CR Propagation & Simulation II

On the transition from Galactic to extragalactic cosmic rays

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Lecture Series
Astroteilchenphysik 2 - Crossing the Desert
Session 6
Zoom conference
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BERGISCHE UNIVERSITÄT WUPPERTAL

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Outline of lecture

1) The transition region in data
    - Spectrum, composition and dipole anisotropy
    - Open questions
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
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Further more subtle features:

- hardening at ~$10^{16.7}$ eV
- **‘2nd knee’:** softening at ~$10^{17.(0...4)}$ eV
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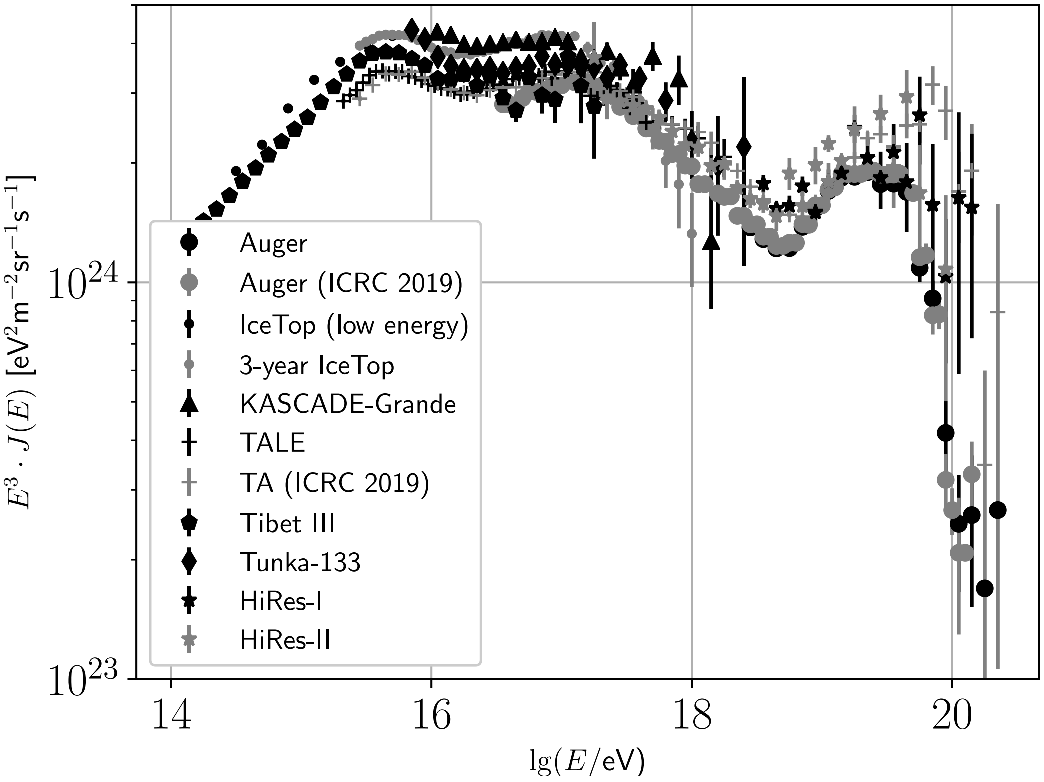
Extragalactic cosmic rays (**EGCR**s) dominate at energies **above ‘ankle’**.

Transition region (= ‘shin’) **unexplained**:

- unaccounted for flux



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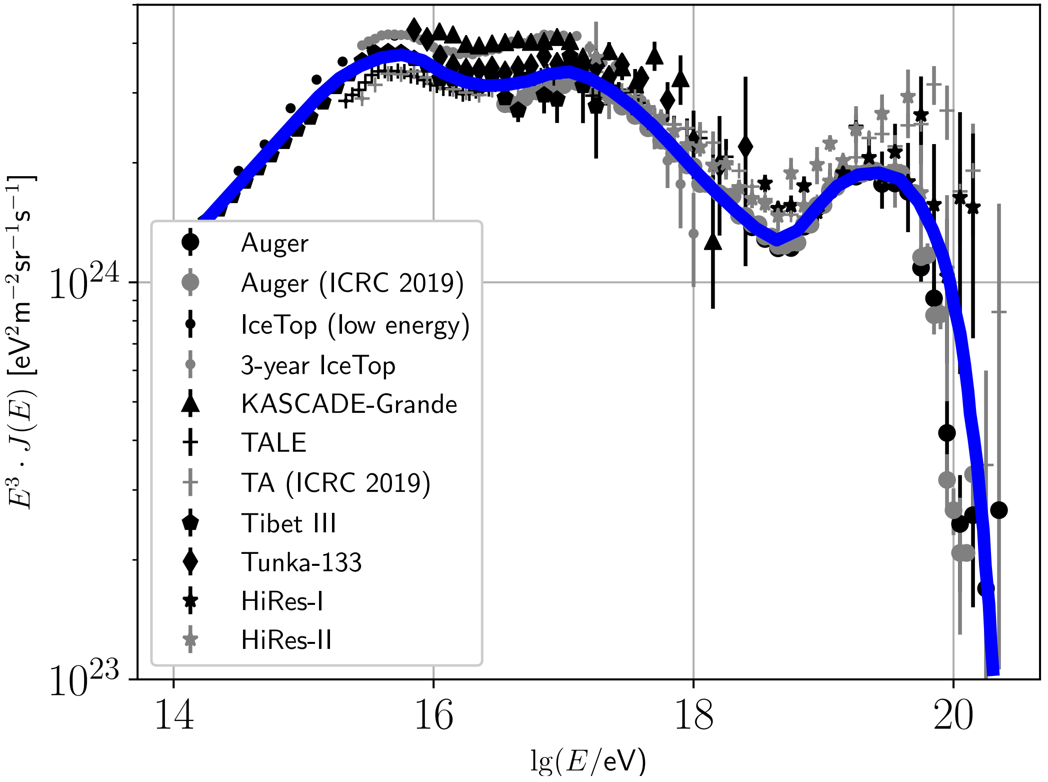

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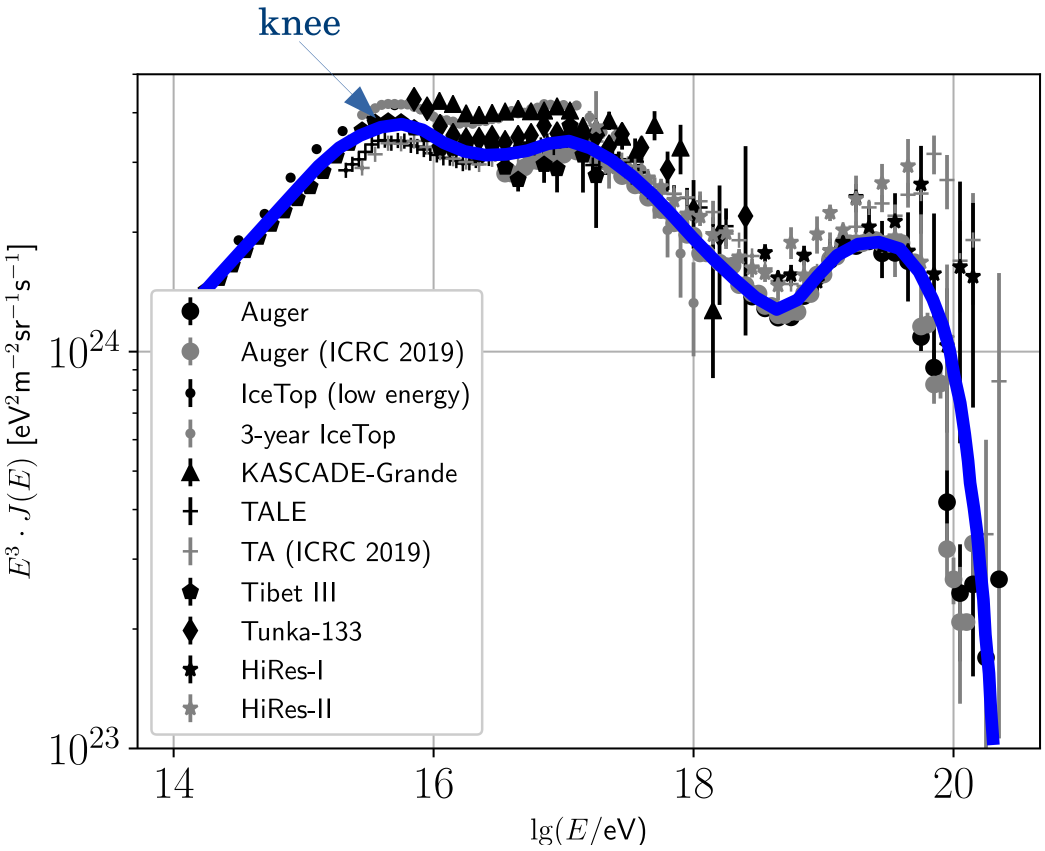

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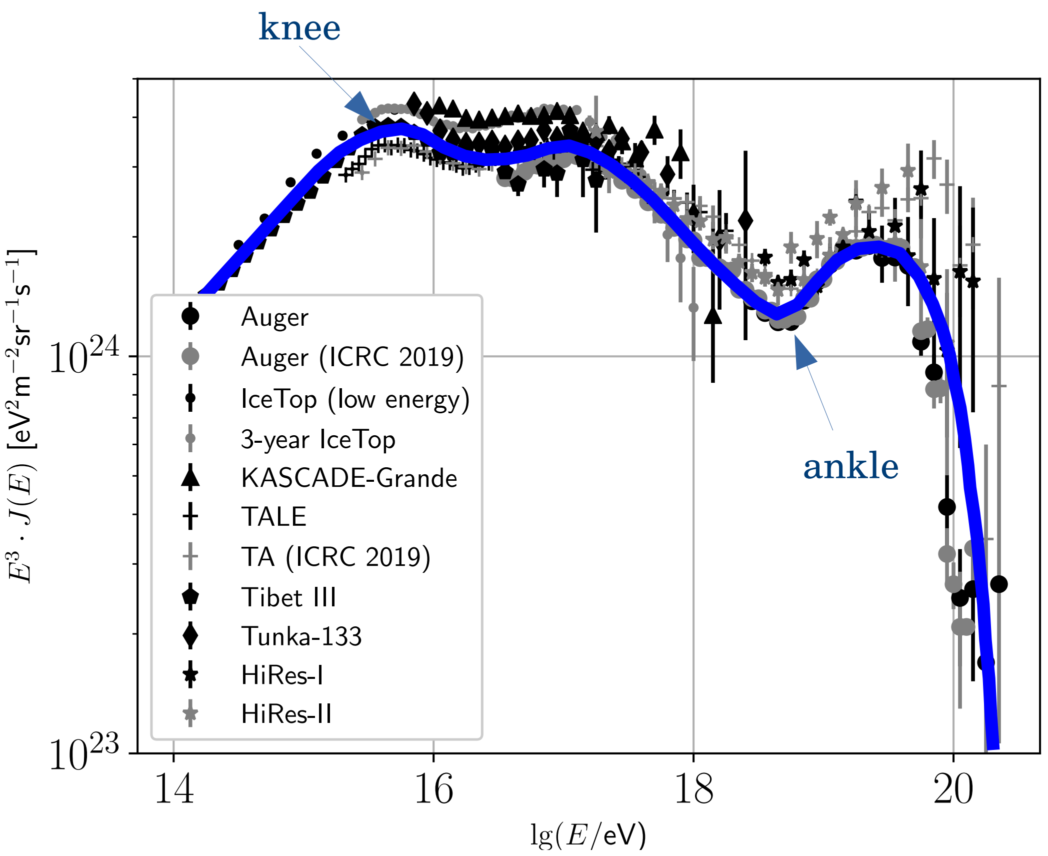

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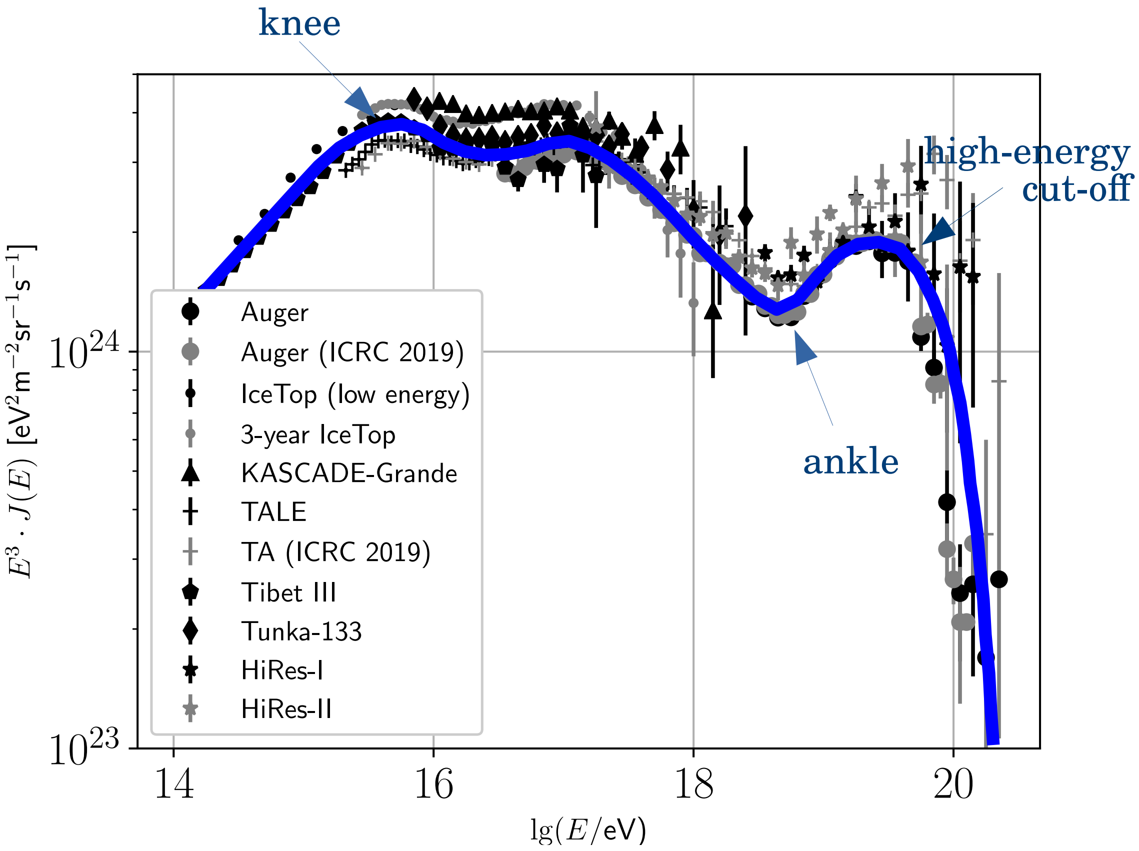

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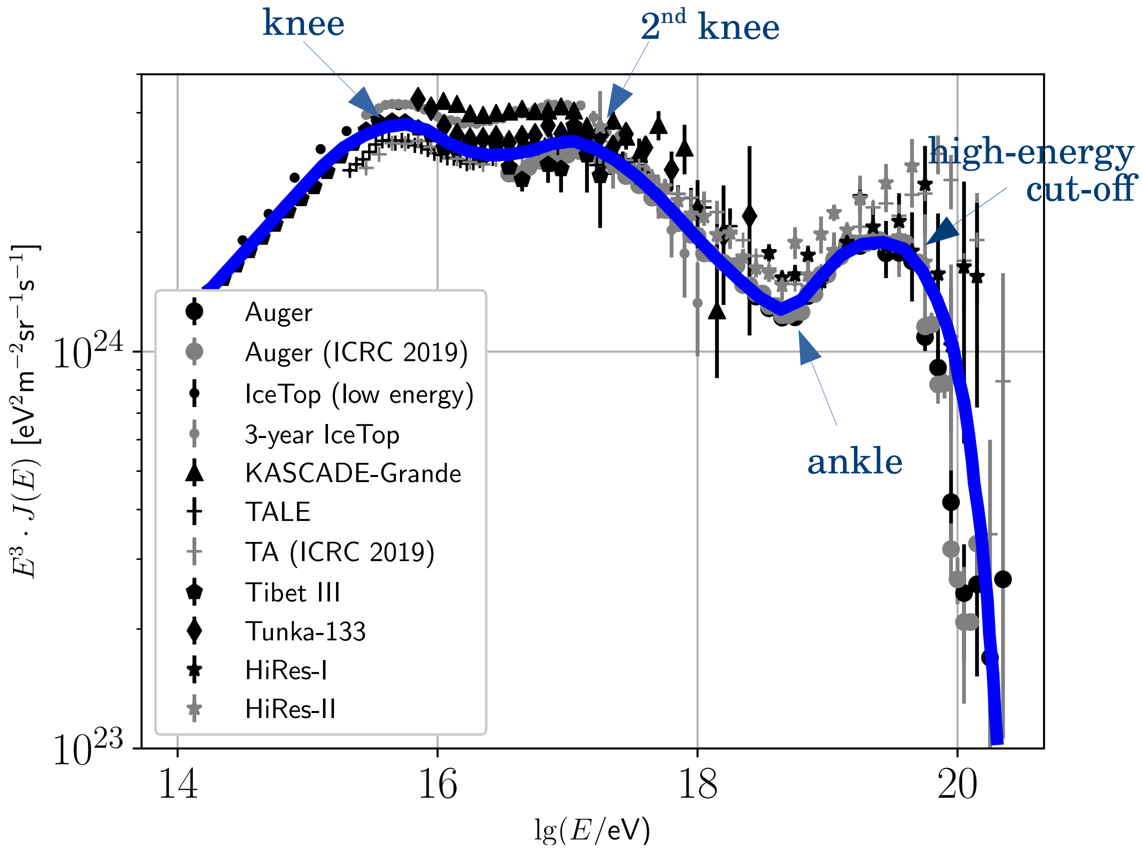

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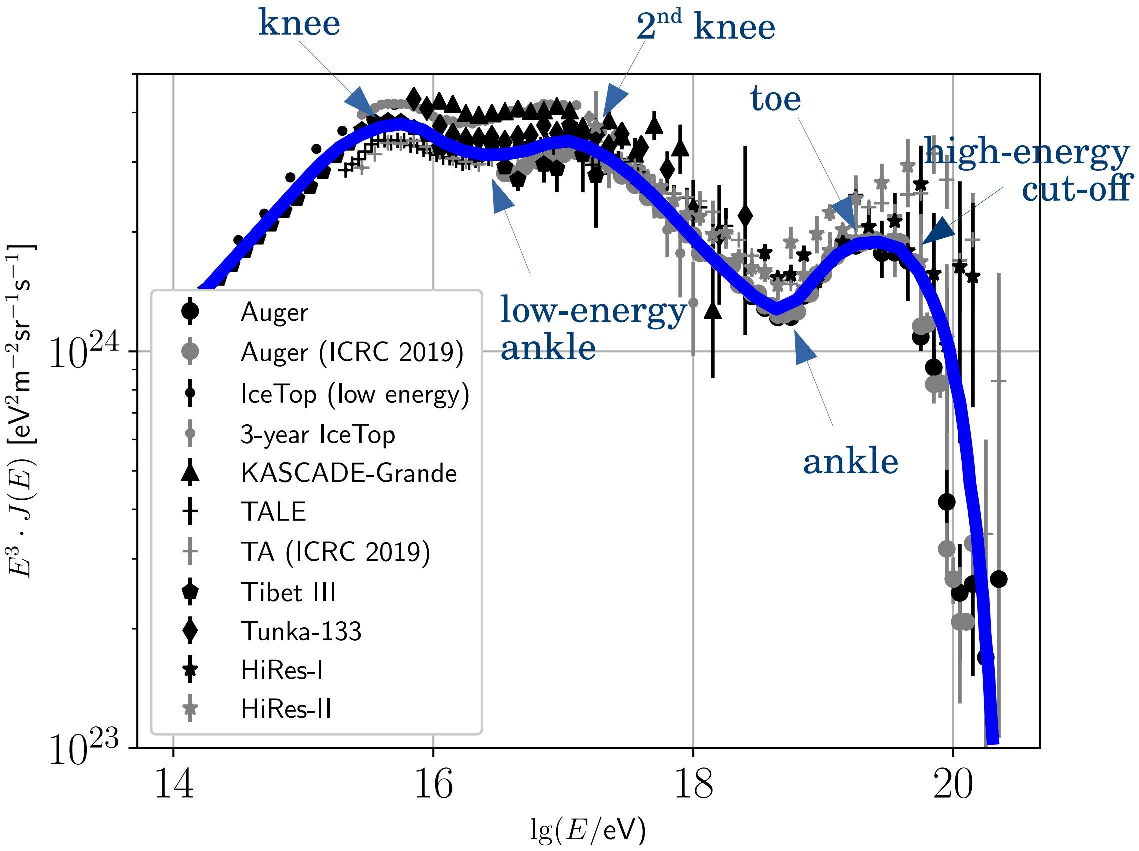

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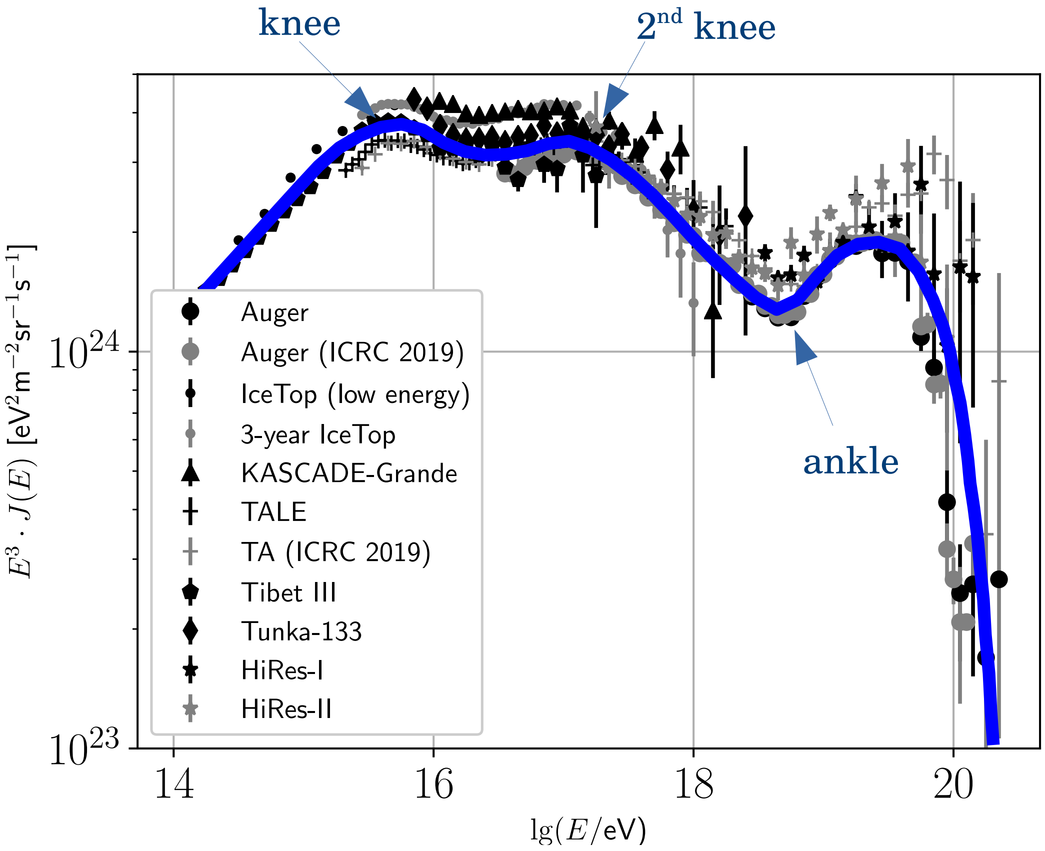

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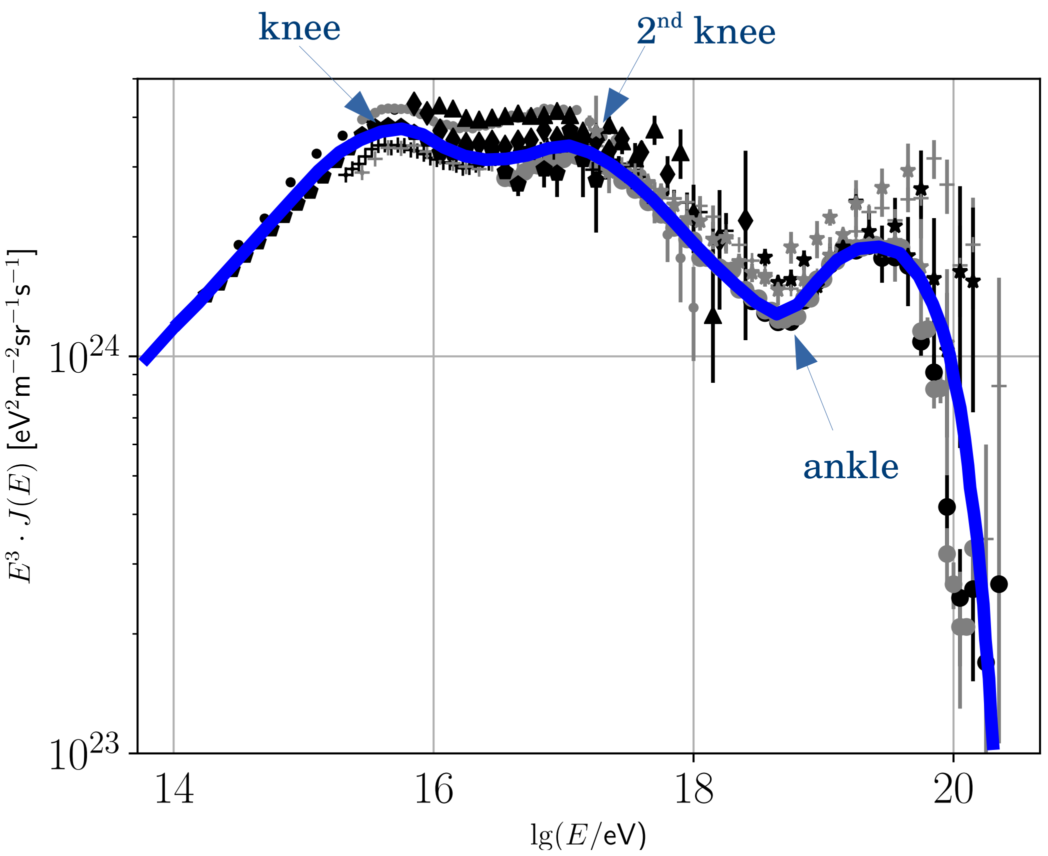

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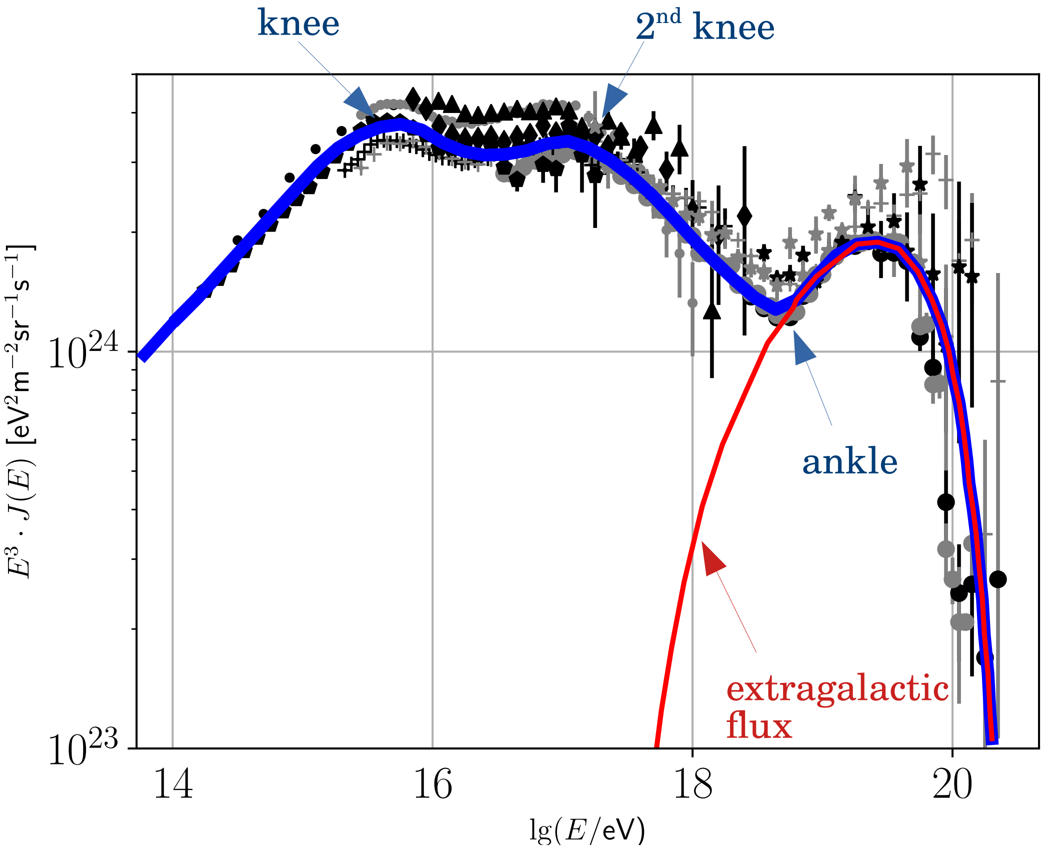

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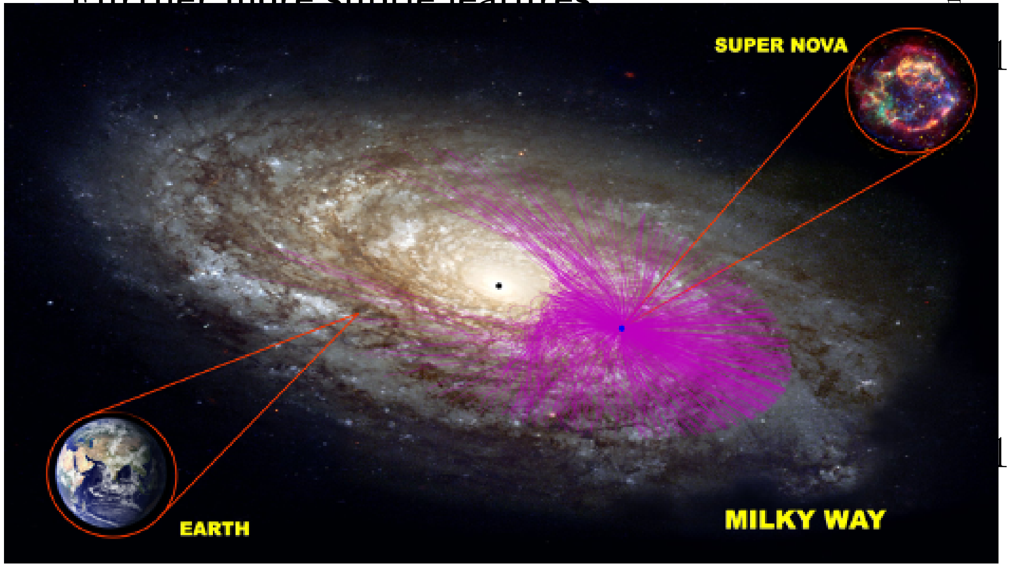

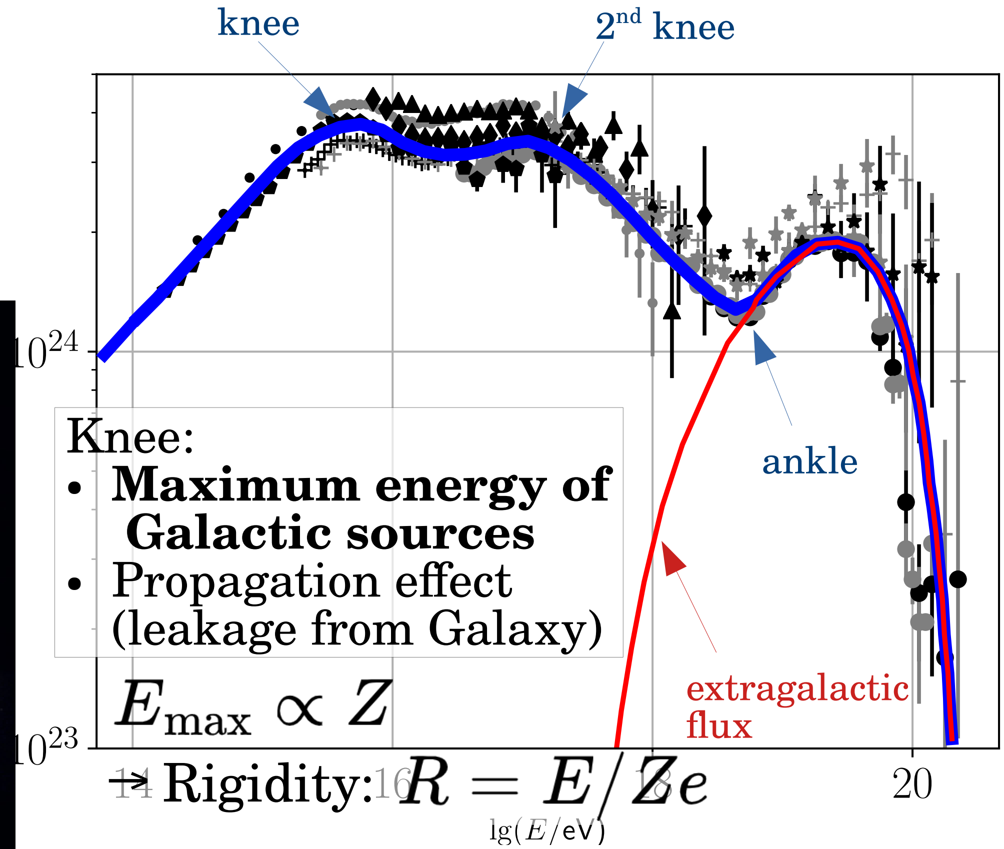

Knee:

- **Maximum energy of Galactic sources**
- Propagation effect (leakage from Galaxy)

$E_{\text{max}} \propto Z$

→ Rigidity: $R = E/Ze$

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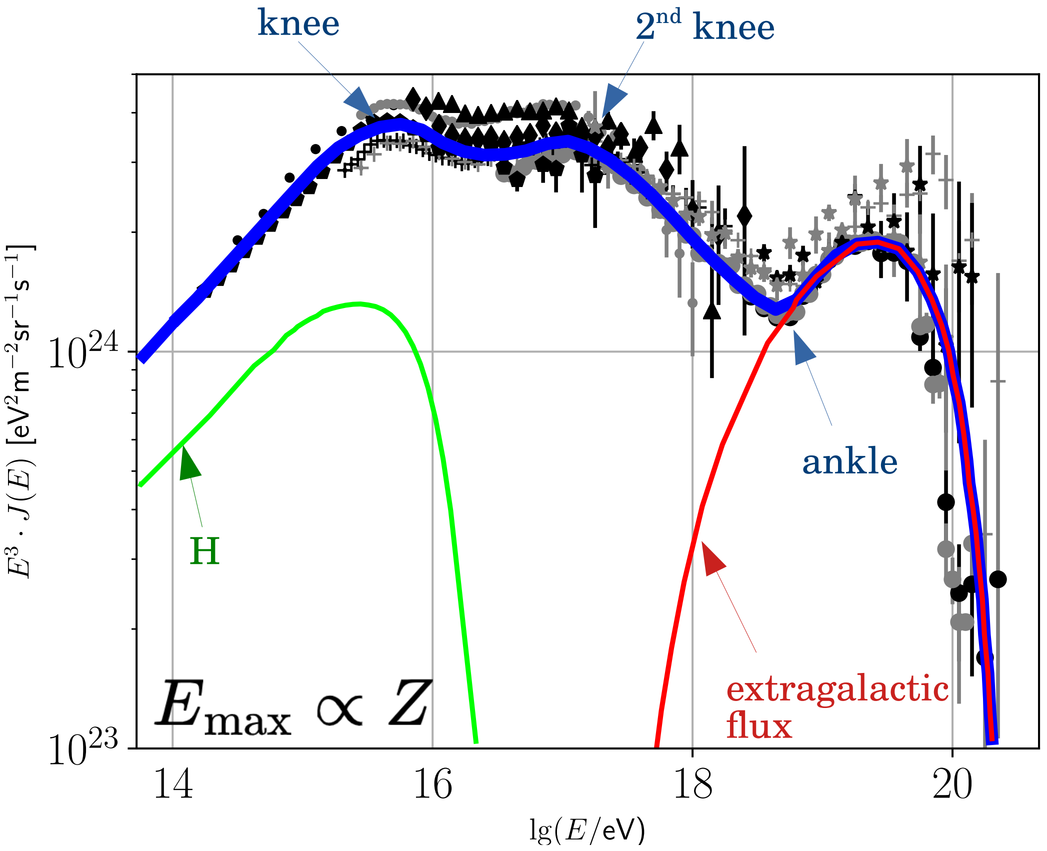

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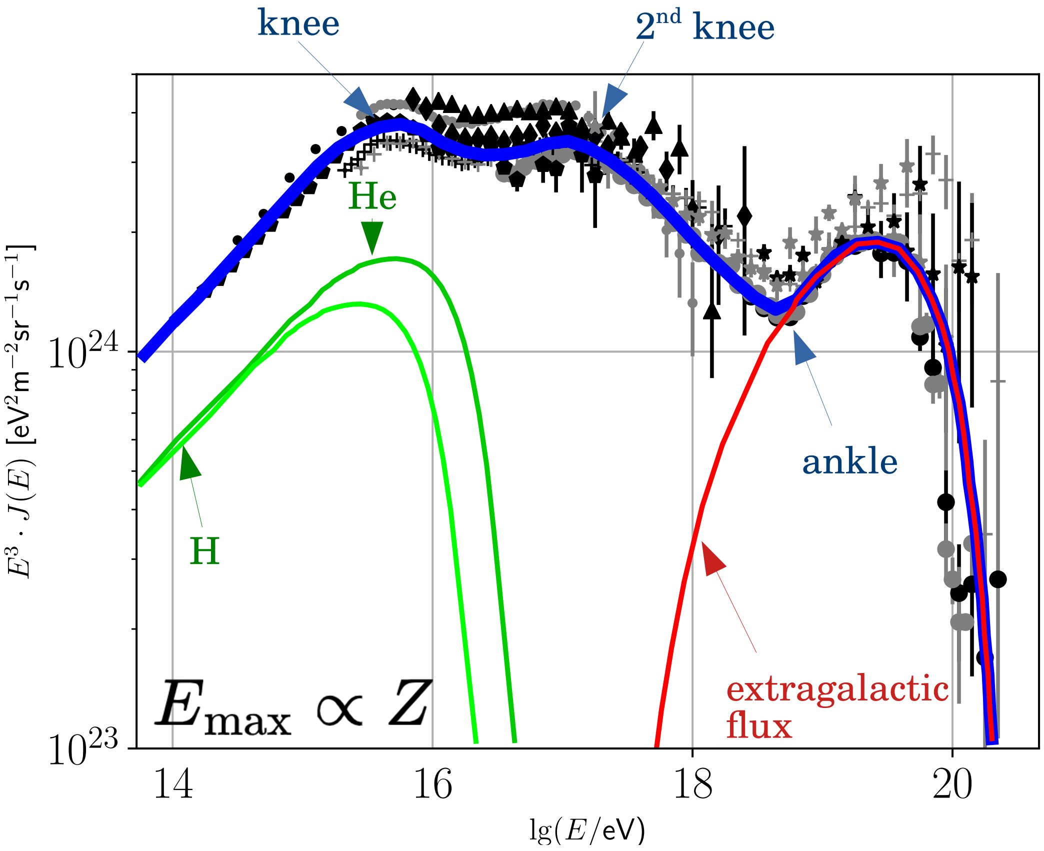

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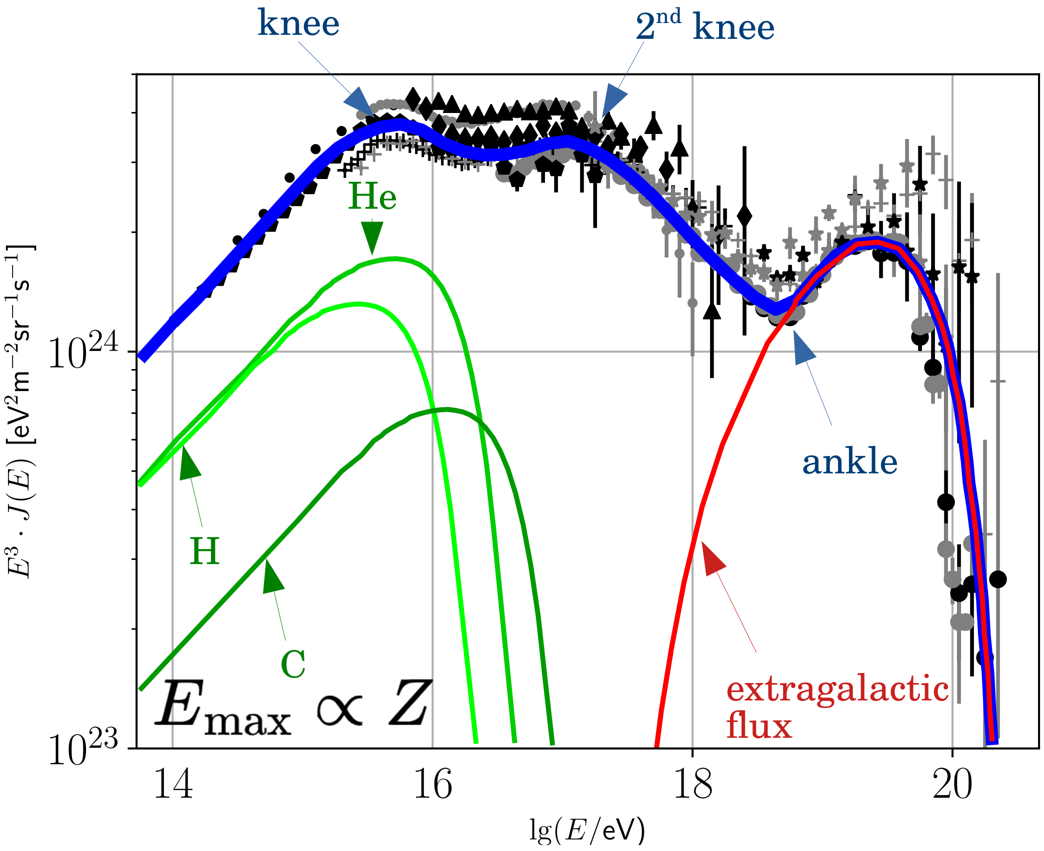

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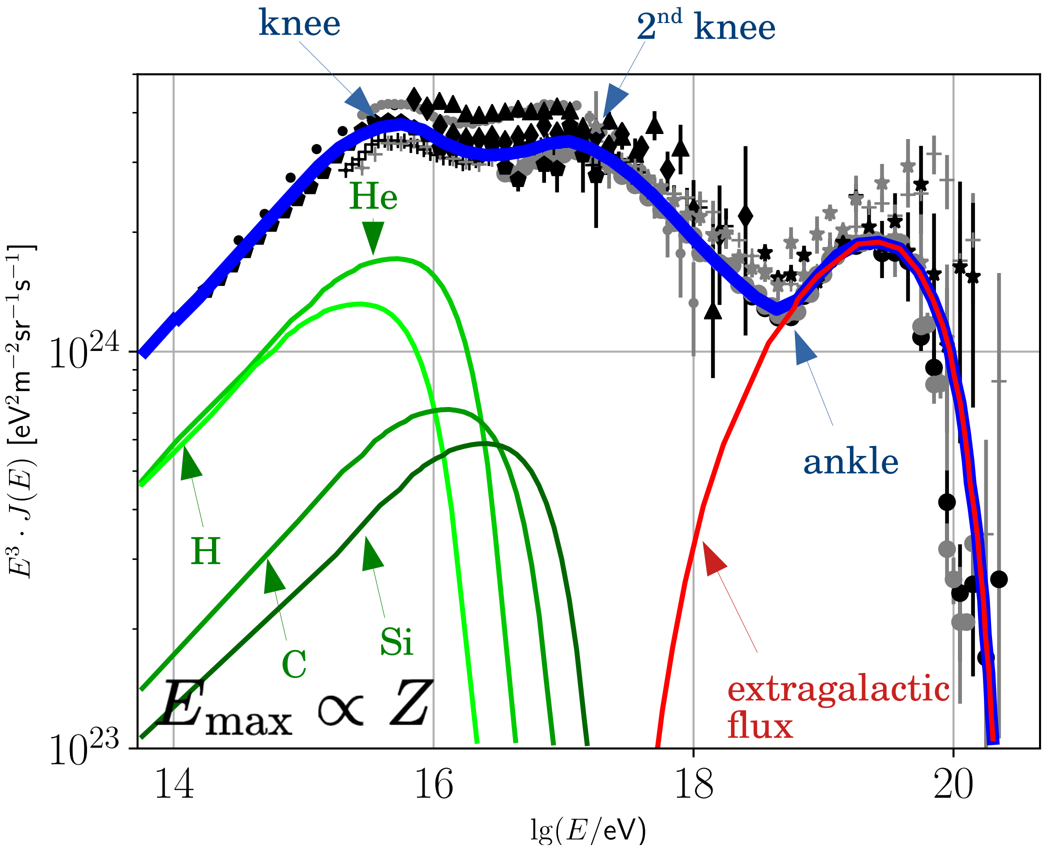

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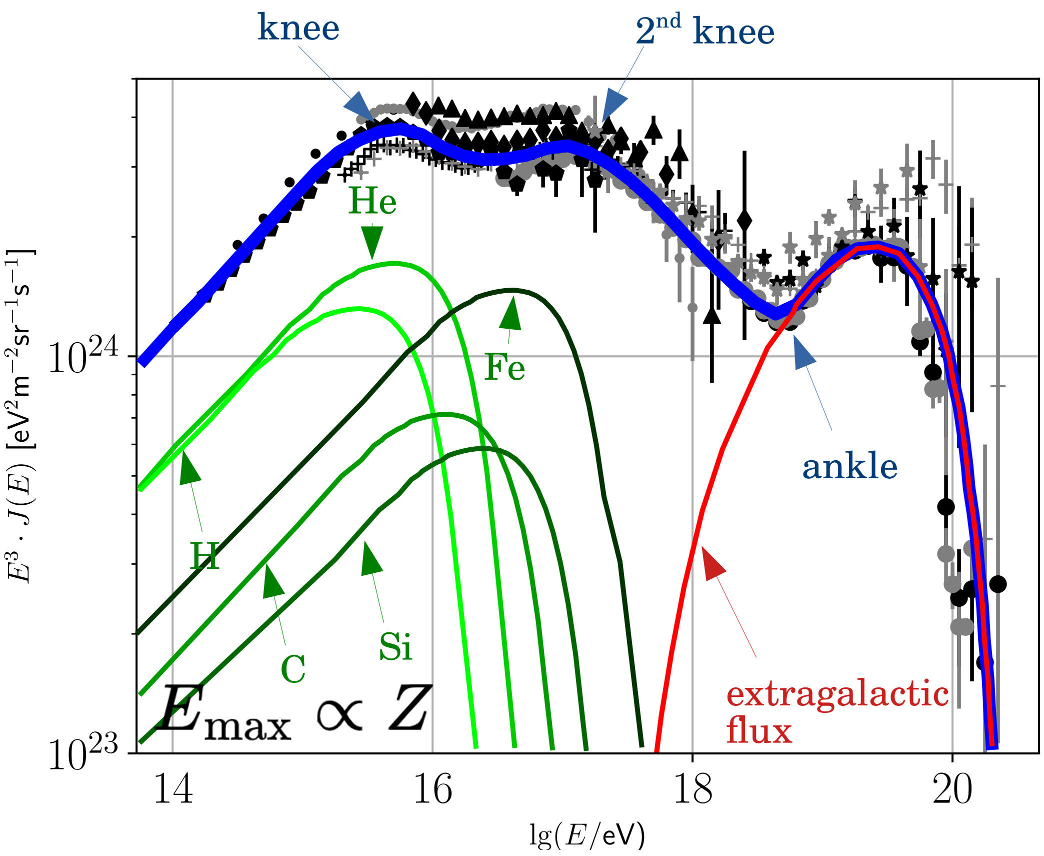

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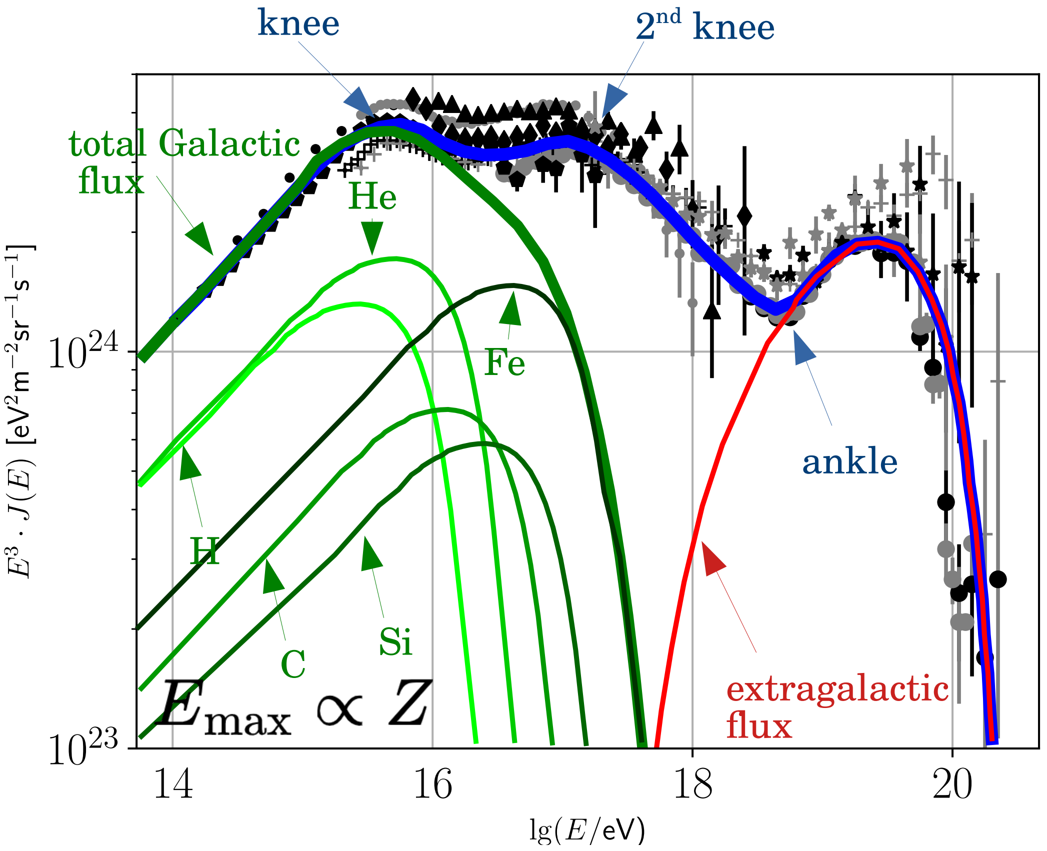


Cosmic ray composition

Compositio
dependent:

- heavier
- maximu
- minimu
- **increas**
high-ene

Increasing
→ **rigidity-**

- source p
acceler
- **propag**
magneti

Interlude:

At ultra-high energies, cosmic ray composition is measured via:

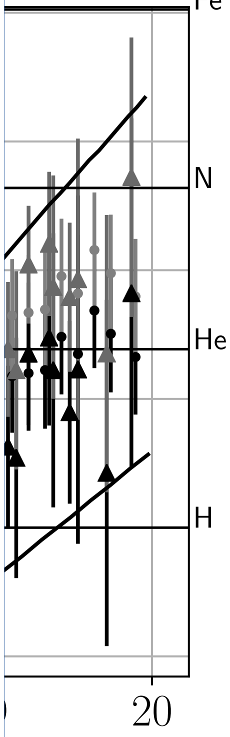
$$\langle \ln A \rangle = \sum_i f_i \cdot \ln A_i$$

A_i: nuclear mass number of nucleus i = H, He, …, Fe

f_i: fraction of nucleus i to total flux

- Measure of mean mass of flux

(2016) A33



Cosmic ray composition

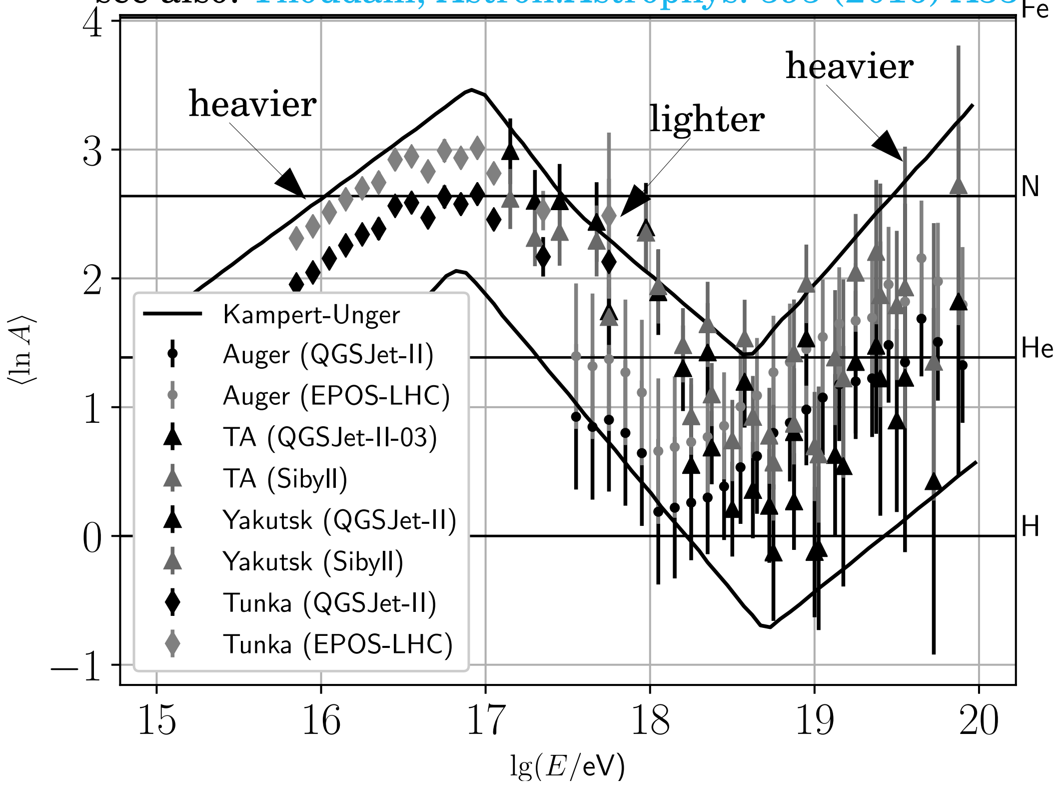
Composition highly energy-dependent:

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

Increasing mean mass
→ **energy-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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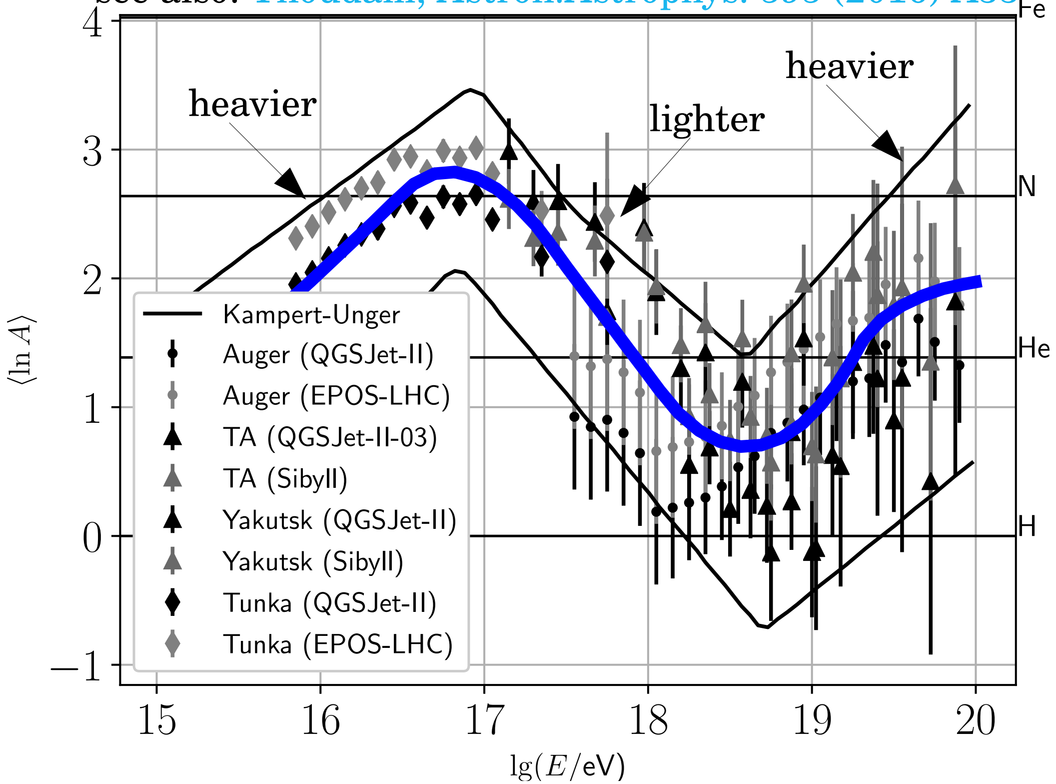


“All” data in one look

Composition:

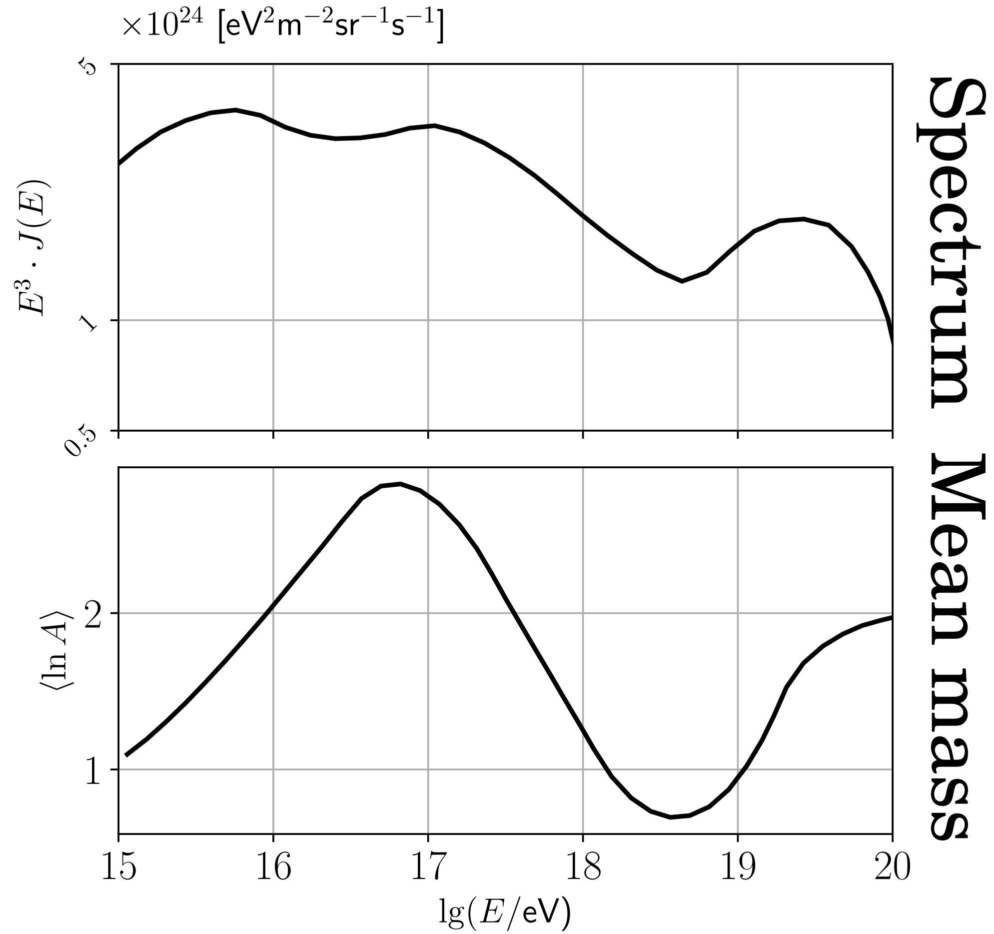
- What **explains ‘2nd knee’** if maximum mean mass is reached well before?
- Why does the composition become **lighter up to the ‘ankle’**?

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)?**

Simulation:

- (Qualitatively) **reproduce features**



Computational challenges and requirements

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

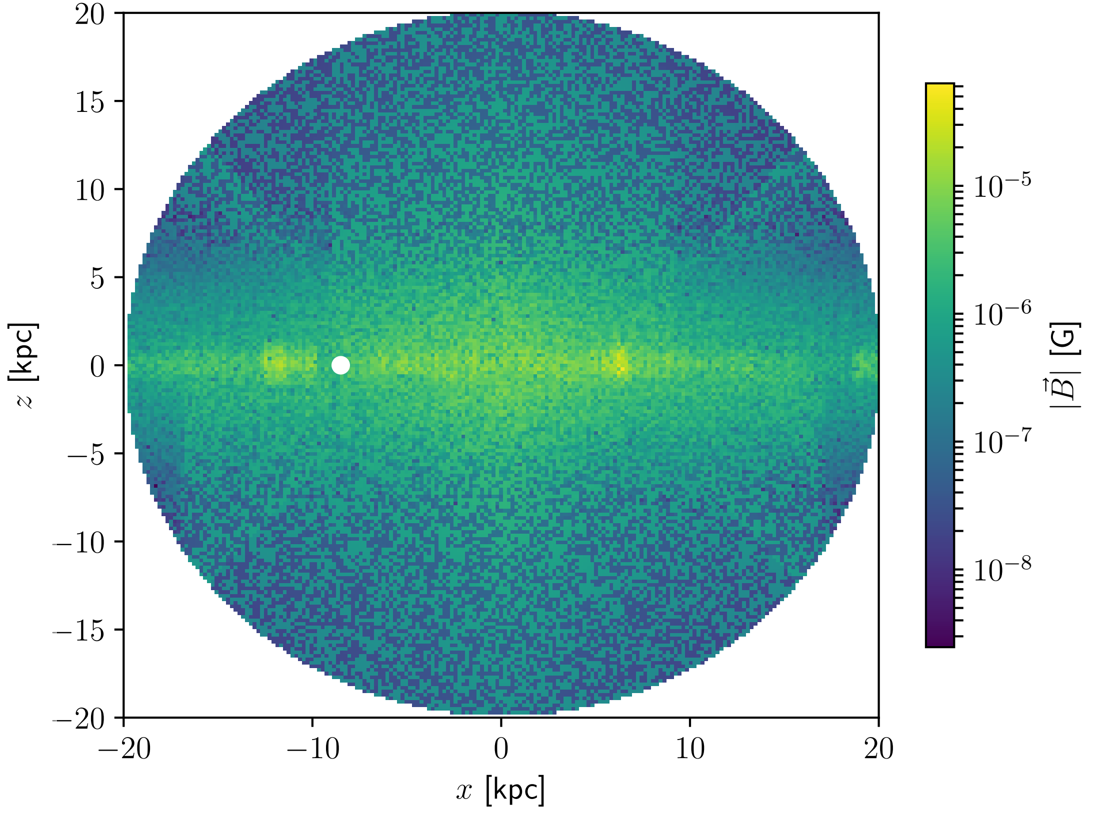
Gyroradius r_g:

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

Transition region = **change in propagation regimes**

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

x-z projection of JF12 field



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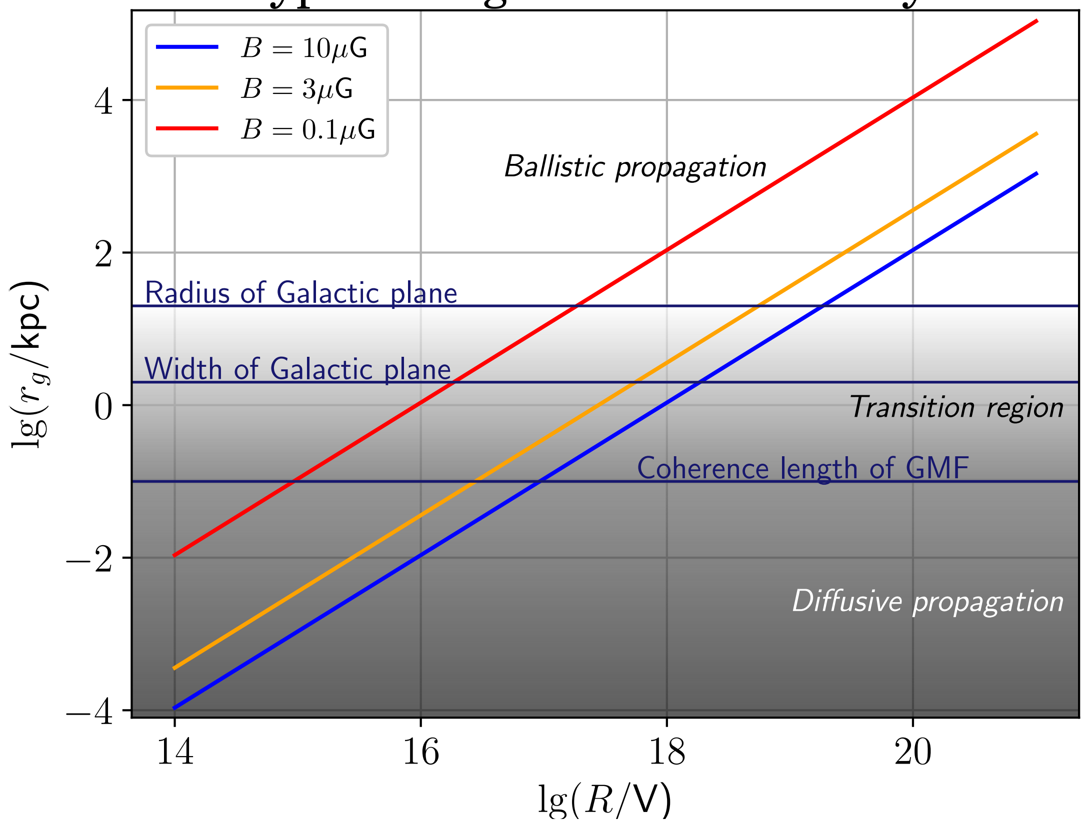

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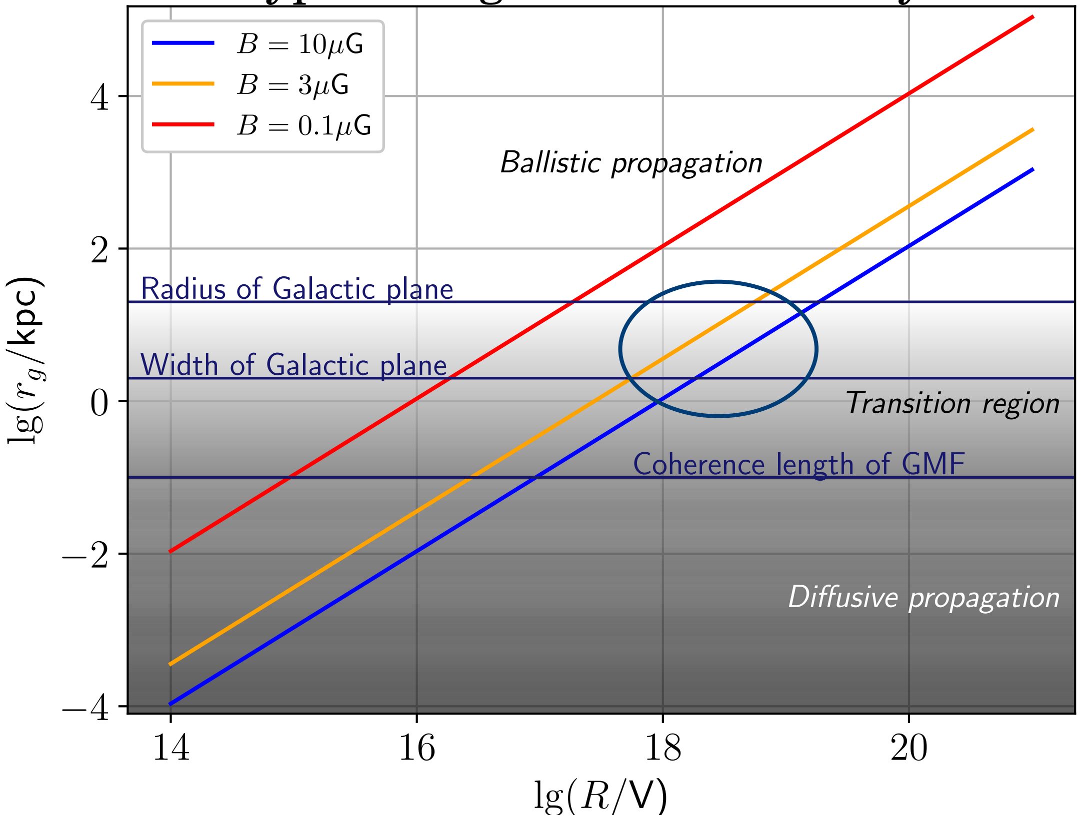


Ballistic propagation

Solve equation of motion:

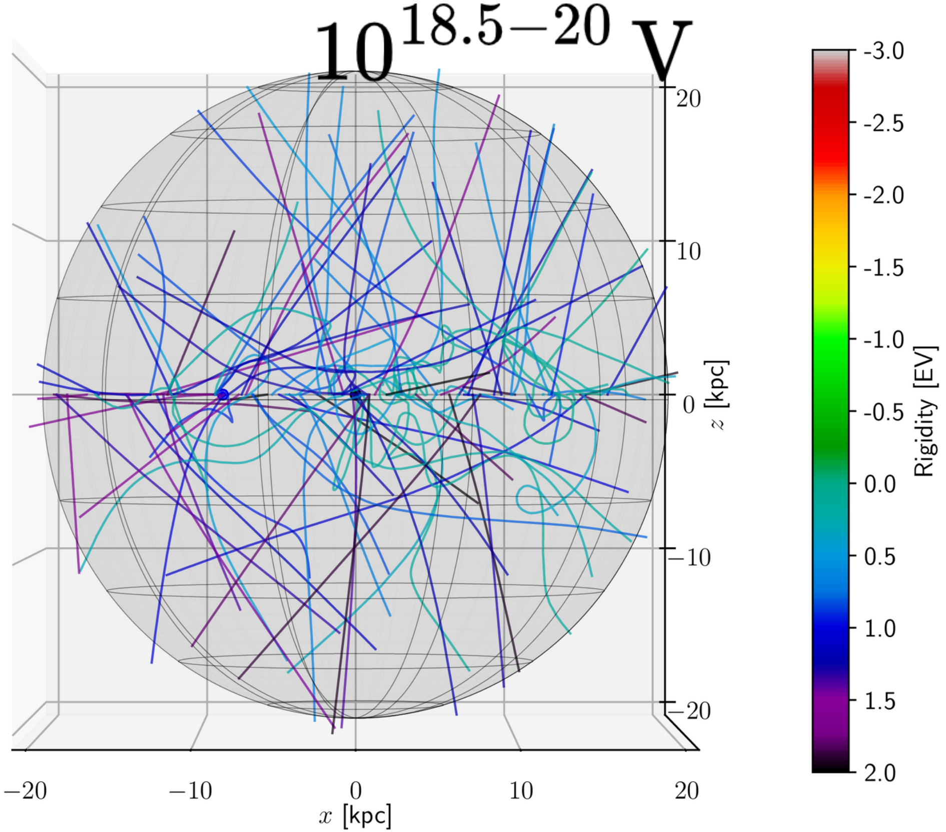
$$\ddot{\vec{r}} = \frac{q}{E/c^2}\left(\vec{v}\times\vec{B}\right)$$

- 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

BUT:

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

Trajectories of ballistically propagating GCRs



Ballistic propagation

Solve equation of motion:

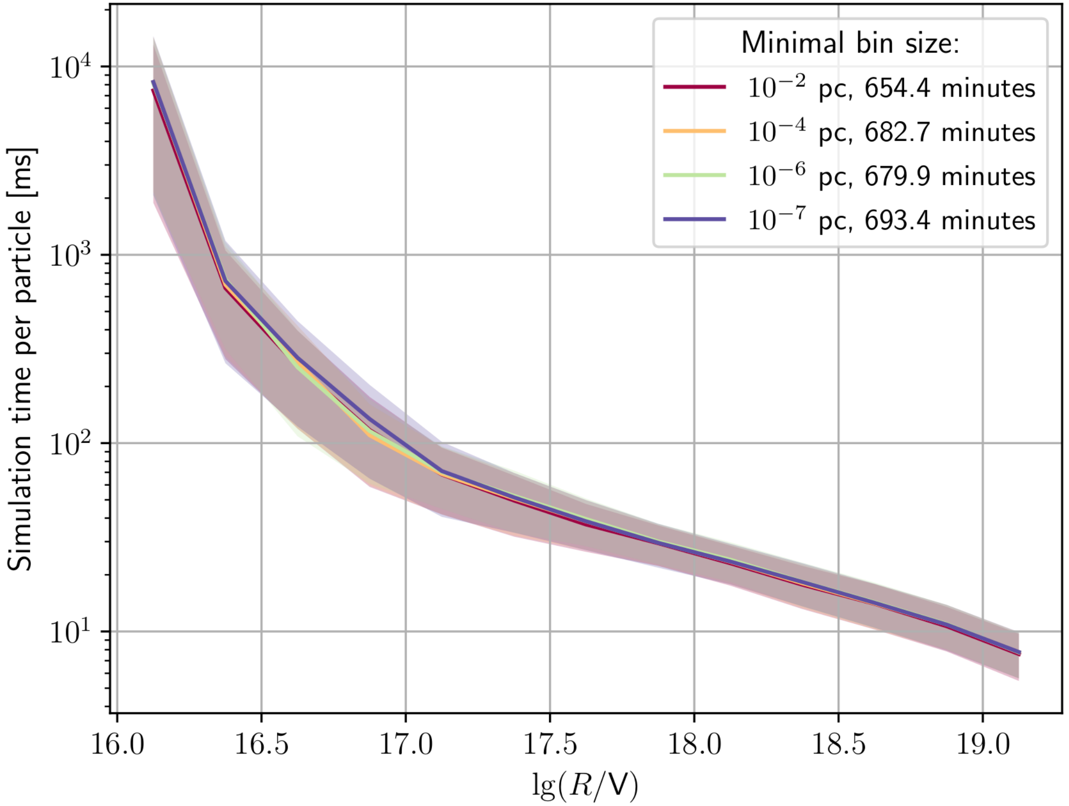
$$\ddot{\vec{r}} = \frac{q}{E/c^2} \left(\vec{v} \times \vec{B}\right)$$

- 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

BUT:

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

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



Diffusive propagation

Solve transport equation:

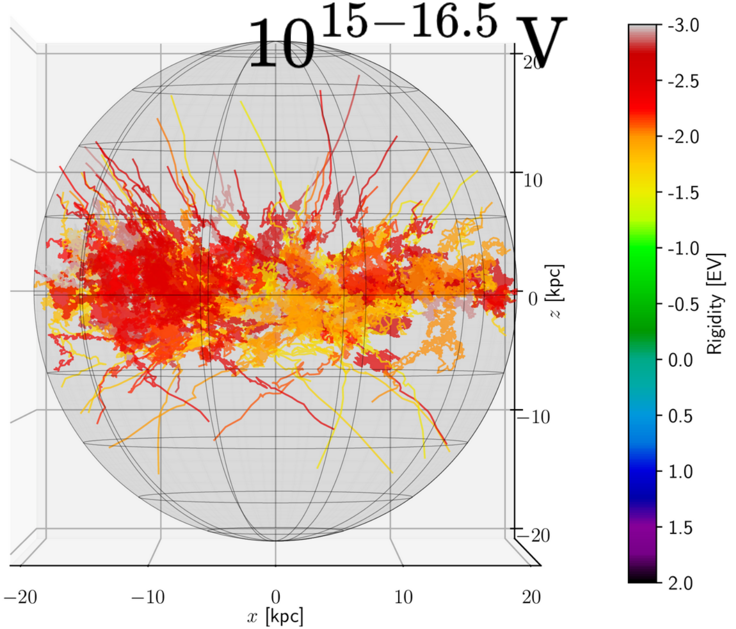
$$\frac{\partial n_l}{\partial t} = \sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left[\left(D_{jk}\cdot\frac{\partial}{\partial x_k}\right) n_l\right] - \frac{\partial}{\partial x_j}[u_j \cdot n_l] + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{n_l}{p^2}\right)\right]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

- multi-particle approach:
  - change of momentum density (macroscopic view)
- best suited when r_g is small & turbulent B-field component dominant
- generally shorter computation times

NOTE:

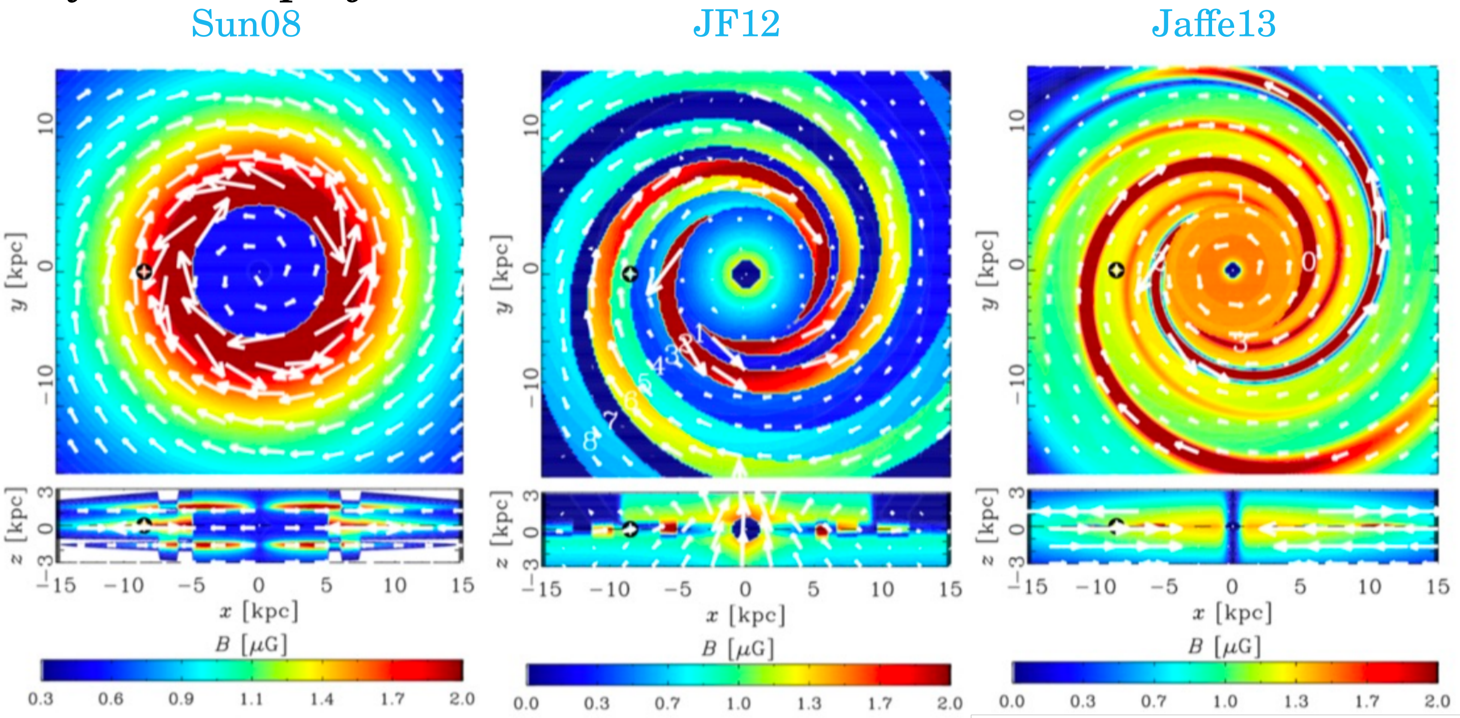
- CRPropa 3 has implement diffusive propagation module via SDEs (JCAP 06 (2017) 046)
- For a full description of the transition region both propagation methods must be applied

Trajectories of diffusively propagating GCRs



Major challenge: GMF model

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



GMF not well known:

- field strength inferred indirectly via observables → uncertainty in quantities, contamination
- ad hoc assumptions necessary (simplifications): morphological features (spiral arms, halo field), field components (regular, turbulent etc.)

Combating the transition region: Propagation in the GMF

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 are Galactic centre)

Source properties:

- $\boldsymbol{R}^{-1}$ injection spectrum, lg(R/V) = **16.0 – 20.0**

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Sources and observers

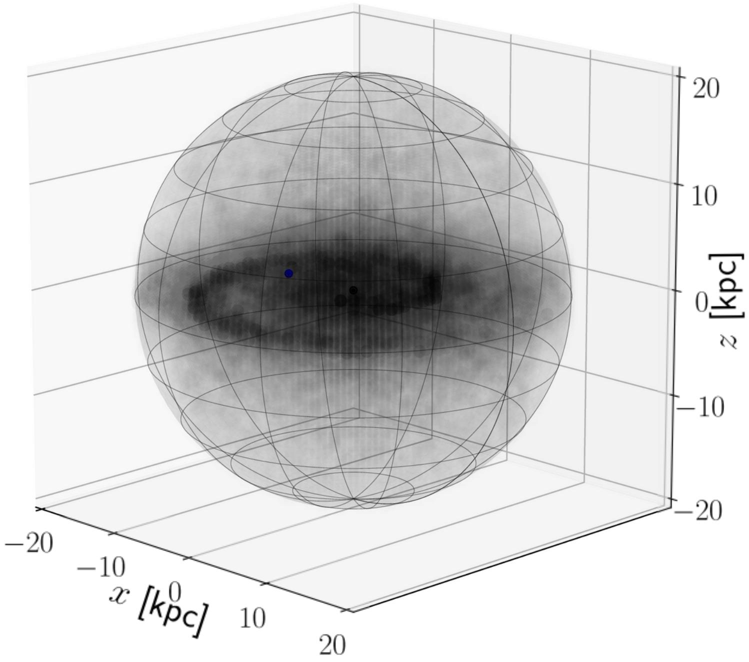
Sources:

- 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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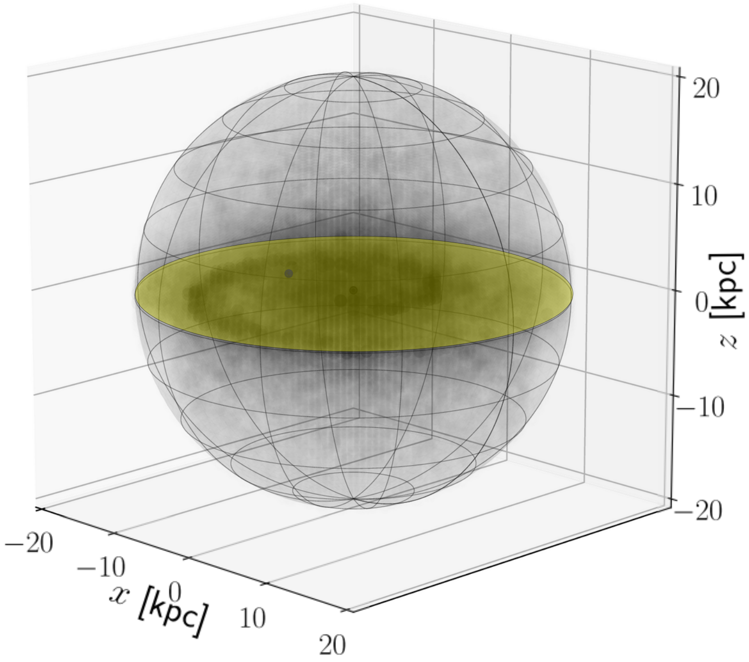
GCR source distribution



Sources and observers

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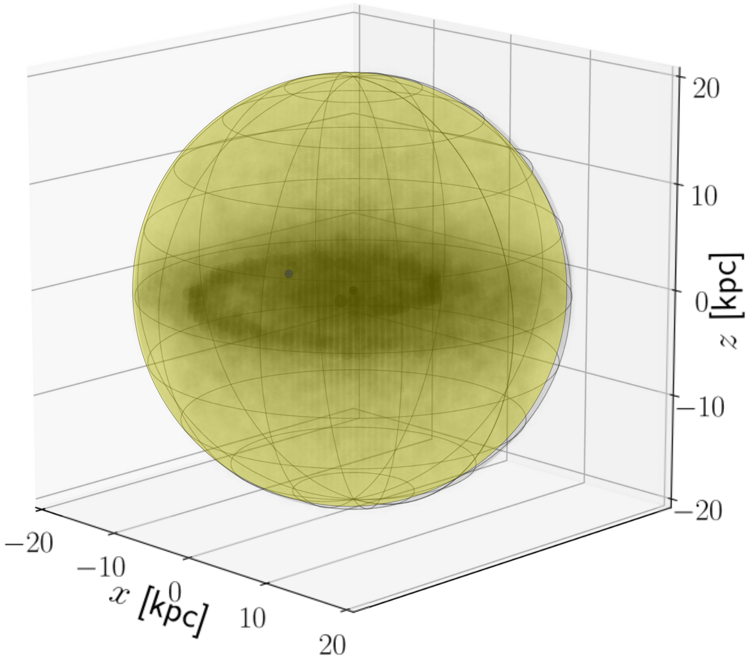
EGCR source distribution



Sources and observers

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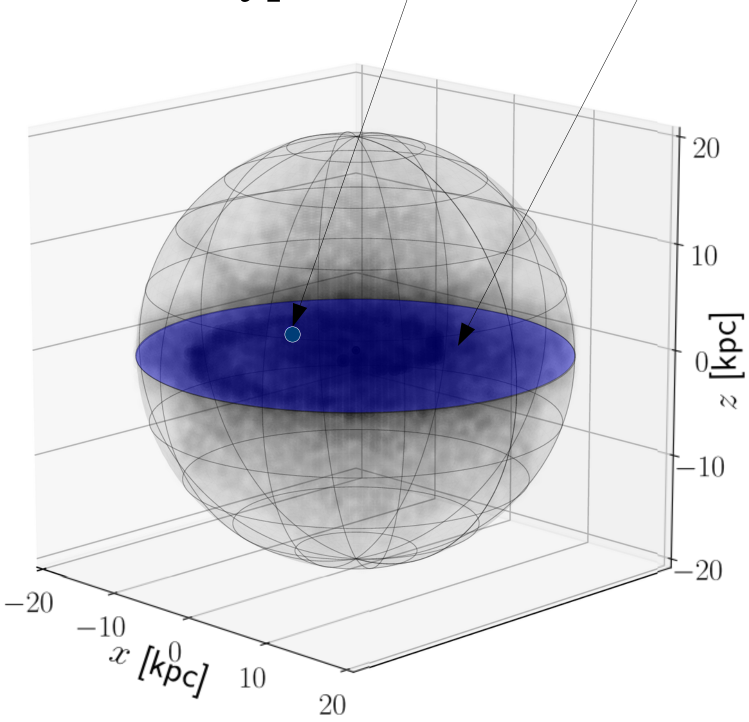
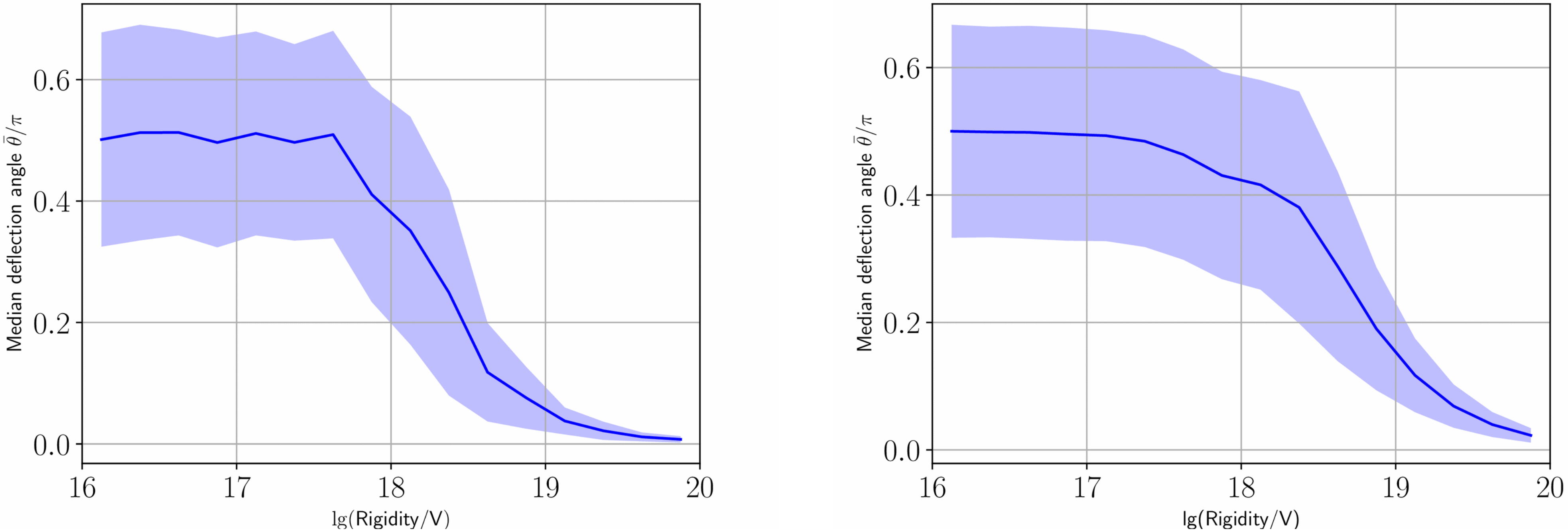
Observer types: Earth and GP



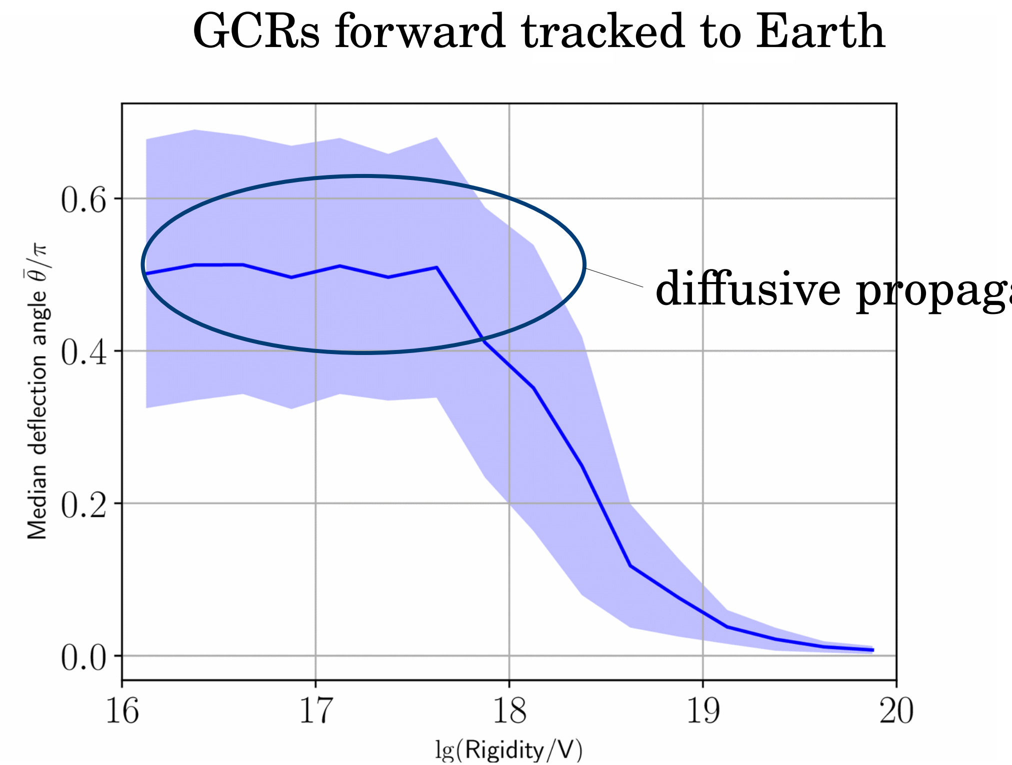
Change in propagation regimes: Deflection angle

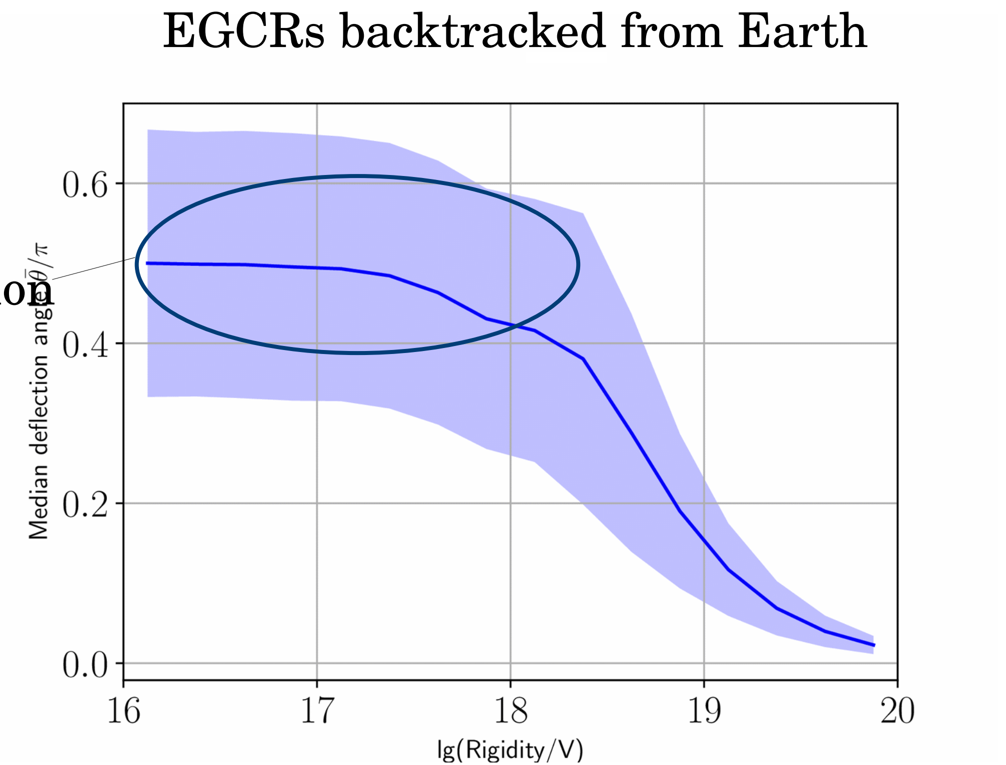
GCRs forward tracked to Earth | EGCRs backtracked from Earth



θ = π/2 for lg(R/V) ≤ 17 → **diffusive** propagation
(see also: Erdman, Astropart.Phys. 85 (2016) 54-64)

Change in propagation regimes: Deflection angle





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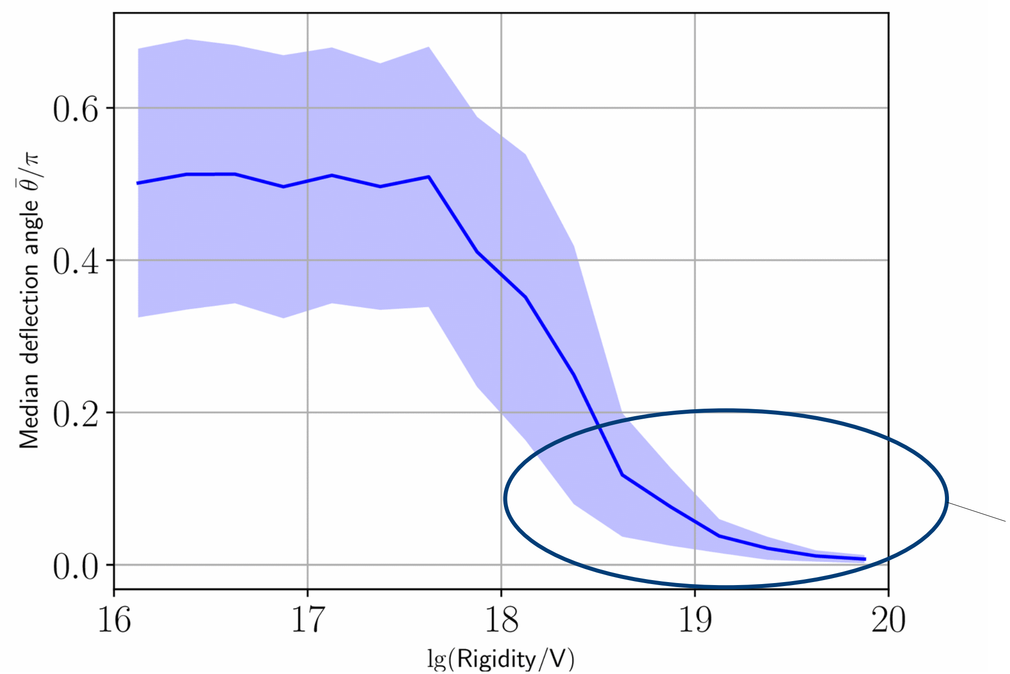
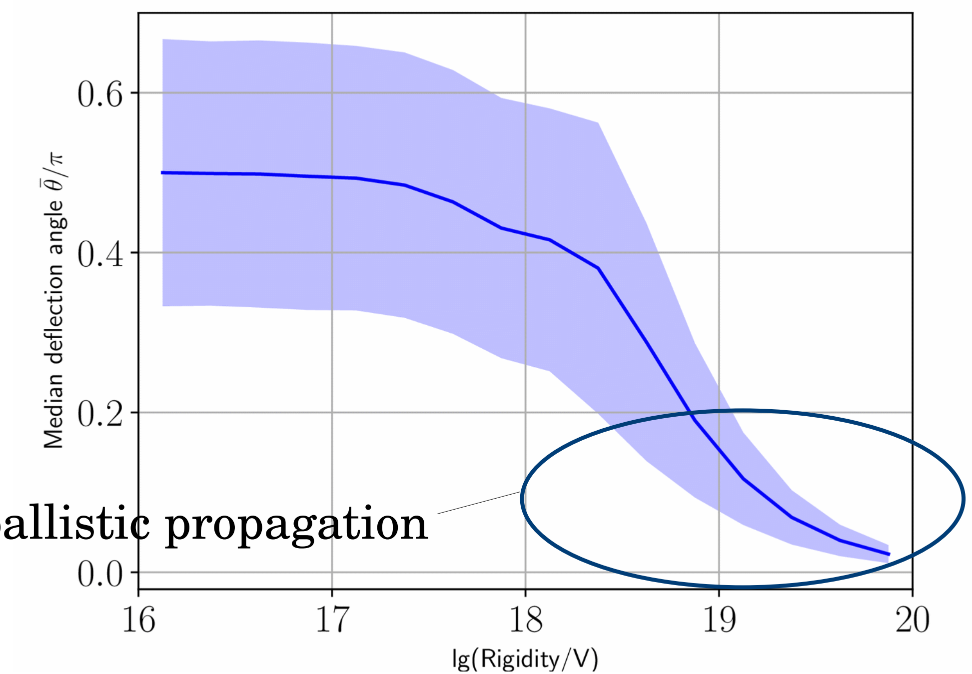
Change in propagation regimes: Deflection angle

GCRs forward tracked to Earth



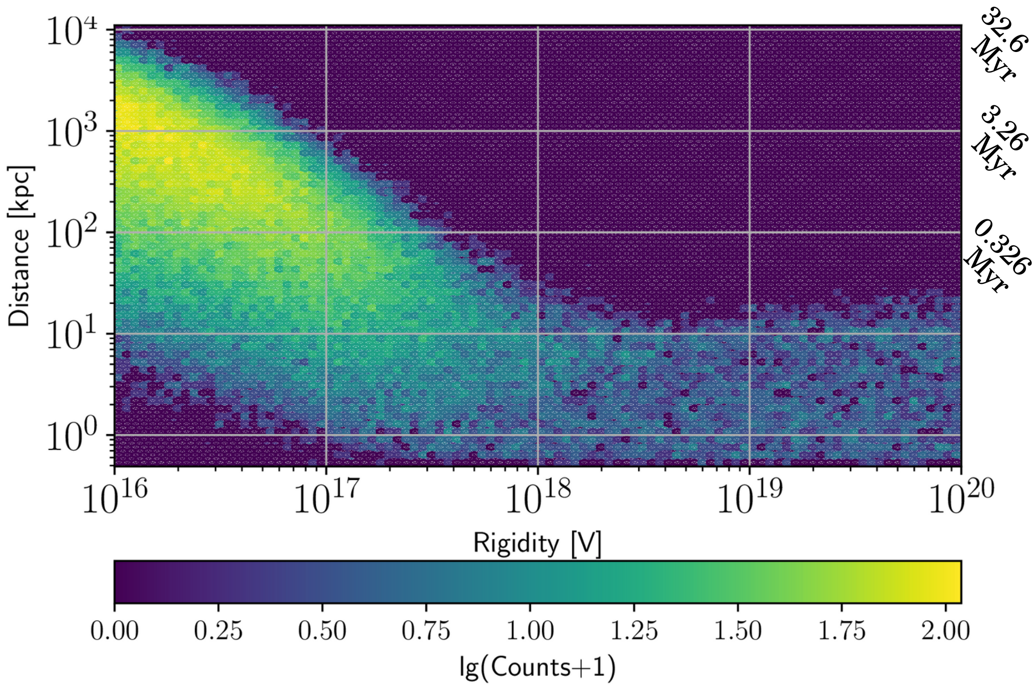
EGCRs backtracked from Earth



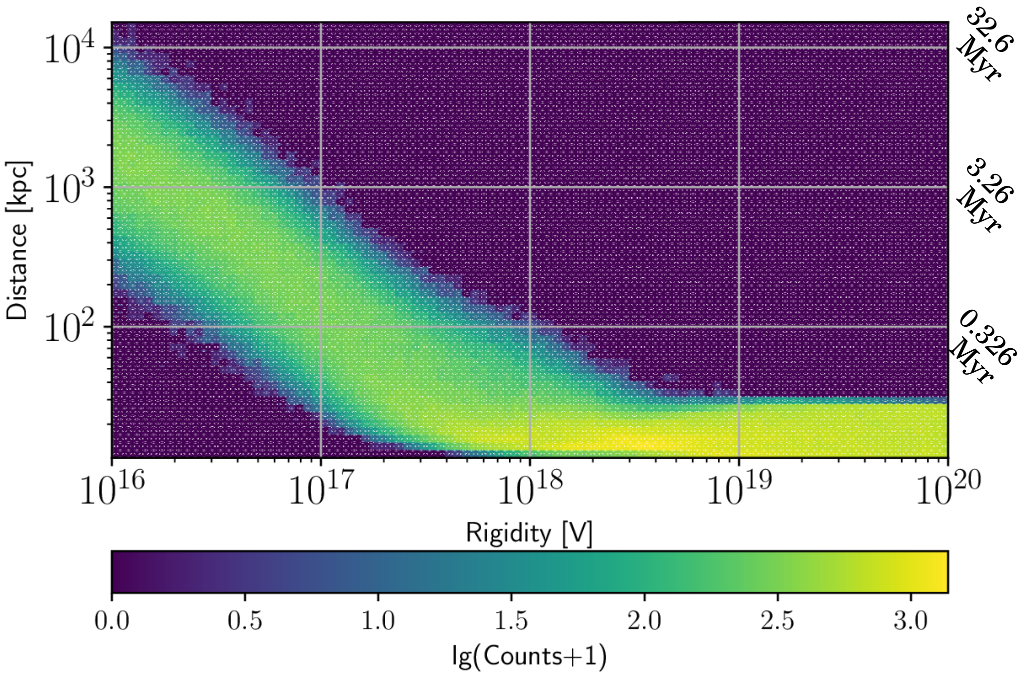
θ = π/2 for lg(R/V) ≤ 17 → **diffusive** propagation
(see also: Erdman, Astropart.Phys. 85 (2016) 54-64)

Change in propagation regimes: Propagation time

GCRs forward tracked to Earth

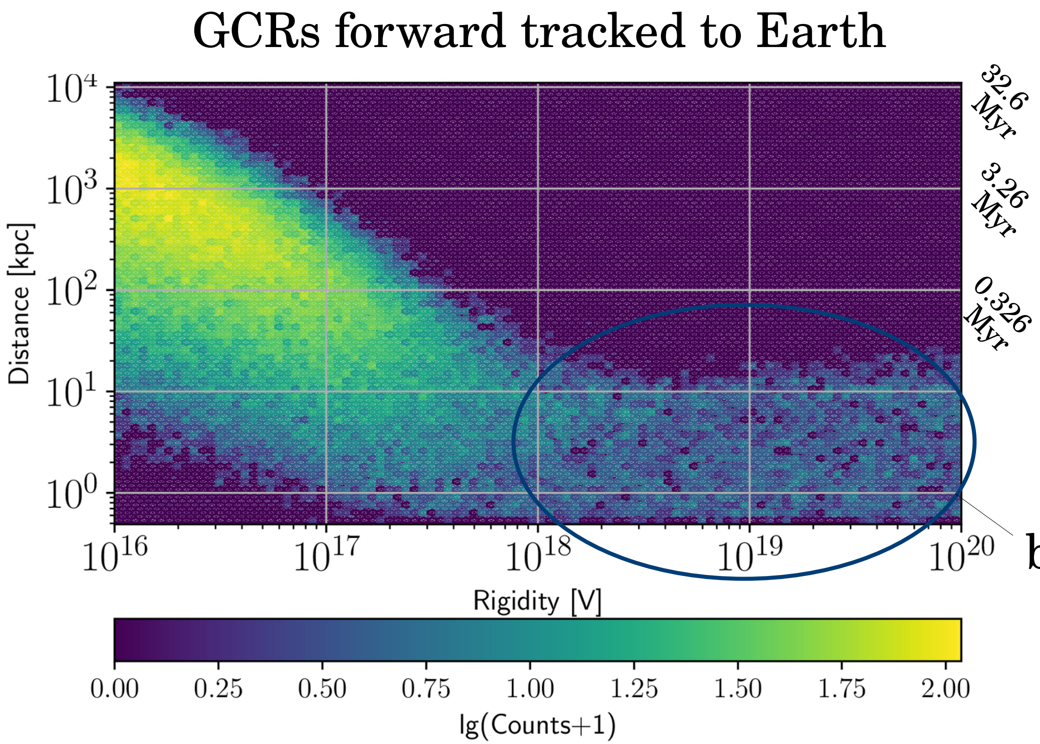


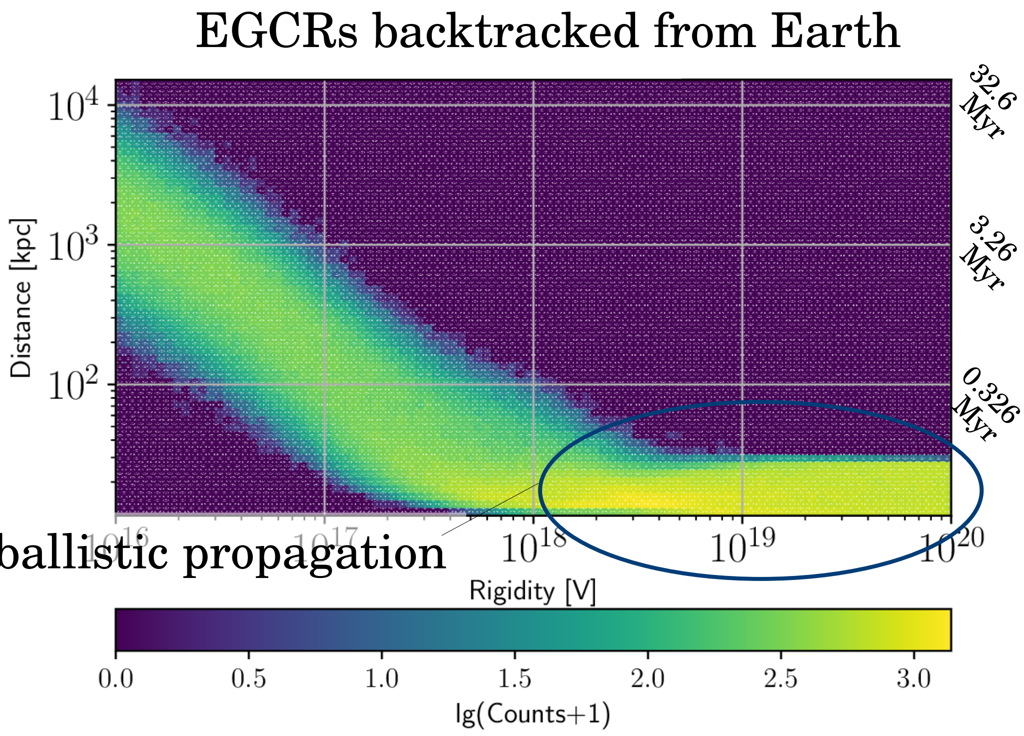
EGCRs backtracked from Earth



Propagation time increases below rigidities of a few EV.

Change in propagation regimes: Propagation time

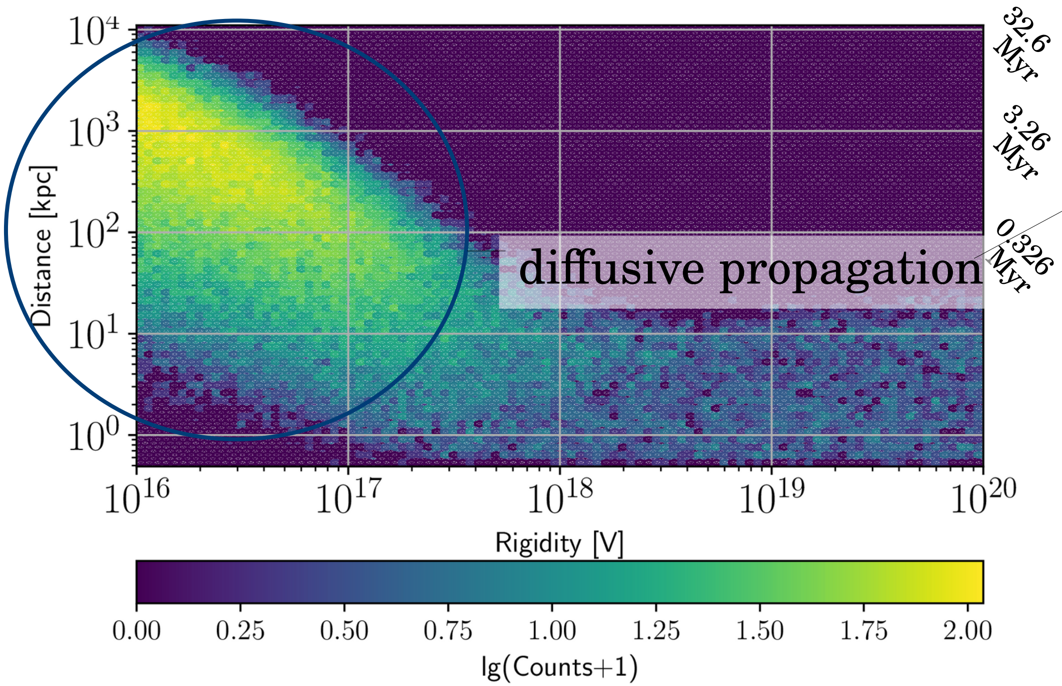




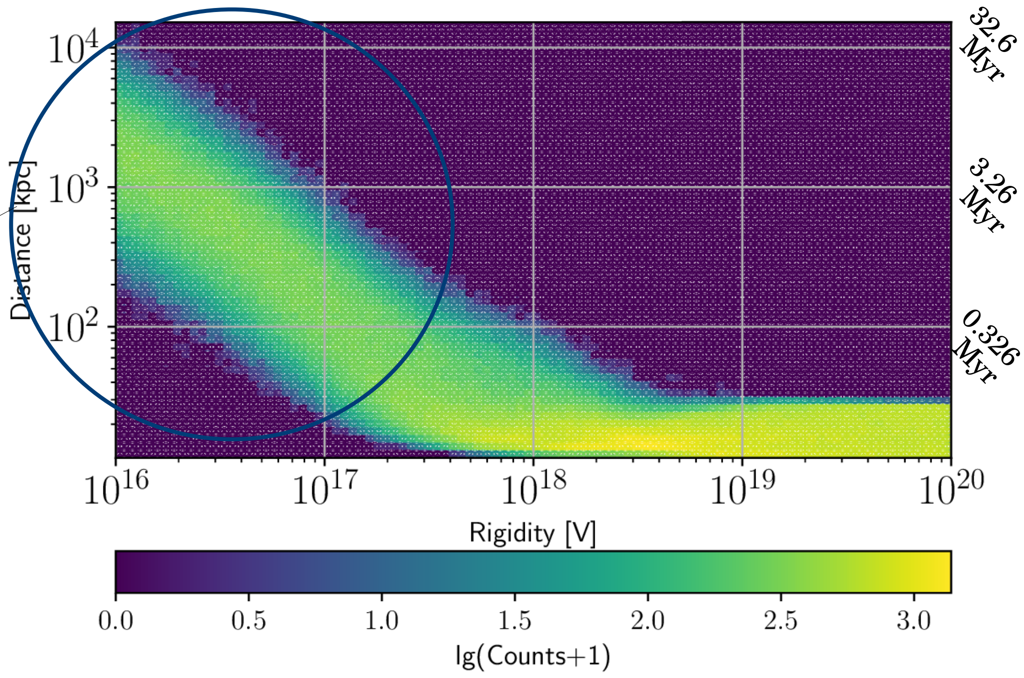
Propagation time increases below rigidities of a few 1 EV.

Change in propagation regimes: Propagation time

GCRs forward tracked to Earth

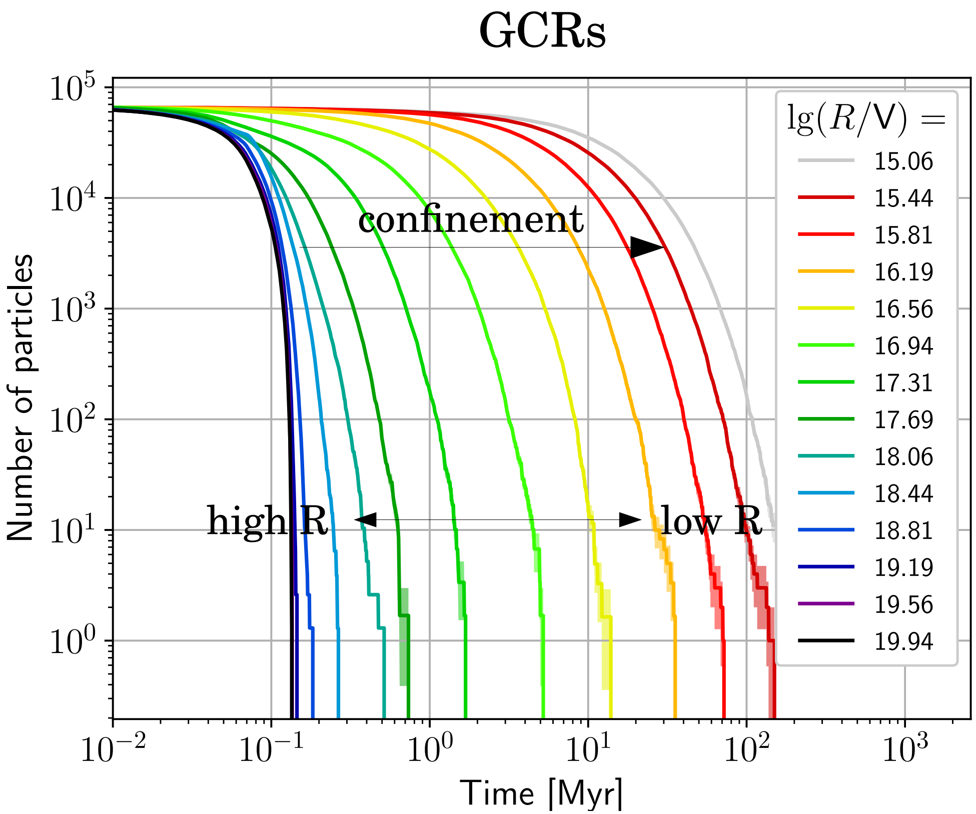


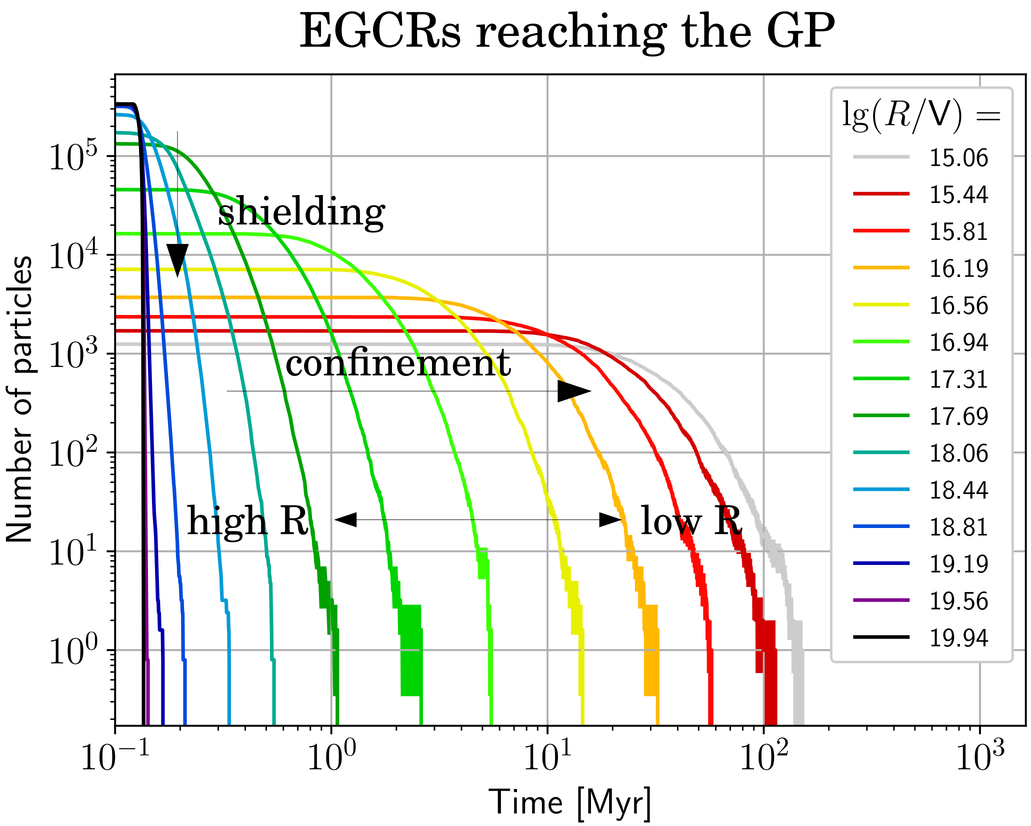
EGCRs backtracked from Earth



Propagation time increases below rigidities of a few 1 EV.

Propagation effects: Galactic residence time

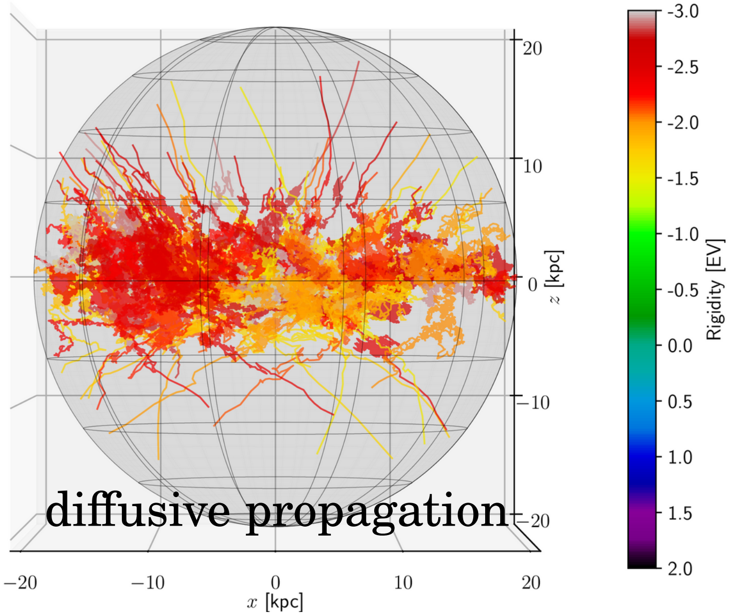




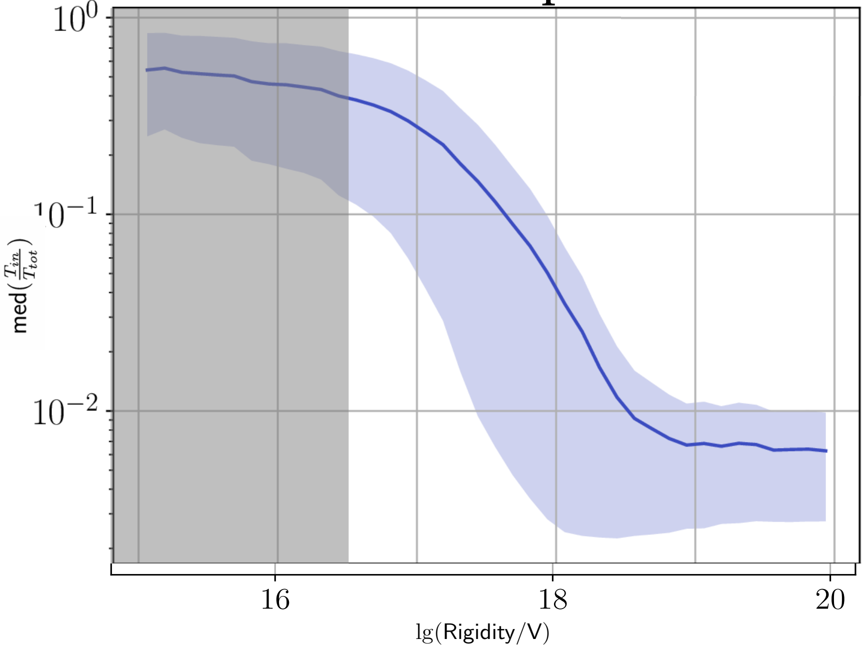
NOTE: Lowest-rigidity particles have residence times up to 100 Myr.

Propagation effects: GCRs – Confinement in GP

Galactic trajectories (lg(R/V) = 15 – 16.5)



Relative time spent in GP

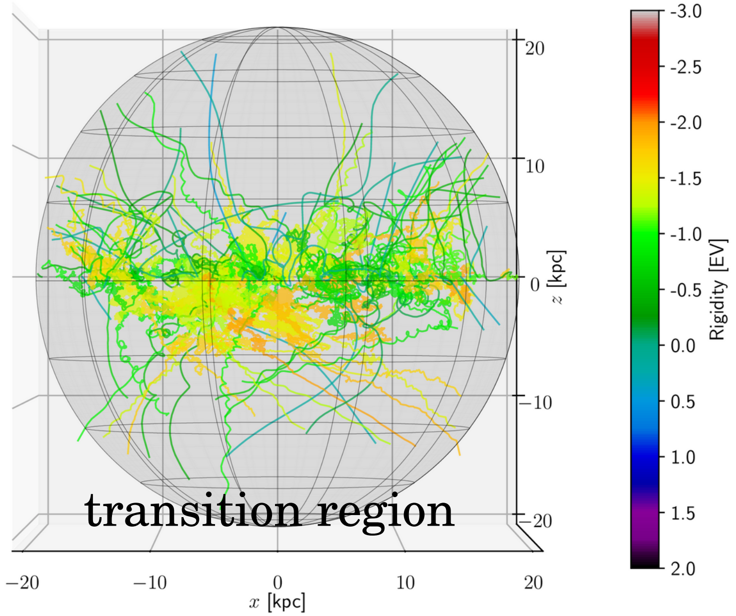


Decreasing confinement in GP **with rigidity.**

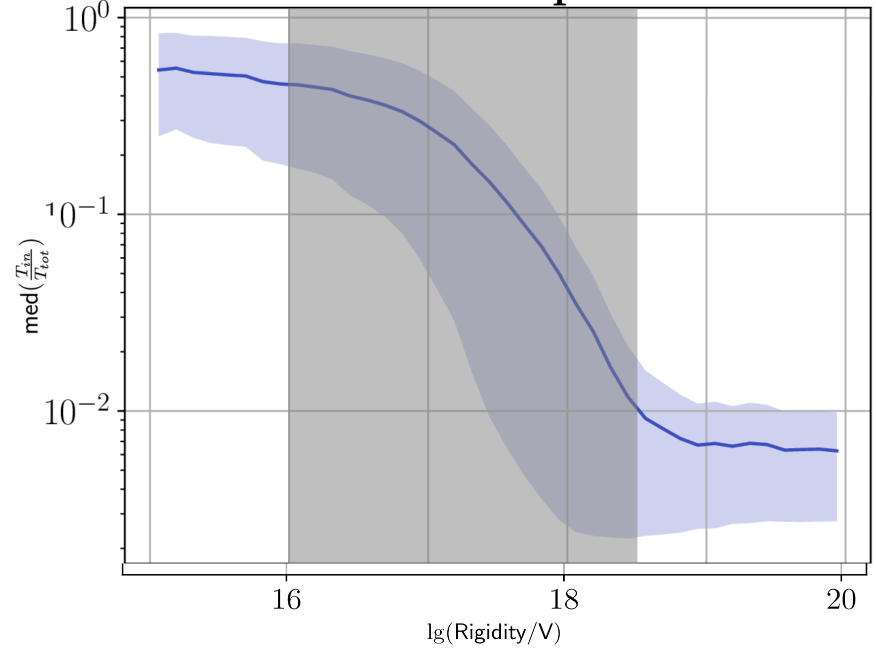
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: GCRs – Confinement in GP

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



Relative time spent in GP

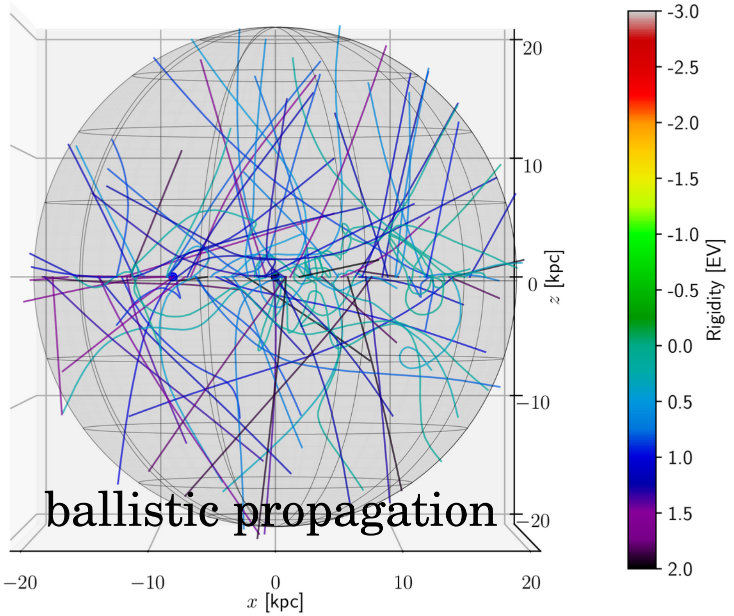


Decreasing confinement in GP **with rigidity.**

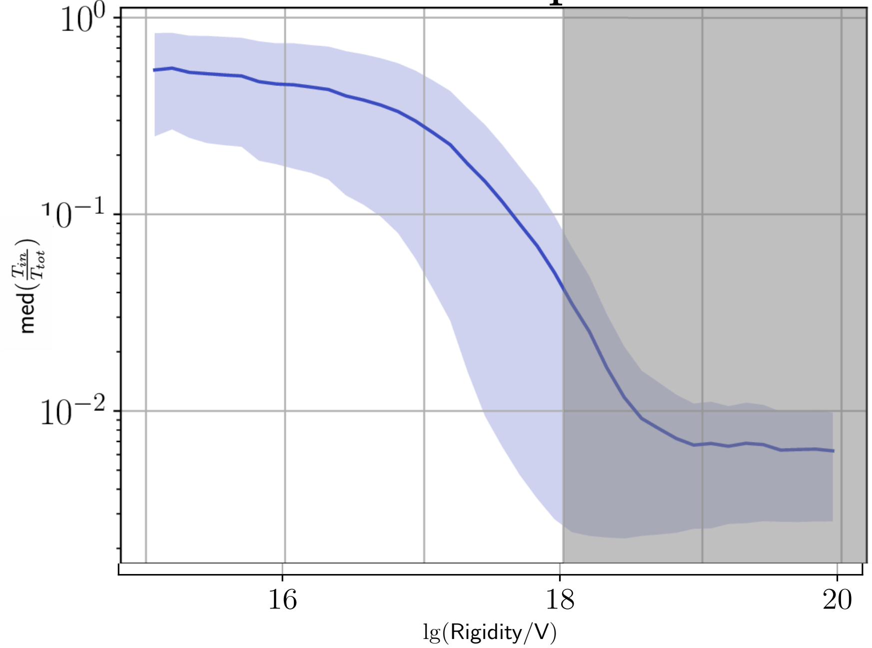
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

Propagation effects: GCRs – Confinement in GP

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



Relative time spent in GP

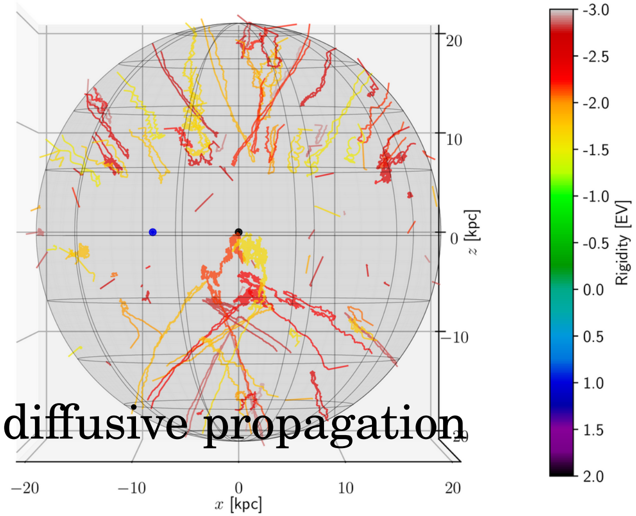


Decreasing confinement in GP **with rigidity.**

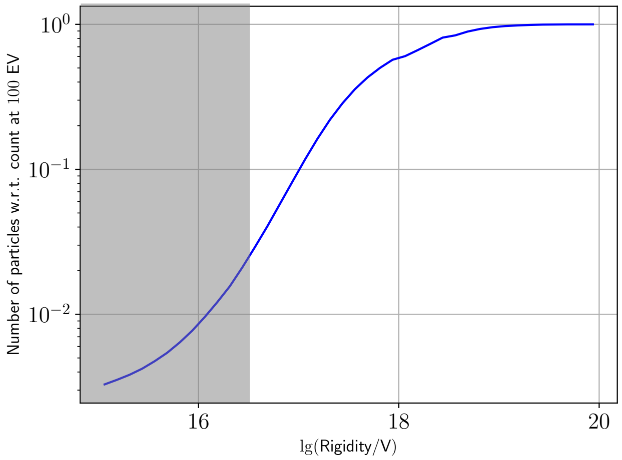
Relative time spent in GP decreases with rigidity; **inflection point at a few EV.**

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

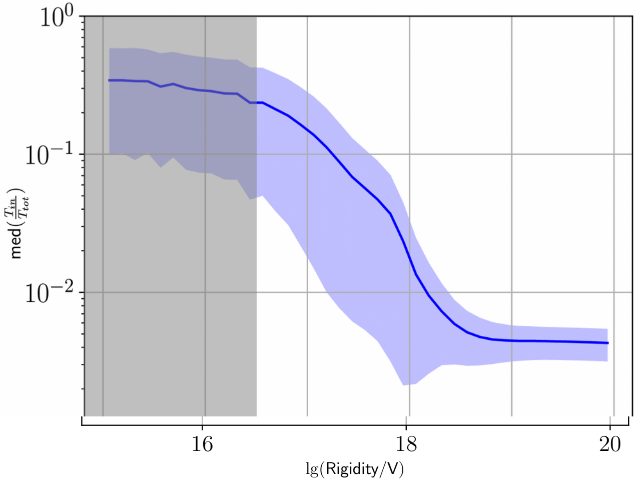
Galactic trajectories
(lg(R/V) = 15 – 16.5)



CR count reaching GP



Relative time spent in GP



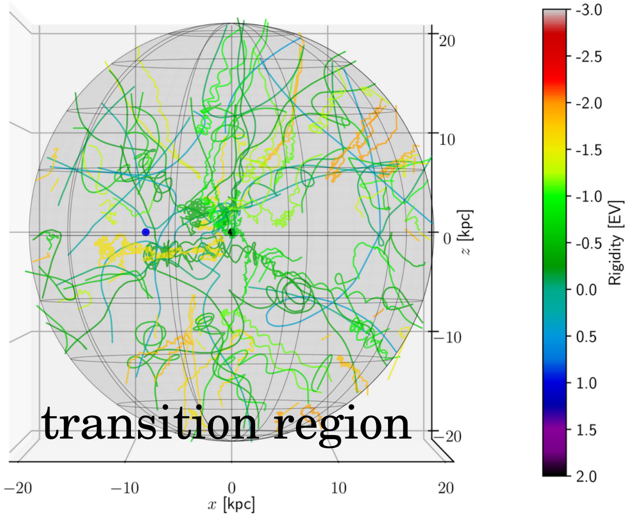
Decreasing shielding from and confinement in GP with rigidity.

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
($\lg(R/\mathrm{V})$ = 16 – 18.5)



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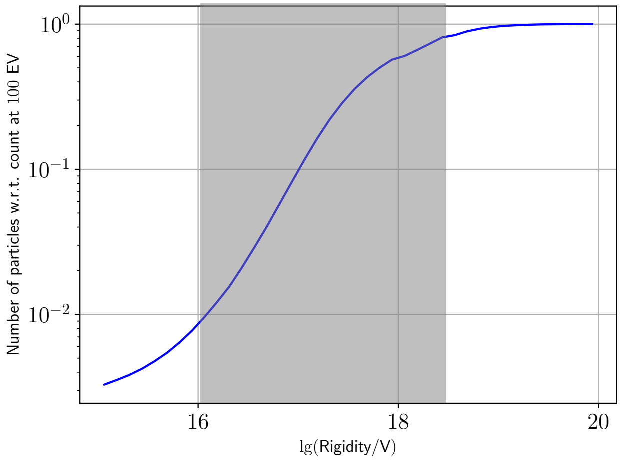
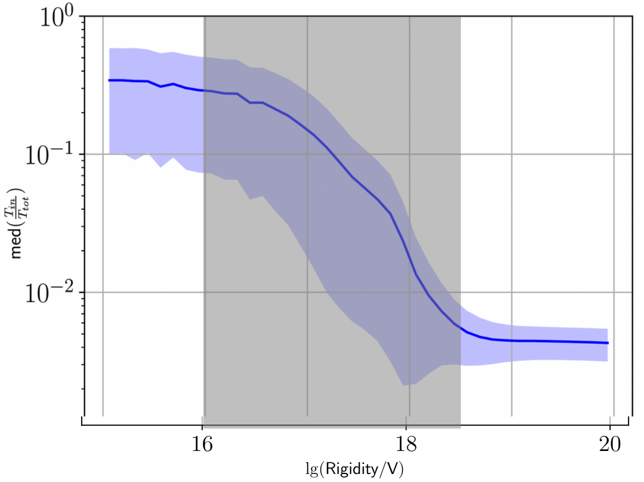


Relative time spent in GP



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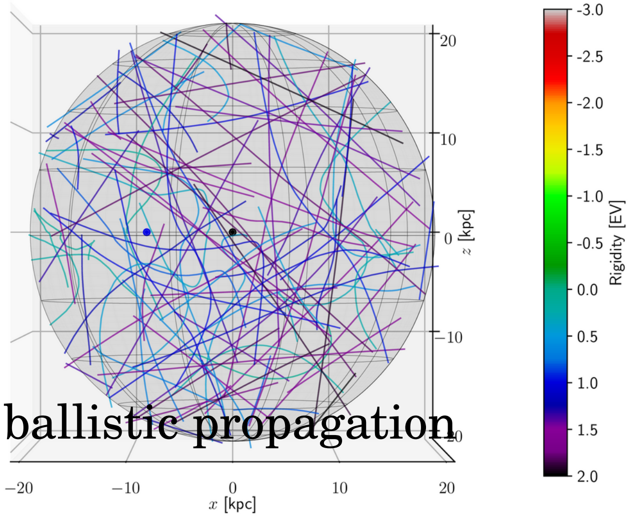
Galactic trajectories
(lg(R/V) = 18 – 20)



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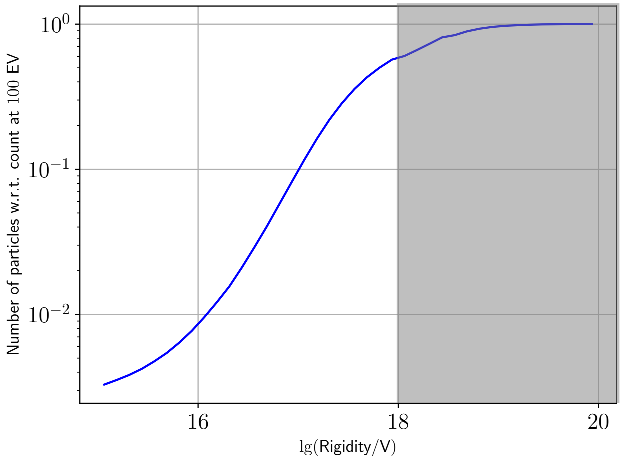

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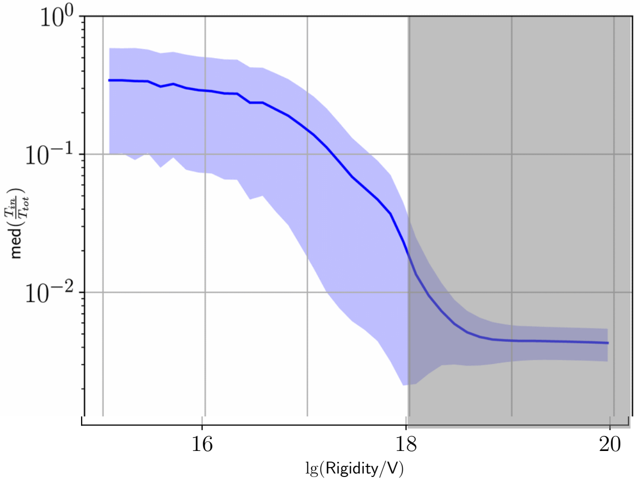


Decreasing shielding from and confinement in GP with rigidity.

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.**

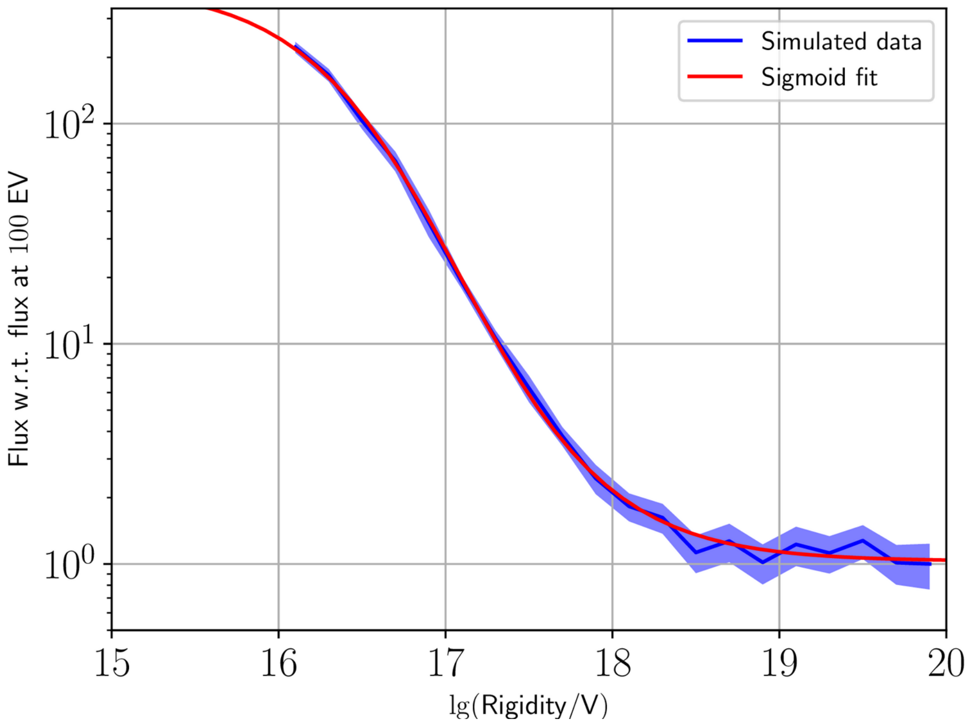
Effect on observables: GCRs – Flux suppression

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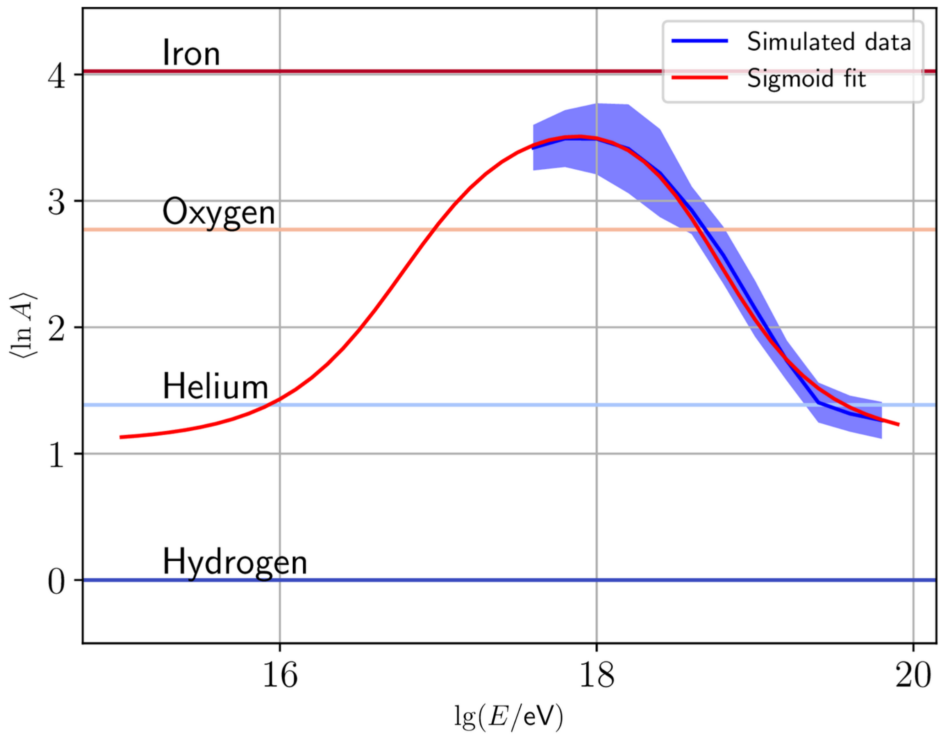
Mixed composition
→ **heavier towards 'ankle'**

Arrival direction distribution:
correlation with GP direction
above 0.1 EV

Mean logarithm of mass number (sigmoid fit)



NOTE: Only propagation effects in GMF!

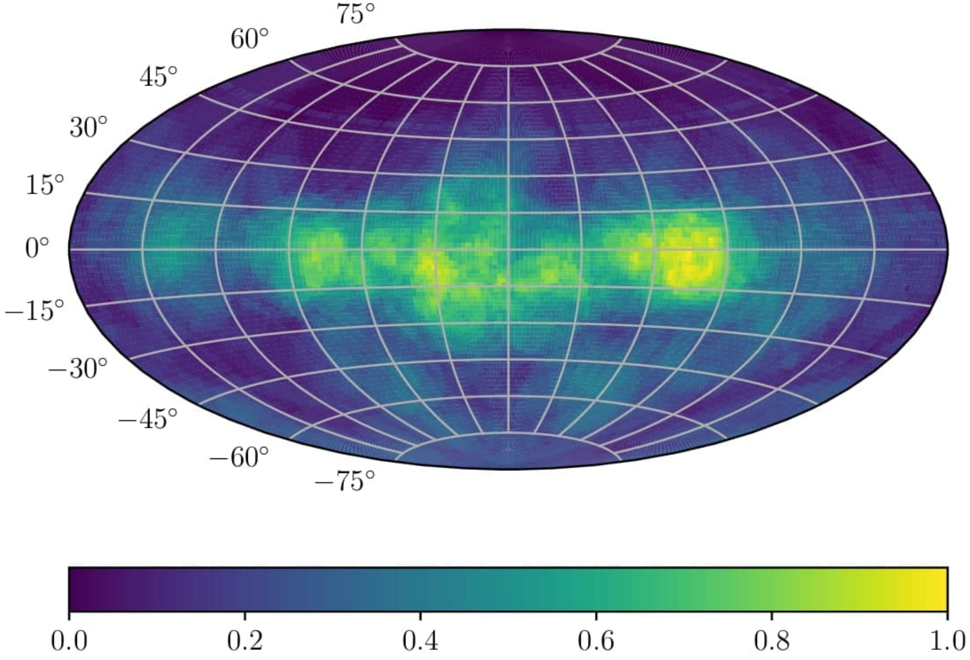
Effect on observables: GCRs – Correlation with source direction (GP)

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

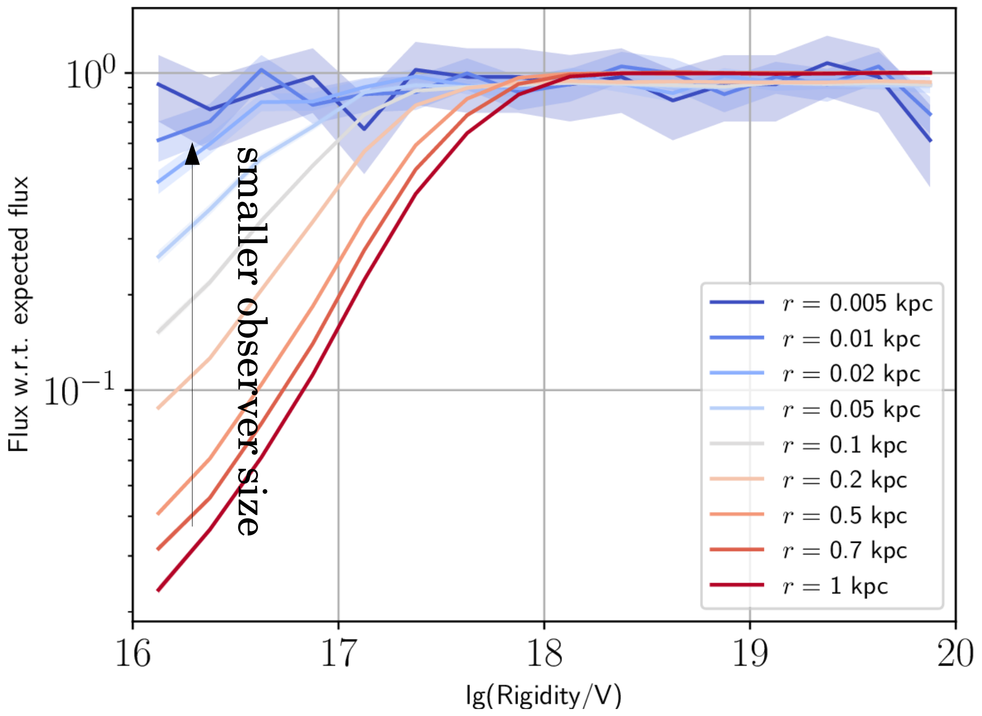
Apparent flux suppression for large observer sphere sizes; effect vanishes as $r \to 0$.

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:

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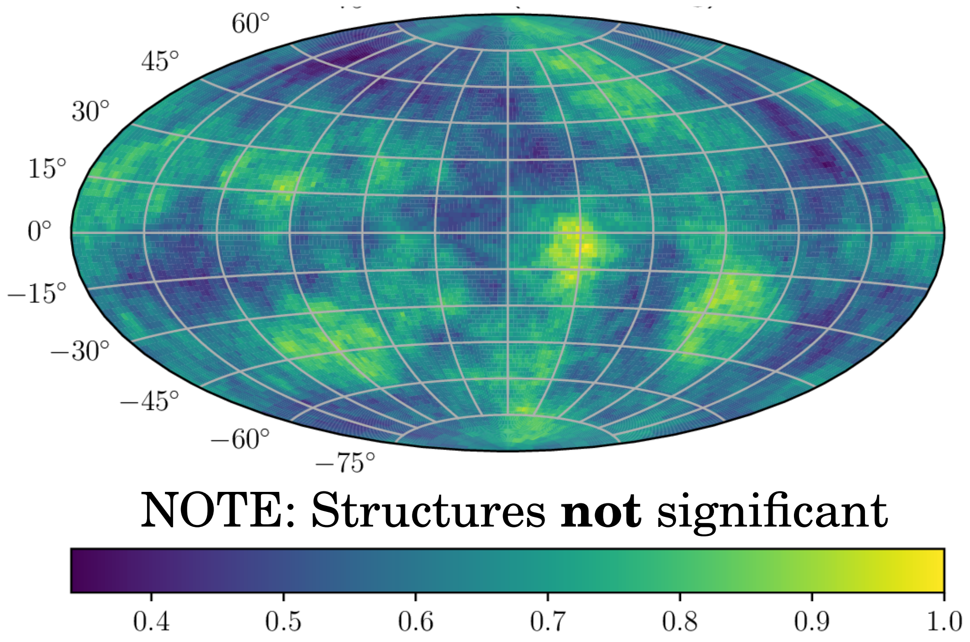
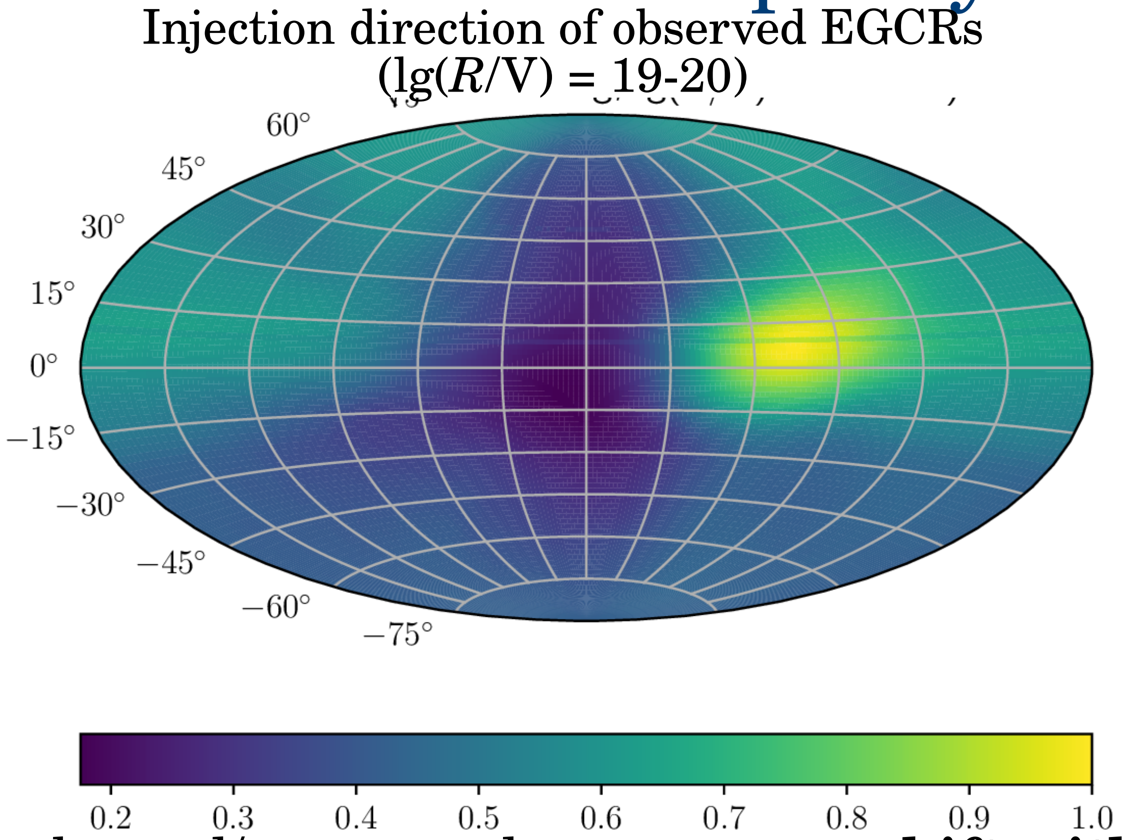
Isotropic arrival direction

Arrival direction distribution



NOTE: Structures **not** significant

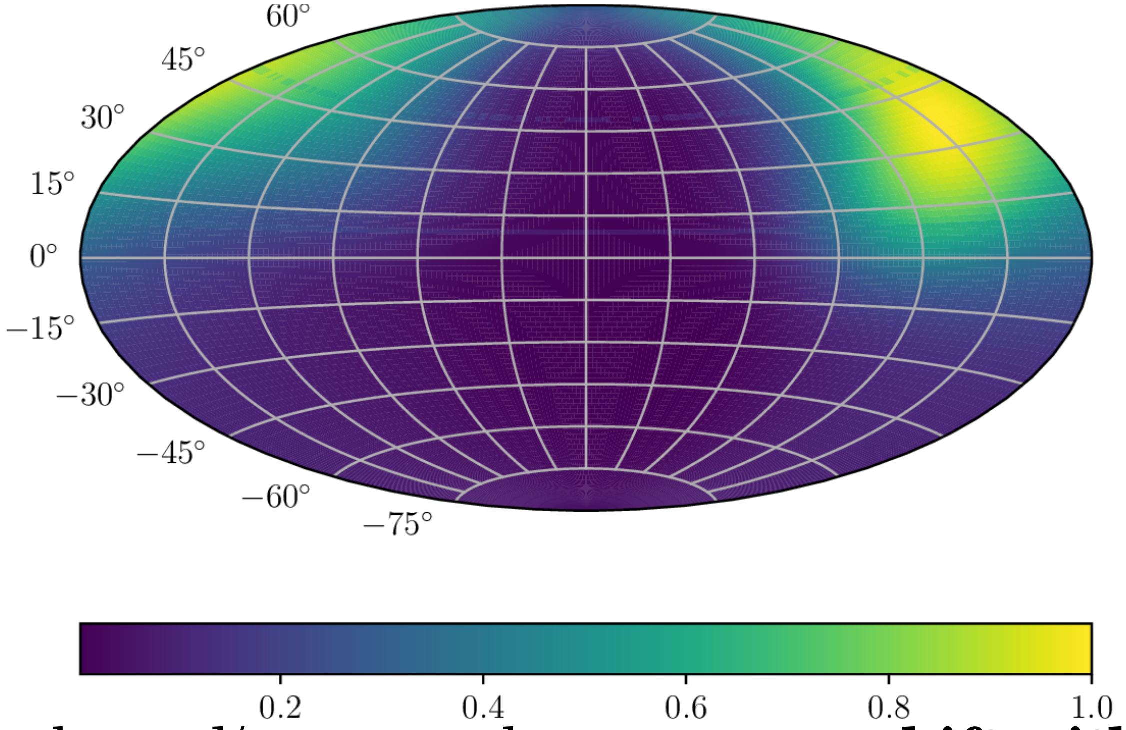
Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy



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

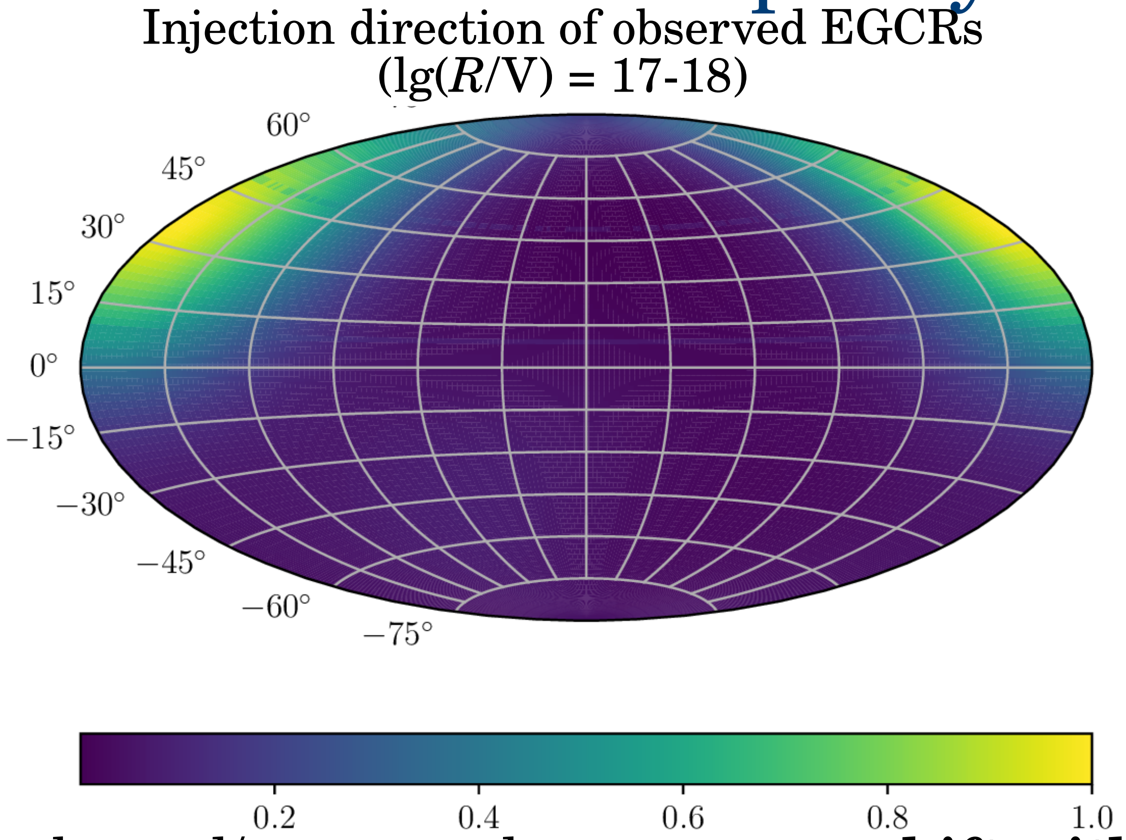
Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy

Injection direction of observed EGCRs
(lg(R/V) = 18-19)



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

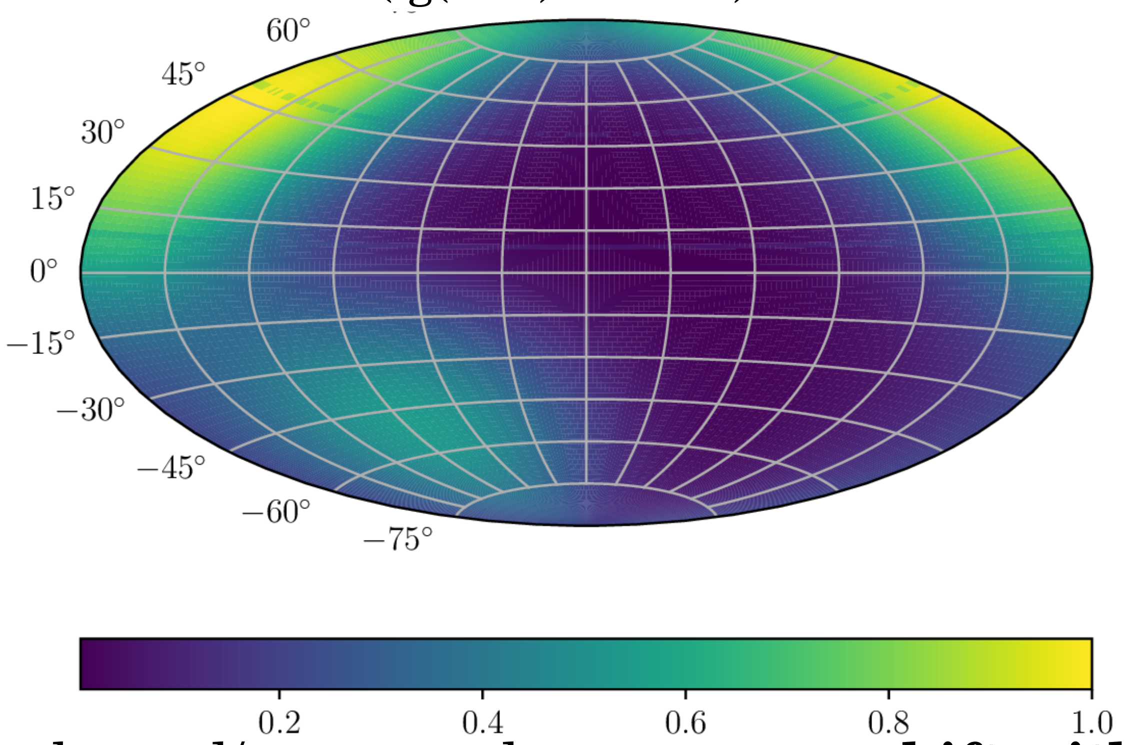
Effect on observables: Anisotropic EGCRs – Why flux modification? Opacity of Galaxy



- 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/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

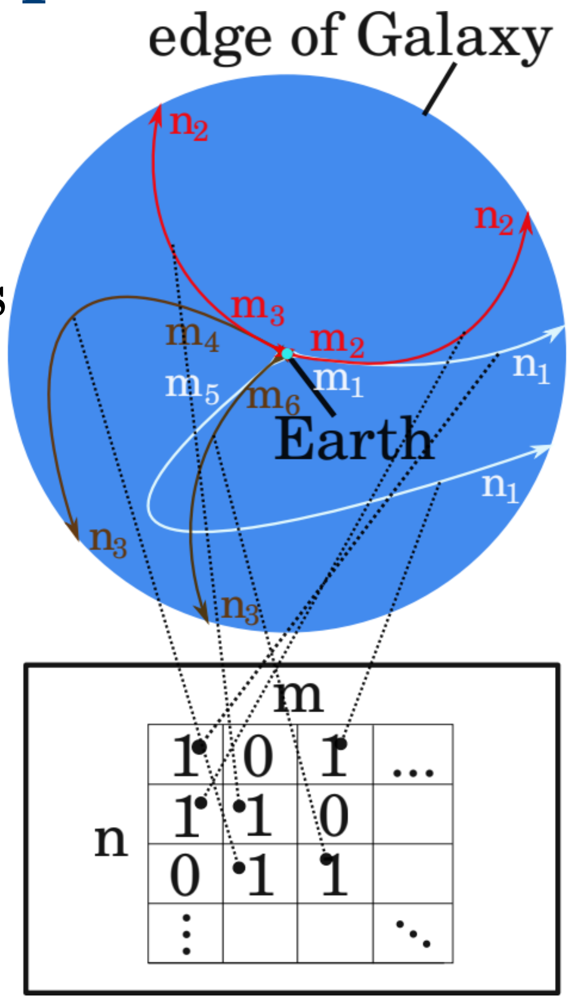
Propagation in GMF can be quantified via lens

- 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**



1	0	1	...
1	1	0	
0	1	1	
⋮			⋱

Effect on observables: Anisotropic EGCRs – Galactic lensing

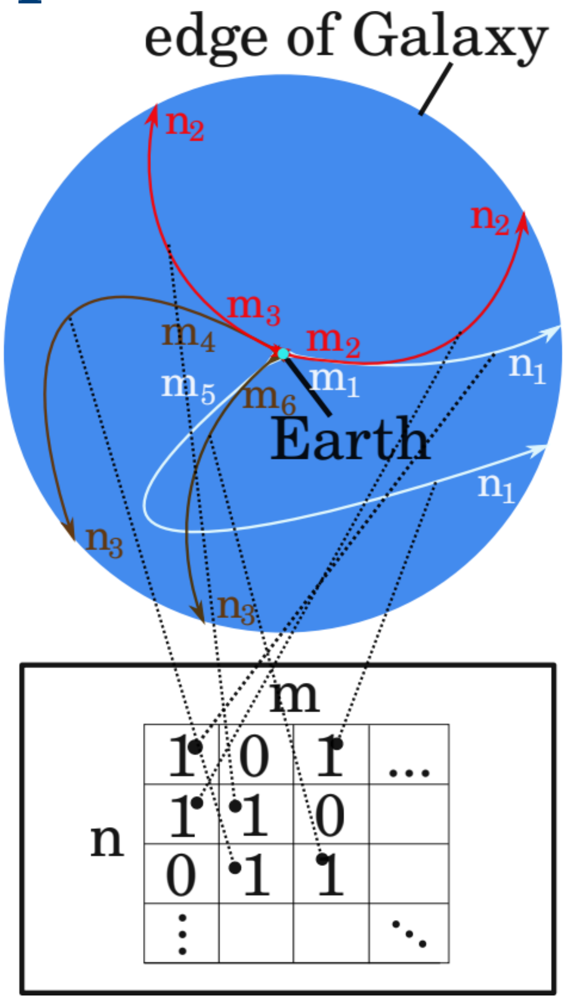
see also: Astropart.Phys. 85 (2016) 54-64 for lensing scheme & Eichmann, JCAP04(2020)047 for parallel work

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**

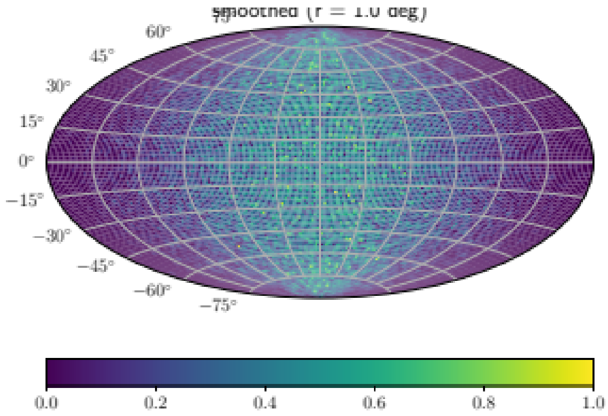
→ calculate arrival direction distribution for any injection direction distribution:

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

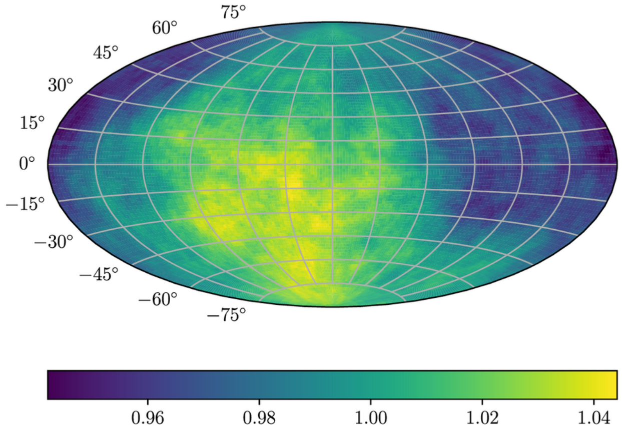


Effect on observables: Anisotropic EGCRs – Galactic lensing

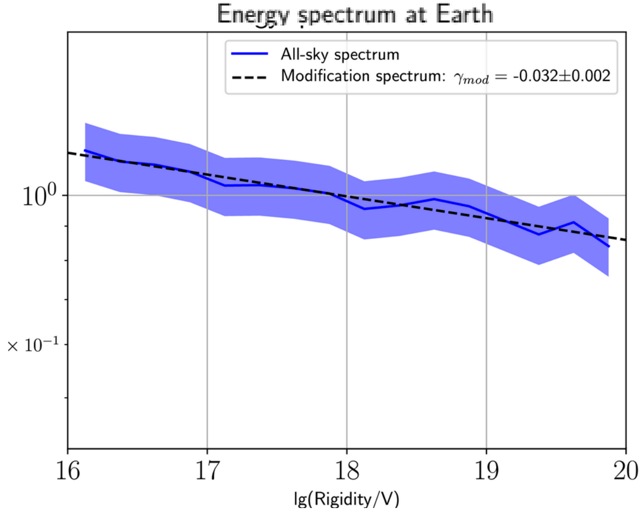
Injected flux



Flux at Earth



Flux at Earth



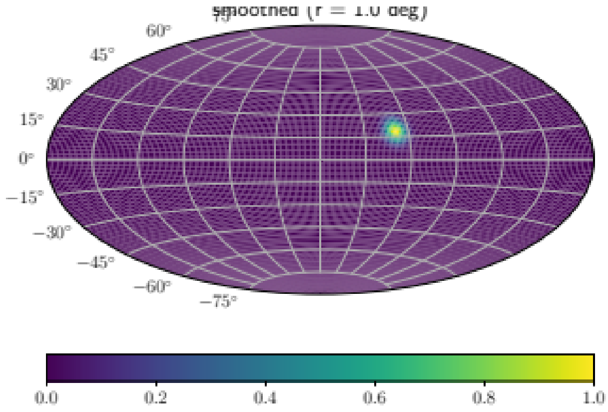
Injection direction distribution: **Pure dipole**

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

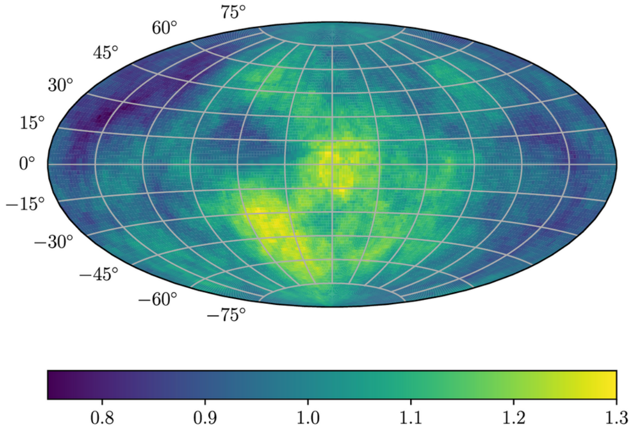
Rigidity spectrum at Earth → **possible flux modification**

Effect on observables: Anisotropic EGCRs – Galactic lensing

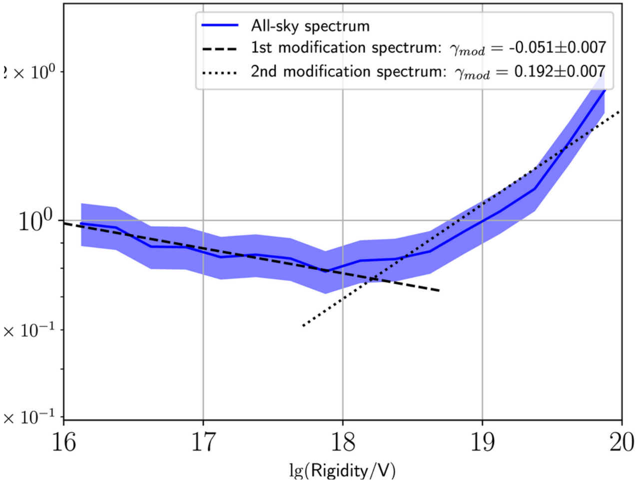
Injected flux



Flux at Earth



Flux at Earth



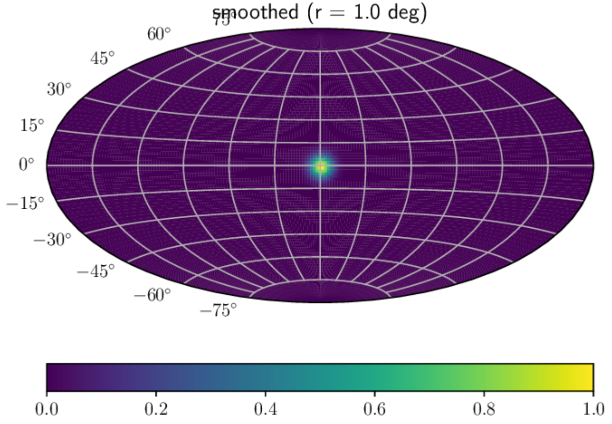
Injection direction distribution: **Pure single-point source** (Cen A)

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

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

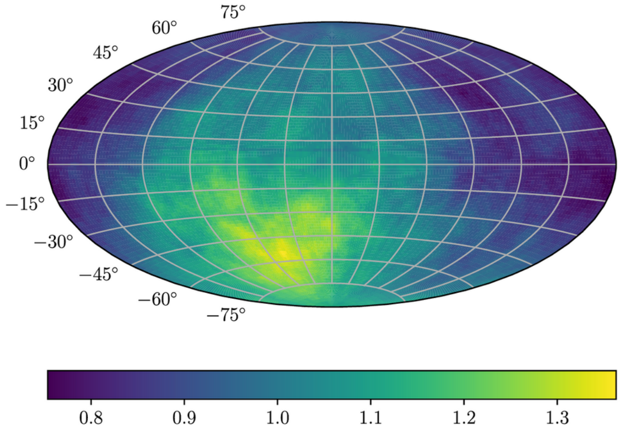
Effect on observables: Anisotropic EGCRs – Galactic lensing

Injected flux



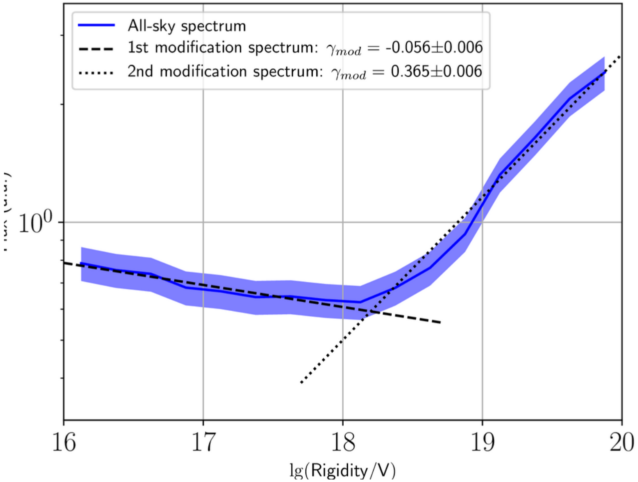
Injection direction distribution: **Pure single-point source** (minimum Galactic transparency; Galactic centre)

Flux at Earth



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

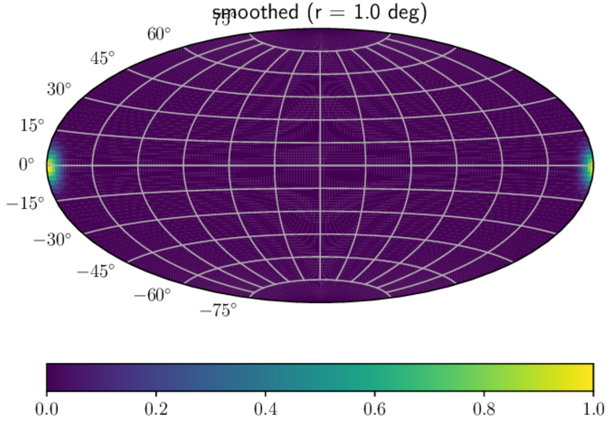
Flux at Earth



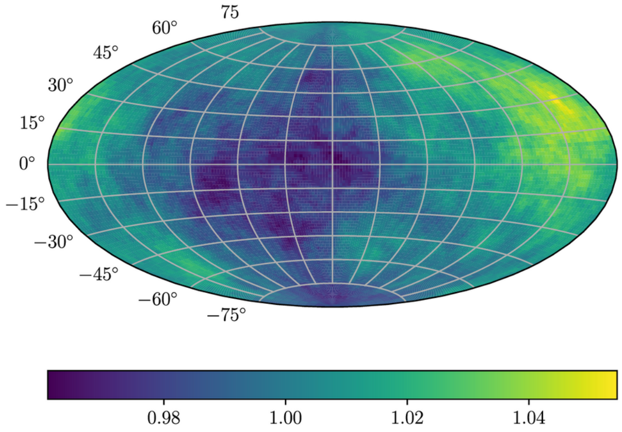
Rigidity spectrum at Earth → **possible flux modification**

Effect on observables: Anisotropic EGCRs – Galactic lensing

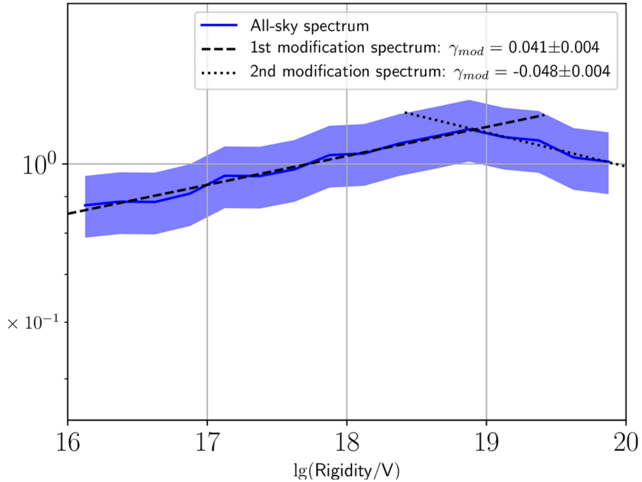
Injected flux



Flux at Earth



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)

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)

Transition region in data:

- multiple **features** in spectrum, composition, …, many of which have an **unknown origin**

  → goal of simulation: **reproduce these data** (qualitatively) to gain understanding of underlying processes

- propagation in GMF:
  - GCRs:
    - **leakage from Galaxy** leads to **'knee'-like feature**

      → significant contribution of **GCRs originating from GP disfavoured**
  - 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**?

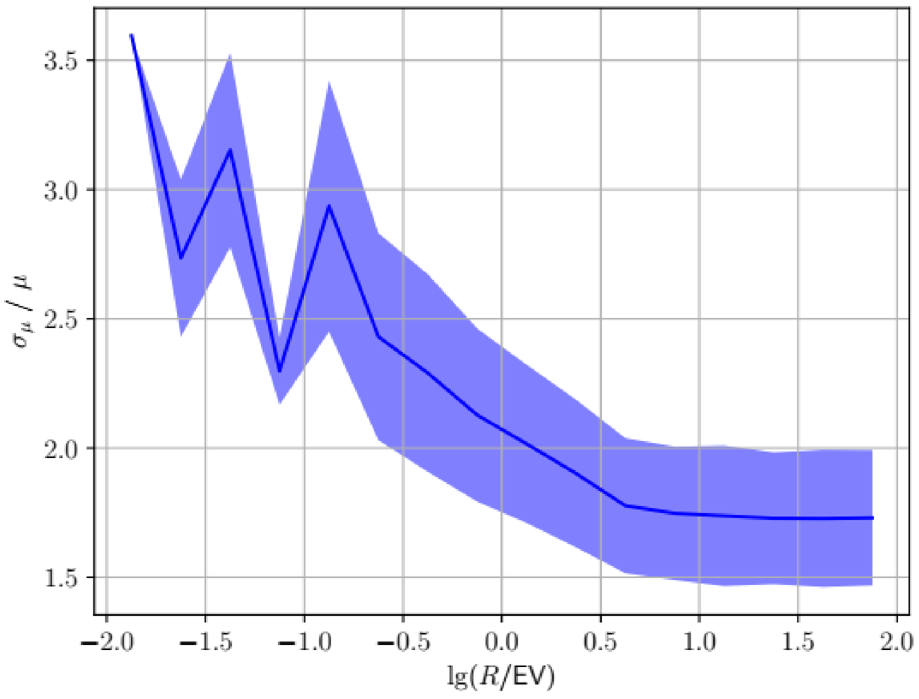
EGCRs:

- 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**?

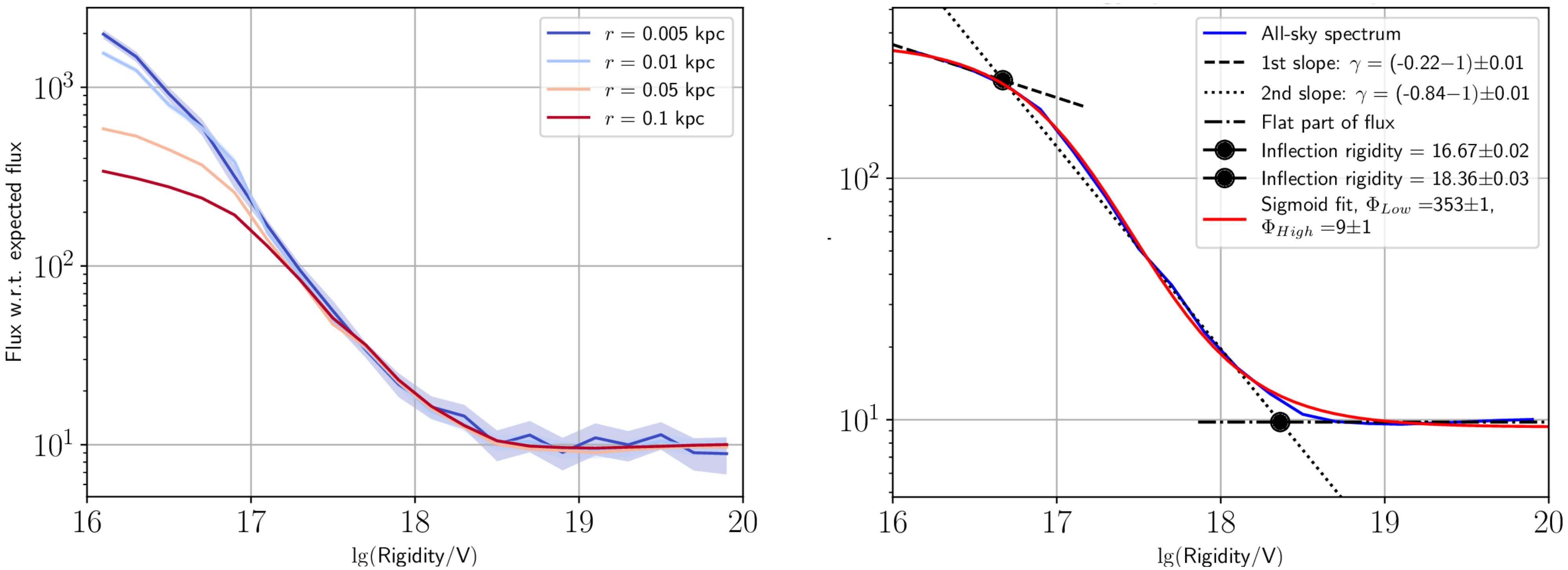
Liouville's Theorem

- 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):

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

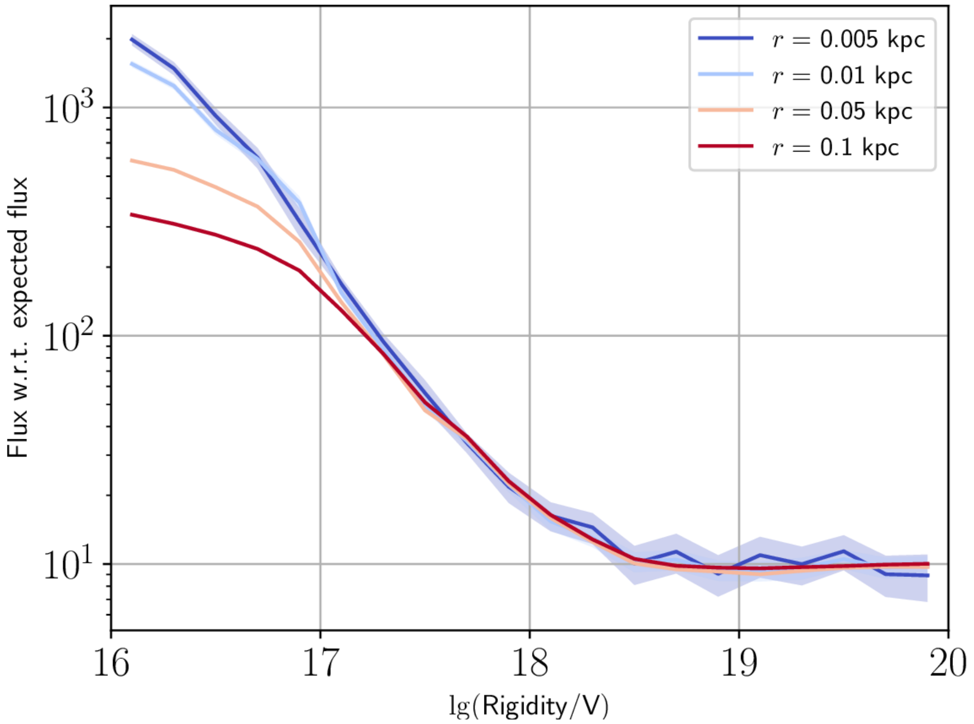


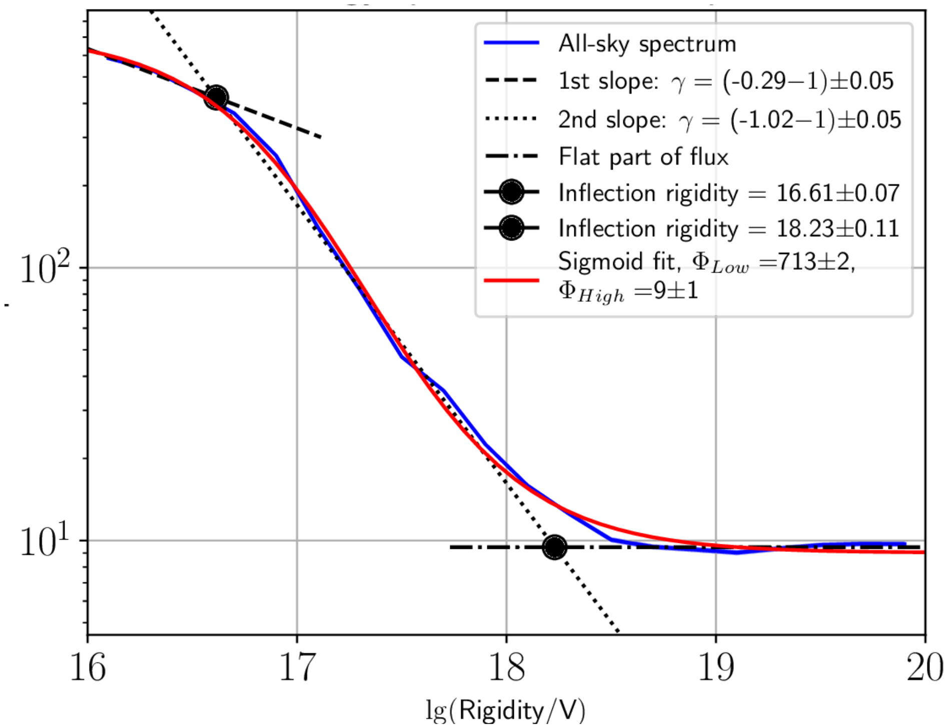
GCRs – Sigmoid fit to flux



- 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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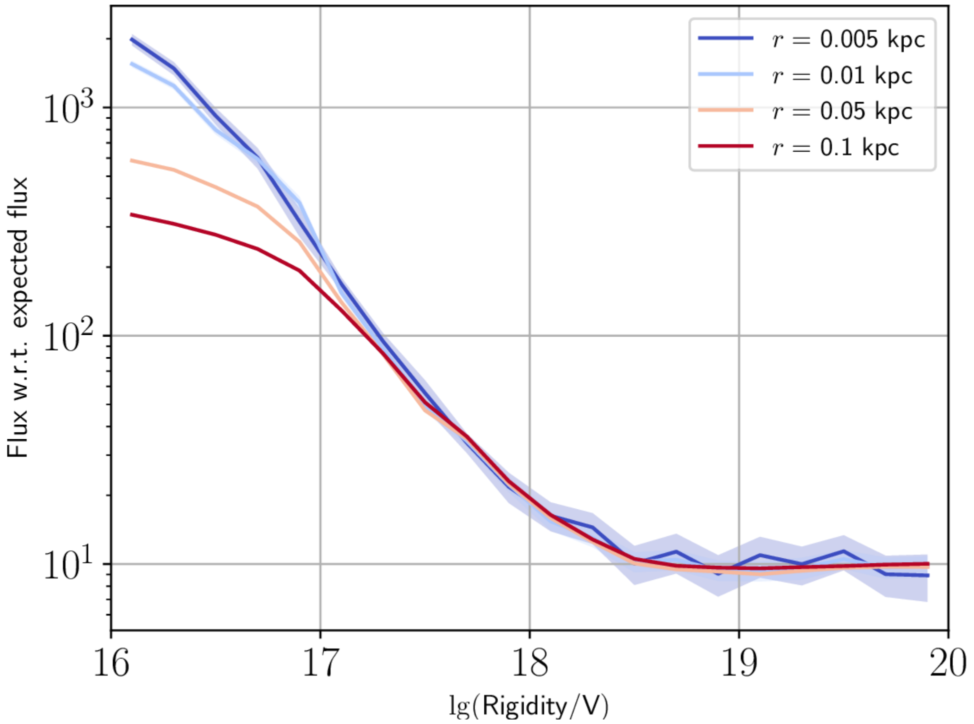
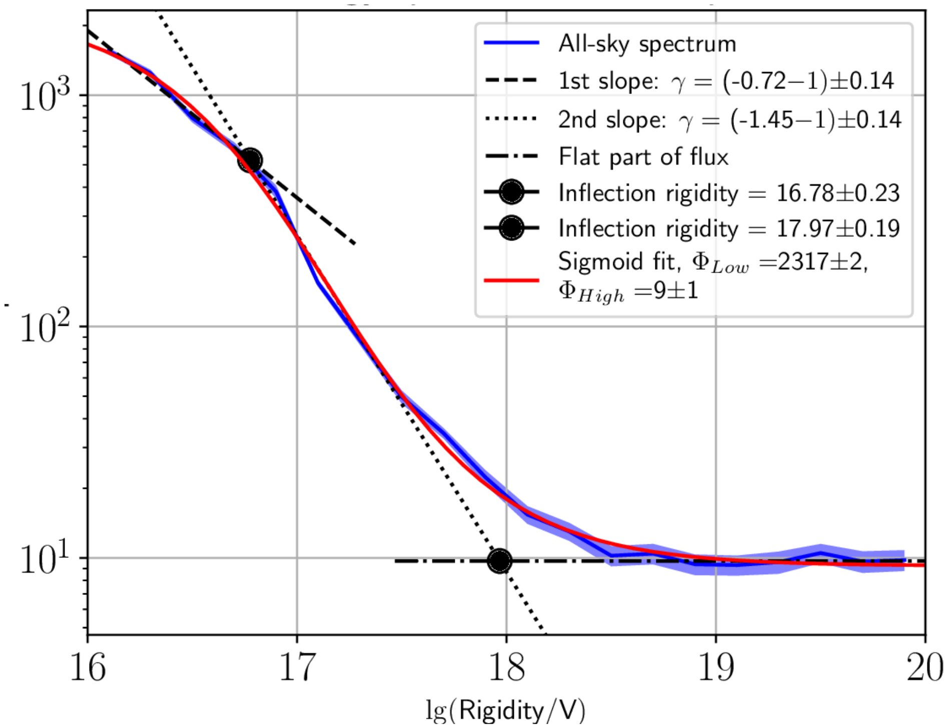
GCRs – Sigmoid fit to flux





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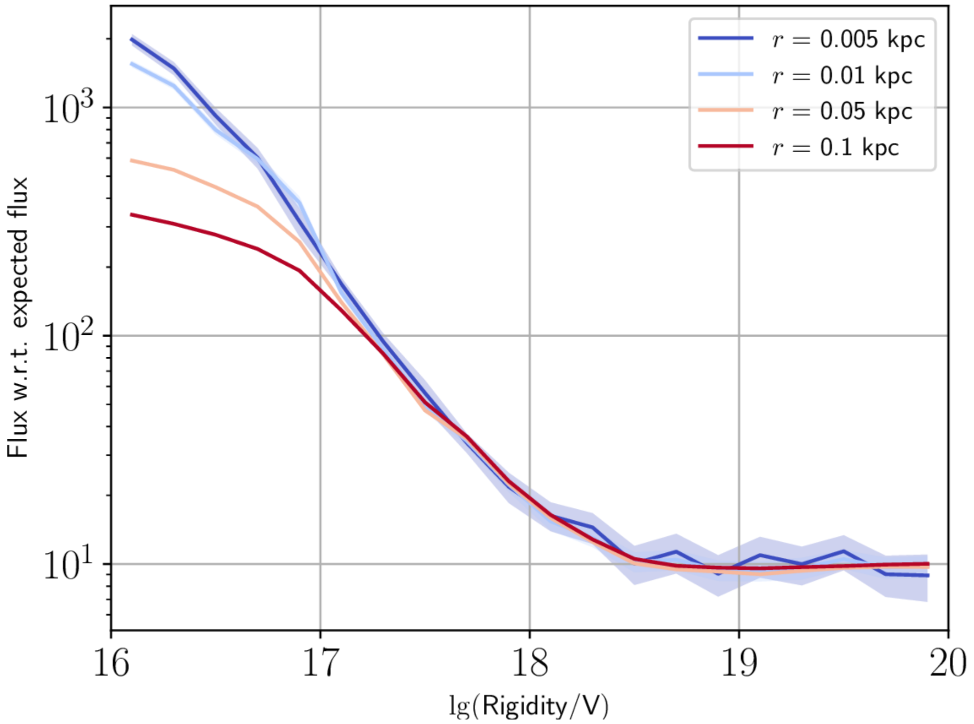
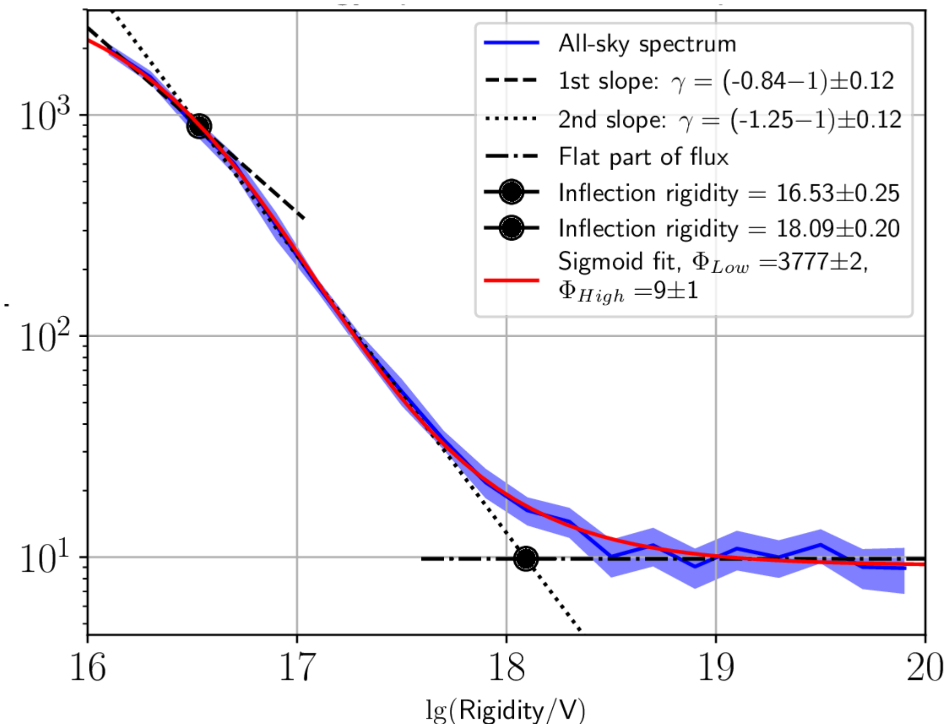
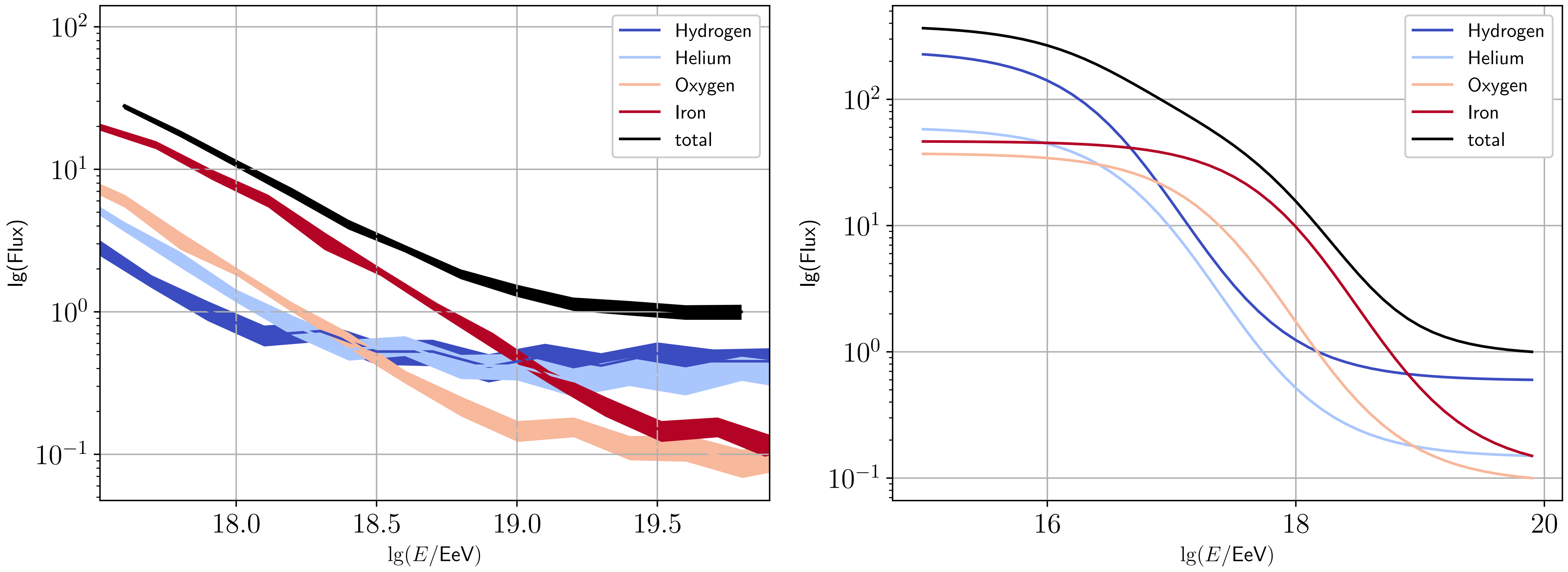
GCRs – Sigmoid fit to flux





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

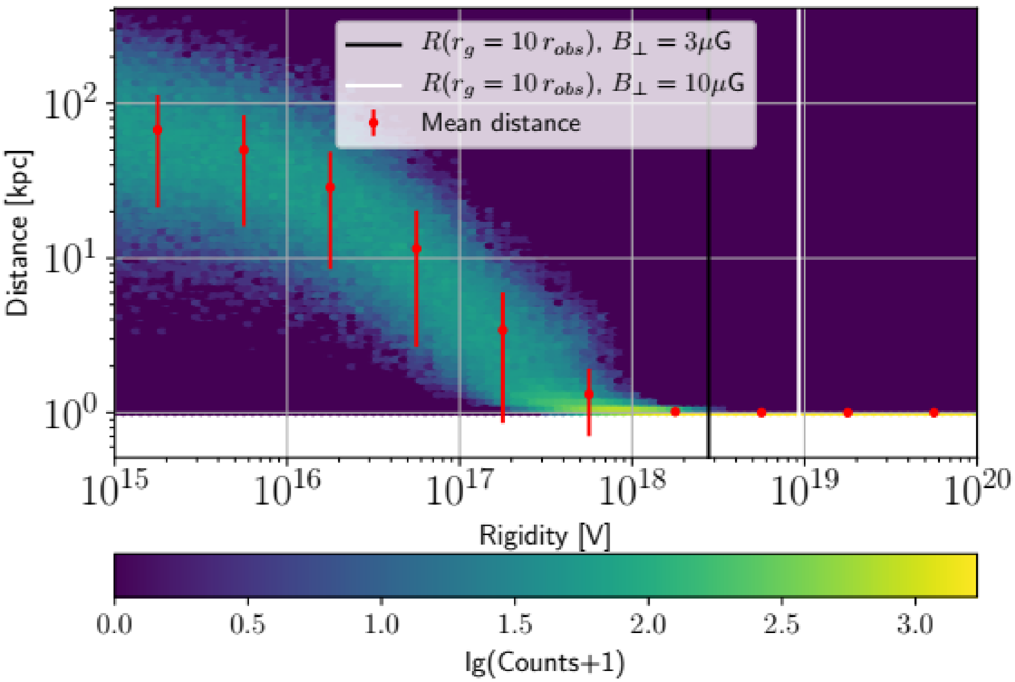
GCRs – Total flux (data and sigmoid fit)



- 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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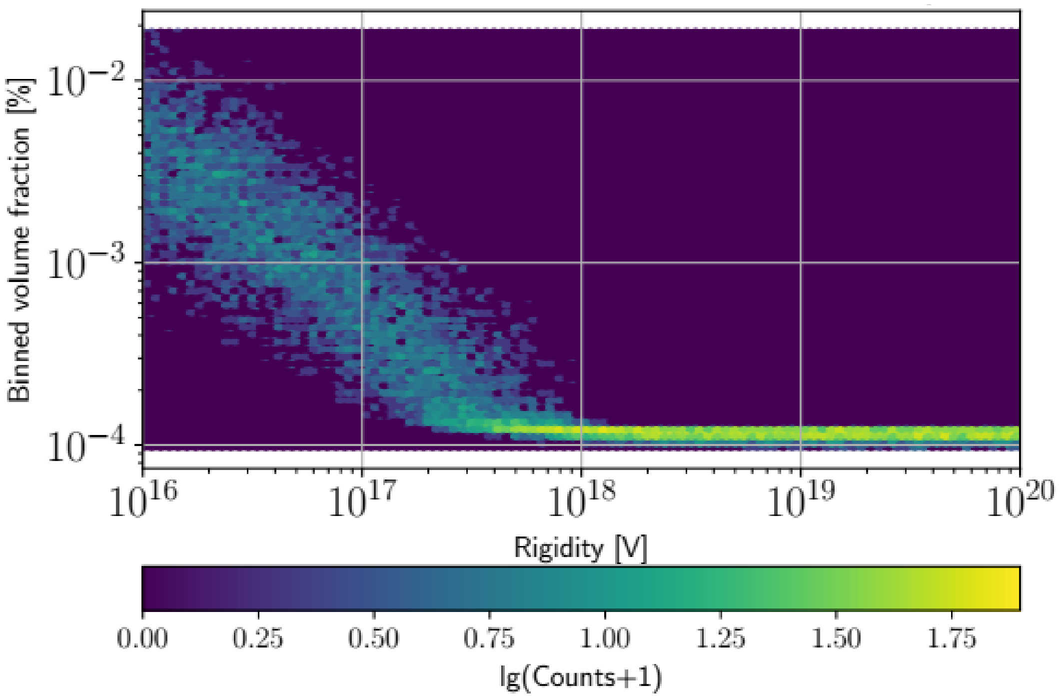
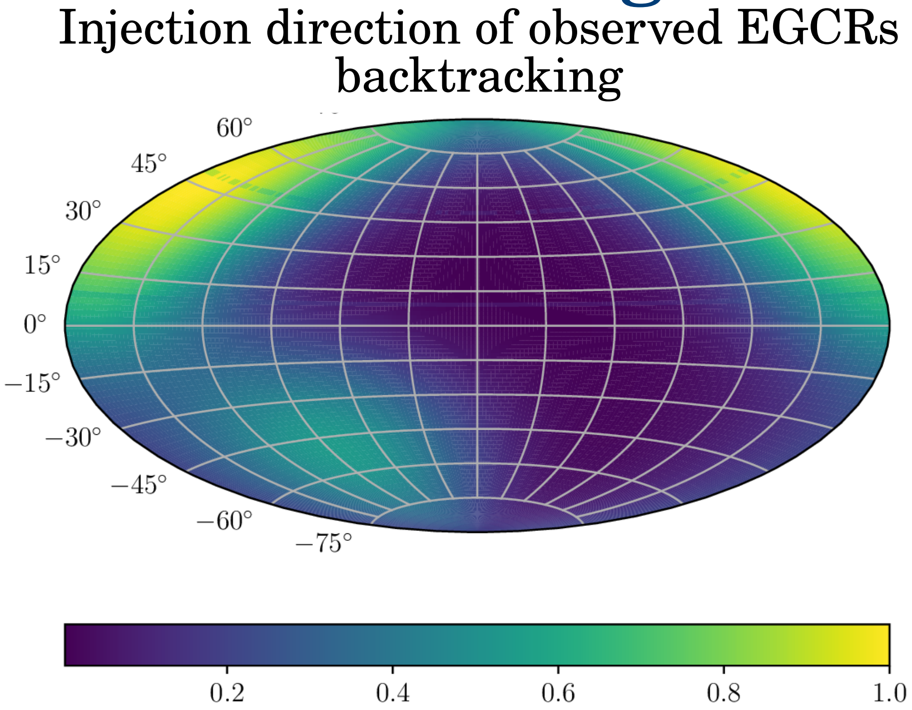
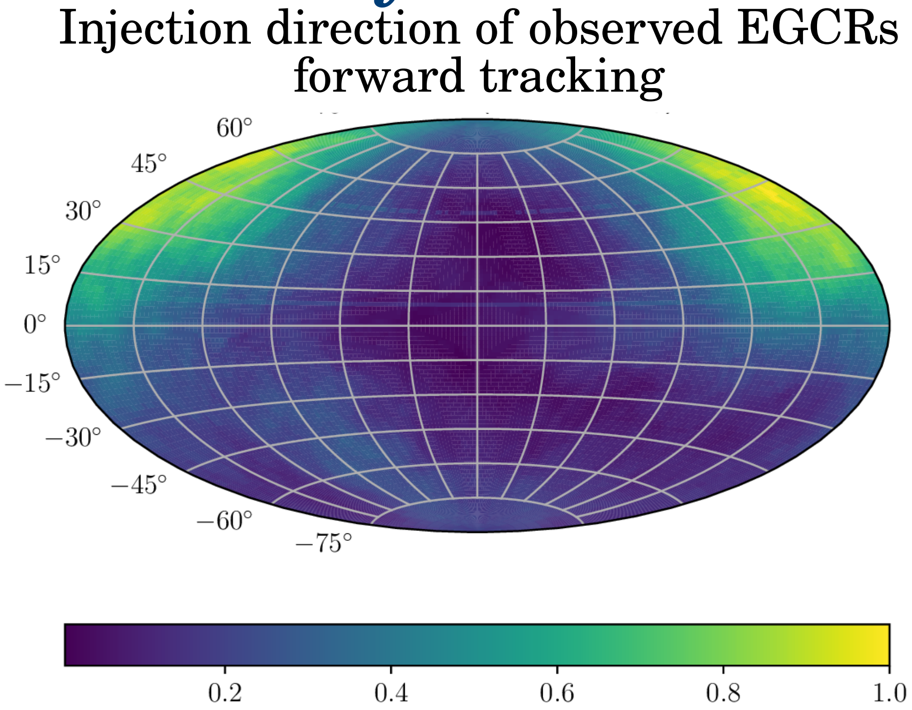


Galactic lensing – time reversibility

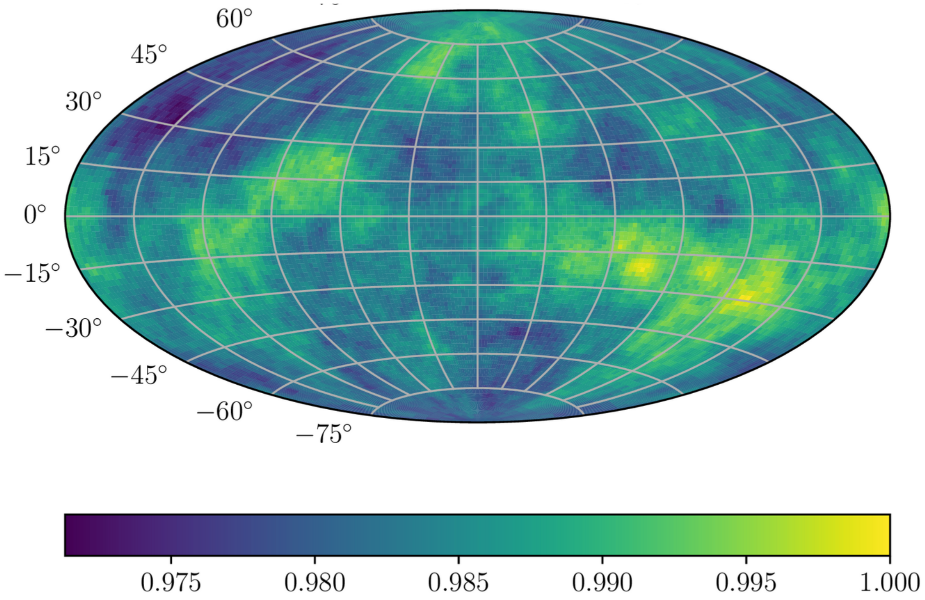




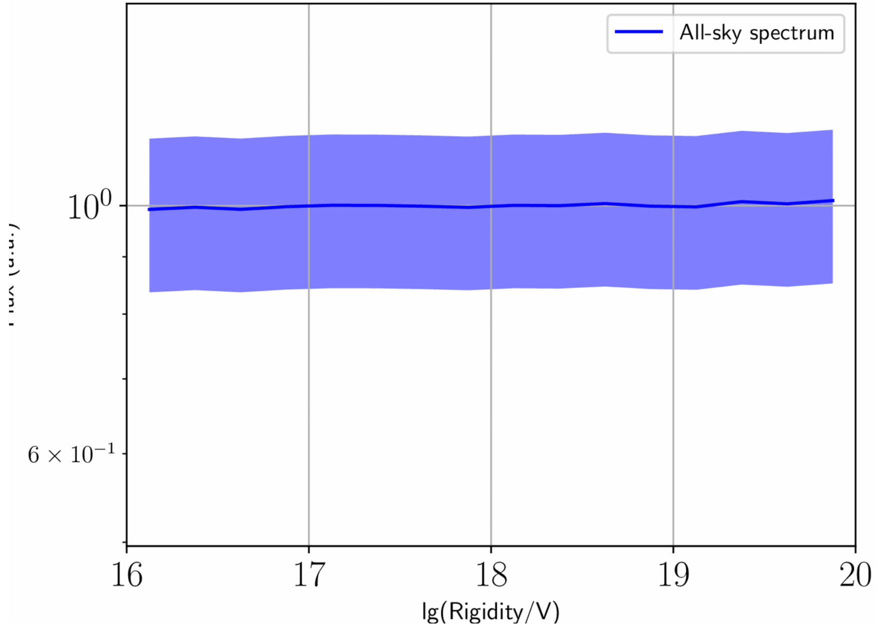
Injection direction distributions of backtracked and forward tracked protons match

Galactic lensing – testing lens

Arrical direciton of lensed isotropic injection distribution



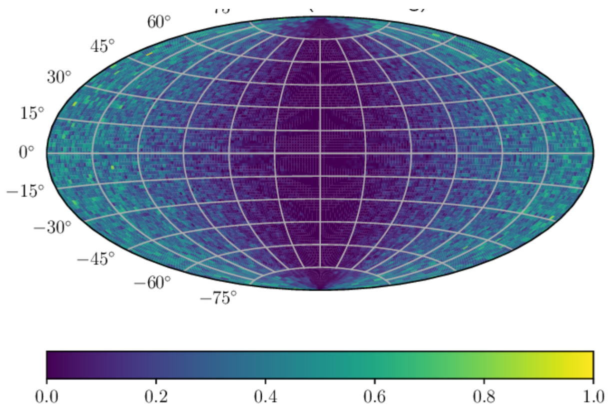
Spectrum of lensed isotropic injection distribution



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

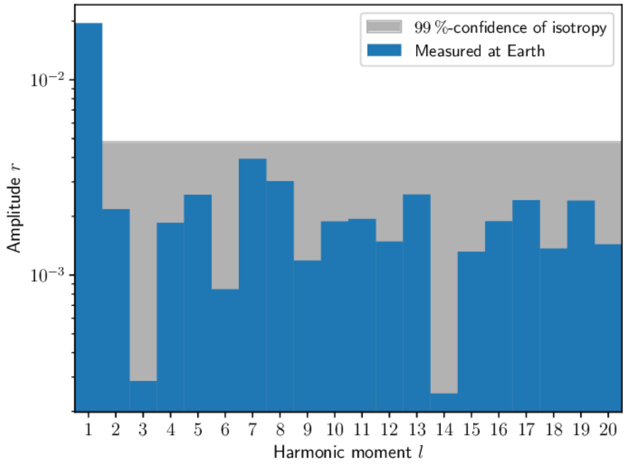
Anisotropic EGCRs – Galactic lensing

Injected flux



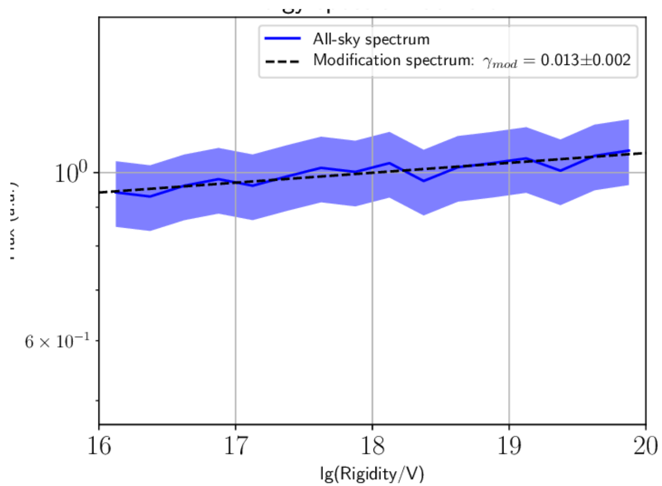
Injection direction distribution: **Pure dipole**

Distribution of moments above 1 EV



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

Flux at Earth



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

Anisotropies

Dipole anisot

- amplitud
- **no signi**
~$10^{16.5}$ eV
- **phase ro**
energy ra
Galactic
energies
→ **extrag**

Small-scale a

- amplitud
strength
correlatio
⇔ **streng**

Interlude:

Arrival direction distribution measured via multipole expansion:

$$I(\alpha,\delta) = 1 + \sum_{l\geq 1}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\pi/2-\delta,\alpha)$$

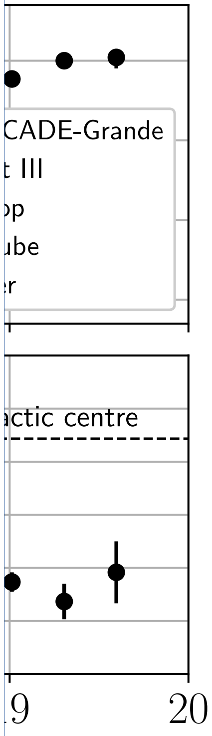
α: right ascension

δ: declination

Y_{lm}: spherical harmonics

- l = 1: dipole anisotropy

(2020) pp.1-98



Anisotropies

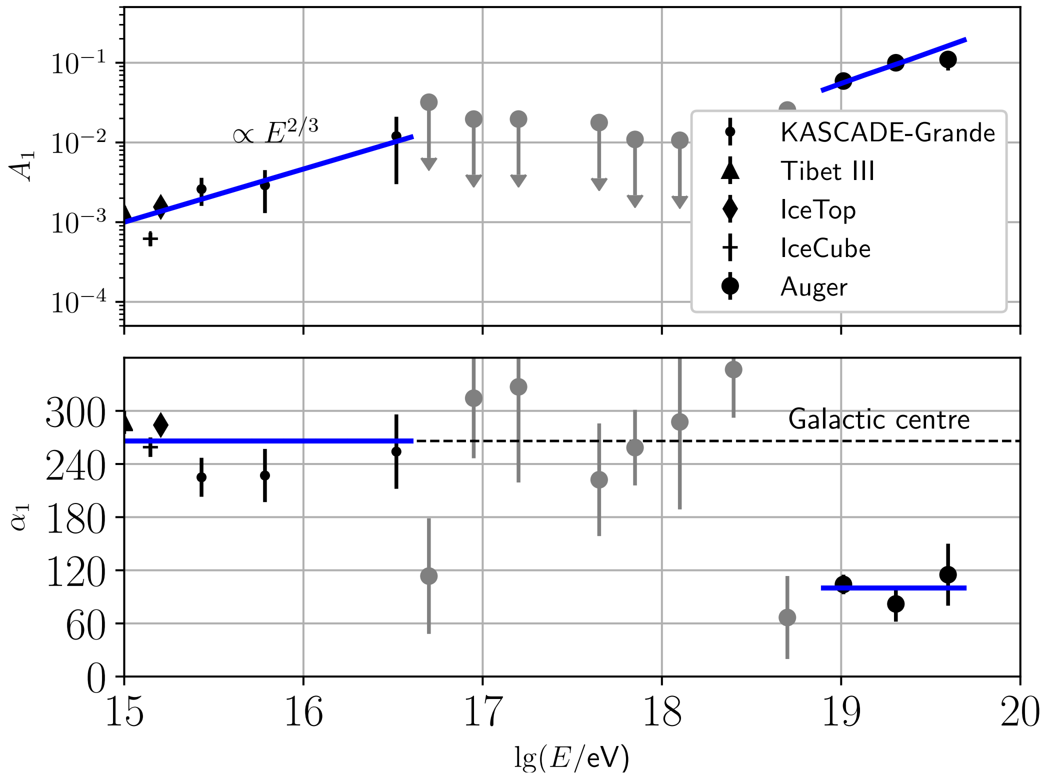
Dipole anisotropy:

- amplitude increases with energy
- **no significant dipole** between $\sim 10^{16.5}$ 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



Major challenge: GMF model

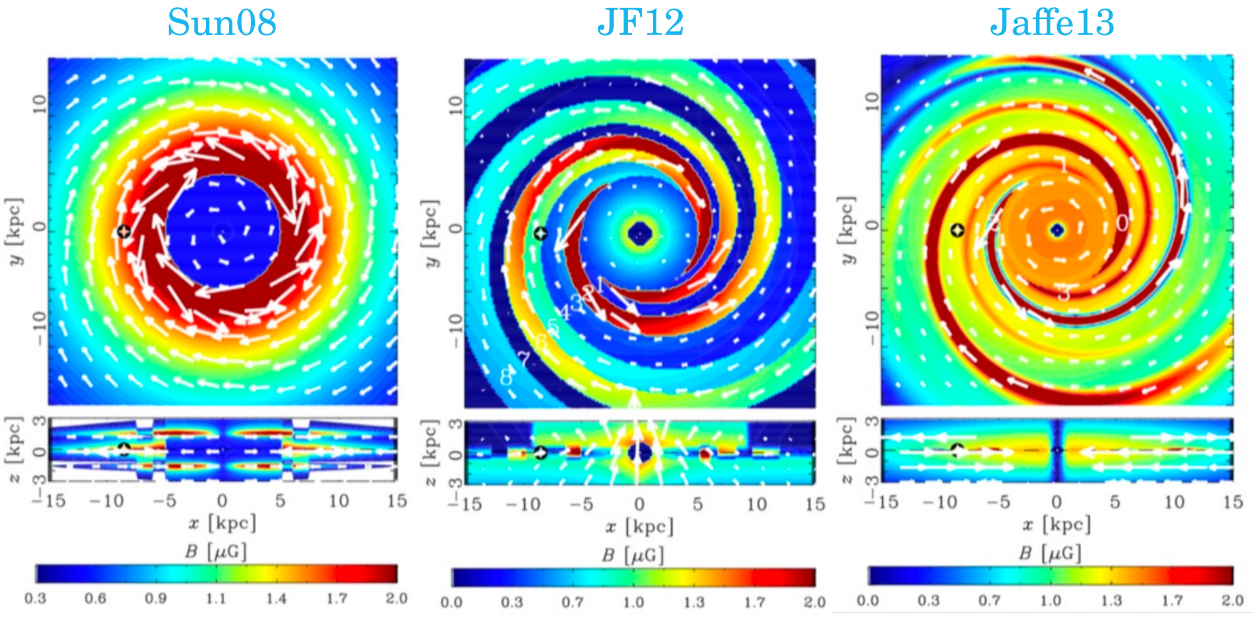
GMF not well known:

- 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, contami

  of 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



Outlook (1)

Combine fluxes:

- GCRs:
  - Test discrete source distribution
  - Include rigidity-dependent cut-off at around “knee” energies

    → fit to ”knee” region

- EGCRs:
  - Realistic source distribution (e.g. 10 brightest AGN/SBGs) and spectra

    → fit to “post” ankle flux

→ retrieve “missing” flux