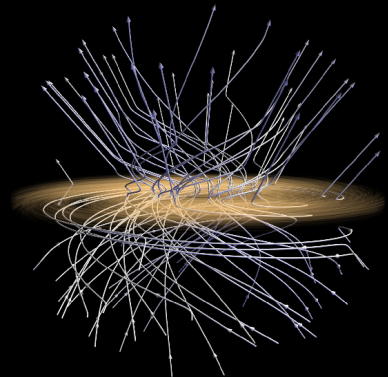
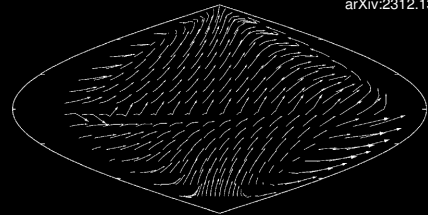


New Models of the Galactic Magnetic Field

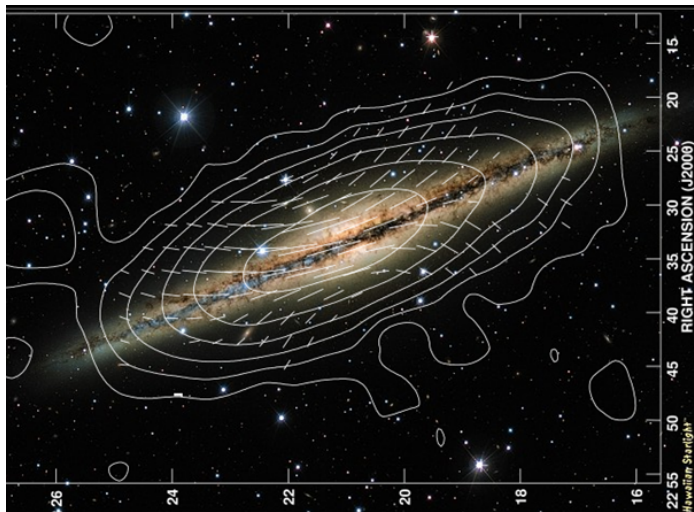
M. Unger (KIT) and G.R. Farrar (NYU)

arXiv:2311.12120

arXiv:2312.13273

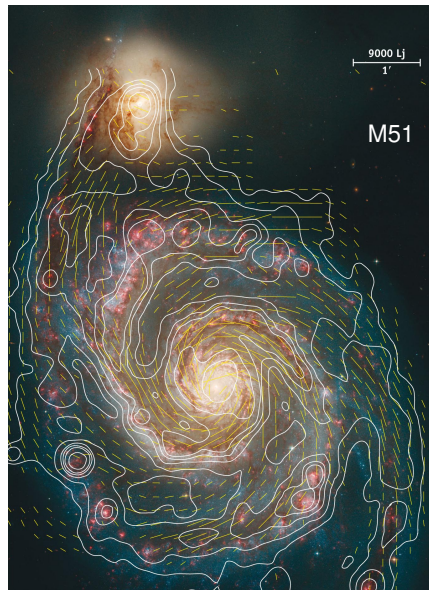


Galactic Magnetism



NGC891, M. Krause MPIfR

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



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

Proto-Galactic?

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

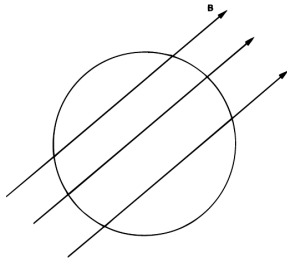


FIG. 1a

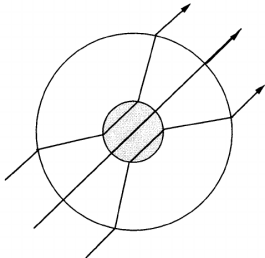


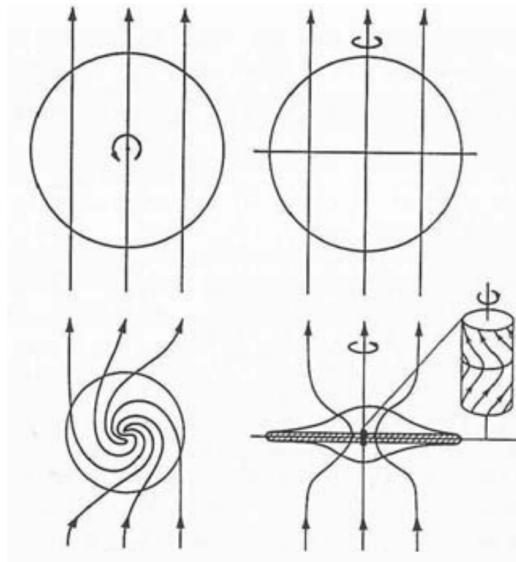
FIG. 1b

Howard&Kulsrud A&A 1990

but:

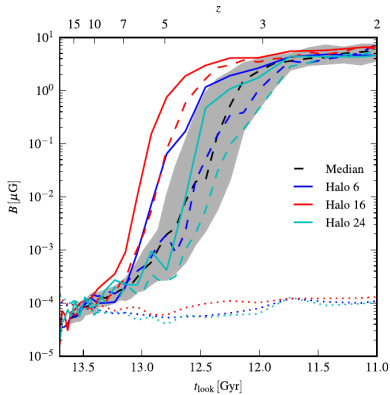
- winding problem ($P_{\text{rot}} \approx 0.2$ Gyr at $r_{\odot}$)
- decay of field in turbulent diffusion $\mathcal{O}(10^8 \text{ yr})$

shearing by differential rotation

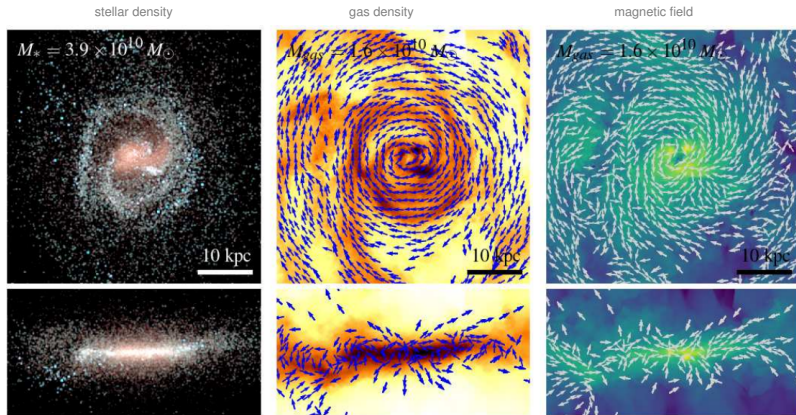


Dynamo Action?

Galaxy simulations:



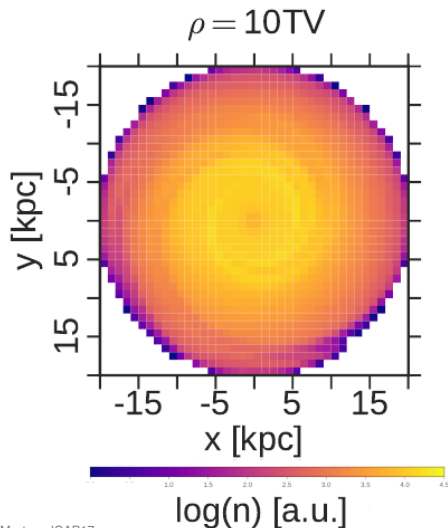
Auriga, Pakmor+MNRAS17



IllustrisTNG, Marinacci+MNRAS17

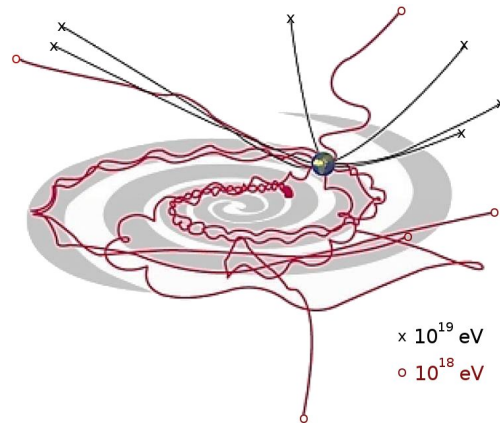
Effect of Galactic Magnetic Field on Cosmic Rays

(anisotropic) diffusion of low energy cosmic rays



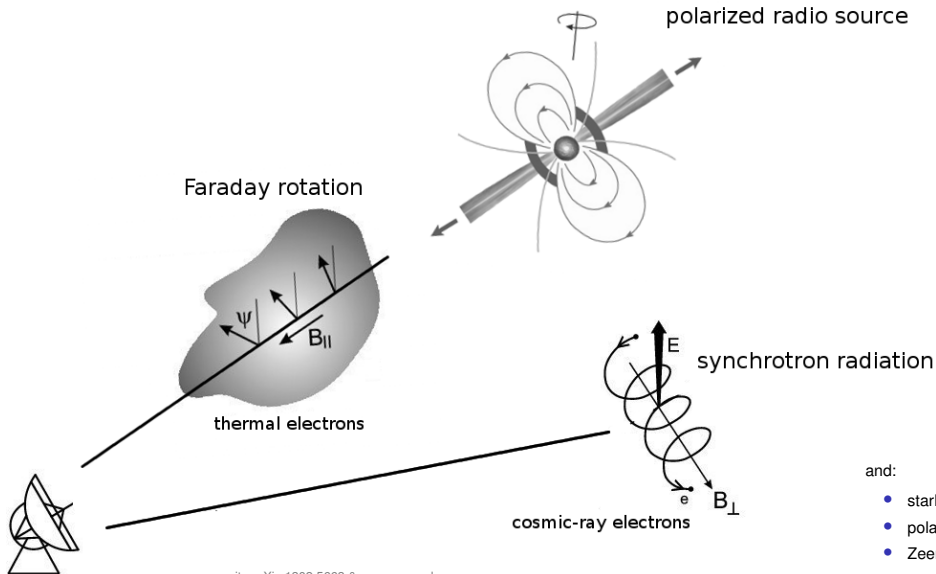
Merten+JCAP17

deflection of ultrahigh-energy cosmic rays



D. Harari

Observational Tracers of the Astrophysical Magnetic Fields



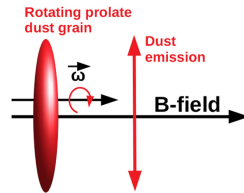
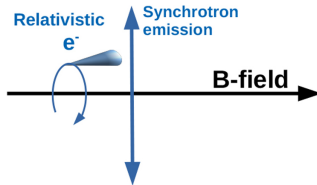
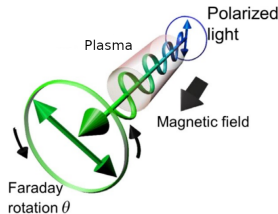
and:

- starlight polarization
- polarized dust emission
- Zeeman effect

Modeling the Coherent Galactic Magnetic Field (GMF)

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

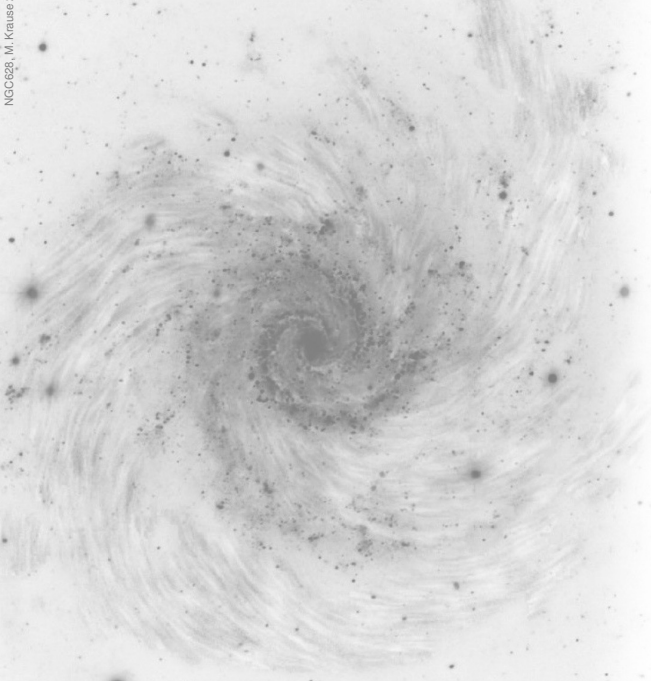
Observables:



adapted from Hasegawa+13 and Pelgrims+18

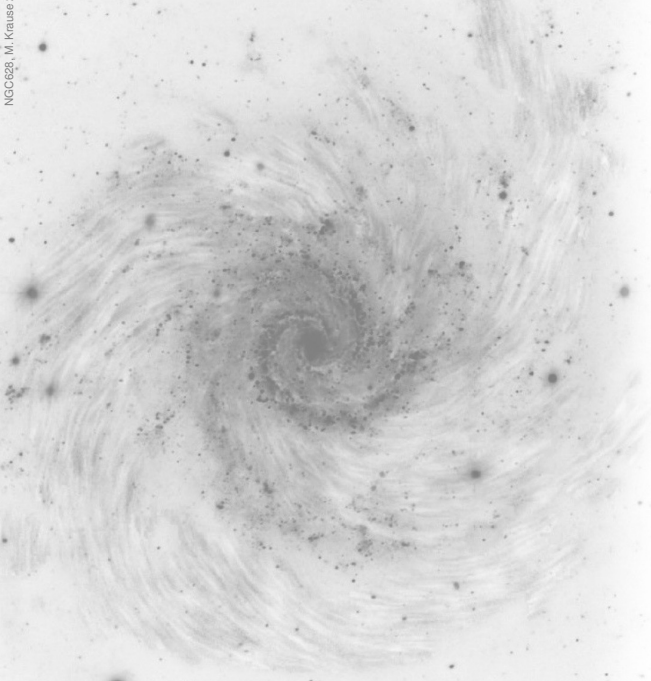
Popular GMF Models:

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



Outline

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

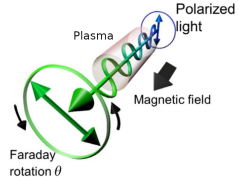
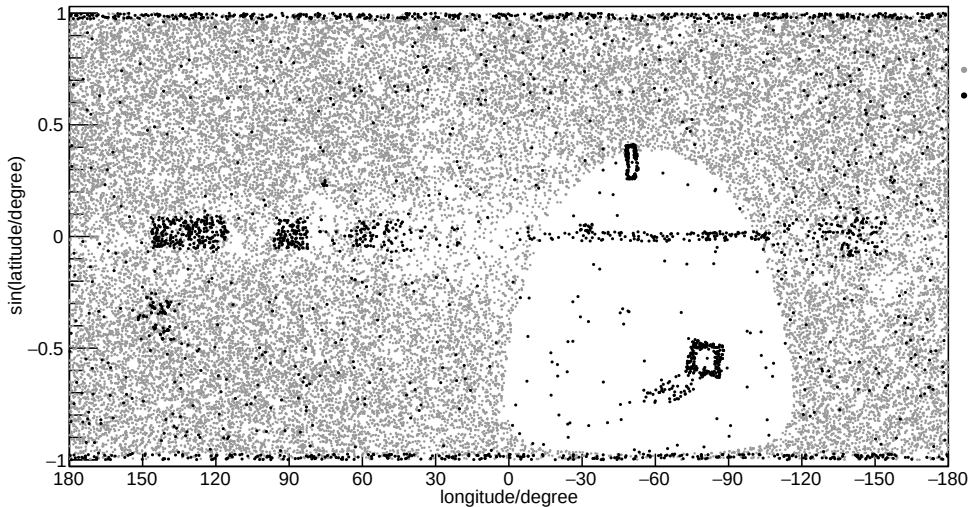


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Extragalactic Rotation Measures (PT11, JF12)

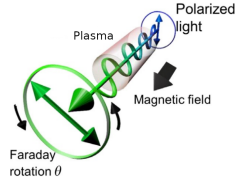
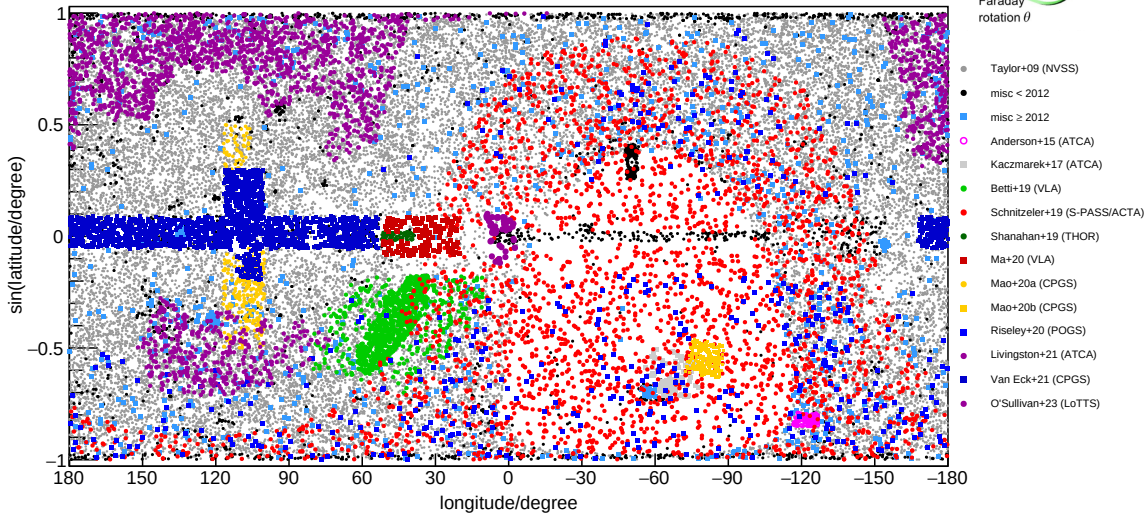
$$\theta = \theta_0 + \text{RM} \lambda^2$$



- Taylor+09 (NVSS)
- misc < 2012

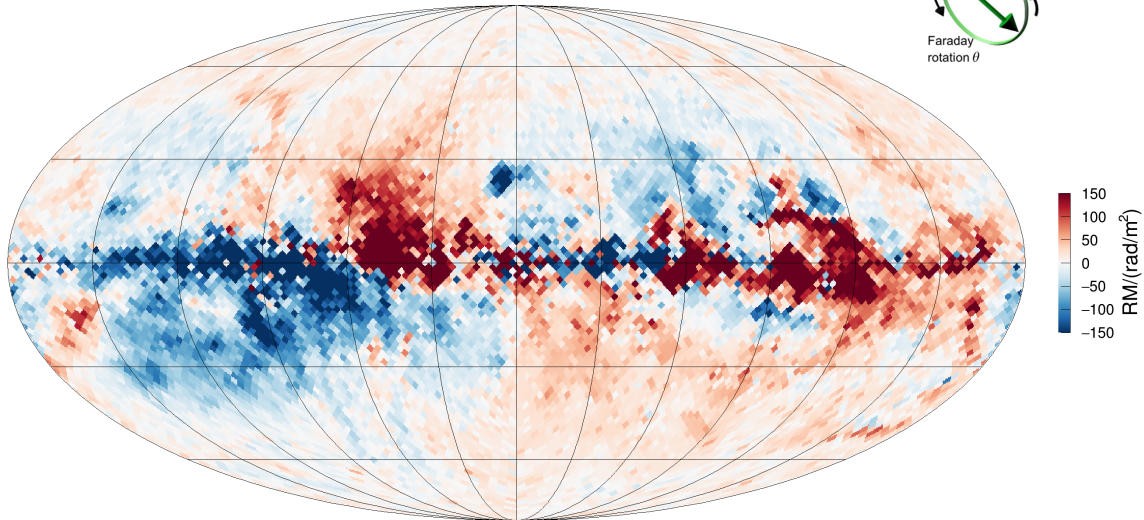
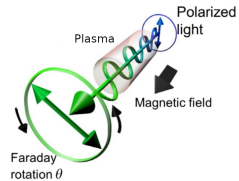
Extragalactic Rotation Measures 2023

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



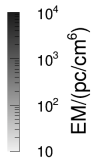
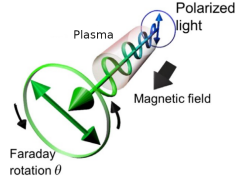
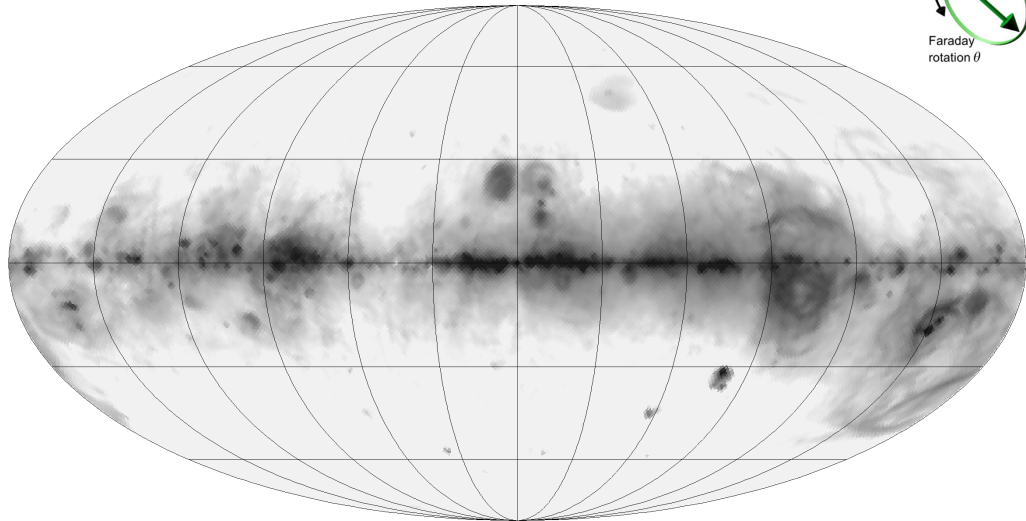
2023 RM Sky

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



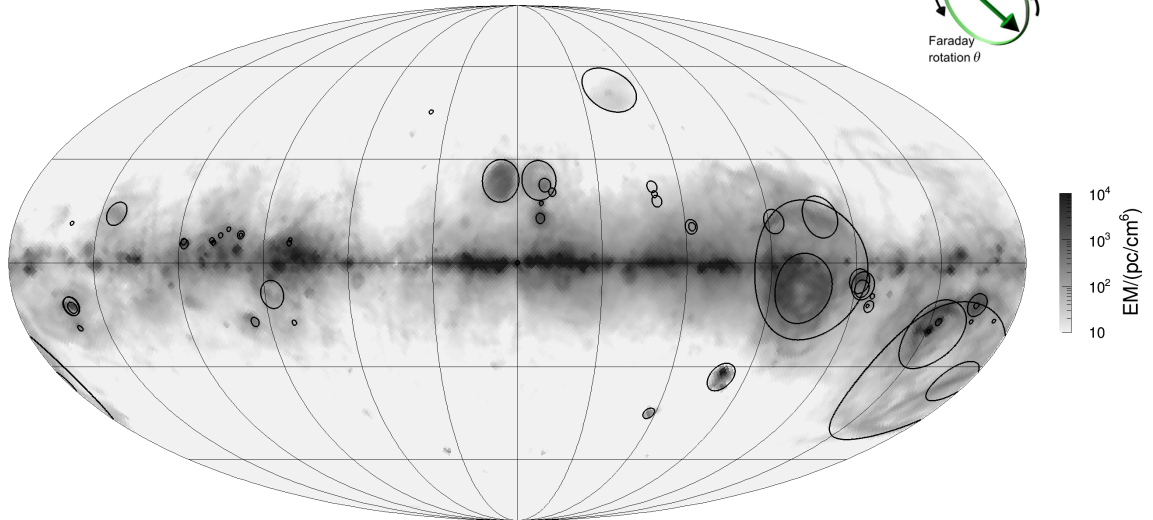
Foreground: HII Regions

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

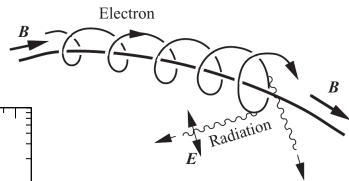
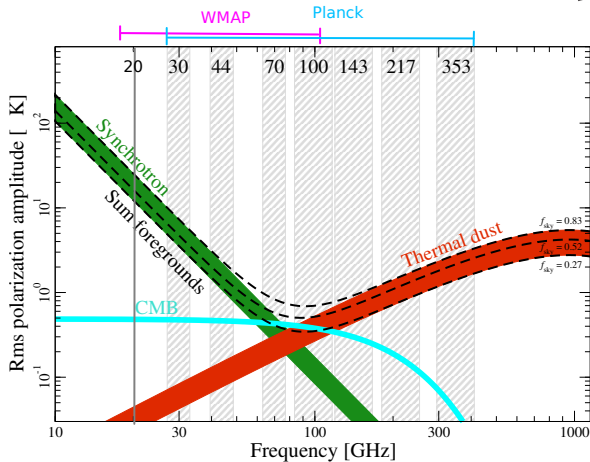


Foreground: HII Regions

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



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
- $\beta_S \sim -3 \rightarrow T_{\text{syn}}(20 \text{ Hz})/T_{\text{syn}}(30 \text{ Hz}) \approx 3.4$

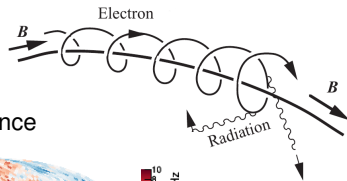
Polarized Synchrotron Emission



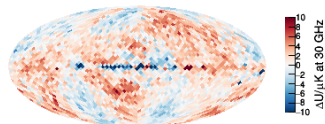
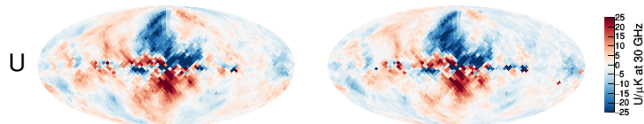
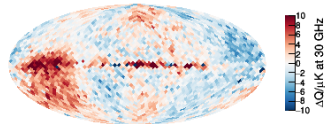
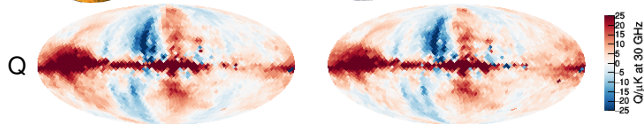
WMAP9



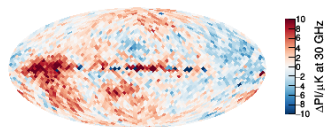
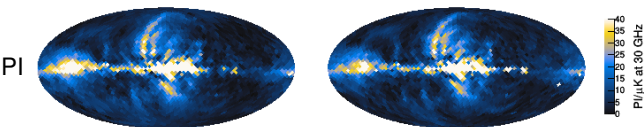
Planck R3.00



difference

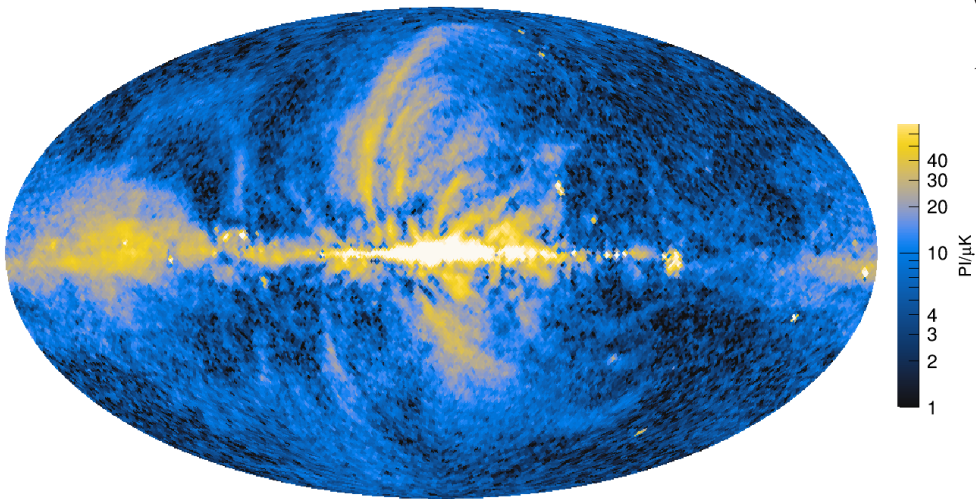
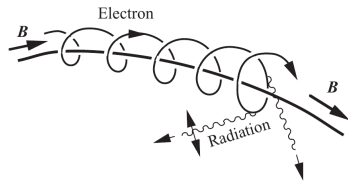


- Stokes Parameters
 $Q/U \propto \int B_{\perp}^2 n_{\text{cre}} dl$
- projected mag. angle
 $\psi = \frac{1}{2} \text{atan}\left(\frac{U}{Q}\right) + \frac{\pi}{2}$
- polarized intensity:
 $PI^2 = Q^2 + U^2$

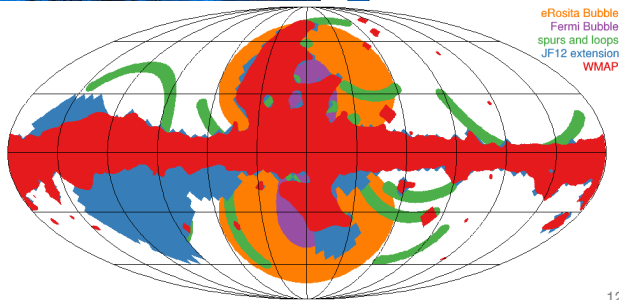
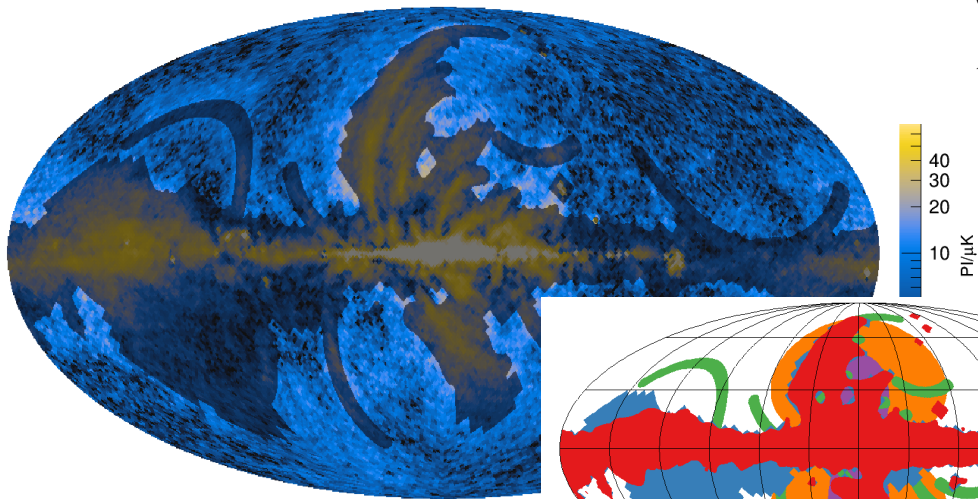
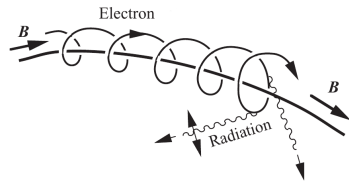


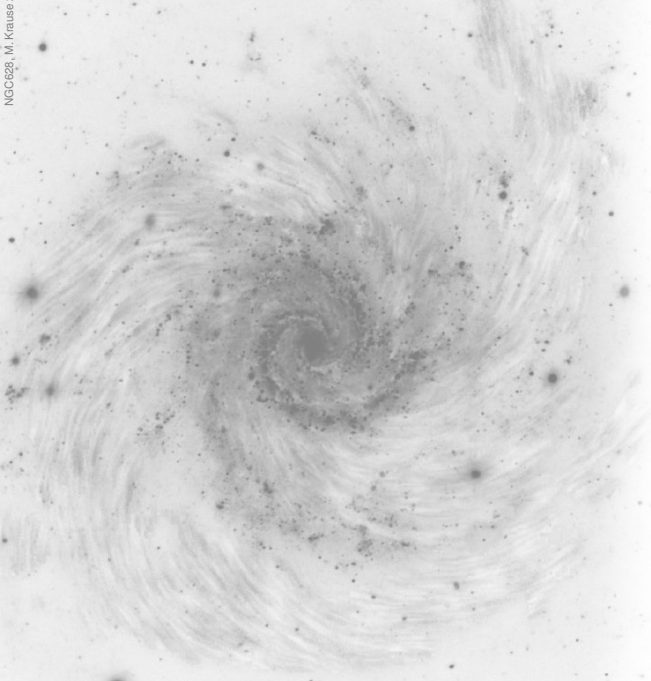
calibration uncertainty? cosmic-ray spectral index?

Combined WMAP-Planck Polarized Emission



Combined WMAP-Planck Polarized Emission



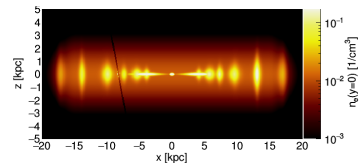
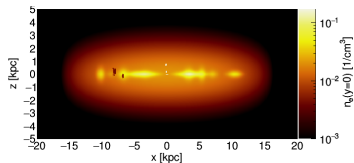
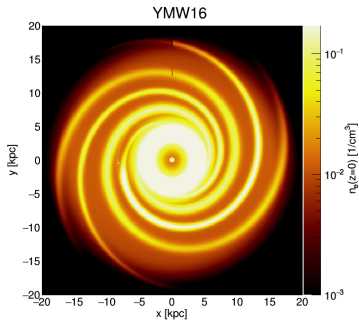
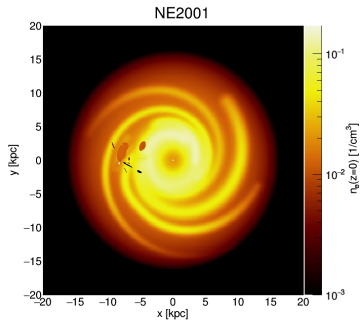


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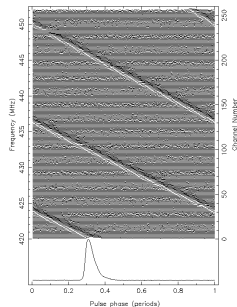
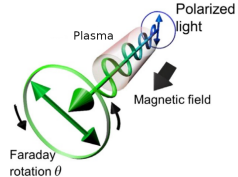
Thermal Electron Models

$$DM \propto \int_{\text{source}}^{\text{observer}} n_e(l) dl$$

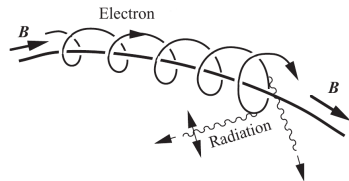


112 pulsar DMs

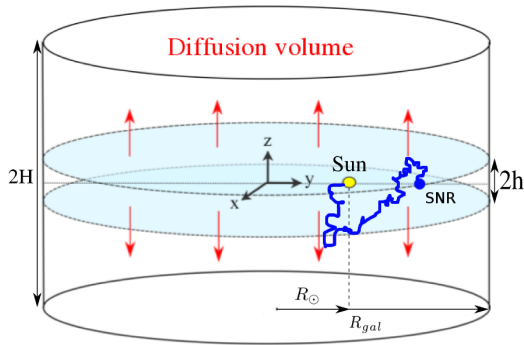
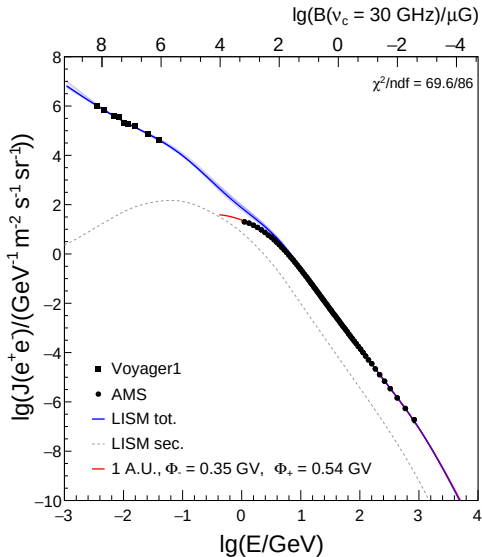
189 pulsar DMs



Cosmic-Ray Electron Model



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



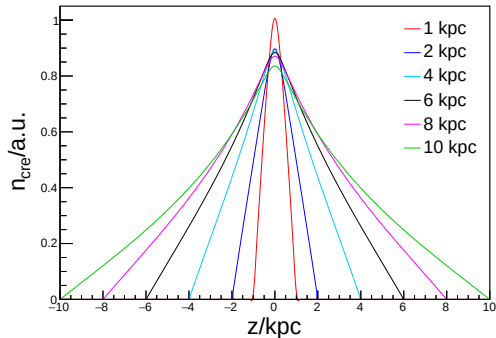
homogenous and isotropic diffusion $D_0 \propto R^\delta$ (rigidity R)

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

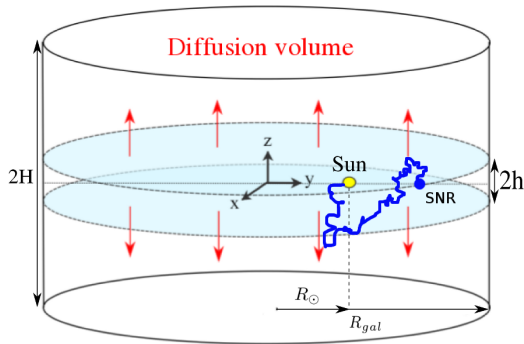
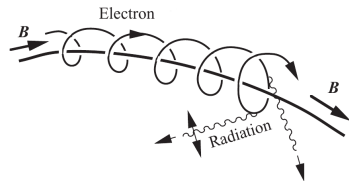
Cosmic-Ray Electron Model

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

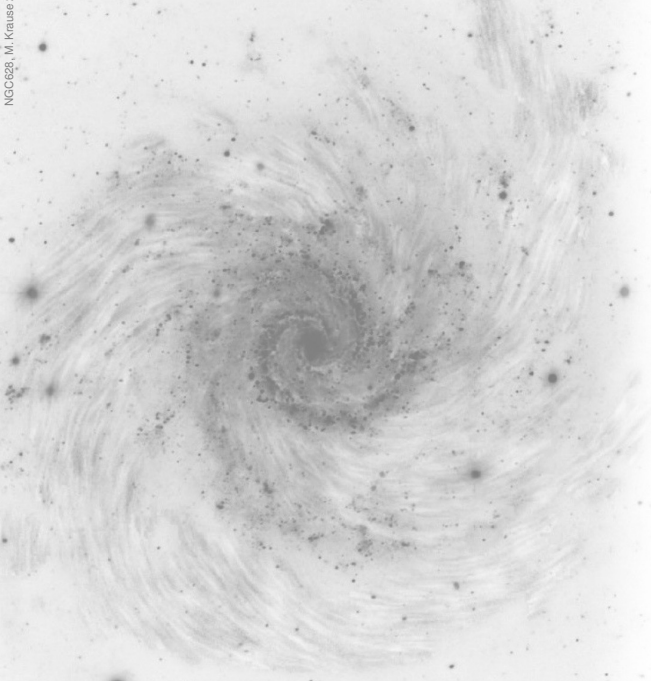
→ large uncertainty in vertical n_{cre} profile!



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



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

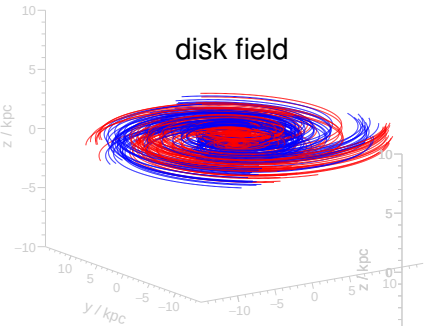


Outline

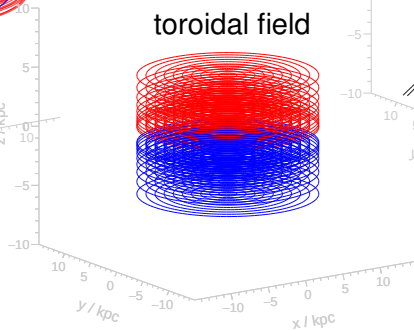
- RM and Synchrotron Data
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- **New GMF Model(s)**
- Results and Implications
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Parametric GMF Components

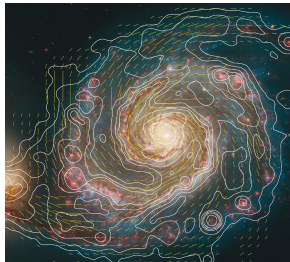
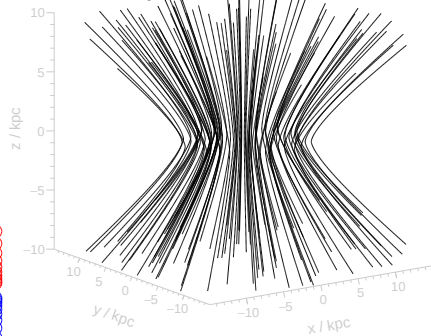
disk field



toroidal field



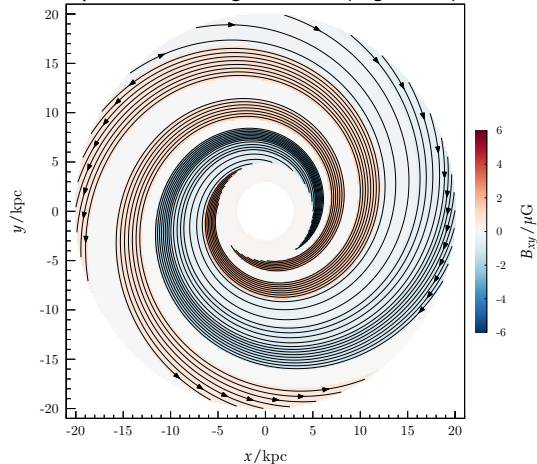
poloidal field



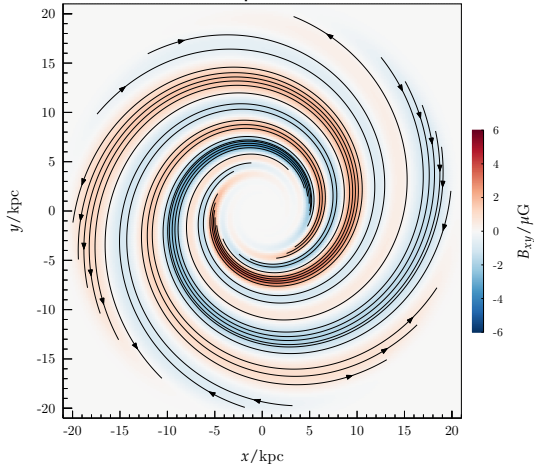
cf. Jansson&Farrar ApJ 757 (2012) 14

New Disk Field Model

previous “wedge”-model (e.g. JF12):



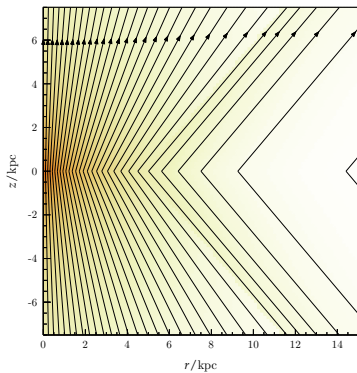
smooth spiral disk field:



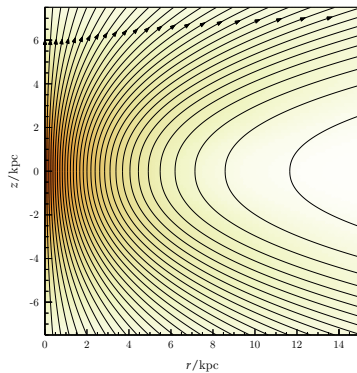
- divergence-free Fourier-expansion of $B_\phi(r)$ at reference radius
- avoids radial discontinuities
- free pitch angle and “magnetic arms” (number of Fourier modes)

Halo X-Field

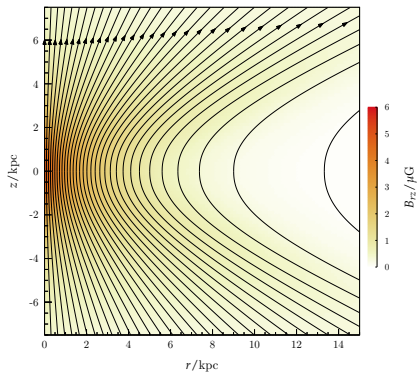
JF12



Ferriere&Terral14

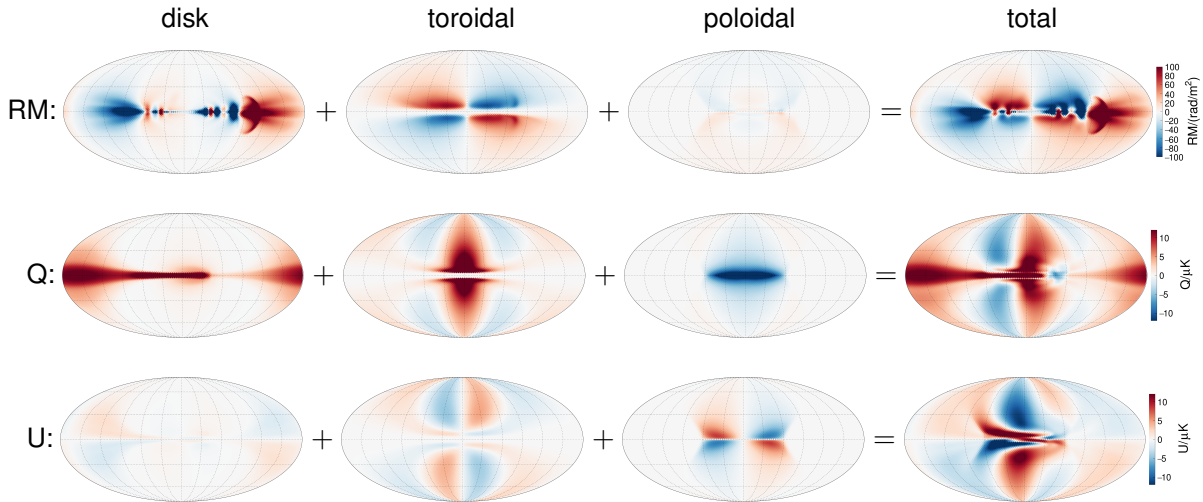


UF23

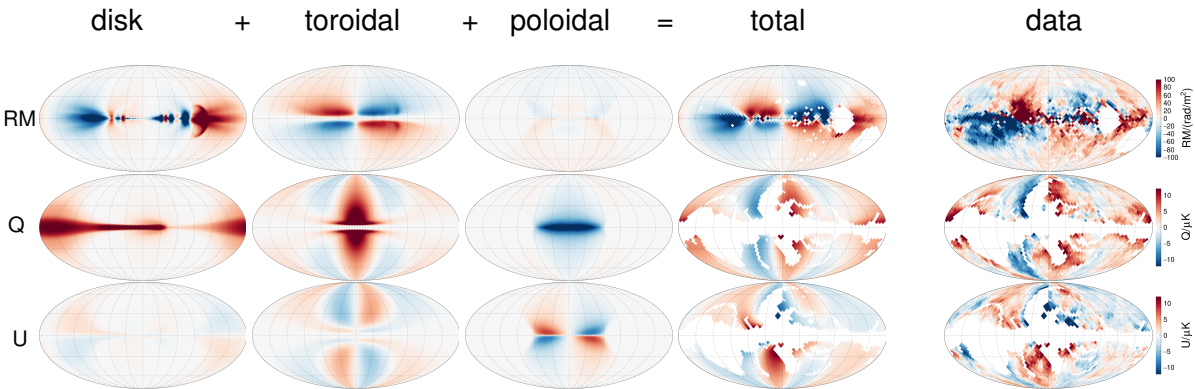


- fix JF12 discontinuities at $z = 0$ and transition to $\theta_X = 49^\circ$

RM and Q&U of “base model”



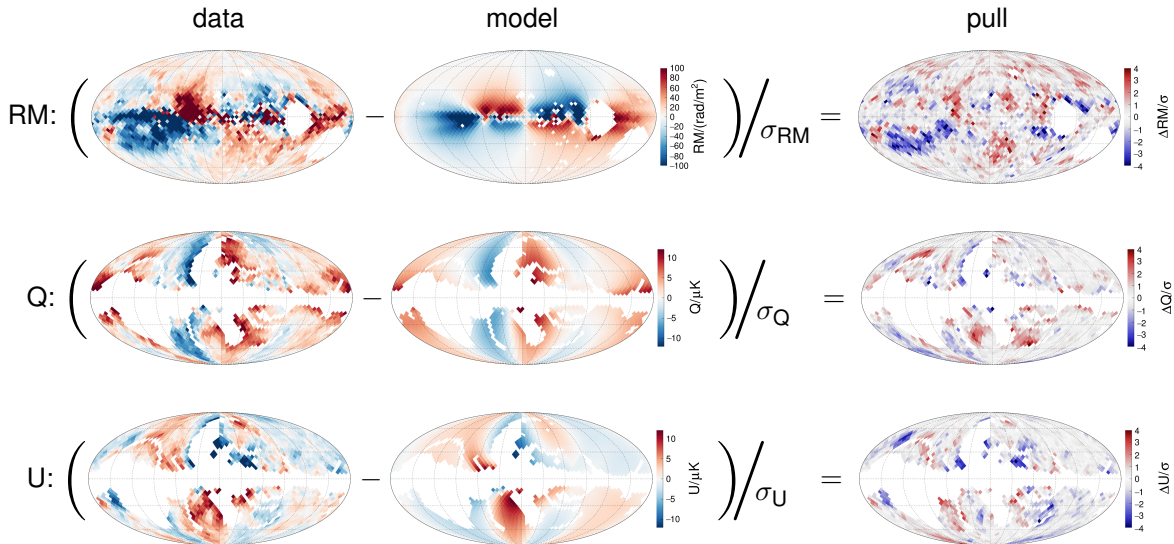
Data and Model



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

Data and Model

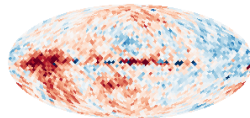
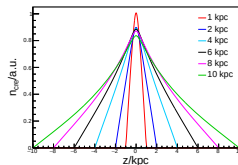
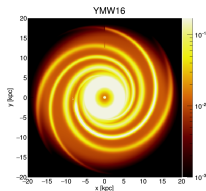
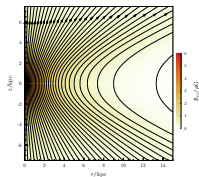
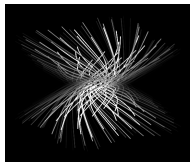
$$\chi^2/\text{ndf} = 7923/6500 = 1.22$$

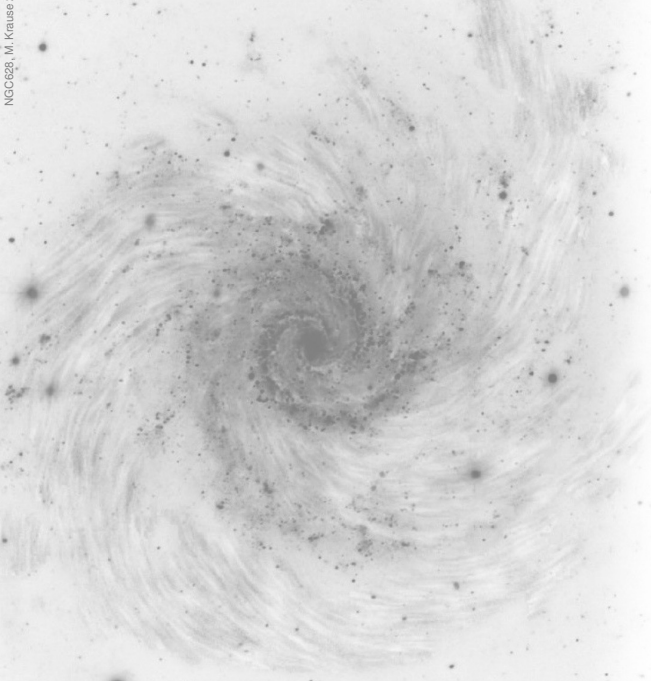


Model Variations

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
nbcrr	n_e - B correlation	1.22
cre	cosmic-ray electron vertical scale height	1.22
syn	use COSMOGLOBE synchrotron maps	1.50





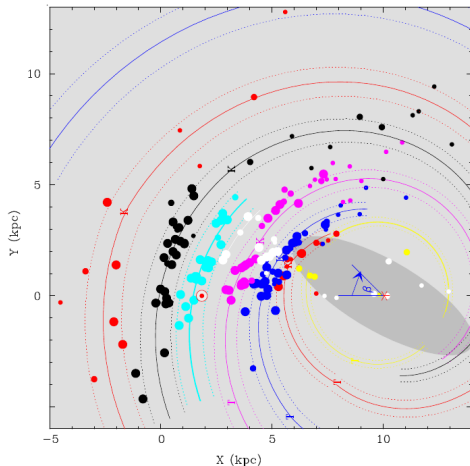
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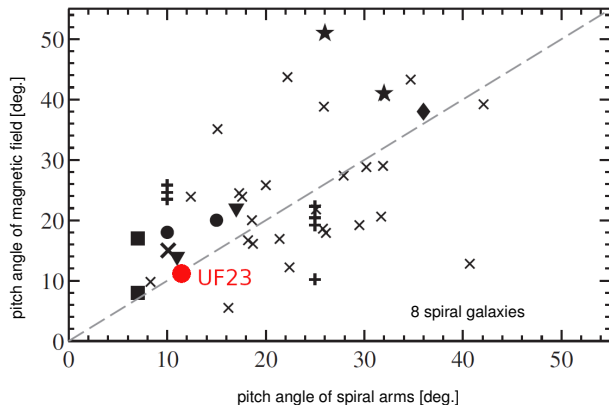
Magnetic Pitch Angle

- 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

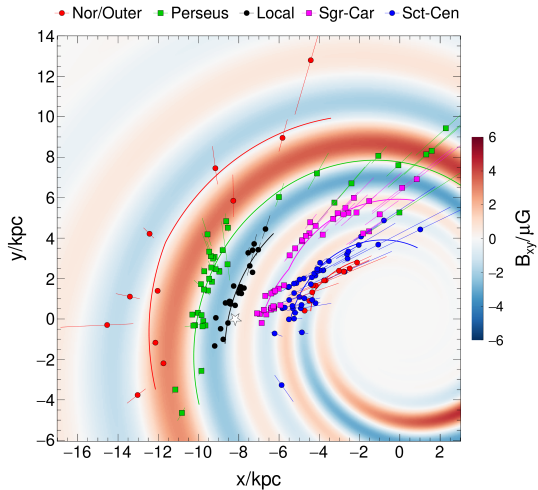


van Eck+ApJ15

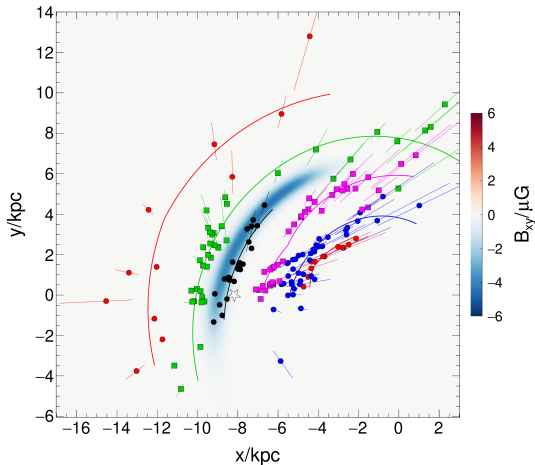


Local Spur or Global Spiral?

“base”



“spur”



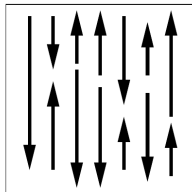
→ both models describe data equally well!

Results – Striation or Correlation?

Longstanding problem: $B(\text{syn}) < B(\text{RM})$

anisotropic/orderd/striated b ?

“base”

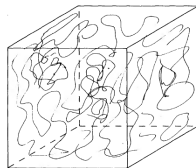


$$\nabla \begin{cases} \text{RM} = 0 \\ \sigma_{\text{RM}} = 0 \\ \text{I} > 0 \\ \text{PI} > 0 \end{cases}$$

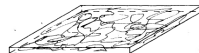


$$\begin{cases} \text{RM} = 0 \\ \sigma_{\text{RM}} > 0 \\ \text{I} = 0 \\ \text{PI} = 0 \end{cases}$$

Jaffe+10



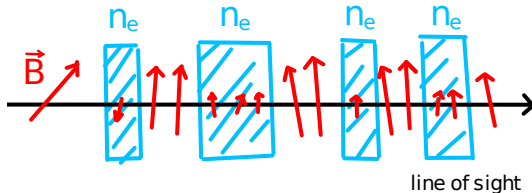
(a)
Before Compression



(b)
After Compression

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

“nbcorr”



Beck+03

→ both models describe data equally well!

Magnetic Halo

- poloidal field needed to describe data

$\Delta\chi^2 > +2100$ wrt to no X-field

- N-S reflection anti-symmetric

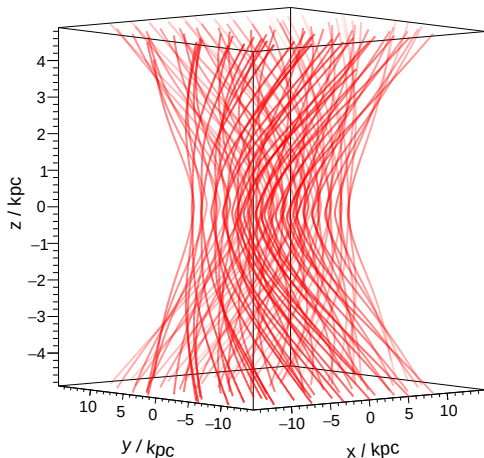
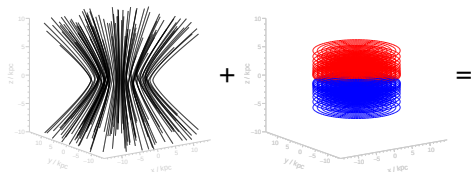
$\Delta\chi^2 > +1700$ wrt to symmetric

- same field strength in N/S hemisphere

- poloidal halo: $\Delta B = (0.1 \pm 0.1) \mu\text{G}$

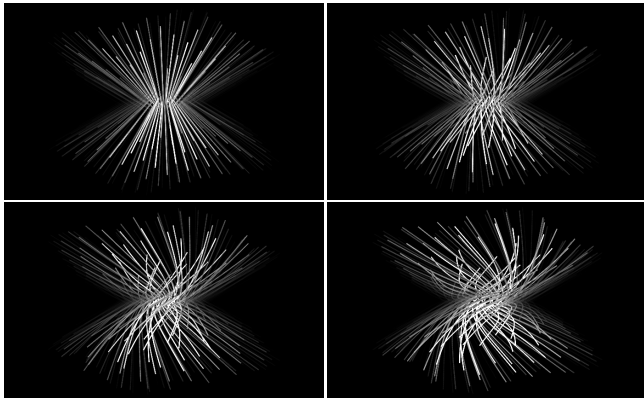
- toroidal halo: $\Delta B = (0.2 \pm 0.4) \mu\text{G}$

- same radial extent of toroidal halo in N/S

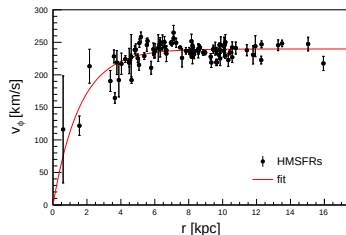


Unified Halo Model

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

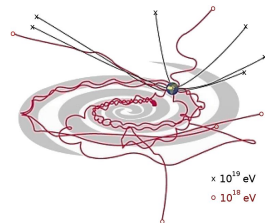
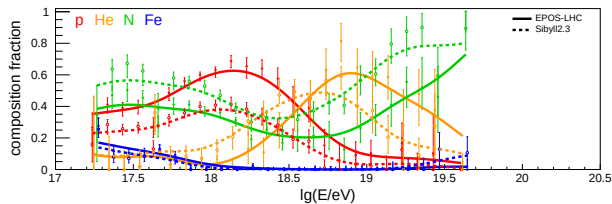


Galactic rotation curve

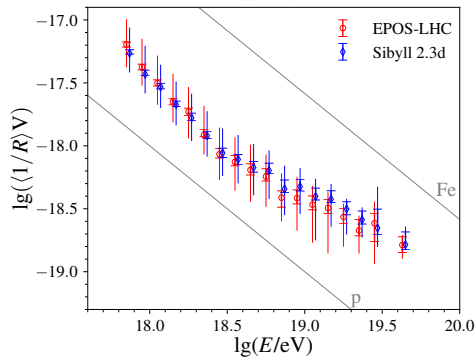


- no separate X- and torodial halo needed! $\rightarrow$ 6 instead of 10 free halo parameters
- “twisting time”: $t = 54.7 \pm 1.1$ Myr $\rightarrow$ effective time (steady state when including dissipation?)

Cosmic-Ray Deflections



D. Harari



- Larmor radius of charged particle in B-field

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

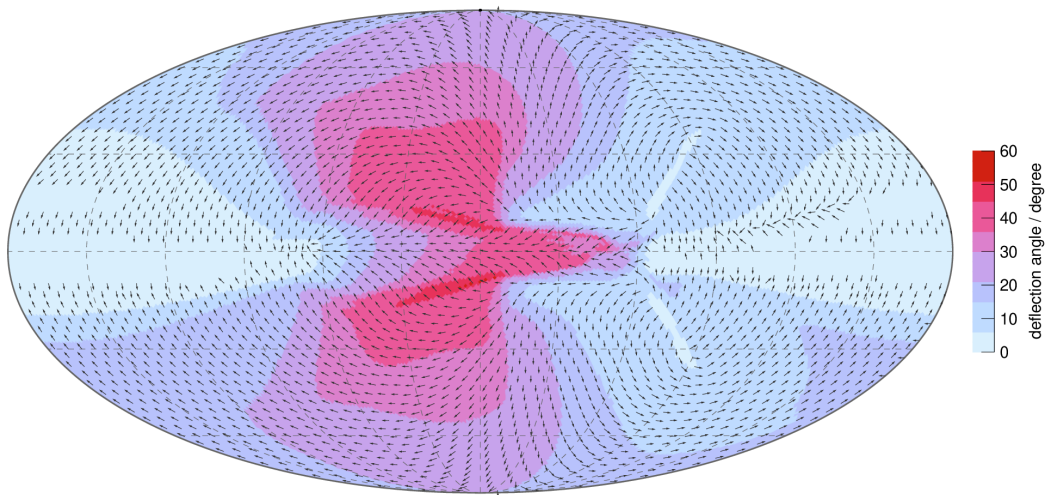
- rigidity

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

- typical GMF deflections (JF12)

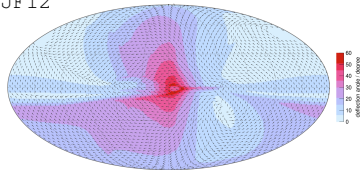
$$\theta_{\text{coh}} \sim 3^\circ \left(\frac{R}{10^{20} \text{ V}} \right)^{-1}$$

Deflections at 20 EV (base model) (backtracking)

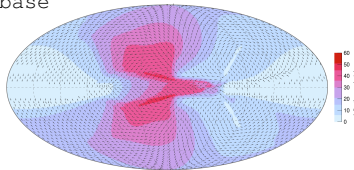


Deflections at 20 EV (model ensemble and JF12) (backtracking)

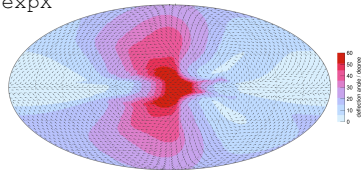
JF12



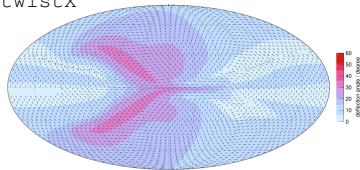
base



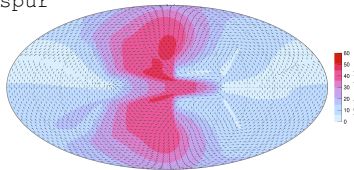
expX



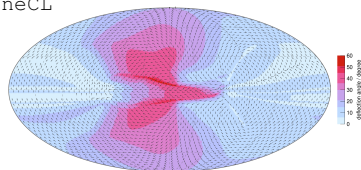
twistX



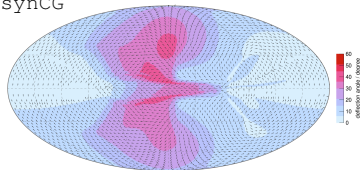
spur



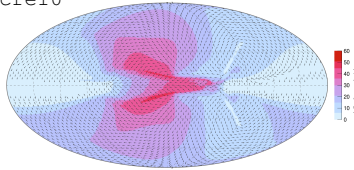
neCL



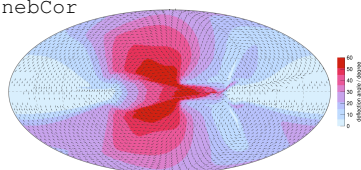
synCG



cre10



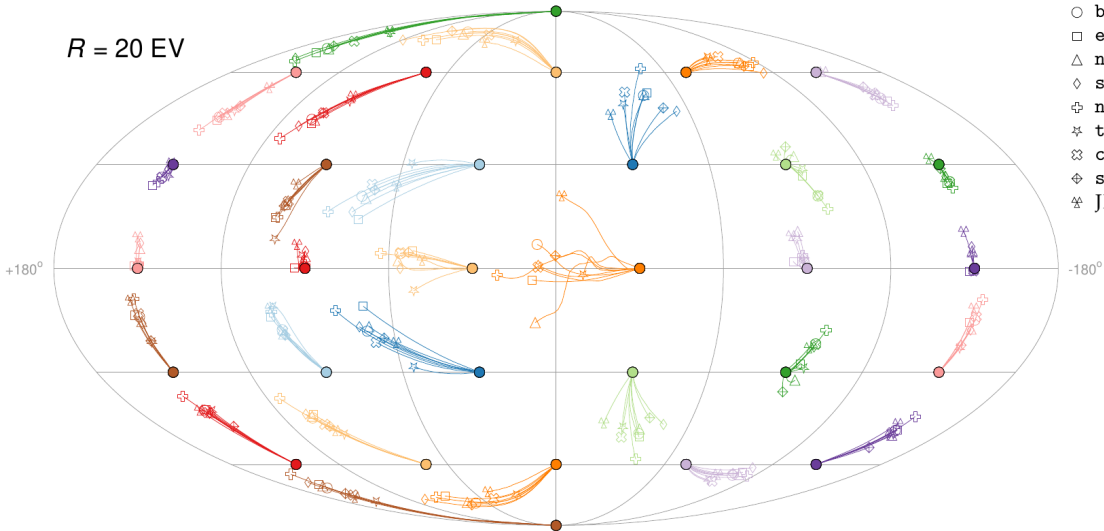
nebCor

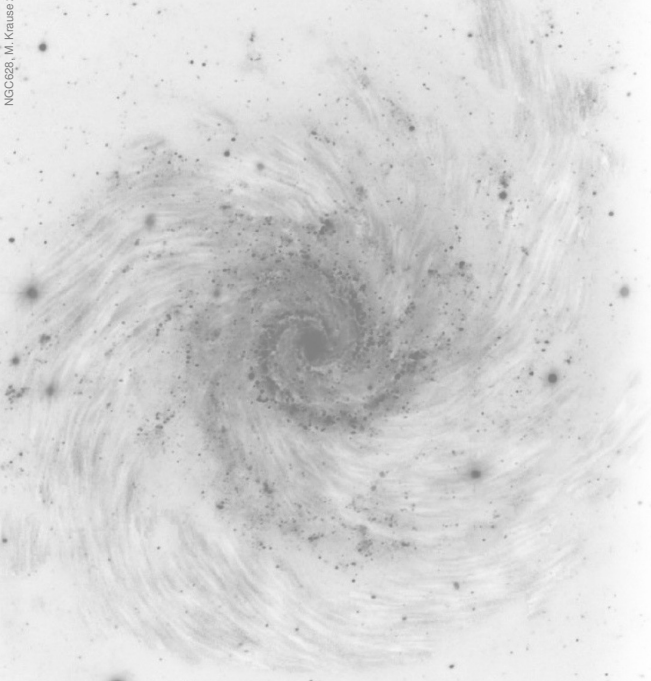


Deflections at 20 EV (backtracking)

$R = 20 \text{ EV}$

- base
- expX
- △ neCL
- ◇ spur
- ⊕ nebCor
- ✱ twistX
- ⊗ cre10
- ⊕ synCG
- ✱ JF12





Summary

New Model(s) of the Coherent GMF

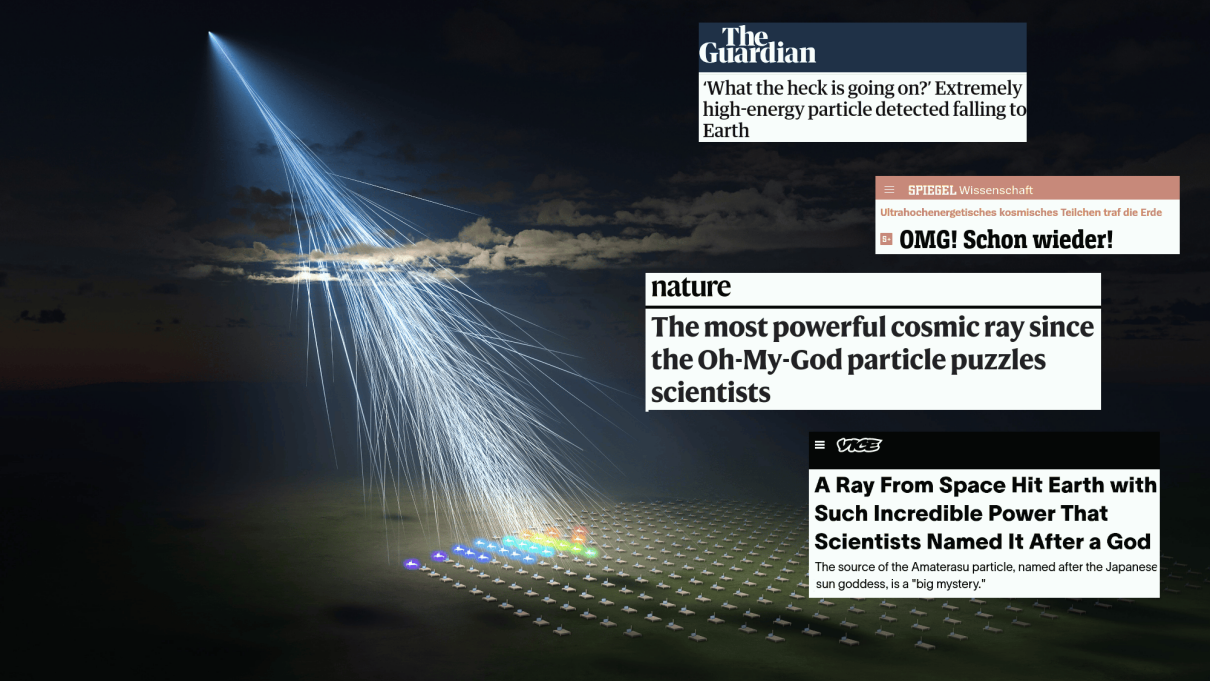
- full-sky RM data
- latest synchrotron sky maps
- improved auxiliary models (n_e and n_{cre})
- smooth disk-field model
- unified halo model

Main Results:

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

Outlook:

- turbulent field using $I_{syn} +$ 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**

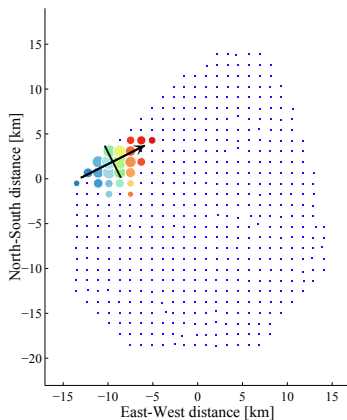
A Ray From Space Hit Earth with Such Incredible Power That Scientists Named It After a God

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

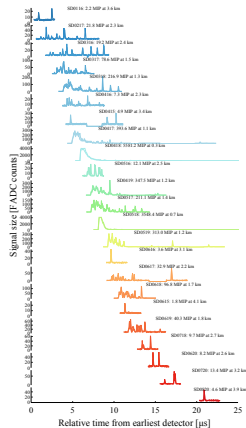
An extremely energetic cosmic ray observed by a surface detector array

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

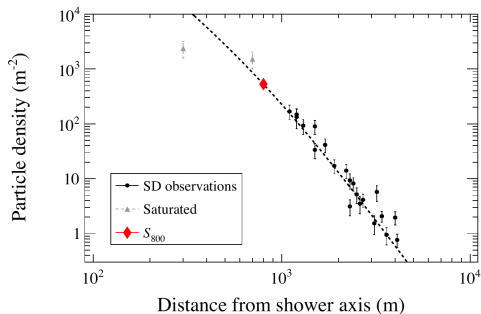
(A) Surface detector array of TA



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

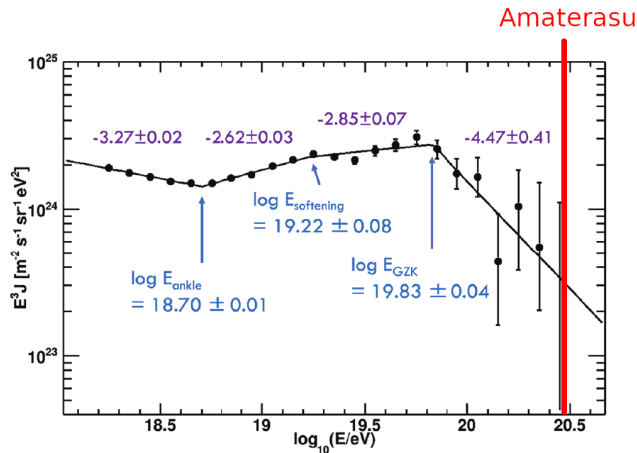


- $E = \left(2.44 \pm 0.29 \text{ (stat.)} {}^{+0.51}_{-0.76} \text{ (syst.)} \right) \times 10^{20} \text{ eV}$
- if Fe: $E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20} \text{ eV}$
- Fe at $-1\sigma_{\text{syst.}}$: $E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$

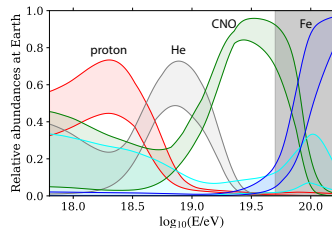


Simplest Assumption: Fe Nucleus from Standard Accelerator

$$(R_{\max} \sim 10^{18.6-18.7} \text{ V})$$

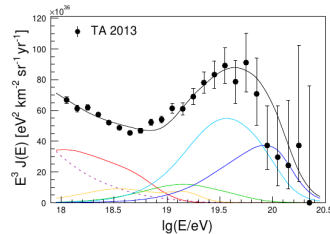


Peters Cycle:



Pierre Auger Coll. 2023

Photodisintegration in source:

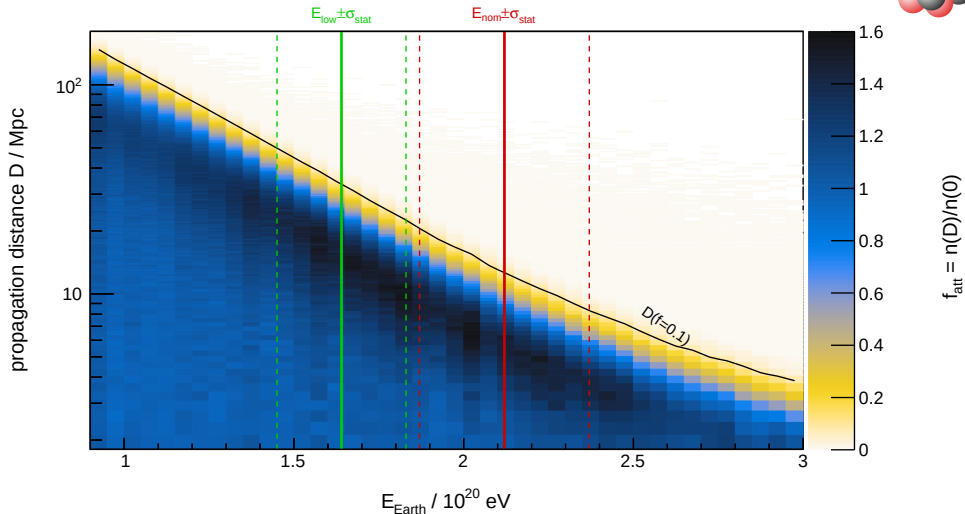
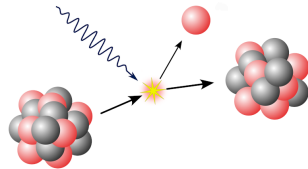


(c) Flux at Earth

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

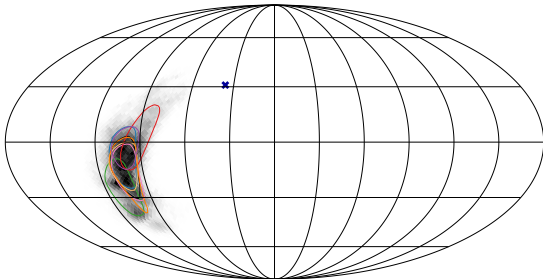
Propagation of Fe in Extragalactic Photon Fields

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

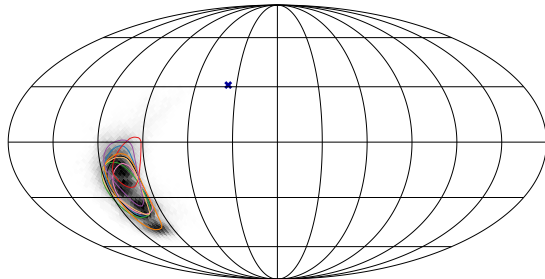


Arrival Direction

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



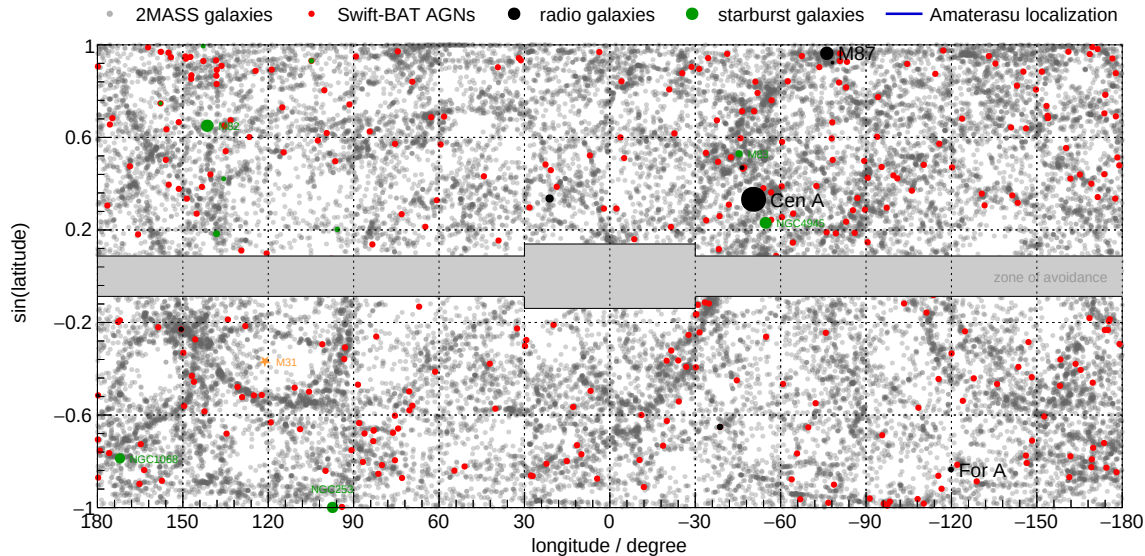
$$E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$$



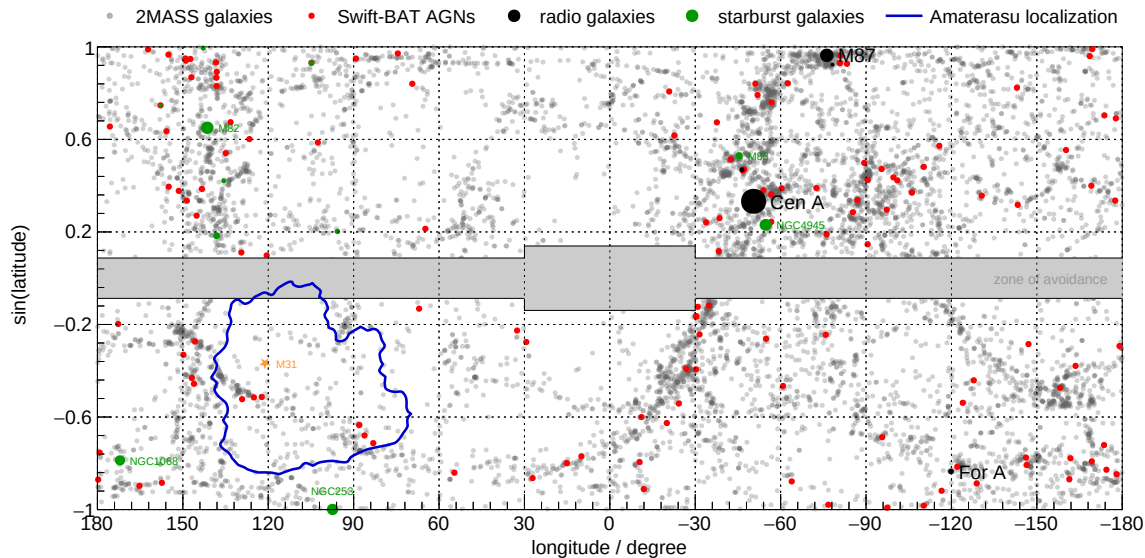
localization uncertainty: 6.6% of 4π or 2726 deg²

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

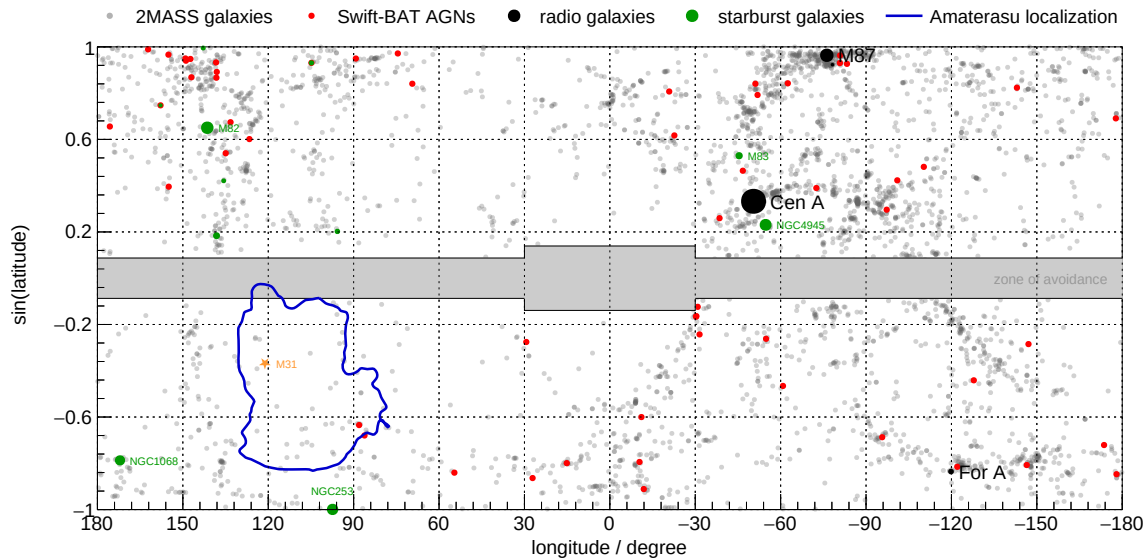
Distribution of galaxies up to D=150 Mpc



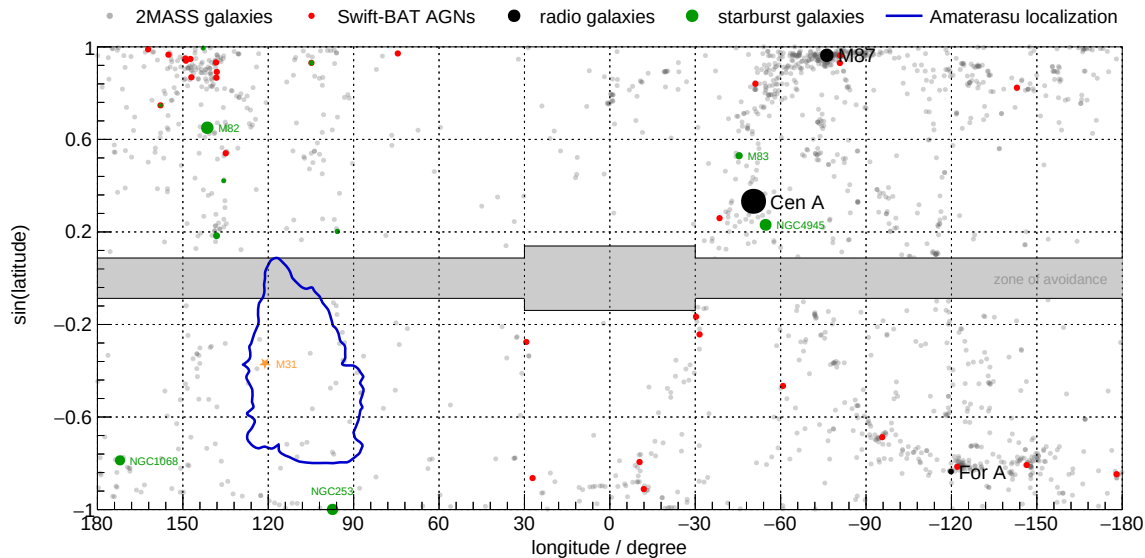
$E_{\text{low}} - 2\sigma$, $D_{0.1}=72$ Mpc



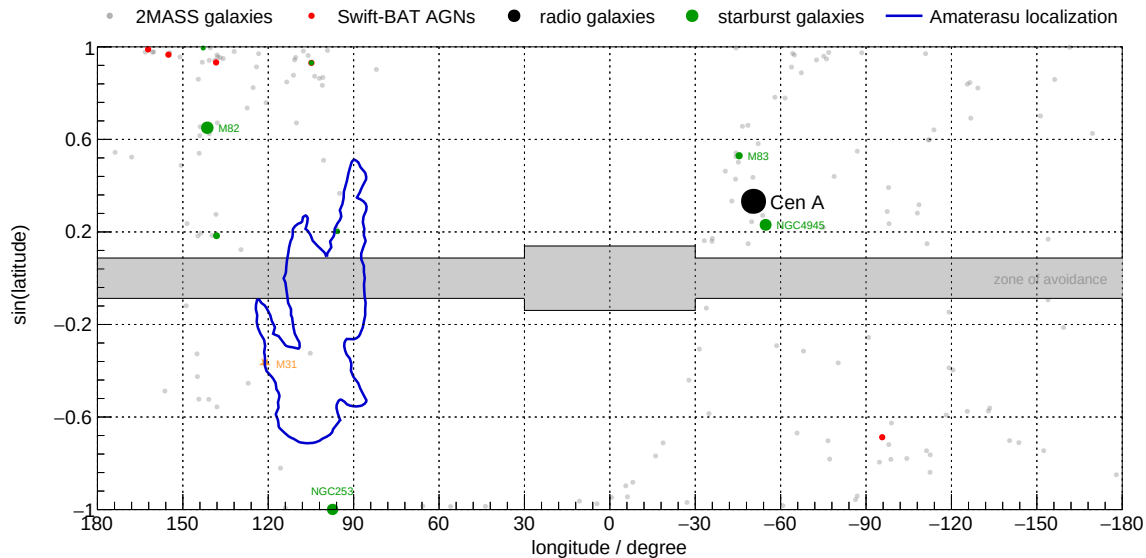
$E_{\text{low}} - 1\sigma, D_{0.1}=42 \text{ Mpc}$



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



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



Amaterasu Particle

- simplest assumption: Fe nucleus
- localization uncertainty (using UF23 ensemble):
→ 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?