The gravitational wave signal from binary super-massive black holes

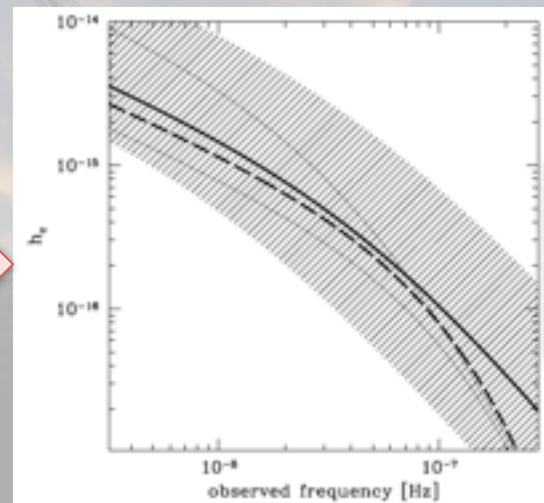
Vikram Ravi

The University of Melbourne, CSIRO etc.

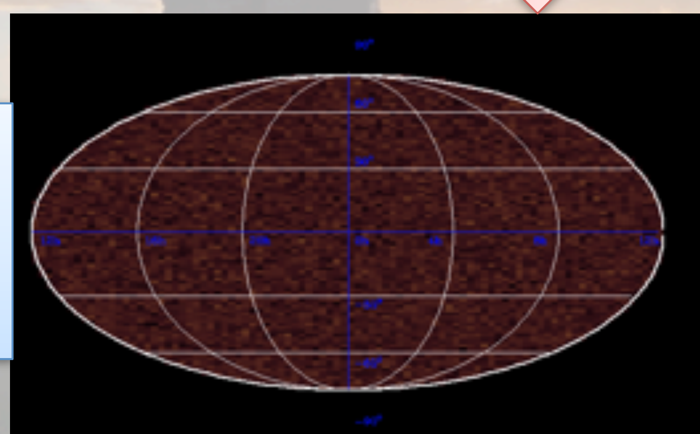
With Stuart Wyithe, George, Ryan

From signal models to detection

Alberto's head



Mean characteristic strain spectrum of GW signal from binaries



Assume this signal induces **random Gaussian** TOA perturbations

GW detector, estimator

What are the shortcomings?

- We don't know that the GW signal from binary super-massive black holes (SMBHs) results in random Gaussian TOA perturbations.

1. Are current GW detection/estimation strategies optimal for binary SMBHs?
2. Can we really compare existing limits on a GWB to model predictions for the mean signal amplitude?

UPPER BOUNDS ON THE LOW-FREQUENCY STOCHASTIC GRAVITATIONAL WAVE BACKGROUND FROM PULSAR TIMING OBSERVATIONS: CURRENT LIMITS AND FUTURE PROSPECTS

F. A. Jenet,[1] G. B. Hobbs,[2] W. van Straten,[1] R. N. Manchester,[2] M. Bailes,[3] J. P. W. Verbiest,[2,3] R. T. Edwards,[2] A. W. Hotan,[4] J. M. Sarkissian,[2] and S. M. Ord[5]

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LIMITS ON THE STOCHASTIC GRAVITATIONAL WAVE BACKGROUND FROM THE
NANOHERTZ OBSERVATORY FOR GRAVITATIONAL WAVES

P. B. Demorest[1], R. D. Ferdman[2], M. E. Gonzalez[3], D. Nice[4], S. Ransom[1], I. H. Stairs[3],
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S. Giampanis[15], F. Jenet[9], V. M. Kaspi[10], J. Lazio[11], A. N. Lommen[12], M. McLaughlin[13],
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Placing limits on the stochastic gravitational-wave background using European Pulsar Timing Array data

R. van Haasteren,[1★] Y. Levin,[2,1] G. H. Janssen,[3] K. Lazaridis,[4] M. Kramer,[4,3] B. W. Stappers,[3,5] G. Desvignes,[6,7,8] M. B. Purver,[3] A. G. Lyne,[9] R. D. Ferdman,[6,7] A. Jessner,[4] I. Cognard,[6,7] G. Theureau,[6,7] N. D'Amico,[10,11] A. Possenti,[11] M. Burgay,[11] A. Corongiu,[11] J. W. T. Hessels,[5,12] R. Smits[3,5] and J. P. W. Verbiest[4]

What are the shortcomings?

Some definitions:

• **Random Gaussian process**: Realisations at every point are normally distributed. Realisations at different points can be covariant with each other.

The GW background is assumed to be…

• **Stochastic**: not deterministic! (sure)

• **Isotropic**: looks the same in every direction. (really?)

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What we did

1. Simulate the population of binary SMBHs
   – We didn't include any radically new binary evolution physics – this is really basic stuff assuming heaps of things!
2. Use these simulations to generate realisations of the induced TOA perturbations for a single pulsar
   – We included perturbations caused by every significant binary
   – These form true pre-fit residuals
3. Compare these realisations with realisations including a signal of the same amplitude modelled as a Gaussian process.
   – We did our analysis in the Fourier domain, **naturally**.

Power spectral density of TOA perturbations *R(t)* (FT = Fourier Transform):

$$PSD = \frac{2}{T_{obs}} \left| FT[R(t)] \right|^2$$

Predicting the distribution of SMBHs – Guo et al. (2011) model

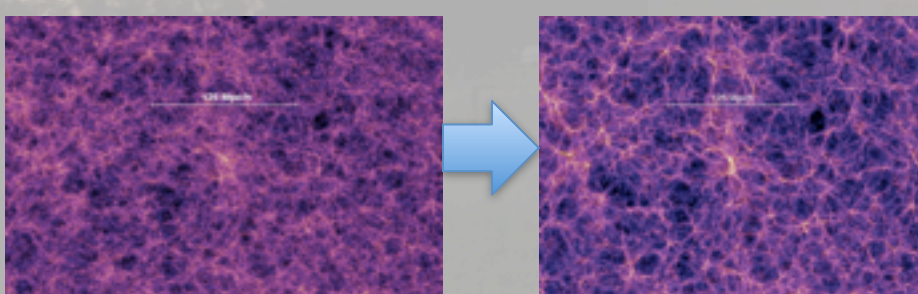
• Based on previous MPA models (e.g., Springel et al. 2005; Croton et al. 2006; De Lucia & Blaizot 2007)

• Uses the Millennium (Springel et al. 2005) and Millennium-II (Boylan-Kolchin et al. 2009) simulations for dark matter halo merger trees.

• Millennium: 685 Mpc a side; Millennium-II: 137 Mpc a side. Both traced 2160^3 particles from z=127 to z=0.

Observations used to tune the model

- z=0 stellar mass function
- Local M_{BH}-M_{Bulge} relation.
- Galaxy luminosity functions
- SFR history (until z=2)



Successful predictions – heaps!

- Matches SDSS galaxy abundance and clustering properties
- Tully-Fisher relation
- Cluster properties
- **BH scaling relations**
- **z<2 AGN luminosity function**
- AGN clustering
- …

Converting lists of SMBH

Form the distribution of the observable number, N, of binary SMBHs per unit h_0, per unit f:

$$\frac{dN}{dh_0 df} = \frac{dN}{dh_0 dz}\frac{dz}{dt}\frac{dt}{df}$$

From G11

From cosmology

From GR

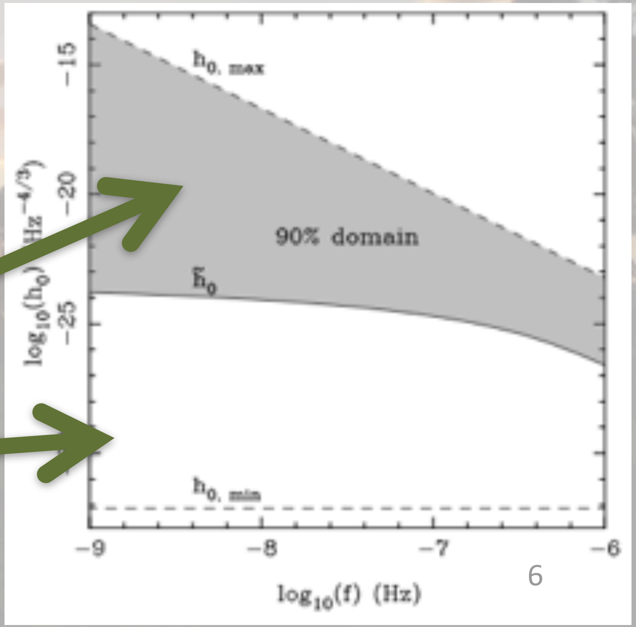
h_0 is the frequency-independent strain squared for a binary

$$h_0 = \sqrt{\frac{128}{15}}\frac{(GM_C)^{10/3}}{c^8 D^2}(\pi(1+z))^{2/3}$$

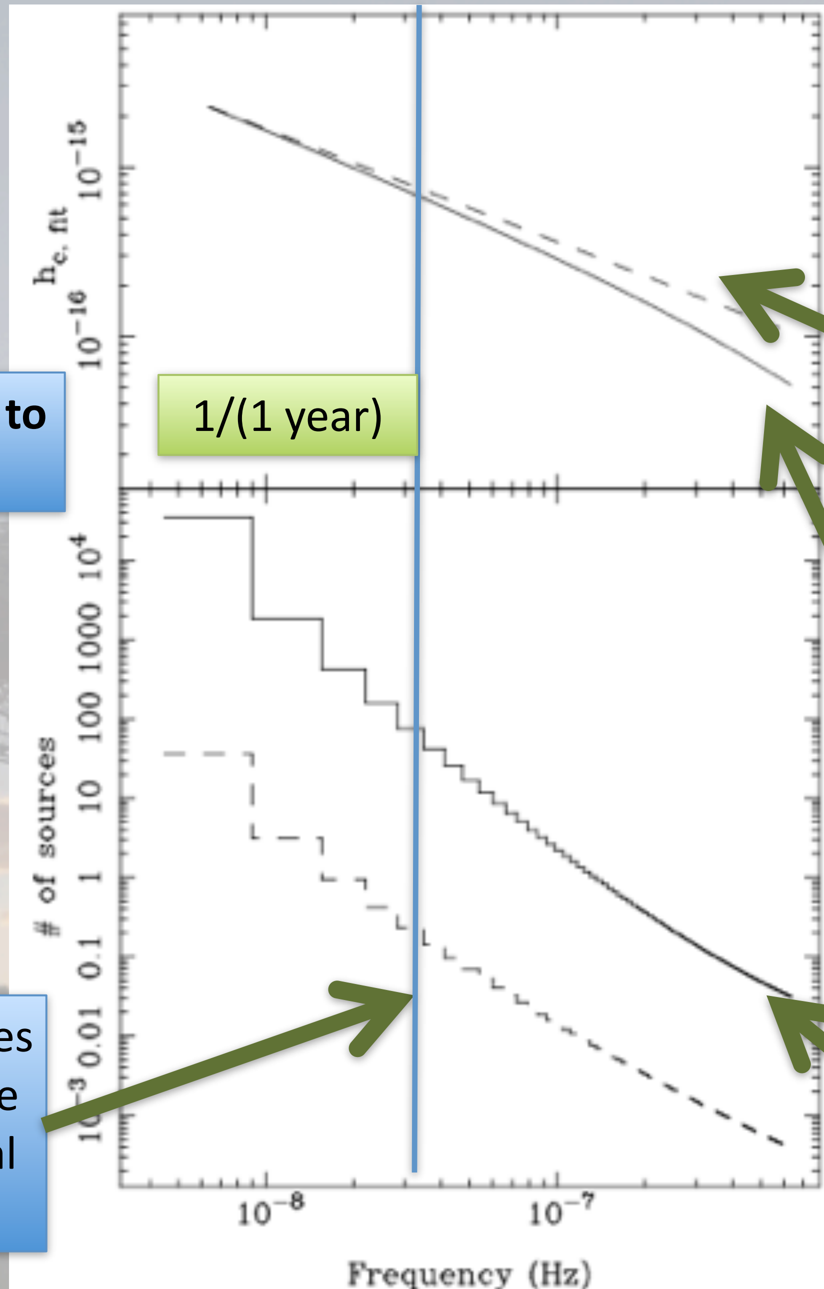
Fit the distribution with an analytic function

Draw sources corresponding on average to 90% of the expected mean induced timing residual PSD

Simulate the remaining power using TEMPO2



A few sources appear to dominate!



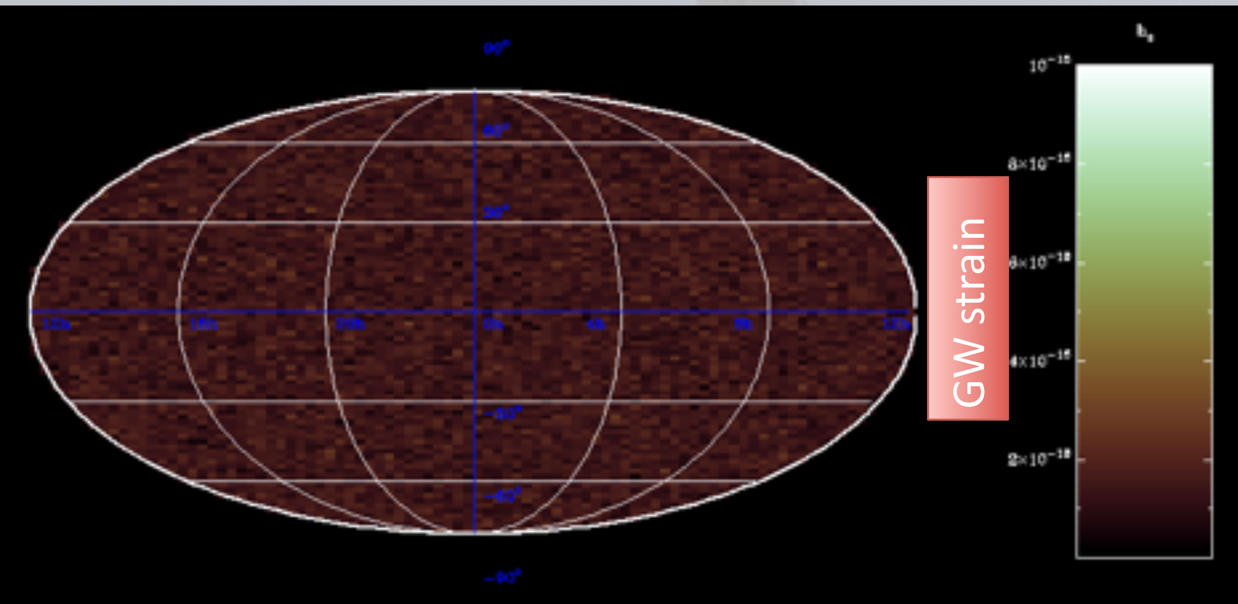
A curve with spectral index -2/3

The mean predicted **characteristic strain spectrum** (curvature caused by last stable orbit prescription)

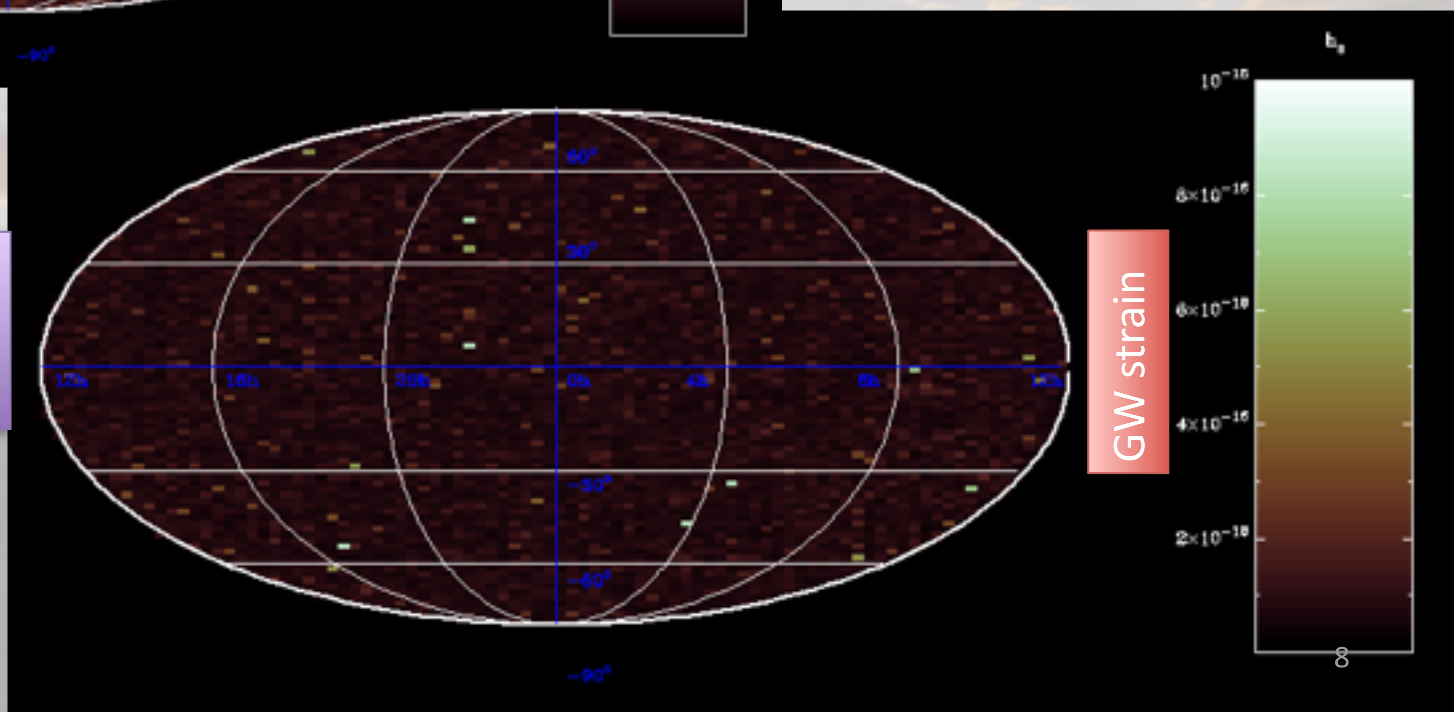
Mean number of sources contributing **50%** of the induced timing residual PSD

Mean number of sources contributing **90%** of the induced timing residual PSD

Comparison with TEMPO2



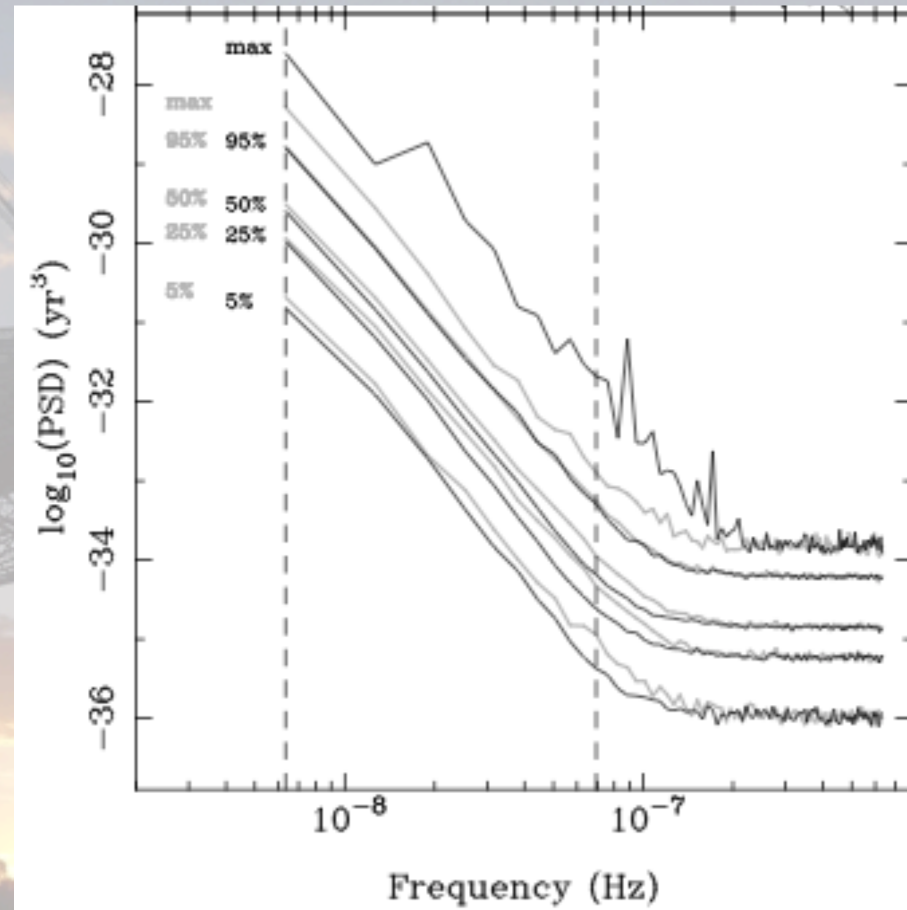
Single realisation of 200,000 sources corresponding to the **TEMPO2 signal**



Single realisation of ~500,000 sources from **our model**

Comparing PSDs of TOA perturbations

- Simulate datasets with:
  - **5 years, 500 regular samples, 1ns Gaussian white noise**
  - Add GW-induced timing residuals from out model
  - Add GW-induced timing residuals from (hacked) TEMPO2 GWbkgrd corresponding to the predicted strain spectrum.
- Compare Cholesky PSDs



"Percentile PSDs"
Thin black: our model
Thick grey: GWbkgrd

Comparing PSDs of TOA perturbations

- Simulate datasets with:

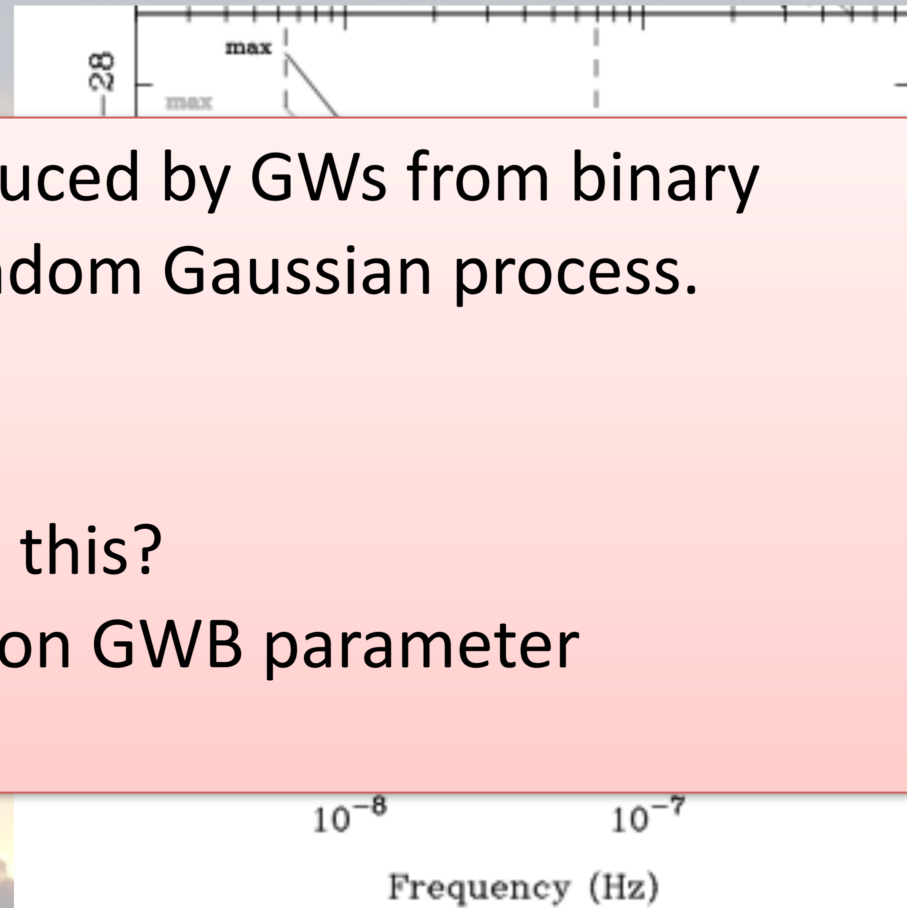
So, the TOA perturbations induced by GWs from binary SMBHs do not represent a random Gaussian process.

Open questions:

- How model-dependent is this?
- What is the effect of this on GWB parameter estimation?

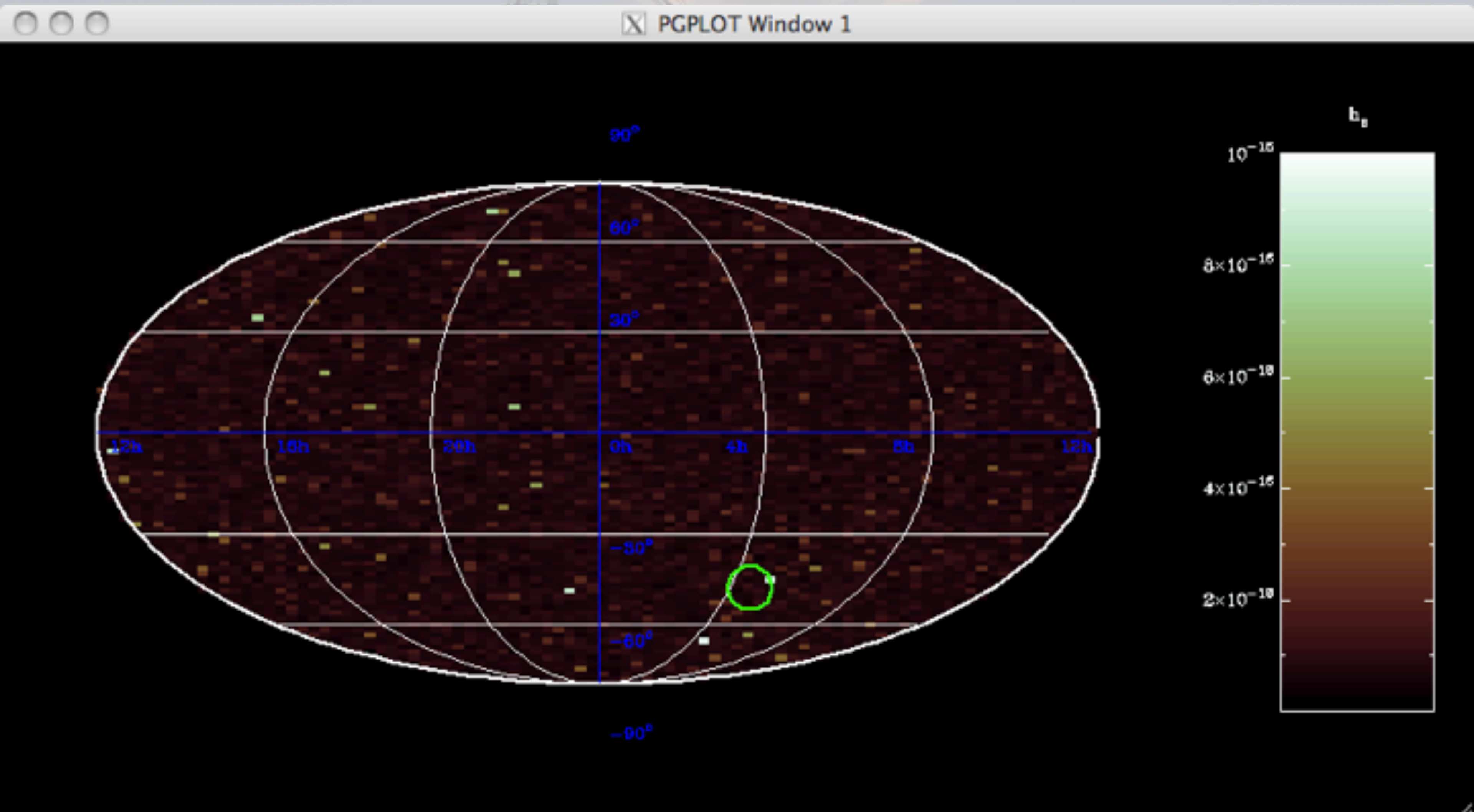
predicted strain spectrum.

- Compare Cholesky PSDs

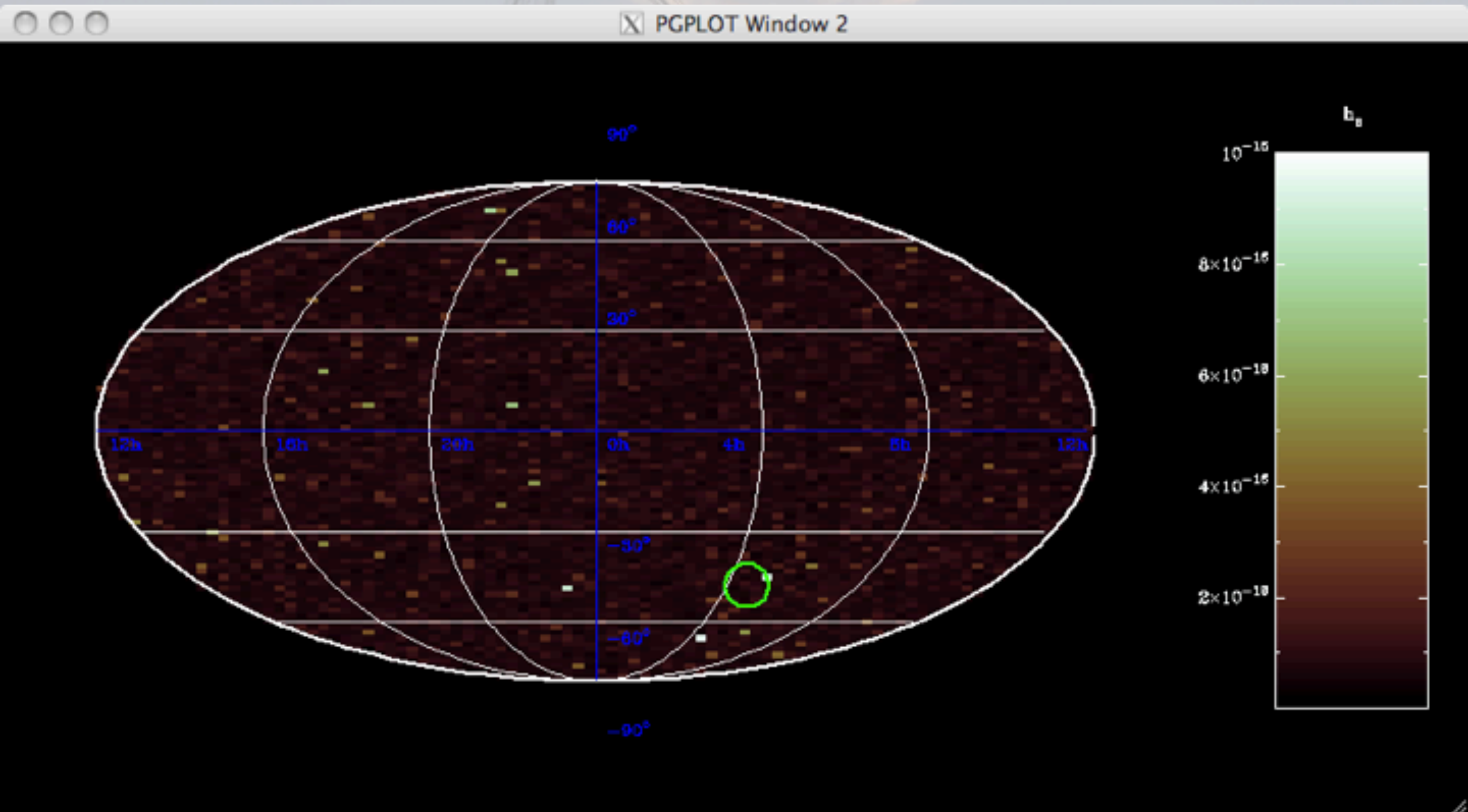


"Percentile PSDs"
Thin black: our model
Thick grey: GWbkgrd

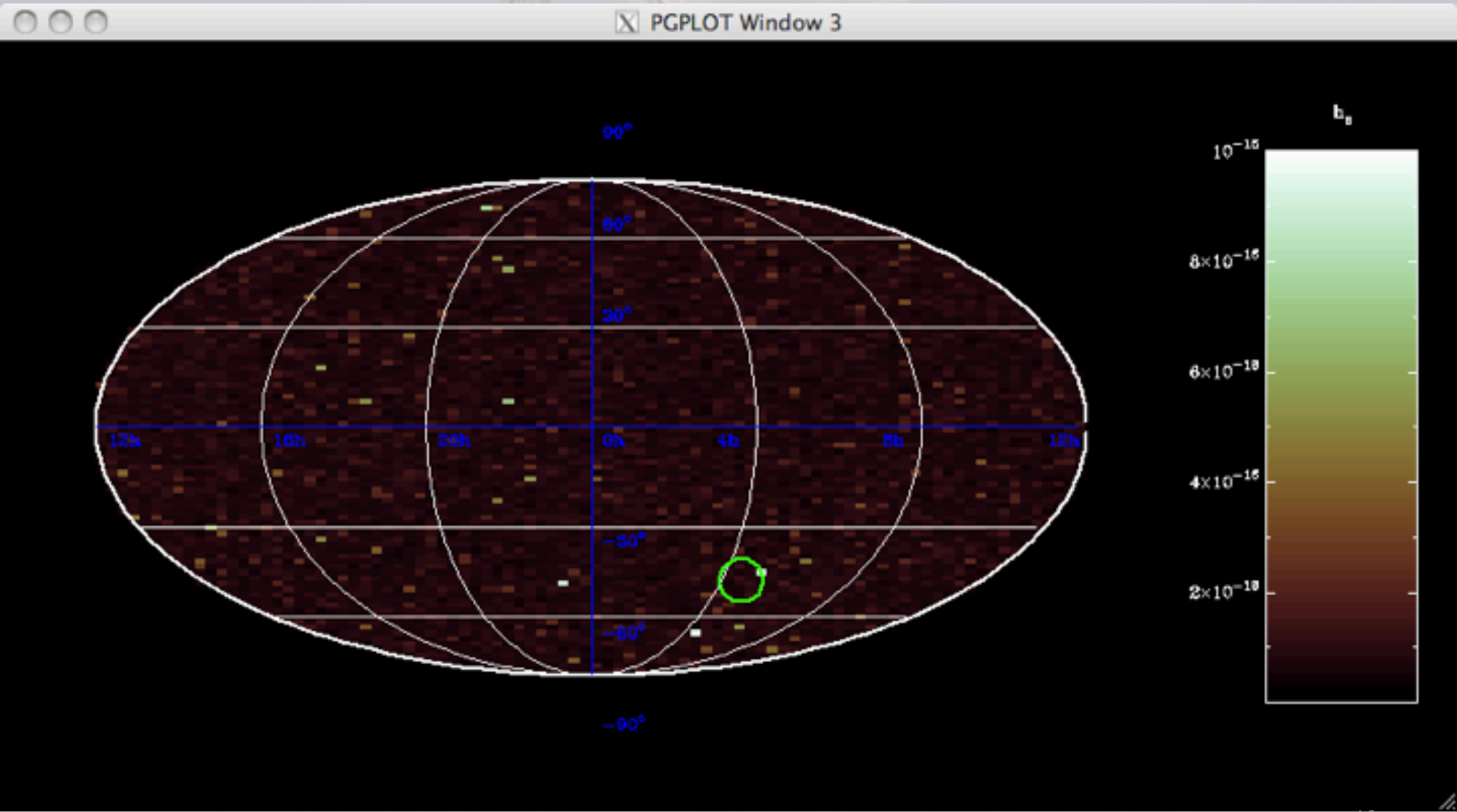
A realisation of the GW sky

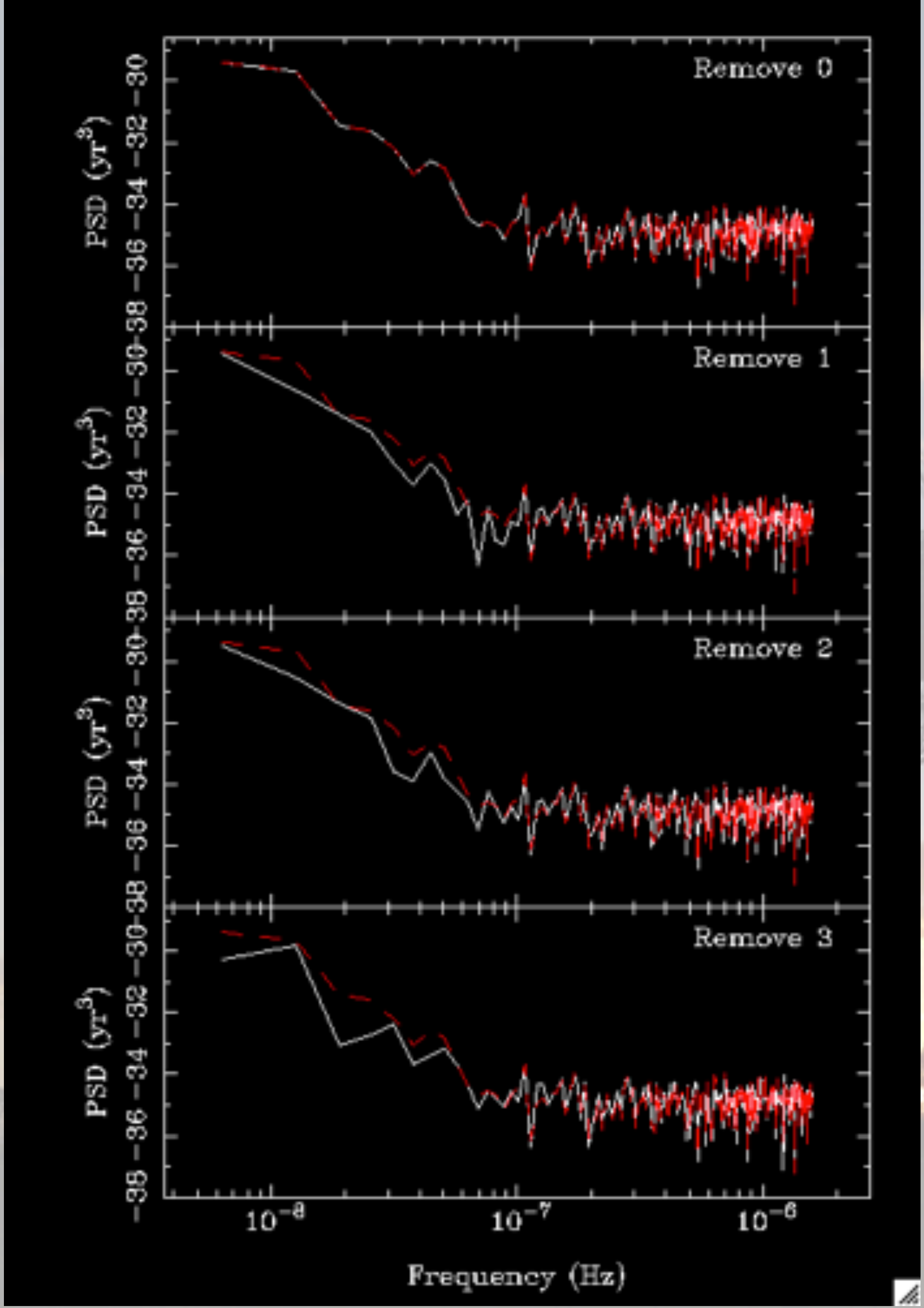


Now take out the sources producing the highest-amplitude TOA perturbations in the lowest 20 spectral bins



And do the same again





Power spectral densities of simulated timing residuals before and after removing the highest-perturbation-amplitude sources in the lowest 20 frequency bins

These are complicated!

But the effect is clear – individual sources dominate some spectral bins!

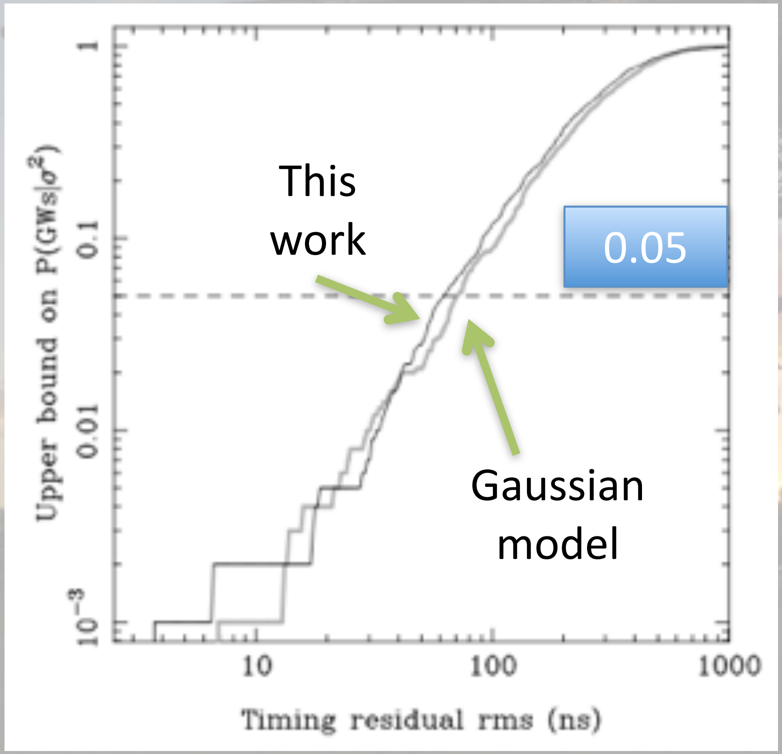
We predict: one single source above the mean total GW-induced timing residual PSD in one of the lowest 10 spectral bins of a 5-year dataset.

Conclusions

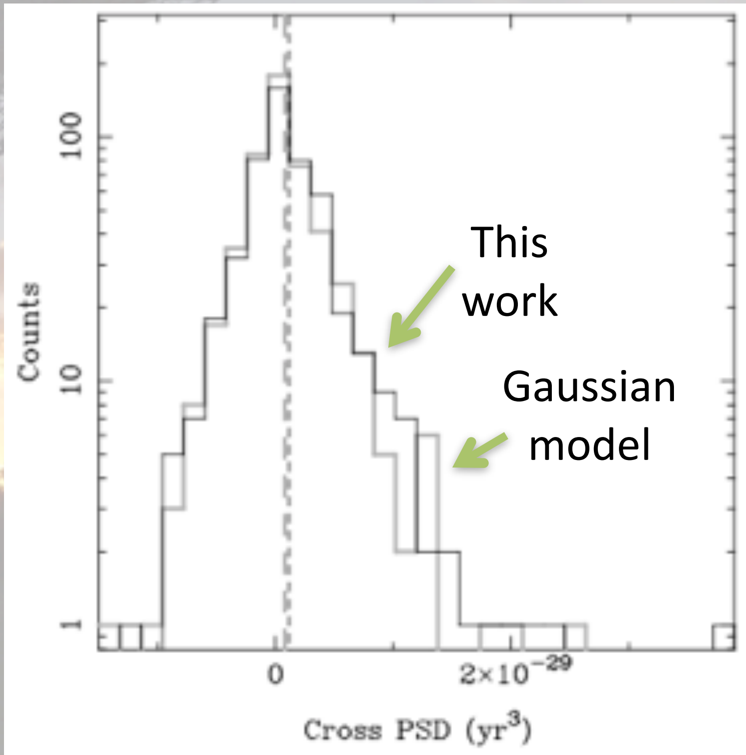
1. There are **clear differences** between GW-induced TOA perturbations from the **predicted binary SMBH distribution**, and perturbations modelled as a **random Gaussian process**.
2. These differences are caused by a **few sources contributing most of the GW-induced TOA perturbation PSD** in every frequency bin of a 5-year dataset.
3. Current techniques used to estimate the GWB amplitude are therefore not completely consistent with the GW signal from binary SMBHs.
4. Given that a few sources appear to dominate the GW-induced TOA perturbations, limit/detection methods that account for this will be more optimal than existing ones.

Does this affect existing limits?

Estimate of P(GWs|rms) for different measured timing residual rms values, using the lowest spectral bin



Distributions of GW-induced correlations between a pair of pulsars in the lowest spectral bin



Does this affect existing limits?

- Existing limits use likelihoods of data/data-statistic given GWs. We predict different likelihoods from the TEMPO2 model. So yes!
- But our estimate is that the effect is marginal. For example, a 95% ruling out of a TEMPO2-simulated signal with our predicted strain spectrum actually rules out the signal with 92% confidence.
- The distributions of the correlation between pulsars are also only slightly different. (but both are still very wide…)