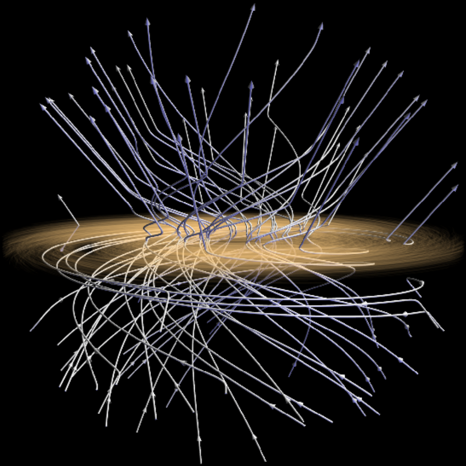
(Towards) a New Global Model of the Galactic Magnetic Field

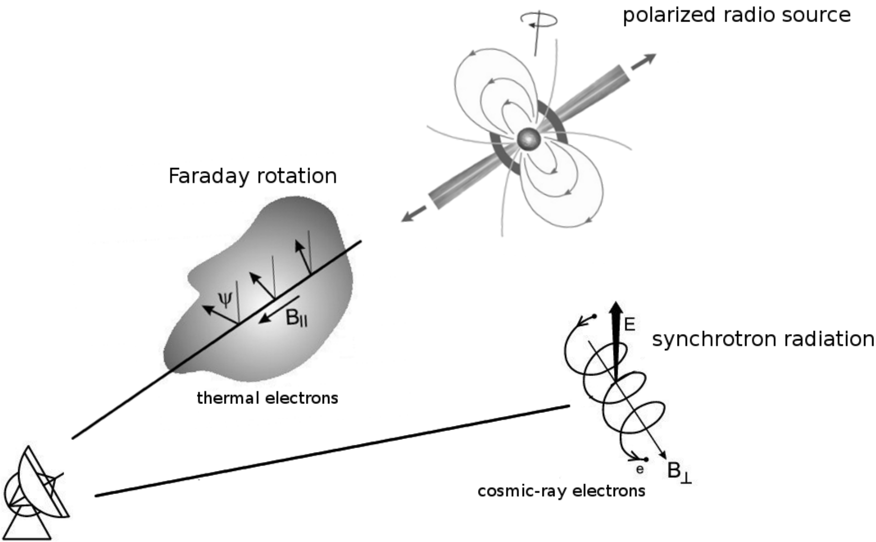
M. Unger (KIT)

in collaboration with G.R. Farrar (NYU)



JF12 visualization by Farrar & Sandstrom

Observational Tracers of the Galactic Magnetic Field



composite arXiv:1302.5663 & www.nrao.edu

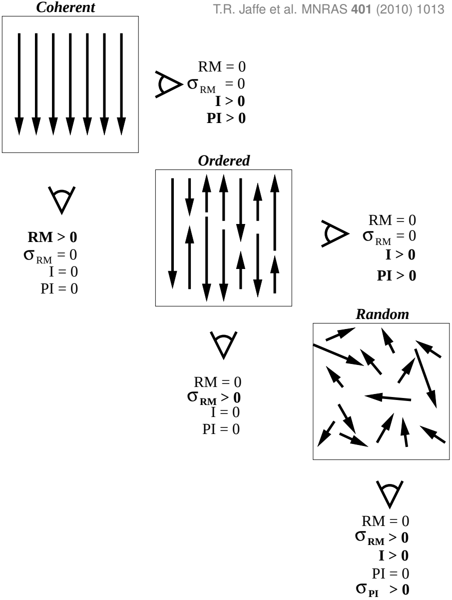
+ starlight polarization, polarized dust emission, Zeeman effect

Observational Tracers of the Galactic Magnetic Field

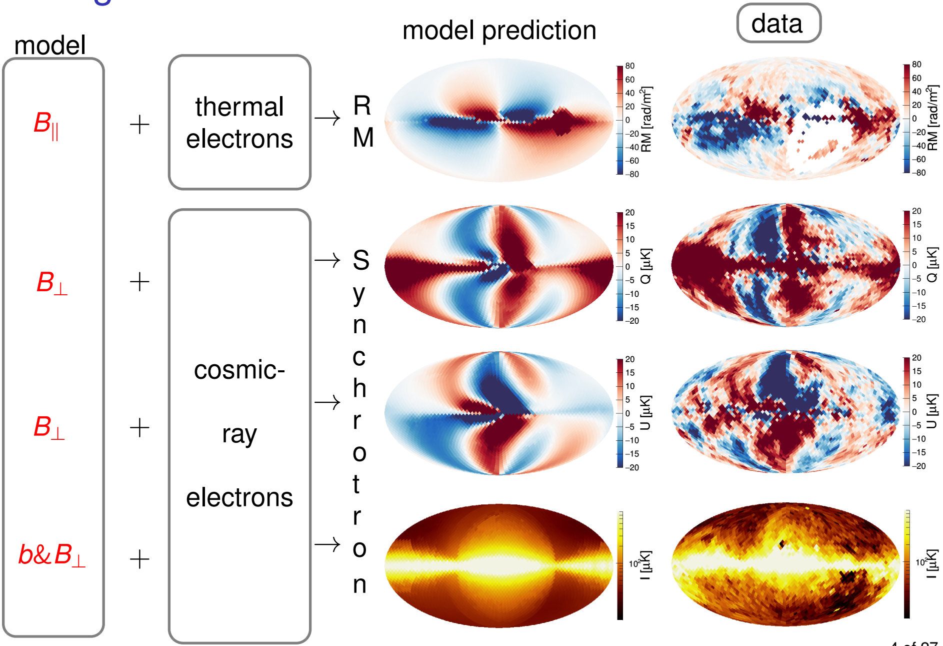
- coherent field B
- random field b
- rotation measure:
  $\mathrm{RM} \propto \int n_e B_{\|}\, \mathrm{d}l$
- Stokes parameters:
  $Q/U \propto \int B_{\perp}^2\, n_{\mathrm{cre}}\, \mathrm{d}l^*$
- proj. magnetic field angle:
  $\langle \psi_{\mathrm{mag}} \rangle = \frac{1}{2}\mathrm{atan}\left(\frac{U}{Q}\right) + \pi/2$
- polarized intensity:
  $\mathrm{PI}^2 = Q^2 + U^2$
- total intensity:
  $\mathrm{I} = I_{\mathrm{coh}} + I_{\mathrm{rand}}$,
  $I_{\mathrm{coh}} \propto B_{\perp}^2$, $I_{\mathrm{rand}} \propto b^{2*}$

* for a cosmic-ray electron spectrum $\mathrm{d}n/\mathrm{d}E \propto E^{-3}$

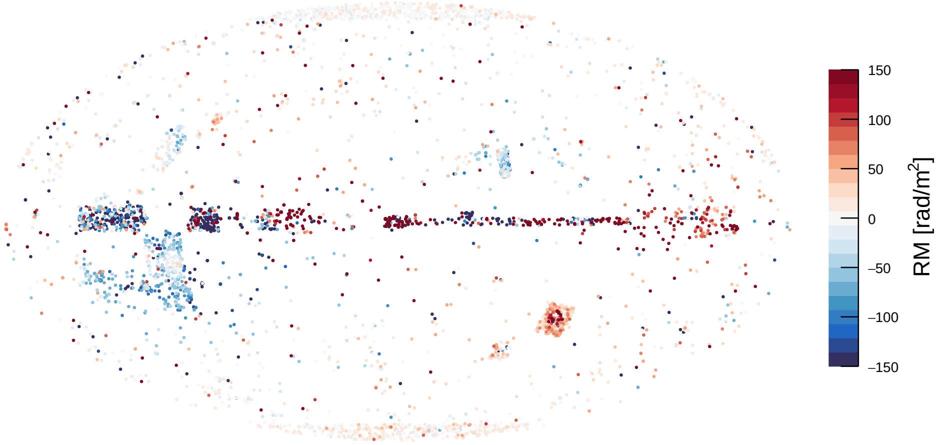
T.R. Jaffe et al. MNRAS **401** (2010) 1013



Fitting GMF Models

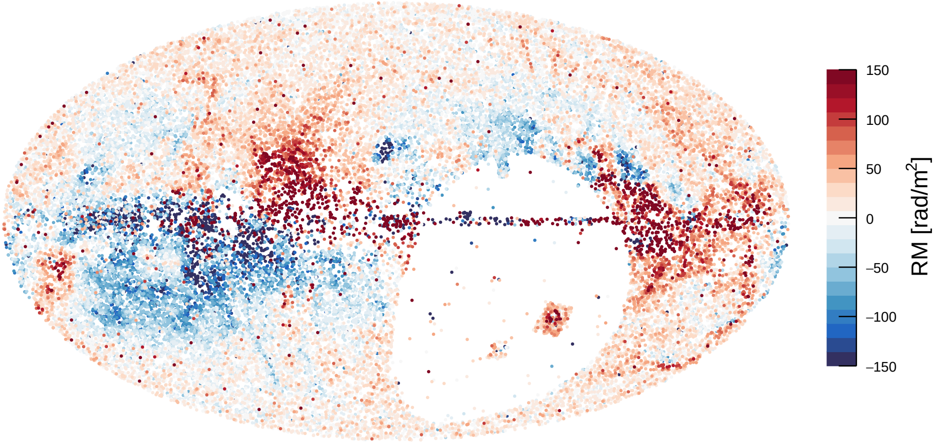


Rotation Measures of Extragalactic Radio Sources



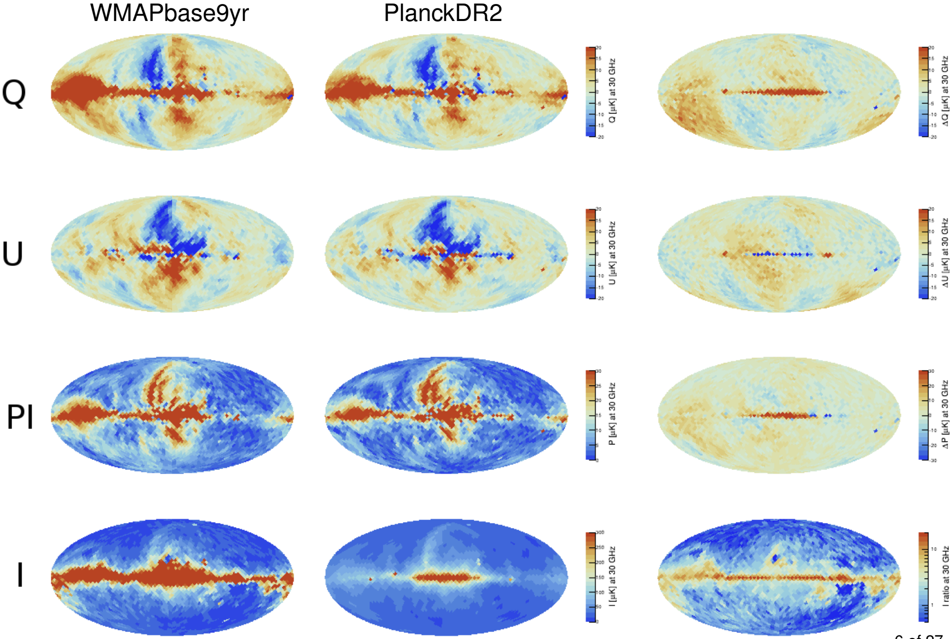
4553 individual RMs (e.g. XuHan14 compilation) and 37543 from NVSS → 38627 after removal of outliers and duplicates (JF12)

Rotation Measures of Extragalactic Radio Sources



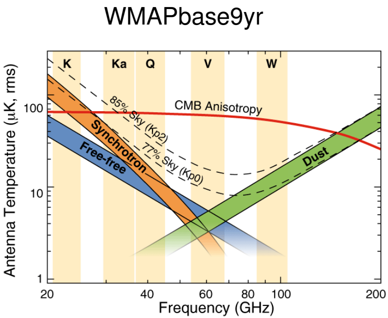
4553 individual RMs (e.g. XuHan14 compilation) and 37543 from NVSS → 38627 after removal of outliers and duplicates (JF12)

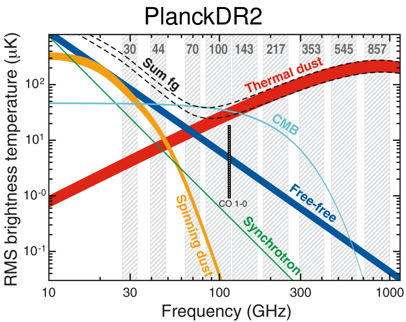
Synchrotron Emission



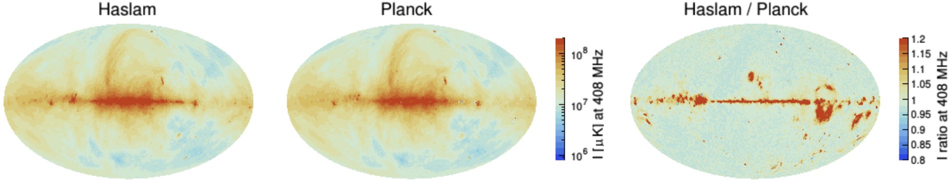
Synchrotron Emission

Component Separation:



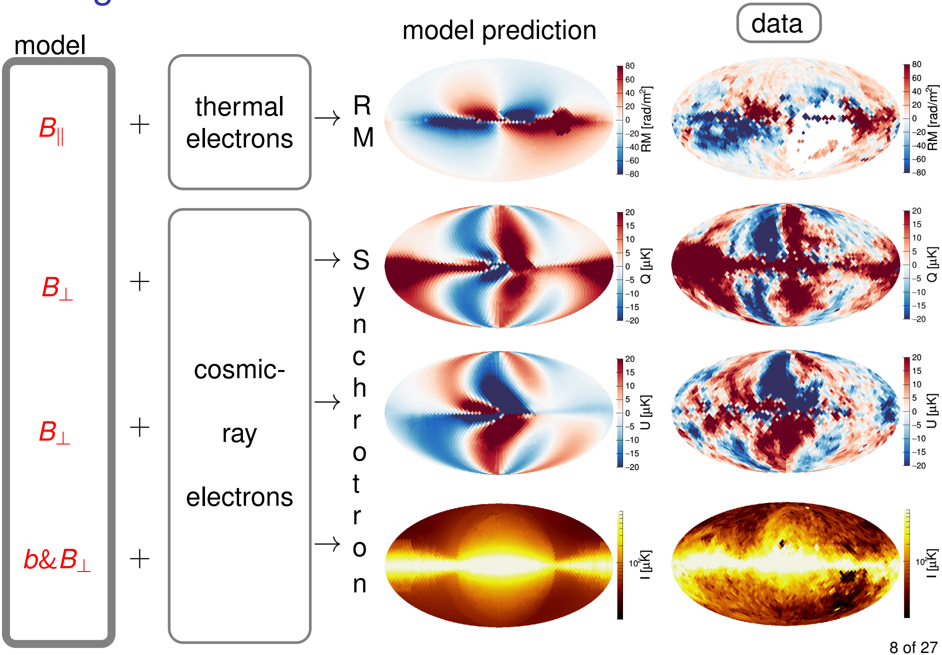


Planck vs. Haslam



destriped and mono/dipole subtracted Haslam from Remazeilles+14

Fitting GMF Models

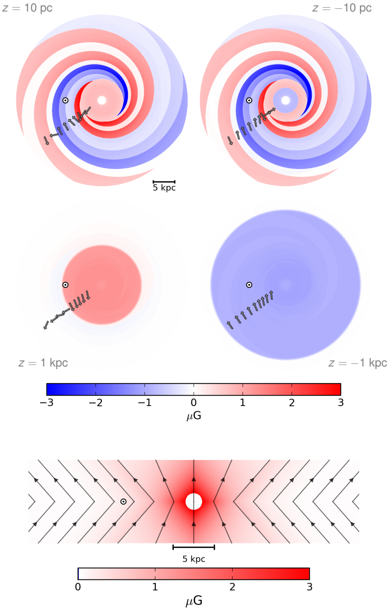


Jansson&Farrar Global Magnetic Field Model (JF12)

three divergence-free components:

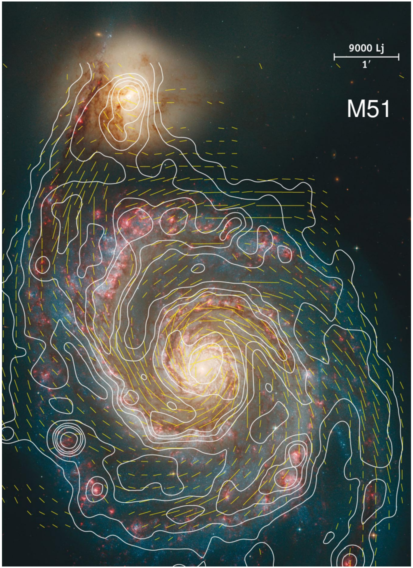
- disk field, ($h \lesssim 0.4$ kpc)
- toroidal halo field ($h_{\rm scale} \sim 5.3$ kpc)
- "X-field" (halo)

- regular field[a]: 21 parameters
- random field[b]: 13 parameters
- striation: 1 parameter
- CR electron norm.: 1 parameter



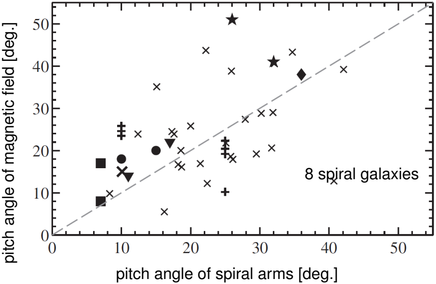
[a] R. Jansson & G.F. Farrar, ApJ **757** (2012) 14
[b] R. Jansson & G.F. Farrar, ApJ **761** (2012) L11

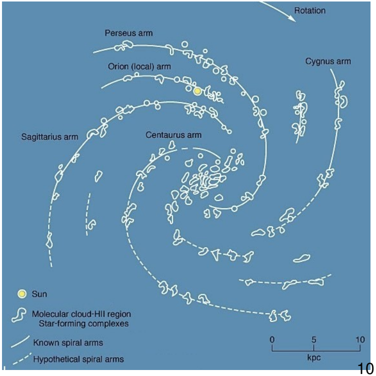
Disk Field



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

C.L. van Eck et al, ApJ **799** (2015) 35

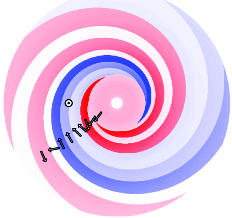


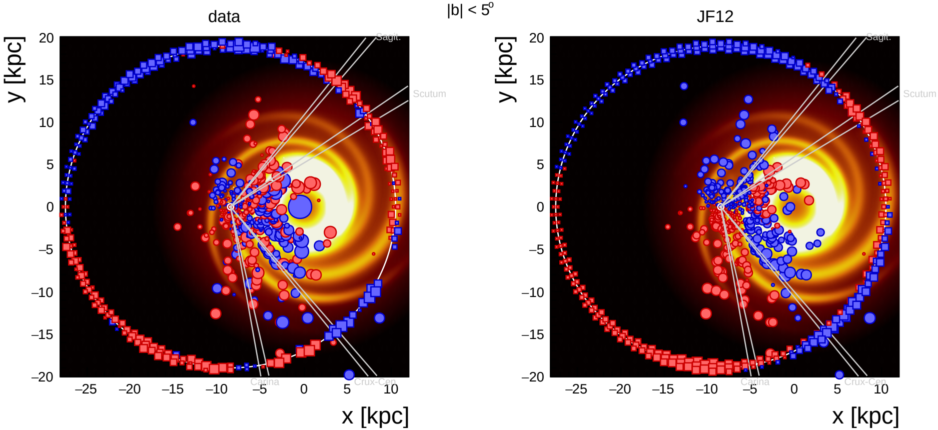


E. Freeland, www.astro.wisc.edu

Disk Field

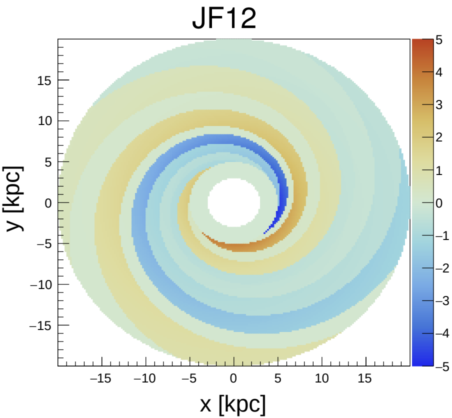
$$\mathrm{RM} \propto \int_d^0 n_e(l)\, B_\parallel\, \mathrm{d}l$$

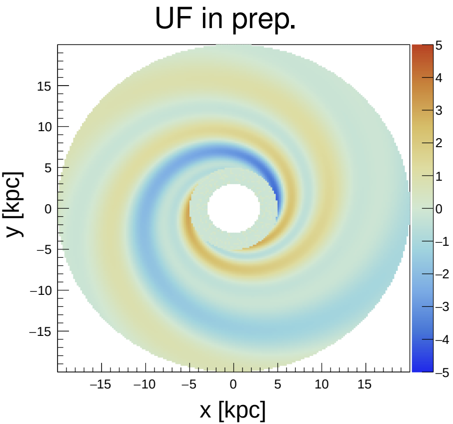




background: NE2001 thermal electrons, squares: extragalactic RMs, circles: pulsar RMs

Improved Disk Field: Smooth, Divergence-Free Spiral

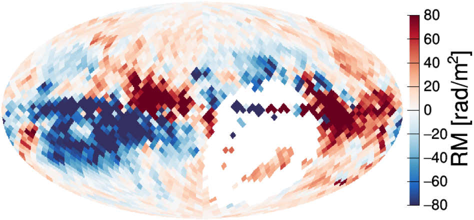


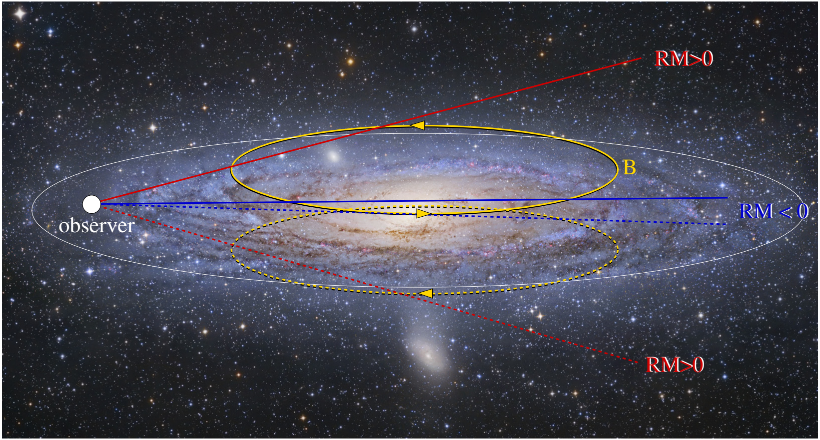


color scale: B field in μG

best-fit pitch angle: $(13.4 \pm 0.7)^\circ$ (JF12: fixed to 11.5°)

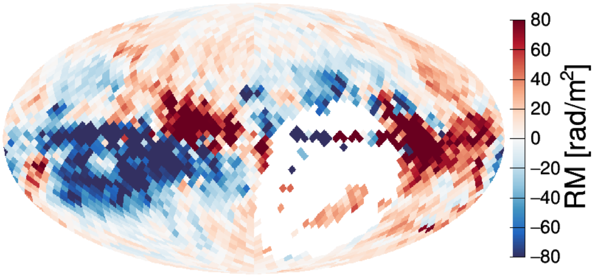
Toroidal Field



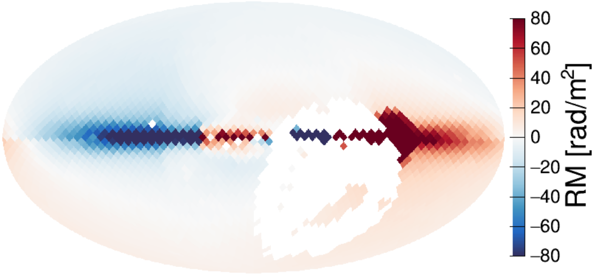


RM, no toroidal Field

data:

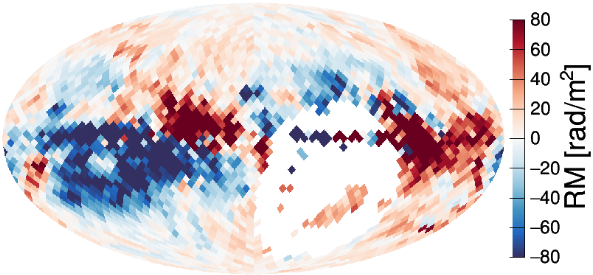


model:

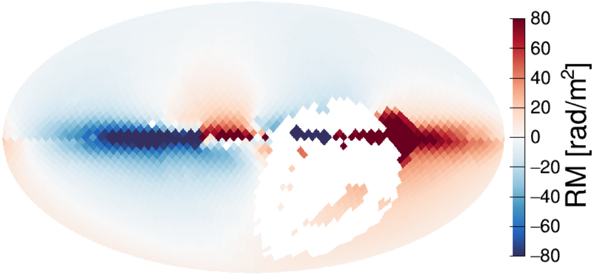


RM, $B_\varphi^{\rm N} = -B_\varphi^{\rm S} = 0.5\ \mu$G

data:

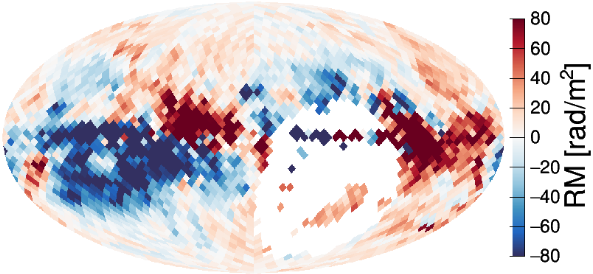


model:

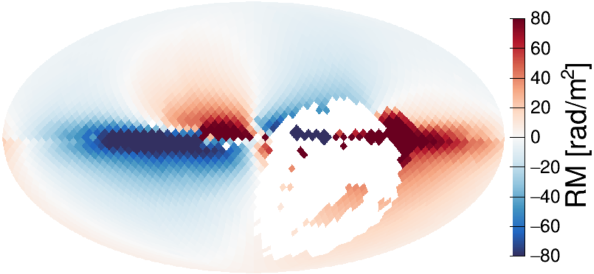


RM, $B_\varphi^{\mathrm{N}} = -B_\varphi^{\mathrm{S}} = 1.0\ \mu$G

data:

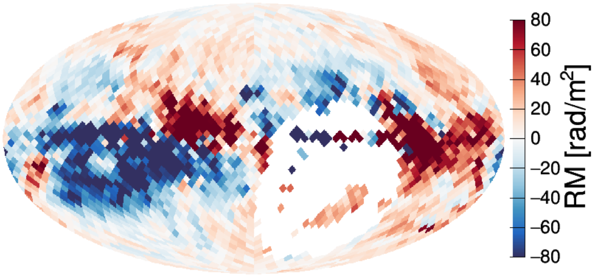


model:

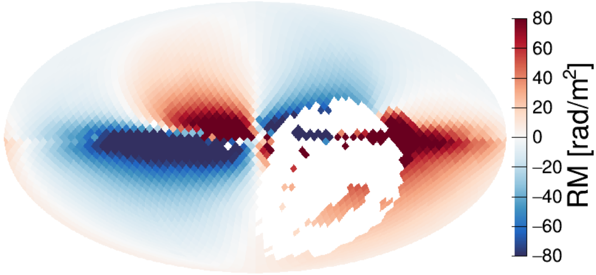


RM, $B_\varphi^{\mathrm{N}} = -B_\varphi^{\mathrm{S}} = 1.5\ \mu\mathrm{G}$

data:

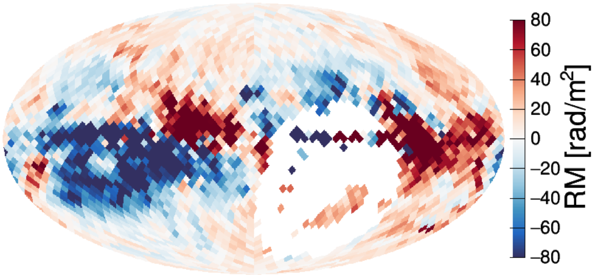


model:

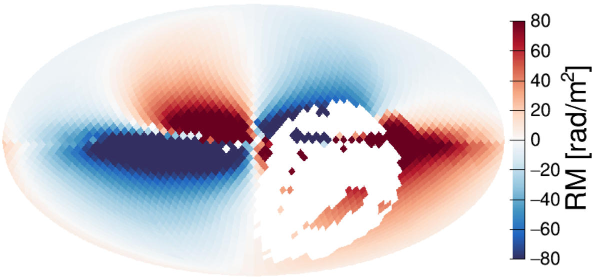


RM, $B_\varphi^{\rm N} = -B_\varphi^{\rm S} = 2.0\ \mu{\rm G}$

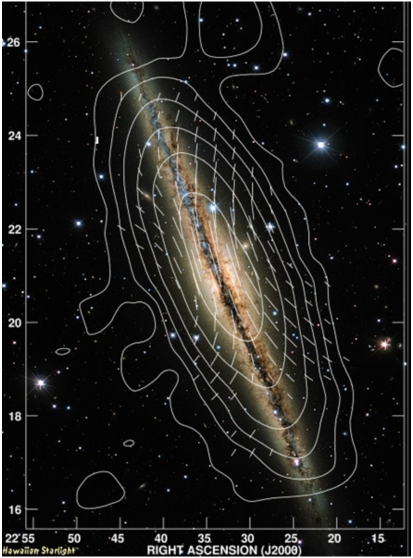
data:



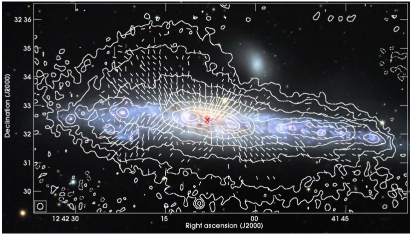
model:



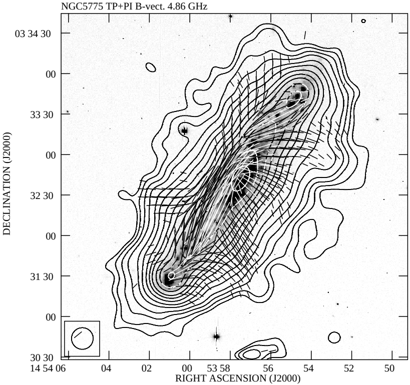
X-field



NGC891, M. Krause MPIfR

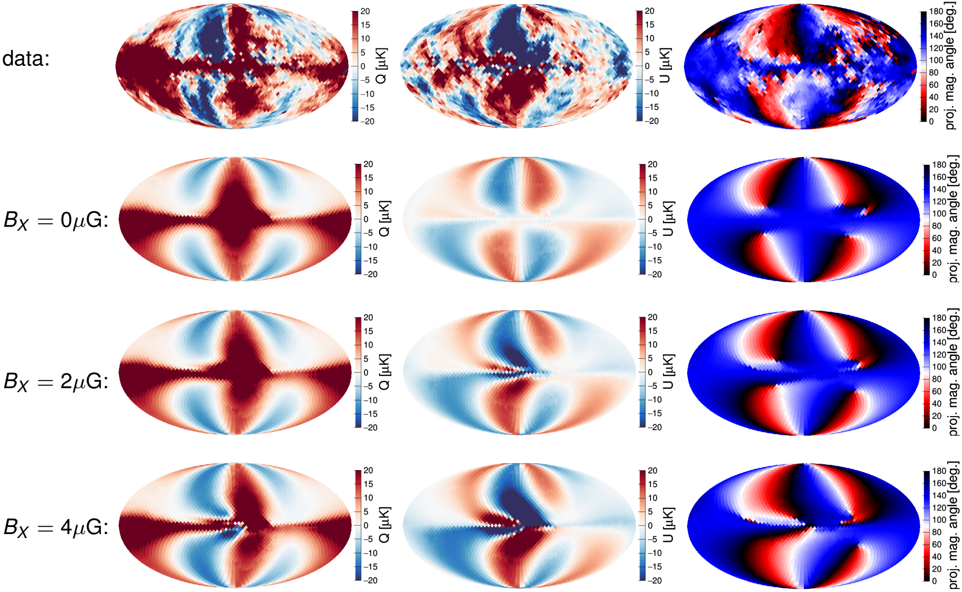


NGC 4631, M. Krause, arXiv:1401.1317



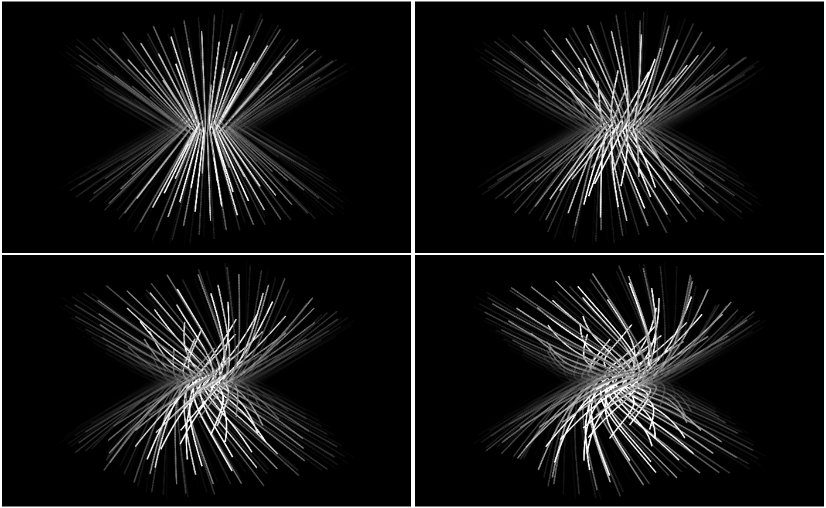
NGC 5775, M. Krause, arXiv:1401.1317

Q/U/ψ_{mag} $\theta_X = 49^\circ$

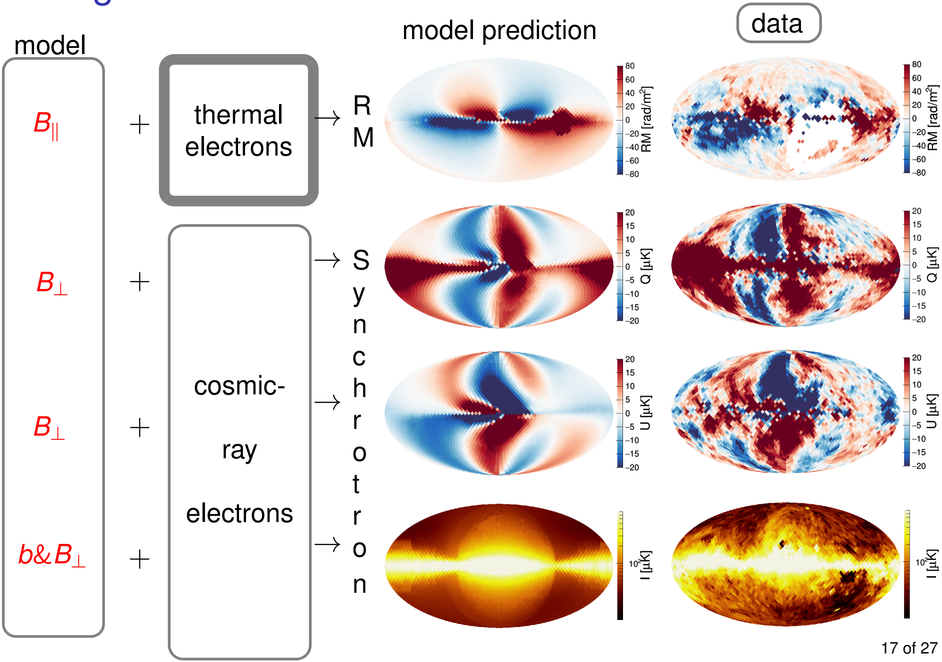


Twisted X-Field

- evolve poloidal field via induction equation
- radial and vertical shear of Galactic rotation generates toroidal field

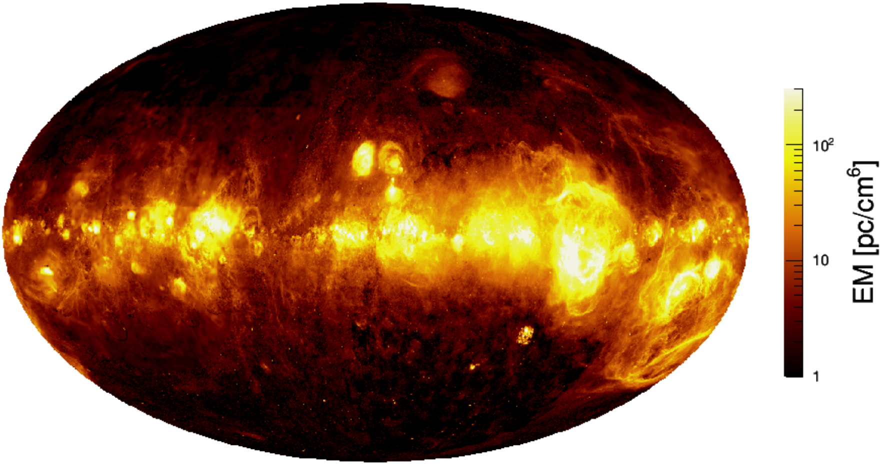


Fitting GMF Models



Thermal Electrons

- **origin:** ionization of ISM by OB stars
- clumps in HII regions, diffuse component
- emission measure $\mathrm{EM} \propto \int_0^\infty n_e^2(l)\,\mathrm{d}l$ from Hα map:

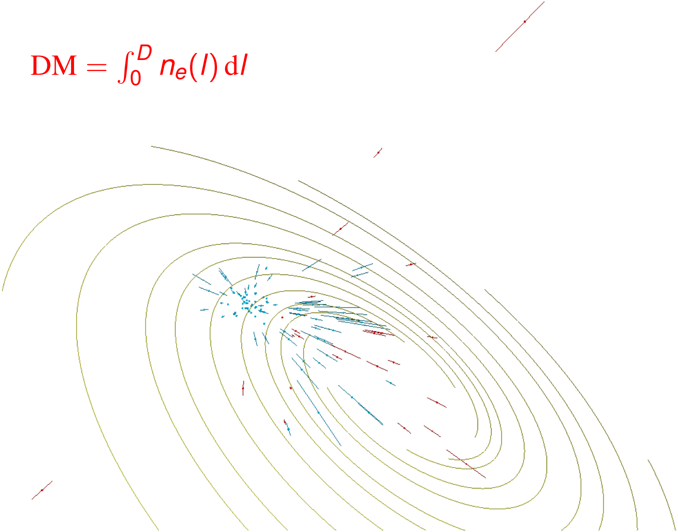


VTSS, SHASSA, WHAM, D. Finkbeiner ApJS **146** (2003) 407

Thermal Electrons

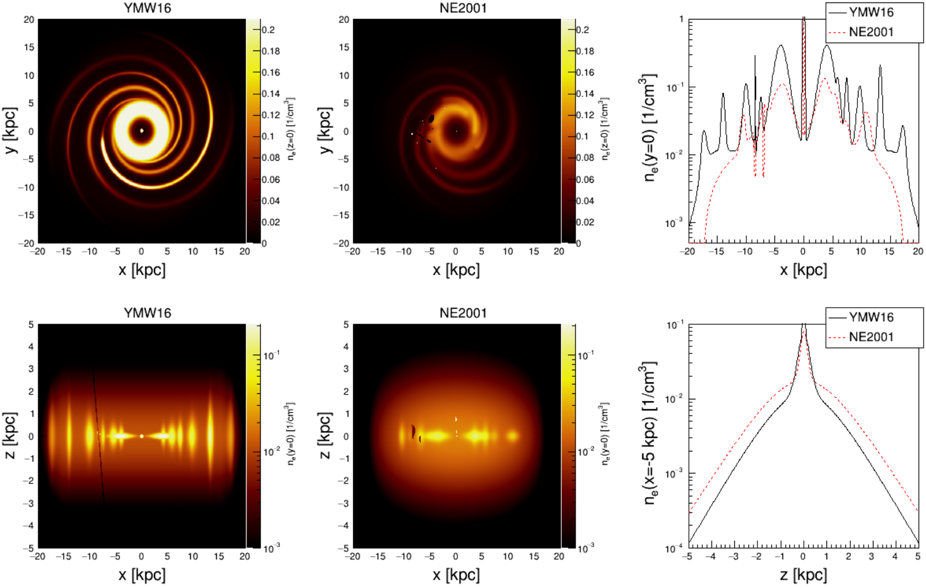
Modeling of thermal electrons mainly based on dispersion measure of Galactic pulsars with distance measurements

$$\mathrm{DM} = \int_0^D n_e(l)\,\mathrm{d}l$$



ATNF pulsar database v1.54

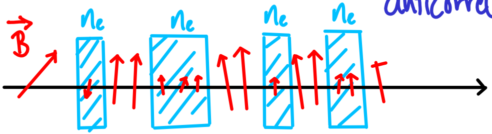
Thermal Electron Models



Yao, Manchester & Wang, ApJ **835** (2017) 32, J. Cordes&T. Lazio, arXiv:0207156 and 0301598

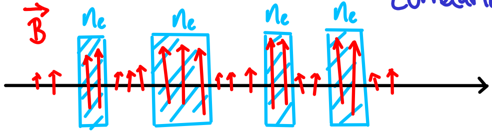
Thermal Electrons, B and b

anticorrelation (pressure equilibrium)



$\hat{B}_{\parallel} < B_{\parallel}^{true}$

correlation (compression)

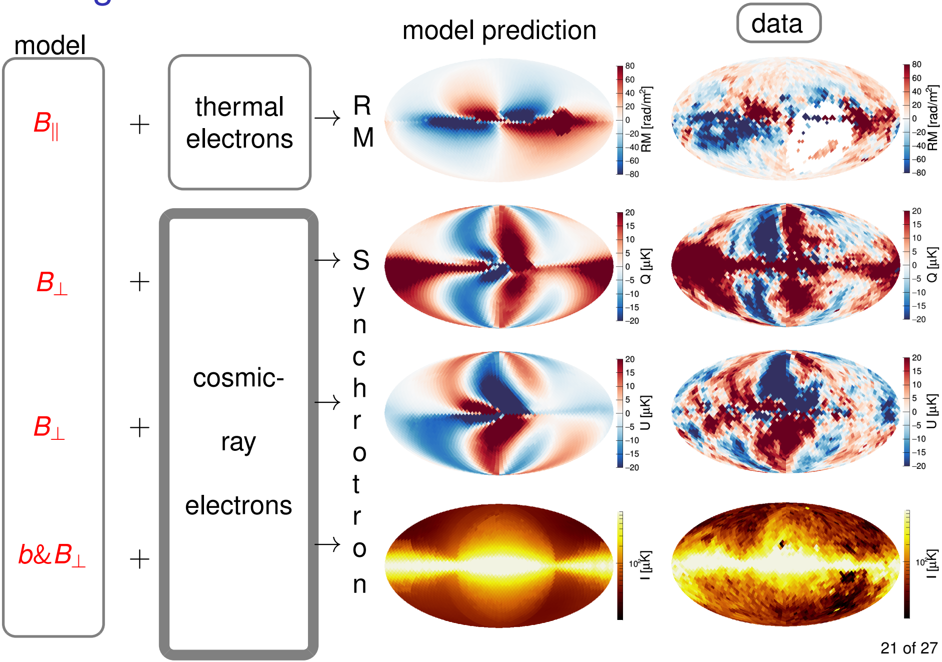


$\hat{B}_{\parallel} > B_{\parallel}^{true}$

$$RM' = RM \left(1 + \frac{2}{3} K \frac{b^2}{B^2 + b^2}\right)$$

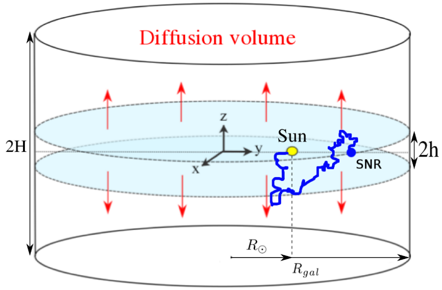
(Beck+03)

Fitting GMF Models

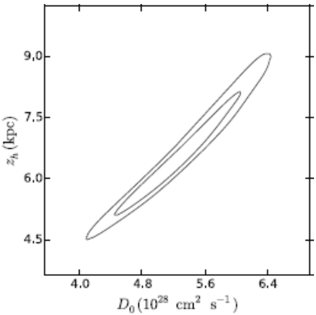


Cosmic-Ray Electrons

- **origin:** acceleration in supernova remnants
- **data:** cosmic-ray electron spectra at Earth, B/C, Be
- **uncertainties:** source distribution, propgation parameters, local environment
- diffusion and cooling in Galactic magnetic field



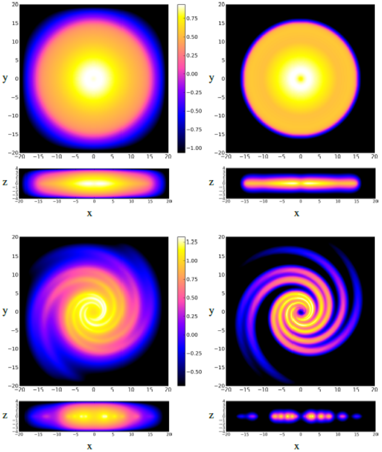
Y. Genolini et al, A&A. **580** (2015) A9



Q. Yuana et al, arXiv:1701.06149

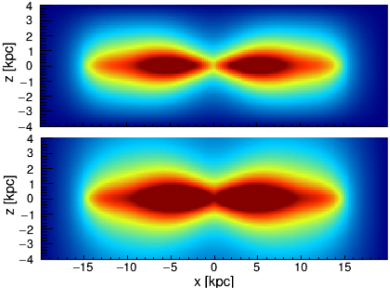
Cosmic-Ray Electron Models

1.1 GeV 1.1 TeV



M. Werner et al, Astropart.Phys. **64** (2015) 18

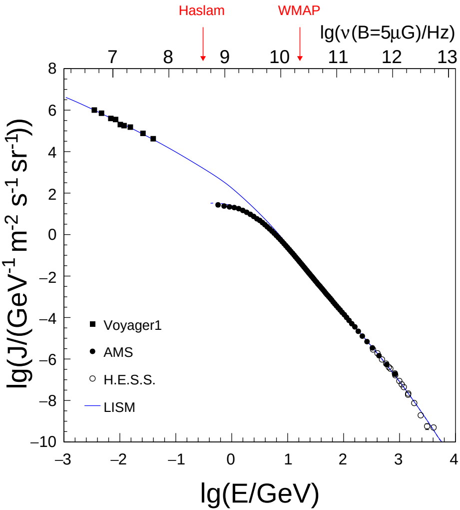
$H = 4$ kpc



$H = 10$ kpc

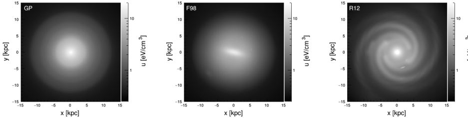
T. Jaffe, private communication

Improved Cosmic-Ray Electron Modeling (UF in prep.)

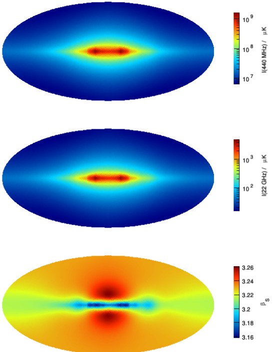


fit DRAGON1 simulations to $e^{\pm}$ data

- 3D ISRF energy density Porter+17



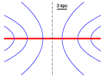
- 3D CR source distribution
- 3D GMF

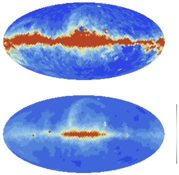


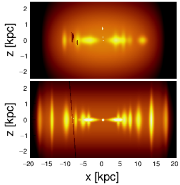
	PD1	DR	PD2
reference	Cummings+16 [?]	Orlando+18 [?]	DiBernardo+13 [?]
diffusion type	constant $[-h_z,\ h_z]$	constant $[-h_z,\ h_z]$	$\propto \exp(z/h_z)$
$\eta/\delta_1/\delta_2/R_{br}$[GV]	1/-0.641/0.578/4.84	1/0.327/0.323/4.0	-0.40/0.57/–/–
$D_0(10\text{ GV})$ $[10^{28}\text{ cm}^2/s]$	5.52	9.33	4.45
h_z [kpc]	4	4	4
$R_D = D_0/h_z$ $[10^{28}\text{ cm}^2/s/\text{kpc}]$	1.38	2.33	1.11
v_A [km/s]	–	8.9	–

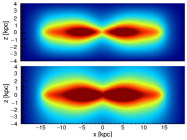
Fit Variations (coherent)

id	disk	toroidal	poloidal	NE	ncre	QU	misc	χ^2/ndf
Parametric models								
a	JF	JF	JF	01	GP_JF	W7	-	1.10
b	JF	JF	FTC	01	GP_JF	W7	-	1.09
c	JF	JFsym	FTC	01	GP_JF	W7	-	1.11
d	JF	JFsym	FTC	01	GP_JF	W7	warp	1.11
e	UF	JFsym	FTC	01	GP_JF	W7	-	1.09
f	UF	UF	UFa	01	GP_JF	W7	-	1.14
g	UF	UF	UFb	01	GP_JF	W7	-	1.09
Synchrotron products								
h	JF	JFsym	FTC	01	GP_JF	W9base	-	1.22
i	JF	JFsym	FTC	01	GP_JF	W9sdc	-	1.24
j	JF	JFsym	FTC	01	GP_JF	W9fs	-	1.11
k	JF	JFsym	FTC	01	GP_JF	W9fss	-	1.22
l	JF	JFsym	FTC	01	GP_JF	P15	-	0.78
Thermal electrons								
m	JF	JFsym	FTC	16	GP_JF	W7	-	1.21
n	UF	JFsym	FTC	16	GP_JF	W7	-	1.14
o	JF	JF	FTC	01	GP_JF	W7	$\kappa = -1$	1.05
p	JF	JF	FTC	01	GP_JF	W7	$\kappa = +1$	1.05
q	JF	JFsym	FTC	01	GP_JF	W7	HIM	1.12
Cosmic-ray electrons								
r	JF	JFsym	FTC	01	O13a	W7	-	1.13
s	JF	JFsym	FTC	01	O13b	W7	-	1.12
t	JF	JFsym	FTC	01	S10	W7	-	1.13

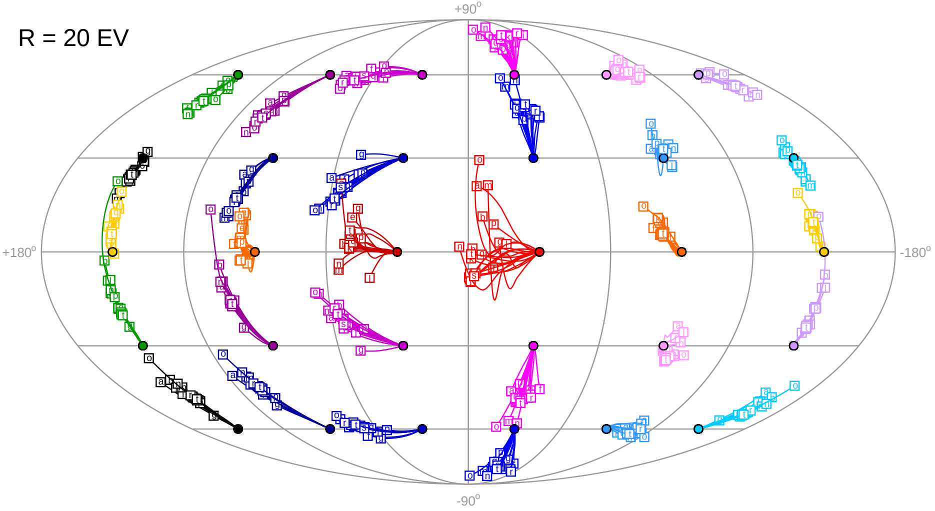




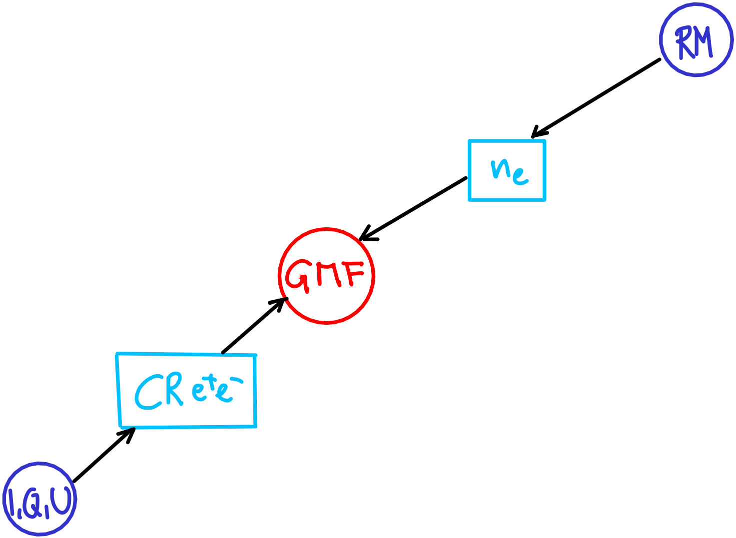




Effect on Back-tracking of UHECRs, $R = E/Z = 20\,\mathrm{EV}$



Summary



Summary