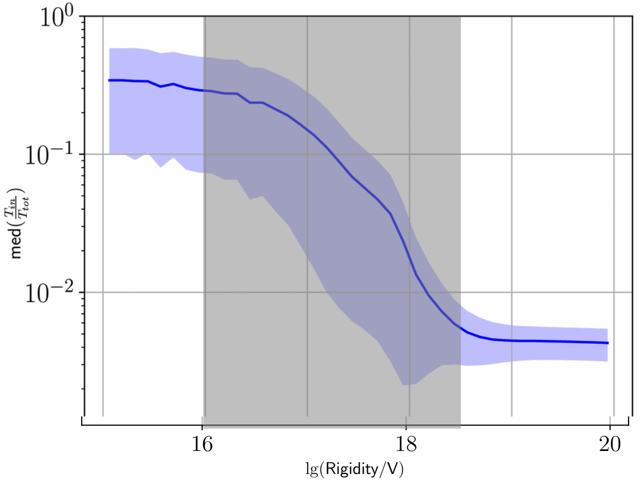
Galactic trajectories ($\lg(R/\mathrm{V})$ = 16 – 18.5)



CR count reaching GP



Relative time spent in GP



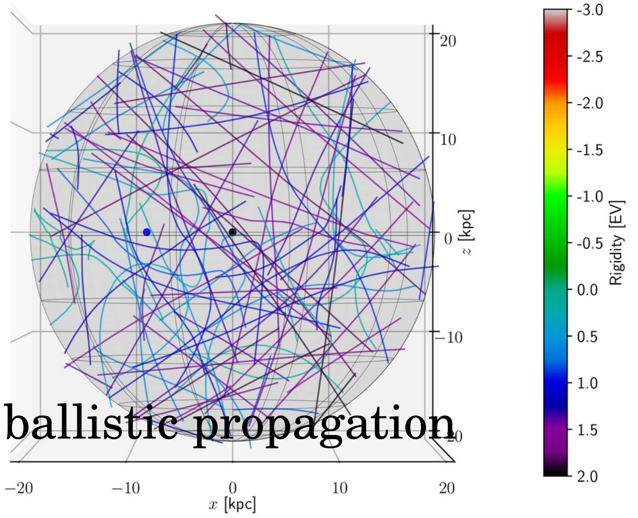
Decreasing shielding from and confinement in GP with rigidity.

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

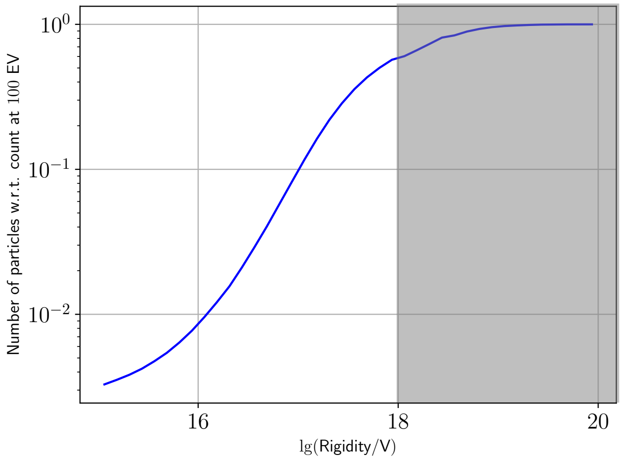
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

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

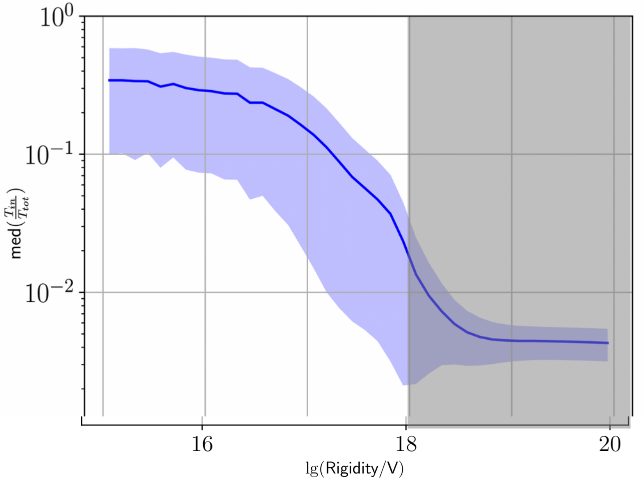
Galactic trajectories
(lg(R/V) = 18 – 20)



CR count reaching GP



Relative time spent in GP



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.**

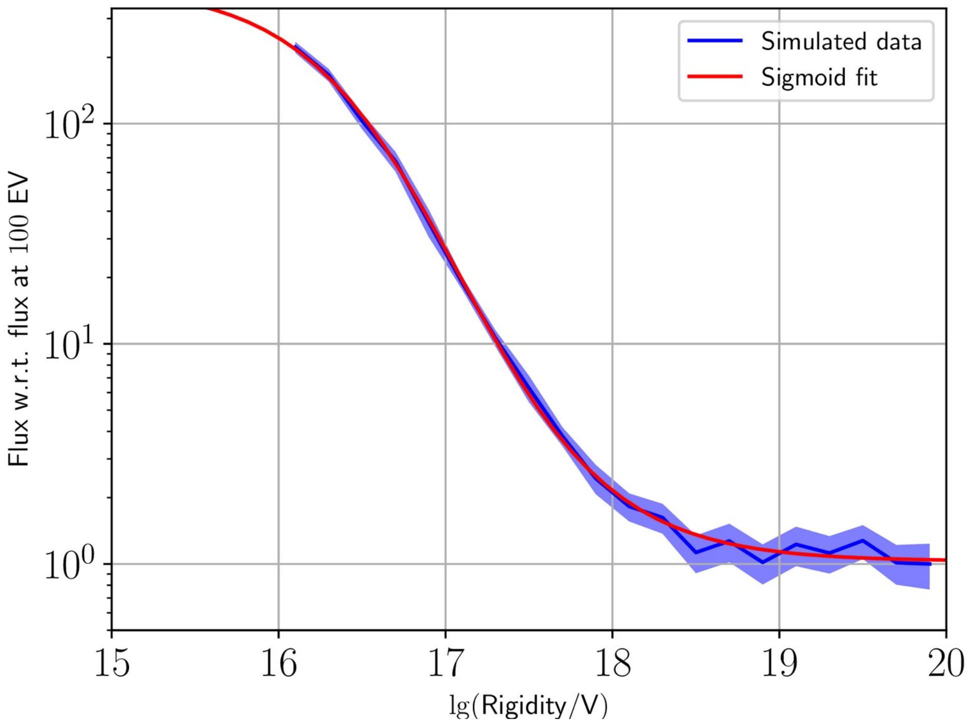
Effect on observables: GCRs – Flux suppression

Decreasing confinement
→ **flux reduction**

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

Arrival direction distribution:
correlation with GP direction
above 0.1 EV

Rigidity spectrum (sigmoid fit)



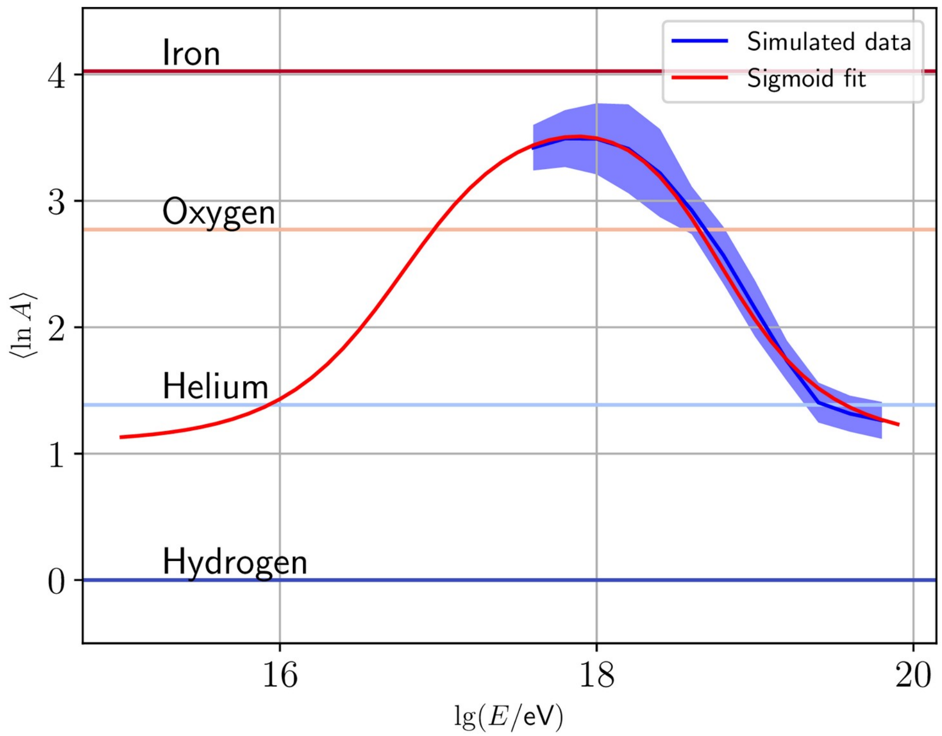
Effect on observables: GCRs – Heavier composition

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!

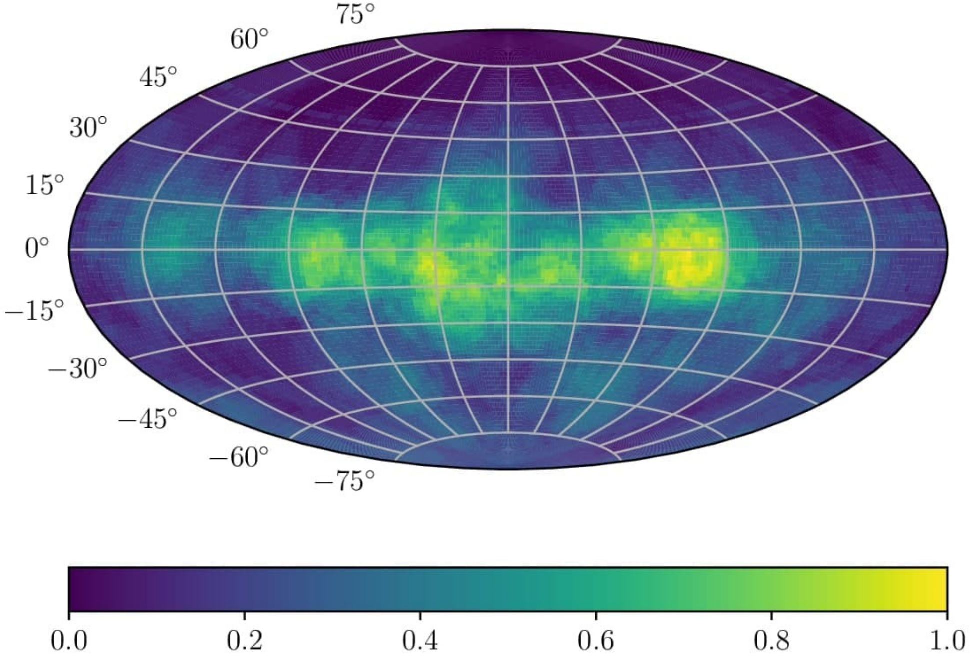
Effect on observables: GCRs – Correlation with source direction (GP)

Decreasing confinement
→ **flux reduction**

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

Arrival direction distribution:
correlation with GP direction
above 0.1 EV

Arrival direction distribution above 0.1 EV



Effect on observables: Isotropic EGCRs – Flux conservation

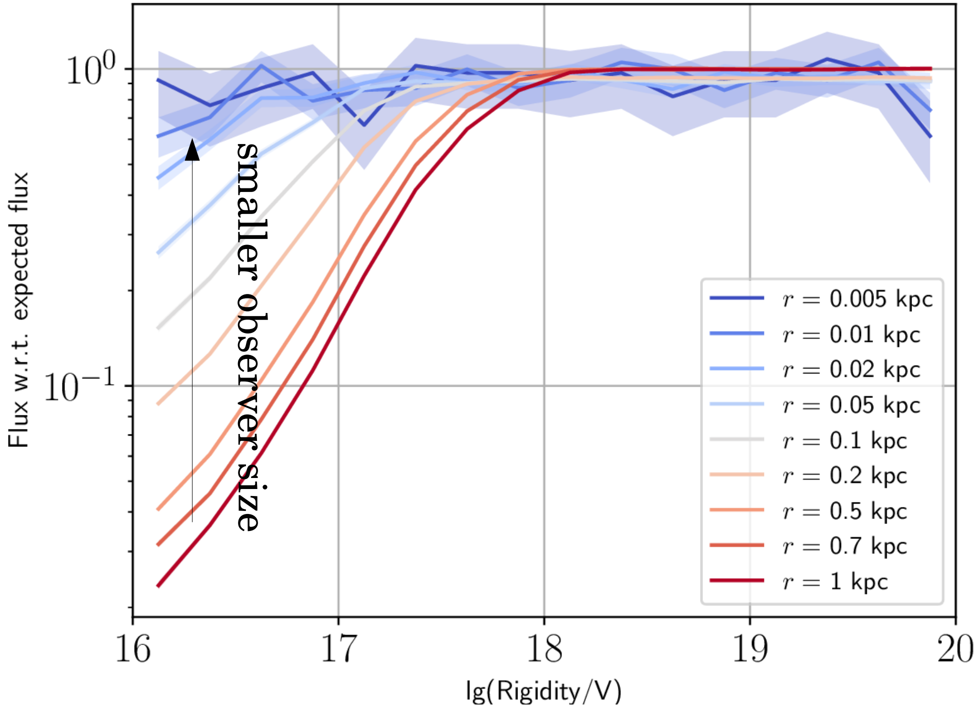
Apparent flux suppression for large observer sphere sizes; effect vanishes as $r \to 0$.

Increased confinement in GP compensates increased shielding:

→ **flux conservation**

Isotropic arrival direction

Rigidity spectrum



Effect on observables: Isotropic EGCRs –Isotropic arrival direction

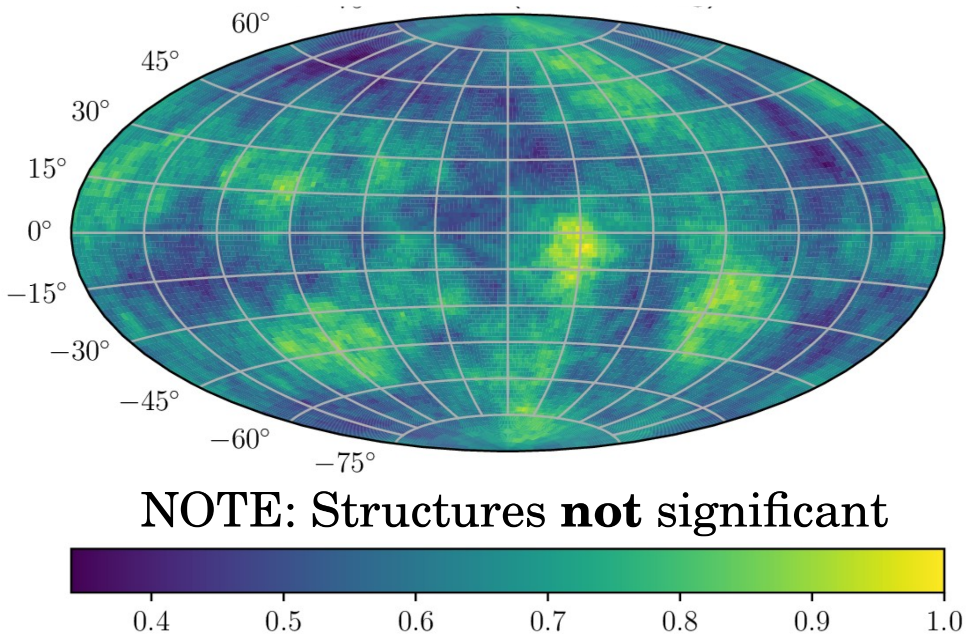
Apparent flux suppression for large observer sphere sizes; effect vanishes as $r \to 0$.

Increased confinement in GP compensates increased shielding:

→ **flux conservation**

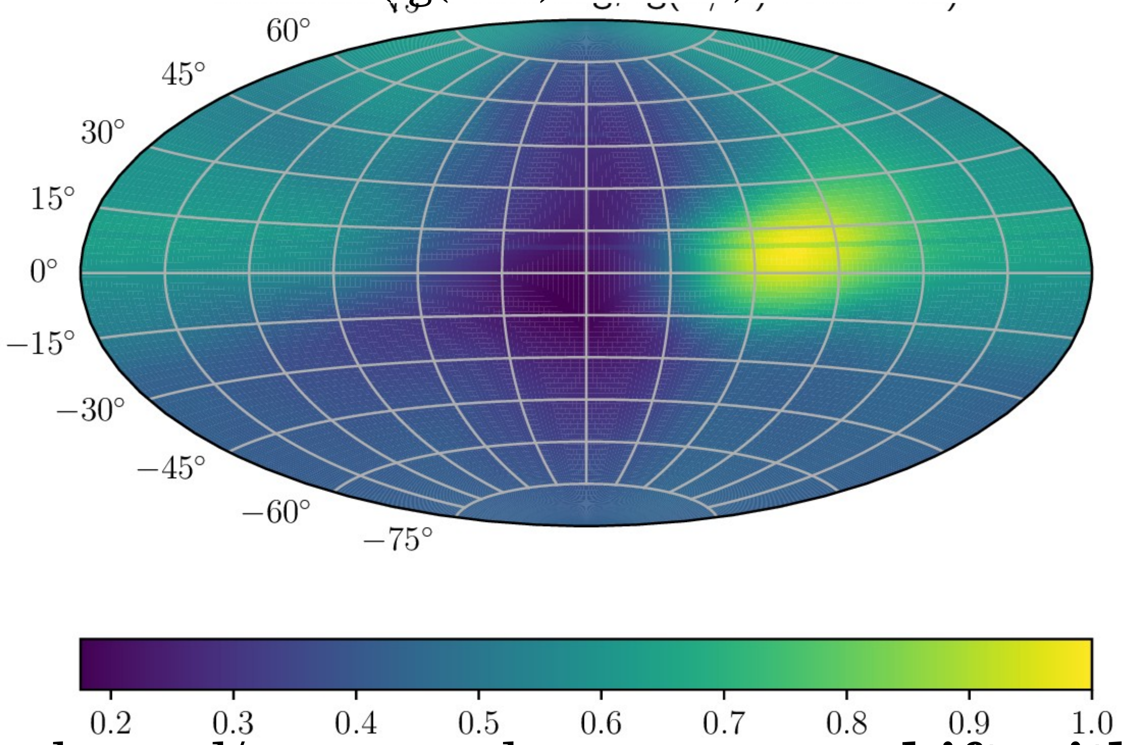
Isotropic arrival direction

Arrival direction distribution



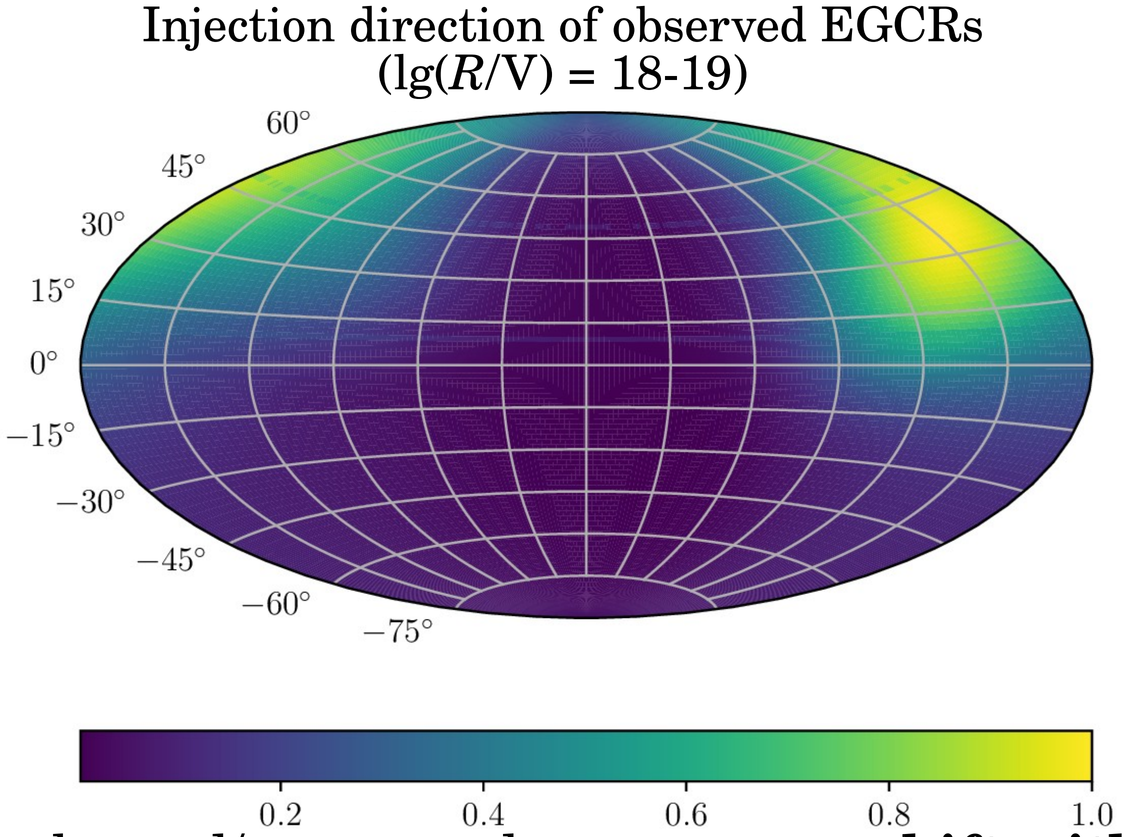
Effect on observables: Anisotropic EGCRs – Opacity of Galaxy

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



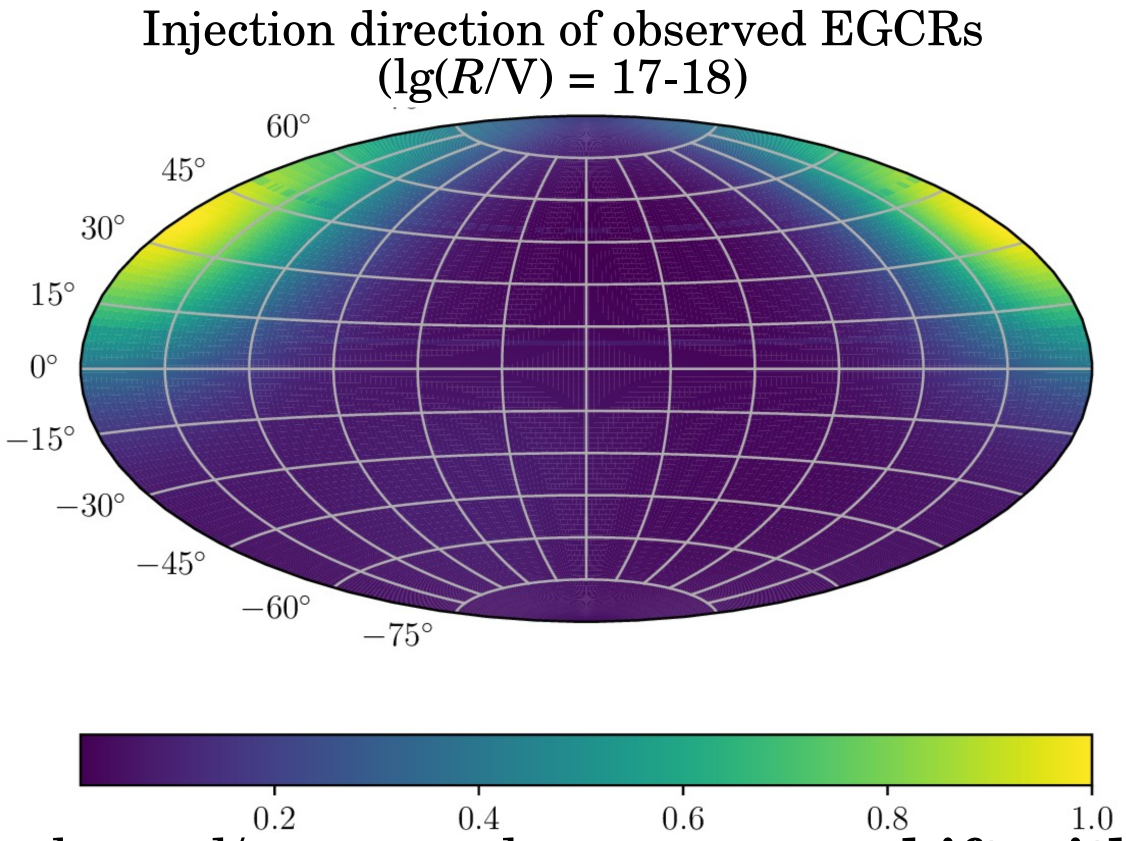
- Regions of enhanced/suppressed transparency **shift with rigidity**

Effect on observables: Anisotropic EGCRs – Opacity of Galaxy



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

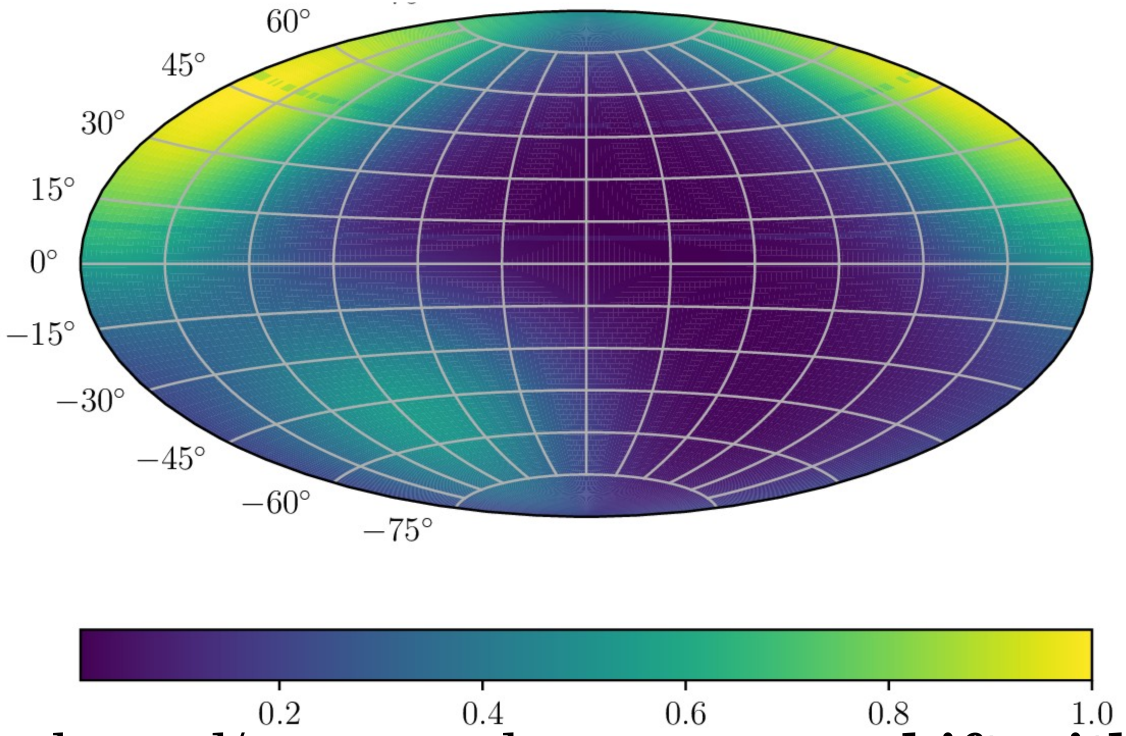
Effect on observables: Anisotropic EGCRs – Opacity of Galaxy



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

Effect on observables: Anisotropic EGCRs – 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

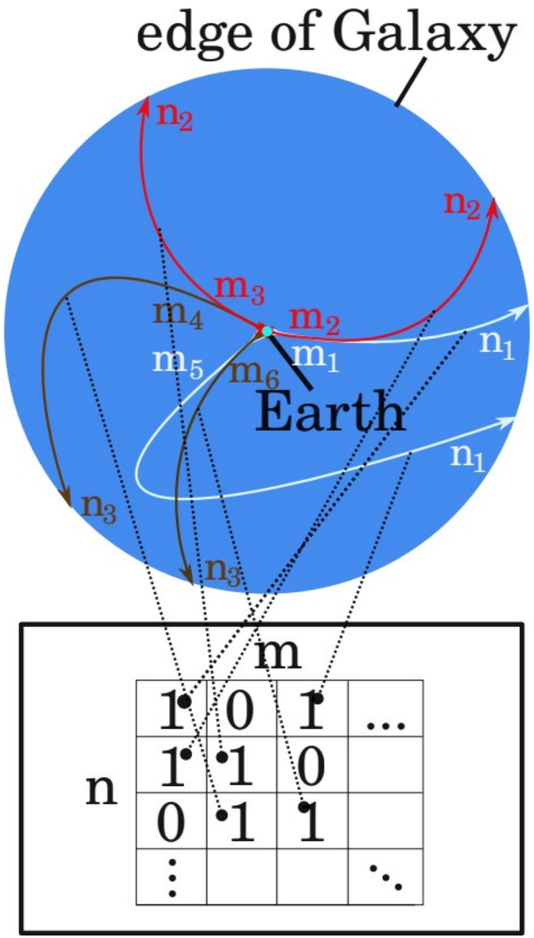
Propagation in GMF can be quantified via lens

- 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 **ascribe numbers** n and m to corresponding **injection and arrival directions**



Effect on observables: Anisotropic EGCRs – Galactic lensing

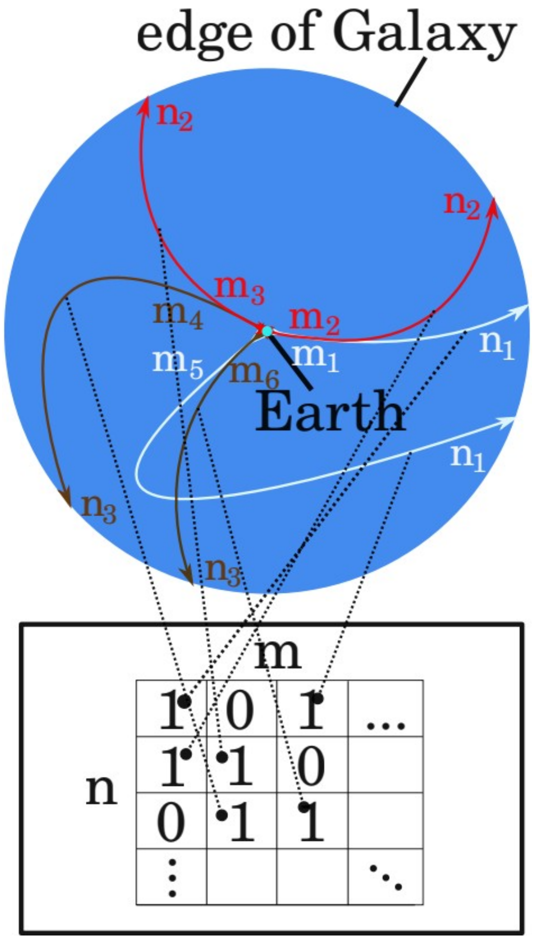
see also: Astropart.Phys. 85 (2016) 54-64 for lensing scheme &
Eichmann, JCAP04(2020)047 for parallel work

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 backtracked particles N) **defines lens**

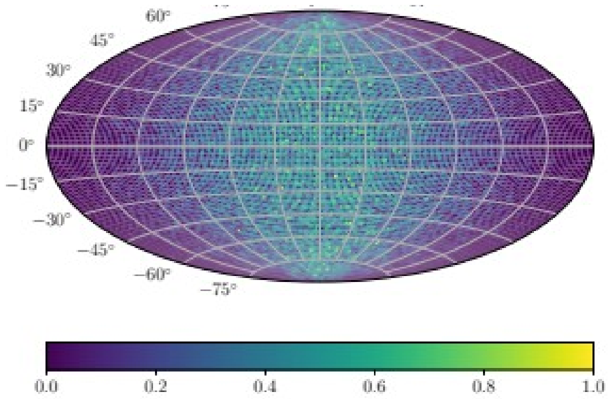
→ calculate arrival direction distribution for any injection direction distribution:

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

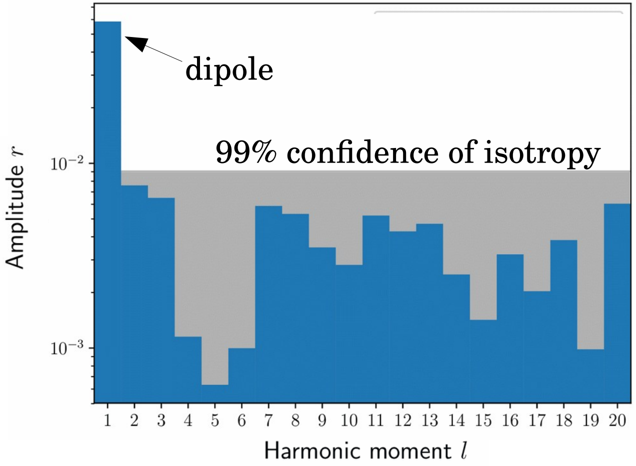


Effect on observables: Anisotropic EGCRs – Galactic lensing

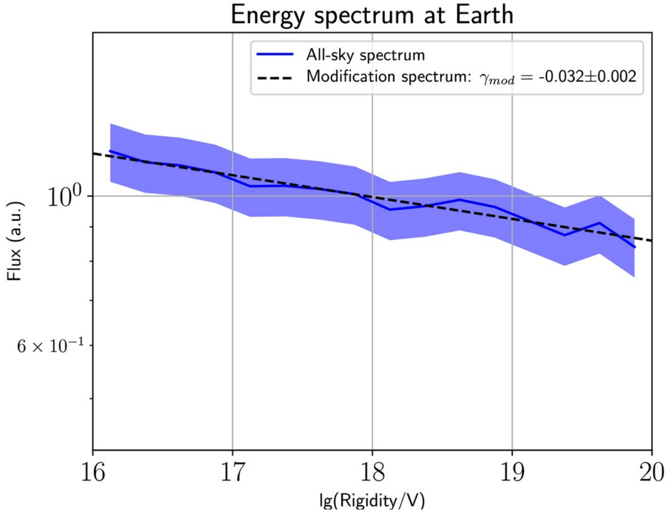
Injected flux



Distribution of moments above 1 EV



Flux at Earth



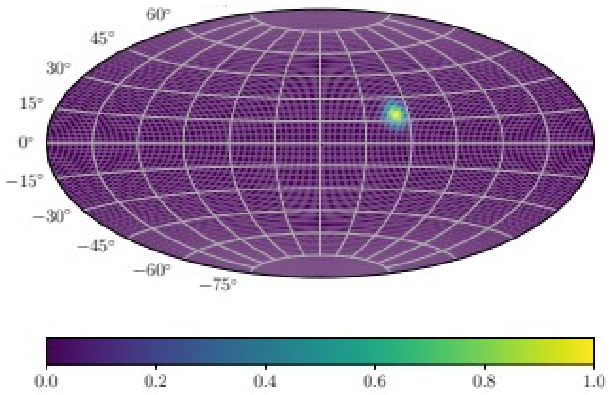
Injection direction distribution: **Pure dipole**

- surviving dipole in arrival direction distribution above 1 EV
- strong isotropisation by GMF at lower energies

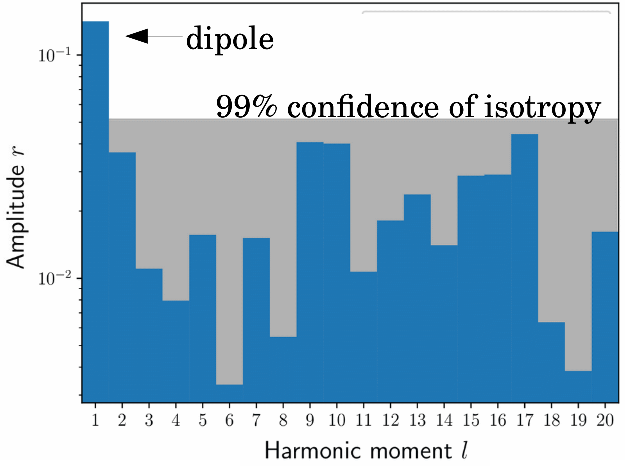
Rigidity spectrum at Earth → **possible flux modification**

Effect on observables: Anisotropic EGCRs – Galactic lensing

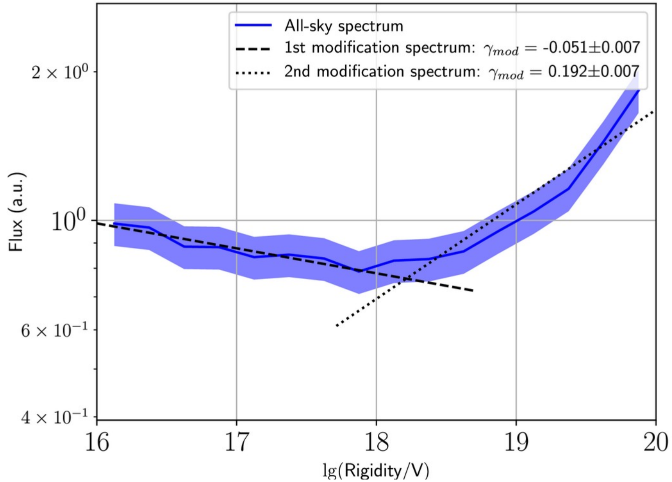
Injected flux



Distribution of moments above 1 EV



Flux at Earth



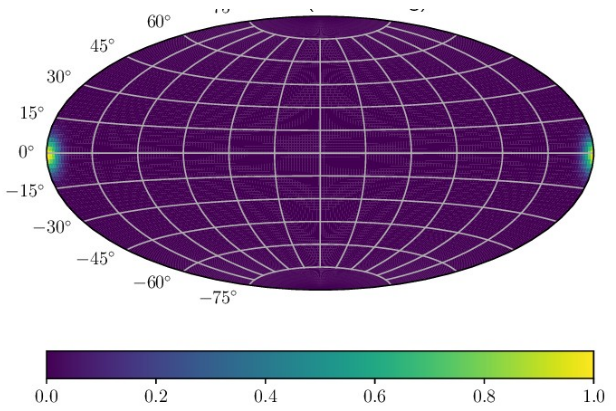
Injection direction distribution: **Pure single-point source** (Cen A)

- surviving dipole in arrival direction distribution above 1 EV
- strong isotropisation by GMF at lower energies

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

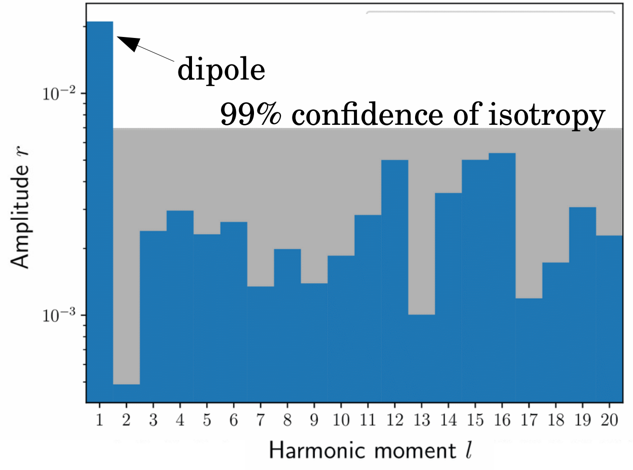
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



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

Distribution of moments above 1 EV



- surviving dipole in arrival direction distribution above 1 EV
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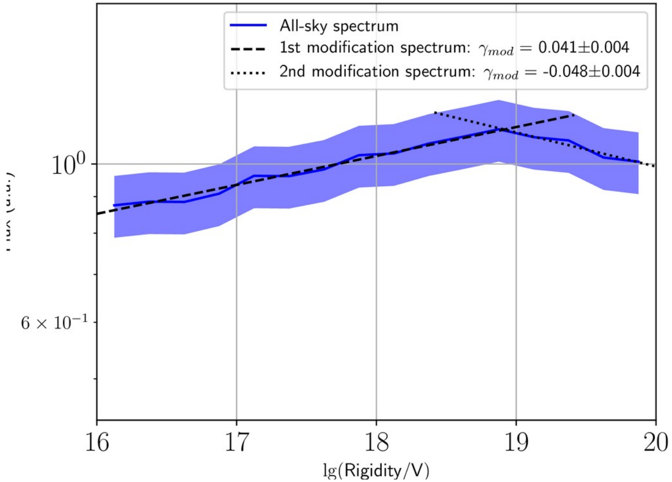
Flux at Earth



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

Summary (1)

Computational challenges:

- **change in propagation regimes**
  - **both propagation methods necessary**, ideally in self-consistent framework
    → CRPropa 3
- **GMF poorly understood**
  - apply **multiple models**
  - improve measurements of observables and associated quality
  - use more input in model creation (see also IMAGINE project)

Summary (2)

Propagation effects:

- Propagation in GMF for $R = 10^{16-20}$ V: **change in propagation regimes from diffusive to ballistic**
- **Inflection point at a few EV** ($r_g \sim$ width of GP) for all observed quantities

Effect on observables:

- GCRs:
  - **Flux suppression** towards higher rigidities; **heavier mixed composition** towards ‘ankle’
  - **Correlation with direction of GP** for rigidities above 0.1 EV
- EGCRs:
  - **Isotropic injection: No flux suppression** and **isotropic arrival direction**
  - **Anisotropic injection**: **Dipole** and **single point source → arrival direction isotropic below 1 EV, possible flux modification**

Summary (3)

Implications for transition:

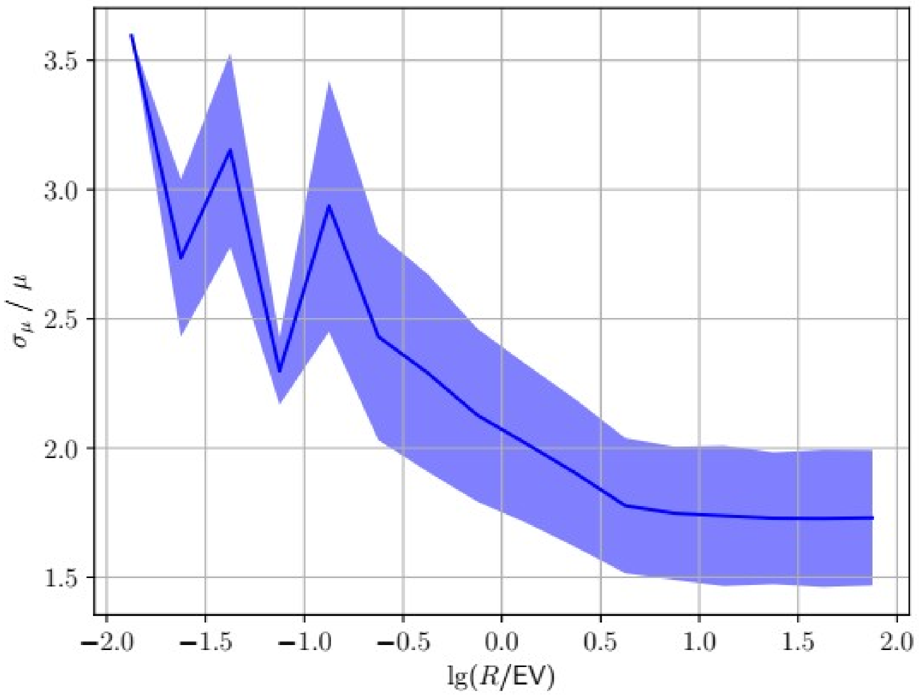
- GCRs:
  - **Propagation in GMF** leads to **‘knee’-like feature**
  - Significant contribution of **GCRs originating from GP disfavoured** at highest energies of ‘shin’ region
- EGCRs:
  - Part of **‘ankle’** may be a **propagation effect in GMF**

Thank you for your attention!

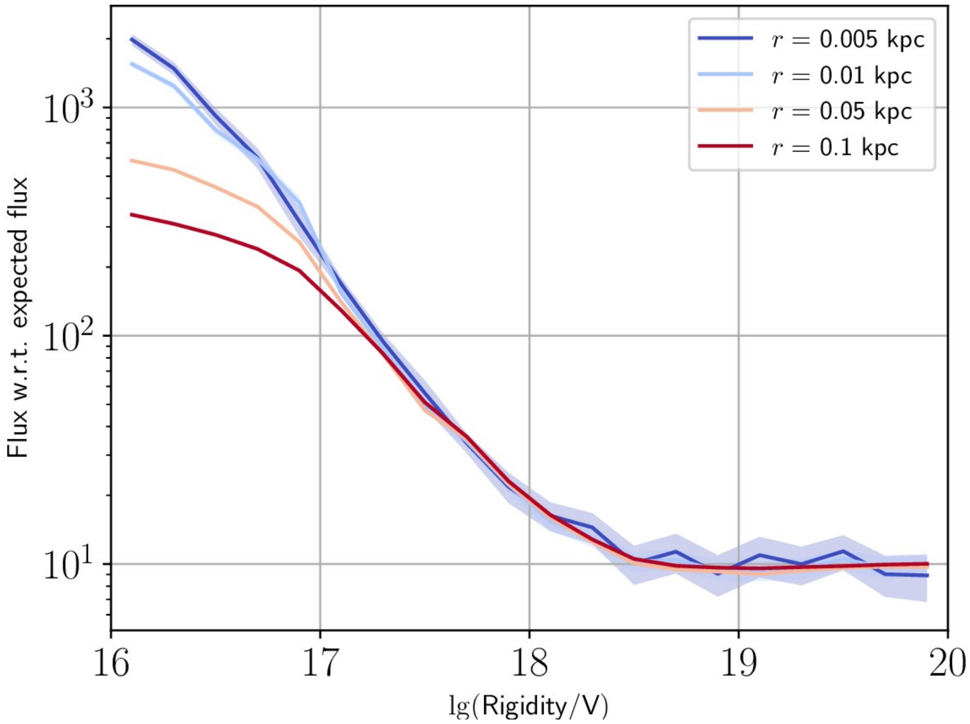
Liouville's Theorem

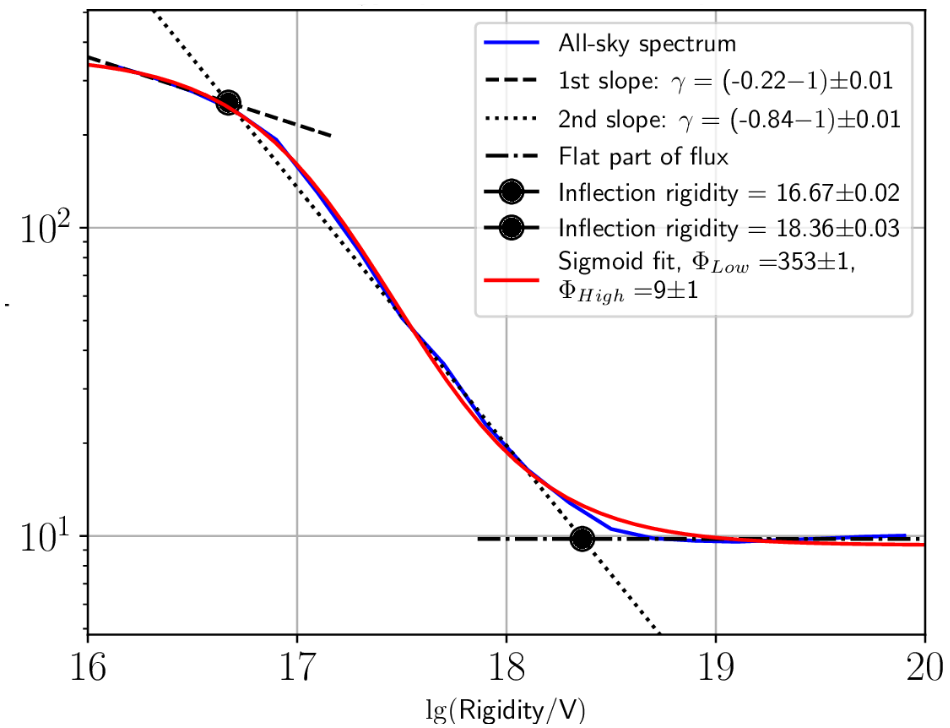
- Objection to flux modification of EGCRs: **Liouville's Theorem**
  - If **phase space density is conserved, so is flux**
  - BUT: If Liouville holds, then **other quantities are conserved, i.a. first adiabtic invariant** ~ classical magnetic moment (APJ 842:54, APJ 830:19):

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



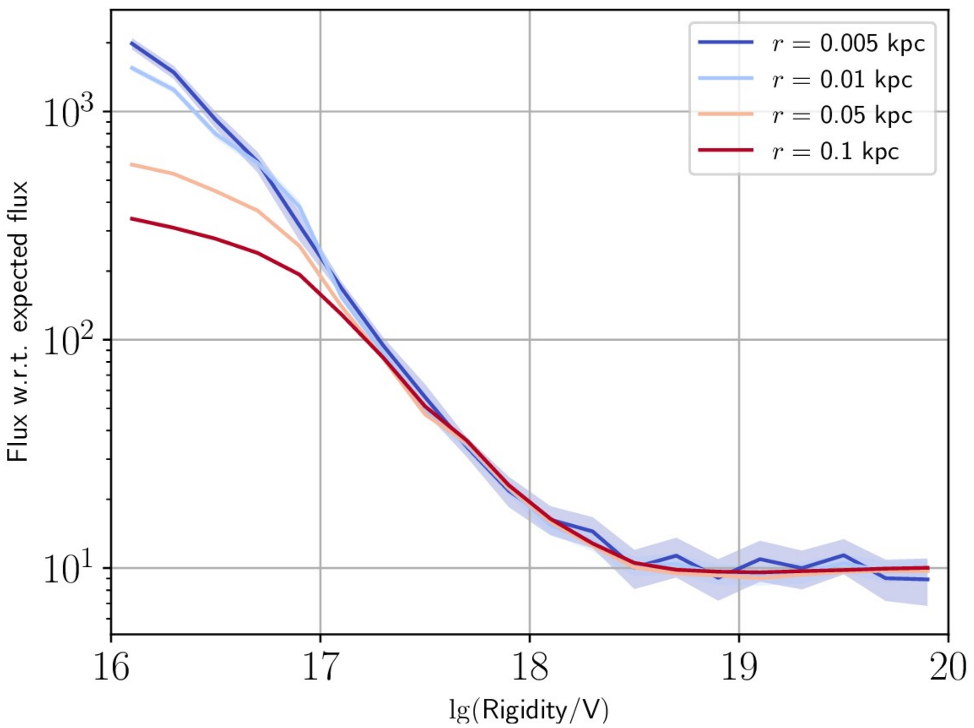
GCRs – Sigmoid fit to flux

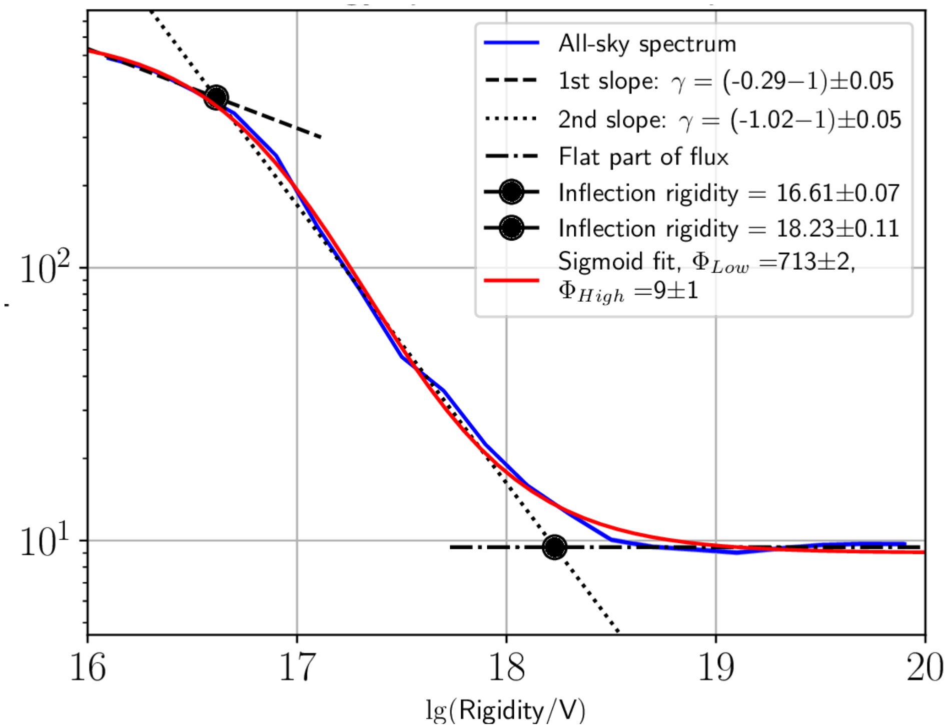




- Flux enhancement towards lower rigidities appears to flatten out → sigmoid fit
- Advantage: wider overlapping energy range of mixed compositions

GCRs – Sigmoid fit to flux





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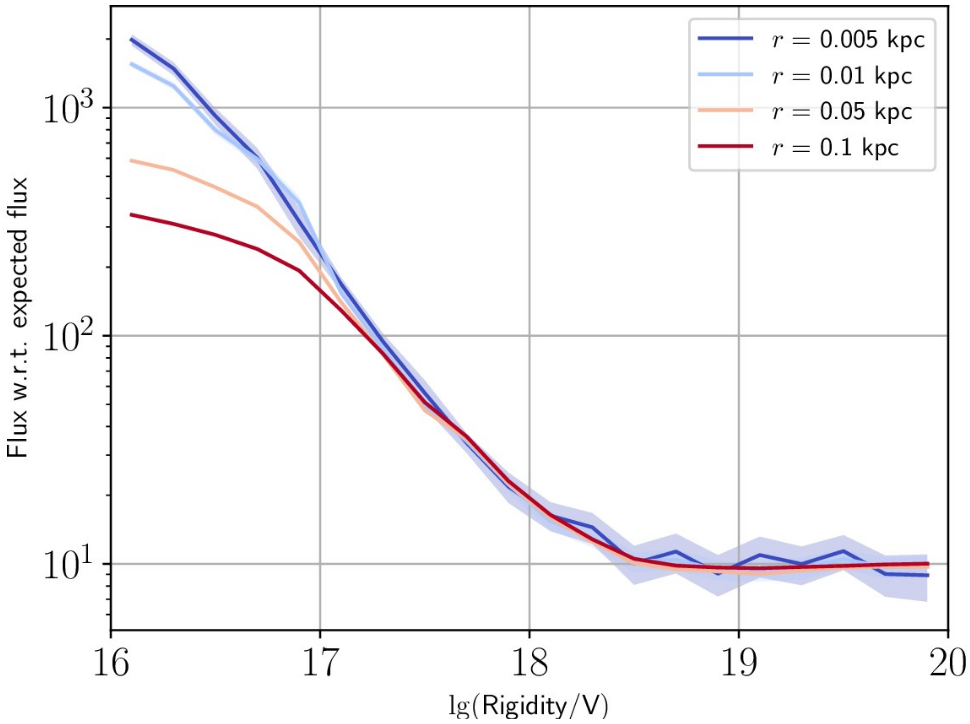
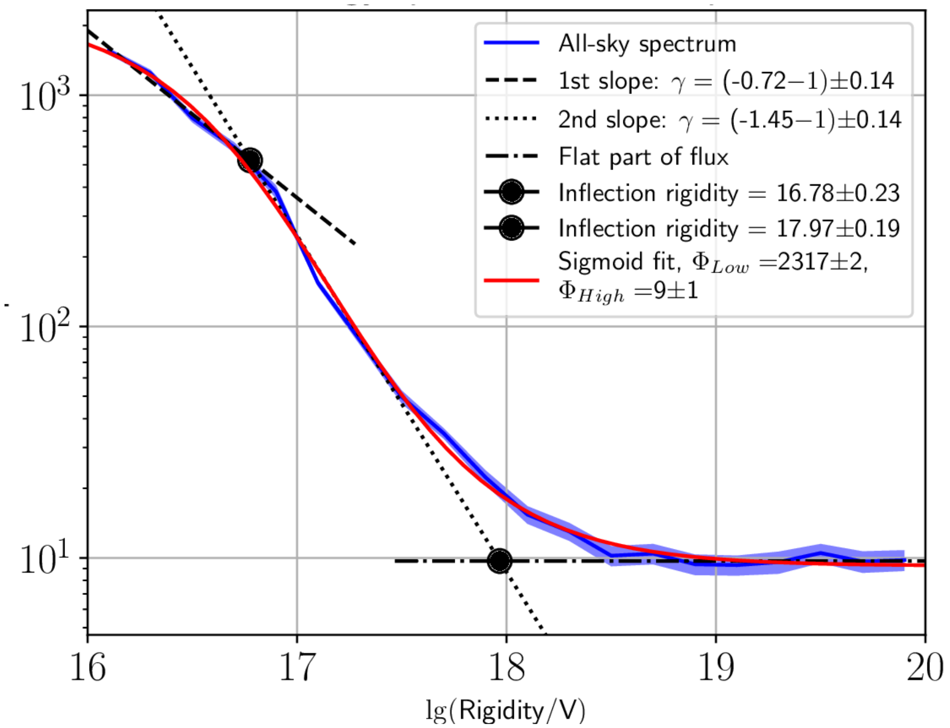
GCRs – Sigmoid fit to flux





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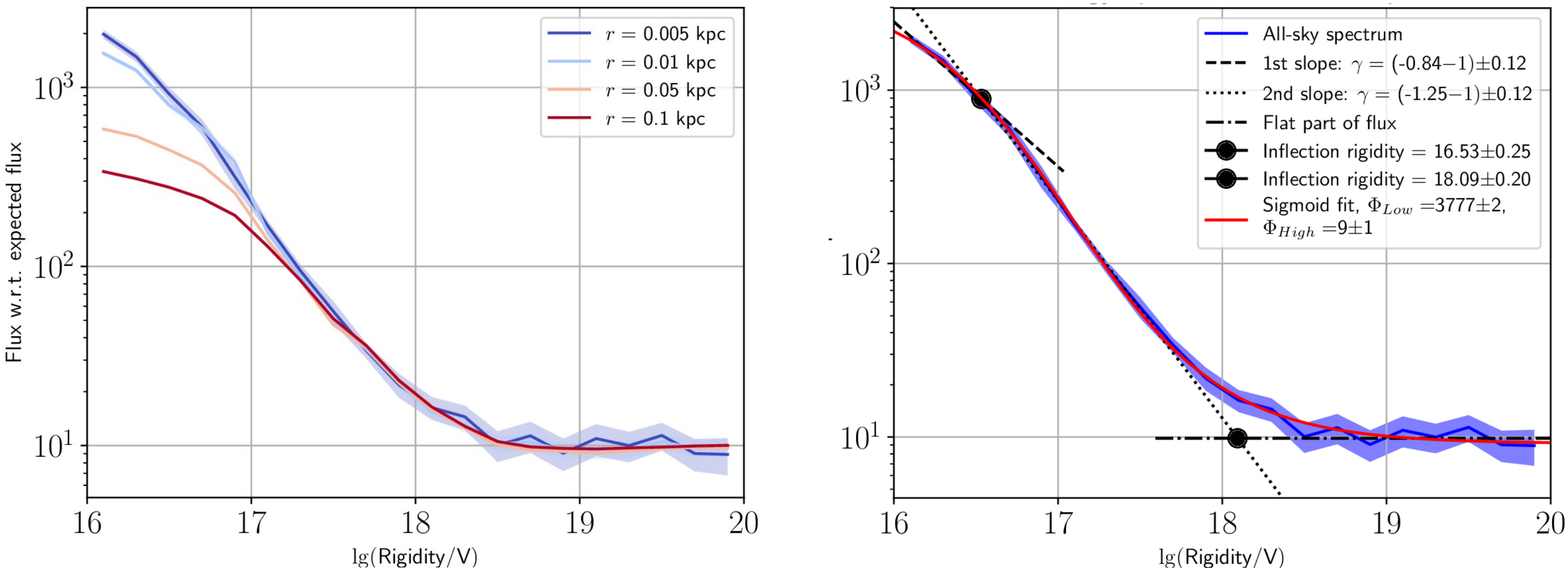
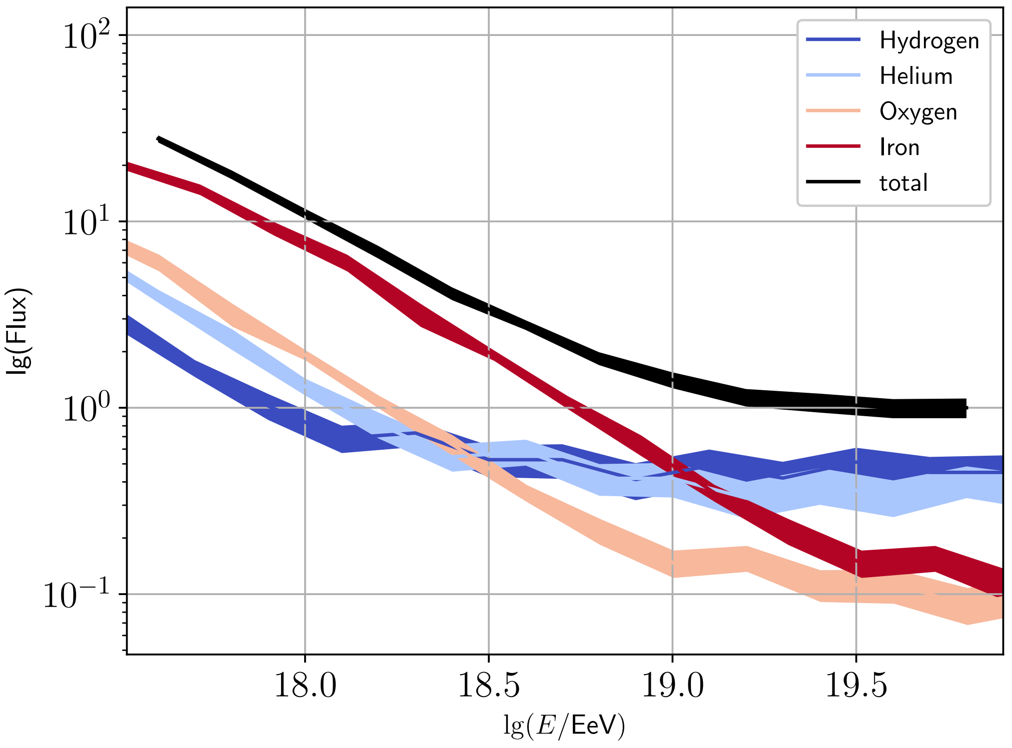
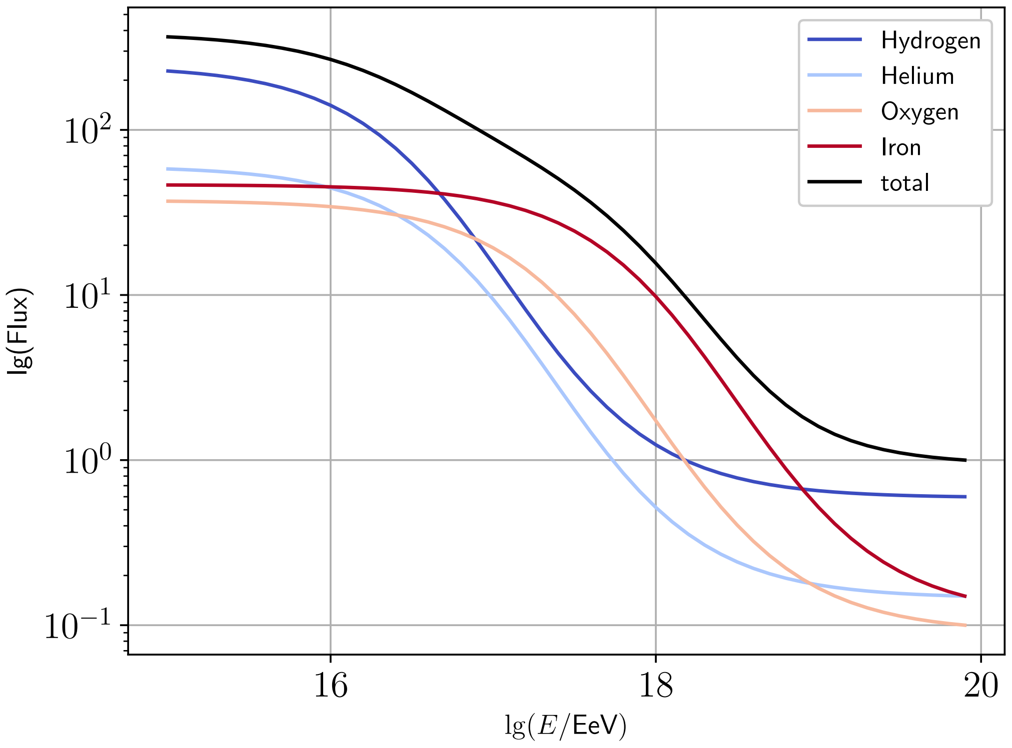
GCRs – Sigmoid fit to flux



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

GCRs – Total flux (data and sigmoid fit)

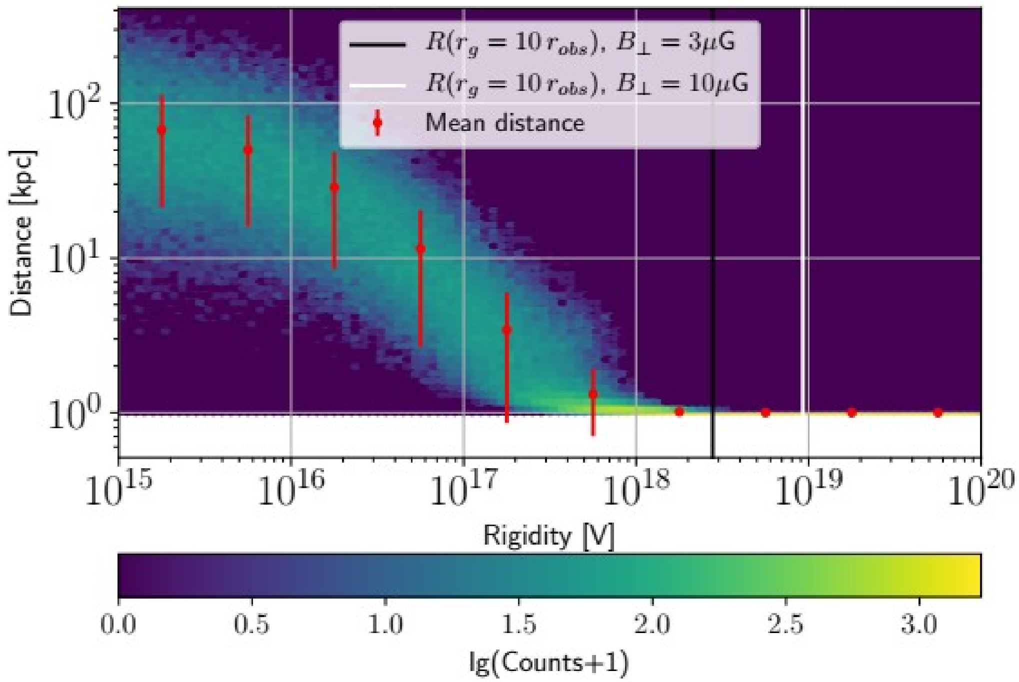




- Onset of flux suppression for mixed composition visible for sigmoid fit

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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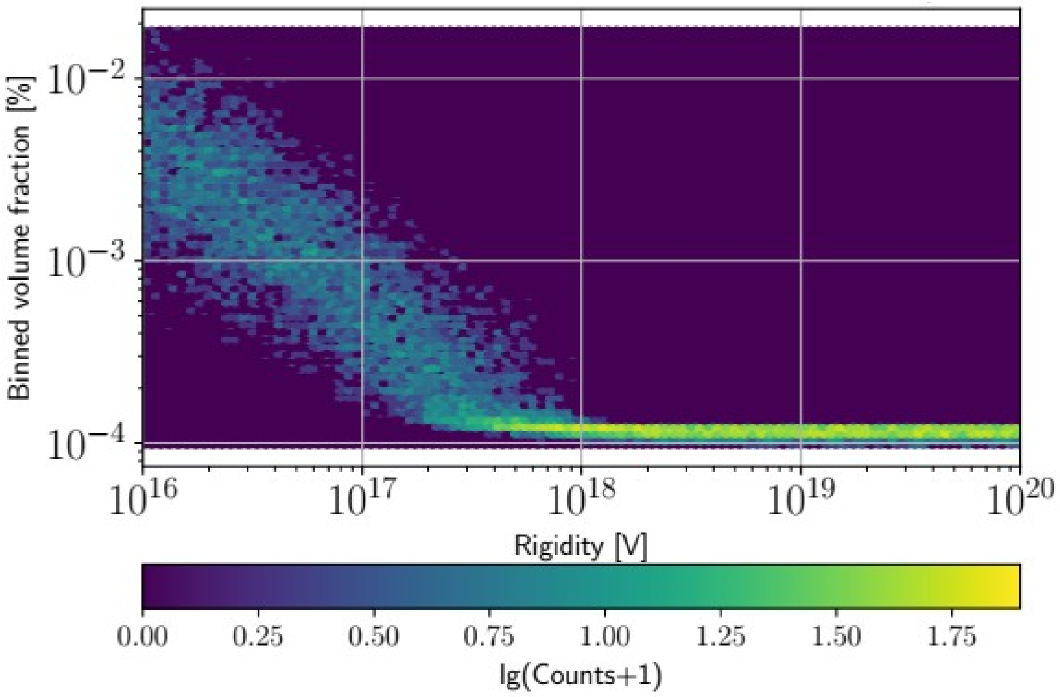
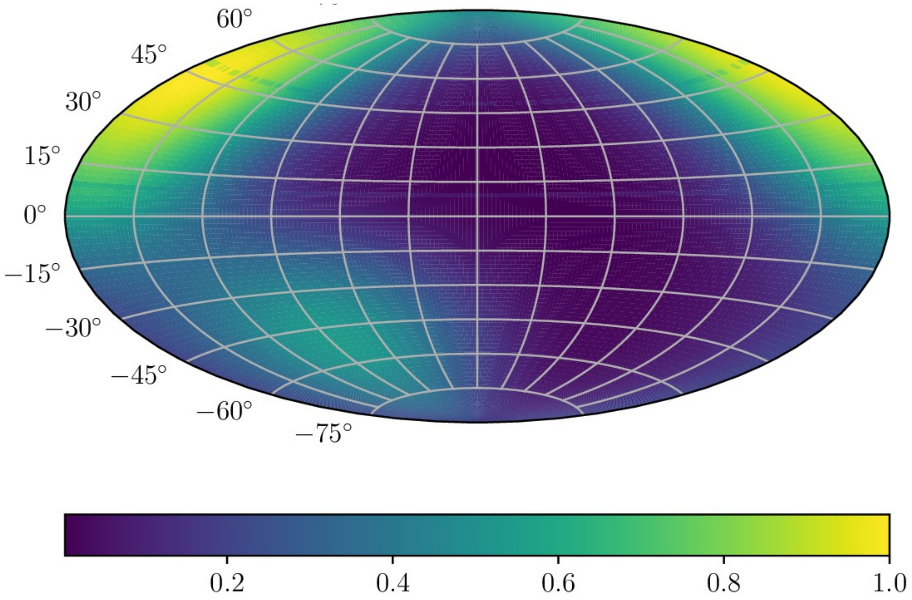
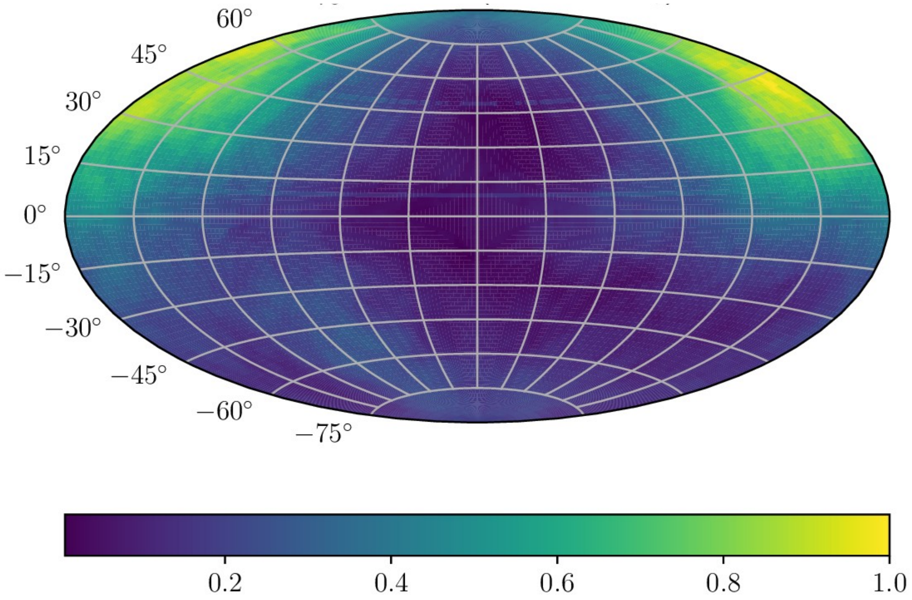


Galactic lensing – time reversibility

Injection direction of observed EGCRs
backtracking



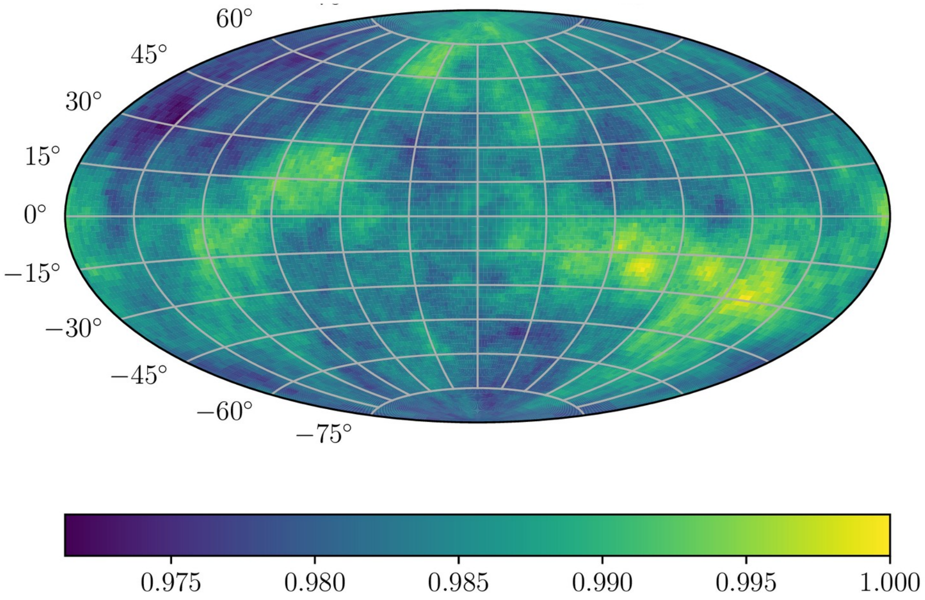
Injection direction of observed EGCRs
forward tracking



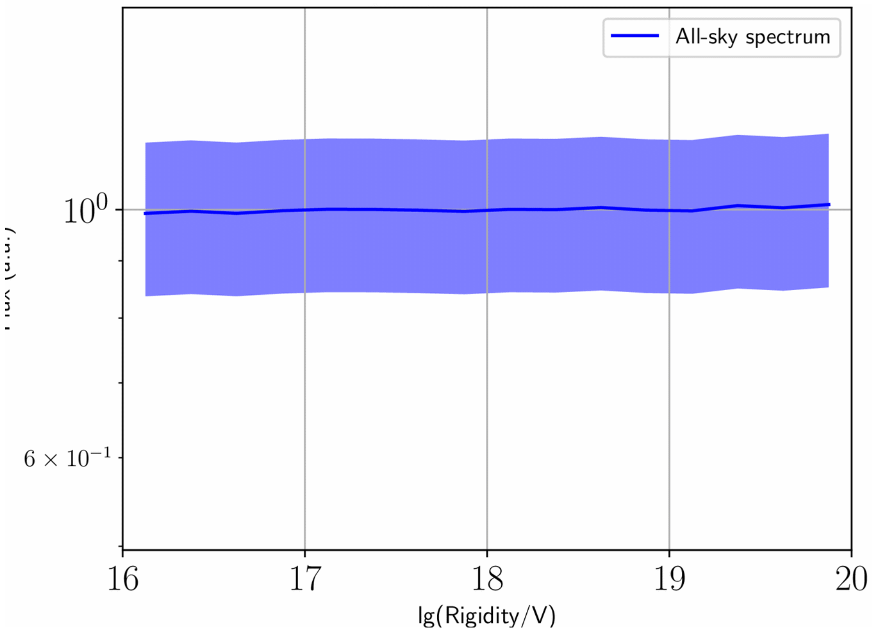
Injection direction distributions of backtracked and forward tracked protons match

Galactic lensing – testing lens

Arrical direciton of lensed isotropic injection distribution



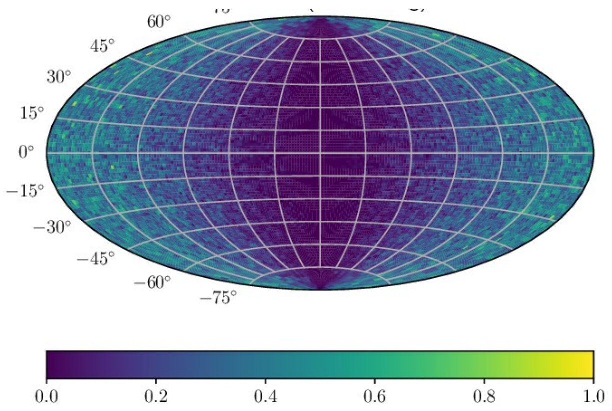
Spectrum of lensed isotropic injection distribution



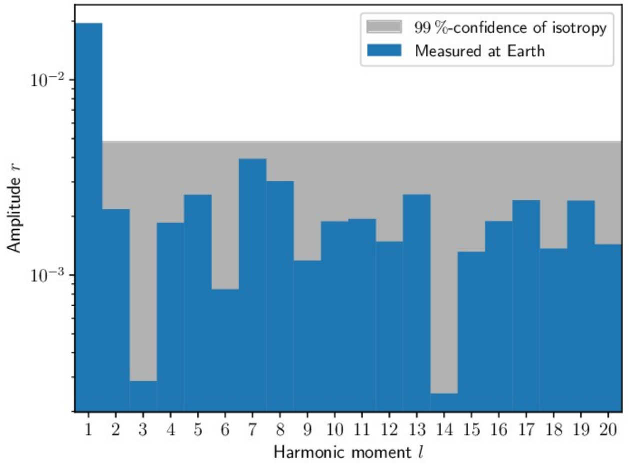
Lensed arrival direction distribution and spectrum of isotropic injection distribution is as expected.

Anisotropic EGCRs – Galactic lensing

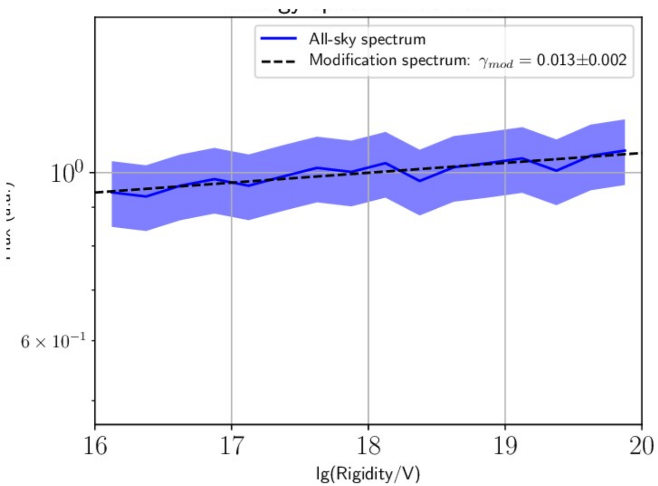
Injected flux



Distribution of moments above 1 EV



Flux at Earth



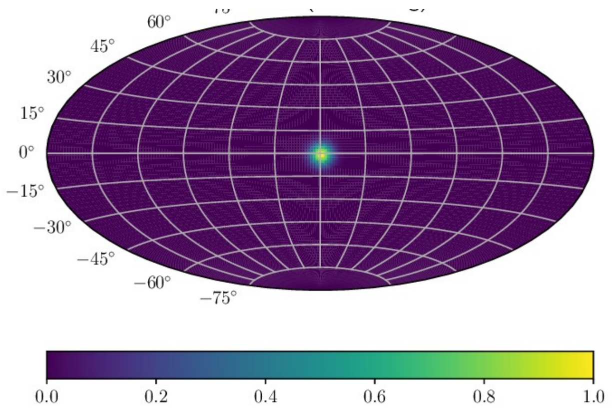
Injection direction distribution: **Pure dipole**

Distribution of harmonic moments of arrival direction distribution above 1 EV → **strong isotropisation by GMF**

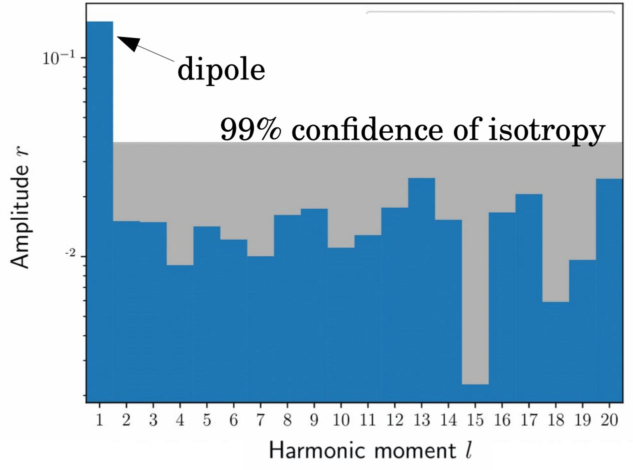
Rigidity spectrum at Earth → **possible flux modification**

Effect on observables: Anisotropic EGCRs – Galactic lensing

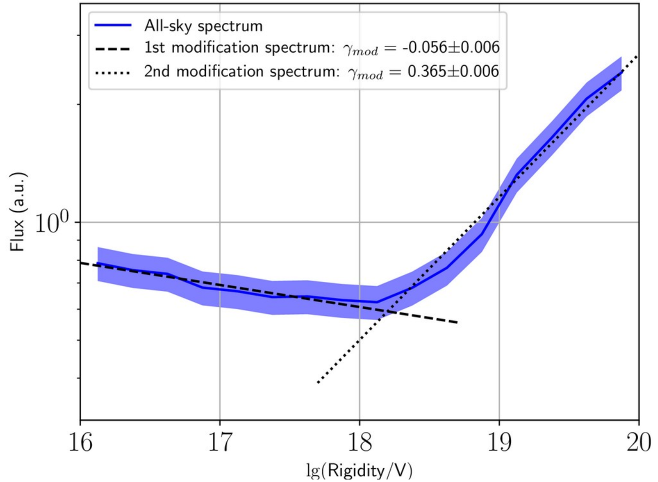
Injected flux



Distribution of moments above 1 EV



Flux at Earth



Injection direction distribution: **Pure single-point source** (minimum Galactic transparency; Galactic centre)

- surviving dipole in arrival direction distribution above 1 EV
- strong isotropisation by GMF at lower energies

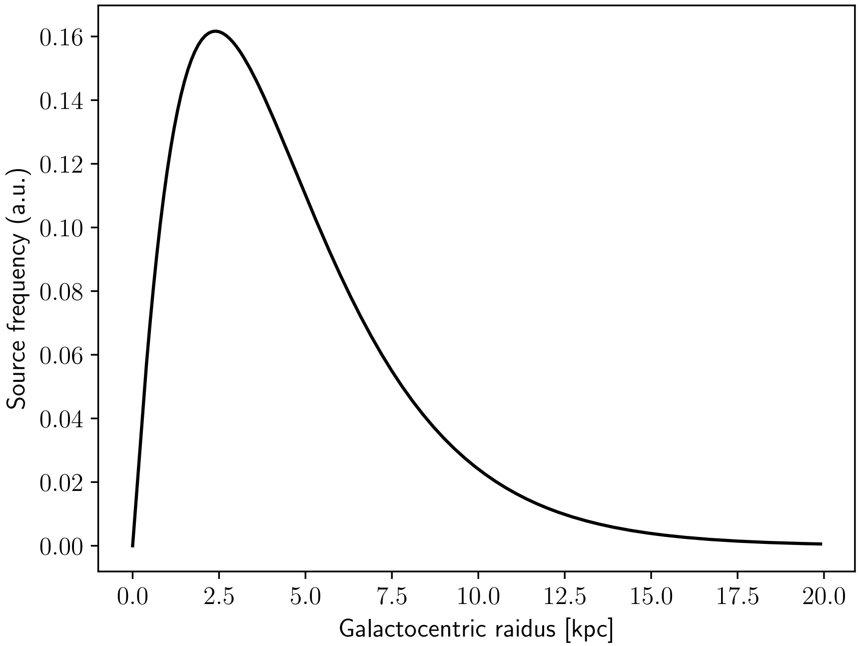
Rigidity spectrum at Earth → **possible flux modification**

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



Goal: Incorporate propagation effects

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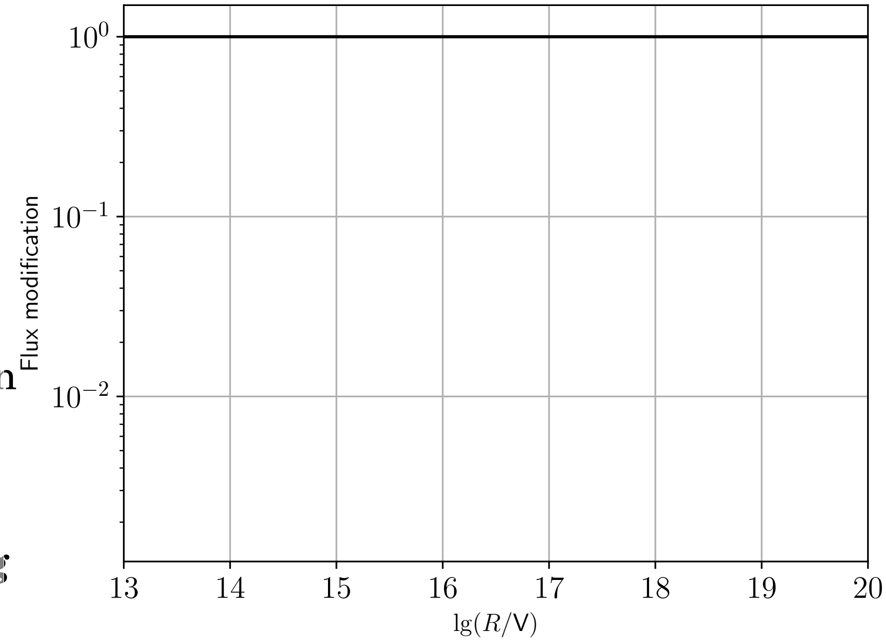
Flux with or without leakage/cut-off



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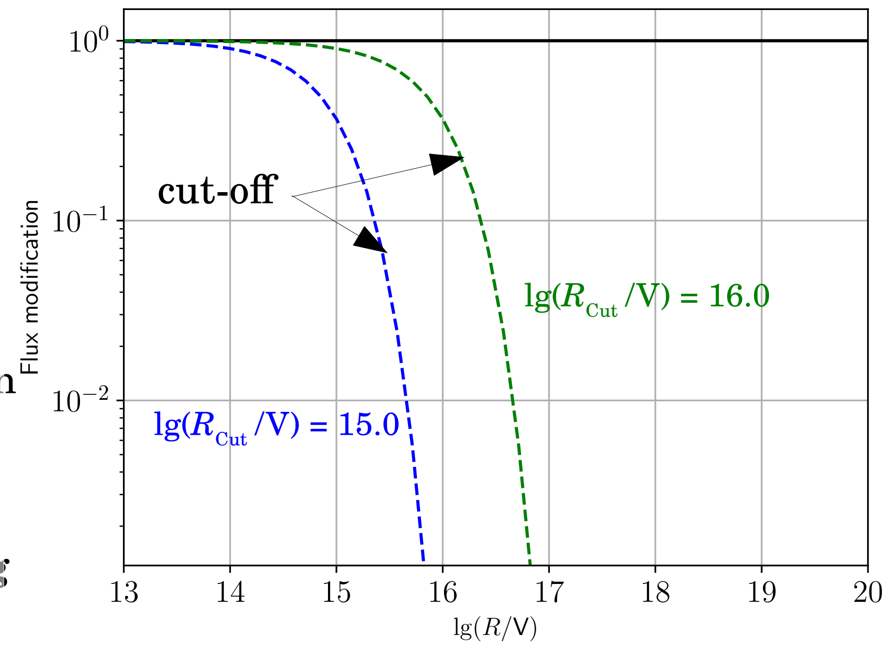

Alex Kääpä a.kaeaepae@uni-wuppertal.de

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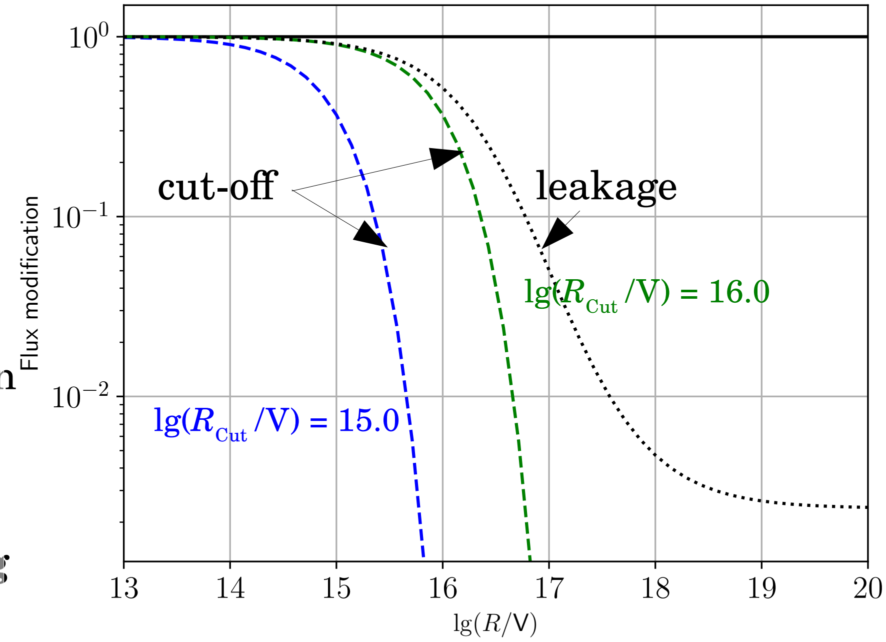

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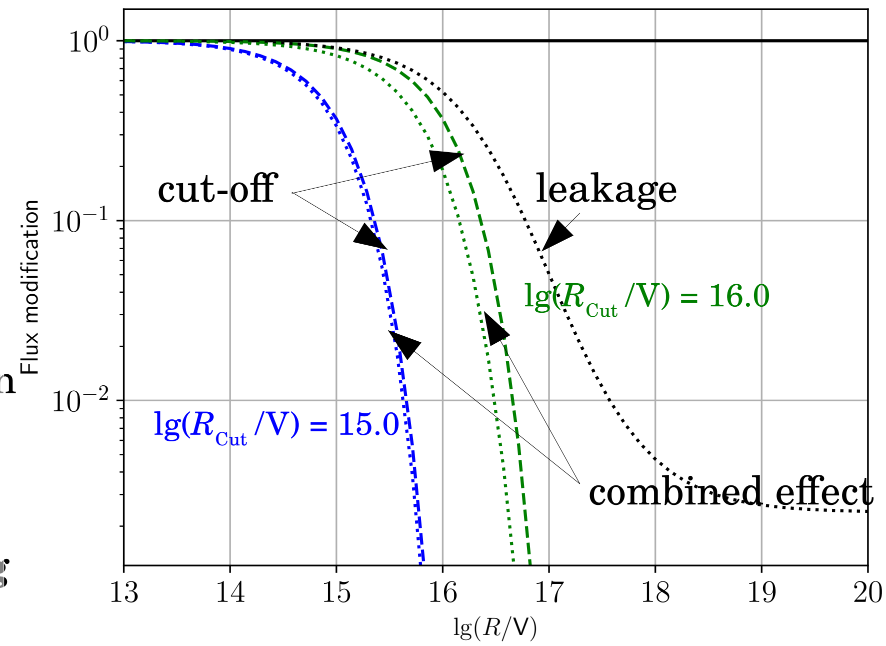

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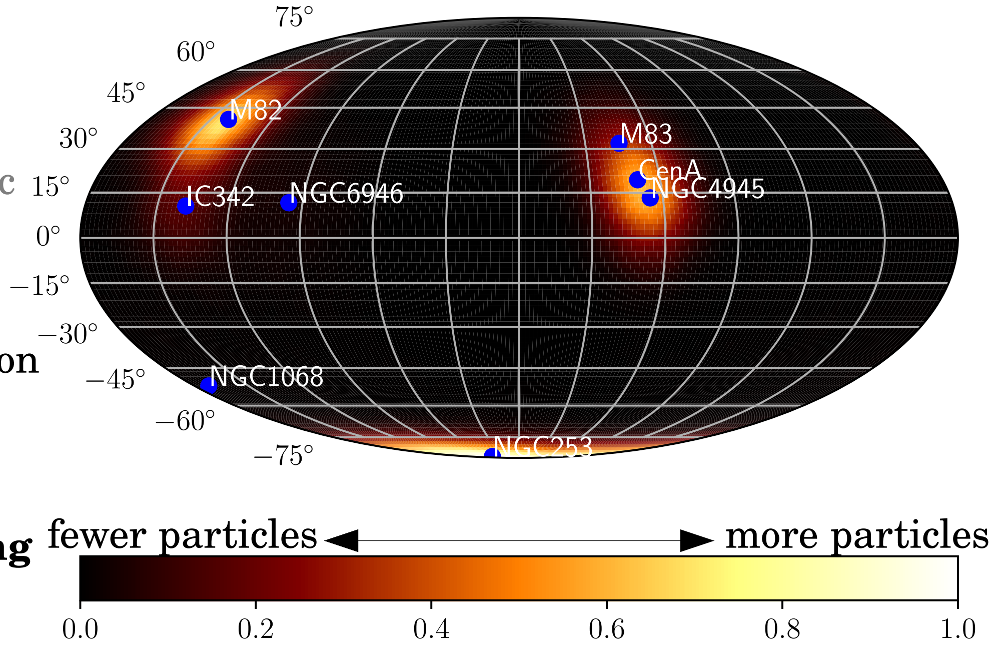
Injection direction distribution of EGCRs



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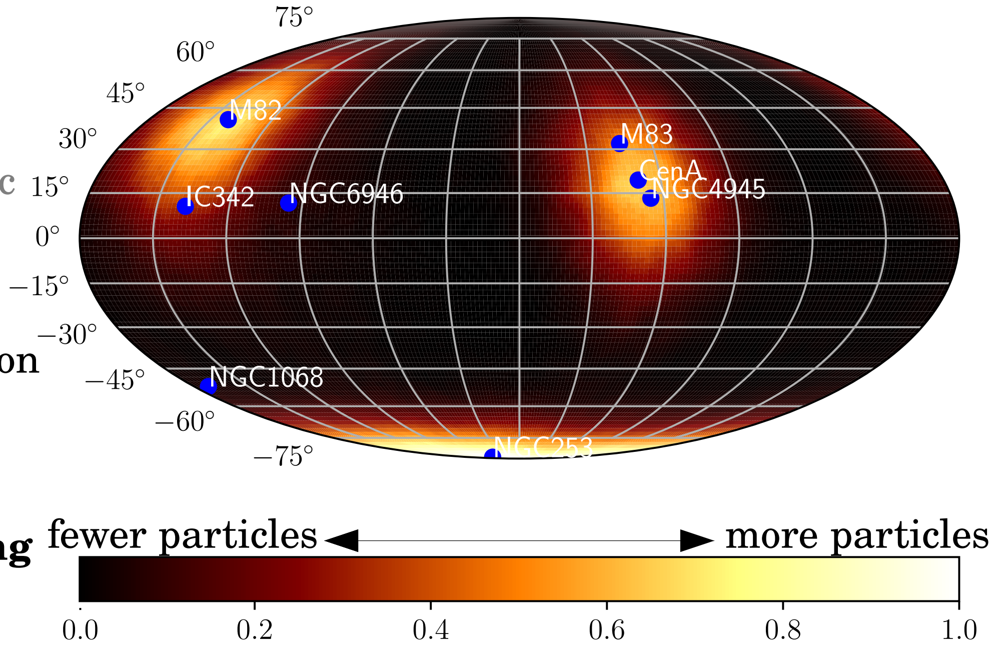

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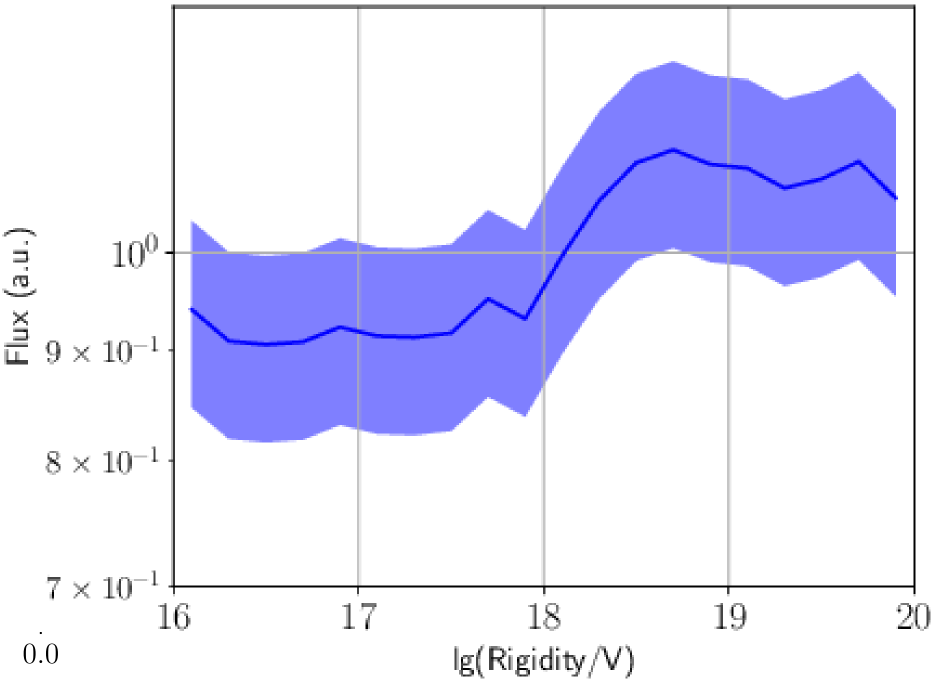
Rigidity spectrum of lensed EGCRs flux



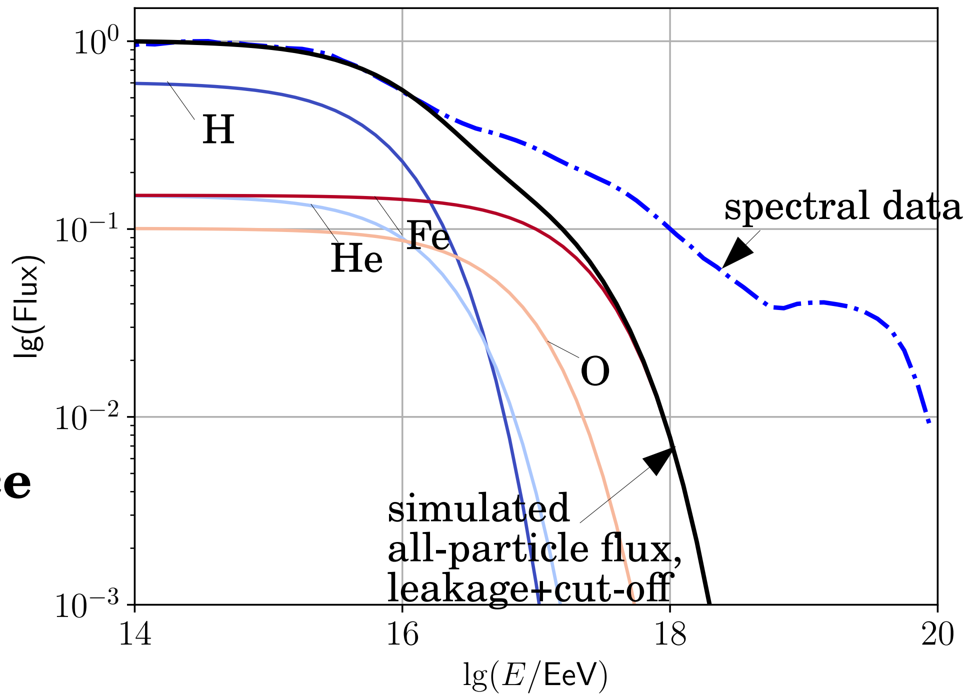
Goal: Incorporate propagation effects

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 ($\lg(R_{\text{Cut}}/\text{V}) = 16.5$)



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- Scale rigidity spectra to **different nuclei**
  → **energy spectra**
- Find **suitable injection spectra:**
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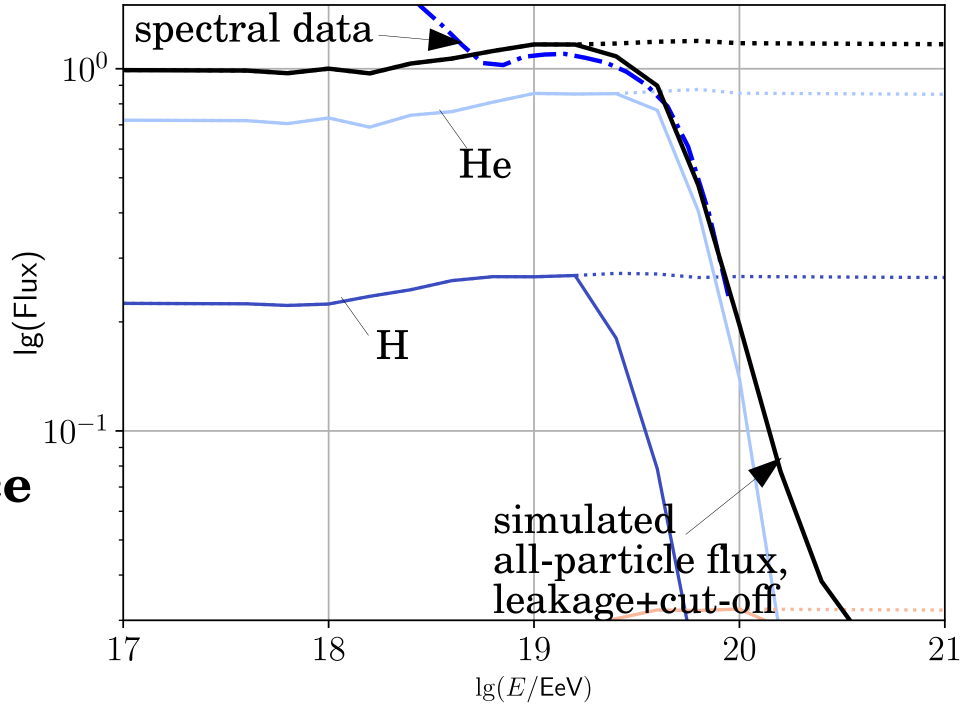
  - **GCR** component to energies around "**knee**"
  - **EGCR** component to **post-"ankle"** energies

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

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



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**

Thank you for your attention!