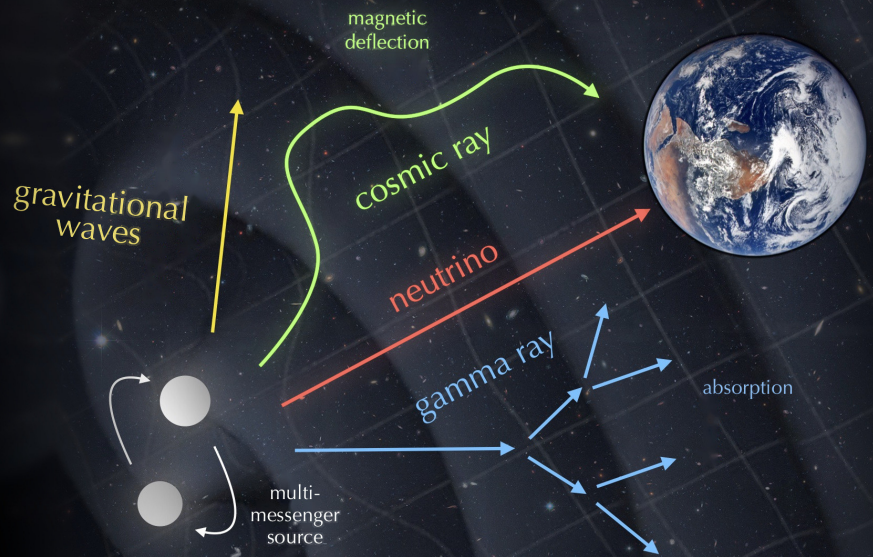
Multi-messenger Observations at UHE: Discussion & Outlook

M. Unger (KIT)



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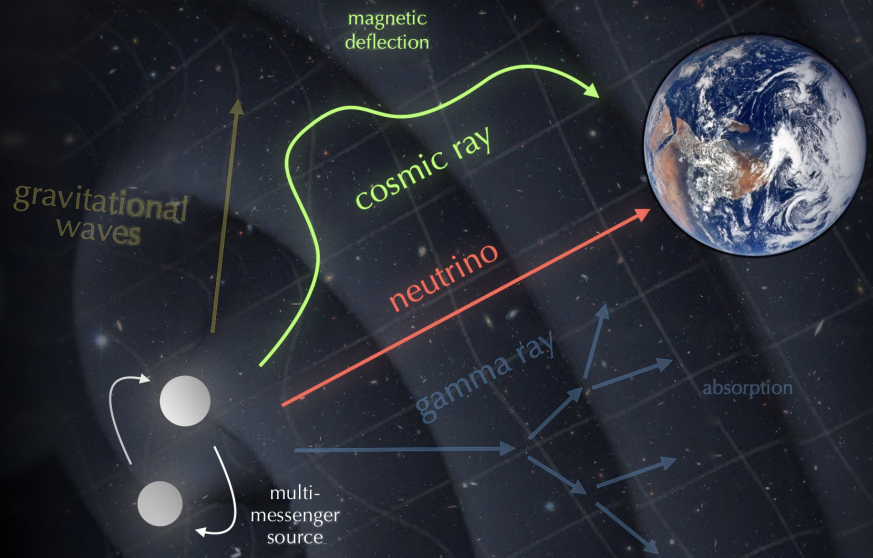
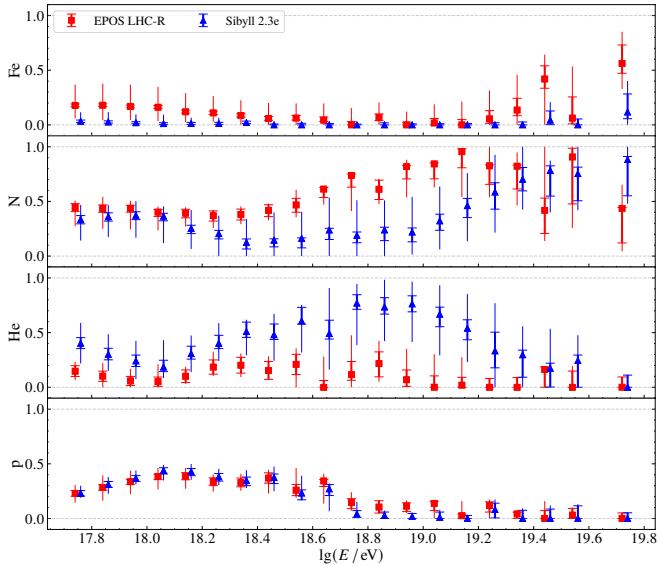


Reminder: UHE Composition

Pierre Auger Coll. PRD 114 (2026) 4, 043016



UHE protons at Earth:

- $E_p \approx 0.5 \ldots 5\,\mathrm{EeV}$

$\rightarrow$ maximum rigidity of accelerators:

protons primary?

- $\mathcal{R}_{\max} \simeq E^p_{\max} = 5\,\mathrm{EV}$

protons secondary?

- $\mathcal{R}_{\max} \simeq A/Z\, E^p_{\max} = 10\,\mathrm{EV}$

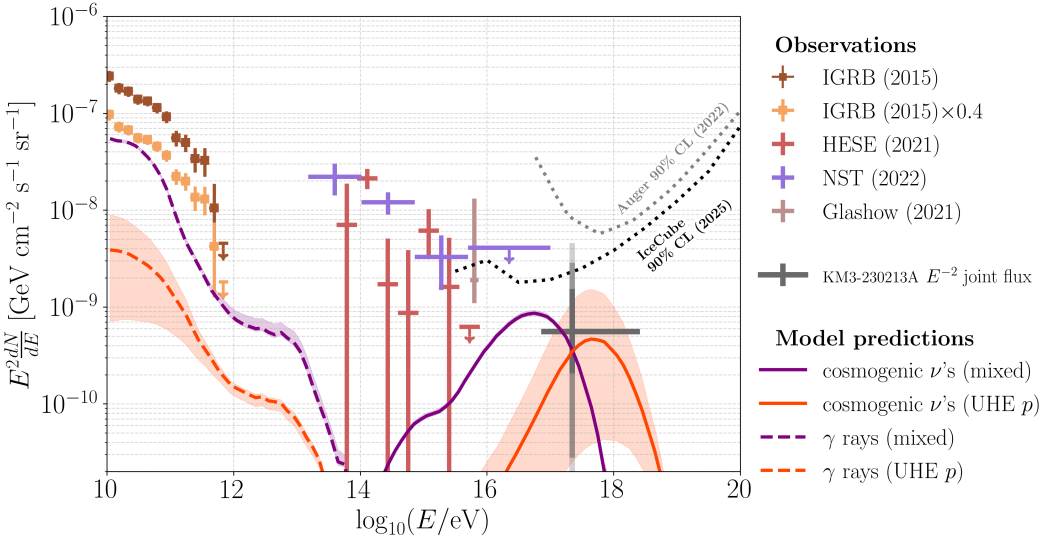
$\rightarrow$ typical neutrino energies

- $E_\nu \simeq \frac{1}{20}\, E_{\mathrm{CR}}/A$

neutrinos associated with UHECRs:

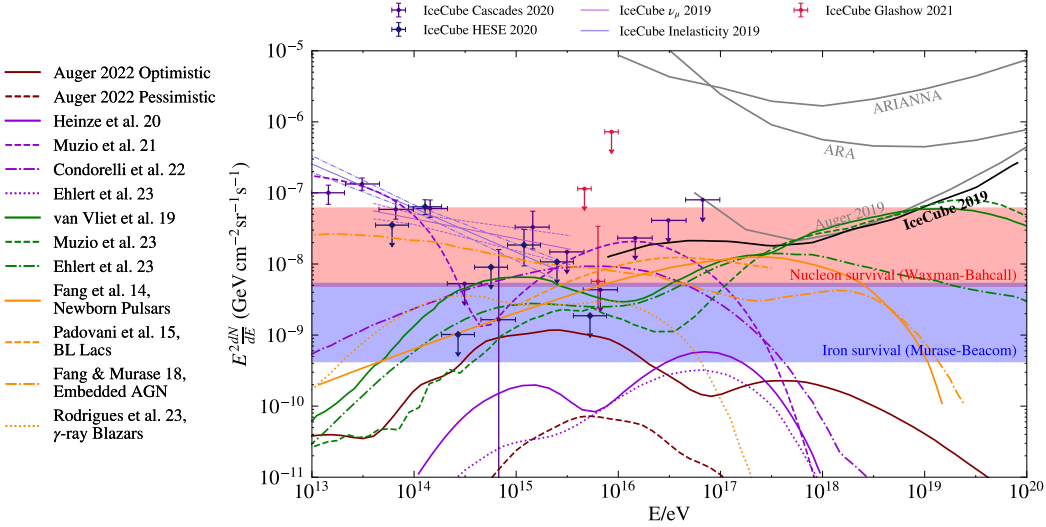
$$12.5\,\mathrm{PeV} \lesssim E_\nu \lesssim 250\,\mathrm{PeV}$$

UHECR-associated Neutrinos – a) cosmogenic: $\lesssim 10^{-9}$ GeV/(cm^2 s sr)



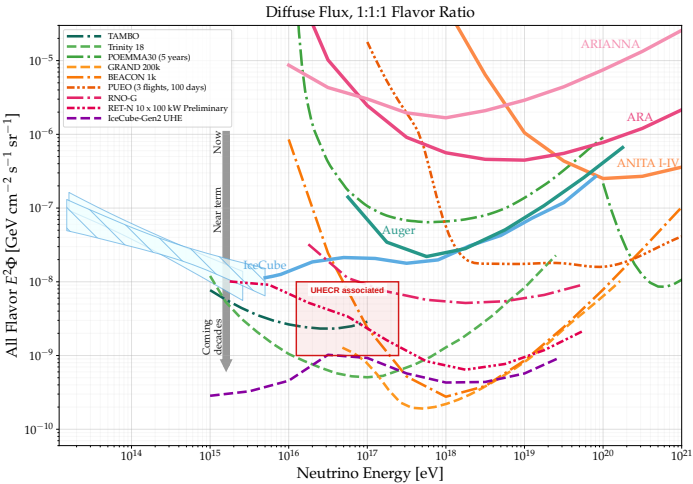
A. Alhebsi et al. arXiv:2603.13476 (single flavor)

UHECR-associated Neutrinos – b) sources: 10^{-9} – 10^{-8} GeV/(cm^2 s sr)



M. Muzio EPJ 234 (2025) 4939

UHECR-associated Neutrinos – c) Future Experiments



M. Ackermann et al. arXiv:2203.08096

- 90% C.L. sensitivity
  $\rightarrow 2.4$ events/decade

10^{-9} GeV/(cm^2 s sr) sensitivity implies
$\mathcal{O}(3-30)$ UHECR-associated ν
from the cosmological source population

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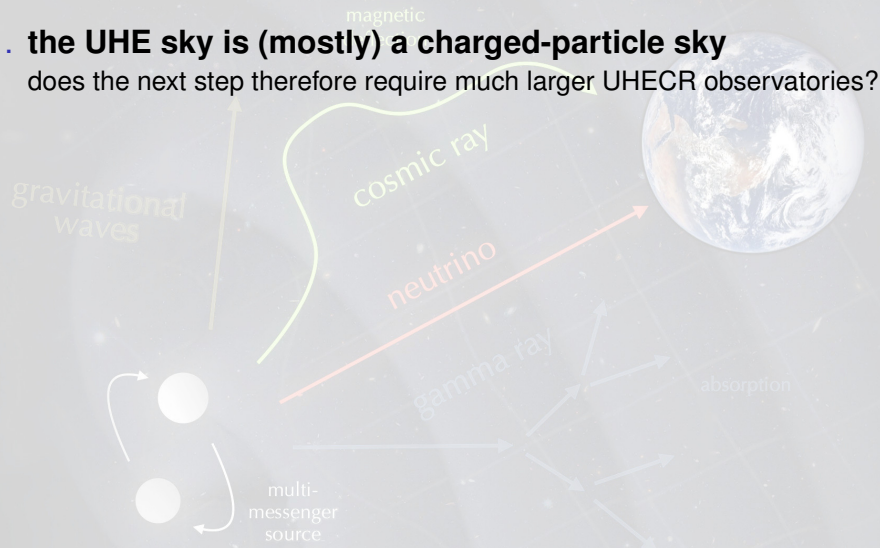
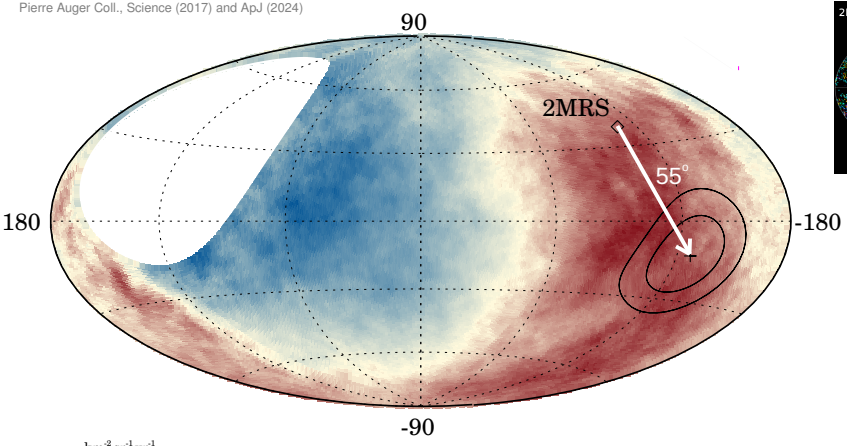
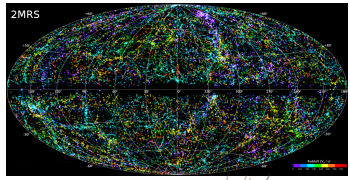
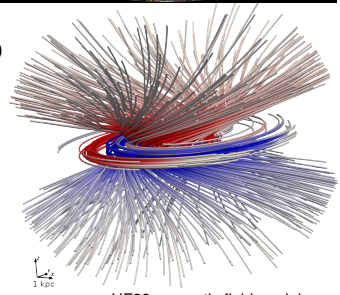


UHE Dipole: Large Scale Structure and Galactic Magnetic Field

Pierre Auger Coll., Science (2017) and ApJ (2024)





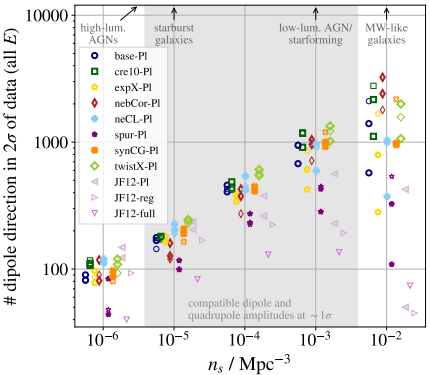


UF23 magnetic field model

amplitude: $7.4 \pm 1\%$, significance: $6.8\ \sigma$ (phase I)

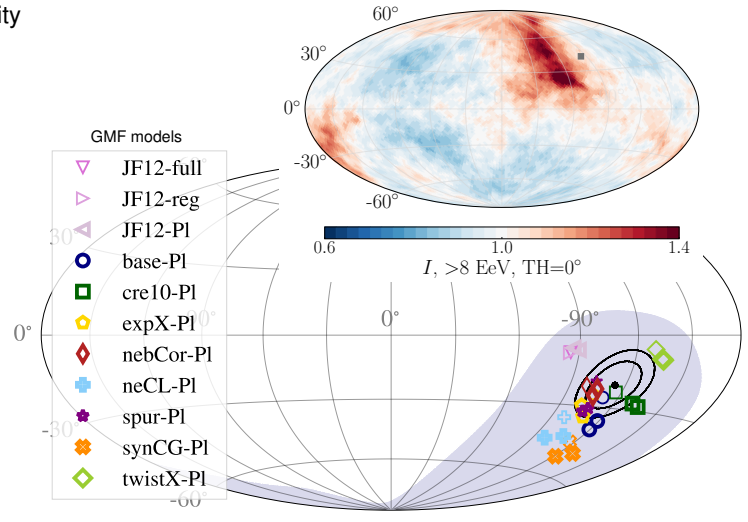
UHE Dipole: Large Scale Structure and Galactic Magnetic Field

compatibility of direction vs. source density



10000 realizations

extragalactic UHECR “illumination”



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

Bister, Farrar, MU , see also Harari+15, Globus+18, Ding+21, Allard+22, Bister+24

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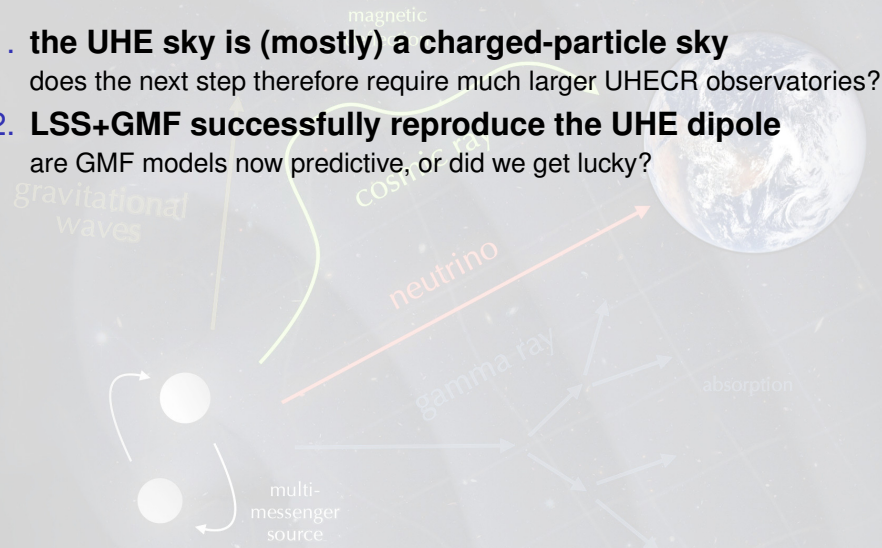
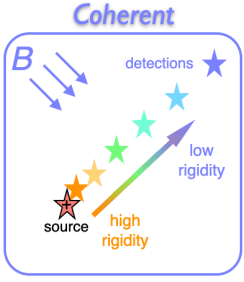
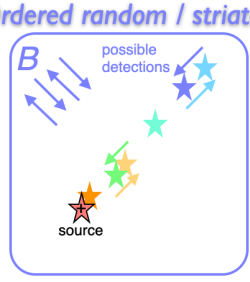
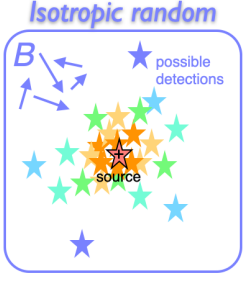
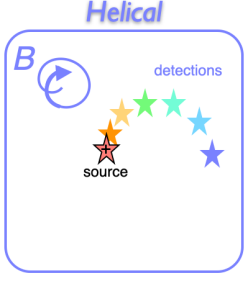


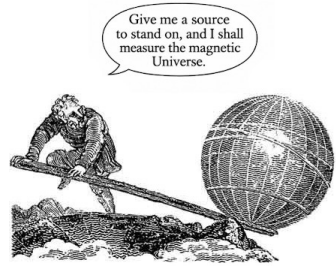
UHECRs as Tracers of Cosmic Magnetic Fields



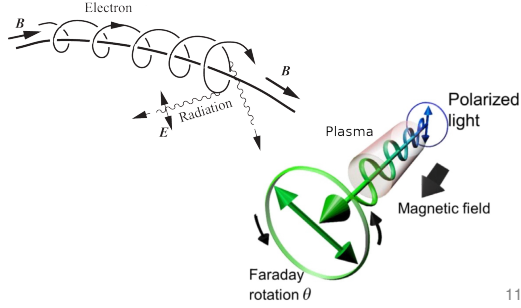








traditional magnetic-field tracers:



Snowmass UHECR White Paper, APP 149 (2023) 102819

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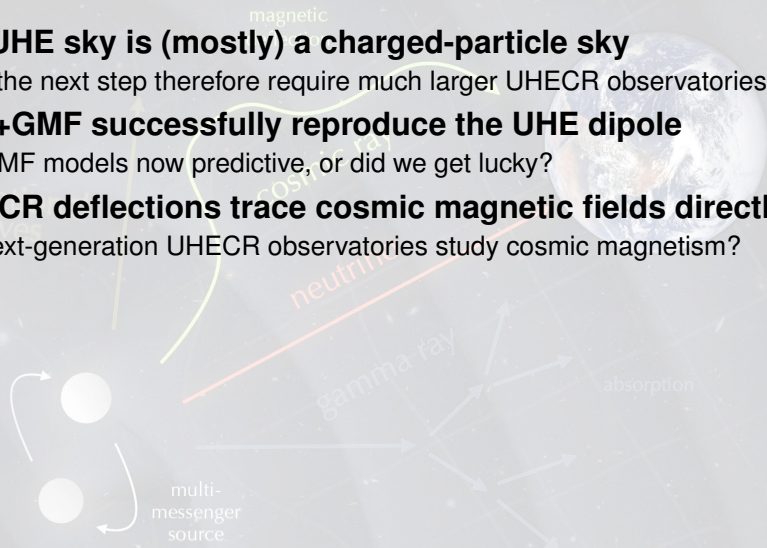
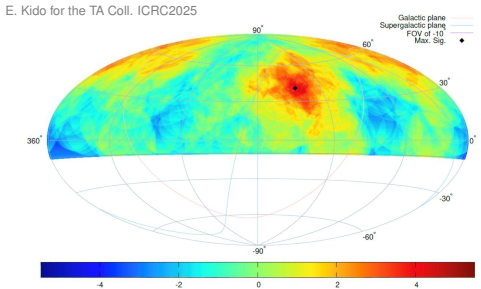
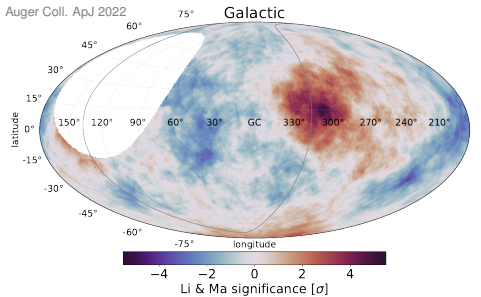


Intermediate-Scale Anisotropies (hot spots)





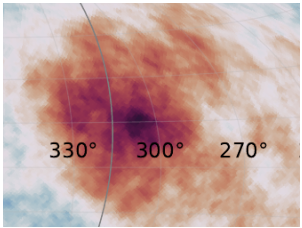
TA hotspot (ICRC25)

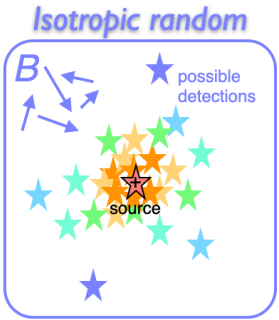
- top-hat 25°, $E > 57$ EeV
- local significance 4.9 σ
- global significance 2.9 σ
- multiplet from M82? 3.0 σ
- correlation with starburst galaxies 4.2 σ

Auger hotspot (ICRC23)

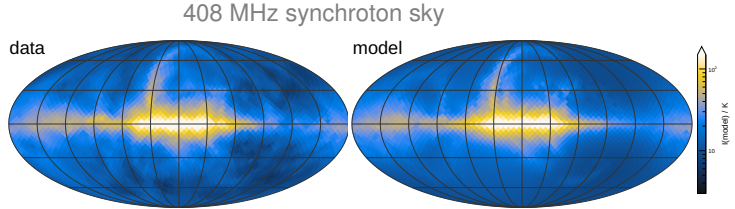
- top-hat 27°, $E > 38$ EeV
- local significance 5.46σ
- global significance 2.1 σ
- at Centaurus A (no angular scan) 4.0 σ
- correlation with starburst galaxies 3.8 σ

Angular Size of Hotspots





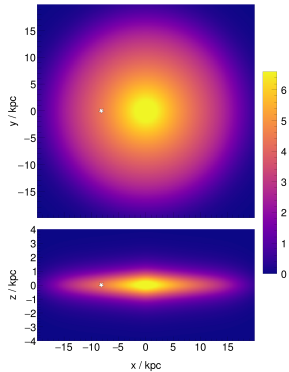
random Galactic magnetic field



implied charge of $\alpha = (15^{+8}_{-4})^\circ$ hotspot

$$Z(\mathrm{Cen}) = \left(19^{+10}_{-5} \pm 2 \pm 3\right) \left(\frac{50\ \mathrm{pc}}{\lambda_c}\right)^{1/2}$$

α GMF ΔE



MU & G.R. Farrar arXiv:2608.21293

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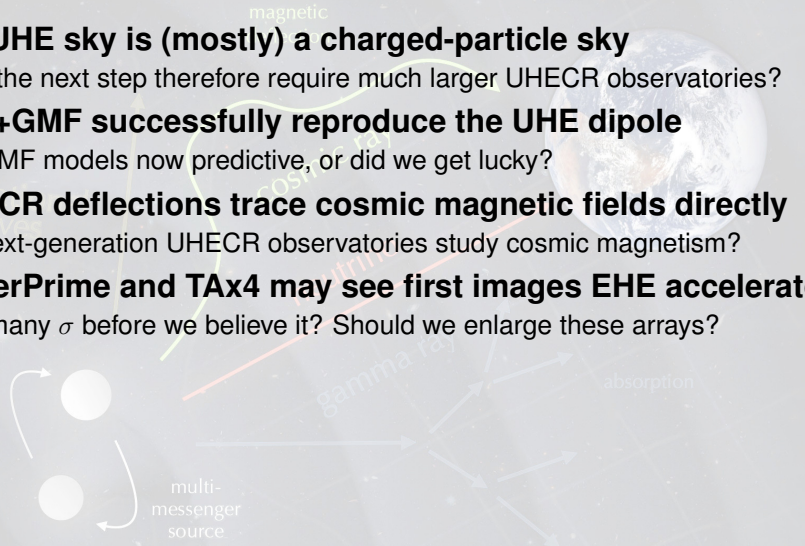
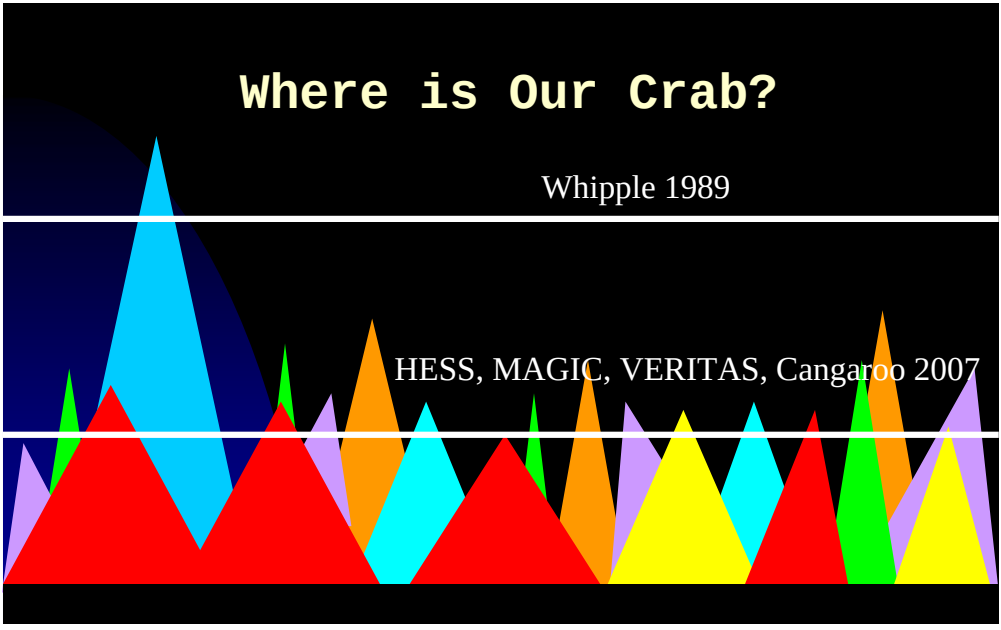


Where is Our Crab?

Whipple 1989



Where is Our Crab?

AugerPrime, TAx4?

GCOS, POEMMA....

adapted from A. Olinto 2007

All or Nothing

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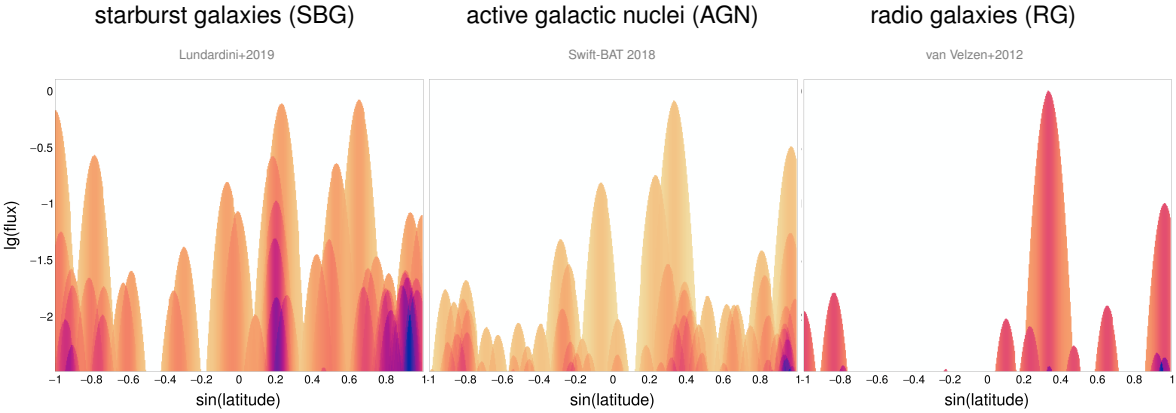
GCOS, POEMMA....

adapted from A. Olinto 2007

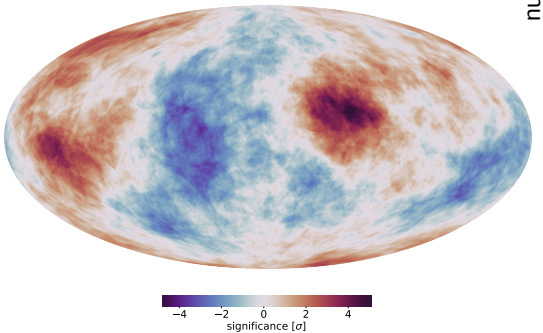
UHE Source Population Studies arXiv:2502.05657

expectations using UHECR flux proxies from galaxy catalogues

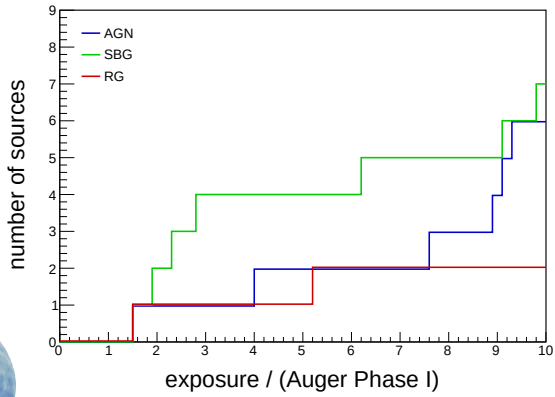


UHE Source Population Studies

- if AugerPrime/TAx4 take a first 5-σ snapshot of a ZeVatron
- then population study possible with a factor 10 $\times$ more exposure



AGN: active galactic nuclei, SBG: starburst galaxies, RG: radio galaxies



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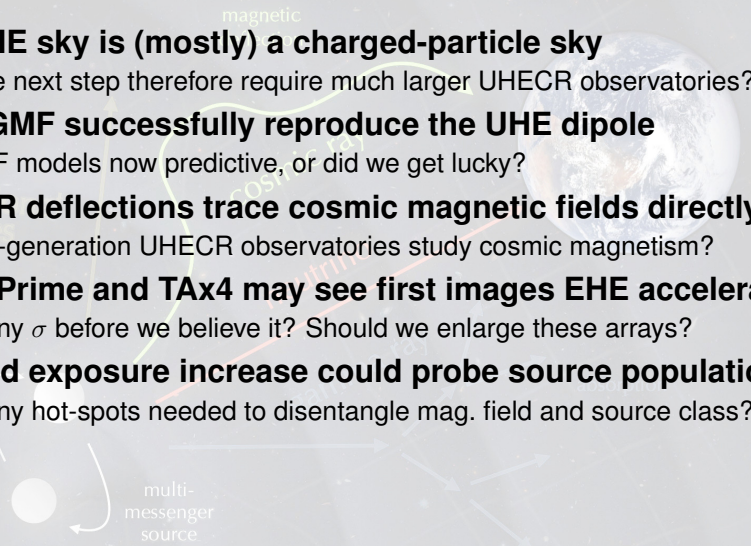
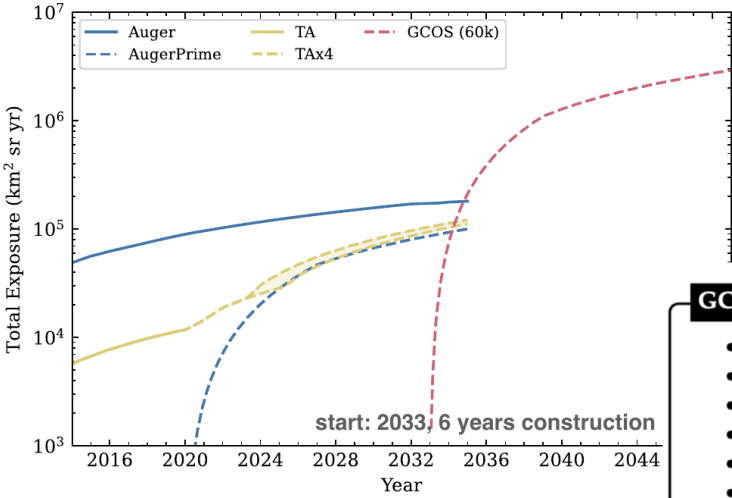
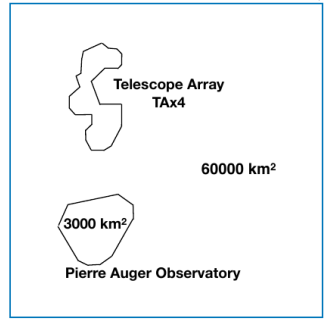


GCOS – Global Cosmic-Ray Observatory



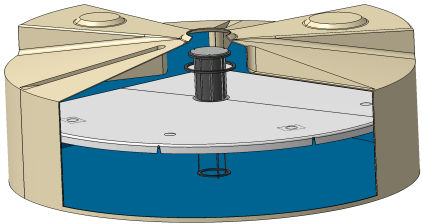


GCOS Requirements

- total area: 60 000 km^2
- number of sites ≥ 2
- trigger threshold: 10^{19} eV
- high-quality threshold: 3×10^{19} eV
- σ_E: 10%, $\sigma_{\ln A}$: 1, σ_θ: 1°
- high duty cycle, low maintenance

GCOS – Global Cosmic-Ray Observatory

surface detector: double-layered WCD (I. Maris)



- 18k stations, spacing 2.2 km
- $E > 10^{19}$ eV (threshold)
- $E > 3 \times 10^{19}$ (high quality)

3rd GCOS workshop 2025 (Tokio)

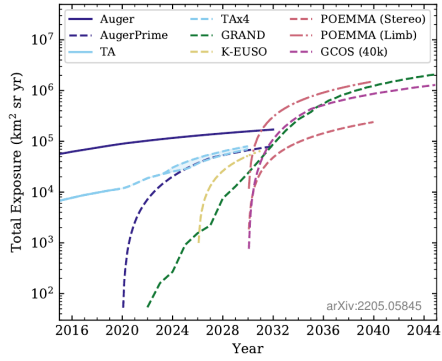
white paper: “Ideas and Requirements for the Global Cosmic-Ray Observatory“ arXiv:2502.05657

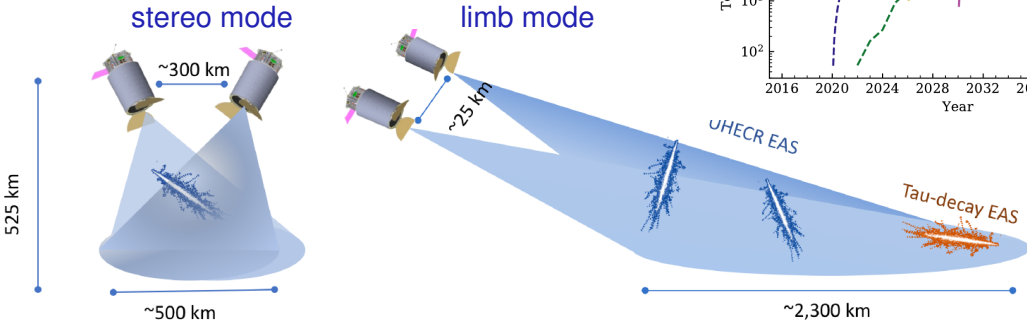
fluorescence detector prototype: FAST (T. Fujii)

D. Mandat et al., JINST 12, T07001 (2017)

M. Malacari et al., Astroparticle Physics 119 (2020) 102430

POEMMA – Detection of Cosmic Rays from Space

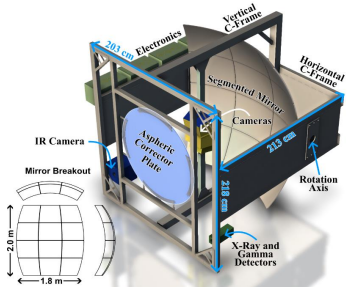


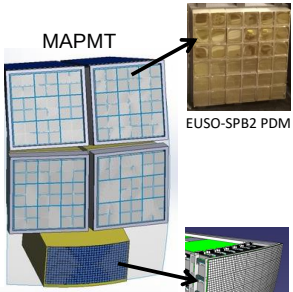


A. Olinto et al JCAP **06** (2021) 007
L. Anchordoqui et al PRD **101** (2020) 023012

ESA M-class mission proposal “M-EUSO” (2025)

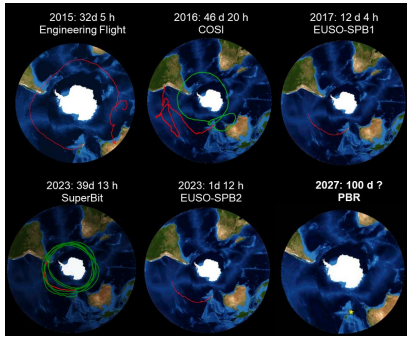
Prototype POEMMA-Balloon with Radio (PBR) – Launch 2028





EUSO-SPB2 PDM

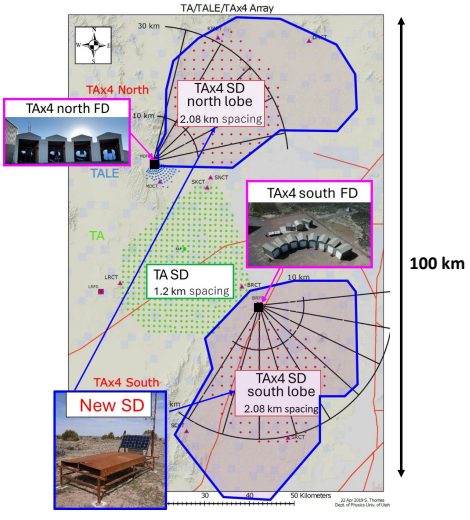
PBR CC Design



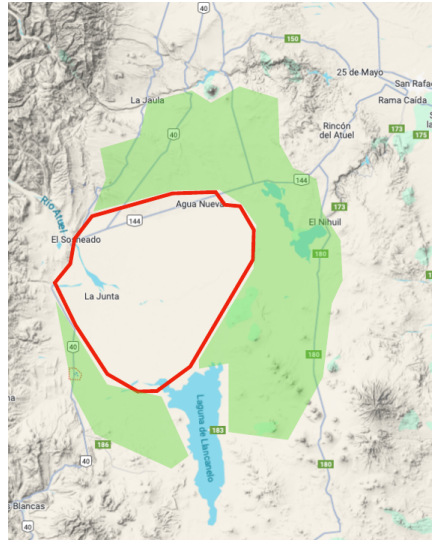
V. Scotti ISVHECRI 2024

Extension of existing facilities see Lorenozo's talk for AugerPrime

in progress: TAx4



possibilities at Auger?



arXiv:2502.05657

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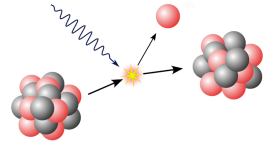
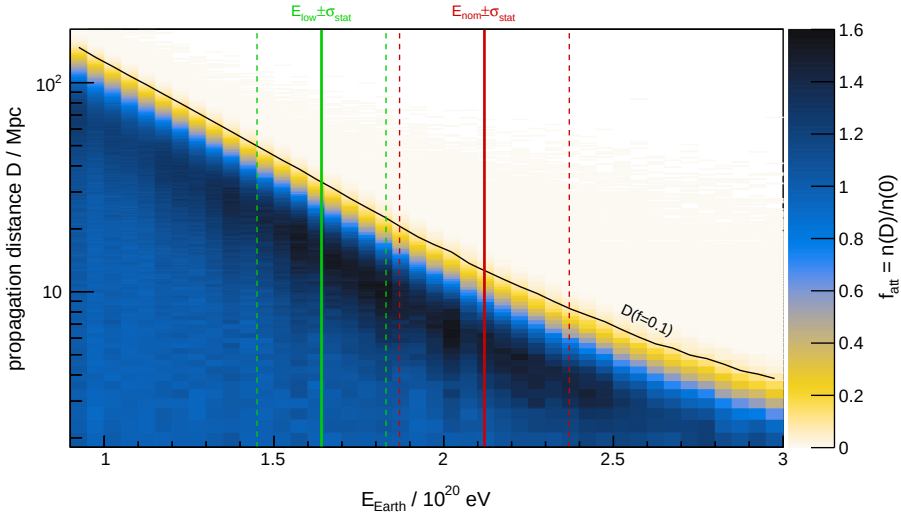
   space or ground or both?

Impact of Energy Uncertainty: ‘Amaterasu” Particle



- factor 5 uncertainty in horizon!



MU&Farrar ApJL 962 (2024)

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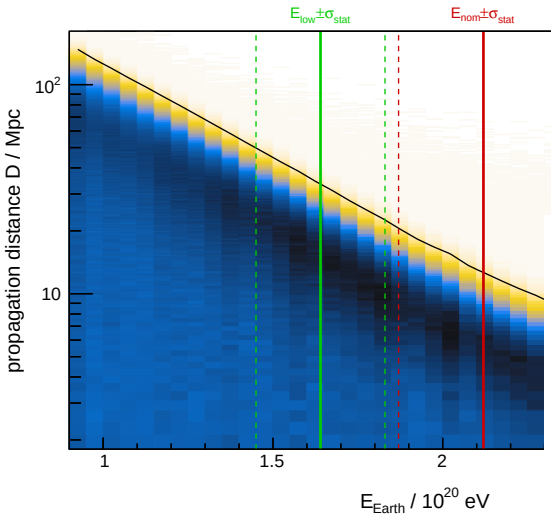
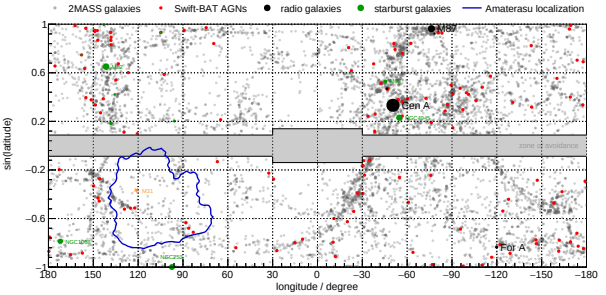
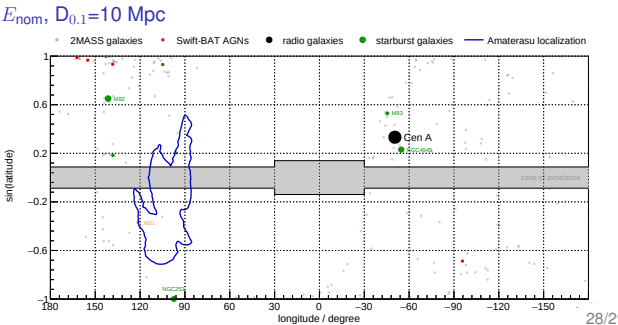
- factor 5 uncertainty in horizon!







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Multi-messenger Observations at UHE: Discussion & Outlook

1. **the UHE sky is (mostly) a charged-particle sky**
   does the next step therefore require much larger UHECR observatories?
2. **LSS+GMF successfully reproduce the UHE dipole**
   are GMF models now predictive, or did we get lucky?
3. **UHECR deflections trace cosmic magnetic fields directly**
   will next-generation UHECR observatories study cosmic magnetism?
4. **AugerPrime and TAx4 may see first images EHE accelerators**
   how many σ before we believe it? Should we enlarge these arrays?
5. **ten-fold exposure increase could probe source population**
   how many hot-spots needed to disentangle mag. field and source class?
6. **GCOS and POEMMA**
   space or ground or both?
7. **energy and mass resolution essential**
   will AugerPrime and the LHC constrain air-shower physics well enough?