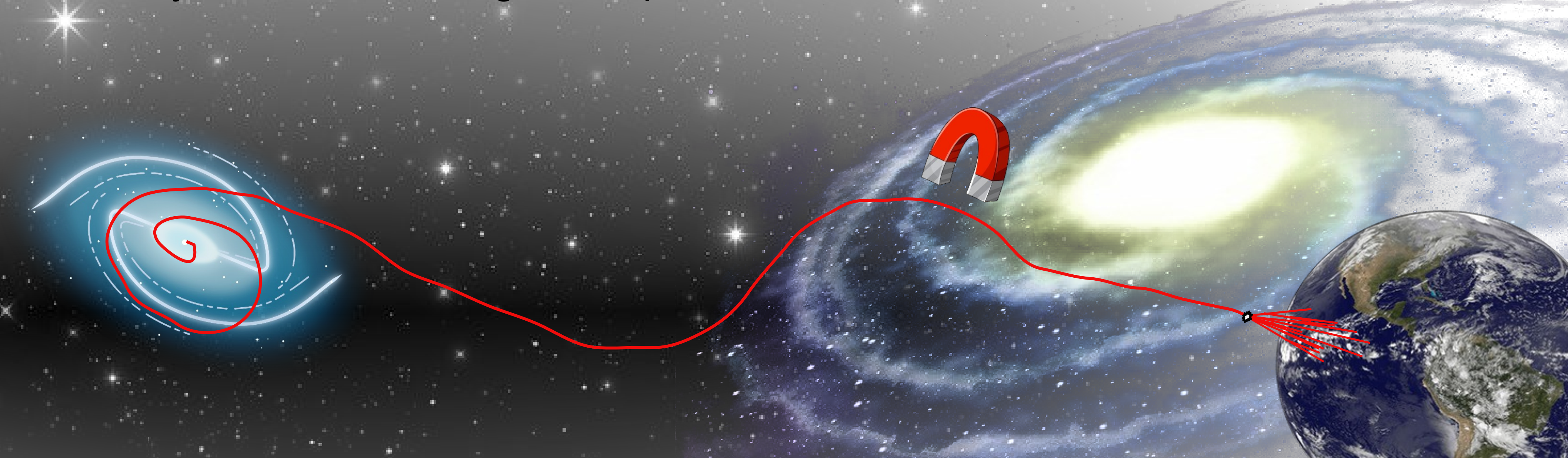
Constraining CR sources from below the ankle to the highest energies

Teresa Bister

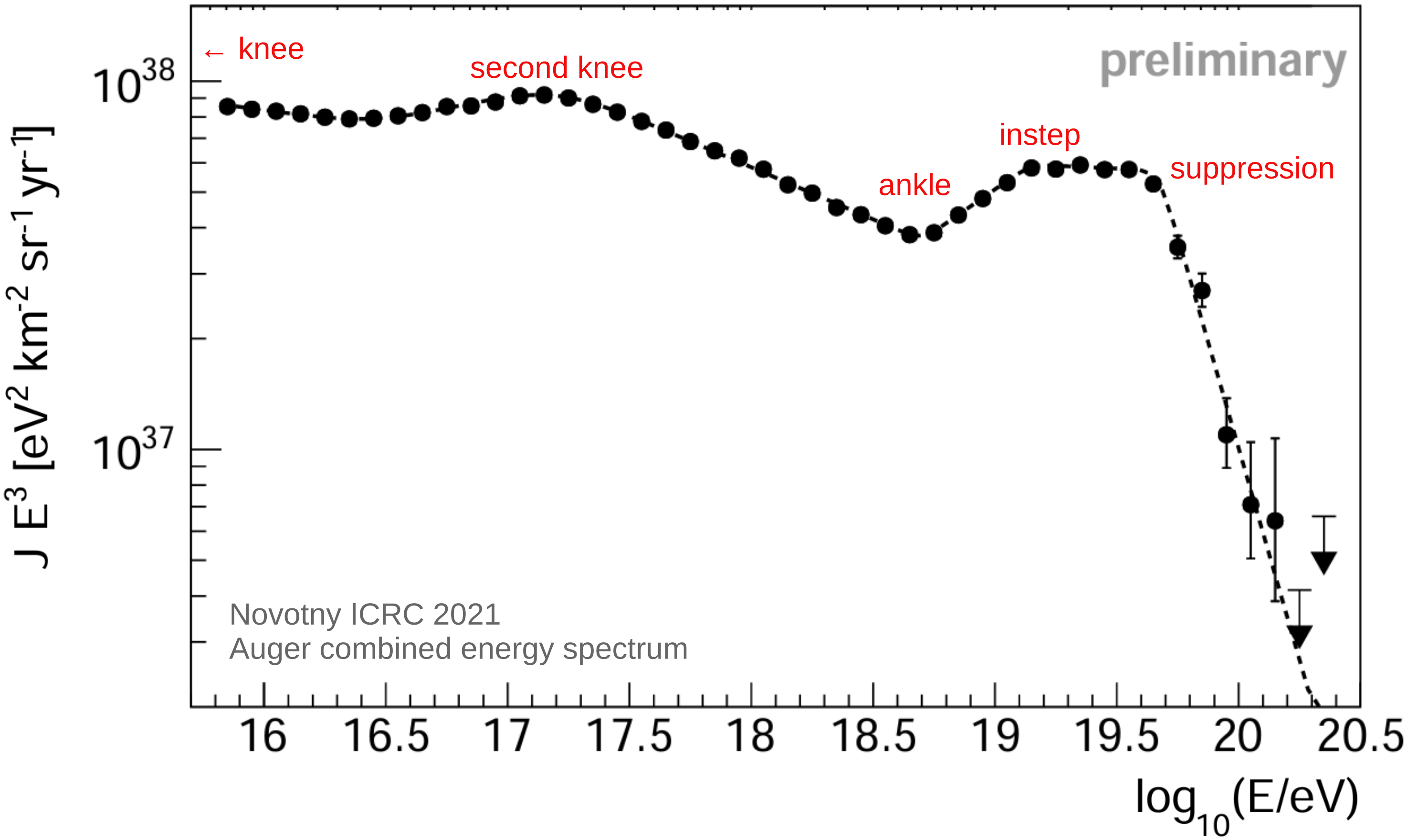
Nikhef

Radboud University

MMSky at extreme energies, September 2026



Energy spectrum of cosmic rays



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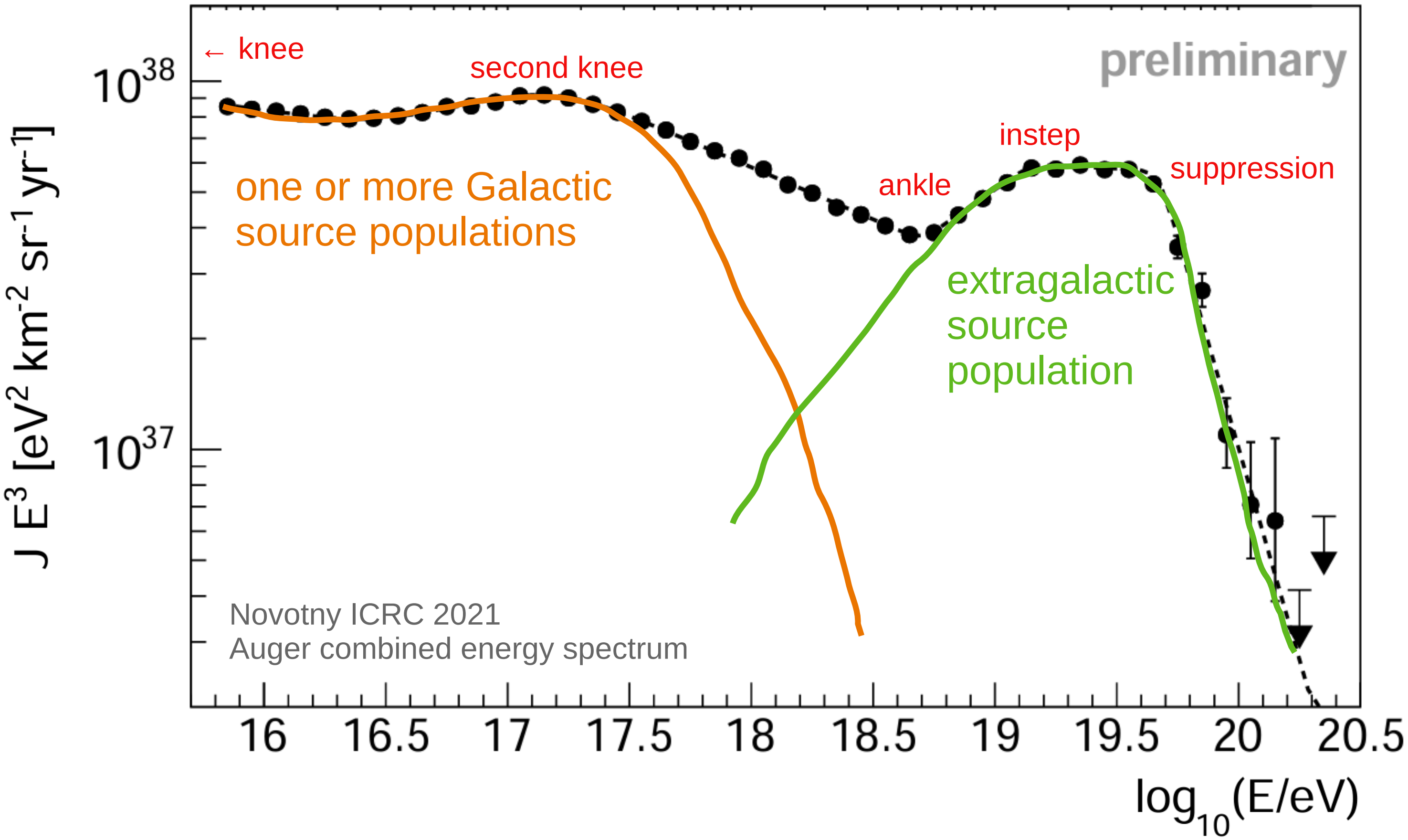
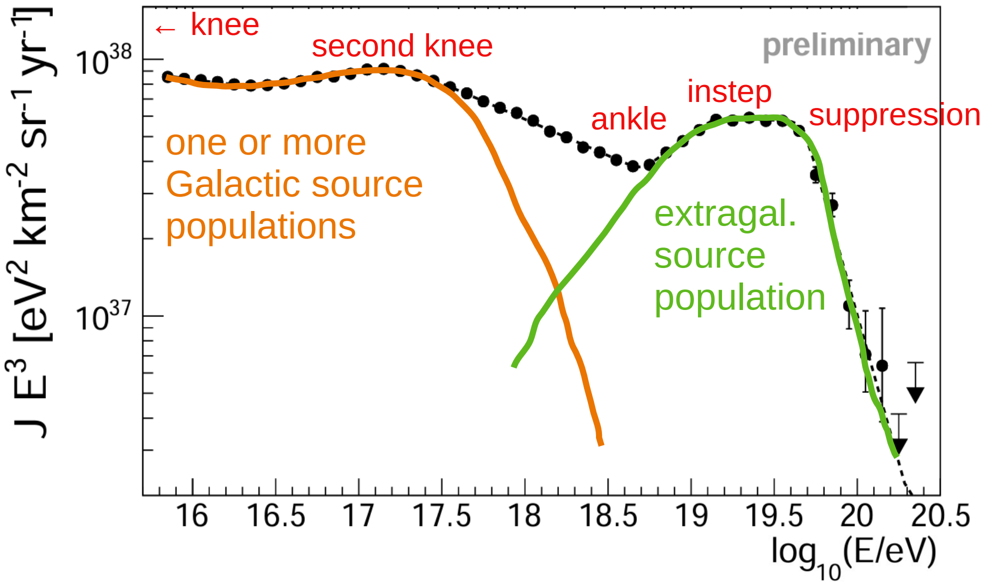
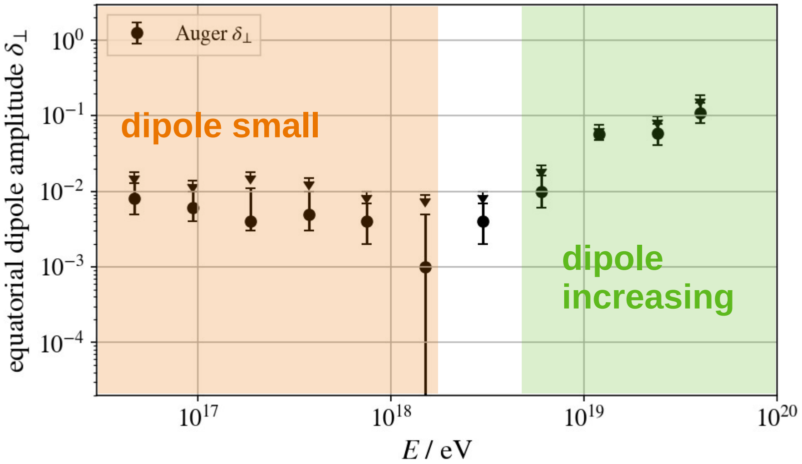
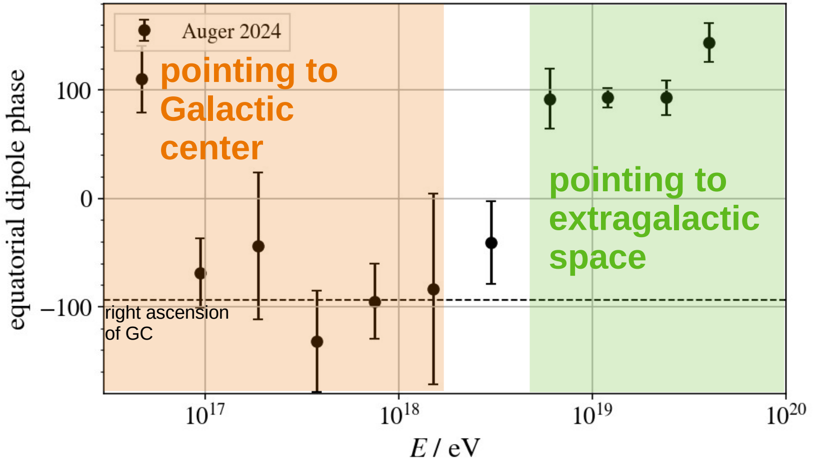


Energy spectrum & anisotropy of cosmic rays







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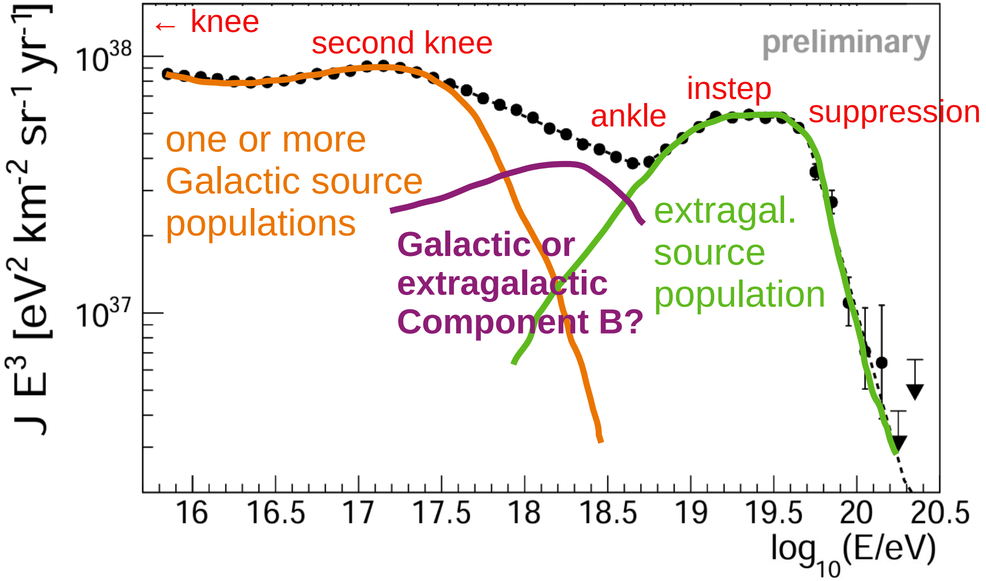

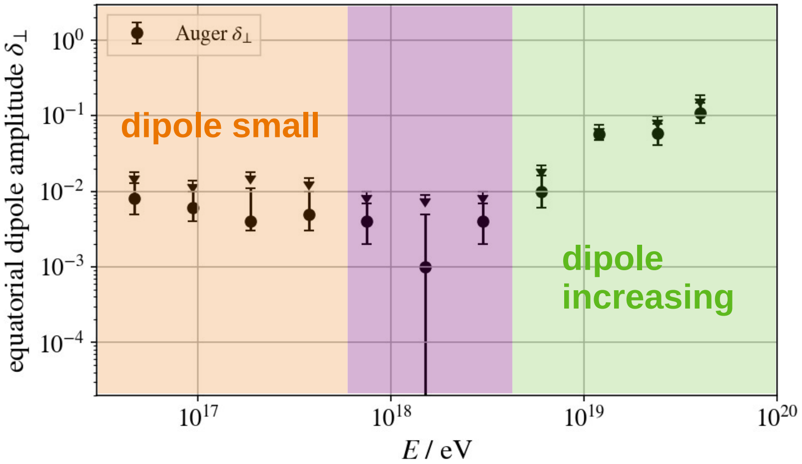

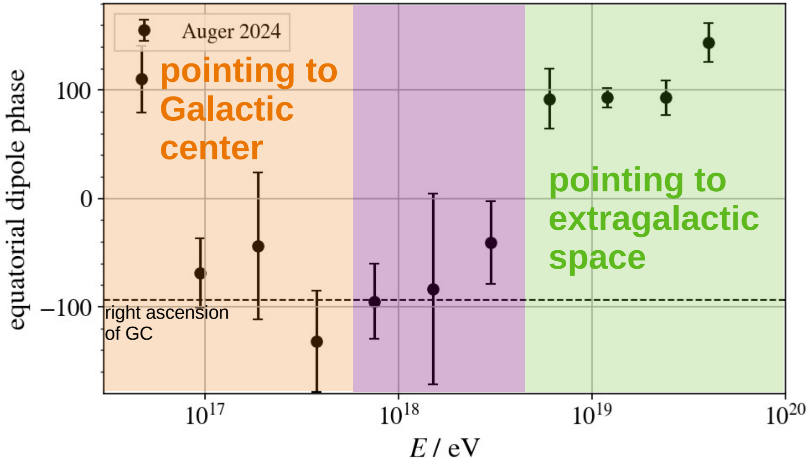

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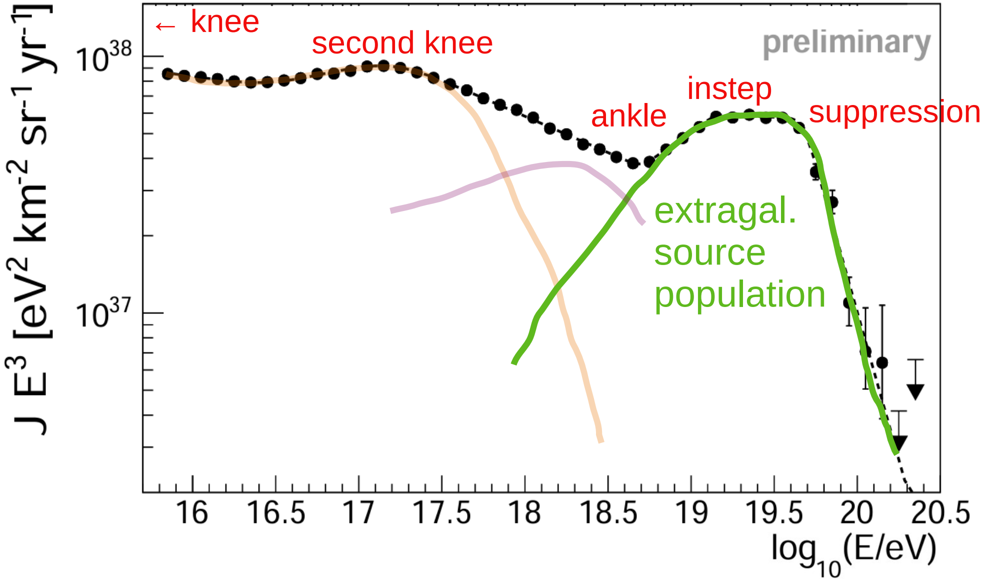
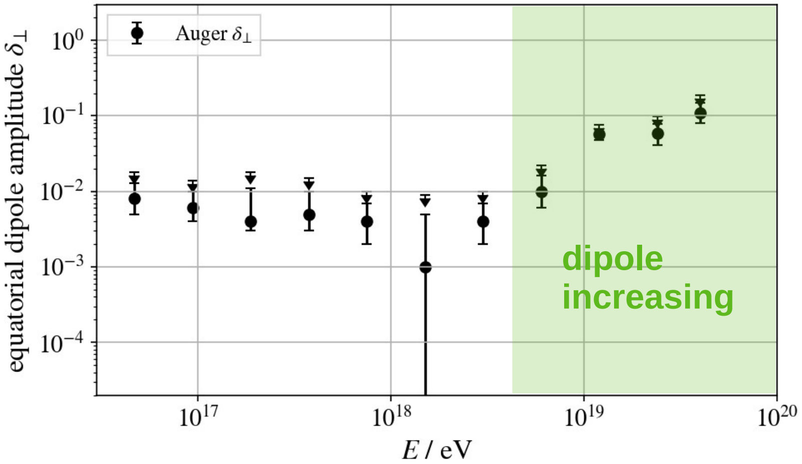
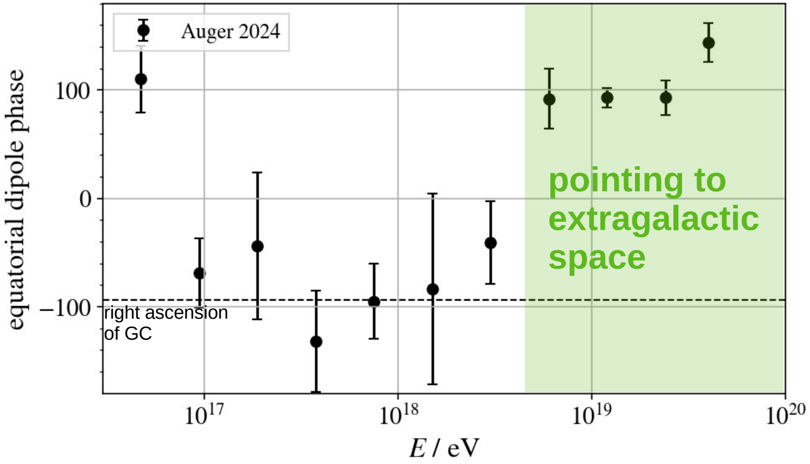
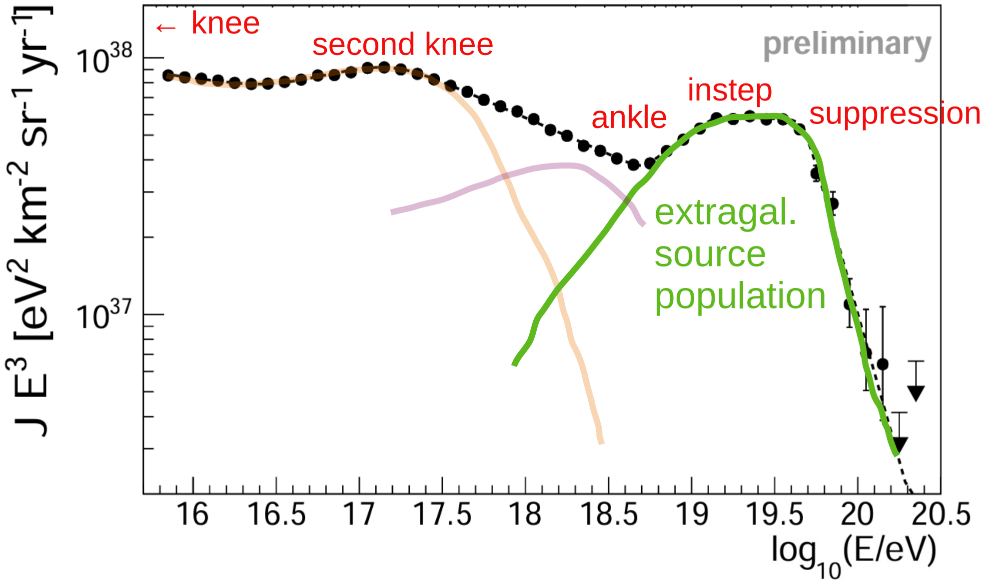
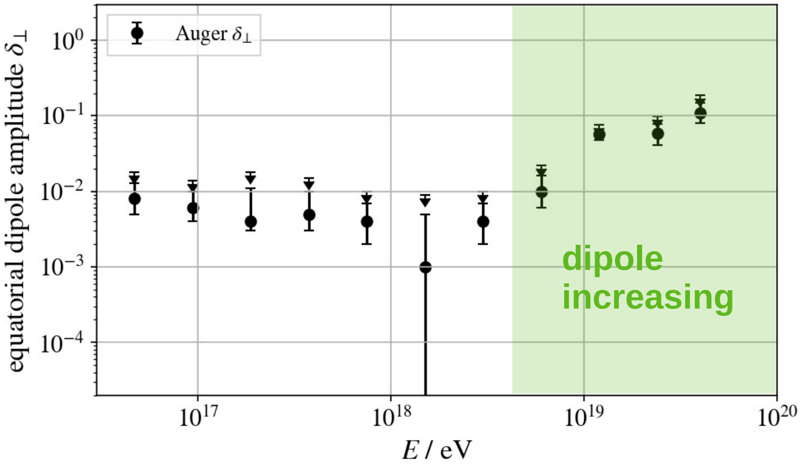


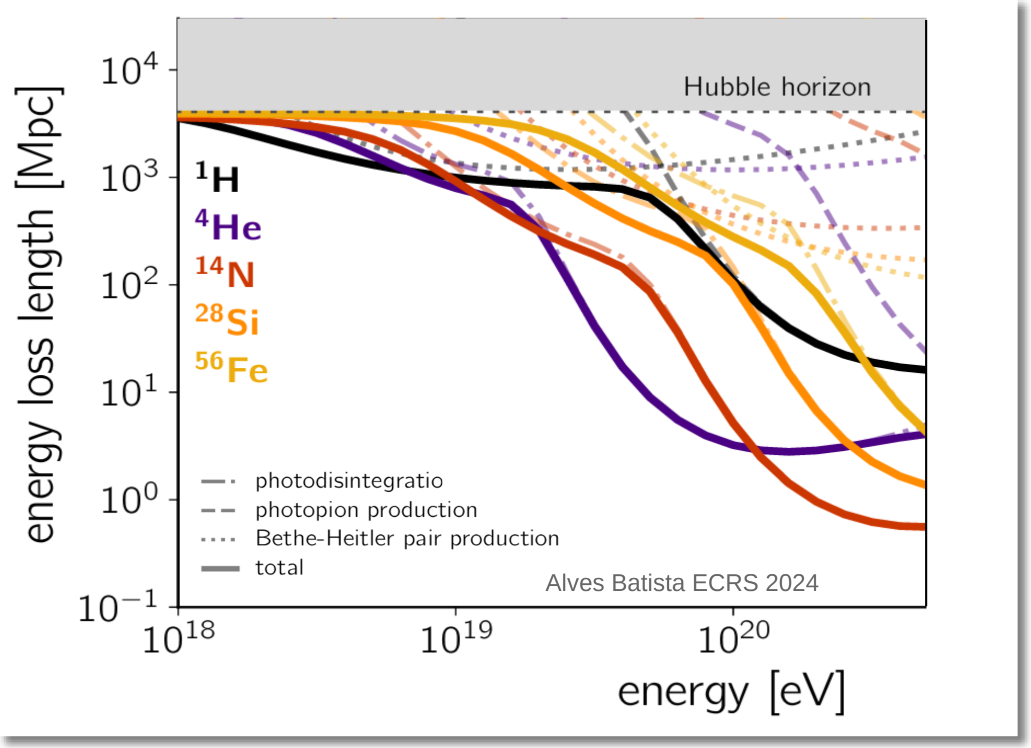




Horizon of extragalactic cosmic rays





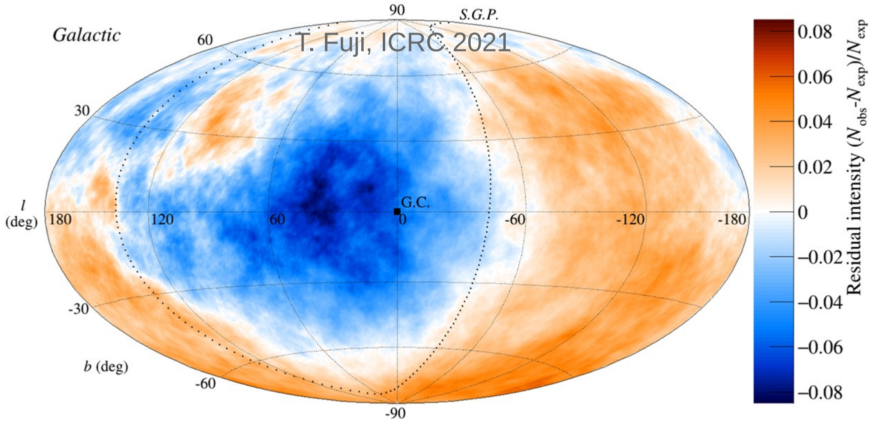


≲ 10 EeV:
CRs can come from almost whole visible universe

≳ 40 EeV
only few nearby sources contribute

Extragalactic cosmic rays: arrival directions

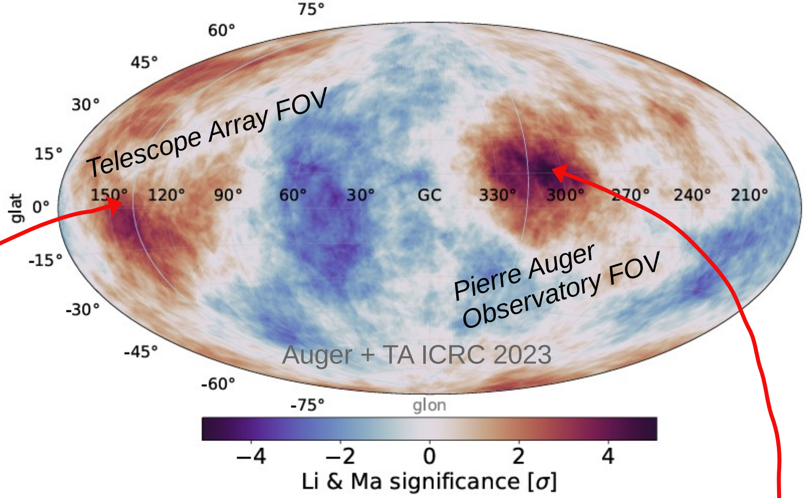
~10 EeV (CRs from ~1000 Mpc):



- 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

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



- 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)

Extragalactic cosmic rays: arrival directions

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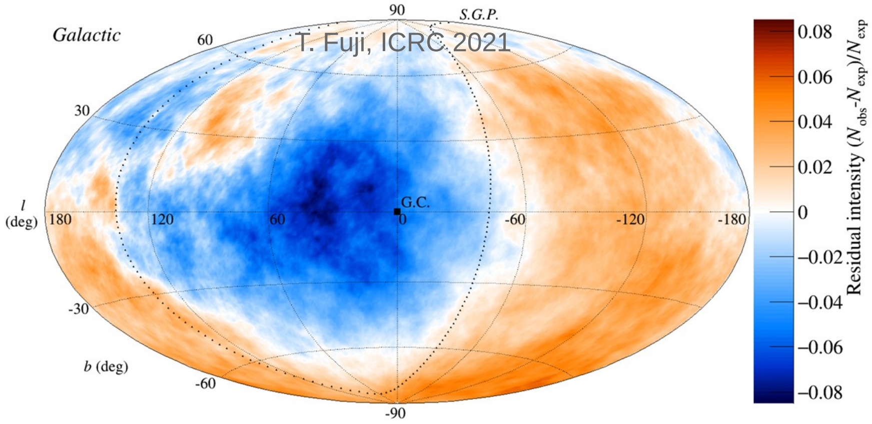

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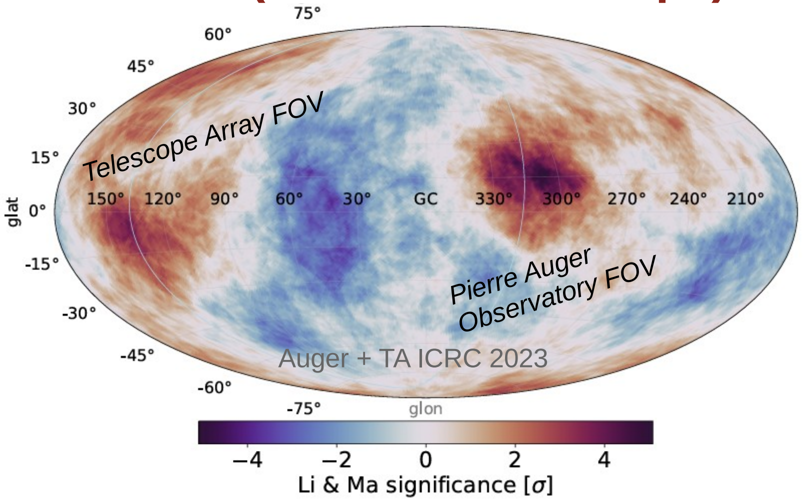
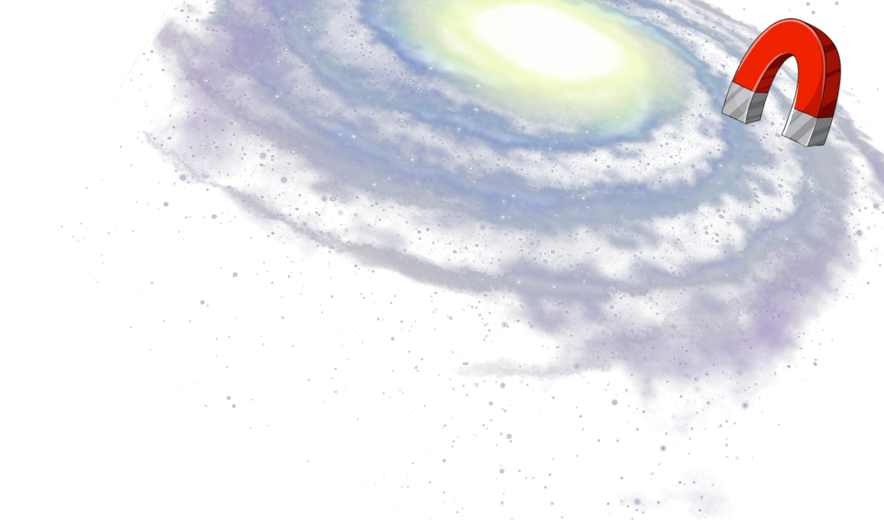


How can we explain these observations?

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

The Galactic magnetic field

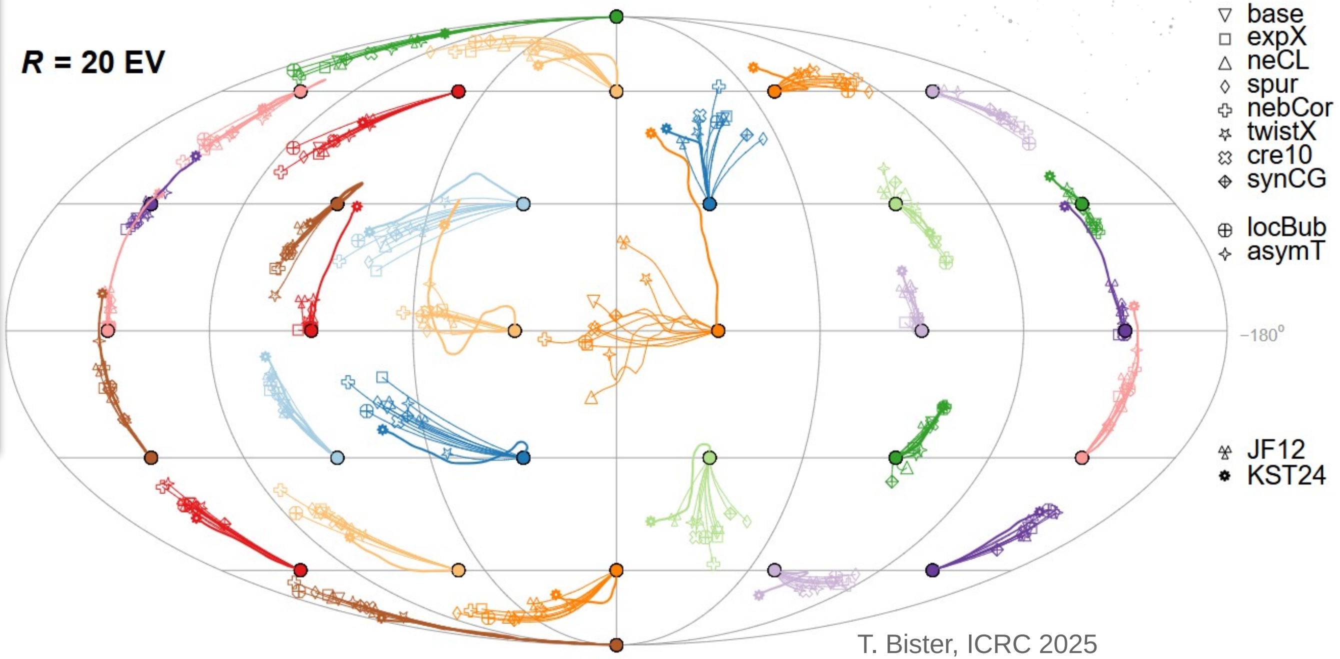


- Milky Way magnetic field ~μG, coherent + turbulent
- **deflection** $\propto Z / E := 1 / R$
- in last three years: Unger & Farrar 2023, 2024, Korochkin et al 2024
  <u>>10 new models for the coherent field released</u>

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

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

➔ **see Michael's talk**



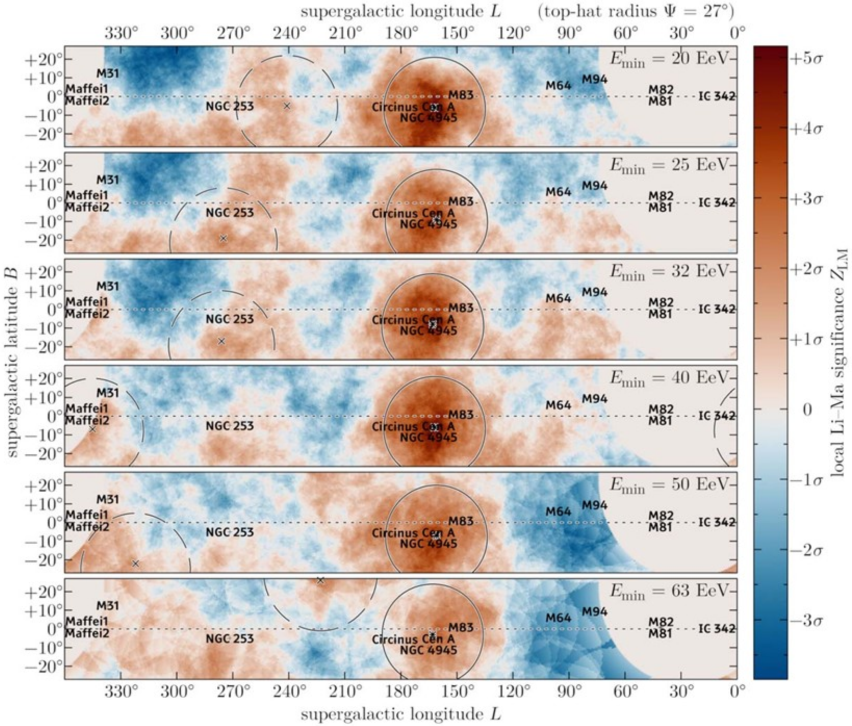
new random field model just released: Unger & Farrar 2026

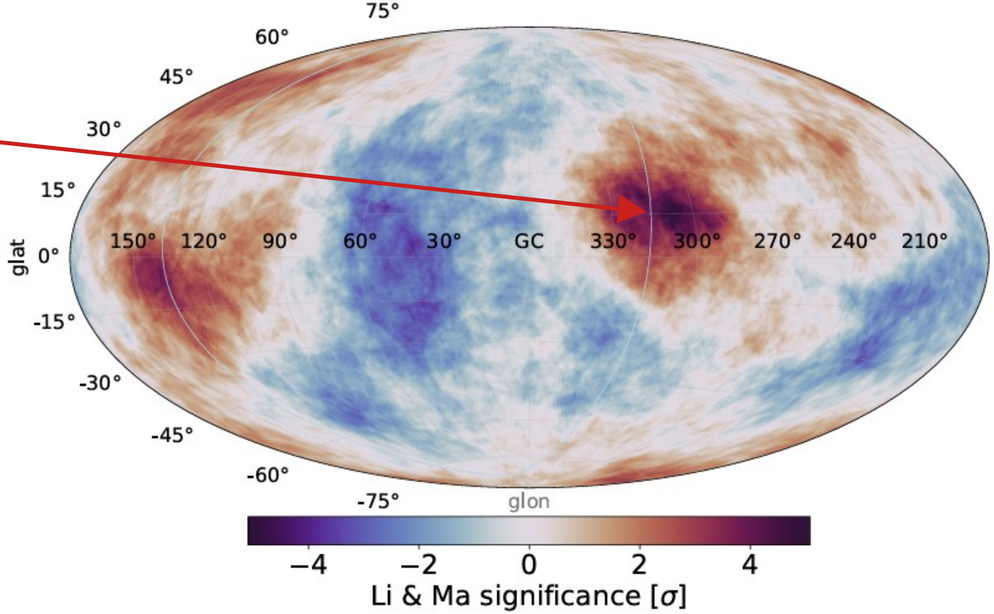
T. Bister, ICRC 2025

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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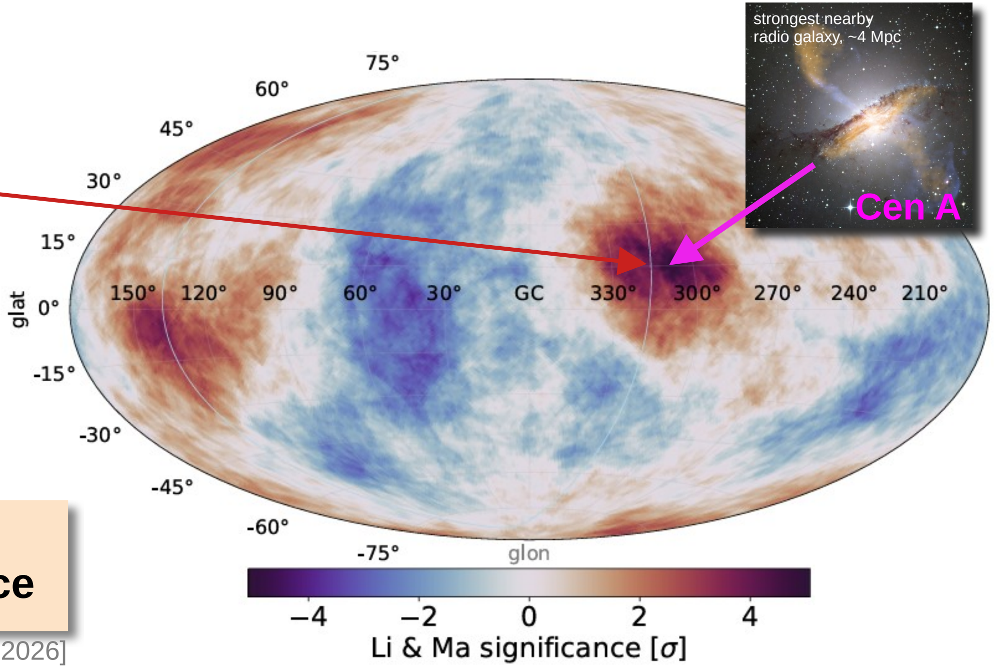
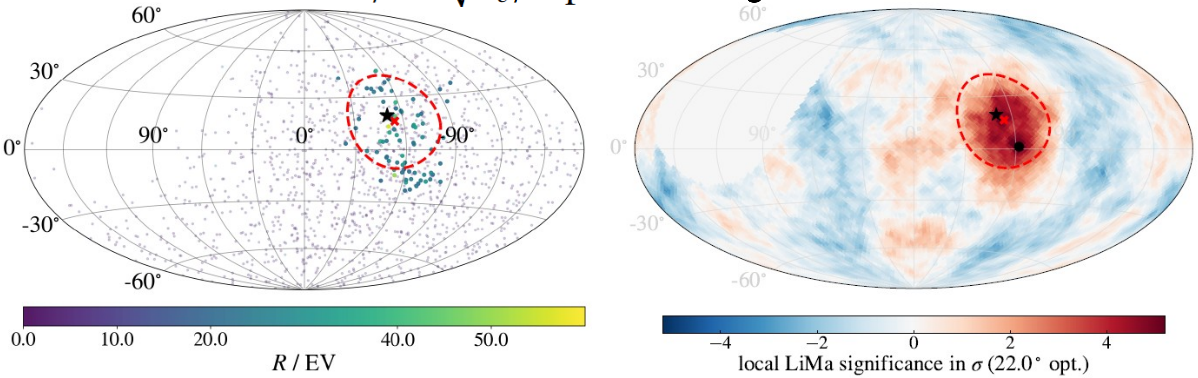


can reproduce excess direction, size, strength in
simulations with new GMF models & Cen A as source

[Bister Astroparticle Physics 2026]

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



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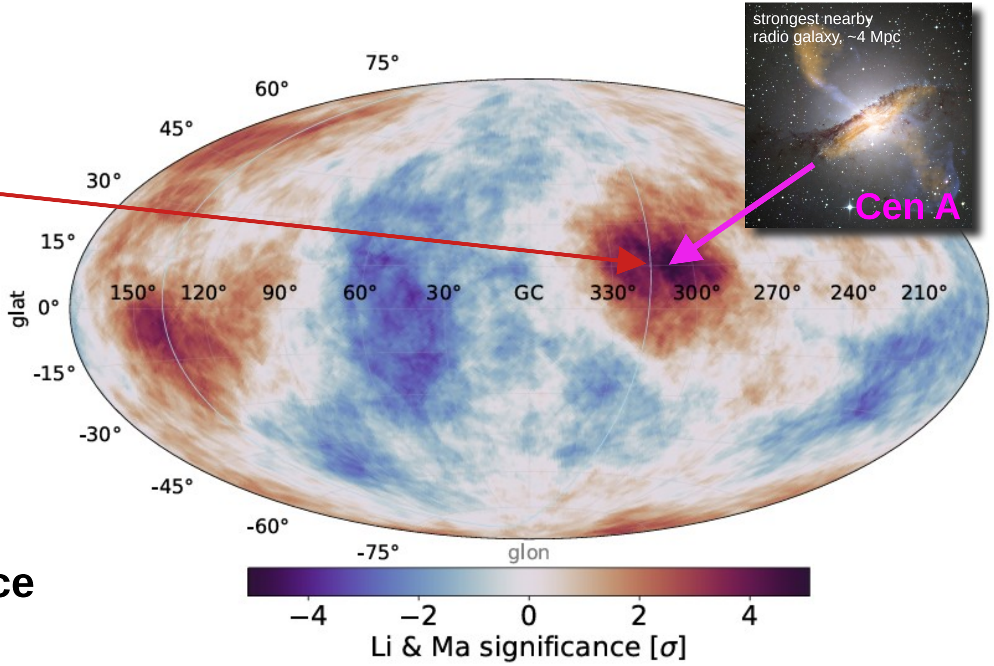

can reproduce excess direction, size, strength in
simulations with new GMF models & Cen A as source

- **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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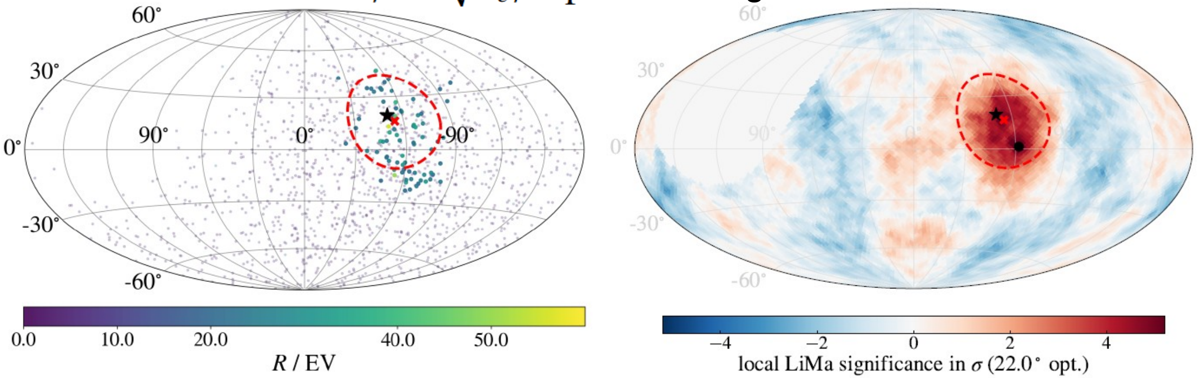

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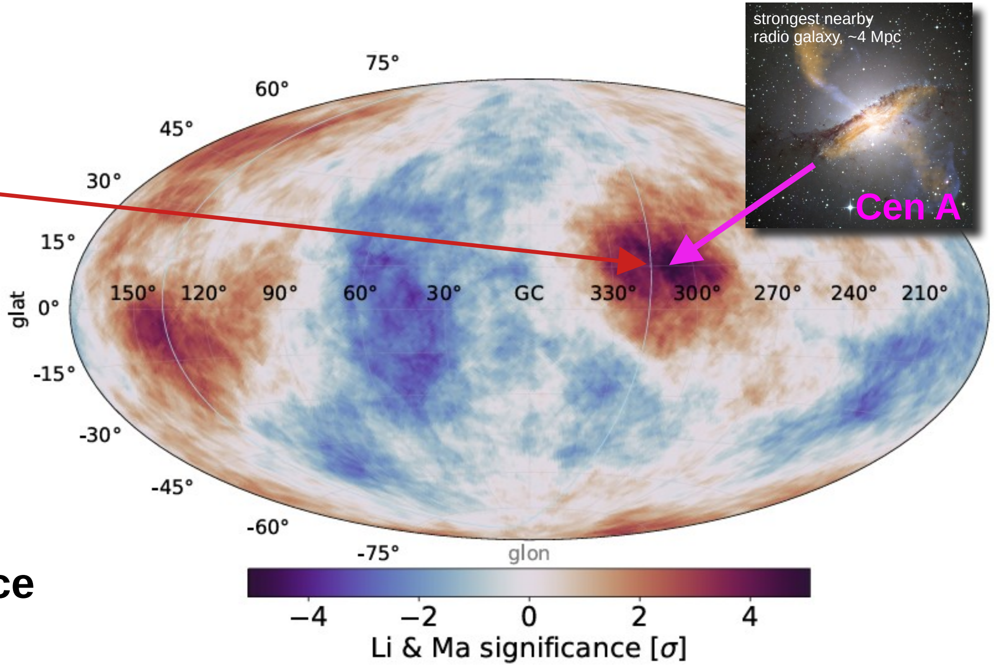

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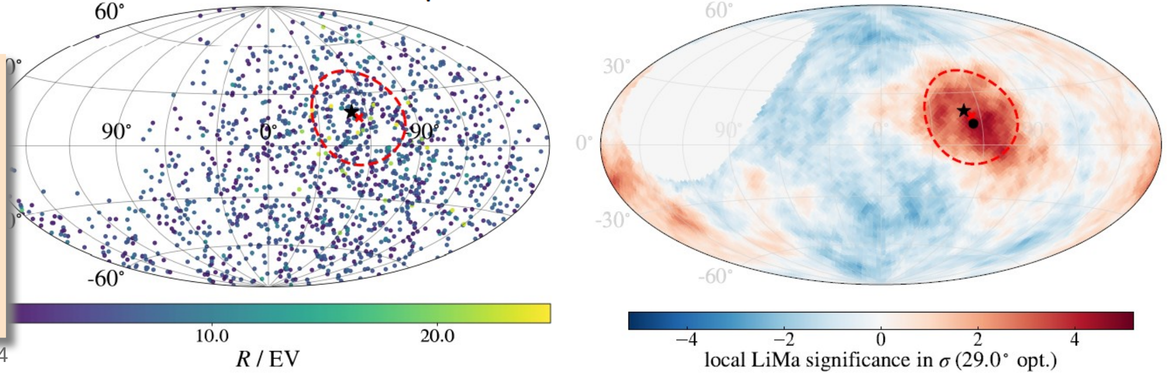
- need additional turbulent magnetic field between source & Earth
  $1 \lesssim B/\mathrm{nG}\sqrt{L_c/\mathrm{Mpc}} \lesssim 30$ for Z~6

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

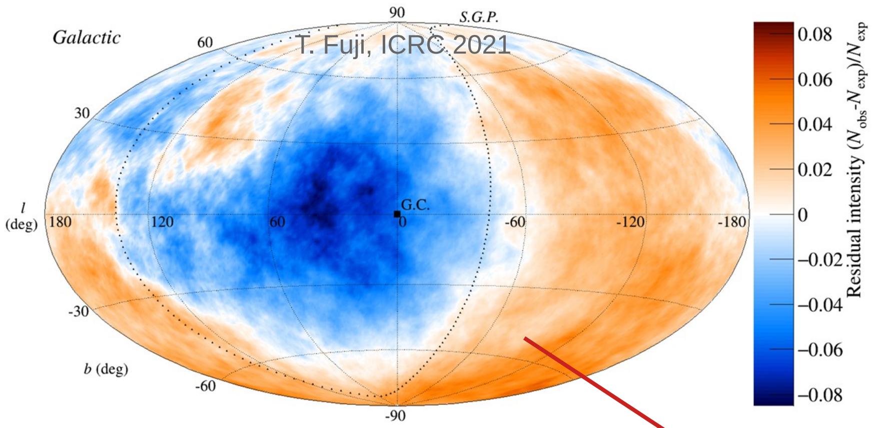


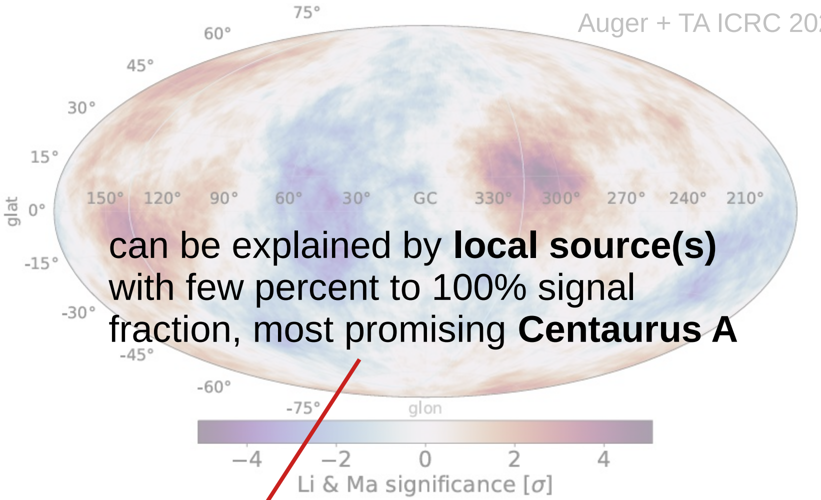
- **cannot exclude signal fraction of 100%**
  - need careful study of lower energies & contributions of Cen-A-like sources, better knowledge of magnetic field between Cen A and Earth

see also Mollerach & Roulet PRD 110 2024

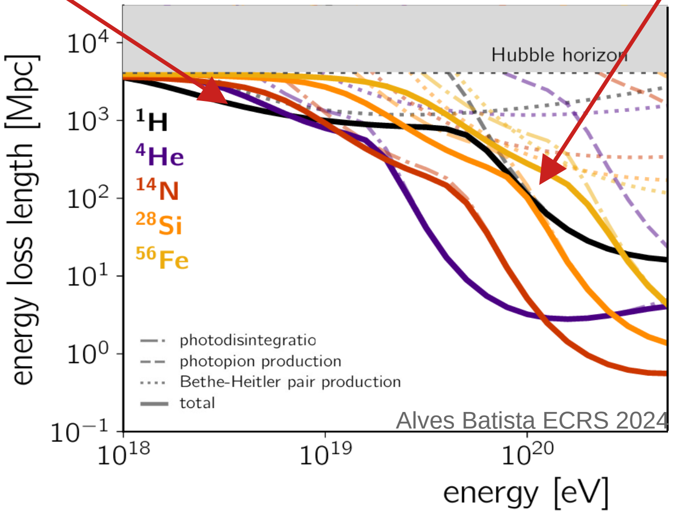
[Bister Astroparticle Physics 2026]

Extragalactic cosmic rays: arrival directions





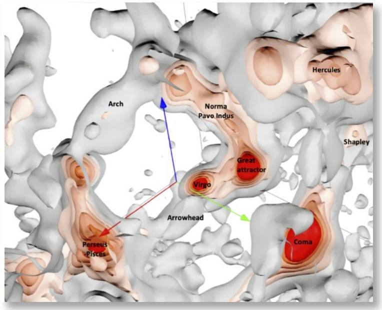
can be explained by **local source(s)** with few percent to 100% signal fraction, most promising **Centaurus A**

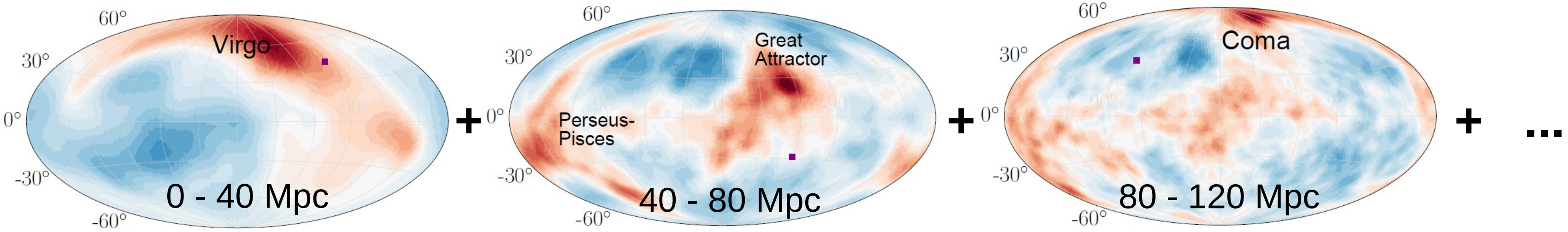


Can the dipole amplitude & direction + energy evolution be explained by sources following the large-scale structure?

Bister & Farrar, ApJ 966 71 (2024)

Spatial extragalactic CR flux

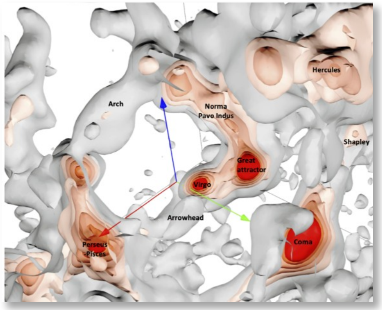


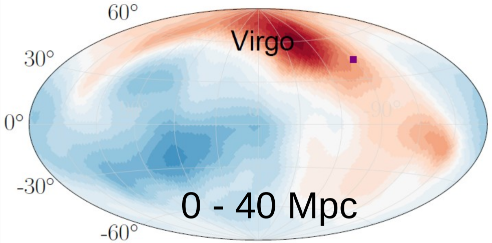


assume CR sources follow matter density (CosmicFlows), extrapolation after 350 Mpc

combined fit to measured spectrum and mass composition (Peters cycle, in-source production of protons),
→ see Denise's talk

Spatial extragalactic CR flux





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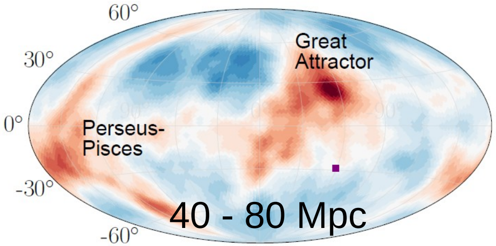

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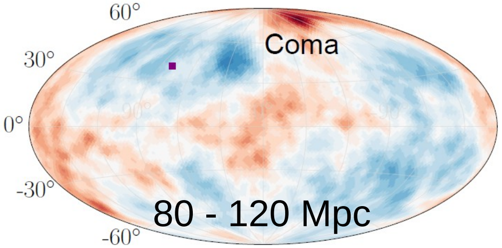

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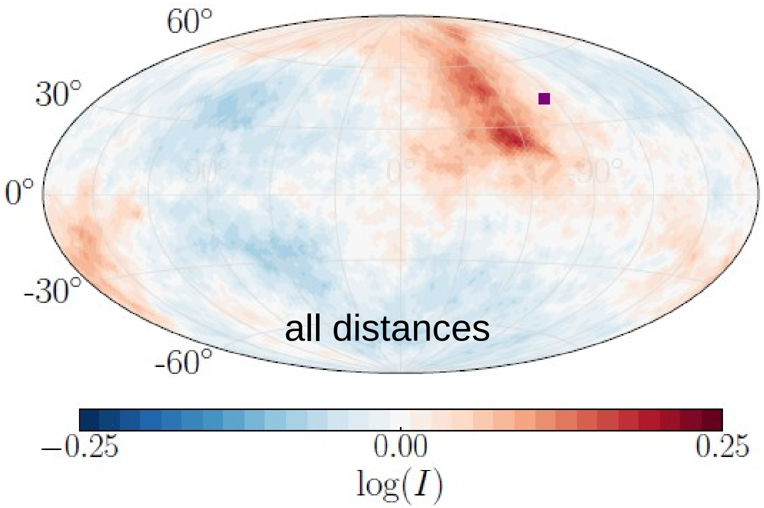
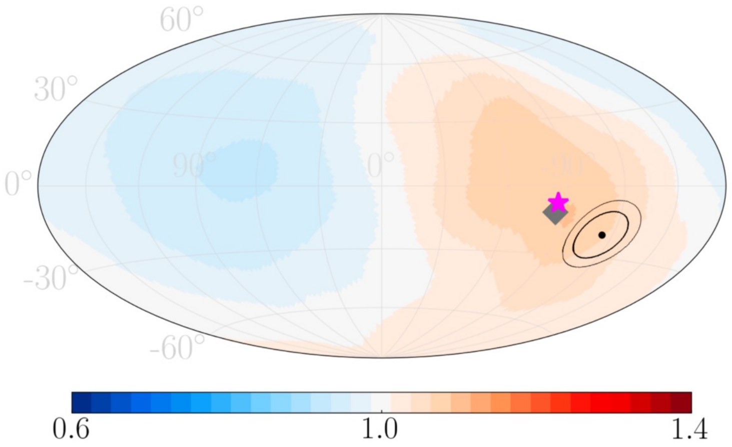


Galactic magnetic field model

CRPropa



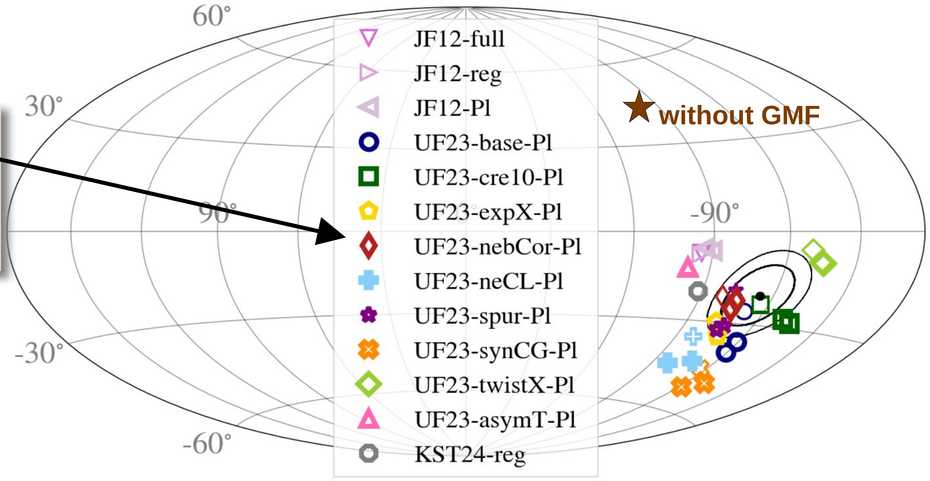
modeled flux at Earth reproduces dipole ✓

UHECR sources likely follow extragalactic matter distribution

Bister, Farrar, Unger
ApJL 975 L21 (2024)

What more can we do?

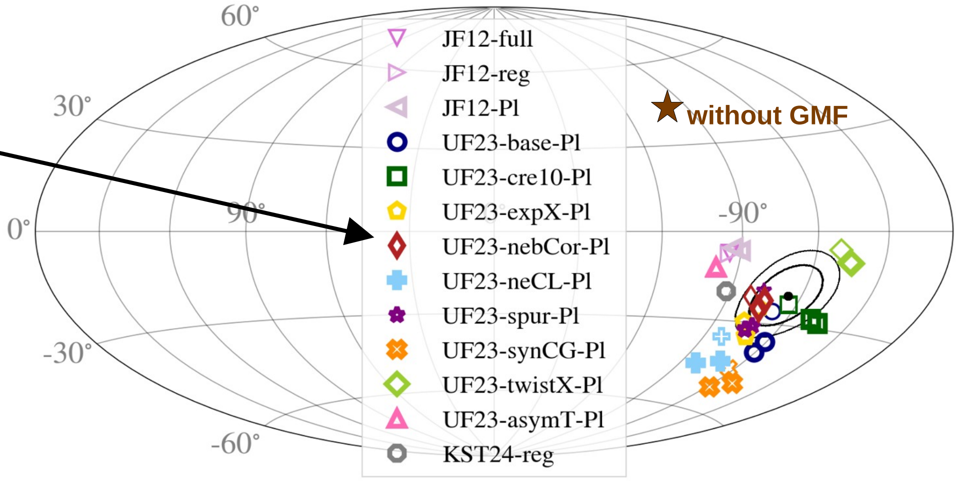
- compare **different Galactic magnetic field models**
  - agreement, systematic uncertainty under control

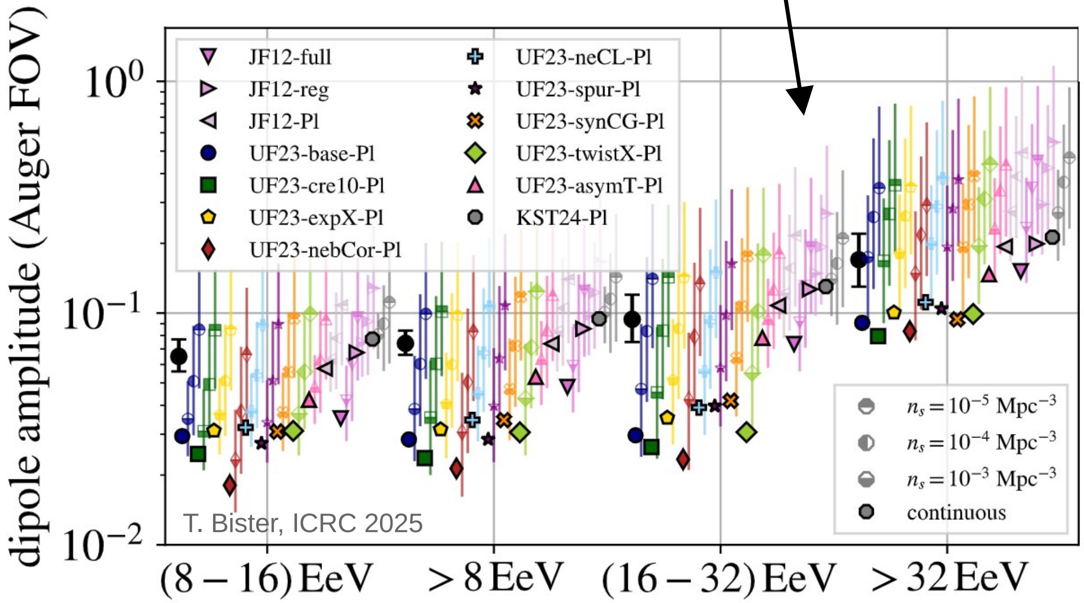


What more can we do?

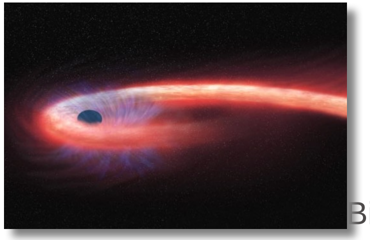
Bister, Farrar, Unger
ApJL 975 L21 (2024)

- compare **different Galactic magnetic field models**
  - agreement, systematic uncertainty under control
- learn more about **density and distribution of sources** from dipole amplitude evolution

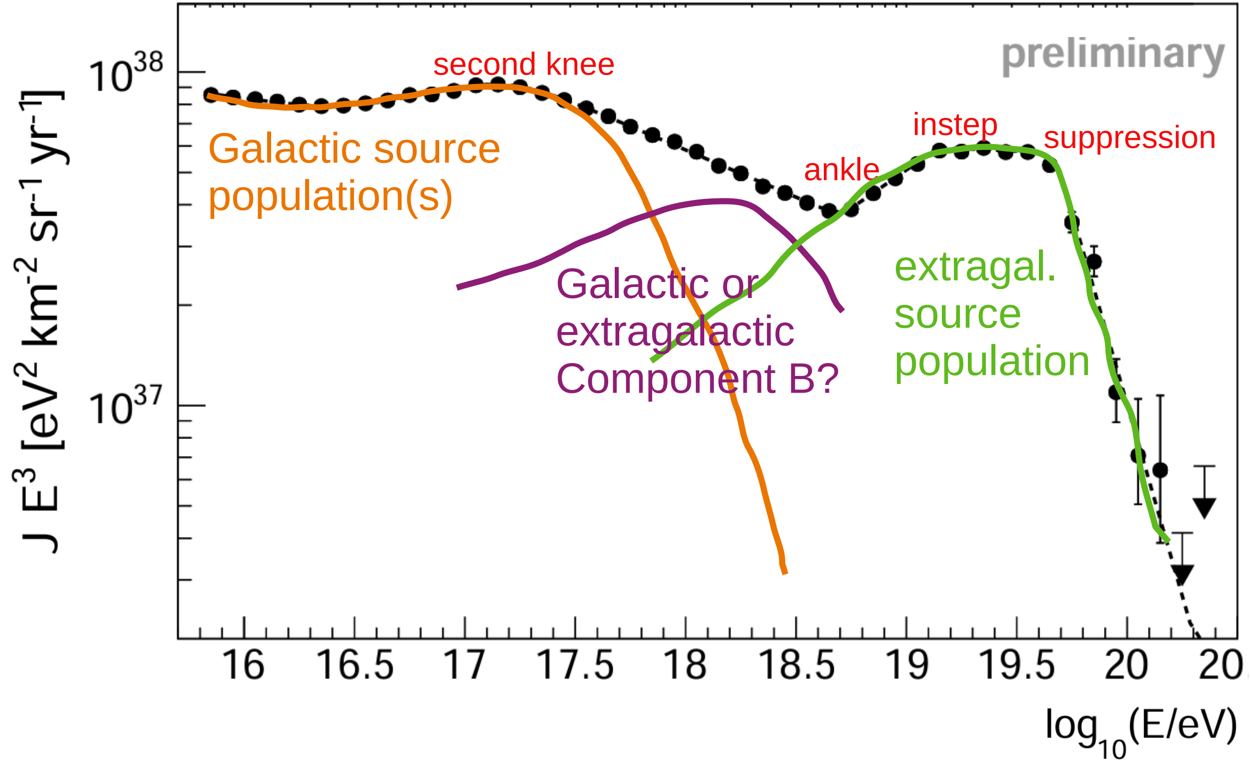


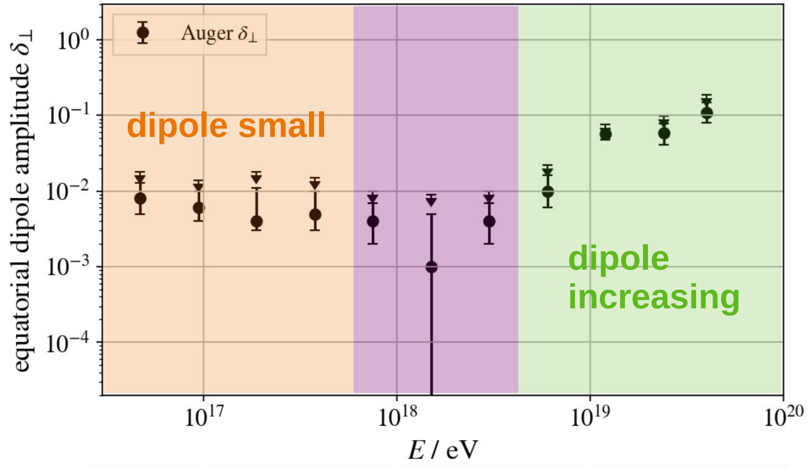


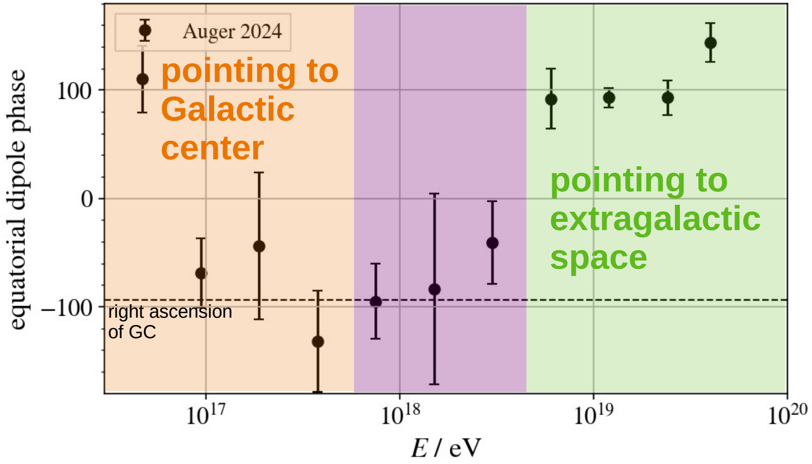
- **very small densities <10^{-6} Mpc^{-3} excluded**
- more common source classes like starburst galaxies or low-luminosity AGNs preferred
- or: **transient** sources like gamma-ray bursts or binary neutron star mergers? → Glennys' talk

Transition from Galactic to extragalactic CR sources







Bister, Oikonomou, Fiorillo arXiV:2608.26933

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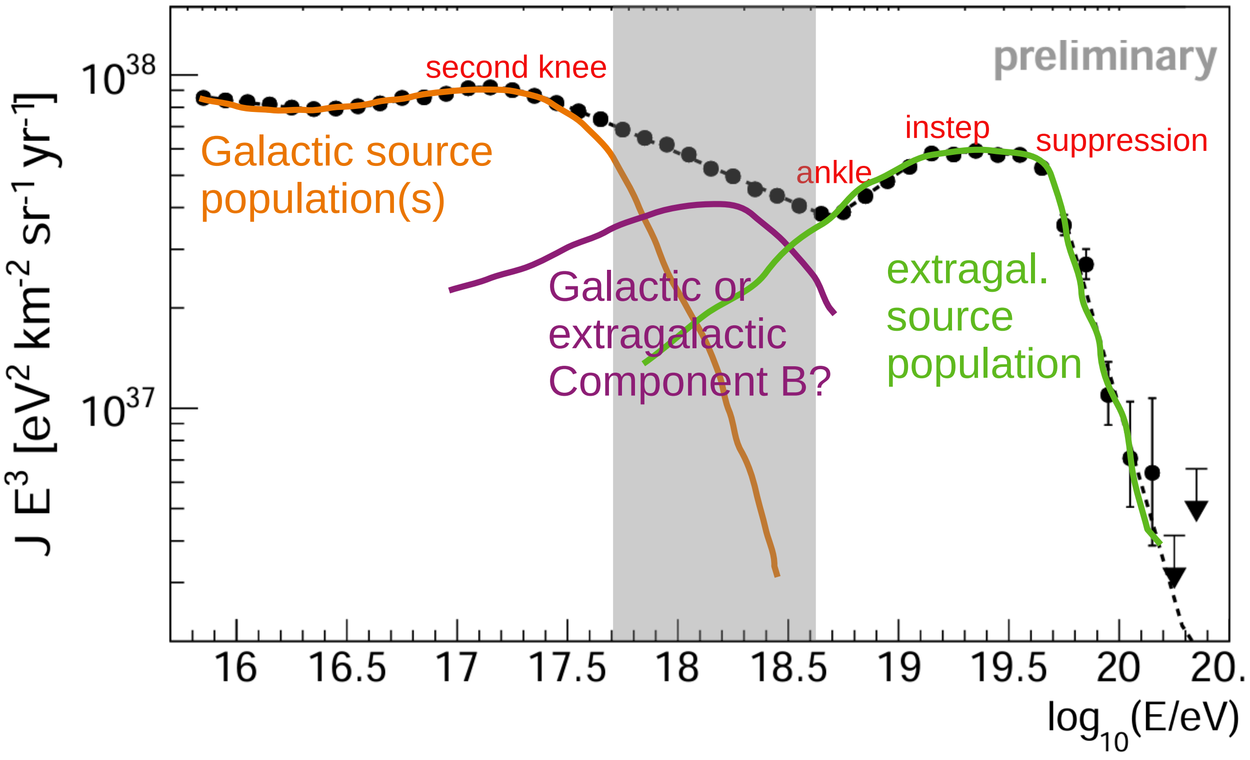
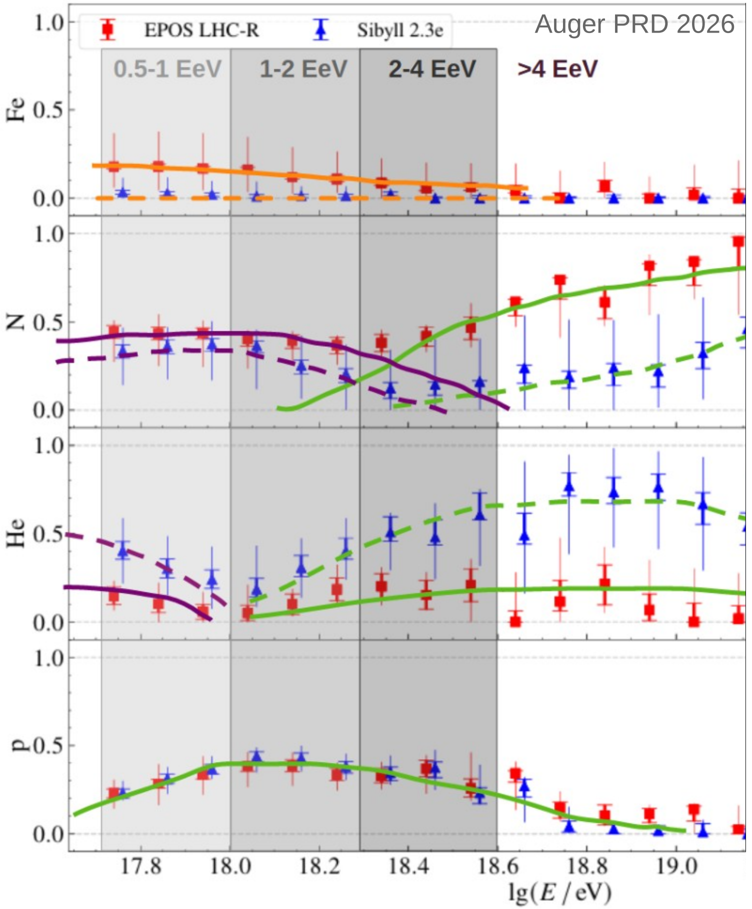
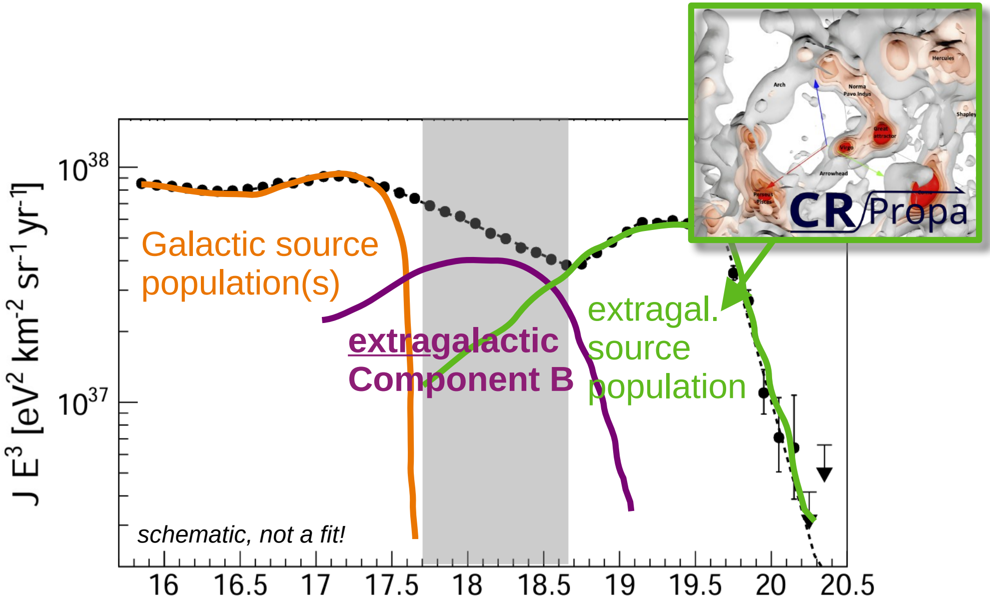




Fe-tail CNO Peters cycle

Bister, Oikonomou, Fiorillo arXiV:2608.26933

Transition at second knee

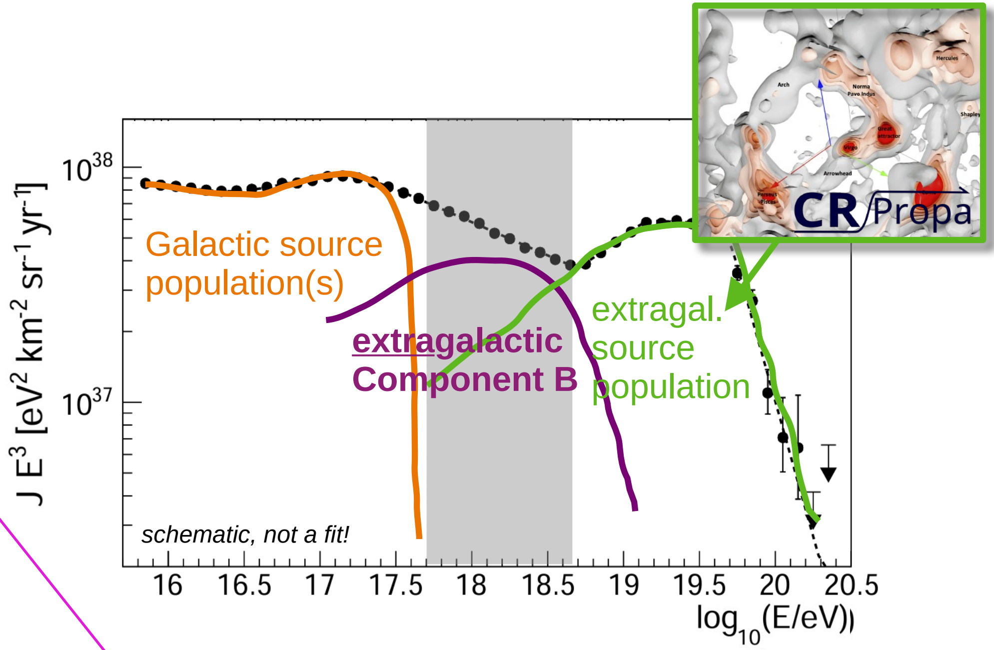


Bister, Oikonomou, Fiorillo arXiV:2608.26933

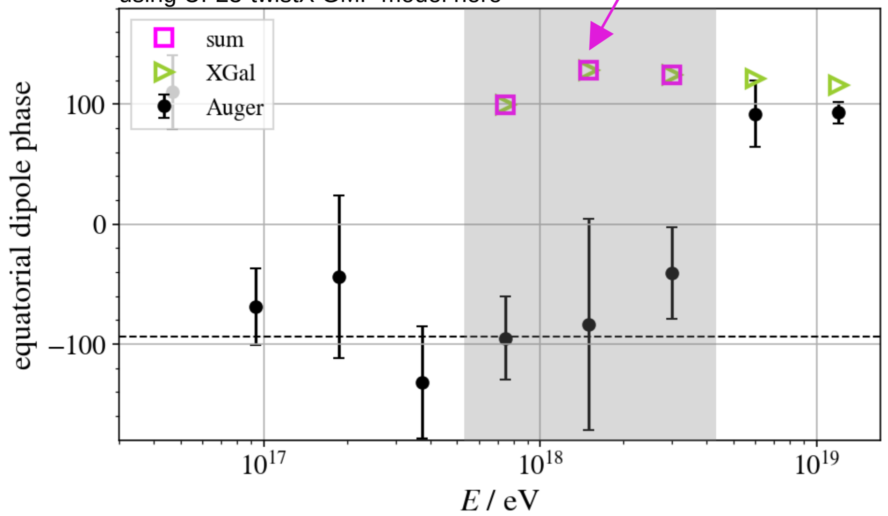
Transition at second knee

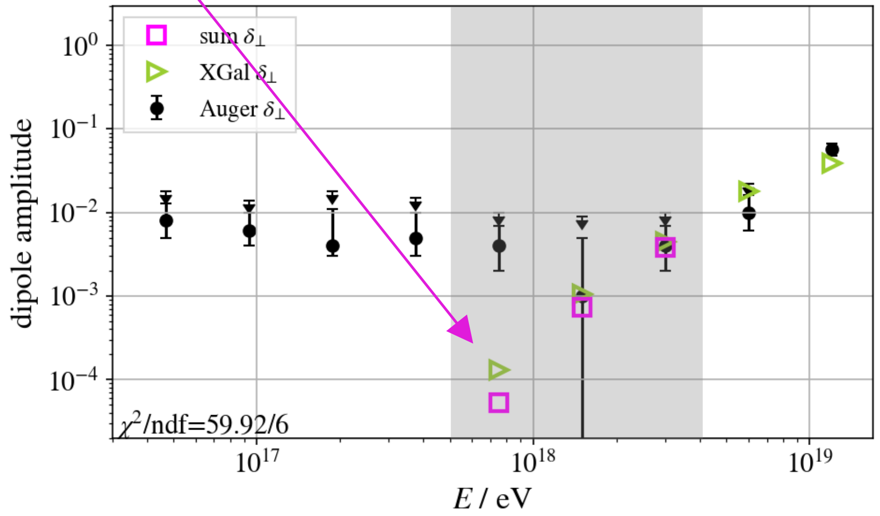
without any Galactic contribution, neither the dipole phase change, nor the ~0.5% amplitude below 1 EeV can be described.

need at least some Galactic contribution above 0.5 EeV!



using UF23-twistX GMF model here





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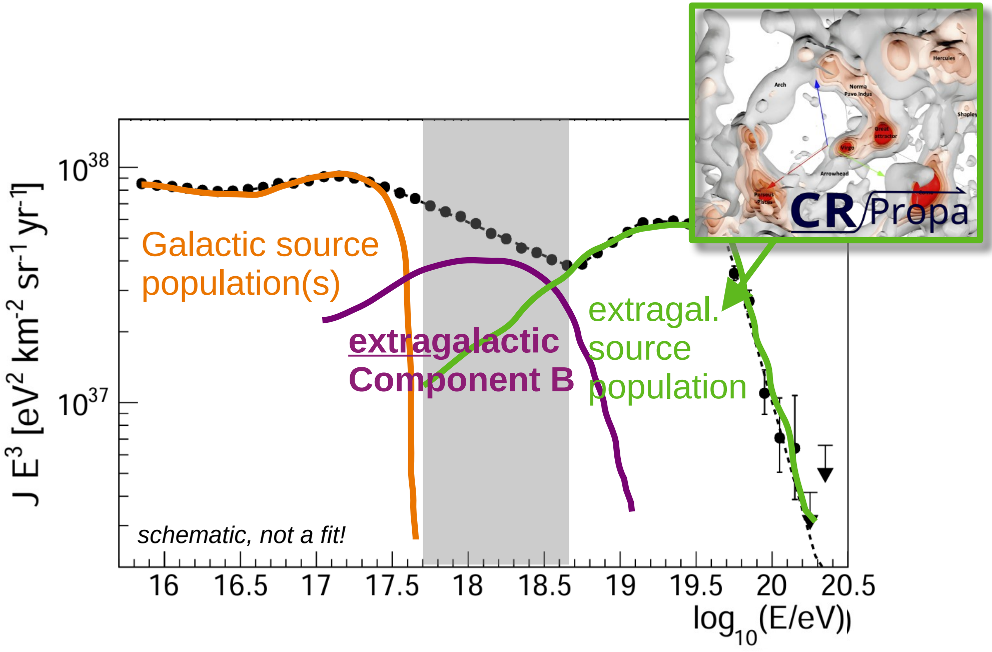
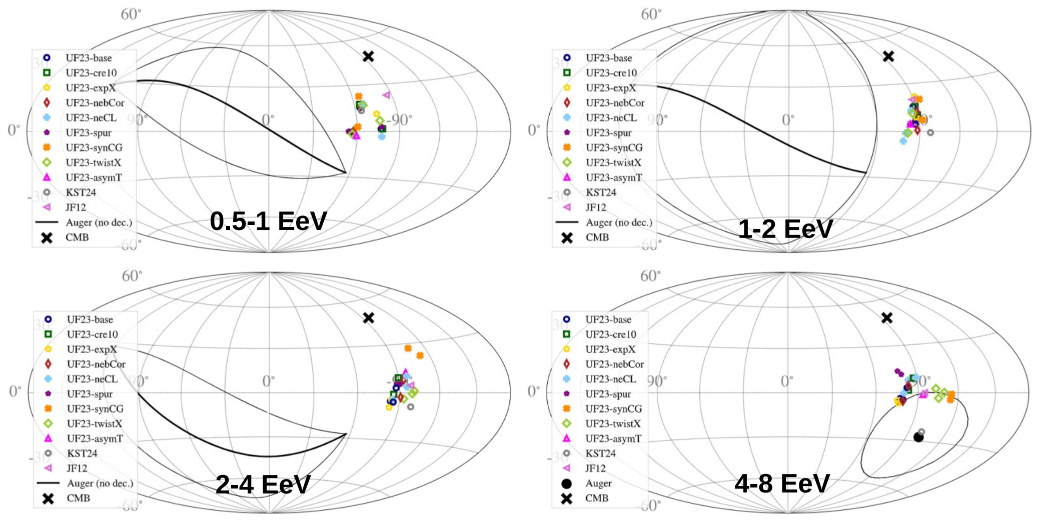
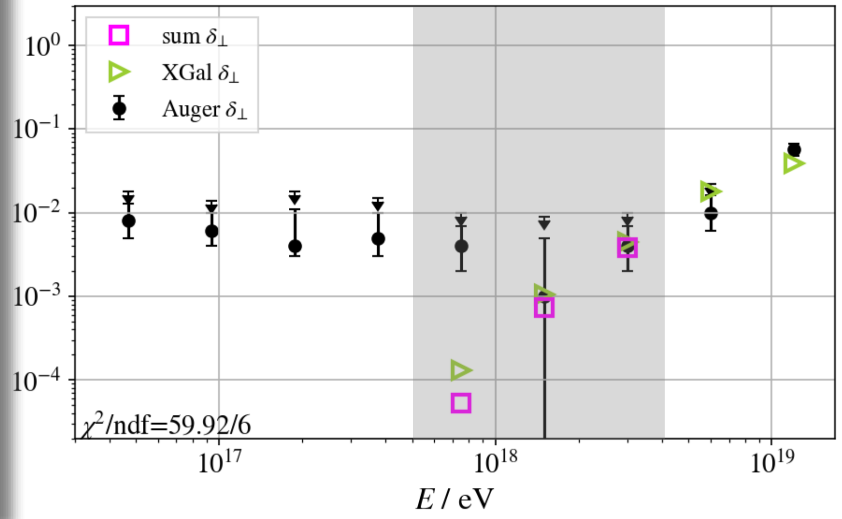


for no GMF model do LSS sources reproduce the dipole direction < 4 EeV



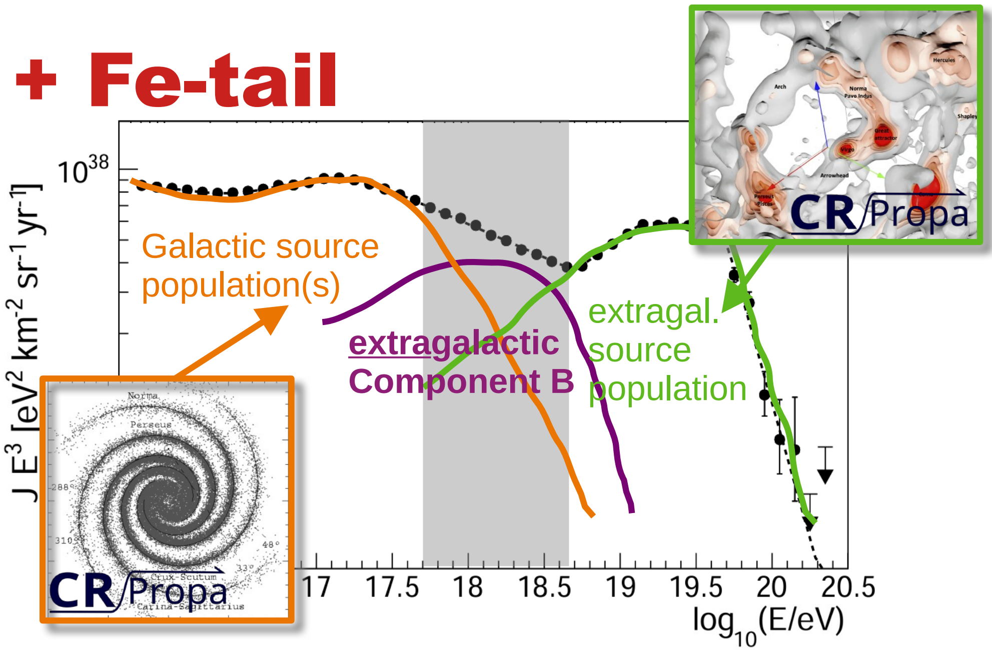
LSS based on CosmicFlows4, CosmicFlows2 similar, Compton-Getting effect included

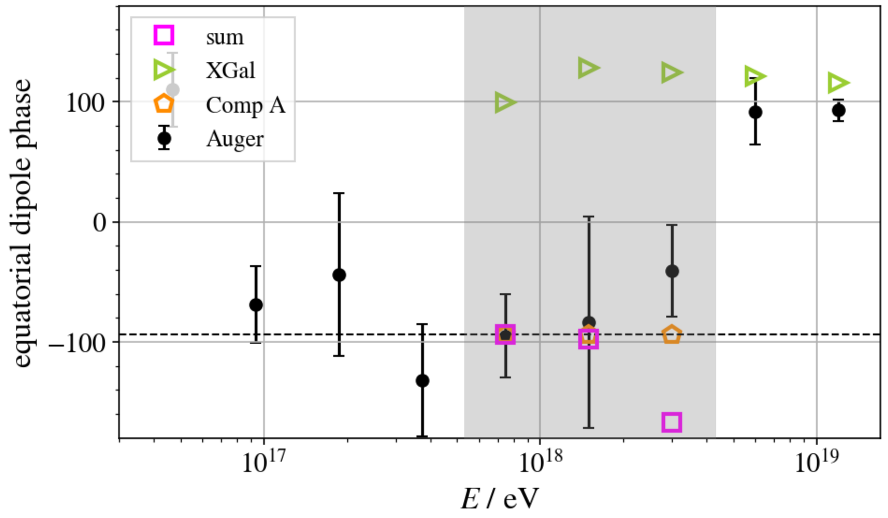


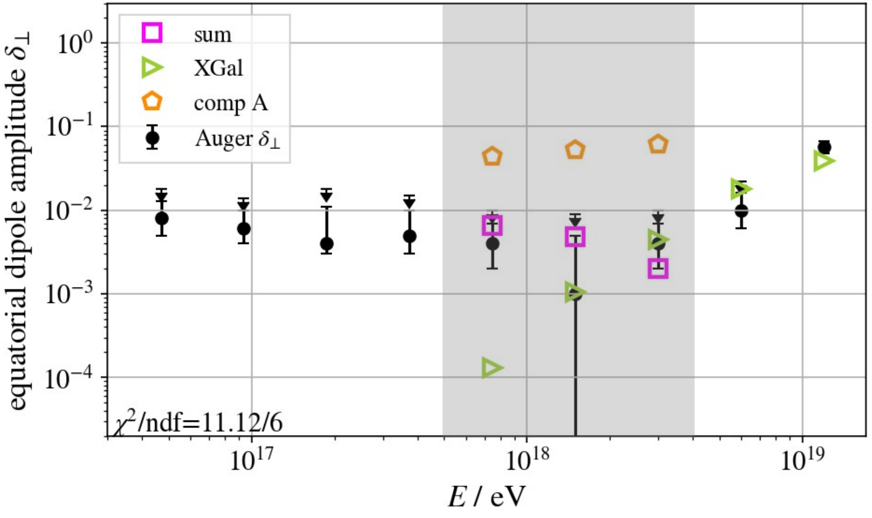
Transition at second knee + Fe-tail

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

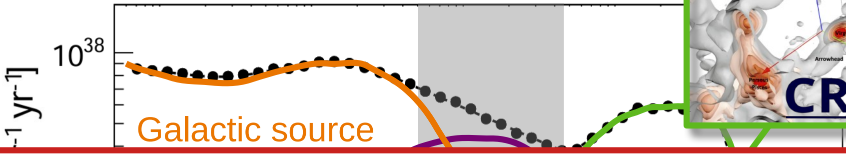


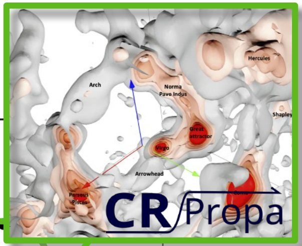


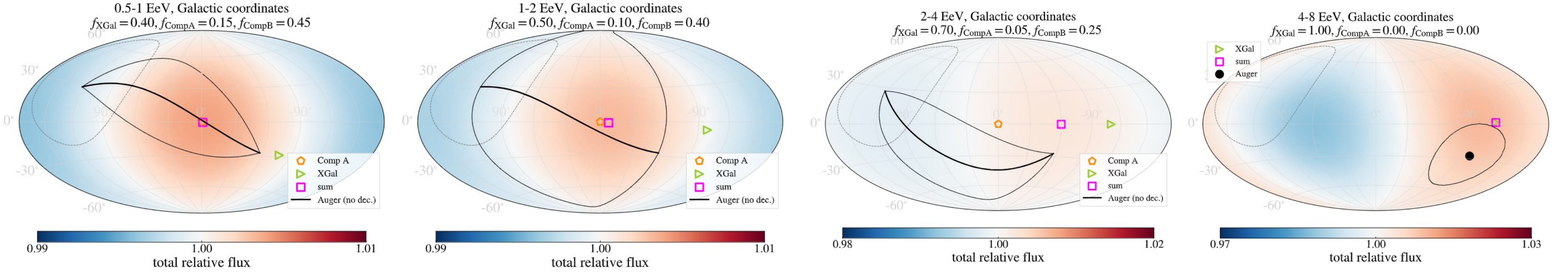


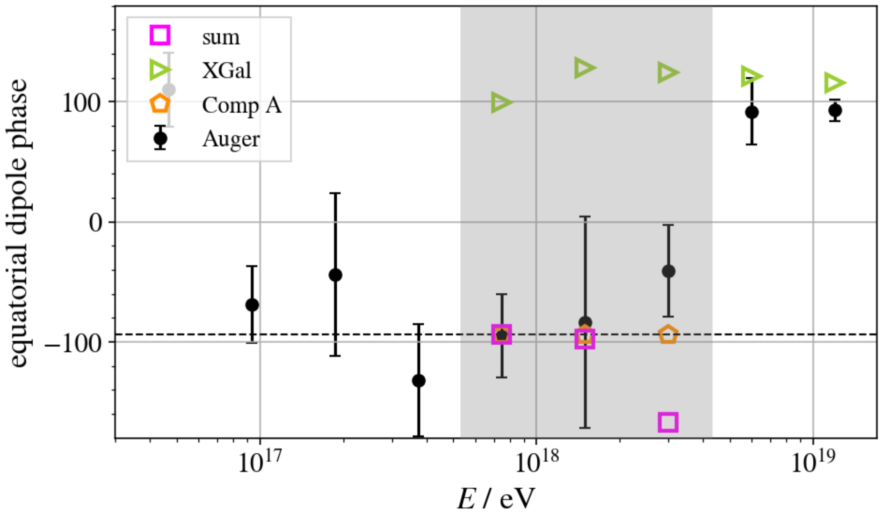
Transition at second knee + Fe-tail

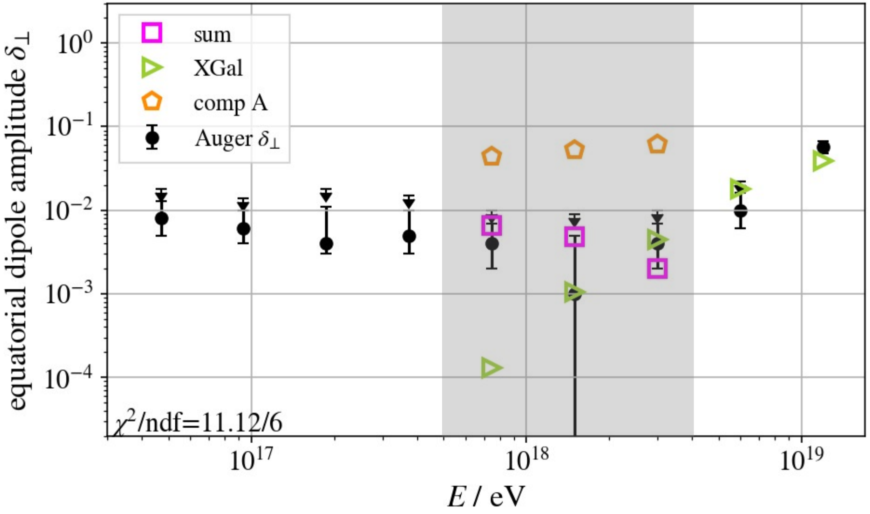
with a **~10% Fe-tail of Component A**







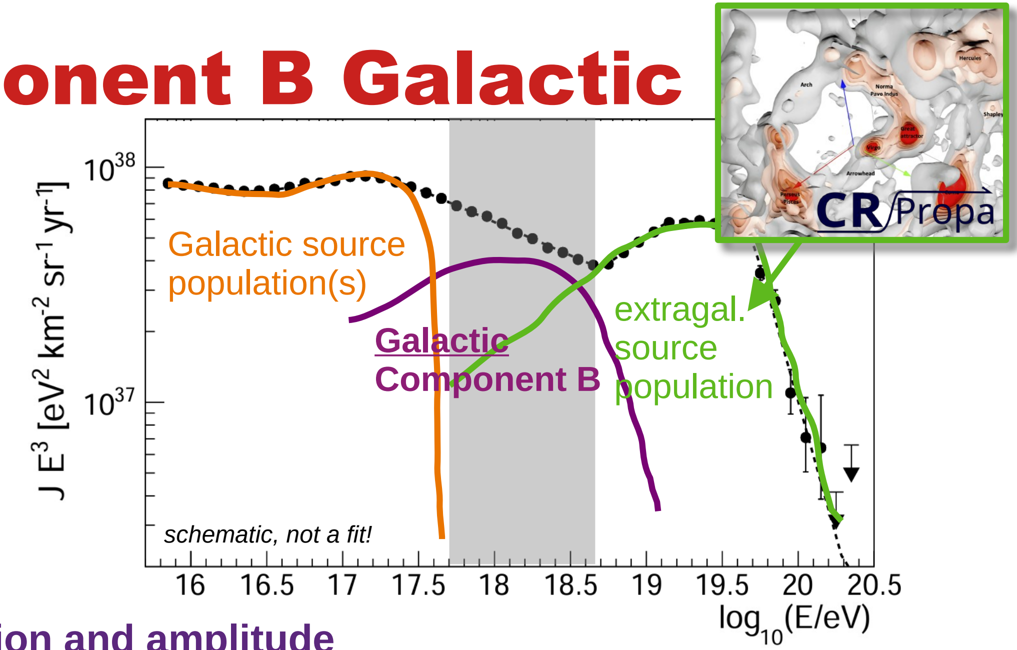




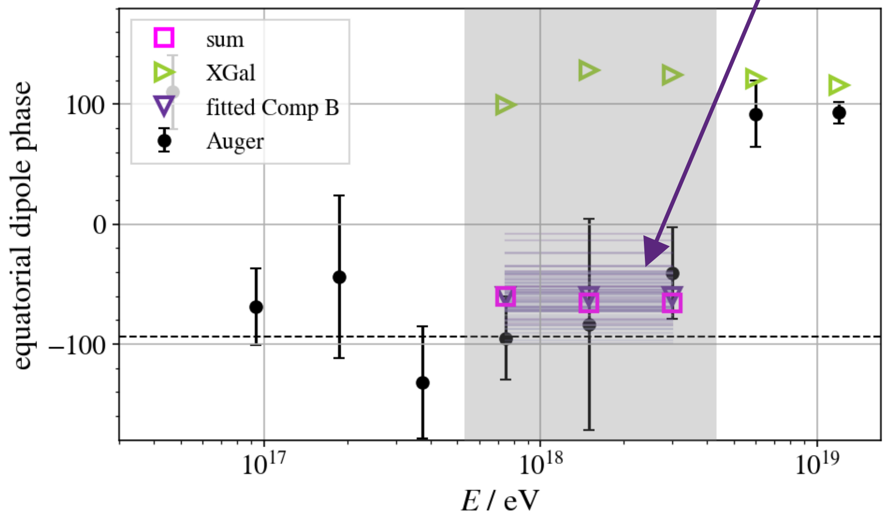
Transition at ankle: Component B Galactic

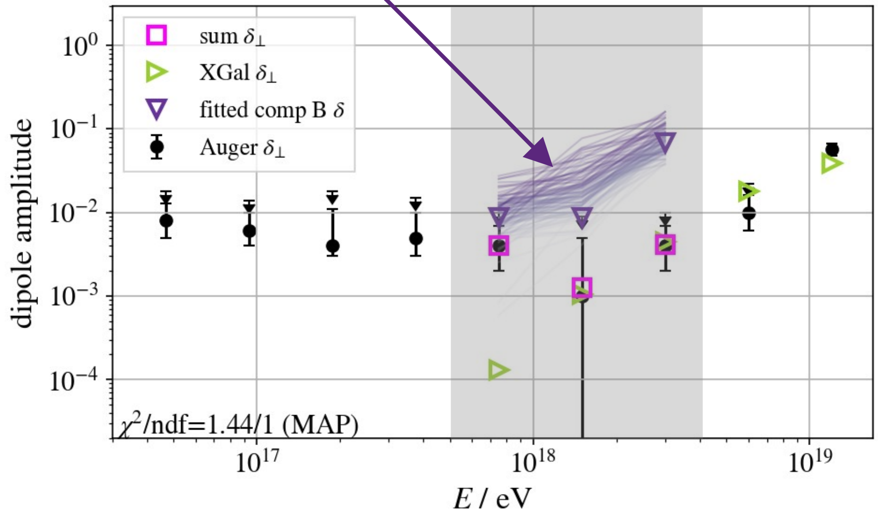
data can be described excellently by Galactic component B with:

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



fit of Component B direction and amplitude





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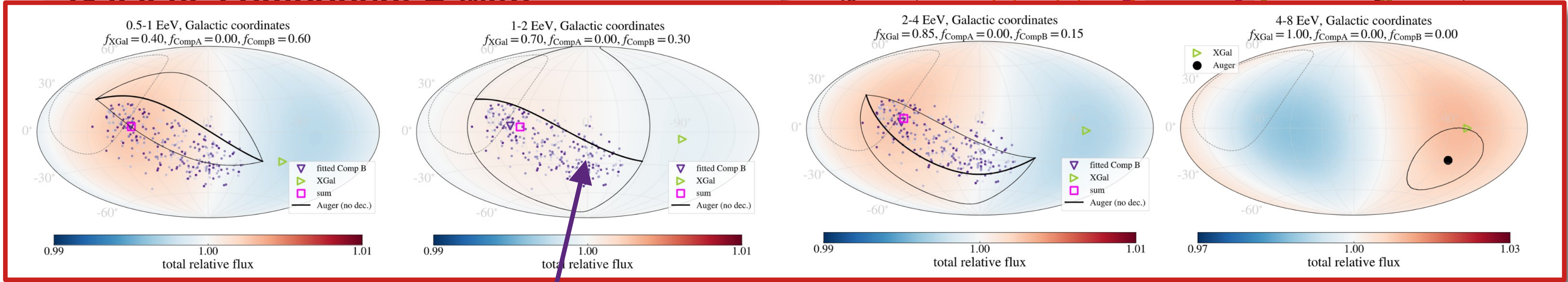

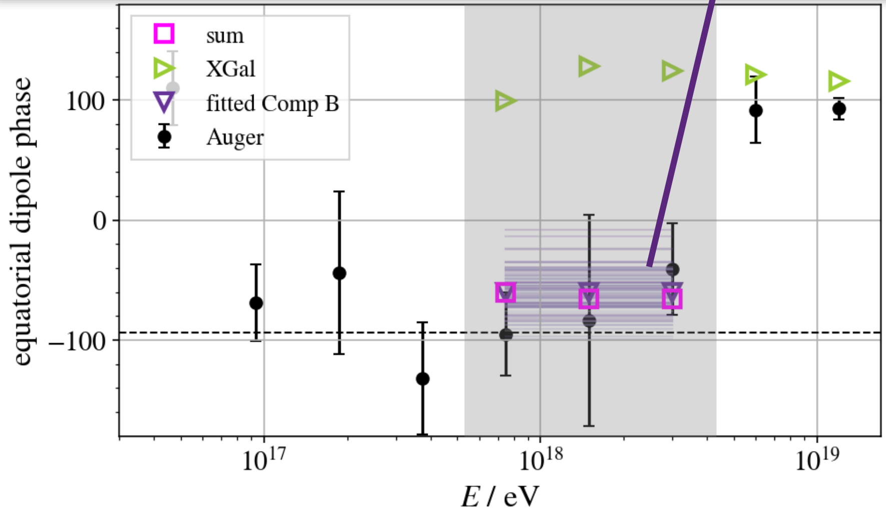

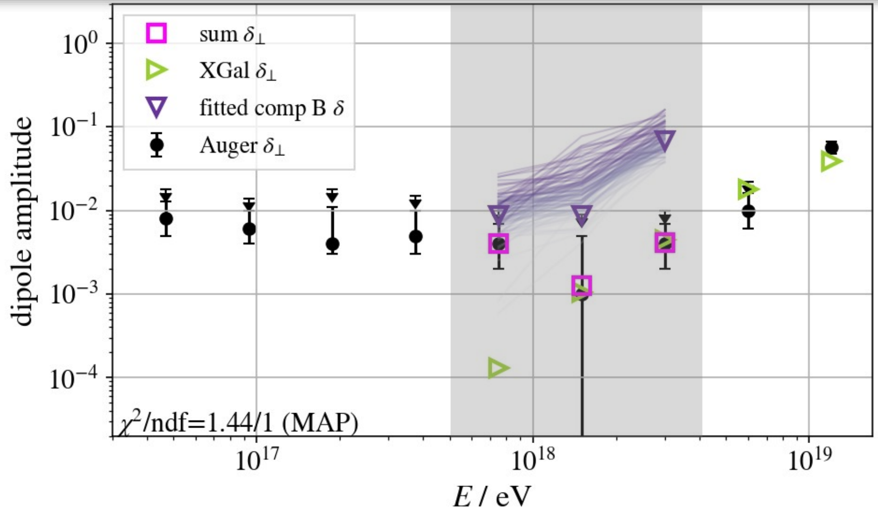

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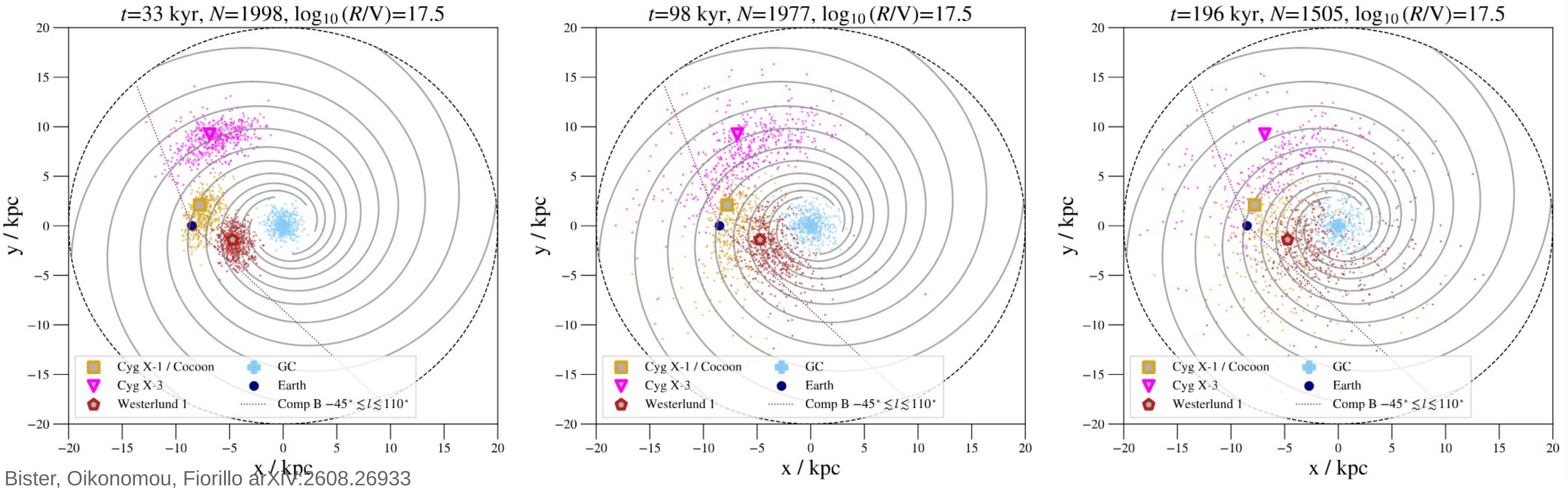
CRPropa simulations of CRs from prominent Galactic γ-ray sources in preferred directions:

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



Bister, Oikonomou, Fiorillo arXiv:2608.26933

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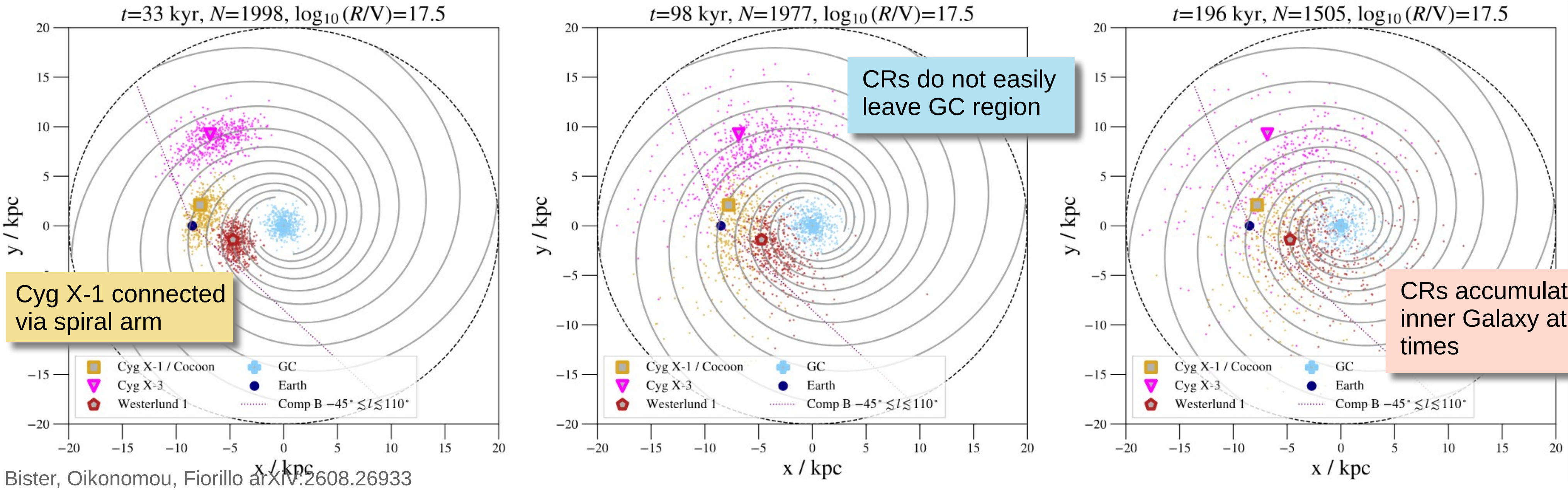

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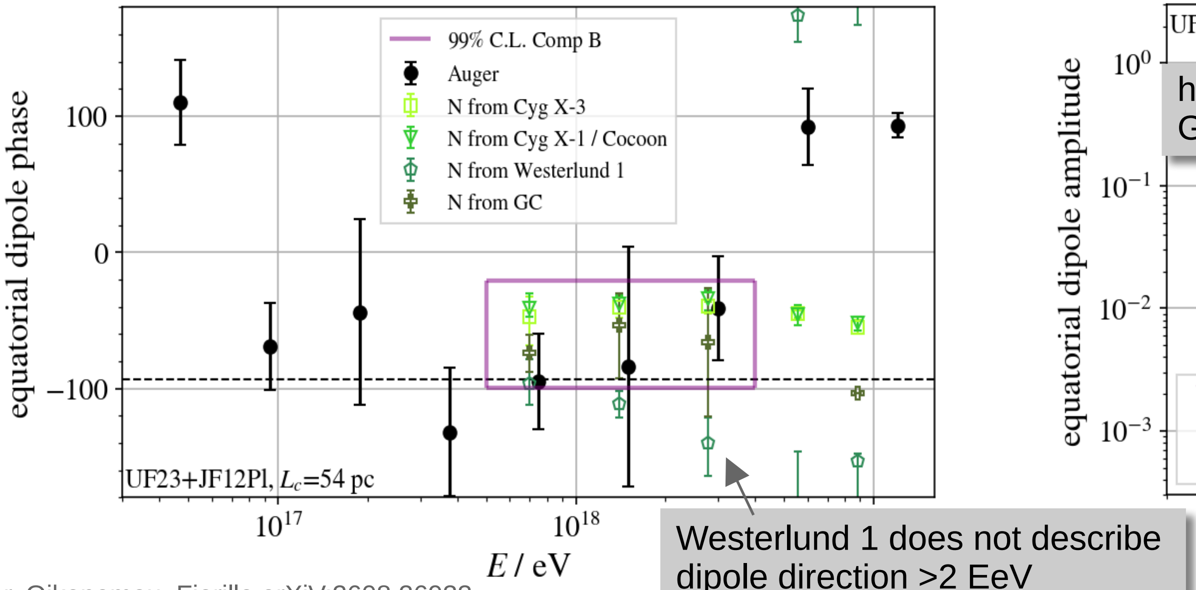

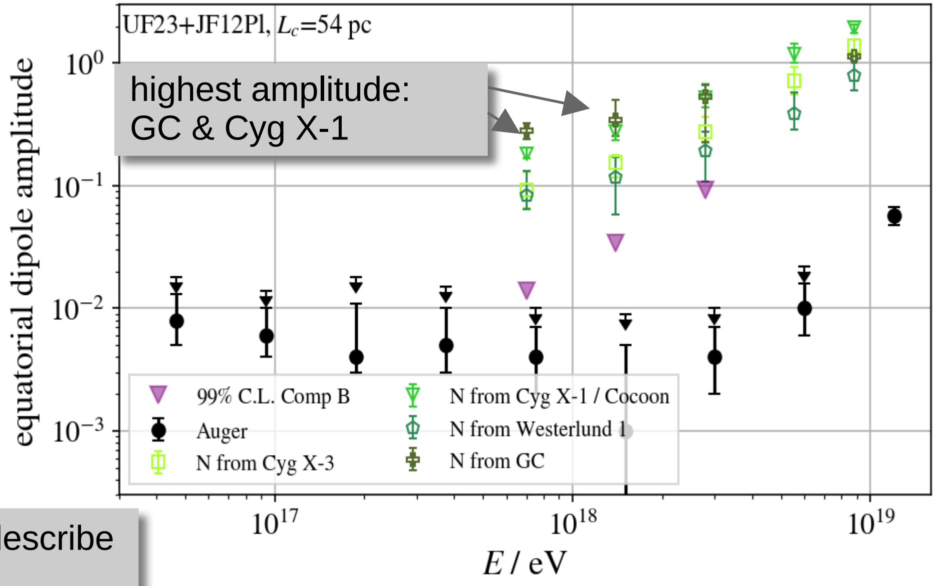

Bister, Oikonomou, Fiorillo arXiv:2608.26933

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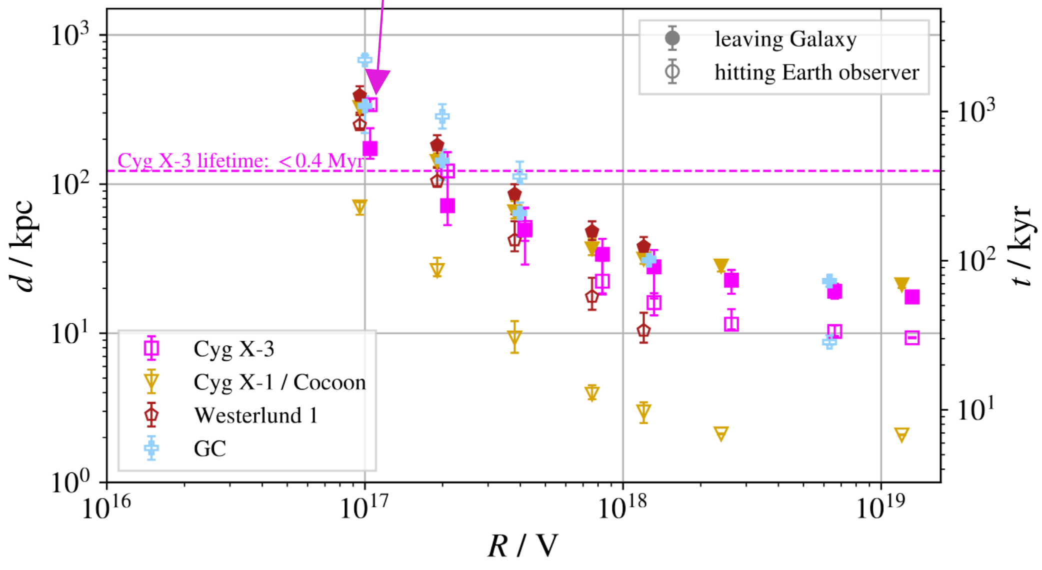
additional problems (see also backup):

- for Cygnus X-3, **propagation time** of > 1 Myr at 0.1 EV **exceeds lifetime** of ~0.1 Myr



diffusive ***ballistic***

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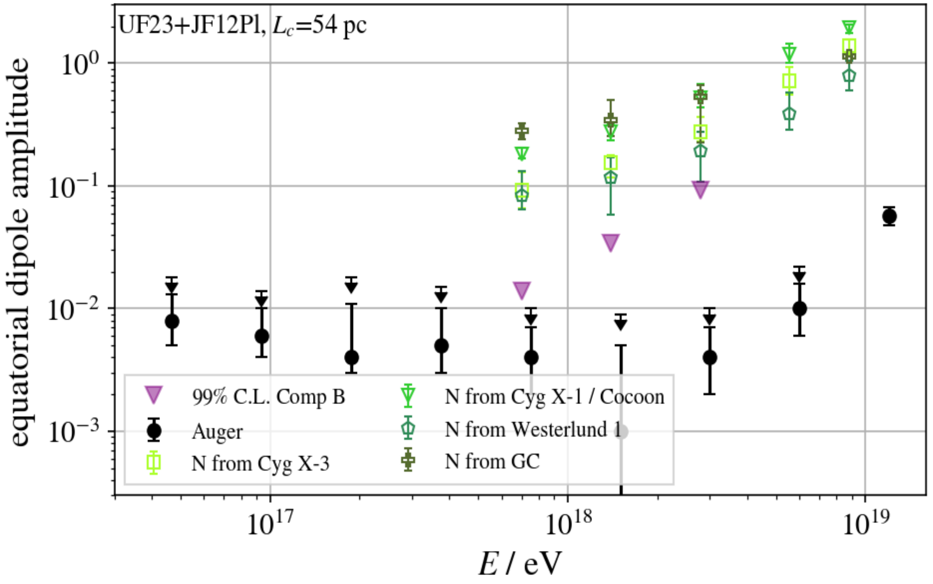

Bister, Oikonomou, Fiorillo arXiV:2608.26933

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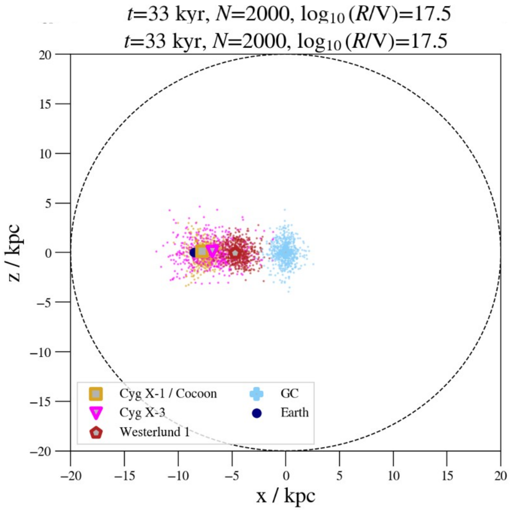

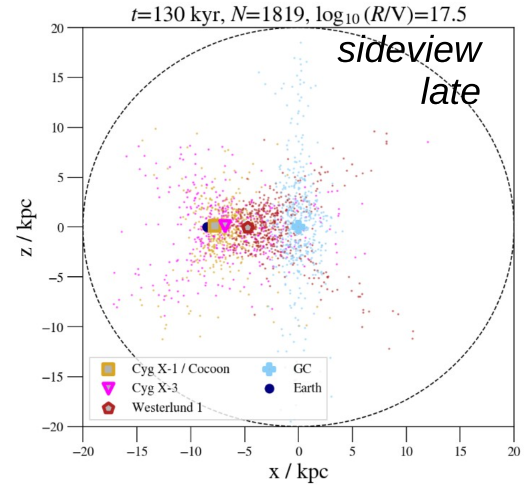

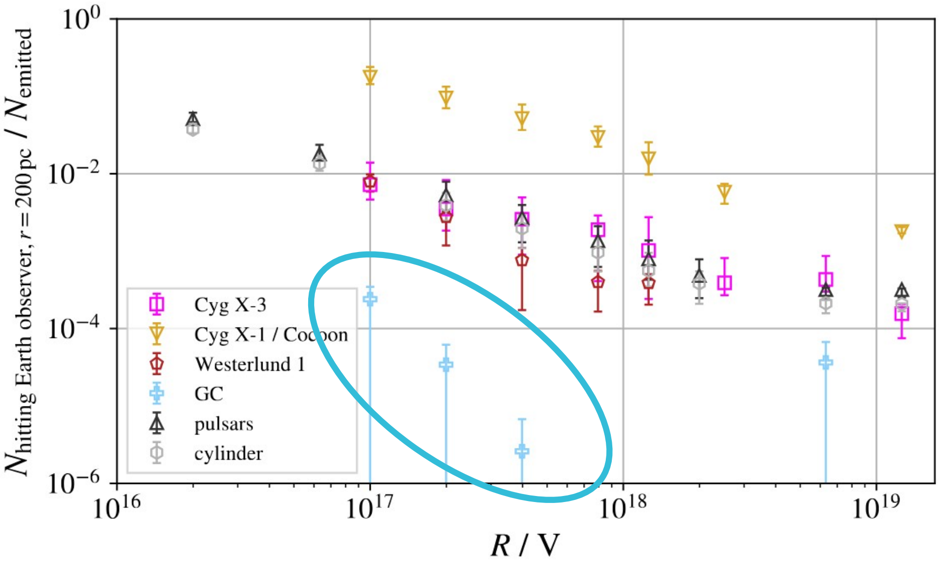

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- **<u>energetics:</u>**
  - source luminosities not sufficient for most sources given simulation hit rates (only for Cygnus OB2)
  - H / He-fluxes of the source overshoot spectrum by factor ~3-6 at lower energies (assuming Wolf-Rayet / solar composition)
  - ➔ see talk by Foteini

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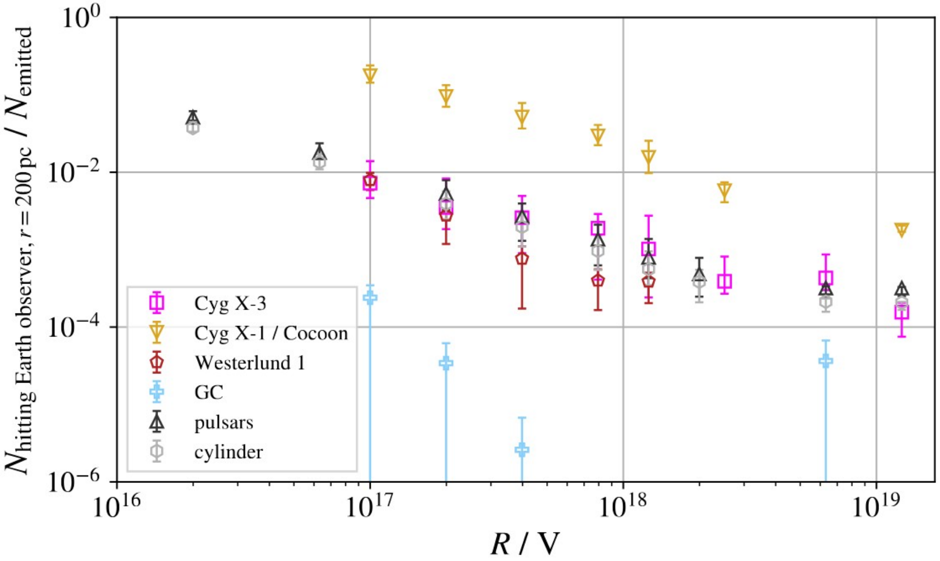

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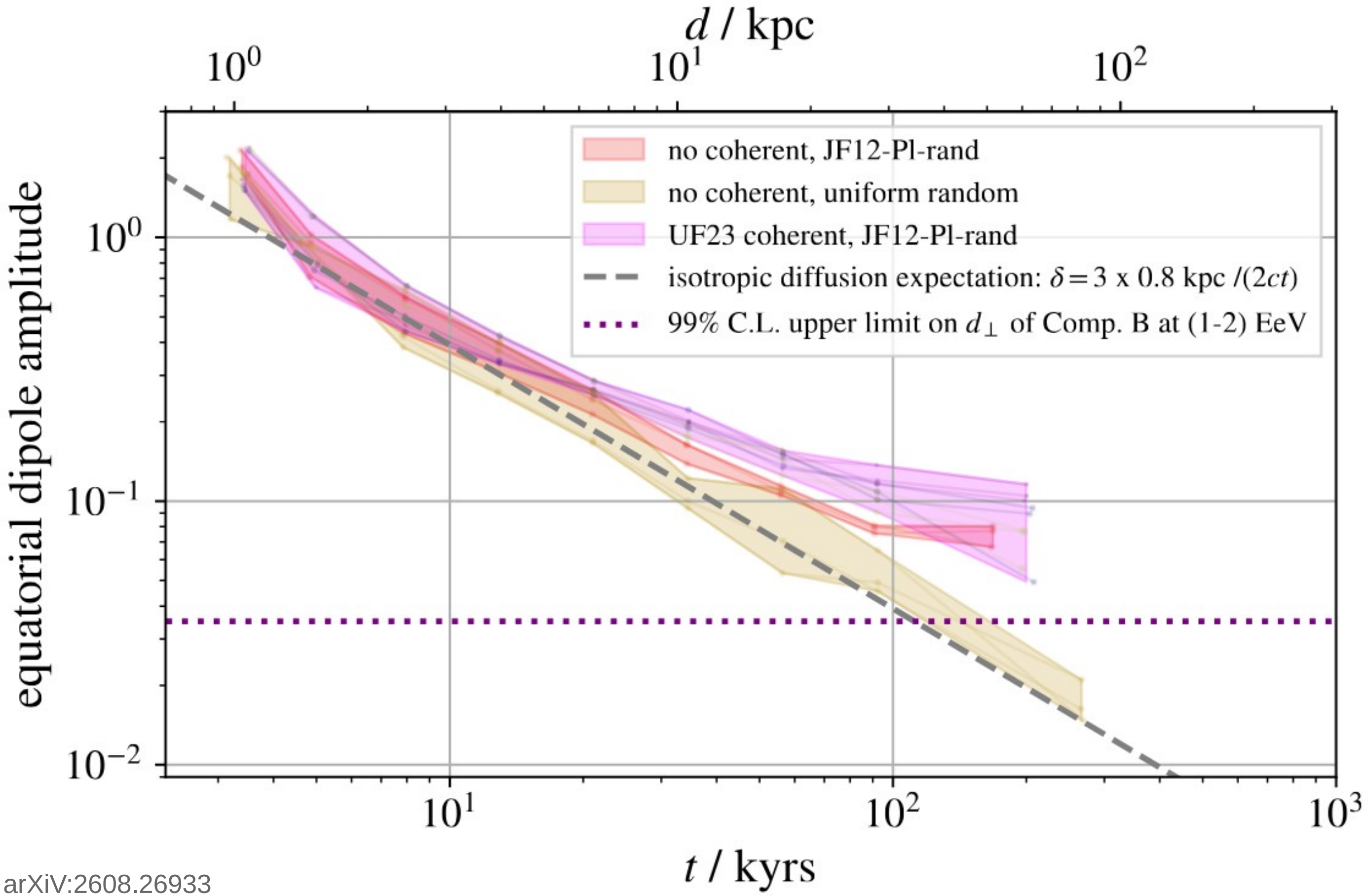
The observed flux of ~40% intermediate elements at ~1 EeV cannot be explained by a steady Galactic source.

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

Bister, Oikonomou, Fiorillo arXiV:2608.26933

Could a nearby transient be the source of Comp. B?

- dipole amplitude expected to decrease with time in fully diffusive regime: $\delta = \frac{3\,d_s}{2\,c\,t}$
  - reproduced this for uniform random field at log10(R/V)=17.3, SNR at 0.8 kpc distance



Bister, Oikonomou, Fiorillo arXiV:2608.26933

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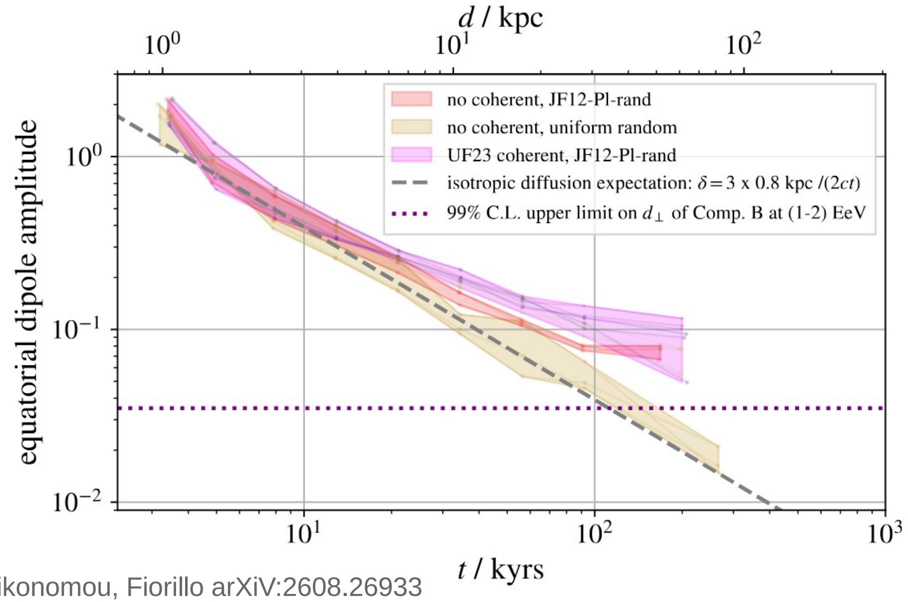
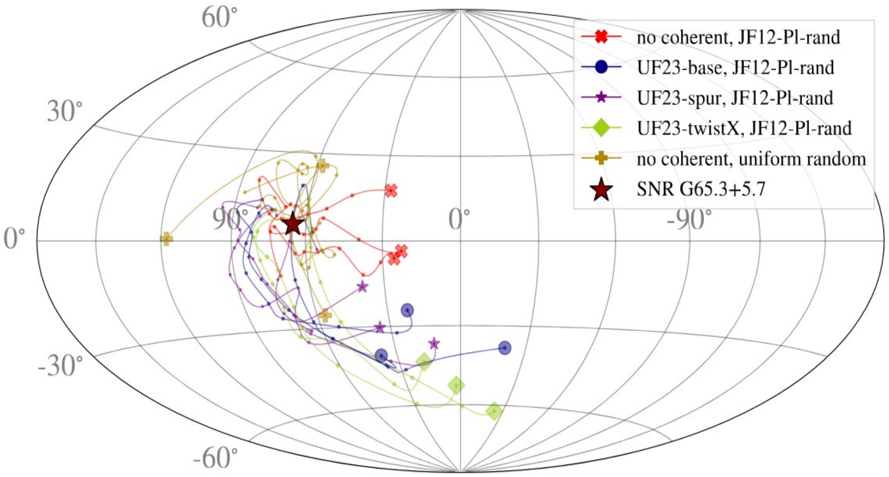
  - ➔ reproduced this for uniform random field at log10(R/V)=17.3, SNR at 0.8 kpc distance
- but: for radially decaying random field, a **residual dipole remains at late times**
  - **always pointing toward GC, source direction info lost**
  - due to accumulation in inner Galaxy
  - coherent GMF additionally increases amplitude

➔ **10% residual dipole at late times too large to be compatible with upper limits on Comp. B**





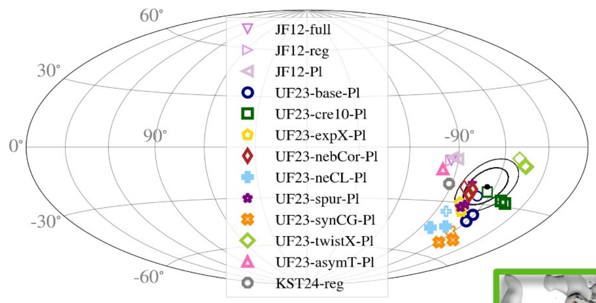
Bister, Oikonomou, Fiorillo arXiV:2608.26933

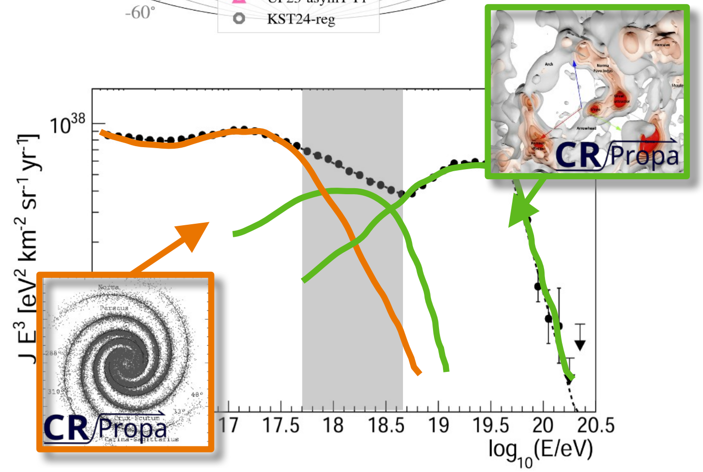
→ *for other source locations see backup*

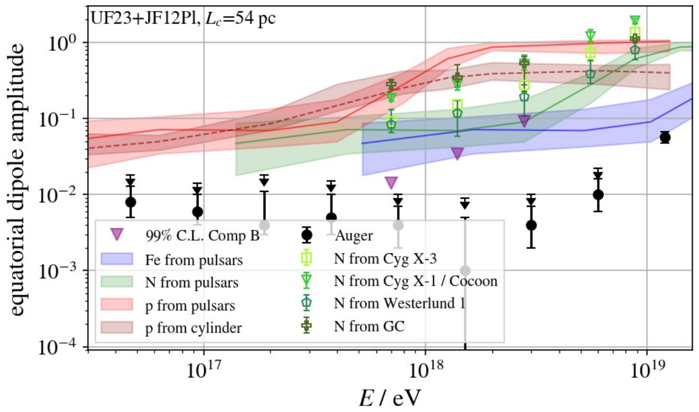
Summary: sources of UHECRs

- **above the ankle:**
  - 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
  - $\gtrsim$ 40 EeV (transients in) nearby candidates like **Centaurus A can explain Centaurus excess** (few percent to 100% signal fraction possible)

- **transition from Galactic to extragalactic sources** likely happens **at the second knee**
  - **~10% Galactic iron tail** at 1 EeV necessary to explain dipole measurements
  - individual and populations of Galactic sources of dominant intermediate (and even heavy) elements **overshoot dipole** amplitude at ~1 EeV by factor ~4 (source distribution) to ~30 (Galactic Center)

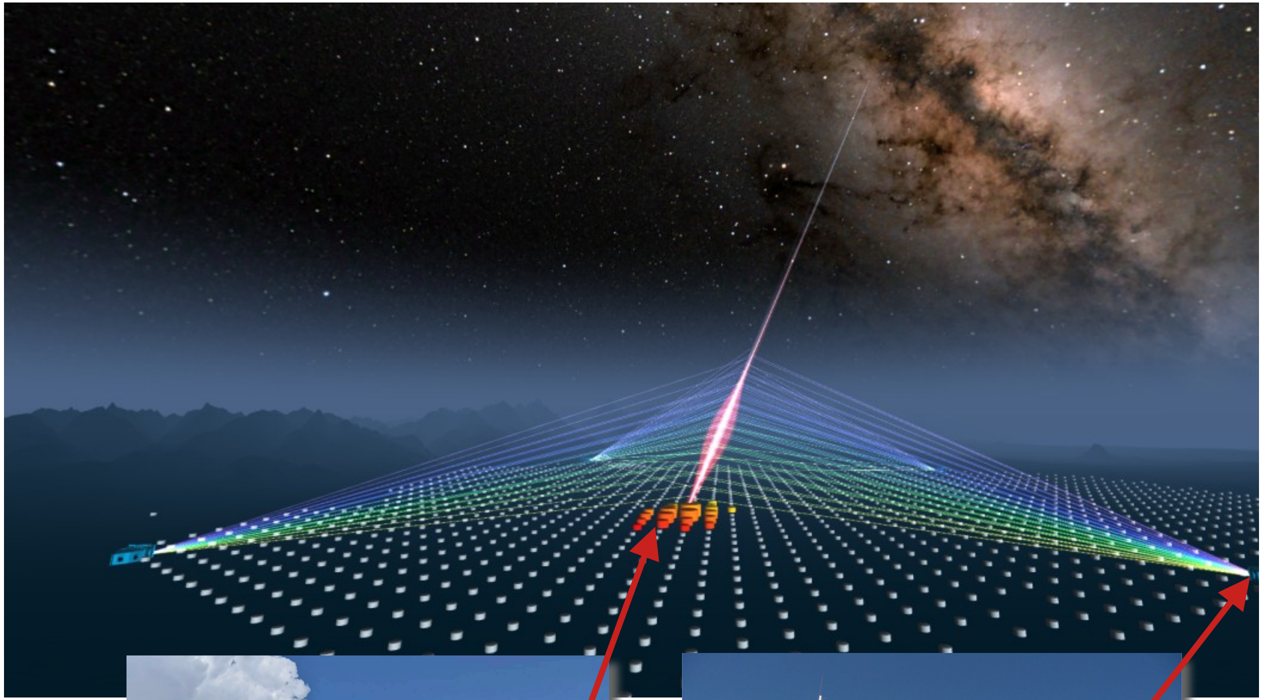






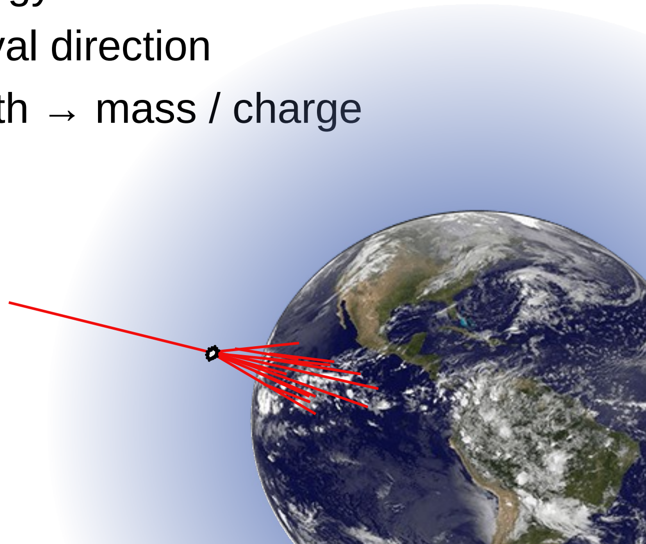
backup

Measuring extensive air showers at the Pierre Auger Observatory

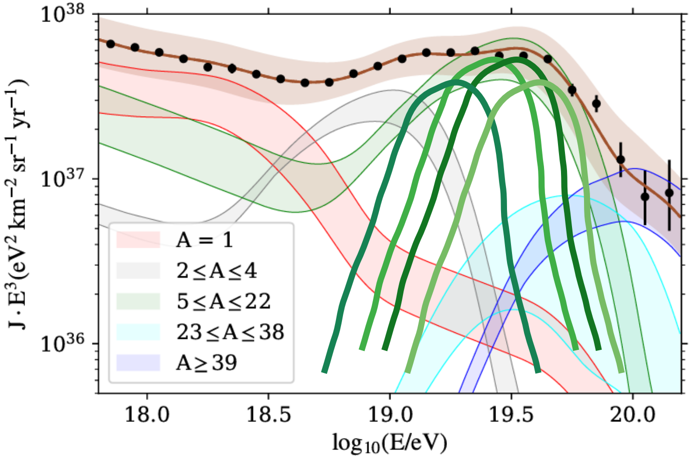


- **Pierre Auger Observatory:**
  - close to Malargüe, Argentina
  - 3000 km^2
    → largest Observatory in the world
  - 1660 surface detector stations,
    4 fluorescence detector sites

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



Energy spectrum and mass composition

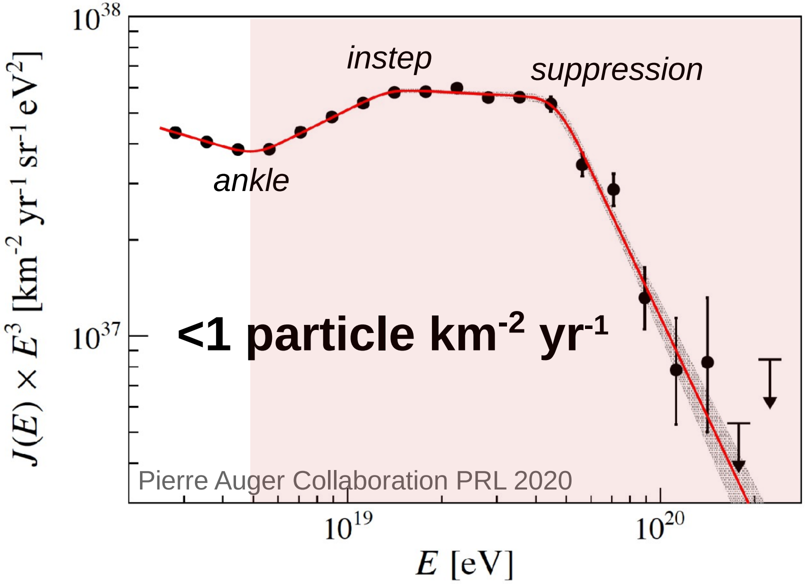


fit model to energy spectrum & mass composition data:

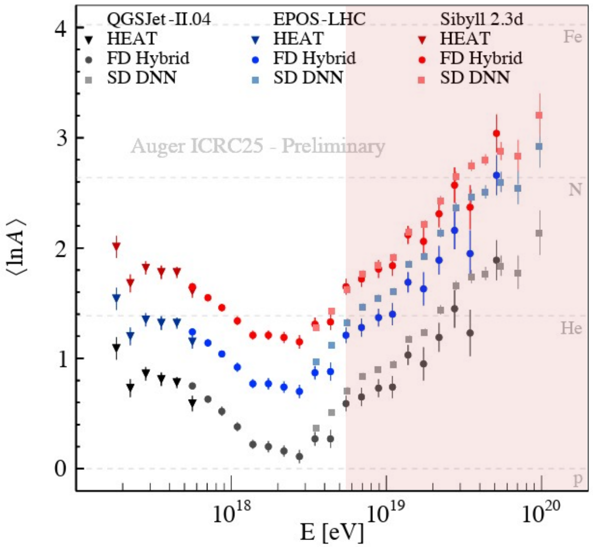
- **homogeneous & extragalactic** sources dominating above ankle
- **acceleration ∝ Z** → mass composition gets heavier
- constrains spectrum and composition emitted at sources:
  - hard spectrum & fast change of mass groups, mixed composition **& almost identical source max. energy**

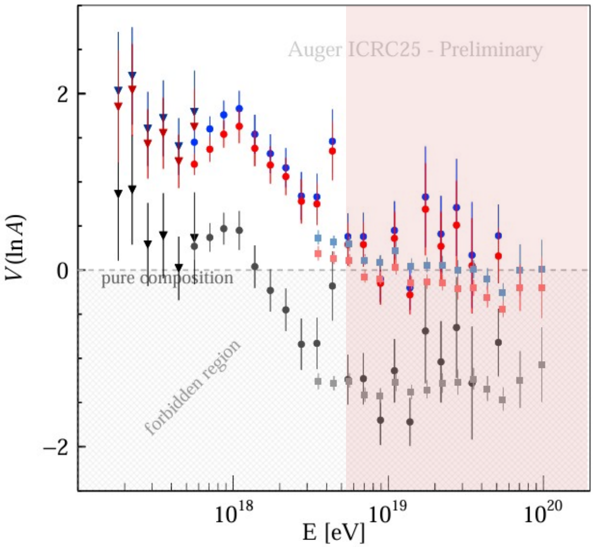
Pierre Auger Collaboration, JCAP 2023

Ehlert, Oikonomou, Unger, PRD 2023



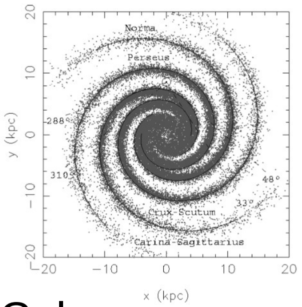
Pierre Auger Collaboration PRL 2020

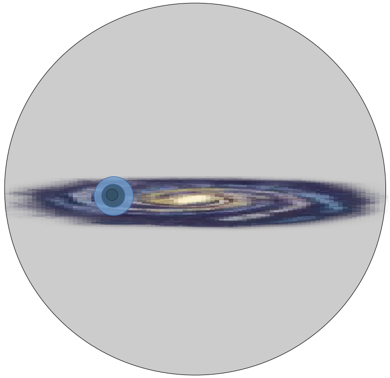




Propating Galactic CRs with CRPropa

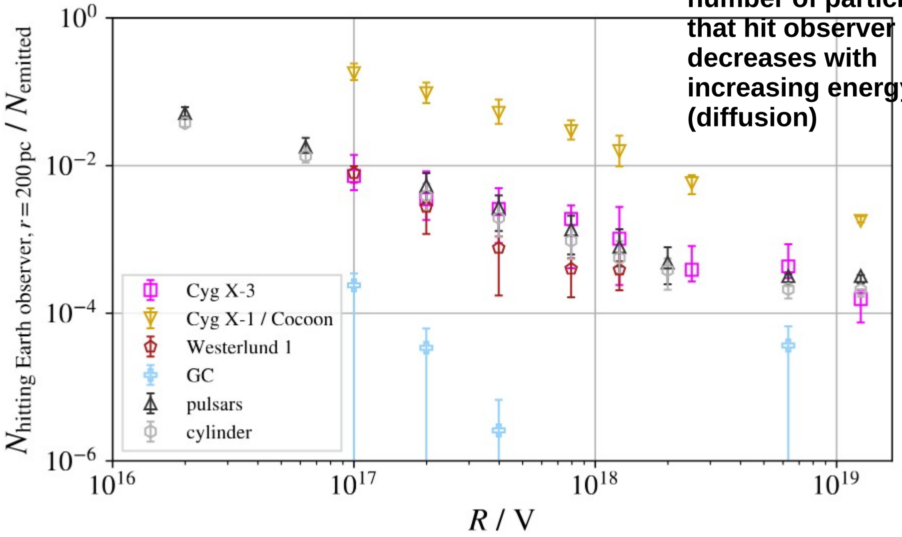
- propagate CRs with different rigidities in the **UF23 GMF model suite**
  - for now: use JF12+Planck random field model with L_c=54 pc
- **sources: GC, Cygnus X1, Cygnus X3, Westerlund 1, nearby SNR, cylinder** (h=200 pc), **pulsar distribution**





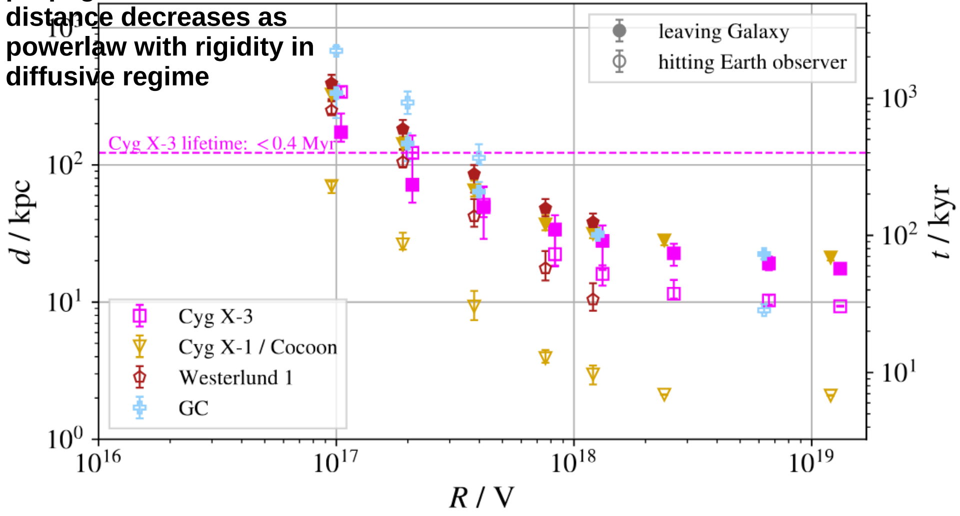
- observers at Earth position with radii 50 pc, 100 pc, 200 pc, 500 pc
- observer with radius 20 kpc around GC that detects particles leaving Galaxy

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



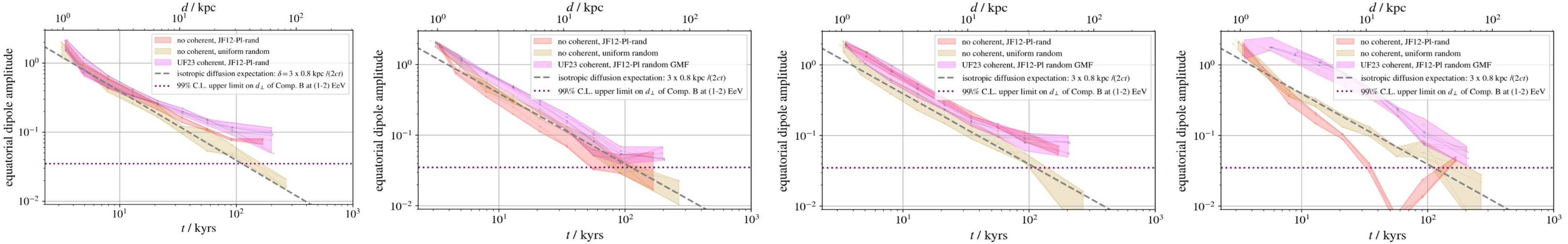
uncertainties always include 8 GMF models and up to 3 random seeds

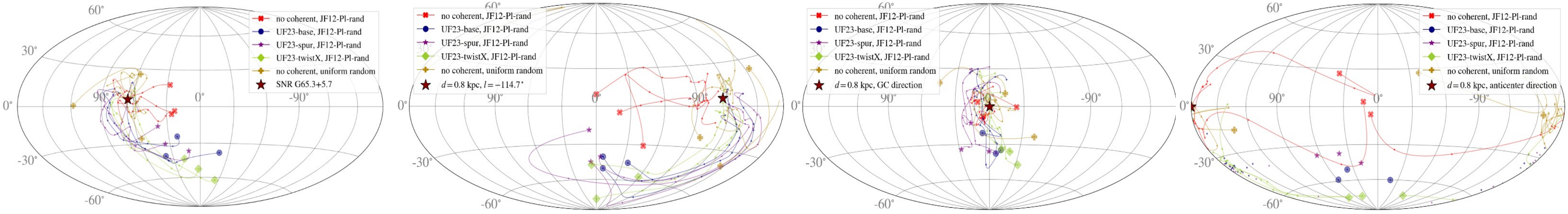
propagation time / distance decreases as powerlaw with rigidity in diffusive regime



Nearby transient source as Component B?

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

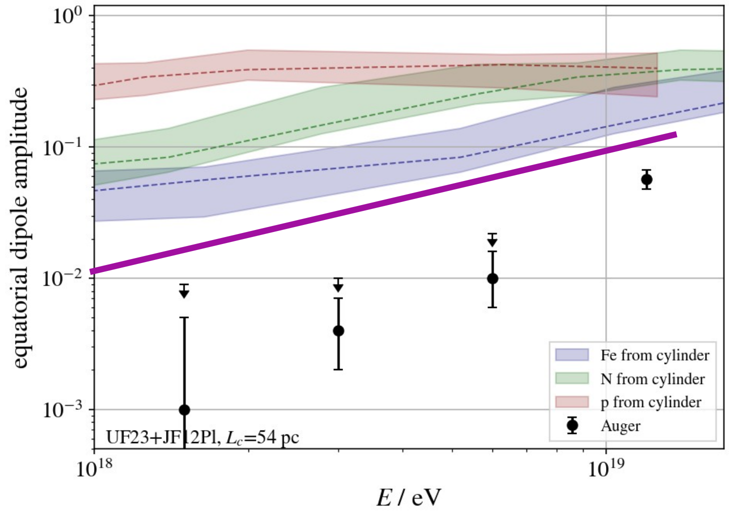




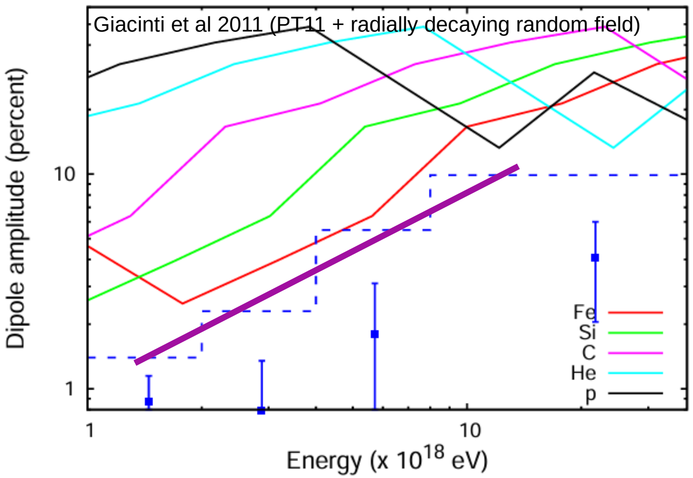
log10(R/V)=17.3

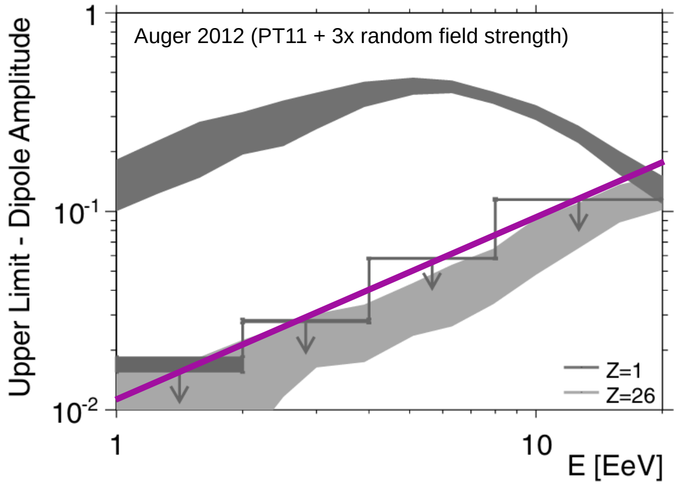
- **residual dipole at late times too large to be compatible with Component B amplitude**
- **due to accumulation of CRs in the inner Galaxy: decreasing random field strength allows faster escape in outer Galaxy**
- **note: source location information lost at late times**

Dipole moment: comparison to previous works



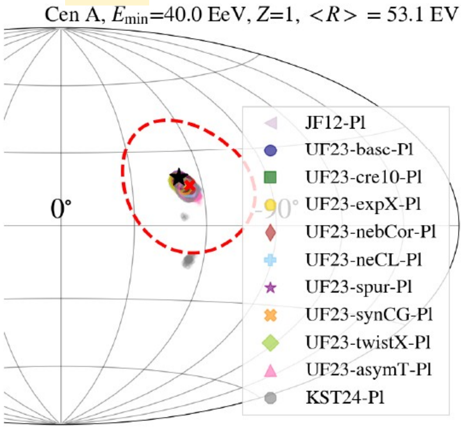
- all based on **homogeneous cylinder of sources,** h~200 pc, r~20 kpc
  - before: backpropagation, now: forward propagation with r_{obs}=200 pc
- **agree quite well:**
  - **iron in rough agreement with old limits, but does not agree with newest data**
  - maximum dipole moment ~30-50% due to homogeneous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





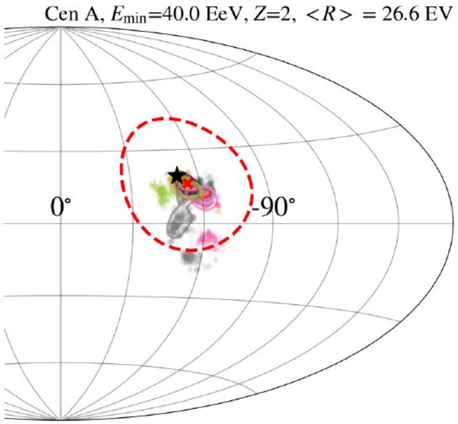
UHECRs from Cen A & magnetic field deflections

Z=1



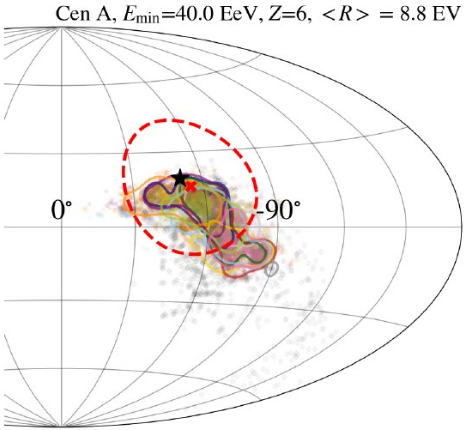
agrees well with excess direction ✔

Z=2



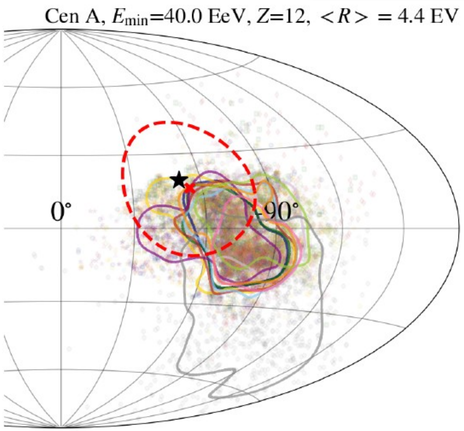
agrees well with excess direction ✔

Z=6



still fits for some GMF models ✔

Z=12

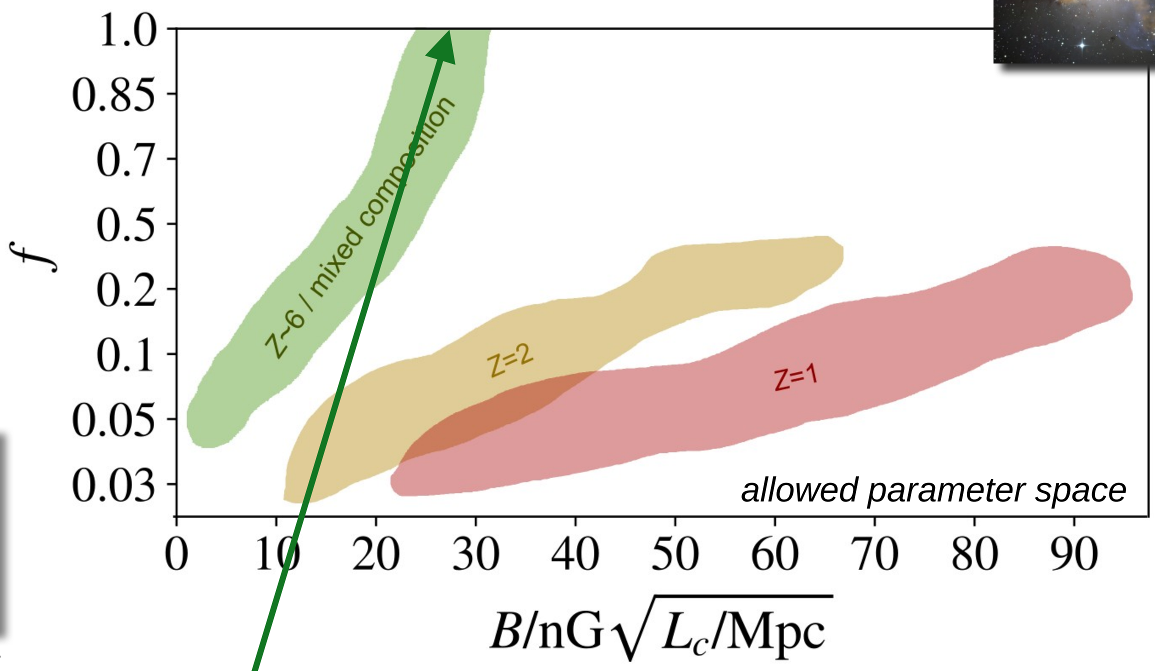


deflections too large ✘

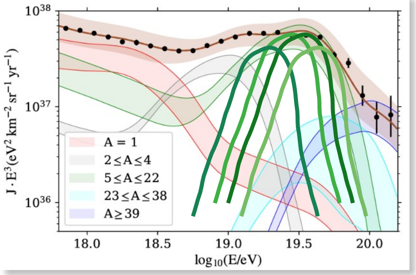
- charge needs to be **Z ≲ 6** to be compatible with excess direction for Cen A
  - for KST24 GMF model, only Z=1 compatible
- figures are for **extragalactic magnetic field zero** → clearly does not reproduce angular scale!
  - ➔ add 2d Gaussian distribution to mimic turbulent EGMF: $\vartheta = 29^\circ \frac{\mathrm{EV}}{E/Z} \frac{B}{\mathrm{nG}} \frac{\sqrt{d L_c}}{\mathrm{Mpc}}$
  - ➔ note: „extragalactic“ here means between Milky Way & source

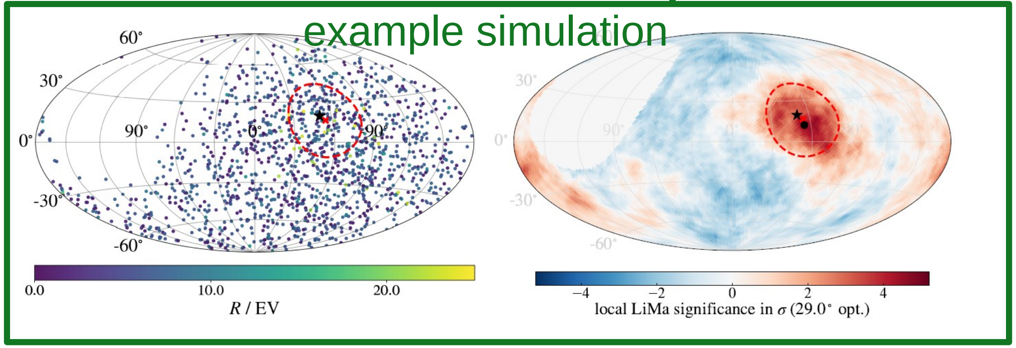
Constraints on the signal fraction & EGMF

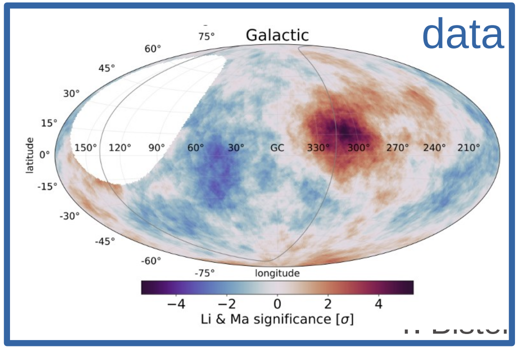
- can reproduce strength, size, direction & energy dependency of excess with Cen A as the source with **Z**$\lesssim$**6**
  - extragalactic magnetic field of zero not allowed
  - **best current constraints** for EGMF between Earth and Cen A
- signal fraction of Cen A up to **100%!**
  - would explain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



see also Mollerach & Roulet PRD 2024

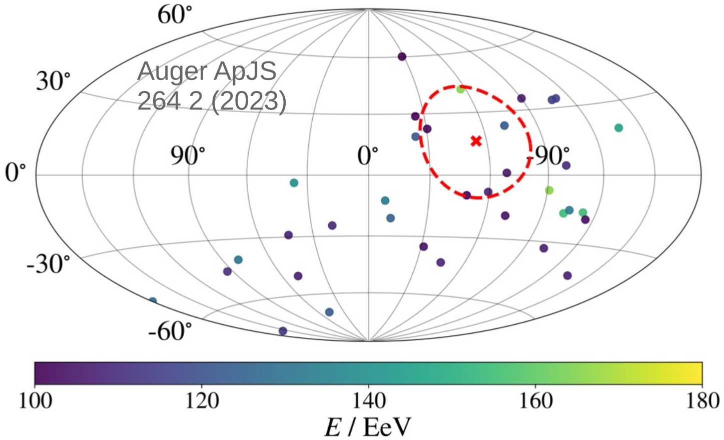




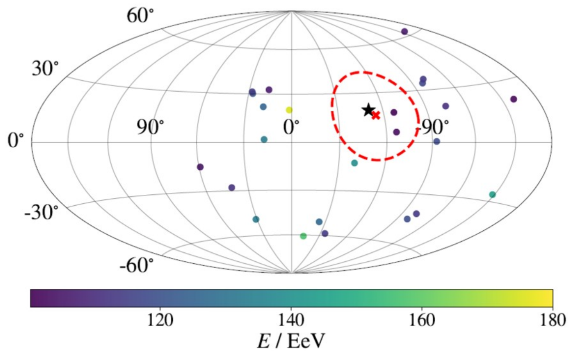


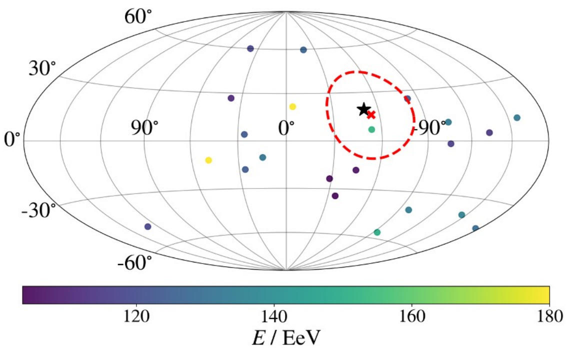
Cen A dominates sky - highest energy events?

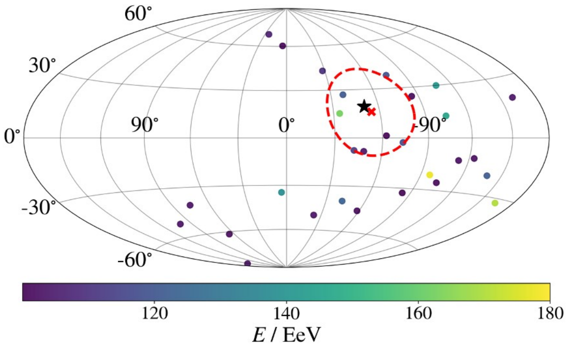
measured distribution of events, E>100 EeV



- **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

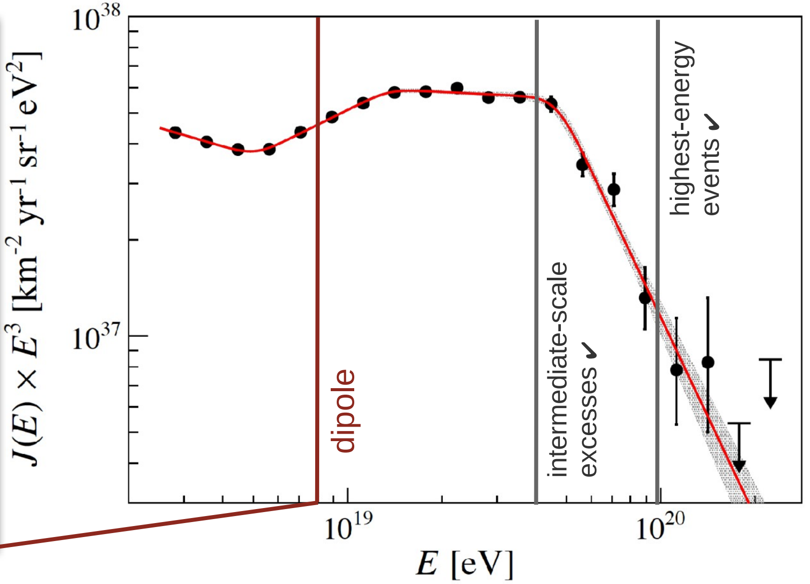
E>100 EeV ✔

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

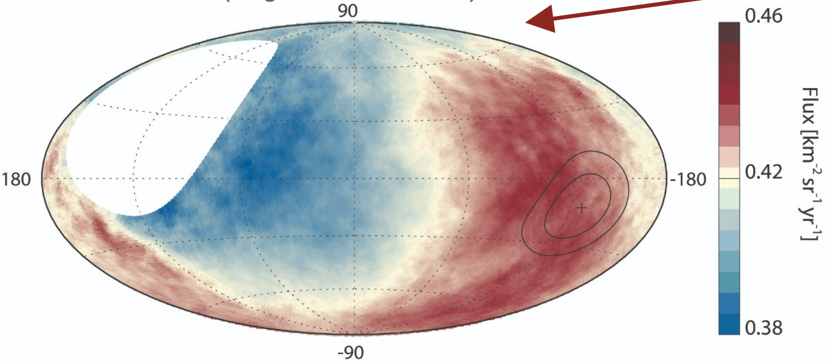
What about lower energies?

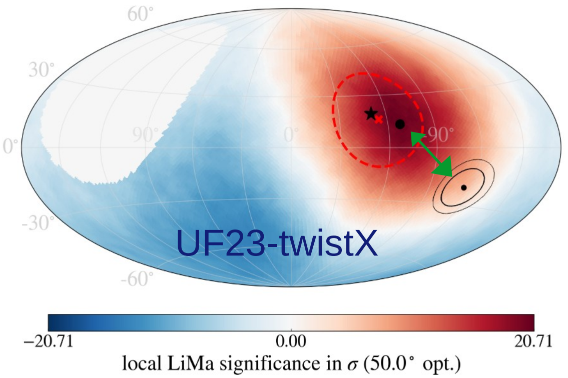
Cen A dominates sky - lower energies and dipole?

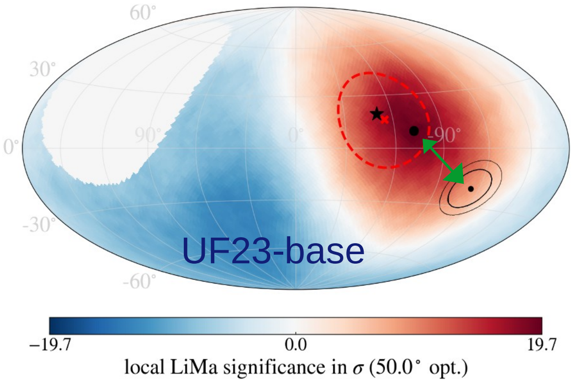
- extending Cen A-only simulations to lower energies
  - dipole flux measured >8 EeV not well reproduced by only Cen A as single source
  - but could structured EGMF work?
- **probably need other sources to explain data <30 EeV**
  - individual sources in the south (e.g. Fornax A), or following large-scale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



(Auger Science 2017)







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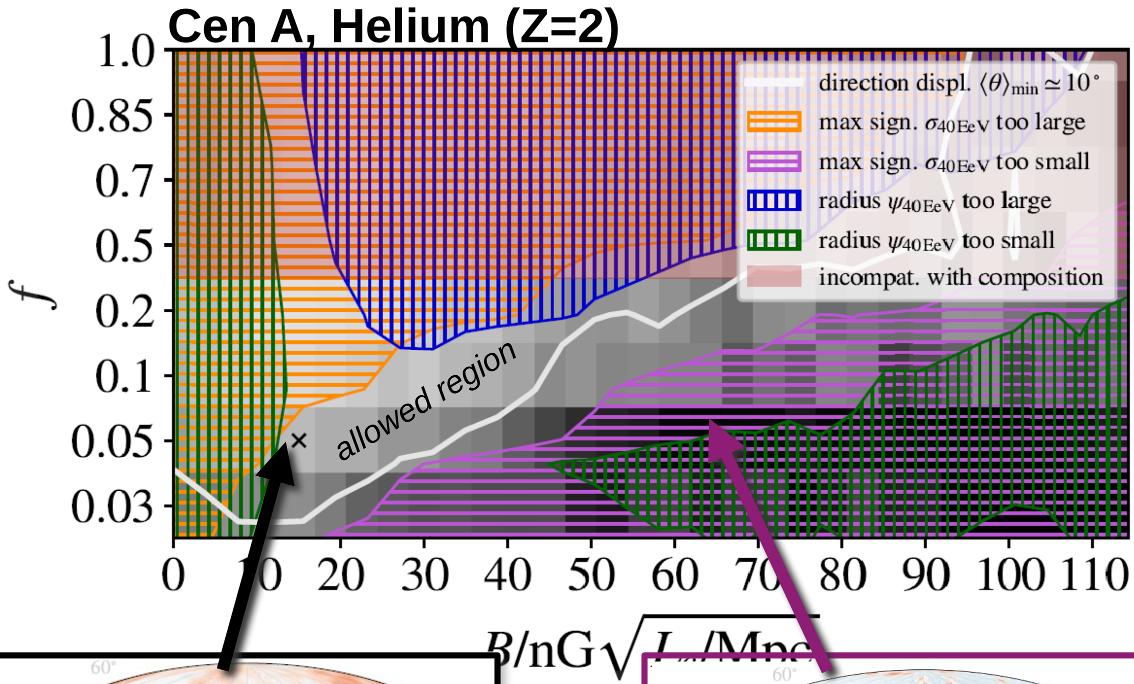
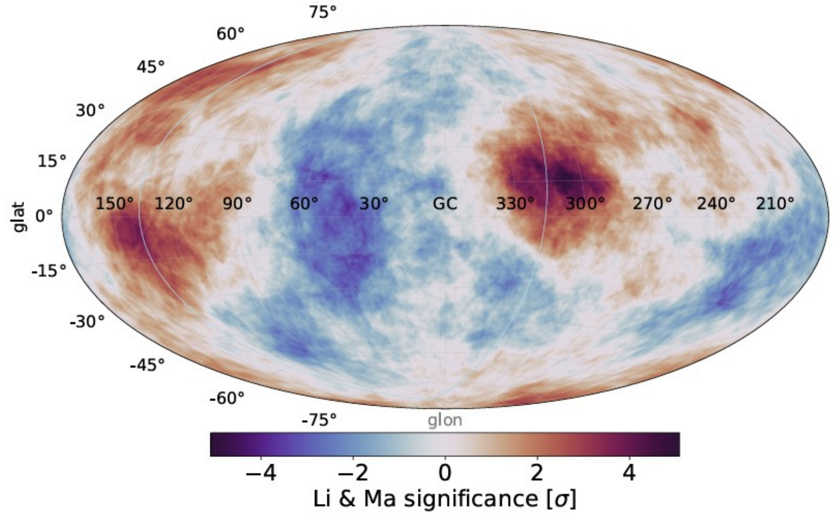
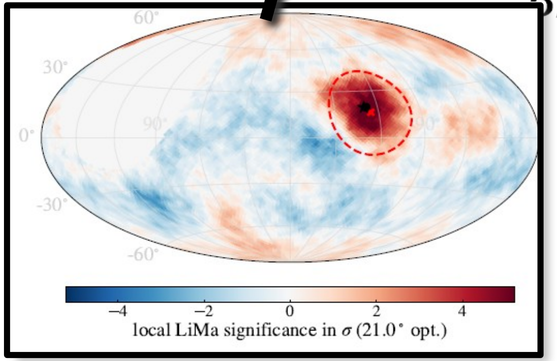
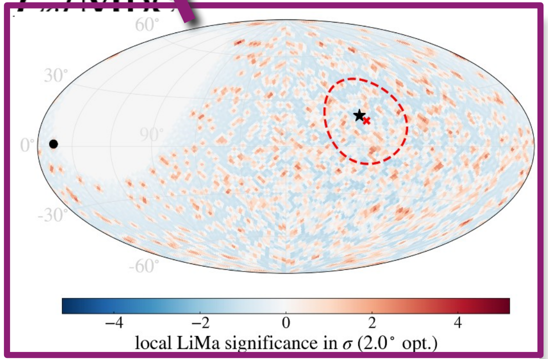
Conditions on signal fraction and EGMF

- for a specific source candidate & charge assumption:
  - ➔ produce 10 random simulations per Galactic magnetic field model
  - ➔ vary signal fraction f and EGMF parameter β_{EGMF}
- apply same analysis as on data and see which ones reproduce excess properties



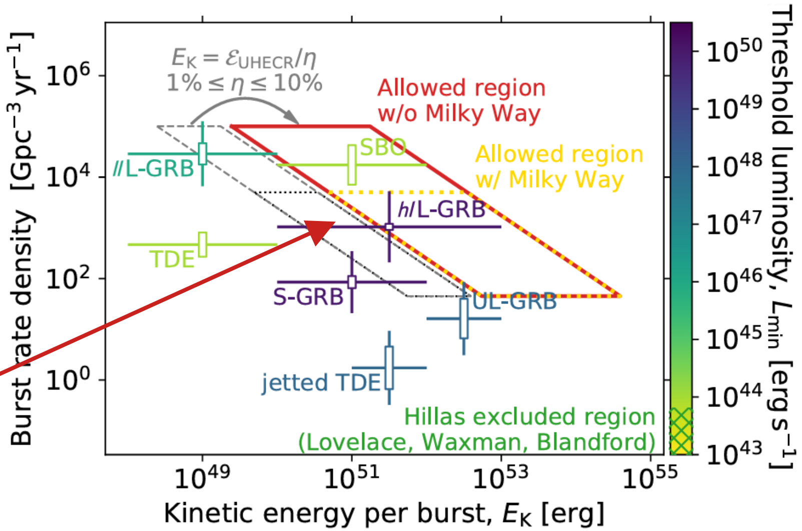


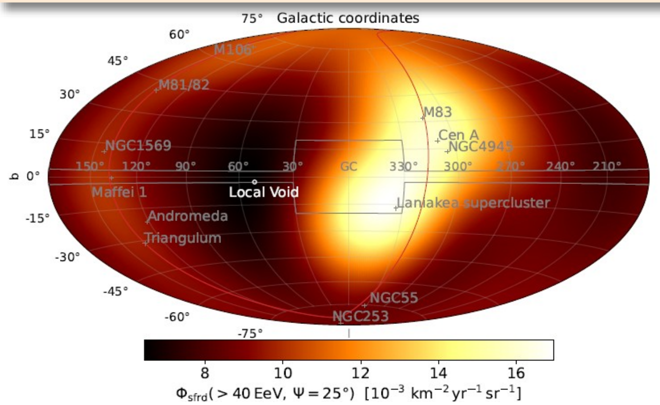


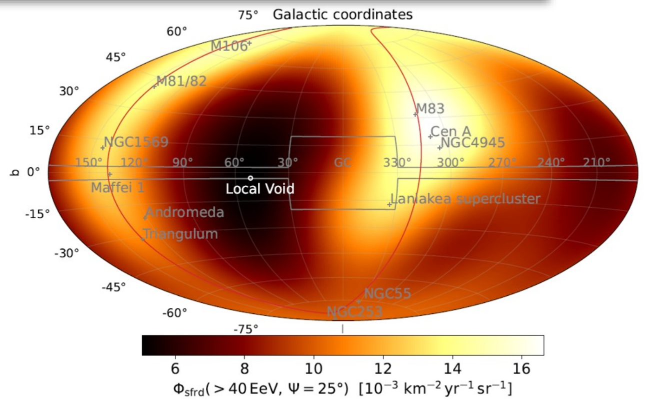


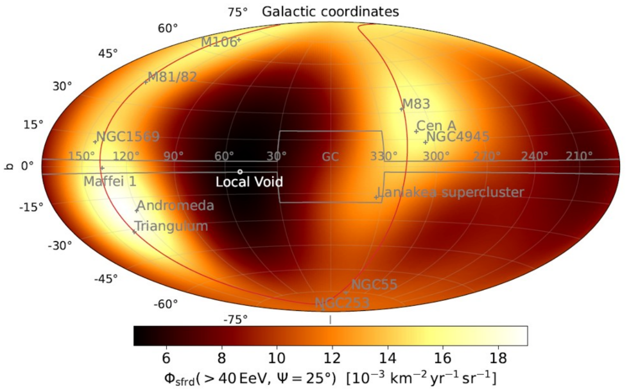
Transient or steady sources?

- 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