Structure in the magnetic field of the Milky Way

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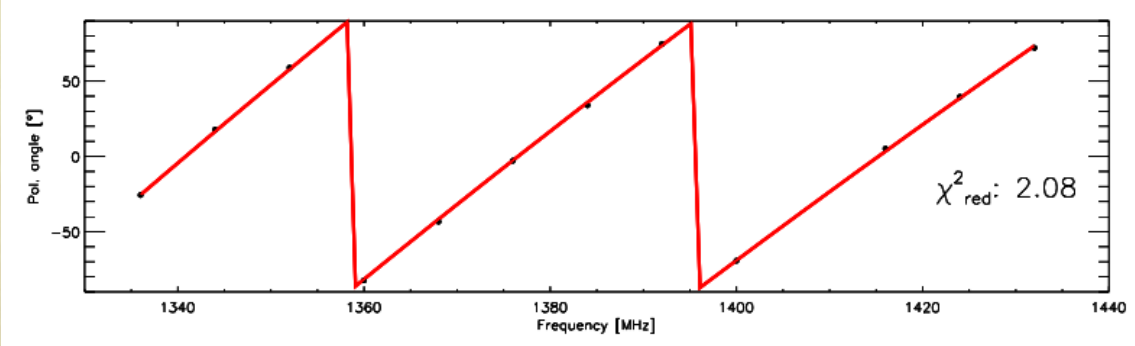
Based on: Schnitzeler 2010, MNRAS, 409, 99

ATCA calibrator PKS 1352-63: RM= -1226 rad/m^2



Abstract

- sigma_RM (Milky Way) follows the same 1/sin|*b*| behaviour as the dispersion measures of infinite lines of sight (|*b*| > 20^{o})

- sigma_RM(*b*) ≈ sqrt{(8/sin|*b*|)^2 + 6^2} rad/m^2 |*b*| > 20^{o} (on scales between 1^{o} – 10^{o}, angular resolution ≈ 45″)

- the Galactic foreground, not the intrinsic RMs of the extragalactic sources themselve, dominates the observed RMs

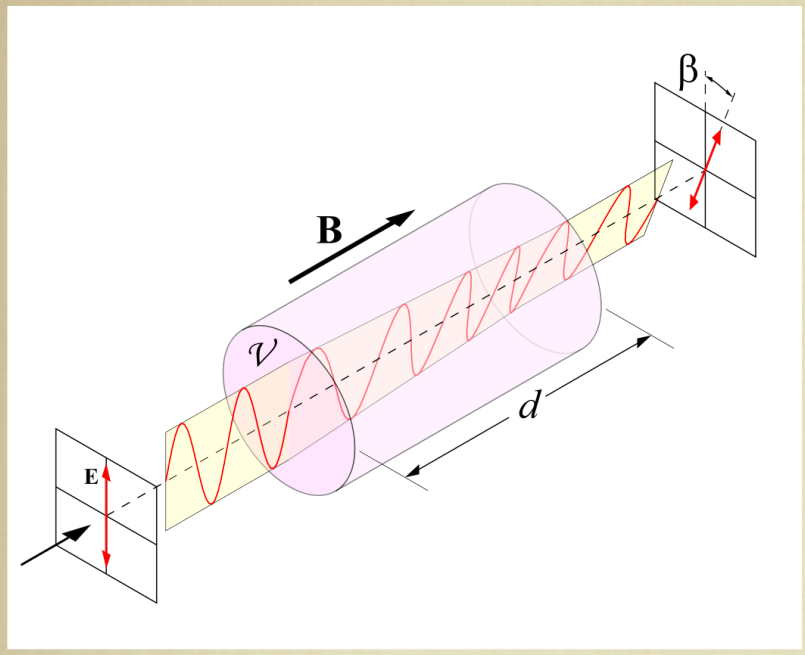
- the extragalactic contribution to sigma_RM is ≈ 6 rad/m^2 (discrete sources + intergalactic fields)

- sigma_$<B_{||}>$ ≤ 0.4 μG (Galactic foreground)

Overview

- Rotation measures; the RM catalogue by Taylor+ 2009
- Correcting sigma_RM for large-scale structure in the Galactic foreground, and for measurement uncertainties in RM.
- The contributions by the Galactic foreground and the extragalactic background
- Physical implications
- Caveat: limited angular resolution
- Future work

Rotation Measures vs. Dispersion Measures



Source: Wikipedia

$$\mathrm{RM} = 0.81 \int_{\mathrm{there}}^{\mathrm{here}} n_{\mathrm{e}} B_{\parallel} d\mathrm{l}$$

Faraday rotation

$$\mathrm{DM} = \int_{\mathrm{there}}^{\mathrm{here}} n_{\mathrm{e}} d\mathrm{l}$$

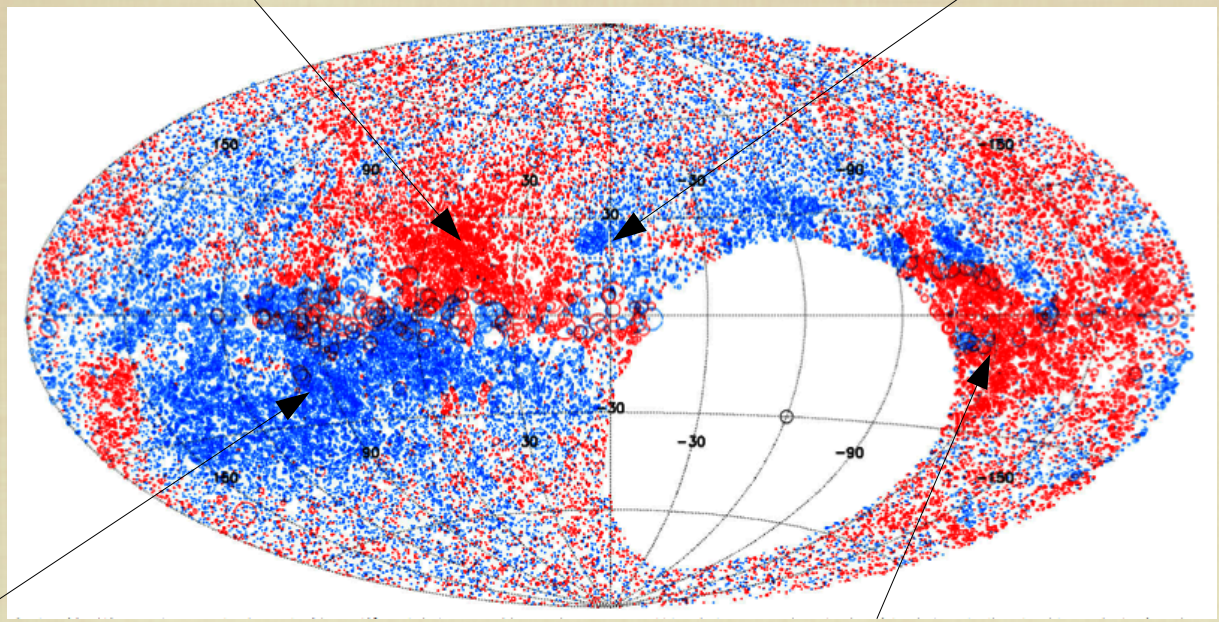
Dispersion Measure

Pulsars: pulse arrival times at different freq.

Getting the big picture requires big surveys

North Polar Spur

HII region surrounding zeta Oph



Gal. coordinate grid,longitudes increase to the left.

Magnetic field pointing towards us (red)/away from us (blue)

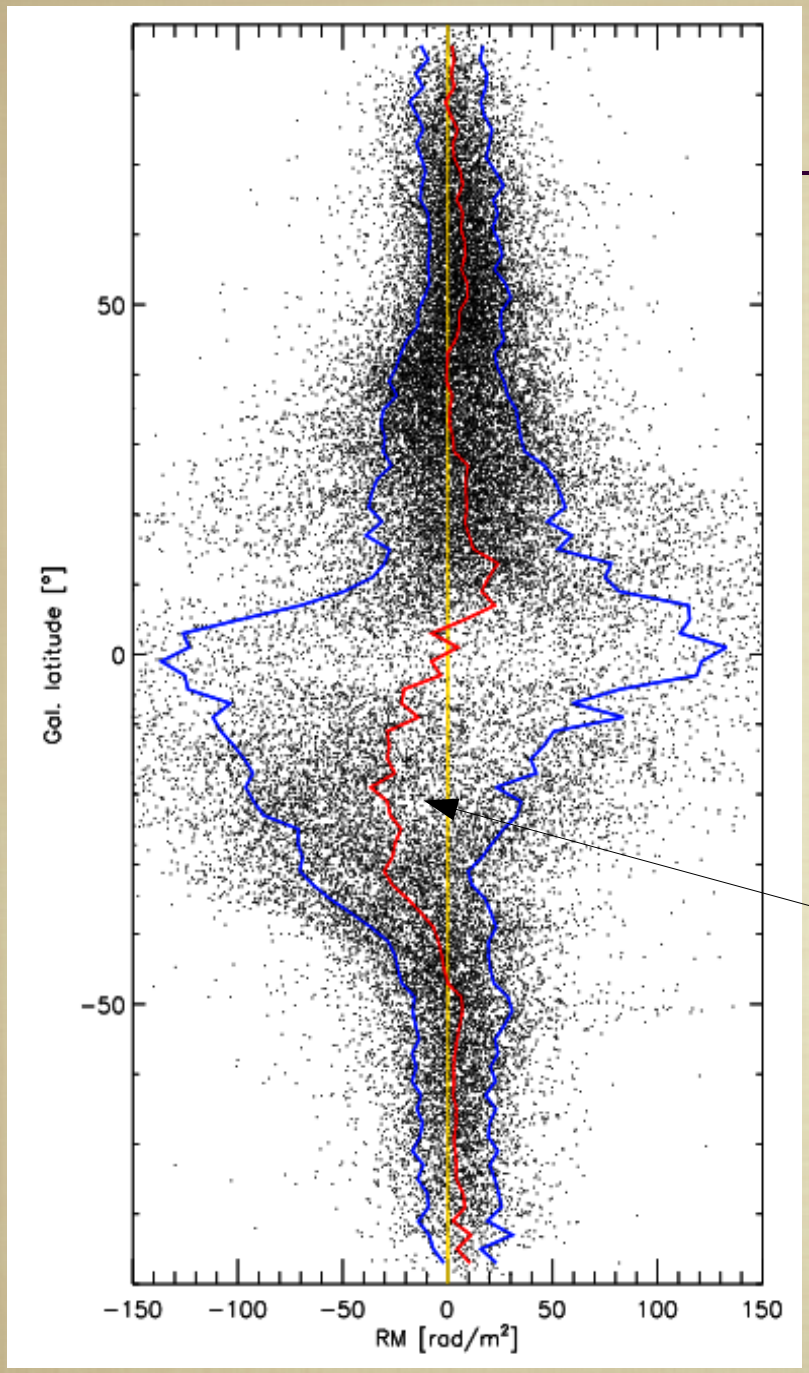
1 source per 1 square degree

"Region A"

(one half of the) Gum nebula

Taylor et al. (2009): RMs for 37,543 sources from the NVSS catalogue (Very Large Array; DEC > -40°)

1 RM per square degree. Median err_RM approximately 11 rad/m^2



RMs in the Galactic halo

The scatter in RMs increases closer to the Galactic plane

red: RM(*b*), averaged over galactic longitude

blue: sigma_RM

2 effects:

1. sources from Region A have very negative RMs
2. no NVSS RMs below DEC= -40°

sigma_RM(*b*)

Calculate sigma_RM in strips along Galactic latitude.

Step 1: Remove the large-scale structure in RM from the Milky Way

Sample RM bins of $5^o/\cos|b| \times 4^o$ (about 20 RMs per bin;
Nyquist sampling of scales > 10^o on the sky)

Model the large-scale structure as a cubic spline fit to the bins

Subtract this spline fit from each RM.

Calculate sigma_RM in each latitude strip: sigma_RM_step1

Step 2: Correct for the contribution of err_RM to sigma_RM

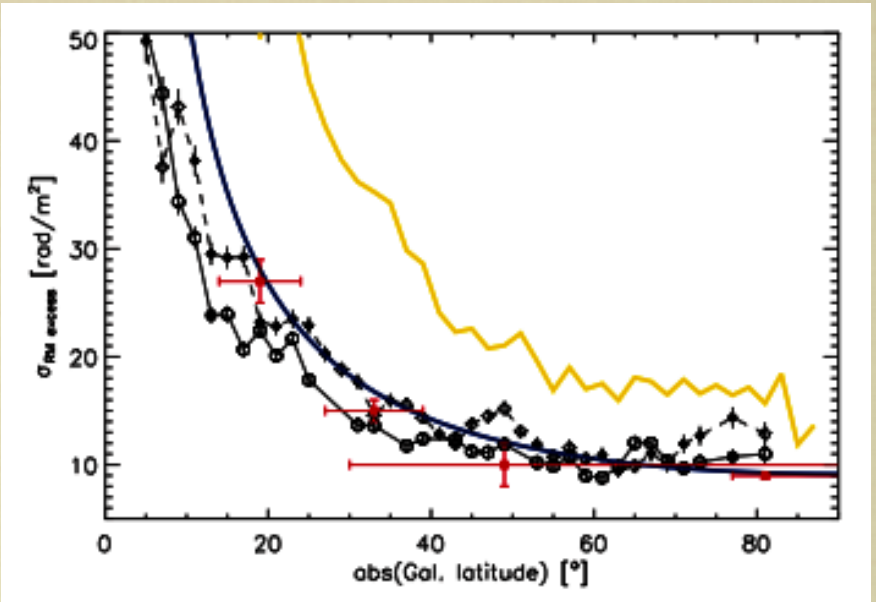
Drawing 1000 RMs randomly for the ensemble gives an
err_RM = 10.4 +/- 0.2 rad/m^2 (Monte Carlo)

sigma_RM_step2^2 = sigma_RM_step1^2 – 10.4^2

sigma_RM(*b*)

yellow: sigma_RM uncorrected

solid/dashed lines: corrected sigma_RM for positive/negative Latitudes. (chi^2_red < 4)



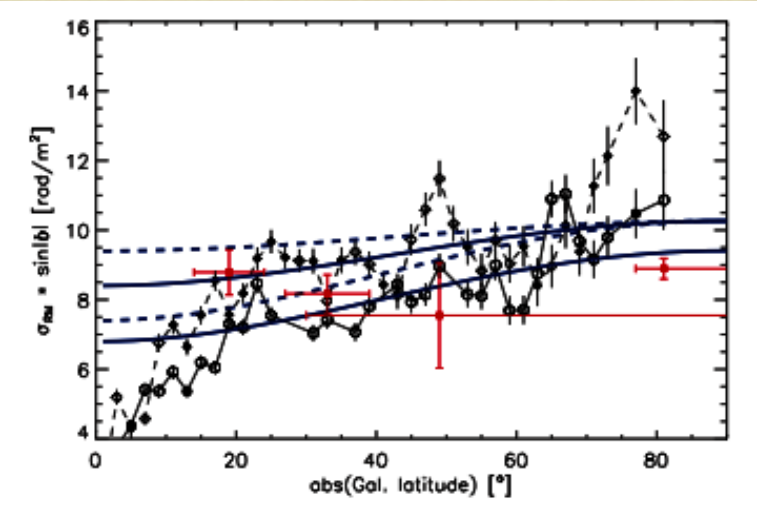
blue: simple model fit:
sigmaRM $\propto$ 1/sin|*b*|

red: independent data from other authors
(Cen A: Feain et al. 2009, LMC: Gaensler et al. 2005, <b> = 49°: Johnston-Hollitt et al. 2004, <b> = 81°: Mao et al. 2010.)
Not shown: SMC data sigmaRM=22 rad/m^2 for <b> = -44° (Mao+ 2008)
A2255 data sigmaRM=19 rad/m^2 for <b> = 35° (Pizzo+2010)

NOTE:
1: also the literature data follow a 1/sin|*b*| dependence
2: cubic spline does a decent job at removing the Galactic foreground

Structure in the Galactic halo: sigma_RM(b) * sin|b|

- Take out the 1/sin|b| dependence:



- Model sigma_RM as

$$\sigma_{\mathrm{RM}}(b) = \sqrt{\left(\frac{\sigma_{\mathrm{RM,MW}}}{\sin|b|}\right)^2 + \sigma^2_{\mathrm{RM,EG}}}$$

- sigma_RM(extragalactic) does not depend on viewing direction → separate foreground from background

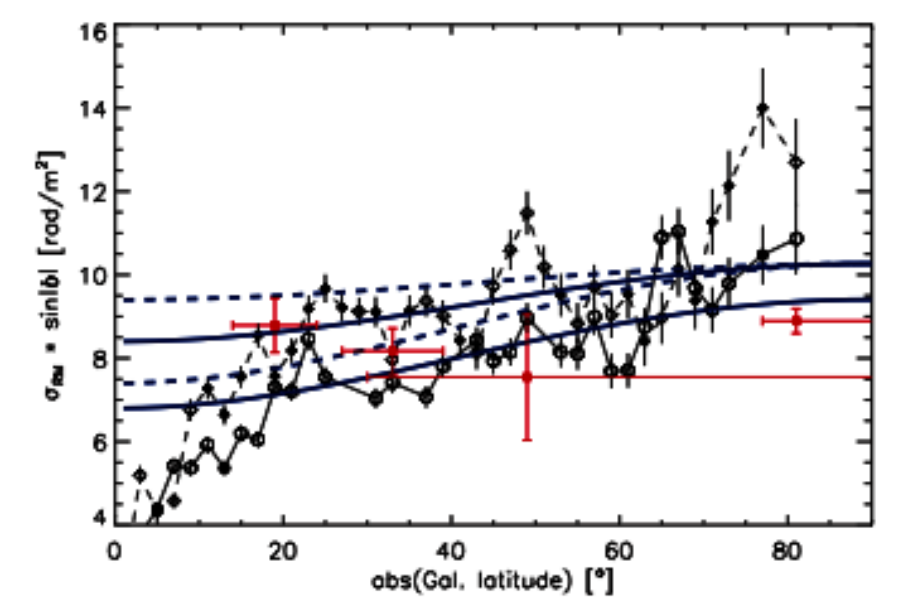
Why should sigma_RM $\propto$ 1/sin|*b*|?

- RM depends on n_e and $B_{||}$
- The free electrons follow an exponential or sech^2 distribution away from the Galactic plane
- Therefore, $DM_\infty \propto 1/\sin|b|$
- $\rightarrow$ try sigma_RM = $1/\sin|b|$

Structure in the Galactic halo: sigma_RM(b) * sin|b|

- Model sigma_RM (corrected) as

$$\sigma_{\mathrm{RM}}(b) = \sqrt{\left(\frac{\sigma_{\mathrm{RM,MW}}}{\sin|b|}\right)^2 + \sigma^2_{\mathrm{RM,EG}}} = \sqrt{\left(\frac{8}{\sin|b|}\right)^2 + 6^2}$$



Best fits:

	MW / EG
$b > 0^o$	6.8 / 6.5 rad/m^2
$b < 0^o$	8.4 / 5.9 rad/m^2

chi^2_red: 4.4/3.9
($b < 0^o$/$b > 0^o$)

Structure in the Galactic halo

- Model sigma_RM (corrected) as

$$\sigma_{\rm RM}(b) = \sqrt{\left(\frac{\sigma_{\rm RM,MW}}{\sin|b|}\right)^2 + \sigma^2_{\rm RM,EG}} = \sqrt{\left(\frac{8}{\sin|b|}\right)^2 + 6^2}$$

- Structure in the Galactic foreground on scales >~ 1° dominates sigma_RM at all Galactic latitudes
  → take care when studying extragalactic RM

- The sigma_RM of extragalactic sources is 6 rad/m^2:
  the same value as found by Leahy (1987)
  (but I was not aware of his work when I calculated this number!)

- This sigma_RM_EG includes the RMs from the sources themselves, plus from intergalactic fields

Upper limits

- The Milky Way might also contribute a sigma_RM component that does not depend on *b*
  → the true sigma_RM_EG < 6 rad/m^2

- Assuming no correlation between n_e and $B_{||}$,
  sigma_RM_MW can be separated into contributions by sigma_n_e and by sigma_$B_{||}$
  Assuming sigma_n_e = 0 (smooth electron density model):
  sigma_$<B_{||}>$ = sigma_RM_MW/{0.81*DM_∞(*b*=90^o)}
  ≈ 0.4μG

Implications

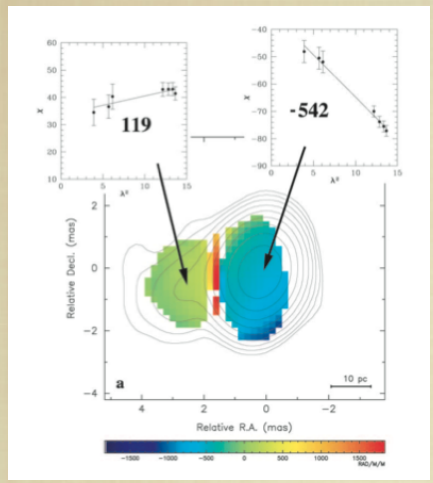
- Studies of the Galactic foreground: average out the extragalactic contribution to RM (Mao+2012)

- Models of the intergalactic magnetic field show that its sigma_RM is several rad/m^2 (Akahori & Ryu 2011)

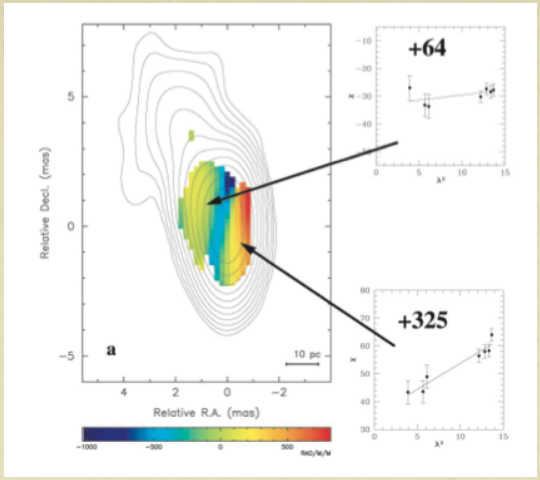
- Does sigma_RM_EG depend on redshift?
  Kronberg+ 2008: yes, Hammond+ 2012, Everett+2012: no
  Need to accurately remove the foreground sigmaRM

- Cosmic ray propagation in the lobes of Centaurus A (e.g. Feain+ 2010)

Caveat: limited angular resolution



0212+735



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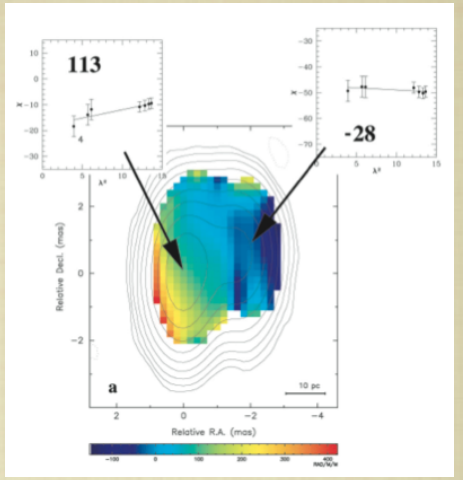
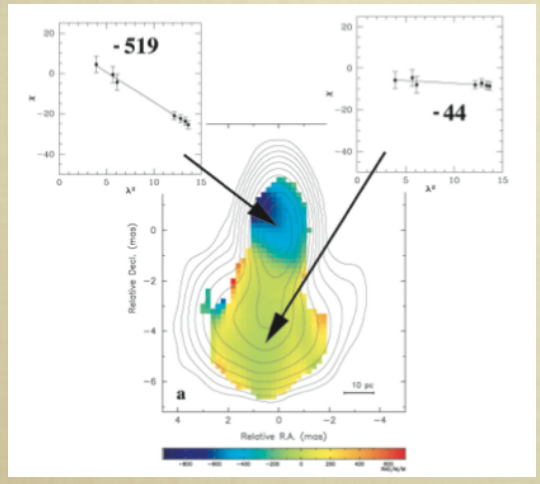


1308+326



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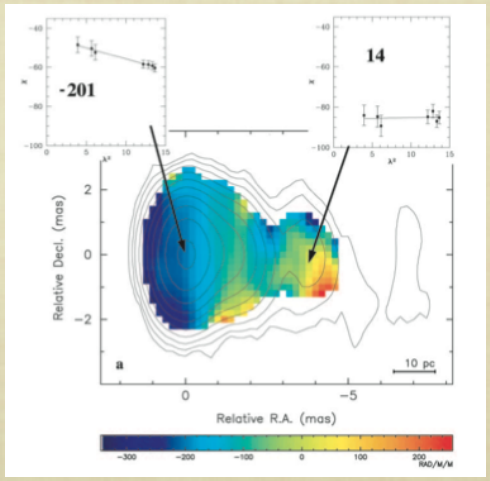
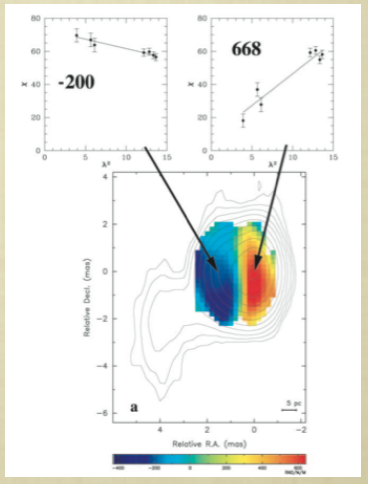


1803+476



2005+403

Examples from Zavala & Talor 2003

Future work (near and far)

Near future

S-PASS (see also E. Carretti's talk on Wednesday)

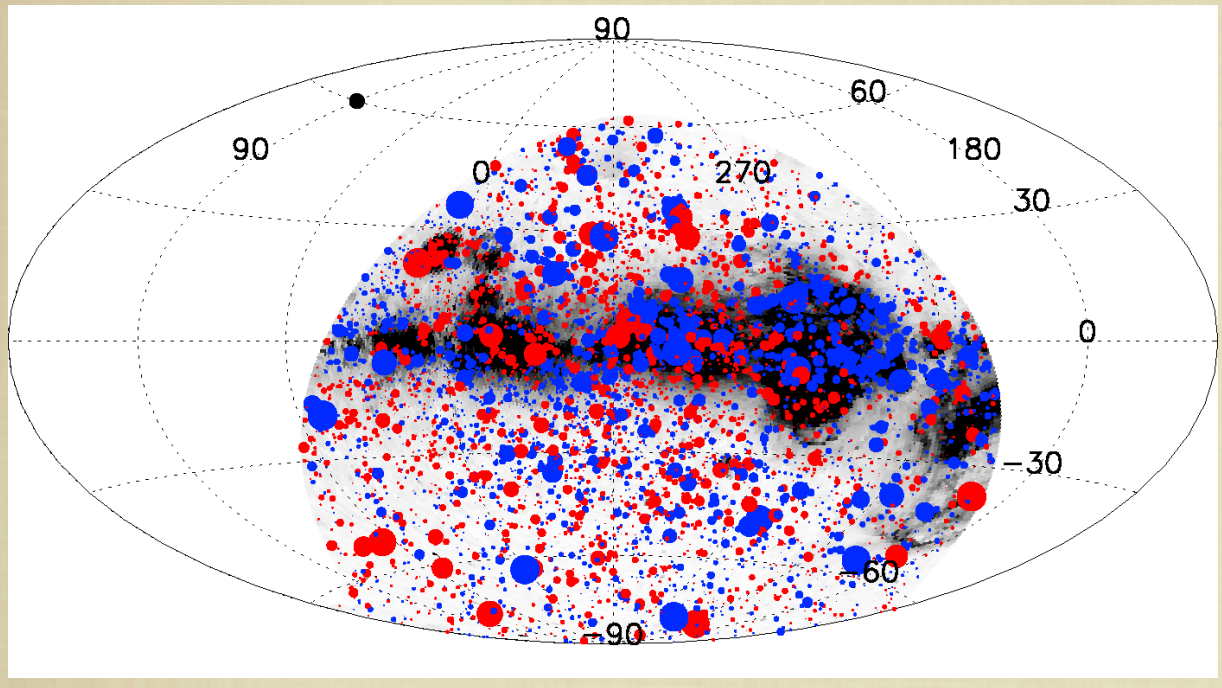
Extend this work to smaller $|b|$: requires accurate models of the free electron density (see also DS 2012)

More distant future

Dense grids of accurate RMs that cover the entire sky: ASKAP, LOFAR, MWA, APERTIF

RMs for point sources in S-PASS

S-PASS: Parkes / 2.3 GHz / 150 MHz bandwidth (PI: E. Carretti)



Gal. coordinate grid, centred on l=315°
Background: Hα intensity (Finkbeiner 2003)

Magnetic field pointing towards us (blue)/away from us (red)

1 source per 4 square degrees

S-PASS covers DEC < 0°, filling the gap below DEC = -40° that is not covered by the NVSS RMs from Taylor+ 2009

RMs for point sources in S-PASS

- 80 hours of ATCA time (March & July) to re-observe 4600 sources
- Improved frequency coverage and sensitivity lead to reliable and accurate RMs; ATCA: 1.3-3.1 GHz, err_RM < 1.5 rad/m^2
- Polarized S/N >~ 50 (PI > 5 mJy)
- Higher angular resolution than S-PASS (2' vs. 9'), but poorer than NVSS RMs (45")

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