Title: Pulsar Timing Arrays

Speakers: Xavier Siemens

Collection: Gravitational Waves Beyond the Boxes II

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Results from the NANOGrav search for nanohertz gravitational waves: cosmic strings and other cosmological sources

Xavier Siemens

Oregon State University

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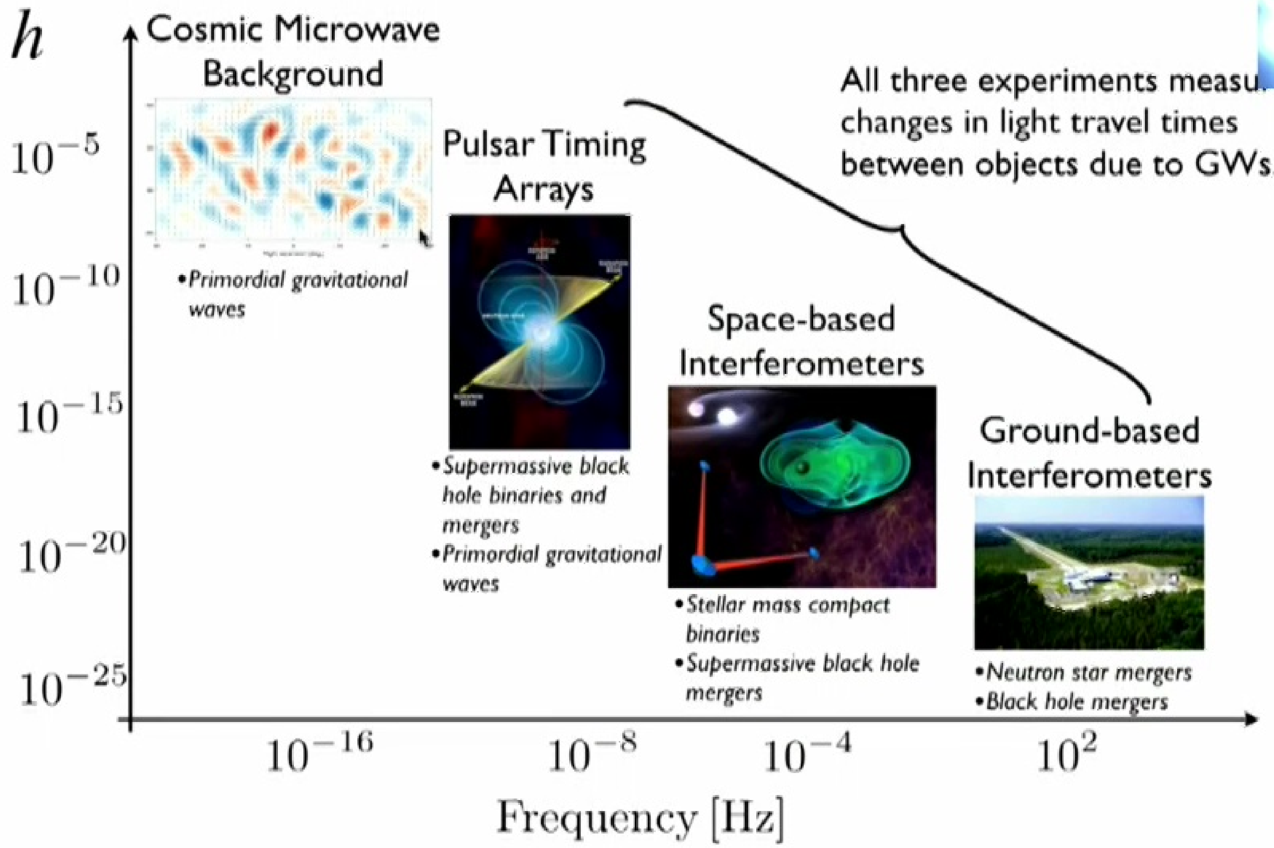
Physics Frontiers Center

The North American Nanohertz Observatory for Gravitational Wave
about 200 students and scientists in the US and Canada working to characte
gravitational wave universe at low frequencies using pulsar timing. Part of a wo
effort including partners in Europe (EPTA), Australia (PPTA), India (InPTA), Chi
and South Africa (SA PTA), which form the International Pulsar Timing Array (IPTA)

NANOGrav became a US National Science Foundation Physics Frontiers Center in 2015

The spectrum of gravitational wave astronomy



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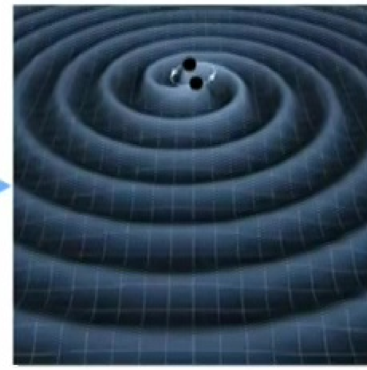
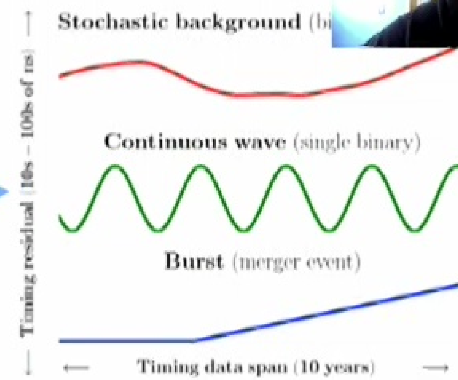
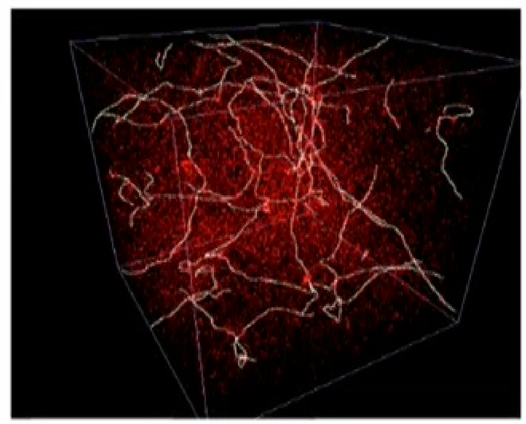
Gravitational wave sources

The most promising sources are supermassive binary black holes (SMBB

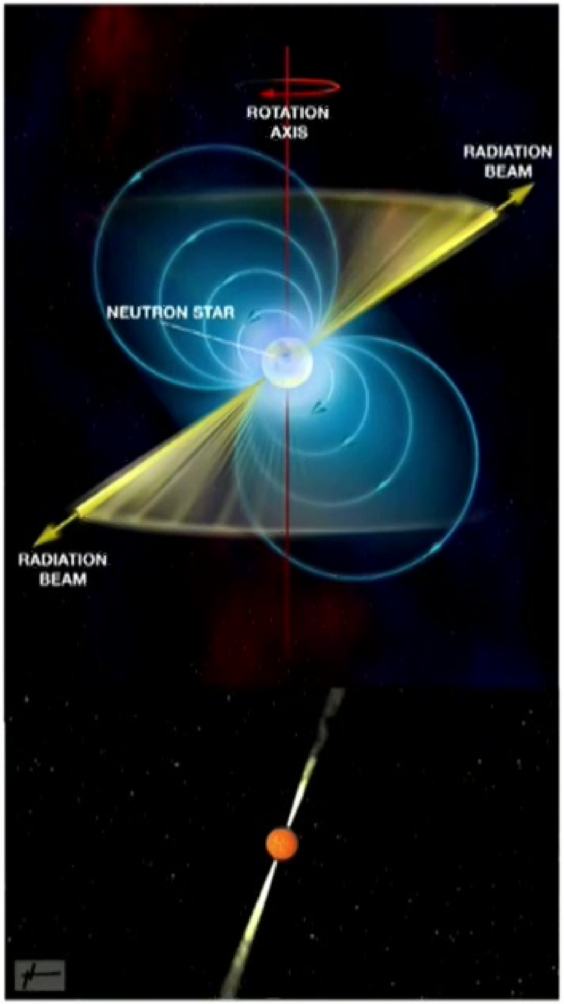




Other sources at nanohertz frequencies include cosmic strings, inflation, and phase transitions in the early universe.



GW detector component 1: pulsars



A pulsar is a type of neutron star

A neutron star is the remains of a dead star

Strong magnetic fields spin rapidly and emit beams of radio waves

Each time the radio beam points toward Earth we see a pulse of radio waves

Pulsars are extreme objects: 1/2 a million earth masses in a region the size of a city; magnetic fields billions of times stronger than we can make on Earth.

GW detector component II: radio telescopes

Our measurements are made with some of the most sensitive radio telescopes in

Arecibo Observatory

Green Bank Telescope

Very Large Array

CHIME

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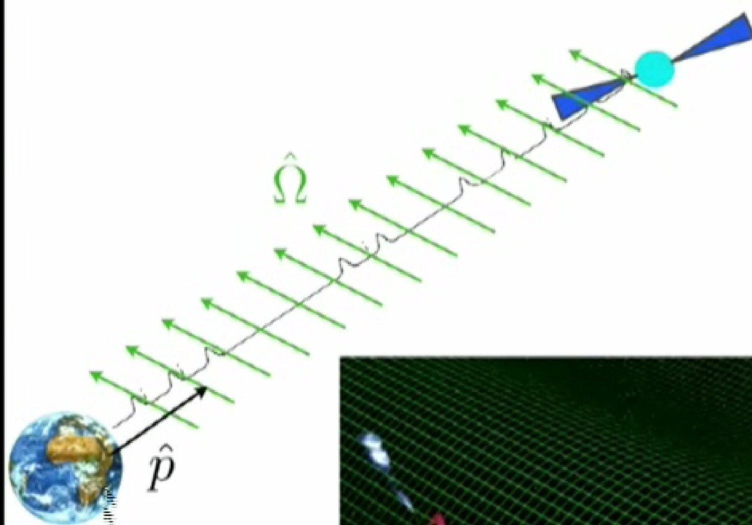
Effect of a gravitational wave on radio pulses

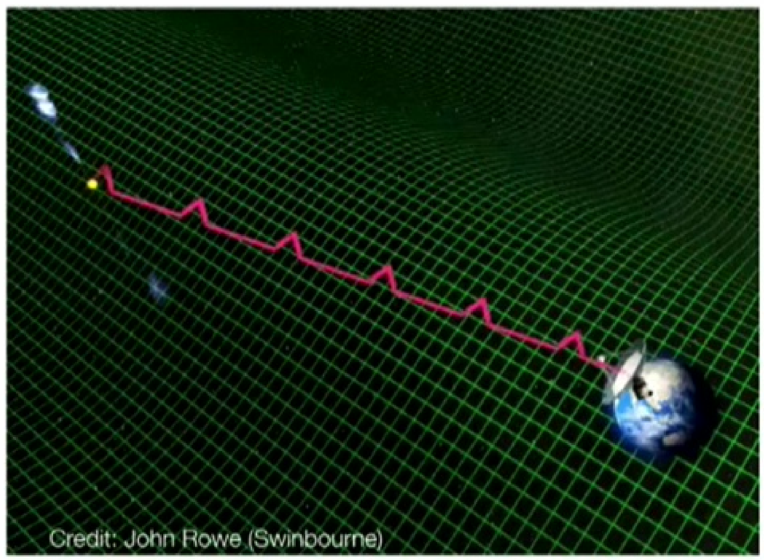


Gravitational waves red (blu[...]) shift the train of pulses from [...] pulsar according to:

$$z \equiv \frac{1}{2}\frac{\hat{p}_i\hat{p}_j}{1+\hat{\Omega}\cdot\hat{p}}\left[h_{ij}^{P} - h_{ij}^{E}\right]$$

Pulsar-term GW

Earth-term GW

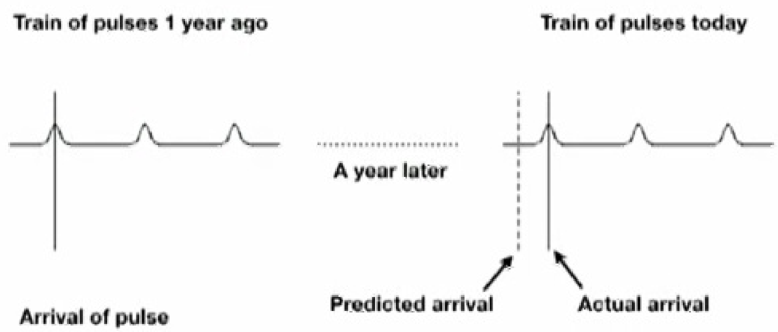


Credit: John Rowe (Swinbourne)

Sazhin (1978)
Detweiler (1979)
Anholm+ (2009)

Our experiment

Keep track of every rotation of the pulsar over many years; then constru
timing model to predict when a particular pulse from a pulsar will arr
our radio telescope. Error in our prediction is called the timing residual.



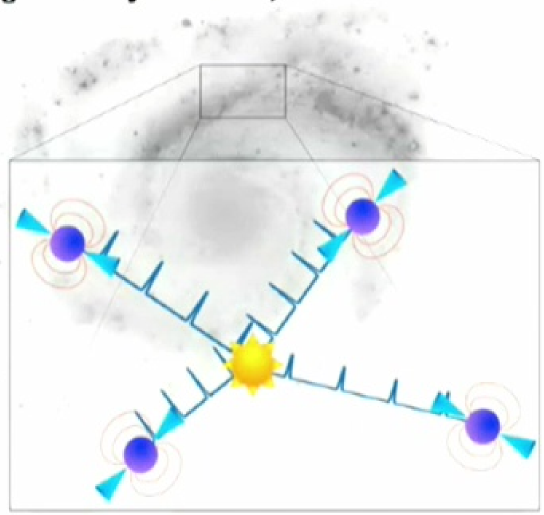
Timing residual = Actual arrival - Predicted arrival

Gravitational waves change the time of arrival of pulses so we can look for gravitational waves in the timing residual data.

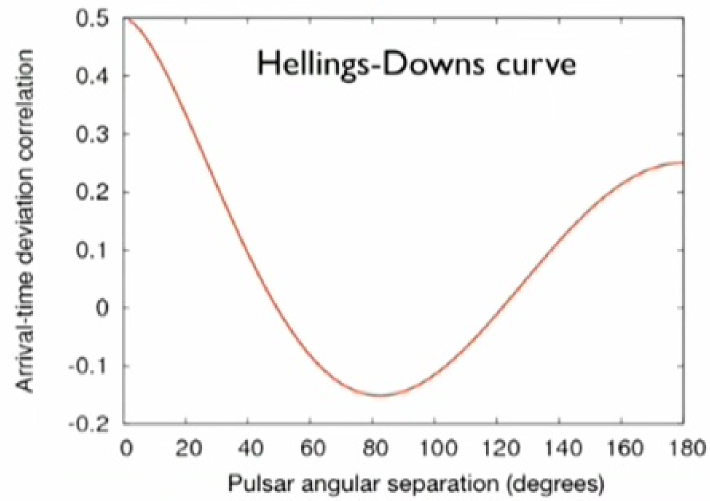
Currently we can predict the arrival times of pulses from our best pulsars to 10s of nanoseconds.

A galactic-scale GW detector: the Pulsar Timing

Image credit: J. Hazboun; NASA



GW perturbations are correlated among different pulsars.



Need to observe an ensemble of MSPs to extract the <u>correlated signal</u> from the noise.

NANOGrav data releases

5-yr: 2005-2010

17 pulsars

9-yr: 2005-2014

37 pulsars

Improved instrumentation, RMS improvement a factor of 2–3 for most pulsars.

11-yr: 2005-2016

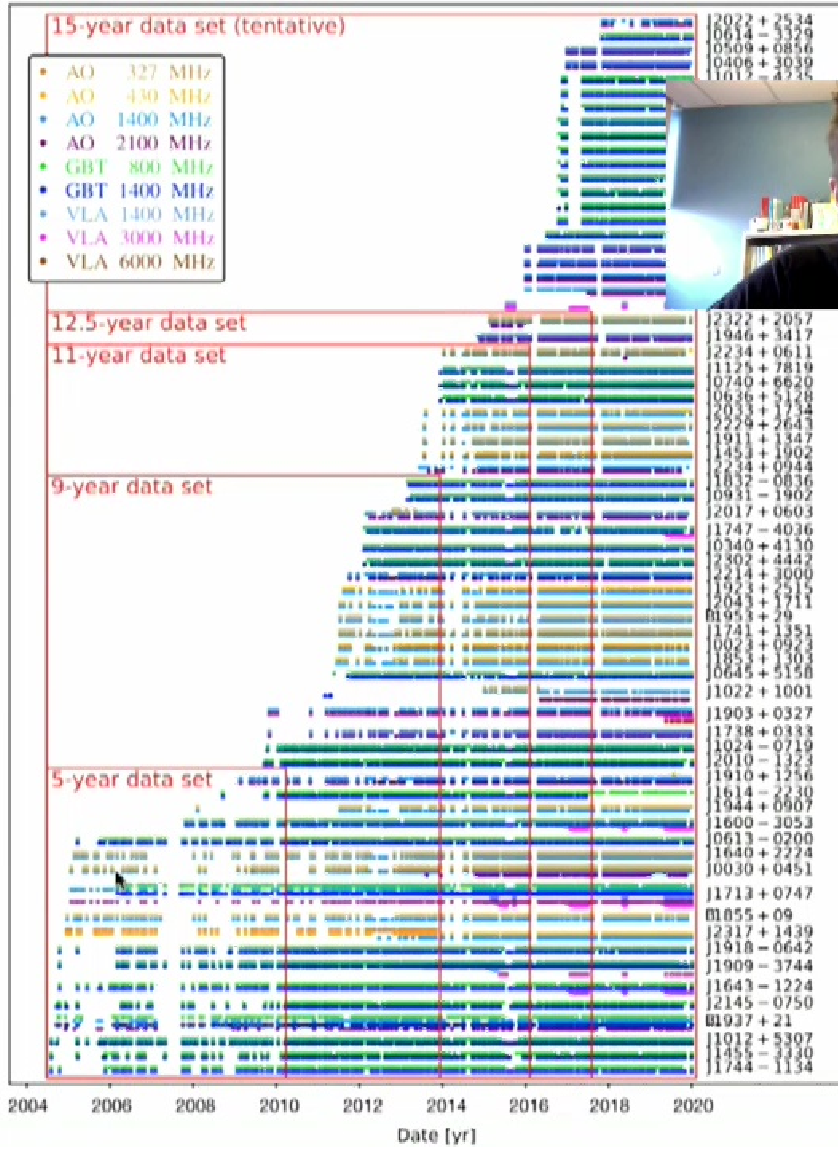
45 pulsars

12.5-yr: 2005-2017.5

47 pulsars

15-yr: 2005-2020

69 pulsars



Credit: David Nice

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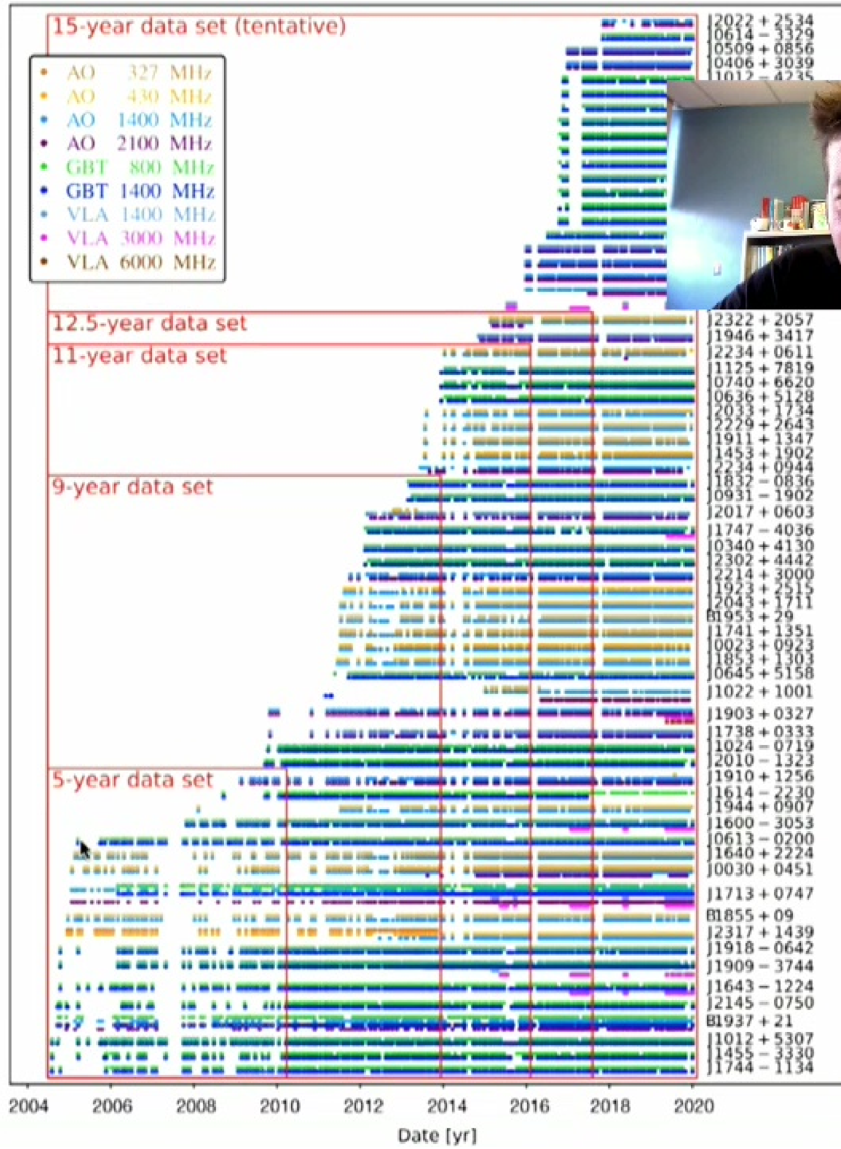

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Galaxy-Size Gravitational-Wave Detector Hints at Exotic Physics

Recent results from a pulsar timing array, which uses dead stars to hunt for gravitational waves, has scientists speculating about cosmic strings and primordial black holes

By Adam Mann on February 3, 2021

Representative illustration of Earth embedded in spacetime that is deformed by the background gravitational waves and its effects on radio signals coming from observed pulsars. Credit: Tonia Klein NANOGrav

The fabric of spacetime may be frothing with gigantic gravitational waves, and the possibility has sent physicists into a tizzy. A potential signal seen in the light from dead stellar cores known as pulsars has driven a flurry of theoretical papers speculating about exotic explanations.

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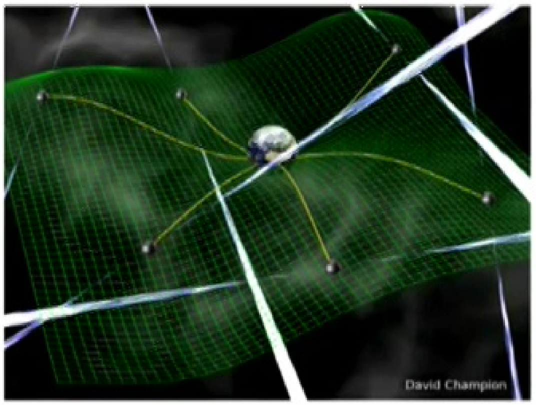
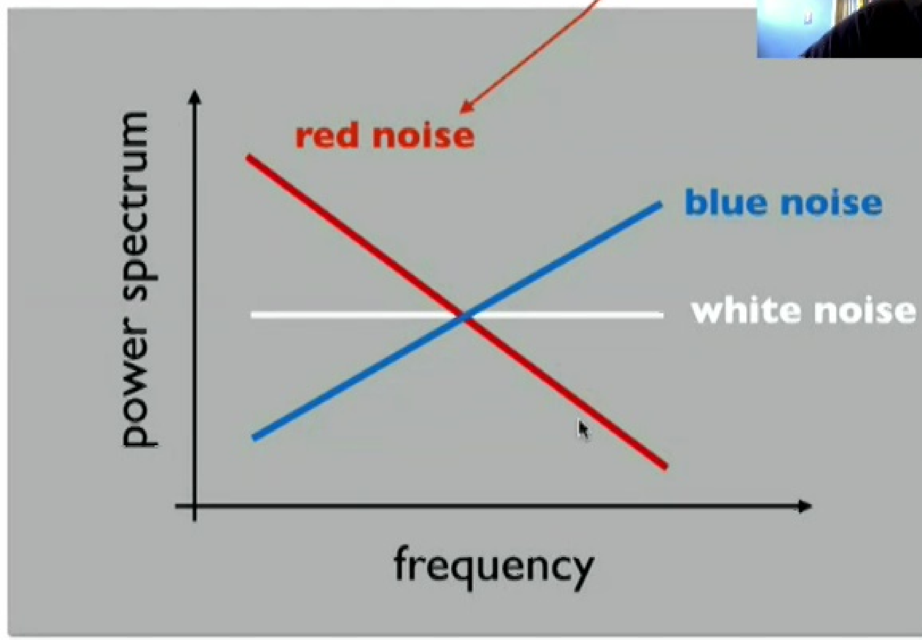
Stochastic backgrounds

Typically noise processes with **more power at low frequencies** (**red noise**





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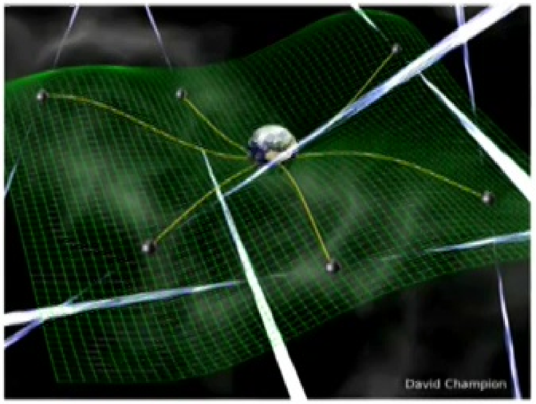

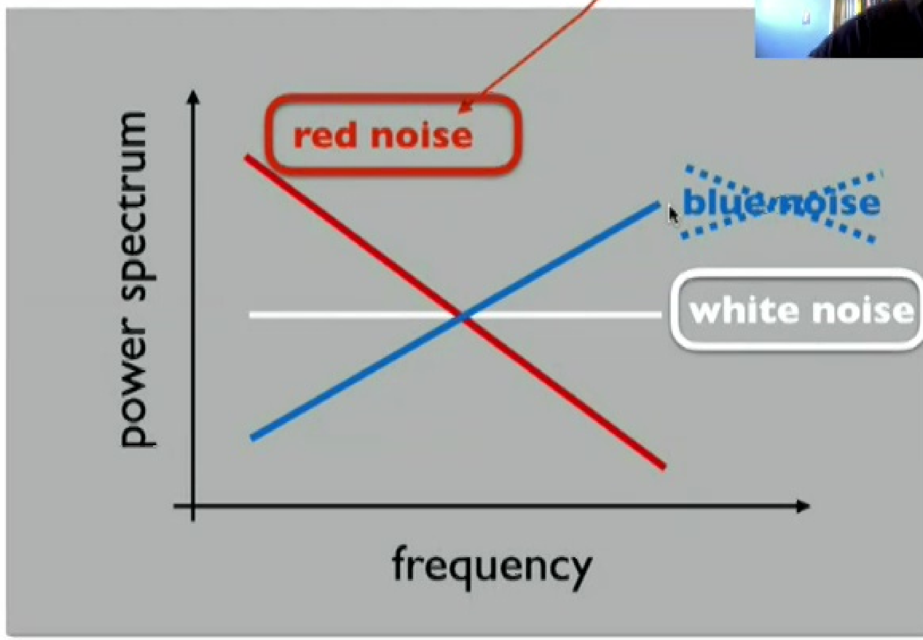

12

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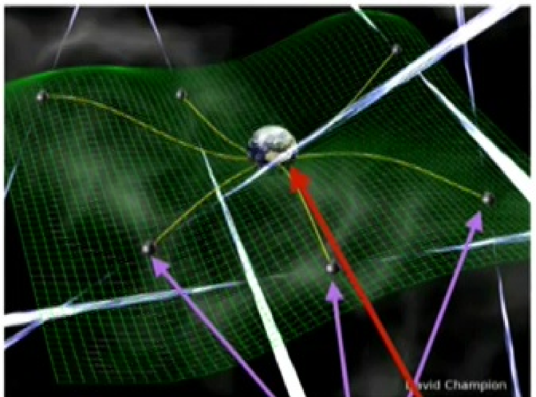
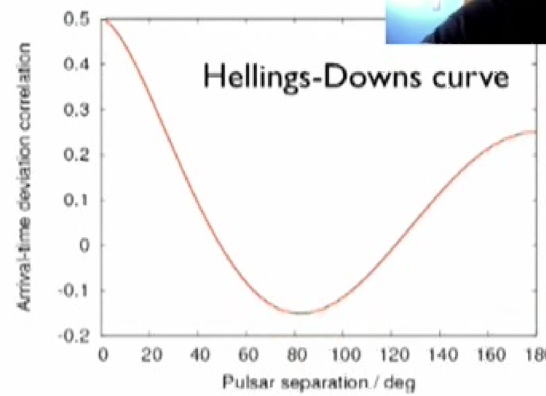


Only earth-term GWs are correlated among different pulsars.



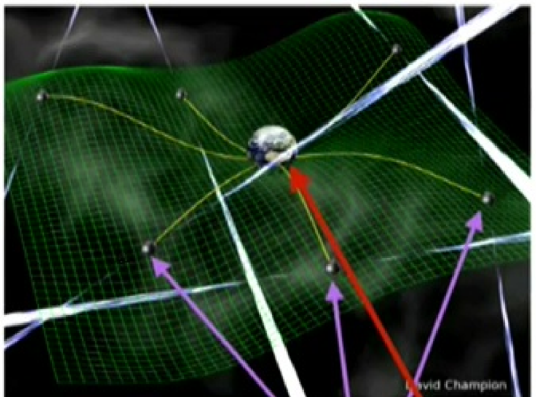
$$z \equiv \frac{1}{2} \frac{\hat{p}_i \hat{p}_j}{1 + \hat{\Omega} \cdot \hat{p}} \left[h_{ij}^{P} - h_{ij}^{E} \right]$$

Same Earth-term GW = correlated signal we look for
Different Pulsar-term GW = Source of (red) noise

13

Stochastic backgrounds

Typically noise processes with **more power at low frequencies** (**red noise**



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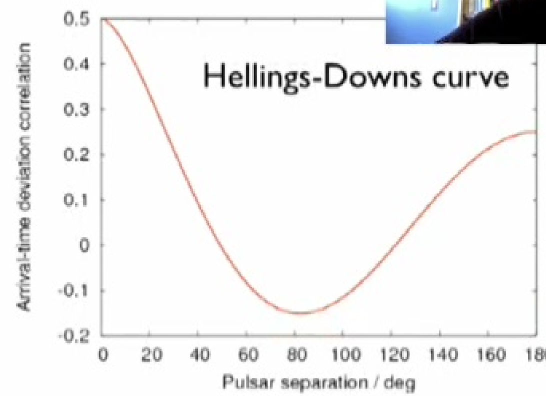

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Same Earth-term GW = correlated signal we look for
Different Pulsar-term GW = Source of (red) noise

Early on: Sensitivity is white noise limited —time→ Later: Sensitivity is pulsar-term GW red noise limited

Best way to beat down pulsar term red noise is to time many pulsars more-or-less independently of their timing precision. [XS et al. CQG 2013]

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Before discussing results: signal model

Pulsar 1		Pulsar 2		Pulsar
Timing Model White Noise Red Noise	+	Timing Model White Noise Red Noise	+ … +	Timing White Noise Red Noise

Credit: Sarah Vigeland

\+

Common signal across pulsars, possibly correlated

The GW stochastic background will first show up in our data as a common red noise process (a red noise process with the same amplitude and spectral index)… in due course we will detect correlations in this red noise between pulsars.

Stochastic background: 12.5-yr GWB results

Pulsar 1		Pulsar 2		Pulsar N
Timing Model White Noise Red Noise	+	Timing Model White Noise Red Noise	+ … +	Timing Model White Noise Red Noise

Credit: Sarah \

NANOGrav Collaboration, submitted, 2020.
Corresponding author: Joe Simon

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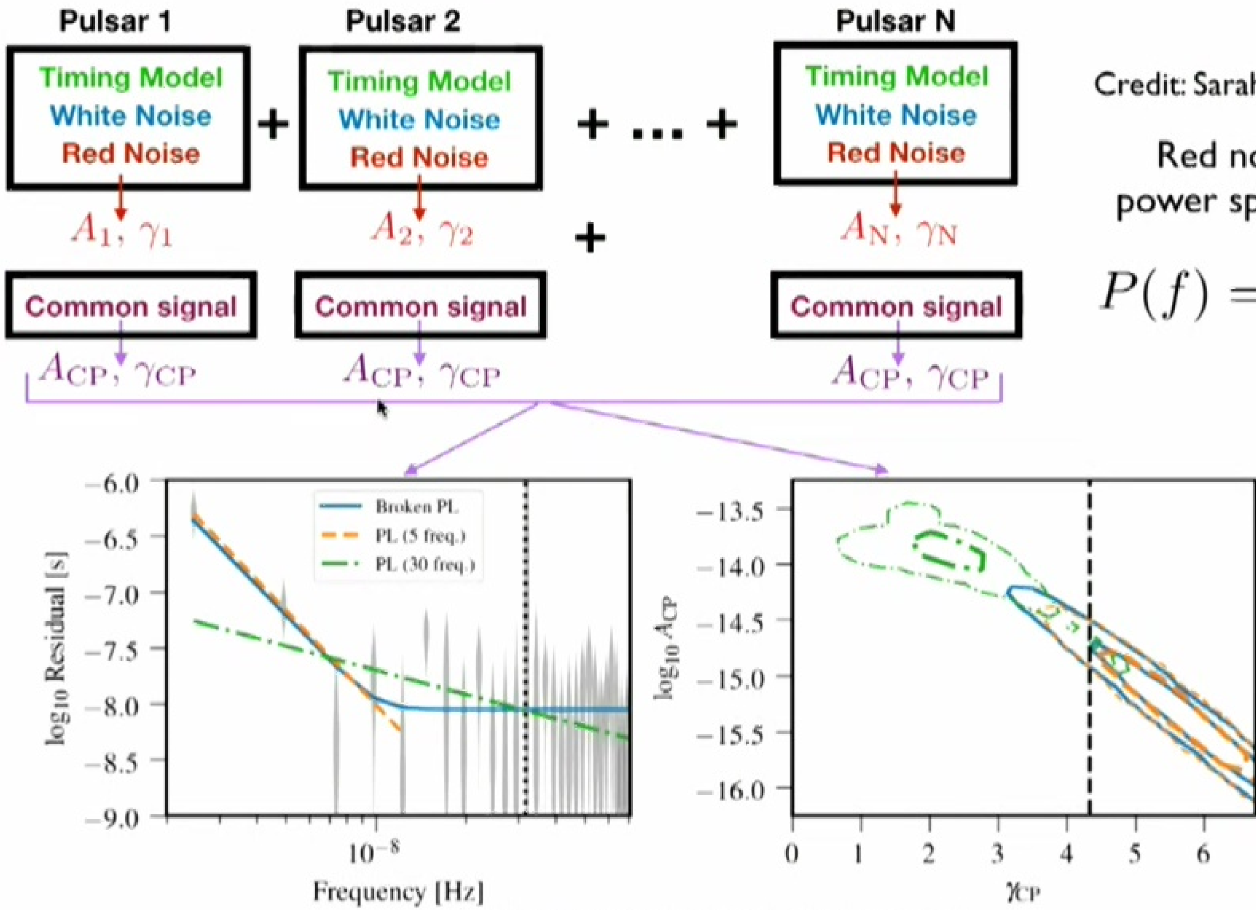
Stochastic background: 12.5-yr GWB results



Credit: Sarah V

Red noise power spectra:

$$P(f) = A_i f^{-\gamma_i}$$

NANOGrav Collaboration, submitted, 2020.
Corresponding author: Joe Simon

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Stochastic background: 12.5-yr GWB results

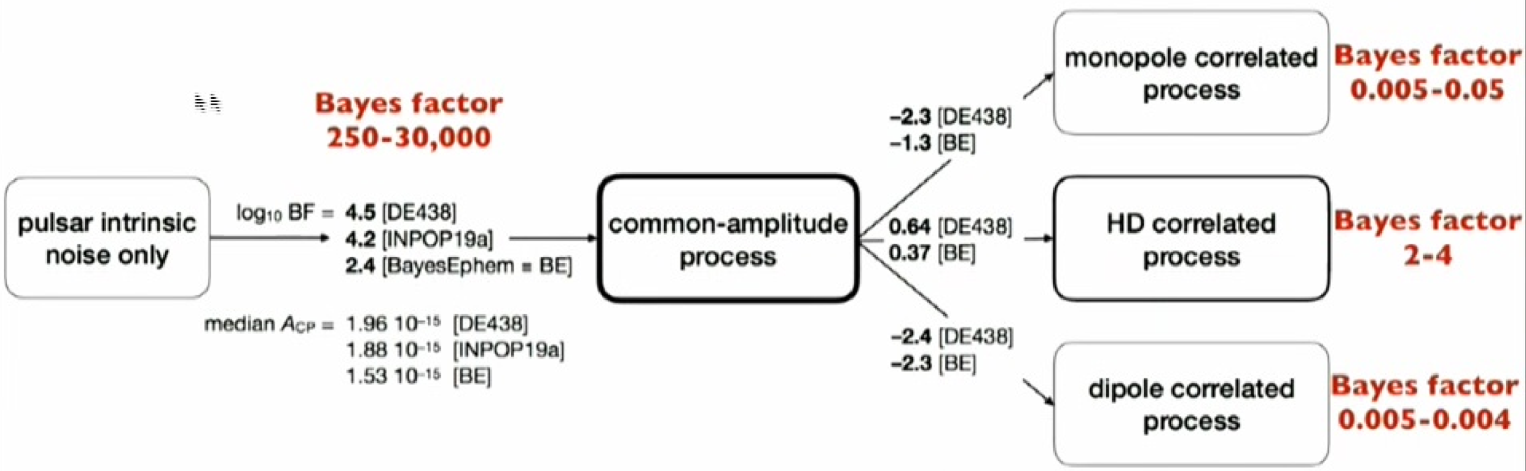
To decide which models are preferred by the data we use the Ba factor, which tells you how much more (or less) likely one model compared to another model.

Is there evidence for a common-amplitude $\gamma = 13/3$ process?

Yes, strong evidence.

Is there evidence for a spatially correlated $\gamma = 13/3$ process?

No strong evidence for HD correlations, moderate evidence against monopole and dipole.



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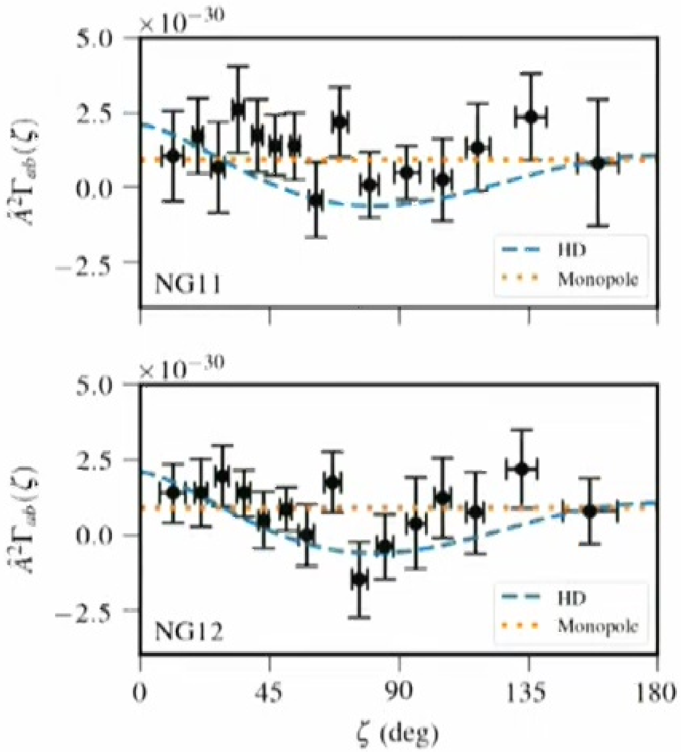
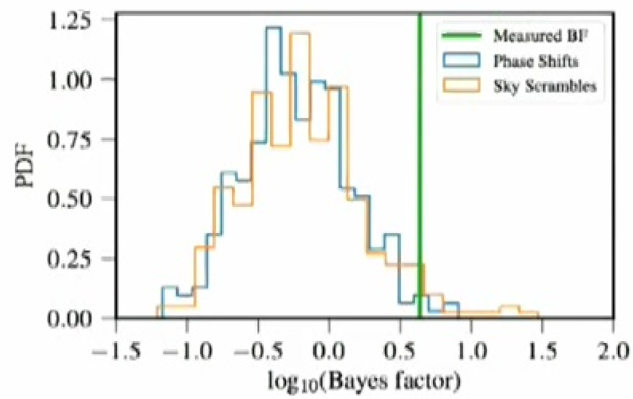


Chances of BF of 2-4 due to noise alone about 10%



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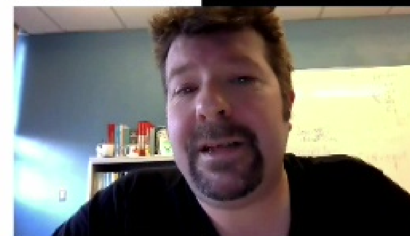

We are seeing a common (same amplitude, spectral index across pulsars) red noise process. We don't yet know what it is.

It has no significant quadrupolar correlations, but disfavors monopolar and dipolar correlations.

Similar results (common red noise) found by our European collaborators (EPTA), our Australian Collaborators (PPTA), and in the latest IPTA dataset!!

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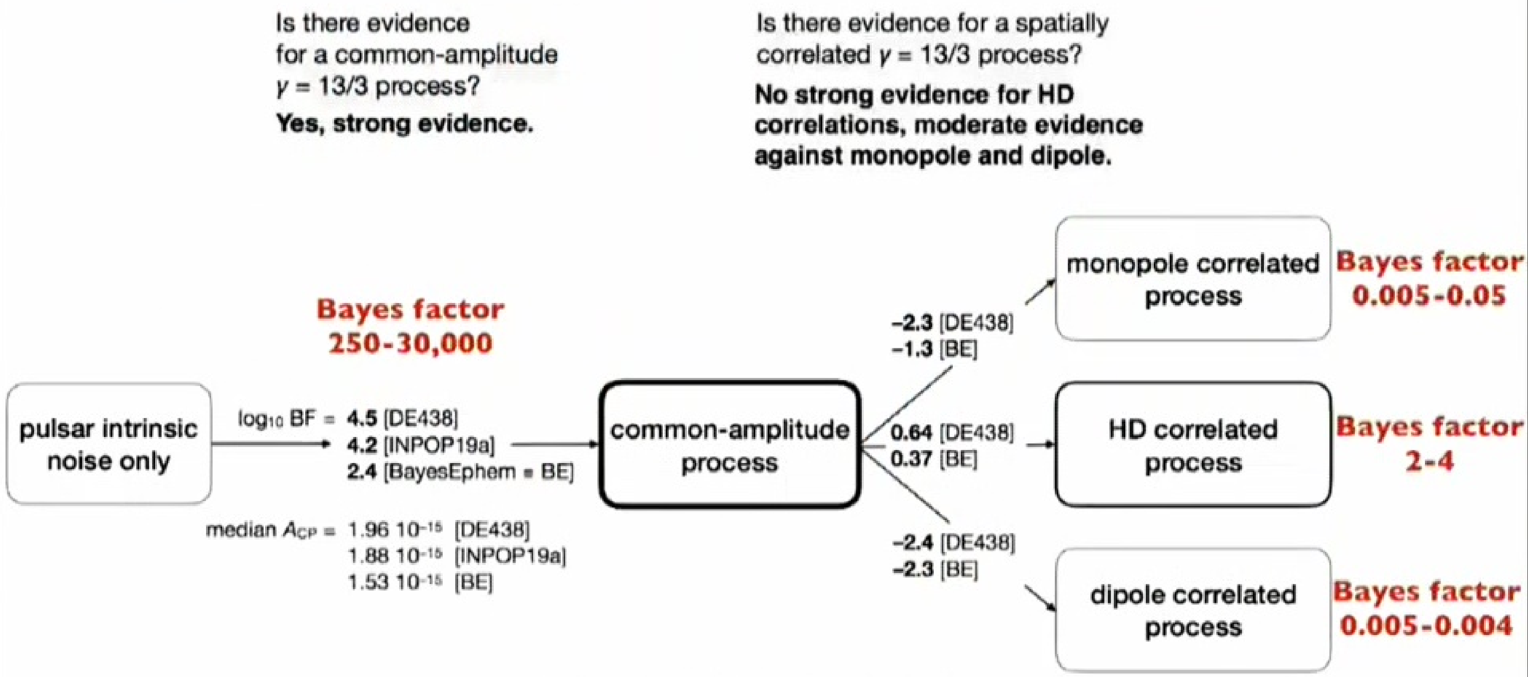

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Stochastic background: 12.5-yr GWB results

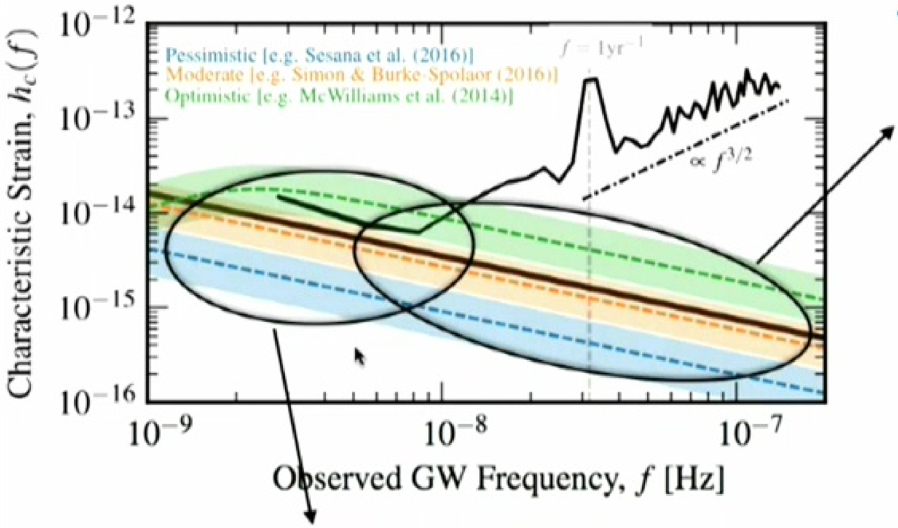
We are analyzing a 15-yr dataset to follow up on this result and are collaborating with our international colleagues, who have their own independent datasets.

Working on a simultaneous publication with EPTA and PPTA with each of our latest datasets.

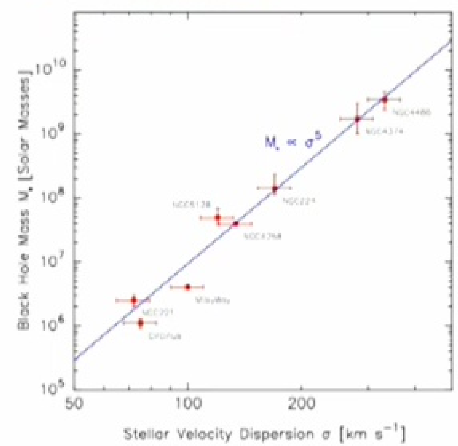
ETA ~ end of 2022.

Stay tuned!!!!

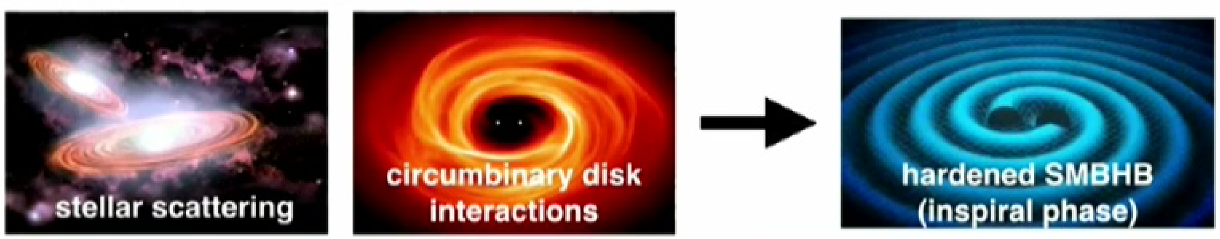
Stochastic backgrounds—astrophysical inference

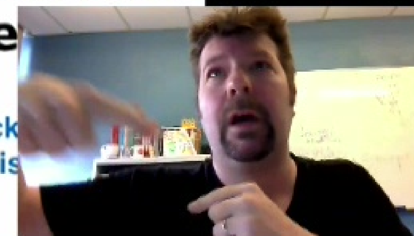


- High frequencies (when black holes are close) dominated by GW emission; spectrum determined by:
  - Galaxy Merger Rates
  - Stalling fraction
  - Black hole-host correlations (i.e., M-sigma, M-M_bulge)



- Low frequency part of spectrum (when black holes are further away) possibly determined by environmental effects (solution to last parsec problem)





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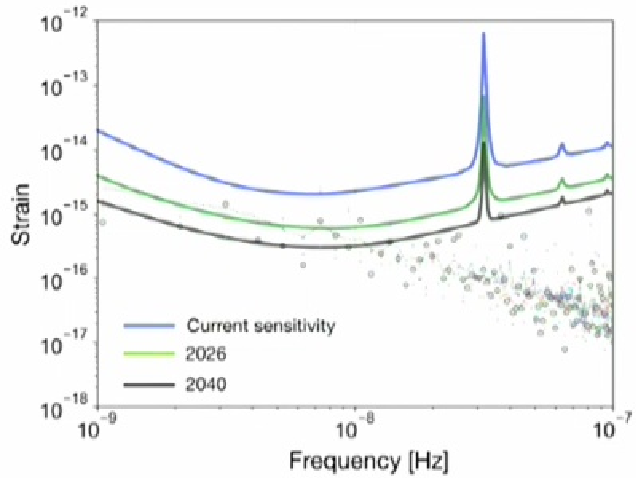
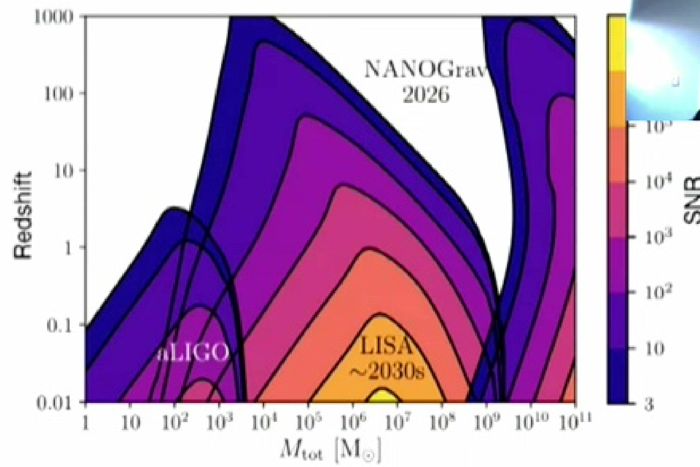
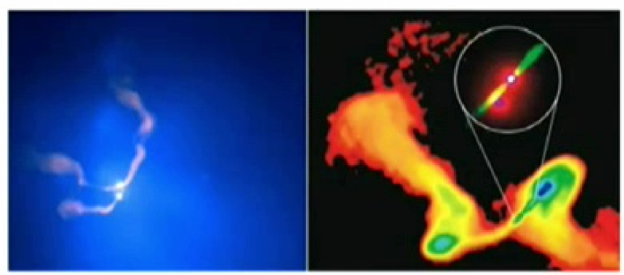
Individual binary black holes





Predictions for individual systems are more uncertain than for the background, but expect to discover our first individual system circa 2025, and a handful of systems by 2030

Exciting multi-messenger astronomy potential



Sensitivity Simulations: Hazboun, Kaiser
Source Simulations: Kelley et al 2017

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Cosmological sources

We expect PTAs to detect GWs from SMBBHs by th first half of this decade. This will be followed by the detection of individual binaries.

What about cosmic strings, inflation, and phase transitions?

How can we distinguish between different sources? How could we detect a stochastic GW signal from other sources with a large foreground from SMBBHs?

These sources are speculative but a positive detection would have profound consequences.

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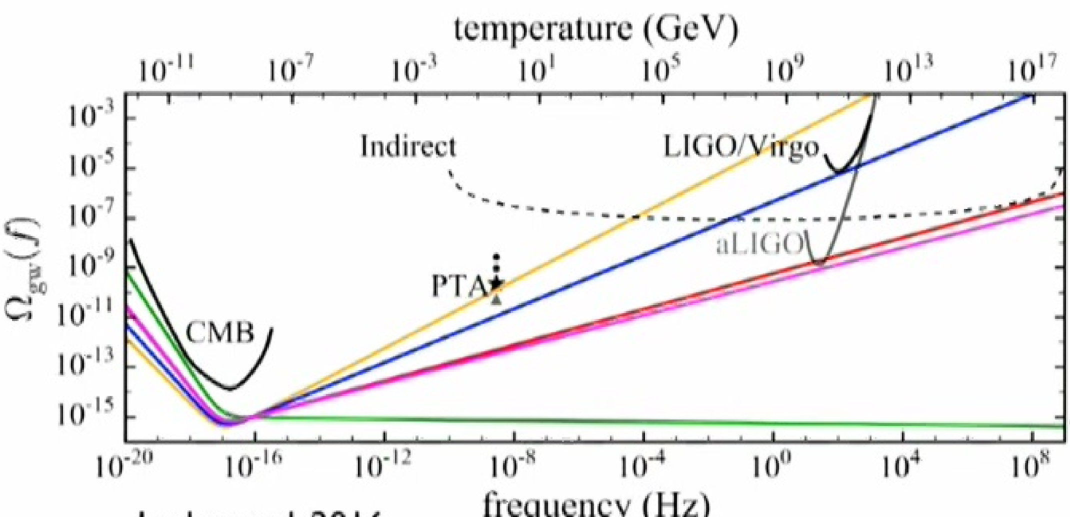
Inflation

Least speculative of the three, part of standard cosmological paradigm

A period of exponential expansion that accounts for the homogeneity, isotropy of the universe. Also seeds density perturbations and produces a background of GWs.



Lasky et al. 2016

Some models have a spectrum that rises at high frequencies.

Standard inflation is (almost) flat at high frequencies, and this will be the model I focus on.

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Inflation

w/. Joe Romano

Power spectrum induced in pulsar timing residuals is

$$P_{\rm gw}(f) = \frac{1}{12\pi^2} h_c^2(f) f^{-3}$$

characteristic strain is

$$h_c^2(f) = \frac{3H_0^2}{2\pi^2}\Omega(f) f^{-2}$$

For (almost) flat standard inflation (very steep red noise process)

$$P_{\rm inf}(f) \approx \frac{1}{8\pi^4} H_0^2 \Omega_0 f^{-5}$$

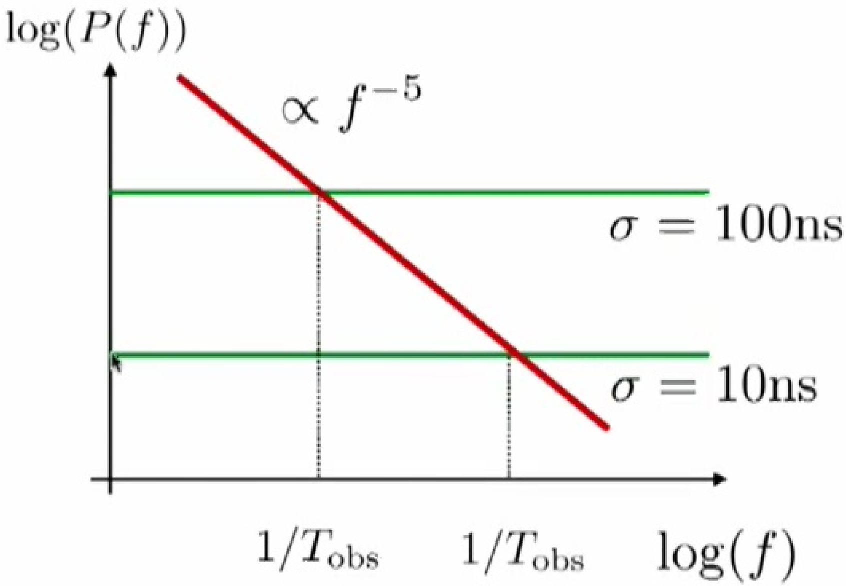
Start with a few basic questions.

Compare inflationary power spectrum with 1) white noise residuals, 2) the SMBBH spectrum

Inflation

Suppose there's no background from SMBBHs, and all we have is white noise in timing residuals.

Q: When does the lowest frequency bin in our data become inflation dominated
A: Surprisingly soon.



$$P_{\text{inf}}(1/T_{\text{obs}}) > 2\sigma^2 \Delta t$$

$$T_{\text{obs}} > \left(\frac{16\pi^4 \sigma^2 \Delta t}{H_0^2 \Omega_0} \right)^{1/5}$$

$$\Omega_0 = 10^{-14}$$

$$\Delta t = 0.05$$

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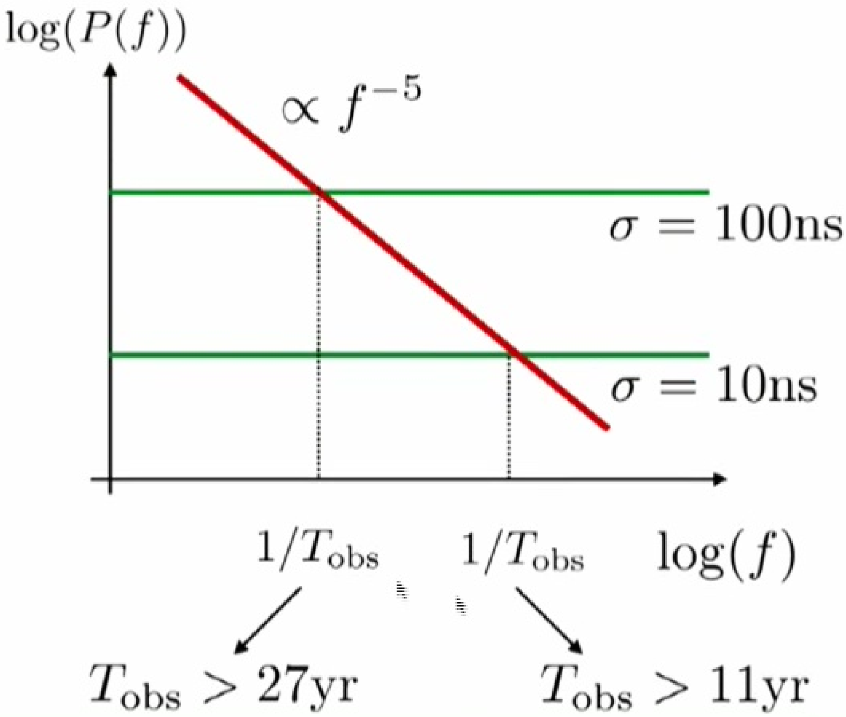

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$$\Omega_0 = 10^{-14}$$

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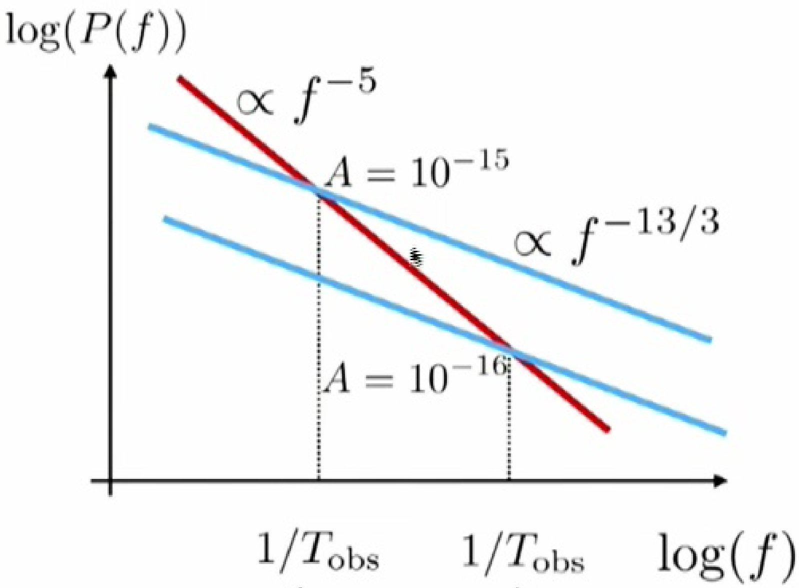
Inflation

Q: If there is a background from SMBBHs (without an environment-induced turnover) when does inflation dominate the lowest frequency bin?
A: Never, in practice



$T_{\rm obs} = 4.4 \times 10^7 {\rm yrs}$ $\quad$ $T_{\rm obs} = 4.4 \times 10^4 {\rm yrs}$

$$h_c(f) = A \left(\frac{f}{f_{\rm yr}} \right)^{-2}$$

$$P_{\rm bhgw}(f) = \frac{A^2}{12\pi^2} f_{\rm yr}^{4/3} f^{-13/3}$$

$$P_{\rm inf}(1/T_{\rm obs}) > P_{\rm bhgw}(1/T_{\rm obs})$$

$$T_{\rm obs} > \left(\frac{2}{3} \frac{\pi^2 A^2}{H_0^2 \Omega_0} f_{\rm yr}^{4/3} \right)^{3/2}$$

$$\Omega_0 = 10^{-14}$$

Inflation

Q: If there is a background from SMBBHs with an environment-induced turnover can inflation dominate the lowest frequency bin?
A: Probably not!

$$\Omega_0 = 10^{-14}$$

$$f_{\rm bend} = 1{\rm yr}^{-1}$$

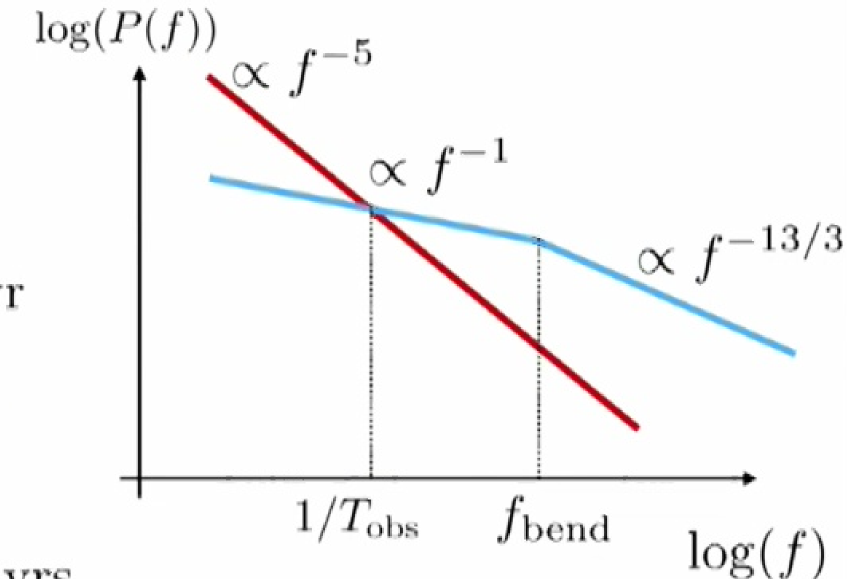
$$A = 10^{-15} \quad T_{\rm obs} > 19{\rm yr}$$

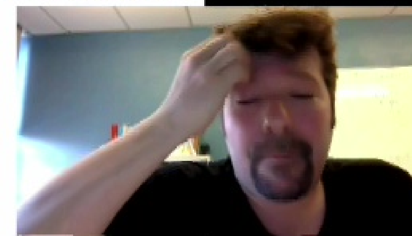
$$A = 10^{-16} \quad T_{\rm obs} > 6{\rm yr}$$

$$f_{\rm bend} = 0.1{\rm yr}^{-1}$$

$$A = 10^{-15} \quad T_{\rm obs} > 128\,{\rm yrs}$$

$$A = 10^{-16} \quad T_{\rm obs} > 40\,{\rm yrs}$$





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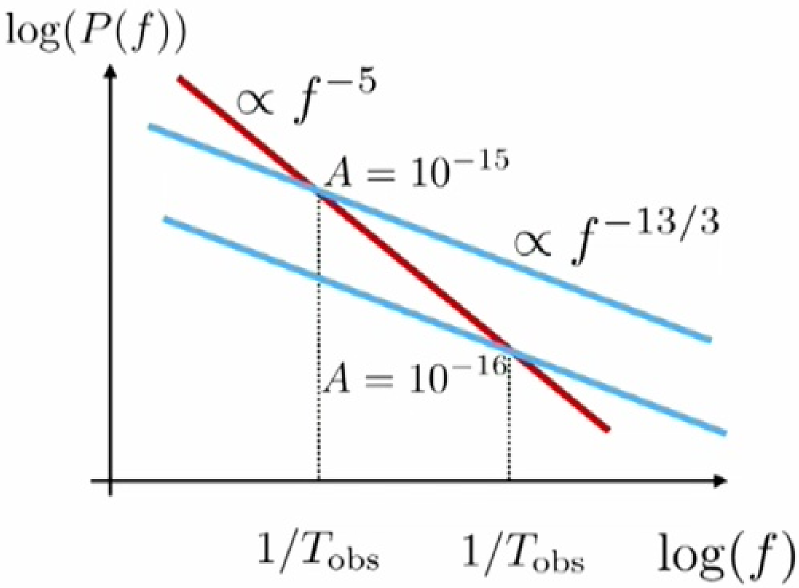

$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{-2}$$

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$$P_{\rm inf}(1/T_{\rm obs}) > P_{\rm bhgw}(1/T_{\rm obs})$$

$$T_{\rm obs} > \left(\frac{2}{3}\frac{\pi^2 A^2}{H_0^2\Omega_0} f_{\rm yr}^{4/3}\right)^{3/2}$$

$$\Omega_0 = 10^{-14}$$

Inflation

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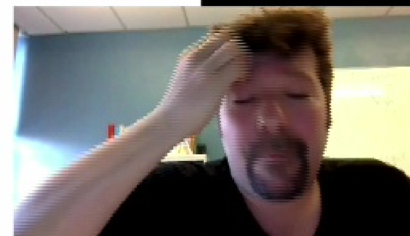

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$$f_{\rm bend} = 1{\rm yr}^{-1}$$

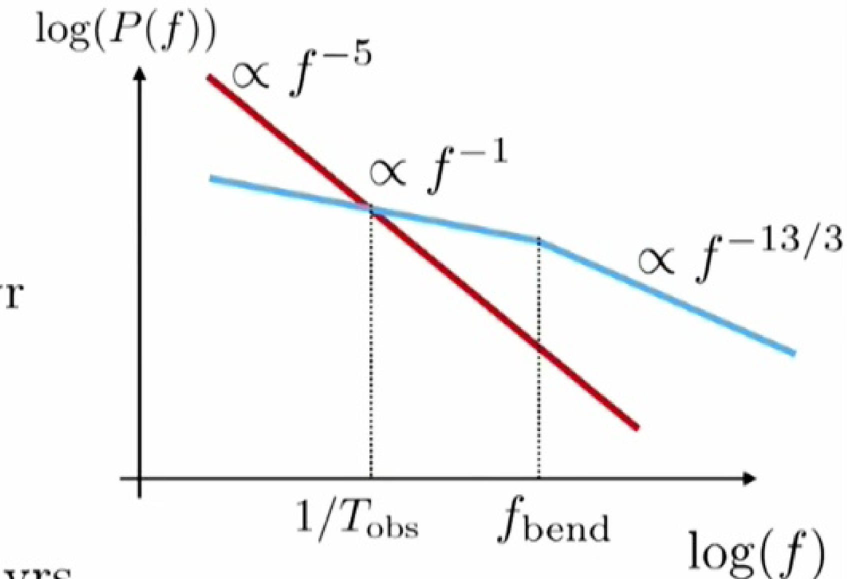
$$A = 10^{-15} \quad T_{\rm obs} > 19{\rm yr}$$

$$A = 10^{-16} \quad T_{\rm obs} > 6{\rm yr}$$

$$f_{\rm bend} = 0.1{\rm yr}^{-1}$$

$$A = 10^{-15} \quad T_{\rm obs} > 128\,{\rm yrs}$$

$$A = 10^{-16} \quad T_{\rm obs} > 40\,{\rm yrs}$$



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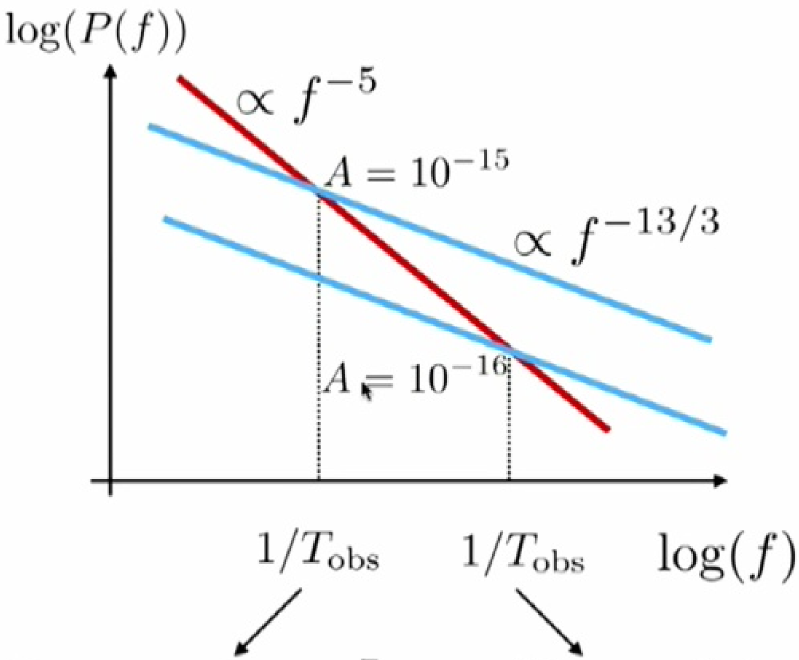

$T_{\rm obs} = 4.4 \times 10^7 {\rm yrs}$ $\quad$ $T_{\rm obs} = 4.4 \times 10^4 {\rm yrs}$

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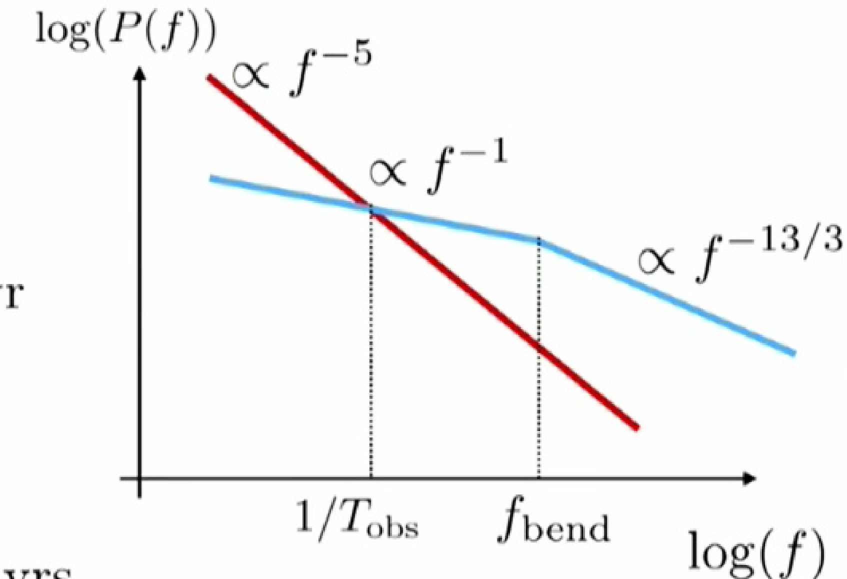


Cosmic strings

Cosmic strings can form in phase transitions in the early universe. Cosr
superstrings are fundamental strings stretched to macroscopic scales by
expansion of the universe.

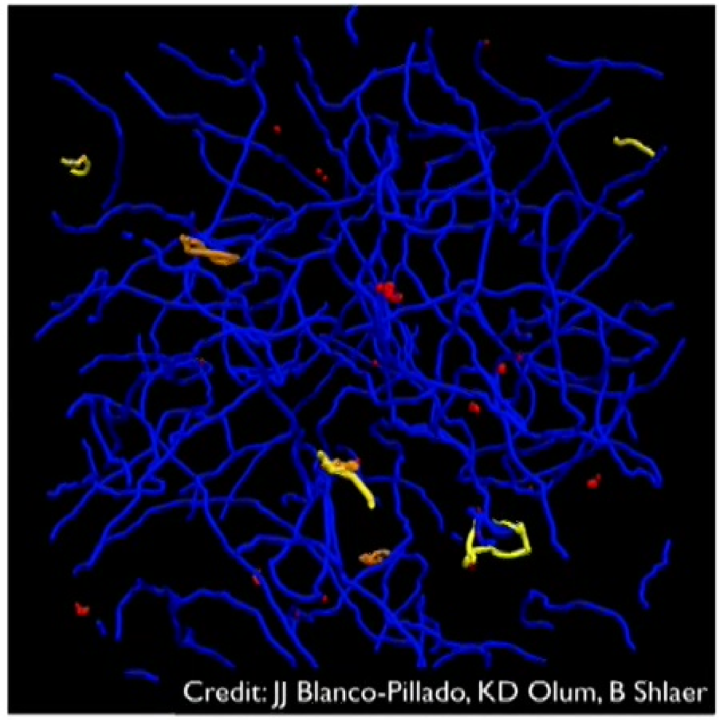
Characterized by mass per unit length μ

Usually expressed with the dimensionless $G\mu$

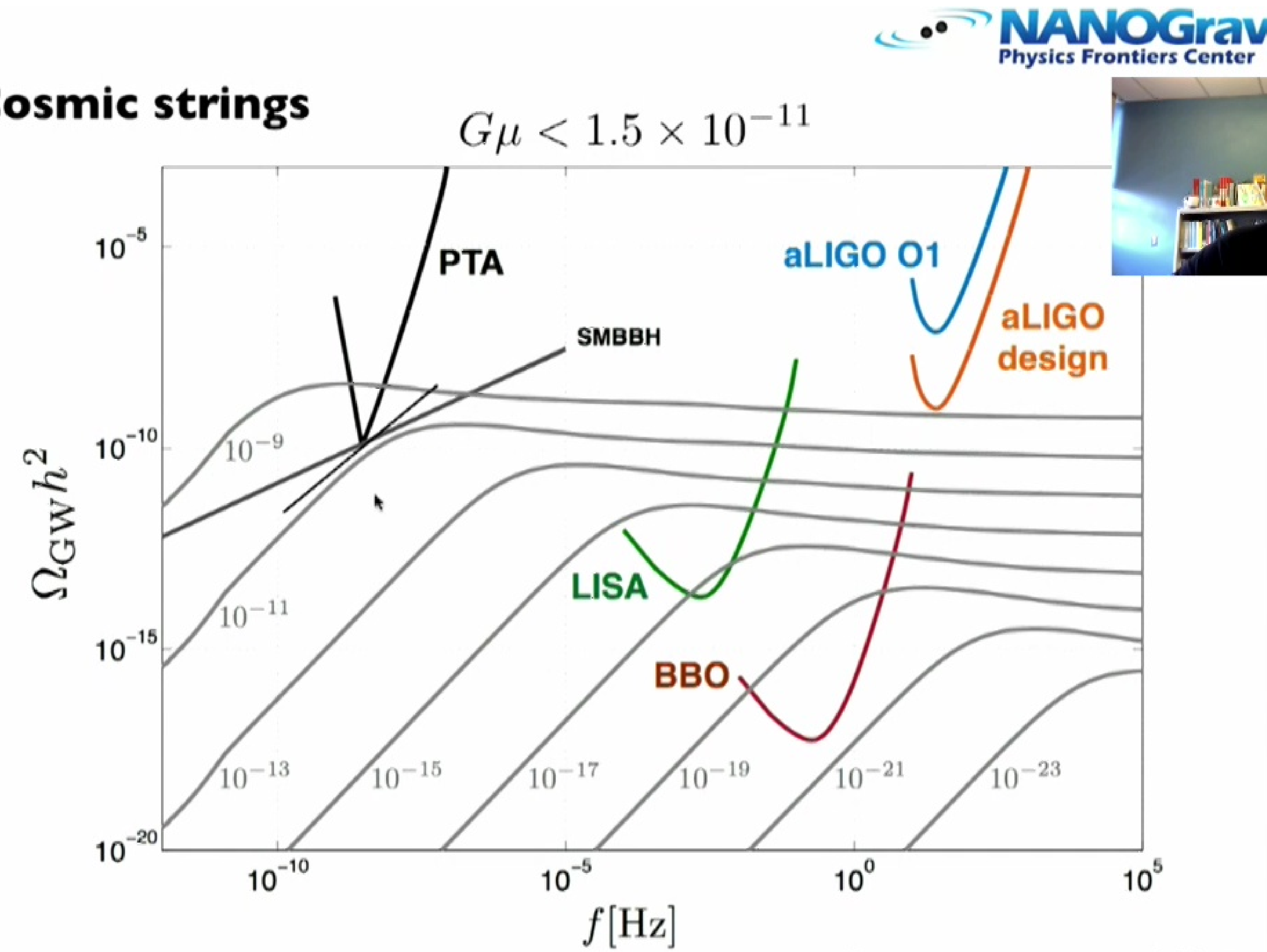
GUT strings $G\mu \sim 10^{-6}$

PTAs are the most sensitive experiment to cosmic strings/ give best constraints

$$G\mu < 1.5 \times 10^{-11}$$

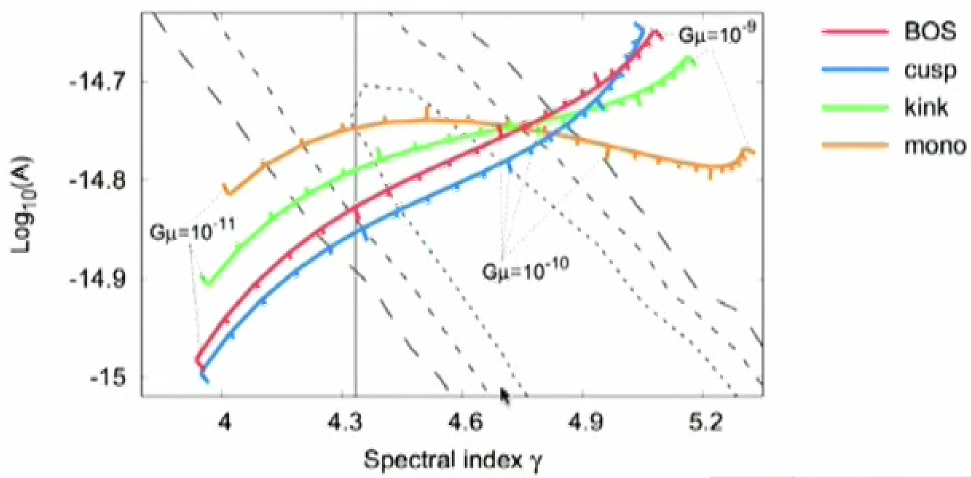


Cosmic strings



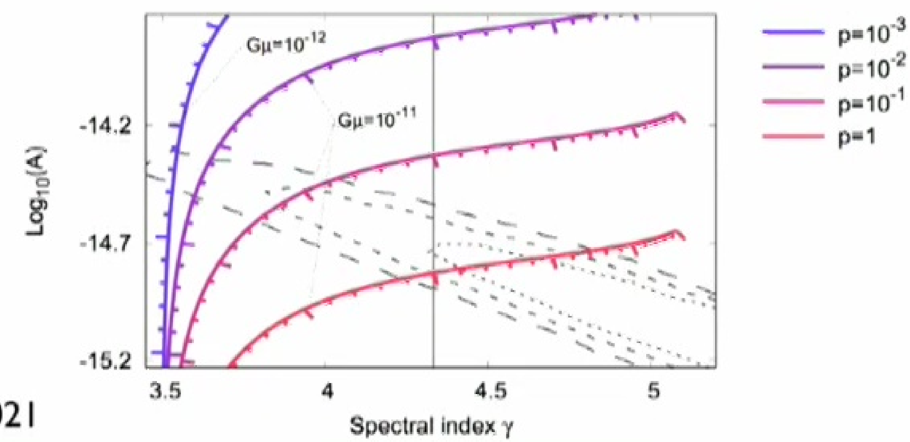
Olum, Blanco-Pillado, XS 2017

Cosmic strings & the NANOGrav 12.5-yr dataset



Similar predictio
different emission
models

Reconnection probability $p \leq 1$ for cosmic superstrings



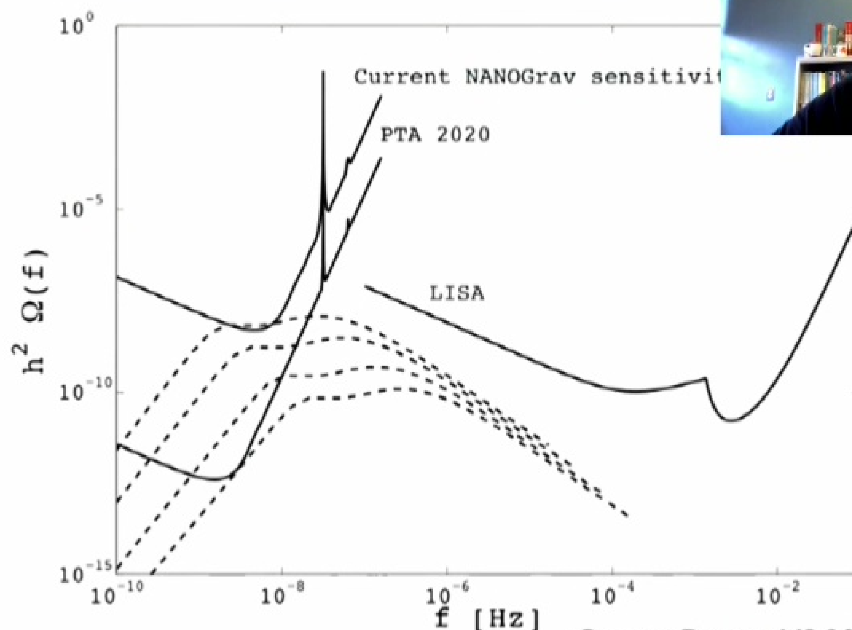
Blanco-Pillado, Olum, and Wachter 2021

NANOGrav Physics Frontiers Center

Phase transitions

Horizon at QCD phase transition time (10 km), stretches to about 1pc or 3 ly today. This is ~ wavelength of PTA GW sensitivity (Witten in the 80s).

Any interesting physics that leads to GW generation, e.g. a 1st order phase transition, will result in a signal potentially detectable by PTAs.



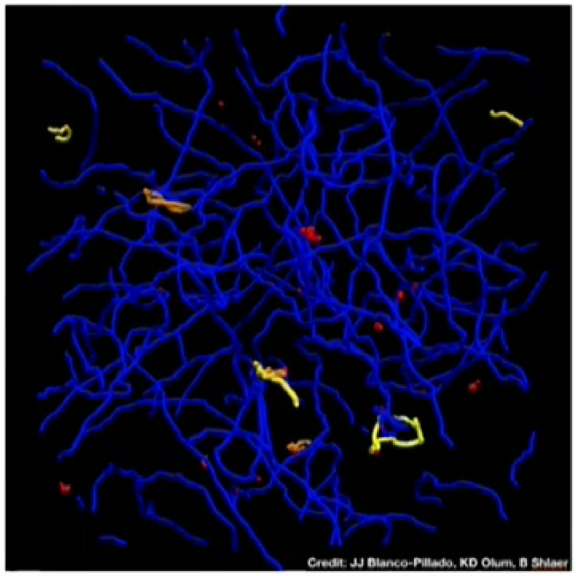
Caprini, Durrer, XS 2011

AFAWK the QCD phase transition is only a cross-over. But if the neutrino chemical potential is sufficiently large it can become first order (and if sterile neutrinos form the dark matter, we expect a large neutrino chemical potential).

Recent paper: Nenorov et al. 2009.14174

Cosmological sources summary

Expect a detection of the stochastic background from SMBHBs in the ne
few years.



Cosmic strings: a big chunk of parameter space already ruled out, when a detection is first made it may be difficult to distinguish between SMBHBs and cosmic strings.

However, distinguishing the two is not just about the spectral index (e.g. anisotropy, spectral features), and LISA will settle any lingering doubts. But let's try to figure this out before 2034…

Phase transitions: interesting physics at the QCD scale could lead to detectable GWs in the PTA band. Potentially the same problem as cosmic strings: hard to distinguish between a QCD first order phase transition and SMBBHs (and cosmic strings!).

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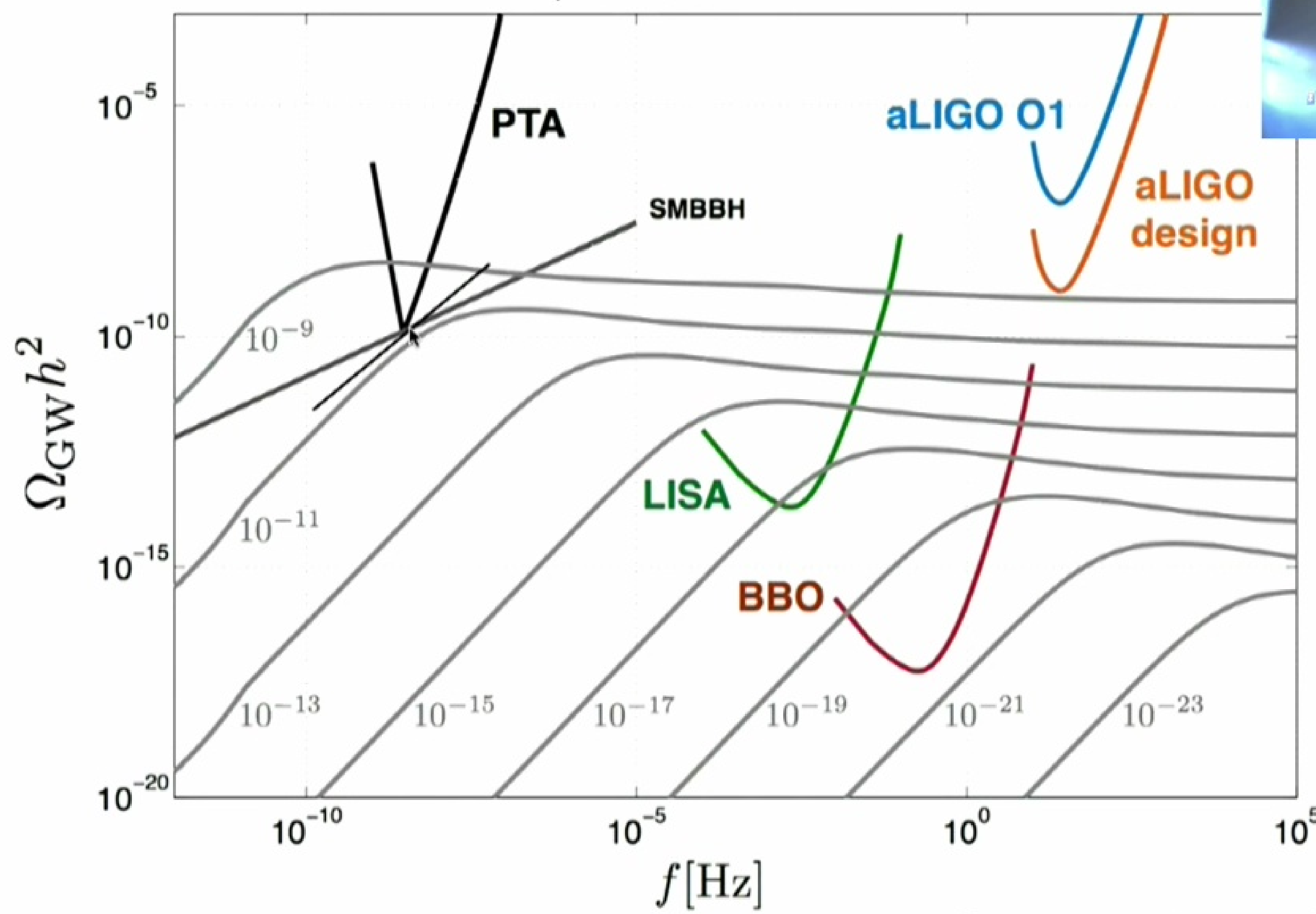
Cosmic strings

$G\mu < 1.5 \times 10^{-11}$



Olum, Blanco-Pillado, XS 2017

NANOGrav Physics Frontiers Center

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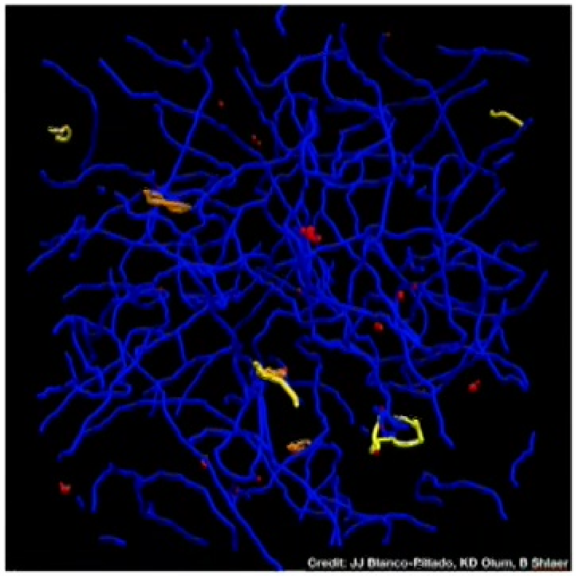

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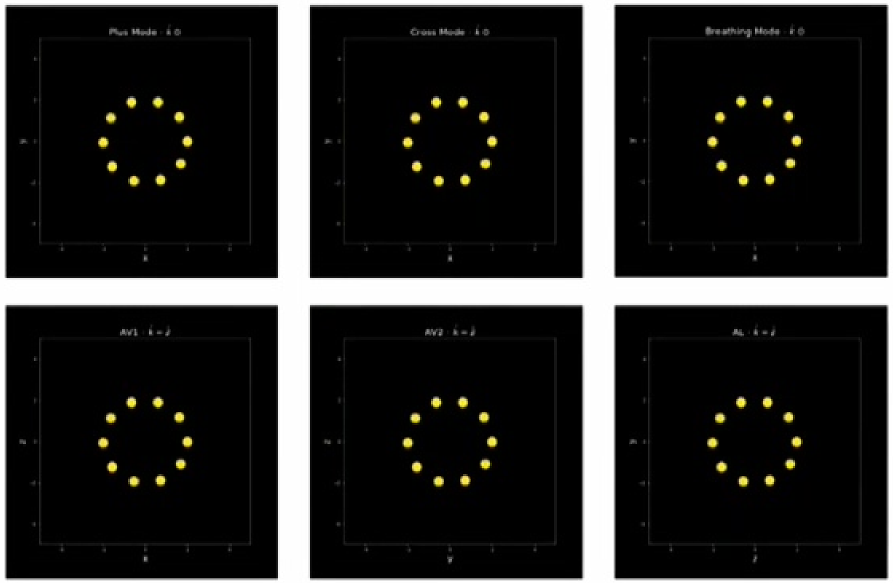
Alternative theories of gravity

GR has two polarizations (+ and x) and GWs travel at the speed of light; gen metric theories of gravity have up to 6 polarizations, and possibly modified dispersion relations. Evidence for any of these rules out GR.



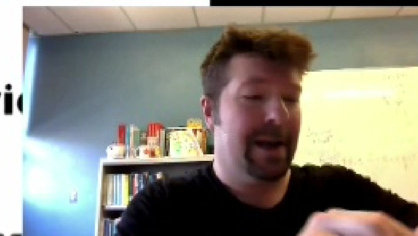
credit: Nima Laal
(https://arxiv.org/abs/2109.14706)

PTAs present some advantages relative to ground-based detectors: PTAs are significantly more sensitive to longitudinal modes than ground based detectors. We have many pulsars (currently timing 72 in NANOGrav) so can reconstruct all 6 polarizations many times over.

NANOGrav Physics Frontiers Center

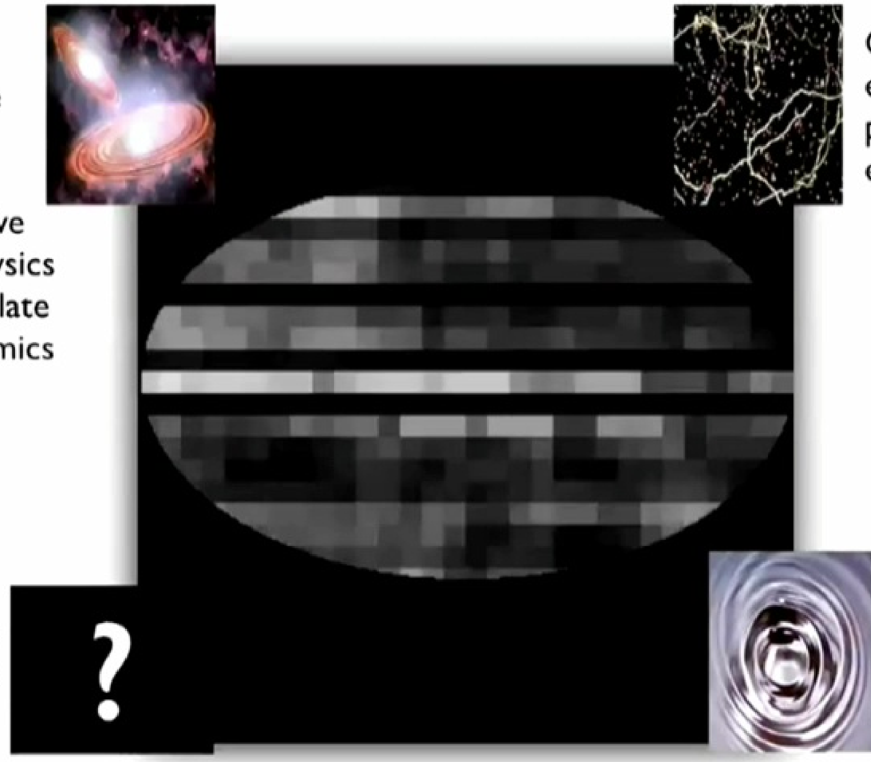
Summary

As the low-frequency GW sky comes into focus, it will offer a **novel vi[...]** of **unique and groundbreaking astrophysics**.



Individual supermassive black hole inspirals and their collective "chorus": physics of accretion, late inspiral dynamics

Cosmic strings: early universe physics/high energy physics



New physics: expect to be surprised

Black hole merger "memory": a surprising prediction of strong field general relativity.