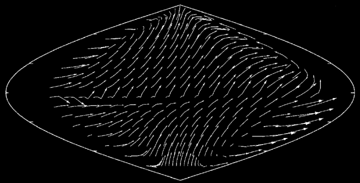
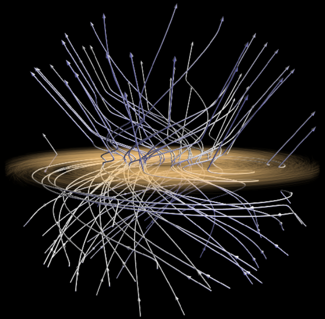
Cosmic Particles in the Galactic Magnetic Field

M. Unger (IAP, KIT)





NGC628 M. Krause 2019; T. Stanev ApJ97; JF12 Farrar&Sandstrom

based on

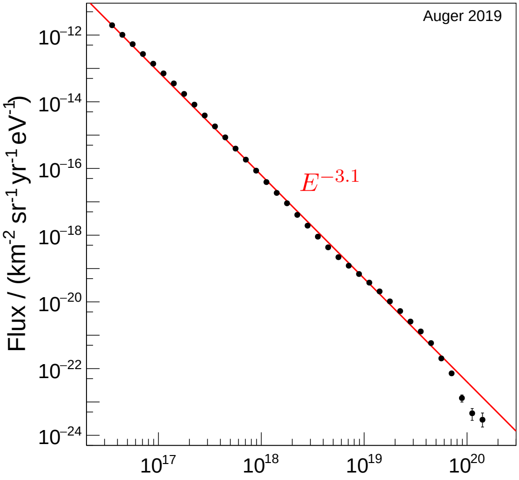
MU & G.R. Farrar "The Coherent Magnetic Field of the Milky Way" arXiv:2311.12120

MU & G.R. Farrar "Where Did the Amaterasu Particle Come From?" arXiv:2312.13273

T. Bister, G.R. Farrar & MU "Large-scale UHECR anisotropy in light of new GMF models" in prep.

KCETA Colloquium, June 20th 2024

Ultrahigh-Energy Cosmic Rays



$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

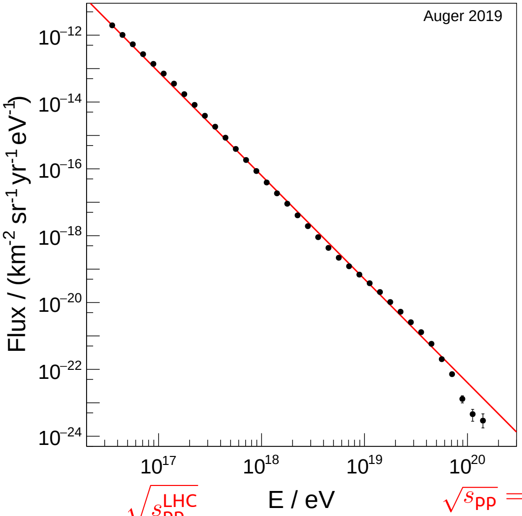
$\sqrt{s_{\text{pp}}^{\text{LHC}}}$

$\sqrt{s_{\text{pp}}} = 450$ TeV

Ultrahigh-Energy Cosmic Rays

$E_{\mathrm{kin}} \sim 4$ TeV

$E^{\mathrm{LHC}}_{\mathrm{beam}} = 7 \times 10^{12}$ eV ←



$\sqrt{s^{\mathrm{LHC}}_{\mathrm{pp}}}$

$\sqrt{s_{\mathrm{pp}}} = 450$ TeV

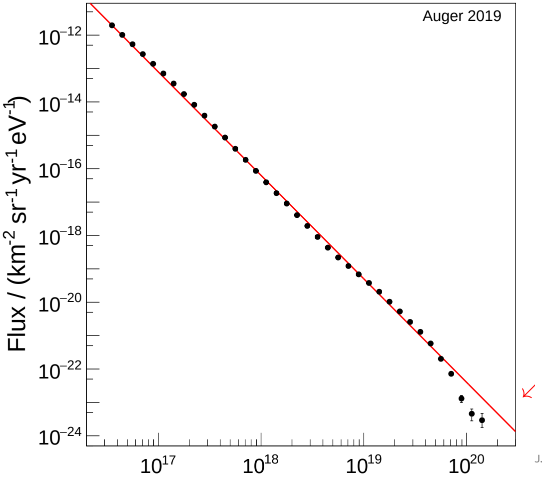
$\sim$20 J!

Serena Williams' 2nd serve

Ultrahigh-Energy Cosmic Rays

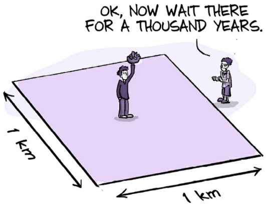
$E_{\mathrm{kin}} \sim 4$ TeV

$E^{\mathrm{LHC}}_{\mathrm{beam}} = 7\times10^{12}$ eV



$\sqrt{s^{\mathrm{LHC}}_{\mathrm{pp}}}$

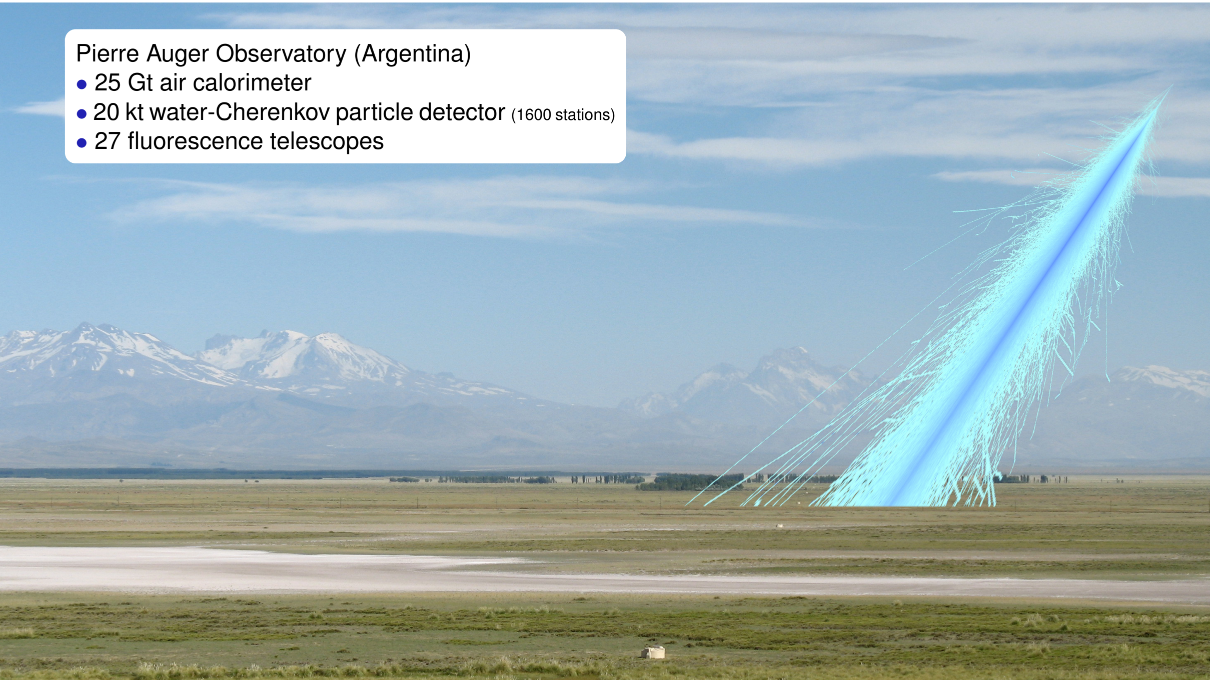
$\sqrt{s_{\mathrm{pp}}} = 450$ TeV



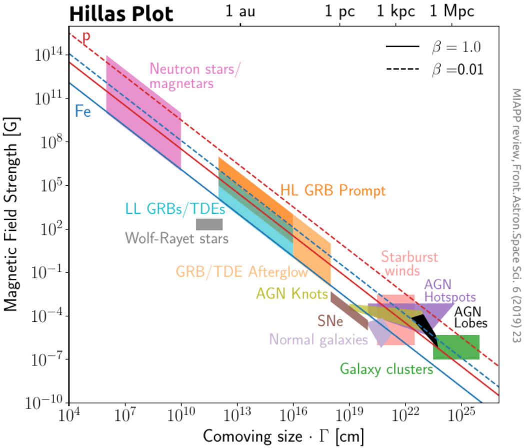
J. Cham&D. Whiteson "We have no idea", Penguin, 2018

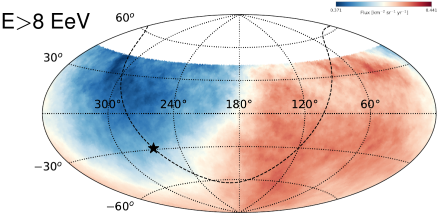
Pierre Auger Observatory (Argentina)

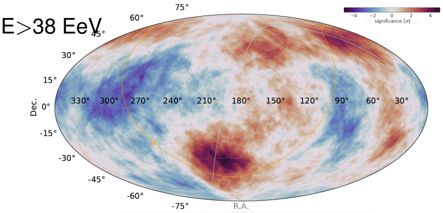
- 25 Gt air calorimeter
- 20 kt water-Cherenkov particle detector (1600 stations)
- 27 fluorescence telescopes

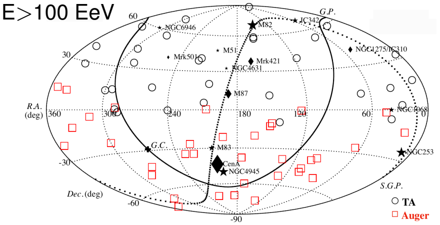


Where are the EeVatrons?





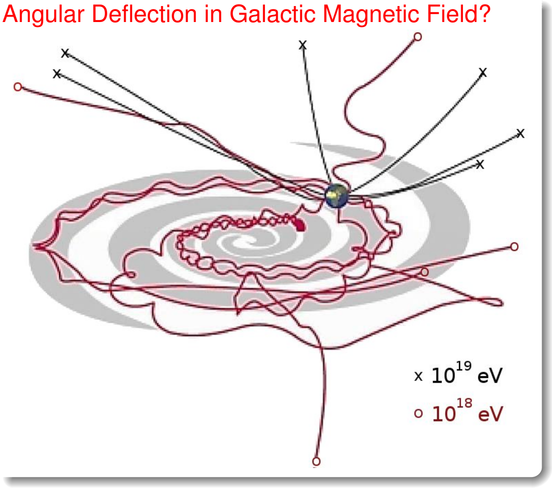


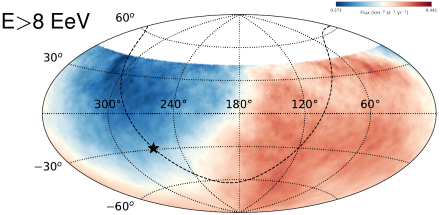


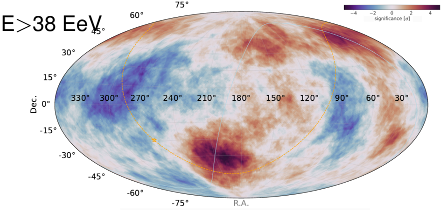
T. Fujii ICRC23, Telescope Array and Pierre Auger Collaboration ICRC23

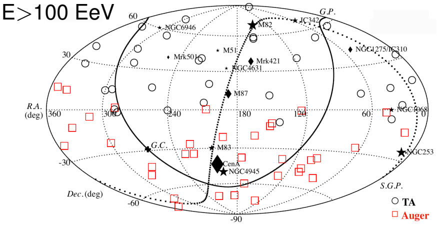
Where are the EeVatrons?

Angular Deflection in Galactic Magnetic Field?



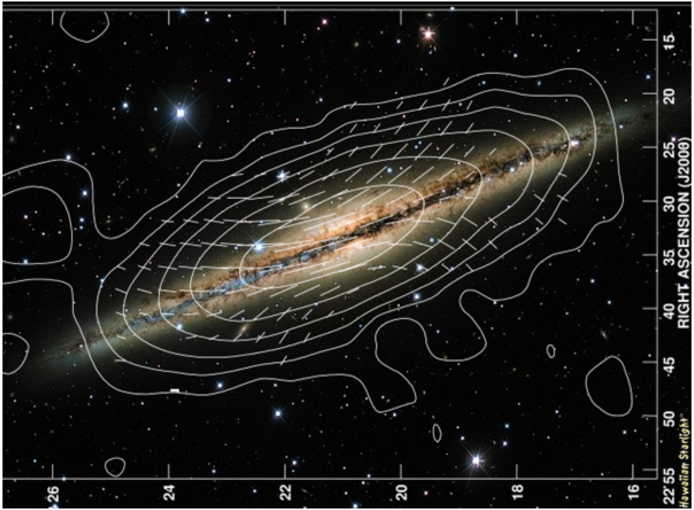




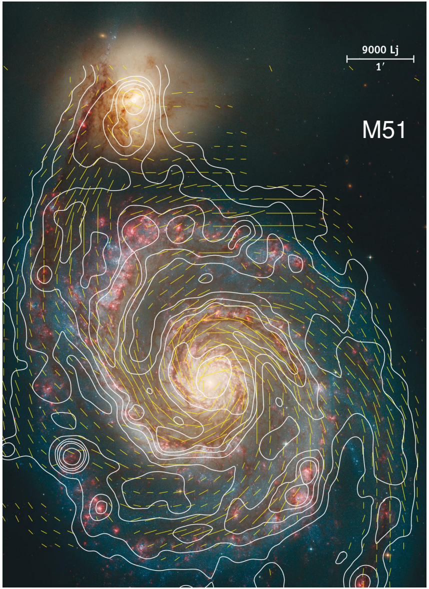


T. Fujii ICRC23, Telescope Array and Pierre Auger Collaboration ICRC23

Galactic Magnetism



NGC891, M. Krause MPIfR



M51, R. Beck (MPIfR), A. Fletcher (Newcastle Univ)

$\mathcal{O}(\mu\text{G})$ large-scale coherent fields! $u_B \approx u_{\text{turb}} \approx u_{\text{CR}}$

Proto-Galactic?

collapse of proto-galactic field $\gtrsim$ 0.1 pG

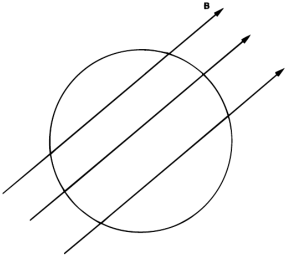


FIG. 1a

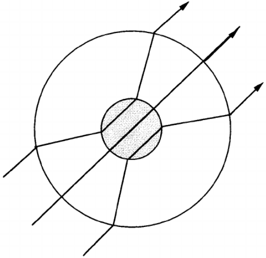
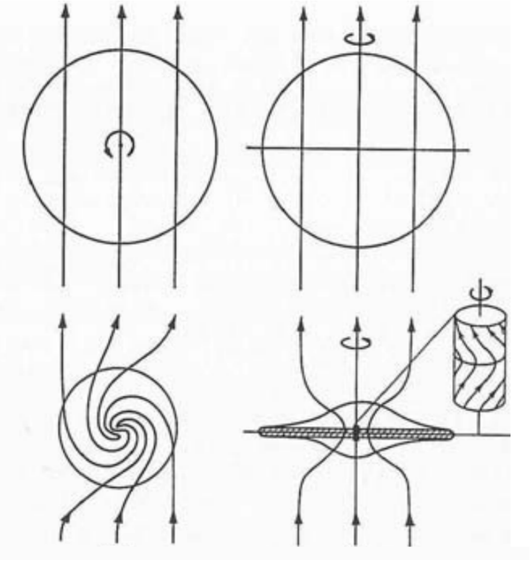


FIG. 1b

Howard&Kulsrud A&A 1990

shearing by differential rotation

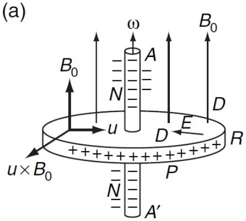


Sofue 1990

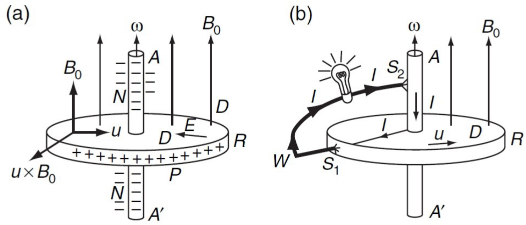
but:

- winding problem ($P_{\rm rot} \approx$ 0.2 Gyr at $r_\odot$)
- decay of field in turbulent diffusion $\mathcal{O}(10^8$yr$)$

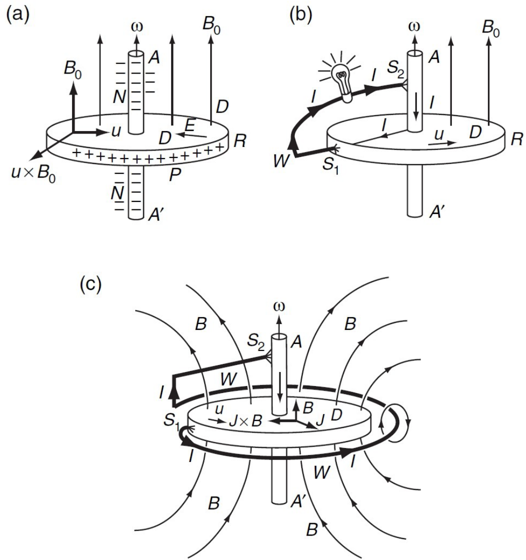
Dynamo Action? "$B_0 + E_{\text{kin}} \to B_1 > B_0$"



Dynamo Action? “$B_0 + E_{\text{kin}} \to B_1 > B_0$”

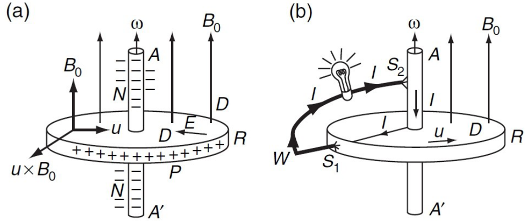


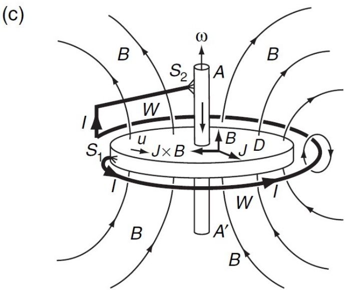
Dynamo Action? "$B_0 + E_{\mathrm{kin}} \rightarrow B_1 > B_0$"



P.H. Roberts (2007)

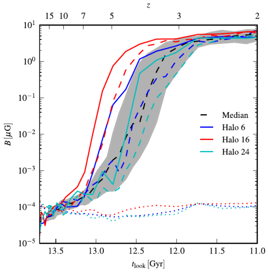
Dynamo Action? "$B_0 + E_{\mathrm{kin}} \rightarrow B_1 > B_0$"

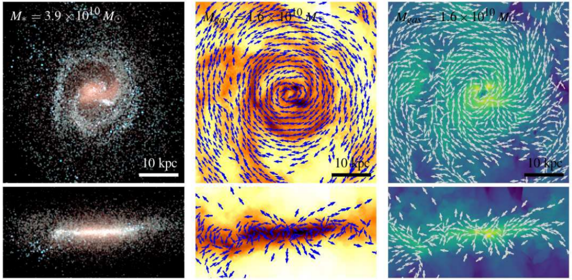




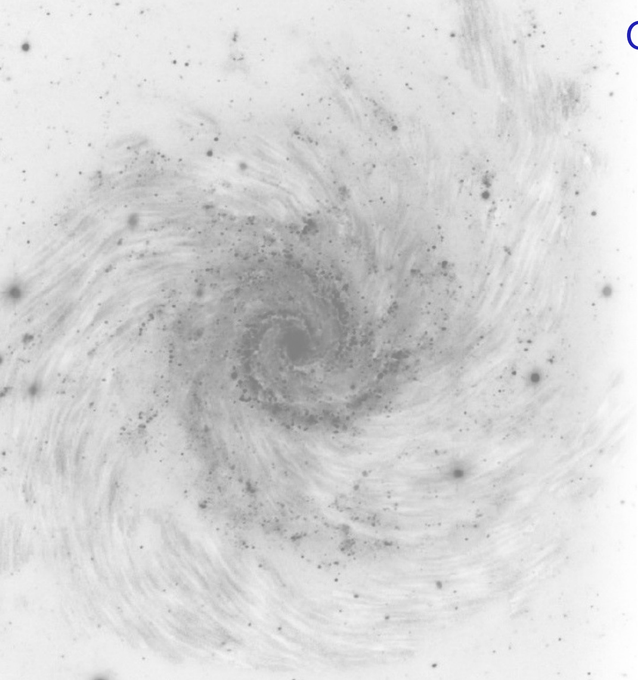
P.H. Roberts (2007)

Galaxy simulations:





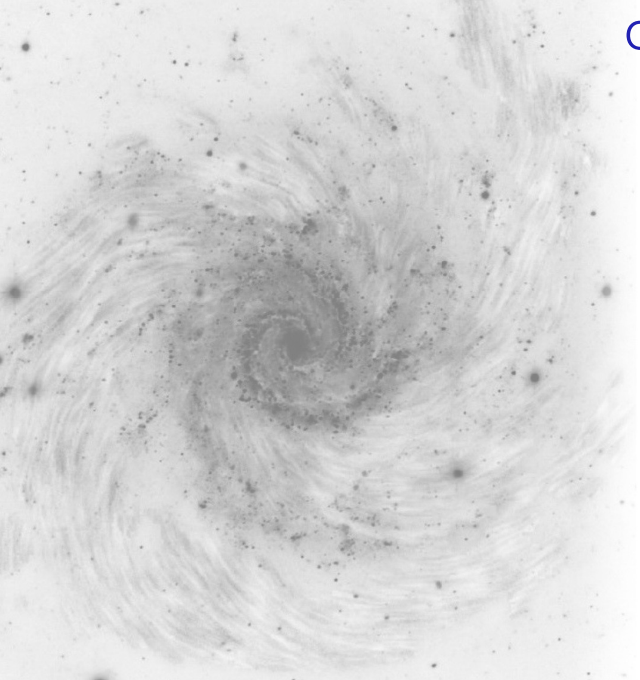
Auriga, Pakmor+MNRAS17; IllustrisTNG, Marinacci+MNRAS17



Outline

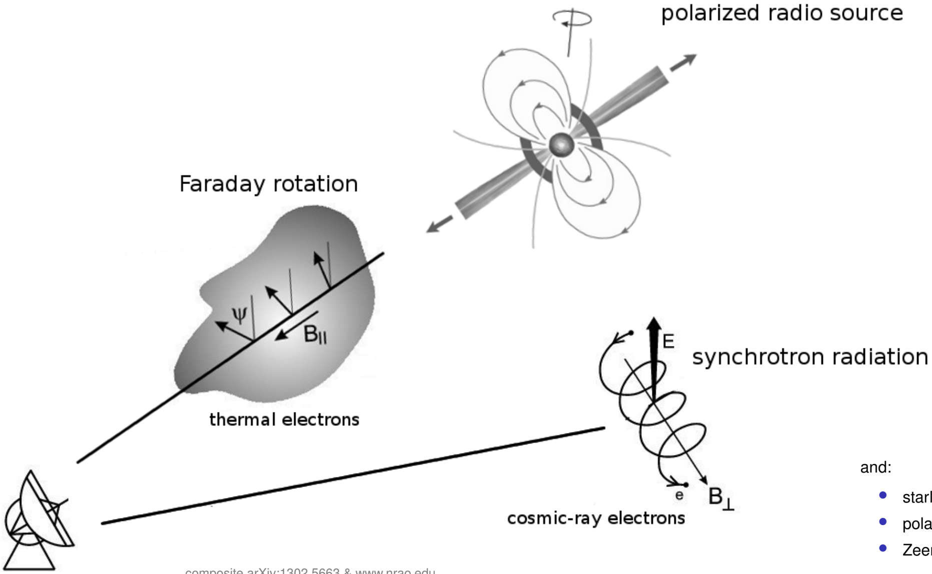
- **Galactic Magnetic Field**
- **Origin of the UHE Dipole**
- **Origin of the Amaterasu Particle**

Outline



- **Galactic Magnetic Field**
- Origin of the UHE Dipole
- Origin of the Amaterasu Particle

Observational Tracers of the Galactic Magnetic Field

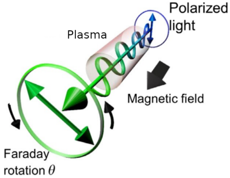


composite arXiv:1302.5663 & www.nrao.edu

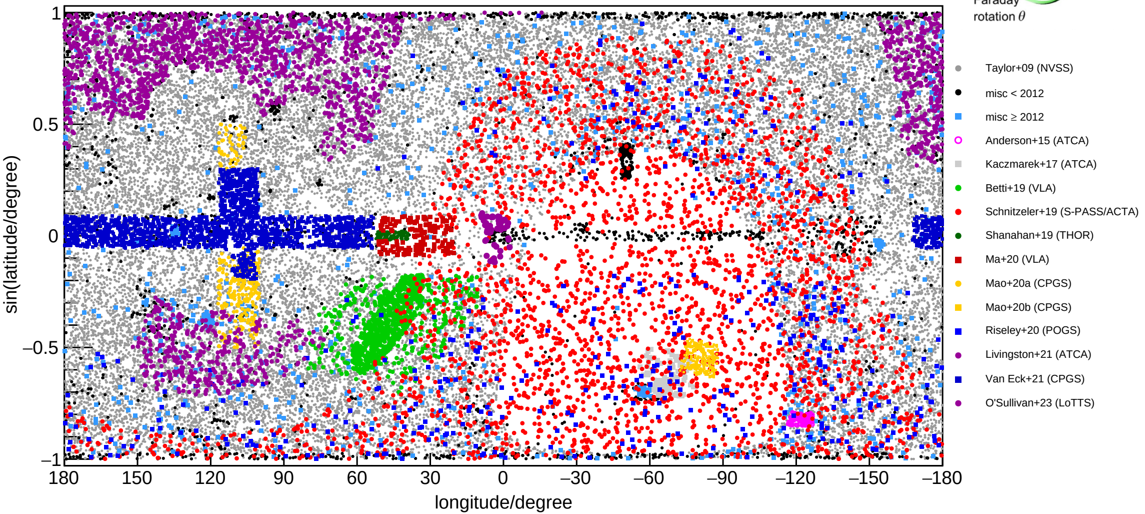
and:

- starlight polarization
- polarized dust emission
- Zeeman effect

Extragalactic Rotation Measures

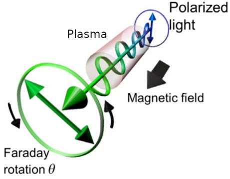


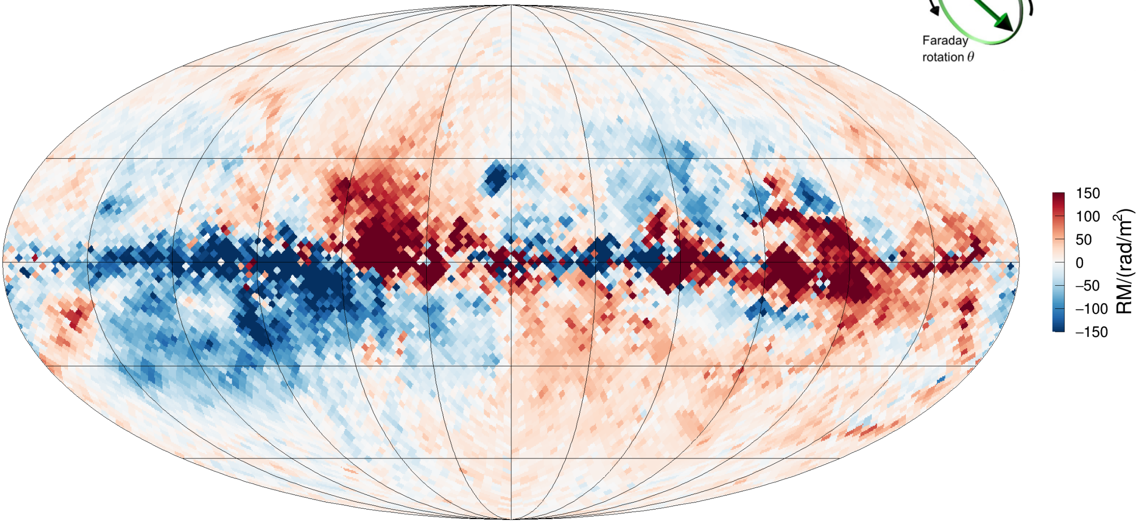
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$



RM Sky

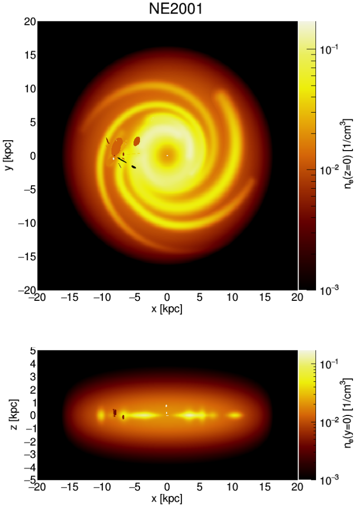
$$\mathrm{RM} \propto \int_{\text{source}}^{\text{observer}} B_{\parallel}(l)\, n_e(l)\, \mathrm{d}l$$



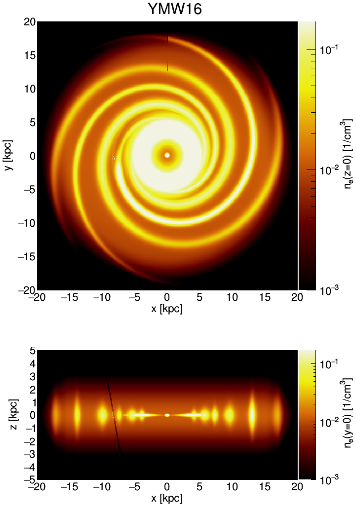


Thermal Electron Models

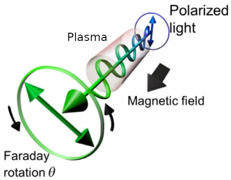
$$\mathrm{DM} \propto \int_{\text{source}}^{\text{observer}} n_e(l)\, \mathrm{d}l$$

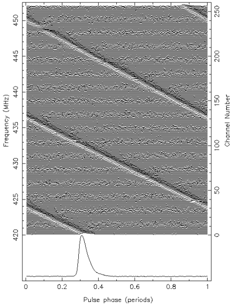


112 pulsar DMs



189 pulsar DMs

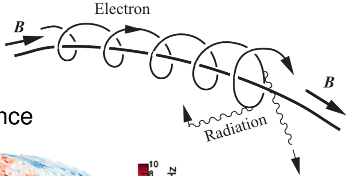


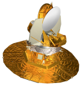


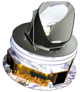
Cordes&Lazio arXiv:0207156

Yao, Manchester & Wang, ApJ 2017

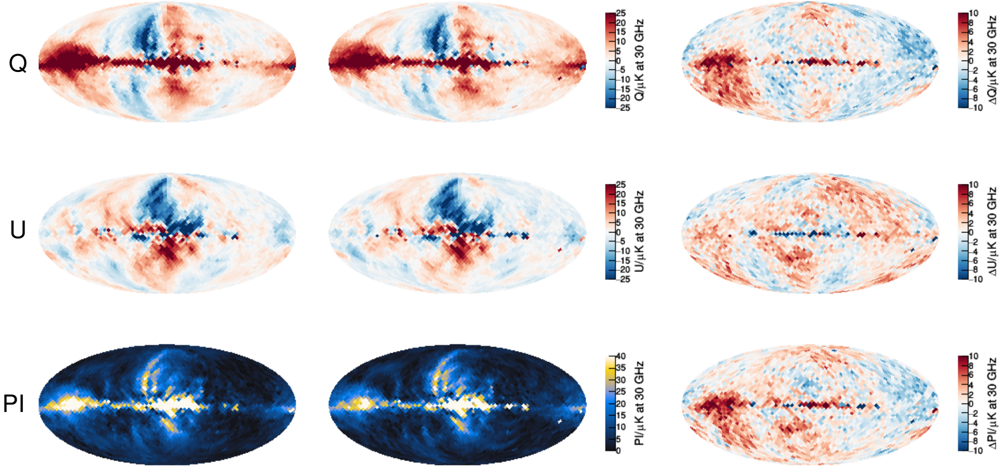
Polarized Synchrotron Emission




WMAP9


Planck R3.00

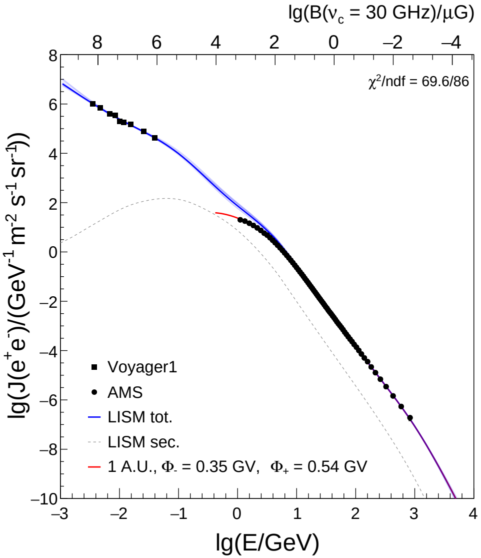
difference



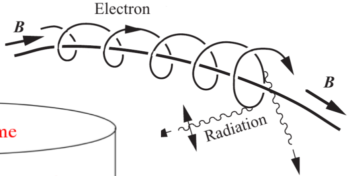
- Stokes Paramters
  $Q/U \propto \int B_{\perp}^{2}\, n_{\mathrm{cre}}\, \mathrm{d}l$
- projected mag. angle
  $\psi = \frac{1}{2}\mathrm{atan}\left(\frac{U}{Q}\right) + \frac{\pi}{2}$
- polarized intensity:
  $\mathrm{PI}^{2} = Q^{2} + U^{2}$

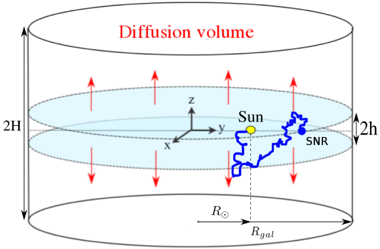
calibration uncertainty? cosmic-ray spectral index?

Cosmic-Ray Electrons



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

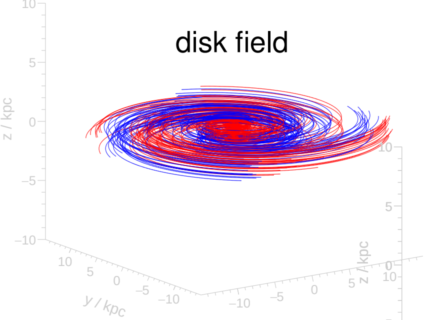


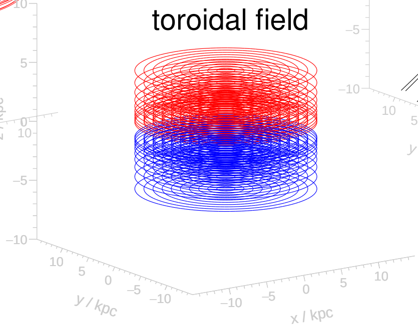


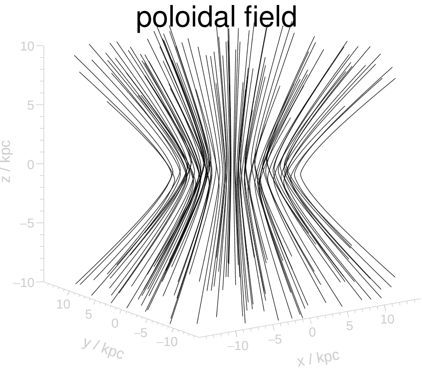
homogenous and isotropic diffusion $D_0 \propto R^\delta$ (rigidity R)

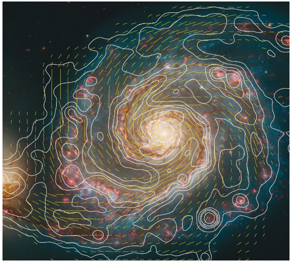
Y. Genolini et al, A&A. **580** (2015) A9

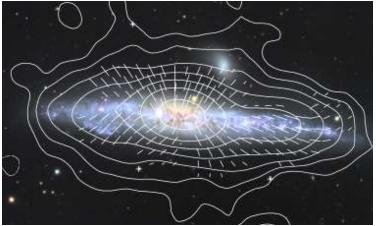
Parametric GMF Components





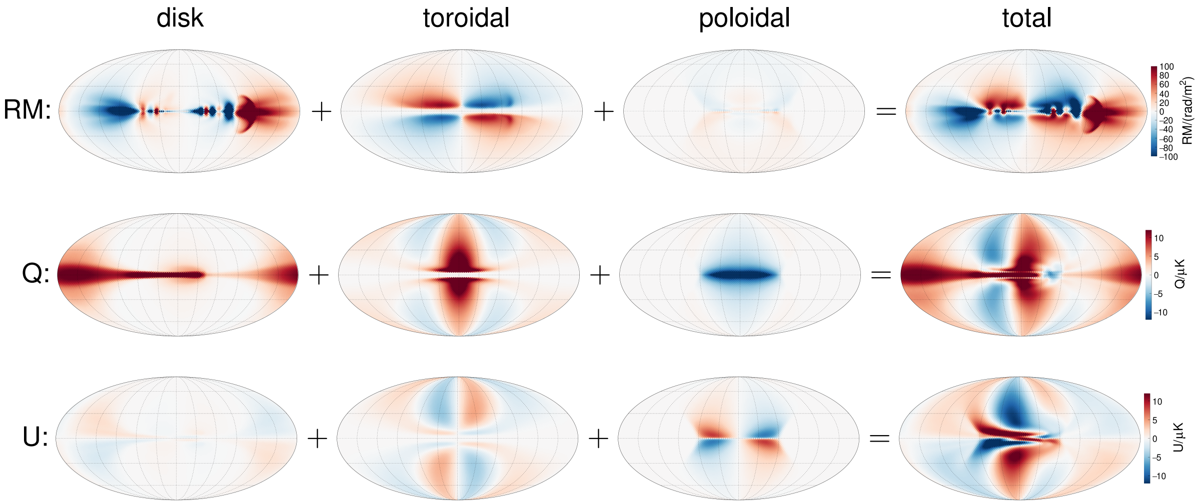




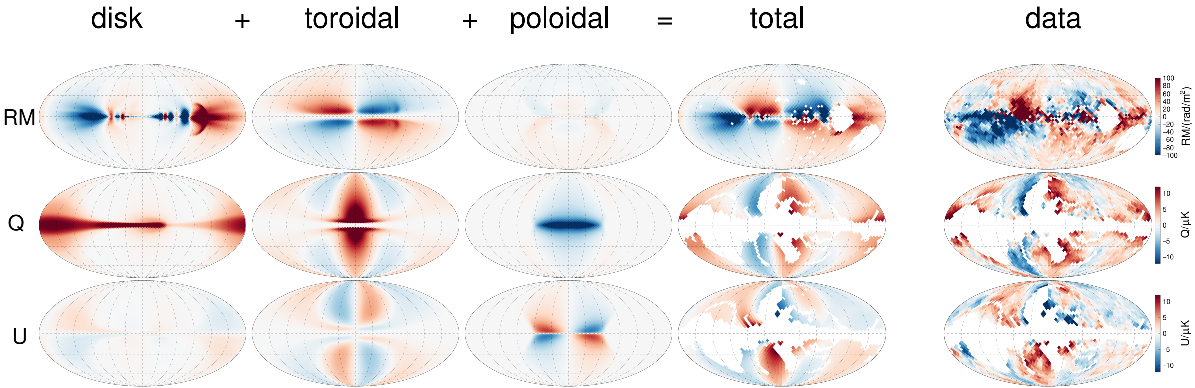


cf. Jansson&Farrar ApJ 757 (2012) 14

RM and Q&U of “base model”



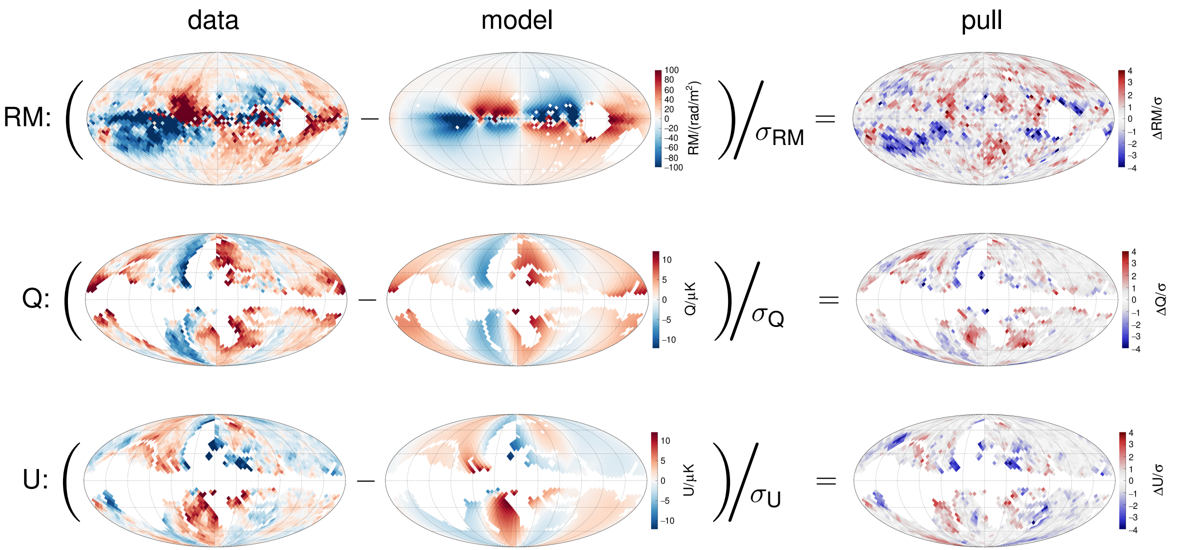
Data and Model



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

Data and Model

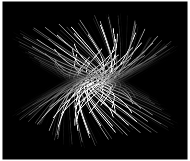
$\chi^2/\text{ndf} = 7923/6500 = 1.22$

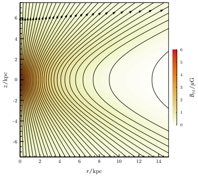


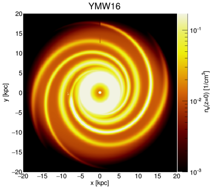
Model Variations

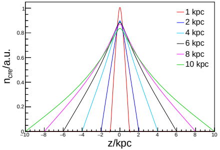
8 variations (subset giving the greatest diversity of CR deflection predictions):

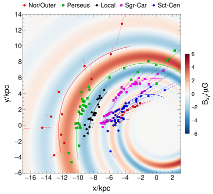
name	variation	χ^2/ndf
base	fiducial model	1.22
xr	radial dependence of X-field	1.30
spur	replace grand spiral by local spur (Orion arm)	1.23
ne	change thermal electron model (NE2001 instead of YMW16)	1.19
twist	unified halo model via twisted X-field	1.26
nbcorr	n_e-B correlation	1.22
cre	cosmic-ray electron vertical scale height	1.22
syn	use CosmoGlobe synchrotron maps	1.50



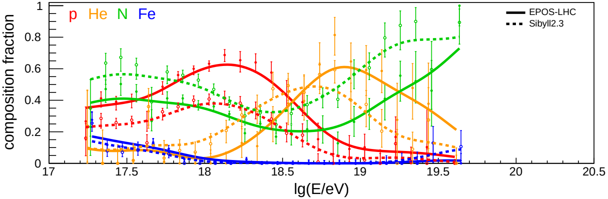


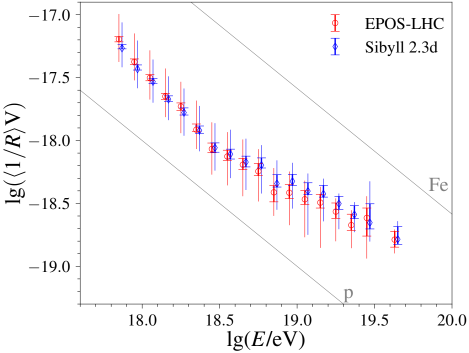


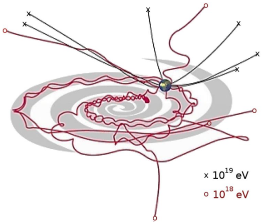




Cosmic-Ray Deflections







D. Harari

- Larmor radius of charged particle in B-field

$$r = 1.1\,\mathrm{kpc}\,\frac{R/10^{18}\,\mathrm{V}}{B/\mu\mathrm{G}}$$

- rigidity

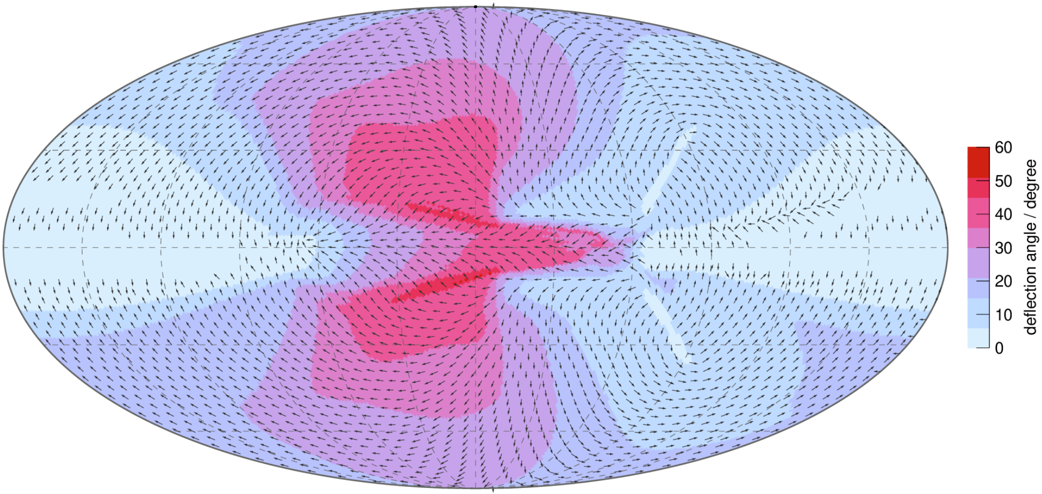
$$R = \frac{cp}{eZ} \overset{e=c=1}{=} \frac{E}{Z}$$

- typical GMF deflections (JF12)

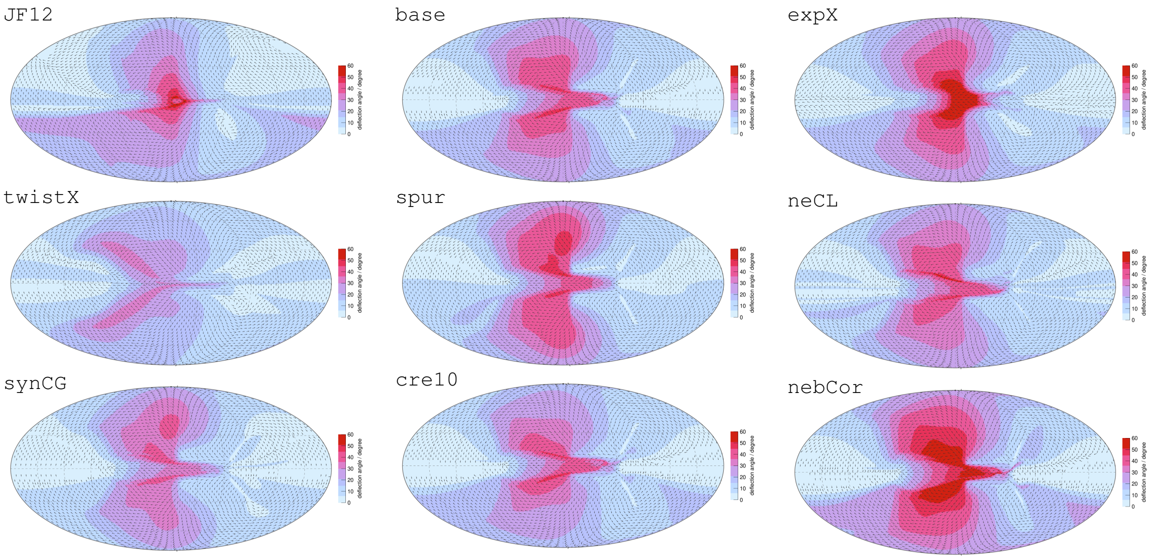
$$\theta_{\text{coh}} \sim 3^\circ \left(\frac{R}{10^{20}\,\mathrm{V}}\right)^{-1}$$

Pierre Auger Coll. 2014, O. Tkachenko for Snowmass 2205.05845

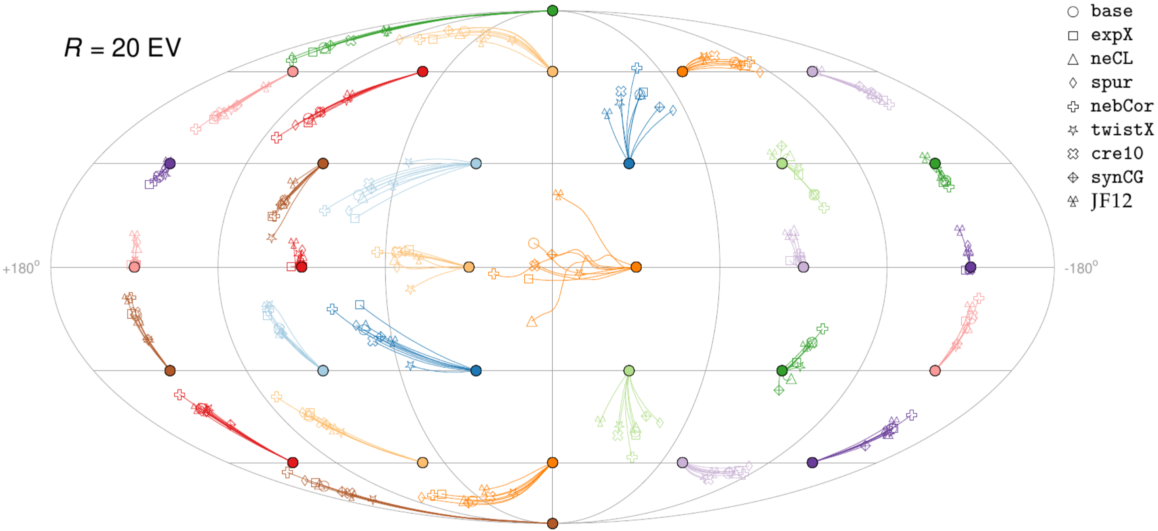
Deflections at 20 EV (base model) (backtracking)



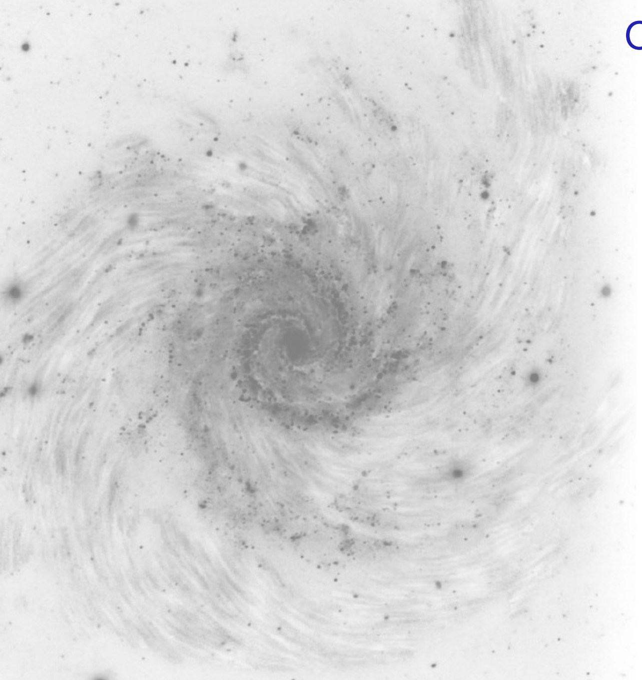
Deflections at 20 EV (model ensemble and JF12) (backtracking)



Deflections at 20 EV (backtracking)



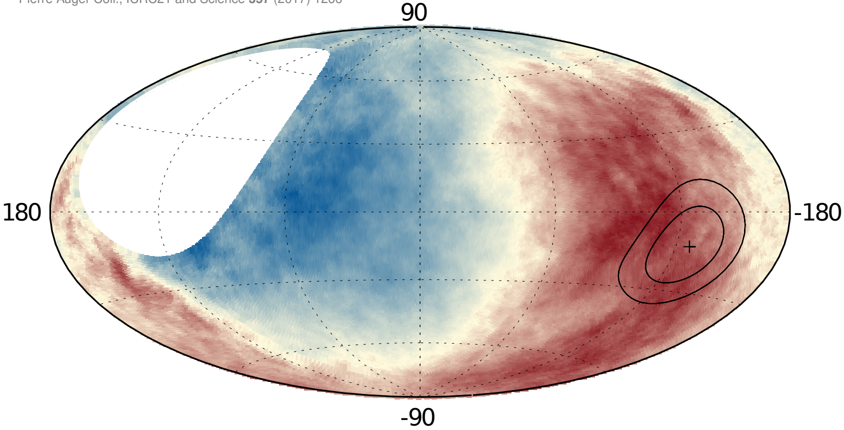
Outline

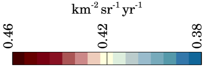


- Galactic Magnetic Field
- **Origin of the UHE Dipole**
- Origin of the Amaterasu Particle

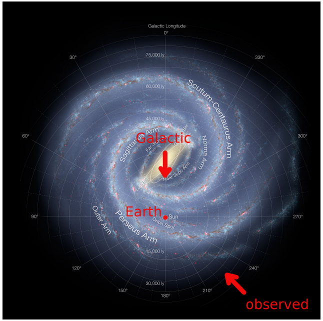
Dipolar Anisotropy of UHECRs (E> 8 EeV) – Galactic Origin?

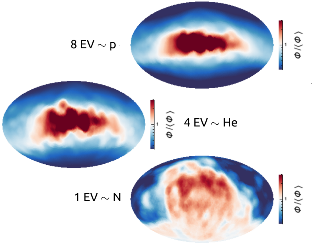
Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266





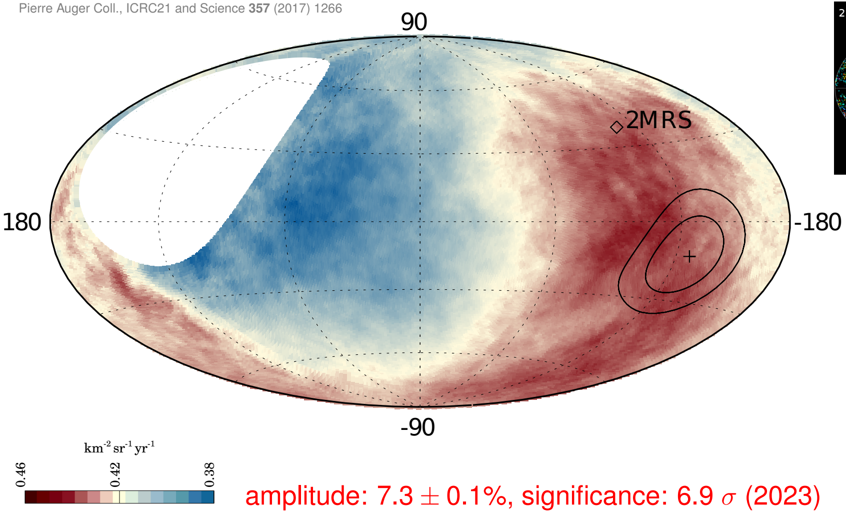
amplitude: 7.3 $\pm$ 0.1%, significance: 6.9 σ (2023)

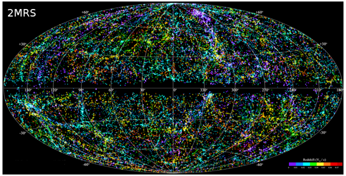




Dipolar Anisotropy of UHECRs (E$>$ 8 EeV) – Extragalactic Origin?

Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266

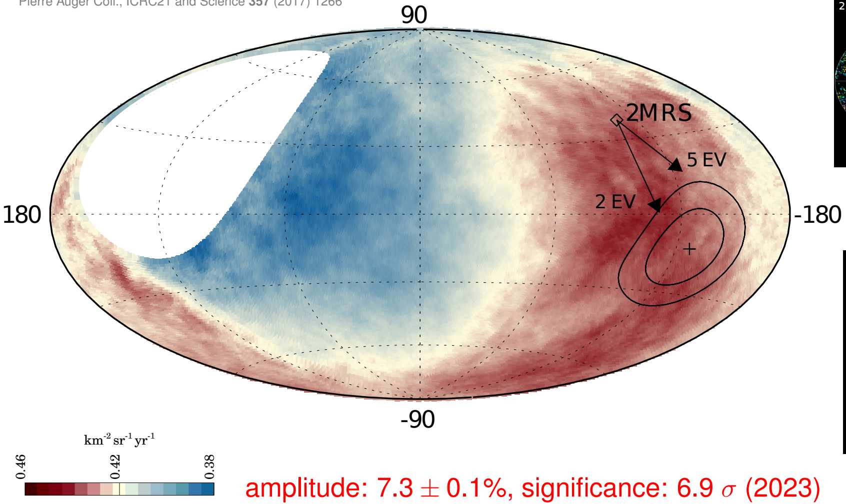


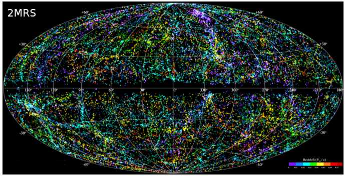


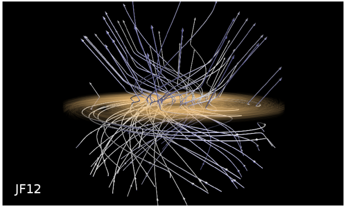
amplitude: 7.3 $\pm$ 0.1%, significance: 6.9 σ (2023)

Dipolar Anisotropy of UHECRs (E> 8 EeV) – Extragalactic Origin?

Pierre Auger Coll., ICRC21 and Science **357** (2017) 1266



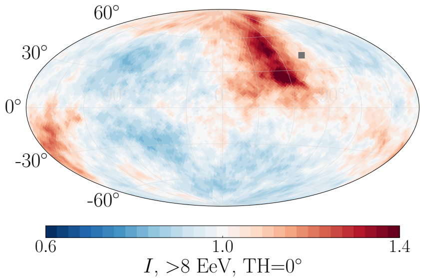




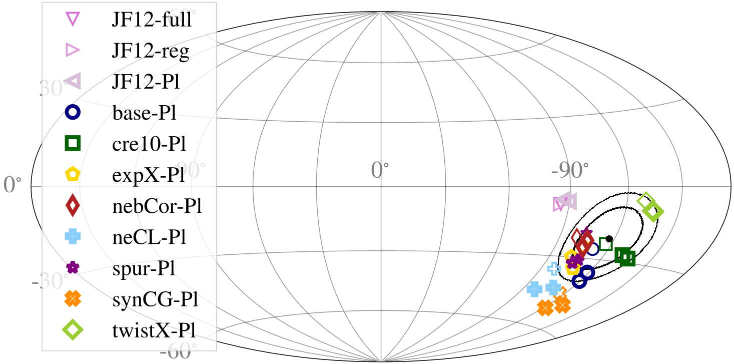
amplitude: 7.3 $\pm$ 0.1%, significance: 6.9 σ (2023)

Compatibility of UHE Dipole with Large-Scale Structure and GMF

extragalactic "illumination"



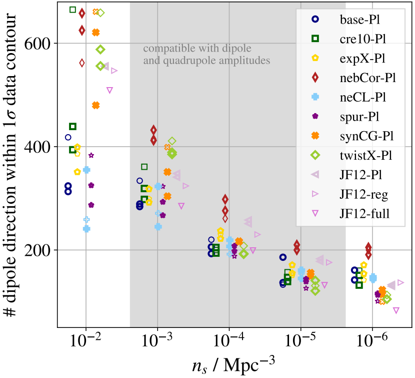
Bister, Farrar, MU in prep., see also Globus+18, Ding+21, Bister+24



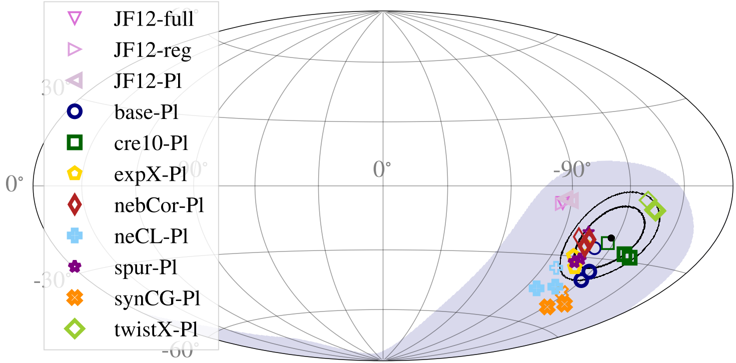
Compatibility of UHE Dipole with Large-Scale Structure and GMF

compatibility of direction vs. source density

Bister, Farrar, MU in prep., see also Globus+18, Ding+21, Bister+24

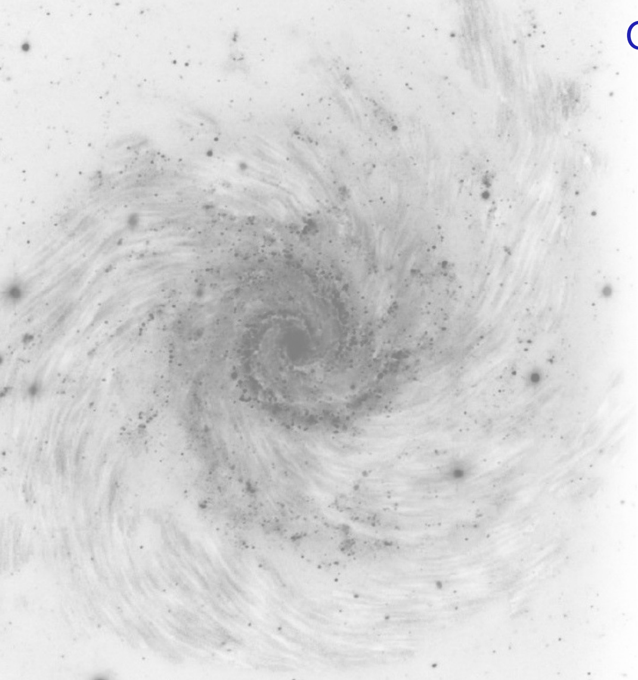


1000 realizations



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

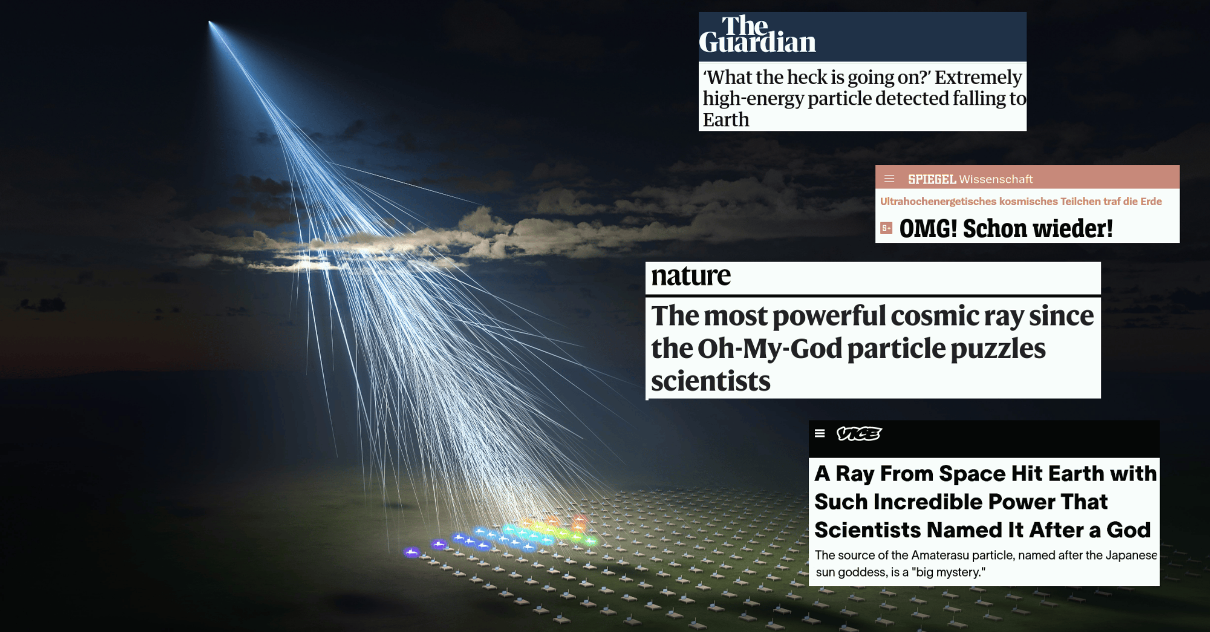
dipole, LSS and GMF compatible if 10^{-5} Mpc^{-3} $\lesssim n_s \lesssim 10^{-3}$ Mpc^{-3} (assuming EGMF negligible)



Outline

- Galactic Magnetic Field
- Origin of the UHE Dipole
- **Origin of the Amaterasu Particle**

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."

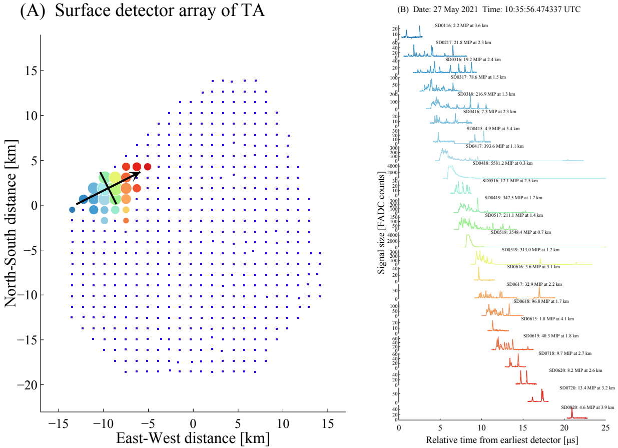
Science

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

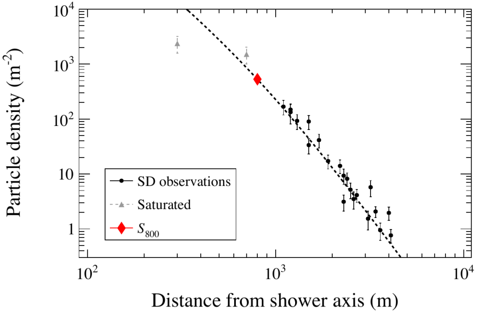
RESEARCH ARTICLE | ASTROPARTICLE PHYSICS

An extremely energetic cosmic ray observed by a surface detector array

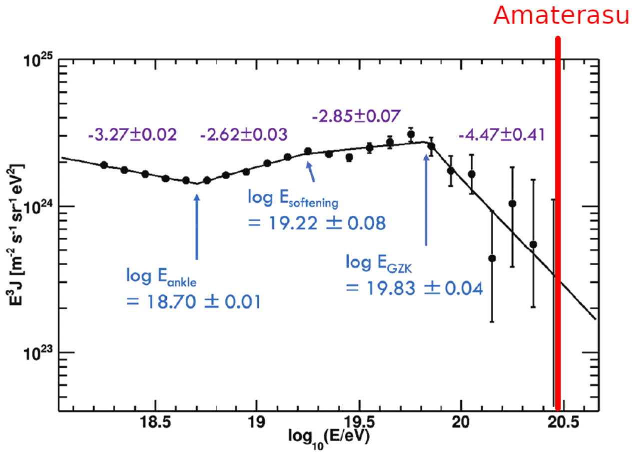
TELESCOPE ARRAY COLLABORATION*†, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL



- $E = \left(2.44 \pm 0.29\,(\text{stat.})\,^{+0.51}_{-0.76}\,(\text{syst.})\right) \times 10^{20}$ 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



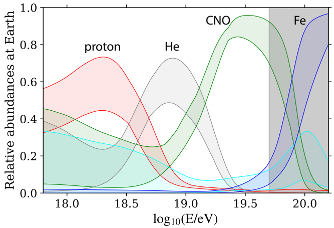
Simplest Assumption: Fe Nucleus from Standard Accelerator ($\mathcal{R}_{\text{max}} \sim 10^{18.6-18.7}$ V)



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

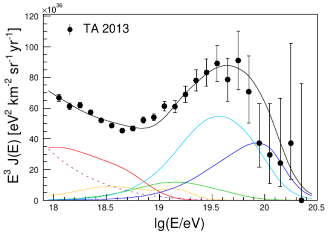
... or ultra-heavy nuclei? G.F. Farrar arXiv:2405.12004 and B.T. Zhang et al arXiv:2405.17409

Peters Cycle:



Pierre Auger Coll. 2023

Photodisintegration in source:

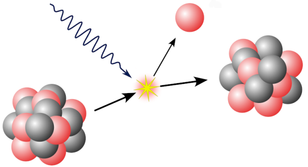


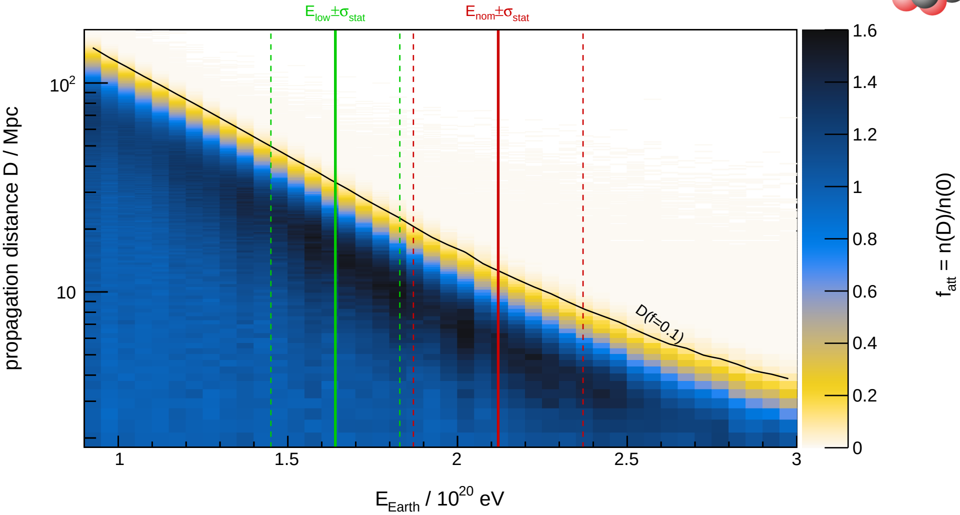
(c) Flux at Earth

MU, Farrar, Anchordoqui PRD15

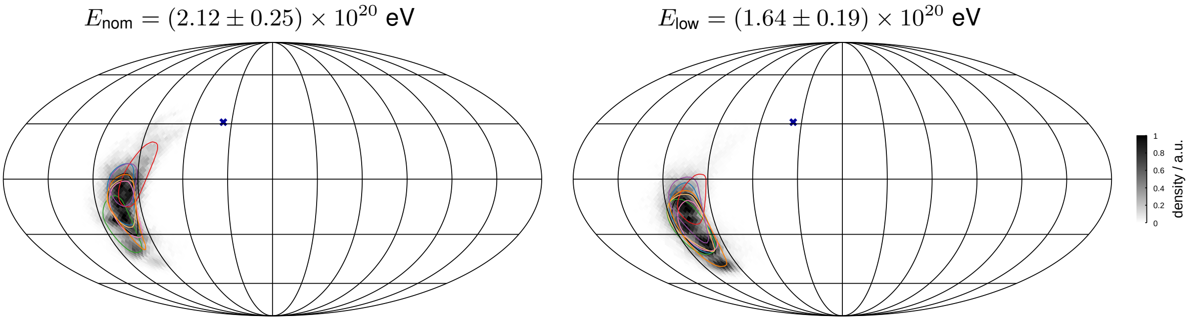
Propagation of Fe in Extragalactic Photon Fields

- horizon between 8 and 50 Mpc





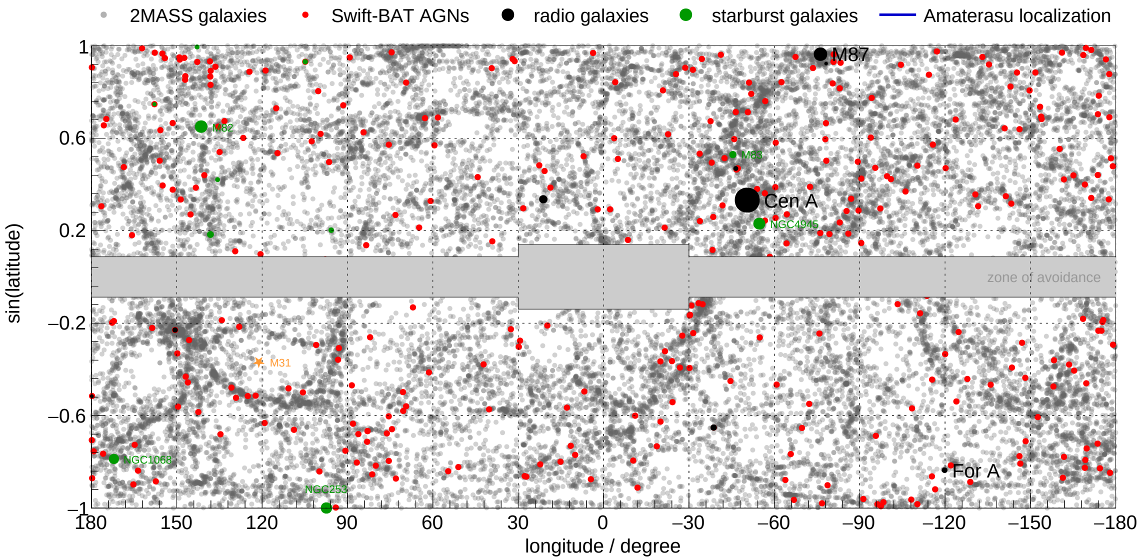
Arrival Direction



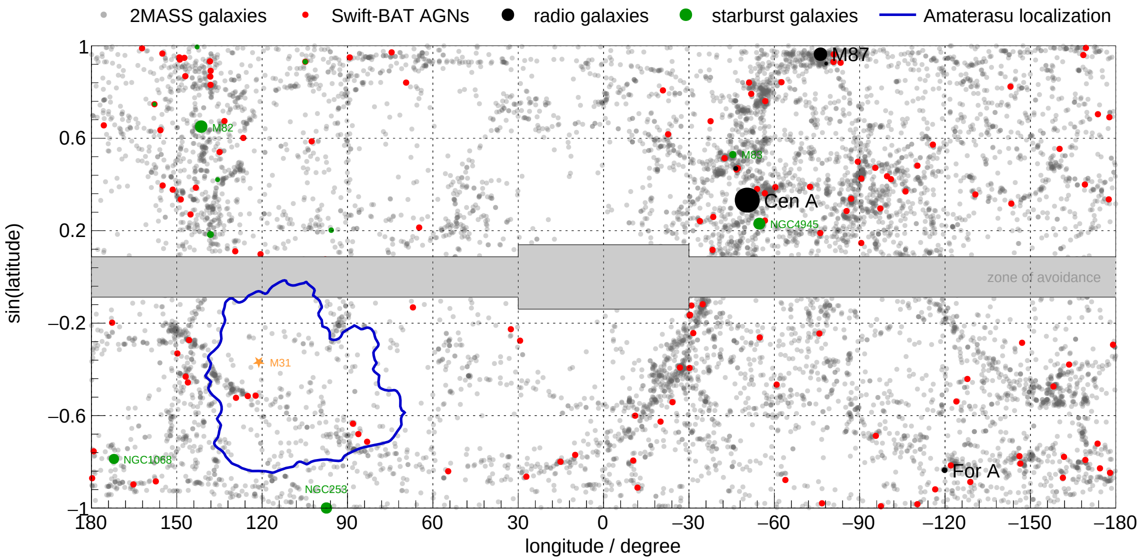
localization uncertainty: 6.6% of 4π or 2726 deg^2

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

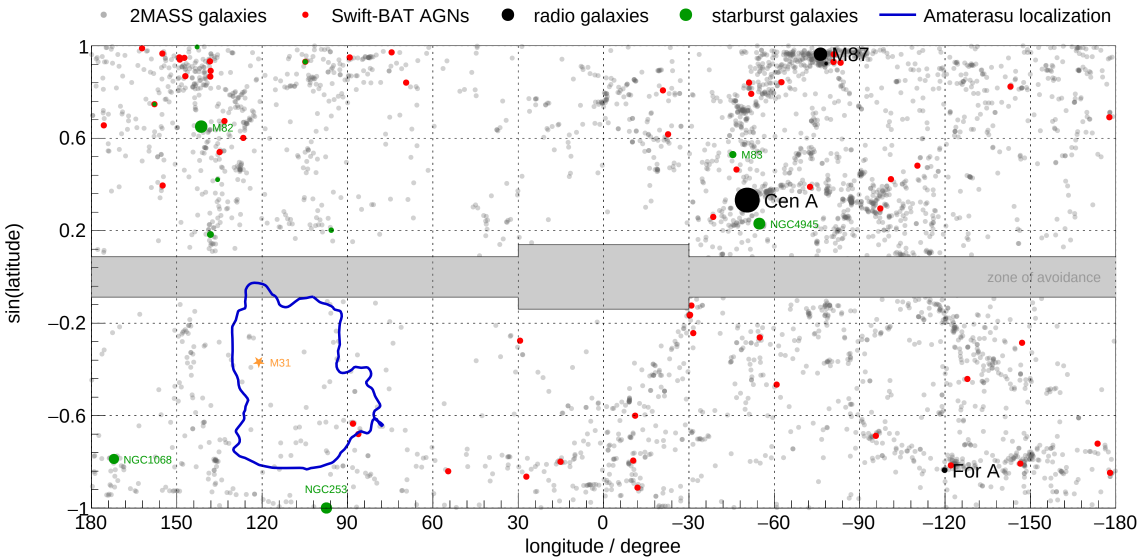
Distribution of galaxies up to D=150 Mpc



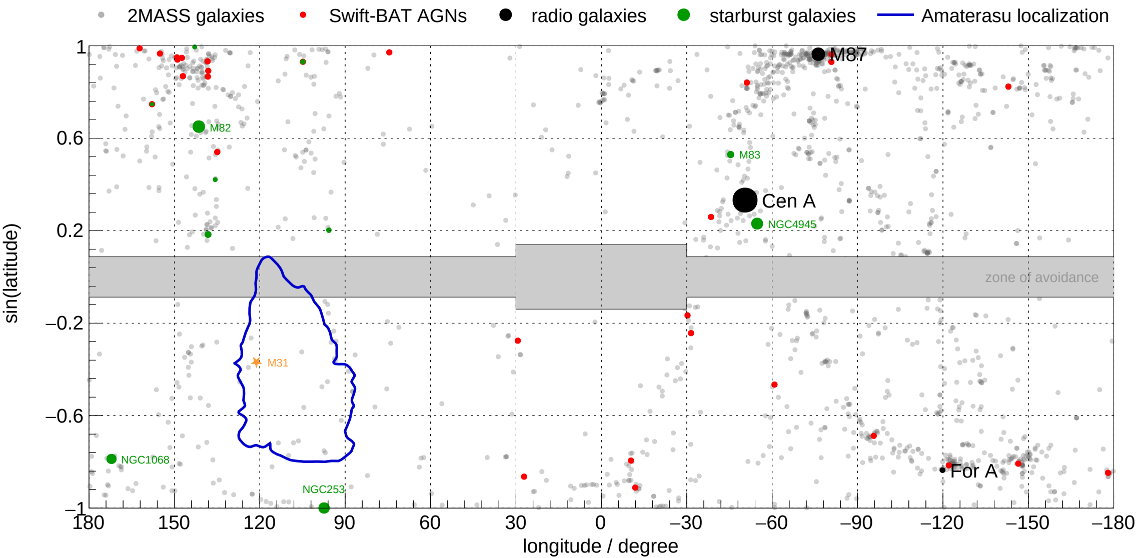
$E_{\text{low}} - 2\,\sigma$, $D_{0.1}$=72 Mpc



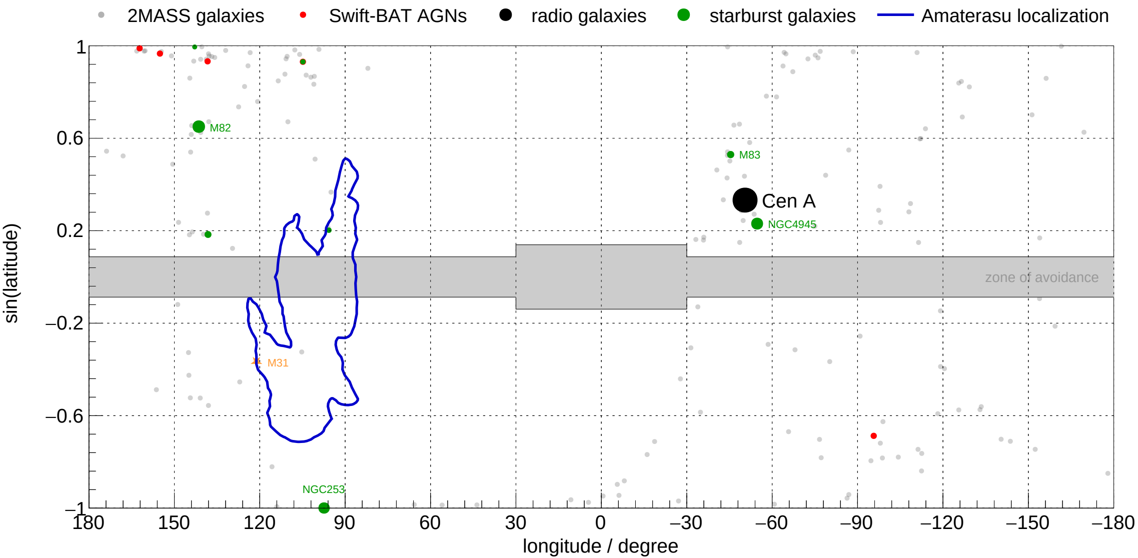
$E_{\text{low}} - 1\,\sigma$, $D_{0.1}$=42 Mpc

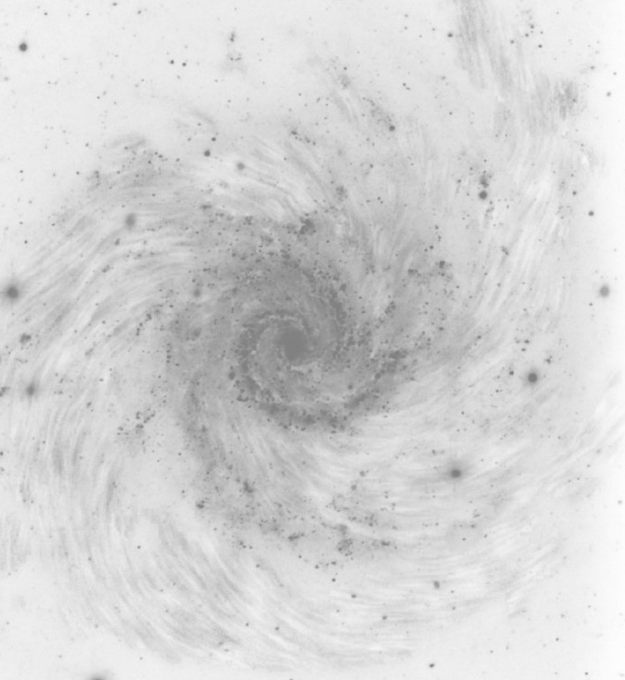


E_{low}, $D_{0.1}$=25 Mpc



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





Conclusions

Galactic Magnetic Field

- deflects arrival directions of UHECRs
- new analysis of coherent magnetic field
  - improved parametric models
  - full-sky RM data
  - synchrotron from WMAP, Planck
  - variation of thermal electron models
  - variation of cosmic-ray electron models
  - striation vs. n_e-b correlations
- model ensemble bracketing uncertainties

Application to UHE Dipole

- consistent with deflected large-scale structure

Application to UHE Amaterasu Particle

- localization uncertainty 6.6% of 4π
- horizon between 8 and 50 Mpc
- none of the “usual suspects” within loc. uncert.
- transient in an otherwise undistinguished galaxy?