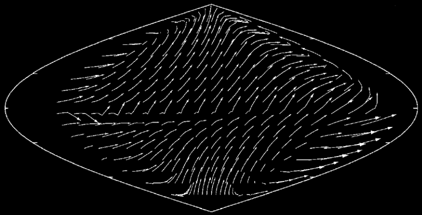
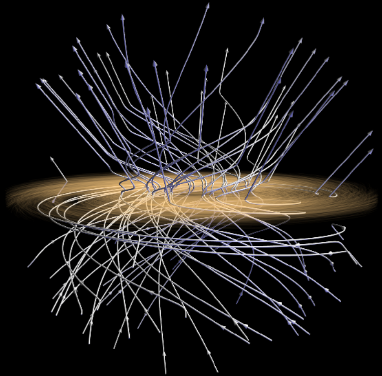
New Models of the Magnetic Field of the Galaxy

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





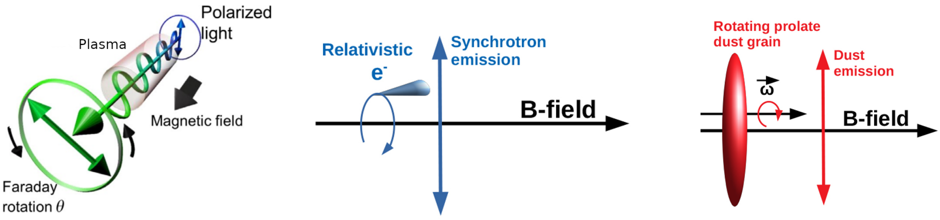
Cosmic-Ray Anisotropy Workshop (CRA) 2023

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

Modeling of 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 ($|b| > 10^\circ$)

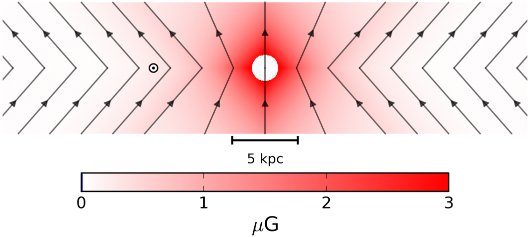
Jansson&Farrar Magnetic Field Model (JF12)

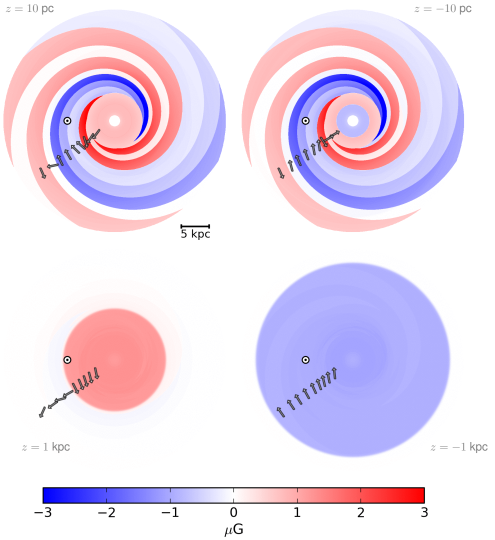
R. Jansson & G.F. Farrar, ApJ **757** (2012) 14

three divergence-free components:

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

- 21 parameters adjusted to 6605 data points





Model Optimization

model

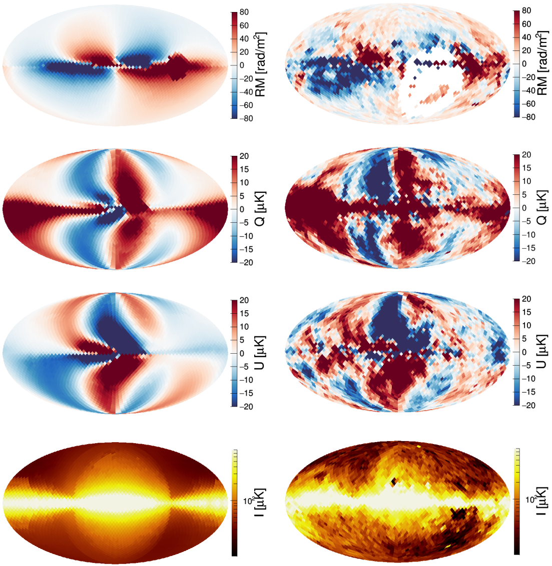
$B_{\parallel}$ + thermal electrons → RM

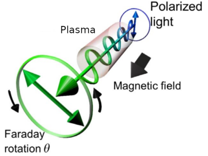
$B_{\perp}$ + cosmic-ray electrons → Synchrotron

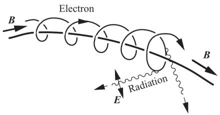
$B_{\perp}$ +

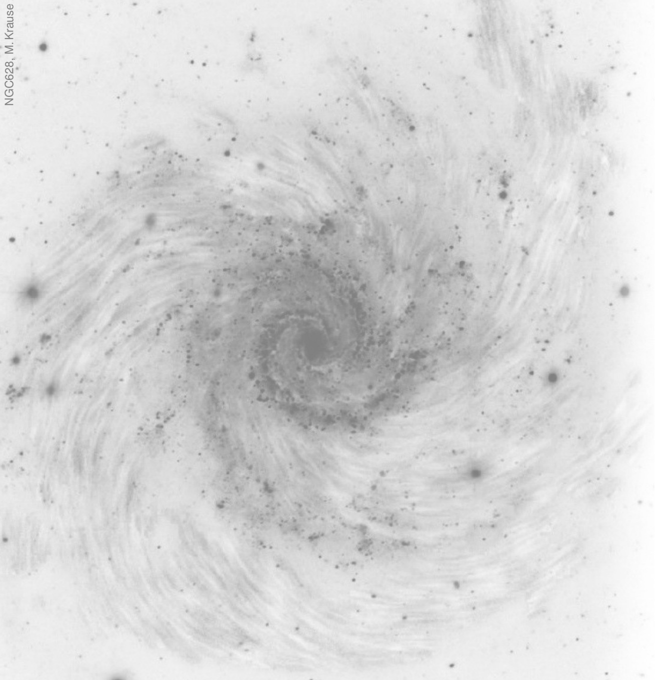
$b\&B_{\perp}$ +

model prediction | data



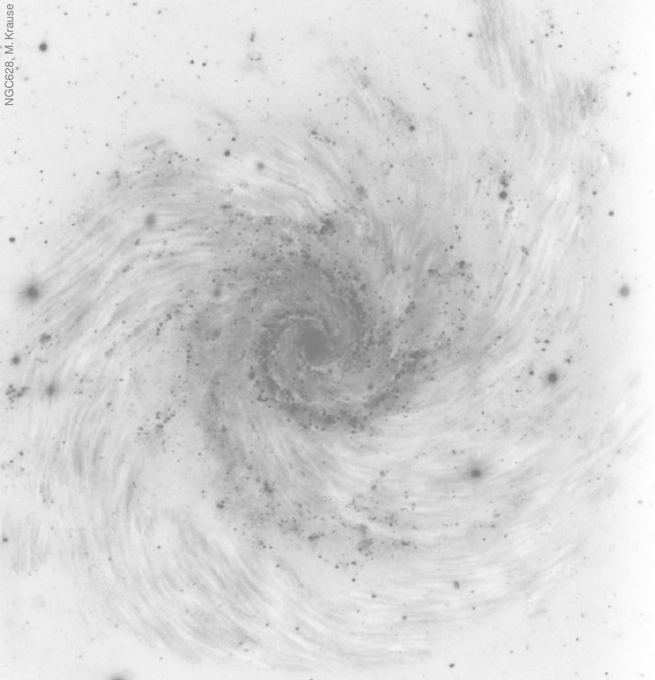






Outline

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



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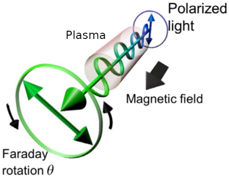
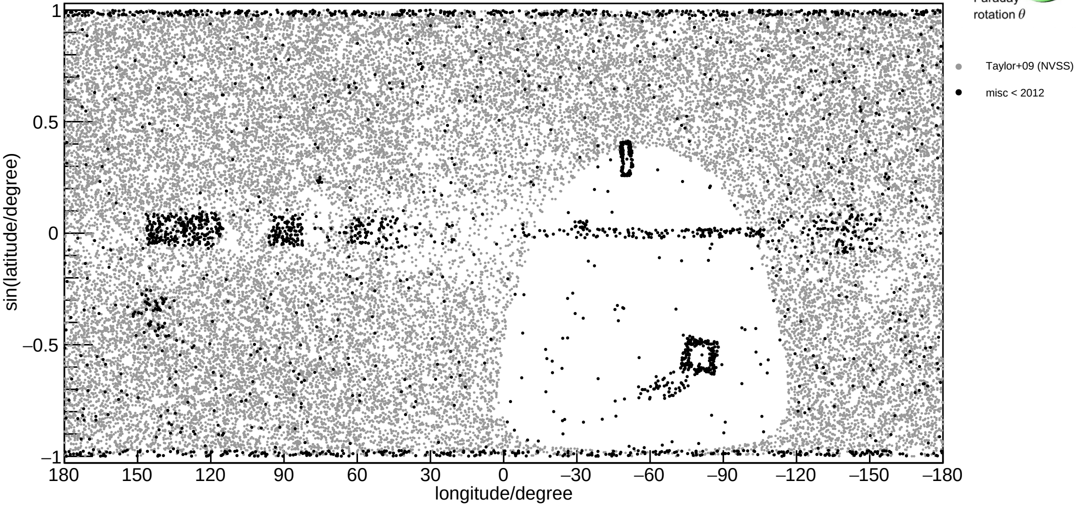
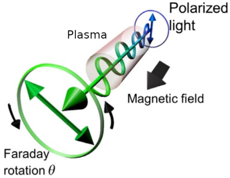
Extragalactic Rotation Measures used for JF12



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



Extragalactic Rotation Measures 2023



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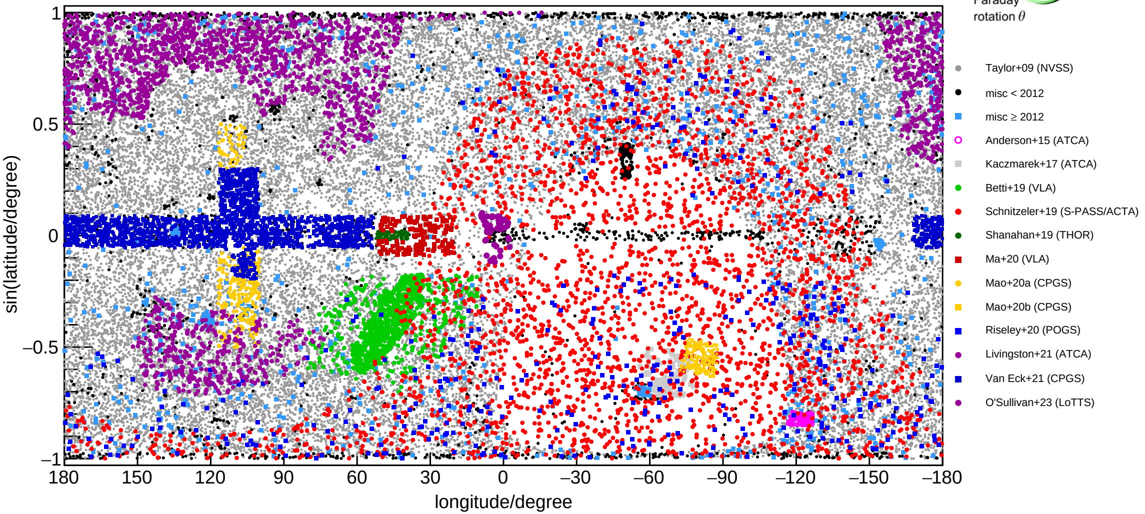
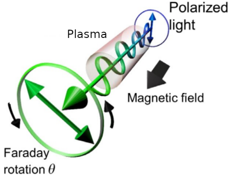
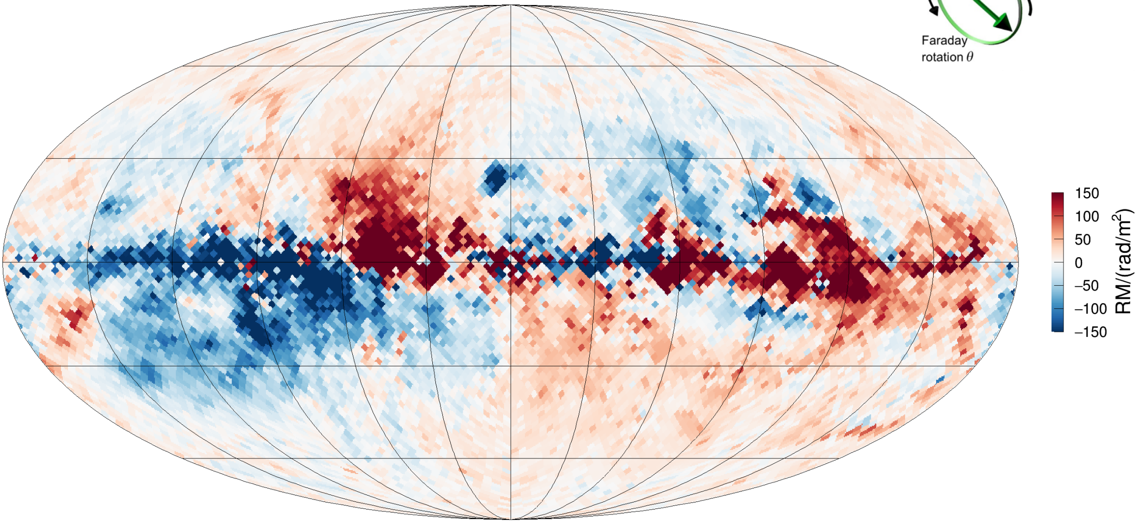


2023 RM Sky

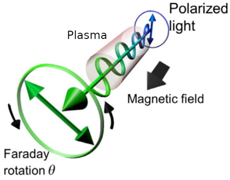
$$\mathrm{RM} \propto \int_{\text{source}}^{\text{observer}} B_{\parallel}(l)\, n_e(l)\, \mathrm{d}l$$

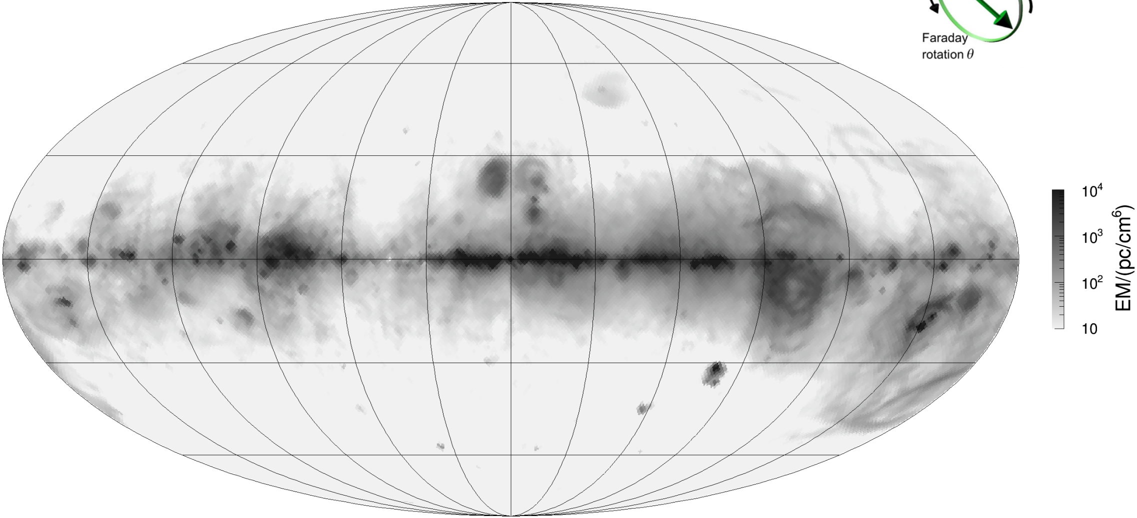




Foreground: HII Regions

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





Foreground: HII Regions

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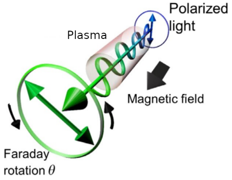
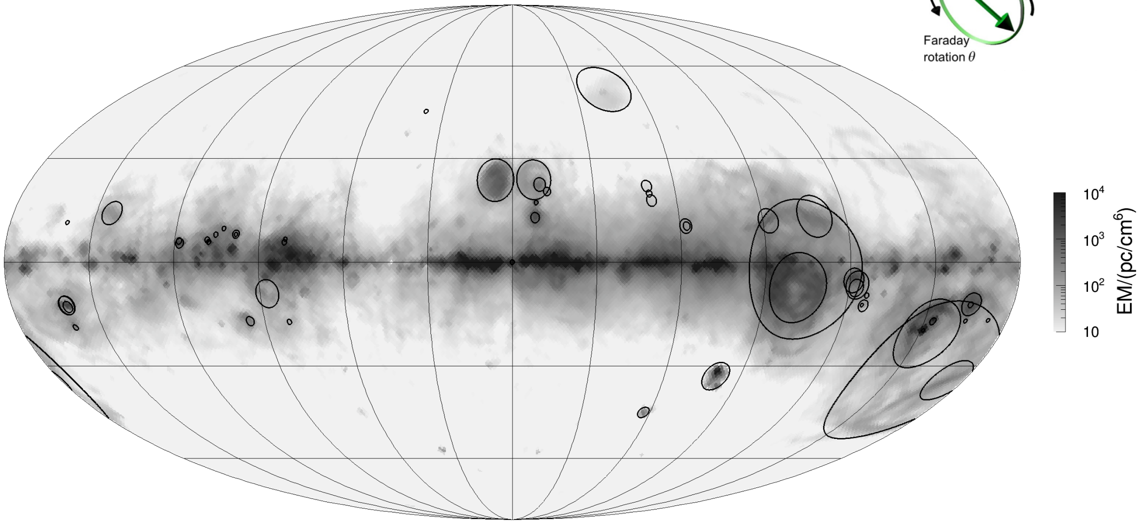
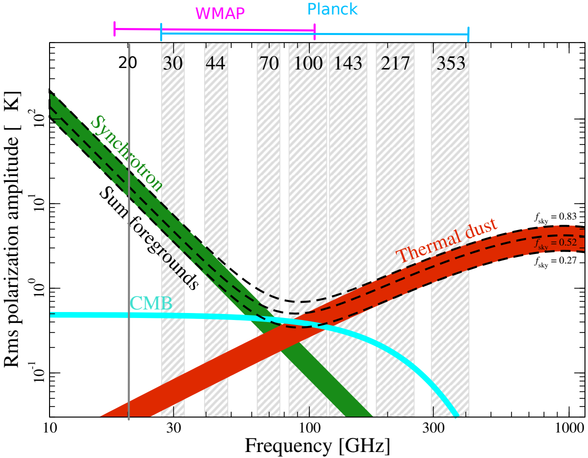
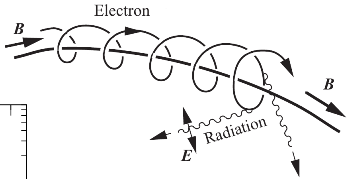




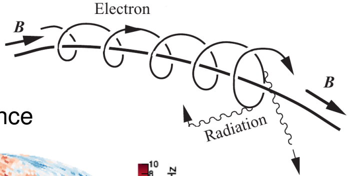
Polarized Synchrotron Emission

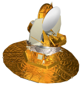




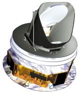
- antenna temperature: $T_{\text{syn}} \propto \nu^{-(p+3)/2} \equiv \nu^{\beta_S}$
- electron spectral index p: ~ 2 at source, ~ 3 after cooling
- $\beta_S \sim -3 \rightarrow T_{\text{syn}}(20 \text{ Hz})/T_{\text{syn}}(30 \text{ Hz}) \approx 3.4$

Polarized Synchrotron Emission





WMAP9



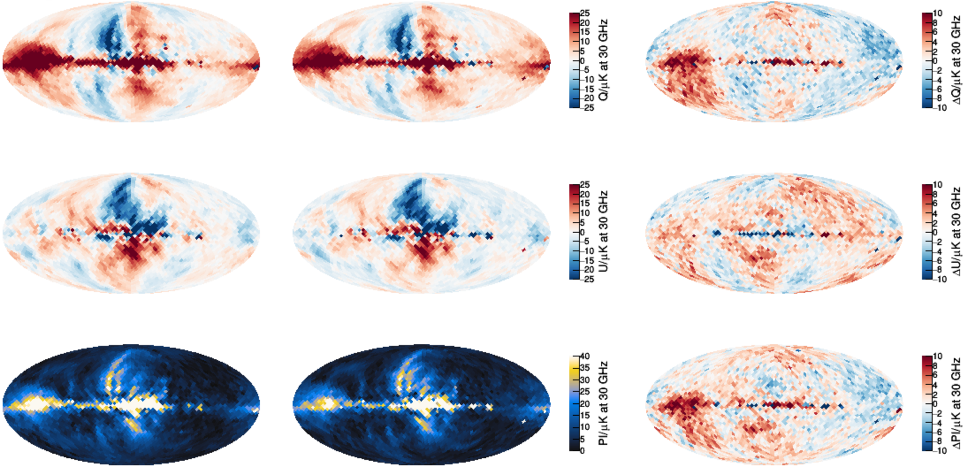
Planck R3.00

difference

Q

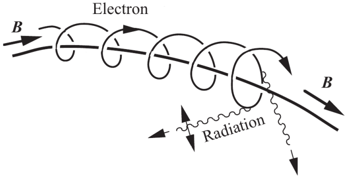
U

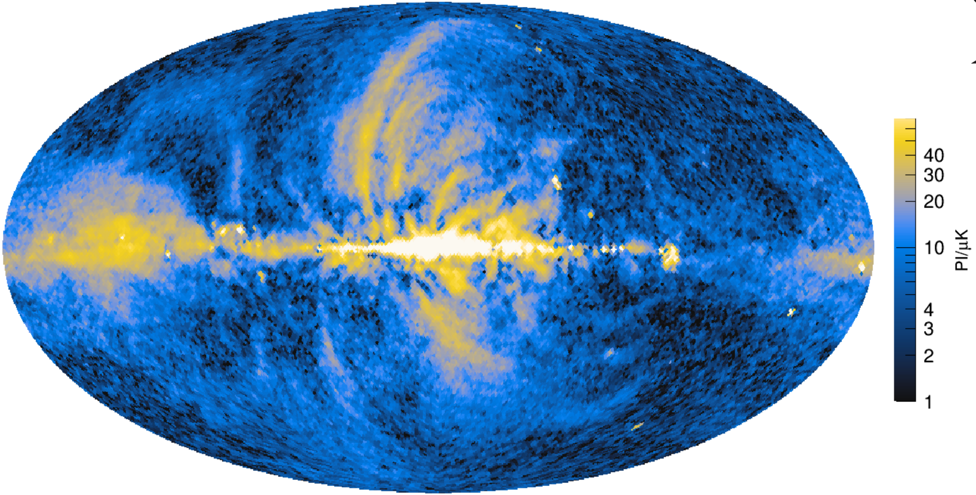
PI



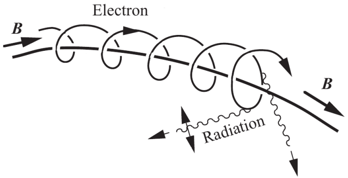
calibration uncertainty? cosmic-ray spectral index?

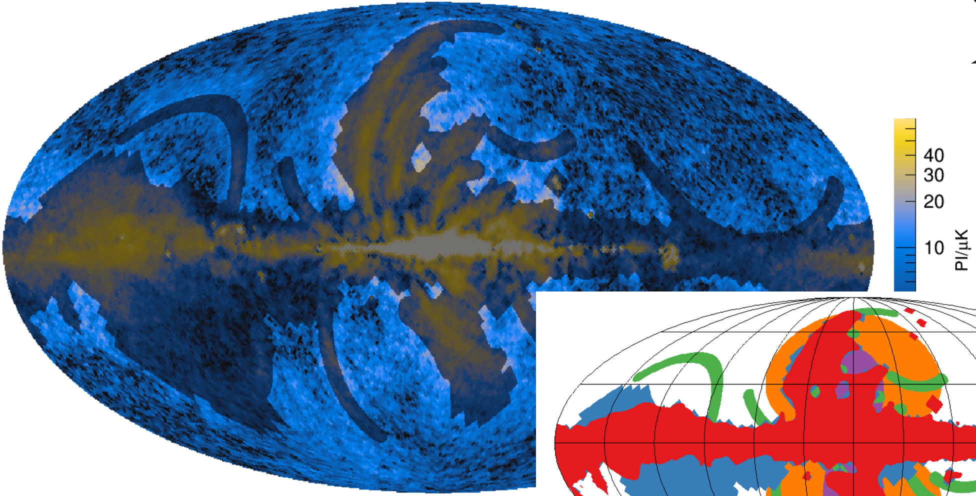
Combined WMAP-Planck Polarized Emission

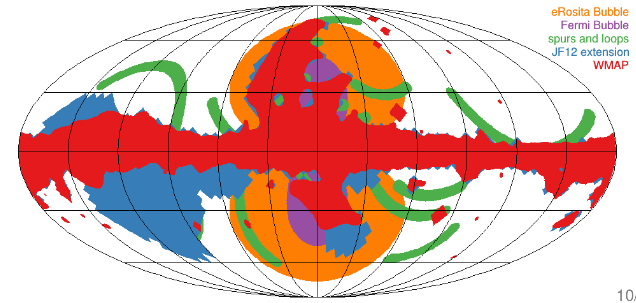


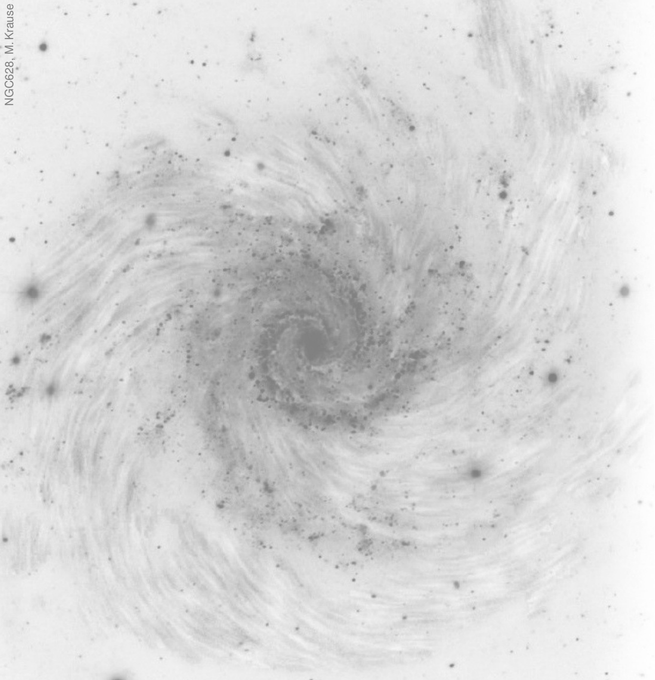


Combined WMAP-Planck Polarized Emission









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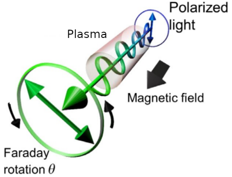
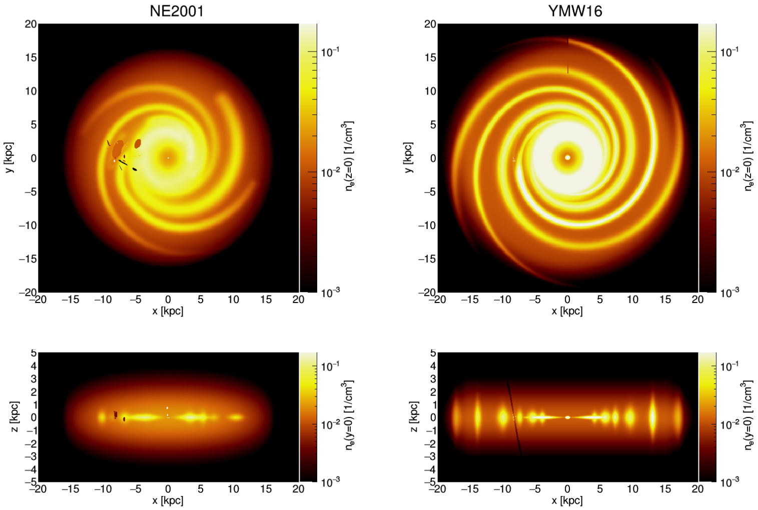
Thermal Electron Models

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





112 pulsar DMs

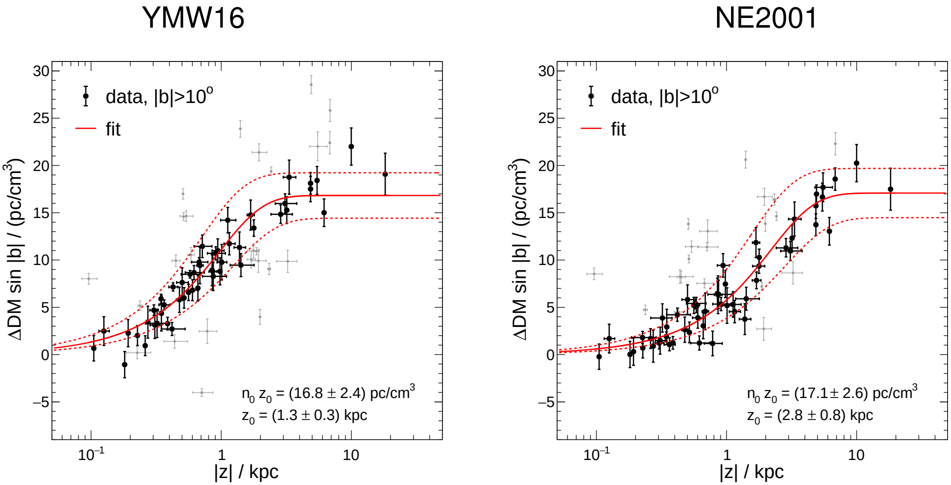
189 pulsar DMs

Cordes&Lazio arXiv:0207156

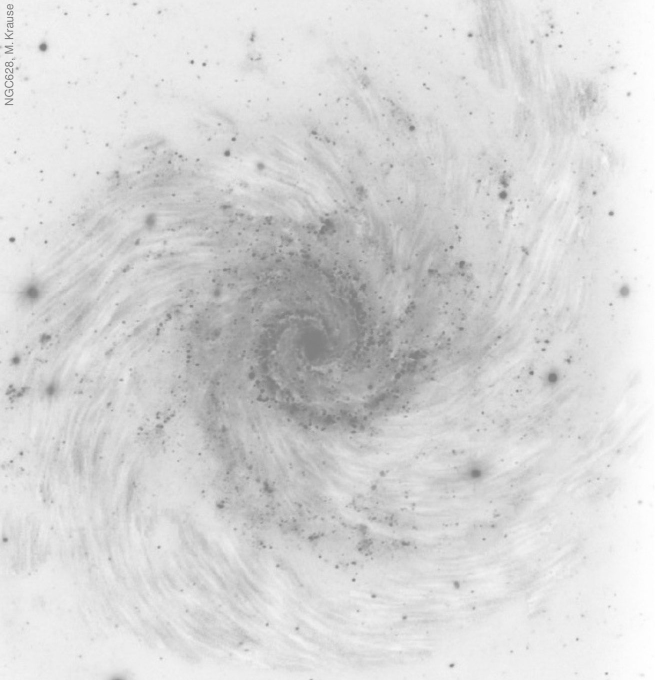
Yao, Manchester & Wang, ApJ 2017

Thermal Electron Halo

reasonably well-constrained from DMs of pulsars in globular clusters



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



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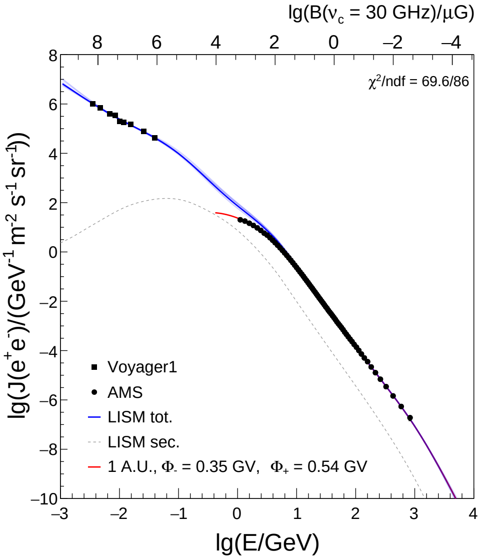
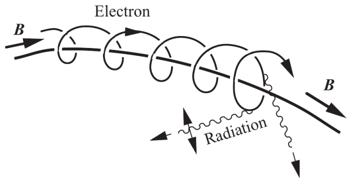
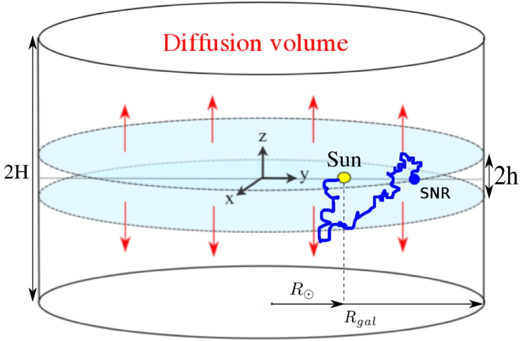
Cosmic-Ray Electron Model







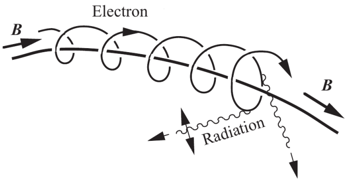
homogenous and isotropic diffusion $D_0 \propto R^\delta$ (rigidity R)

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

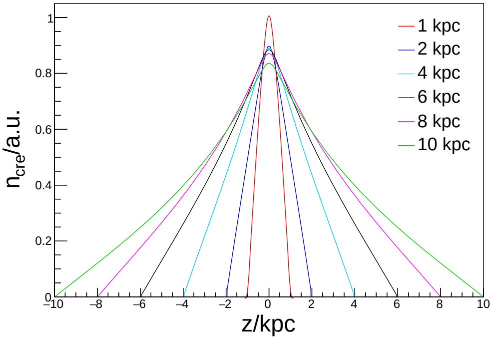
DRAGON calculation constrained by local lepton flux and D_0/H from B/C https://github.com/cosmicrays/DRAGON

Cosmic-Ray Electron Model

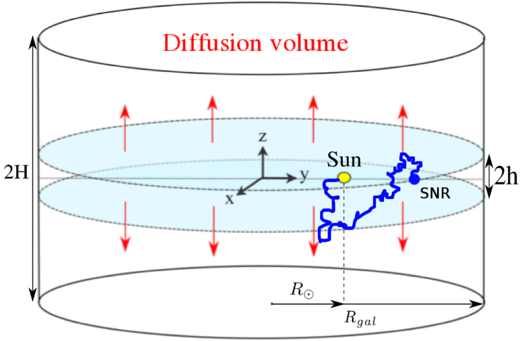
- $D_0/H = \mathrm{const}$ from B/C
- halo half-height H currently not well constrained Weinrich+20, Evoli+20, Maurin+22



→ large uncertainty in vertical n_{cre} profile!



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



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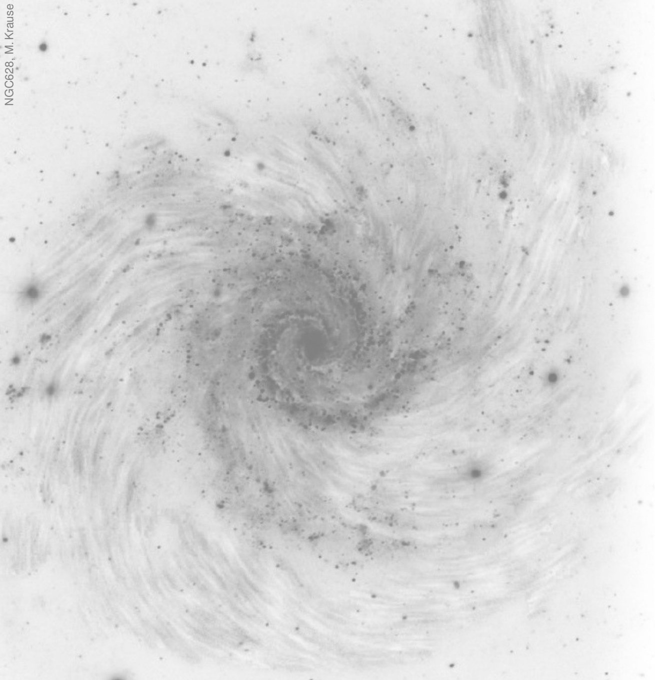
NGC628, M. Krause

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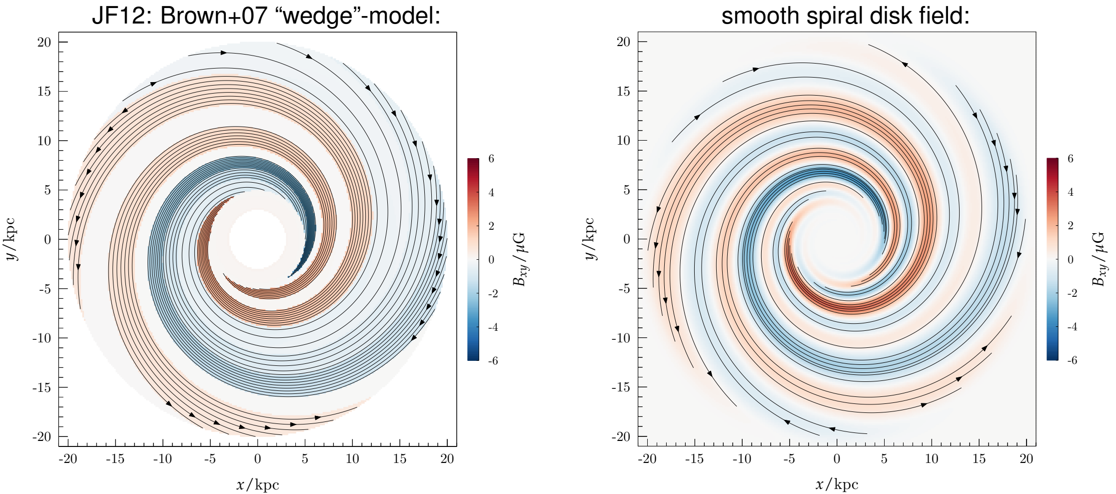
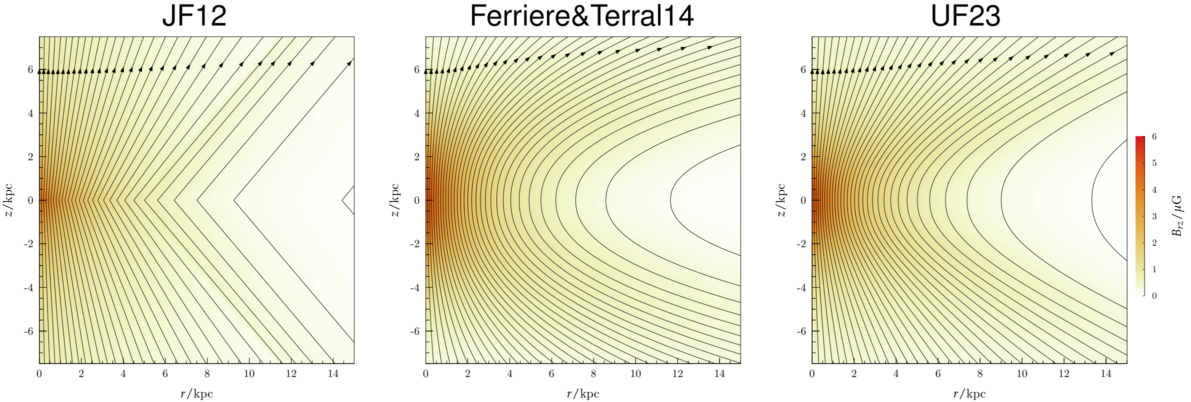
GMF Model Improvements – Disk Field



- 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)

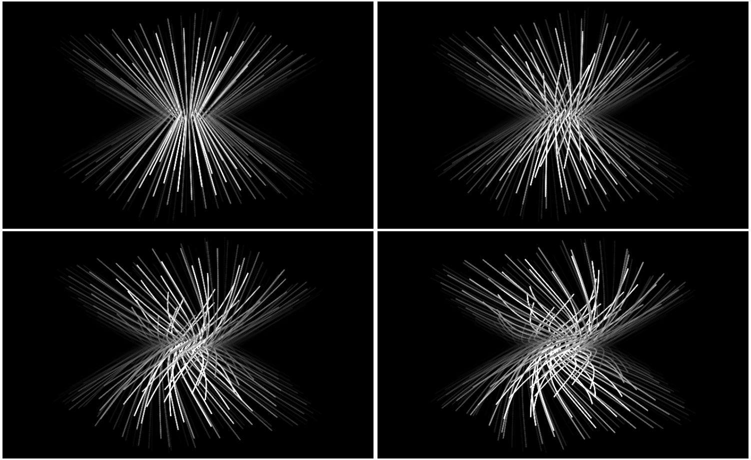
GMF Model Improvements – Halo X-Field



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

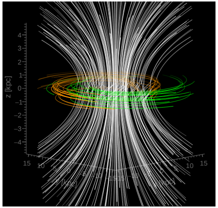
GMF Model Improvements – Halo Field

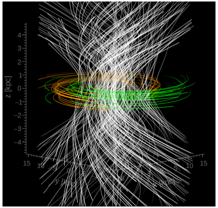
- evolve X-field via ideal induction equation $\partial_t \mathbf{B} = \nabla \times (\mathbf{v}_{\text{rot}} \times \mathbf{B})$
- radial and vertical shear of Galactic rotation generates toroidal field

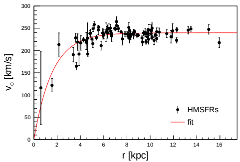


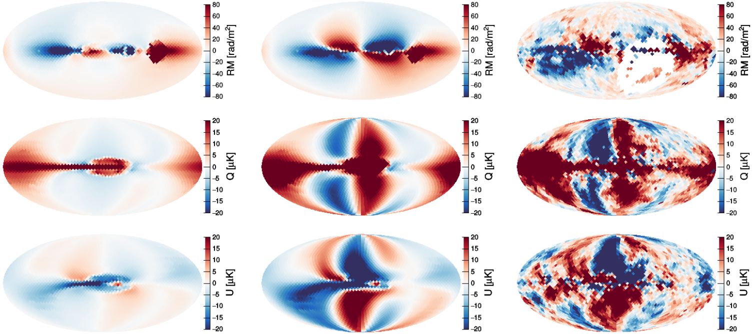
- no separate X- and torodial halo needed!

“Twisted X-field”

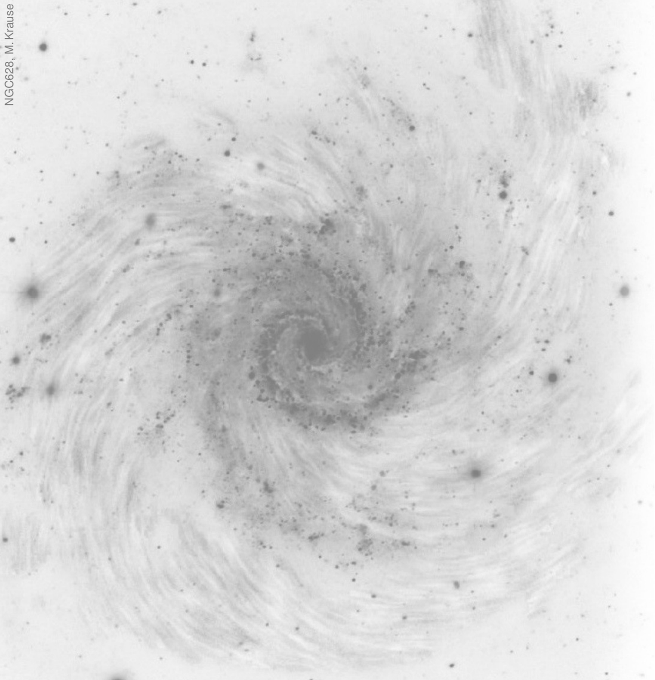








(a) t = 0 Myr (b) t = 70 Myr (c) data



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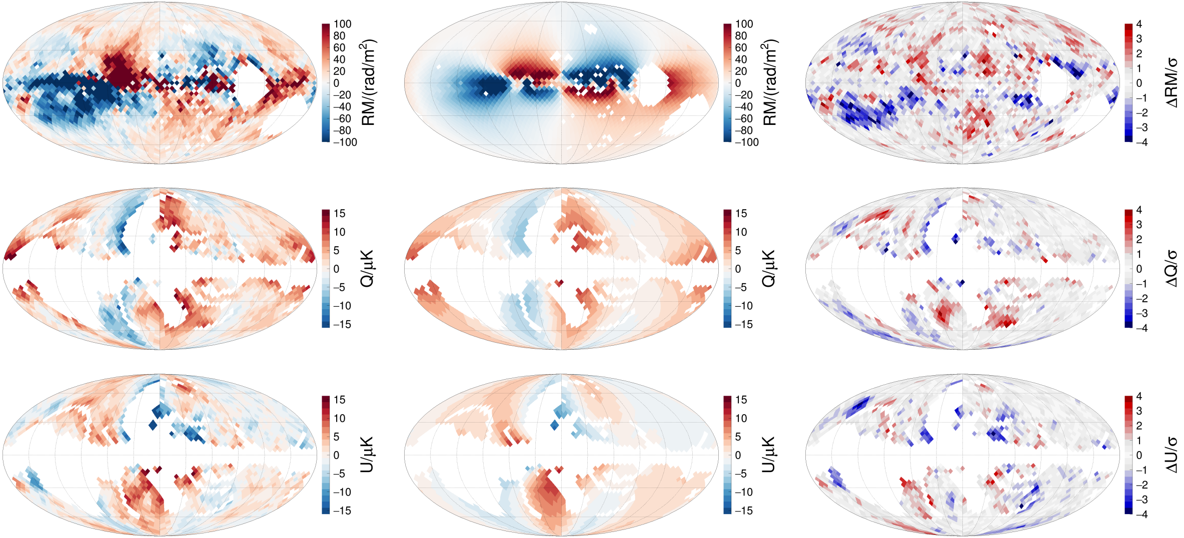
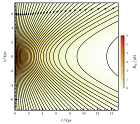
Fit of RM/Q/U ($\chi^2/\mathrm{ndf} = 7759/6500 = 1.19$)

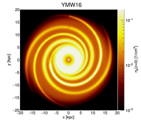


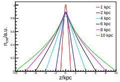
model describes large-scale features of 6520 data points with only 20 parameters!

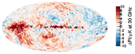
UF23 Model Variations

id	disk	halo toroidal	halo poloidal		n_e model	κ	h_{cre} (kpc)	QU	χ^2/ndf
Parametric models									
a	UF	JFsym	UF	logistic	YMW16	0	6	(W+P)/2	7923 / 6500 = 1.22
b	UF	twist	UF	logistic	YMW16	0	6	(W+P)/2	8324 / 6504 = 1.28
c	UF	JFsym	UF	gauss	YMW16	0	6	(W+P)/2	8298 / 6500 = 1.28
d	UF	JFsym	UF	sech2	YMW16	0	6	(W+P)/2	8381 / 6500 = 1.29
e	UF	JFsym	UF	expo	YMW16	0	6	(W+P)/2	8431 / 6500 = 1.30
f	UF	JFsym	FTc	logistic	YMW16	0	6	(W+P)/2	7926 / 6500 = 1.22
Thermal electrons									
g	UF	JFsym	UF	logistic	NE2001	0	6	(W+P)/2	7759 / 6500 = 1.19
h	UF	twist	UF	logistic	NE2001	0	6	(W+P)/2	8180 / 6504 = 1.26
i	UF	JFsym	UF	gauss	NE2001	0	6	(W+P)/2	8079 / 6500 = 1.24
j	UF	JFsym	UF	logistic	YMW16	-0.4	6	(W+P)/2	7905 / 6500 = 1.22
Cosmic-ray electrons									
k	UF	JFsym	UF	logistic	YMW16	0	8	(W+P)/2	7940 / 6500 = 1.22
l	UF	JFsym	UF	logistic	YMW16	0	10	(W+P)/2	7939 / 6500 = 1.22
Synchrotron Map									
m	UF	JFsym	UF	logistic	YMW16	0	6	CG23	9758 / 6500 = 1.50
n	UF	JFsym	UF	logistic	NE2001	0	6	CG23	9551 / 6500 = 1.47
o	UF	JFsym	UF	logistic	YMW16	0	6	P	11013 / 6500 = 1.69
p	UF	JFsym	UF	logistic	YMW16	0	6	W	8845 / 6500 = 1.36





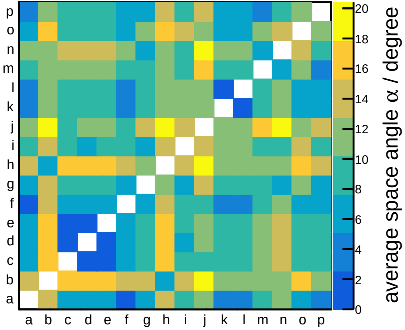


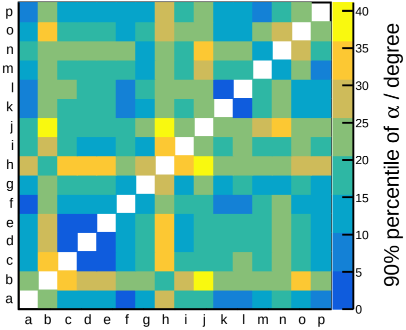


UF23 Model Ensemble

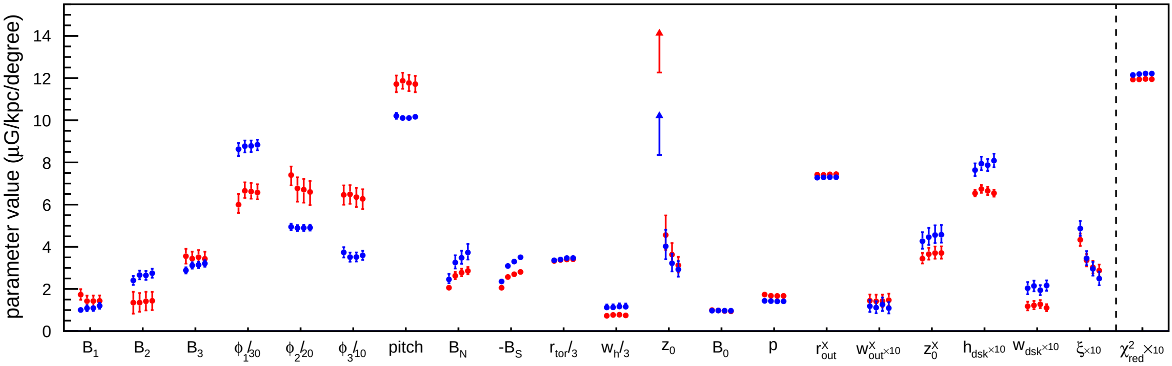
id	name	disk	halo toroidal	halo poloidal		n_e model	κ	h_{cre} (kpc)	QU	χ^2/ndf
1	base	UF	JFsym	UF	logistic	YMW16	0	6	(W+P)/2	1.22
2	xr	UF	JFsym	UF	expo	YMW16	0	6	(W+P)/2	1.30
3	ne	UF	JFsym	UF	logistic	NE2001	0	6	(W+P)/2	1.19
4	κ	UF	JFsym	UF	logistic	YMW16	-0.4	6	(W+P)/2	1.22
5	twist	UF	twist	UF	logistic	NE2001	0	6	(W+P)/2	1.26
6	cre	UF	JFsym	UF	logistic	YMW16	0	10	(W+P)/2	1.22
7	syn	UF	JFsym	UF	logistic	YMW16	0	6	CG23	1.50

deflection angle differences at 10 EV:





Example: Thermal and Cosmic-Ray Models

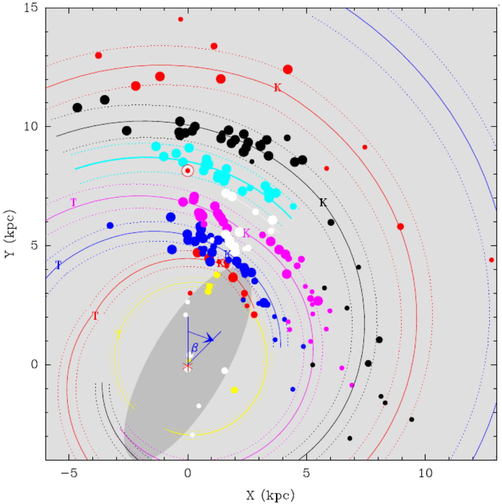


NE2001, YMW16, left to right $h_{\rm cre} = 4, 6, 8, 10$ kpc

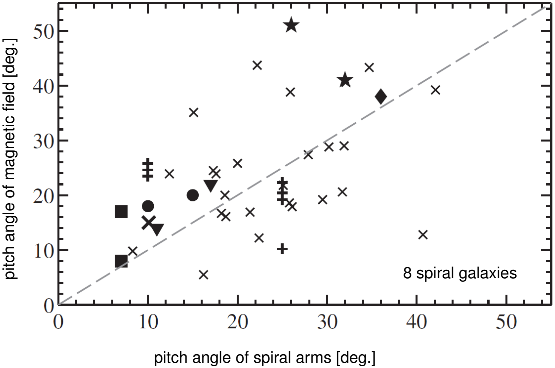
Magnetic Pitch Angle

- 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



The RM-PI Puzzle

Longstanding Problem:

derived field $\widehat{B}(\mathrm{RM}) < \widehat{B}(\mathrm{PI})$

Proposed Solutions:

- $n_{\text{cre}} - B$ correlations: $\widehat{B}(\mathrm{PI}) > B_{\text{true}}$

  $\rightarrow$ not observed in MHD simulations $(l < l_{\text{outer}})$ Seta+18

- anisotropic ("striated") random fields: $\widehat{B}(\mathrm{PI}) > B_{\text{true}}$

  prescription:

  $$B = (1+\xi)B_0$$ Jansson&Farrar ApJ12

  (striation enhances PI but not RM!)

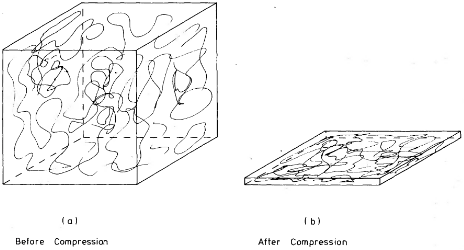
- $n_e - B$ anti-correlation: $\widehat{B}(\mathrm{RM}) < B_{\text{true}}$

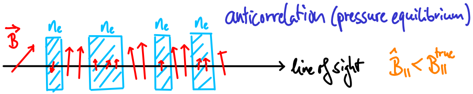
  prescription:

  $$\mathrm{RM} = \mathrm{RM}_0 \left(1 + \frac{2}{3}\,\kappa\,\frac{\langle b^2\rangle}{B^2+\langle b^2\rangle}\right)$$ Beck+A&A03

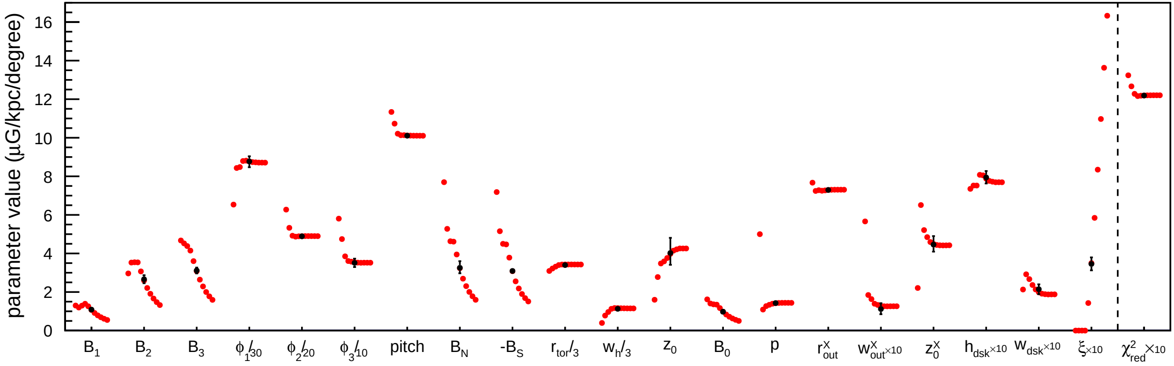
  (anti-correlation diminishes RM)

Laing MNRAS80





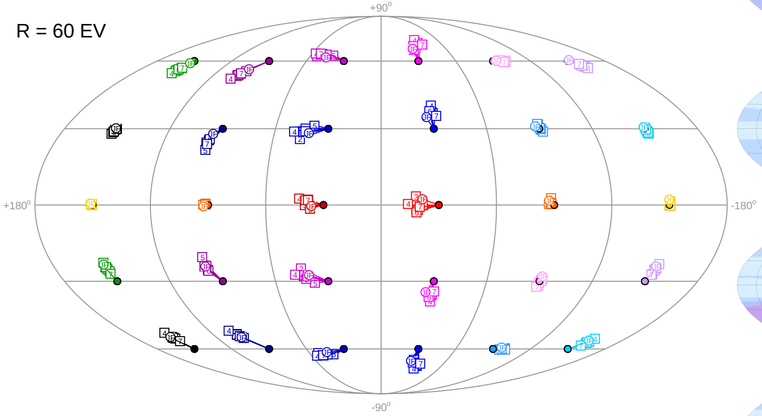
The RM-PI Puzzle

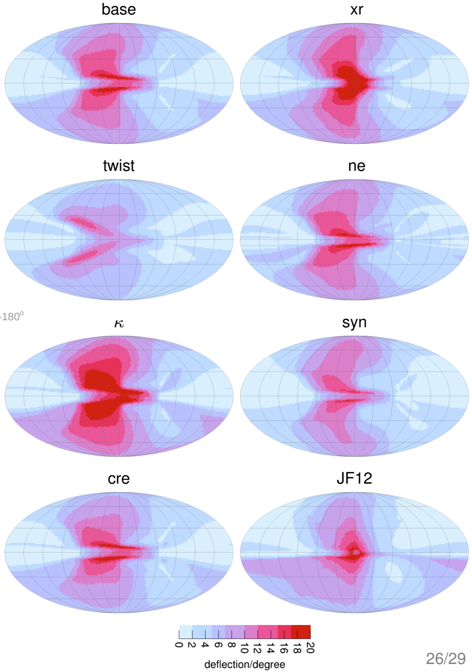


left to right: $\kappa = -1 ... +1$, black point is $\kappa = 0$

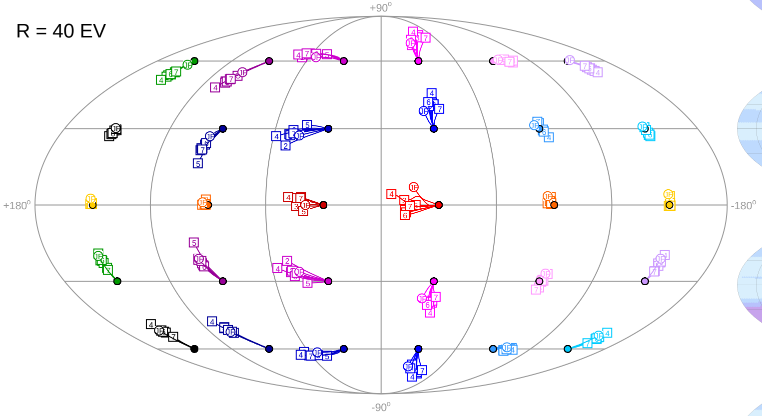
- no stration needed at $\kappa \sim -0.4$
- χ^2 minimum at $\kappa = -0.4$ ($\Delta\chi^2 = -23$ wrt. $\kappa = 0$)

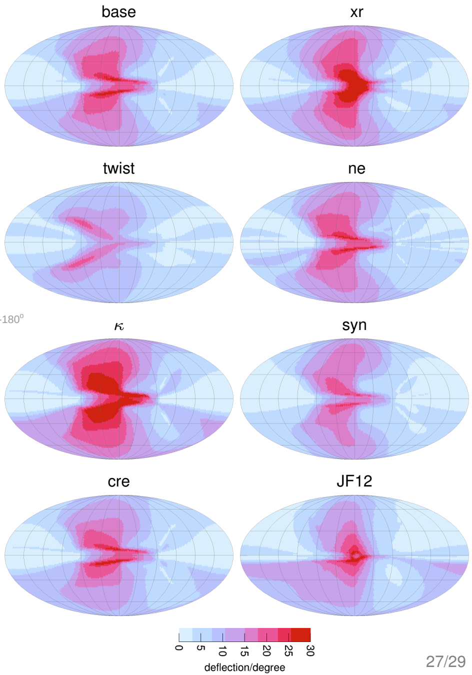
Cosmic-Ray Deflections, R=60 EV



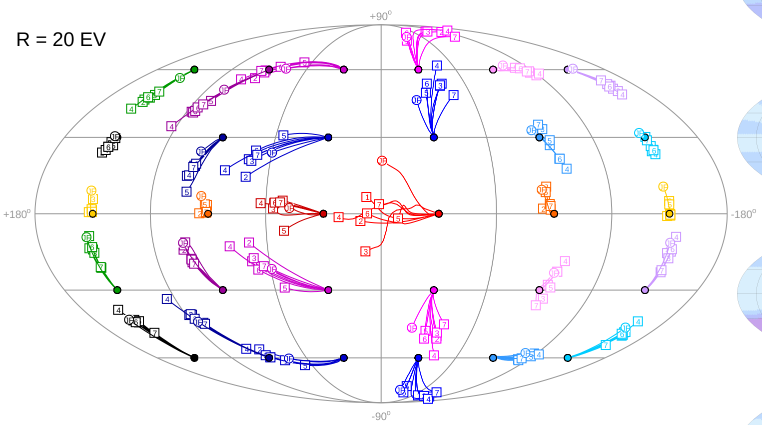


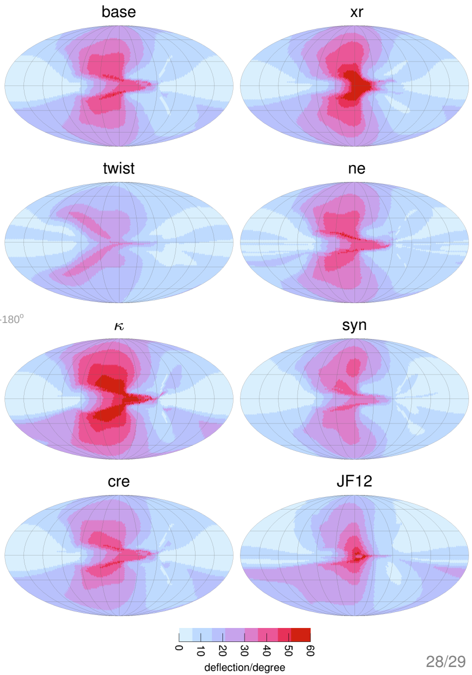
Cosmic-Ray Deflections, R=40 EV





Cosmic-Ray Deflections, R=20 EV





Summary

Major Overhaul of JF12 GMF Model

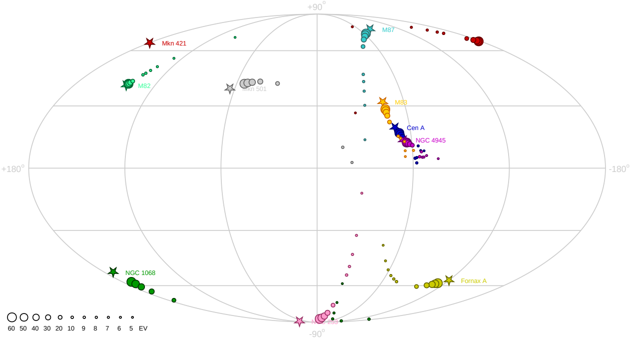
- new RM data
- new synchrotron sky maps
- improved auxillary models (n_e and n_{cre})
- smooth disk-field
- unified halo model

Main Results:

- JF12 dipolar X-field robust ↯ dynamo?
- magnetic pitch $\sim$ spiral pitch ↯ coherent?
- $n_e - B$ anti-corr. is alternative to striation
  $\rightarrow$ larger B estimates
- GMF model ensemble
  $\rightarrow$ cosmic-ray deflection uncertainties

Outlook

Apply to CR Analysis



Incorporate New Data (existing and future)
pulsar RMs, low-frequency QU, I_{syn} + variances, dust pol. tomography, ...

Foreground Modelling
local bubble, loops and spurs.