Reconstructing the Galactic free electron density

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with
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Outline:

1. **The Physics**
   pulsar dispersion and free electron density

2. **The Reconstruction Algorithm**
   dealing with uncertain distances

3. **The Reconstruction**
   comparison with the NE2001 model

4. **Summary**

The Physics

The Physics

The Interstellar Medium

Extremely dilute matter between stars

- Average density $10^{-20} \times$ density of air

ISM – 99% gas

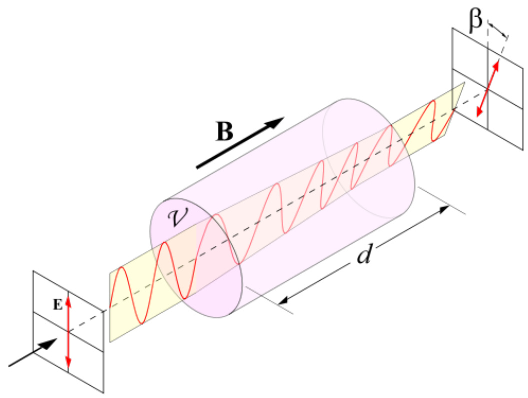
- Cold regions with molecular gas
- Cold & warm regions with atomic gas
- Warm regions with ionized gas
  $\longrightarrow$characterized by **free electron density**

The Physics

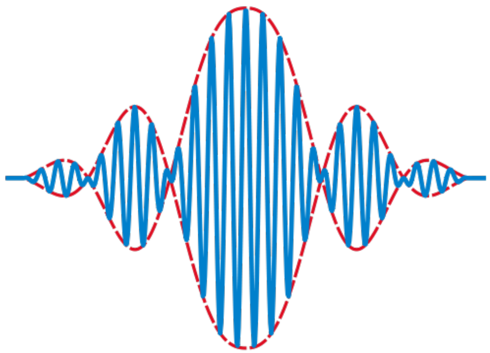
The Free Electron Density n_e

Influence of electromagnetic radiation

Faraday rotation

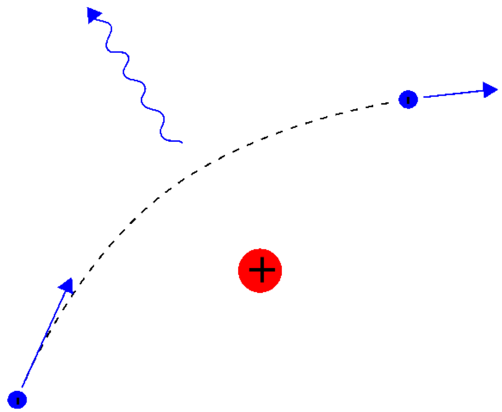


dispersion

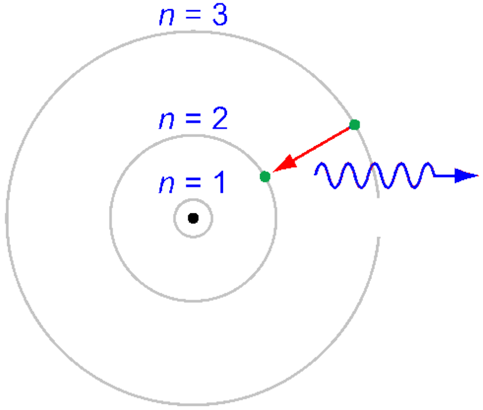


Emission of electromagnetic radiation

free free emission



H-alpha emission

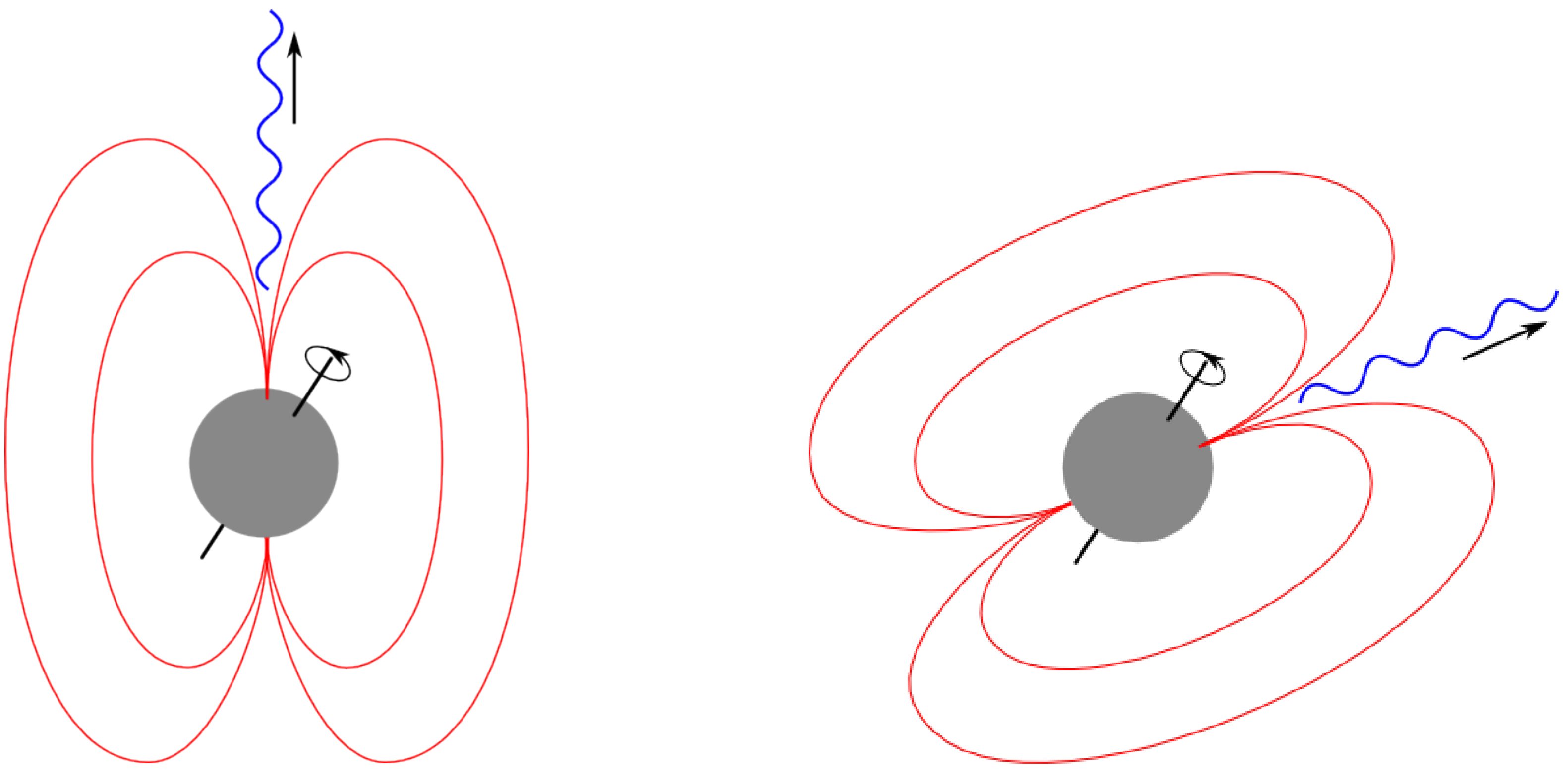


The Physics

Pulsars

Rapidly rotating neutron stars

- Magnetic moment not aligned with rotational axis
  → induces radiation



The Physics

Pulsars

Rapidly rotating neutron stars

- Magnetic moment not aligned with rotational axis
  $\longrightarrow$ induces radiation

- Emitted radiation travels through ISM
  - Many frequencies emitted at the same time
  - Dispersion – ν-dependent velocity
  - Different arrival time

  $\rightarrow$ **dispersion measure** DM

The Physics

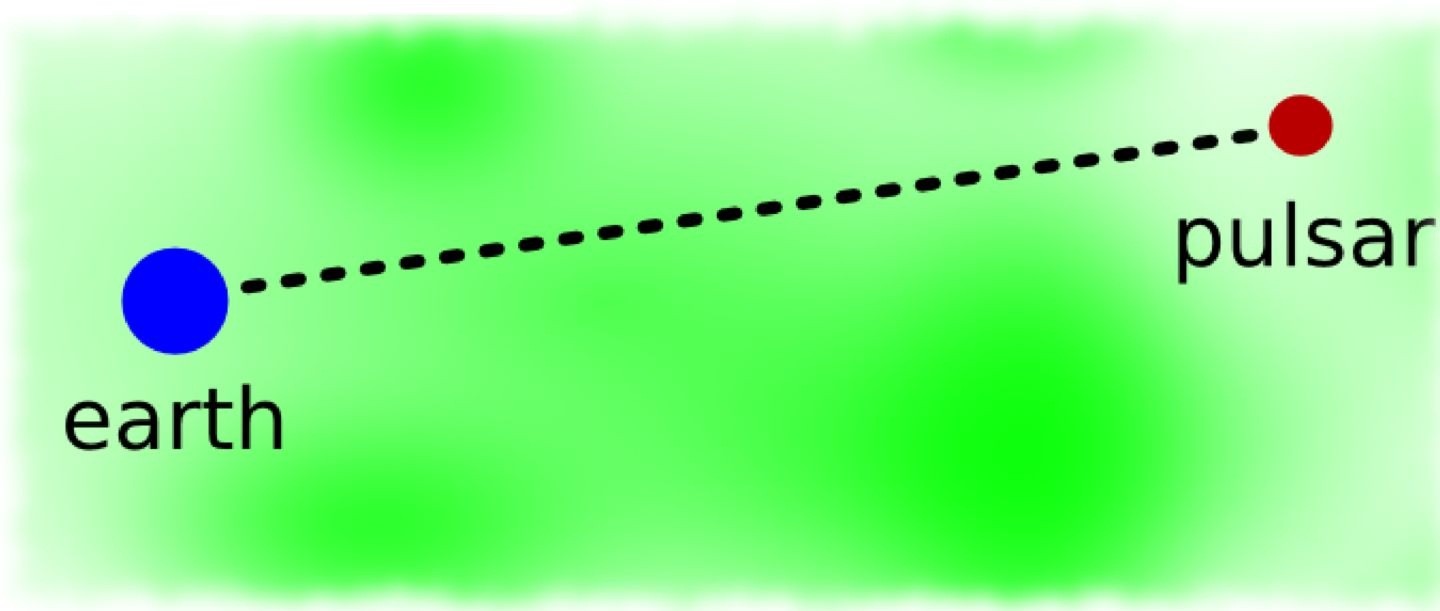
Dispersion Measure

The radiation dispersion time

$$t = k_{\mathrm{DM}} \times \frac{\mathrm{DM}}{\nu^2}$$

is proportional to the line integral over the free electron density

$$\mathrm{DM} = \int_0^d n_e \, \mathrm{d}r$$



The Reconstruction Algorithm

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Prior Information

1. Densities are positive definite.
   The free electron density can vary over several orders of magnitude and correlations are important.

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The Reconstruction Algorithm

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The Reconstruction Algorithm

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2. We have (a priori) no distinguished position or direction.

$$S(\vec{x}, \vec{y}) = S(|\vec{x} - \vec{y}|)$$ statistical homogeneity & isotropy

$\Longrightarrow$ S fully described by power spectrum $p(k)$,

but $p(k)$ unknown.

The Reconstruction Algorithm

Uncertain Pulsar Distances

Upper limit of the response integral unknown

$$d = Rn_e + \eta \qquad\qquad (Rn_e)_i = \int_{\text{earth}}^{\text{pulsar } i} n_e \, \mathrm{d}r$$

Likelihood in the form of

$$\mathcal{P}(d \mid s \quad) = \mathcal{G}(d - Rn_e, N)$$

only valid for known distances.

The Reconstruction Algorithm

Uncertain Pulsar Distances

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Likelihood in the form of

$$\mathcal{P}(d \mid s, a) = \mathcal{G}(d - Rn_e, N)$$

only valid for known distances (a_i being the distance of pulsar i).

Actual likelihood is the distance marginalized likelihood

$$\mathcal{P}(d \mid s) = \int \mathcal{D}a \, \mathcal{P}(d \mid s, a) \, \mathcal{P}(a)$$

. . . cannot be solved analytically & computationally too expensive.

The Reconstruction Algorithm

Uncertain Pulsar Distances

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$$d = Rn_e + \eta \qquad\qquad (Rn_e)_i = \int_{\text{earth}}^{\text{pulsar } i} n_e \, \mathrm{d}r$$

Solution:

Find effective response $\tilde{R}$ and effective noise covariance $\tilde{N}$ to approximate

$$\mathcal{P}(d \mid s) \approx \mathcal{G}(d - \tilde{R}n_e, \tilde{N})$$

The Reconstruction Algorithm

Uncertain Pulsar Distances

Pulsar distances a_i uncertain

$$(Rn_e)_i = \int_0^\infty \mathrm{d}r \; n_e \; \theta(a_i - r)$$

Effective response

$$(\tilde{R}n_e)_i = \int_0^\infty \mathrm{d}r \; n_e \; P(r < a_i)$$

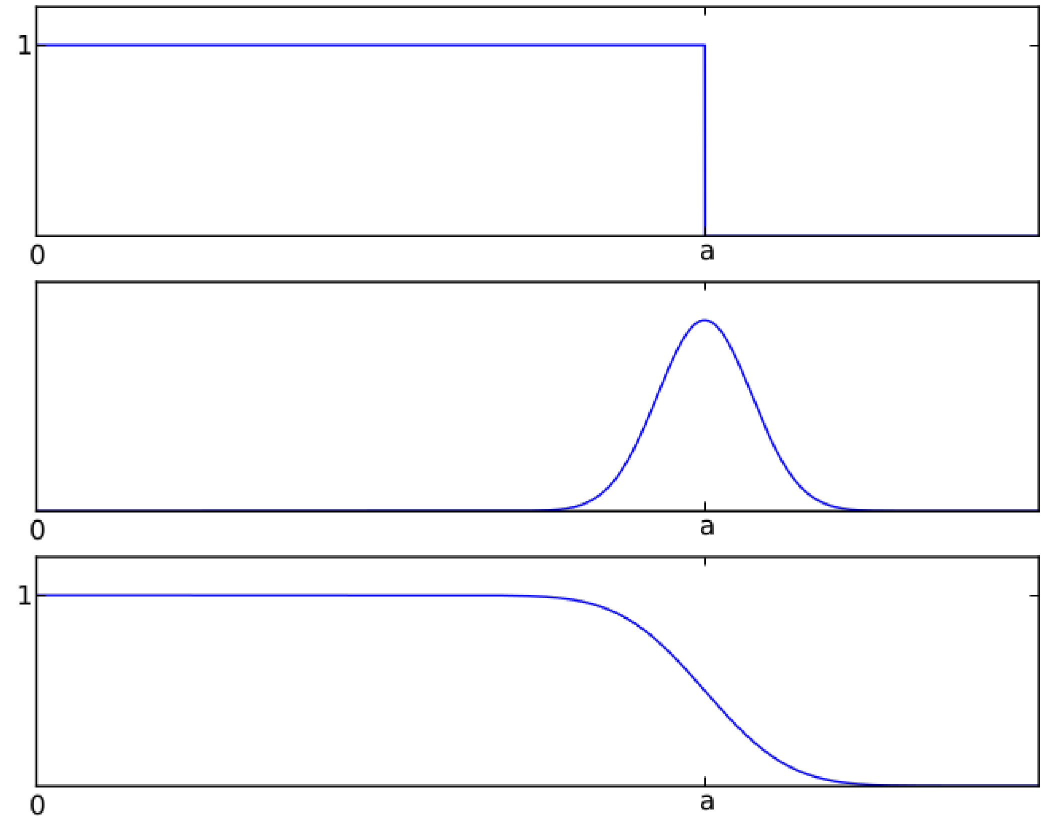
The Reconstruction Algorithm

Uncertain Pulsar Distances

response for known distance

distance PDF

effective response

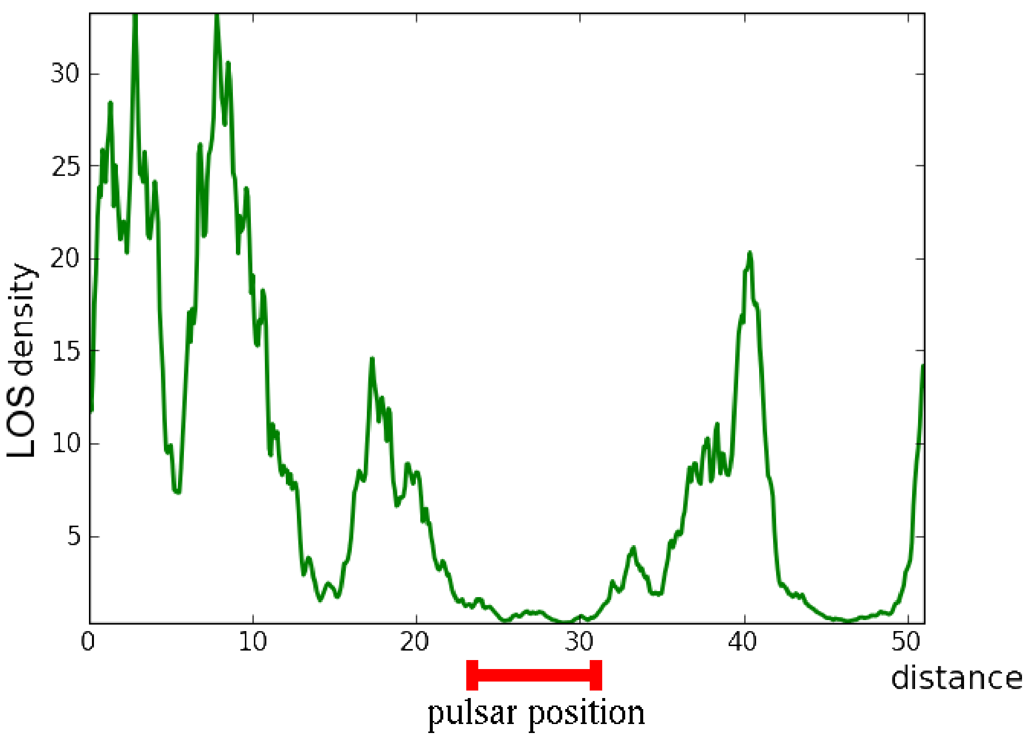


The Reconstruction Algorithm

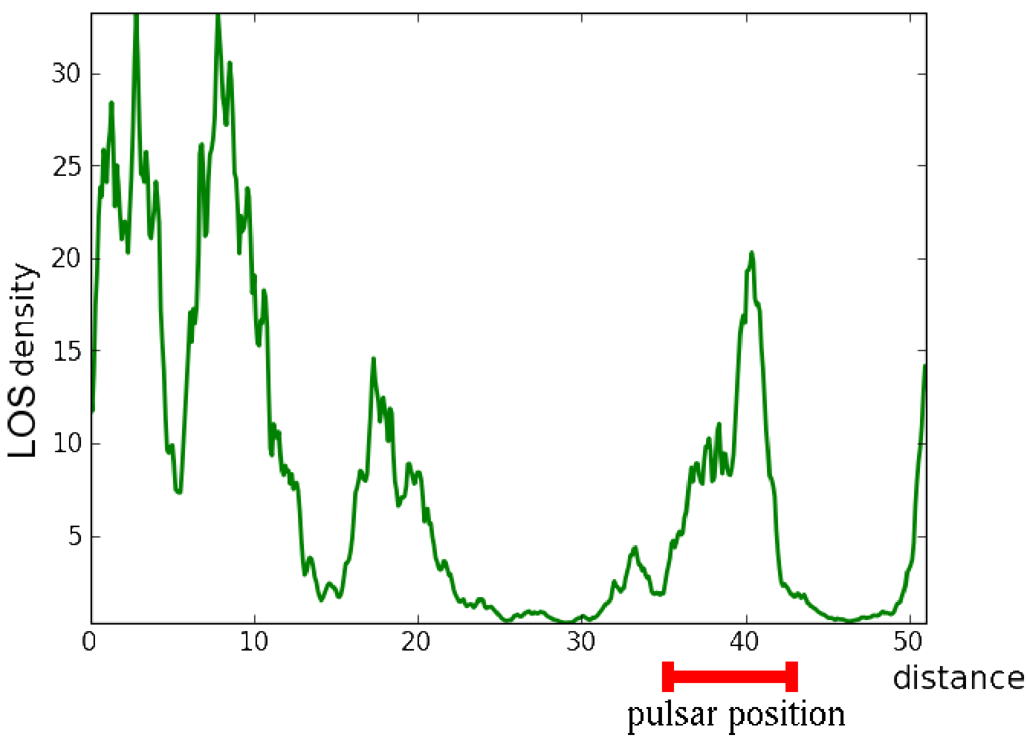
Uncertain Pulsar Distances

Effective noise covariance $\tilde{N}$ depends on the local density around the pulsar.

fairly low effective error



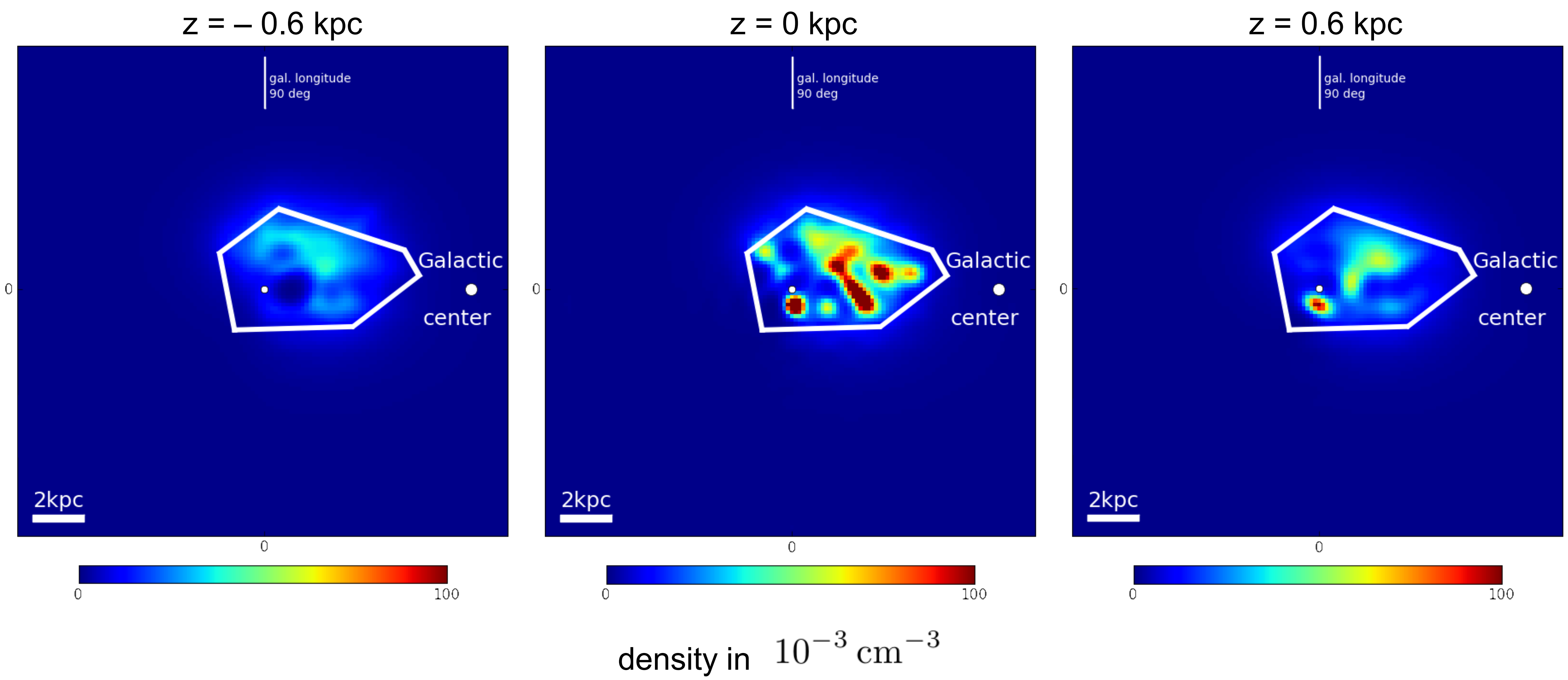
high effective error



The Reconstruction

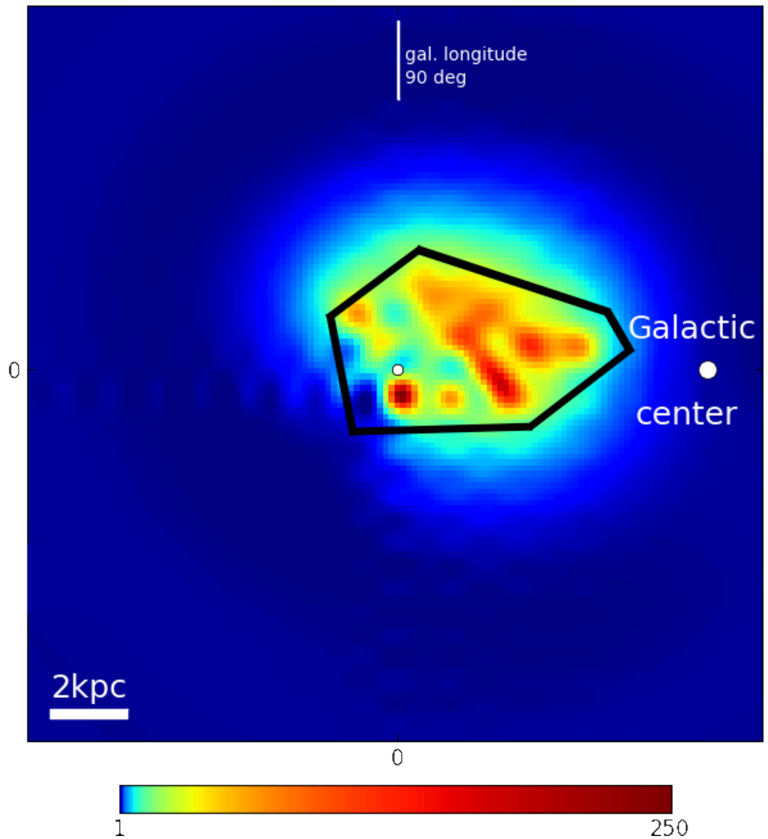
The Reconstruction

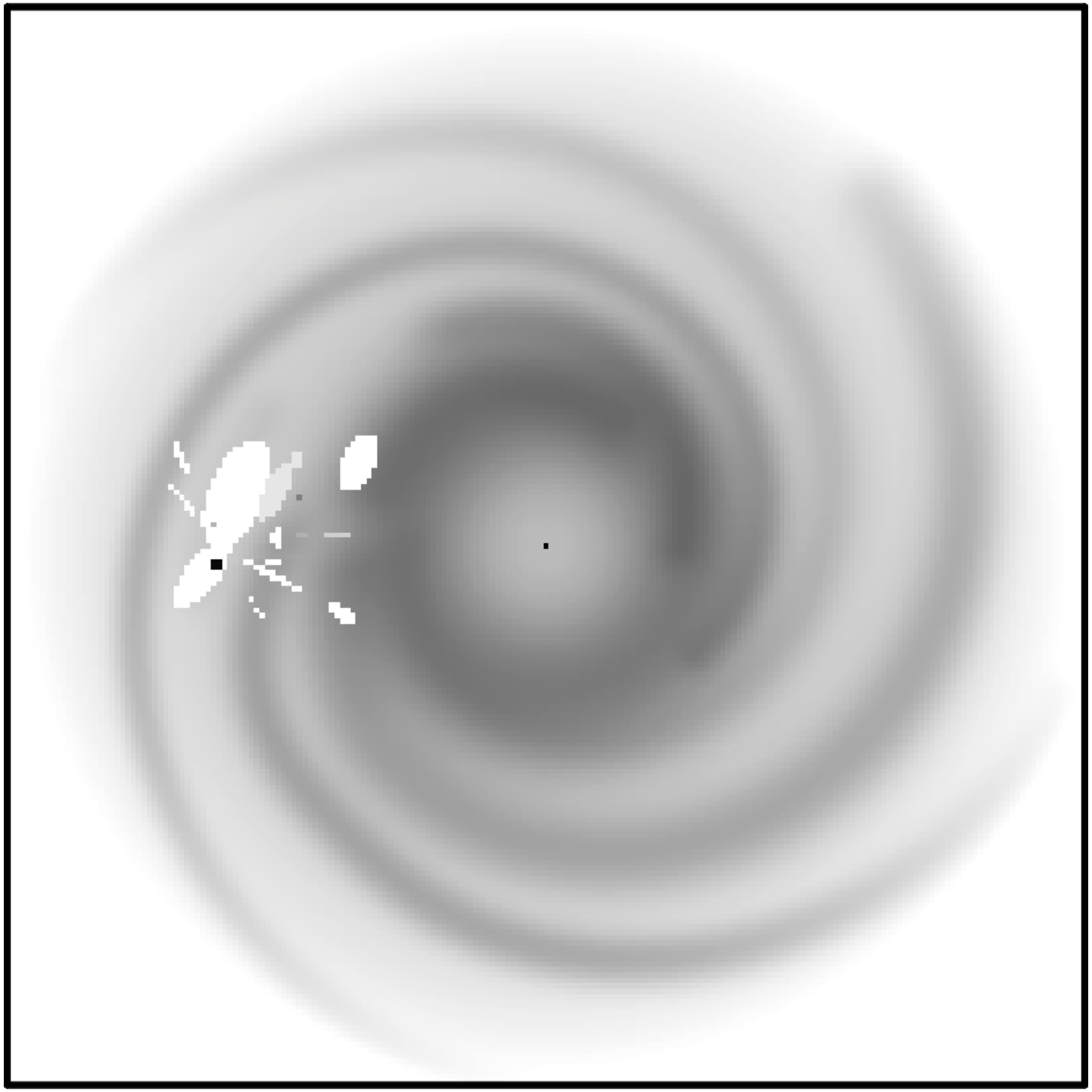
Reconstruction Close to the Galactic Plane



The Reconstruction

Comparison with NE2001

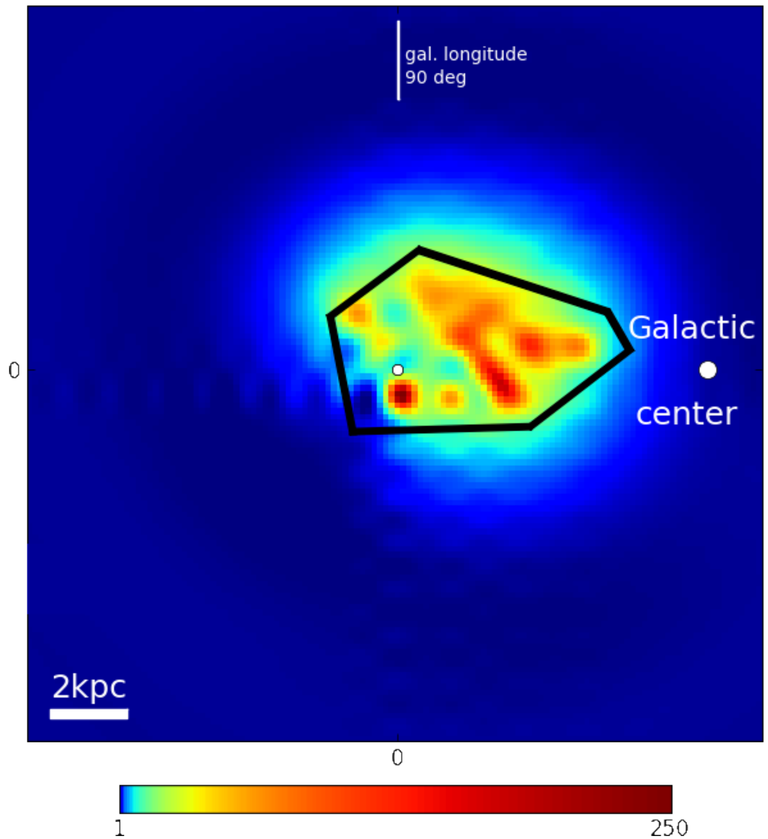




Logarithmic plot of the free electron density in the Galactic plane

The Reconstruction

Comparison with NE2001



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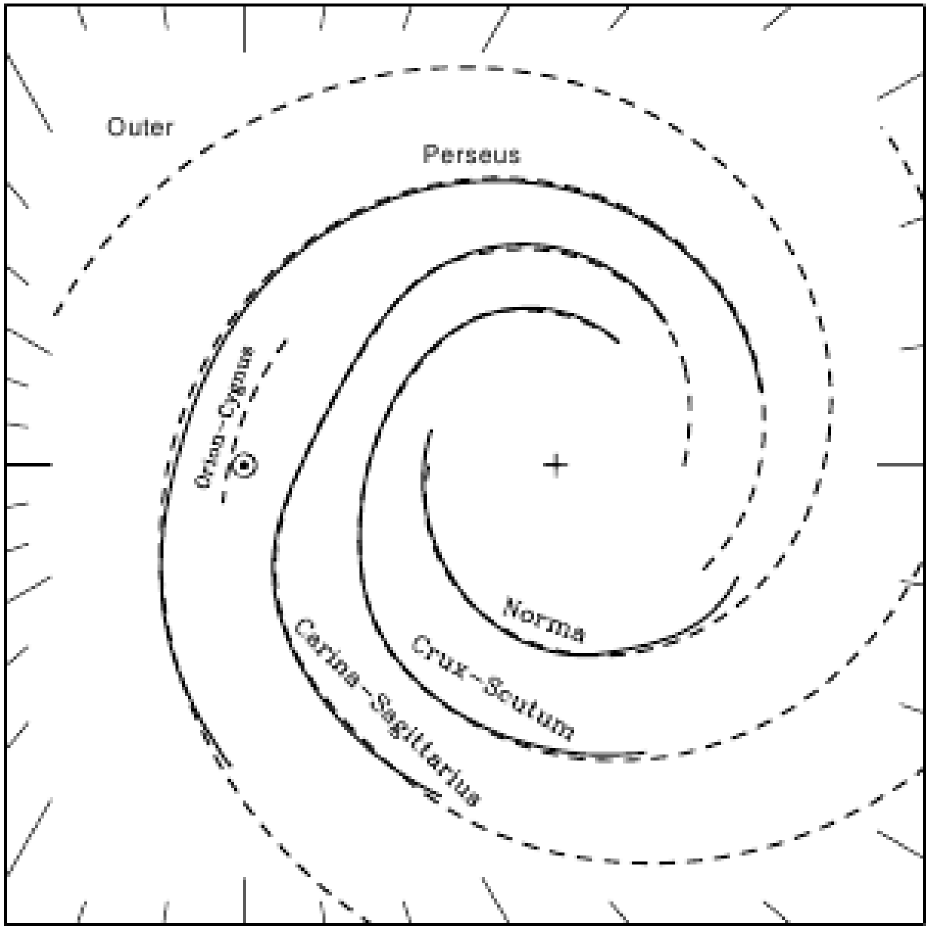


spiral arms according to NE2001

The Reconstruction

Vertical Drop-off

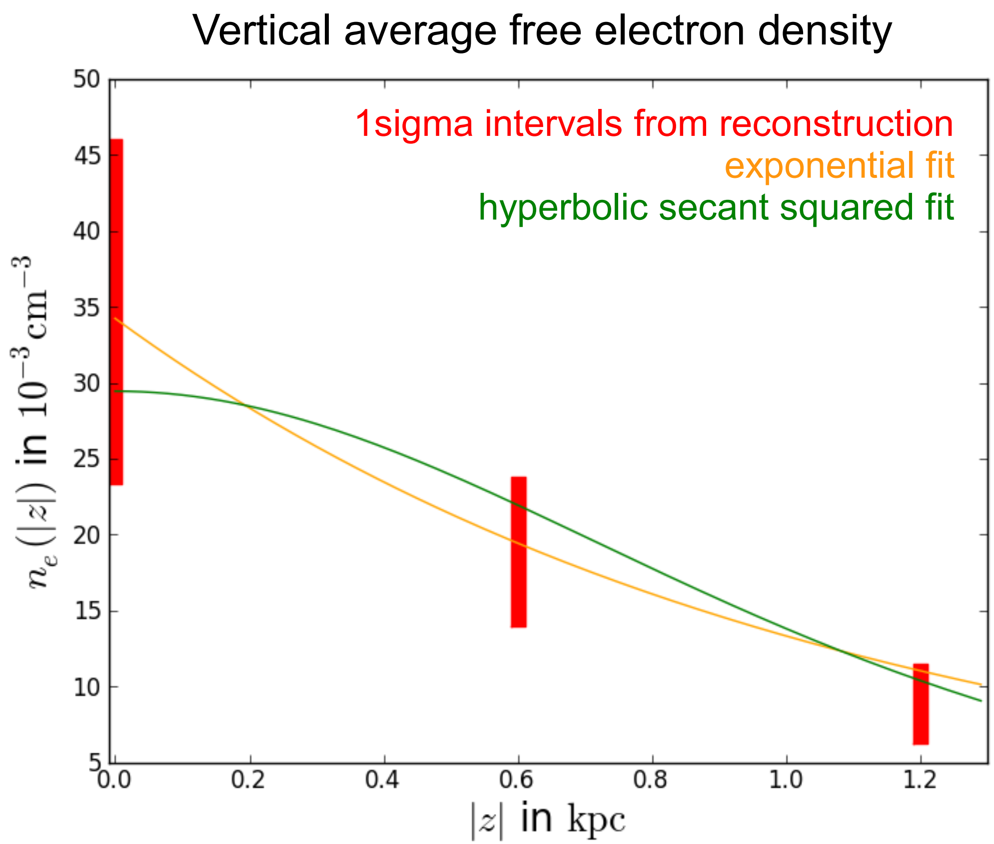
Vertical drop-off of average density

fitted to $n_e \propto \exp\left(-\frac{|z|}{H}\right)$

yields $H \approx (1.06 \pm 0.53)\ \mathrm{kpc}$

fitted to $n_e \propto \mathrm{sech}^2\left(\frac{|z|}{H}\right)$

yields $H \approx (1.08 \pm 0.44)\ \mathrm{kpc}$



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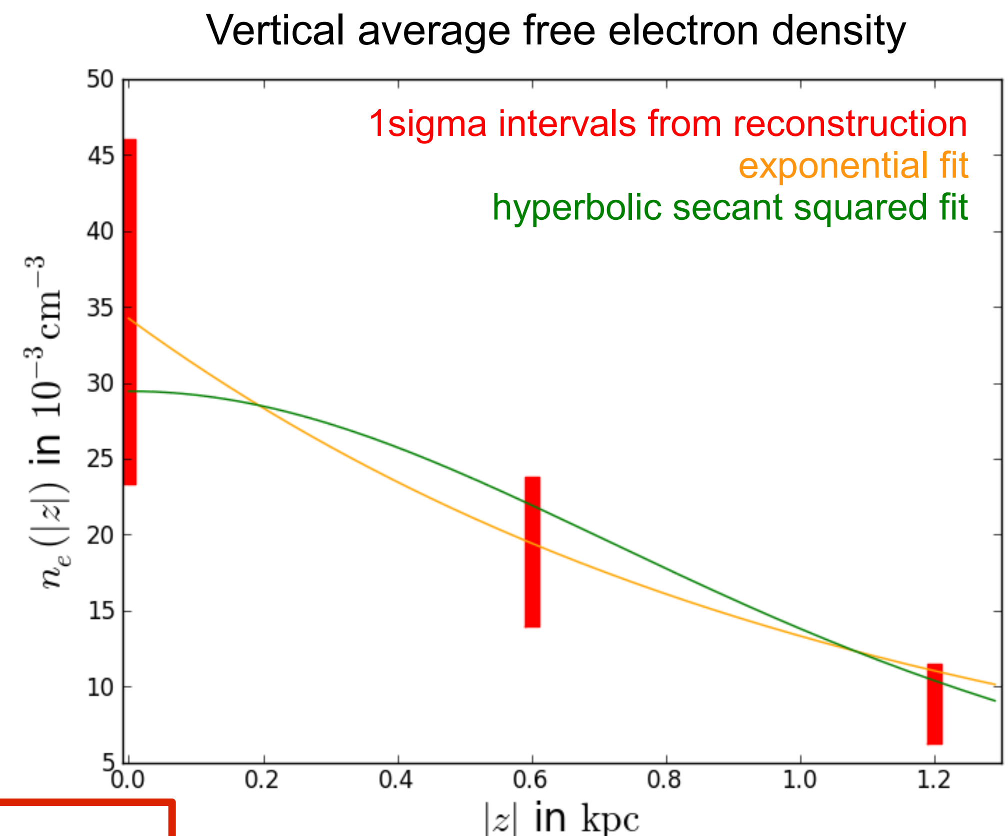

From literature:

$H \approx 0.95\,\mathrm{kpc}$	Cordes & Lazio (2002)
$H \approx 1.83^{+0.12}_{-0.25}\,\mathrm{kpc}$	Gaensler et al. (2008)
$H \approx (1.6 \pm 0.3)\,\mathrm{kpc}$	Schnitzeler (2012)

Summary

Reconstruction of the Galactic free electron density possible.

Pulsar dispersion measures are an excellent probe if complemented by an independent distance estimate.

Uncertainty of distance estimates can be dealt with.

A reconstruction from 68 pulsars already shows significant structure.

Vertical drop-off of the free electron density is in agreement with literature.

References

Cordes & Lazio (2002)

Gaensler et al. (2008)

Schnitzeler (2012)

Selig et al. (2013)

Information field theory
http://www.mpa-garching.mpg.de/ift/

Numerical calculations done with NIFTY
http://www.mpa-garching.mpg.de/ift/nifty/

The Reconstruction

Uncertainty of the Logarithmic Density