Title: Detecting gravitational waves from supermassive binary black holes with pulsar timing

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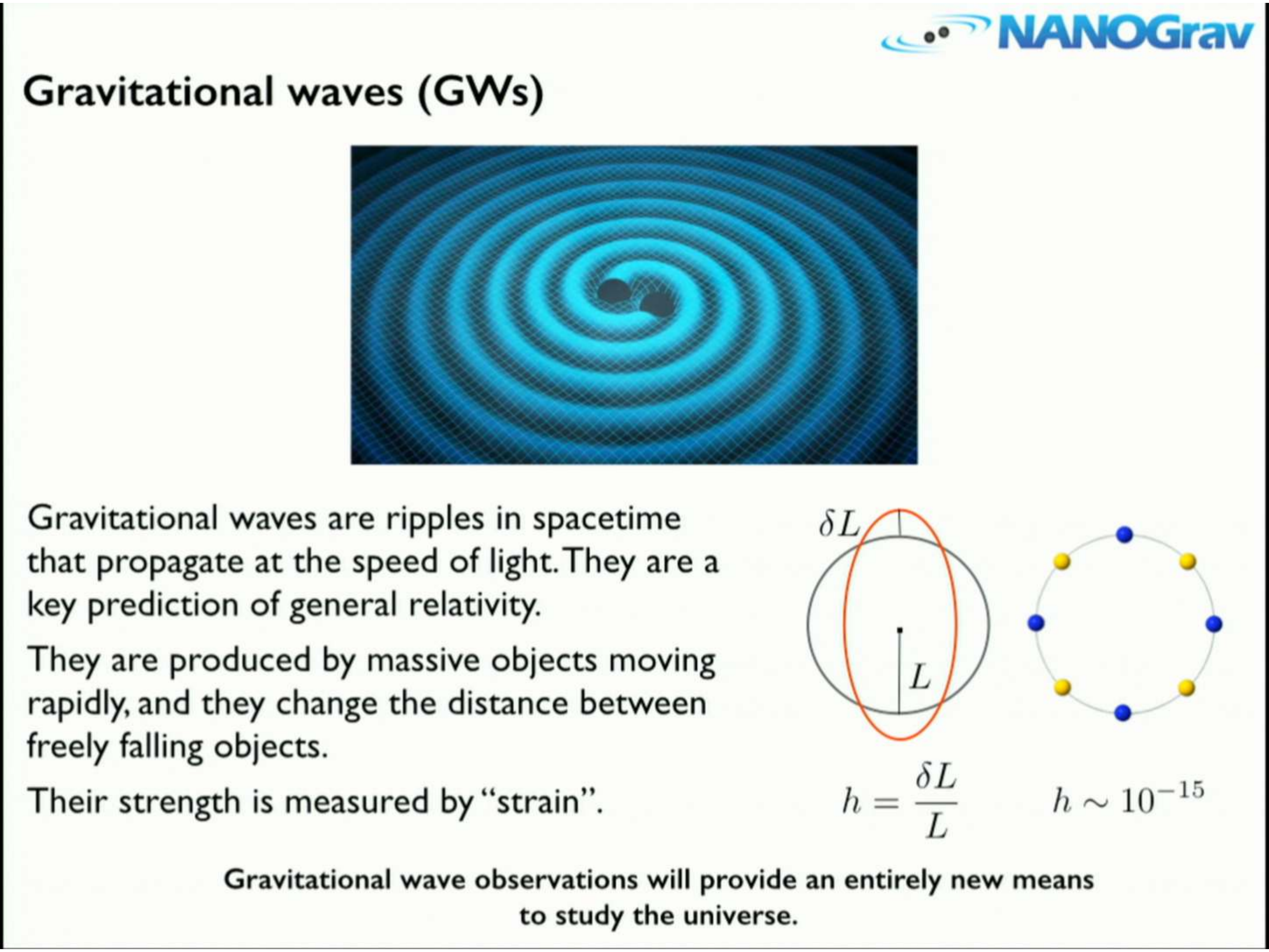
Abstract: I will discuss the current status of the NANOGrav pulsar timing array, and the prospects for a detection of the stochastic background produced by the mergers of supermassive black holes.

NANOGrav

The North American Nanohertz Observatory for Gravitational Waves: about 50 students and scientists in the US and Canada working to characterize the gravitational wave universe at low frequencies using pulsar timing. Part of a world-wide effort including European and Australian partners.



Gravitational waves (GWs)

Gravitational waves are ripples in spacetime that propagate at the speed of light. They are a key prediction of general relativity.

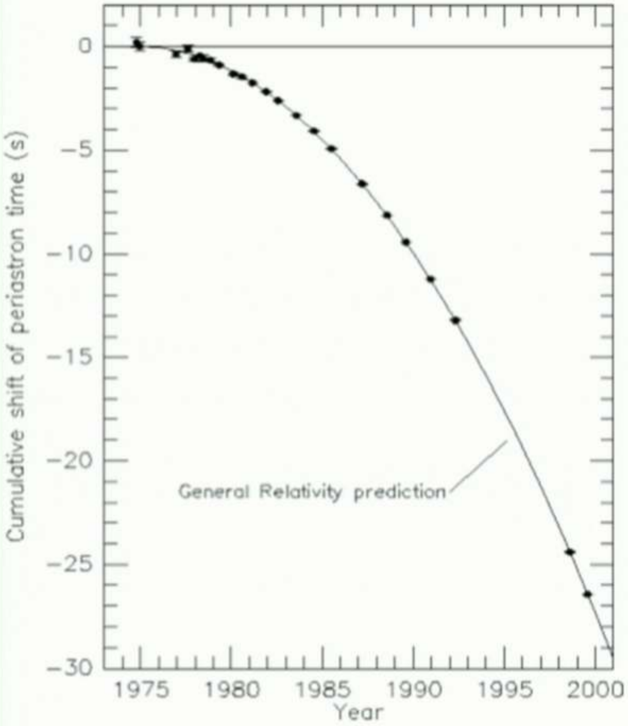
They are produced by massive objects moving rapidly, and they change the distance between freely falling objects.

Their strength is measured by "strain".

$$h = \frac{\delta L}{L} \qquad h \sim 10^{-15}$$

Gravitational wave observations will provide an entirely new means to study the universe.

Evidence for GWs

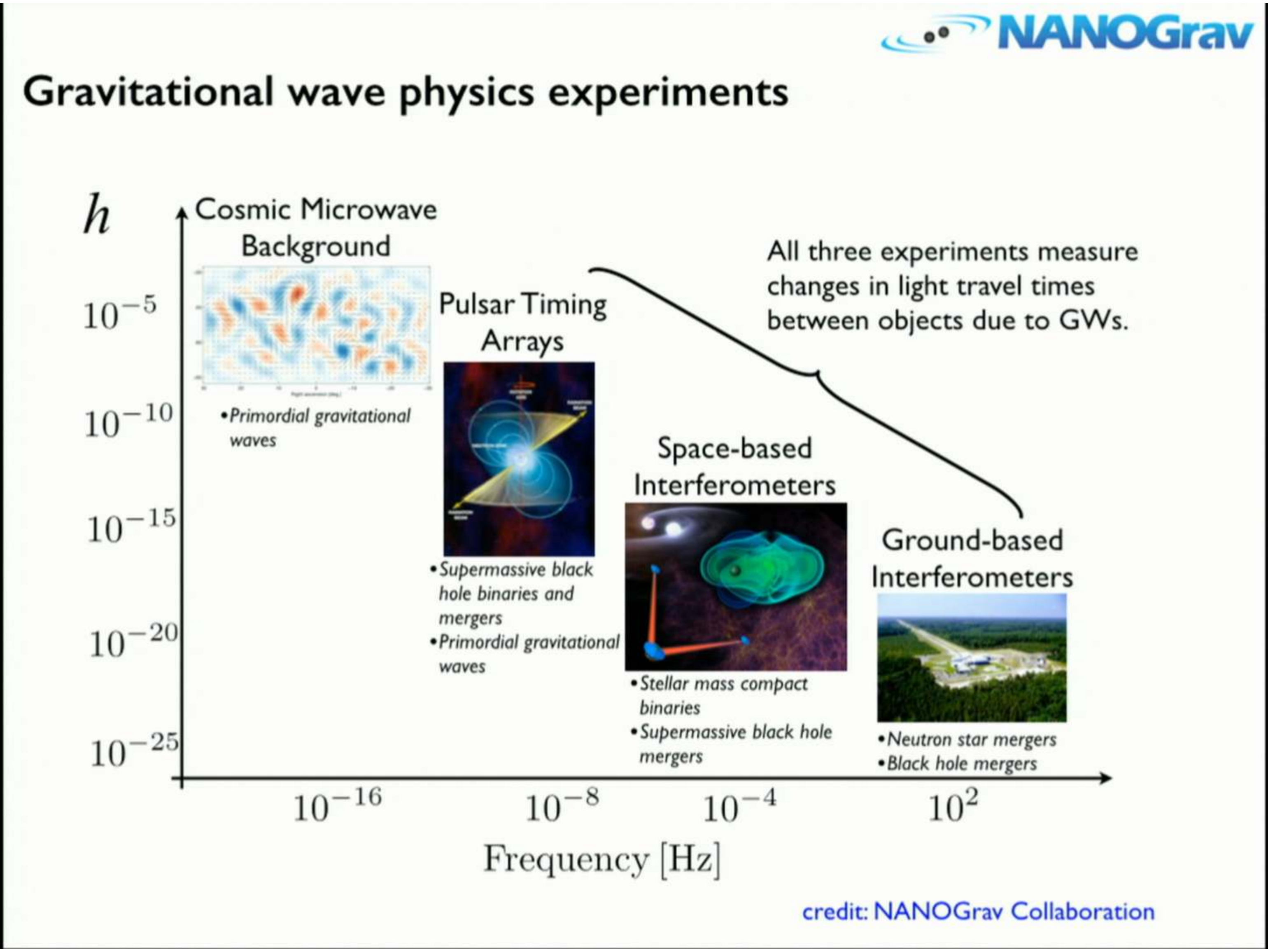



Credit: Jillian Bornak

- Hulse and Taylor observed a rotating neutron star in a binary for 25 years

- Found orbit decay consistent with gravitational wave emission (Nobel prize 1993)

Now we're trying to detect GWs directly and build a telescope



Gravitational wave physics experiments

Cosmic Microwave Background

- *Primordial gravitational waves*

Pulsar Timing Arrays

- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

Space-based Interferometers

- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

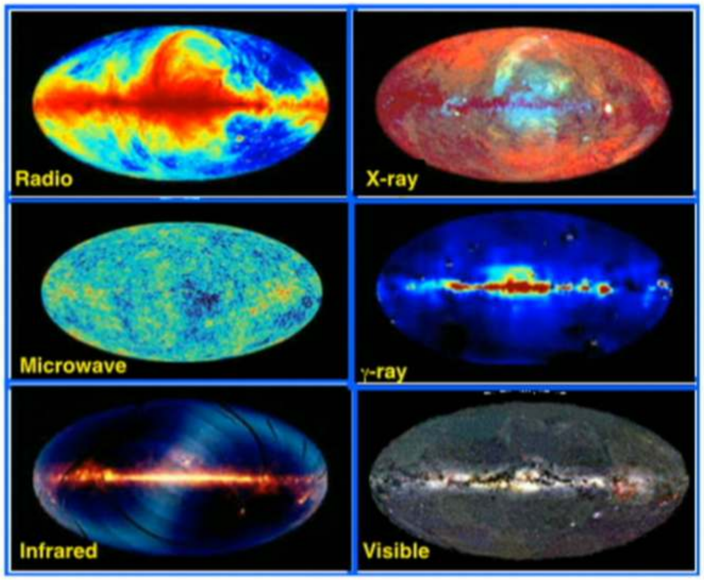
Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

All three experiments measure changes in light travel times between objects due to GWs.

credit: NANOGrav Collaboration

Analogy with electromagnetic observations



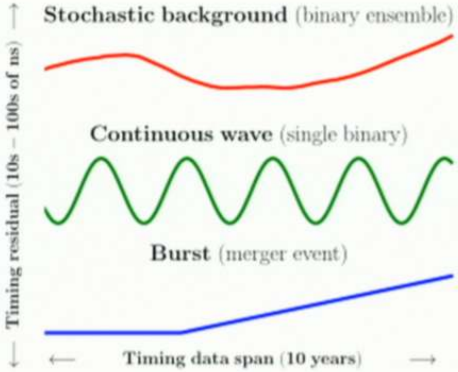
Observations in different parts of the EM spectrum have provided us with invaluable complementary insights and knowledge about our universe.

When a new part of phase space is revealed there are always new discoveries.

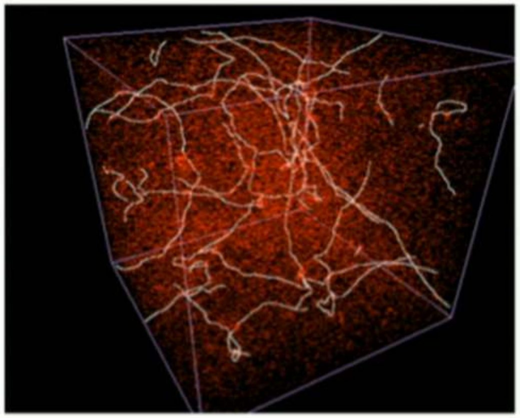
Our goal is to inaugurate the era of low-frequency GWs.

Gravitational wave sources

The most promising sources are supermassive binary black holes (SMBBHs):



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

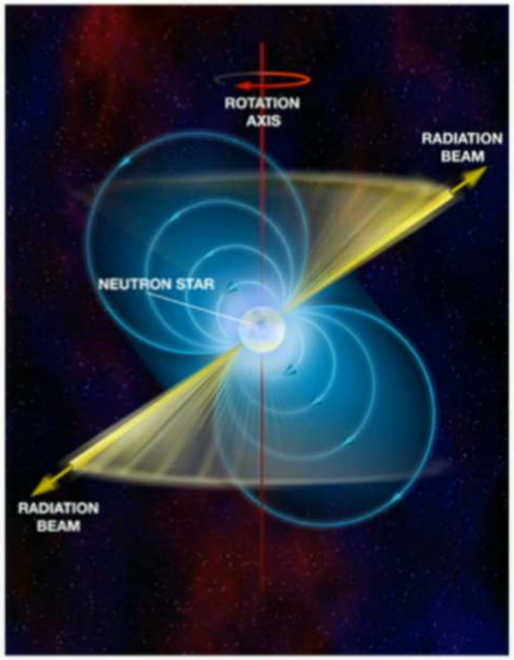


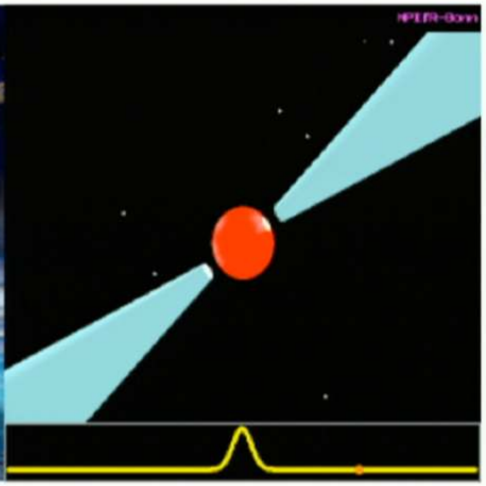
Pulsars

Pulsars are a type of neutron star which have strong magnetic fields, spin rapidly, and emit beams of radio waves along their magnetic axes.

Masses of about a solar mass, radii of about 10km.

Nuclear density—aside from black holes the most extreme objects in the universe.





Rotate with periods of milliseconds to seconds

Celestial lighthouses/clocks

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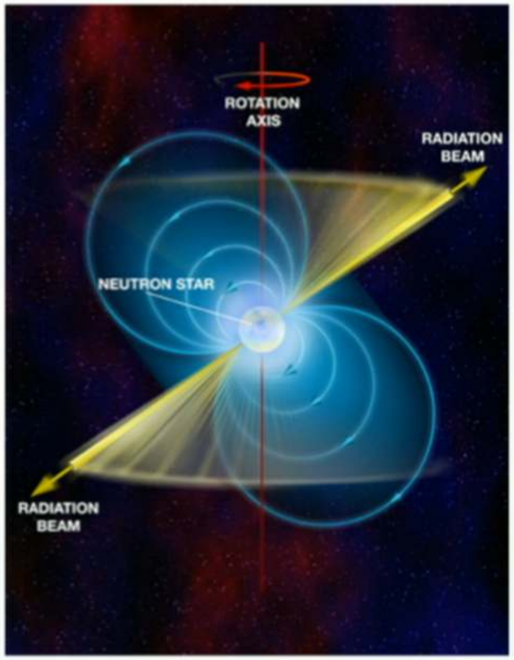

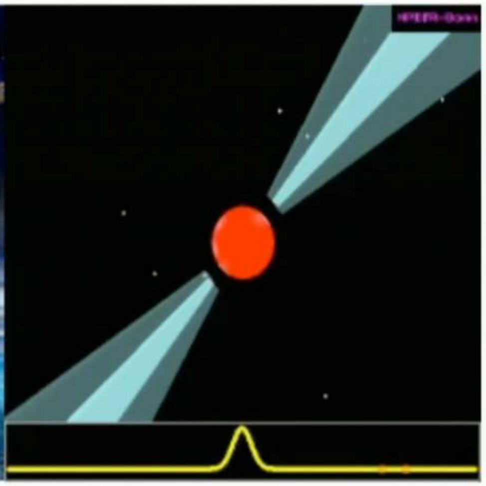

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Celestial lighthouses/clocks

Pulsar timing

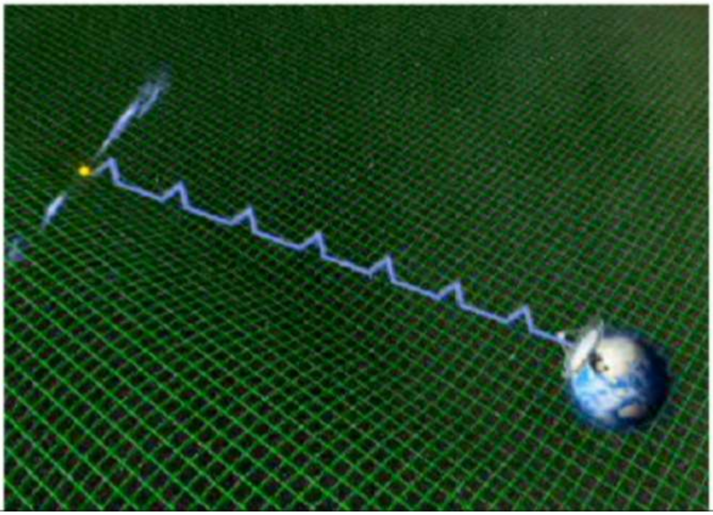
Millisecond pulsars (MSPs) have periods < 20 ms and rotate rapidly with a long term stability that rivals atomic clocks. Millisecond pulsars are Nature's celestial clocks:

E.g.: Rotational period of PSR J1713+0747 on Tuesday Oct 28 2014 10:00 EDT:

0.0045701365287363 +/- 0.0000000000000001 s

at midnight Nov 30 2019 it will be 0.0045701365300853 +/- 0.0000000000000001 s

GWs perturb the times of arrival of pulses at levels that will be measurable.



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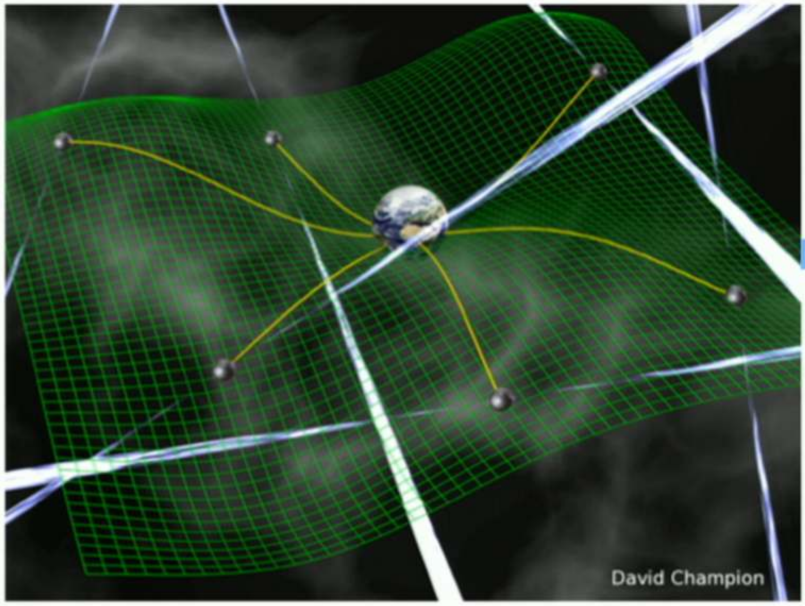
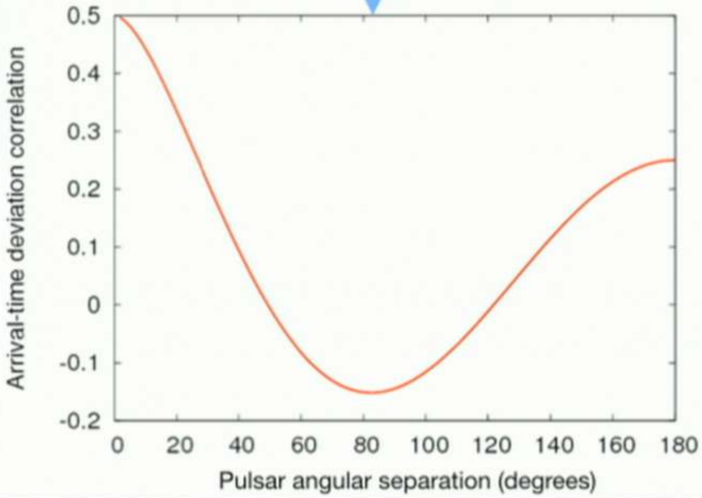
A galactic-scale GW detector: the Pulsar Timing Array


David Champion

GW perturbations are correlated among different pulsars.



Need to observe an ensemble of MSPs to extract the correlated signal from the noise.

The Green Bank Telescope and Arecibo Observatory

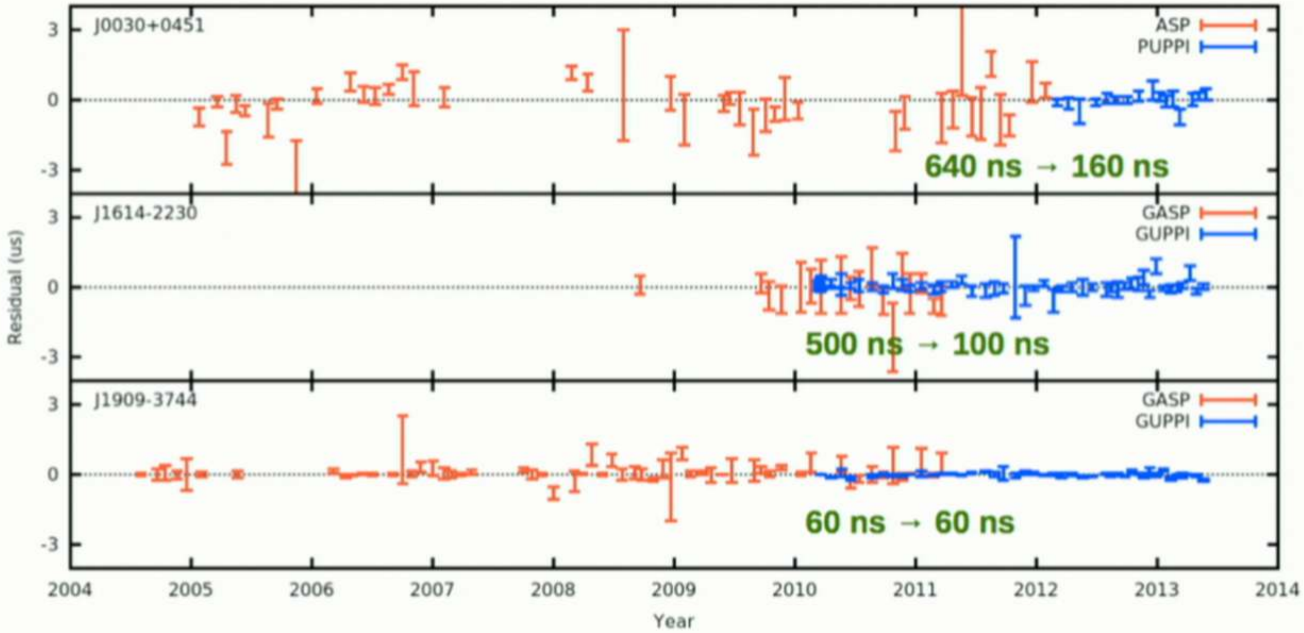
Our measurements are made with the two most sensitive radio telescopes in the world:

Arecibo Observatory (AO), PR
World's largest
radio telescope

Green Bank Telescope (GBT), WV
World's largest steerable
radio telescope

Soon CHIME will contribute to our data sets at low frequencies

NANOGrav Observing Status



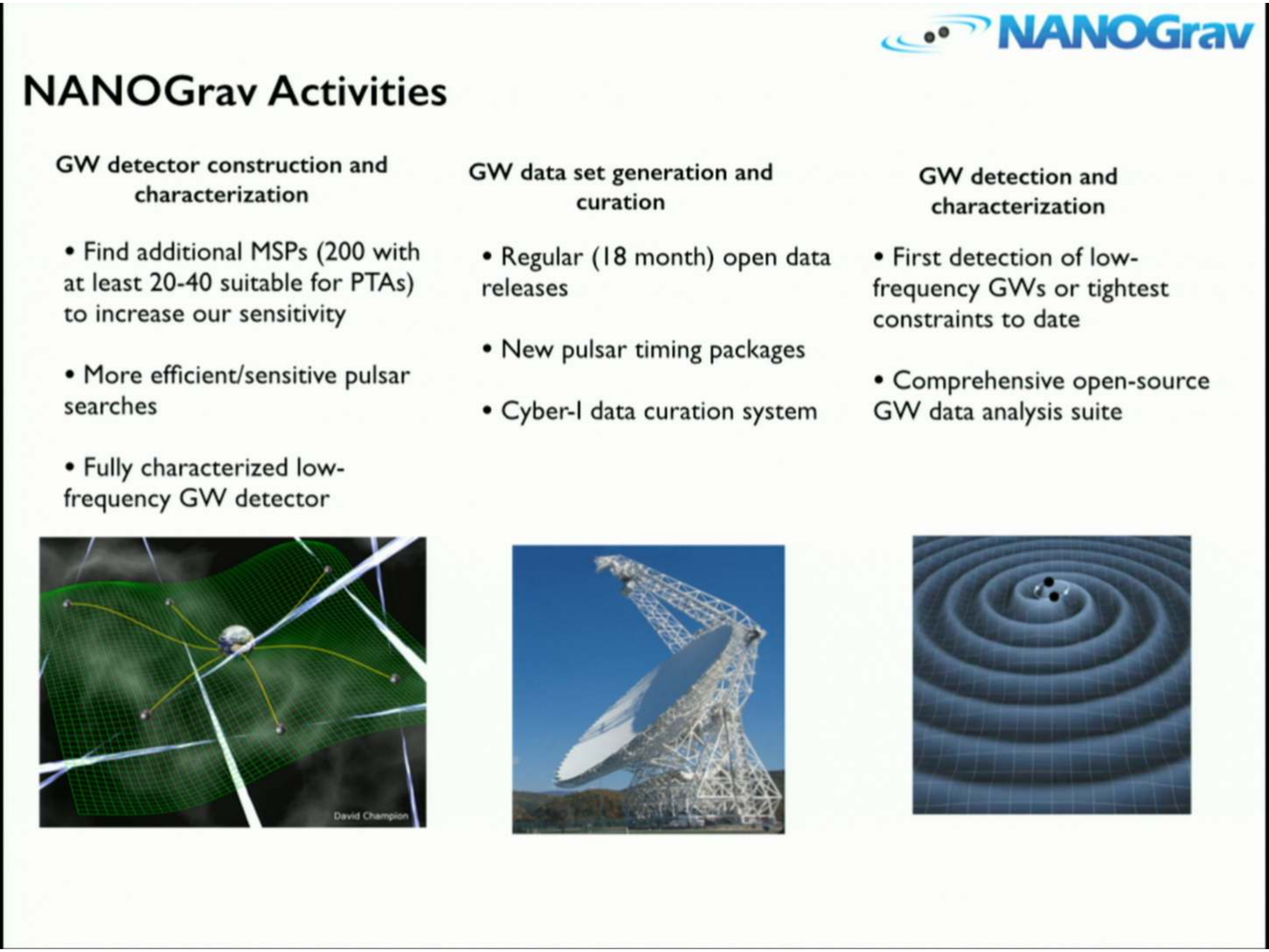
640 ns → 160 ns

500 ns → 100 ns

60 ns → 60 ns

We observe 42 pulsars at the GBT and Arecibo, roughly every three weeks, at two radio frequencies.

We search for GWs in “timing residuals”, calculated over long time spans.



NANOGrav Activities

GW detector construction and characterization

- Find additional MSPs (200 with at least 20-40 suitable for PTAs) to increase our sensitivity
- More efficient/sensitive pulsar searches
- Fully characterized low-frequency GW detector

GW data set generation and curation

- Regular (18 month) open data releases
- New pulsar timing packages
- Cyber-I data curation system

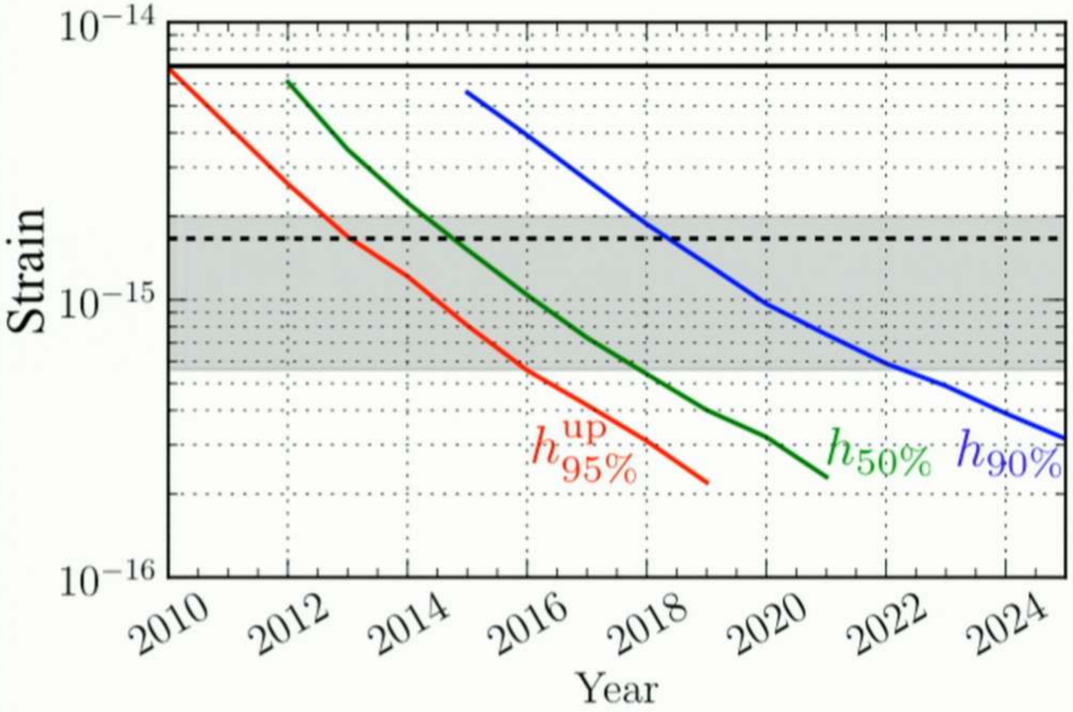
GW detection and characterization

- First detection of low-frequency GWs or tightest constraints to date
- Comprehensive open-source GW data analysis suite

NANOGrav

Our goals

Making a detection of the stochastic background produced by SMBBHs, inaugurating the era of low-frequency GWs.



credit: NANOGrav Collaboration

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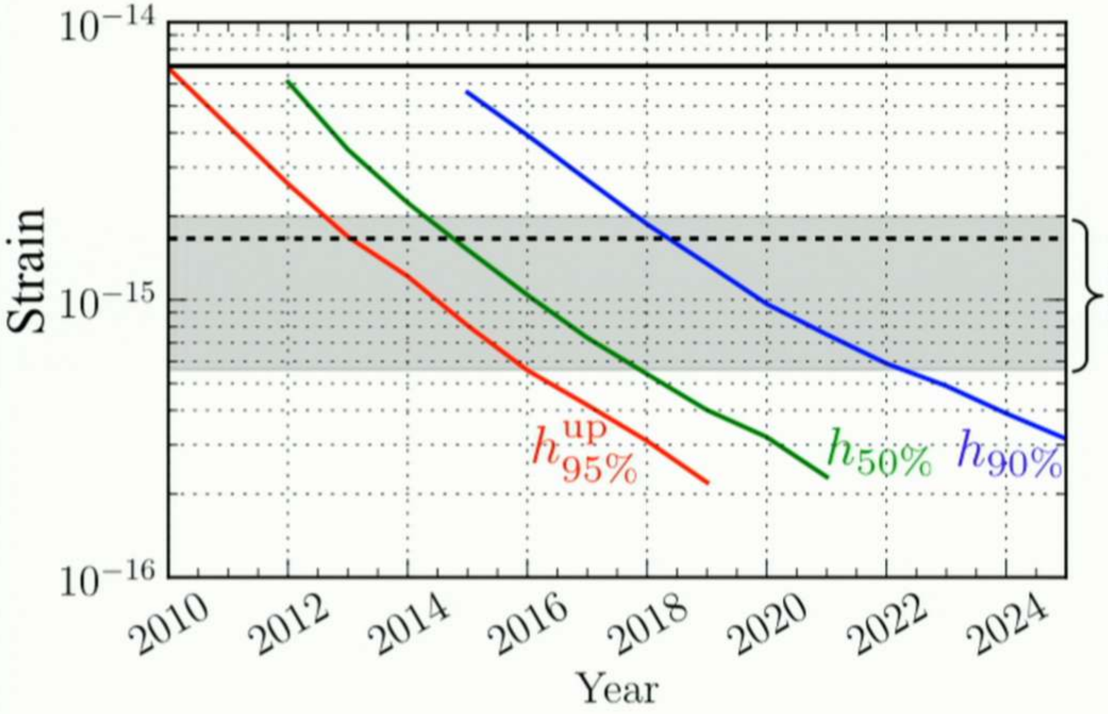

Expected amplitude range for SMBBH background

credit: NANOGrav Collaboration

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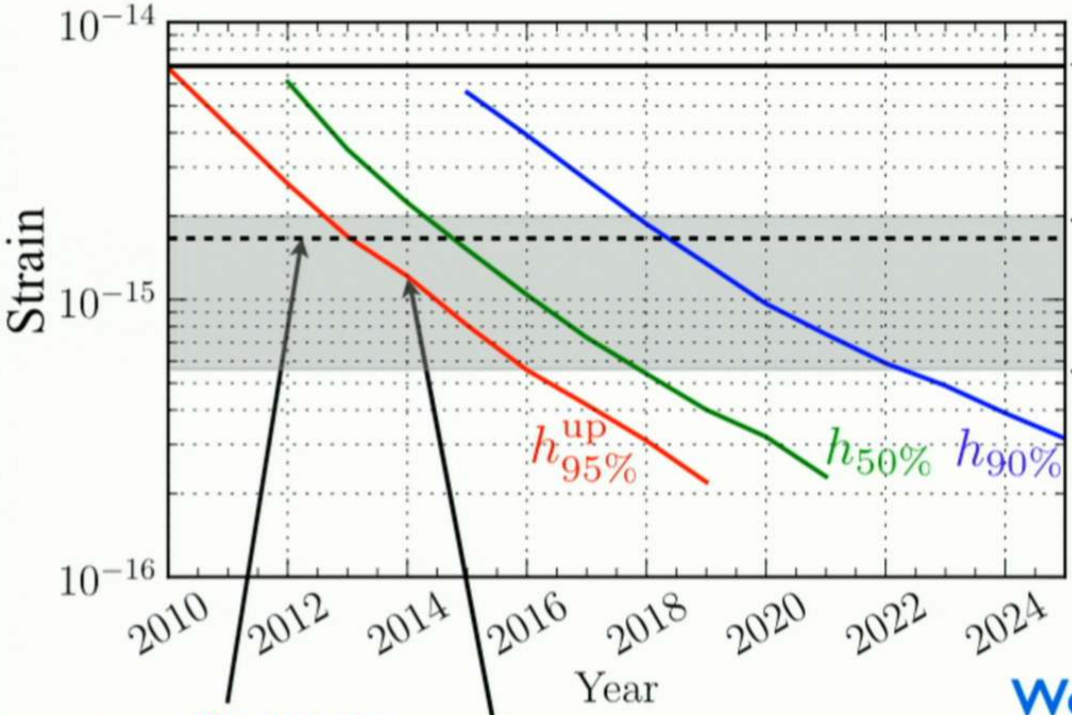


NANOGrav 2010 upper limit (Demorest et al 2013)

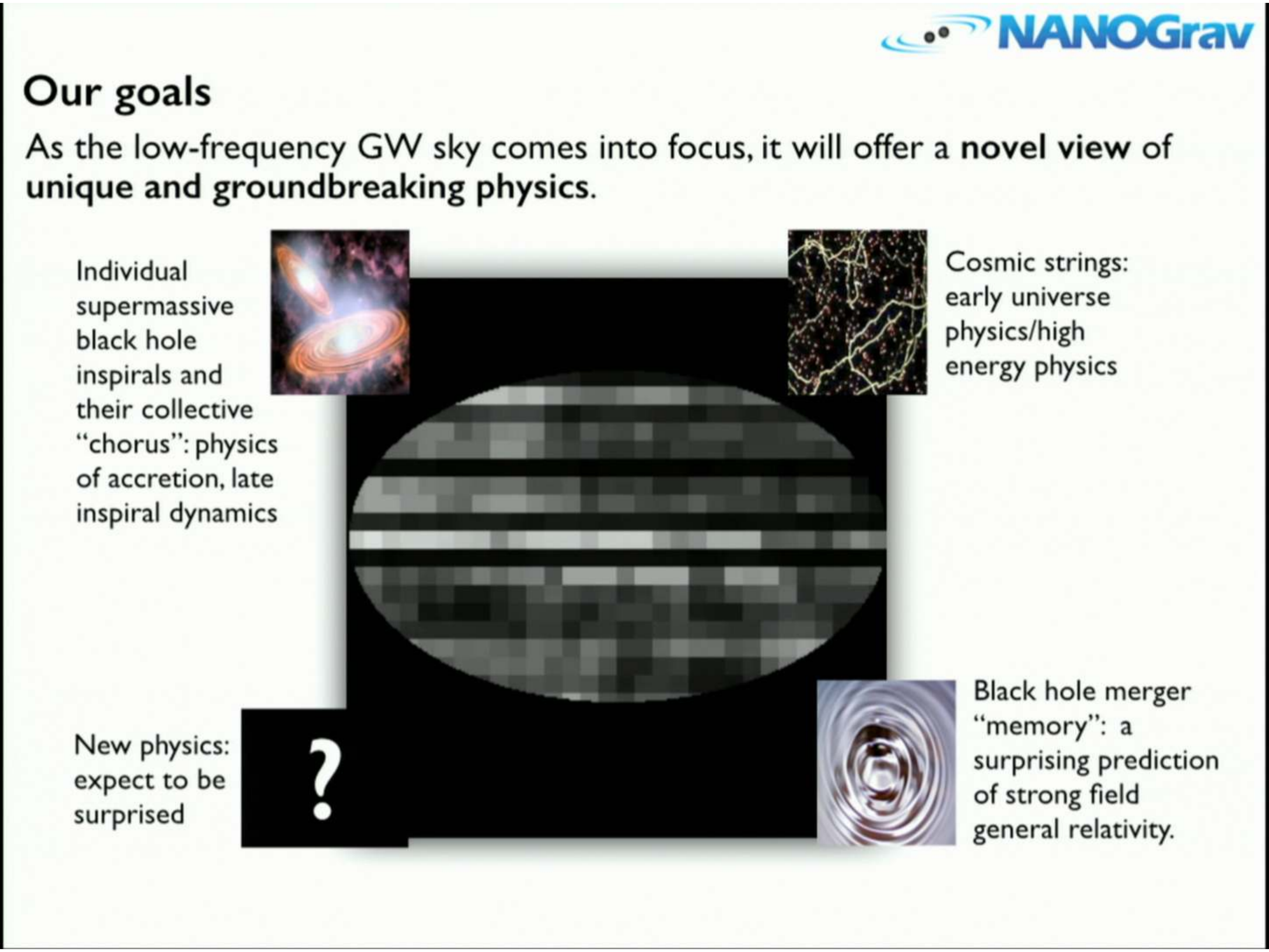
Expected amplitude range for SMBBH background

NANOGrav **PRELIMINARY** 2014 sensitivity from current data

Projected NANOGrav 2014 sensitivity

We are already in astrophysically interesting territory!

credit: NANOGrav Collaboration



Our goals

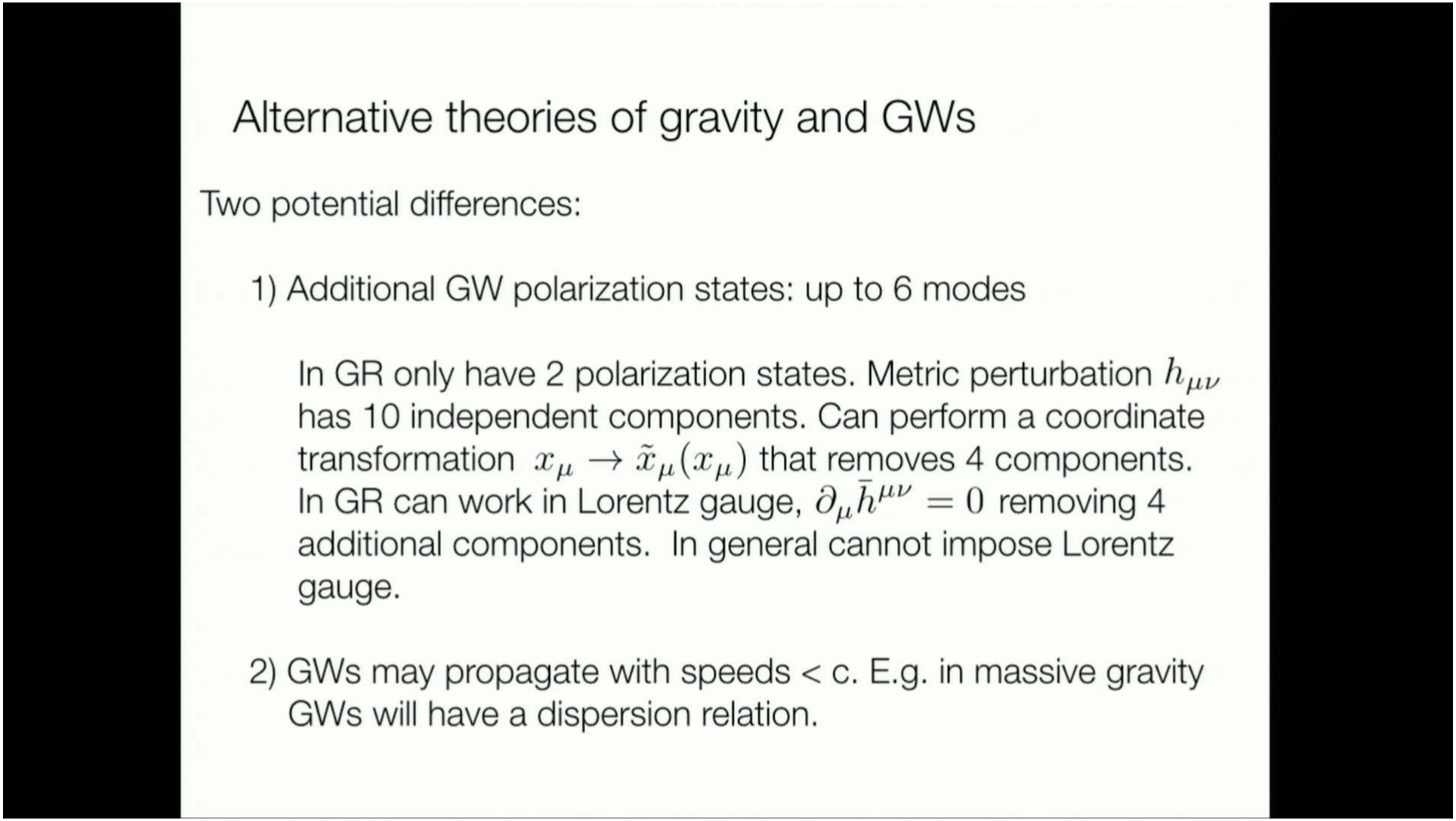
As the low-frequency GW sky comes into focus, it will offer a **novel view** of **unique and groundbreaking physics**.

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.



Alternative theories of gravity and GWs

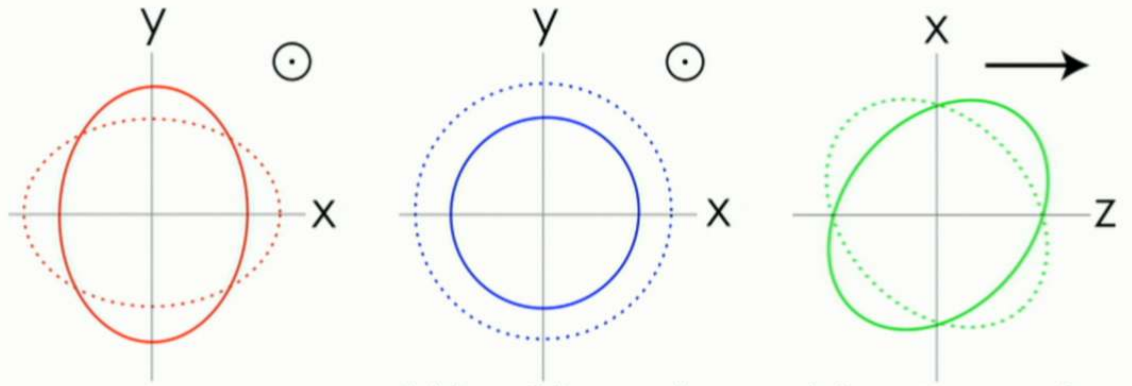
Two potential differences:

1) Additional GW polarization states: up to 6 modes

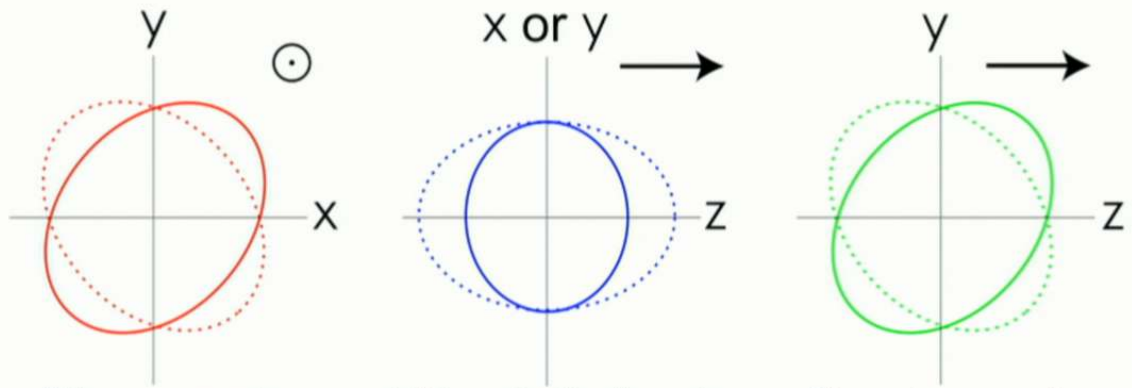
In GR only have 2 polarization states. Metric perturbation $h_{\mu\nu}$ has 10 independent components. Can perform a coordinate transformation $x_\mu \to \tilde{x}_\mu(x_\mu)$ that removes 4 components. In GR can work in Lorentz gauge, $\partial_\mu \bar{h}^{\mu\nu} = 0$ removing 4 additional components. In general cannot impose Lorentz gauge.

2) GWs may propagate with speeds < c. E.g. in massive gravity GWs will have a dispersion relation.

Additional polarization states



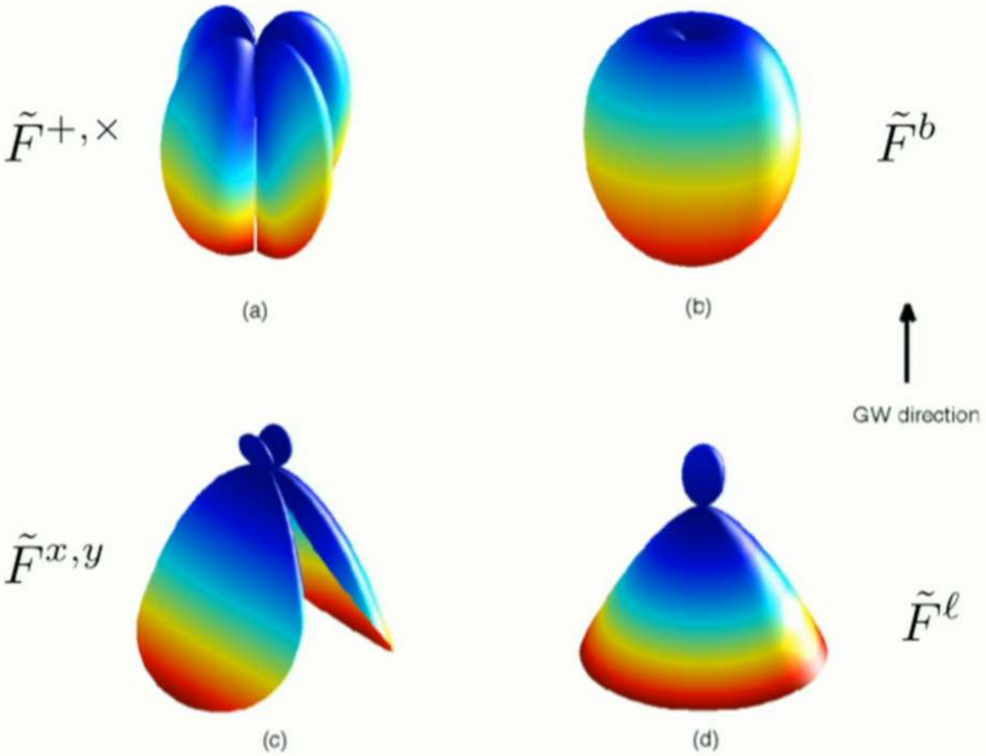
(a) plus mode (c) breathing mode (e) vector-x mode



(b) cross mode (d) longitudinal mode (f) vector-y mode

Figure from Nishizawa et al. 2009

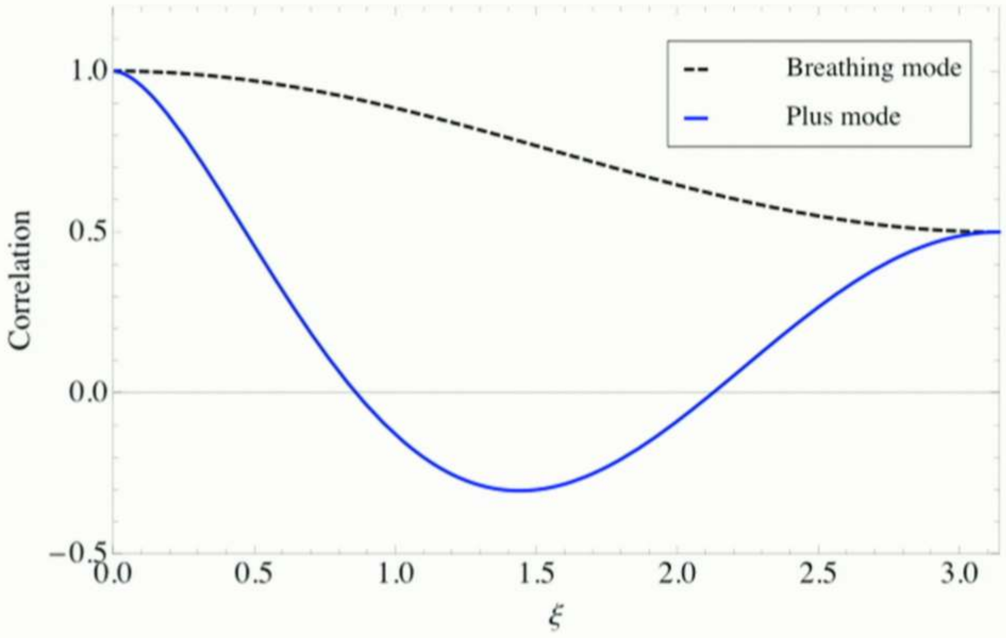
Antenna pattern response functions for pulsar-Earth system



(a) (b) (c) (d)

Effect on stochastic backgrounds

Change the expected shape of the Hellings-Downs curve



Blue curve is Hellings-Downs curve (1983)

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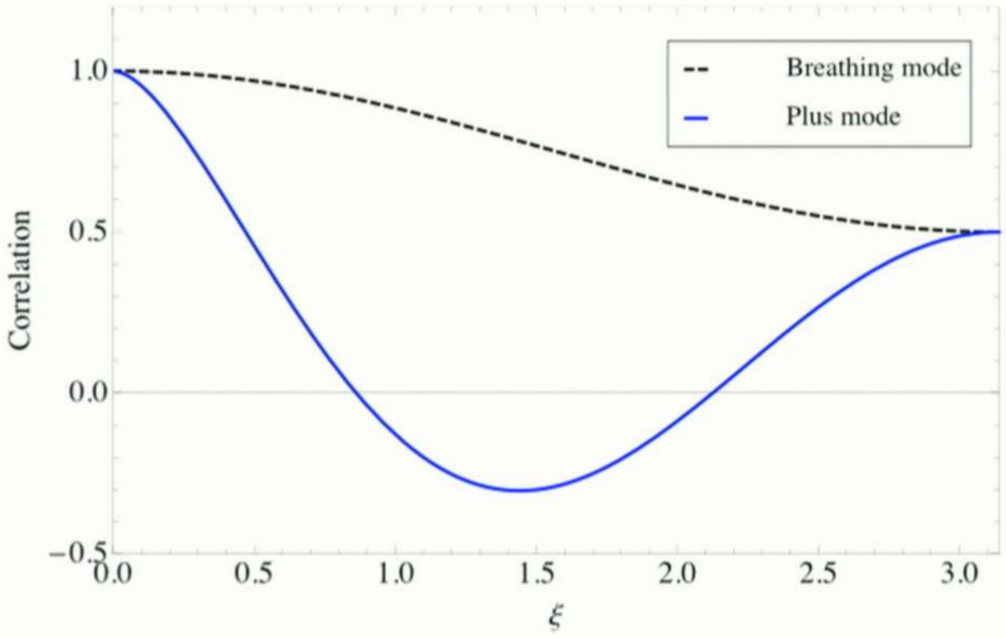

Blue curve is Hellings-Downs curve (1983)

Conclusions

- Pulsar timing experiments can be used to observe the low frequency GW universe
- A detection is possible within the decade
- These experiments can be used to test gravity in a new way