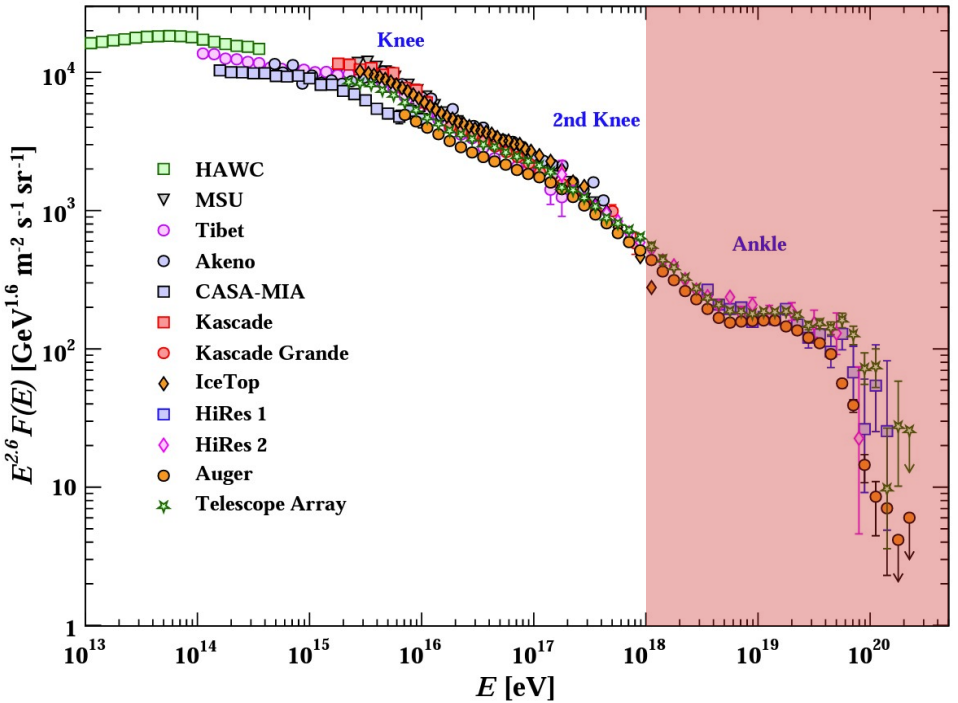
Searching for the sources of Ultra-high-energy cosmic rays

Teresa Bister
Lunteren, 03.11.2023

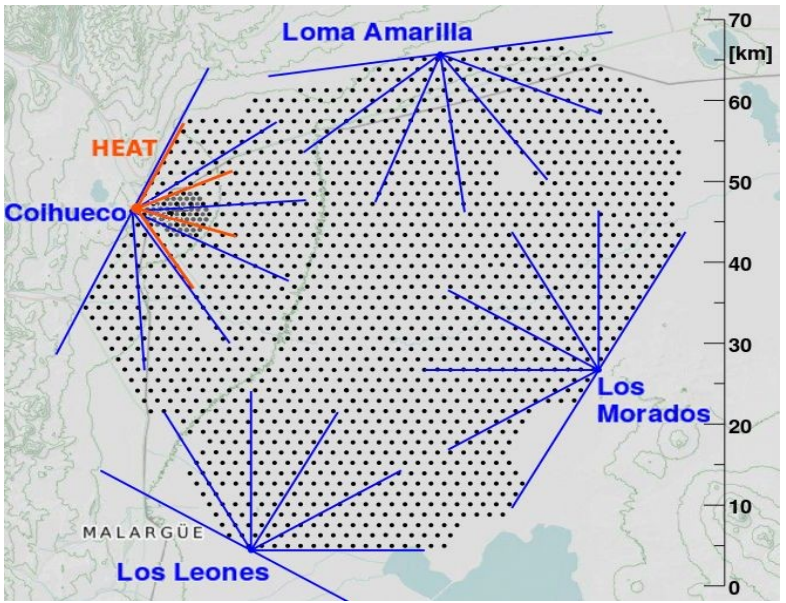
Radboud University

Ultra-high-energy cosmic rays (UHECRs)



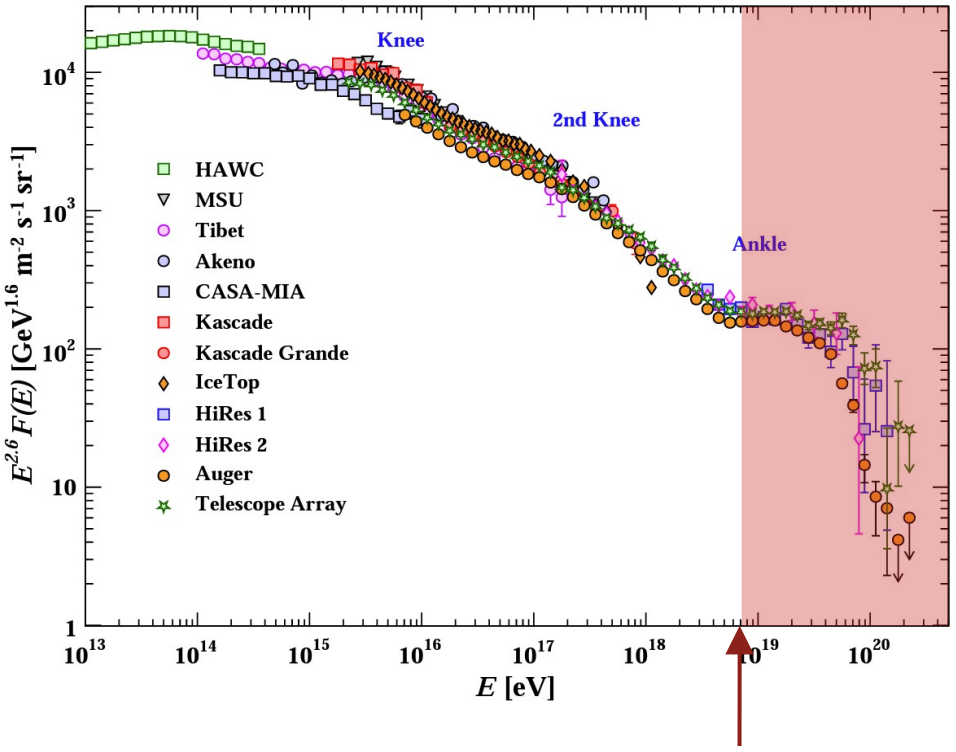
What are the sources of cosmic rays with energies > EeV?

→ study data by world's largest observatory: Pierre Auger Observatory in Argentina

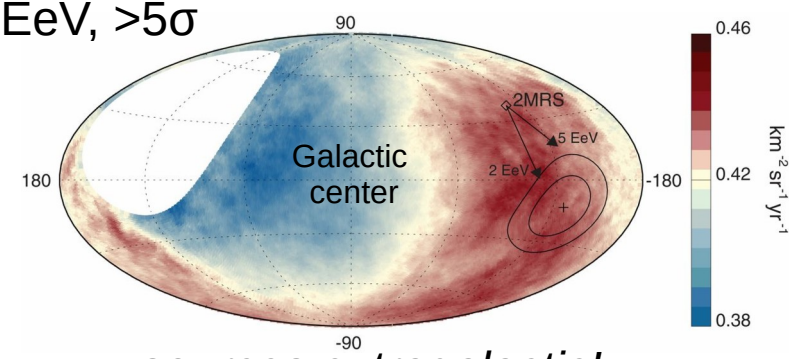


27 fluorescence telescopes
and 1660 water-cherenkov detectors

Ultra-high-energy cosmic rays (UHECRs)

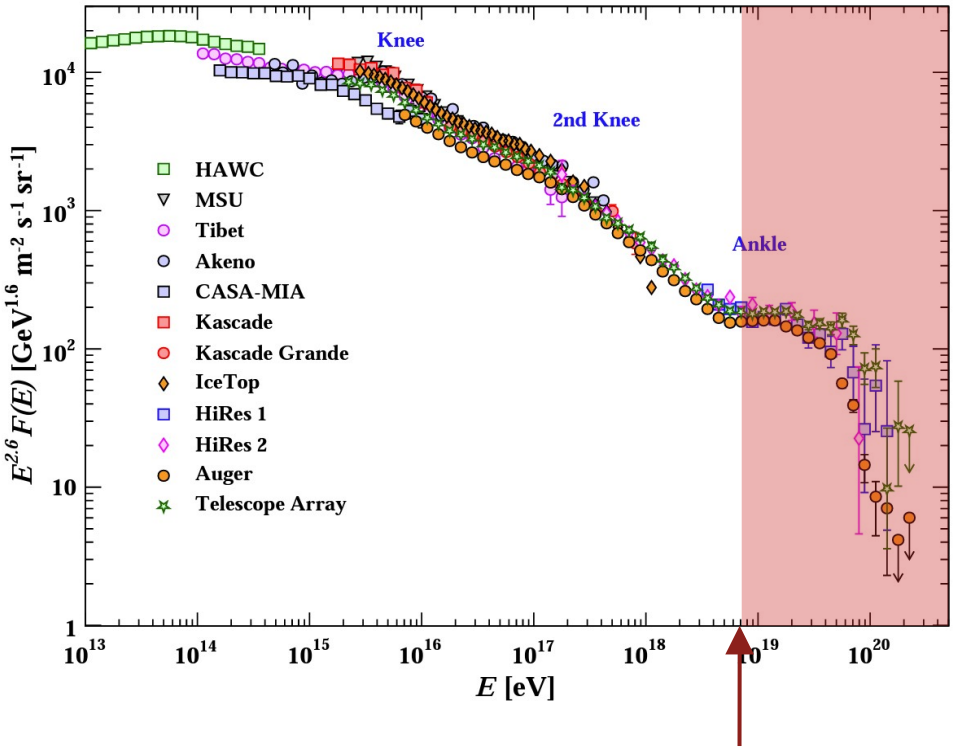


dipole > 8 EeV, >5σ



→ *sources extragalactic!*

Ultra-high-energy cosmic rays (UHECRs)



with increasing energy:
→ shrinking propagation horizon
→ less magnetic field deflections

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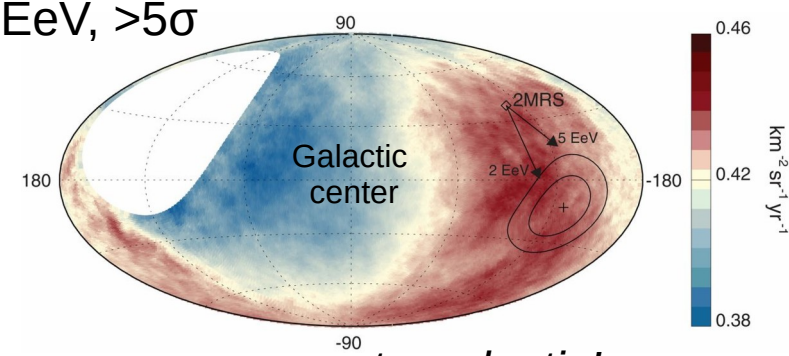

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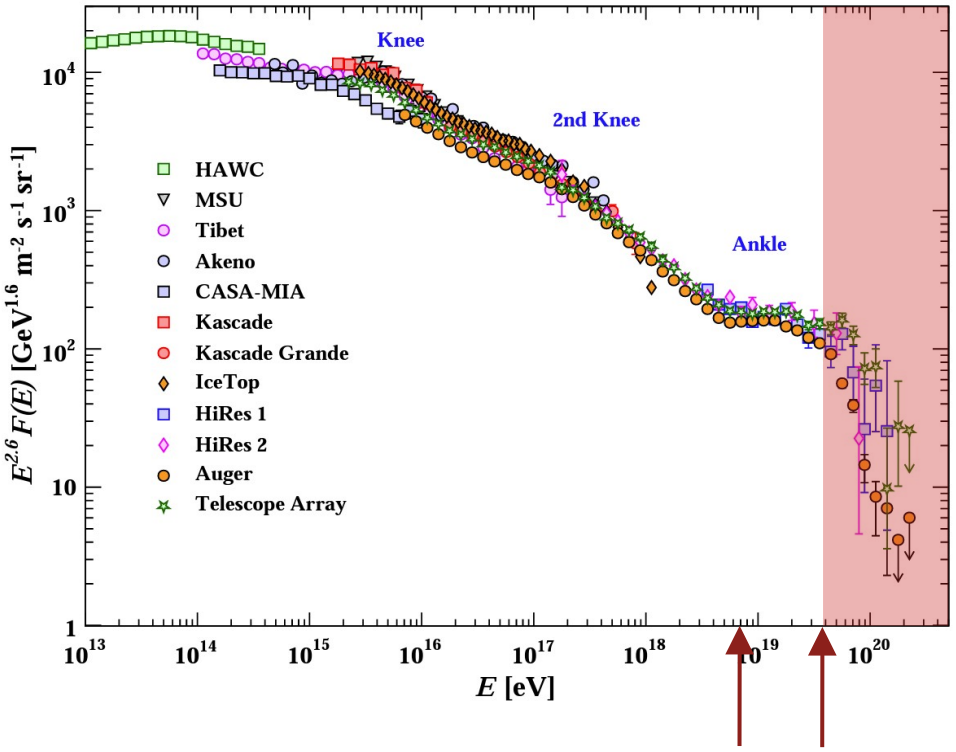

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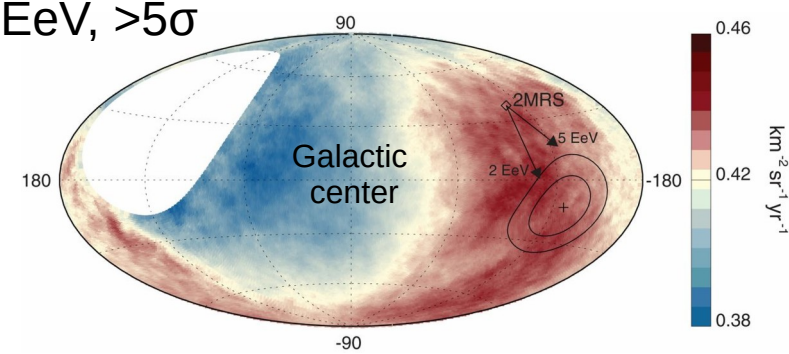
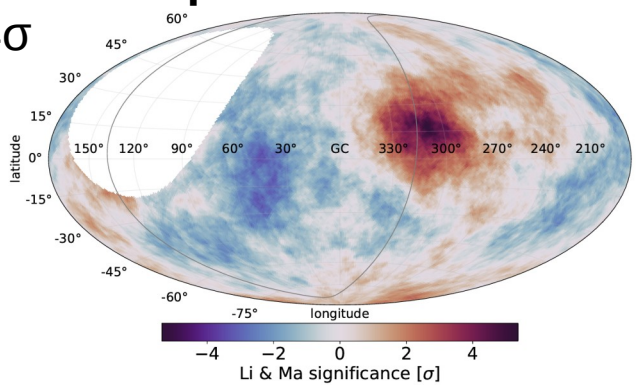
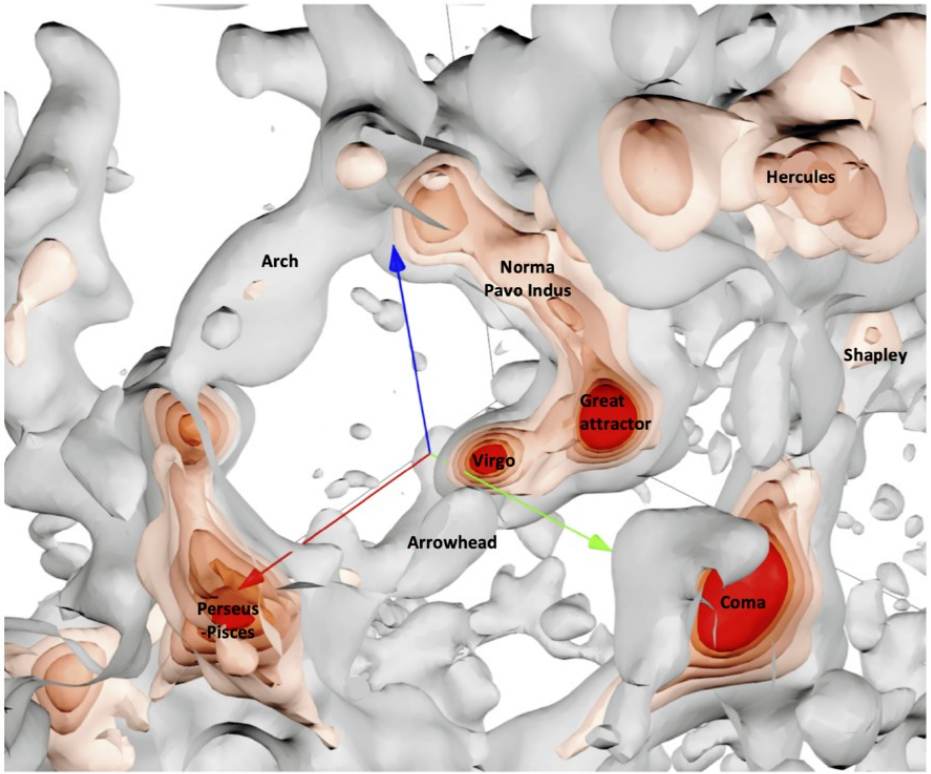


small-scale anisotropies
> 40 EeV, ~4σ



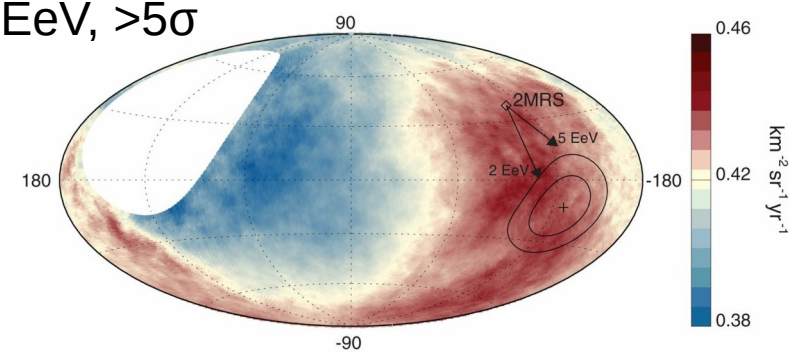
Dipole → UHECR sources?

The Pierre Auger Collaboration, Science 2017
Bister & Farrar, in prep.



extragalactic matter density

dipole > 8 EeV, >5σ

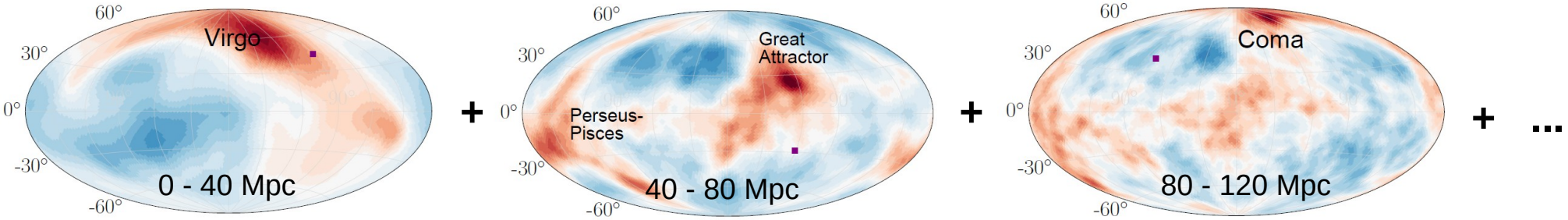


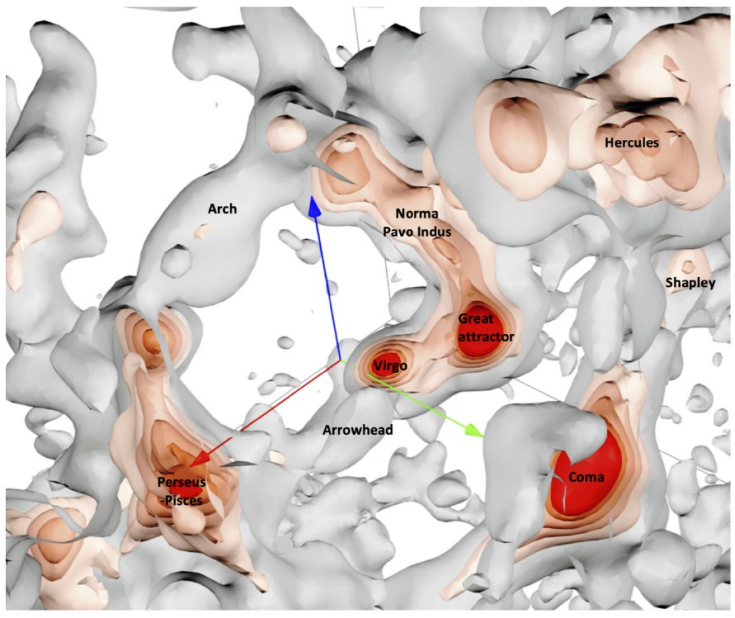
dipole can be explained by extragalactic sources following the **large-scale structure of the universe**

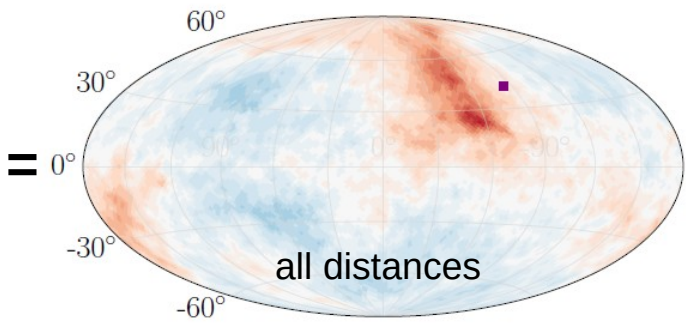
+ deflection by Galactic magnetic field

Bister & Farrar, in prep.

UHECR flux from Large Scale Structure







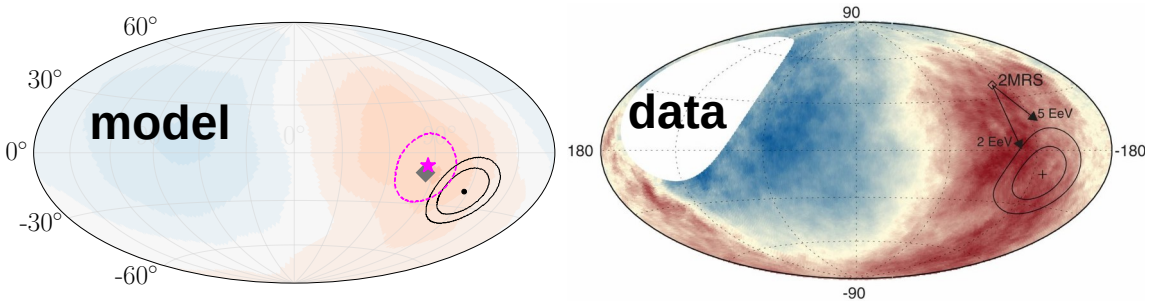
expected flux at the edge of our Galaxy

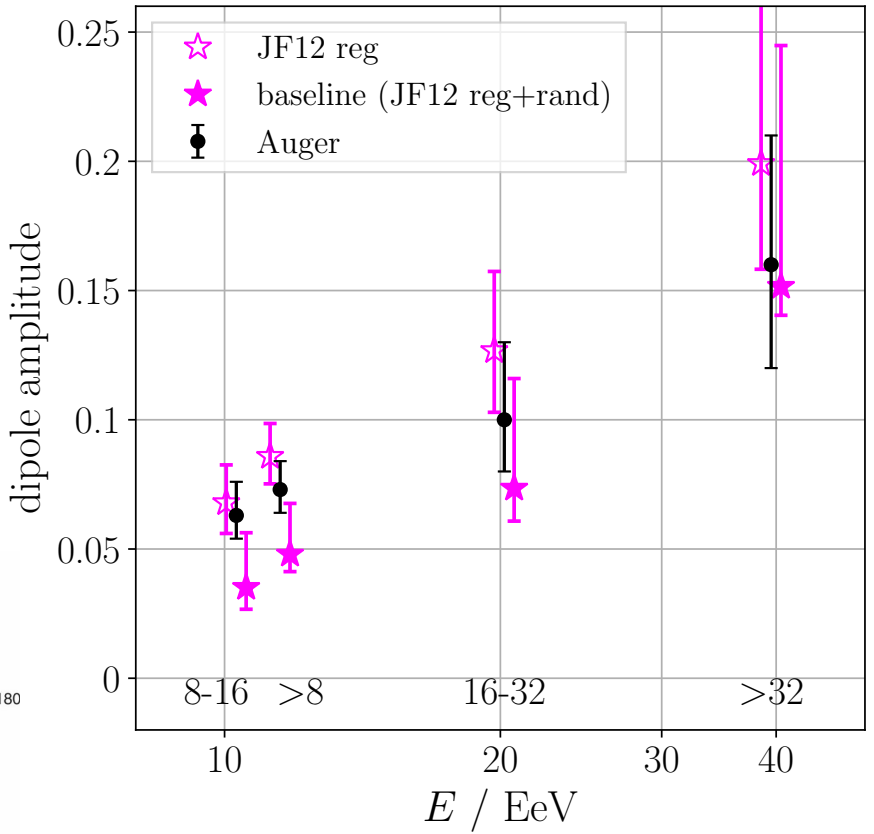
✔ *takes into account energy losses + interactions during propagation*

✔ *adapted injected spectrum and particle types to best describe the measured data*

Measurements at Earth (after Galactic magnetic field)

- **our model agrees well with data!**
- to reproduce data dipole amplitude:
  - turbulent magnetic fields: not too strong
  - possibility to constrain (extra-) Galactic magnetic field!
- direction not perfectly reproduced: constrain coherent Galactic magnetic field?

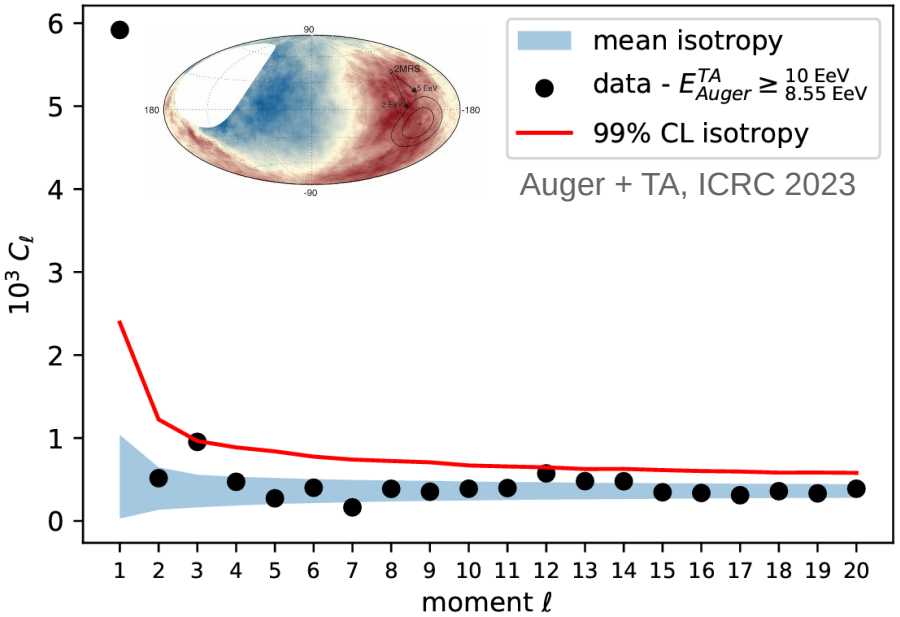




What else can we learn about the sources using this model?

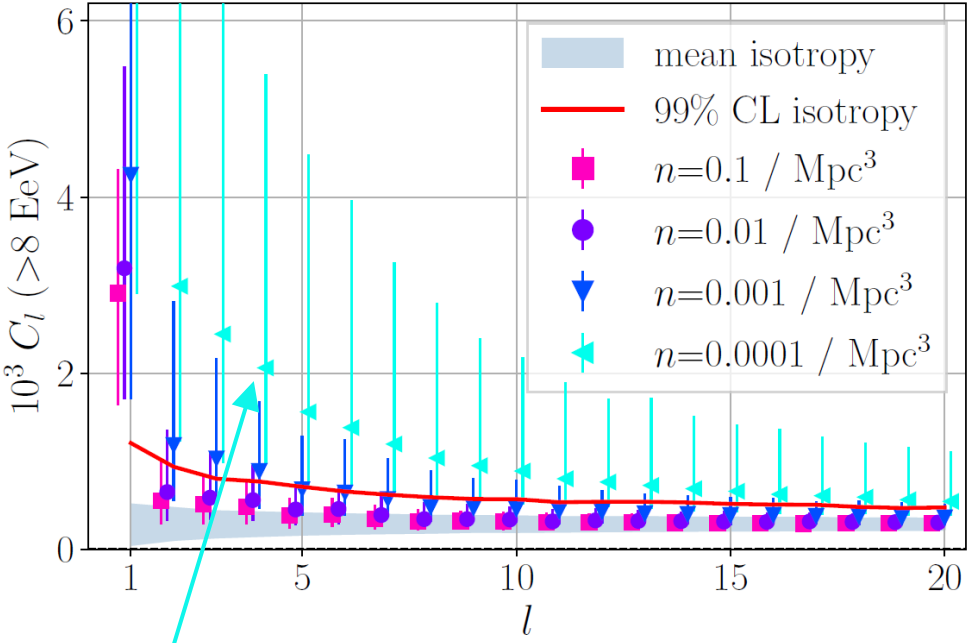
Power spectrum ↔ source number density

data:



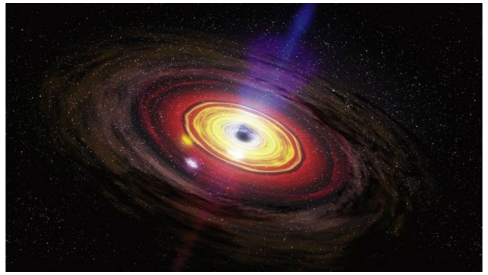
- only dipole significant
- higher order multipoles compatible with isotropy

model:
sample sources from Large Scale Structure



number density **n ≲ 10^{-4} / Mpc^3:**
too anisotropic! (higher energy even more constrainining, see backup)

Constraining source number density



low-luminosity AGNs ✔
~~high-luminosity AGNs~~

low-luminosity GRBs ✔
~~high-luminosity GRBs~~

common starburst galaxies ✔
~~strongest starbursts only~~

→ **unexpected!**

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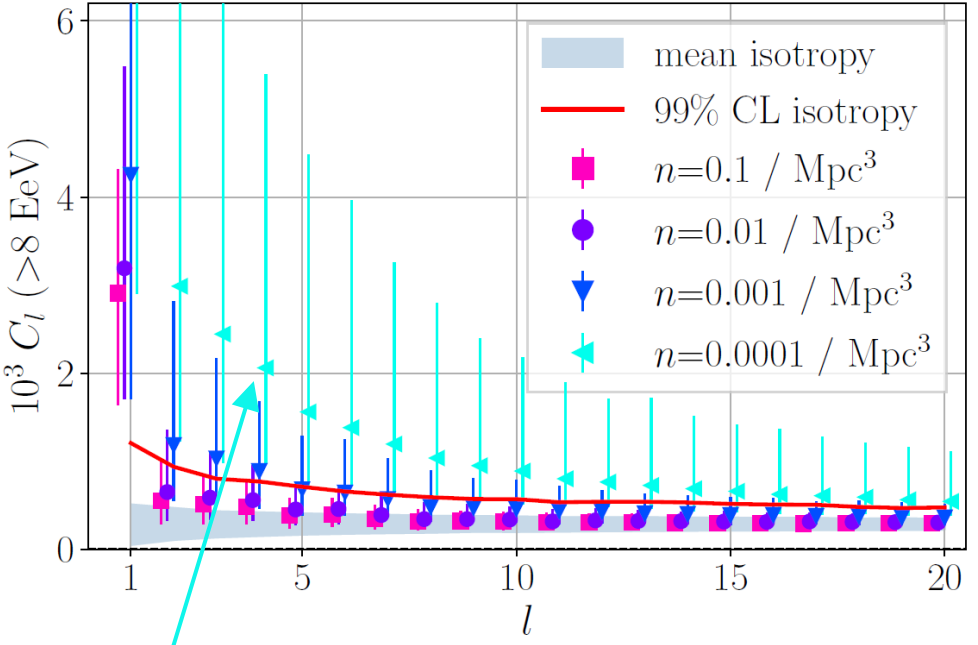
sample sources from Large Scale Structure



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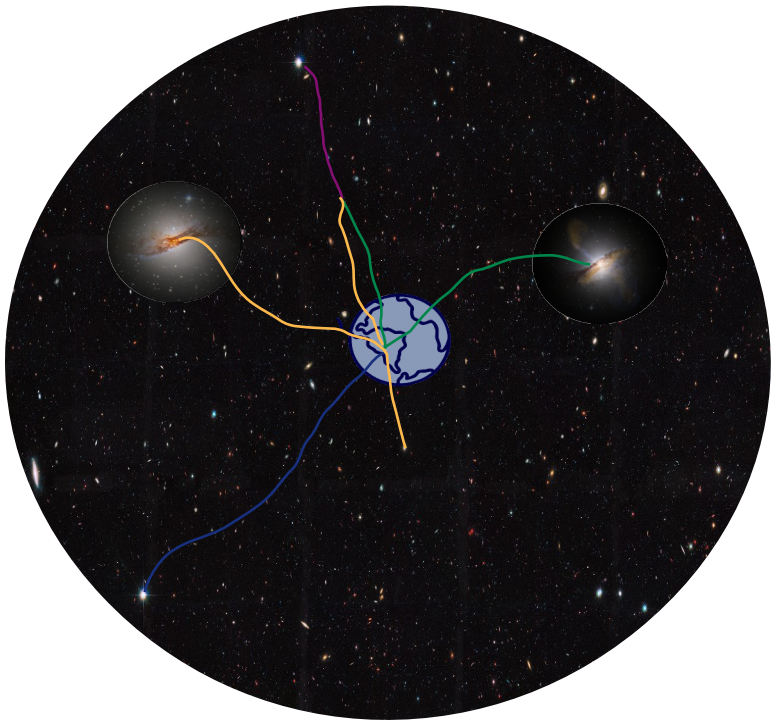
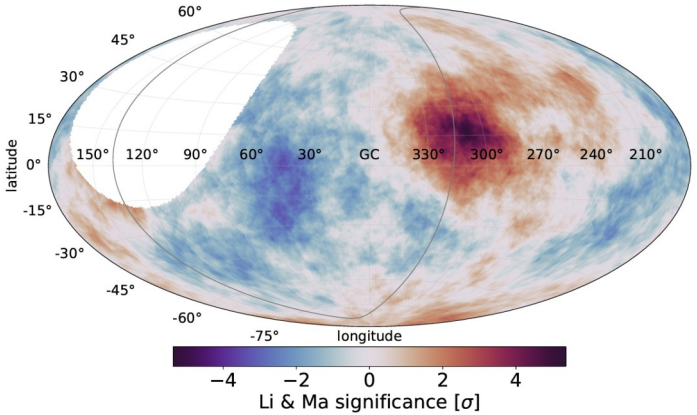
At the highest energies?

TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration, submitted to JCAP

- smaller propagation horizon + less deflections:
  → possibility to **identify individual sources**
- build similar model:
  homogeneous background sources + nearby candidates





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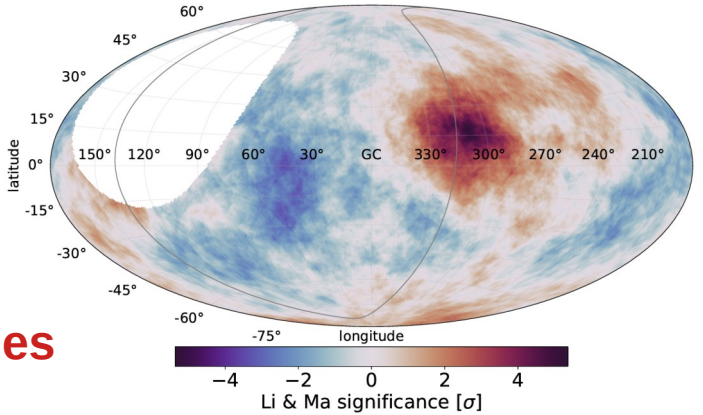

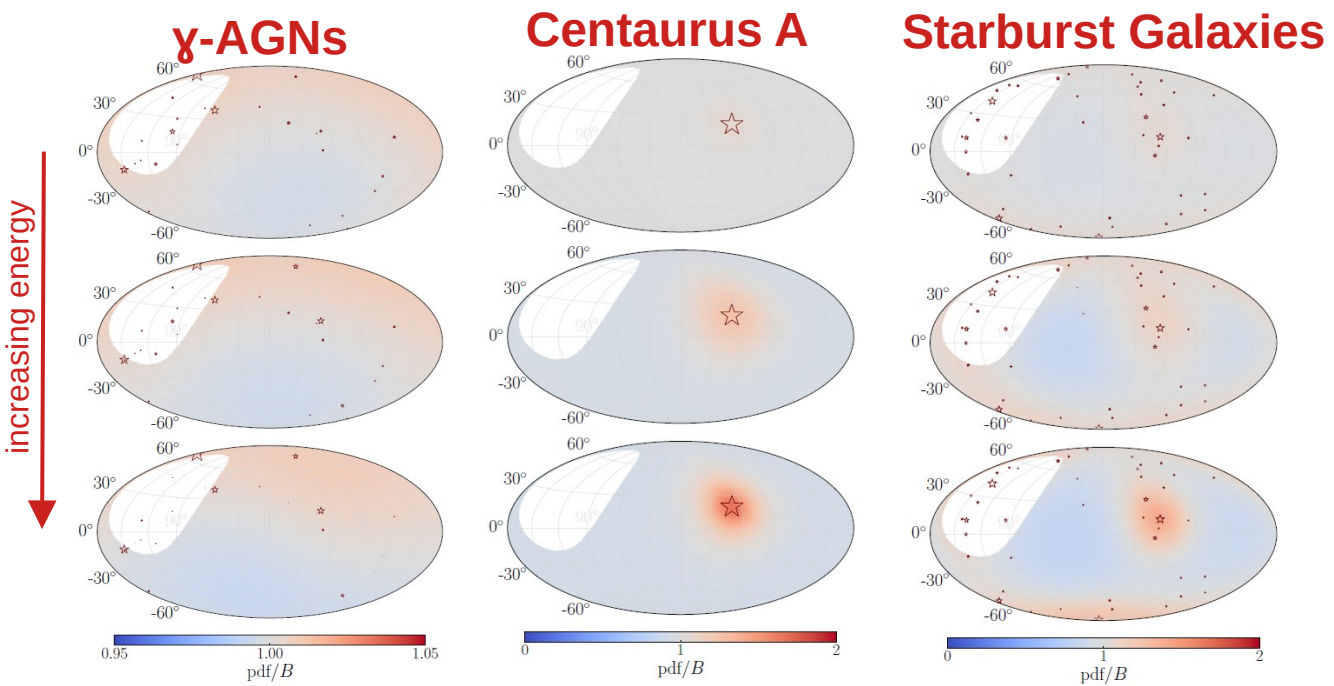

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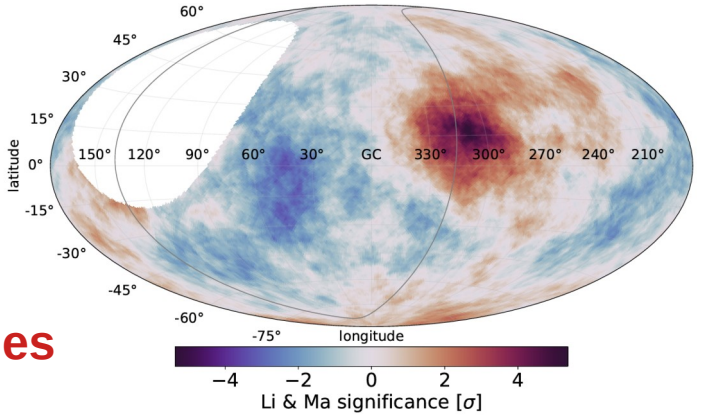

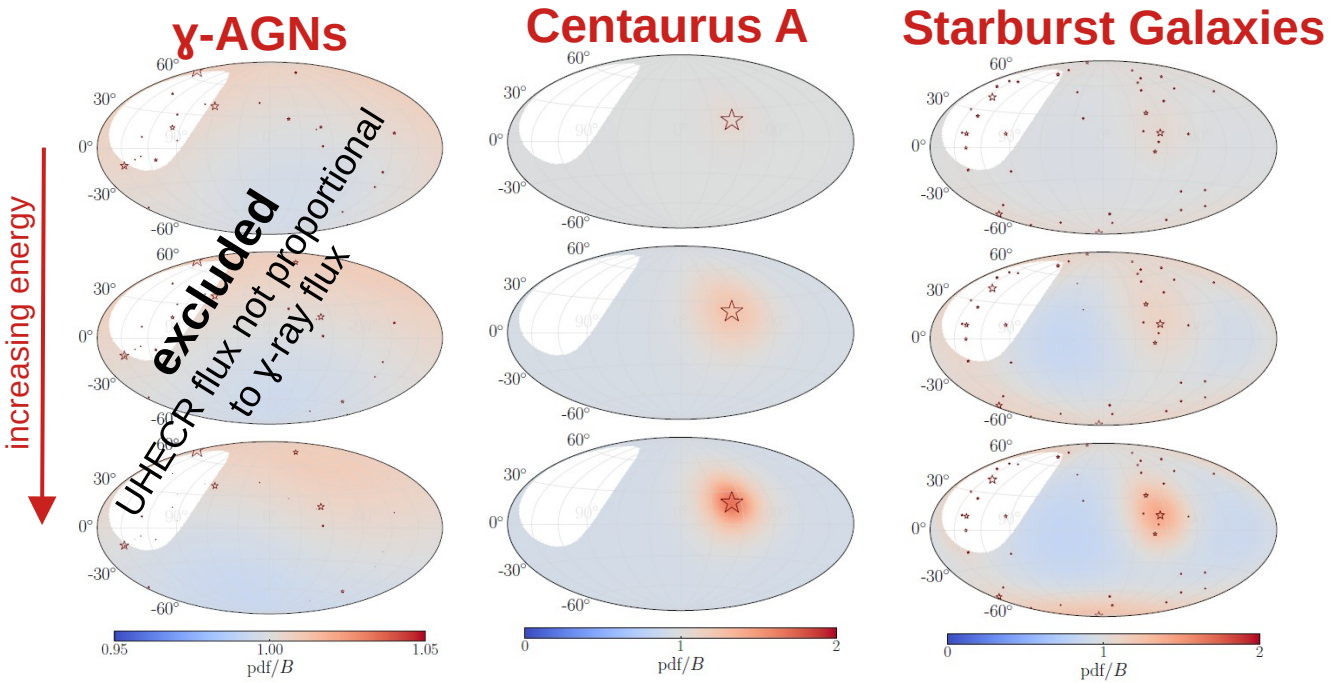

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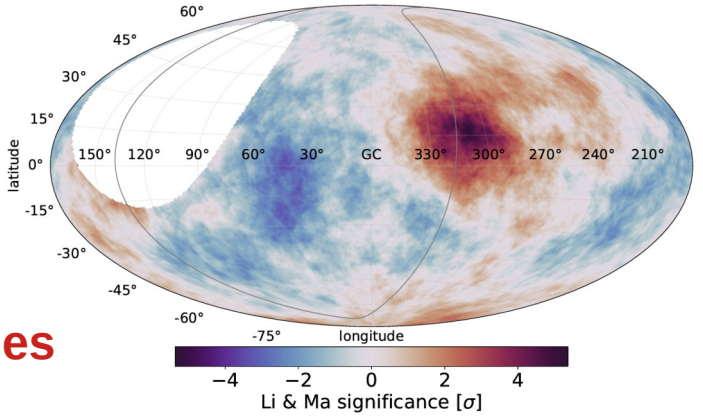
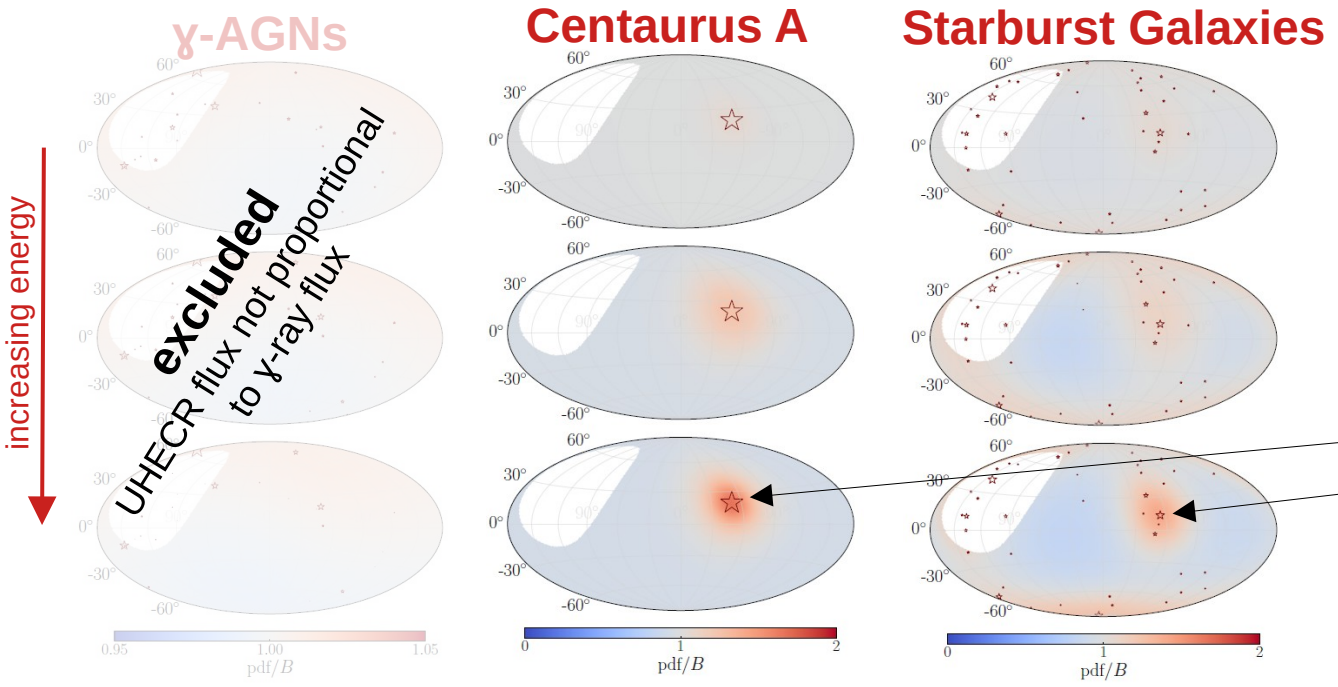


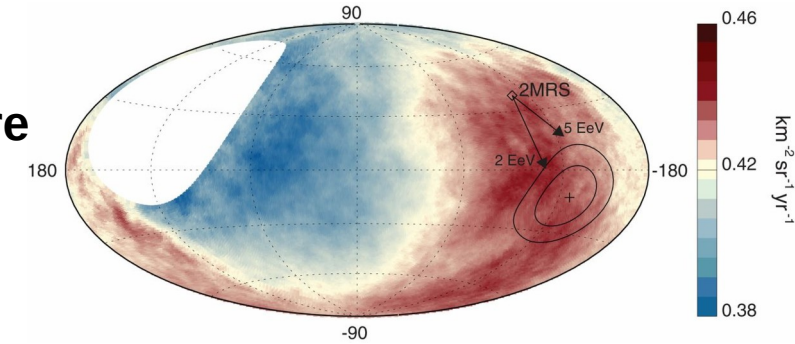


- **starburst galaxies: 4.5σ**
- mostly due to Centaurus A / NGC 4945 region

Summary and open questions

- promising progress in search for UHECR sources:

- **~8 EeV: sources most likely follow large scale structure & have a large density > 10^{-4} / Mpc^3**
  - *But, what exactly are they?*
    low-luminosity AGNs, transients, starburst galaxies, ...?



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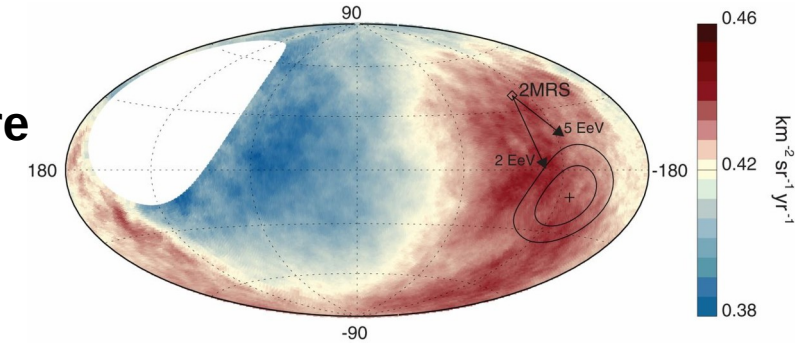
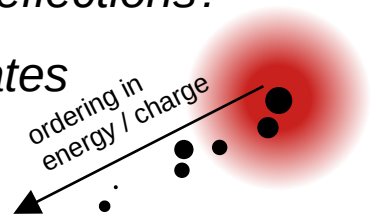
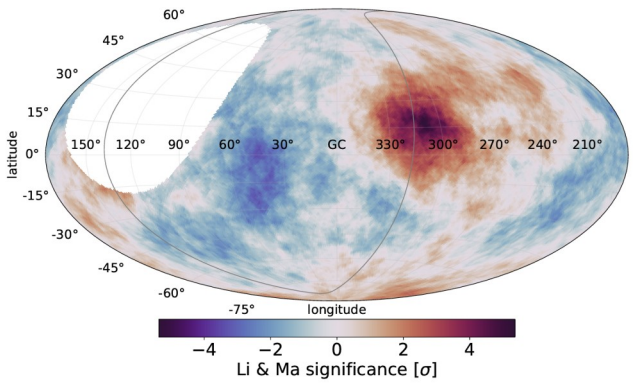
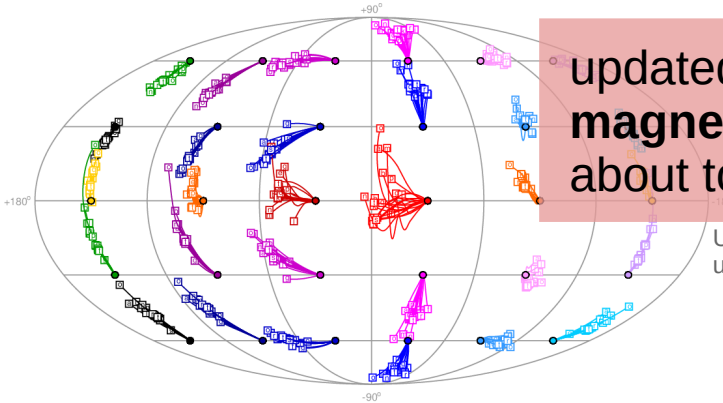


- **> 40 EeV: individual source candidates describe data well**: starburst galaxies, Centaurus A
  - *But, what about Galactic magnetic field deflections?*
  - *Can we identify individual source candidates from deflection signatures?*
  - *How to bridge the gap between the observations at different energies?*





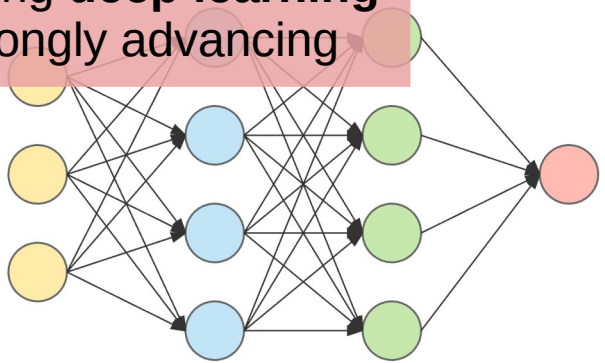
Outlook



updated **Galactic magnetic field models** about to be released

Unger and Farrar 2017, update in preparation

Data reconstruction using **deep learning** strongly advancing



Pierre Auger Collaboration, JINST 2021
J. Glombitza for the Pierre Auger Collaboration, PoS ICRC 2023
J. Schulte, TB, M. Erdmann, PoS ICRC 2023

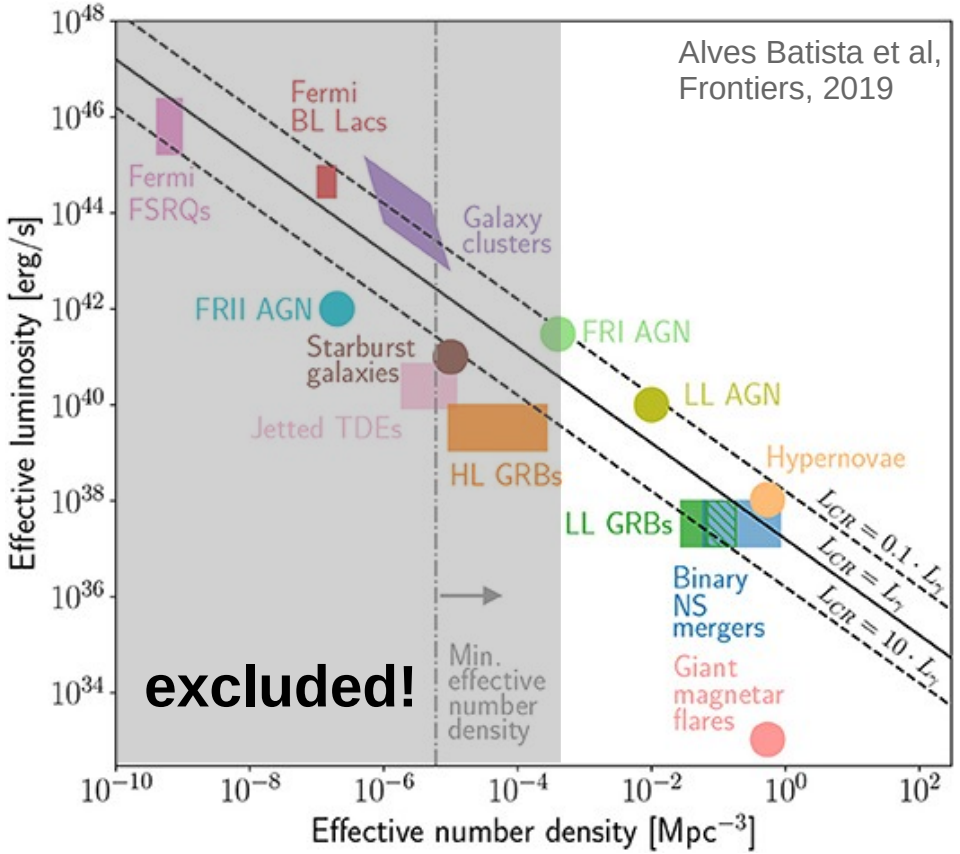
Upgrade of the Observatory almost finished: **AugerPrime**
→ better mass reconstruction

Pierre Auger Collaboration, arXiv:1604.03637

⇨ ***will probably identify the sources in the nearby future!***

Backup

Constraining source number density

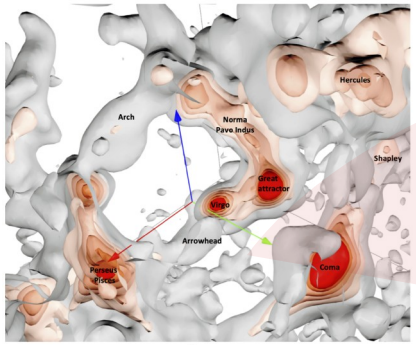


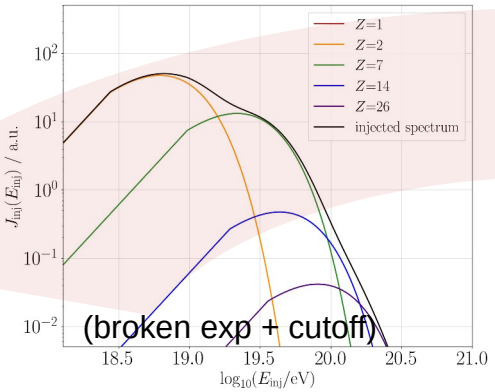
consequences for possible sources:

- must be numerous enough
- like low-luminosity active galactic nuclei, gamma ray bursts, normal galaxies...

Fit principle

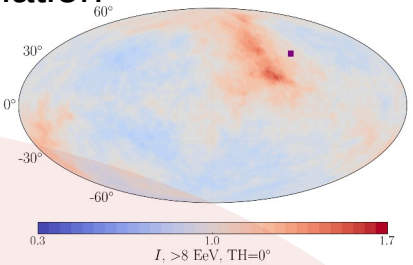
injection following LSS
all source following **Peters cycle**



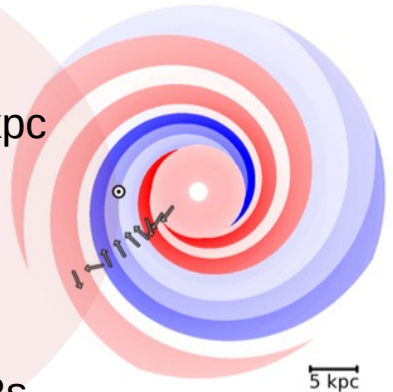


(broken exp + cutoff)

propagation with CRPropa
→ gives “illumination“



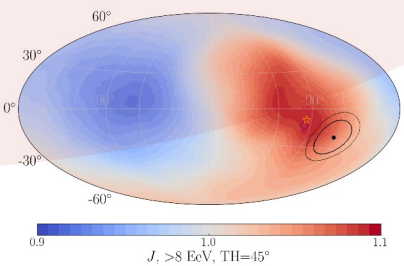
Galactic magnetic field
deflections: JF12, l_c=30 kpc



adapt injection, via likelihood:

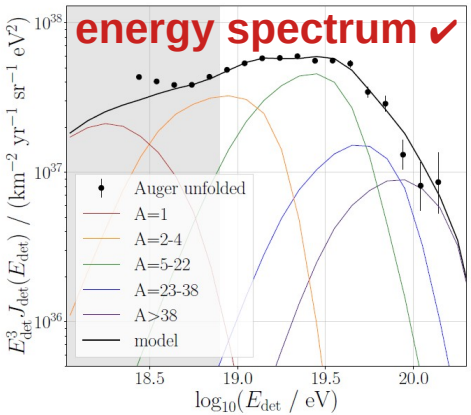
- compare model to data from Pierre Auger Observatory
  - dx, dy, dz in 3 energy bins
  - unfolded energy spectrum
  - shower depth distributions

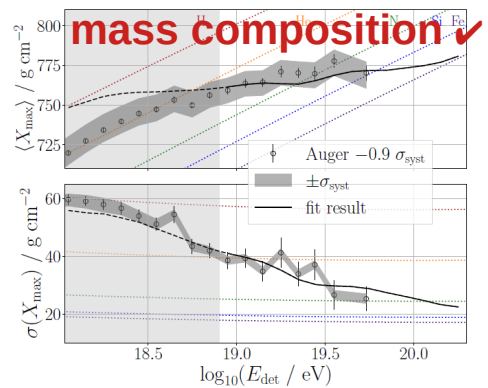
on Earth: calculate energies, charges + directions of incoming CRs



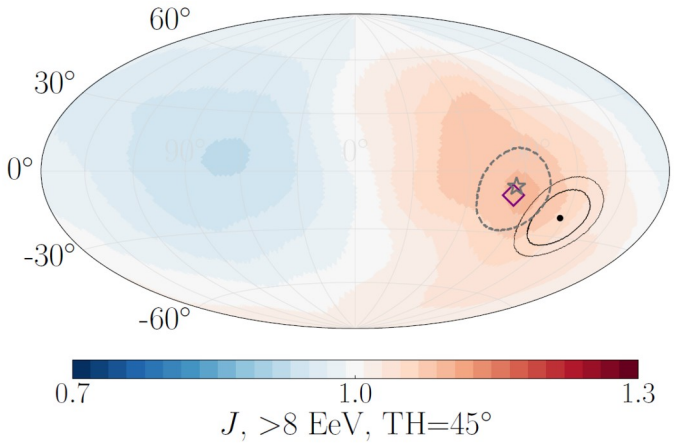
Measurements at Earth (after Galactic magnetic field)

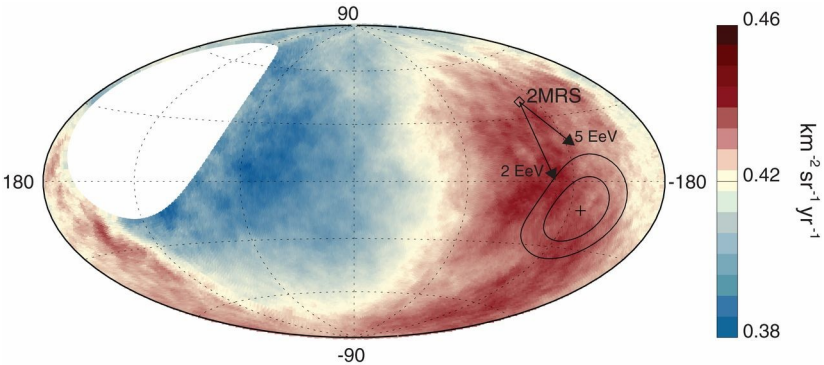
model describes:





arrival directions (✔)





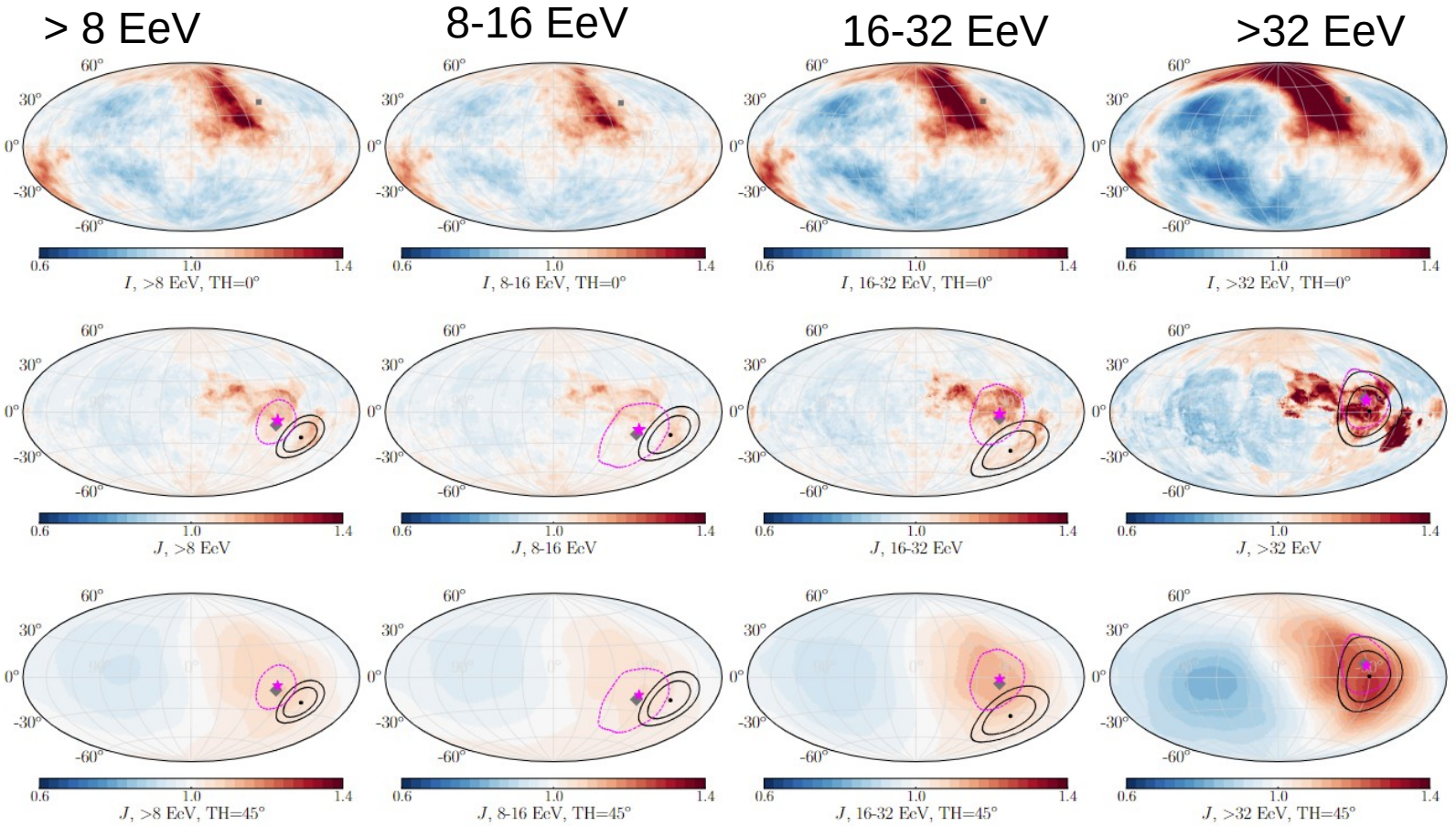
→ **dipole amplitude** slightly too small

→ **dipole direction** not perfectly reproduced

→ update of Galactic magnetic field model? (Unger & Farrar, in prep.)

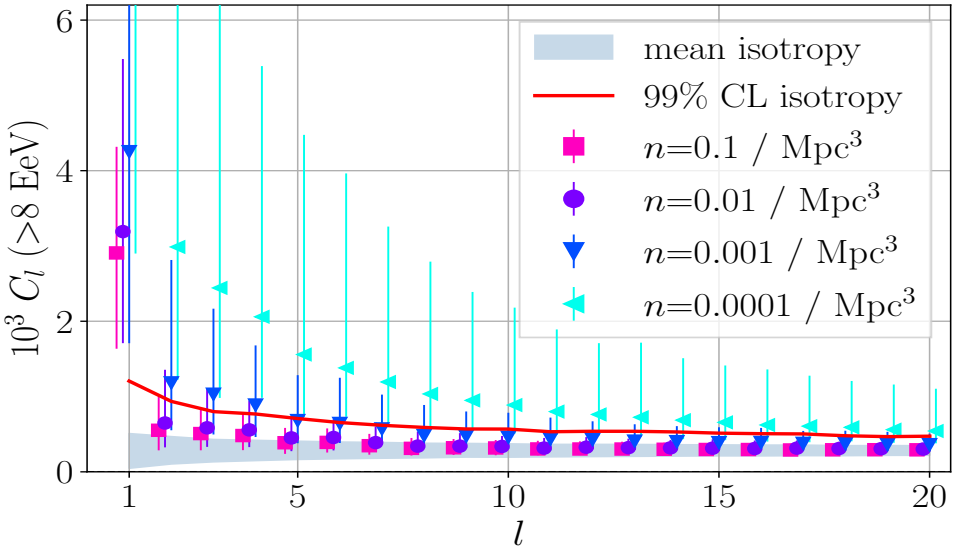
What else can we learn about the sources using this model?

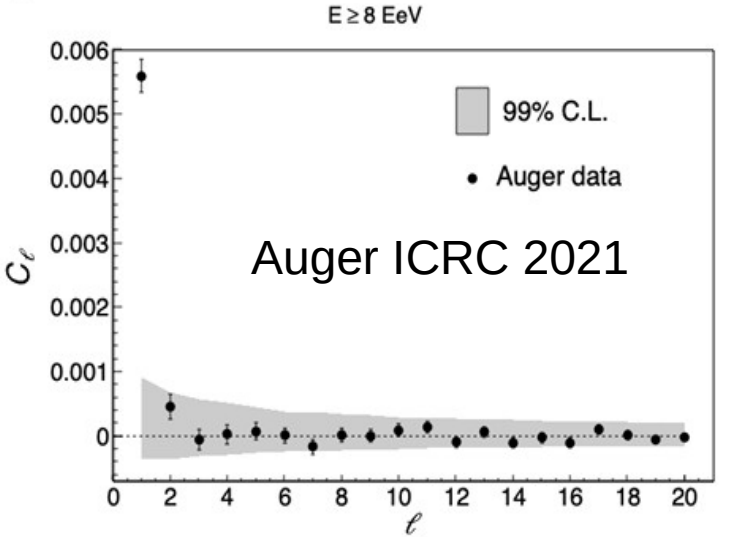
Dipole direction predictions



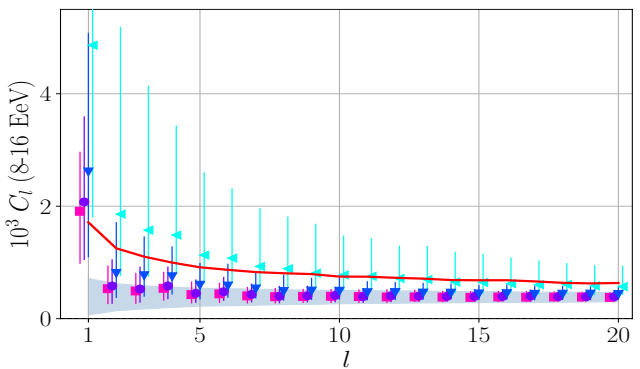
dipole direction at lower energies not perfect (GMF update?)

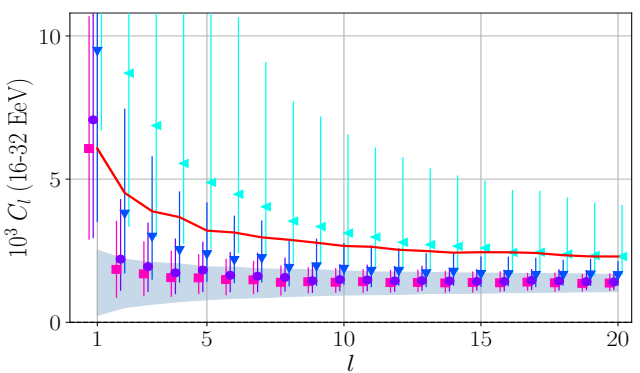
Constraints by power spectrum

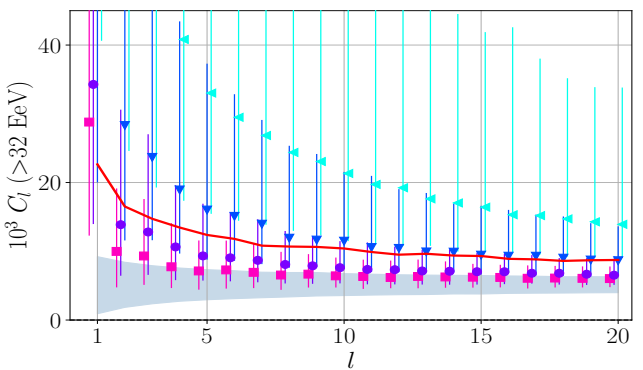




<10^{-4} / Mpc^3: too anisotropic especially at large energies







Effect of GMF / EGMF variations