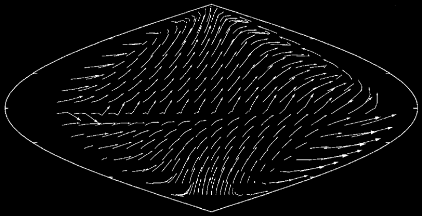
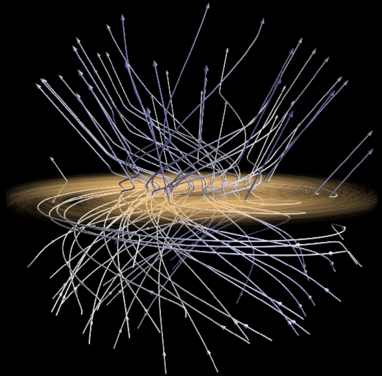
News from the Galactic Magnetic Field
(...and the Origin of the Amaterasu Particle)

M. Unger (KIT) in collaboration with G.R. Farrar (NYU)

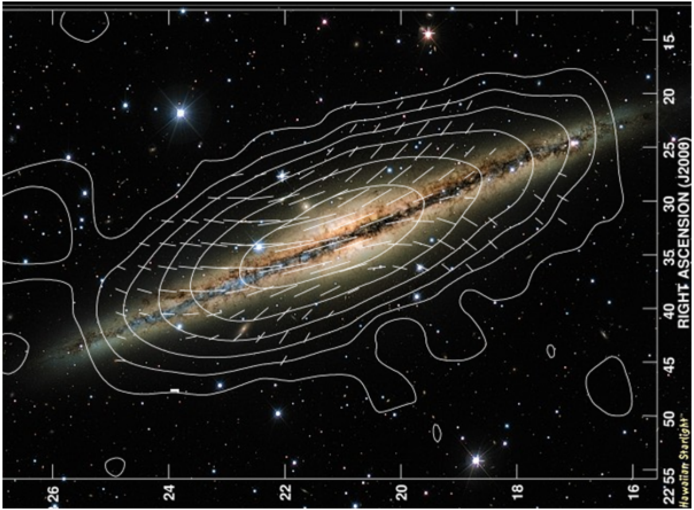




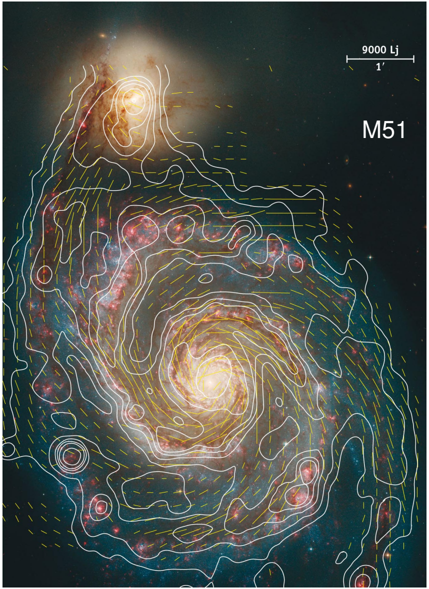
NGC628 M. Krause 2019; T. Stanev ApJ97; JF12 Farrar&Sandstrom

Astro & Theory Seminar, NTNU, Feb 06th 2024

Galactic Magnetism



NGC891, M. Krause MPIfR



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

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

Proto-Galactic?

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

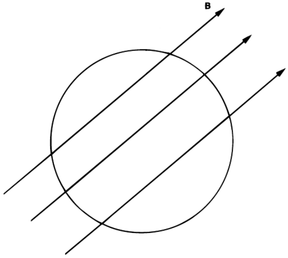


FIG. 1*a*

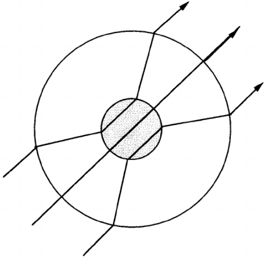
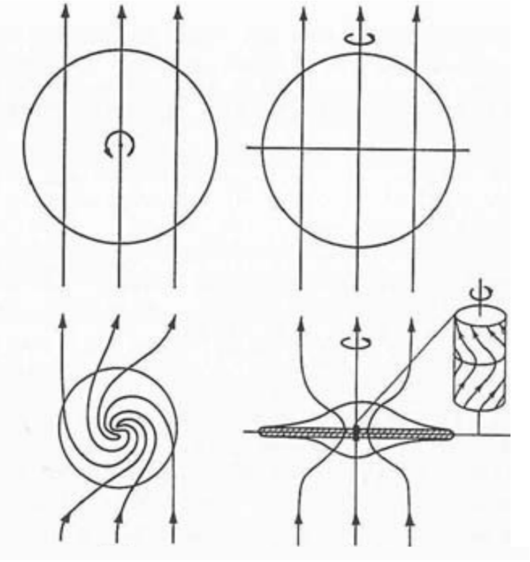


FIG. 1*b*

Howard&Kulsrud A&A 1990

shearing by differential rotation

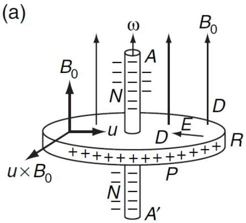


Sofue 1990

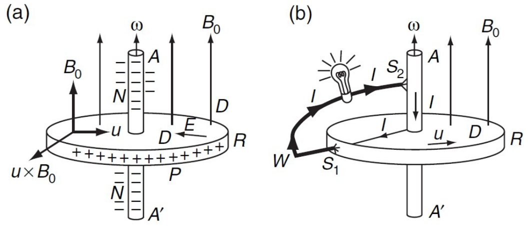
but:

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

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

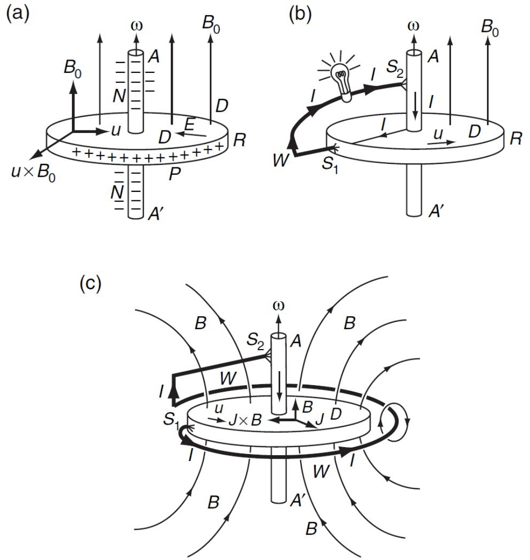


Dynamo Action? “$B_0 + E_{\text{kin}} \to B_1 > B_0$”



P.H. Roberts (2007)

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



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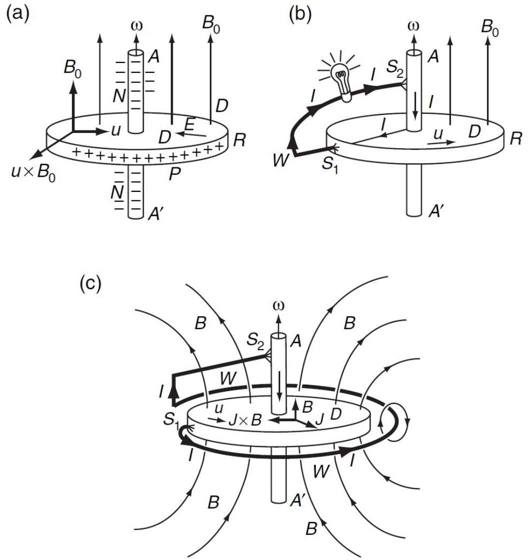
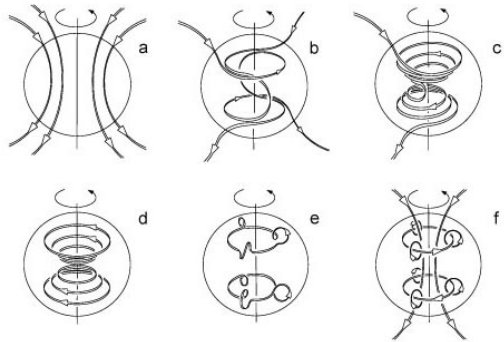


P.H. Roberts (2007)

Ω effect: toroidal field from poloidal seed field

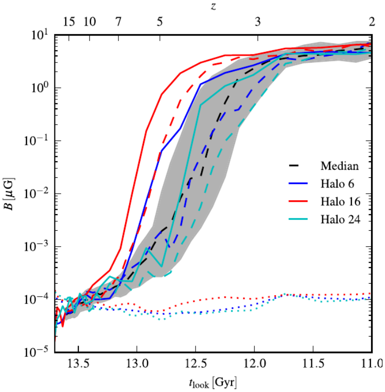


Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

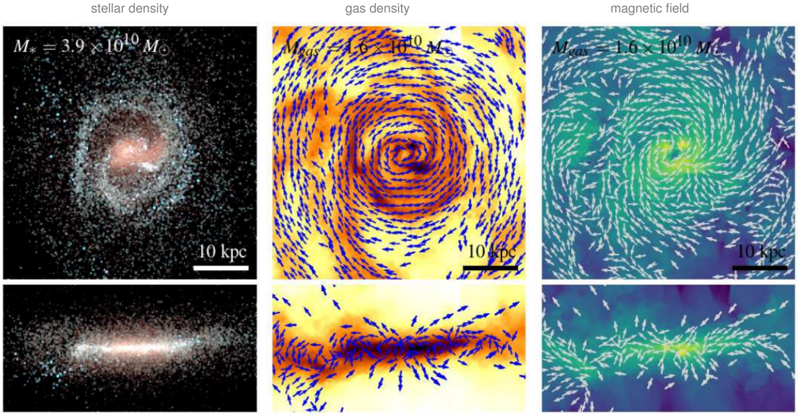
α effect: poloidal field from turbulence and convection

Dynamo Action?

Galaxy simulations:



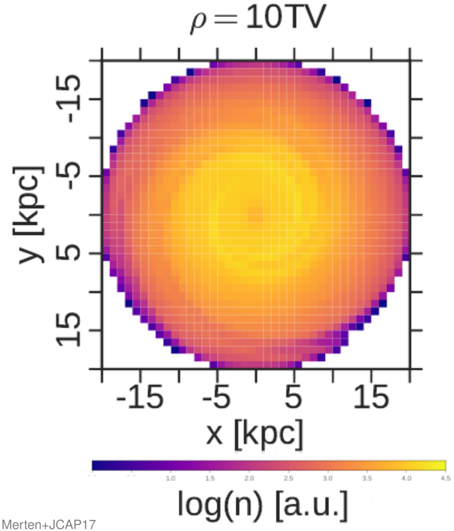
Auriga, Pakmor+MNRAS17



IllustrisTNG, Marinacci+MNRAS17

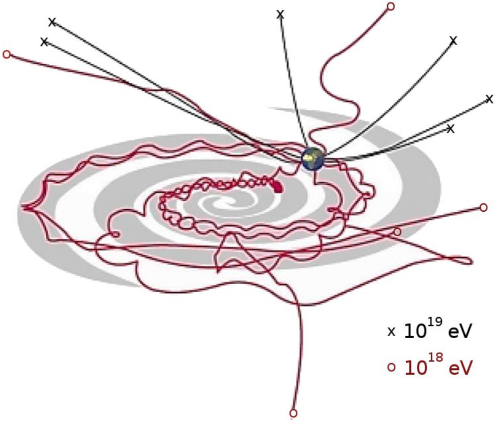
Effect Galactic Magnetic Field on Charged Particles (Cosmic Rays)

(anisotropic) diffusion of low energy cosmic rays



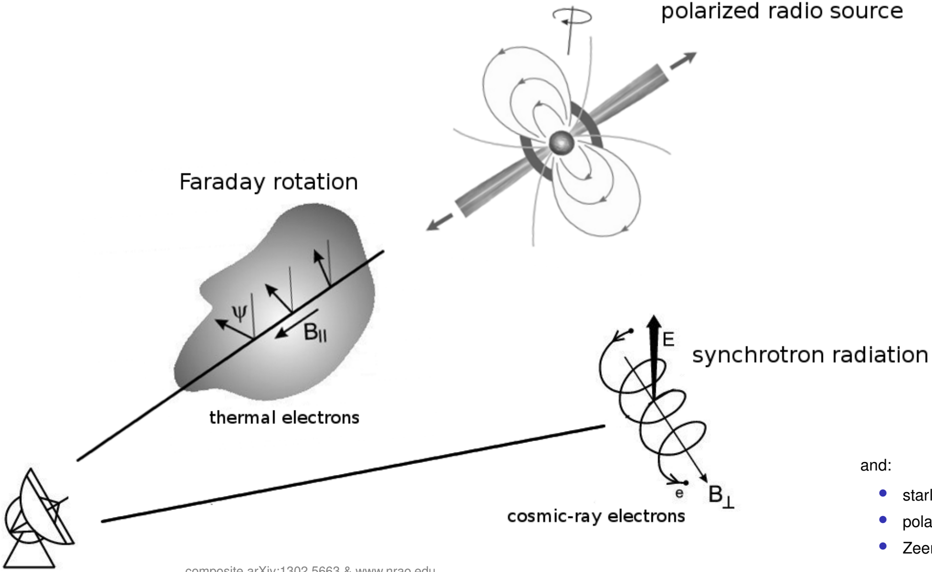
Merten+JCAP17

deflection of ultrahigh-energy cosmic rays



D. Harari

Observational Tracers of the Astrophysical Magnetic Fields



and:

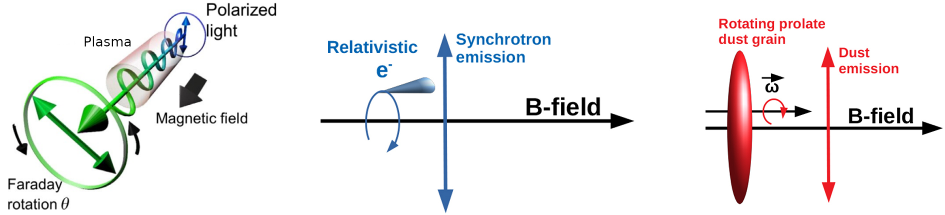
- starlight polarization
- polarized dust emission
- Zeeman effect

composite arXiv:1302.5663 & www.nrao.edu

Modeling the Coherent Galactic Magnetic Field (GMF)

Aim: Describe large-scale structure of GMF with simple parametric forms

Observables:



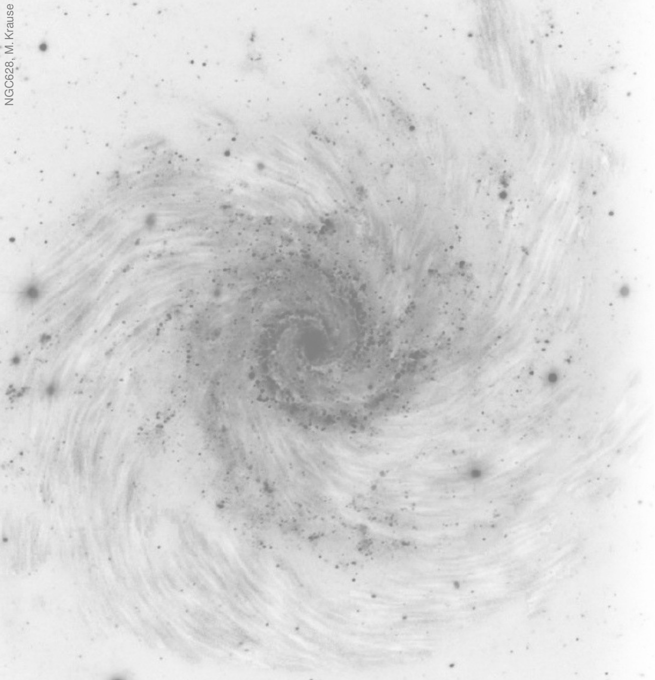
adapted from Hasegawa+13 and Pelgrims+18

Popular GMF Models:

	S97	Jaffe10*	PT11	JF12	Planck16	TF17**
parameter fit	✗	✓	✓	✓	✗	✓
extragalactic RMs	✗	✓	✓	✓	✗	✓
polarized synchrotron	✗	✓	✗	✓	✓	✗
polarized dust	✗	✗	✗	✗	✓	✗
$\nabla \mathbf{B} = 0$	✗	✗	✗	✓	✗	✓

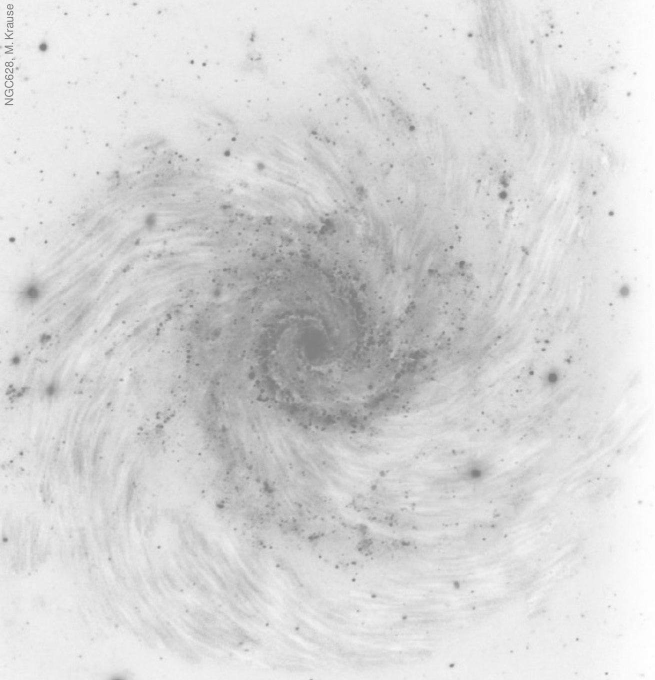
Stanev ApJ97, Jaffe+ MNRAS10, Pshirkov+ ApJ11, Jannsson&Farrar ApJ12, Planck Coll. A&A16, Terral&Ferriere A&A17

* only disk field ** Galactic plane excluded ($|b| > 10^\circ$)



Outline

- **RM and Synchrotron Data**
- **Thermal & CR Electrons**
- **New GMF Model(s)**
- **Results and Implications**
- **(Amaterasu Particle)**



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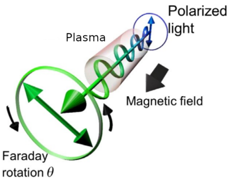
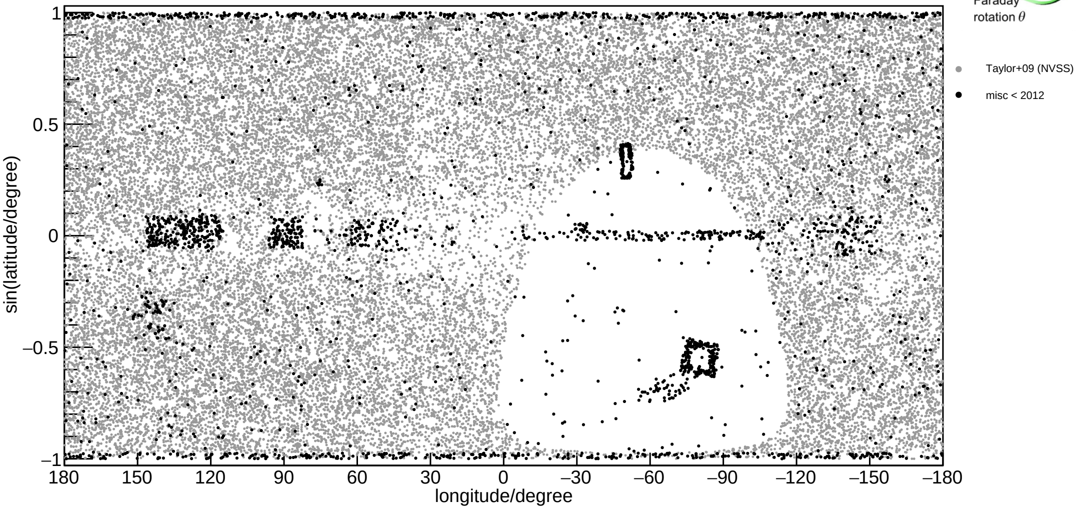
Extragalactic Rotation Measures (PT11, JF12)

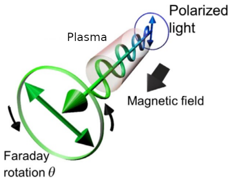
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

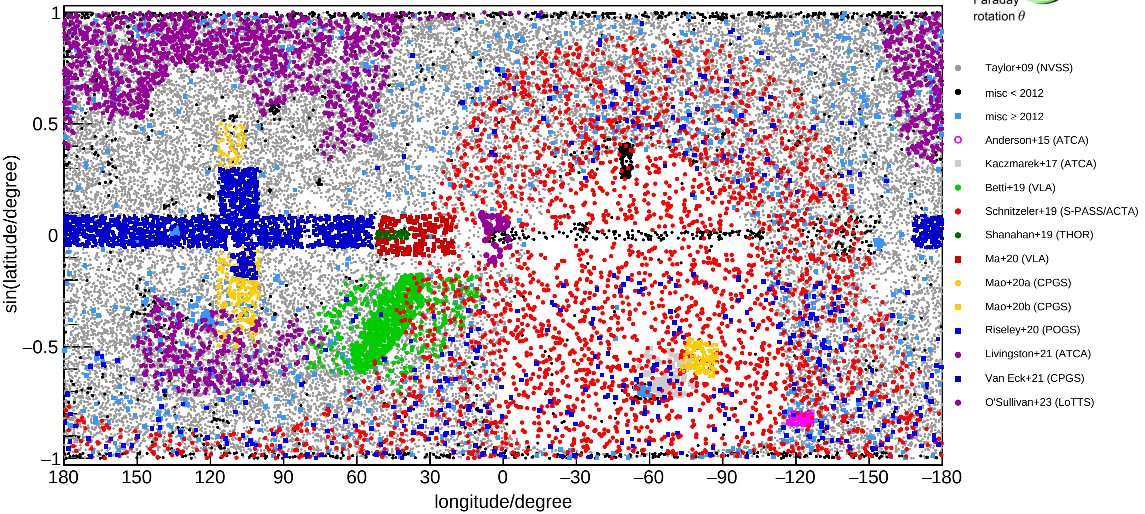




Extragalactic Rotation Measures 2023

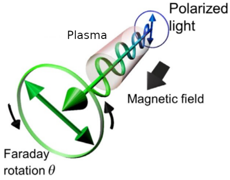
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

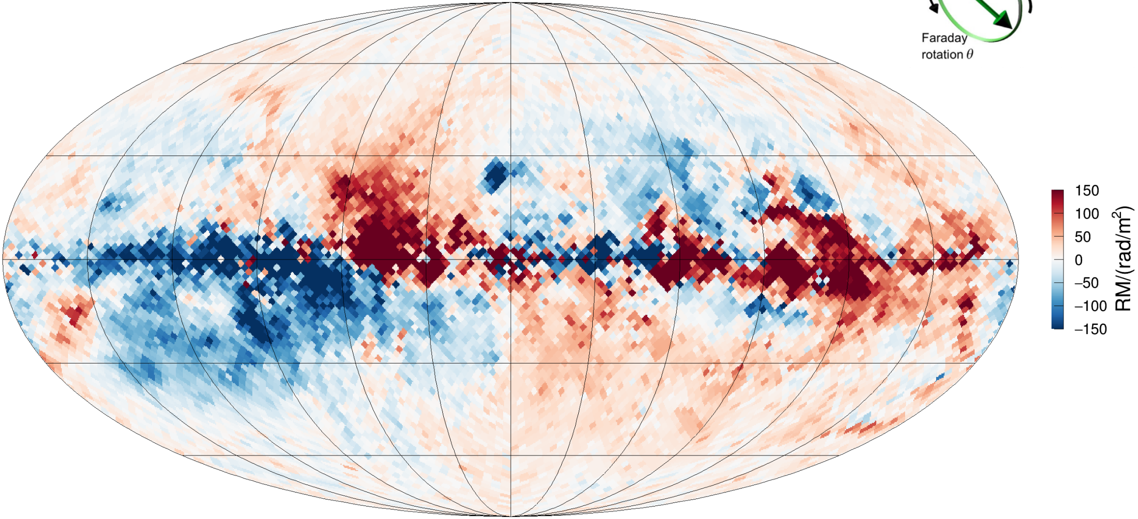




2023 RM Sky

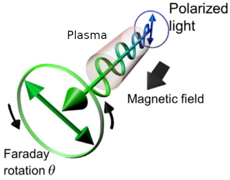
$$\mathrm{RM} \propto \int_{\text{source}}^{\text{observer}} B_{\|}(l)\, n_e(l)\, \mathrm{d}l$$

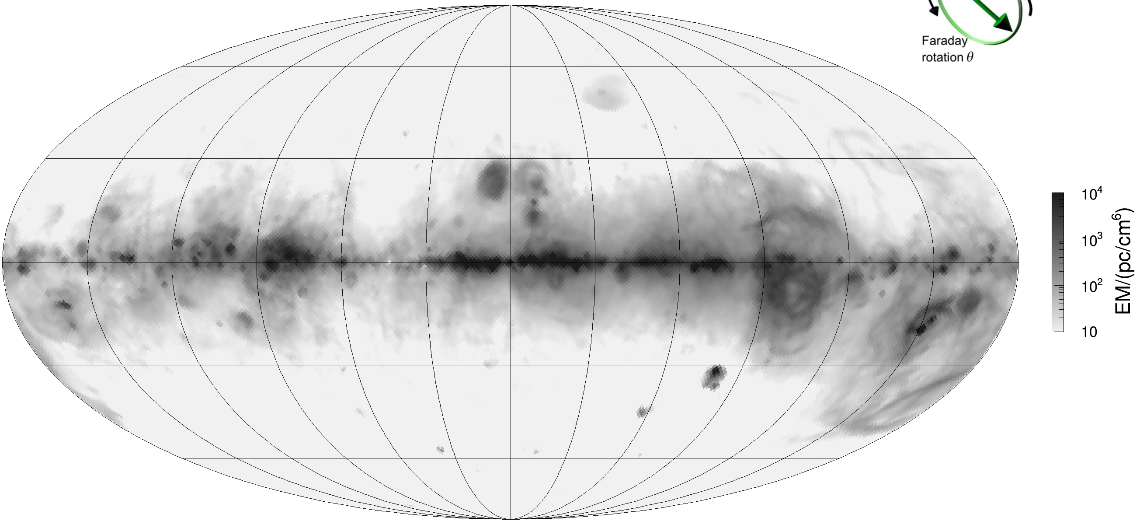




Foreground: HII Regions

$$\mathrm{EM} \propto \int_{\text{source}}^{\text{observer}} n_e(l)^2\,\mathrm{d}l$$





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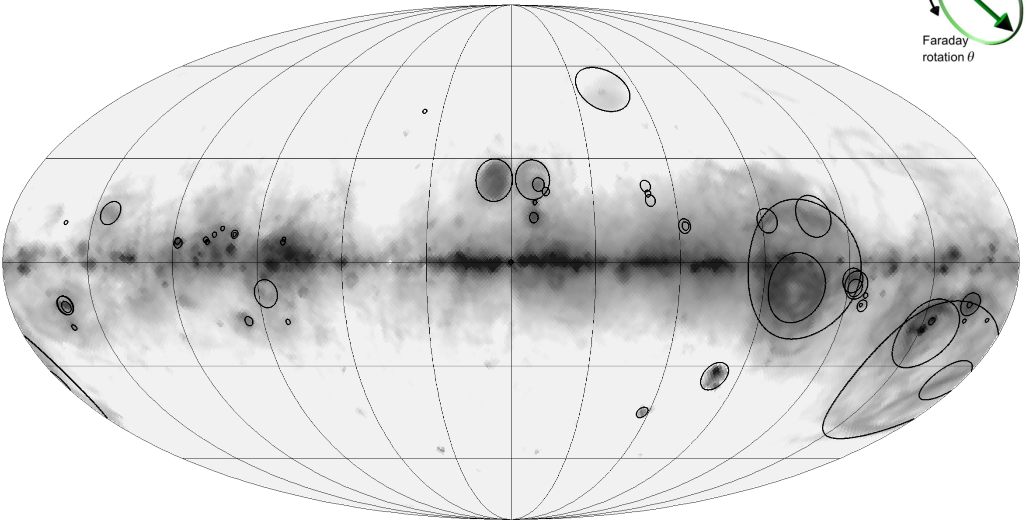
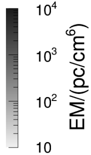
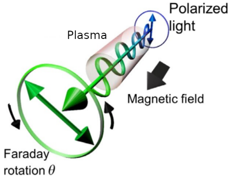
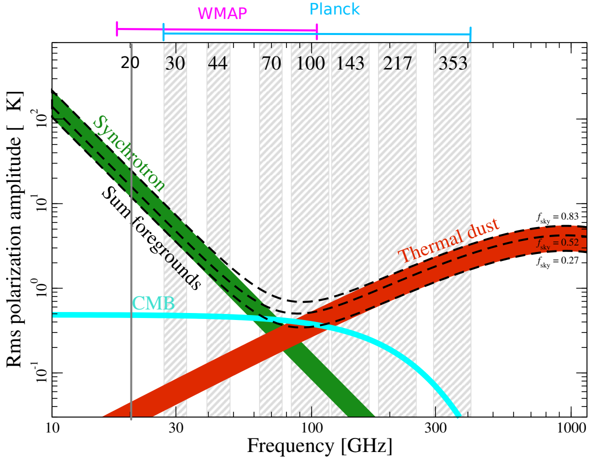
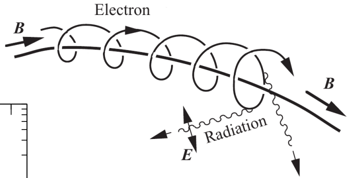






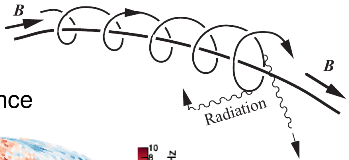
Polarized Synchrotron Emission

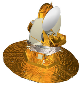




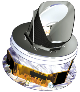
- antenna temperature: $T_{\text{syn}} \propto \nu^{-(p+3)/2} \equiv \nu^{\beta_S}$
- electron spectral index p: ~ 2 at source, ~ 3 after cooling
- $\beta_S \sim -3 \to T_{\text{syn}}(\text{20 Hz})/T_{\text{syn}}(\text{30 Hz}) \approx 3.4$

Polarized Synchrotron Emission





WMAP9



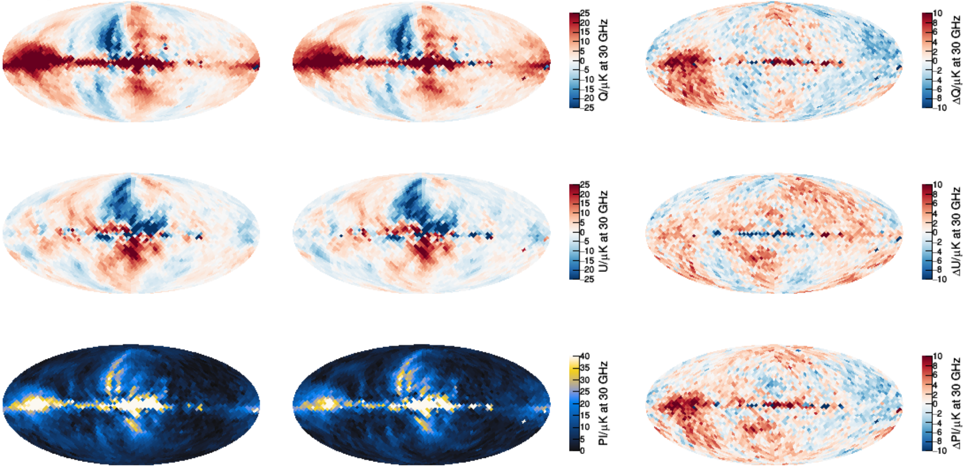
Planck R3.00

difference

Q

U

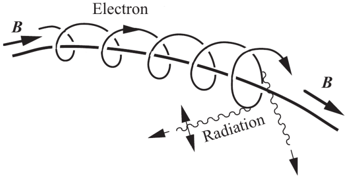
PI

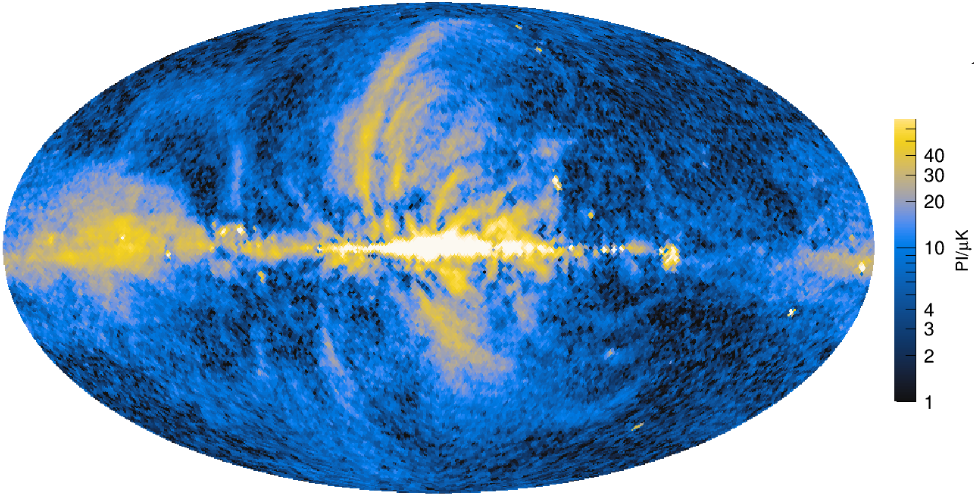


- Stokes Paramters
  $Q/U \propto \int B_\perp^2 \, n_{\mathrm{cre}} \, \mathrm{d}l$
- projected mag. angle
  $\psi = \frac{1}{2}\mathrm{atan}\left(\frac{U}{Q}\right) + \frac{\pi}{2}$
- polarized intensity:
  $\mathrm{PI}^2 = Q^2 + U^2$

calibration uncertainty? cosmic-ray spectral index?

Combined WMAP-Planck Polarized Emission





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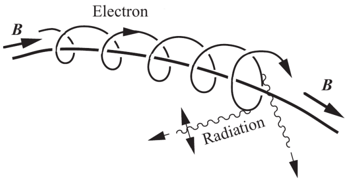

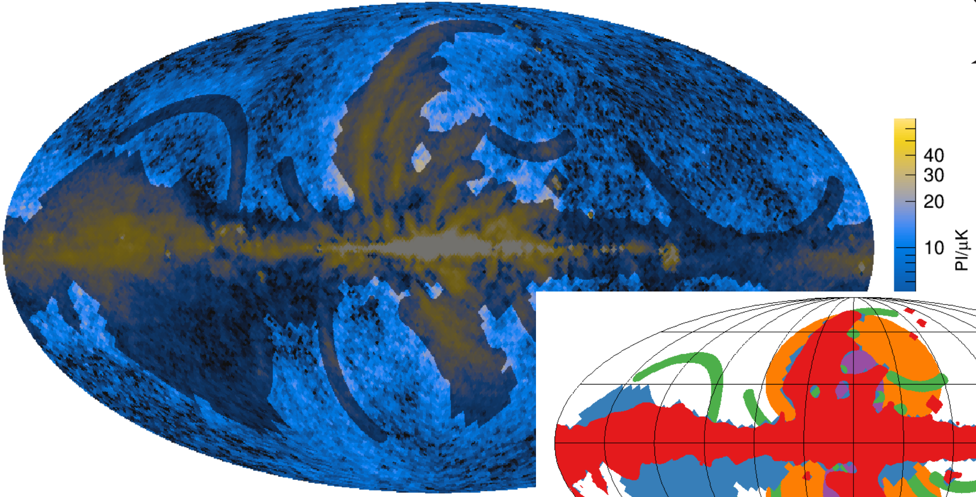

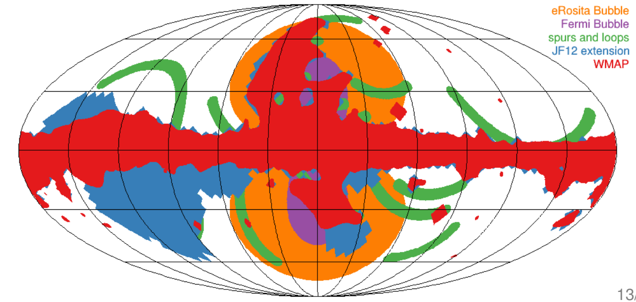

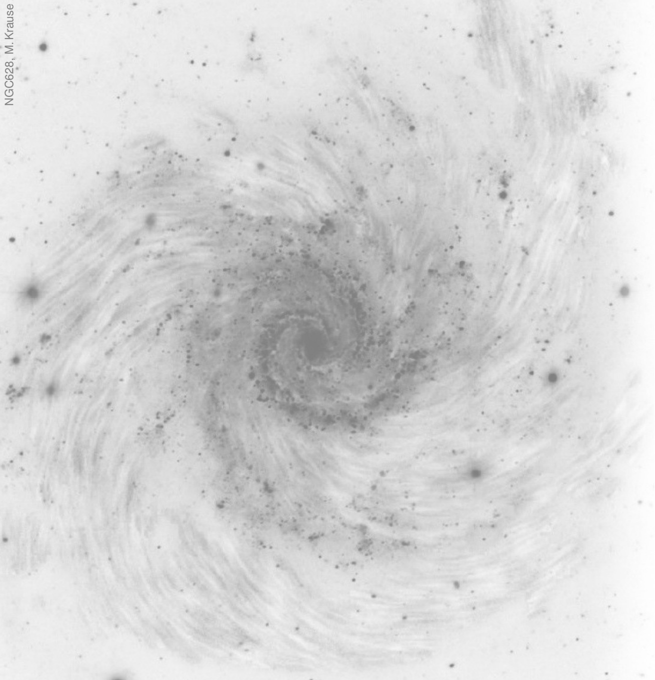

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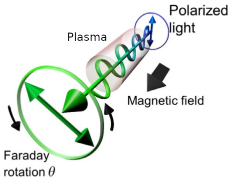
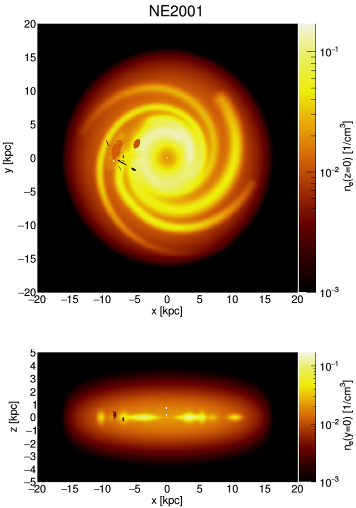
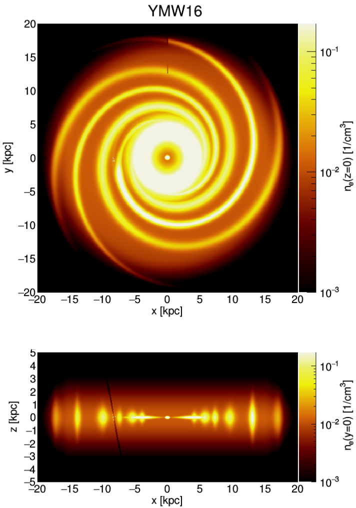
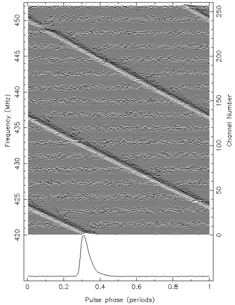
Thermal Electron Models

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









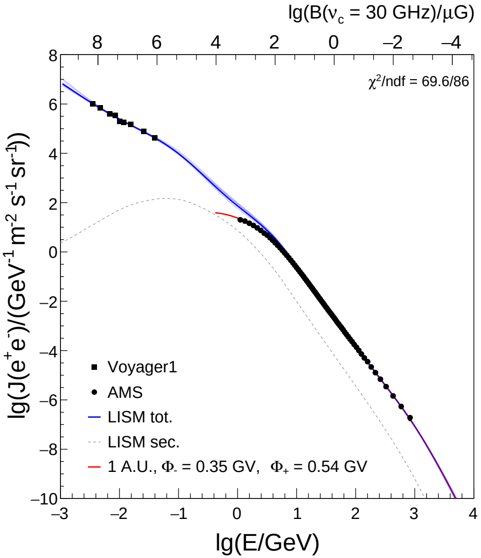
112 pulsar DMs

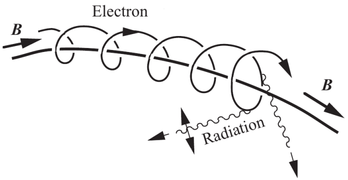
189 pulsar DMs

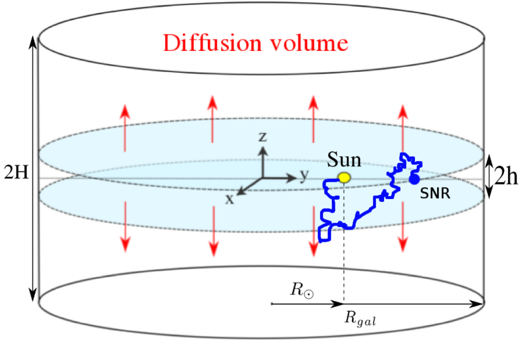
Cordes&Lazio arXiv:0207156

Yao, Manchester & Wang, ApJ 2017

Cosmic-Ray Electron Model







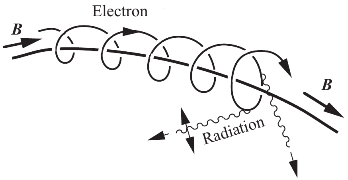
Y. Genolini et al, A&A. **580** (2015) A9

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

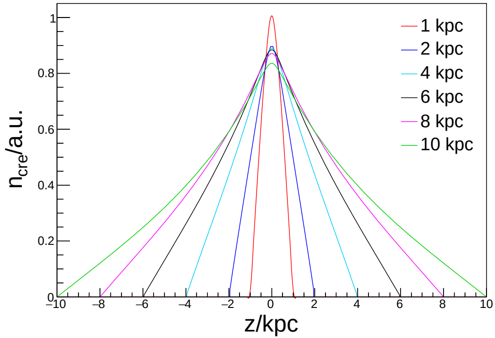
DRAGON calculation constrained by local lepton flux and D_0/H from B/C https://github.com/cosmicrays/DRAGON

Cosmic-Ray Electron Model

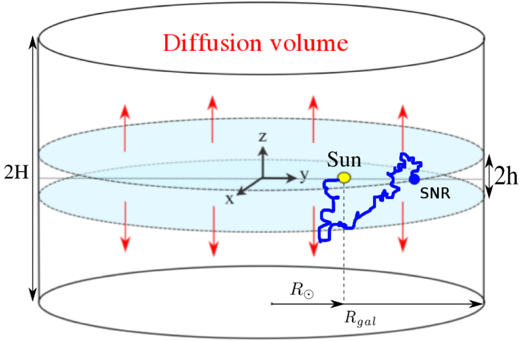
- $D_0/H = \mathrm{const}$ from B/C
- halo half-height H currently not well constrained Weinrich+20, Evoli+20, Maurin+22



$\rightarrow$ large uncertainty in vertical n_{cre} profile!



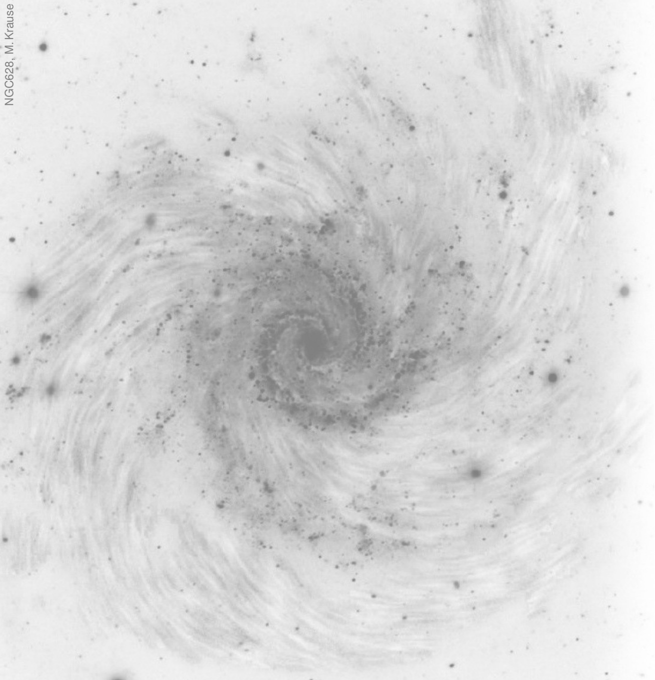
example: $r = 5\mathrm{kpc}$, $E = 10\mathrm{GeV}$



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

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

Outline



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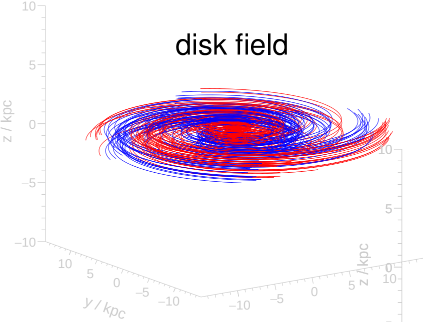
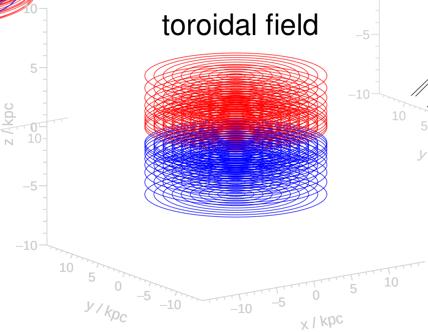
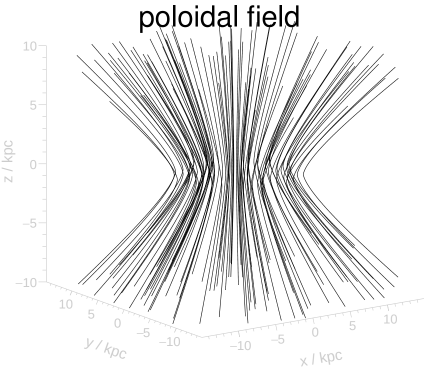
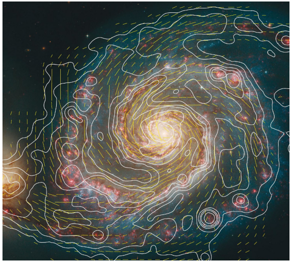
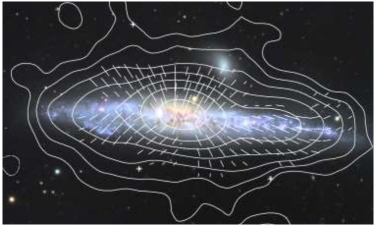
Parametric GMF Components





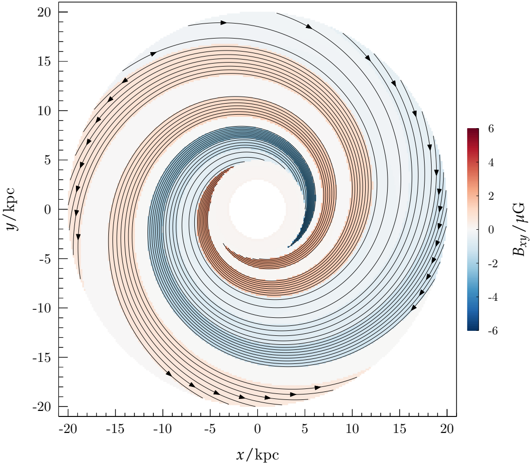




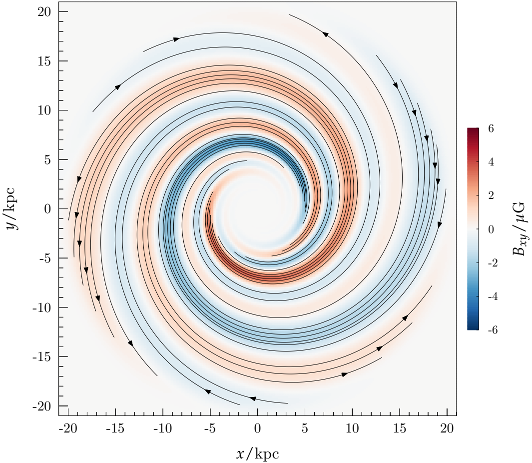


New Disk Field Model

previous “wedge”-model (e.g. JF12):

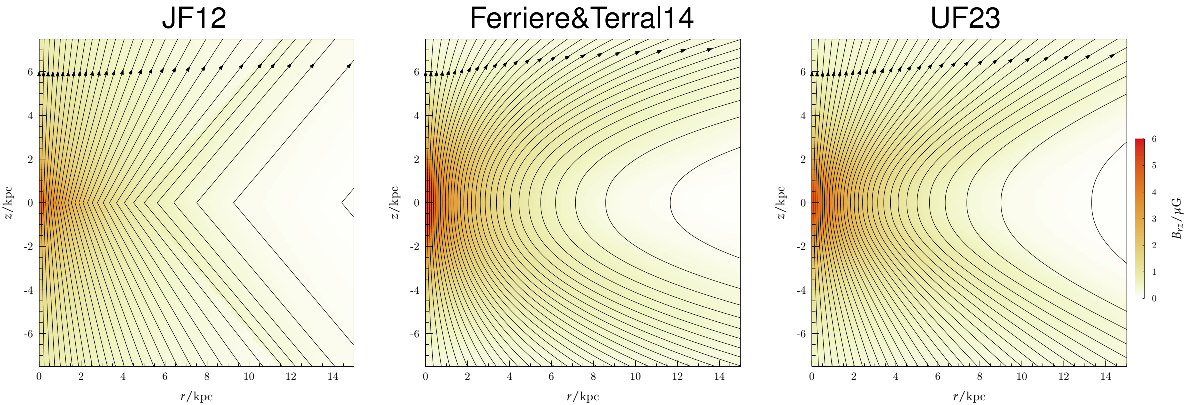


smooth spiral disk field:



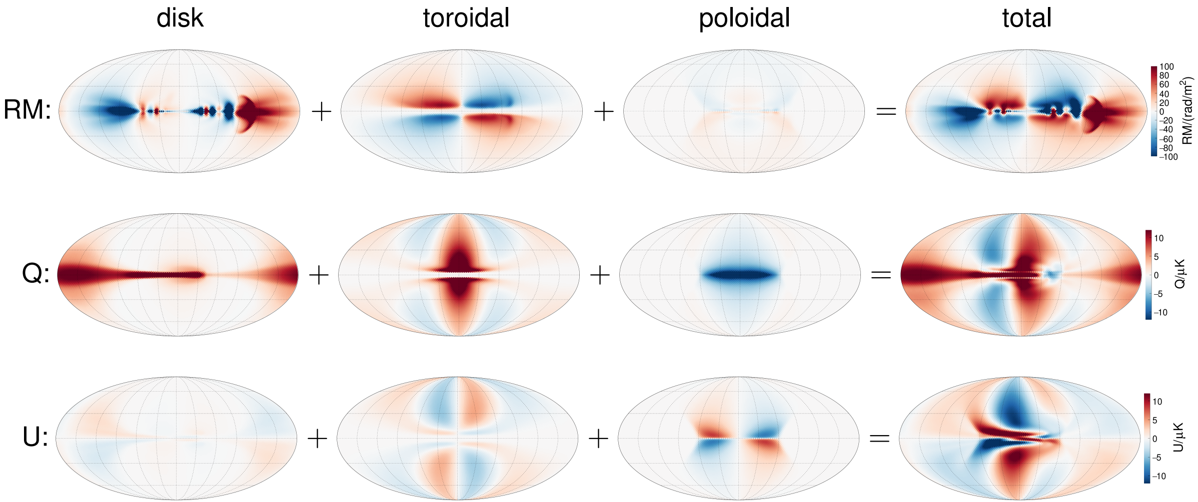
- divergence-free Fourier-expansion of $B_\phi(r)$ at reference radius
- avoids radial discontinuities
- free pitch angle and “magnetic arms” (number of Fourier modes)

Halo X-Field

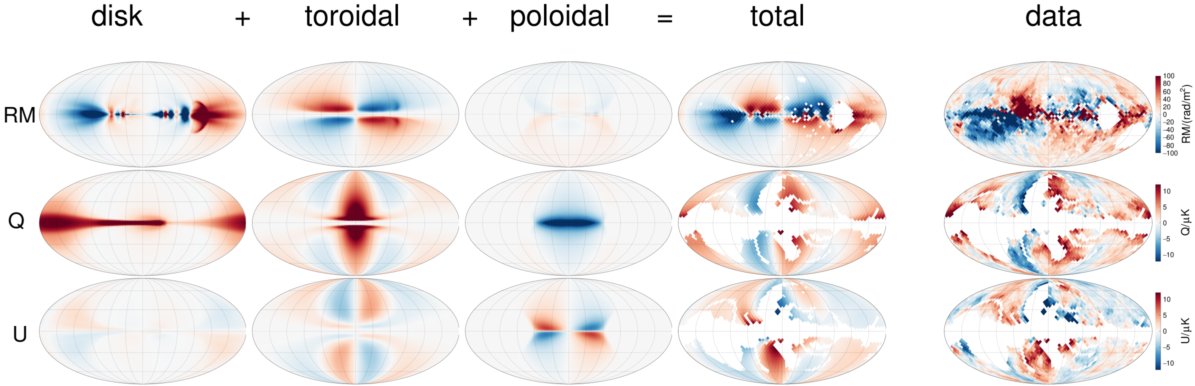


- fix JF12 discontinuities at $z = 0$ and transition to $\theta_X = 49°$

RM and Q&U of “base model”



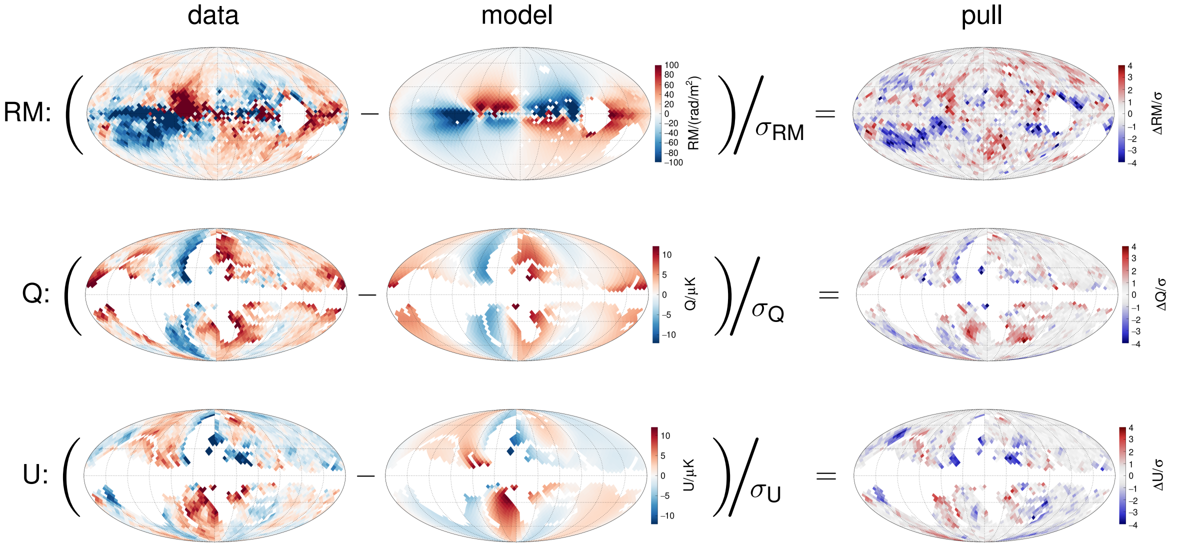
Data and Model



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

Data and Model

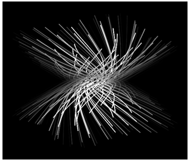
$$\chi^2/\mathrm{ndf} = 7923/6500 = 1.22$$

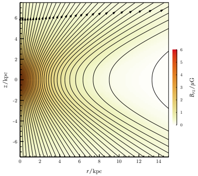


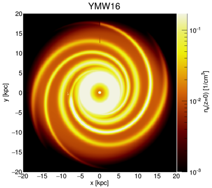
Model Variations

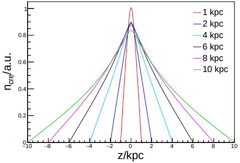
8 variations (subset giving the greatest diversity of CR deflection predictions):

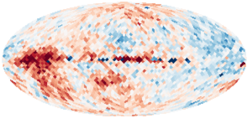
name	variation	χ^2/ndf
base	fiducial model	1.22
xr	radial dependence of X-field	1.30
spur	replace grand spiral by local spur (Orion arm)	1.23
ne	change thermal electron model (NE2001 instead of YMW16)	1.19
twist	unified halo model via twisted X-field	1.26
nbcorr	n_e-B correlation	1.22
cre	cosmic-ray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

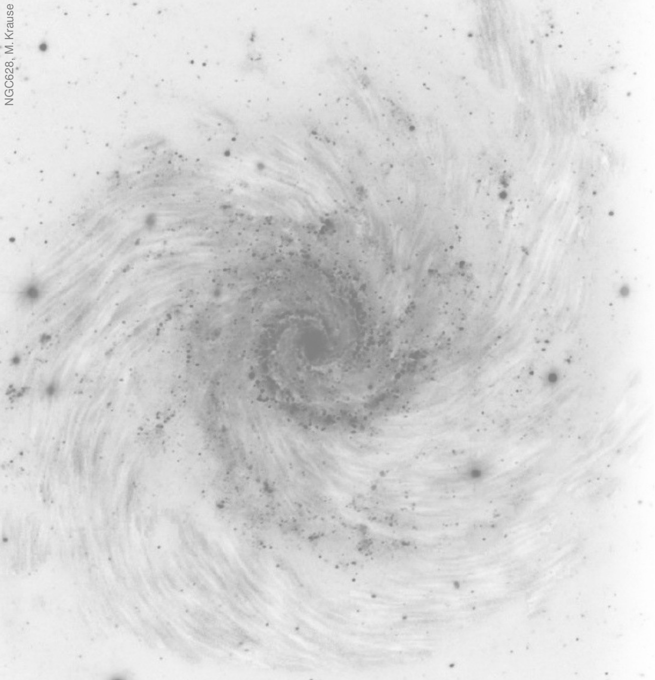












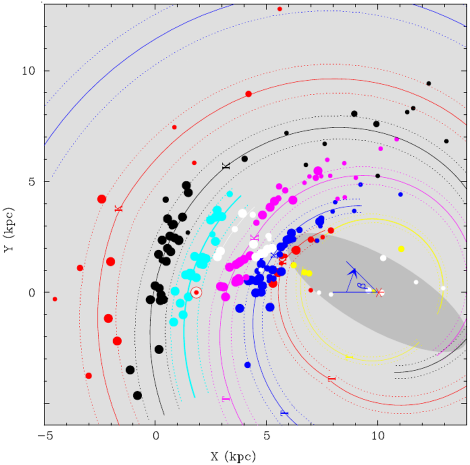
Outline

- RM and Synchrotron Data
- Thermal & CR Electrons
- New GMF Model(s)
- **Results and Implications**
- (Amaterasu Particle)

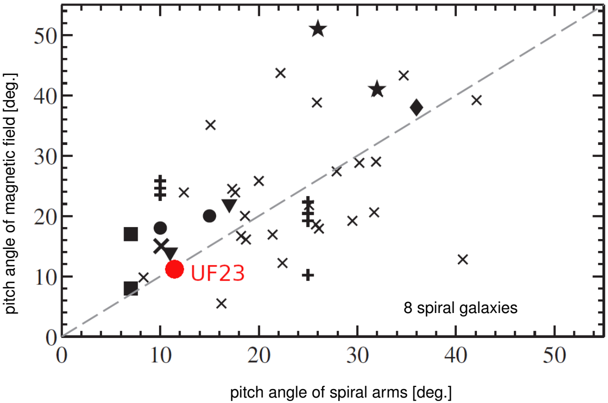
Magnetic Pitch Angle

- fitted magnetic pitch angle in disk $(11 \pm 1)^\circ$ (error dominated by n_e)
- pitch angle of local arm $(11.4 \pm 1.9)^\circ$ (fit of HMSFR with parallaxes)

Reid+ApJ19

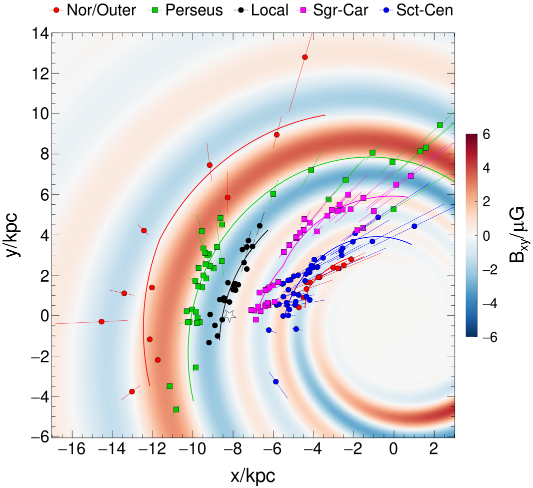


van Eck+ApJ15

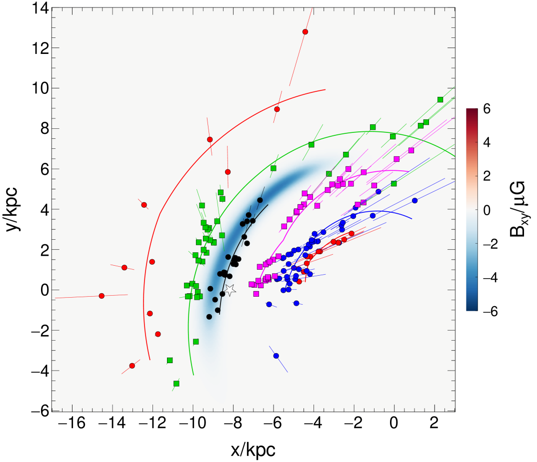


Local Spur or Global Spiral?

“base”



“spur”



→ both models describe data equally well!

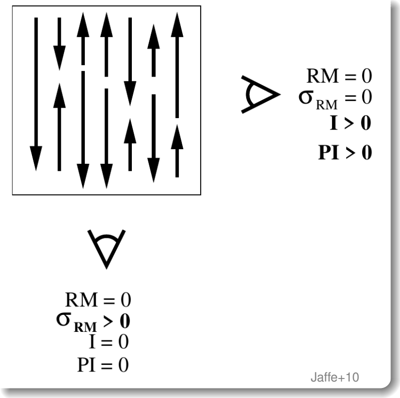
Results – Striation or Correlation?

Longstanding problem: B(syn) < B(RM)

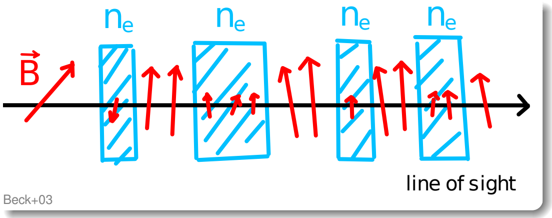
anisotropic/orderd/striated b?

anti-correlation b-n_e (pressure equ.)?

"base"



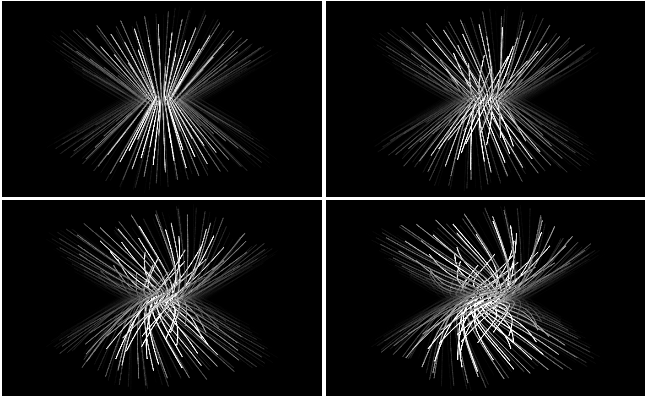
"nbcorr"



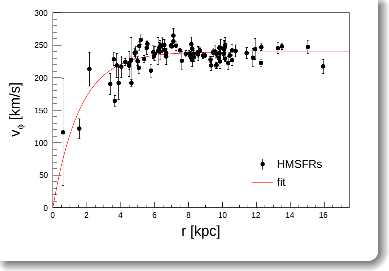
→ both models describe data equally well!

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

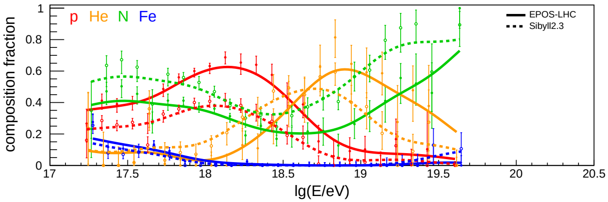


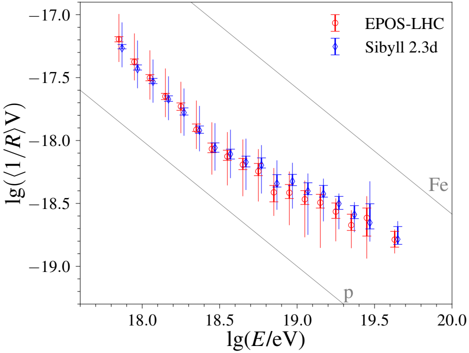
Galactic rotation curve

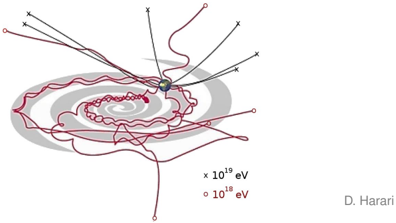


- no separate X- and torodial halo needed!
- “twisting time”: $t = 54.7 \pm 1.1$ Myr $\rightarrow$ effective time (steady state when including dissipation?)

Cosmic-Ray Deflections







- Larmor radius of charged particle in B-field

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

- rigidity

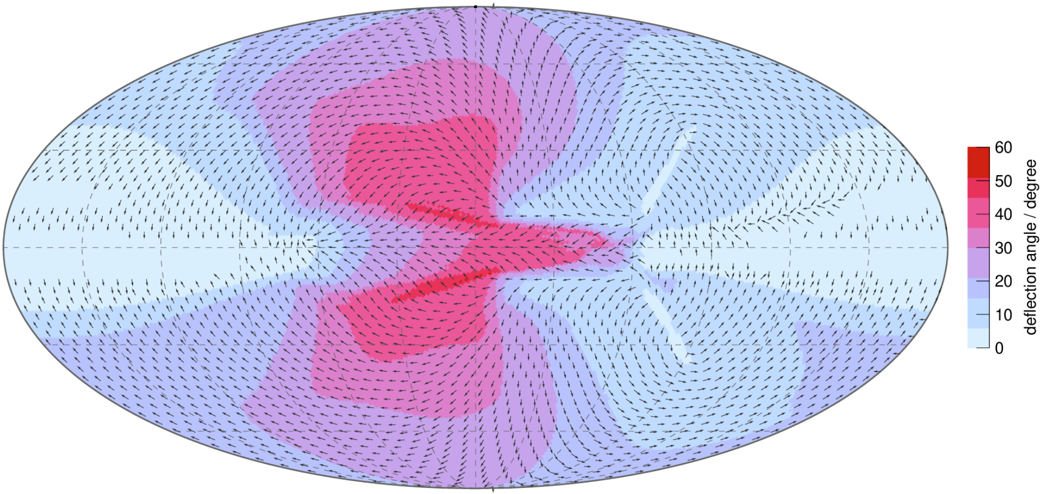
$$R = \frac{cp}{eZ} \overset{e=c=1}{=} \frac{E}{Z}$$

- typical GMF deflections (JF12)

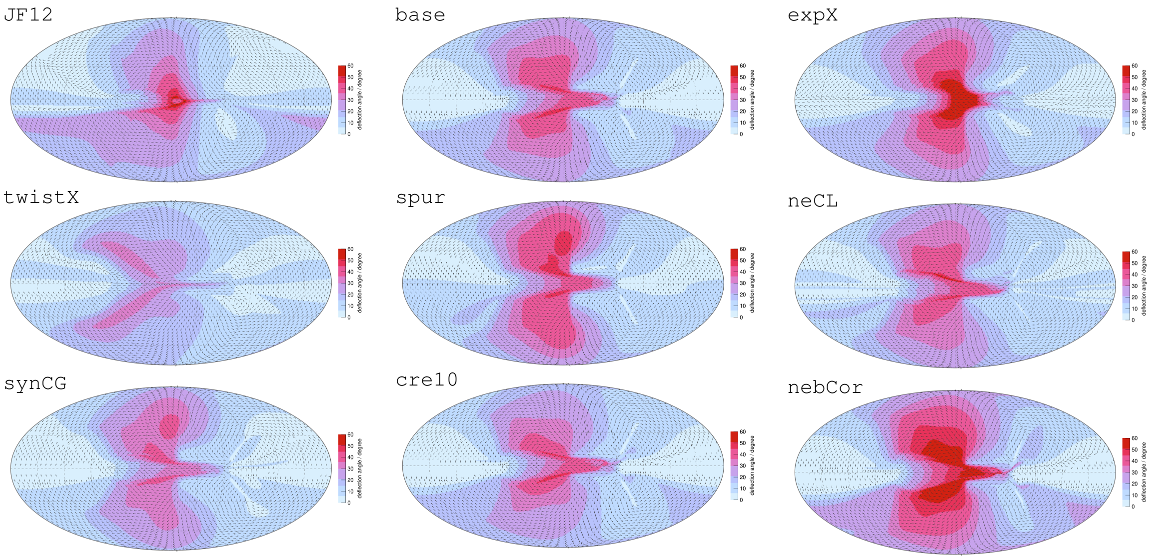
$$\theta_{\text{coh}} \sim 3^\circ \left(\frac{R}{10^{20}\,\text{V}}\right)^{-1}$$

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

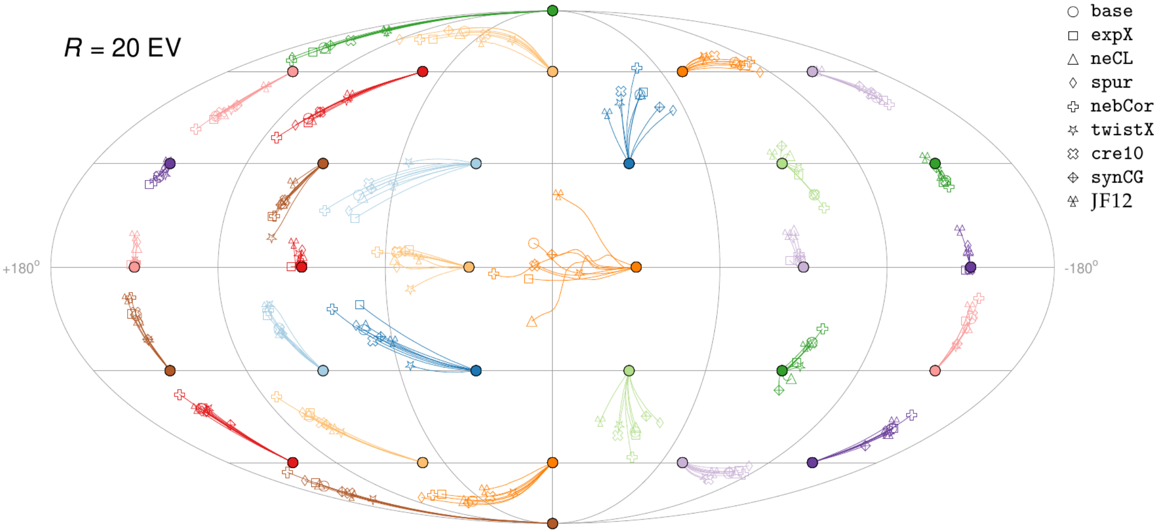
Deflections at 20 EV (base model) (backtracking)



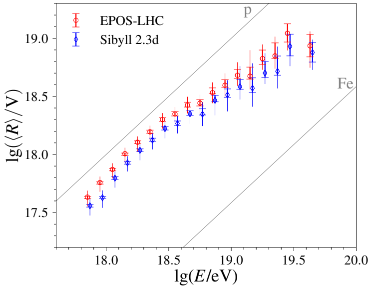
Deflections at 20 EV (model ensemble and JF12) (backtracking)



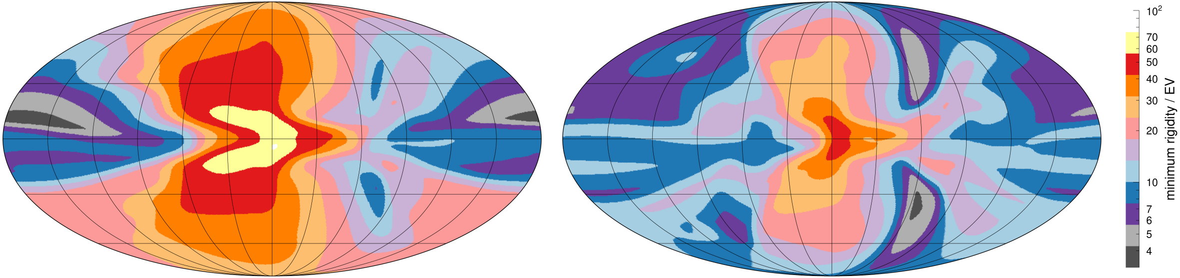
Deflections at 20 EV (backtracking)



Rigidity Threshold for Nuclear Astronomy

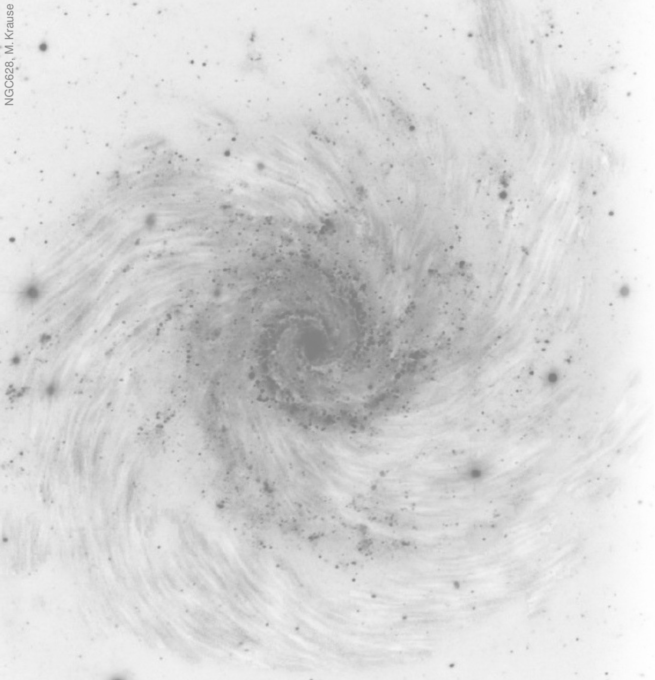


rigidity at which ...



... deflections $\leq 20°$
median threshold at 20 EV

... deflection difference $\leq 20°$
median threshold at 10 EV



Summary

New Model(s) of the Coherent GMF

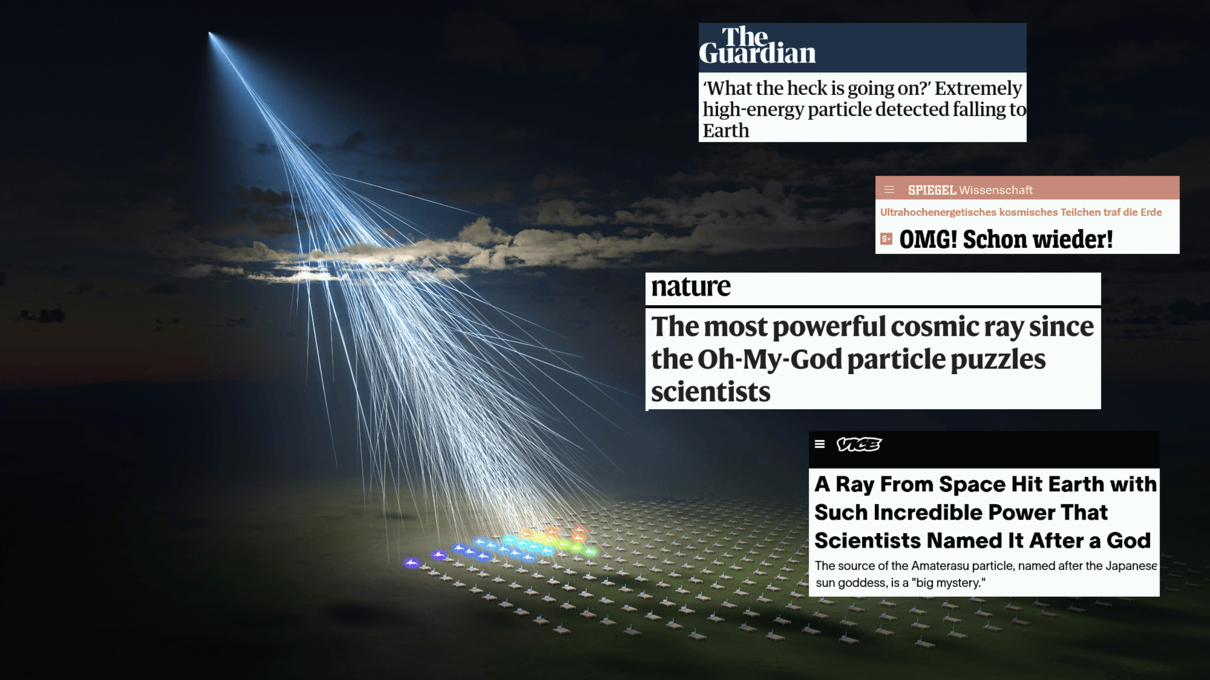
- full-sky RM data
- latest synchrotron sky maps
- improved auxillary models (n_e and n_{cre})
- smooth disk-field model
- unified halo model

Main Results:

- JF12 dipolar X-field robust $\lightning$ dynamo?
- magnetic pitch $\sim$ spiral pitch $\lightning$ coherent?
- local spur (Orion) or Grand Spiral?
- $n_e - B$ anti-corr. is alternative to striation $\rightarrow$ larger B estimates
- GMF model ensemble $\rightarrow$ uncertainties for deflection, diffusion, axion conversion,...

Outlook:

- turbulent field using $\mathrm{I}_{\mathrm{syn}}$ + variances
- pulsar RMs, low-frequency QU, dust pol., ...
- foreground modeling local bubble, loops,.


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

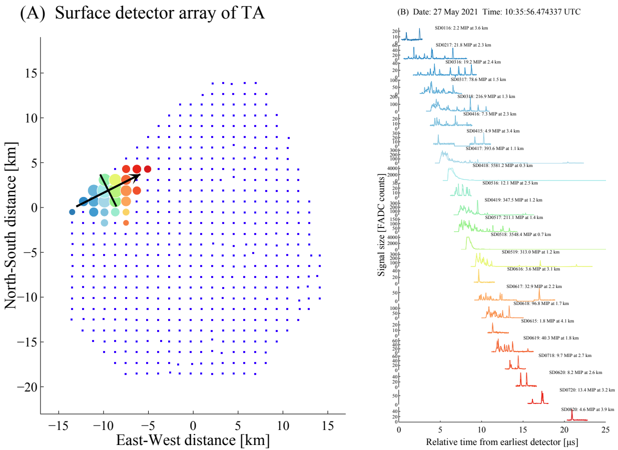
HOME > SCIENCE > VOL. 382, NO. 6673 > AN EXTREMELY ENERGETIC COSMIC RAY OBSERVED BY A SURFACE DETECTOR ARRAY

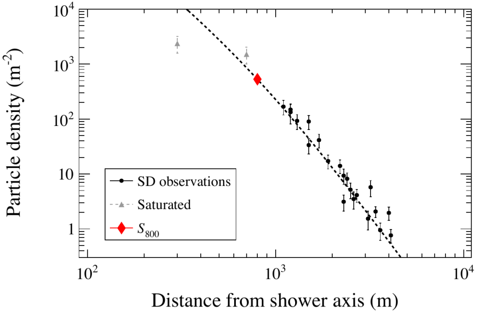
RESEARCH ARTICLE | ASTROPARTICLE PHYSICS

An extremely energetic cosmic ray observed by a surface detector array

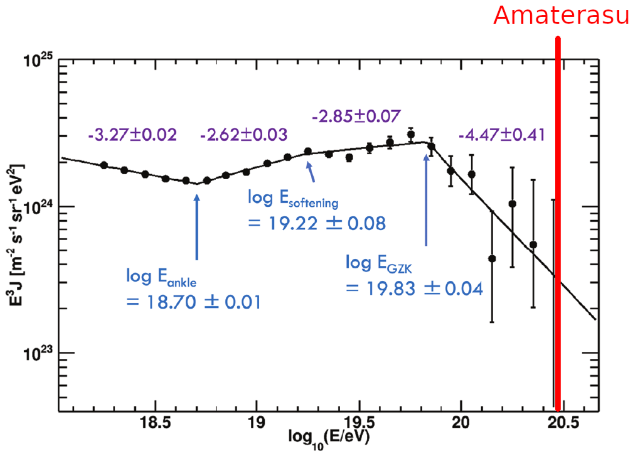
TELESCOPE ARRAY COLLABORATION*†, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL

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



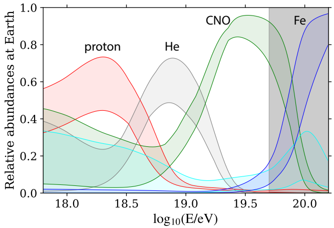


Simplest Assumption: Fe Nucleus from Standard Accelerator ($\mathcal{R}_{\mathrm{max}} \sim 10^{18.6-18.7}$ V)



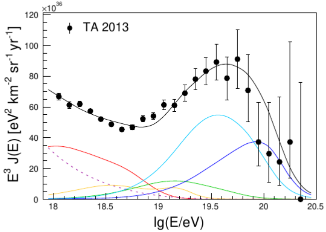
TA 14-year SD spectrum, Kim et al, EPJ Conf **283** (tm2023) 02005

Peters Cycle:



Pierre Auger Coll. 2023

Photodisintegration in source:

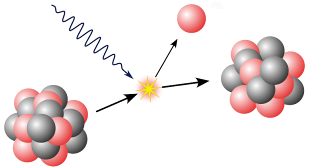


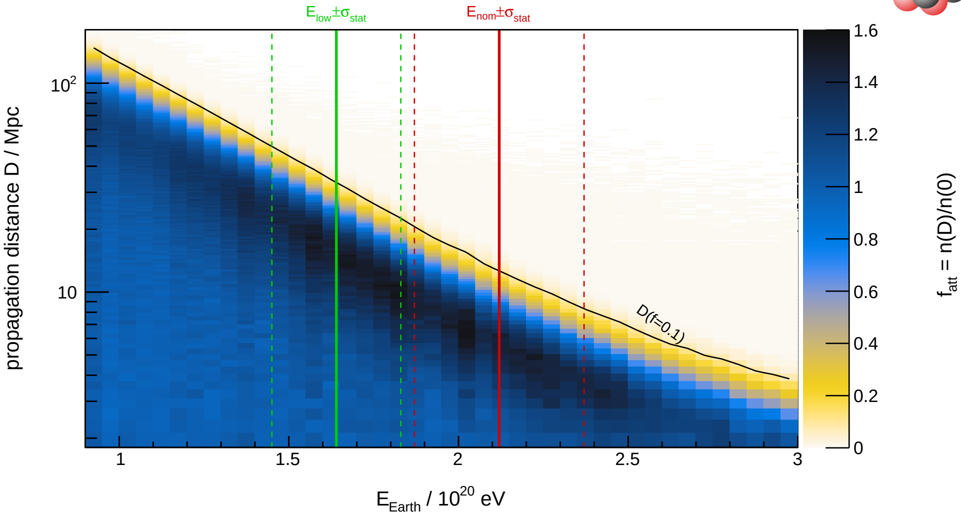
(c) Flux at Earth

MU, Farrar, Anchordoqui PRD15

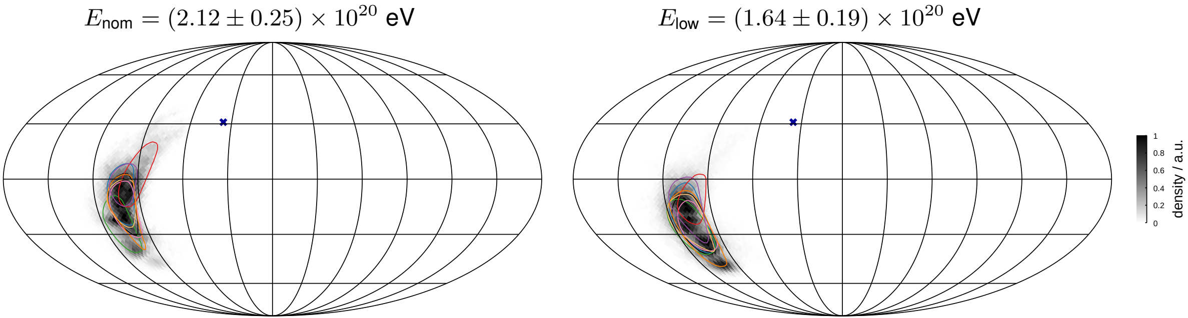
Propagation of Fe in Extragalactic Photon Fields

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





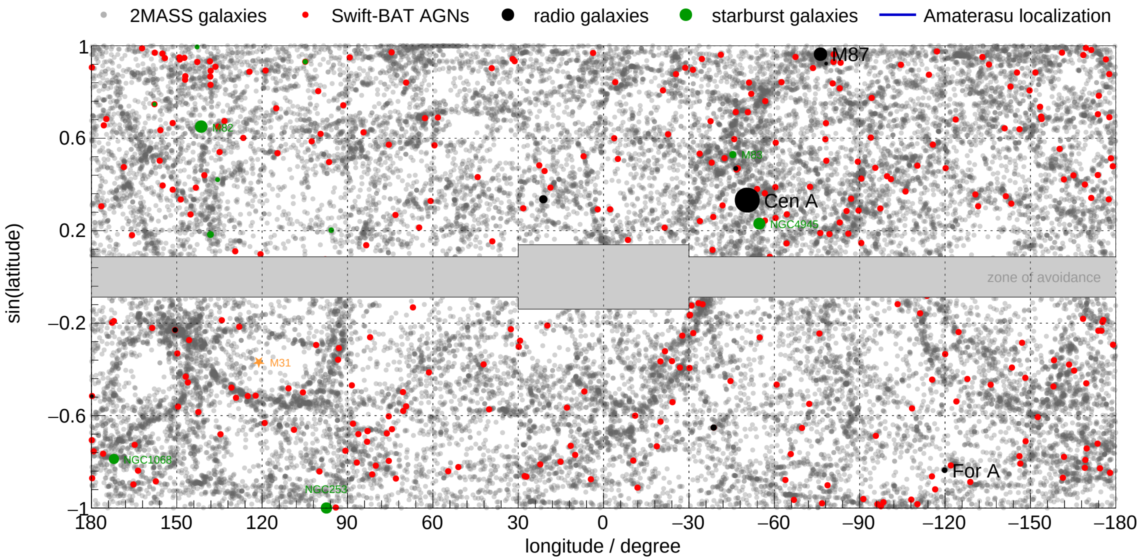
Arrival Direction



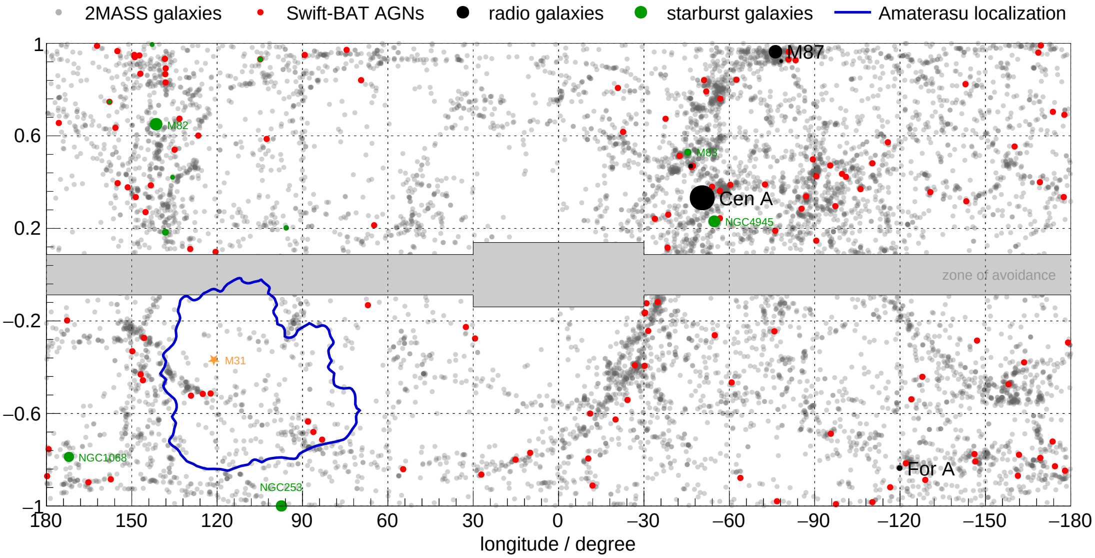
localization uncertainty: 6.6% of 4π or 2726 deg^2

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

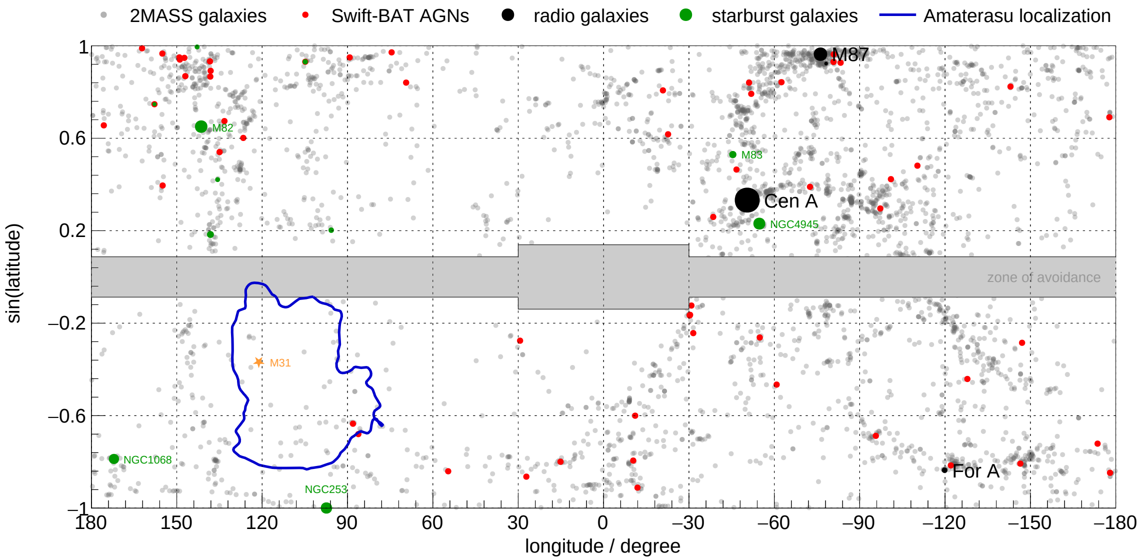
Distribution of galaxies up to D=150 Mpc



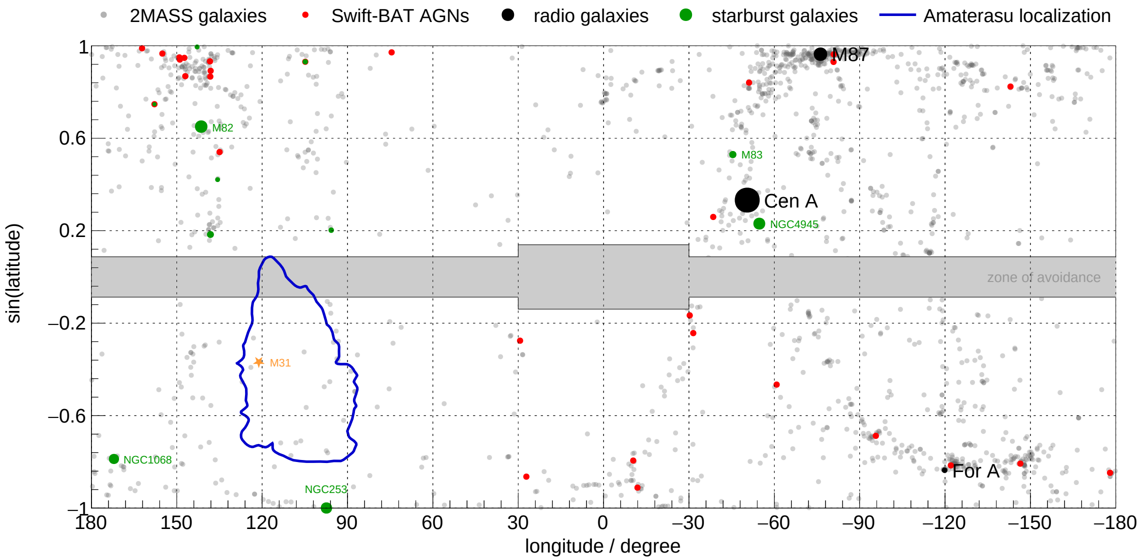
$E_{\text{low}} - 2\,\sigma$, $D_{0.1}$=72 Mpc



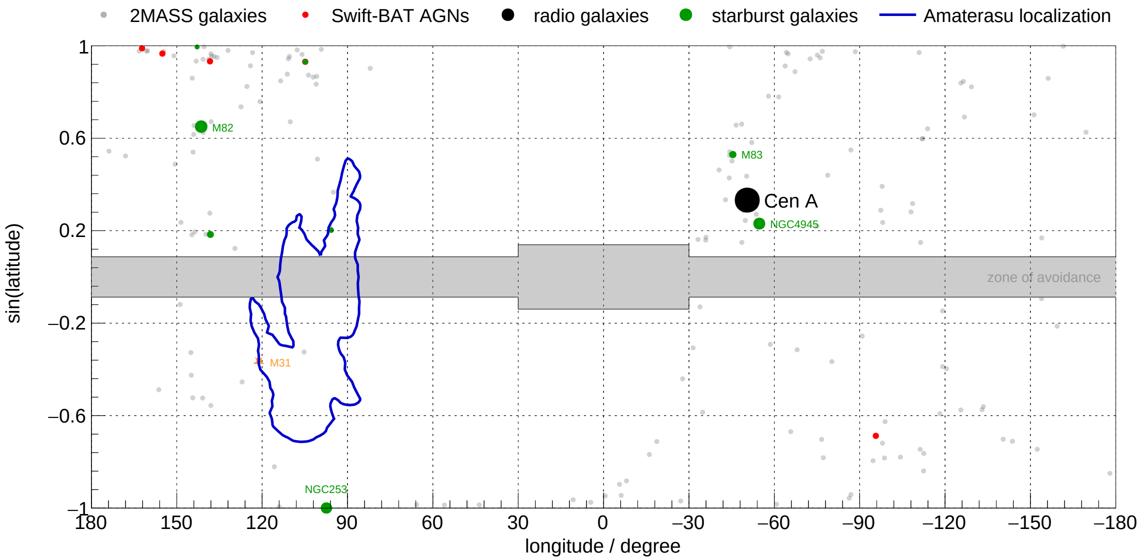
$E_{\text{low}} - 1\,\sigma$, $D_{0.1}$=42 Mpc

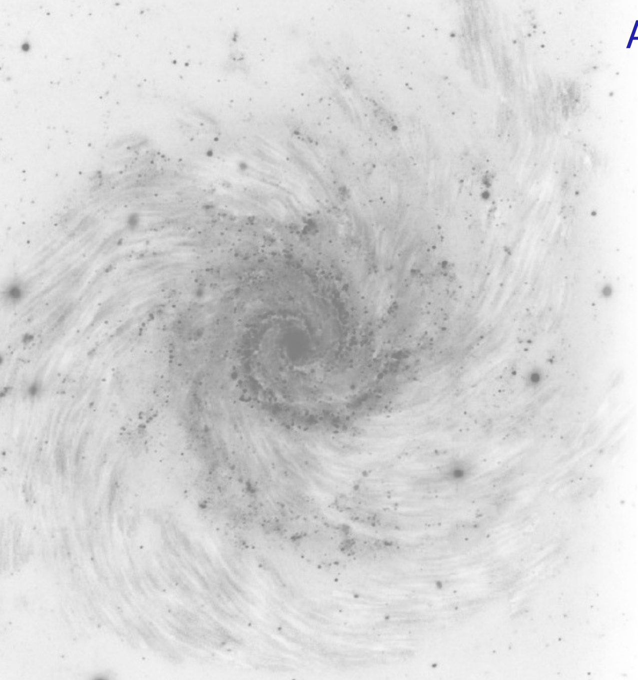


E_{low}, $D_{0.1}$=25 Mpc



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





Amaterasu Particle

- simplest assumption: Fe nucleus
- localization uncertainty (using UF23 ensemble): $\rightarrow$ direction within 2726 deg^2 (6.6% of 4π)
- horizon between 8 and 50 Mpc
- accurate energy essential! (both, stat. and syst.!)
- none of the “usual suspects” within localization uncertainty
- starburst galaxy NGC 6946? (flux proxy is 10% of NGC4945 and M82)
- Andromeda (M31)?
- transient event in an otherwise undistinguished galaxy?