Interpreting the data of the Pierre Auger Observatory

Teresa Bister
KIT, October 2024

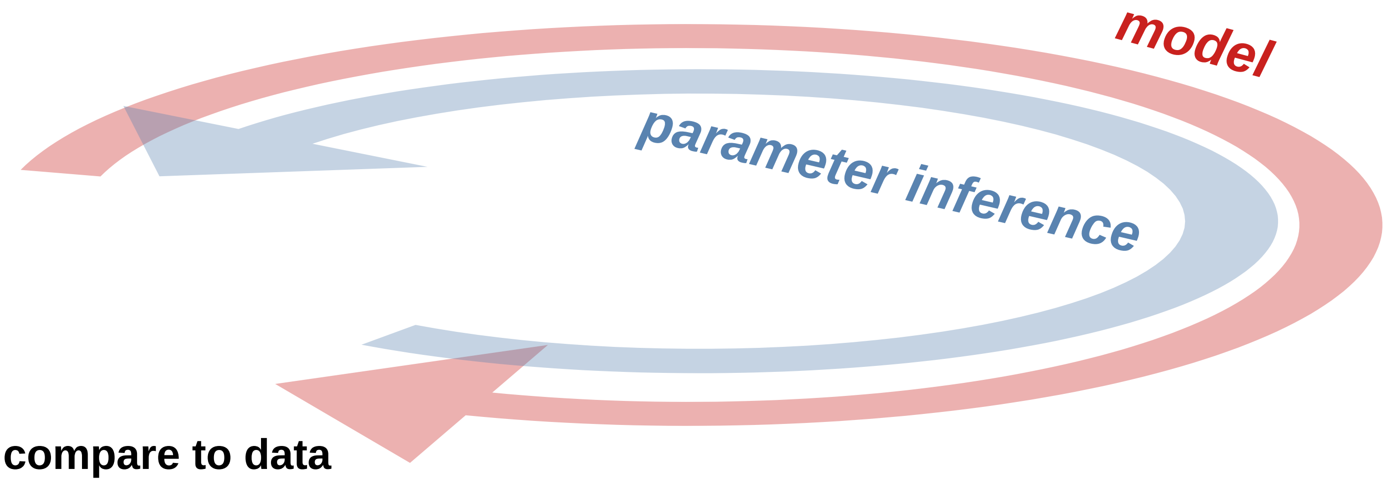
PIERRE AUGER OBSERVATORY

Radboud University

Nikhef

Modeling UHECRs from sources to detection

main aim: learn more about the sources of UHECRs

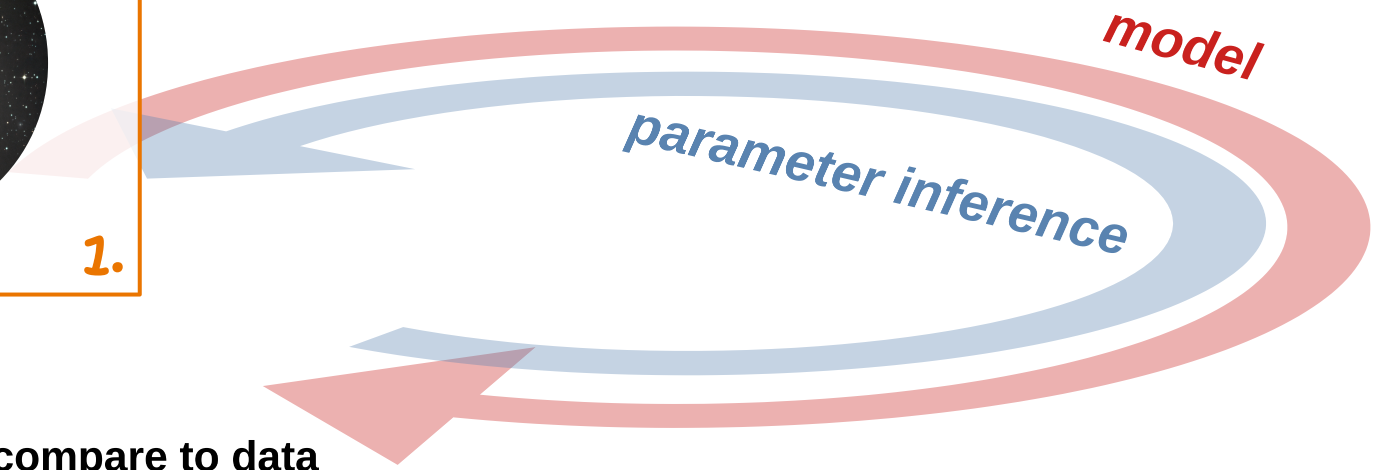


Modeling UHECRs from sources to detection

main aim: learn more about the sources of UHECRs

sources emit UHECRs

1.

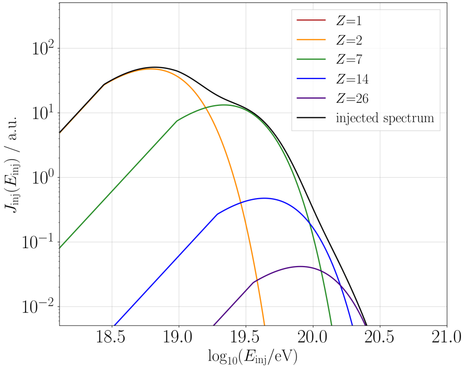


compare to data

Modeling UHECRs from sources to detection

sources emit UHECRs

2. injection



usual assumptions:

- **maximum energy prop. to charge number Z: “Peters cycle“**
- shape: power-law + cutoff:

spectral index — rigidity cutoff

$$\tilde{Q}_A(E) = \tilde{Q}_{0A}\left(\frac{E}{E_0}\right)^{-\gamma}\begin{cases}1, & E \le Z_A\,R_{\mathrm{cut}}\\ \exp\left(1-\frac{E}{Z_A\,R_{\mathrm{cut}}}\right), & E > Z_A\,R_{\mathrm{cut}}\end{cases}$$

element contributions

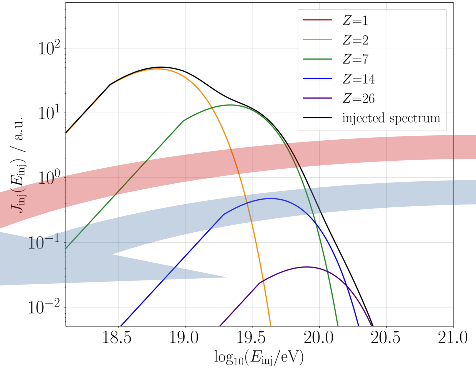
- model 5 representative elements (H, He, N, Si, Fe)

compare to data

Modeling UHECRs from sources to detection

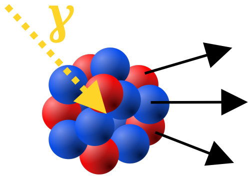
sources emit UHECRs

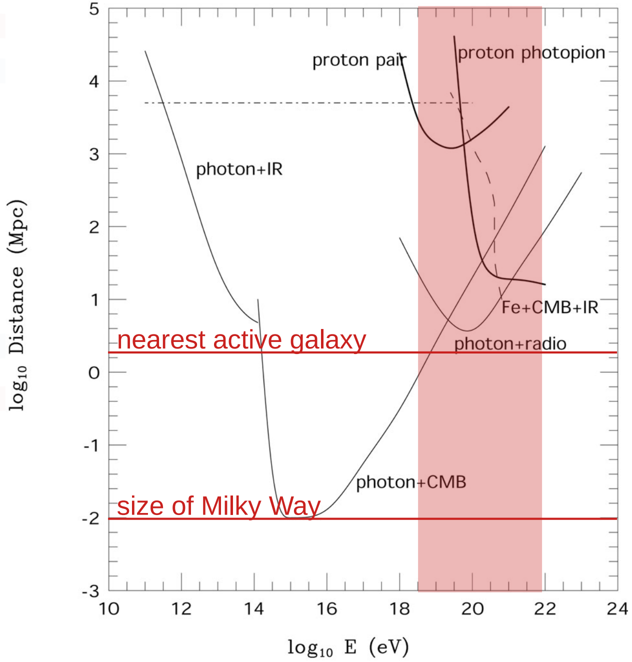
injection



3.

propagation through extragalactic space



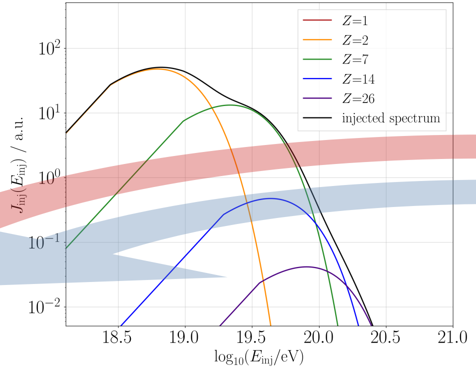


compare to data

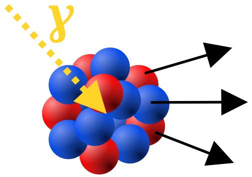
Modeling UHECRs from sources to detection

sources emit UHECRs

injection



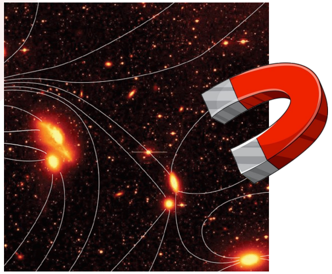
propagation through extragalactic space



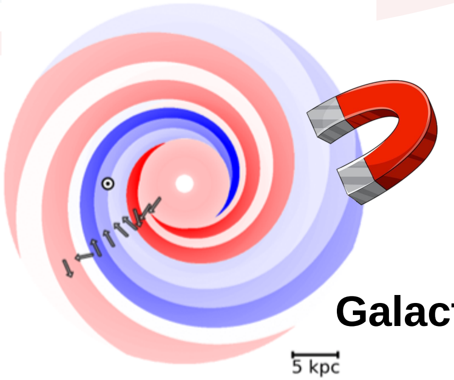
4. & 5.

need models

extragalactic magnetic field



both deflect particles proportionally to Z/E = 1/R („rigidity“)



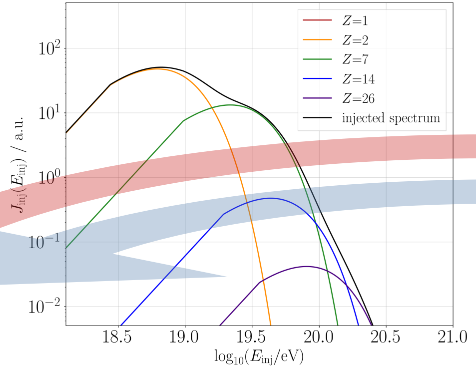
Galactic magnetic field

compare to data

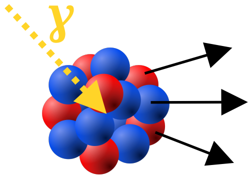
Modeling UHECRs from sources to detection

sources emit UHECRs

injection



propagation through extragalactic space



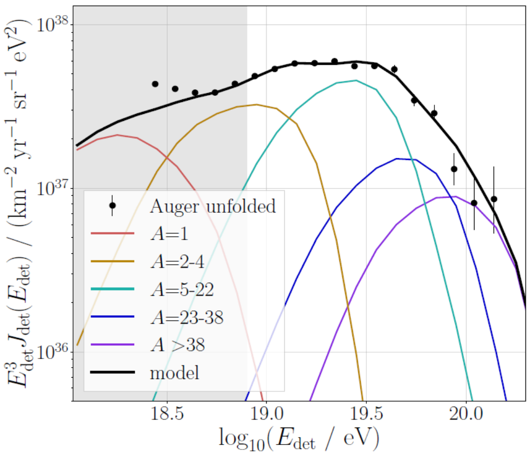
extragalactic magnetic field

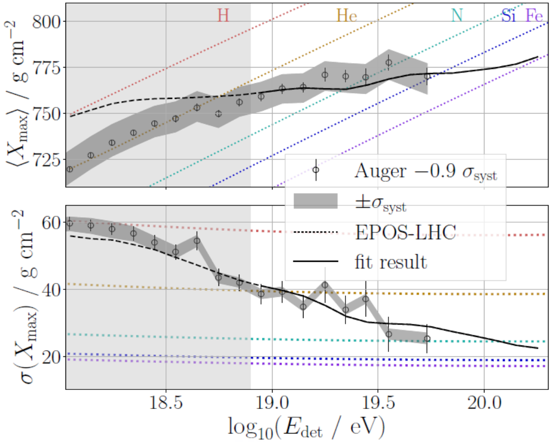
6.

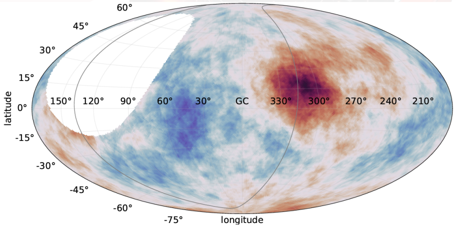
compare to data

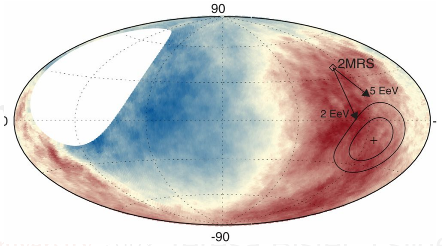
- energy spectrum
- mass composition
- arrival directions

likelihood







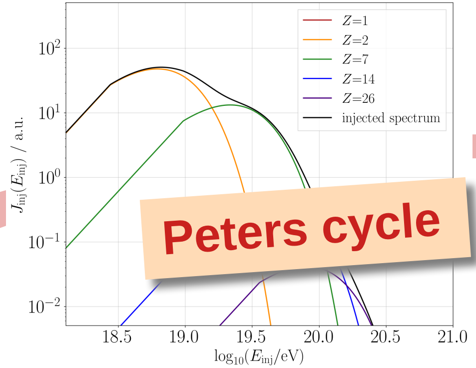


Combined fit of spectrum and composition

source distribution

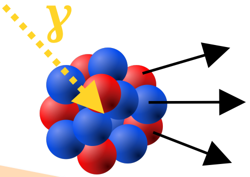
homogeneous
(2 populations)

injection



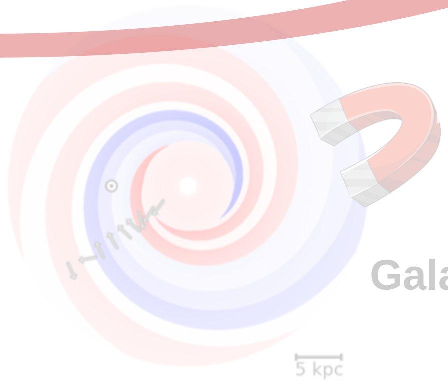
Peters cycle

propagation through extragalactic space



CRPropa

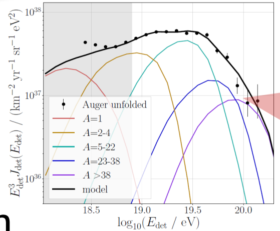
extragalactic magnetic fields

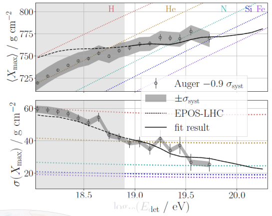


Galactic magnetic fields

compare to data

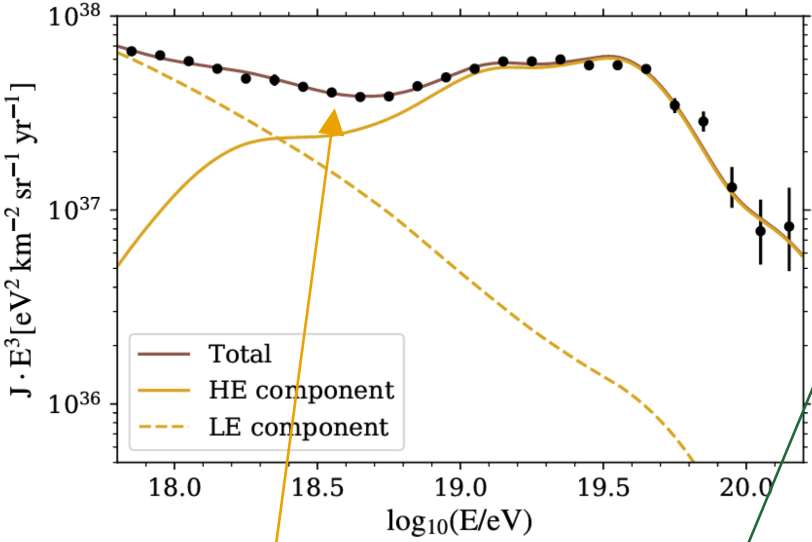
- energy spectrum
- mass composition
- arrival directions

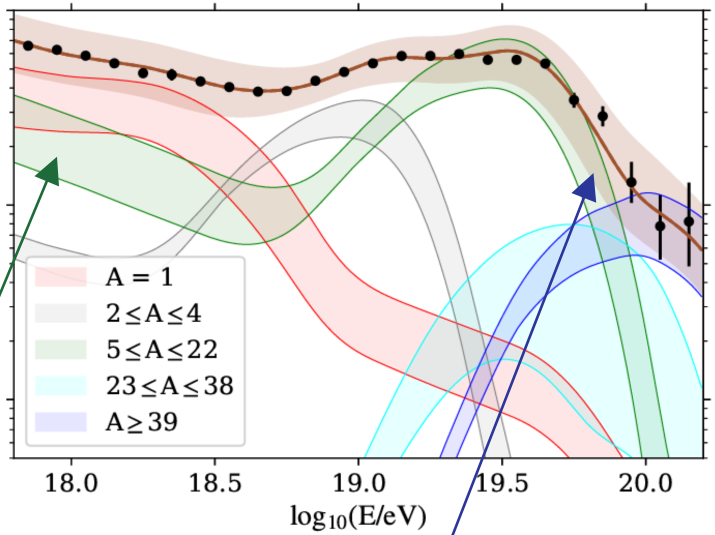




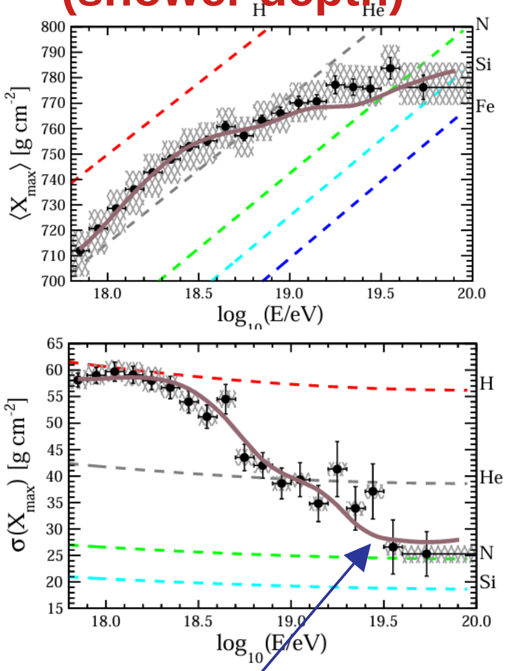
Model predictions on Earth

energy spectrum





mass composition (shower depth)



ankle: transition between two populations

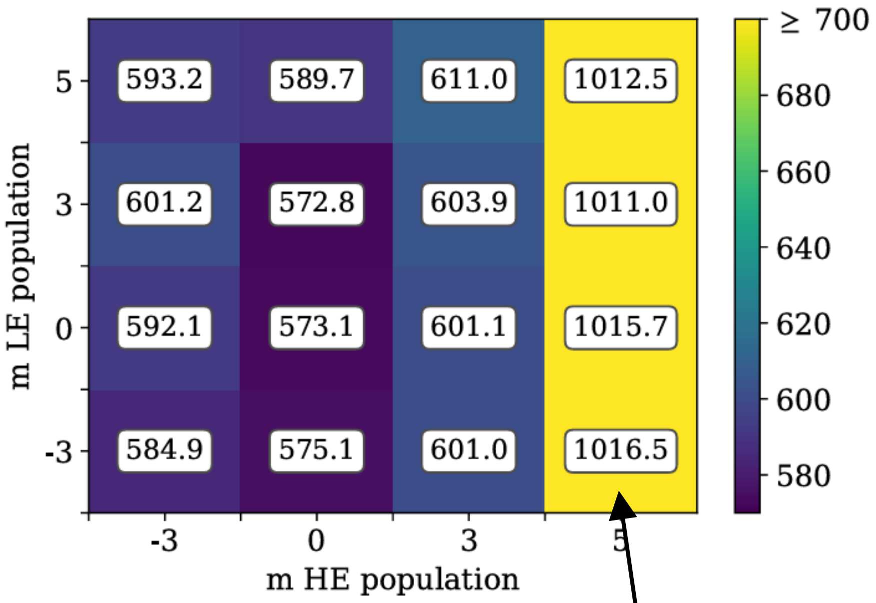
conclusions stable with regards to **systematic effects**

transition between element groups

to describe composition getting heavier
+ small mixing + pronounced features in spectrum

Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$

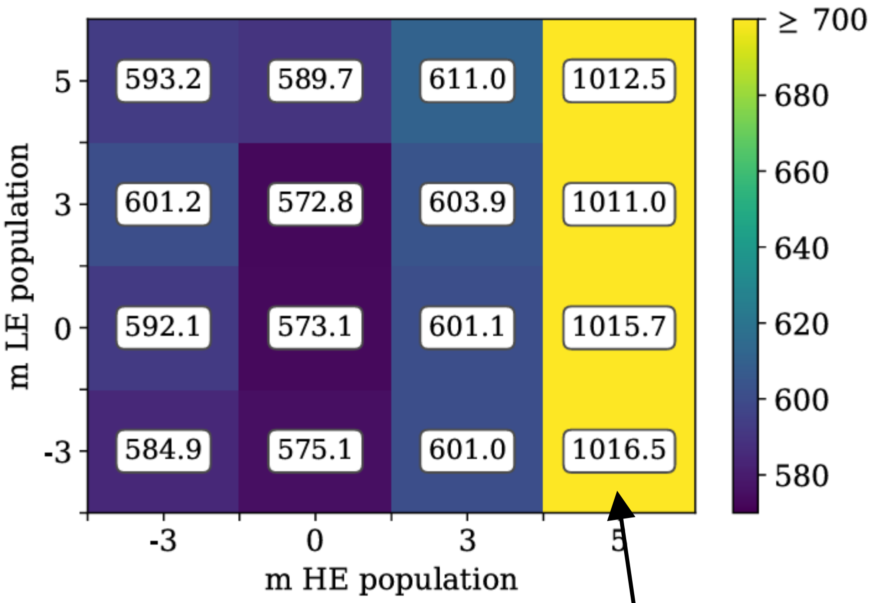


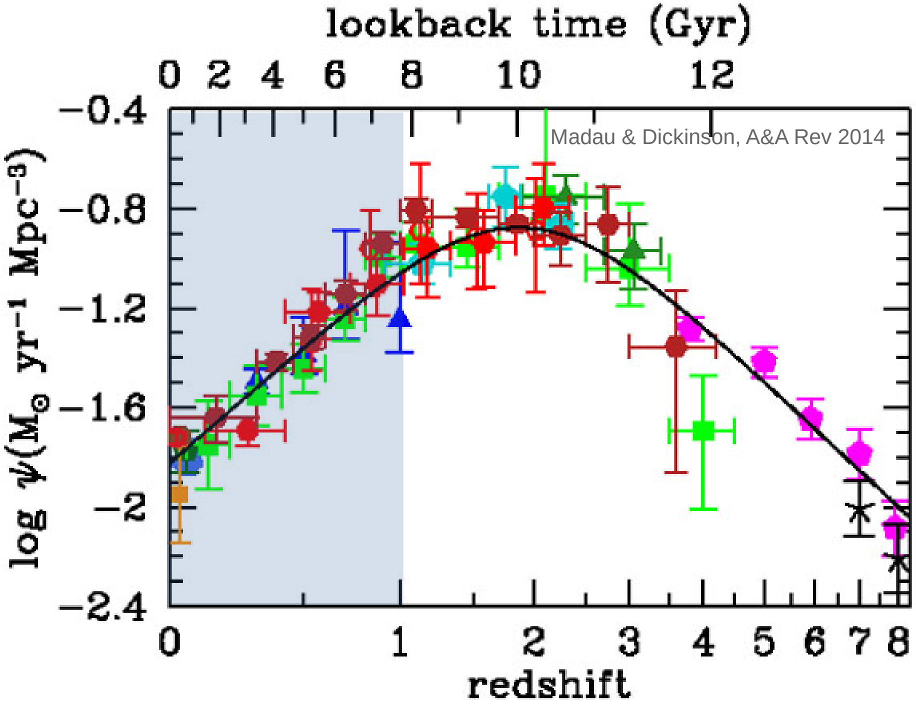
strong evolution of high-energy population disfavored

Pierre Auger Collaboration JCAP05(2023)024

Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$



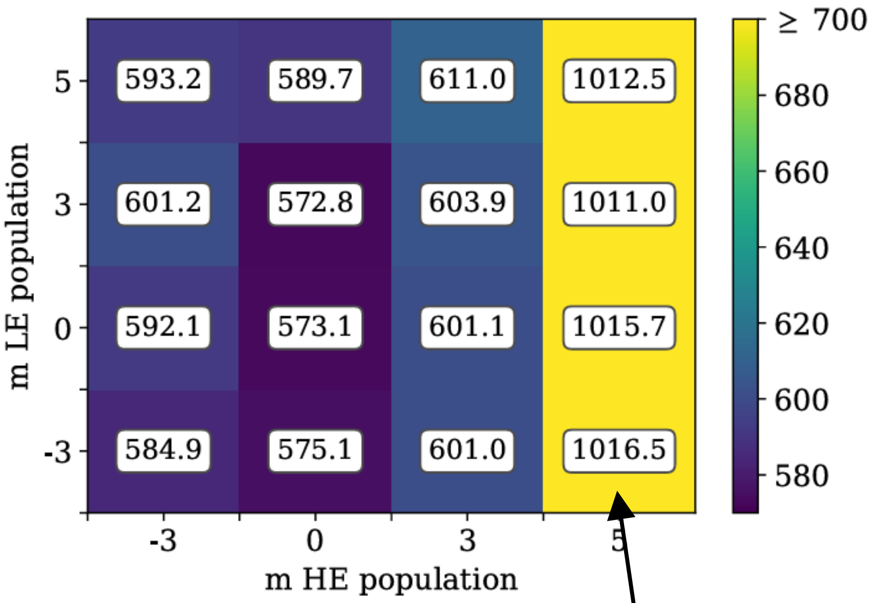


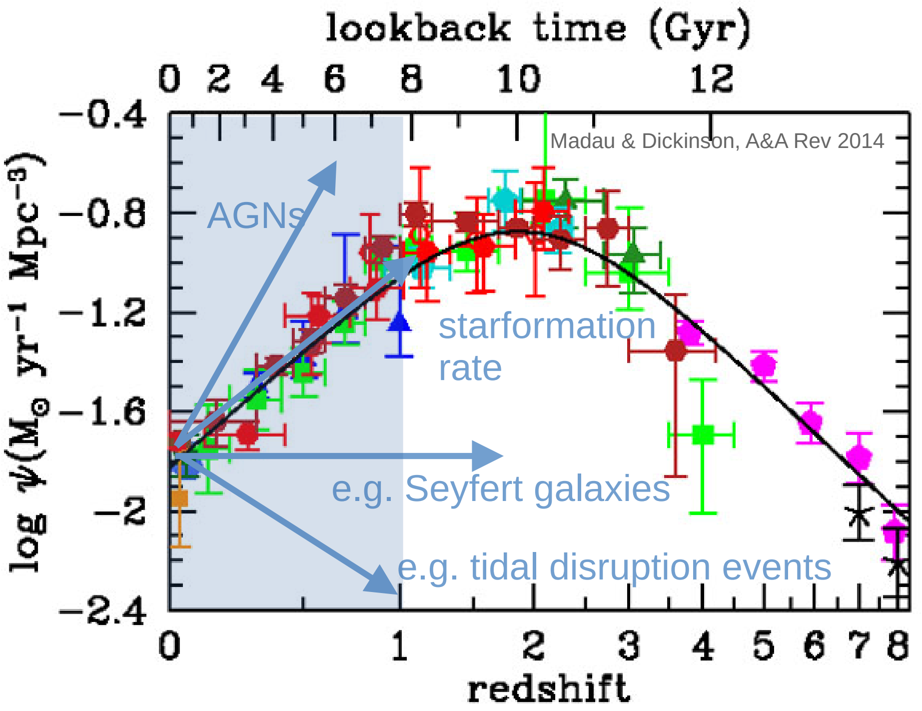
strong evolution of high-energy population disfavored

Pierre Auger Collaboration JCAP05(2023)024

Model predictions for the source evolution

test cosmological source evolution $\psi(z) \propto (1+z)^m$





strong evolution of high-energy population disfavored

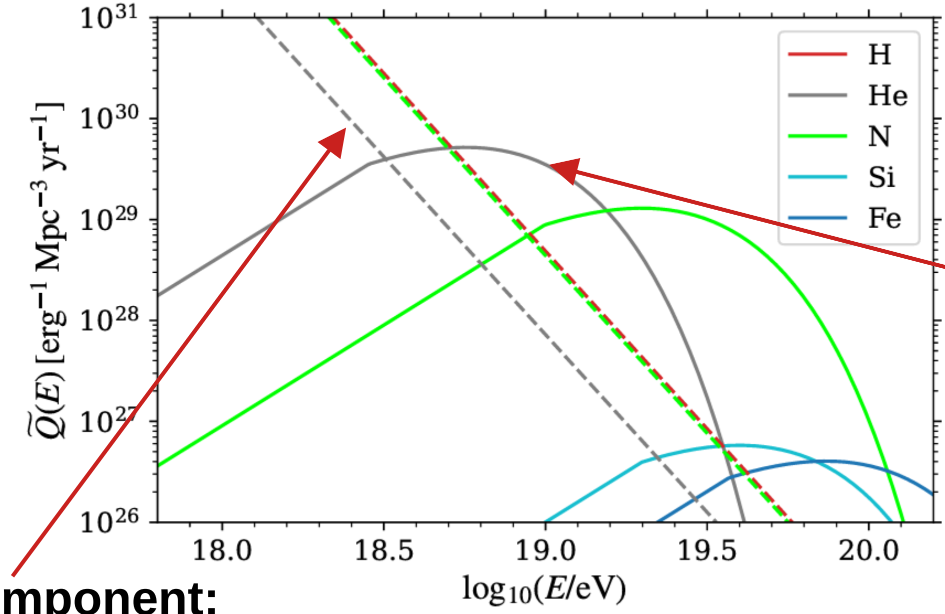
Model predictions: source injection

Peters cycle
+ broken exponential cutoff

spectral index — rigidity cutoff

$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \le Z_A R_{\text{cut}} \\ \exp\left(1 - \frac{E}{Z_A R_{\text{cut}}}\right), & E > Z_A R_{\text{cut}} \end{cases}$$

element contributions



high-energy component:

→ intermediate mass composition (not compatible with all-protons)

→ low rigidity cutoff O(1 EeV)

→ very hard spectrum ɣ < 0

→ shock acceleration: ɣ ~ +2

low-energy component:

→ H+He+N, very soft spectrum ɣ~3.5

→ rigidity cutoff unconstrained

Pierre Auger Collaboration JCAP 05 024 (2023)

Why is the spectral index so unexpectedly hard?

possible explanations:

1) **source evolution**

   e.g. Pierre Auger Collaboration JCAP 05 024 (2023)

2) systematic effects

   e.g. Pierre Auger Collaboration JCAP 01 022 (2024)

3) interactions/magnetic confinement in source environment

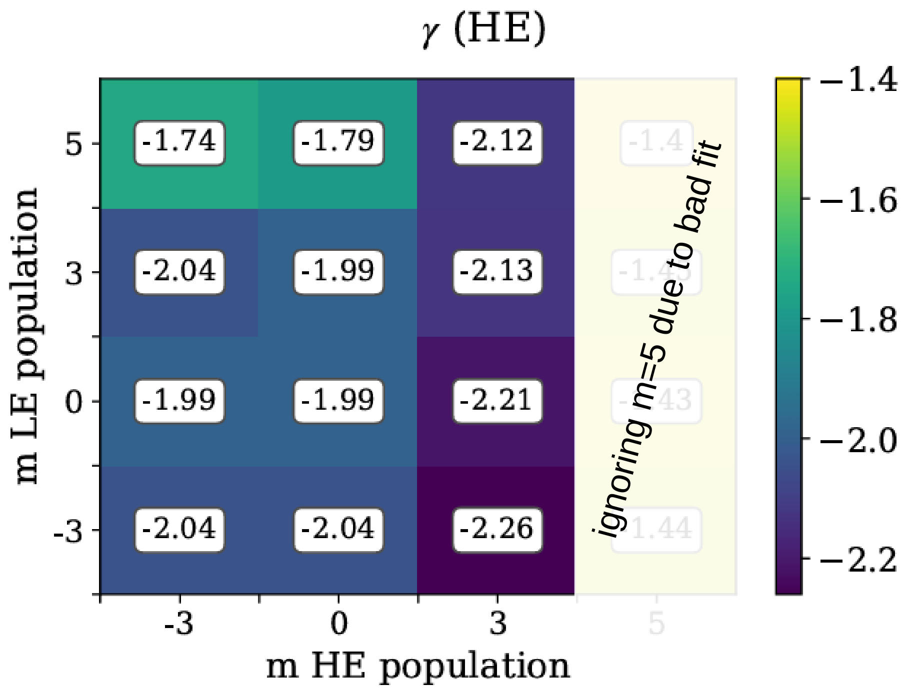
   e.g. Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)

4) cutoff shape

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

5) extragalactic magnetic field

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)



softer evolution:
→ less distant sources
→ less low-energy secondaries
→ softer spectrum ok (=more low-energy primaries)
→ but: effect not big

T. Bister, PhD thesis

Why is the spectral index so unexpectedly hard?

possible explanations:

1) source evolution

    e.g. Pierre Auger Collaboration JCAP 05 024 (2023)

2) systematic effects

    e.g. Pierre Auger Collaboration JCAP 01 022 (2024)

3) interactions/magnetic confinement in source environment

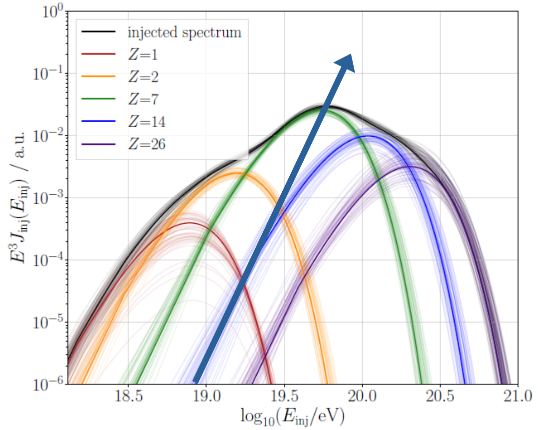
    e.g. Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)

4) cutoff shape

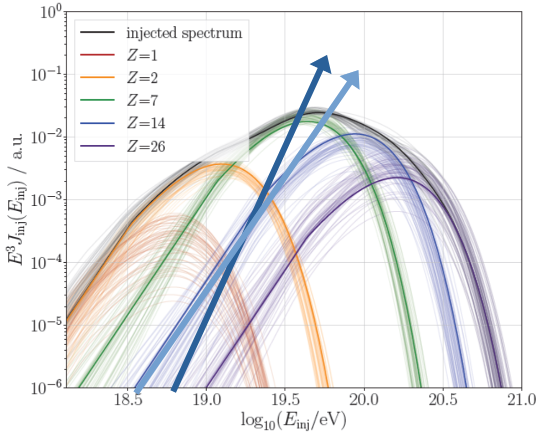
    e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

5) extragalactic magnetic field

    e.g. Pierre Auger Collaboration JCAP 07 094 (2024)



$$\gamma = -2.21^{+0.36}_{-0.29}$$



including best-fit shift of -0.9σ in X_{max} scale:

$$\gamma = -1.04^{+0.44}_{-0.33}$$

true composition on Earth is heavier
→ spectral index can become softer

Why is the spectral index so unexpectedly hard?

possible explanations:

1) source evolution

   e.g. Pierre Auger Collaboration JCAP 05 024 (2023)

2) systematic effects

   e.g. Pierre Auger Collaboration JCAP 01 022 (2024)

3) **interactions/magnetic confinement in source environment**

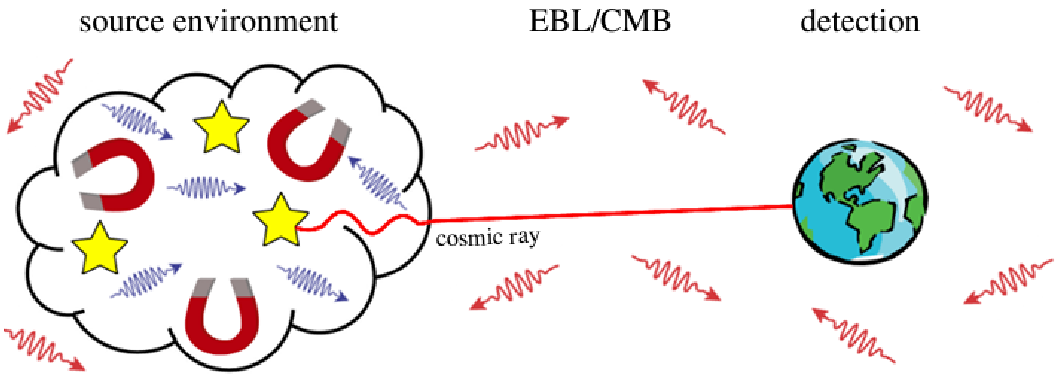
   e.g. Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)

4) cutoff shape

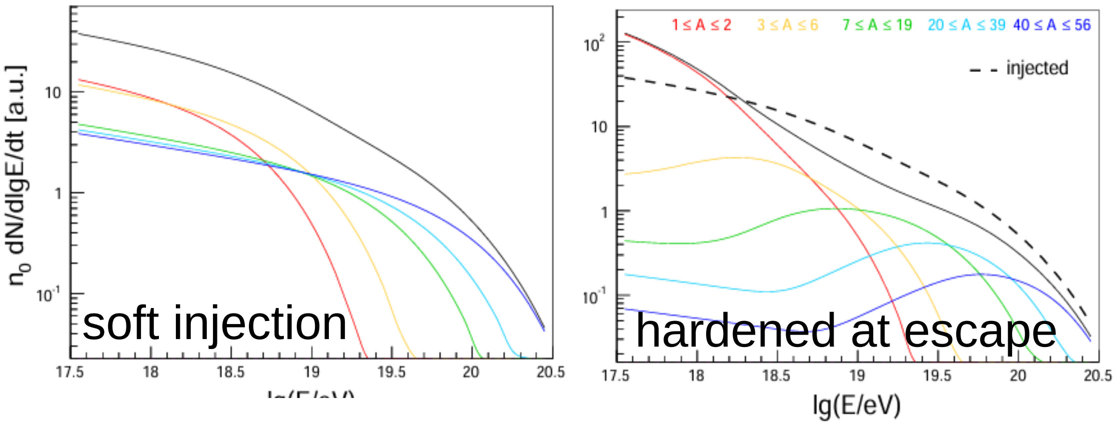
   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

5) extragalactic magnetic field

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)



high E: easier to escape
low E: more likely to interact



Why is the spectral index so unexpectedly hard?

possible explanations:

1) source evolution

   e.g. Pierre Auger Collaboration JCAP 05 024 (2023)

2) systematic effects

   e.g. Pierre Auger Collaboration JCAP 01 022 (2024)

3) interactions/magnetic confinement in source environment

   e.g. Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)

4) **cutoff shape**

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

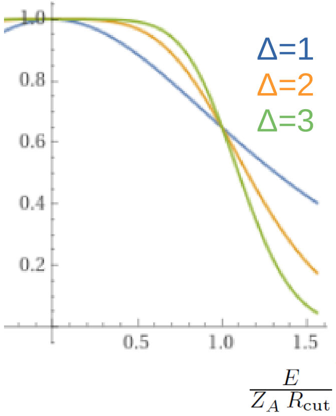
5) extragalactic magnetic field

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

$$\tilde{Q}_A(E) = \tilde{Q}_{0A} \left(\frac{E}{E_0}\right)^{-\gamma} \begin{cases} 1, & E \leq Z_A R_{\mathrm{cut}} \\ \exp\left(1 - \frac{E}{Z_A R_{\mathrm{cut}}}\right), & E > Z_A R_{\mathrm{cut}} \end{cases}$$

replace by:

$$\mathrm{sech}\left(\left(\frac{E}{Z_A R_{\mathrm{cut}}}\right)^{\Delta}\right)$$

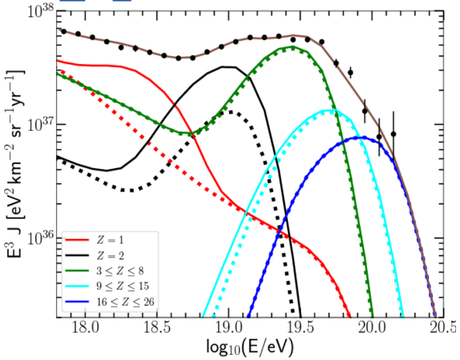


best-fit spectral index:

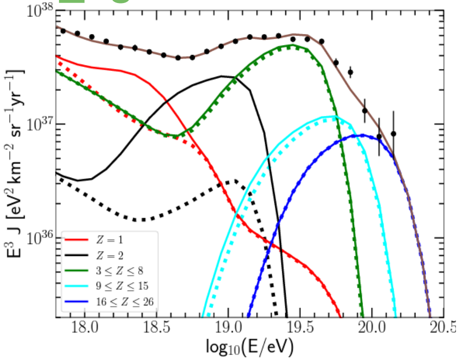
Δ	γ_H
1	-2.19
2	0.16
3	0.56

Δ=2 also predicted by simulations of magnetic acceleration, see *Comisso, Farrar, Muzio arXiv:2410.05546*

Δ=1



Δ=3



Why is the spectral index so unexpectedly hard?

possible explanations:

1) source evolution

   e.g. Pierre Auger Collaboration JCAP 05 024 (2023)

2) systematic effects

   e.g. Pierre Auger Collaboration JCAP 01 022 (2023)

3) interactions/magnetic confinement in source environment

   e.g. Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)

4) cutoff shape

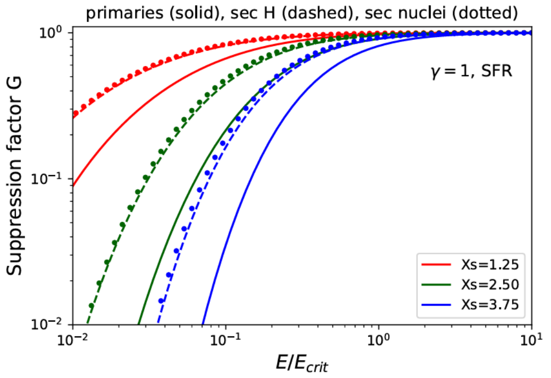
   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

5) **extragalactic magnetic field**

   e.g. Pierre Auger Collaboration JCAP 07 094 (2024)

best-fit spectral index:

	no EGMF	with EGMF
Δ	γ_H	γ_H
1	-2.19	-2.19
2	0.16	1.03
3	0.56	1.43



EGMF can have strong effect on injection, but only for:

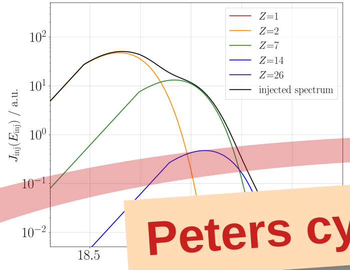
- steep injection cutoff $\Delta>1$
- & source densities < 10^{-3} Mpc^{-3}
- & very strong field strengths B~10-200 nG between nearest sources & Earth

➔ then: can reach γ~2

Adding arrival directions as an observable

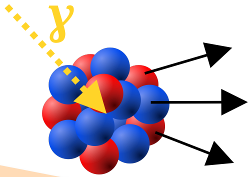
source distribution

injection



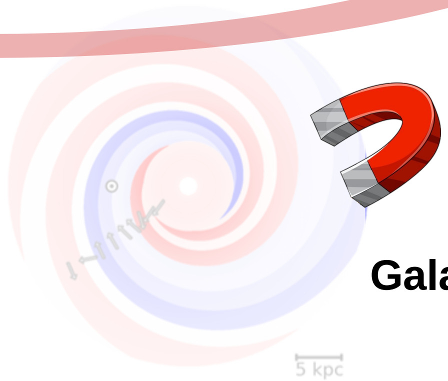
Peters cycle

propagation through extragalactic space



CRPropa

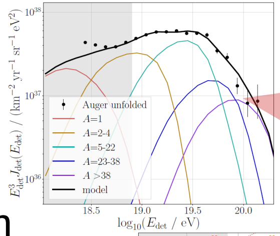
extragalactic magnetic fields

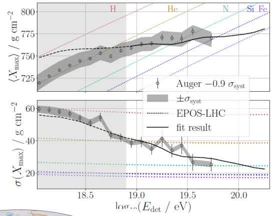


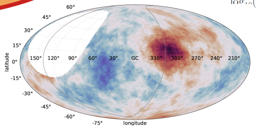
Galactic magnetic fields

compare to data

- energy spectrum
- mass composition
- **arrival directions**

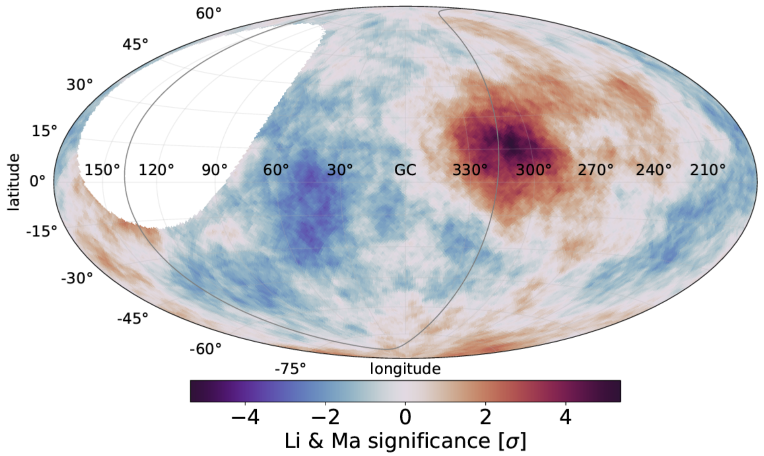






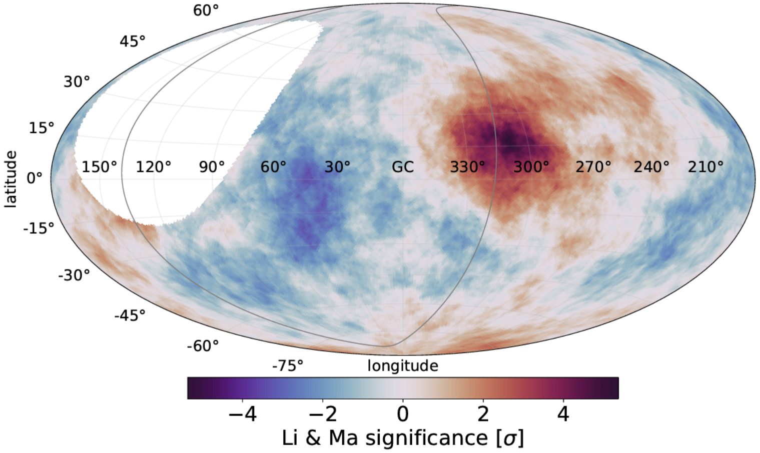
What do the arrival directions look like at ~40 EeV?

sky in cosmic rays at E > 40 EeV:

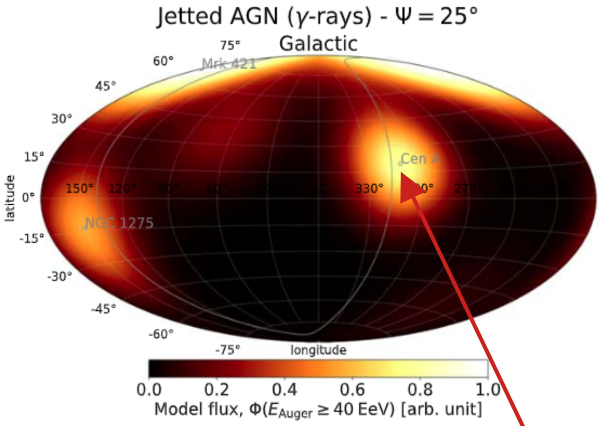


What do the arrival directions look like at ~40 EeV?

sky in cosmic rays at E > 40 EeV:

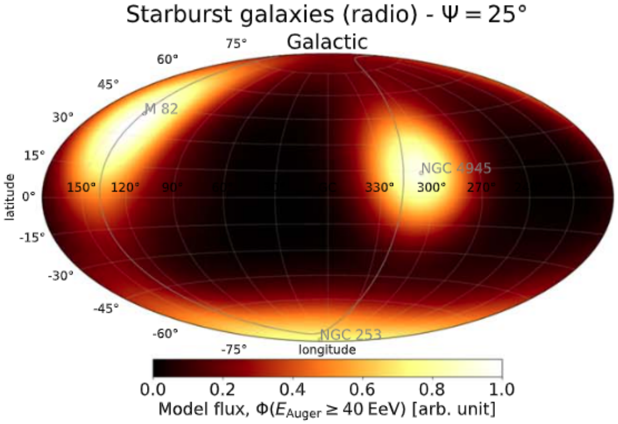


jetted active galactic nuclei (γ-AGNs):



nearest AGN: *Centaurus A*

starburst galaxies (SBGs):



Nearby starburst galaxies or active galactic nuclei could explain the measured arrival directions based on their directions & fluxes

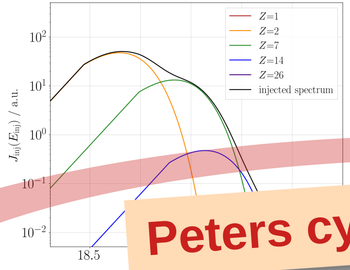
TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

Adding arrival directions to the model

source distribution

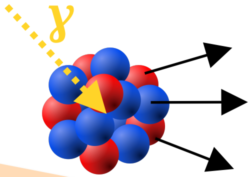
homogeneous + catalog

injection



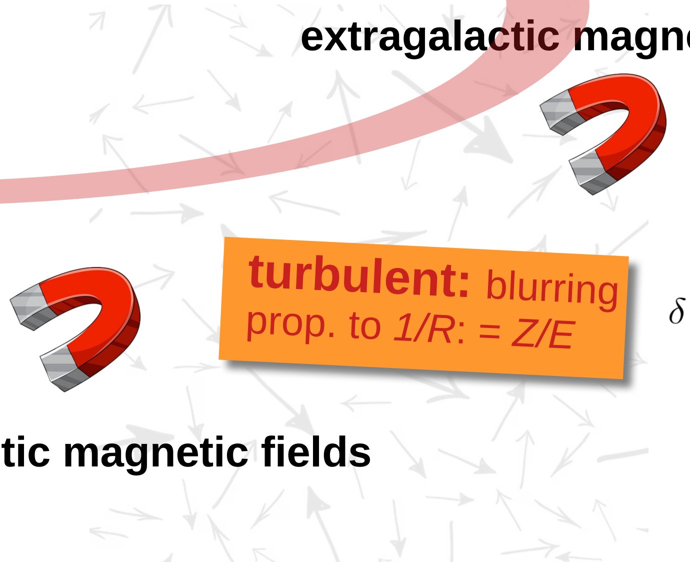
Peters cycle

propagation through extragalactic space



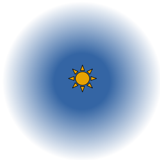
CRPropa

extragalactic magnetic fields



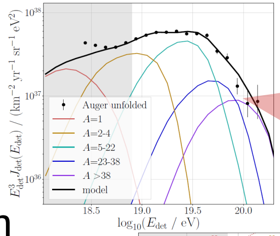
turbulent: blurring prop. to *1/R*: = *Z/E*

$$\delta = \frac{\delta_0}{R/10\ \mathrm{EV}}$$

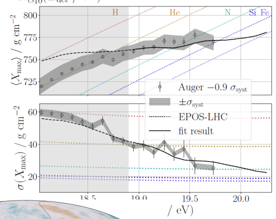


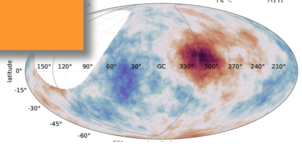
Galactic magnetic fields

compare to data



- energy spectrum
- mass composition
- **arrival directions E>16 EeV**



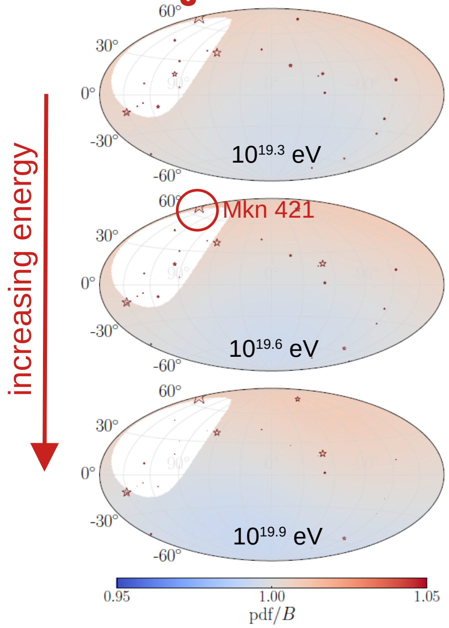


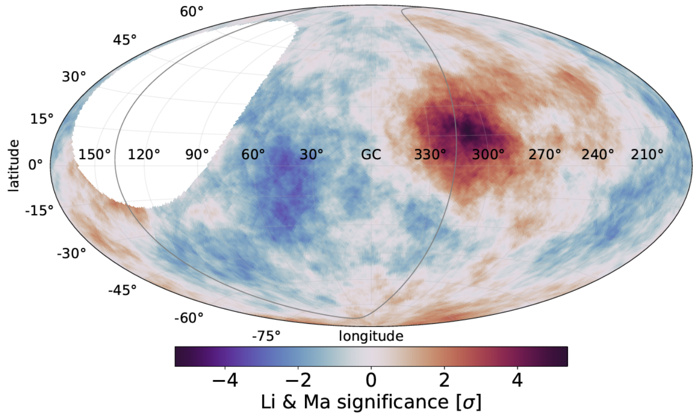
Best-fit model: arrival directions

γ-AGNs

Centaurus A

Starburst Galaxies





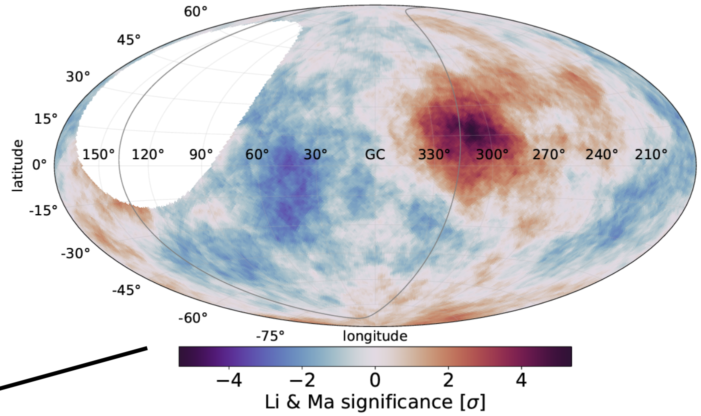
TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

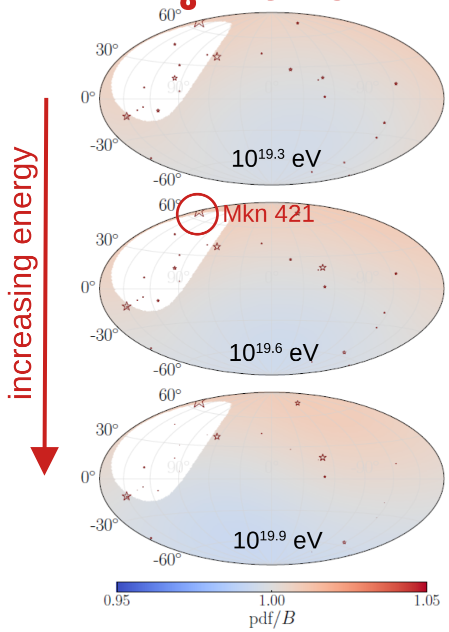
Best-fit model: arrival directions

ɣ-AGNs

Centaurus A

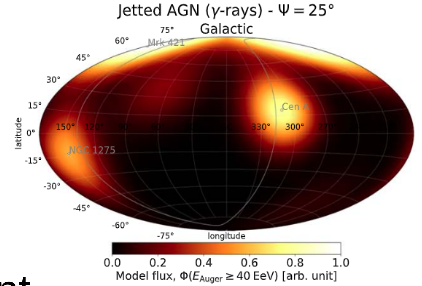
Starburst Galaxies





does not describe data well!

- blazar Mkn 421 severely overweighted
- UHECR flux not proportional to ɣ-ray flux
- changes to simplified model: propagation, energy-dependent catalog contribution, rigidity-dependent blurring
  - ɣ-AGN model actually not in agreement



TB for the Pierre Auger Collaboration, PoS ICRC 2023
The Pierre Auger Collaboration JCAP01(2024)022

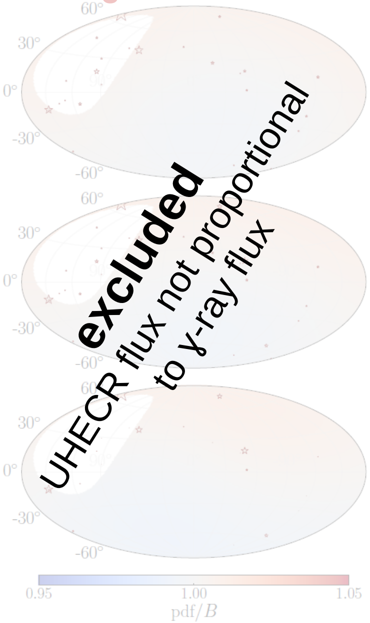
Best-fit model: arrival directions

γ-AGNs

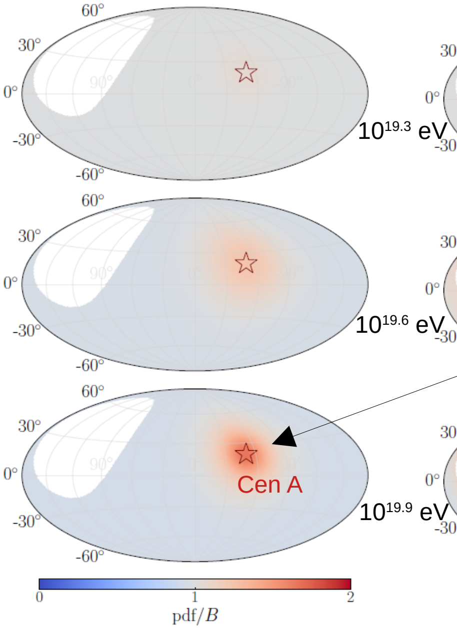
Centaurus A

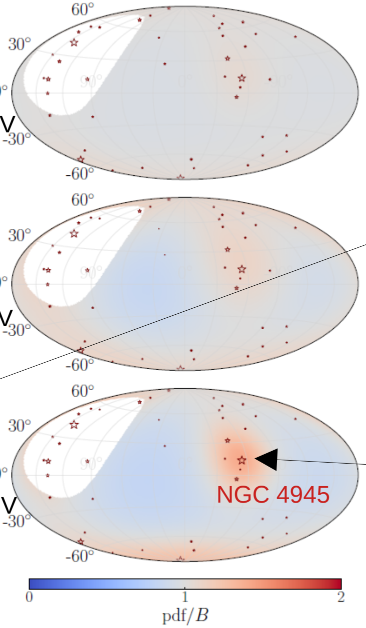
Starburst Galaxies

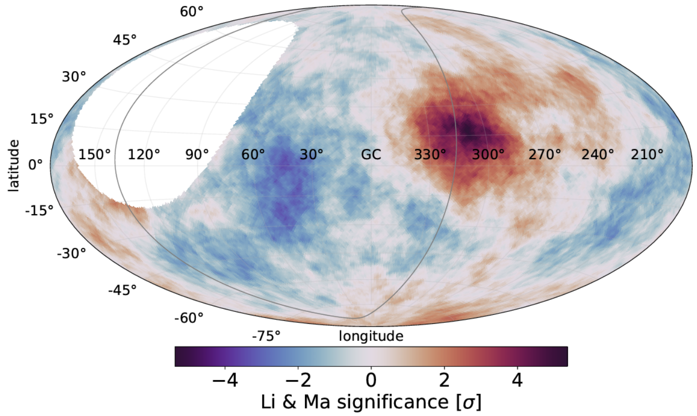
increasing energy



excluded
UHECR flux not proportional
to γ-ray flux



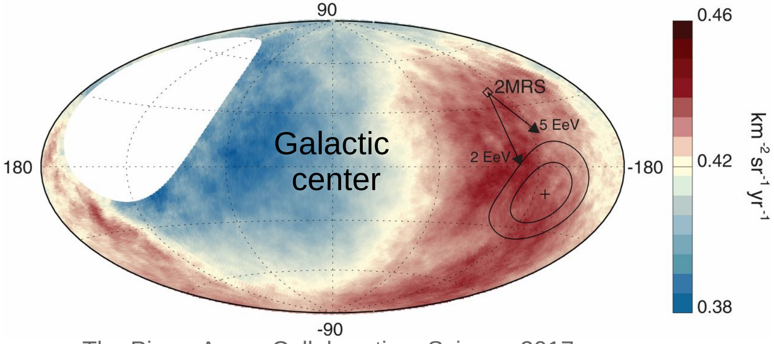




- **starburst galaxy model favored with 4.5σ significance over homogeneous model!**
- mostly due to Centaurus A / NGC 4945 region

What about lower energies?

Cosmic-ray sky at E > 8 EeV:

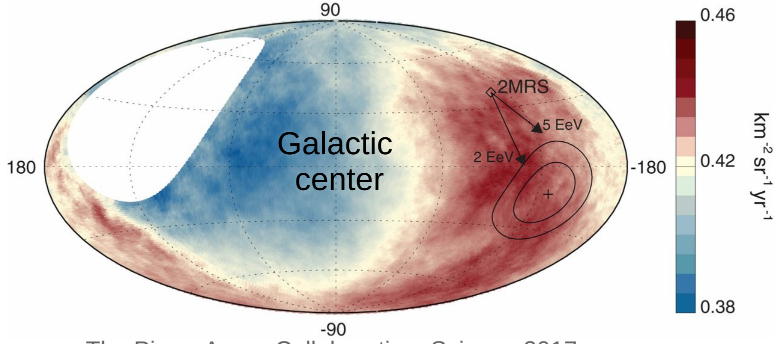


The Pierre Auger Collaboration, Science 2017

- **dipole with significance >5σ**
- no significant quadrupole or higher moments
- not aligned with Galactic center
  - → **sources extragalactic!**

What about lower energies?

Cosmic-ray sky at E > 8 EeV:

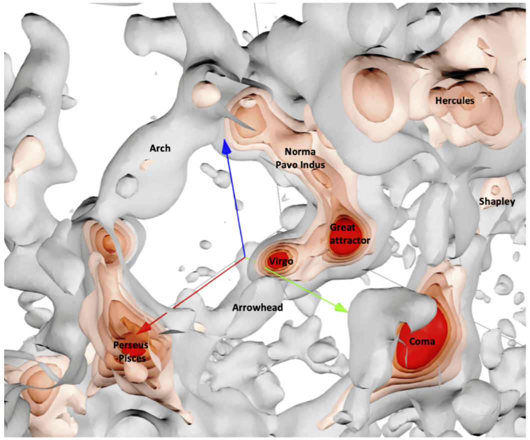


The Pierre Auger Collaboration, Science 2017

- **dipole with significance >5σ**
- no significant quadrupole or higher moments
- not aligned with Galactic center
  - → **sources extragalactic!**

sources at lower energy:

- → larger horizon
- → more sources contribute, not dominated by nearby candidates



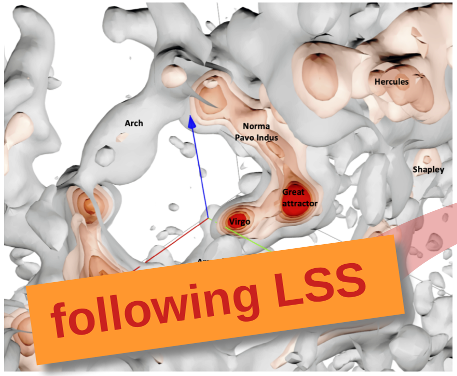
→ dipole can be explained by extragalactic sources following the **large-scale structure of the universe**

+ deflection by Galactic magnetic field

e.g. Ding, Globus, Farrar ApJL 913 L13 (2021)
Globus, Piran, Hoffman, Carlesi, Pomarede MNRAS 484 (2019)
Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)
The Pierre Auger Collaboration arXiv:2408.05292
...

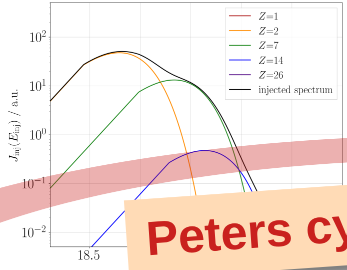
Include arrival directions: large-scale

source distribution



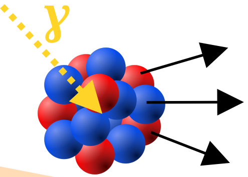
following LSS

injection



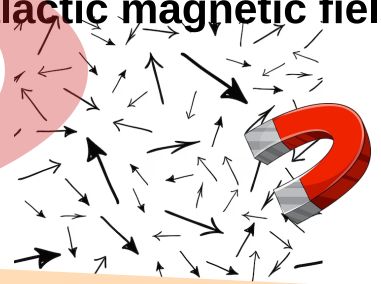
Peters cycle

propagation through extragalactic space

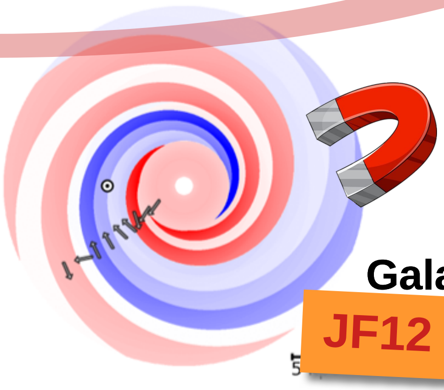


CRPropa

extragalactic magnetic fields



turbulent (or neglected)

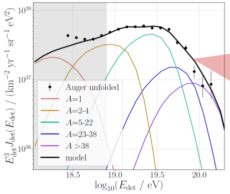


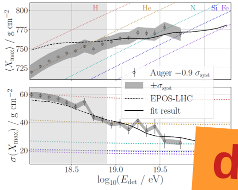
Galactic magnetic fields

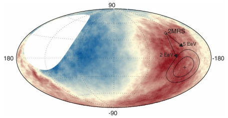
JF12 (& UF23 models)

compare to data

- energy spectrum
- mass composition
- arrival directions
- (multimessenger)

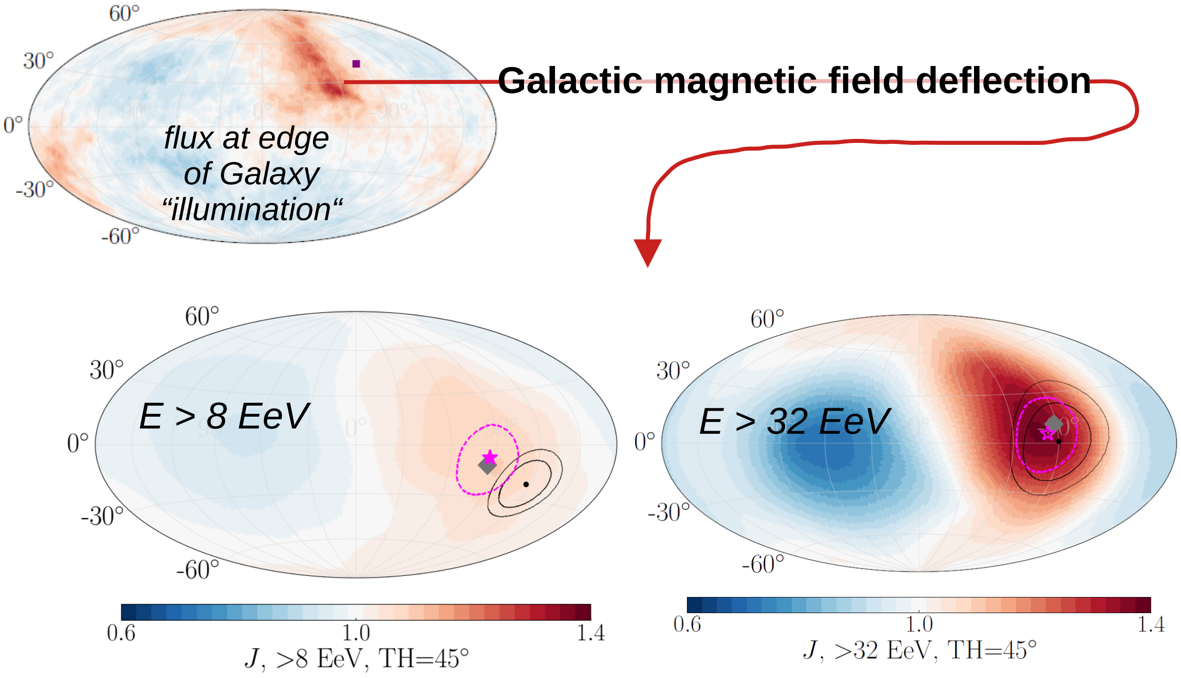


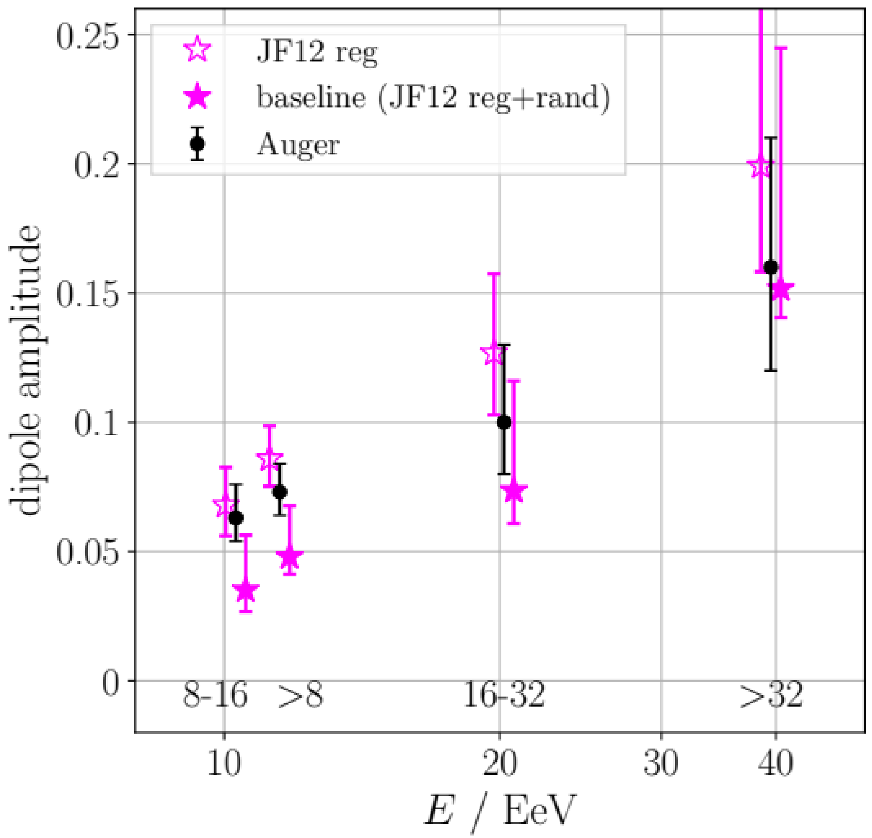




dipole E>8 EeV

Dipole predictions using JF12

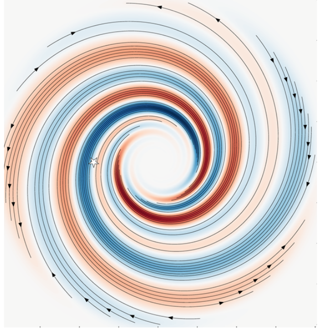




- dipole amplitude + energy evolution ✓
- dipole direction not perfect at lower energy
  → **update of GMF model?**

Using new magnetic field models

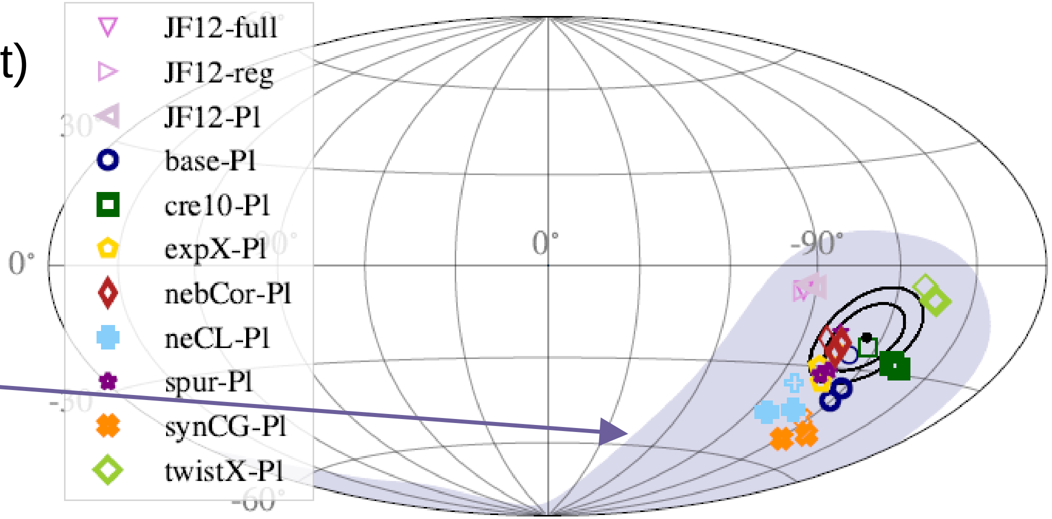
8 new GMF models recently became available (UF23)



Unger & Farrar,
ApJ 2024 970 95

- all predict the dipole direction close to measured one!
  - ➔ but none fits perfectly at all energies
- **models quite similar**
  - ➔ uncertainties on GMF (random & turbulent) do not obstruct conclusions on sources
  - ➔ cannot reject any model
- **biggest uncertainty: from cosmic variance**

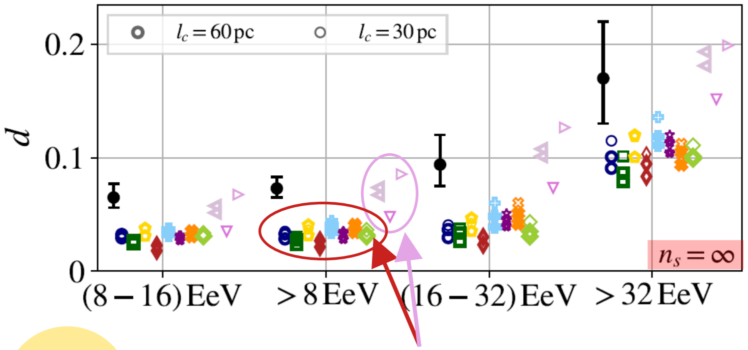
$n_s = 10^{-3}$ Mpc^{-3}

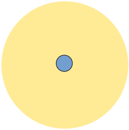


E > 8 EeV

➔ *What value is realistic for the source density n_s?*

Dipole & quadrupole amplitudes with UF23

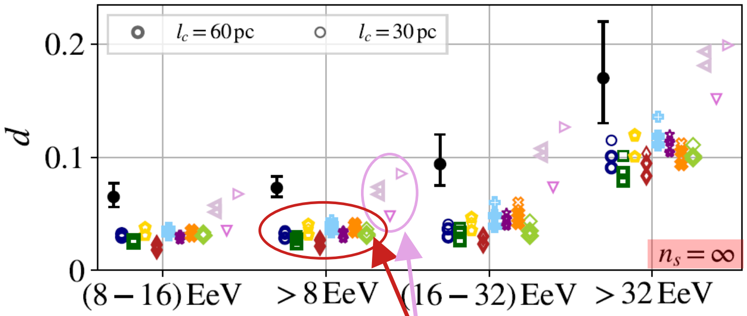


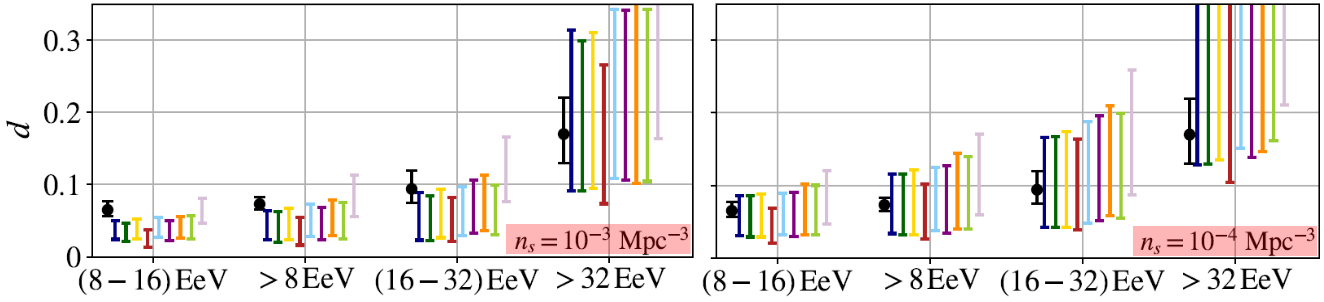


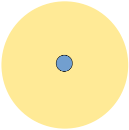
dipole amplitude around half of JF12

→ for UF23 models: continuous model disfavored

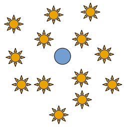
Dipole & quadrupole amplitudes with UF23



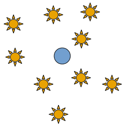




dipole amplitude around half of JF12

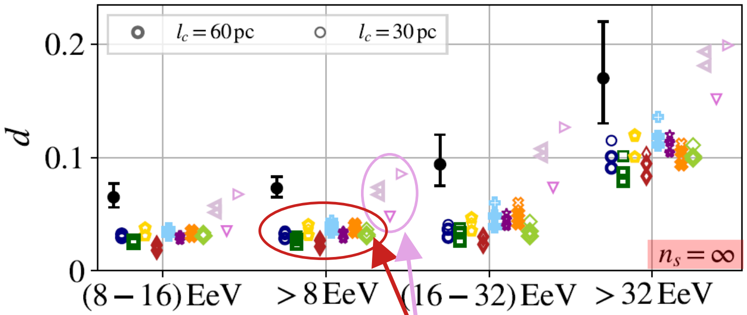


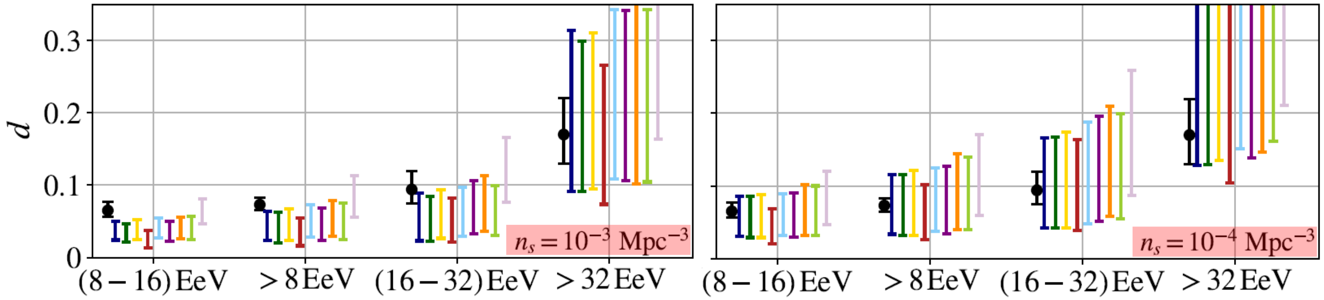
for **densities 10^{-3} to 10^{-4} Mpc^{-3}**
→ good compatibility with dipole amplitude

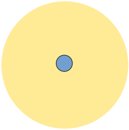


→ **for UF23 models: continuous model disfavored**

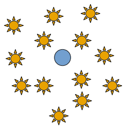
Dipole & quadrupole amplitudes with UF23





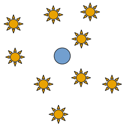


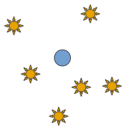
dipole amplitude around half of JF12



for **densities 10^{-3} to 10^{-4} Mpc^{-3}**

→ good compatibility with dipole amplitude

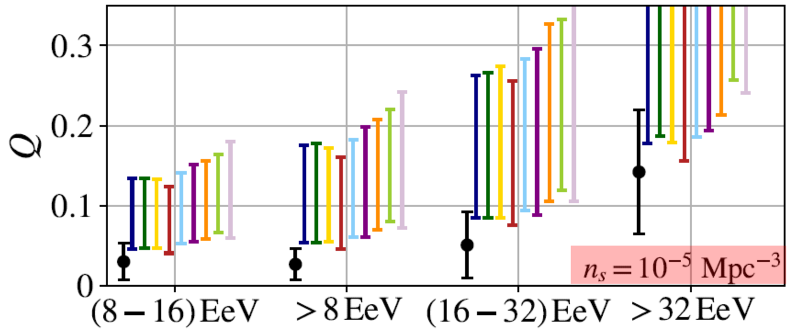




for densities < 10^{-5} Mpc^{-3}:

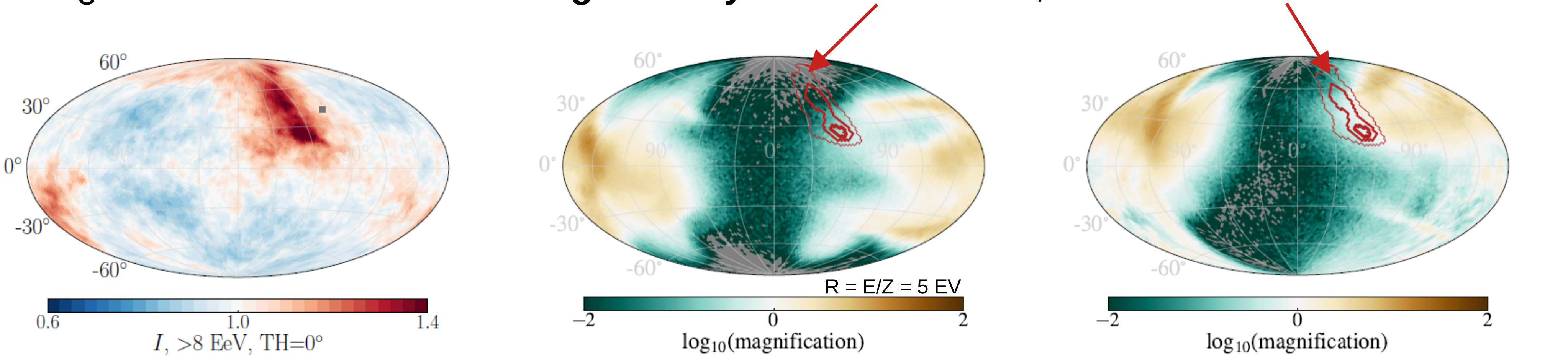
→ **too large quadrupole**

→ and dipole direction becomes more random for smaller densities



Why is the dipole amplitude so small with UF23?

- highest flux illumination is **demagnified by *all* UF23 models**, different to JF12



illumination E>8 EeV

UF23 base + Planck

JF12 + Planck

- magnification has unexpectedly large influence on dipole amplitude

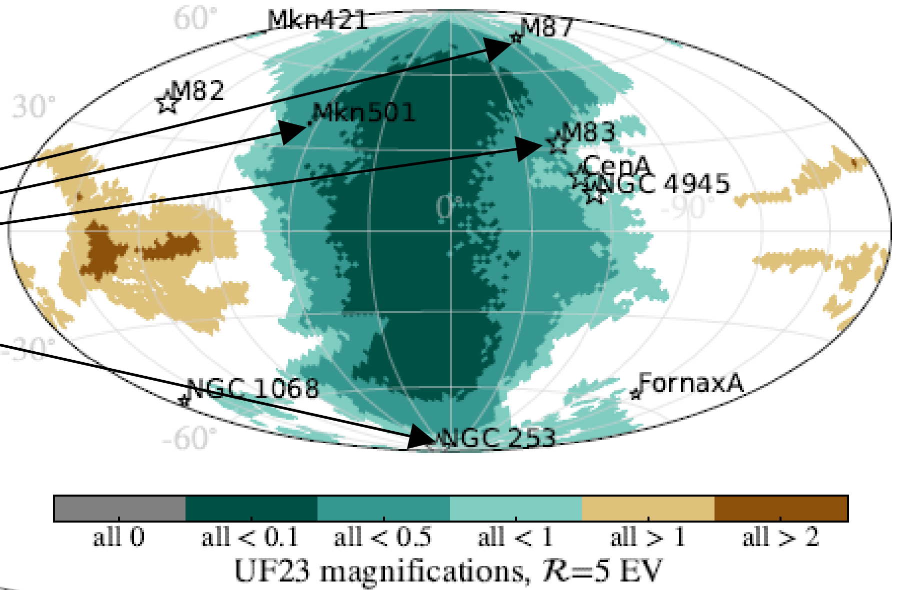
- **caution: due to uncertainties on LSS model + random magnetic field model + EGMF:**
  → source density etc. with large uncertainties

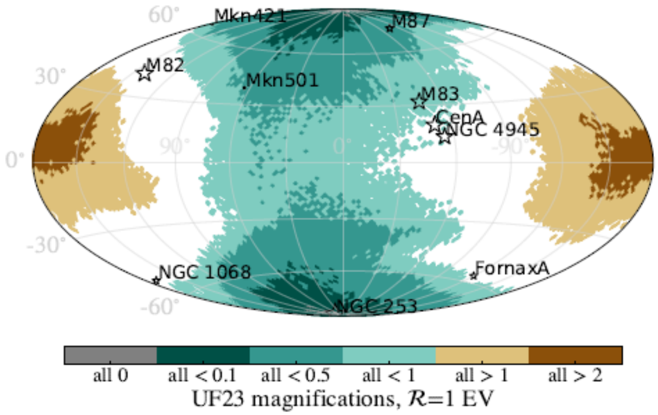
Bister, Farrar, Unger, ApJL 975 L21

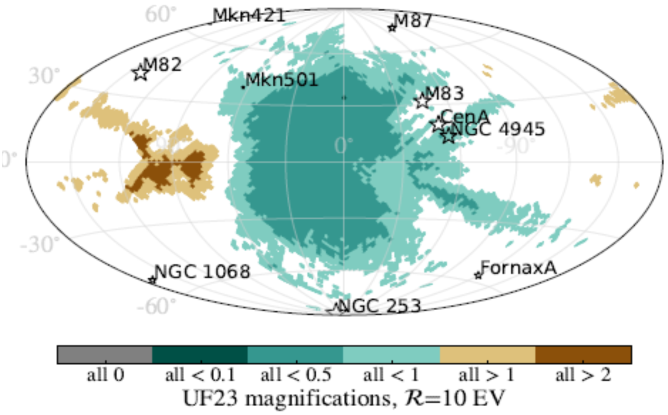
Magnification rigidity dependency

consequence of demagnification in UF23 models:

- **many source candidates in central demagnification area**
- might not see many CRs from them, at least not with rigidity R = E/Z < 5 EV

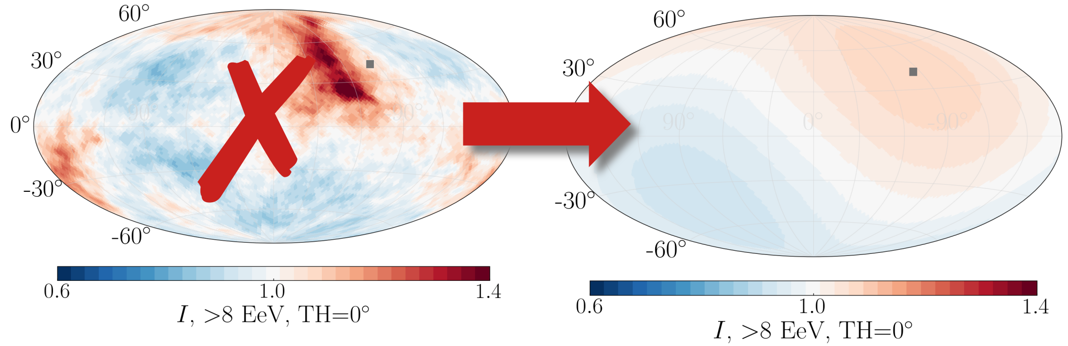


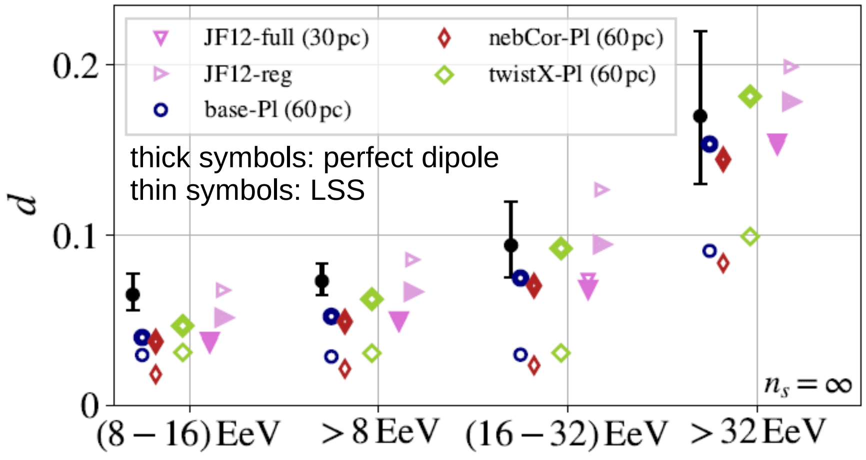




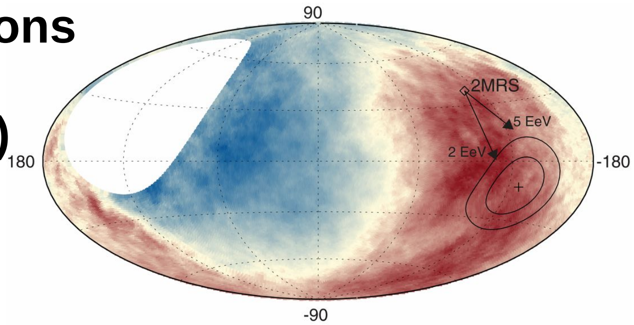
Dipolar illumination

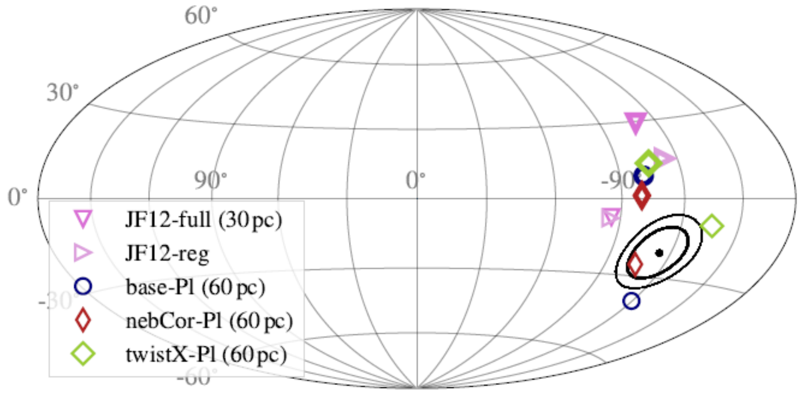
replace the illumination by dipole component:





- consequence of sensitive interplay between illumination & magnification
  - **quite different predictions of amplitude (factor 2) & direction (by 20°-60°)**

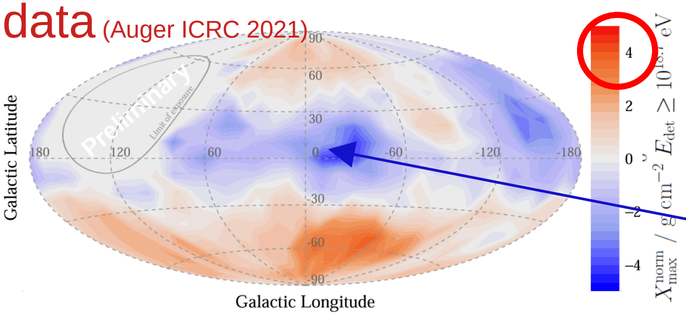




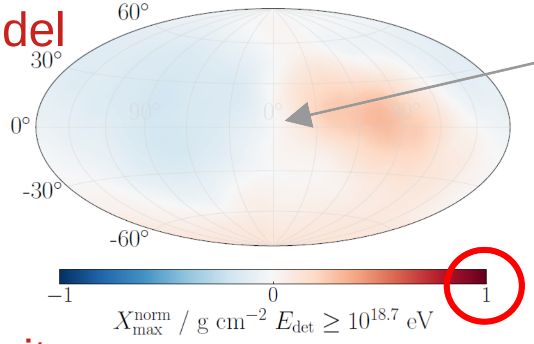
(a) energy > 8 EeV

Outlook: composition-dependent anisotropies

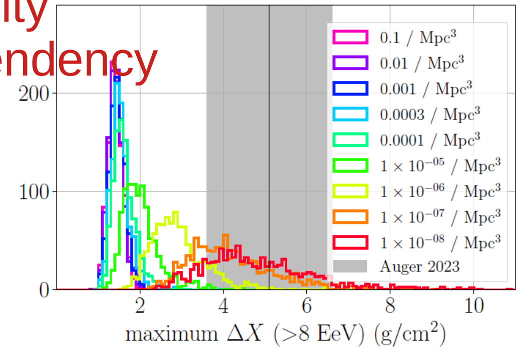
data (Auger ICRC 2021)



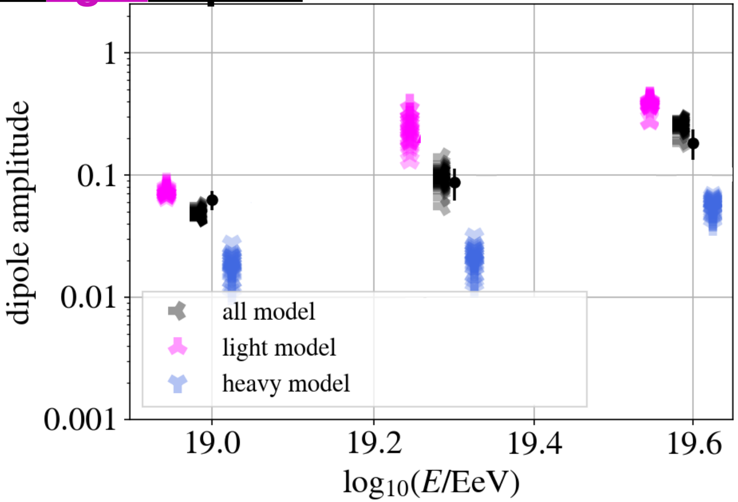
model



density dependency



- **composition-dependent arrival direction analyses** possible with neural networks, AugerPrime etc.
  - ➔ important to compare to model predictions
- e.g. **heavier composition from Galactic plane** (~3σ)
  - ➔ LSS model does not reproduce this & very small densities needed
- **split between heavy & light dipole**
  - larger amplitude for light dipole expected
  - directions also predictable



Conclusions

- UHECR picture becomes clearer and clearer
  - ➔ models important to understand data

➔ **> 8 EeV: sources most likely follow large-scale structure**
- Galactic magnetic field models lead to good agreement with measured anisotropies

➔ **> 40 EeV: individual source candidates describe data**
- like starburst galaxies, Centaurus A ~4.5σ significance

- **promising future:** detector upgrades underway (AugerPrime & TAx4), better composition differentiation, machine learning data...