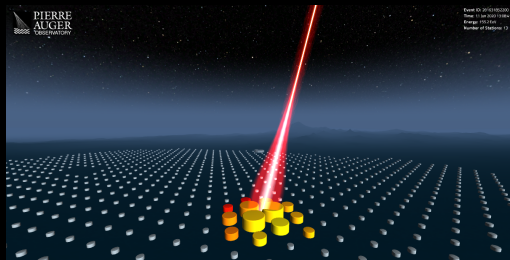
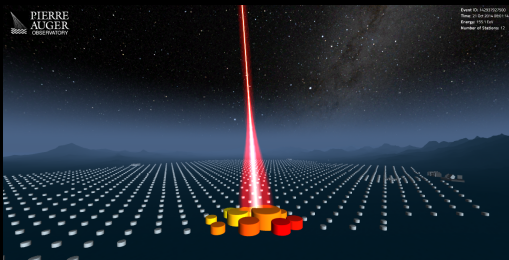
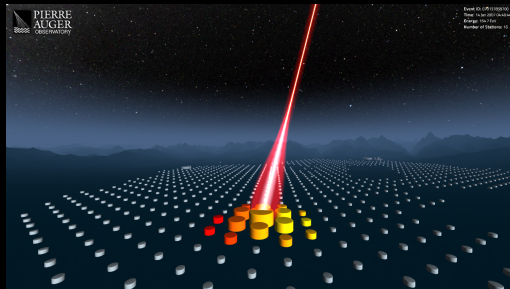
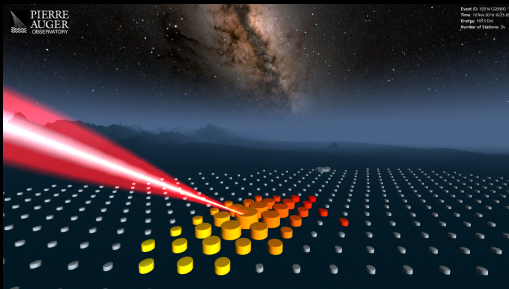


Where Do Ultra-High-Energy Particles Come From? Michael Unger (KIT)

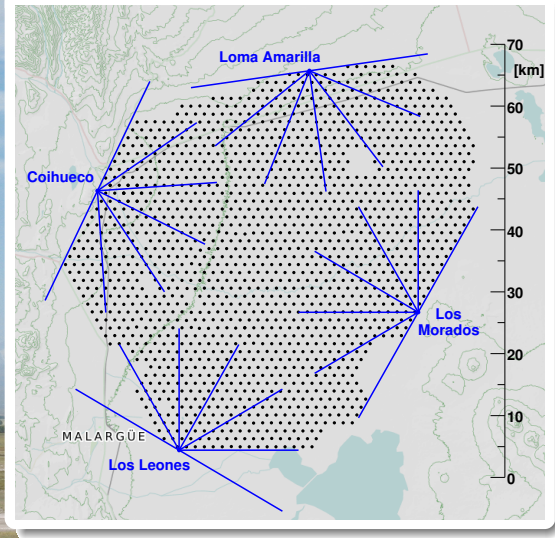






The Pierre Auger Observatory

- 25 Gt air calorimeter
- area: 3000 km²
- 1600 surface detectors:
 - 12 t water-Cherenkov
 - 3.8 m² scintillator
 - 30-80 MHz radio antennas
- 27 fluorescence telescopes



UHECR Observations

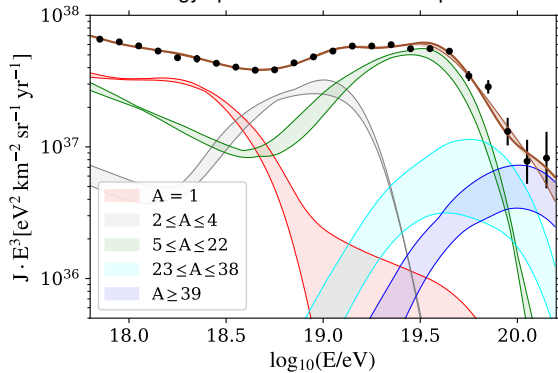
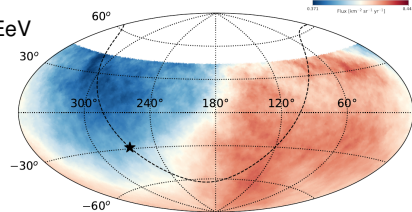
Telescope Array (USA)



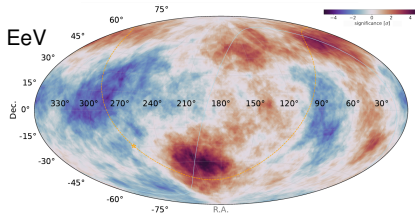
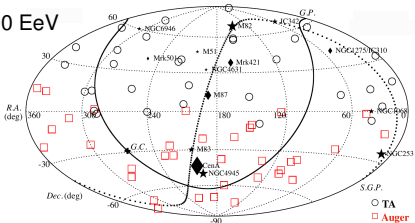
Pierre Auger Observatory (Argentina)



energy spectrum and mass composition

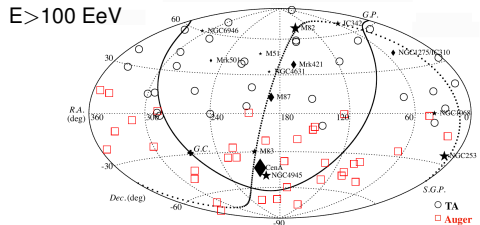
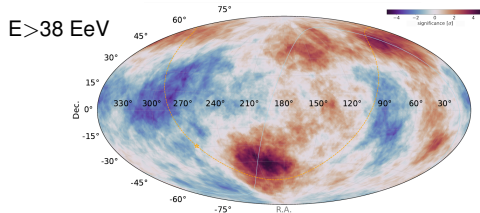
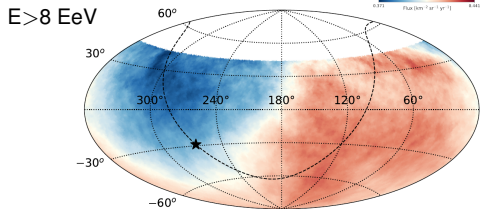
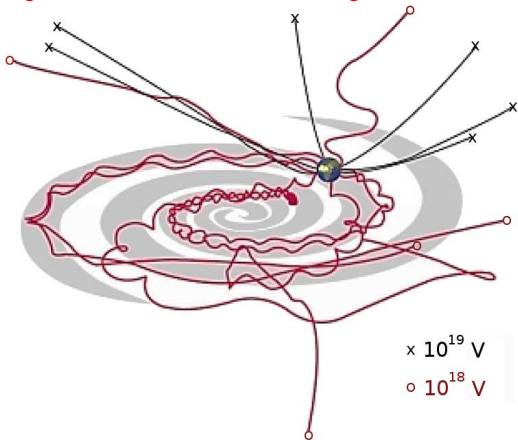
 $E > 8 \text{ EeV}$ 

$E > 38 \text{ EeV}$

 $E > 100 \text{ EeV}$ 

UHECR Observations

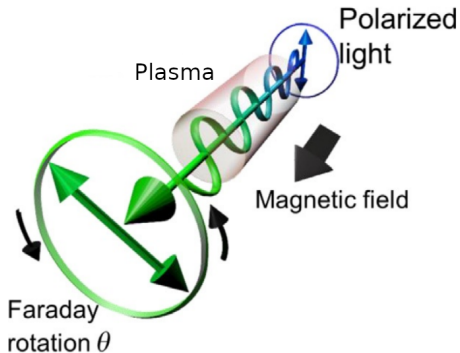
Angular Deflection in Galactic Magnetic Field?



Observational Tracers of the Galactic Magnetic Field (GMF) used in this work

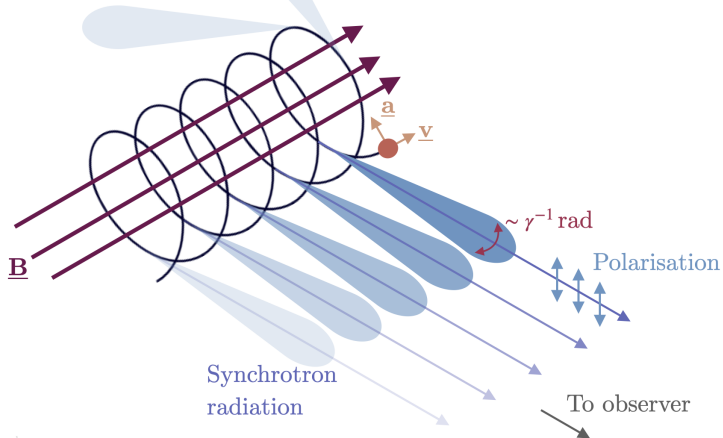
Faraday Rotation

of extragalactic radio sources



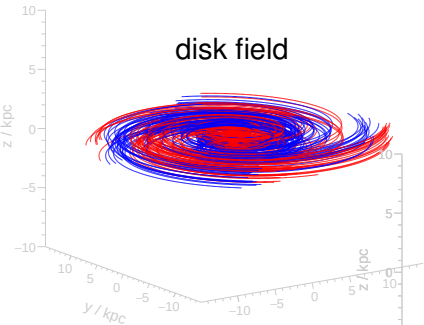
Synchrotron Radiation

of cosmic-ray electrons

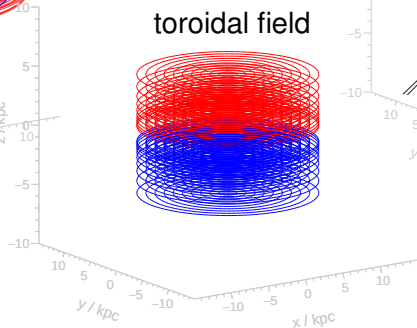


Parametric GMF Components

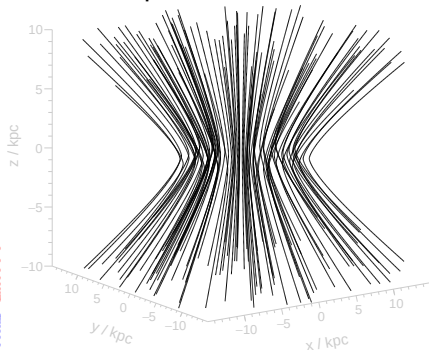
disk field



toroidal field



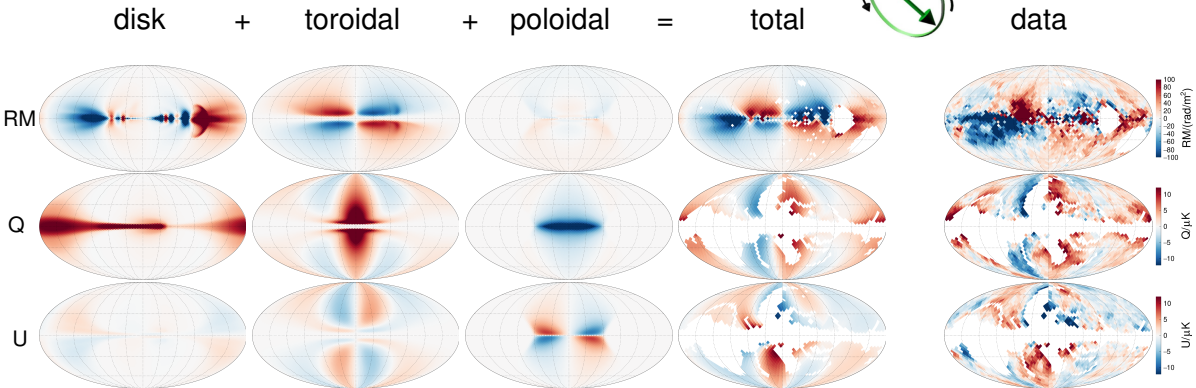
poloidal field



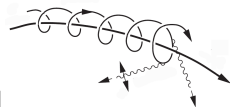
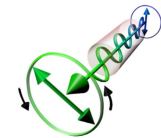
UF23 solenoidal field components
(major refinement of JF12 functions)



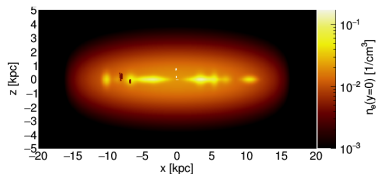
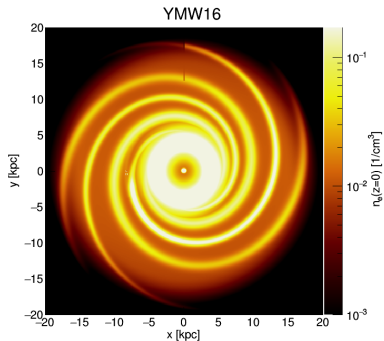
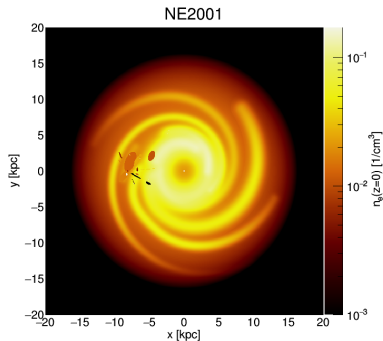
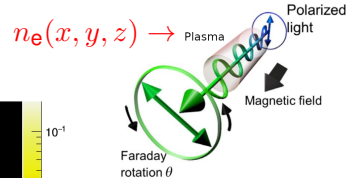
Adjustment of Model Parameters to Data



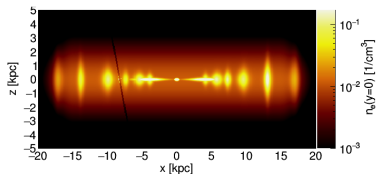
- 6520 data points
- 15-20 parameters
- typical reduced $\chi^2/n_{\text{df}} = 1.2 \dots 1.3$, depending on model



Uncertainties: Thermal Electron Models

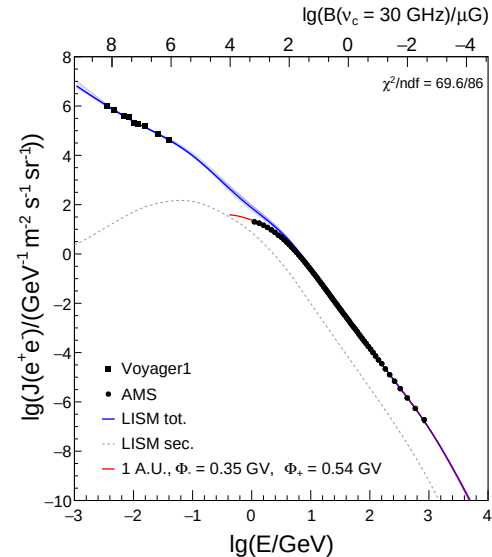


112 pulsar DMs

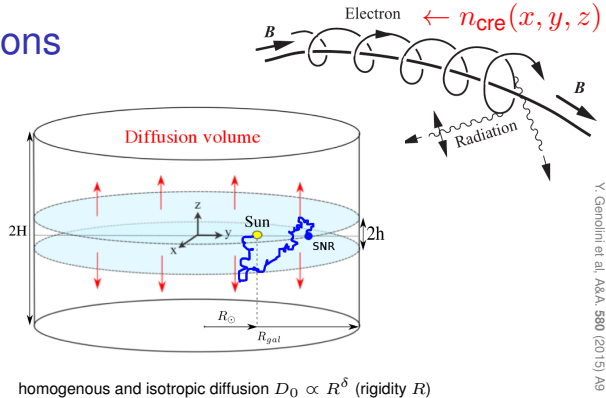


189 pulsar DMs

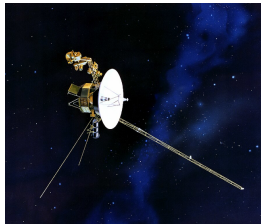
Uncertainties: Cosmic-Ray Electrons



constrained by local lepton flux and D_0/H from B/C



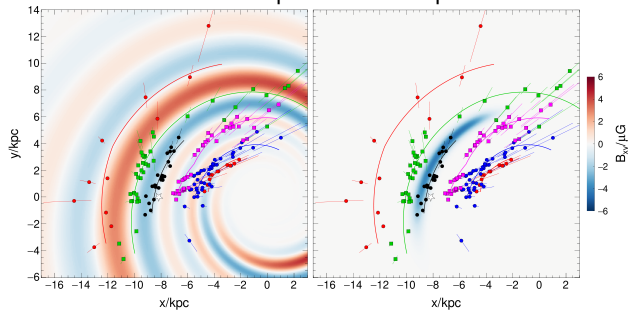
Y. Genolini et al, A&A, 580 (2015) A9



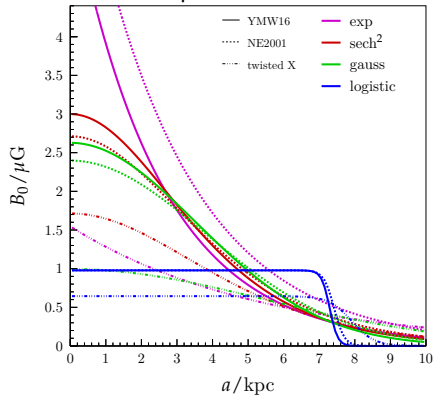
Uncertainties: Model Assumptions

Examples:

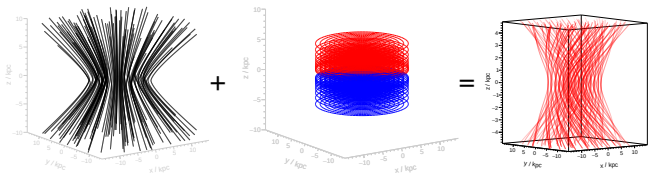
Global Spiral or Local Spur?



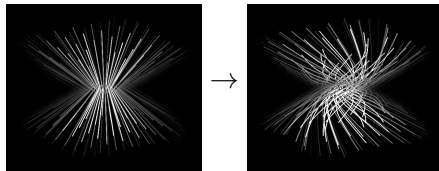
radial dependence of X-field?



X-field and toroidal field or twisted X-field?

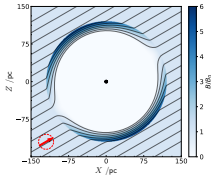
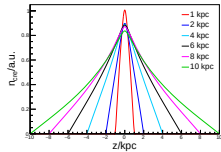
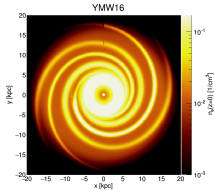
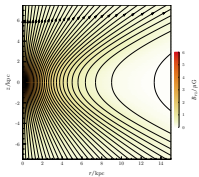
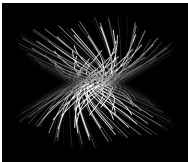


or

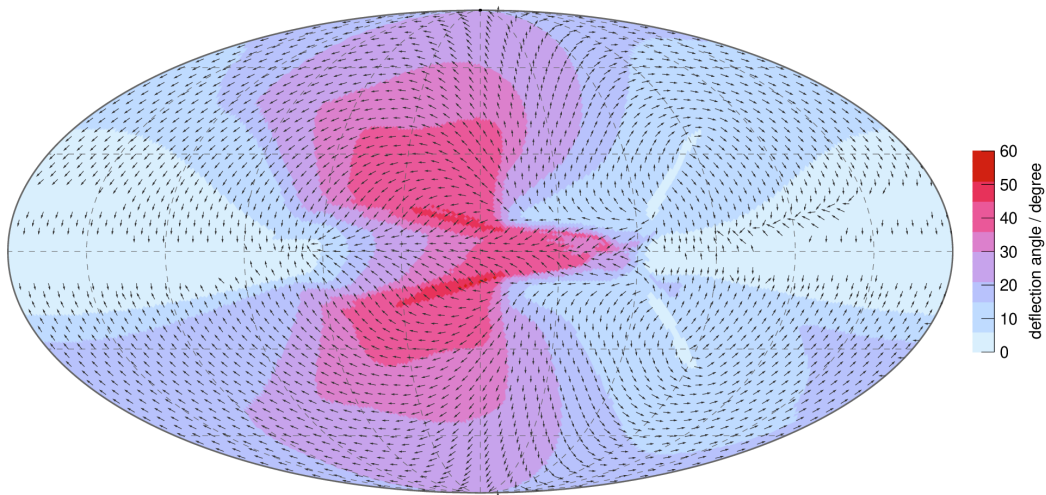


9 variations (subset of ~ 200 models giving the greatest diversity of CR deflection predictions):

name	variation	χ^2/ndf
base	fiducial model	1.22
expX	radial dependence of X-field	1.30
spur	replace grand spiral by local spur (Orion arm)	1.23
neCL	change thermal electron model (NE2001 instead of YMW16)	1.19
twistX	unified halo model via twisted X-field	1.26
nebCor	n_e - B correlation	1.22
cre10	cosmic-ray electron vertical scale height	1.22
synCG	use COSMOGLOBE synchrotron maps	1.50
locBub	local bubble (<u>preliminary</u> , spherical approximation)	1.17

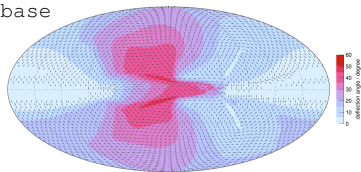


Deflections at 20 EV (base model) (backtracking)

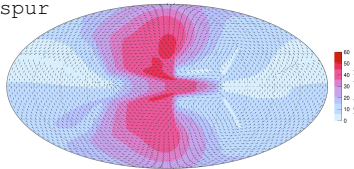


Deflections at 20 EV (backtracking)

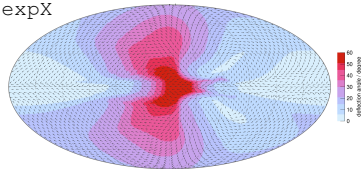
base



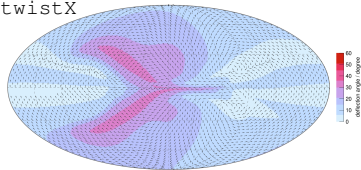
spur



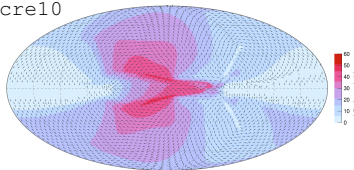
expX



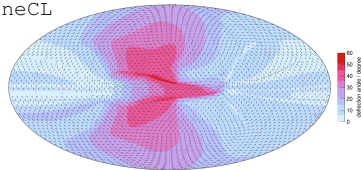
twistX



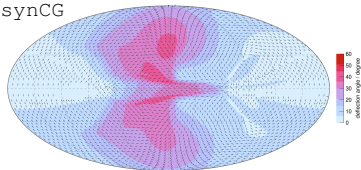
cre10



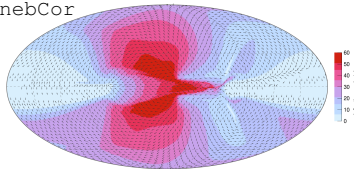
neCL



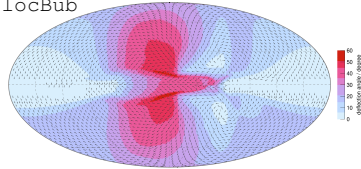
synCG



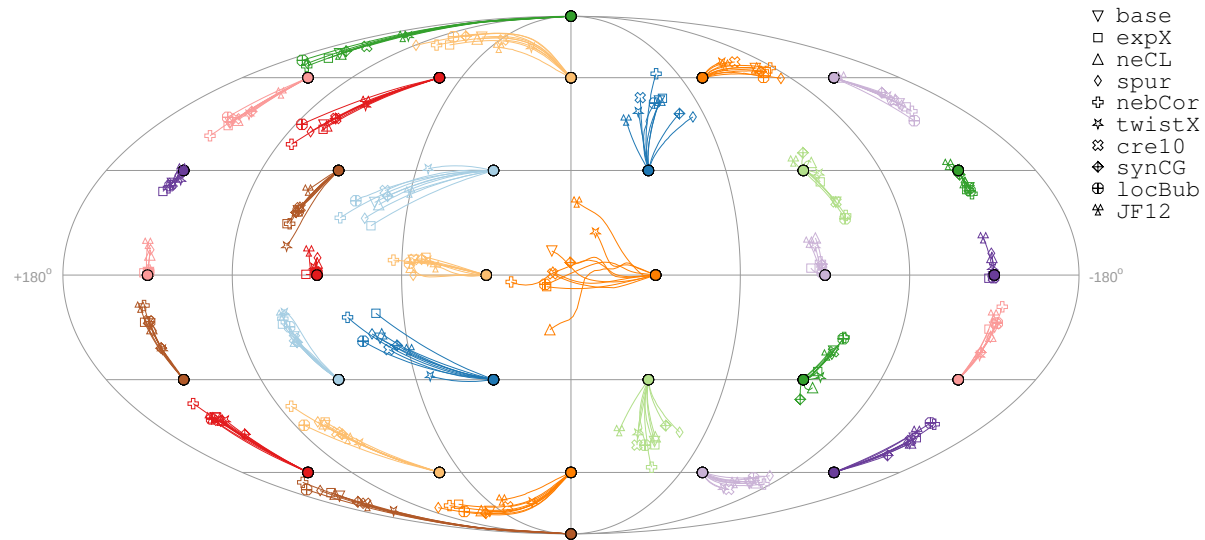
nebCor



locBub



Deflections at 20 EV (backtracking)



Application: Localization of the “Amaterasu” Particle

**The
Guardian**

‘What the heck is going on?’ Extremely high-energy particle detected falling to Earth

SPiEGEL Wissenschaft

Ultrahochenergetisches kosmisches Teilchen traf die Erde

5+ **OMG! Schon wieder!**

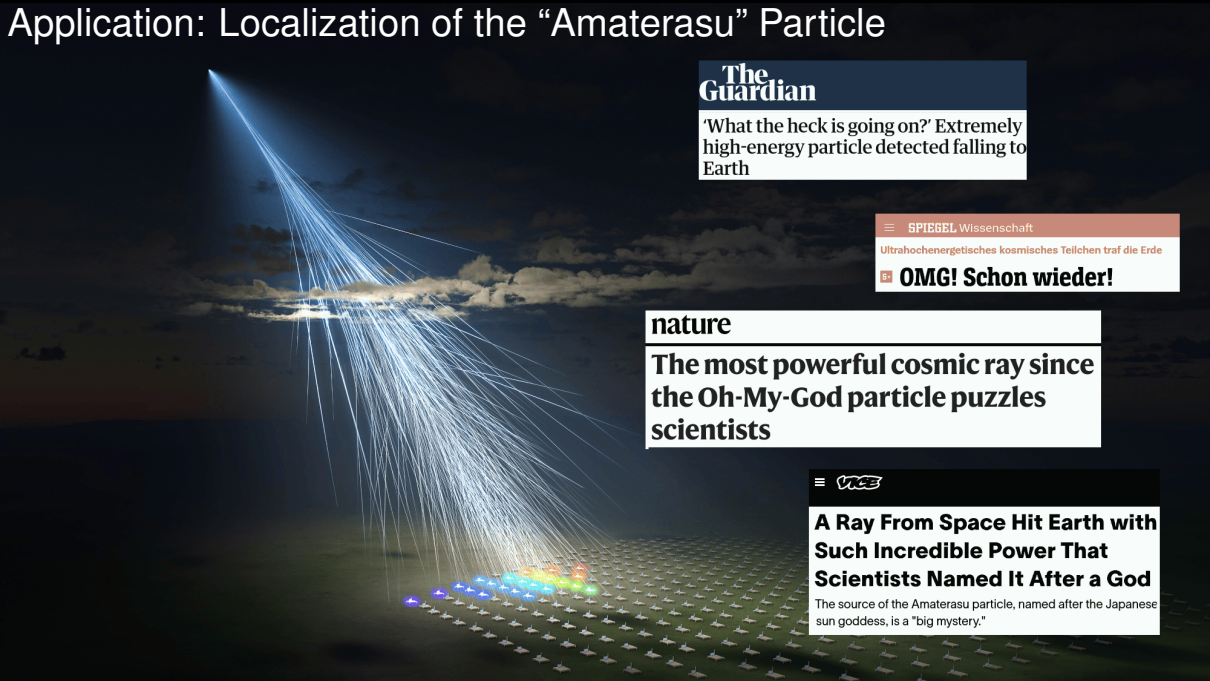
nature

The most powerful cosmic ray since the Oh-My-God particle puzzles scientists

VICE

A Ray From Space Hit Earth with Such Incredible Power That Scientists Named It After a God

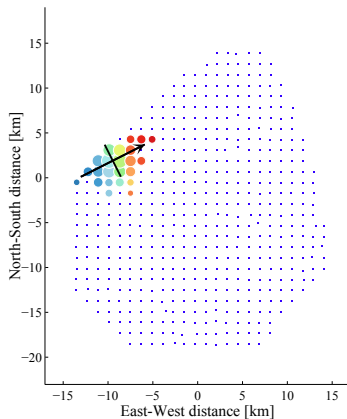
The source of the Amaterasu particle, named after the Japanese sun goddess, is a “big mystery.”



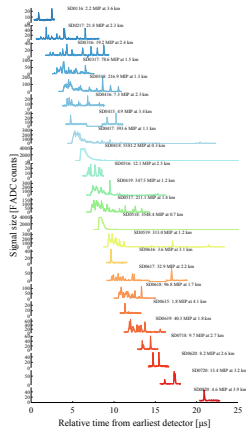
An extremely energetic cosmic ray observed by a surface detector array

TELESCOPE ARRAY COLLABORATION^{††}, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL

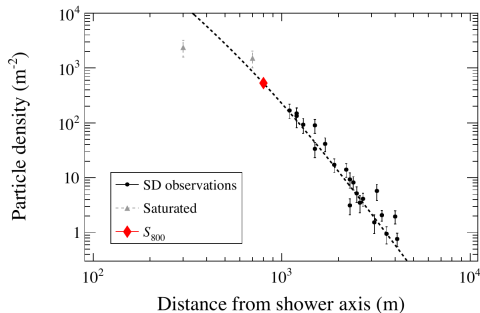
(A) Surface detector array of TA



(B) Date: 27 May 2021 Time: 10:35:56.474337 UTC

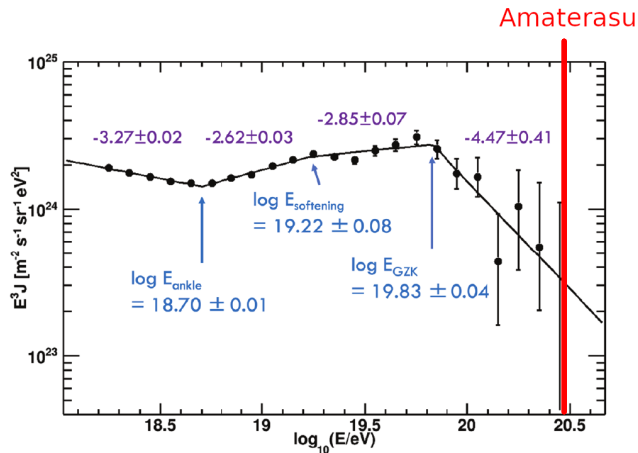


- $E = \left(2.44 \pm 0.29 \text{ (stat.) } {}^{+0.51}_{-0.76} \text{ (syst.)} \right) \times 10^{20} \text{ eV}$
- if Fe: $E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20} \text{ eV}$
- Fe at $-1\sigma_{\text{syst}}$: $E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$

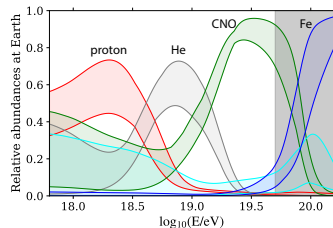


Simplest Assumption: Fe Nucleus from Standard Accelerator

$$(\mathcal{R}_{\max} \sim 10^{18.6-18.7} \text{ V})$$

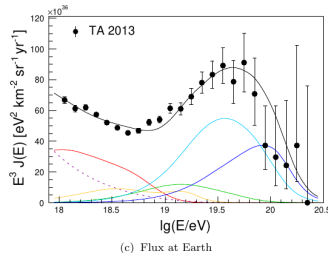


Peters Cycle:



Pierre Auger Coll. 2023

Photodisintegration in source:

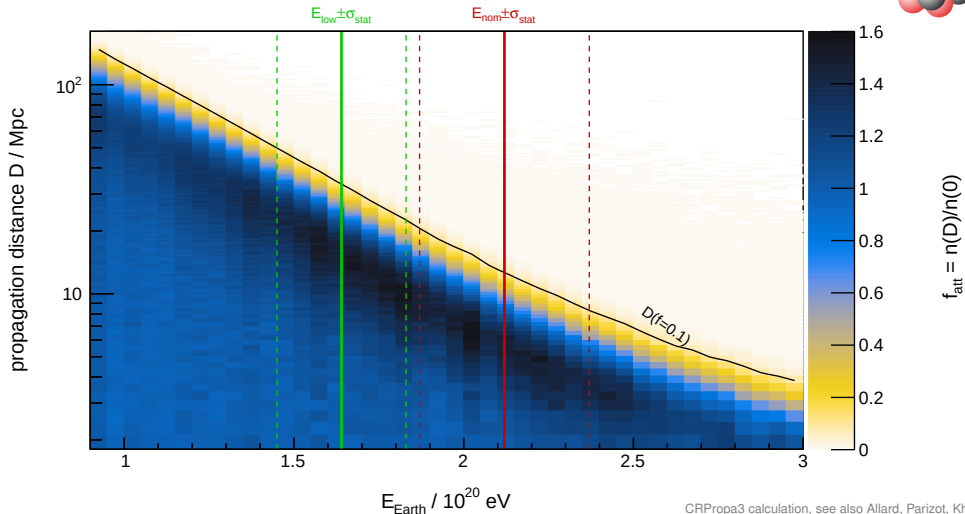
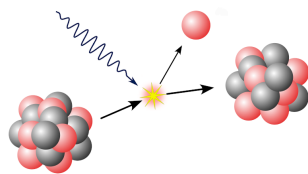


TA 14-year SD spectrum, Kim et al, EPJ Conf **283** (tm2023) 02005

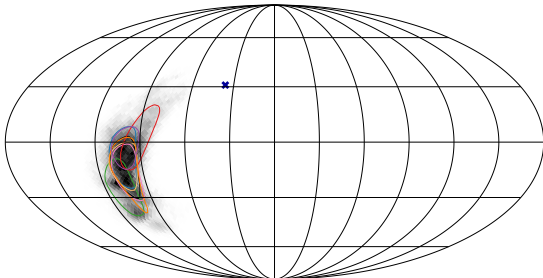
... or ultra-heavy nuclei? G.F. Farrar arXiv:2405.12004 and B.T. Zhang et al arXiv:2405.17409

Propagation of Fe in Extragalactic Photon Fields

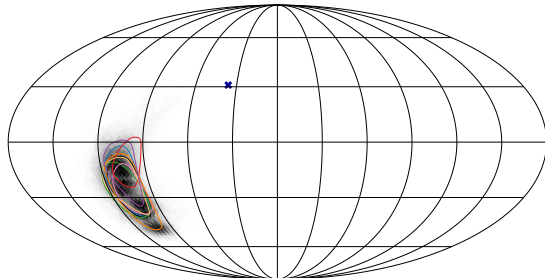
- horizon between 8 and 50 Mpc



$$E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20} \text{ eV}$$



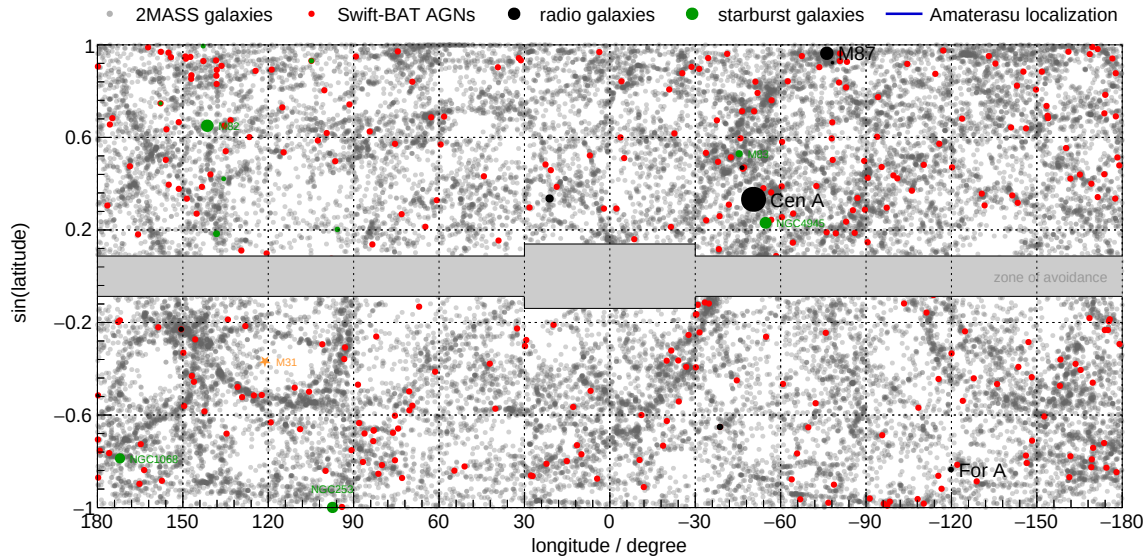
$$E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$$



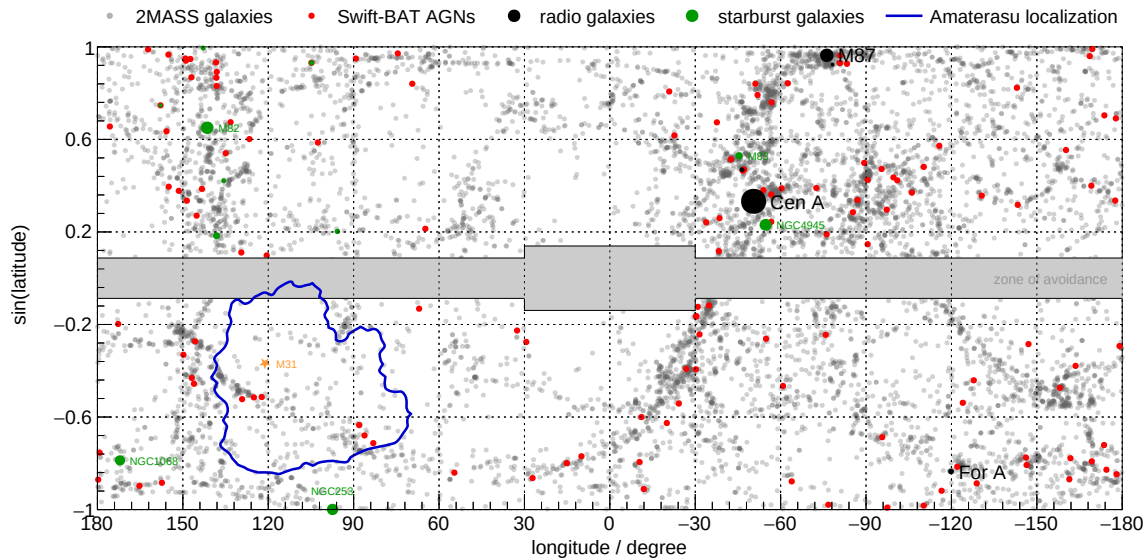
localization uncertainty: **6.6% of 4π or 2726 deg^2**

uncertainty of coherent deflection, random field, Galactic variance, TA energy scale, statistical uncertainty of E

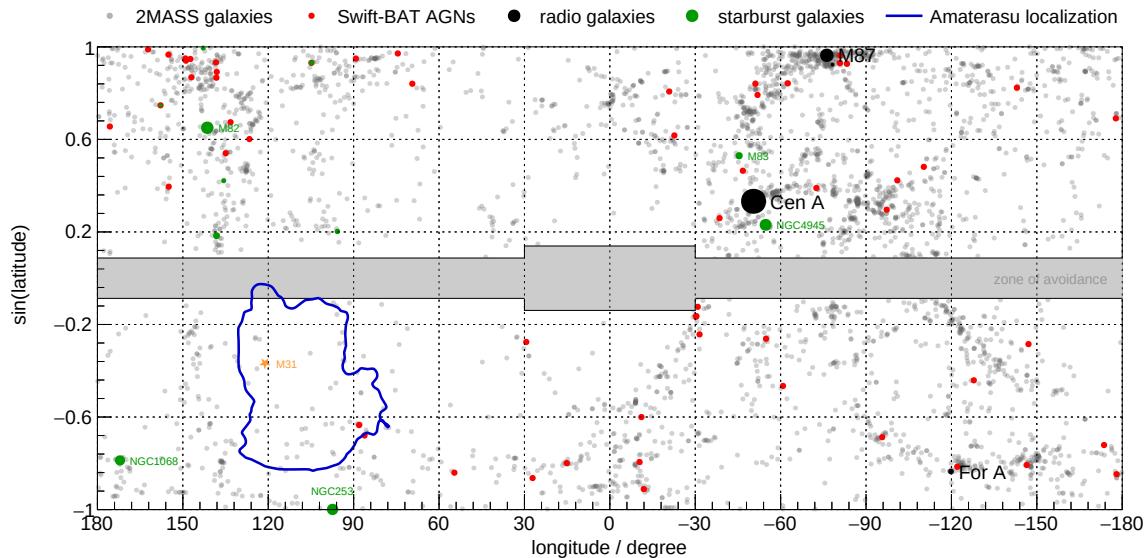
Distribution of galaxies up to D=150 Mpc



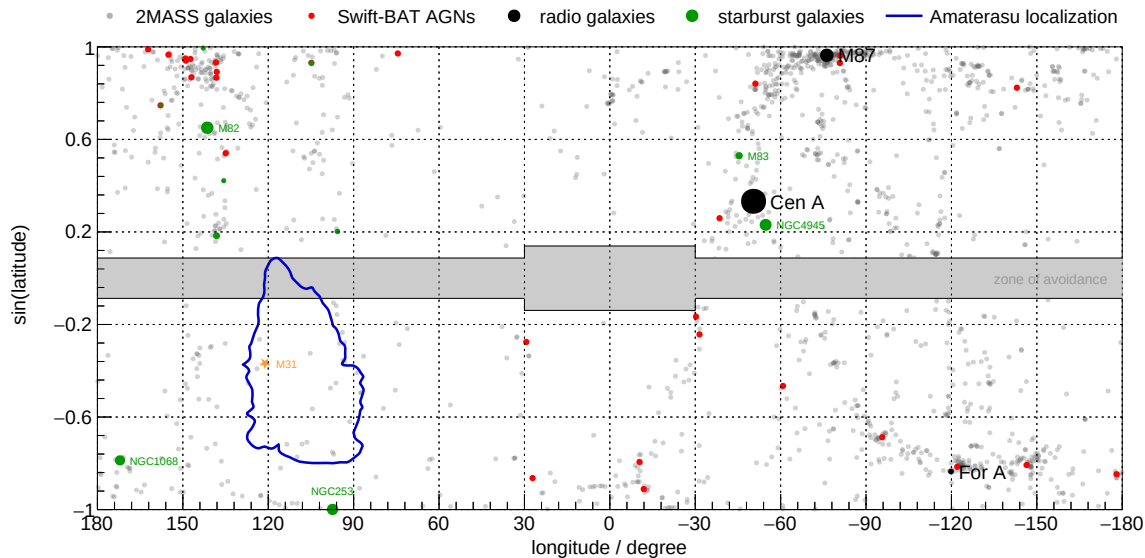
$E_{\text{low}} - 2\sigma$, $D_{0.1}=72$ Mpc



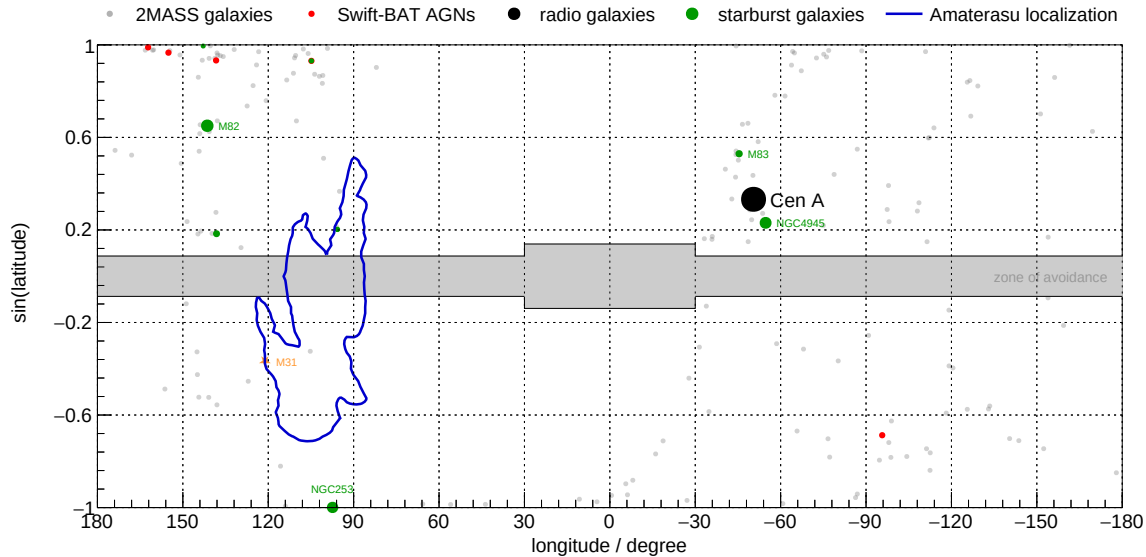
$E_{\text{low}} - 1\sigma$, $D_{0.1}=42$ Mpc



E_{low} , $D_{0.1}=25$ Mpc

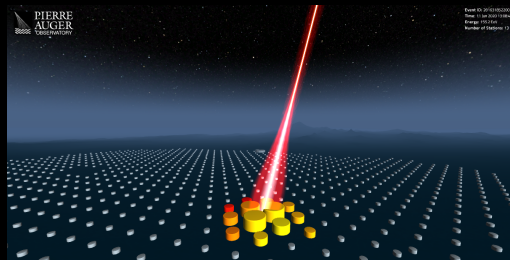
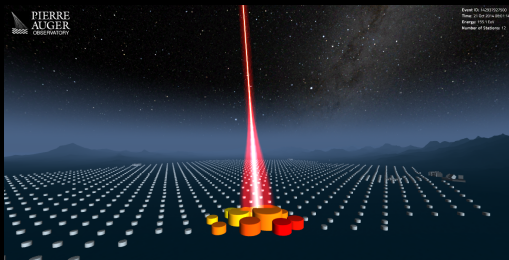
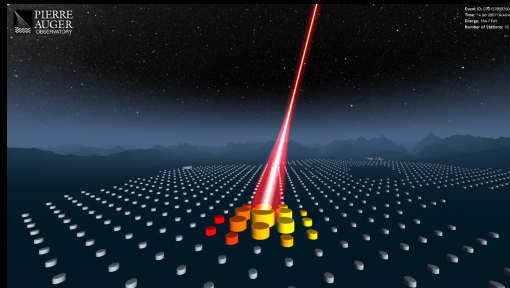
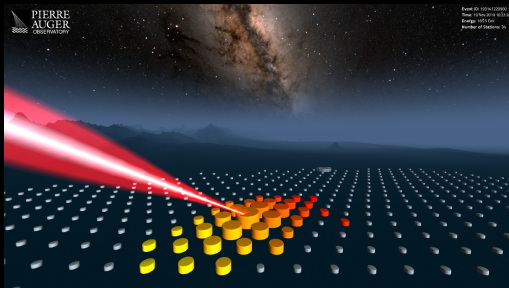


E_{nom} , $D_{0.1}=10$ Mpc



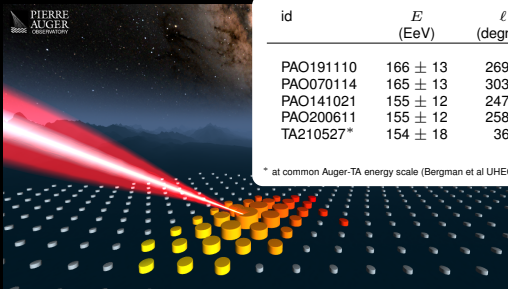
Top 4 UHE Auger Events

Auger Coll. ApJS. 264 (2023) 50



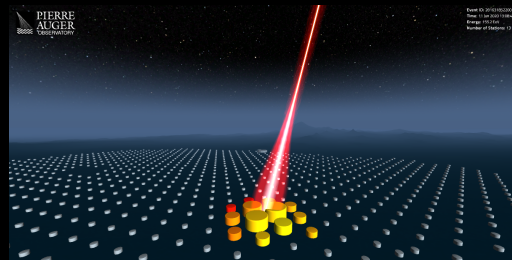
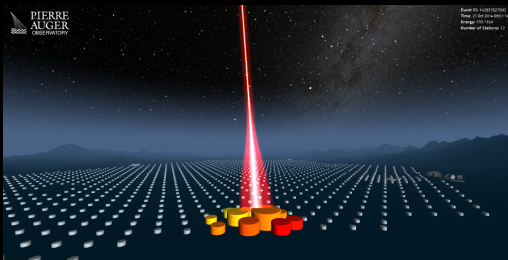
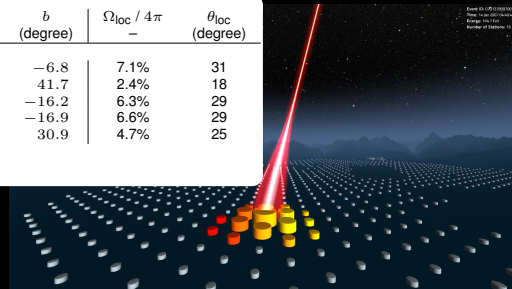
Top 4 UHE Auger Events

Auger Coll. ApJS. 264 (2023) 50



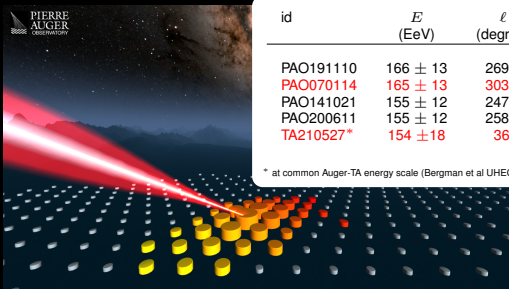
id	E (EeV)	ℓ (degree)	b (degree)	$\Omega_{\text{loc}} / 4\pi$ —	θ_{loc} (degree)
PAO191110	166 ± 13	269.1	-6.8	7.1%	31
PAO070114	165 ± 13	303.0	41.7	2.4%	18
PAO141021	155 ± 12	247.6	-16.2	6.3%	29
PAO200611	155 ± 12	258.3	-16.9	6.6%	29
TA210527*	154 ± 18	36.2	30.9	4.7%	25

* at common Auger-TA energy scale (Bergman et al UHECR22)



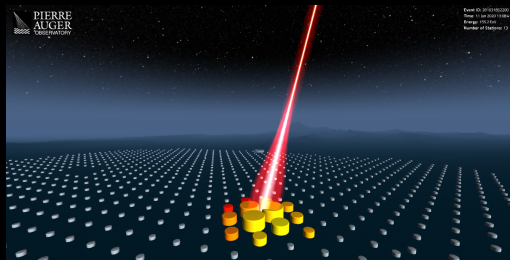
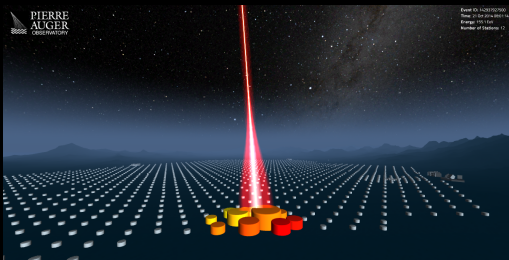
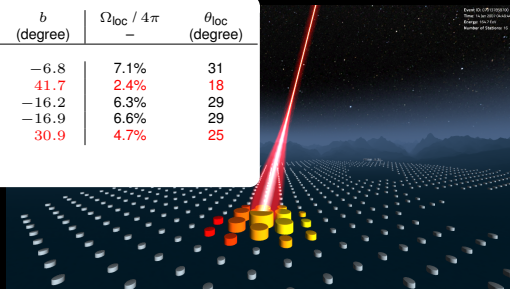
Top 4 UHE Auger Events

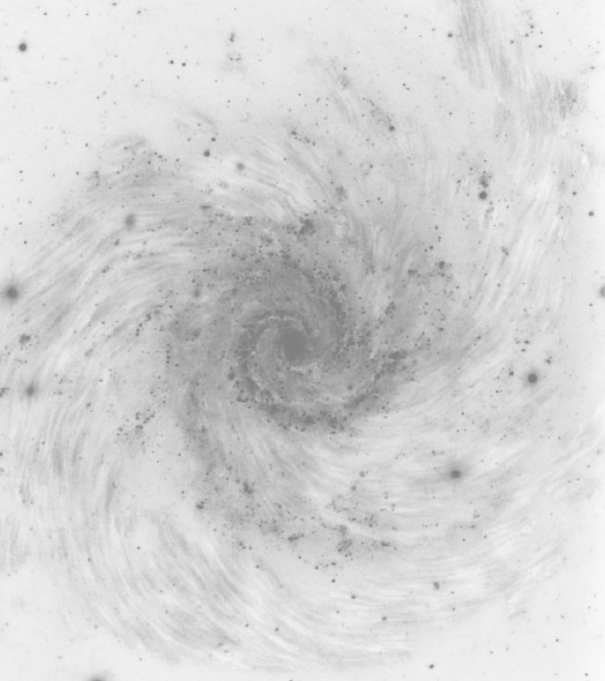
Auger Coll. ApJS. 264 (2023) 50



id	E (EeV)	ℓ (degree)	b (degree)	$\Omega_{\text{loc}} / 4\pi$ —	θ_{loc} (degree)
PAO191110	166 ± 13	269.1	-6.8	7.1%	31
PAO070114	165 ± 13	303.0	41.7	2.4%	18
PAO141021	155 ± 12	247.6	-16.2	6.3%	29
PAO200611	155 ± 12	258.3	-16.9	6.6%	29
TA210527*	154 ± 18	36.2	30.9	4.7%	25

* at common Auger-TA energy scale (Bergman et al UHECR22)





Summary

Ultra-High-Energy Cosmic Rays

- Pierre Auger Observatory and Telescope Array
- Where are the ZeVatrons??

Galactic Magnetic Field

- key to interpret UHE arrival directions
- new analysis of coherent magnetic field
- model ensemble bracketing uncertainties

Application to top 5 UHE Particles

- simplest assumption: Fe nucleus
- best localization uncertainties within 2-5% of 4π
- horizon between 8 and 50 Mpc
- none of the “usual suspects” within loc. uncert.
- transient in an otherwise undistinguished galaxy?