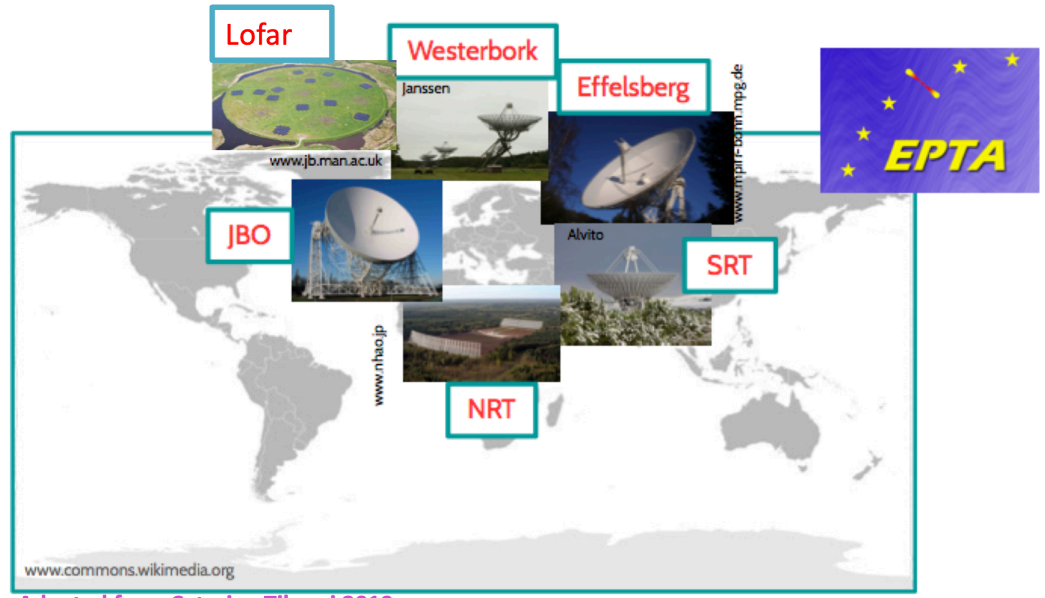

Adapted from Caterina Tiburzi 2019

EPTA results & implications for early Universe physics

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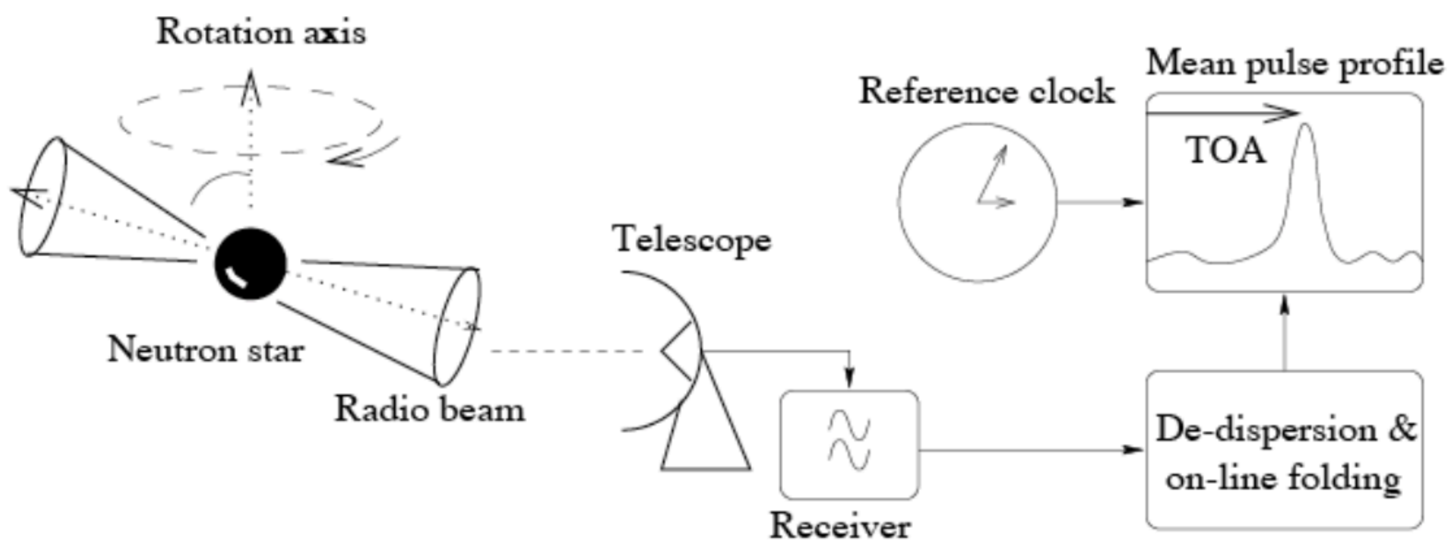
INAF – Osservatorio Astronomico di Cagliari (Italy)
for the EPTA collaboration

CMBS4 Collaboration Meeting, 1 August 2023

Outline

- Principles behind Pulsar Timing Arrays
- Latest EPTA results
- Sources detectable with PTAs
- SMBHB background
- Cosmological backgrounds
- Inflationary scenarios

Pulsars as clocks for GW detection

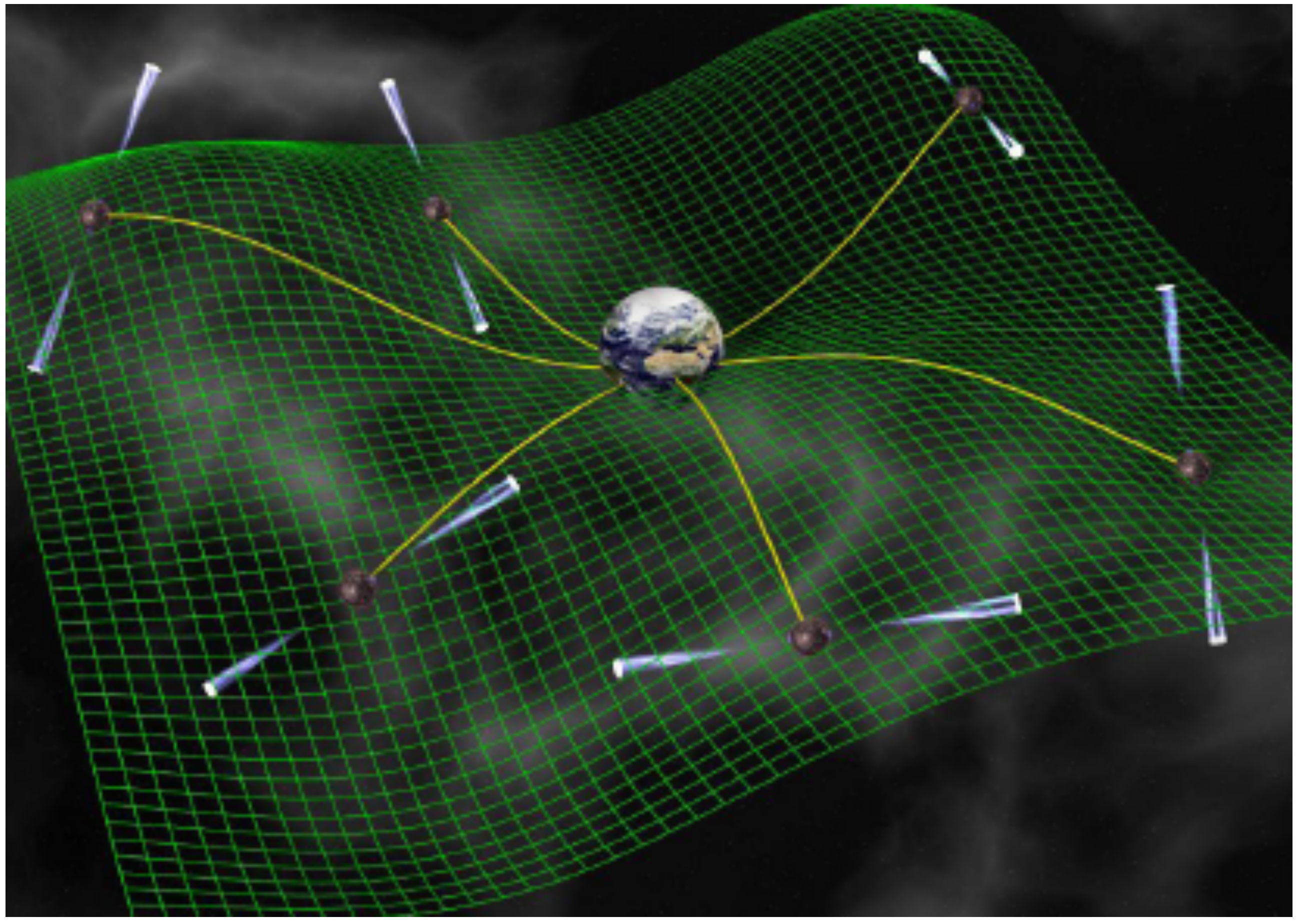


(Lorimer & Kramer 2005)

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



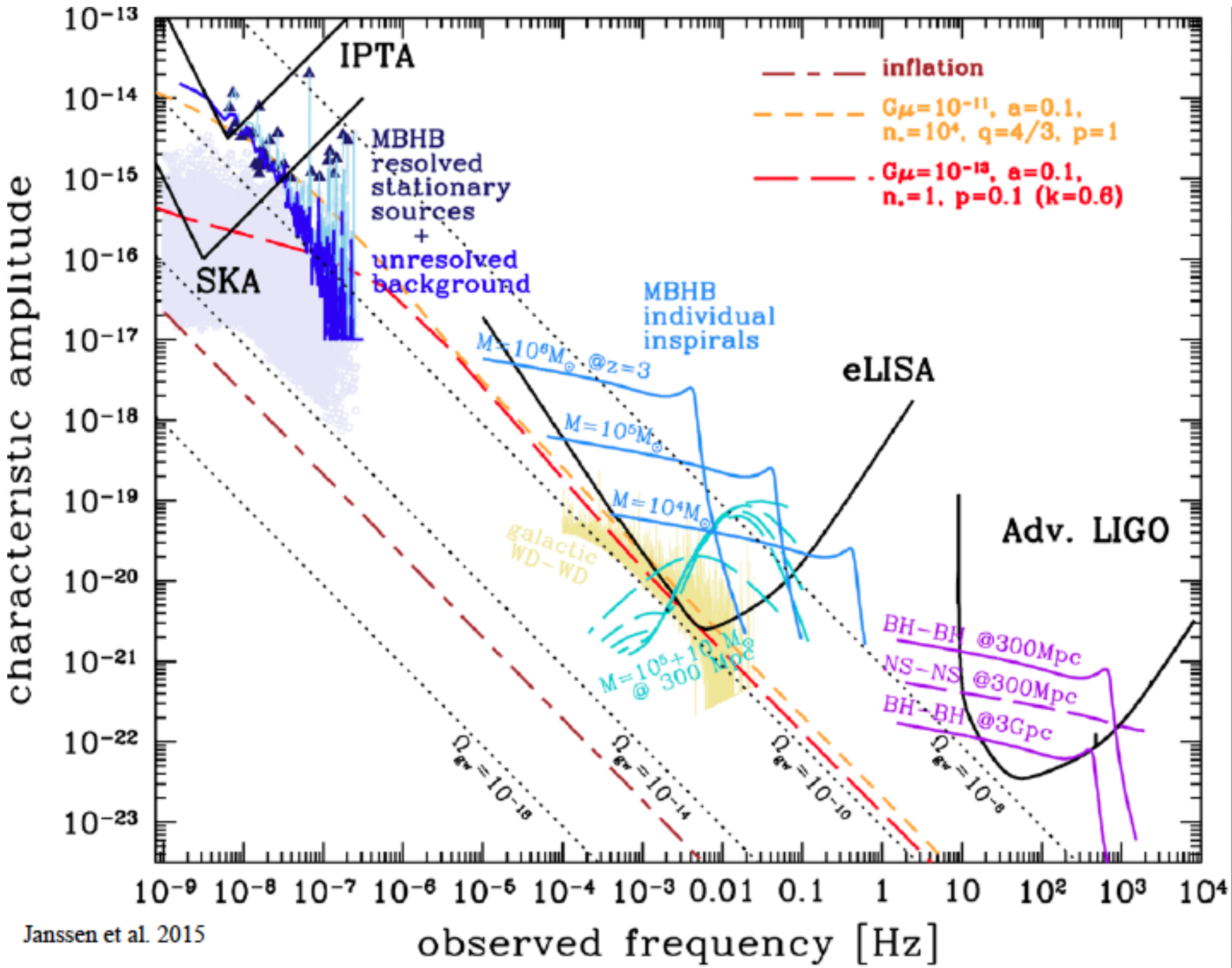
D. Champion

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

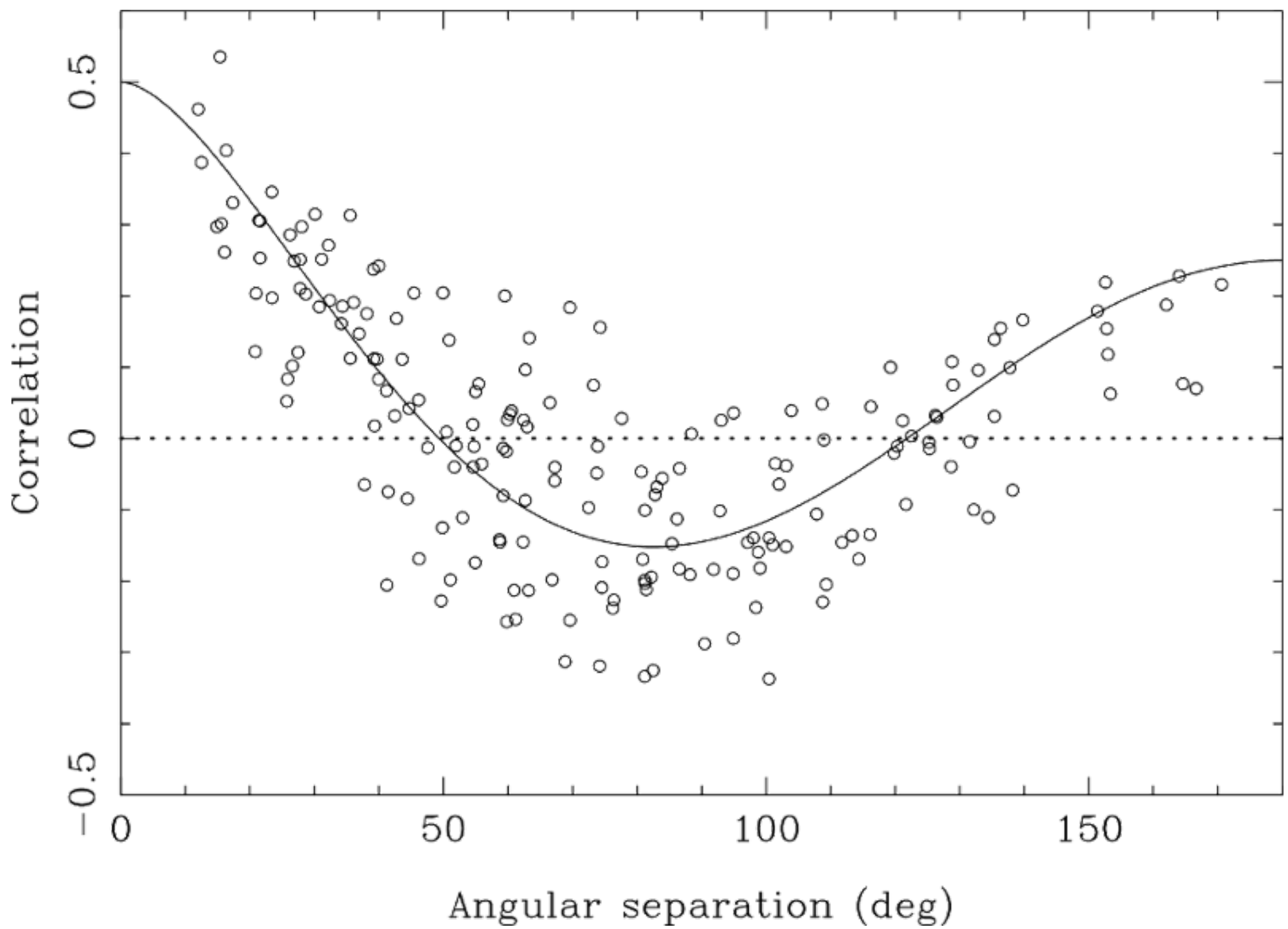
PTAs: frequencies in nanohertz regime

Corresponds to timelines of ~1-30 years

Sources: SMBHBs in slow inspiral, mostly monochromatic

Cosmological sources

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

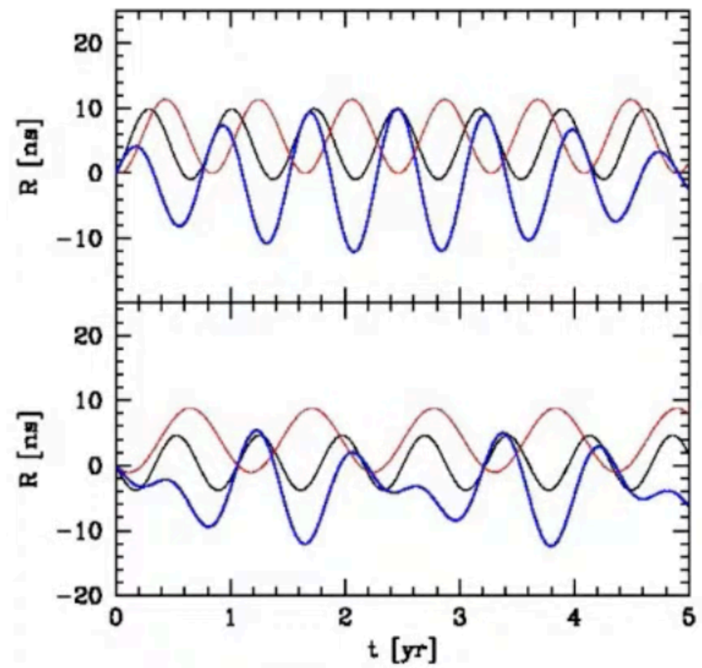
Search methods based on likelihood function

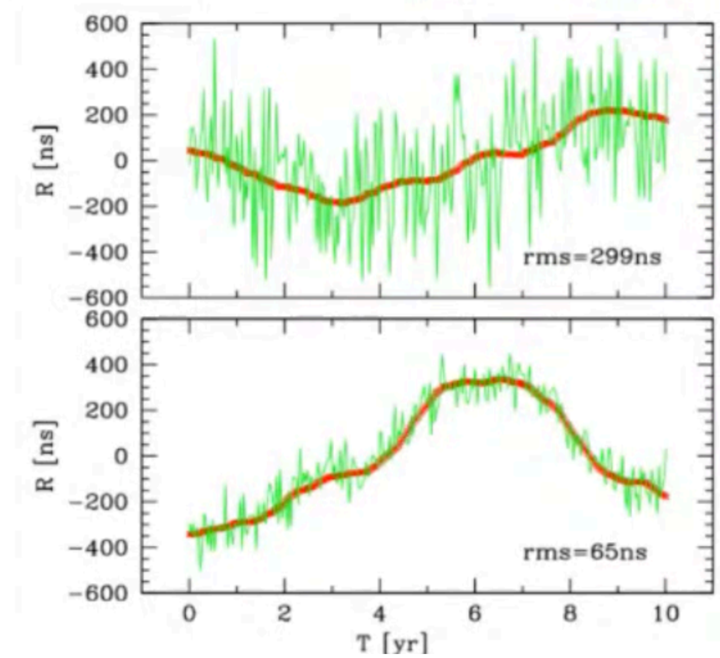
Supermassive Black Hole Binaries

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

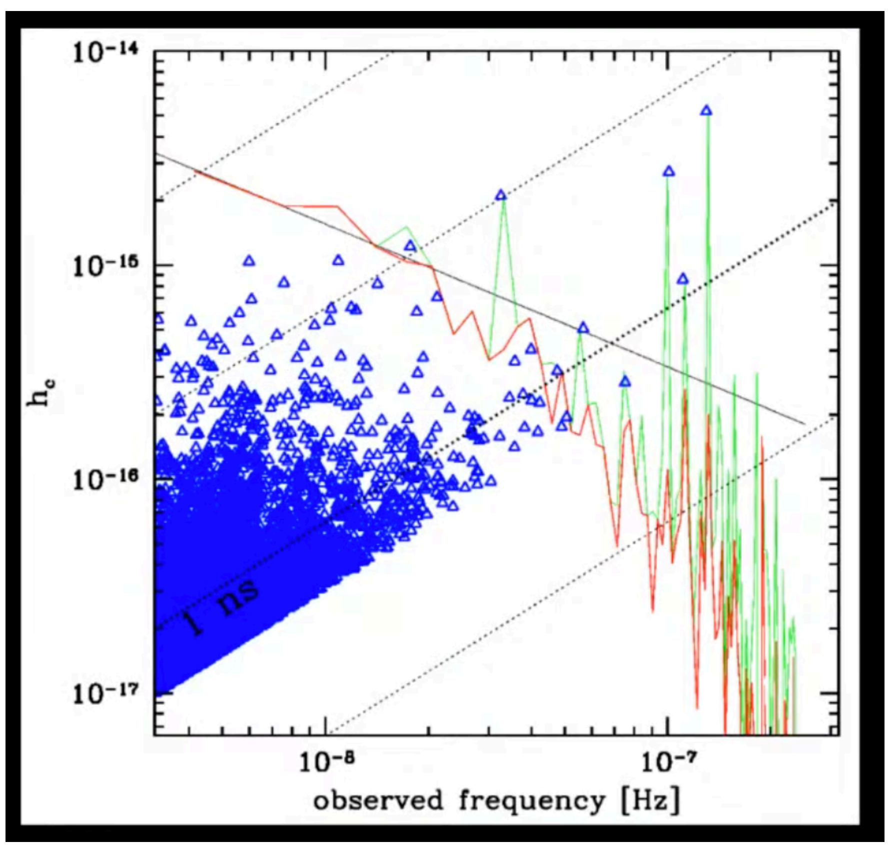
- Where and when do first SMBH seeds form?
- How do they grow?
- Role of galaxy evolution?
- Merger rate?

SMBHB sources





Individual GW source



GW background:
Red noise in timing residuals

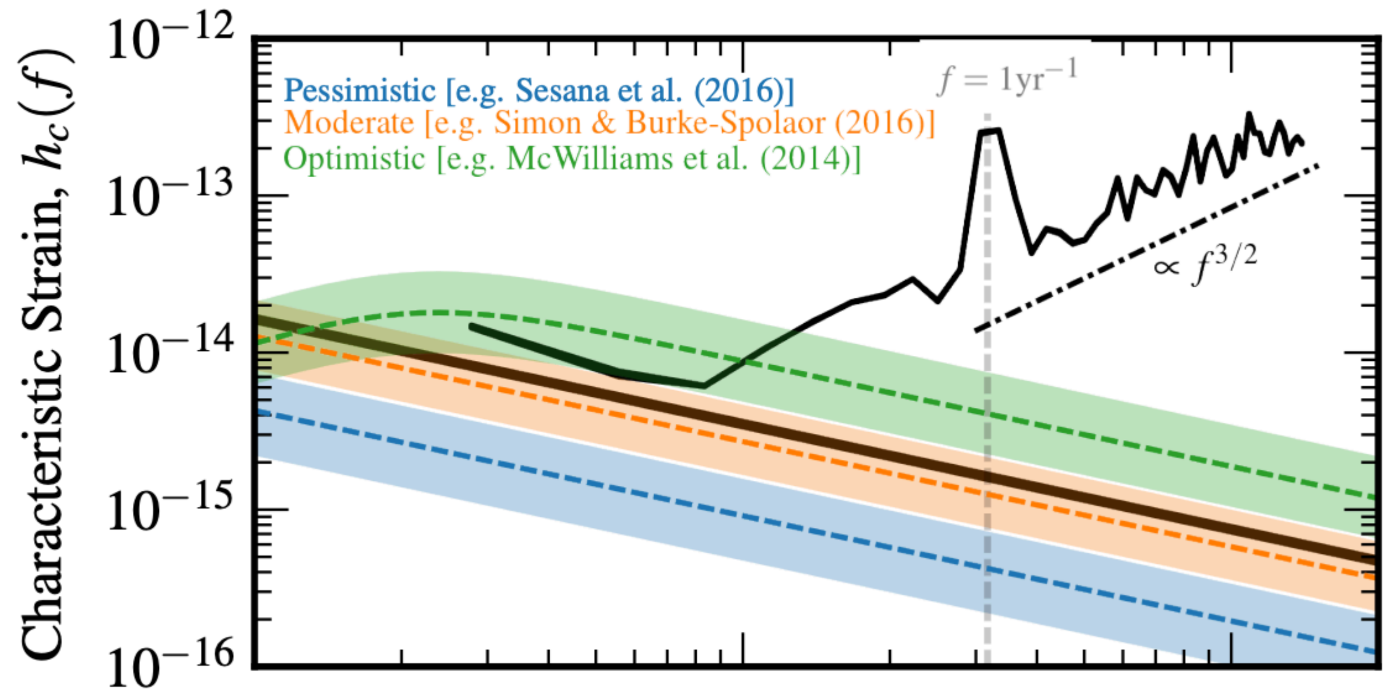
Phinney 2003

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

Plots by S. Burke-Spolaor/A. Sesana

PTAs: constraints on SMBHB background

Getting to where we can expect signal



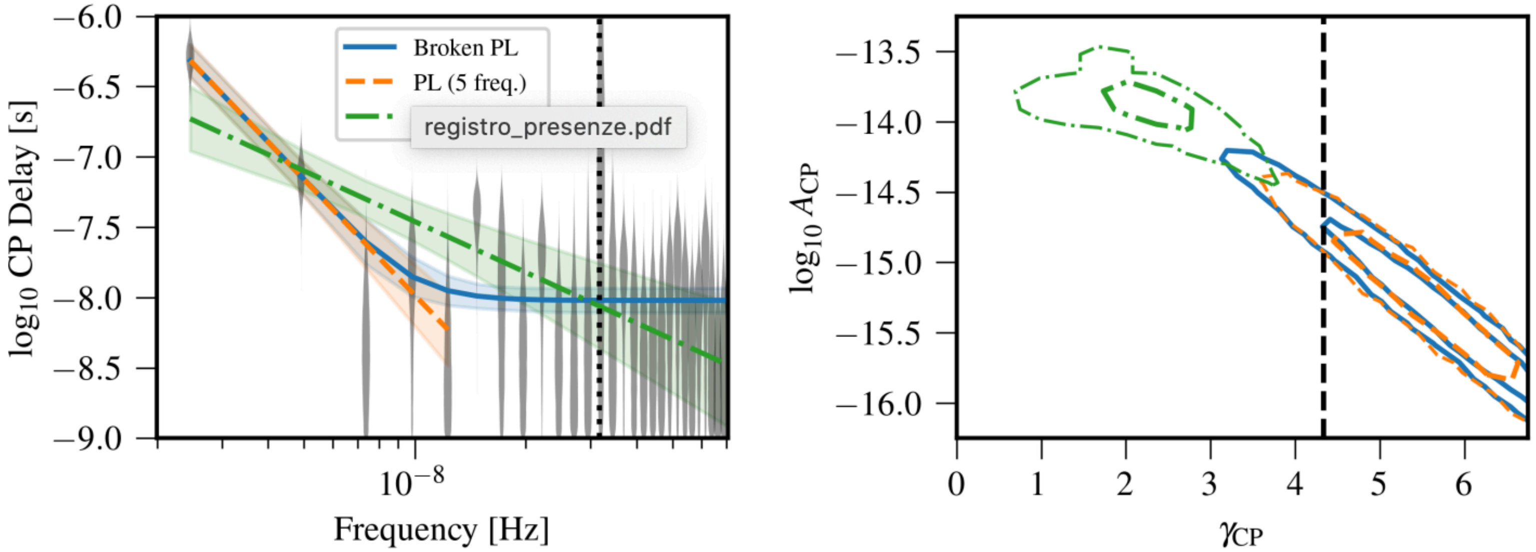
Arzoumanian 2018

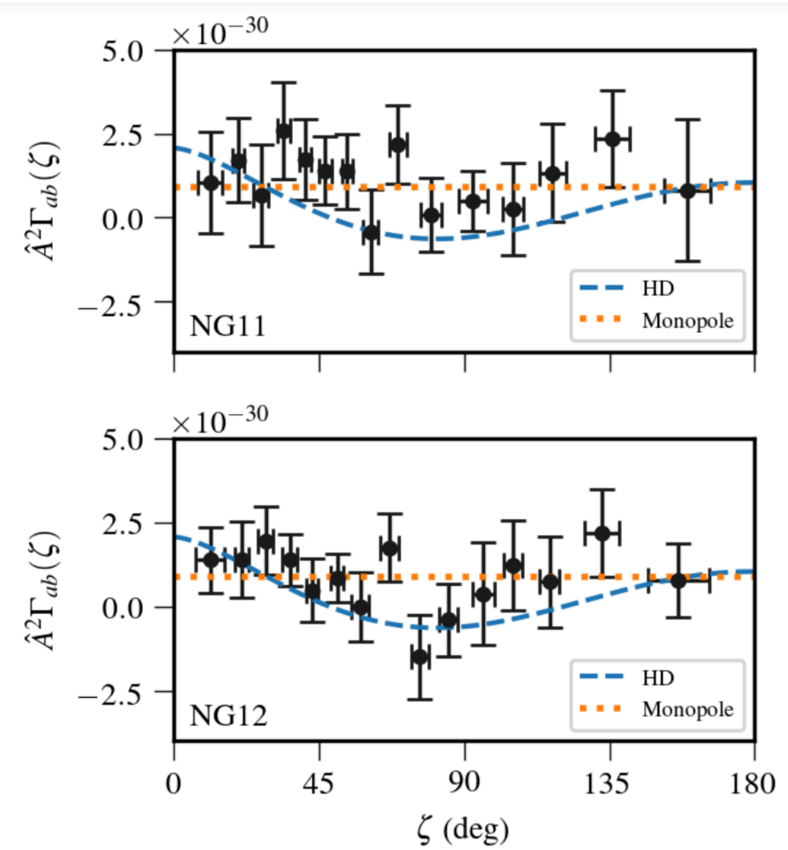
Upper limits (non-detection) on background

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

Detection of common red signal (2020)

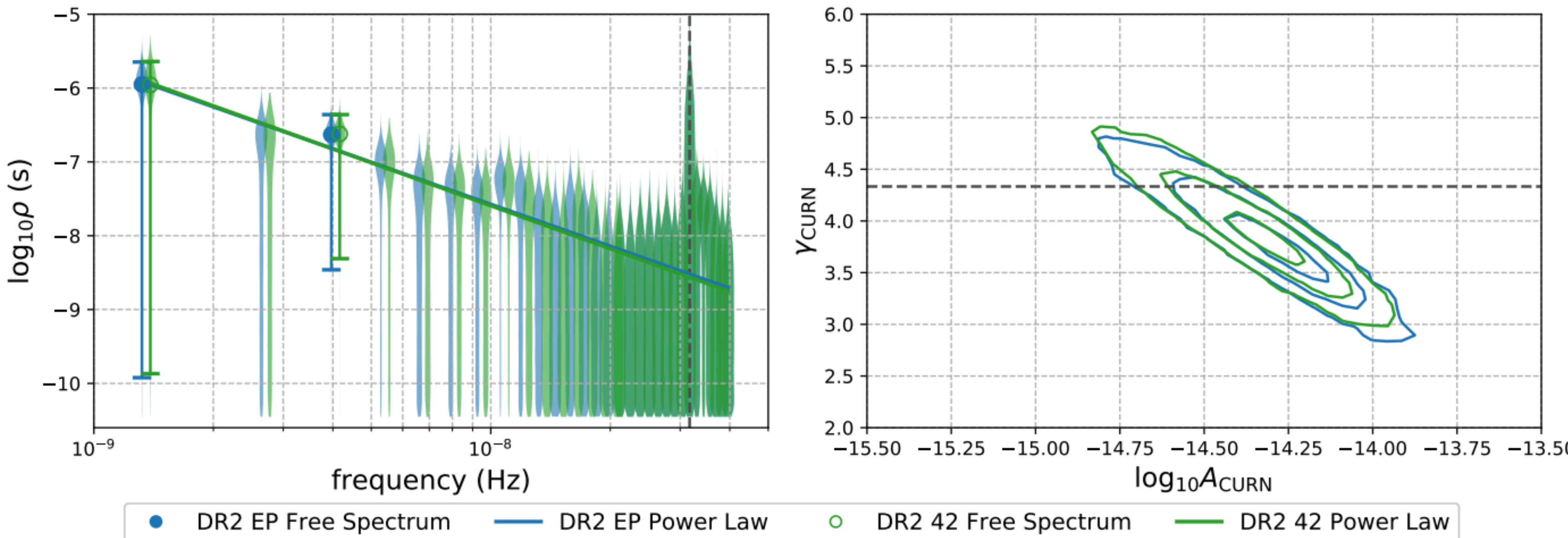
NANOGrav: 12.5 year data analysis
Bayesian analysis of 43 pulsars
Accounting for solar system ephemerides





No evidence of HD correlation

Common red signal seen in several datasets



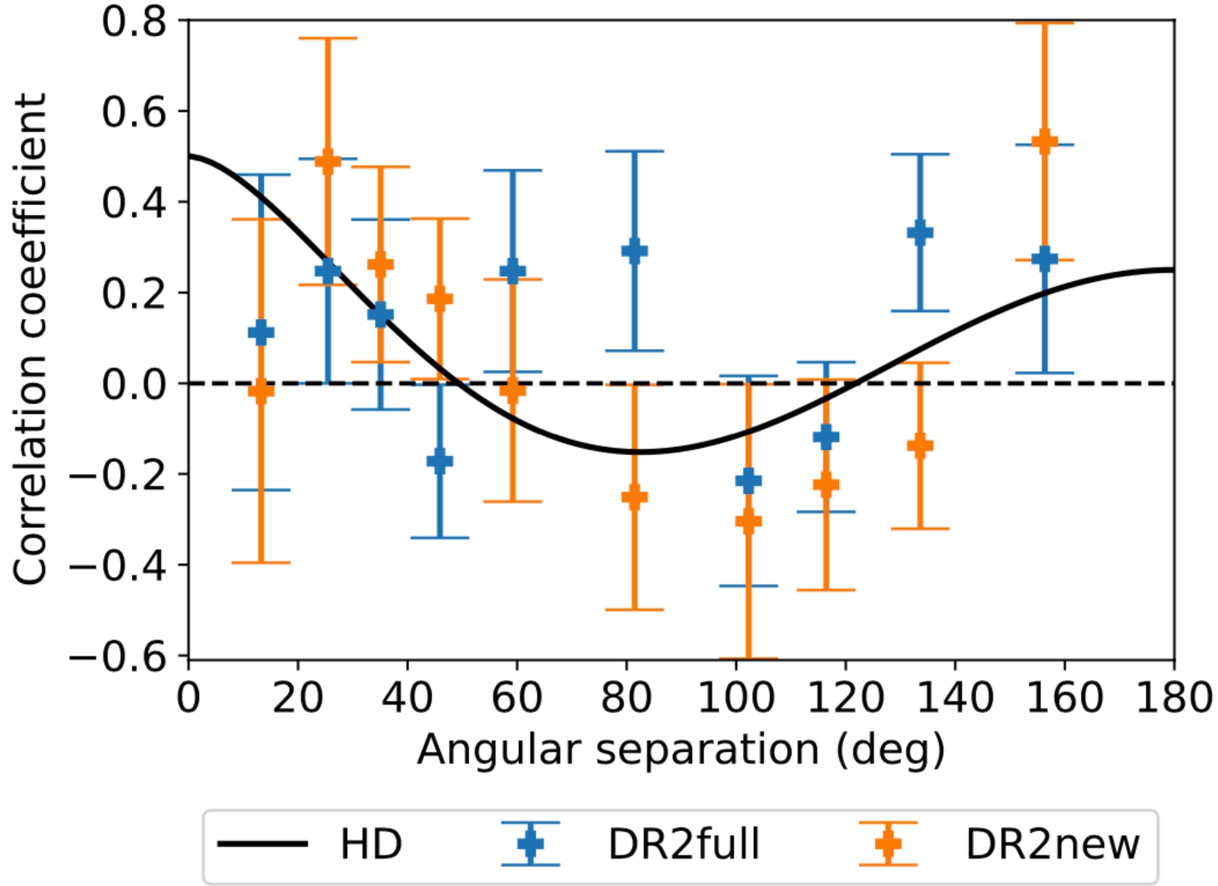
EPTA: Chen 2021

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)

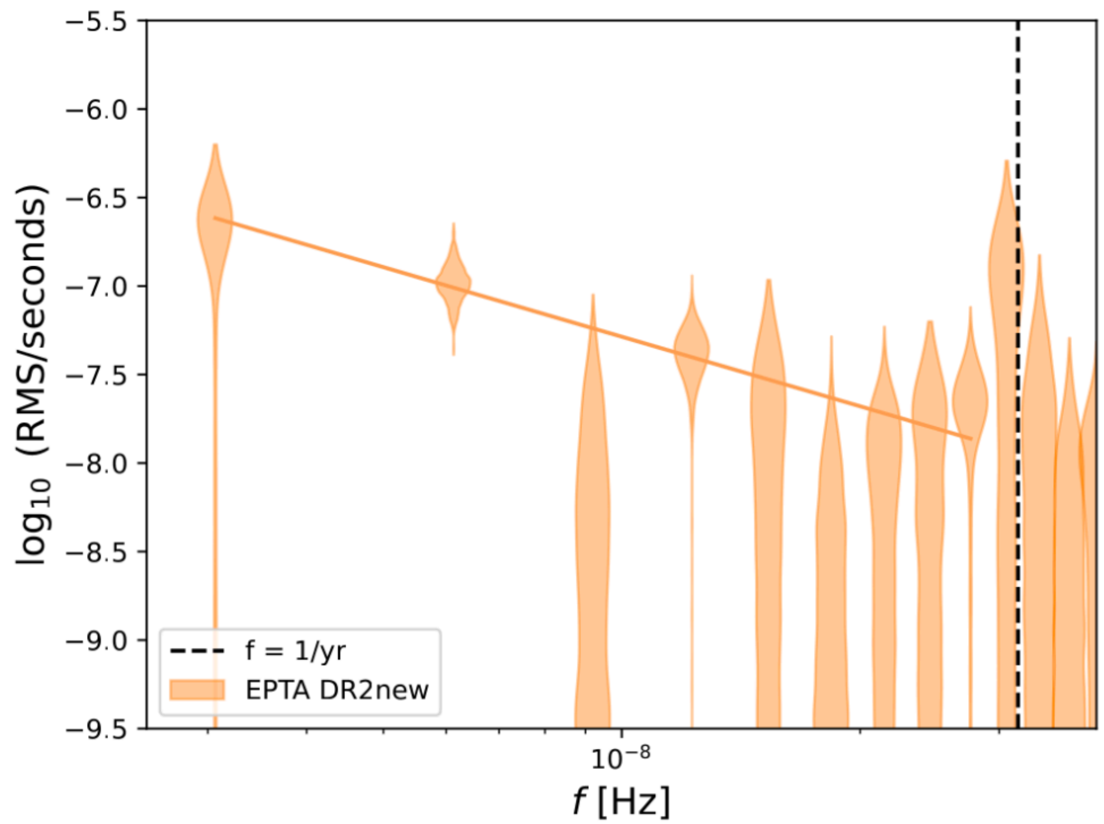


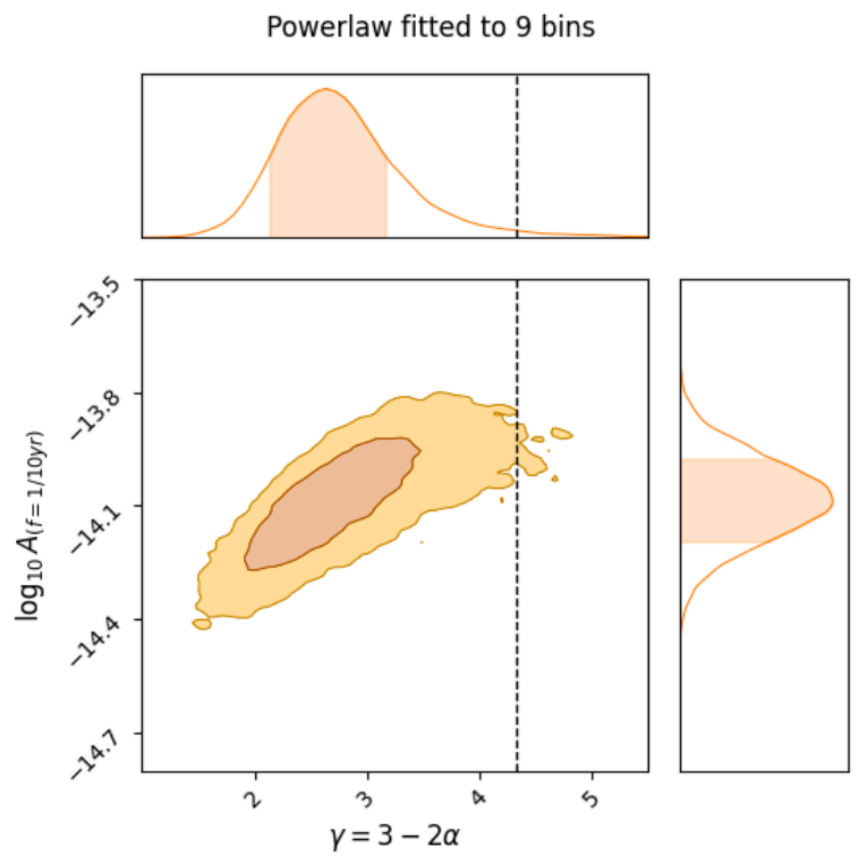
Hellings & Downs correlation
BF ~ 60
Signal consistent with GW

Consistent with results from NANOGrav, PPTA, CPTA

Antoniadis 2023 (arXiv:2306.16214)

EPTA Data Release 2 (2023)

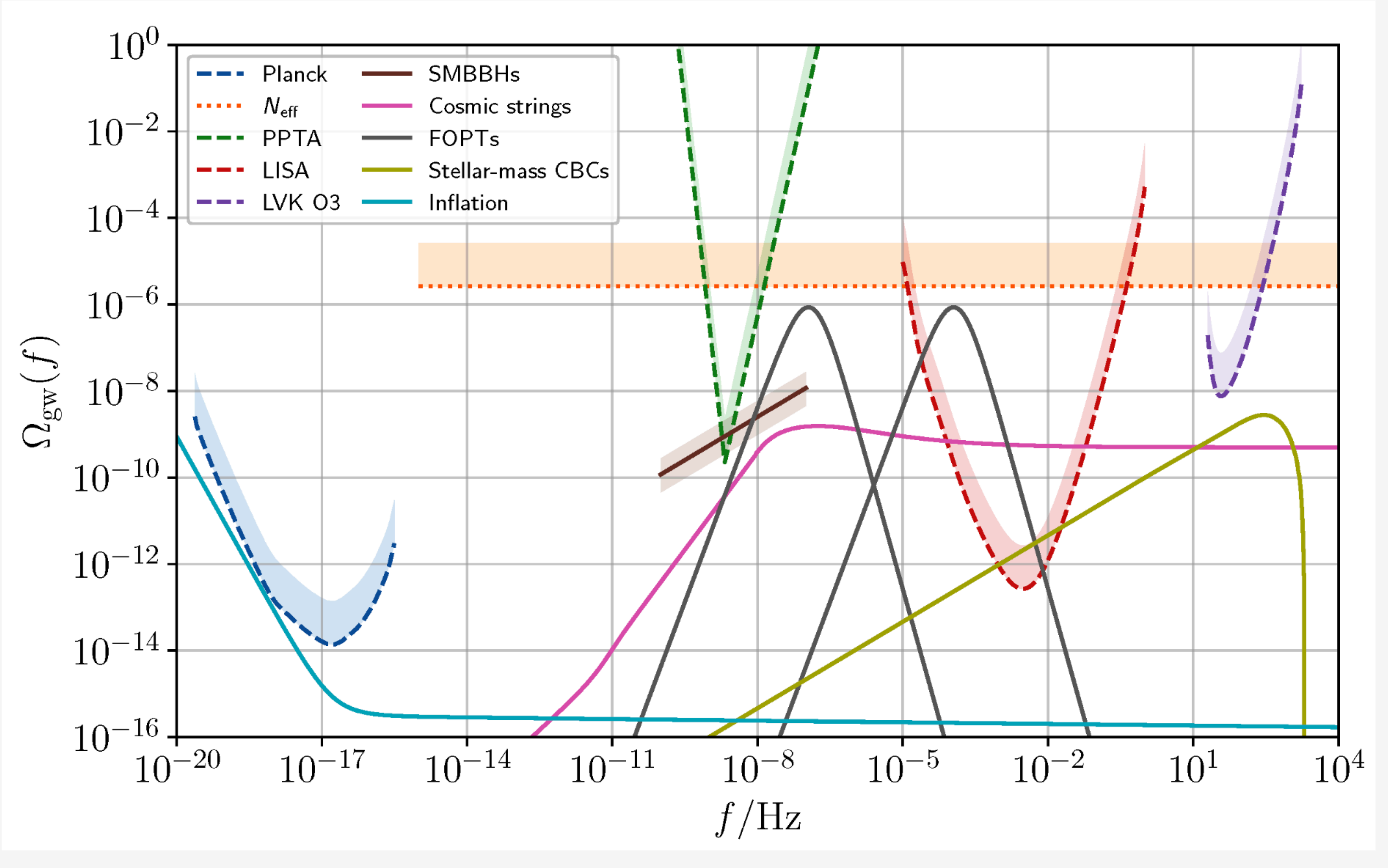




Antoniadis 2023 (arXiv:2306.16912)

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

Possible GW sources



SMBHBs

Inflation

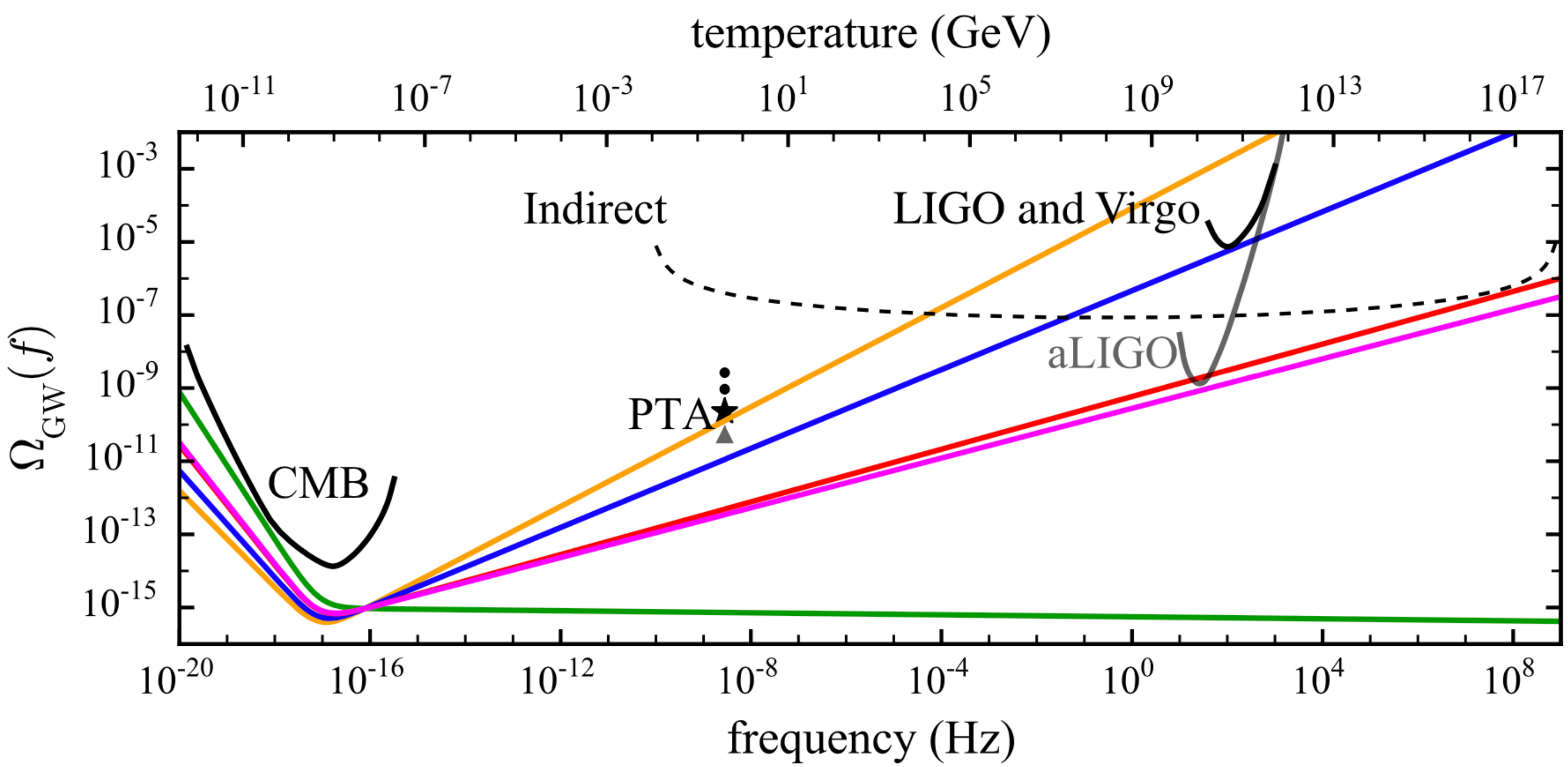
Phase transitions

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

Scalar perturbations/ Primordial black holes

Renzini 2022

GWs from Early Universe: inflation

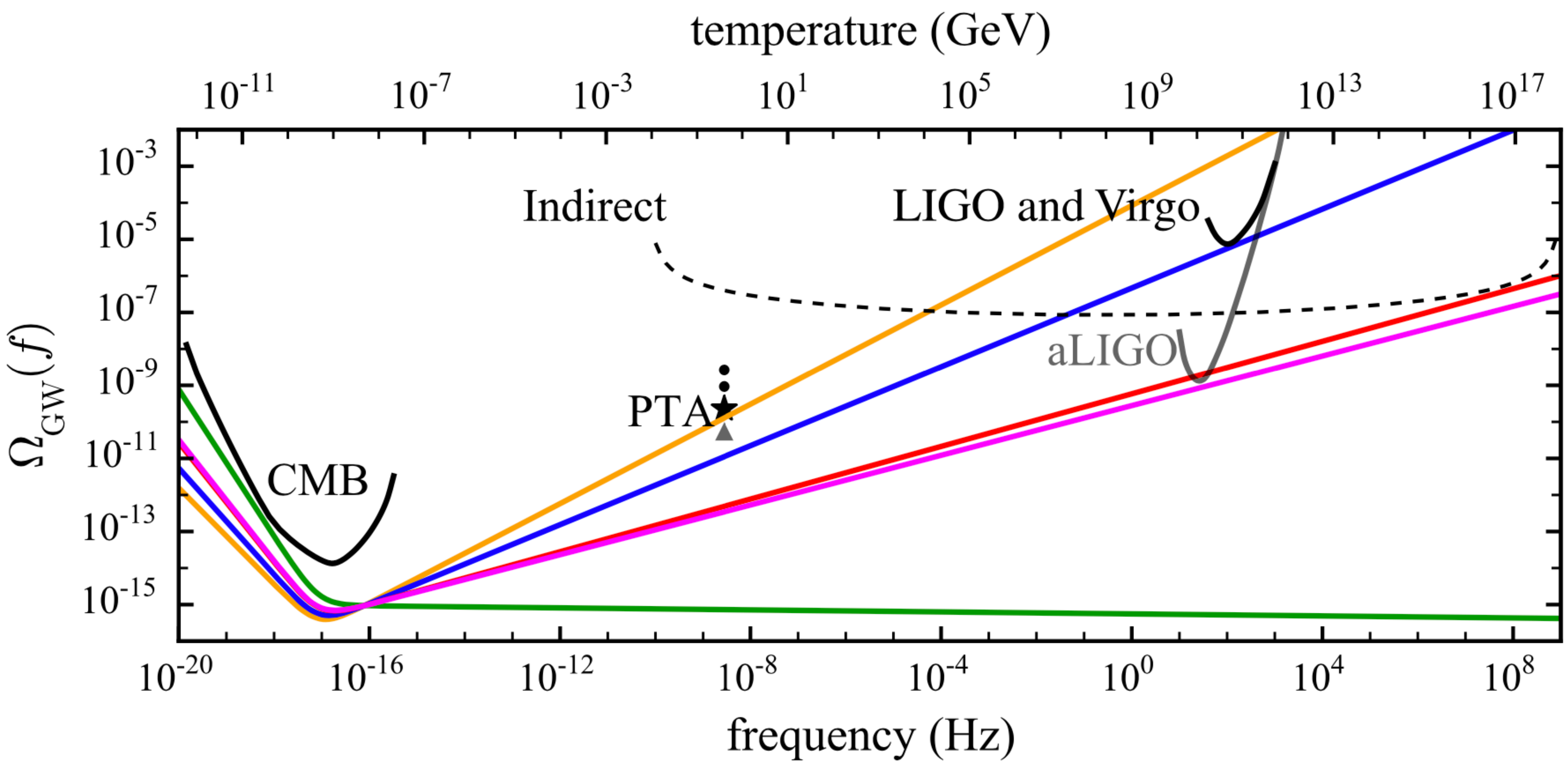


Lasky 2016

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

Consistency relation $n_t = -r/8 < 0$

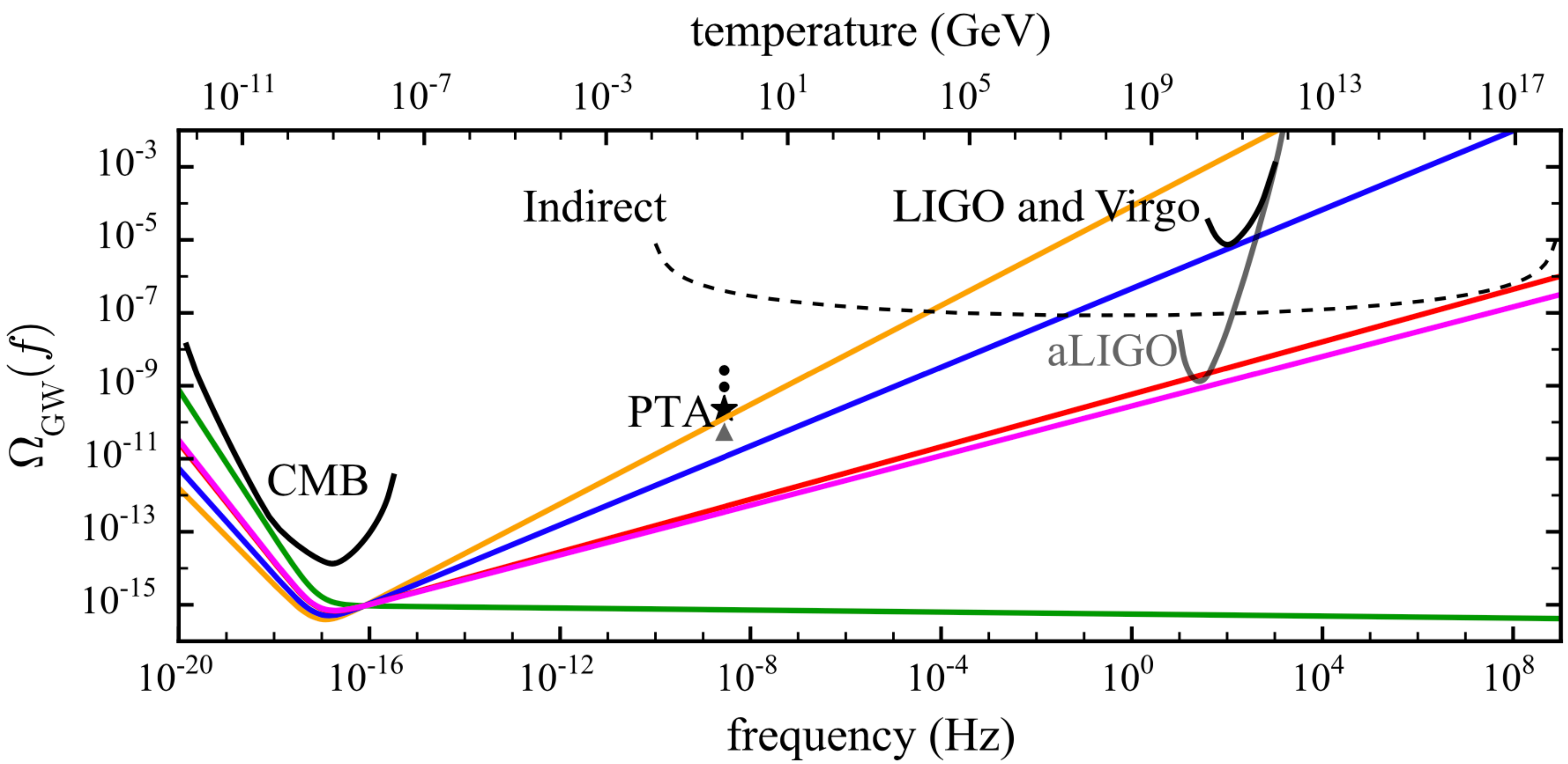
GWs from Early Universe: inflation



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



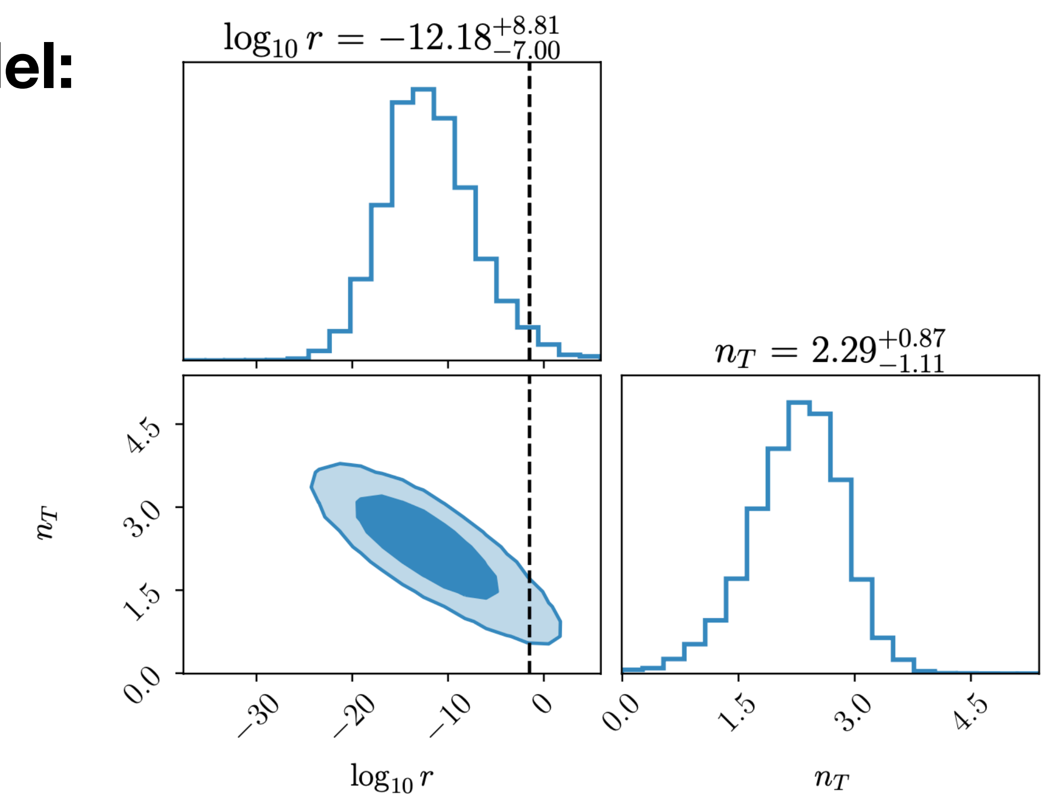
Lasky 2016

- At large scales, CMB can constrain or hopefully detect scalar-to-tensor ratio r + spectral index ns, but not ideal for spectral index nt
- At small scales, PTAs can determine spectral index nt

Inflationary GW

Use EPTA DR2new with the following model:

$$\Omega_{\rm GW}(f) = \frac{3}{128}\Omega_{\rm rad}\, r\, \mathcal{P}_{\mathcal{R}}^{*}\left(\frac{f}{f_*}\right)^{n_T}\left[\frac{1}{2}\left(\frac{f_{\rm eq}}{f}\right)^2 + \frac{16}{9}\right]$$
$$\approx 1.5\times 10^{-16}\left(\frac{r}{0.032}\right)\left(\frac{f}{f_*}\right)^{n_T},$$



Antoniadis 2023 (arXiv:2306.16912)

We find:

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

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

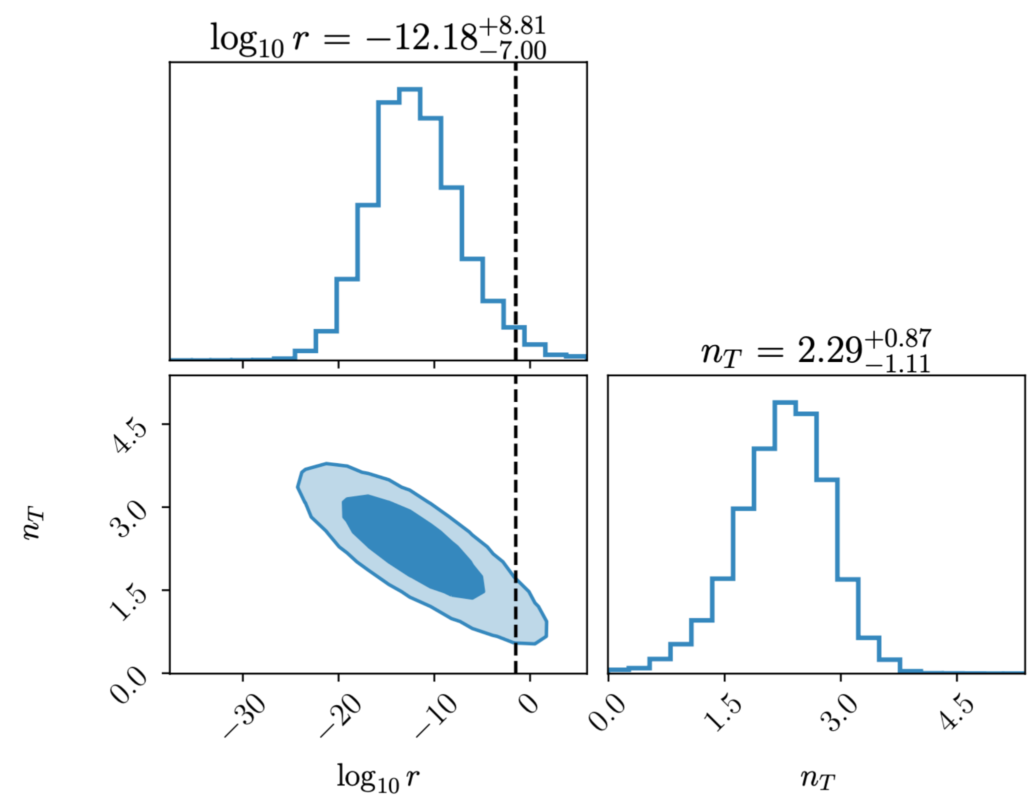
This makes sense since:

$$\gamma \simeq 2.7$$
$$\gamma = 5 - n_T$$

Inflationary GW

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

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



Antoniadis 2023 (arXiv:2306.16912)

Find relationship between r and nt:

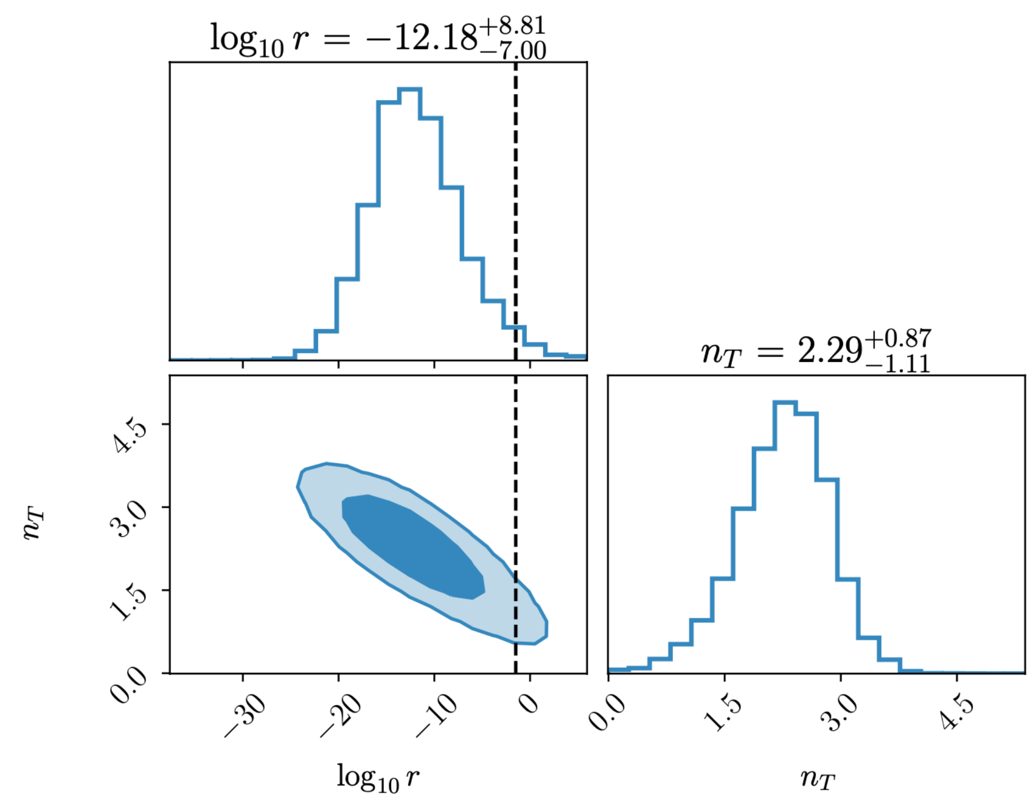
$$n_T = a \log_{10}\left(\frac{r}{0.032}\right) + b.$$

Our analysis gives $a = -0.16$ and $b = 0.70$

Notes:
SMBHB background expected to be more important… like a "foregound"
Really small r & correlation between r and nt
due to simplistic model with fixed nt?

Inflationary GW

Taking w=1/3 for radiation leads to nt~2.3
Not consistent with slow-roll inflation (nt=0)



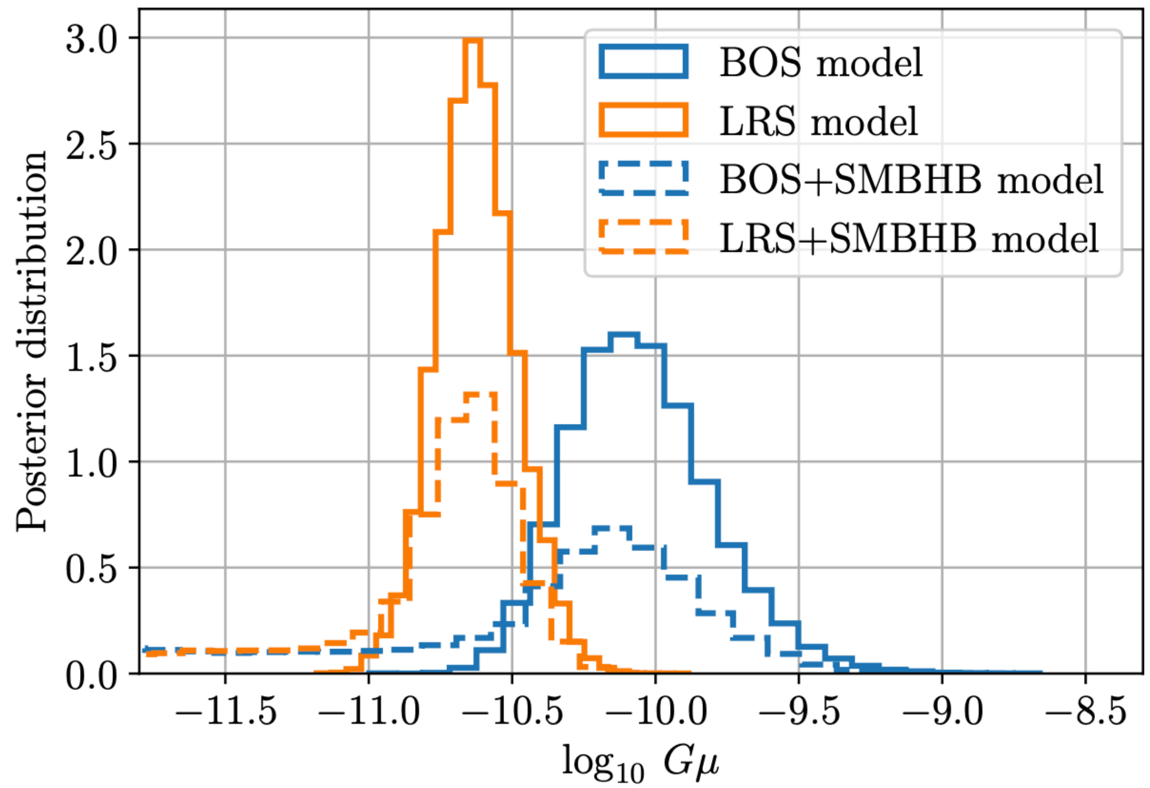
$$\gamma = 5 - n_T + \frac{2(1-3w)}{3w+1}$$

If we allow for a stiff EOS w>1/3, still not compatible with nT=0

By broadening gamma > 3, nT=0 is compatible with observed signal

Consequences about EOS to be explored further

Cosmic strings

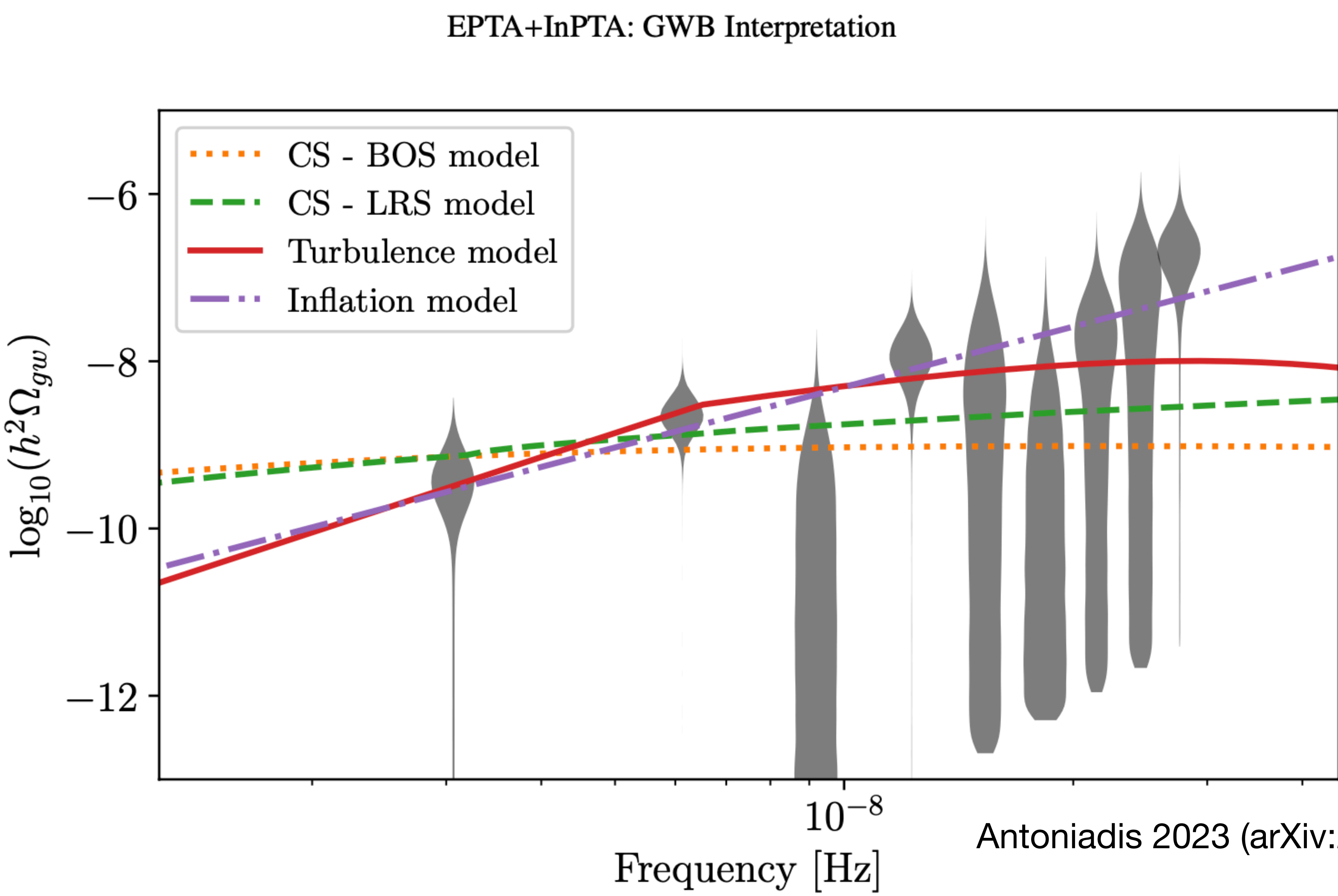


Antoniadis 2023 (arXiv:2306.16912)

Cosmic strings (alone) not blue-tilted enough to produce GW signal seen in EPTA DR2
But can place constraint on string tension that is better than CMB or LVK

$$\log_{10} G\mu \; < \; -9.77$$

Cosmological models



Antoniadis 2023 (arXiv:2306.16912)

Cosmic strings (alone) not blue-tilted enough to produce GW signal seen in EPTA DR2

Other models are possible

Outlook

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

- Combining the data from the various PTAs —> IPTA dataset
- 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
- Possible cosmological background origin:

Non-standard blue-tilted inflationary scenario
Excess in primordial spectrum of scalar perturbations
Turbulence in QCD phase transition

- Cosmic string models disfavored (not blue-tilted enough, place constraint)