Toward identifying ultra-high-energy cosmic-ray sources with improved magnetic field modeling

Teresa Bister

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TeV Particle Astrophysics
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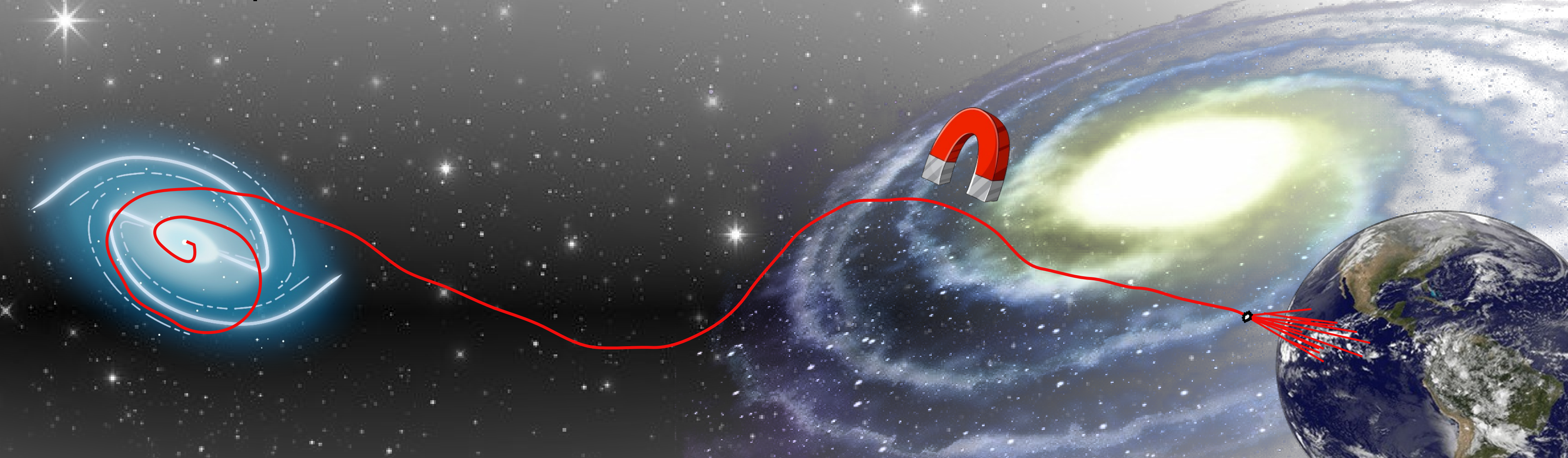
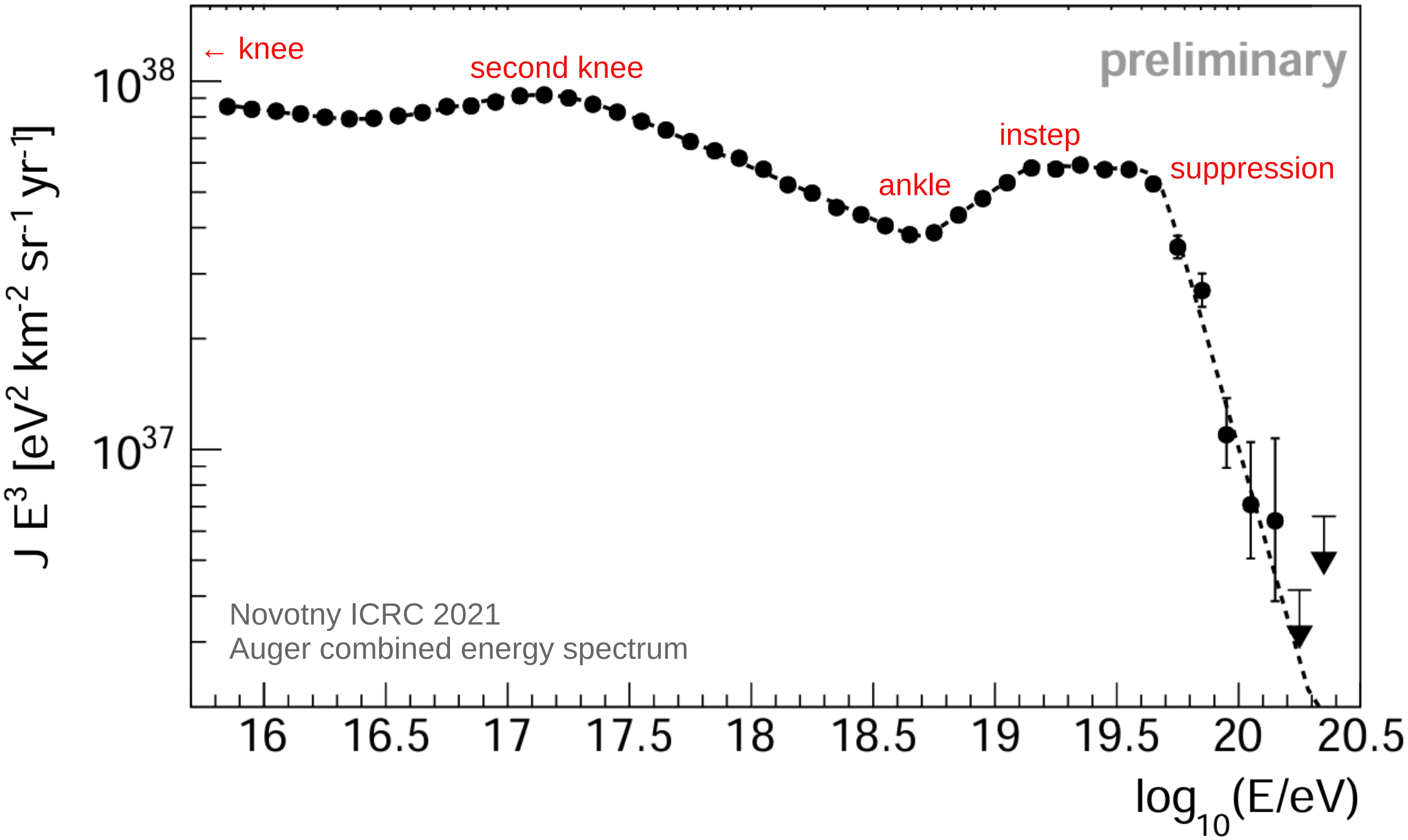
Tendo
Japan
August 30 - September 4, 2026

Nikhef
Radboud University



Energy spectrum of cosmic rays



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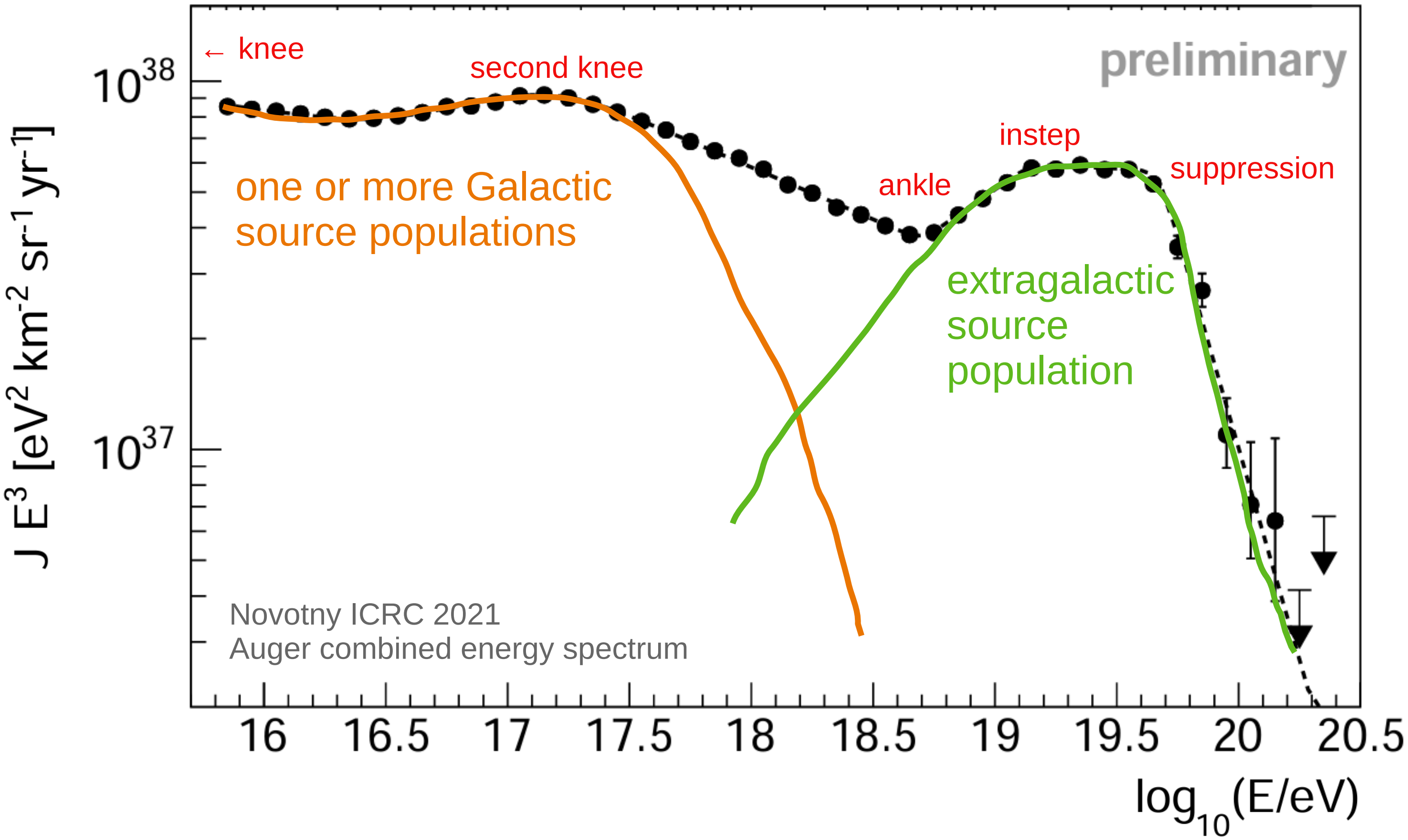
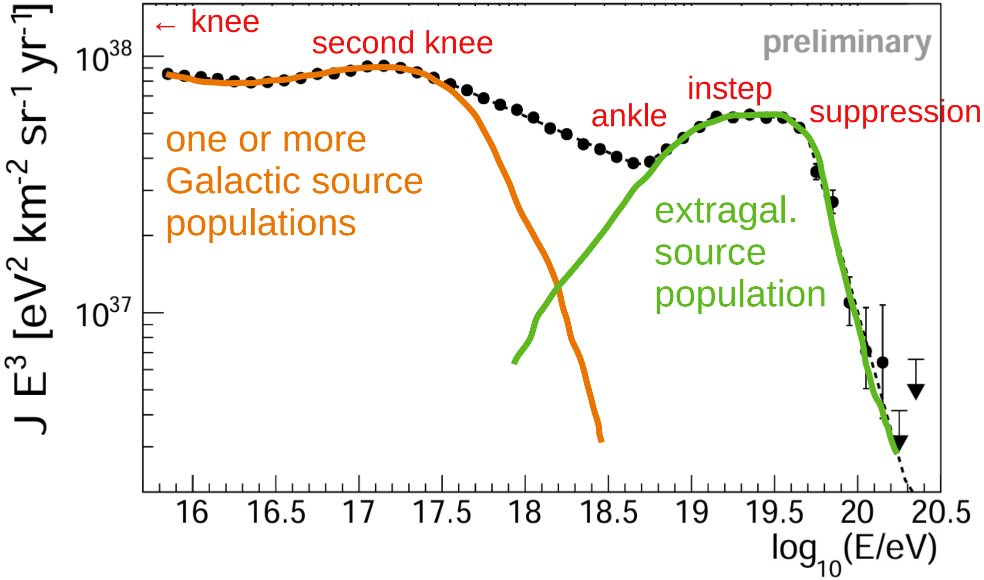
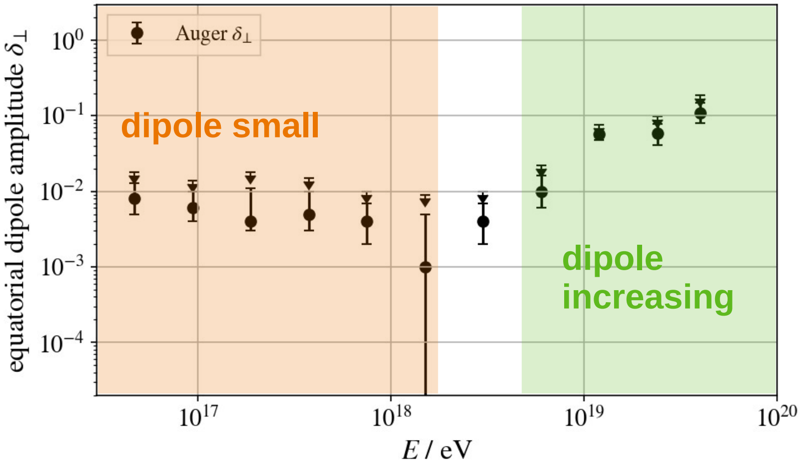
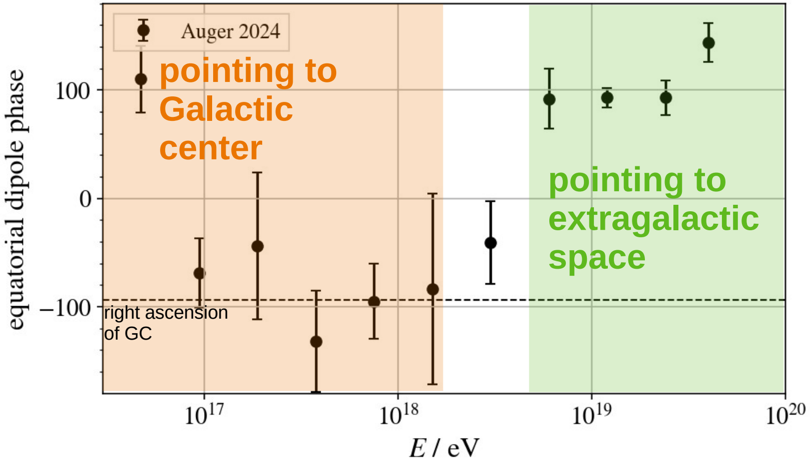


Energy spectrum & anisotropy of cosmic rays







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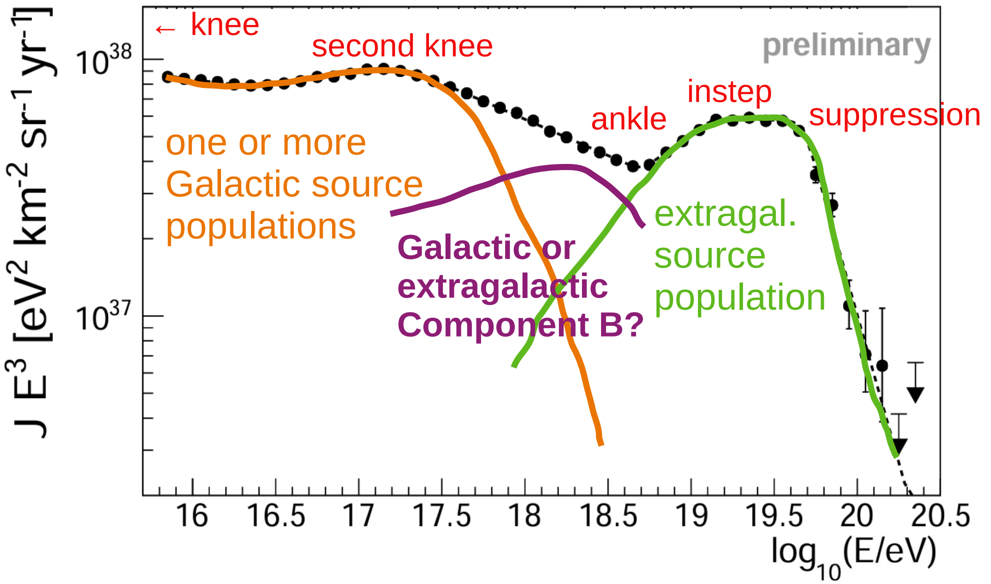

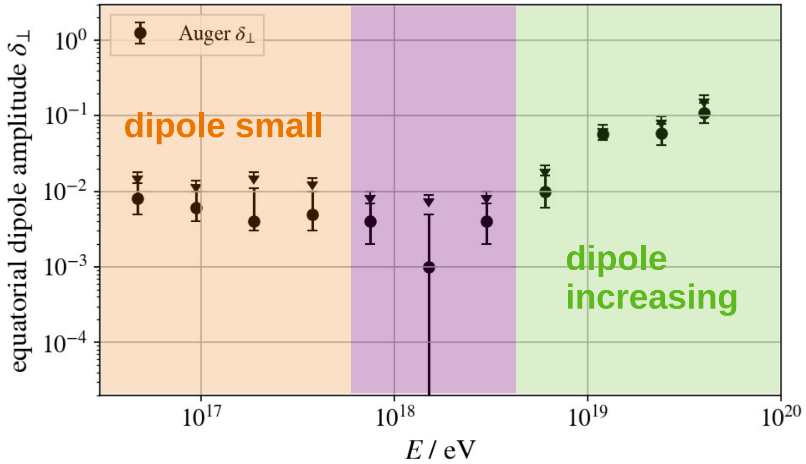

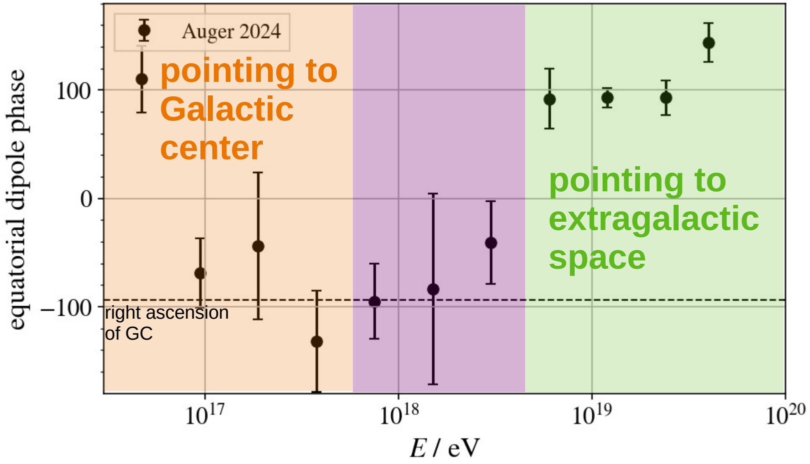

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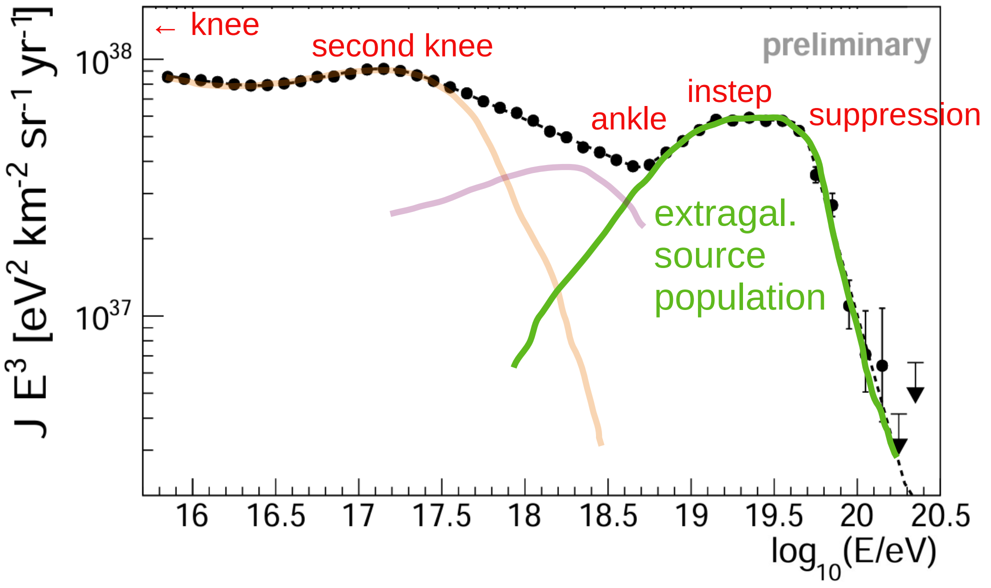
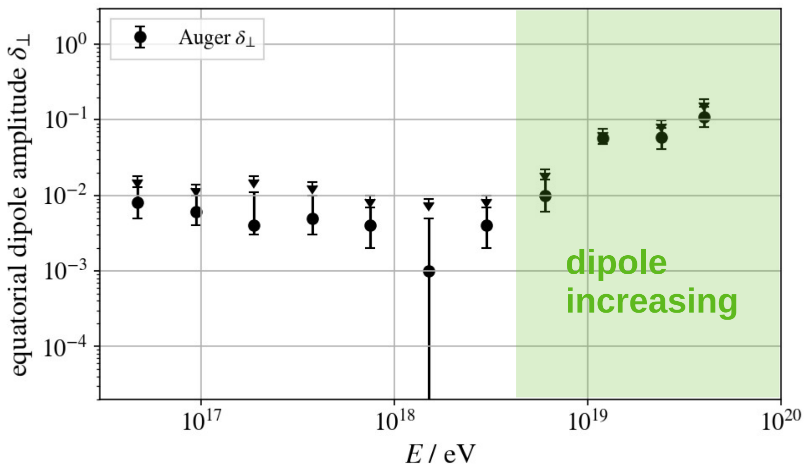
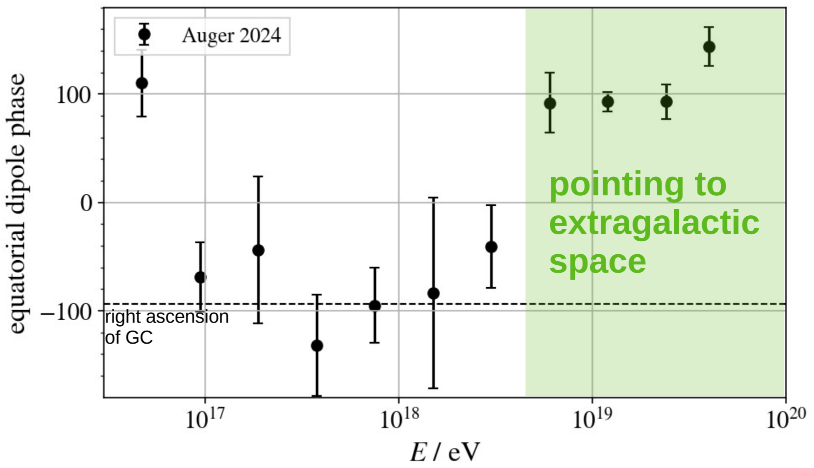
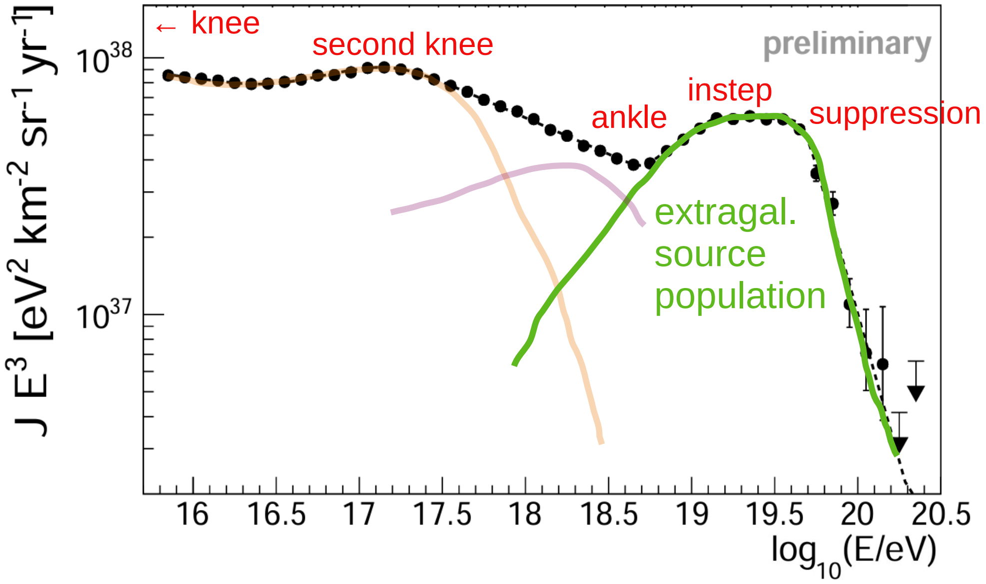
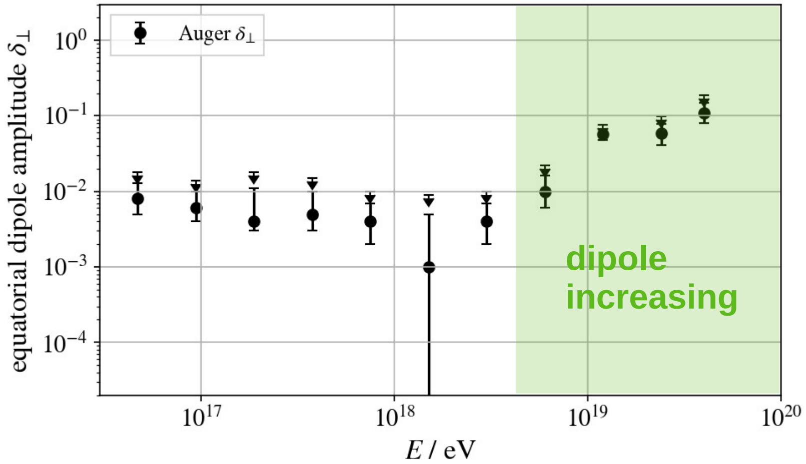


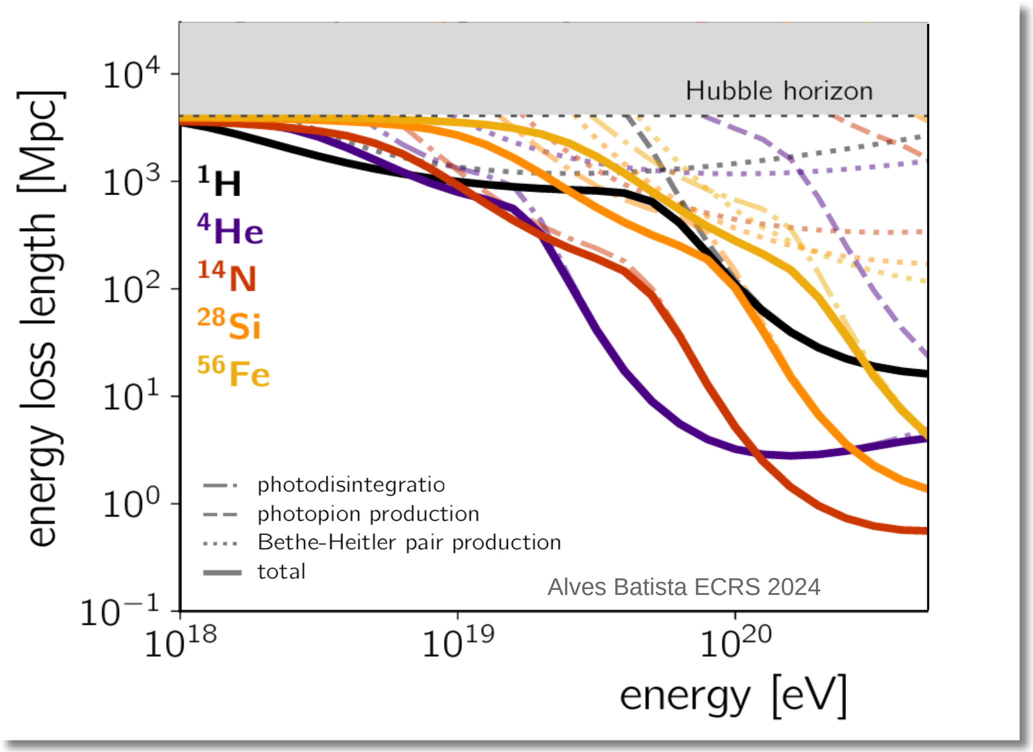




Horizon of extragalactic cosmic rays





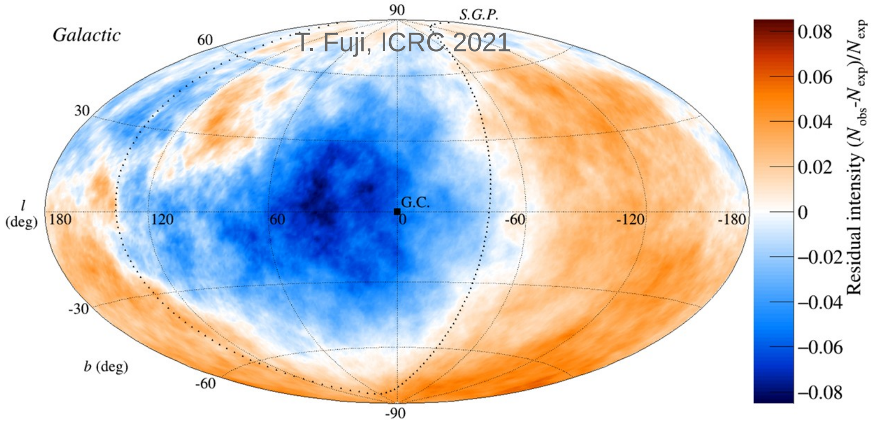


$\lesssim$ 10 EeV:
CRs can come from almost whole visible universe

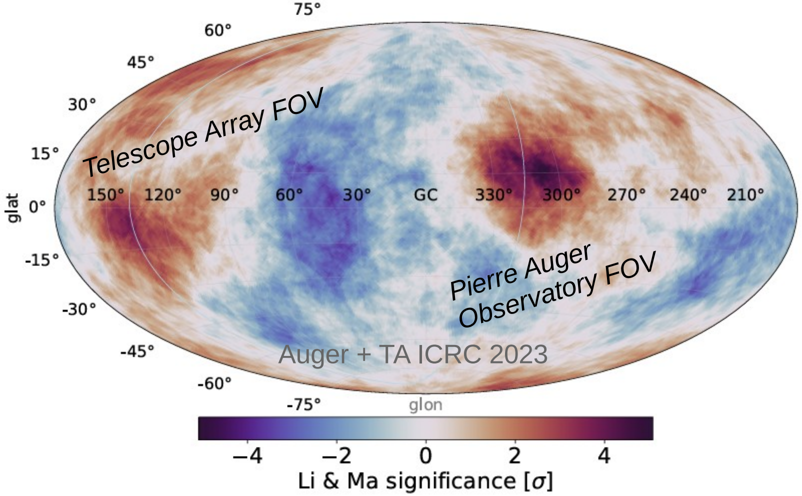
$\gtrsim$ 40 EeV
only few nearby sources contribute

Extragalactic cosmic rays: arrival directions

$\lesssim$ 10 EeV (CRs from ~1000 Mpc):



$\gtrsim$ 40 EeV (CRs from ~200 Mpc):



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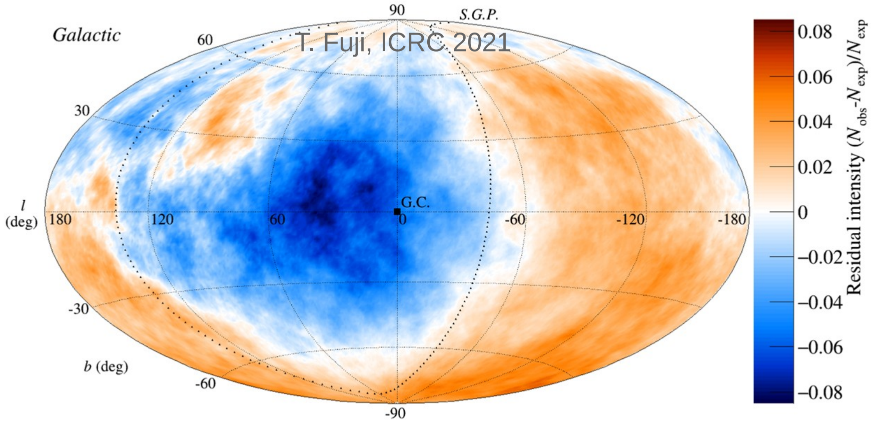

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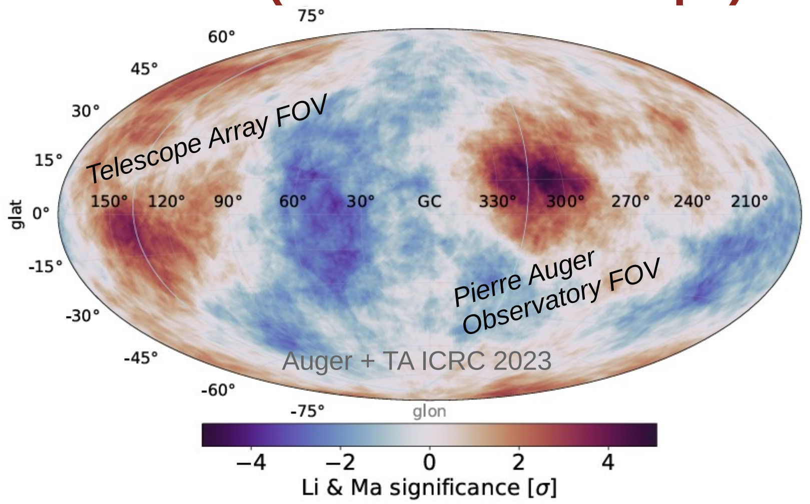

- sky is quite isotropic
  - only **dipole** significant >8 EeV
  - amplitude ~6% at 8 EeV, rising with the energy

Auger Science 2018

→ **observational proof that CRs are extragalactic** at these energies

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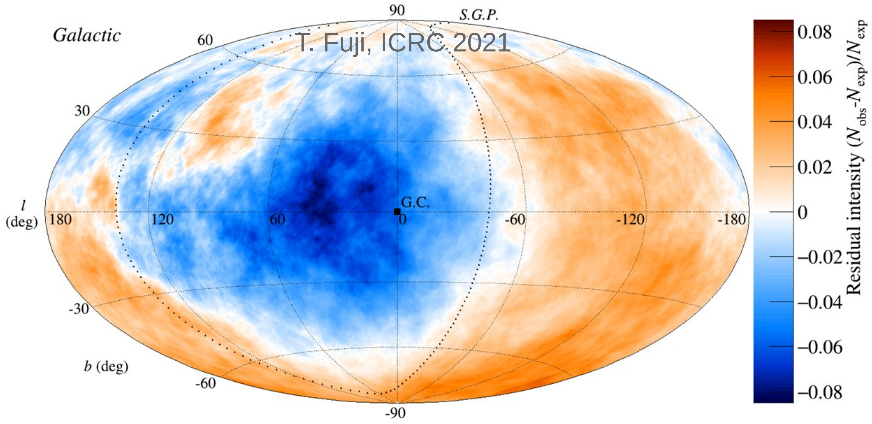

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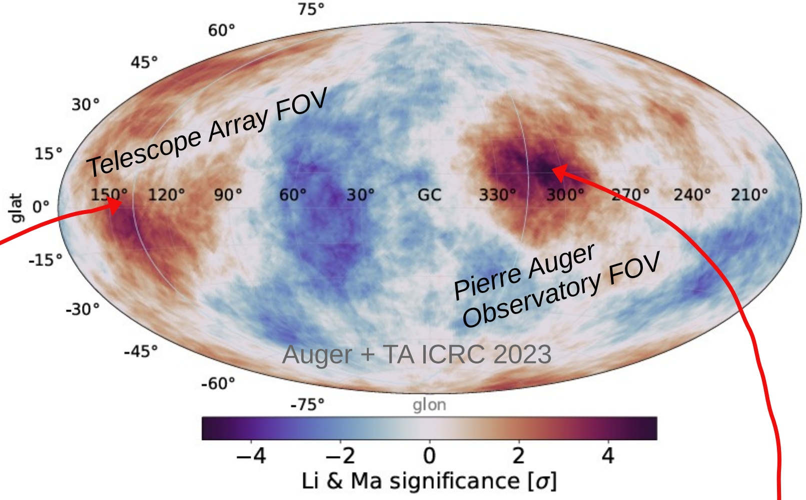

- overdensities in Telescope Array FOV with ~3σ post-trial significance
- most significant overdensity: **Centaurus excess** in Auger FOV
  - **~4σ** post-trial significance, 27° radius
  - ~3° from radio galaxy Centaurus A (~4 Mpc)

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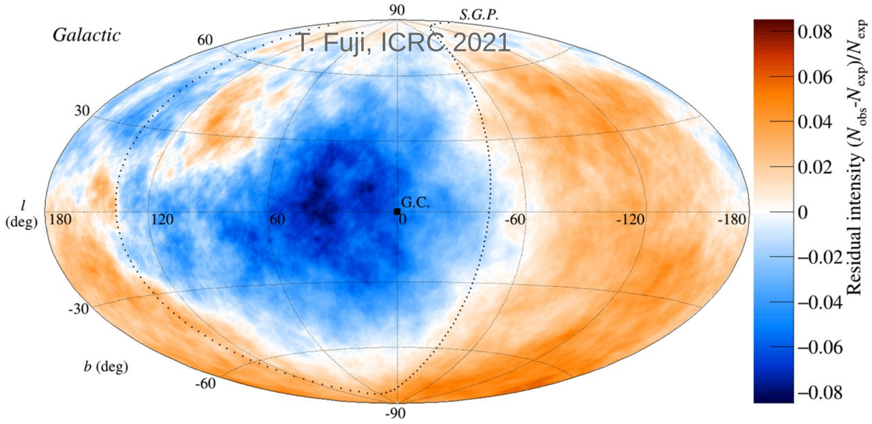

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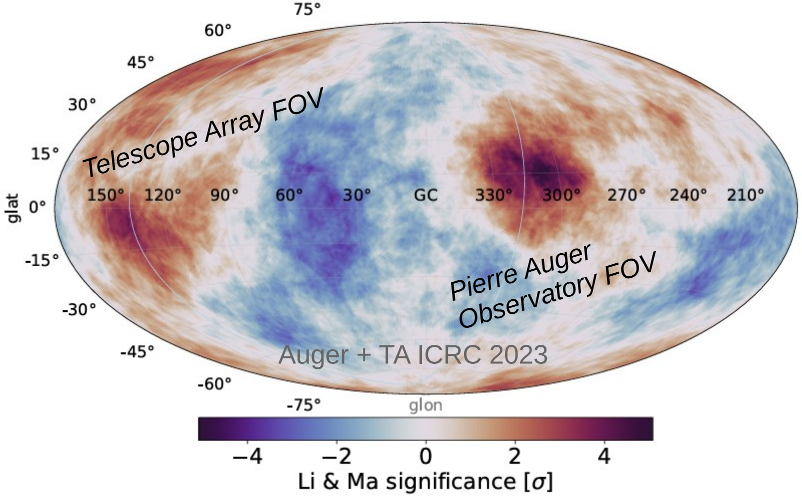
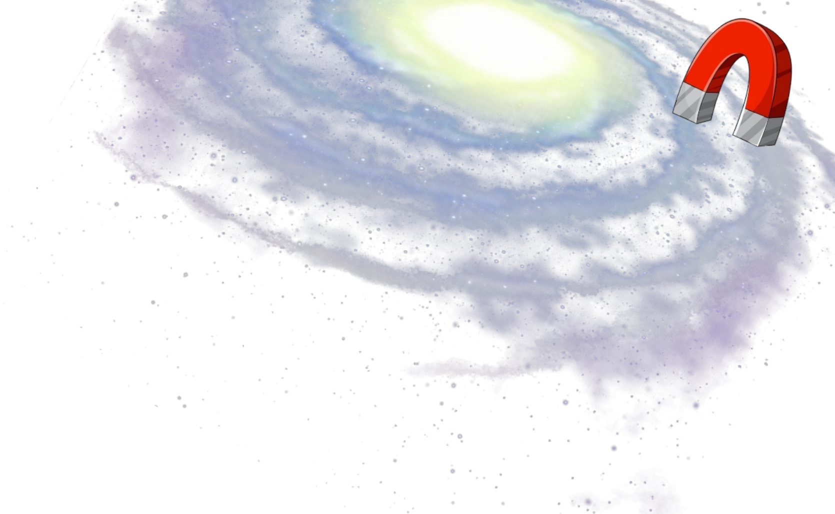


How can we explain these observations?

To interpret cosmic-ray arrival direction data, magnetic field deflections need to be considered!

The Galactic magnetic field

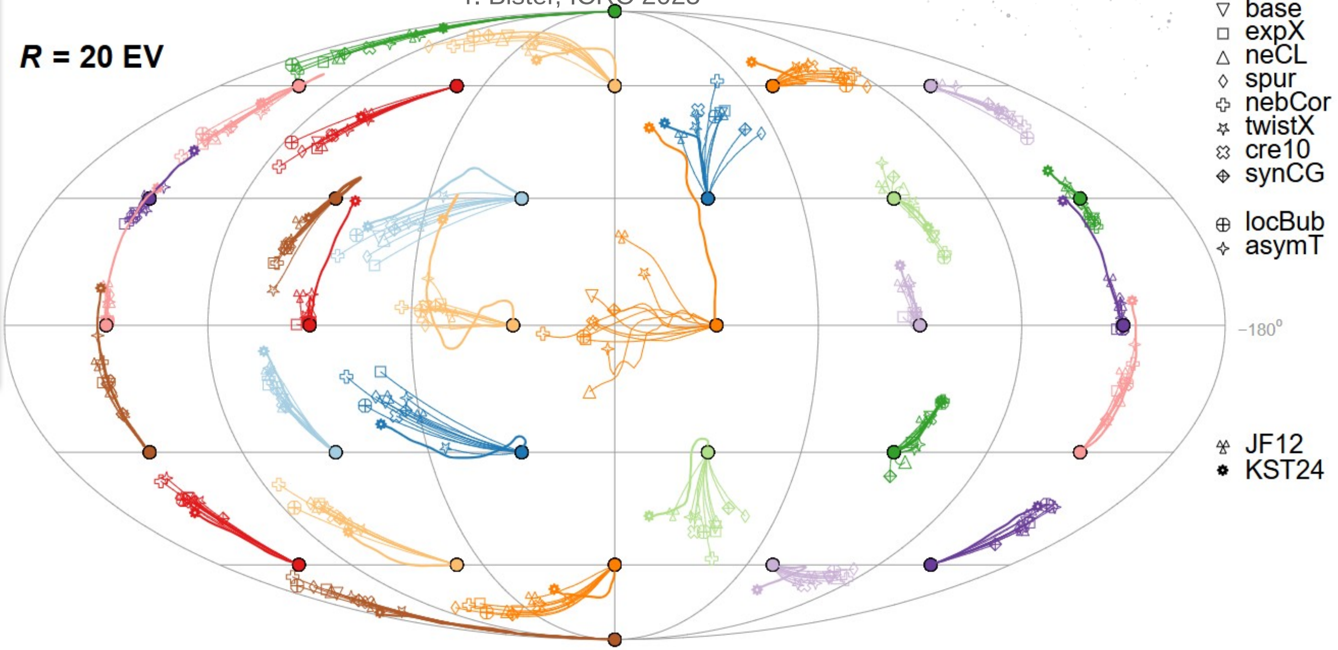


- Milky Way magnetic field ~μG, coherent + turbulent
- **deflection** $\propto Z / E := 1 / R$
- in last three years: Unger & Farrar 2023, 2024, Korochkin et al 2024
  <u>>10 new models for the coherent field released</u>

→ based on varying assumptions about electron distribution, parameterization...

→ reasonable agreement between models, enables **estimate of systematic uncertainty**

T. Bister, ICRC 2025

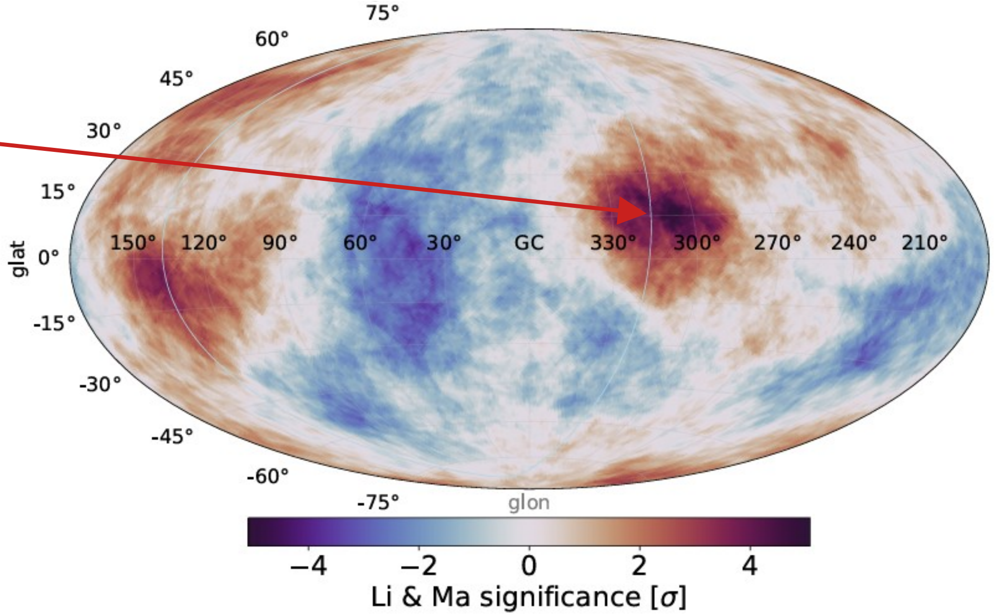


new random field model just released: Unger & Farrar 2026

The Centaurus excess

Properties of the excess: [Auger ICRC 2023]

- local significance: 5.1σ for E_{min} = 40 EeV
- angular size: 27° for E_{min} = 40 EeV
- excess extends to E_{min} = 20 EeV, direction stable
  [Auger ApJ 984 2025]



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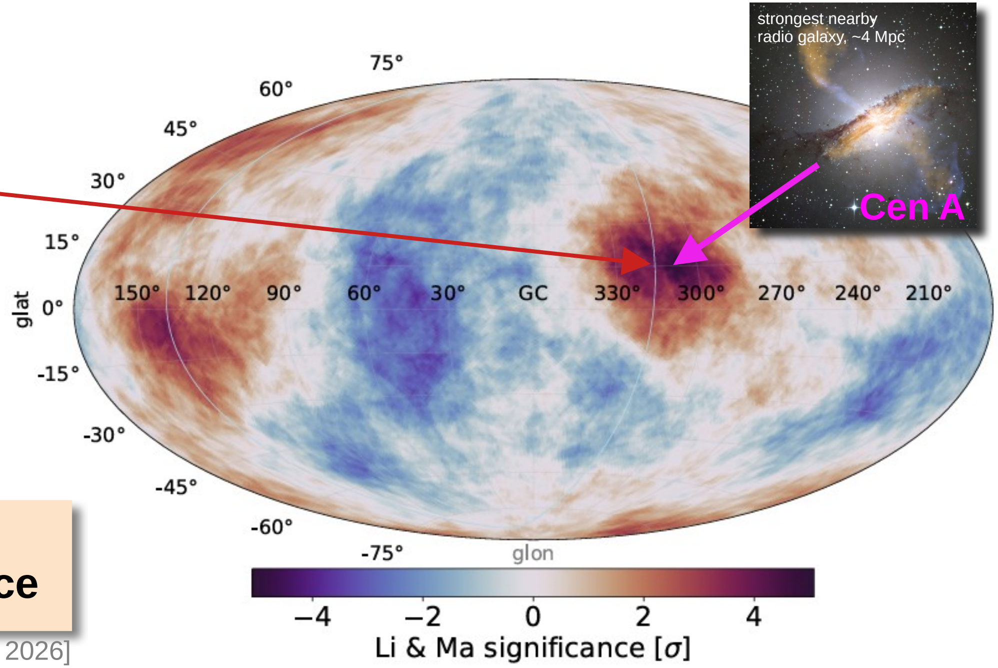
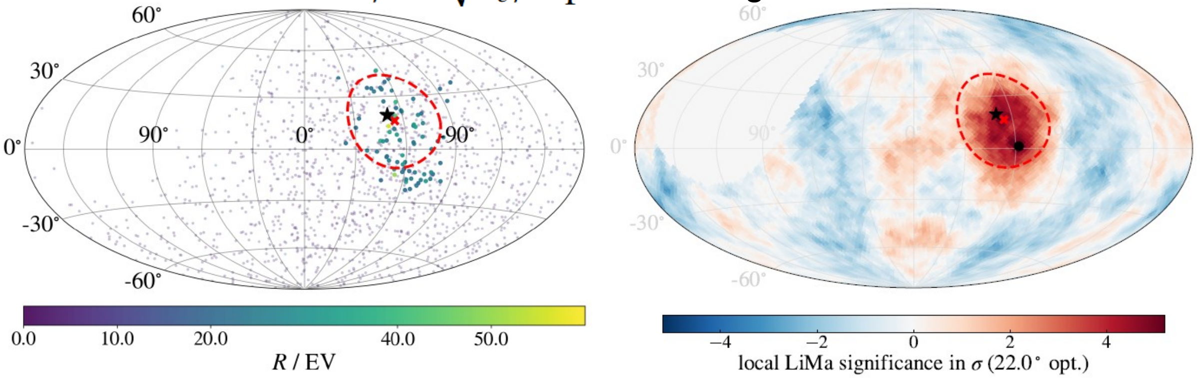


can reproduce excess direction, size, strength in
simulations with new GMF models & Cen A as source

[Bister Astroparticle Physics 2026]

Z=2, $B/\mathrm{nG}\sqrt{L_c/\mathrm{Mpc}}$ =15, signal fraction 5%



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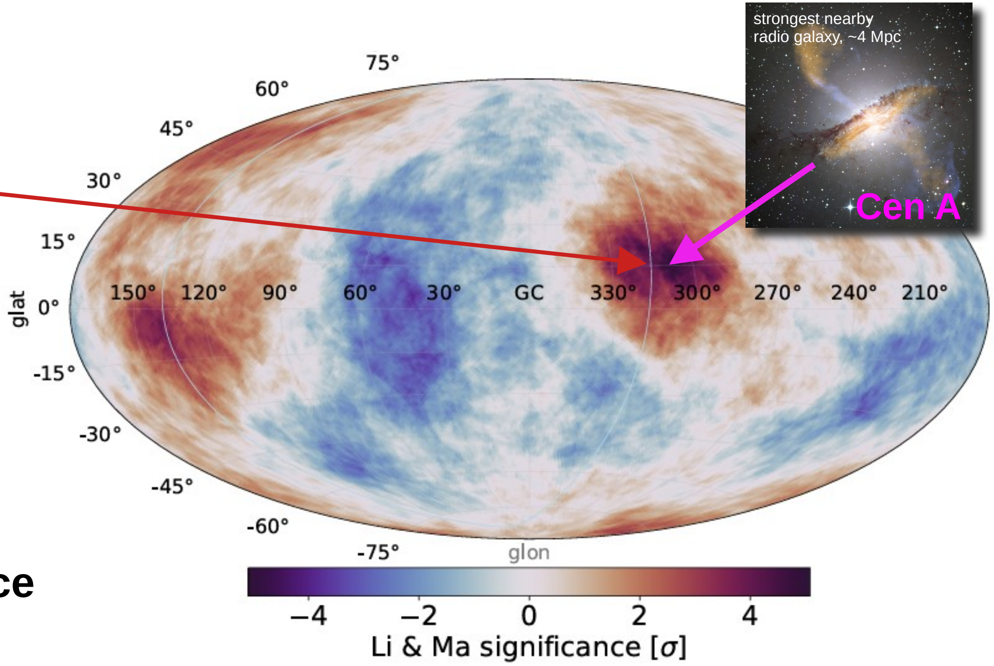

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- **need additional turbulent magnetic field between source & Earth**
  $1 \lesssim B/\mathrm{nG}\sqrt{L_c/\mathrm{Mpc}} \lesssim 30$ for Z~6

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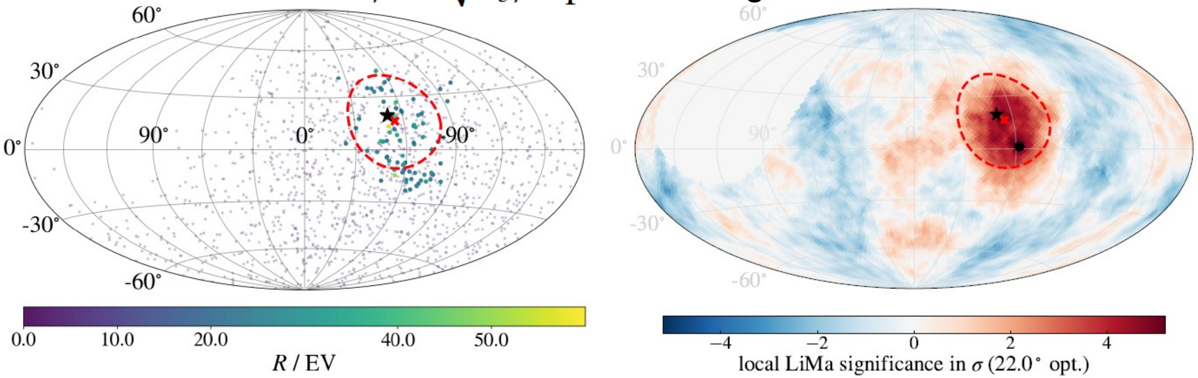

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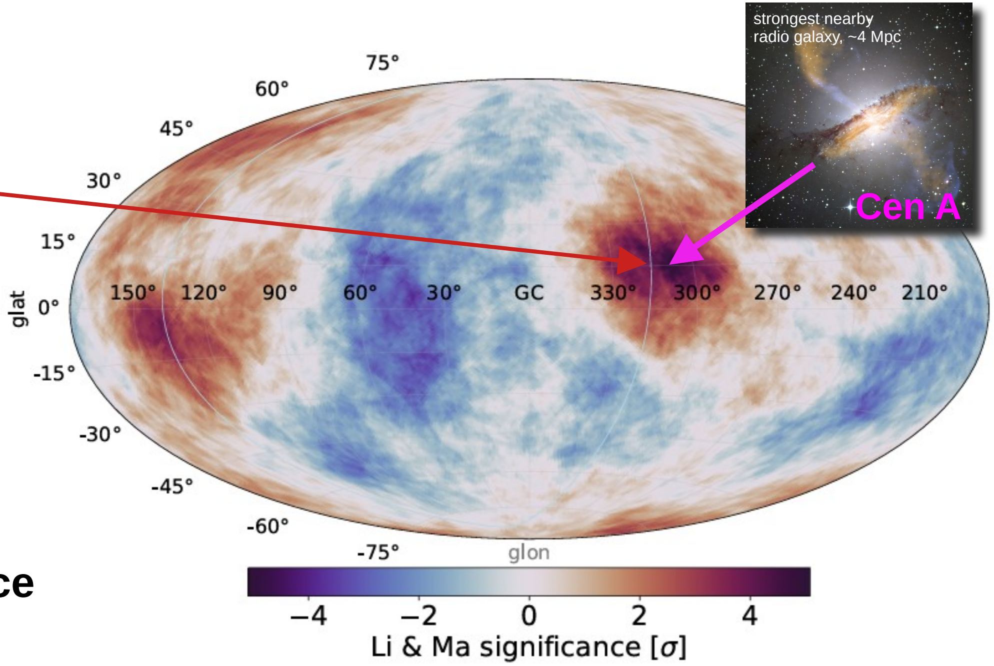

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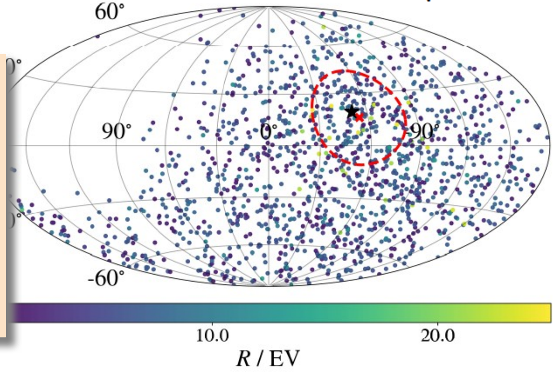
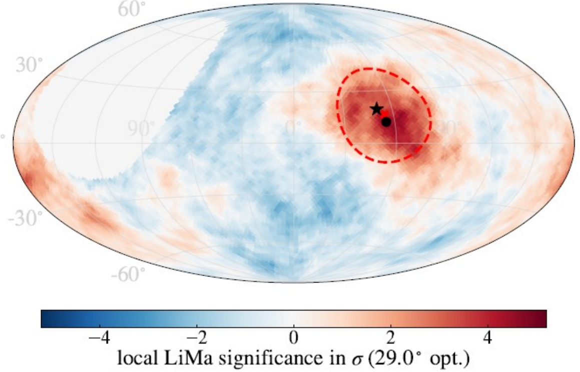
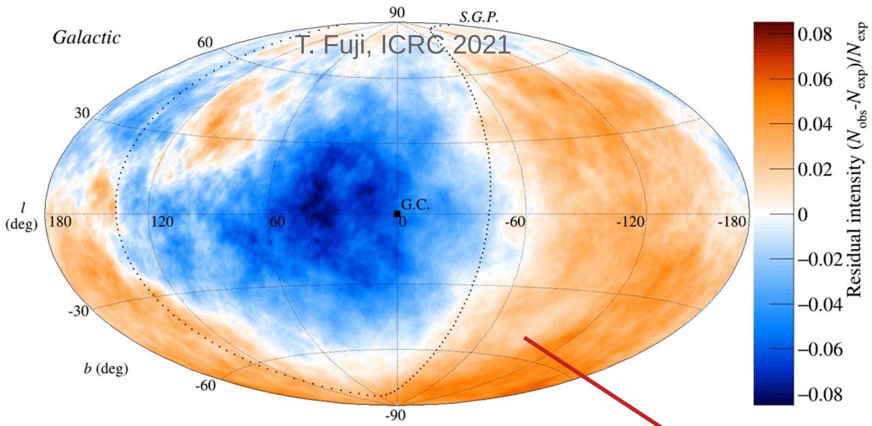
- **cannot exclude signal fraction of 100%**
  - need careful study of lower energies & contributions of Cen-A-like sources, better knowledge of magnetic field between Cen A and Earth

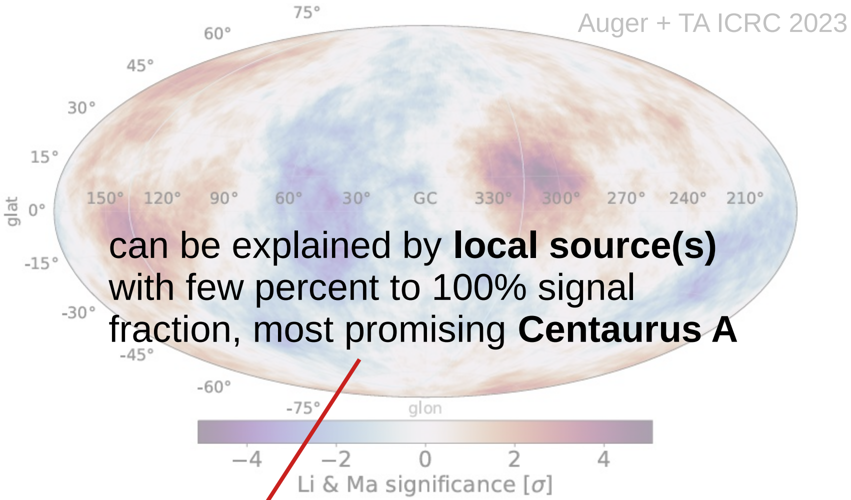
Z=mixed, $B/\mathrm{nG}\,\sqrt{L_c/\mathrm{Mpc}}$ =26, signal fraction 100%



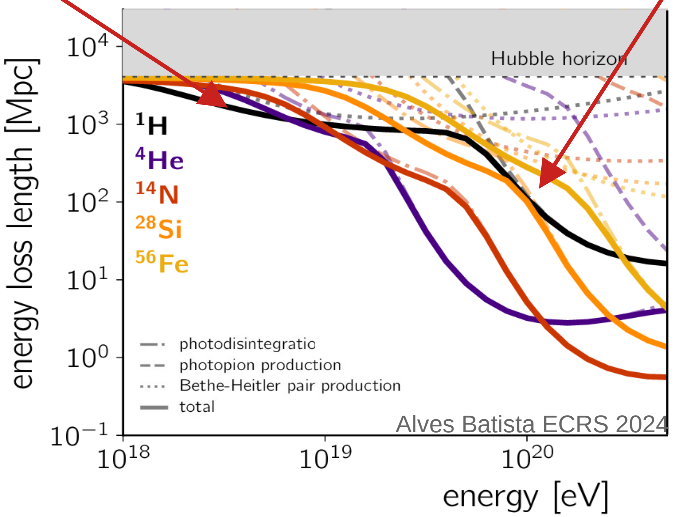


Extragalactic cosmic rays: arrival directions





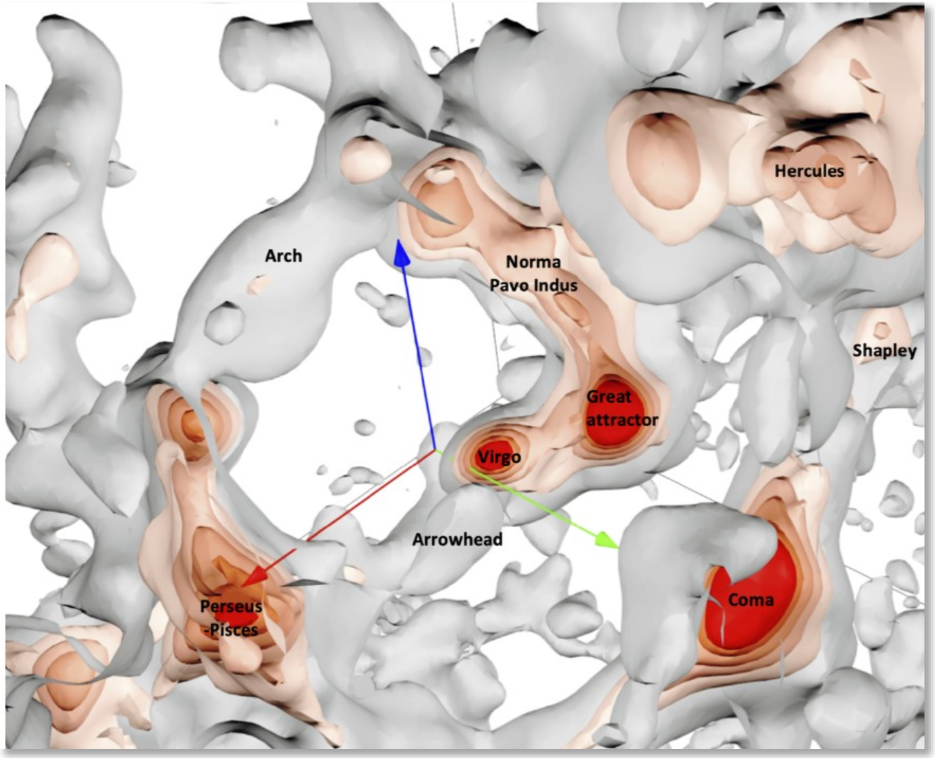
can be explained by **local source(s)** with few percent to 100% signal fraction, most promising **Centaurus A**



Can the dipole amplitude & direction + energy evolution be explained by sources following the large-scale structure?

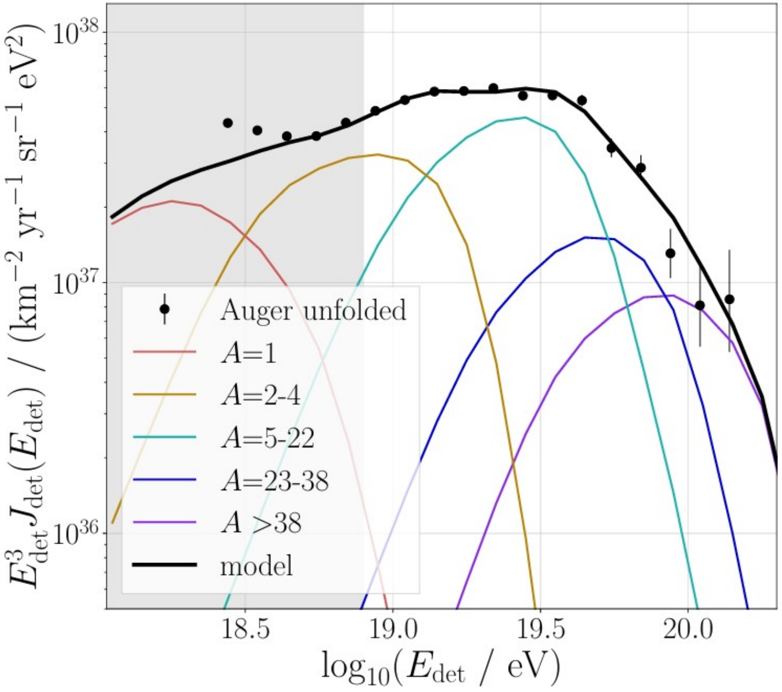
Extragalactic CR source population

assume CR sources follow matter density (CosmicFlows) + extrapolation after 350 Mpc

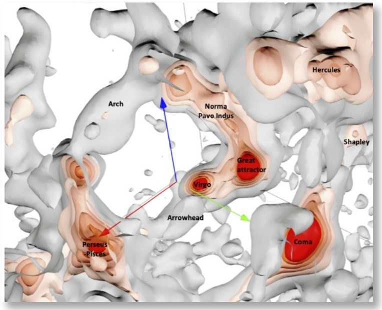


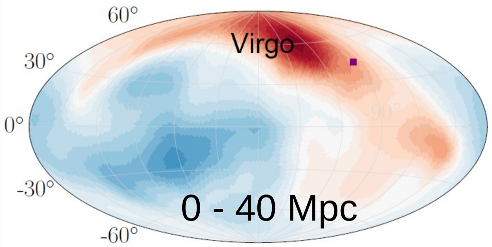
combined fit to measured spectrum and mass composition:

- Peters cycle (acceleration prop. to Z), gets progressively heavier
- hard spectrum, little mixing



Spatial extragalactic CR flux





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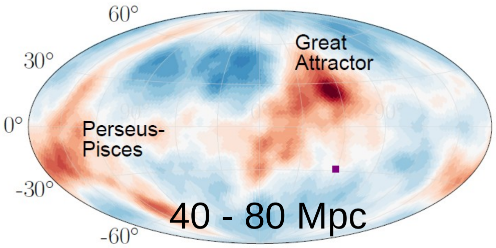

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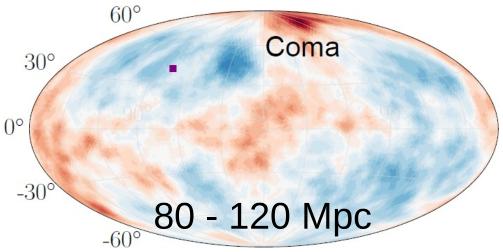

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Bister & Farrar, ApJ 966 71 (2024)

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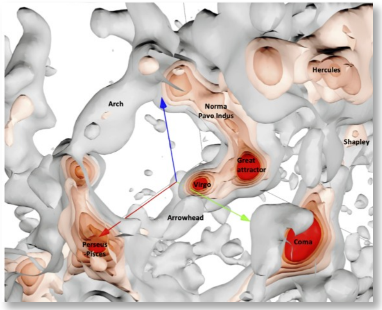

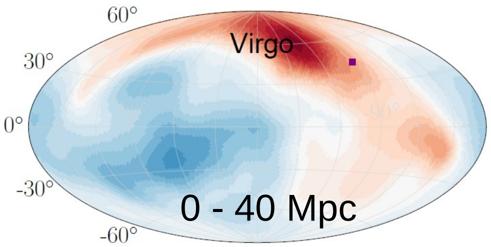

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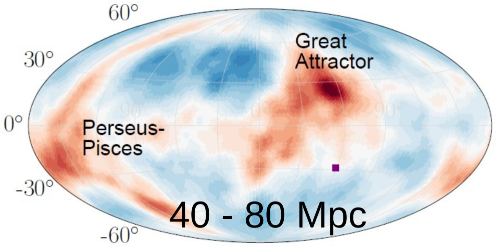

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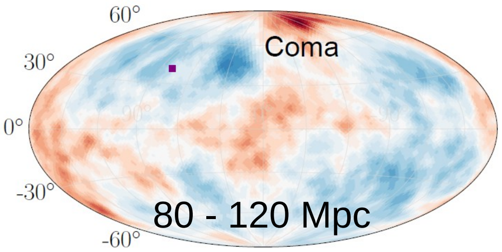

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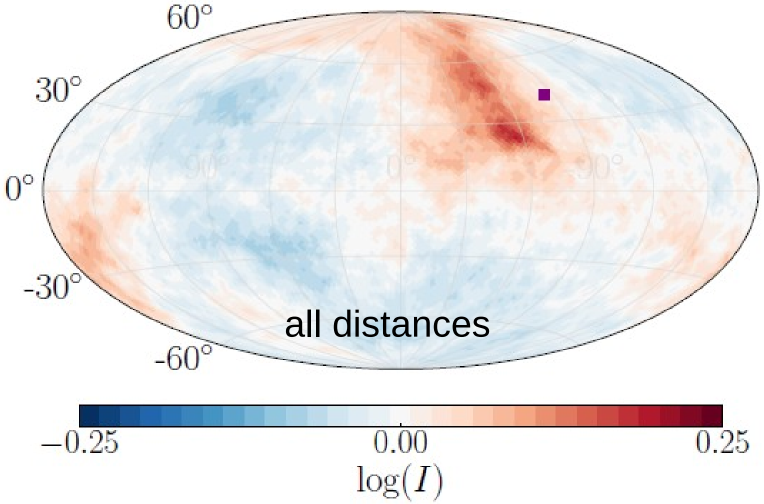

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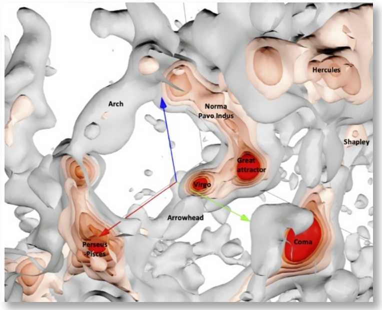

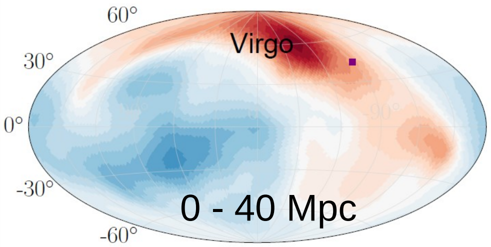

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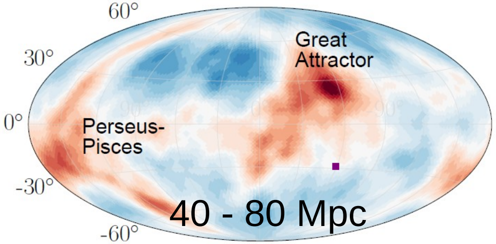

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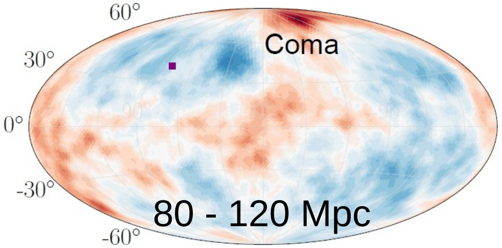

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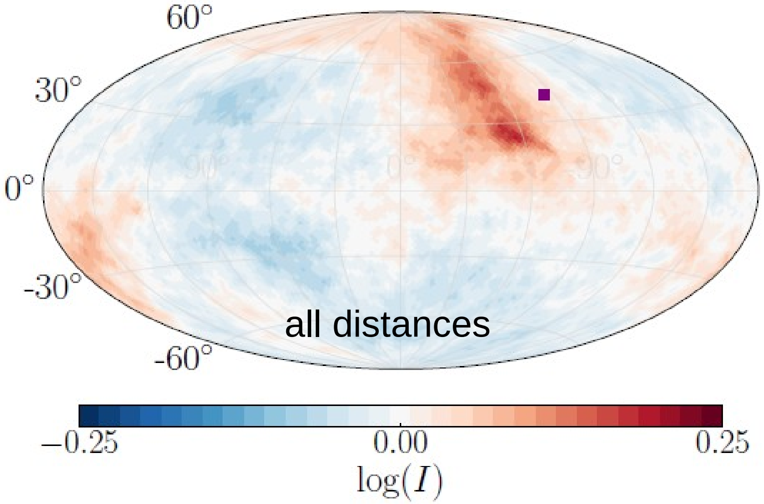
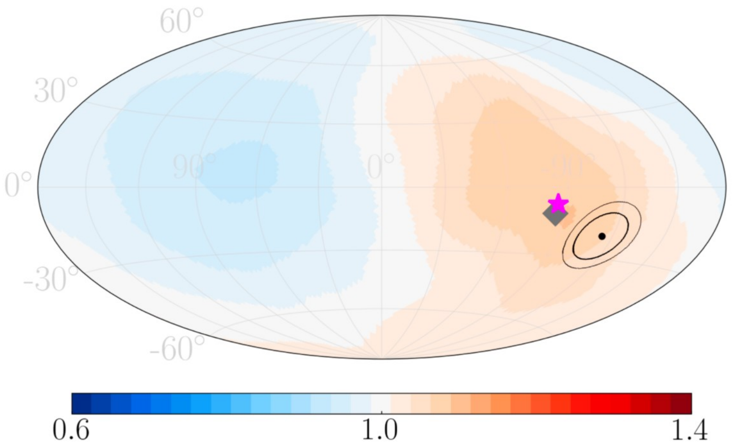


Galactic magnetic field model

CRPropa



modeled flux at Earth reproduces dipole ✓

Bister & Farrar, ApJ 966 71 (2024)

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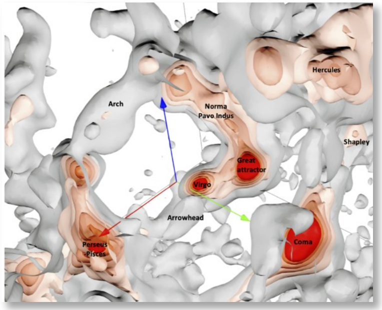

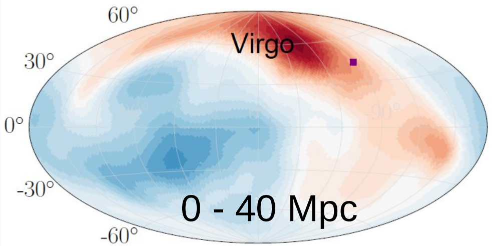

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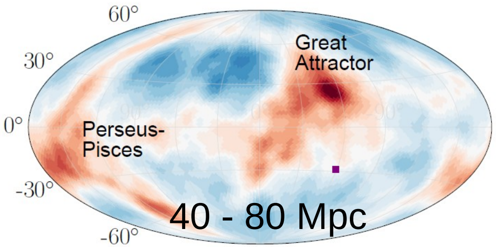

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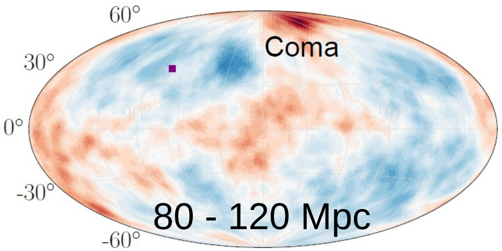

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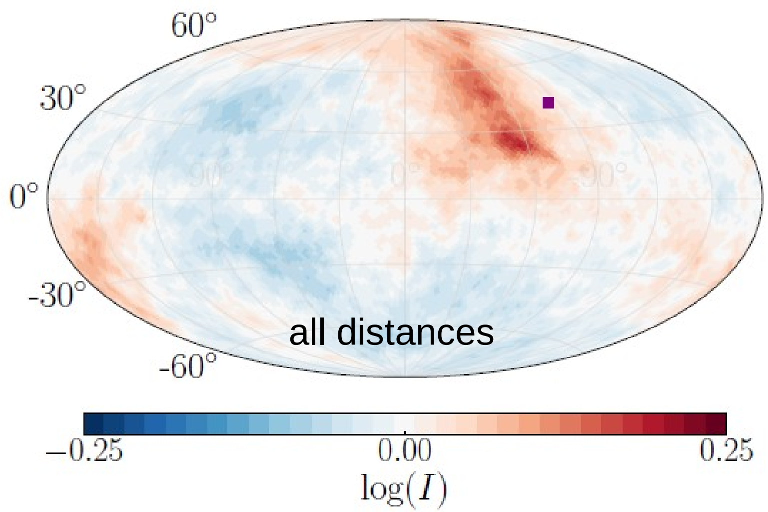

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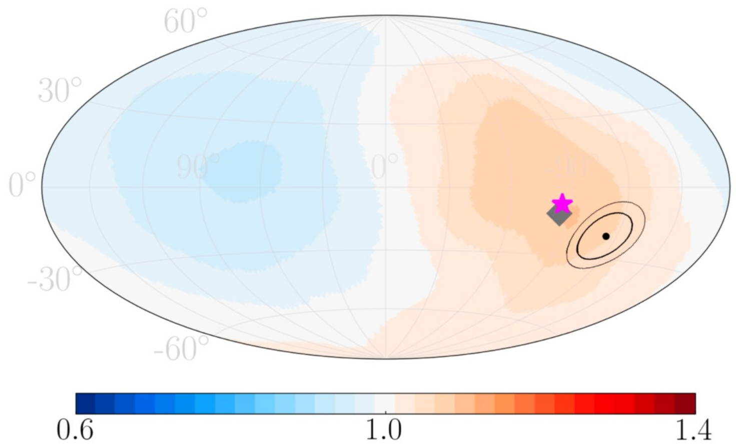


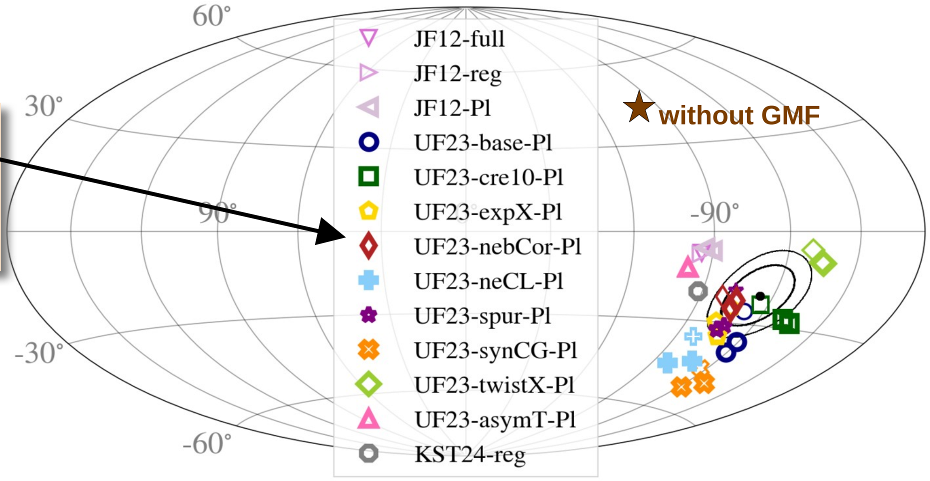
modeled flux at Earth reproduces dipole ✓

UHECR sources likely follow extragalactic matter distribution

Bister, Farrar, Unger
ApJL 975 L21 (2024)

What more can we do?

- compare **different Galactic magnetic field models**
  - agreement, systematic uncertainty under control



in the future: use UHECR anisotropies to inform Galactic magnetic field modeling?

Bister, Farrar, Unger
ApJL 975 L21 (2024)

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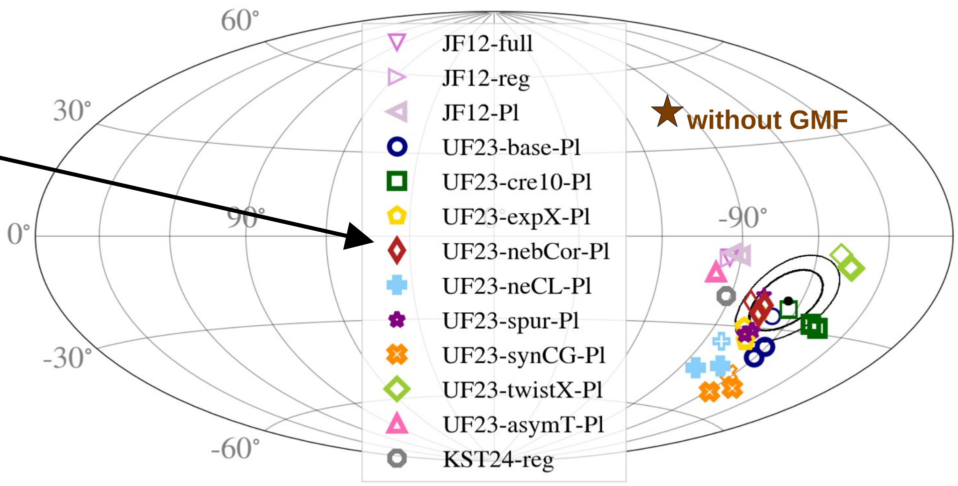

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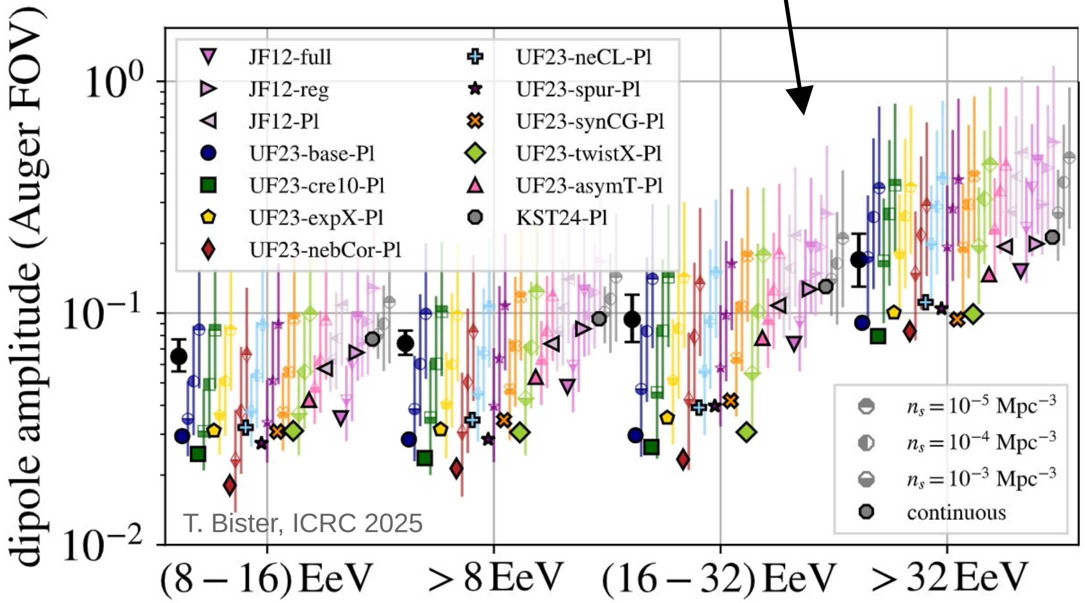
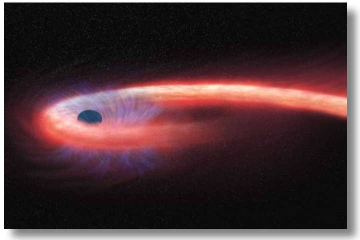
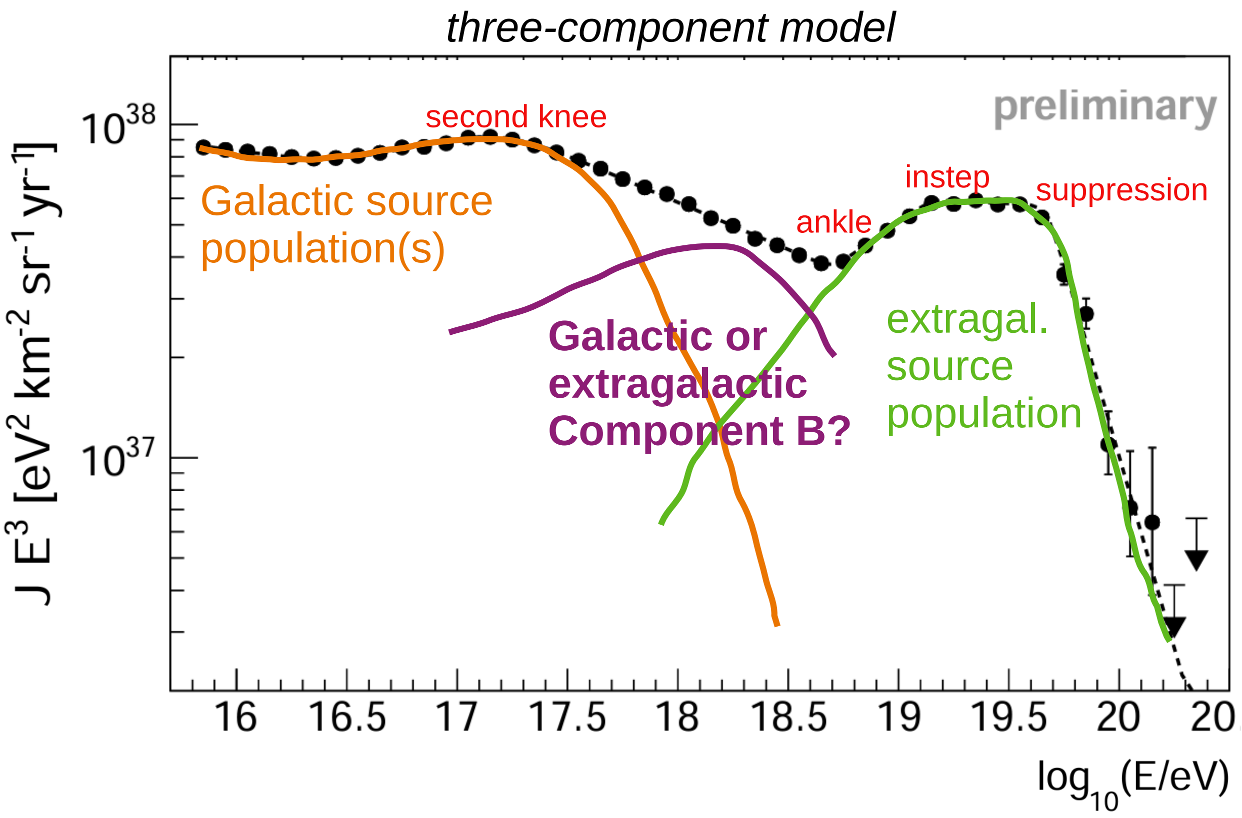
  - agreement, systematic uncertainty under control
- learn more about **density and distribution of sources** from dipole amplitude evolution

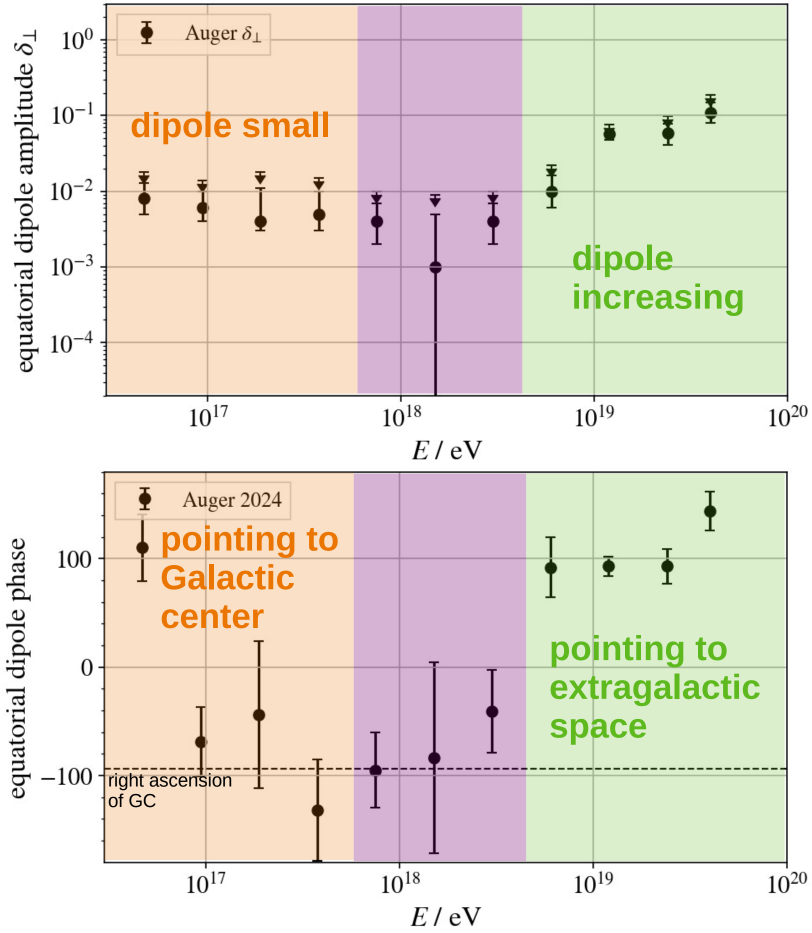


- **very small densities <10^{-6} Mpc^{-3} excluded**
- more common source classes like starburst galaxies or low-luminosity AGNs preferred
- or: **transient** sources like gamma-ray bursts or binary neutron star mergers?



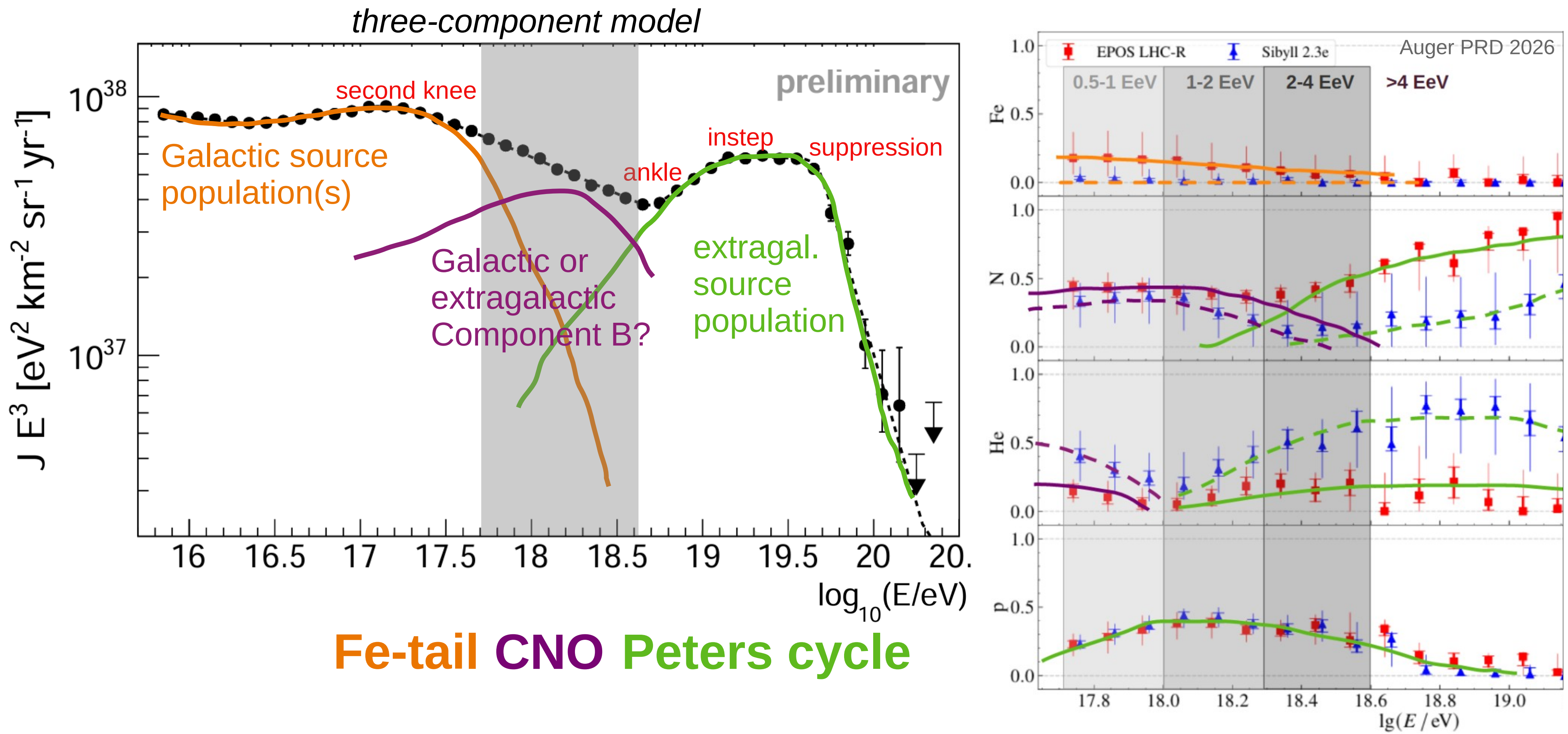
Transition from Galactic to extragalactic CR sources





Bister, Oikonomou, Fiorillo arXiV:2608.26933

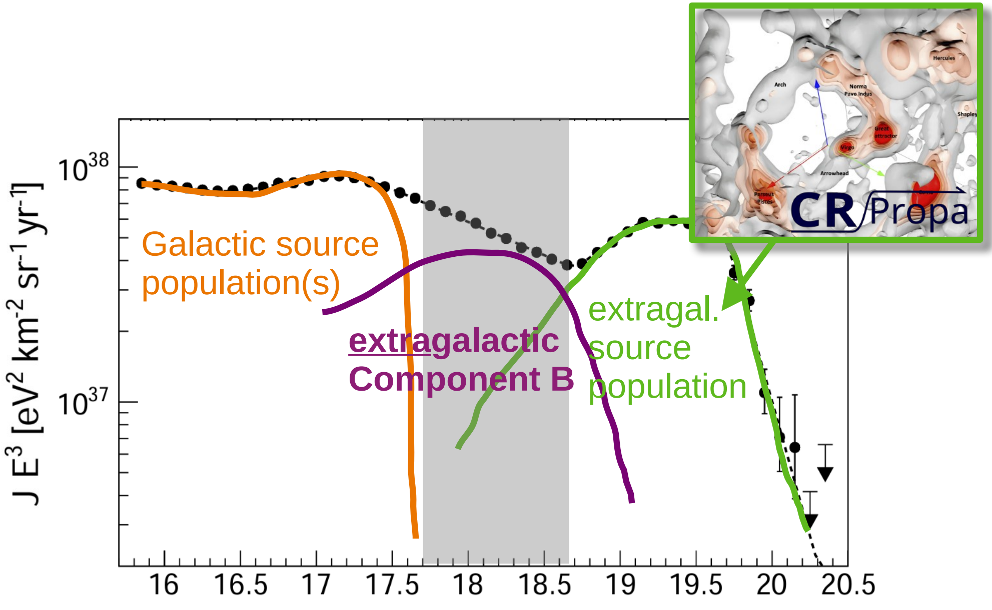
Transition from Galactic to extragalactic CR sources



Fe-tail CNO Peters cycle

Bister, Oikonomou, Fiorillo arXiV:2608.26933

Transition at second knee



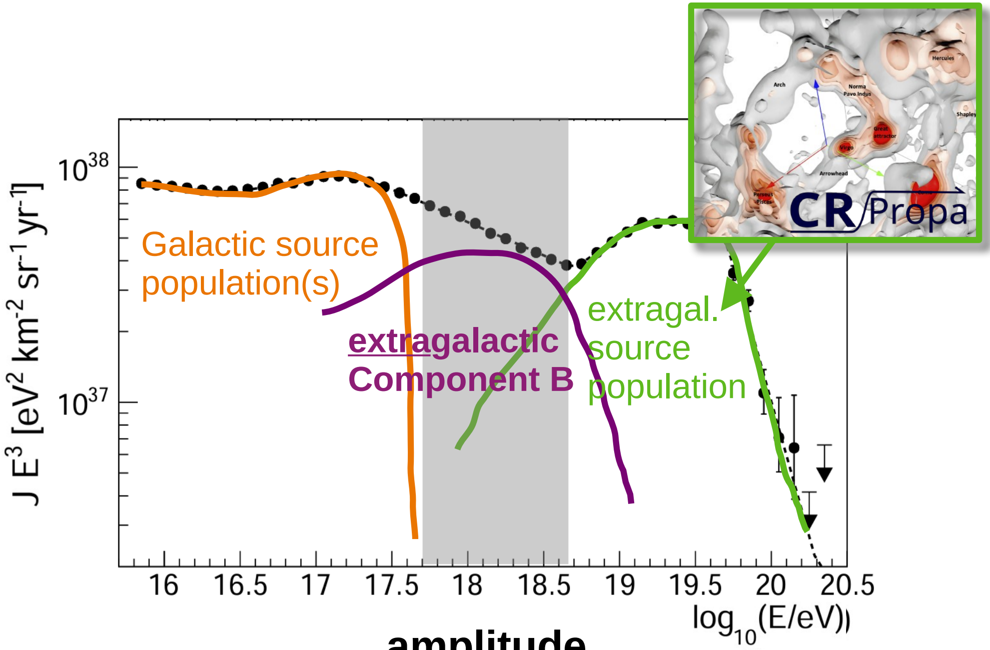
Bister, Oikonomou, Fiorillo arXiV:2608.26933

Transition at second knee

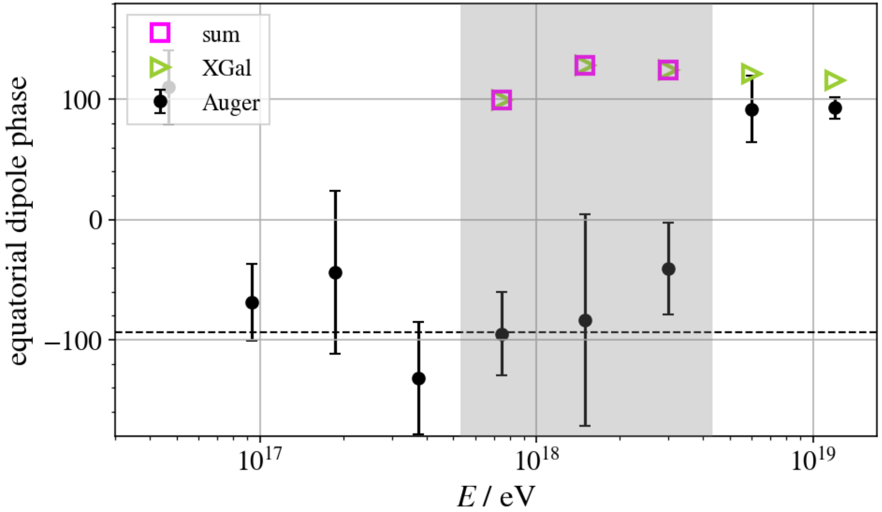
without any Galactic contribution, neither the <u>dipole phase change</u>, nor the ~0.5% <u>amplitude below 1 EeV</u> can be described.

need at least some Galactic contribution above 0.5 EeV!

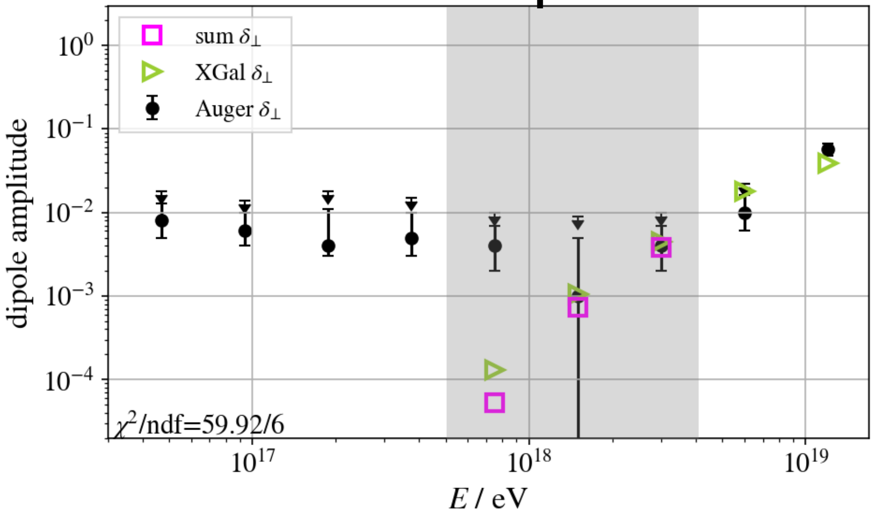
using UF23-twistX GMF model here, see backup for more GMF models



direction



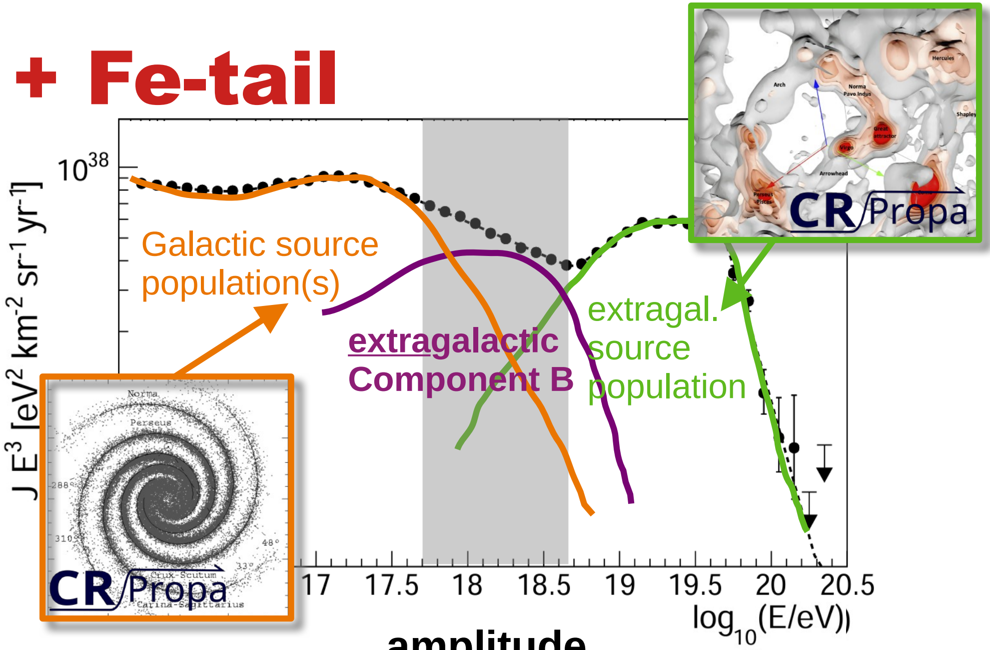
amplitude



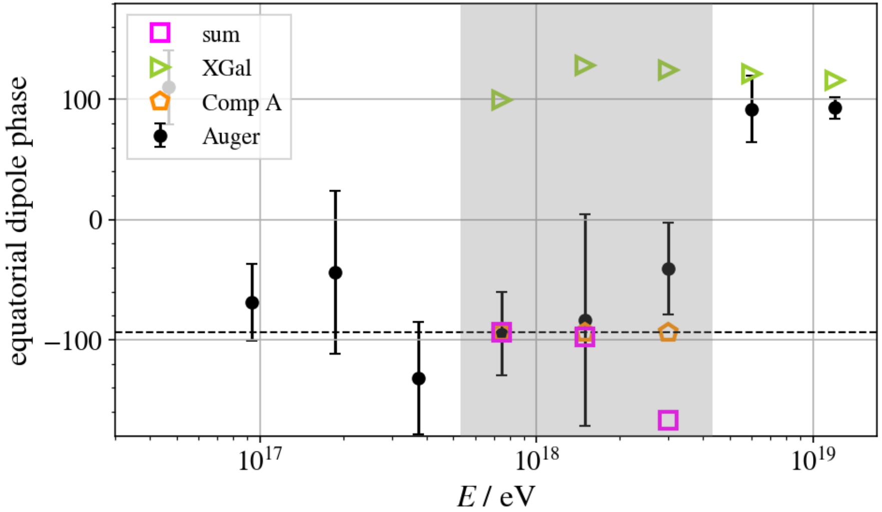
Transition at second knee + Fe-tail

with a **~10% Fe-tail of Component A following Galactic matter distribution**, the dipole amplitude and phase change can be described without finetuning!

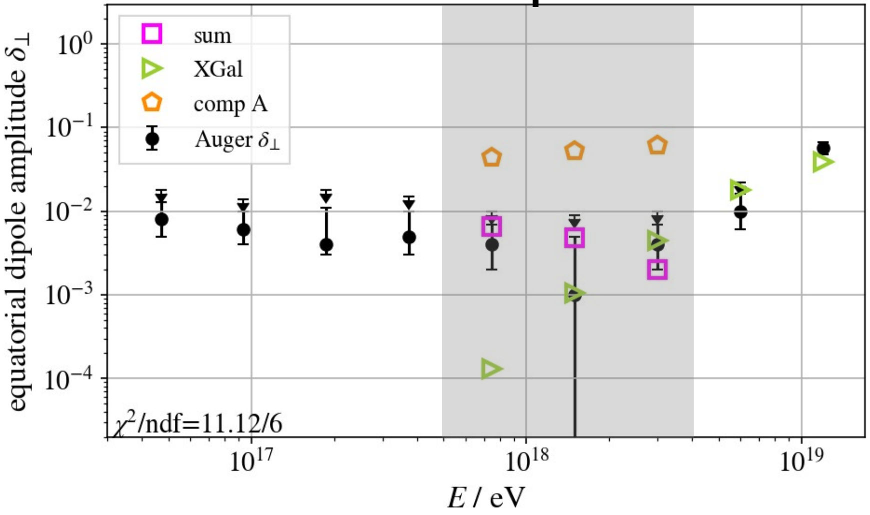
using UF23 GMF model suite, see backup for CRPropa simulations details



direction



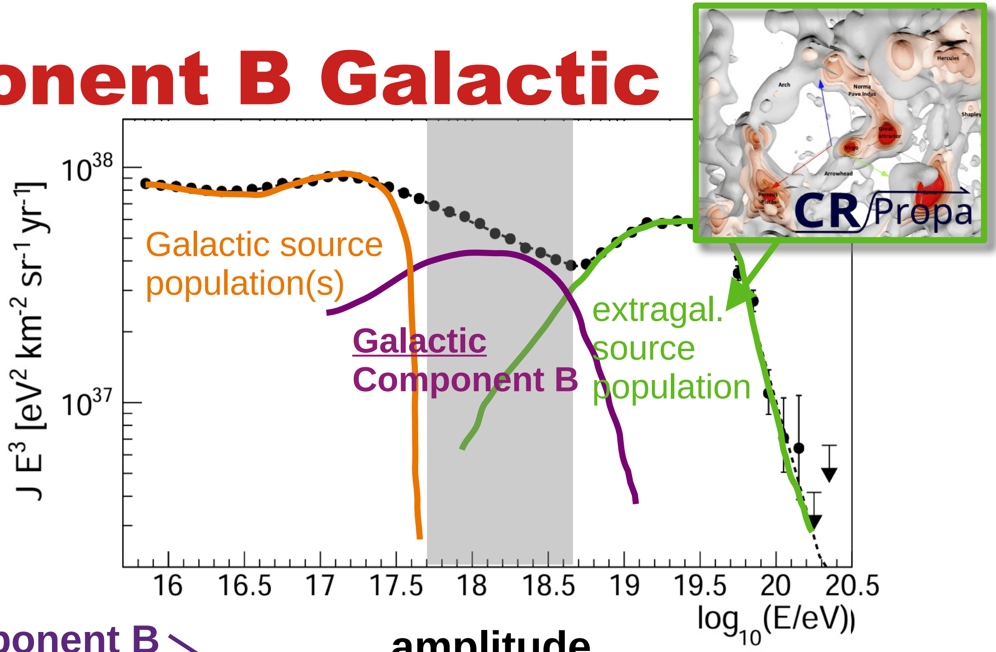
amplitude



Transition at ankle: Component B Galactic

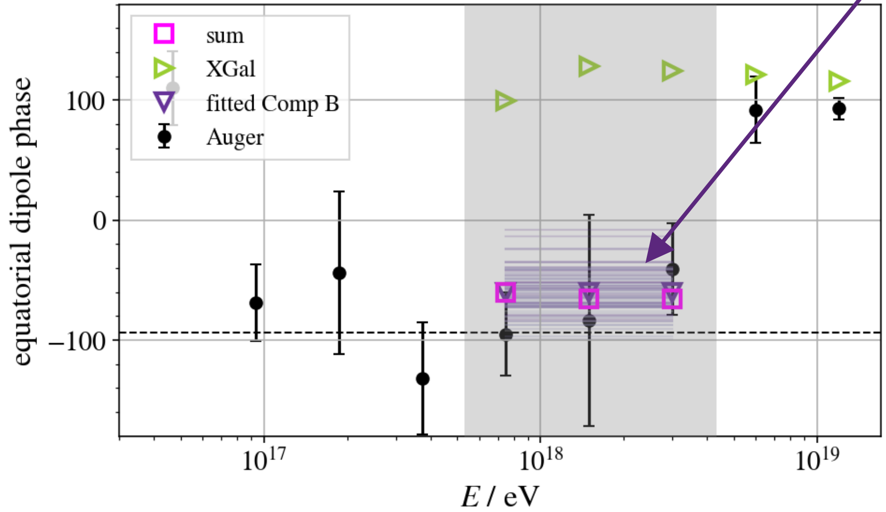
data can be described excellently by Galactic component B with:

- ~1% - 10% amplitude at 0.5 to 4 EeV
- pointing towards Galactic coordinates -45° $\lesssim$ l $\lesssim$ 110°, -45° $\lesssim$ b $\lesssim$ 30°

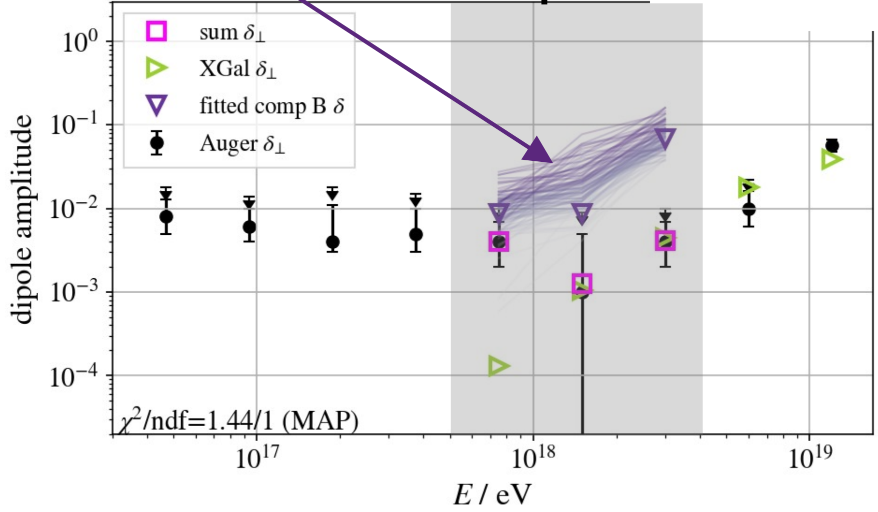


fit of Component B

direction



amplitude



Transition at ankle: Component B Galactic

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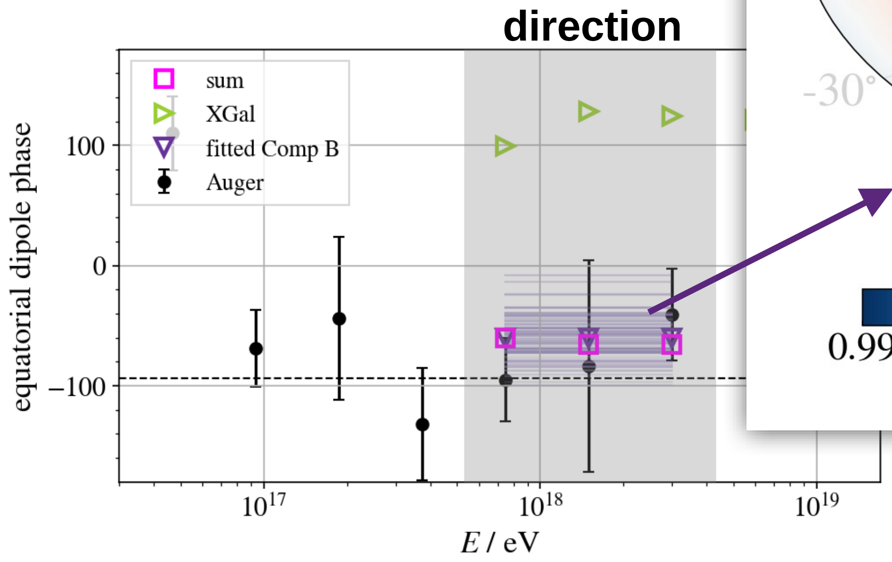

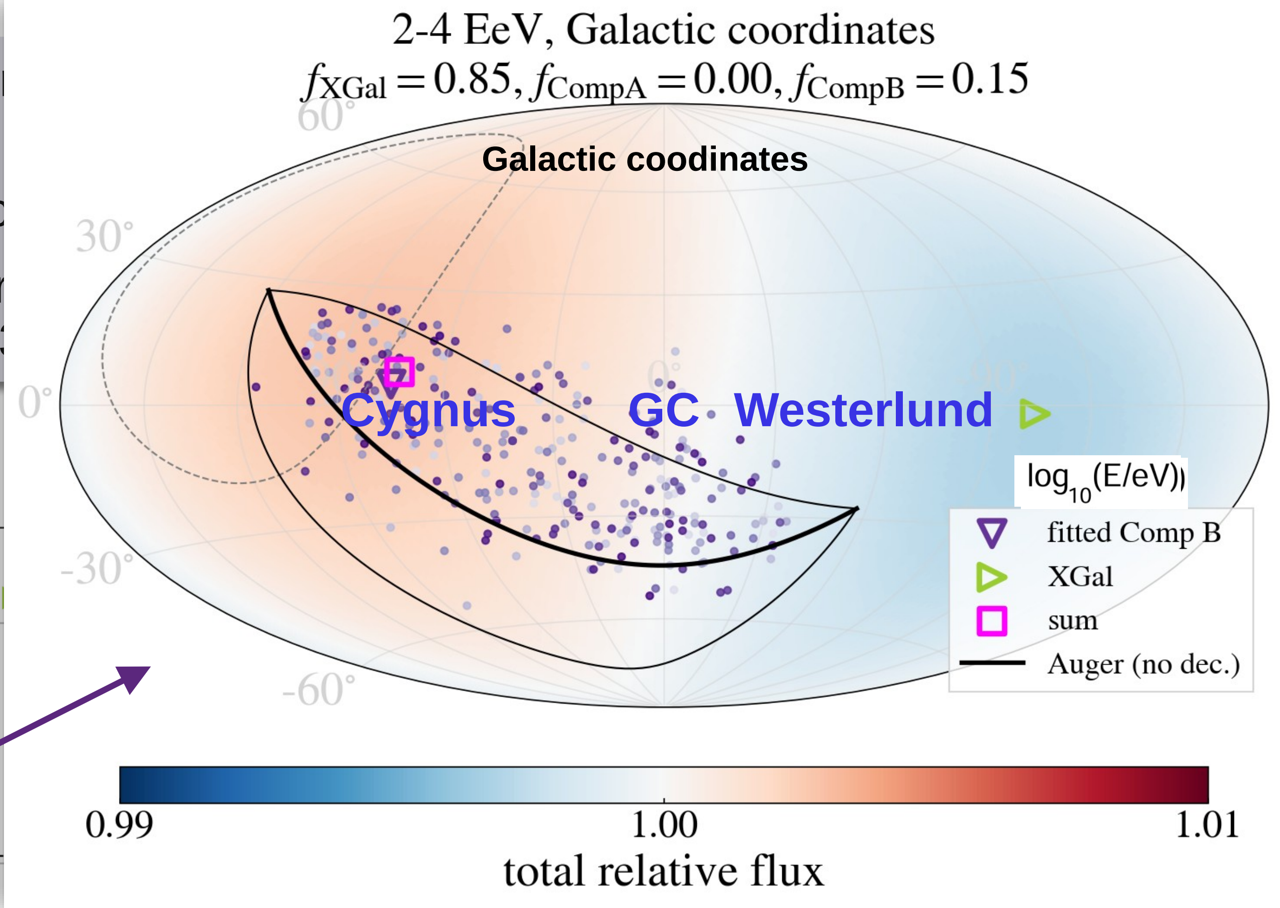

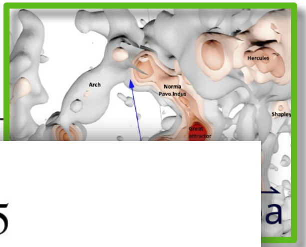

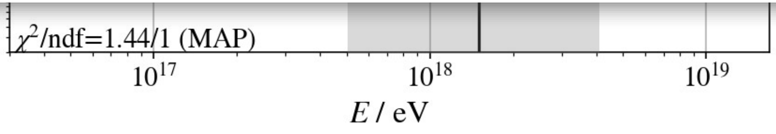

Is there any Galactic source that fulfills that?

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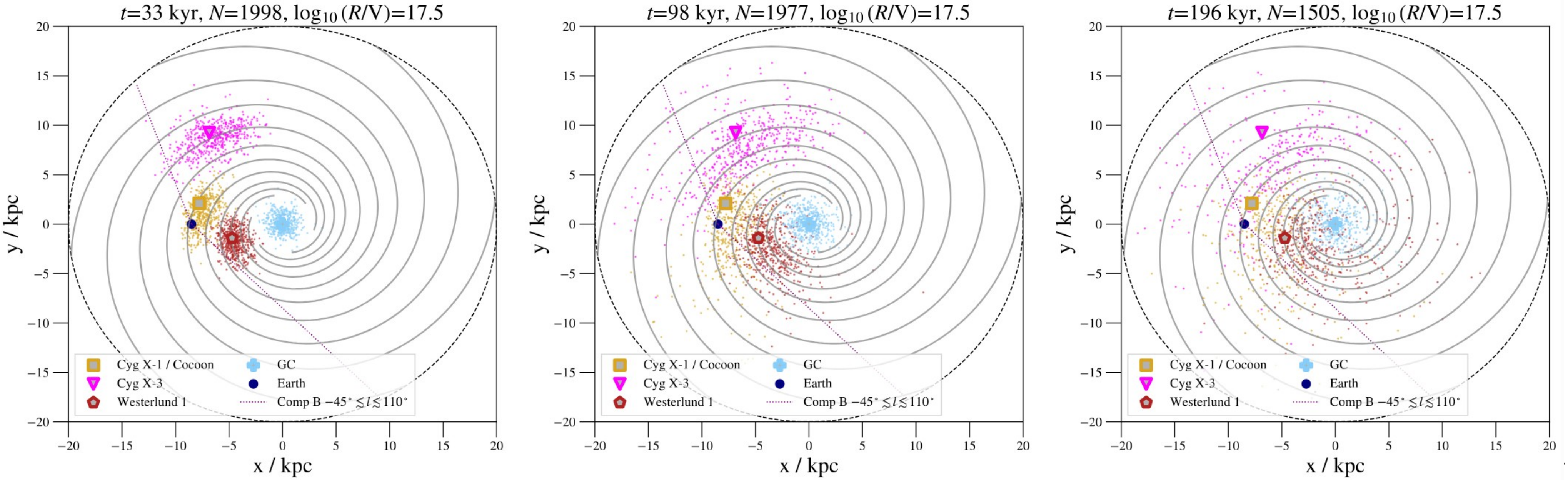
CRPropa simulations of CRs from prominent Galactic γ-ray sources in preferred directions:

Galactic Center, Cygnus X-1 / X-3, Westerlund 1



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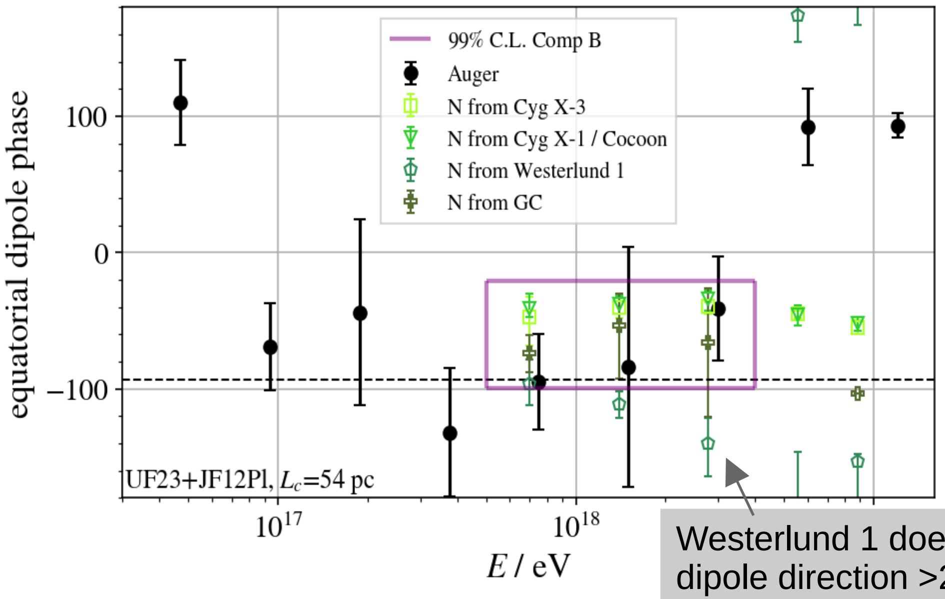
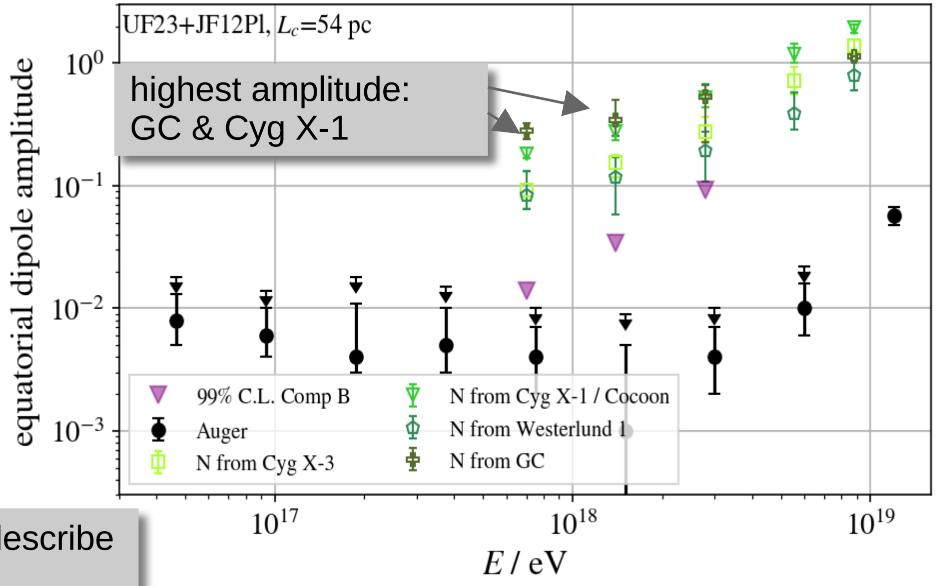
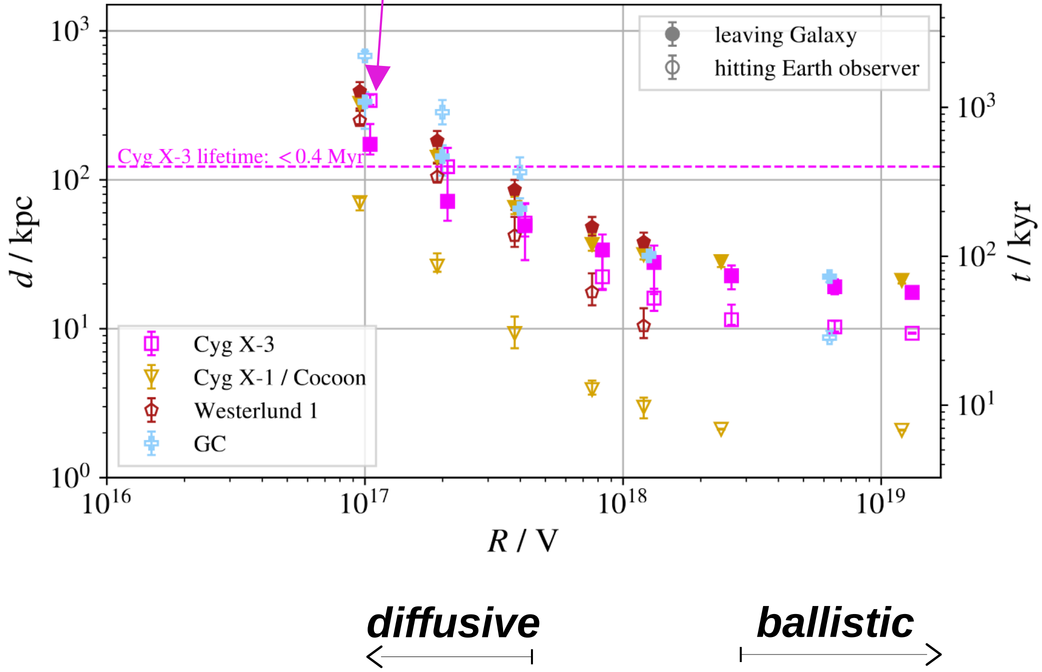




Is there any Galactic source that fulfills that?

additional problems (see also backup):

- for Cygnus X-3, **propagation time** <0.1 EV **exceeds lifetime** of ~0.1 Myr



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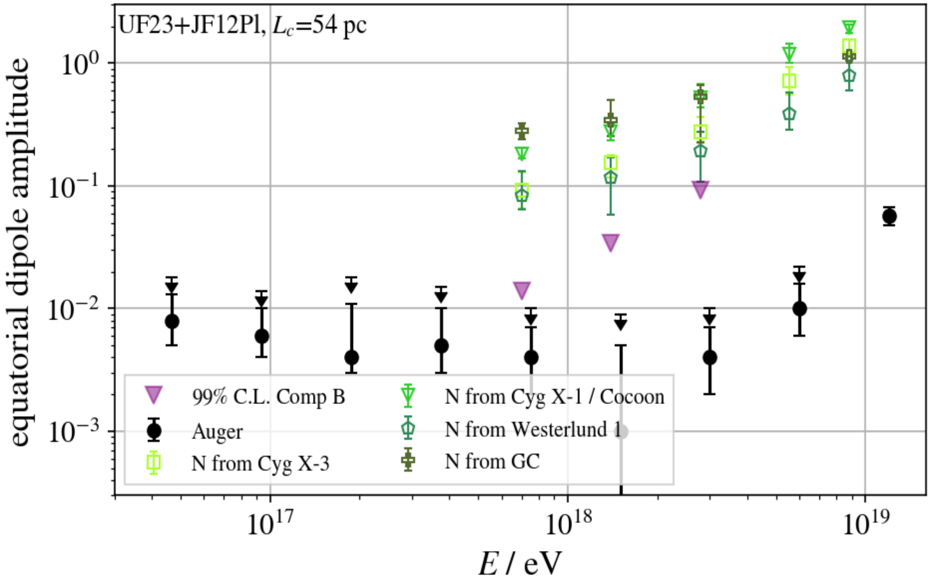

Bister, Oikonomou, Fiorillo arXiv:2608.26933

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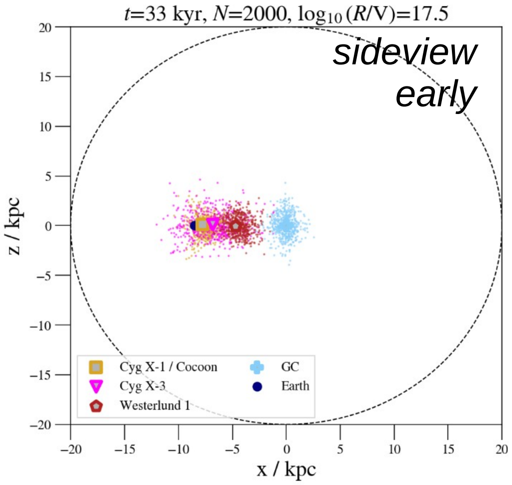

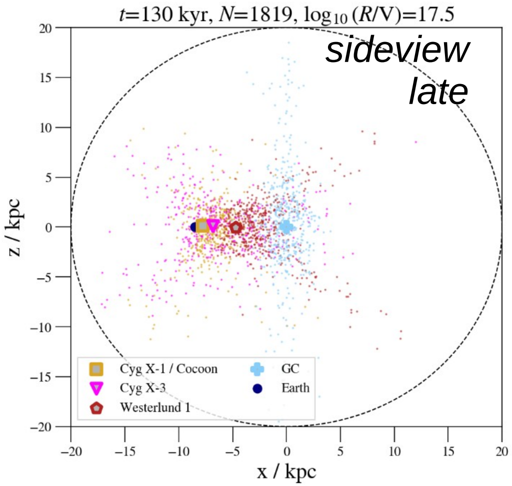

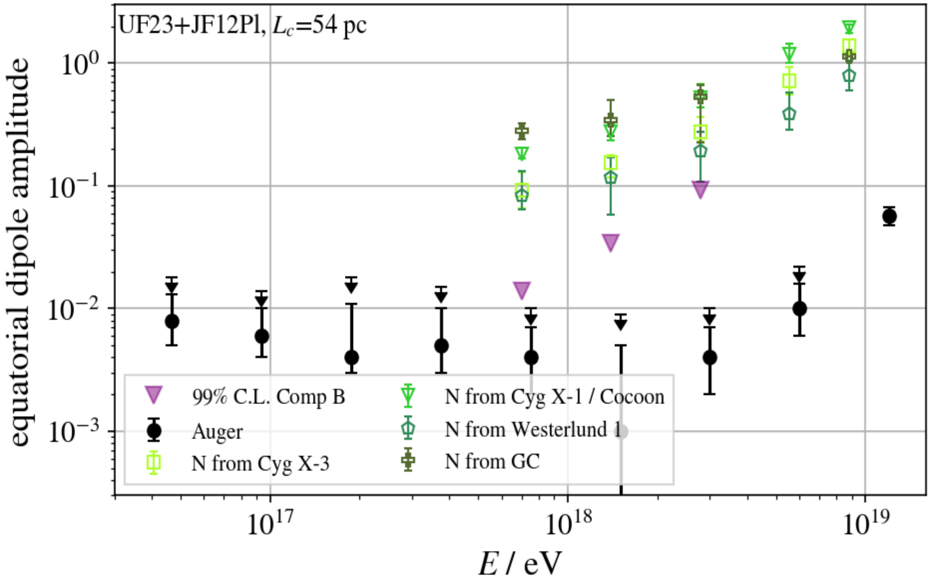

Bister, Oikonomou, Fiorillo arXiV:2608.26933

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  - source luminosities not sufficient for most sources given simulation hit rates (only for Cygnus OB2)
  - H / He-fluxes of the source overshoot spectrum by factor ~3-6 at lower energies (assuming Wolf-Rayet / solar composition)

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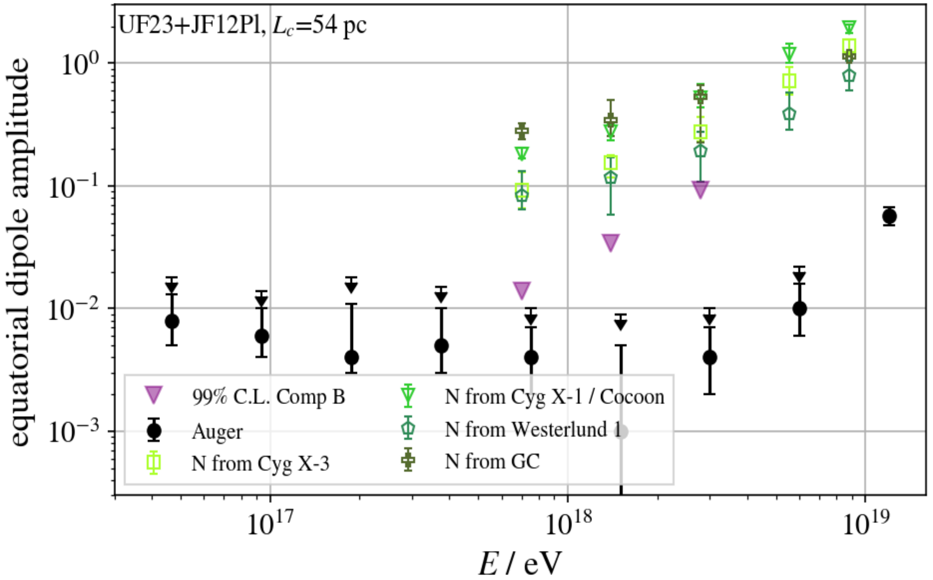

Bister, Oikonomou, Fiorillo arXiV:2608.26933

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Galactic Center, Cygnus X-1 / X-3, Westerlund 1

➔ **all of them overshoot 99% C.L. upper limit on Component B amplitude**

The observed flux of ~40% intermediate elements at ~1 EeV cannot be explained by a Galactic source.

A transition at the second knee is preferred, with a ~10% iron-tail of Galactic Comp. A providing the dipole phase change.

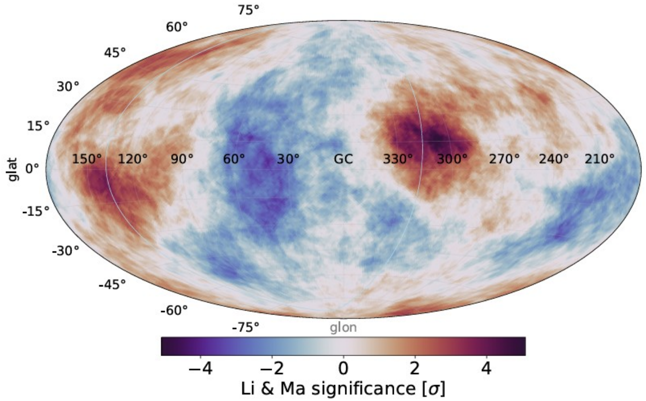
Which Galactic sources are responsible?

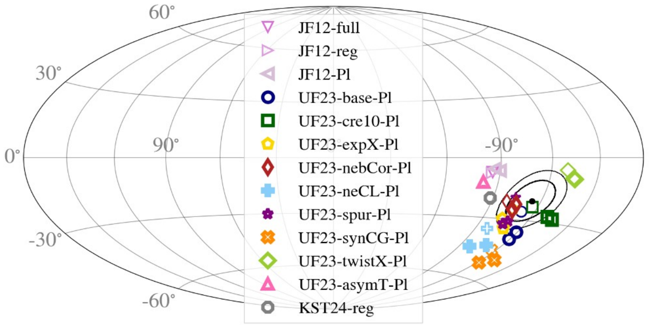
Bister, Oikonomou, Fiorillo arXiV:2608.26933

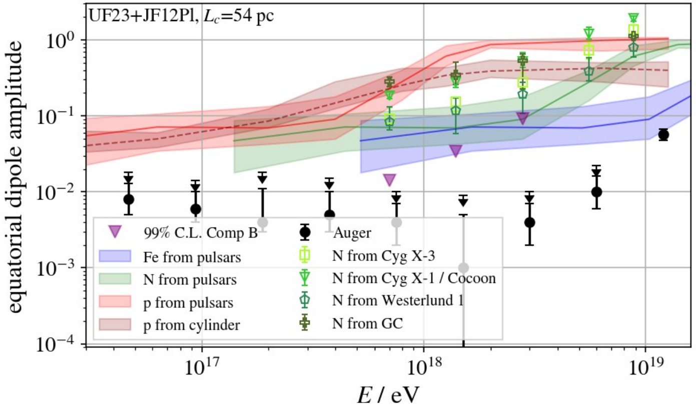
Summary: sources of UHECRs

- <u>**above the ankle:**</u>
  - sources are **extragalactic**
  - they probably follow the **large-scale structure** $\gtrsim$ 8 EeV & have relatively **large density** $\gtrsim 10^{-5}$ Mpc^{-3}
    - unclear if transient or steady sources
  - at $\gtrsim$ 40 EeV (transients in) nearby candidates like **Centaurus A can explain Centaurus excess**

- <u>**transition from Galactic to extragalactic sources**</u> likely happens **at the second knee**
  - **~10% Galactic iron tail** at 1 EeV necessary to explain dipole measurements
  - individual and populations of doninant Galactic sources of intermediate (and even heavy) elements **overshoot dipole** amplitude at ~1 EeV

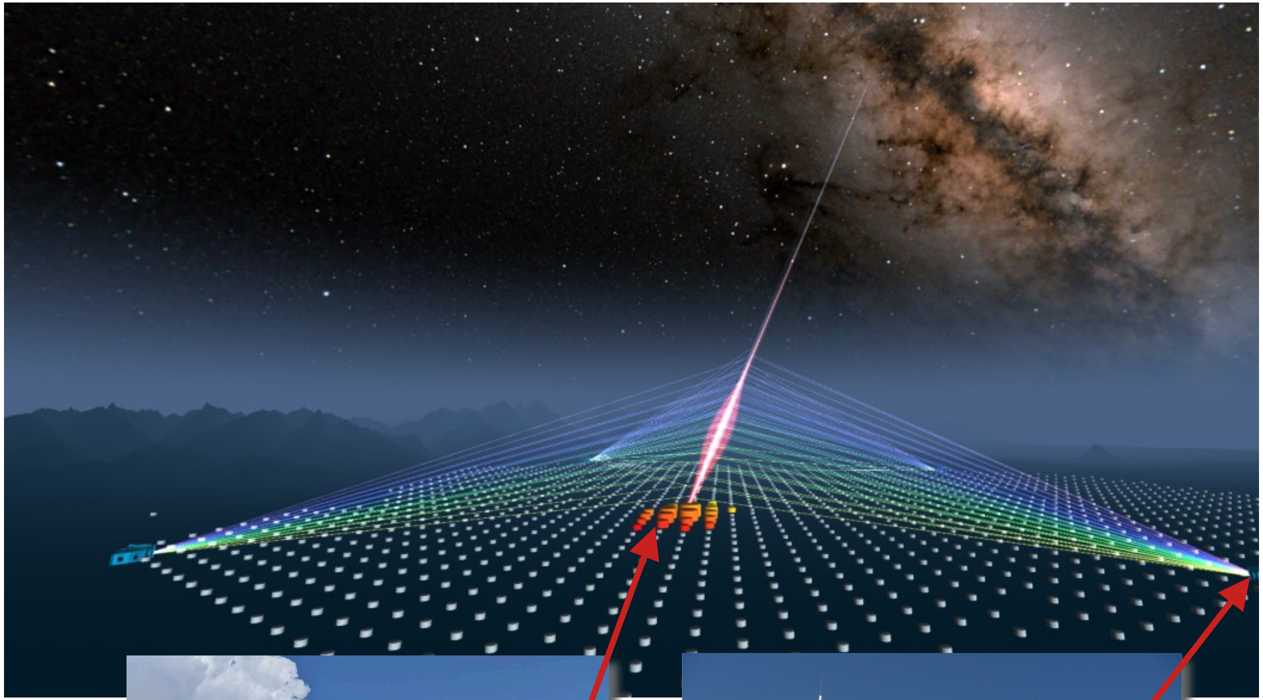






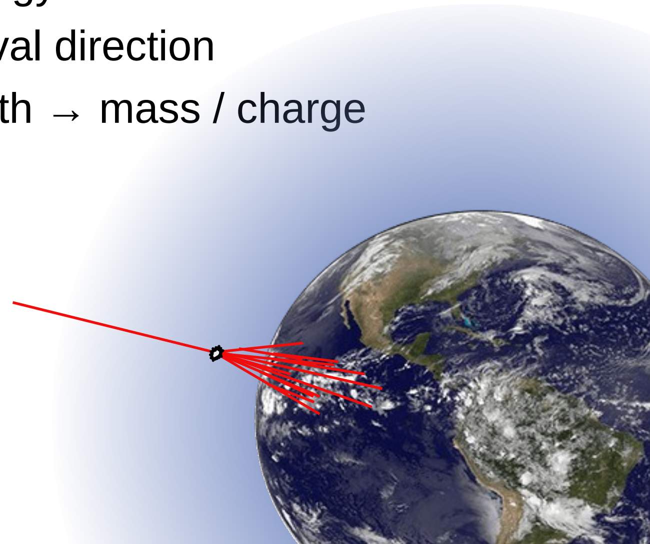
backup

Measuring extensive air showers at the Pierre Auger Observatory

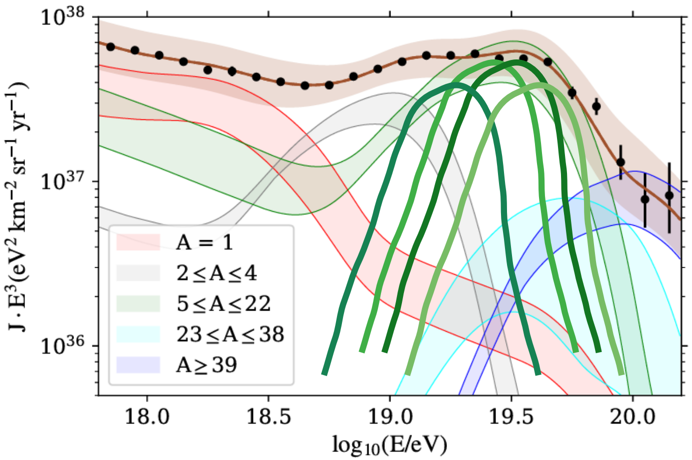


- **Pierre Auger Observatory:**
  - close to Malargüe, Argentina
  - 3000 km²
    → largest Observatory in the world
  - 1660 surface detector stations,
    4 fluorescence detector sites

- <u>reconstruction of:</u>
  - ➔ energy
  - ➔ arrival direction
  - ➔ depth → mass / charge



Energy spectrum and mass composition

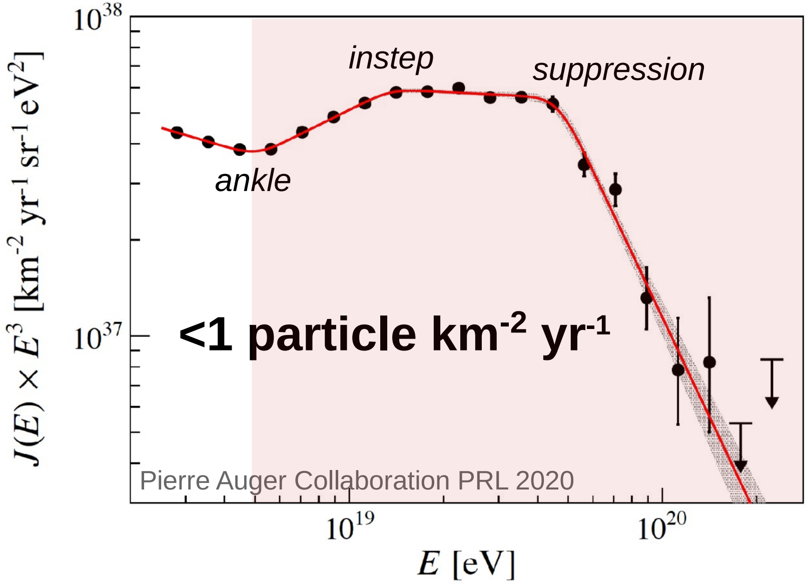


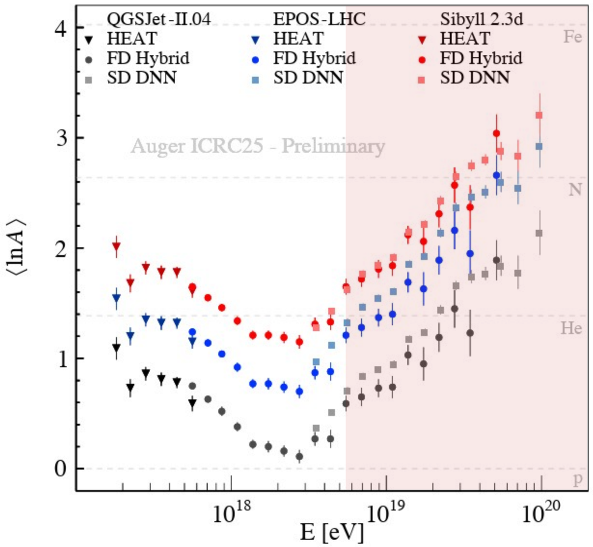
fit model to energy spectrum & mass composition data:

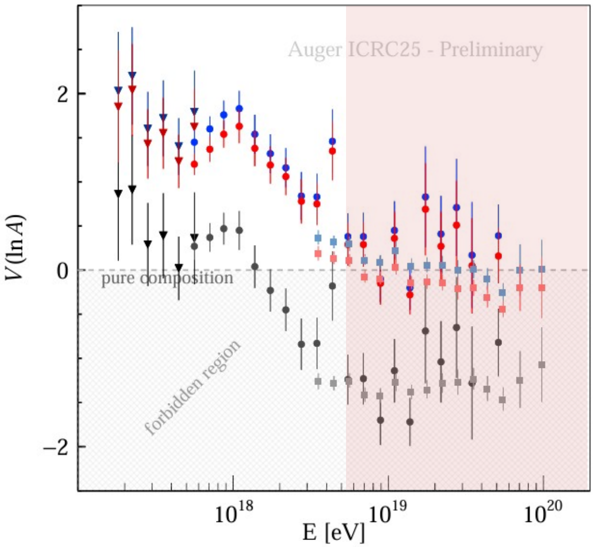
- **homogeneous & extragalactic** sources dominating above ankle
- **acceleration ∝ Z** → mass composition gets heavier
- constrains spectrum and composition emitted at sources:
  - hard spectrum & fast change of mass groups, mixed composition **& almost identical source max. energy**

Pierre Auger Collaboration, JCAP 2023

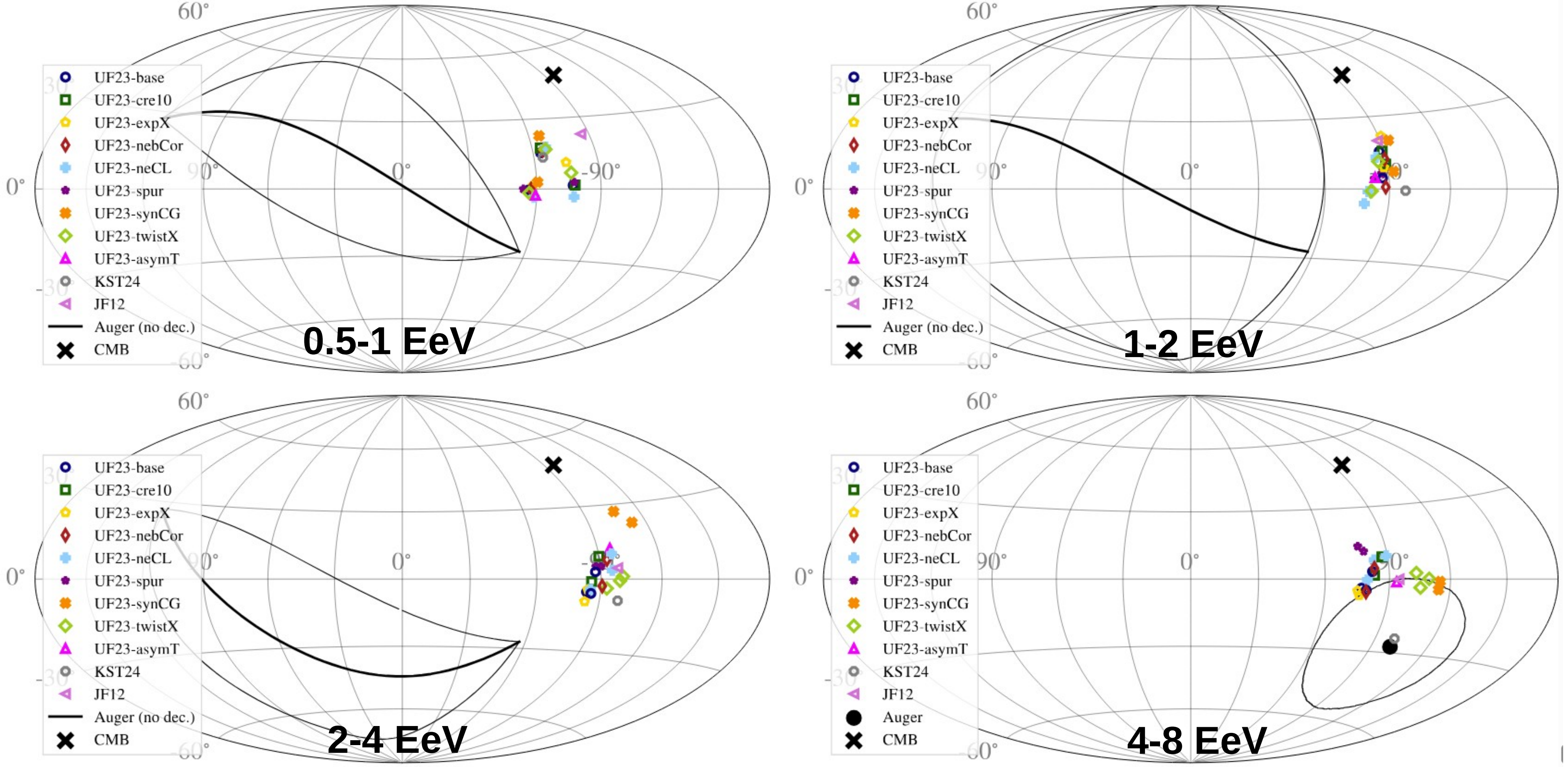
Ehlert, Oikonomou, Unger, PRD 2023







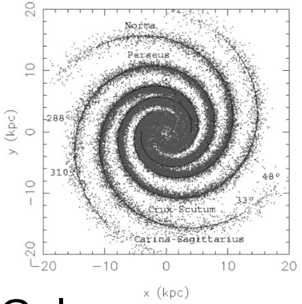
Dipole of extragalactic CRs following CosmicFlows4

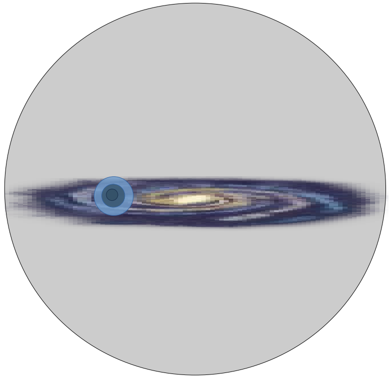


→ **direction does not fit <4 EeV for any GMF model (including also Compton-Getting effect)**

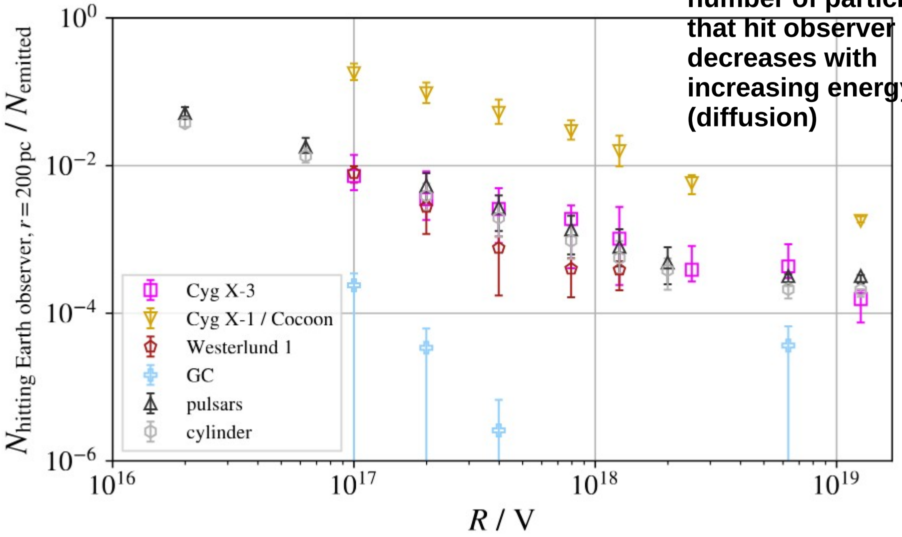
Propating Galactic CRs with CRPropa

- propagate CRs with different rigidities in the **UF23 GMF model suite**
  - for now: use JF12+Planck random field model with L_c=54 pc
- **sources: GC, Cygnus X1, Cygnus X3, Westerlund 1, nearby SNR, cylinder** (h=200 pc), **pulsar distribution**
- observers at Earth position with radii 50 pc, 100 pc, 200 pc, 500 pc
- observer with radius 20 kpc around GC that detects particles leaving Galaxy



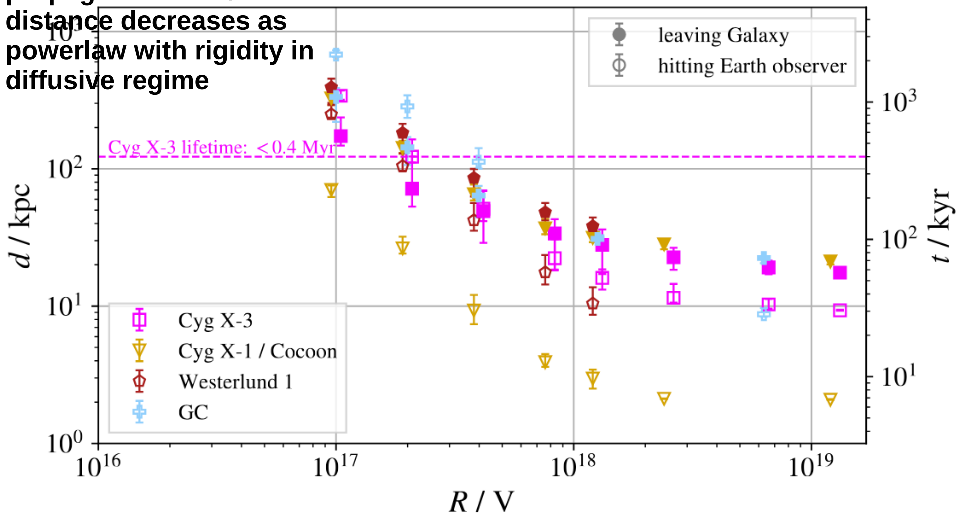


number of particles that hit observer decreases with increasing energy (diffusion)



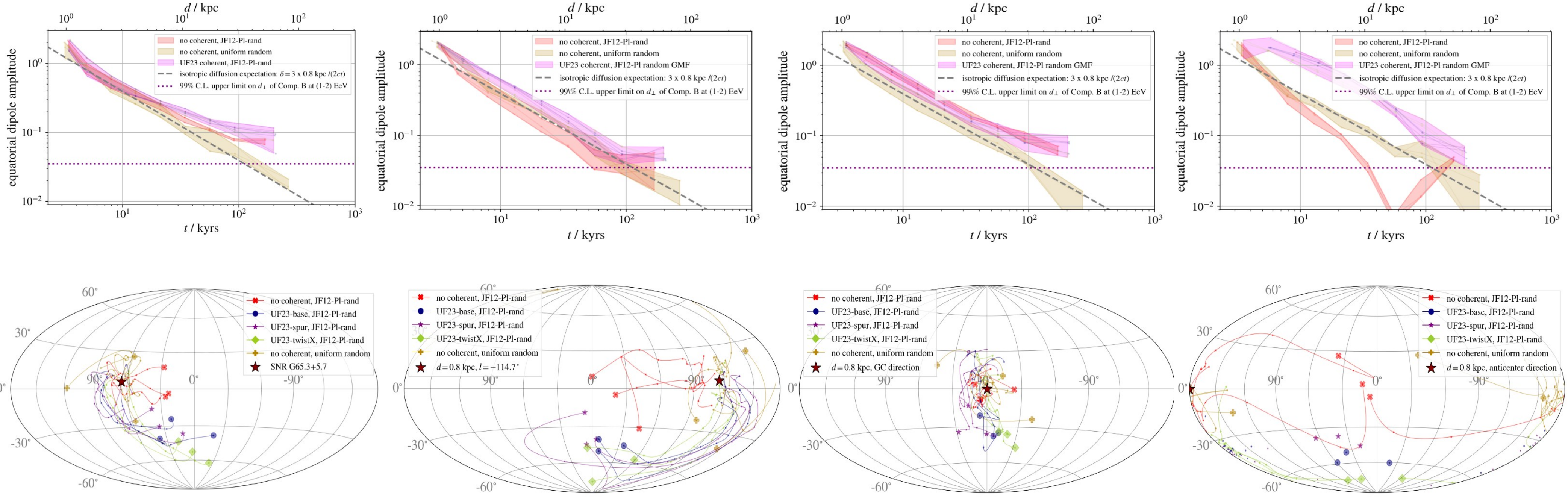
uncertainties always include 8 GMF models and up to 3 random seeds

propagation time / distance decreases as powerlaw with rigidity in diffusive regime



Nearby transient source as Component B?

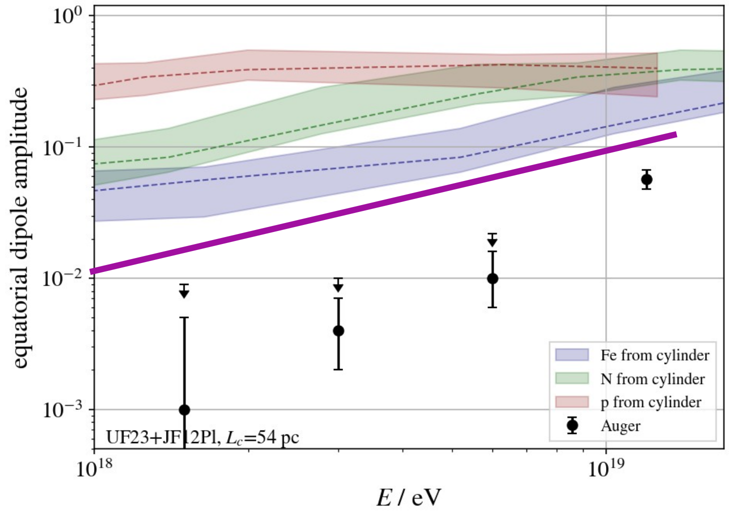
SNR (d=0.8 kpc) | **opposite side** | **GC** | **anticenter**



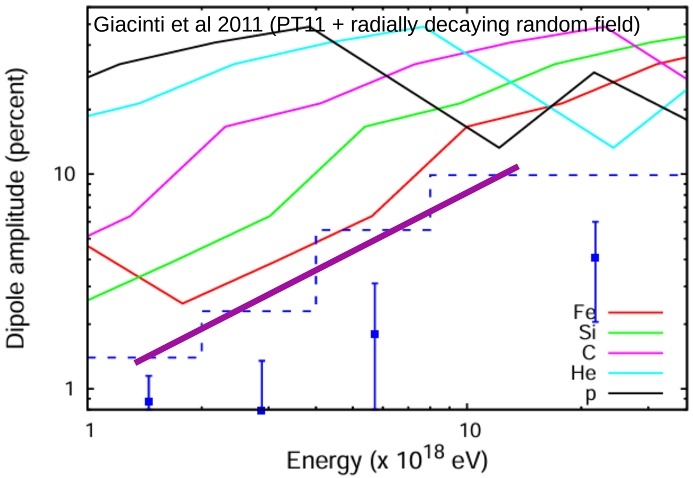
log10(R/V)=17.3

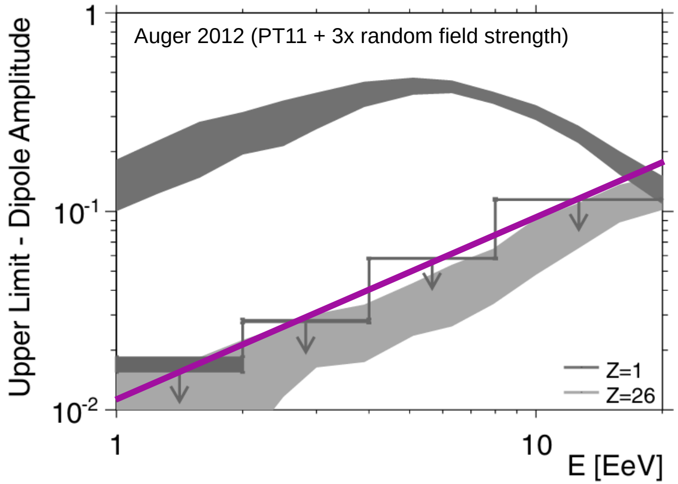
- **residual dipole at late times too large to be compatible with Component B amplitude**
- **due to accumulation of CRs in the inner Galaxy: decreasing random field strength allows faster escape in outer Galaxy**
- **note: source location information lost at late times**

Dipole moment: comparison to previous works



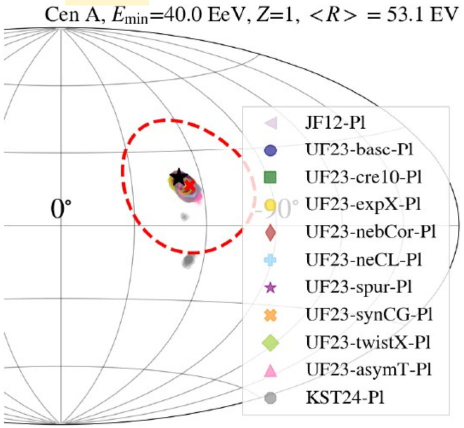
- all based on **homogeneous cylinder of sources,** h~200 pc, r~20 kpc
  - before: backpropagation, now: forward propagation with r_{obs}=200 pc
- **agree quite well:**
  - **iron in rough agreement with old limits, but does not agree with newest data**
  - maximum dipole moment ~30-50% due to homogeneous distribution of sources in disk





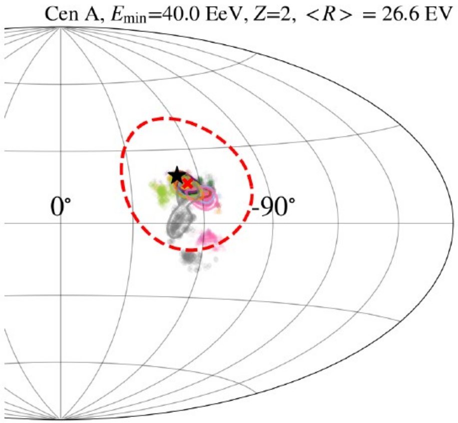
UHECRs from Cen A & magnetic field deflections

Z=1



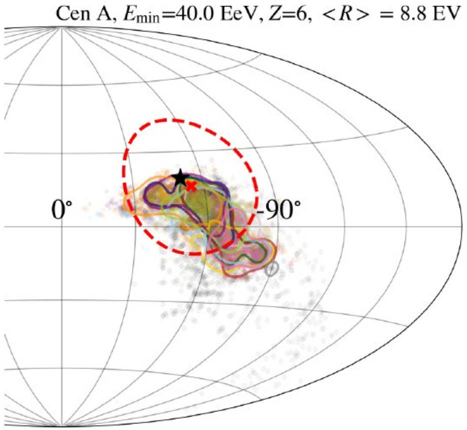
agrees well with excess direction ✔

Z=2



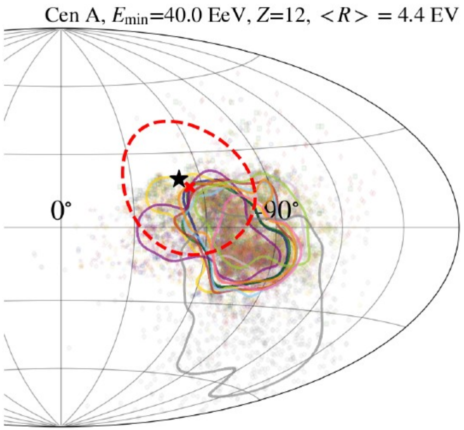
agrees well with excess direction ✔

Z=6



still fits for some GMF models ✔

Z=12



deflections too large ✘

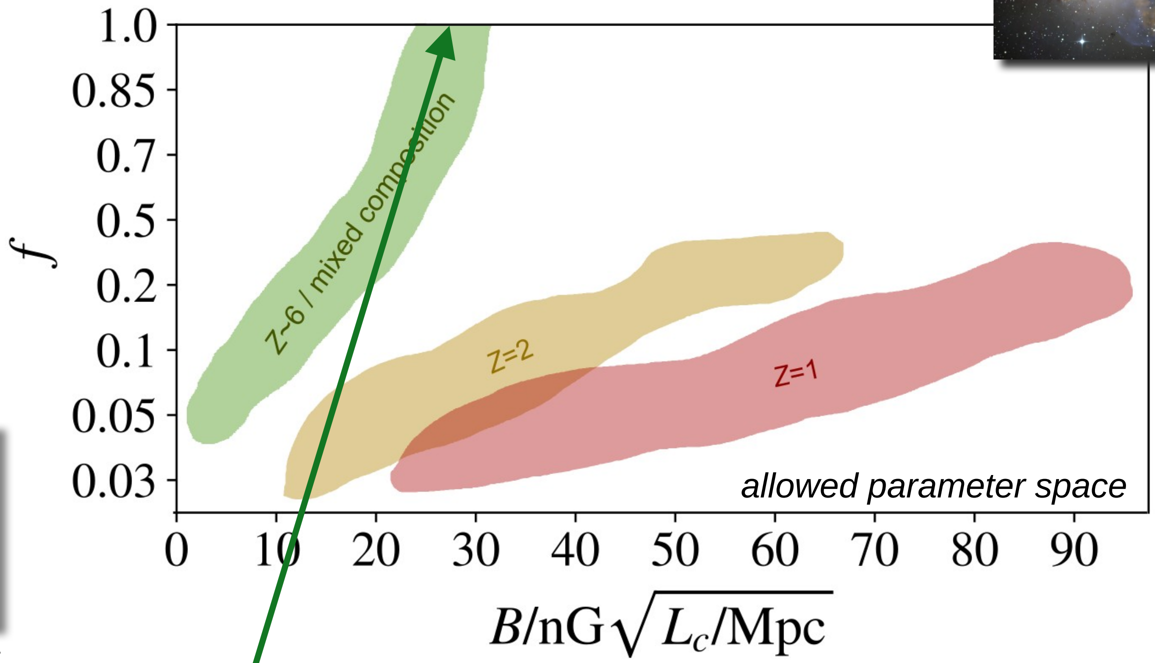
- charge needs to be **Z ≲ 6** to be compatible with excess direction for Cen A
  - for KST24 GMF model, only Z=1 compatible

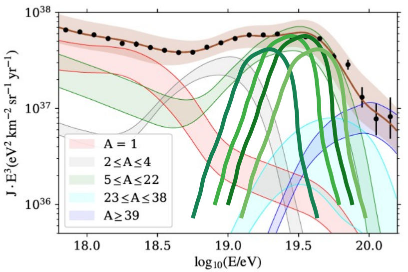
- figures are for **extragalactic magnetic field zero** → clearly does not reproduce angular scale!
  - ➔ add 2d Gaussian distribution to mimic turbulent EGMF: $\vartheta = 29^\circ \frac{\mathrm{EV}}{E/Z} \frac{B}{\mathrm{nG}} \frac{\sqrt{d L_c}}{\mathrm{Mpc}}$
  - ➔ note: „extragalactic“ here means between Milky Way & source

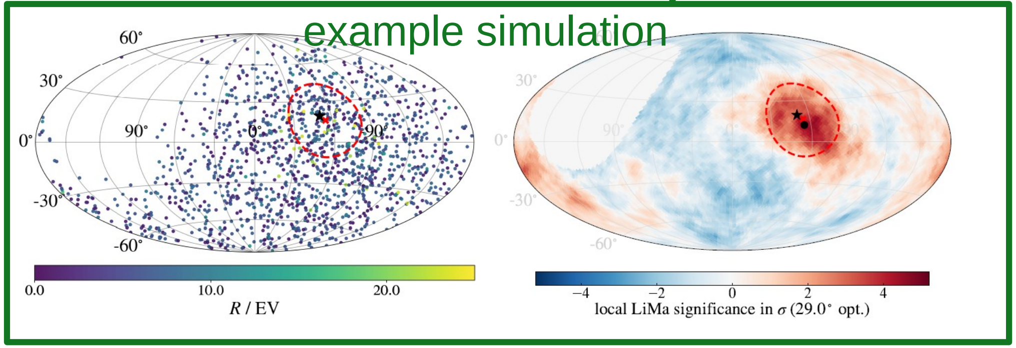
Constraints on the signal fraction & EGMF

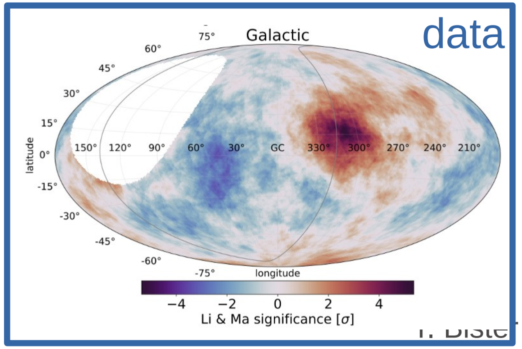
- can reproduce strength, size, direction & energy dependency of excess with Cen A as the source with **Z** $\lesssim$ **6**
  - extragalactic magnetic field of zero not allowed
  - **best current constraints** for EGMF between Earth and Cen A
- signal fraction of Cen A up to **100%!**
  - would explain „similarity“ of sources
  - does it work over whole energy range?

see also Mollerach & Roulet PRD 2024



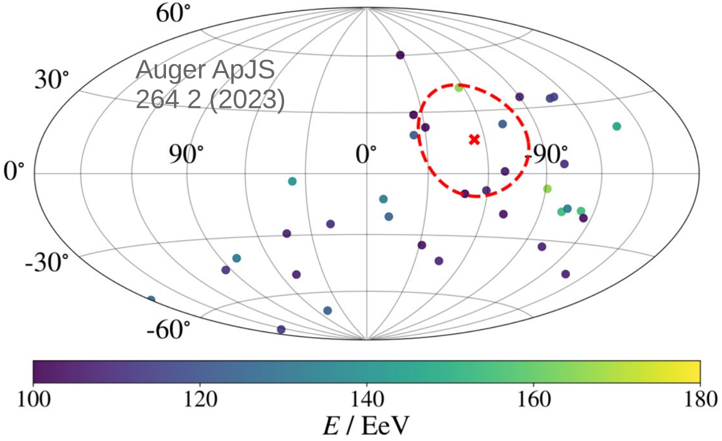




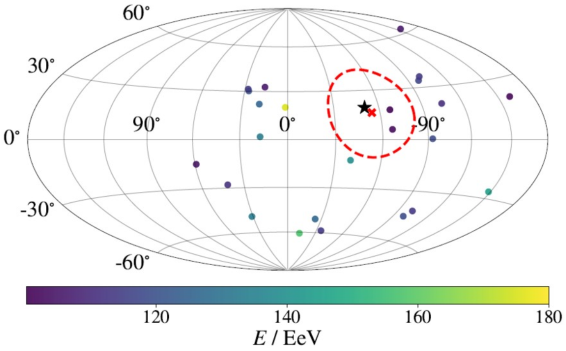


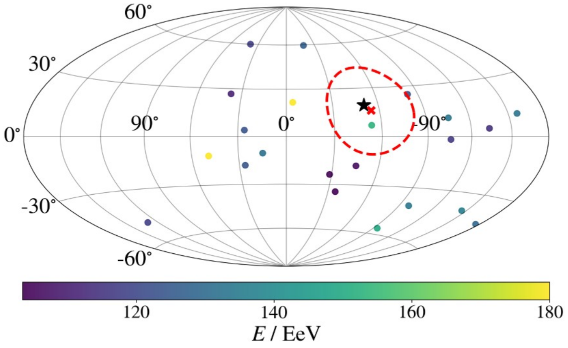
Cen A dominates sky - highest energy events?

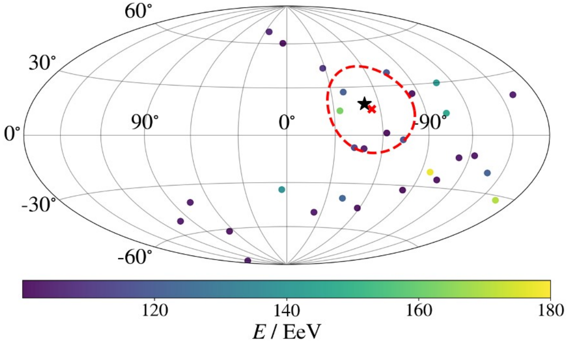
measured distribution of events, E>100 EeV



- **unexpectedly isotropic,** do not correlate well with any source candidates after correcting for Galactic magnetic field
  [M. Bianciotto for Auger, ICRC 2025]
  - ➔ transient sources? ultra-heavy elements? BSM physics? ...
- <u>or just one source and very strong local EGMF</u>







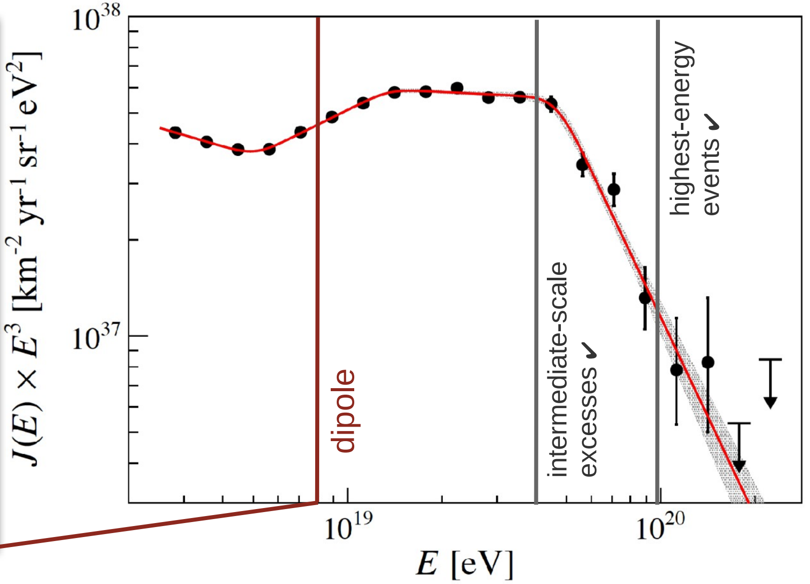
simulated distributions of events with E>100 EeV ✔

(3 simulations with UF23-base, β_{EGMF}=26, mixed composition)

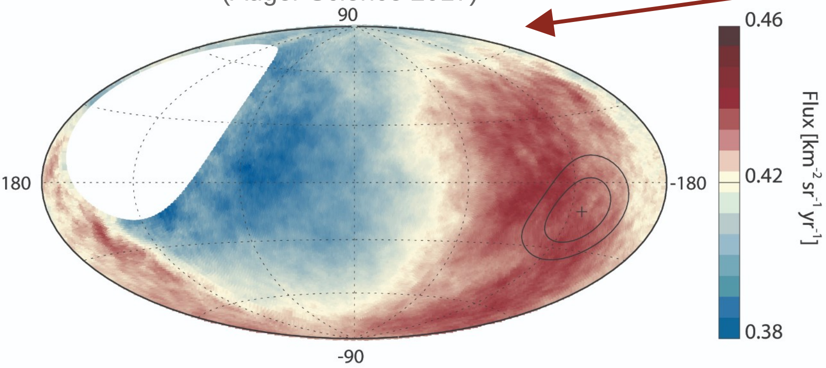
What about lower energies?

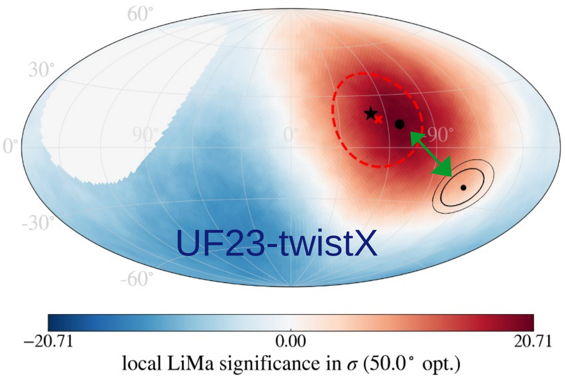
Cen A dominates sky - lower energies and dipole?

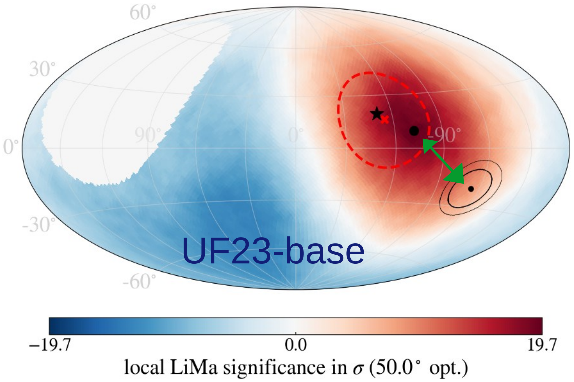
- extending Cen A-only simulations to lower energies
  - dipole flux measured >8 EeV <u>not</u> well reproduced by only Cen A as single source
  - but could structured EGMF work?
- **probably need other sources to explain data <30 EeV**
  - individual sources in the south (e.g. Fornax A), or following large-scale structure?



(Auger Science 2017)

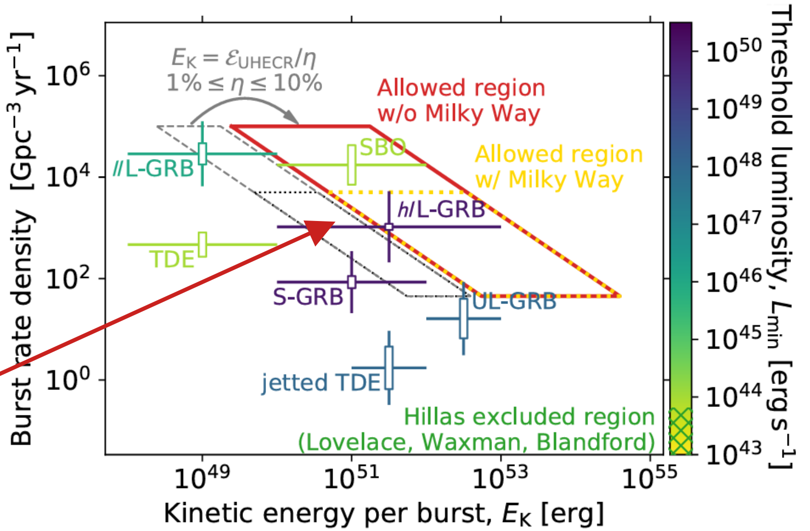


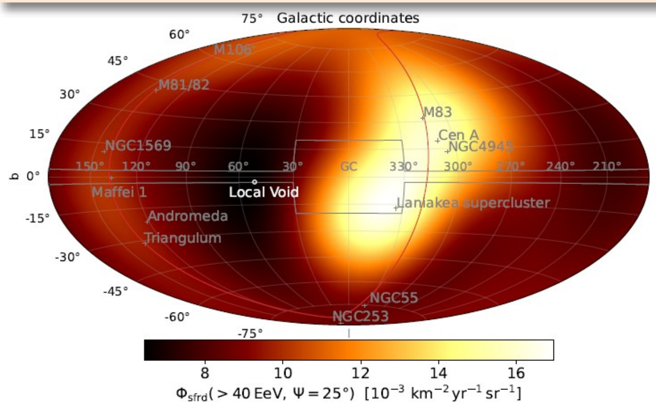


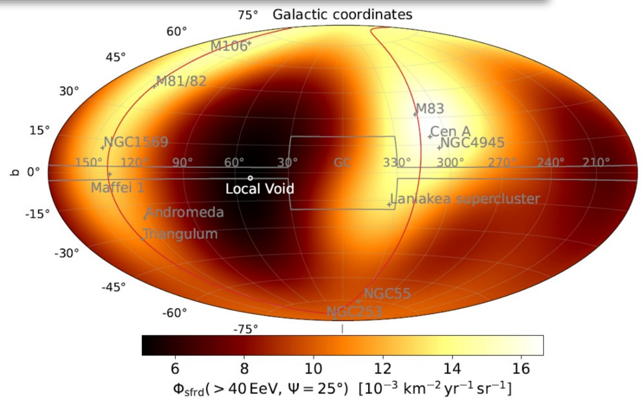


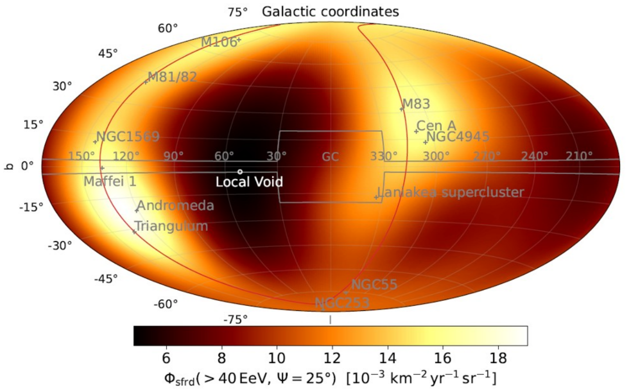
Transient or steady sources?

- model from Marafico, Biteau, Condorelli, Deligny, Bregeon 2024
- **assumption: UHECR sources are transients that occur proportionally to SFR (or SMD) in every galaxy**
- catalog: near-infrared flux-limited sample from Biteau 2021
- injection: broken power law, fit to spectrum and Xmax
- **result: used Centaurus excess and TA hotspot to constrain burst rate density → best-estimate long GRBs**
- **note: results may differ with Galactic magnetic field & using event-level Auger data** (Bister & Biteau UHECR 2024)









small burst rate density:
local galaxies do not contribute
→ observer between bursts

large burst rate density:
almost continuous emission
→ local galaxies dominate