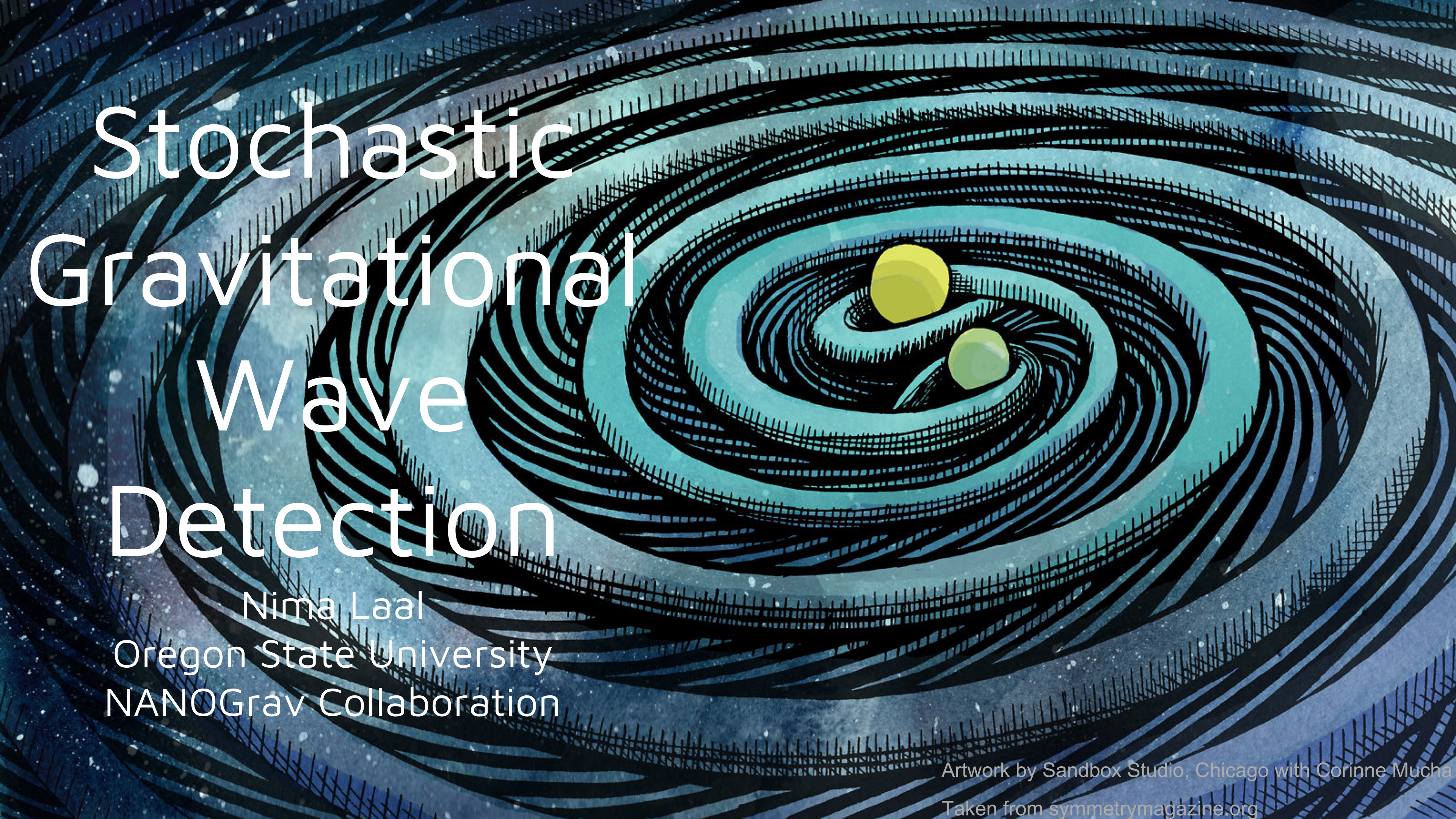

Stochastic Gravitational Wave Detection

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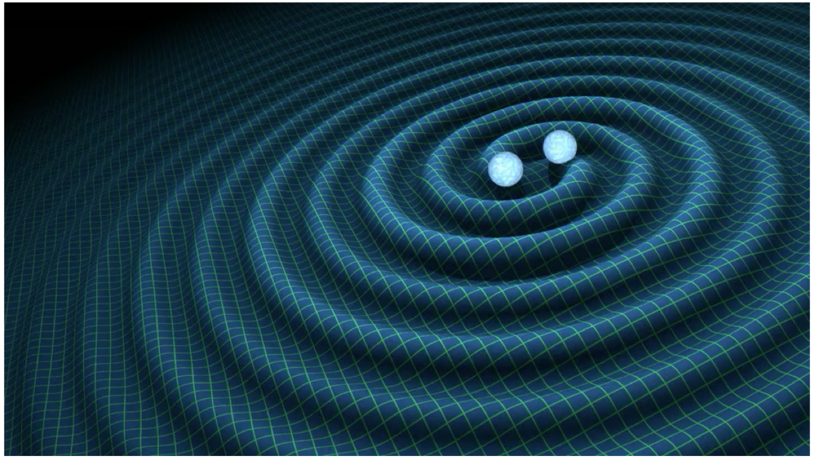
Artwork by Sandbox Studio, Chicago with Corinne Mucha
Taken from symmetrymagazine.org

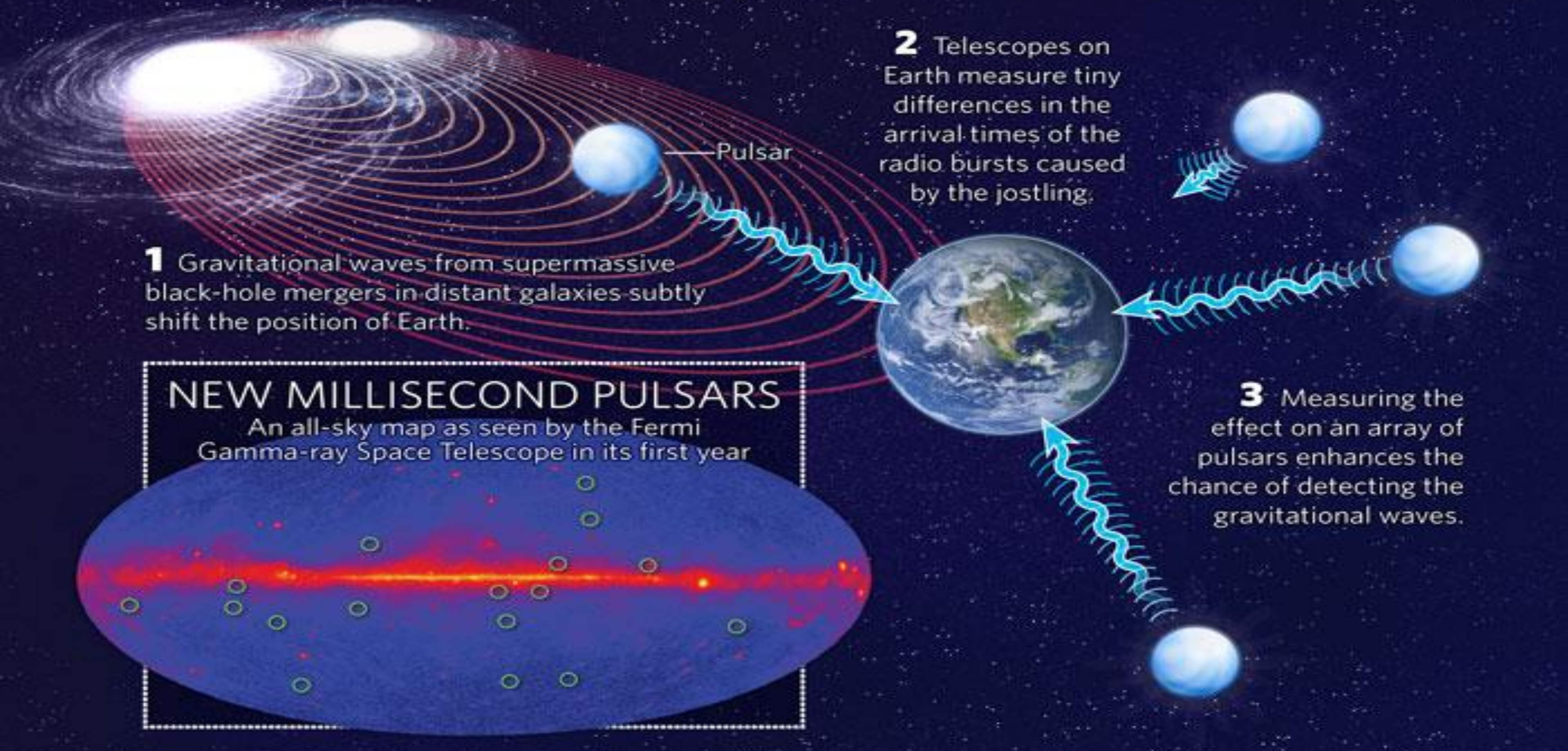
Stochastic Gravitational Wave Background (SGWB)



- Sources are:
  - isotropic
  - independent
  - point-like
  - many
  - far away
- Gravitational waves from such sources **correlate** photons' geodesics. **Pulsar Timing Array (PTA)** is used to observe the correlations.

Animation by R. Hurt - Caltech / JPL

HUNTING GRAVITATIONAL WAVES USING PULSARS



1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.

2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.

3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.

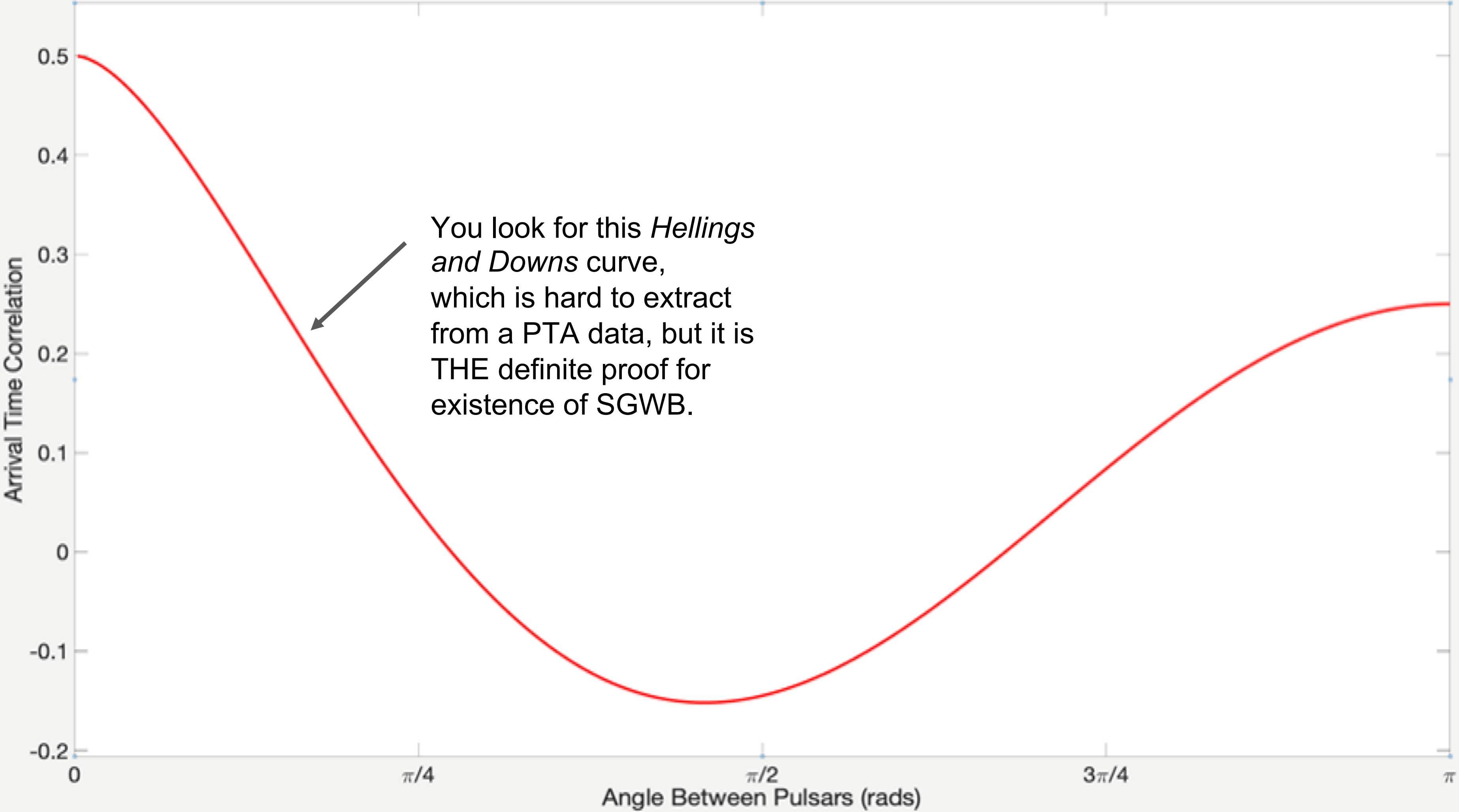
NEW MILLISECOND PULSARS

An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year

Credit: NASA/DOE/Fermi LAT Collaboration via Nature

The Problem of Detection

Stochastic gravitational wave behaves like noise in a PTA data set; however, it is not the only source of noise. So, how to tell if a noise is SGWB?

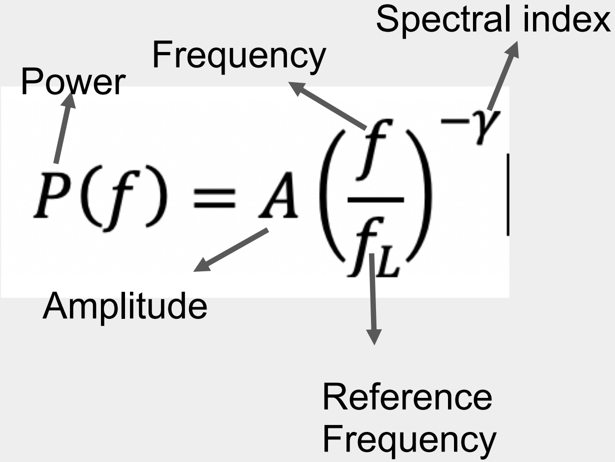


You look for this *Hellings and Downs* curve, which is hard to extract from a PTA data, but it is THE definite proof for existence of SGWB.

The First Step: Noise Analysis

The easiest way to distinguish noises from each other is through their power spectral density.

The Powerlaw Model:



Spectral index

Frequency

Power

$$P(f) = A\left(\frac{f}{f_L}\right)^{-\gamma}$$

Amplitude

Reference Frequency

Colored Noise

Terminology

- The most common colored noises in a PTA data set are:
  - Red: any noise with **positive** spectral index
  - White: any noise with **zero** spectral index

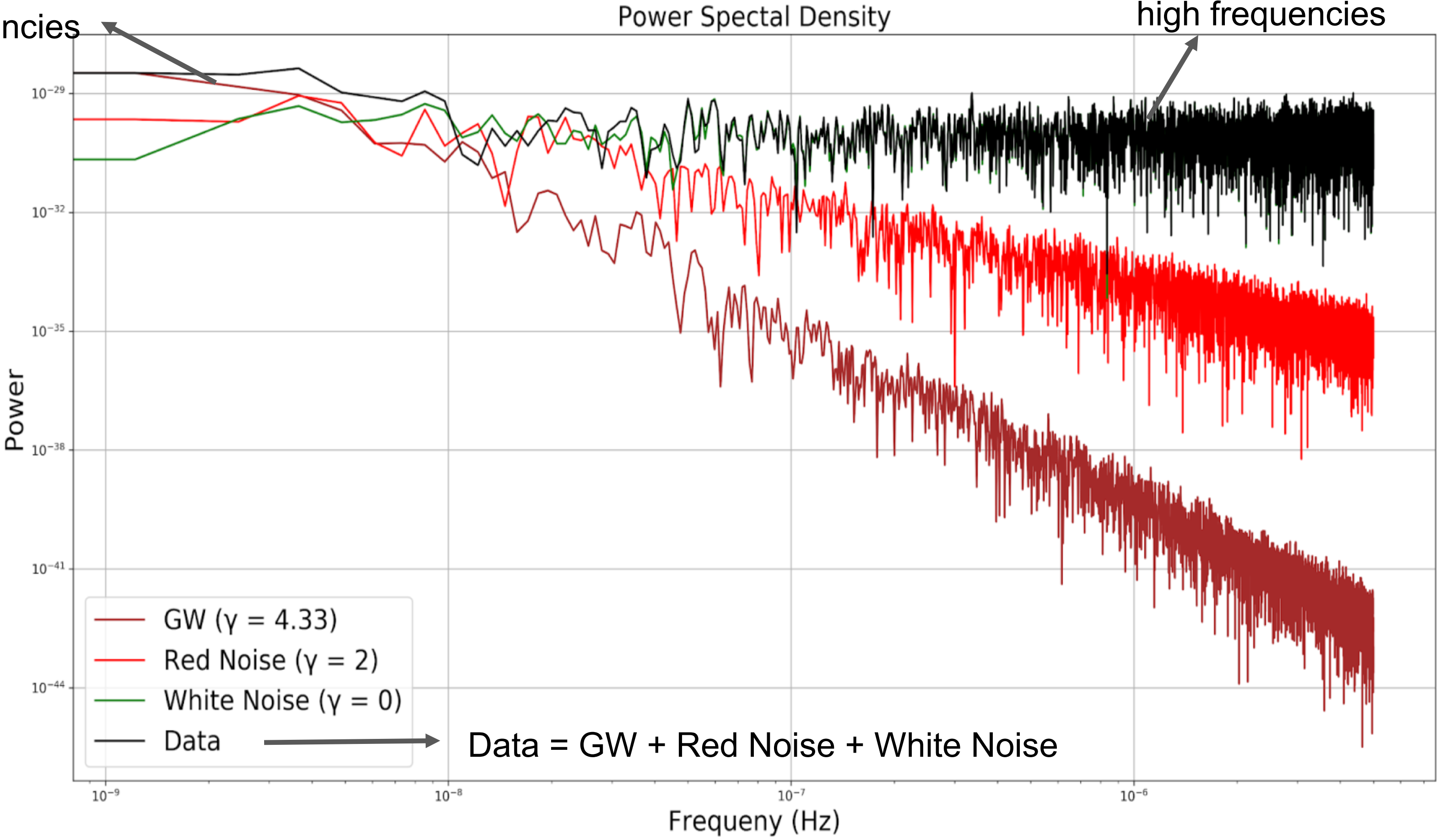
A Toy Model

A pulsar with only one white, one red, and one SGWB component and **all deterministic signals removed**

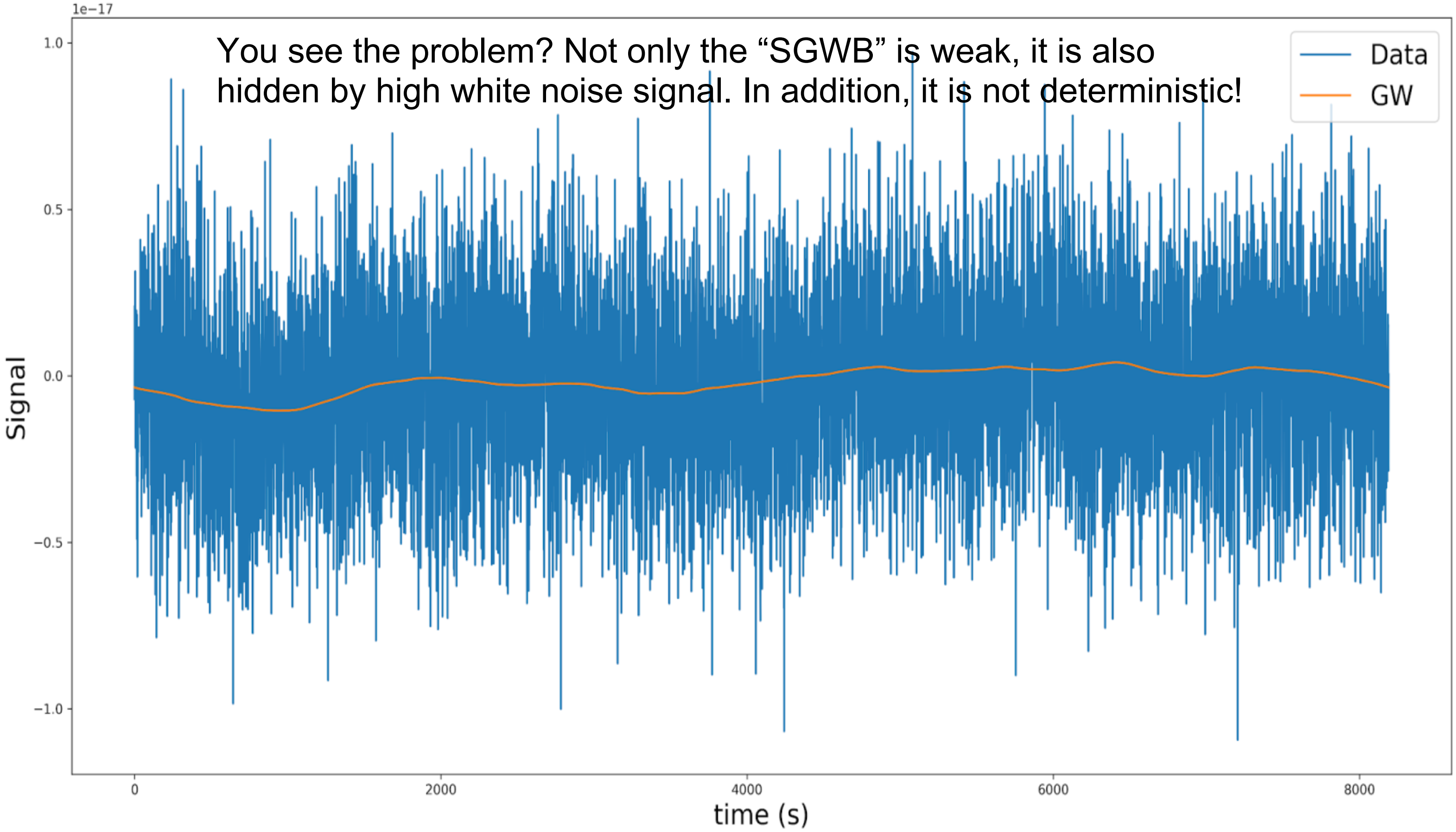
All surviving signals are assumed to be random noises following a powerlaw spectral density model with SGWB noise having a spectral index of $\boldsymbol{\gamma} = 13/3$ (red noise).

Red noise could dominate at low frequencies

White noise dominates at high frequencies



Data = GW + Red Noise + White Noise



You see the problem? Not only the “SGWB” is weak, it is also hidden by high white noise signal. In addition, it is not deterministic!

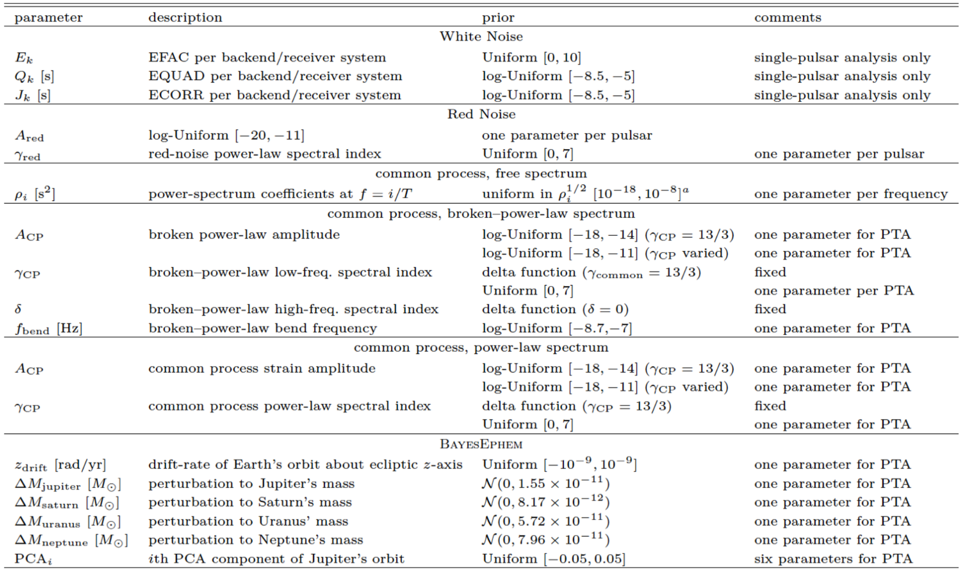
In reality…

- SGWB is Red, and that is a problem!
- Deterministic signals need to be removed
    - spin down period, ephemeris variation, pulsar sky location variation, equipment change,…
- Stochastic signals need to be understood and well modeled
    - SGWB, receiver noise, clock noise, interstellar medium fluctuations, …
- Our models become computationally expensive

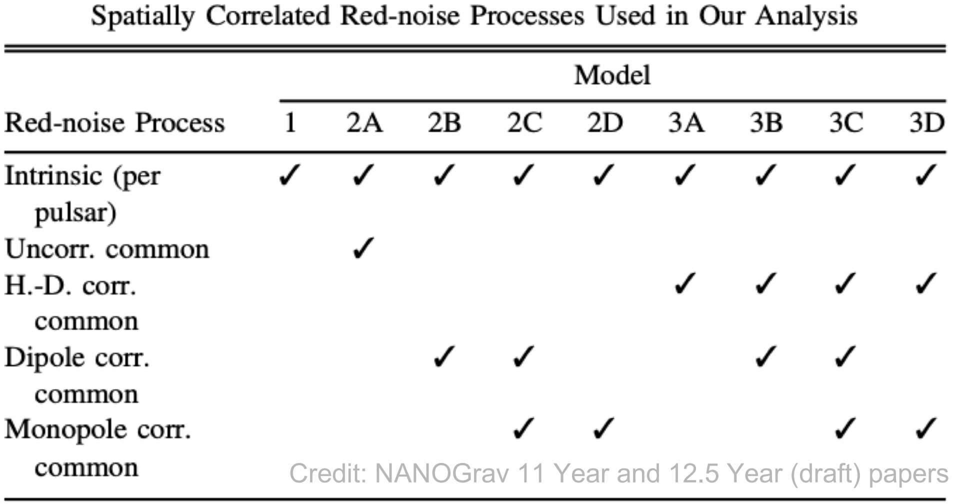
So, how do we do the noise analysis?

- We simply wait long enough (so far 15 years) for the red noises to dominate the white noises (at least in low frequencies)
- We focus more on the lower frequency bins of our data.
- While waiting, we constantly improve the effectiveness of our Bayesian models in detecting any trace of a Red noise process that can potentially be a SGWB.

We Detect!



parameter	description	prior	comments
White Noise			
E_k	EFAC per backend/receiver system	Uniform $[0, 10]$	single-pulsar analysis only
Q_k [s]	EQUAD per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
J_k [s]	ECORR per backend/receiver system	log-Uniform $[-8.5, -5]$	single-pulsar analysis only
Red Noise			
$A_{\rm red}$	log-Uniform $[-20, -11]$	one parameter per pulsar	
$\gamma_{\rm red}$	red-noise power-law spectral index	Uniform $[0, 7]$	one parameter per pulsar
common process, free spectrum			
ρ_i [s^2]	power-spectrum coefficients at $f = i/T$	uniform in $\rho_i^{1/2}$ $[10^{-18}, 10^{-8}]^a$	one parameter per frequency
common process, broken–power-law spectrum			
$A_{\rm CP}$	broken power-law amplitude	log-Uniform $[-18, -14]$ ($\gamma_{\rm CP} = 13/3$)	one parameter for PTA
		log-Uniform $[-18, -11]$ ($\gamma_{\rm CP}$ varied)	one parameter for PTA
$\gamma_{\rm CP}$	broken–power-law low-freq. spectral index	delta function ($\gamma_{\rm common} = 13/3$)	fixed
		Uniform $[0, 7]$	one parameter per PTA
δ	broken–power-law high-freq. spectral index	delta function ($\delta = 0$)	fixed
$f_{\rm bend}$ [Hz]	broken–power-law bend frequency	log-Uniform $[-8.7, -7]$	one parameter for PTA
common process, power-law spectrum			
$A_{\rm CP}$	common process strain amplitude	log-Uniform $[-18, -14]$ ($\gamma_{\rm CP} = 13/3$)	one parameter for PTA
		log-Uniform $[-18, -11]$ ($\gamma_{\rm CP}$ varied)	one parameter for PTA
$\gamma_{\rm CP}$	common process power-law spectral index	delta function ($\gamma_{\rm CP} = 13/3$)	fixed
		Uniform $[0, 7]$	one parameter for PTA
BayesEphem			
$z_{\rm drift}$ [rad/yr]	drift-rate of Earth's orbit about ecliptic z-axis	Uniform $[-10^{-9}, 10^{-9}]$	one parameter for PTA
$\Delta M_{\rm jupiter}$ [$M_\odot$]	perturbation to Jupiter's mass	$\mathcal{N}(0, 1.55 \times 10^{-11})$	one parameter for PTA
$\Delta M_{\rm saturn}$ [$M_\odot$]	perturbation to Saturn's mass	$\mathcal{N}(0, 8.17 \times 10^{-12})$	one parameter for PTA
$\Delta M_{\rm uranus}$ [$M_\odot$]	perturbation to Uranus' mass	$\mathcal{N}(0, 5.72 \times 10^{-11})$	one parameter for PTA
$\Delta M_{\rm neptune}$ [$M_\odot$]	perturbation to Neptune's mass	$\mathcal{N}(0, 7.96 \times 10^{-11})$	one parameter for PTA
PCA$_i$	ith PCA component of Jupiter's orbit	Uniform $[-0.05, 0.05]$	six parameters for PTA



Spatially Correlated Red-noise Processes Used in Our Analysis

	Model								
Red-noise Process	1	2A	2B	2C	2D	3A	3B	3C	3D
Intrinsic (per pulsar)	✓	✓	✓	✓	✓	✓	✓	✓	✓
Uncorr. common		✓							
H.-D. corr. common						✓	✓	✓	✓
Dipole corr. common			✓	✓			✓	✓	
Monopole corr. common				✓	✓			✓	✓

Credit: NANOGrav 11 Year and 12.5 Year (draft) papers