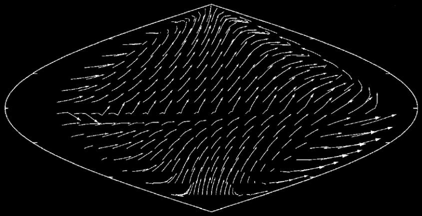
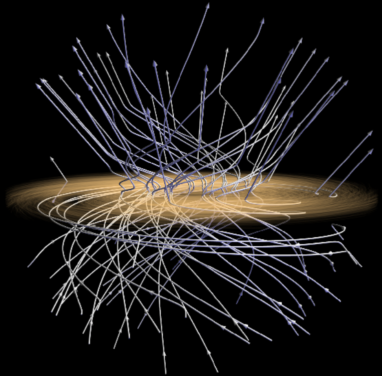
Constraining the Global Structure of the Coherent Galactic Magnetic Field

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

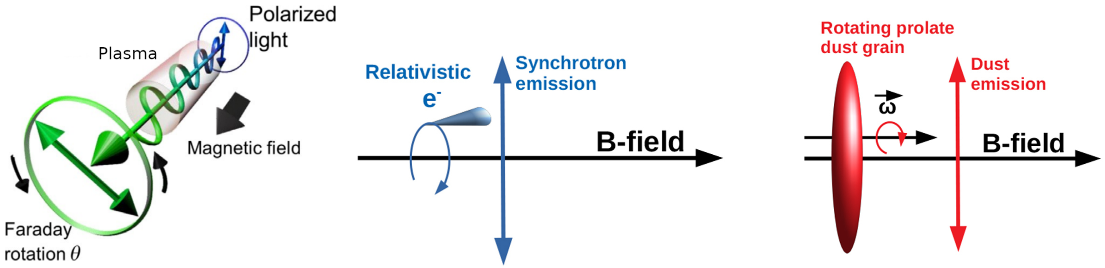




NGC628 M. Krause 2019; T. Stanev ApJ97; JF12 Farrar&Sandstrom

Modeling of the Coherent Galactic Magnetic Field (GMF)

Observables:



adapted from Hasegawa+13 and Pelgrims+18

Popular Models in UHECR:

	S97	PT11	JF12	Planck16	TF17
parameter fit	✗	✓	✓	✗	✓
extragalactic RMs	✗	✓	✓	✗	✓*
polarized synchrotron	✗	✗	✓	✓	✗
polarized dust	✗	✗	✗	✓	✗

T. Stanev ApJ 1997, Pshirkov et al ApJ 2011, R. Jannsson&G.R. Farrar ApJ 2012, Planck Collab. A&A 2016, Terral&Ferriere A&A 2017

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

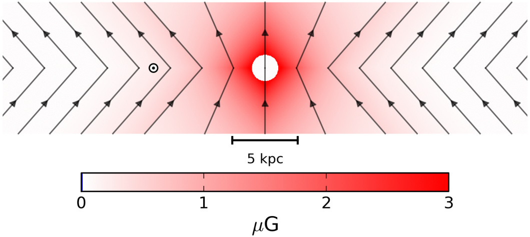
Jansson&Farrar Global Magnetic Field Model (JF12)

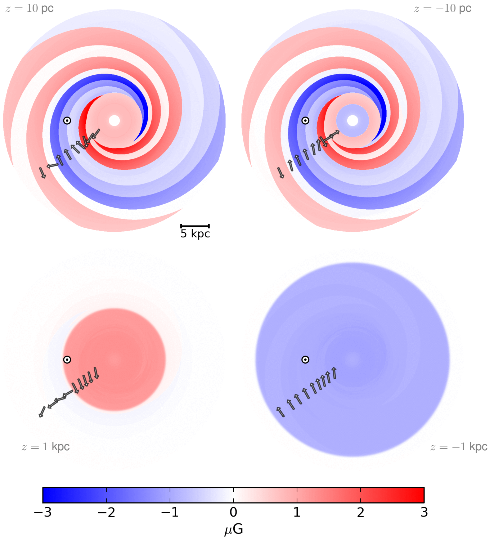
R. Jansson & G.F. Farrar, ApJ **757** (2012) 14

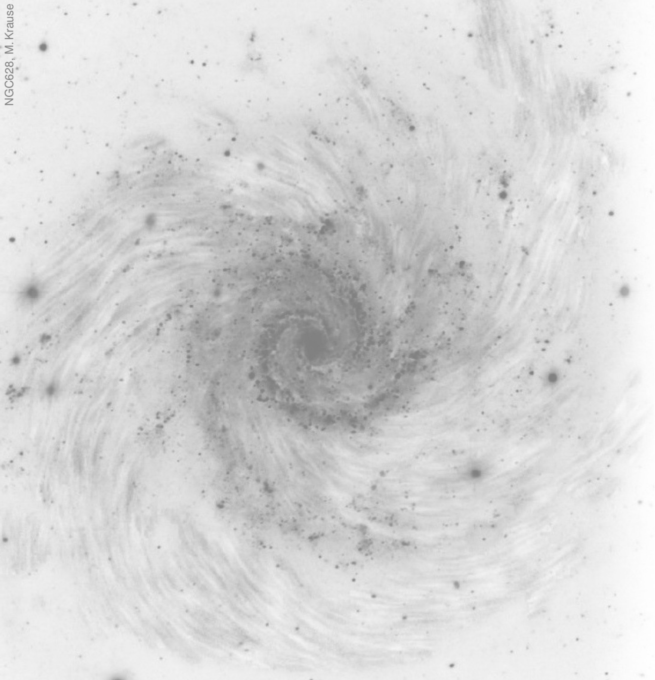
three divergence-free components:

- disk field, ($h \lesssim 0.4$ kpc)
- toroidal halo field ($h_{\mathrm{scale}} \sim 5.3$ kpc)
- "X-field" (halo)

- 21 parameters adjusted to 6605 data points

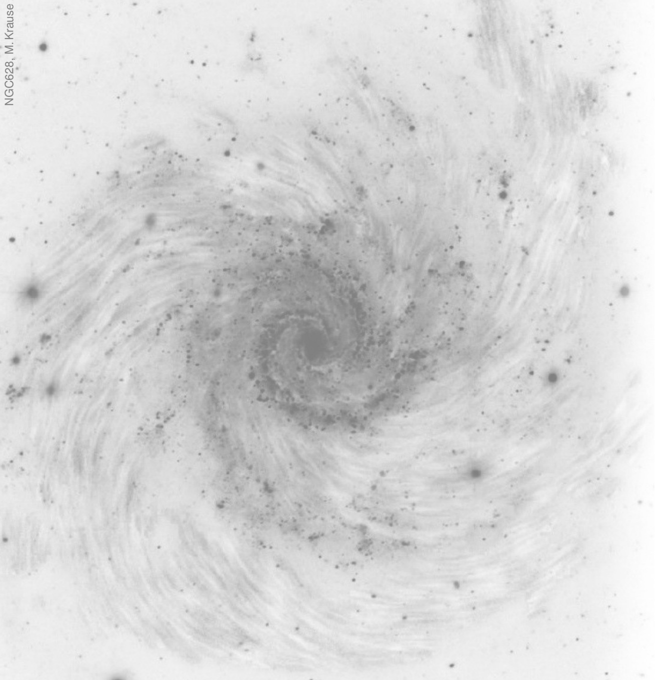






Outline

- **RM and Synchrotron Data**
- **Thermal Electrons**
- **Cosmic-Ray Electrons**
- **Parametric Models**
- **Preliminary Results**



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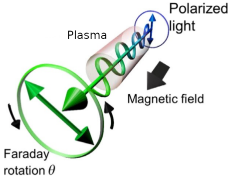
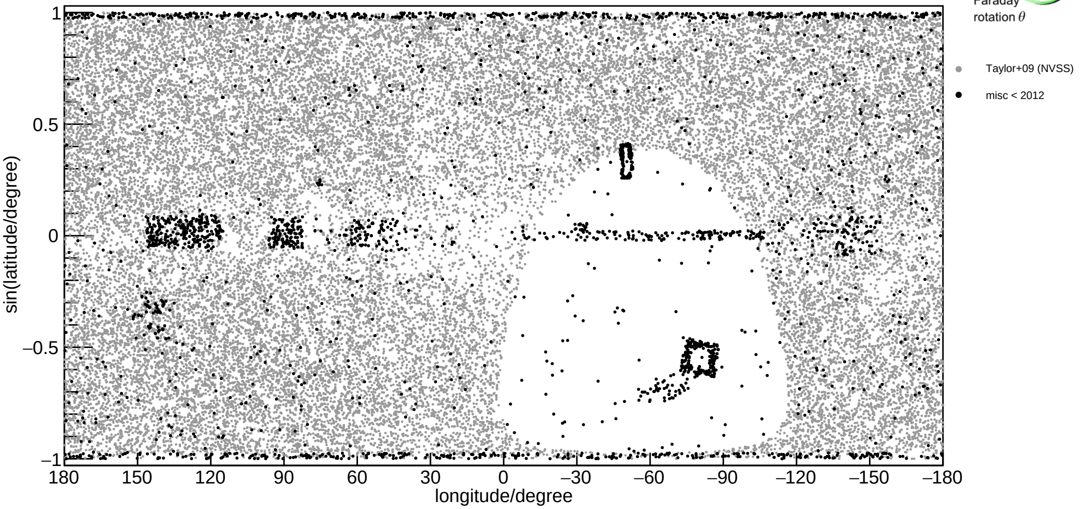
Extragalactic Rotation Measures used for JF12

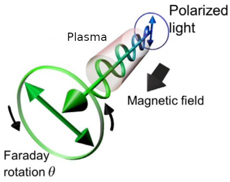
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

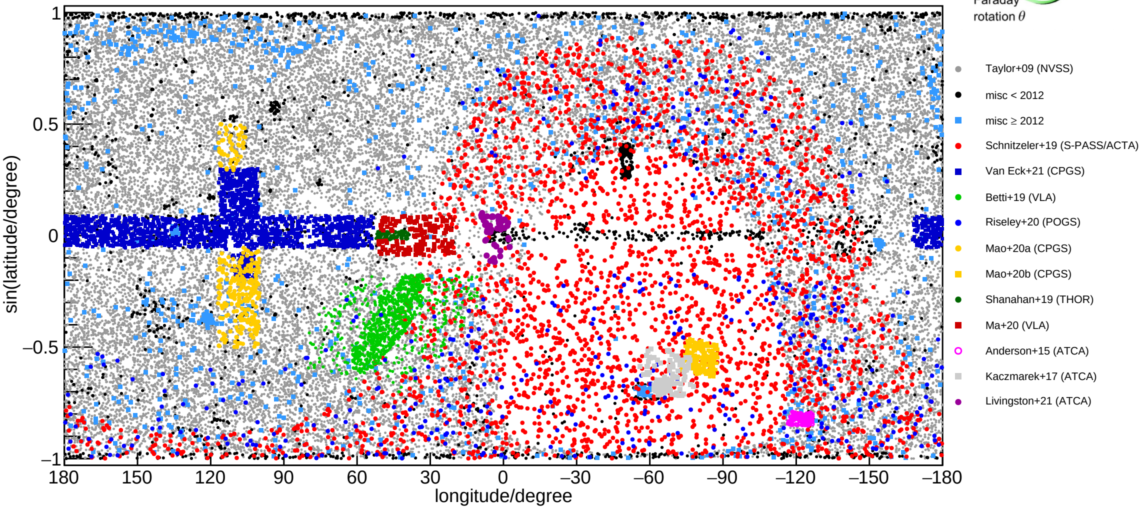




Extragalactic Rotation Measures 2022

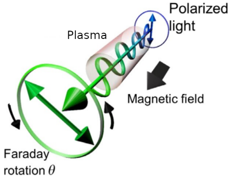
$$\theta = \theta_0 + \mathrm{RM}\,\lambda^2$$

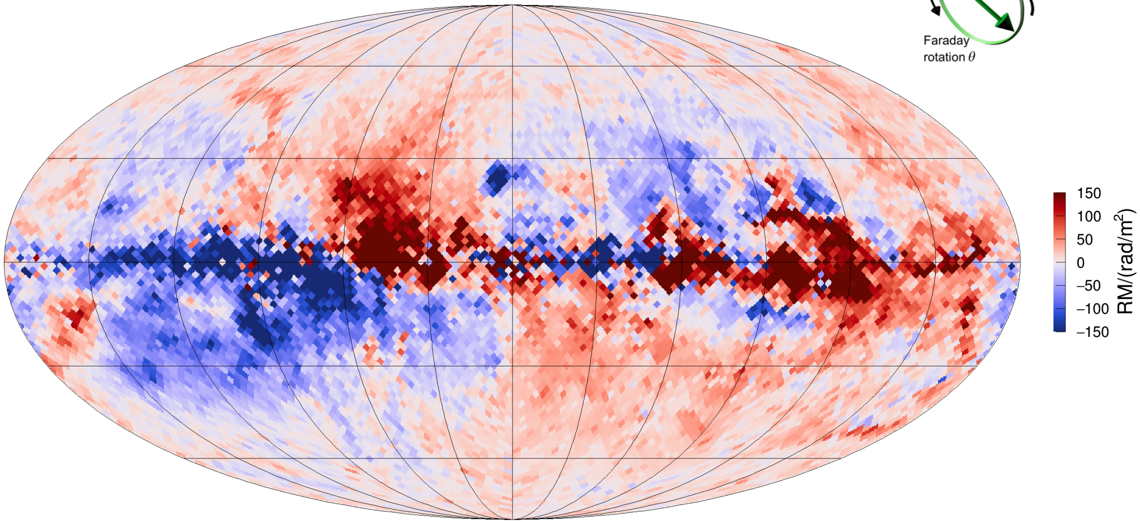




2022 RM Sky

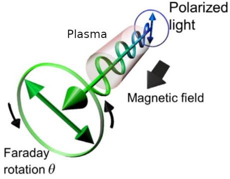
$$\mathrm{RM} \propto \int_{\text{source}}^{\text{observer}} B_{\parallel}(l)\, n_e(l)\, \mathrm{d}l$$

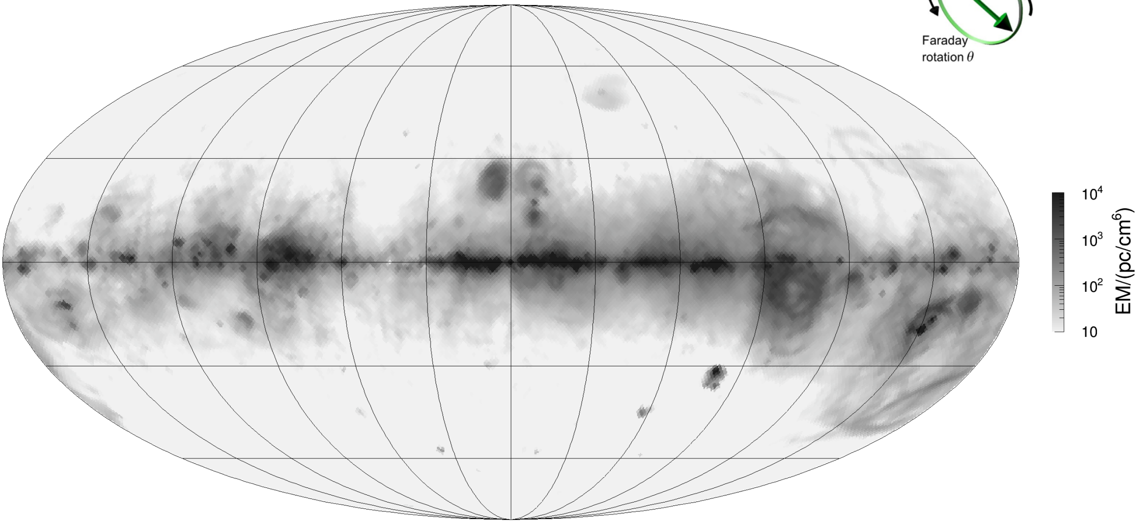




Foreground: HII Regions

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





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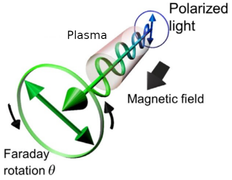
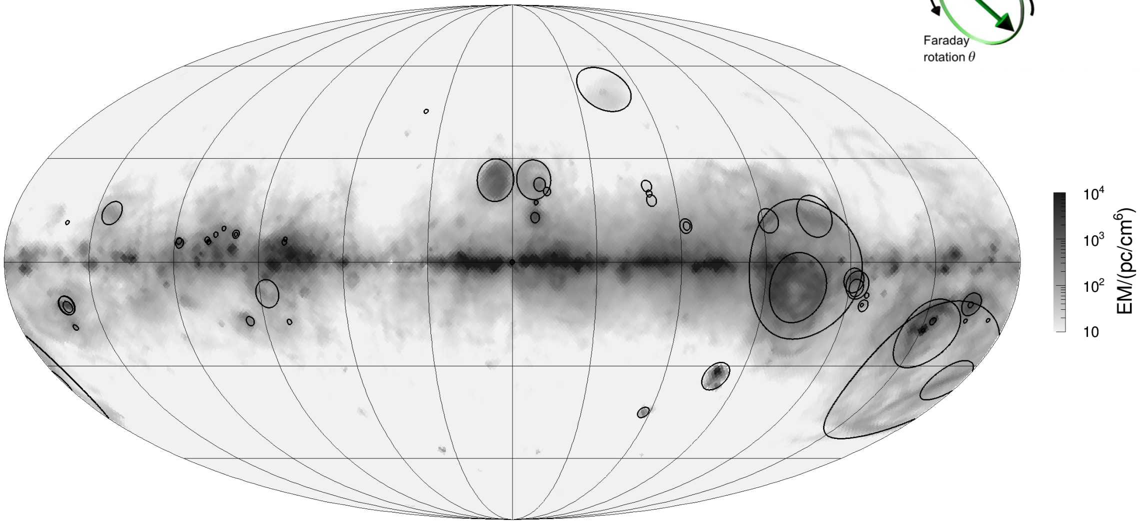
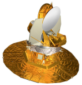
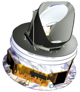




Polarized Synchrotron Emission

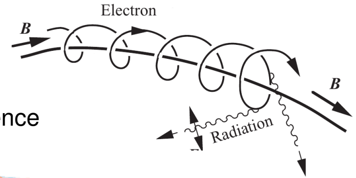


WMAP9



Planck R3.00

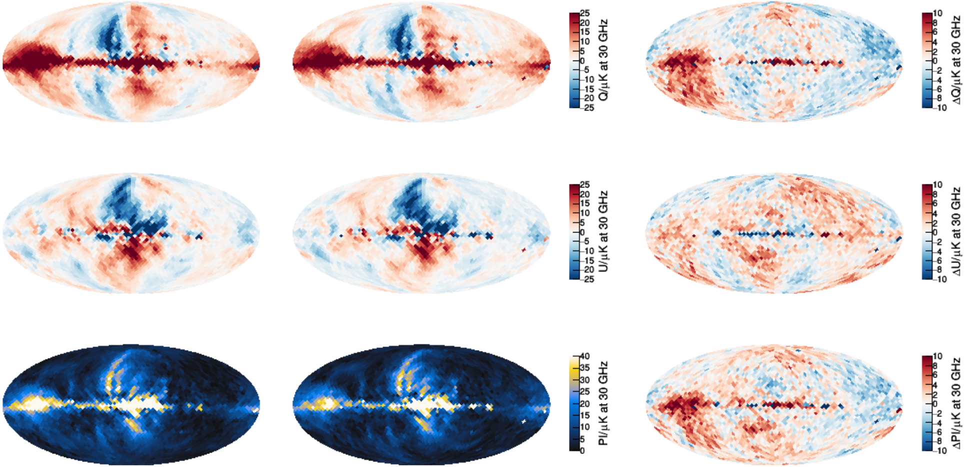
difference



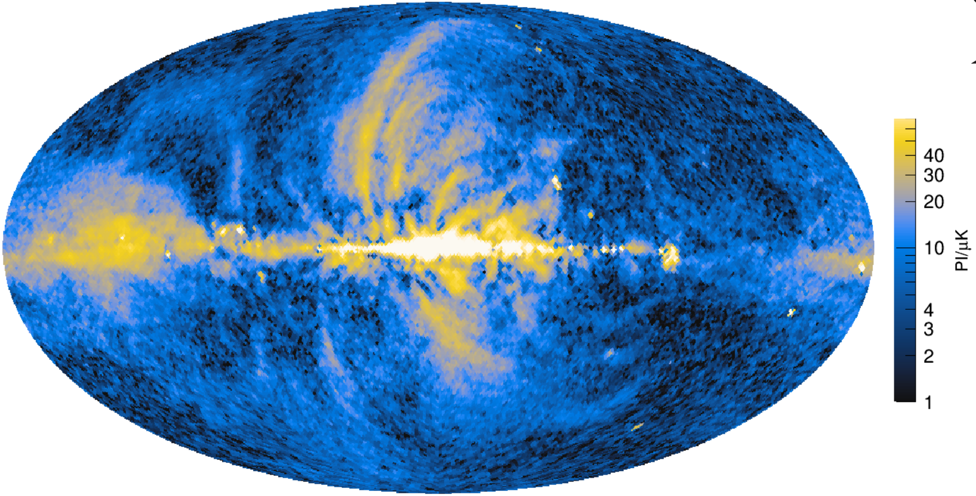
Q

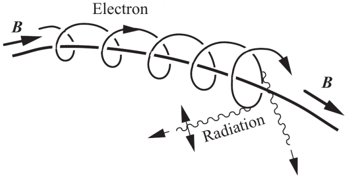
U

PI



Combined WMAP-Planck Polarized Emission





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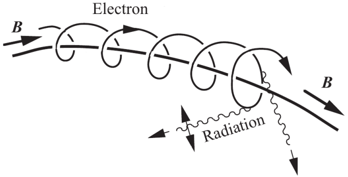

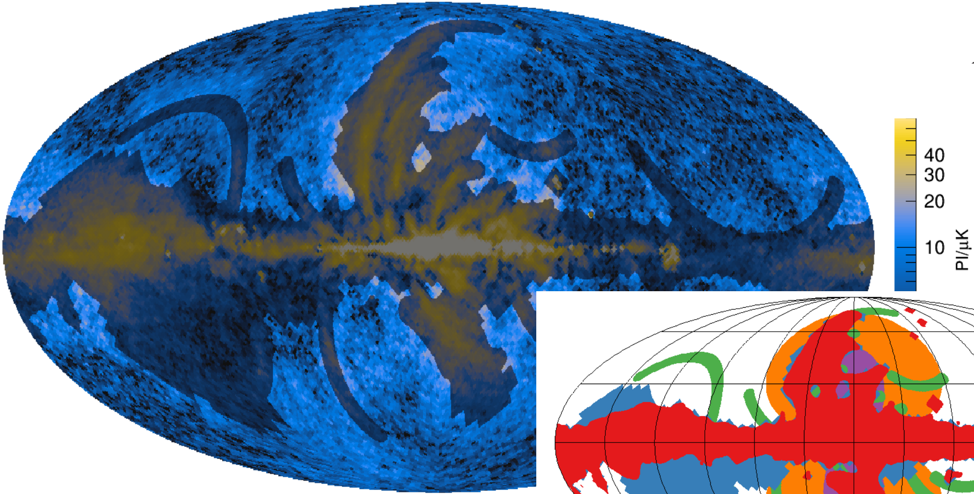

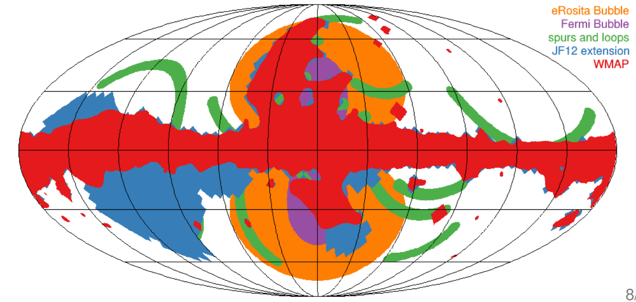

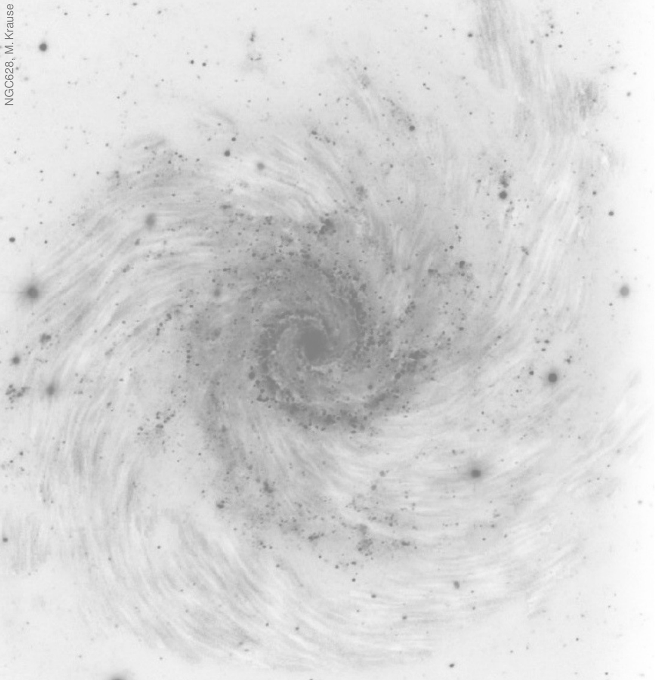

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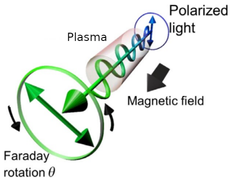
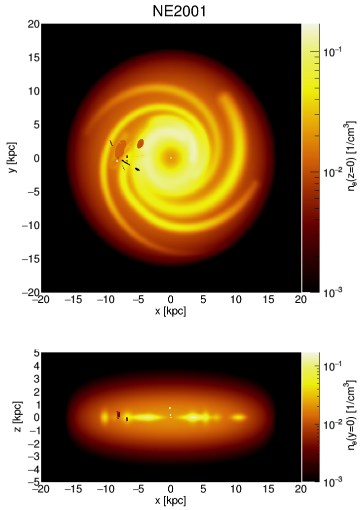
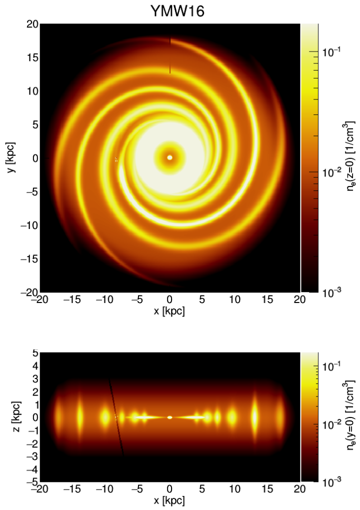
Thermal Electron Models

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





112 pulsar DMs



189 pulsar DMs

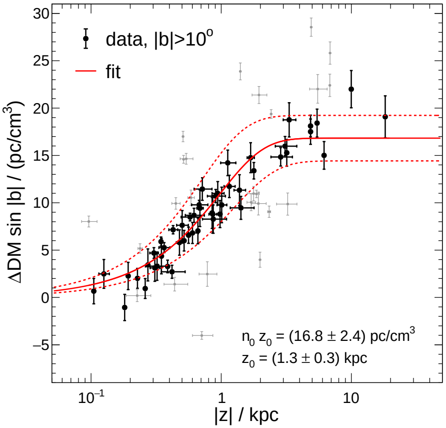
Cordes&Lazio arXiv:0207156

Yao, Manchester & Wang, ApJ 2017

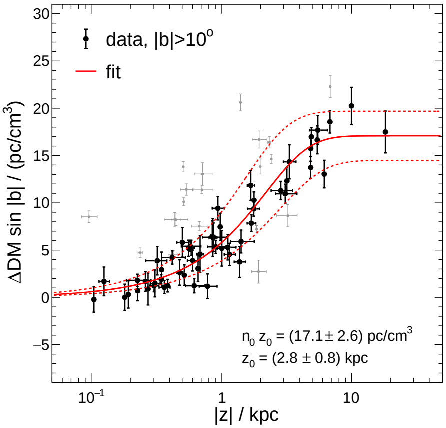
Thermal Electron Halo

reasonably well-constrained from DMs of pulsars in globular clusters

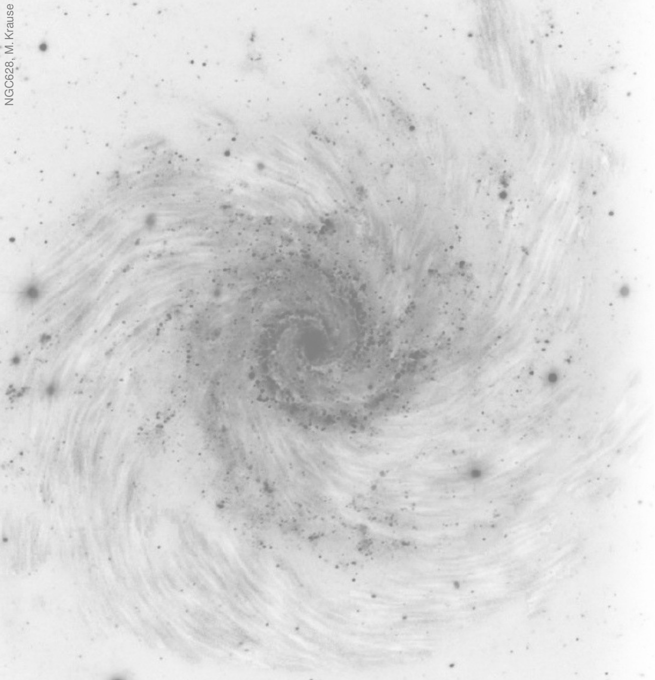
YMW16



NE2001



$\Delta\mathrm{DM}$: data-model residual without exponential halo (preliminary)



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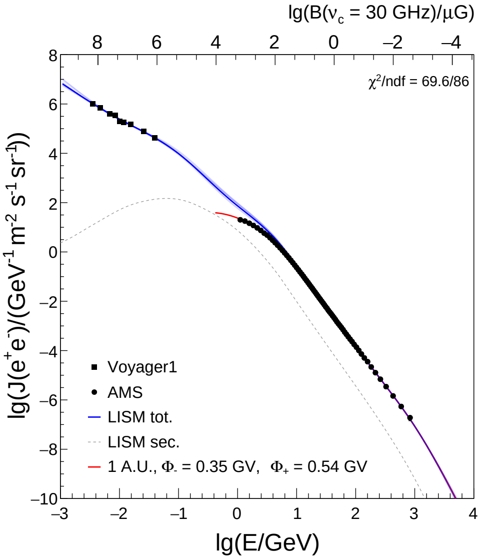
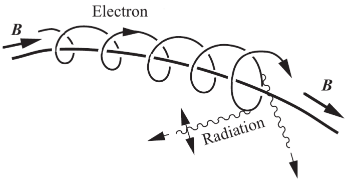
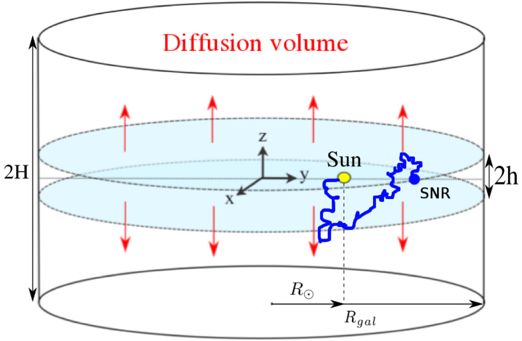
Cosmic-Ray Electron Model







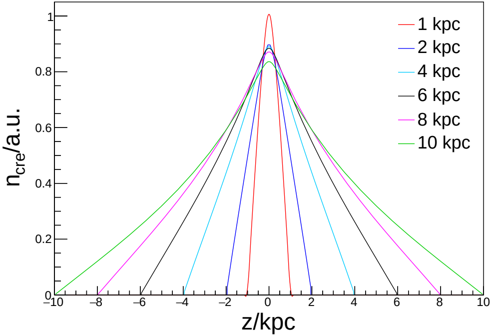
Y. Genolini et al, A&A. **580** (2015) A9

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

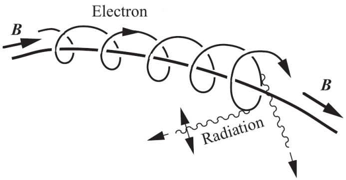
Cosmic-Ray Electron Model

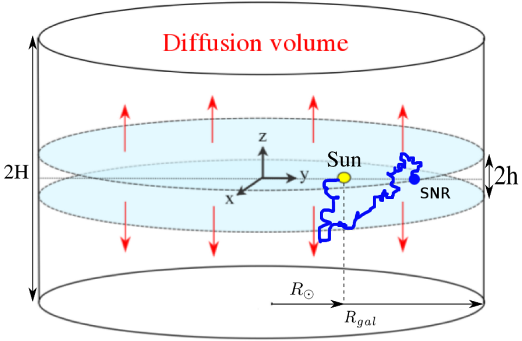
- $D_0/H = \mathrm{const}$ from B/C
- halo half-height H currently not well constrained Weinrich+20, Evoli+20, Maurin+22

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



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





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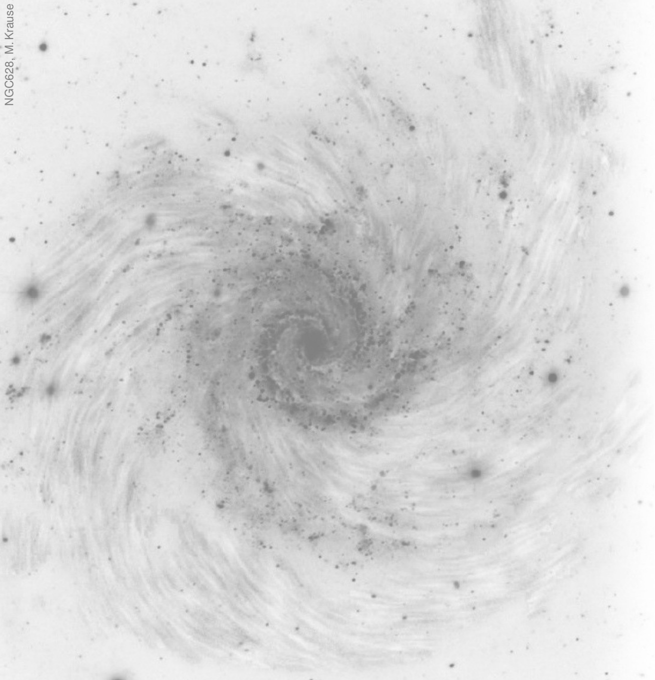

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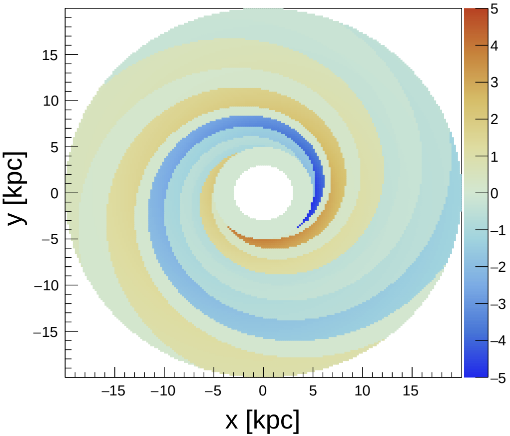
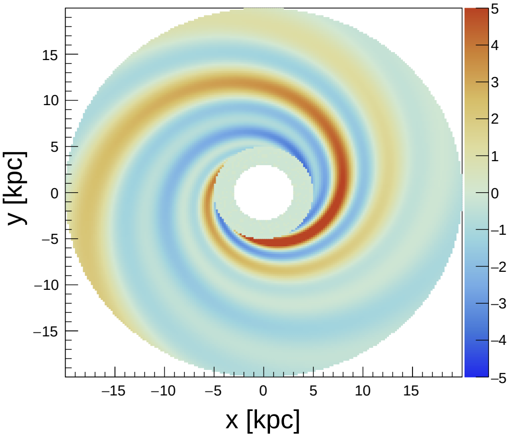
GMF Model Improvements – Disk Field

JF12: Brown+07 “wedge”-model:



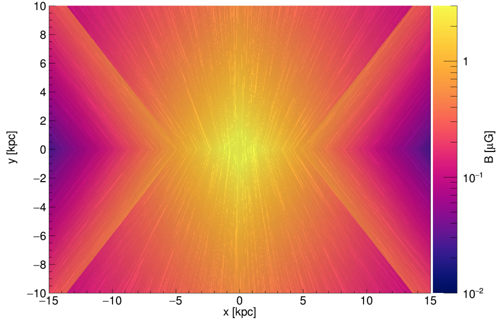
smooth spiral disk field:



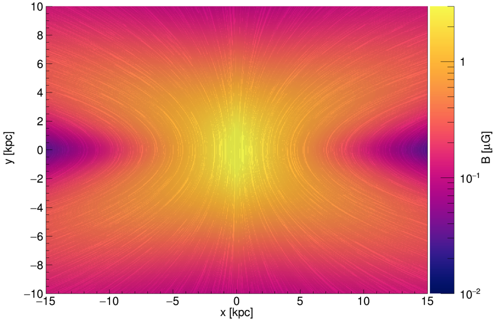
- divergence-free Fourier-expansion of $B_\phi(r)$ at reference radius
- avoids sharp radial discontinuities of JF12
- free pitch angle and “magnetic arms” (number of Fourier modes)

GMF Model Improvements – X-Field

JF12 X-field



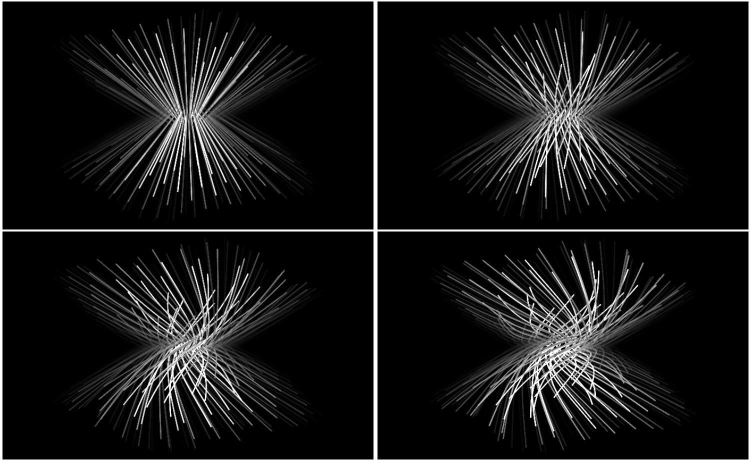
Ferriere&Terral14 “Model C” (FTC)



- JF12: discontinuities at $z = 0$ and transition to $\theta_X = 49^\circ$
- smooth FTC X-field model, but $\theta_X = f(r, z)$

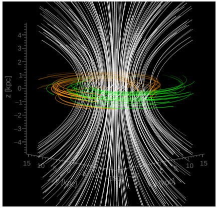
GMF Model Improvements – Halo Field

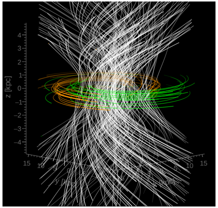
- evolve X-field via ideal induction equation $\partial_t \mathbf{B} = \nabla \times (\mathbf{v}_{\rm rot} \times \mathbf{B})$
- radial and vertical shear of Galactic rotation generates toroidal field

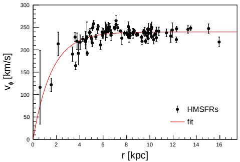


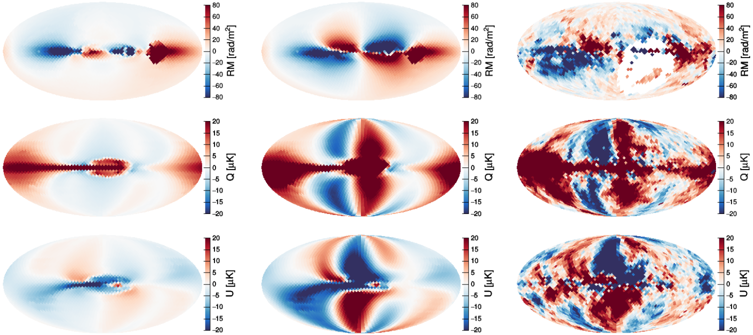
$\rightarrow$ no separate X- and torodial halo needed!

“Twisted X-field”

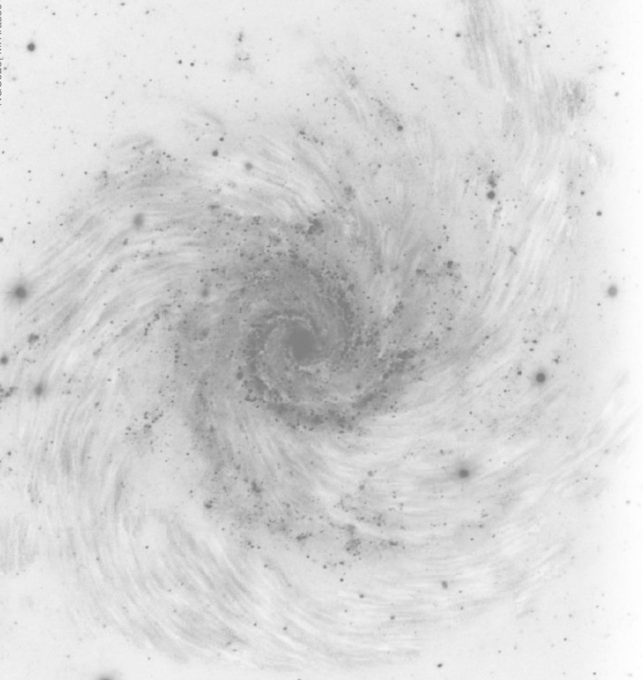








(a) t = 0 Myr (b) t = 70 Myr (c) data


NGC628, M. Krause

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Aim: GMF Model Variations Using Newest Data

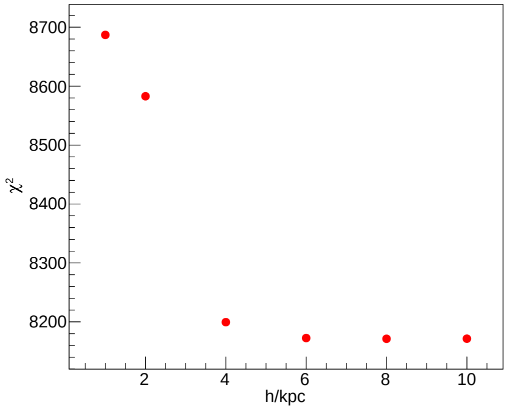
- **2+1 GMF models**:

component \ variation	JF22	UF22a	UF22b
disk	Brown07 spiral	Fourier spiral	Fourier spiral
toroidal halo	JF12	JF12	twisted X
poloidal halo	JF12	FT14	

- **2 thermal electron models**: NE2001, YMW16
- **4 CR electron models**: (diffusion height $H = 4, 6, 8, 10$ kpc)

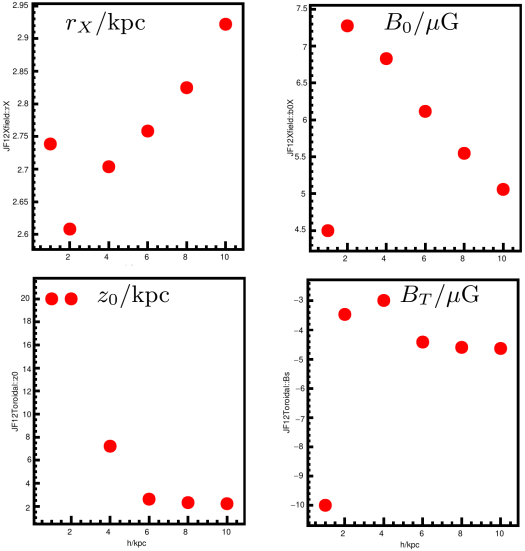
$\rightarrow$ 1 (best-fit) "fiducial" model
$\rightarrow$ 23 variations to estimate uncertainties (lower limit)

Example: Influence of Diffusion Height H



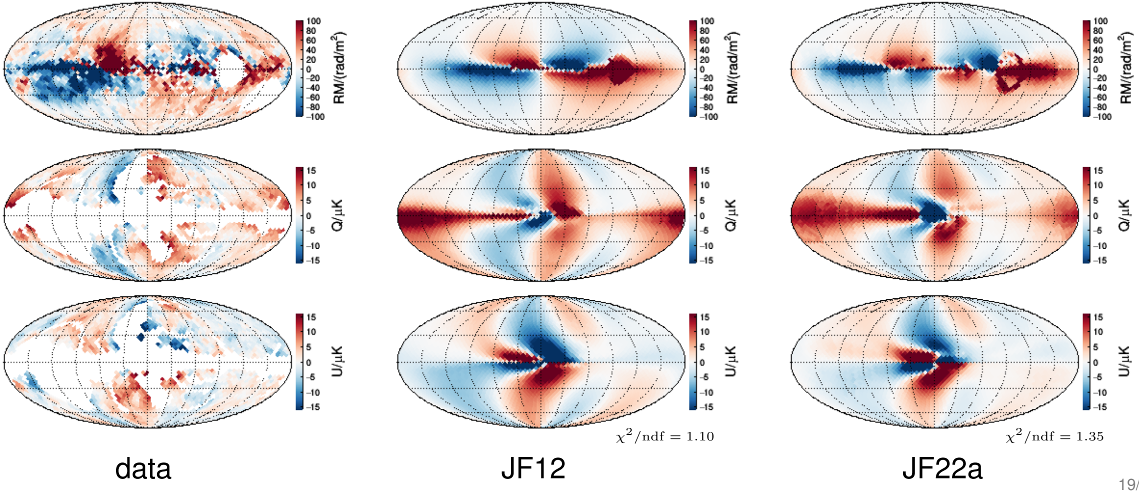
(npar = 23, ndf = 6499)

$B_X \propto B_0 \exp(-r/r_X)$, $B_T \propto B_T \exp(-z/z_0)$



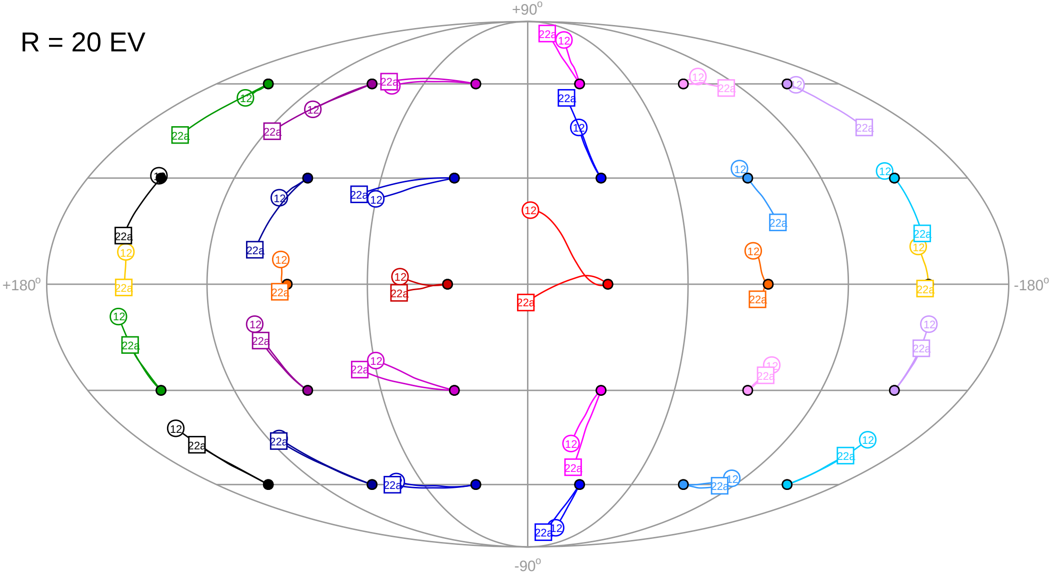
Refit of JF12

	JF12	JF22
RM data	2011	2022
QU	WMAP7	WMAP9&Planck
RM mask	none	HII
PI mask	35%	35%+spurs
thermal electrons	NE2001	YMW16
cosmic-ray electrons	GALPROP E^{-3}	DRAGON PD 4 kpc
Xfield at GC	0 within r = 1 kpc	continous



Deflections: JF12 vs JF22a

R = 20 EV



Summary and Outlook

Major Overhaul of JF12

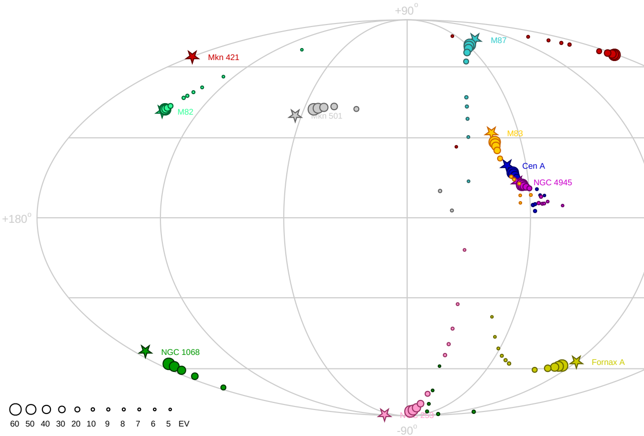
- new RM data
- new synchrotron sky maps
- improved auxillary models (n_e and $n_{\rm cre}$)
- smooth disk-field
- unified halo model

Model Variations → Uncertainties:

- parametric model choices
- $n_{\rm cre}$ and n_e models

Next up:

- random field, $n_e - B$ correlations, foregrounds: local bubble, spurs,...



JF12 coherent defeflections

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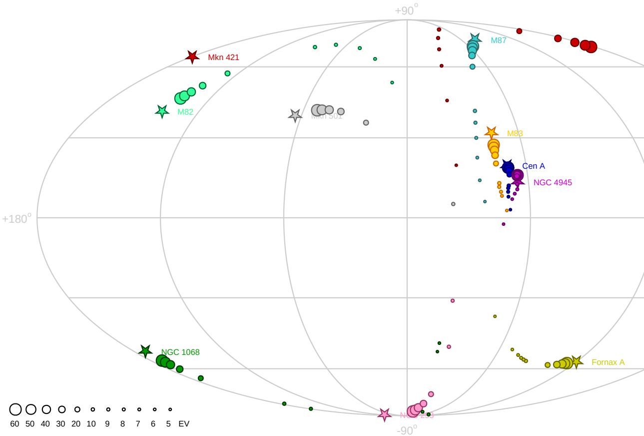

JF22a coherent defeflections