The Galactic Magnetic Field and UHECR Deflections

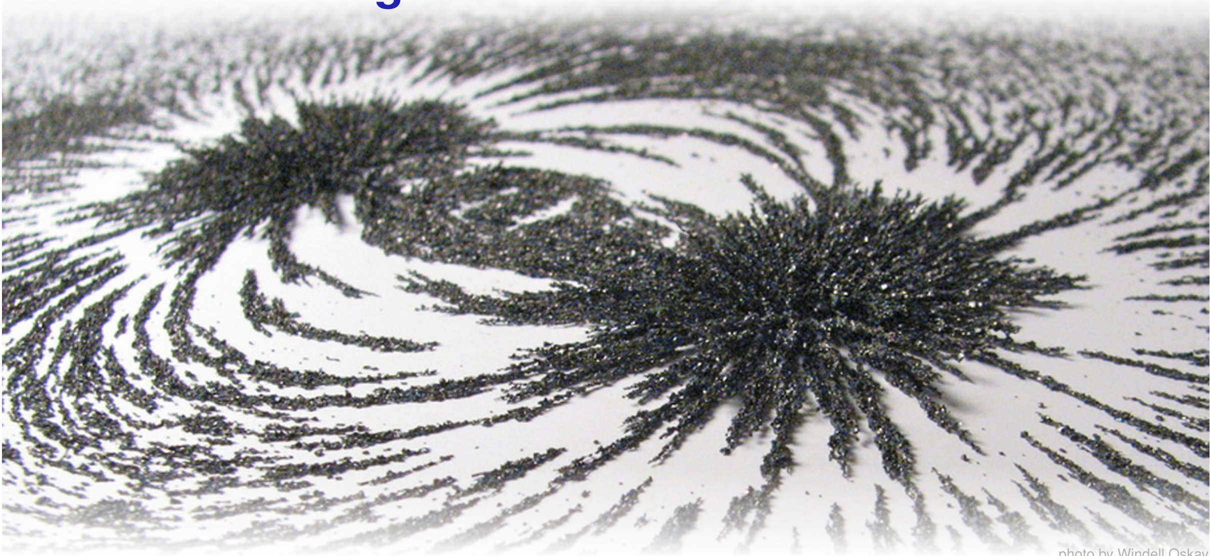


photo by Windell Oskay

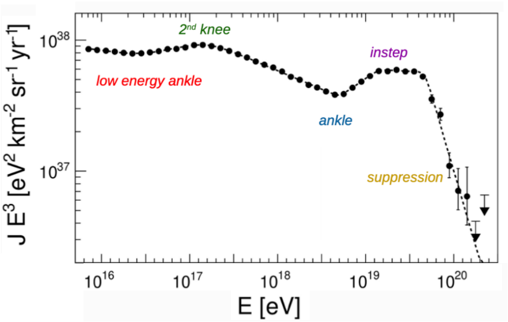
M. Unger, G.R. Farrar *The Coherent Magnetic Field of the Milky Way* ApJ 970 (2024) 95
M. Unger, G.R. Farrar *Where Did the Amaterasu Particle Come From?* ApJL 962 (2024) L5
V. Pelgrims, M. Unger, I.C. Maris *An analytical model for the magnetic field in the thick shell of super-bubbles* arXiv:2411.06277

UHECR Anisotropies

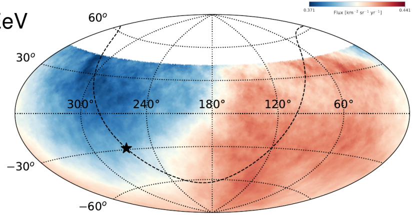
Telescope Array (USA)

Pierre Auger Observatory (Argentina)

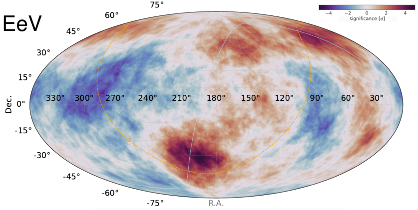
energy spectrum:



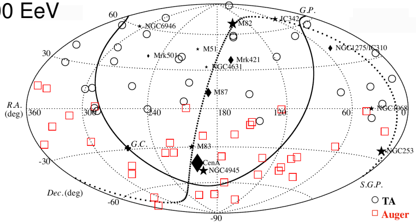
E>8 EeV



E>38 EeV



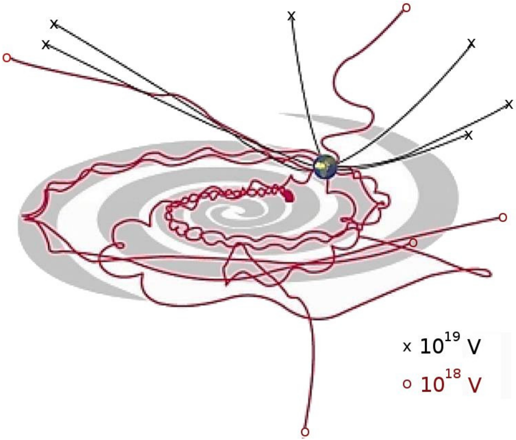
E>100 EeV



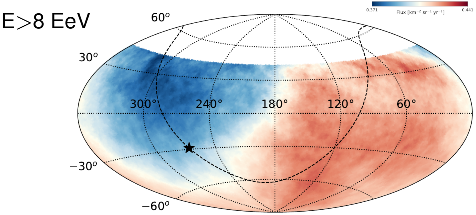
T. Fujii ICRC23, Telescope Array and Pierre Auger Collaboration ICRC23

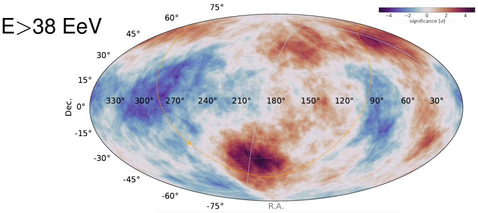
UHECR Anisotropies

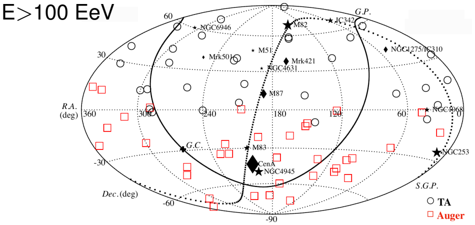
angular deflection in Galactic magnetic field



knowledge of GMF is needed to interpret data!



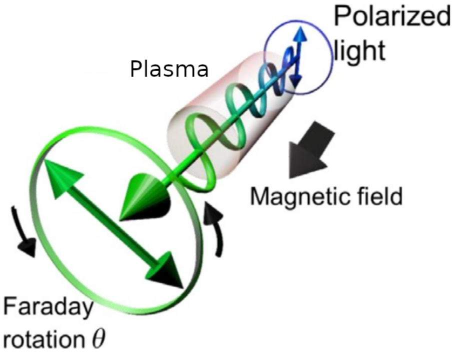




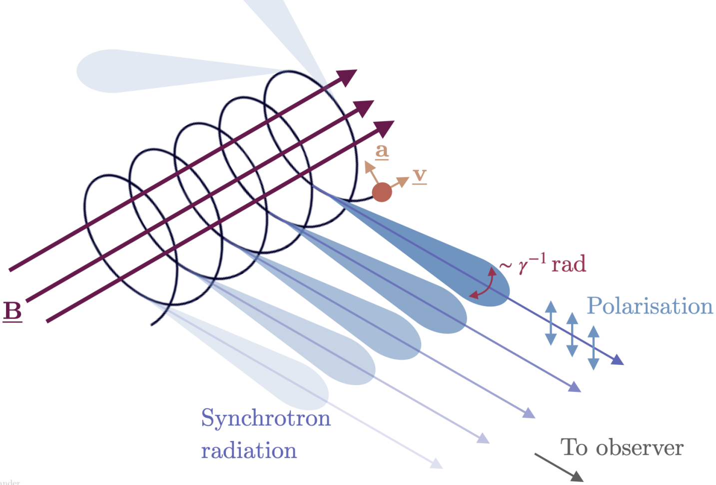
T. Fujii ICRC23, Telescope Array and Pierre Auger Collaboration ICRC23

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

Faraday Rotation
of extragalatic radio sources

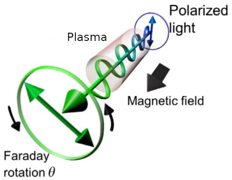


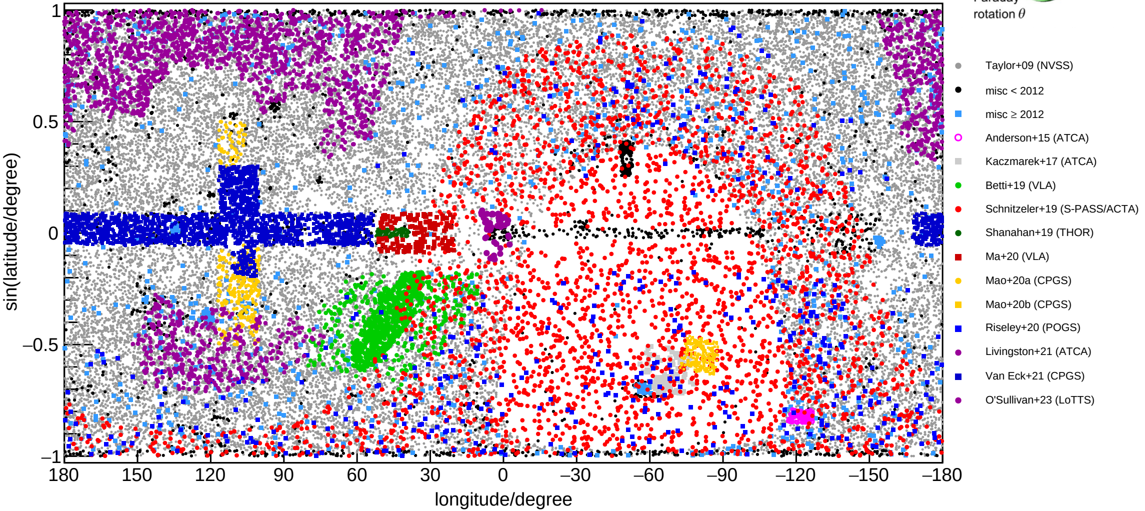
Synchrotron Radiation
of cosmic-ray electrons



Extragalactic Rotation Measures

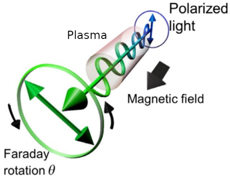
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

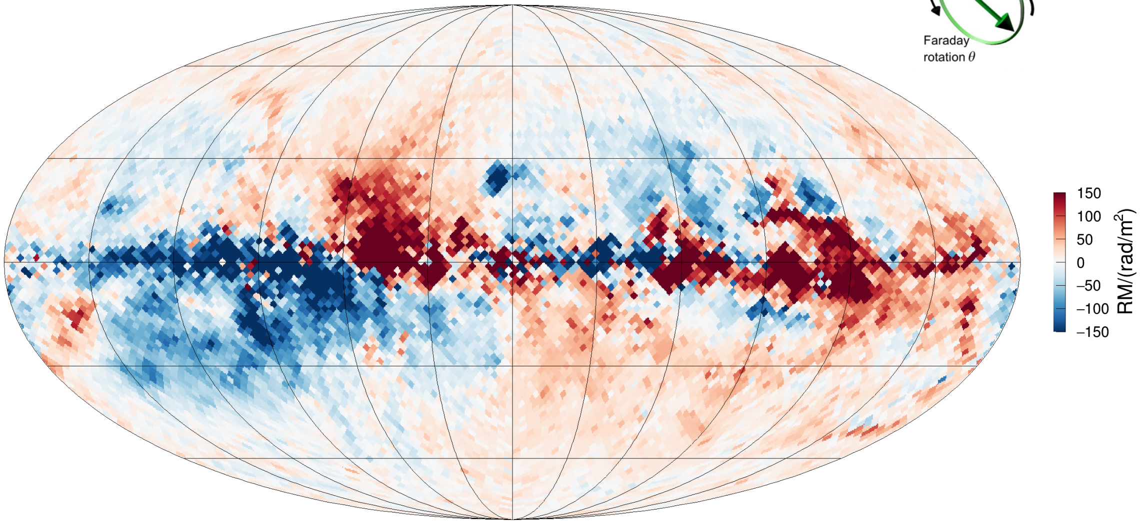




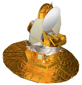
RM Sky

$$\mathrm{RM} \propto \int_{\text{source}}^{\text{observer}} B_{\parallel}(l)\, n_e(l)\, \mathrm{d}l$$

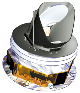




Polarized Synchrotron Emission

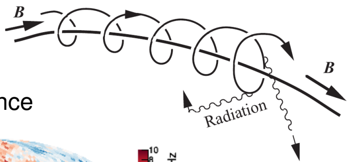


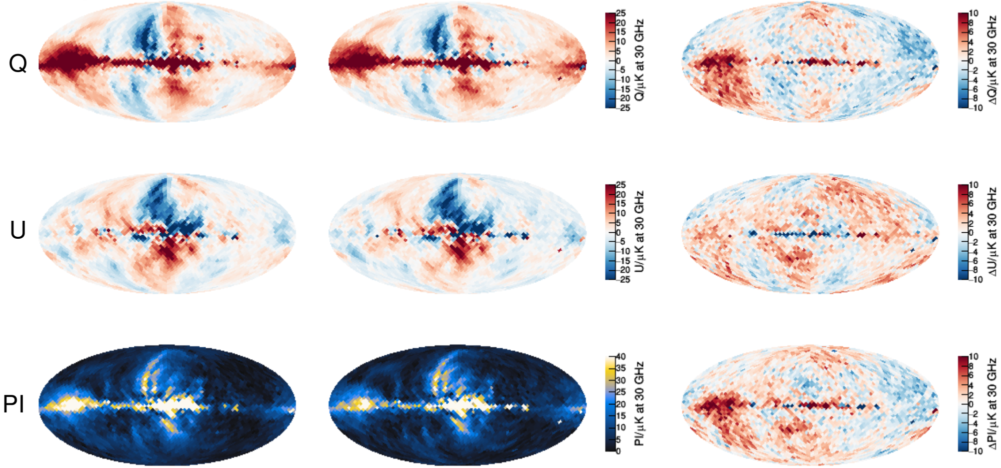
WMAP9



Planck R3.00

difference

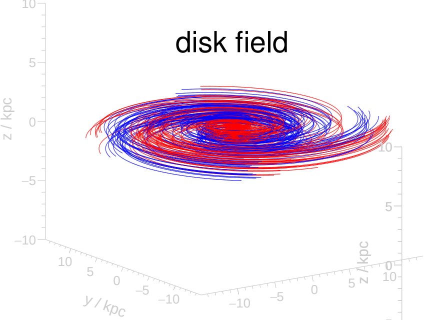


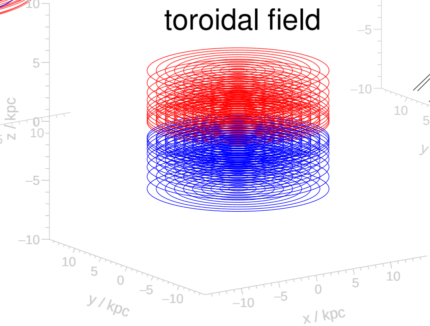


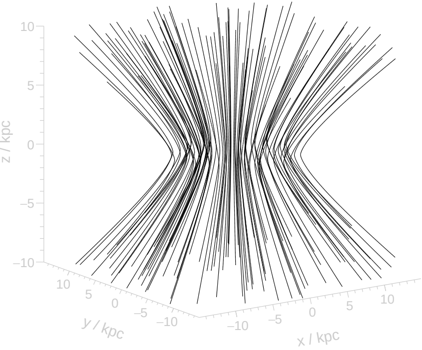
- Stokes Paramters
  $Q/U \propto \int B_\perp^2 \, n_{\rm cre} \, \mathrm{d}l$
- projected mag. angle
  $\psi = \frac{1}{2}\mathrm{atan}\left(\frac{U}{Q}\right) + \frac{\pi}{2}$
- polarized intensity:
  $\mathrm{PI}^2 = Q^2 + U^2$

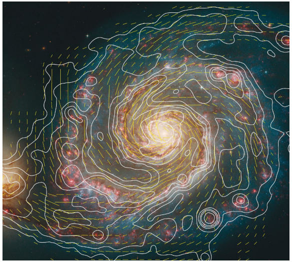
calibration uncertainty? cosmic-ray spectral index?

Parametric GMF Components

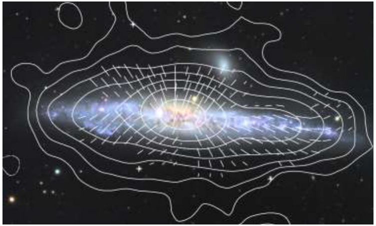






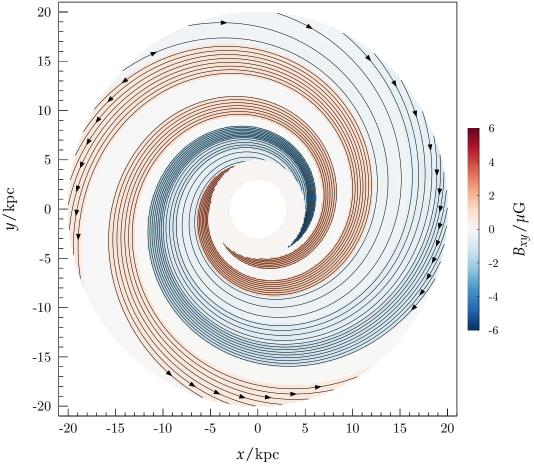


UF23 solenoidal field components
(major refinement of JF12 functions)

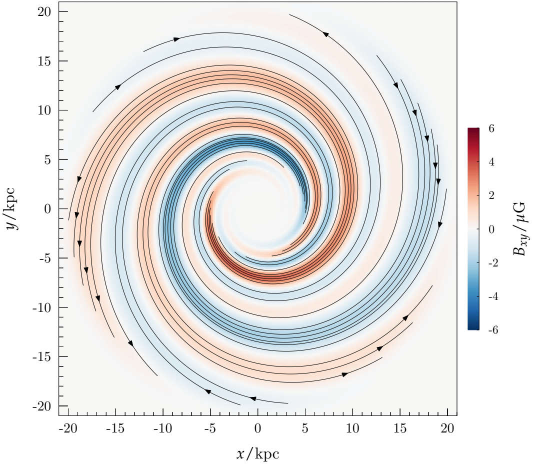


New Disk Field Model

previous “wedge”-model (e.g. JF12):

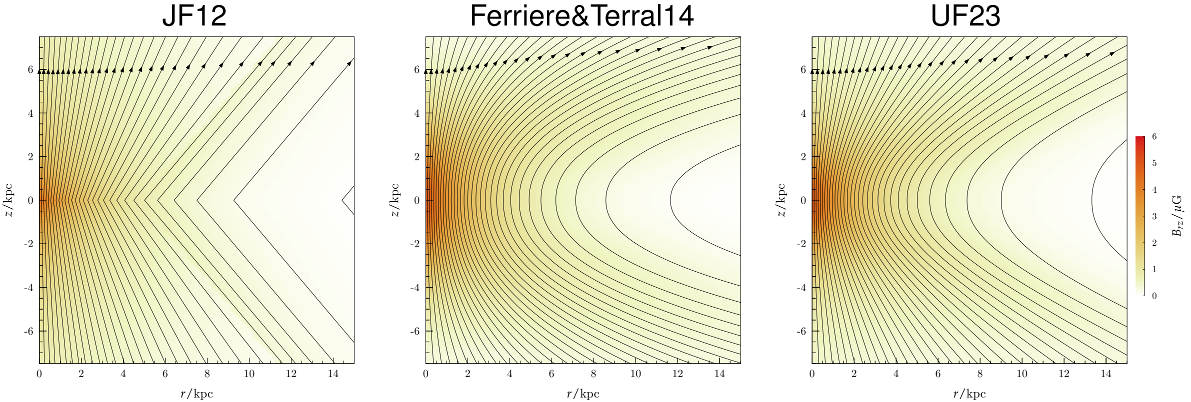


smooth spiral disk field:



- divergence-free Fourier-expansion of $B_\phi(r)$ at reference radius
- avoids radial discontinuities
- free pitch angle and “magnetic arms” (number of Fourier modes)

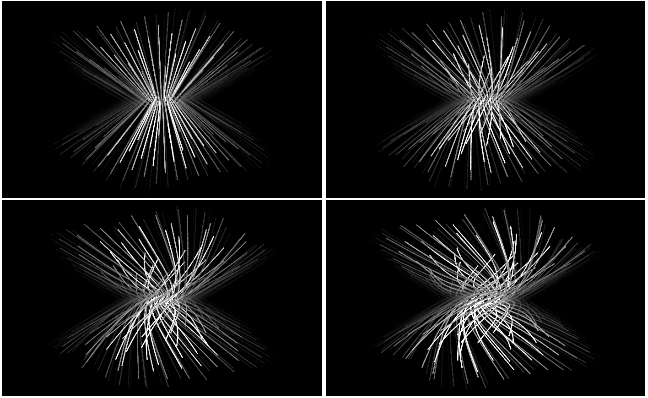
Halo X-Field



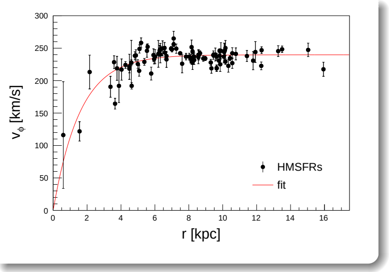
- fix JF12 discontinuities at $z = 0$ and transition to $\theta_X = 49°$

Unified Halo Model

- evolve X-field via ideal induction equation $\partial_t \mathbf{B} = \nabla \times (\mathbf{v}_{\mathrm{rot}} \times \mathbf{B})$
- radial and vertical shear of Galactic rotation generates toroidal field

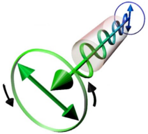


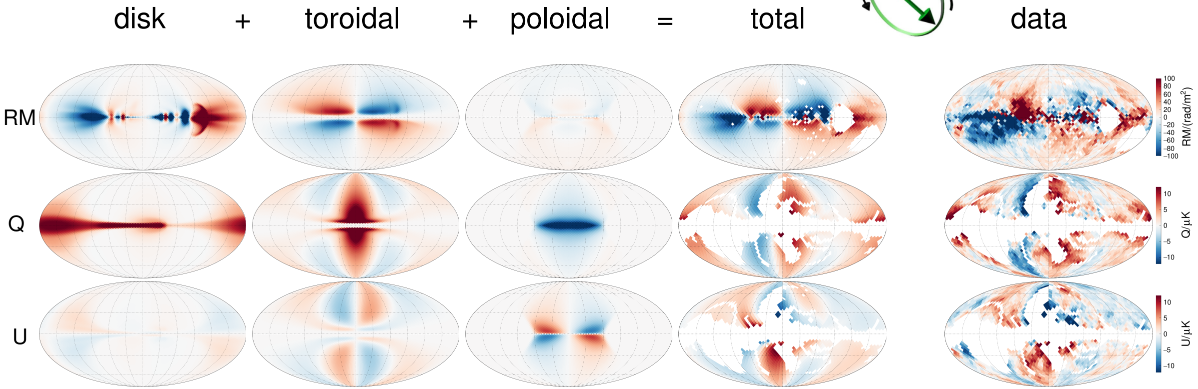
Galactic rotation curve



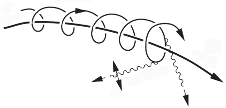
- no separate X- and torodial halo needed! $\rightarrow$ 6 instead of 10 free halo parameters

Adjustment of Model Parameters to Data



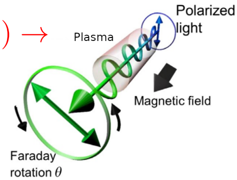


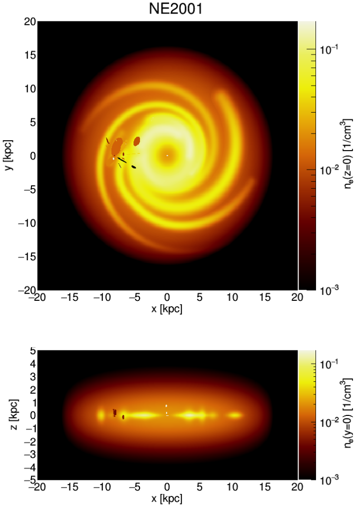
- 6520 data points
- 15-20 parameters
- typical reduced $\chi^2/n_{\text{df}} =$ 1.2...1.3, depending on model



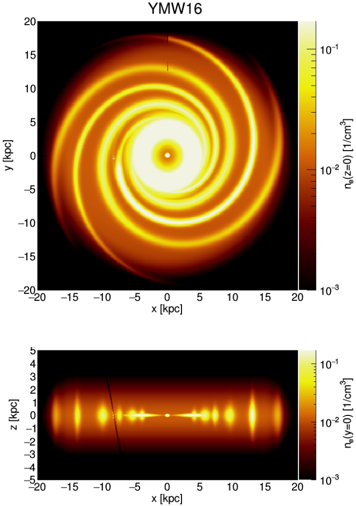
Uncertainties: Thermal Electron Models

$n_e(x, y, z) \rightarrow$



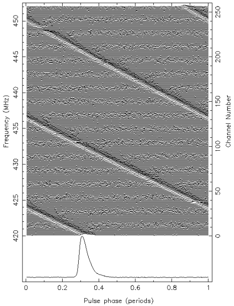


112 pulsar DMs



189 pulsar DMs

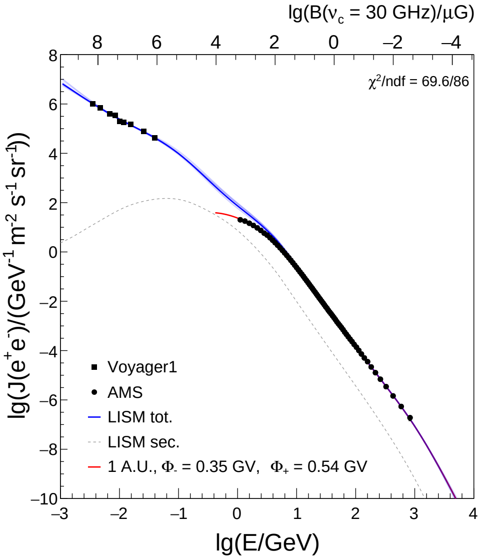
$$\mathrm{DM} \propto \int_{\text{source}}^{\text{observer}} n_e(l)\, \mathrm{d}l$$

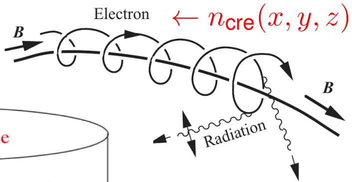


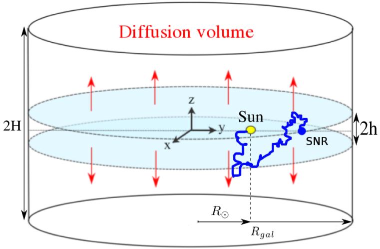
Cordes&Lazio arXiv:0207156

Yao, Manchester & Wang, ApJ 2017

Uncertainties: Cosmic-Ray Electrons







homogenous and isotropic diffusion $D_0 \propto R^\delta$ (rigidity R)

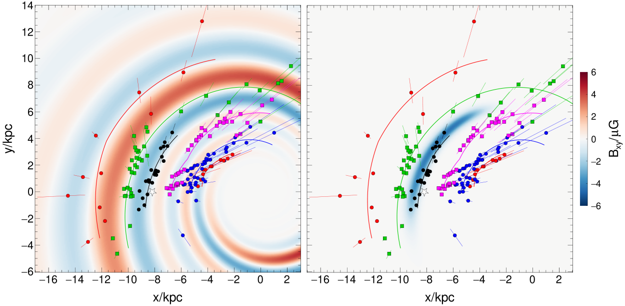
Y. Genolini et al, A&A. **580** (2015) A9

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

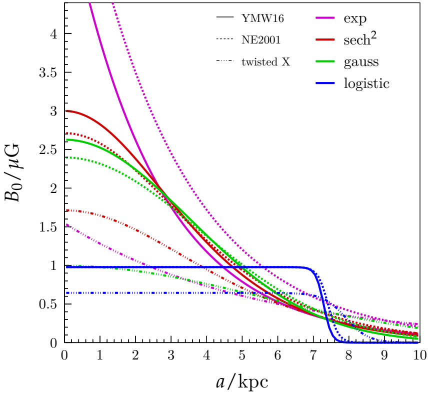
Uncertainties: Model Assumptions

Examples:

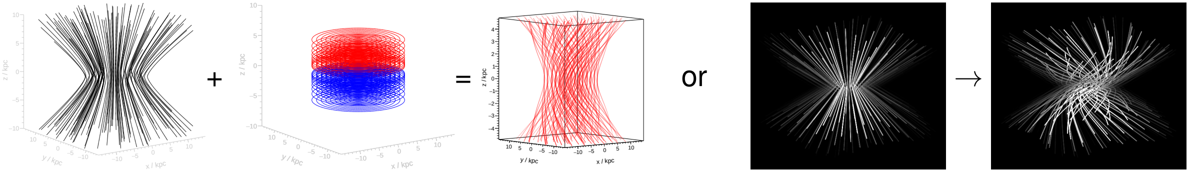
Global Spiral or Local Spur?



radial dependence of X-field?

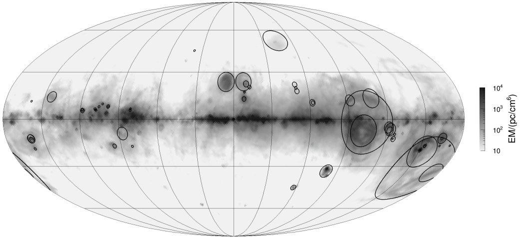


X-field and toroidal field or twisted X-field?

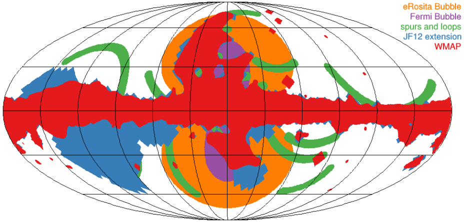


Uncertainties: Foregrounds a) Small-Scale Structures

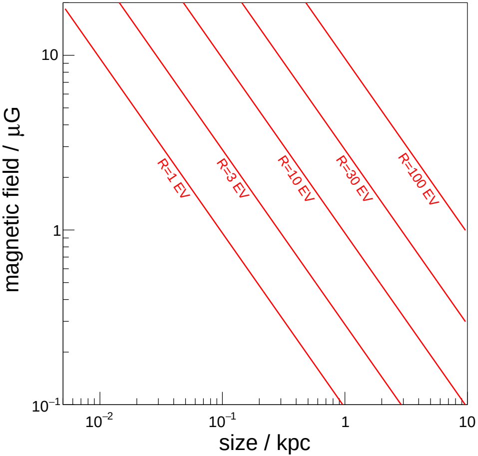
mask HII regions (atypical n_e)



mask loops and spurs (atypical B and n_{cre})



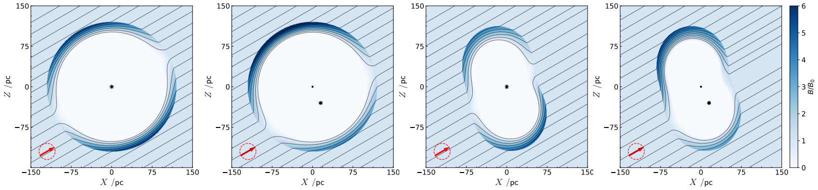
deflection angle < 5°



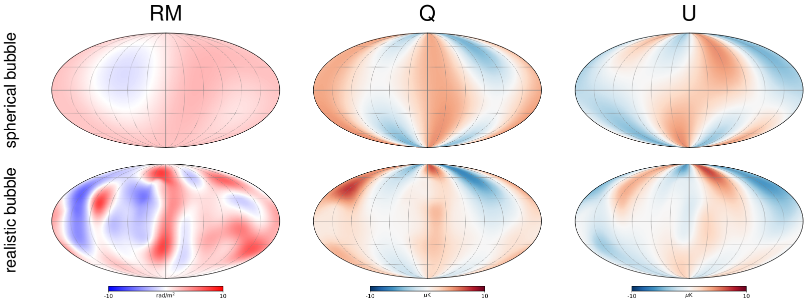
distinction small- and large-scale not always unambiguous, e.g. North Polar Spur or Fan Region (see A. Korochkin's talk)

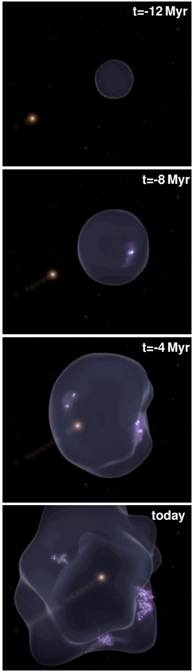
Uncertainties: Foregrounds b) Local Bubble

examples of solenoidal bubble fields:



contribution to Faraday rotation and synchrotron emission:





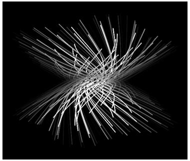
C. Zucker et al. www.cfa.harvard.edu/

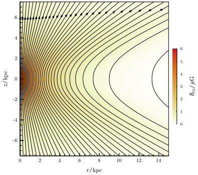
→ see talk by Vincent Pelgrims for more details (see also talk by A. Korochkin)

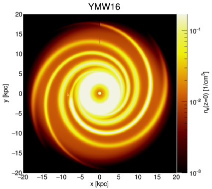
Model Variations

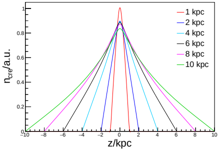
9 variations (subset of ∼200 models giving the greatest diversity of CR deflection predictions):

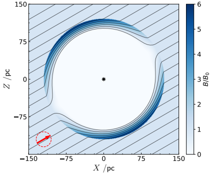
name	variation	χ^2/ndf
`base`	fiducial model	1.22
`expX`	radial dependence of X-field	1.30
`spur`	replace grand spiral by local spur (Orion arm)	1.23
`neCL`	change thermal electron model (NE2001 instead of YMW16)	1.19
`twistX`	unified halo model via twisted X-field	1.26
`nebCor`	n_e-B correlation	1.22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



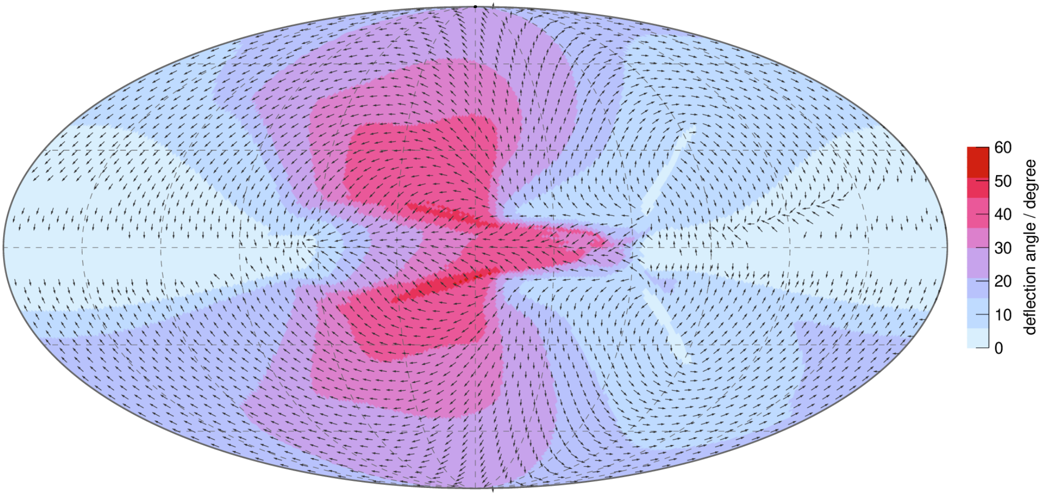




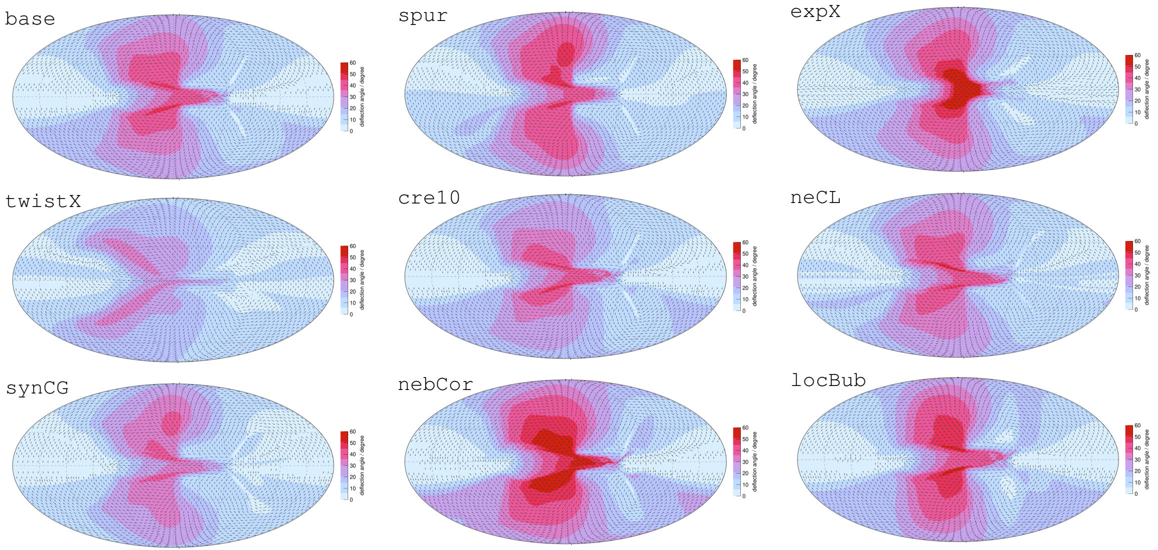




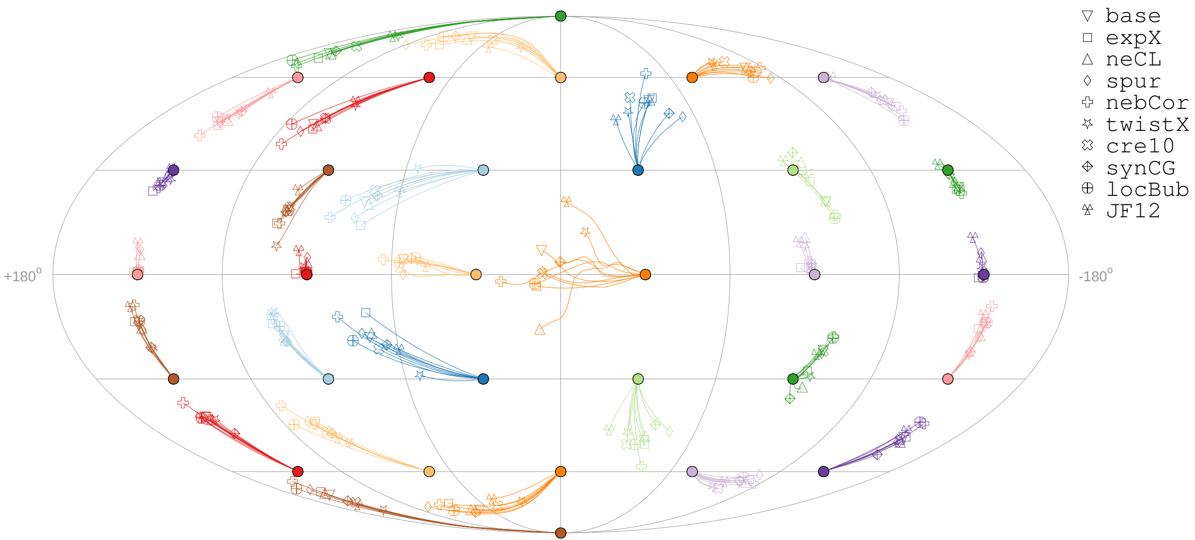
Deflections at 20 EV (base model) (backtracking)



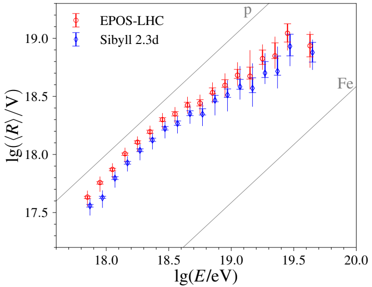
Deflections at 20 EV (backtracking)



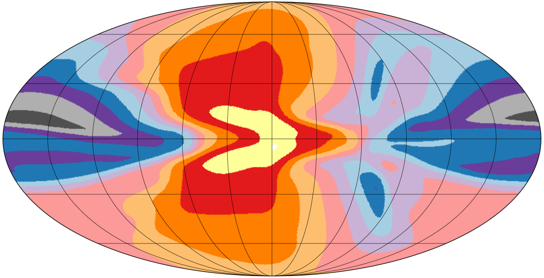
Deflections at 20 EV (backtracking)

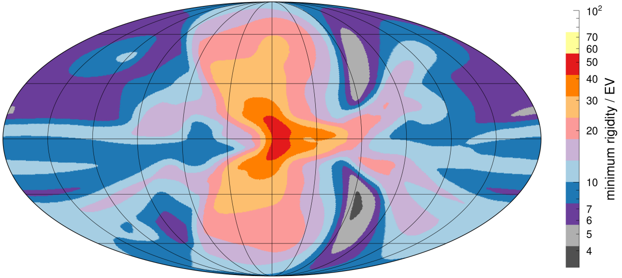


Rigidity Threshold for Nuclear Astronomy



rigidity at which ...





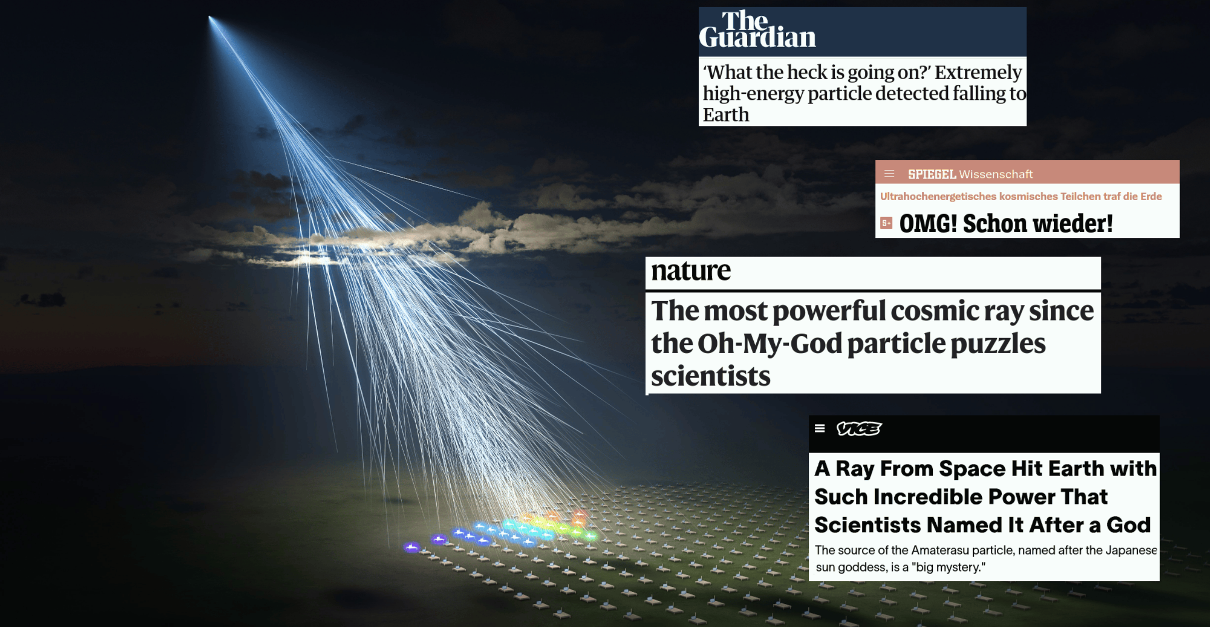
... deflections $\leq 20^\circ$

median threshold at 20 EV

... deflection difference $\leq 20^\circ$

median threshold at 10 EV

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

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."

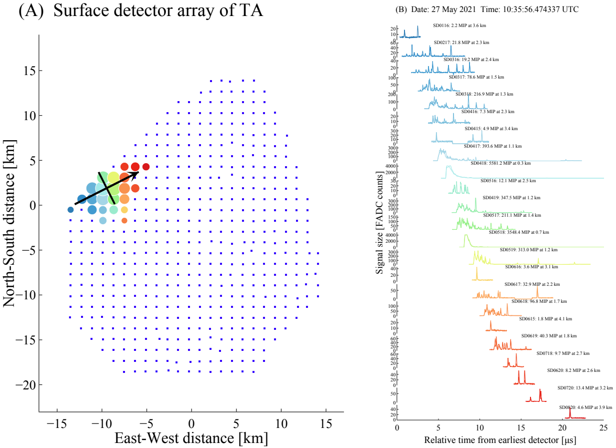
Science

HOME > SCIENCE > VOL. 382, NO. 6673 > AN EXTREMELY ENERGETIC COSMIC RAY OBSERVED BY A SURFACE DETECTOR ARRAY

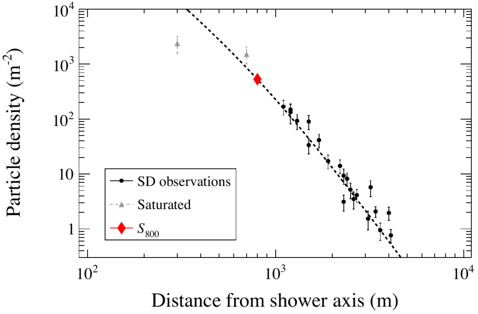
RESEARCH ARTICLE | ASTROPARTICLE PHYSICS

An extremely energetic cosmic ray observed by a surface detector array

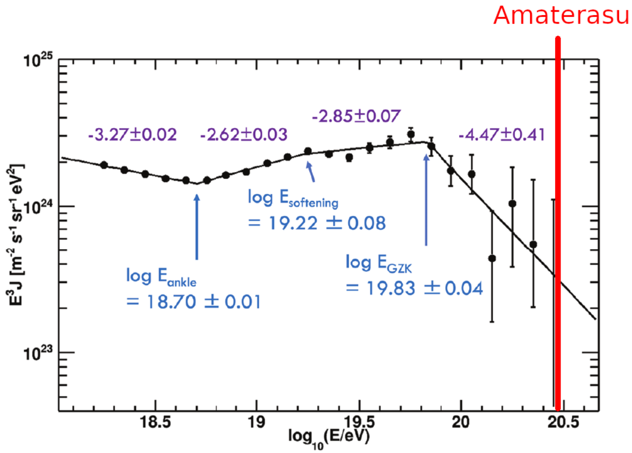
TELESCOPE ARRAY COLLABORATION*†, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL



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

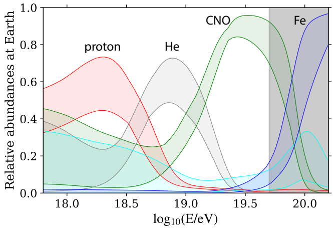


Simplest Assumption: Fe Nucleus from Standard Accelerator ($\mathcal{R}_{max} \sim 10^{18.6-18.7}$ V)



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

Peters Cycle:



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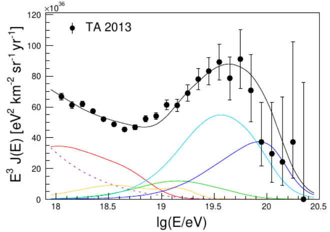
Photodisintegration in source:

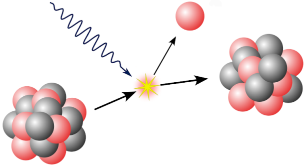


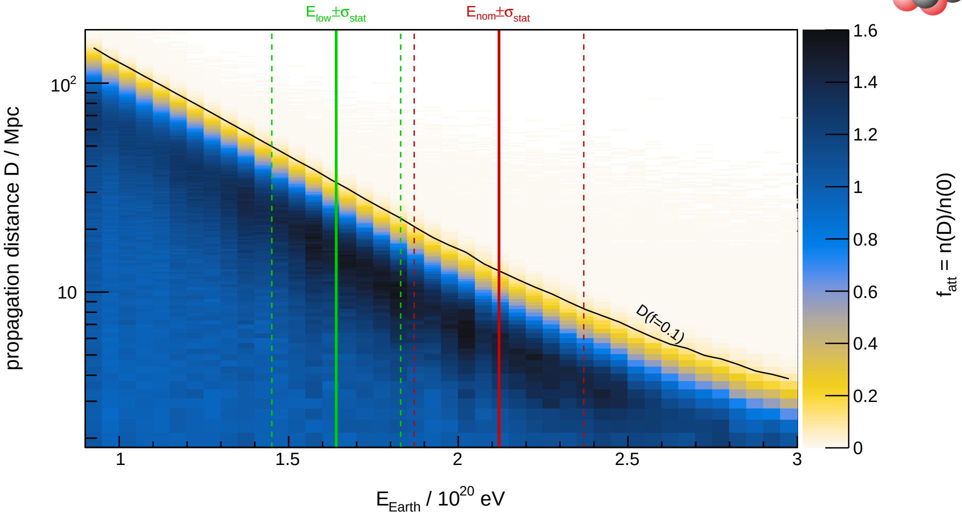
(c) Flux at Earth

MU, Farrar, Anchordoqui PRD15

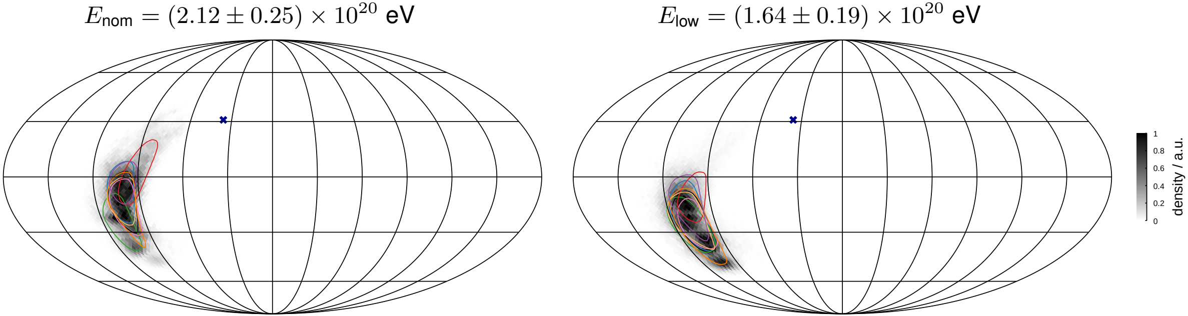
Propagation of Fe in Extragalactic Photon Fields

- horizon between 8 and 50 Mpc
- factor 240 uncertainty source volume!





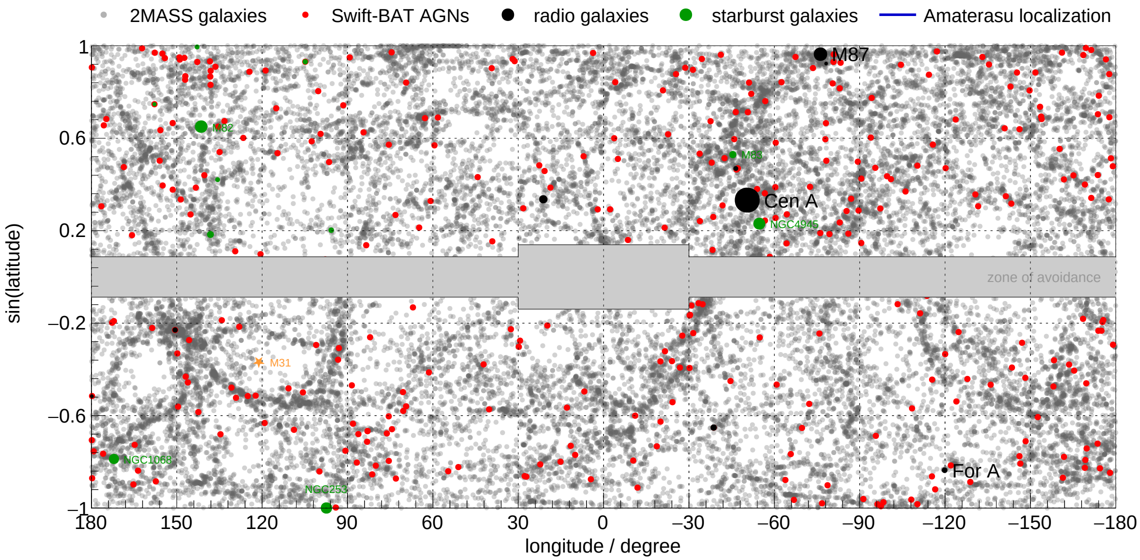
Arrival Direction



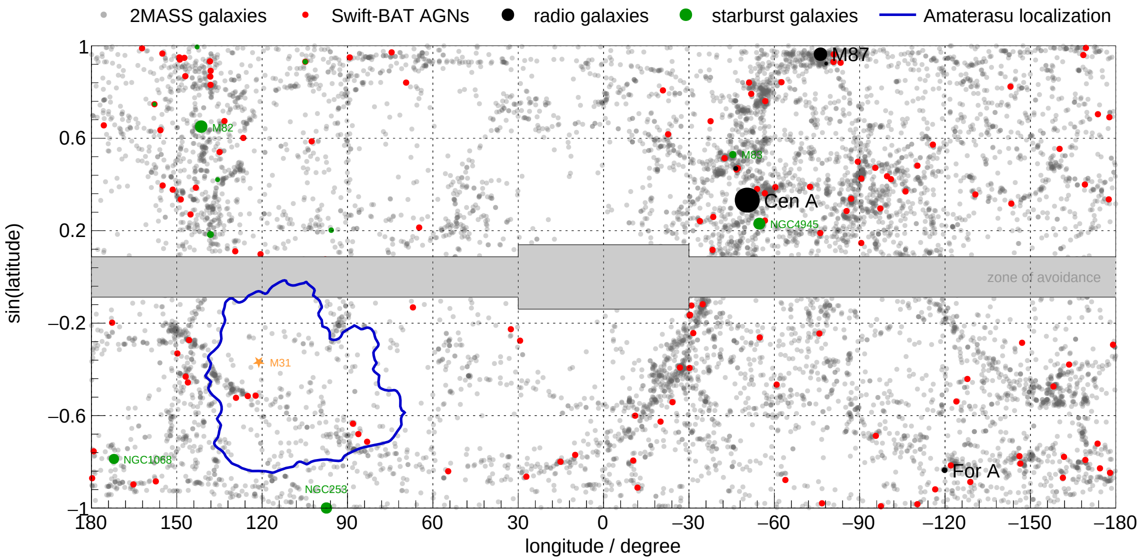
localization uncertainty: 6.6% of 4π or 2726 deg^2

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

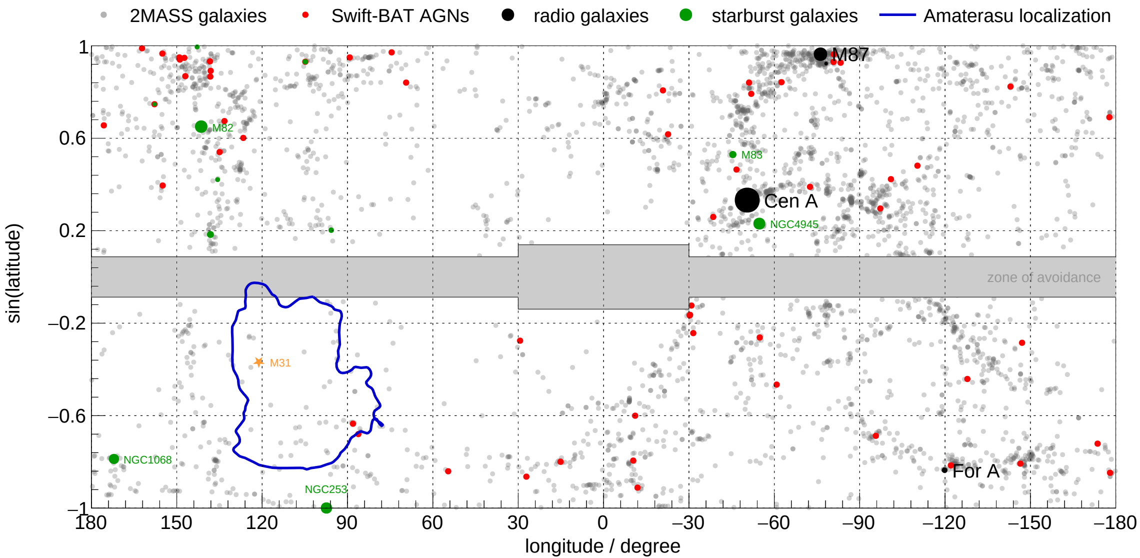
Distribution of galaxies up to D=150 Mpc



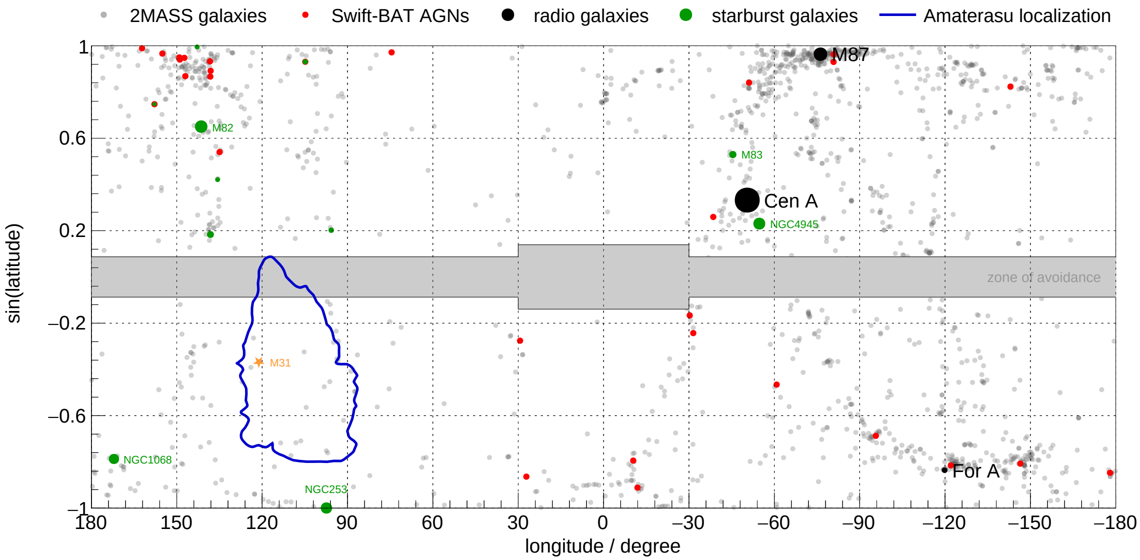
$E_{\text{low}} - 2\,\sigma$, $D_{0.1}$=72 Mpc



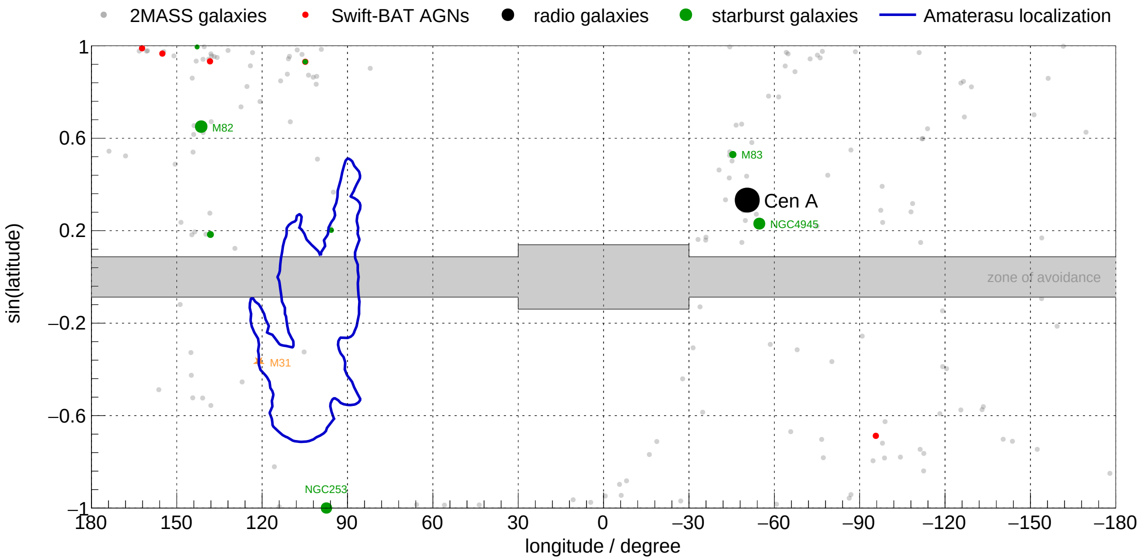
$E_{\mathrm{low}} - 1\,\sigma$, $D_{0.1}$=42 Mpc



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



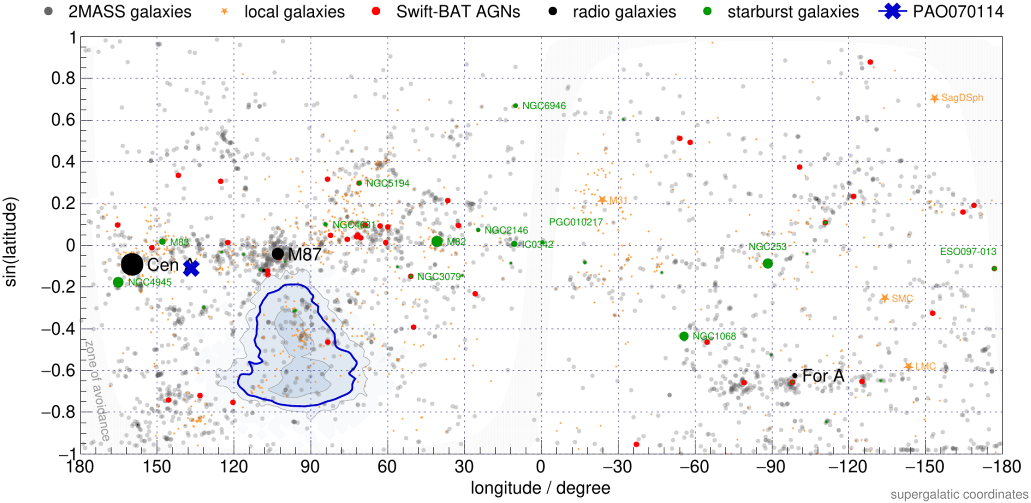
E_{nom}, $D_{0.1}$=10 Mpc



Application: Arrival Direction of the Top 4 Auger Events

Pierre Auger Coll., ApJS 264 (2023) 50

id	E (EeV)	$\sigma_{stat.}$ (EeV)	R.A. (degree)	Dec. (degree)	$\Omega_{loc} / 4\pi$ –	θ_{loc} (degree)
PAO191110	166	13	128.9	−52.0	7.1%	31
PAO070114	165	13	192.9	−21.2	2.4%	18
PAO141021	155	12	102.9	−37.8	6.3%	29
PAO200611	155	12	107.2	−47.6	6.6%	29



supergalatic coordinates

Summary and Outlook

UF23 model ensemble: (MU&G.R. Farrar ApJ 970 (2024) 95)

- fit to newest RM, Q, U data
- major refinement of JF12 GMF components
- uncertainty of coherent GMF for UHECR tracking (...and other applications)
- test association of UHE arrival directions with source candidates

Availability:

- GitHub link (C++)
- CRPropa link (C++)
- gammaALPs link (python)

Next Steps:

- include more data to decrease uncertainties (pulsar RMs, dust, ...)
- explore further sources of uncertainty (functional forms, foregrounds, n_{e}, n_{cre})
- extend analysis to turbulent component