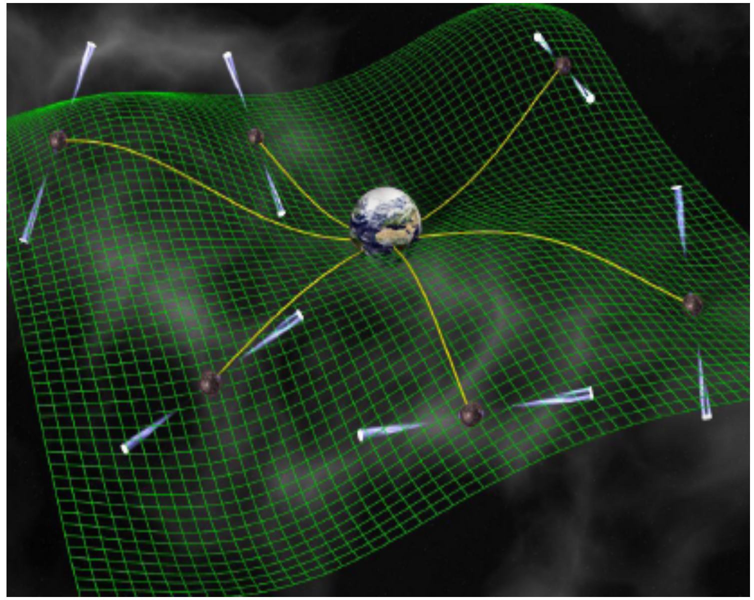

Pulsar Timing Arrays (PTAs)
Science & Perspectives

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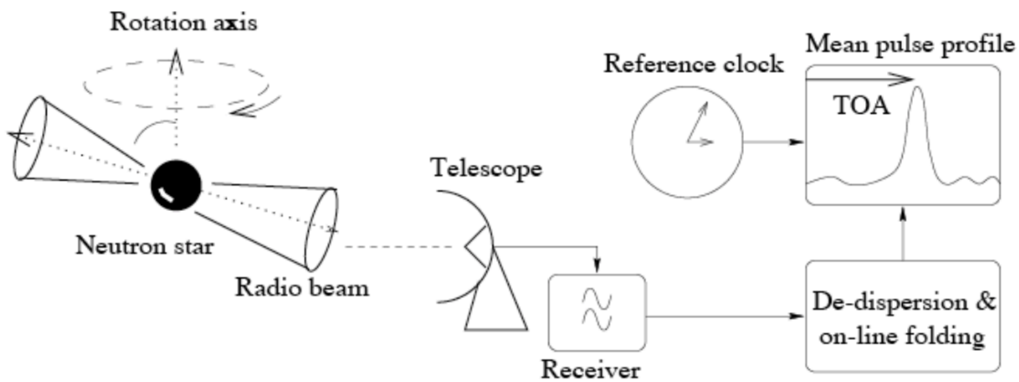
INAF – Osservatorio Astronomico di Cagliari (Italy)

Outline

- Principles behind PTAs
- Sources detectable with PTAs
- Constraints and predictions
- Outlook

Pulsars as clocks for GW detection

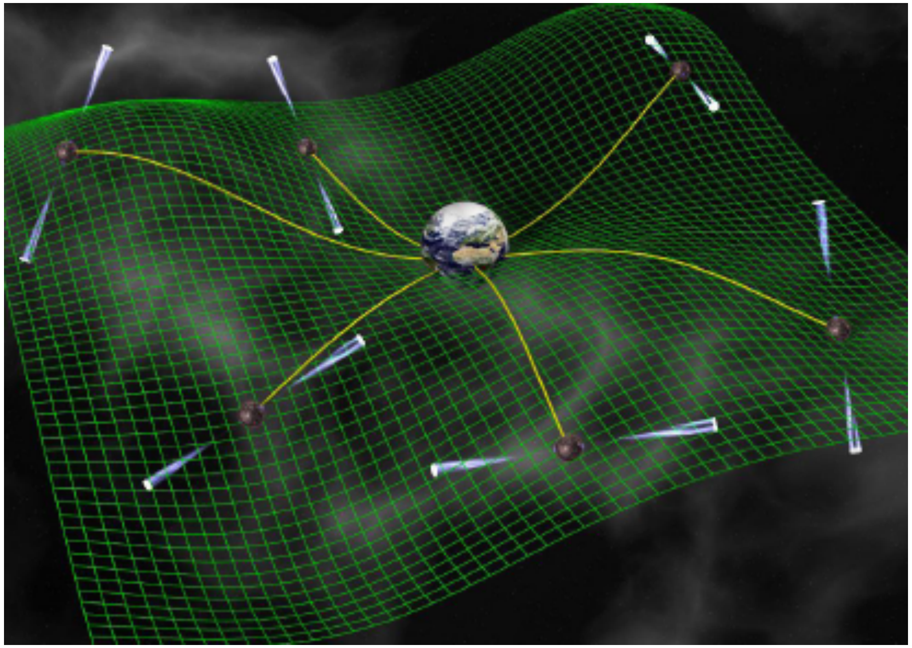


(Lorimer & Kramer 2005)

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 Arrays for GW detection

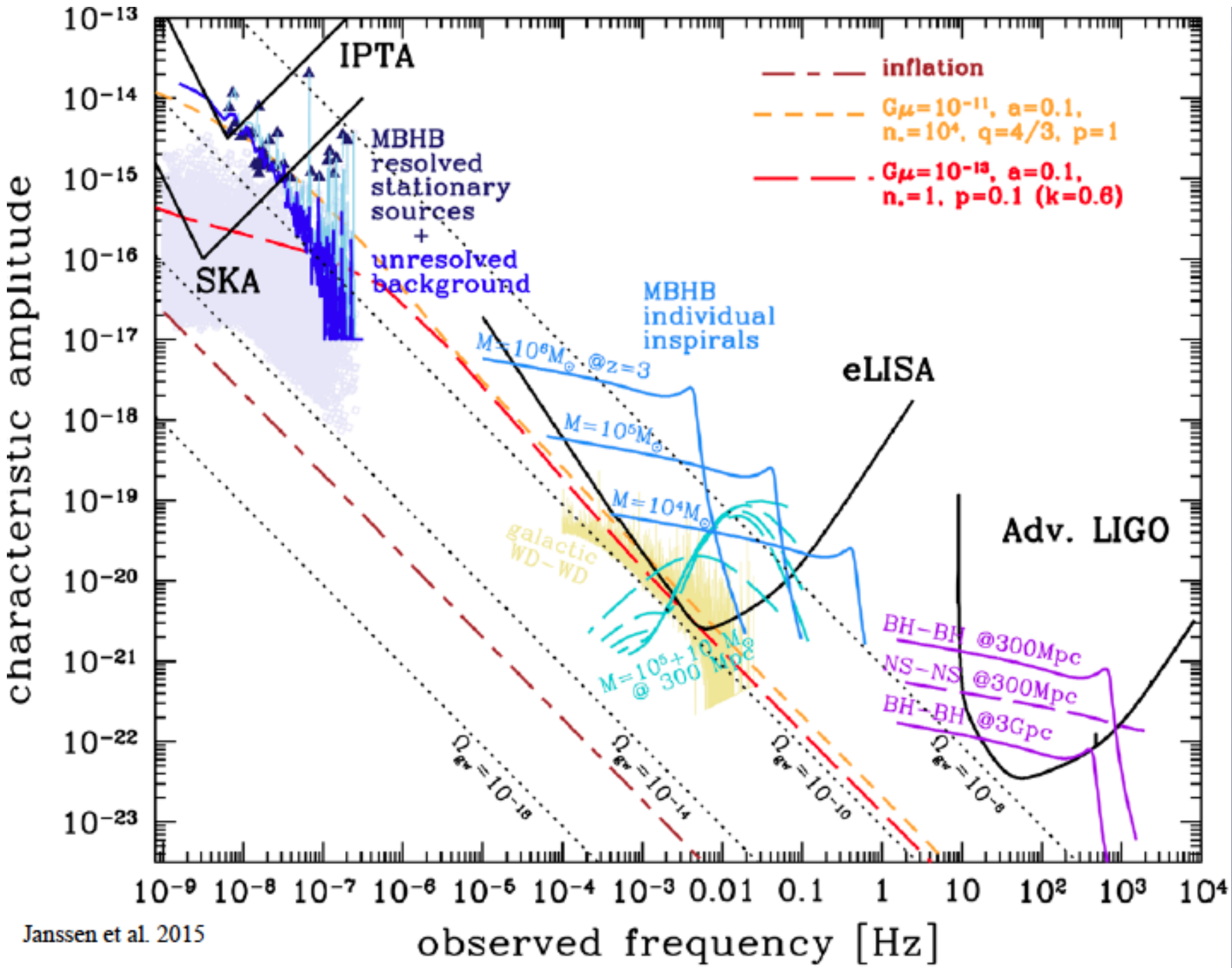


D. Champion

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

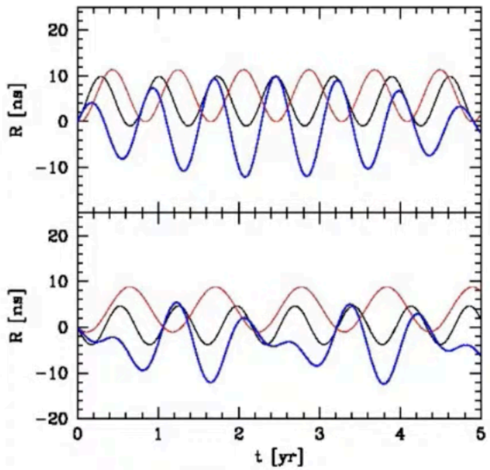
Cosmological sources

Supermassive Black Hole Binaries

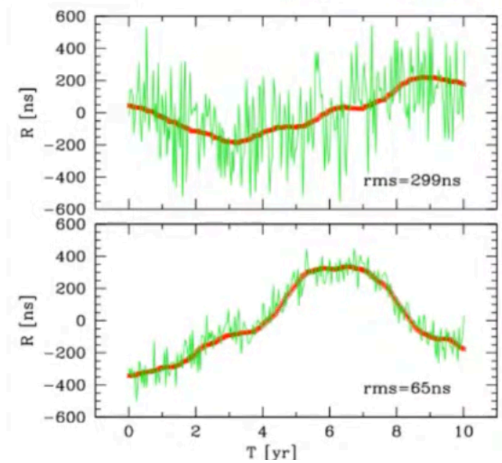
- SMBHBs found in centers of galaxies
- Want to study formation and evolution of SMBHBs
- Hierarchical scenario of structure formation

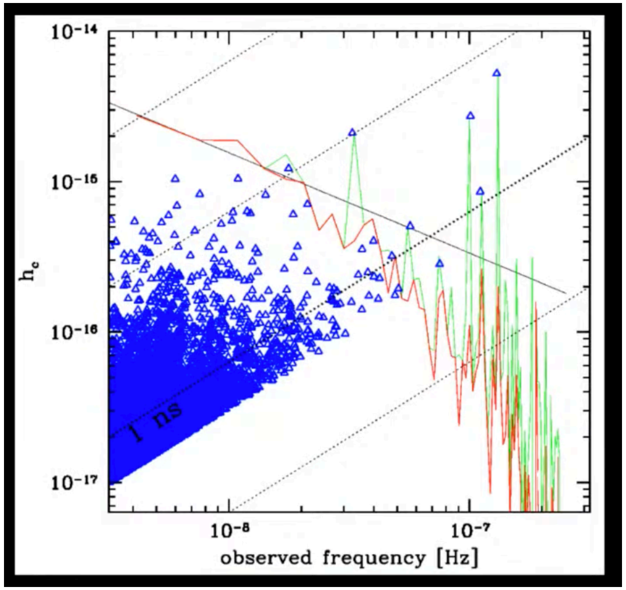
- Where and when do first SMBH seeds form?
- How do they grow?
- Role of galaxy evolution?
- Merger rate?

SMBHB sources



Individual GW source





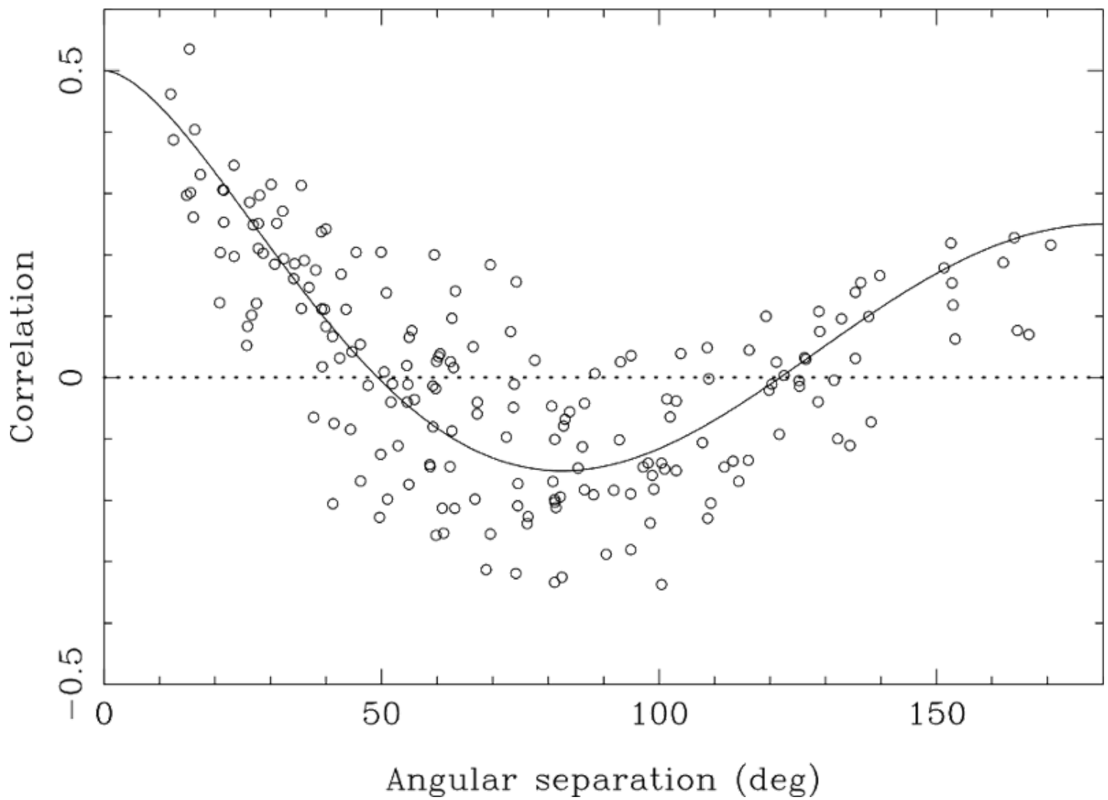
GW background:
Red noise in timing residuals

Phinney 2003

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

Plots by A. Sesana

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



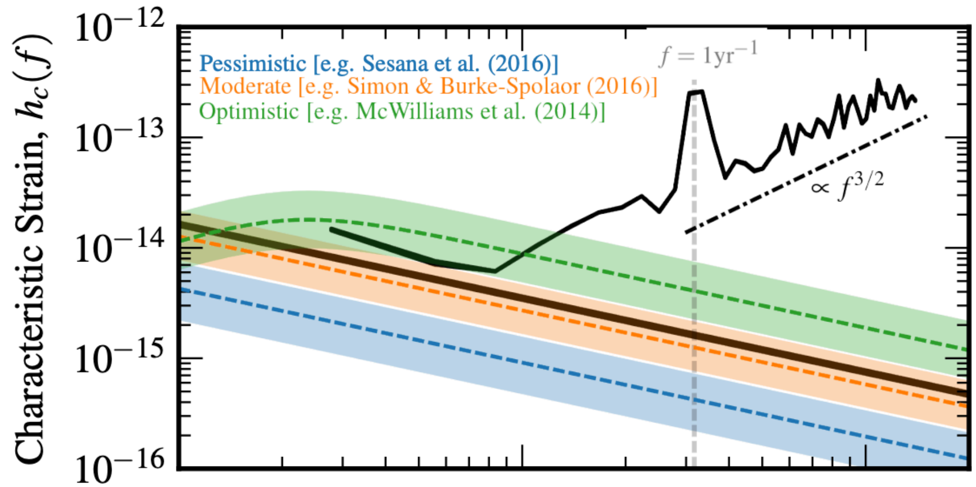
Hellings & Downs 1983

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

Search methods based on likelihood function

PTAs: constraints on SMBHB background

Getting to where we can expect signal

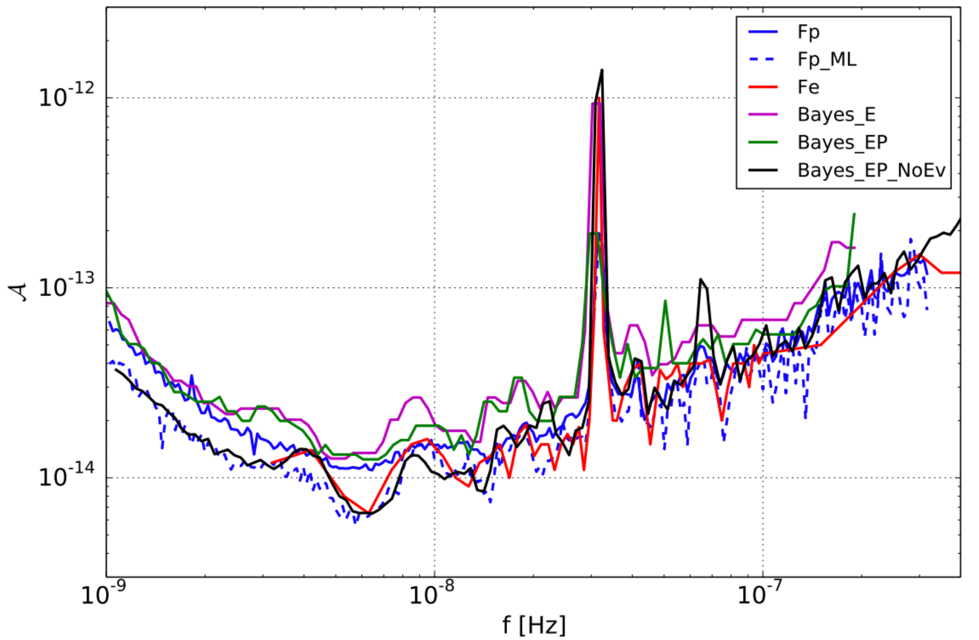


Arzoumanian 2018

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)

Upper limits on continuous GW



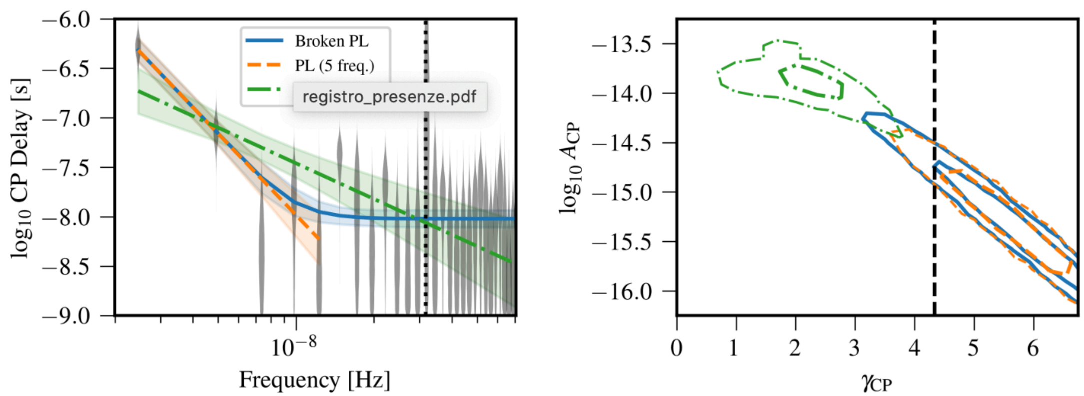
EPTA: Babak 2015

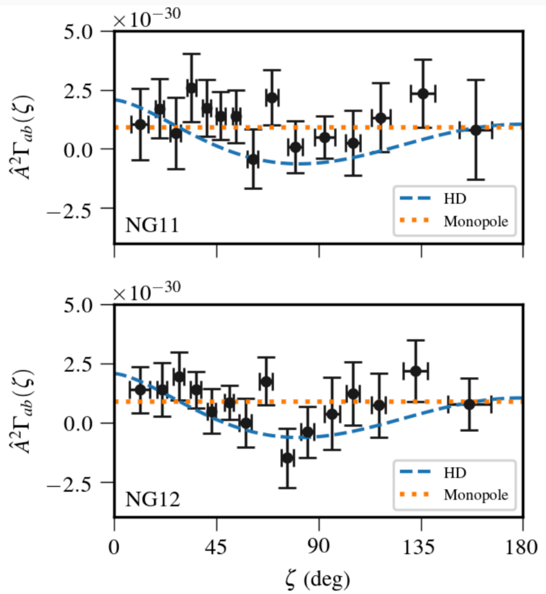
Triangulate -> sky location (tens of square degrees), tens of thousands of potential galaxies

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

Detection of common red signal (2020)

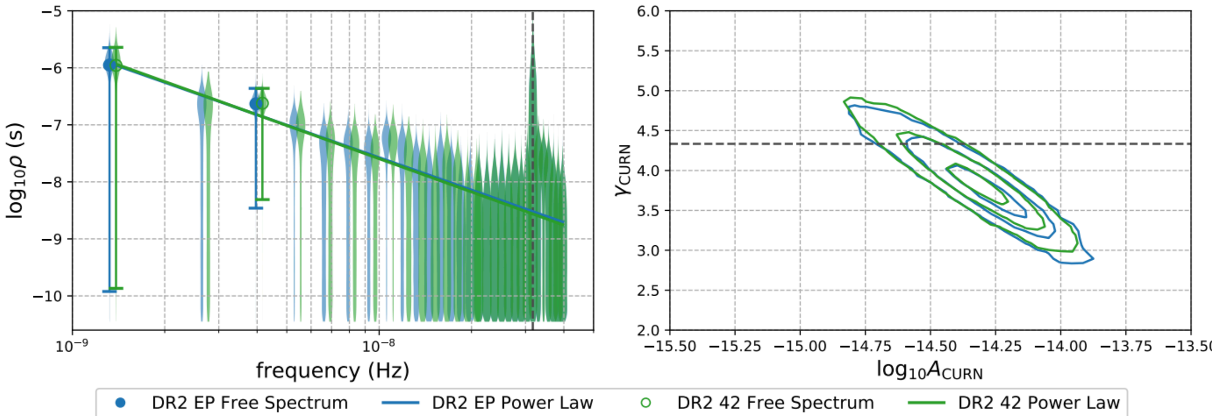
NANOGrav: 12.5 year data analysis
Bayesian analysis of 43 pulsars
Accounting for solar system ephemerides





No evidence of HD correlation

Common red signal seen in several datasets

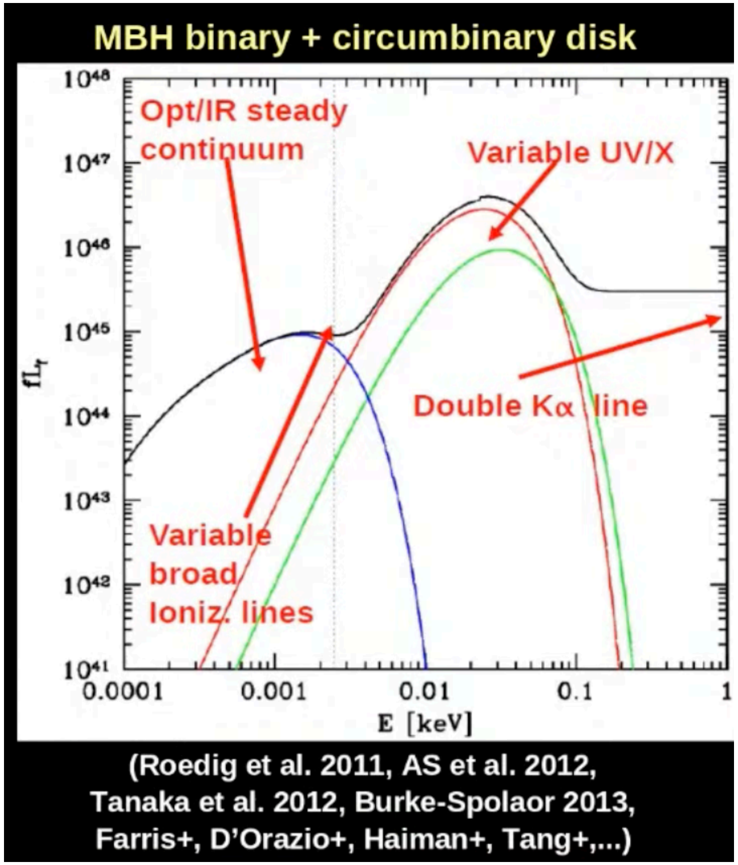


EPTA: Chen 2021

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")

Electromagnetic counterparts? MBH binary + circumbinary disk

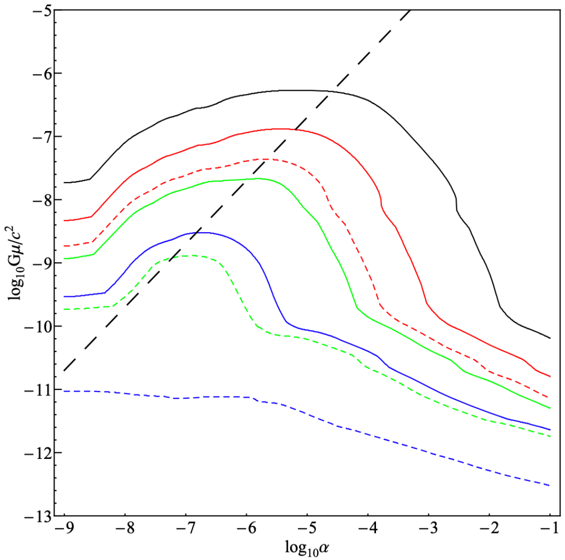


Cosmology

Constraints on cosmic strings

Other possible sources:

First order phase transition
Domain walls
Primordial black holes
Inflation
Axion-like particles



Sanidas 2012

Outlook

To detect GW, need to achieve higher sensitivity. This can be done by:

- Collecting more data at the same telescopes (to obtain longer dataspans)
- Using MeerKAT, FAST in operation since 2017
- Using SKA

Conclusion

- PTAs can be used to detect GWs at nanohertz frequencies
- SMBHB are brightest expected sources
- Can learn about dynamics and merger of massive black holes (merger rate density, environment coupling, eccentricity etc.)
- Detection of a common red process consistent with GW background
- If confirmed, consistent in particular with SMBHB background
- Investigate cosmological backgrounds

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

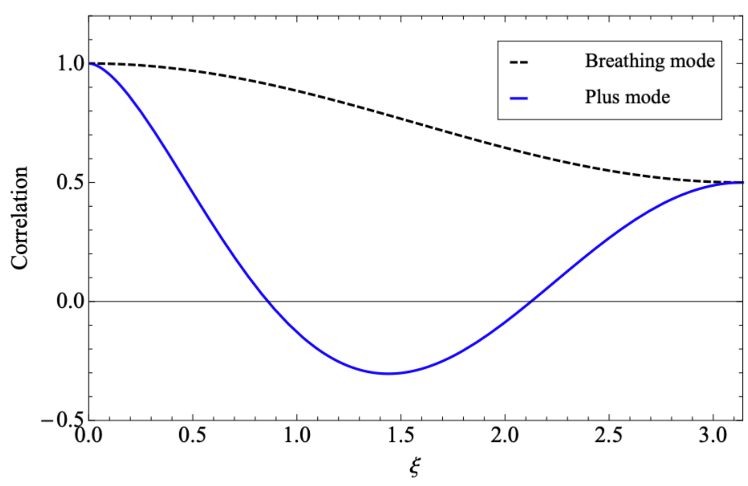
The International Pulsar Timing Array checklist for the detection of nanohertz gravitational waves

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]

Additional considerations

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

Modified H&D curve for alternative theories of gravity



Chamberlin 2011