Detecting Gravitational Waves with Pulsar Timing Arrays

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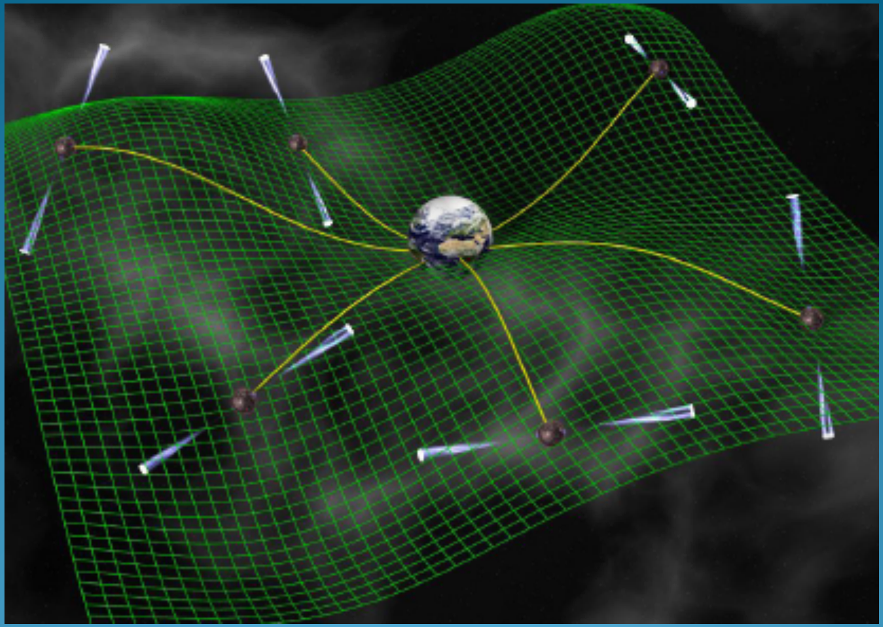
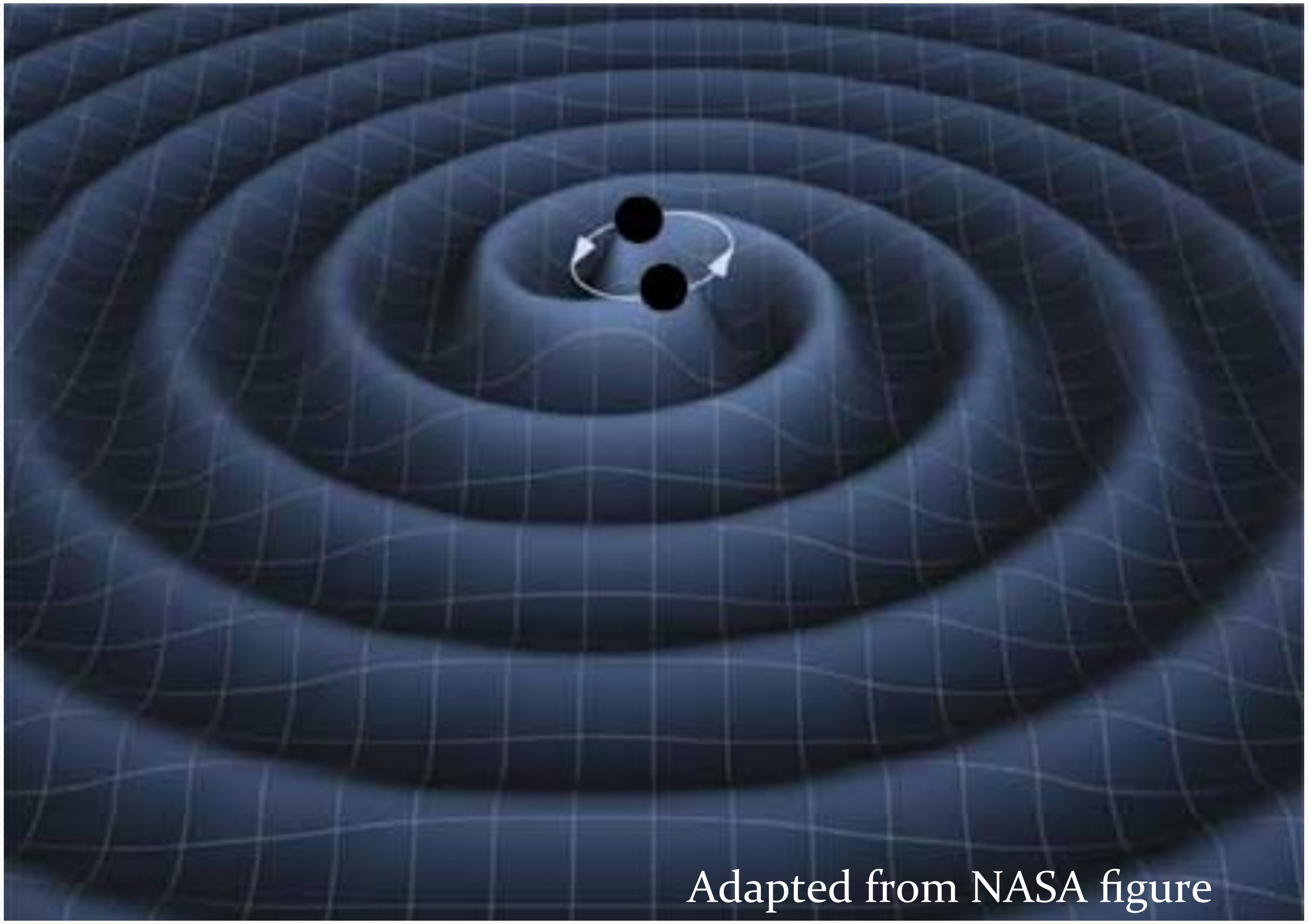


IPTA Student Week 2017, Sèvres, France

Outline

- Introduction to Gravitational Wave detectors
- Introduction to Pulsar Timing Arrays
- Stochastic GW background
- Effect of GW on pulsar signal
- Optimal statistic: Hellings & Downs curve
- Detection techniques

GW: ripples in curvature of space-time that propagate throughout the universe



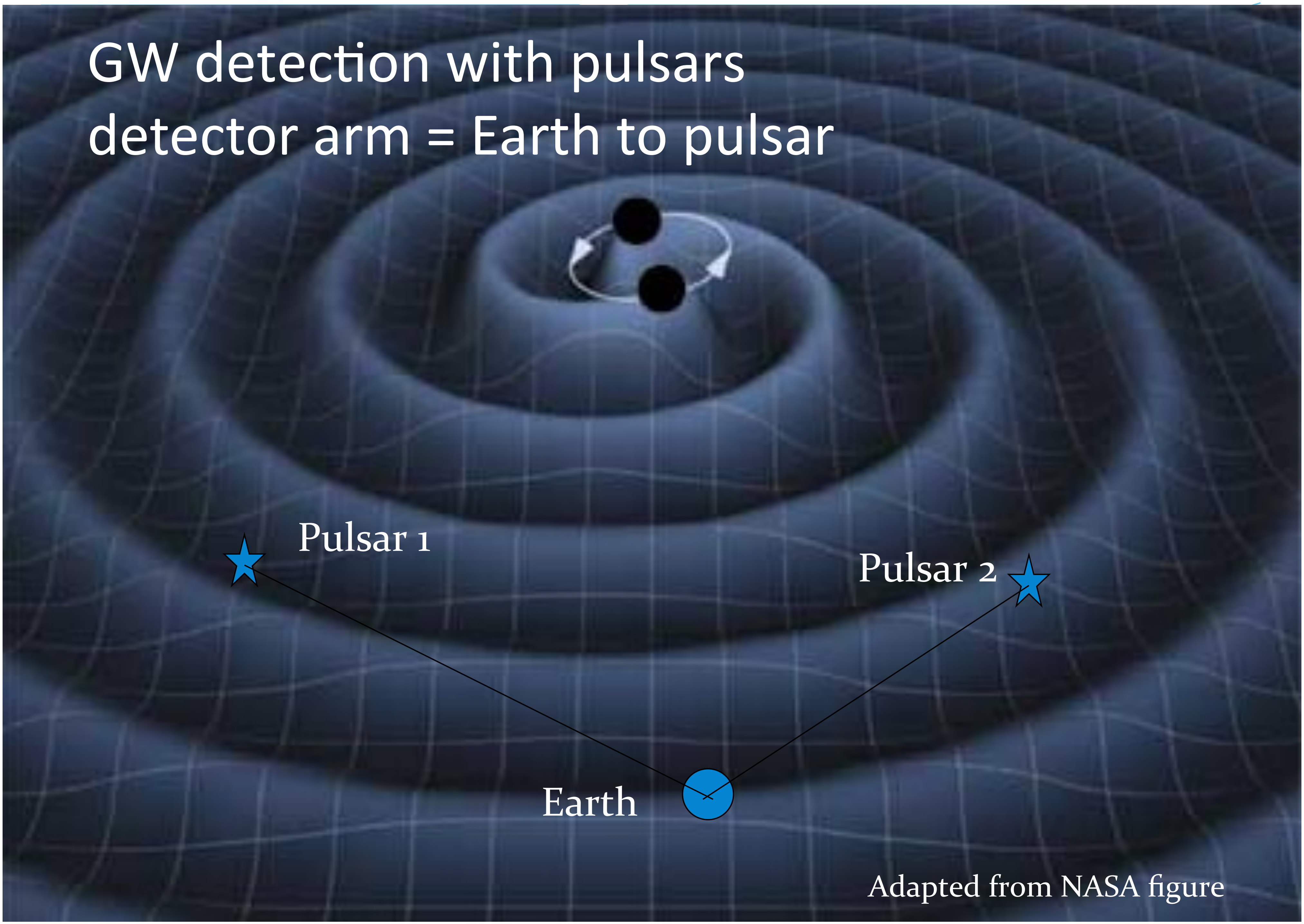
Adapted from NASA figure

GW detection with ground-based laser interferometers (LIGO, Virgo, GEO)

Photo Courtesy of Virgo

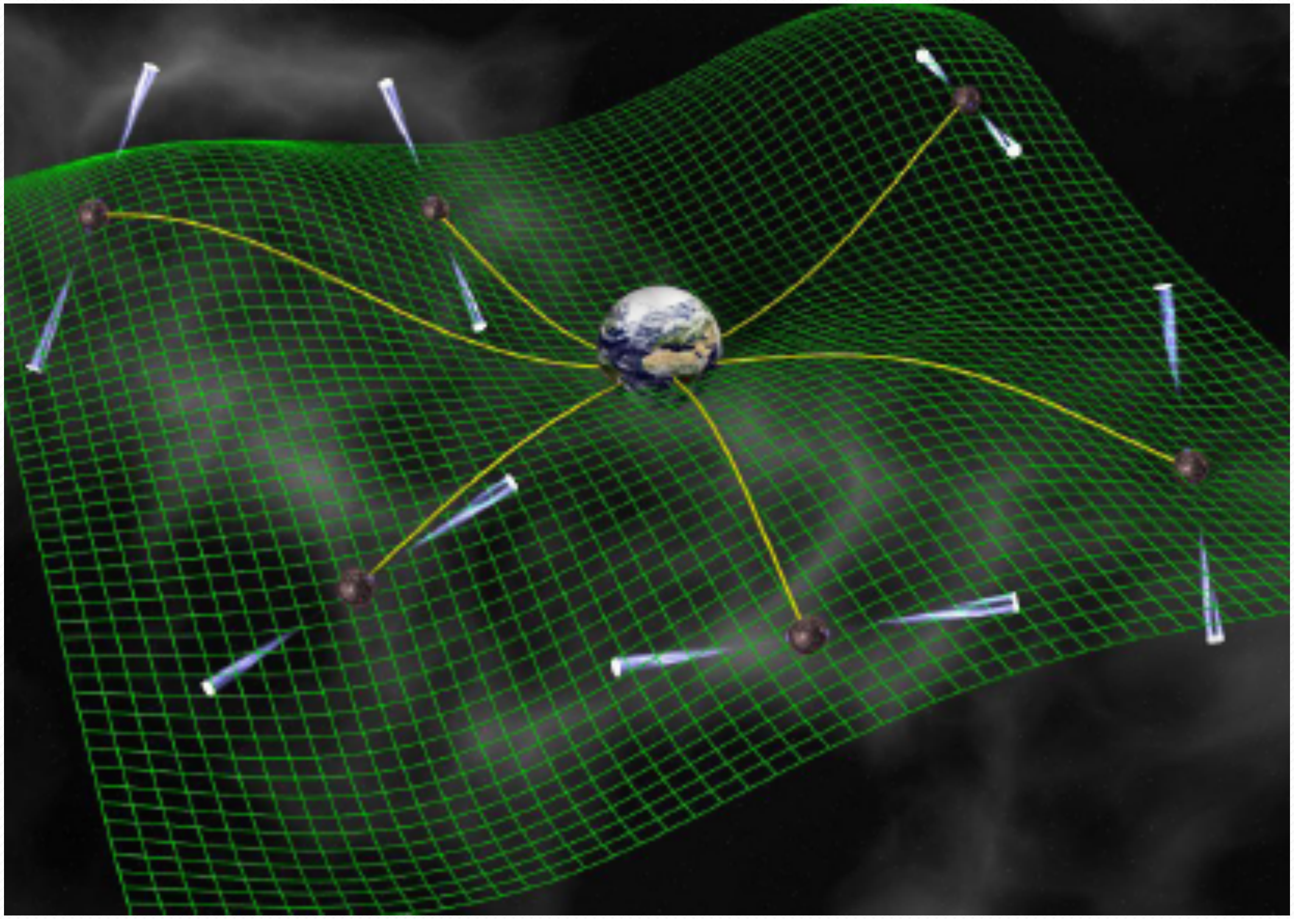
Adapted from
NASA figure

GW detection with pulsars
detector arm = Earth to pulsar



Adapted from NASA figure

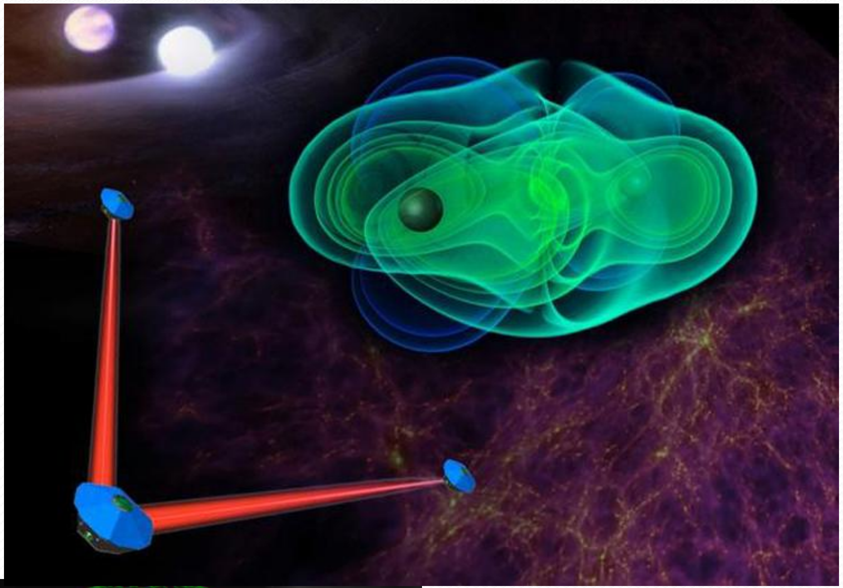
Pulsar Timing Array ~ 30 pulsars



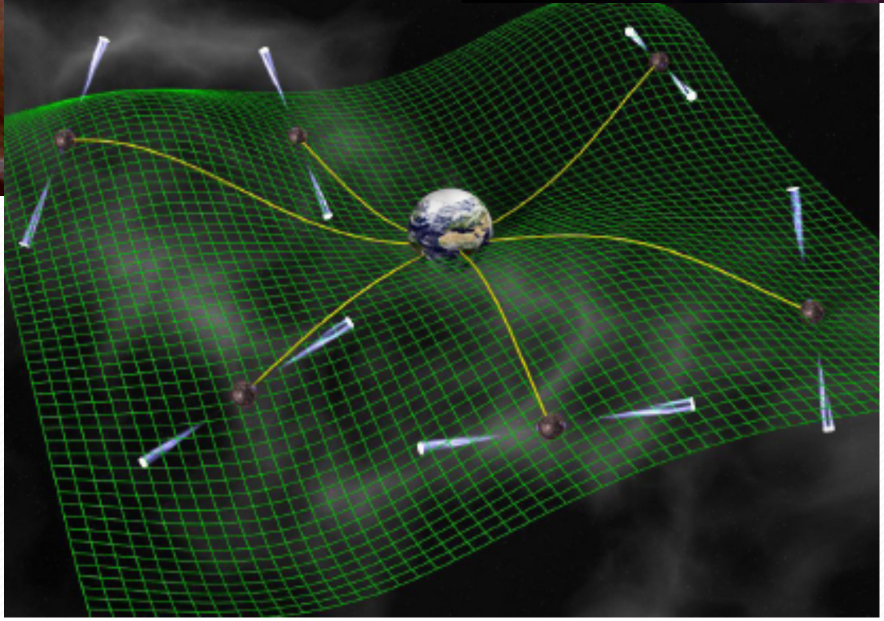
David Champion

Gravitational Wave Detectors

LIGO/VIRGO

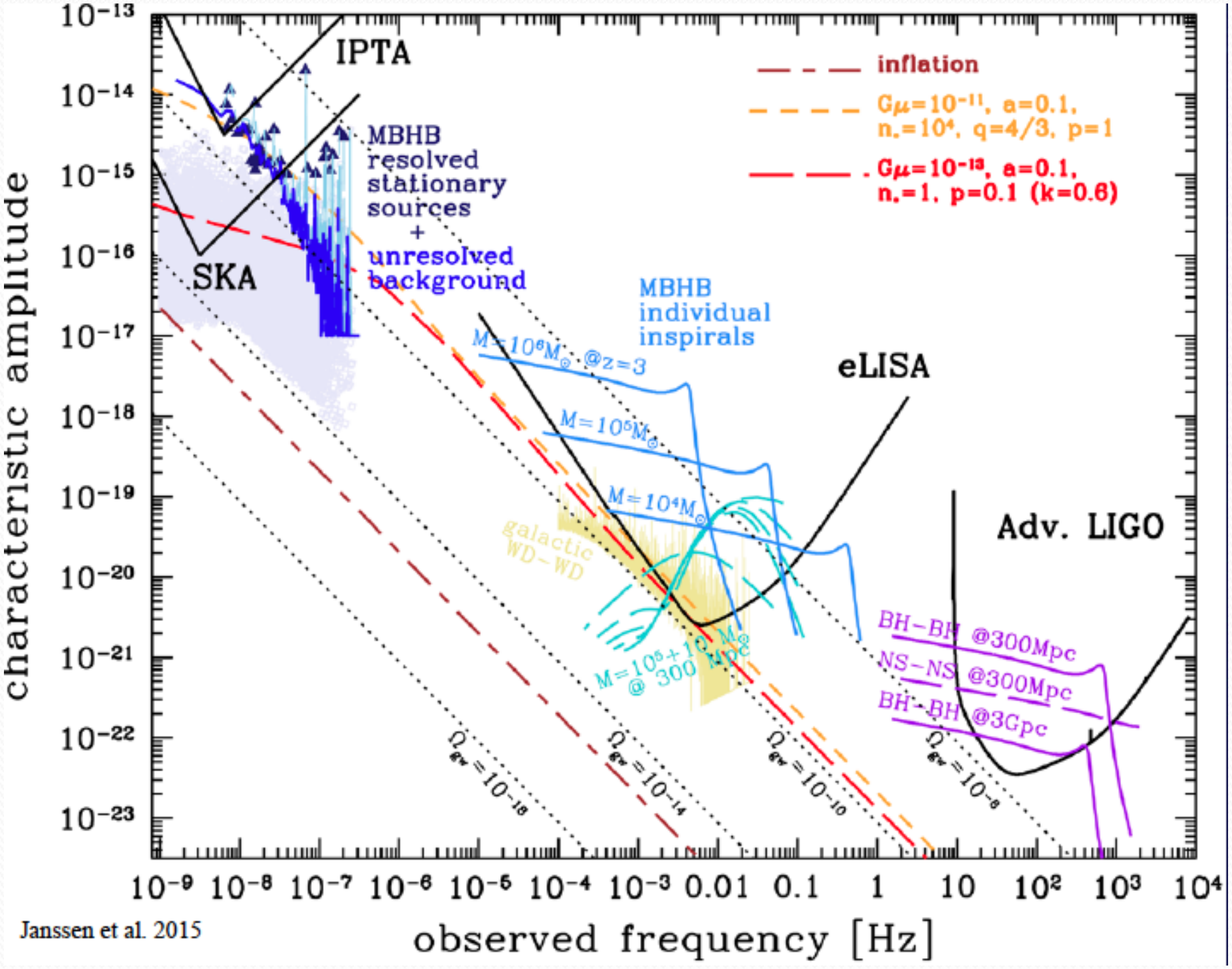


eLISA



PTA

PTAs: complementary to LIGO and eLISA



Janssen et al. 2015

PTAs:
frequencies
in nanohertz
regime

Corresponds
to timelines
of ~1-30 years

The International Pulsar Timing Array (IPTA) collaboration:

Image source, clockwse from upper left: http://www.gb.nrao.edu/; http://www.astron.nl/; http://www.mpifr-bonn.mpg.de/english/index.html; http://gmrt.ncra.tifr.res.in/; http://www.flickr.com/photos/shami_chatterjee/455275921/; http://www.srt.inaf.it/; http://www.obs-nancay.fr/; http://www.jb.man.ac.uk/; http://www.naic.edu/

NANOGrav

EPTA

PPTA

Detecting GW using PTAs

- GW perturb space-time between Earth and pulsars
- MSPs act as “cosmic clocks” thanks to their extraordinarily precise rotation period
- Pulsar timing: precise measurement of pulsar properties: position, rotation period, period derivative, proper motion, parallax, orbital parameters + GW signal?
- Pulsar timing array: use many pulsars; one is not enough to discriminate GW signal

Achieve GW detection using 20 pulsars
at ~ 100 ns for 5 years
(Jenet et al. 2006)

Need to increase sensitivity of PTA

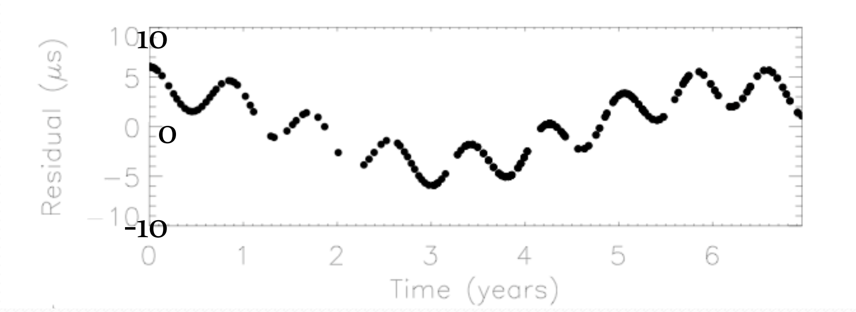
- Better telescopes, receivers, backends, software
- Observe over long time span (5-30 years)
- Increase number of observations (higher cadence)
- Increase number of MSPs (pulsar searches)
- Use MSPs with good TOA precision ~ 100 ns
- Use MSPs with low red noise
- Good noise characterization

John Rowe Animation/ATNF, CSIRO

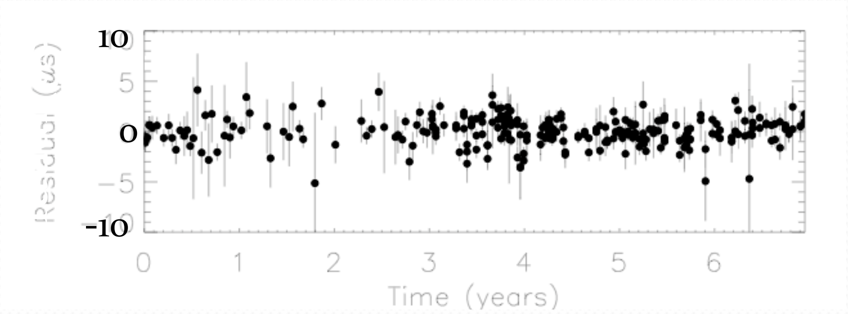
GW signature in Pulsar Timing Residuals

Single continuous GW source

Proposed surpermassive black hole binary system: 3C66B.
Emitted GW should generate detectable fluctuations in pulsar signals.
Ruled out thanks to pulsar timing observations of B1855+09.



Simulated residuals due to 3c66b



Data from Kaspi, Taylor, Ryba 1994

Jenet et al, 2004

Stochastic GW background

A stochastic GW background is a random GW signal that must be characterized statistically. It is produced by the superposition of many independent, weak, unresolved GW signals, and is therefore most likely Gaussian-distributed.

It can be cosmological or astrophysical.

Cosmological: GW left over from the very early universe (inflation period); cosmic strings

Astrophysical: Supermassive black hole binary background (SMBHB)

Cosmological background expected to be isotropic; astrophysical background could be isotropic or anisotropic.

Stochastic GW background

GW background defined by characteristic strain:

$$h_c(f) = A \left(\frac{f}{\mathrm{yr}^{-1}} \right)^{\alpha}$$

where f is GW frequency, A amplitude, and alpha the spectral index
In the case of SMBHB background, alpha = -2/3

Red spectrum: excess power at low frequencies. Overcome low amplitude by observing for long periods of time. However beware of red timing noise!

GW signature in pulsar timing residuals

Idea of using pulsars to detect low-frequency GW first developed by Sazhin (1978) and Detweiler (1979):

They computed expected induced residuals from GW

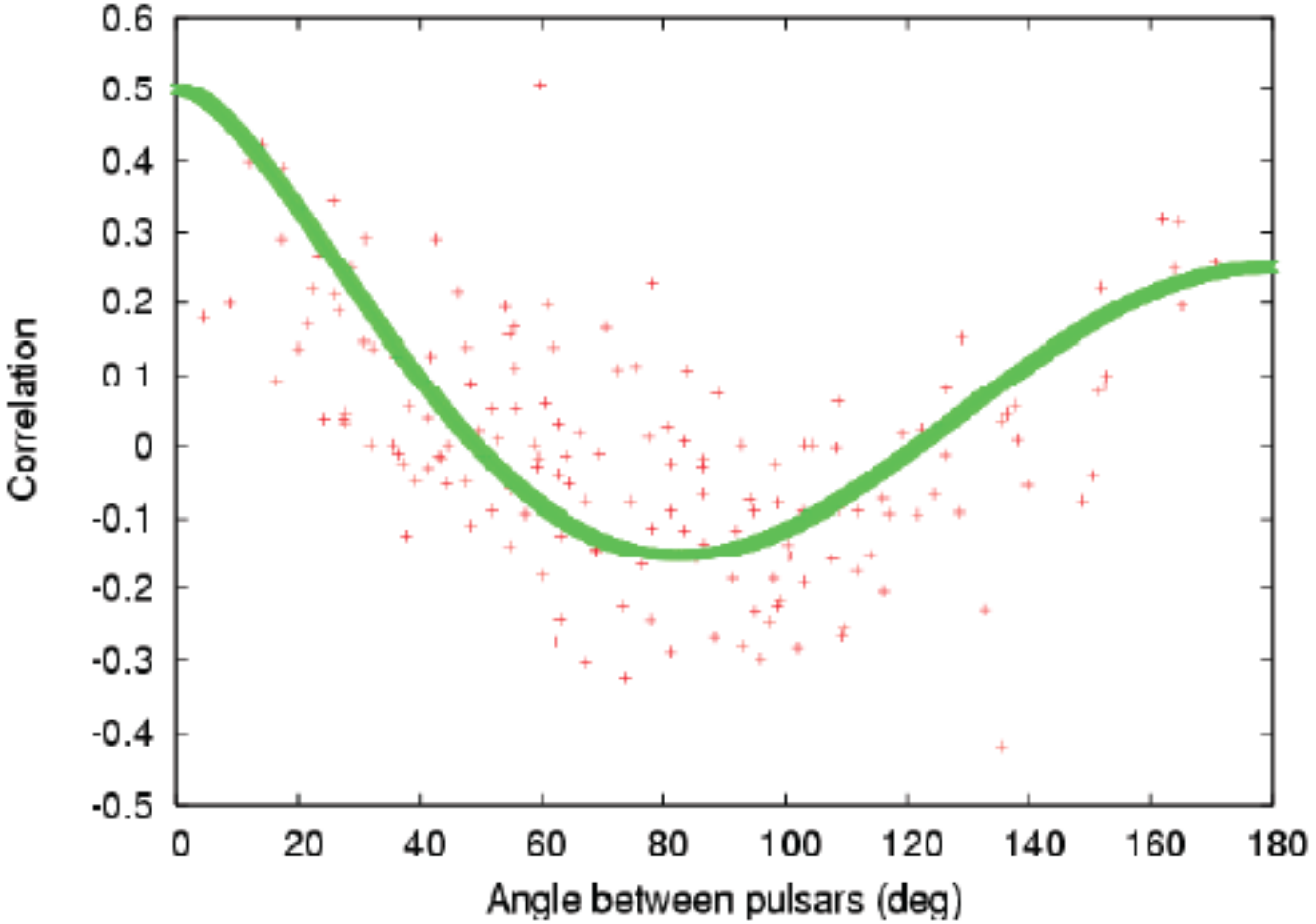
Followed by work of Hellings & Downs (1983)

Studying spatial correlations of the timing signals of a group of pulsars at different sky locations

Correlation is calculated in terms of angles between pulsar pairs

Cross-correlation also called "overlap reduction function"

Optimal statistic: Hellings & Downs curve Overlap reduction function



Courtesy of R. Jenet and G. Hobbs. Original picture from Hellings & Downs (1983)

GW detection techniques

- GW detection pipelines use the "optimal statistic" (HD curve) to search for GW
- Various methods in IPTA used for estimating pulsar parameters; modeling timing noise; search pipelines
- Frequentist and Bayesian methods are both used; sometimes as a combination
- Maximum likelihood function: used in both frequentist and bayesian techniques.

in bayesian statistics: update prior probabilities in order to obtain posterior probabilities

in frequentist approach: parameters are found by maximizing the likelihood

- While the goal of search pipelines is to detect GW, non-detections are still useful by placing upper limits on a stochastic background

Conclusion

- PTAs are well-placed to detect nanohertz-frequency GW in the next 5-10 years
- A combination of frequentist and bayesian (but mostly bayesian!) search techniques are used
- Can improve our “detector” by finding new MSPs, increasing observation cadence and time span, upgrading our instruments and software
- Need to accurately model timing noise