Limits on the nHz gravitational wave Universe from the European Pulsar Timing Array

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EPTA

Overview

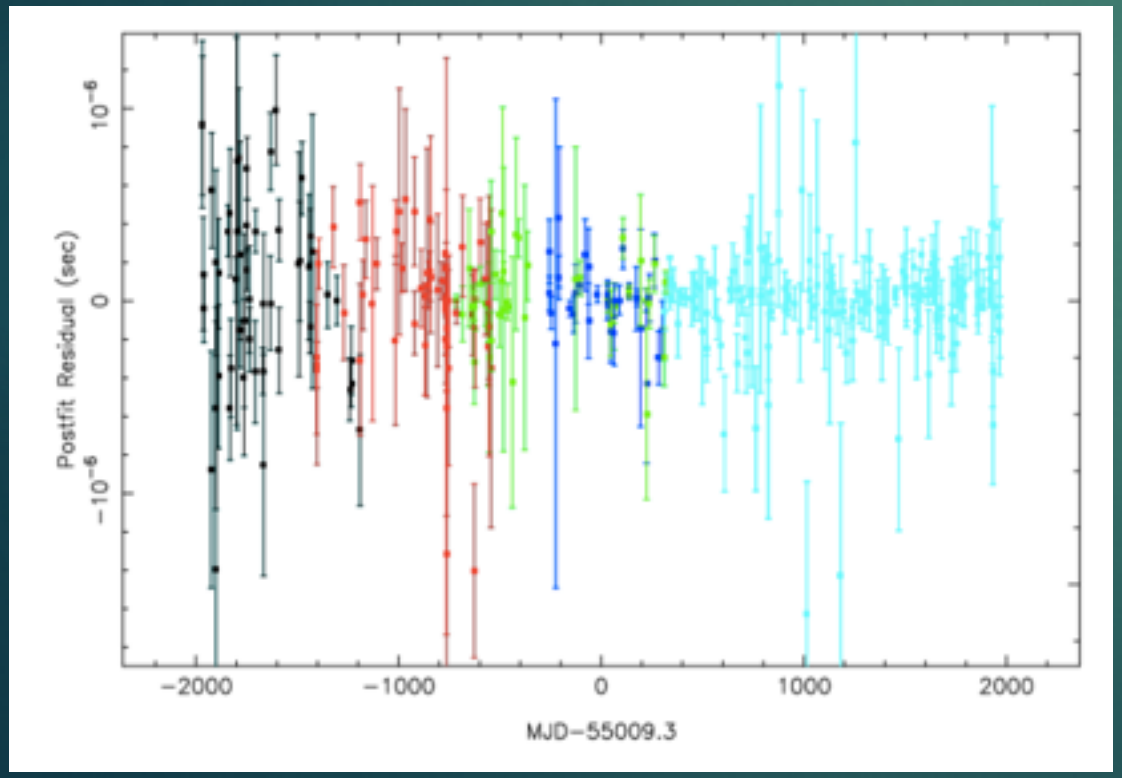
European Pulsar Timing Array Limits on:
- Isotropic Stochastic Background
- Anisotropic Stochastic Background

Future Prospects:
- New systems, LEAP.
- New analysis methods.

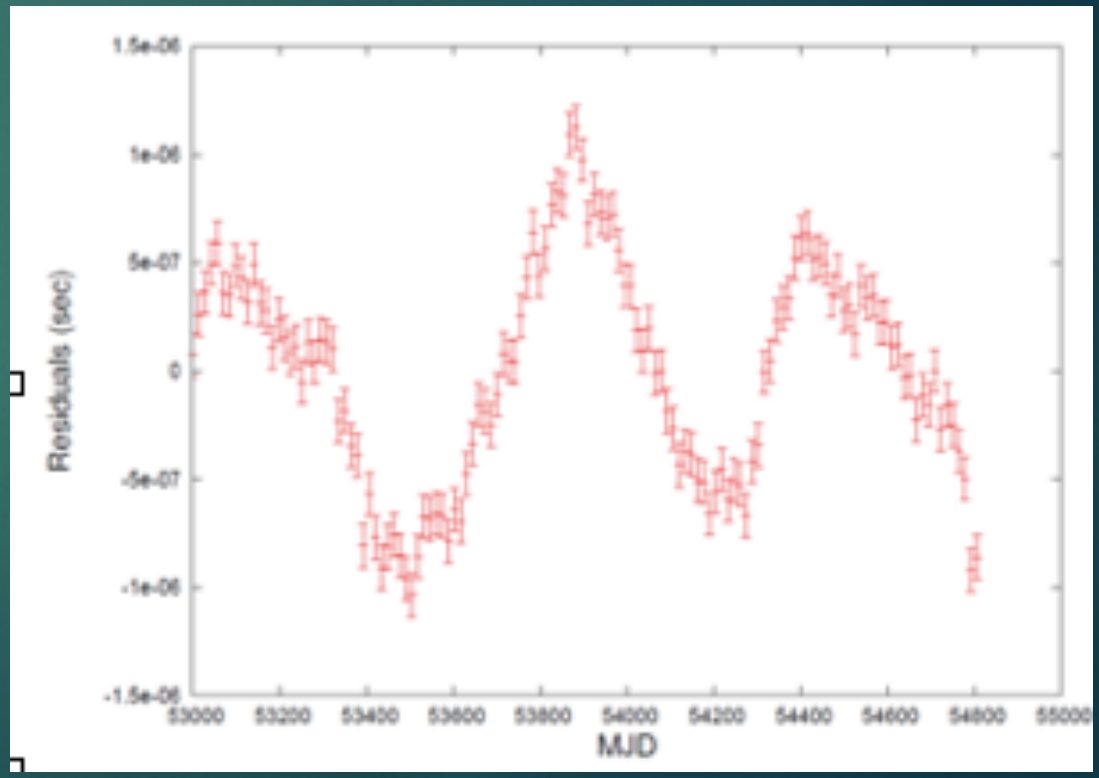
The GW Signal

As discussed earlier in the week (M. Kramers talk):
Have a timing model for a pulsar.
Subtract predicted arrival times of pulses from observed -> get residuals

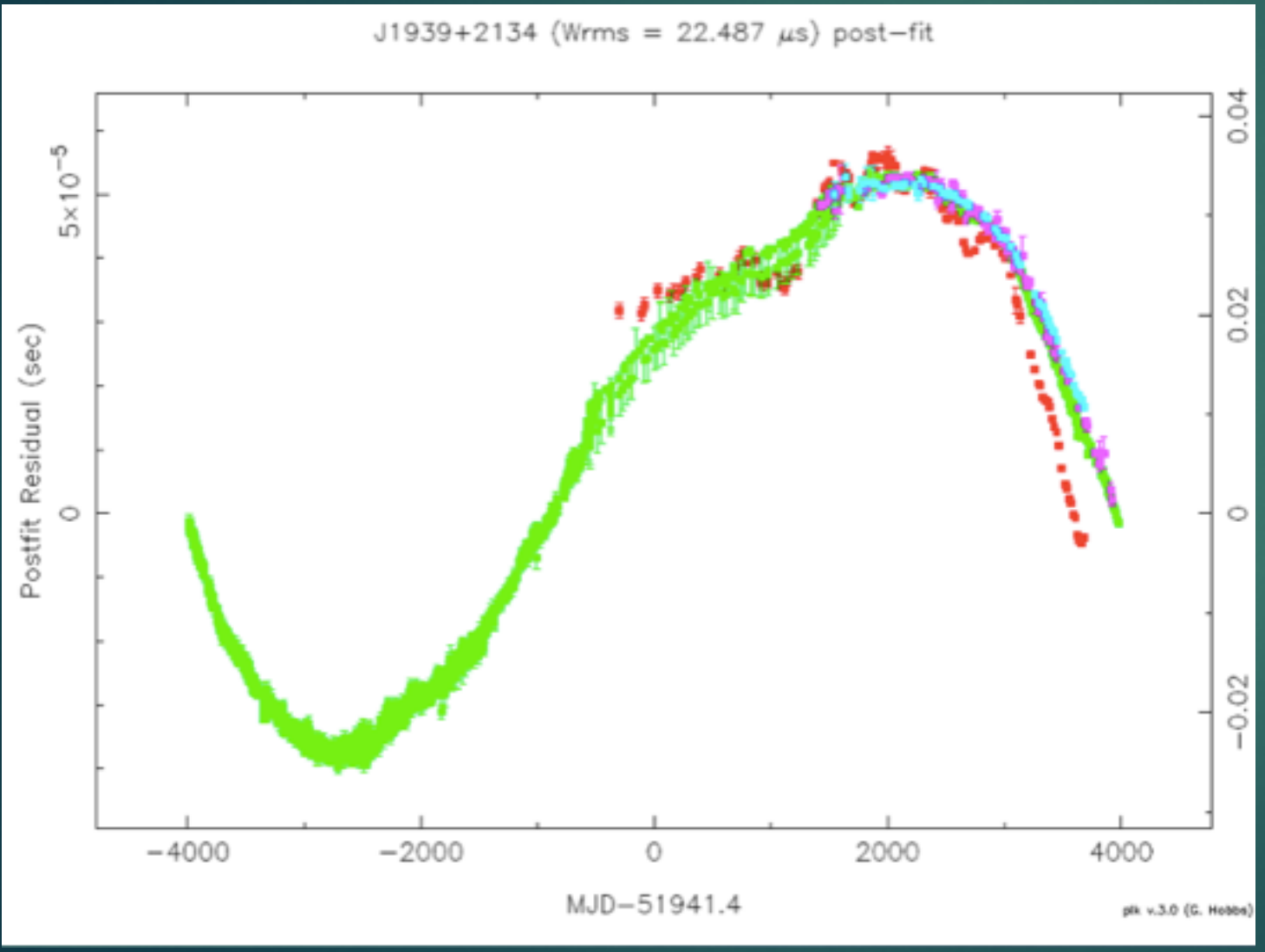
If timing model is enough, residuals basically white:



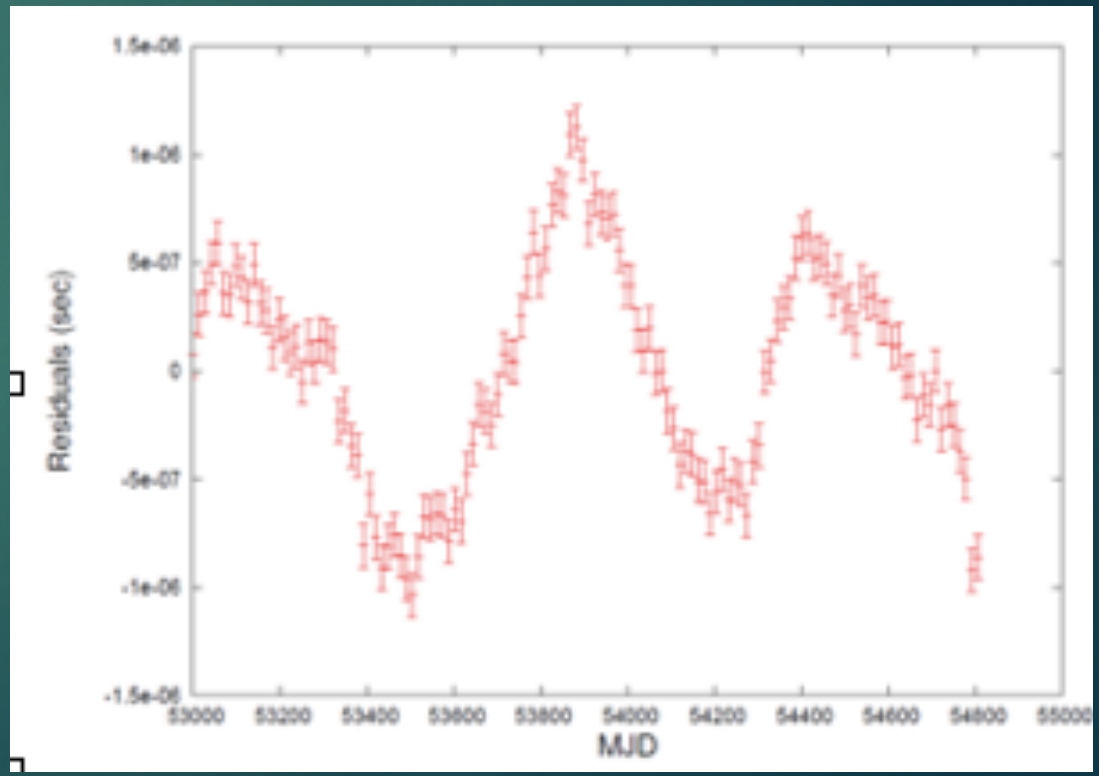
GWs induce red timing noise signal in residuals:



The GW Signal



But real data can have plenty going on without needing to invoke GWs :(



Isotropic Background Limits

Lots of things can look like GWs:

Angular correlation between pulsars allows us to discriminate between:

(for example)

Intrinsic Timing Noise
(Uncorrelated between pulsars)

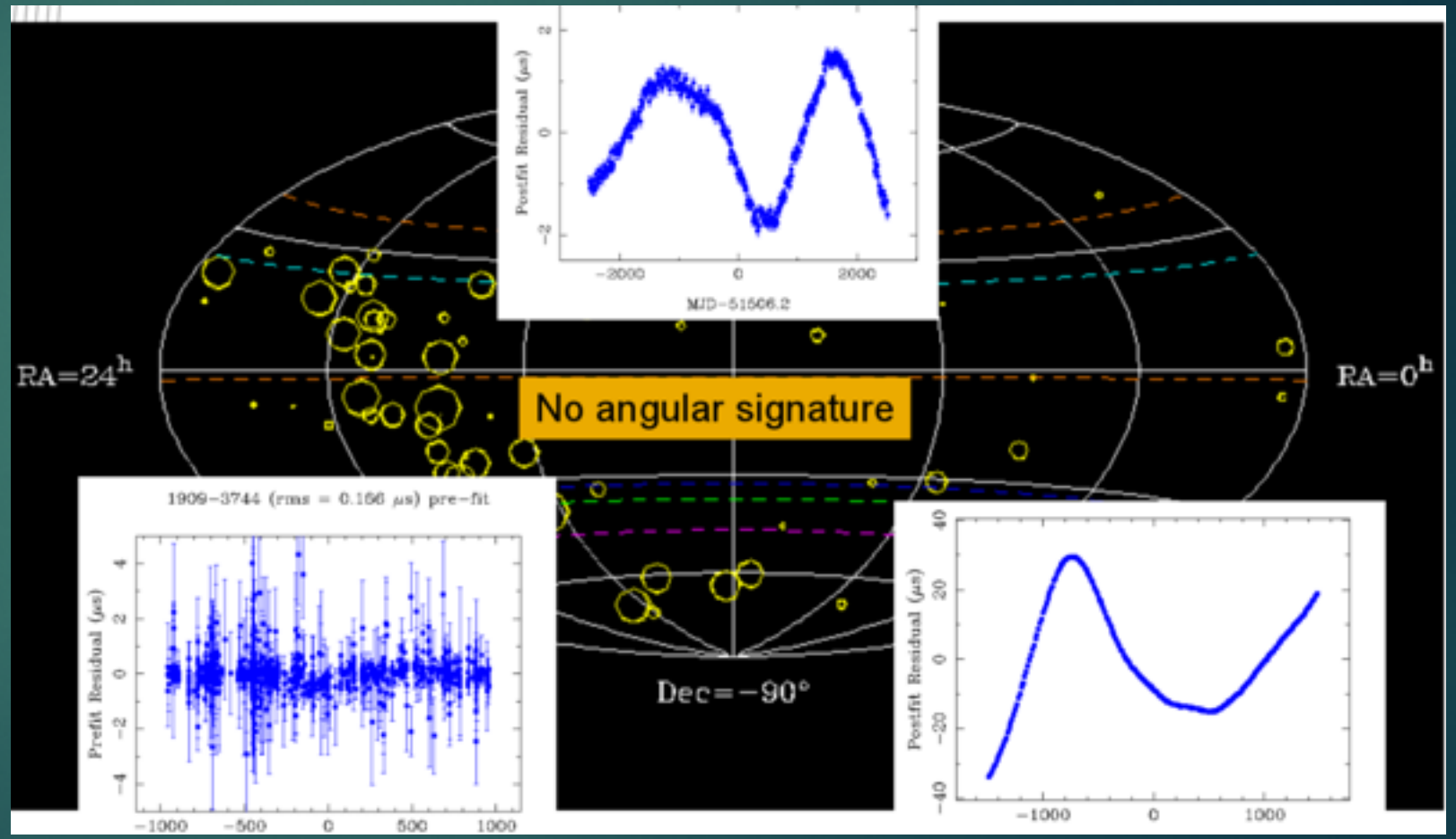


Image credit: George Hobbs

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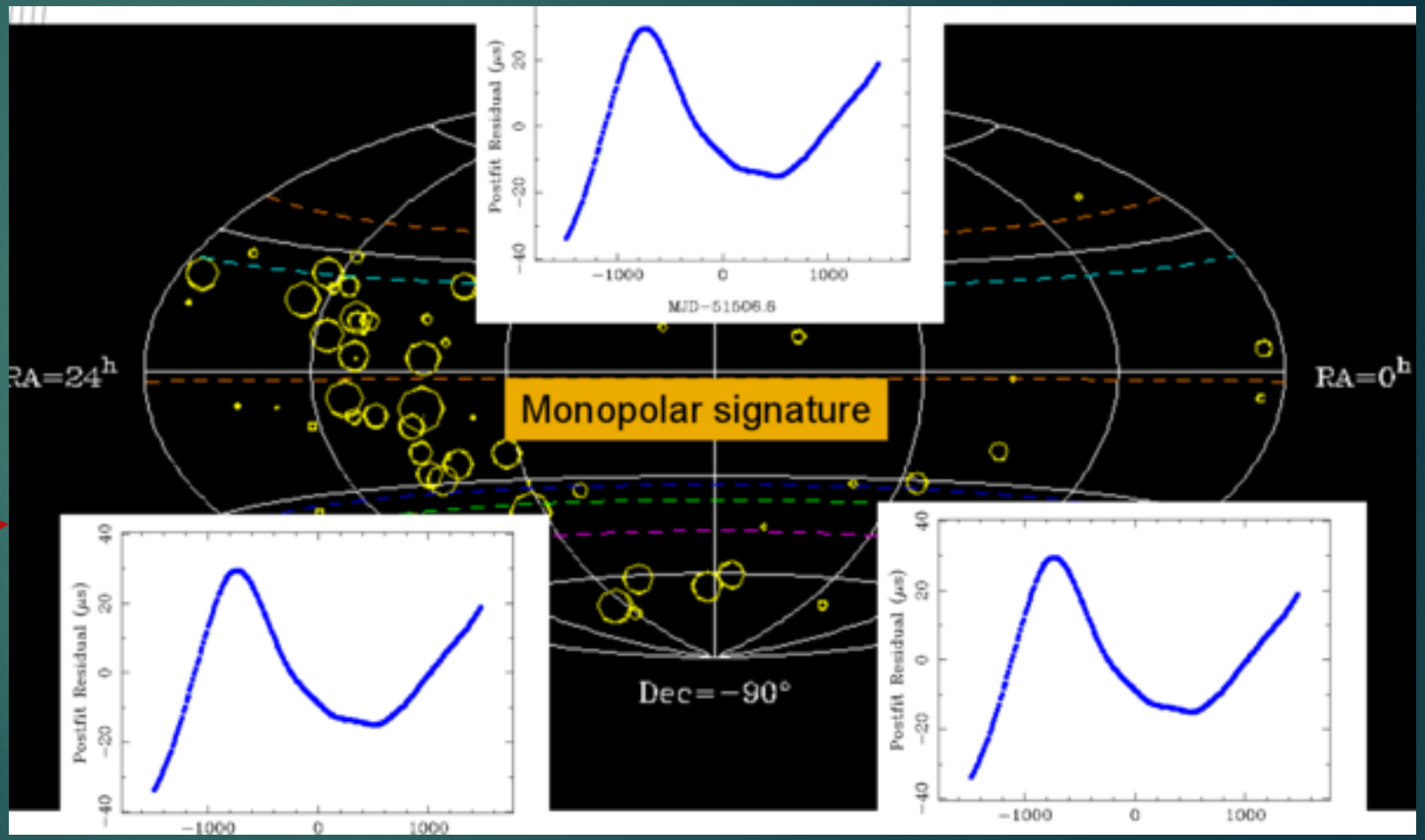

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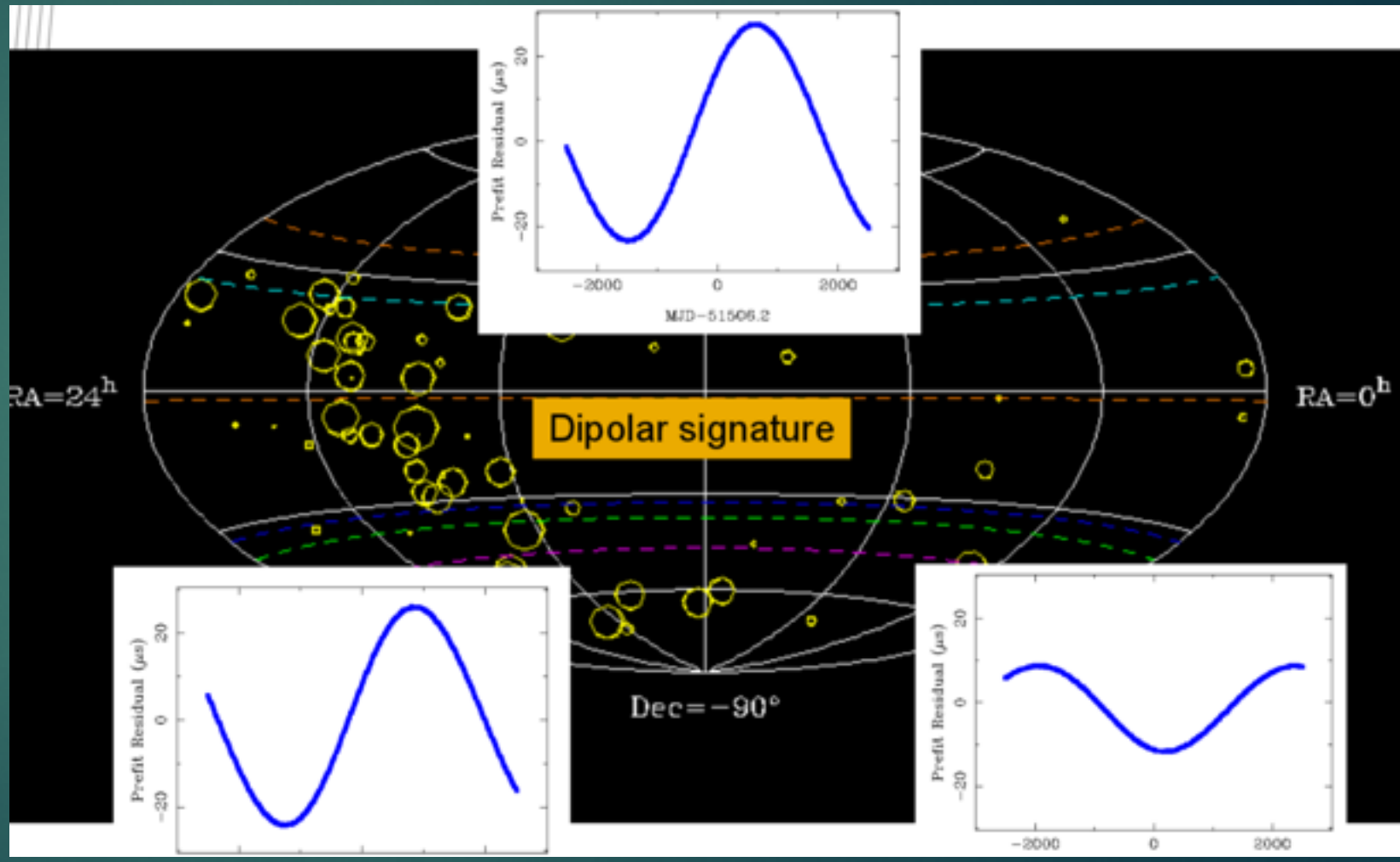

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And Gravitational Waves!
(Quadrupole correlation)

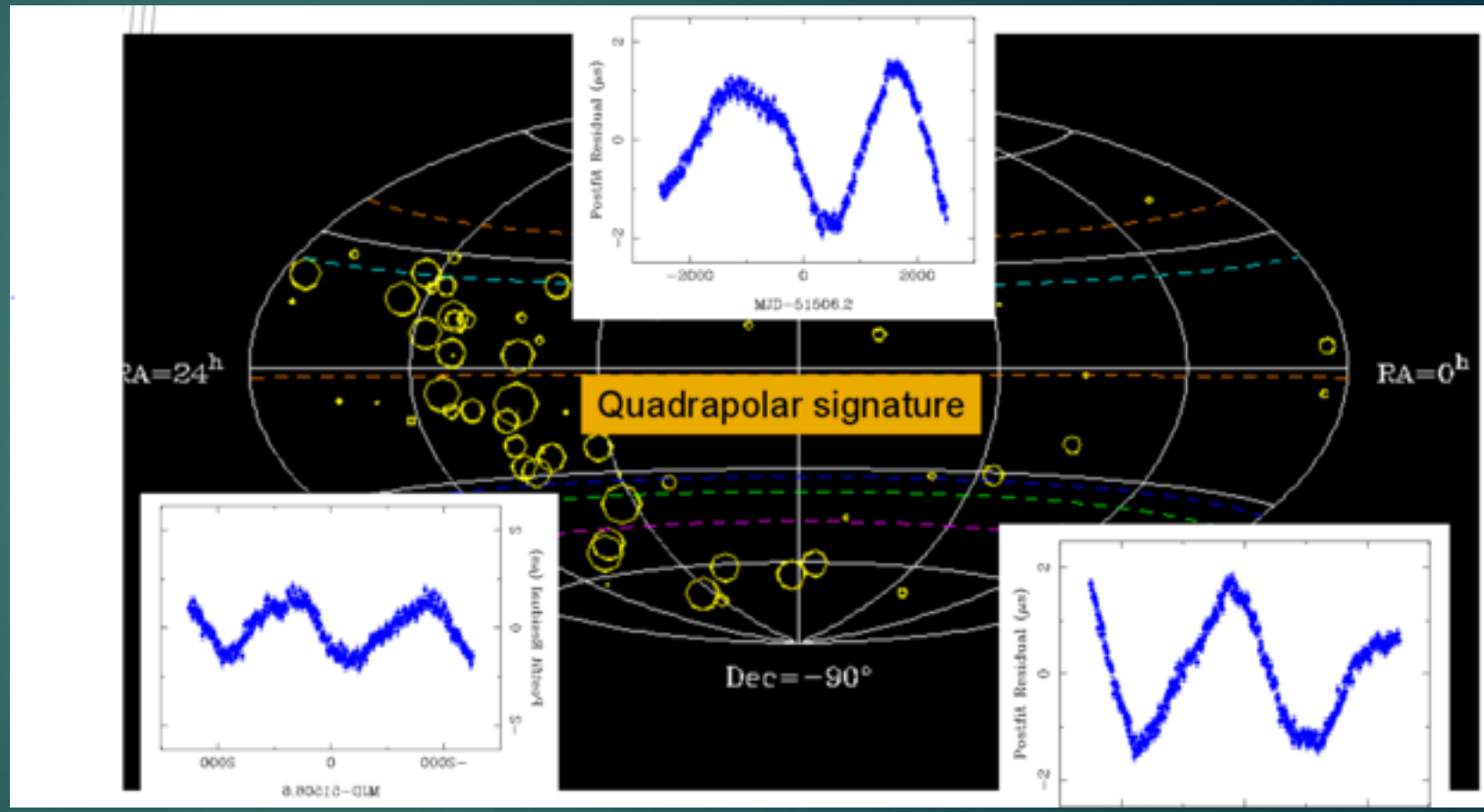
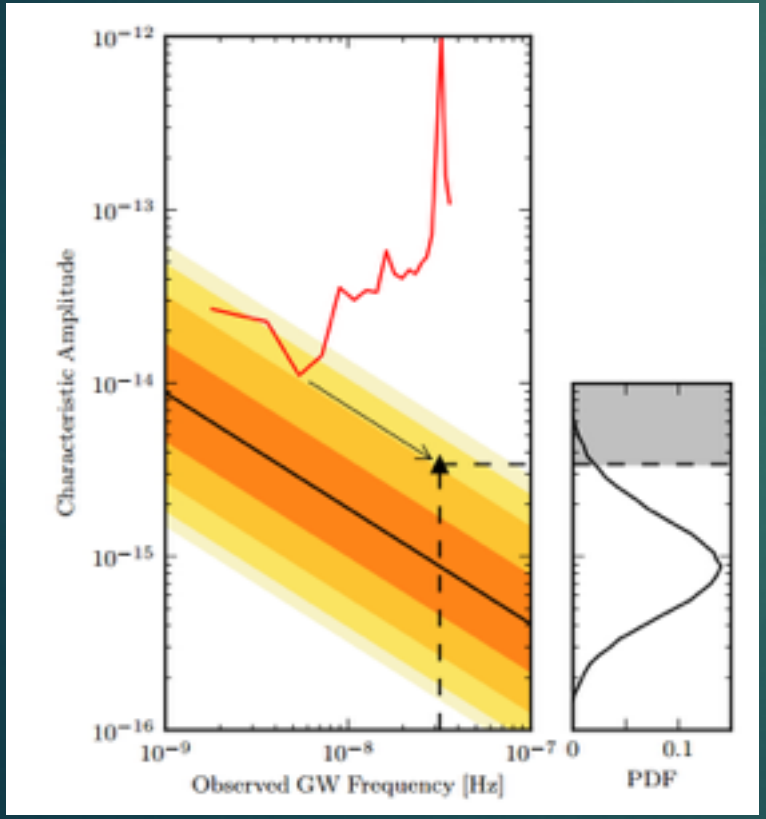


Image credit: George Hobbs

Isotropic Background Limits

All contributions correlated in the data (Tiburzi 2015)

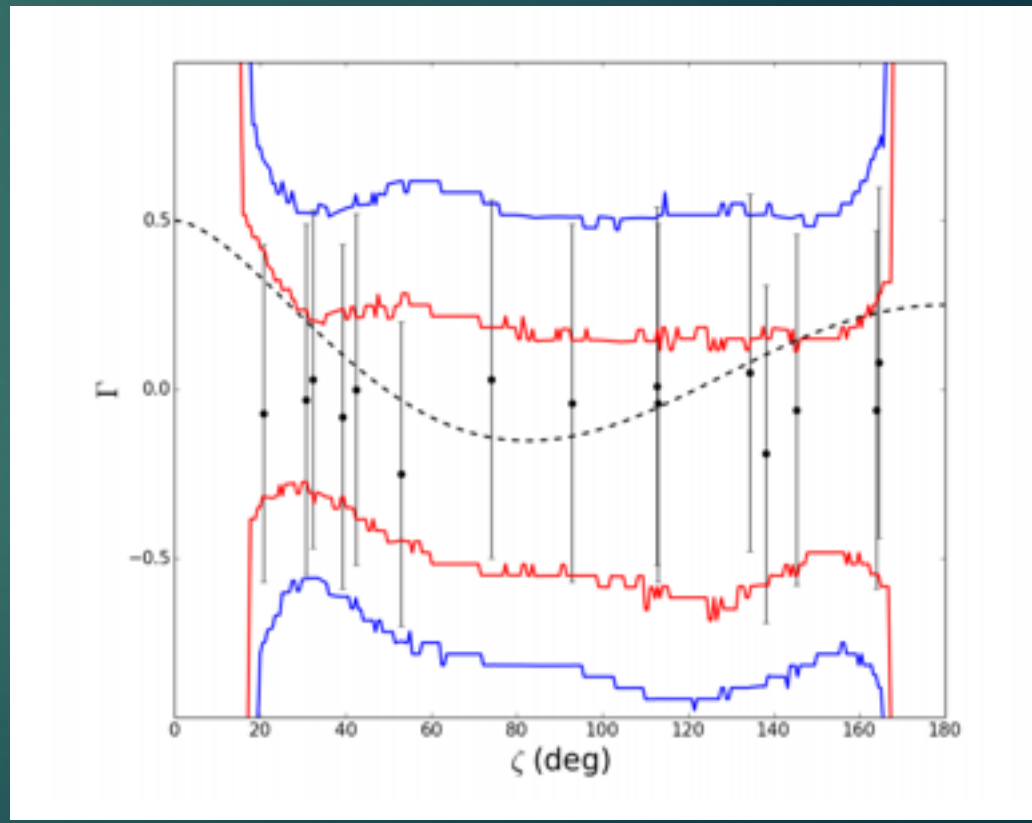
EPTA limit – Simultaneously estimate contributions from these four sources of correlated noise.
Use best six pulsars from EPTA 2015 data set (See talk by G. Desvignes previously)
18 years of data



Figures: Lentati et. al. 2015

Power Law Limit:
$A < 3E\text{-}15$ at $f=1yr^{-1}$
2x better than last EPTA limit

Directly obtain confidence intervals on correlation between signals – consistent with anything



For Astrophysical interpretation see Alberto Sesana's upcoming talk

Anisotropic Stochastic Background

Distribution of sources likely not isotropic.

Use spherical harmonics to model distribution of power on the sky.

Additional prior:
Amplitude is positive!

Pixelate sky model – keep only solutions with:

$$P(\hat{\Omega}) \propto \frac{dN}{d\hat{\Omega}} \propto \sum_{l,m} c_{lm} Y_{lm}(\hat{\Omega}) \geq 0, \quad \forall\, \hat{\Omega}.$$

See:
Mingarelli et. al. 2013
Taylor & Gair 2013

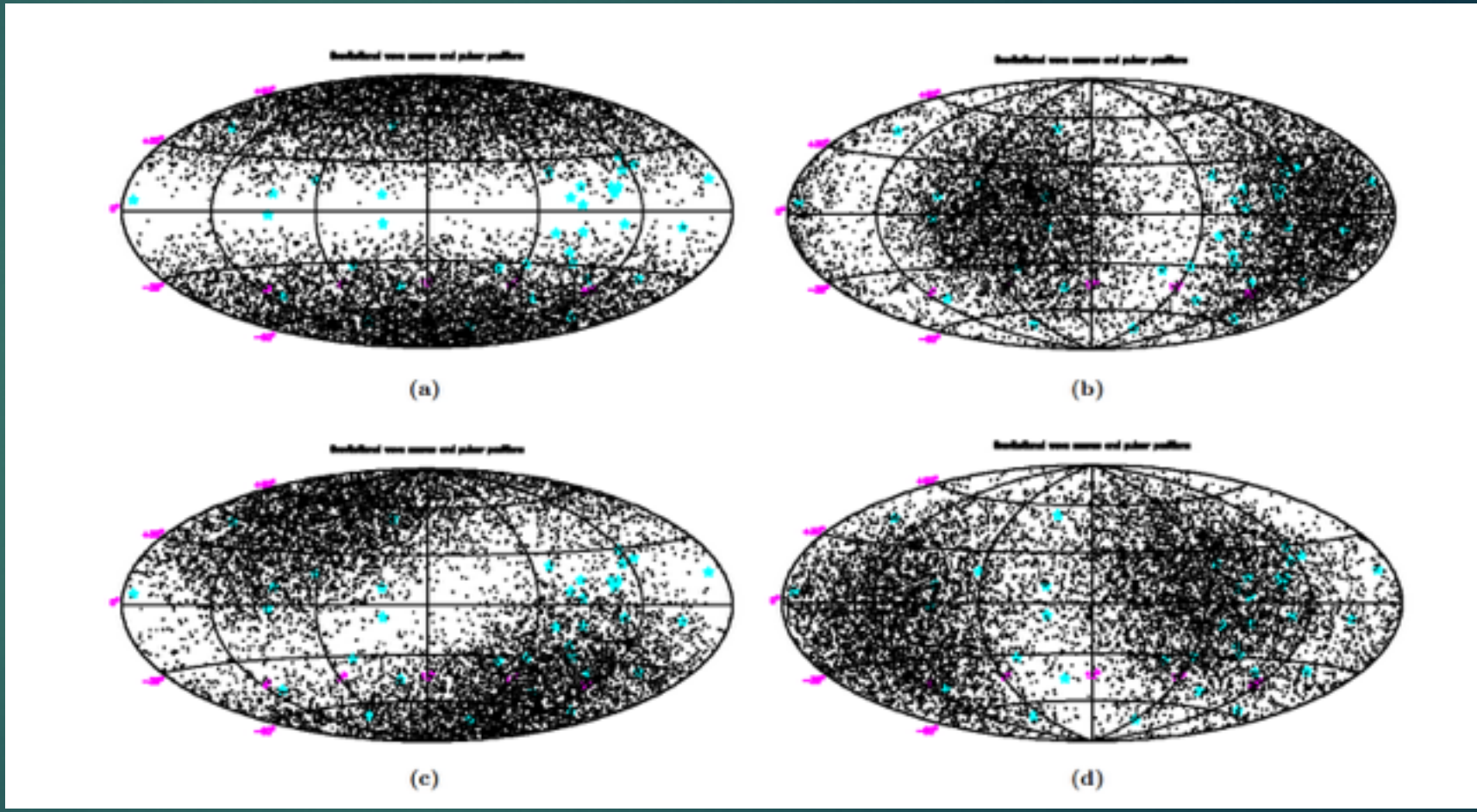


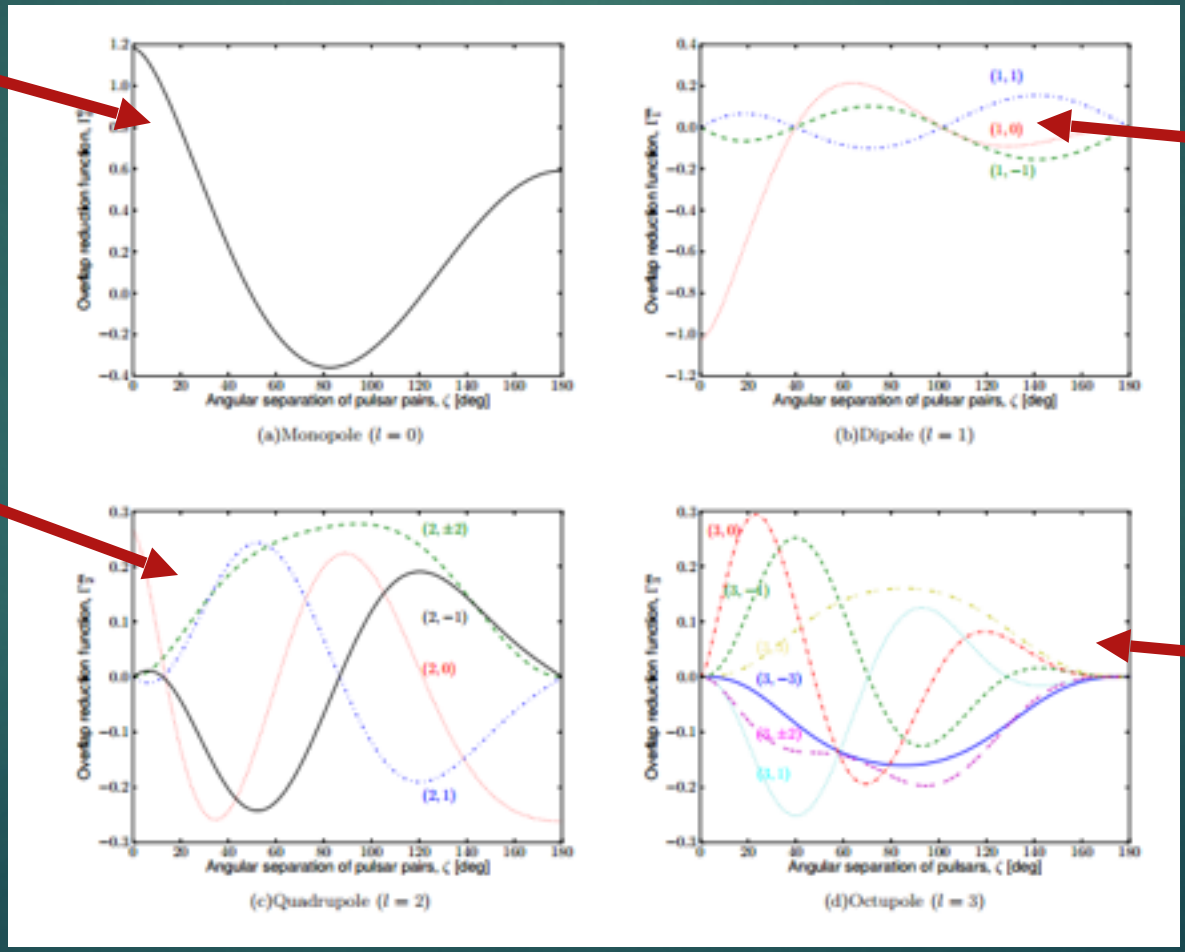
Figure: Taylor & Gair 2013

Anisotropic Stochastic Background

Different Spherical harmonic components give different correlations.

Monopole (Isotropy)
Gives Hellings-Downs curve.

Quadrupole

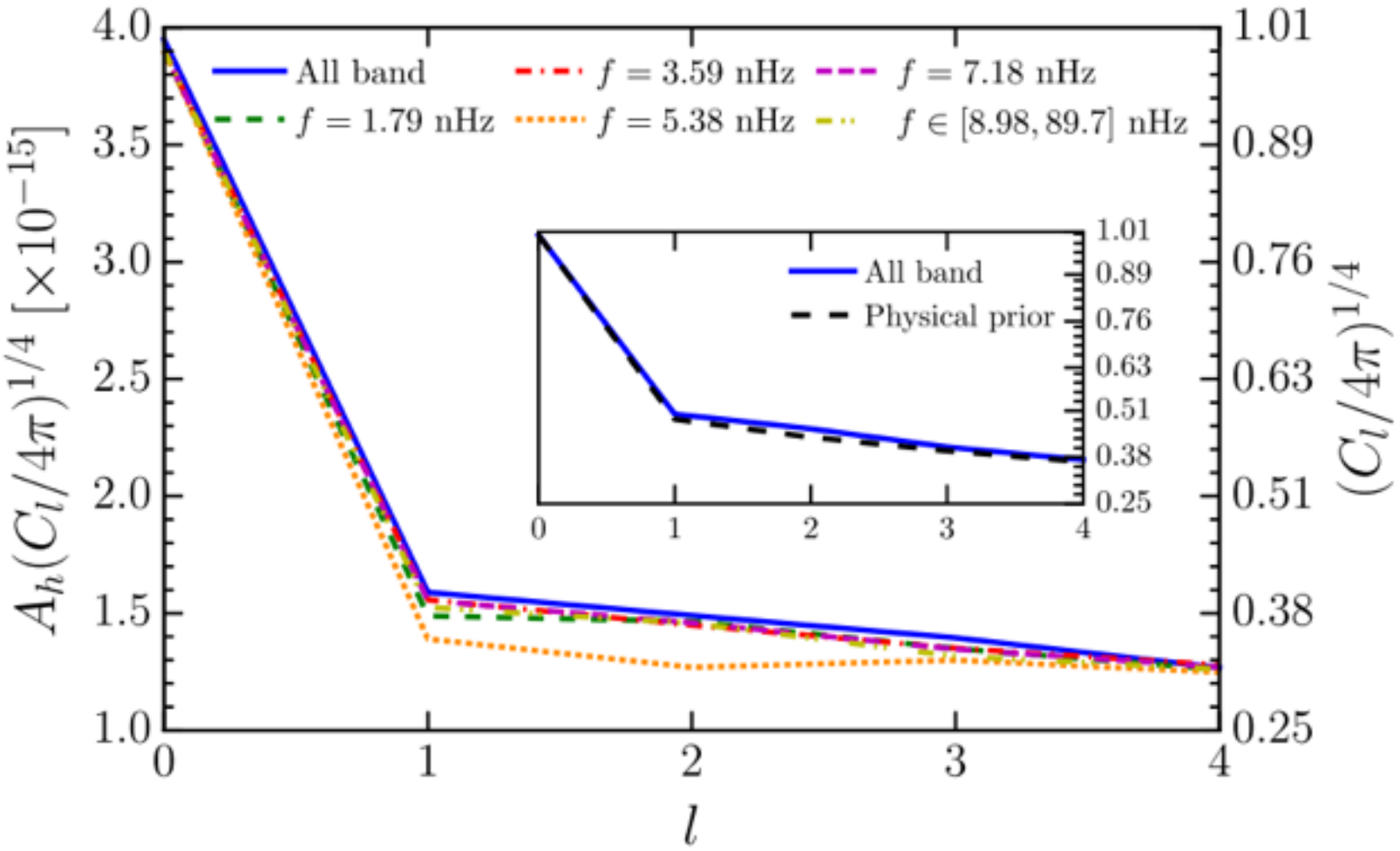


Dipole

Octopole

Figure:
Mingarelli et. al. 2013

Anisotropic Limits – EPTA 2015 Dataset

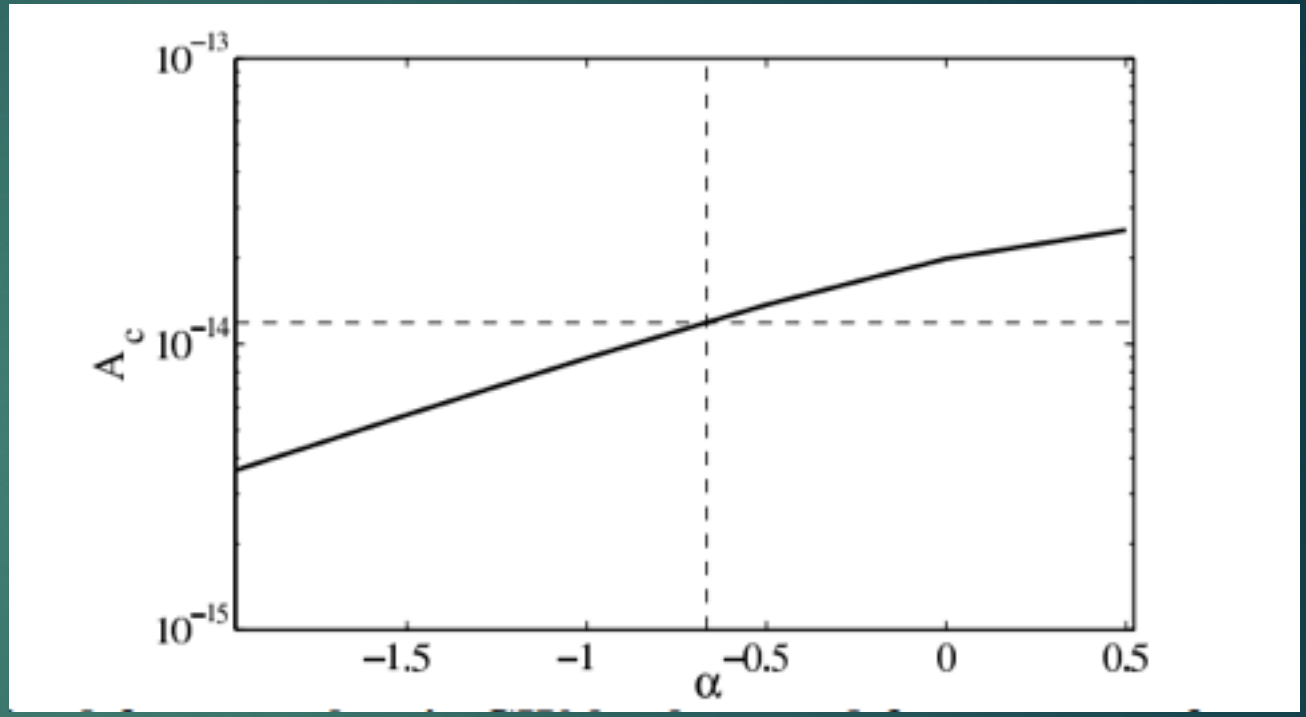


Data provides no constraints on anisotropy (yet!).

Upper limits at each scale the result of physical prior.

Figure:
Taylor et. al. 2015

Future Prospects - LEAP



3 years of data with 4 pulsars:
Limit = 1.2×10^{-14}

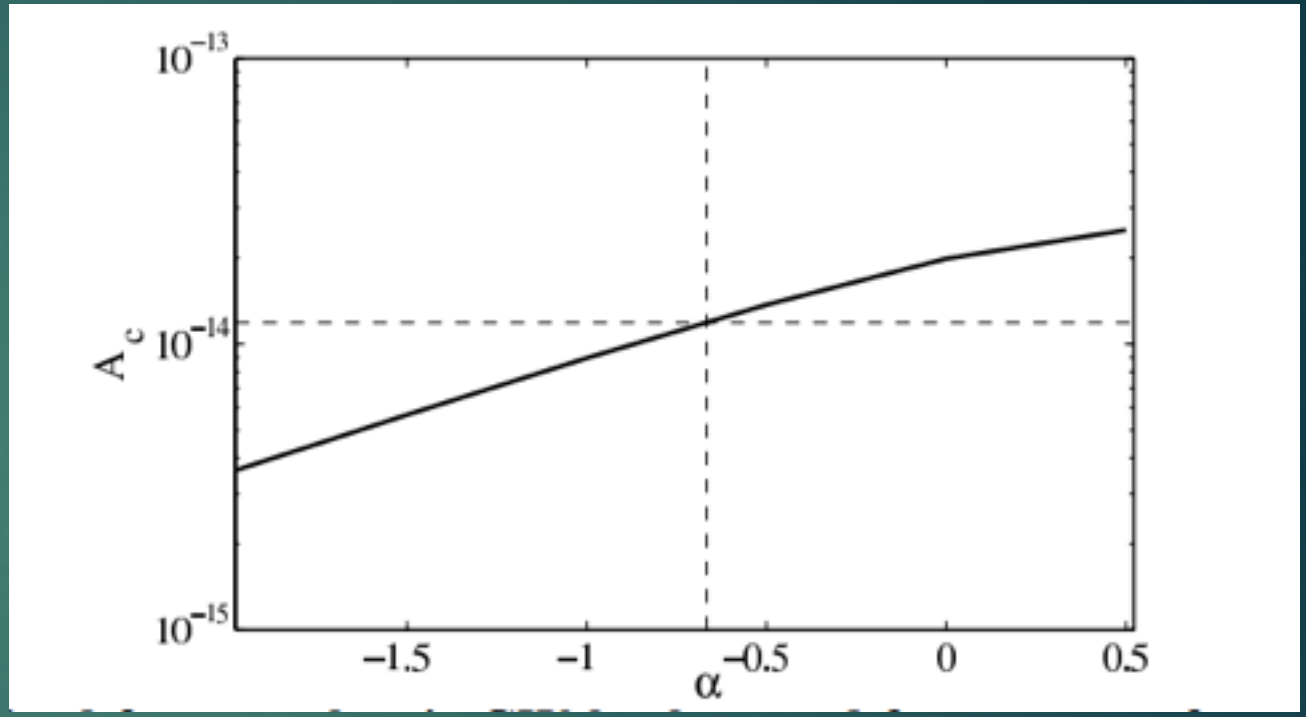
Assuming standard scaling laws will better current limits in another 3 years.

Future Prospects - LEAP

- Coherently add pulsar observations from the five 100m-class European telescopes.

- Comparable in aperture to the illuminated Arecibo dish, but able to cover – 30 < dec < 90.

- See Bassa et al 2015 for details.
- Monthly observations of 23 pulsars.
- Now approximately 4 years of data.



3 years of data with 4 pulsars:
Limit = 1.2×10^{-14}

Assuming standard scaling laws will better current limits in another 3 years.

Future Prospects - New Systems

All current EPTA limits from legacy data only (old systems).
All telescopes have new, more sensitive observing systems.

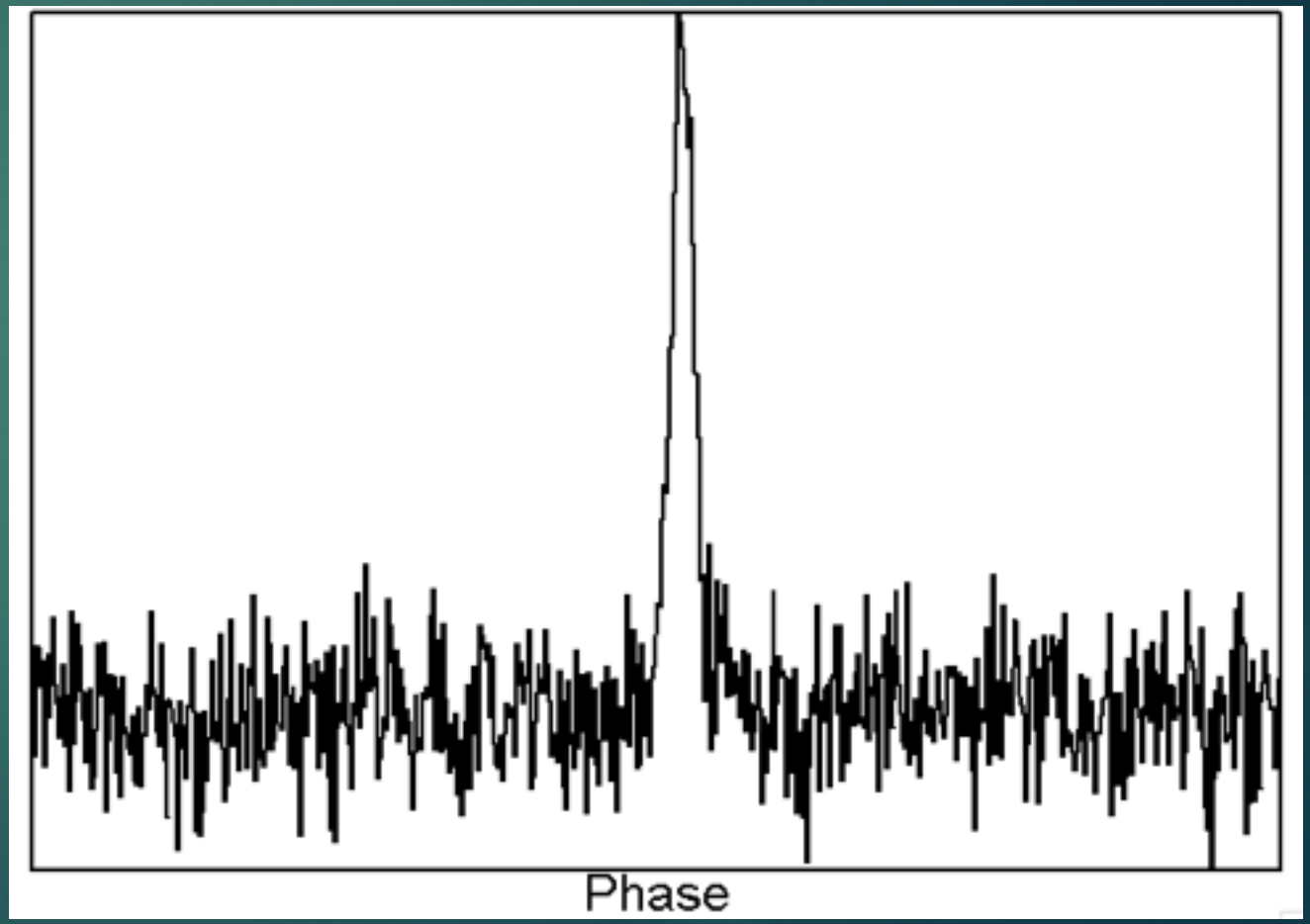
E.g. Westerbork 8 years 300-1400MHz
Jodrell Bank, Nançay and Effelsberg 4-5 years new data

In combination with LEAP, significant improvement in GW limits to be expected with the next EPTA data set.

Improvements to methodology

Quick recap: Making ToAs:

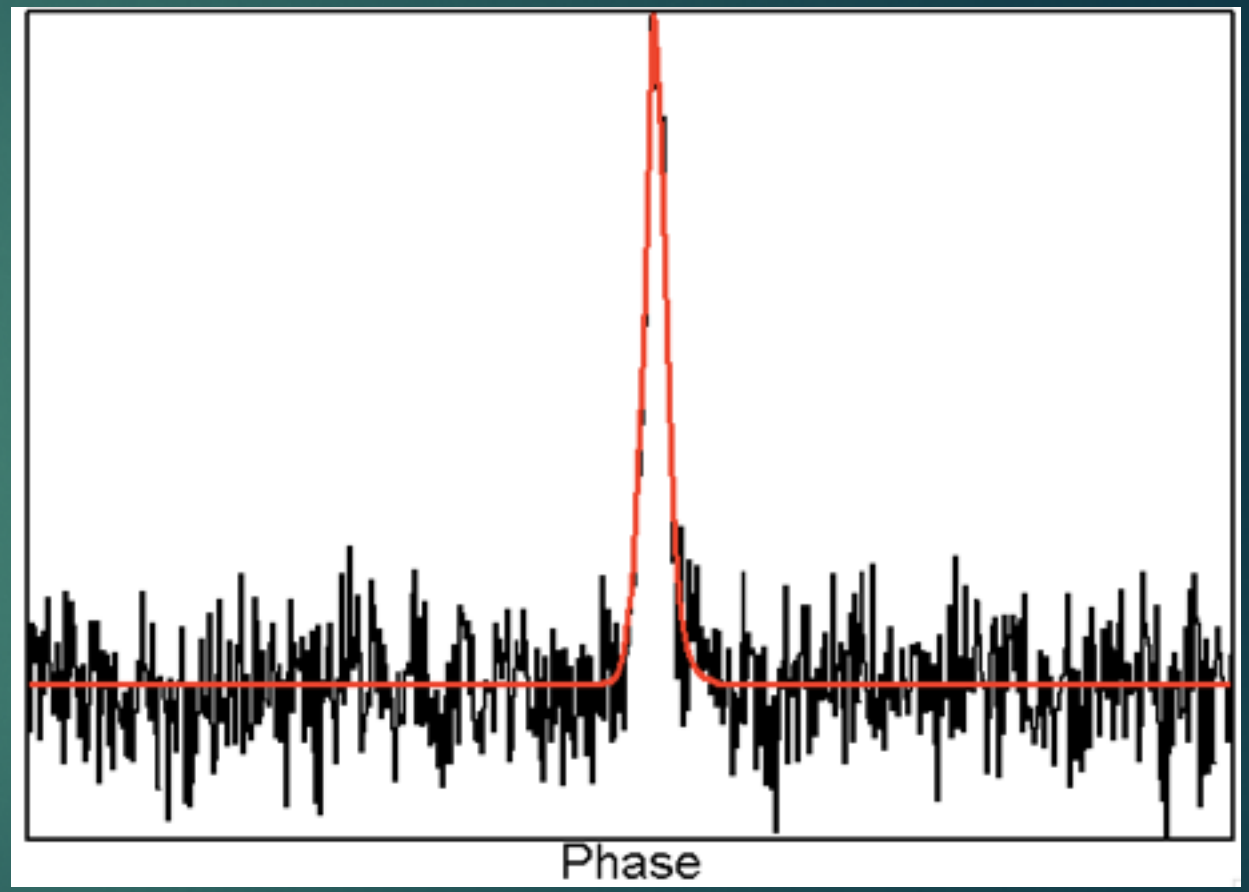
1) Make an observation
2) Fold single pulses to get average profile



Improvements to methodology

Quick recap: Making ToAs:

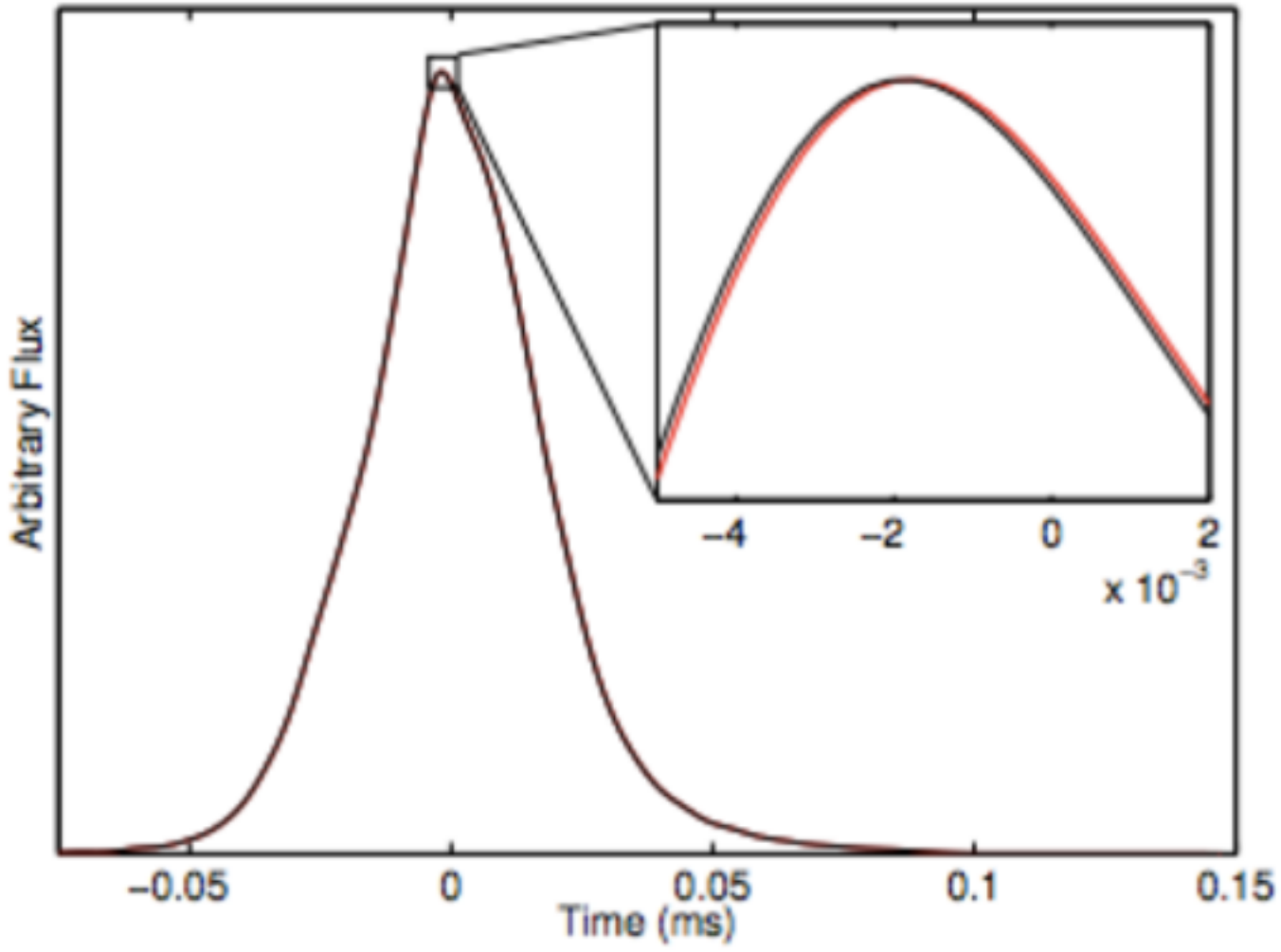
1) Make an observation
2) Fold single pulses to get average profile
3) Take a model for your average profile
4) Fit for arrival time



Assumptions: Noise is uncorrelated, Gaussian
Profile shape is stationary

Both Often Wrong!

Improvements to methodology



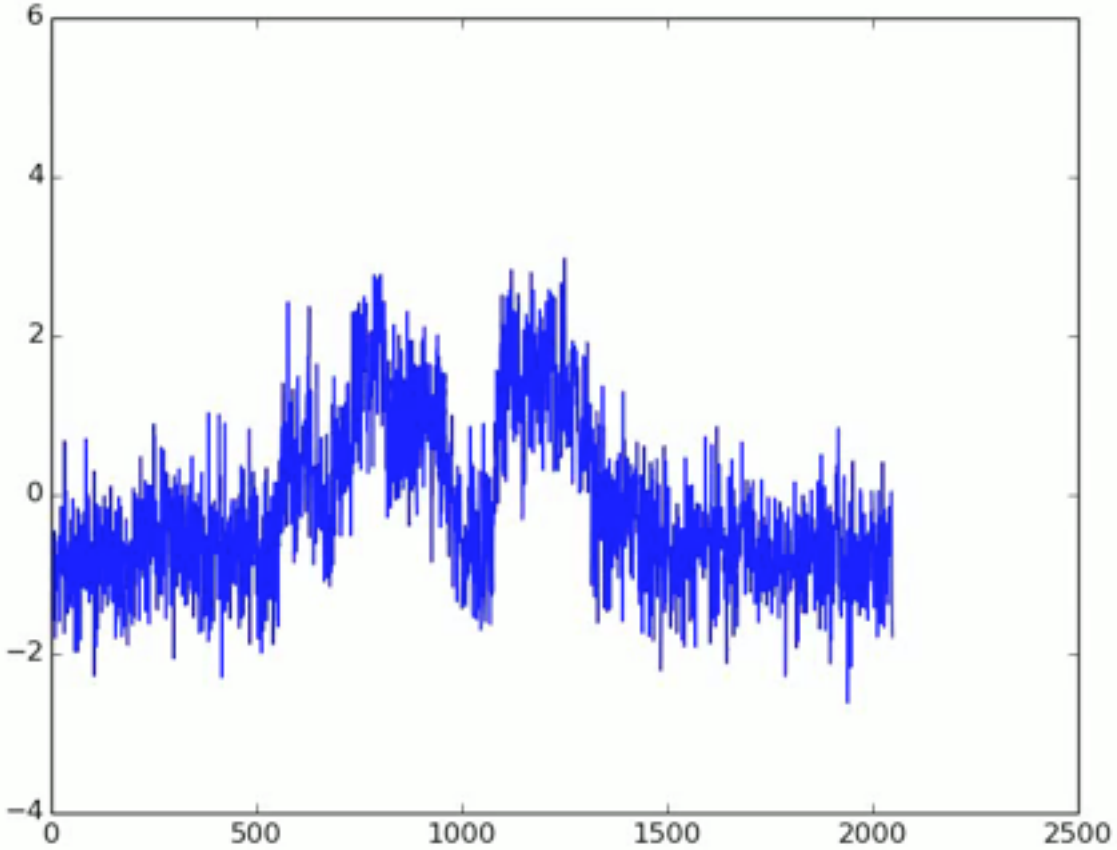
Detecting GWs is hard!

100ns perturbation to arrival time.

Much less than a phase bin even in new observations

Improvements to methodology

Profile Residuals at 10cm for the MSP PSR J0437-4715



Gross!

Definitely not white..

Lots of shape variation (intrinsic/calibration)

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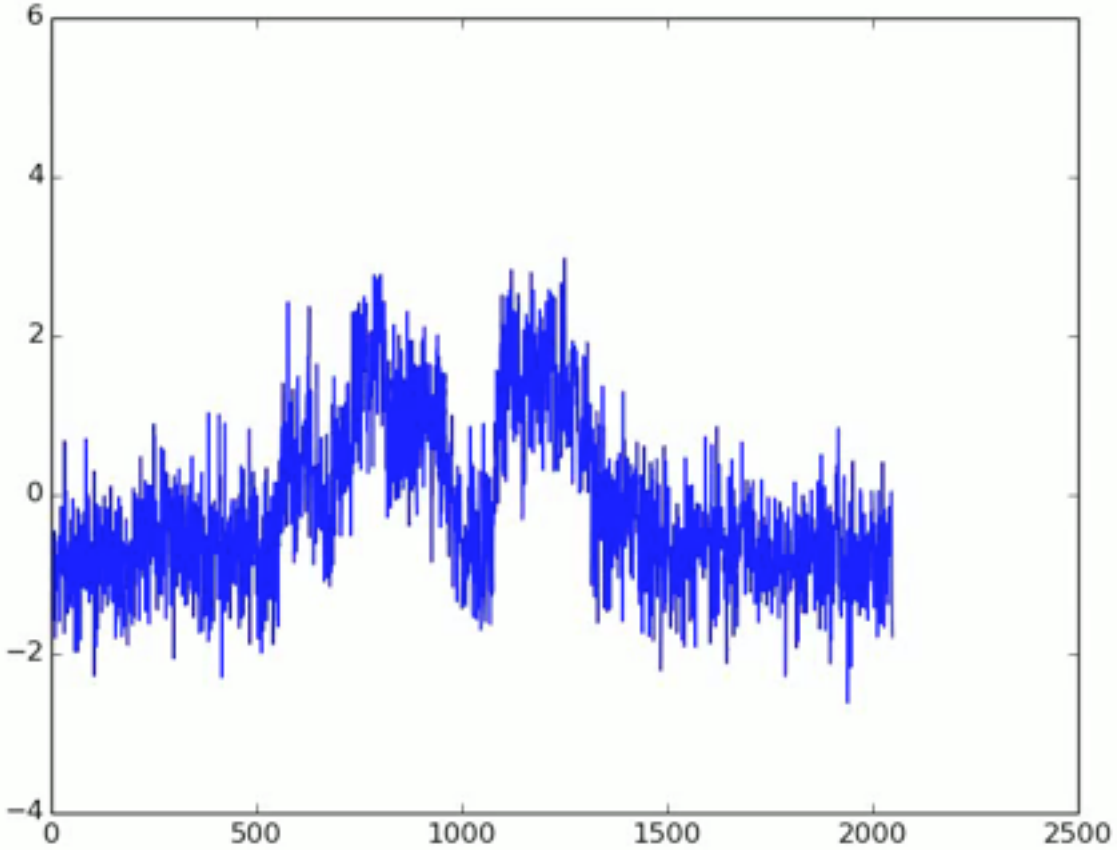

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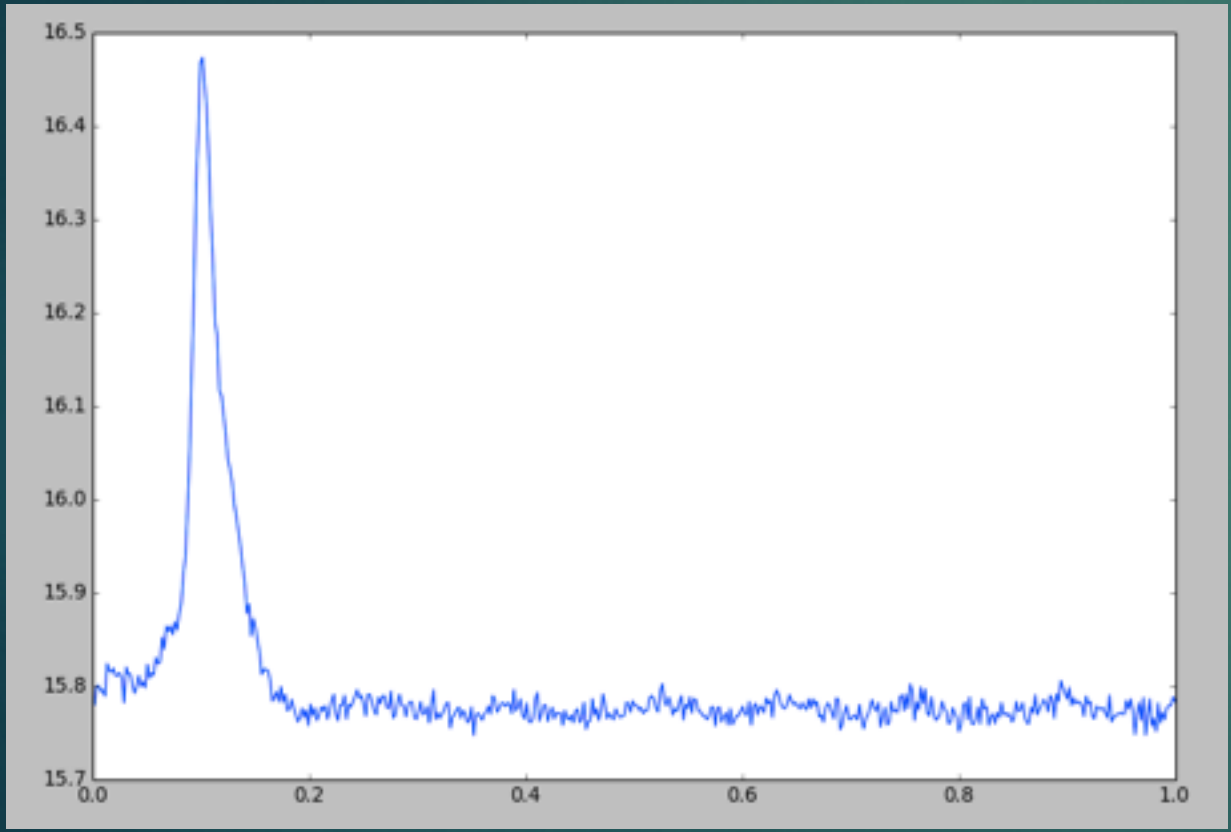
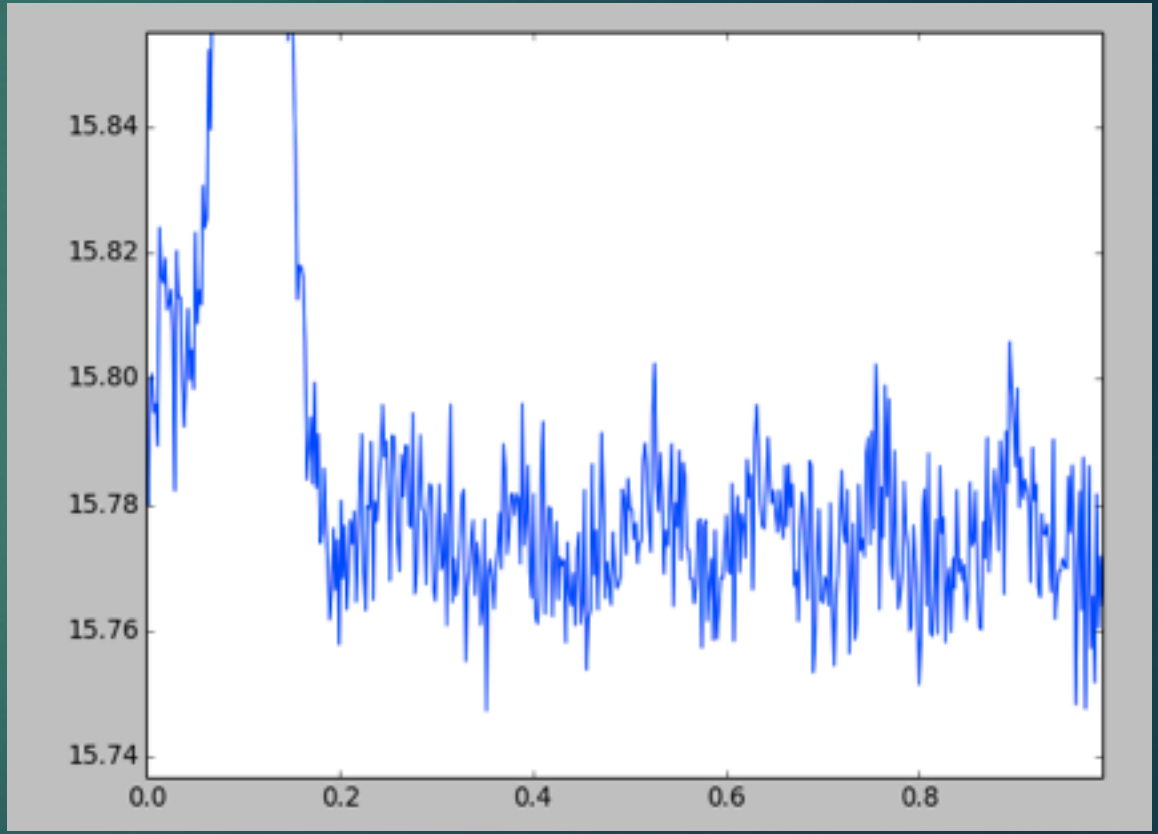
Improvements to methodology

Correlated profile noise
PSR J1713+0747 at 1.4GHz with Nançay



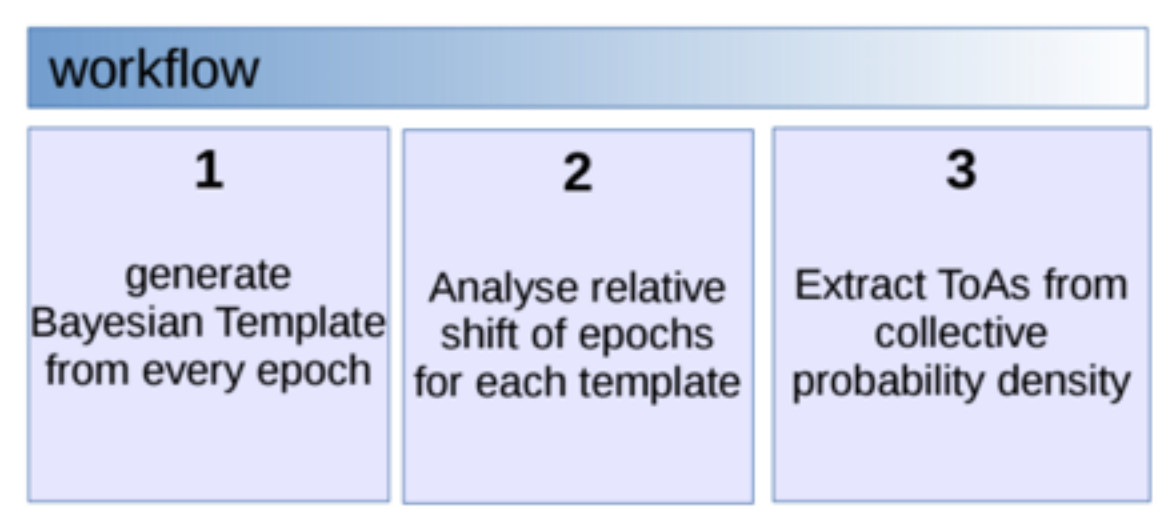


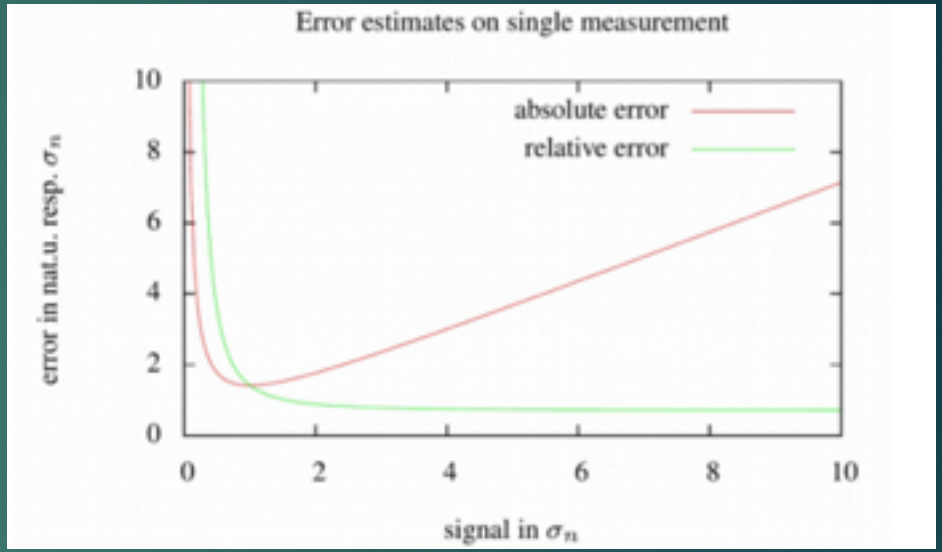
All impacts on arrival time at the same level as GWs

Improvements to methodology - I

Bayesian Template Generation

Imgrund et al., 2015MNRAS.449.4162I



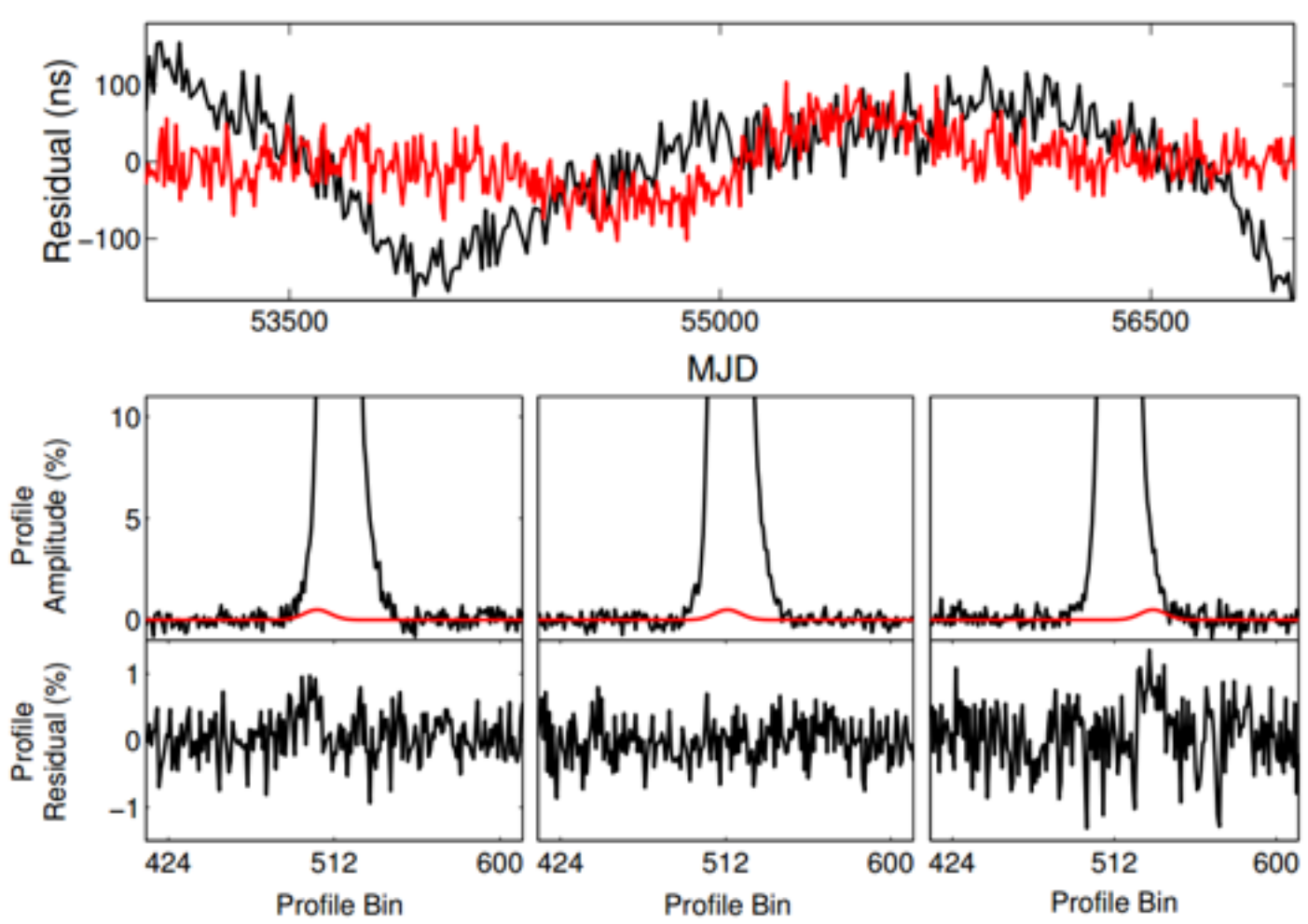


Example: Classical: 1422ns RMS, 28 red.Chi
Bayesian: 1189 ns RMS 1.5 red. Chi

brightest signals have **largest errorbars**
single **pulses vary**
→ just **integrating destroys information**

Improvements to methodology - II

Profile Domain Analysis:



Don't make time of arrivals.
Work directly with profile data.

Model profile, shape variation etc simultaneously with timing analysis.

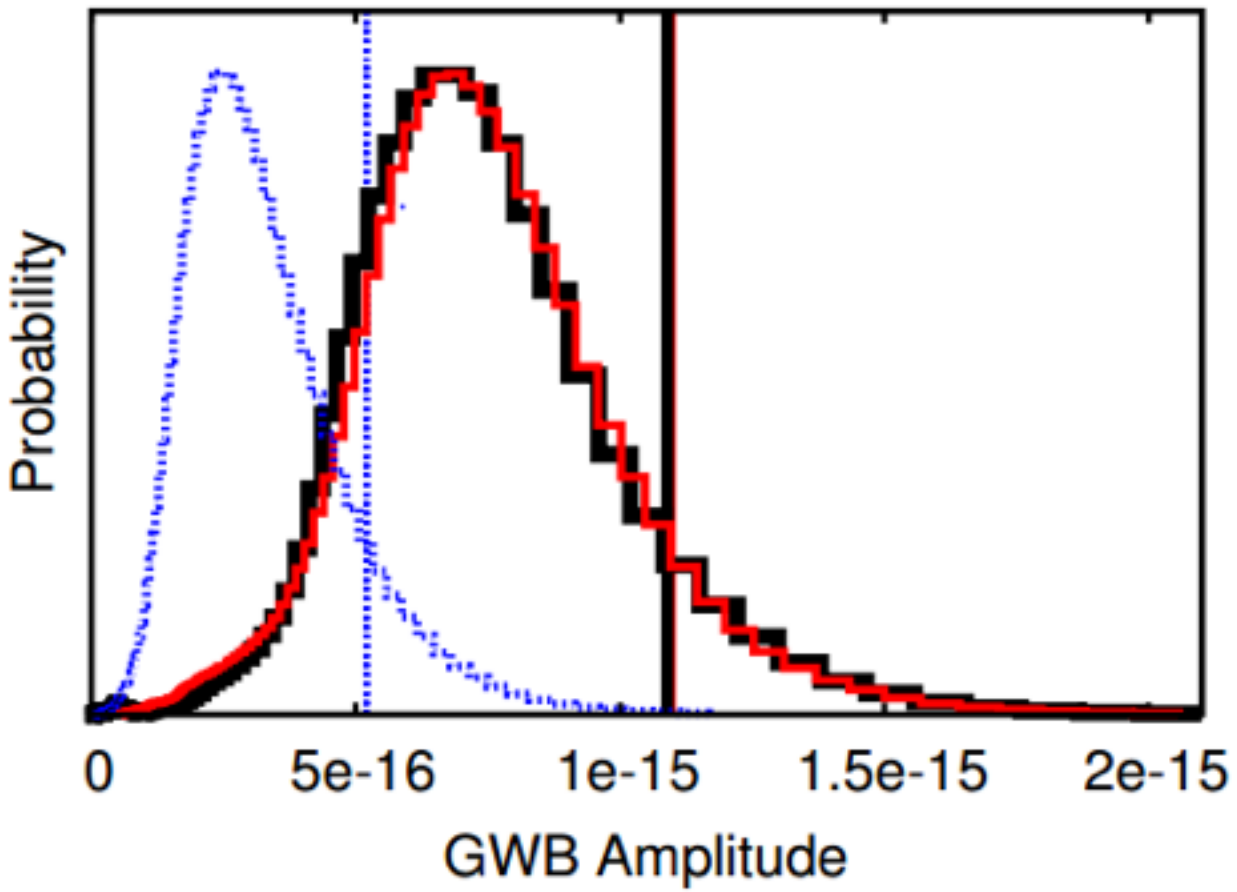
Lentati, Hobson & Alexander 2015
Lentati & Shannon 2015

Shape Variation in profile data results in shifts in arrival times.

Standard analysis: Shifts and shape change totally covariant.
Profile domain: Shifts and shape change decoupled.

Improvements to methodology - II

Profile Domain Analysis:



Standard analysis: Shifts and shape change totally covariant.
Profile domain: Shifts and shape change decoupled.

Upper limits significantly improved in the presence of shape variation.

From Previous Simulation

Summary

EPTA Isotropic Limits – 3E-15
- Include models for clock and errors in solar system ephemeris

First Anisotropic limits

All using just the legacy data.

Many years of new data waiting to be added in.
LEAP also producing ToAs, can be included in EPTA limit.

New Bayesian analysis techniques – improving sensitivity to GWs:
- Template generation
- Profile domain timing

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Cheers