PHASE TRANSITIONS AND GRAVITATIONAL WAVES

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Phase transitions and gravitational waves

Gravitational waves as windows into the early Universe

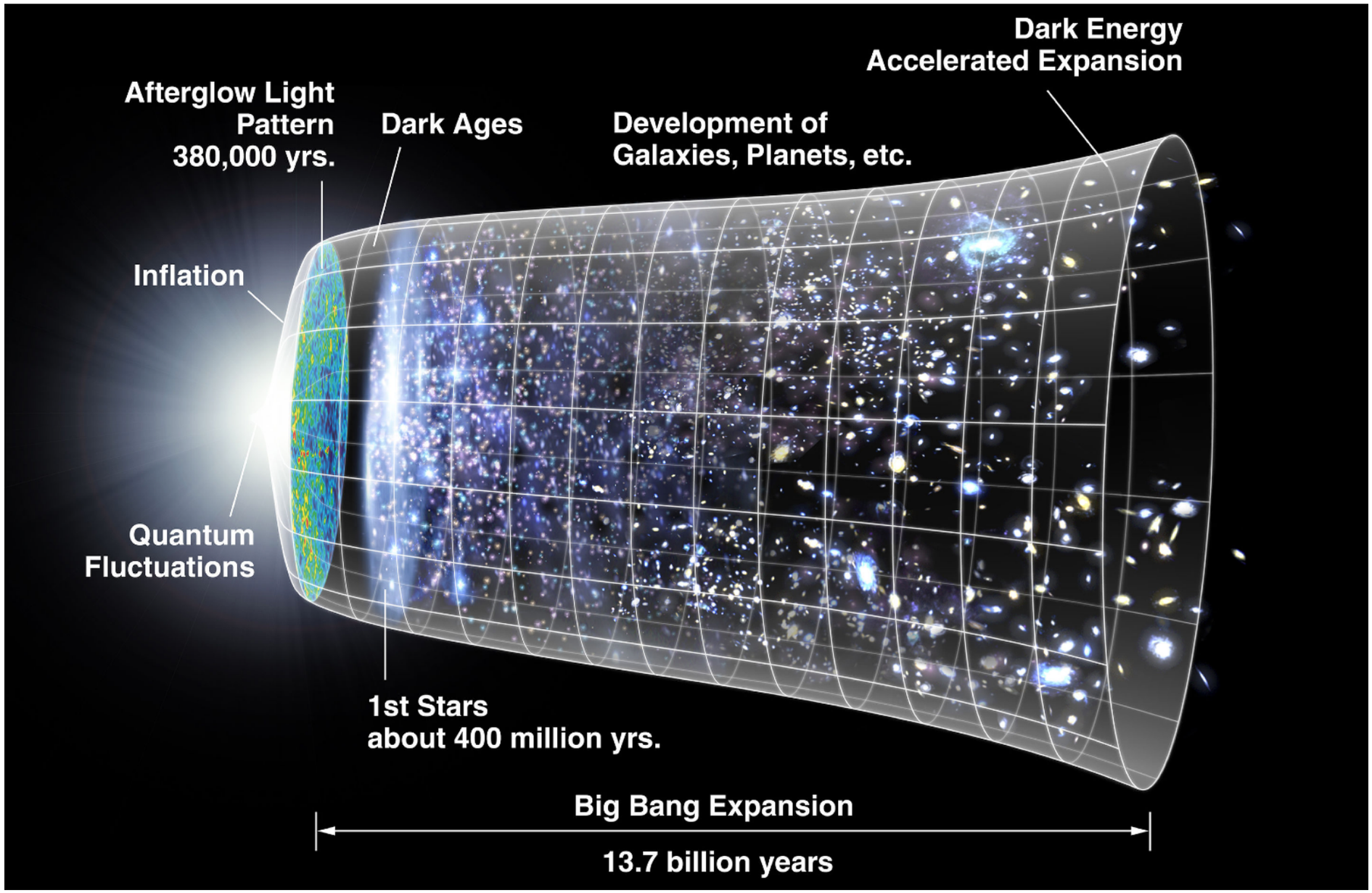
Gravitational waves from first order phase transitions

- The basics
- Some recent (and upcoming) results

The NANOGrav signal and GWs from PTs

What do we know about the early Universe?

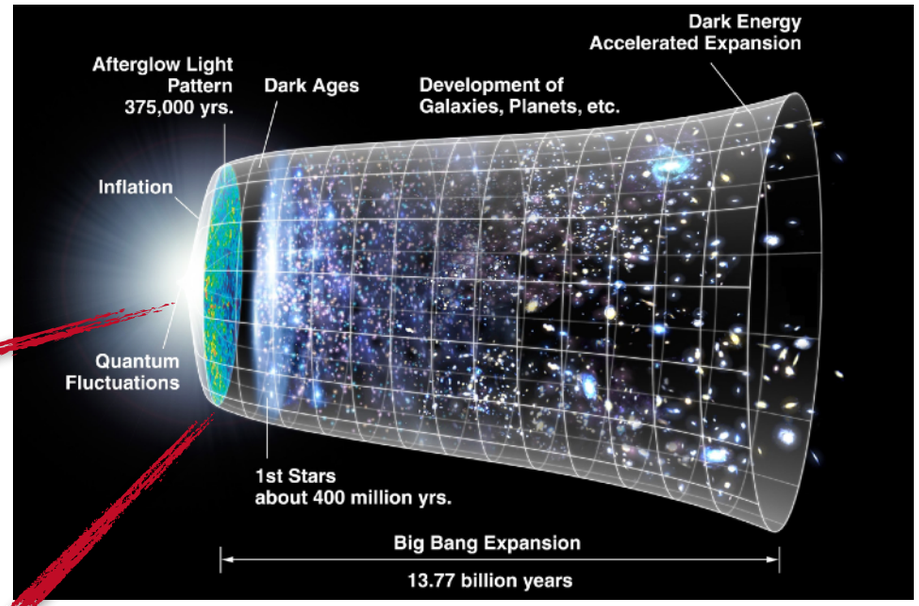
Thermal History

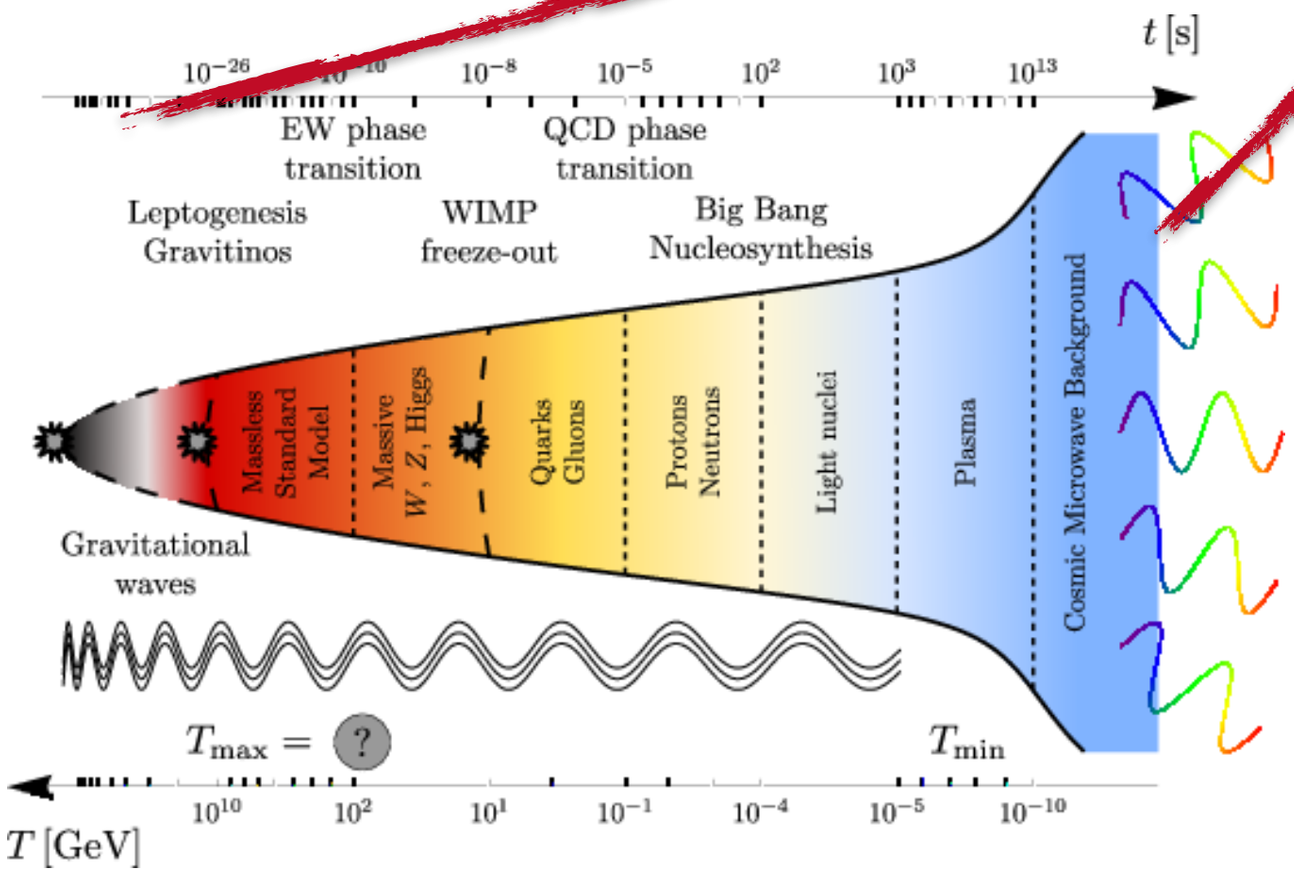


Gravitational Waves?

Zoom into interesting region

New window into early universe





e.g.

Electroweak symmetry breaking

Baryogenesis

Dark matter production

GWs & early Universe

CMB encodes information about the state of the universe at the time of its emission

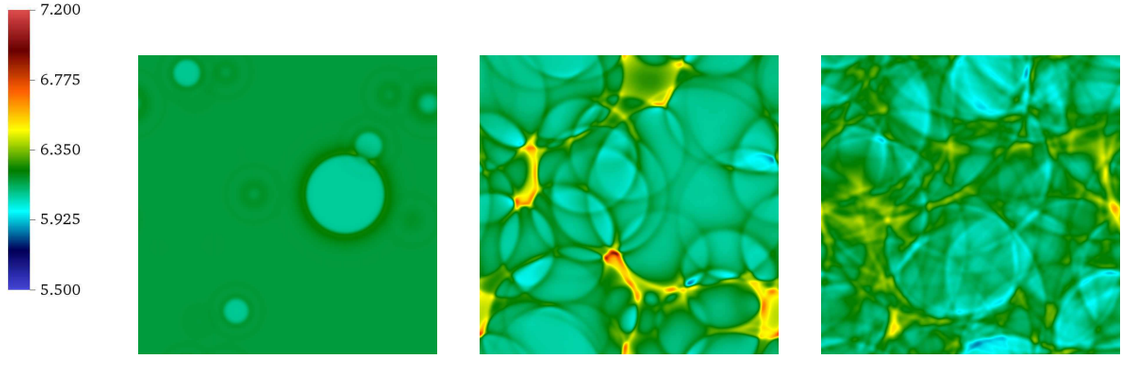
- Densities of matter, radiation, dark matter
- Fluctuations, Hubble rate, …

GWs could do the same

- For earlier times
- For different periods!
- Need a strong source (CMB photons are just there!)

Primordial sources of GWs

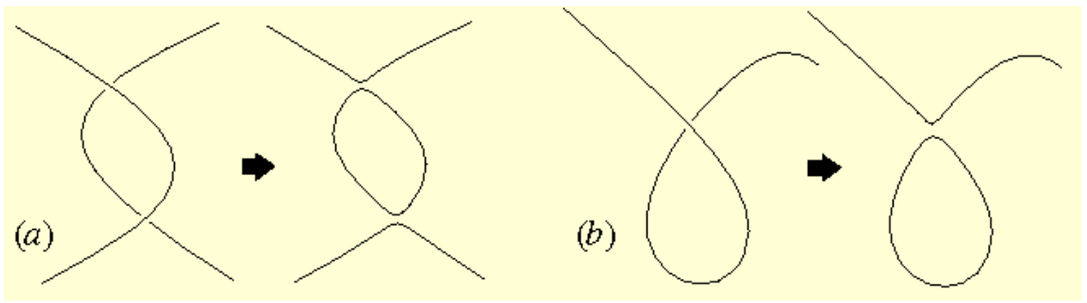
First order phase transitions (symmetry breaking)

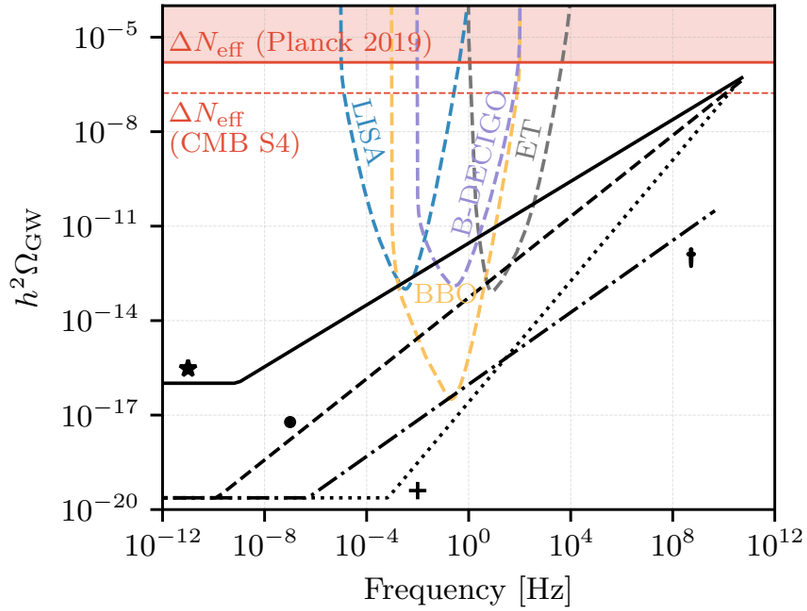


from Hindmarsh et al

Inflation/Reheating

Cosmic strings





Opferkuch, PS, Stefanek, 2019

GWs from Phase Transitions

QFT at finite temperature → symmetry restoration

For first order PT

- Need barrier here

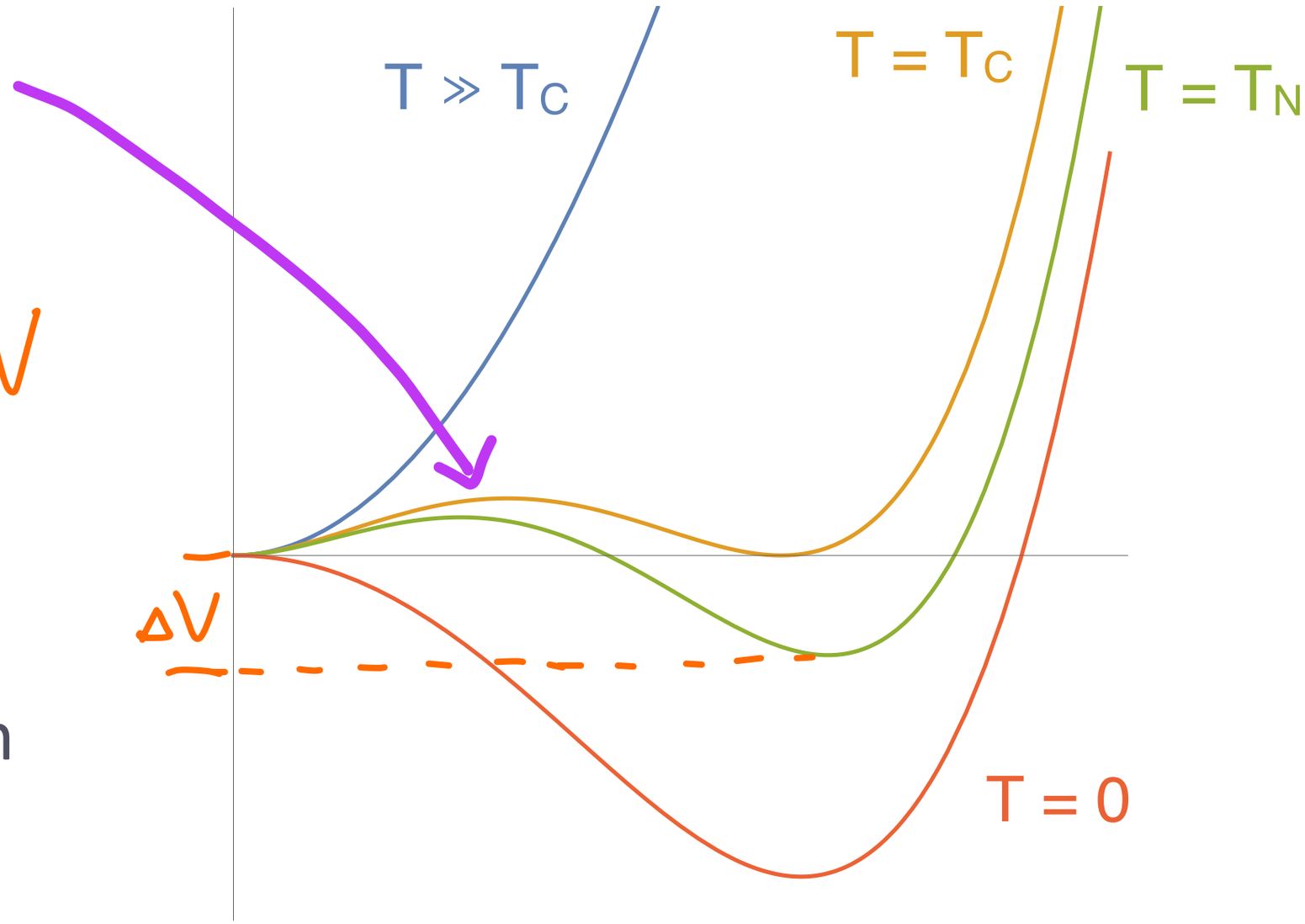
PT occurs at T_N

Potential energy

↓

GWs

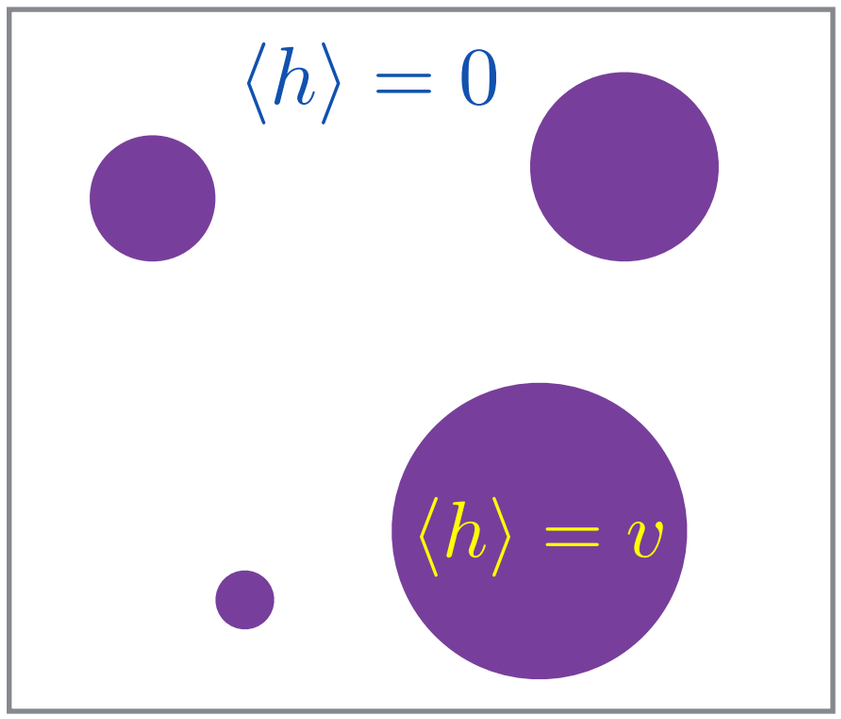
Not in SM! Possible in BSM scenarios

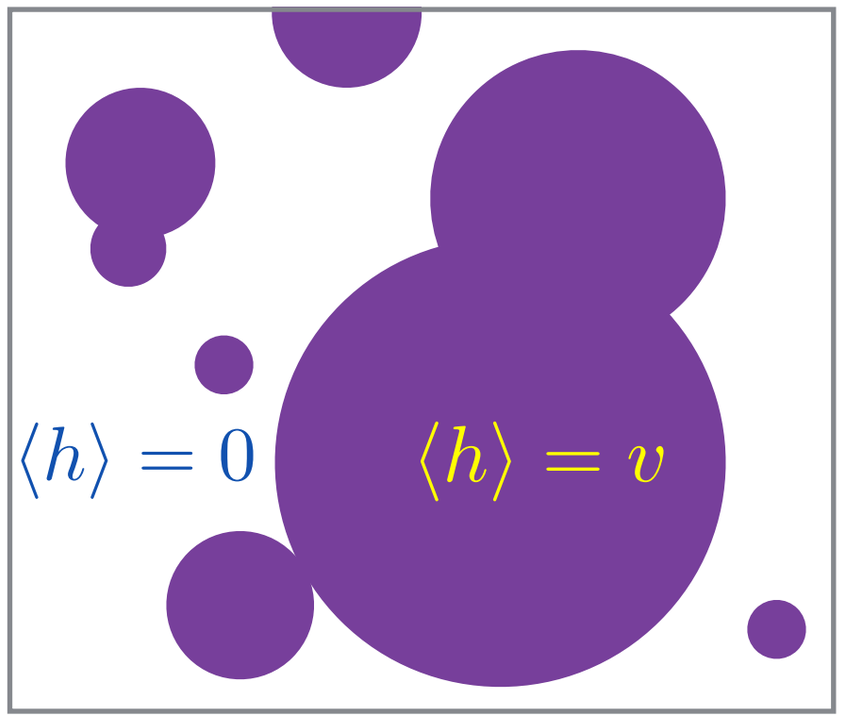


GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves

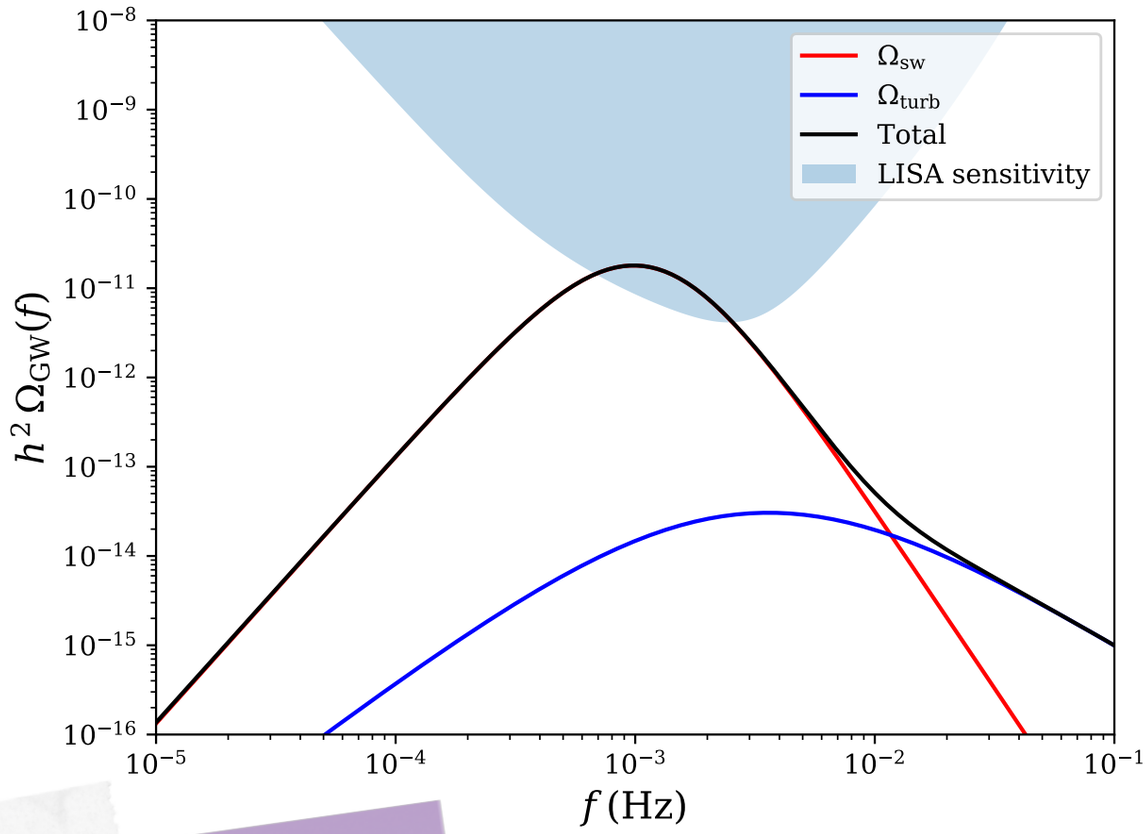




PT signal

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_*

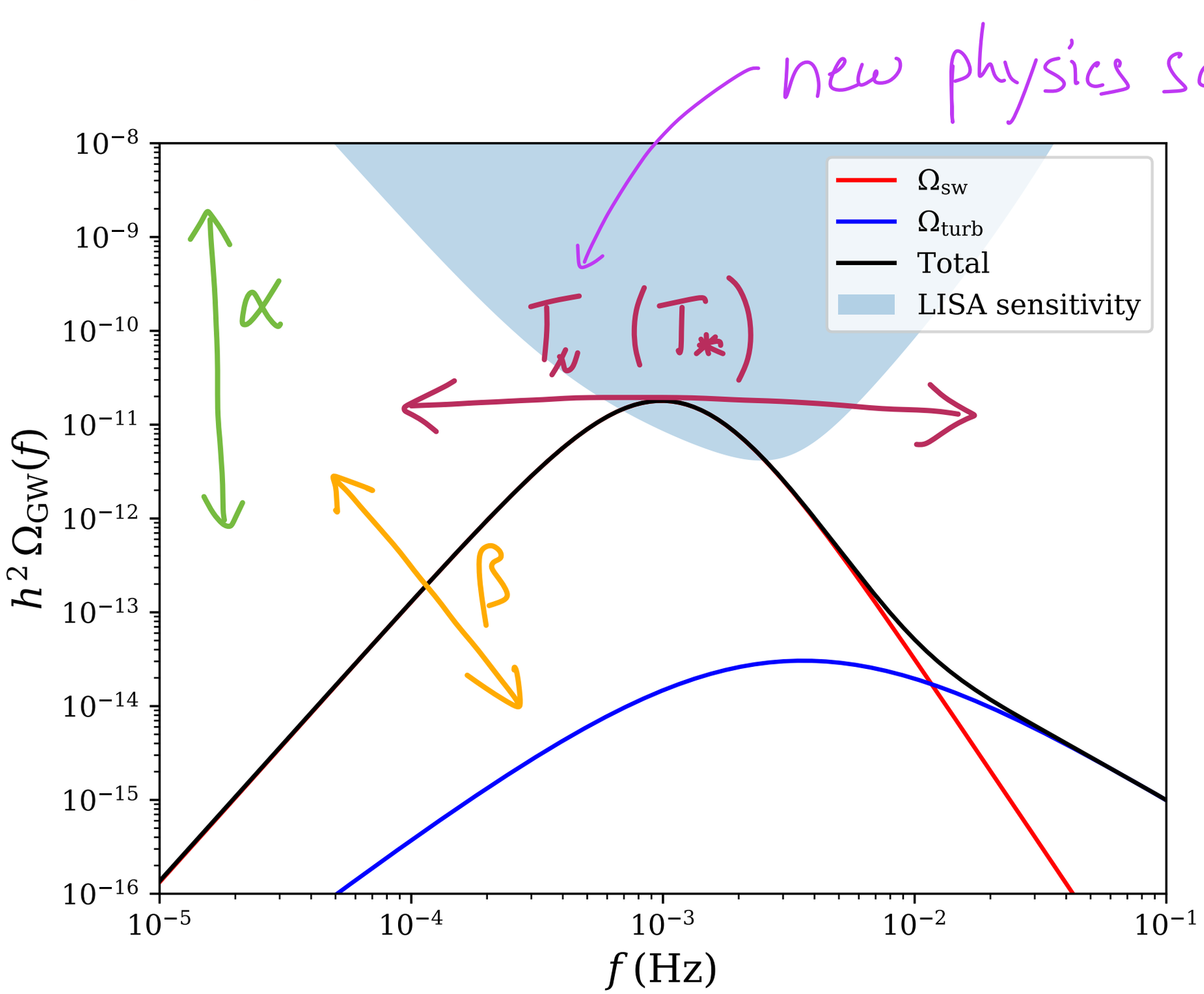


Three physical contributions

- Bubble wall collisions
- Turbulence
- Sound waves

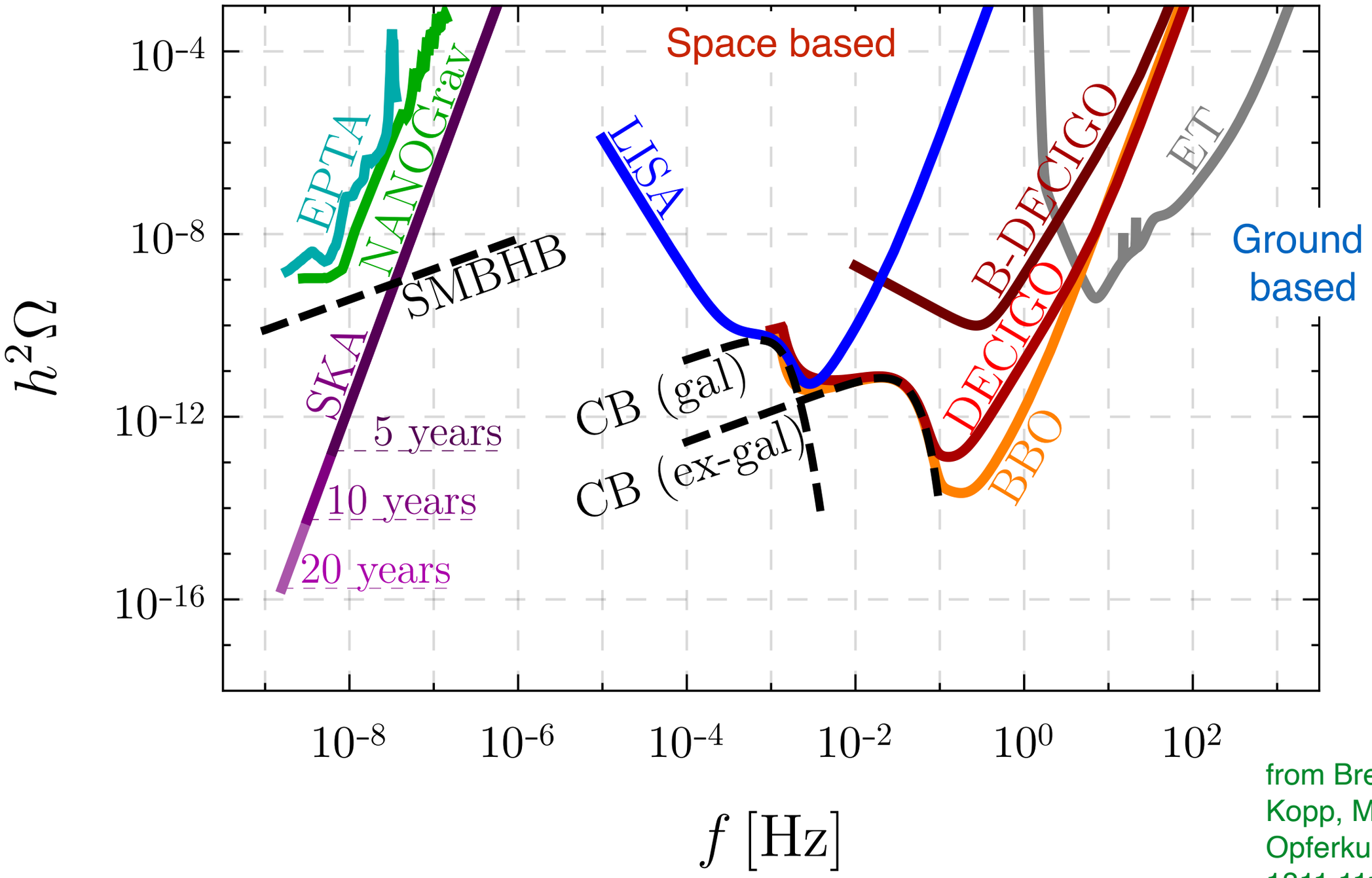
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Signal properties



Frequency ranges

New physics scale GeV TeV PeV

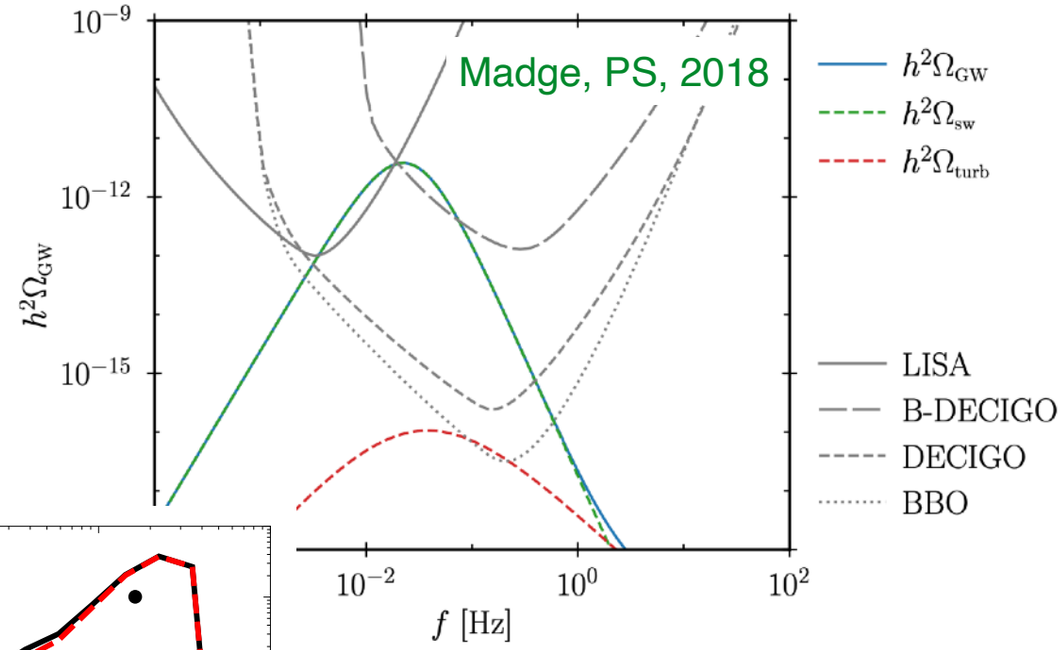


from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

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

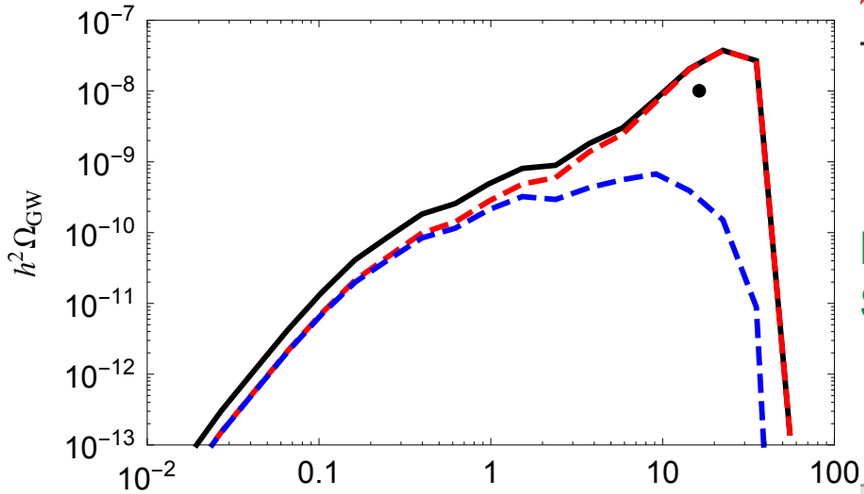
Phase transition

- Peak position depends on critical temperature



Audible axions:

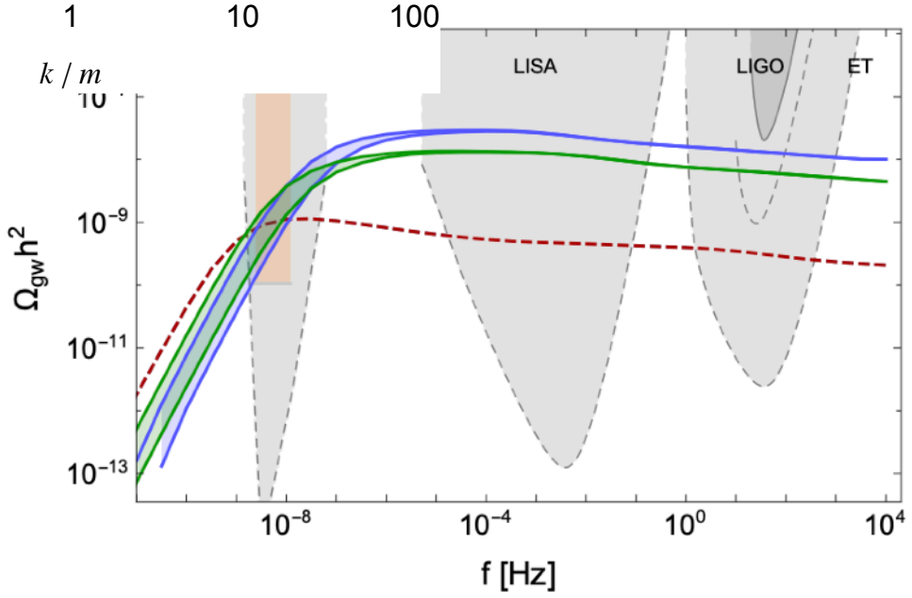
- Peaked but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum



Buchmuller, Domcke, Schmitz, 2021

Some recent progress

(with my personal bias, sorry!)

Computing the GWs from PTs is hard I

Gauge fields are finite temperature are problematic

Slow convergence of perturbation theory, non-perturbative methods partially required

Dimensional reduction + 3D lattice can overcome this

HIP-2022-11/TH
NORDITA 2022-030

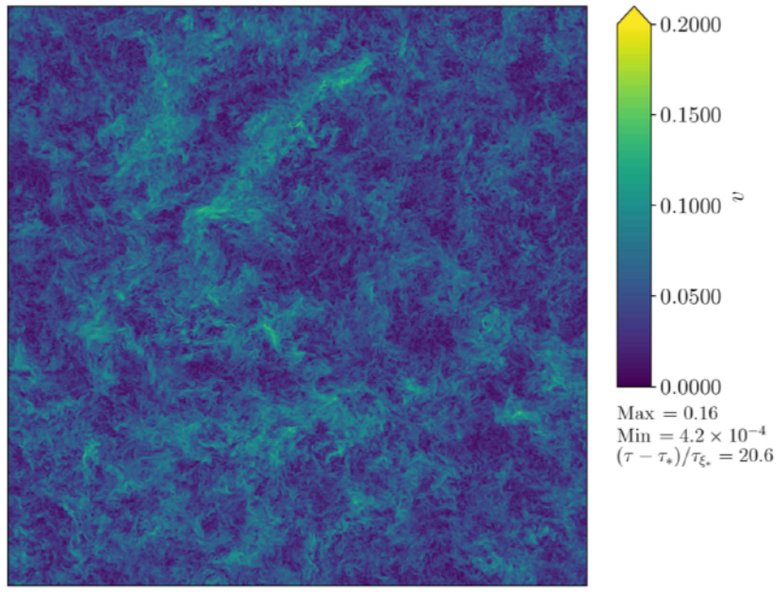
DRalgo: a package for effective field theory approach for thermal phase transitions

Andreas Ekstedt[a,b,c,*], Philipp Schicho[d,†], and Tuomas V. I. Tenkanen[e,f,g,‡]

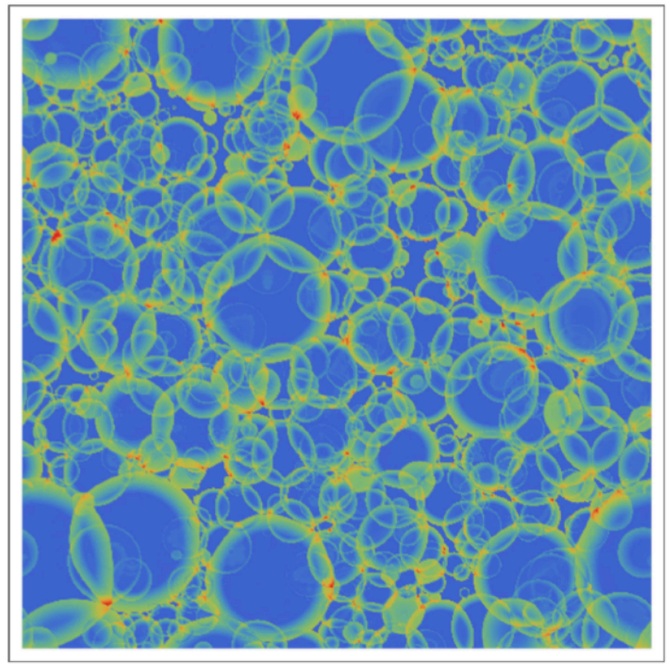
Computing the GWs from PTs is hard II

Expanding bubbles source sound waves in plasma

- Requires hydro simulations
- For each parameter point!



Auclair, Caprini, Cutting, Hindmarsh, Rummukainen, Steer, Weir, 2022



Jinno, Konstandin, Rubira, 2021

Many simulations, signal models are improving!

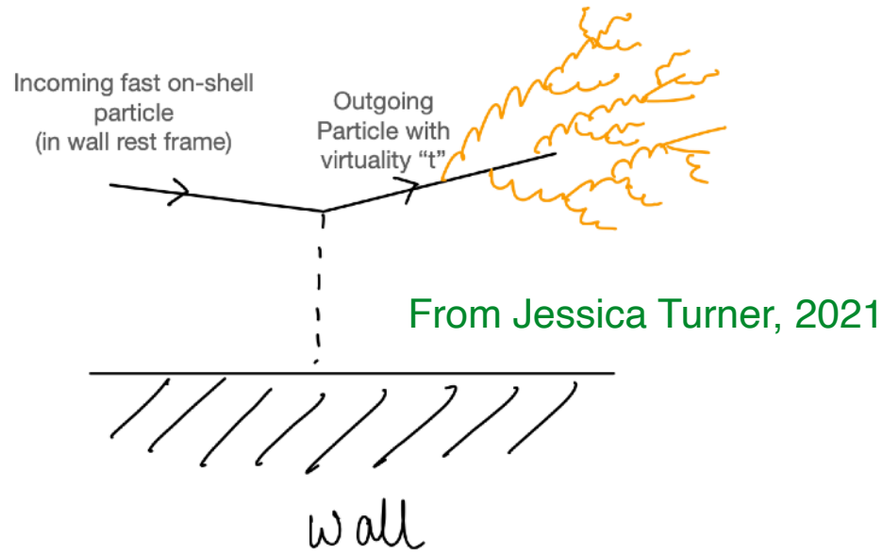
Computing the GWs from PTs is hard III

Bubble wall velocity still open question

- Strictly non-equilibrium
- Runaway?
  - Yes (Boedeker and Moore, 2009 [leading order])
  - No (Boedeker and Moore, 2017 [NLO])

New attempts using:

- Resummation
  Höche, Kozaczuk, Long, Turner, Wang, 2020
- N-Body simulations
  Lewicki, Vaskonen, Veermäe, 2022
- To be continued… :)



From Jessica Turner, 2021

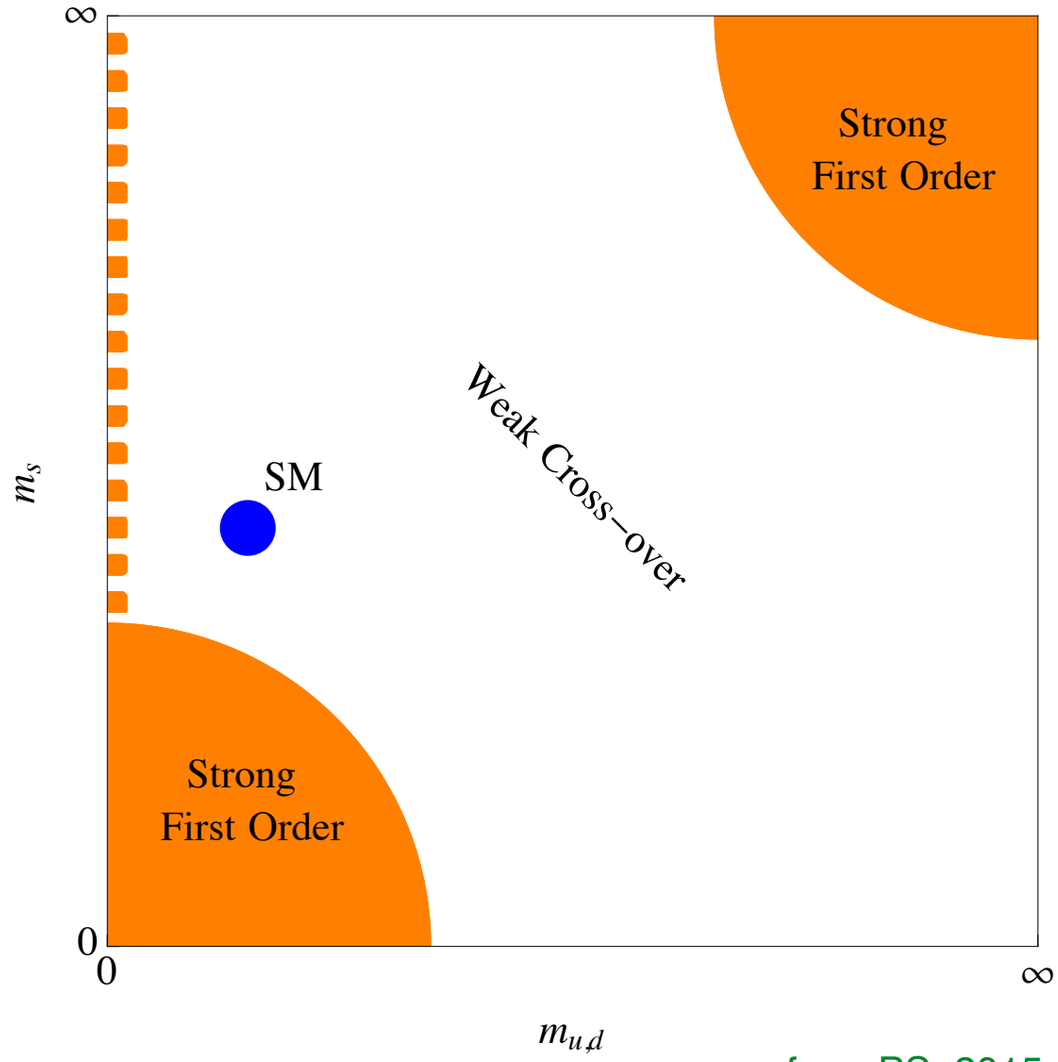
Strongly coupled PTs are also difficult

Nonabelian SU(N) dark sectors appear in many BSM scenarios (composite DM, twin Higgs, string theory)

Confinement PT is first order for many choices of N and N_f

Non-perturbative PT

- Difficult to predict GW signal

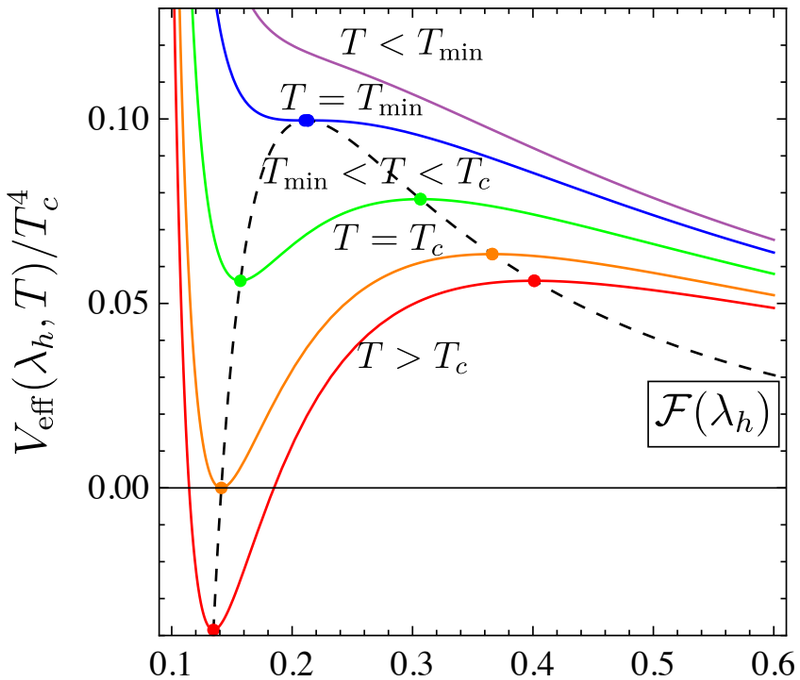


from PS, 2015

Strongly coupled PTs are also difficult

Computed thermal effective potential in improved holographic QCD

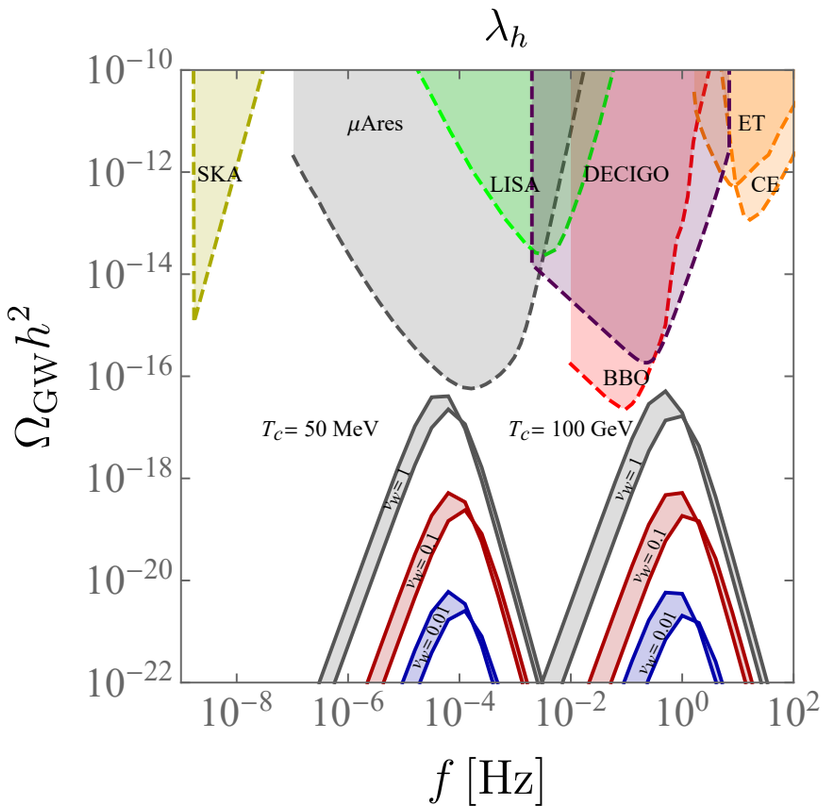
- Fit to reproduce finite T lattice data



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

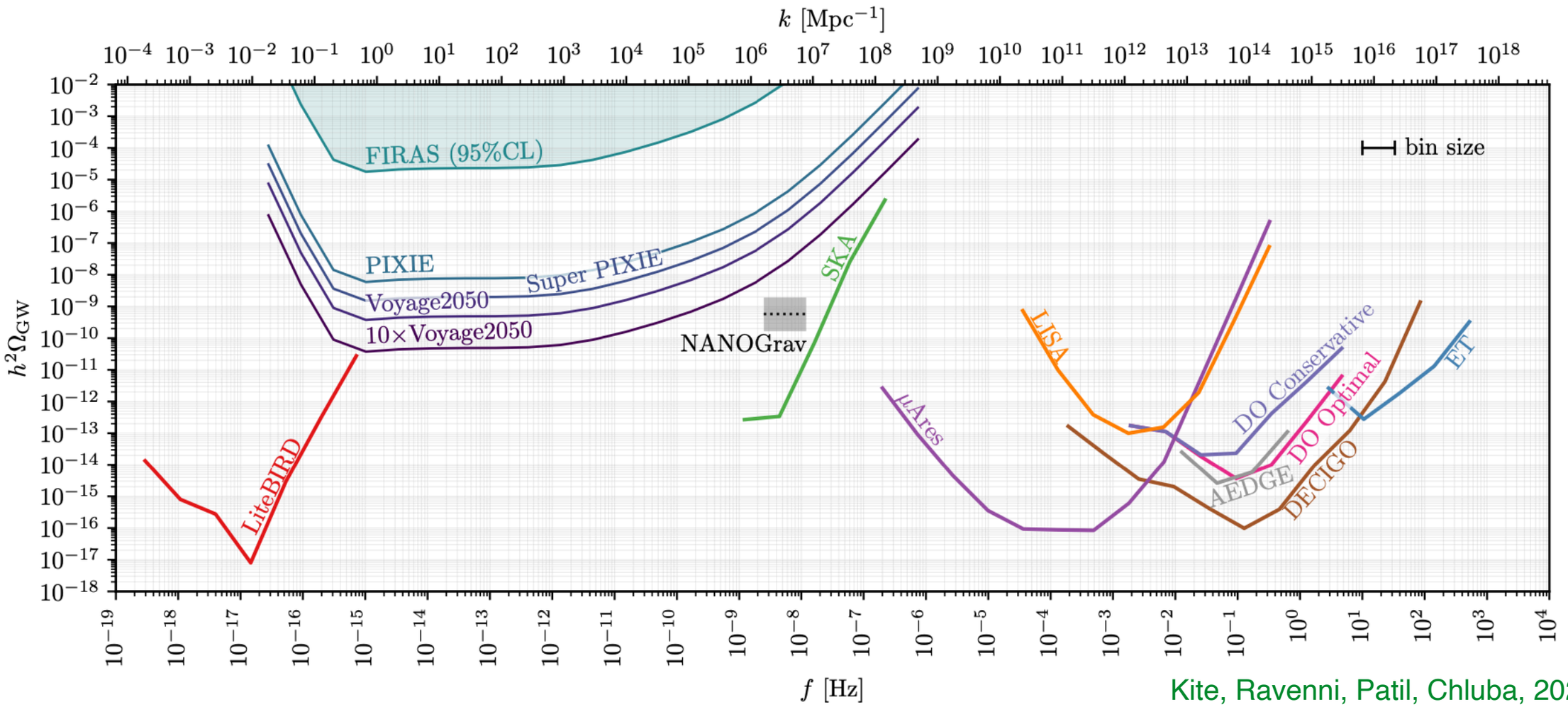
Enrico Morgante, Nicklas Ramberg, PS, in preparation

except for the wall velocity…



Probing sub-MeV phase transitions

Very low frequency GWs induce CMB spectral distortions

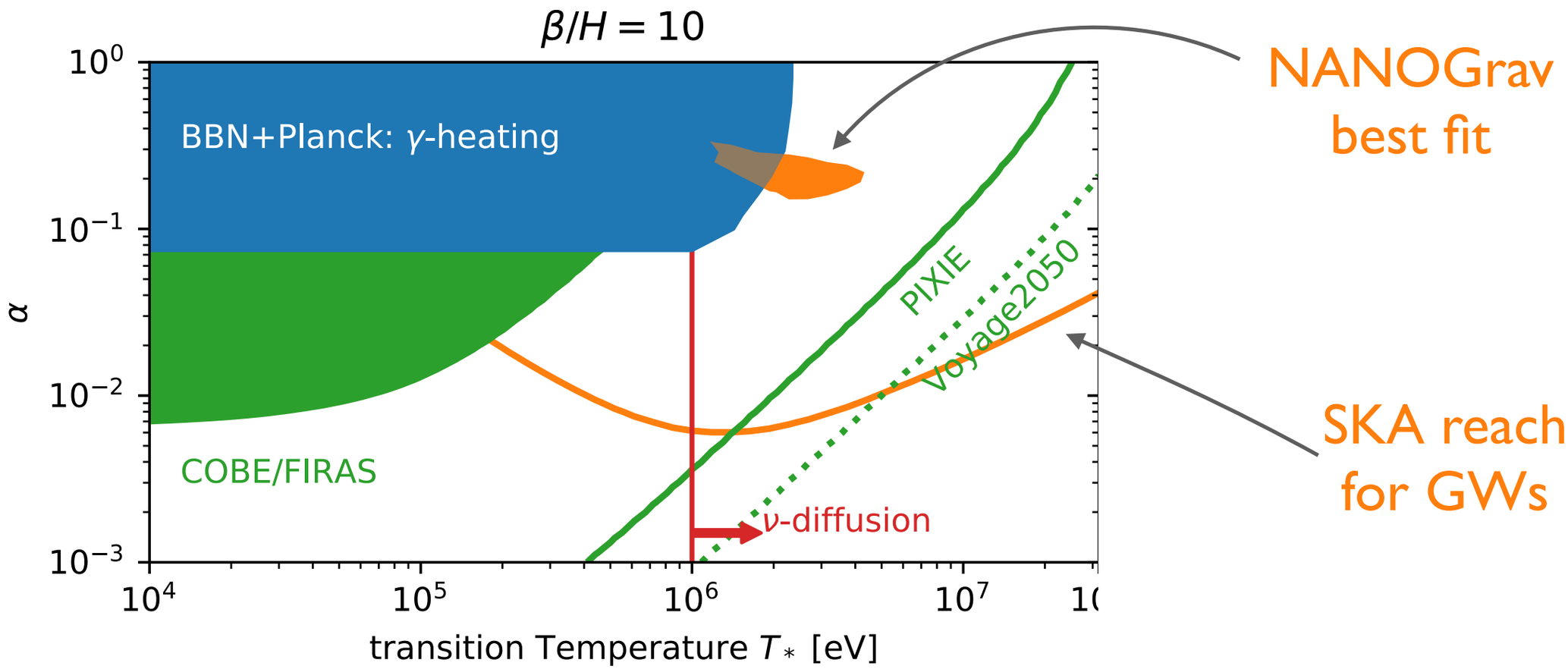


Kite, Ravenni, Patil, Chluba, 2021

Probe sources that give peaked GW spectra (like PTs)

Probing sub-MeV phase transitions

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

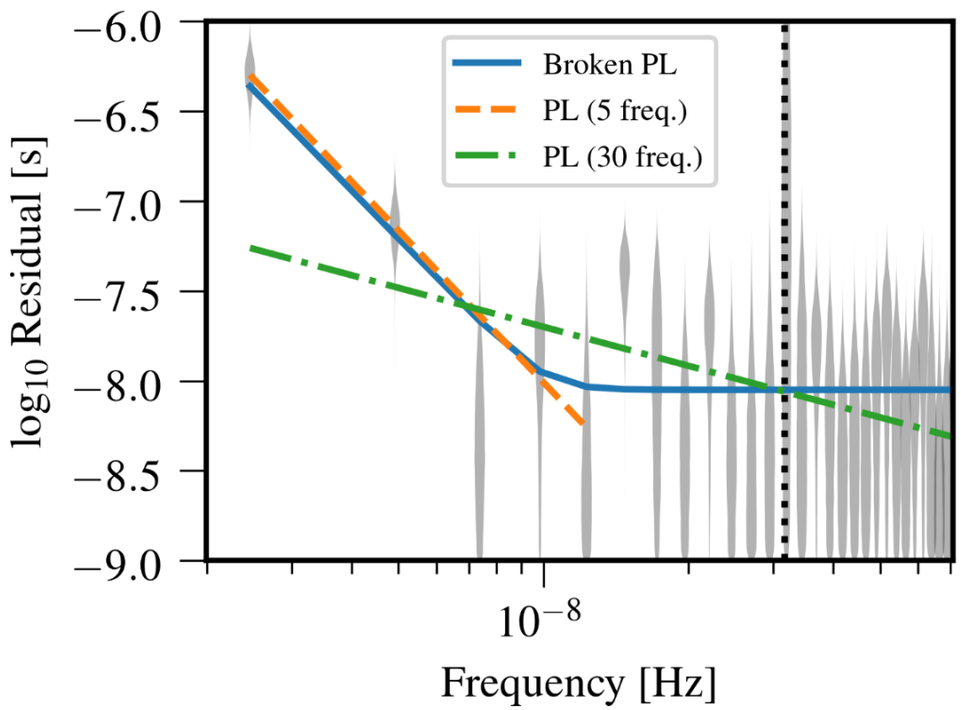


More sensitive! Multi-messenger cosmology!

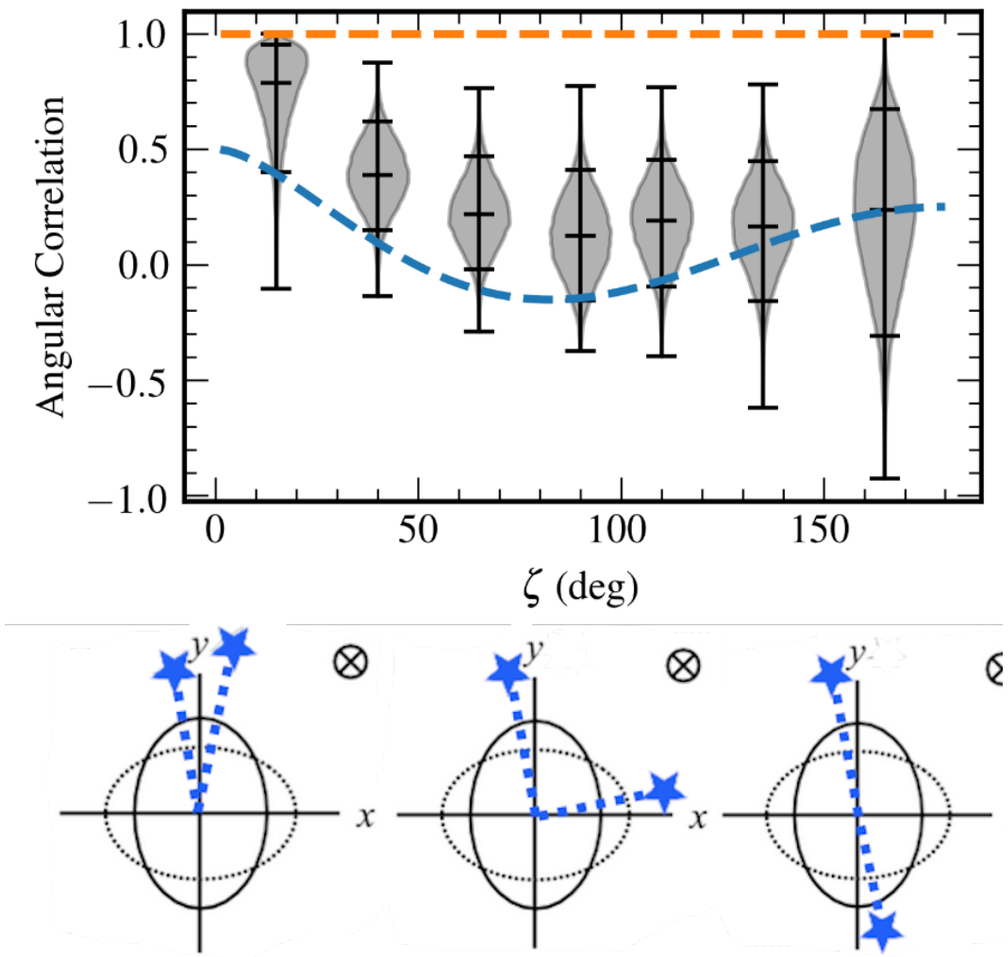
Nicklas Ramberg, Wolfram Ratzinger, PS, to appear

NANOGrav saw something!

Significant Strain at low frequencies



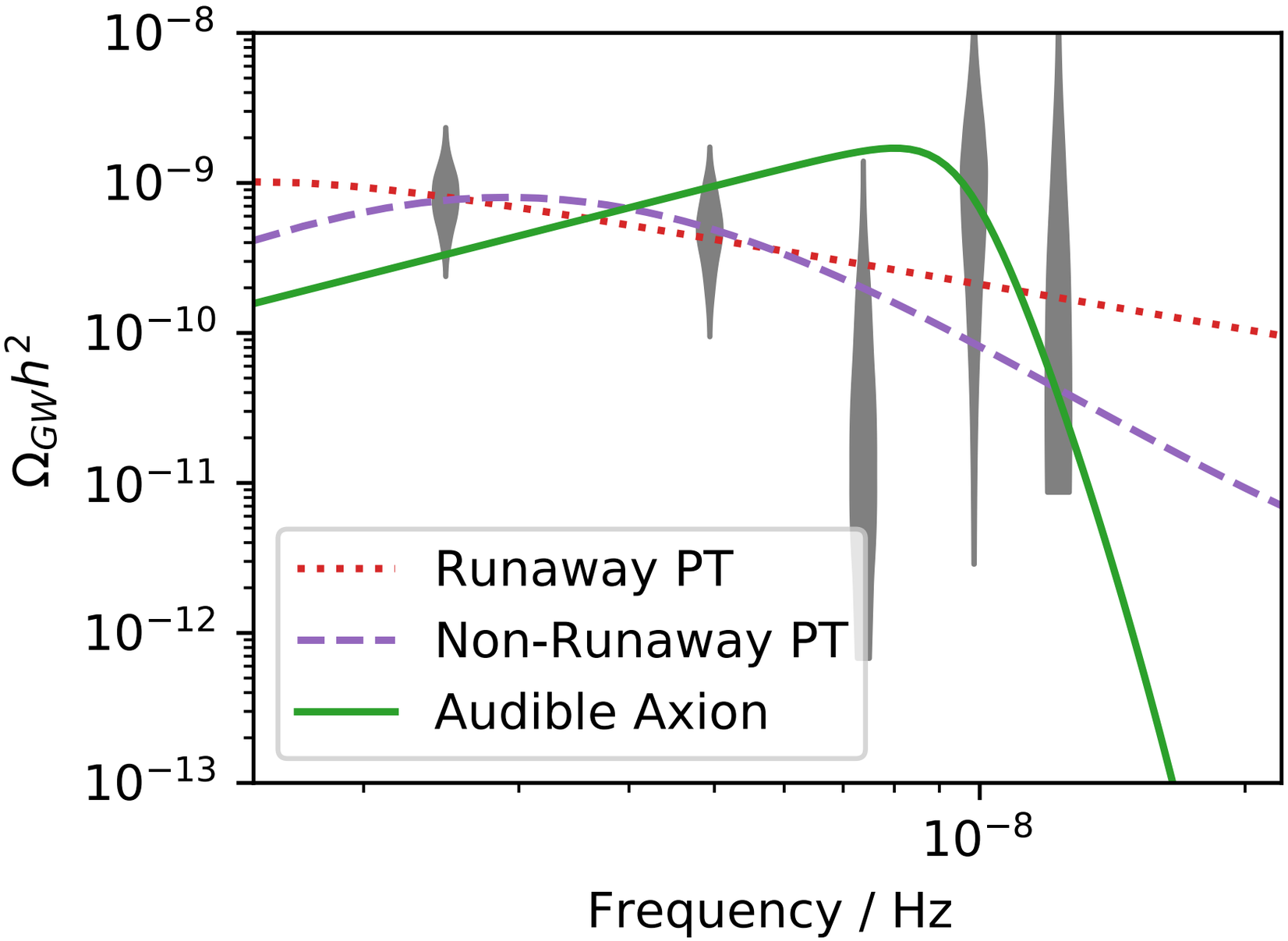
No 4σ evidence for Quadrupole



From NANOGrav collaboration, 2009.04496

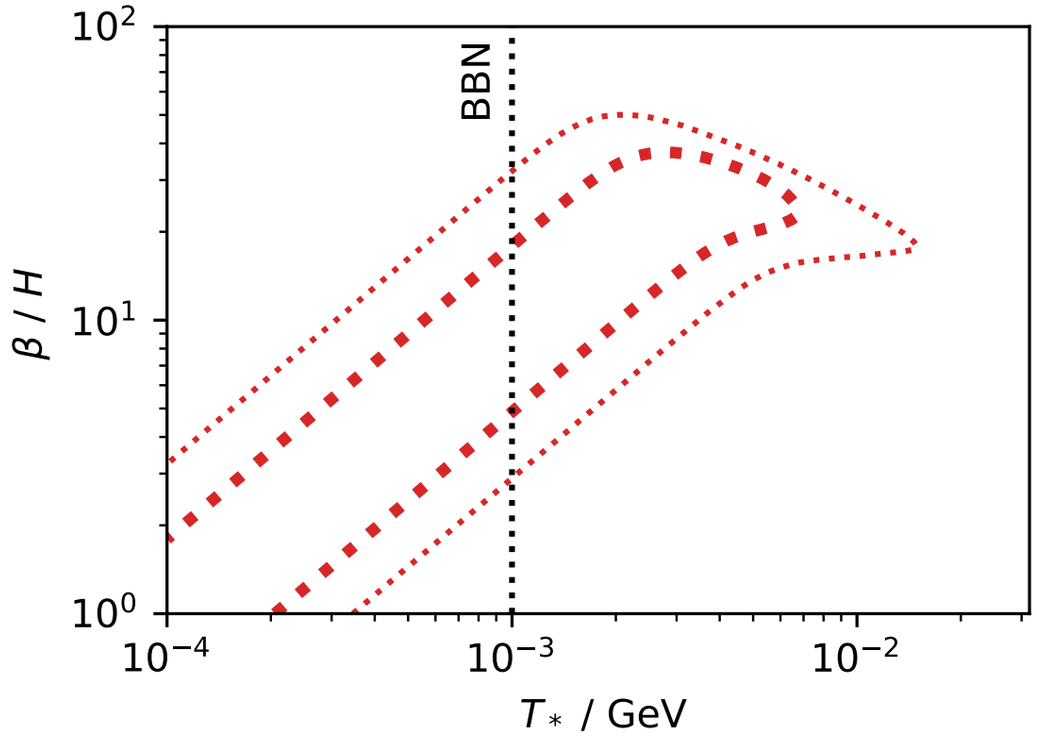
Now also consistent signals in PPTA, EPTA and IPTA - still not fully conclusive though

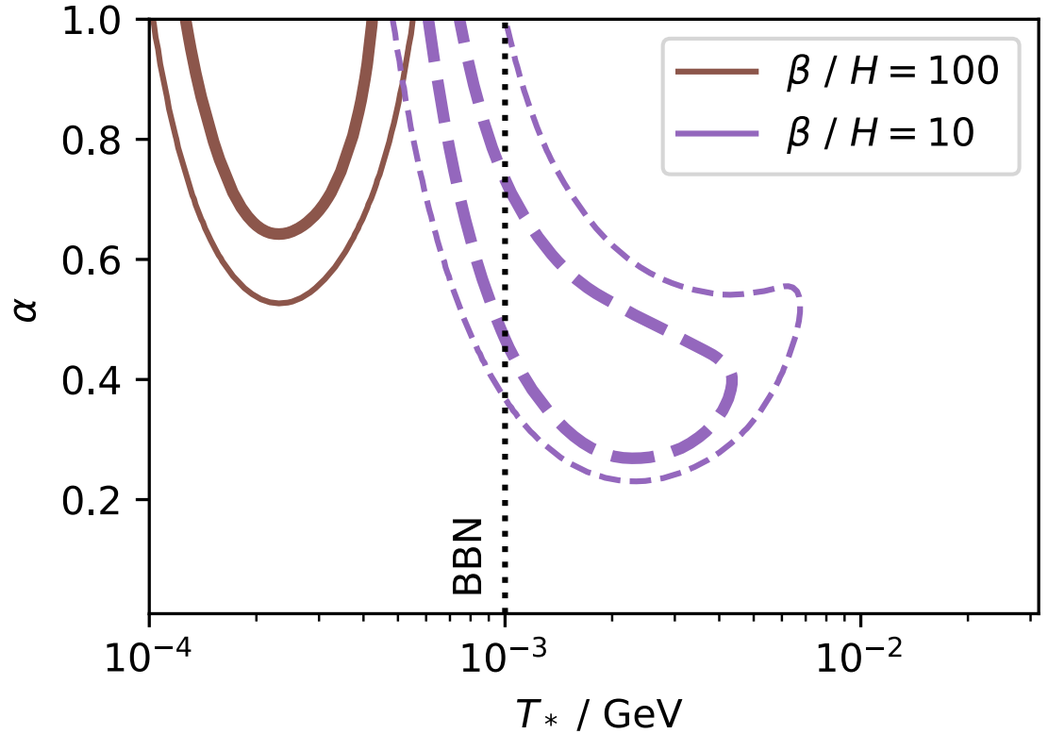
Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



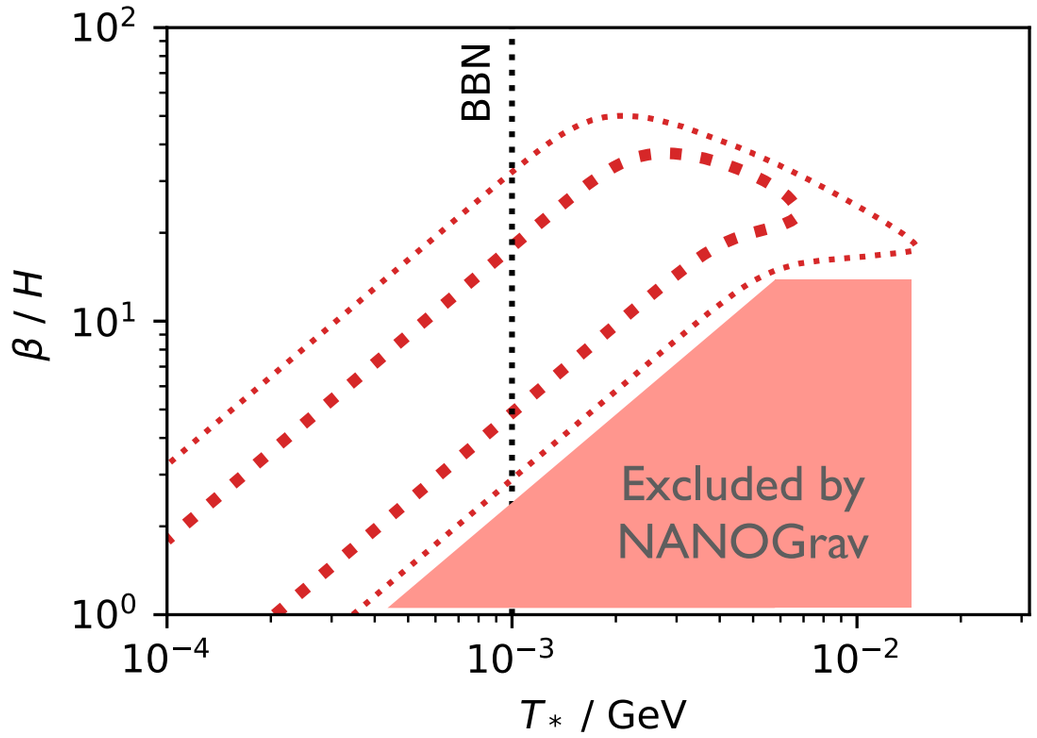


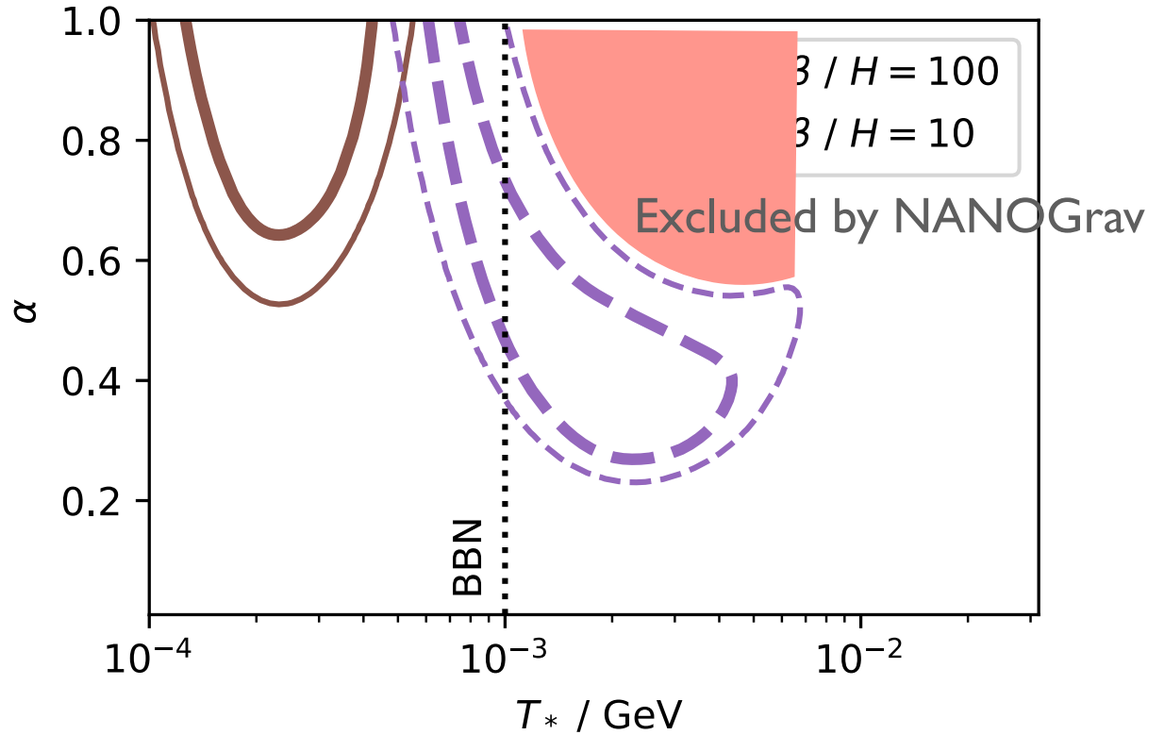
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Also here, challenging to build model that does not break cosmology (BBN and/or N_{eff})

Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition





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

Some model parameters excluded by PTA data now!

Wolfram Ratzinger & PS, 2009.11875

Summary

GWs offer new window into the early Universe

Can probe dynamics of otherwise invisible dark sectors, purely through gravitational interactions

GWs from phase transitions probe presence of new symmetries (and their breaking)

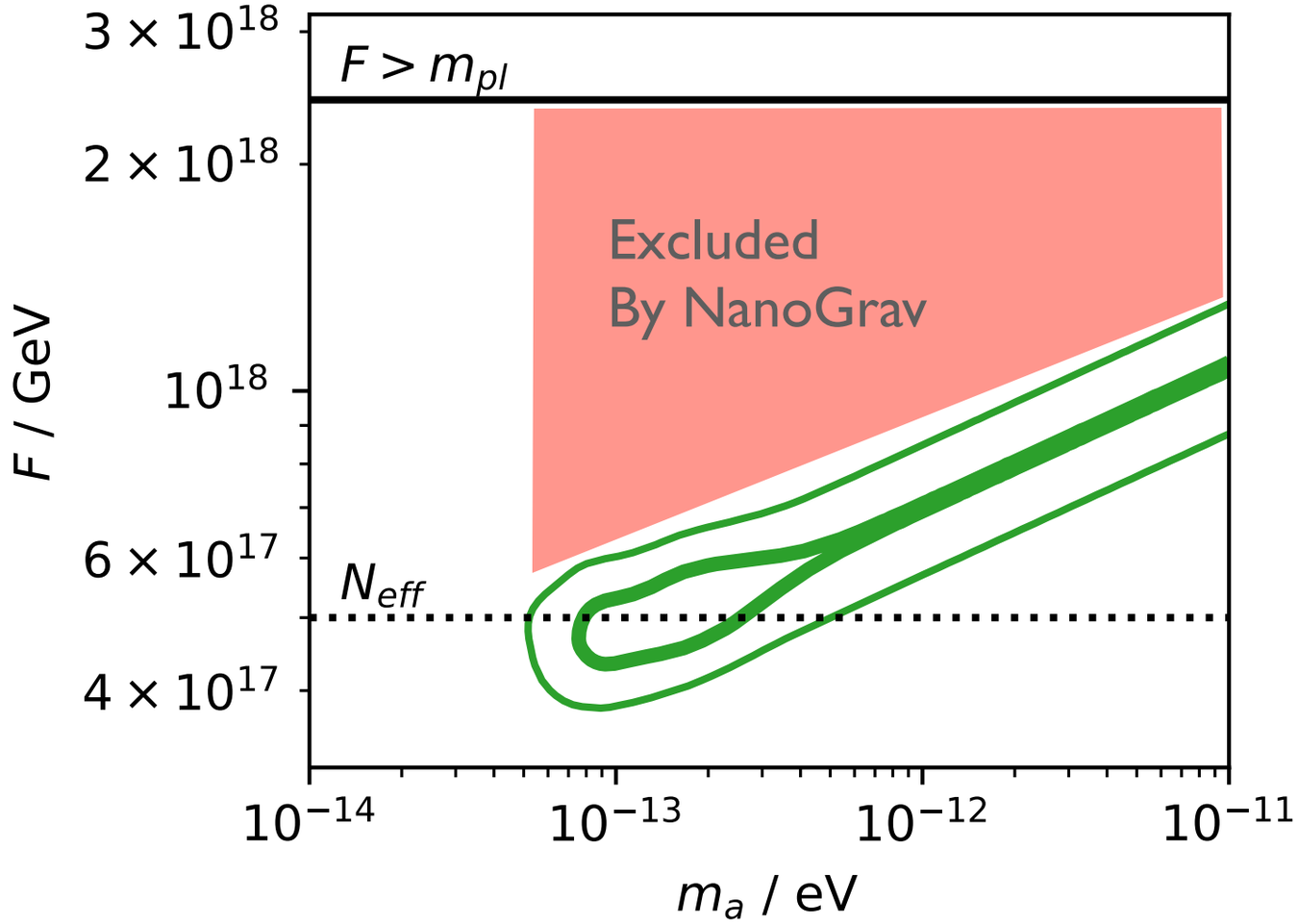
- Large theory effort to improve predictions on many frontiers

PTA data already constrains new physics models

- Possibly first hint for primordial GW background

New data expected in near and far future!

Example: Audible Axion

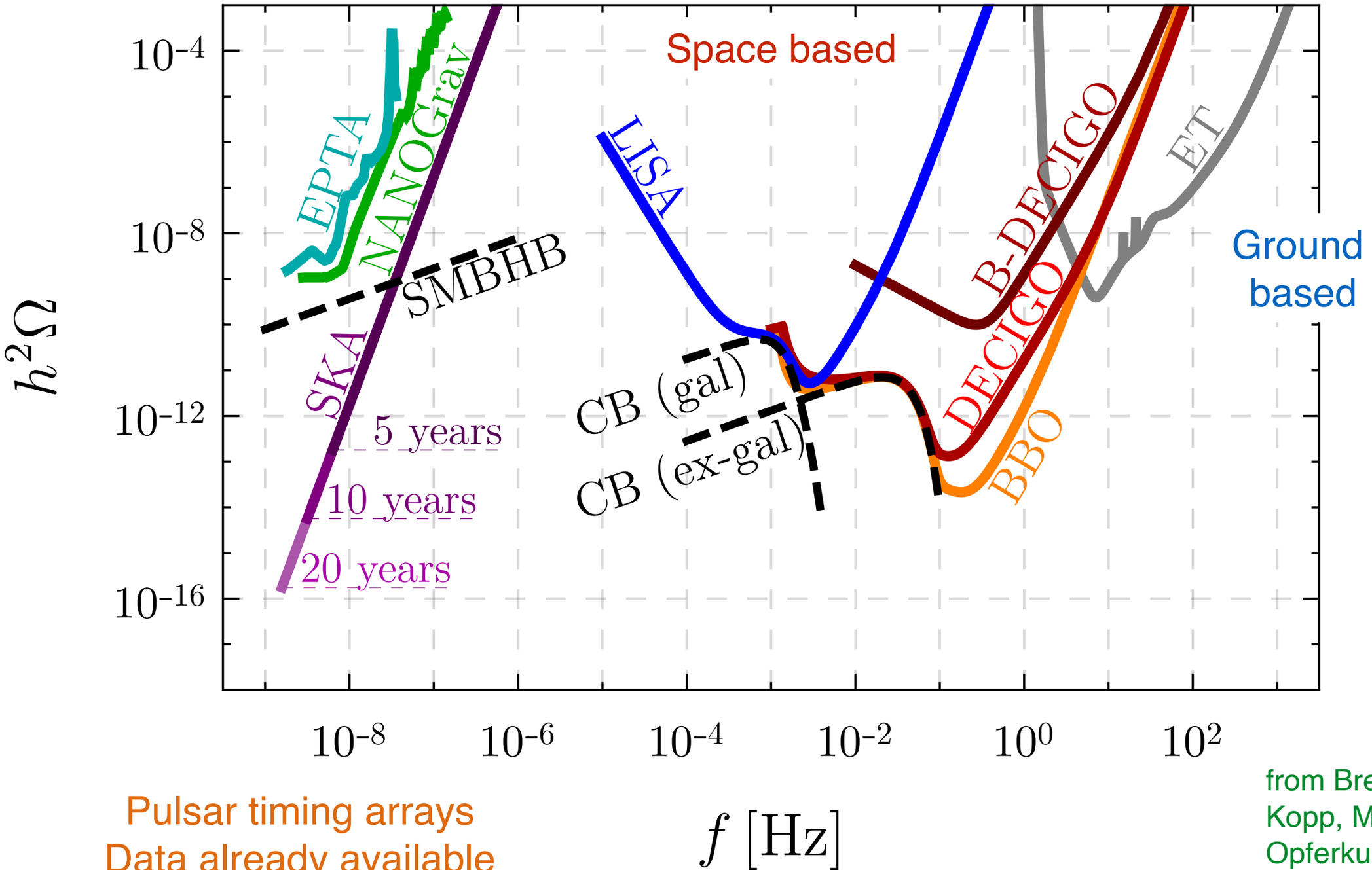


Parameter reconstruction already possible

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

Wolfram Ratzinger & PS, 2009.11875

Frequency ranges



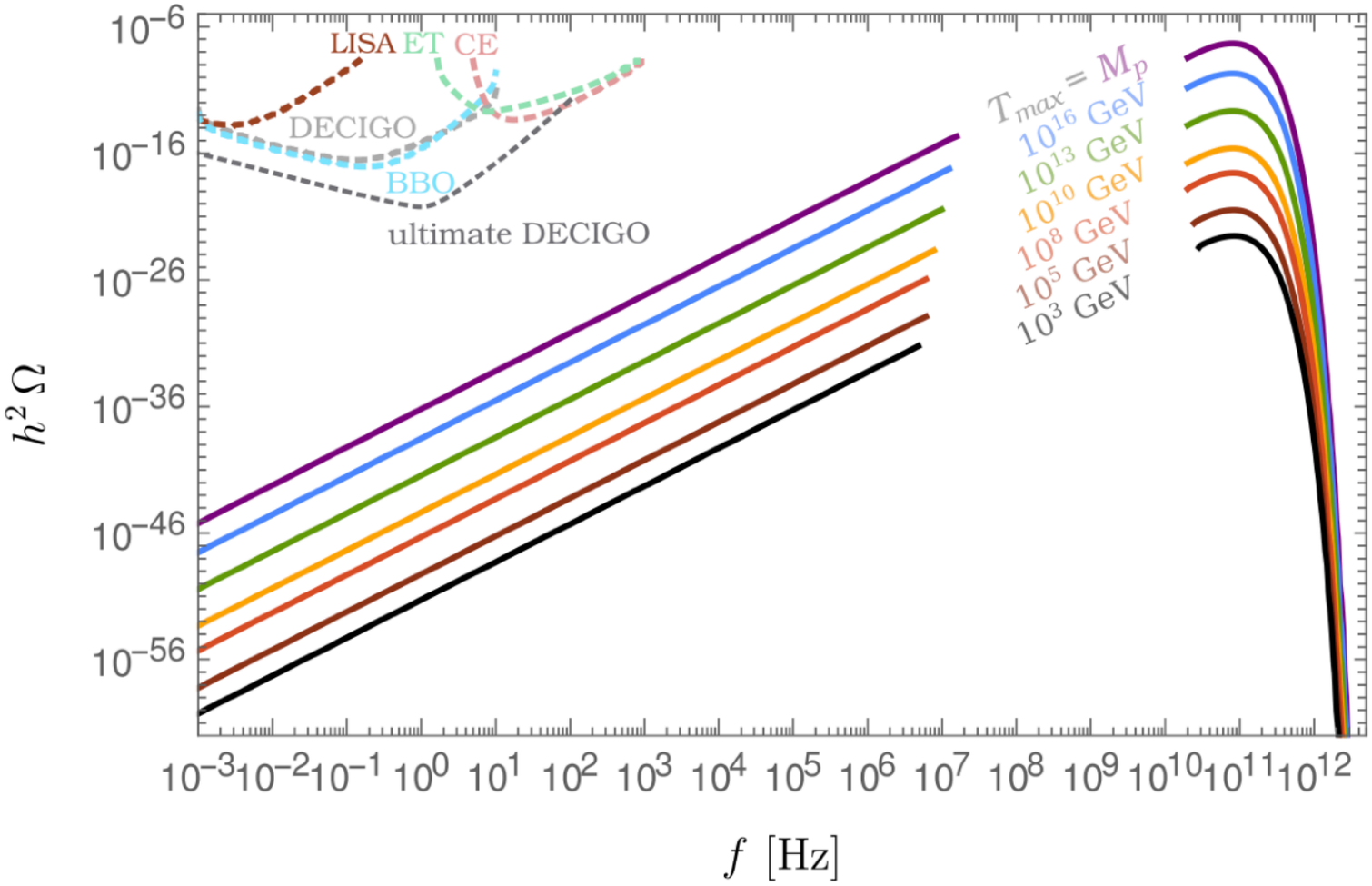
Pulsar timing arrays
Data already available

from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

Standard model

The hot early Universe sources GWs!

- Classical picture: thermal fluctuations source tensor fluctuations
- Quantum picture: gluon + gluon -> graviton



From Ringwald, Schütte-Engel, Tamarit, 2020

Original computations:
Ghiglieri, Laine, 2015
Ghiglieri, Jackson, Laine, Zhu, 2020