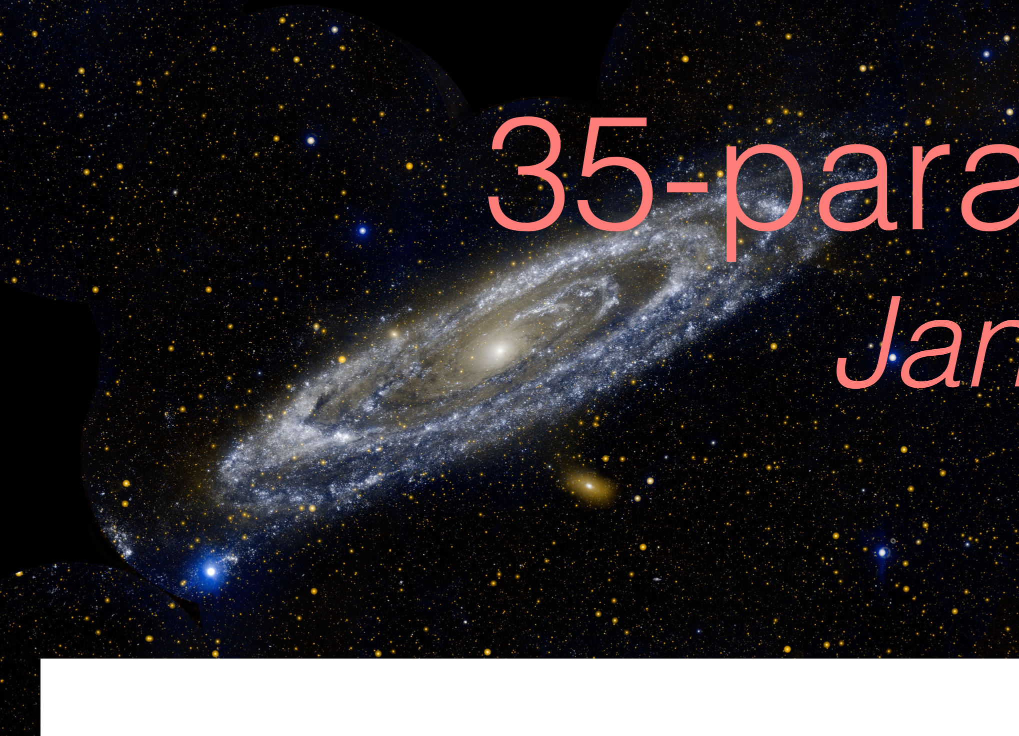
PROGRESS MODELING THE GALACTIC MAGNETIC FIELD

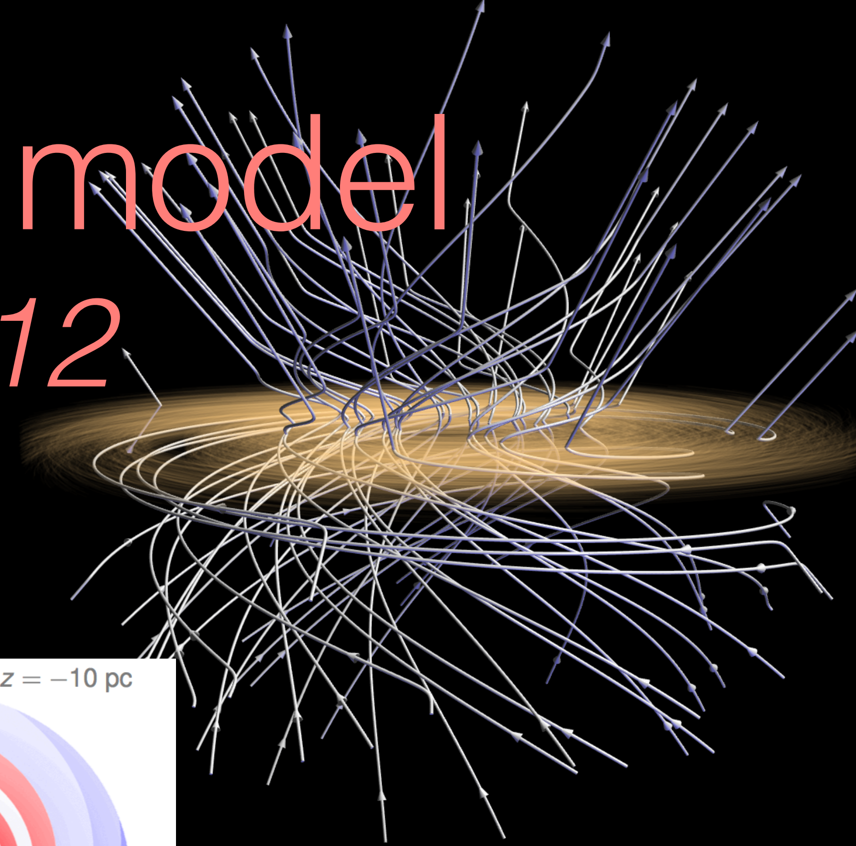
Glennys R. Farrar (NYU) and Michael Unger (KIT)

ICRC, Madison WI, July 27, 2019



35-parameter GMF model

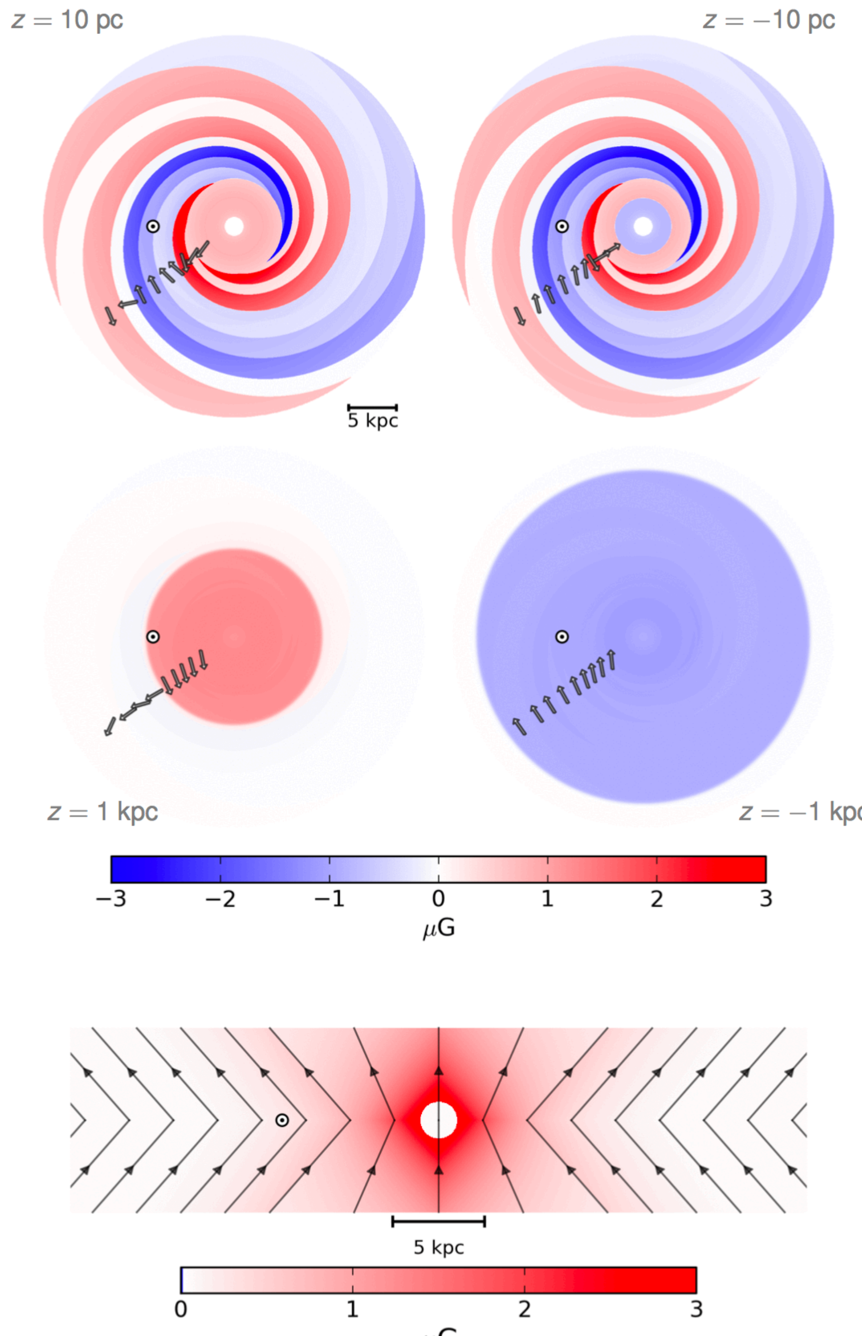
Jansson-Farrar 2012



three (divergence-free!) components:

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

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



<u>**JF12 used:**</u>

40k RMs (mostly NVSS)

WMAP Q,U,I

NE2001 n_e

n_{cre} GALPROP

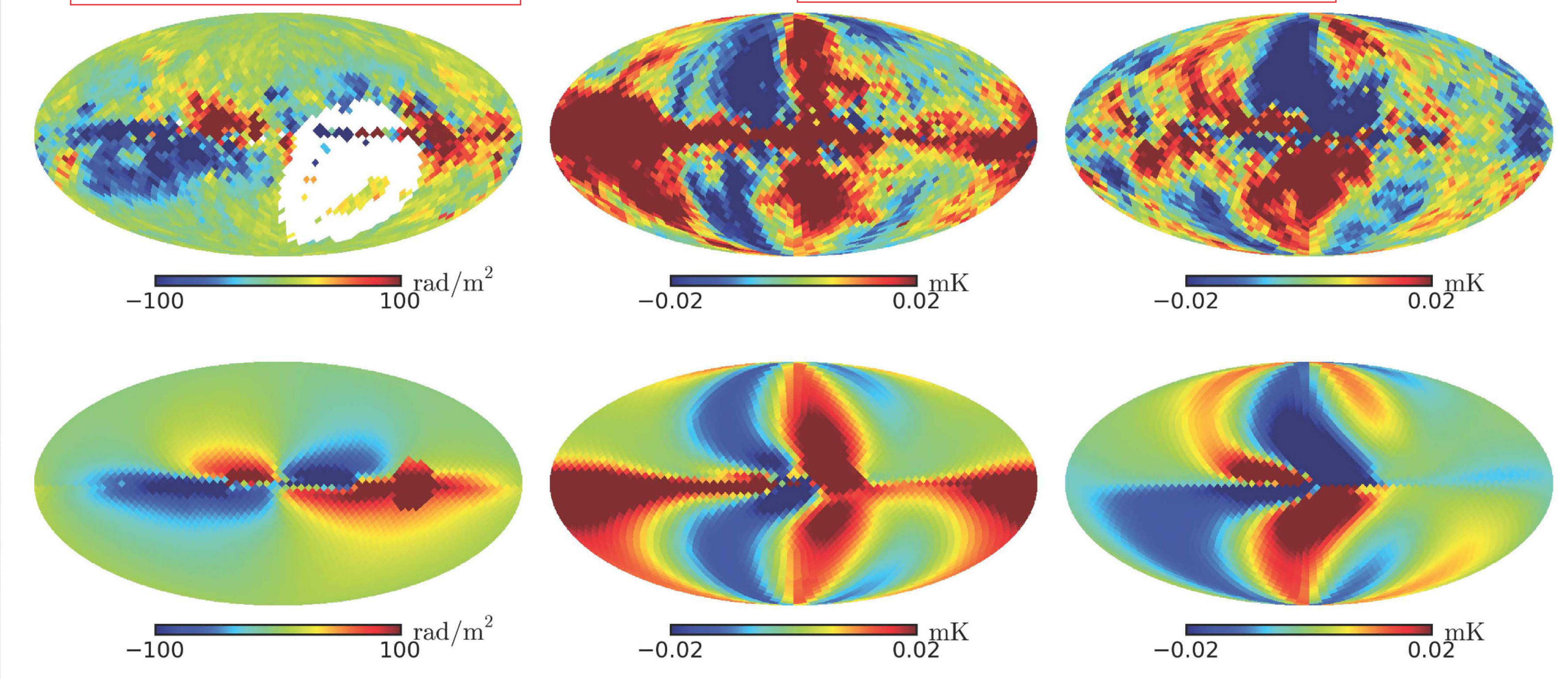
[a] R. Jansson & G.F. Farrar, ApJ **757** (2012) 14
[b] R. Jansson & G.F. Farrar, ApJ **761** (2012) L11

JF12 CAPTURES MAIN FEATURES

but many improvements are needed (UF19!)

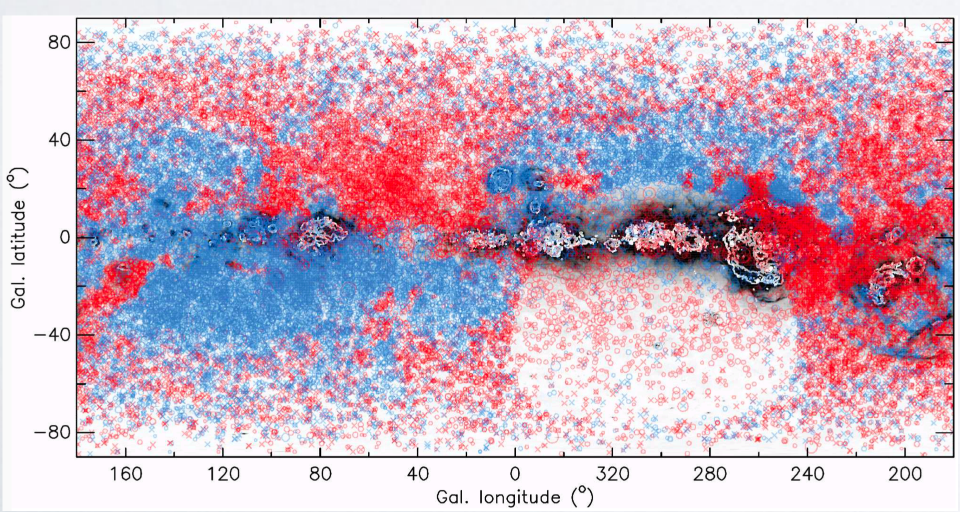
$$\mathrm{RM} \propto \int n_e B_{\parallel} \, \mathrm{d}l$$

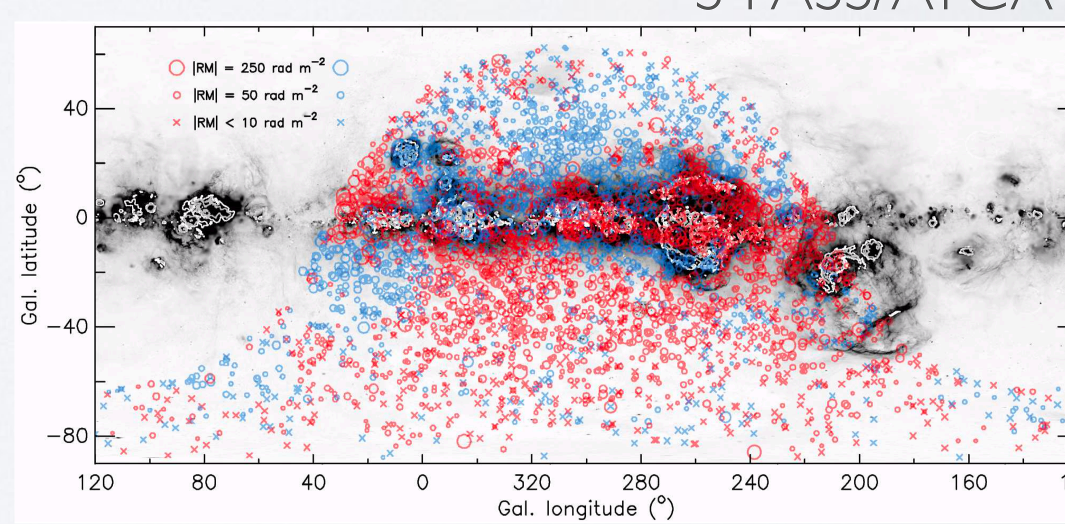
$$Q/U \propto \int B_{\perp}^2 \, n_{\mathrm{cre}} \, \mathrm{d}l$$



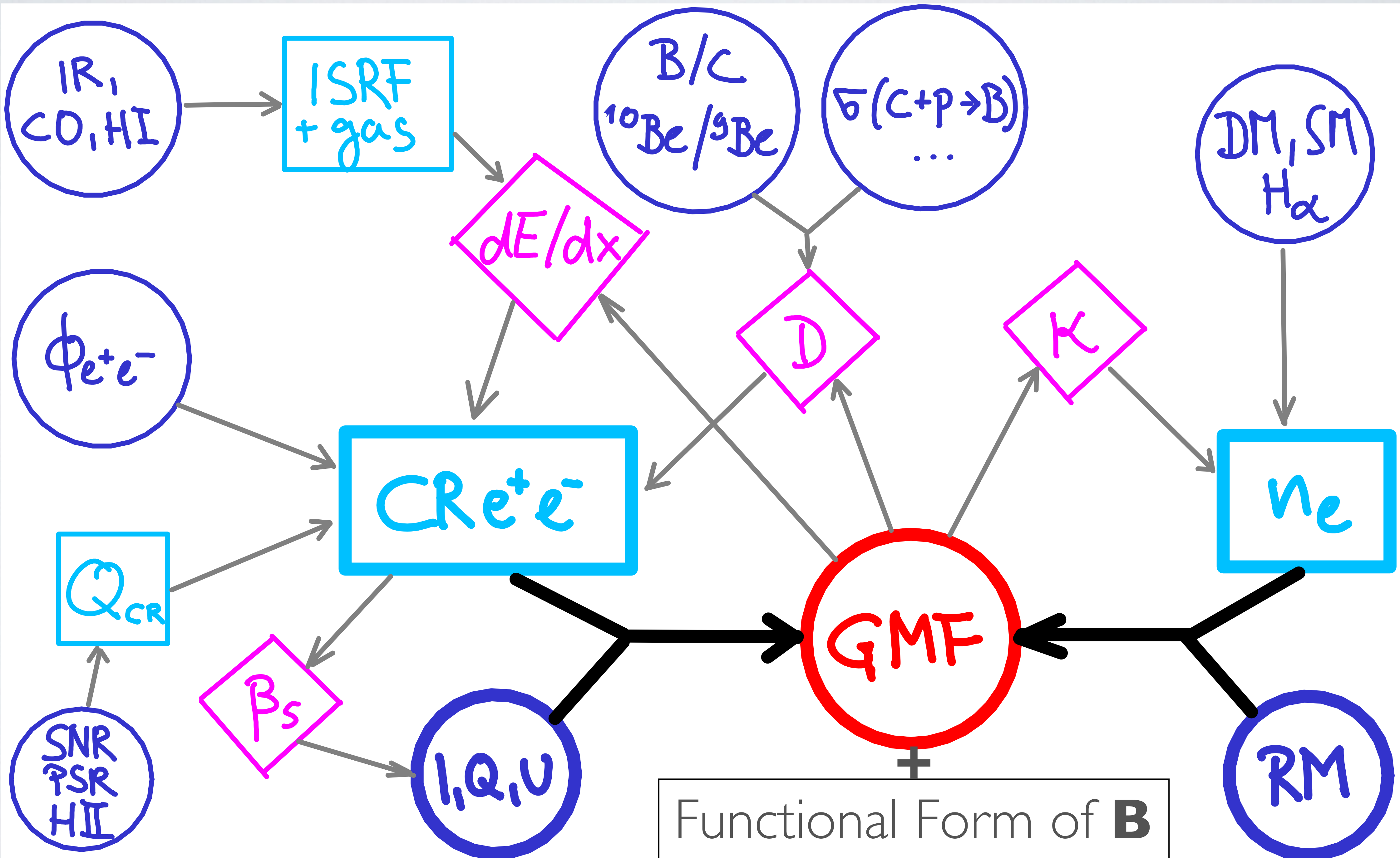
Data in blank region has finally been released; well predicted by JF12

S-PASS/ATCA Schnitzeler+19





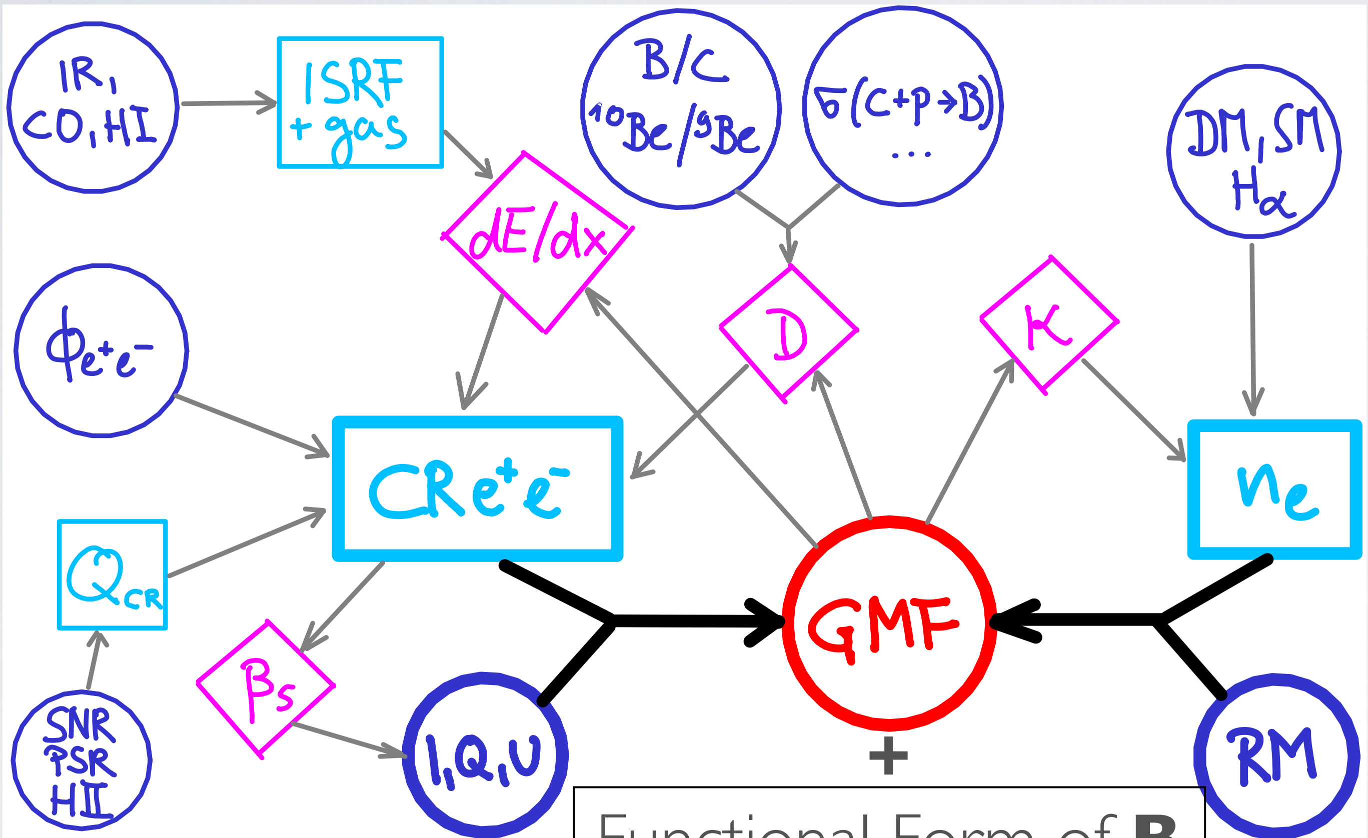
UNGER-FARRAR 2019?



+

Functional Form of **B**
(divergence-free)

TODAY'S TALK



+

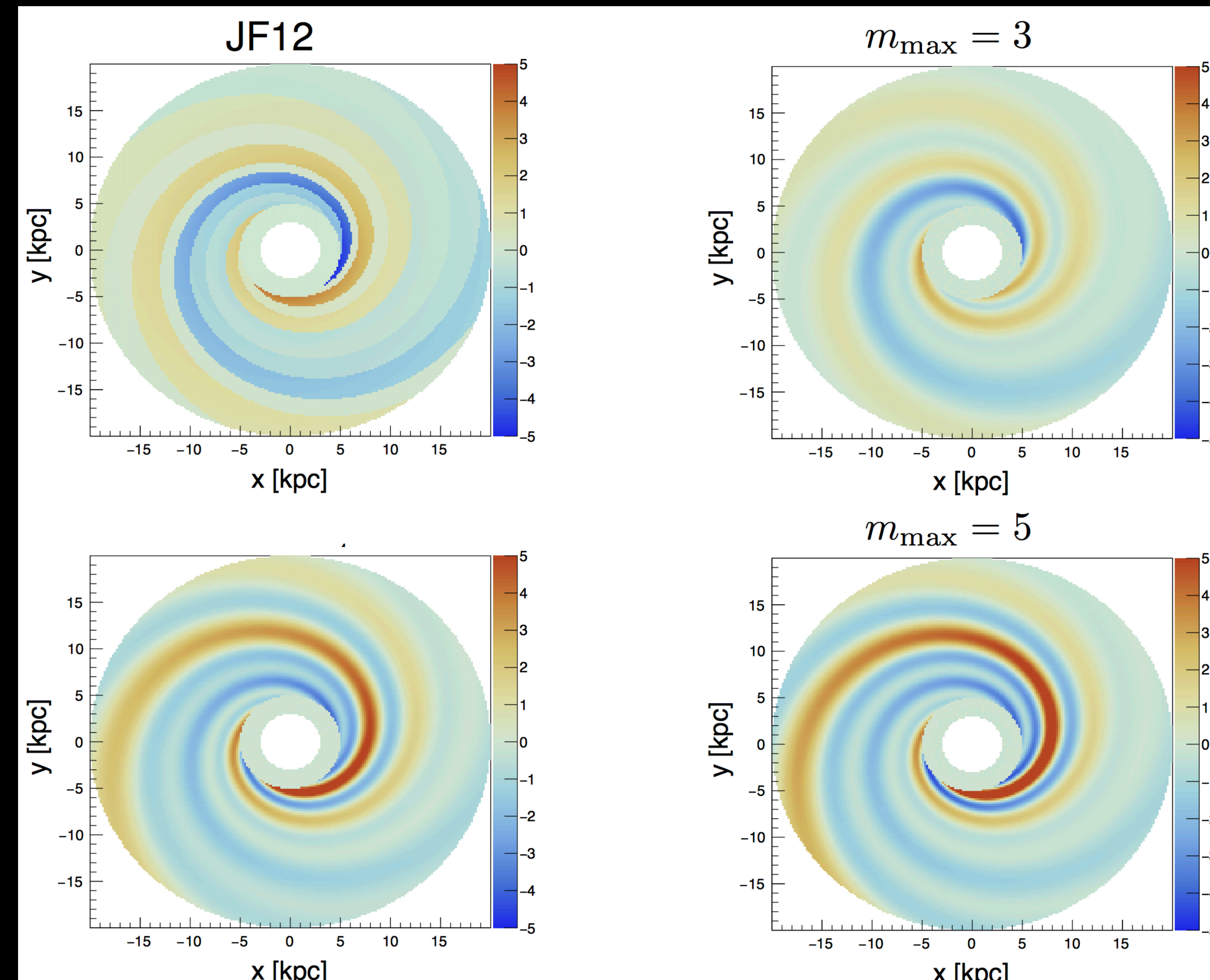
Functional Form of **B**
(divergence-free)

- Progress on modeling functional form of **B**
- **Random field** [& coherence length]
- Impact of coherent GMF on UHECR dipole anisotropy

Functional form of disk and halo fields

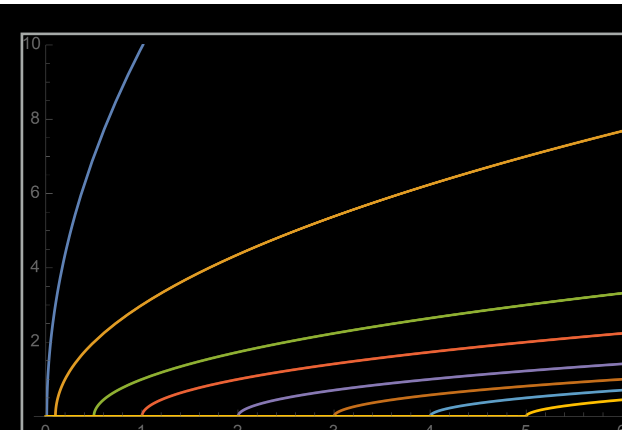
- Fourier spiral: fit pitch angle and arm spacing as well as B_i's:
  - *Better fit, fewer parameters…*
  - *Must fix discontinuity at molec. ring*
- Smoother poloidal fields with more general parameterization
  - *Still not flexible-enough form.*
- Allow for flux transfer between disk and halo *[none found]*
- Allow for warp and flare of disk *[small effect]*

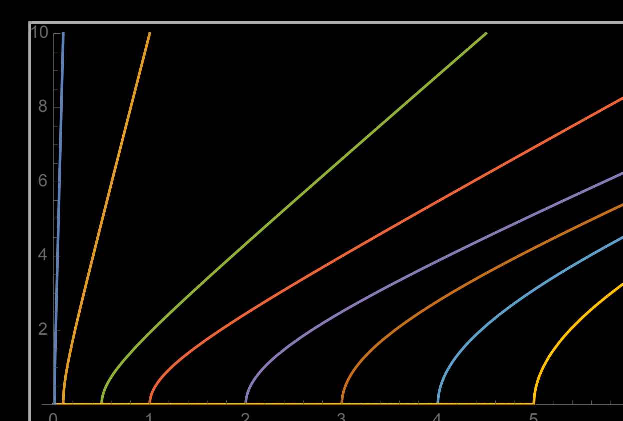
UF19: more refined form; twisted-poloidal structure confirmed



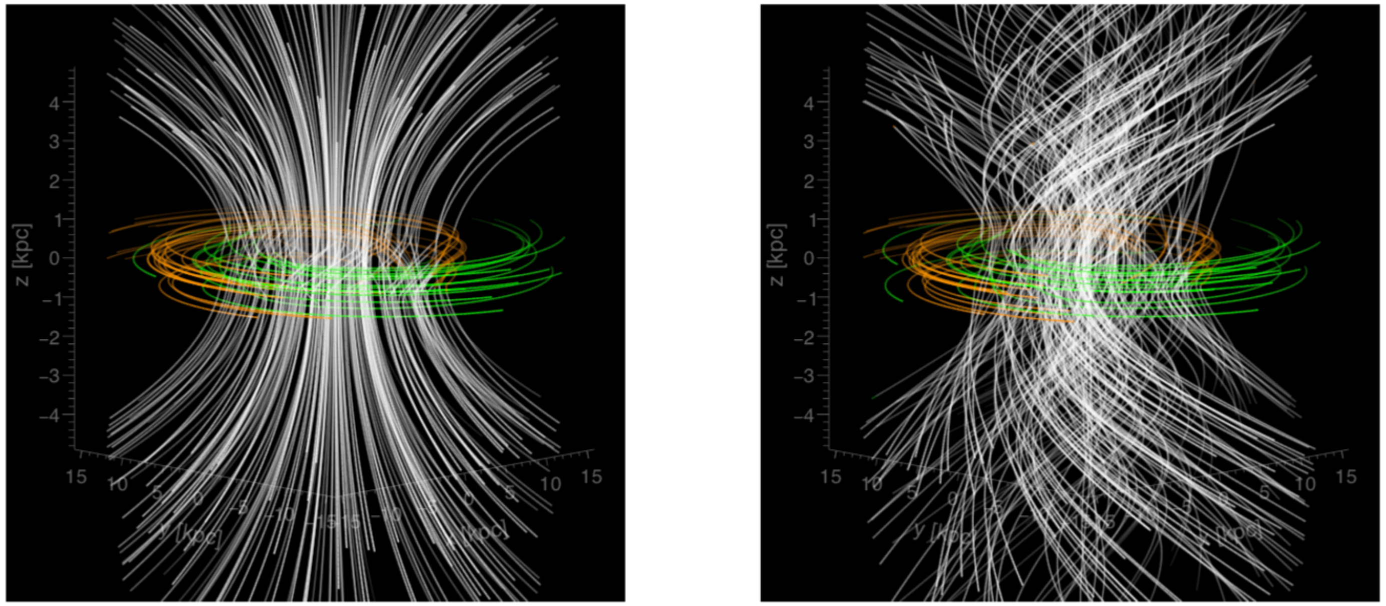
$$\mathbf{B}(r,\phi) = (\sin\alpha, \cos\alpha, 0)\ \frac{r_0}{r}\ B(r_0)$$

$$B(r_0) = \sum_{i=1}^{n} B_i \cos\left(m_i(\phi_0 - \phi_i^*)\right)$$



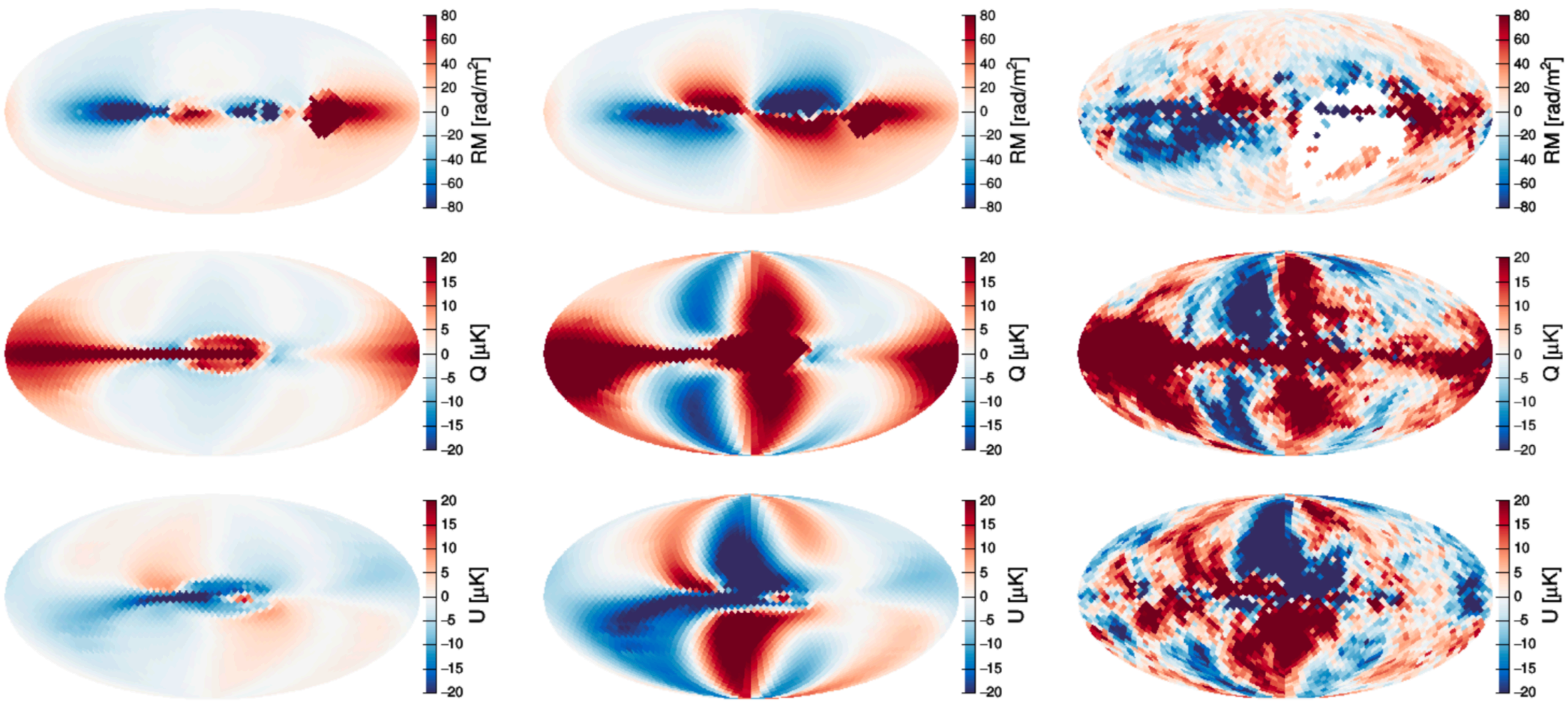


TOROIDAL HALO FROM DIFFERENTIAL ROTATION



$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) = \begin{pmatrix} -\frac{v}{r}\,\partial_\phi B_r \\ \partial_z(vB_z) + \partial_r(vB_r) \\ -\frac{v}{r}\,\partial_\phi B_z \end{pmatrix}$$

excellent fit
more physical



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

UF arXiv:1901.04720

UF19 random field modeling

observed synchrotron intensity along one line of sight in direction **n**:

$$I_{\mathrm{tot}} = I_{\mathrm{rand}} + \Pi^{-1} I_{\mathrm{pol}} \propto \int_0^\infty \kappa(r\mathbf{u}) \left(b(r\mathbf{u})^{\frac{p+1}{2}} + B_\perp(r\mathbf{u})^{\frac{p+1}{2}} \right) \mathrm{d}r$$

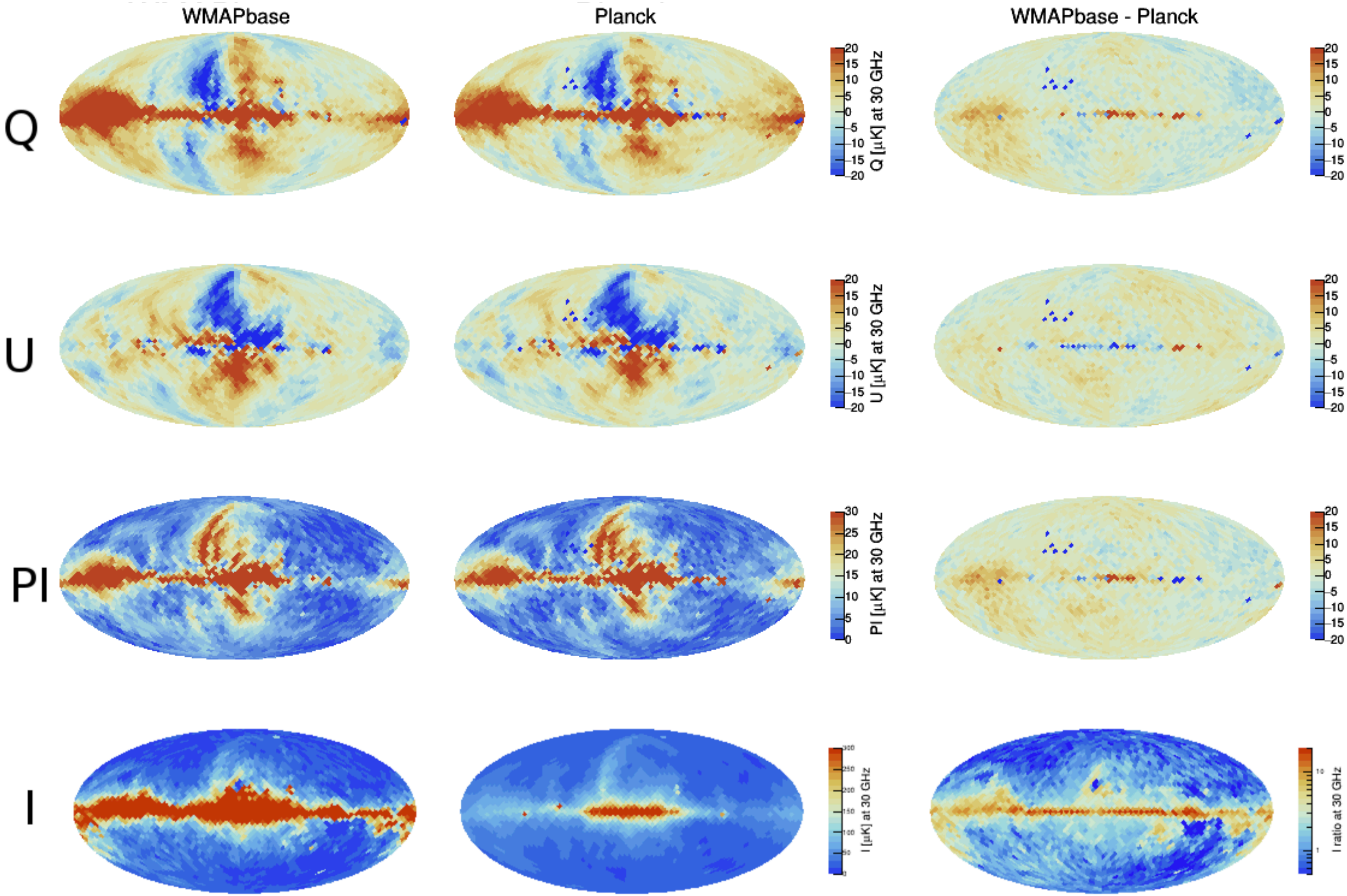
(random field **b**, projected coherent and striated field $B_\perp = \mathbf{u} \times (\mathbf{B} \times \mathbf{u})$, polarization fraction $\Pi = (p+1)/(p+\frac{7}{3})$; cosmic-ray electron energy spectrum $n_{\mathrm{cre}} = \kappa\, E^{-p}$)

Objective: Determine **b** from I_{tot}

	UF19	JF12	comment
I_{tot}	408 MHz	22 GHz	contamination by AME at $\geq$ 10 GHz
I_{pol}	data	model	loops & Perseus emission not modeled
n_{cre}	$n(x, y, z, E, b, B)$	$\alpha\, \kappa(r, h)\, E^{-3}$	no self-consistent electron cooling
foreground	SNR, ff(H_α, RRL)	ff(H_α)	H_α dust-attenuated at low b
integrator	RUQI	HAMMURABI	Hammurabi bug corrected

ff: free-free emission, RRL: radio recombination lines, I_{tot}(JF12): WMAPbase, I_{tot}(UF19): Haslam, $\kappa(r, h)$ from GALPROP "71Xvarh7S"

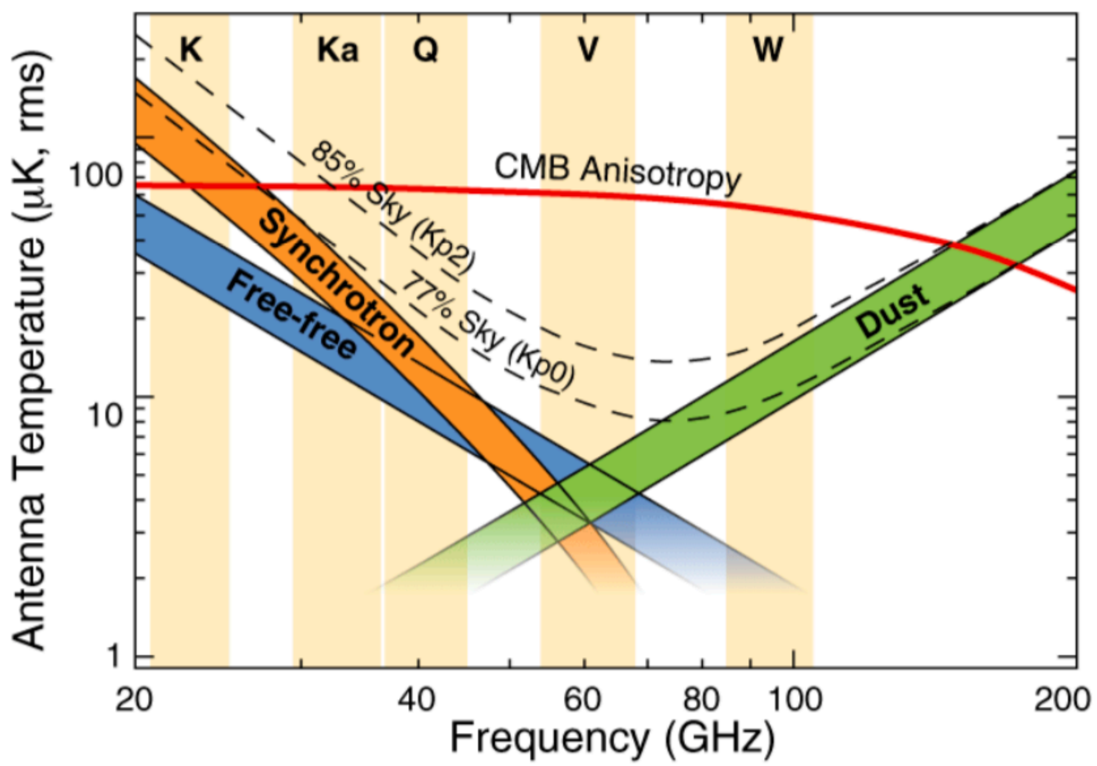
Synchrotron Emission Products (Planck and WMAP)



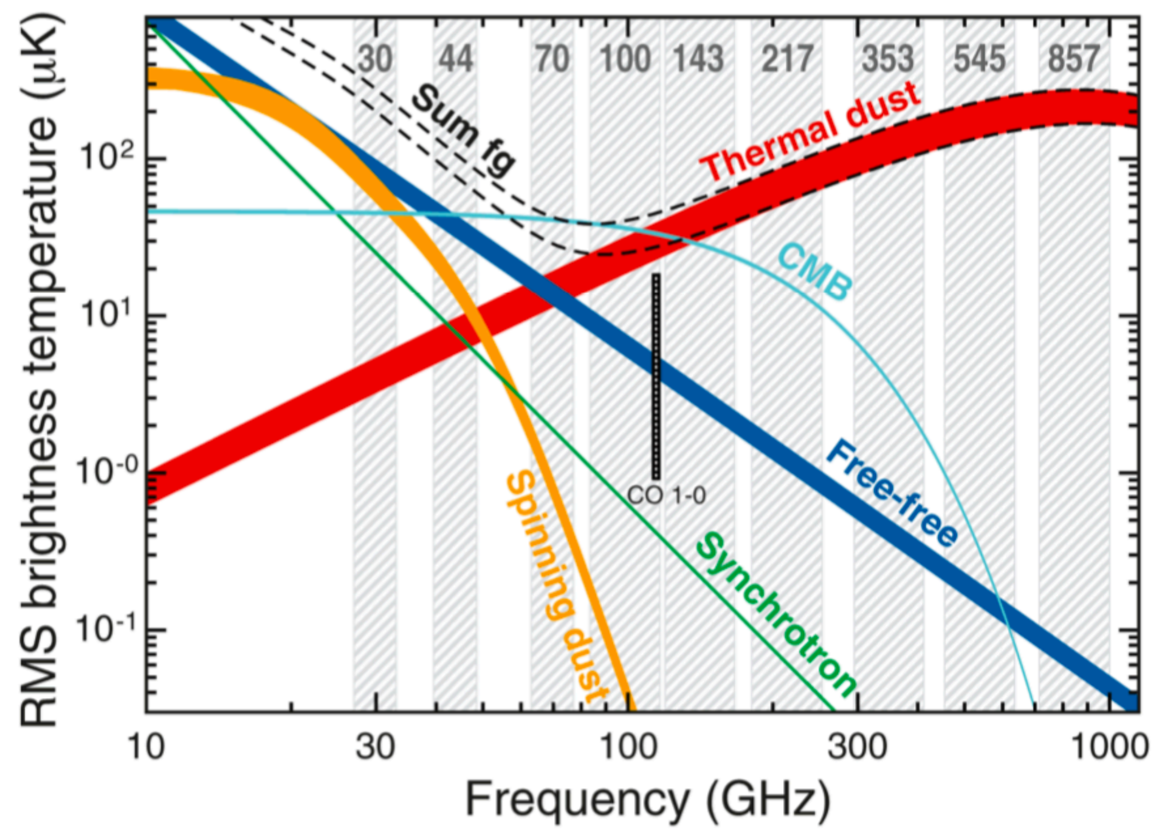
Synchrotron Emission

Component Separation:

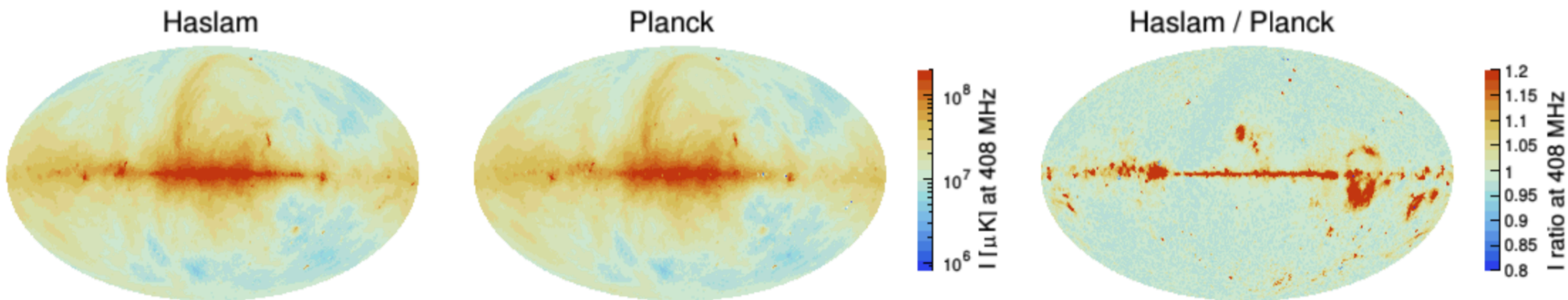
WMAPbase9yr



Planck

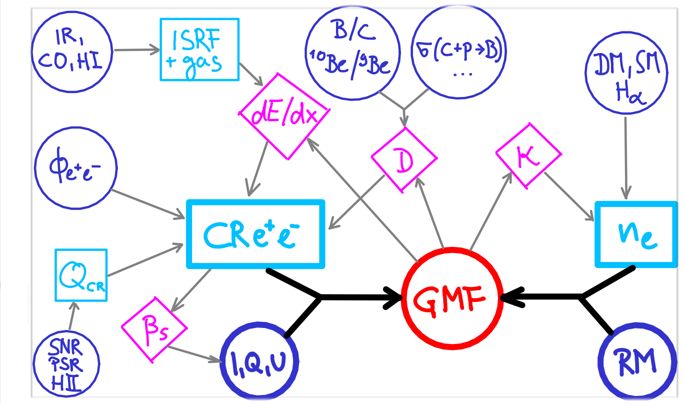


Planck vs. Haslam

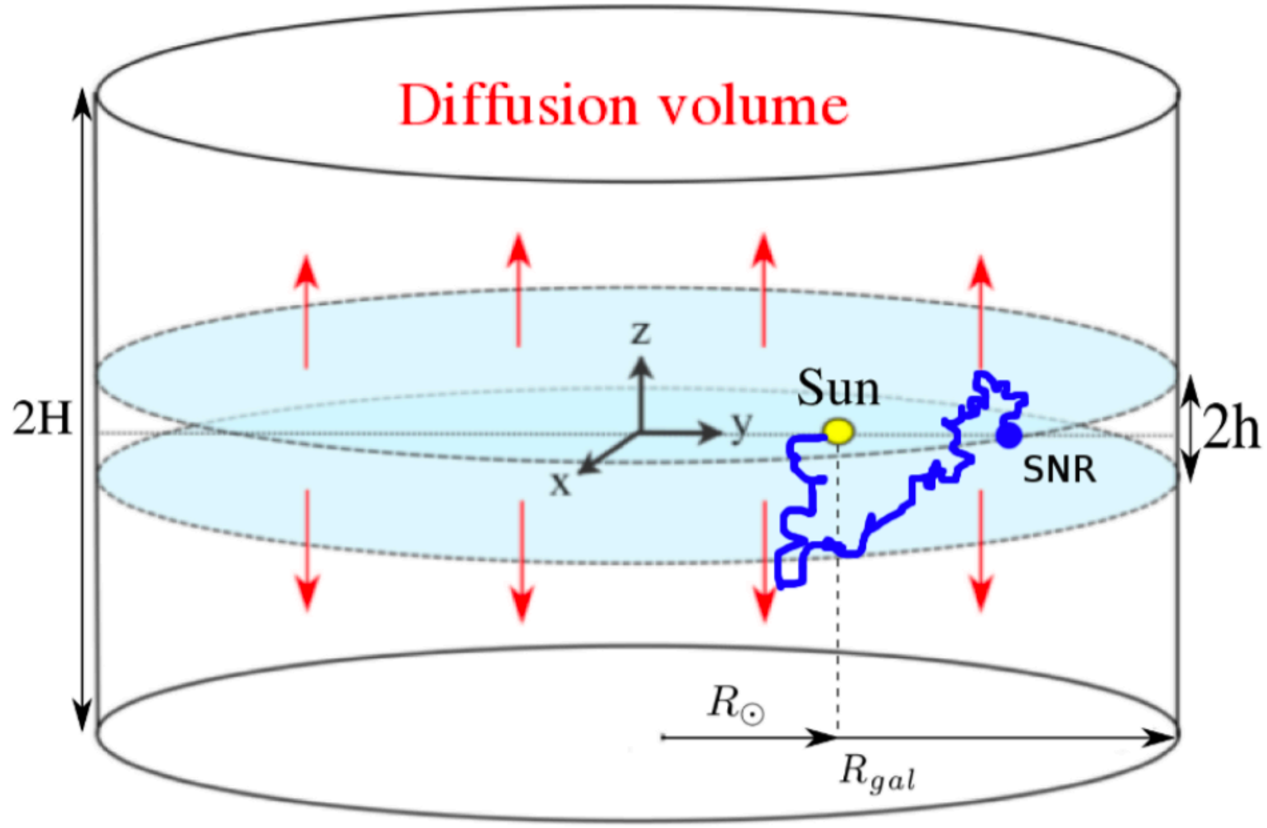


destriped and mono/dipole subtracted Haslam from Remazeilles+14

Cosmic-Ray Electrons

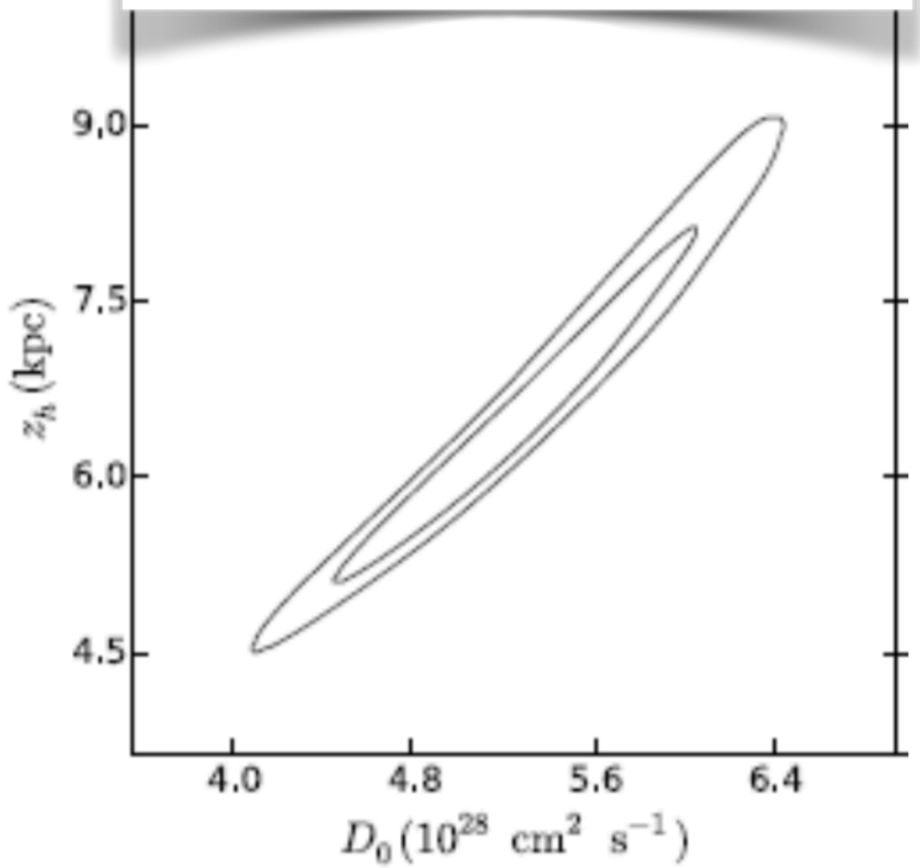


- **origin:**
  - primary e^-: acceleration in supernova rem
  - secondary $e^{\pm}$: $p + p_{\mathrm{ISM}}$
  - primary $e^{\pm}$: pulsar wind nebulae
- **data:** cosmic-ray electron spectra at Earth, B/C, Be
- diffusion and cooling in Galactic magnetic field



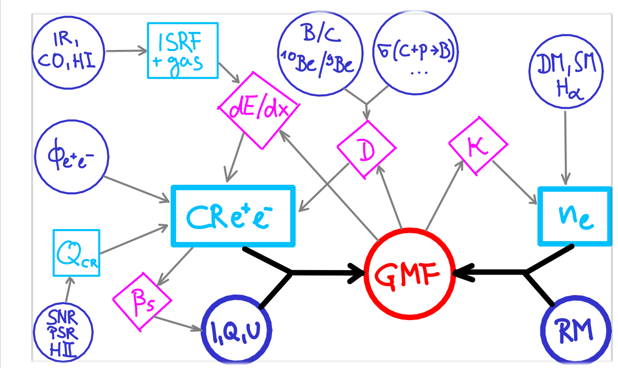
Y. Genolini et al, A&A. **580** (2015) A9

D & box height are degenerate

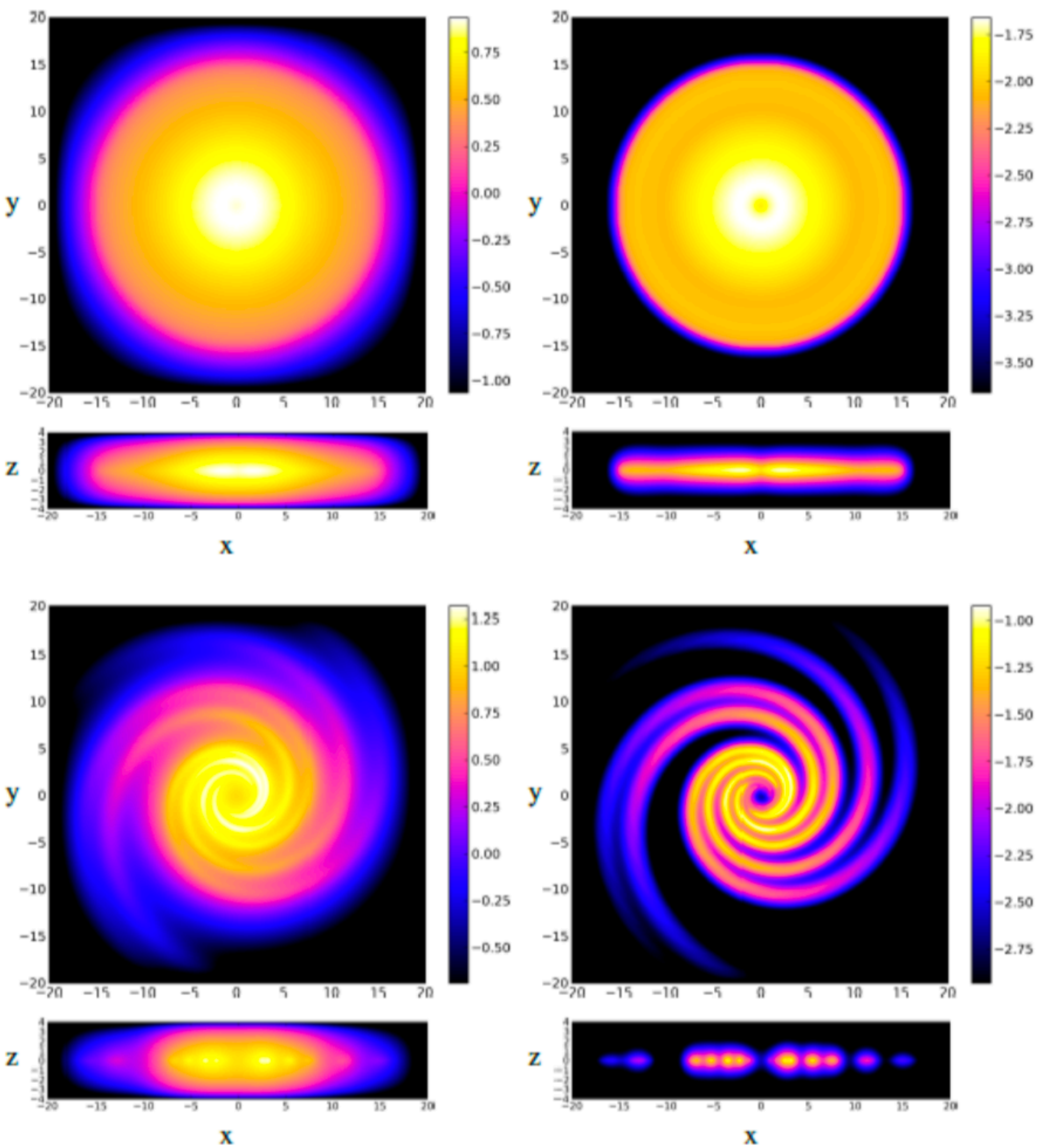


Yuana+2017

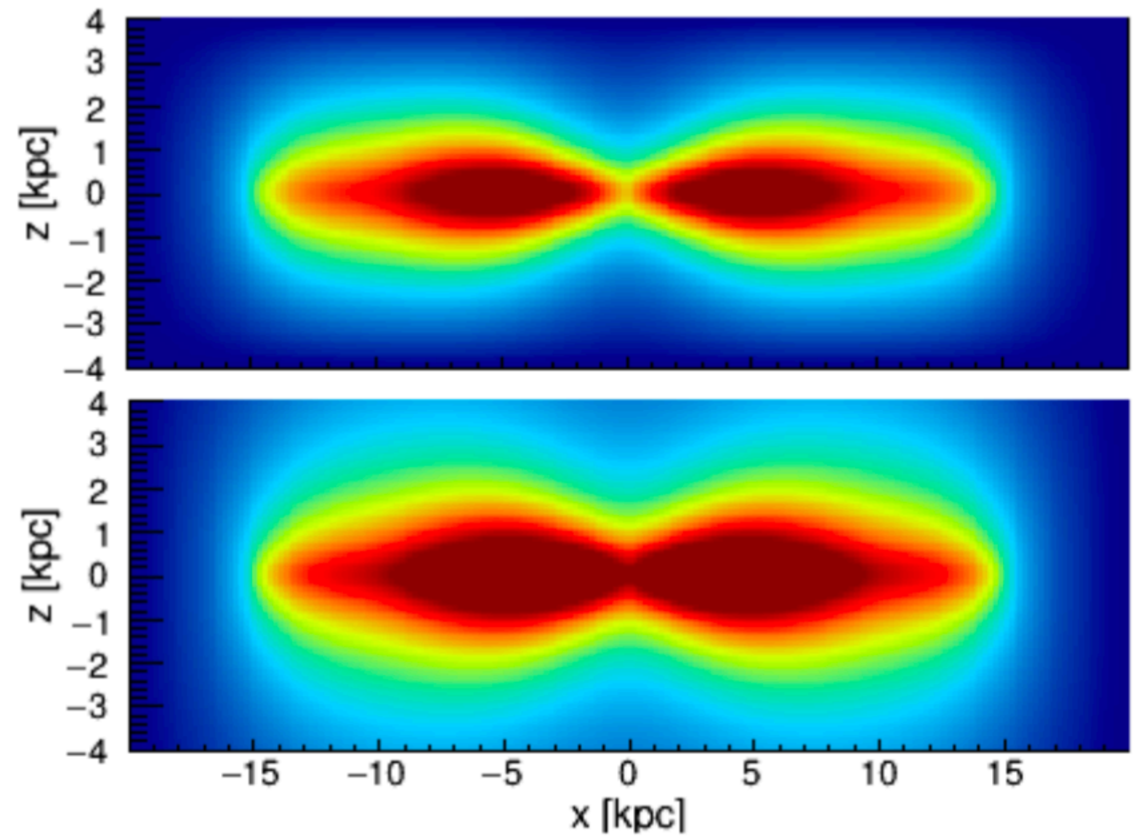
Planck's CR electron Models: differ in 3D



1.1 GeV 1.1 TeV



$H = 4$ kpc

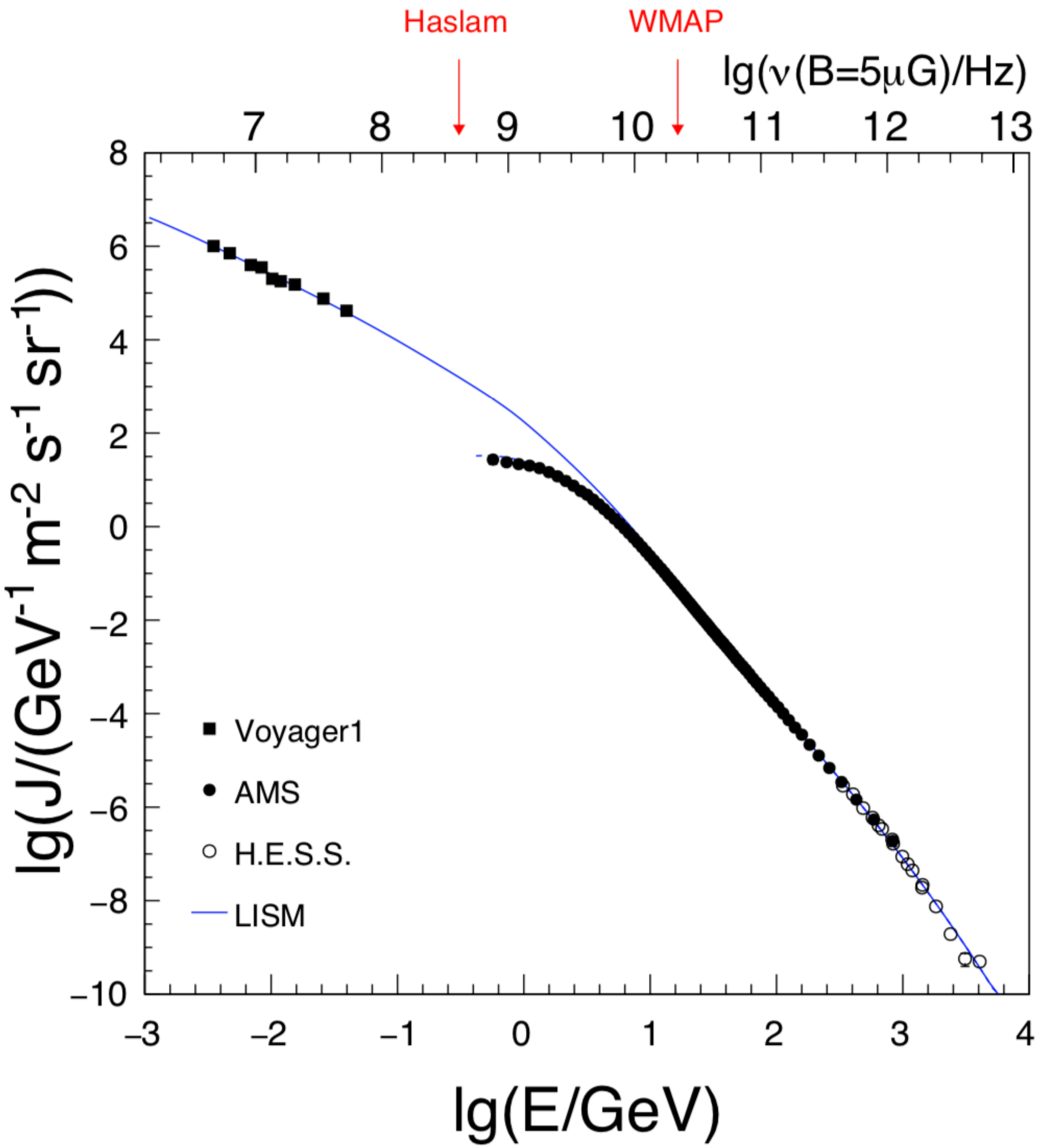


$H = 10$ kpc

T. Jaffe, private communication

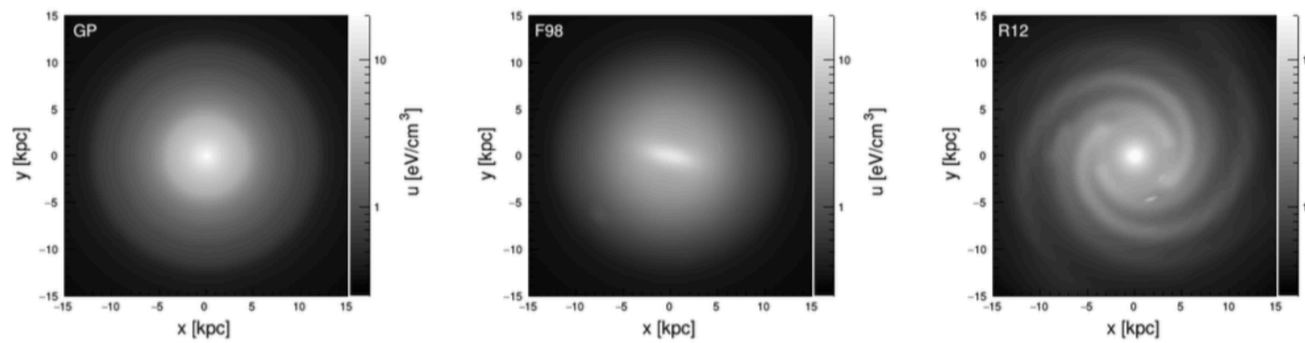
M. Werner et al, Astropart.Phys. **64** (2015) 18

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

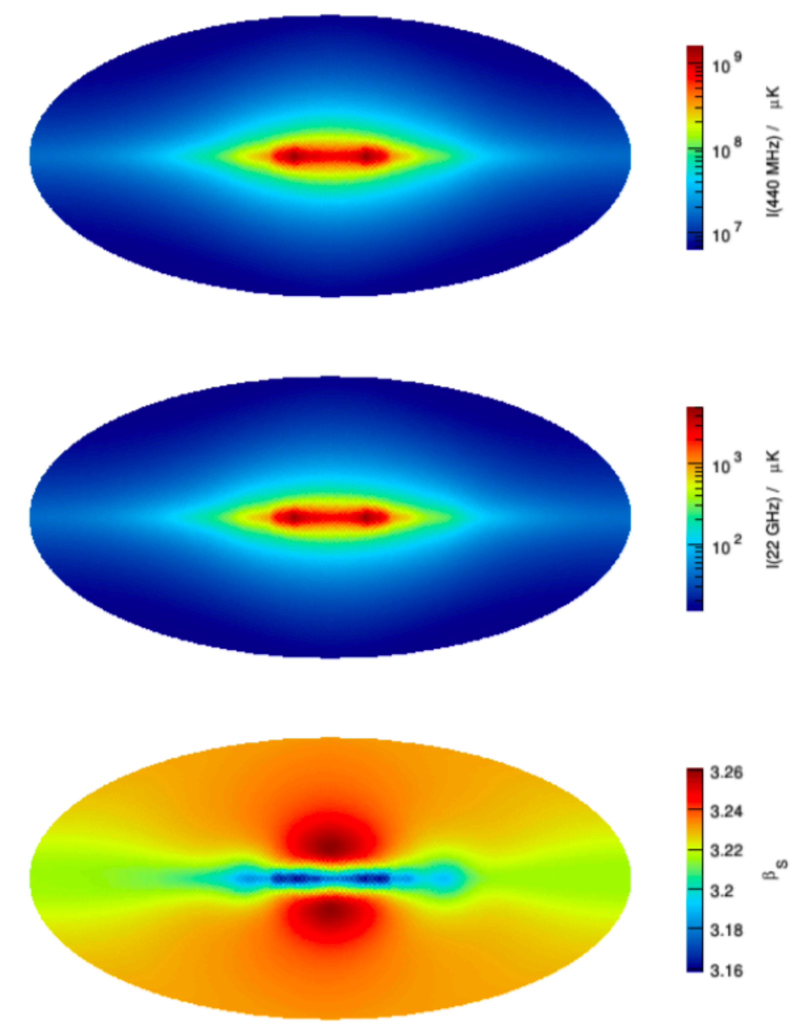


fit DRAGON simulations to e$^{\pm}$ data

- 3D ISRF energy density Porter+17



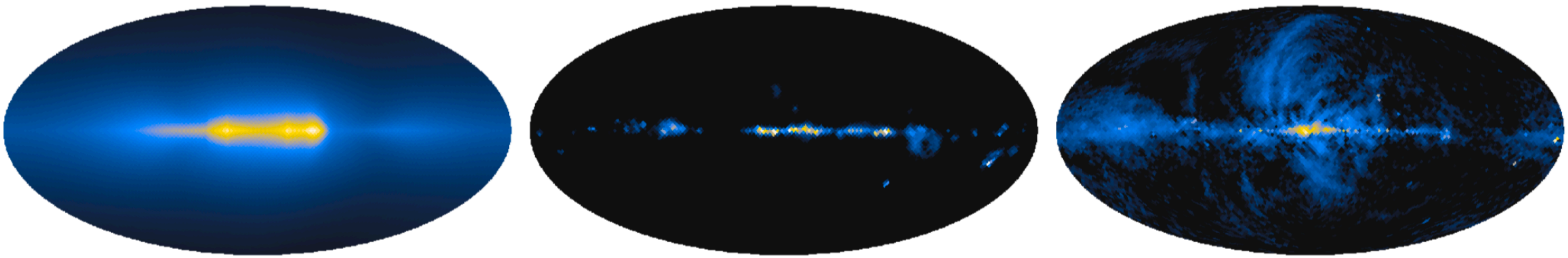
- 3D CR source distribution
- 3D GMF



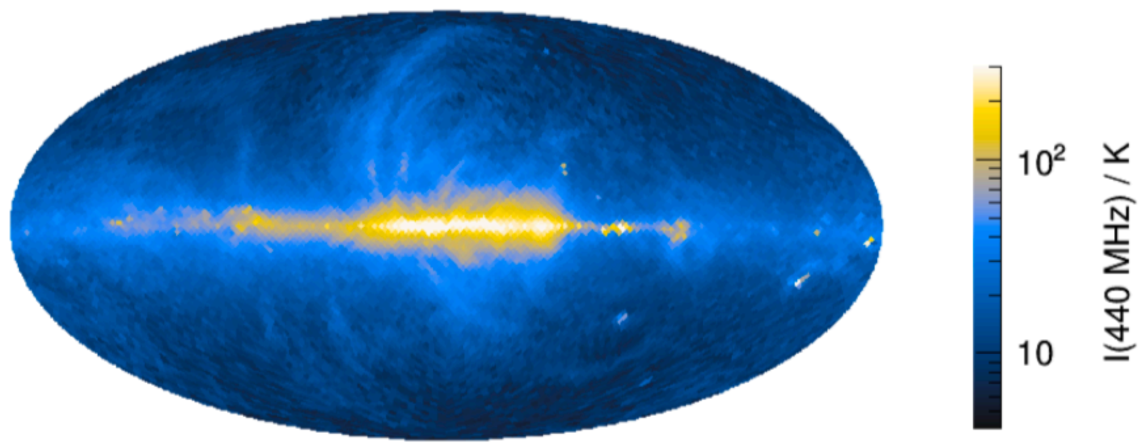
	PD1	DR	PD2
reference	Cummings+16	Orlando+18	DiBernardo+13
diffusion type	constant $[-h_z,\ h_z]$	constant $[-h_z,\ h_z]$	$\propto \exp(z/h_z)$
$\eta/\delta_1/\delta_2/R_{\rm br}$[GV]	1/-0.641/0.578/4.84	1/0.327/0.323/4.0	-0.40/0.57/–/–
$D_0(10\ \text{GV})\ [10^{28}\ \text{cm}^2/s]$	5.52	9.33	4.45
h_z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

Deriving $B_{\rm rand}$ from I

$I(B_{\rm rand})$ + $I_{\rm free\text{-}free}$ + $I_{\rm coh}$



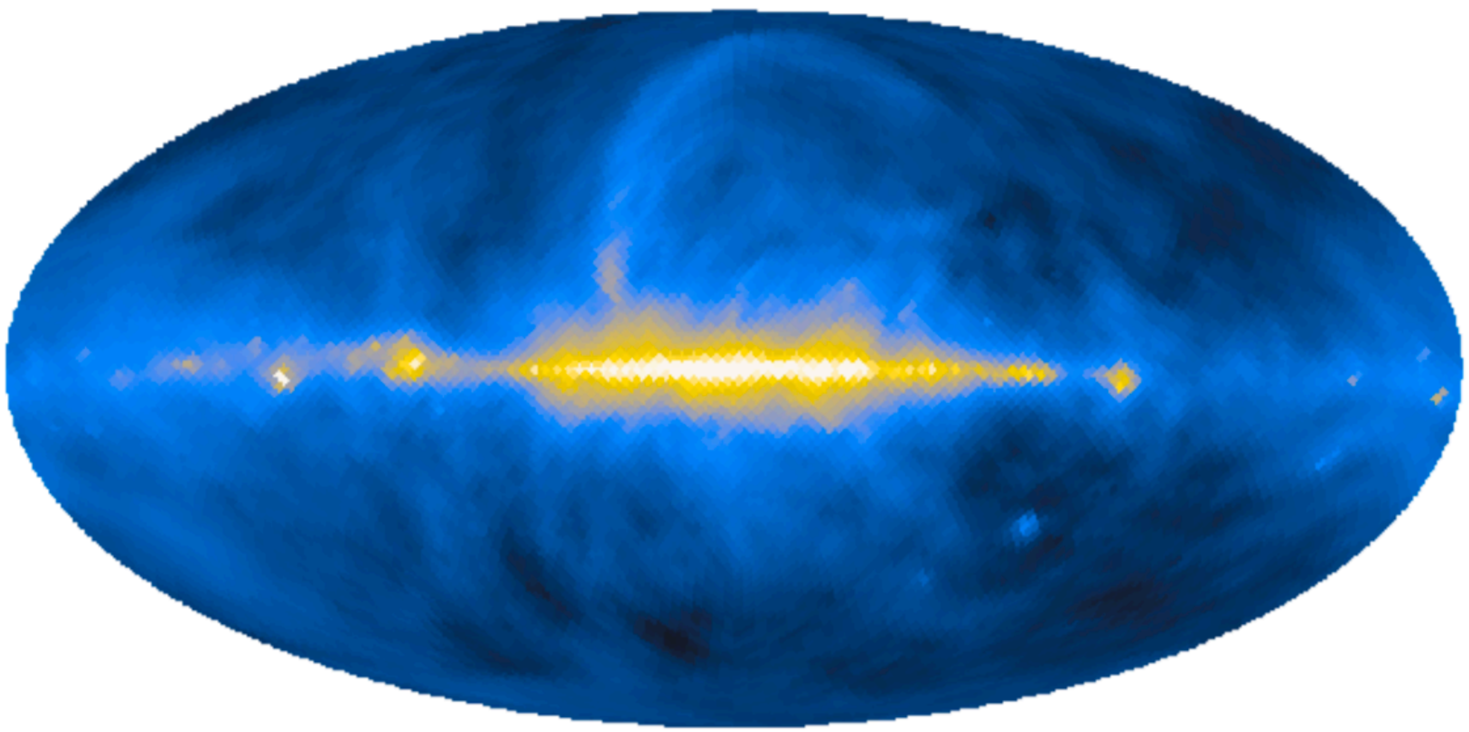
=

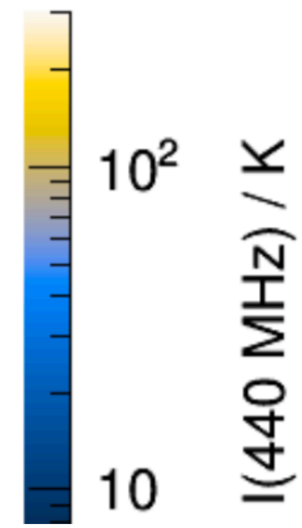


- fitted model prediction $I(B_{\rm rand})$ (using specific $n_{\rm cre}$ model)
- free-free from H_α data (de-attenuated and scattering-corrected, Bennet+15)
- $I_{\rm coh} = 1/\Pi \times (0.408/22.5)^{\beta_S} \times \mathrm{PI}$ (PI from WMAP, polarization fraction $\Pi \sim 0.7$)

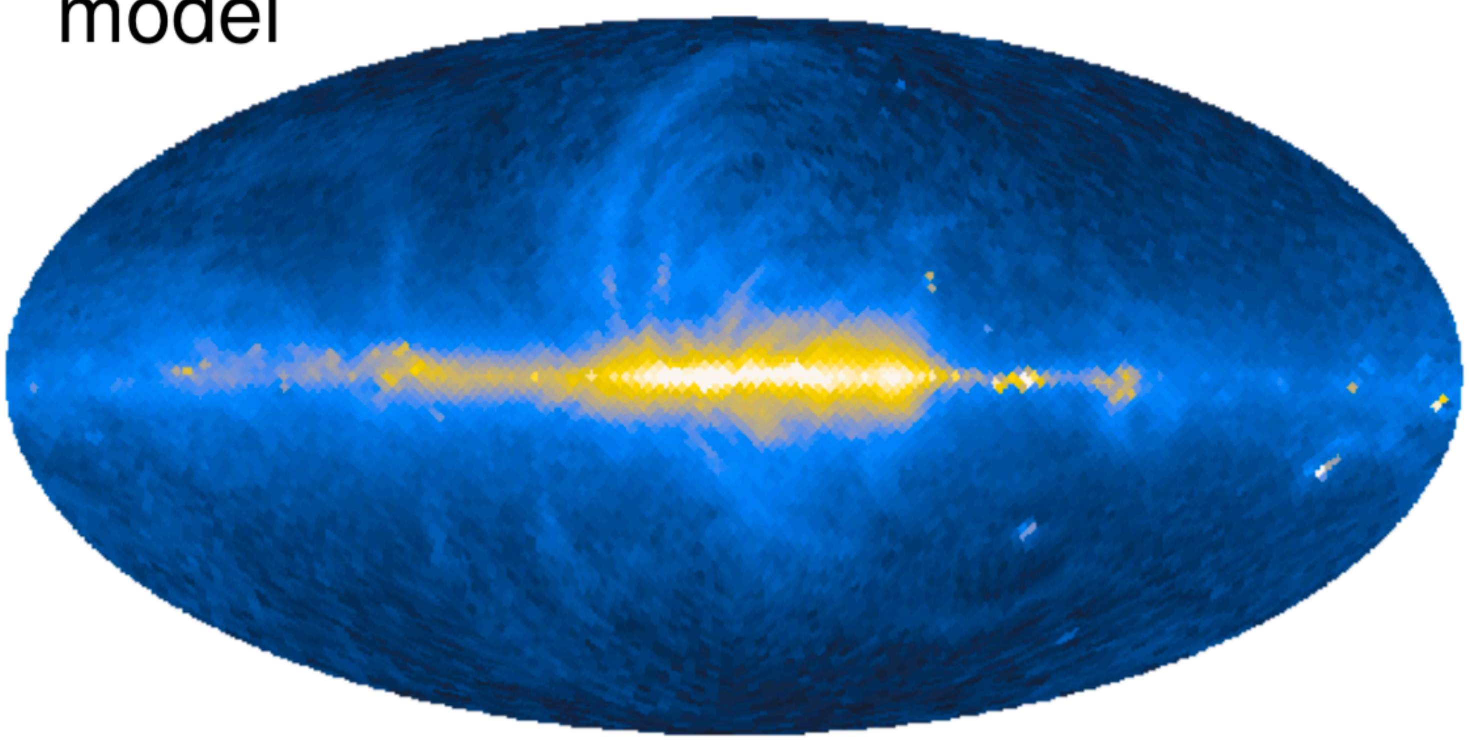
Deriving B_{rand} from I (preliminary)

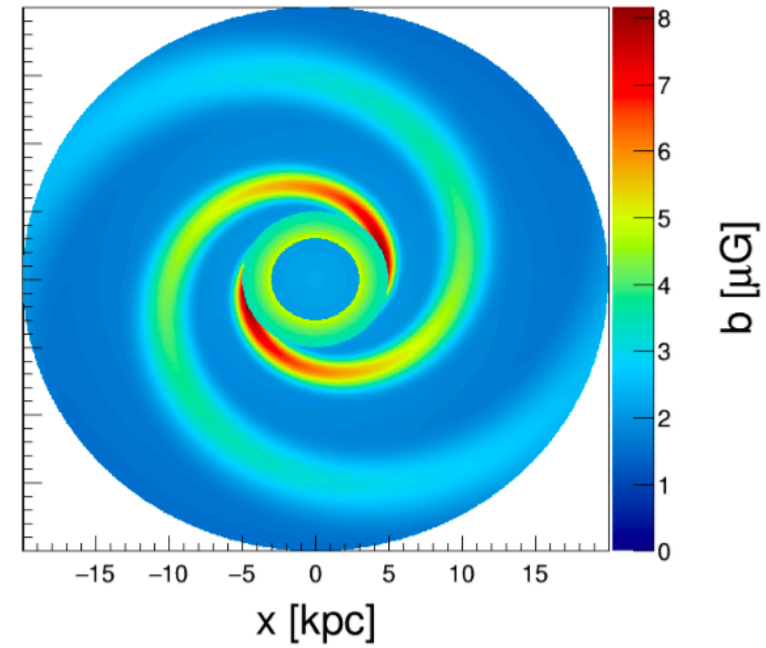
Haslam intensity

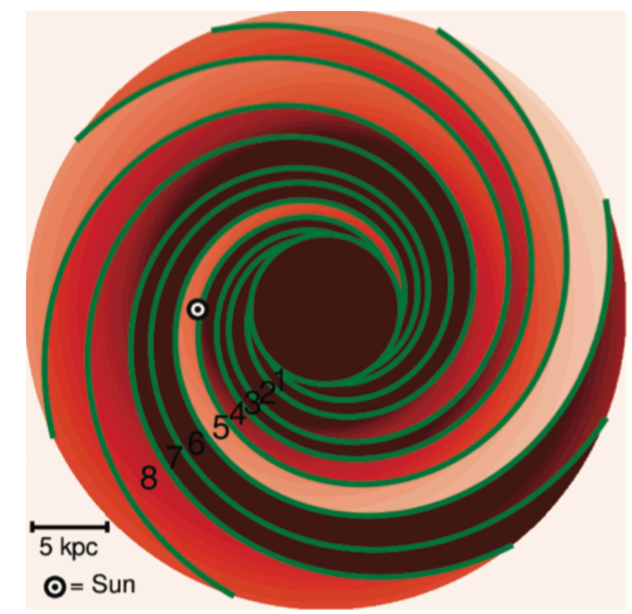




model

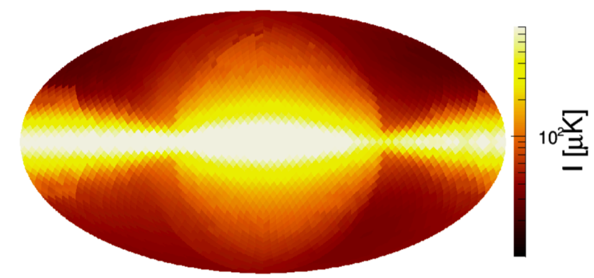




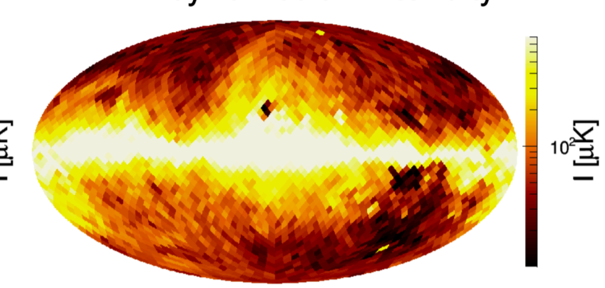


Analogous comparison JF12

model

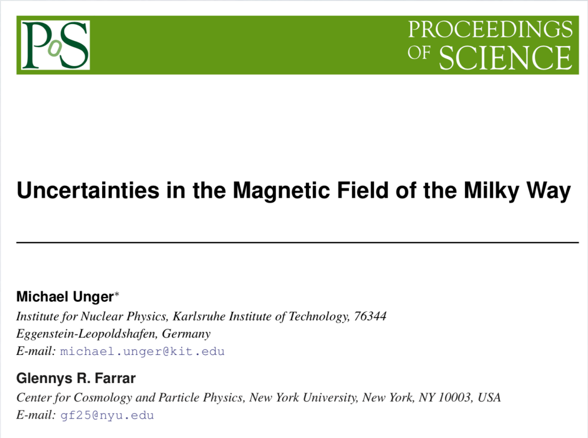


WMAP synchrotron intensity



GMF UNCERTAINTY ↔ UHECR DEFLECTIONS

Uncertainties in UHECR deflections
from uncertainties in JF12 coherent field model,
from uncertainties in input (I_{rand}, n_e, n_{cre}) and parameterization


PROCEEDINGS OF SCIENCE

Uncertainties in the Magnetic Field of the Milky Way

Michael Unger*
Institute for Nuclear Physics, Karlsruhe Institute of Technology, 76344 Eggenstein-Leopoldshafen, Germany
E-mail: michael.unger@kit.edu

Glennys R. Farrar
Center for Cosmology and Particle Physics, New York University, New York, NY 10003, USA
E-mail: gf25@nyu.edu

id	disk model	toroidal model	poloidal model	thermal electrons	cosmic-ray electrons	synchrotron data product	misc.	χ^2/ndf
Parametric models								
a	JF	JF	JF	NE2001	GP_{JF}	WMAP7	-	1.10
b	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	-	1.09
c	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	-	1.11
d	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	warp	1.11
e	UF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	-	1.09
f	UF	UFa		NE2001	GP_{JF}	WMAP7	-	1.14
g	UF	UFb		NE2001	GP_{JF}	WMAP7	-	1.09
Synchrotron products								
h	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9base	-	$1.22^{\dagger}$
i	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9sdc	-	$1.24^{\dagger}$
j	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9fs	-	$1.11^{\dagger}$
k	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP9fss	-	$1.22^{\dagger}$
l	JF	JFsym	FTC	NE2001	GP_{JF}	Planck15	-	$0.78^{\dagger}$
Thermal electrons								
m	JF	JFsym	FTC	YMW17	GP_{JF}	WMAP7	-	1.21
n	UF	JFsym	FTC	YMW17	GP_{JF}	WMAP7	-	1.14
o	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	$\kappa = -1$	1.05^{*}
p	JF	JF	FTC	NE2001	GP_{JF}	WMAP7	$\kappa = +1$	1.05^{*}
q	JF	JFsym	FTC	NE2001	GP_{JF}	WMAP7	HIM	1.12
Cosmic-ray electrons								
r	JF	JFsym	FTC	NE2001	O13a	WMAP7	-	1.13
s	JF	JFsym	FTC	NE2001	O13b	WMAP7	-	1.12
t	JF	JFsym	FTC	NE2001	S10	WMAP7	-	1.13

Table 1: Summary of model variations investigated in this paper. The original JF12 model corresponds to the first row (model a) and the reference model is given in the third row (model 3). The goodness of fit for describing the RM, Q and U data is given in the last column with the exception for the combined fits of coherent and random field (marked with a *), where the χ^2 also includes the contribution from the total intensity I. The χ^2s of the fits with different synchrotron data products (marked with a †) used different weights in the fits derived from these products.

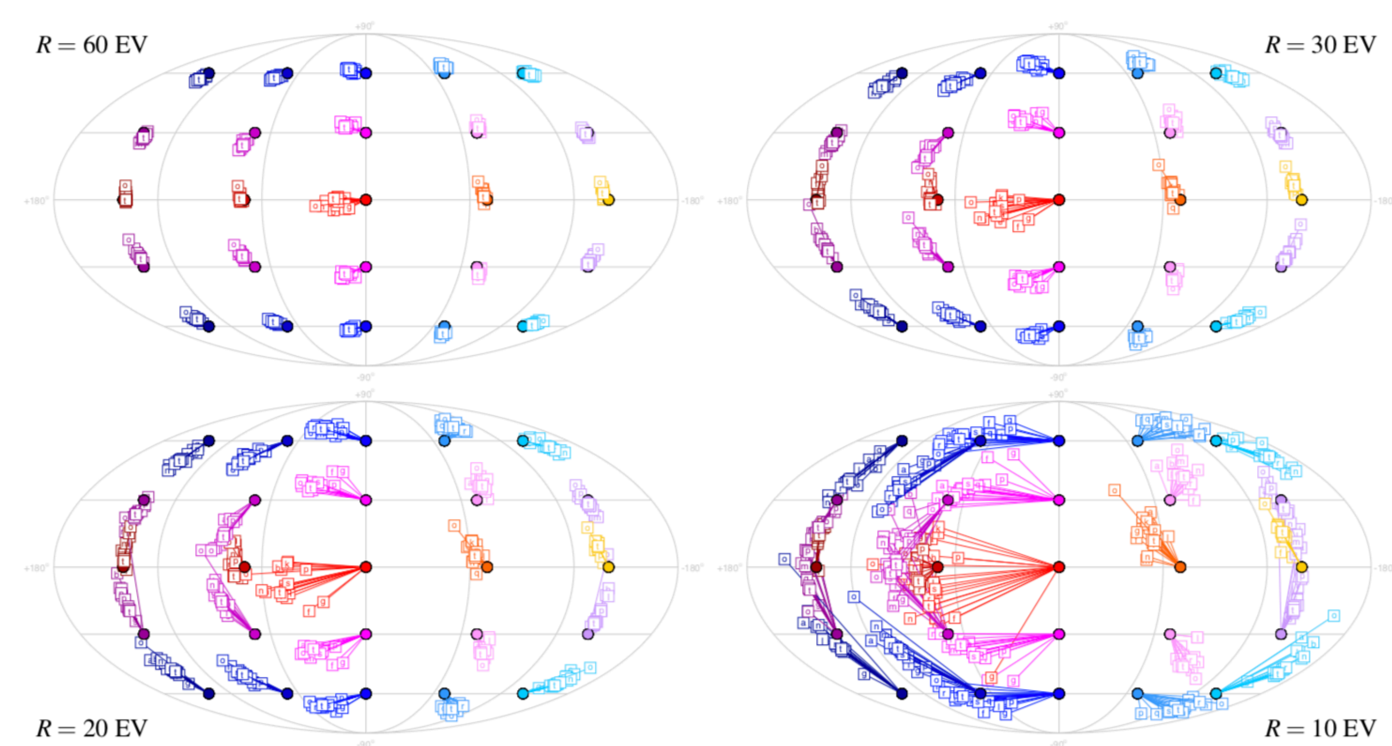


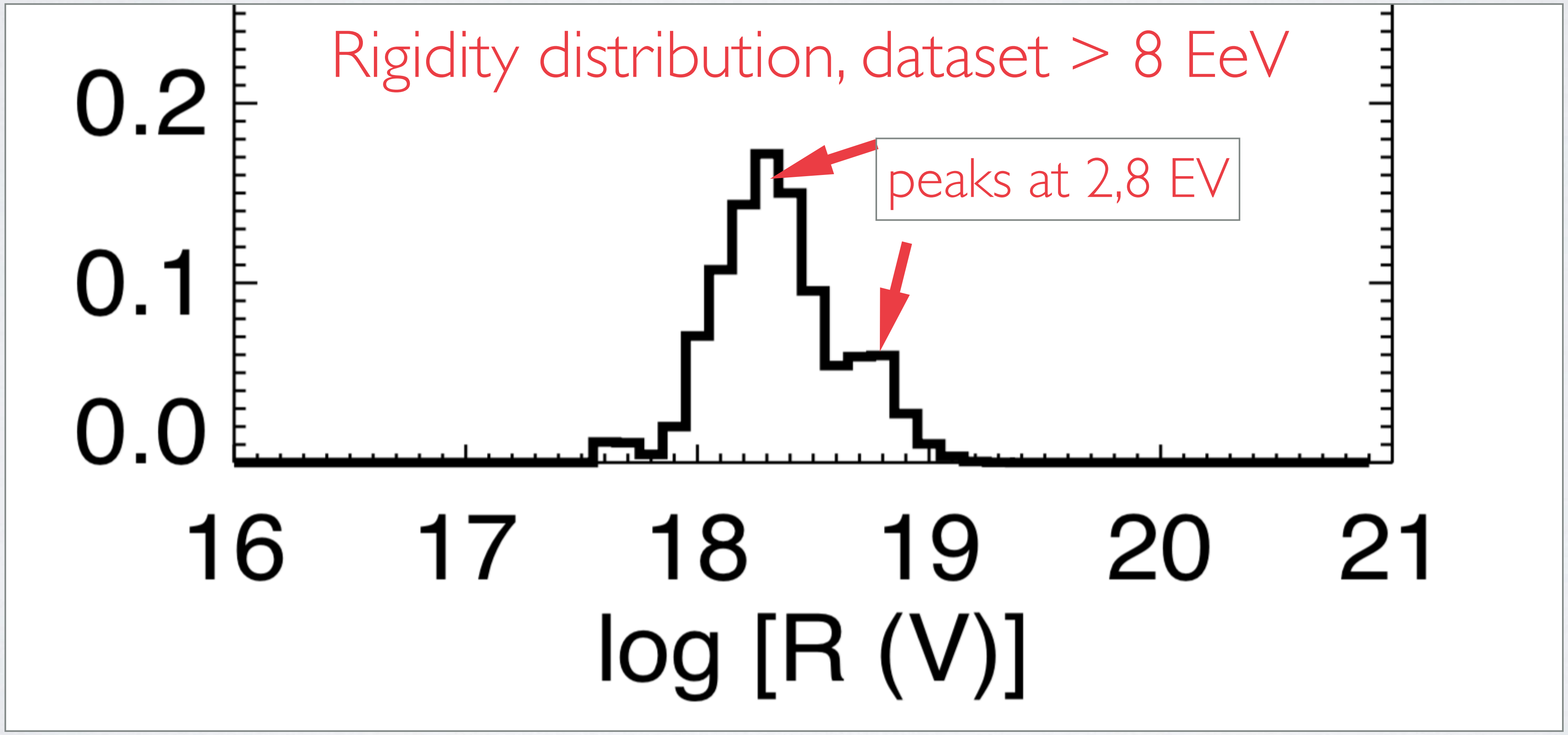
Figure 2: Backtracking of charged particles at different rigidities from a regular grid of initial directions (dots) through different models of the coherent GMF. The resulting directions outside of the Galaxy are denoted by squares and the letters correspond to the models listed in Table 1. The sky maps are in Galactic coordinates and the particle rigidities indicated in corners of each panel.

Unger-Farrar astro-ph 1707.02339

UNCERTAINTY IN DIPOLE ANISOTROPY FROM COHERENT GMF UNCERTAINTY?

Extragalactic illumination:*

- peaks ~ Virgo at hi E/Z,
- ~2MRS dipole at low E/Z



*Globus et al … , DingGlobusFarrar in prep2019 (Ding, Tues CRI 11d)

N.b.: Random Field Deflections are VERY important

L_{coh} = 100 pc L_{coh} = 30 pc

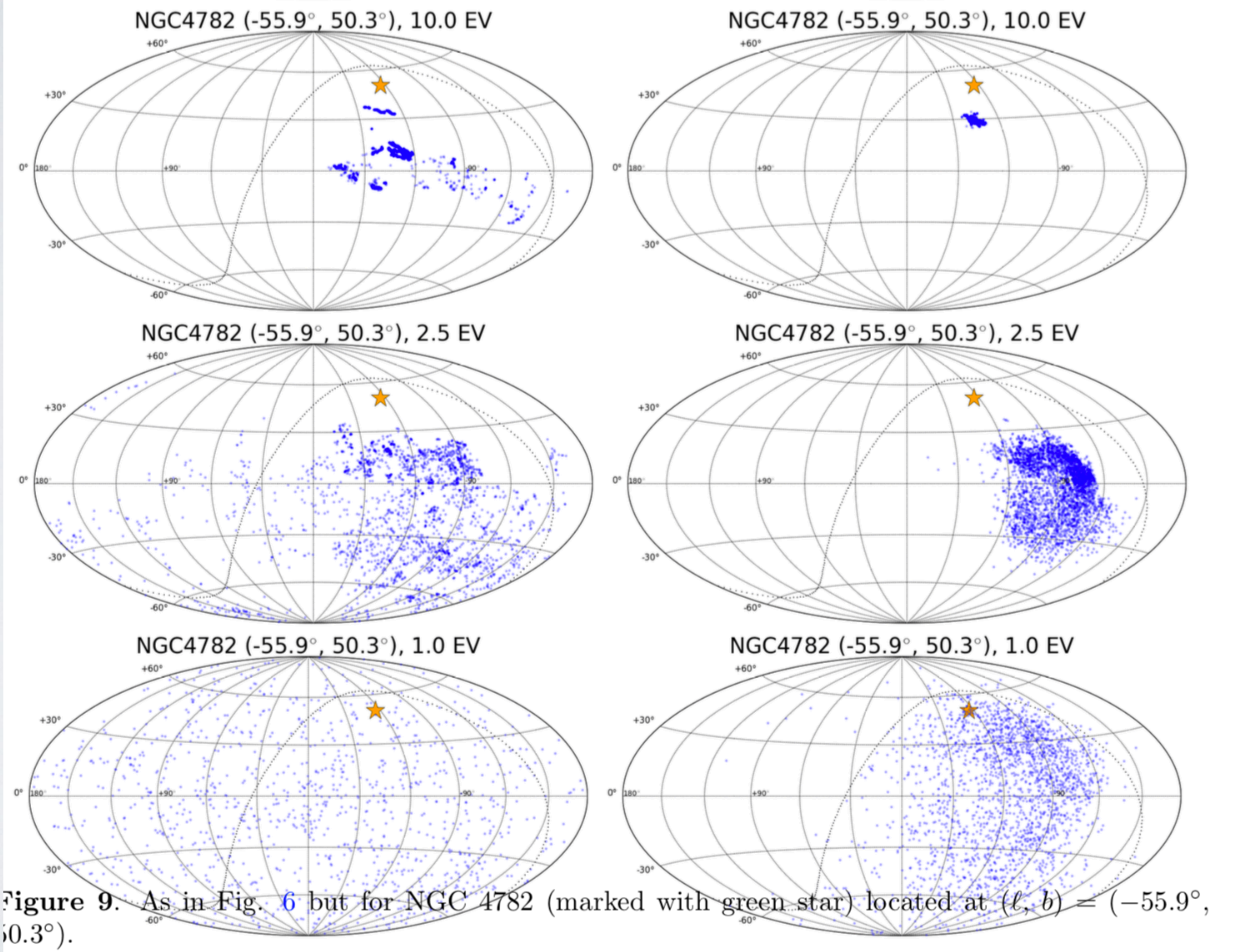
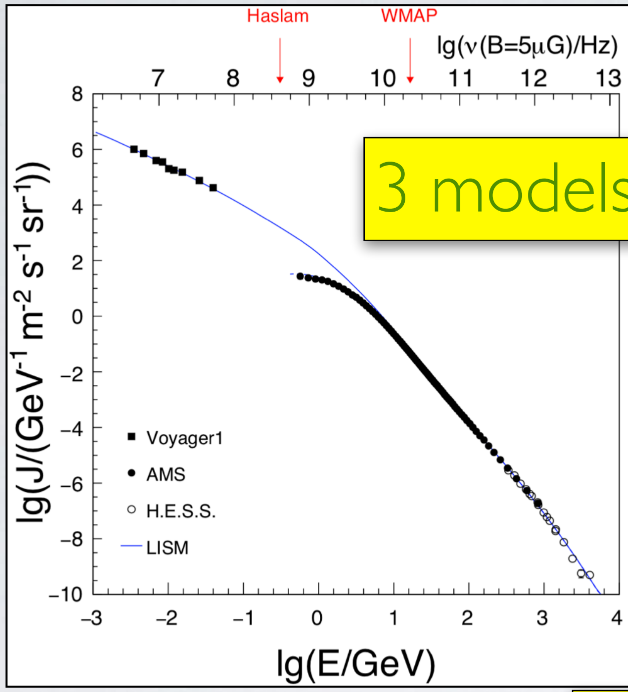


Figure 9. As in Fig. 6 but for NGC 4782 (marked with green star) located at $(\ell, b) = (-55.9°, 50.3°)$.

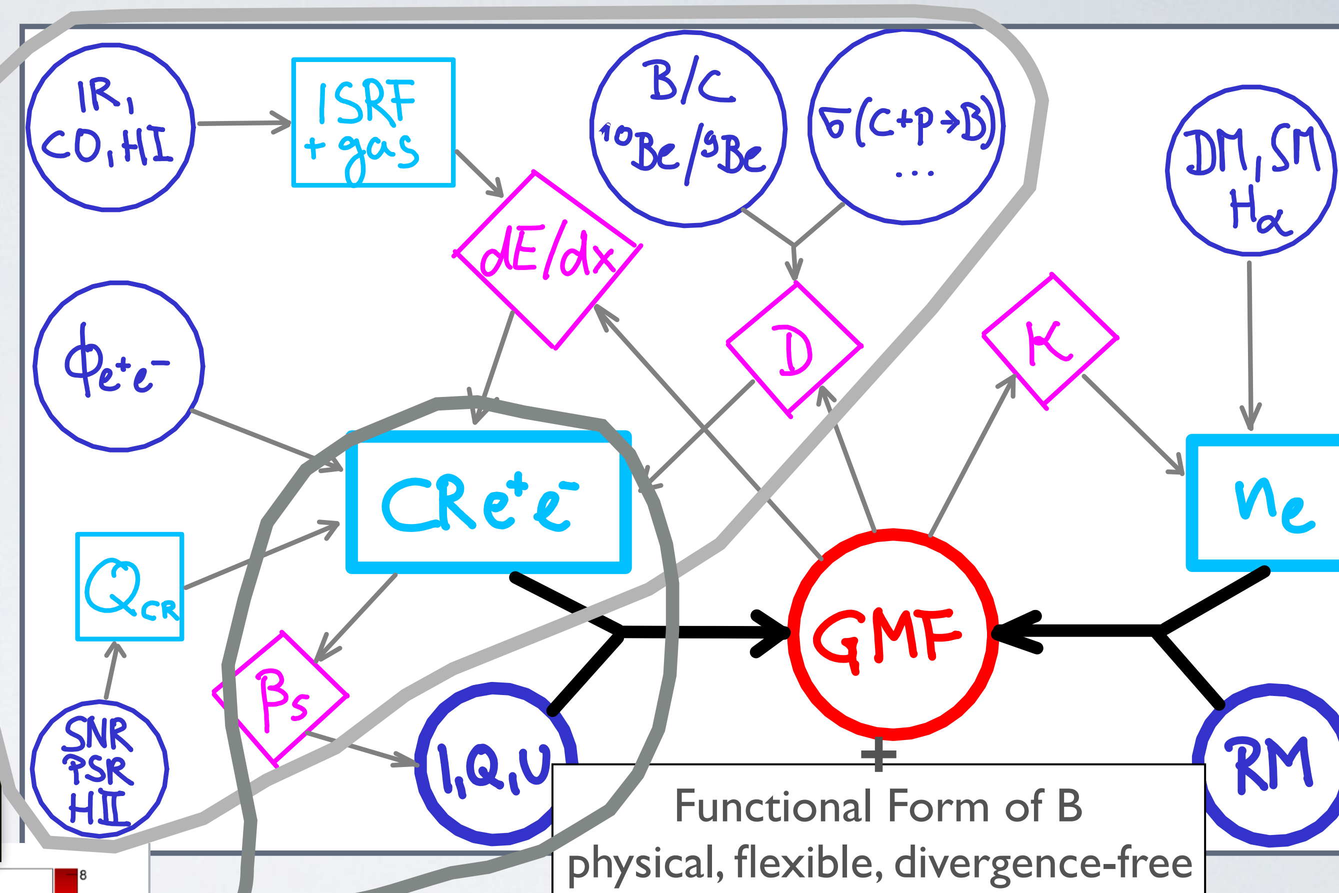
Farrar-Sutherland 2017; JCAP 2019

PROGRESS MODELING THE GMF

M. Unger
G. Farrar



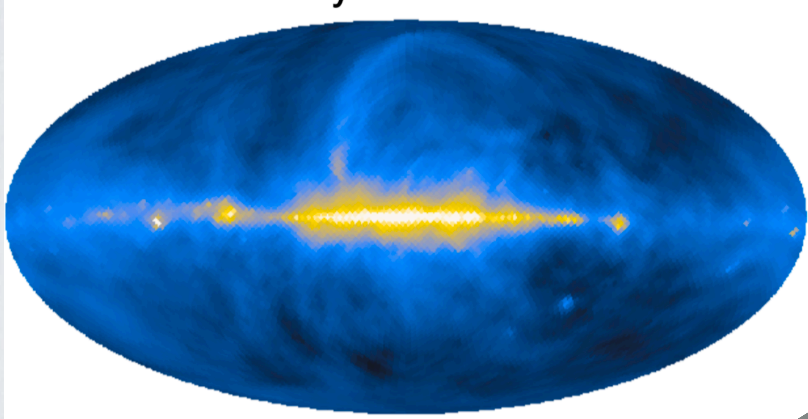
3 models of n_{cre}



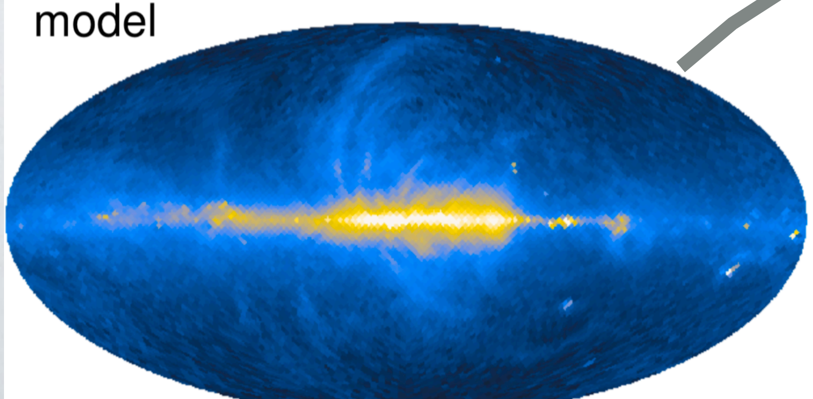
Functional Form of B
physical, flexible, divergence-free

Improved determination of synchrotron emission

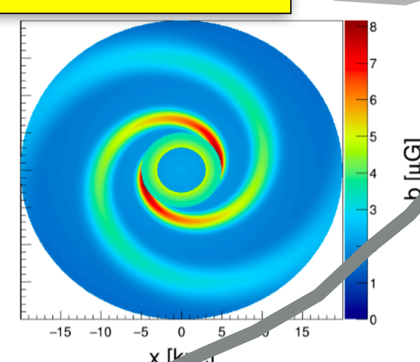
Haslam intensity



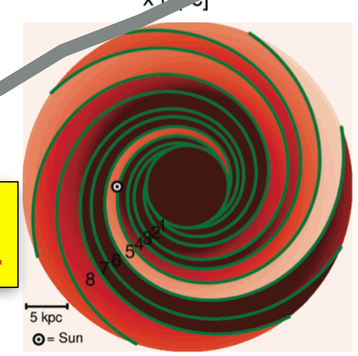
model



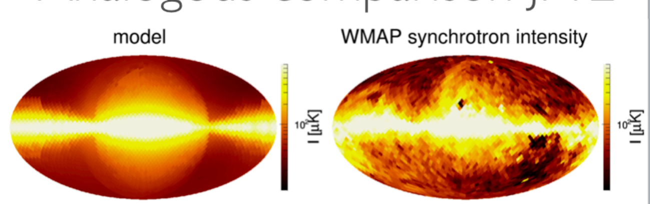
$B_{rand,UF19}$ (prelim)

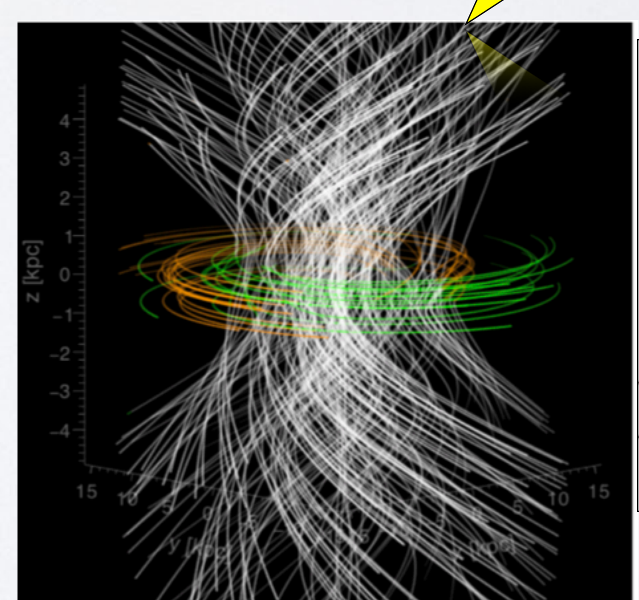


$B_{rand,JF12}$

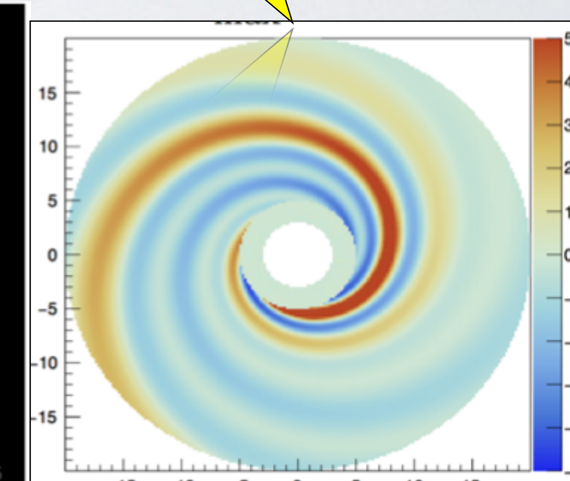


Analogous comparison JF12





Toroidal field from differential rotation



Fourier spiral