Limits On The nHz Gravitational Wave Universe From Pulsar Timing Arrays

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..and why they're limits.

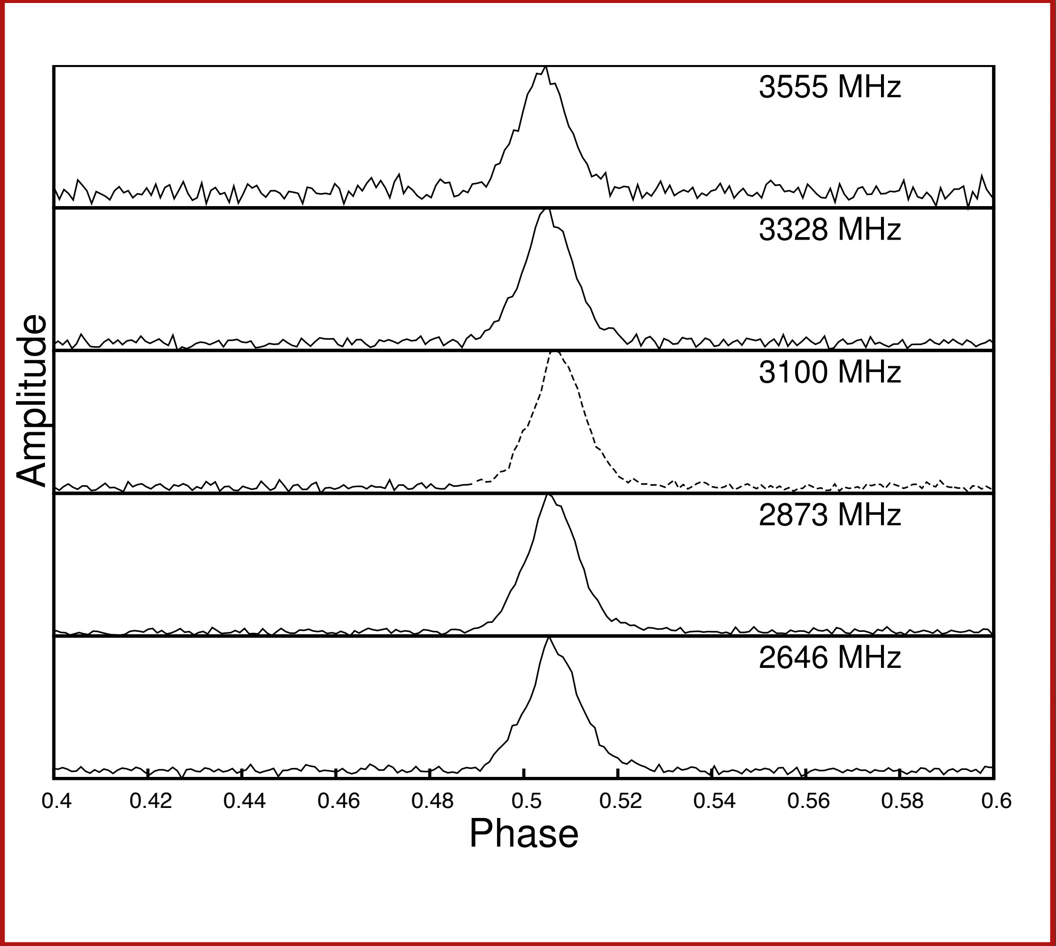
- Data problems:
  Understanding your instrument (the pulsar)

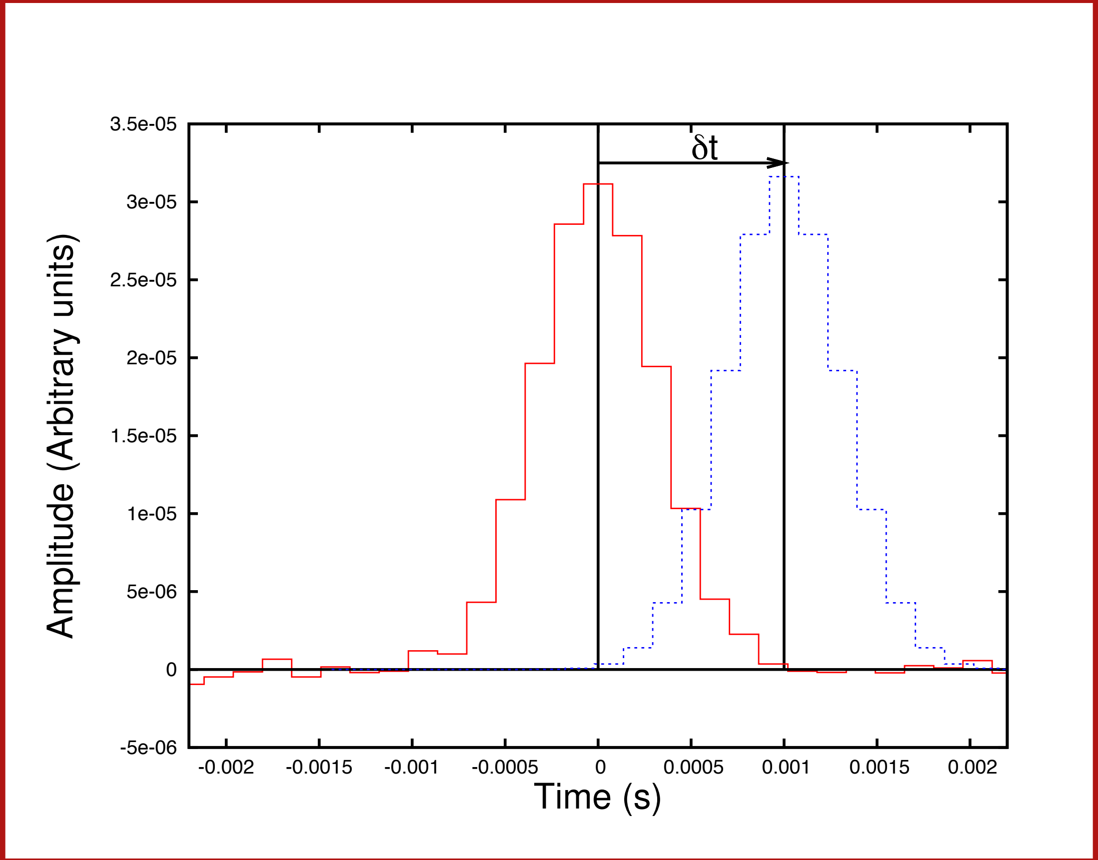
- Astrophysical problems:
  Current limits getting interesting/depressing

- Computational problems:
  High dimensionality
  Big data sets

Pulsar Timing

A single observation gives you an integrated pulse as a function of frequency.
Standard timing practice - Fit a template to that pulse to determine its arrival time and uncertainty.

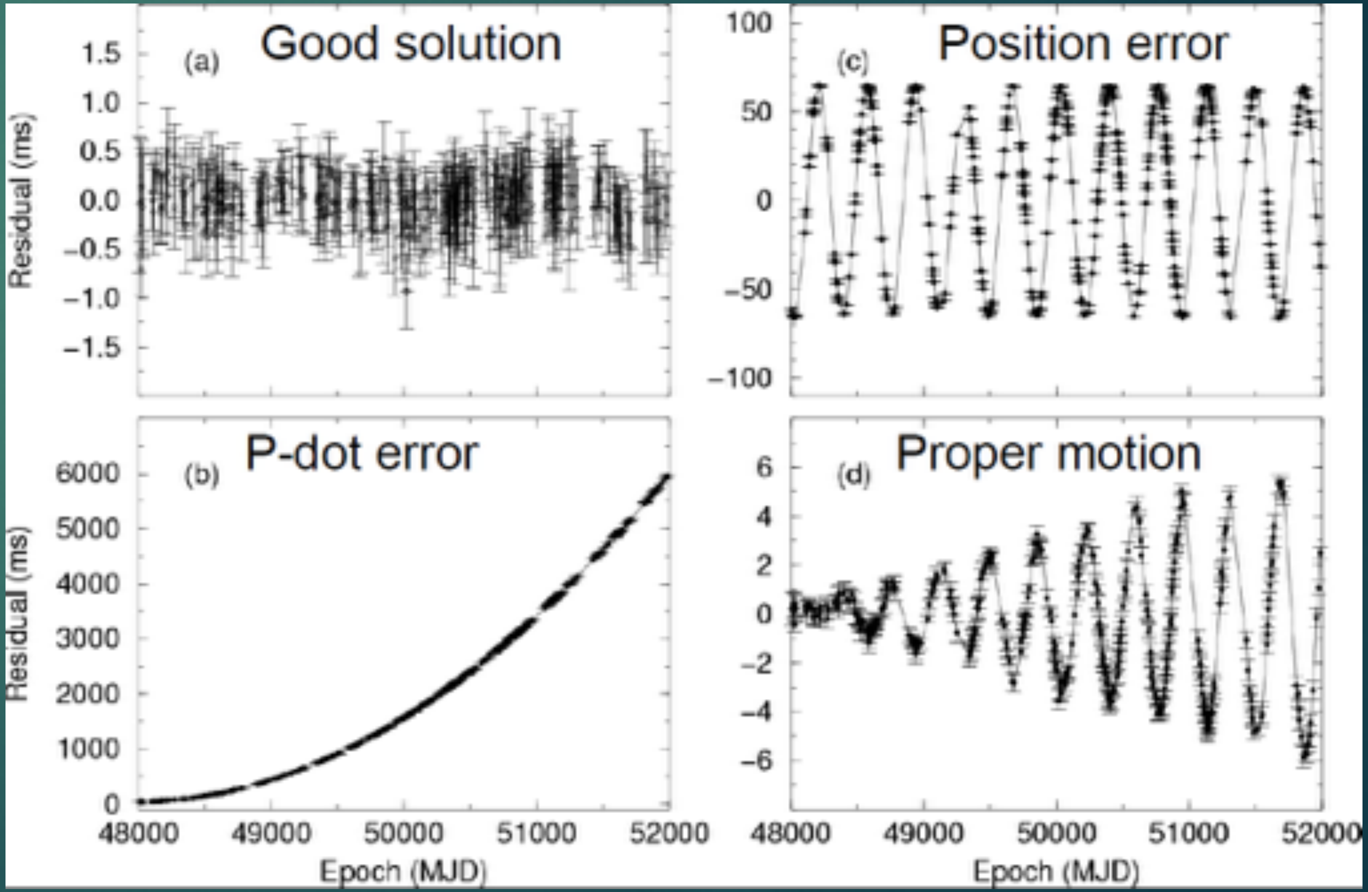




Pulsar Timing

End up with a list of arrival times.
Fit a model to those arrival times that describes the rotation of the pulsar.
Unambiguously account for every rotation of a pulsar over years.

```
fake.rf 1440.00000000 50000.5596442486829569 0.01000
fake.rf 1440.00000000 50014.5214183779942054З 0.01000
fake.rf 1440.00000000 50028.4831922727260185O 0.01000
fake.rf 1440.00000000 50042.4449662034725925З 0.01000
fake.rf 1440.00000000 50056.4067401774566192 0.01000
fake.rf 1440.00000000 50070.368514094175029 0.01000
fake.rf 1440.00000000 50084.3302880027247674 0.01000
fake.rf 1440.00000000 50098.2920619810354061 0.01000
fake.rf 1440.00000000 50112.2538359119632716 0.01000
fake.rf 1440.00000000 50126.2156098206822960 0.01000
fake.rf 1440.00000000 50140.1773837585983955 0.01000
fake.rf 1440.00000000 50154.1391576939677108 0.01000
```



Pulsars are very precise clocks

E.g. PSR J0437-4715

At 00:00 UT Jan 18 2011

Period = 5.7574519420243 ms
+/- 0.0000000000001 ms

Last digit changes by 1
every half hour

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At 00:00 UT Jan 18 2011

Period = 5.7574519420243 ms
+/- 0.0000000000001 ms

Last digit changes by 1
every half hour

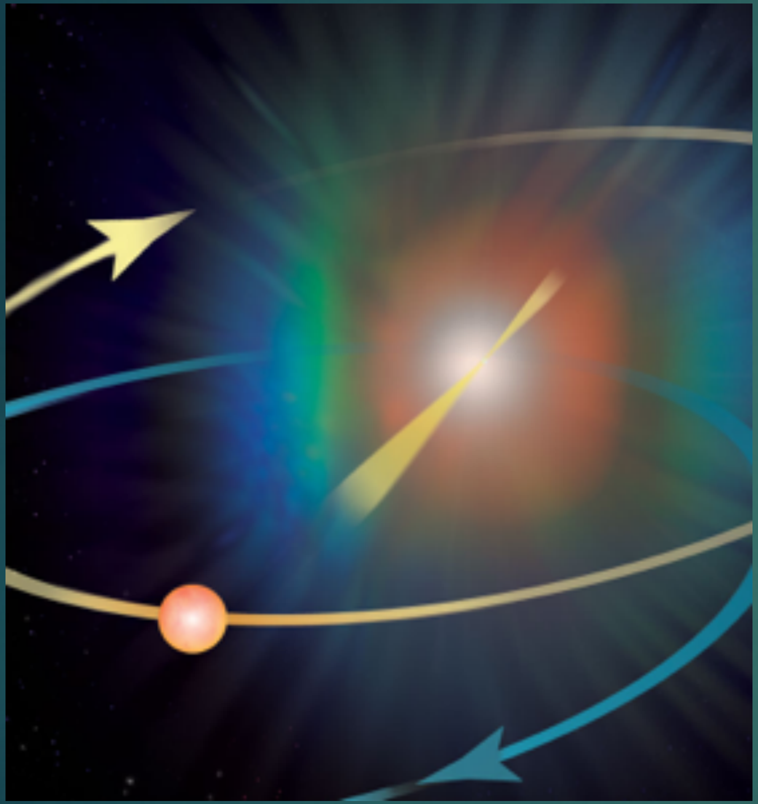
Pulsar is a binary:
Orbital radius about
1.44 x the sun's radius
($\sim 10^{11}$ cm)

Extremely circular:
Difference between the semi-major
and semi-minor axes measured
through timing to be:

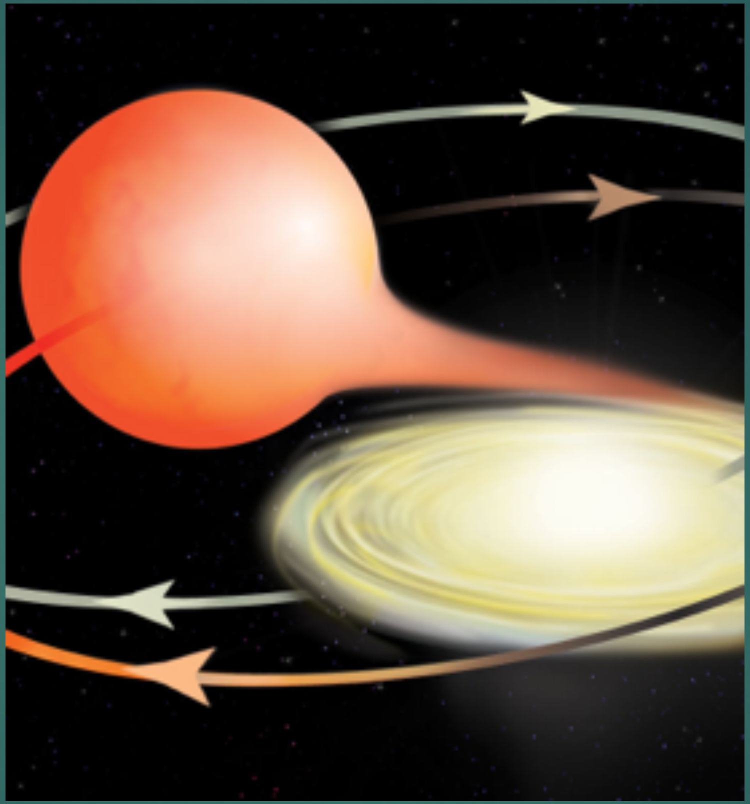
18.59 +/- 0.01 cm

Can use this precision to do incredible science

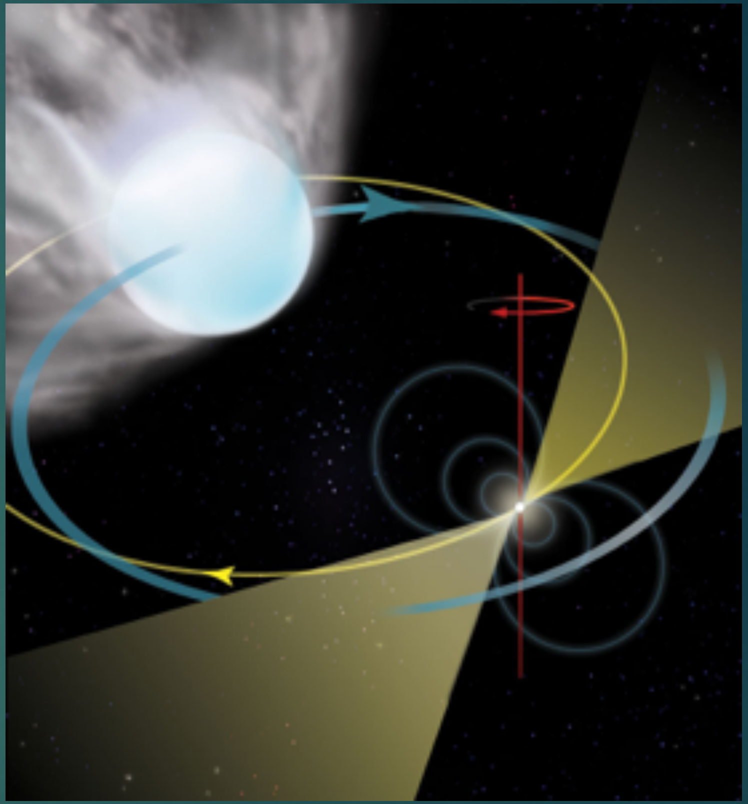
Millisecond Pulsars



Supernova produces neutron star



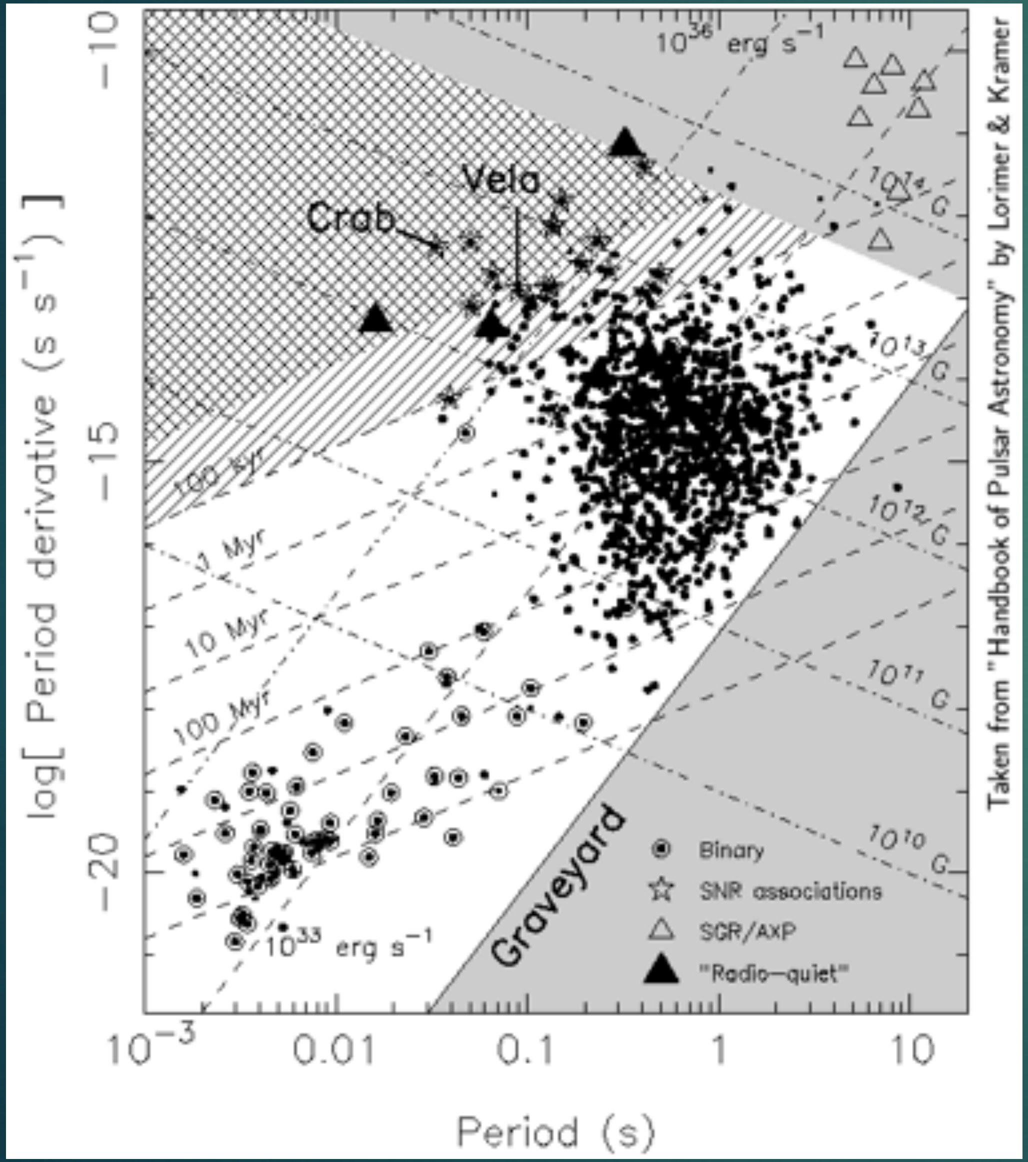
Companion red giant transfers matter to neutron star



Neutron star 'spun up' to millsecond periods

Figs: NRAO

Millisecond Pulsars



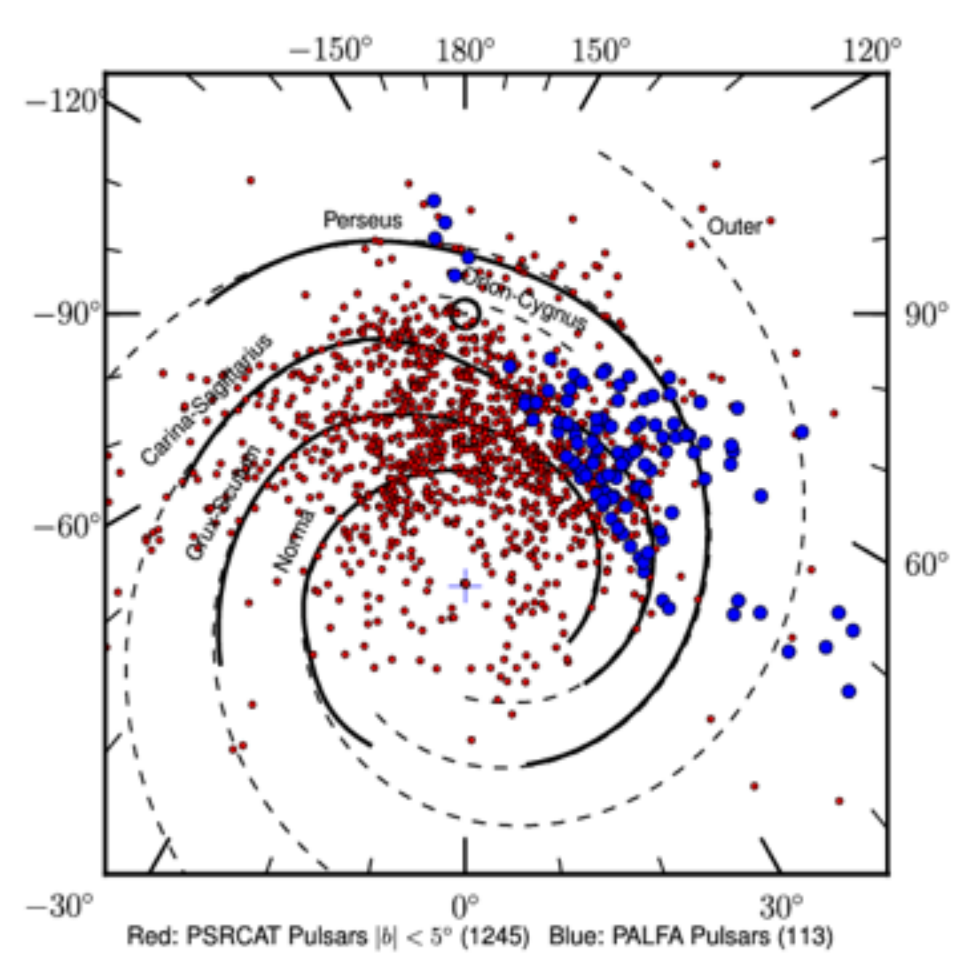
Compared to slow pulsars:

Smaller magnetic fields
Smaller period derivative
-> More Stable rotator

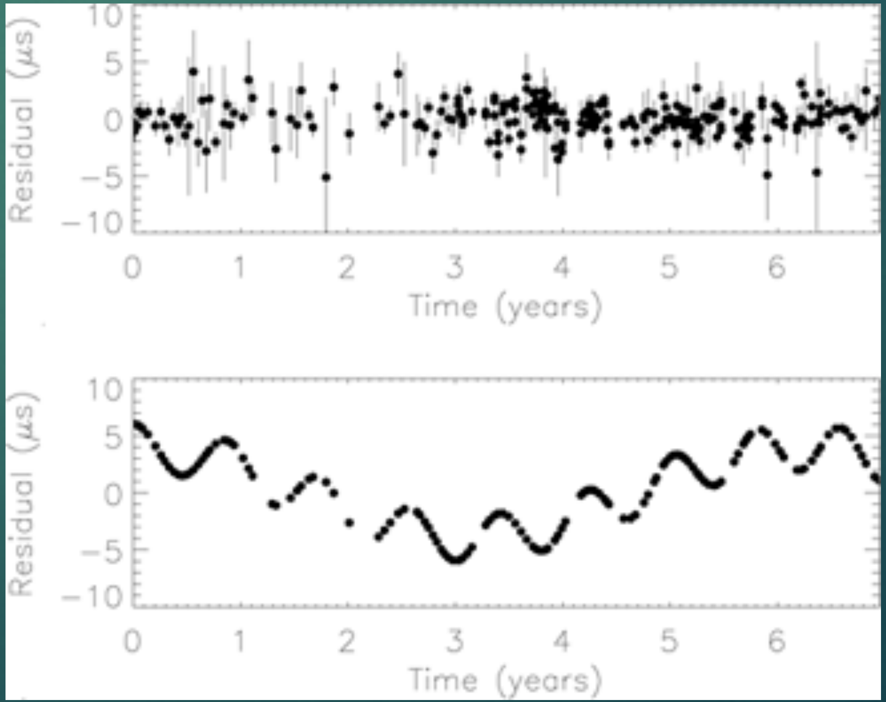
Lots of binary MSPs
Not many binary slow pulsars

Using Pulsars to detect Gravitational Waves

- Also far away ~ 1kpc = $3x10^{19}$ meters

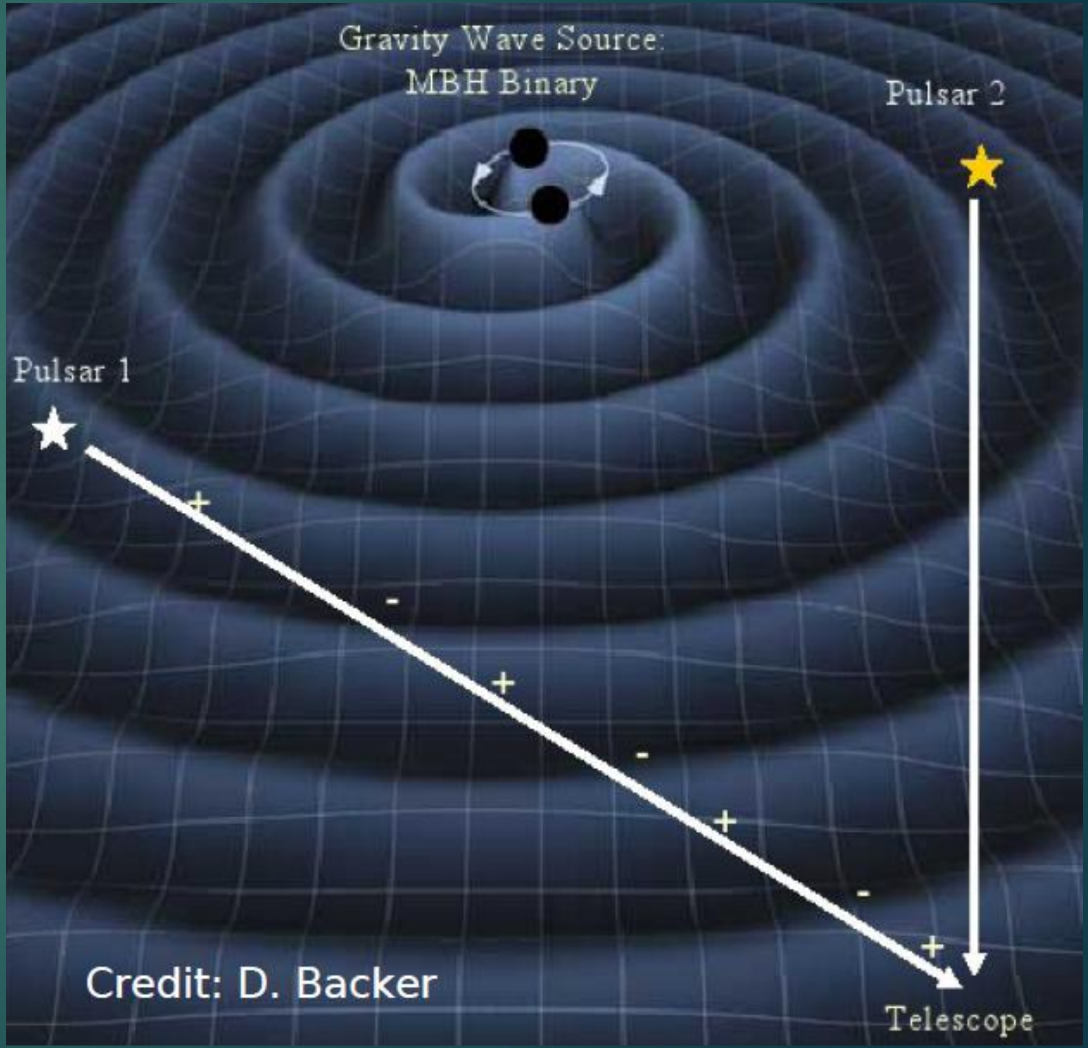


- Change in path length from GWs:
- ~ few hundred meters = few tens of ns



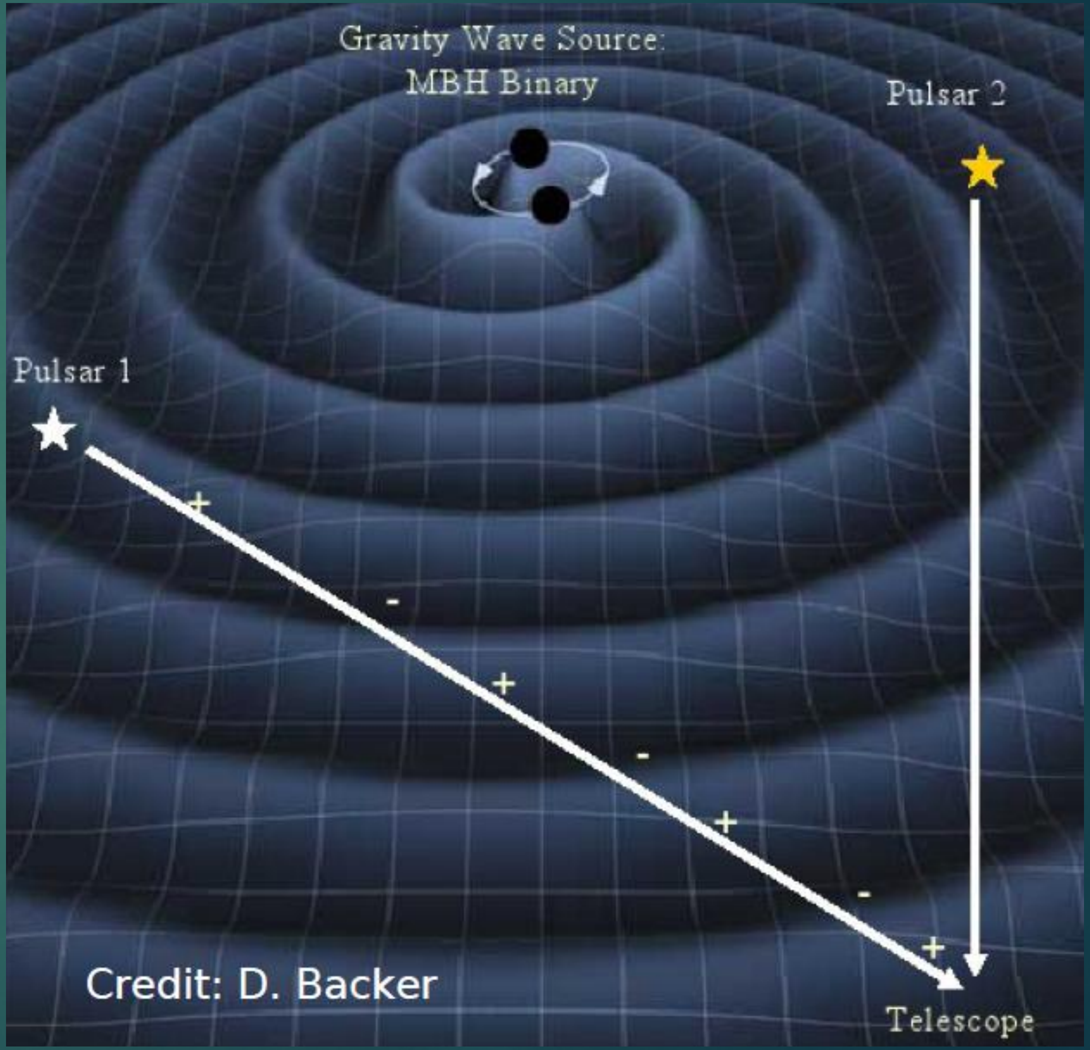
Using Pulsars to detect Gravitational Waves

- Analogy to LIGO :
- pulsars are arms of detector



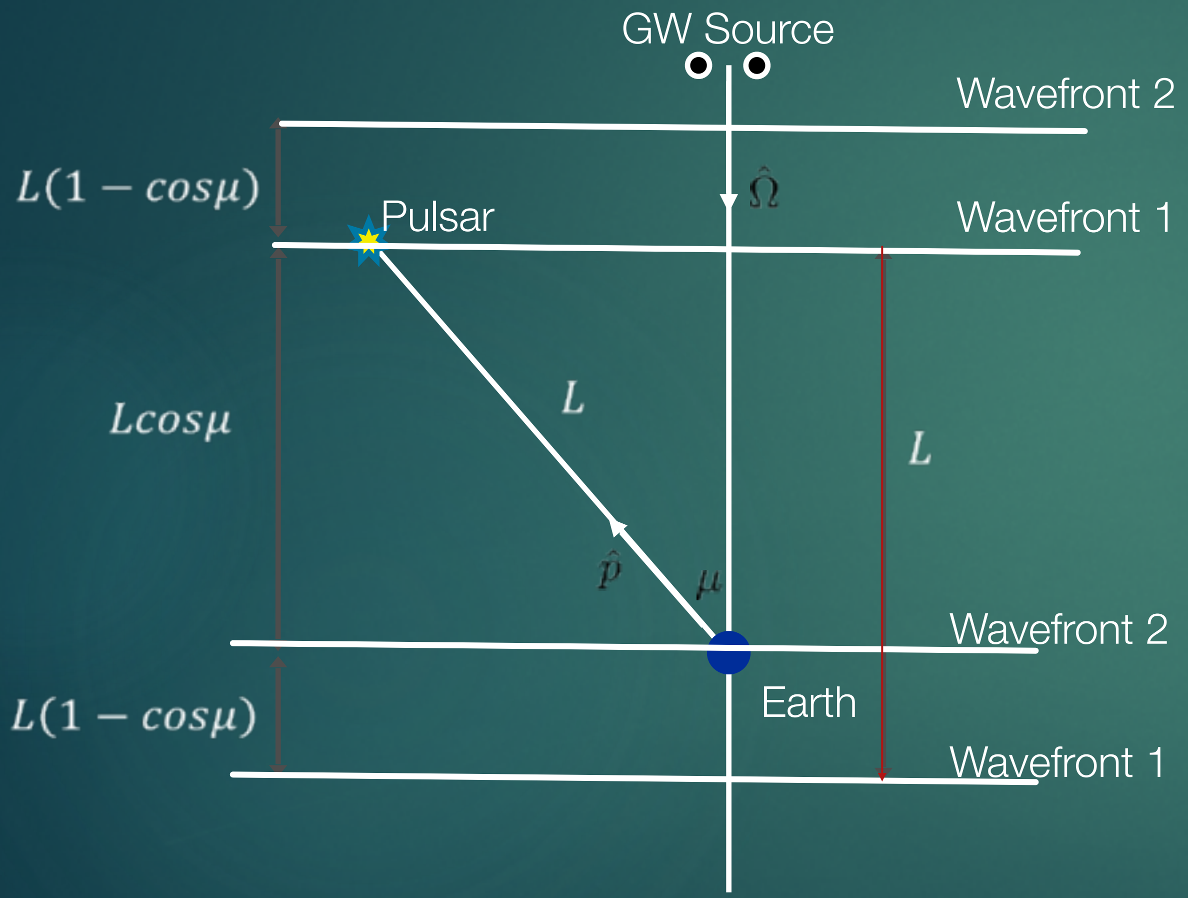
Using Pulsars to detect Gravitational Waves

- Principle source - Merging supermassive black hole binaries
- Expect a background of low amplitude sources
- Bright single sources
- Two components to signal:
  - Pulsar Term
  - Earth Term



Credit: D. Backer

Plane Wave Expansion



- Perturbation at the pulsar at a time t_p
- Perturbation at the Earth at a time t_e

$$t_p = t_e - L(1 - cos\mu)$$

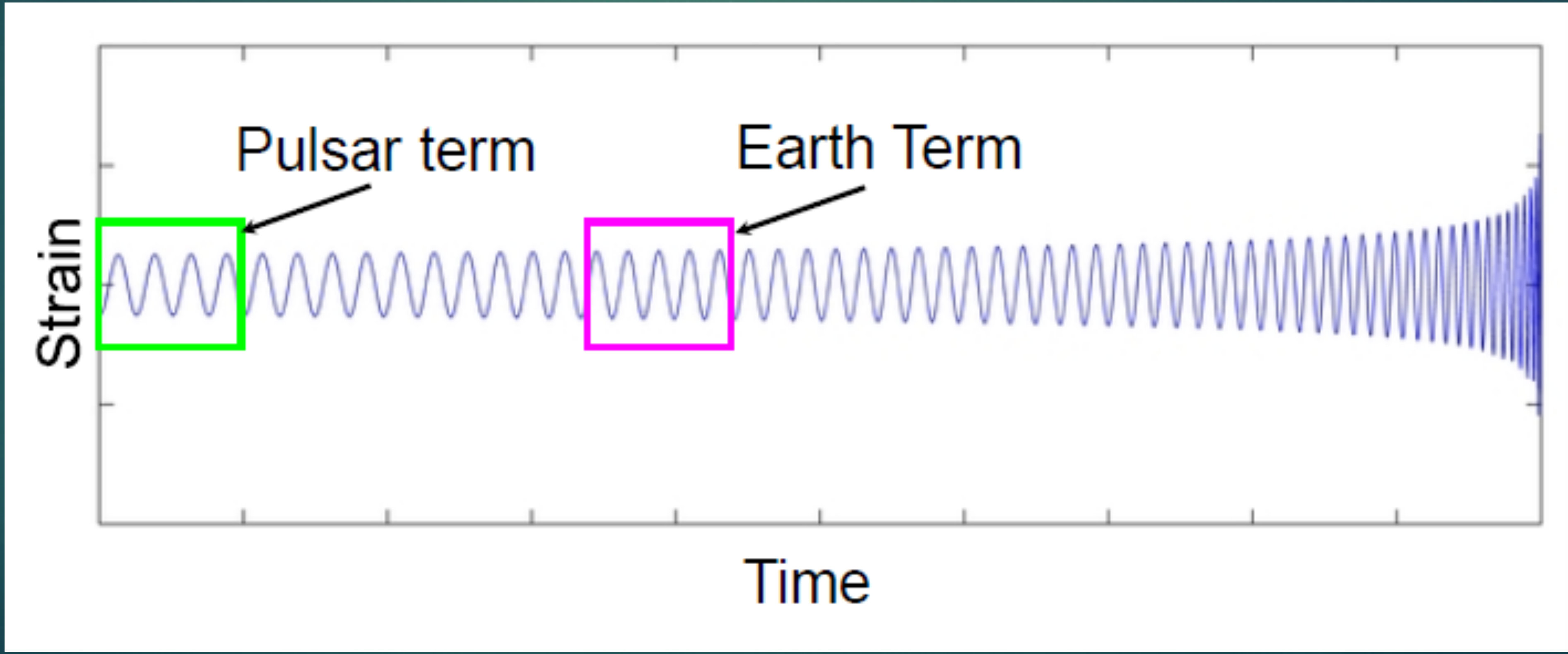
- Measure the difference between the two:

$$\Delta h_{ij} = h_{ij}(t_p, \widehat{\Omega}) - h_{ij}(t_e, \widehat{\Omega})$$

Delay is purely geometric

$$t_p = t_e - L(1 - cos\mu)$$

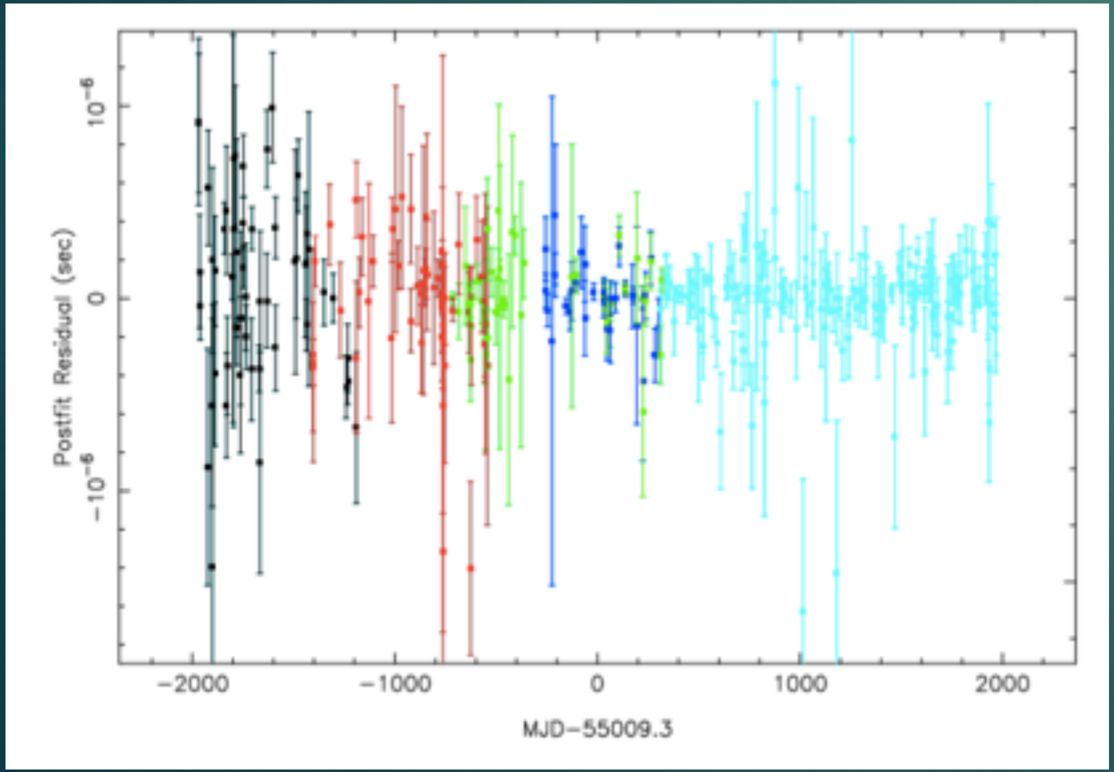
L~1 kpc, can see frequency evolution over very large time scales.



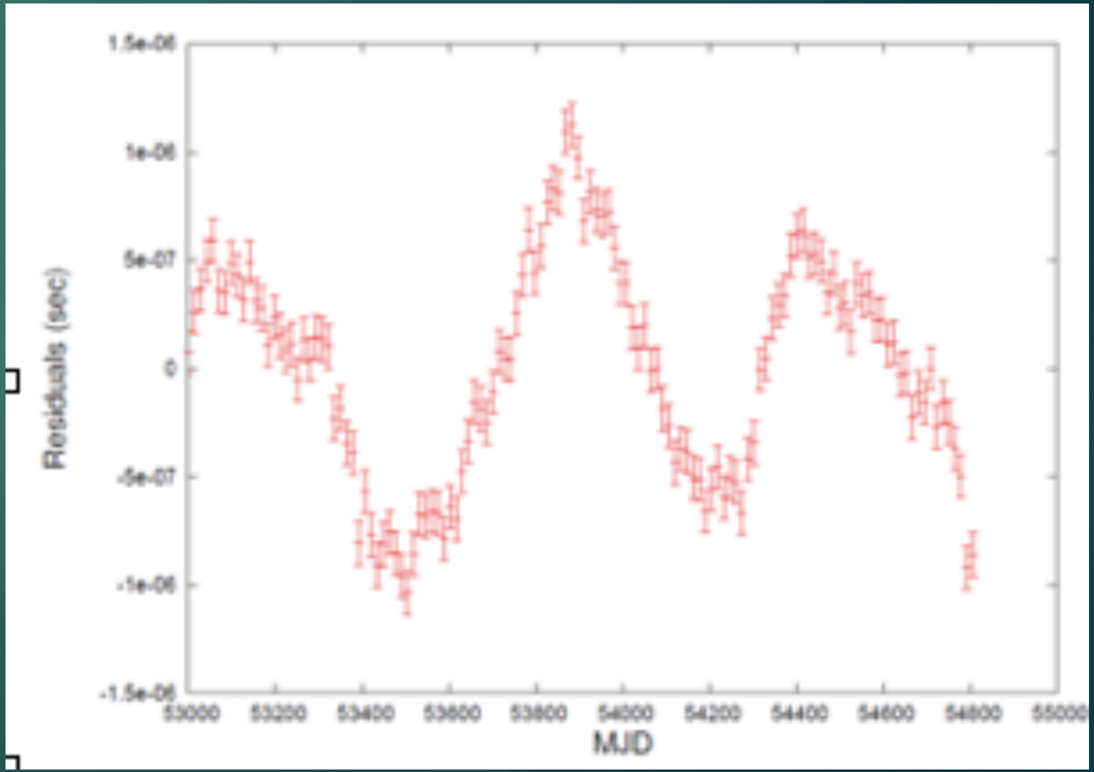
The GW Signal

So:
Have a timing model for a pulsar.
Subtract predicted arrival times of pulses from observed -> get residuals

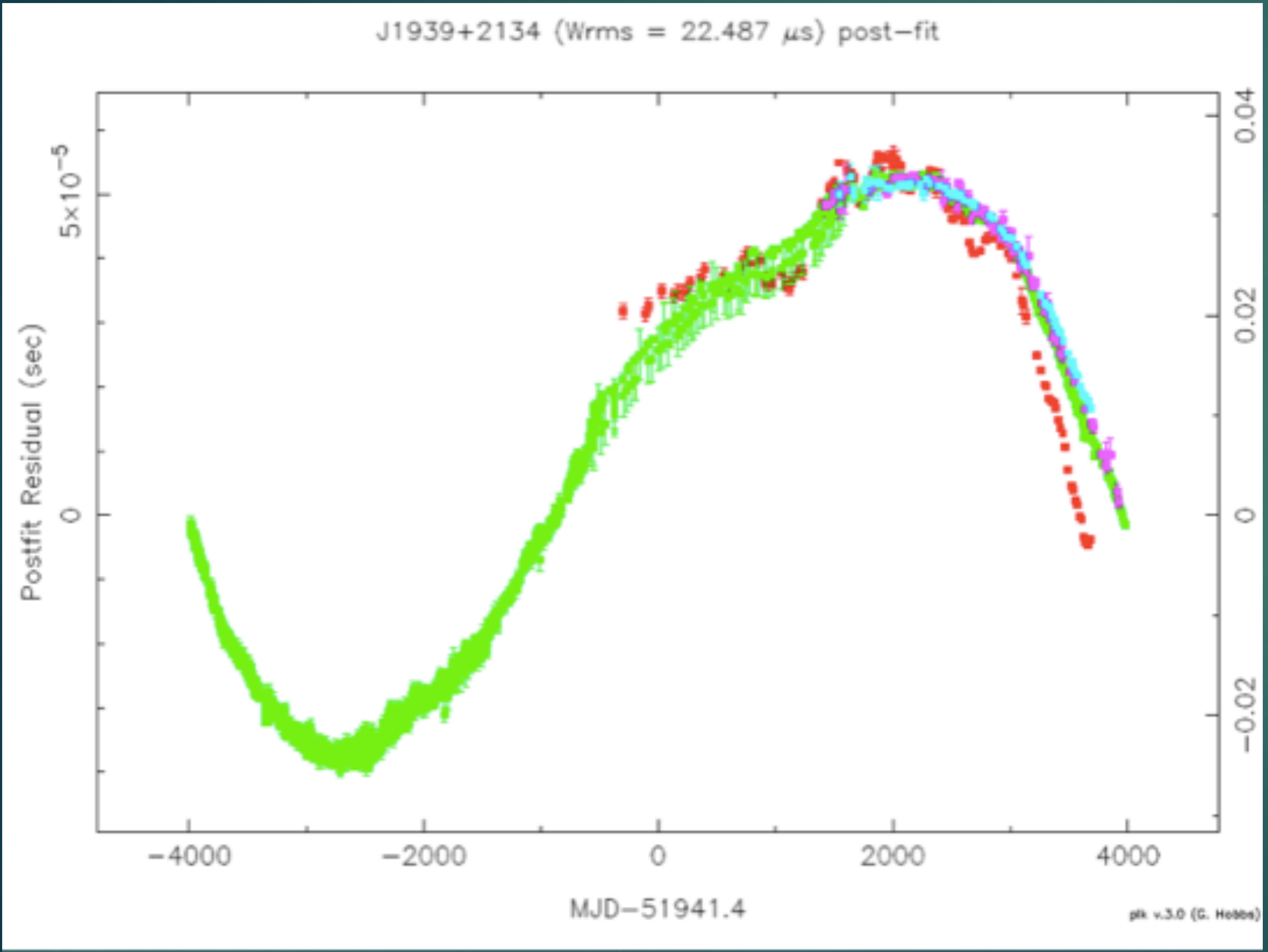
If timing model is enough, residuals basically white:



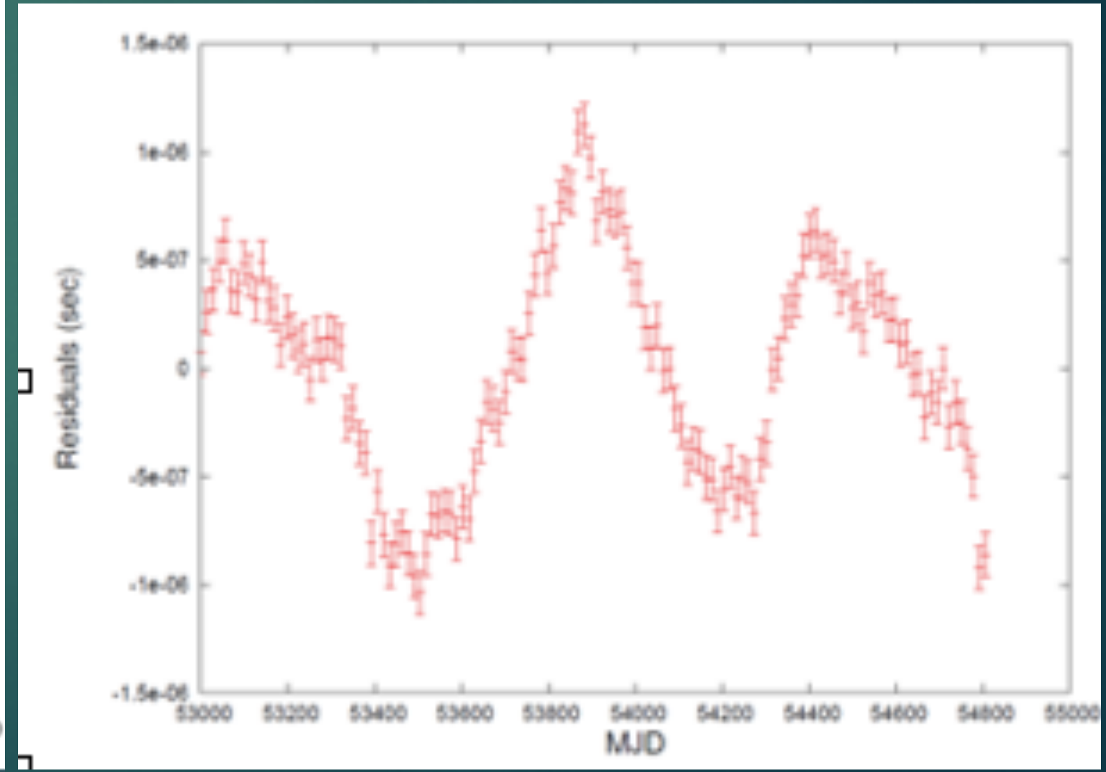
GWs induce red timing noise signal in residuals:



The GW Signal



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



The GW Signal

Lots of things can look like GWs:

Angular correlation between pulsars allows us to discriminate between:

(for example)

Intrinsic Timing Noise
(Uncorrelated between pulsars)

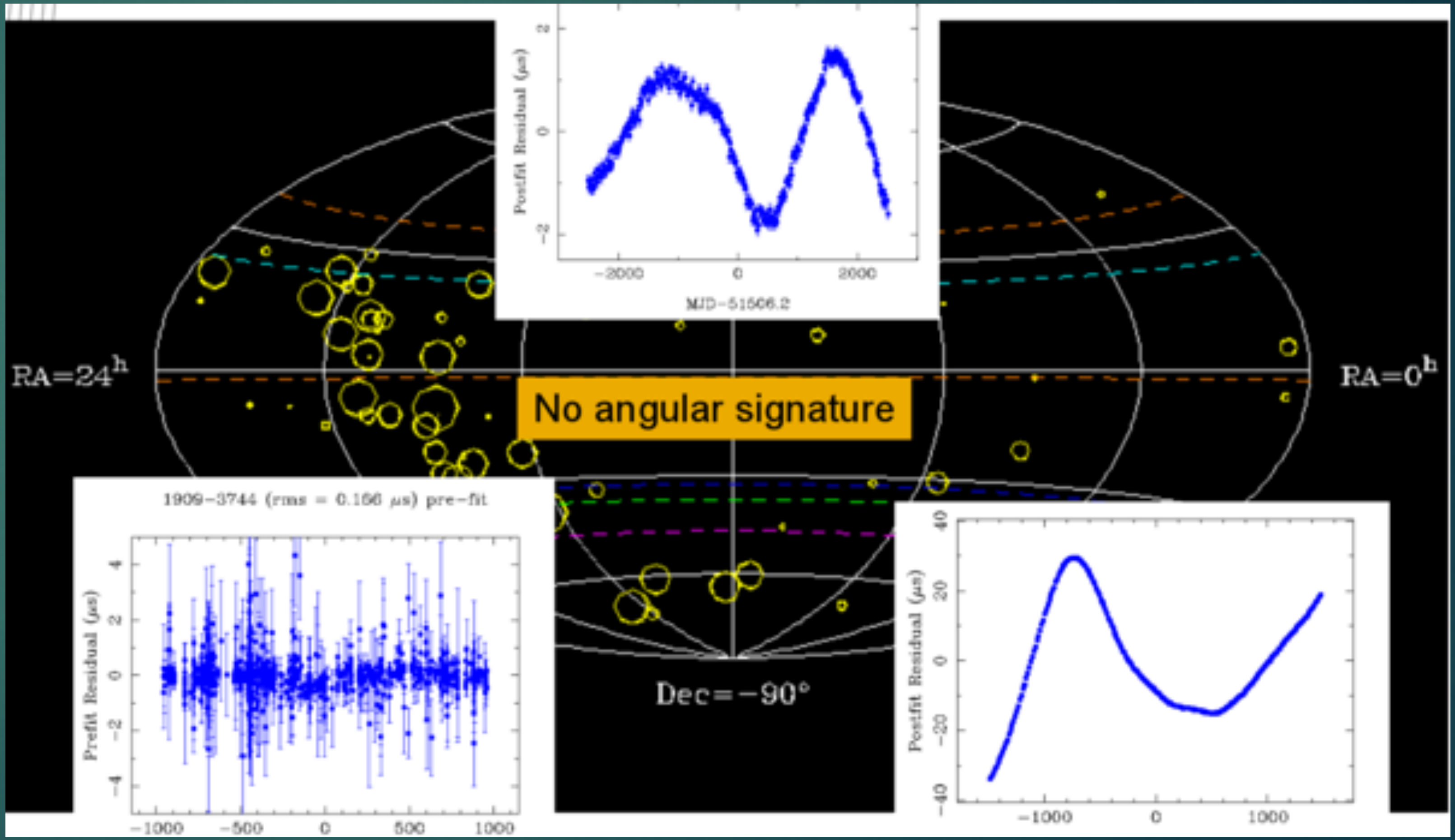


Image credit: George Hobbs

The GW Signal

Lots of things can look like GWs:

Angular correlation between pulsars allows us to discriminate between:

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Errors in time standard
(Monopole correlation)

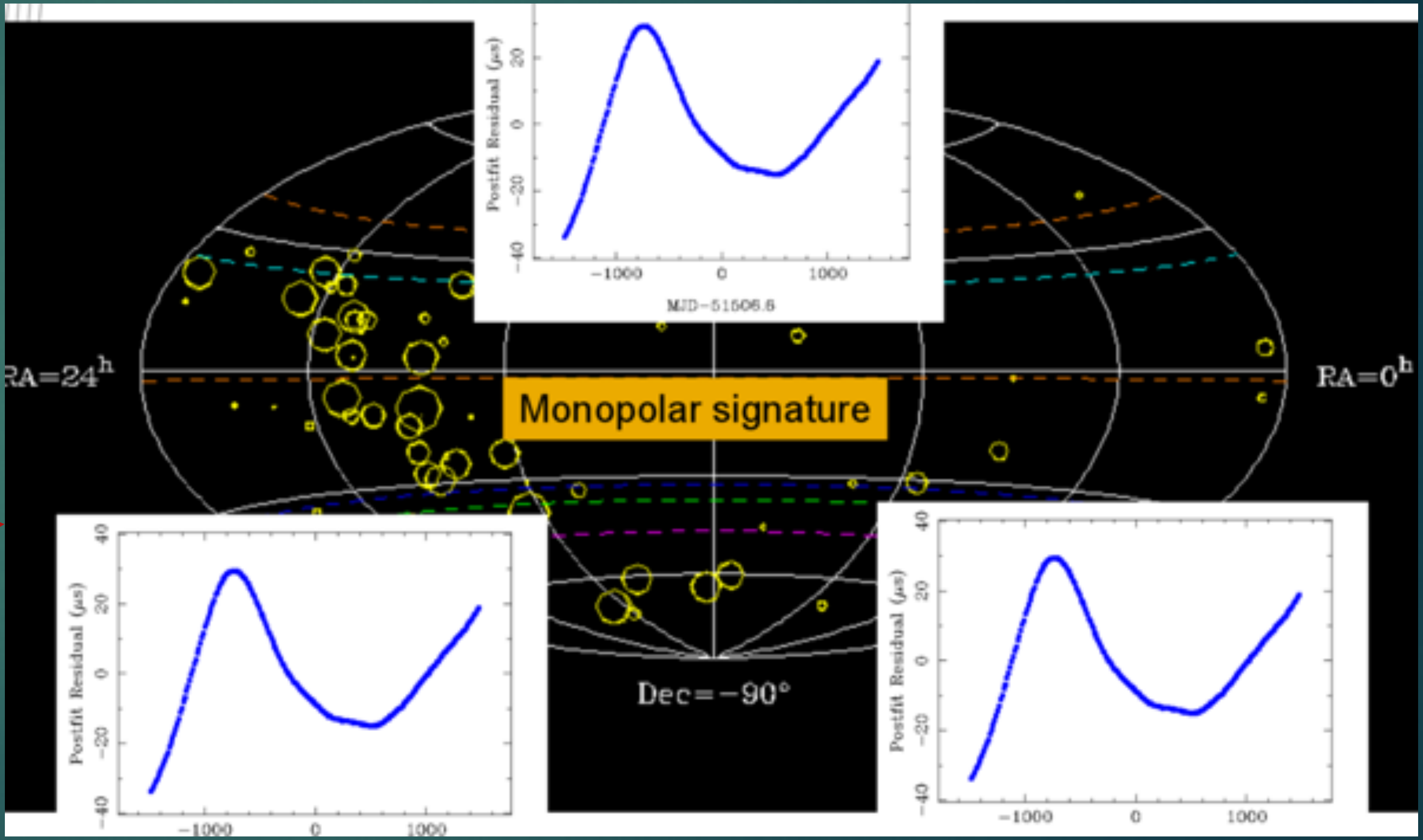

Image credit: George Hobbs

The GW Signal

Lots of things can look like GWs:

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Errors in planet masses
(Dipole correlation)

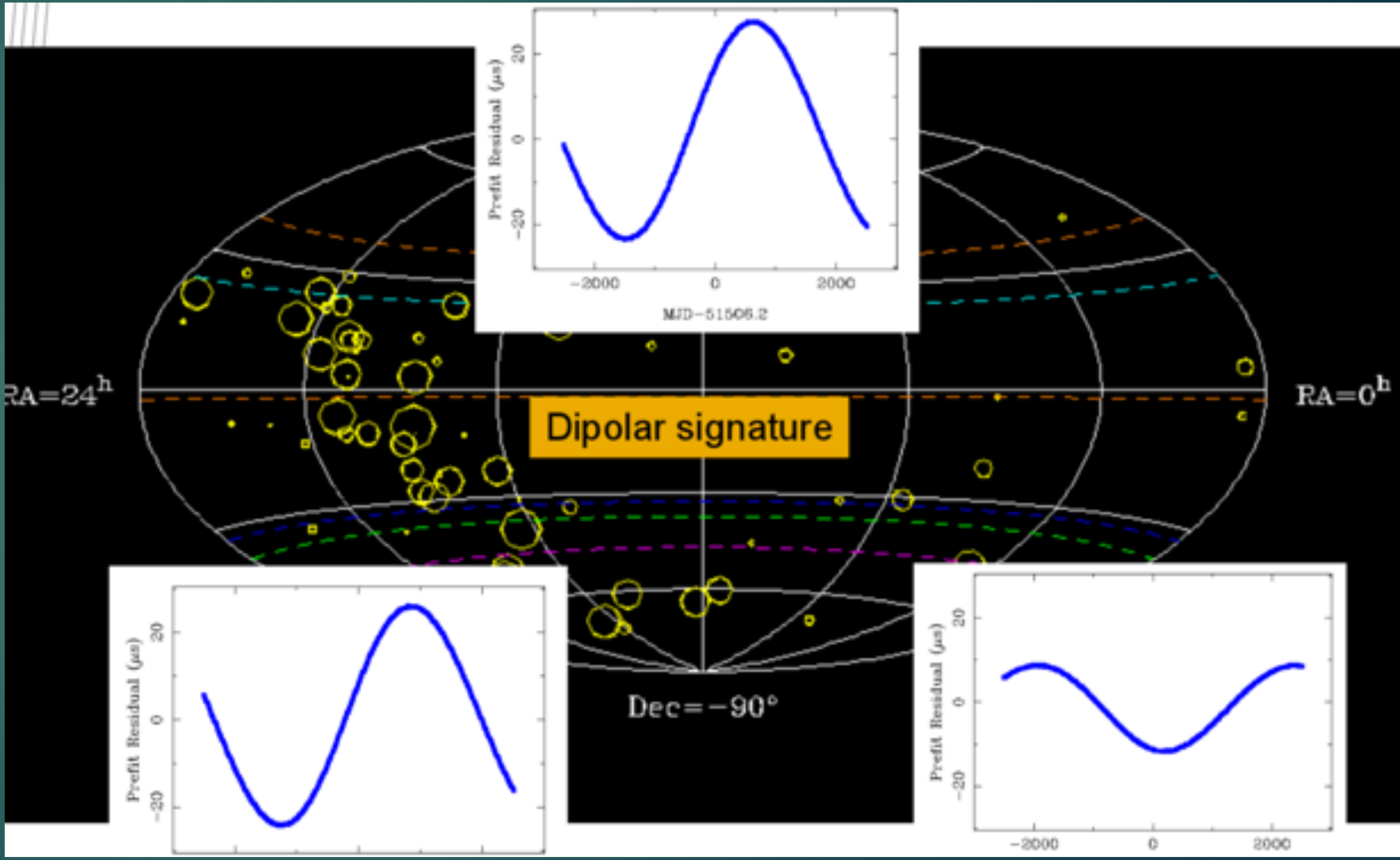


Image credit: George Hobbs

The GW Signal

Lots of things can look like GWs:

Angular correlation between pulsars allows us to discriminate between:

(for example)

Intrinsic Timing Noise
(Uncorrelated between pulsars)

Errors in time standard
(Monopole correlation)

Errors in planet masses
(Dipole correlation)

And Gravitational Waves!
(Quadrupole correlation)

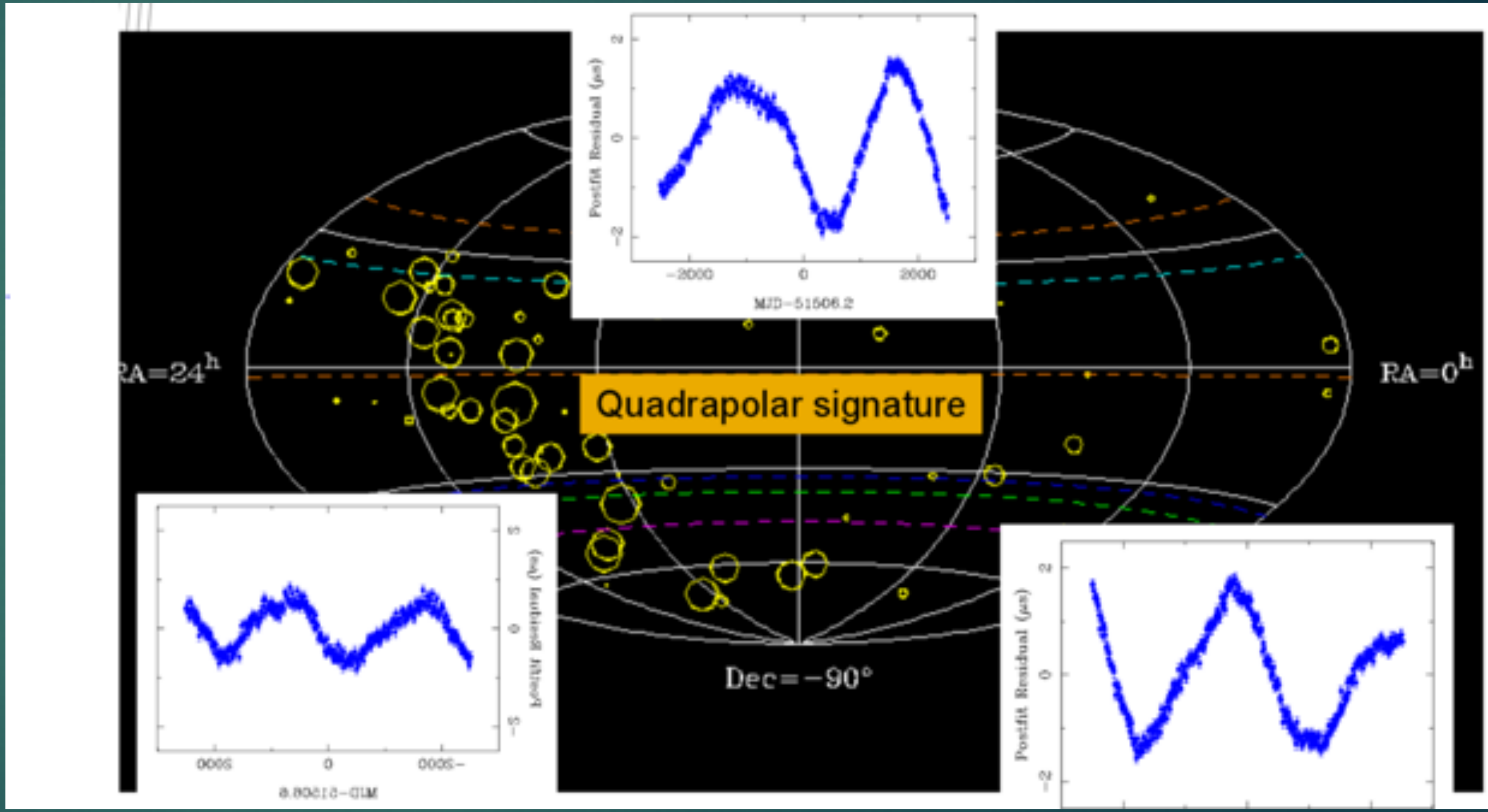
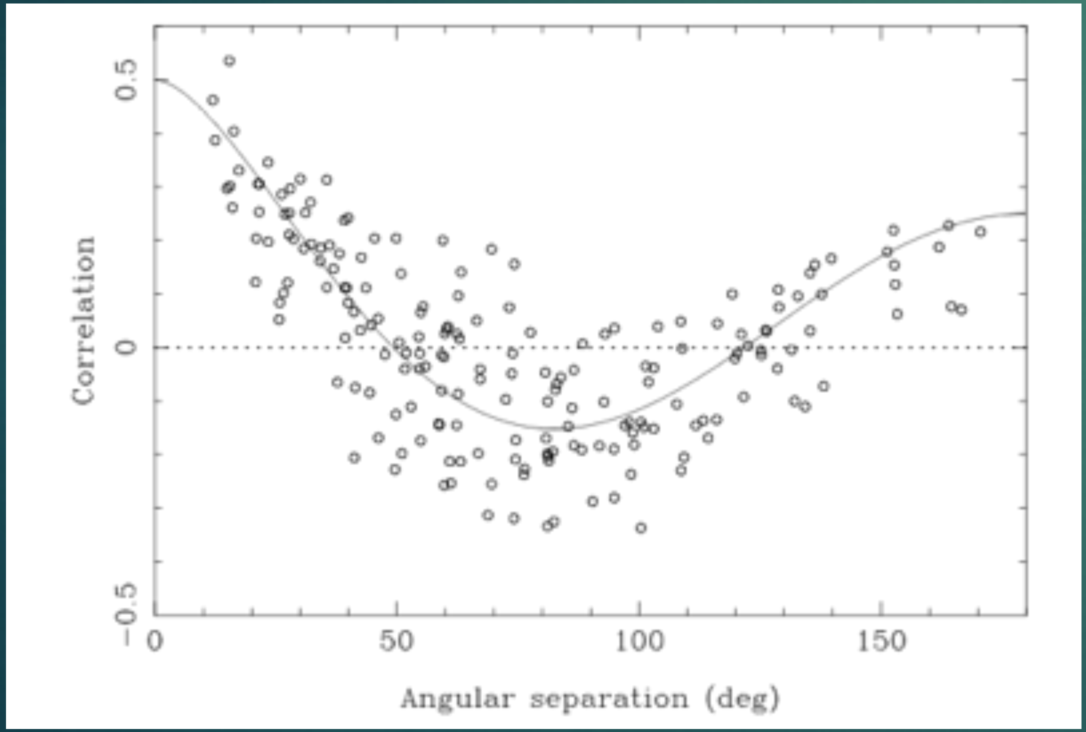


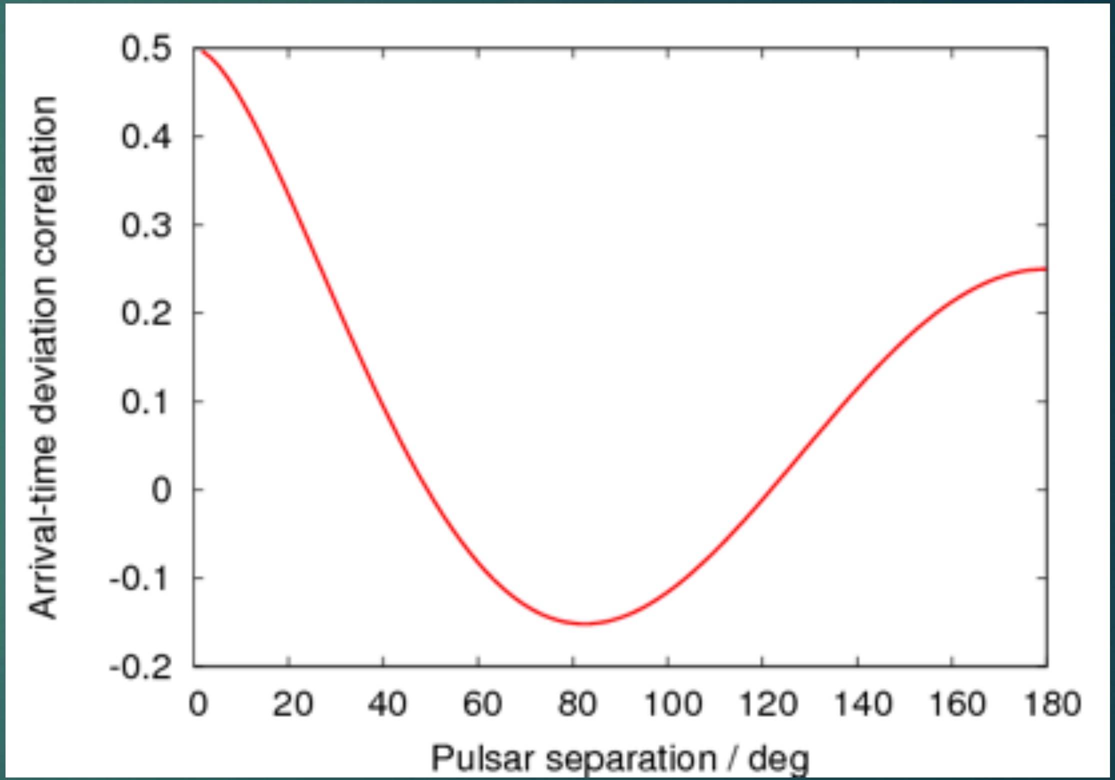
Image credit: George Hobbs

The Hellings-Downs Curve

For an isotropic background the correlation has an analytic solution – depends on angular separation of pulsars on the sky:



Simulated data



Smoking Gun of a real GW detection.


Green Bank, West Virginia
Westerbork, The Netherlands
Effelsberg, Germany
Pune, India
Arecibo, Puerto Rico
IPTA
Goostrey, United Kingdom
Nancay, France
San Basilio, Italy
Parkes, Australia

Some Predictions

20 pulsars
100ns white residuals
Detection in 5 years (e.g. Jenet et. al. 2004)

Current IPTA data set:
40 pulsars
20 years of data
Some < 100ns
….. So wheres the detection?

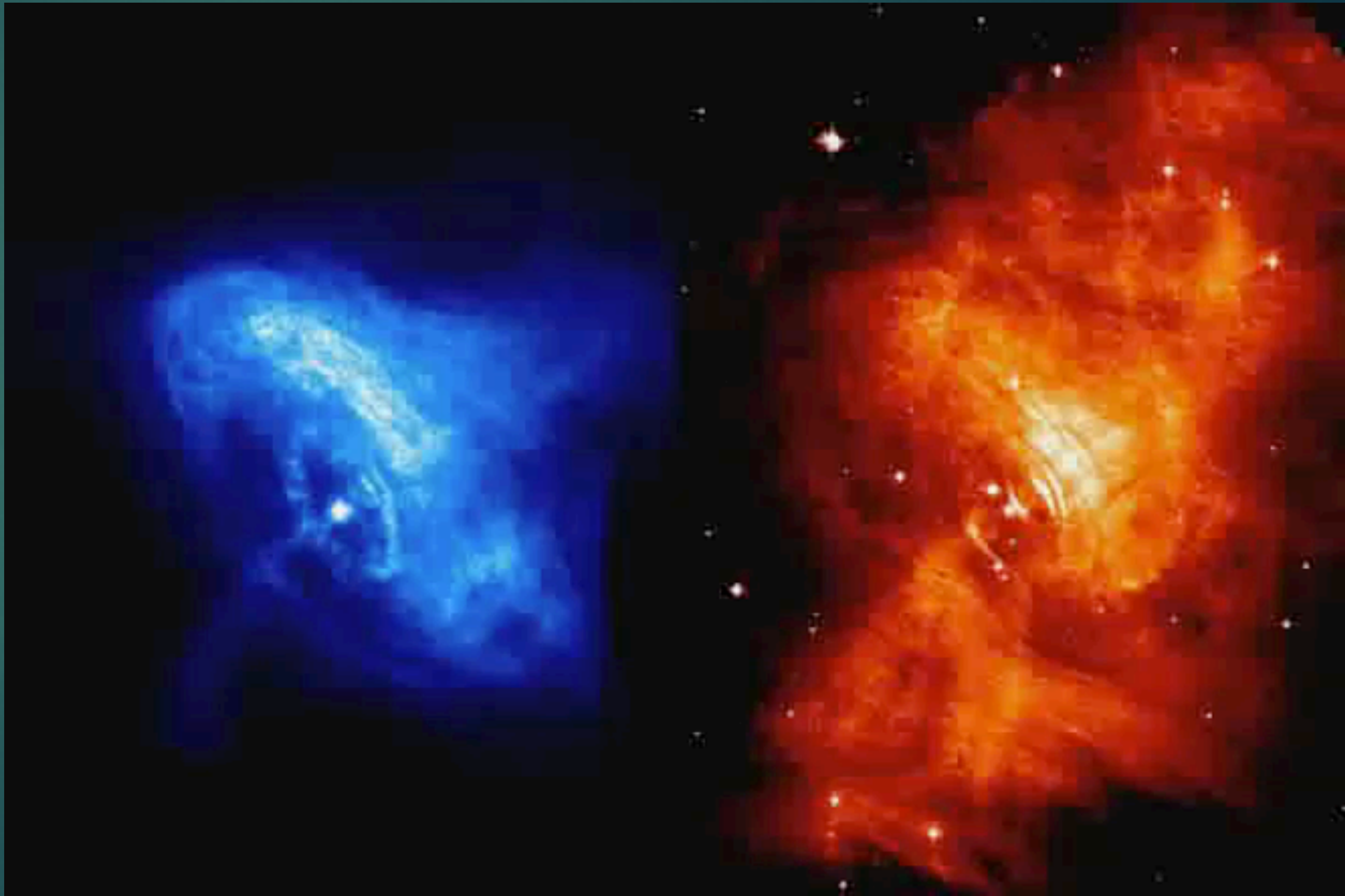
Data Problems

Some Pulsars are very precise clocks

This is the crab pulsar →

Radiation from the pulsar creates shocks That are felt for ~ 10 light years

Fig: NASA



Some Pulsars are very precise clocks

Crab super nova seen from Earth in 1054

Pulsar rotates ~ 30 times a second.

Pulsar wind causes period of rotation to slow by 38ns per day

Most Pulsars are rubbish clocks

But Crab not a stable rotator:

Period of rotation has significant variation with time

No good for GW science.

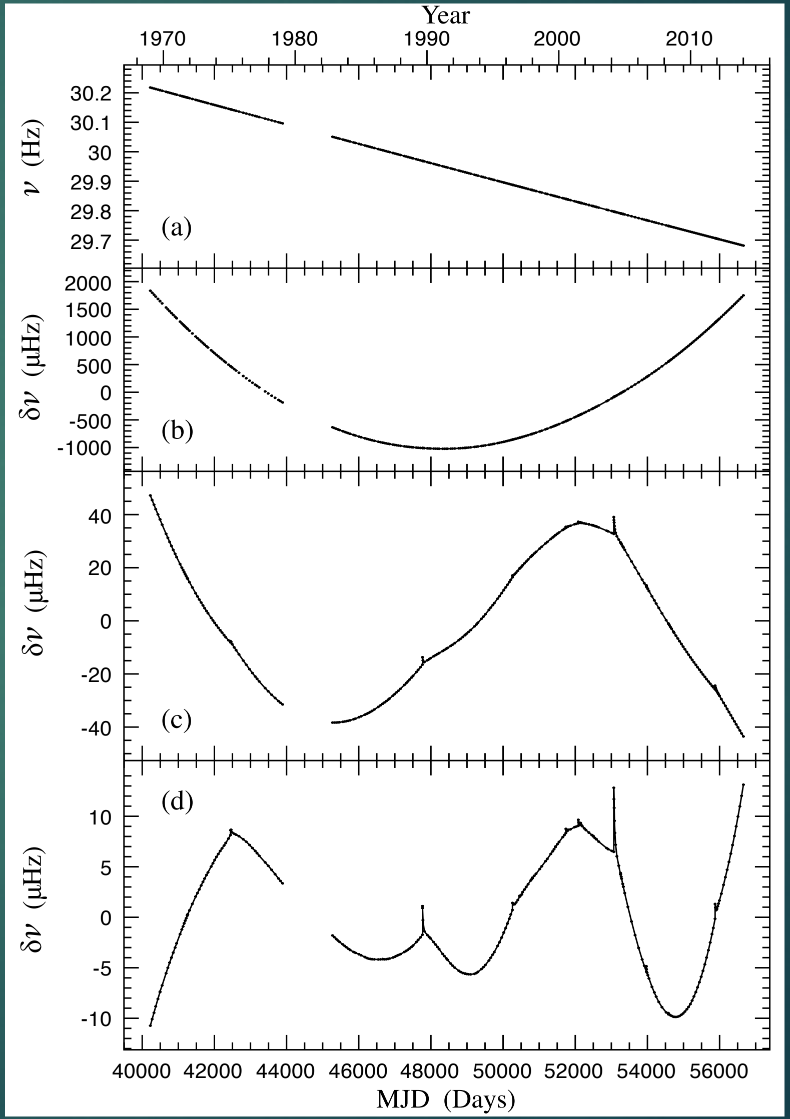


Fig: Lyne et al 2014

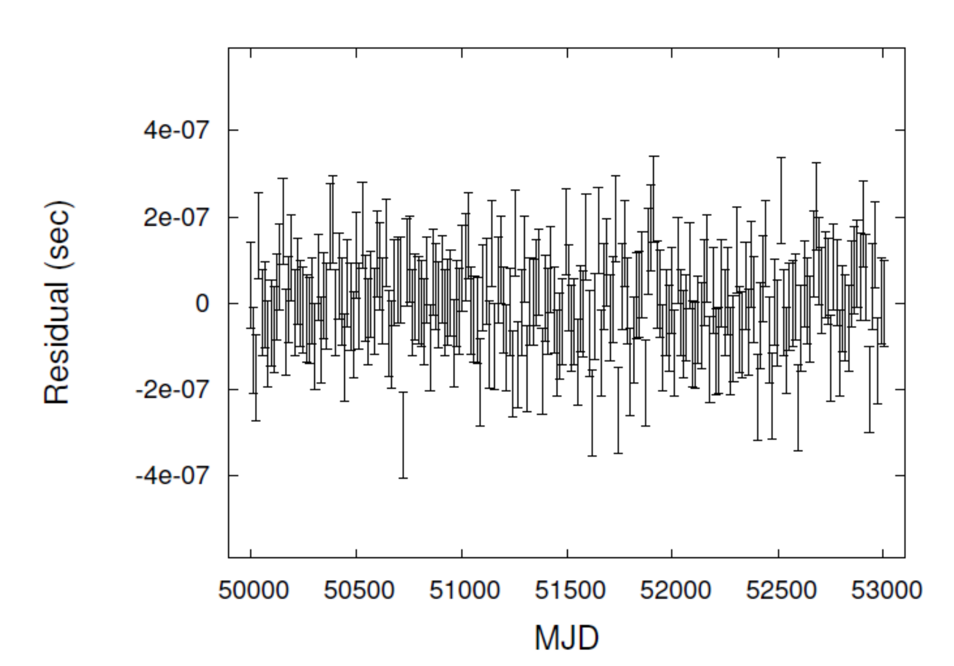
Most Pulsars are rubbish clocks

The SKA will find about 15 000 new pulsars.

Will find a host of high precision MSPs.

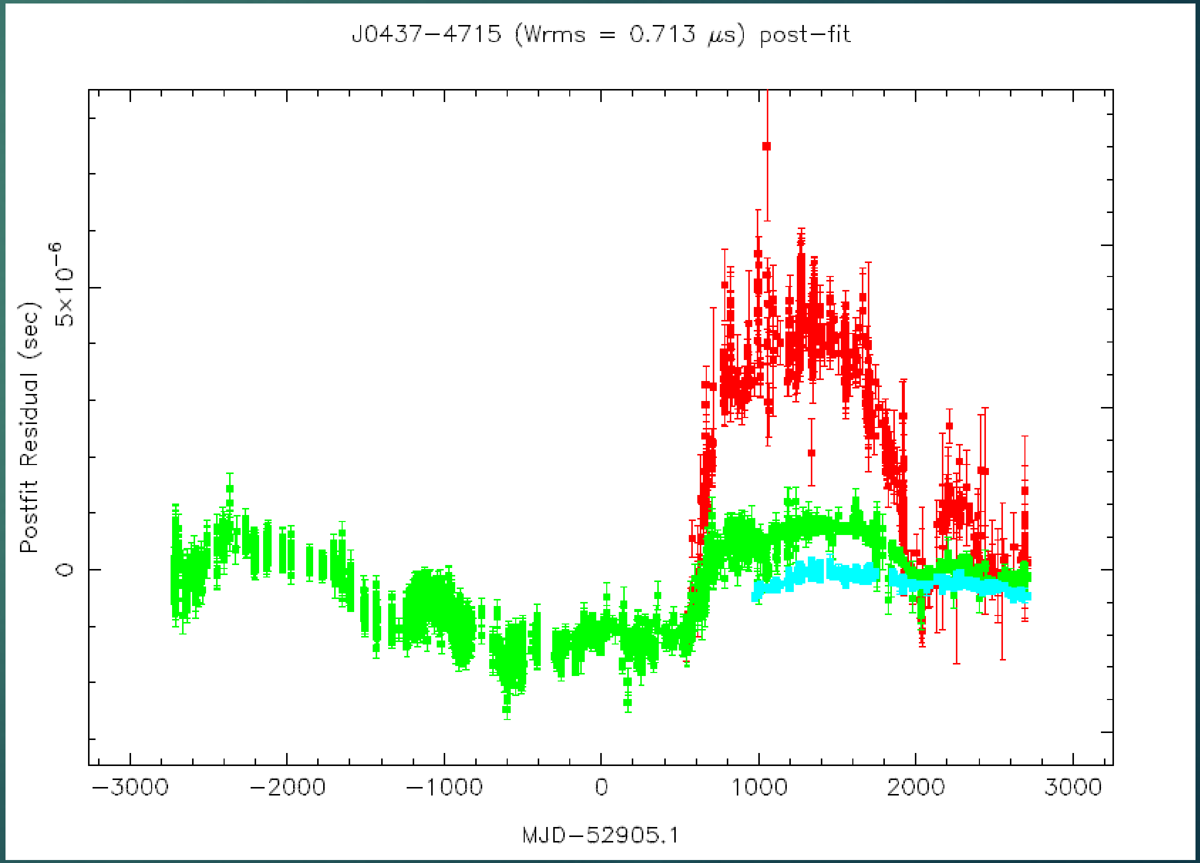
Will significantly improve timing precision on many of the ones we have already.

Data Challenges



<- 100 ns white noise (as per predictions)

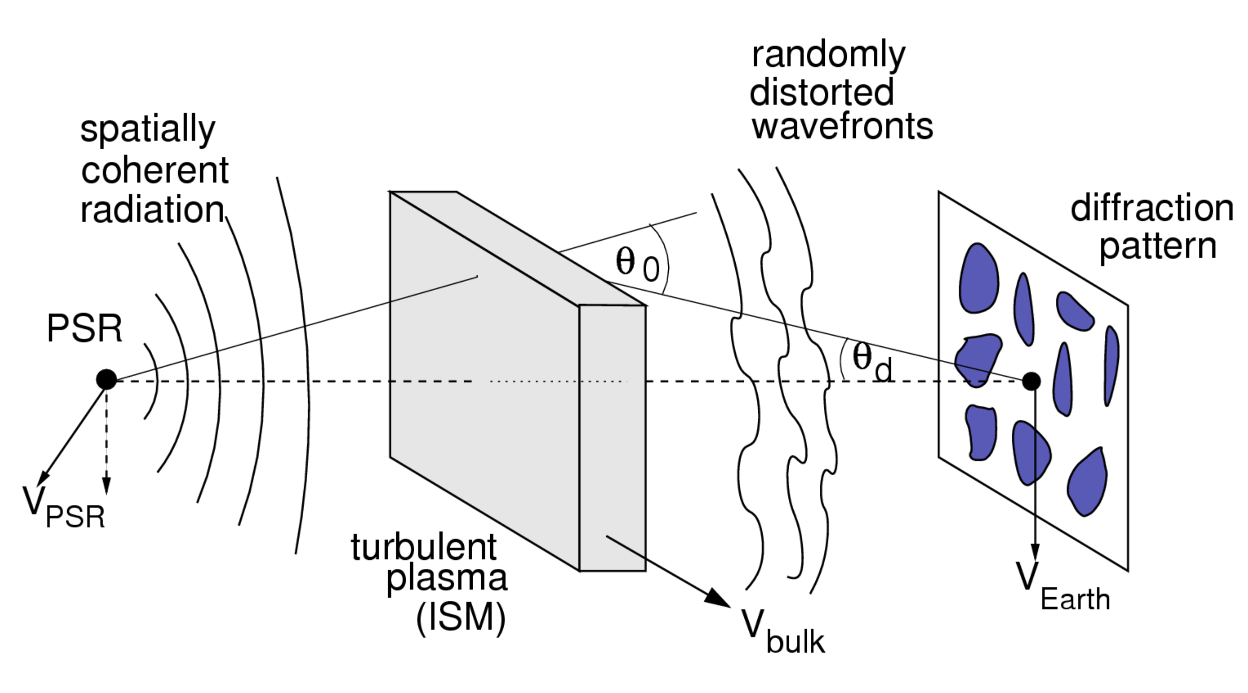
Actual Data ->



J0437-4715
(That great one i mentioned earlier…)

Data Challenges

In this case noise mostly due to the interstellar medium.



Dependent on observing frequency

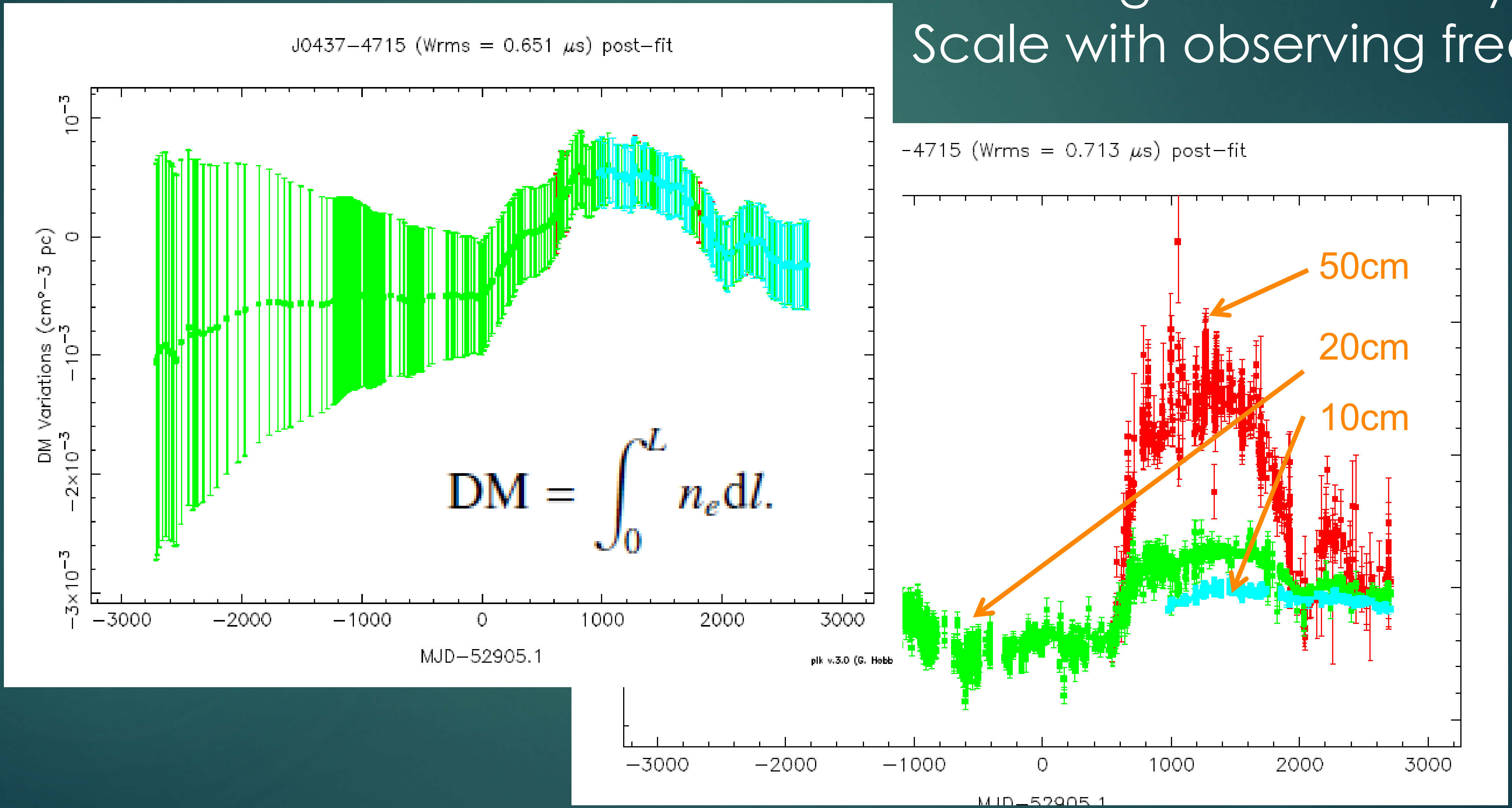
$$t_g(\nu) = K\, DM/(\nu^2)$$

$$K \equiv 4.15 \times 10^{15}\ \mathrm{Hz}^2\ \mathrm{cm}^3\ \mathrm{pc}^{-1}\ \mathrm{s}$$

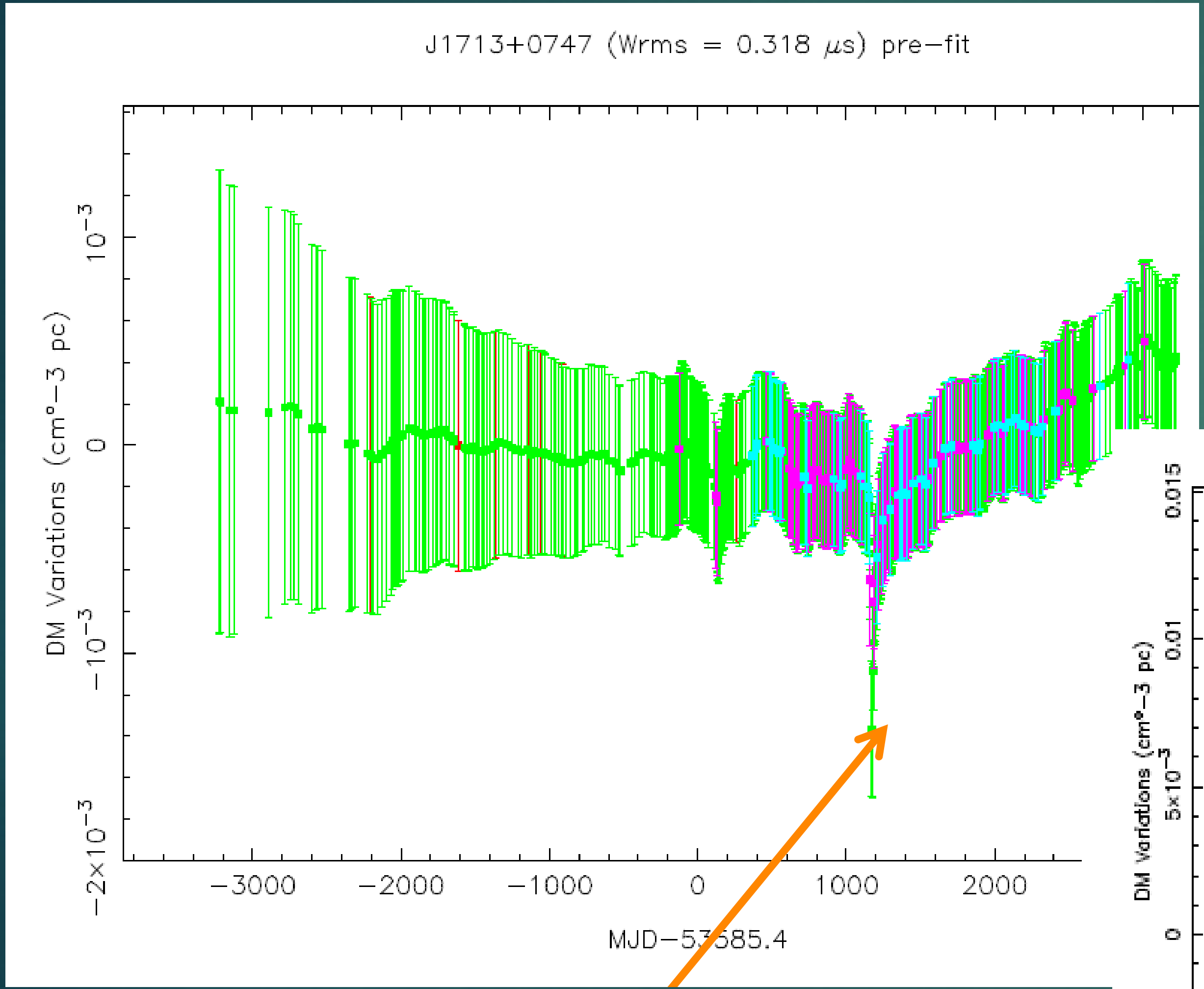
$$\mathrm{DM} = \int_0^L n_e \mathrm{d}l.$$

Data Challenges

Model signal statistically -
Scale with observing frequency

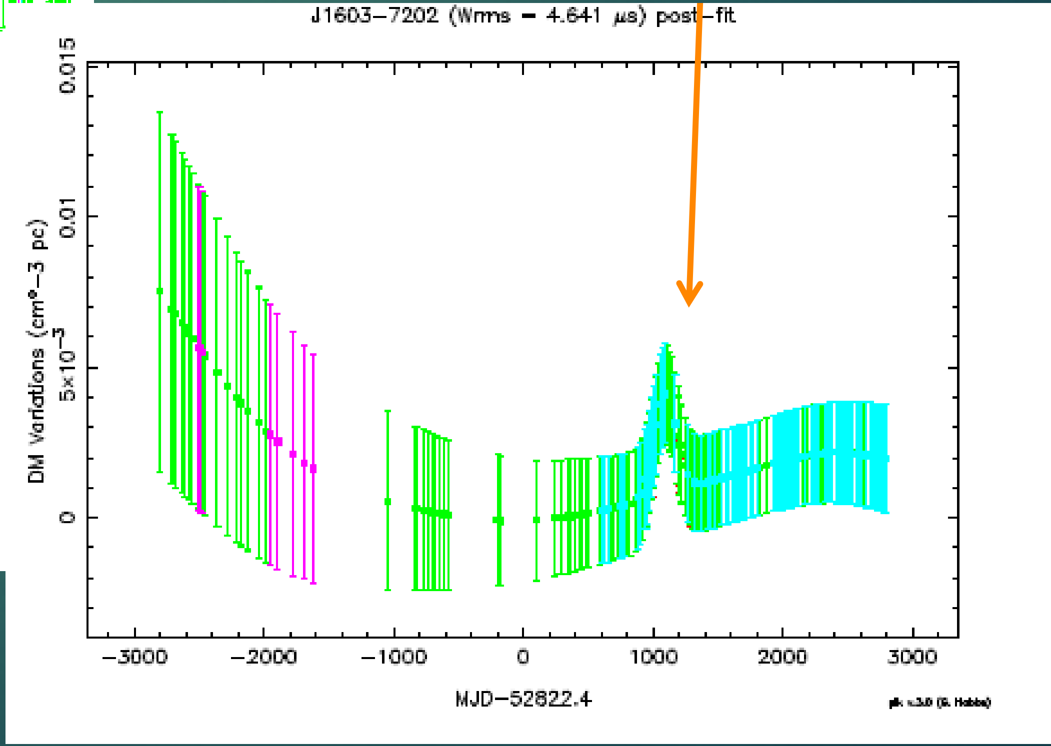


Data Challenges



But the signal isn't stationary…

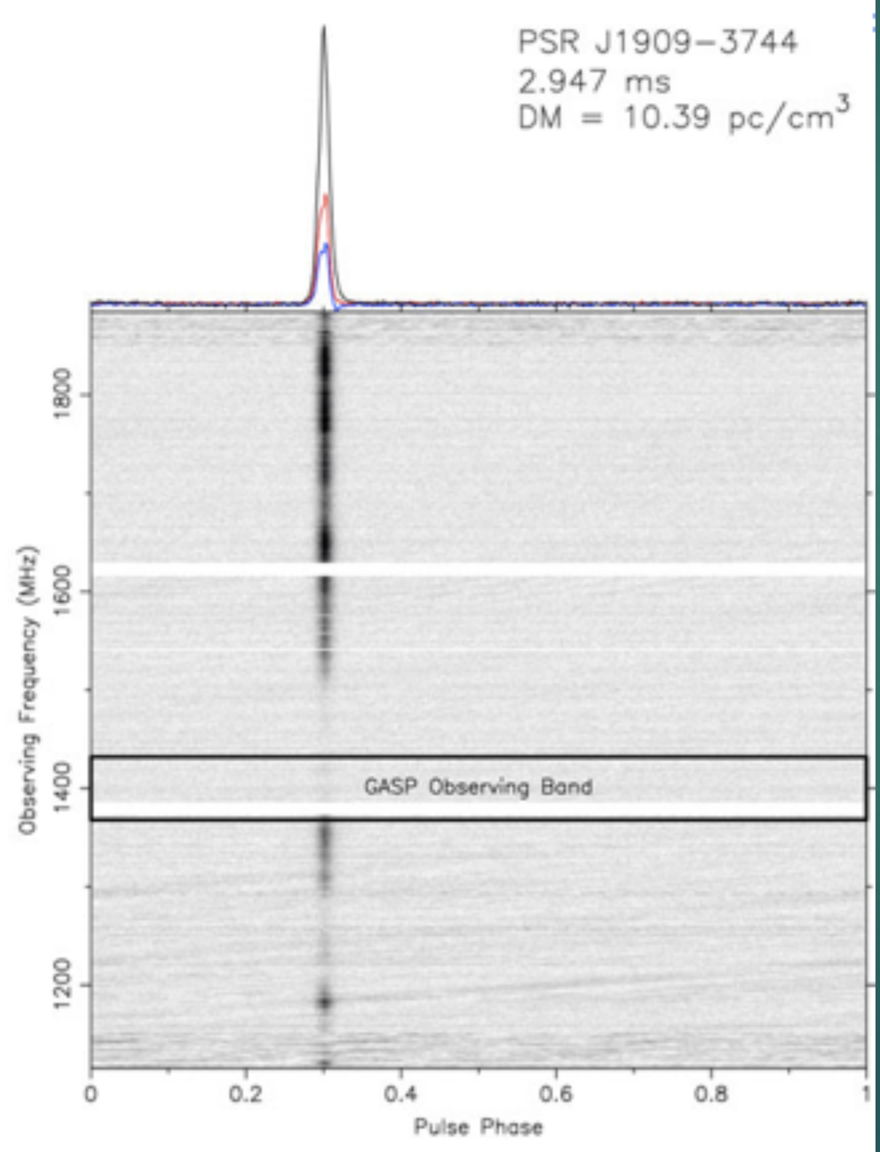
Over density in the ISM



Void in the ISM

Figs: Lentati et al 2016

Data Challenges



So just increase the bandwidth right?

Massive increase over the last few years
Further increases to come

~4GHz simultaneous bandwidth for up coming systems.

Data Challenges

More than just DM though:
Scattering, ‘frequency-dependent DM’
Can really hurt:

PPTA Limits for PSR J1909-3744:
10cm only : 1e-15
10+20cm: 9e-16
10+20+50: 2e-15

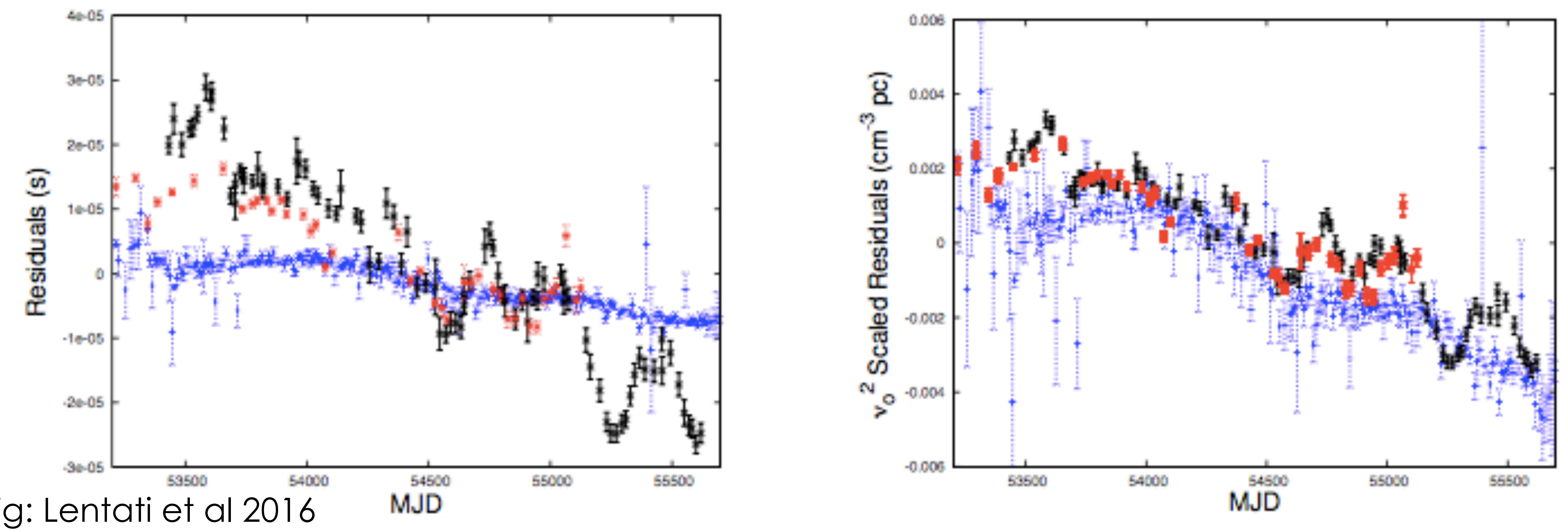


Fig: Lentati et al 2016

Data Challenges

Better modelling can make a huge difference (Lentati et al 2016)
60% increase in sensitivity compared to 'standard' models

With the next IPTA data set can do even better (> factors of 2)

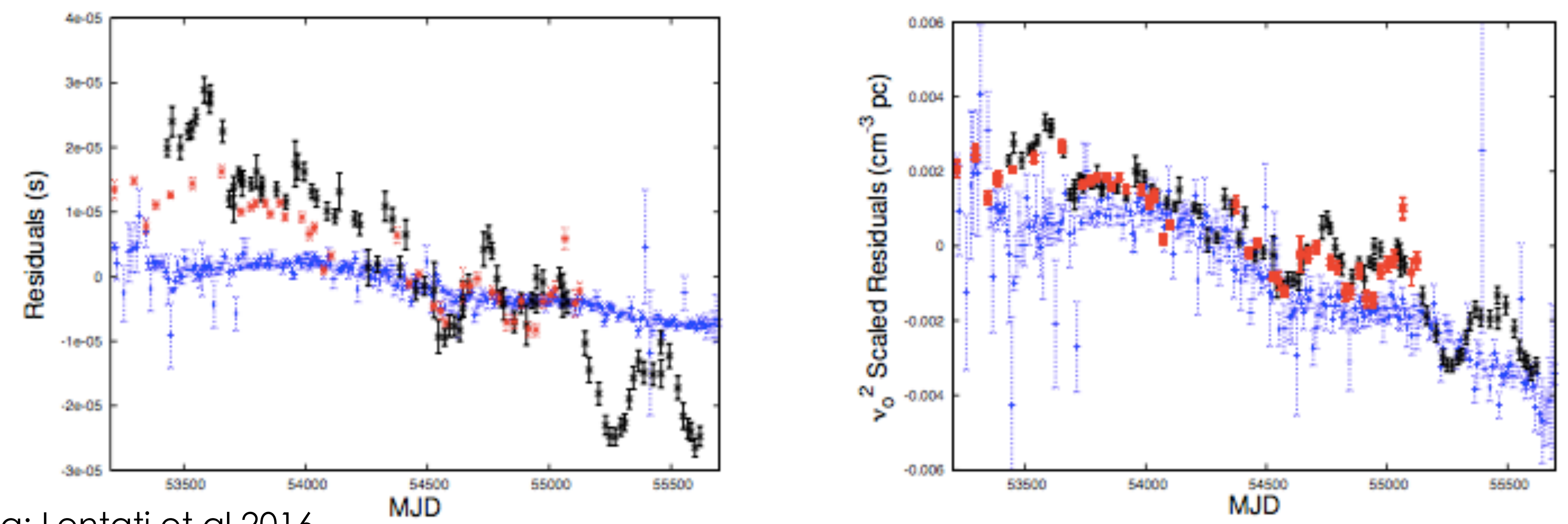
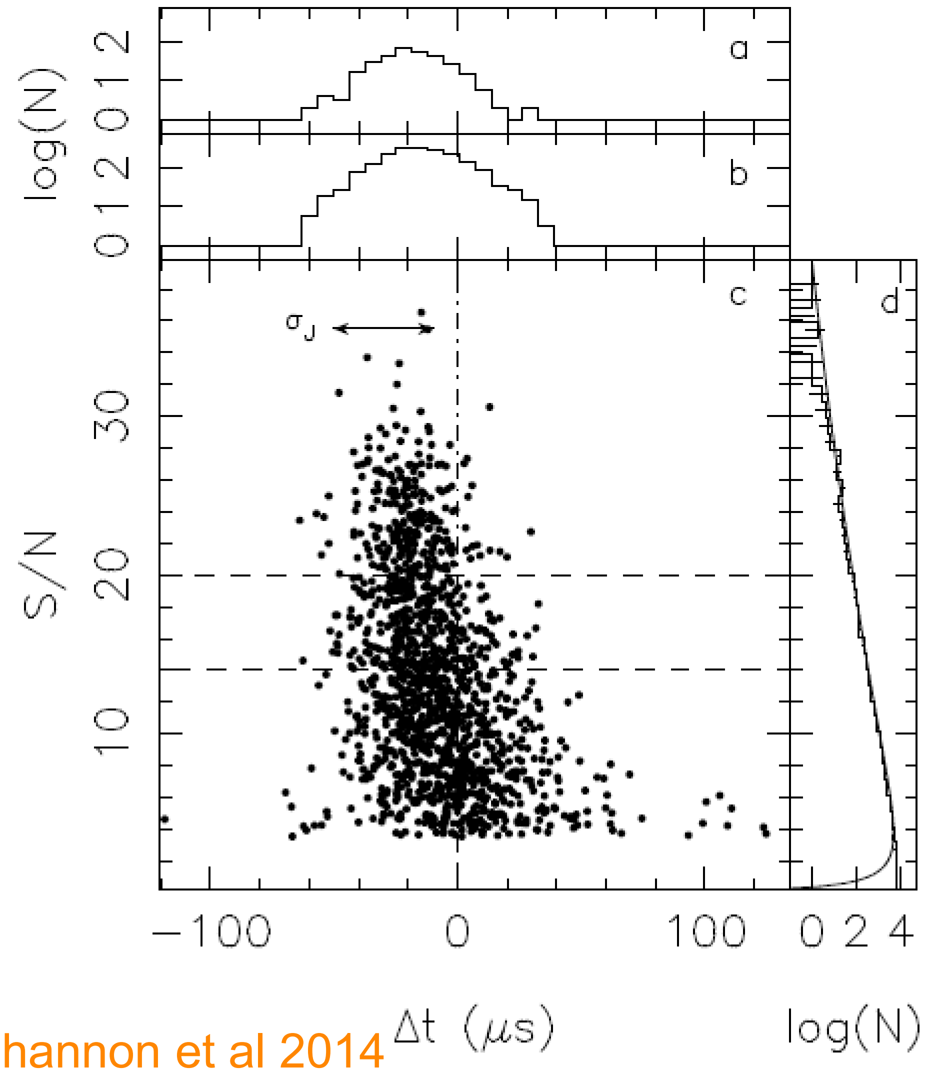


Fig: Lentati et al 2016

Data Challenges



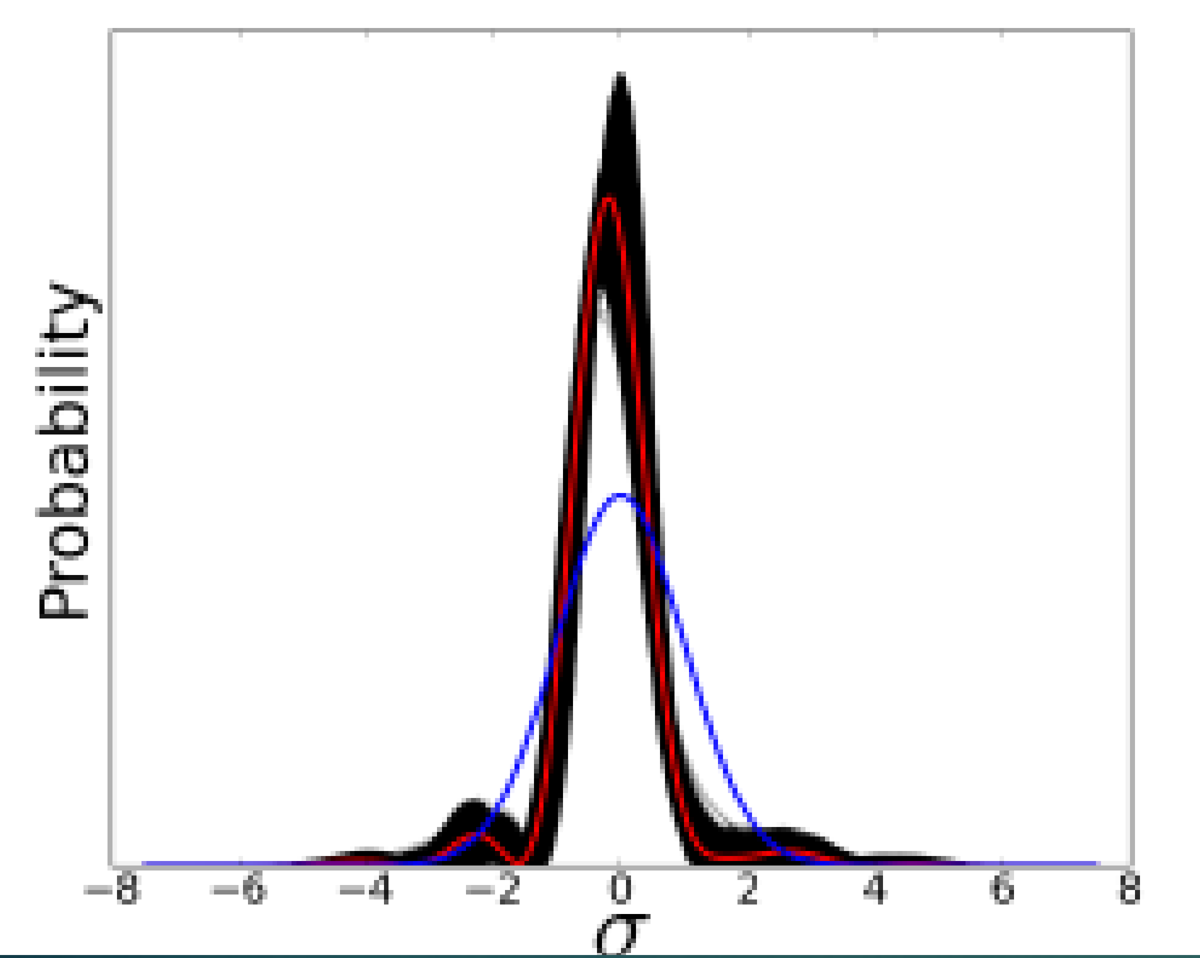
Shannon et al 2014

Intrinsic high frequency variation in arrival time of pulses

Better telescopes won't help.

Already at the limit for some pulsars.

Data Challenges



Intrinsic high frequency variation in arrival time of pulses

Better telescopes won't help.

Already at the limit for some pulsars.

Not necessarily Gaussian either.

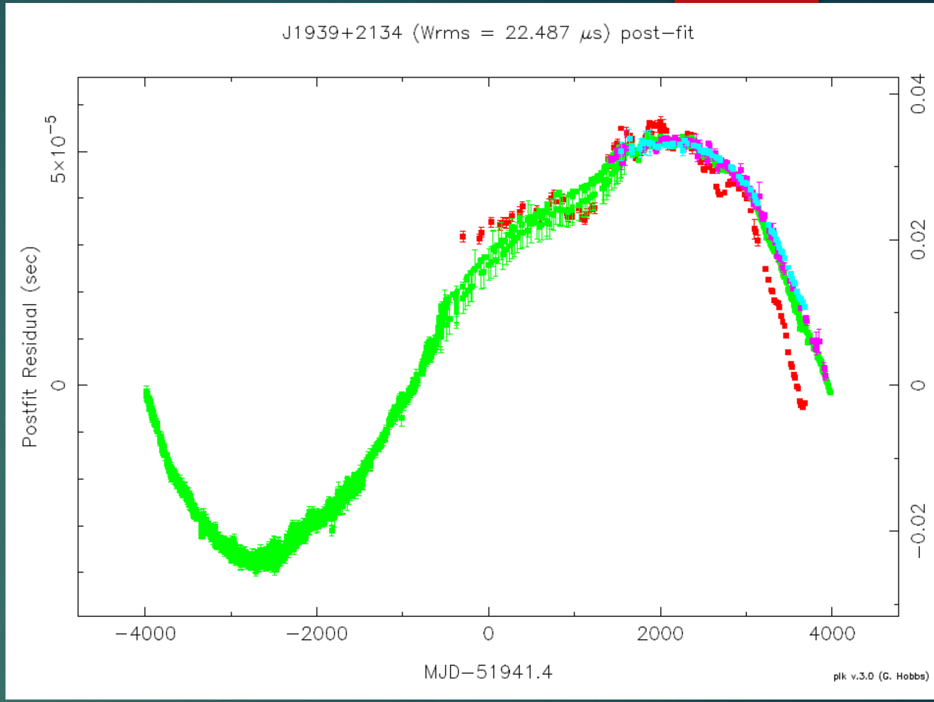
Fig: Lentati et al 2015

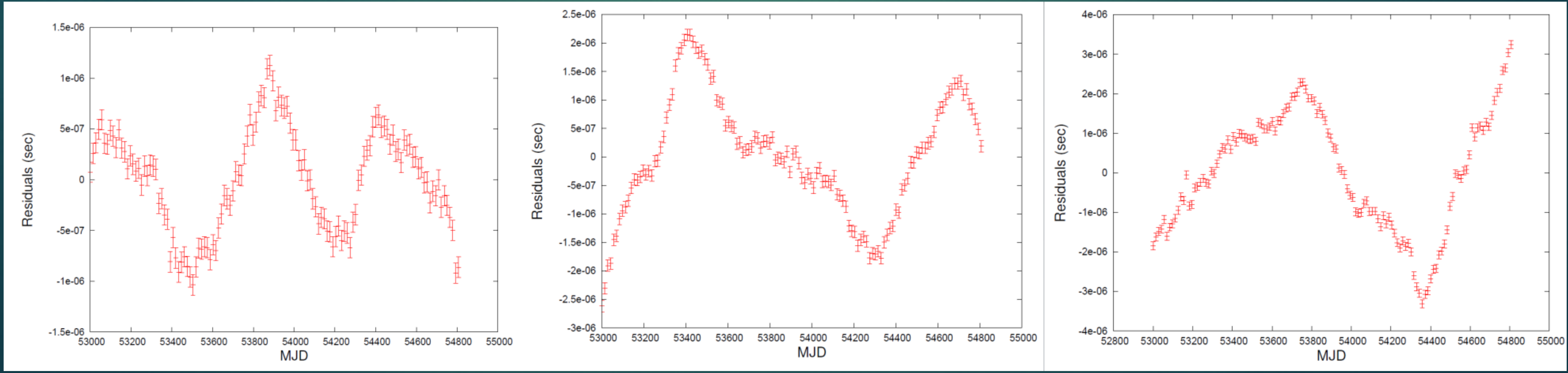
Data Challenges

Intrinsic low frequency variation
in the arrival times (like Crab) - known as Timing Noise

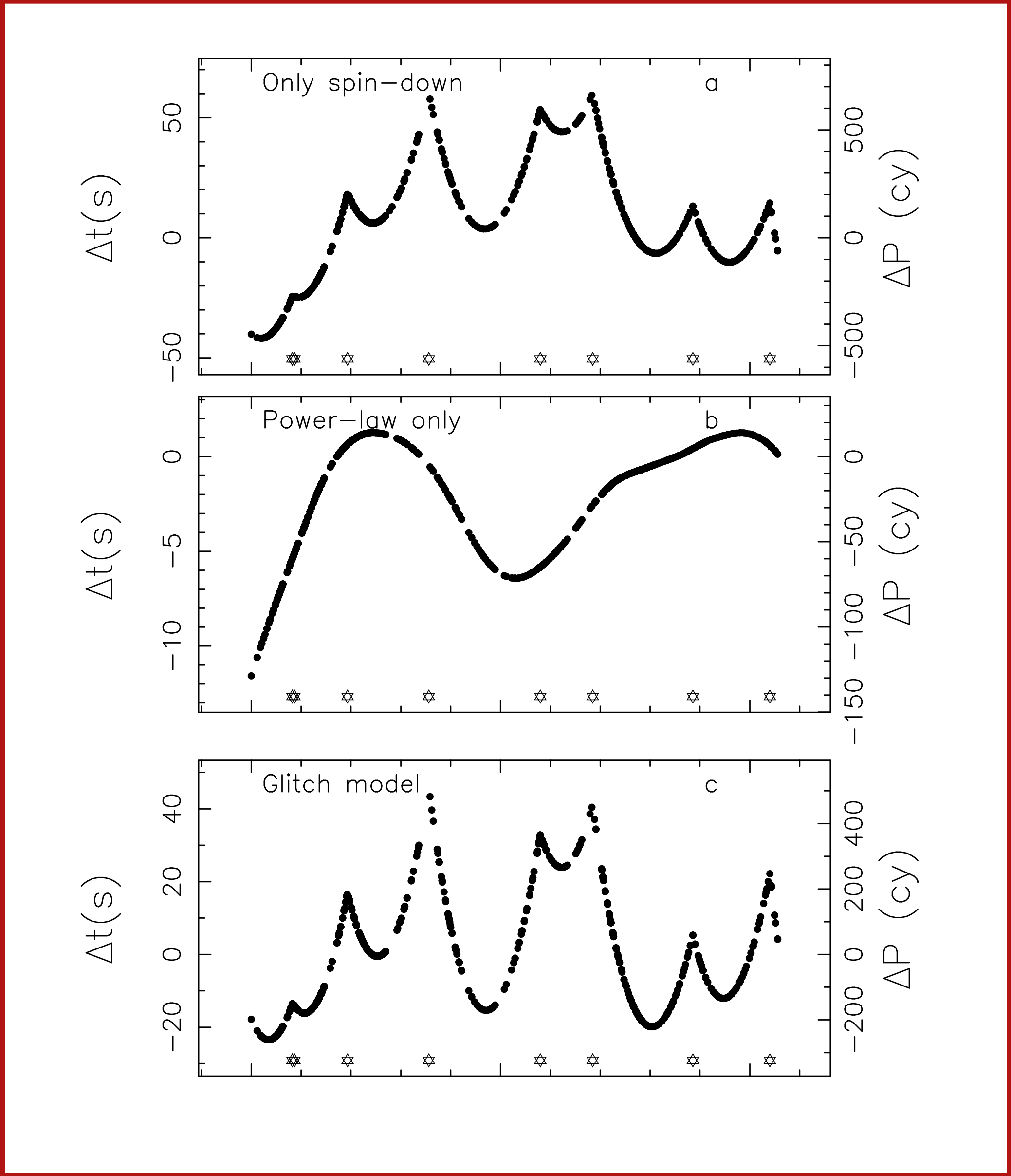
Either from magnetosphere or core…
Origins not understood very well.

Stochastic process as with DM - but in one pulsar
it can look just like gravitational waves (below).





Data Challenges



Timing Noise from the core:

<- Vela (Young slow pulsar)

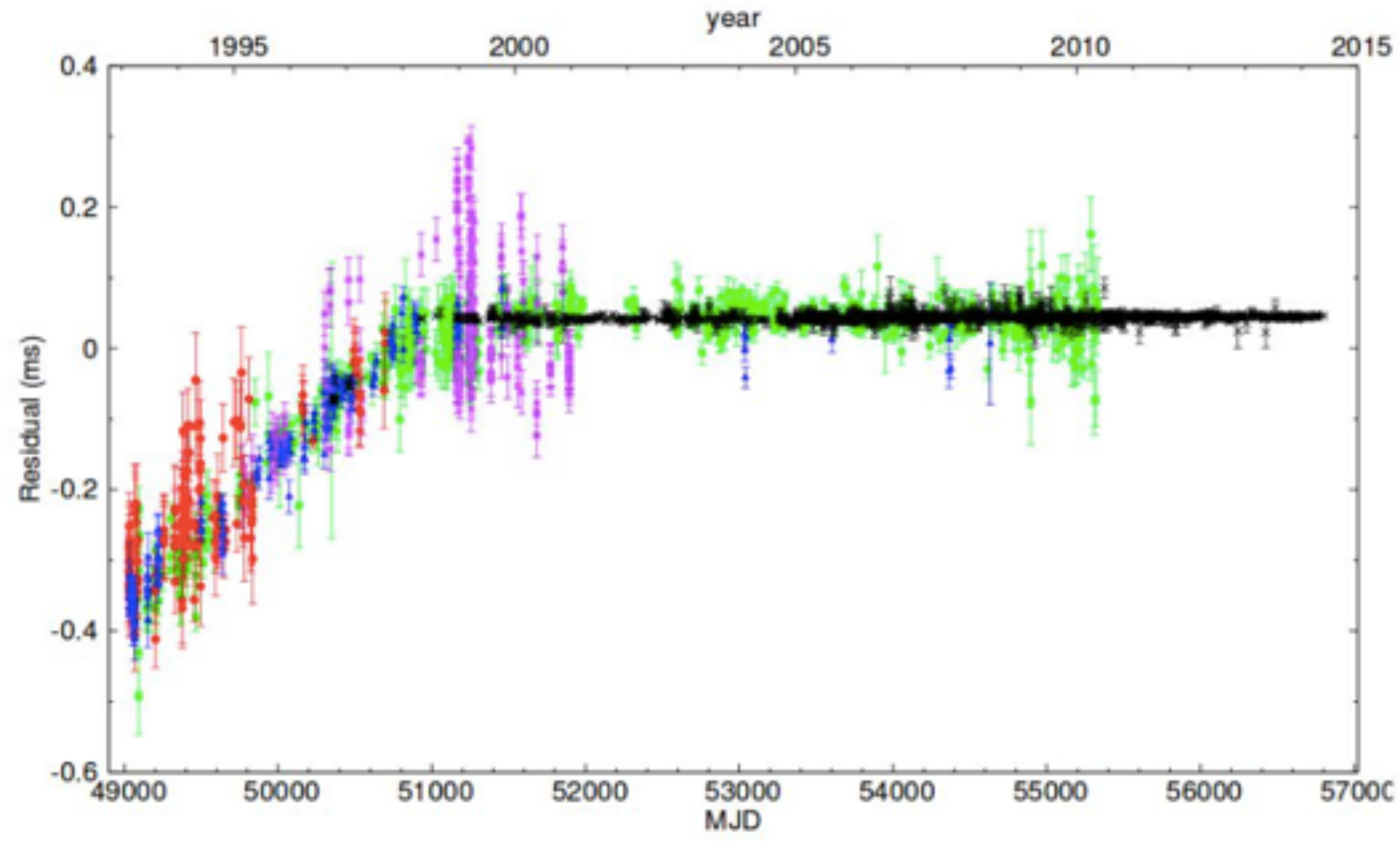
Glitches - sudden changes in rotation rate
Accompanied (in this case)by long (~1000 day) decays

Maybe associated with the transfer of angular momentum between the superfluid interior and solid crust of the neutron star.

Common in young pulsars
But two glitches found in millisecond pulsars

Fig: Shannon et al 2016

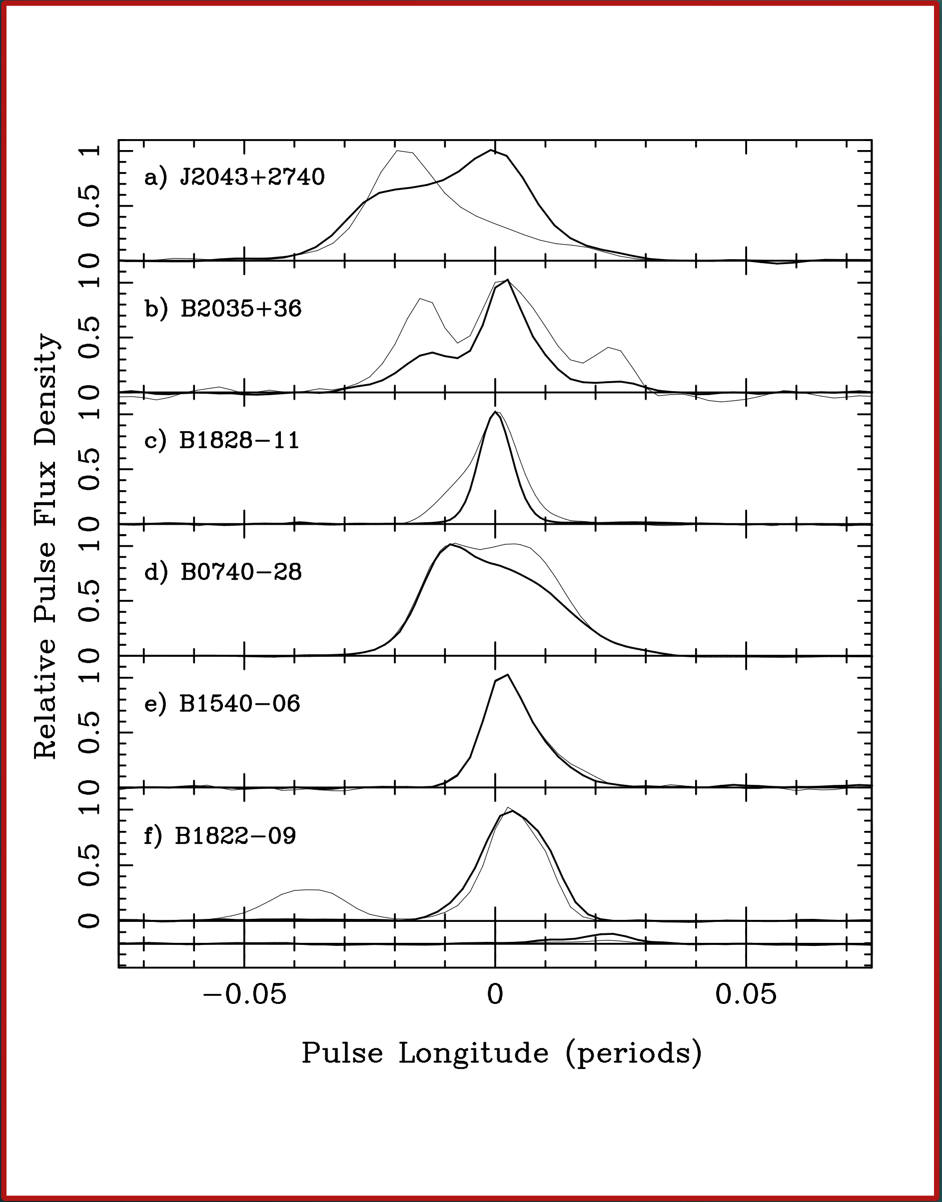
Data Challenges



Glitch in the MSP J0613
McKee et al 2016

Sounds like bad news?
Glitches are not so hard.
Put it in the model, decreases long term sensitivity, but at least somewhat deterministic.

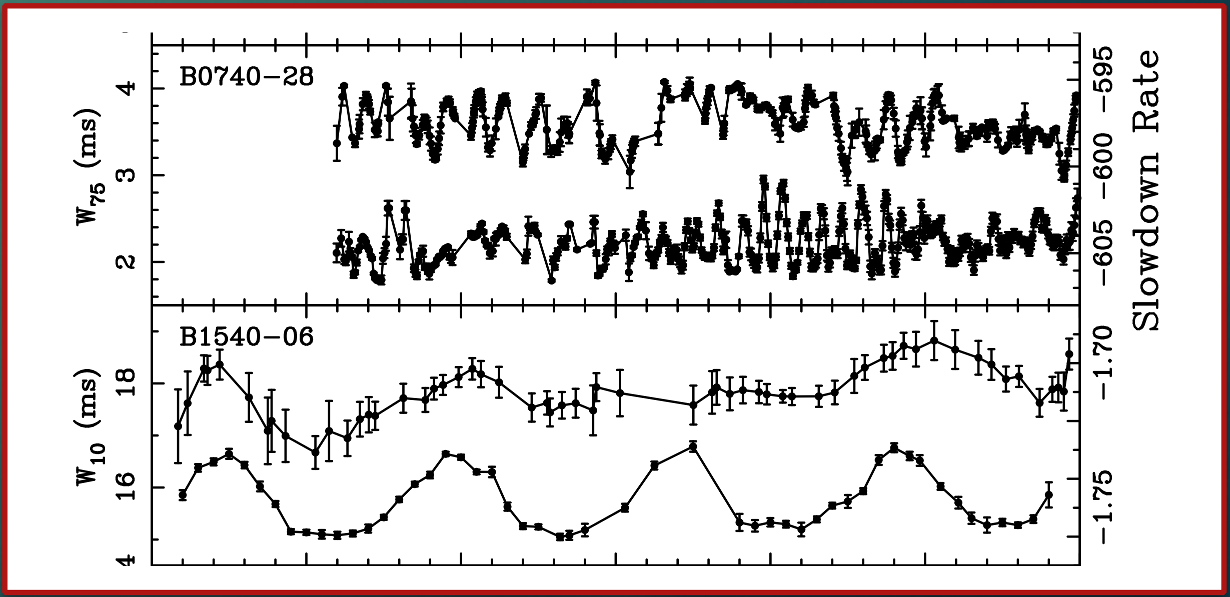
Data Challenges



Timing Noise from the magnetosphere:
Less extreme: Switching to different states

Observe change in pulse shape:
Rate of energy loss is different
different spin down rate

Figs: Lyne et al 2010



Data Challenges

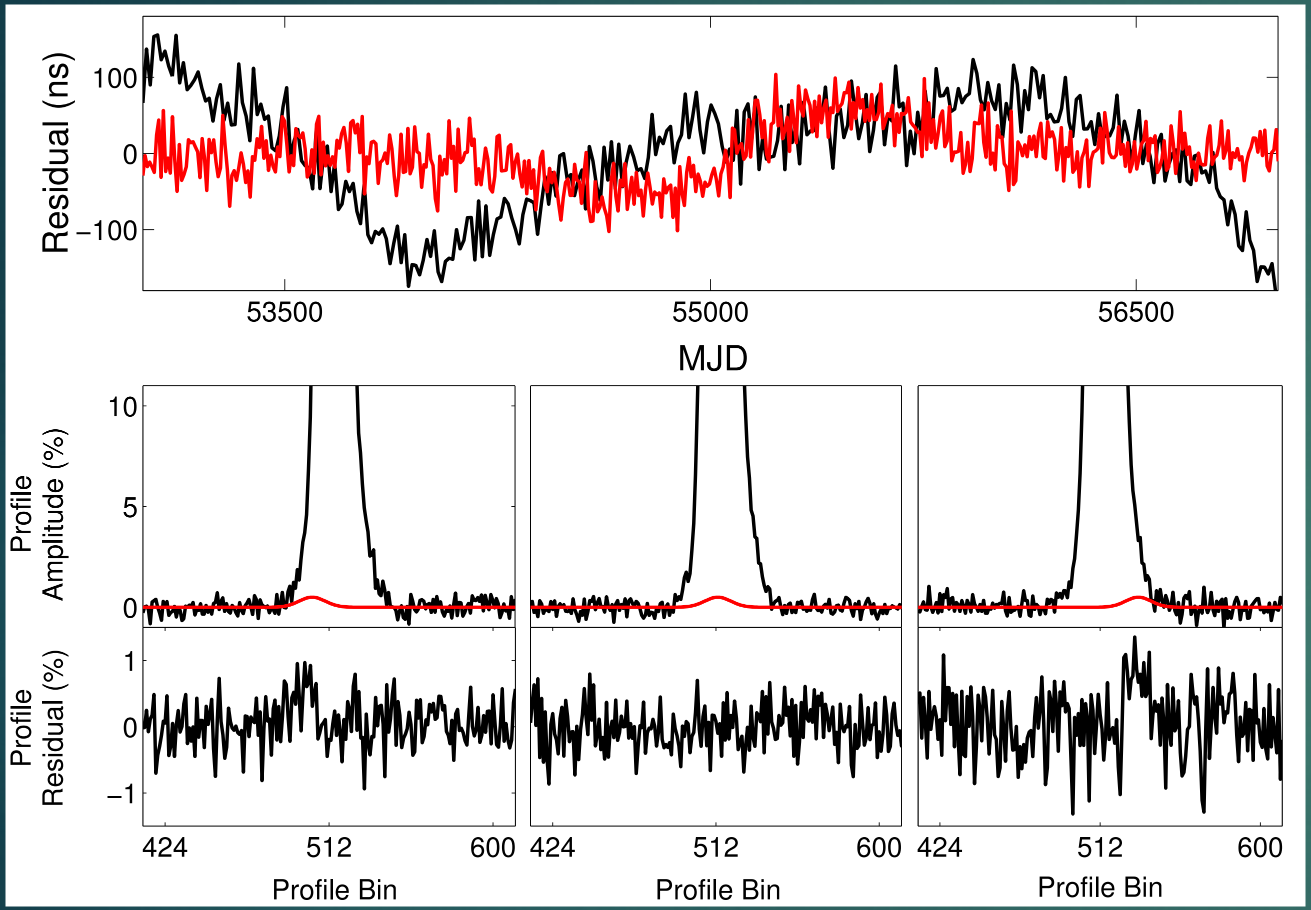


Fig: Lentati & Shannon 2015

But:
Profile change can lead to 'timing noise' in the arrival times due to mismatch between template and profile data.

<- Simulation

Change in pulse shape lead to observed timing noise when comparing profile to stationary model.

Black curve = signal from GWs at current upper limit.

Red = residual induces from < 1% change in profile shape

Data Challenges

Time-correlated profile change seen in young pulsars a lot
Recently seen in a millisecond pulsar too.
The shift in the residuals isn't an actual shift. Just mismatch between template and data. (Shannon et al 2016, Liu et al 2015)

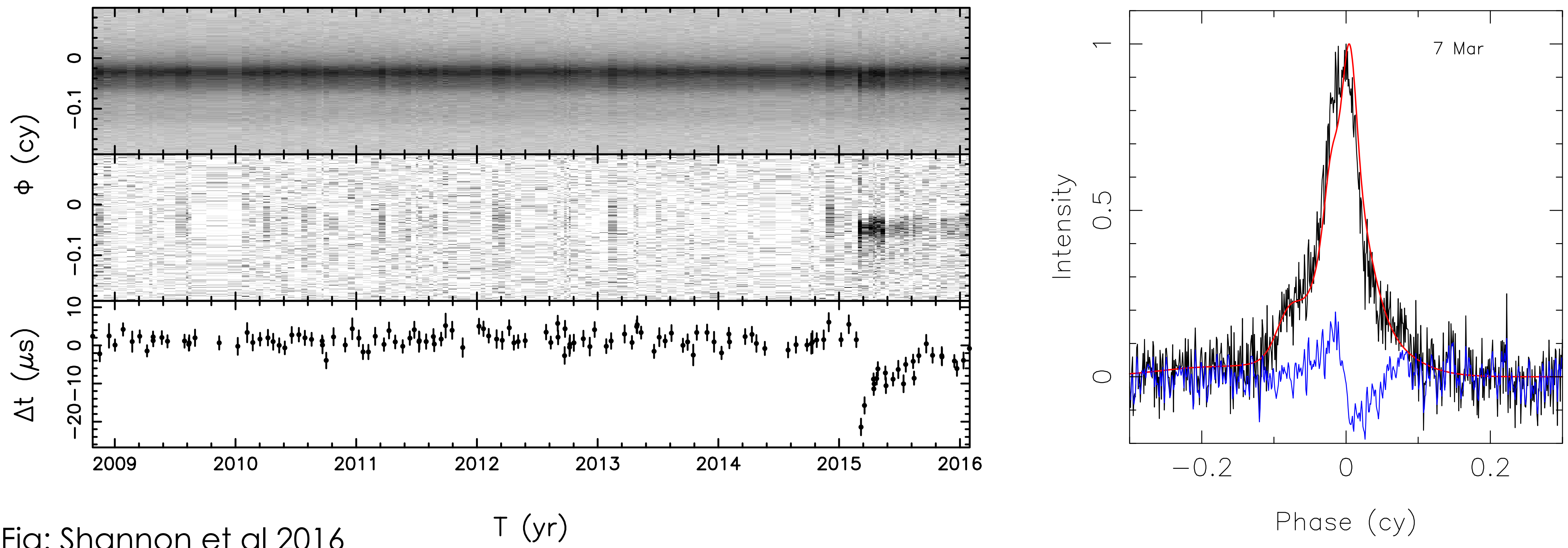


Fig: Shannon et al 2016

Data Challenges

Different approach: Profile domain timing
Don’t make time of arrivals.
Simultaneously estimate model for profile and pulsar timing parameters.
Decouple shape change from shifts.

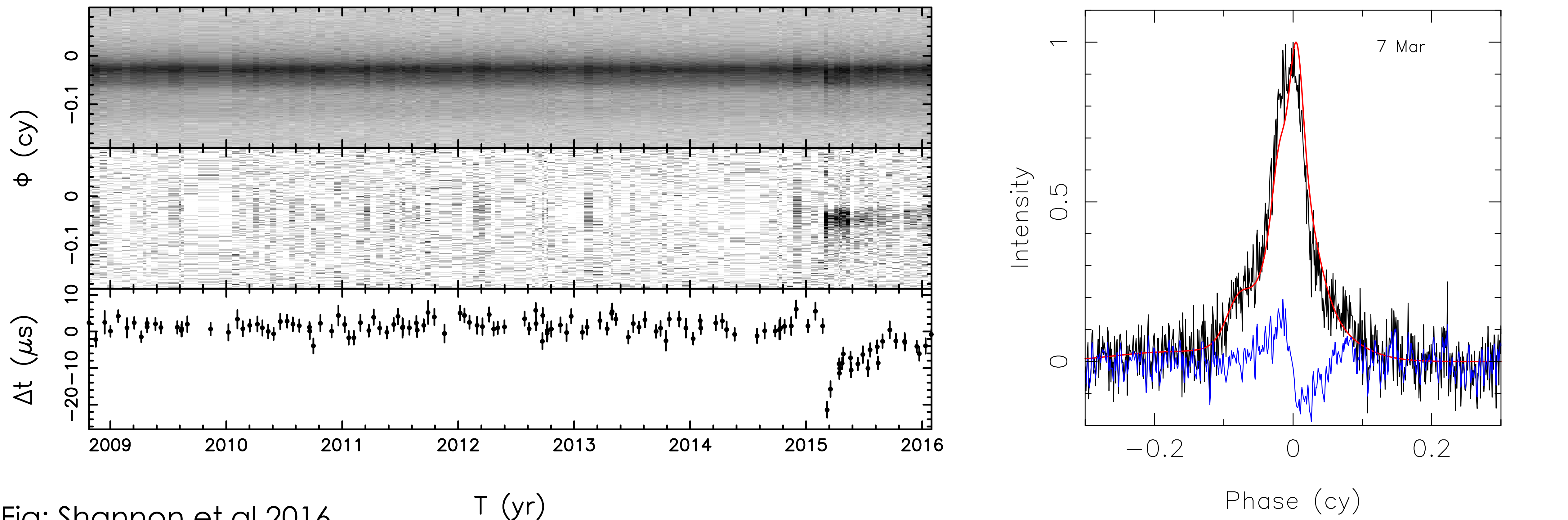


Fig: Shannon et al 2016

Data Challenges

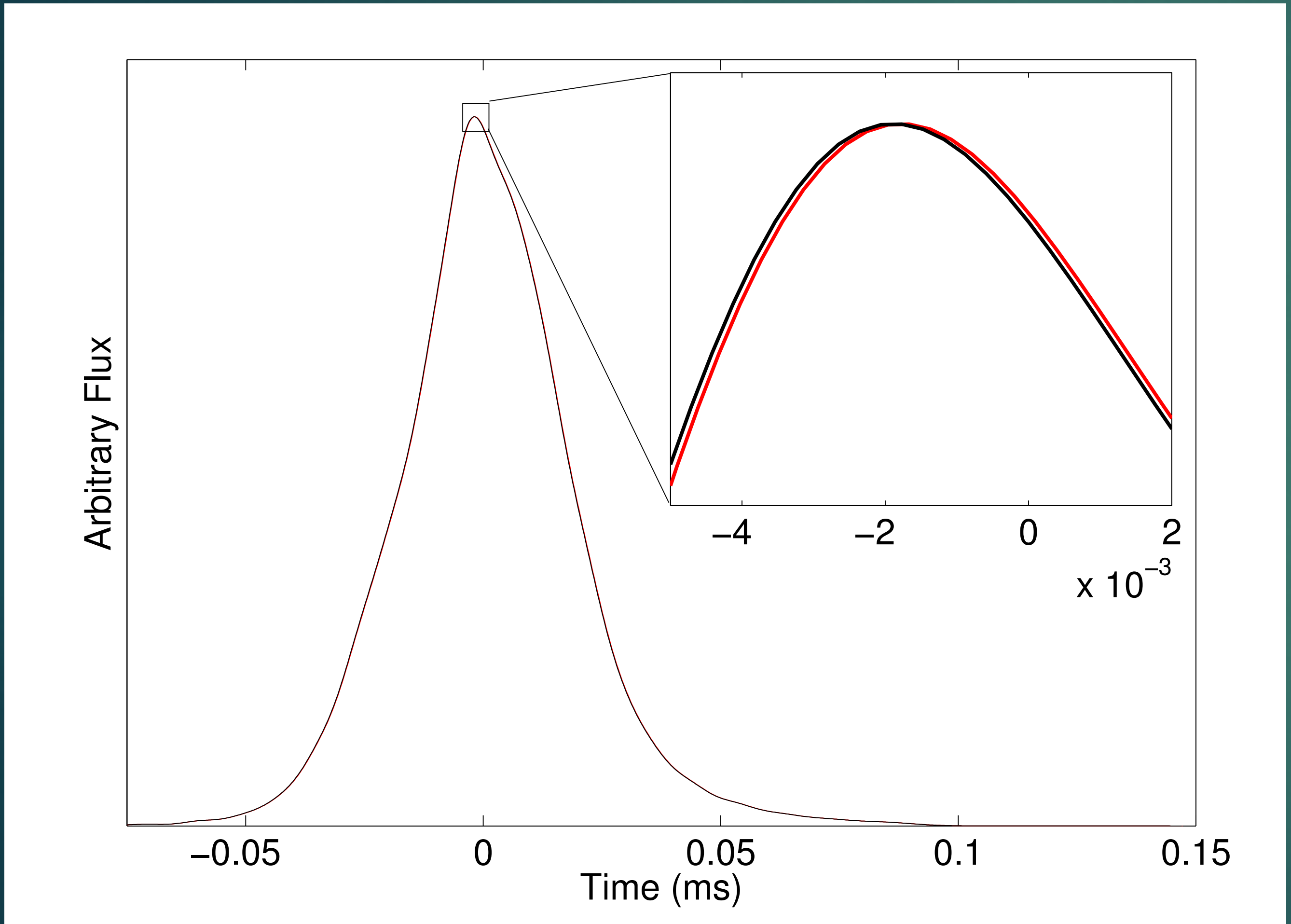


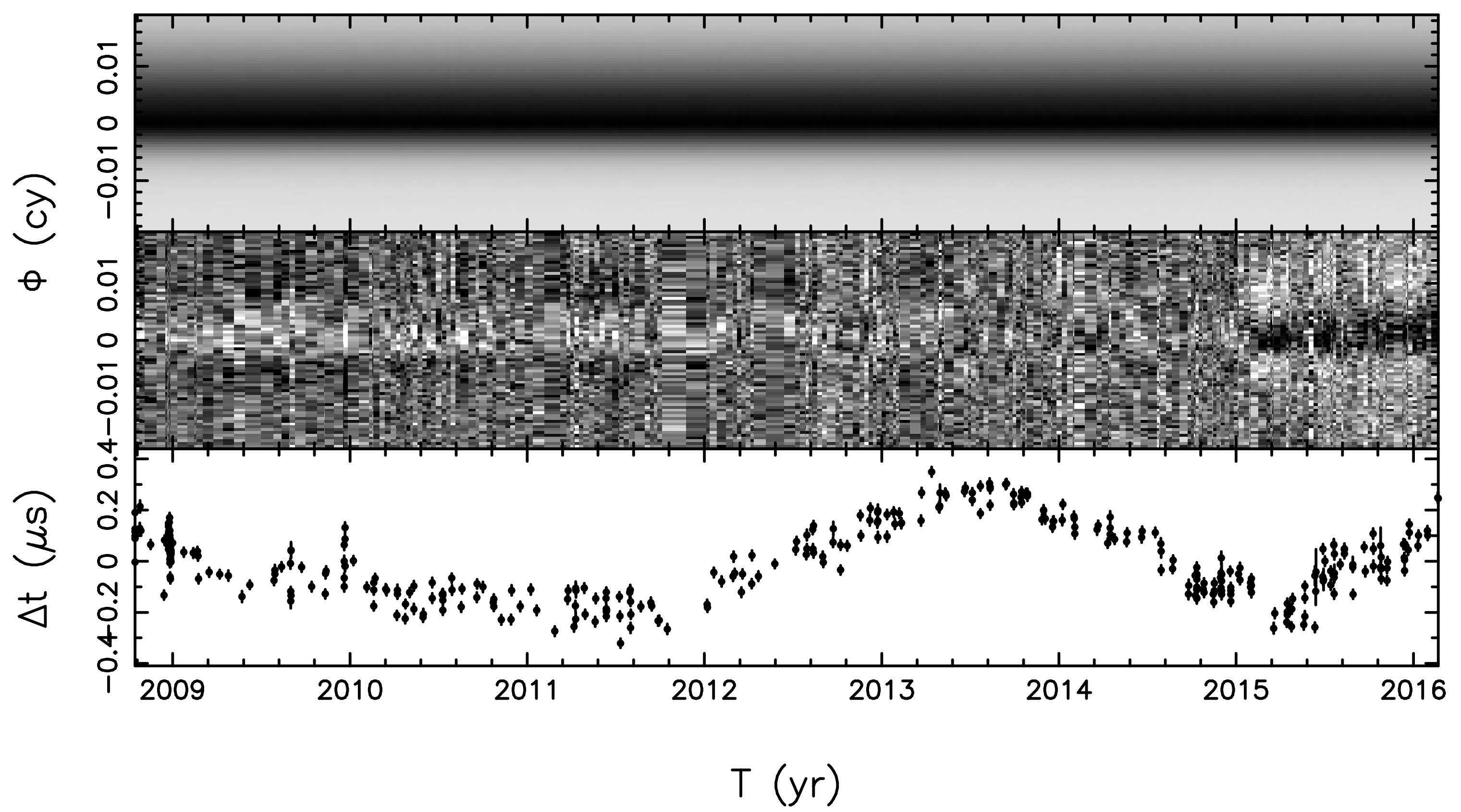
Fig: Lentati & Shannon 2015

Need to be accurate: Shift due to GWs is only a tenth of a phase bin.

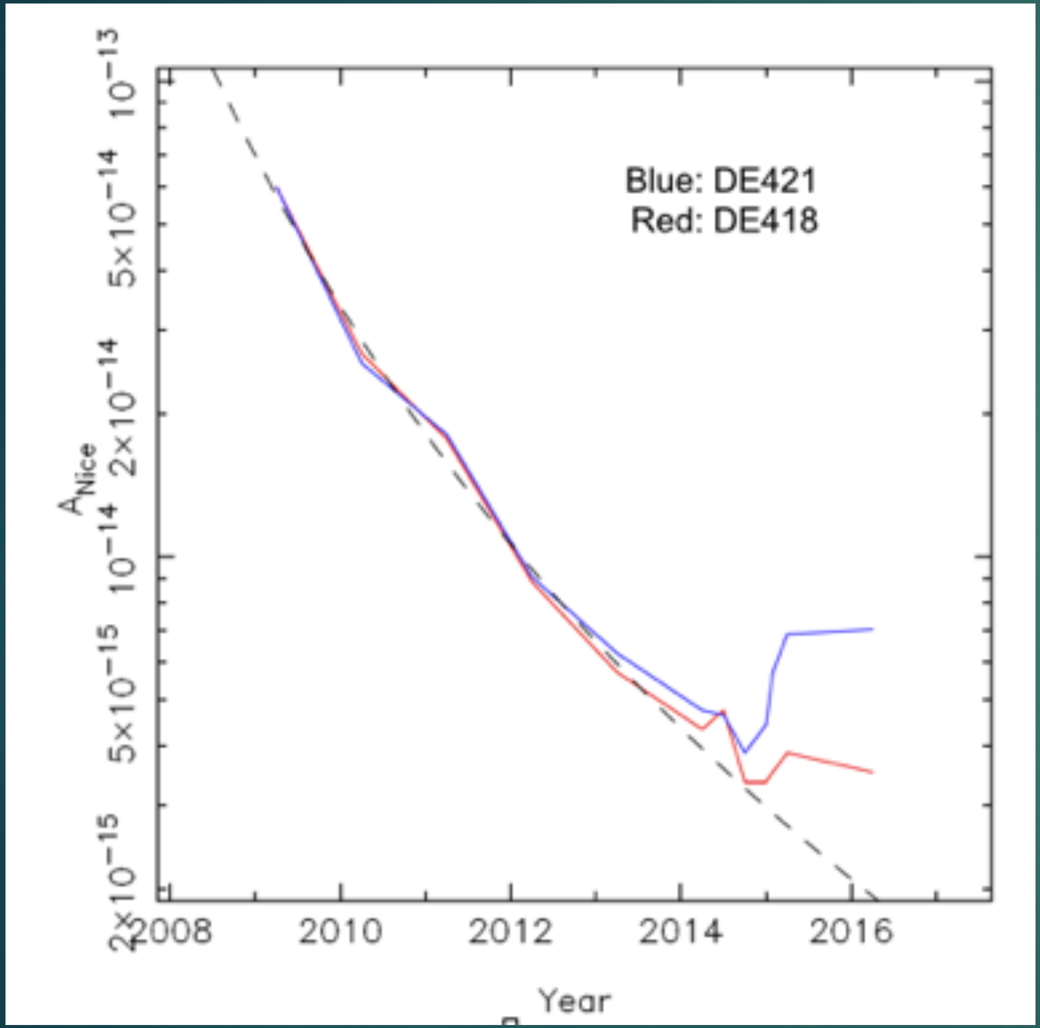
Standard timing approach makes it difficult/impossible to distinguish timing noise due to shifts, from timing noise due to changing profile and mismatched template.

Data Challenges

May be seeing discrete profile changes in other MSPs : J0437-4715 (again).
If we can model profile change simultaneously with spin down change could significantly decrease covariance of timing noise and GWs.



Data Challenges (Last One)



PPTA limit as a function of time:
Dashed line = Theoretical decrease for noise only
Different colours are different models for the Solar System (JPL Ephemeris)

Limits now depend on this :(

Fig: Ryan Shannon

Data Challenges (Last One)

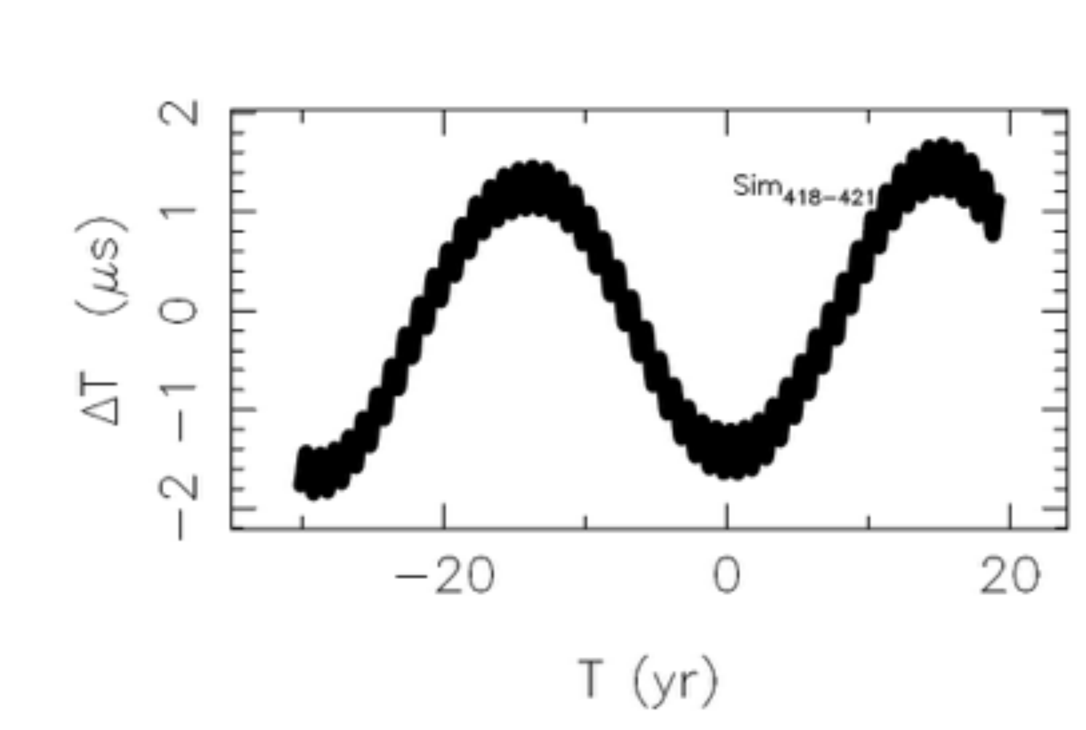


Fig: Ryan Shannon

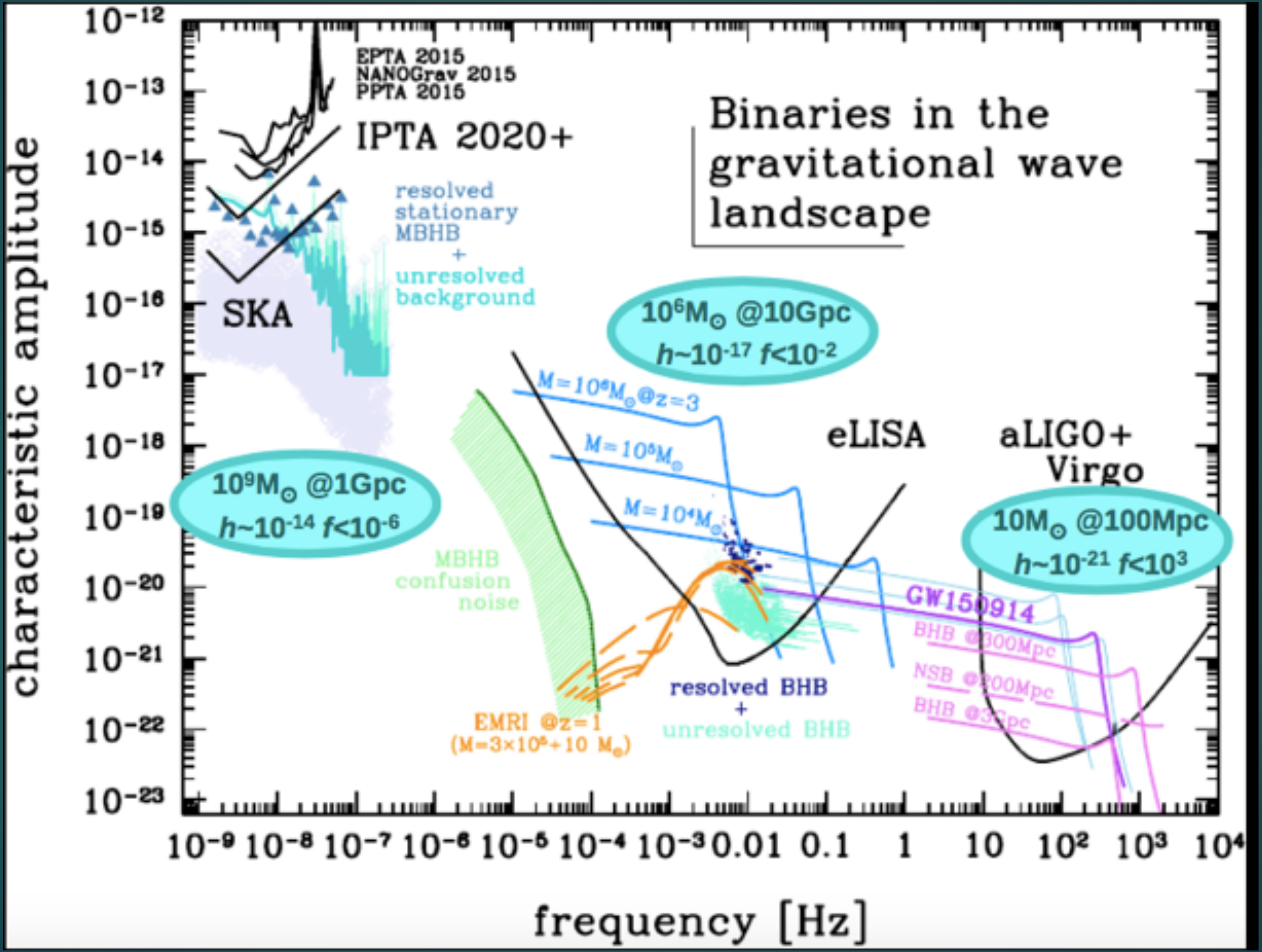
Simulated arrival times over > 40 years

Simulated in DE418 and measured in DE421

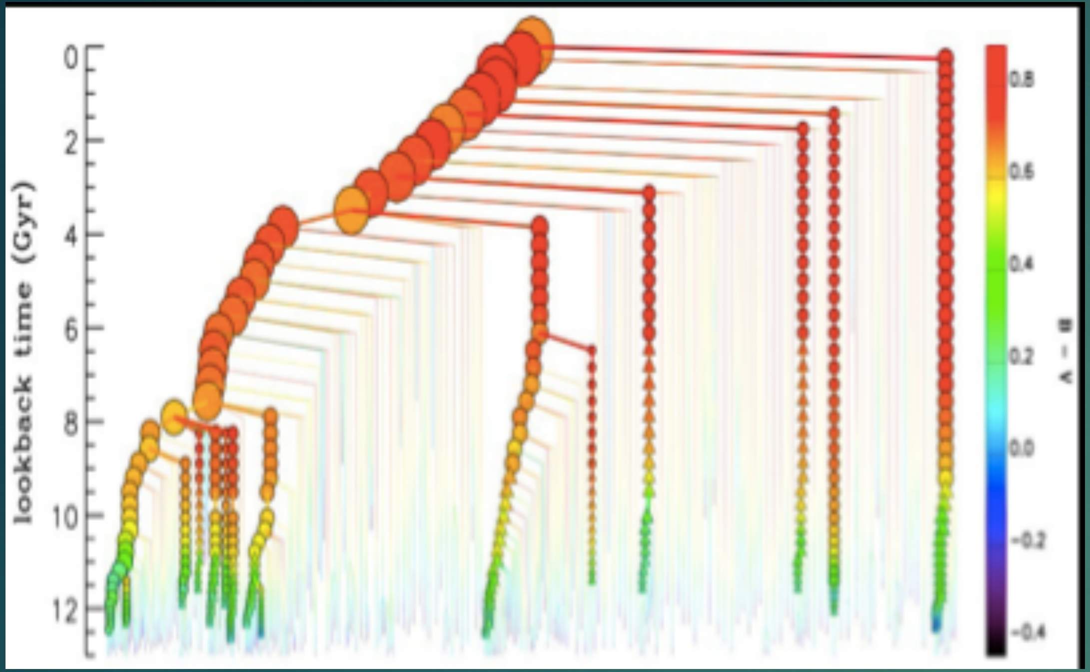
Looks like Saturn..

Cool! But Annoying..

Back on topic..

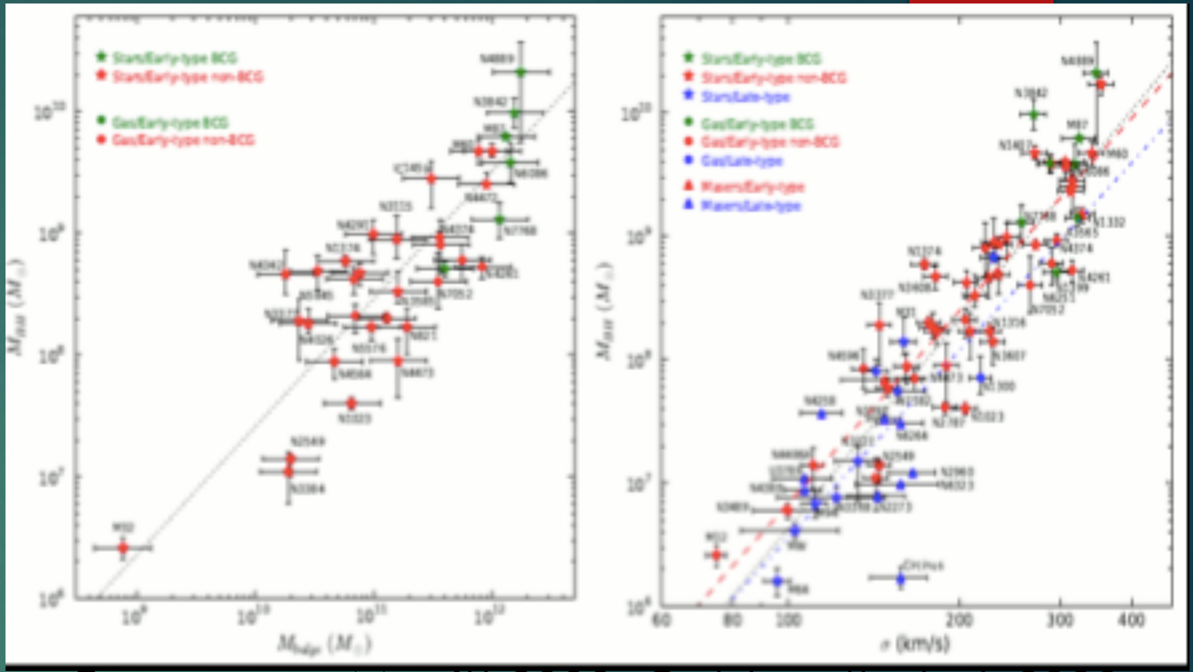


The SMBHB sky - to First Order



De Lucia et al 2006

+

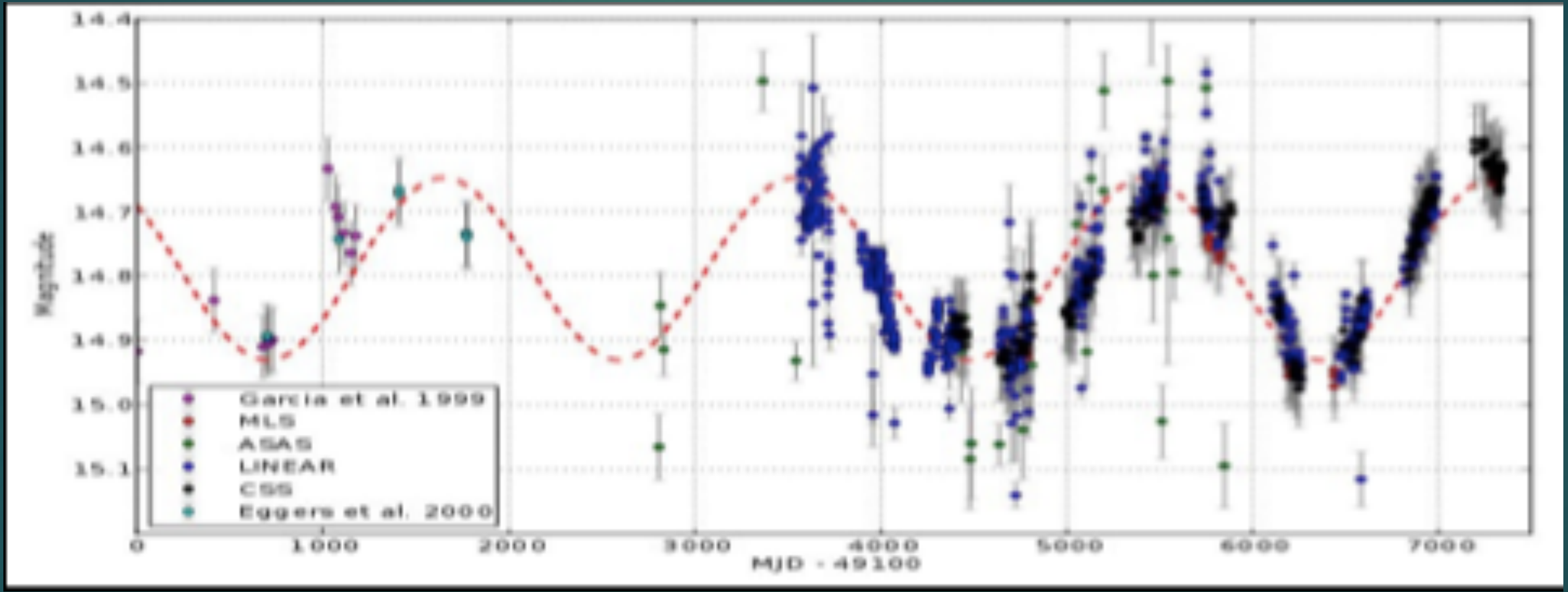


Ferrarese & Merritt 2000, Gebhardt et al. 2000

*Where and when do the first MBH seeds form?
*How do they grow along the cosmic history?
*What is their role in galaxy evolution?
*What is their merger rate?
*How do they pair together and dynamically evolve?

The SMBHB sky - to First Order

Certainly some compelling candidates



E.g. Graham et al 2015
< 0.1pc separation
$10^{8.5}$ solar mass

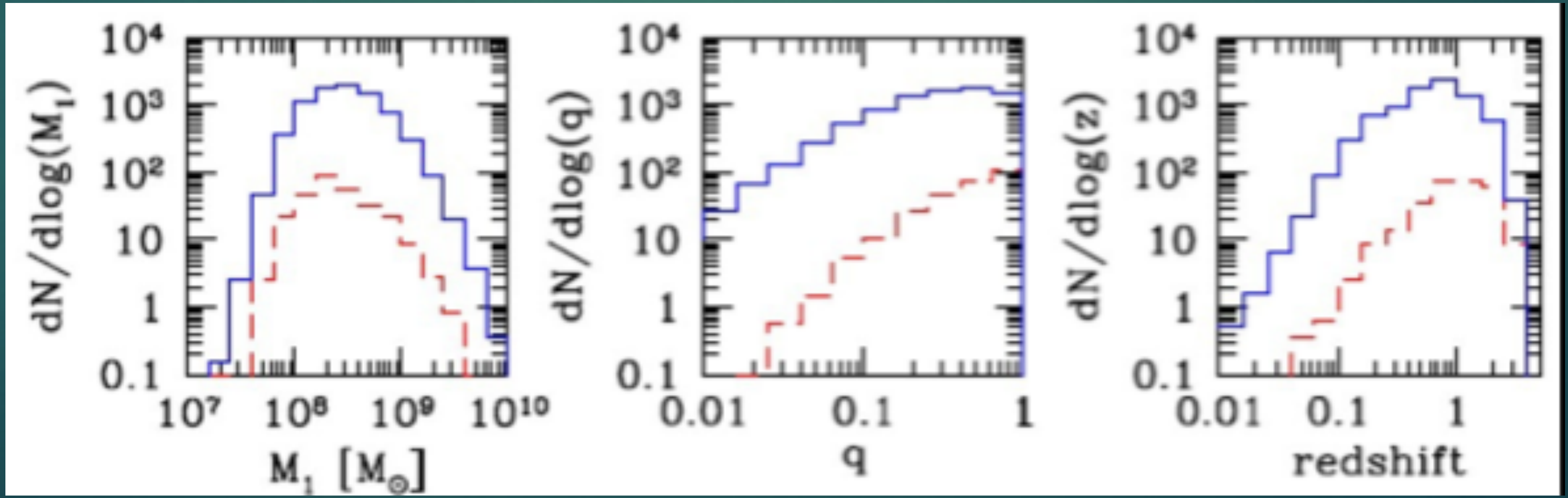
The SMBHB sky - to First Order

So assume all binaries are circular, they will form a stochastic background

with a red power spectrum
(Phinney 2001):

$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

with the signal dominated be extremely massive (> 10^8 solar mass)
relatively low red shift ($z < 1$) MBH binaries (AS et al 2008, 2012)



Astrophysical Problems

Canonical assumptions of ‘vanilla’ models:

- All Galaxy mergers result in a SMBHB merger
- SMBH scale with properties of host galaxy
- SMBHB are driven by the emission of GWs in the PTA band.

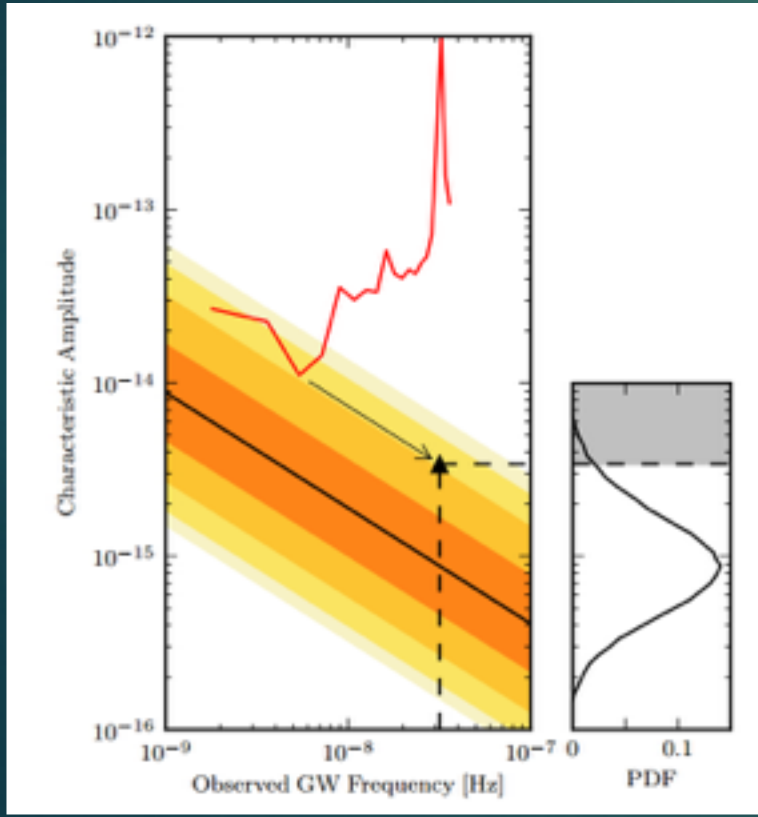
Basically a ‘best case’ scenario.

Problems:

Merger rate not well known.
Scaling relations uncertain
Interaction with the environment (energy loss through non GW channels)

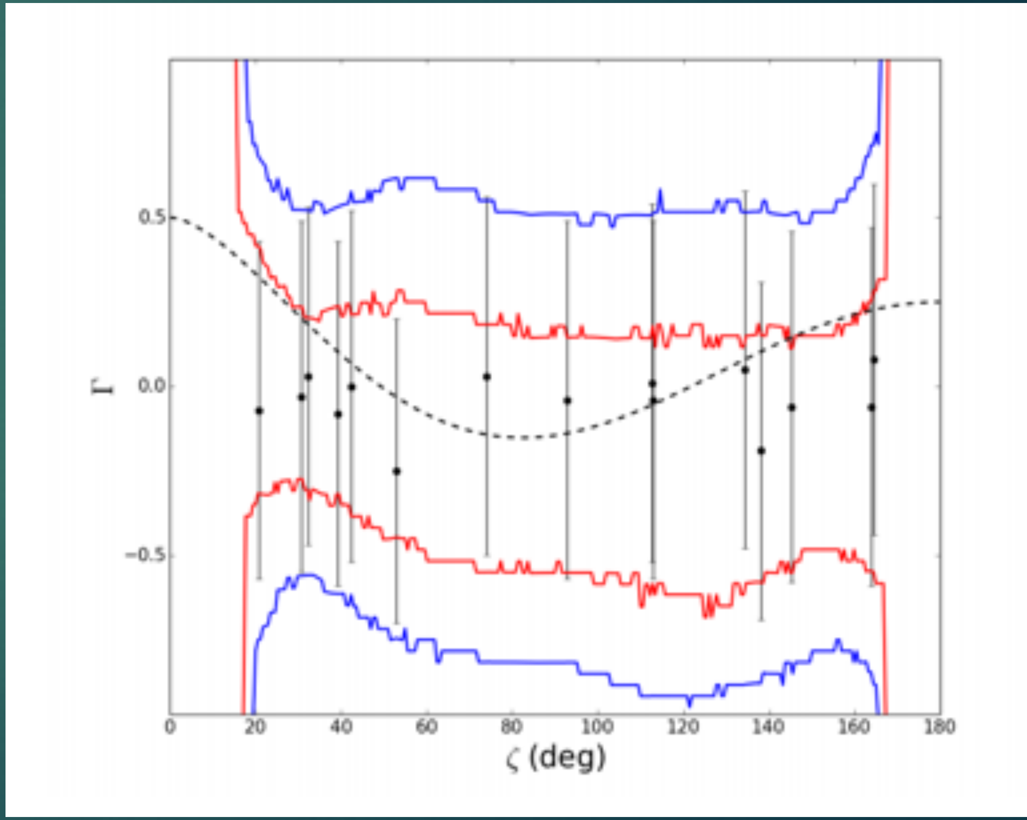
Astrophysical Problems

EPTA limit – Simultaneously estimate contributions from the four main sources of correlated noise, as all contributions correlated in the data (Tiburzi 2015).
Use best six pulsars from EPTA 2015 data set : 18 years of data



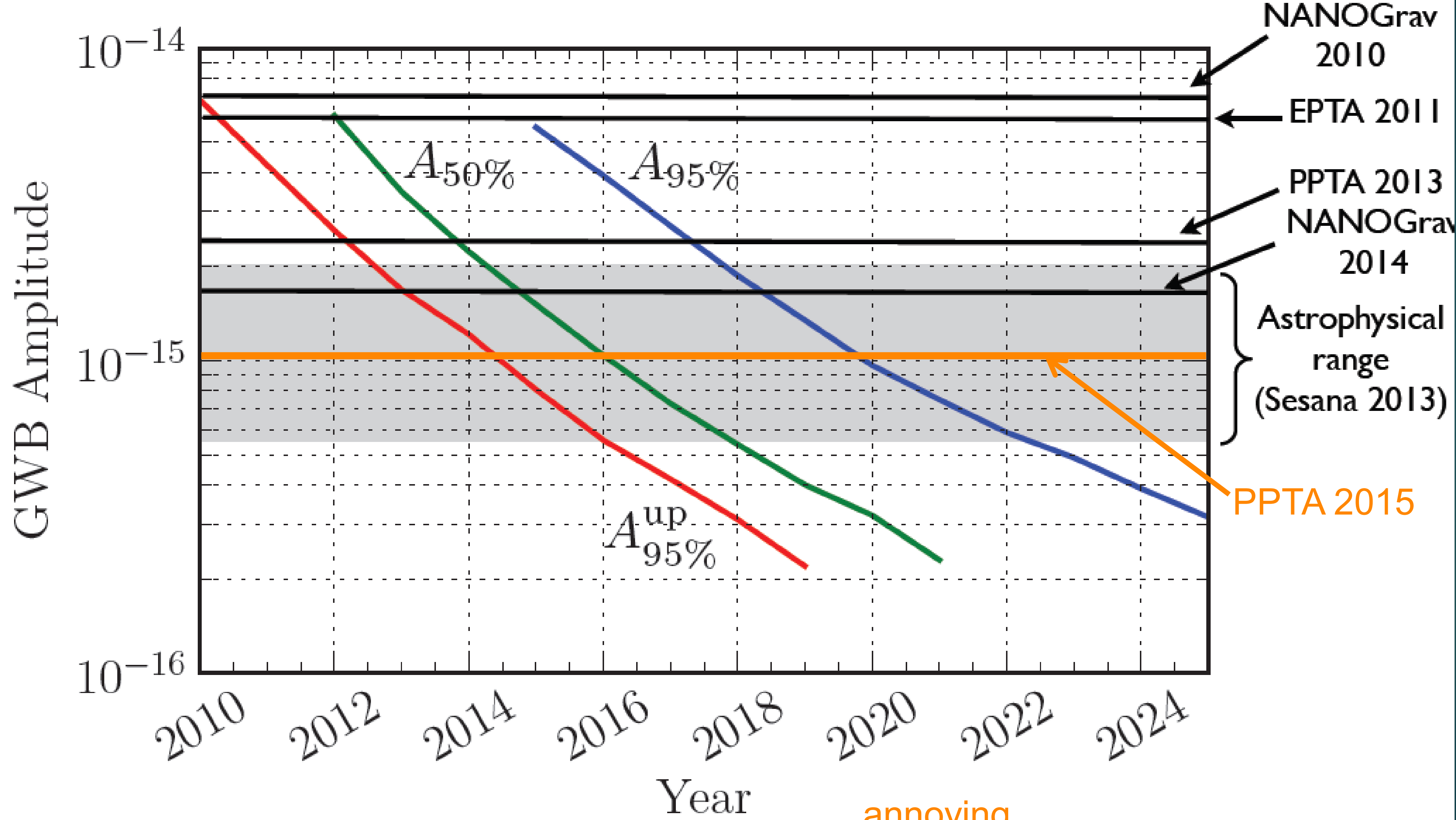
Power Law Limit:
A < 3E-15 at $f=1yr^{-1}$
2x better than last EPTA limit

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



Figures: Lentati et. al. 2015

Astrophysical Problems



We are already in astrophysically ~~interesting~~ annoying territory!!

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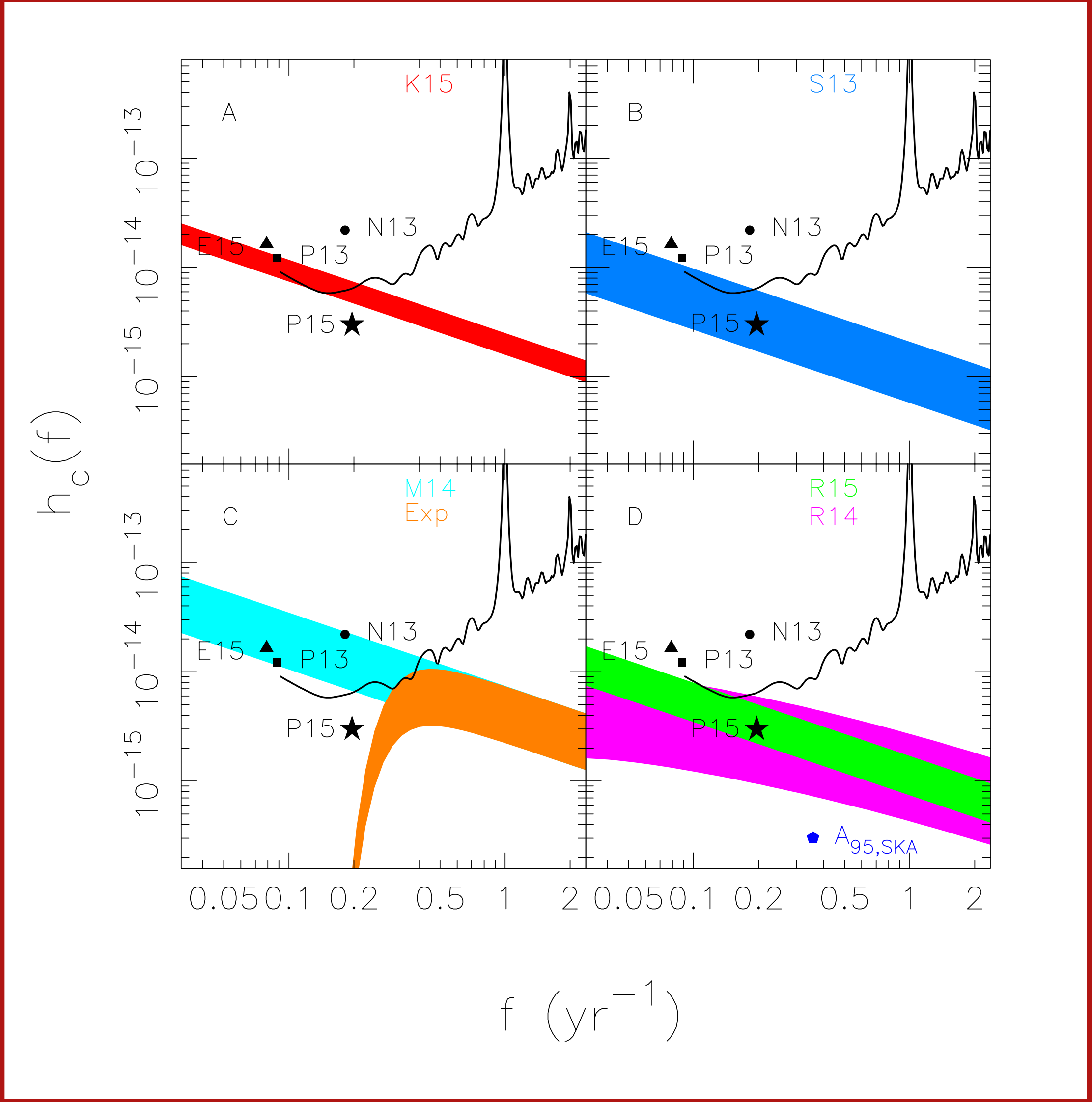
Fig: Xavi Siemens
IPTA meeting 2015

Astrophysical Problems



Ruled out large fractions of (then) published models.

Main source of GWs in pulsar timing band is merging super massive black hole binaries.

Limits have significant implications for Cosmology:

Merges less frequent?

Energy lost through environment?

Mergers stalling?

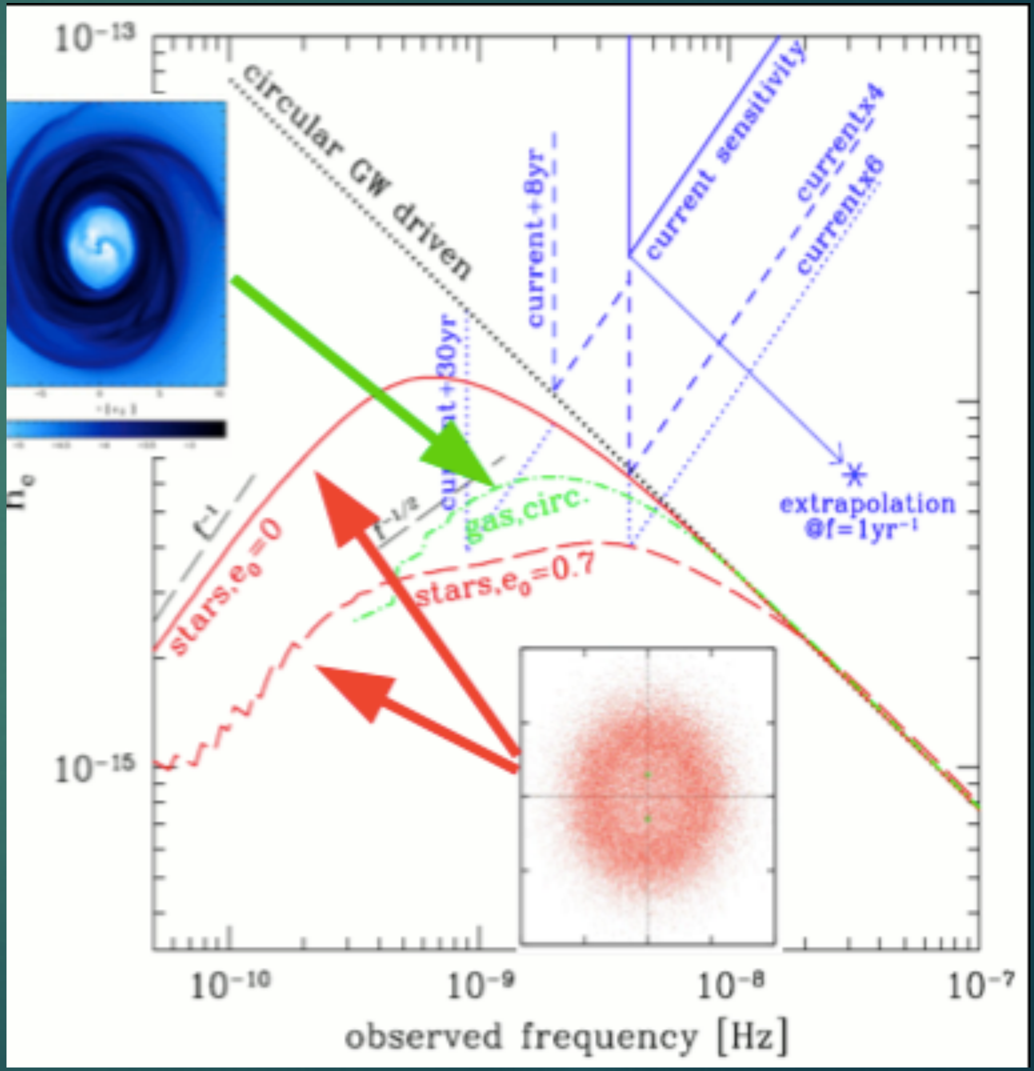
Lots of questions!

Fig: Shannon et al 2015

Astrophysical Problems - Environment

Interaction with gaseous/stellar environment suppresses the signal at the lowest frequencies.

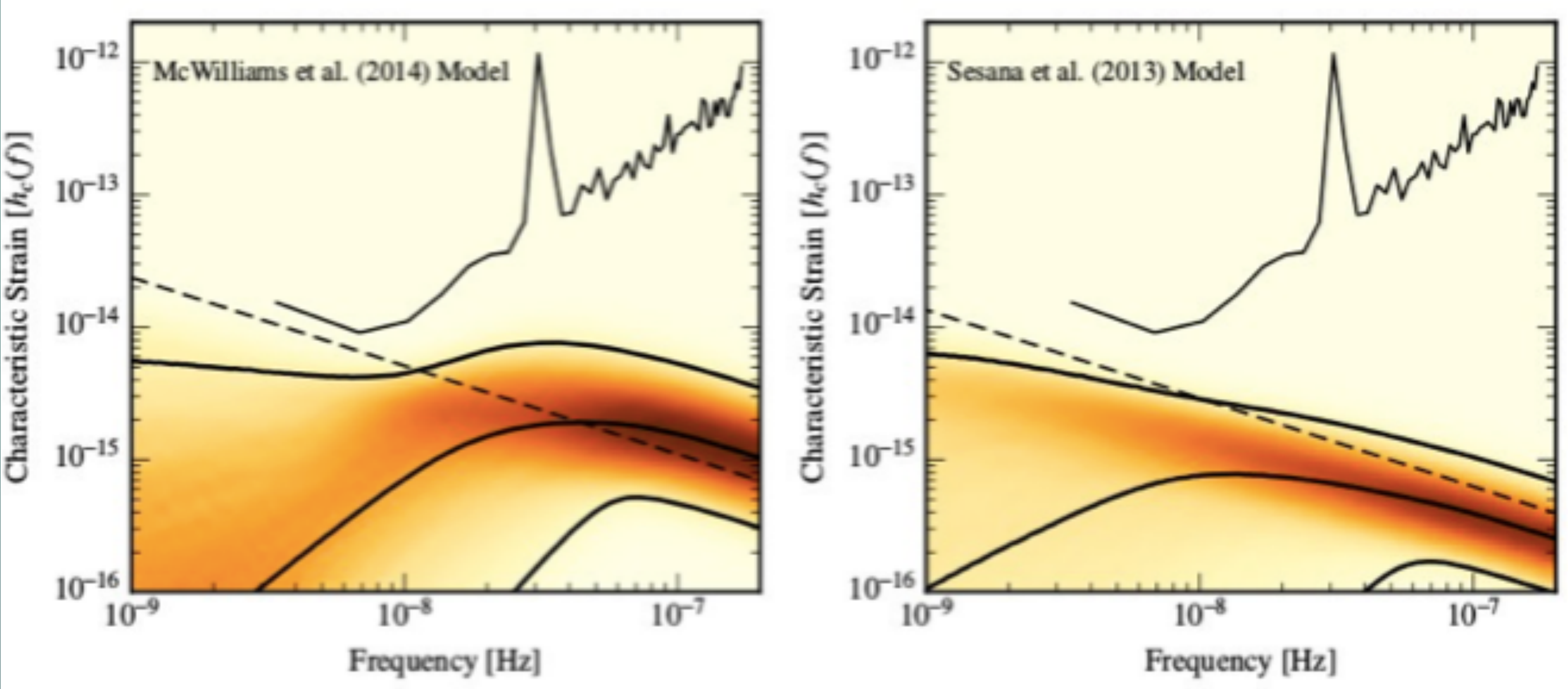
Eccentricity has a similar effect



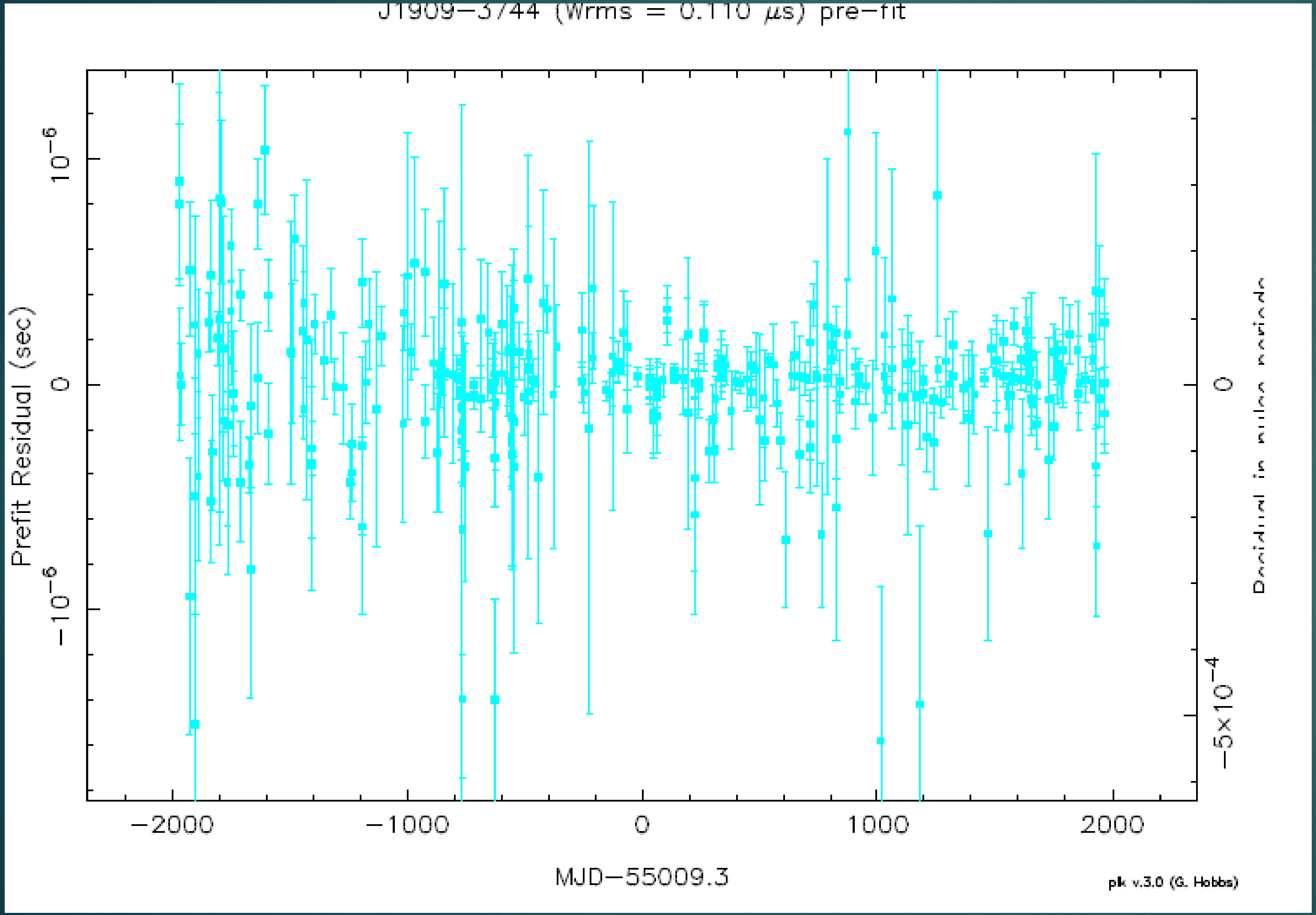
Astrophysical Problems - Environment

Broken power-law models can mimic possible environmental effects (Sampson et al 2015).

Can potentially determine if a non-detection provides any evidence for a turnover in the spectrum.



Astrophysical Problems



11 years of data for a particular pulsar

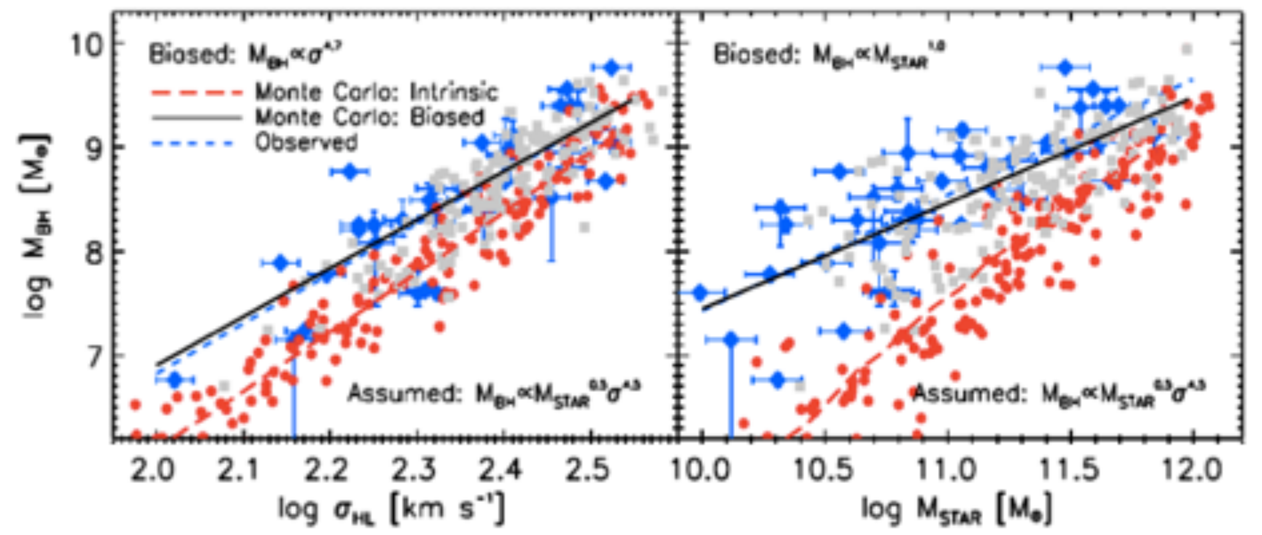
3GHz data (avoid ISM)

100ns rms

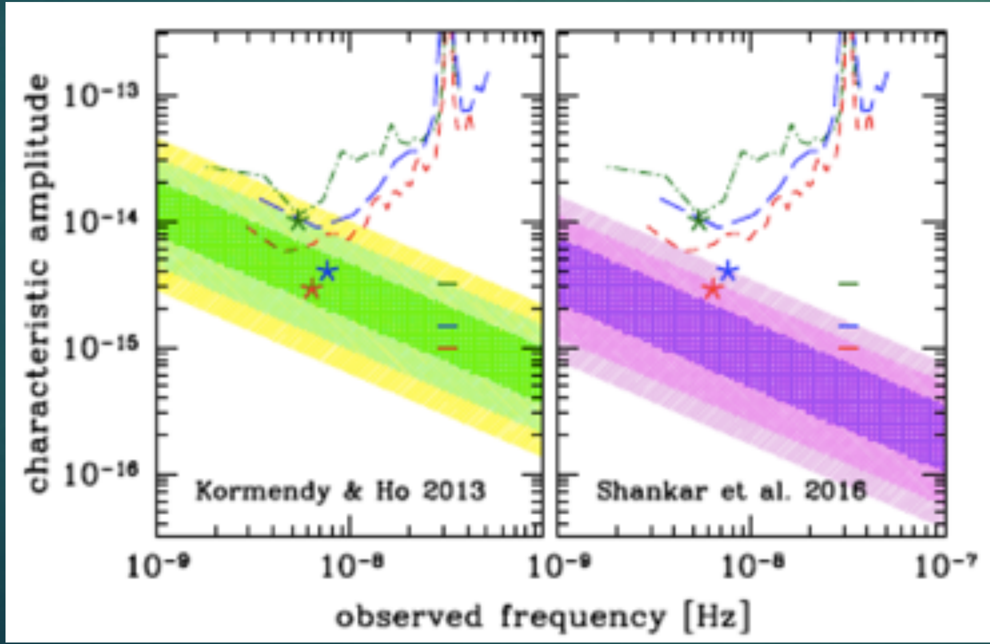
no evidence for low frequency timing noise of *any* kind.

What is the amplitude of the GW signal in the pulsar timing band?

Astrophysical Problems

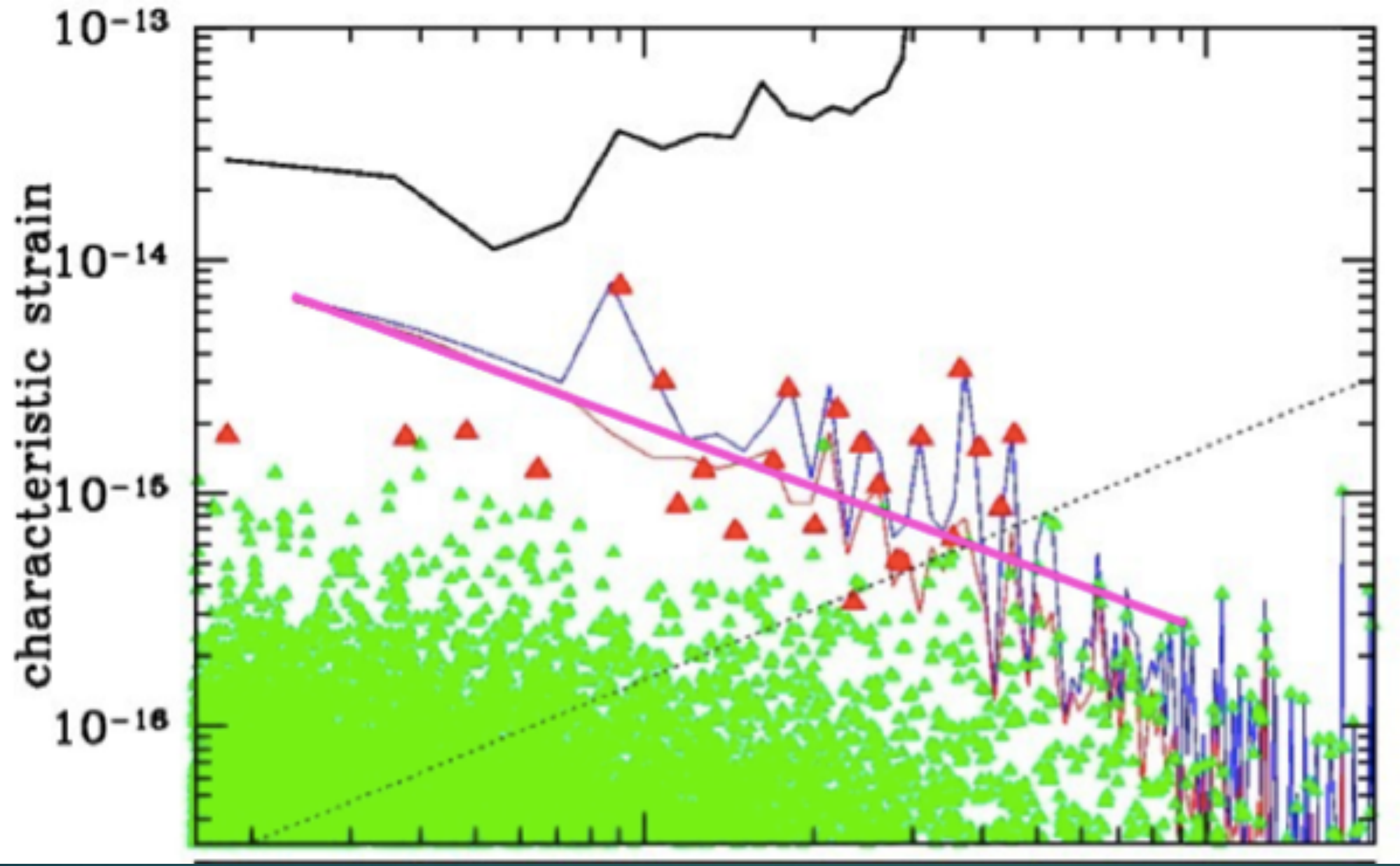


BH-galaxy relations maybe biased high
(Shankar et al 2016)



If so, amplitude may be 3x lower,
(Sesana 2016)
pushes back detection by ~7 yrs

Astrophysical Problems



Signal isn't smooth
Nor Gaussian
Maybe Anisotropic
Will have bright sources

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

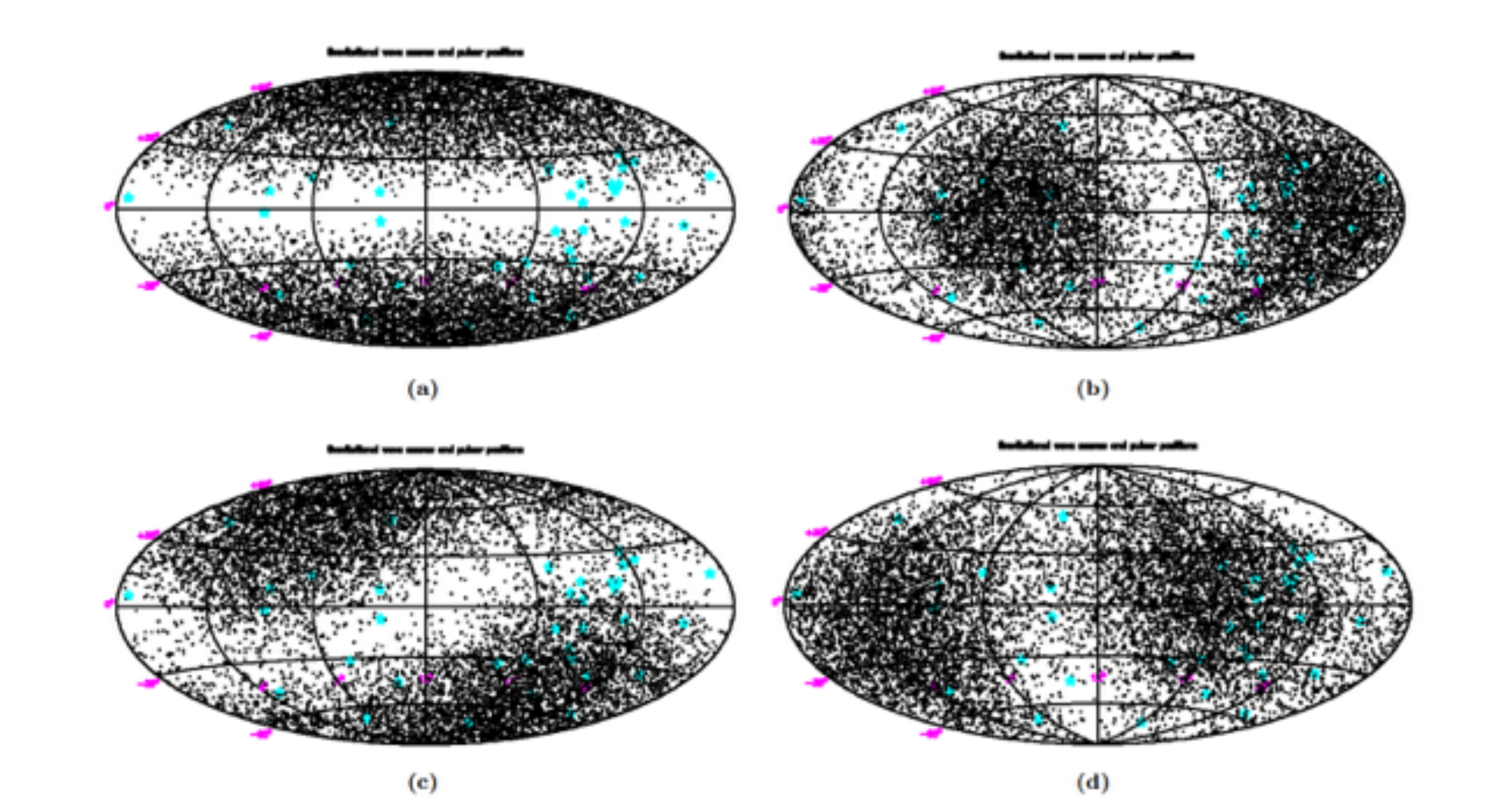


Figure: Taylor & Gair 2013

Anisotropic Stochastic Background

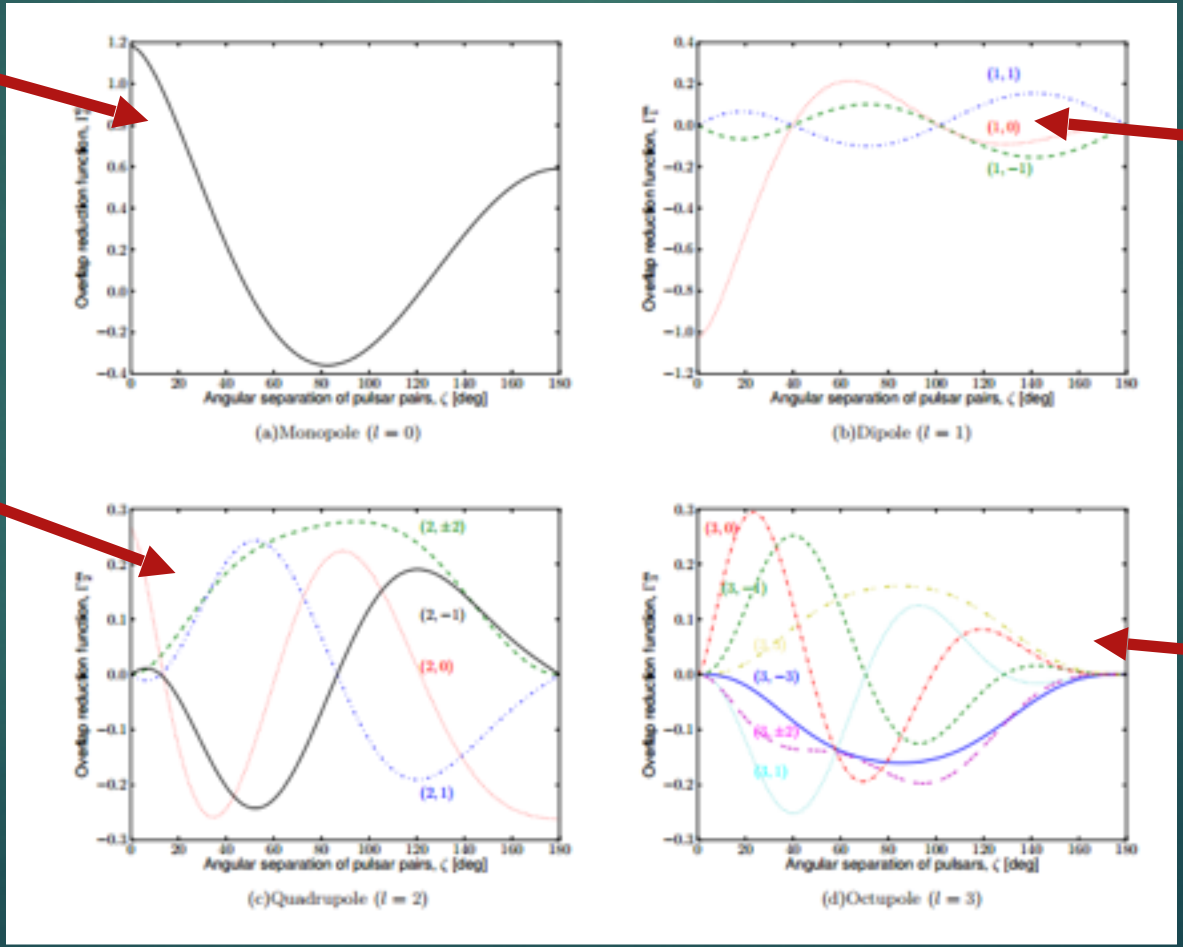
Different Spherical harmonic components give different correlations.

Monopole (Isotropy)
Gives Hellings-Downs curve.

Quadrupole

Dipole

Octopole



(a)Monopole ($l = 0$)

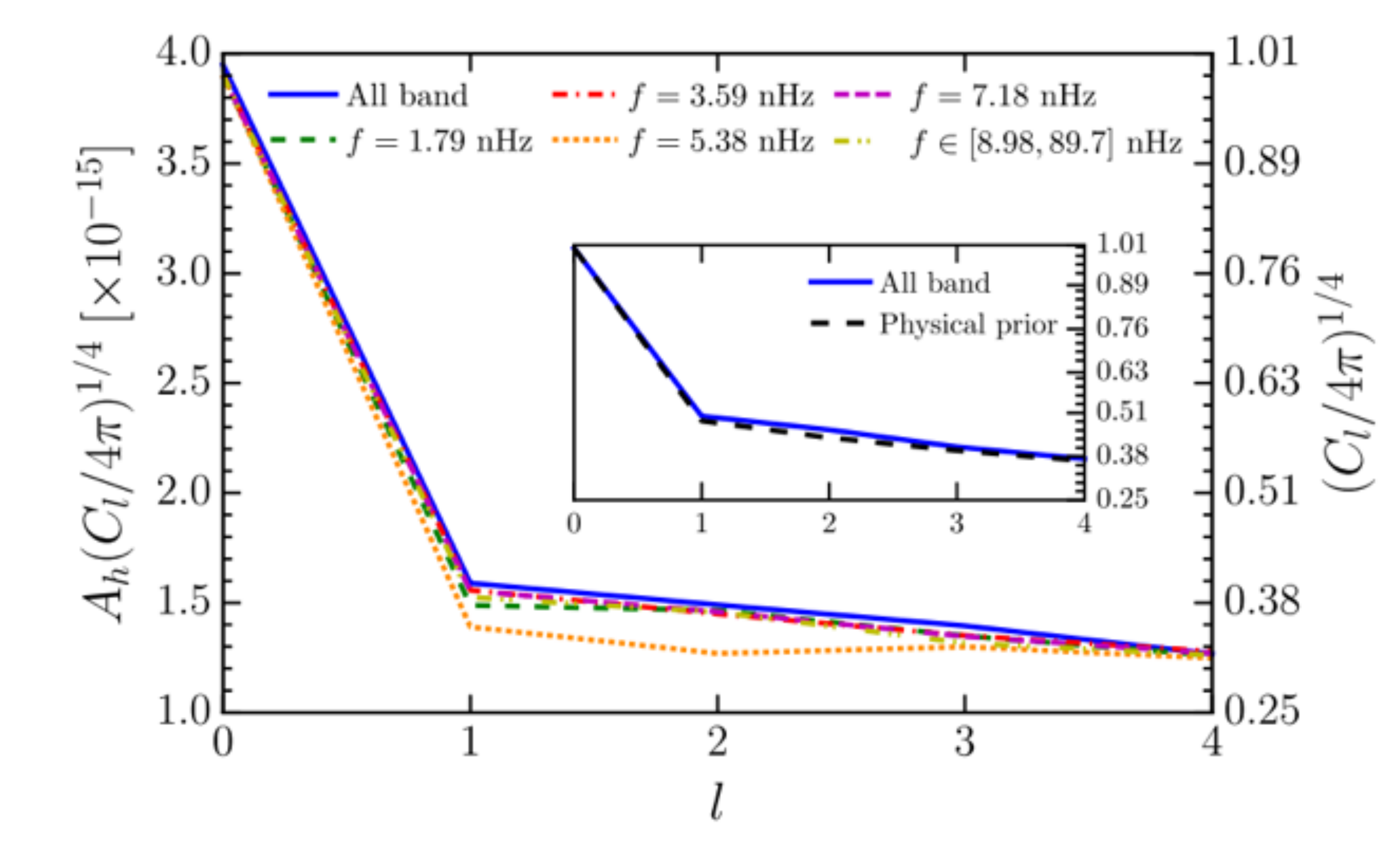
(b)Dipole ($l = 1$)

(c)Quadrupole ($l = 2$)

(d)Octupole ($l = 3$)

Figure:
Mingarelli et. al. 2013

Anisotropic Limits – EPTA 2015 Dataset

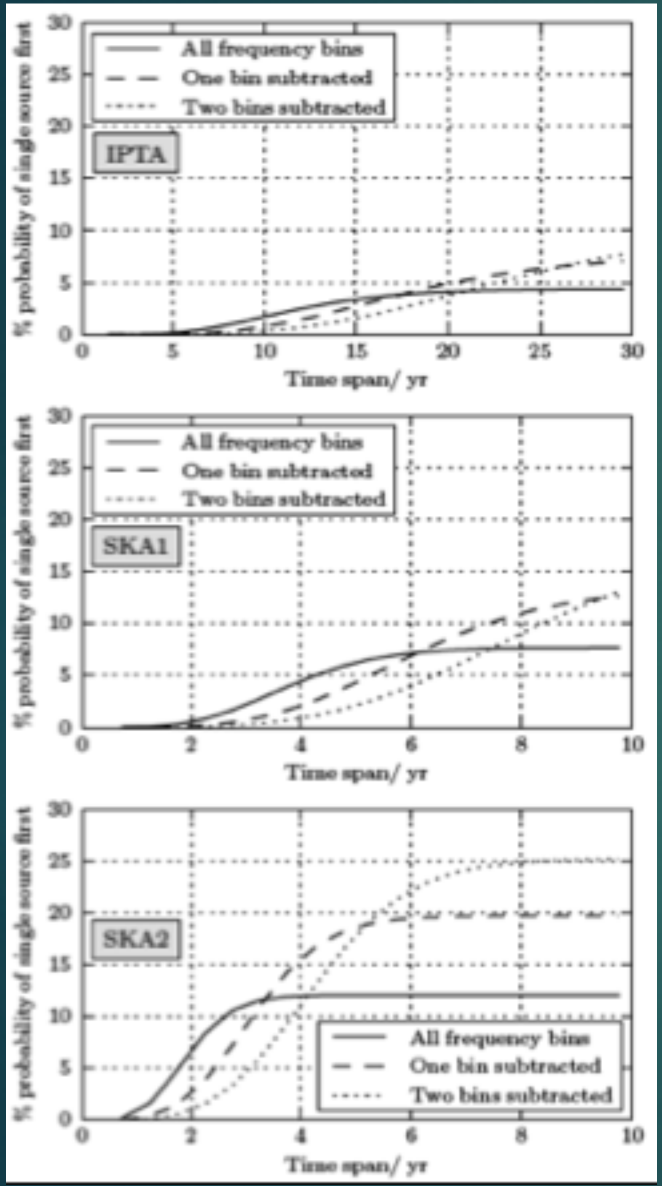


Data provides no constraints on anisotropy (yet!).

Upper limits at each scale the result of physical prior.

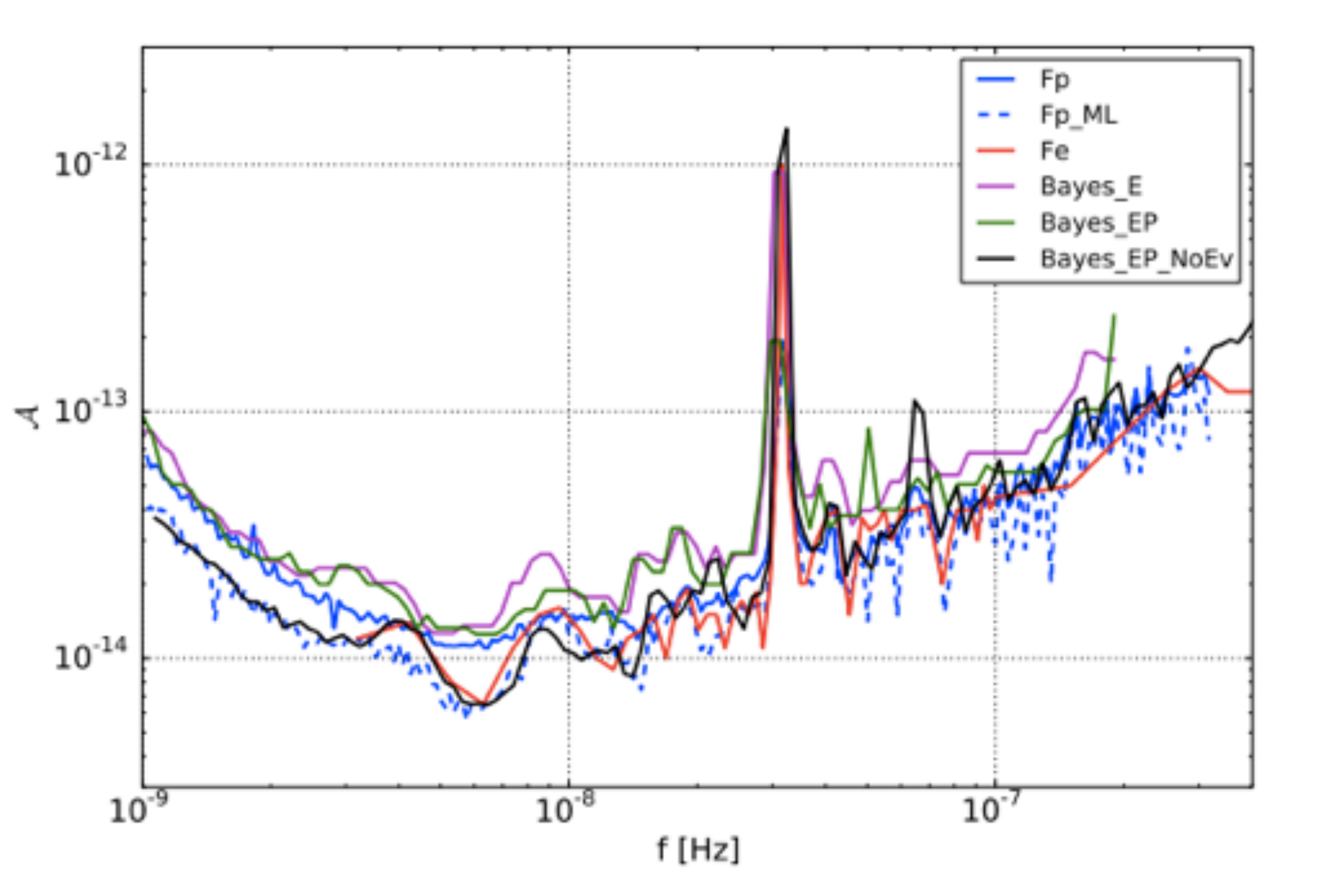
Figure:
Taylor et. al. 2015

First detections?



(Rosado et al 2015)
Will probably be a stochastic background first, however non-negligible probability of a single source.

Single Sources



Current best limits from EPTA (Babak et al 2015)

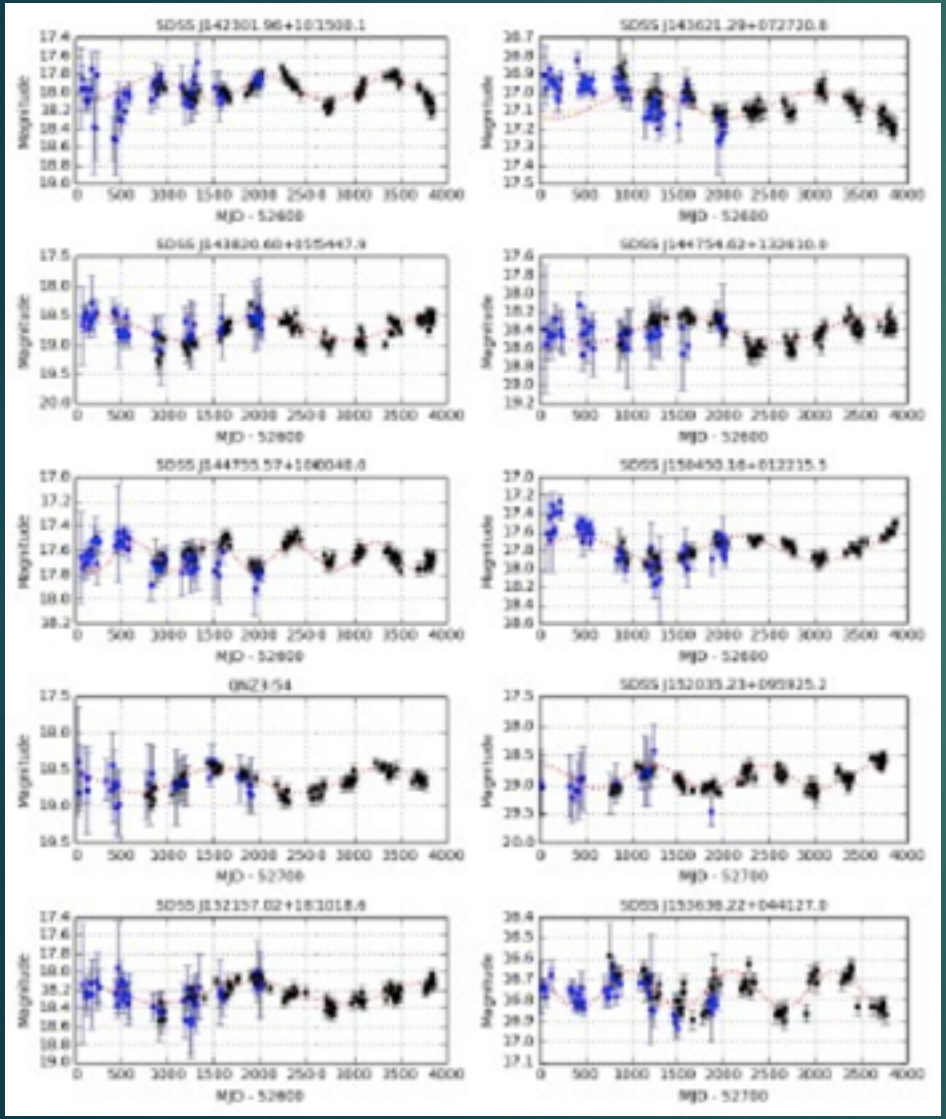
Exclude the presence of sub-centiparsec binaries with chirp mass 10^9 solar masses out to 25Mpc, and 10^{10} solar masses out to 1Gpc ($z \approx 0.2$).

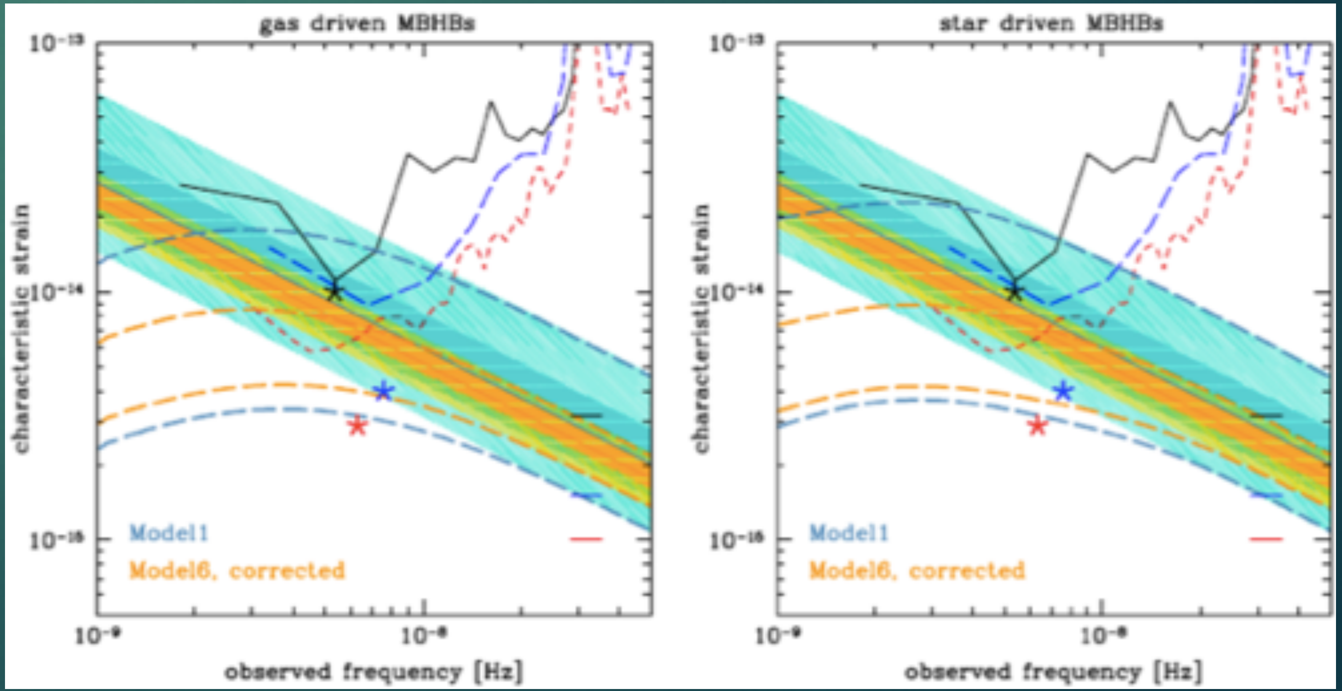
Single Sources

Catalina survey:

9yr baseline, 250000 QSO
111 period light curves
many have period, redshift, mass, sky location

(Sesana in prep (i think?))
Can use sample to compute merger rate and use it to generate GW signal.
PTAs can already rule it out.



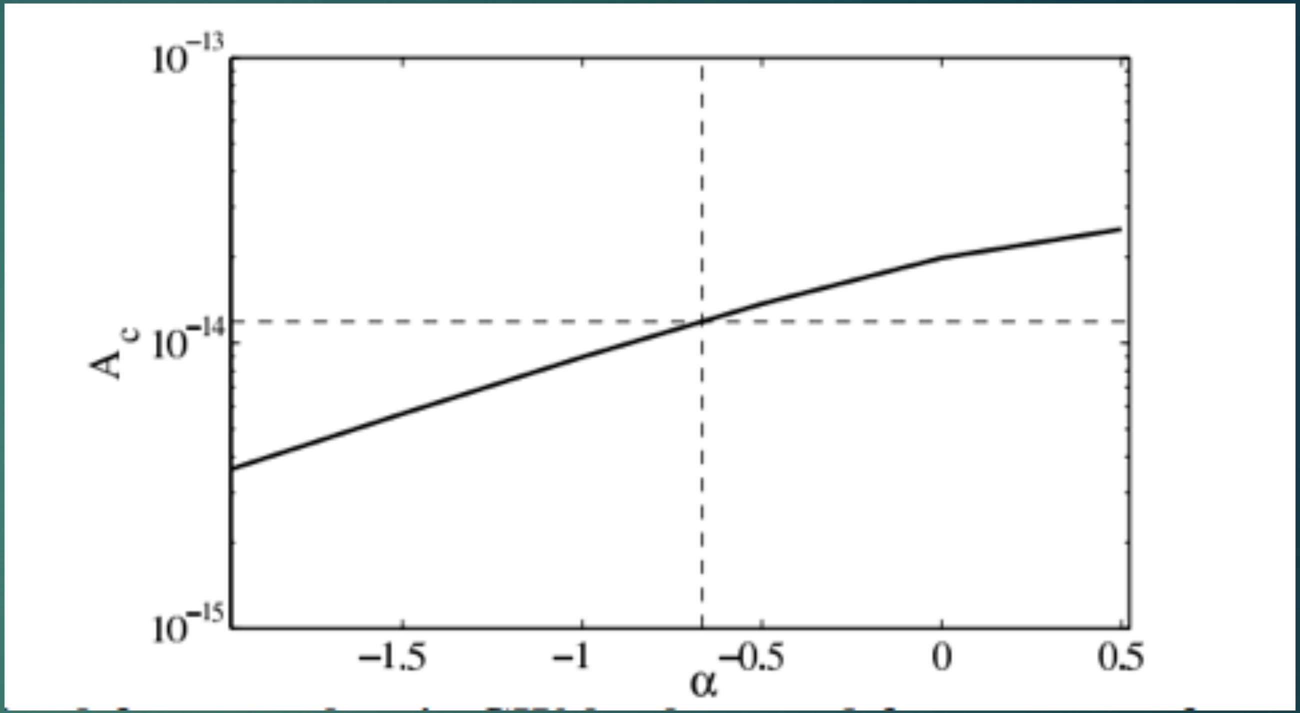


Future Prospects - LEAP

•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.

Computational Challenges

But dimensionality becoming a big issue:

One pulsar can have 100 parameters

Total can be thousands

Most parameters are related to modelling the white noise:

Not very covariant with low frequency noise

Can fix based on single pulsar analysis

Reduces total parameter space to 50-100

So can use multinest/MCMC

But not ideal.

Options - Different samplers for large dimensional problems

Gibbs Sampling (Van Haasteren et al 2014)

Hailtonian Sampling (lentati et al 2013)

In general though still a big problem

Summary

Pulsars can do a lot of things. But that means you have to model a lot things.

Current limits rule out 'vanilla' models. Lots of dials to turn.

Potentially a lot to be learned about the astrophysics of SMBHBs and galaxy mergers.

But detections could be two, or twenty years away.

Summary

Pulsars can do a lot of things. But that means you have to model a lot things.

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Cheers