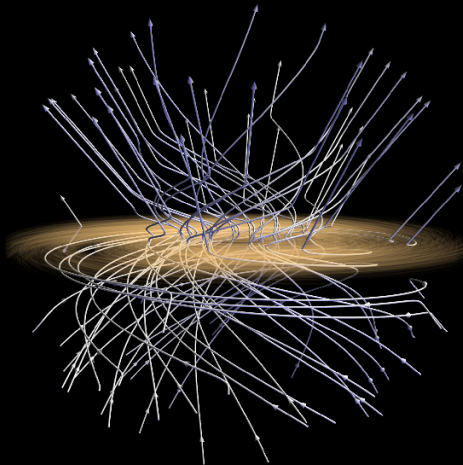


Global Modeling of the Galactic Magnetic Field and Thermal Electrons

M. Unger^{1,2} & G.R. Farrar¹

¹New York University, ²Karlsruhe Institute of Technology



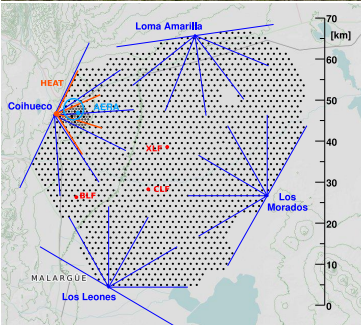
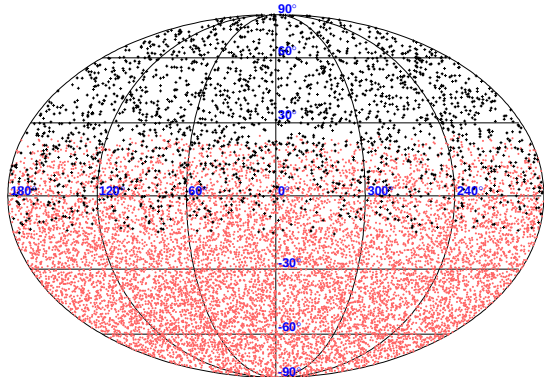
Global Modeling of the Galactic Magnetic Field: Arrival Directions of Ultrahigh Energy Cosmic Rays*

Pierre Auger Observatory (Argentina)



* one of many useful application of global GMF models!

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



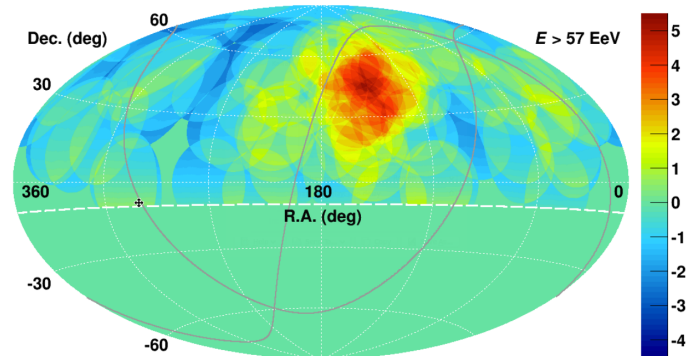
Pierre Auger and TA Collaborations, ApJ **794** (2014) 2, 172

Global Modeling of the Galactic Magnetic Field: Arrival Directions of Ultrahigh Energy Cosmic Rays*

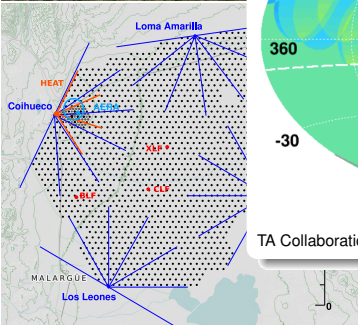
Pierre Auger Observatory (Argentina)

* one of many useful application of global GMF models!

TA “Hot Spot”:

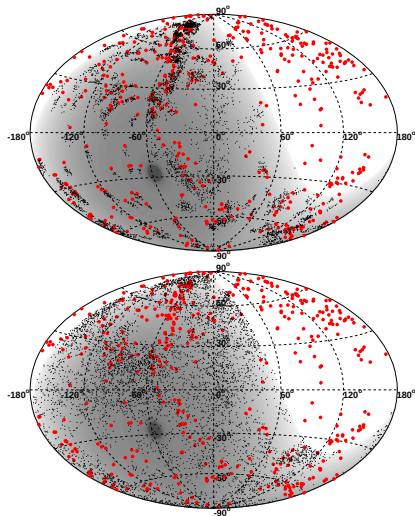


TA Collaboration ApJ **790** (2014) L21

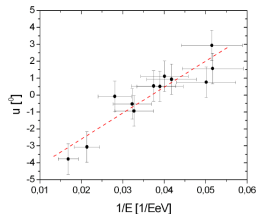
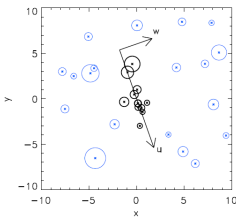
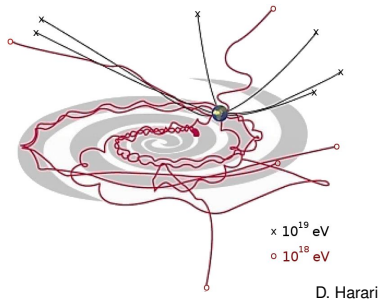


Global Modeling of the Galactic Magnetic Field: Arrival Directions of Ultrahigh Energy Cosmic Rays

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



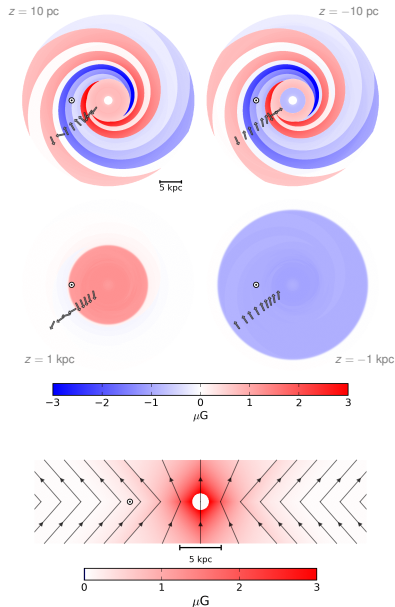
red: simulated sources, black: arrival direction at Earth



Jansson&Farrar Global Magnetic Field Model (JF12)

three (divergenceless!) components:

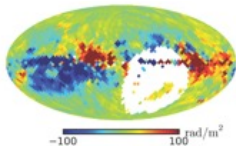
- ▶ disk field, ($h \lesssim 0.4$ kpc)
- ▶ toroidal halo field ($h_{\text{scale}} \sim 5.3$ kpc)
- ▶ “X-field” (halo) **NEW**
- ▶ regular field^a: 21 parameters
- ▶ random field^b: 13 parameters
- ▶ striation: 1 parameter
- ▶ CR electron norm.: 1 parameter



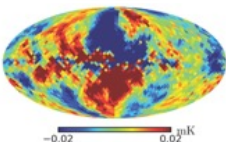
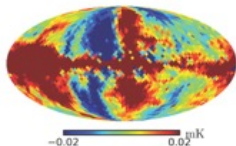
JF12 Model (Regular Field)

Data:

- ▶ extragalactic RMs

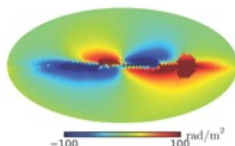


- ▶ WMAP Stokes Q and U

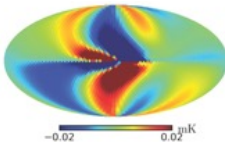
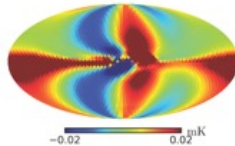


Model:

- ▶ $\text{RM} \propto \int_{-\infty}^0 B_{\parallel}(l) n_e(l) dl$



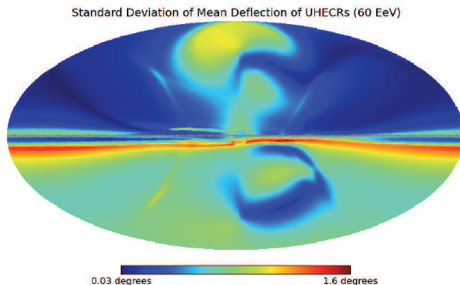
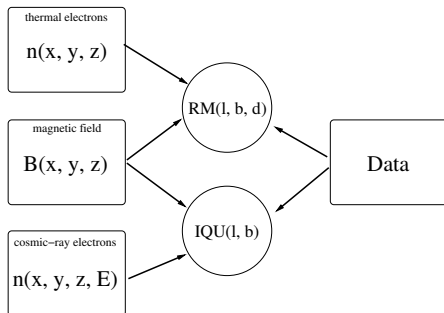
- ▶ $Q/U \propto \int_{-\infty}^0 B_{\perp}(l)^{\frac{p+1}{2}} n_{\text{cre}}(l) dl$



thermal electron density $n_e(l)$, CR electron density $n_{\text{cre}}(l)$ and spectrum E^p

Model Uncertainties

Example:
Statistical (!) uncertainties cosmic-ray deflections in regular field:



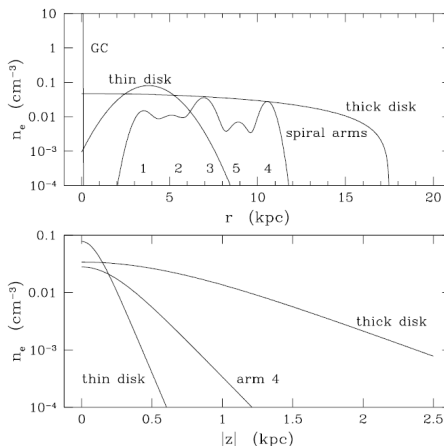
G.R. Farrar, CRP 15 (2014) 339

What about underlying model assumptions??

Thermal Electrons: NE2001 Model

J. Cordes&T. Lazio, arXiv:0207156 and 0301598

- ▶ spiral arms
- ▶ thin and thick disk
- ▶ local ISM
- ▶ ad-hoc “clumps”
- ▶ ad-hoc “voids”

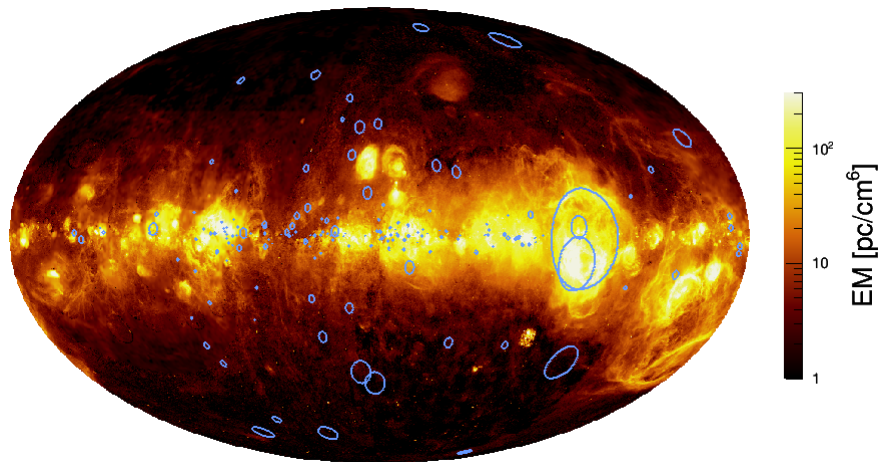


“Superposed with the large-scale and local-ISM components are clumps of excess electron density that we infer from the database of measurements as outliers from the smooth model.”

(C&L 2002, each pulsar line of sight is discussed in C&L (2003)).

NE2001 “clumps” vs. $H\alpha$ Data

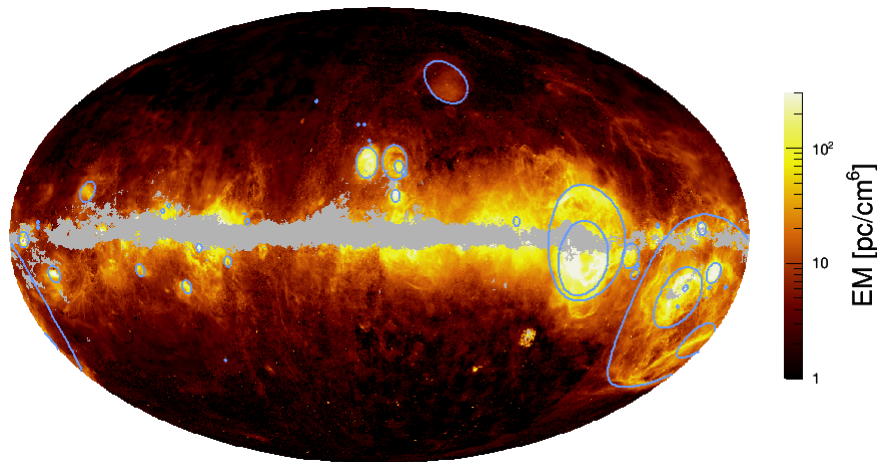
- ▶ emission measure $EM \propto \int_0^\infty n_e^2(l) dl$ from $H\alpha$ map
- ▶ NE2001 “clumps” + Gum



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

NE2001 “clumps” vs. $H\alpha$ Data

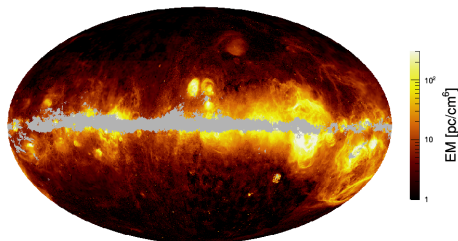
- ▶ emission measure $EM \propto \int_0^\infty n_e^2(l) dl$ from $H\alpha$ map
- ▶ classical HII regions ($\tau(\text{SFD}) < 2$)



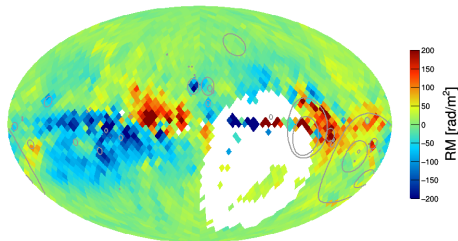
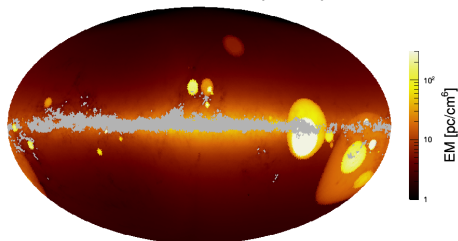
VTSS, SHASSA, WHAM (D. Finkbeiner ApJS **146** (2003) 407)

EM (top) and RM (bottom)

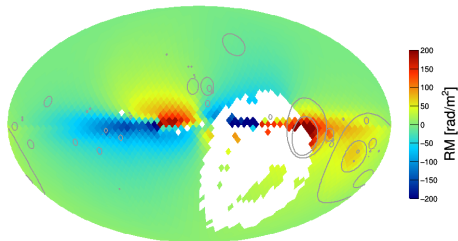
data



NE2001+HII+ τ (SFD)

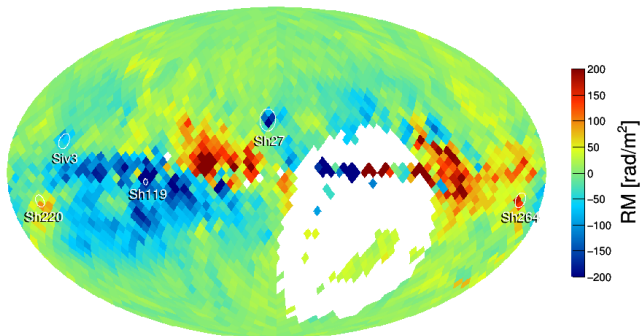


data



NE2001+HII+JF12

HII B-field Estimates vs. Regular (!) JF12

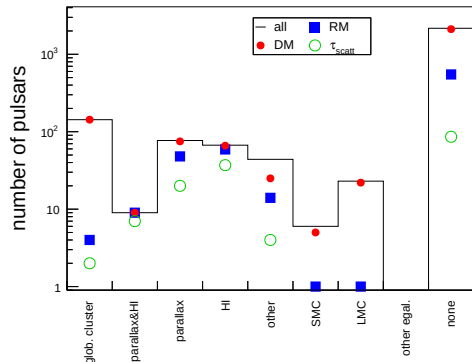
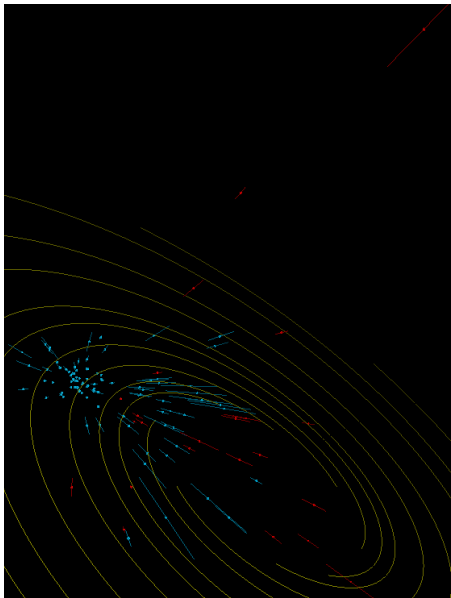


	JF12 $B_{\parallel}$ [μG]	estimated $B_{\parallel}$ [μG]
S27	-0.2	-6.1 ± 2.8^b
Sh119	-1.1	-19.9 ± 5.3^a
Sh220	+0.0	-6.3 ± 2.4^b
Sh264	+0.6	$+1.3 \pm 1.3^a, +2.2 \pm 1.5^b,$
Siv3	-0.4	-2.5 ± 1.5^b

^aC. Heiles, Y.H. Chu, T.H. Troland, ApJ **247** (1981) 77

^bL. Harvey-Smith, G.J. Madsen, B.M. Gaensler, ApJ **736** (2011) 83

NE2001 vs. Pulsar DMs



- ▶ 123 line of sights with dispersion measure $DM = \int_0^D n_e(l)dl$ and $\sigma(D)/D < 1/3$ (LMC/SMC excluded).

ATNF pulsar database v1.54

G. Desvignes et al, MNRAS 458 (2016) 3341

www.astro.cornell.edu/~shami/psrvlb/parallax.html

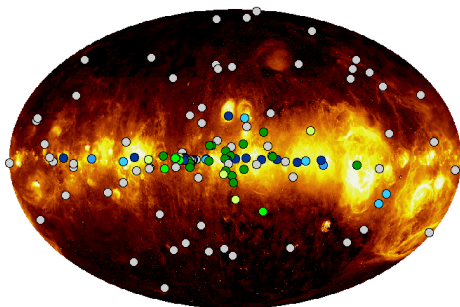
psrpop.phys.wvu.edu/LKbias/about.php

www.physics.mcmaster.ca/~harris/mwgc.dat

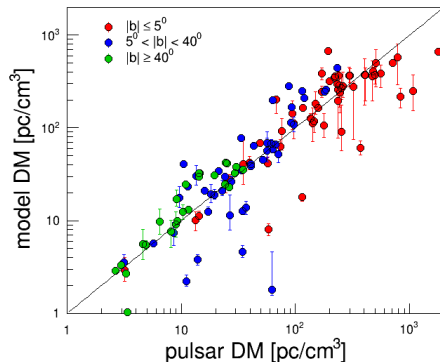
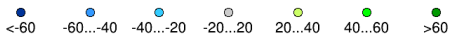
red: globular clusters, blue: individual pulsars

NE2001 vs. Pulsar DMs

original NE2001 model:

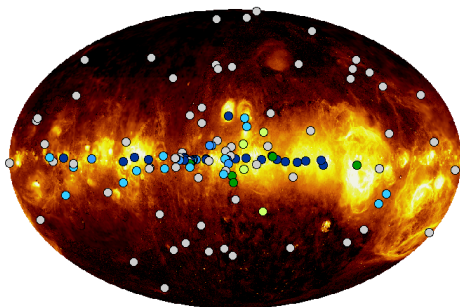


DM(model) - DM(pulsar) [pc/cm^3]:

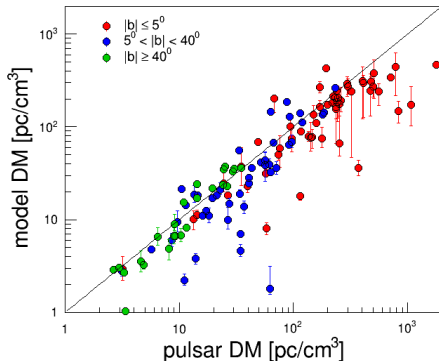
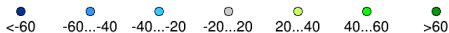


NE2001 vs. Pulsar DMs

re-tuned^a thick-disk scale height (used for JF12): $0.97 \rightarrow 1.83$ kpc



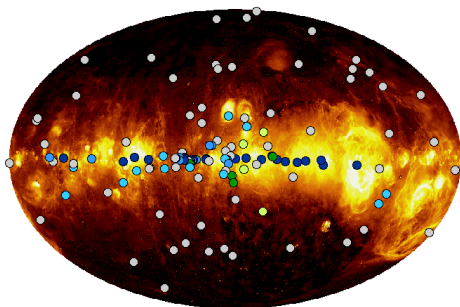
DM(model) - DM(pulsar) [pc/cm^3]:



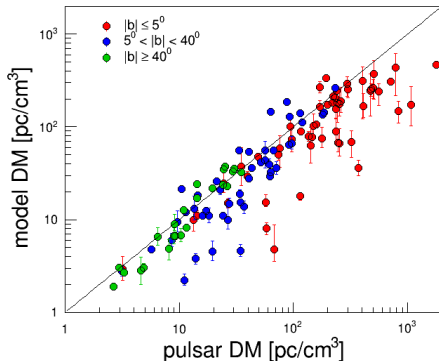
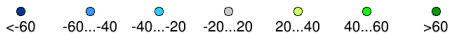
^aB. Gaensler et al, PASA **25** (2008) 184, also D. Schnitzeler, MNRAS **427** (2012) 664.

NE2001 vs. Pulsar DMs

Removing ad-hoc NE2001 clumps, adding 47 nearby HII regions

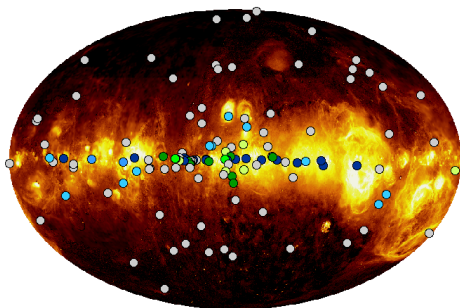


DM(model) - DM(pulsar) [pc/cm^3]:

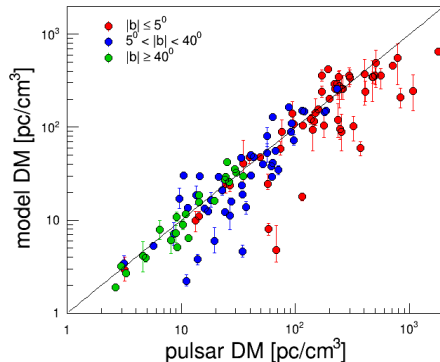
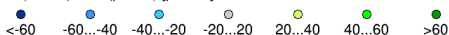


NE2001 vs. Pulsar DMs

Refit with double-exponential thick disk (for illustration)



DM(model) - DM(pulsar) [pc/cm^3]:



remaining “outliers” mainly in GP, including more HII may tighten scatter

Summary

Ongoing studies: Effect of thermal electron uncertainties on global GMF fit

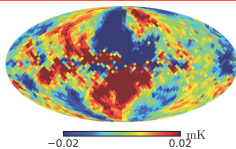
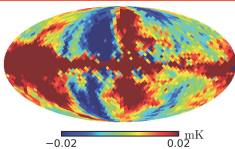
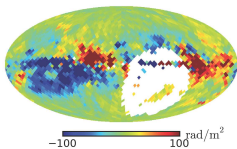
- ▶ better modeling of local distribution of n_e helpful to understand fluctuations and “locality” of extragalactic RMs
- ▶ in preparation: WHAM(ν)+3D Dust.
- ▶ re-tune NE2001

Further improvements / studies for a successor to JF12 (and more realistic GMF uncertainties):

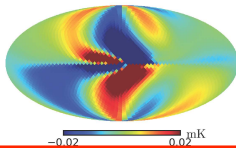
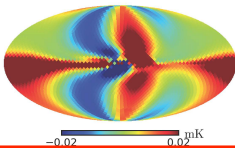
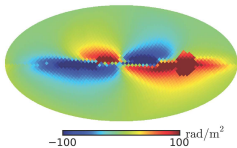
- ▶ cosmic ray electrons
- ▶ functional forms used in JF12
- ▶ functional forms used in NE2001
- ▶ correlation of n_e and B
- ▶ ...

backup

Spiraling X-field ↔ distinctive L-R, up-down pattern in Q, U



Observed data

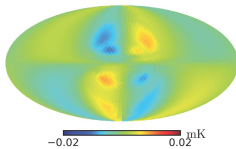
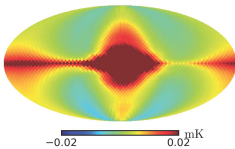
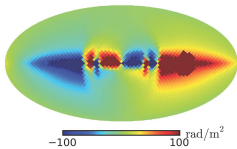


Simulated data

JF 2012

$\chi^2 = 1.096$ per d.o.f.

for 6605 observables



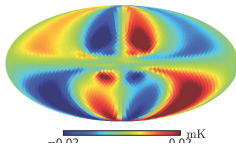
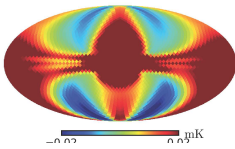
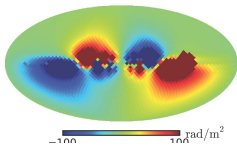
Pshirkov+ 2011

$\chi^2 = 2.66$ per dof

No X-field

Sun et al., 2010

$\chi^2 = 1.67$ per dof



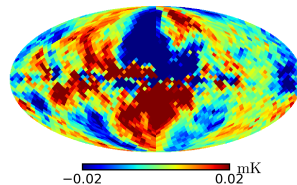
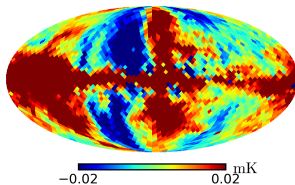
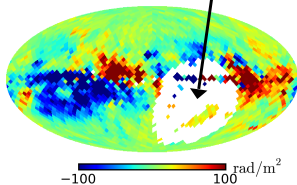
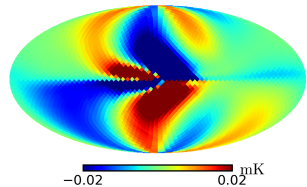
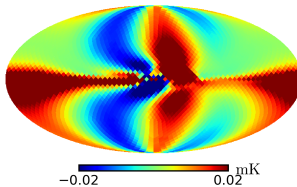
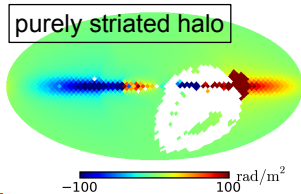
The halo field is DIRECTED, not just striated

RM

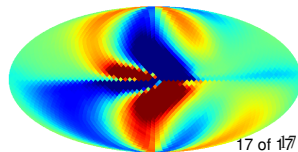
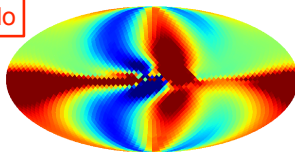
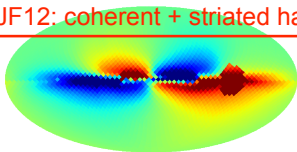
Stokes Q

Stokes U

purely striated halo



JF12: coherent + striated halo



Independent evidence for JF12 X-field, from orientation of Supernova Remnants

Jennifer West, IAU DD.6.03

The Connection between Supernova Remnants and the Galactic Magnetic Field

(A&A, submit)

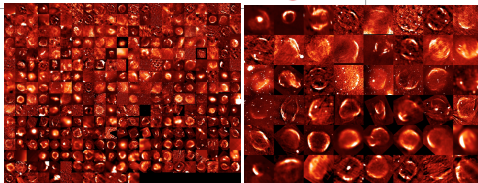
Jennifer West, PhD Candidate
University of Manitoba, Canada

Supervisor: Samar Safi-Harb (U. of Manitoba, Canada)
Collaborators: Tess Jaffe (IRAP, Toulouse, France), Roland Kothes (NRC Herzberg, Canada), Tom Landecker (NRC Herzberg, Canada), Tyler Foster (Brandon U., Canada)

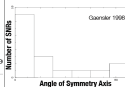
INNOVATION CANADA
Canada Research Chair in Astrophysics
Funding provided by the Government of Canada

UNIVERSITY OF MANITOBA

NSERC
CRSNG

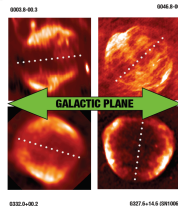


Is there a connection between the Galactic Magnetic Field and Supernova Remnants?

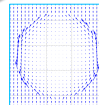


Gaensler (1998): a highly significant tendency for the axes of these SNRs to be aligned with the Galactic plane

Lockband et al. (1989): no preferred orientation between the angle of symmetry and the Galactic plane



Orientation relative to model prediction



Predicted - observed

