Gravitational Wave Signals in Modified Cosmologies

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Probing Non-Standard Cosmologies with the Stochastic GW Background

- What contributes to the stochastic GW background?
  - Astrophysical processes (e.g., BH & neutron star mergers)
  - Cosmology: inflation, cosmic strings, etc.
  - **GW are induced by curvature perturbations at second order!**

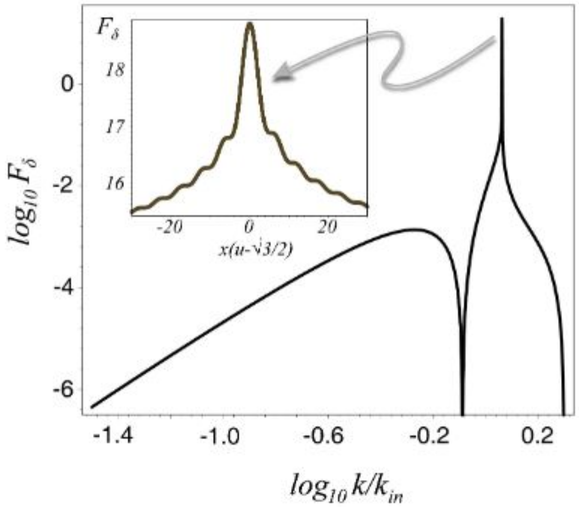
    K. Ananda, C. Clarkson, D. Wands, Phys.Rev.D 75 (2007) 123518
- Key Questions:
  - What does this signal look like?
  - How does the cosmological history of the universe affect these?

Curvature-Induced Gravitational Waves

Why interesting? Resonance-like enhancement!

First pointed out in *K. Ananda, C. Clarkson, D. Wands, Phys Rev D 75 (2007) 123518*

Modified curvature power spectrum: $\mathcal{P}_\zeta(k) \propto \delta(k - k_{\rm in})$



Why? Oscillating gravitational potential
↔ oscillating sound wave
resonantly produces GW

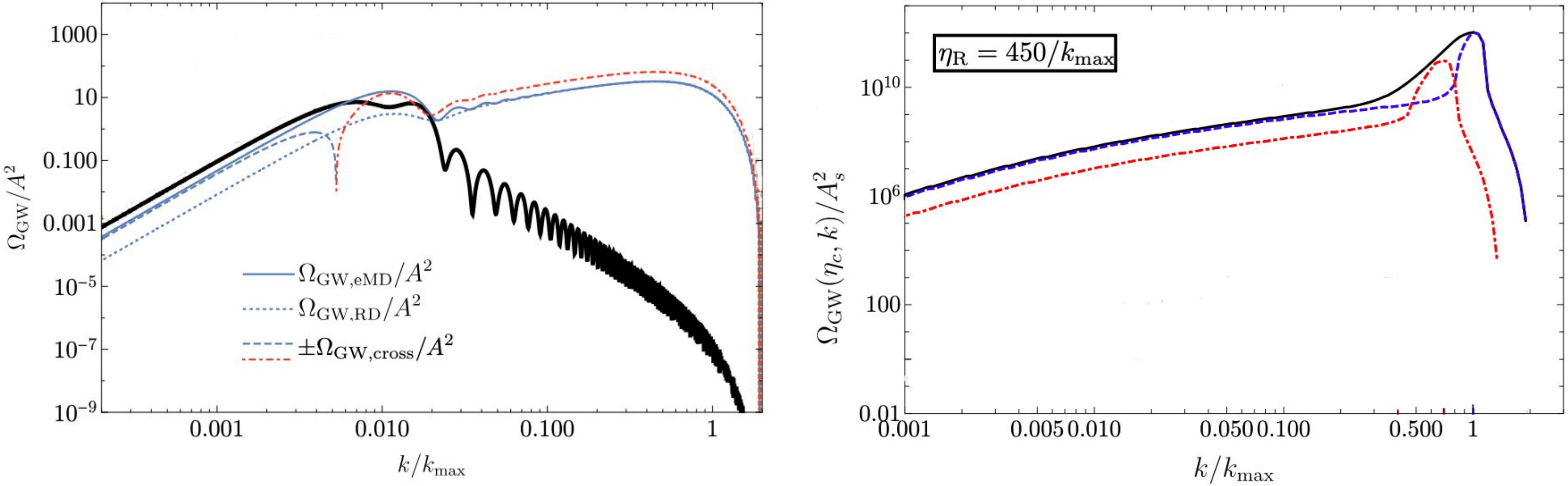
Inomata et. al.
Phys.Rev.D 101 (2020) 12, 123533

Curvature-Induced Gravitational Waves

- Option 1: Modify $\mathcal{P}_\zeta(k)$ like in Ananda et. al. (Will return to this later)
- Option 2: Use inflationary curvature spectrum- How does cosmological evolution affect it?
  - Consider an early matter dominated epoch

Induced GW with Early Matter Dominated Epoch

Depends sensitively on how the eMD epoch **ENDS**



Left: Slow end- signal is suppressed because of a cancellation between modes that enter in MD & RD

K. Inomata, K. Kohri, T. Nakama, T. Terada, JCAP 10 (2019) 071

Induced GW with Early Matter Dominated Epoch

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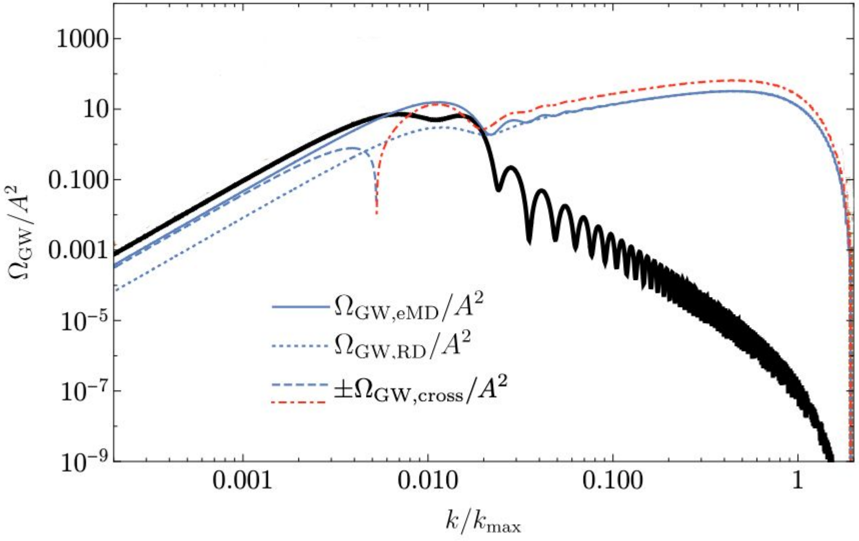
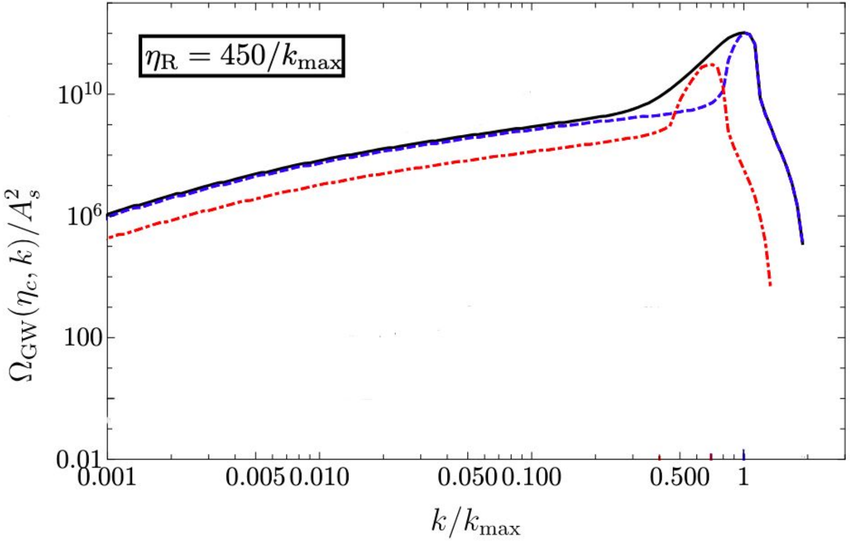


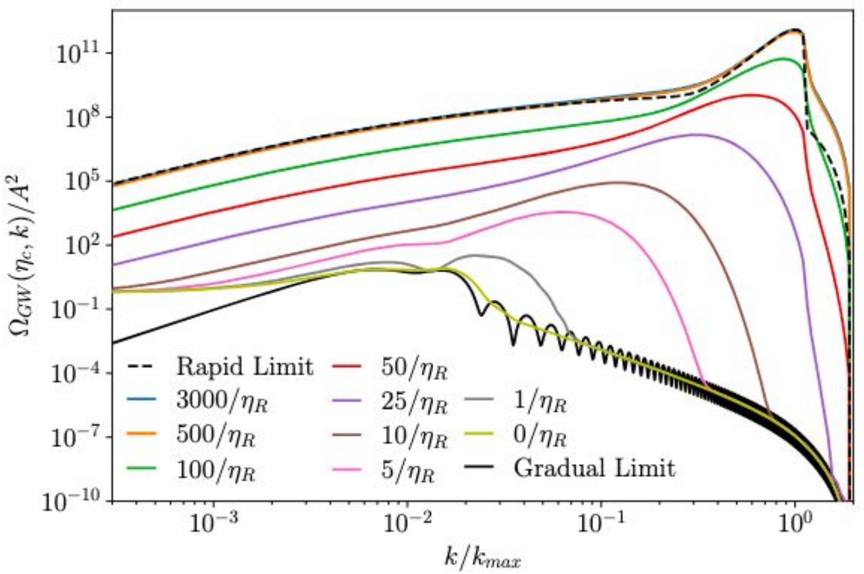


Right: Instantaneous end-
Resonance-like enhancement!

K. Inomata, K. Kohri, T. Nakama, T. Terada, Phys.Rev.D 100 (2019) 043532

This Resonance…

- My question:
  Instantaneous → infinite slope → signal depends on Φ'
  How sure are we that this is real???



Used tanh profile for matter decay rate

M. Pearce, L. Pearce, G. White, C. Balazs, JCAP 06 (2024) 021

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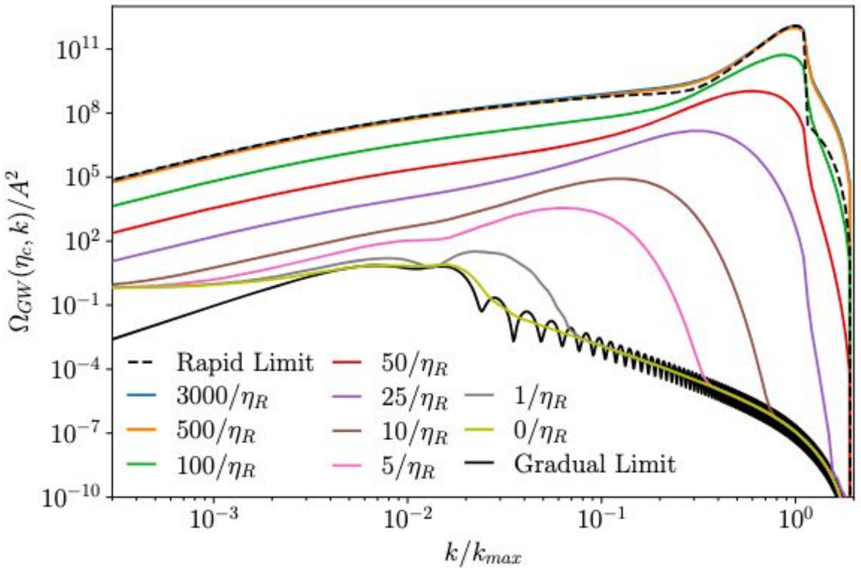
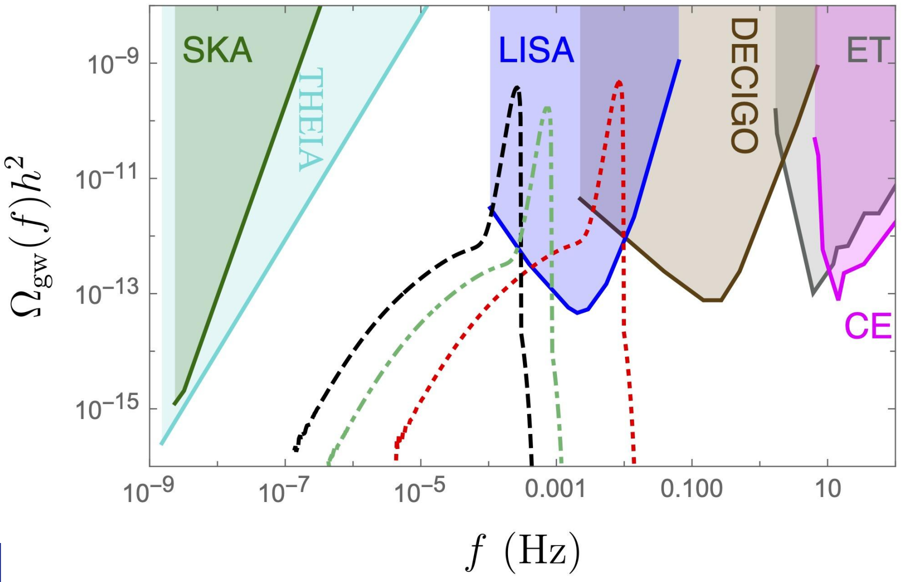


Used tanh profile for matter decay rate
M. Pearce, L. Pearce, G. White, C. Balazs,
JCAP 06 (2024) 021

Cause: Sudden decay leads to oscillating sound waves in radiation bath
Resonantly produce GW
K. Inomata et. al.
Phy.Rev.D 101 (2020) 12, 123533

How Can We Get a “Fast” Phase Transition?

- Need heavy objects whose decays speed up:
  - PBHs: *K. Inomata et. al. Phy.Rev.D 101 (2020) 12, 123533*
  - Q-balls: *G. White., L. Pearce, D. Vagie, A. Kusenko PRL 127 (2021) 18, 181601*



Temp scales: eMD starts around 10^4 GeV, ends around 10^2 GeV.

How Can We Get a “Fast” Phase Transition?

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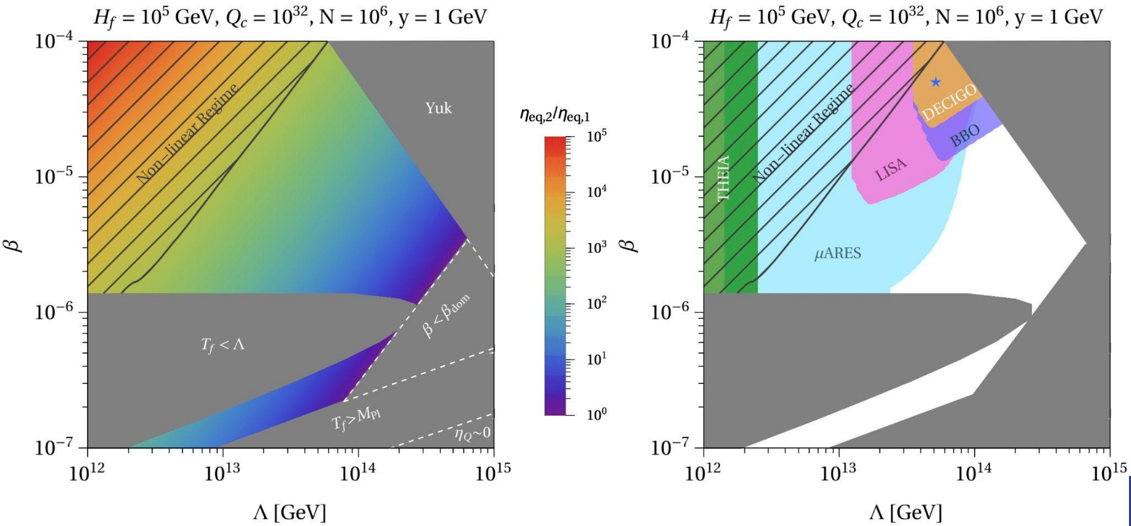
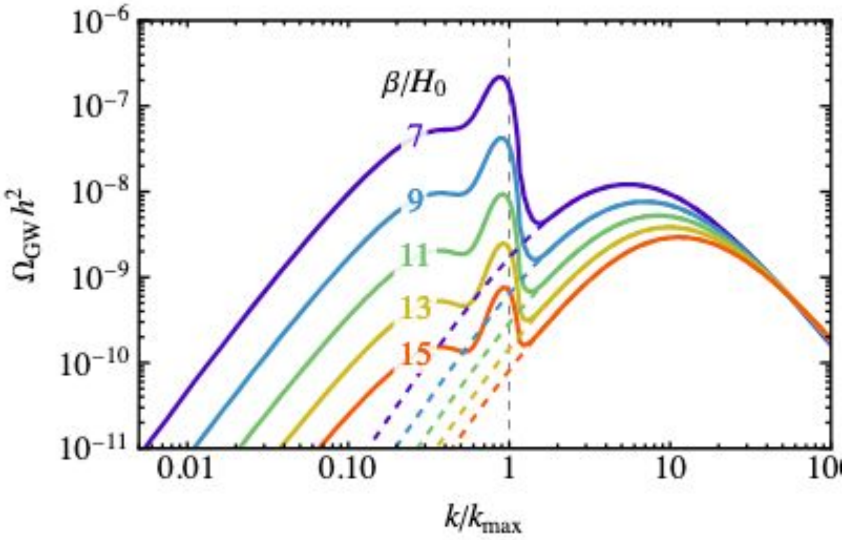
  - PBHs: *K. Inomata et. al. Phy.Rev.D 101 (2020) 12, 123533*
  - Q-balls: *G. White., L. Pearce, D. Vagie, A. Kusenko PRL 127 (2021) 18, 181601*
    - Can be embedded in e.g., high scale SUSY
      M. Flores et. al. Phys.Rev.D 108 (2023) 12, 123002



What About Modifying Curvature Power Spectrum?

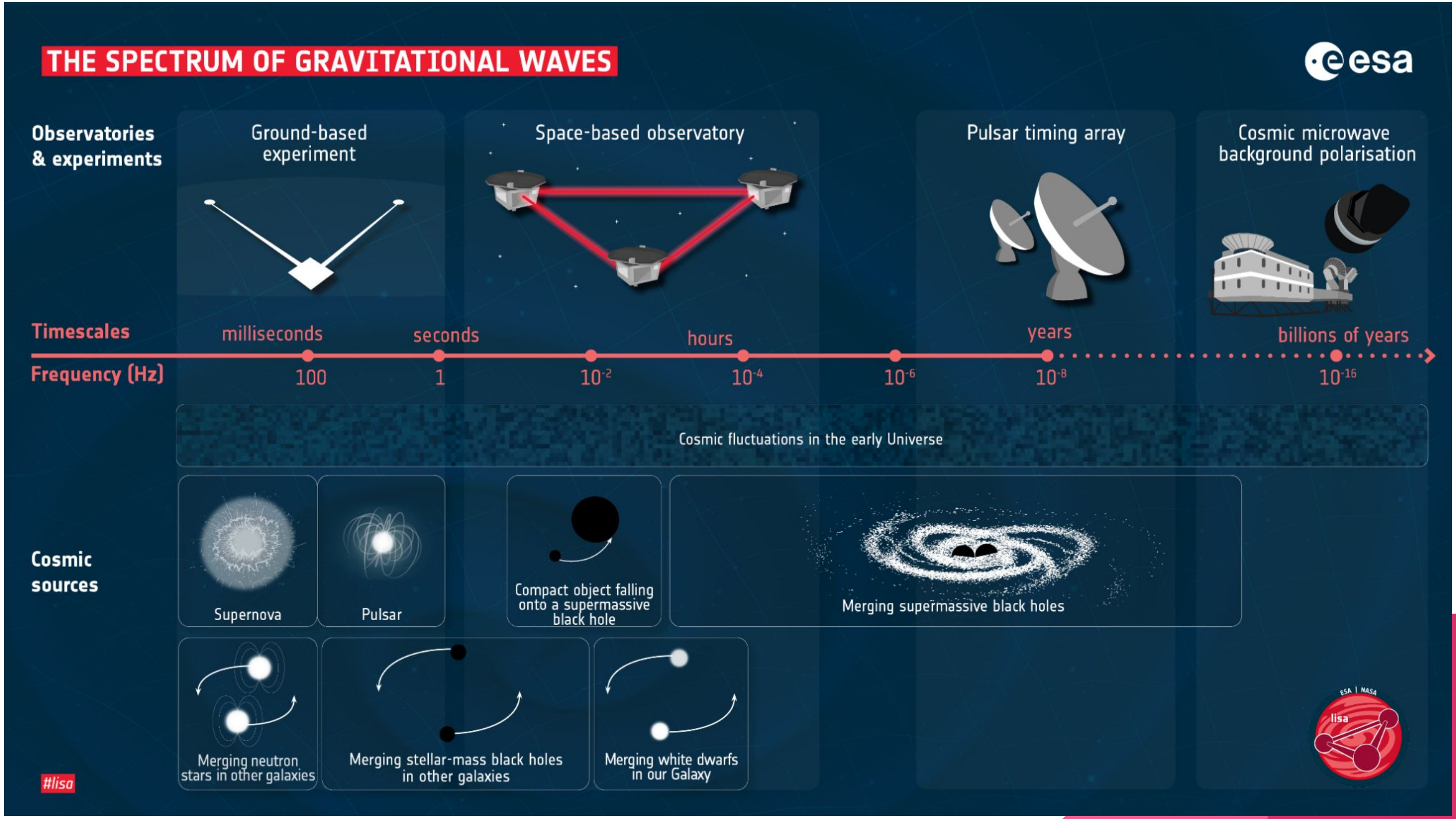
- Need to modify curvature power spectrum on superhorizon scales
- Phase transitions give $\mathcal{P}_\zeta \propto k^3$
  - *M. Lewicki, P. Toczek, and V. Vaskonen, arXiv:2402.04158*



What Else?

- Work has also been done with kination instead of early matter domination
  - *G. Domenech, S. Pi, M. Sasaki, JCAP 08 (2020) 017*
- Connects to pulsar timing arrays
  - *E.g., K. Harigaya, K. Inomata, T. Terada Phys Rev D 108 (2023) 12, 123538*

Landscape of GW Observations



Stochastic GW Background (low frequency)

Sources:

- Population of unresolved supermassive black hole binaries
- Early Universe physics (e.g., inflation, phase transitions, topological defects, enhanced scalar perturbations)

Observations:

- Current: evidence from pulsar timing array (PTA) experiments
- Upcoming: LISA will probe higher frequencies

PTAs

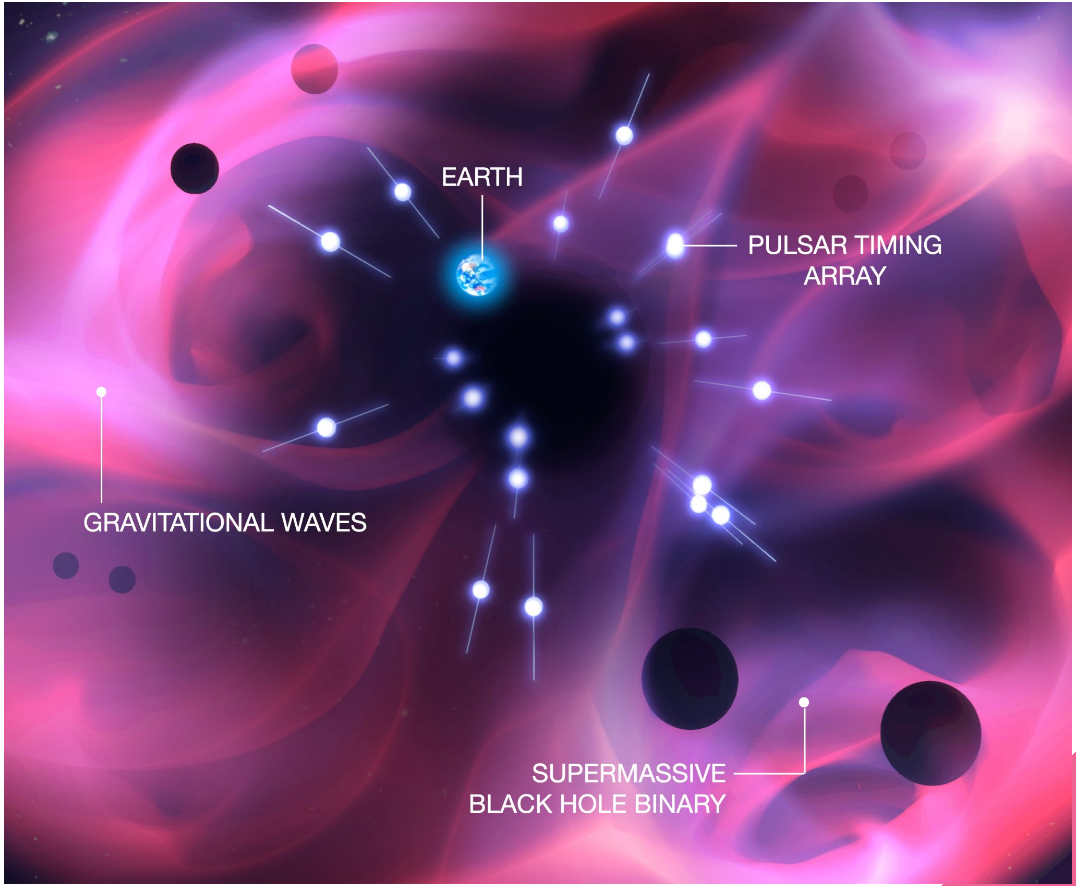
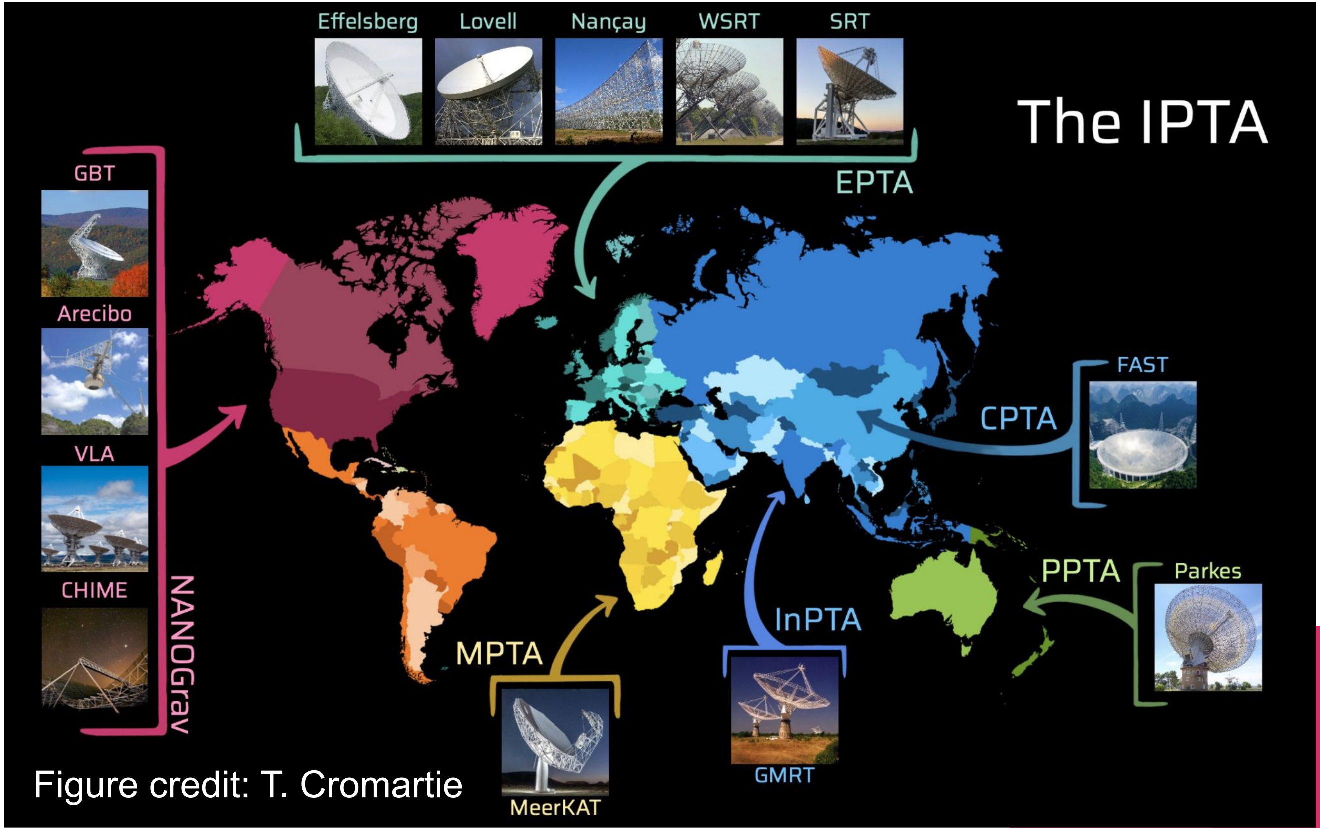


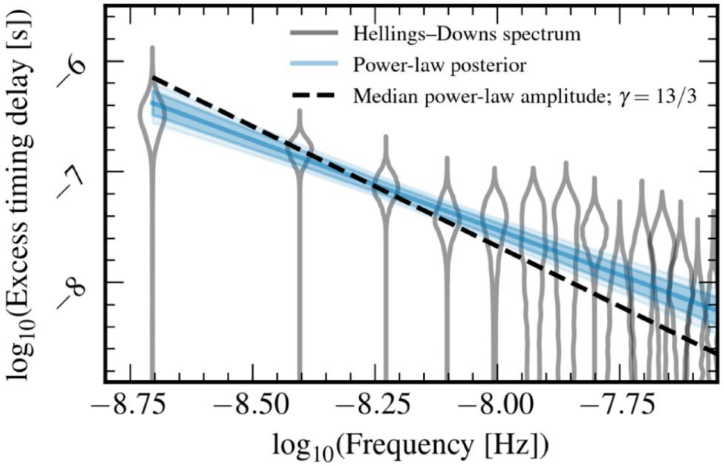
Figure credit: Andreas Freise

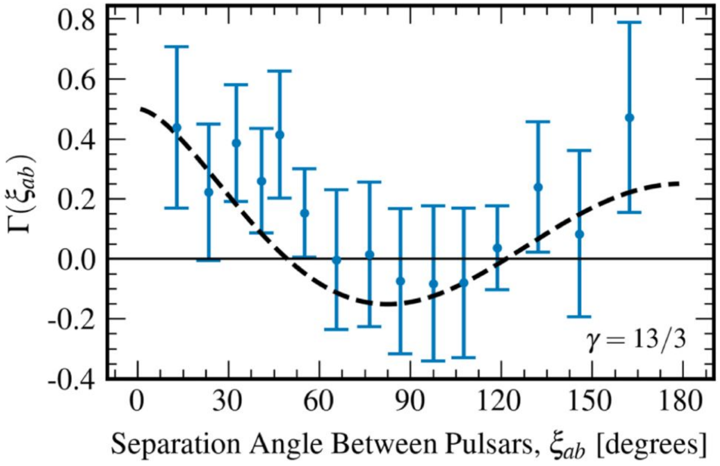
PTA Experiments

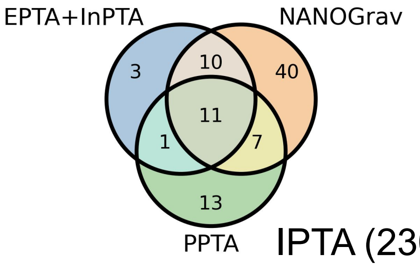


Evidence for SGWB

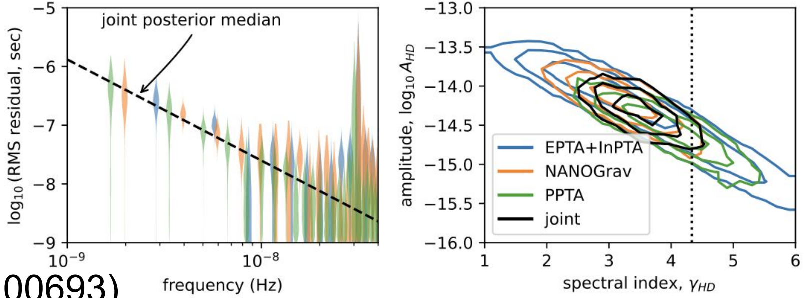
NANOGrav (2306.16213)



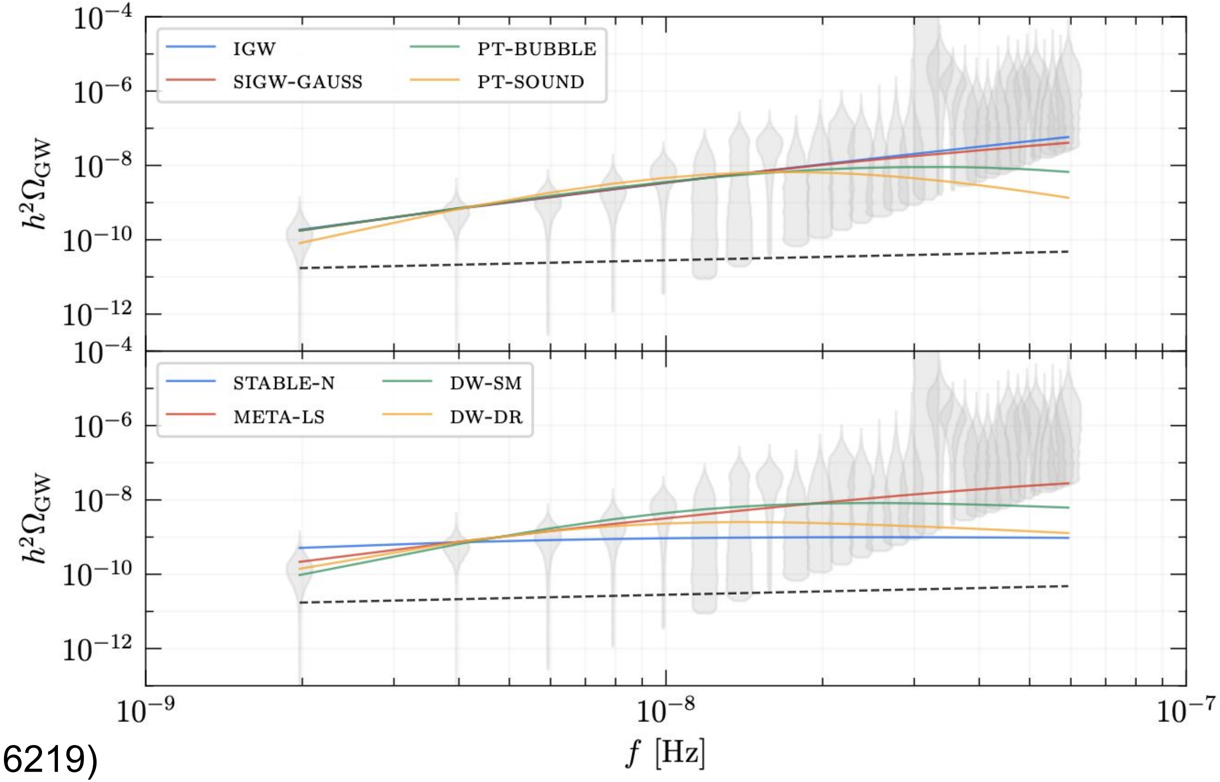




IPTA (2309.00693)

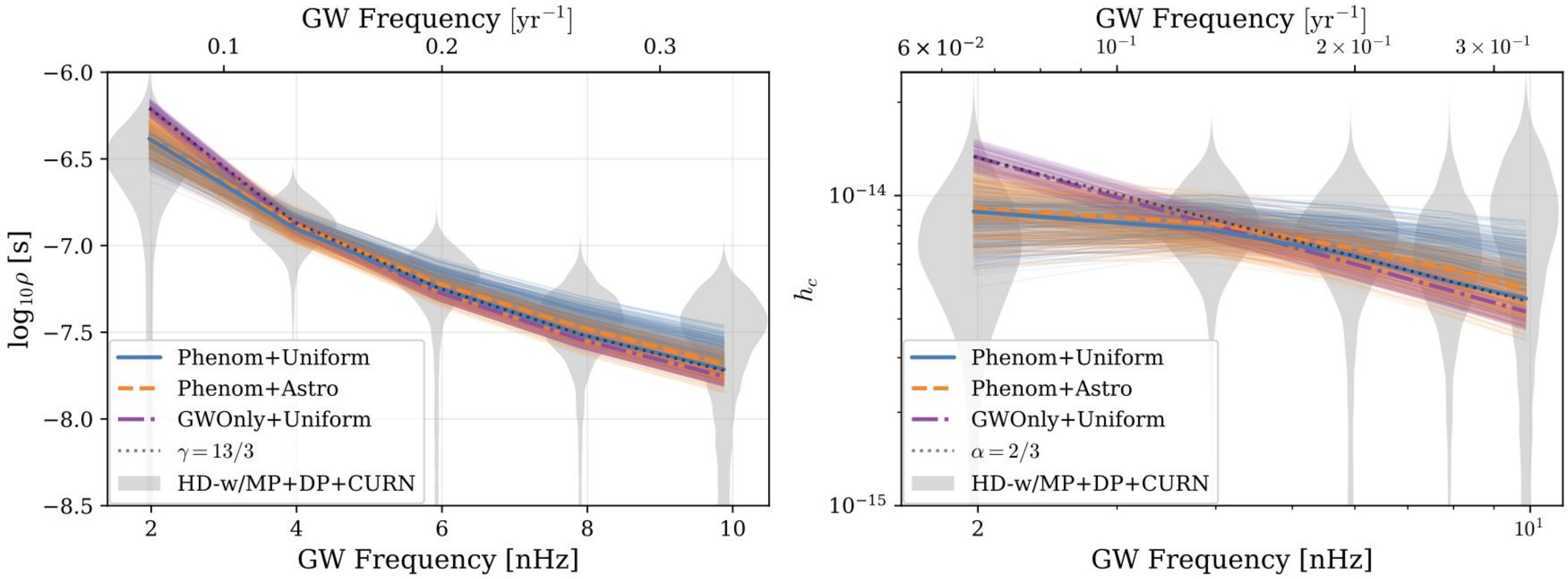


New-Physics Interpretation



NANOGrav (2306.16219)

Astrophysics interpretation



NANOGrav (2306.16220)

Discuss!

Back-Up Slides (Lauren)

Formalism (1)

Conformal Newtonian Gauge (using conformal time η):

$$ds^2 = -a^2 (1 + 2\Phi)\, d\eta^2 + a^2 \left((1 - 2\Psi)\, \delta_{ij} + \frac{1}{2} h_{ij} \right) dx^i\, dx^j$$

Fourier components of tensor modes satisfy equation of motion:

$$h''_{\vec{k}}(\eta) + 2\mathcal{H} h'_{\vec{k}}(\eta) + k^2 h_{\vec{k}}(\eta) = 4 S_{\vec{k}}(\eta)$$

with the source expressed in terms of the gravitational potential:

$$S_{\vec{k}} = \int \frac{d^3 q}{(2\pi)^{3/2}} e_{ij}(\vec{k}) q_i q_j \left(2\Phi_{\vec{q}} \Phi_{\vec{k}-\vec{q}} + \frac{4}{3(1+w)} \left(\mathcal{H}^{-1} \Phi'_{\vec{q}} + \Phi_{\vec{q}} \right) \left(\mathcal{H}^{-1} \Phi'_{\vec{k}-\vec{q}} + \Phi_{\vec{k}-\vec{q}} \right) \right)$$

GWs are a second order effect

Following 1804.08577; earlier references mentioned later

Formalism (2)

Solve via Green's function approach: $a(\eta)h_{\vec{k}}(\eta) = 4\int^{\eta} d\bar{\eta}\, G_{\vec{k}}(\eta,\bar{\eta})a(\bar{\eta})S_{\vec{k}}(\bar{\eta})$

Green's function solves: $G''_{\vec{k}}(\eta,\bar{\eta}) + \left(k^2 - \frac{a''(\eta)}{a(\eta)}\right)G_{\vec{k}}(\eta,\bar{\eta}) = \delta(\eta-\bar{\eta})$

Gravitational potential obeys: $\Phi''_{\vec{k}}(\eta) + \frac{6(1+w)}{(1+3w)\eta}\Phi'_{\vec{k}}(\eta) + wk^2\Phi_{\vec{k}}(\eta) = 0$

Express in terms of transfer function $\Phi_{\vec{k}} = \Phi(k\eta)\phi_{\vec{k}}$

which is normalized to 1 at early times and

$$\left\langle \phi_{\vec{k}}\phi_{\vec{k}'} \right\rangle = \delta(\vec{k}+\vec{k}')\cdot\frac{2\pi^2}{k^3}\left(\frac{3+3w}{5+3w}\right)^2 \mathcal{P}_\zeta(k)$$

Following 1804.08577; earlier references mentioned later

Formalism (3)

Putting it all together, the GW power spectrum is:

$$\mathcal{P}_h(\eta, k) = 4\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2 - (1+v^2-u^2)^2}{4vu}\right)^2 I^2(v,u,x)\mathcal{P}_\zeta(kv)\mathcal{P}_\zeta(ku)$$

where $I(v,u,x) = \int_0^x d\bar{x}\frac{a(\bar{\eta})}{a(\eta)}kG_k(\eta,\bar{\eta})f(v,u,\bar{x})$

and the source is

$$f(v,u,\bar{x}) = \frac{6(w+1)}{3w+5}\Phi(v\bar{x})\Phi(u\bar{x}) + \frac{6(1+3w)(w+1)}{(3w+5)^2}\left(\bar{x}\partial_{\bar{\eta}}\Phi(v\bar{x})\Phi(u\bar{x}) + \bar{x}\partial_{\bar{\eta}}\Phi(u\bar{x})\Phi(v\bar{x})\right) + \frac{3(1+3w)^2(1+w)}{(3w+5)^2}\bar{x}^2\partial_{\bar{\eta}}\Phi(v\bar{x})\partial_{\bar{\eta}}\Phi(u\bar{x})$$

Following 1804.08577; earlier references mentioned later