UHECR Anisotropies

Glennys Farrar
New York University

in collaboration with Teresa Bister, Radboud Univ.

building on work with Chen Ding and Noemie Globus Ap.J.Lett.2021

Today talk

- Large Scale Structure & UHECR anisotropy
- “Bias”
- Composition anisotropies
- Source density constraints
- Astrophysical implications of source density constraints
- if time: limits on local GRB protonic contribution

What we know about UHECRs:

- No single (apparent) dominant source (or source class ???)
- Complex composition
- Highest energy Galactic CRs overlap the lowest energy extragalactic UHECRs

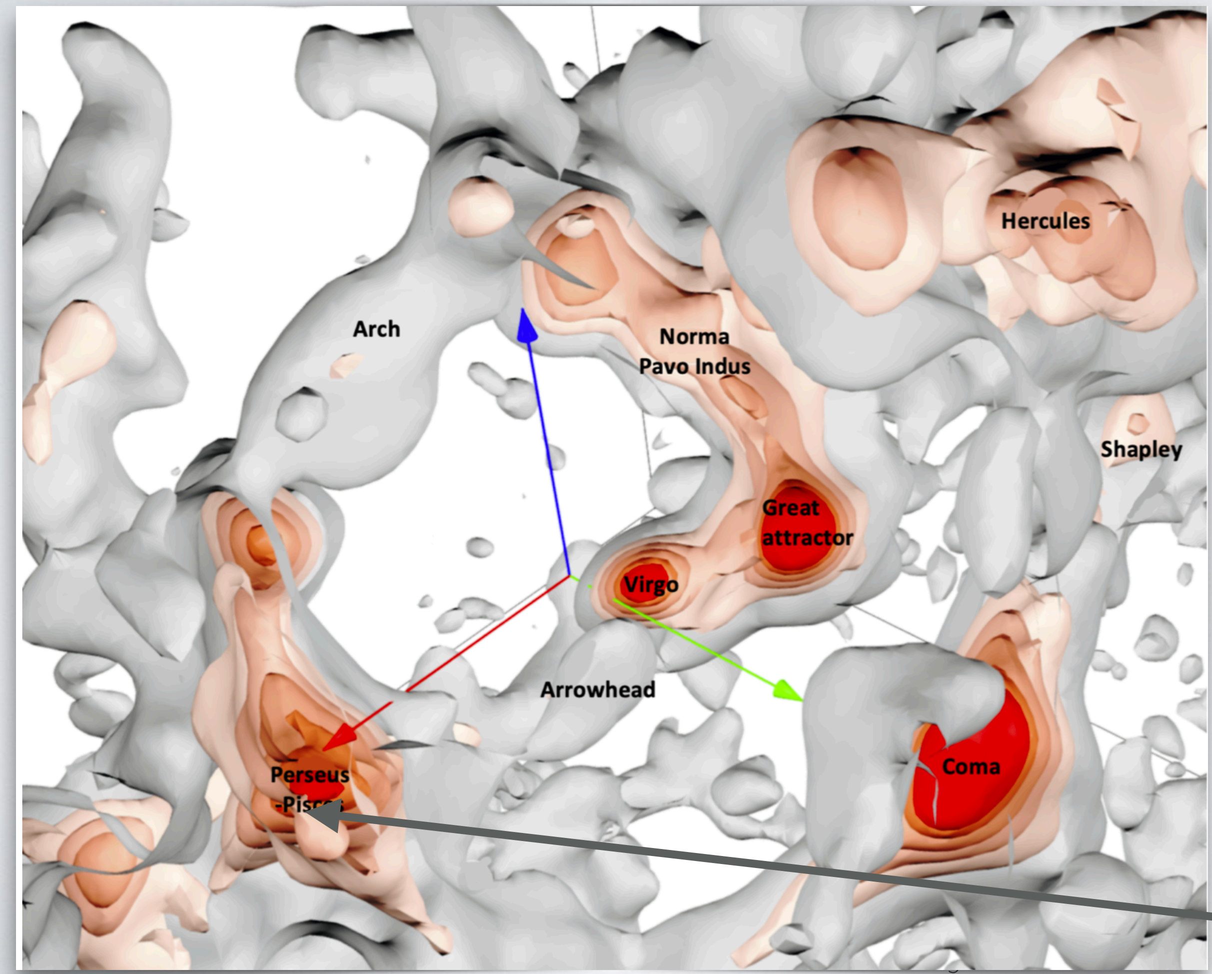
✦ Spectrum shaped by acceleration, propagation and interactions near source

  - Multi-messenger approach is essential

What we NEED TO know:

- Are sources weak and abundant or strong and rare?
- What are the principal source types?
    - ✦ Sources may not all be visible today (e.g., transients)
- What are the sources' spectra and composition?
    - ✦ Are UHECR sources (approximately) standardized?
- Better knowledge of magnetic fields
- Task requires fortitude & collective effort…

Source distribution ⇔ local matter distribution, *with bias*



DGF 21/ BF23 use JF12
Cosmicflows-2 (Hoffmann+18)

DGF 21: crude treatment of extragalactic propagation

BF23: accurate propagation; self-consistent fit to composition

<u>Future work</u>

UF23 magnetic field models (inc. random)

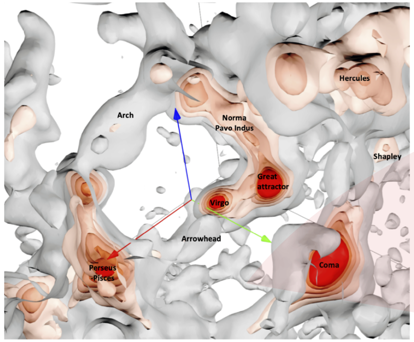
Pomerede+20 discovered South Pole Wall @~160 Mpc Cosmicflows-3

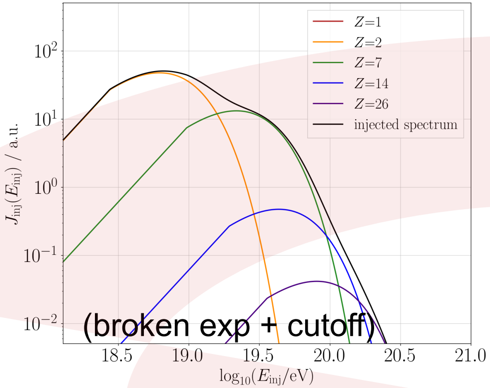
Our analysis:

injection following LSS

Cosmicflows2 *thanks to N. Globus*

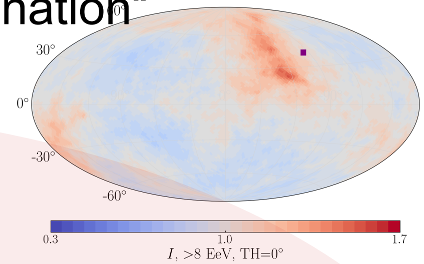
CRs: **Peters cycle**





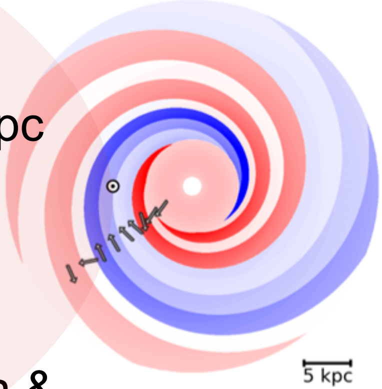
propagation with CRPropa

→ gives "illumination"

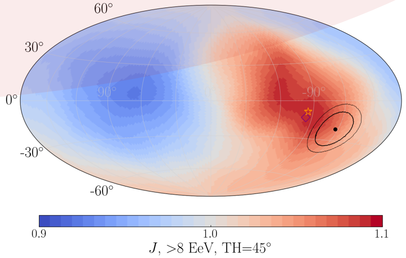


Galactic magnetic field

deflections: JF12, l_c=30 kpc



on Earth: spectrum, composition & directions of observed CRs

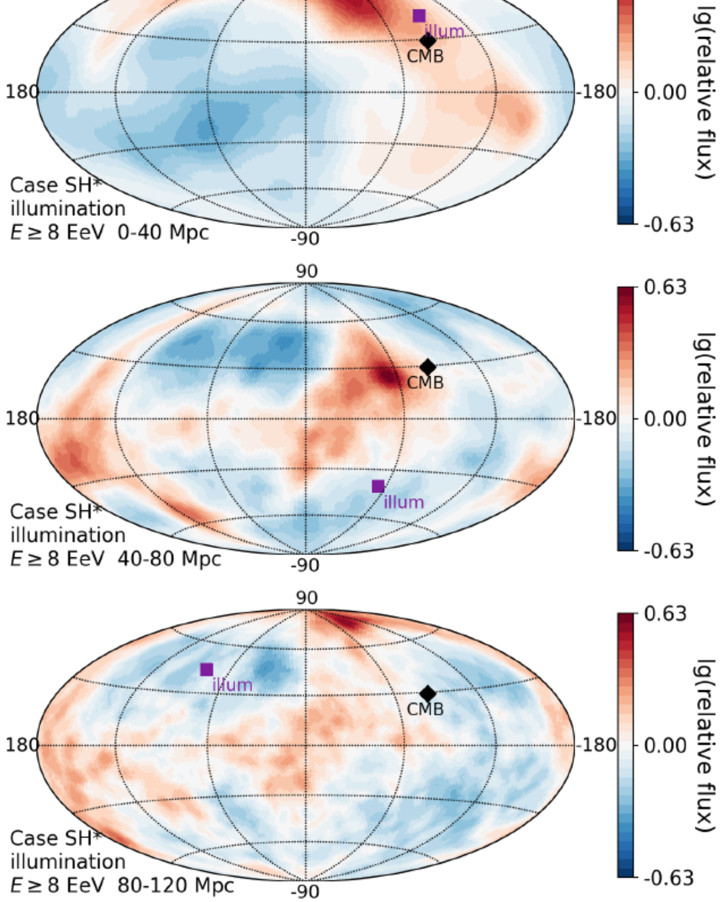


adapt injection, via likelihood:

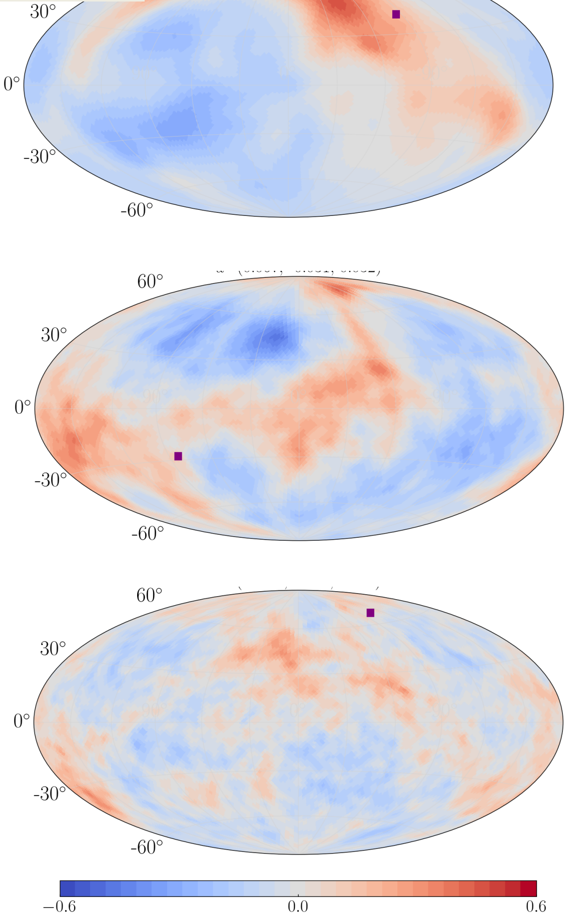
- compare model to data from Pierre Auger Observatory
  - dipole direction + amplitude in 3 energy bins
  - unfolded energy spectrum
  - shower depth distributions

More accurate Illumination Maps (DGF was pretty good but not perfect)

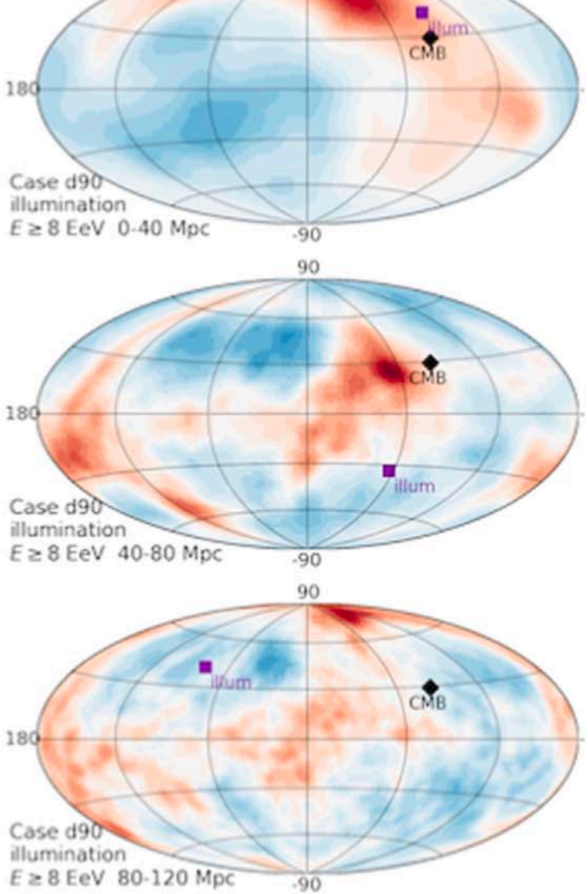
DGF- SH:



now:



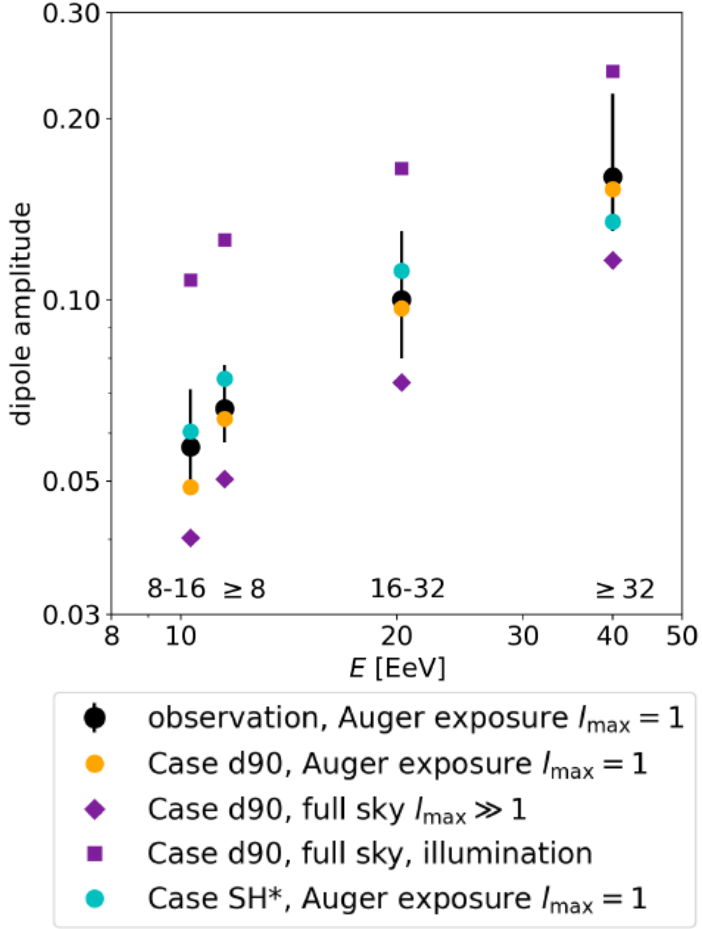
DGF- d90



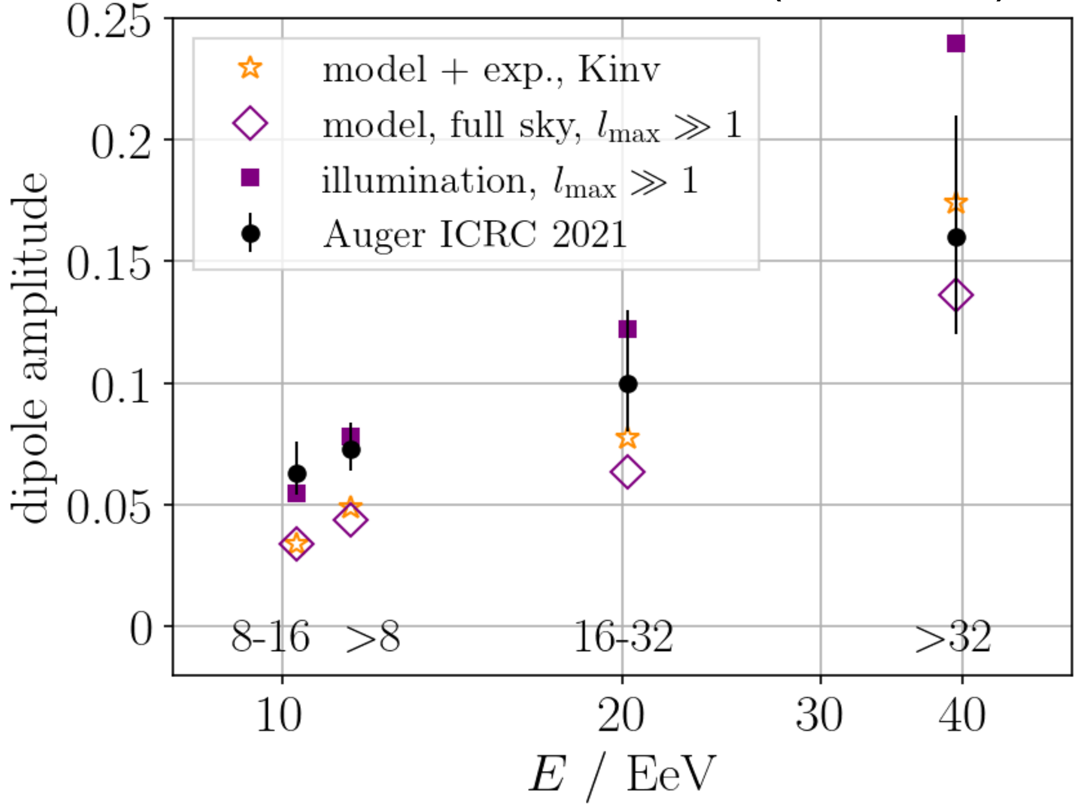
differences increase with distance due to change in propagation modeling

Dipole amplitude predictions

DGF21



Bister-Farrar (this work)

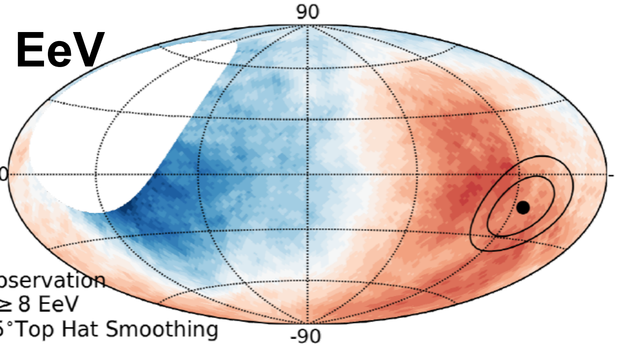


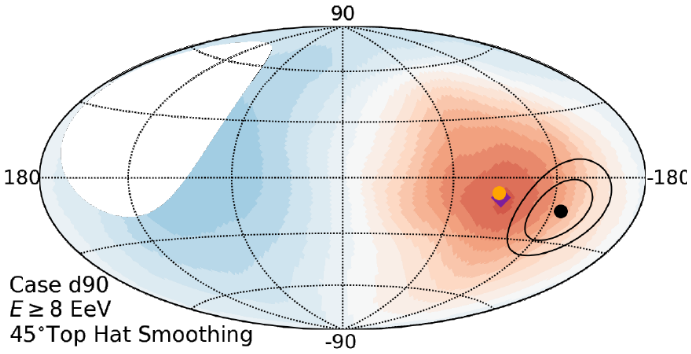
Amplitude too small at low E
(sensitive to strength and L_{coh} of GMF)

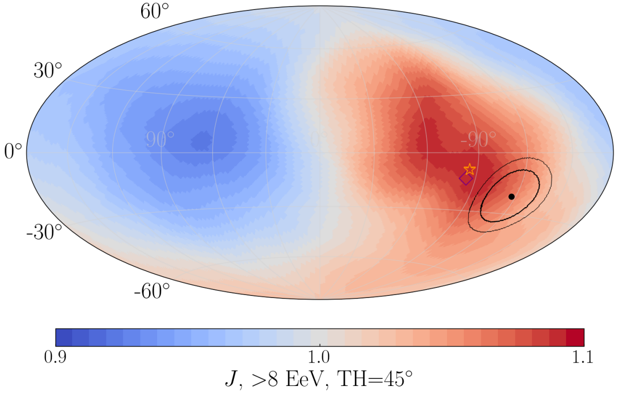
Dipole direction

DATA (Auger 2018): | *DGF:* | *now:*

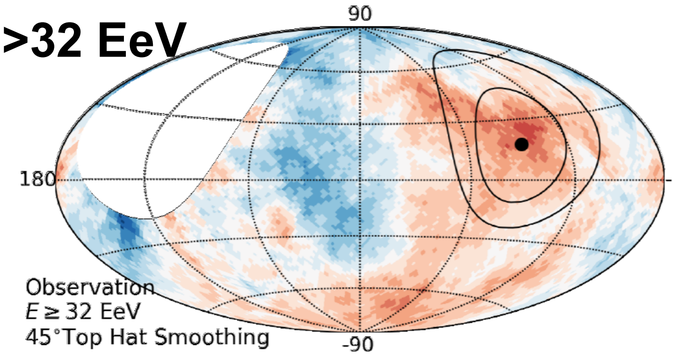
> 8 EeV

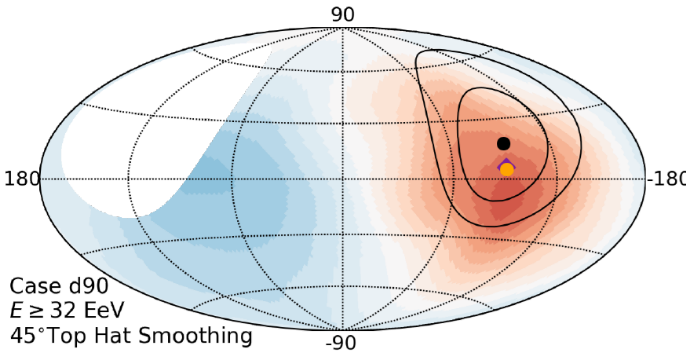


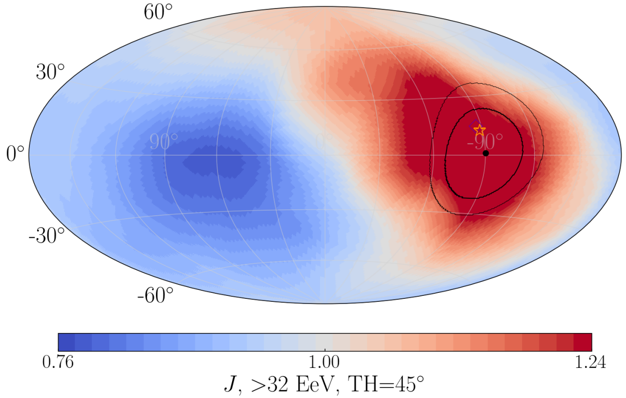




>32 EeV

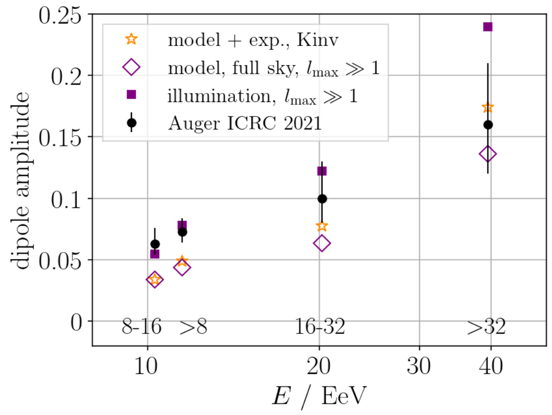


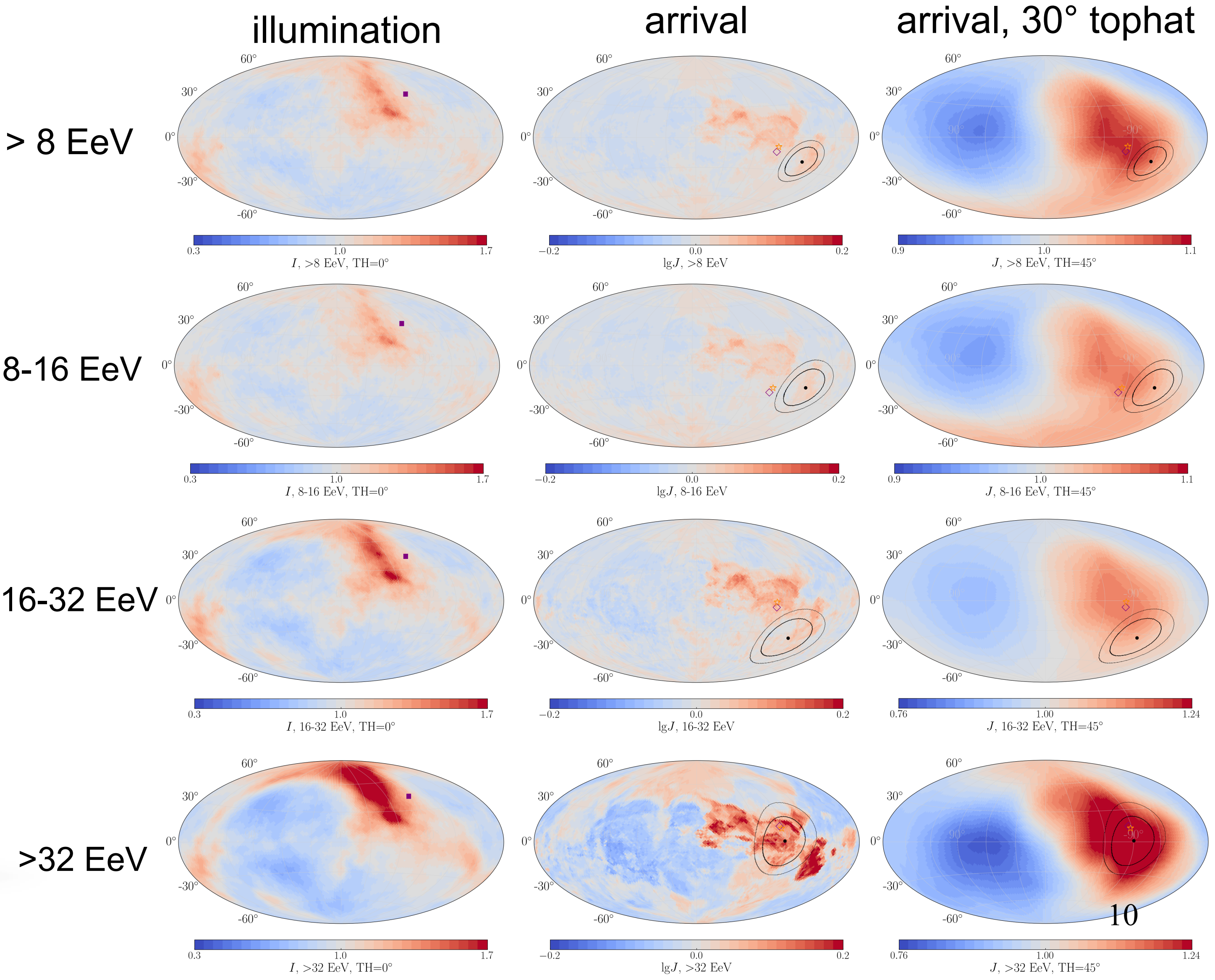




predictions close to measured direction within model uncertainties

Energy Dependence





As energy increases:

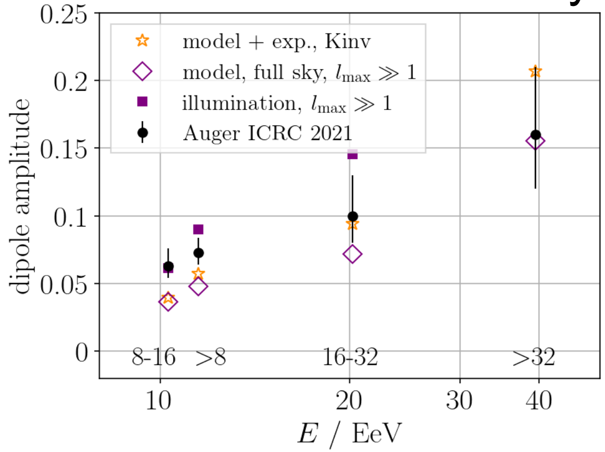
- more anisotropy in illumination (from propagation)
- dipole amplitude increases (mostly propagation+turbulent GMF)
- direction almost unchanged (mostly coherent GMF; rigidity ~ constant)

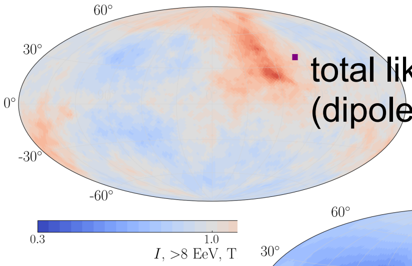
New Studies: 1 — “BIAS”

- Large Scale Structure model of UHECR anisotropy: good
- “Bias”
- Composition anisotropies
- Source density constraints
- Astrophysical implications of source density constraints

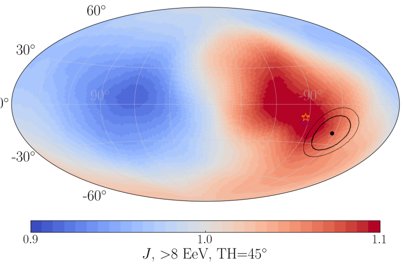
Too anisotropic without low-density regions

cut **~3%** of lowest density

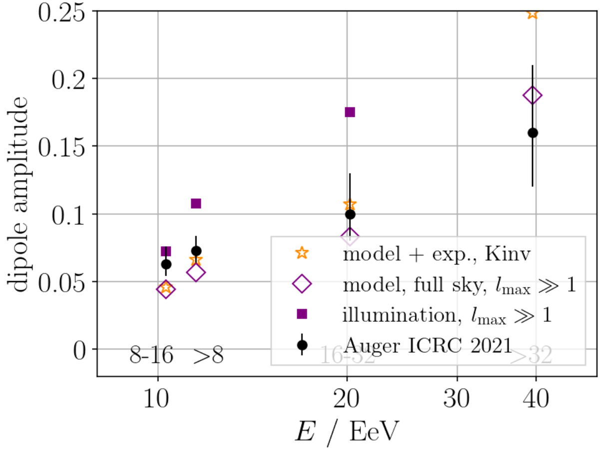


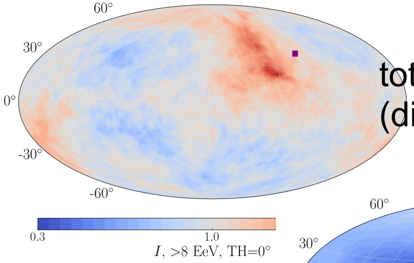


total likelihood -0.7
(dipole -0.6)

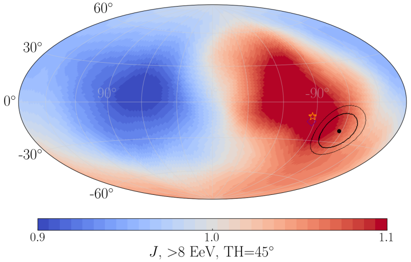


cut **~13%** of lowest density

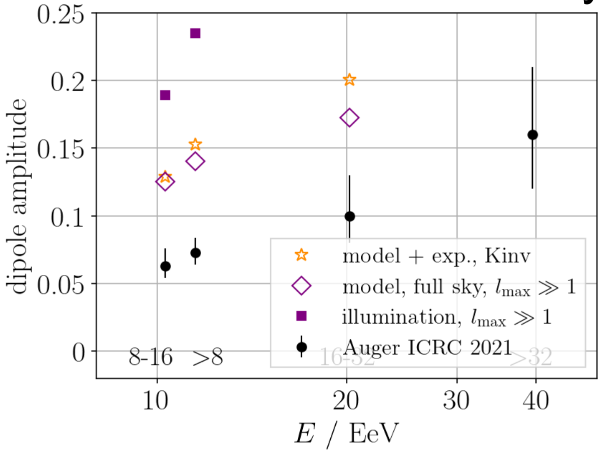


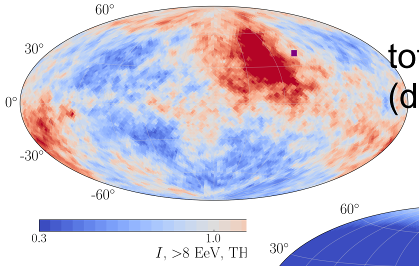


total likelihood -5
(dipole -1)

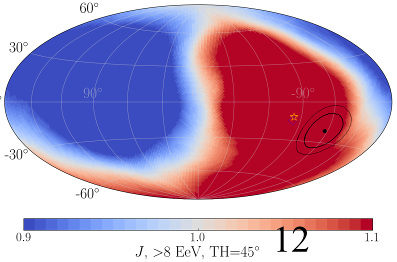


cut **~50%** of lowest density



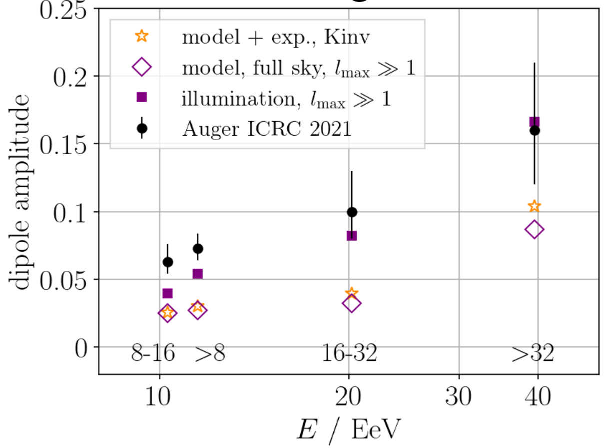


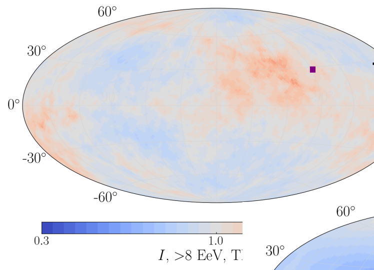
total likelihood -43
(dipole -40)



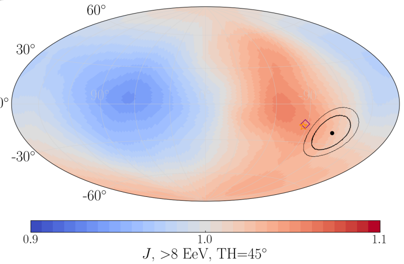
Need both low- & high-density regions in LSS

cut **~0.5%** of highest density

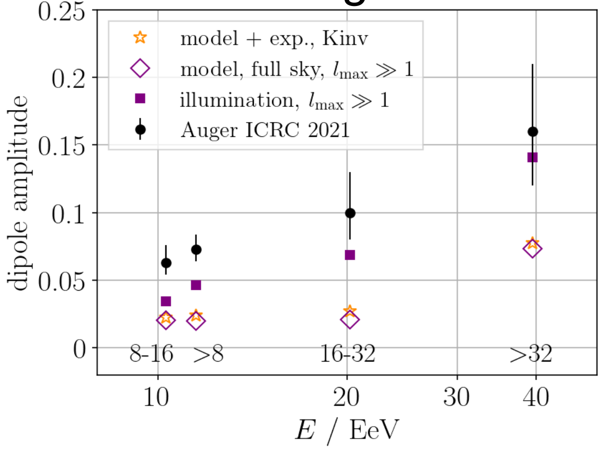


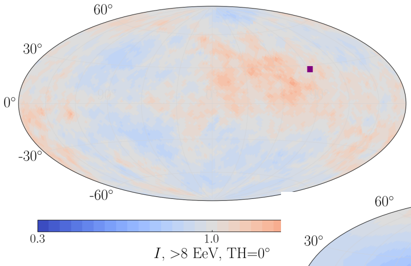


total likelihood -4
(dipole -2)

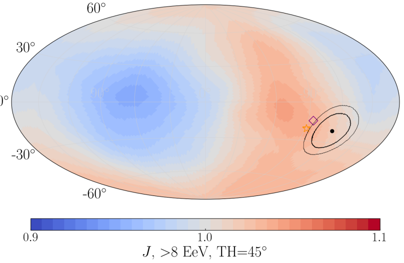


cut **~1%** of highest density

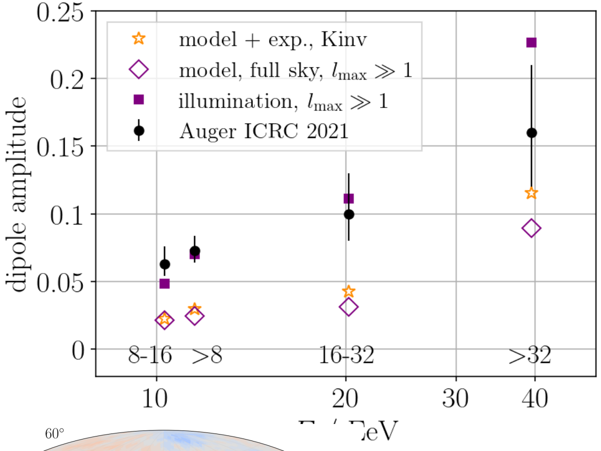


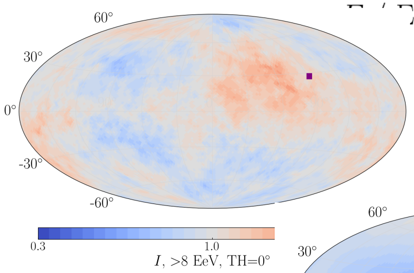


total likelihood
-7
(dipole -4)

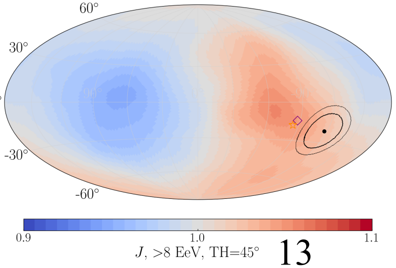


cut **~13%** of lowest density + 0.5% of highest density



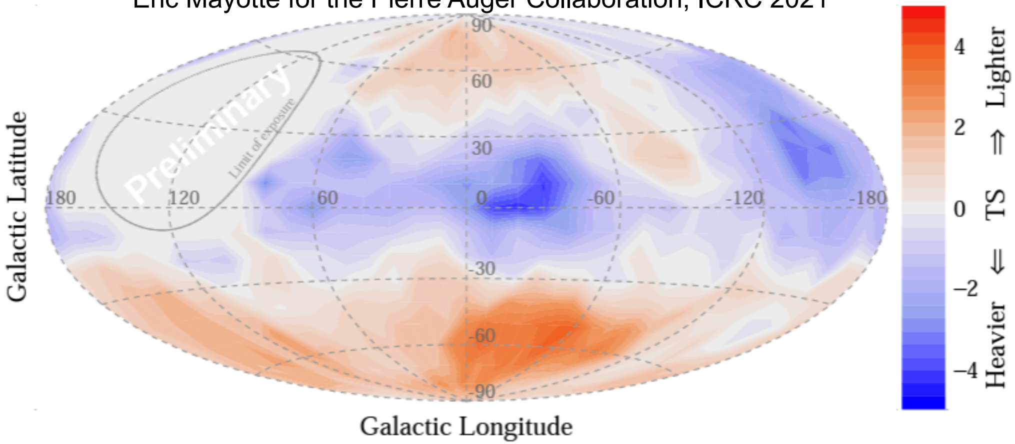


total likelihood -4
(dipole -3)



Composition anisotropy

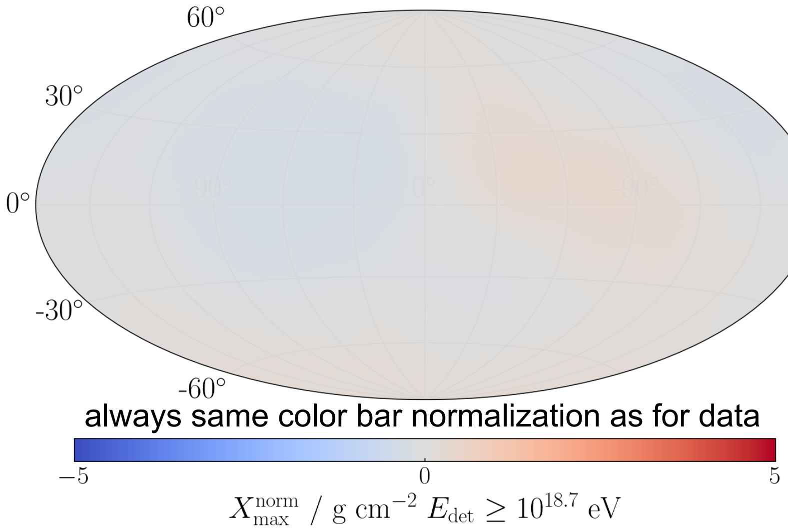
Eric Mayotte for the Pierre Auger Collaboration, ICRC 2021



Auger FD: composition anisotropy > 5 EeV

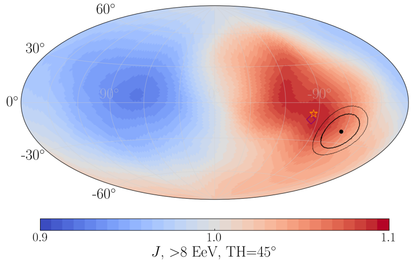
(red regions ~5 g/cm^2 lighter than mean, blue regions ~5 g/cm^2 heavier)

→ larger magnetic field in Galactic plane captures heavy particles?

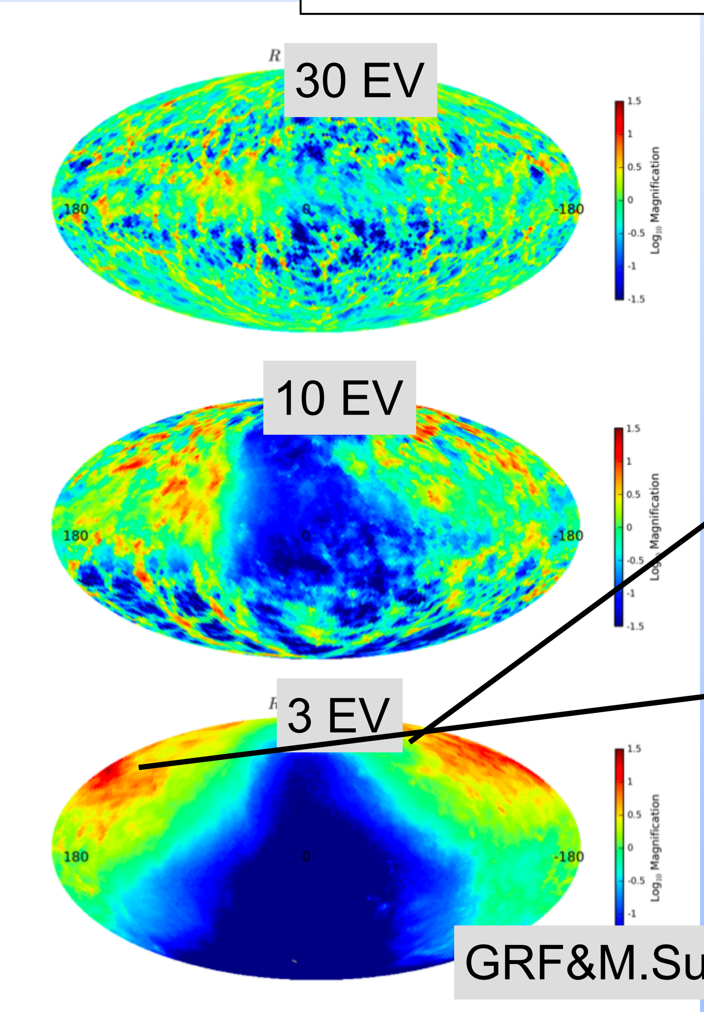


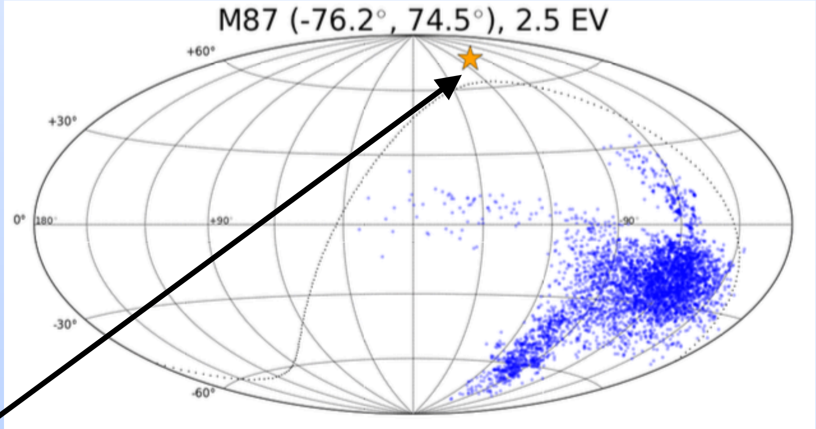
LSS injection + JF12 GMF → very **small composition anisotropies** (also in DGF21)

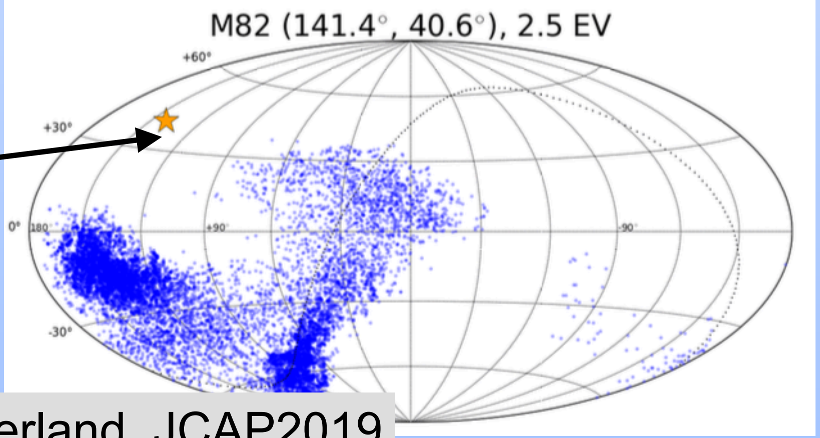
lighter regions weakly correlated with flux



Rigidity-dependent Magnification can generate Composition anisotropy







GRF&M.Sutherland, JCAP2019

p: $R_{min} = E_{min}$
C: $R_{min} = E_{min}/6$

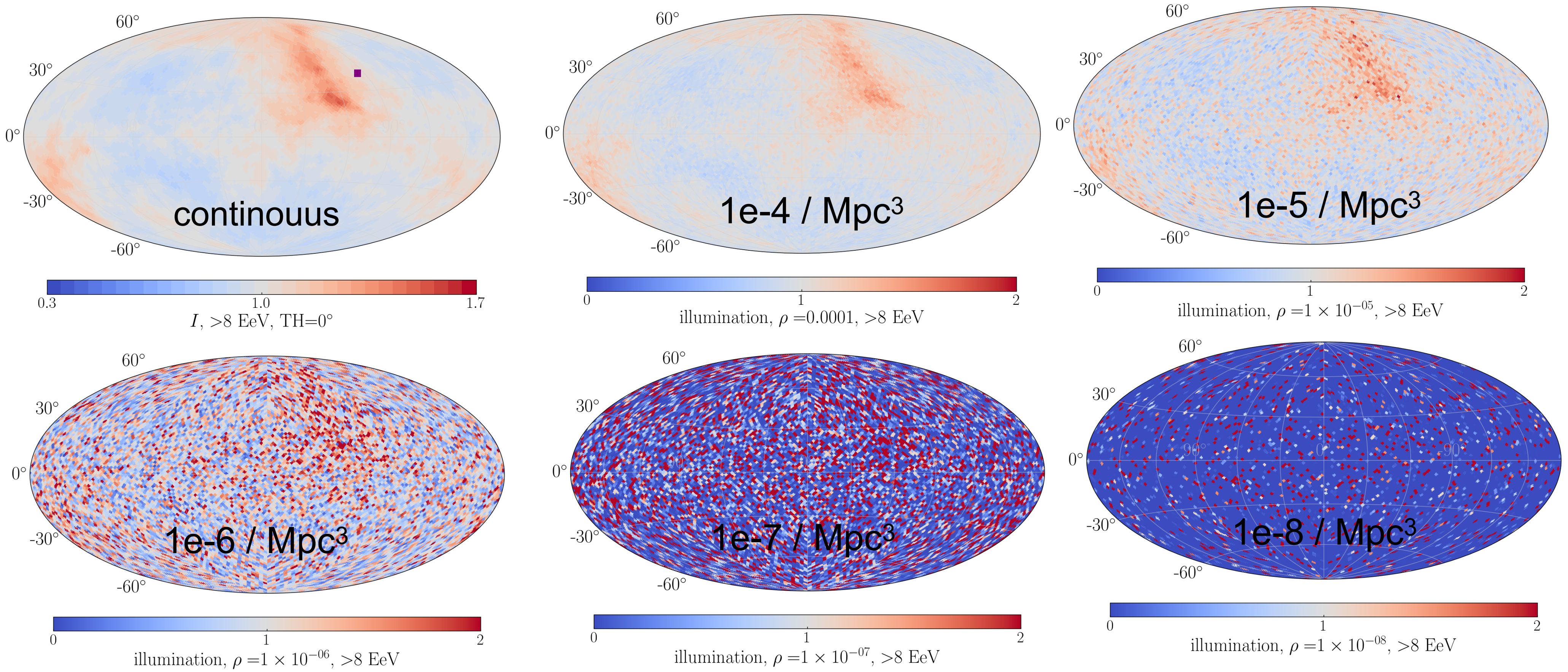
Higher rigidities less deflected

in this example, lighter components are more prominent above GP, heavier found below

New Studies: 3 — Source density

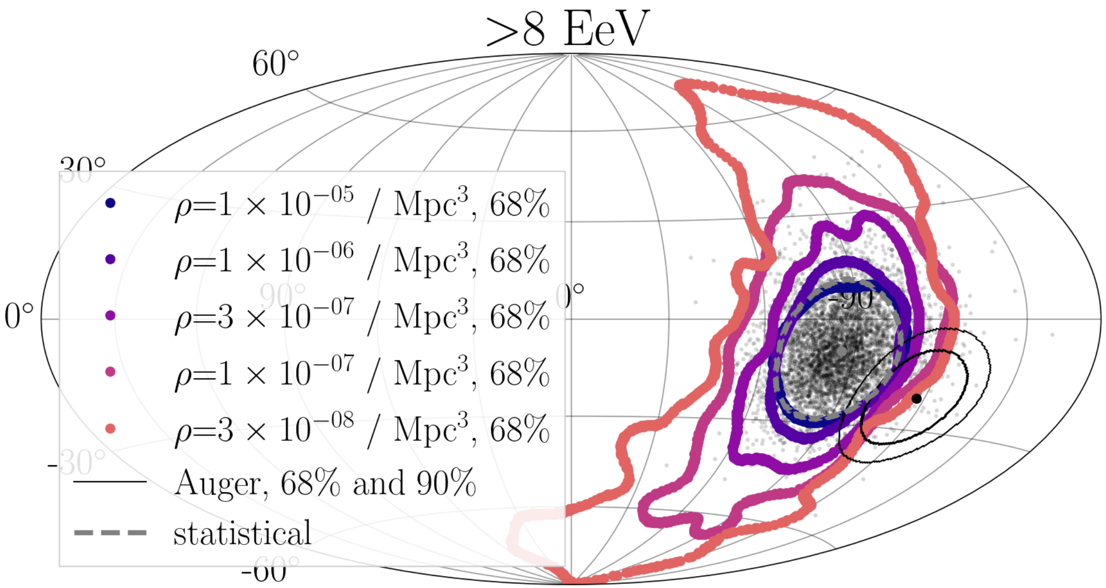
- Large Scale Structure model of UHECR anisotropy: GOOD but improvable
- "Bias" disfavored
- Composition anisotropies possible with low source density
- Source density constraints
- Astrophysical implications of source density constraints

Sampling source density: illumination maps



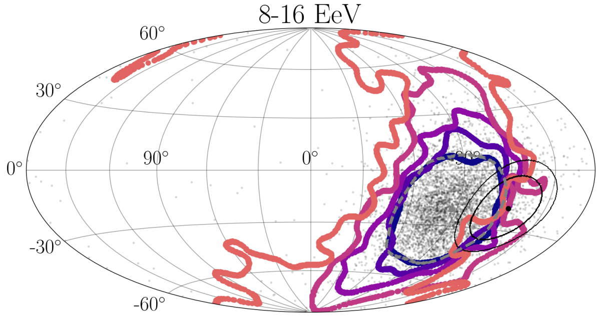
Can we place limits on the source density by studying the predicted model arrival directions?

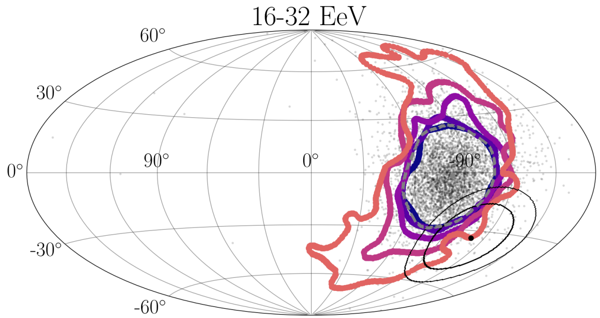
Sampling source density: Dipole Direction

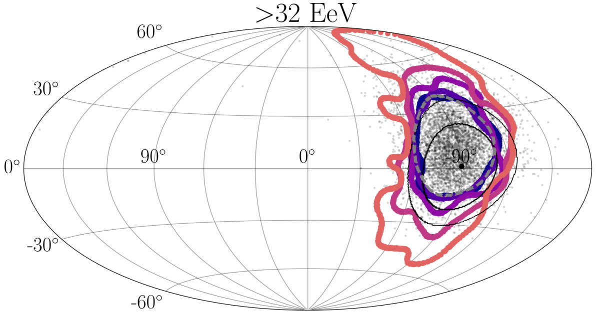


skymap: 68% contours of dipole direction

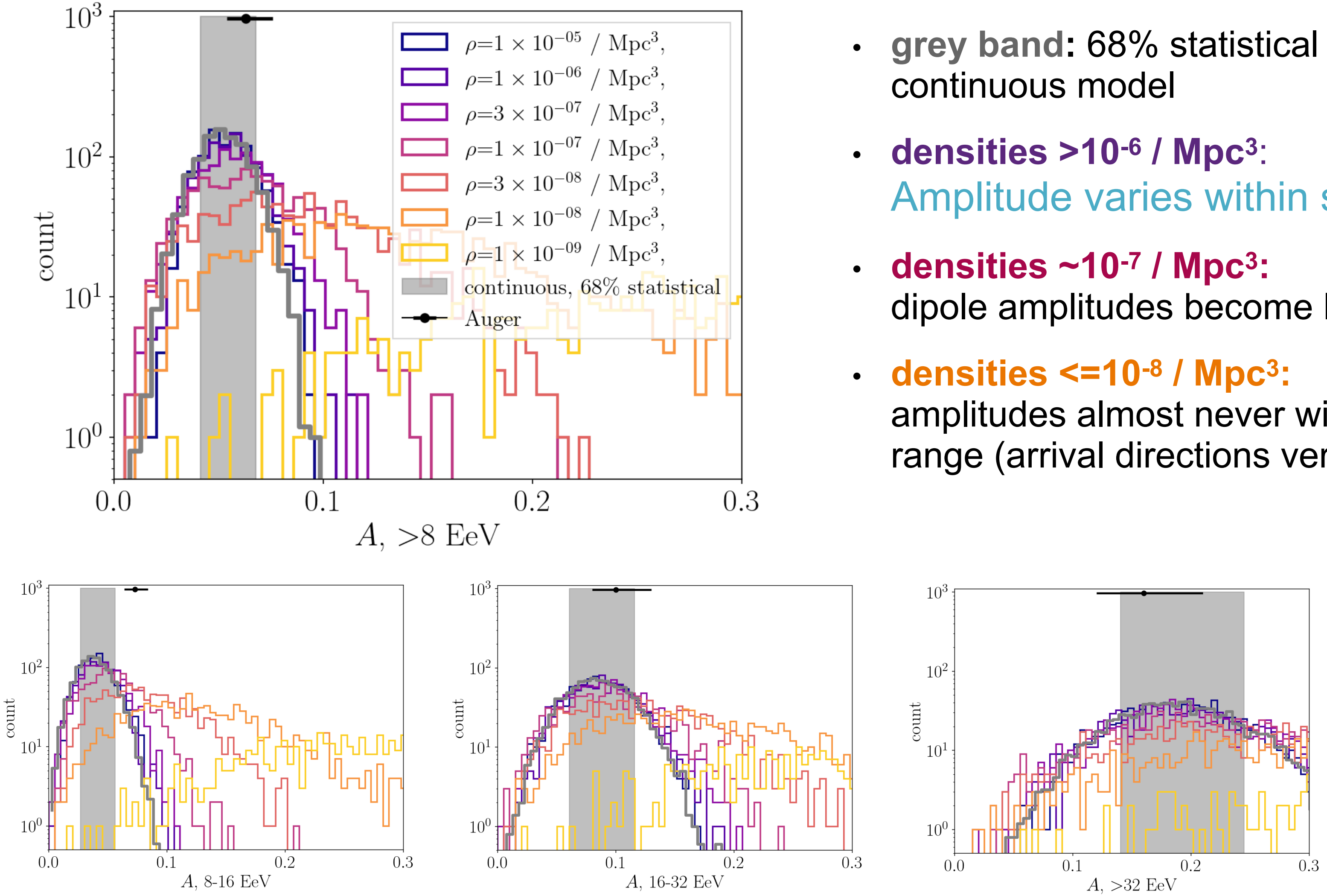
- **grey**: dipole directions from drawing N_{CRs} from continuous density model → **statistical uncertainty**
- **densities >10^{-6} / Mpc^3:** **Dipole direction varies within statistical**
- **densities ~10^{-7} / Mpc^3:** **Dipole direction varies significantly**
- **densities <=10^{-8} / Mpc^3:** dipole direction is random







Sampling source density: Dipole Amplitude

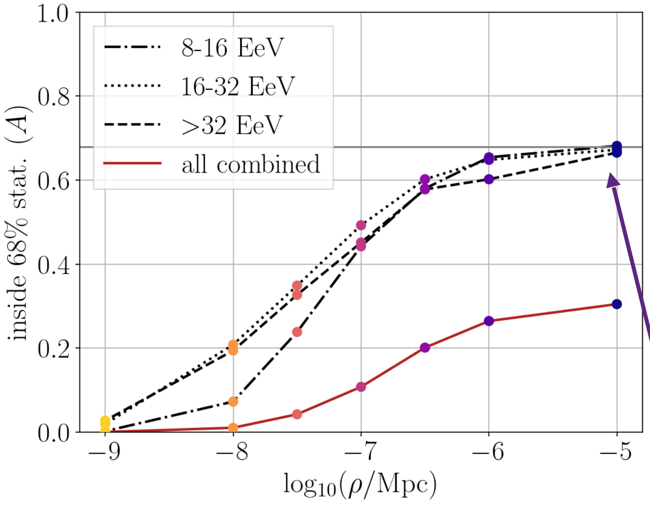


- **grey band**: 68% statistical uncertainty in continuous model
- **densities >10^{-6} / Mpc^3**: Amplitude varies within stat. uncertainty
- **densities ~10^{-7} / Mpc^3:** dipole amplitudes become larger
- **densities <=10^{-8} / Mpc^3:** amplitudes almost never within statistical range (arrival directions very anisotropic)

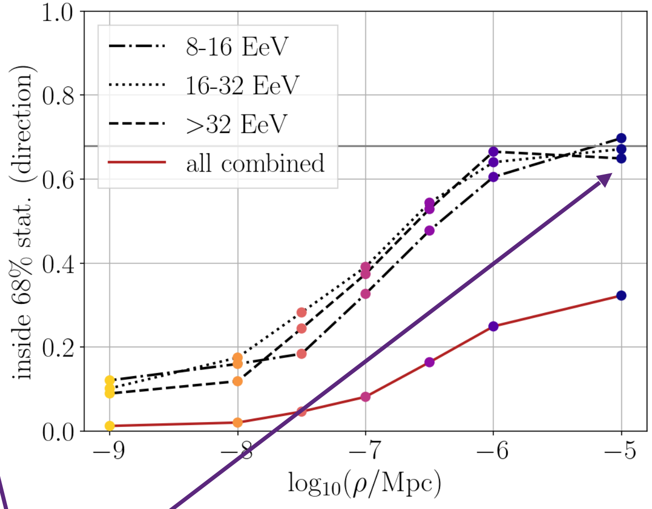
Sampling source density: Dipole Amplitude and Direction

fraction within statistical uncertainty:

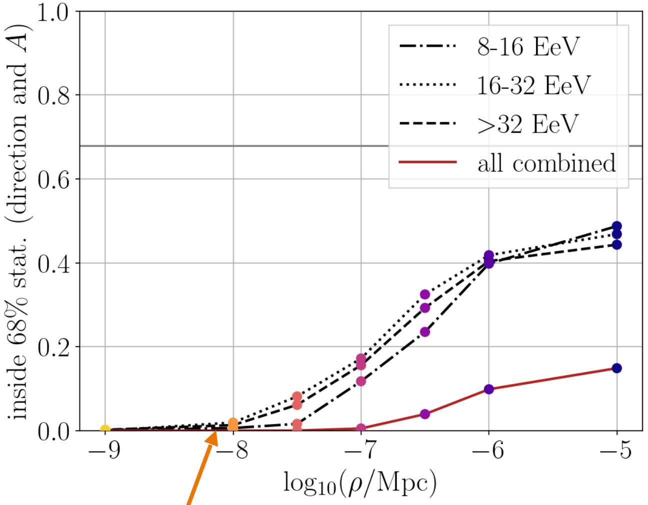
dipole amplitude



dipole direction



amplitude and direction combined

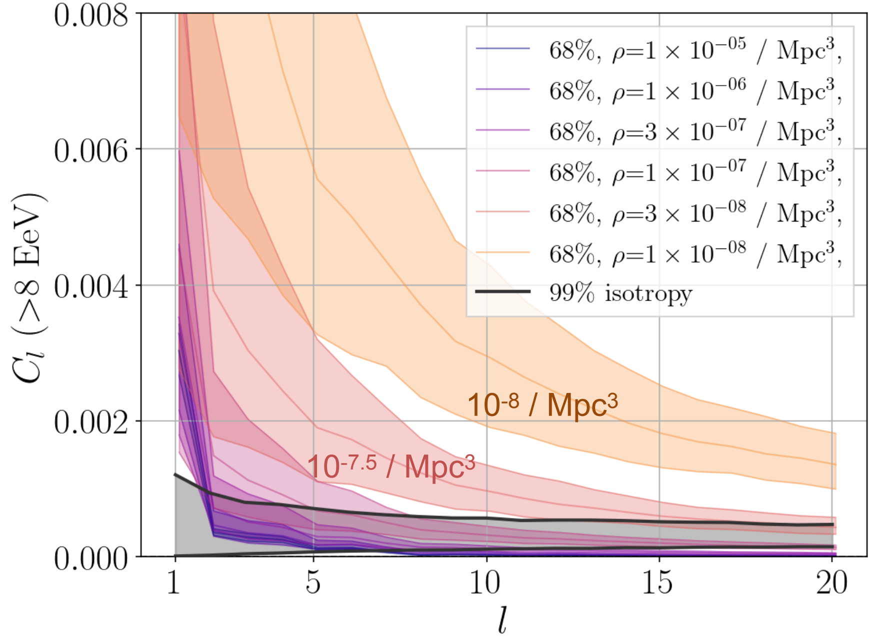


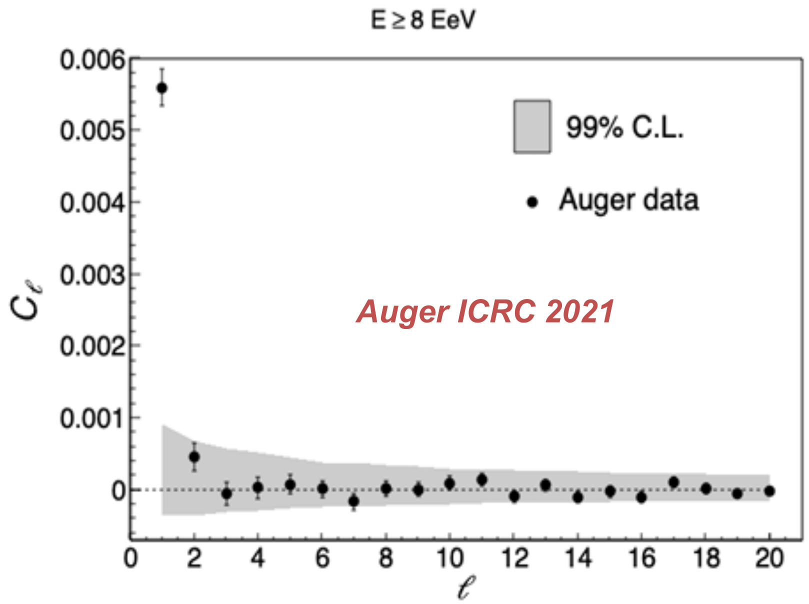
densities >10^{-6} / Mpc^3:

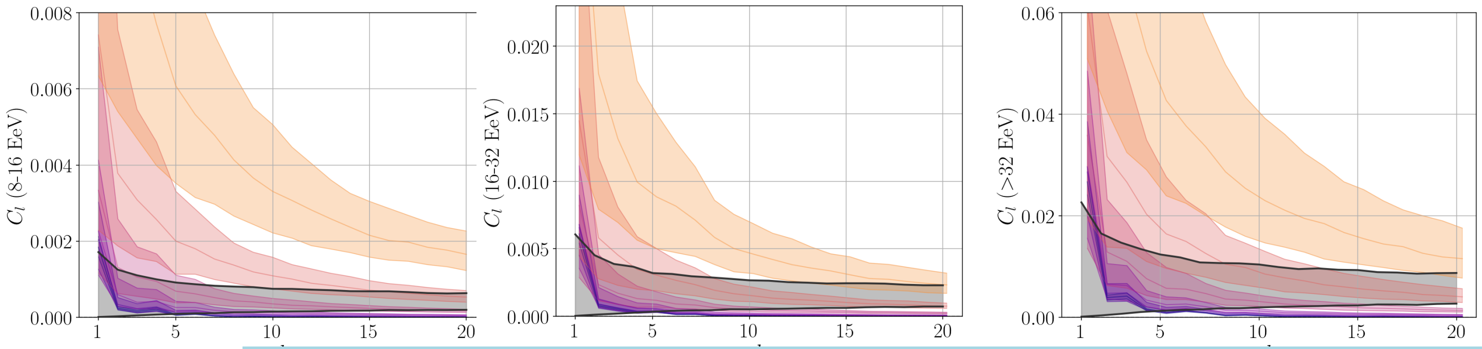
- behave as continuous model: 68% within 68% statistical
- combining direction & amplitude: almost independent ($0.68^2 = 0.46$)

densities <=10^{-8} / Mpc^3:
number of examples where dipole direction & amplitude fit at the same time: 0 / 1000

Sampling source density: Angular Power Spectrum







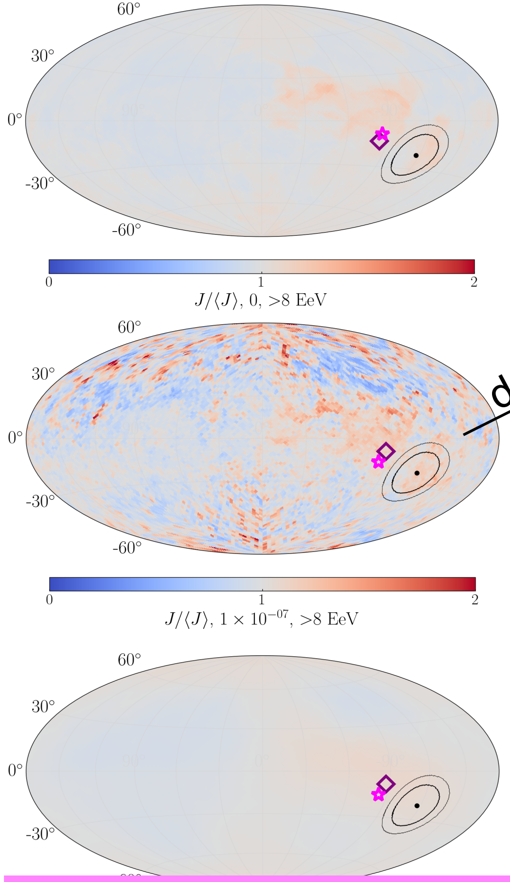
✓ densities > 10^{-6} / Mpc³

✘ densities < 10^{-7} / Mpc³

c_l's are even more constraining on source density than dipole

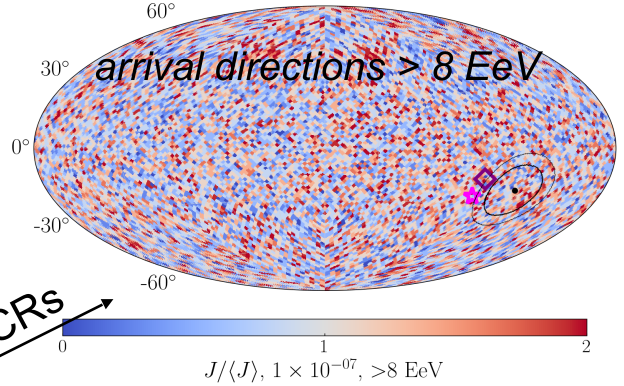
Composition anisotropy? Example @10^{-7} / Mpc^3 that describes dipole direction & amplitude well

arrival > 8 EeV

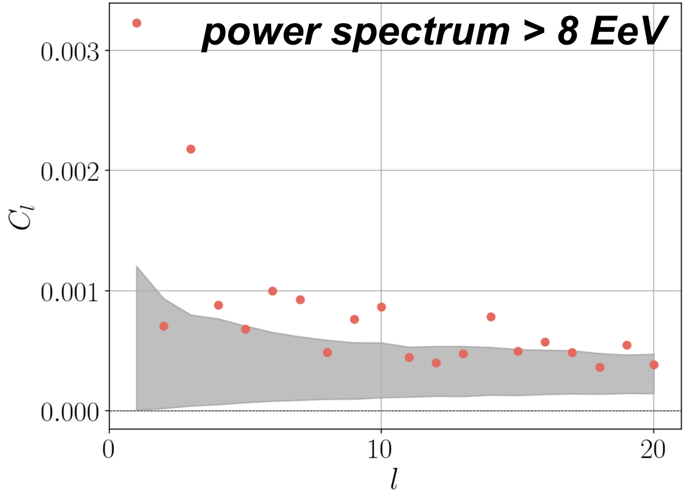


draw 44000 CRs

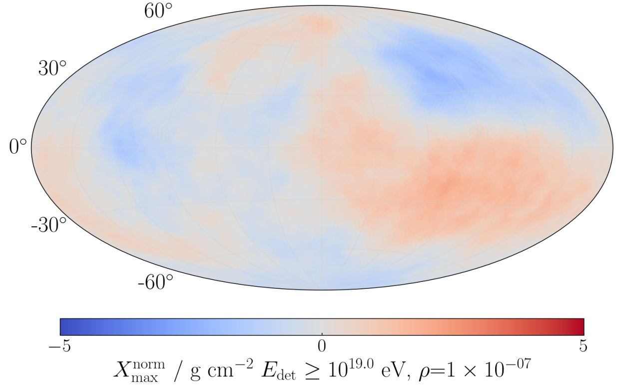
arrival directions > 8 EeV

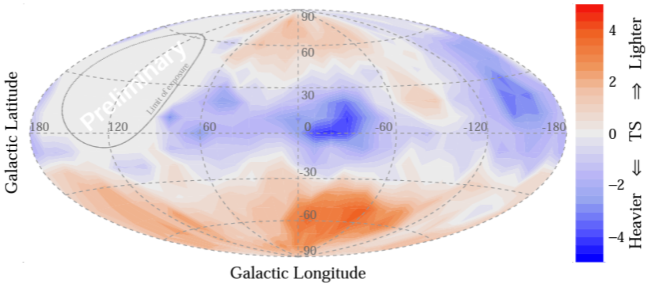


power spectrum > 8 EeV



composition anisotropy > 8 EeV





Hard to get such a big composition anisotropy while respecting other constraints

Astrophysical considerations

- Large Scale Structure model of UHECR anisotropy: GOOD but improvable
- “Bias” disfavored
- Composition anisotropies possible with low source density
- Source density constraints
- Astrophysical considerations of source density constraints

Energetics condition on accelerators

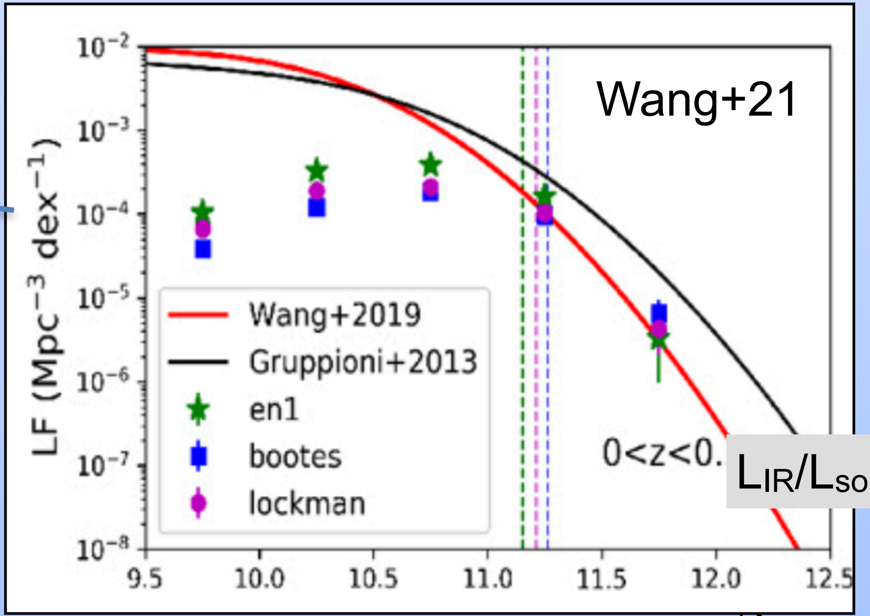
(see GF+A.Gruzinov ApJ2009 for derivations)

- Acceleration requires: size x B > 10^{16} $R_{18.5}$ Γ^{-1} (Larmor radius fits)
- Poynting Luminosity ~ c/6 Γ^4 B^2 L^2 ~ 10^{42} $(R_{18.5})^2$ erg/s ➜ (roughly!!!)

  Minimum Bolometric Luminosity of UHECR sources ~ **$10^{42.5}$ $(R_{18.5})^2$ erg/s**
- Volumetric UHECR power (Muzio, Unger, GF2019): $10^{44.8}$ erg/s Mpc^{-3}
- ➜ $n_{src} \lesssim 10^{-3}$ Mpc^{-3} energetics requirement gives a weak limit

Density conditions on UHECR accelerators (BF23: need $n \gtrsim 10^{-6}$ Mpc^{-3})

- Luminous IR galaxies (aka starburst galaxies)
  - GF, A. Berlind, I. Zaw ApJL 2009: enhanced correlation LIRG & UHECRs >57 EeV
  - $\gtrsim$ 50% of local AGN qualify as SBG (Xie+21)
  - $n_{SBG} \approx 10^{-4}$ Mpc^{-4}

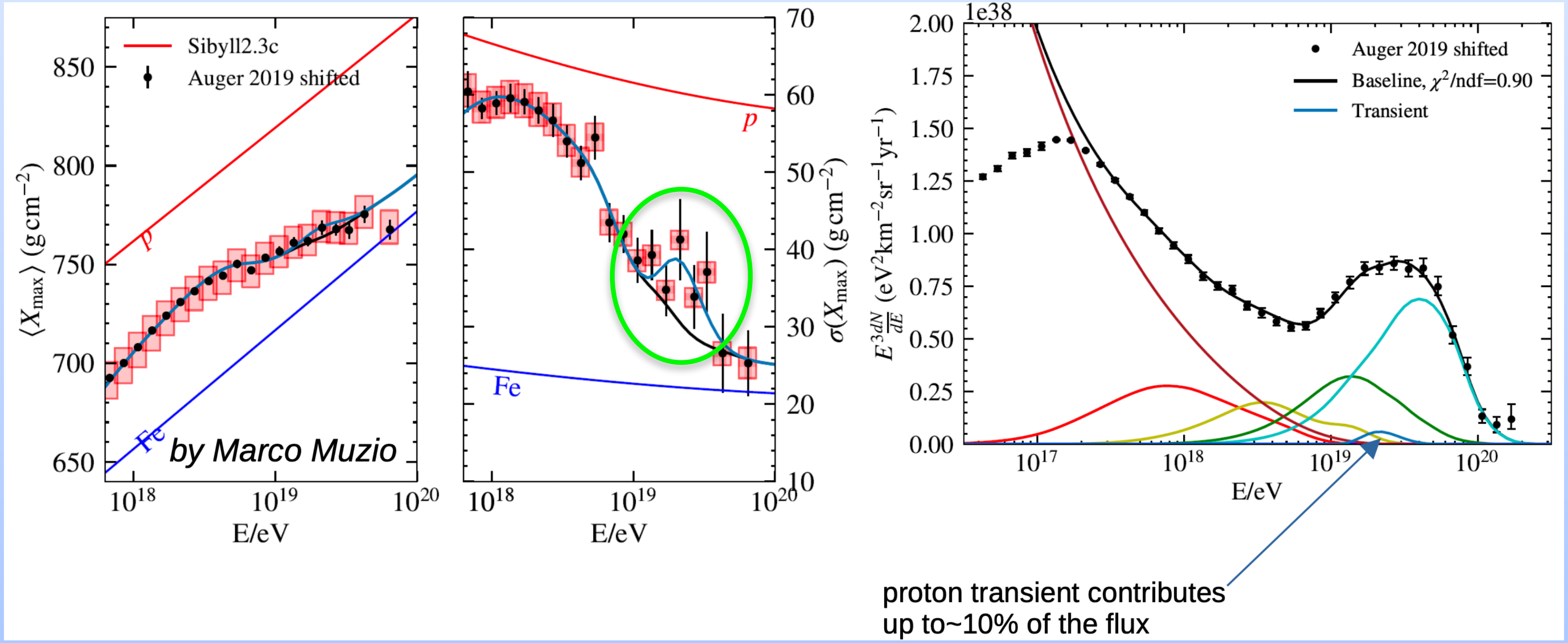


- Fotopoulou+16 $n_{XAGN} \sim 10^{-6}$ Mpc^{-4}
  - X-ray (5-10 keV) AGN ($L_X > 10^{44}$ erg/s)

$L_{sol} = 3.8\ 10^{33}$ erg/s

Possible contribution of local GRBs to Auger?

(Bister, GF, Muzio, in prep)

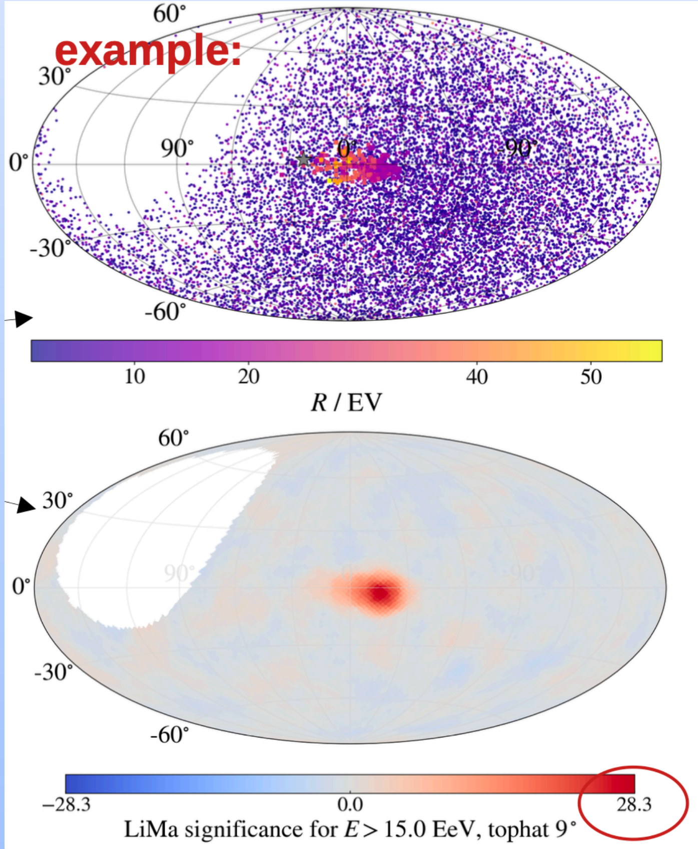


Motivations: transient source ↔ factor-2 energy range
MUF21: fit improves with some protons

G. Farrar, CRA23

Possible contribution of local GRBs to Auger?

KILLED BY ANISOTROPY CONSTRAINTS



Need ~ 80 protonic transients to "hide" them
Auger's anisotropy limits are ***very*** sensitive!

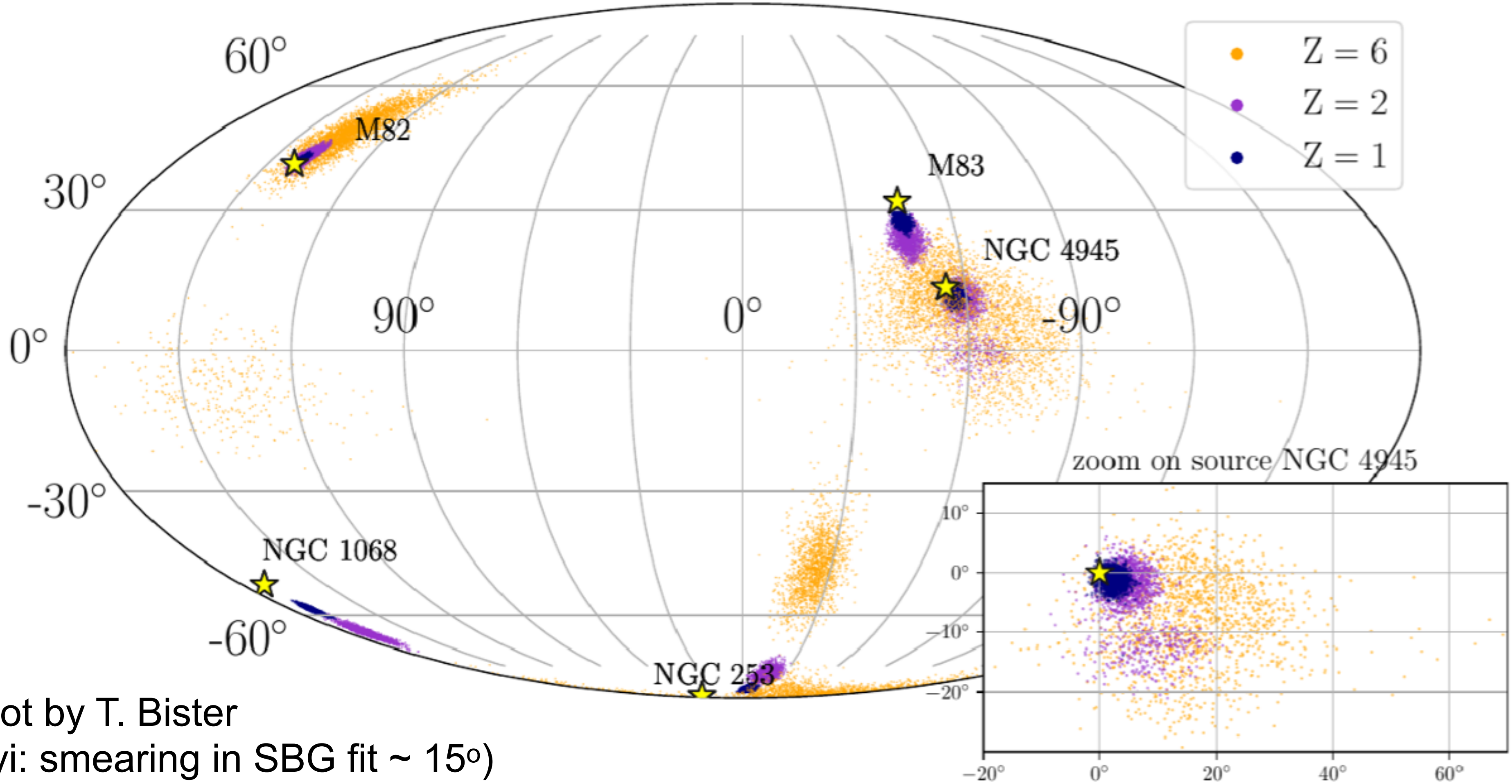
G. Farrar, CRA23

Summary

- Teresa Bister+GF 2023: fixed approximations in Ding, Globus, Farrar ApJL21
  - Large Scale Structure still gives generally good accounting of Auger anisotropies
  - Predicted dipole magnitude is somewhat low: random field smaller than in JF12 model or L_{coh} < 30 pc
  - TO-DO: explore uncertainties from Large Scale Structure and GMF model uncertainties
- New constraints on source density and "UHECR bias"
  - Source density >~ 10^{-6} Mpc^{-3}
  - Auger dipole prefers no "UHECR bias" (UHECR sources distributed in all mass density regions)
- Other topics:
  - Combined constraints of dipole magnitude & direction, & lack of higher multipoles, is hard to reconcile with composition anisotropy reported by Auger-FD.
  - Transient(s) with light composition (e.g., GRBs) cannot be responsible for "fine structure" in Auger spectrum and σ(Xmax)

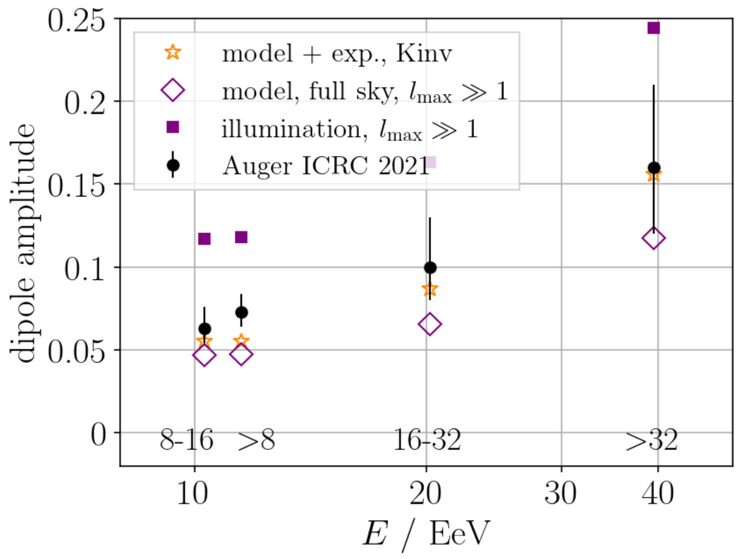
BACKUP

JF12 GMF impact on SBG images (50 EeV)



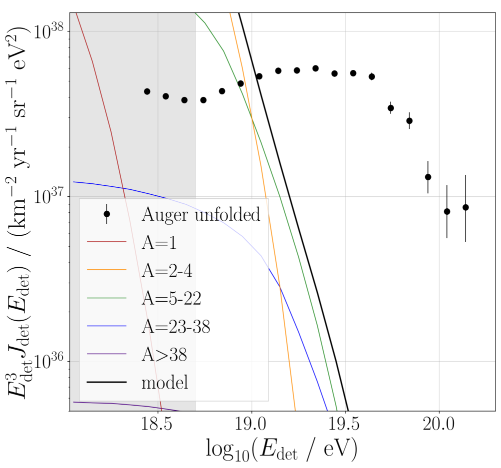
Plot by T. Bister
(fyi: smearing in SBG fit ~ 15^{o})

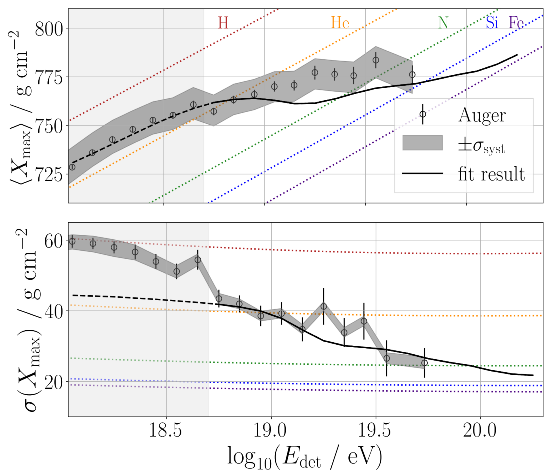
Fit only dipole (not spectrum & composition)



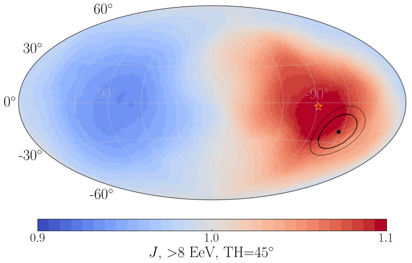
LSS model can describe direction and especially amplitude very well!

but: then spectrum + composition not described

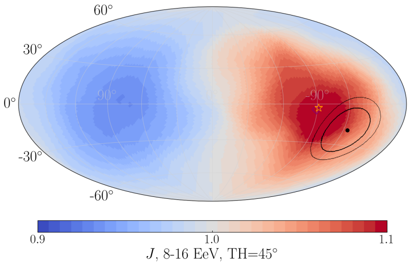




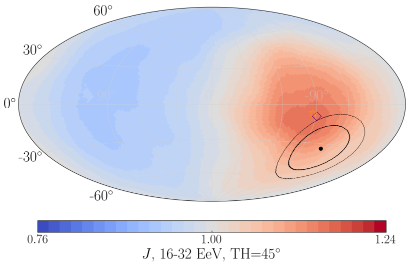
> 8 EeV



8-16 EeV



16-32 EeV



>32 EeV