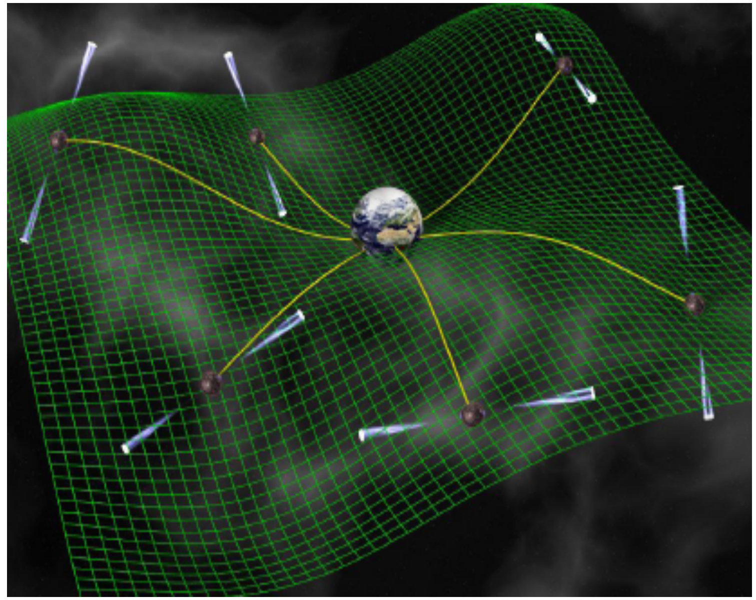


Detecting low-frequency gravitational waves with Pulsar Timing Arrays

Delphine Perrodin

INAF - Osservatorio Astronomico di Cagliari

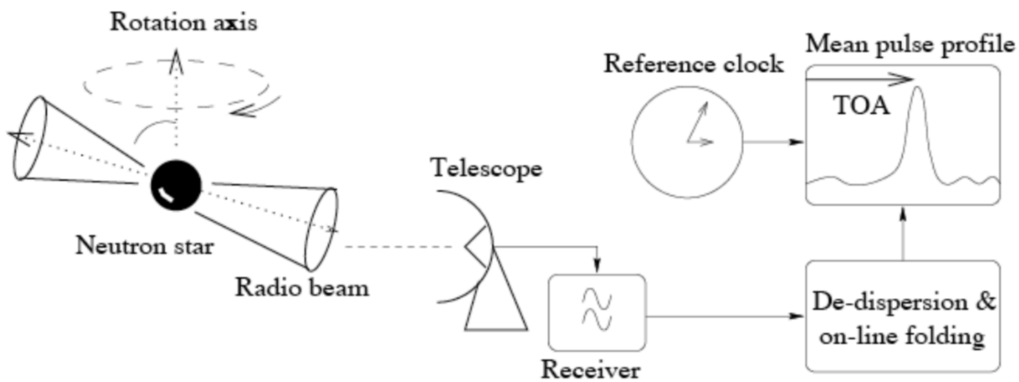
For the EPTA collaboration, including M. Burgay, C. Tiburzi, A. Possenti (INAF-OAC)
A. Chalumeau, G. Shaifullah, A. Sesana (Milano-Biccoca) + M. Crosta (INAF - Torino)

SIGRAV meeting, Trieste, 5 September 2023

Outline

- Principles behind Pulsar Timing Arrays
- PTA collaborations and radio telescopes (e.g. SRT, LEAP)
- Expected signature of GW in pulsar timing residuals
- Latest EPTA results
- Future steps / outlook

Pulsars as clocks for GW detection

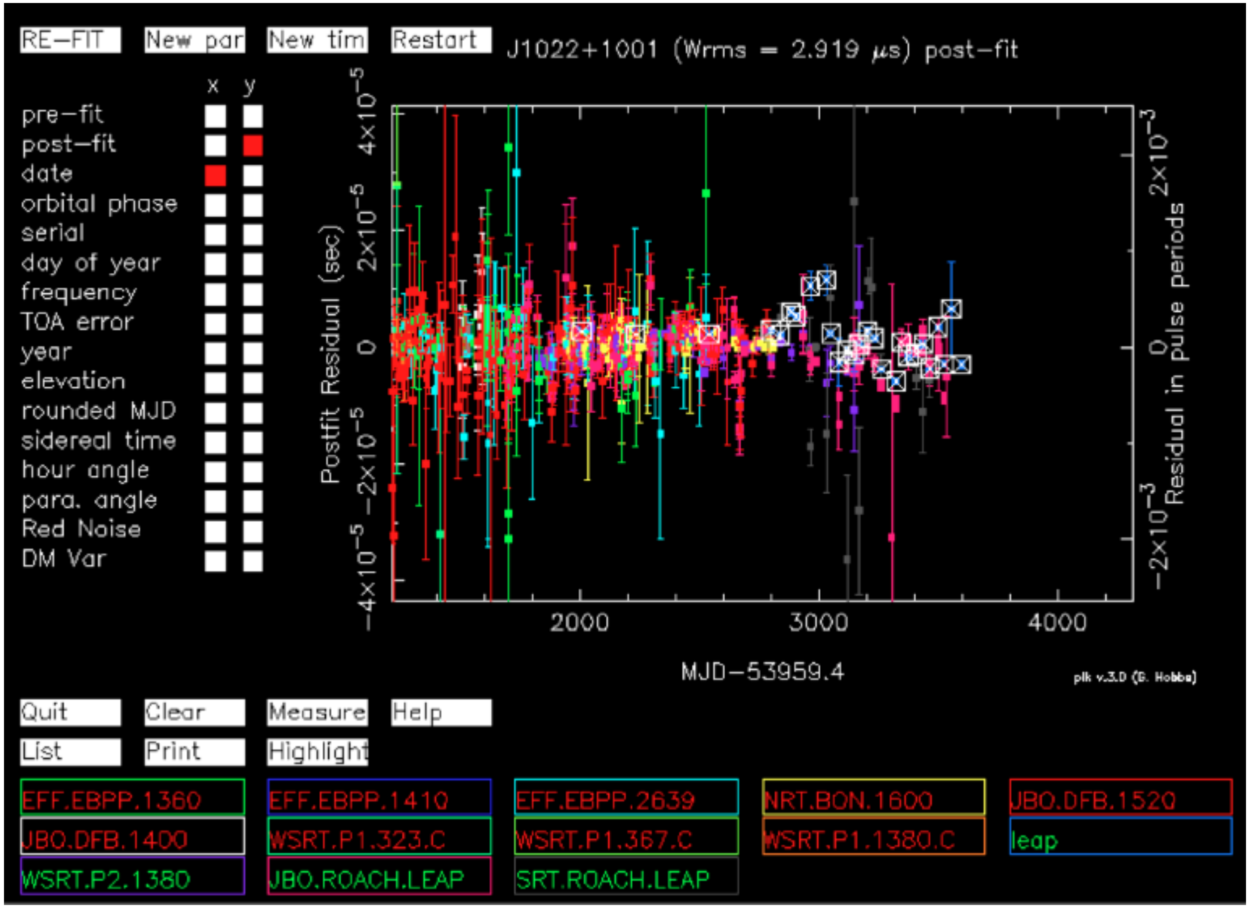


(Lorimer & Kramer 2005)

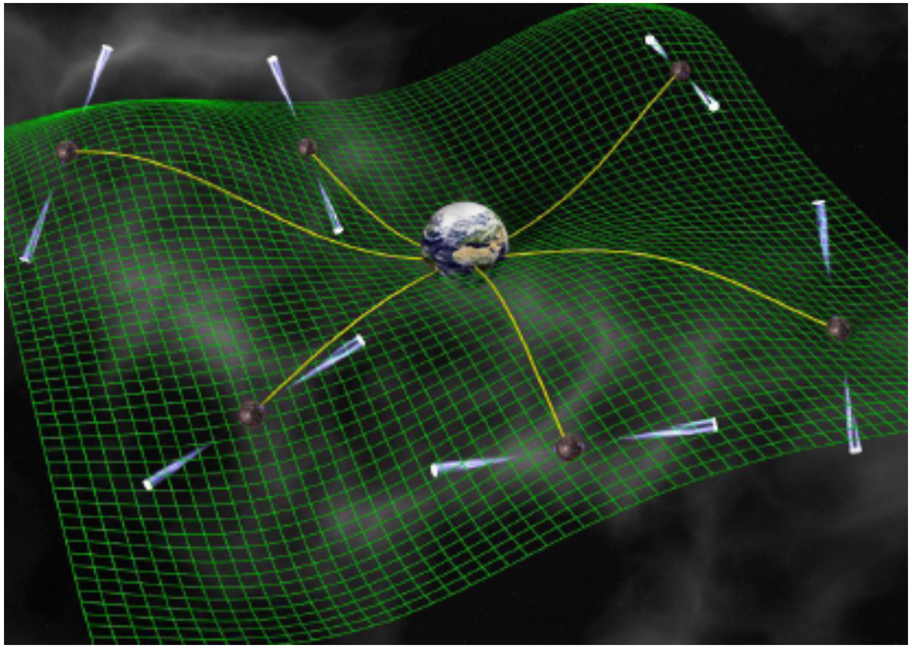
Observe pulsars and measure times-of-arrival (TOAs)
Find the model that best fits TOAs
Calculate timing residual:

Residual = TOA(expected) - TOA(measured)

Pulsar timing residuals



Pulsar Timing Arrays for GW detection

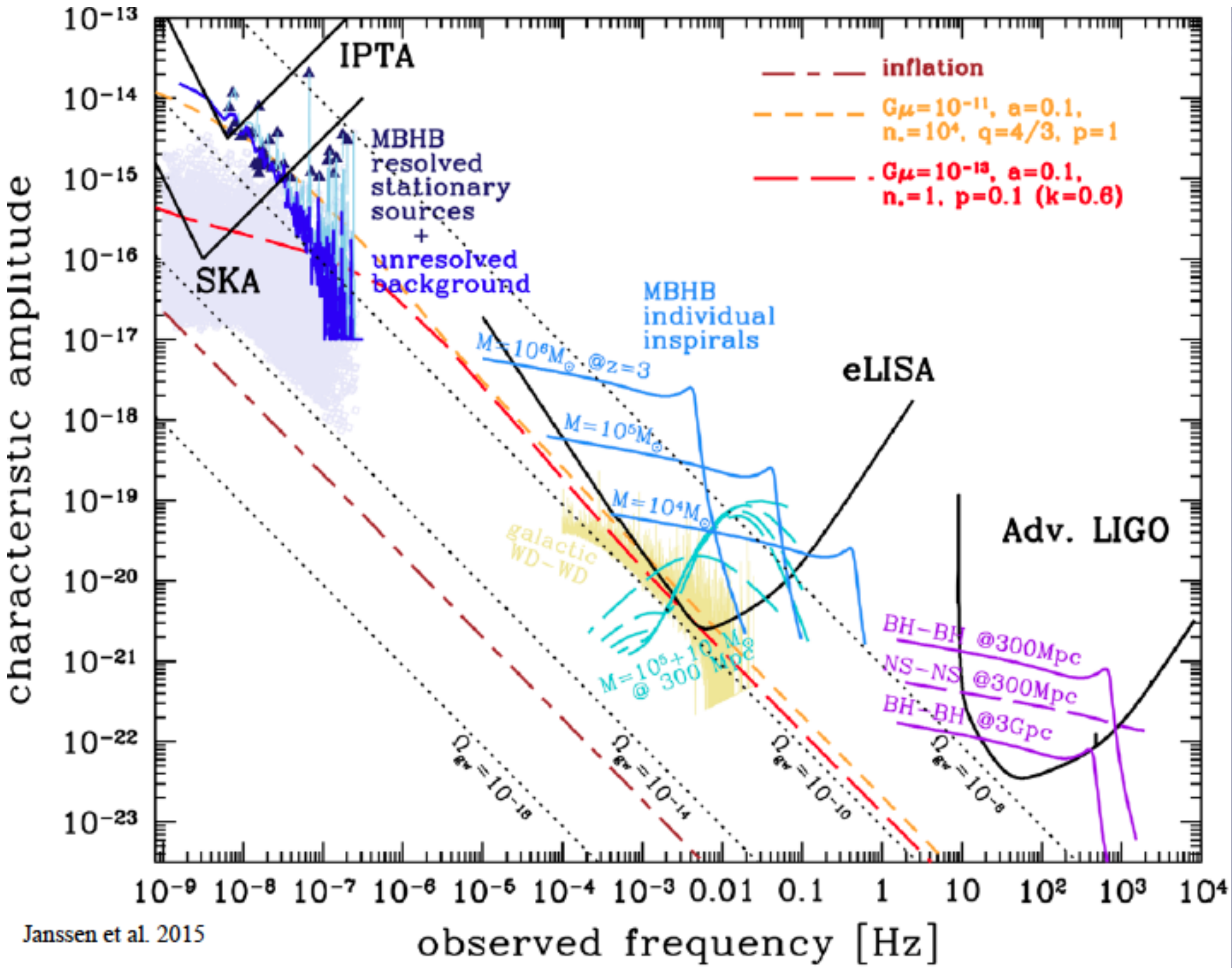


D. Champion

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

PTAs: complementary to LVK and LISA



Janssen et al. 2015

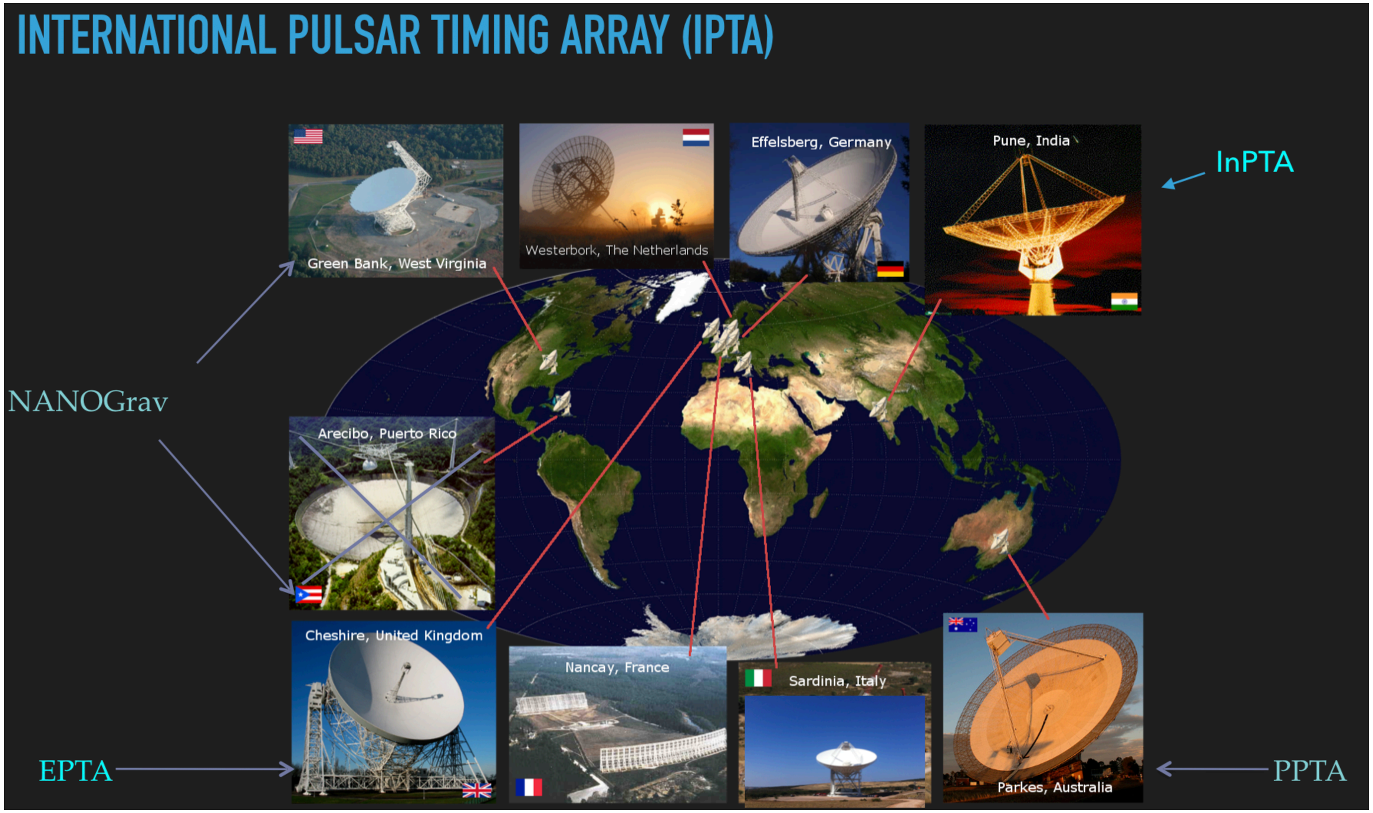
PTAs: frequencies in nanohertz regime

Corresponds to timelines of ~1-30 years

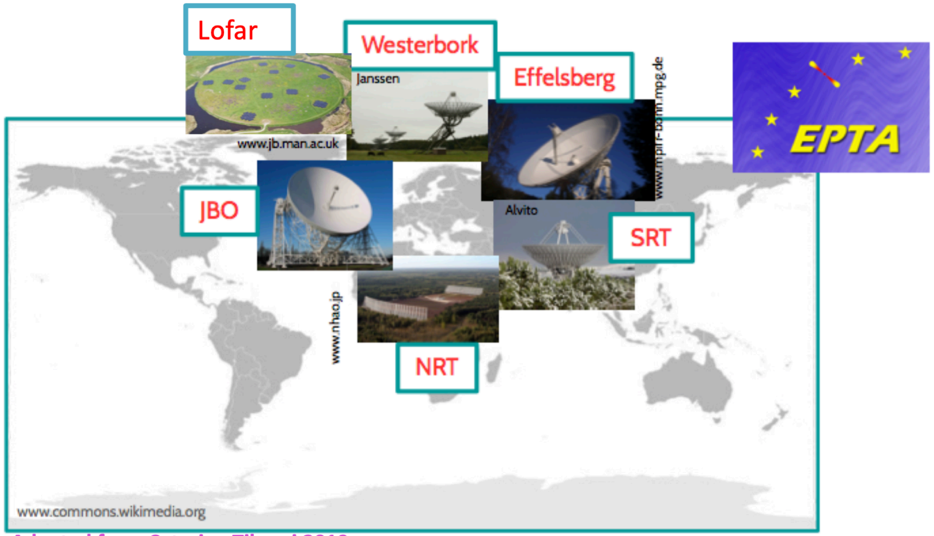
Sources: SMBHBs in slow inspiral, mostly monochromatic

Cosmological sources

International Pulsar Timing Array (IPTA)



European Pulsar Timing Array (EPTA)



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)

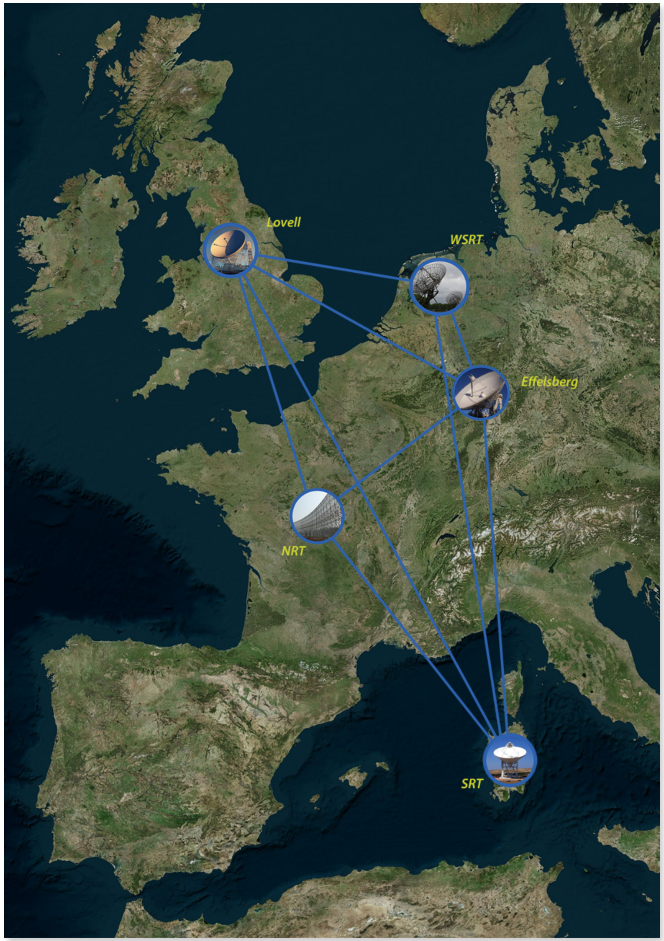
- In San Basilio (Sardinia), inaugurated in 2013
- Fully-steerable 64-m diameter dish
- Can host 20 receivers, 6 focal positions
- Wide frequency range (300 MHz to 115 GHz) with active surface
- Dual L/P (1300-1800 MHz and 300-400 MHz) band receiver ideal for pulsar observations
- So far, pulsar observations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

SRT Sardinia Radio Telescope

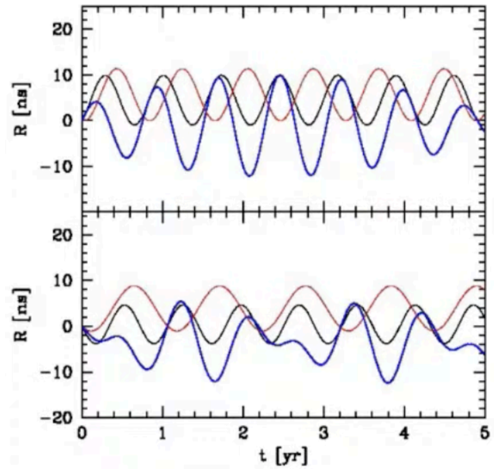
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Large European Array for Pulsars (LEAP)

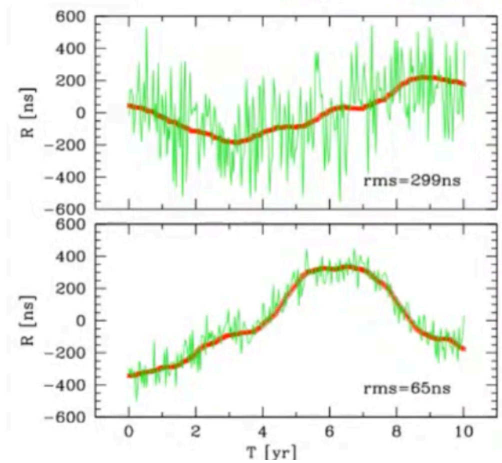
- EPTA's "sixth telescope"
- Monthly simultaneous observations of ~22 pulsars at L-band (BW=128 MHz) at 4 EPTA telescopes in baseband mode
- Coherently combine baseband data to produce combined baseband and archive files
- Sensitivity equivalent to 194-m dish (~ SKA-1); boost sensitivity at L-band
-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

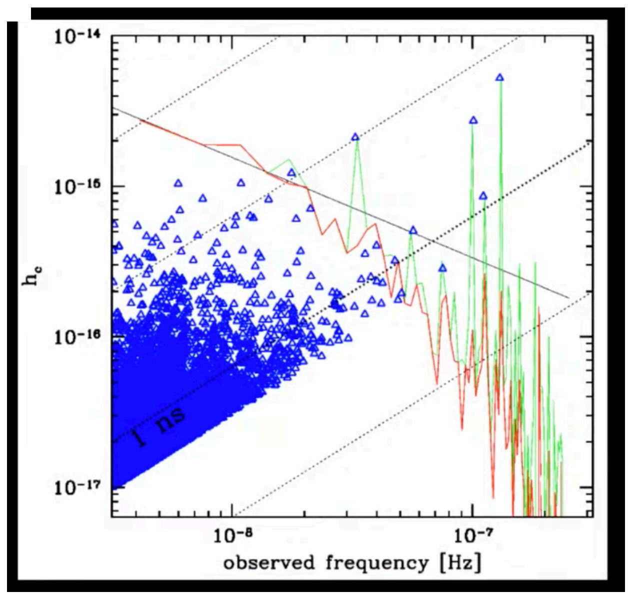


Imprint of SMBHB GW source on timing residuals



Individual GW source





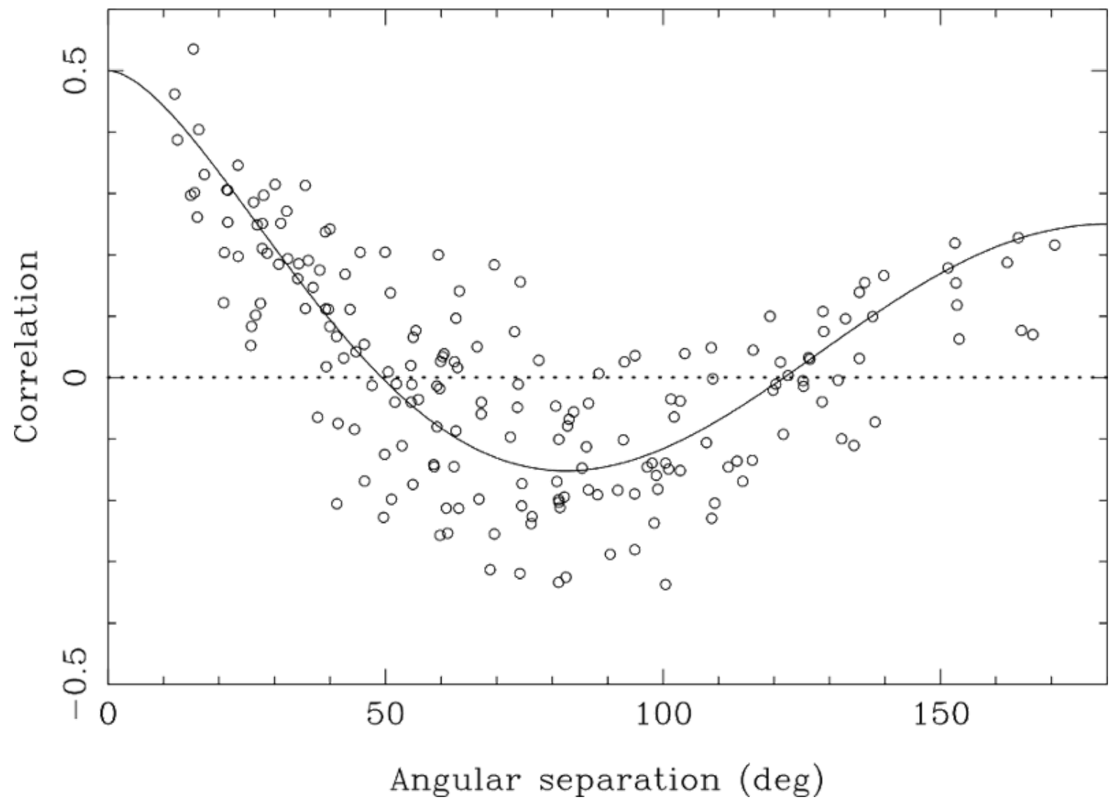
GW background:
Red noise in timing residuals

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



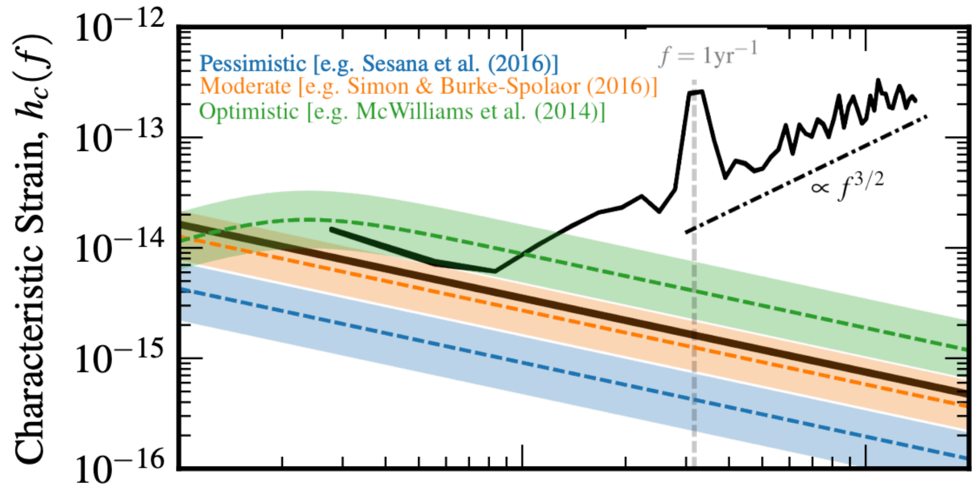
Hellings & Downs 1983

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



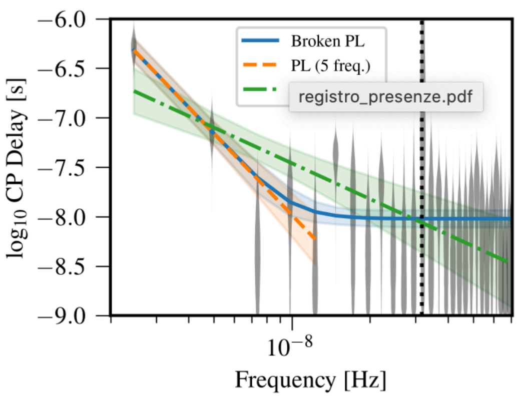
Arzoumanian 2018

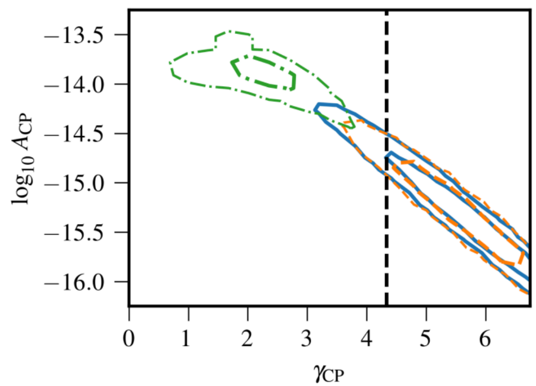
Upper limits (non-detection) on background

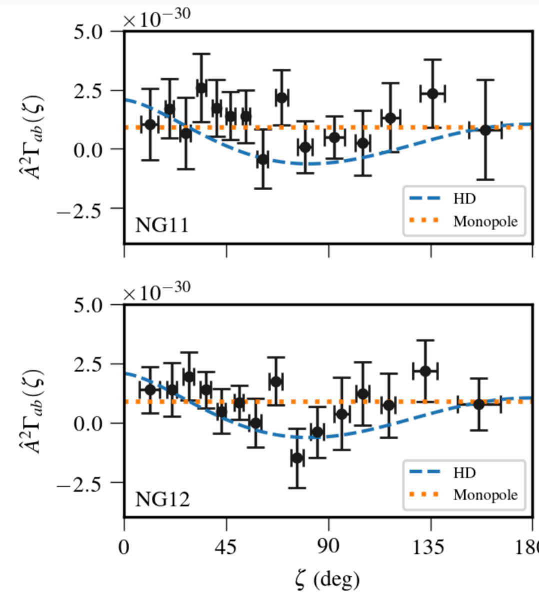
NANOGrav: Arzoumanian et al. (2015)
EPTA: Lentati et al (2015)
PPTA: Shannon et al (2015)
IPTA: Verbiest et al (2016)

Detection of common red signal (2020)

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

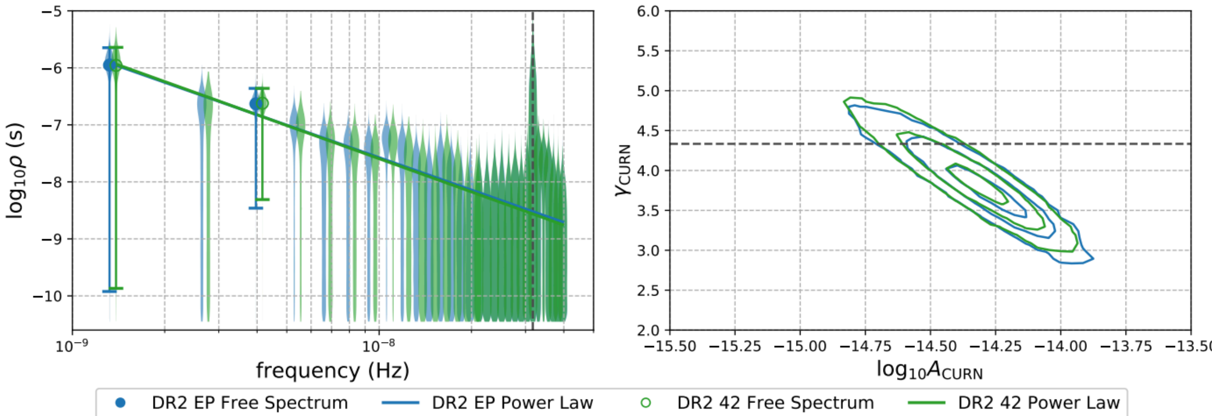






No evidence of HD correlation

Common red signal seen in several datasets



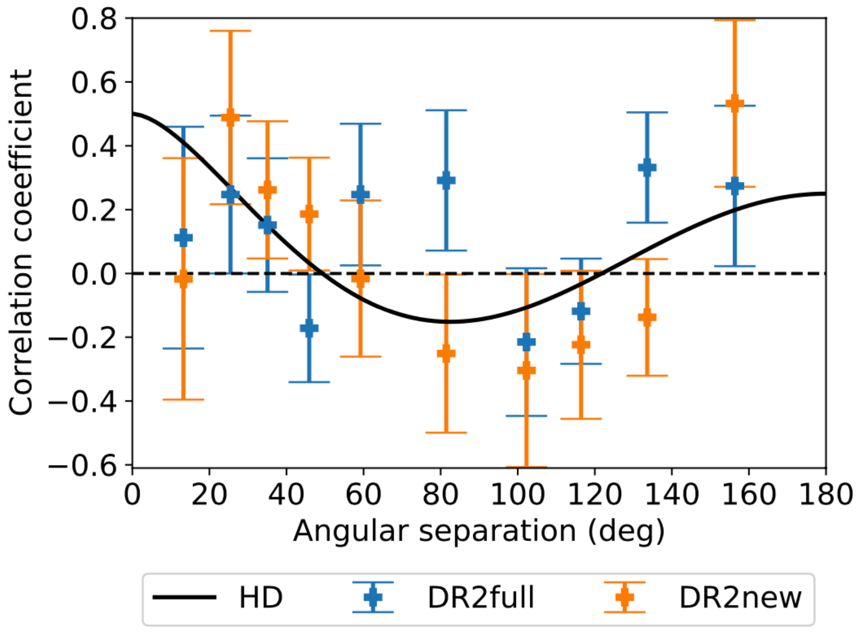
EPTA: Chen 2021

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")

EPTA Data Release 2 (2023) + InPTA

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

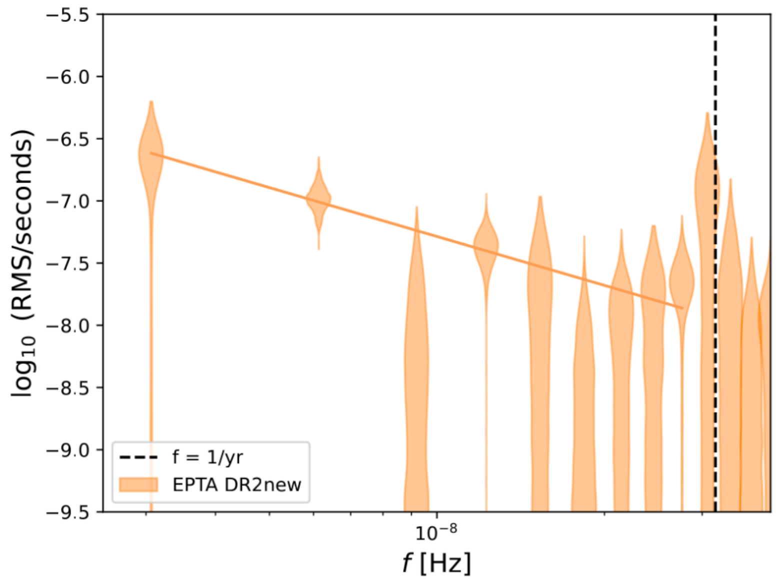


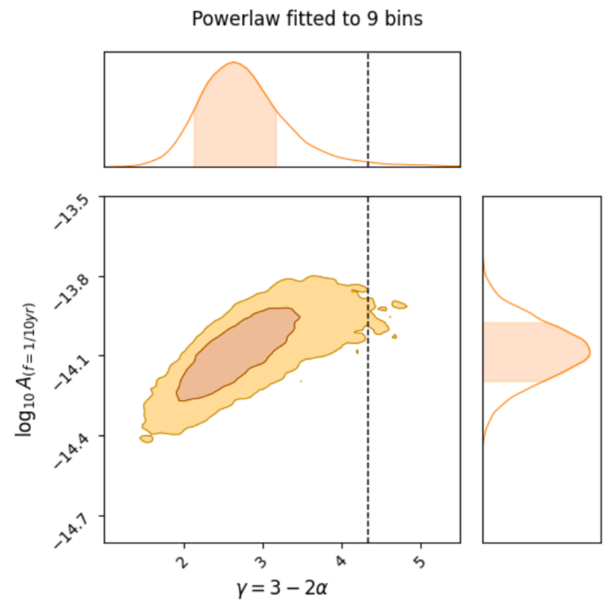
Antoniadis 2023 (arXiv:2306.16214)

Hellings & Downs correlation
BF ~ 60
Signal consistent with GW

Consistent with results from NANOGrav, PPTA, CPTA

EPTA Data Release 2 (2023)



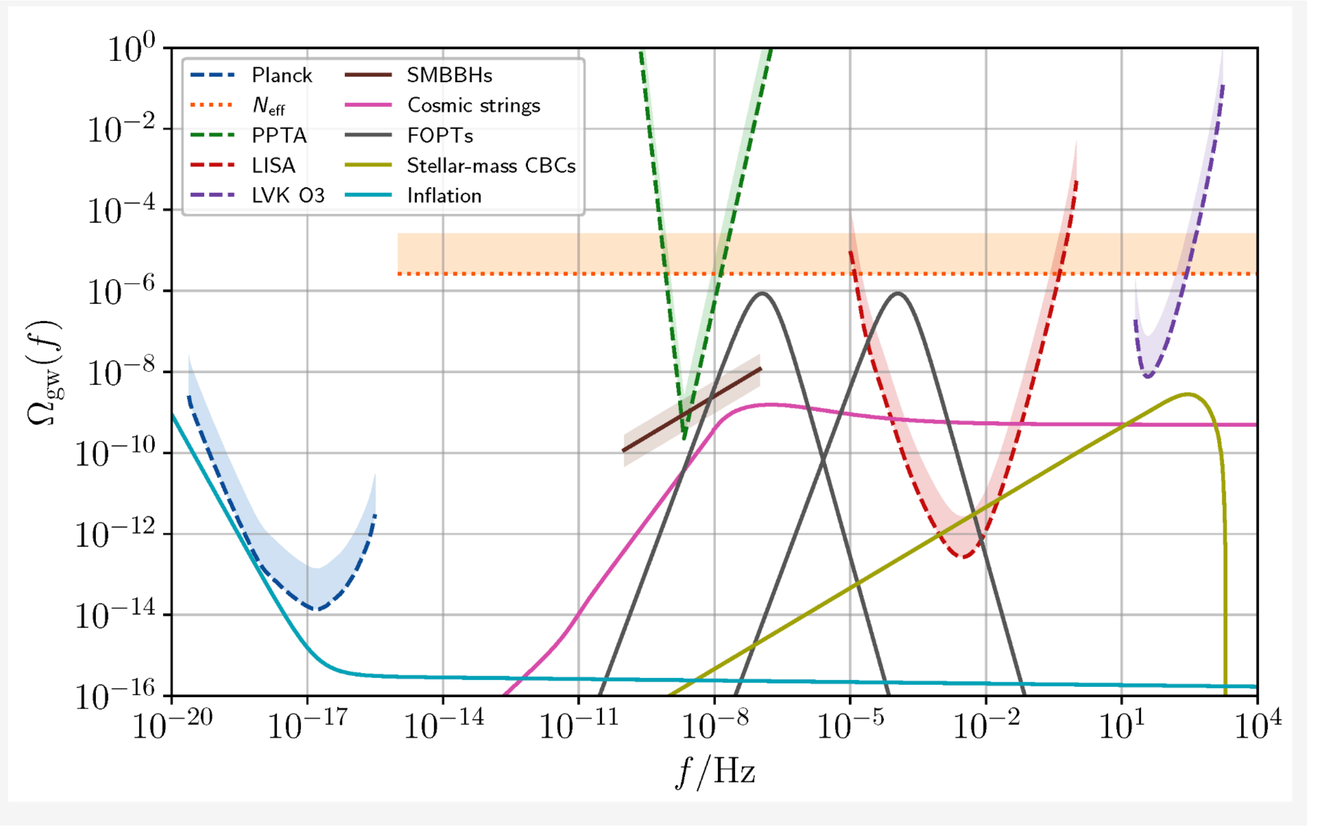


Antoniadis 2023 (arXiv:2306.16912)

using DR2new
Gamma ~ 2.7 (low)
A ~ - 14 (huge!)
Consistent with SMBHB origin

See G. Shaifullah's talk for details on the timing dataset
See A. Chalumeau's talk for the analysis of pulsar timing noise

Possible GW sources



SMBHBs

Inflation

Axion-like particles

Phase transitions

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

Scalar perturbations/ Primordial black holes

Renzini 2022

See A. Sesana's talk for science implications

Summary

- PTAs can be used to detect GWs at nanohertz frequencies
- SMBHB are brightest expected sources
- Detection of a common red process consistent with GW background, and in particular with SMBHB background
- Possible cosmological background origin

Roadmap for the future:
e.g. HD curve correlation at 5 sigma

The International Pulsar Timing Array checklist for the detection of nanohertz gravitational waves

Bruce Allen,[1] Sanjeev Dhurandhar,[2] Yashwant Gupta,[3] Maura McLaughlin,[4] Priyamvada Natarajan,[5,6] Ryan M. Shannon,[7,8] Eric Thrane,[9,10] and Alberto Vecchio[11]

Outlook: how to achieve a 5sigma detection?

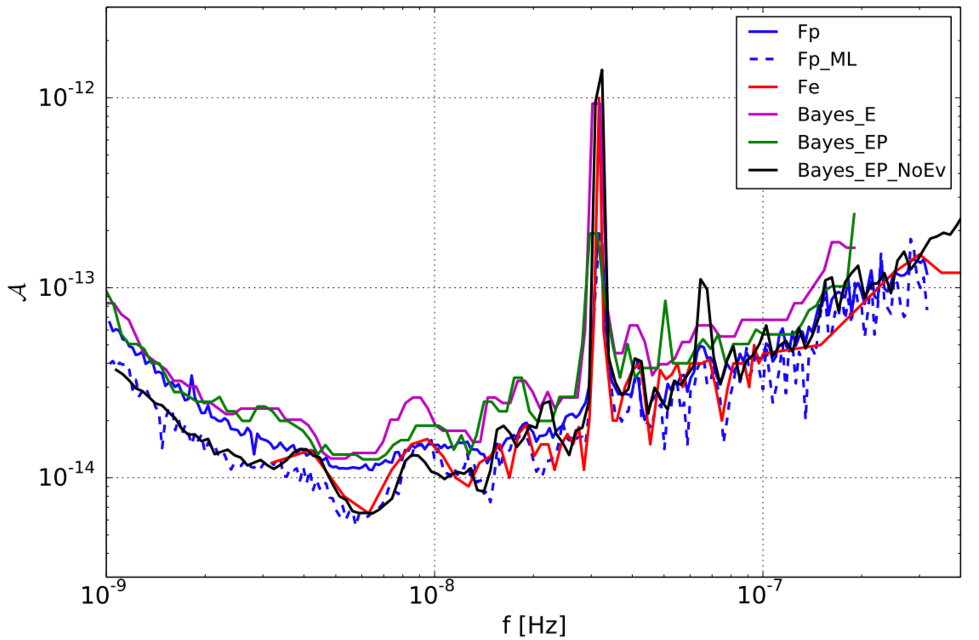
To detect GW with a high significance, we need to achieve a higher sensitivity.
This can be done by:

- Combining the data already collected by the various PTAs to form a global IPTA dataset (ongoing work)
- Collecting more data at the same telescopes (to obtain longer dataspans)
- Using MeerKAT, FAST in operation since 2017 and in the future, SKA
- Working together (IPTA-DAWG) to understand systematics at various telescopes around the world in order to achieve better data combination
- Better understanding effects of the interstellar medium and solar wind
- Use Gaia in parallel with PTAs to search for GW

PTA expertise in Italy (Cagliari + Milan)

- **PTA expertise: observing, data reduction, data combination and GW data analysis**
- **Members of EPTA and LEAP and operators/users of the SRT, experience with commissioning of telescope and instrumentation**
- **Expert users of MeerKAT and members of MeerTime**
- **Contribute to IPTA working groups: observing strategy, data combination, detection, SKA observing, instrumentation, data preparation**
- **Members of SKA working groups on pulsars**
- **Theoretical GW expertise at University Milano-Bicocca (A. Sesana's group)**
- **Combining PTA and Gaia data at Bicocca and INAF-Torino (M. Crosta's group)**
- **Italy in a strategic position to develop capabilities for GW detection and GW science with PTAs**

Upper limits on continuous GW



EPTA: Babak 2015

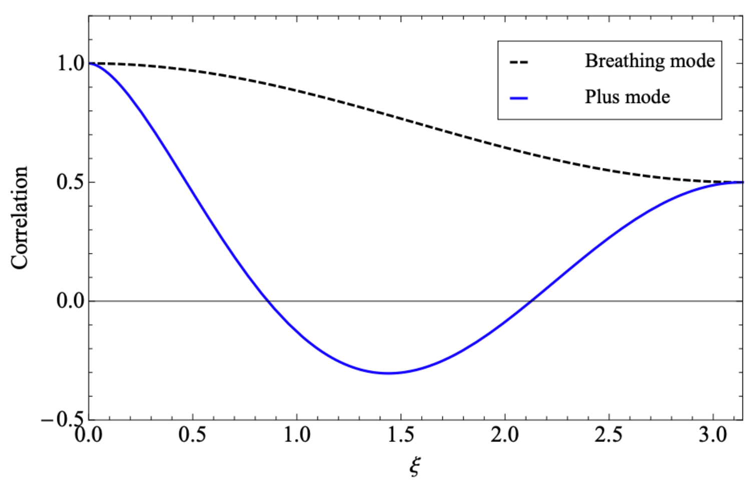
Triangulate -> sky location (tens of square degrees), tens of thousands of potential galaxies

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