Radboud University

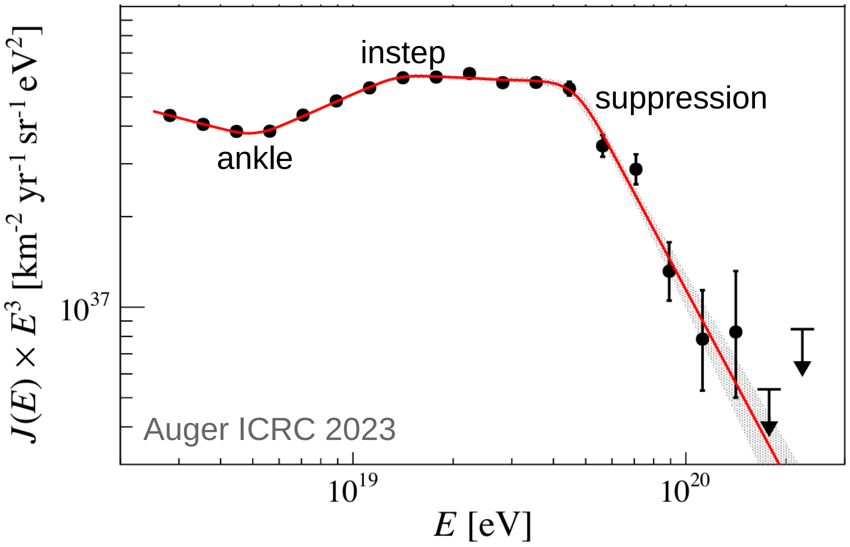
Nikhef

Review
Search for UHECR sources

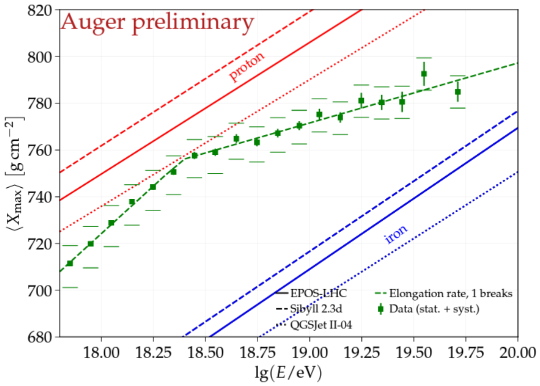
Teresa Bister

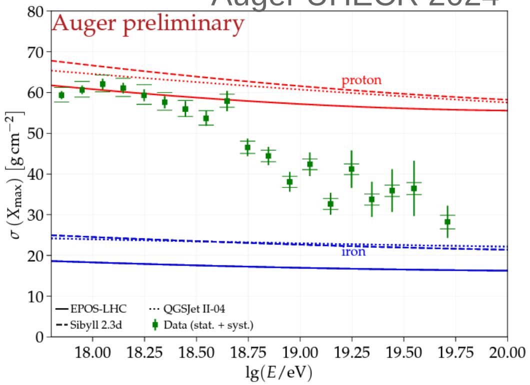
Paris, December 2024

UHECR source characteristics from the combined fit of spectrum and composition



Auger UHECR 2024





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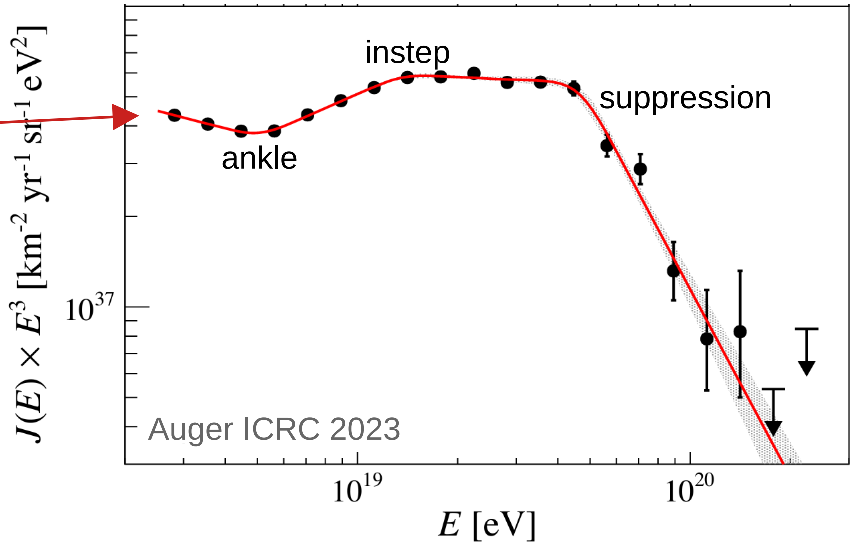
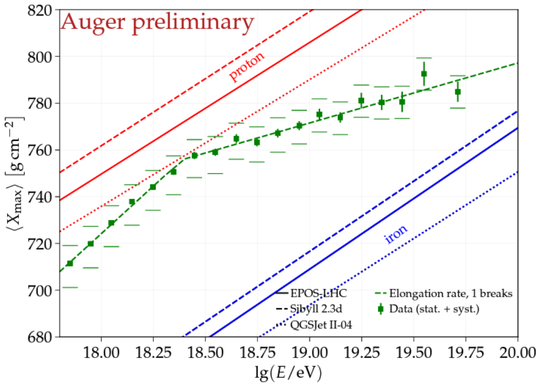
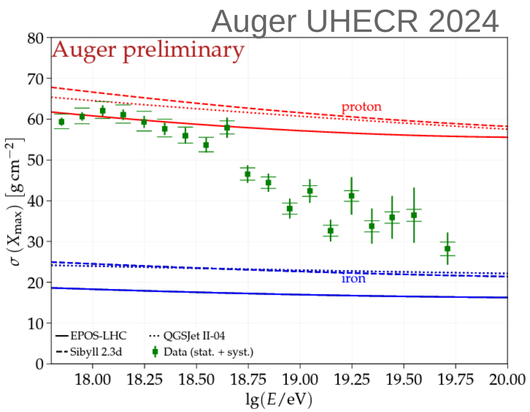
from the combined fit of spectrum and composition

UHECR data from Auger:

- pronounced features in the energy spectrum
- transition from light composition at the ankle to heavy composition at the cutoff
- small mixing visible in σ(Xmax)







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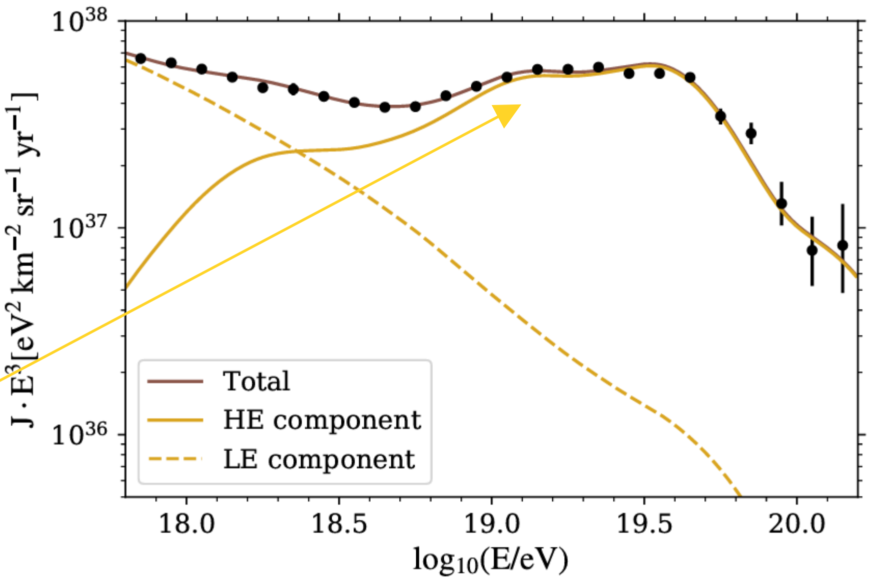

can be described by:

1) population of extragalactic sources dominating from ankle energy

Aloisio, Berenzinsky, Blasi JCAP 10 020 (2014)
Mollerach & Roulet PRD 101 103024 (2020)
Pierre Auger Collaboration JCAP 05 024 (2023)

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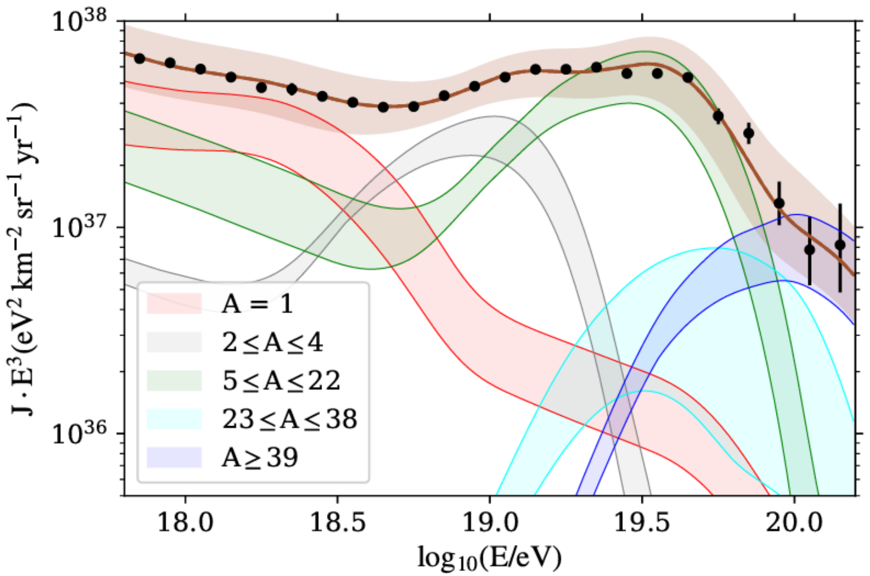
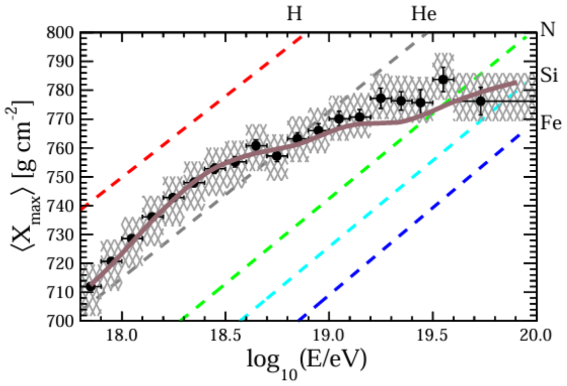
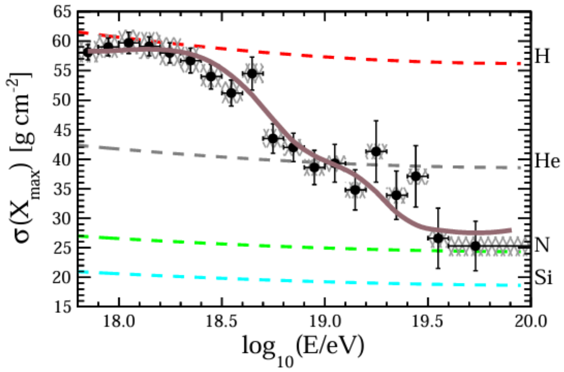


<u>can be described by:</u>

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)

→ for alternative scenarios see
Muzio, Unger, Anchordoqui PRD 109 (2024)





Gaisser, Stanev, Tilav Frontiers of Physics 8 (2013)
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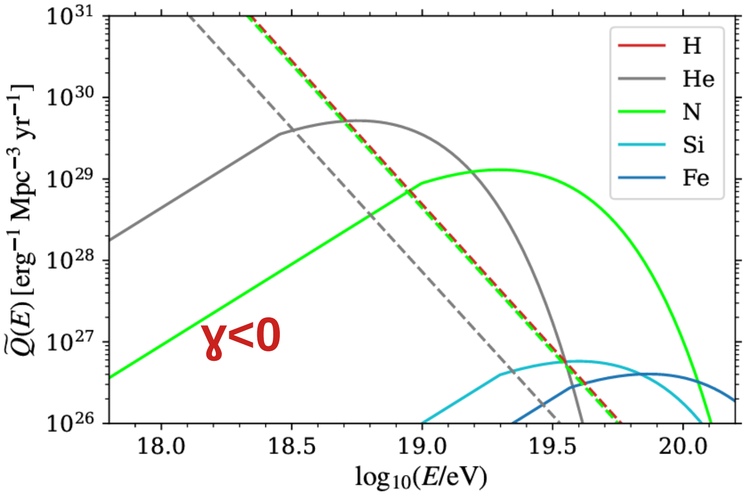

<u>**can be described by:**</u>

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)
3) very hard injection spectrum

Note that the spectral index value is highly influenced by:

- interactions & magnetic confinement in source environment
  Unger, Farrar, Anchordoqui, PRD 92 123001 (2015)
- cutoff shape
  Pierre Auger Collaboration JCAP 07 094 (2024)
  Comisso, Farrar, Muzio arXiv:2410.05546
- extragalactic magnetic field
  Pierre Auger Collaboration JCAP 07 094 (2024)
  Mollerach & Roulet PRD 101 103024 (2020)
- source evolution
  Alves Batista, de Almeida, Lago, Kotera JCAP 01 002 (2019)
  Heinze, Fedynitch, Boncioli, Winter ApJ 873 88 (2019)

Aloisio, Berenzinsky, Blasi JCAP 10 020 (2014)
Luce et al ApJ 936 62 (2022)
Pierre Auger Collaboration JCAP 05 024 (2023)

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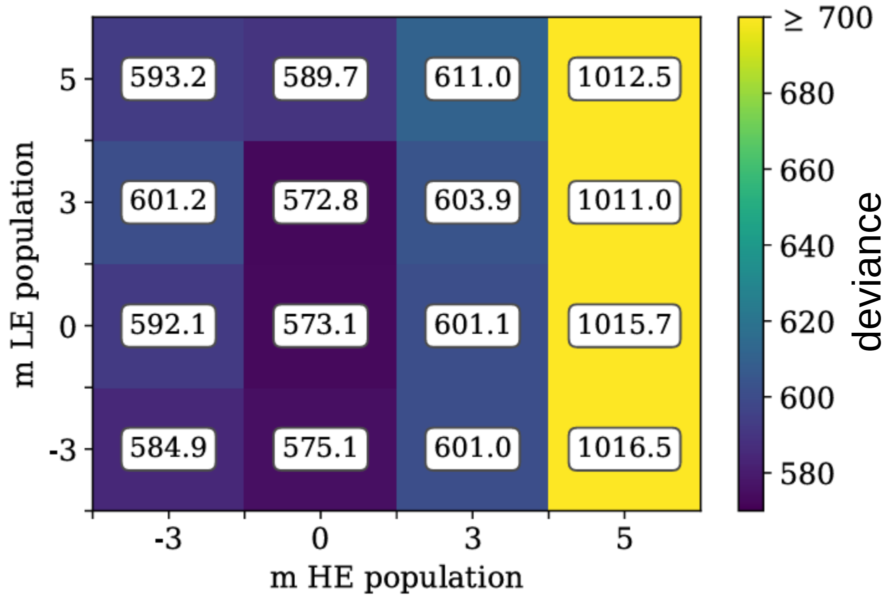

can be described by:

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)
3) very hard injection spectrum
4) not too strong source evolution

- also excluded by neutrino limits
  C. Petrucci (Auger) PoS ICRC 1520 (2023)
  Alves Batista, de Almeida, Lago, Kotera JCAP 01 002 (2019)
  Heinze, Fedynitch, Boncioli, Winter ApJ 873 88 (2019)
  Muzio, Unger, Wissel PRD 107 (2023)
- disfavors intermediate luminosity AGNs
  Hasinger, Miyaji, Schmidt A&A 441 (2005)

Pierre Auger Collaboration JCAP 05 024 (2023)

UHECR source characteristics from the combined fit of spectrum and composition

UHECR data from Auger:

- pronounced features in the energy spectrum
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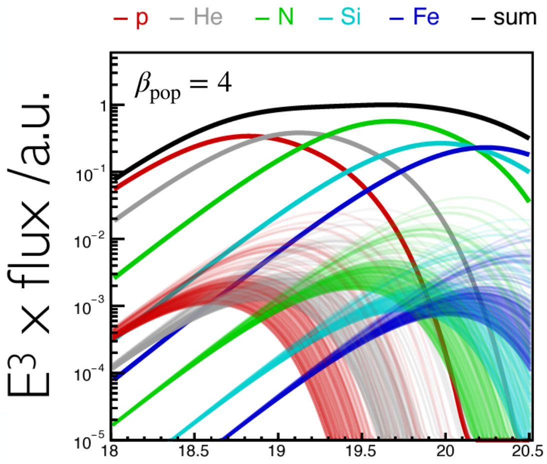
variation of source maximum energy:

$$\frac{dN}{dE_{max}} \propto E_{max}^{-\beta_{pop}}$$



<u>**can be described by:**</u>

1) population of extragalactic sources dominating from ankle energy
2) following Peters cycle (acceleration ∝ Z)
3) very hard injection spectrum
4) not too strong source evolution
5) almost identical sources

→ values of $\beta_{pop} \gtrsim$ σ(5) preferred

→ to not produce too large mass mixing

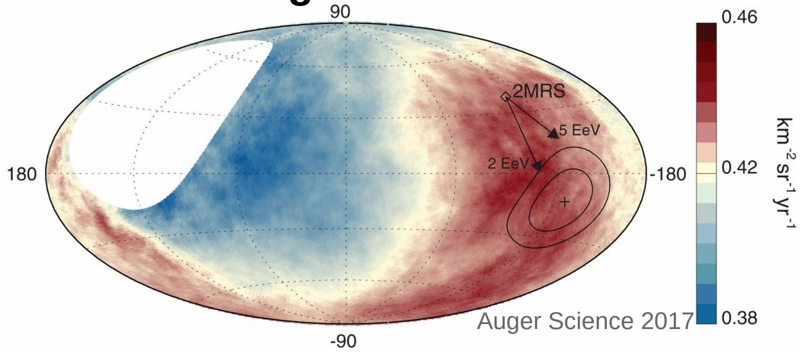
Ehlert, Oikonomou, Unger PRD 107 2023

→ see also following talk by Glennys

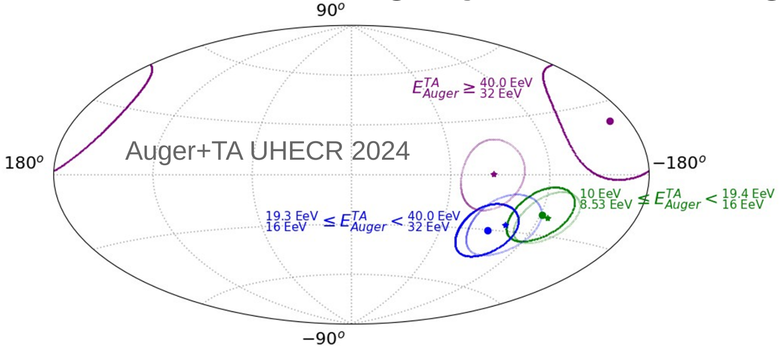
Pierre Auger Collaboration JCAP 05 024 (2023)

UHECR dipole status

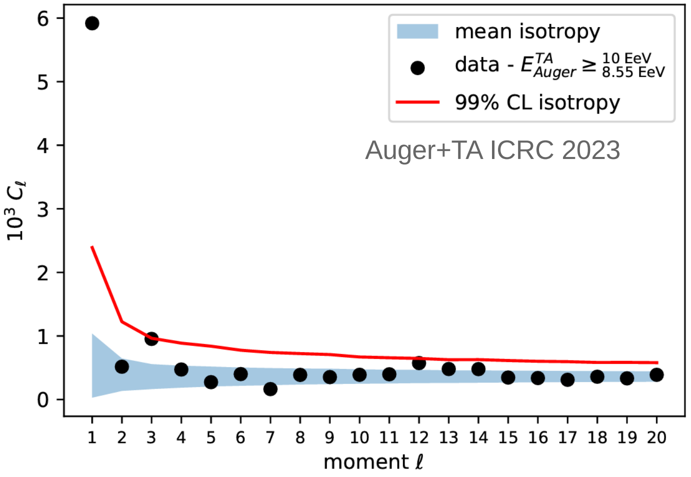
current significance 6.8σ



direction moves slightly with the energy



only dipole, no higher moments



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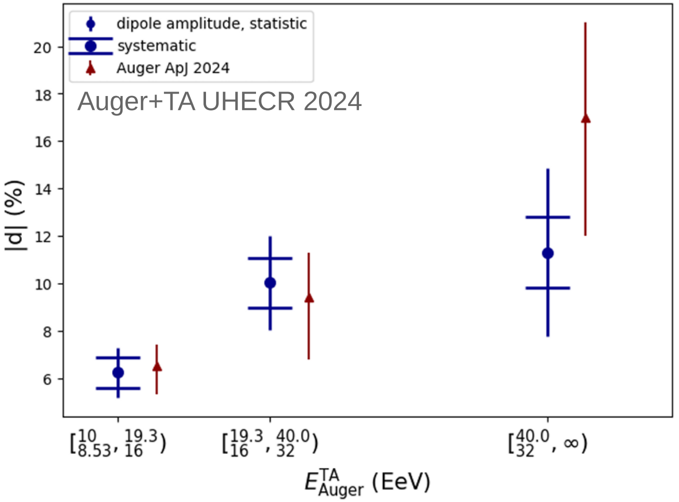

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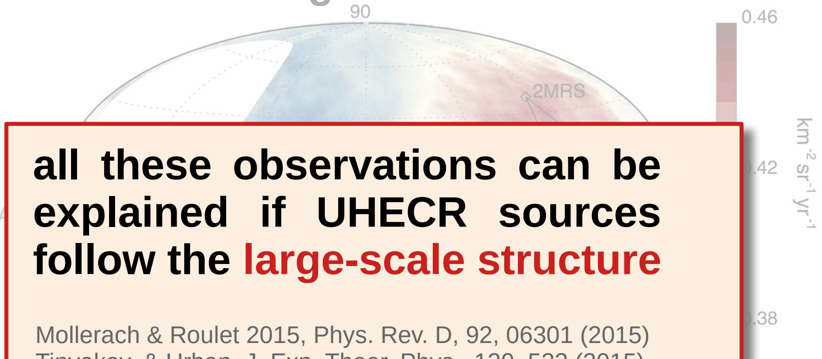
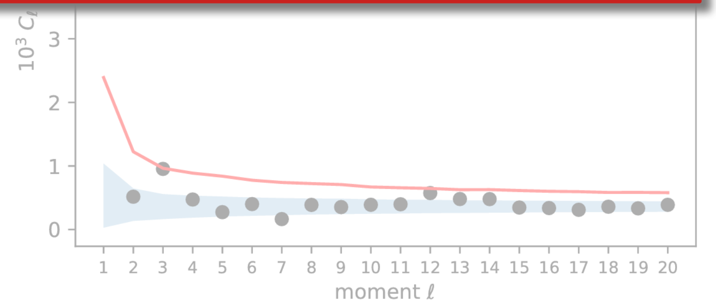


all these observations can be explained if UHECR sources follow the large-scale structure

Mollerach & Roulet 2015, Phys. Rev. D, 92, 06301 (2015)
Tinyakov, & Urban, J. Exp. Theor. Phys., 120, 533 (2015)
Globus & Piran, ApJL, 850, L25 (2017)
Tinyakov & di Matteo MNRAS 476 (2018)
Globus, Piran, Hoffman, Carlesi, Pomarede MNRAS 484 (2019)
Ding, Globus, Farrar ApJL 913 L13 (2021)
Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)
Bister & Farrar ApJ 966 71 (2024)
Bister, Farrar, Unger ApJL 975 L21 (2024)
The Pierre Auger Collaboration, arXiv:2408.05292



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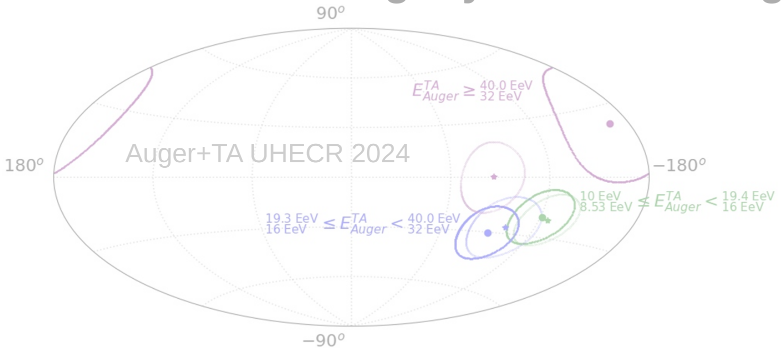

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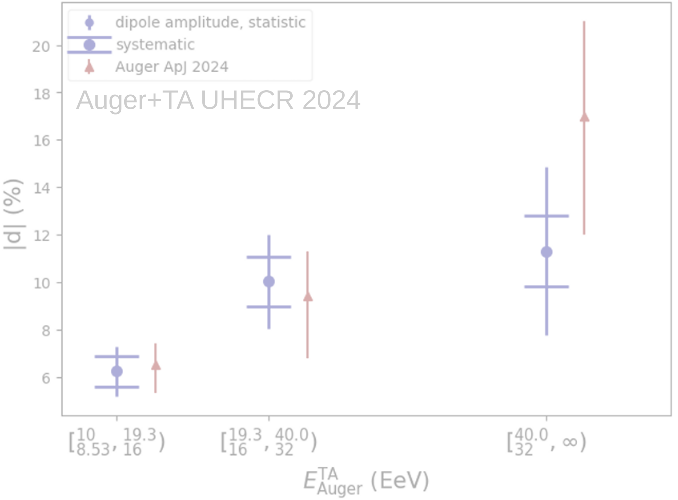

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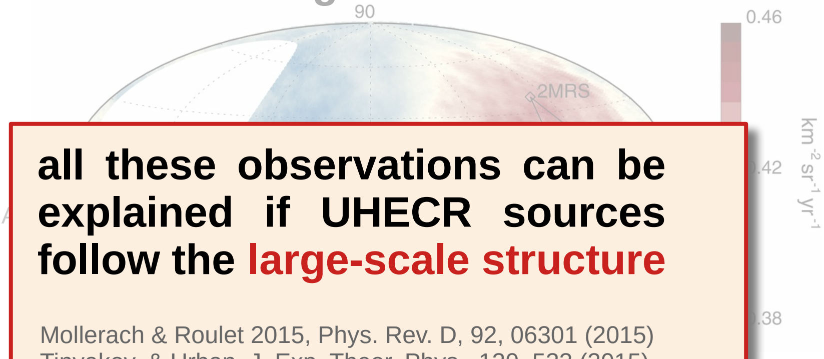

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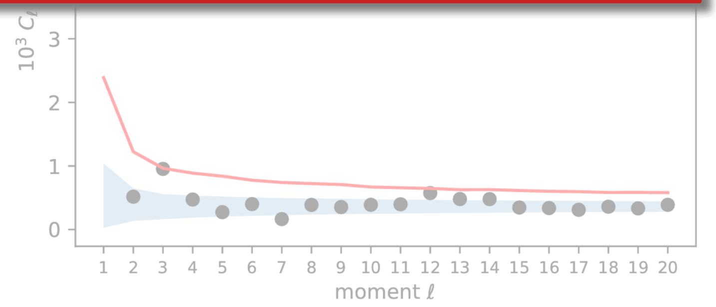
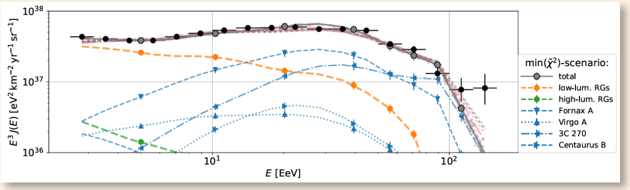
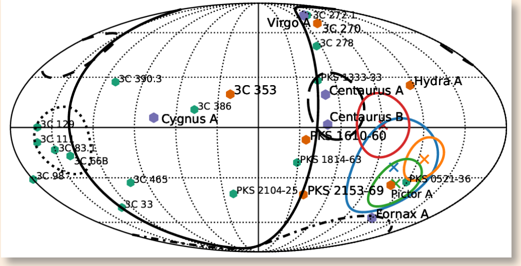


alternatives

- **few sources produce dipole**
  - e.g. description of spectrum, composition & anisotropies by catalog of individually modeled radio galaxies



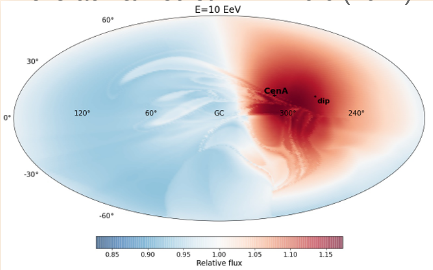


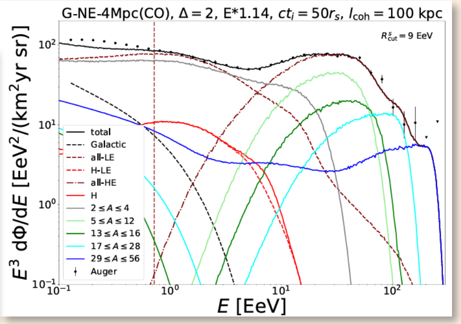
Eichmann, Kachelrieß, Oikonomou, JCAP 07 006 (2022)

  - Cen A as single dominating source
    - need very strong magnetic field $B_{\rm rms}\sqrt{l_{\rm coh}} \simeq 20\,{\rm nG}\sqrt{100\,{\rm kpc}}$ & still very strong anisotropy

see also:
Isola, Lemoine & Sigl, PRD 65 2 (2001)
Keivani, Farrar & Sutherland Astrop. Phys. 61 47 (2015)
Matthews, Bell, Blundell & Araudo MNRAS Lett. 497 (2018)

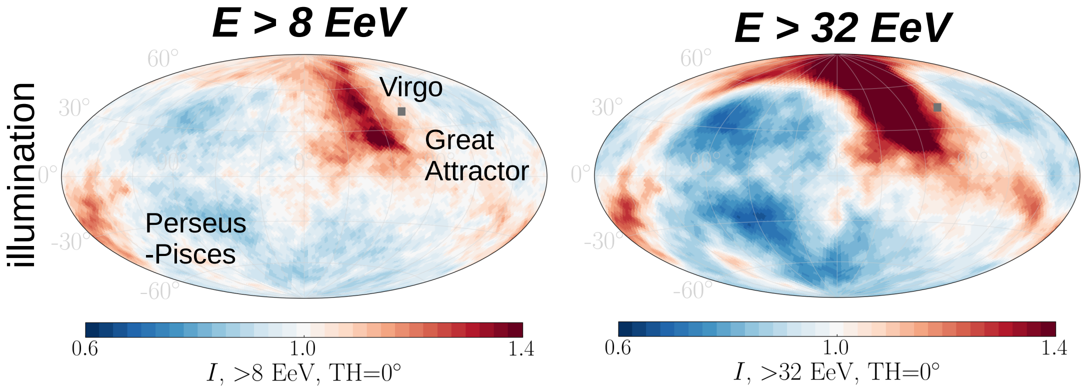
Mollerach & Roulet PRD 110 6 (2024)





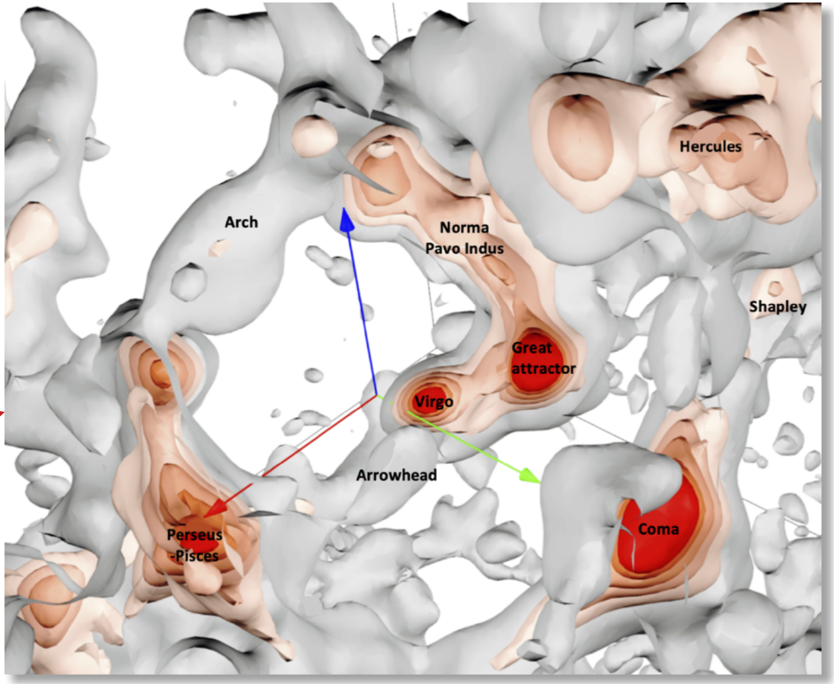
- **homogeneously distributed sources with relatively small source density** → *see later*

UHECR Flux from the large-scale structure



here using CosmicFlows (dark) matter distribution

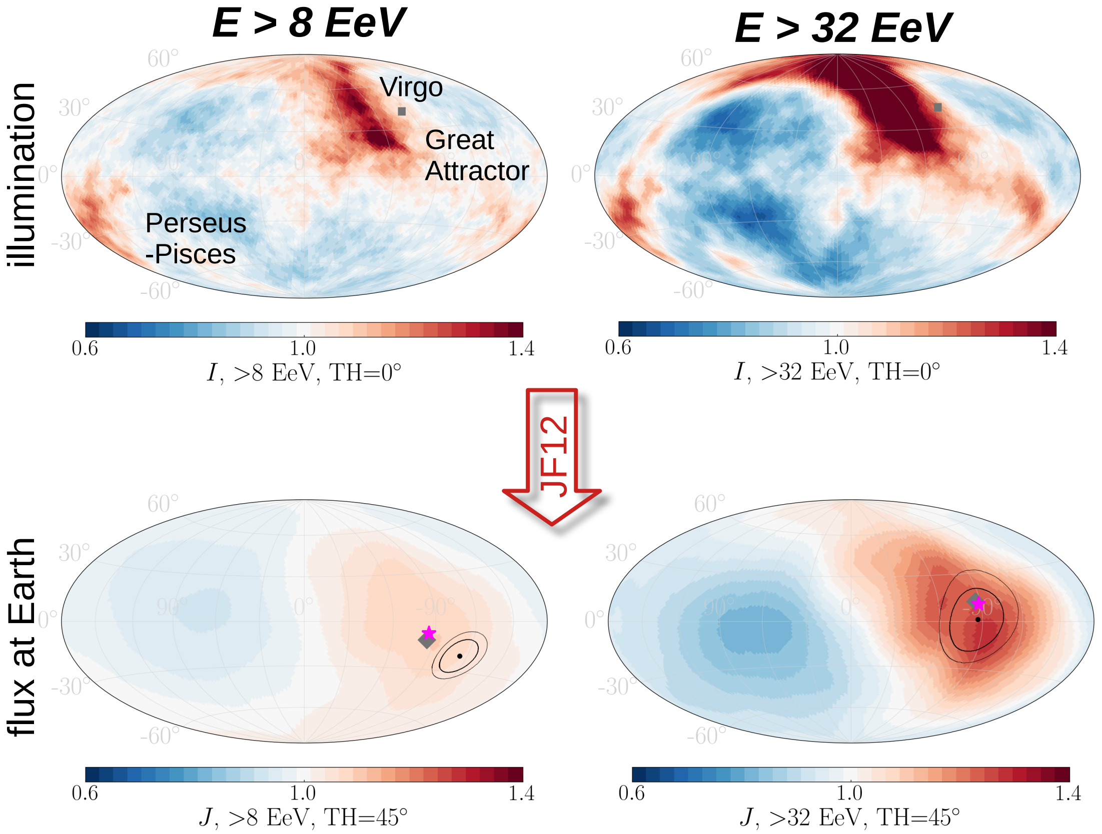
- up to 350 Mpc, beyond isotropic extrapolation
- >8 EeV: ~30% of UHECR flux from beyond 350 Mpc
  >32 EeV: ~5%



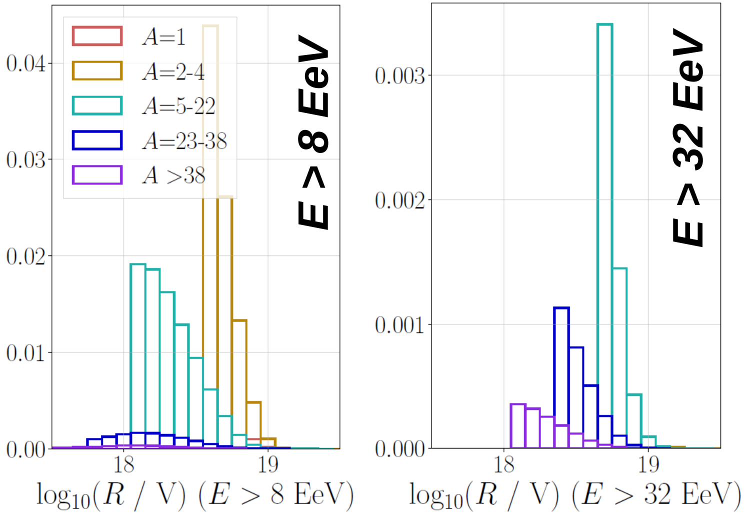
Tully et al. AJ 146 86 (2013)

Ding, Globus, Farrar ApJL 913 L13 (2021)
Bister & Farrar ApJ 966 71 (2024)

Predicted dipole directions (JF12 GMF model)



- **dipole mostly originates from Virgo + Great Attractor**
- no significant overdensity in Perseus-Pisces direction after GMF
- **change with amplitude from changing propagation horizon,** not changing rigidity



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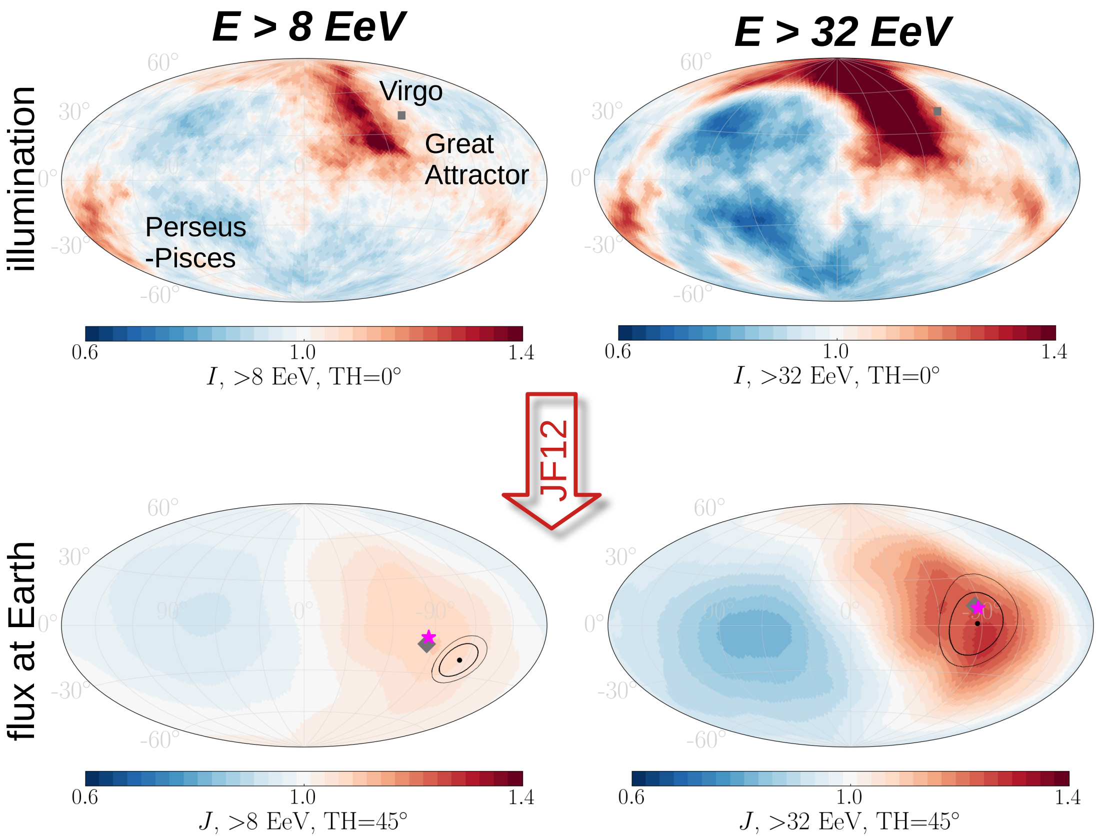

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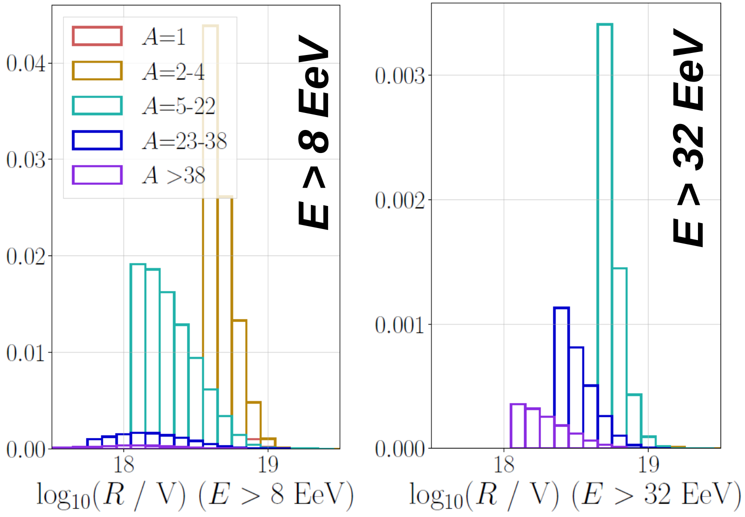
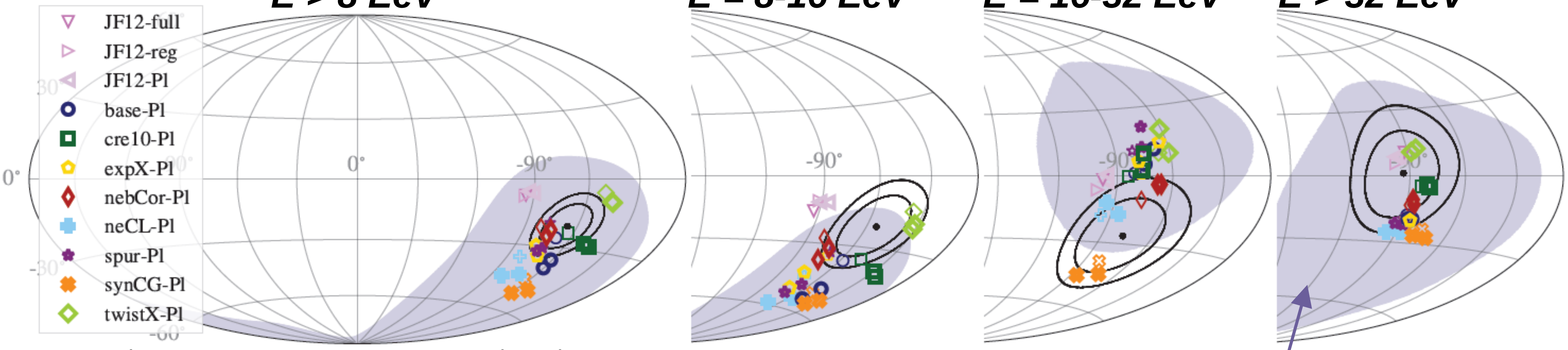


➡ **dipole direction close to measured with JF12 ✔**
What about newer models?

Bister & Farrar ApJ 966 71 (2024)

Predicted dipole directions

E > 8 EeV — *E = 8-16 EeV* — *E = 16-32 EeV* — *E > 32 EeV*



Bister, Farrar, Unger ApJL 975 L21 (2024)

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

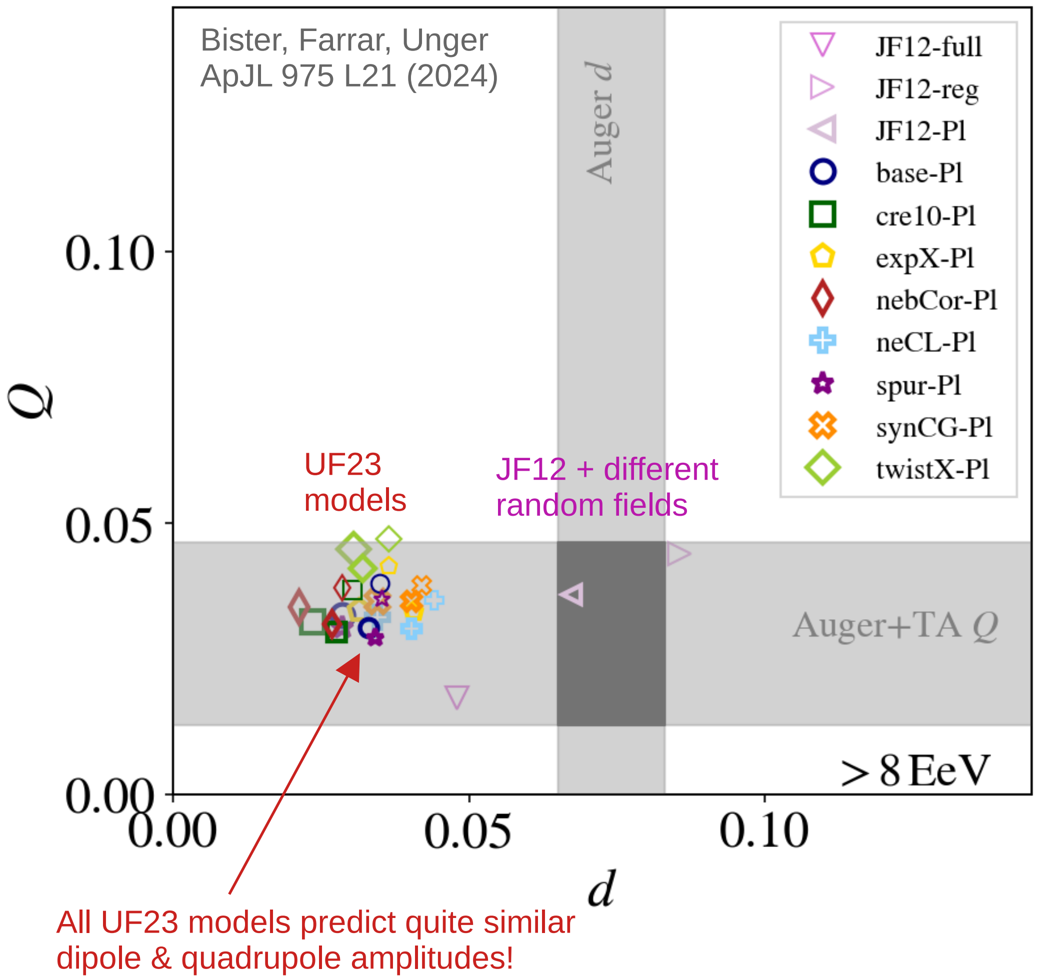
- **all UF23 models predict the dipole direction close to measured one**
  - but, none fits perfectly at all energies
  - the models are quite similar
- **uncertainties on GMF (coherent & turbulent) subdominant to uncertainty from source locations**

biggest uncertainty on dipole direction: from cosmic variance

Dipole & Quadrupole amplitudes

- **dipole amplitudes of UF23 models significantly smaller than JF12**
  - ➔ continuous model incompatible with data

What source number density leads to agreement with dipole and quadrupole?



Dipole & Quadrupole amplitudes

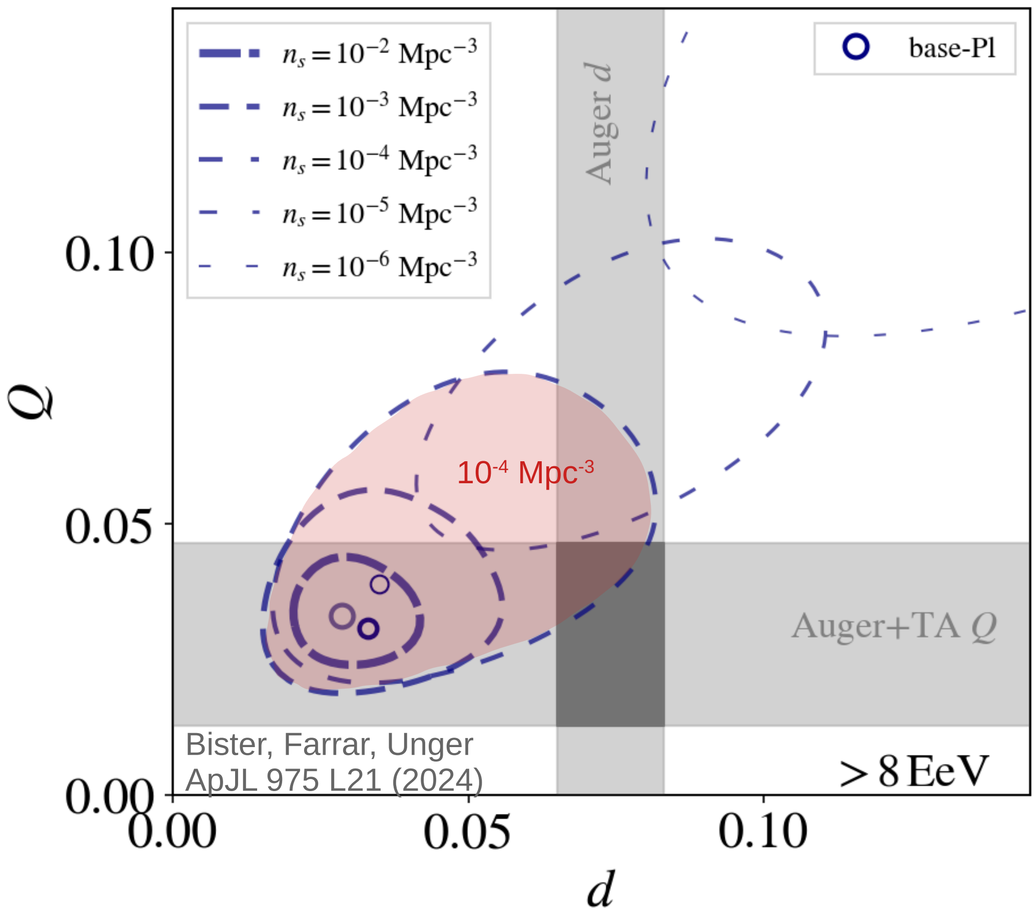
- **dipole amplitudes of UF23 models significantly smaller than JF12**
  - ➔ continuous model incompatible with data

What source number density leads to agreement with dipole and quadrupole?

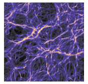
➔ **need source number density ~10^{-4} Mpc^{-3}** for compatibility with dipole and quadrupole amplitudes with UF23

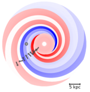
➔ **cosmic variance again dominant over differences between GMF models**

see also Allard, Aublin, Baret, Parizot A&A 664 A120 (2022)



Further uncertainties on the source number density


EGMF → can decrease compatible density when it smoothes the anisotropy Bister & Farrar ApJ 966 71 (2024)


Galactic random field → updates hopefully soon

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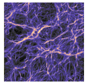

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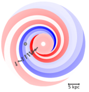

Galactic random field → updates hopefully soon

composition → probably minor uncertainty Bister & Farrar ApJ 966 71 (2024)

- weak correlation with LSS: **UHECRs are heavier at the highest energies**
  Telescope Array Collaboration PRL 133 041001 & PRD 110 022006 (2024); Ding, Globus & Farrar ApJL 913 L13 (2021)

$n_s=10^{-4}$ Mpc^{-3}

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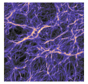
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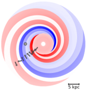
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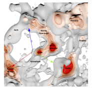
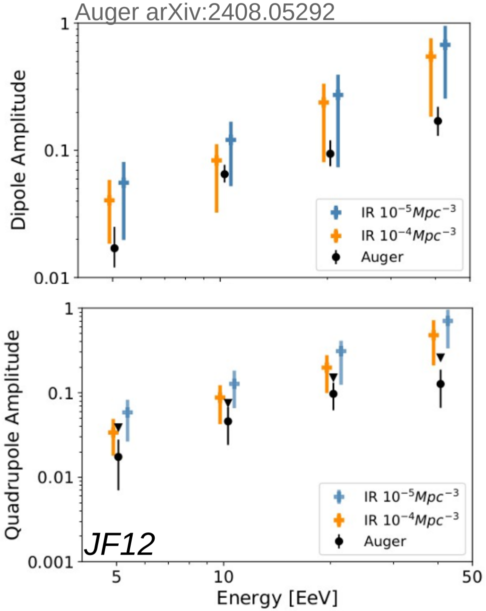
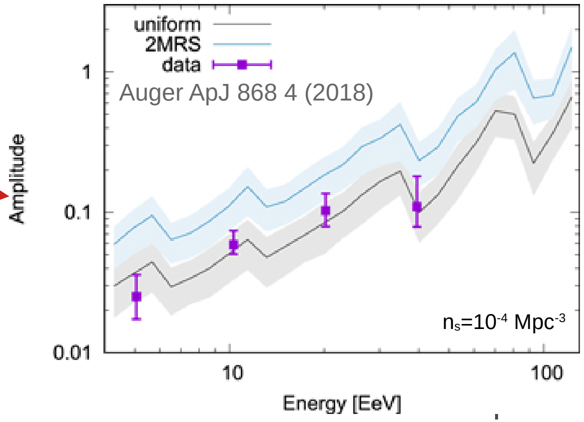

LSS model → update of CosmicFlows: Valade et al Nat. Astronomy (2024)

- **compatible** number density estimates between **2MRS & CosmicFlows**
- dipole could also arise due to **homogeneous source distribution**
  e.g. Guedes Lang, Taylor & de Souza PRD 103 (2021); Allard, Aublin, Baret & Parizot A&A 664 A120 (2022); Bister & Farrar ApJ 966 71 (2024); Auger ApJ 868 4 (2018), Harari, Mollerach & Roulet PRD 92 (2015)
  - note: direction non-informative in that case
  - typically need smaller densities for enough anisotropy





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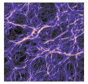

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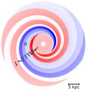

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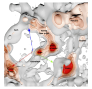
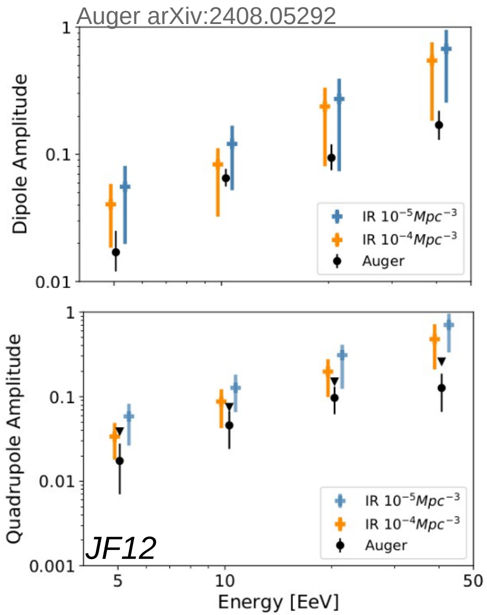
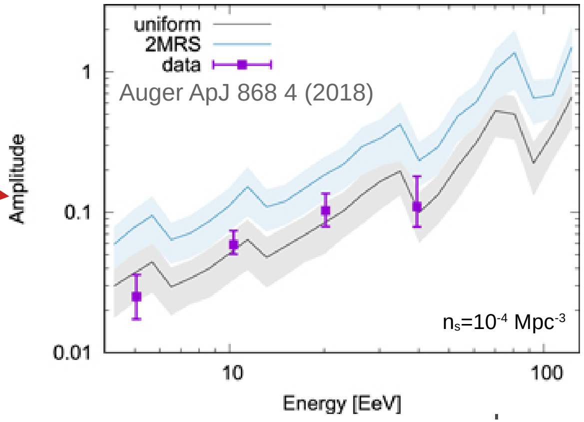
- weak correlation with LSS: **UHECRs are heavier at the highest energies**
  Telescope Array Collaboration PRL 133 041001 & PRD 110 022006 (2024); Ding, Globus & Farrar ApJL 913 L13 (2021)



LSS model → update of CosmicFlows: Valade et al Nat. Astronomy (2024)

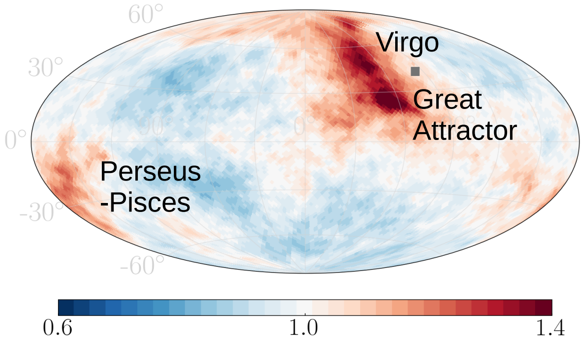
- **compatible** number density estimates between **2MRS & CosmicFlows**
- dipole could also arise due to **homogeneous source distribution**
  e.g. Guedes Lang, Taylor & de Souza PRD 103 (2021); Allard, Aublin, Baret & Parizot A&A 664 A120 (2022); Bister & Farrar ApJ 966 71 (2024); Auger ApJ 868 4 (2018), Harari, Mollerach & Roulet PRD 92 (2015)
  - note: direction non-informative in that case
  - typically need smaller densities for enough anisotropy





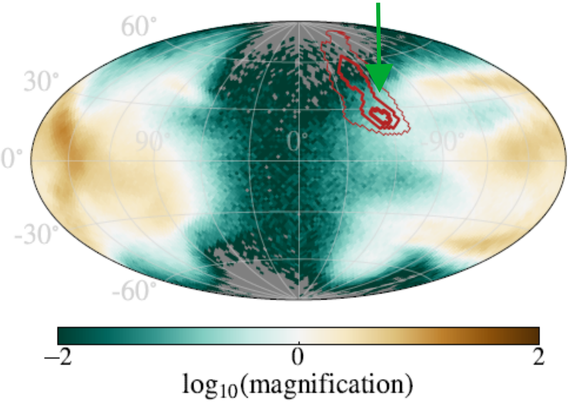
note: other number density estimates e.g. from the highest energy events also have to rely on model assumptions
see e.g. Kuznetsov JCAP 04 042 (2024), Auger JCAP 1305 009 (2013)

Why is the dipole amplitude so small with UF23?



illumination E>8 EeV

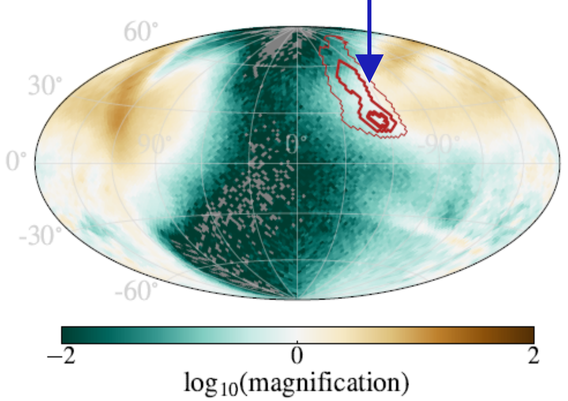
demagnified by all UF23 models



UF23 base + Planck

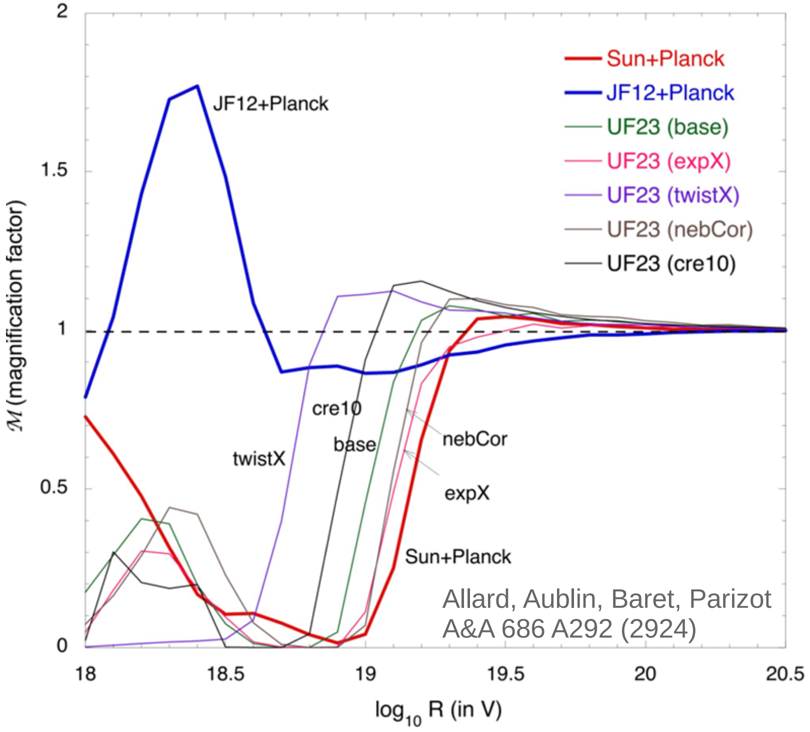
R = E/Z = 5 EV

magnified by JF12



JF12 + Planck

magnification of Virgo direction:



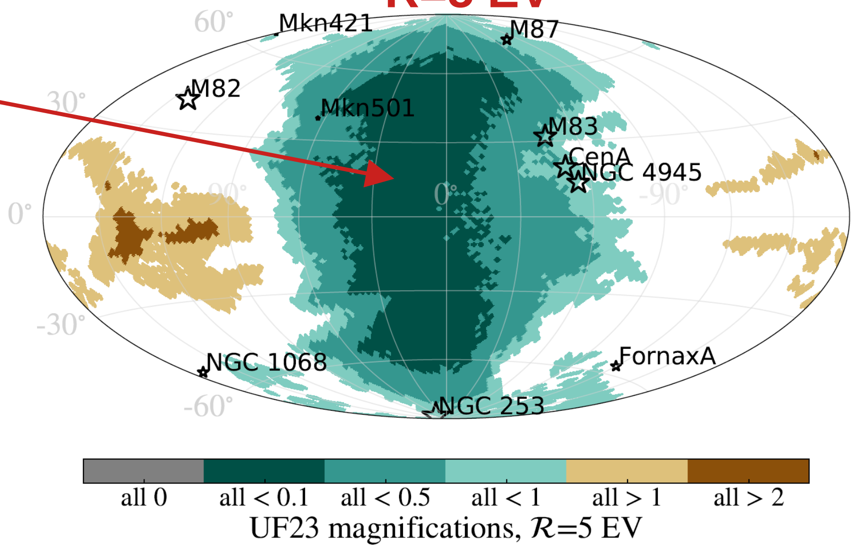
Bister, Farrar, Unger ApJL 975 L21 (2024)

Demagnification - agreement & source candidates

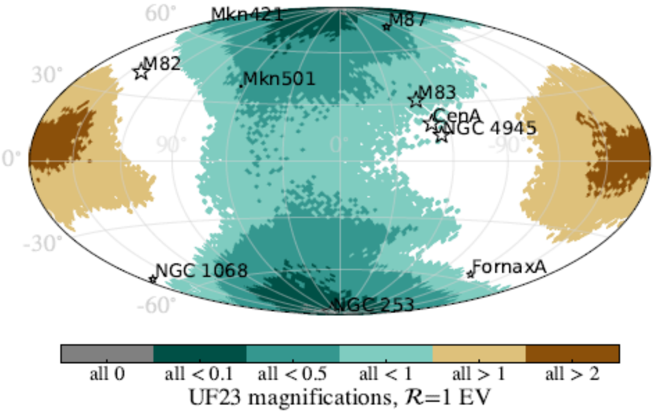
all UF23 models + random field variations agree on central demagnification area

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

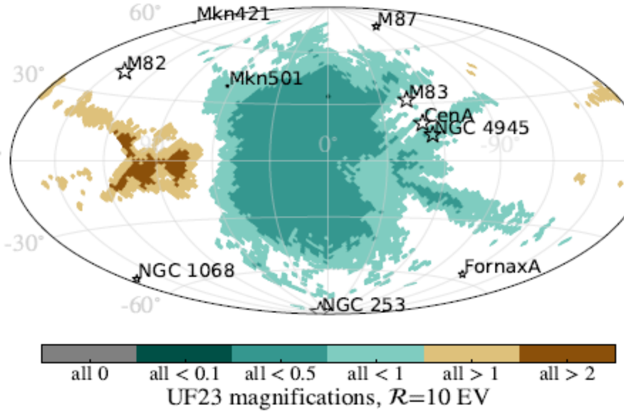
R=5 EV



R=1 EV



R=10 EV



white region:
no agreement between all 8 UF23 models

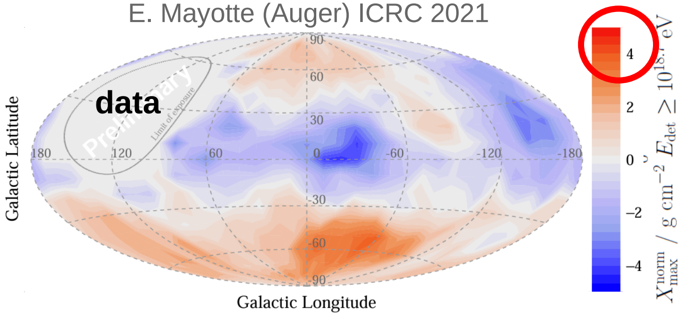
Composition-dependent anisotropies

heavier composition from Galactic plane (~3σ)

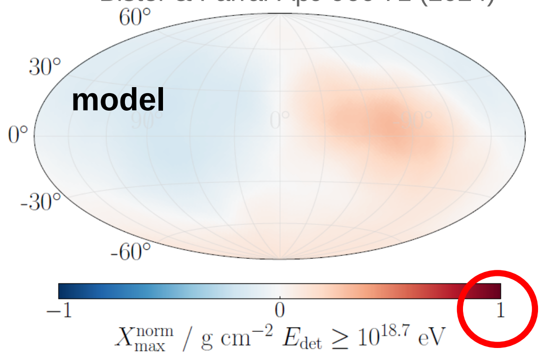
E. Mayotte (Auger) ICRC 2021

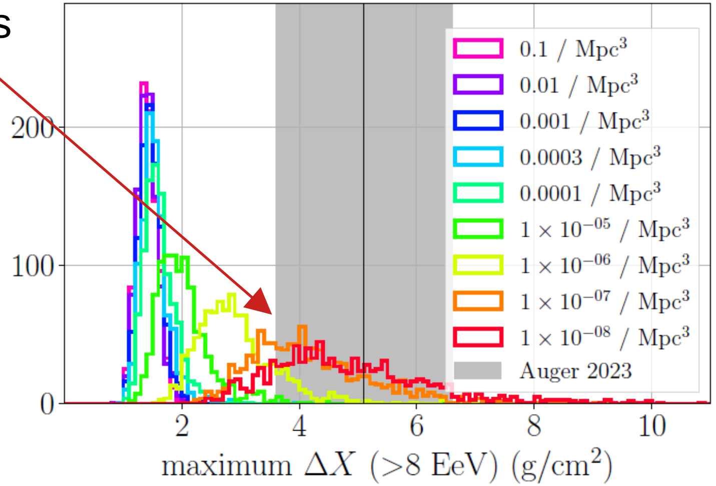
→ LSS model does not reproduce it + need extremely small densities

E. Mayotte (Auger) ICRC 2021



Bister & Farrar ApJ 966 71 (2024)





Bister & Farrar ApJ 966 71 (2024)

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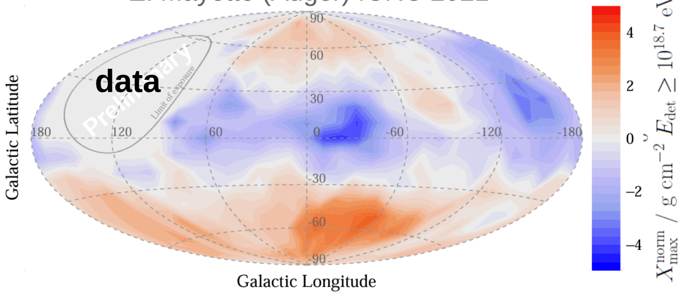
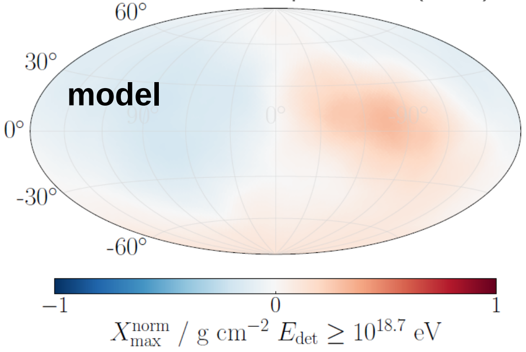
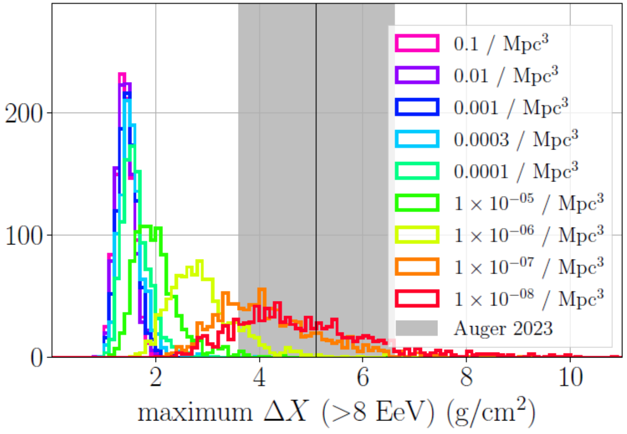


Bister & Farrar ApJ 966 71 (2024)



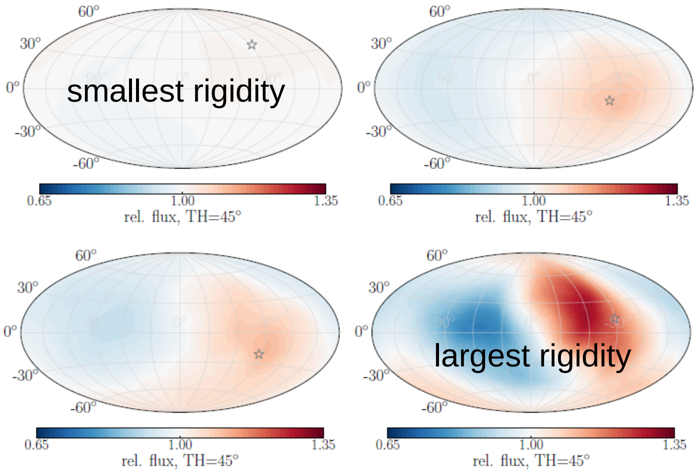


rigidity dependency of the dipole

→ larger amplitude expected for higher rigidity

→ direction also affected

→ results on Auger data to be released see E. Martins (Auger) UHECR 2024

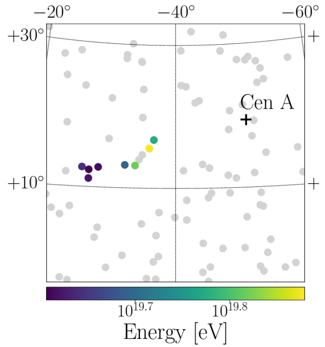


Bister & Farrar ApJ 966 71 (2024)

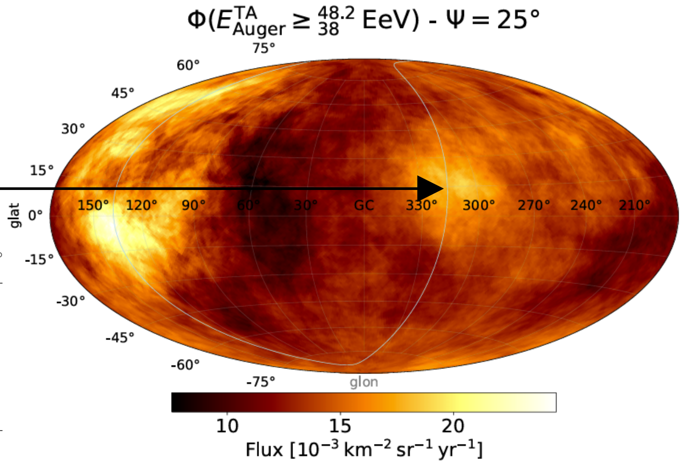
soon: also include charge in smaller-scale anisotropy studies
L. Apollonio (Auger) UHECR 2024

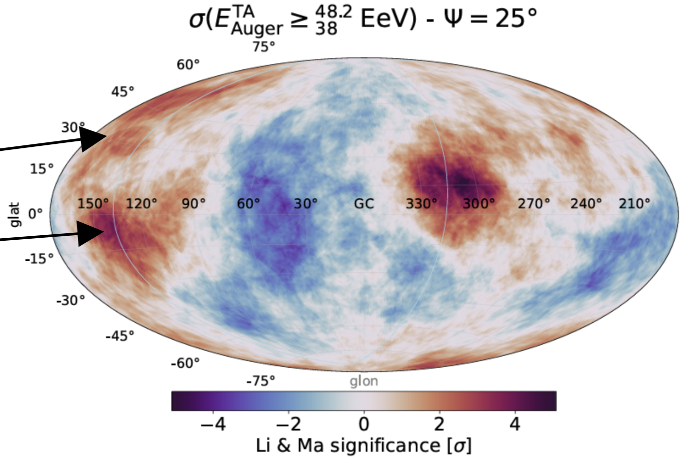
Status of smaller-scale anisotropies

- **Auger:** Auger ApJ 935 170 (2022), ICRC 2023
  - scan: no significant overdensities >32 EeV (p_{post} = 2%)
  - **Cen A correlation currently 4.0σ post-trial**
  - no autocorrelation, no correlation with Galactic / supergalactic plane (all p_{post} > 10%)
  - no significant multiplets (target Cen A: p=0.012)
    Auger JCAP 06 017 (2020)



Auger + TA ICRC 2023

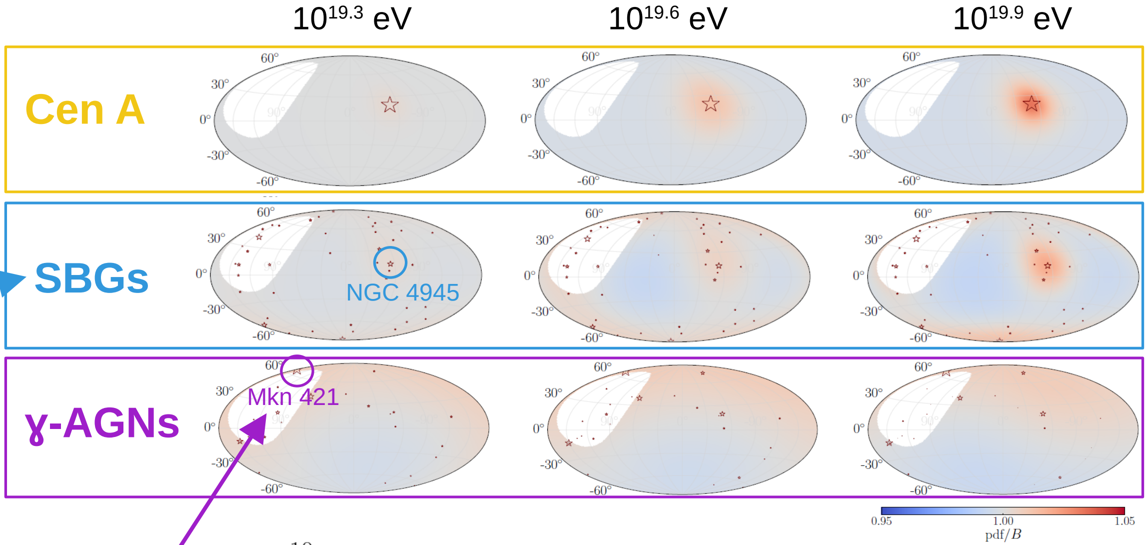


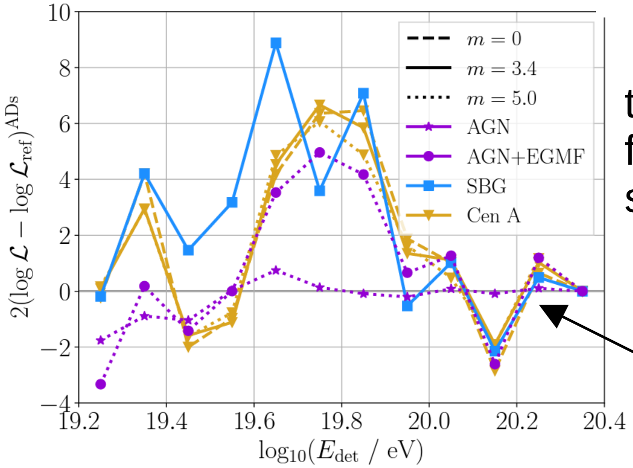


- **TA:** TA UHECR 2024
  - **hotspot** significance keeps growing, post-trial: 2.9σ
  - **Perseus-Pisces** overdensity currently at 3.7σ local
  - but: neither is seen by Auger despite comparable exposures Auger ICRC 2023 & arXiv:2407.06874

Correlation with catalog sources

- **Cen A:** 4.0 (Auger ICRC 2023)
- **SBGs:** 4.4σ (Auger+TA UHECR 2024)
  3.8σ (Auger ICRC 2023)
  - 4.5σ when including energy-dependent model fit to spectrum, composition, and arrival directions
    Auger JCAP 01 022 2024,
    TB (Auger) ICRC 2023
- **ɣ-AGNs:** strongly **disfavored** by fit
  - UHECR flux ∝ ɣ-ray flux overweights blazars
    - corrections for beaming?
      de Oliveira, Lang, Batista arXiv:2408.11624





test statistic as function of energy, sum gives total TS

highest energy events not close to source candidates

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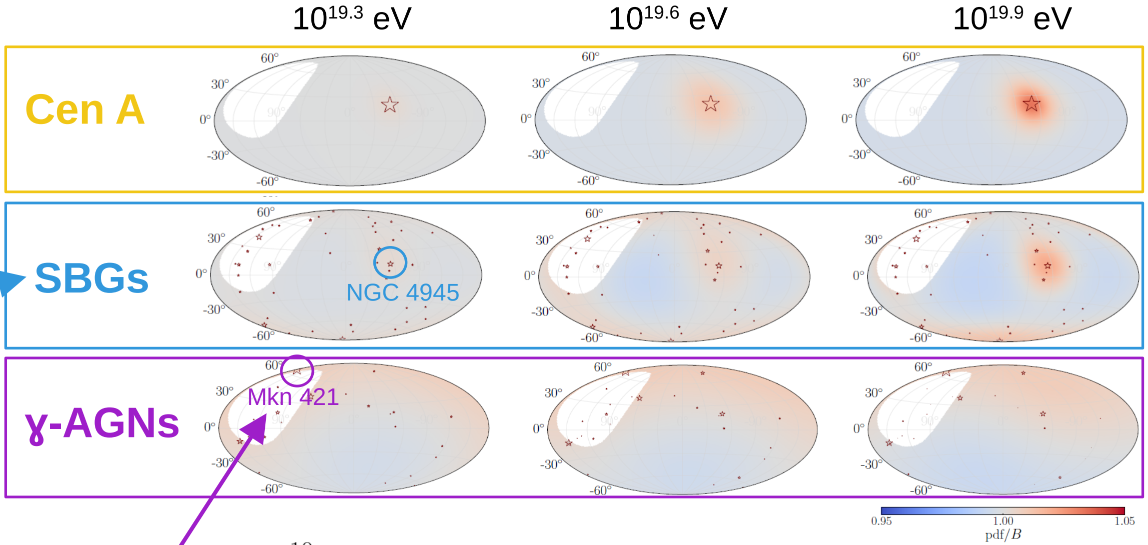

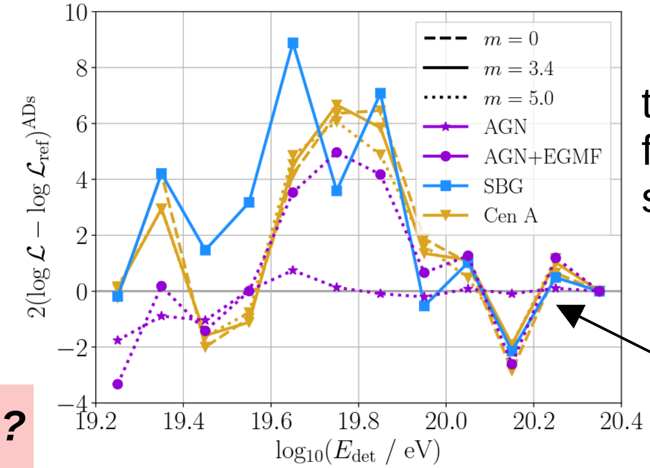

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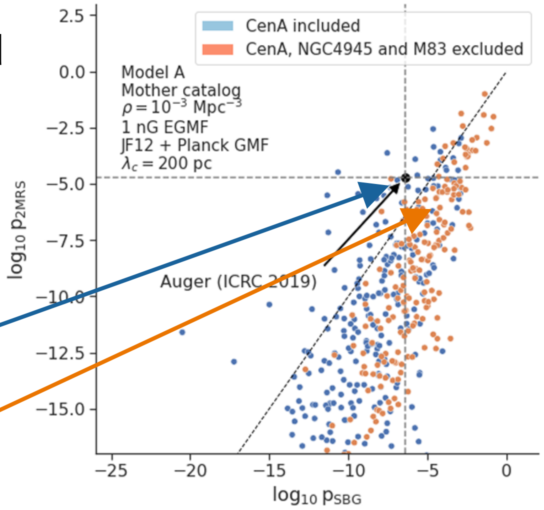
highest energy events not close to source candidates

But, What about coherent magnetic field deflections?

Smaller-scale anisotropies and the GMF

Allard, Aublin, Baret, Parizot
A&A 686 A292 (2924)

- **in simulations based on 2MRS + GMF:**
  - possible but not easy to reproduce the observed correlation with SBGs & 2MRS
  - even harder when excluding Cen A, NGC4945 & M83



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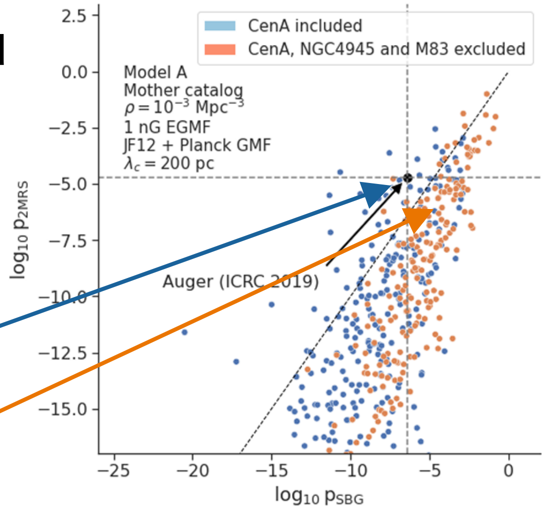
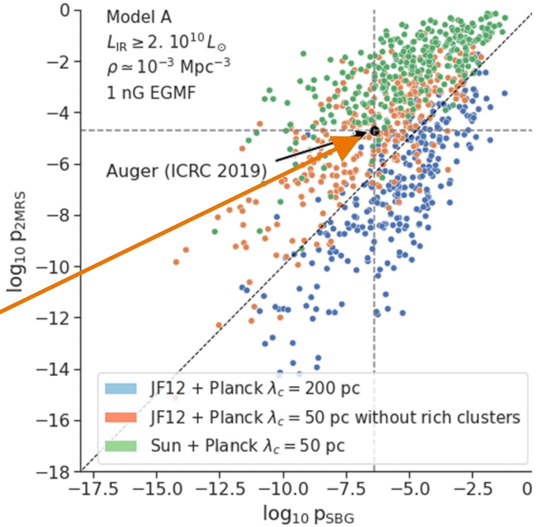


- becomes easier when using IR cut (**selecting high SFR**)
  - easiest when excluding clusters with JF12 due to strong Virgo contribution



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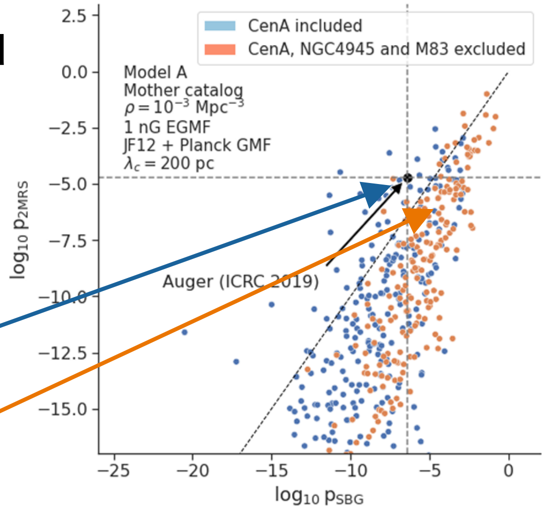
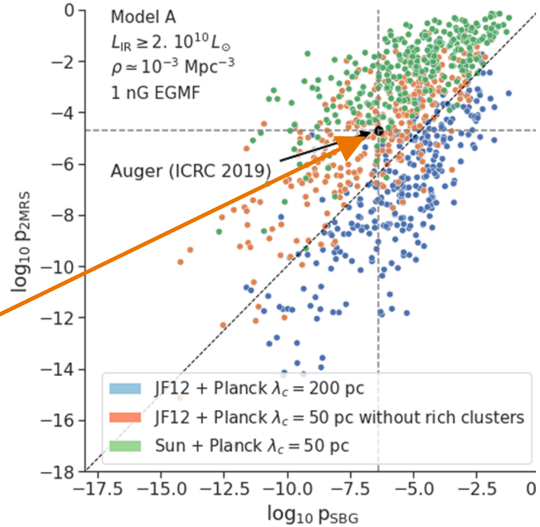
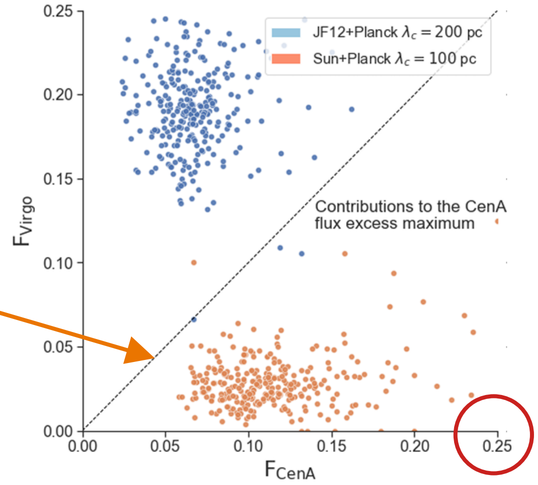




- **subdominant contribution to Cen A hotspot by Cen A**
- Sun GMF model demagnifies Virgo



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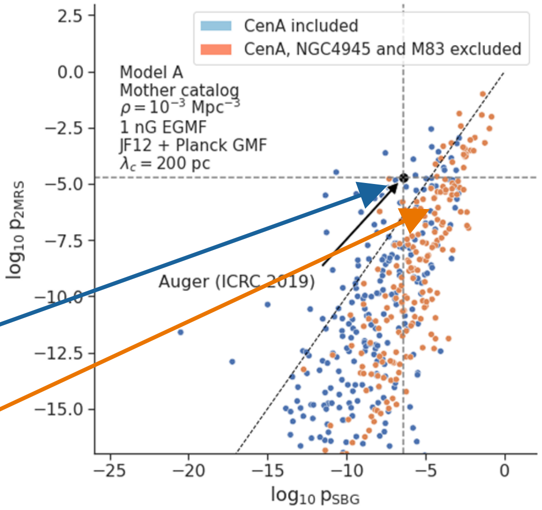

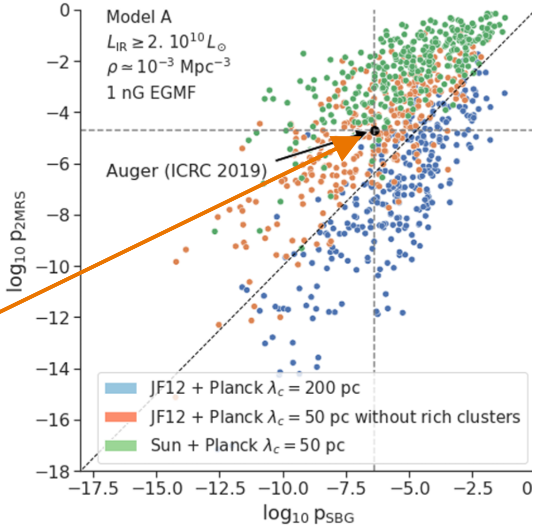

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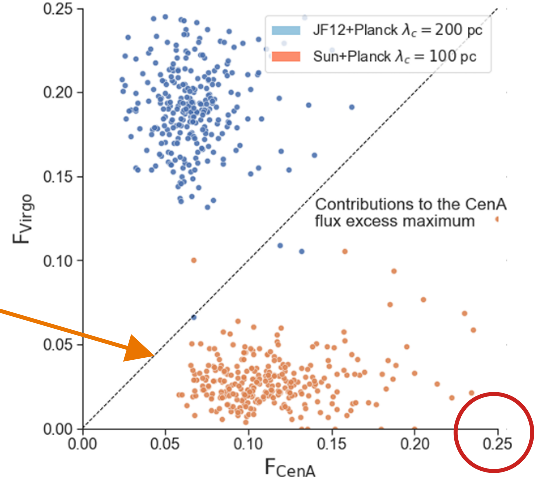
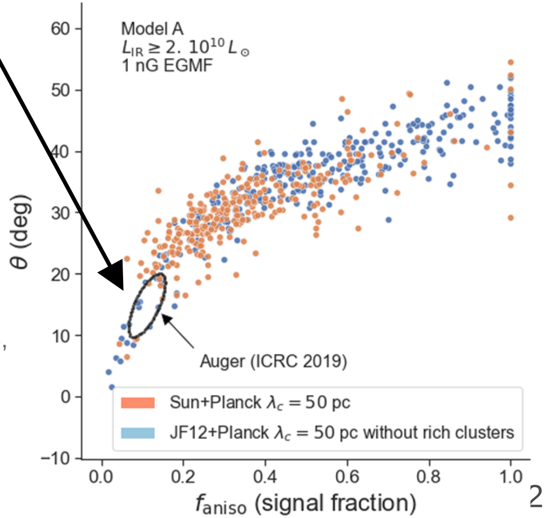


- signal fraction and blurring hard to reconcile
  - ➔ **difficult to interpret values if GMF has large impact**
- see also:
  M. Kuznetsov (Auger+TA) ICRC 2023,
  Higuchi et al ApJ 949 107 (2023),
  L. Deval UHECR 2024



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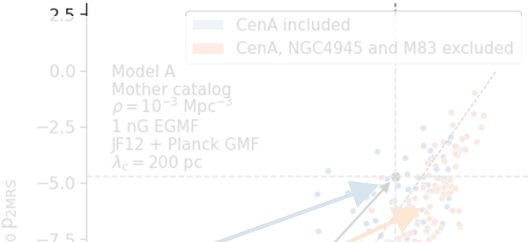
- in simulations based on 2MRS + GMF:
  - possible but not easy to reproduce



- subdominant contribution to Cen A hotspot by Cen A

But, why the correlation with starbursts?

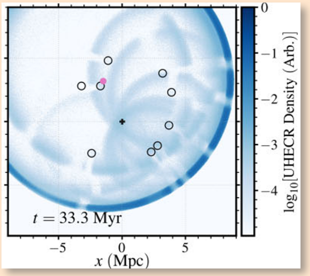
What about the 90% unassociated flux?

Are there other possible explanations for the observations?

e.g. →

echoes from the council of Giants (original source Cen A)
Taylor, Matthews & Bell MNRAS 524 (2023)

correlation of transient sources with SFR
Marafico et al. ApJ 972 4 (2024)



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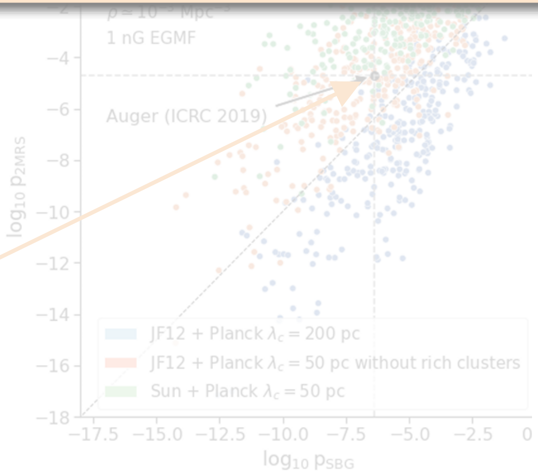

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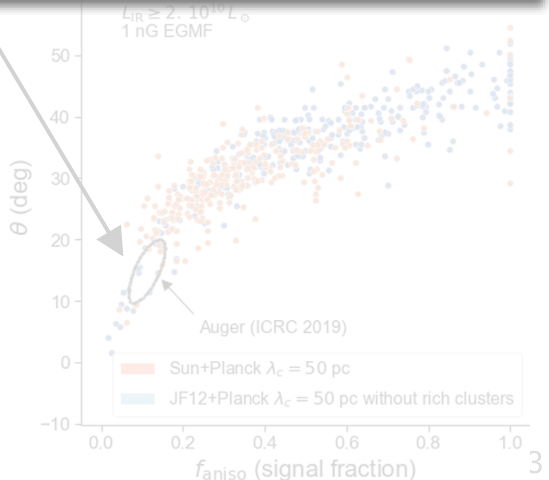
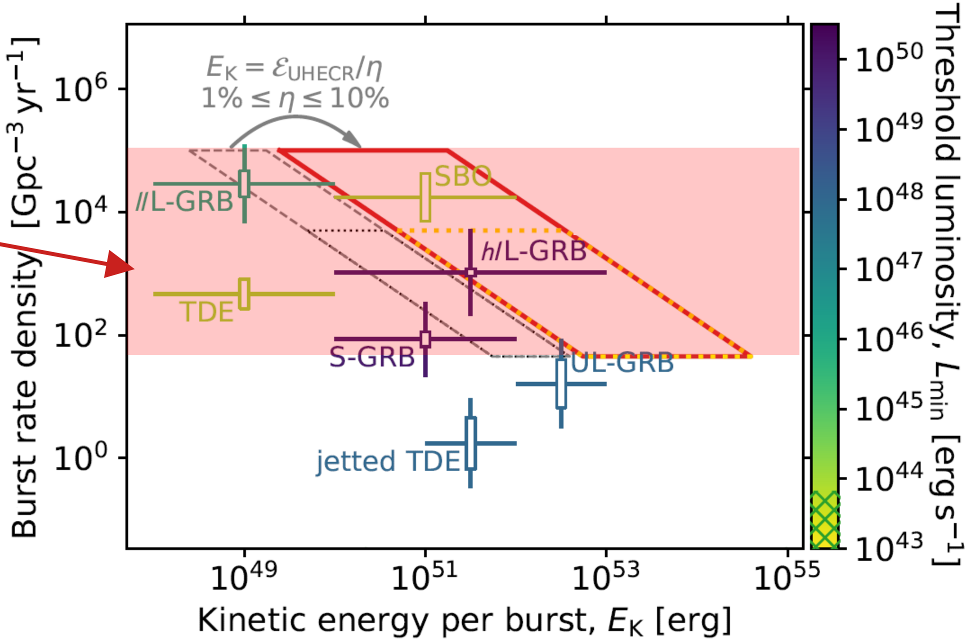


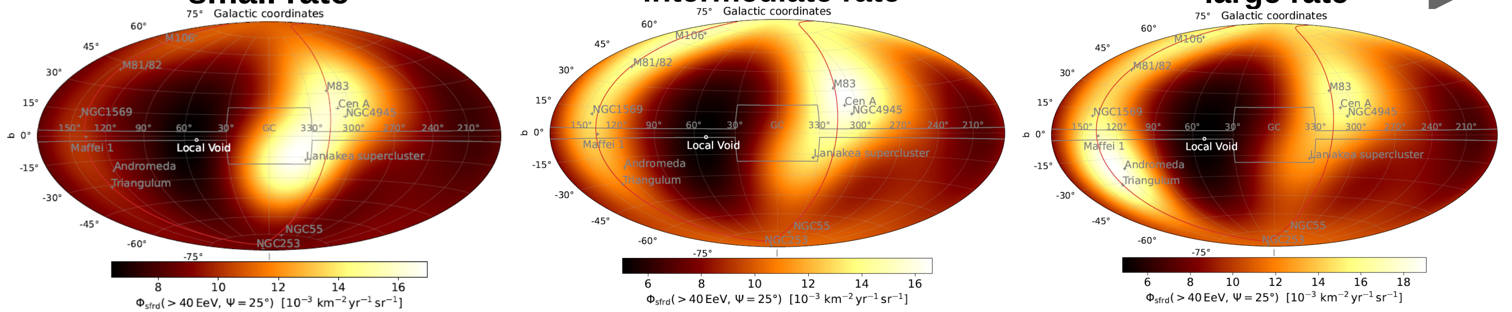
Marafico et al. ApJ 972 4 (2024)

Transient UHECR model

- model based on **UHECRs produced in transients ∝ SFR in every galaxy**
- constrain transient burst rate by comparing flux overdensity in **Cen A & TA hotspot region:**
  assuming dominating time delay from Local Sheet with B_{rms}~0.5-20 nG
  - ➔ note: 2/3 of Cen A overdensity from Laniakea supercluster
- considering also sufficient produced energy to supply UHECR flux: **long GRBs favored**
- model does **not yet include GMF deflections**
  → see Bister & Biteau UHECR 2024



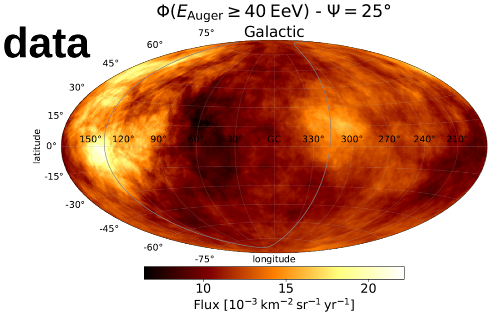
small rate — intermediate rate — large rate →



no contribution from local sources

almost continuous

data



Information from highest energy events

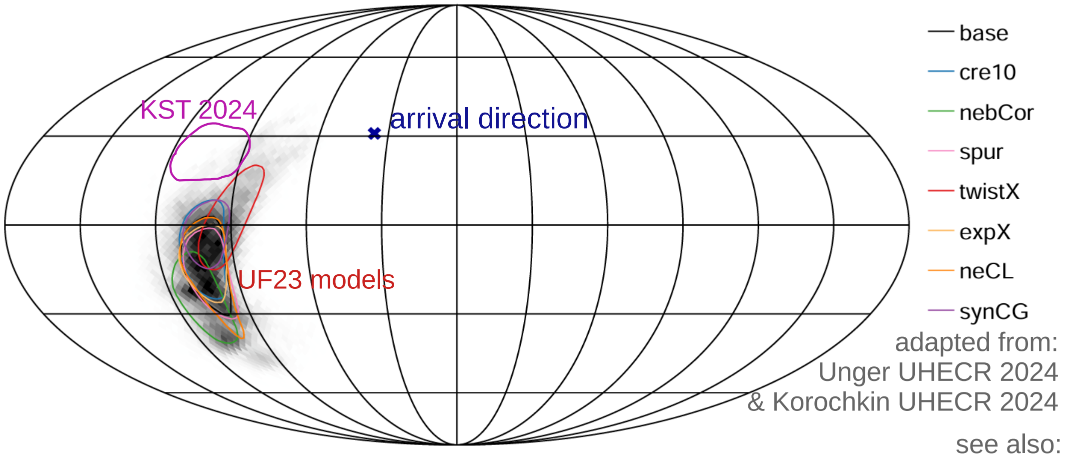
Where do the highest energy events point to?

- backtracking **Amaterasu event** with E=244 EeV, suppose Fe
  (TA Science 382 2023)

  with all newest GMF models:

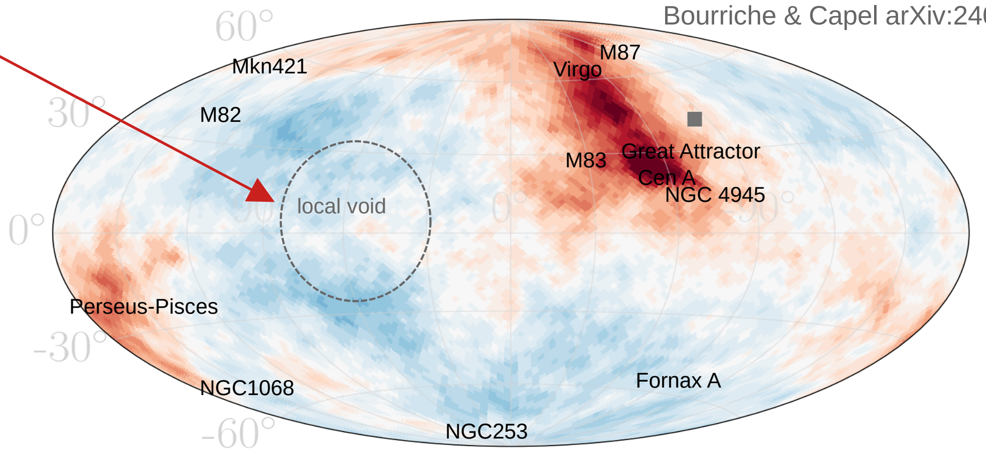
  → direction nowhere close to interesting source candidates, rather close to local void

  → same goes for 4 highest-energy Auger events → *Michael's talk*



adapted from:
Unger UHECR 2024
& Korochkin UHECR 2024

see also:
Unger & Farrar ApJL 962 L5 (2024)
Kuznetsov JCAP 04 042 (2024)
Bourriche & Capel arXiv:2406.16483

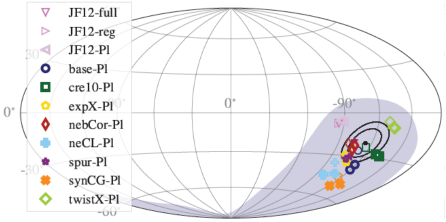


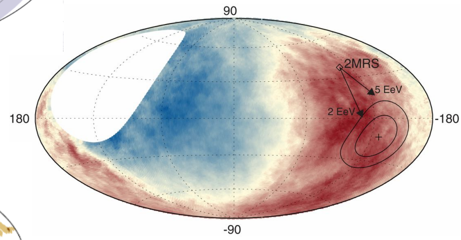
→ **supports transient origin**

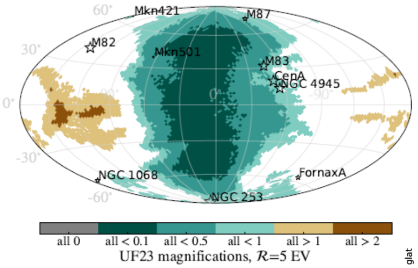
→ **and / or: ultraheavy particles?**
Farrar arXiv:2405.12004
Zhang et al. arXiv:2405.17409

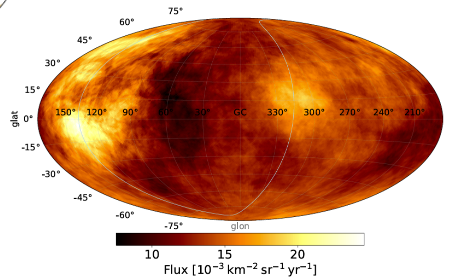
Conclusions

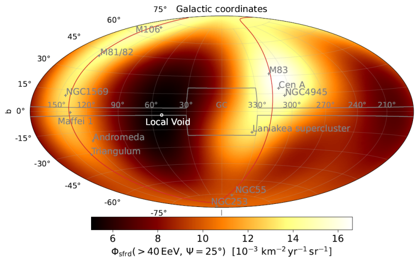
- UHECR sources are very different from what was expected
  - ➔ emit heavy composition, hard spectrum, all very similar...
- **large-scale anisotropies** can be well explained if UHECR sources follow the **large-scale structure**
  - ➔ new insights using new Galactic magnetic field models
  - ➔ preferred source number density $n_s \sim 10^{-4}$ Mpc^{-3} (with large uncertainties)
- **intermediate-scale anisotropies** may come partially from local source candidates
  - ➔ SBGs or Cen A can explain all observables - but also when including coherent GMF? (deflections + demagnification)
  - ➔ more definite answers soon with mass-sensitive arrival-direction studies? see L. Apollonio (Auger) UHECR 2024
- **highest energy events** point towards transient origin

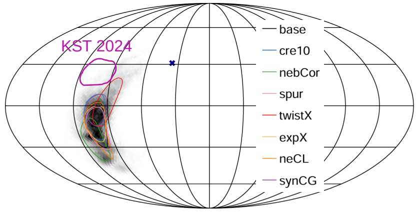






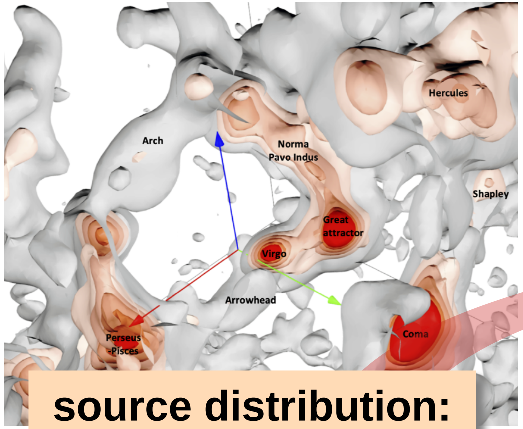






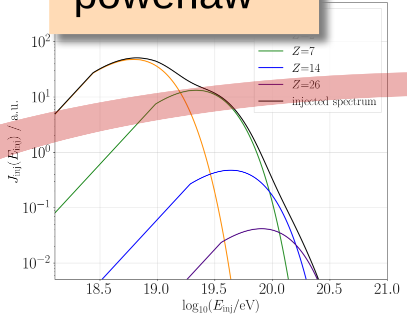
backup

The LSS model and fit to the data

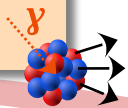


source distribution:
following LSS from CosmicFlows

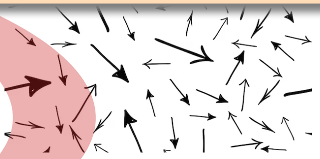
injection:
broken-exp. powerlaw

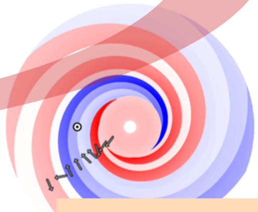


propagation:
CRPropa

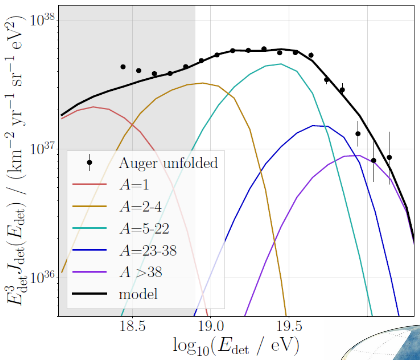


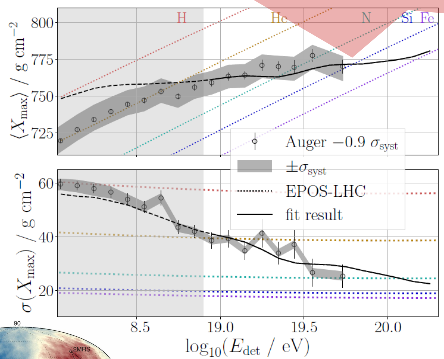
extragalactic magnetic field:
neglected /
turbulent approximation

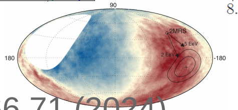




Galactic magnetic field:
JF12 & UF23 models







likelihood fit, E>8 EeV

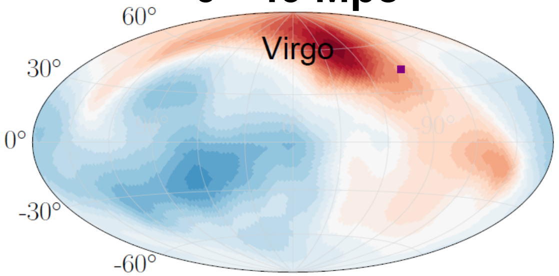
- energy spectrum
- mass composition
  Xmax distr. + scale uncertainty
- dipole moments
  8-16 EeV, 16-32 EeV, >32 EeV

Bister & Farrar ApJ 966 71 (2024)

UHECR flux from the Large Scale Structure

skymaps for E>8 EeV

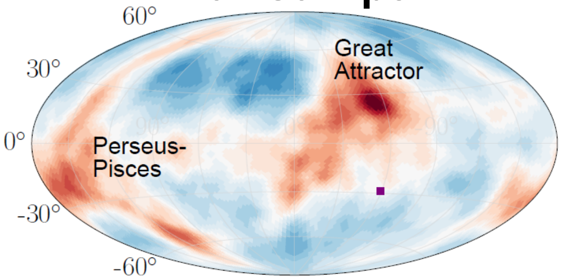
0 - 40 Mpc



~10% of flux >8 EeV
~40% of flux >32 EeV

+

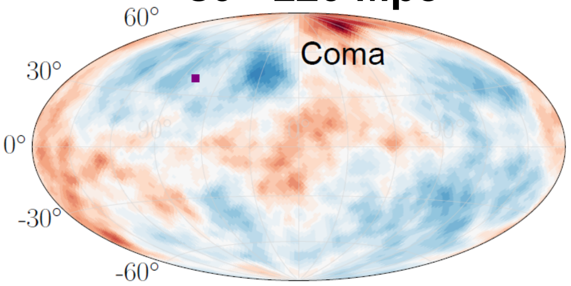
40 - 80 Mpc



~10% of flux >8 EeV
~20% of flux >32 EeV

+

80 - 120 Mpc

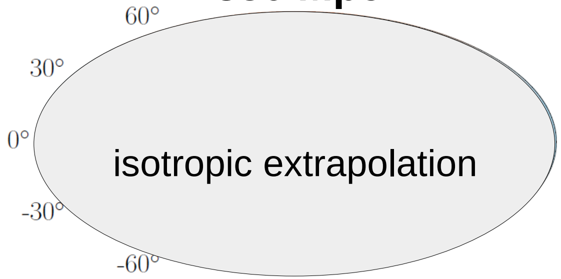


~8% of flux >8 EeV
~15% of flux >32 EeV

+ ...

+

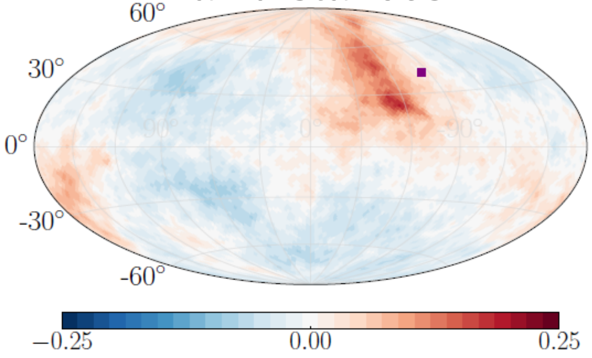
>350 Mpc



~30% of flux >8 EeV
~5% of flux >32 EeV

=

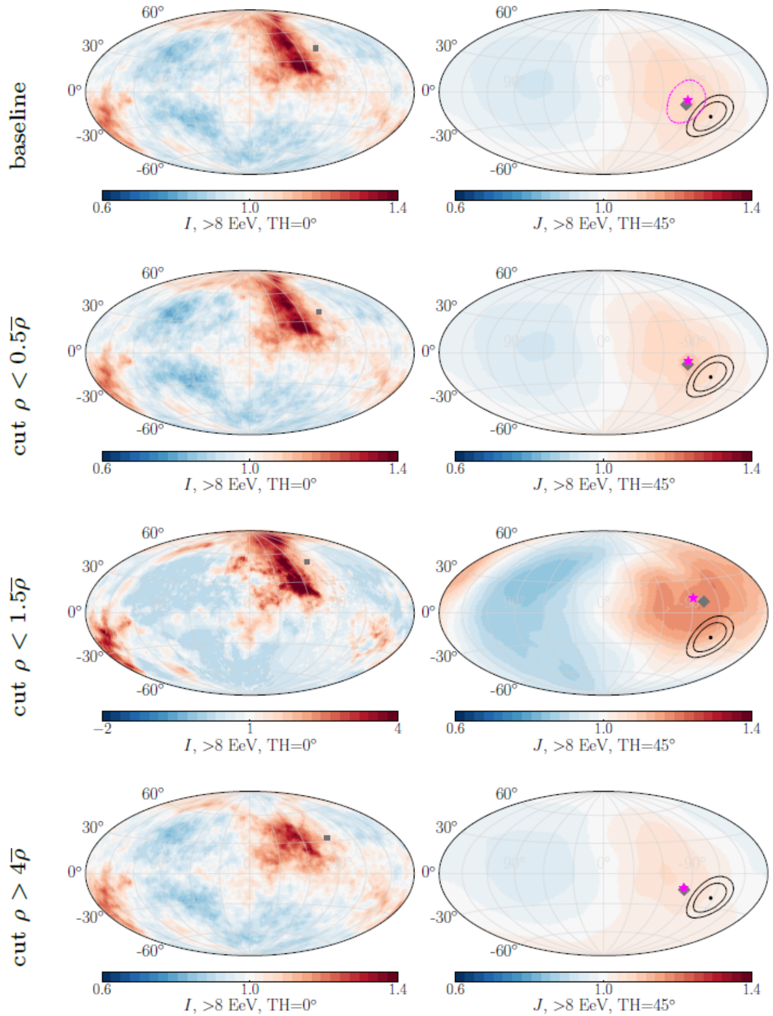
all distances



expected flux at the edge of our Galaxy

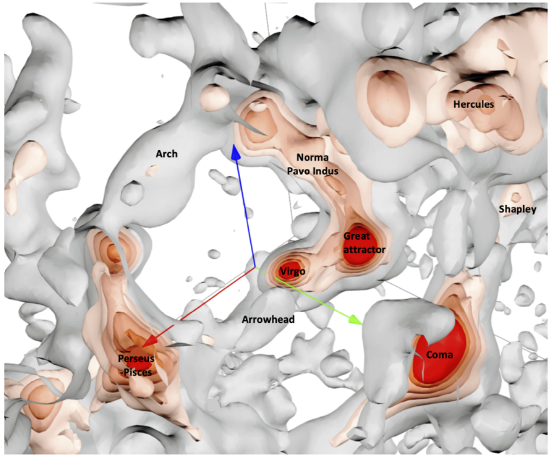
„illumination“

Bias between matter density and UHECR sources



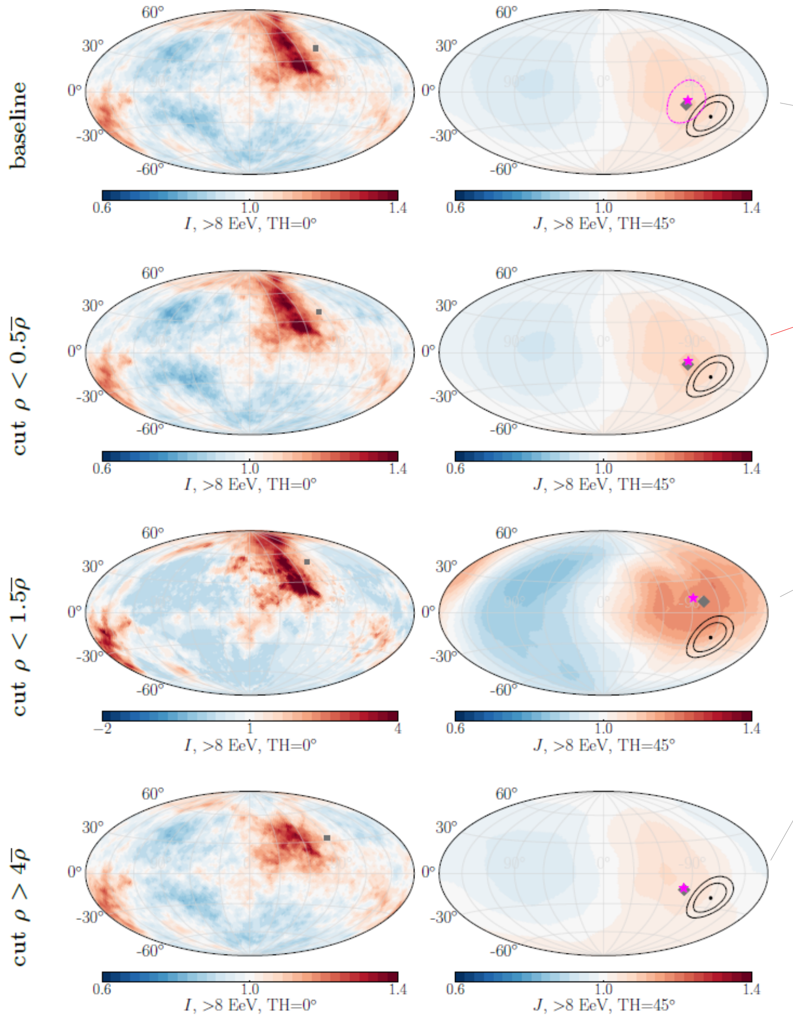
*Is there a **bias** between the UHECR source distribution and the (dark) matter distribution / LSS?*

→ simple test:
cut away densest / least dense regions of LSS



Bister & Farrar ApJ 966 71 (2024)

Bias between matter density and UHECR sources

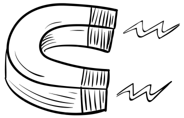


color: likelihood

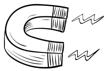
$\rho_{\max}/\bar{\rho}$ \ $\rho_{\min}/\bar{\rho}$	no cut	0.5	0.75	1.0	1.25	1.5
no cut	0.0	0.5	-0.1	-17.3	-49.1	-97.5
4.0	-3.6	-2.5	-0.4	-8.4	-28.3	-62.9
1.5	-27.1	-24.7	-19.3	-12.1	-16.4	
1.0	-64.8	-61.1	-54.7			
0.75	-107.0	-93.9				

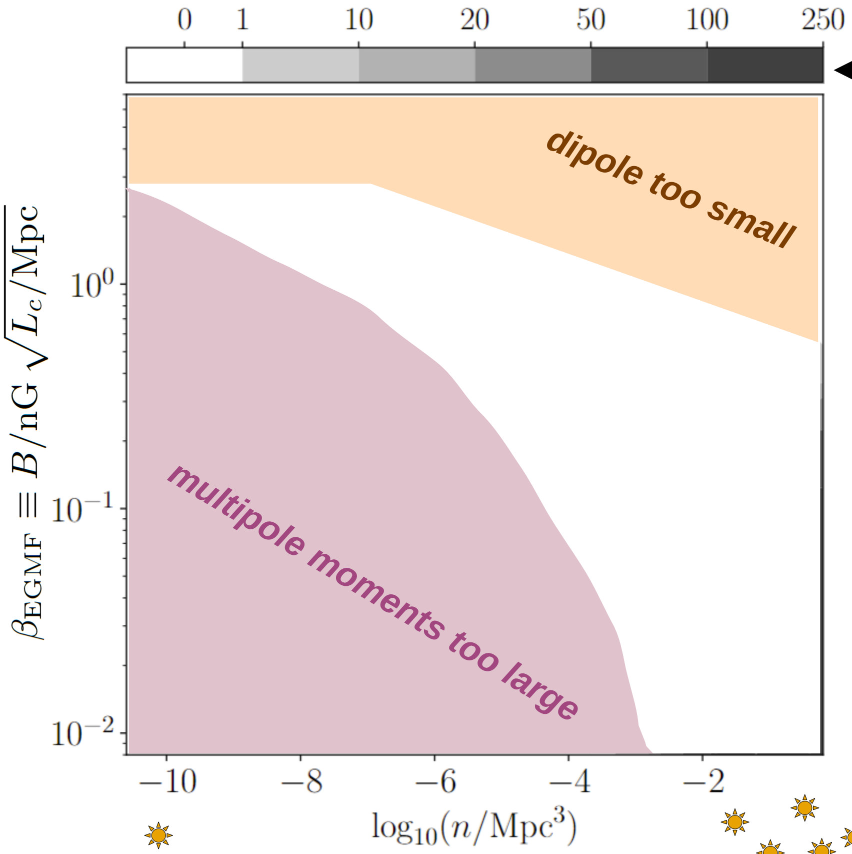
- sources in matter-dense and average regions, no definite conclusion on low-density regions
- **(dark) matter density (almost) unbiased proxy for UHECR source density**

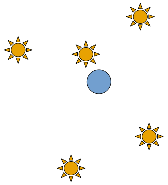
Source density and extragalactic magnetic field



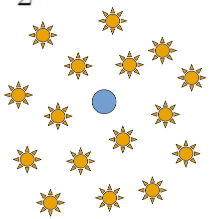
extragalactic magnetic field



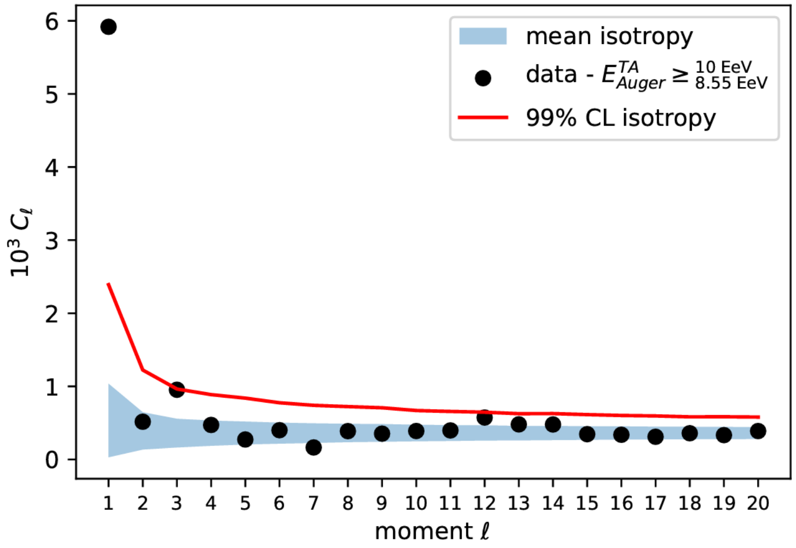




source number density

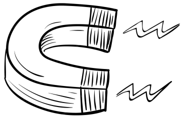


„How many of 1000 random simulations have a large enough dipole and small enough higher multipole moments?“

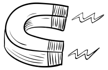


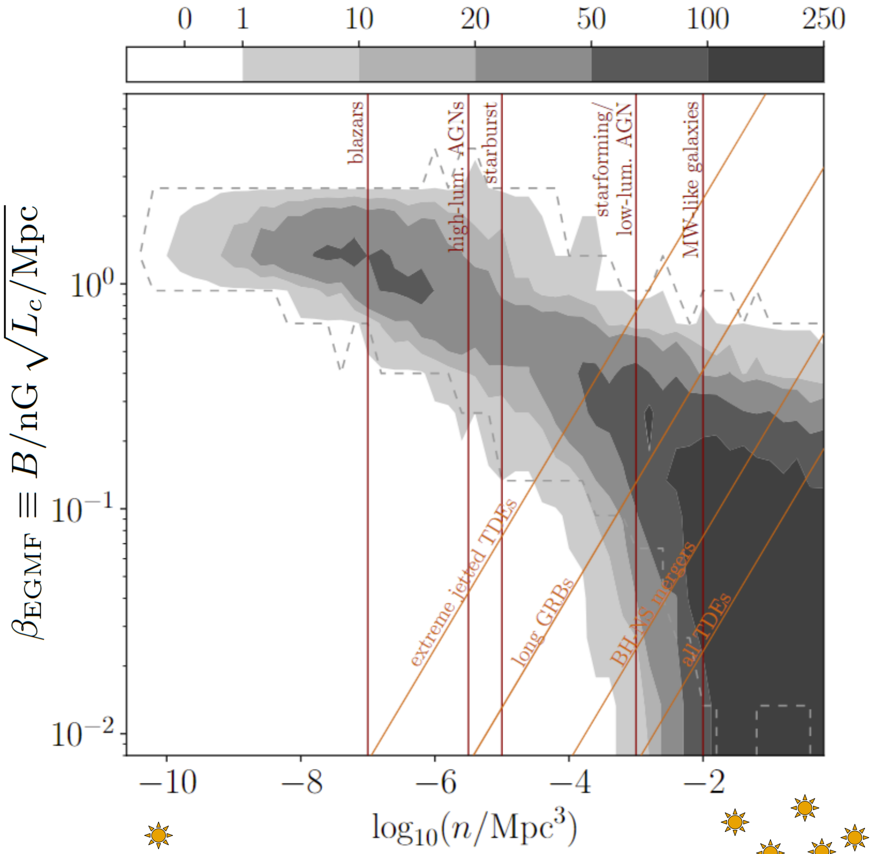
Bister & Farrar ApJ 966 71 (2024)

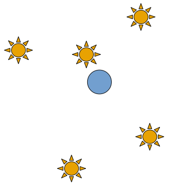
Source density and extragalactic magnetic field



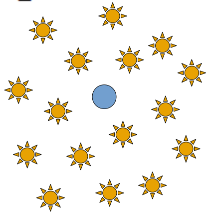
extragalactic magnetic field





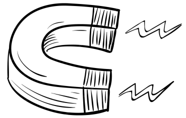


source number density

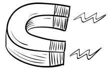


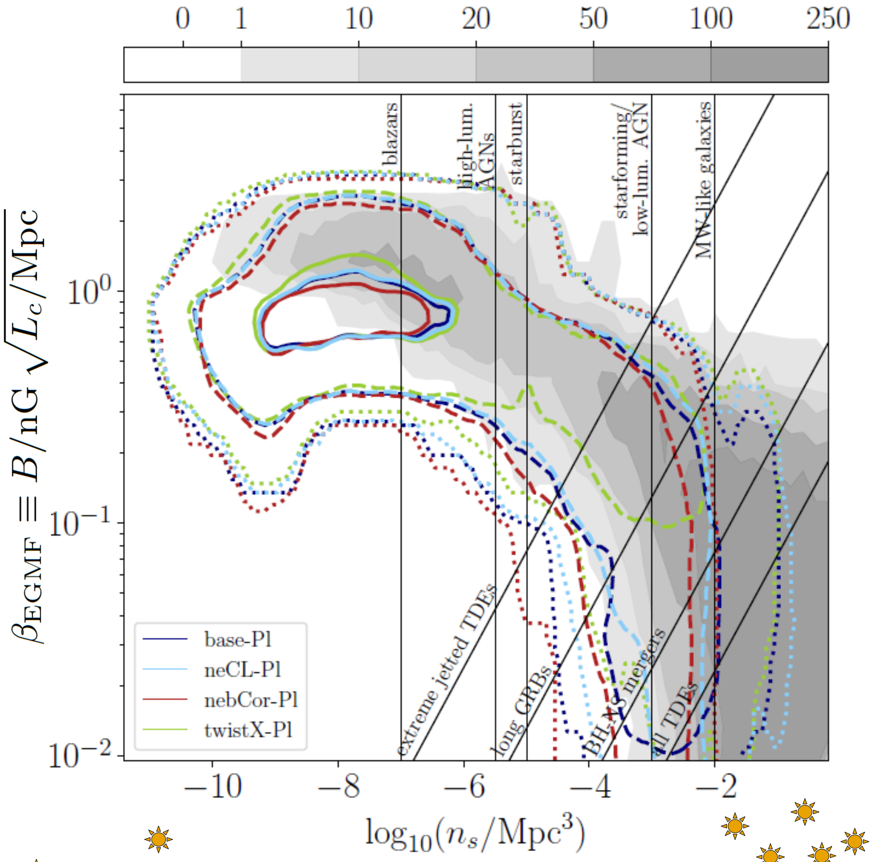
- **rare sources** (e.g. starbursts) ↔ **strong EGMF**
  - max. 3 nG $Mpc^{1/2}$
- **negligible EGMF** ↔ sources must be **common**, (e.g. Milky-Way-like galaxies)
  - or: **frequent** in case of **transients** like BH-NS mergers, tidal disruption events

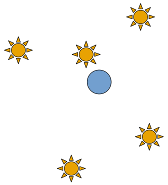
Source density and extragalactic magnetic field

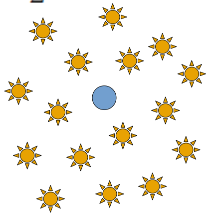


extragalactic magnetic field







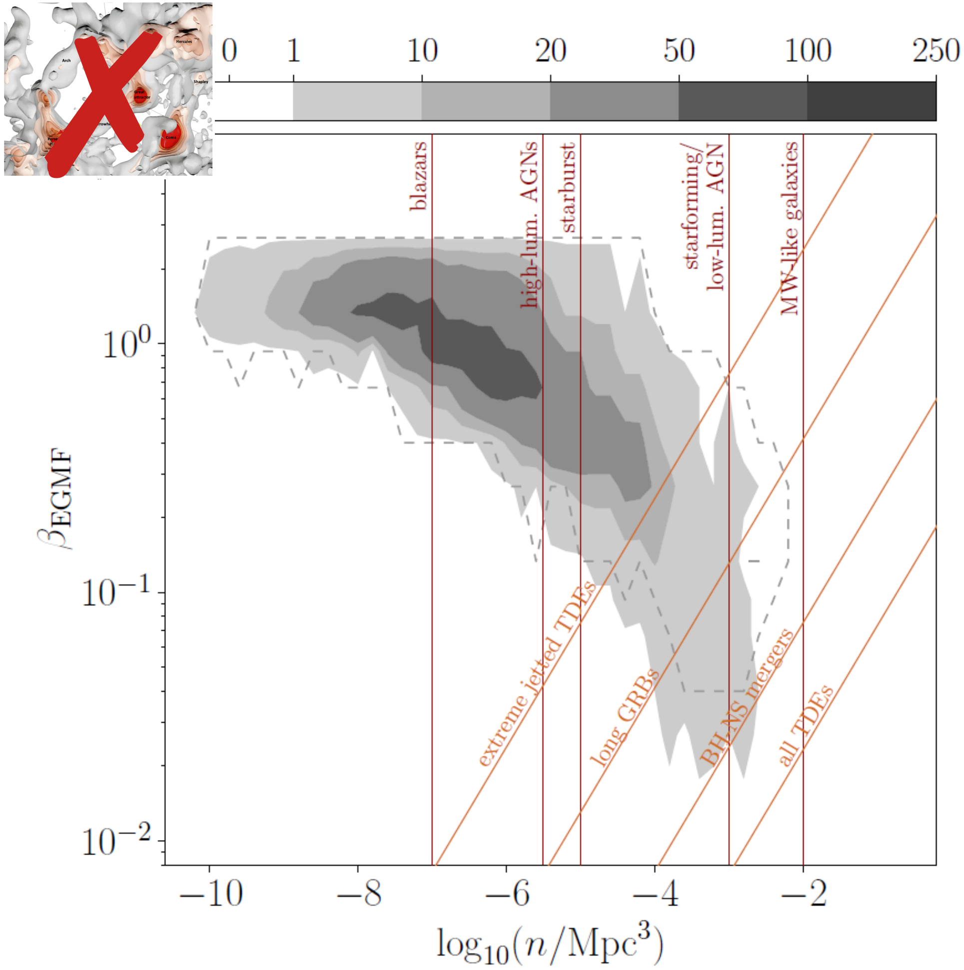


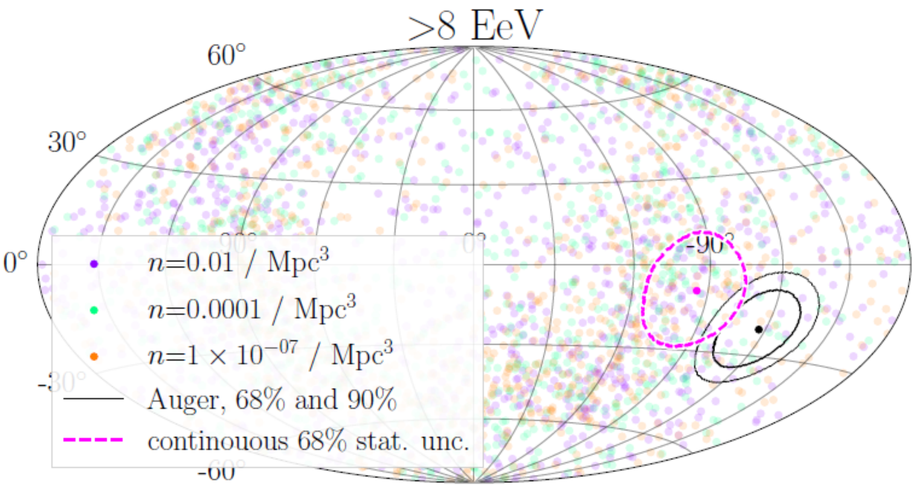
source number density

- with UF23 models, smaller source densities are preferred
- due to decreased dipole amplitude (magnification)
- note: large uncertainties due to random GMF model (currently still JF12-Planck) & simplified EGMF treatment

Bister, Farrar, Unger ApJL 975 L21 (2024)

Homogeneous source distribution?



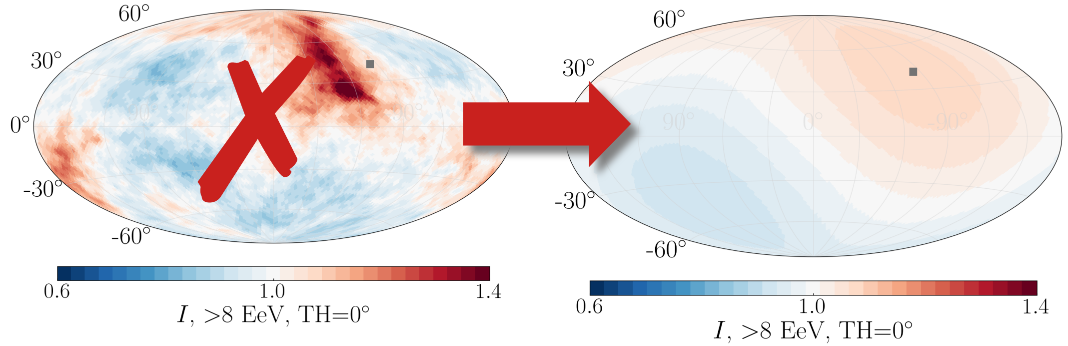


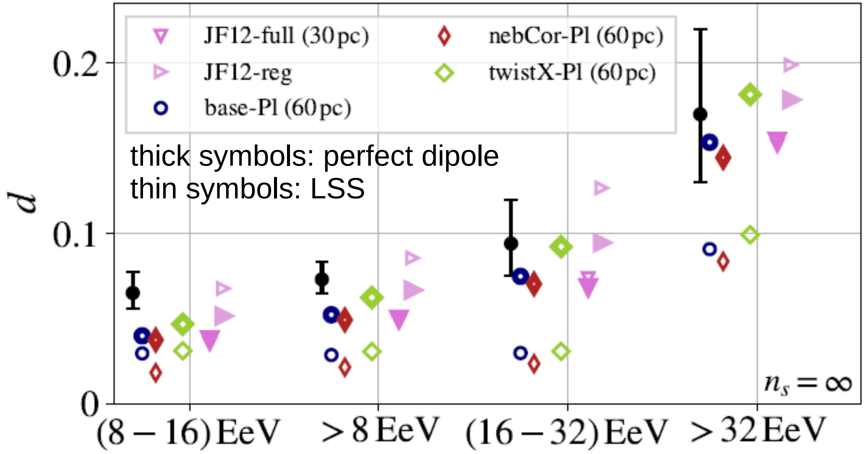
- homogeneous distribution less likely, only for rare sources and considerable EGMF
- dipole direction not predictable

Bister & Farrar ApJ 966 71 (2024)

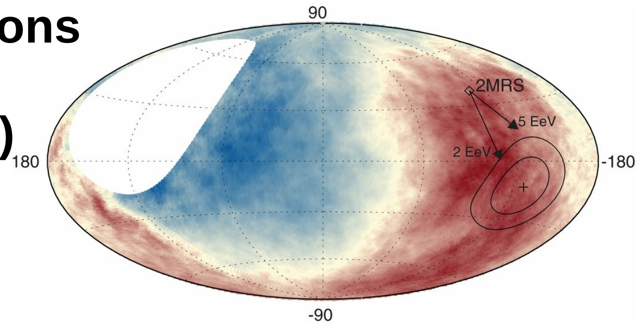
Sensitivity to the LSS model illumination

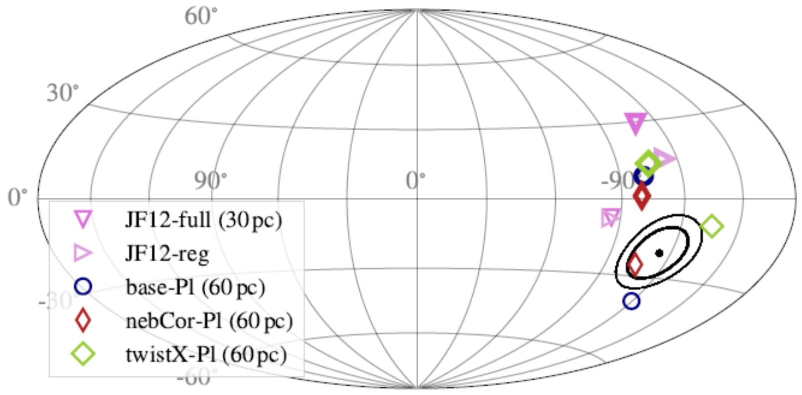
replace the illumination by dipole component:





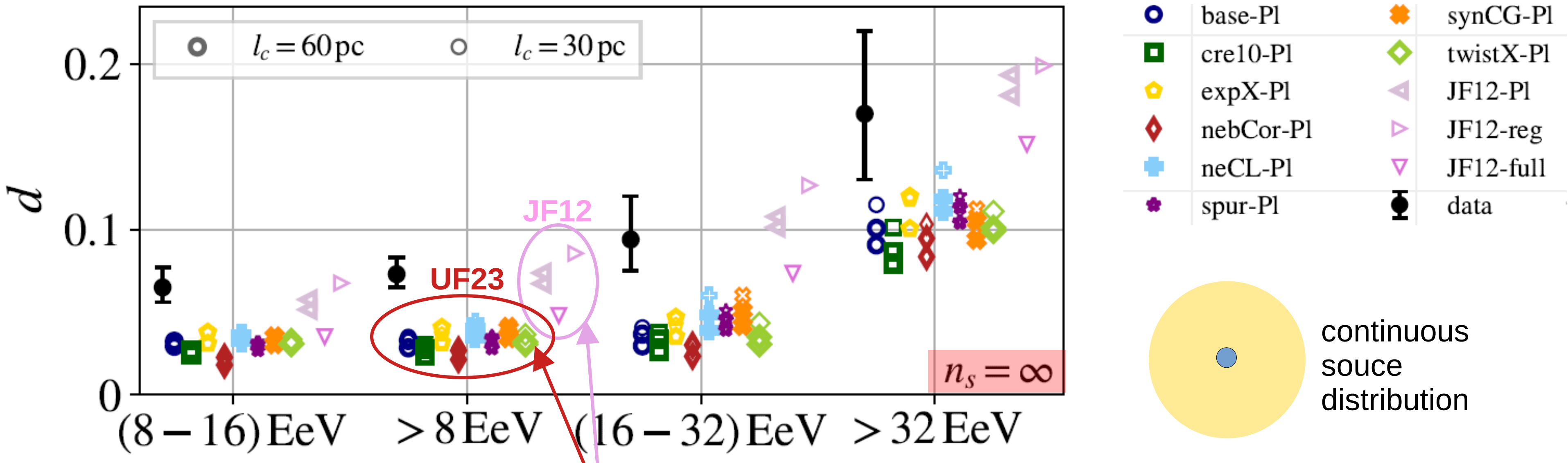
- consequence of sensitive interplay between illumination & magnification
  - **quite different predictions of amplitude (factor 2) & direction (by 20°-60°)**





(a) energy > 8 EeV

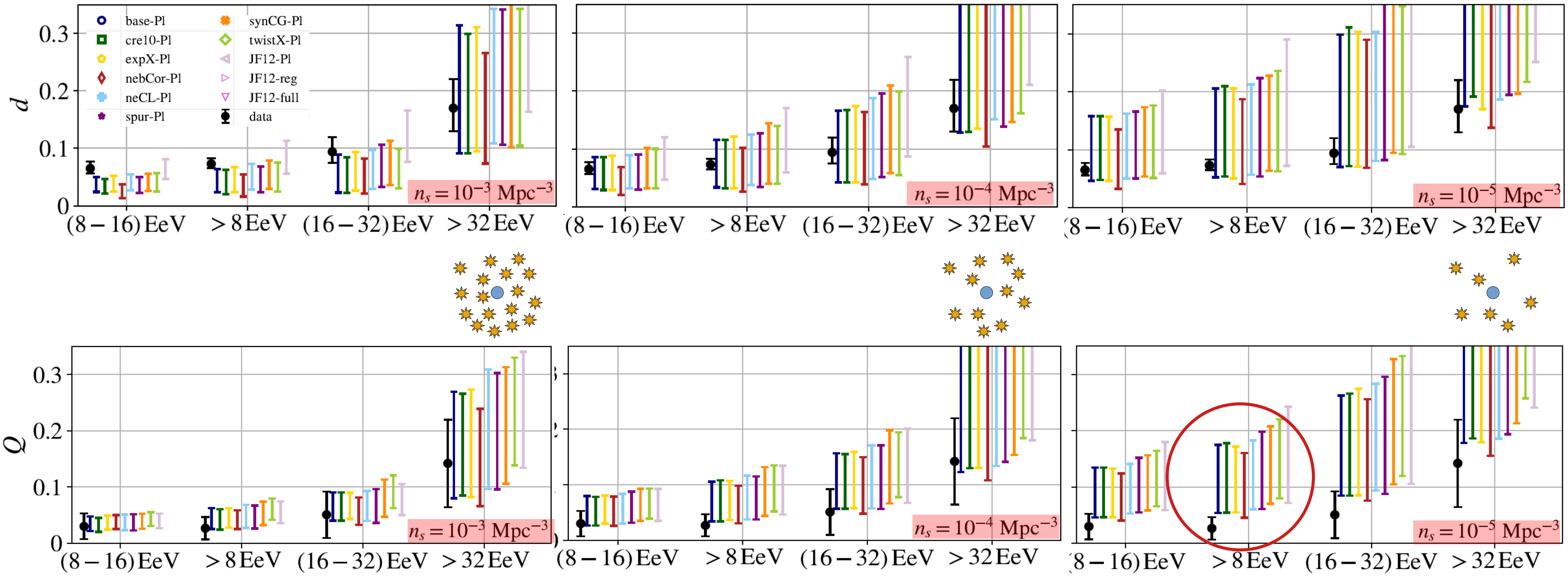
Predicted dipole amplitude: continuous sources



dipole amplitudes for UF23 models are around half of JF12

→ for UF23 models:
continuous model disfavored

Predicted dipole & quadrupole amplitudes



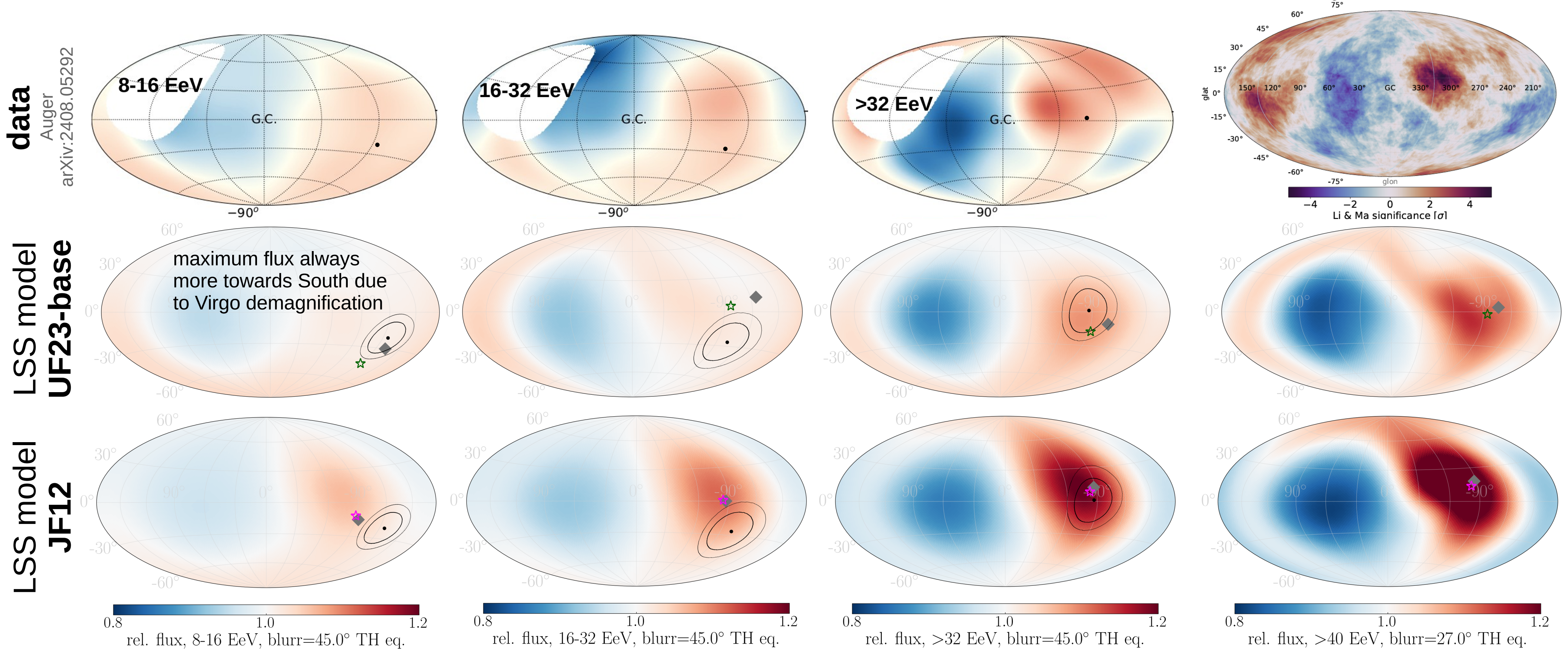
for **densities ~10^{-3} Mpc^{-3} to >10^{-5} Mpc^{-3}**

→ compatibility with dipole and quadrupole amplitudes

→ note: dipole direction more random for smaller densities

LSS model flux energy dependency

Auger + TA ICRC 2023



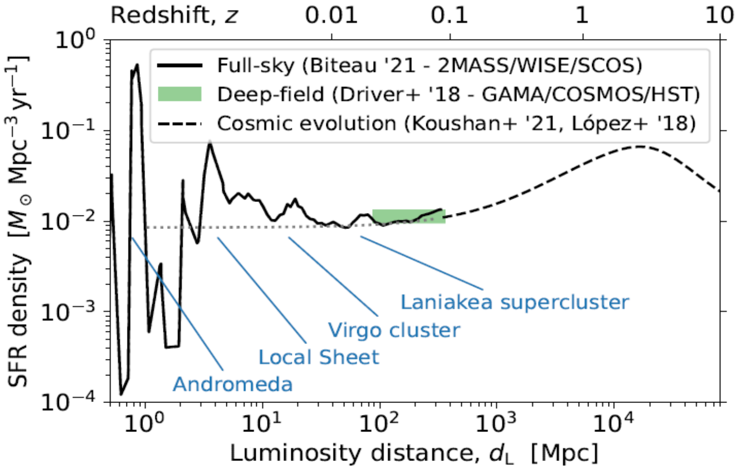
Can capture structures approximately by LSS model (GMF model depedency)

Do we need additional local sources to describe the data >40 EeV?

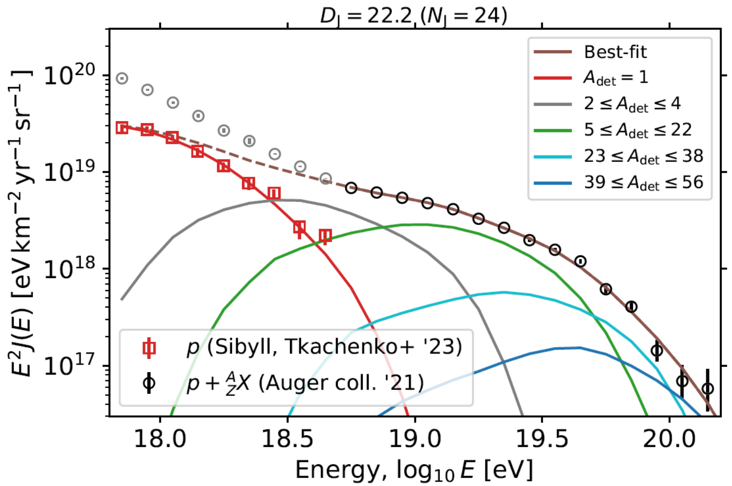
Transient model

- **assumption: UHECR sources are transients that occur proportionally to SFR in every galaxy**

- **<u>catalog:</u> near-infrared flux-limited sample from *Biteau 2021***
  - 400.000 galaxies, up to 350 Mpc
  - beyond: isotropic extrapolation following SFR
  - correction *c* for incompleteness mostly as function of distance + galaxy cloning to fill up GP region beyond 11 Mpc

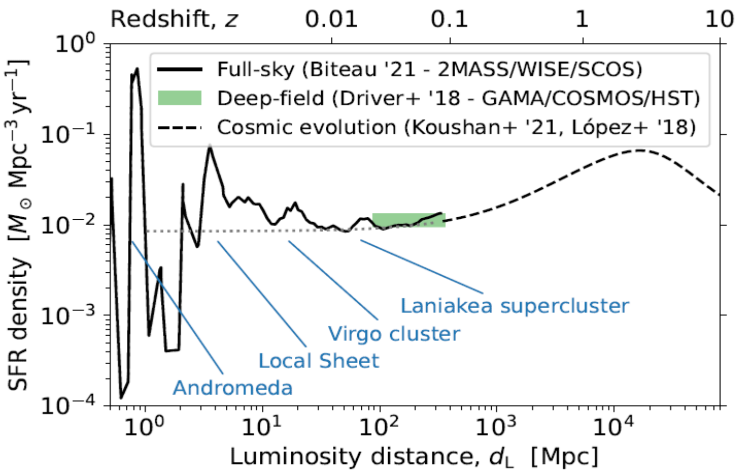


- **<u>model:</u> *Marafico, Biteau, Condorelli, Deligny, Bregeon 2024***
  - injection: broken power law, fit to spectrum and Xmax
  - injection rate S_i proportional to SFR$_i$ and burst rate k
  - time spreading due to magnetic field delays: $\Delta\tau$
    - parameter $k \cdot \Delta\tau$ determines visible galaxy contributions

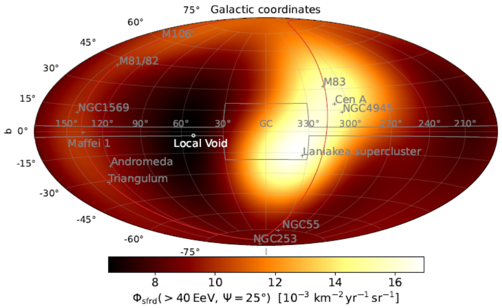


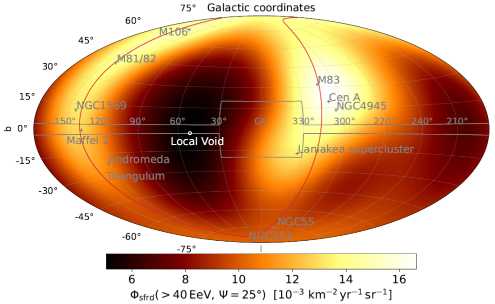
Transient UHECR model

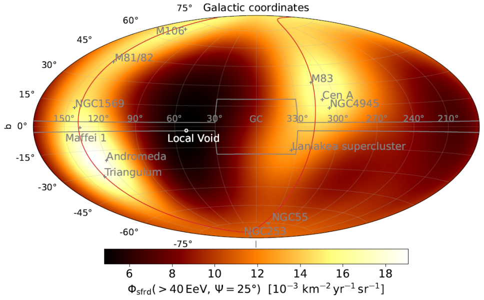
- **catalog:** near-infrared flux-limited sample from Biteau ApJS 256 15 (2021) 400.000 galaxies, up to 350 Mpc
  - no contribution from bright X-ray clusters due to magnetic trapping (e.g. Virgo, Perseus) Condorelli, Biteau, Adam ApJ 957 80 (2023)
- injection: broken power law, fit to spectrum and Xmax
- take into account **time delay due to magnetic fields**
- injection rate S_i proportional to SFR_i and **burst rate** k



small k — **intermediate** k — **large** k







local galaxies do not contribute → observer between bursts

almost continuous emission → local galaxies dominate

constrain burst rate k by comparison to data: