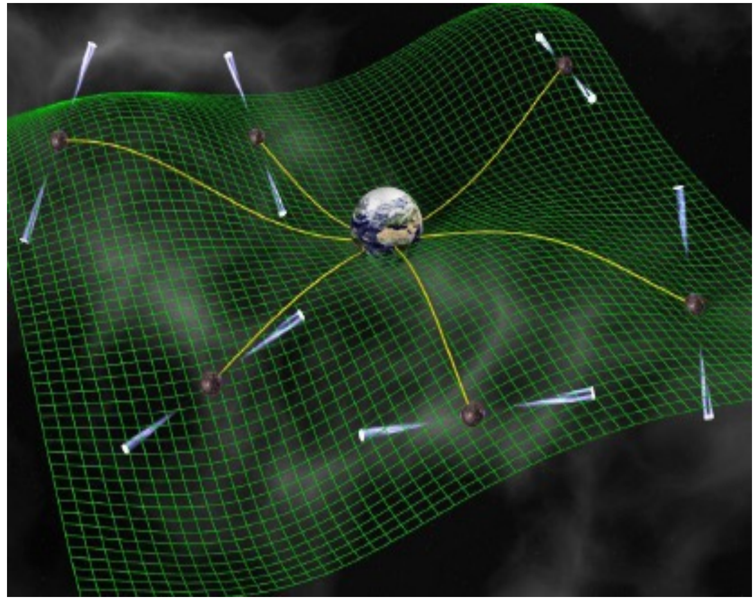


Nanohertz gravitational wave background

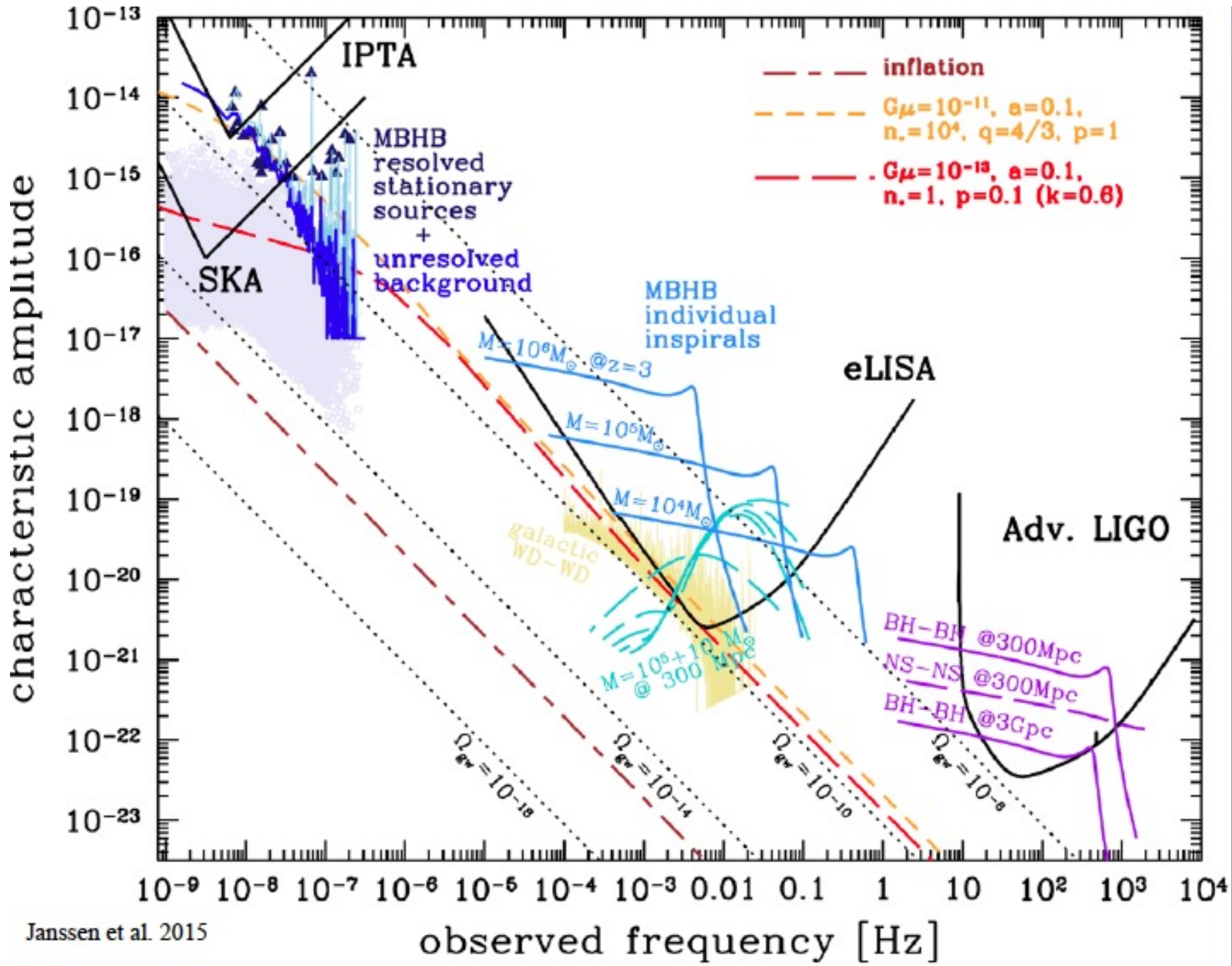
Pulsar Timing Arrays

Delphine Perrodin

INAF - Osservatorio Astronomico di Cagliari (Italy)

International School of Subnuclear Physics, Erice, 15 June 2024

Gravitational wave spectrum



Janssen et al. 2015

Pulsar Timing Arrays probe GW frequencies in nanohertz regime

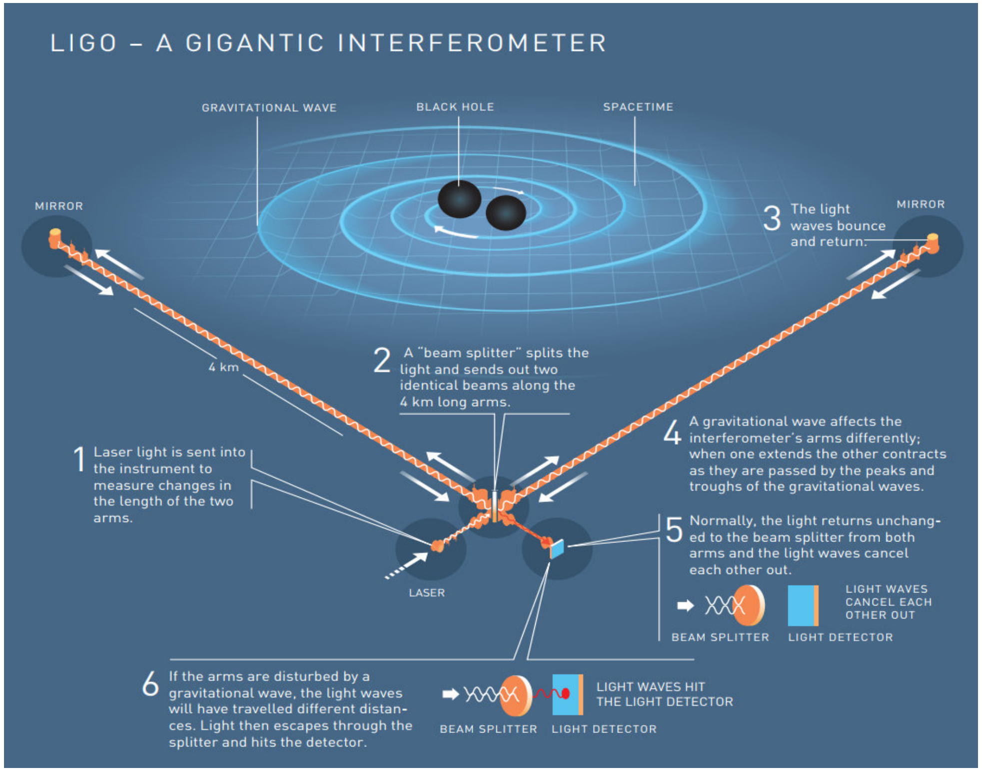
Timelines of ~1-30 years

Binary sources: GW frequency twice the orbital frequency

At nHz frequencies: supermassive black hole binaries in slow inspiral, mostly monochromatic

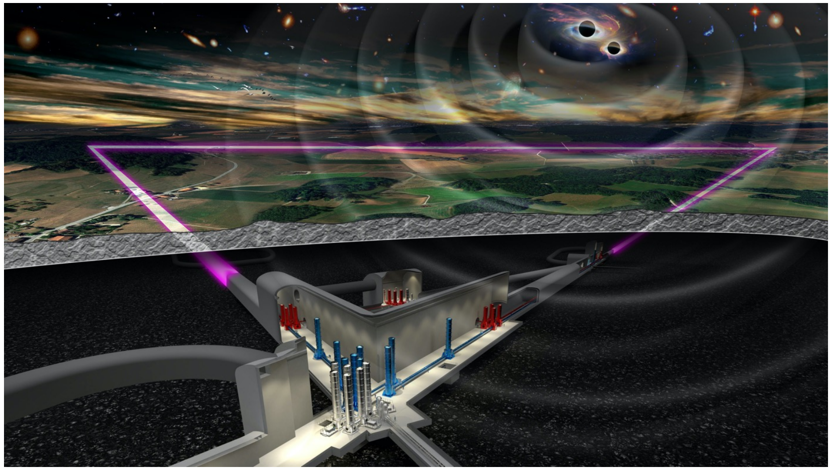
Cosmological sources

Gravitational wave detectors



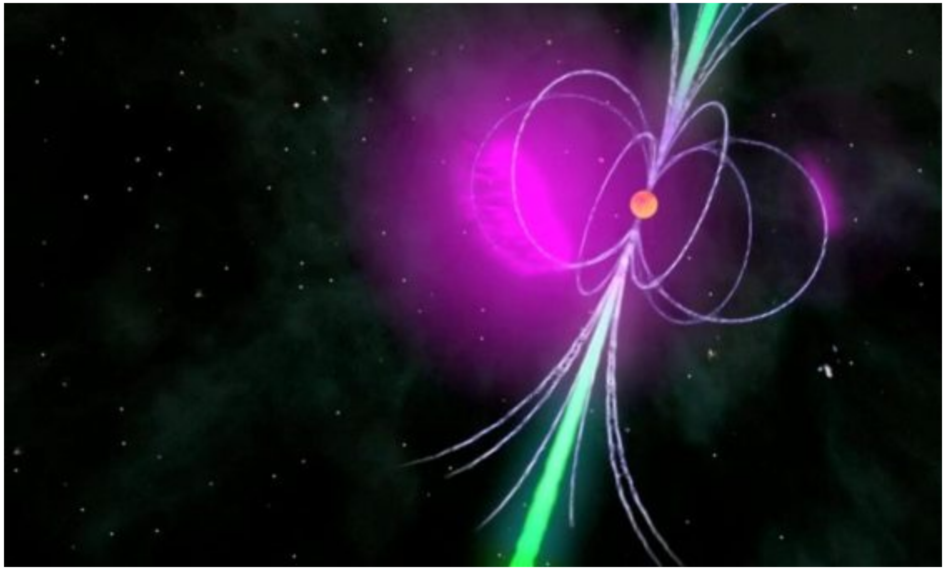
credits: LIGO

Einstein Telescope

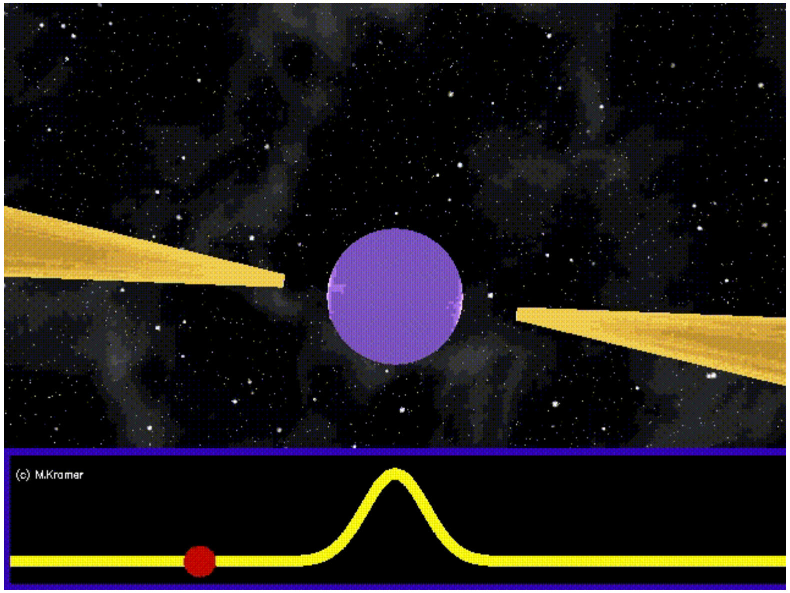


credits: NIKHEF

Pulsars and the lighthouse effect

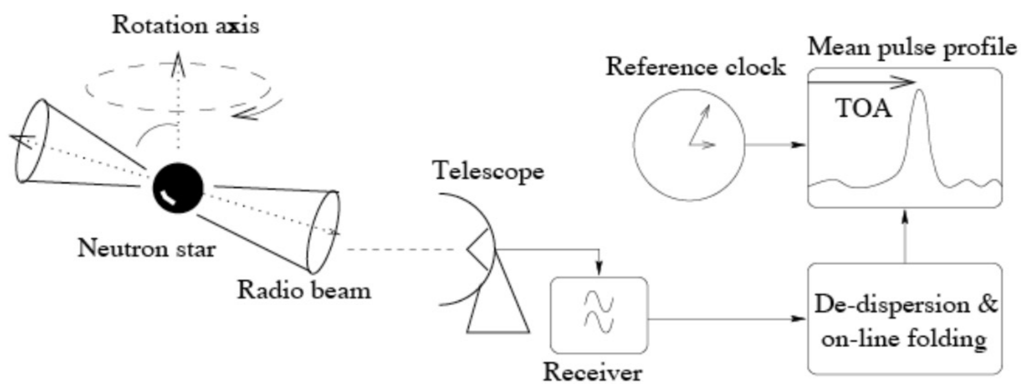


Credits: NASA/Fermi/Cruz de Wilde



Credits: M. Kramer/A. Possenti

Pulsars as clocks for GW detection

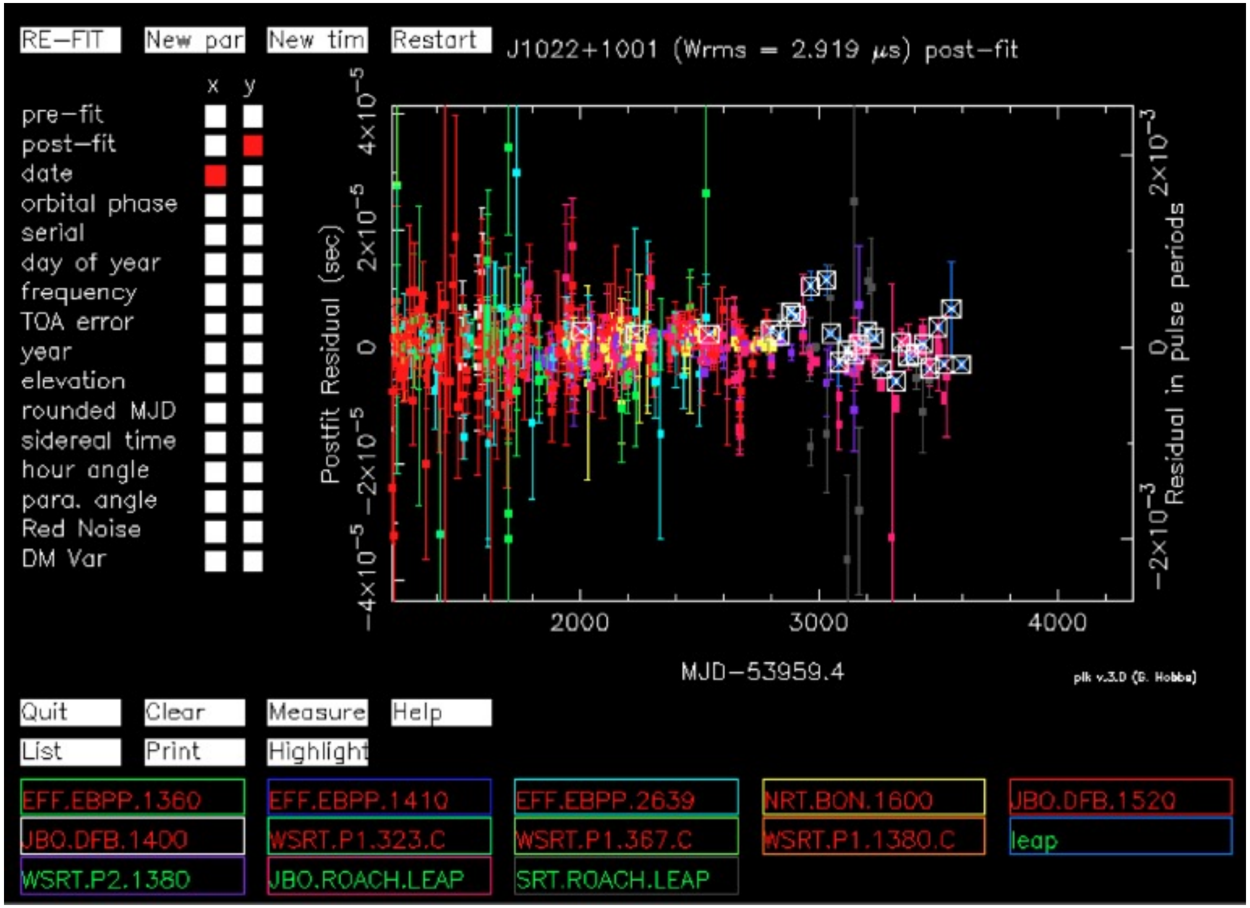


(Lorimer & Kramer 2005)

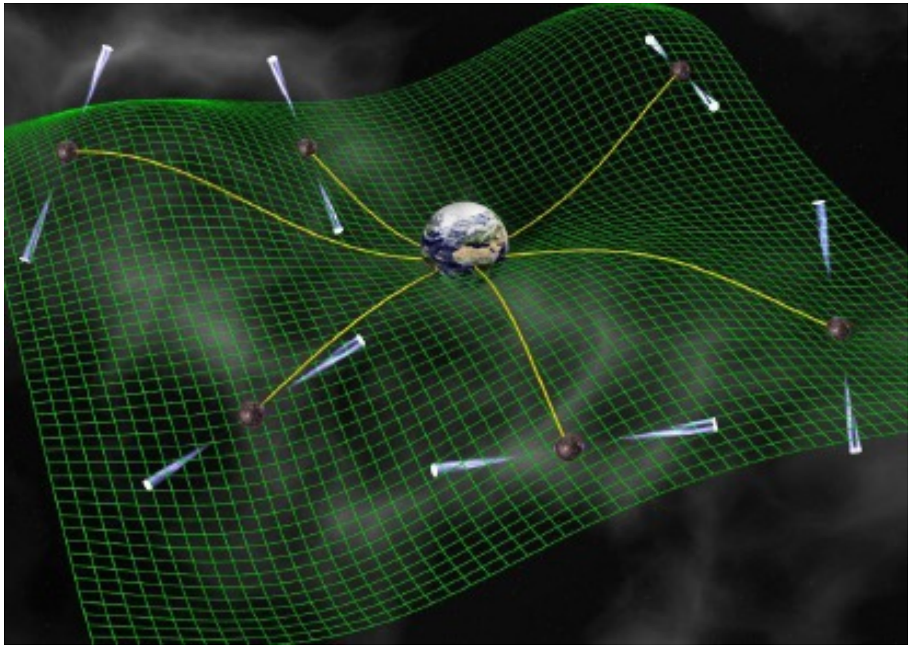
Observe pulsars and measure times-of-arrival (TOAs)
Find the model that best fits TOAs
Calculate timing residual:

Residual = TOA(expected) - TOA(measured)

Pulsar timing residuals



Pulsar Timing Arrays for GW detection

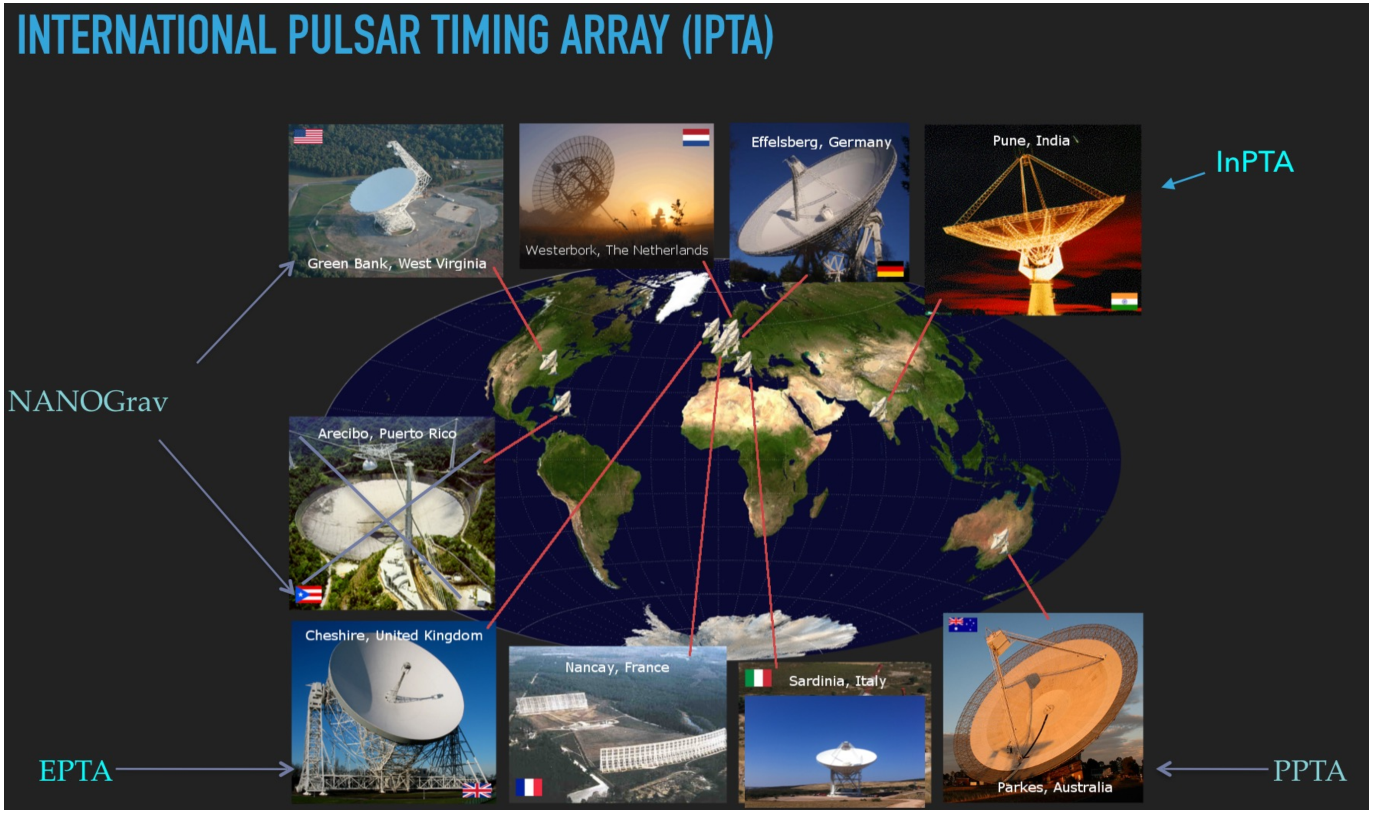


D. Champion

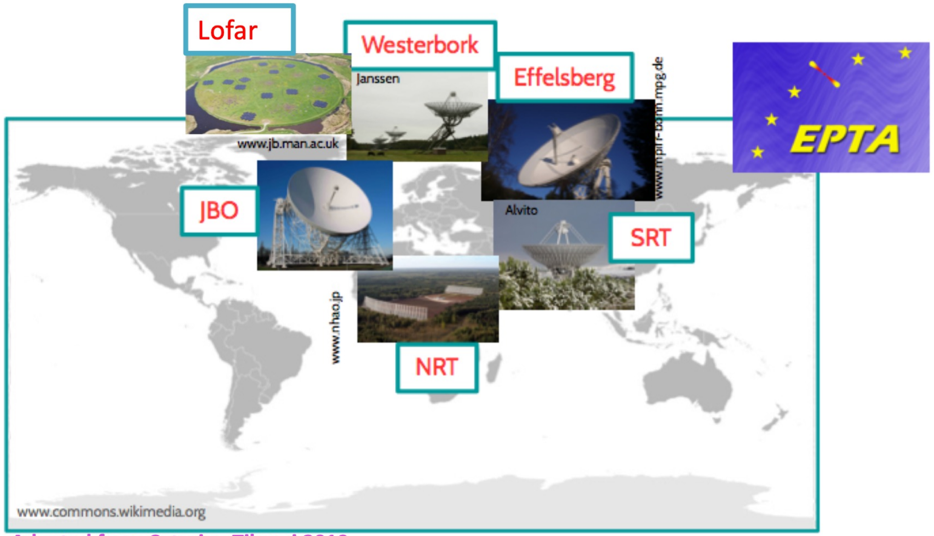
Pulsar Timing Arrays (PTAs) use an array of millisecond pulsars (MSPs) and Earth as test masses.

GWs affect the space-time between Earth and pulsars, introducing offsets in pulsar times-of-arrival (TOAs) and therefore affecting timing residuals

International Pulsar Timing Array (IPTA)



European Pulsar Timing Array (EPTA)



Adapted from Caterina Tiburzi 2019

The Sardinia Radio Telescope (SRT) is the latest addition to the EPTA

and to the Large European Array for Pulsars (LEAP) project that performs simultaneous observations at all 5 EPTA telescopes

Located south of other EPTA telescopes, SRT can observe southern pulsars such as J1909-3744

The Sardinia Radio Telescope (SRT)

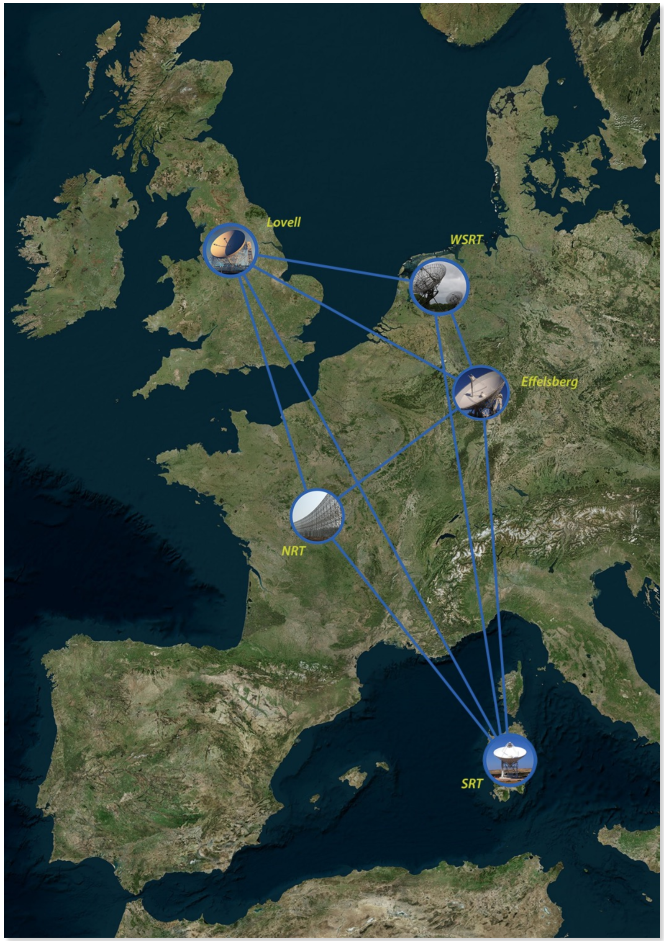
- In San Basilio (Sardinia), inaugurated in 2013
- Fully-steerable 64-m diameter dish
- Can host 20 receivers, 6 focal positions
- Wide frequency range (300 MHz to 115 GHz) with active surface
- Dual L/P (1300-1800 MHz and 300-400 MHz) band receiver ideal for pulsar observations
- So far, pulsar observations with DFB and ROACH backends

SRT Sardinia Radio Telescope

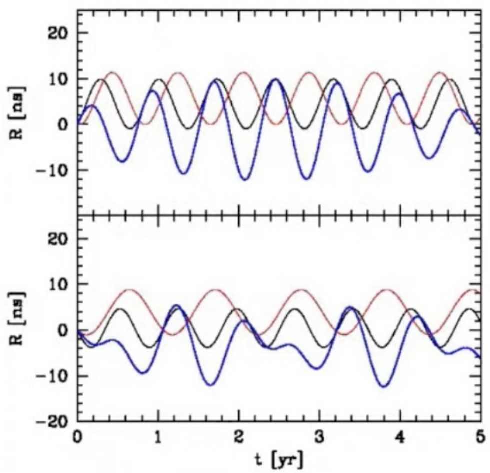
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

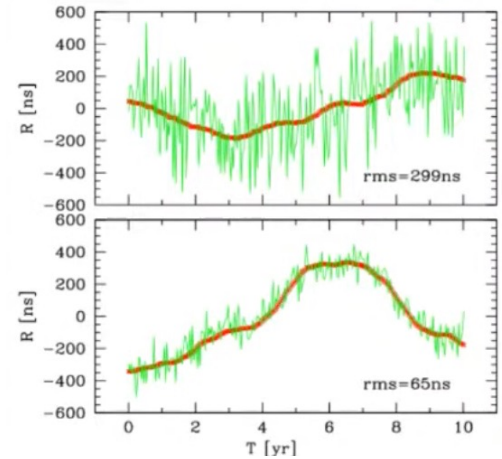
Large European Array for Pulsars (LEAP)

- EPTA's "sixth telescope"
- Monthly simultaneous observations of ~22 pulsars at L-band (BW=128 MHz) at 4 EPTA telescopes in baseband mode
- Coherently combine baseband data to produce combined baseband and archive files
- Sensitivity equivalent to 194-m dish (~ SKA-1); boost sensitivity at L-band
- Declination range: 85 N - 30 S

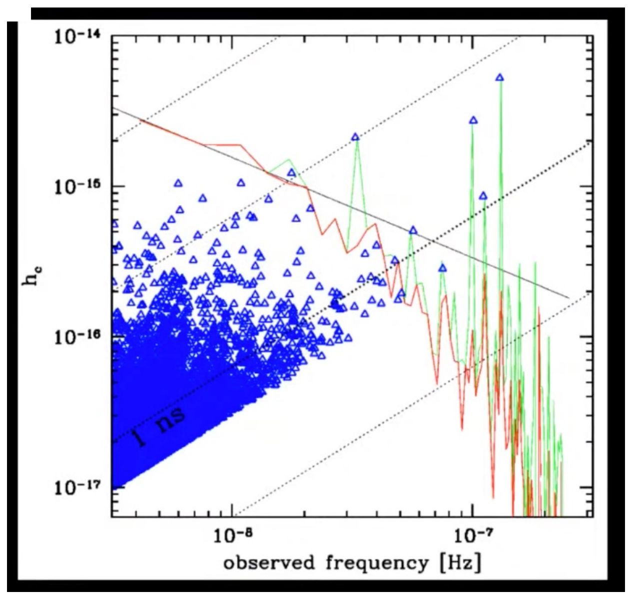


Imprint of SMBHB GW source on timing residuals





Individual GW source



GW background:
Red noise in timing residuals

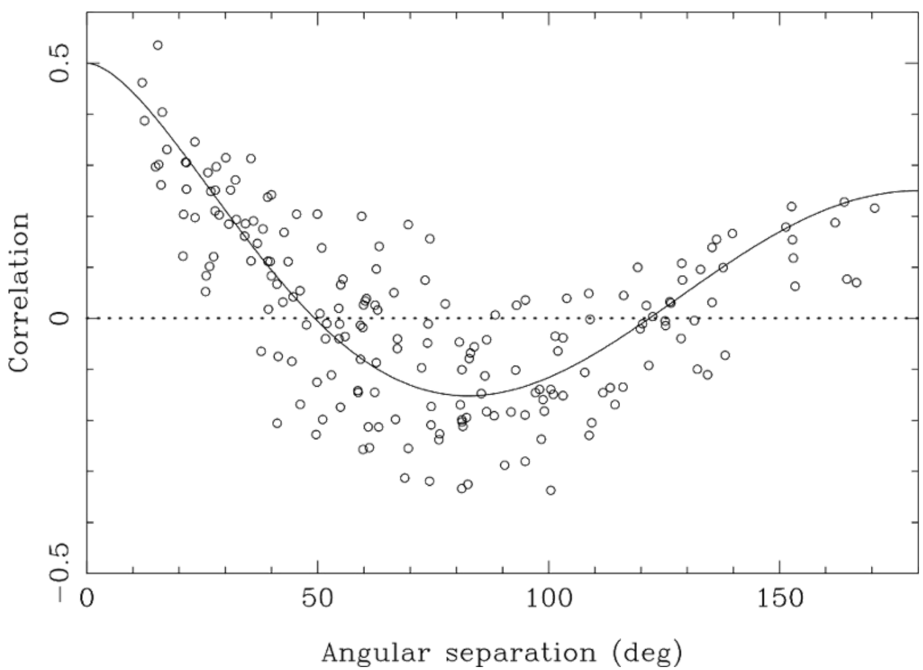
Phinney 2003

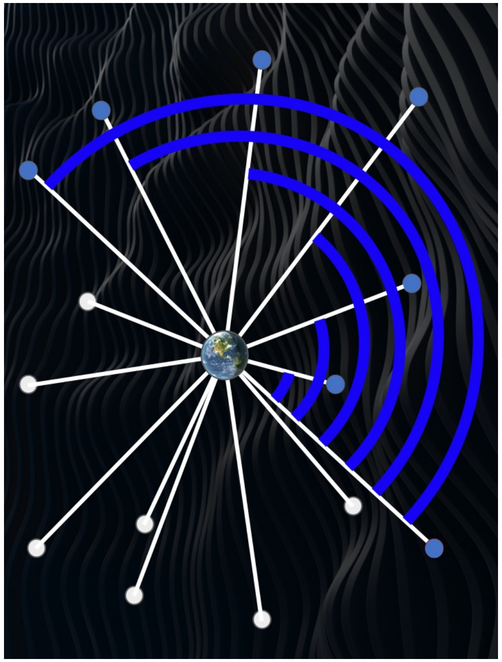
$$h_c(f) = A\left(\frac{f}{\mathrm{yr}^{-1}}\right)^{-2/3}$$

Plots by S. Burke-Spolaor/A. Sesana

Optimal statistic for detection of a GW background: Hellings & Downs curve

Hellings & Downs 1983





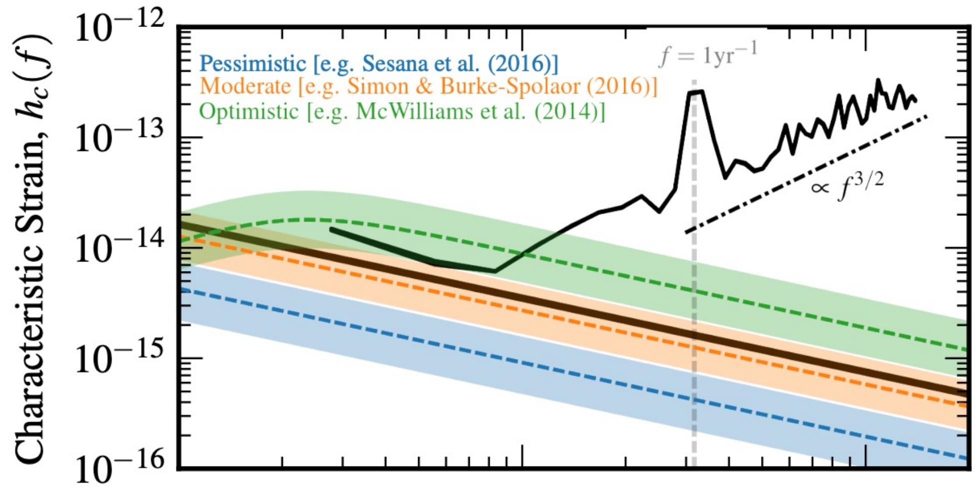
Parthasarathy

Detection achieved by studying correlation of residuals between different pairs of pulsars

Search methods based on likelihood function

PTAs: constraints on SMBHB background

> 2015: getting to where we can expect signal



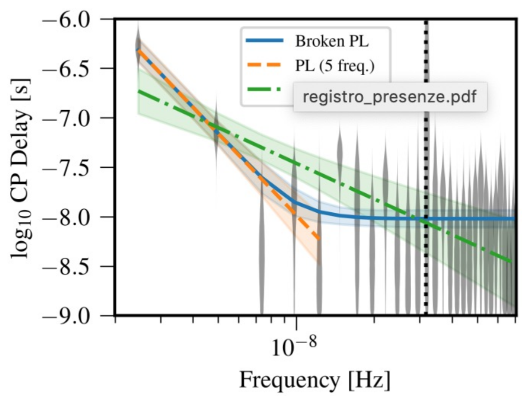
Arzoumanian 2018

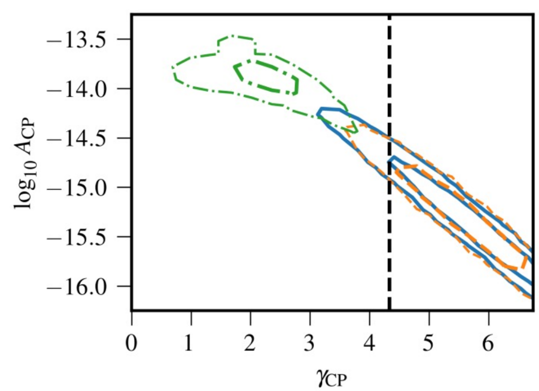
Upper limits (non-detection) on background

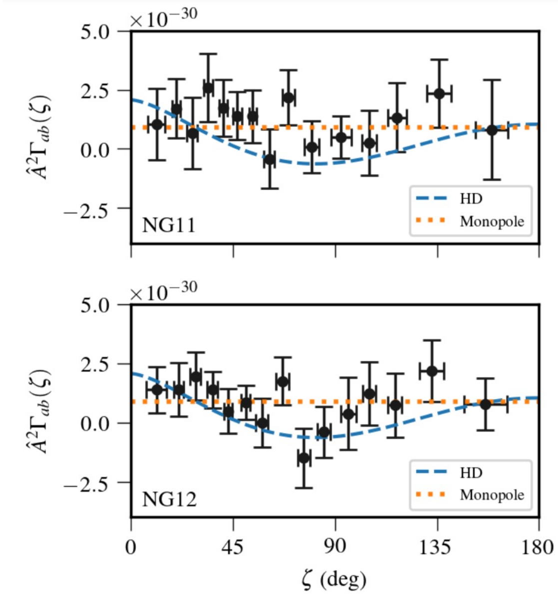
NANOGrav: Arzoumanian et al. (2015)
EPTA: Lentati et al (2015)
PPTA: Shannon et al (2015)
IPTA: Verbiest et al (2016)

Detection of common red signal (2020)

NANOGrav: 12.5 year data analysis
Bayesian analysis of 43 pulsars
Accounting for solar system ephemerides

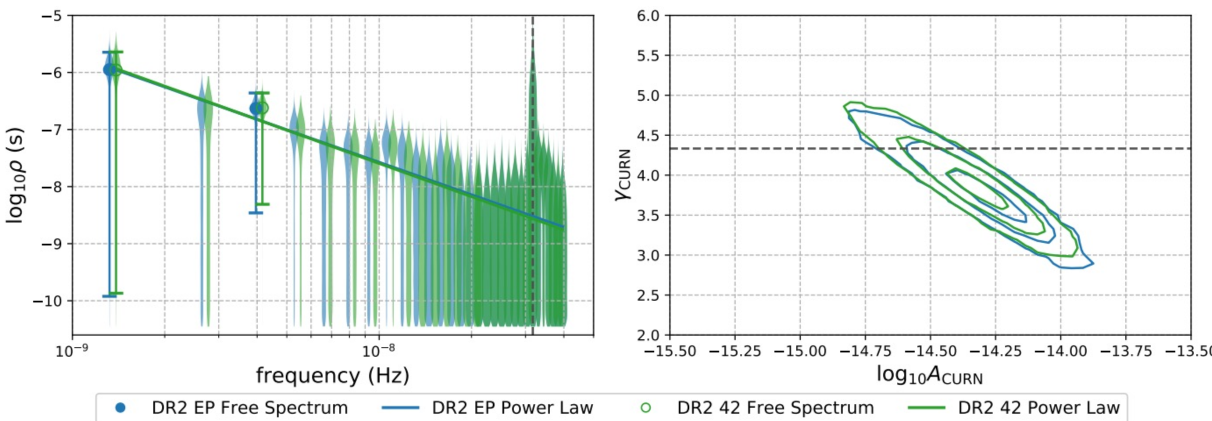






No evidence of HD correlation

Common red signal seen in several datasets



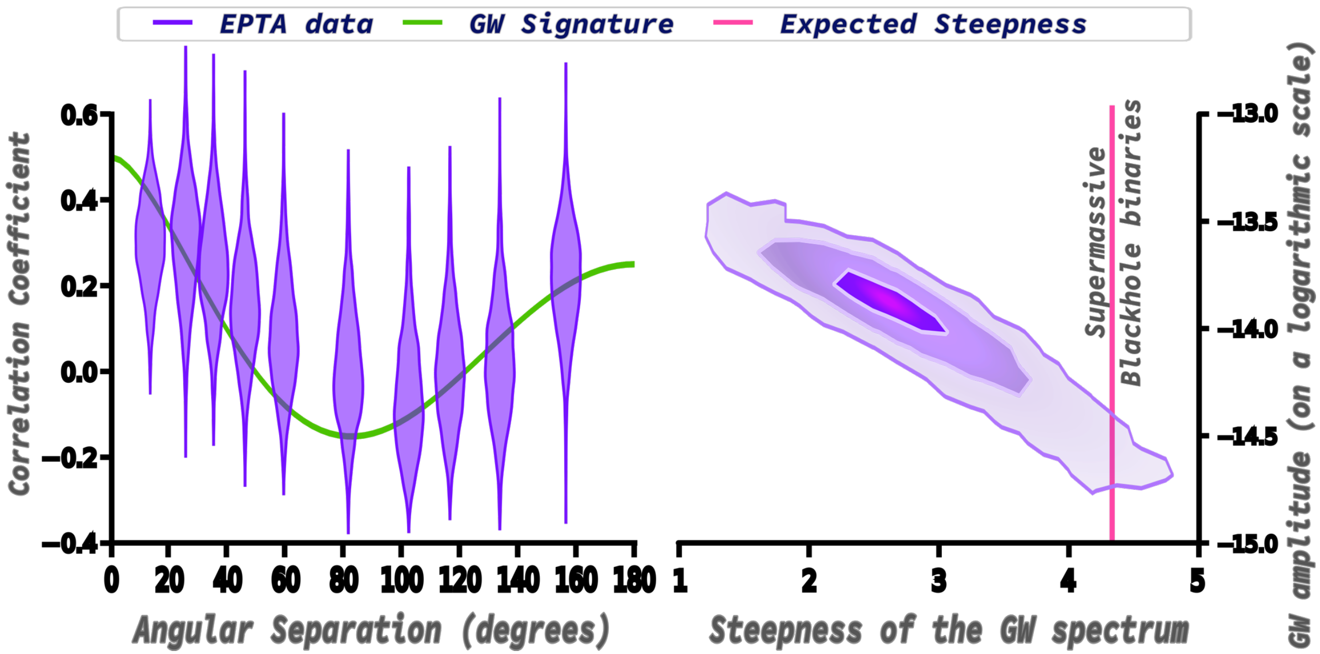
EPTA: Chen 2021

PPTA: Goncharov 2021
IPTA: Antoniadis 2022

- Detection of common red process consistent with GW background signal
- Consistent in particular with SMBHB GW background
- Common red process not the same as correlation
- But makes sense to first have red process then correlation later on (“precursor”)

Evidence for a GW background in PTA data

EPTA DR2: pulsar timing residuals for 25 pulsars over ~ 25 years
EPTA "DR2new": only new backends (last 10 years)

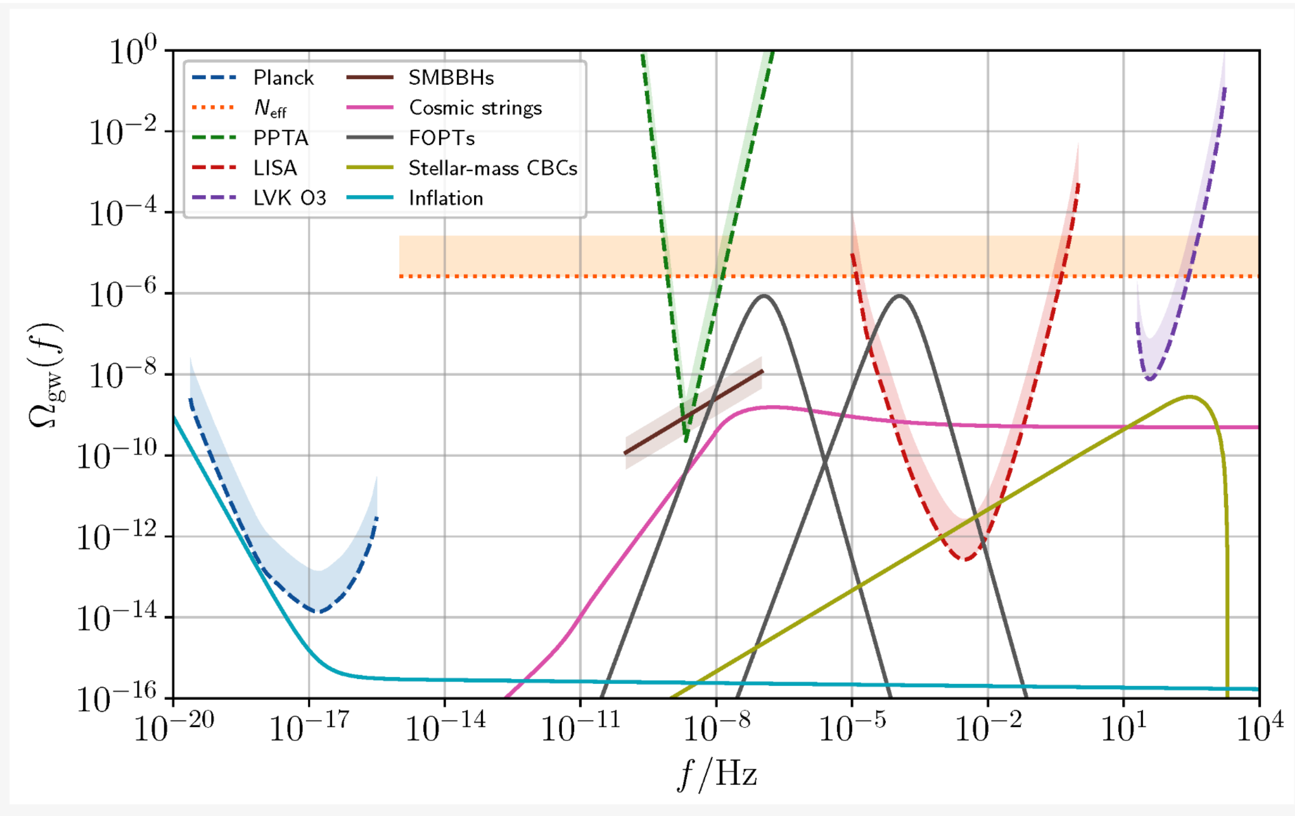


Consistent with results from NANOGrav, PPTA, CPTA (June 2023)

Gamma ~ 2.7 (low)
A ~ - 14 (huge!)
Consistent with SMBHB origin

A higher significance is needed to confirm this result and to identify its origin
This can be achieved by improving the timing sensitivity of pulsar observations

Possible GW sources



Renzini 2022

SMBHBs

Inflation

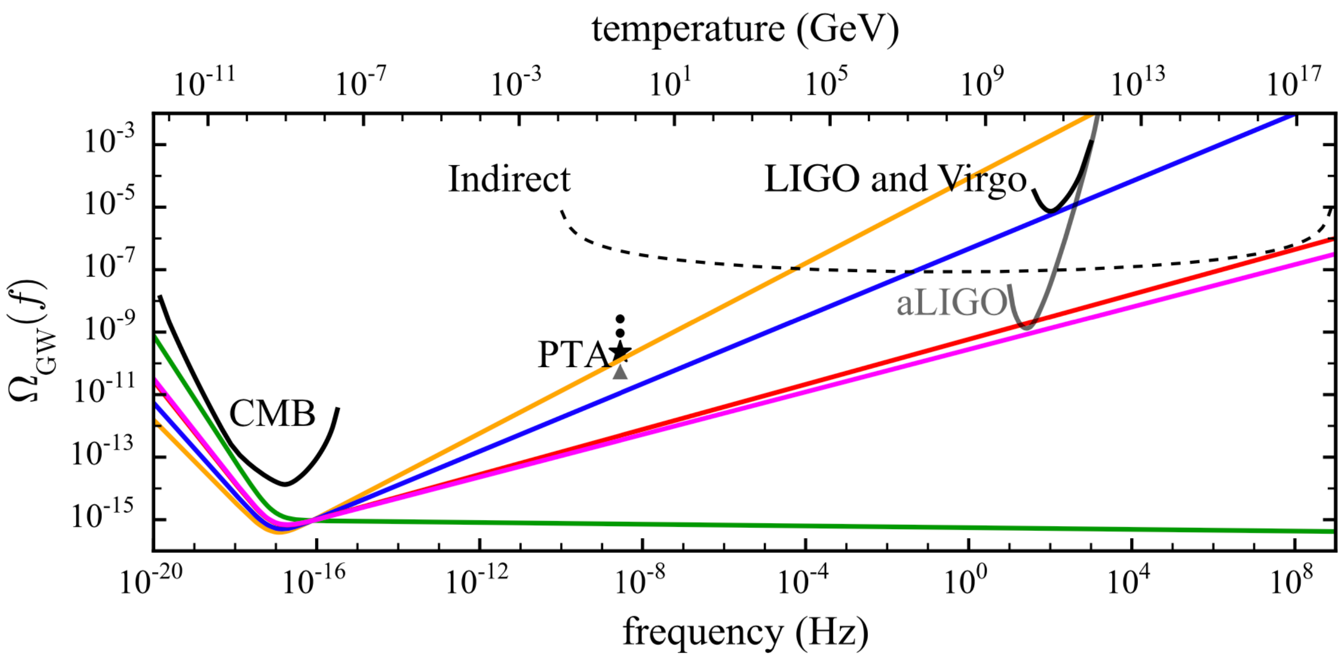
Axion-like particles

Phase transitions

Topological defects (cosmic strings/domain walls) leftover after phase transitions

Scalar perturbations/ Primordial black holes

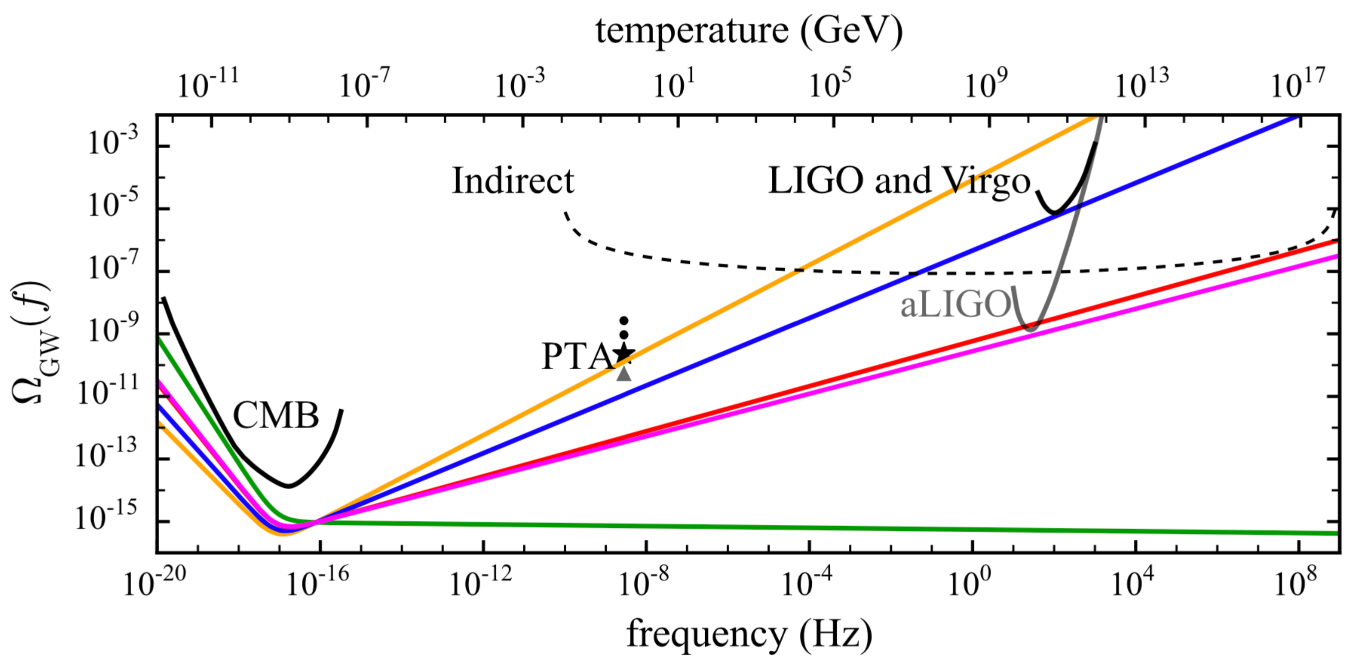
GWs from Early Universe: inflation



Lasky 2016

Single-field slow-roll inflation red-tilted: only detectable by CMB
Not detectable by PTAs or ground-based interferometers

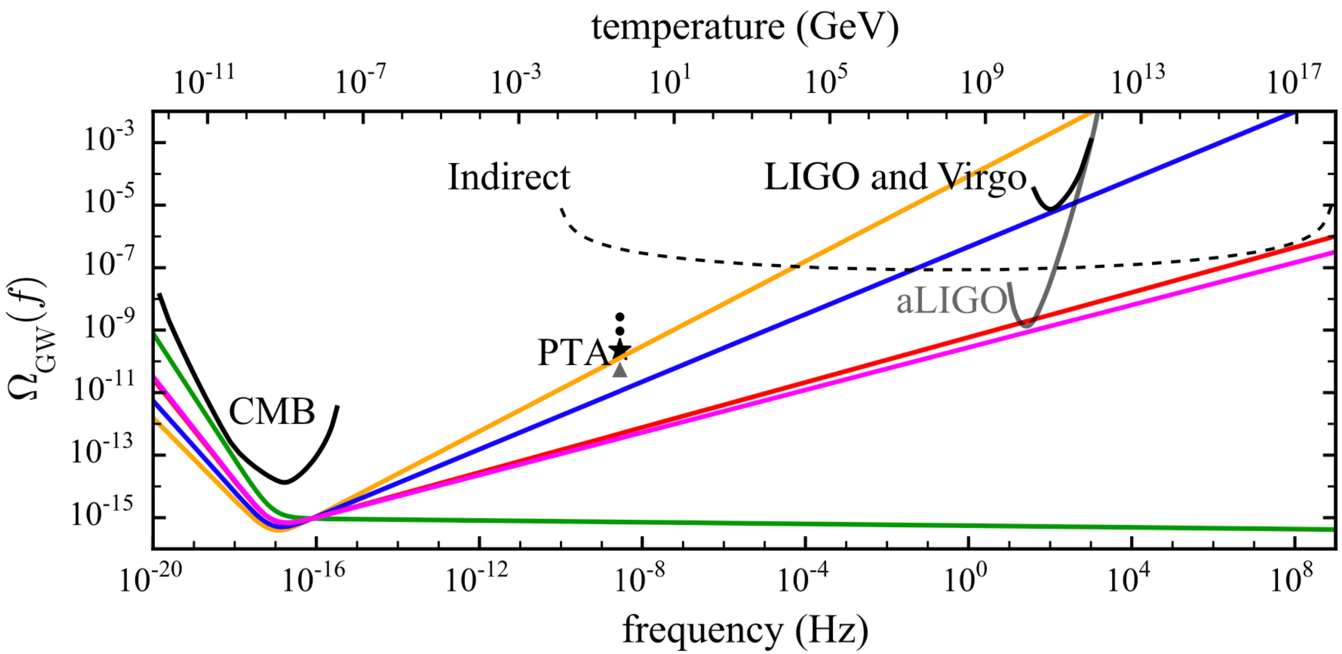
GWs from Early Universe: inflation



Lasky 2016

Need more exotic scenarios that can create a blue tilt
e.g. adding extra fields during inflation
axion inflation model
varying of GW speed during inflation
modified gravity theories
enhanced scalar perturbations at small scales/primordial black holes
adding phase with stiff equation of state
Potential for discovery of new physics!

GWs from Early Universe: inflation



Lasky 2016

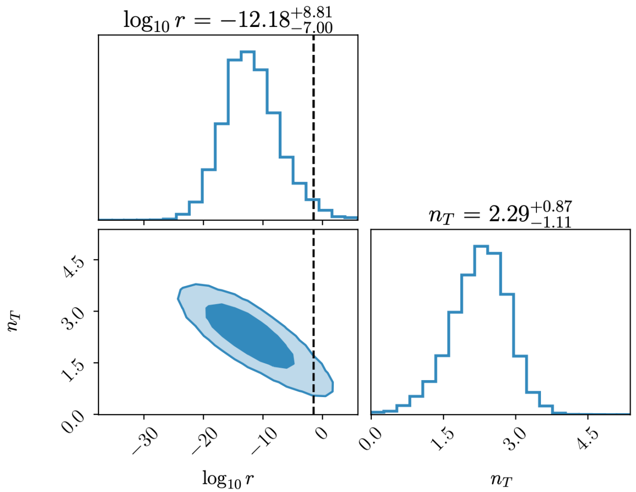
- At large scales, CMB can constrain or hopefully detect scalar-to-tensor ratio r + spectral index n_s, but not ideal for spectral index n_T
- At small scales, PTAs can determine spectral index n_T
- Help ET find background!

Cosmological background in EPTA results?

Use EPTA DR2new with the following model:

$$\Omega_{GW}(f) = \frac{3}{128}\Omega_{rad}\, r\, \mathcal{P}^*_{\mathcal{R}} \left(\frac{f}{f_*}\right)^{n_T} \left[\frac{1}{2}\left(\frac{f_{eq}}{f}\right)^2 + \frac{16}{9}\right]$$

$$\approx 1.5 \times 10^{-16} \left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T},$$



Antoniadis 2023 (arXiv:2306.16912)

r: tensor-to-scalar ratio (~ amplitude of GW)
n_T: tensor spectral index (GW signal)

If we fit EPTA signal with cosmological signal, we find:

$$\log_{10} r = -12.18^{+8.81}_{-7.00}$$

$$n_T = 2.29^{+0.87}_{-1.11}$$

But SMBHB background expected to be more important… like a "foregound"

Summary

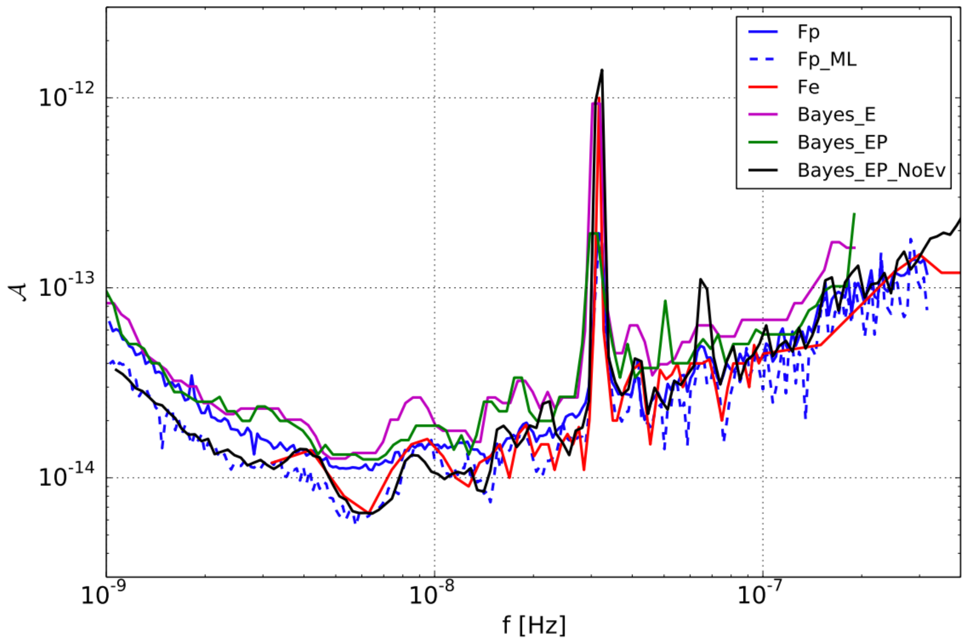
- □PTAs can be used to detect GWs at nanohertz frequencies -> complementary to LISA and LVK/ET
- □Evidence for a GW background!
- □SMBHBs are brightest expected sources
- □Possible cosmological background origin (e.g inflation with blue tilt)
- □Model foreground SMBHBs and background cosmological signal
- □CMB detection -> constrain GW amplitude (r)
- □PTAs can find GW spectral index (n_T) and help ET find cosmological background

Outlook

Need to increase sensitivity of PTA data

- ☐Combine all PTA data to form a more sensitive IPTA dataset
- ☐Improve instrumentation at radio telescopes
- ☐Improve LEAP for better sensitivity
- ☐Synergies with Gaia / astrometric methods
- ☐Mitigation of interstellar medium effects
- ☐Mitigation of effects of solar wind
- ☐Synergies with ET (cosmological background)
- ☐Search for modified gravity (e.g. extra GW polarizations) in PTA data

Upper limits on continuous GW



EPTA: Babak 2015

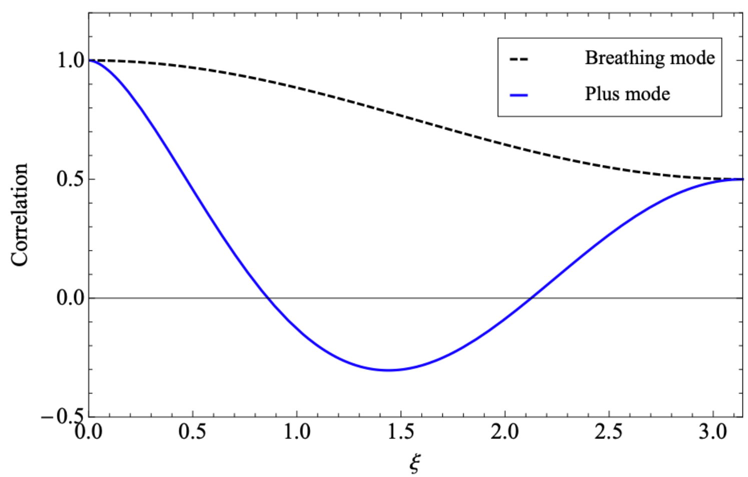
Triangulate -> sky location (tens of square degrees), tens of thousands of potential galaxies

Limits on amplitude -> rule out massive binaries at less than 200 Mpc (beyond Coma)

Additional considerations

Modified H&D curve for anisotropy (Mingarelli 2013, Taylor 2015)

Modified H&D curve for alternative theories of gravity



Chamberlin 2011