THE NANOGRAV ANOMALY or

Stochastic Gravitational Wave Backgrounds and their Implications for Particle Physics

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Alpine Particle Physics Symposium

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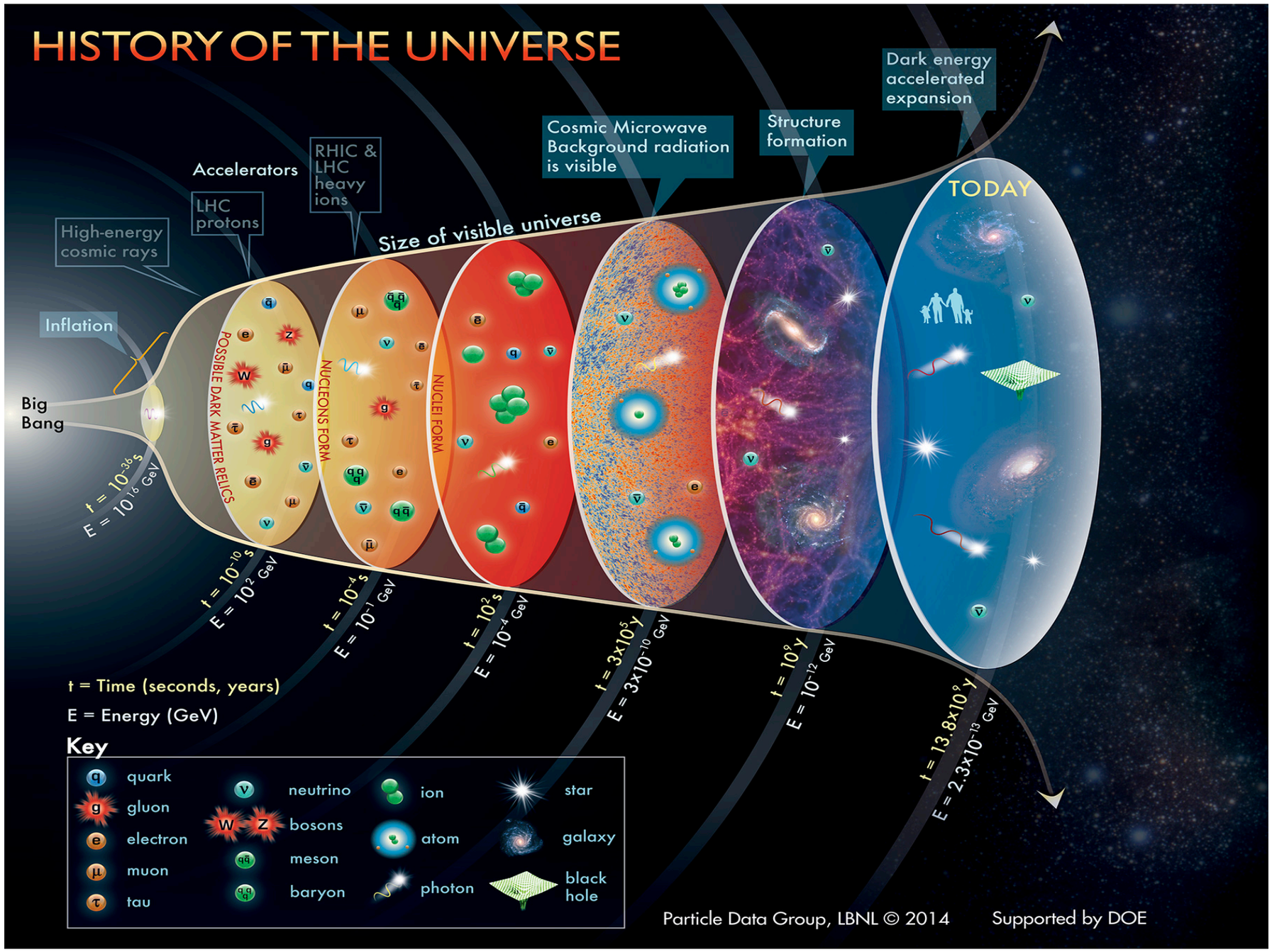
Gravitational waves as windows into the early Universe

Searches for NanoHz GWs with pulsar timing arrays

Implications for particle physics

Thermal history and particle physics



Thermal history and particle physics

Early universe holds the key to many fundamental open questions in particle physics

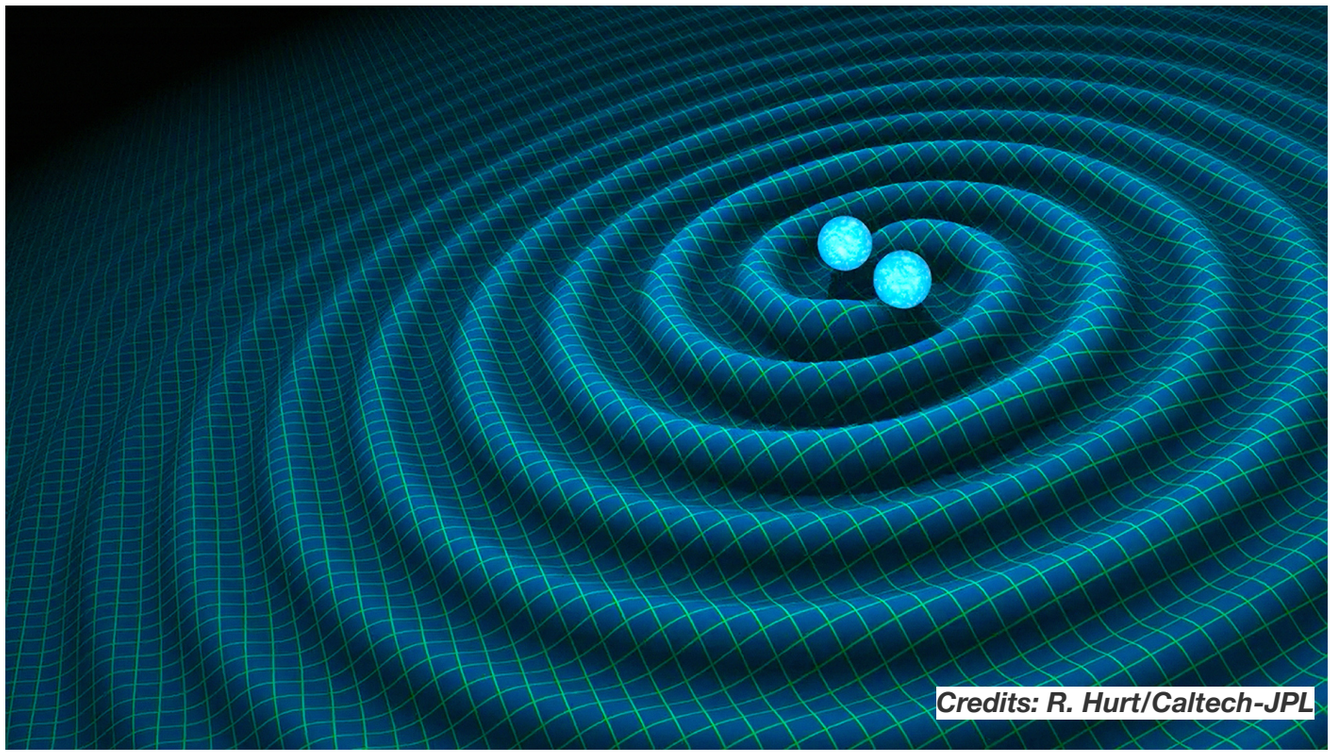
- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating

Gravitational waves as messengers from the early Universe

Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background



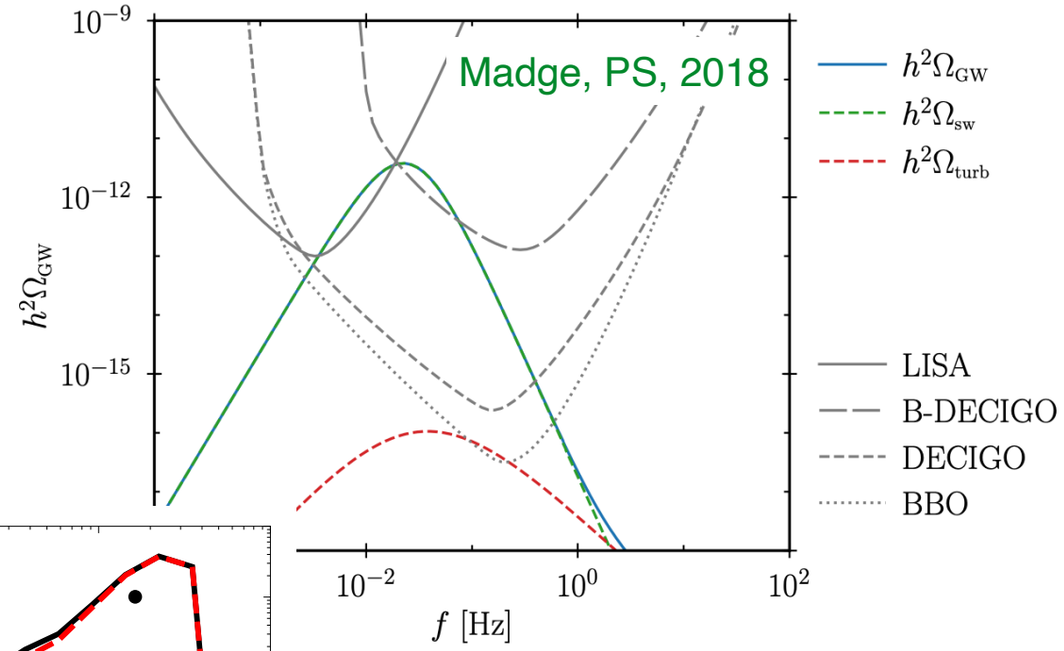
Relevant scale: Hubble radius ↔ GW wavelength

GW frequency $f_{\rm GW} \sim T_*$ Age of Universe

Signal shape and frequency is characteristic for the source. Examples:

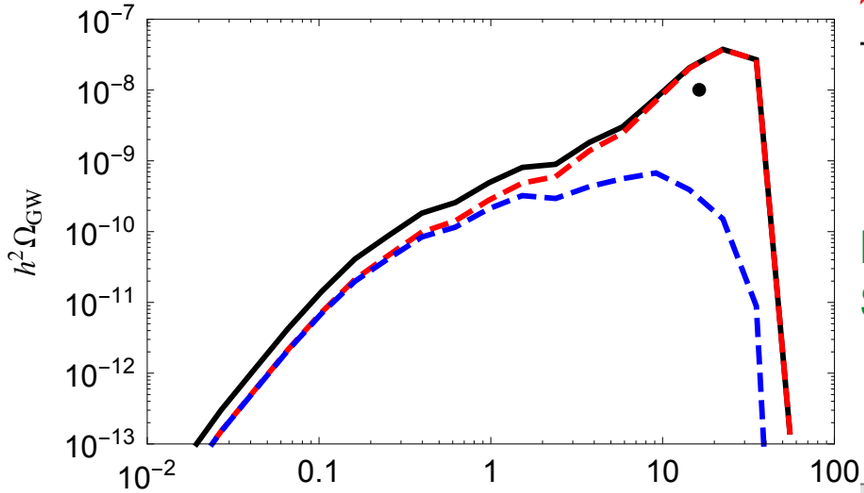
Phase transition

- Peak position depends on critical temperature



Audible axions:

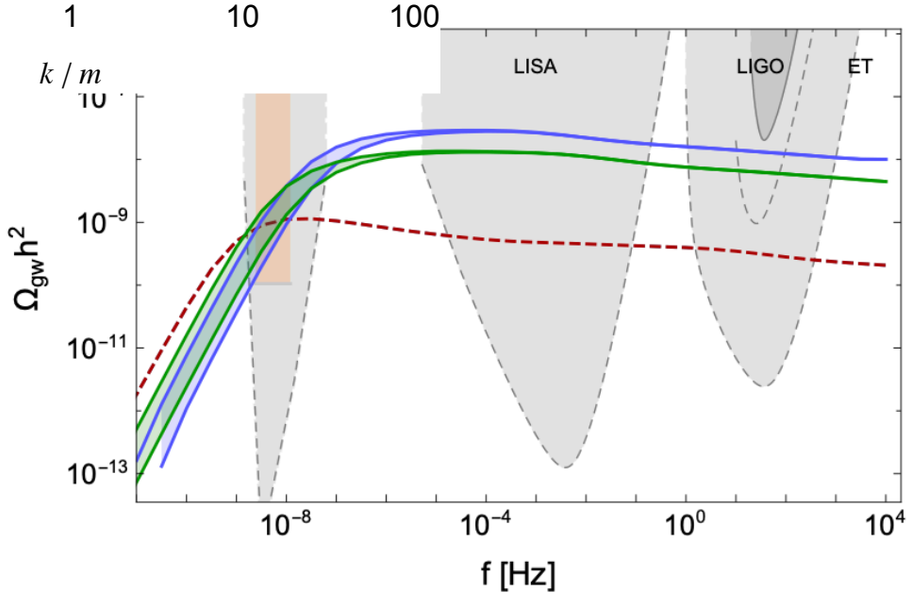
- Peaked but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum

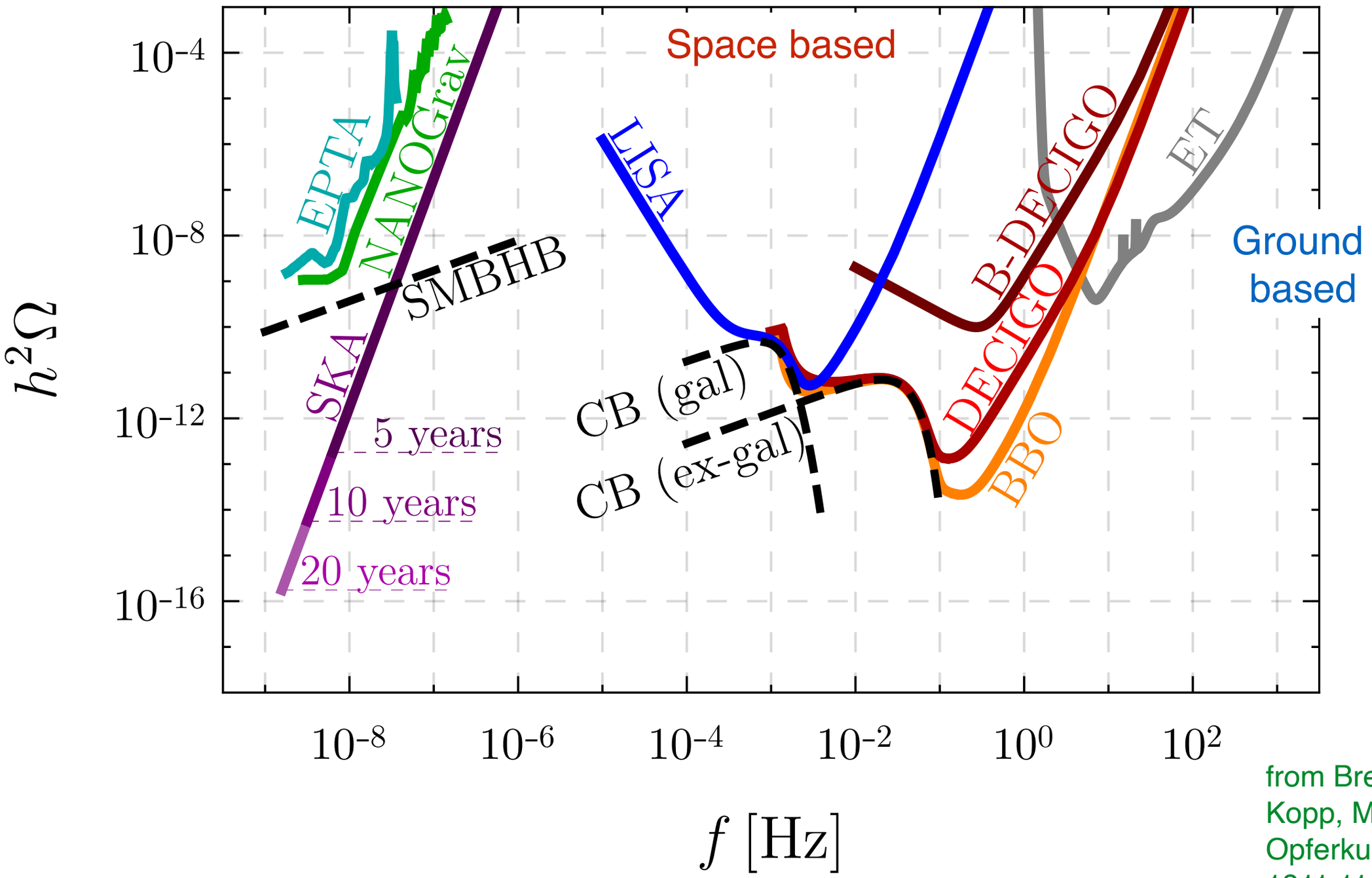


Buchmuller, Domcke, Schmitz, 2021

Frequency ranges

New physics scale

MeV GeV TeV PeV



from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

Gravitational waves as windows into the early Universe

Searches for NanoHz GWs with pulsar timing arrays

Implications for particle physics

What is a Pulsar Timing Array?

NANOGrav
Physics Frontiers Center

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NEWS & EVENTS

NANOGrav Finds Possible ‘First Hints’ of Low-Frequency Gravitational Wave Background

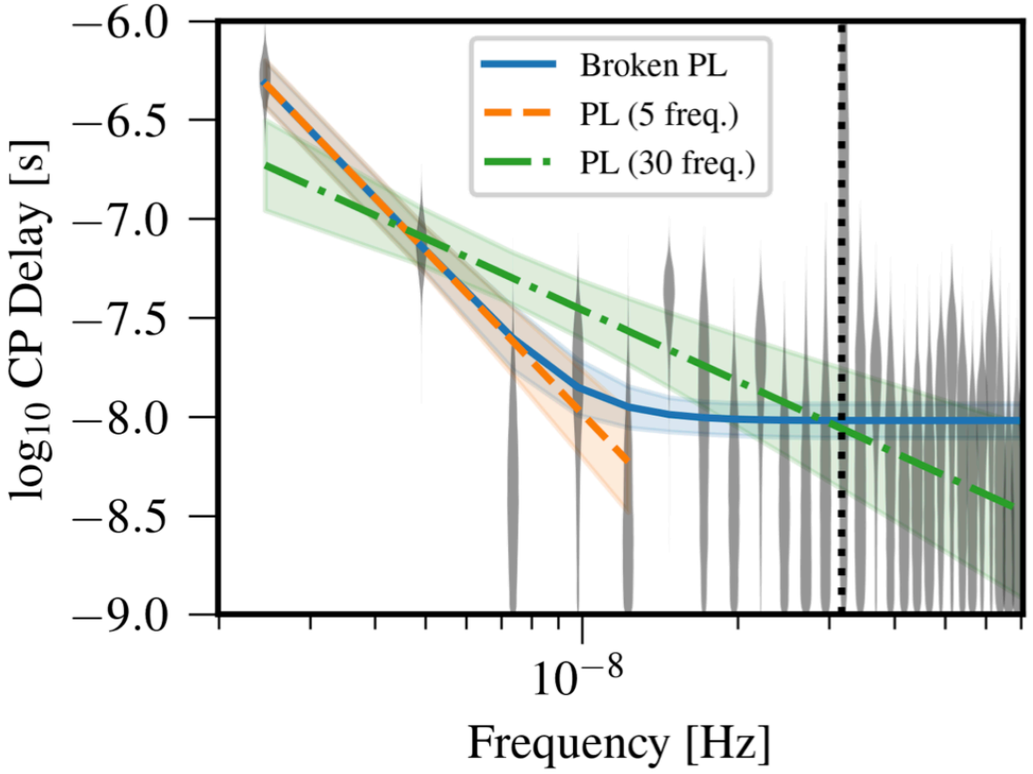
In data gathered and analyzed over 13 years, the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has found an intriguing low-frequency signal that may be attributable to gravitational waves.

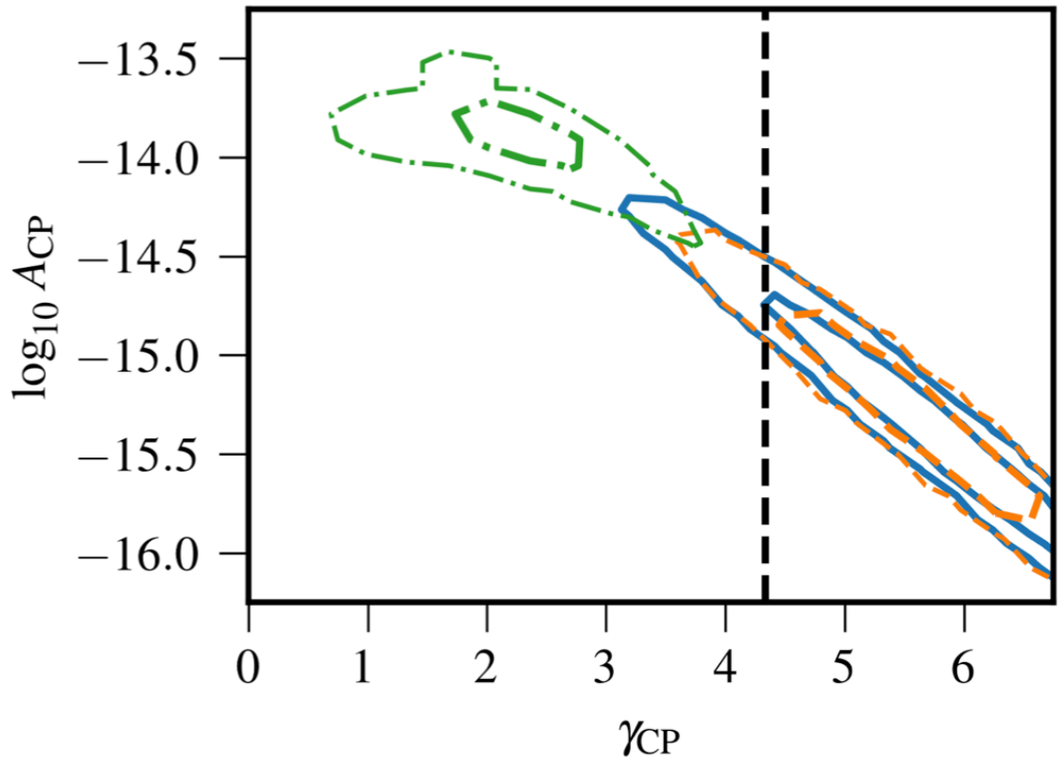
PUB: 11 JAN 2021

arXiv:2009.04496

NANOGrav Finds Possible 'First Hints' of Low-Frequency Gravitational Wave Background

arXiv:2009.04496





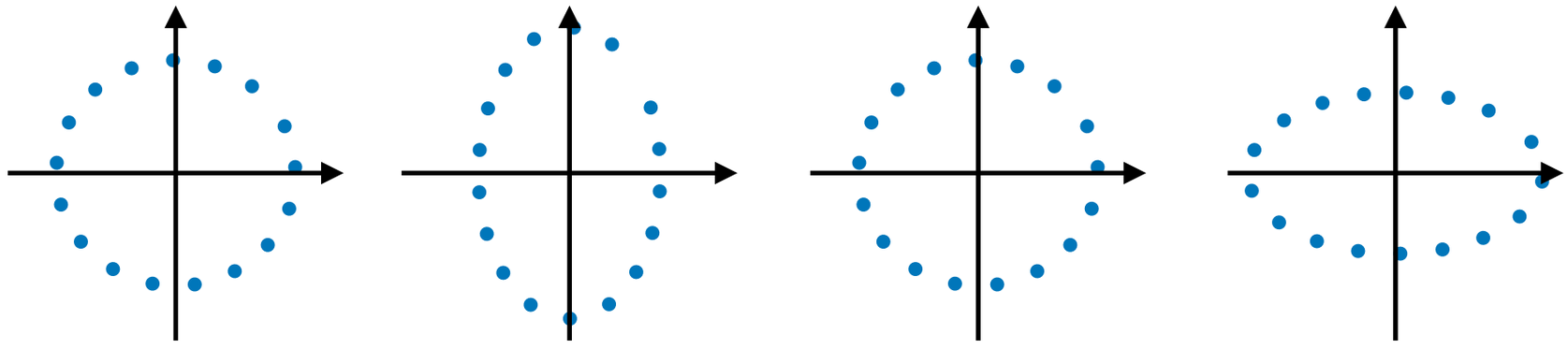
Fit with free spectrum (violins) or simple power law signals

Strong preference over BG only hypothesis (Bayes factor > 10'000)

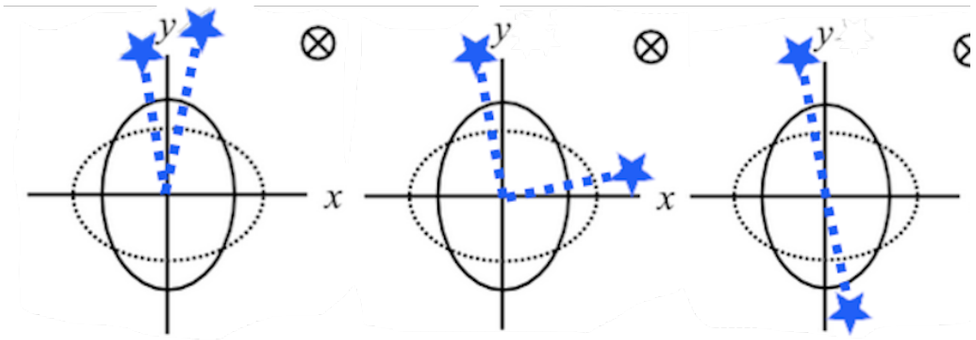
$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{f_{\mathrm{year}}} \right)^{\alpha}$$

$$\gamma = 3 - 2\alpha$$

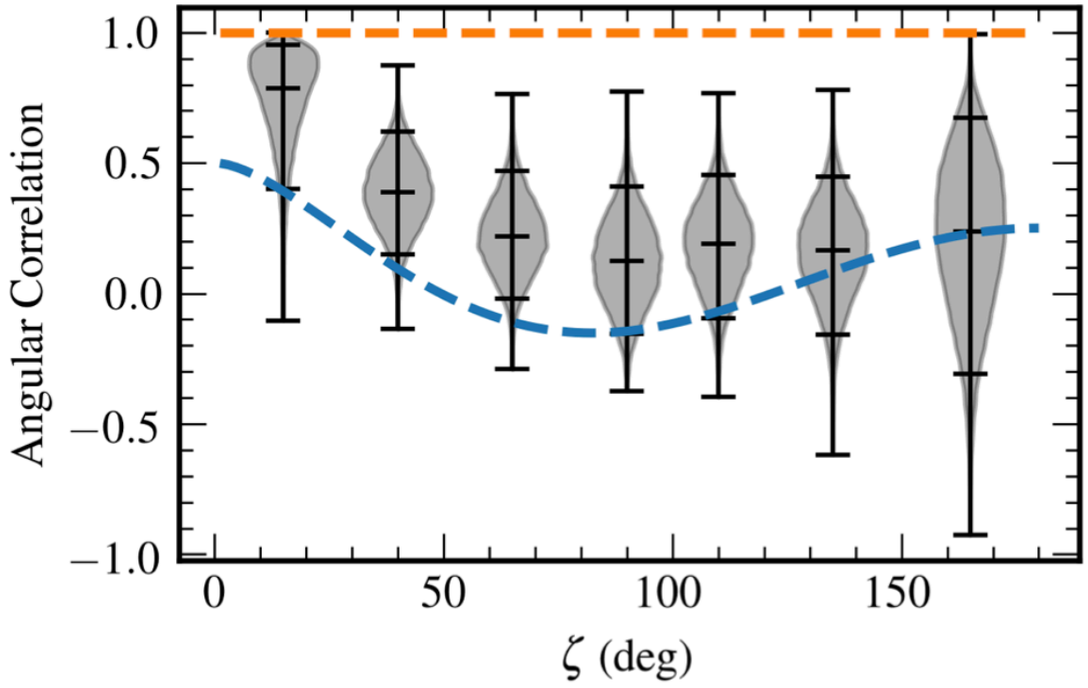
GWs are quadrupole radiation



Angular correlation in pulsar response (Helling Downs)



No conclusive evidence for HD correlation (yet)

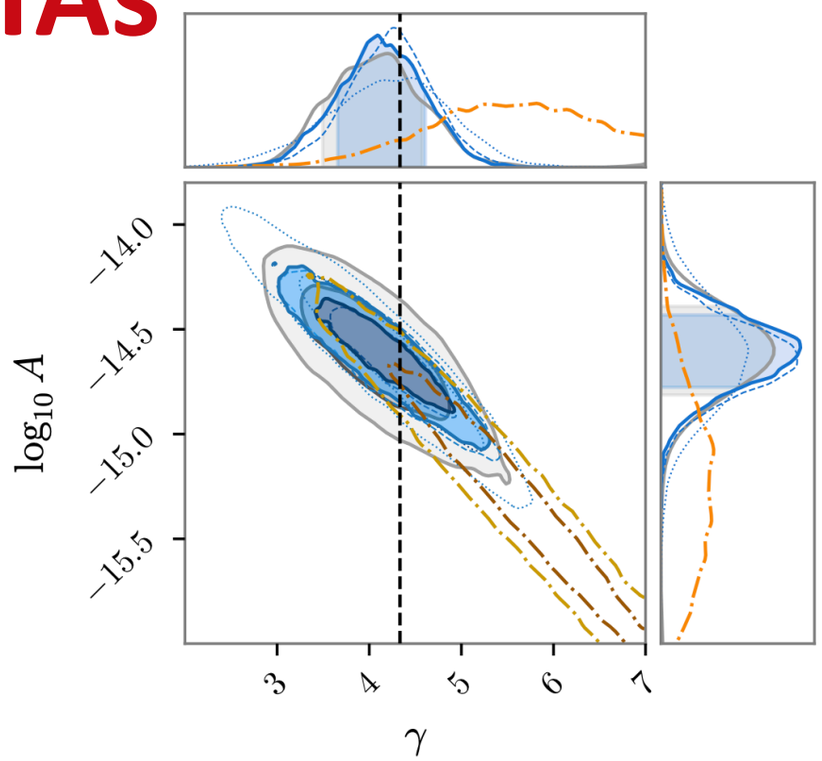


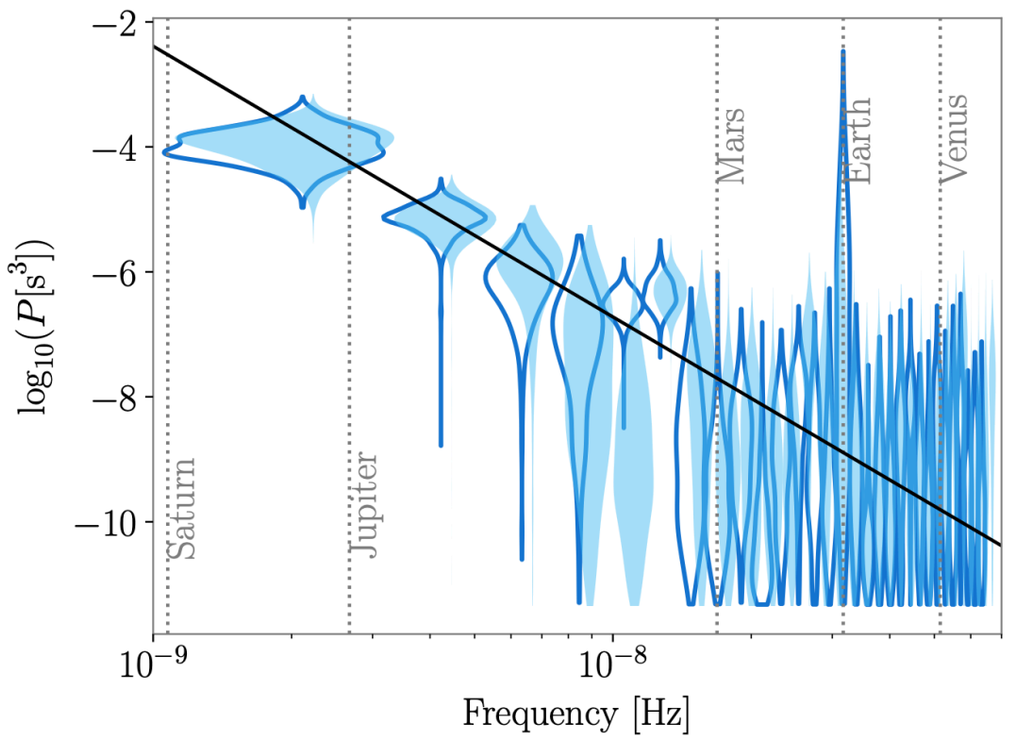
arXiv:2009.04496

Other PTAs

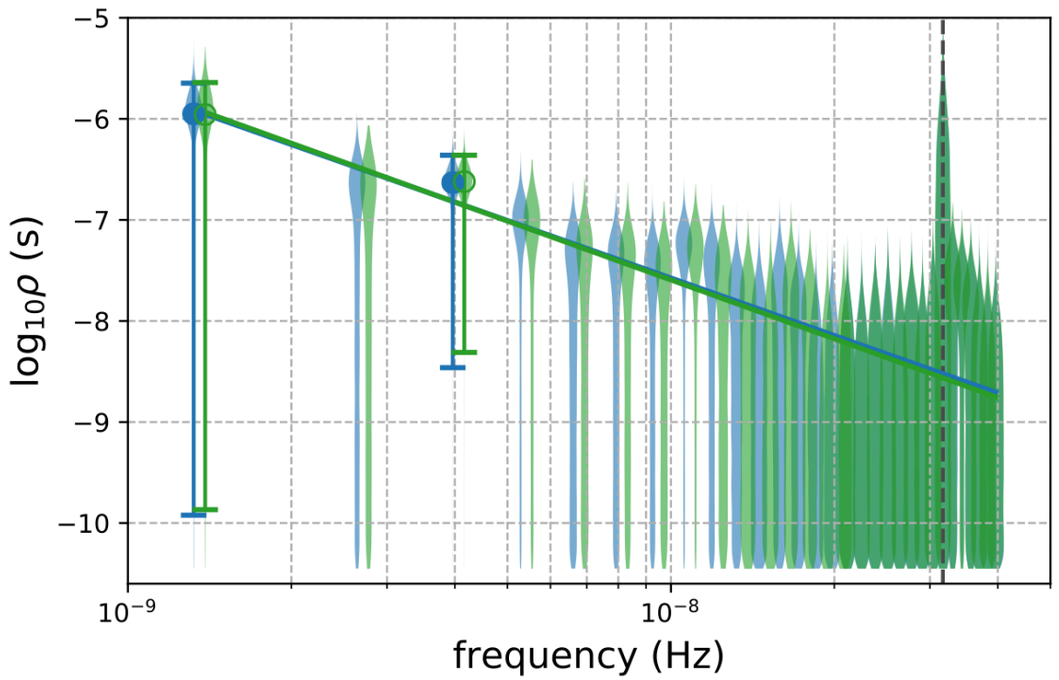
Parkes PTA
(Australia)

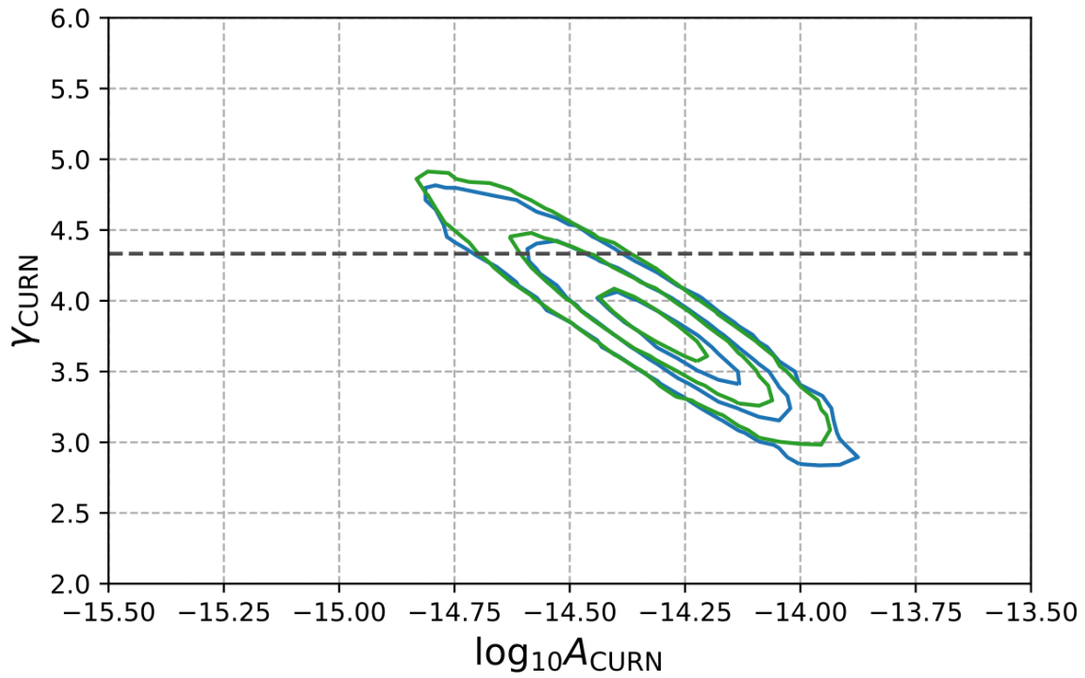
arXiv:2107.12112





European PTA
arXiv:2110.13184





DR2 EP Free Spectrum — DR2 EP Power Law — DR2 42 Free Spectrum — DR2 42 Power Law

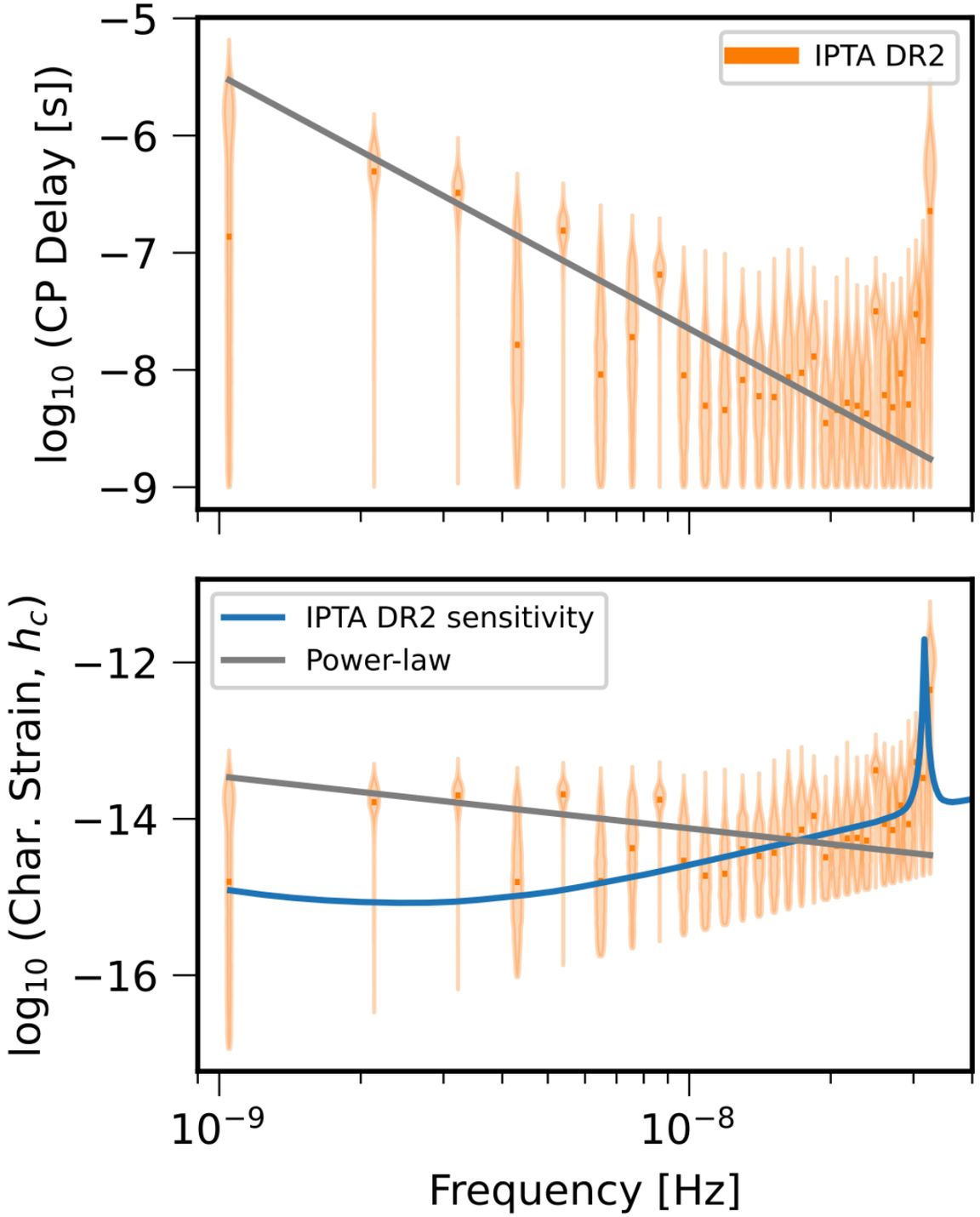
International PTA

Combination of data, but using older data

Again strong evidence for “something”, but no conclusive evidence for quadrupole correlation

Model comparison	$\log_{10}$ BF
HD vs CP	0.3111(6)
CP vs Pulsar Noise	8.2*
CP vs Monopole	4.67(2)
CP vs Dipole	2.28(3)

arXiv:2201.03980

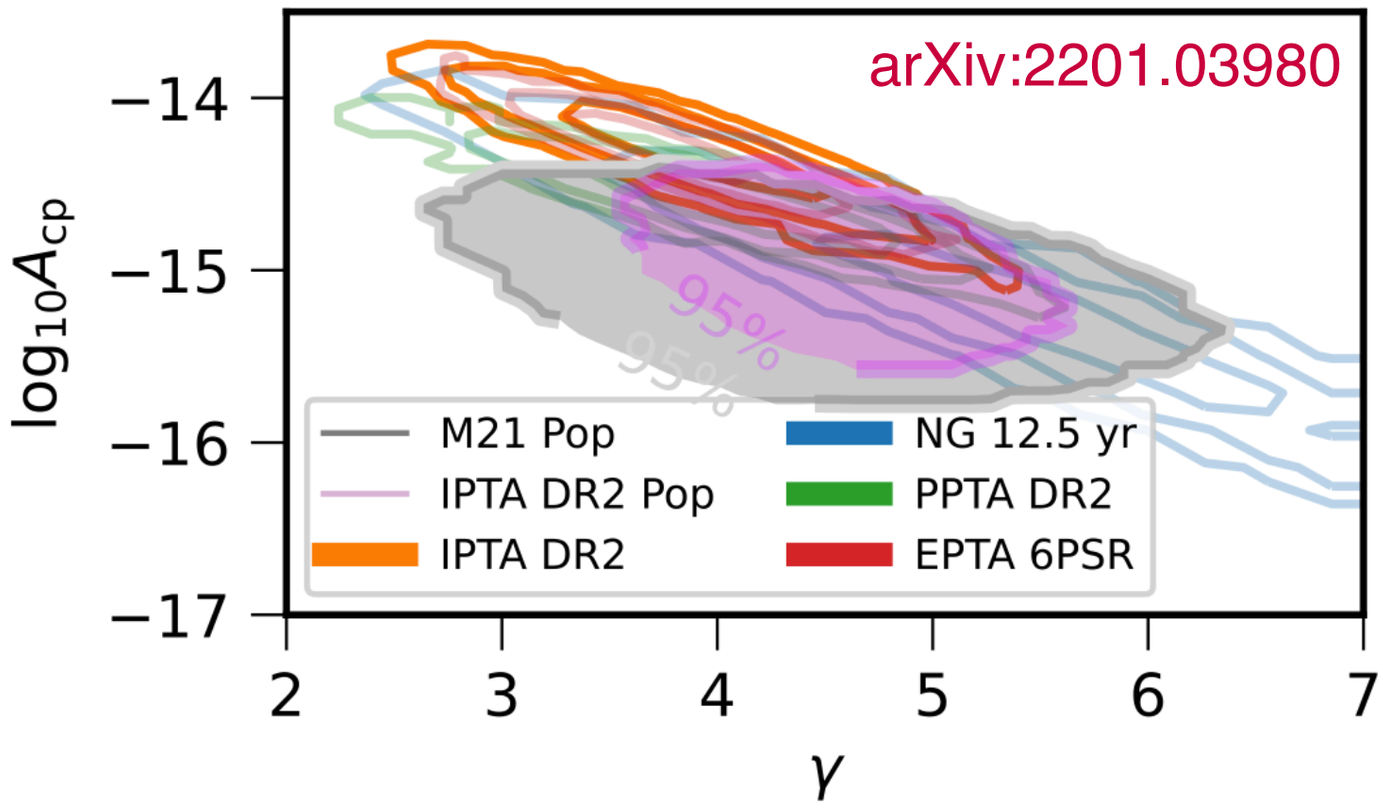


Not an anomaly?

There is an expected background from supermassive black hole binaries (SMBHB)!

Expected slope of $\gamma = 13/3$, but can vary in practice

Amplitude a bit high for pure Astro signal



- Room for new physics contribution!

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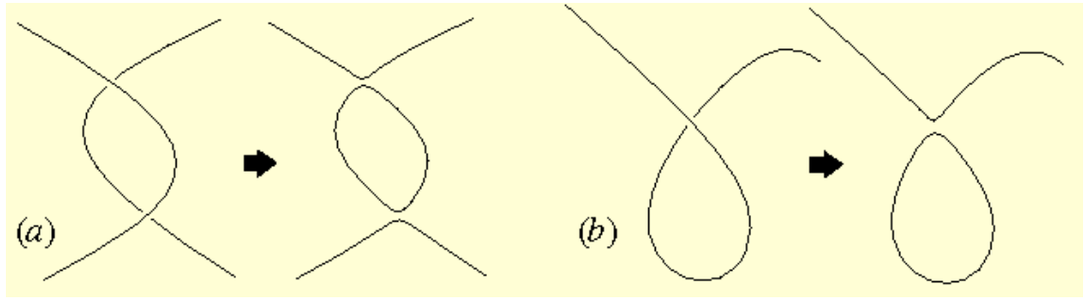
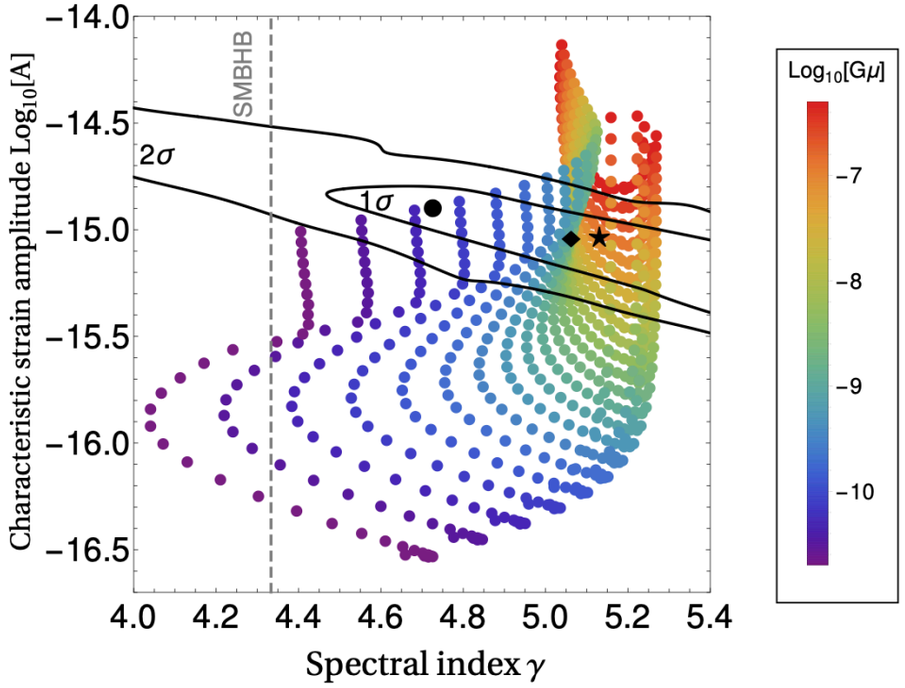
Implications for particle physics

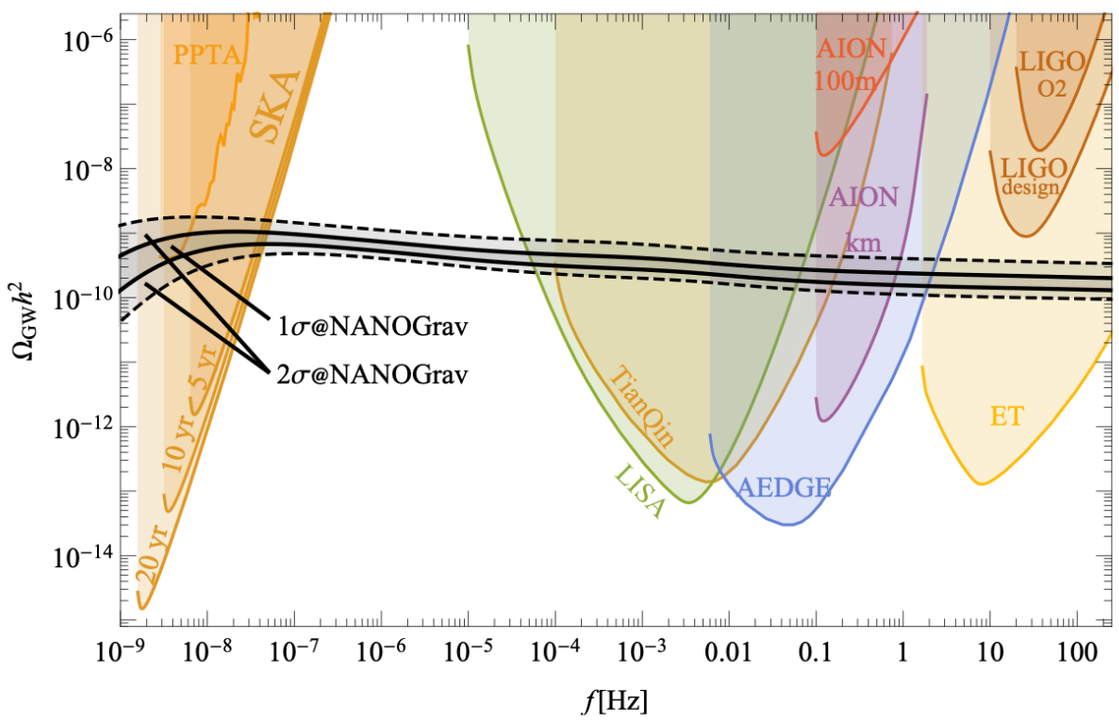
Simple power laws: Inflation or cosmic strings

Strings work better though!



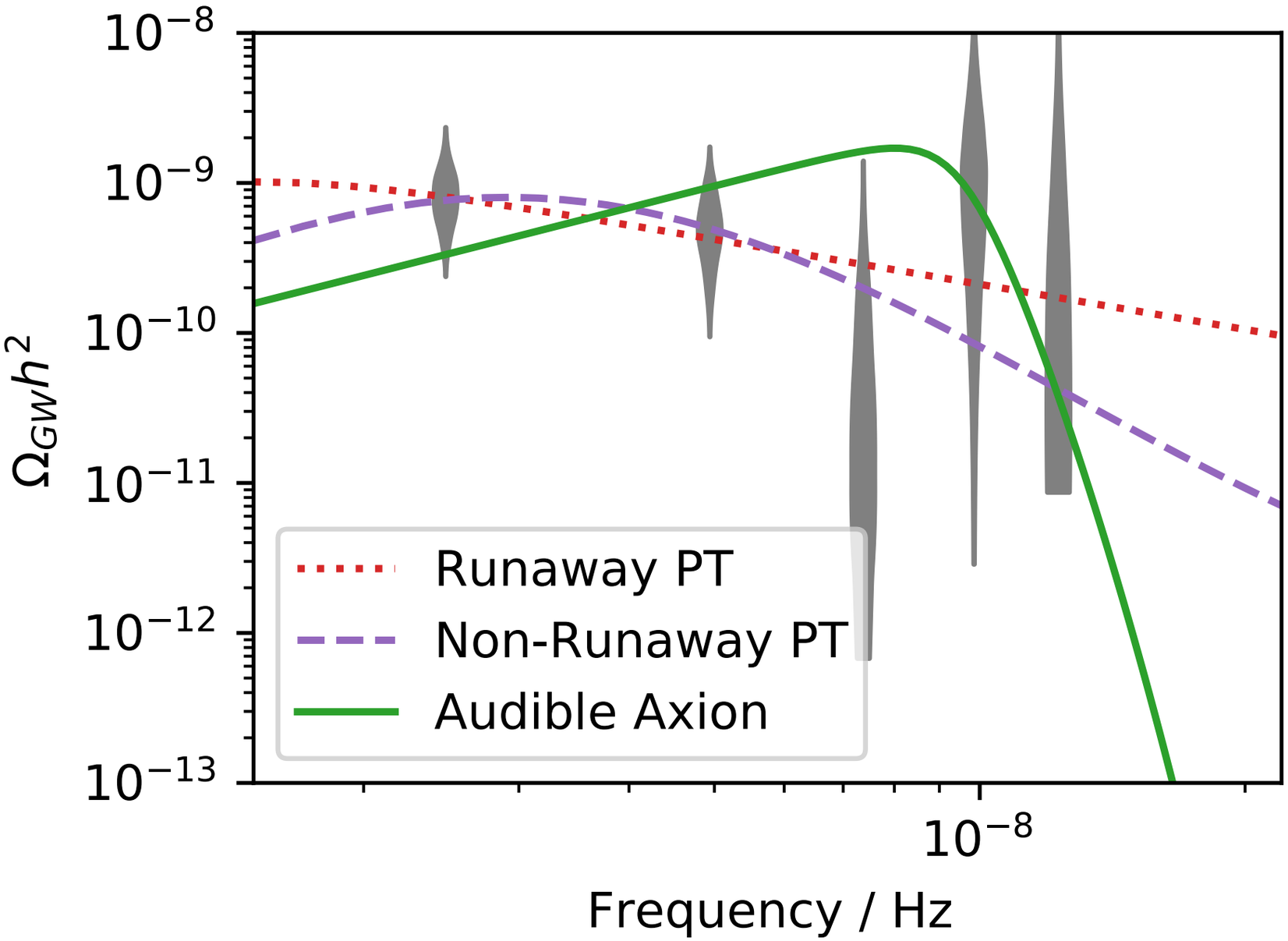


Blasi, Brdar, Schmitz, 2009.06607



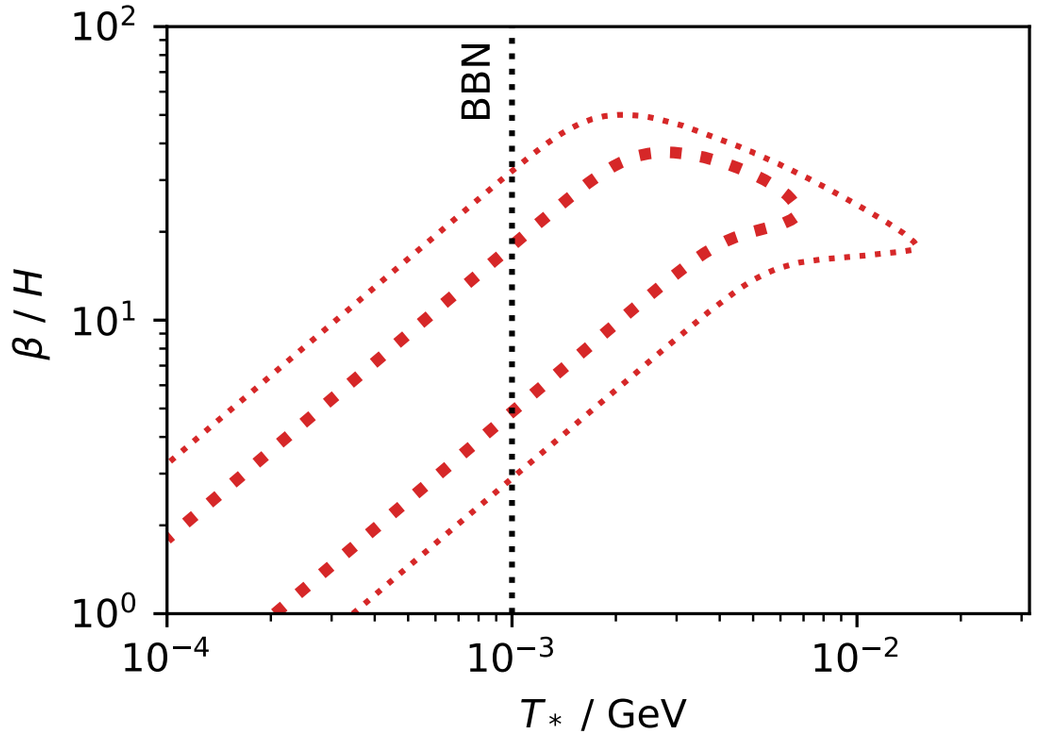
Ellis, Lewicki, 2009.06555

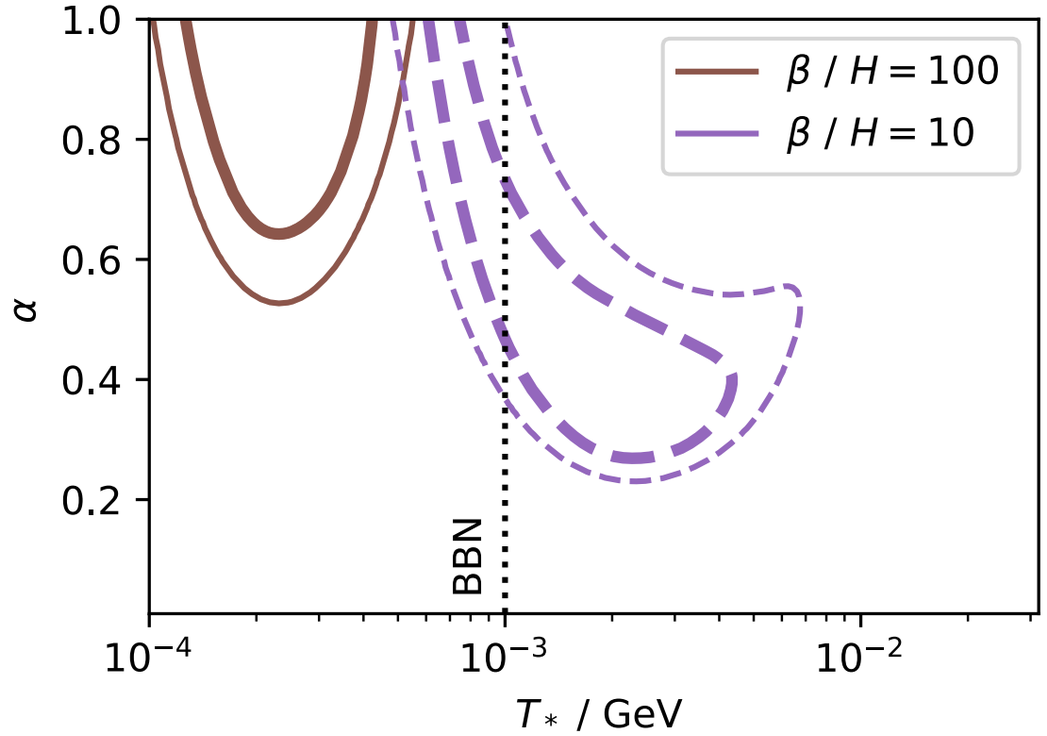
Broken power laws: PTs and axions



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition





Generic PT parameterisation, best fit with PT at temperatures in few MeV range

A dark sector at the few MeV scale? X17?!? Neutrino masses?

Wolfram Ratzinger & PS, 2009.11875

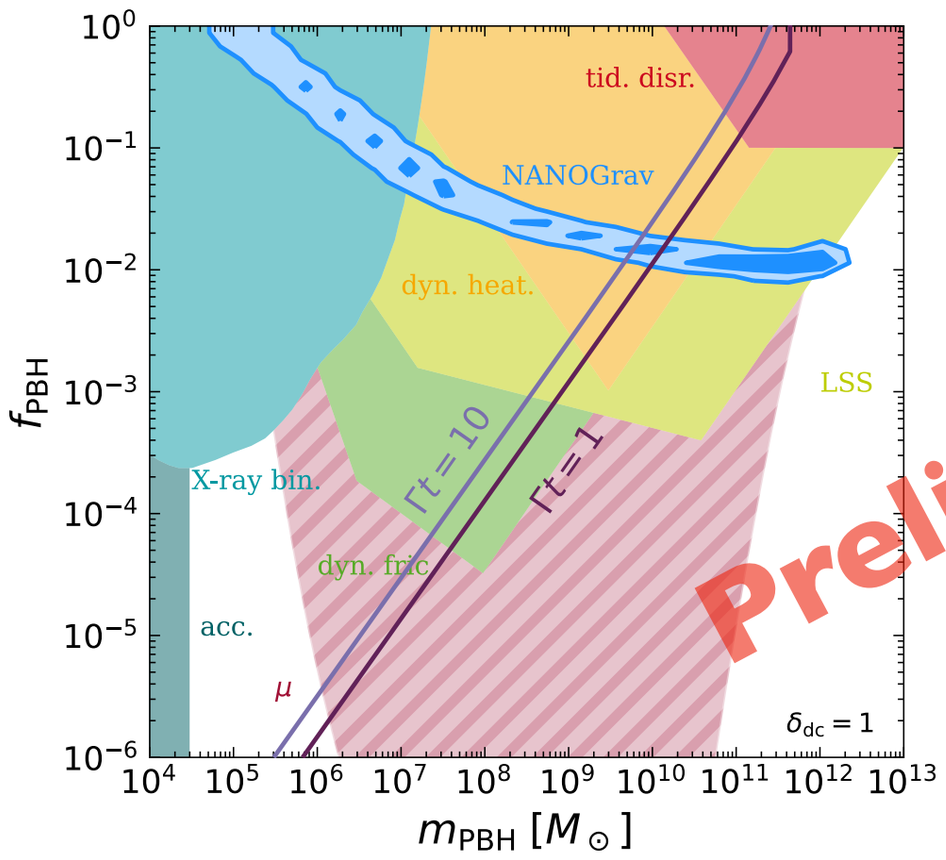
More BHs?

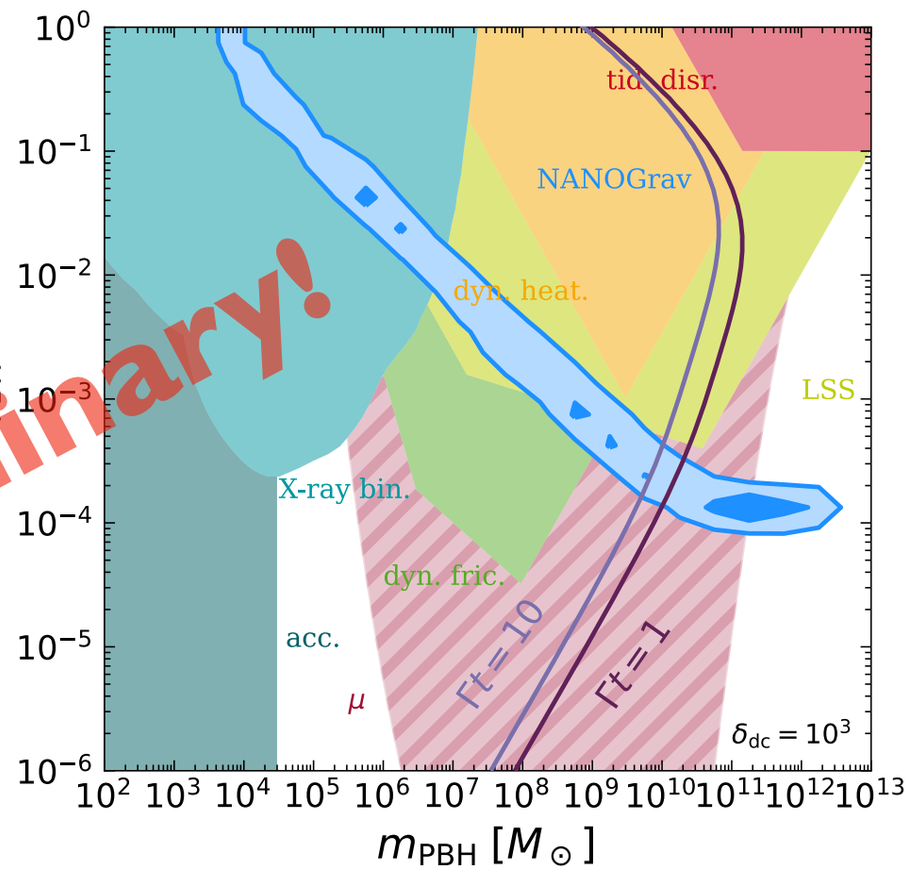
Signal from mergers “stupendously” large primordial BH?

Atal, Sanglas, Triantafyllou, 2012.14721

Only possible with large clustering!

Depta, Schmidt-Hoberg, PS, Tasillo, in preparation



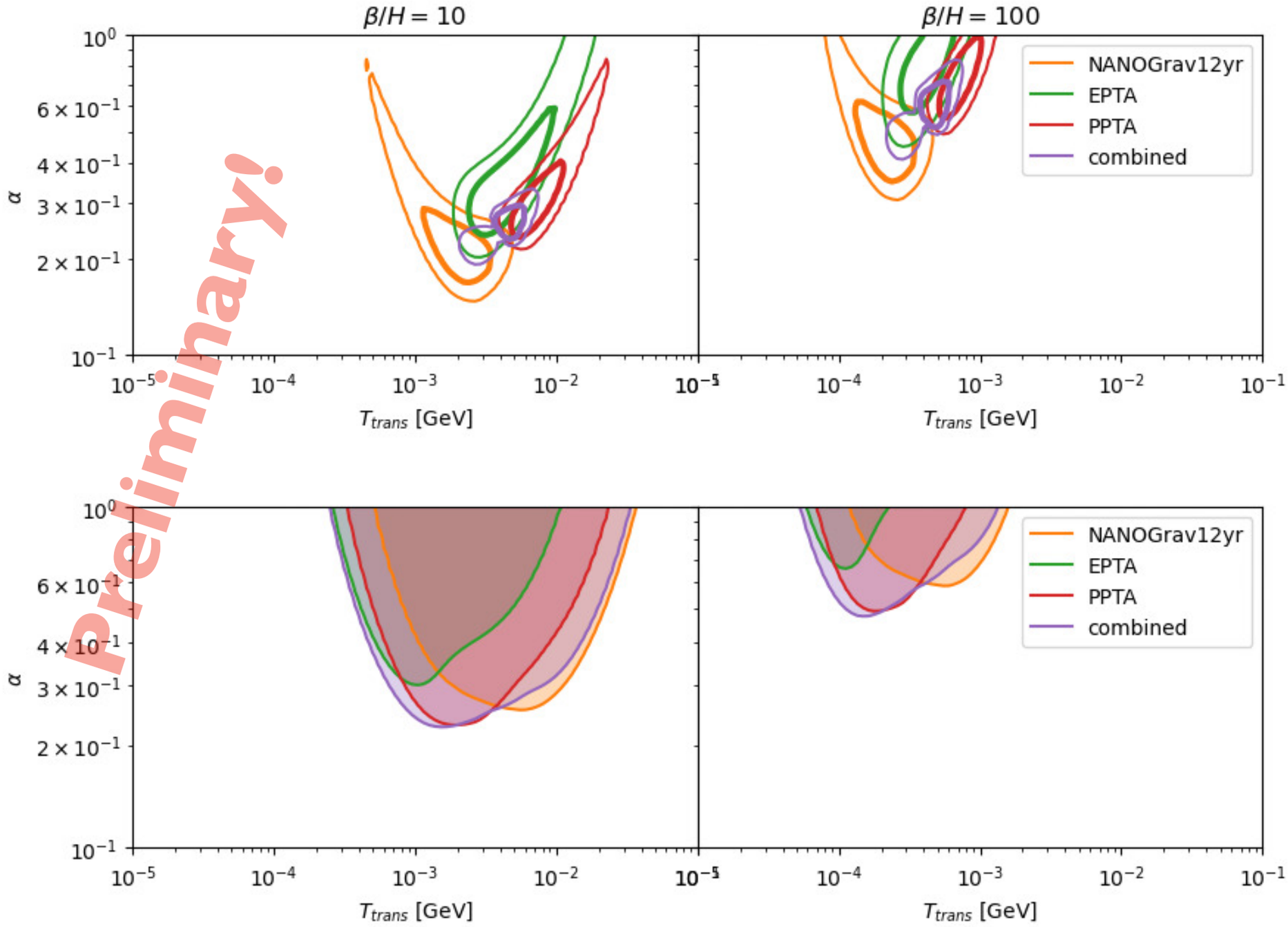


Preliminary!

Phase transitions revisited

Fit to all PTA data

Also: Model exclusion



Madge, Morgante, Puchades, Ramberg, Ratzinger, Schenk, PS, in preparation

Model discrimination

GW spectra, chirality

- With more PTA data (+ other GW detectors)

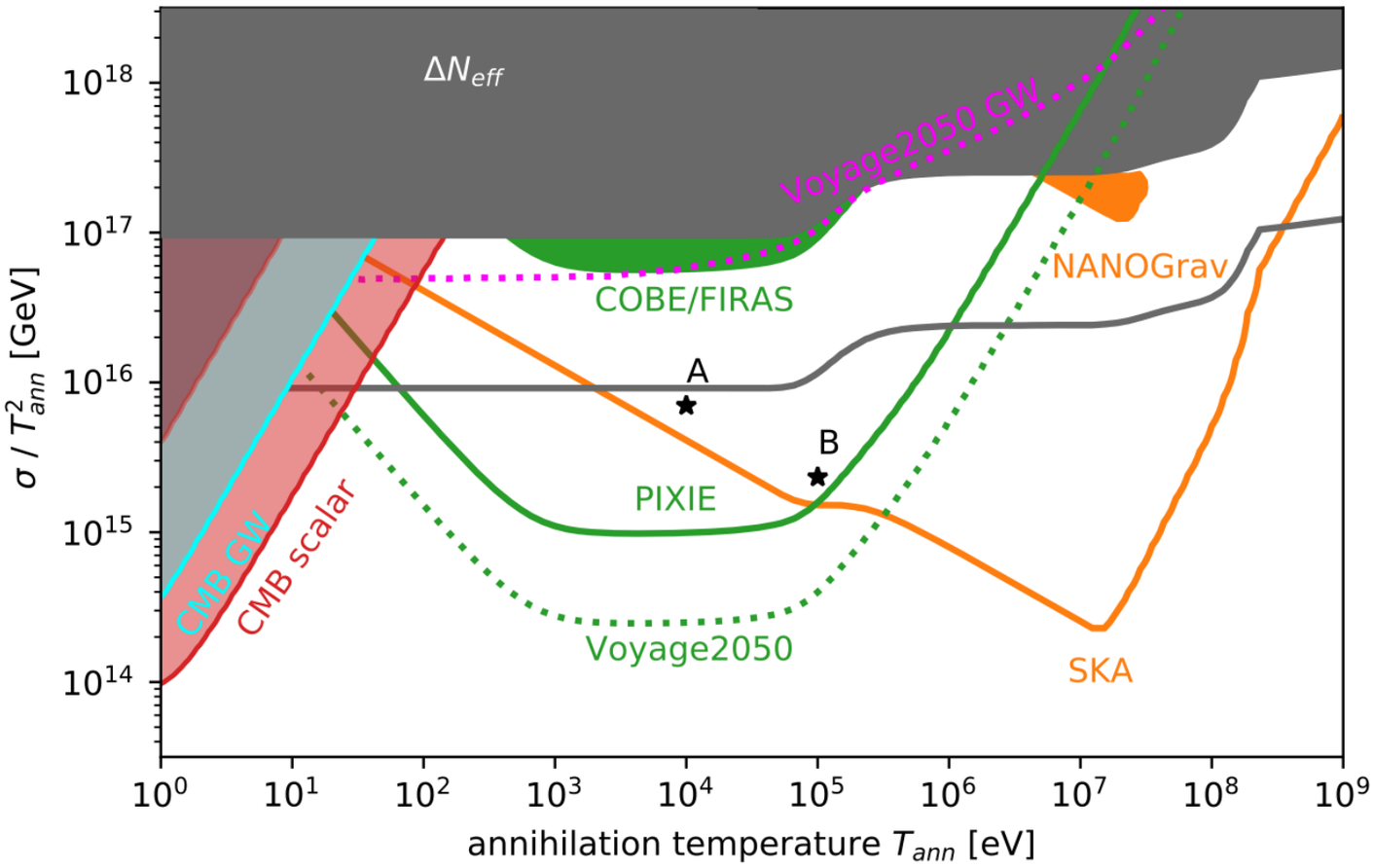
Cosmology

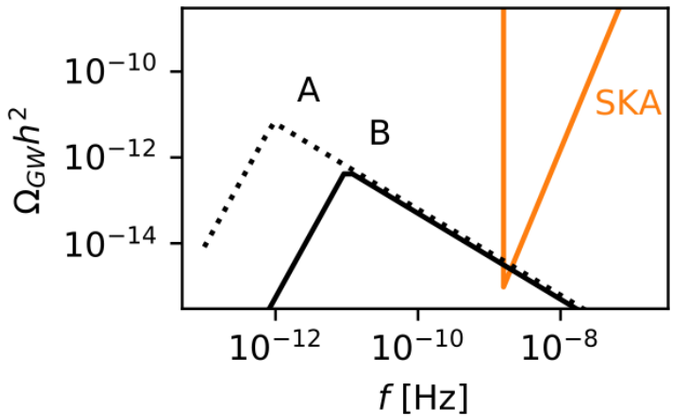
- Many sources contribute to $N_{\rm eff}$, should not upset BBN
- Requires concrete models

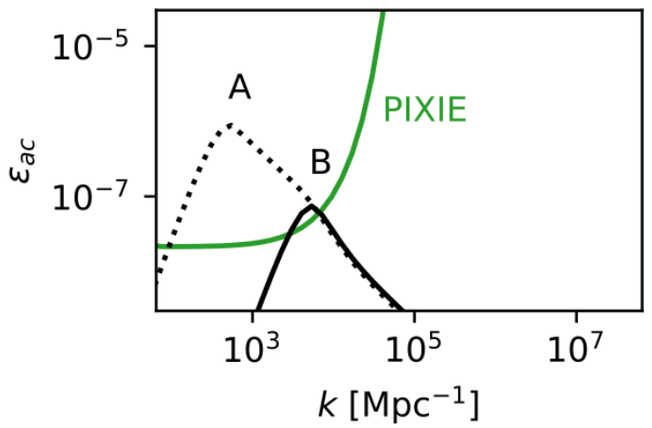
CMB spectral distortions

- Strong GW sources imply large anisotropies “somewhere”
- Anisotropies couple at least gravitationally to SM plasma
- We are close to CMB decoupling → spectral distortions

Example GW source: Annihilating domain walls







Spectral distortions already probe parameter space

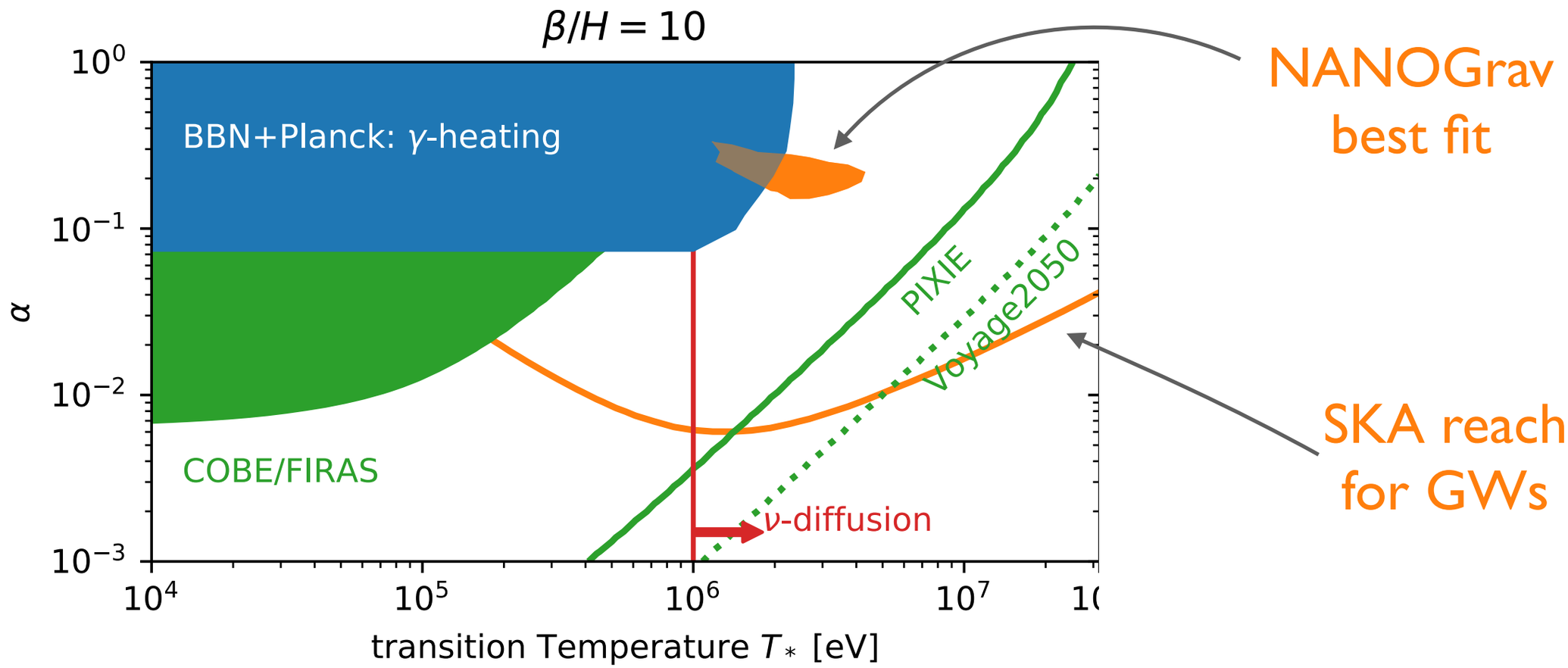
Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Probing sub-MeV phase transitions

Can also directly probe the scalar (density) fluctuations induced by PTs in a dark or visible sector



More sensitive! Multi-messenger cosmology!

Ramberg, Ratzinger & PS, 2209.14313

Summary

GWs offer new window into the early Universe

- A stochastic GW background could tell us about unknown dynamics in the early Universe, pre-CMB

PTA data shows first evidence of such a GW background

- Lot more data expected in the coming years
- Should eventually see SMBHB signal, plus maybe a new physics contribution :)

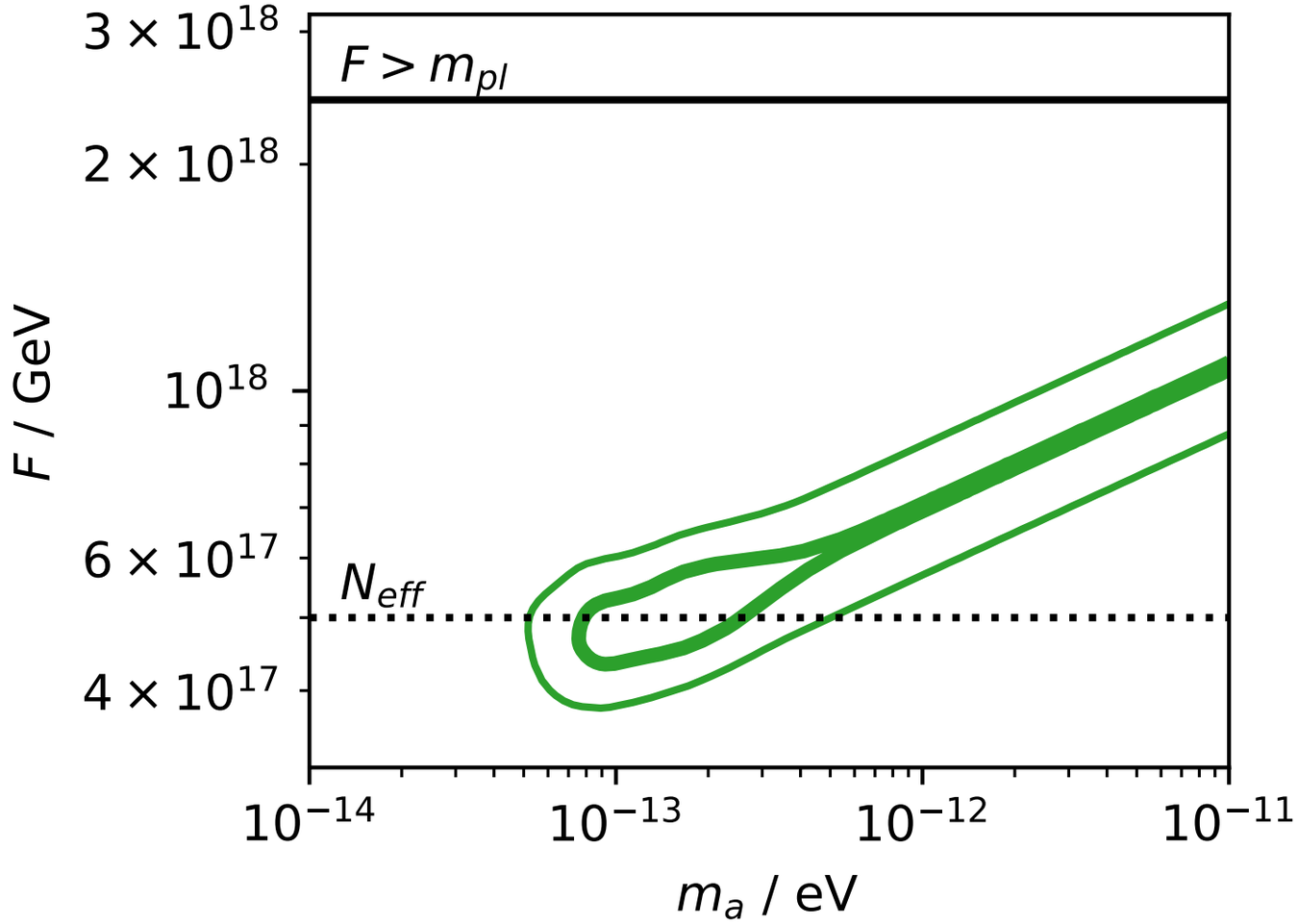
Model discrimination will require additional astro/cosmo data, e.g. spectral distortions, N_{eff} , …

Lot of fun to work on this right now!

Thank you for organising this wonderful conference!

Stuff :)

Example: Audible Axion



Parameter reconstruction already possible

Non-trivial constraints from cosmology (N_{eff})

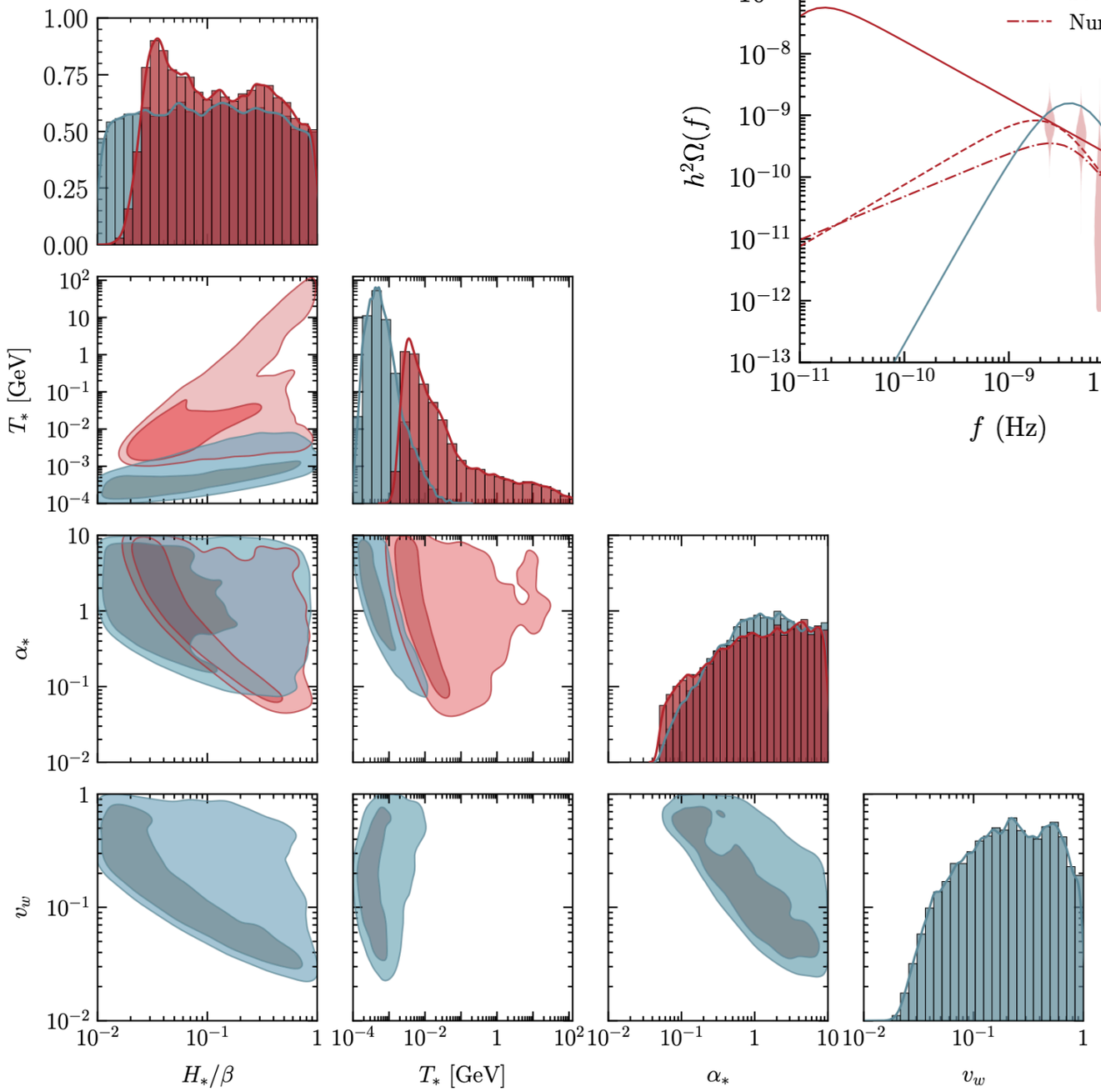
Wolfram Ratzinger & PS, 2009.11875

NANOGrav search for GWs from PTs

Fit to full timing data, including all PT parameters

Assuming either sound wave (blue) or bubble collision(red) source

NANOGrav collaboration, 2104.13930



GWs from Phase Transitions

QFT at finite temperature → symmetry restoration

For first order PT

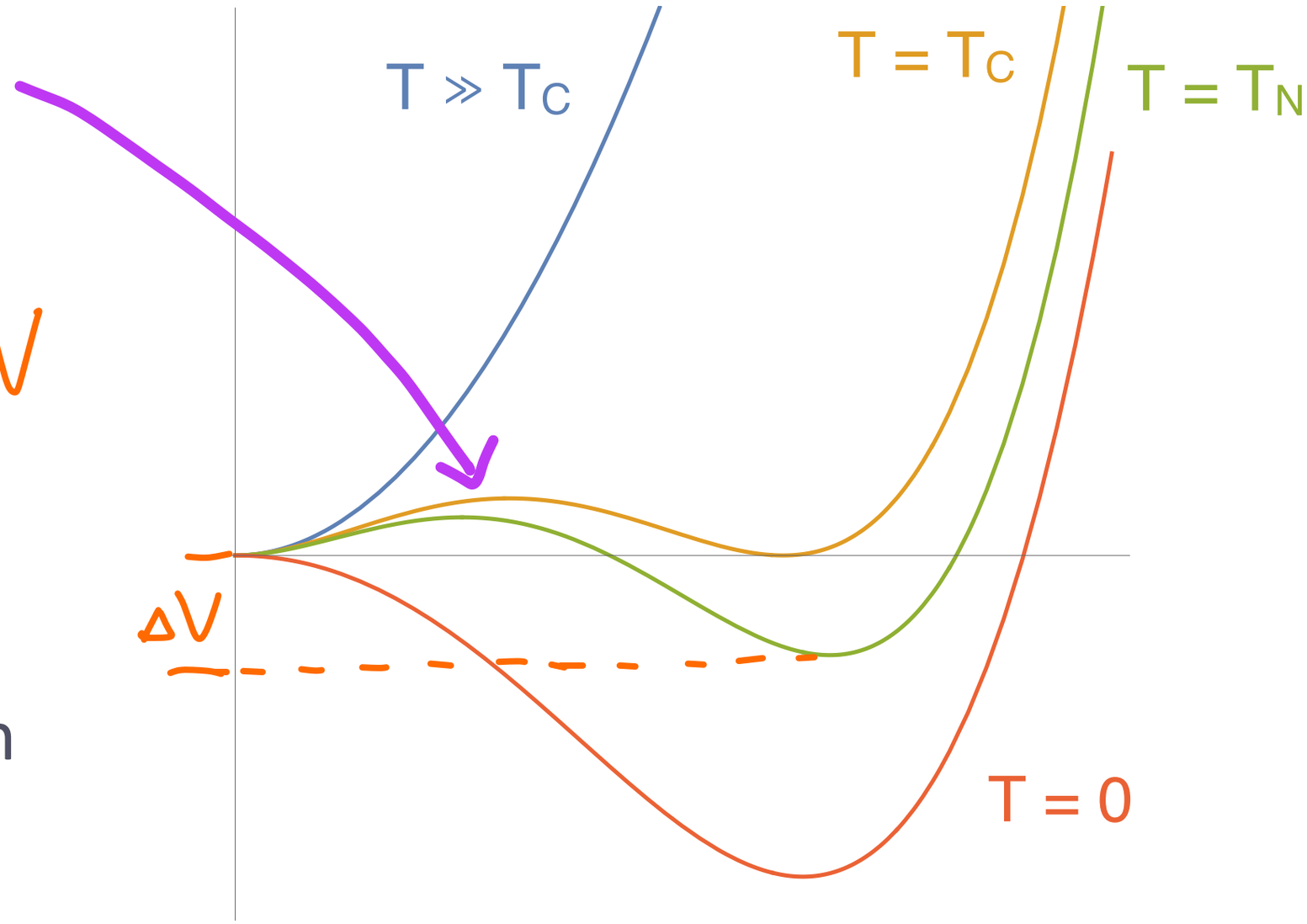
- Need barrier here

PT occurs at T_N

Potential energy

GWs

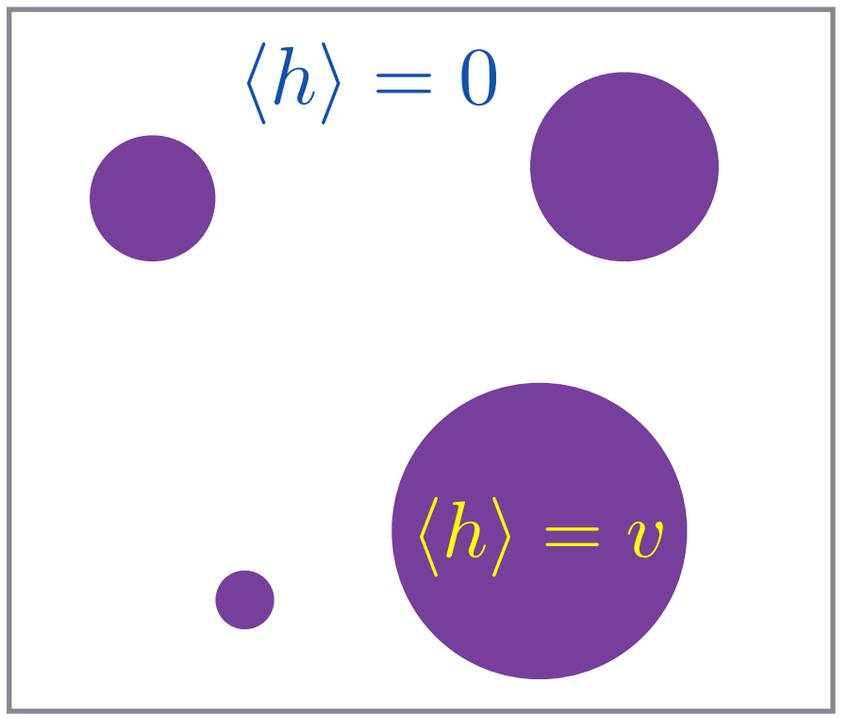
Not in SM! Possible in BSM scenarios

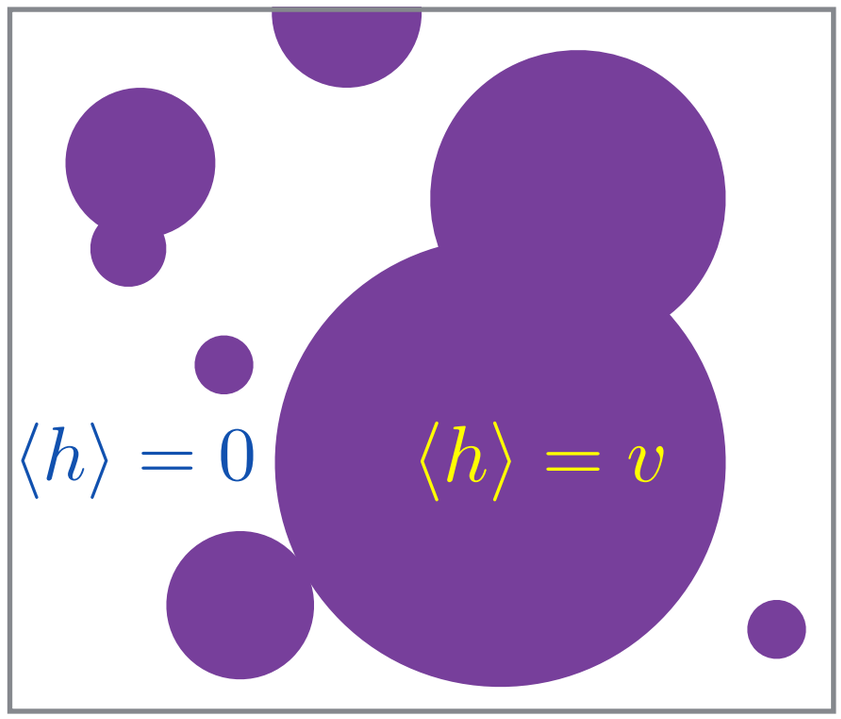


GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves





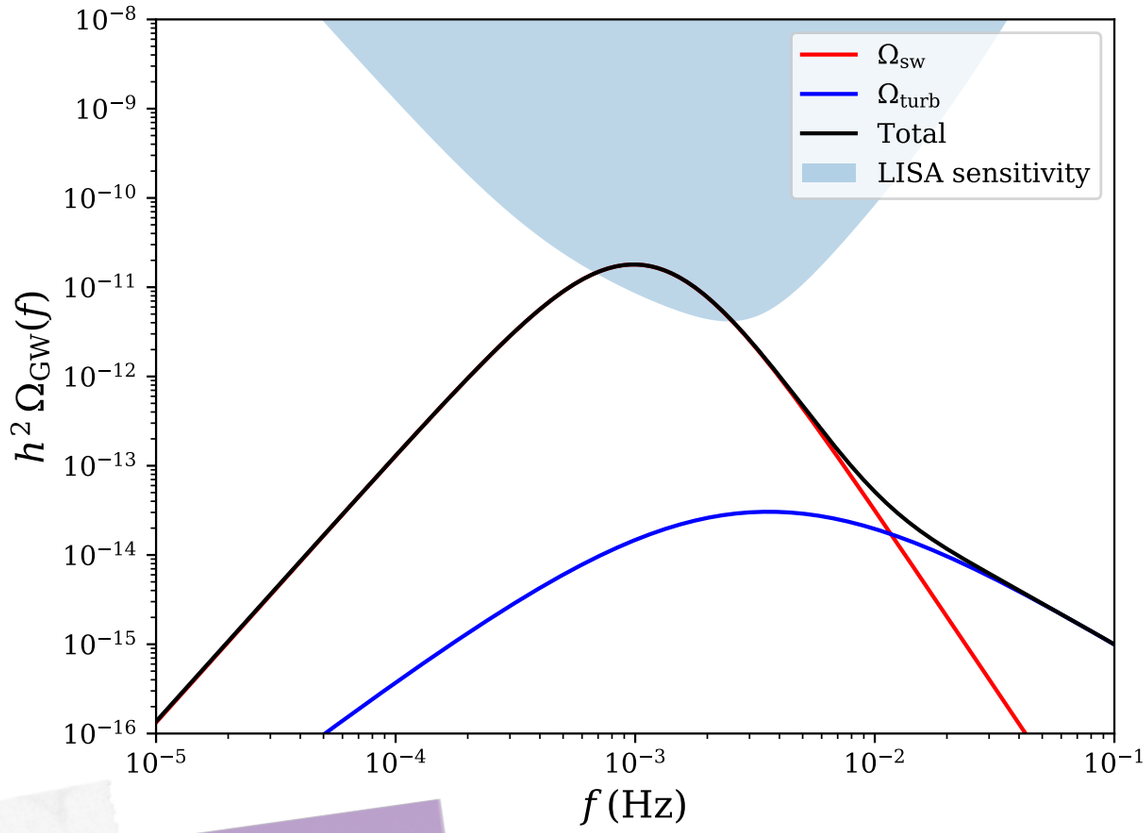
PT signal

PT characterised by few parameters:

- Latent heat $\alpha \approx \dfrac{\Omega_{\rm vacuum}}{\Omega_{\rm rad}}$
- Bubble wall velocity v
- Bubble nucleation rate β
- PT temperature T_*

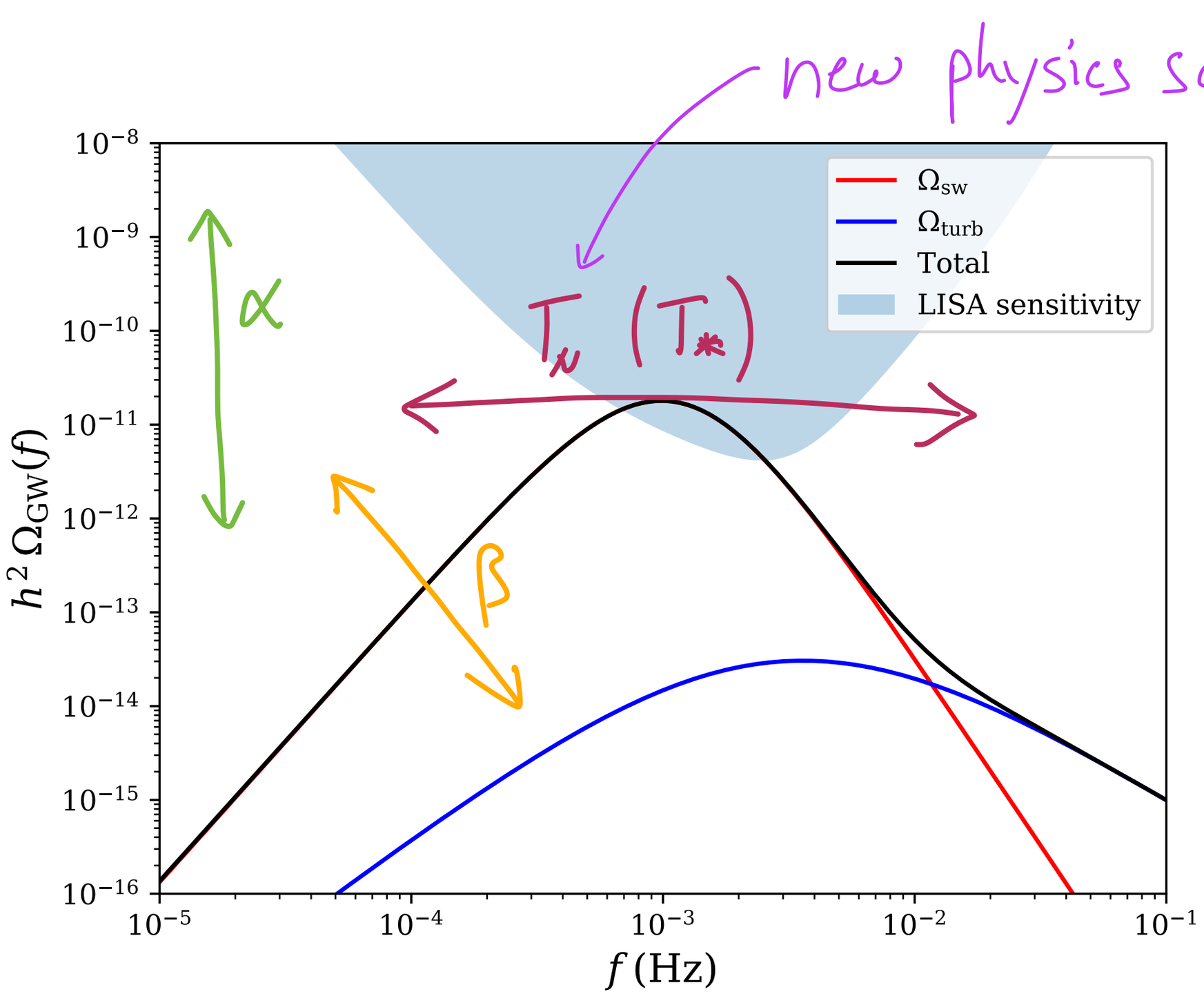
Three physical contributions

- Bubble wall collisions
- Turbulence
- Sound waves



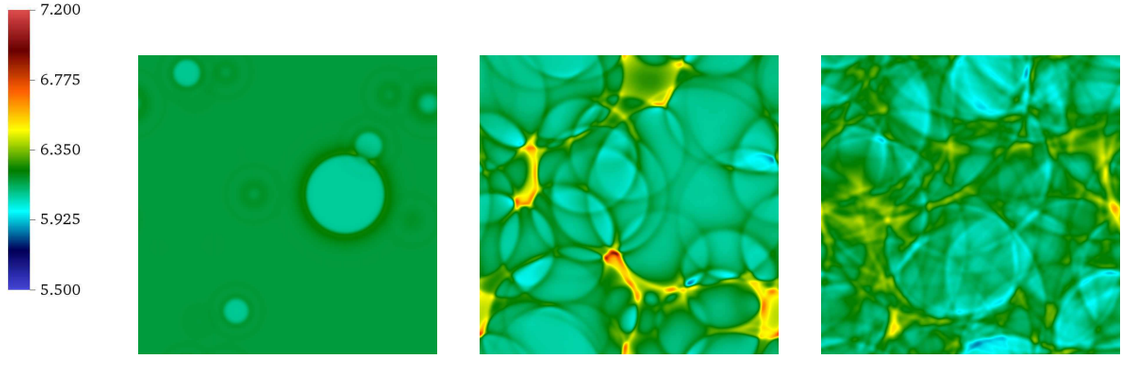
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Signal properties



Primordial sources of GWs

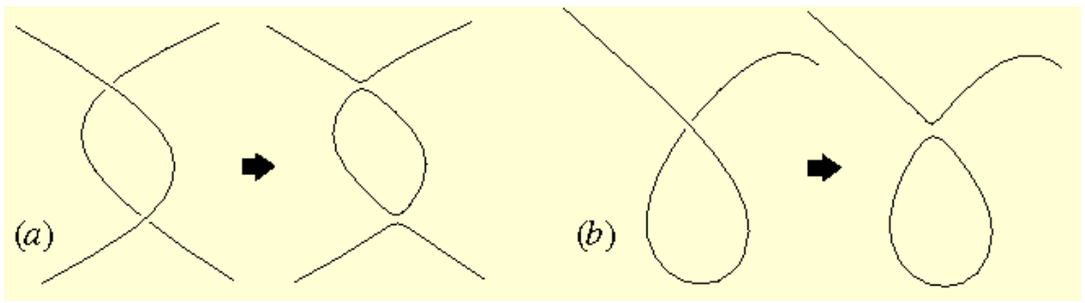
First order phase transitions (symmetry breaking)

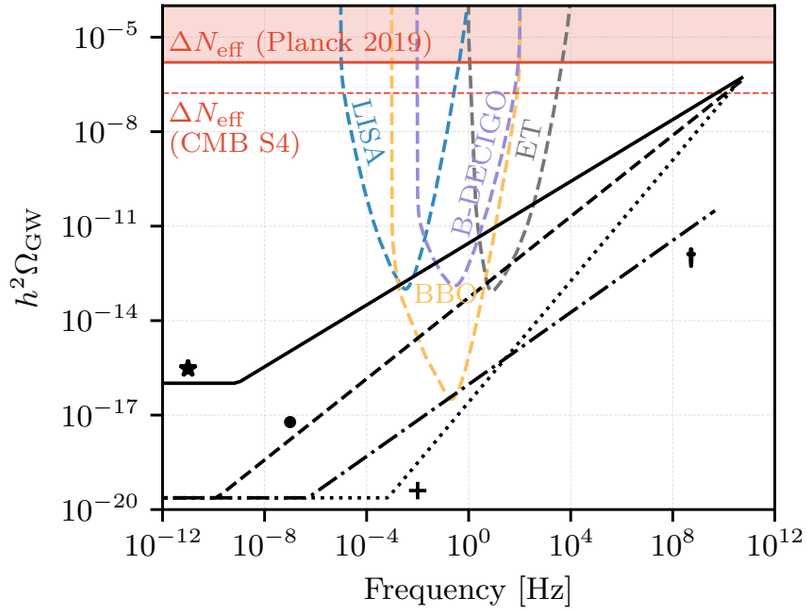


from Hindmarsh et al

Inflation/Reheating

Cosmic strings



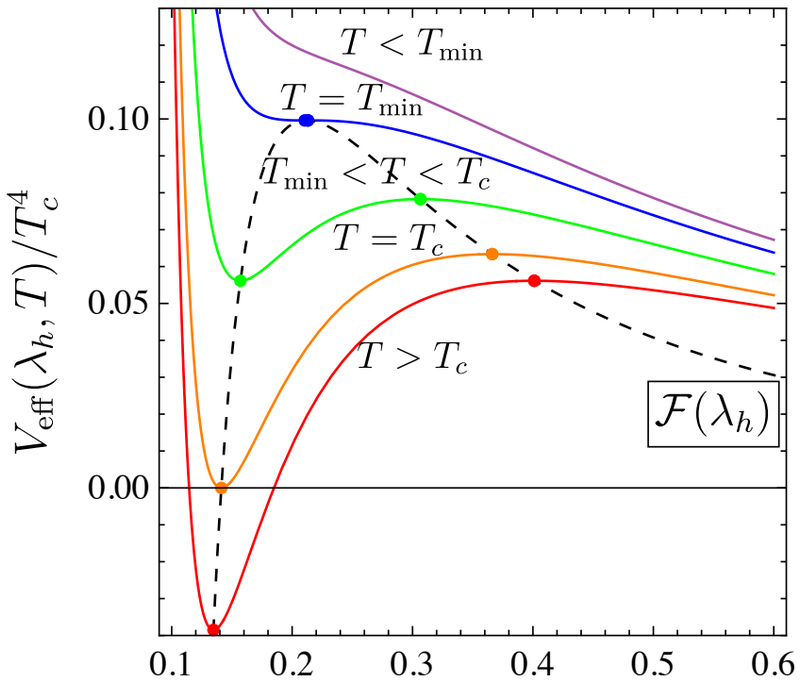


Opferkuch, PS, Stefanek, 2019

Strongly coupled PTs are also difficult

Computed thermal effective potential in improved holographic QCD

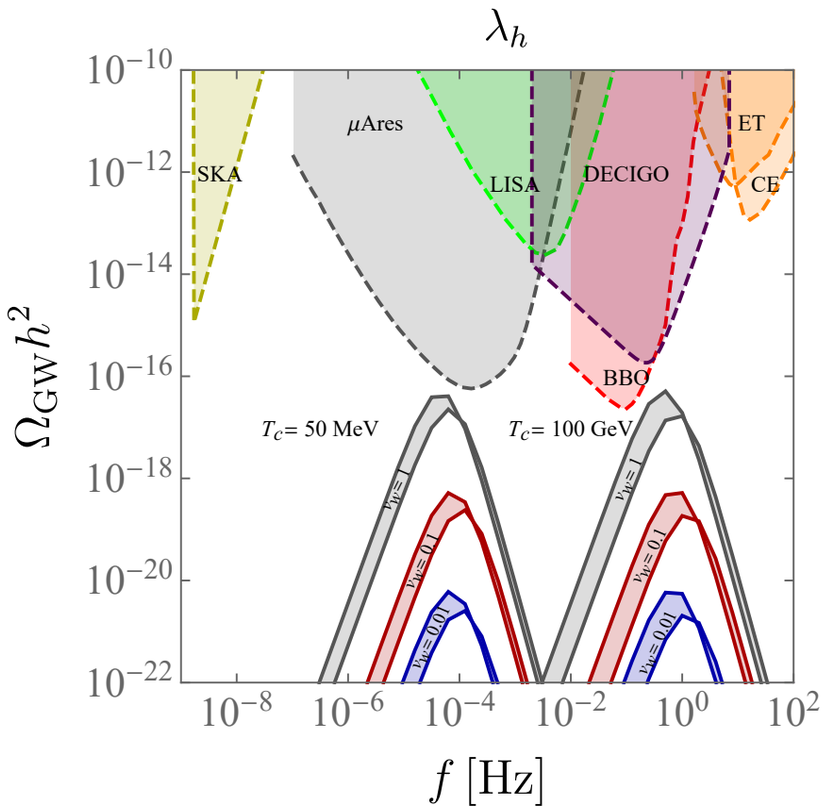
- Fit to reproduce finite T lattice data



First prediction for GW spectra of QCD-like dark sectors from holography

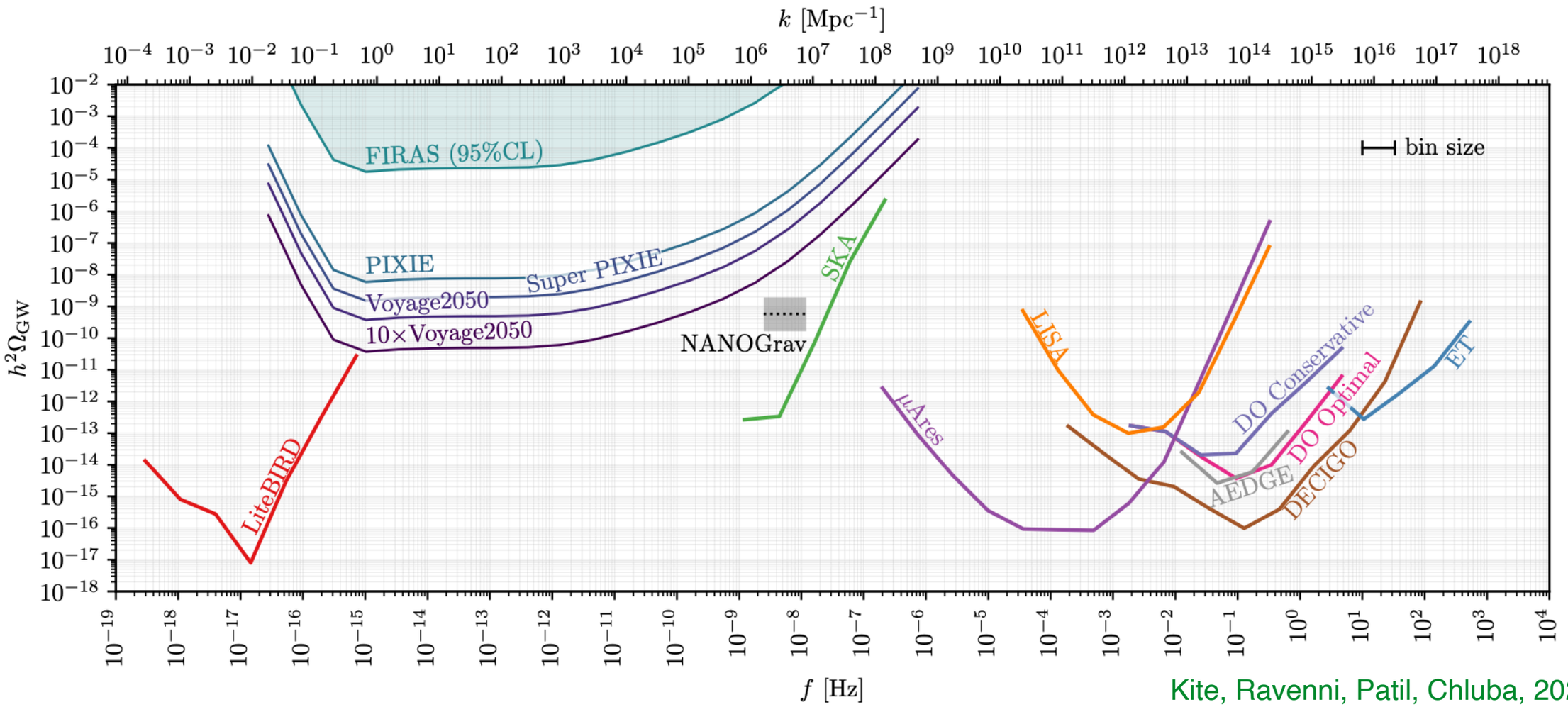
Enrico Morgante, Nicklas Ramberg, PS, in preparation

except for the wall velocity…



Probing sub-MeV phase transitions

Very low frequency GWs induce CMB spectral distortions



Kite, Ravenni, Patil, Chluba, 2021

Probe sources that give peaked GW spectra (like PTs)

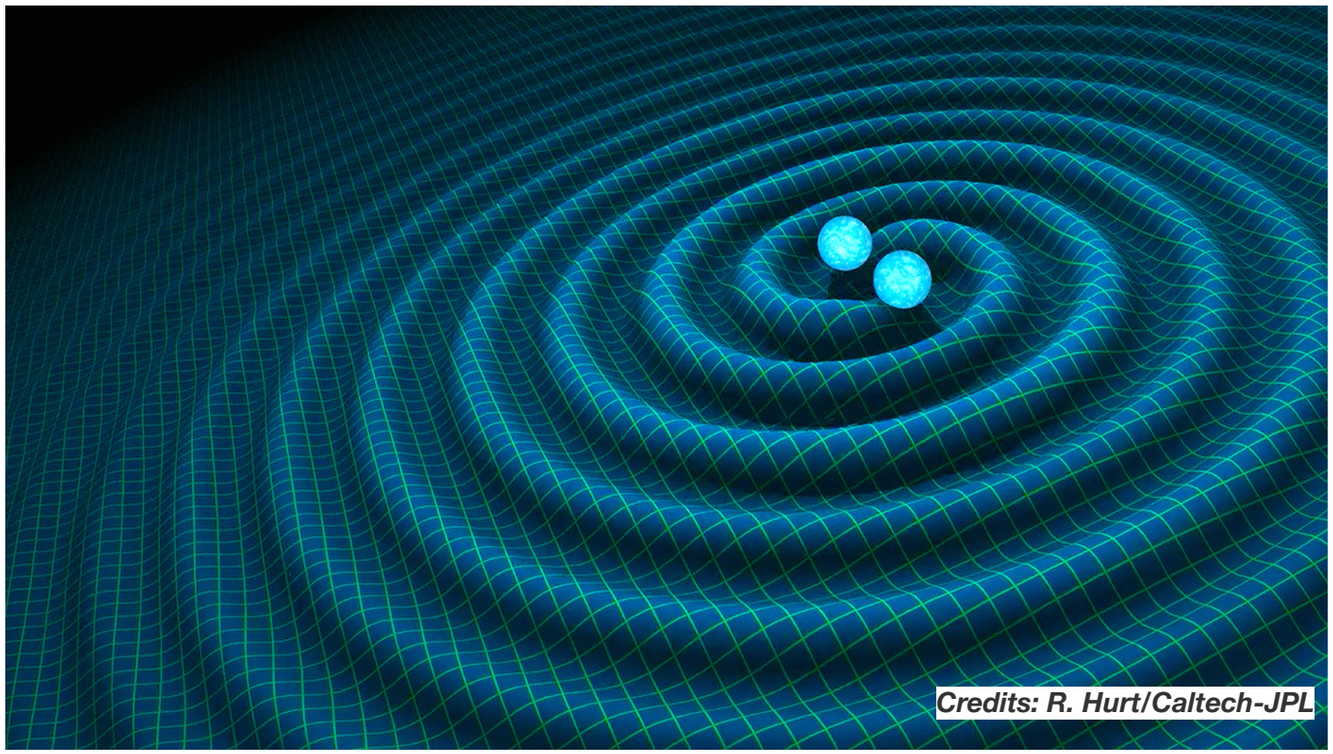
Gravitational waves as messengers from the early Universe

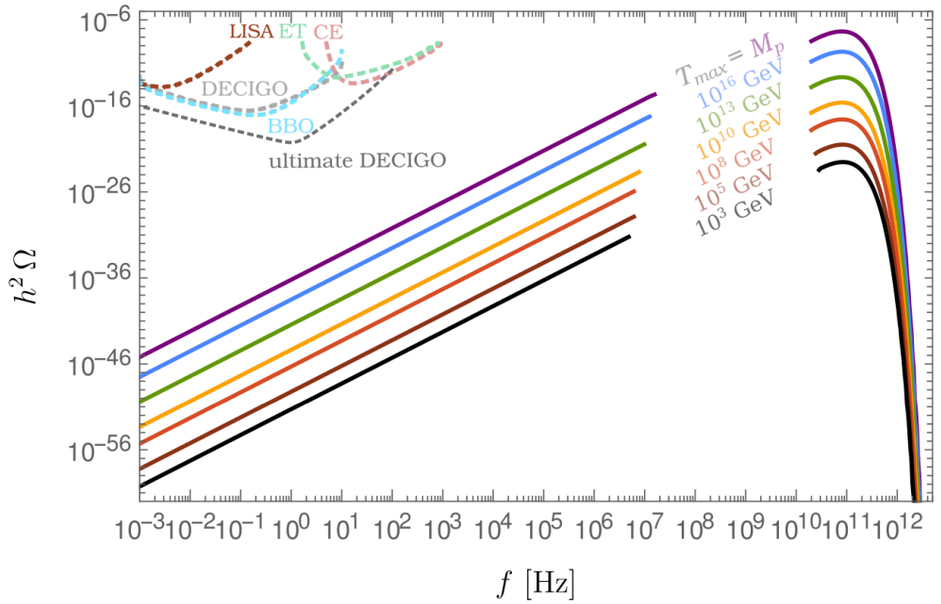
Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background

Or with very very (very!) high temperatures





From Ringwald, Schütte-Engel, Tamarit, 2020

original computation: Ghilieri & Laine 2015

Thermal History