Astrophysical signals and noise in pulsar timing array observations

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Outline

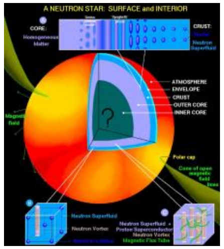
- Noise in pulsar timing measurements
- Interpreting the Parkes Pulsar timing array limit on the GWB in the context of SMBH/Galaxy evolution models (Shannon et al. 2013, Science)
  - **Bottom line: We are now using GWs to study supermassive black holes!**
- Searches for continuous waves in PTA data
- Advancing the PTA detector
  - More pulsars, more collecting area, judicious observing strategy

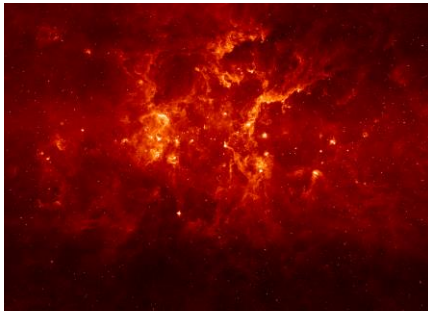
Contributions to Pulsar Arrival Times

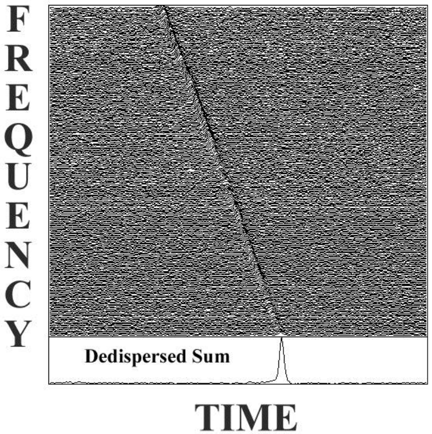
- *Pulsar spindown*
- *Intrinsic variation in shape and/or phase of emitted pulses (jitter)*
- Reflex motion from companions.
- Pulsar position, proper motion, distance
- *Gravitational Waves*
- *Warm electrons in the ISM*
- Solar system ephemeris
- *Errors in time standards*

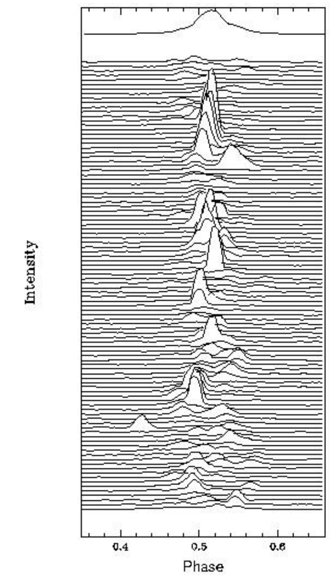
Pulsar

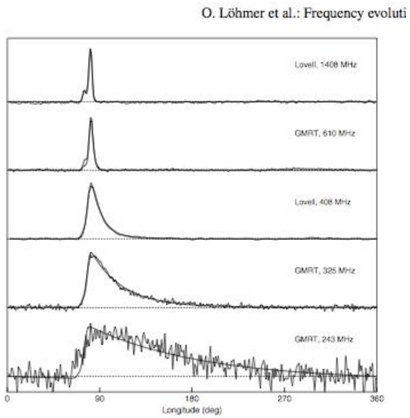
Earth







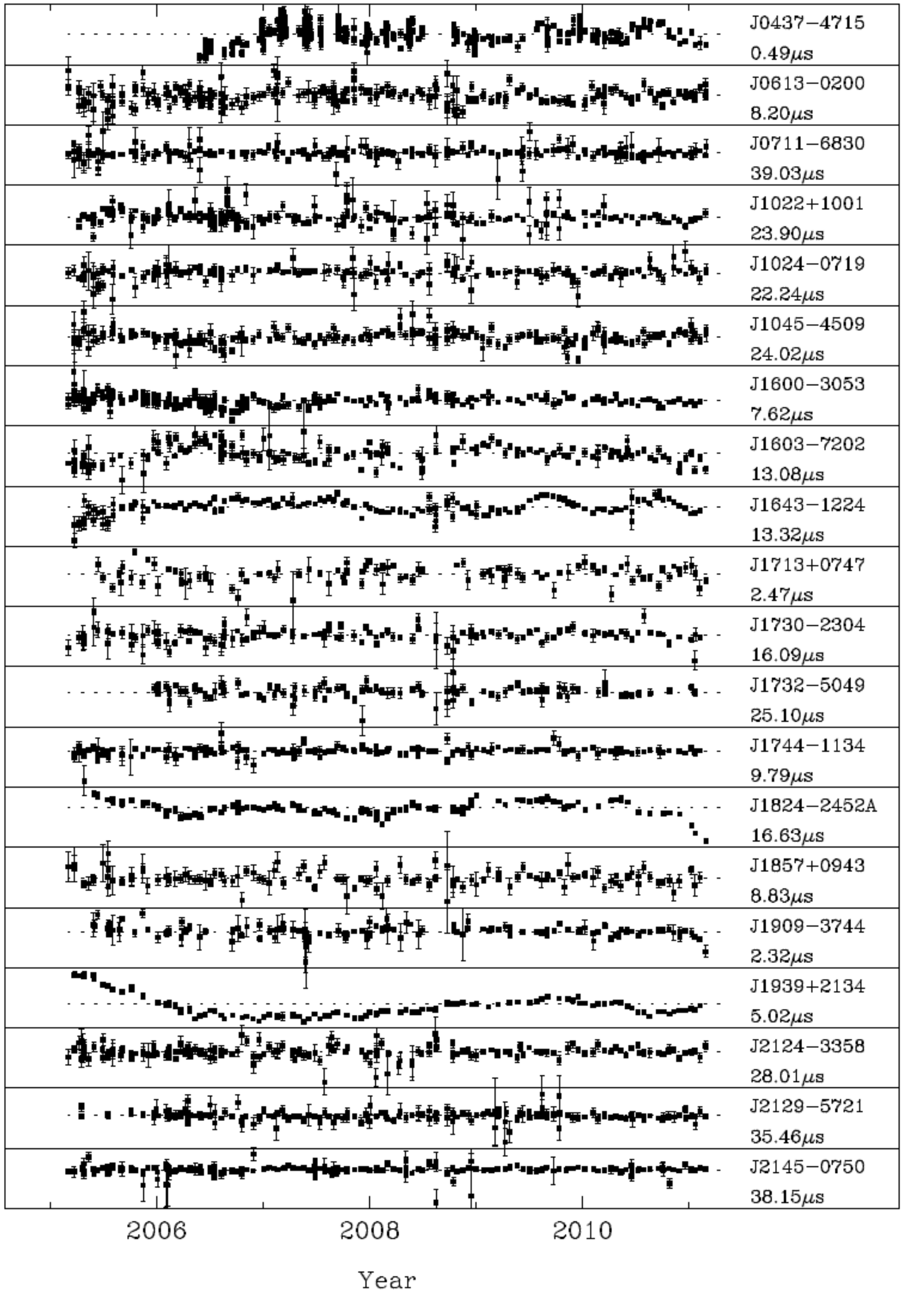




The PPTA Project

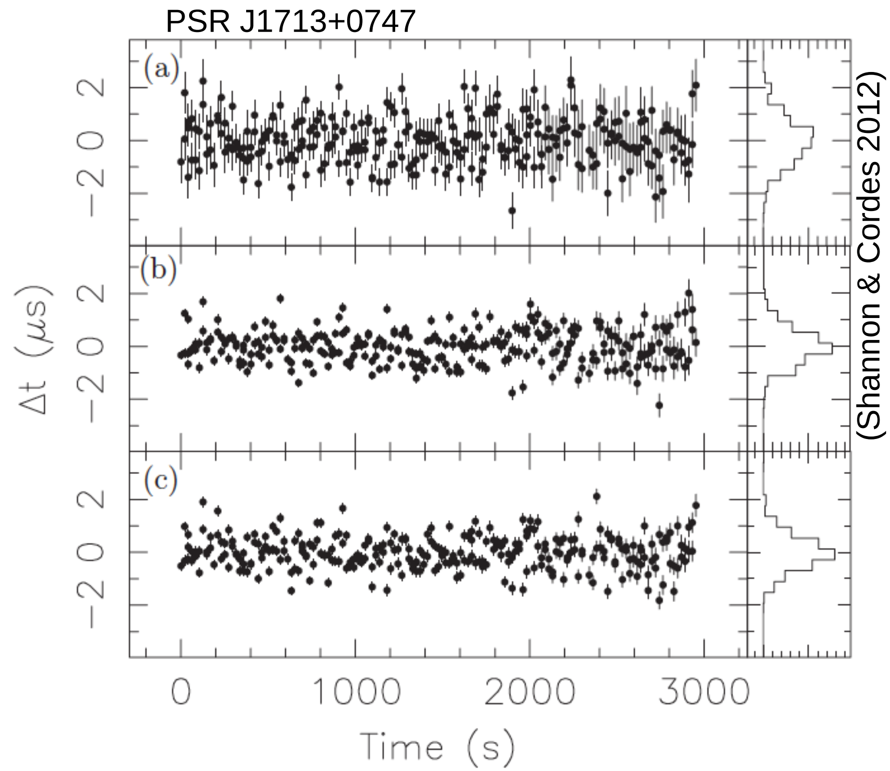
Parkes (Australia) 64 metre telescope

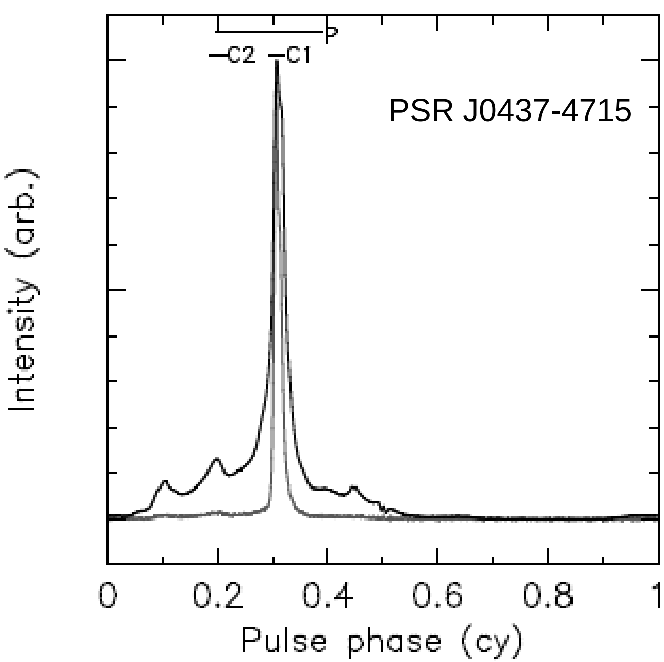
- ~ 20 pulsars south of declination +24 degrees (10 year datasets+ archival data on some pulsars)
- First data release published in 2013 – raw data and (processed) TOAs can be found at **data.csiro.au**
- Most pulsars show evidence red-noise process and many show excess white noise

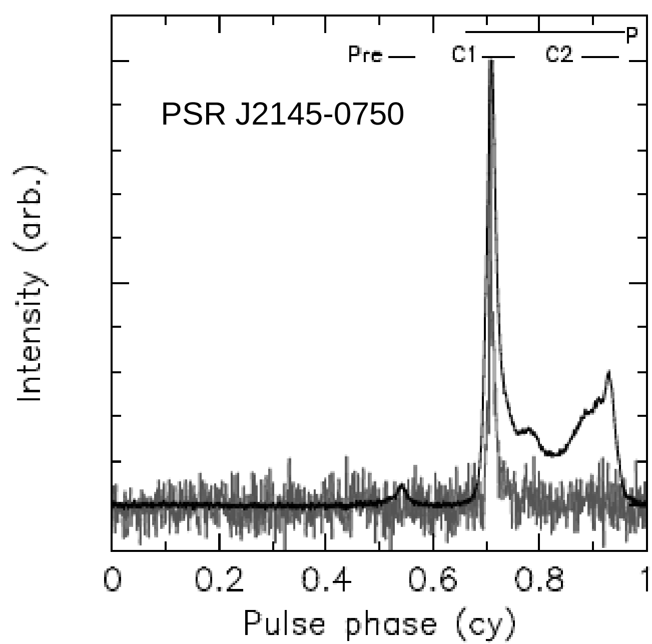


Pulse-shape variations

- Expect white noise based on finite SNR of observations (radiometer noise)
- Individual pulses look different from one another but converge to stable shape
- These variations bias estimates of TOA uncertainties
- Shape variations correlate over wide bandwidths
- **Jitter noise**







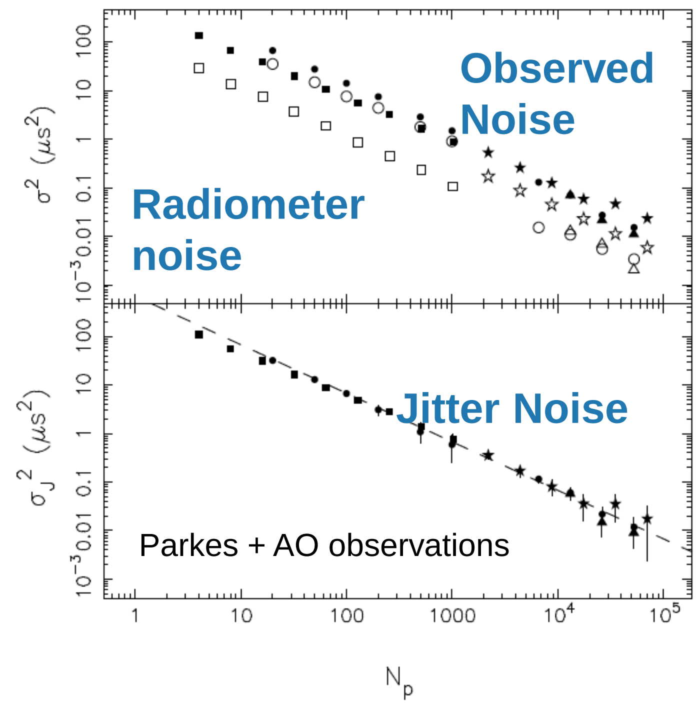
(Shannon et al. submitted)

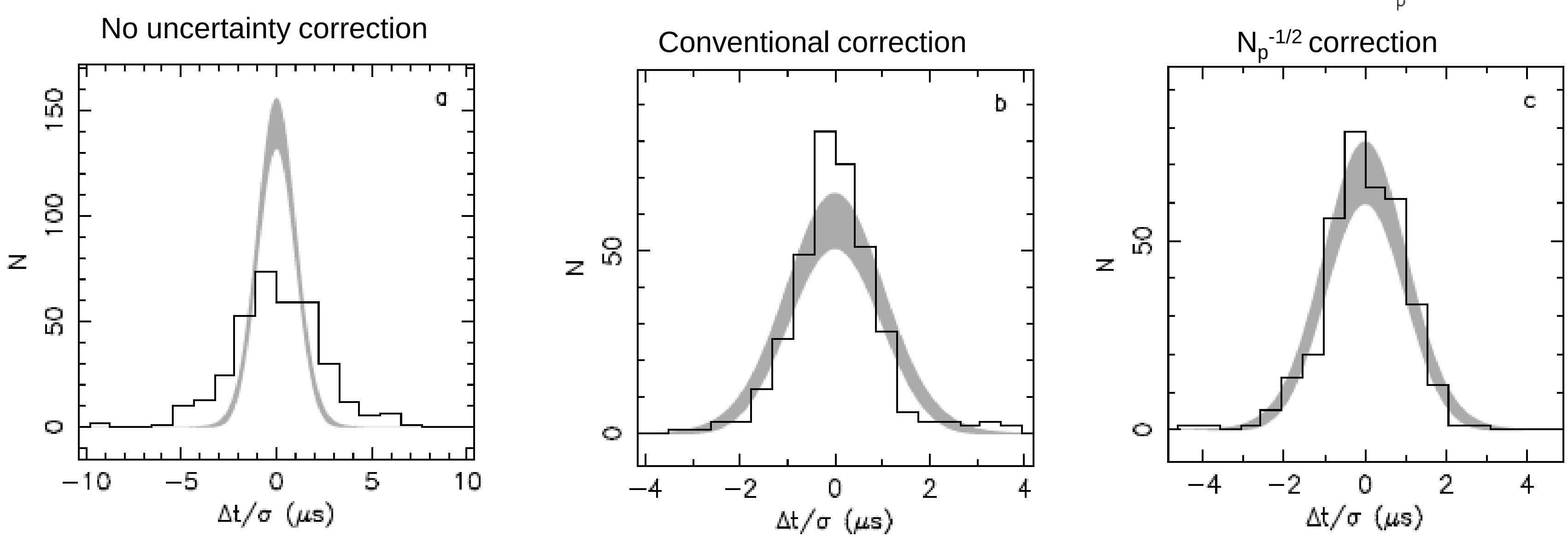
Accounting for pulse-shape variations in timing models

- In general jitter noise level scales proportion to $N_p^{-1/2}$. Common between different telescopes/instruments.

- Including physically derived errors produces Gaussian datasets with lower white noise levels.

- Introduces 10-200 ns of additional rms error per $hr^{-1/2}$ of observation.

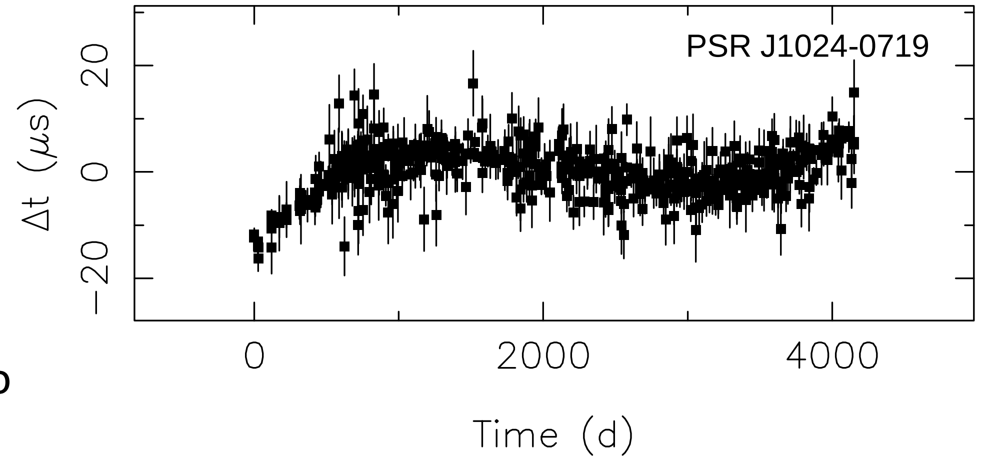




(Shannon et al. submitted)

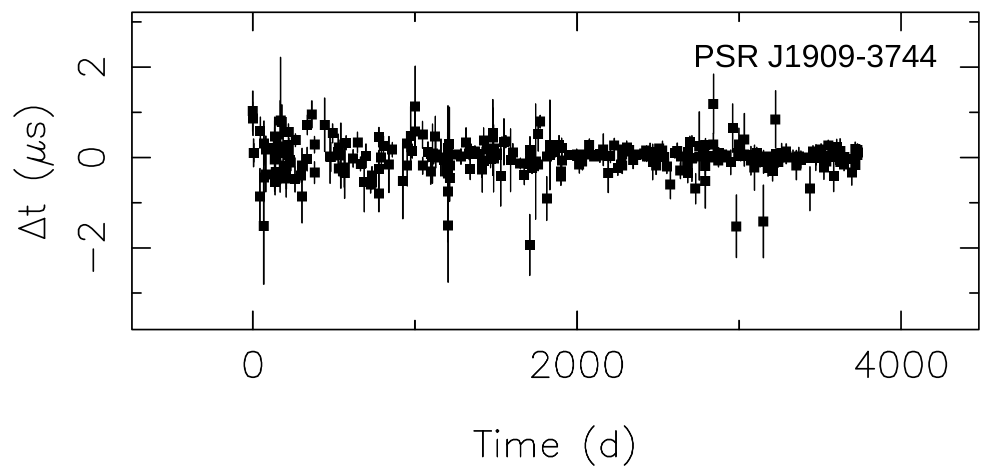
Red noise

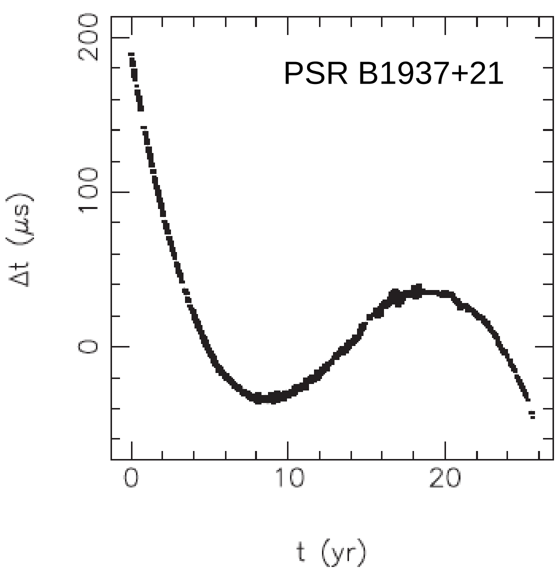
- Most young pulsars show red spin noise
  - Rotation instabilities?
  - Magnetospheric torque changes?
  - Open question: is this a generic property of MSPs too?
  - Can have similar spectral properties to GWB



- Solution: need to (at least) model the presence of red noise in datasets
- Triage bad pulsars

2003 **Last week**





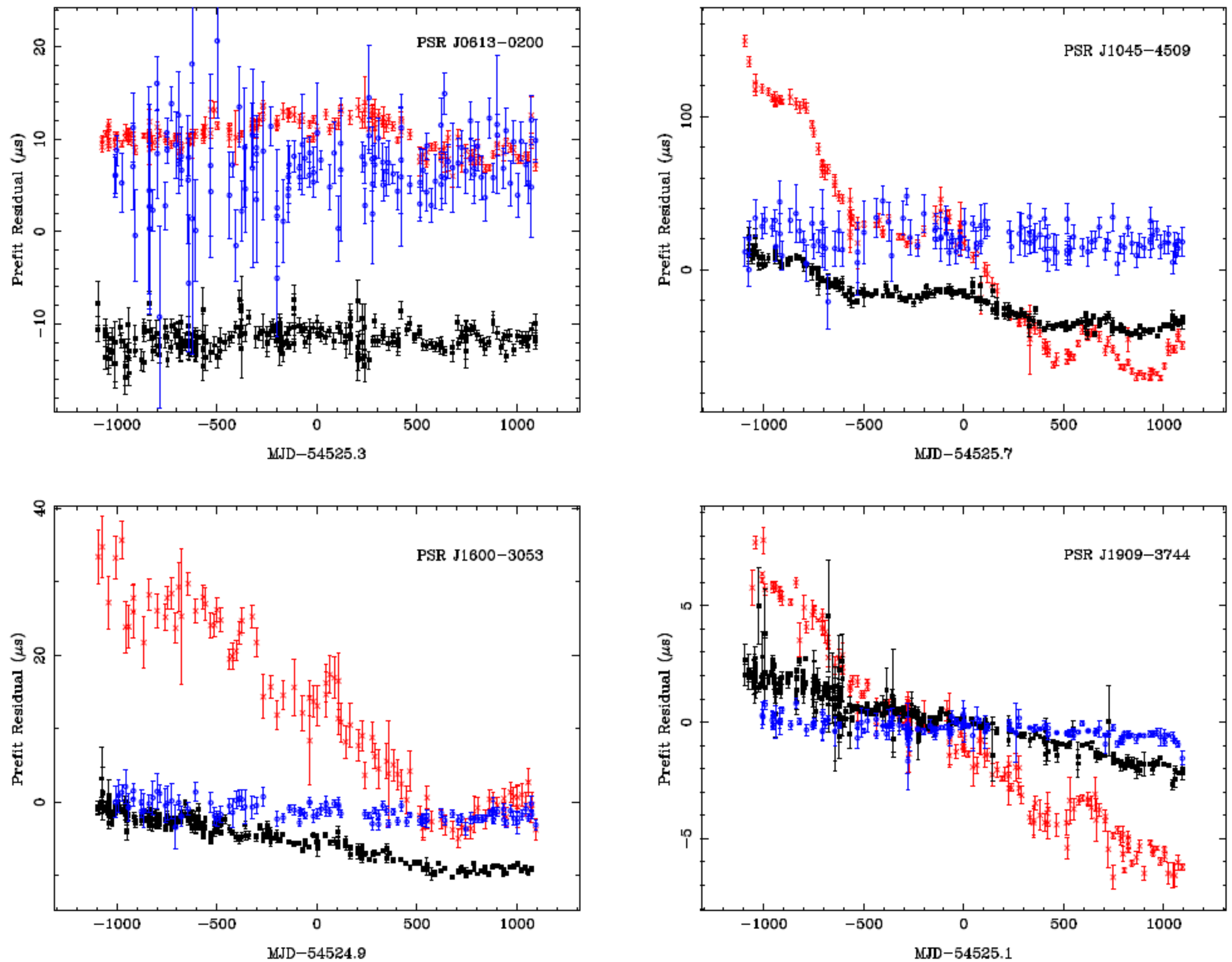
Or is it an asteroid belt (Shannon et al. 2013)?

The interstellar medium

Largest red signal in data set: Variations in dispersion measure (DM). Proportional to λ^2.

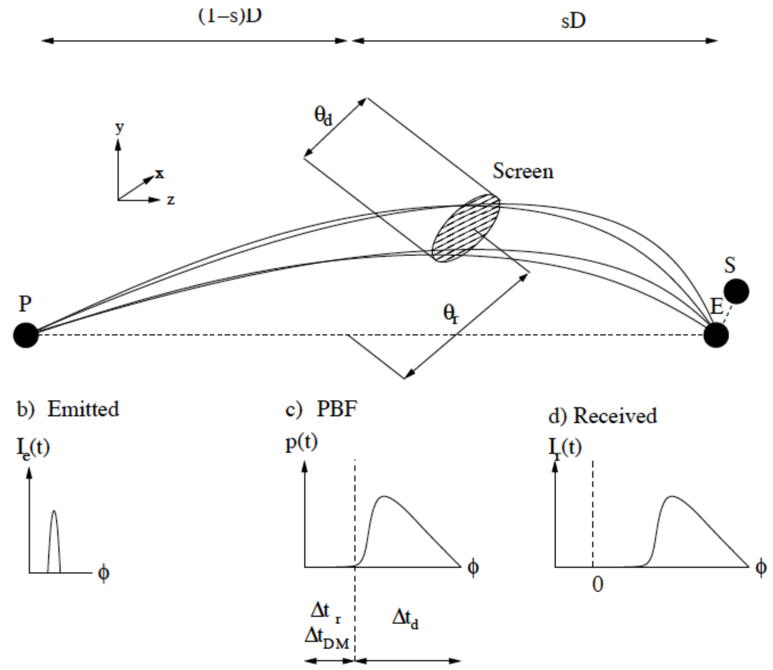
Need to remove **red signal** associated with DM variations without removing red signal associated with GWB

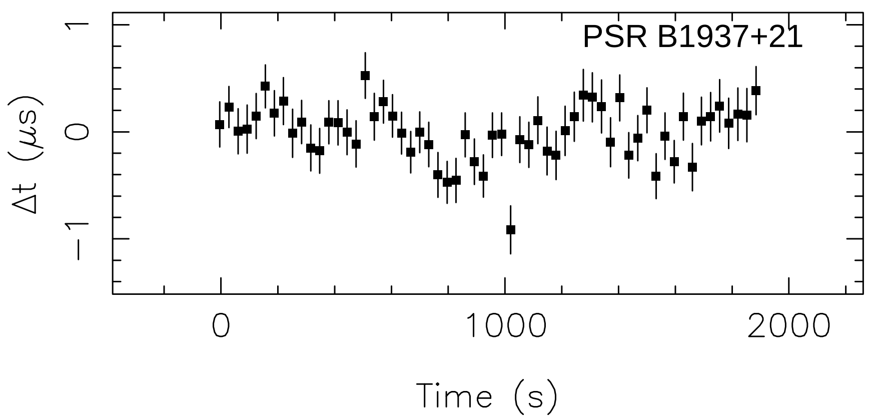
Include model of λ-independent in DM correction algorithm (Shannon 2011, Keith et al. 2013, Lee et al. 2014, Lentati et al. 2014)



Multi-path propagation

- Multi-path propagation causes broadening of pulse signal.
  - Proportional to λ^2 to $\lambda^{6.4}$
- Broadening is variable with time
- Strongest for distant pulsars observed at low frequencies
- Solution:
  - Observe at higher radio frequency
  - Explore mitigation methods (Demorest 2012)





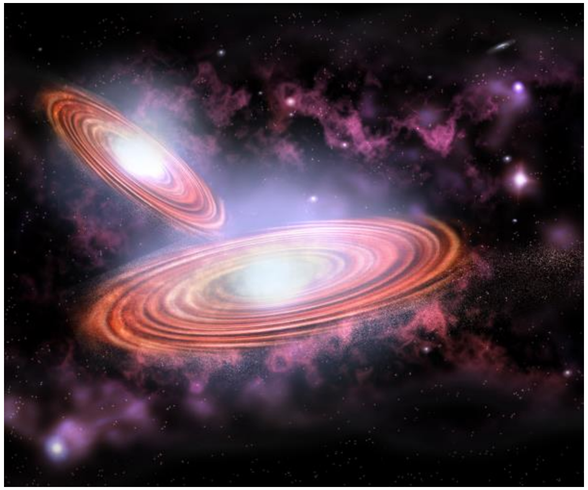
Sources of GWs in Pulsar Band

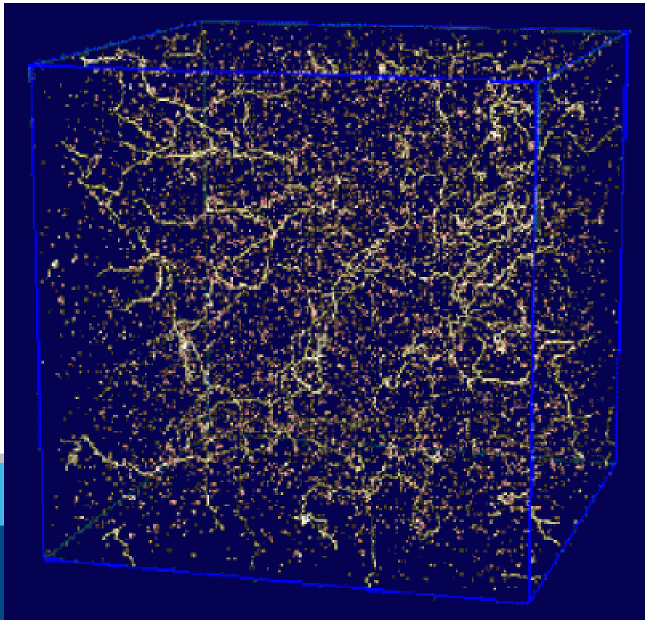
- *Sensitive to GWs with frequencies between 3 and 300 nHz (get TOAs every week for 10 years)*

- **Massive Black Hole Binaries** (Jaffe & Backer 2003, Sesana et al. 2008, Ravi et al. 2012)

- **Cosmic Strings and Super Strings** (Damour & Vilenkin 2005, Sandias et al. 2012)

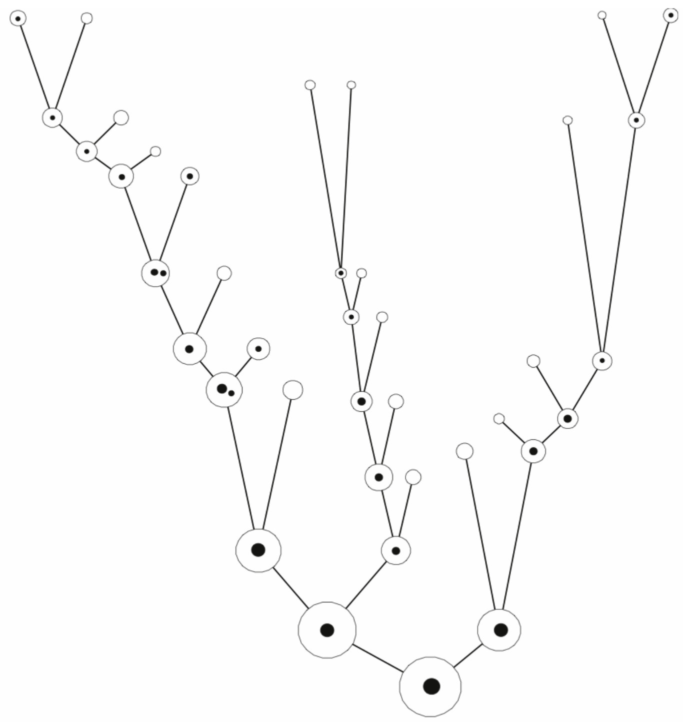
- **Cosmological QCD Phase Transition** (Witten 2007, Caprini et al. 2010).





A Recipe for producing a GWB from SMBH

- Black holes formed early in the universe at the centres of the first galaxies
- After galaxies merge, black holes dynamically dragged to centre
- When MBHs get close, they become prodigious emitters of GWs
- After merger, resultant GH gains mass through accretion (Quasar phase)
- Process repeats many times for each current galaxy (10?).



M. Volonteri

Why do we care about supermassive black holes?

- How do galaxies form? Why do today's galaxies look the way they do? What did the first galaxies look like?
- Supermassive black holes play a crucial role in governing the formation of galaxies through the process of feedback.
- There is a strong correlation between SMBH properties and the properties of their host Galaxies.
- It is difficult to observe merging binary supermassive black holes in any other way.
  - Too close together to resolve using optical telescopes.
  - Reside in dense environments.

The Stochastic Background

The stochastic background is the superposition of GWs from many sources

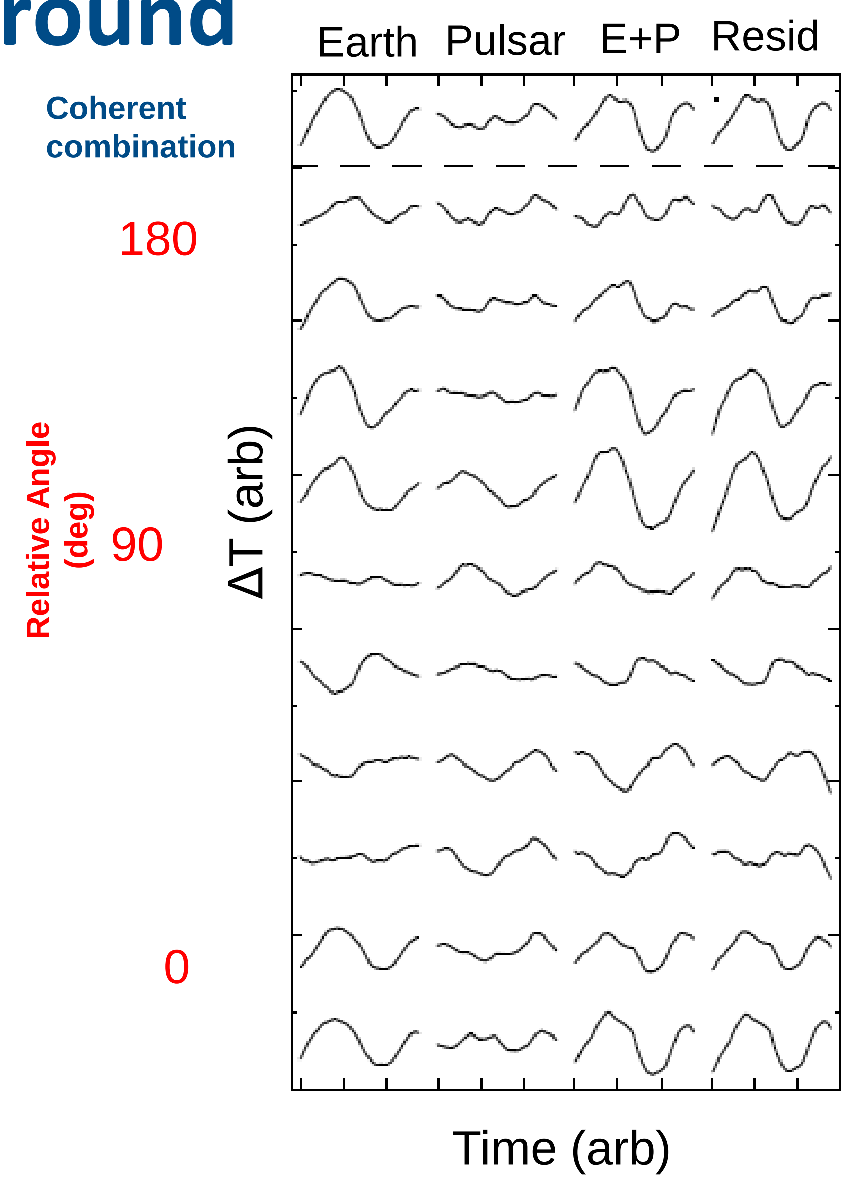
Background induces **red power spectrum** in residuals (more power at lowest frequency of GWs).

The background is characterized by a strain amplitude spectrum.

For MBH binary the spectrum is expected to be:

$$h_c(f) = 10^{-15}\left(\frac{f}{1\ \mathrm{yr}^{-1}}\right)^{-2/3}$$

RMS contributions to residuals ~**20 ns** over 5 years: need to combine signal from a group of pulsars (pulsar timing array, PTA).



Constraining the GWB

Developed a **detection statistic** (DS) based on power spectra of residual time series

- Easier to deal with power spectra
- Account for spectral leakage

- **DS** is estimator of strength of GWB
  - Non-negatively biased (does not underestimate strength of the GWB strength)

- Combine pulsars: weighted sum of each spectral bin in the PTA.

- Model: accounts for all plausible signals
  - Common GW signal
  - White noise (radiometer + pulse shape variations + scintillation)
  - Red noise (Spin noise ++)

A_b: detection statistic
P_j: measured power spectra
W_j: white noise
g_j: shape of GWB
M_j: model of red noise

$$\hat{A}_b^2 = \frac{\sum_{ij} (P_j(f_i) - W_j) g_j(f_i) / M_j^2(f_i)}{\sum_{ij} \left[g_j(f_i) / M_j(f_i) \right]^2}$$

An Algorithm for Constraining the GWB

- Calculate test statistic DS for real data (***observed DS***)

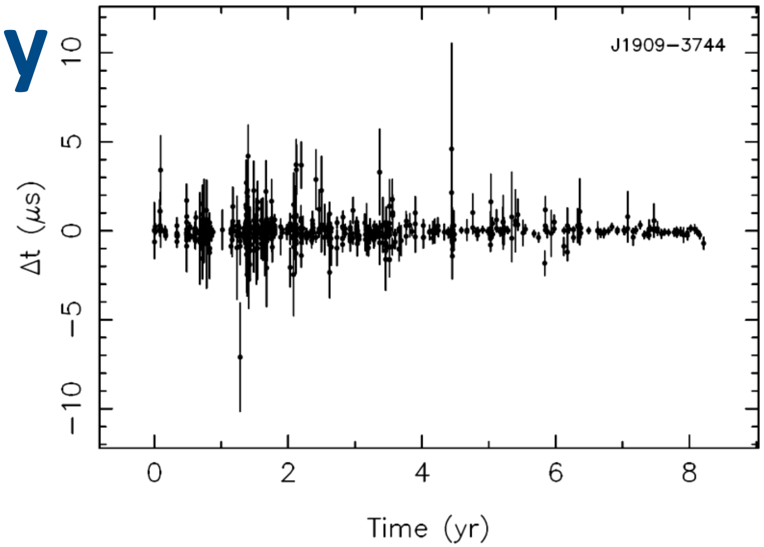
- Simulations
  - Form ideal site TOAs
  - Add white noise consistent with observations
  - Add GW of strength (***A***) and spectral shape ($\boldsymbol{\alpha}$)~(e.g., $\boldsymbol{\alpha}$ = -2/3)
  - Calculate **simulated DS**
  - On average, simulated DS increases as *A* increases

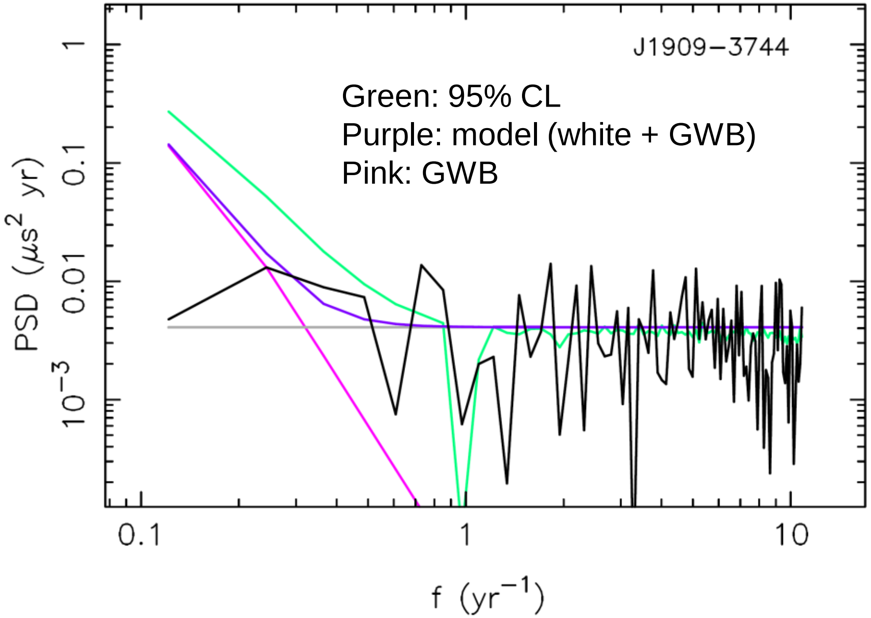
- Find value of $\mathbf{A_{95}}$ such that 95% of the time the simulated DS exceeds the observed DS: **This is the 95% confidence limit.**

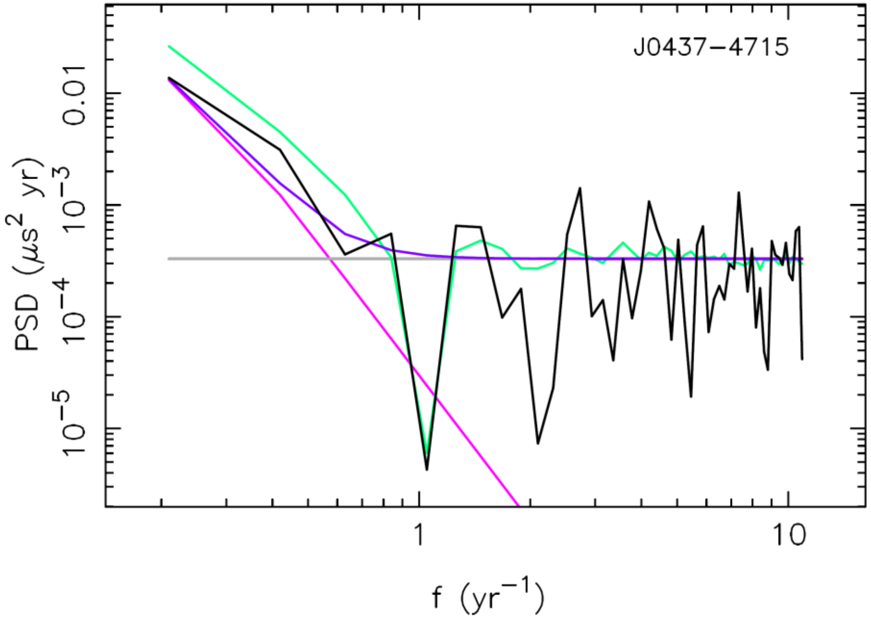
Parkes Pulsar Timing Array

- Monitoring 20 millisecond pulsars since 2005
  - Many pulsars extended using archival data

- Multi-frequency observation to mitigate interstellar propagation (Keith et al. 2013)







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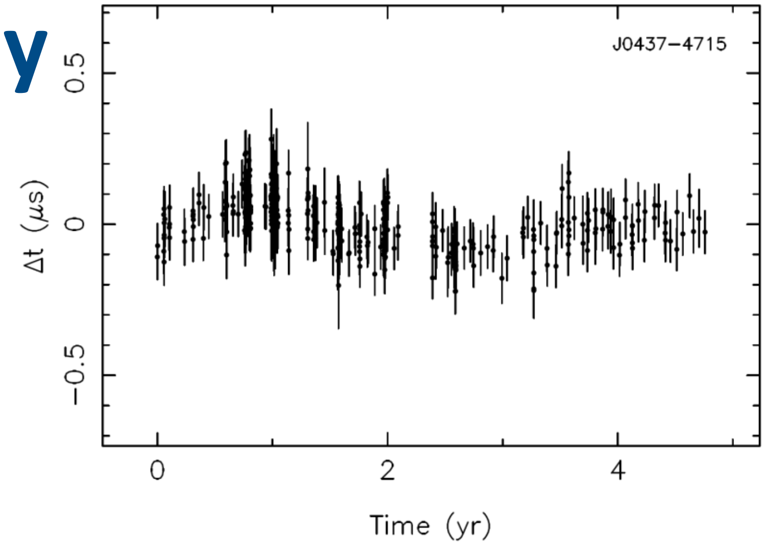
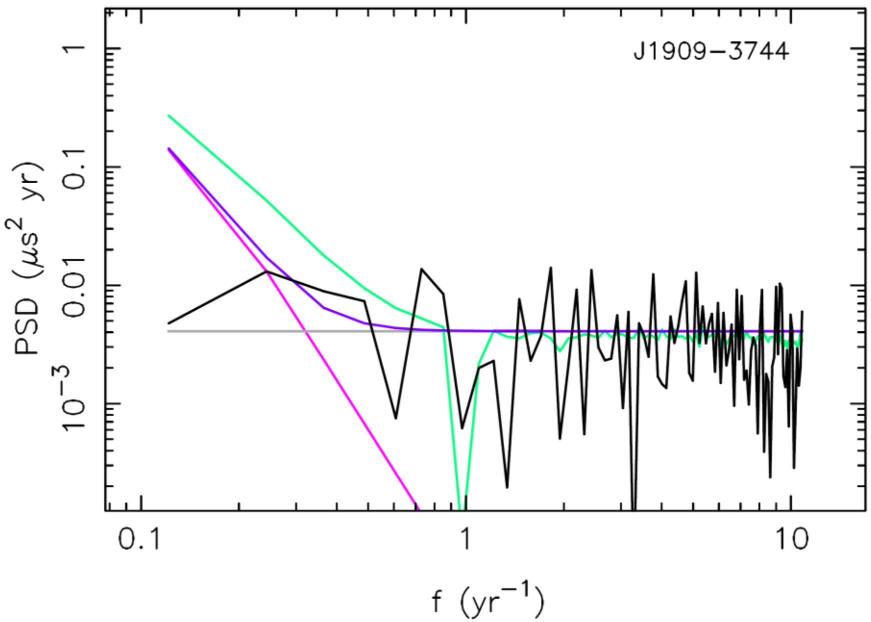
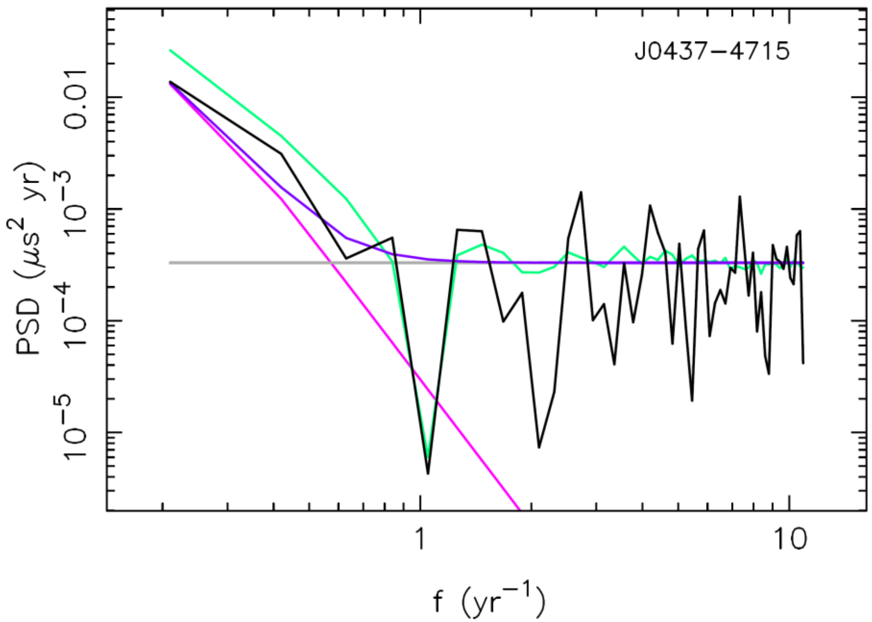


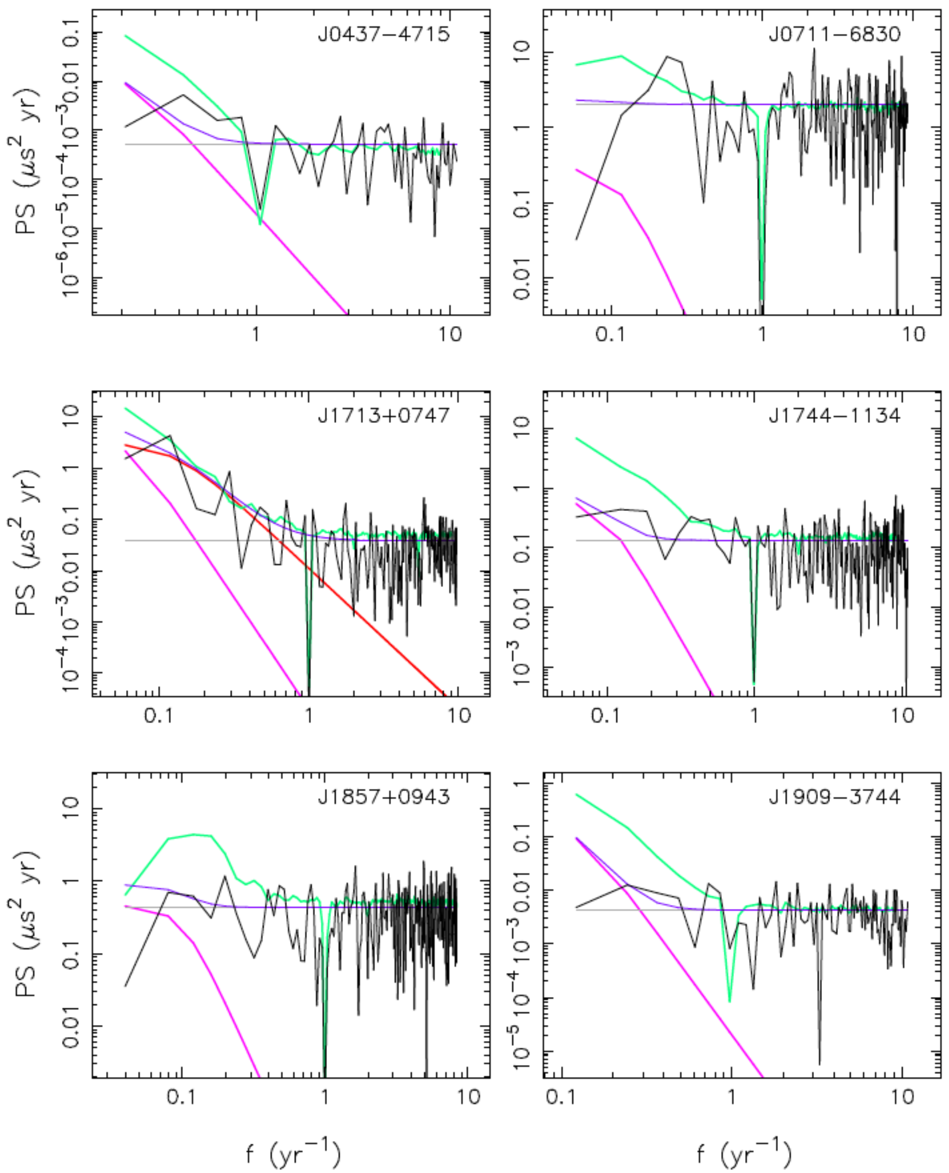




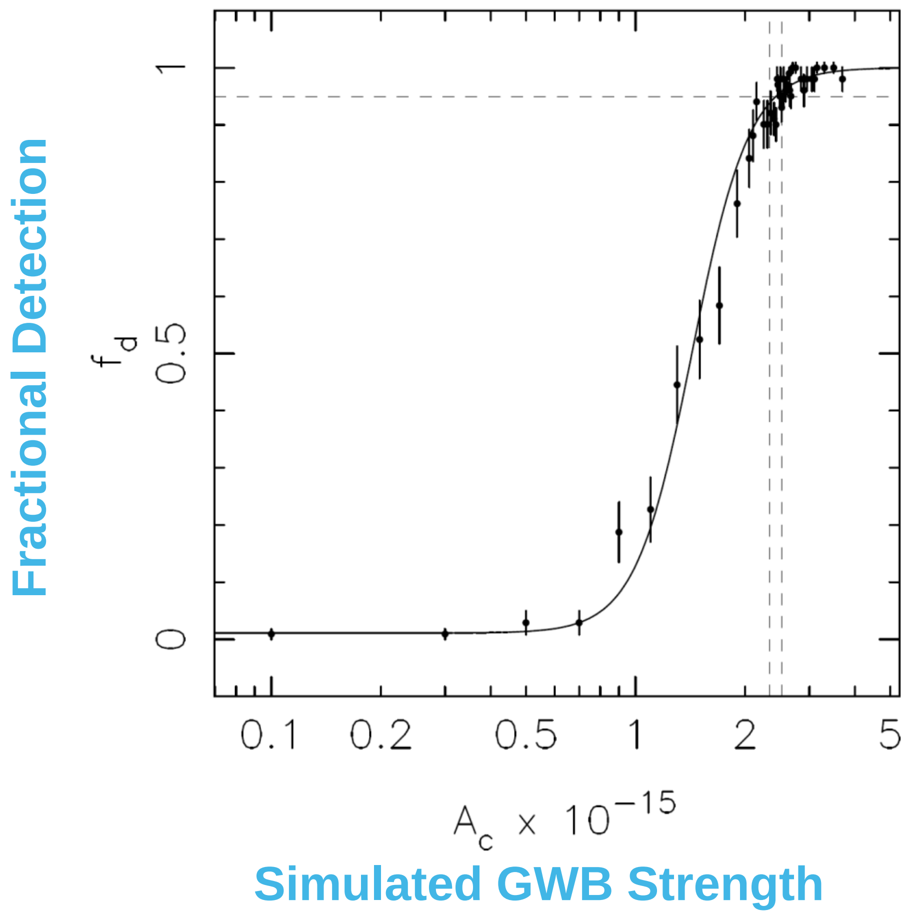
Power spectra of *best* PPTA Pulsars

These pulsars dominate the limit.

Only PSR J1713+0747 has additional modelled red noise



The Combined PPTA Limit



With 95% confidence (α=-2/3)
$A_{95} < (2.4 \pm 0.1) \times 10^{-15}$

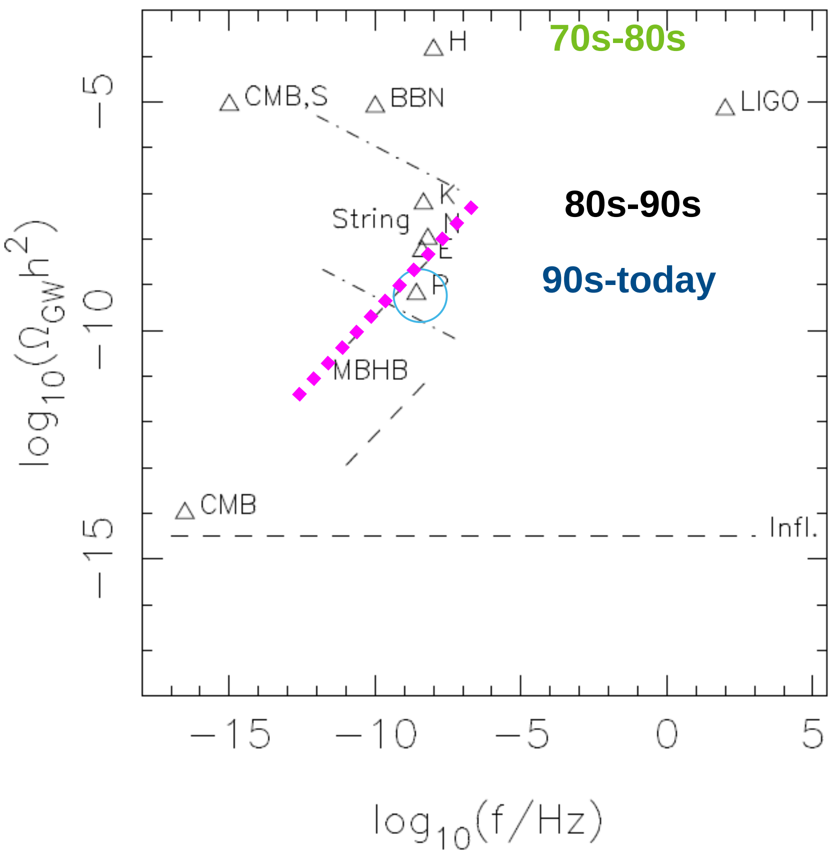
Limits for other types of GWB
($\alpha = -1$; $A_{95} < 10^{-15}$)
($\alpha = -7/6$; $A_{95} < 0.7 \times 10^{-15}$)

PPTA Limit on Background

PPTA Limit $A < 2.4\times10^{-15}$

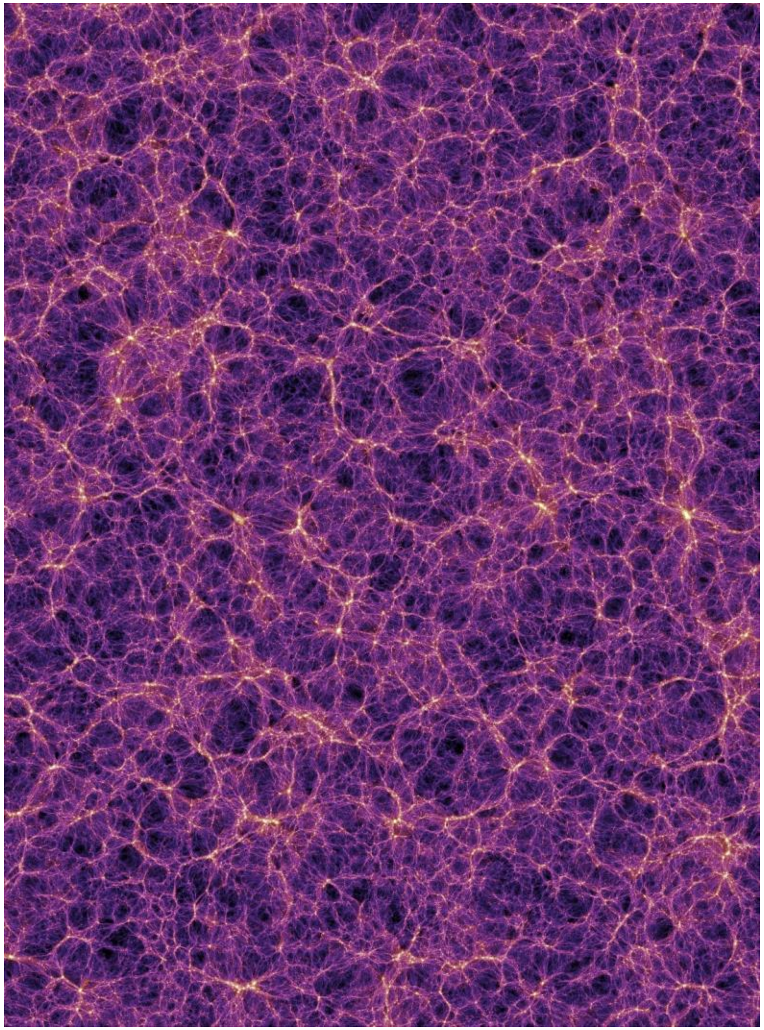
Sesana et al. (2008):
-- Averaged many models together then calculated error based on uncertainty
--Expect GWB somewhere between $A_{yr} = 2\times10^{-16}$ and 4×10^{-15} (Mean 8×10^{-16})

Foreshadowing: We have entered an interesting portion of parameter space!



The GWB in the Millennium Paradigm (Ravi et al. 2012 ApJ)

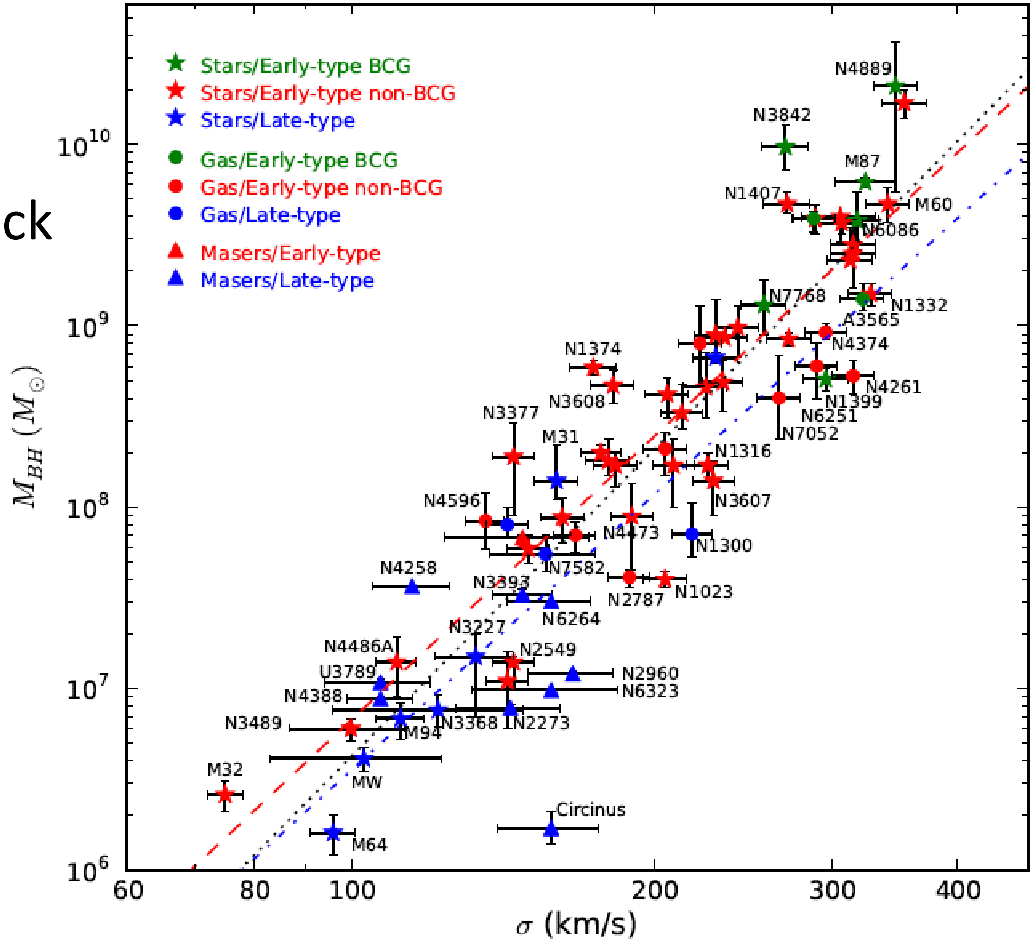
- Use **Millennium dark matter simulations** to trace large scale structure and evolution
- Use Semi-analytic model (Guo et al. 2011) for galaxy+SMBH formation and evolution.
- **Produce self-consistent model for GW signal:**
  - Matches evolution/growth of structure in universe
  - Quasar luminosities function, star formation rate
- Add in GWs
  - Coalescence by merger alone
  - Circular orbits
- Produces modestly non-Gaussian background



Springel et al. (2006)

SMBHs are bigger than previously thought

- New black hole mass function
  - Revised measurements of black hole-bulge mass relationship (McConnell & Ma 2012)
  - Average black hole mass increases by factor of 1.8
  - Can change masses of SMBH without affecting self-consistency of models

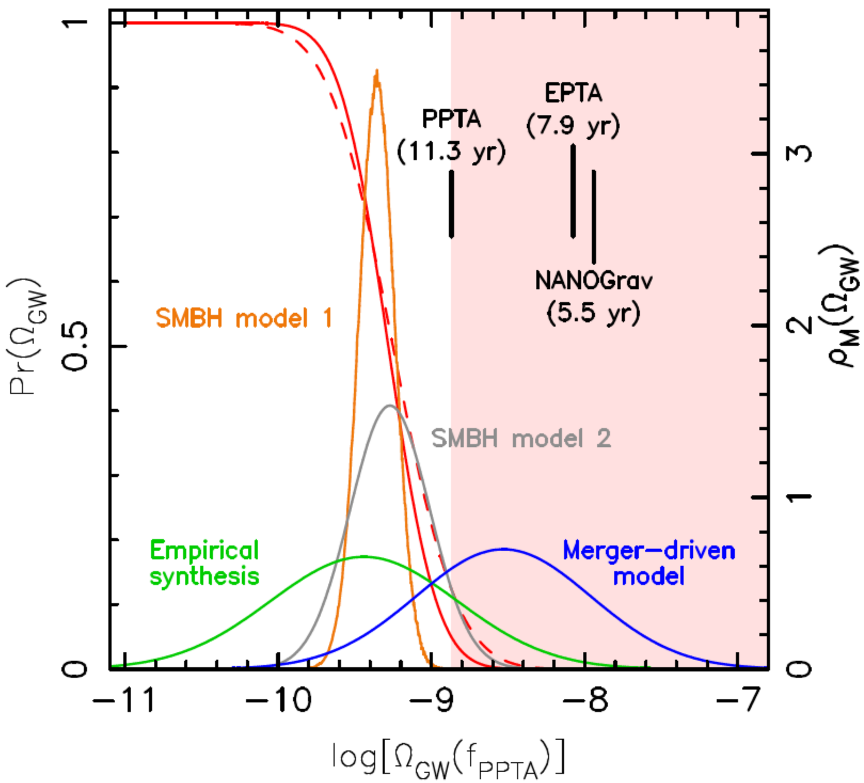


McConnell & Ma (2012)

Comparing models to the PPTA Limit

- **McWilliams et al. (2012)**
  - Assumes all growth (both in galaxies and black holes) is **merger-driven** at z < 1
  - Rule out model with ~ 90% confidence
- **Sesana (2013)**
  - Survey plausible range for GWB strength
  - Based on all observational uncertainties
  - Exclude~ 45% of parameter space
- **Investigating the millennium paradigm**
  - **Non-Gaussian limit A < 2.7x10^{-15}**
  - Use millennium dark matter simulations + accompanying semi-analytic models
  - This paradigm set to match all electromagnetic observation (star formation rate, quasar luminosity function)

Shannon et al. (2013)

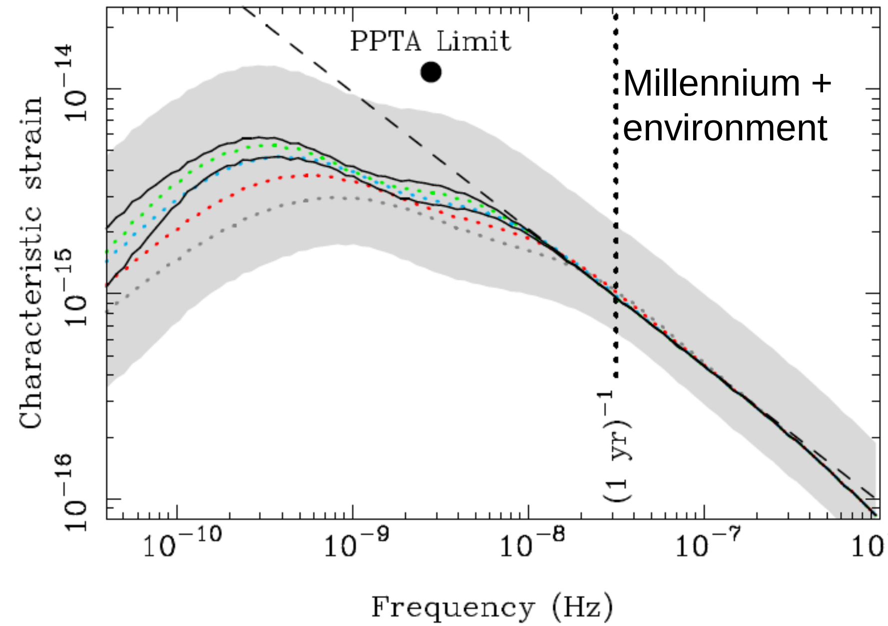


Ways to modify the SMBH background

- Environment
  - Plays a role in solving "final parsec" problem,
  - **Q: Does it influence signal at 10 nHz?**
  - **A: Maybe.** If centres of galaxies are full of stars, can attenuate signal

- Eccentricity
  - Eccentric binaries circularise by the time they reach PTA band, unless environment takes hold

- Mass and merger rate.
  - SMBH masses getting larger (largest SMBH grown through mergers)



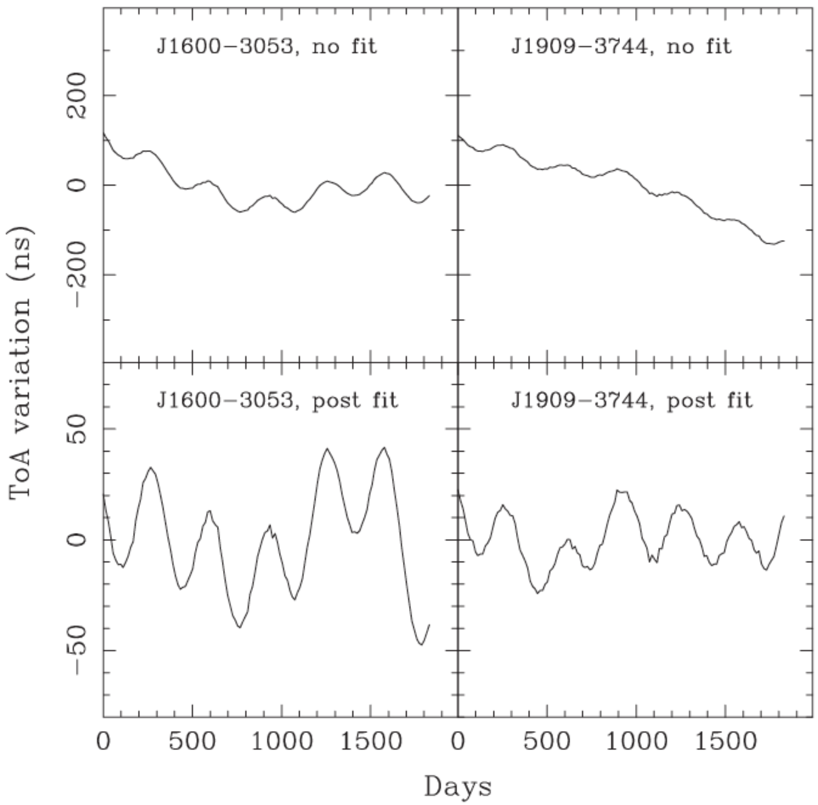
Ravi et al. (2014)

Empirical model

Searching for continuous-wave sources

- If there is a binary system that is sufficiently massive and sufficiently close its signal may be detected: continuous wave

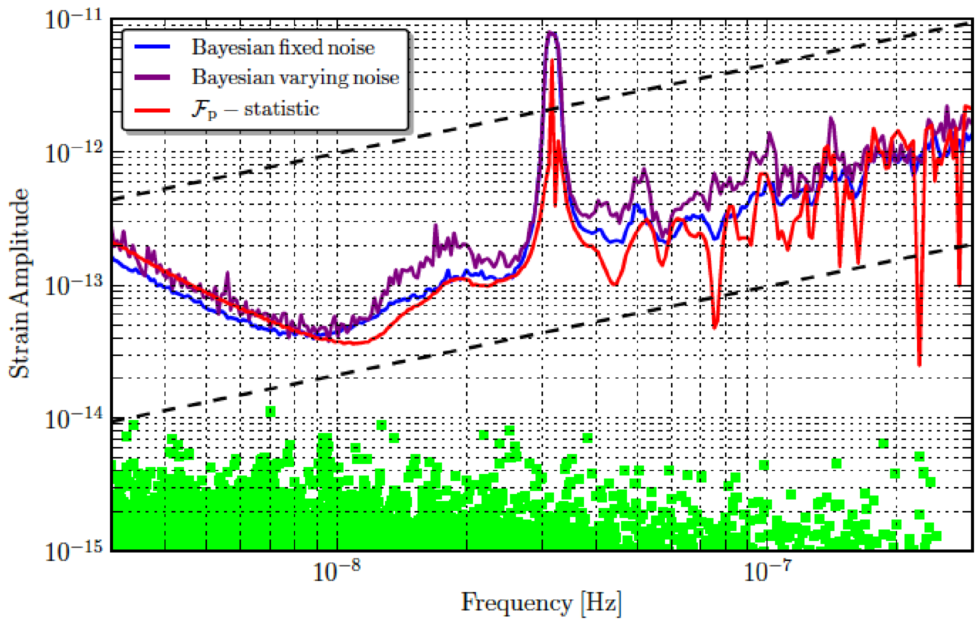
- Example: Realisation of GWB from Ravi et al. (2012):
  - 1-2 of 100 realizations of the GWB has a strong nearby single source



Ravi et al. (2012)

Limits on continuous gravitational waves

- Arzoumanian et al, submitted. (Study led by Justin Ellis, UWM).
- Search NANOGrav 5-year datasets using Bayesian and frequentist methodolgy



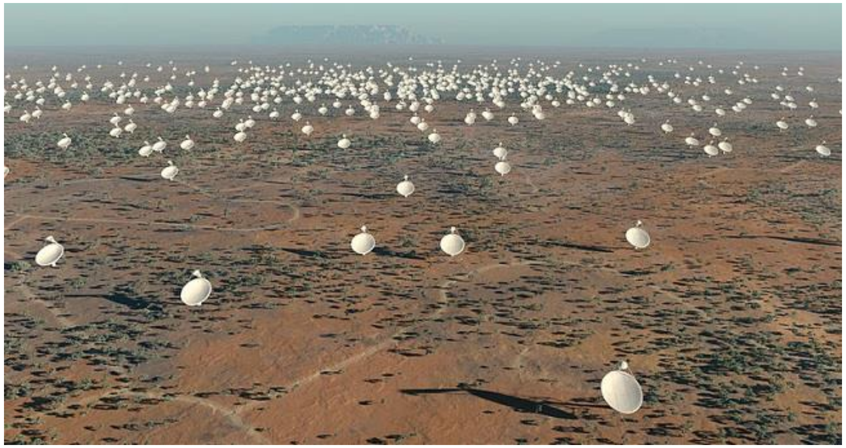
Improving Sensitivity: short-term

- **International Pulsar Timing Array**
- Improved instrumentation
  - Wide (radiofrequency) bandwidth receiving systems
  - Increases sensitivity, observing throughput, better correction for refractive interstellar medium
- Additional telescope time
  - Increase sensitivity
  - Better understand systematics / improve calibration of the signal
- Observe more pulsars
  - Large-area sky surveys for new pulsars
- Optimise scheduling

Effelsberg ultra broad-band feed

Improving Sensitivity: longer-term

- New Facilities on the horizon:
- MeerKAT Array (South Africa)
  - 100-metre class interferometer
- Qitai Radio Telecope (XInjiang, China)
  - 100-metre class single dish
- Five-hundred metre Aperture Spherical Telescope (FAST, Guizhou, China),
  - 300-metre class single dish
- Square Kilometre Array:
  - 10x FAST
-
- Need to account for astrophysical noise when developing hardware / scheduling observations on new telescopes



Summary

- Our understanding of **astrophysical noise** is improving and guiding PTA observations
- Limits on GWB are being used to constrain the massive black hole population. We **can now test models of galaxy evolution**.
- IPTA dataset should immediately improve limit
- New facilities / longer datasets /more pulsars will enable us to detect GWs with pulsars.
- **Thank you**

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