There and back again. A scientists tale.

(An overview of single-source detection algorithms)

By:
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Outline

- Brief overview of signal model.
- Current prospects (?).
- Current detection algorithms and results.
- Looking towards the future.

Signal Model

- For most single source detection algorithms (continuous) we assume a signal that has the form

$$s(t;\vec{\lambda}) = \boxed{F^{+}(\hat{\Omega})}\boxed{\Delta s_{+}(t;\vec{\lambda})} + \boxed{F^{\times}(\hat{\Omega})}\boxed{\Delta s_{\times}(t;\vec{\lambda})}$$

Antenna Pattern Functions

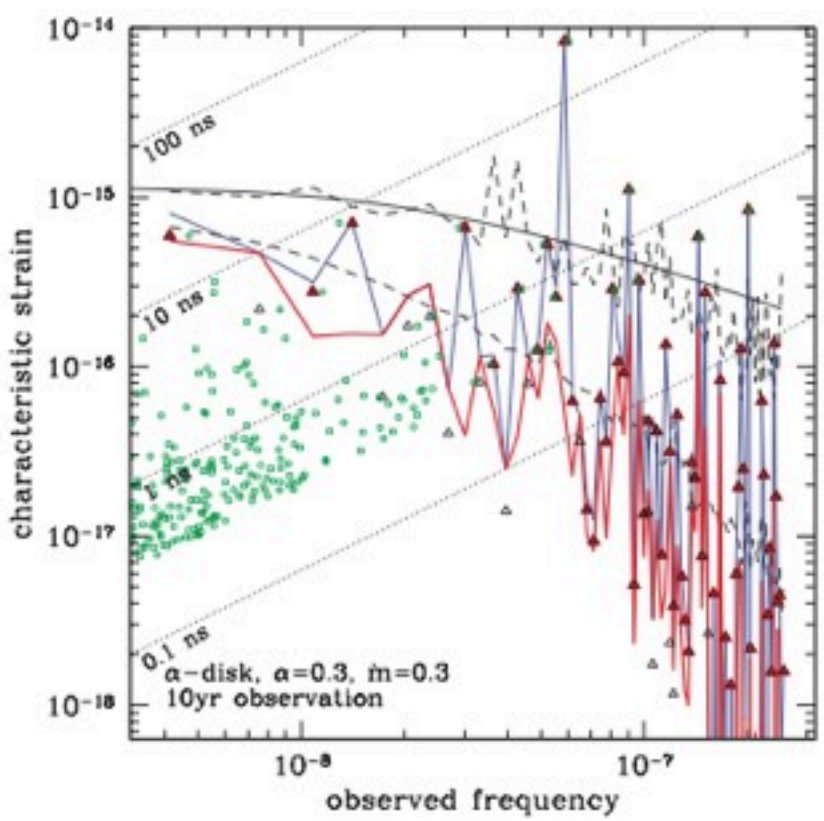
Sinusoids

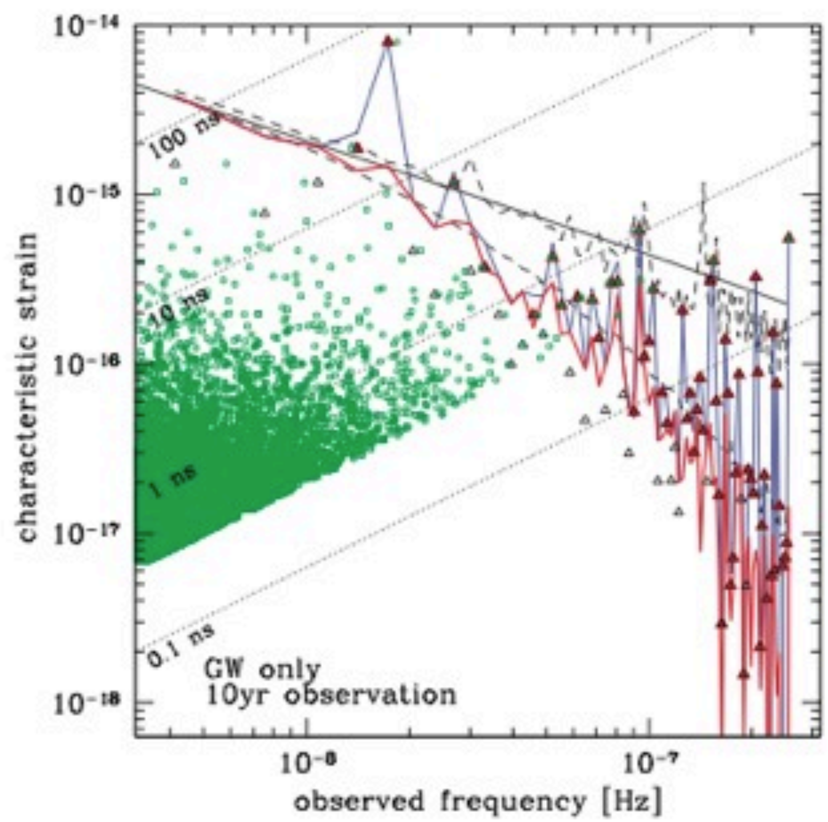
- Function of 8 parameters: $\vec{\lambda} = \{\theta, \varphi, \iota, \mathcal{M}, D, f, \psi, \phi_0\}$

- Earth and Pulsar Terms: $\Delta s_A(t;\vec{\lambda}) = s_A(t_p;\vec{\lambda}) - s_A(t_e;\vec{\lambda})$

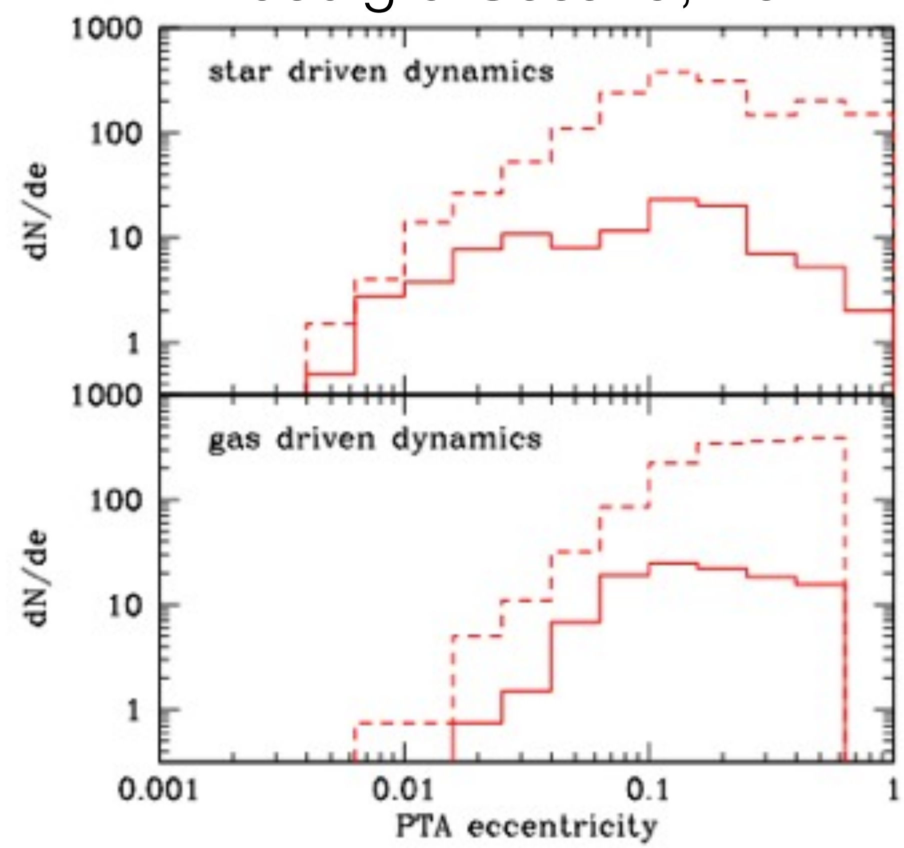
Current Prospects (?)

Kocsis & Sesana, 2011





Roedig & Sesana, 2011



Overall we will be dominated by the stochastic GW background. However, single “bright” resolvable sources may stand out above the background.

Expected that many sources will have non-negligible eccentricity. (However algorithms that assume circular orbits should still be ok.)

Legacy papers

The Doppler Response to Gravitational Waves from a Binary Star Source

Hugo Wahlquist[1]

Received February 20, 1987

USING PULSARS TO DETECT MASSIVE BLACK HOLE BINARIES VIA GRAVITATIONAL RADIATION: SAGITTARIUS A* AND NEARBY GALAXIES

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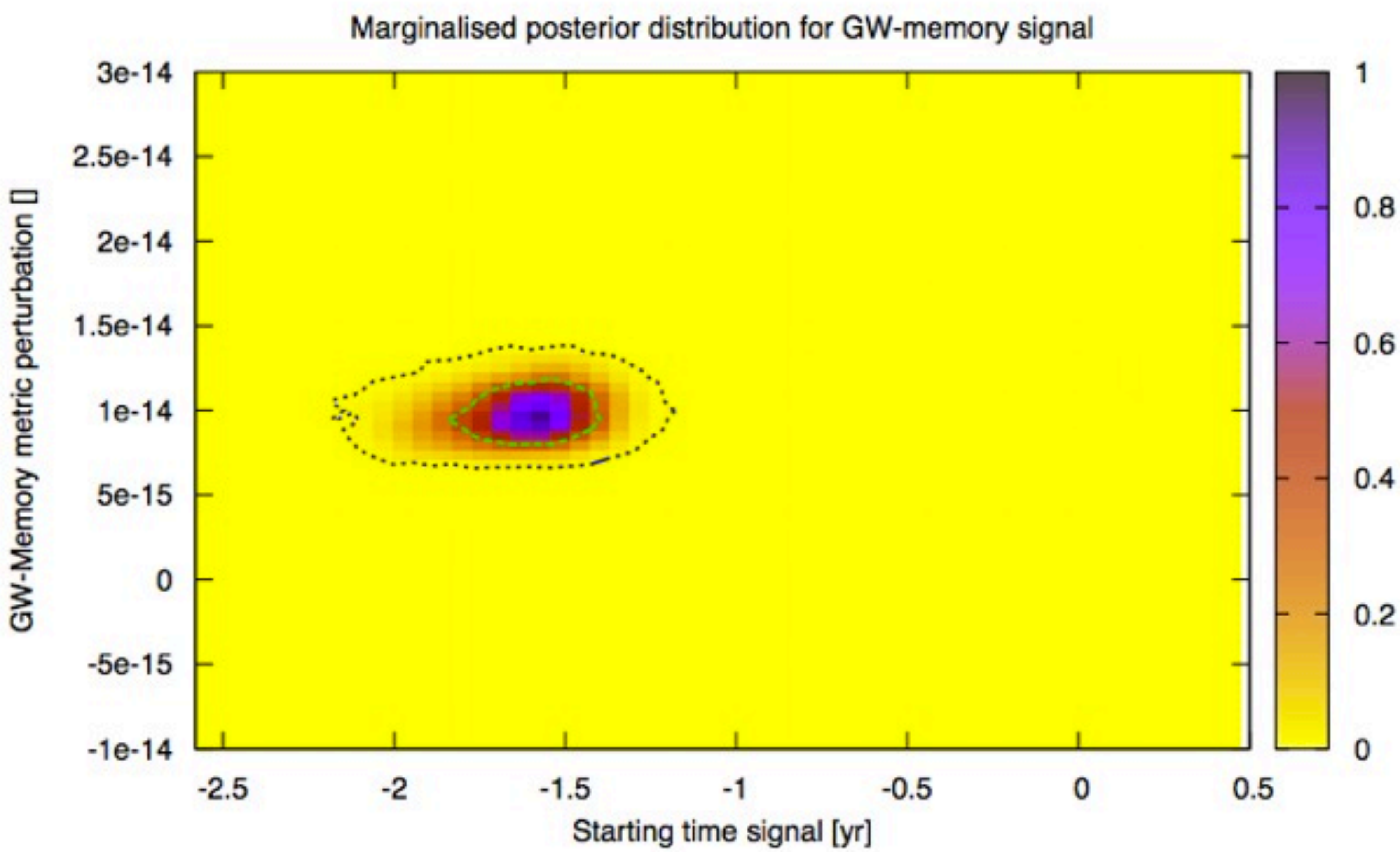
Received 2001 April 20; accepted 2001 July 25

CONSTRAINING THE PROPERTIES OF SUPERMASSIVE BLACK HOLE SYSTEMS USING PULSAR TIMING: APPLICATION TO 3C 66B

Fredrick A. Jenet,[1] Andrea Lommen,[2] Shane L. Larson,[3] and Linqing Wen[4]
Received 2003 October 10; accepted 2004 January 20

van Haasteren & Levin (2009)

- Bayesian method for detecting single sources (memory) that fully takes account of timing model by marginalizing over all timing parameters. Basis for current EPTA single source algorithms.

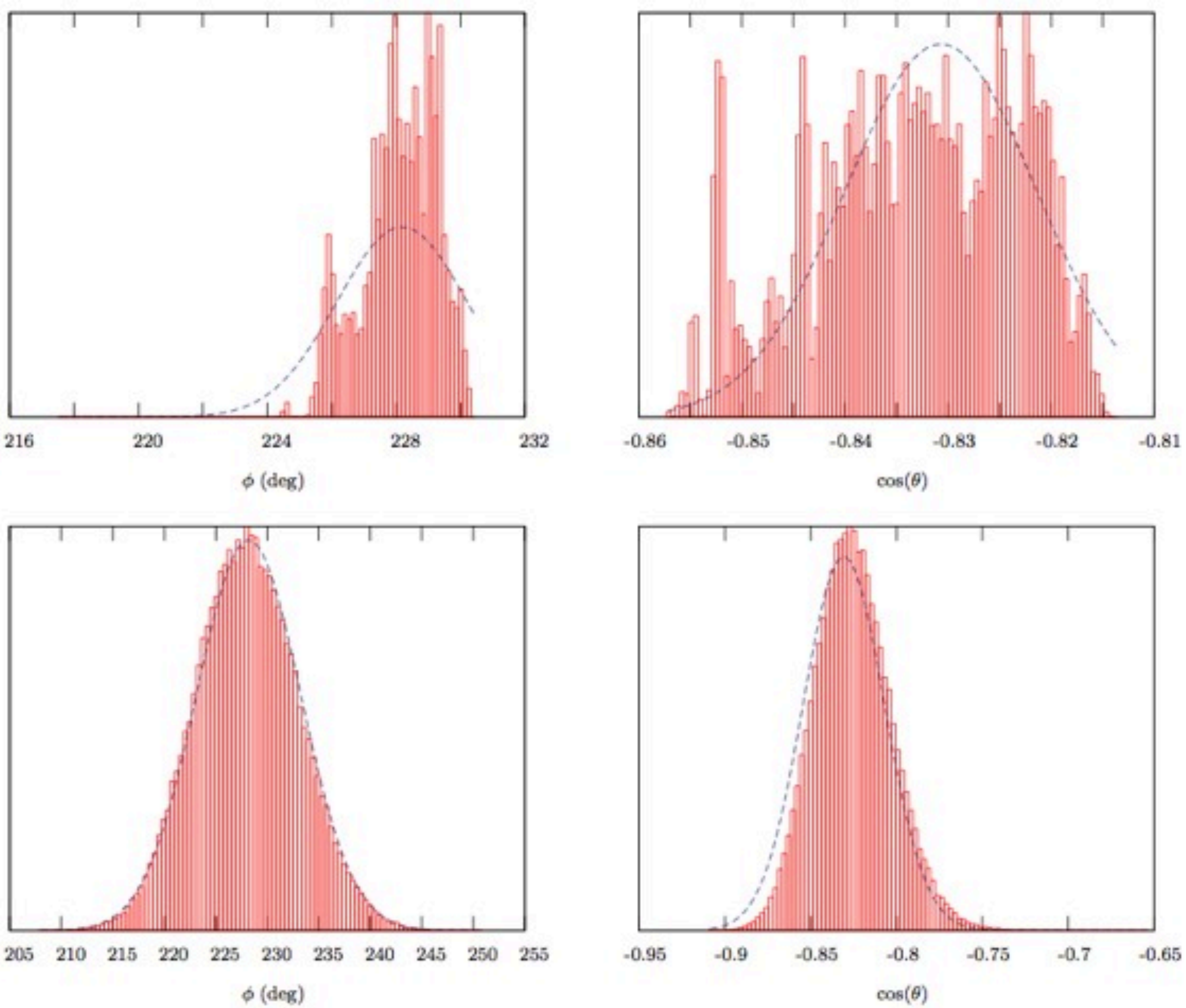


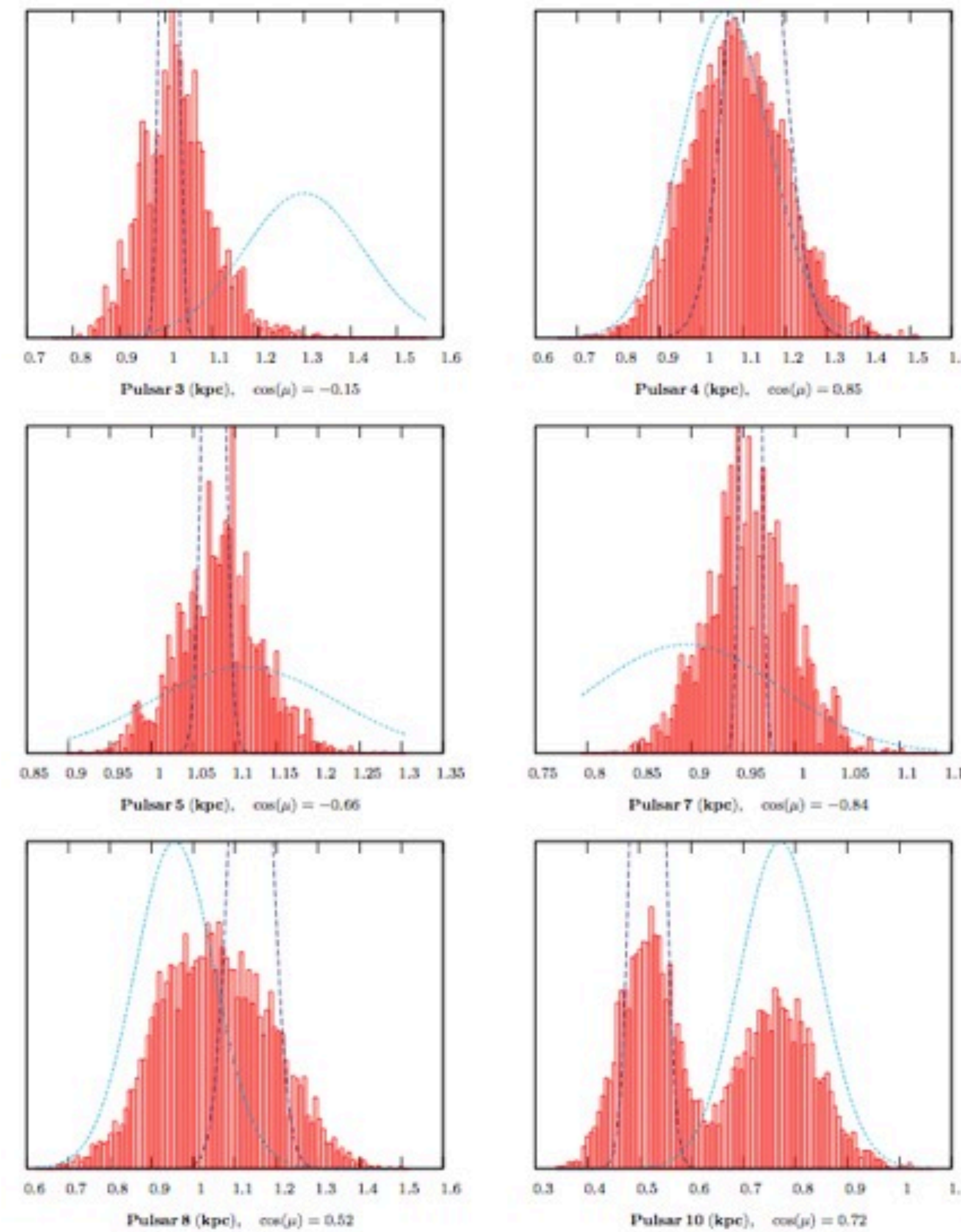
Conclusion: GW memory effects unlikely to be detected with current PTAs

Corbin & Cornish (2010)

- LISA-like MCMC pipeline applied to simulated PTA data.
- Makes use of pulsar term to increase SNR by factor of 2 and to break degeneracy between chirp mass and distance. Inclusion of pulsar term also leads to better sky localization (2.6 deg^2).
- Focuses on parameter estimation and not so much on detection (uses SNR=20).
- Does not use timing model. Models data as signal+noise.

Corbin and Cornish (2010) cont.



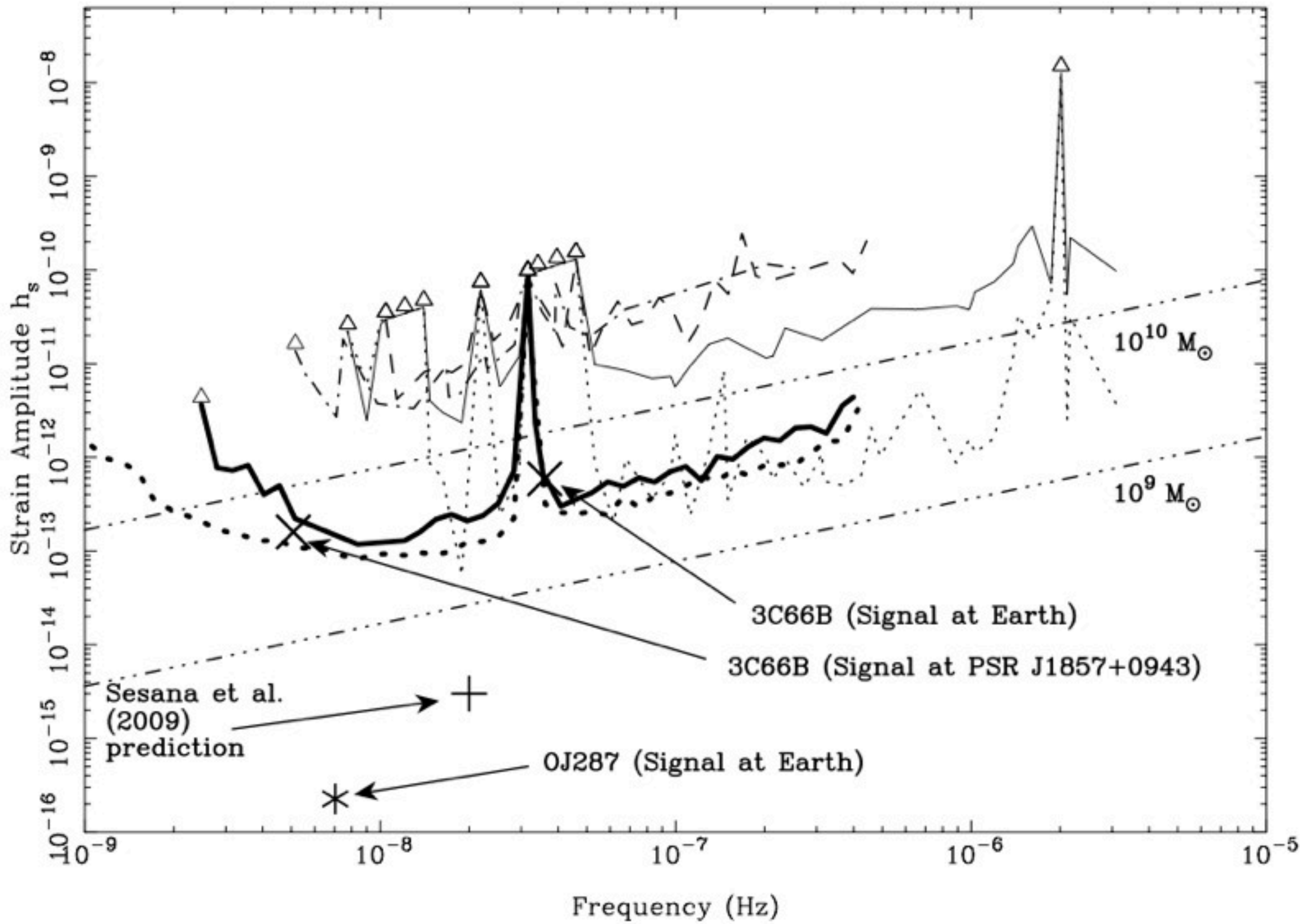


Pulsar Term yields better sky localization and in some cases GW signal improves pulsar distance measurements

Yardley et al. (2010)

- First and *only* published limit on single sources using real PTA data.
- Uses Lomb-Scargle based power spectrum and many injections to produce upper limits and sensitivity curves for PPTA data set.
- Results can be used to place an upper bound on the number of coalescing binary systems of a given chirp mass as a function of redshift. Current observations do not yet rule out any likely GW sources.

Yardley et al. (2010) cont.

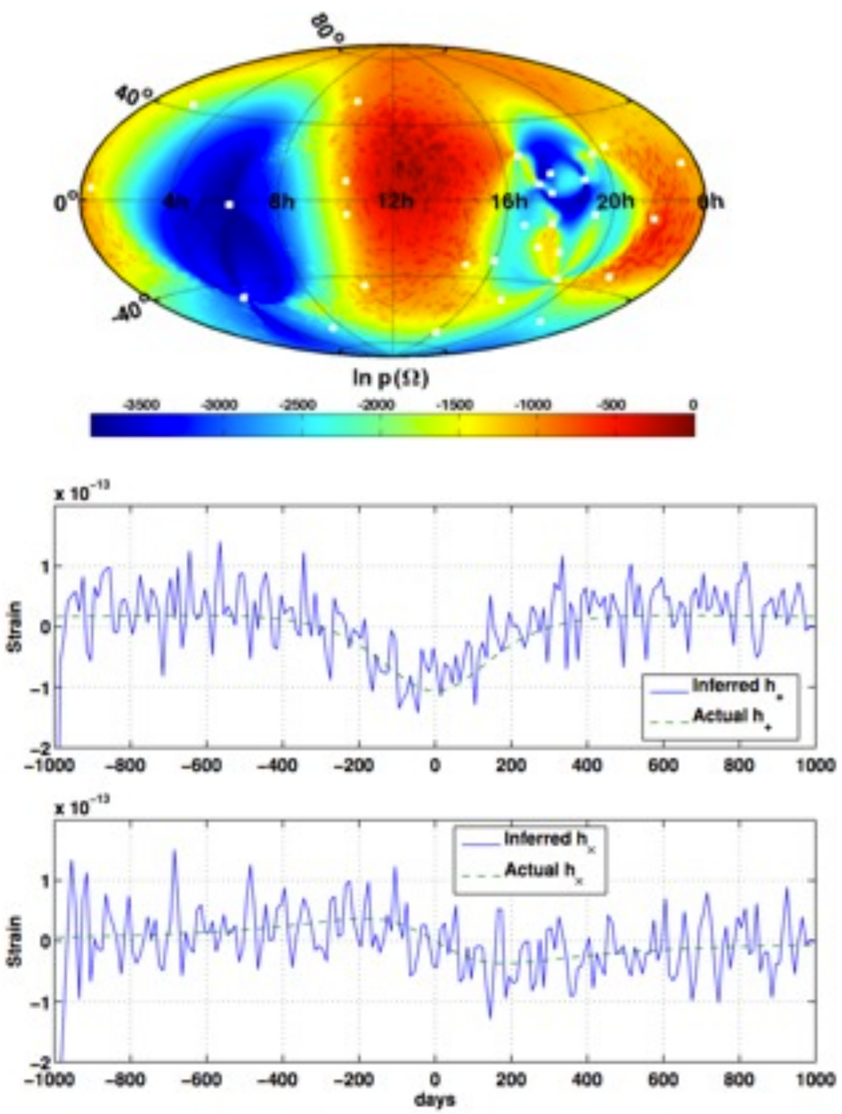


Finn & Lommen (2010)

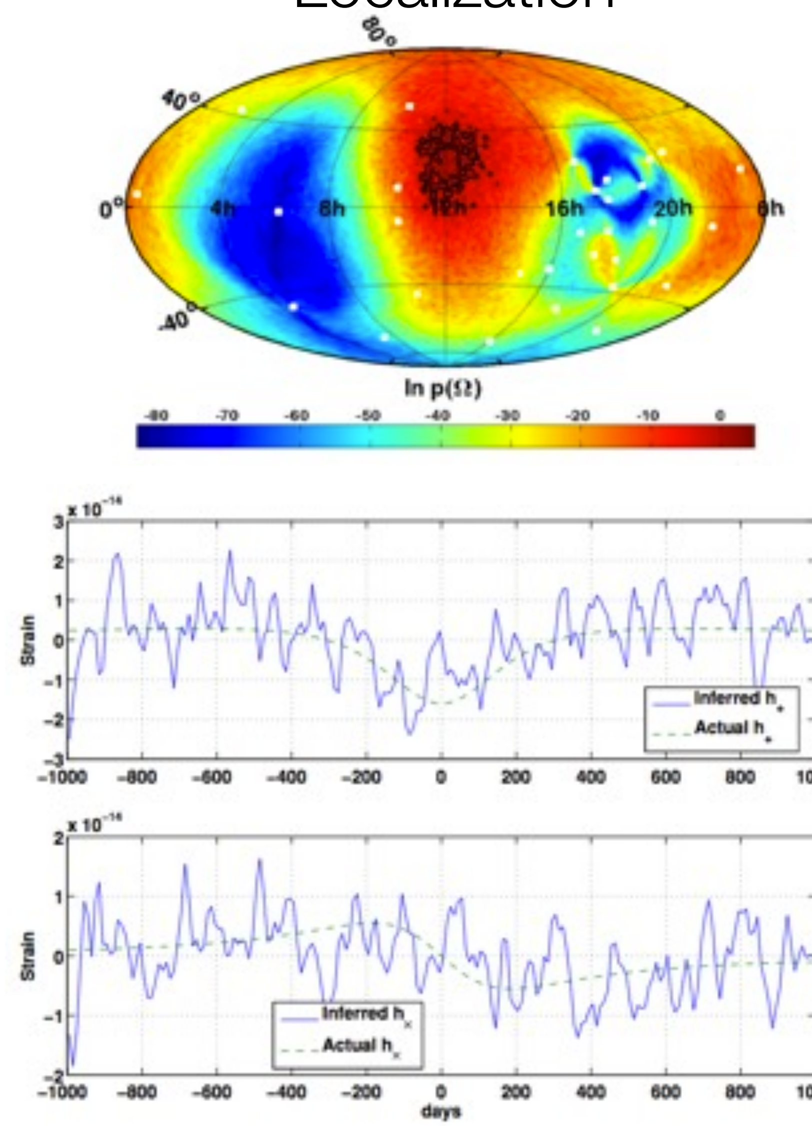
- General Bayesian method to detect GW bursts from a variety of sources.
- Breaks problem up into three distinct categories: detection, localization and characterization.
- The full data analysis pipeline based on the methods in this paper is available in the BayesGWDA Matlab package at http://sourceforge.net/projects/nanosoft/files/BayesGWDA/

Finn & Lommen (2012) cont.

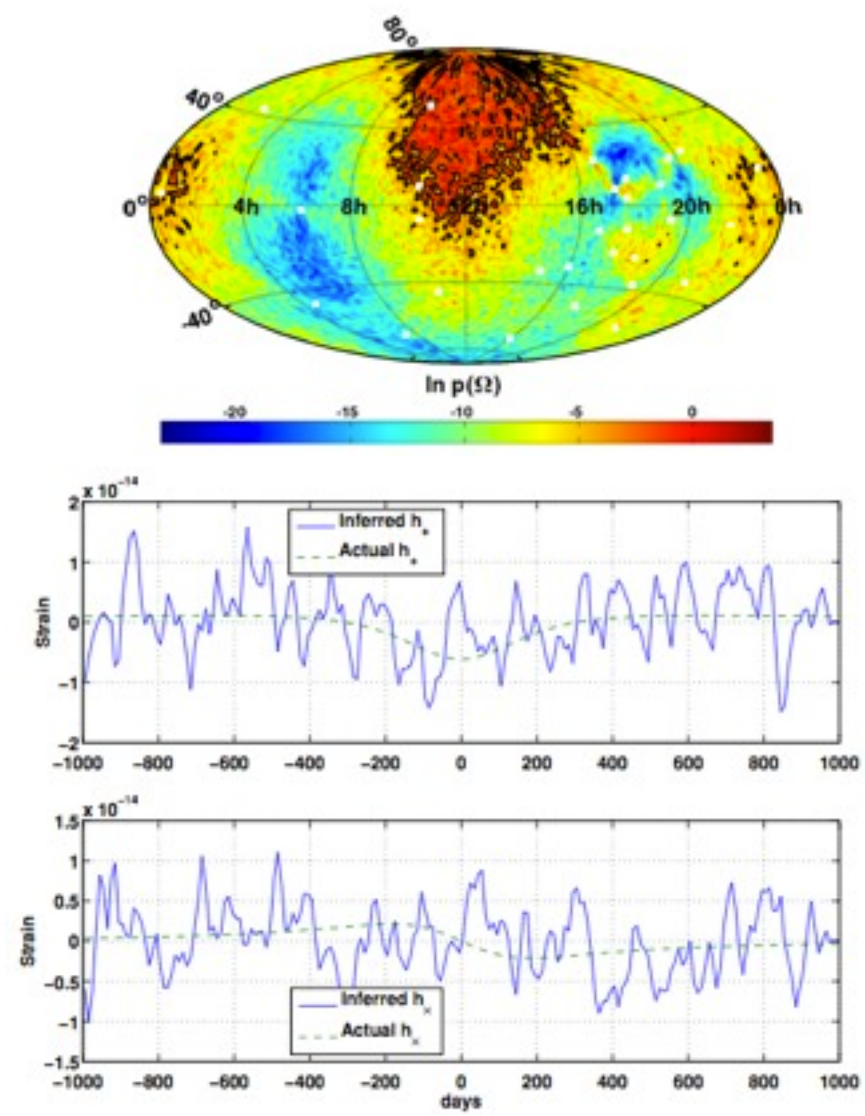
Characterization



Localization



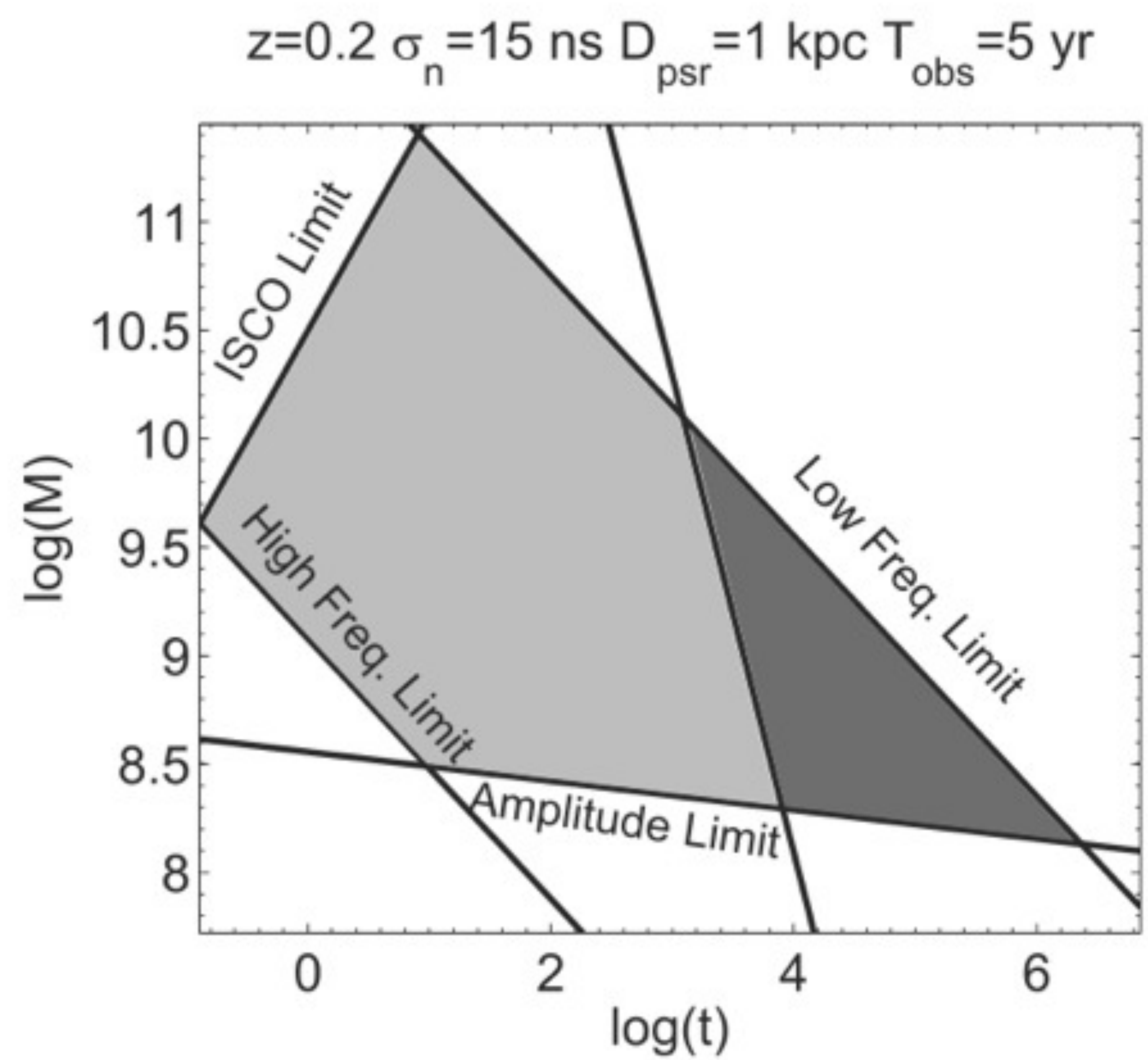
Detection



Signal	$\ln B(\mathbf{d})$	$\Delta\Omega_{90\%}$ (deg^2)	ρ^2
Strong	3.8×10^3	$\ll 1$	$3.8 \times 10^{+1}$
Moderate	6.6×10^1	5.8×10^2	8.7×10^{-1}
Weak	2.2×10^0	4.2×10^3	2.1×10^{-1}
Absent	-8.4×10^0	1.2×10^4	7.9×10^{-2}

Lee et al. (2011)

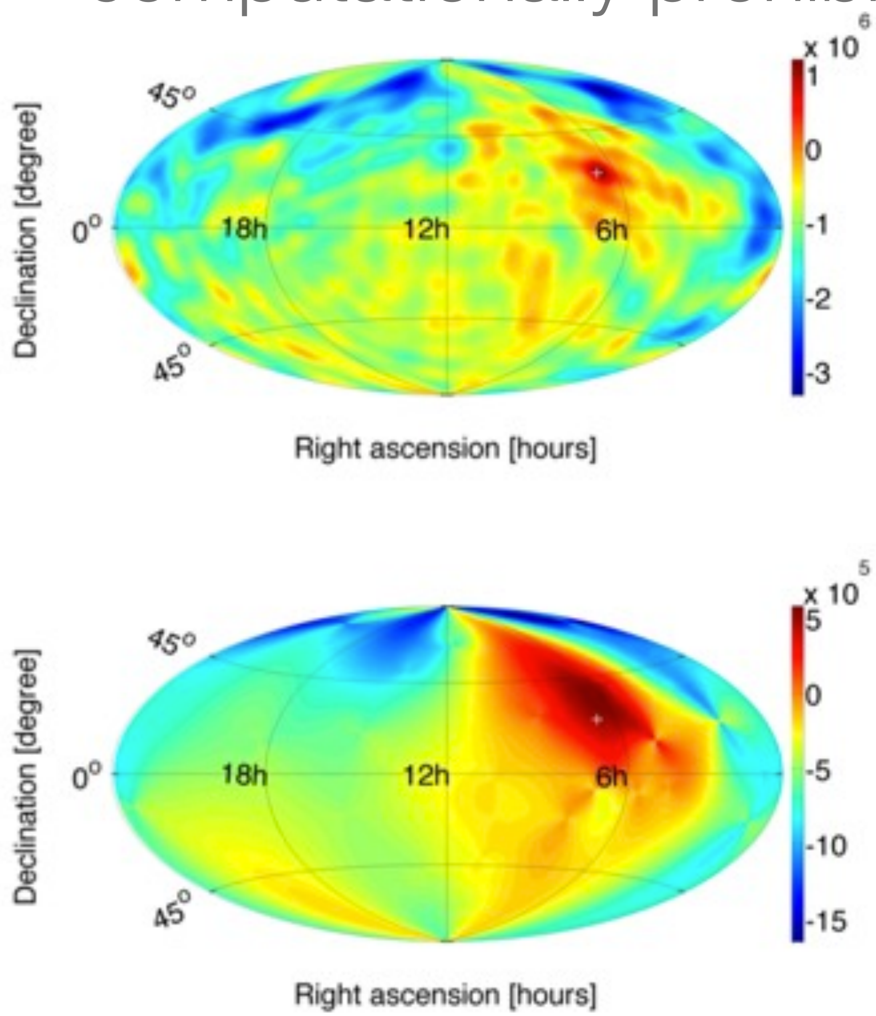
- Explore parameter space of SMBHBs.
- Uses Ziv-Zakai bounds to calculate measurability of SMBHB parameters.
- Show that along with parallax measurements can measure pulsar distance with GW observations.
- Assume SKA-like PTA.

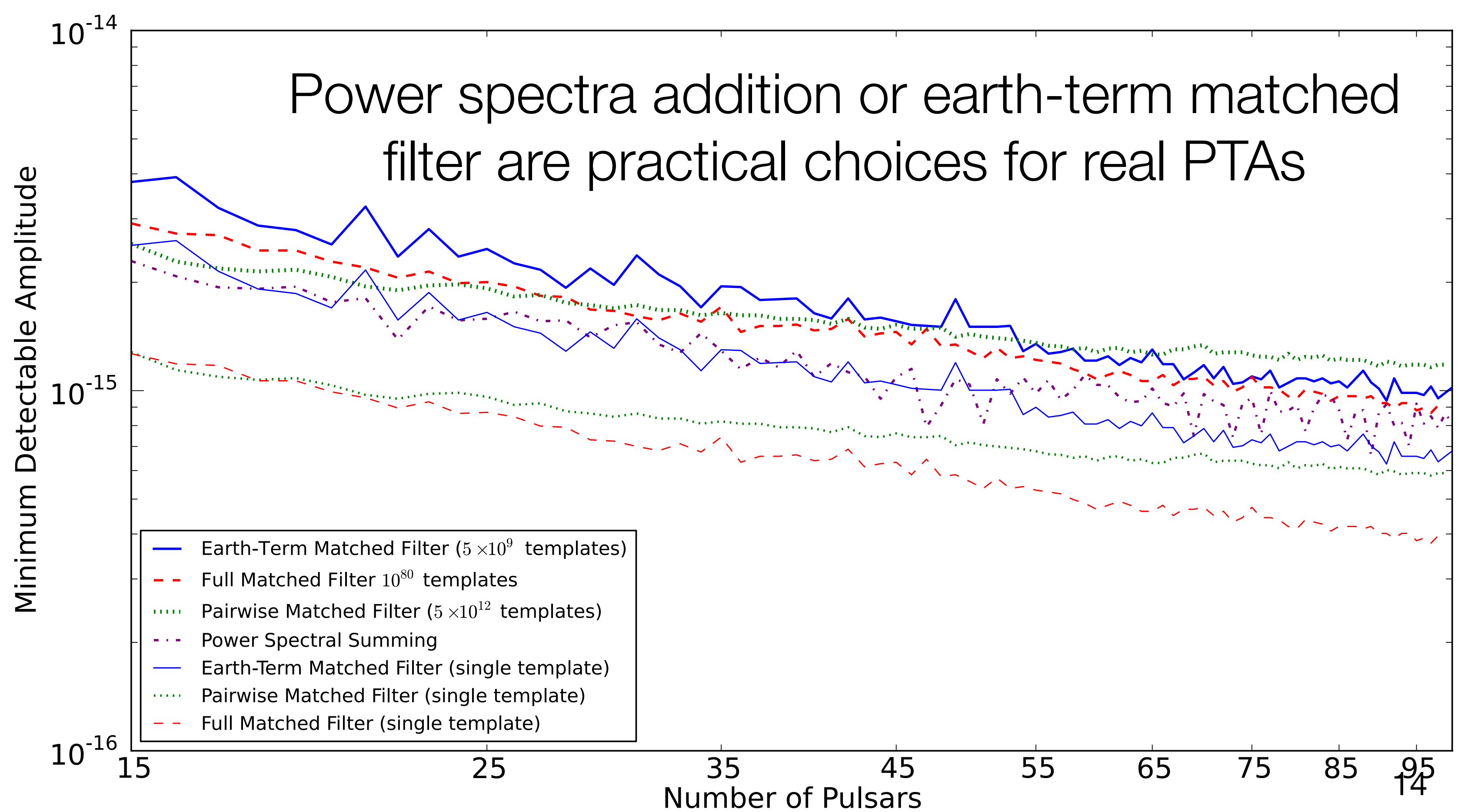


Ellis et al. (2012a)

- Compare various detection statistics for completely monochromatic signals through monte-carlo simulations.

- Show that matched filter explicitly including the pulsar distance is computationally prohibitive (at least for a grid based search)





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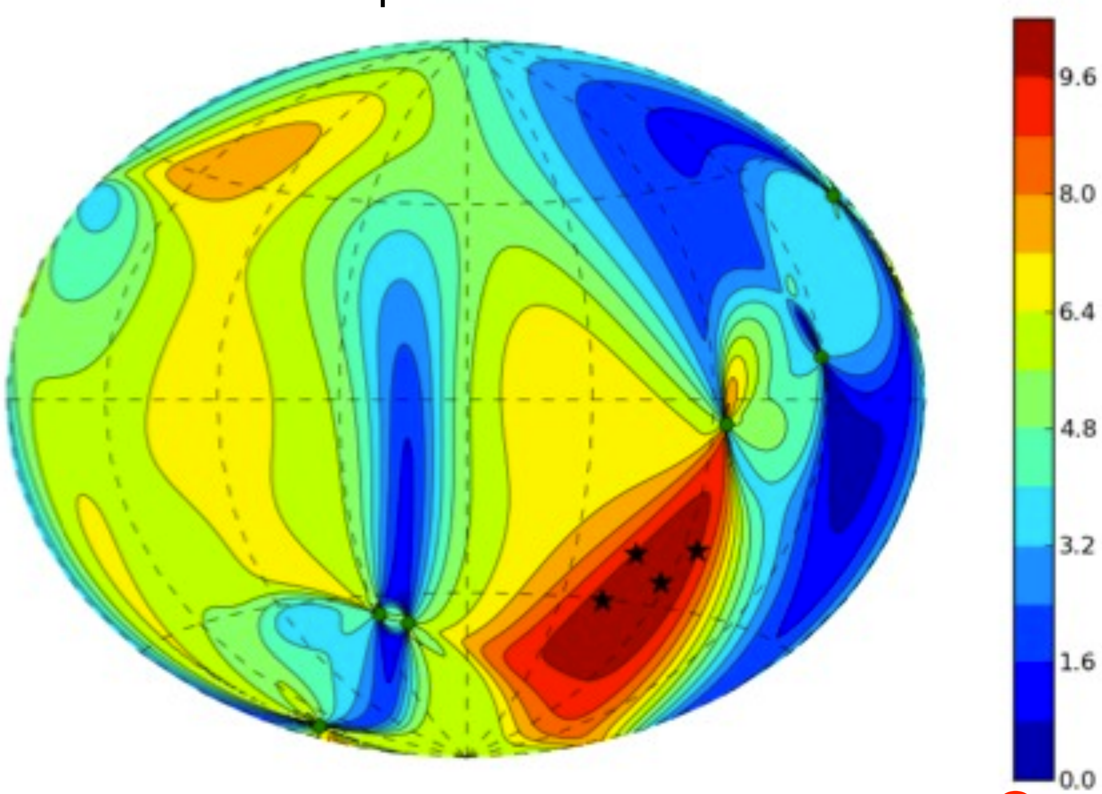
Babak & Sesana (2012)

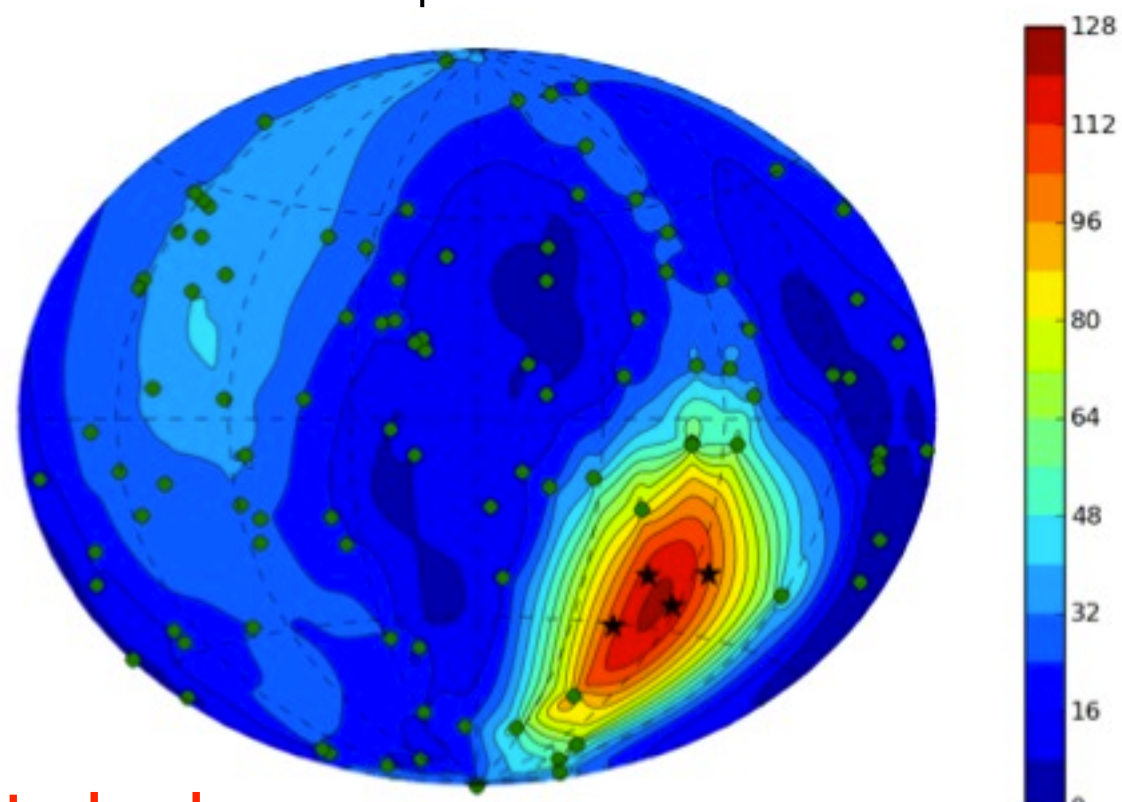
- First paper to deal with multiple single-sources. Show that many individual sources can be resolved with PTAs.

- Takes advantage of the fact that at higher frequencies there will not be a stochastic background but instead several semi-resolvable sources.

6 pulsars



100 pulsars



See talk later today by
Stanislav Babak

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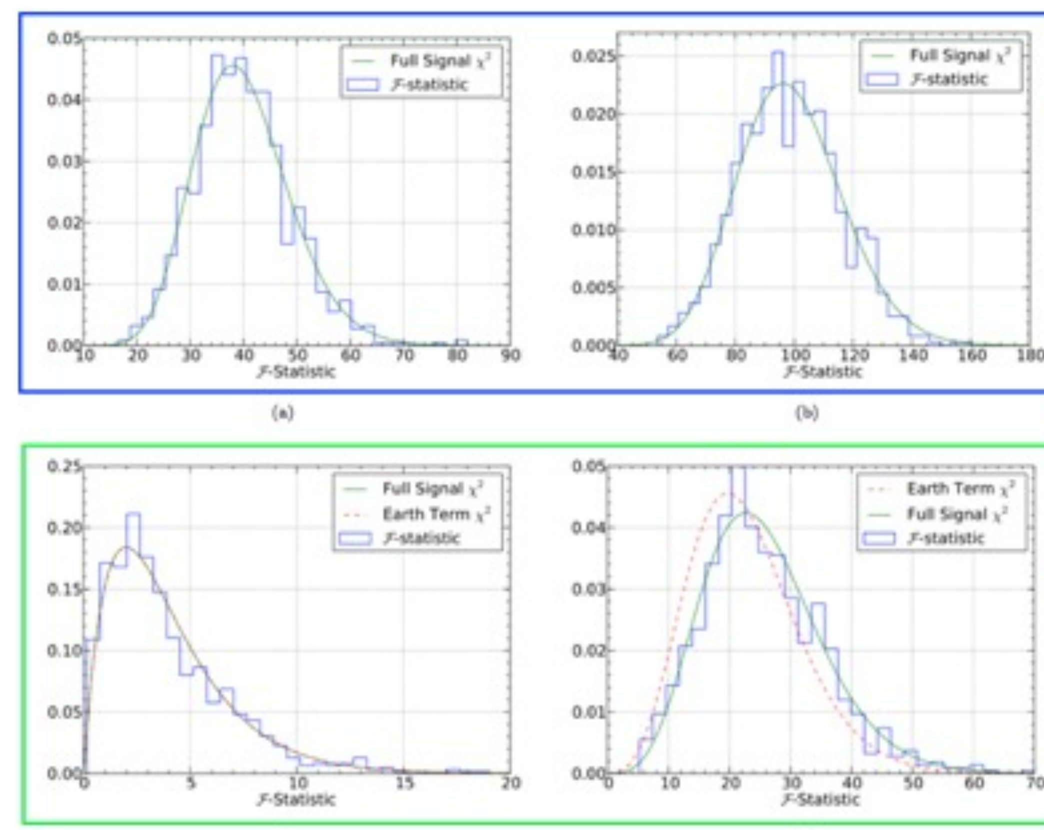
Ellis et al. (2012b)

- Build on Babak and Sesana (2012) to construct realistic detection statistic that takes timing model, irregular sampling and correlated colored noise into account.

- Treat pulsar term as a noise source and derive a coherent and incoherent detection statistic that maximizes over many GW parameters.

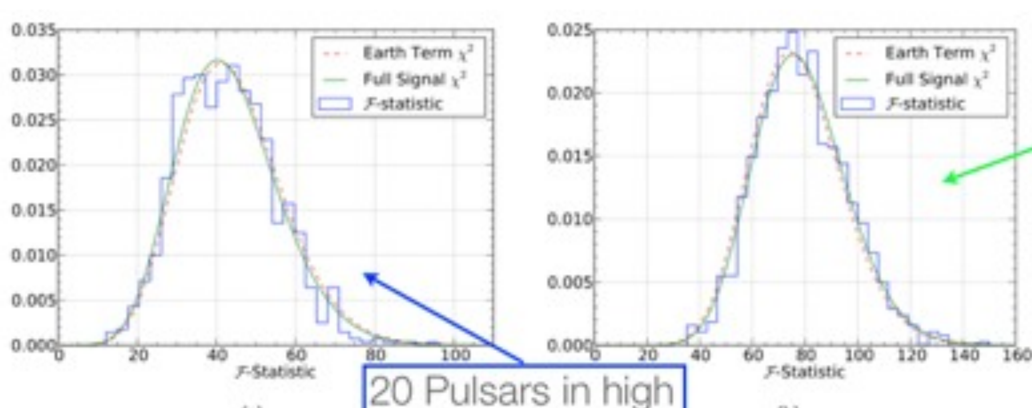
Chi square with 2M d.o.f

Chi square with 4 d.o.f



Incoherent F-statistic

Coherent F-statistic



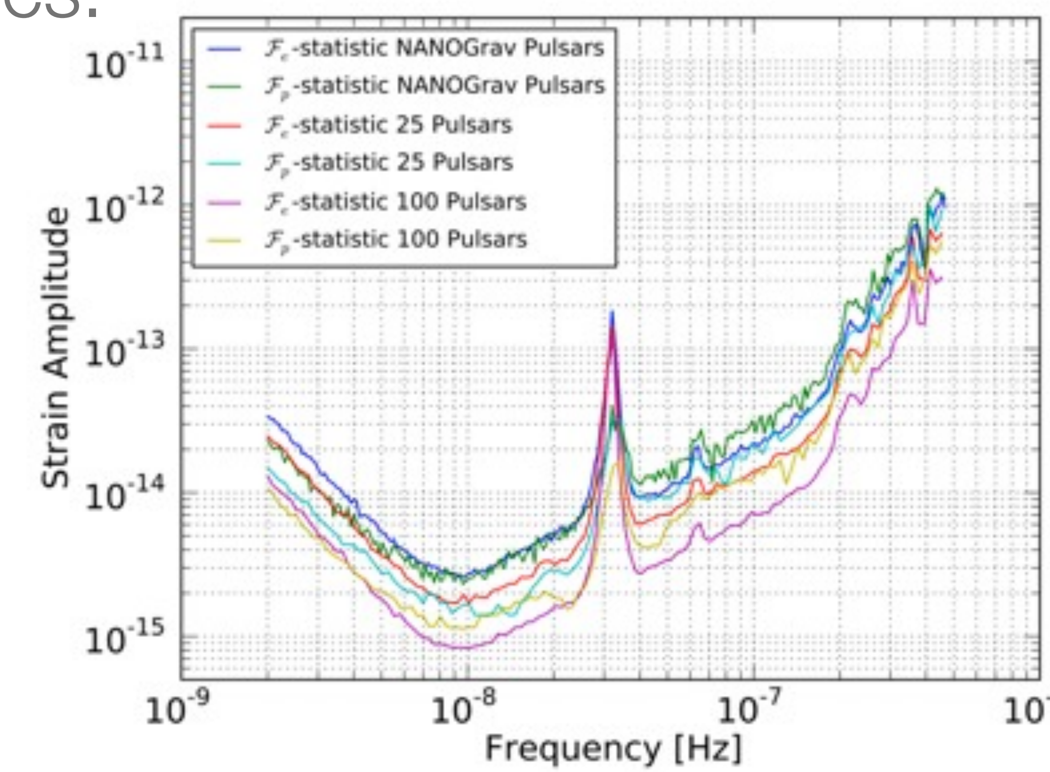
50 pulsars in low frequency regime

20 Pulsars in high frequency regime

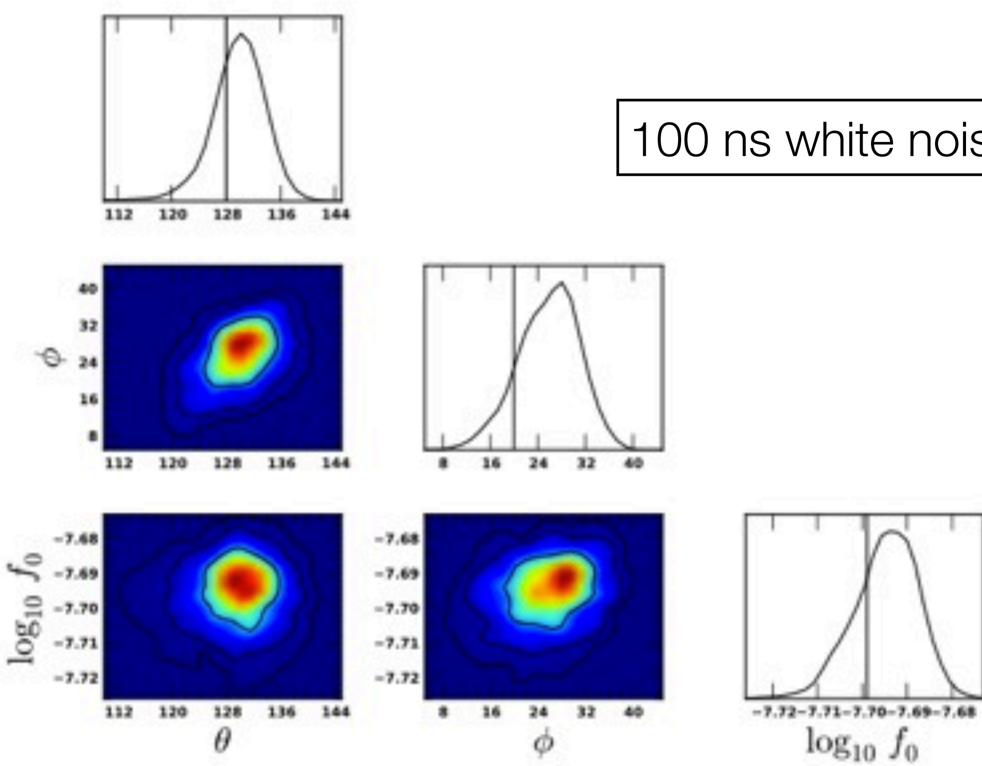
Ellis et al. (2012b) cont.

- Outline detection pipeline and methods for producing sensitivity curves and upper limits with both statistics.

- Test efficacy on simulated data sets with and without red noise.

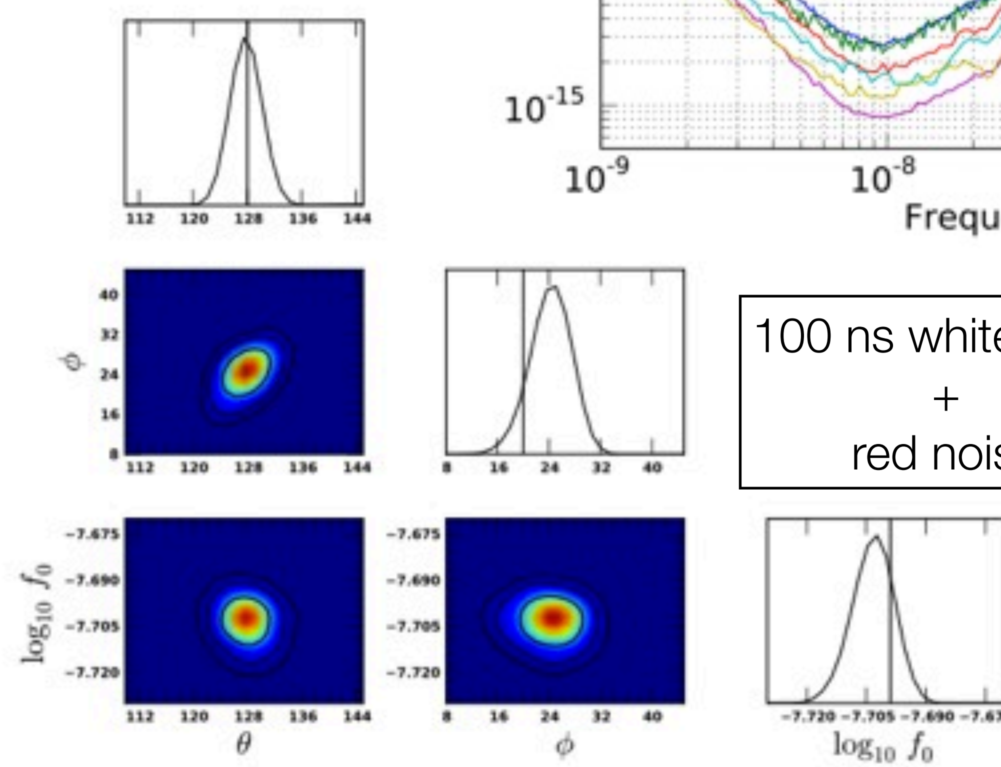


100 ns white noise



(a)

100 ns white noise
+
red noise



(b)

Maximization of GW phases at pulsar

In low frequency limit, the full signal is: $s_\alpha(t) = \sum_{i=0}^{M} \left[(\cos\Phi_\alpha - 1)\delta_{ij} + \sin\Phi_\alpha \varepsilon_{ij}\right] a^j A^i$

where, $\varepsilon = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

The likelihood function is then:

$$\ln\Lambda = \sum_{\alpha=1}^{M} \big[b(\cos^2\Phi_\alpha - \sin^2\Phi_\alpha) + c\cos\Phi_\alpha + d\sin\Phi_\alpha + f\sin\Phi_\alpha\cos\Phi_\alpha\big]$$

where,

$$b = -\frac{1}{2}M_\alpha^{ij}a_i a_j$$
$$c = N_\alpha^i a_i + M_\alpha^{ij}a_i a_j$$
$$d = N_\alpha^i \varepsilon_{ij} a^j$$
$$f = -M_\alpha^{ij}\varepsilon_{\ell j} a_i a^\ell$$

Maximizing the likelihood w.r.t the phase, we get the quartic equation

$$0 = (4f^2 + 16b^2)x^4 + (4fd + 8cb)x^3 + (c^2 - 4f^2 - 16b^2)x^2 + (-2fd - 8cb)x + f^2 - c^2$$

where, $x = \cos\Phi_\beta$

This equation is guaranteed 1 unique solution. We can use the physical solutions to solve for the phase and plug back into the likelihood.

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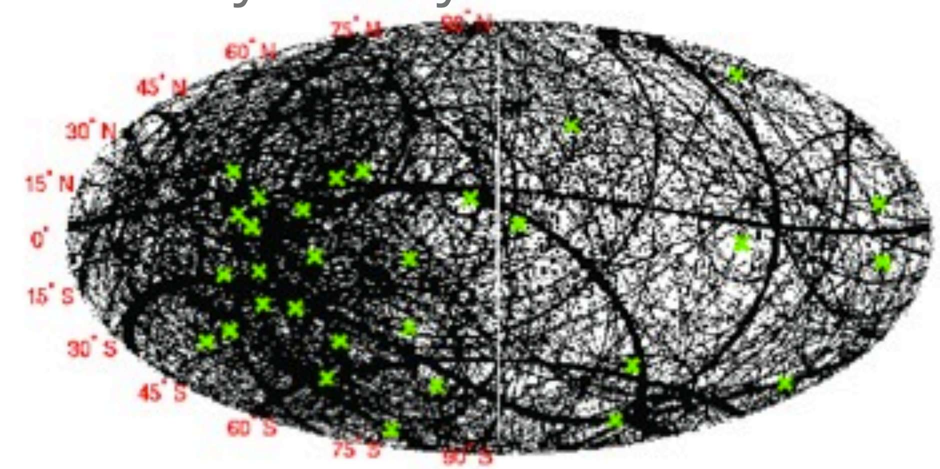
Pitkin (2012)

- Extends burst search to include pulsar terms. Usually pulsar term is ignored because the signal may be separated by delays on the order of the pulsar distance.

- May be lucky enough for a GW burst to be in a part of the sky where the signal will be observed in at least one pulsar pair.

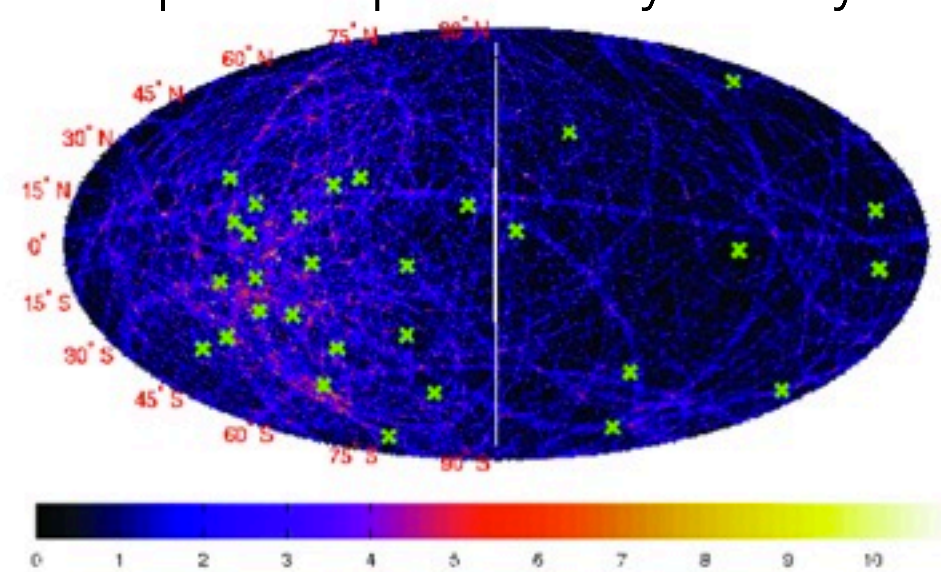
- Future work will apply to realistic datasets.

- Will greatly increase temporal coverage



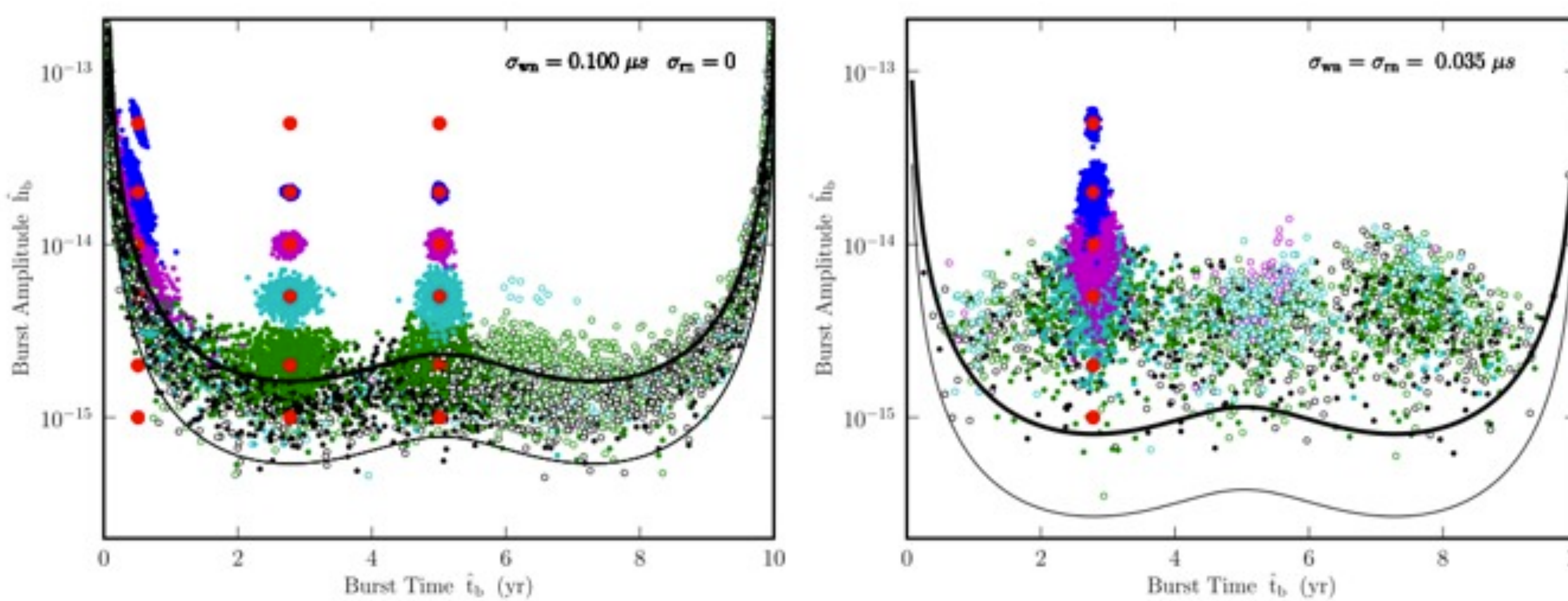
at least 1 source separated by < 10 yrs

# of pairs separated by < 10 yrs



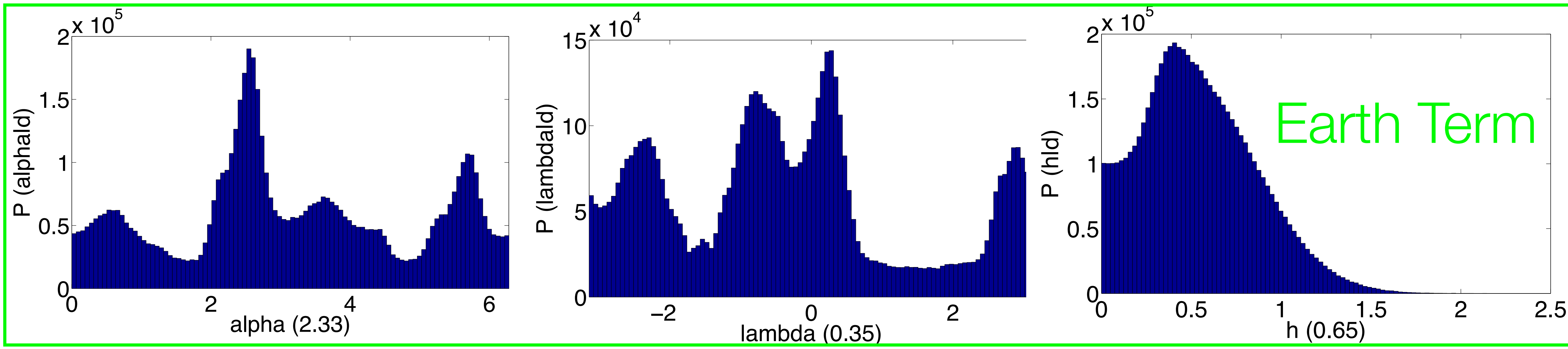
Cordes & Jenet (2012)

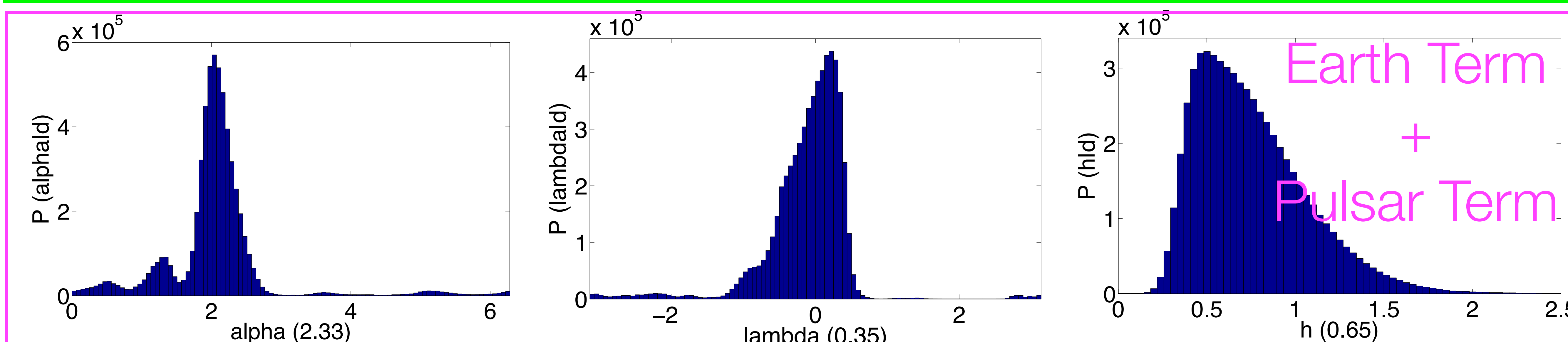
- Looks at detectability of GW bursts in Earth terms and/or pulsar terms.
- Show that burst rate and amplitude distribution may favor detection in pulsar terms rather than earth terms.
- Perform least squares fit for burst epoch and estimate amplitude.



Xihao Deng (see talk later today)

- Bayesian method that includes pulsar term as unknown phase for each pulsar.
- Uses MCMC method to search the full 7+Npsr dimensional search space.





tempo2 global fitting

- Uses tempo2 global fitting to fit GW parameters simultaneously with timing model parameters.

- Fits for 4 amplitudes that depend on sky location for every frequency.

Where we need to go in the future

- Develop/finish end-to-end data analysis pipelines and make publicly available (verification).
- Produce sensitivity curves/upper limits for all datasets (and combined datasets!) for different detection methods and compare!
- Be sure to include effect of pulsar timing model in data analysis methods.
- Begin to explore other types of sources (eccentric binaries/ Post-Newtonian effects etc.)