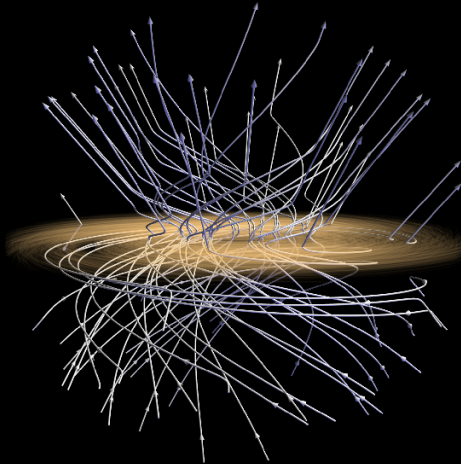


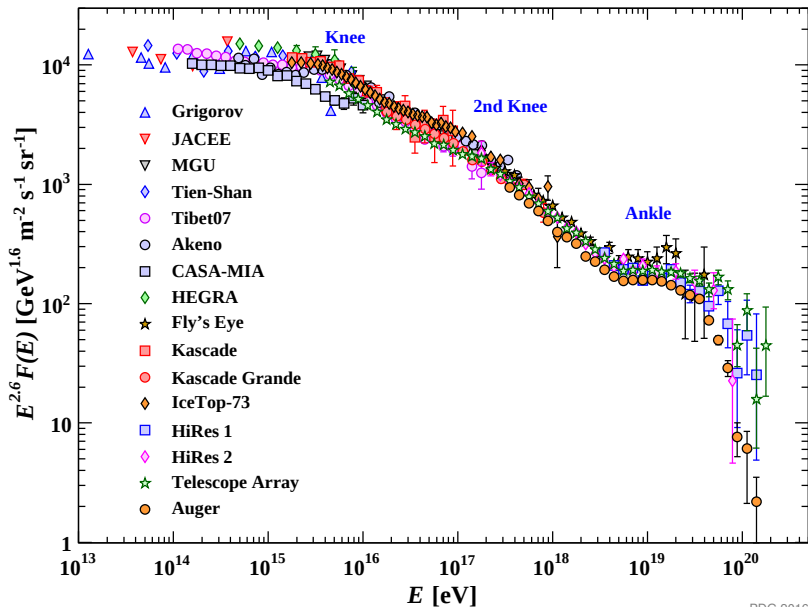
Ultrahigh Energy Cosmic Rays and the Galactic Magnetic Field

M. Unger (KIT)

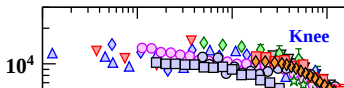
in collaboration with G.R. Farrar (NYU)



Ultrahigh Energy Cosmic Rays



Ultrahigh Energy Cosmic Rays



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Ultra-high-Energy Cosmic-Ray Nuclei from Black Hole Jets: Recycling Galactic Cosmic Rays through Shear Acceleration

Shigeo S. Kimura, Kohta Murase, B. Theodore Zhang, May 14, 2017, 10 pp.

e-Print: [arXiv:1705.05927 \[astro-ph.HE\]](#) | [PDF](#)

Ultra-high energy cosmic rays from white dwarf pulsars and the Hillas criterion

Ronaldo V. Lobato (Sao Paulo, Inst. Tech. Aeronautics & Rome U. & ICRA, Pescara), Jaziel G. Coelho (Sao Jose, INPE), M. Malheiro (Sao Paulo, Inst. Tech. Aeronautics), Mar 17, 2017.

Conference: C18-05-23.4

e-Print: [arXiv:1703.06208 \[astro-ph.HE\]](#) | [PDF](#)

Ultra-high-energy cosmic rays from tidally-ignited stars

Rafael Alves Batista (Oxford U.), Joseph Silk (Oxford U. & Paris, Inst. Astrophys. & Johns Hopkins U. & AIM, Saclay & IRFU, Saclay), Feb 22, 2017, 5 pp.

e-Print: [arXiv:1702.06978 \[astro-ph.HE\]](#) | [PDF](#)

Ultra-high energy cosmic ray nuclei from remnants of dead quasars

Roberto J. Moncada (Amer. Museum Natural Hist. & City Coll., N.Y.), Rafael A. Colon, Juan J. Guerra (Amer. Museum Natural Hist. & Lehman Coll.), Matthew J. O'Dowd, Luis A. Anchordoqui (Amer. Museum Natural Hist. & Lehman Coll. & CUNY, Graduate School - U. Ctr.), Jan 31, 2017, 14 pp.

Published in JHEAp 13-14 (2017) 32-45

Ultra-High-Energy Cosmic Rays from local Radio galaxies

Björn Eichmann (Ruhr U., Bochum, RAPP Ctr. & Ruhr U., Bochum & Ruhr U., Astron. Inst.), J. Becker Tjus, L. Merten (Ruhr U., Bochum), Jan 24, 2017, 22 pp.

e-Print: [arXiv:1701.06792 \[astro-ph.HE\]](#) | [PDF](#)

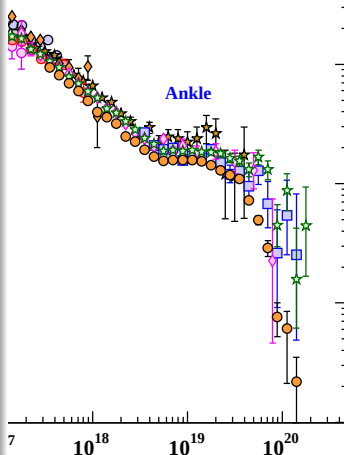
Ultra-high energy cosmic rays from nonrelativistic quasar outflows

Xiawei Wang, Abraham Loeb (Harvard U.), Nov 22, 2016, 5 pp.

Published in Phys. Rev. D 95 (2017) no. 6, 063007

2nd Knee

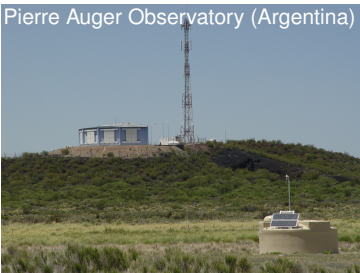
Ankle



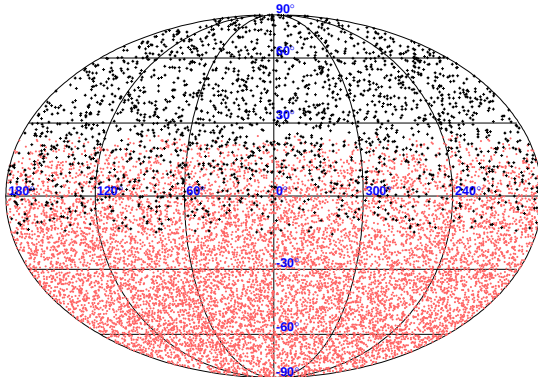
E [EeV]

PDG 2016

Arrival Directions of UHECRs

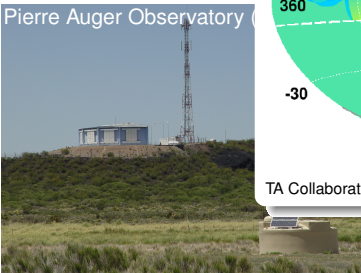
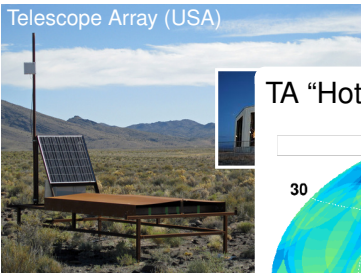


Cosmic-Ray Sky above 10^{19} eV:

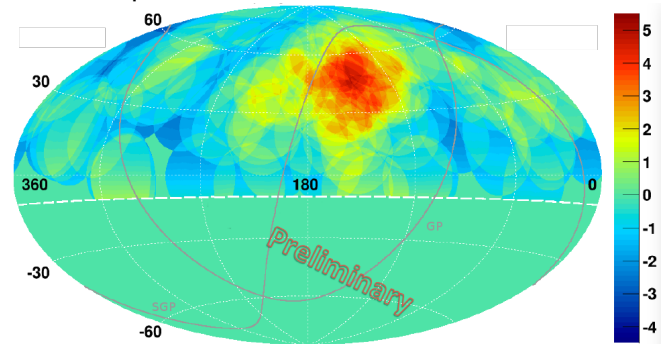


Pierre Auger and TA Collaborations, ApJ **794** (2014) 2, 172

Arrival Directions of UHECRs



TA “Hot Spot”:



TA Collaboration ApJ **790** (2014) L21 & UHECR16, $E > 5.7 \times 10^{19}$ eV, $P = 3.7 \times 10^{-4}$

Arrival Directions of UHECRs

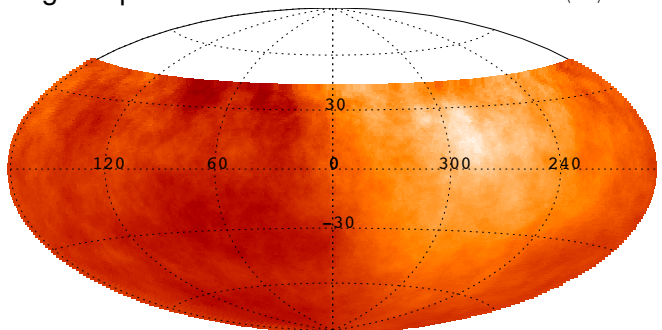
Telescope Array (USA)



Pierre Auger Observatory (Argentina)



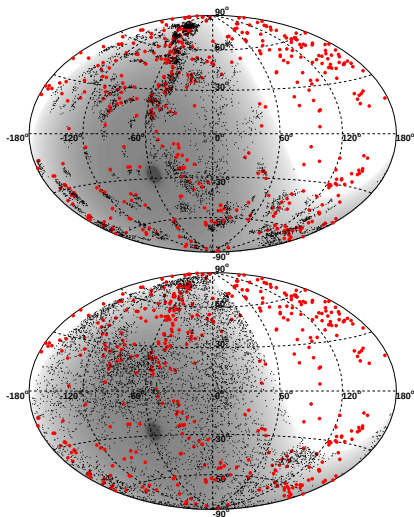
Auger Dipole:



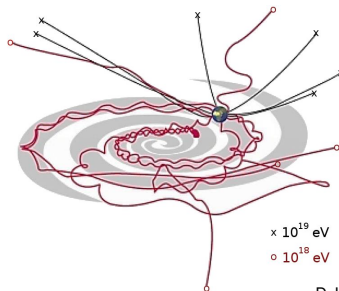
Pierre Auger Collab., *Astrophys.J.* **802** (2015) 111, $E > 8 \times 10^{18}$ eV, $P = 6.4 \times 10^{-5}$

Deflection in Galactic Magnetic Field

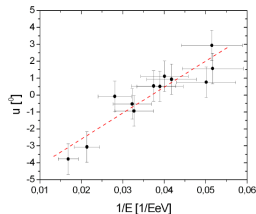
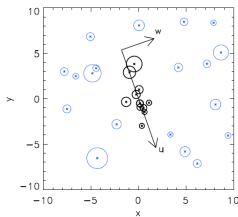
$E > 10^{19.7}$ eV, $Z = 1$ (top) and 6 (bottom)



red: simulated sources, black: arrival direction at Earth

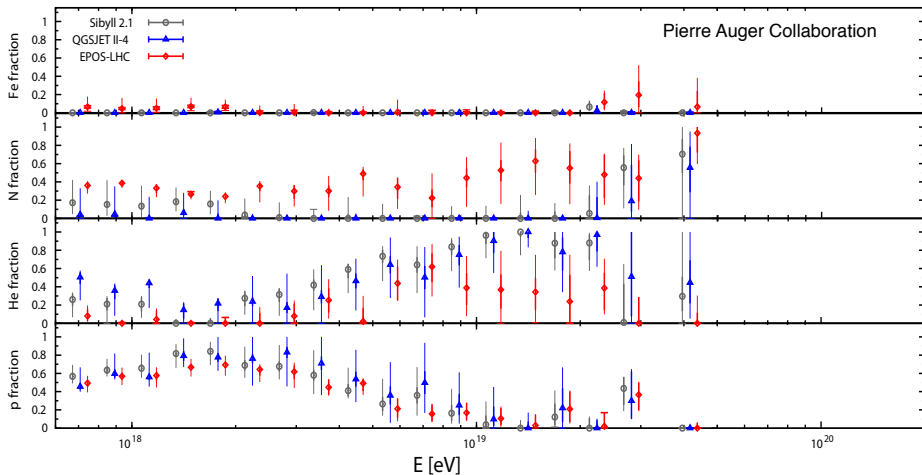


D. Harari



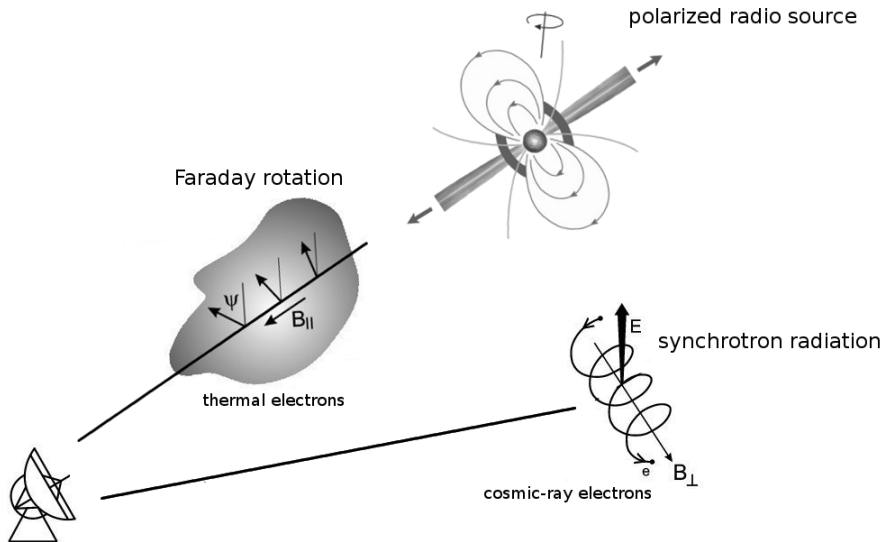
Pierre Auger Coll., APP **35** (2012) 354

Mass (and Charge) Composition of UHECRs



Pierre Auger Collab., Phys.Rev. **D90** (2014) no.12, 122006

How to Measure the Galactic Magnetic Field



How to Measure the Galactic Magnetic Field

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

- ▶ coherent field B
- ▶ random field b
- ▶ rotation measure:

$$RM \propto \int n_e B_{\parallel} dl$$
- ▶ Stokes parameters:

$$Q/U \propto \int B_{\perp}^2 n_{\text{cre}} dl^*$$
- ▶ proj. magnetic field angle:

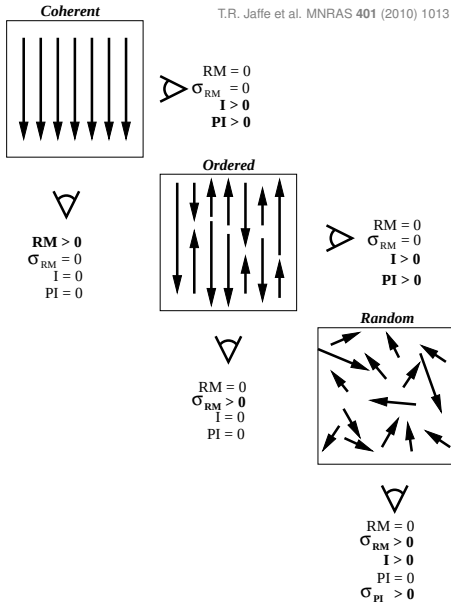
$$\langle \psi_{\text{mag}} \rangle = \frac{1}{2} \text{atan}\left(\frac{U}{Q}\right) + \pi/2$$
- ▶ polarized intensity:

$$PI^2 = Q^2 + U^2$$
- ▶ total intensity:

$$I = I_{\text{coh}} + I_{\text{rand}},$$

$$I_{\text{coh}} \propto B_{\perp}^2, I_{\text{rand}} \propto b^2^*$$

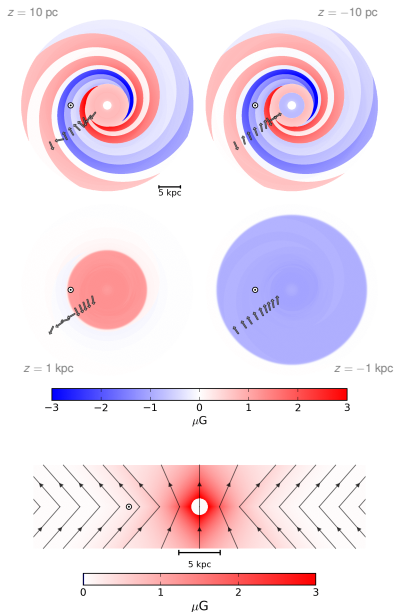
* for a cosmic-ray electron spectrum $dn/dE \propto E^{-3}$



Jansson&Farrar Global Magnetic Field Model (JF12)

three (divergence-free!) components:

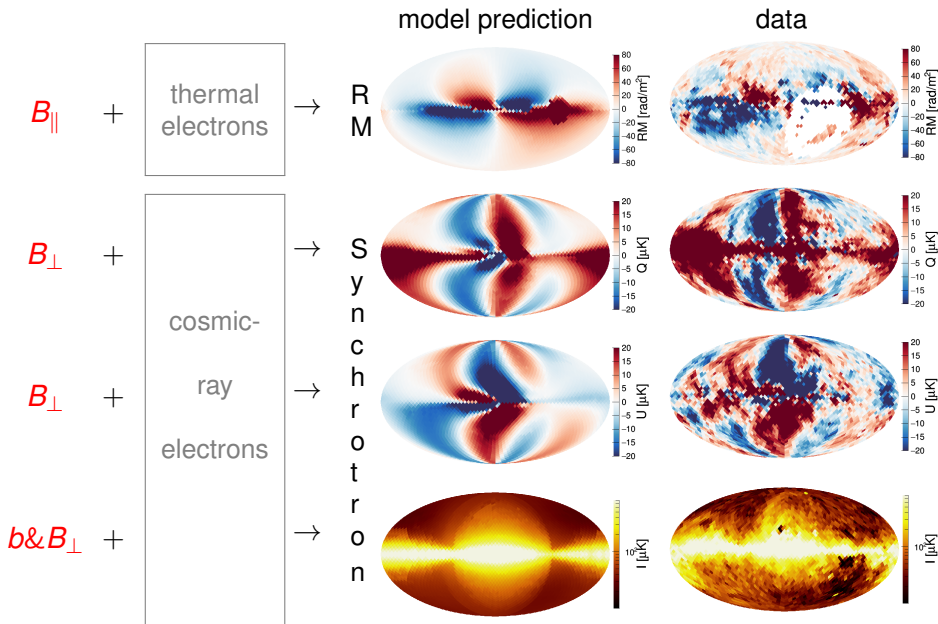
- ▶ disk field, ($h \lesssim 0.4$ kpc)
- ▶ toroidal halo field ($h_{\text{scale}} \sim 5.3$ kpc)
- ▶ “X-field” (halo) **NEW**
- ▶ regular field^a: 21 parameters
- ▶ random field^b: 13 parameters
- ▶ striation: 1 parameter
- ▶ CR electron norm.: 1 parameter



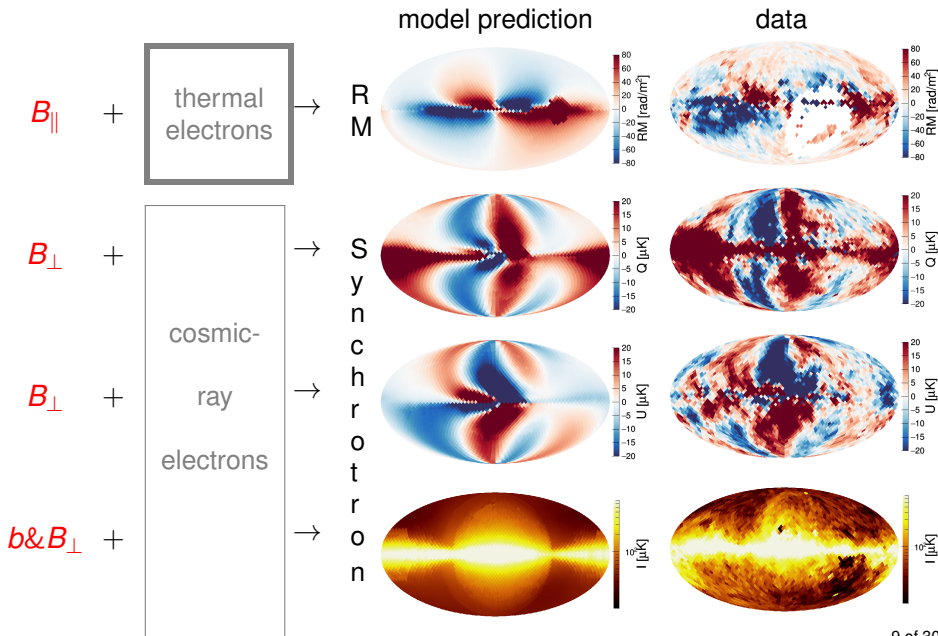
^aR. Jansson & G.F. Farrar, ApJ **757** (2012) 14

^bR. Jansson & G.F. Farrar, ApJ **761** (2012) L11

Fitting GMF Models

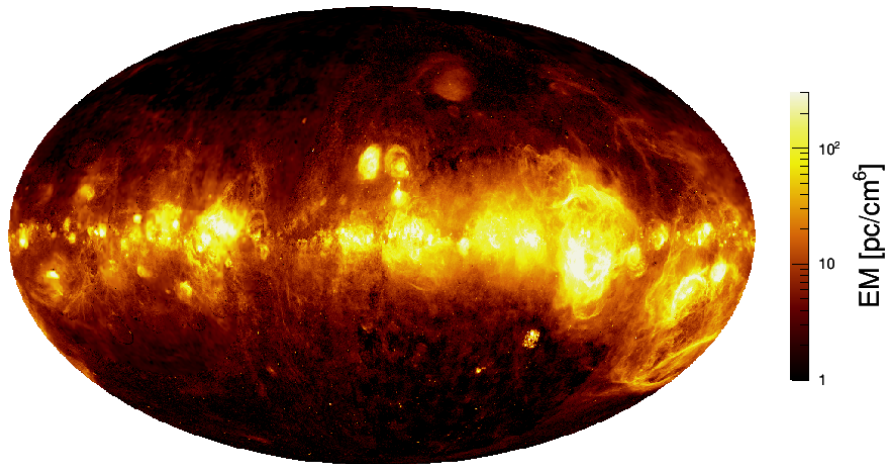


Fitting GMF Models



Thermal Electrons

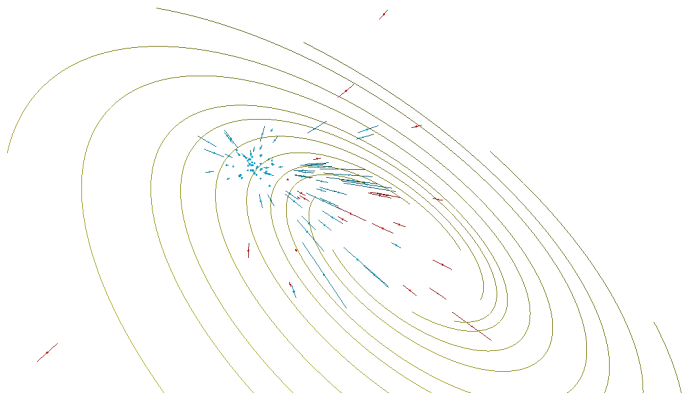
- ▶ **origin:** ionization of ISM by OB stars
- ▶ clumps in HII regions, diffuse component
- ▶ emission measure $EM \propto \int_0^\infty n_e^2(l) dl$ from $H\alpha$ map:



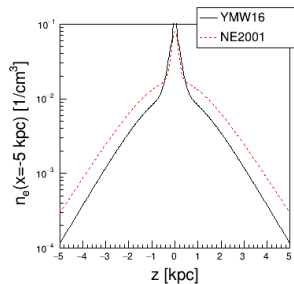
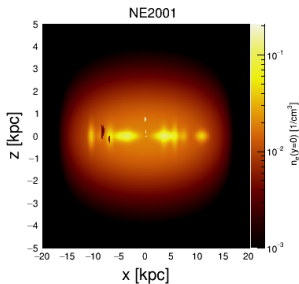
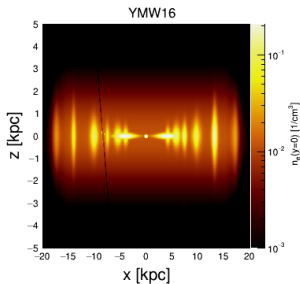
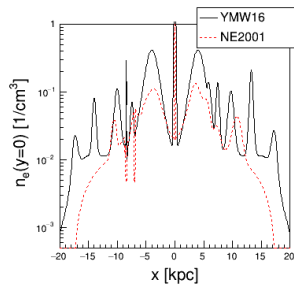
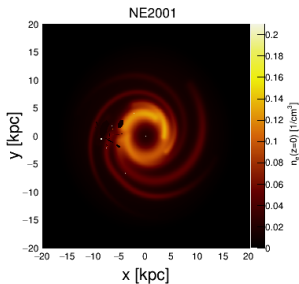
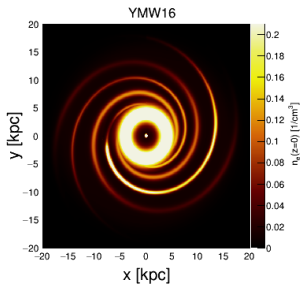
Thermal Electrons

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

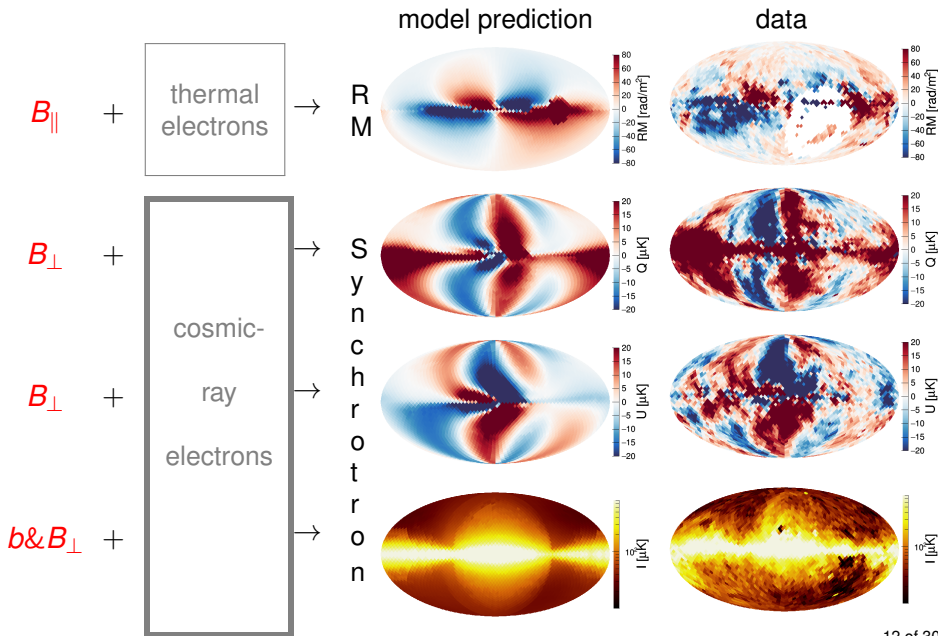
$$DM = \int_0^D n_e(l) dl$$



Thermal Electron Models

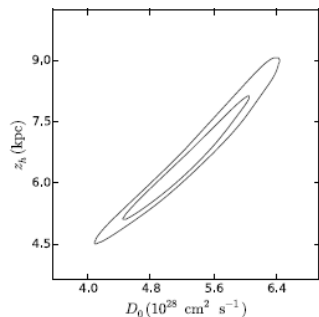
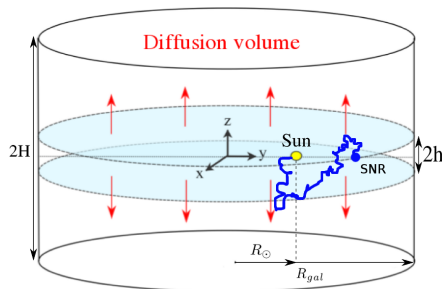


Fitting GMF Models



Cosmic-Ray Electrons

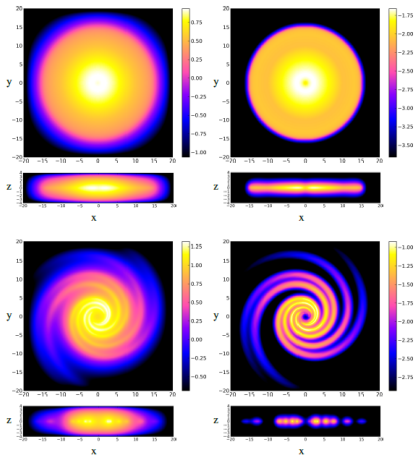
- ▶ **origin:** acceleration in supernova remnants
- ▶ **data:** cosmic-ray electron spectra at Earth, B/C, Be
- ▶ **uncertainties:** source distribution, propagation parameters, local environment
- ▶ diffusion and cooling in Galactic magnetic field



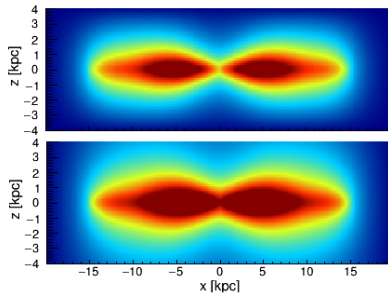
Cosmic-Ray Electron Models

1.1 GeV

1.1 TeV



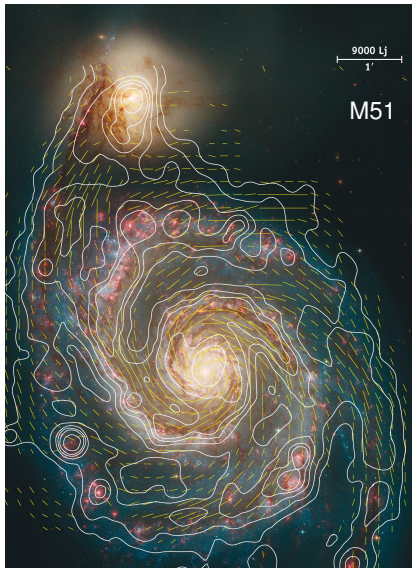
$H = 4$ kpc



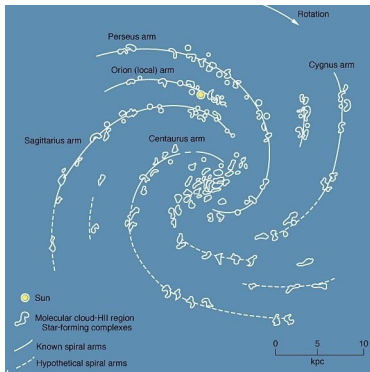
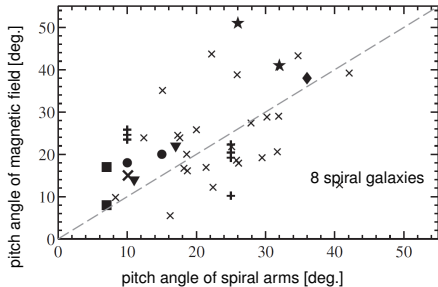
$H = 10$ kpc

T.Jaffe, private communication

Disk Field

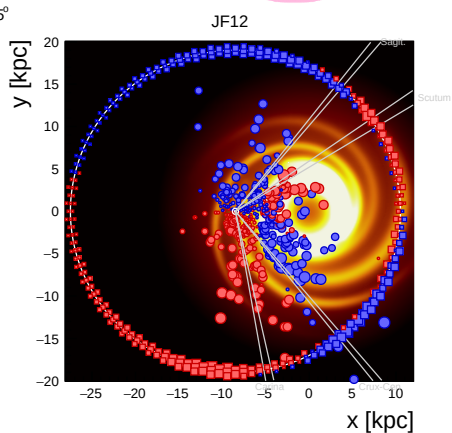
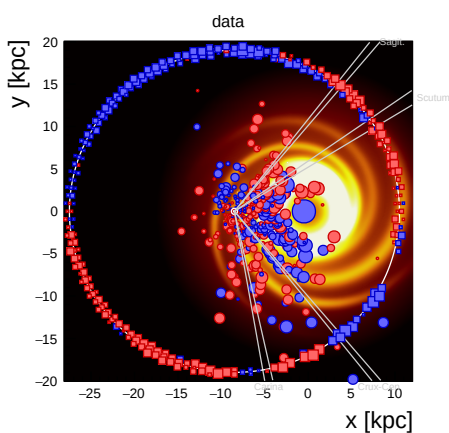
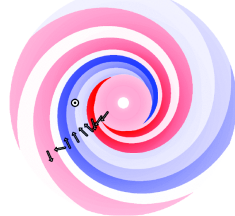


M51, R. Beck (MPIfR), A. Fletcher (Newcastle Univ)

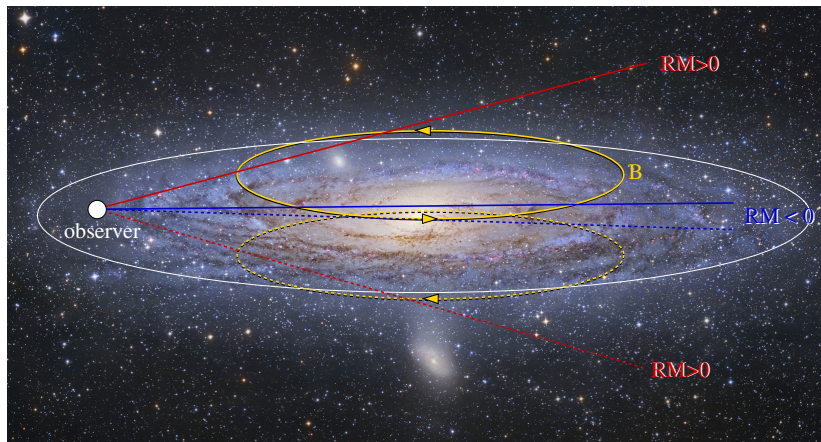
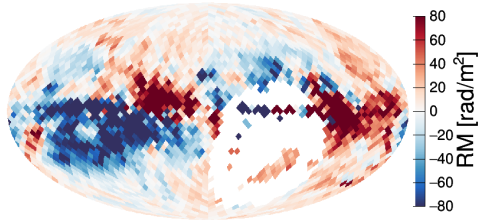


Disk Field

$$RM \propto \int_d^0 n_e(l) B_{\parallel} dl$$

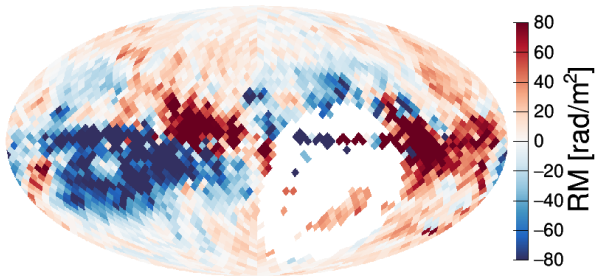


Toroidal Field

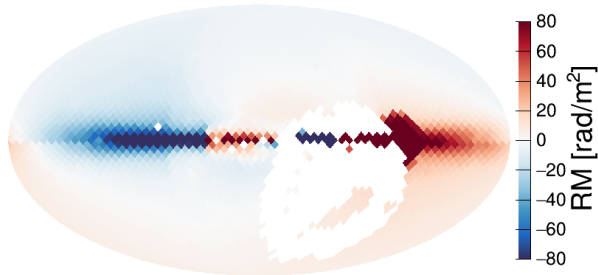


RM, no toroidal Field

data:

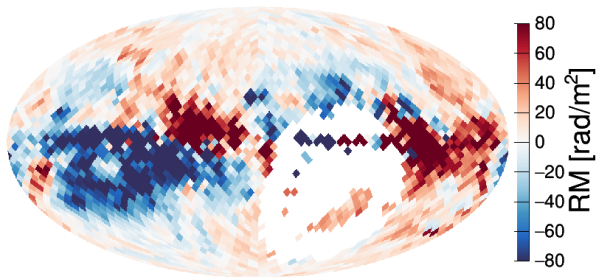


model:

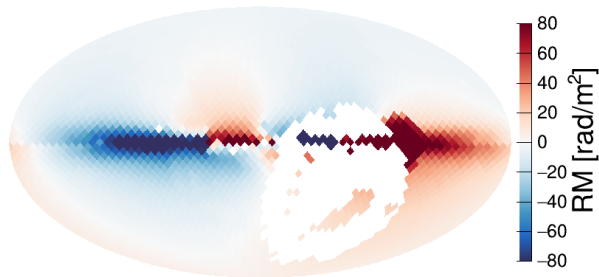


$$\text{RM}, B_{\varphi}^{\text{N}} = -B_{\varphi}^{\text{S}} = 0.5 \mu\text{G}$$

data:

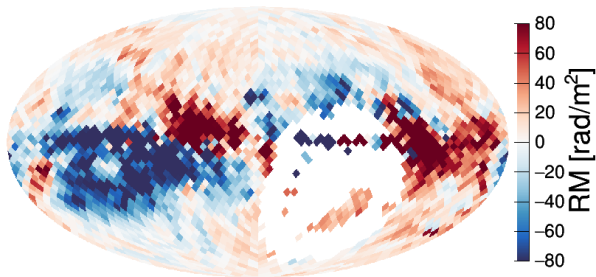


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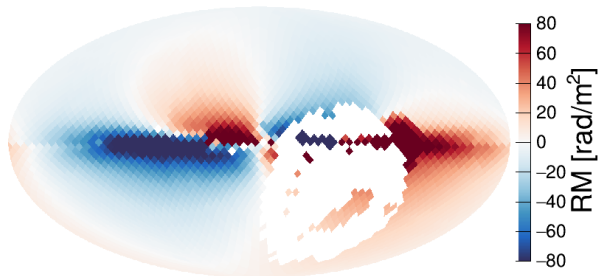


$$\text{RM}, B_{\varphi}^{\text{N}} = -B_{\varphi}^{\text{S}} = 1.0 \mu\text{G}$$

data:

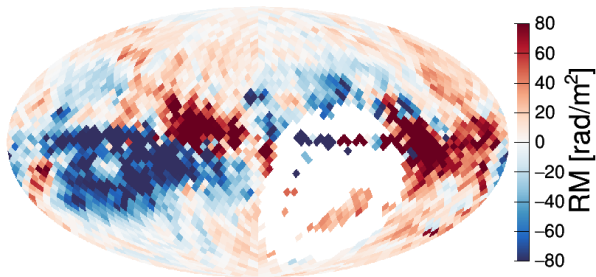


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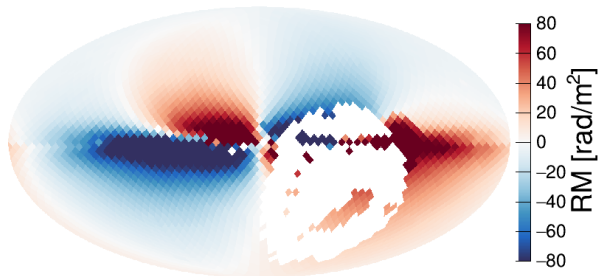


$$\text{RM}, B_{\varphi}^{\text{N}} = -B_{\varphi}^{\text{S}} = 1.5 \mu\text{G}$$

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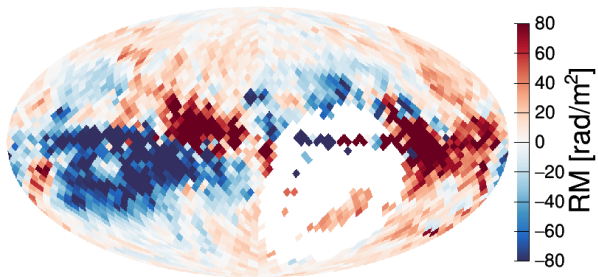


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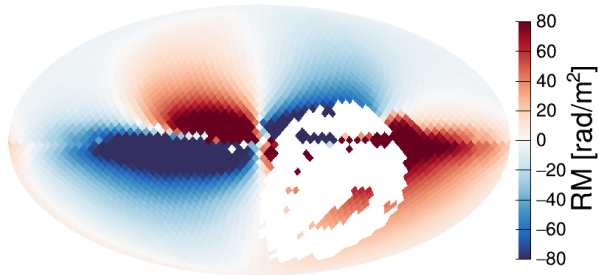


$$\text{RM}, B_{\varphi}^{\text{N}} = -B_{\varphi}^{\text{S}} = 2.0 \mu\text{G}$$

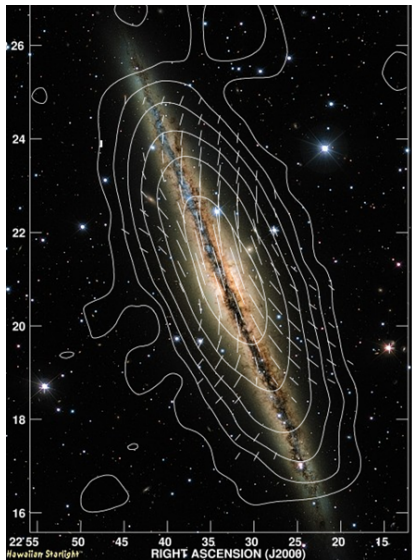
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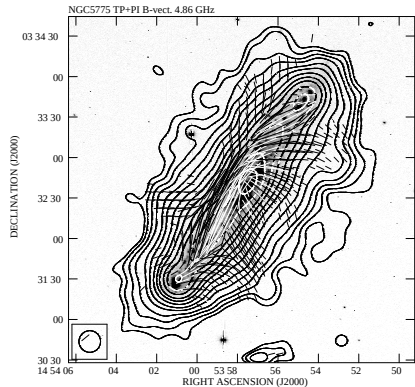
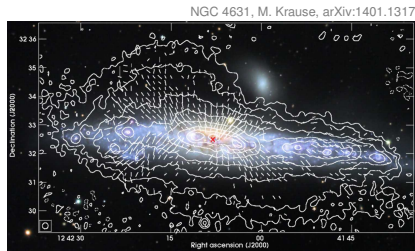
model:



X-field

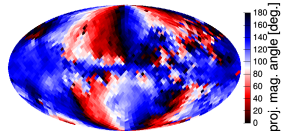
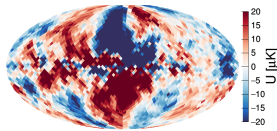
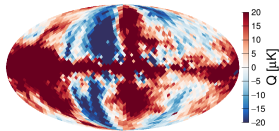


NGC891, M. Krause MPIfR

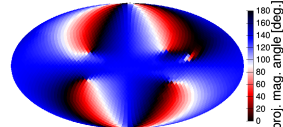
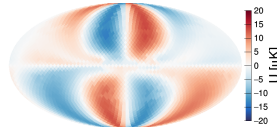
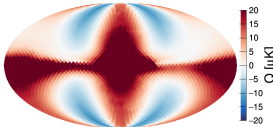


$Q/U/\psi_{\text{mag}}$, no X-field

data:

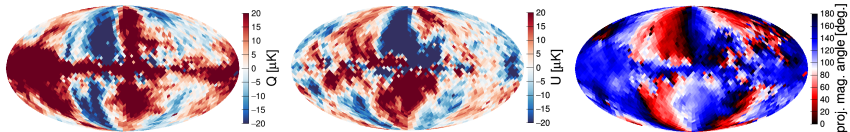


model:

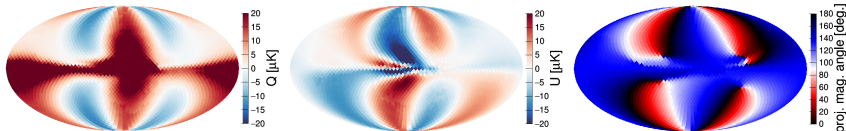


$$Q/U/\psi_{\text{mag}}, B_z(0) = 2 \mu\text{G}, \theta_X = 49^\circ$$

data:

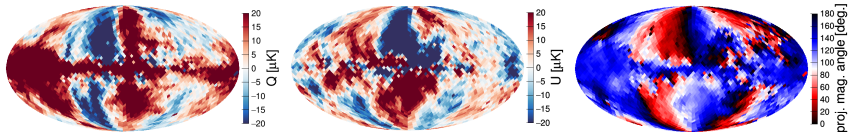


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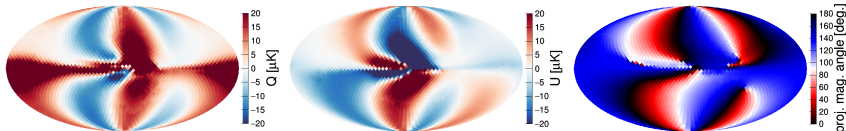


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4 \mu\text{G}, \theta_X = 49^\circ$$

data:

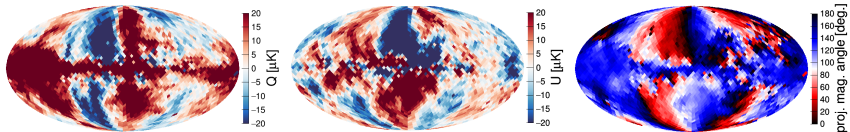


model:

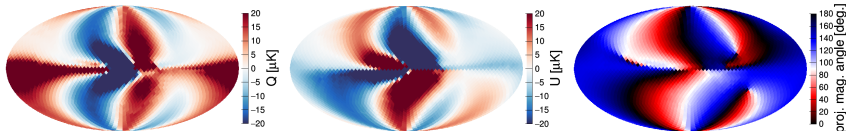


$$Q/U/\psi_{\text{mag}}, B_z(0) = 6 \mu\text{G}, \theta_X = 49^\circ$$

data:

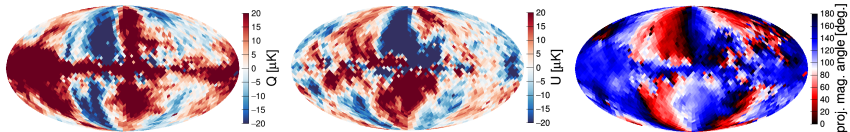


model:

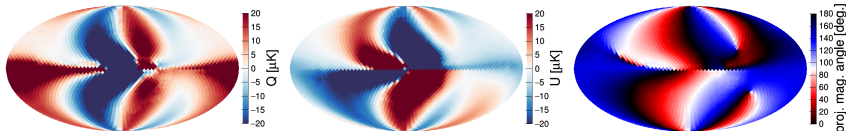


$$Q/U/\psi_{\text{mag}}, B_z(0) = 8 \mu\text{G}, \theta_X = 49^\circ$$

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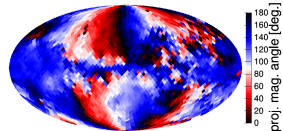
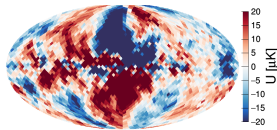
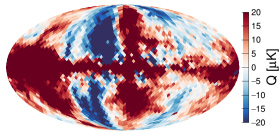


model:

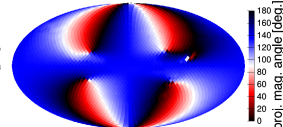
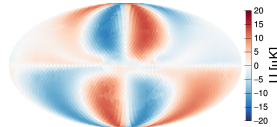
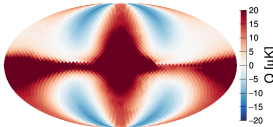


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 0^\circ$$

data:

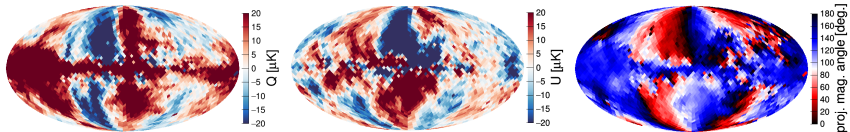


model:

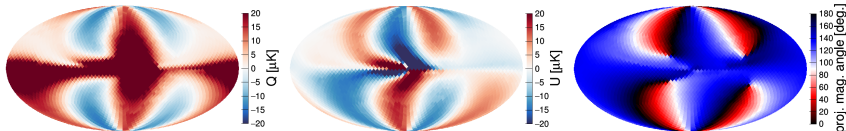


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 15^\circ$$

data:

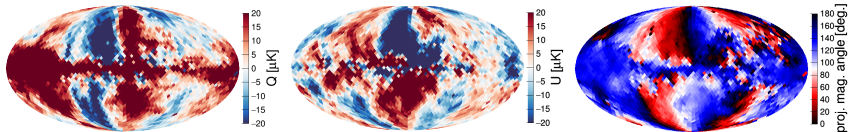


model:

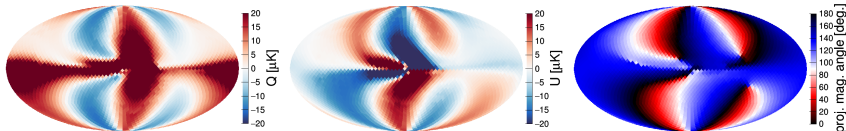


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 30^\circ$$

data:

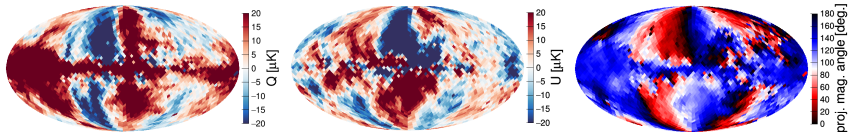


model:

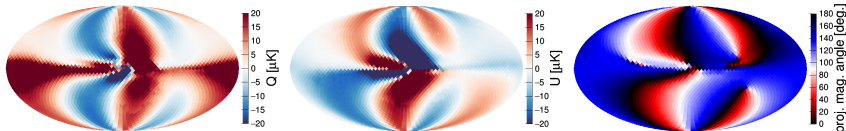


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 45^\circ$$

data:

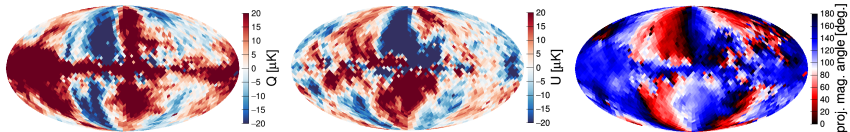


model:

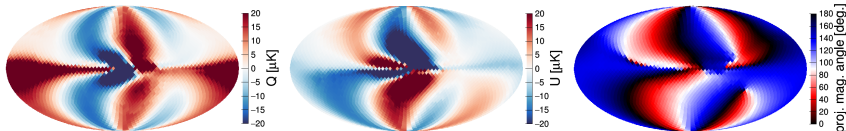


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 60^\circ$$

data:

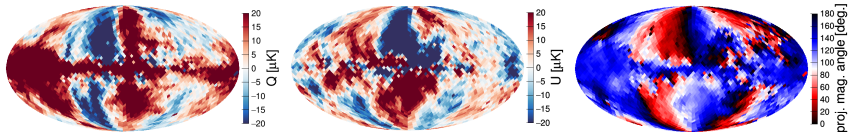


model:

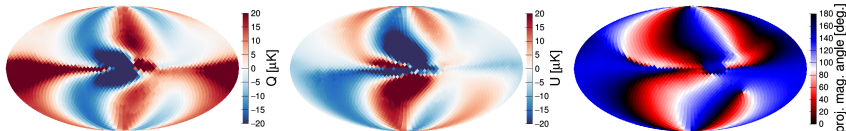


$$Q/U/\psi_{\text{mag}}, B_z(0) = 4.5 \mu\text{G}, \theta_X = 75^\circ$$

data:



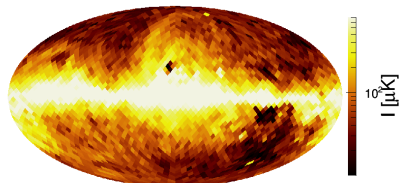
model:



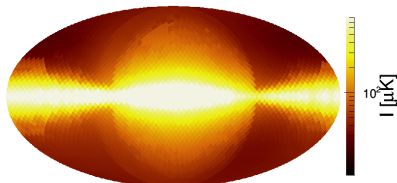
Random Field

total synchrotron intensity:

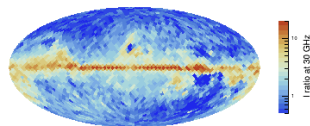
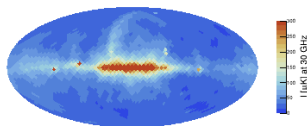
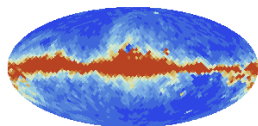
data (WMAP)



model (spiral&halo)



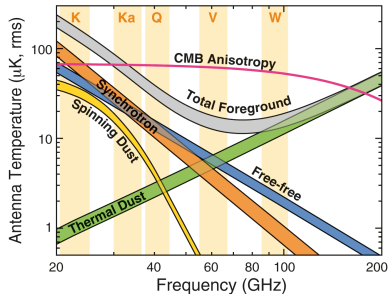
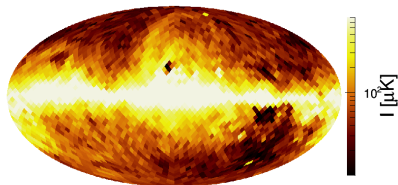
WMAP (left) vs. Planck (right):



- large difference in disk (anomalous microwave emission)
- random field from synchrotron uncertain by up to factor $\sqrt{30}$

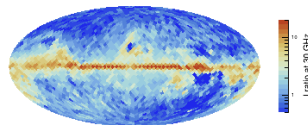
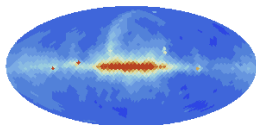
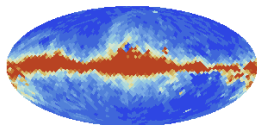
Random Field

total synchrotron intensity:
data (WMAP)



lambda.gsfc.nasa.gov

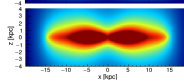
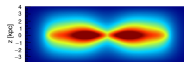
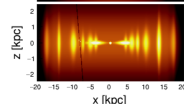
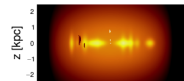
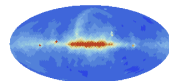
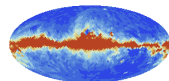
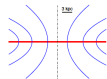
WMAP (left) vs. Planck (right):



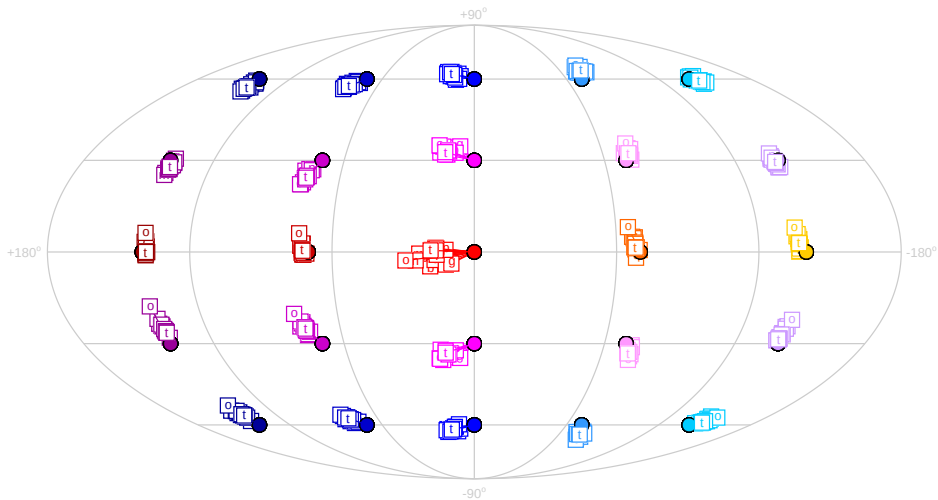
- large difference in disk (anomalous microwave emission)
- random field from synchrotron uncertain by up to factor $\sqrt{30}$

Fit Variations (coherent)

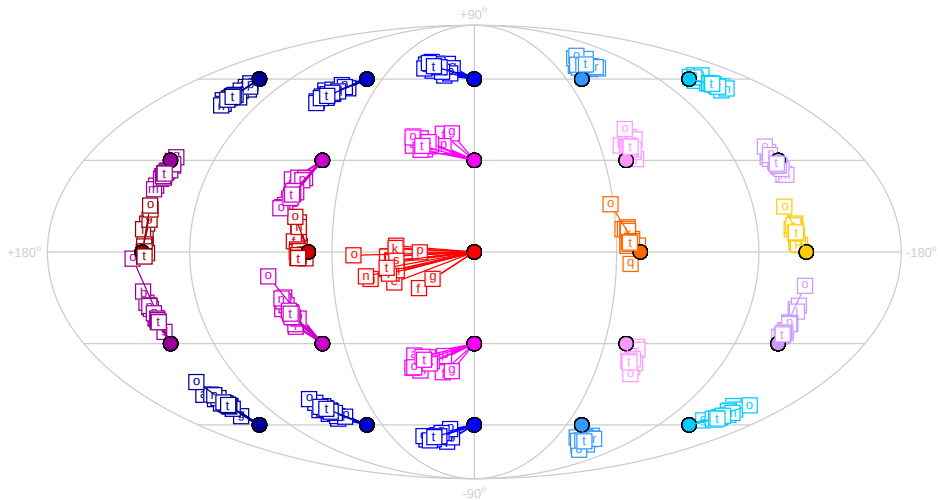
id	disk	toroidal	poloidal	NE	ncre	QU	misc	χ^2/ndf
Parametric models								
a	JF	JF	JF	01	GP_JF	W7	-	1.10
b	JF	JF	FTC	01	GP_JF	W7	-	1.09
c	JF	JFsym	FTC	01	GP_JF	W7	-	1.11
d	JF	JFsym	FTC	01	GP_JF	W7	warp	1.11
e	UF	JFsym	FTC	01	GP_JF	W7	-	1.09
f	UF	UF	UFa	01	GP_JF	W7	-	1.14
g	UF	UF	UFb	01	GP_JF	W7	-	1.09
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



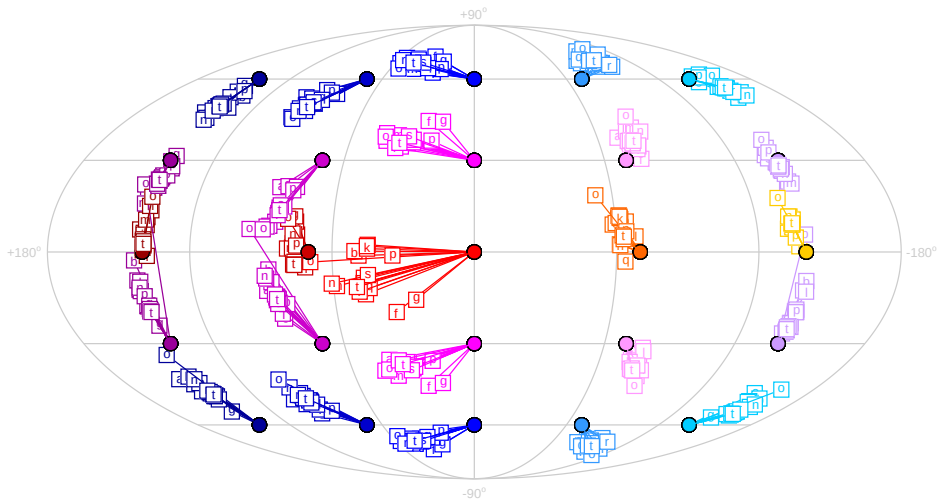
Back-tracking, $R = E/Z = 60$ EV



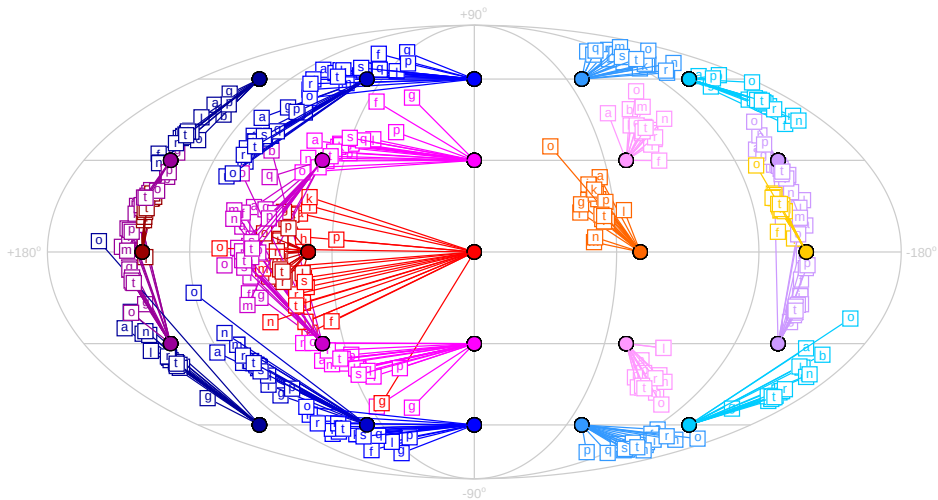
Back-tracking, $R = E/Z = 30$ EV



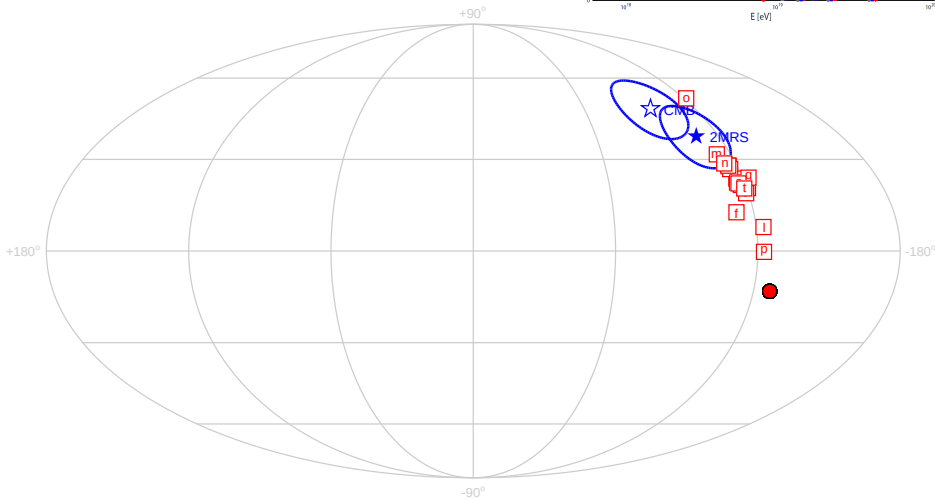
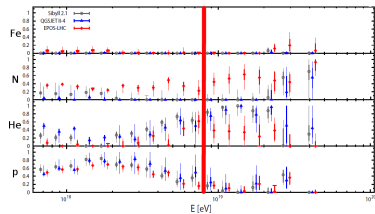
Back-tracking, $R = E/Z = 20 \text{ EV}$



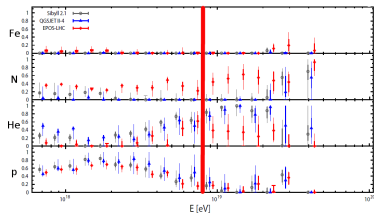
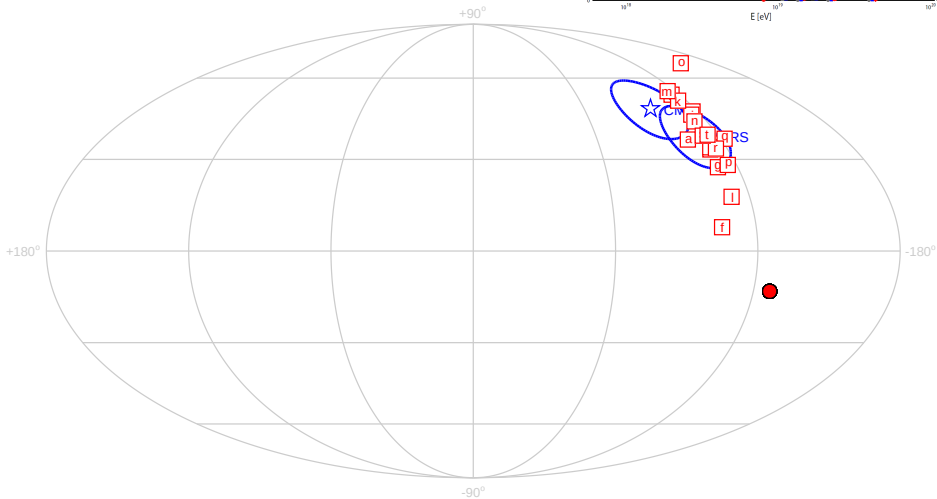
Back-tracking, $R = E/Z = 10$ EV



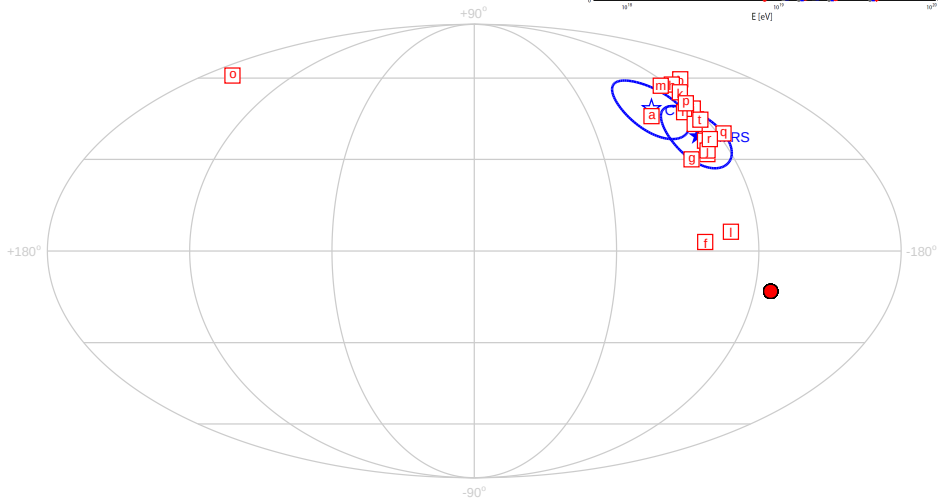
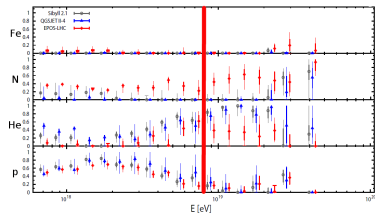
Auger Dipole, 10 EeV, $\langle Z \rangle = 1.7$



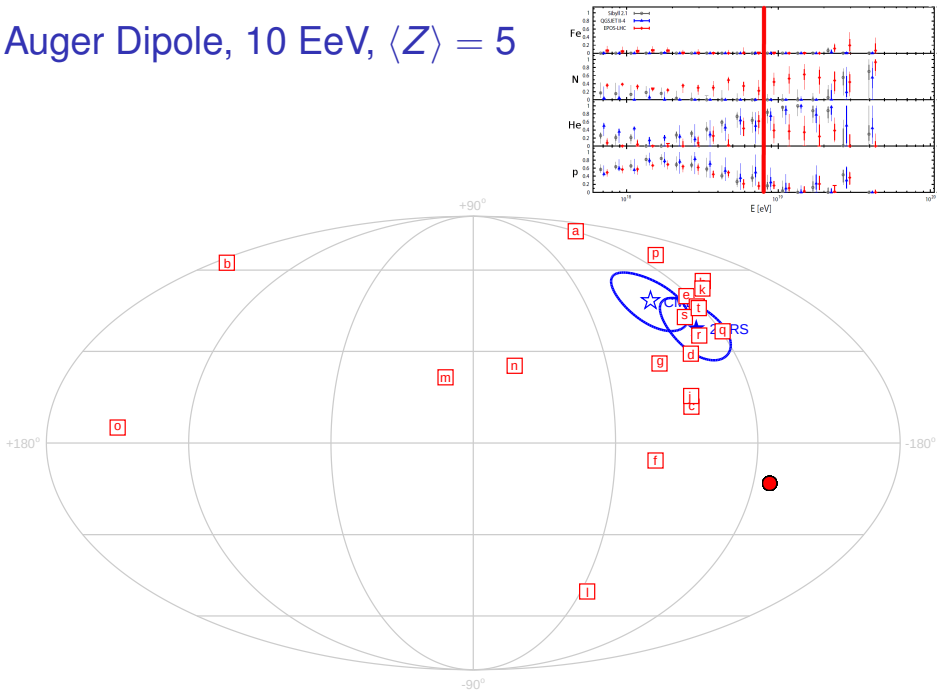
Auger Dipole, 10 EeV, $\langle Z \rangle = 2.5$



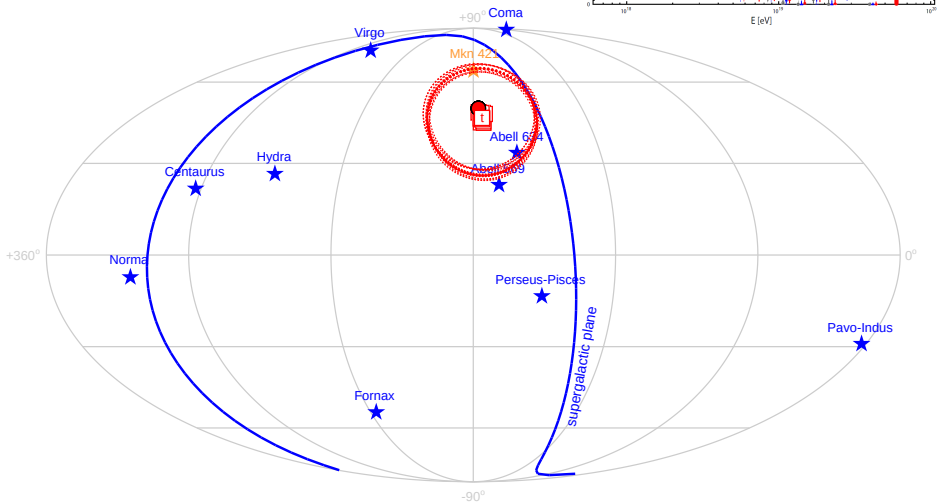
Auger Dipole, 10 EeV, $\langle Z \rangle = 3.3$



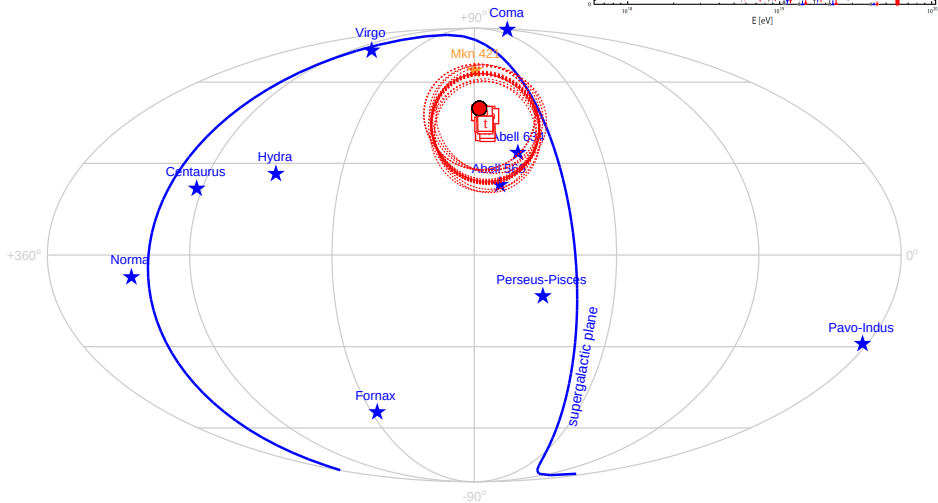
Auger Dipole, 10 EeV, $\langle Z \rangle = 5$



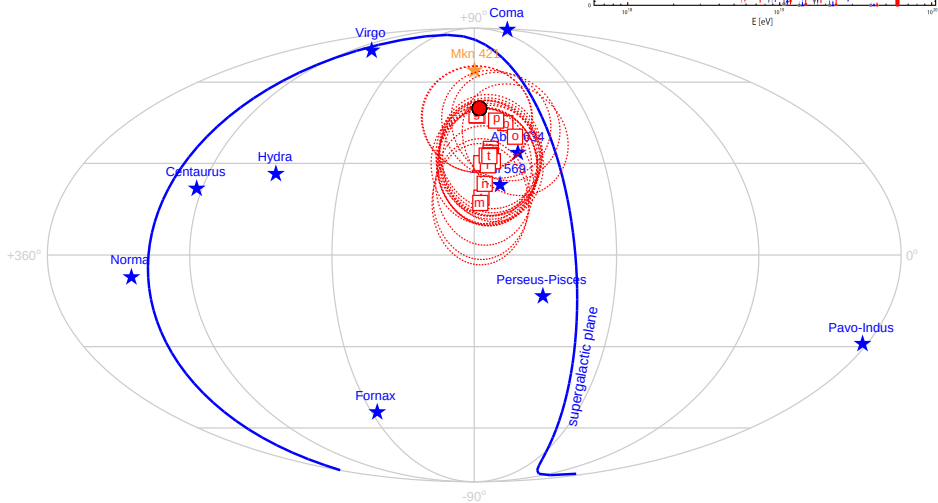
TA Hot Spot, 60 EeV p



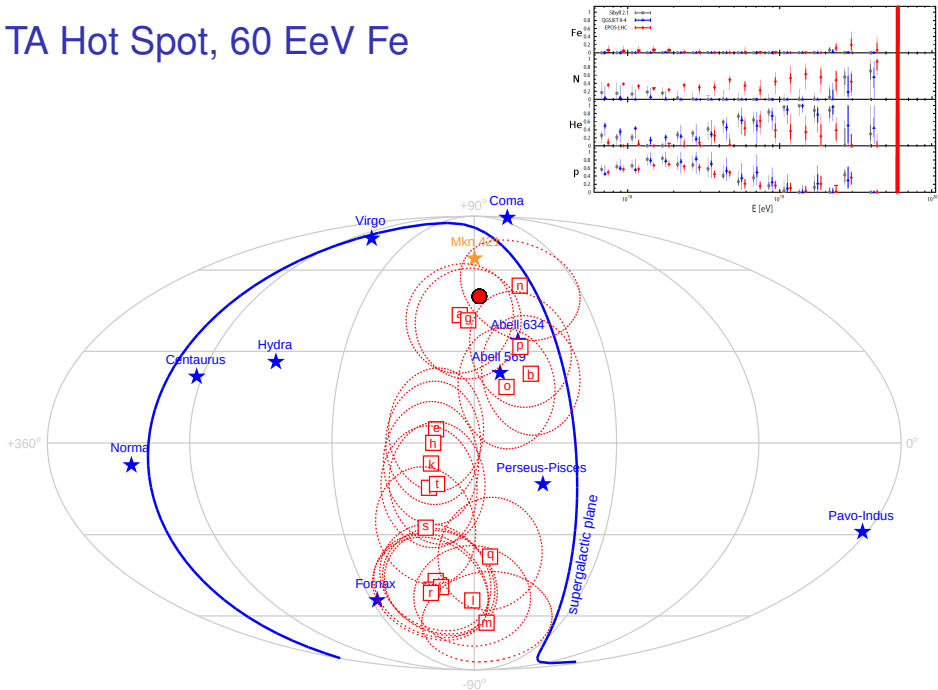
TA Hot Spot, 60 EeV He



TA Hot Spot, 60 EeV N



TA Hot Spot, 60 EeV Fe



Summary

- ▶ Galactic magnetic field important for the interpretation of the arrival directions of ultra-high energy cosmic rays
- ▶ lower limit on deflection uncertainty due to modeling uncertainties (work in progress)
- ▶ current model variations give similar deflections for $E/Z \sim 5...10$ EV

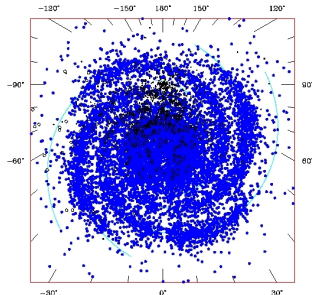
Outlook

AugerPrime and TAx4



Pierre Auger Coll., arXiv:1604.03637

improved modeling with new data



J.M. Cordes, SKA