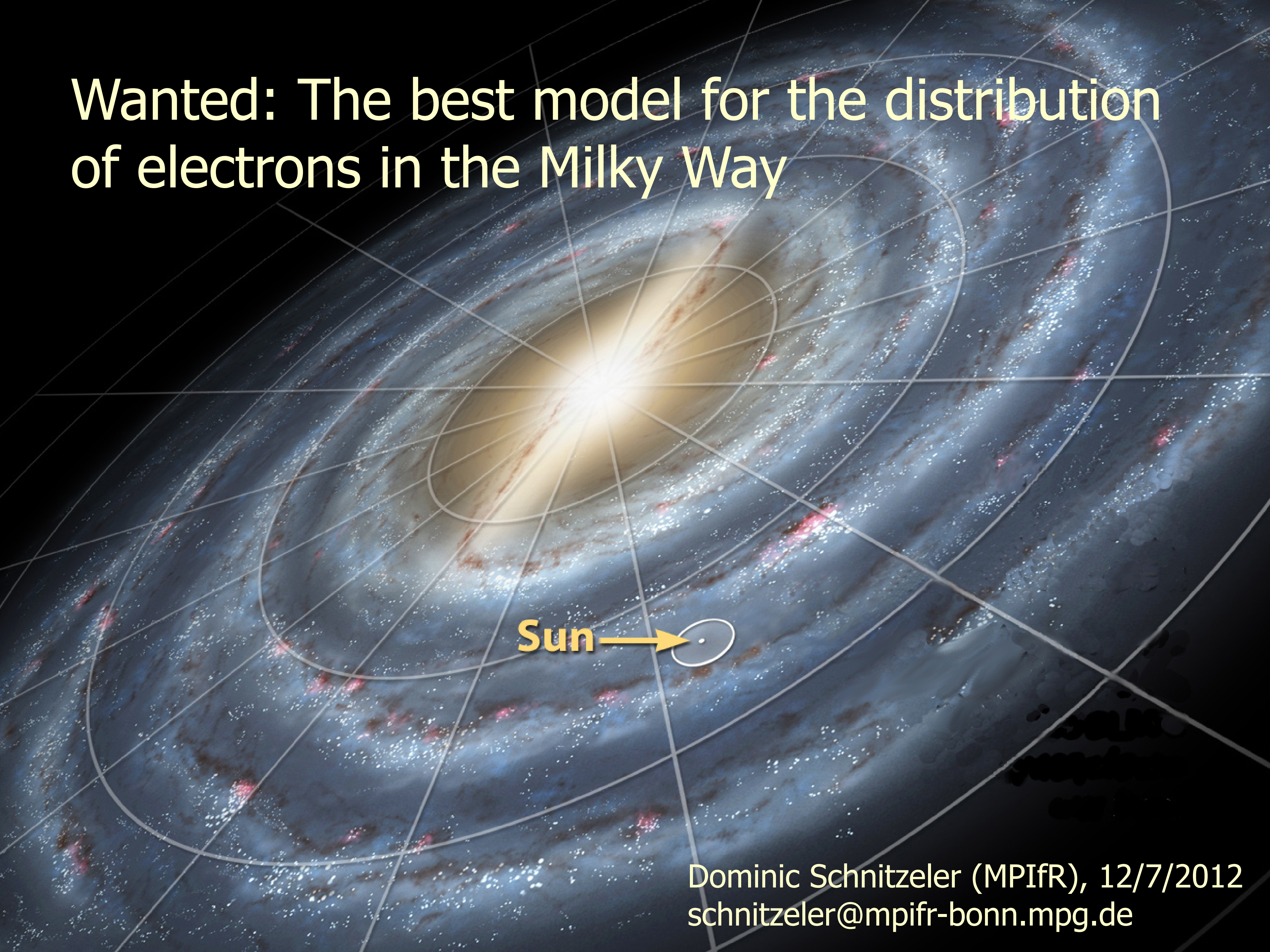
Wanted: The best model for the distribution of electrons in the Milky Way



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Abstract

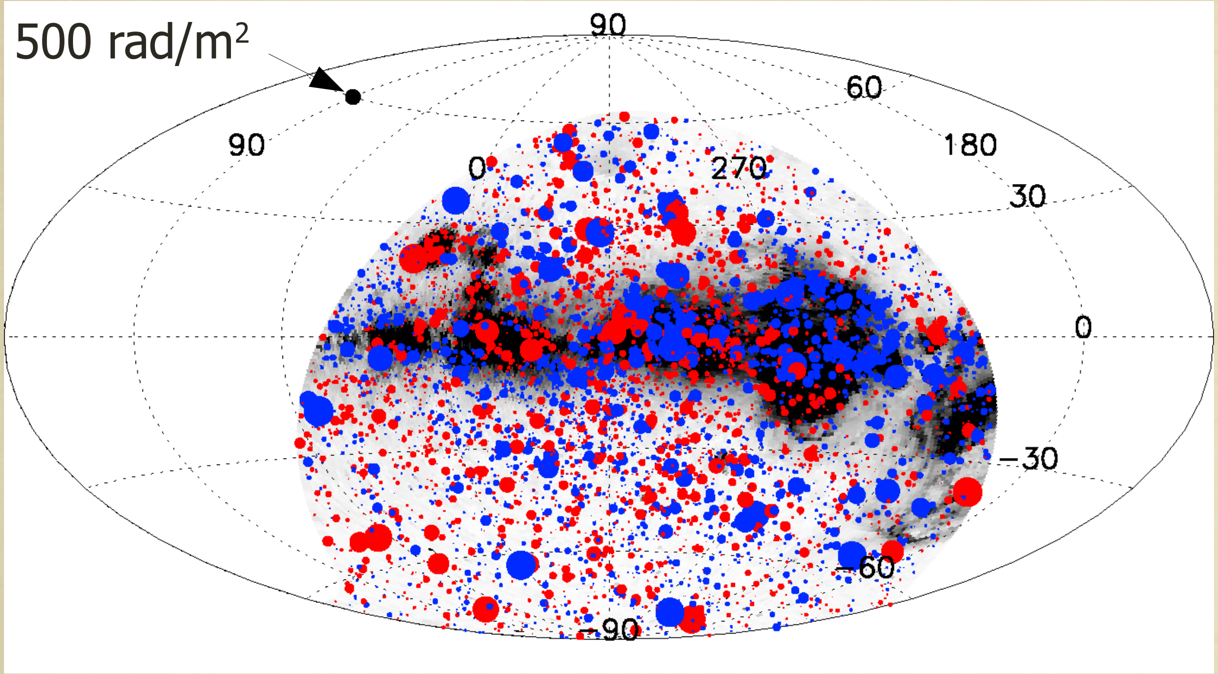
- NE2001 is not the most accurate n_e model
- Most n_e models can predict DM within a factor of 1.5-2 for 75% of the lines of sight
- TC93 + a thick disk of 1.6 kpc predicts DM best out of all 12 n_e models that we tested
- Replacing the thick disk from NE2001 by the thick disk proposed by Gaensler et al. 2008 does not work
- A few pulsars lie behind HII regions, and their DM cannot be predicted by any of the current models

Overview

- n_e models → 3D distribution of pulsars, structure of the Galactic magnetic field; S-PASS/ATCA point-source survey
- We tested 12 n_e models using 68 pulsars at known distances (parallaxes, in globular clusters)
- Quantitative comparison between the models
- Results from our analysis

Big surveys: The next generation

5102 polarized compact S-PASS sources (> 5 mJy pol. int.)
(S-PASS: Parkes / 2.3 GHz / 150 MHz bandwidth / PI: Ettore Carretti)



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

1 source/
4 square degrees

central Galactic longitude: 315°

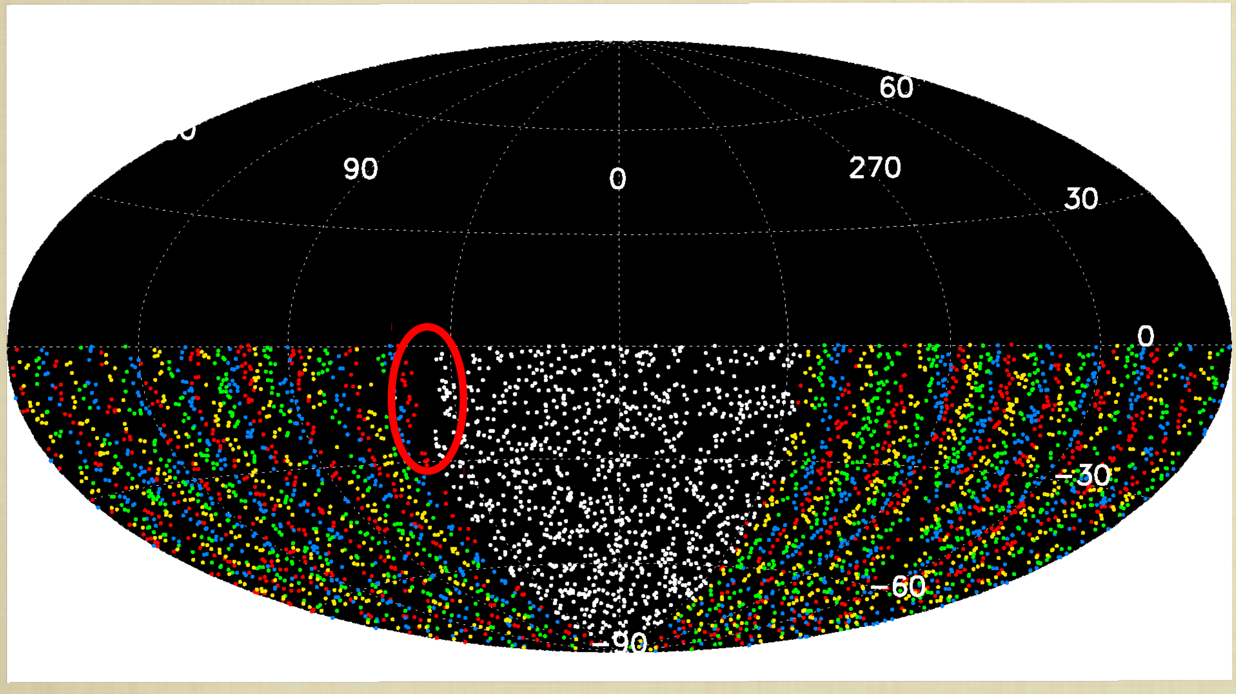
Re-observed 4600 sources with the ATCA
: larger bandwidth, more accurate RMs (60 rad/m^2 → 1.5 rad/m^2)

S-PASS/ATCA observations (March & July 2012)

4600 target sources in 80 hours (→ S-PASS is FAST!)

1.3-3.1 GHz band / P > 25 sigma and > 0.1% I / err_RM < 1.5 rad/m^2 (PI: DS)

36 seconds integration time/source, 12 seconds slew time (on average)

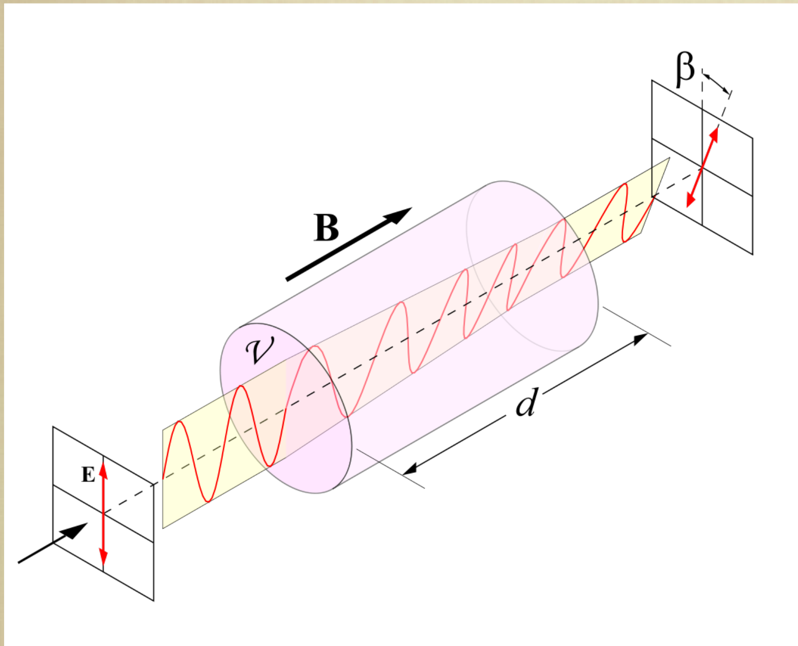


Equatorial coordinates

Red/blue/green/yellow = 23/24/25/26th of March 2012

White = 17th of July 2012

Rotation/Dispersion/Emission Measures



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

Faraday rotation

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

Dispersion Measure

Pulsars: pulse arrival times at different freq.

$$\mathrm{EM} = \int_{\mathrm{there}}^{\mathrm{here}} n_{\mathrm{e}}^2 d\mathrm{l}$$

Emission Measure

Intensity of the Hα line at 656 nm (rest freq.)

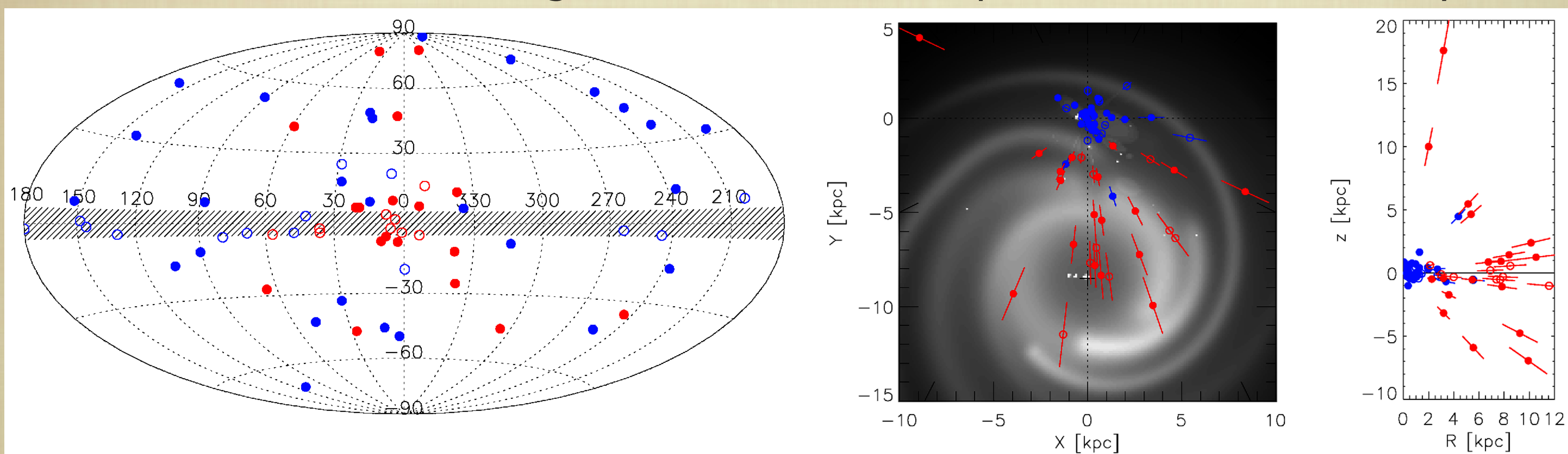
The 12 n_e models

Exponential models	*with a single scale height*
BM08	h=0.9 kpc, $DM_{infty,perp}$ = 21.7 $cm^{-3}pc$
GMCM08	h=1.8 kpc, $DM_{infty,perp}$ = 25.6 $cm^{-3}pc$
M1	h=1.6 kpc, $DM_{infty,perp}$ = 24.4 $cm^{-3}pc$
Plane-parallel	*2-component models with a radial scale length*
GBCa,b	Gomez et al. (2001): exponential or $sech^2$ radial and *z* dependencies
Multi-component	*models*
TC93	Model by Taylor & Cordes (1993)
NE2001	Model by Cordes & Lazio ('a': Web interface / 'b': Fortran)
NE2001c	NE2001 (Fortran) + thick disk from GMCM08
M2,3	TC93 / NE2001 with a new thick disk
M4	M2 + uses $DM_{infty}(EM_{infty})$ to predict DM at infinity

How to test models of Galactic n_e?

- Use 68 pulsars with know distances, err_dist < 0.25 dist; (parallaxes, inside globular clusters)

Galactic coordinate grid top-down view sideways view



Blue: isolated pulsars
Red: pulsars in globular cluster

(plane through the
Sun and the pulsar)

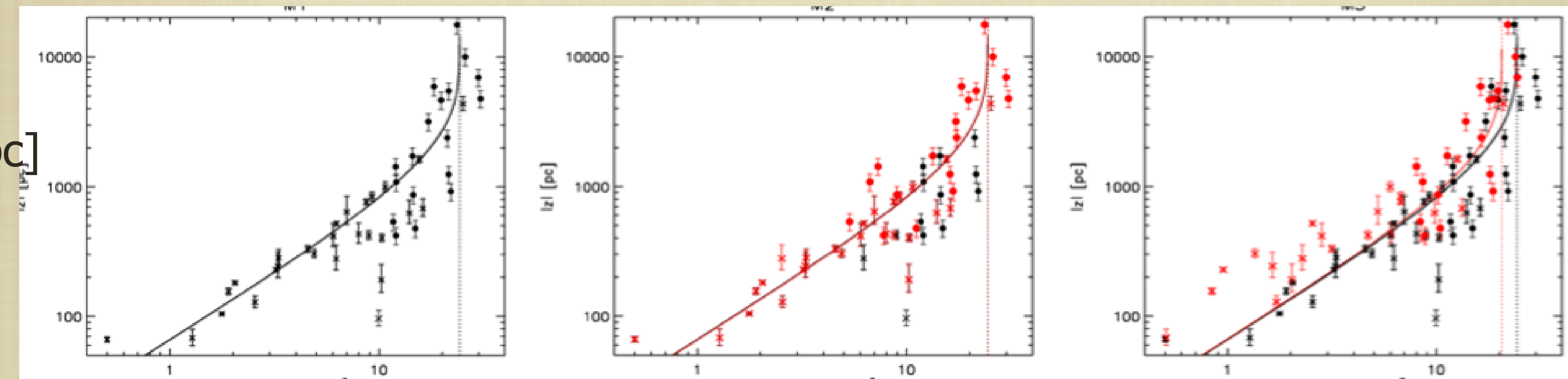
- Use subset of 45 pulsars at |*b*| > 5° (filled circles) + away from HII regions to constrain model parameters

M1,2,3: thick disk/TC93++/NE2001++

- Crosses: isolated pulsars / Circles: pulsars in globular clusters
- $DM_{infty,perp}$ set by 8 sightlines at $|z| > 4$ kpc off the plane

M1 ($|b| > 32.5^{o}$) M2 (= based on TC93) M3 (=based on NE2001)

z [pc]



DM x sin(|b|) [cm^{-3} pc]

$DM_{infty,perp}$ = 24.4	24.4	20.5 cm^{-3}pc
h = 1.6	1.6	1.3 kpc

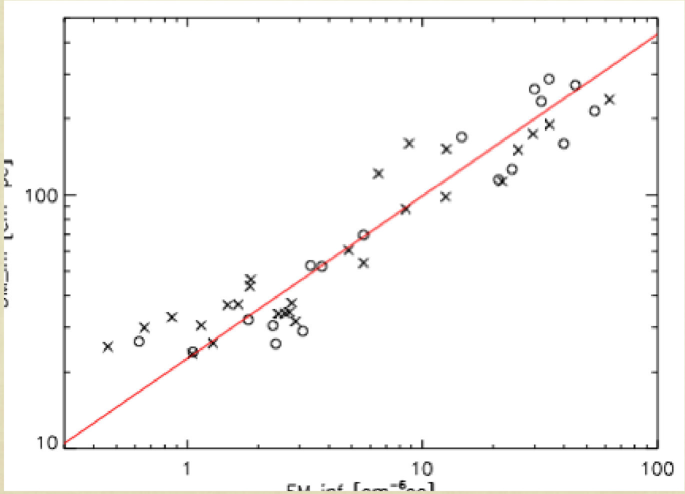
- NE2001 is fitted best with an exponential scale height of 1.3 +/- 0.2 kpc

M4: use the Emission Measure as proxy

- All models that use an exponential scale height assume that all sightlines have the same $DM_{infty,perp}$
- Variations in DM_{infty} might be predicted from the Emission Measure
- M4: derive DM_{infty} from EM, then correct for the finite distance to the pulsar by using TC93, NE2001, M2, ...

M4: use the Emission Measure as proxy

- Take the Hα intensities from Finkbeiner (2003),
- Correct these for interstellar extinction, and calculate EM_{infty}
- Only for $|b| > 5^o$ are the extinction corrections from Schlegel et al. (1998) reliable → M4 only works there



DM_inf [$cm^{-3}pc$] (from observed DM + M2)

EM_inf [$cm^{-6}pc$] (from Hα intensity + interstellar extinction)

x : isolated pulsar
o : pulsar in globular cluster

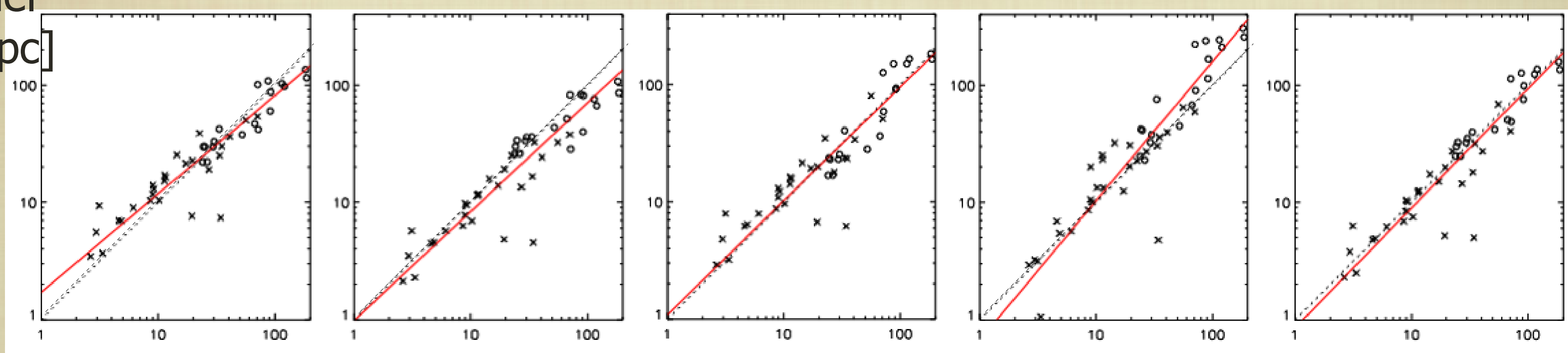
Fitted line:
$DM_{infty} = 22.66\ EM_{infty}^{0.64}$

How to test these 12 models?

- Use 45 pulsars at |*b* | > 5° with know distances (parallaxes, association with globular clusters)
- Plot DM_model against DM_observed to look for systematic effects

DM model [cm^{-3}pc]

BM08 GMCM08 TC93 NE2001 M2



DM_obs [cm^{-3}pc]

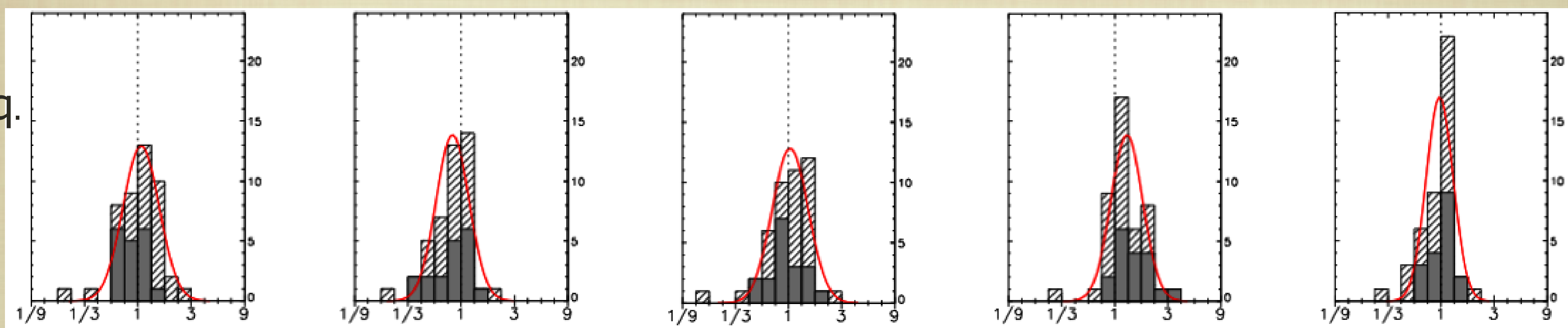
x : isolated pulsar
o : pulsar in globular cluster

How to test these 12 models?

- Focus on relative instead of absolute deviations between DM_model and DM_observed

BM08 GMCM08 TC93 NE2001 M2

freq.



DM_model/DM_obs

psr in globular clusters

isolated psr

How to test these 12 models?

- When we talk about a model that predicts DM within a factor of (say) 2, we (implicitly) assign the same weight to DM_model = 2 DM_obs as to DM_model = ½ DM_obs

- Quantify this by introducing

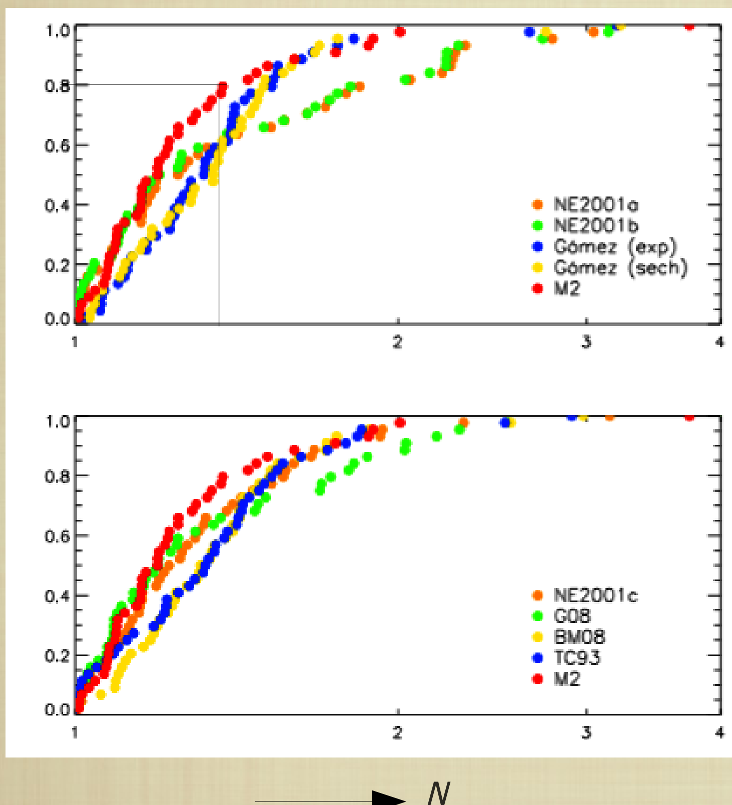
  N = DM_model/DM_obs   DM_model > DM_obs
  = 1/ (DM_model/DM_obs)   otherwise

- this way: $N >= 1$ for all pulsars

- Allows for a quantitative comparison of how well n_e models predict DM

How to test these 12 models?

- Plot the cumulative distribution of *N*



<u>Idea</u>: a perfect model has all *N*=1, so its cumulative distr. is a vertical line at *N*=1

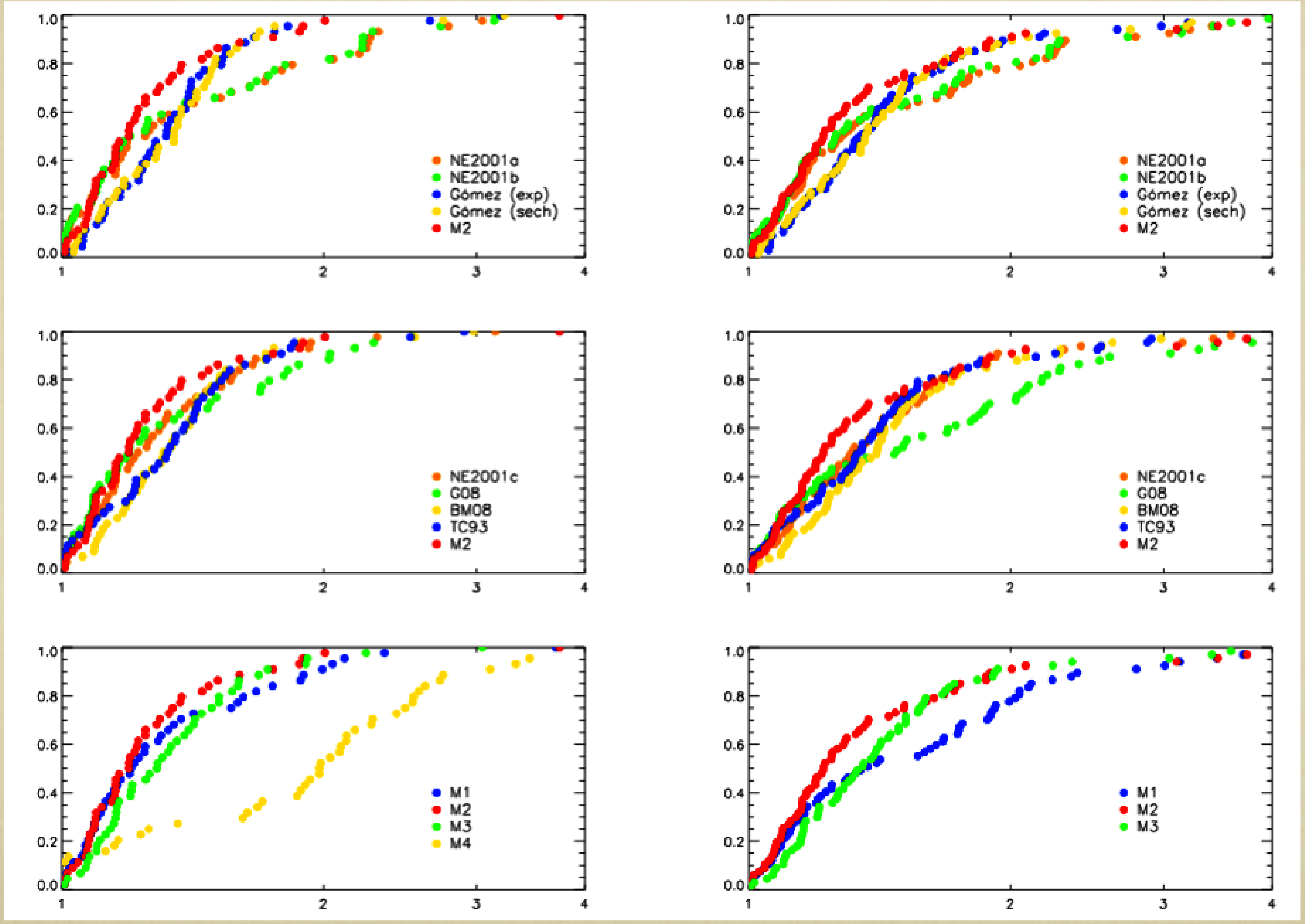
In this figure, the model that describes the data best has all *N* very close to 1, and rises quicker than (= lies above) the other models.

Model *name* predicts the DM of … % of sightlines within a factor of ...

→ At |*b*| > 5° our model M2 predicts DM more accurately than the other models for about 80% of the pulsars in our sample (*N* ≈ 1.4: DM_model lies within 40% of DM_observed)

How to test these 12 models?

45 selected lines of sight (*left*) vs. all 68 lines of sight (*right*)



Summary & Conclusions

- We developed a metric to test how well 8 n_e models from the literature + 4 new models predict the DM of pulsars at known distances.
- Most models predict DM to within 50-100% for 3 out of 4 pulsars. Our model M2 performs (slightly) better, also when all 68 pulsars are included
- NE2001 performs poorly; possibly because the many additional n_e components in this model are not sampled well by the Galactic distribution of our pulsar test sample.

For <~ 10% of sightlines all models perform poorly ($N > 2$).
We identified pulsars whose DM are predicted poorly by most models (= sign of additional DM components that are not included in the models)

Models++

Code: **MK06** A new map of ionized gas in the Milky Way

What does the Milky Way look like to an outside observer? We can easily determine the structure of nearby galaxies like the Andromeda nebula and the Magellanic clouds, but finding an answer to the above question is much more complicated since we live inside the Milky Way. An accurate map of how the ionized gas is distributed throughout the Milky Way is key for our understanding of the 3-dimensional distribution of pulsars, and for deriving the structure of the magnetic field of the Milky Way from polarization observations of pulsars and extragalactic sources.

IMPRS Ph.D. project (3 yrs) to develop a better n_e model
Supervisors: DS, Michael Kramer, Aristeidis Noutsos, Joris Verbiest

For more information:
http://www3.mpifr-bonn.mpg.de/old_mpifr/imprs/projects/#MK

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M2: radial extent of the thick disk