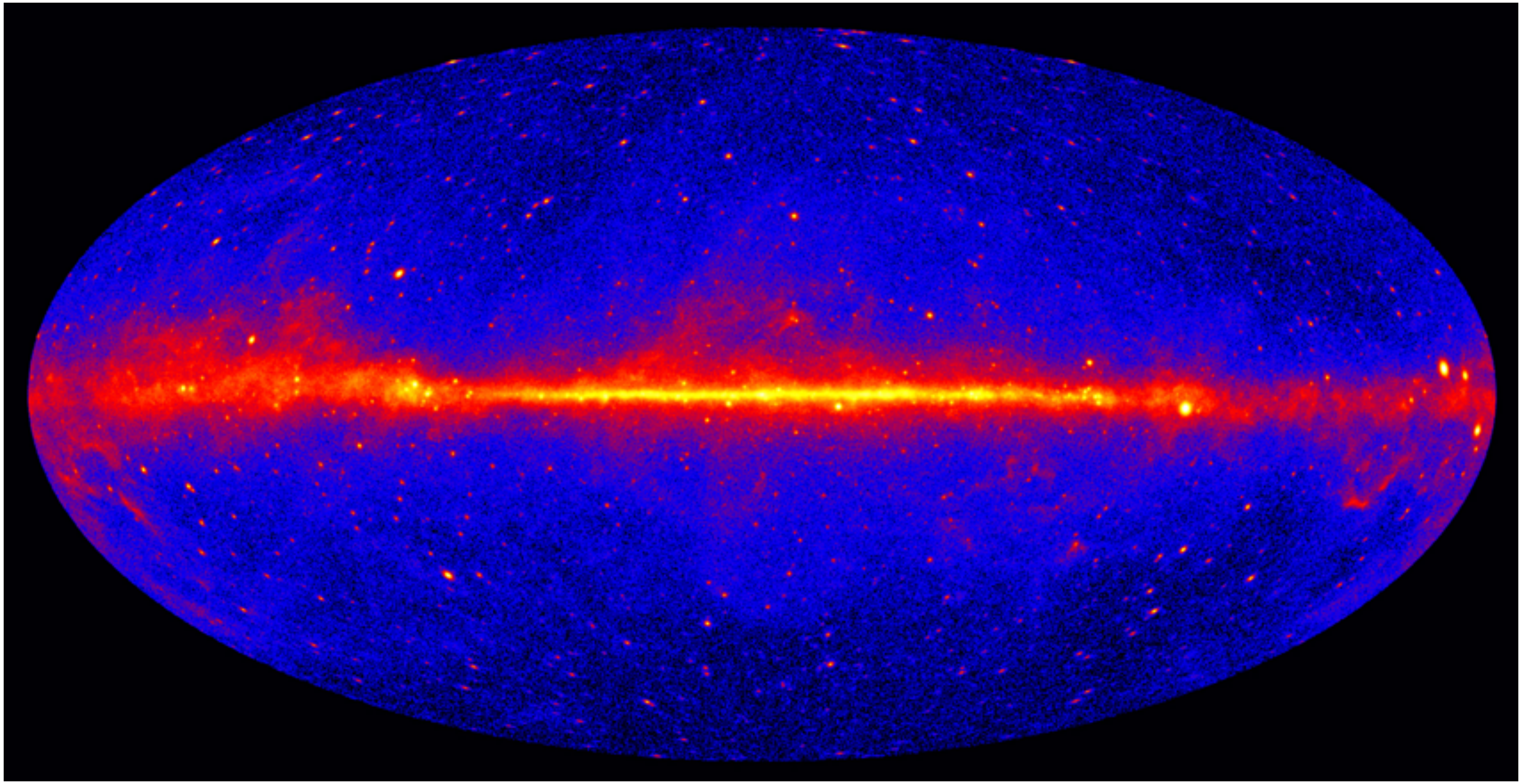
Population synthesis of Fermi LAT sources: A Bayesian analysis using posterior predictive distributions

T. D. P. Edwards, F. Calore, and C. Weniger



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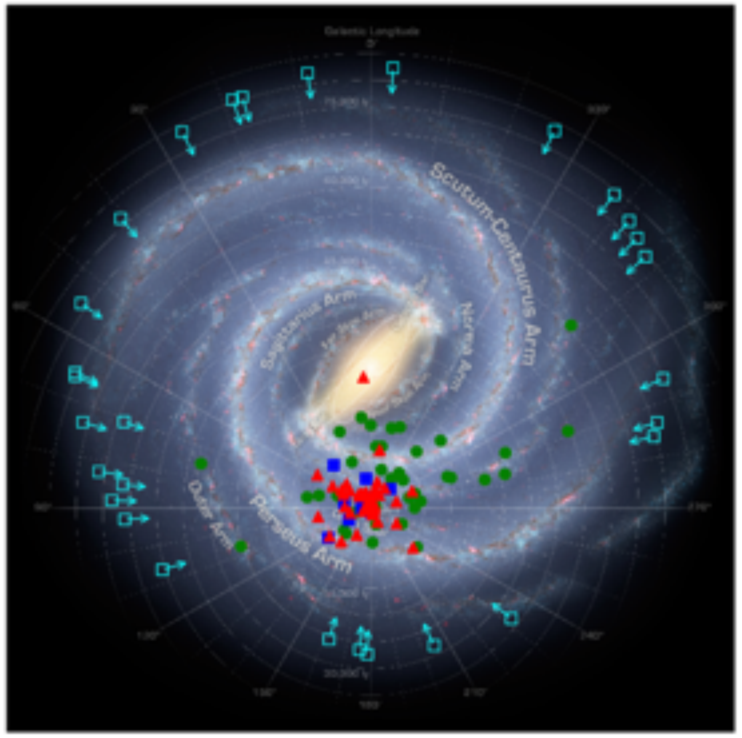
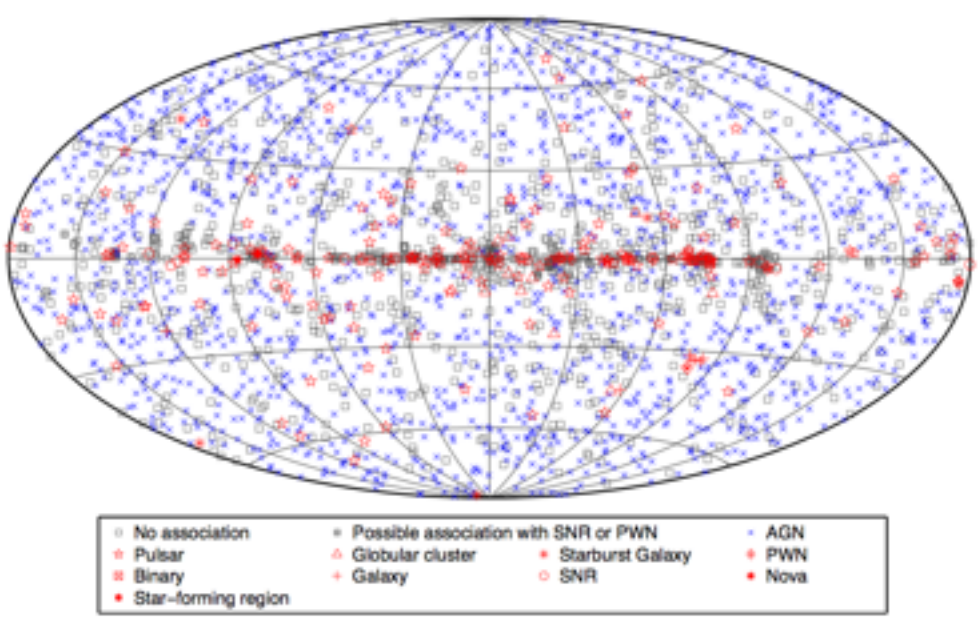
Talk overview



Fermi-LAT collaboration 2013



Fermi-LAT collaboration 2015

- Luminosity function of millisecond pulsars
- Distance uncertainties

- Unassociated objects - how we deal with these
- 3FGL demographics
- Future work

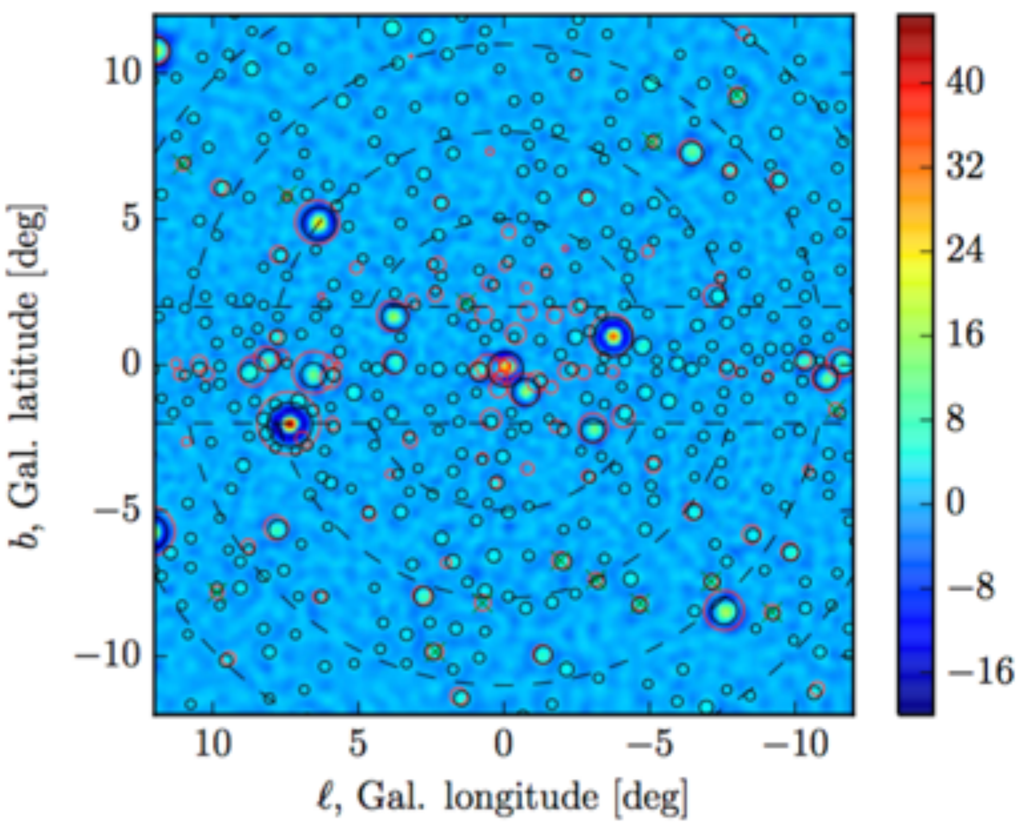
Goals

- To provide realistic error bars on the gamma ray luminosity function of MSPs
- To simultaneously find constraints on a variety of models and provide probabilistic statements about the likelihood of a source existing in a given class

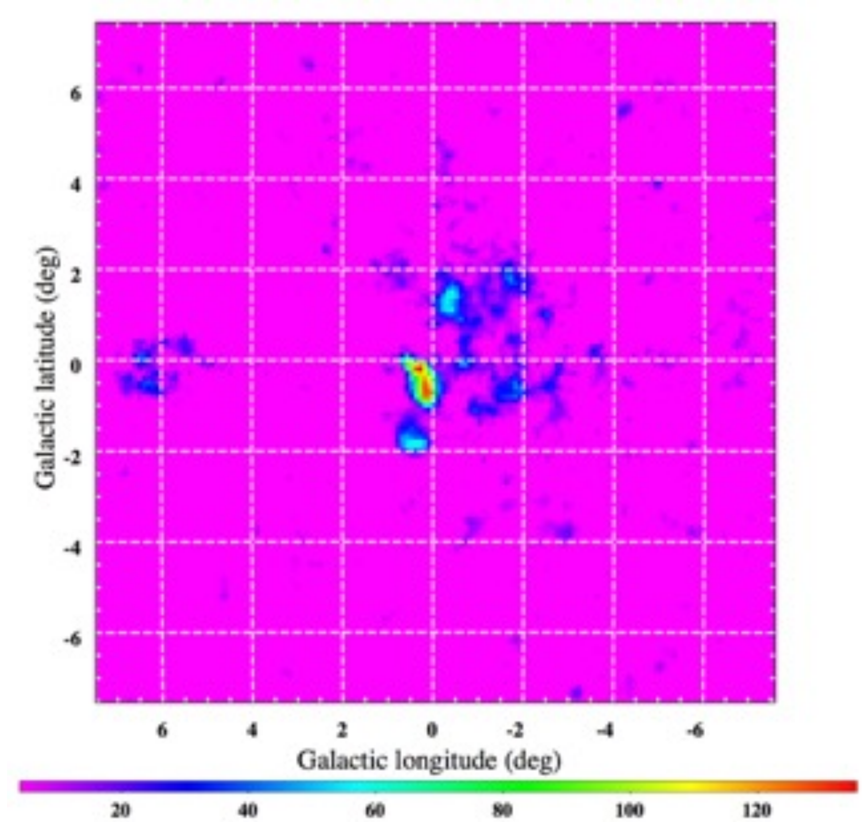
Previous Work

- Many previous attempts to constrain the MSP luminosity function - we will attempt to contain all of these studies within our analysis
- Machine learning classifiers have been used to analyse the 3FGL data and provide possible source class associations - our work should be complementary and additive to these methods

Introduction - why is this interesting…



Bartels et al. 2015

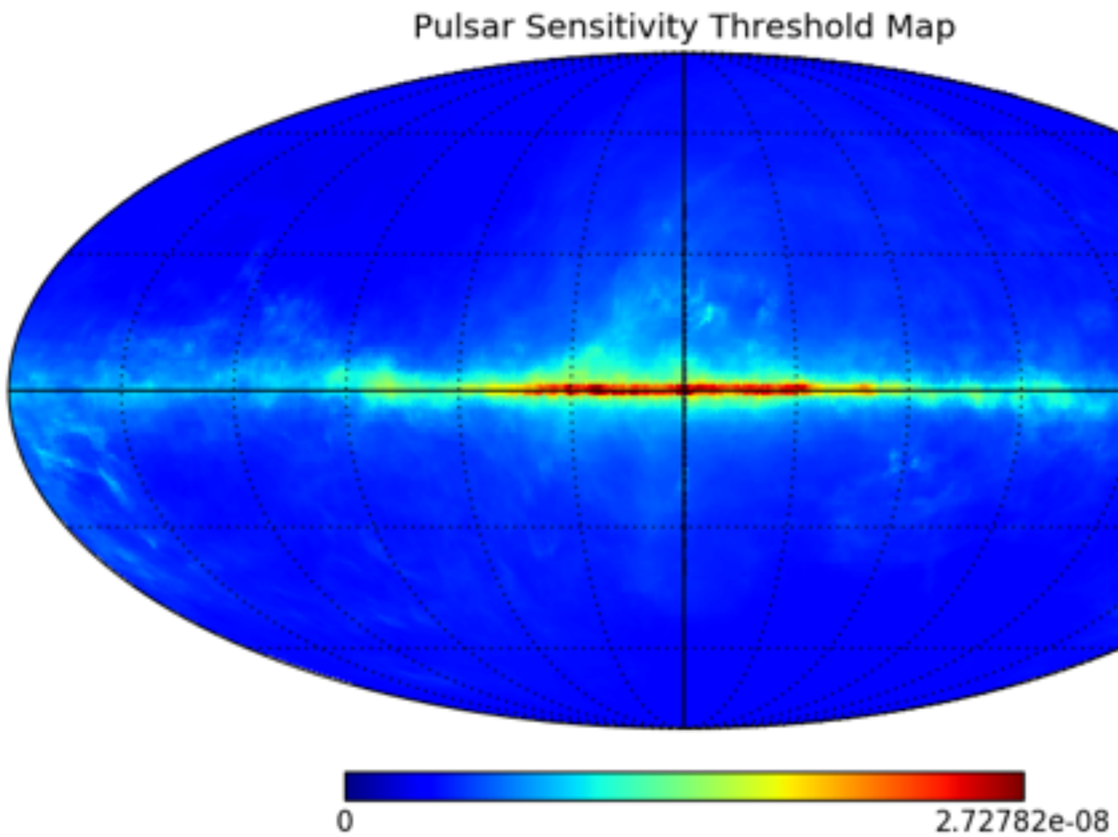


Fermi-LAT collaboration 2015

The Fermi-LAT galactic centre excess (GCE)

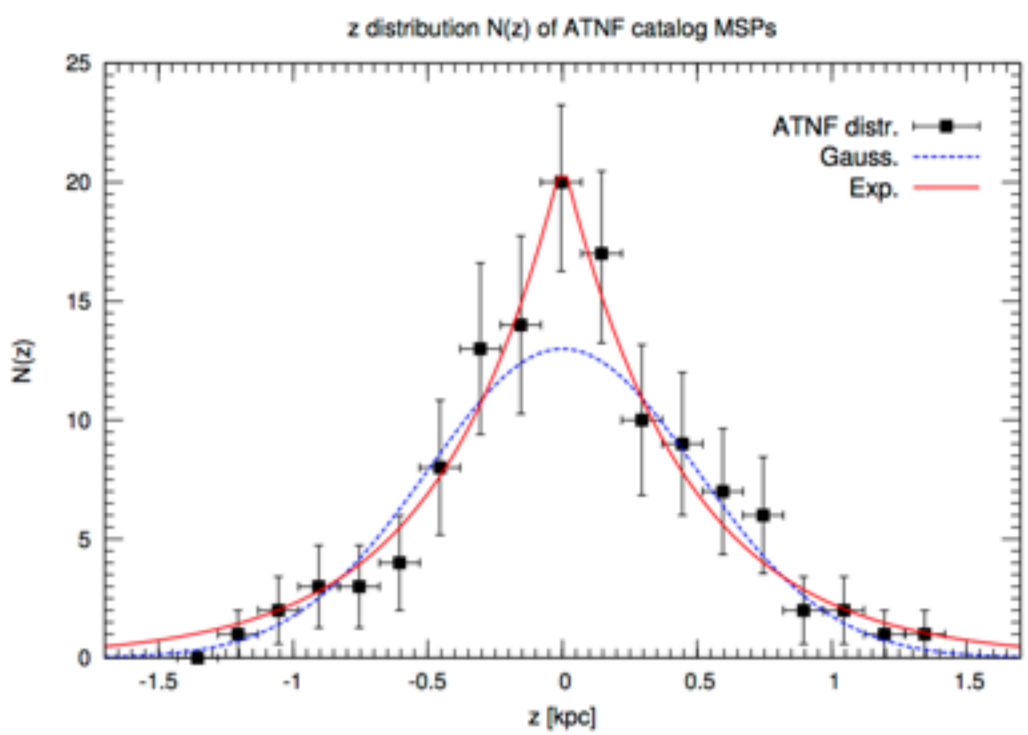
Potential population of below threshold point sources in the bulge

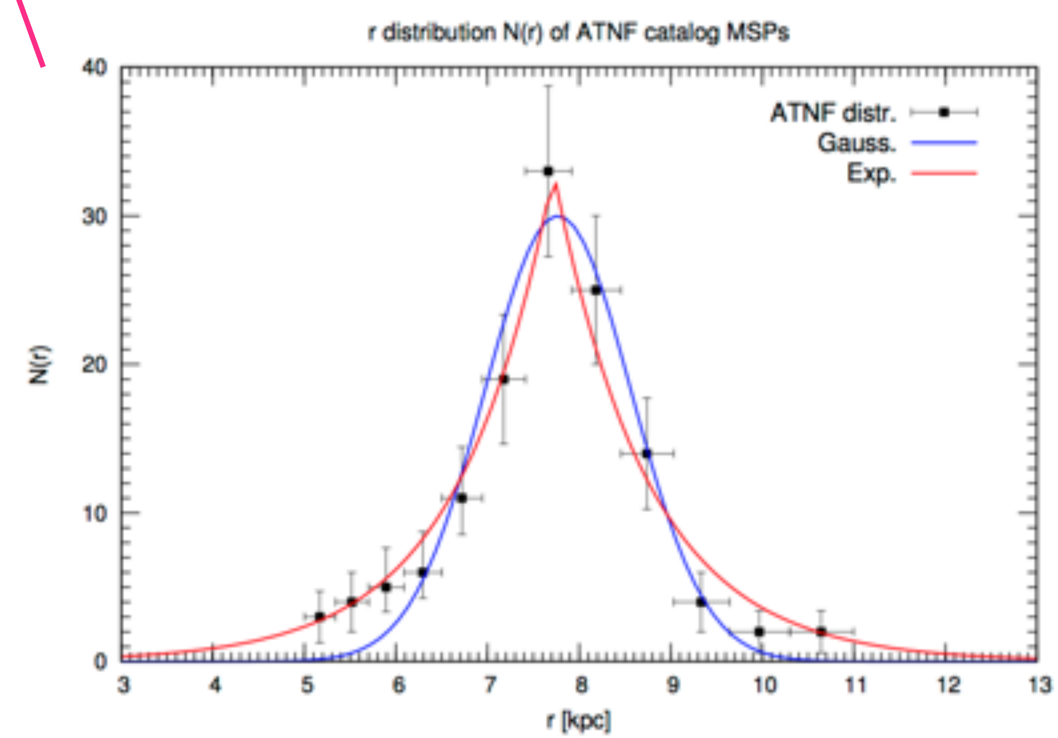
MSP luminosity function



$$\frac{dN}{dL} \propto L^{-\alpha}$$

$$\mathcal{L} = e^{-\mu}(C)^n \prod_{i=1}^{n} 4\pi D_i^4 \, L_i^{-\alpha} \, n\left(D_i, l_i, b_i\right) \, \Gamma\left(S_i, l_i, b_i\right)$$





Calore et al. 2014

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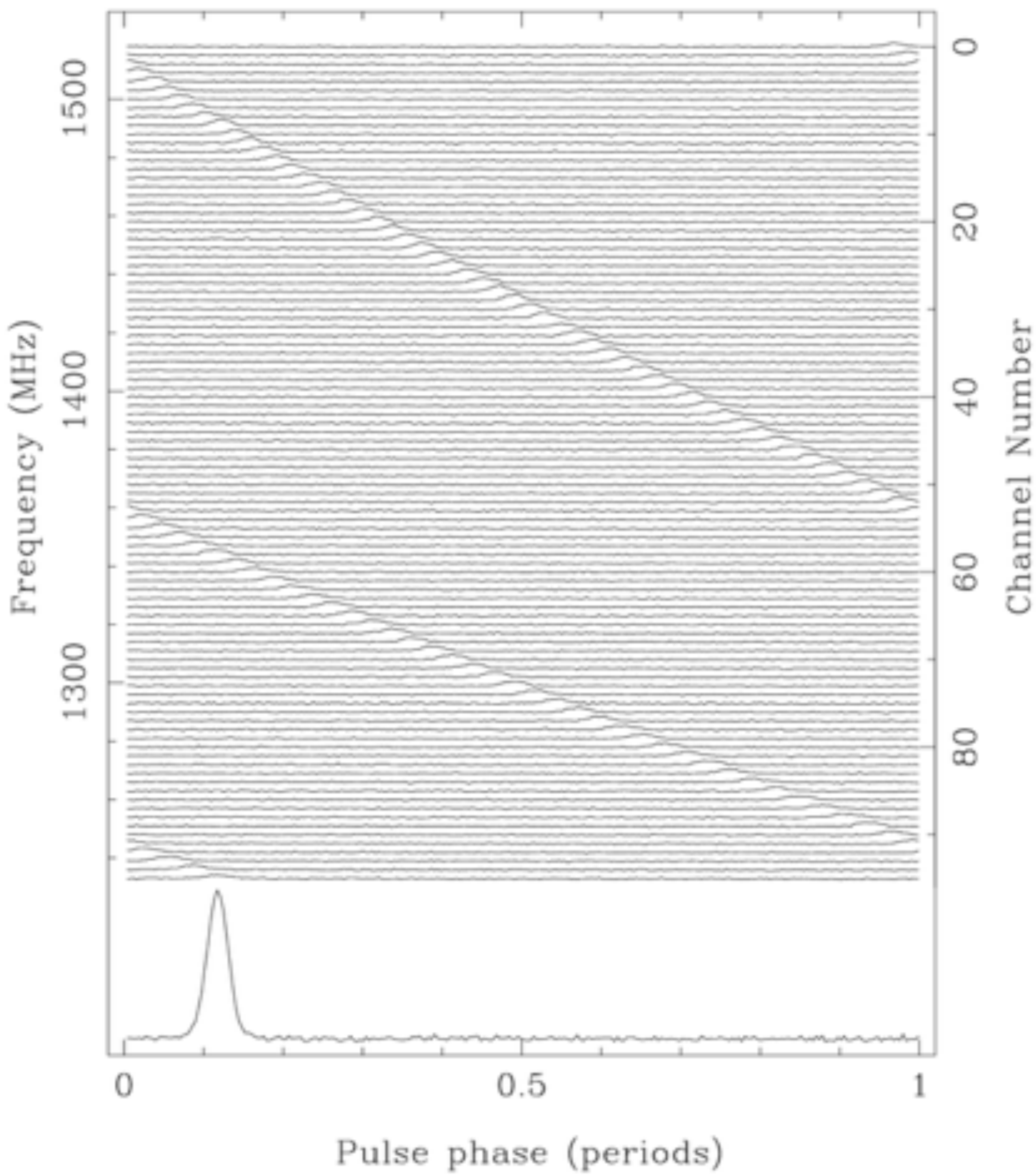
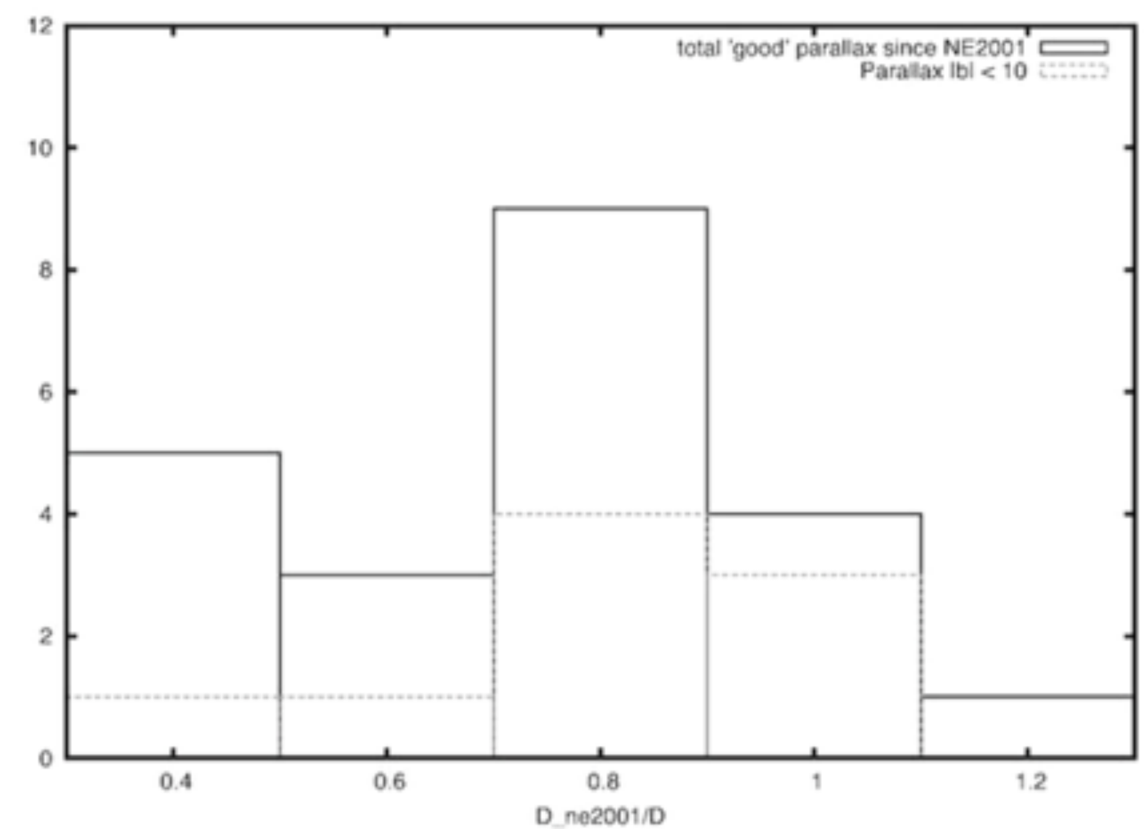
Distance Uncertainties



$$DM \equiv \int_0^D n_e dl$$

DM = Dispersion measure i.e. a frequency dependent delay of a broadband pulse due to the electron density along the line of sight

n_e = Number density of electrons - requires a model for distribution of electrons throughout the galaxy i.e. NE2001



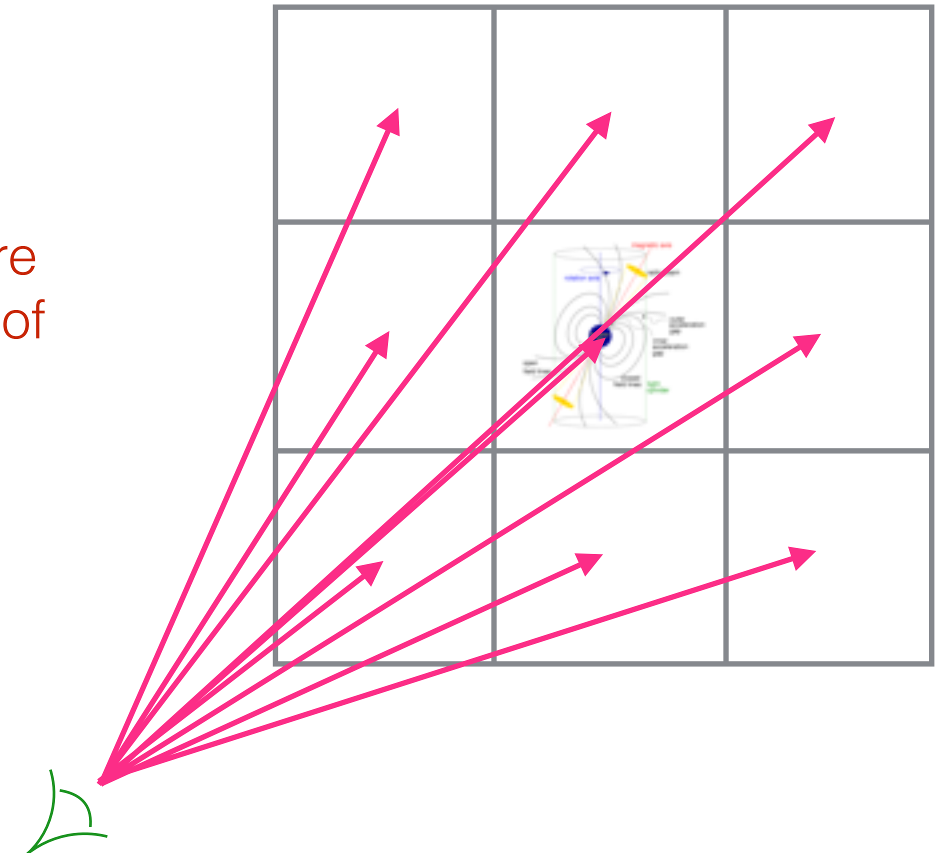
Mallory S.E. Roberts 2011

NE2001 model seems to systematically underestimate distances for |b| >10 deg leading to underestimates of luminosities

What can we do?

The dispersion measure is a very well measured quantity therefore errors come from the electron density model

Errors also come from positional uncertainty if there happens to be a clump of electrons along the line of sight



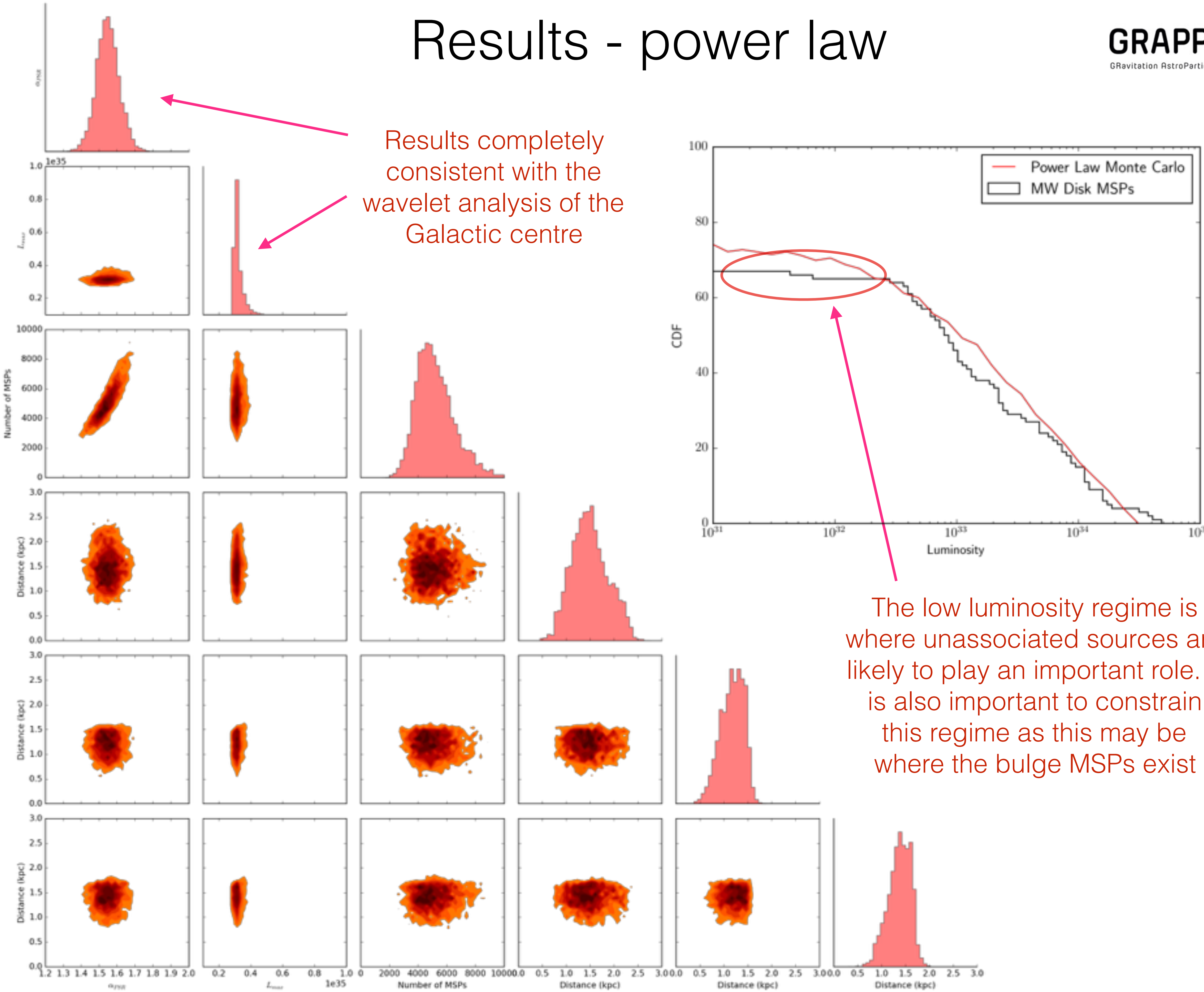
$$P(\theta|d) = \int dD P(\theta|D, d) P(D|d)$$

$$P(D|D_m, D_v) = \frac{1}{D_v\sqrt{2\pi}} \exp\left[-\frac{(\ln D - D_m)^2}{2D_v^2}\right]$$

Multiple line of sights in a grid around the object to estimate the variance of the distance calculation D_v

Allow free distances for the 3 brightest pulsars with lognormal prior distributions

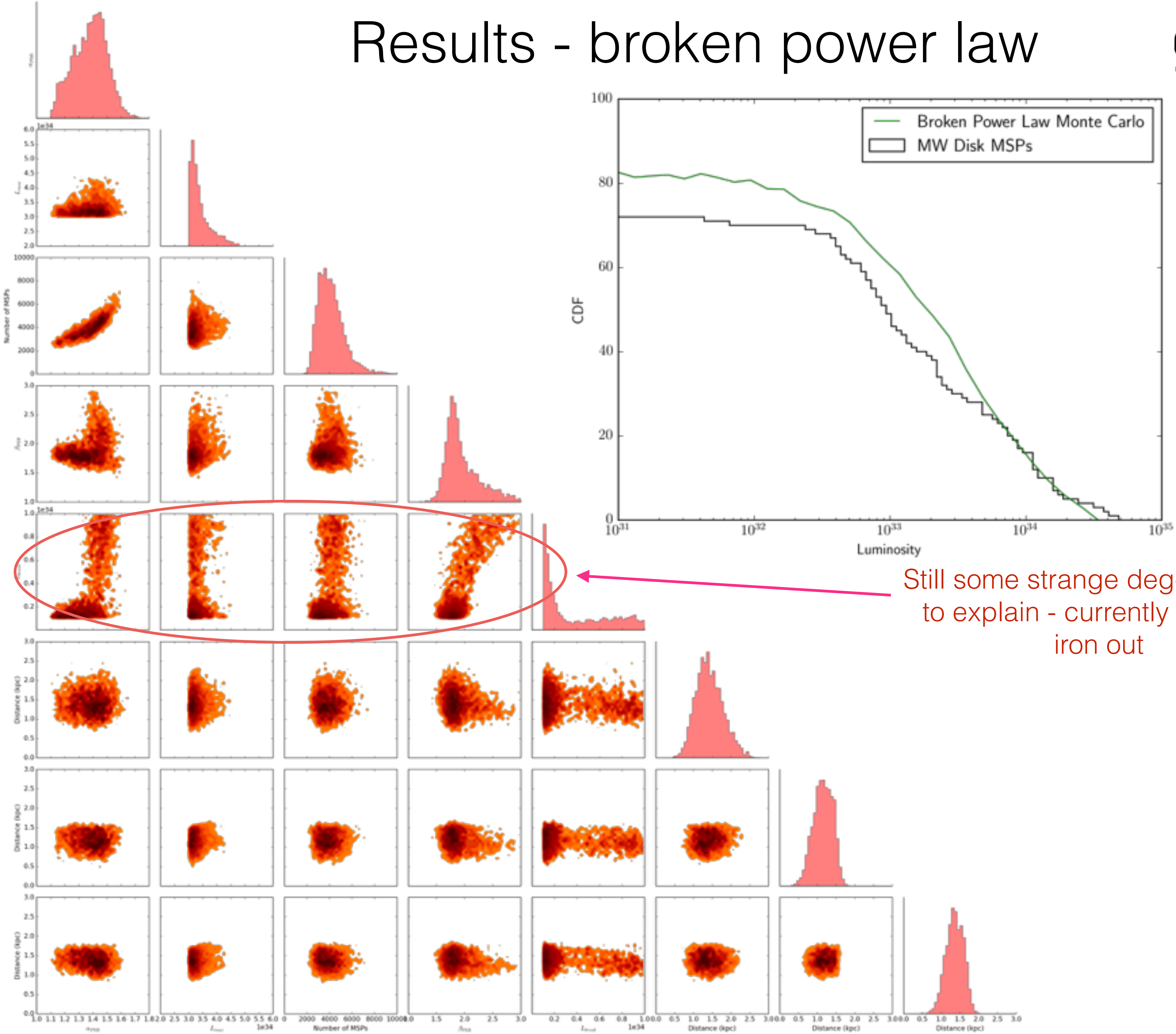
Results - power law



Results completely consistent with the wavelet analysis of the Galactic centre

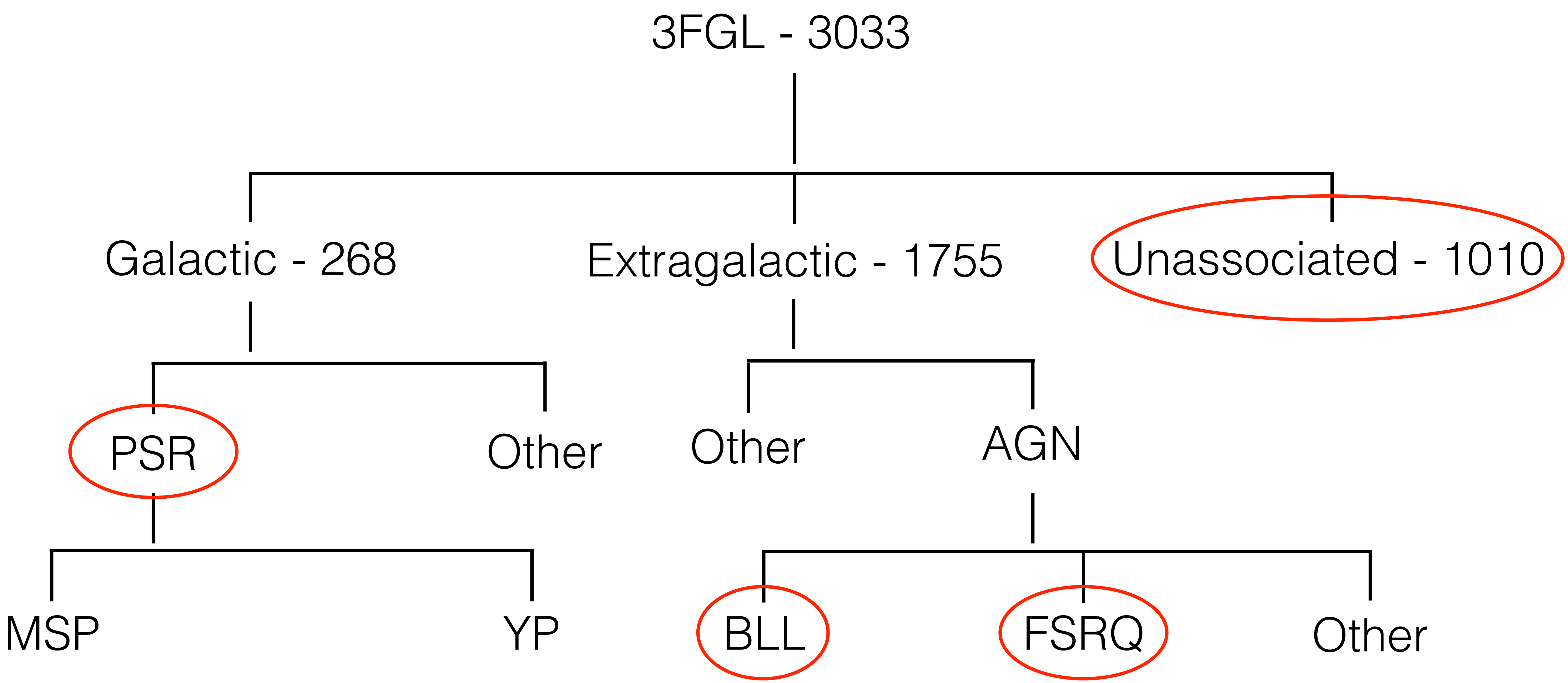
The low luminosity regime is where unassociated sources are likely to play an important role. It is also important to constrain this regime as this may be where the bulge MSPs exist

Results - broken power law



Still some strange degeneracies to explain - currently trying to iron out

3FGL populations



Theory: Inference

Model parameters

$$P(\theta, \vec{k}|D) = \frac{\prod_i \mathcal{L}(D|d,\theta)P(k)P(\theta)}{P(D)}$$

Source class vector

$$\vec{k} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \vdots & \vdots & \vdots \end{pmatrix}$$

$$\sum_{\vec{k}} P(\theta, \vec{k}|D) = P(\theta|D) = \frac{\sum_{\vec{k}} \prod_i \mathcal{L}(D|d,\theta)P(k)P(\theta)}{P(D)}$$

$$= \frac{\prod_i \sum_k \mathcal{L}(D|d,\theta)P(k)P(\theta)}{P(D)}$$

= Associated object

= Unassociated object

Theory: Association

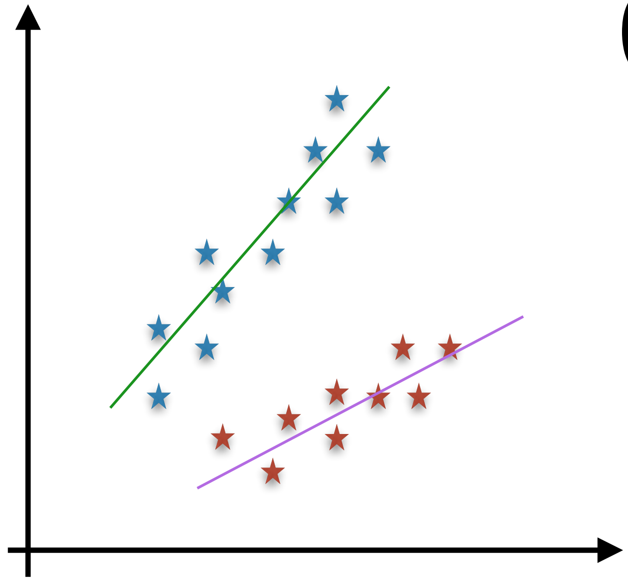
$$P(k_i|D) \propto \int d\theta \sum_{\substack{\vec{k} \\ k_i \text{ fixed}}} \prod_j \mathcal{L}_j(D_j|k_j,\theta)P_j(k_j)P(\theta)$$

$$P(k_i|D) \propto \int d\theta \mathcal{L}_i(D_i|k_i,\theta)P_i(k_i) \underbrace{\sum_{\substack{\vec{k} \\ k_i \text{ fixed}}} \prod_{j\neq i} \mathcal{L}_j(D_j|k_j,\theta)P_j(k_j)P(\theta)}_{\approx \sum_{\vec{k}} \prod_j \mathcal{L}_j(D_j|k_j,\theta)P_j(k_j)P(\theta)}$$

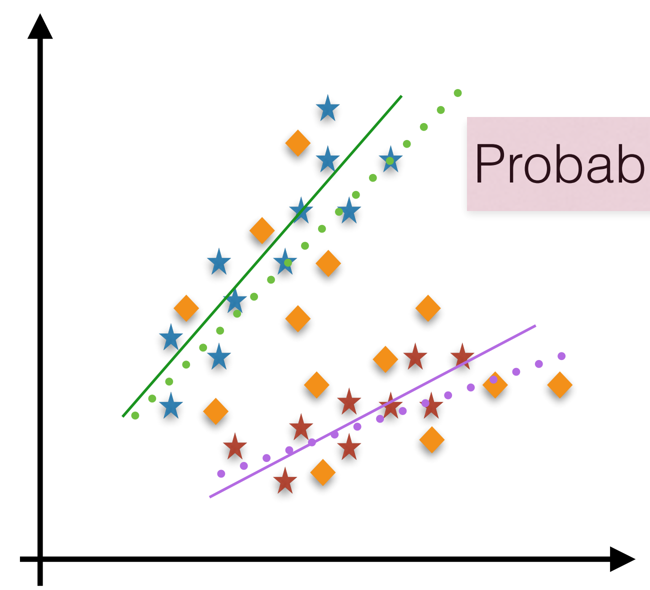
Approximation: Fit with individual source missing is well approximated by a fit to the entire data set

Posterior for the entire data set

Cartoon Example

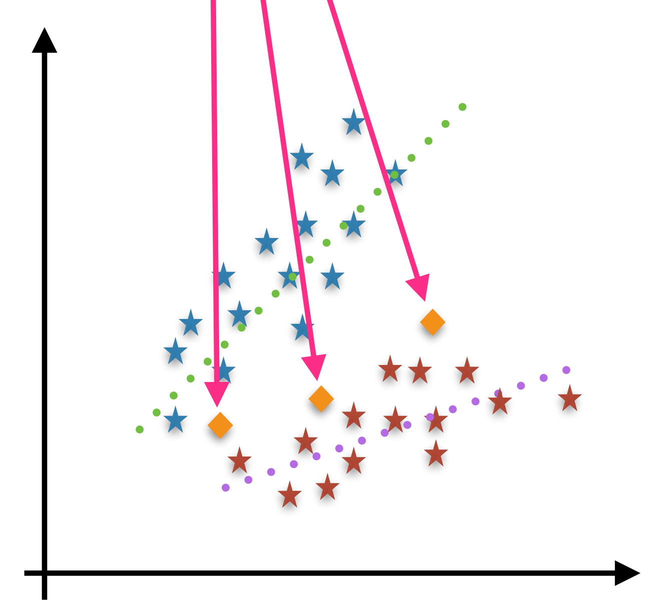


Now we can add unassociated sources



Probabilistic statements about the remaining

Perform Association procedure



Likelihood Function

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$$\mathcal{L} = \frac{dN}{dS}\frac{dN}{dE}\Gamma(S|l,b) V C_s S(l,b)$$

Instead of latitude cuts we use full galactic spatial distributions to build pdf's galactic coordinates l and b on the sky

Additionally we compare the integrated flux in different energy bins provided by the 3FGL meaning that the spectra normalisations are not free parameters but derived by the energy flux S we get for each sources

Broken power laws for the AGN source count distributions. For pulsars we marginalise over the distance and luminosity to construct the directional independent source count distribution

Parameter	Min.	Median	Max.
Spectral_Index	0.5	2.2	3.1
Variability_Index[b]	3.0	4.0	11.0
Flux_Density[c]	-35.4	-28.2	-19.9
Unc_Energy_Flux100[d]	-28.5	-27.6	-24.8
Signif_Curve[b]	-5.8	0.4	4.4
hr_{12}	-1	-0.1	1
hr_{23}	-1	-0.1	1
hr_{34}	-1	-0.2	1
hr_{45}	-1	-0.3	1

[a]For the YNG vs MSP models we also used the Galactic latitude (GLAT) of the source, as a predictor parameter.

[b]Number represents the log of the original value contained in the catalog.

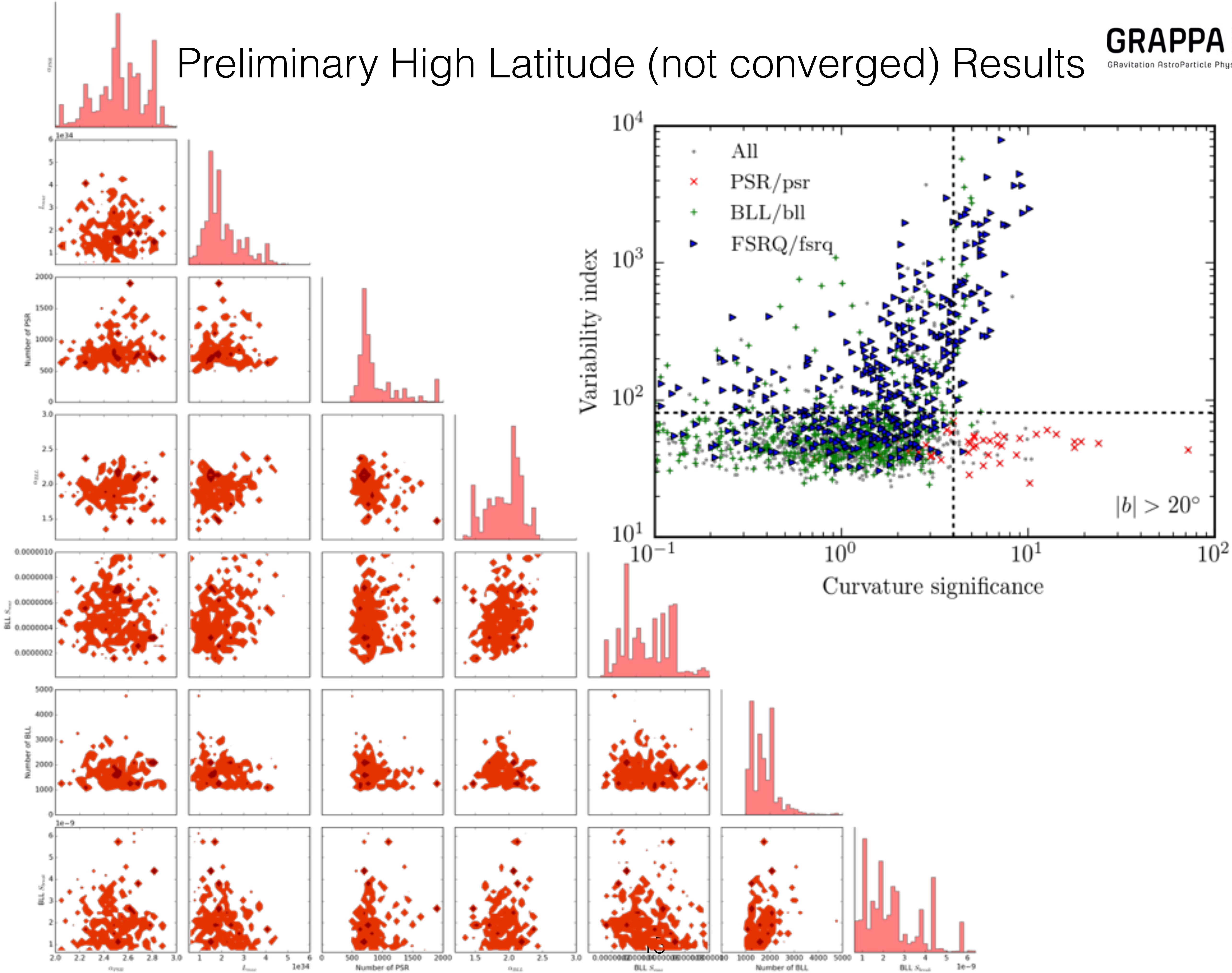
[c]In photon cm^{-2} MeV^{-1} s^{-1} (log of the original value contained in the catalog).

[d]In erg cm^{-2} s^{-1} (log of the original value contained in the catalog).

Saz Parkinson et al. 2016

$$\frac{dN}{dS} = \int dL dD \delta\left(S - \frac{L}{4\pi D^2}\right)\frac{dN}{dL}P(D|l,b)$$

Preliminary High Latitude (not converged) Results



Benefits vs Downfalls

- Allows us to simultaneously constrain both models of a variety of populations whilst providing statistically rigorous source class association statements

- We are able to include unassociated sources into our analysis which may well contribute to the best fit model parameters

- Method is non-trivial to implement in a completely general way - unlike machine learning classifiers

- Scans currently take a long time to run due to the multiple monte carlo simulations - may be difficult to implement for many more source classes

Future Work

- With association of high latitude sources we can dissect the composition of the high latitude gamma-ray emission (IGRB) through population synthesis studies, also combining with recent results from 1point-pdf of gamma-ray counts
- Associations in the disk: study contribution from “new” source populations such as bulge MSP
- Reducing the number of unassociated sources might improve significantly the limit on DM annihilation from DM subhalos
- Add in additional discriminating terms such as the 2pt correlation function