Effects of the Galactic magnetic field on the spectrum, composition and arrival direction of cosmic rays

Alex Kääpä

Cosmic Ray Anisotropy Workshop

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BERGISCHE UNIVERSITÄT WUPPERTAL

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Cosmic ray (CR) energy spectrum

- Galactic (G) models describe region below ‘knee’, extragalactic (EG) region above ‘ankle’
- transition region not well understood
- extensions up-/down-ward exist but depend on poorly understood parameters
- research goal:
  - study effects of Galactic magnetic field (GMF), i.e., escape of GCRs from the Galaxy & shielding of EGCRs when entering the Galaxy
  - reproduce features in spectrum, composition and arrival direction

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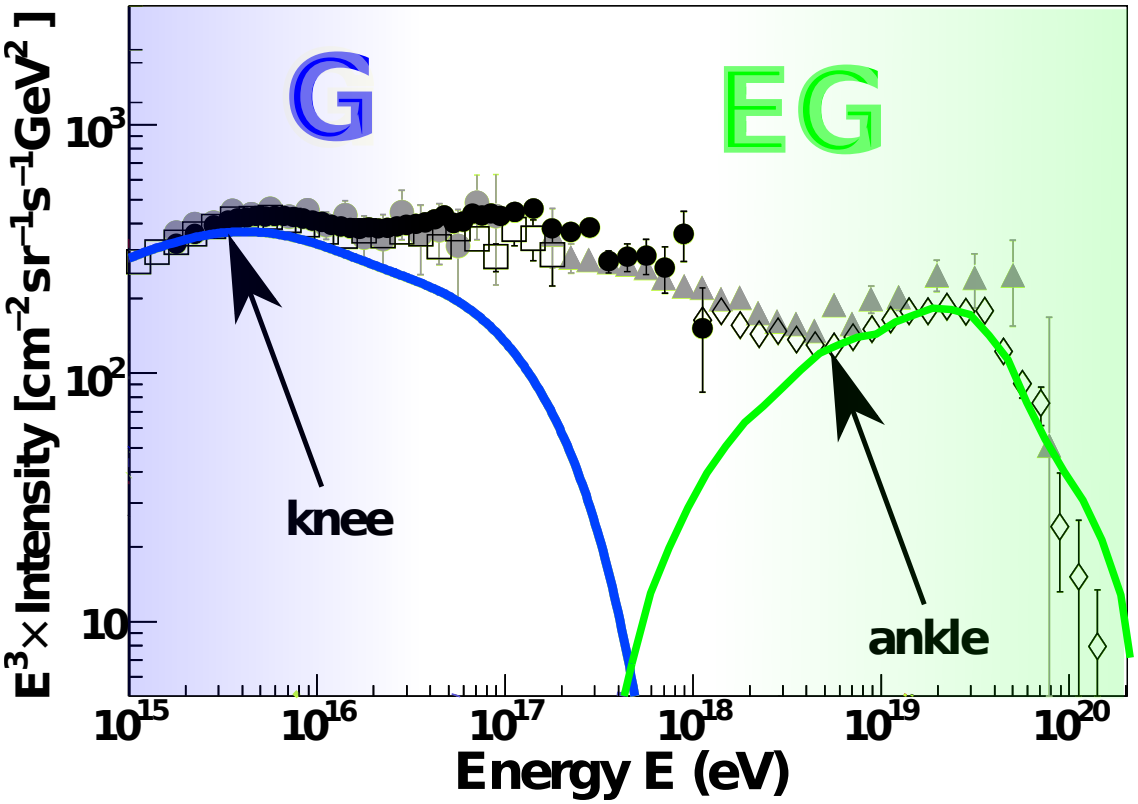


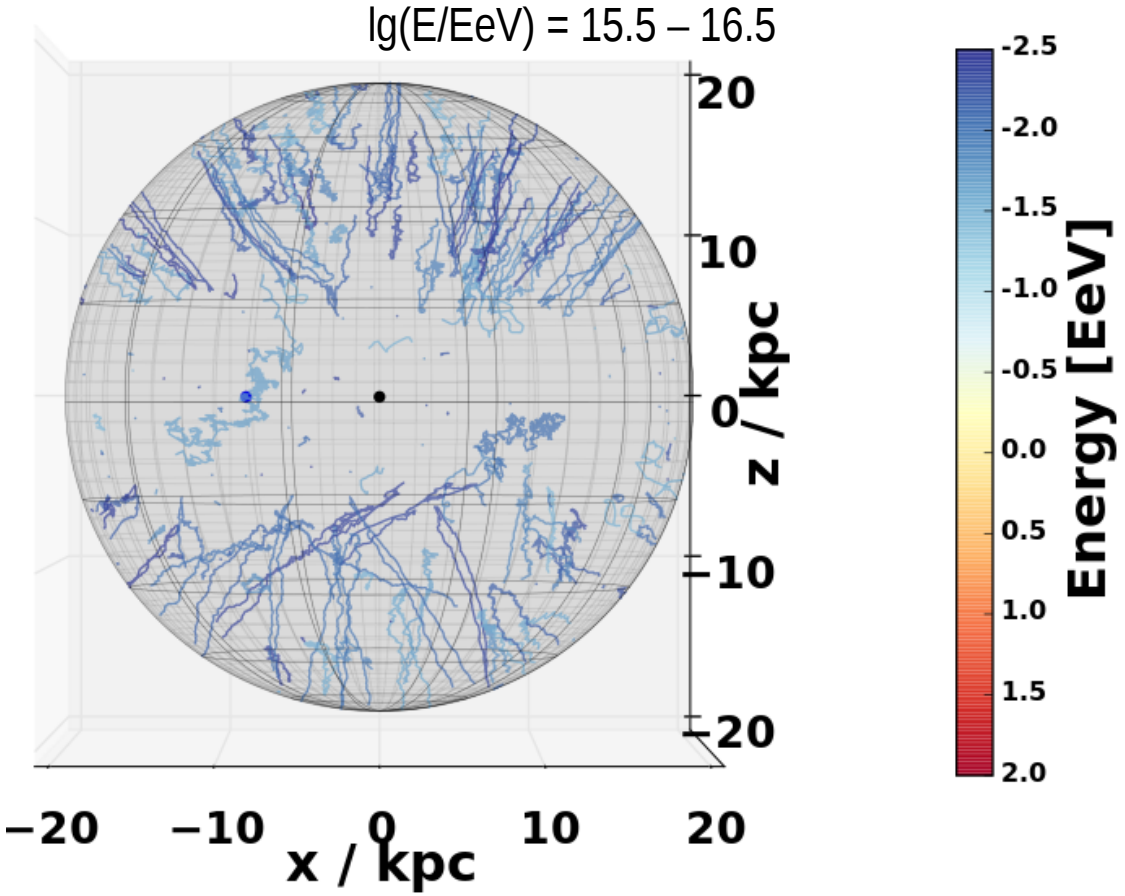
Effects of GMF: Galactic trajectories of EGCRs

- low-ridigity particles **shielded** from Galaxy
- **concentration effect** in Galactic plane for intermediate rigidities
- hardly any to **no deflections** at highest rigidities

→ expected effect on spectrum: spectral **hardening** towards higher energies

→ expected effect on composition: **heavier** towards higher energies

→ effects may be **latitude-dependent** (possible anisotropies)



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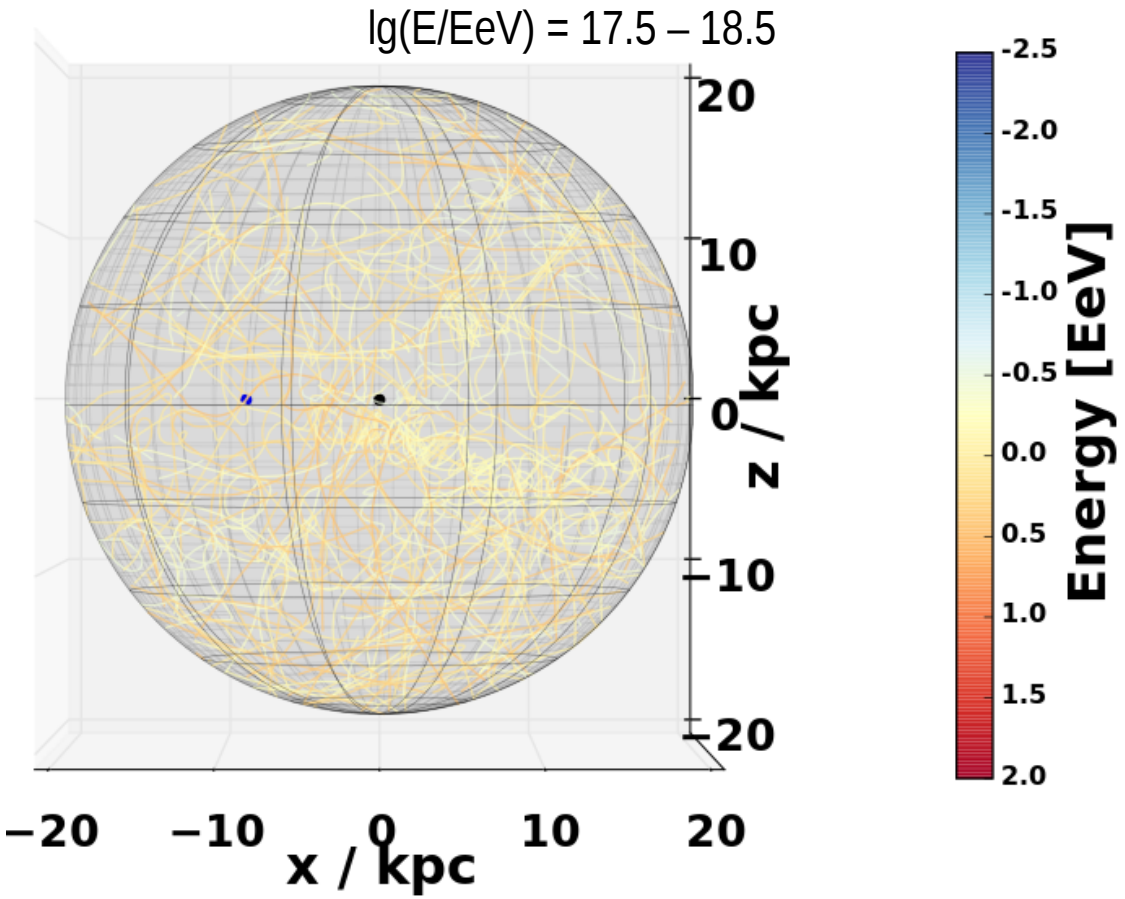

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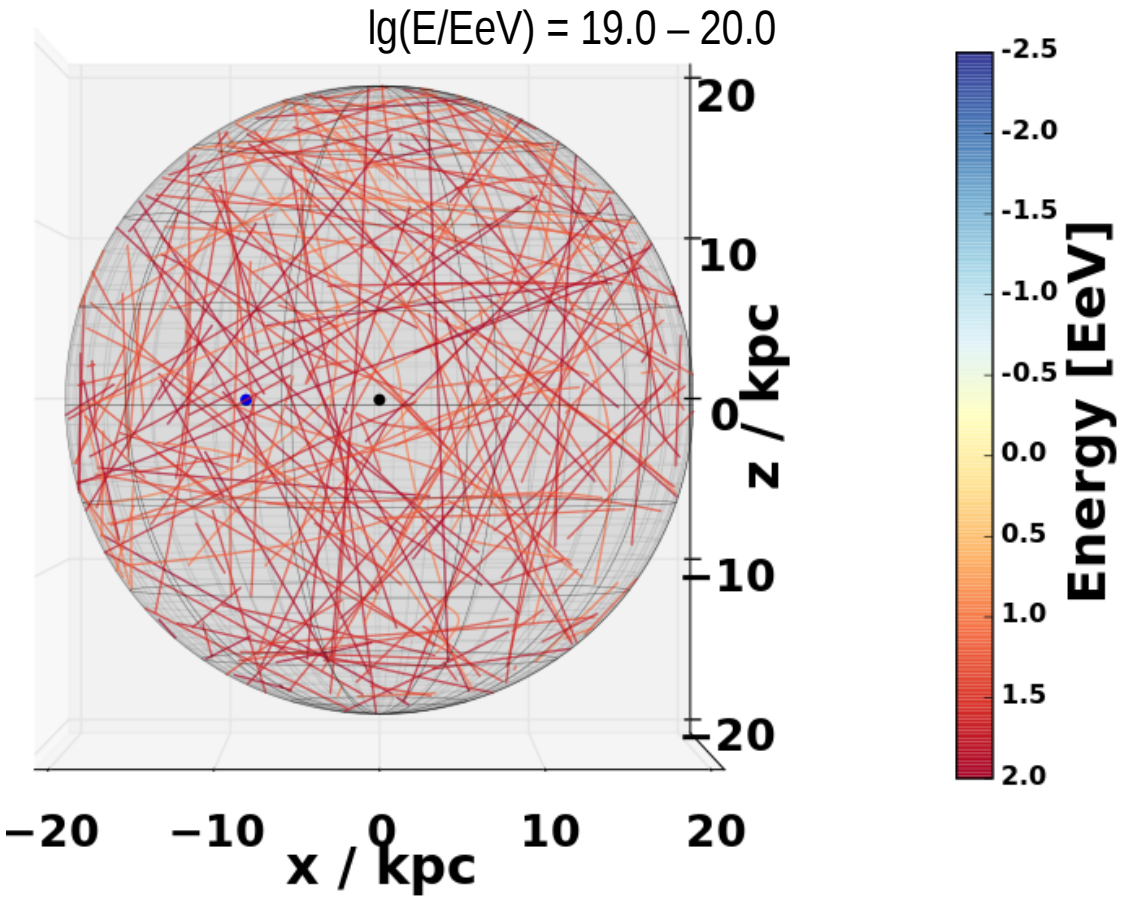

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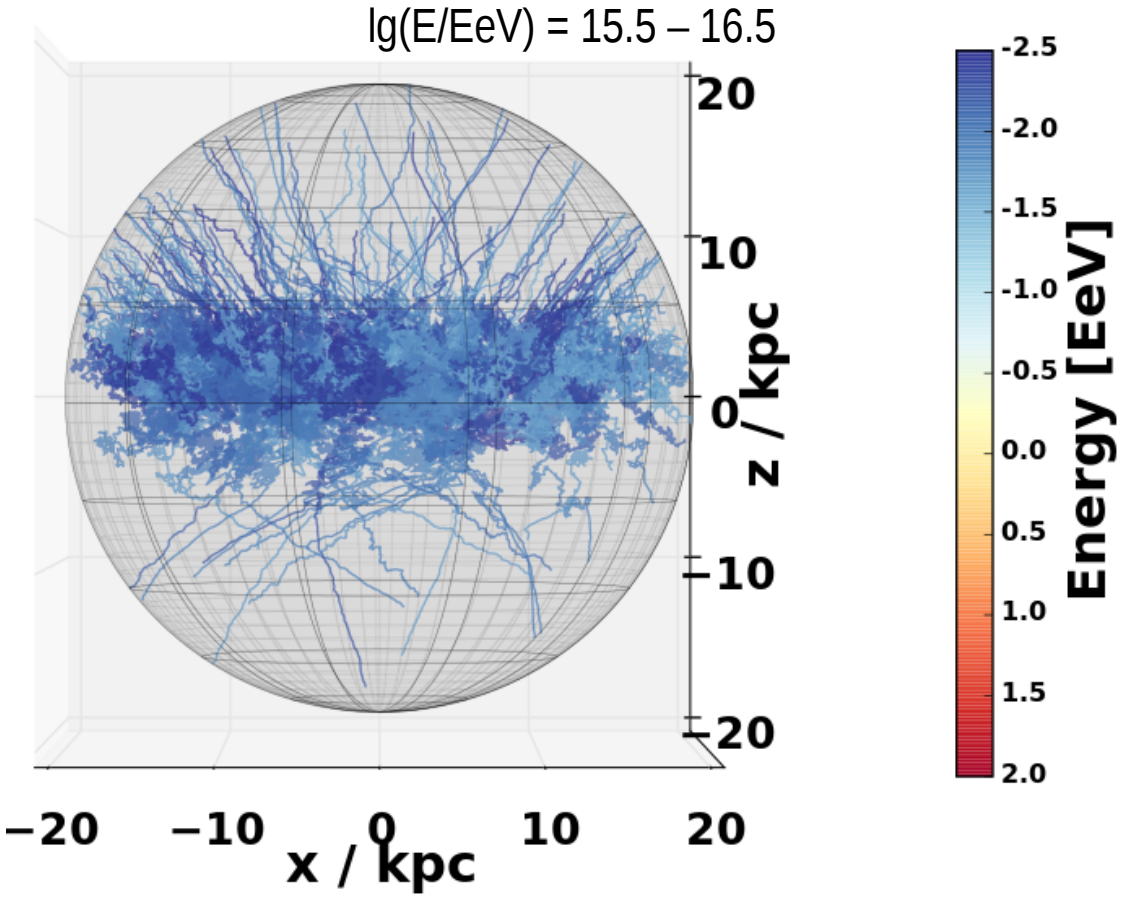

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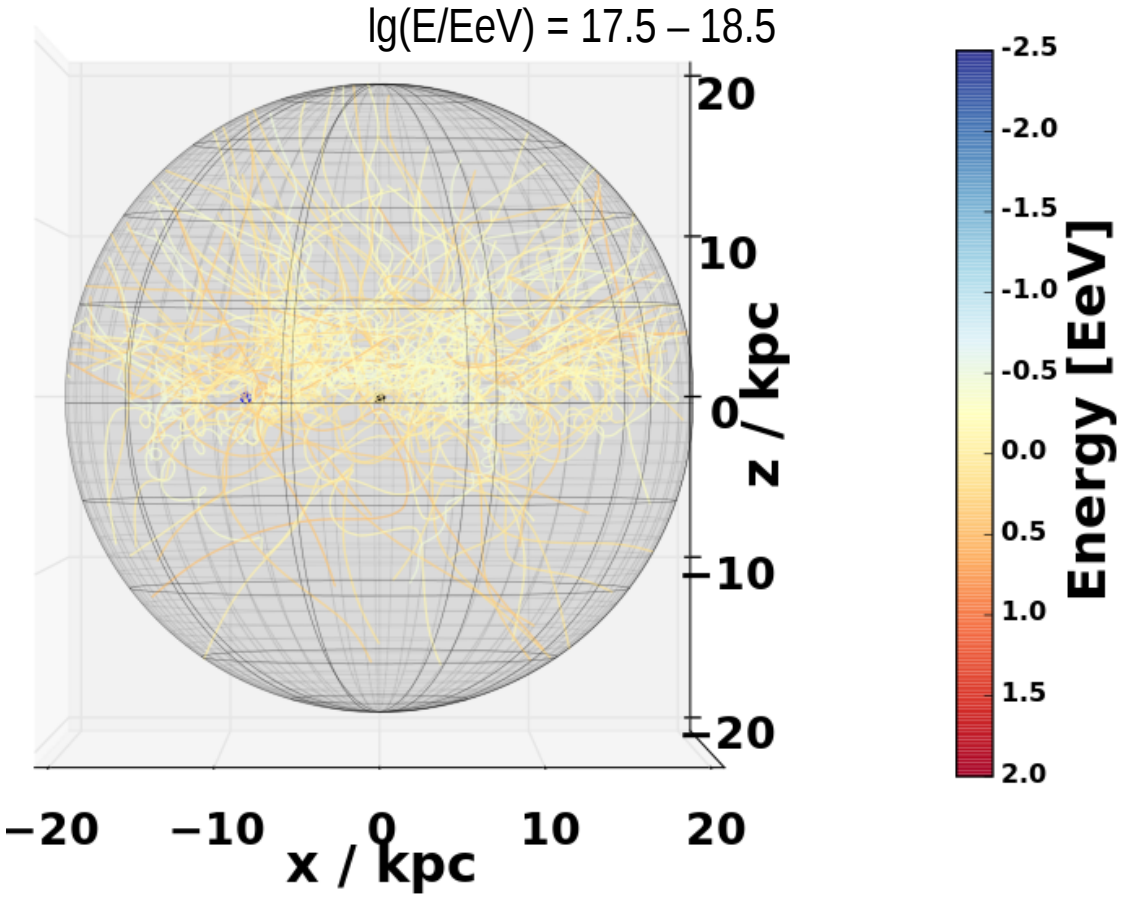

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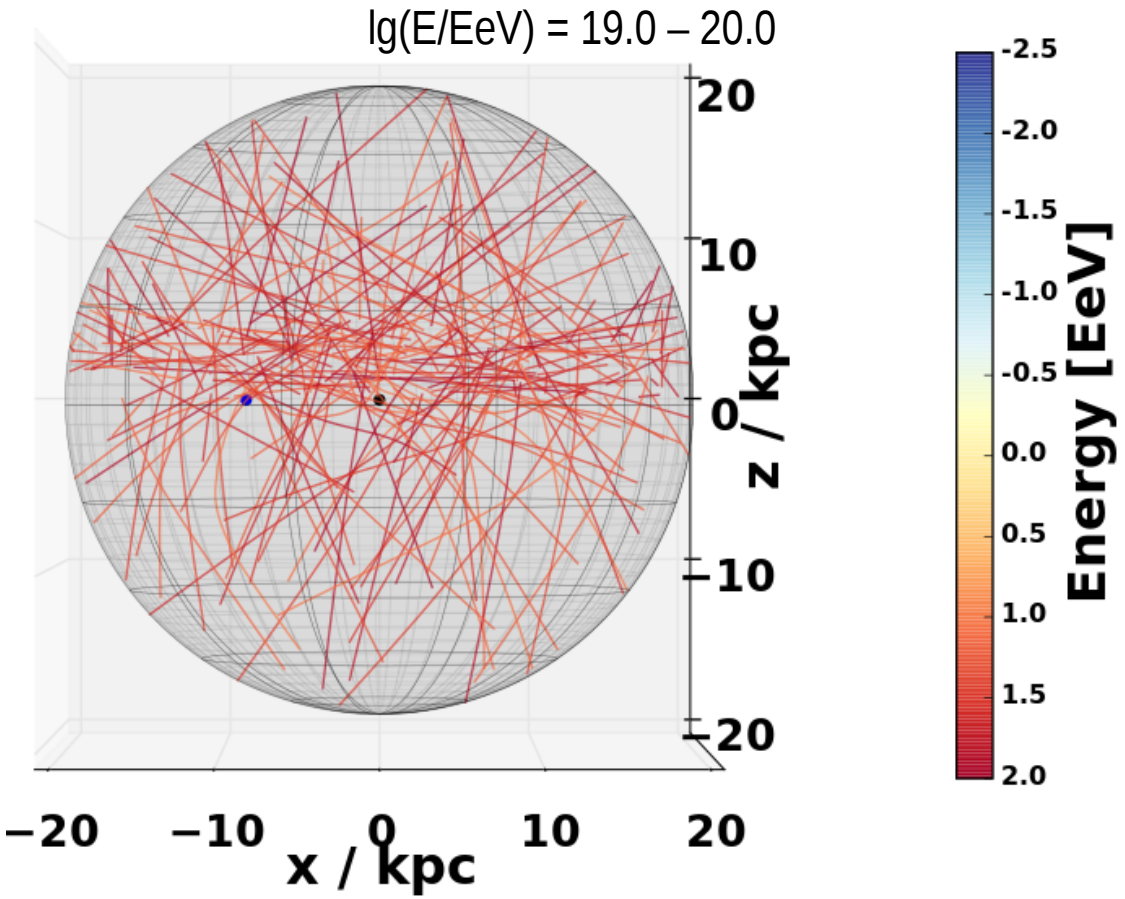


Procedure: Simulation with CRPropa3

Forward-tracking of protons:

- Only deflections → results only rigidity-dependent
- Effects on spectrum, composition and arrival direction
- Fit to data to determine expected EG and G contributions

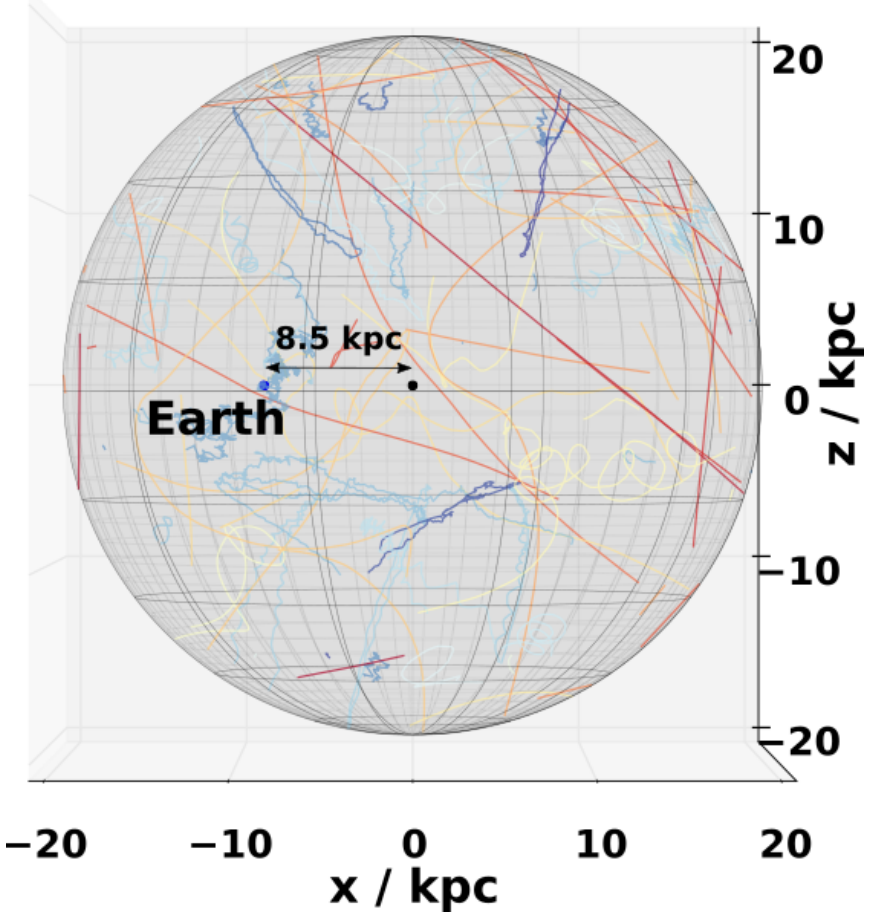
Galactic magnetic field model:

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

Energy spectrum

Modification of EGCR energy spectrum:

- Inject 10^9 particles with **E^{-1} spectrum from 'edge of Galaxy'** (= 20 kpc shell around Galactic Centre (GC))
- Rigidity range: **lg(E/eV) = 15.5 – 20.0** (pre-knee to post-ankle for protons)
- Measure spectrum at **'Earth'** (= 100 pc observer sphere at (-8.5 kpc, 0, 0) in Galactic coordinates)
- Look at **on- and off-plane** component ($p_{z,cut}$ = 0.5 ↔ latitude = 30°) for anisotropy analysis



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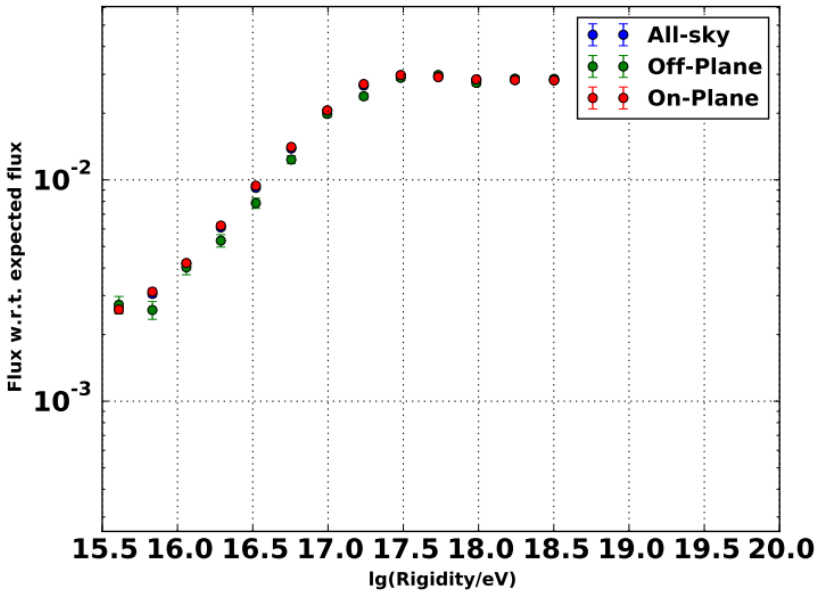
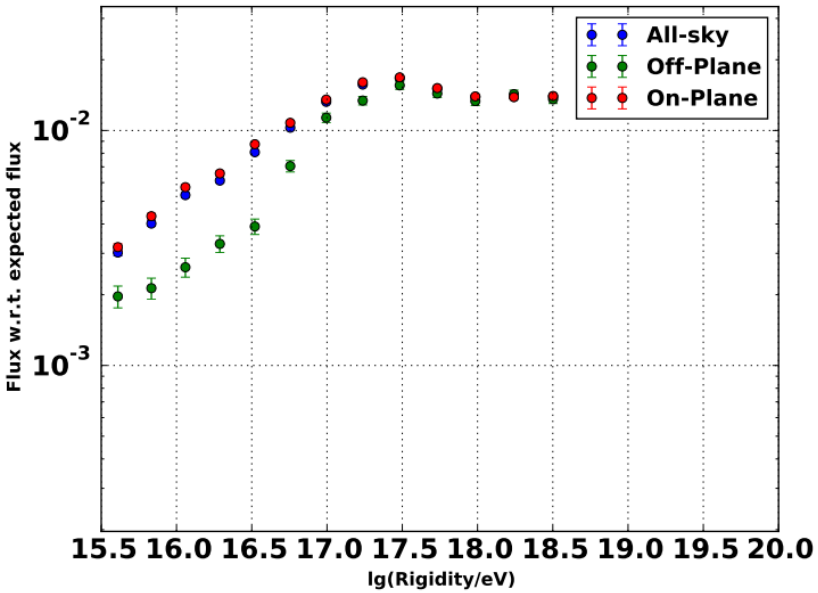


including random component



only regular component

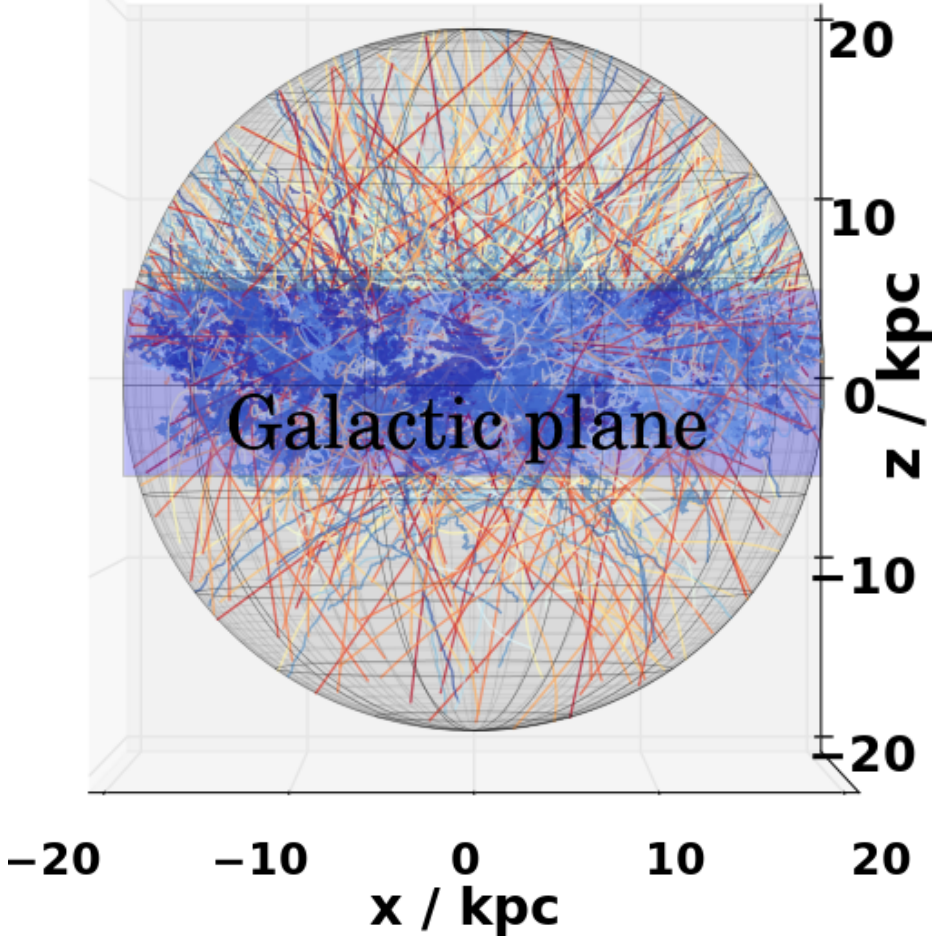
- reduction of flux towards lower rigidities → **spectral hardening**
- reduction of flux **latitude-dependent**: CRs are **concentrated into Galactic plane** (GP)
- latitude-dependence **even more pronounced with only regular component**

Modification of GCR energy spectrum:

- Track 10^5 particles injected with **E^{-1} spectrum within 'Galactic plane'**
  (= 20 kpc radius, 10 kpc thick cylinder)
- Rigidity range: **lg(E/eV) = 15.5 – 20.0**
  (pre-knee to post-ankle for protons)
- Measure **rigidity distribution as a function of time**:

  → **re-inject distribution** at regular time intervals (≪ escape time) until **steady state** is reached

  → derive **spectrum from relative size** of each rigidity at steady state regime



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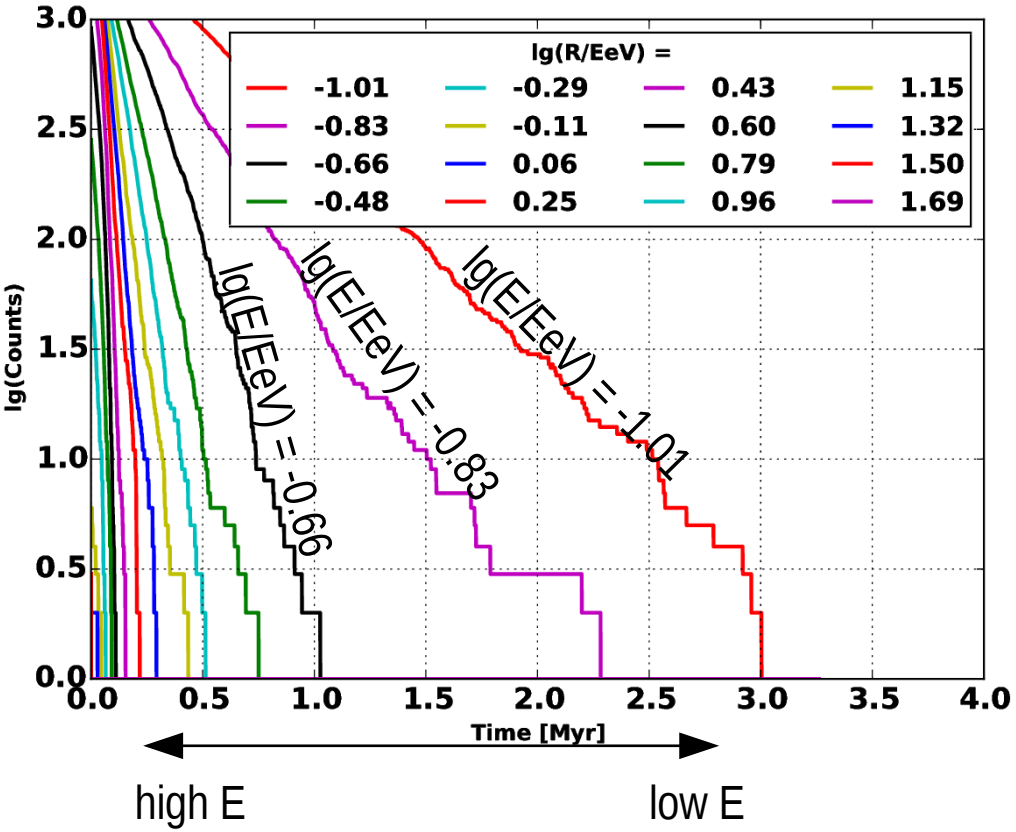

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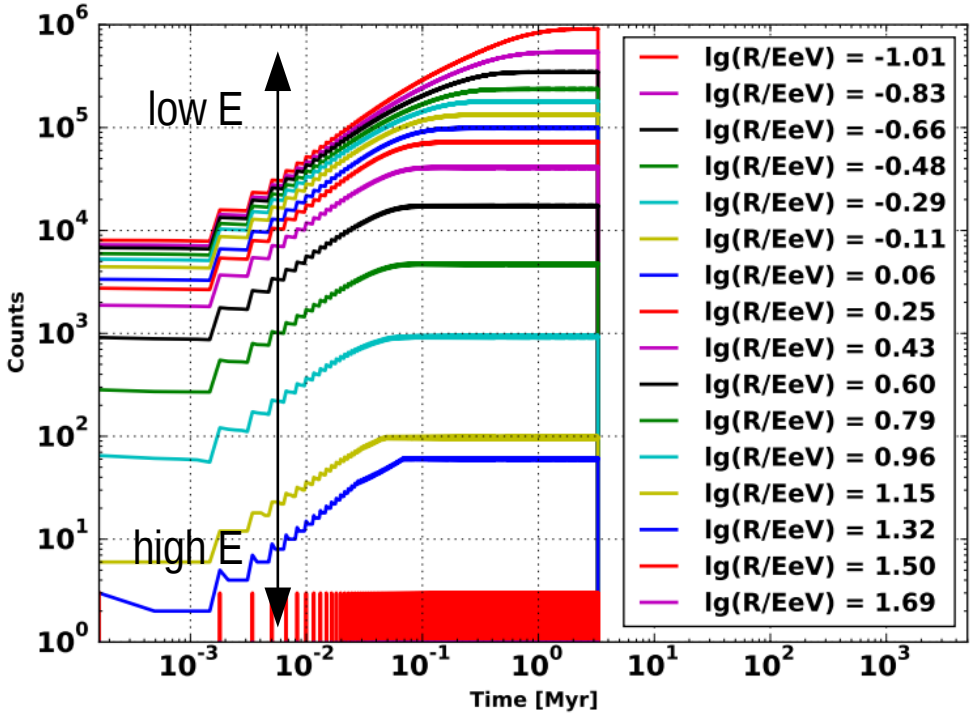

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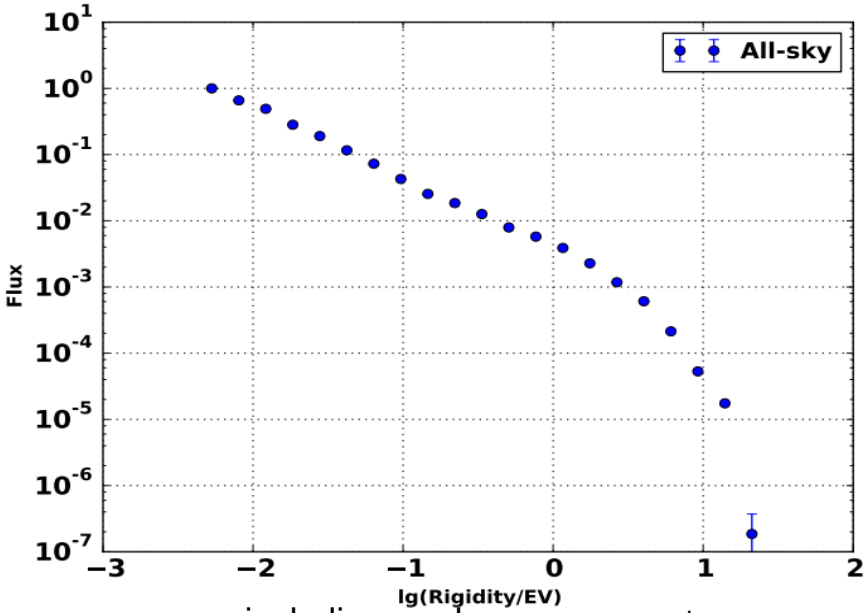
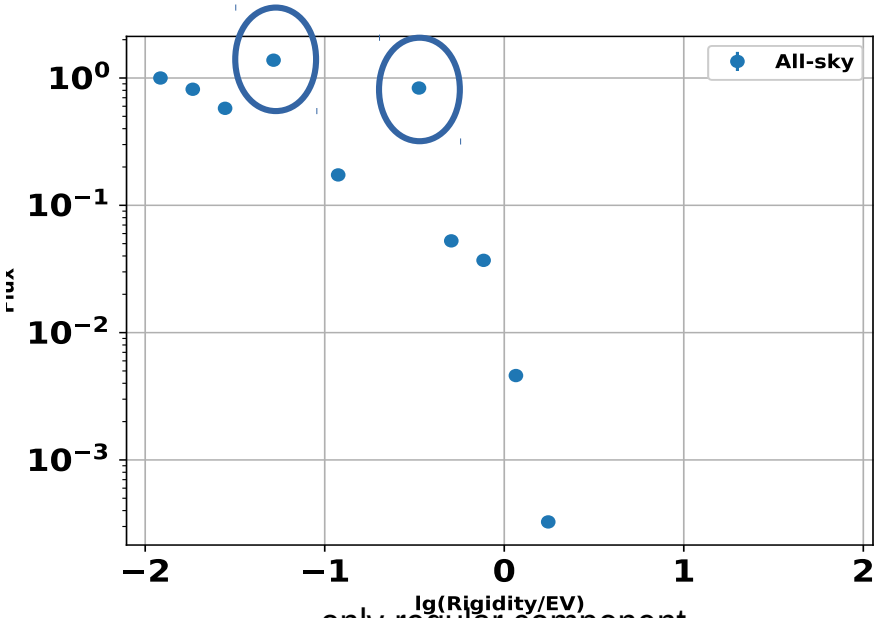


including random component

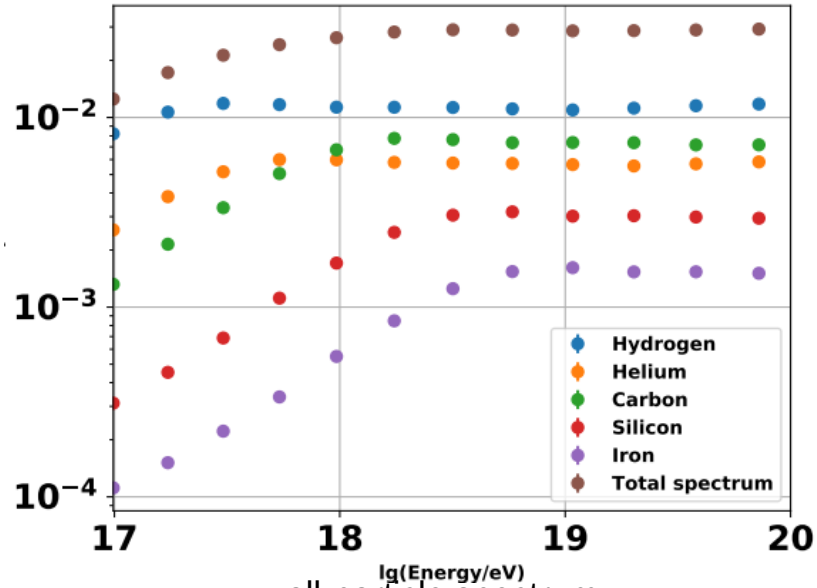


only regular component

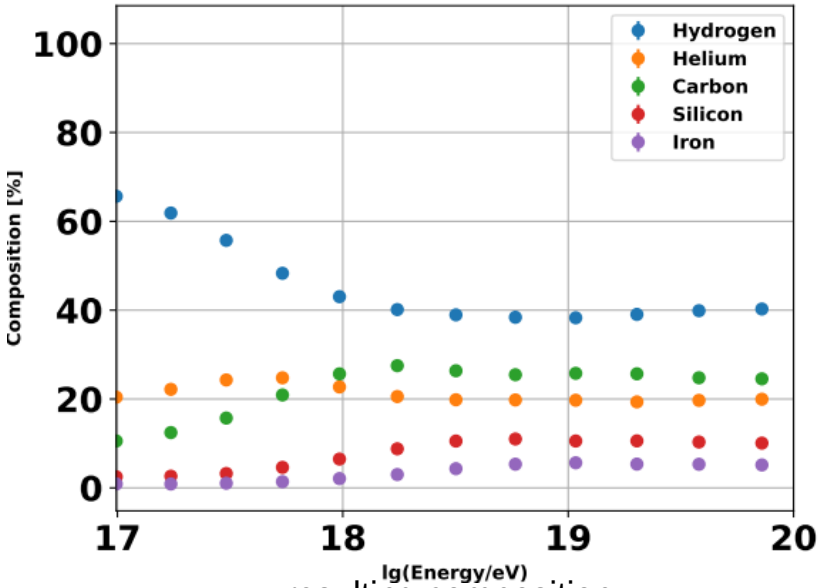
- reduction of flux towards higher rigidities → **spectral softening**
- reduction of flux **even more pronounced with only regular component**, however **with some jumps**, due to **trapping of individual particles in GP** (harder to escape closed loop without random component)

Composition & Anisotropy

Effects on EGCR composition (all-sky)



all-particle spectrum



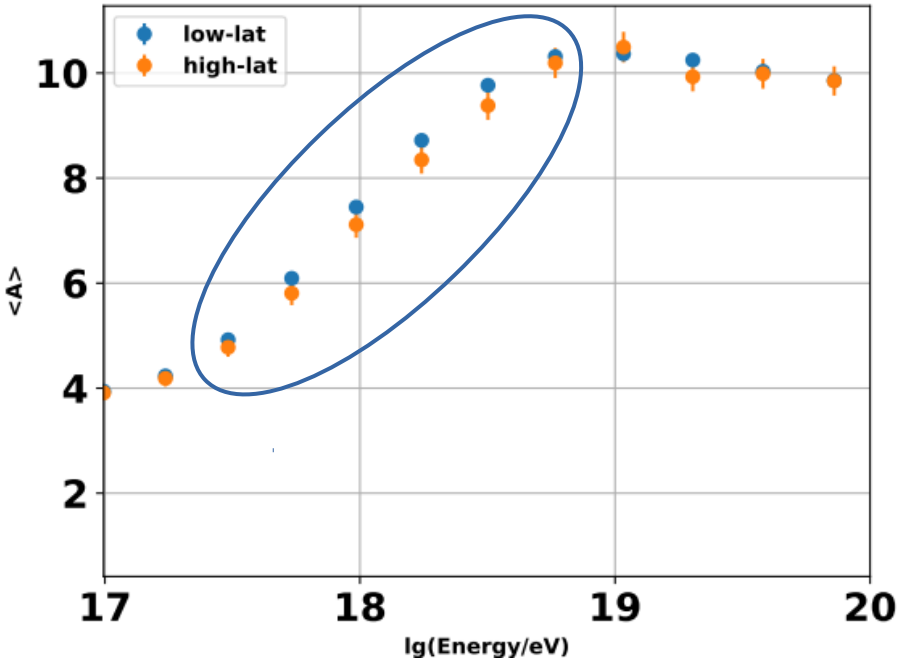
resulting composition

- inject mixed example composition (p, He, C, Si, Fe) = (0.4, 0.2, 0.25, 0.1, 0.05)

  → flux reduction **slows down** depending on contribution of heavier nuclei

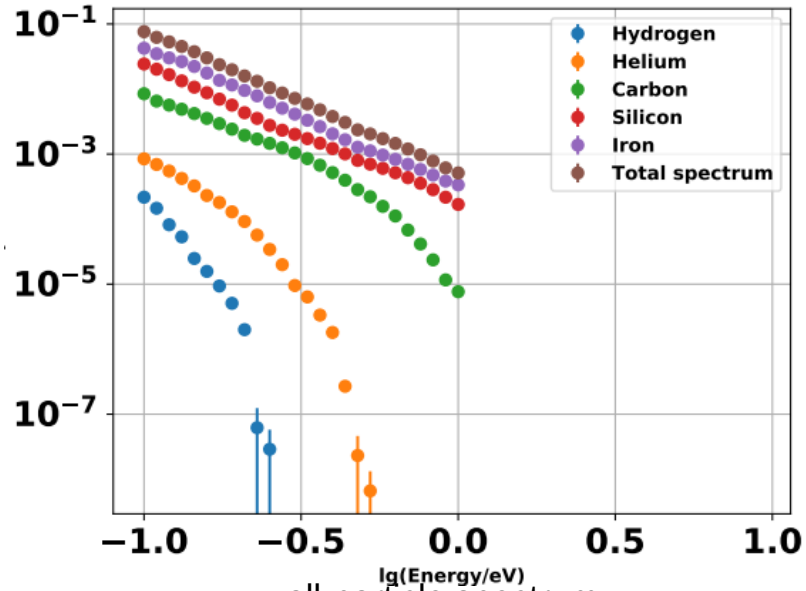
  → composition becomes **lighter towards lower energies**

Effects on EGCR composition (latitude-dependent)



- **compare** energy-dependent **composition for high-lat and low-lat region** (cut-off at 30°)
- → indication of **heavier** composition in **low-lat region** with **increasing energy**, or within **intermediate ridigity region** (due to **concentration effect** in GP)

Effects on GCR composition



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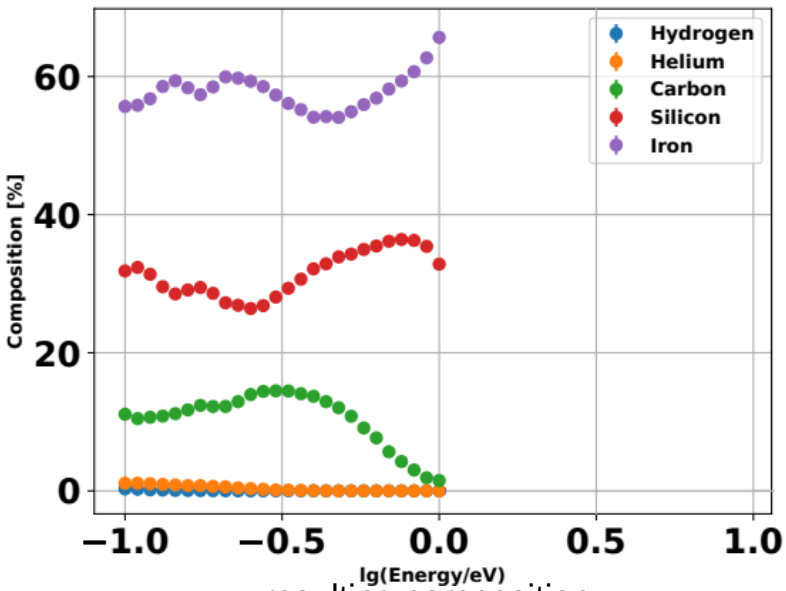


resulting composition

- inject mixed example composition (p, He, C, Si, Fe) = (0.4, 0.2, 0.25, 0.1, 0.05)

  → **heavier** particles are **trapped longer** and **dominate the flux for higher energies**

- **anisotropy studies not possible** for this study but generally expected to **correlate with GP**

Results

- Deflections in GMF:
  - EGCRs are shielded for low R, concentrated in GP for mid R and hardly affected for high R
  - GCRs are captured for low R and gradually escape with higher R

    → effect on spectrum: **softening for GCRs and hardening for EGCRs**

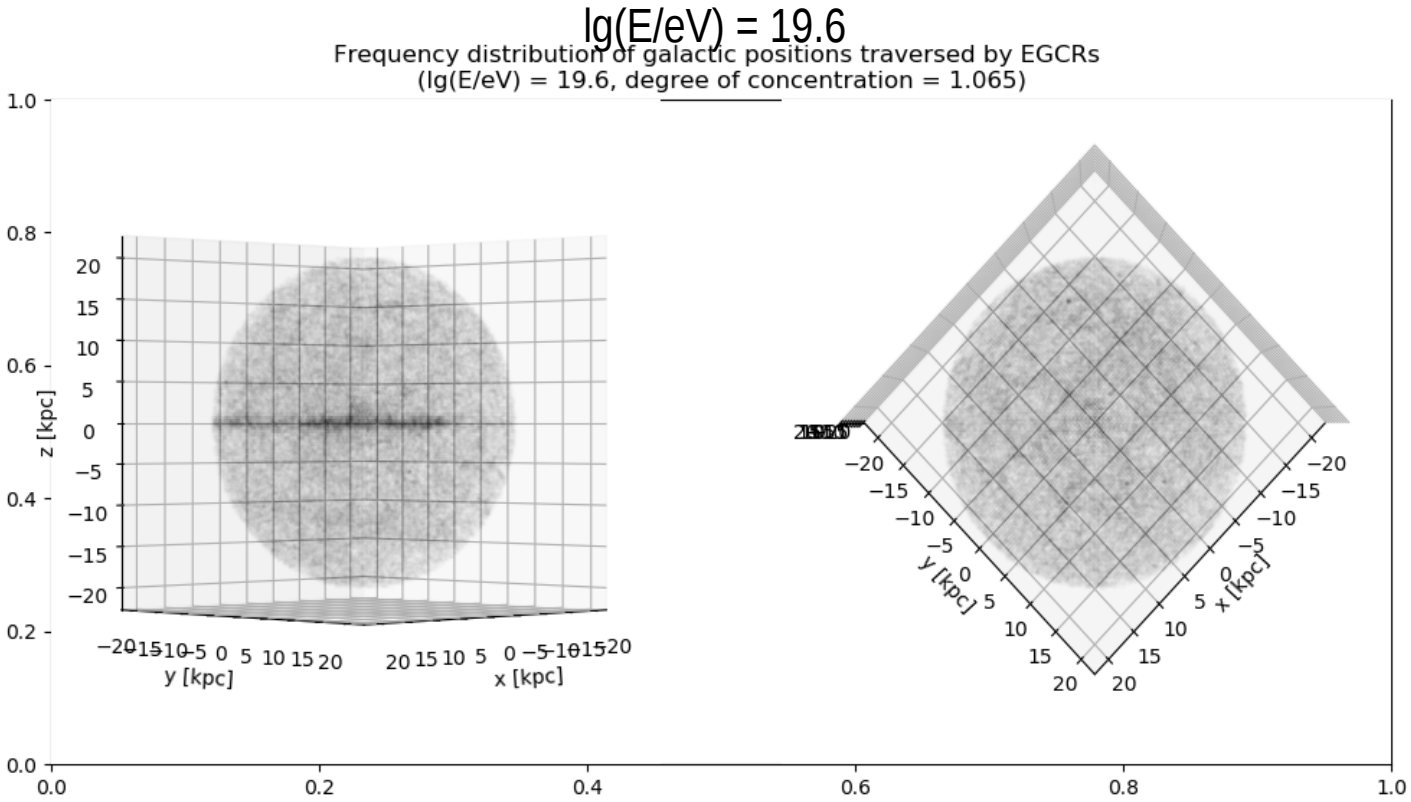
    → heavier composition with increasing energy for both GCRs as well as EGCRs
    → dependence on Galactic latitude: **heavier/lighter compositions on- and off-plane** (in mid-R region)

Outlook

- Extend simulations to lower energies to incorporate ‘knee’ energy for heaviest CRs
- Repeat composition studies for more realistic CR injection compositions
- Use realistic source distributions to estimate arrival direction anisotropies for EGCRs
- Fit to Auger data to determine contribution of GCRs and EGCRs to flux

Thank you for your attention!

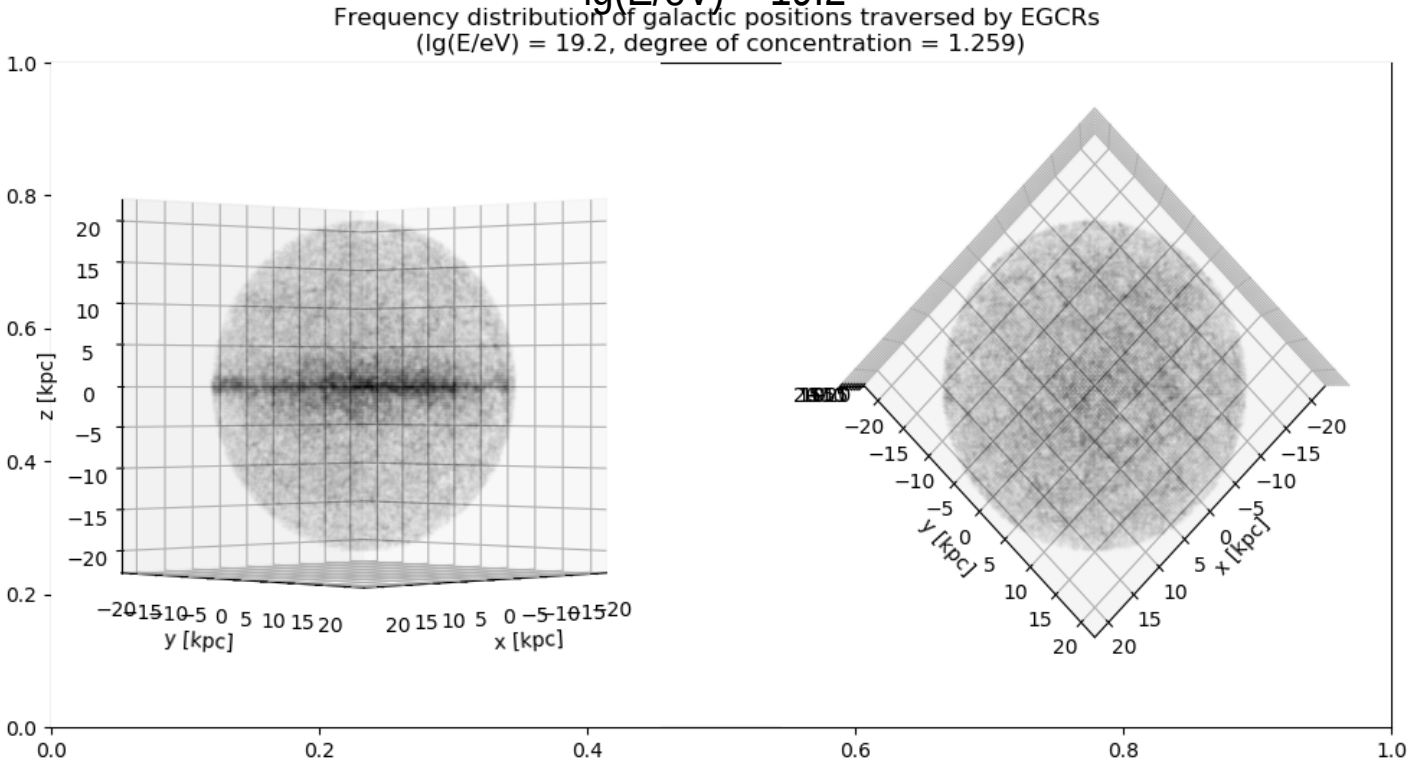
Backup - Density in Galaxy



- increasing concentration in Galactic plane with decreasing energy

Backup - Density in Galaxy

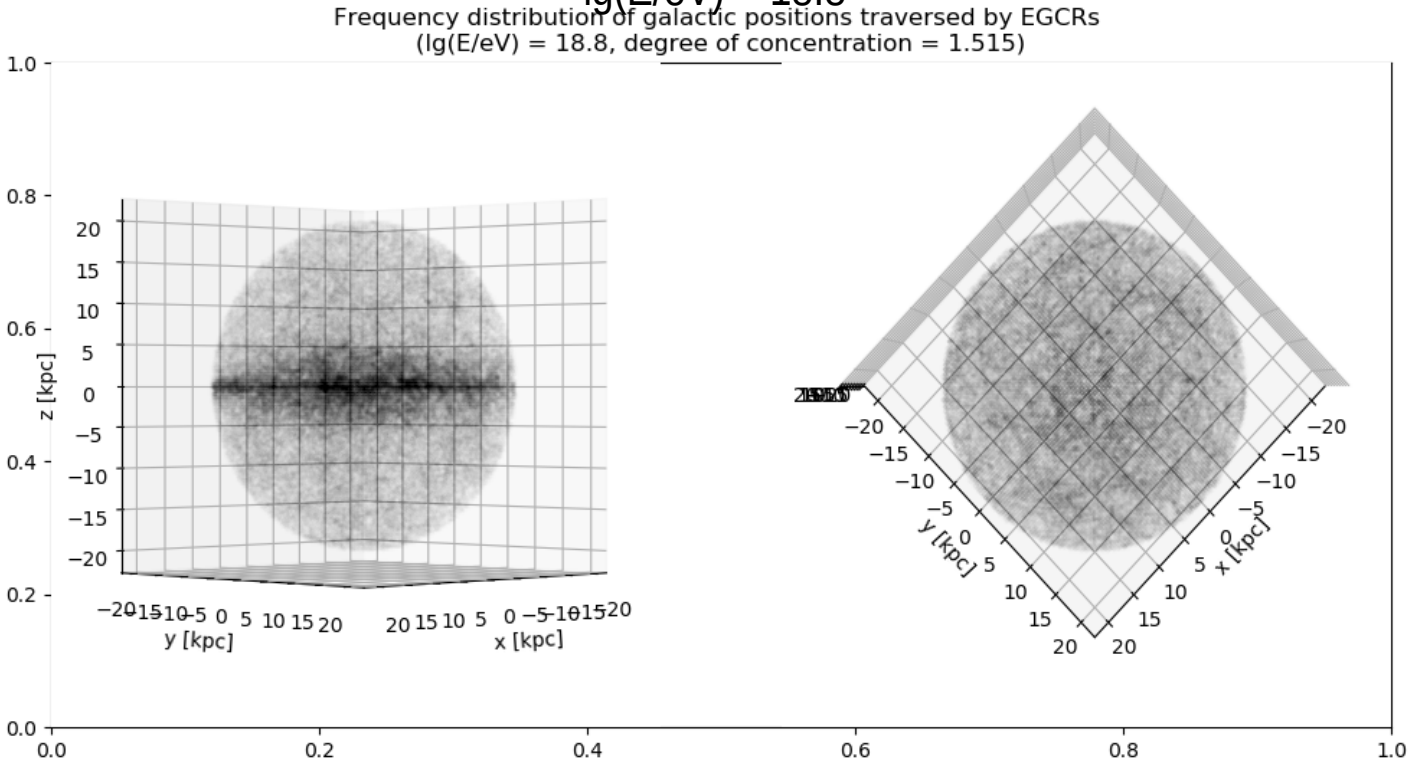
lg(E/eV) = 19.2



- increasing concentration in Galactic plane with decreasing energy

Backup - Density in Galaxy

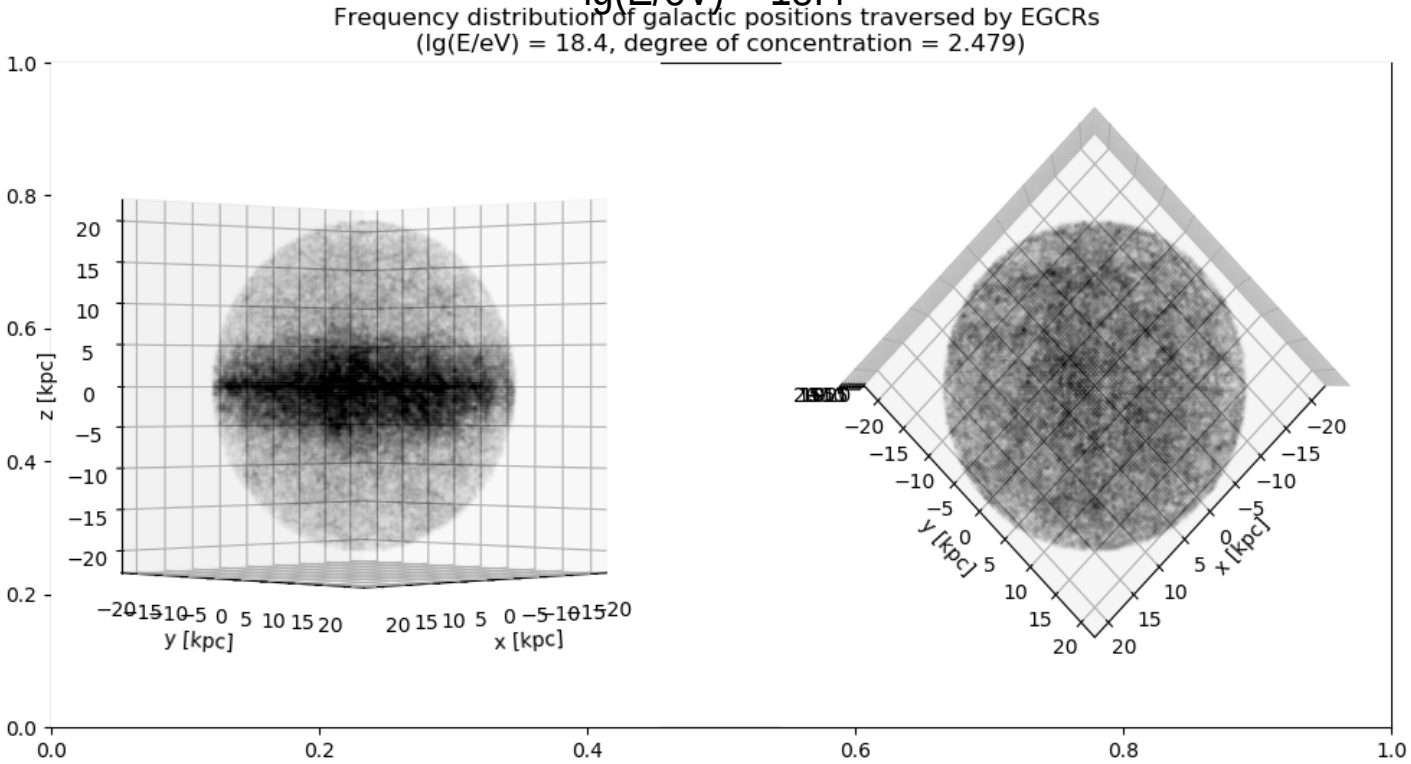
lg(E/eV) = 18.8



- increasing concentration in Galactic plane with decreasing energy

Backup - Density in Galaxy

lg(E/eV) = 18.4



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