On the transition from Galactic to extragalactic cosmic rays

Alex Kääpä

ICRC 2021
Berlin
Plenary Talk
Zoom conference
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BERGISCHE UNIVERSITÄT WUPPERTAL

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List of contributions on “transition”:

1) Self-trigger radio prototype array for GRAND (13/7/21, 18:00, Indico-ID: 381)
2) Combined fit of the energy spectrum and mass composition across the ankle with the data measured at the Pierre Auger Observatory (13/7/21, 18:00, Indico-ID: 547)
3) Results from the KASCADE-Grande data analysis (13/7/21, 18:00, Indico-ID: 565)
4) Cosmic-Ray Studies with the Surface Instrumentation of IceCube (13/7/21, 18:00, Indico-ID: 780)
5) The depth of the shower maximum of air showers measured with AERA (13/7/21, 18:00, Indico-ID: 1208)
6) The Giant Radio Array for Neutrino Detection (GRAND) project (14/7/21, 12:00, Indico-ID: 191)
7) Cosmic Ray Energy Spectrum measured by the TALE Fluorescence Detector (14/7/21, 12:00, Indico-ID: 851)
8) Measurement of carbon and oxygen fluxes in cosmic rays with the DAMPE experiment (14/7/21, 18:00, Indico-ID: 1136)
9) What if new physics sets in above 50 TeV? Cosmic-ray air-shower simulations with increased cross-section and multiplicity (14/7/21, 18:00, Indico-ID: 1170)
10) Update on the large-scale cosmic-ray anisotropy search at the highest energies by the Telescope Array Experiment (15/7/21, 12:00, Indico-ID: 145)
11) The Surface Array planned for IceCube-Gen2 (15/7/21, 18:00, Indico-ID: 442)
12) Study of mass composition of cosmic rays with IceTop and IceCube (16/7/21, 18:00, Indico-ID: 659)
13) Performance of SKA as an air shower observatory (1/7/21, 18:00, Indico-ID: 1122)
14) Simulation study for the future IceCube-Gen2 surface array (20/7/21, 12:00, Indico-ID: 843)
15) Highlight: Extragalactic cosmic ray sources (21/7/21, 14:00, Indico-ID: 1470)

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:

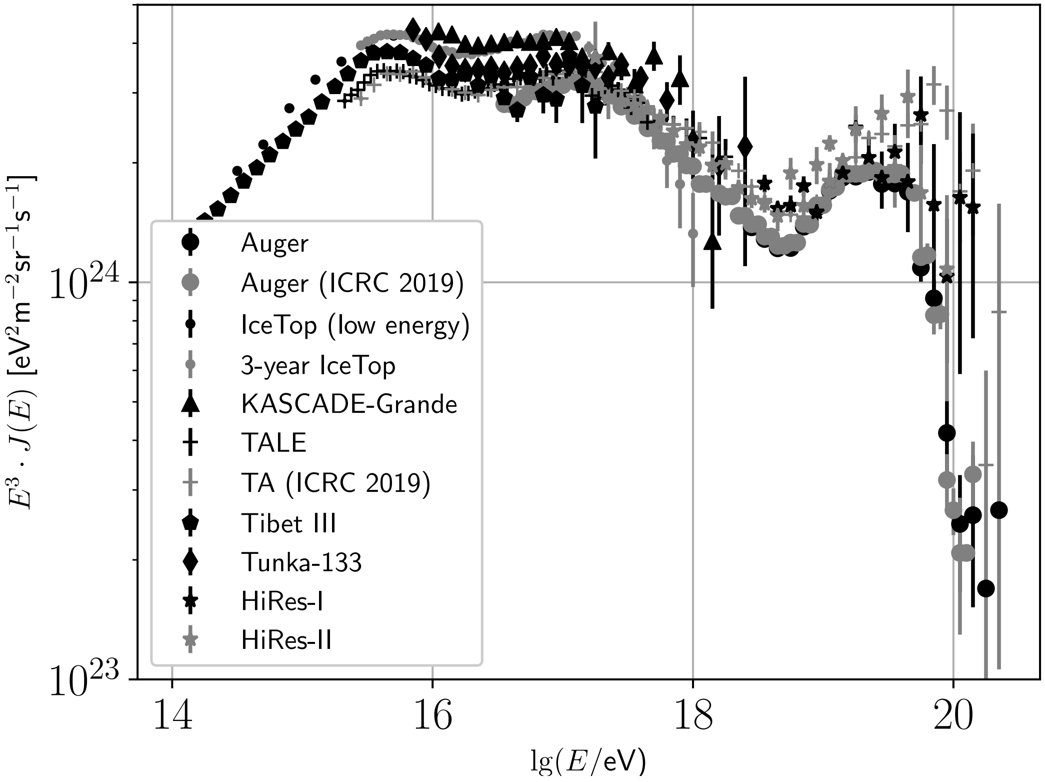
- hardening at ~$10^{16.7}$ eV
- **'2nd knee':** softening at ~$10^{17.(0...4)}$ eV
- 'toe': softening at ~$10^{19.1}$ eV

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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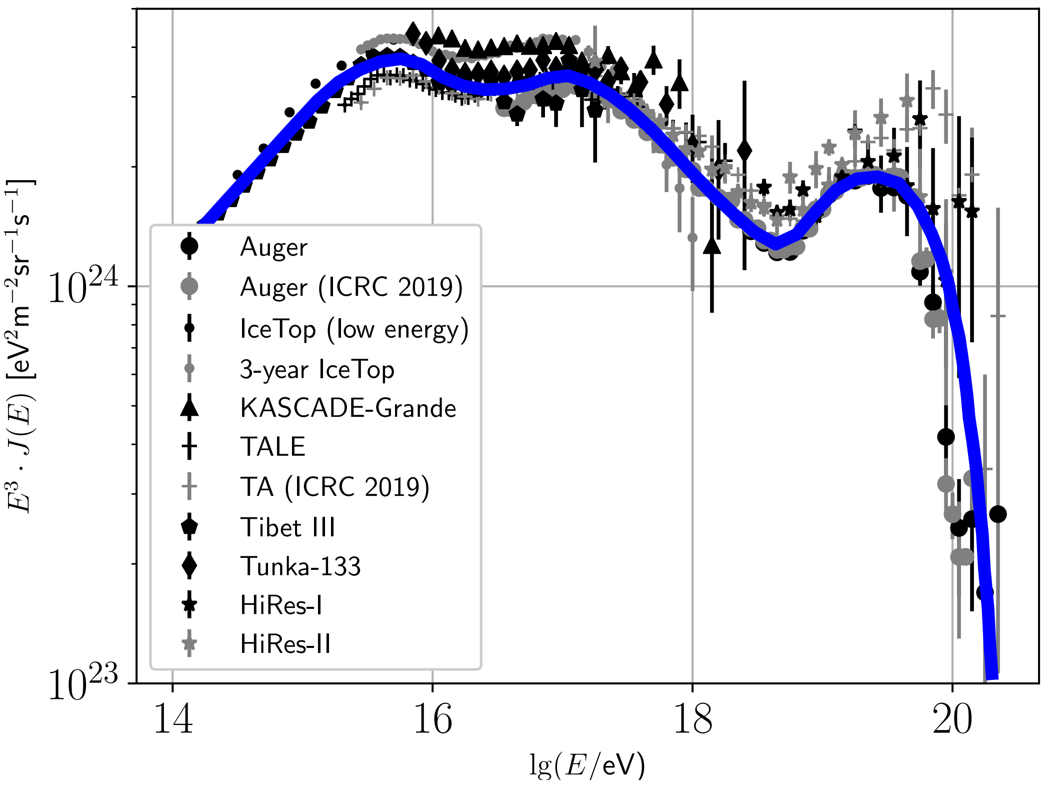

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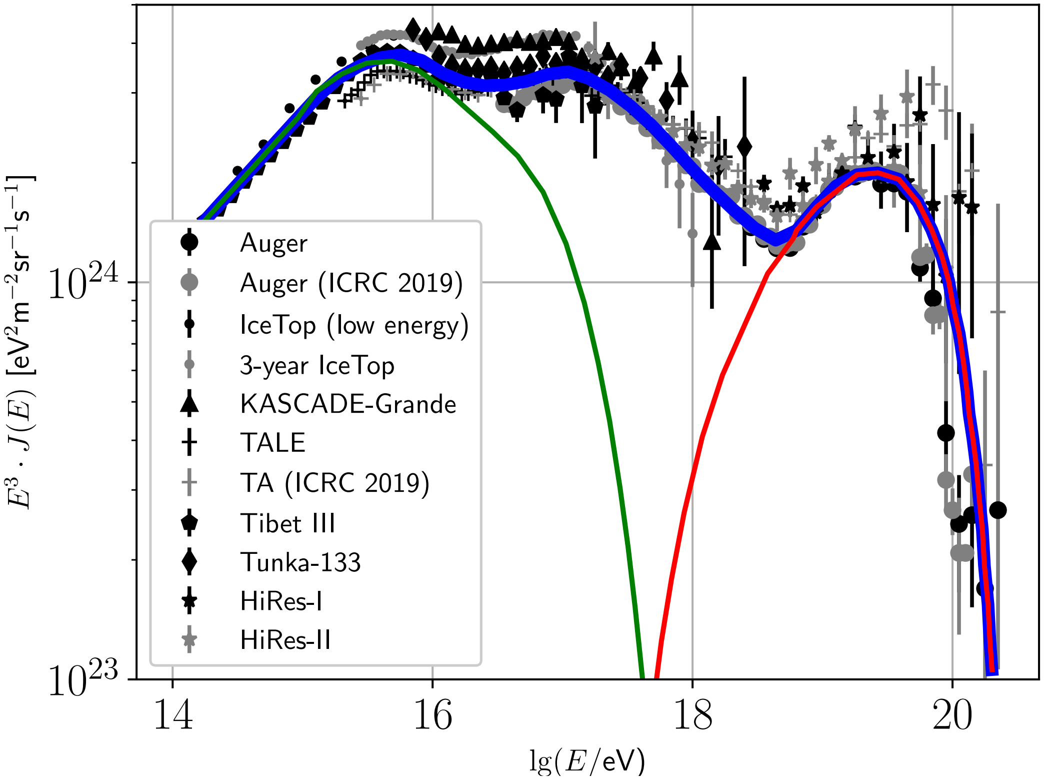
see also: Thoudam, Astron.Astrophys. 595 (2016) A33



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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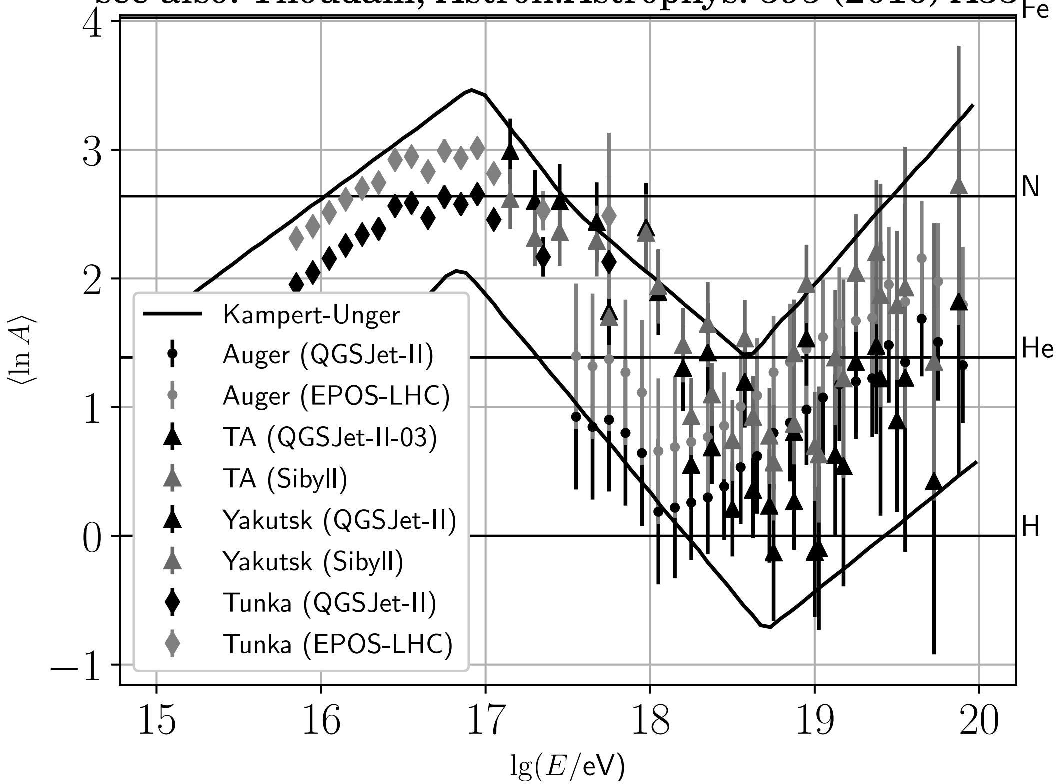

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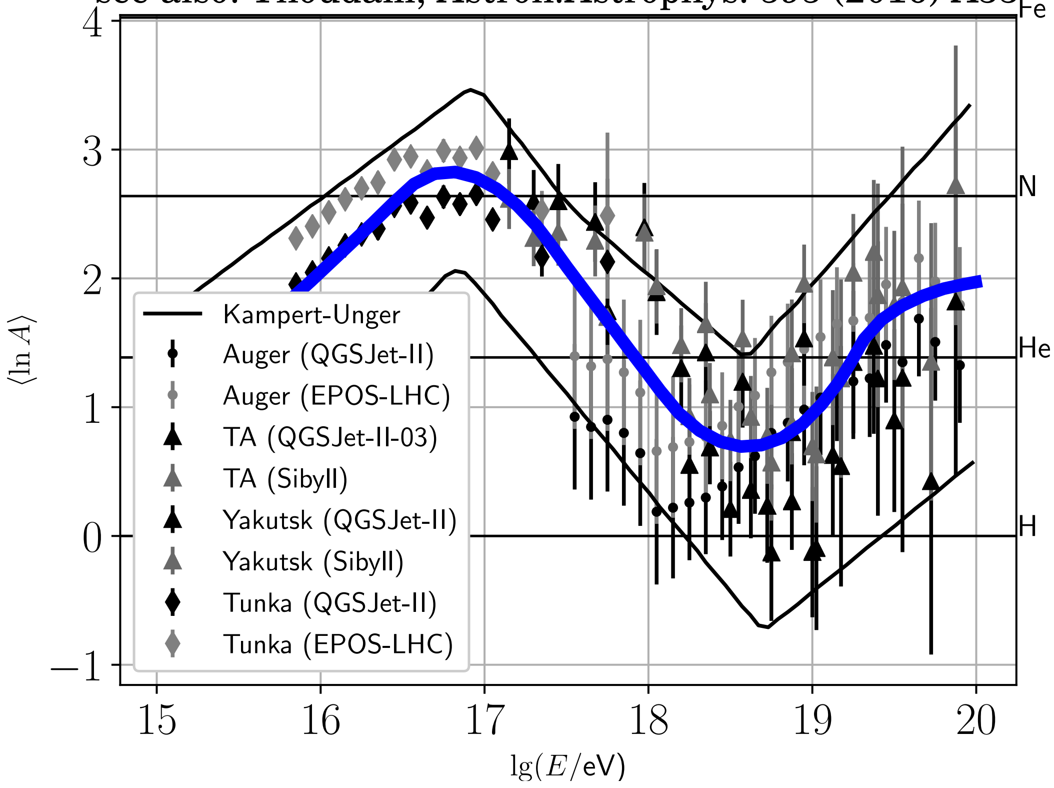


Anisotropies

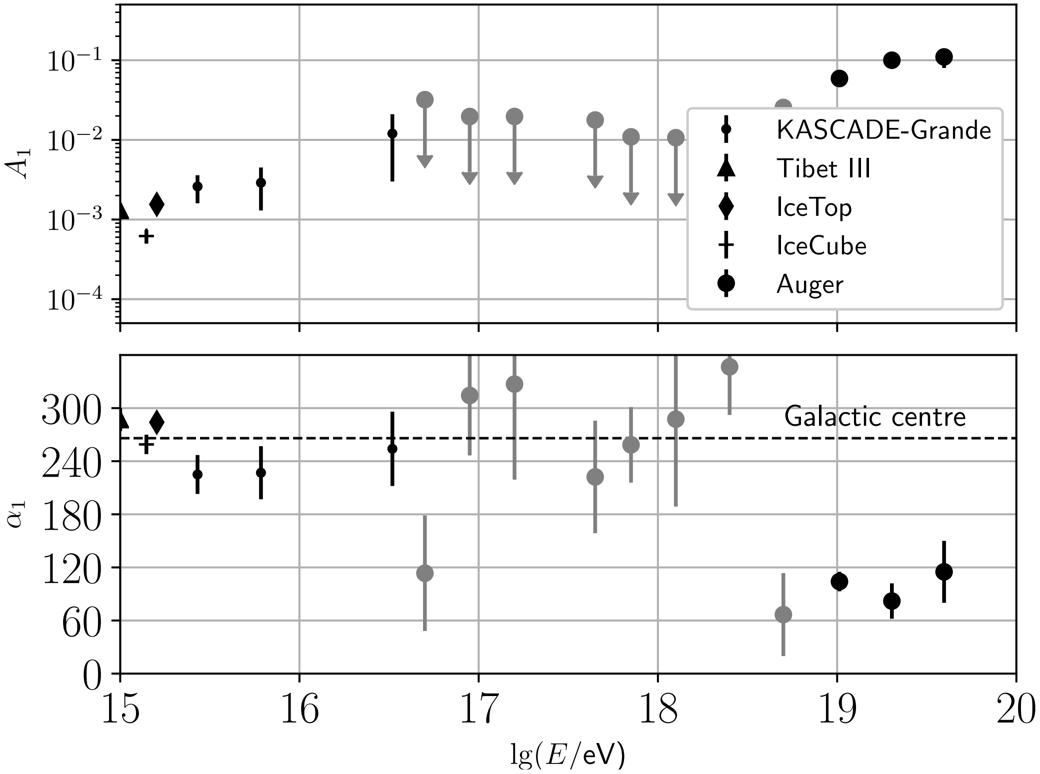
Dipole anisotropy:

- 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



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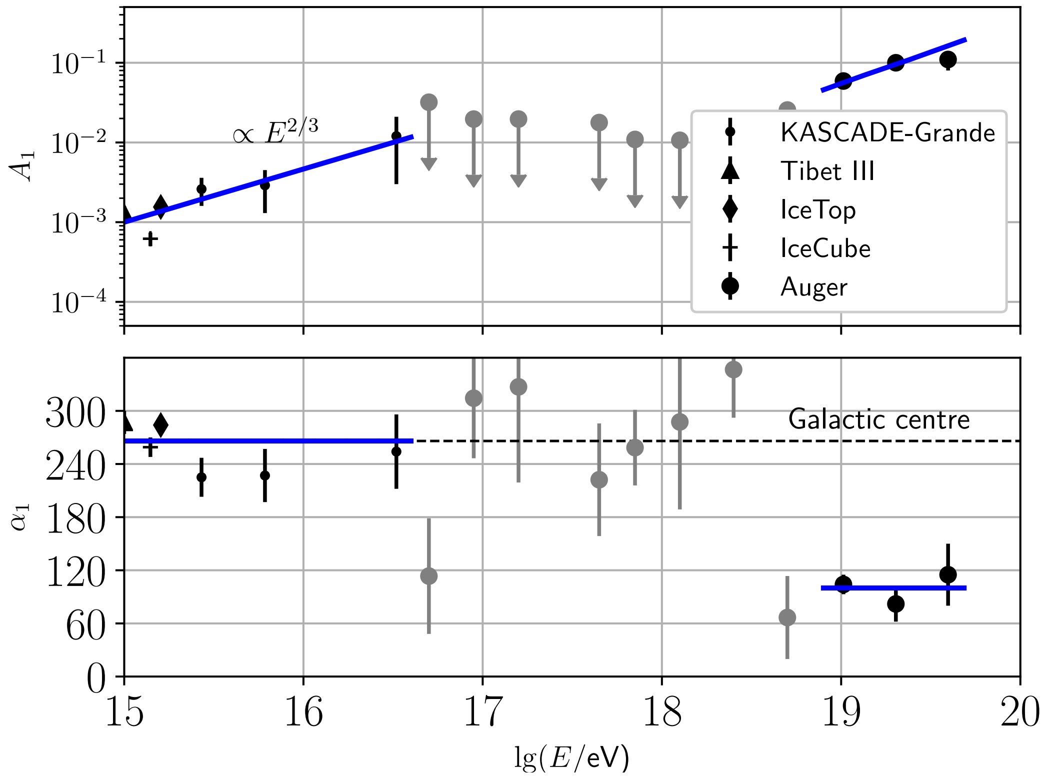


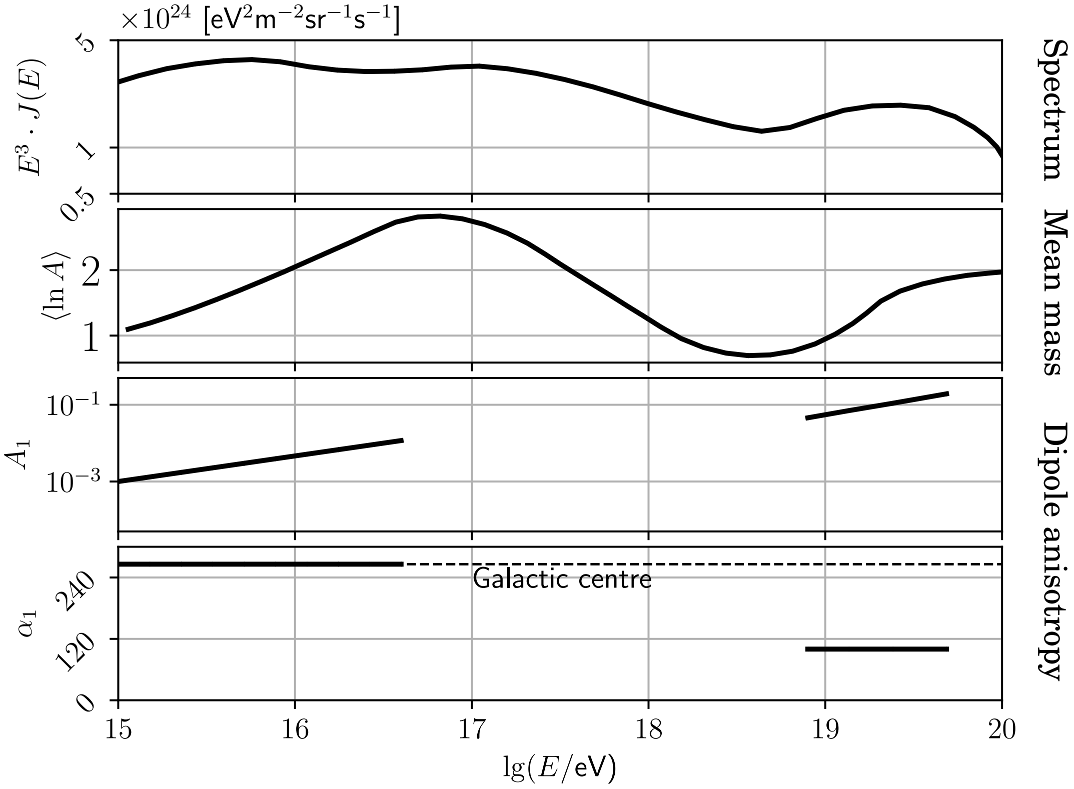
“All” data in one look

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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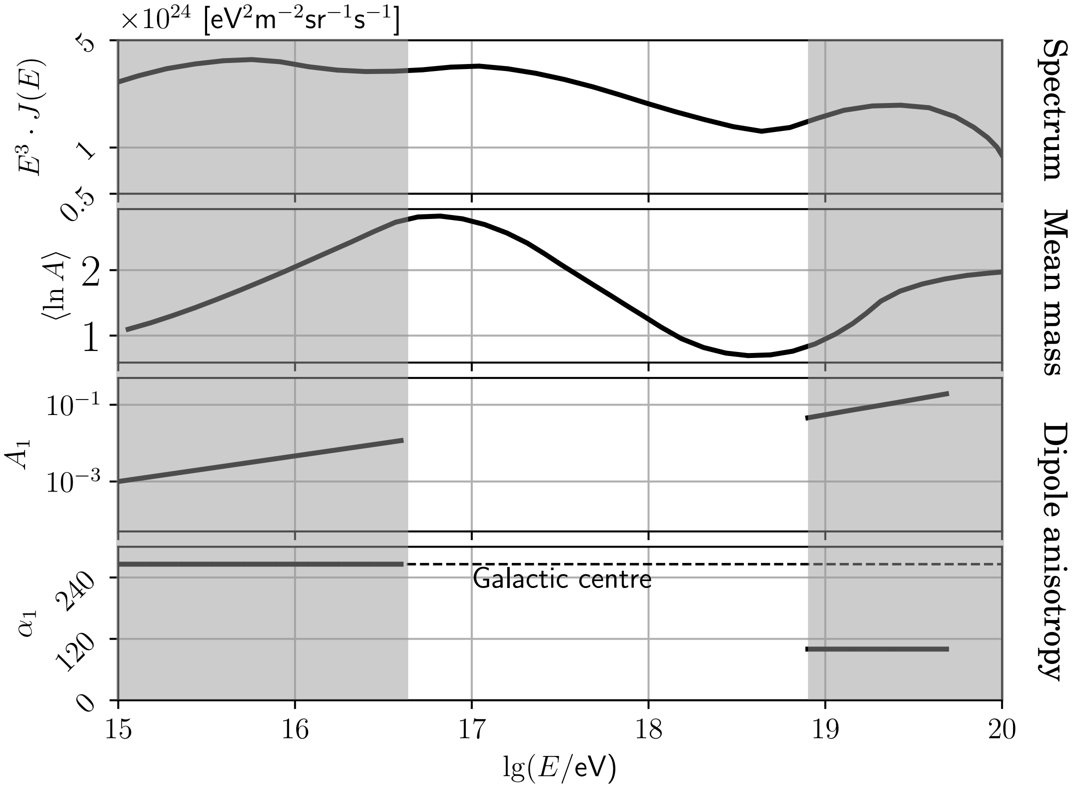


Galactic magnetic field (GMF)

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

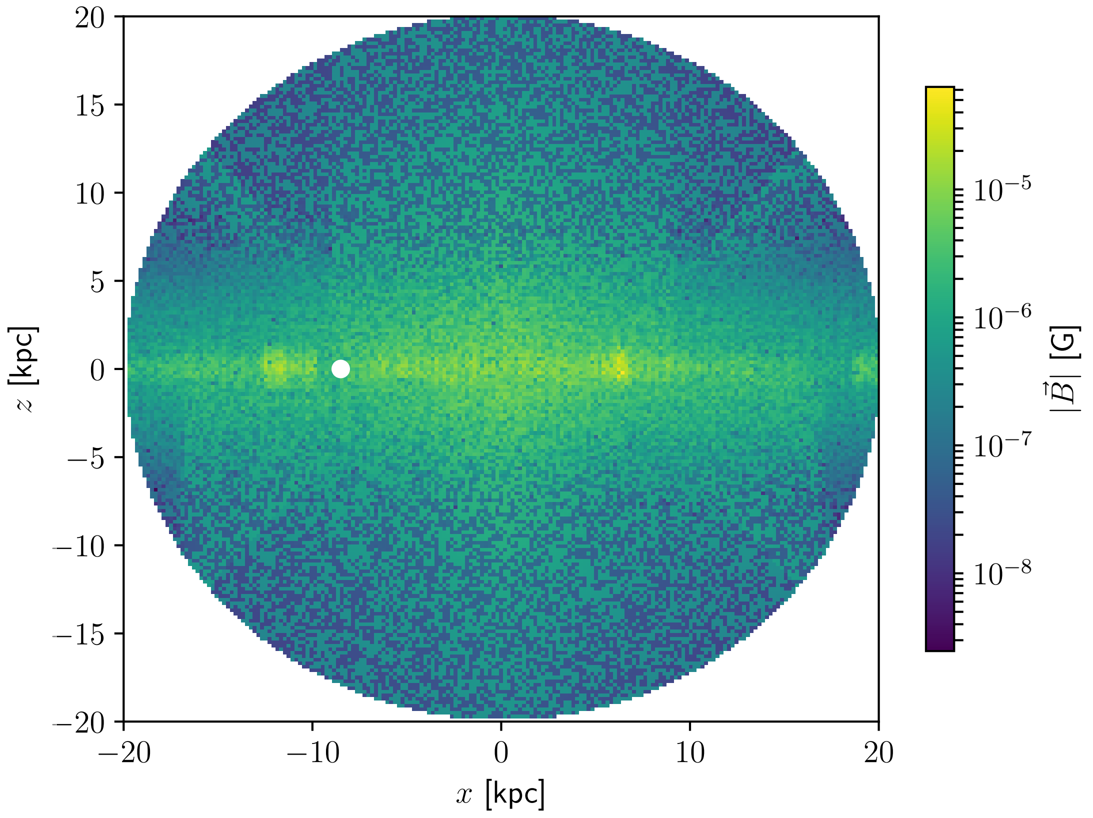
Gyroradius r_g:

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

Transition region = **change in propagation regimes**

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

x-z projection of JF12 field



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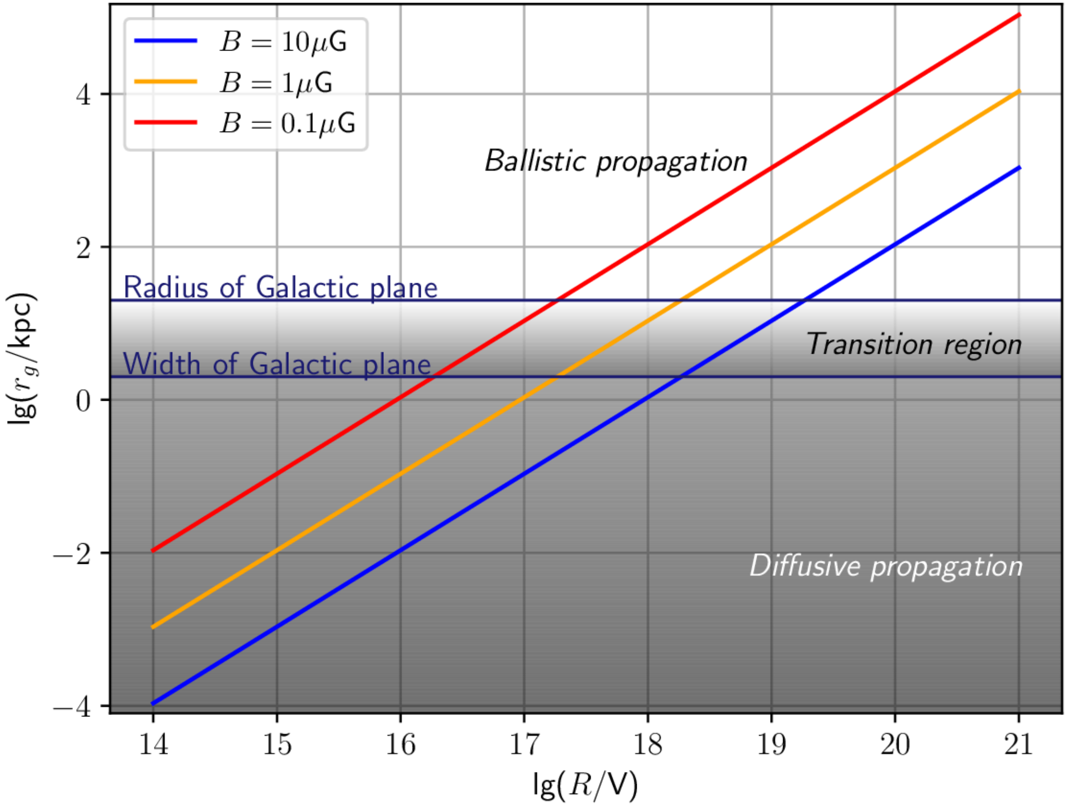
Change of gyroradius with rigidity plus typical length scales of Galaxy



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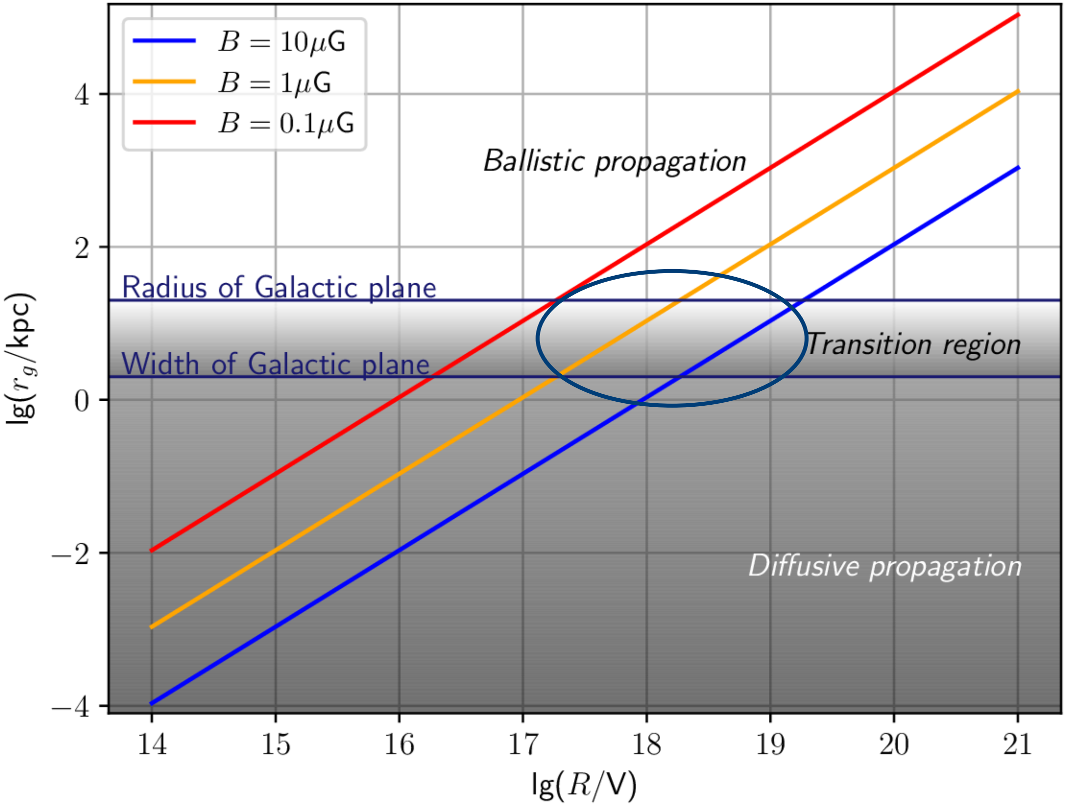


Procedure: Simulation with CRPropa3

JCAP 1605 (2016) no. 05, 038

Forwardtrack protons:

- Backtracking GCRs leads to “degenerate” source position distribution (cannot differentiate between source in GP and particle crossing GP during propagation).
- Backtracking of EGCRs is not sensitive to flux modification.

No interactions:

- Only deflections → results can be scaled to all nuclei (important for composition)
- Rigidity range: lg(R/V) = 16.0 – 20.0 (large overlapping energy range for all nuclei)
- Injection spectrum: R^{-1}

Galactic magnetic field model:

- JF12 (ApJ 757 14x; including regular, random and striated components)

Sources and observers

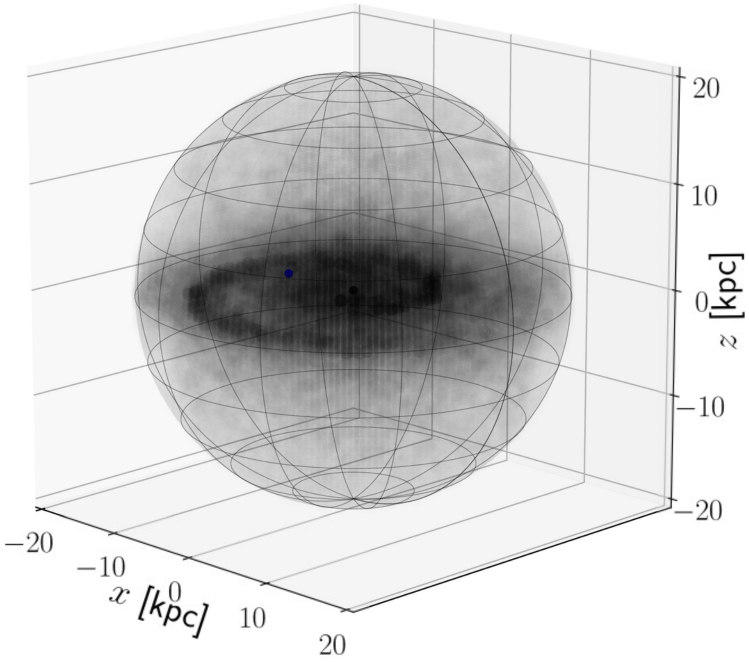
Sources:

- 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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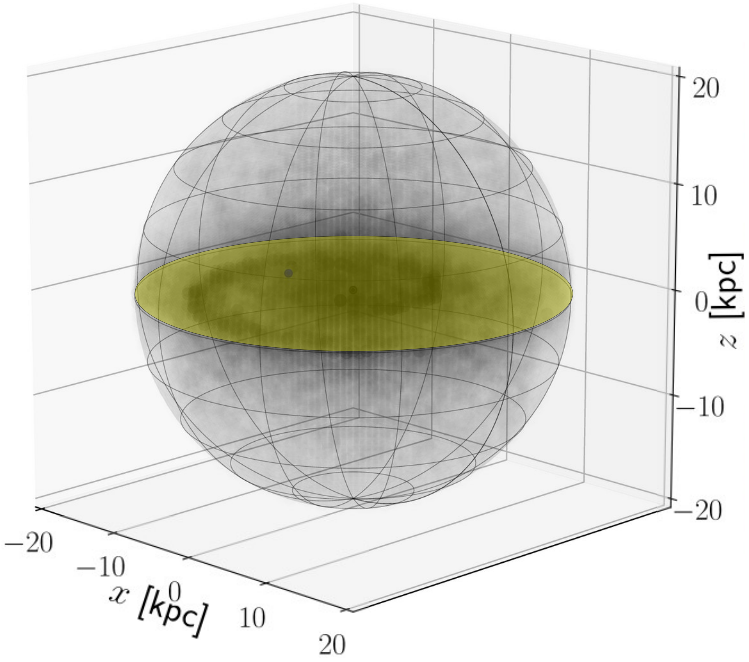
GCR source distribution



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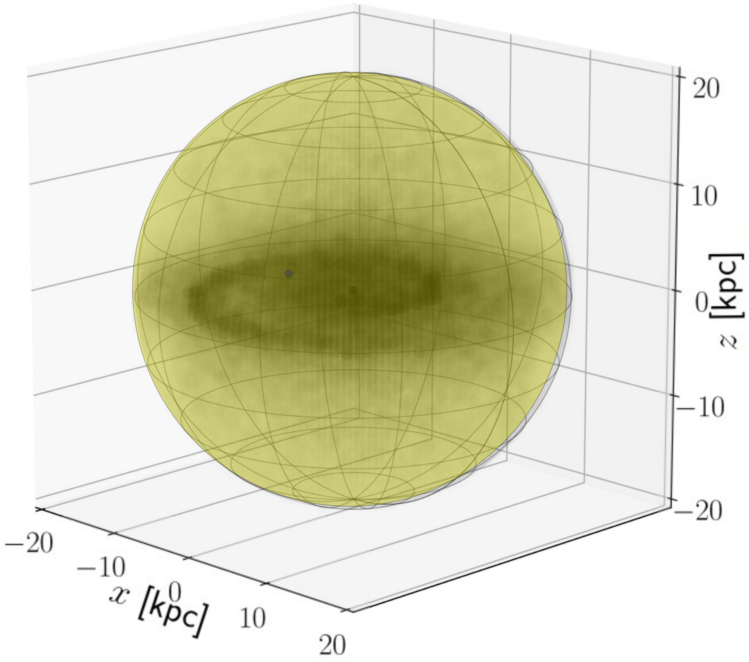
EGCR source distribution



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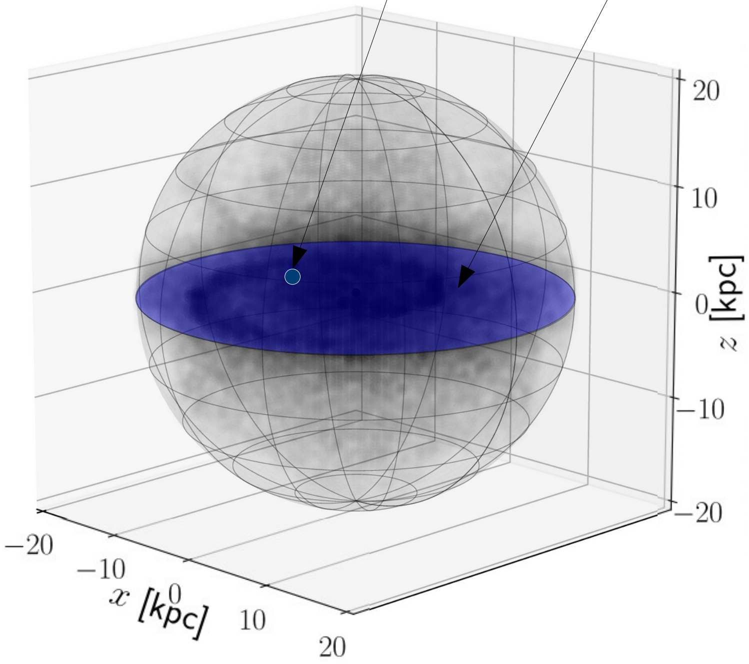
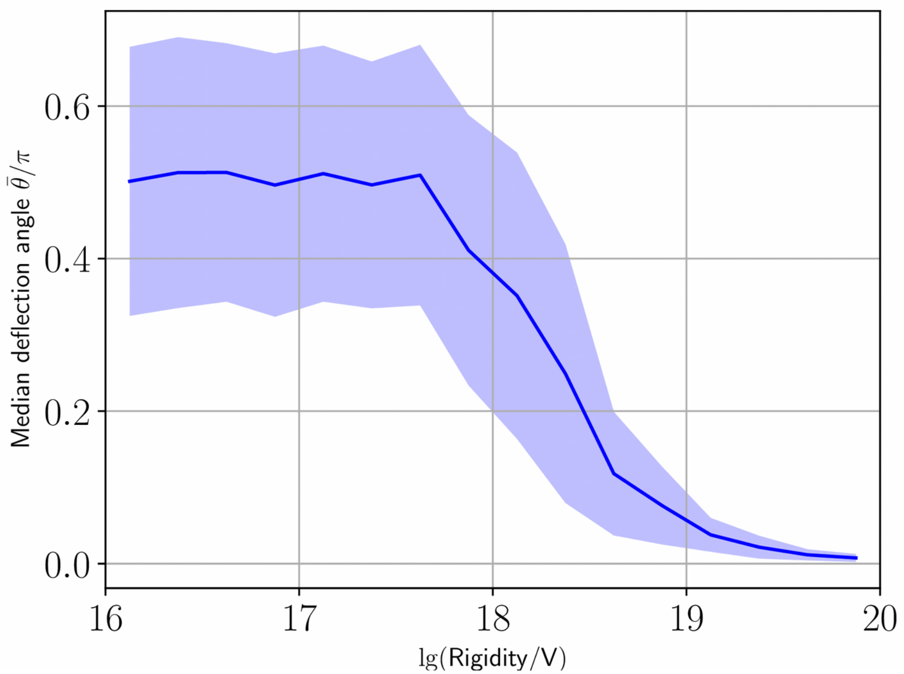
Observer types: Earth and GP



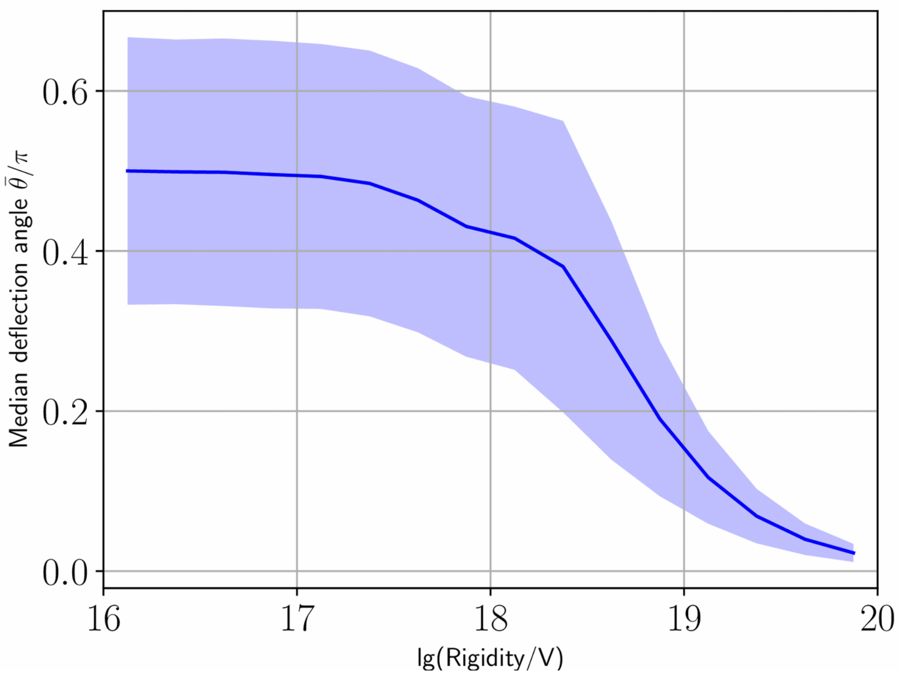
Propagation Effects

Injection/arrival direction deflection angle

GCRs forward tracked to Earth

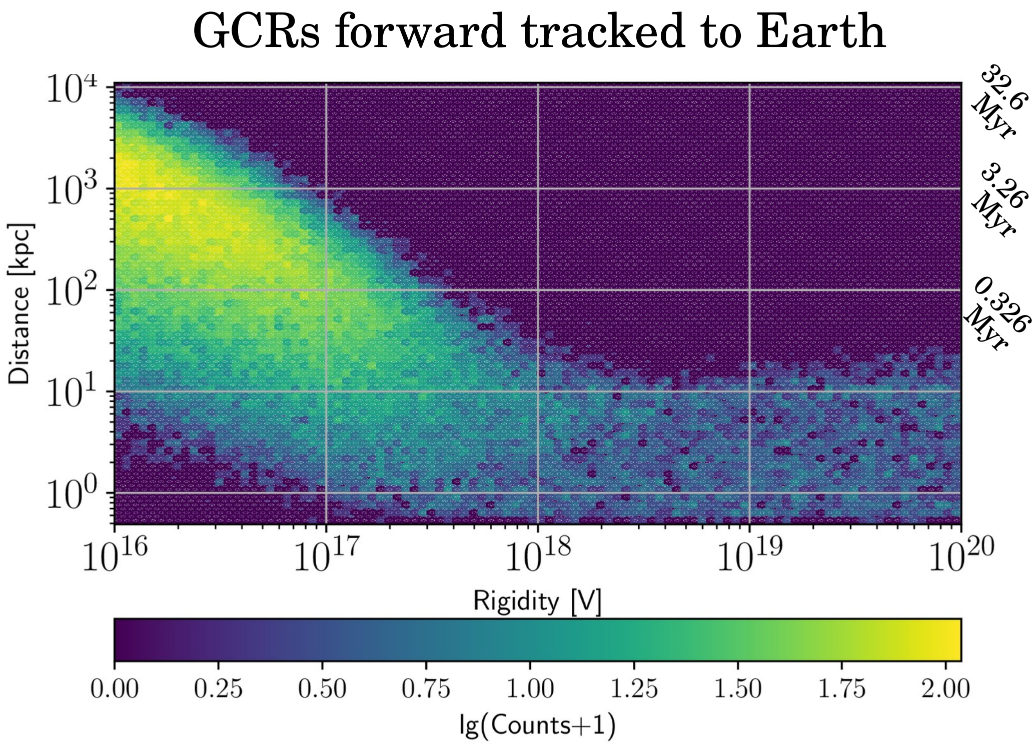


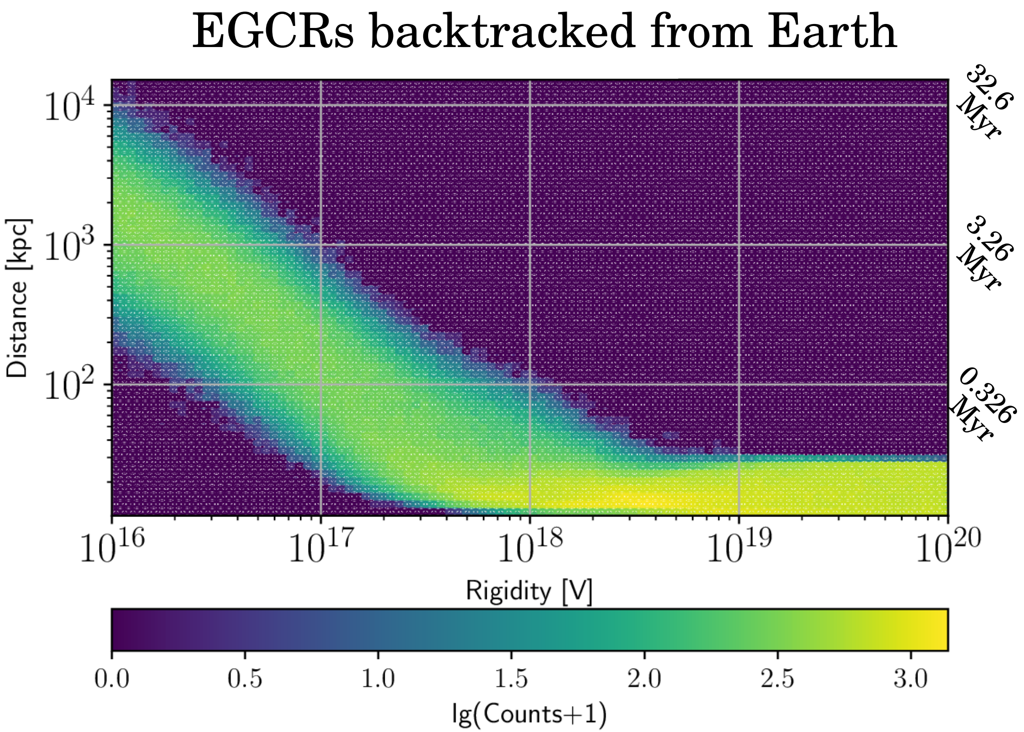
EGCRs backtracked from Earth



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

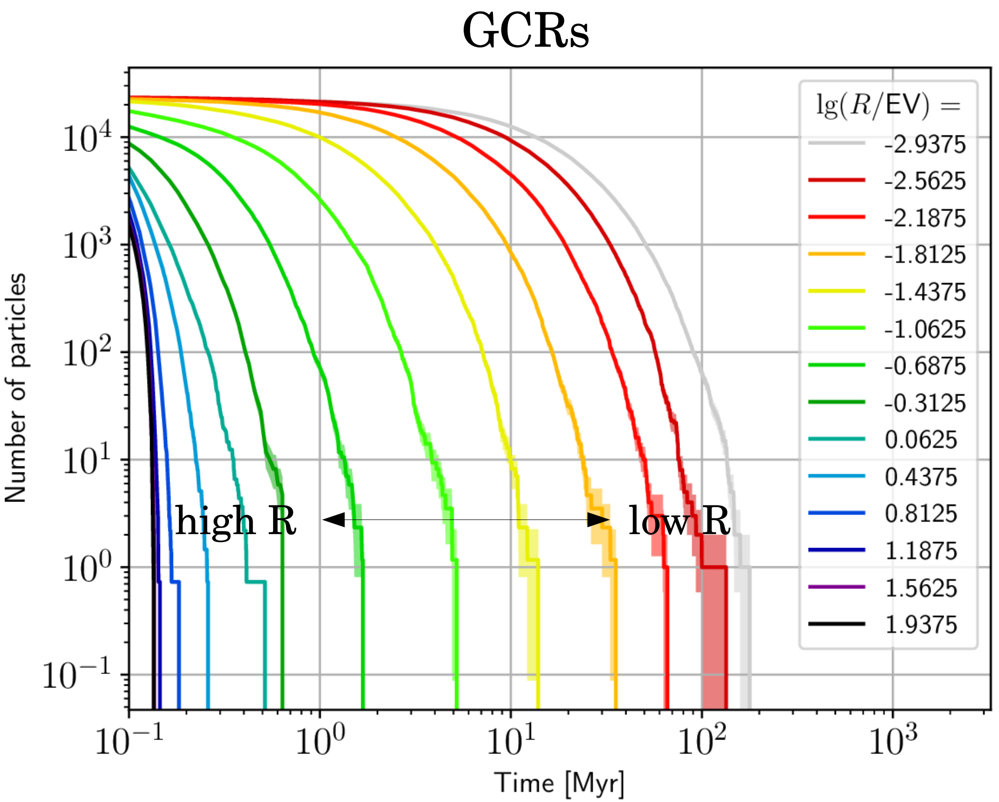
Propagation time to Earth

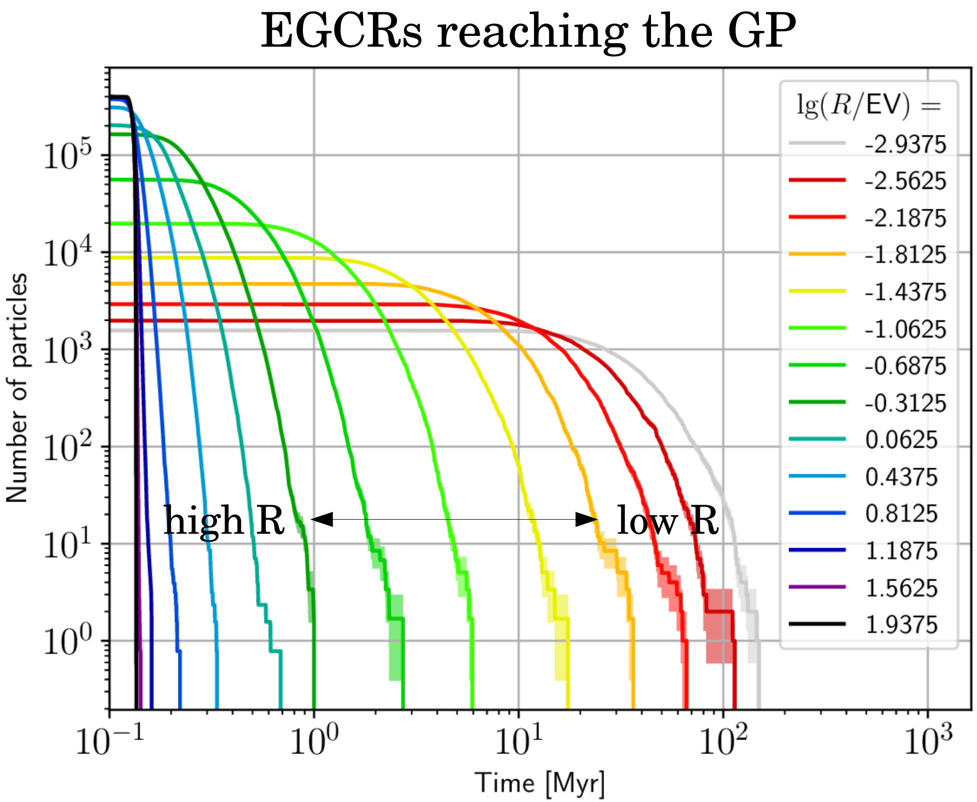




Propagation time increases below rigidities of a few 1 EV.

Galactic residence time

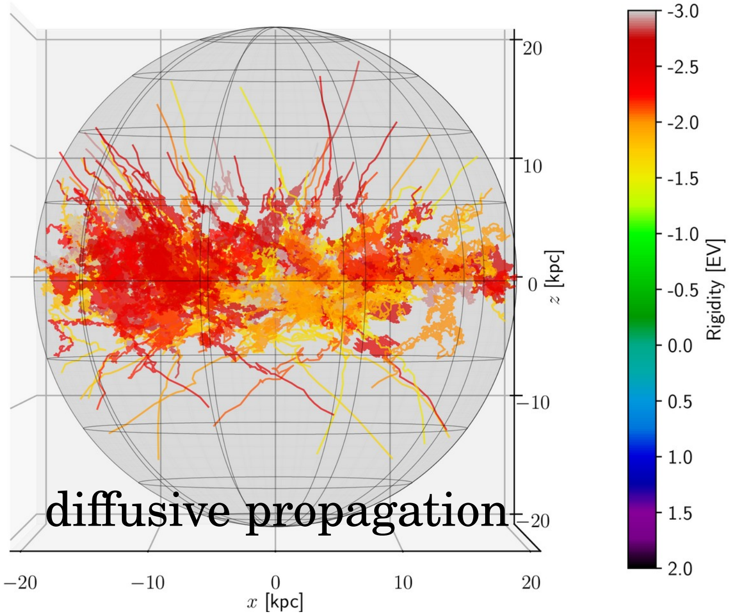




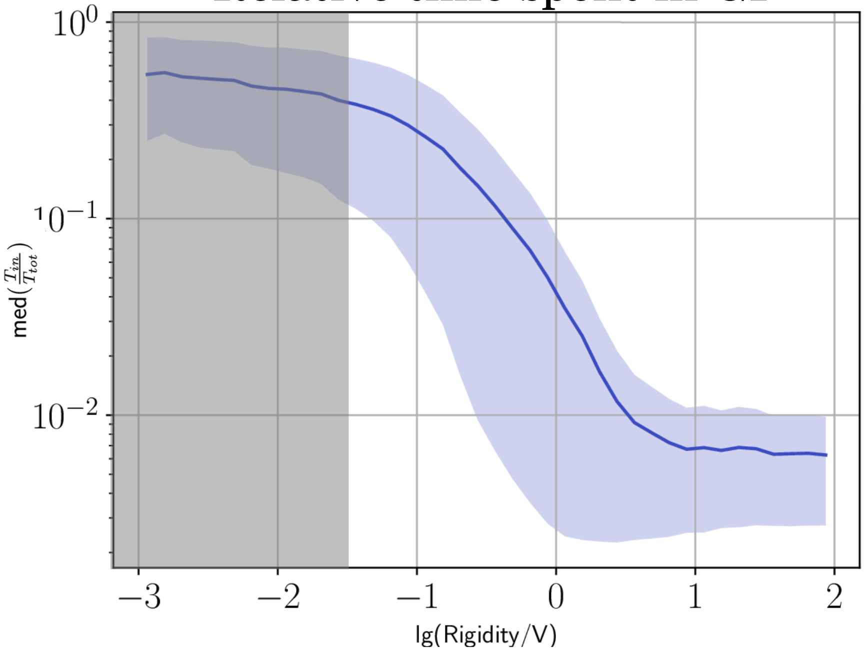
Lowest-rigidity particles have residence times up to 100 Myr.

GCRs – Confinement in GP

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



Relative time spent in GP

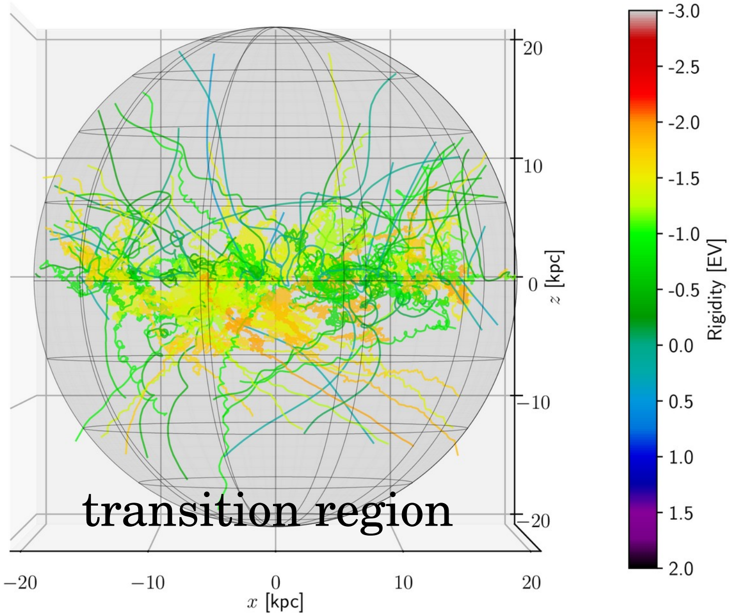


Decreasing confinement in GP **with rigidity.**

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

GCRs – Confinement in GP

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



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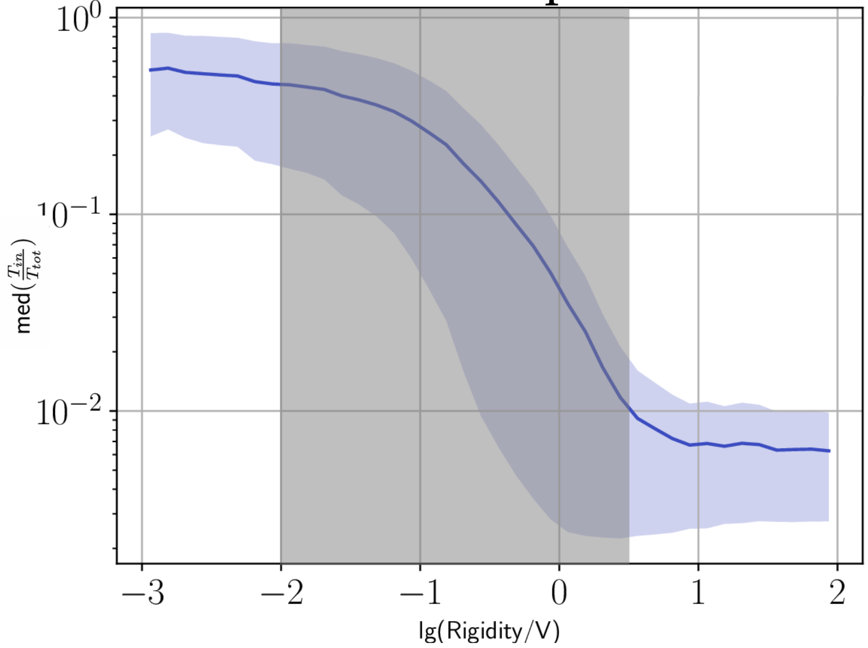

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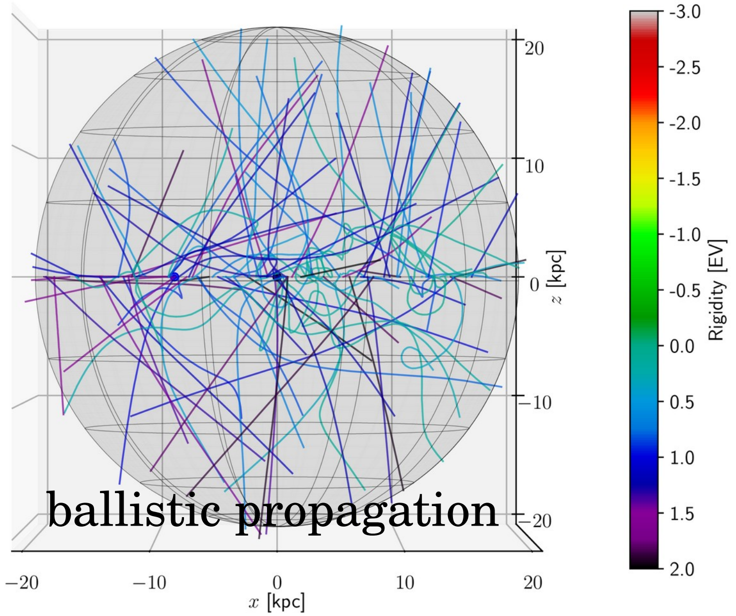

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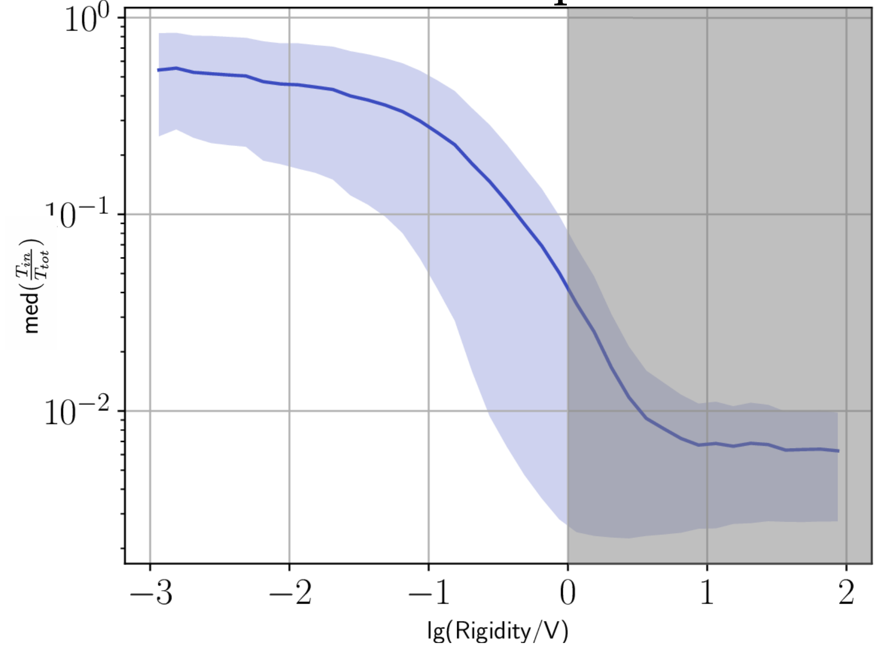

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EGCRs – Shielding from vs. confinement in GP

Galactic trajectories
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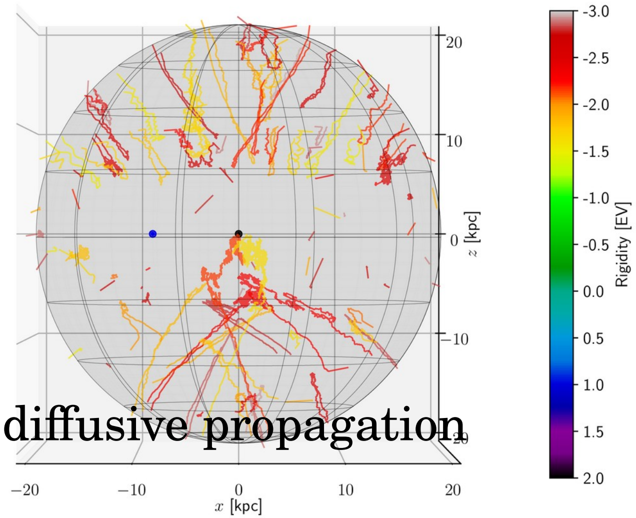
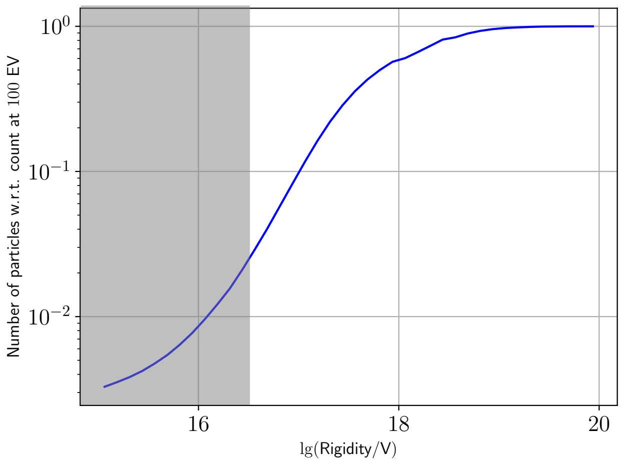


CR count reaching GP



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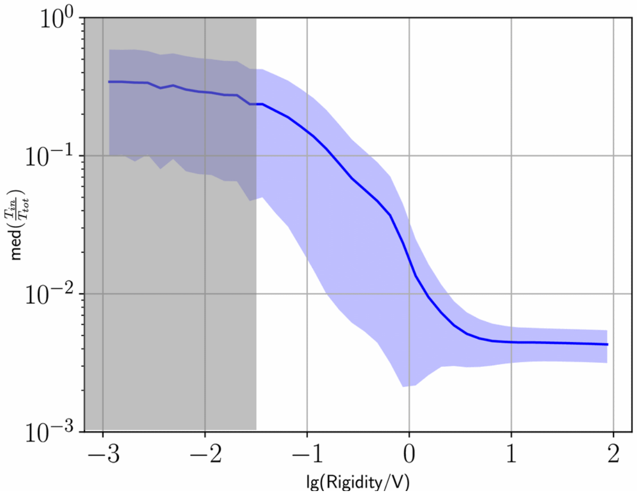

Decreasing shielding from and confinement in GP with rigidity.

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.**

EGCRs – Shielding from vs. confinement in GP

Galactic trajectories
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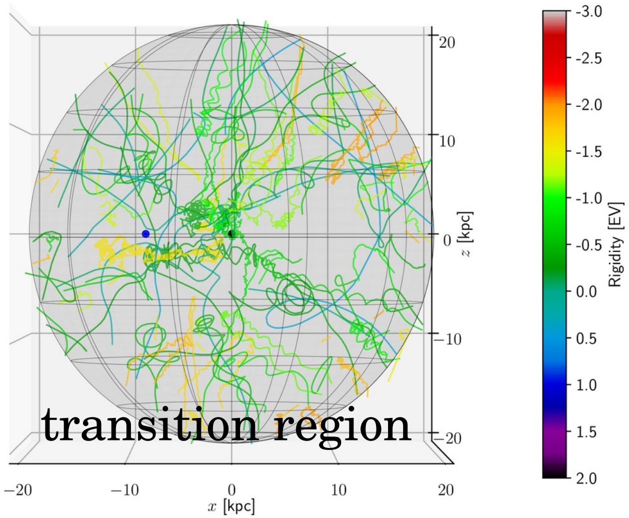

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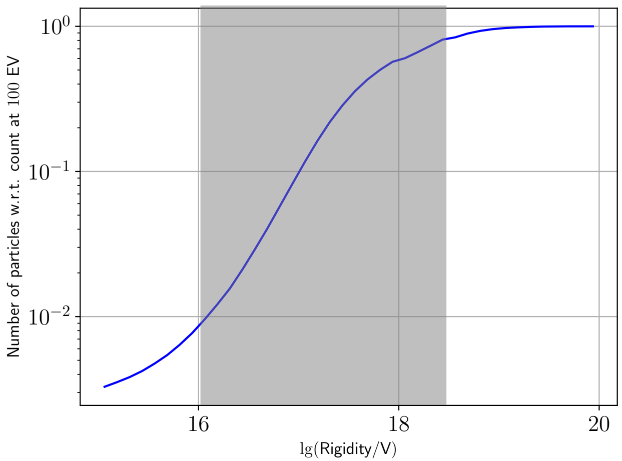

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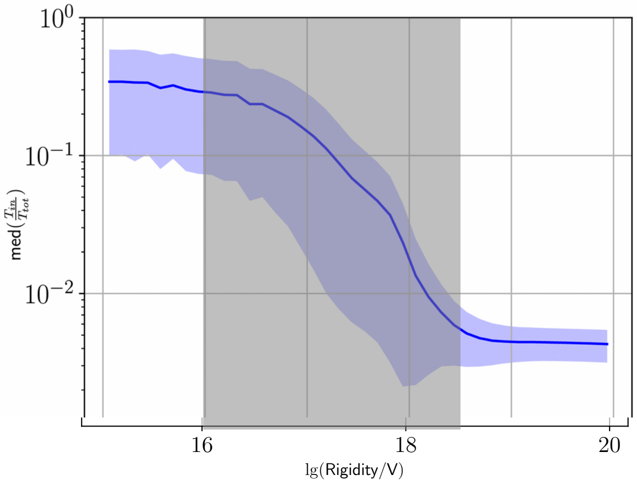

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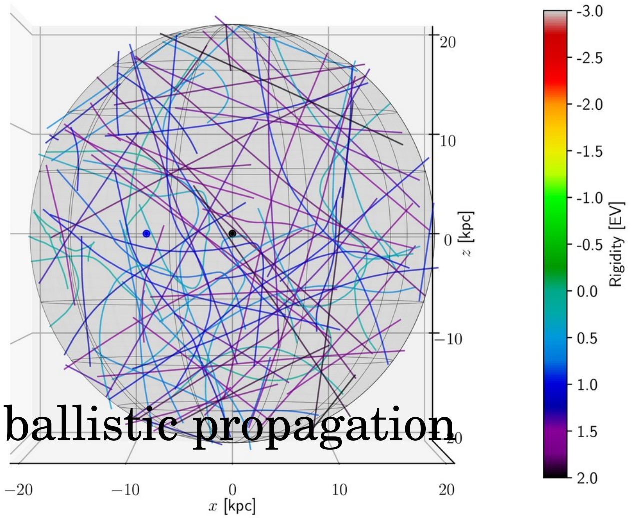

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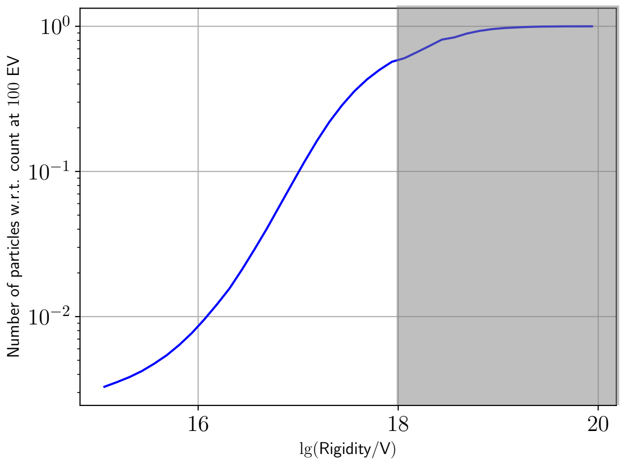

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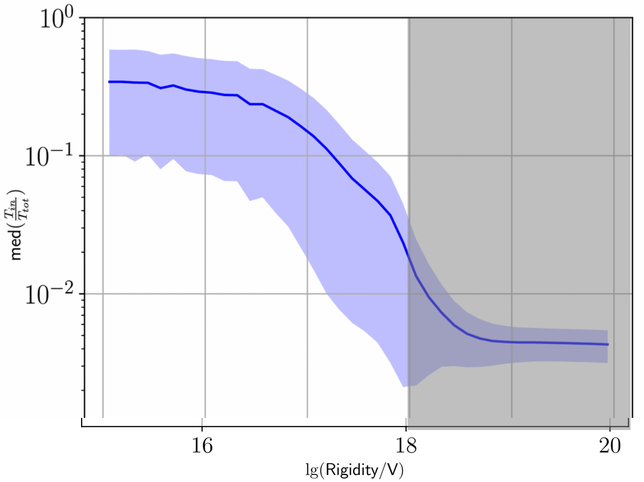

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Effect on observables

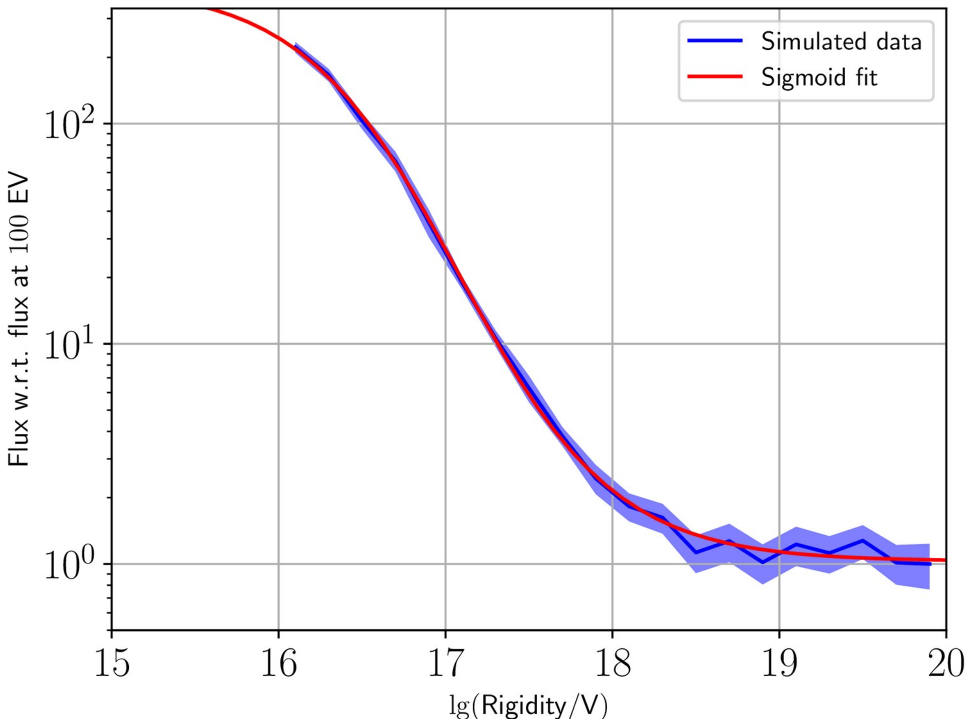
GCRs – Flux suppression

Decreasing confinement
→ **flux reduction**

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

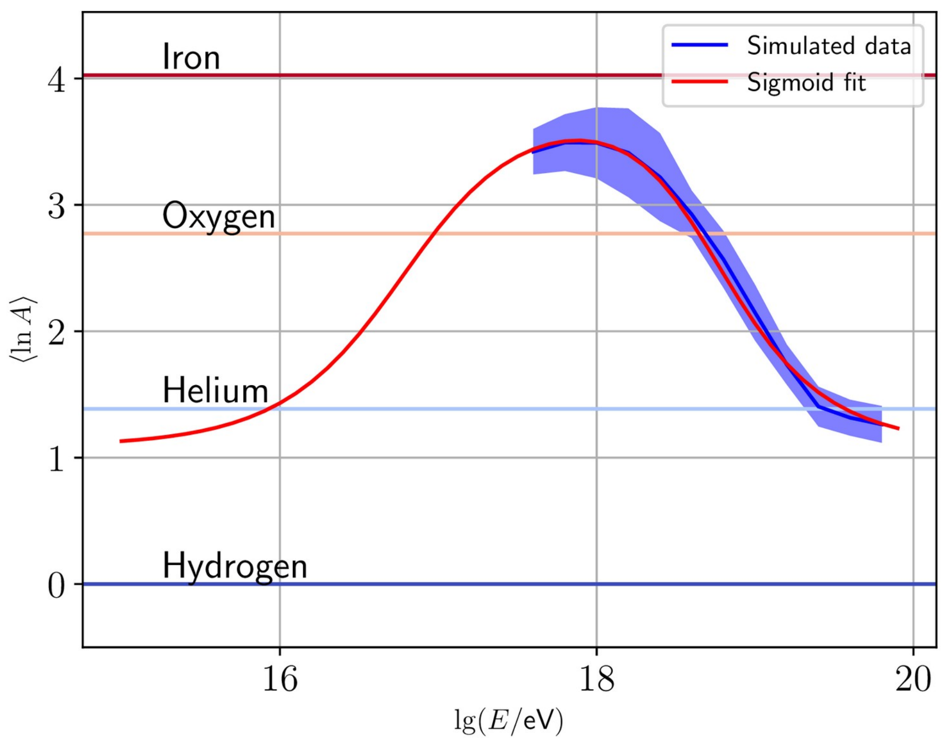
Arrival direction distribution:
correlation with GP direction
above 0.1 EV

Rigidity spectrum (sigmoid fit)



GCRs – Heavier composition

Mean logarithm of mass number (sigmoid fit)



Decreasing confinement
→ **flux reduction**

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

Arrival direction distribution:
correlation with GP direction
above 0.1 EV

NOTE: Only propagation effects in GMF!

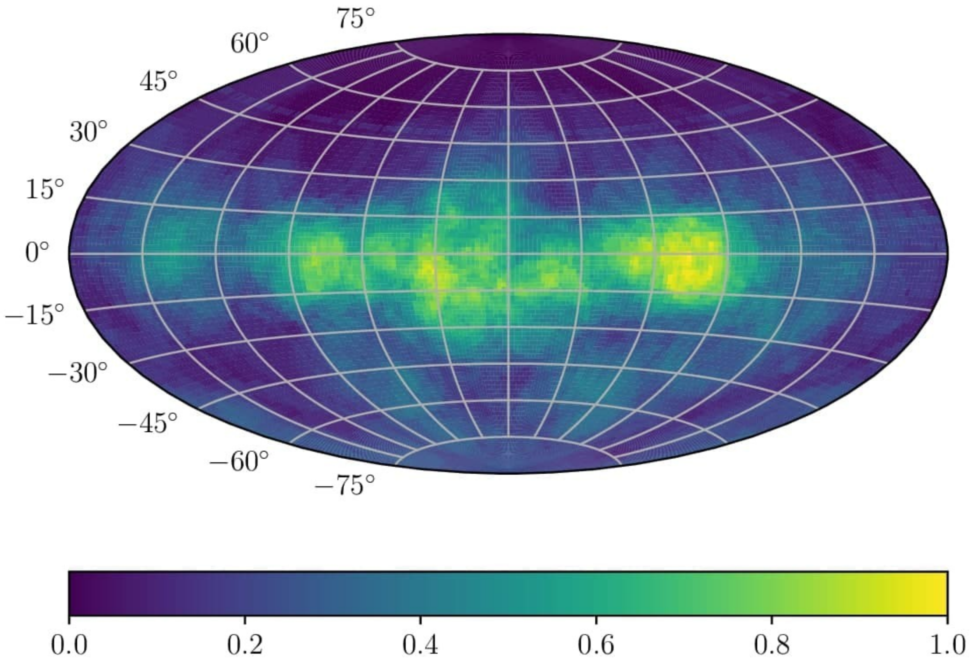
GCRs – Correlation with GP direction

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



Isotropic EGCRs – Flux conservation

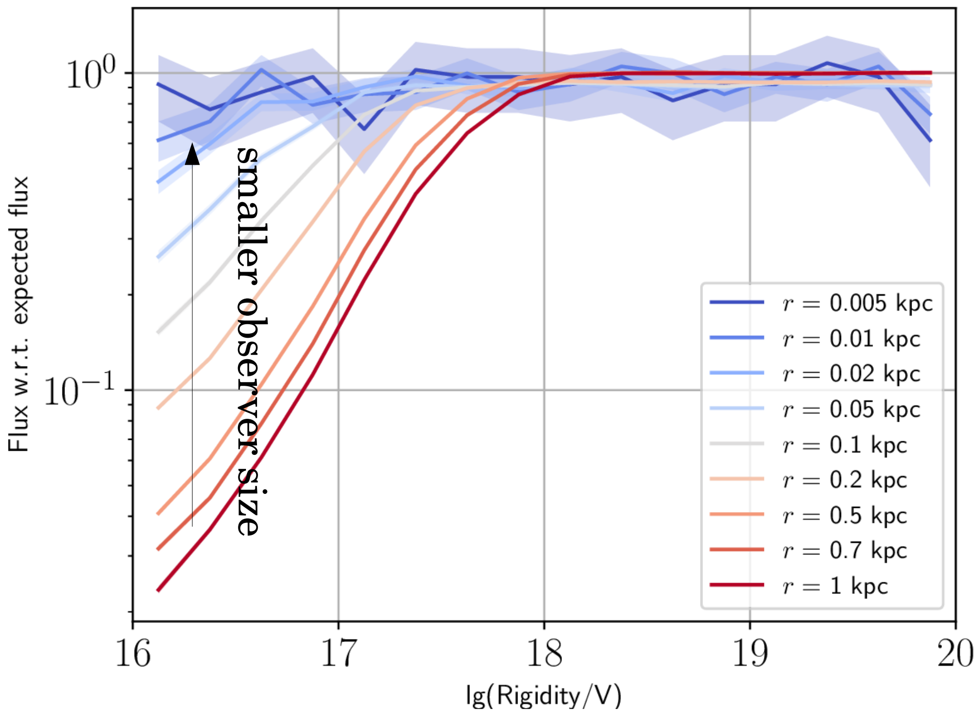
Apparent flux suppression for large observer sphere sizes; effect vanishes as $r \to 0$.

Increased confinement in GP compensates increased shielding:

→ **flux conservation**

Isotropic arrival direction

Rigidity spectrum



Isotropic EGCRs – Isotropic arrival direction

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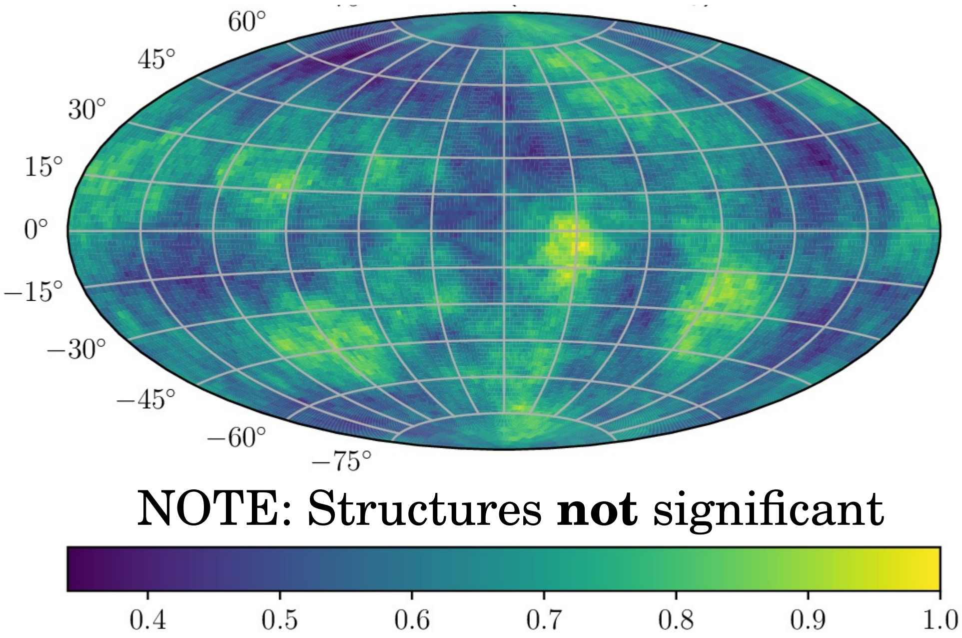
Increased confinement in GP compensates increased shielding:

$\rightarrow$ **flux conservation**

Isotropic arrival direction

Arrival direction distribution



NOTE: Structures **not** significant

Galactic lensing

Creation of Galactic lens

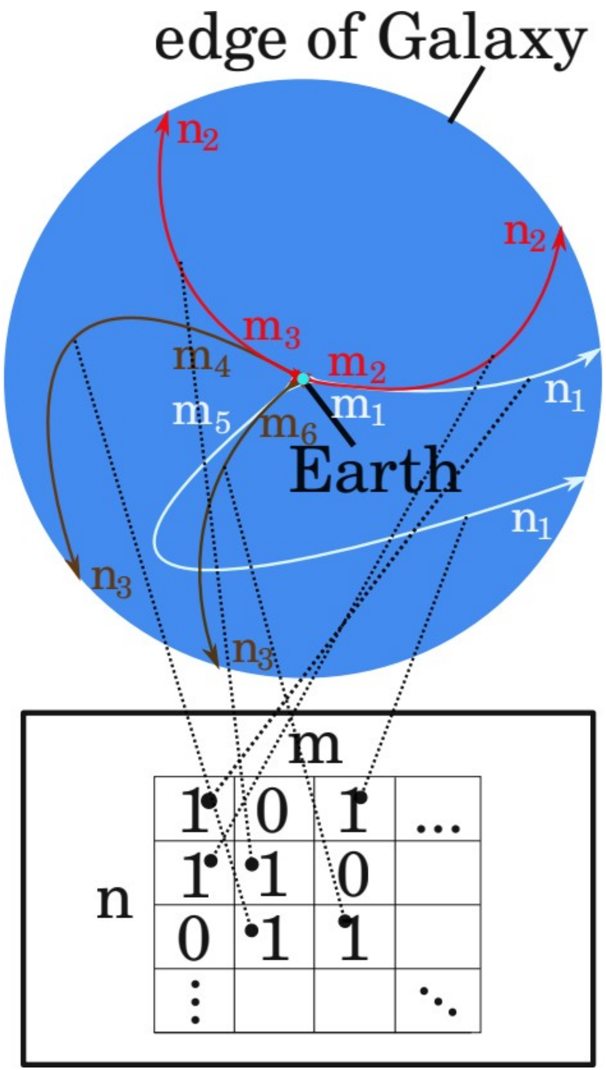
see also: Astropart.Phys. 85 (2016) 54-64 for lensing scheme & Eichmann, JCAP04(2020)047 for parallel work

1 **backtrack** N anti-particles from Earth **to edge of Galaxy in** a given **magnetic field:**

- JF12 field (including random & striated components with default settings)
- $N = 5 \cdot 10^7$

2 **ascribe** HEALPix **pixel** n and m **to** each corresponding **injection and arrival direction:**

- $12 \times 64^2 = 49152$ pixels (maximum resolution in CRPropa)



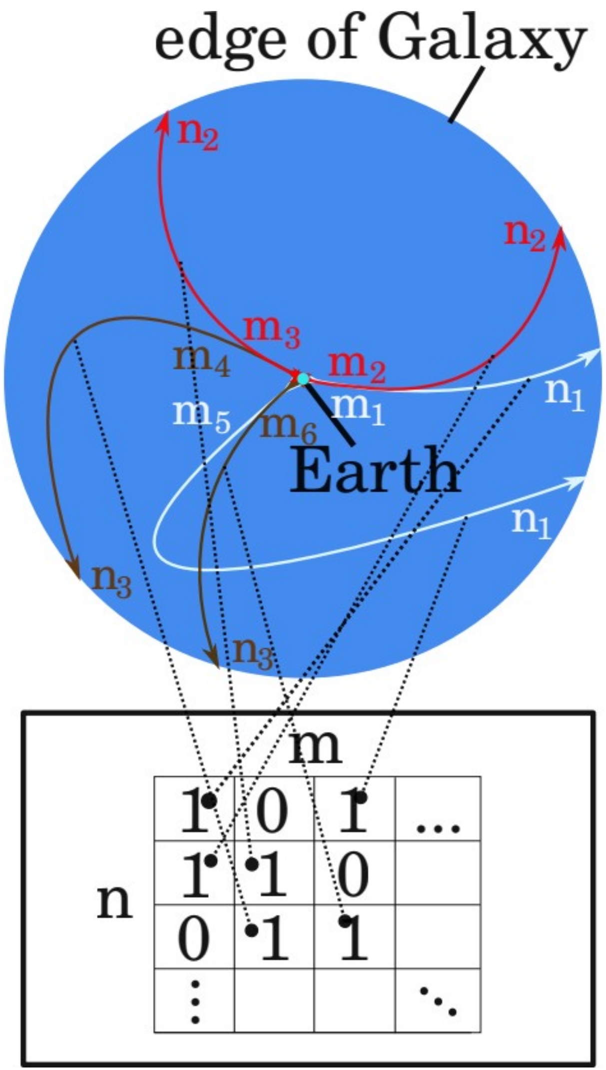
Creation of Galactic lens

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)

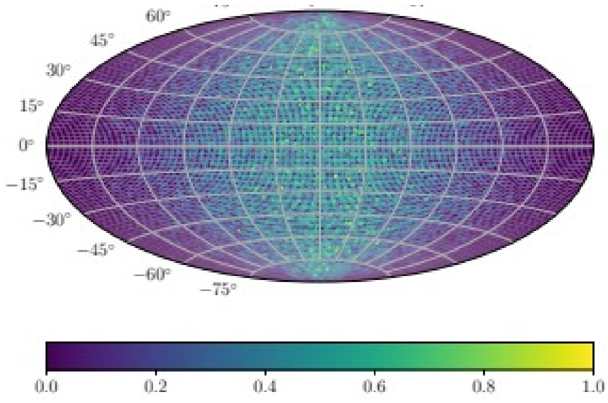
- spans matrix L ($l_{nm} = o$) which signifies the **distribution of arrival directions** m at the observer point for each **injection direction** n

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

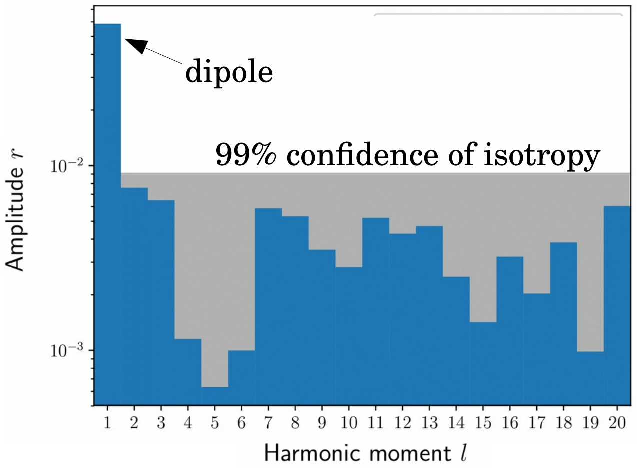


Anisotropic EGCRs – Galactic lensing

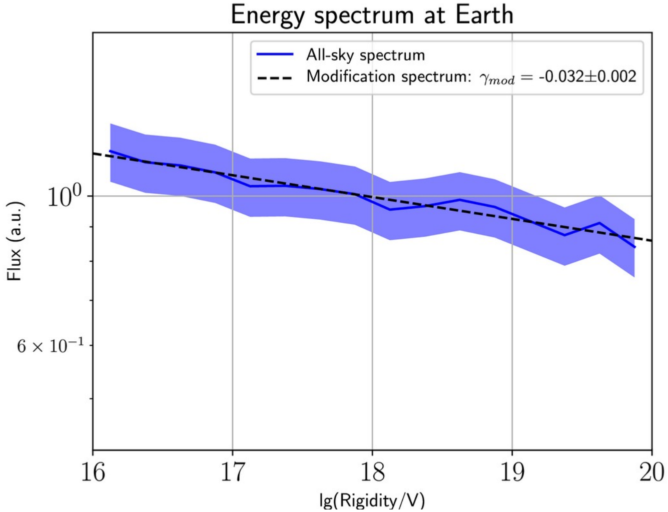
Injected flux



Distribution of moments above 1 EV



Flux at Earth



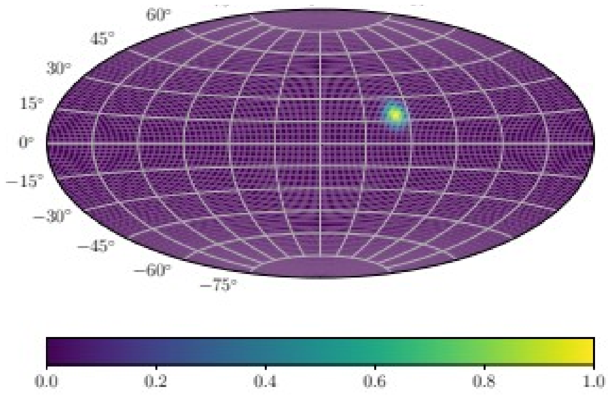
Injection direction distribution: **Pure dipole**

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

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

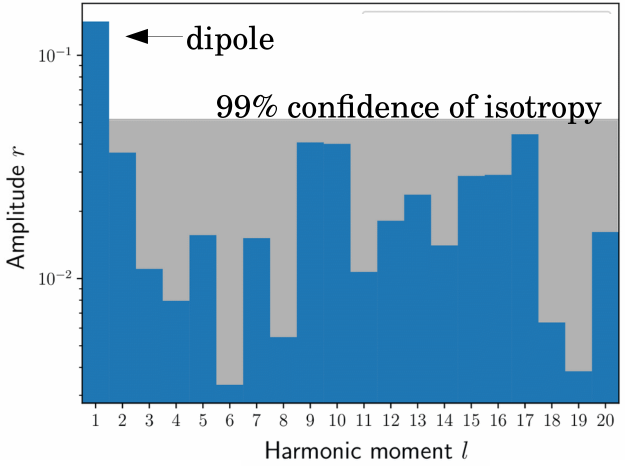
Anisotropic EGCRs – Galactic lensing

Injected flux



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

Distribution of moments above 1 EV



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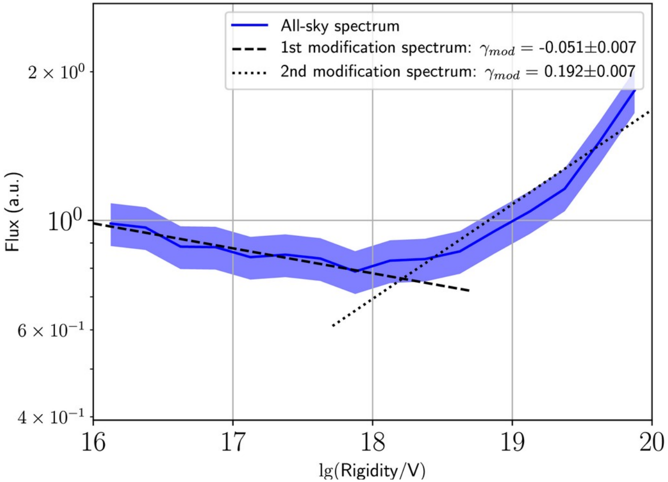
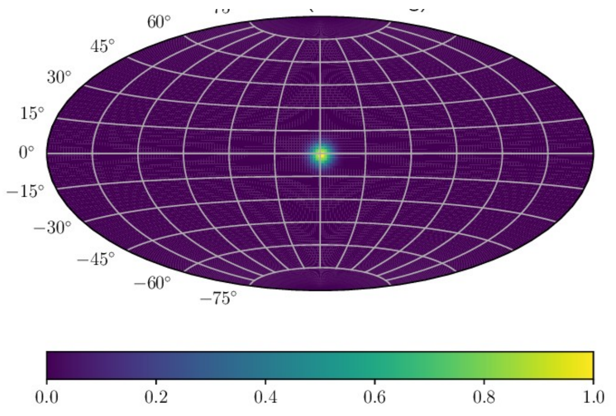
Flux at Earth



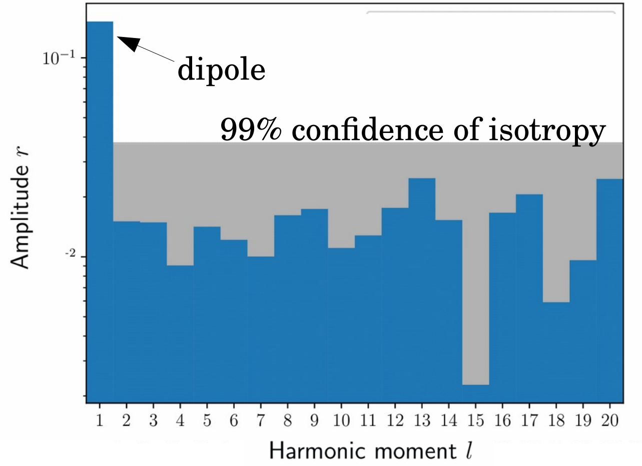
Rigidity spectrum at Earth → **possible flux modification**

Anisotropic EGCRs – Galactic lensing

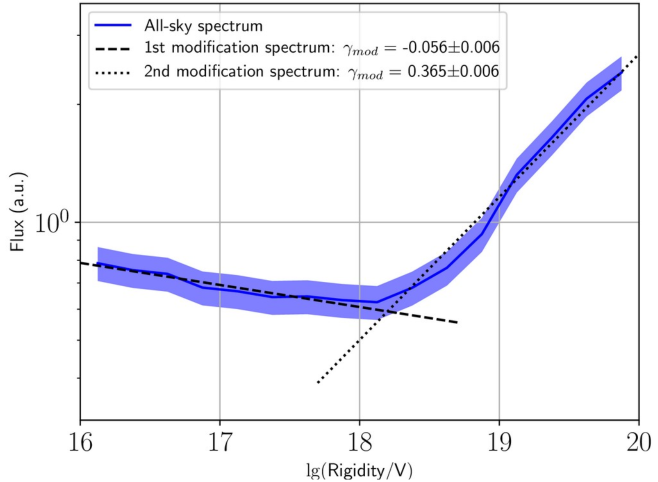
Injected flux



Distribution of moments above 1 EV



Flux at Earth



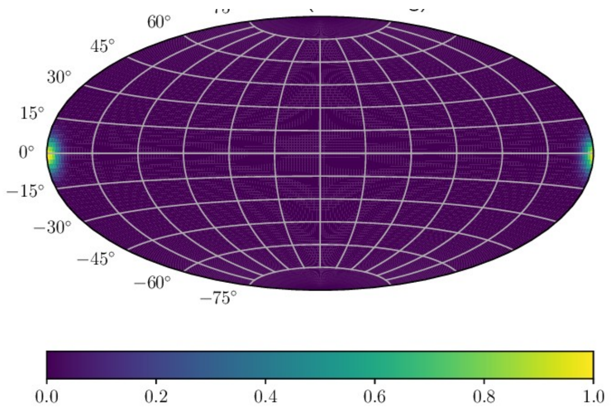
Injection direction distribution: **Pure single-point source** (minimum Galactic transparency; Galactic centre)

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

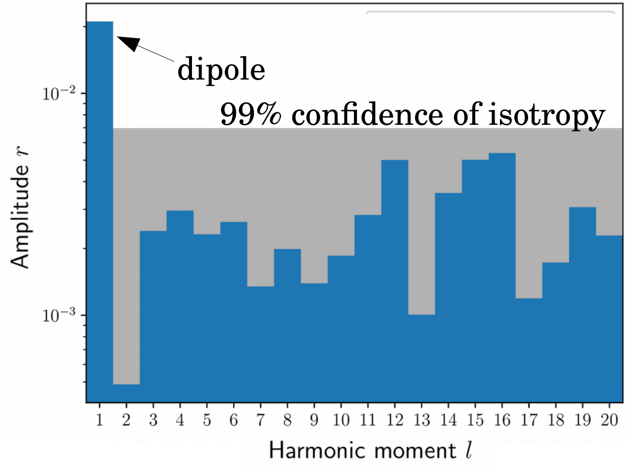
Rigidity spectrum at Earth → **possible flux modification**

Anisotropic EGCRs – Galactic lensing

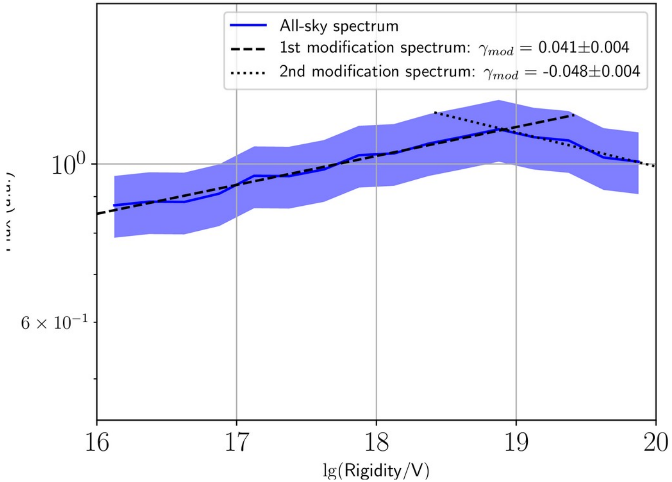
Injected flux



Distribution of moments above 1 EV



Flux at Earth



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

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

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

Summary (1)

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 (2)

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!

Open questions

Propagation effects:

- How does the change in propagation regimes manifest?
- Do propagation features arise?

GCRs:

- How **strongly** are they **contained**/How easily do they diffuse out of the Galaxy?
- What **effect** does this have **on** the GCR **flux**?

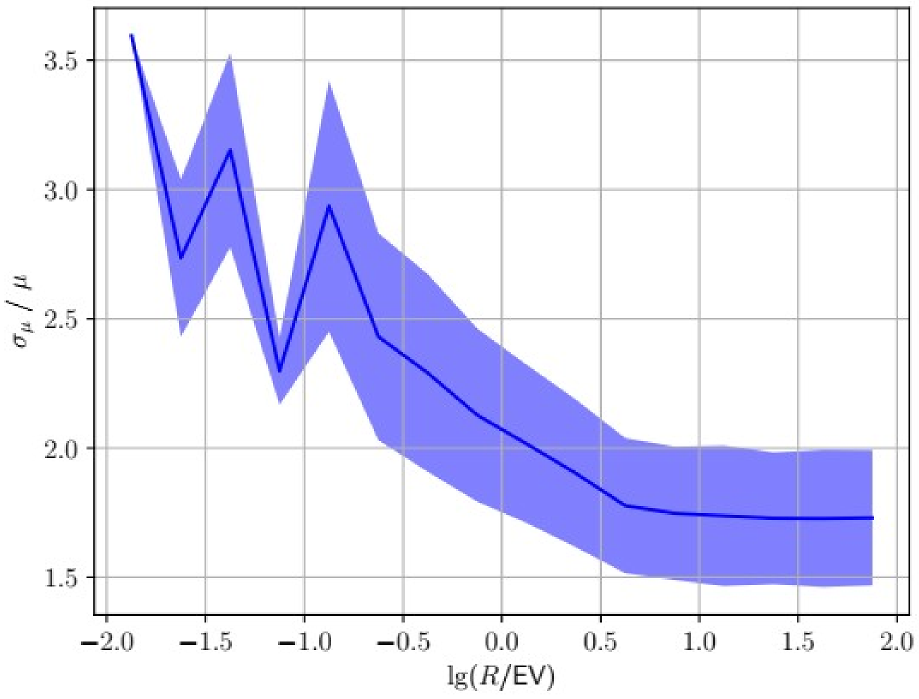
EGCRs:

- How **strongly** are they **shielded** by the GMF?
- How are they **deflected** by the GMF **once** they have **entered** the **Galactic plane**?
- Does this lead to **flux modification**?

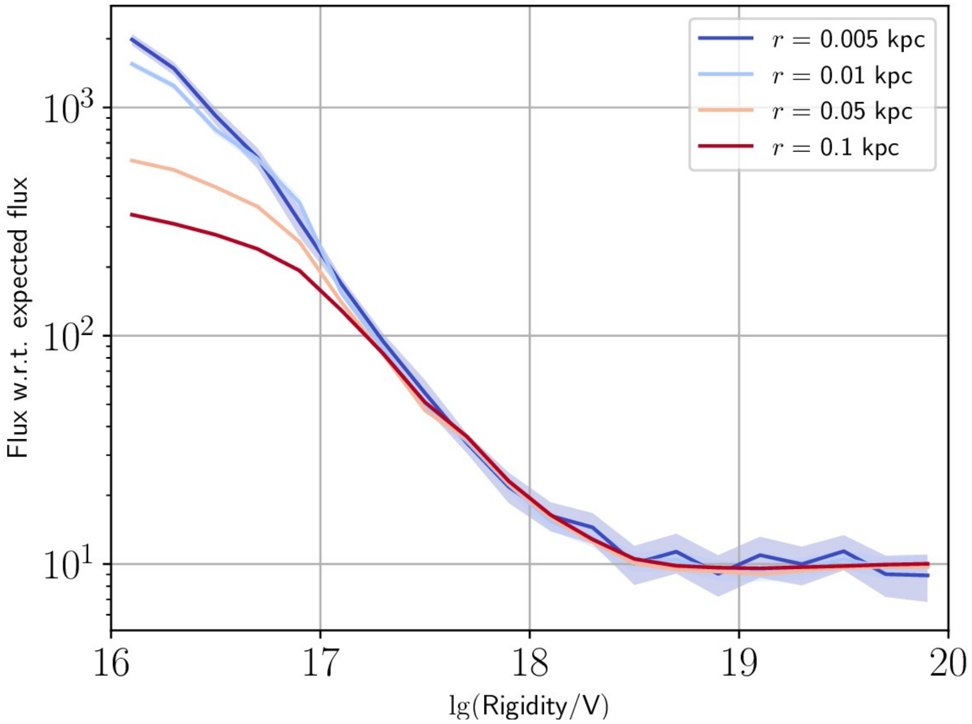
Liouville's Theorem

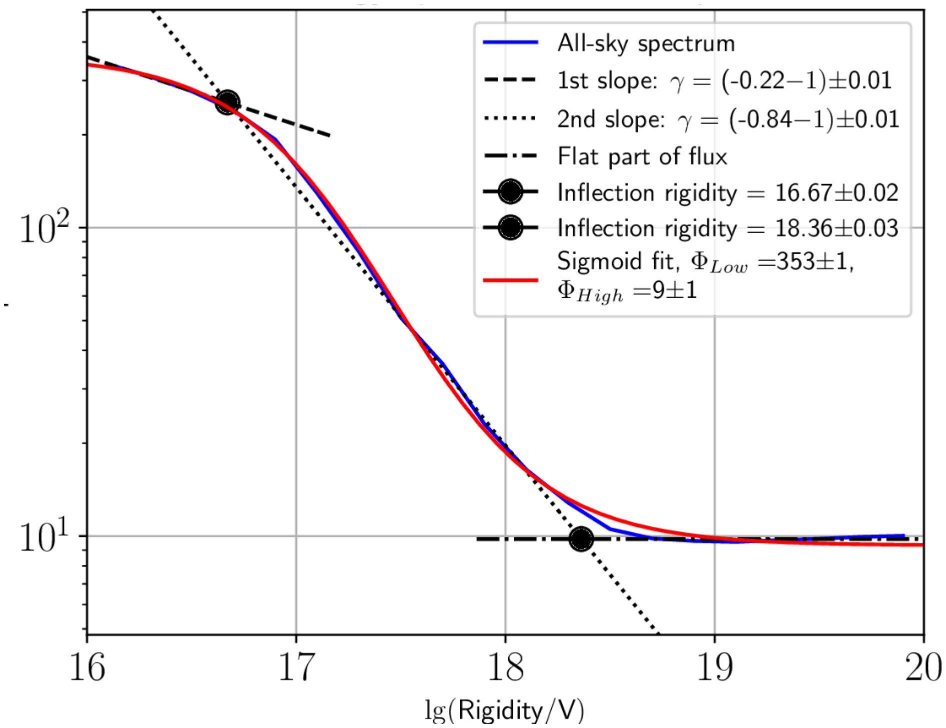
- Objection to flux modification of EGCRs: **Liouville's Theorem**
  - If **phase space density is conserved, so is flux**
  - BUT: If Liouville holds, then **other quantities are conserved, i.a. first adiabtic invariant**
    ~ classical magnetic moment (APJ 842:54, APJ 830:19):

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



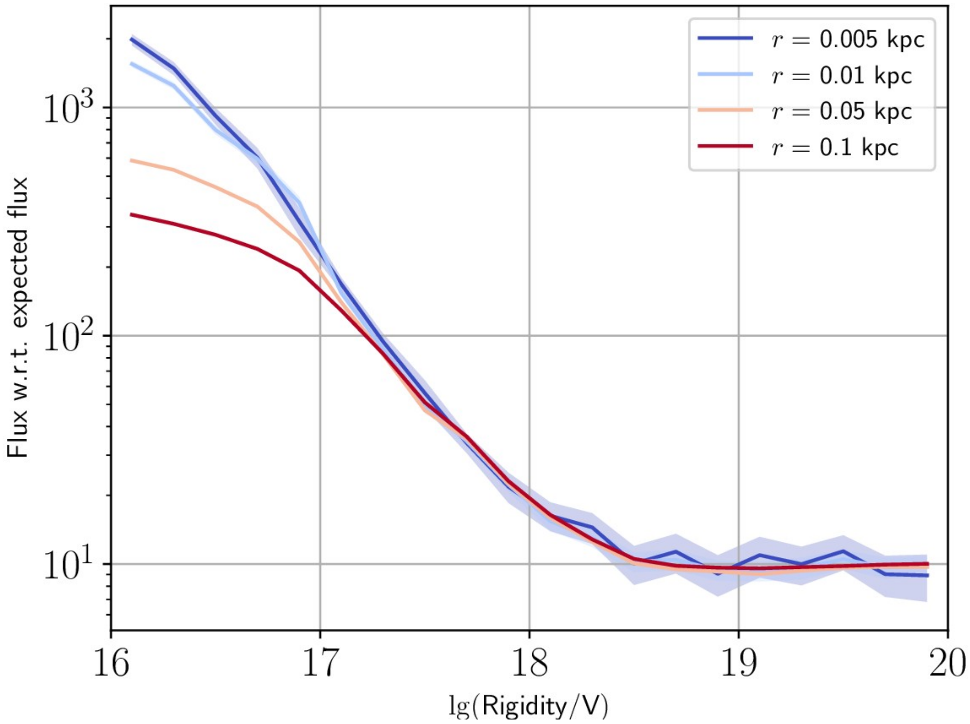
GCRs – Sigmoid fit to flux

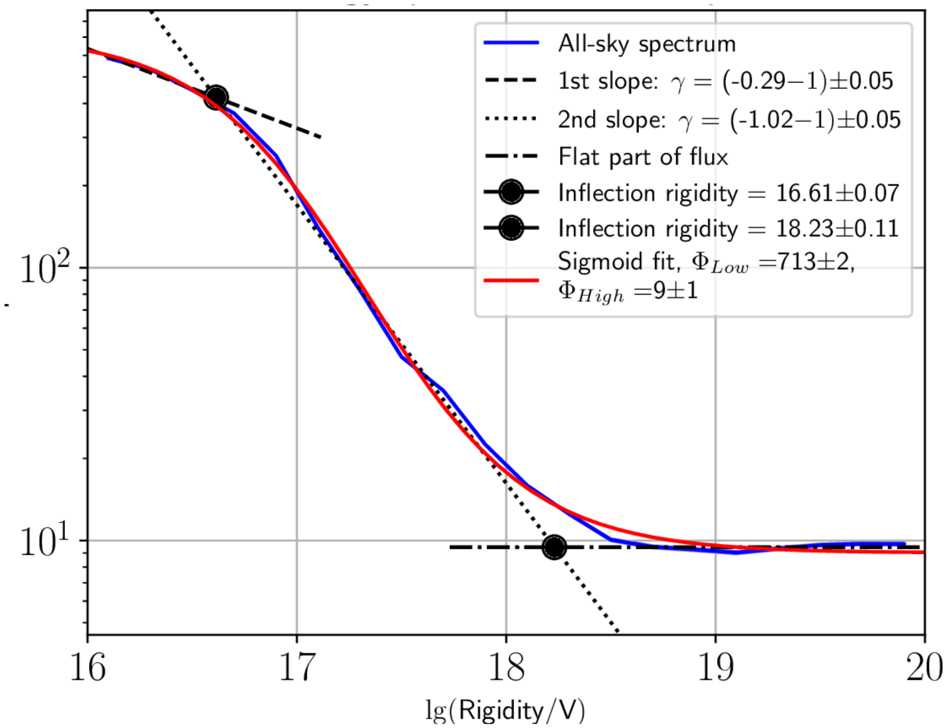




- Flux enhancement towards lower rigidities appears to flatten out → sigmoid fit
- Advantage: wider overlapping energy range of mixed compositions

GCRs – Sigmoid fit to flux





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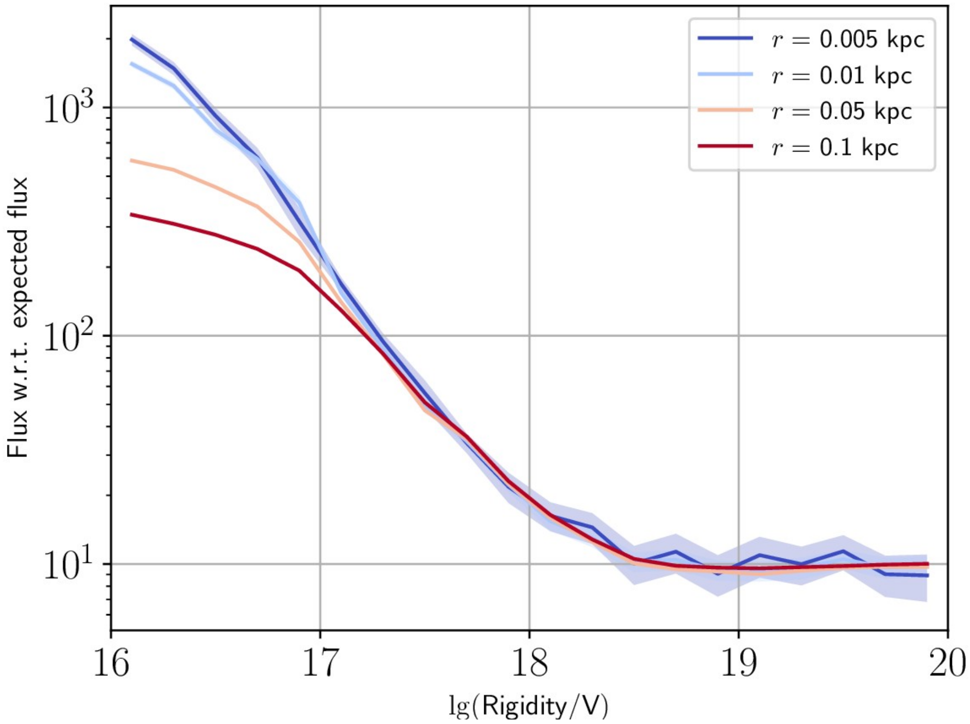

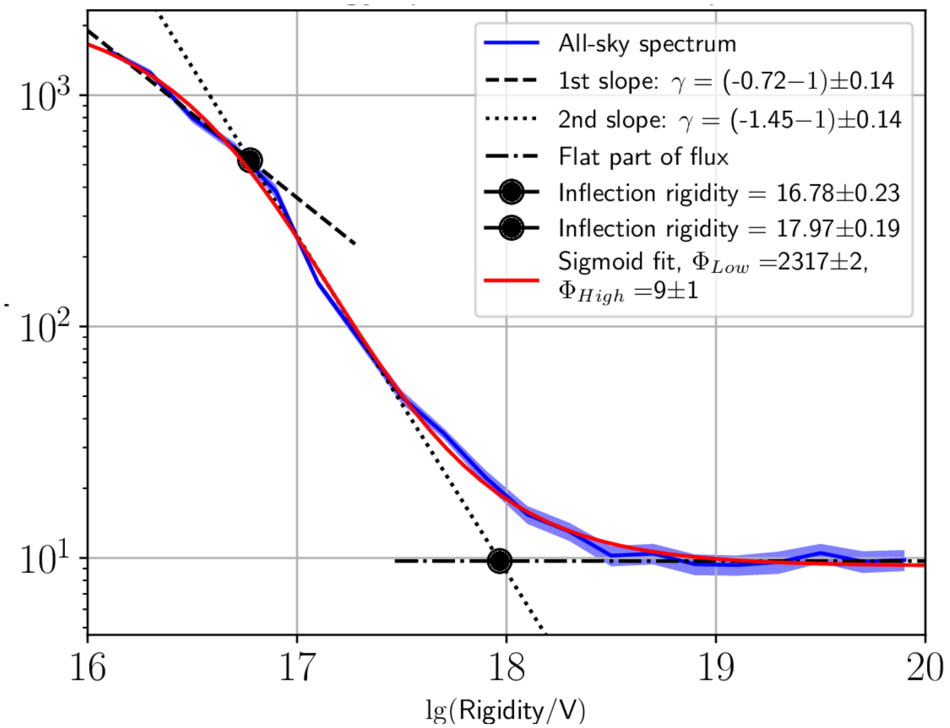

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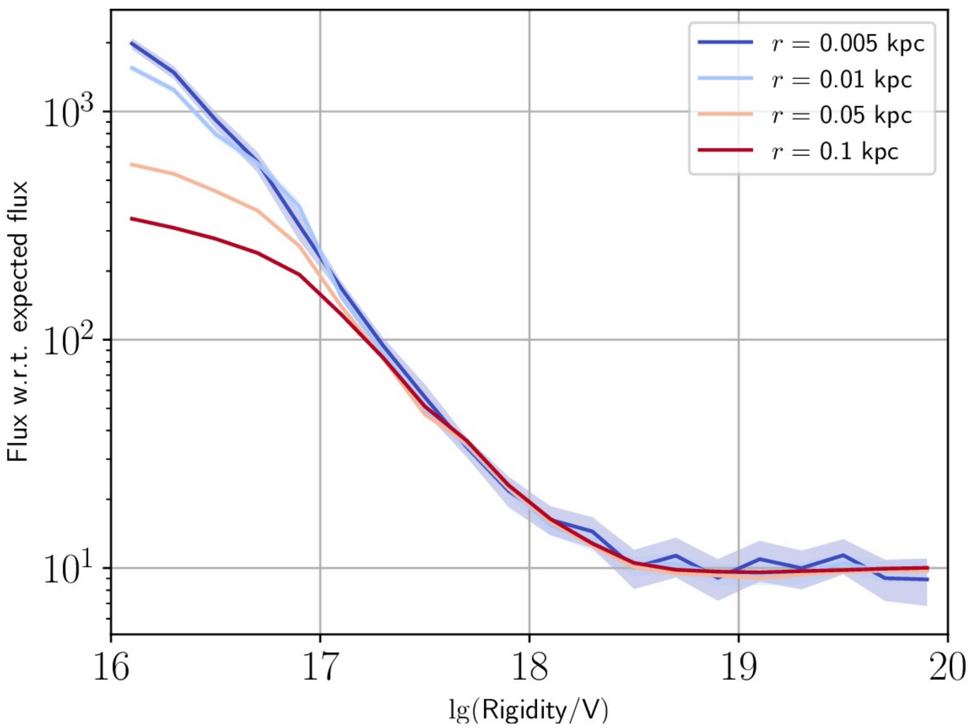
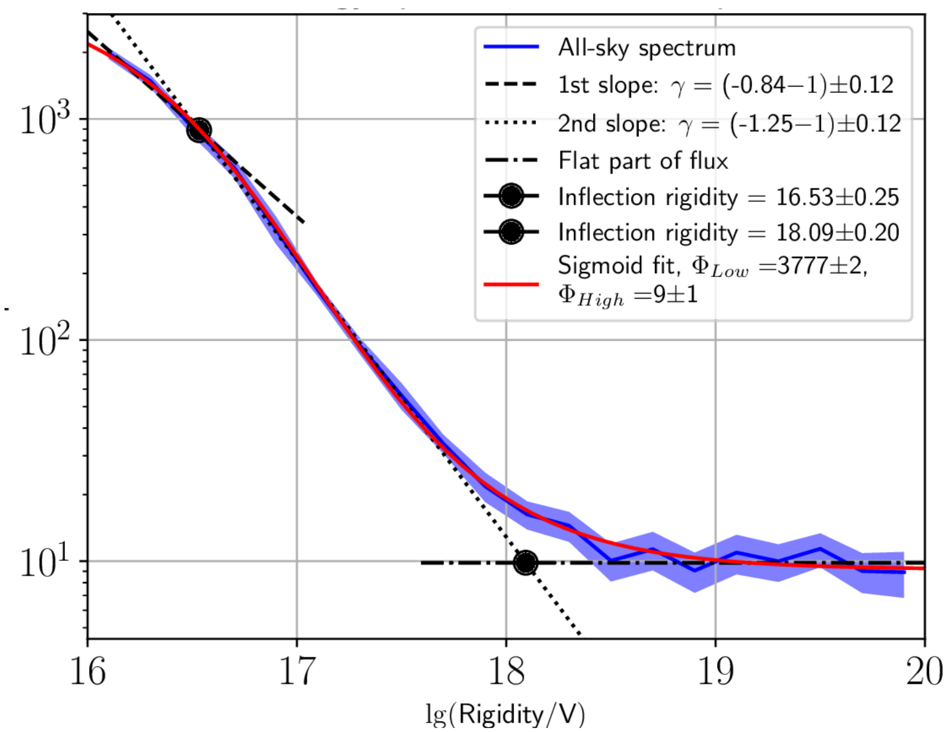
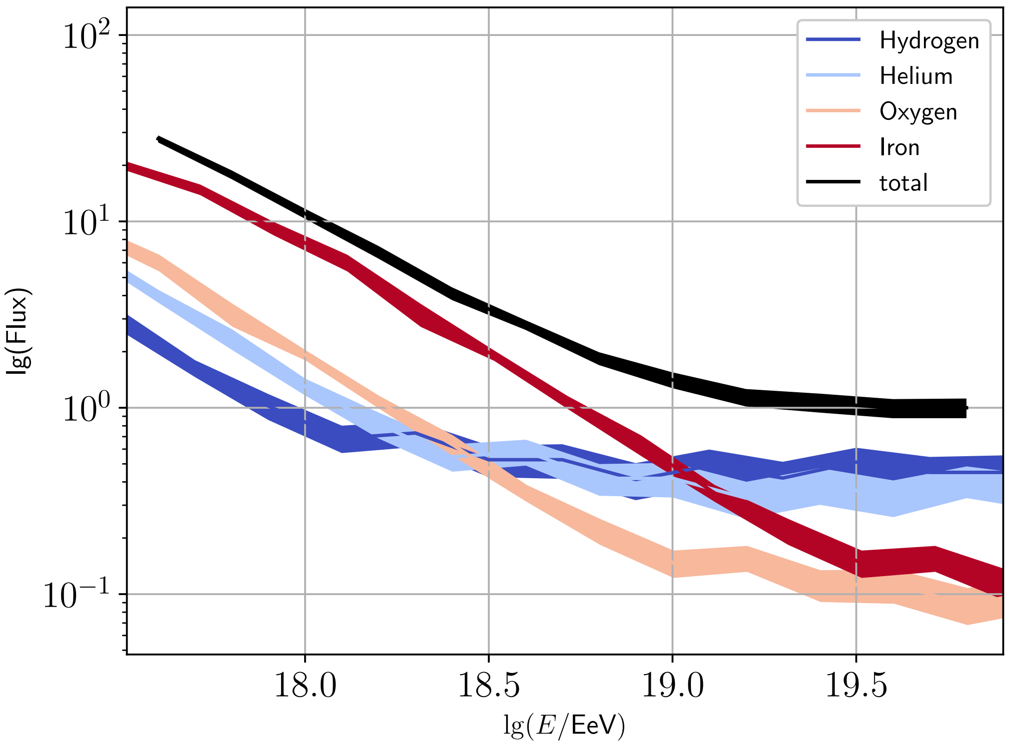
GCRs – Sigmoid fit to flux

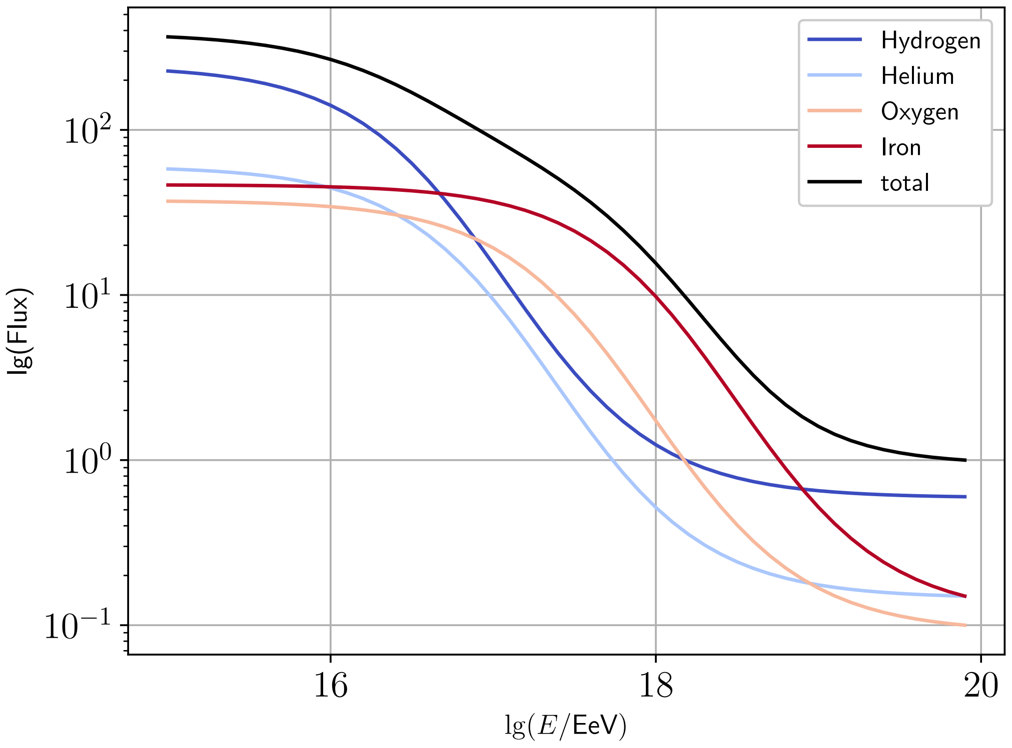




- Flux enhancement towards lower rigidities appears to flatten out → sigmoid fit
- Advantage: wider overlapping energy range of mixed compositions

GCRs – Total flux (data and sigmoid fit)

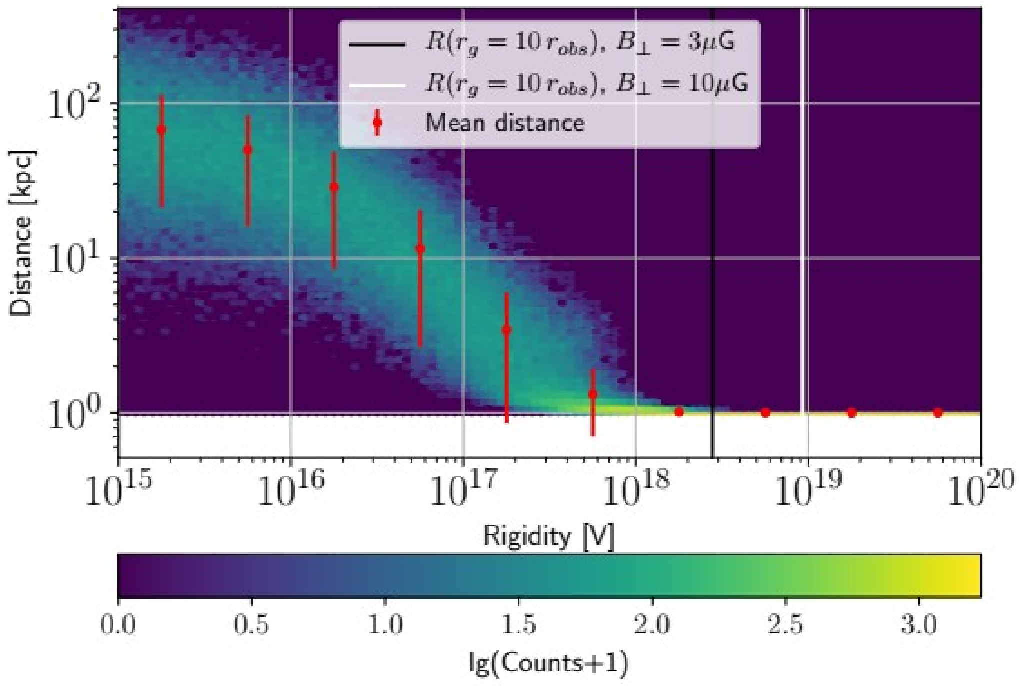




- Onset of flux suppression for mixed composition visible for sigmoid fit

On the modification of EGCR energy spectrum

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



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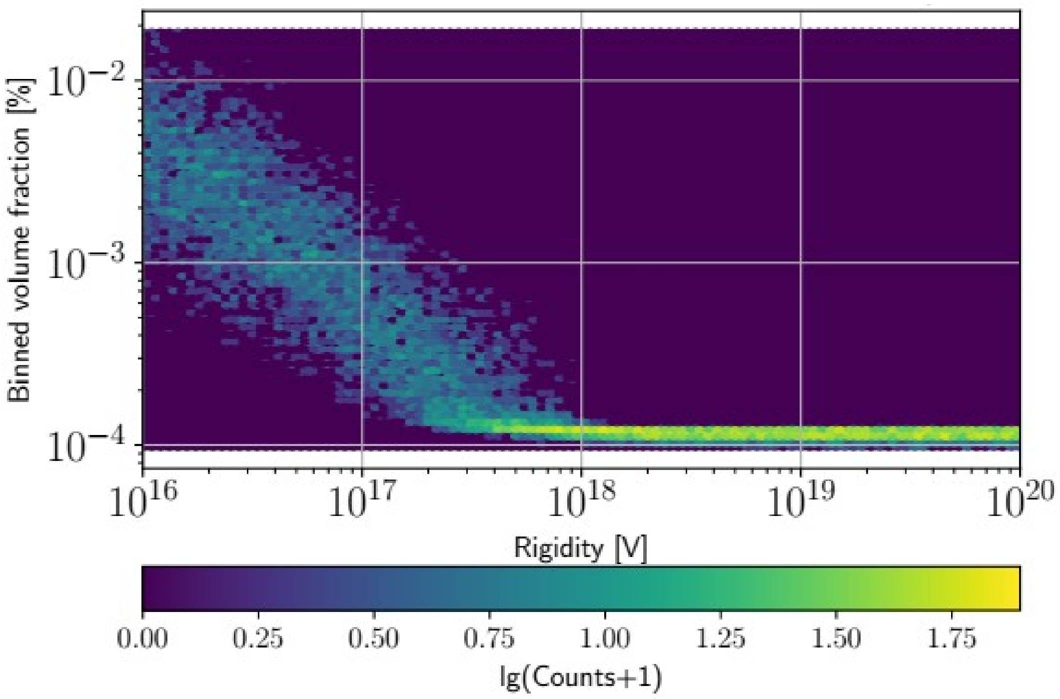
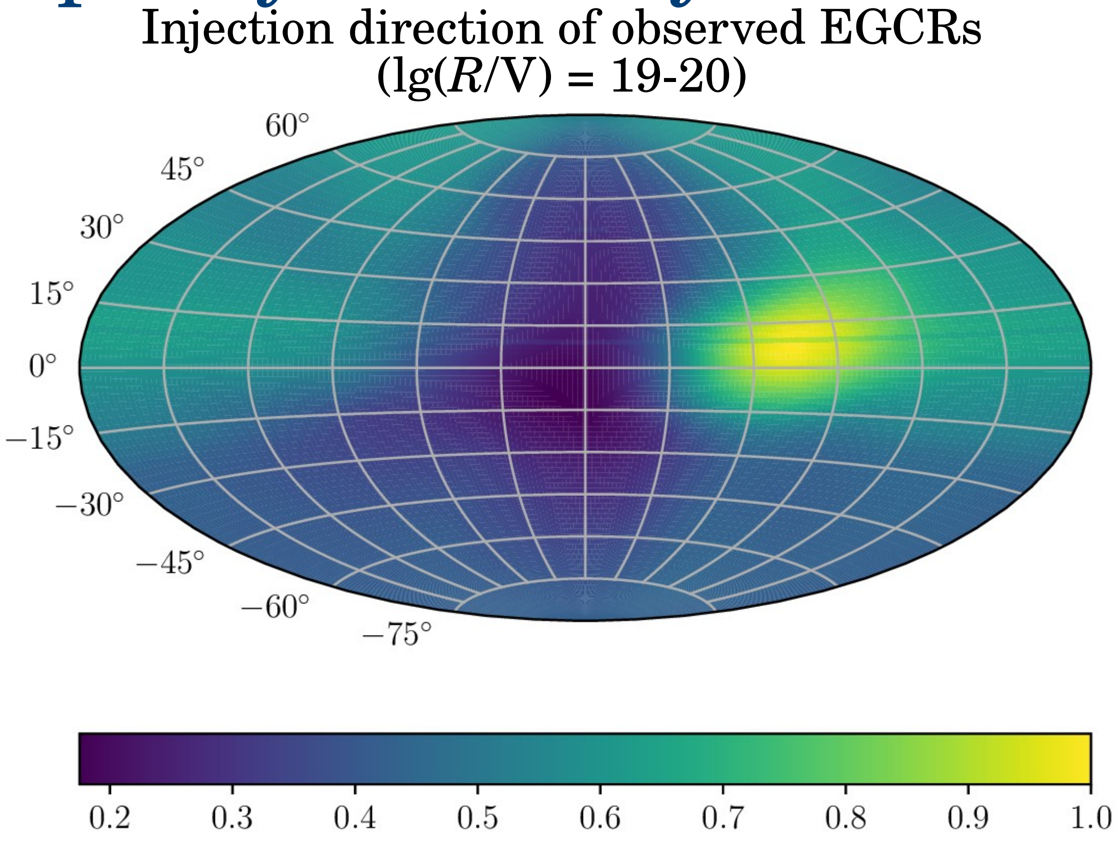
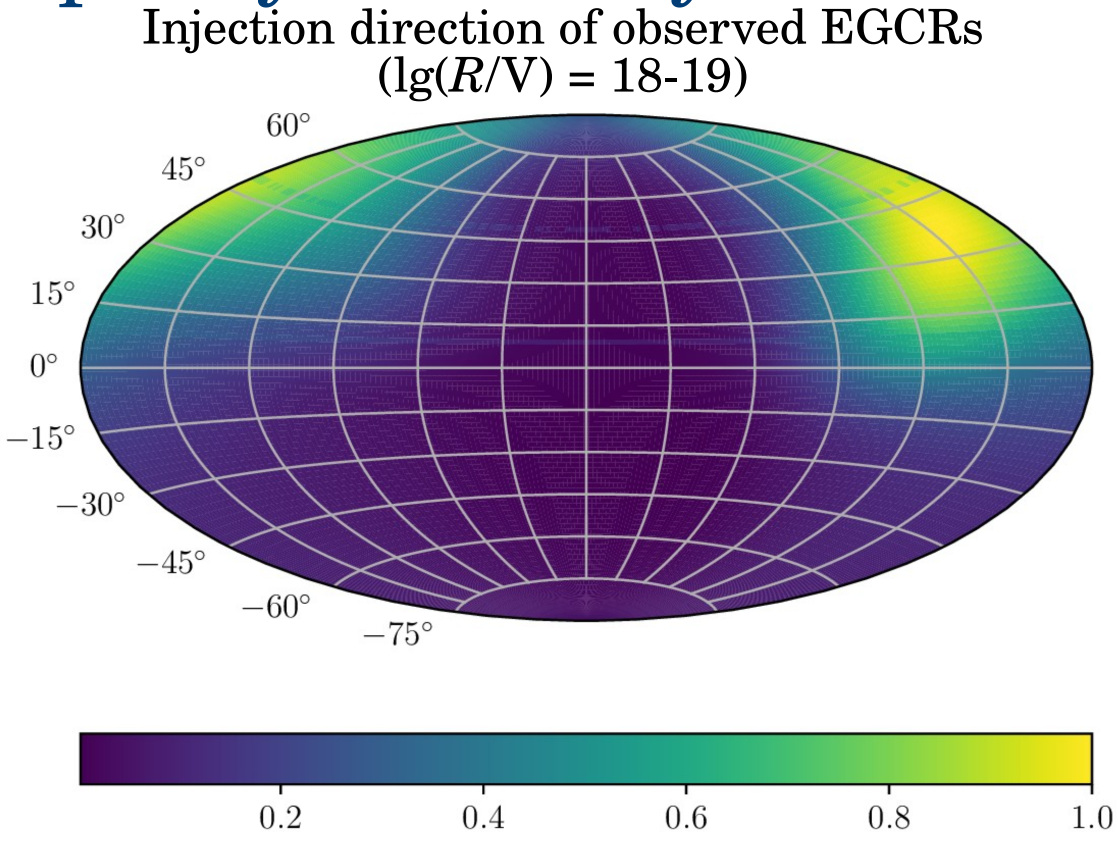


EGCRs – Opacity of Galaxy



- Regions of enhanced/suppressed transparency shift with rigdity

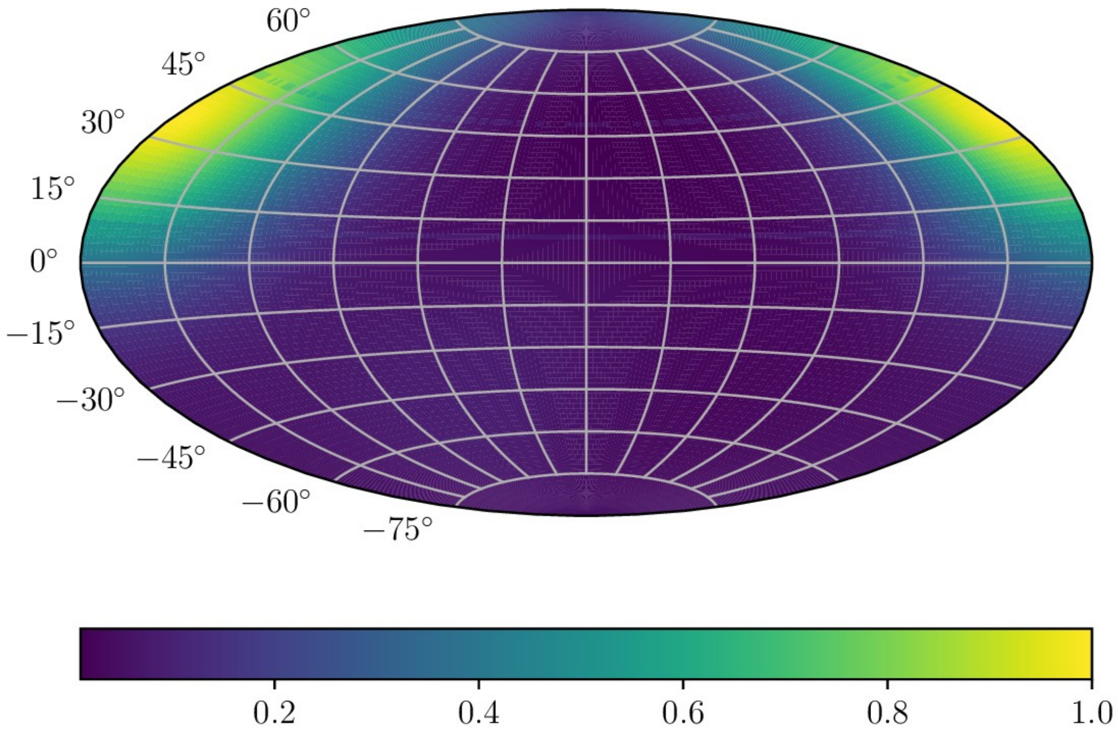
EGCRs – Opacity of Galaxy



- Regions of enhanced/suppressed transparency shift with rigdity

EGCRs – Opacity of Galaxy

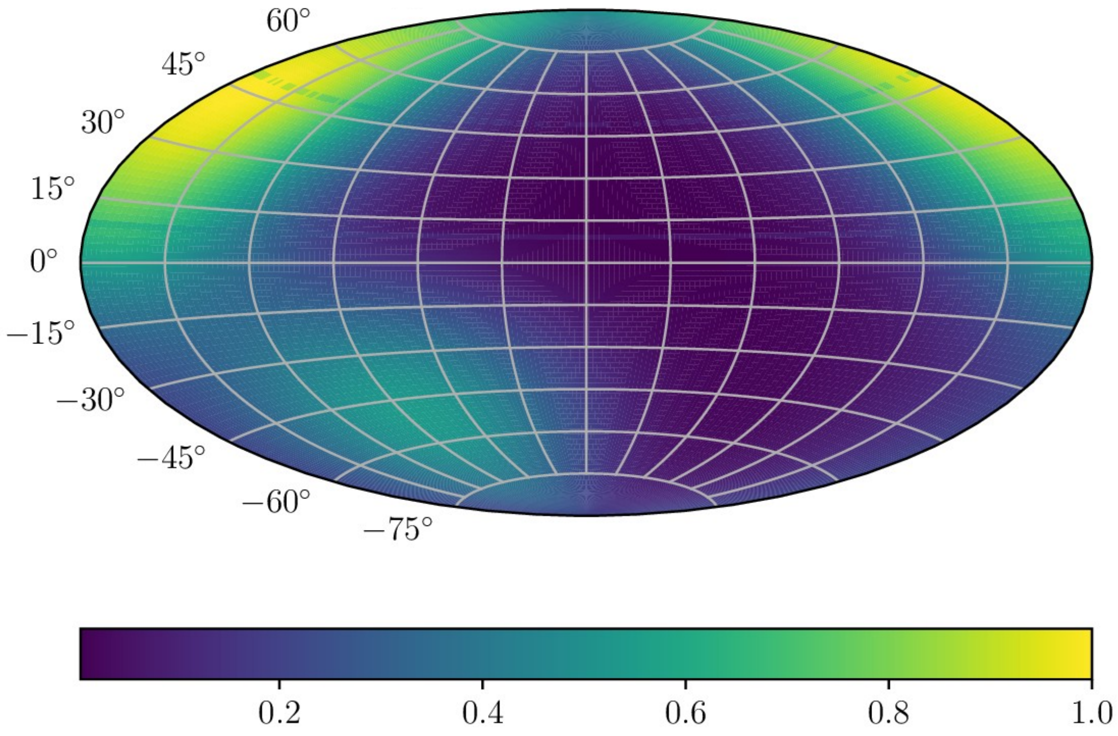
Injection direction of observed EGCRs
(lg(R/V) = 17-18)



- Regions of enhanced/suppressed transparency shift with rigdity

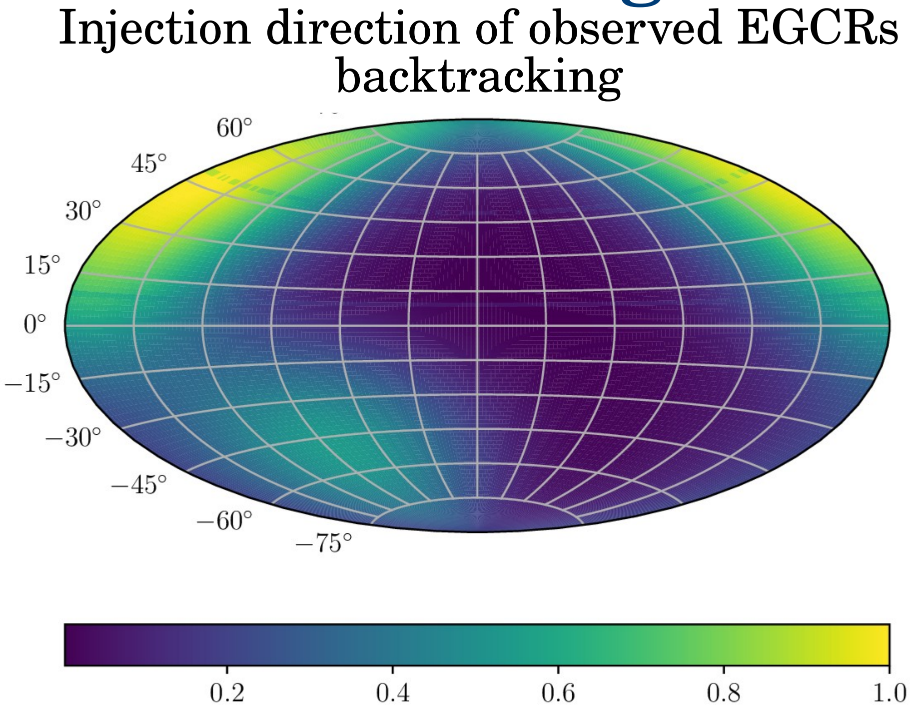
EGCRs – Opacity of Galaxy

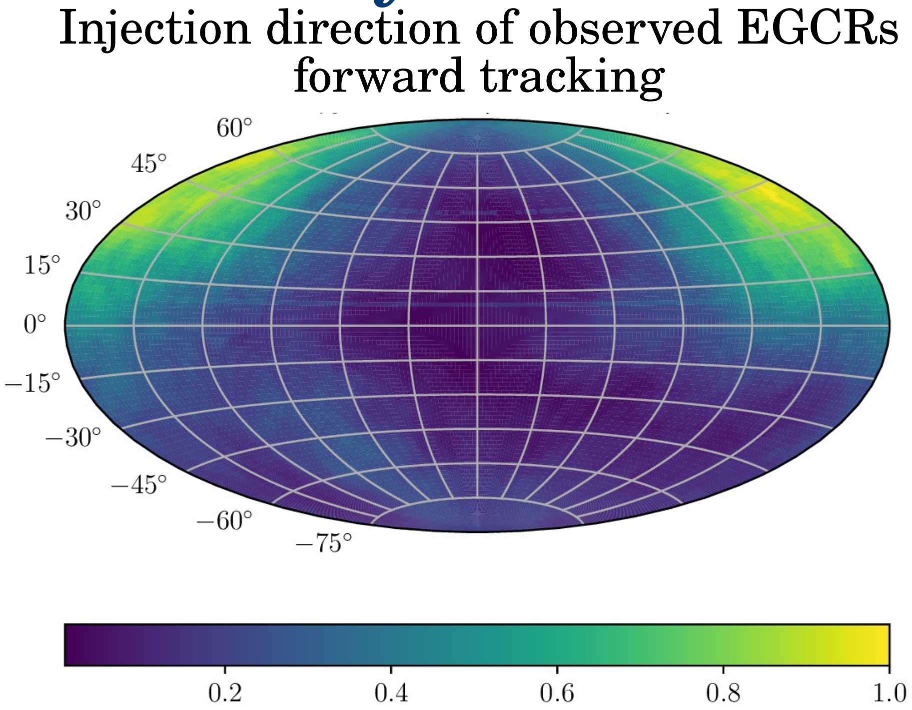
Injection direction of observed EGCRs
(lg(R/V) = 16-17)



- Regions of enhanced/suppressed transparency shift with rigdity

Galactic lensing – time reversibility

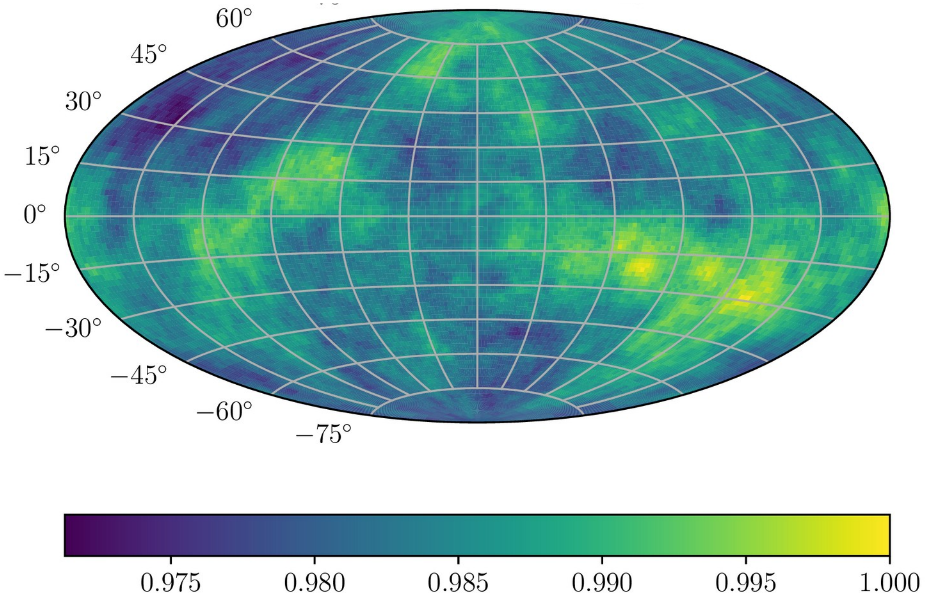




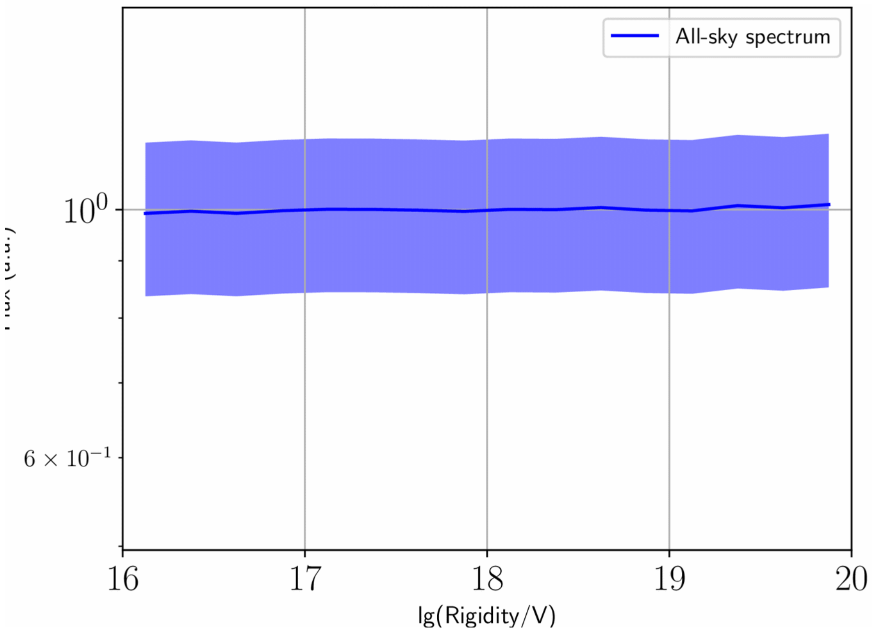
Injection direction distributions of backtracked and forward tracked protons match

Galactic lensing – testing lens

Arrical direciton of lensed isotropic injection distribution

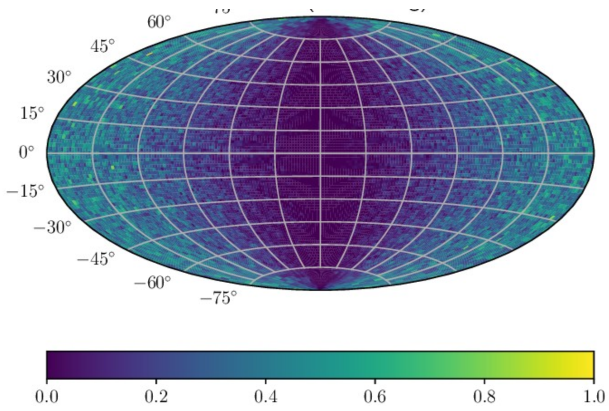
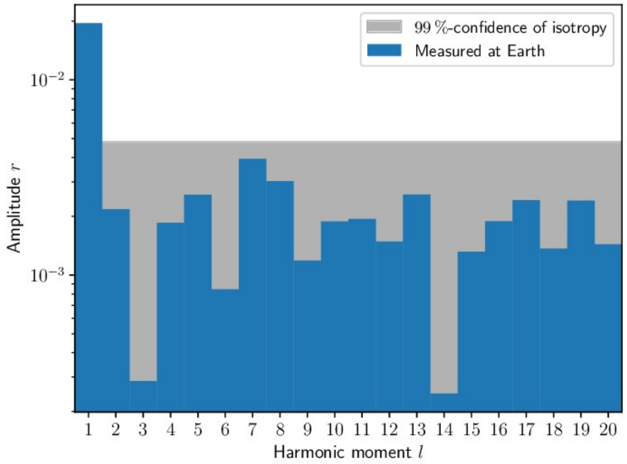
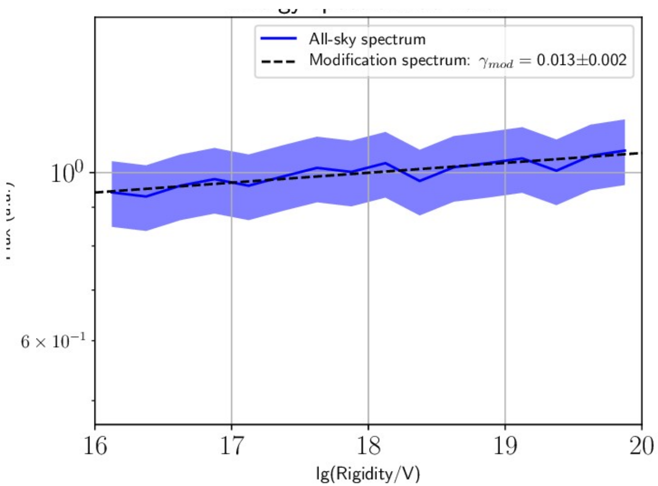


Spectrum of lensed isotropic injection distribution



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**