GRAVITATIONAL WAVES AS PROBES OF NEW PHYSICS

Pedro Schwaller

Mainz University

Cluster of Excellence PRISMA+

Pushing the limits of theoretical physics
10 years MITP

JGU Mainz **May 9, 2023**

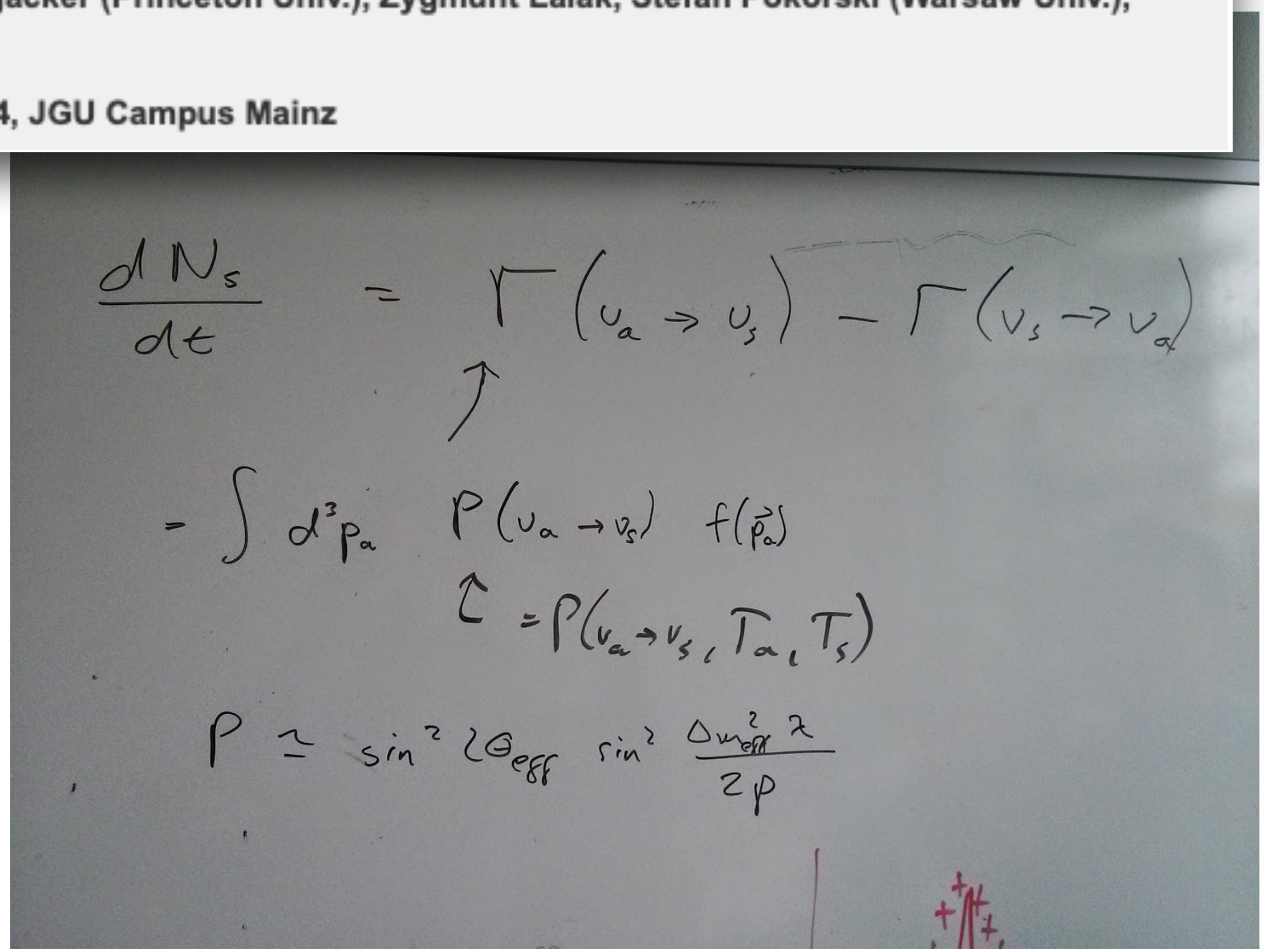
10 years of MITP

My first MITP participation

Probing the TeV scale and beyond

Organizers: Paul Langacker (Princeton Univ.), Zygmunt Lalak, Stefan Pokorski (Warsaw Univ.), James Wells (CERN)

June 30 - July 25, 2014, JGU Campus Mainz



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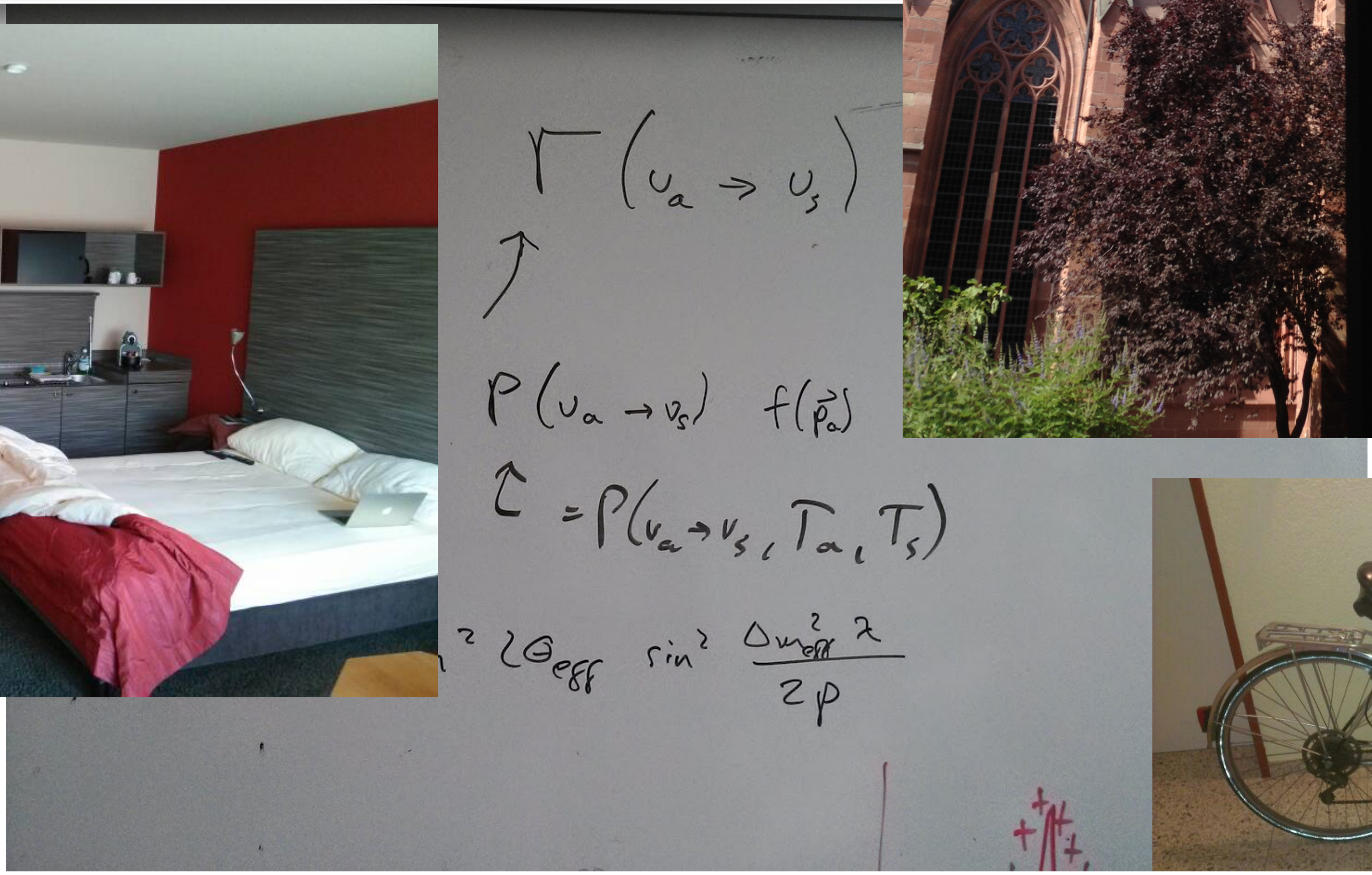

10 years of MITP

First time organiser

The TeV Scale: A Threshold to New Physics?

Organizers: Csaba Csaki (Cornell Univ.), Christophe Grojean (DESY), Pedro Schwaller (DESY) and Andreas Weiler (TU Munich)

June 12 - July 7, 2017, JGU Campus Mainz

10 years of MITP

First ti

The TeV

Organizers:
Andreas We

June 12 - Ju

Gravitational waves at MITP

4th LISA Cosmology Working Group Workshop

Organizers: Chiara Caprini (APC Paris), Valerie Domcke (APC Paris), Germano Nardini (Bern Univ.), Pedro Schwaller (JGU Mainz)

October 16 - 20, 2017, JGU Campus Mainz

Gravitational waves at MITP

4th LISA Cosmology Working Group Workshop

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June 4 - 15, 2018	**The Sound of Spacetime: The Dawn of Gravitational Wave Science**
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Gravitational waves at MITP

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May 20 - June 7, 2019	The Mysterious Universe: Dark Matter – Dark Energy – Cosmic Magnetic Fields

Summer School

Date	Summer School
July 22 - August 9, 2019	Non-perturbative Phenomena and the Early

Gravitational waves at MITP

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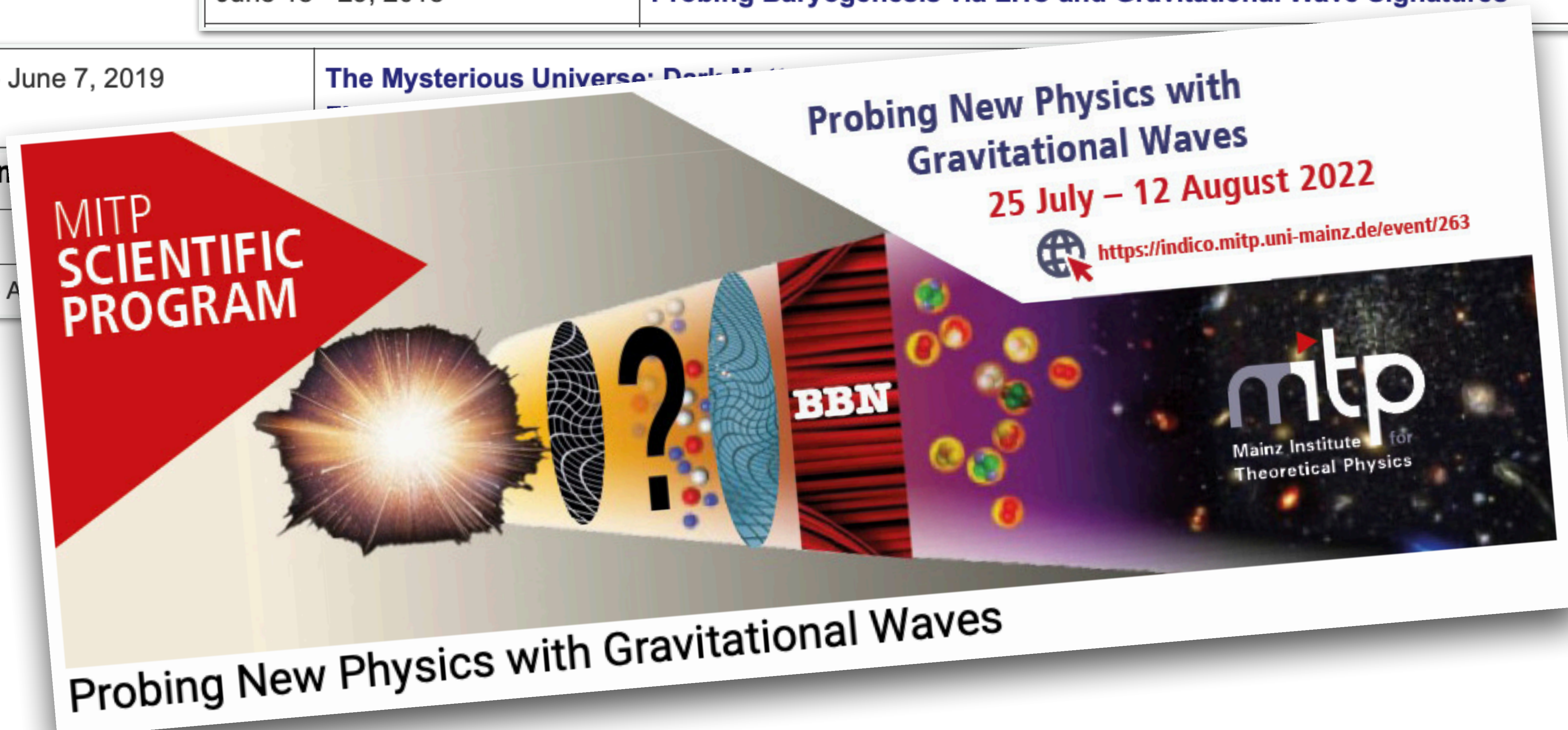
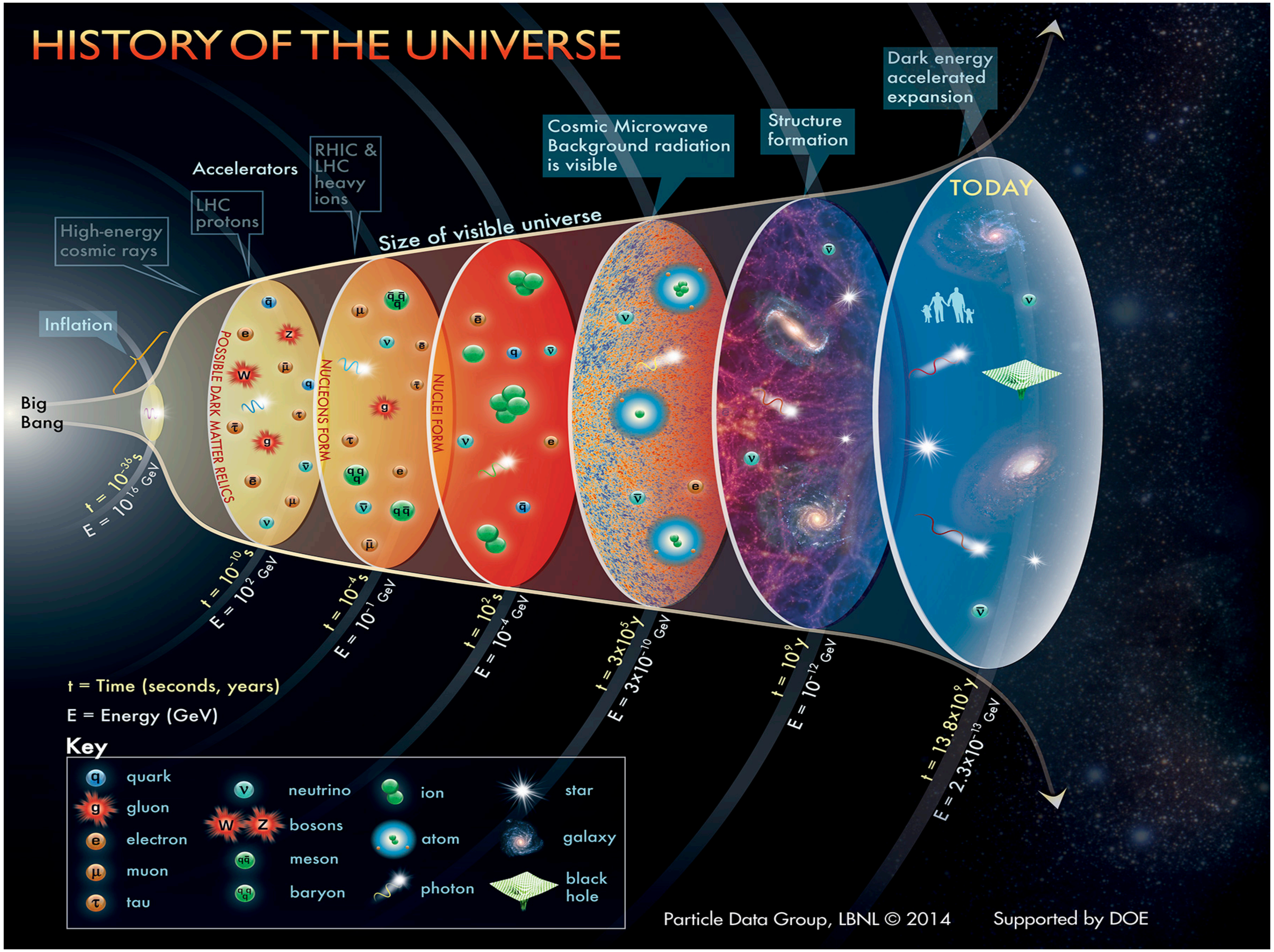
Summ

Date
July 22 - A



Thermal history and particle physics



Thermal history and particle physics

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

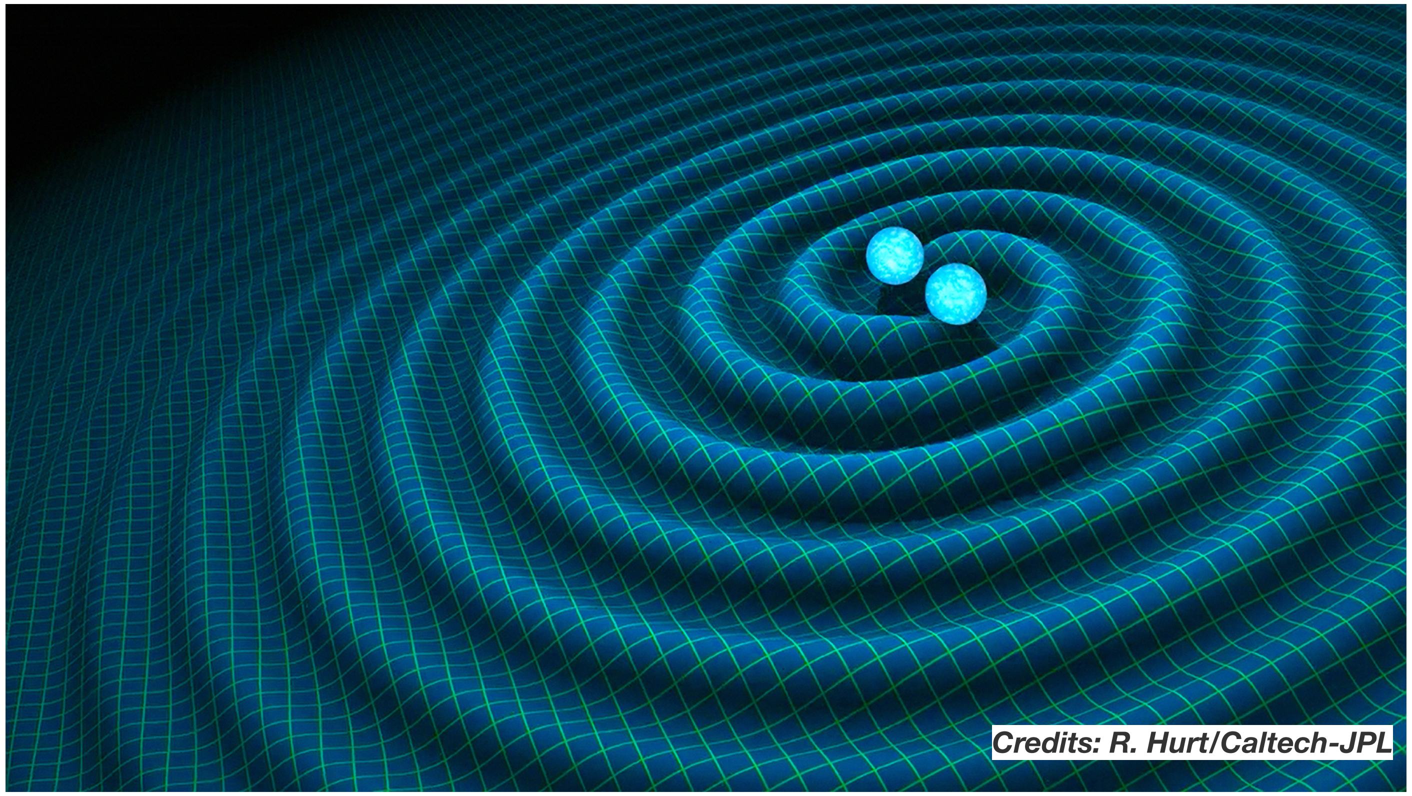
- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating

Gravitational waves as messengers from the early Universe

Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background



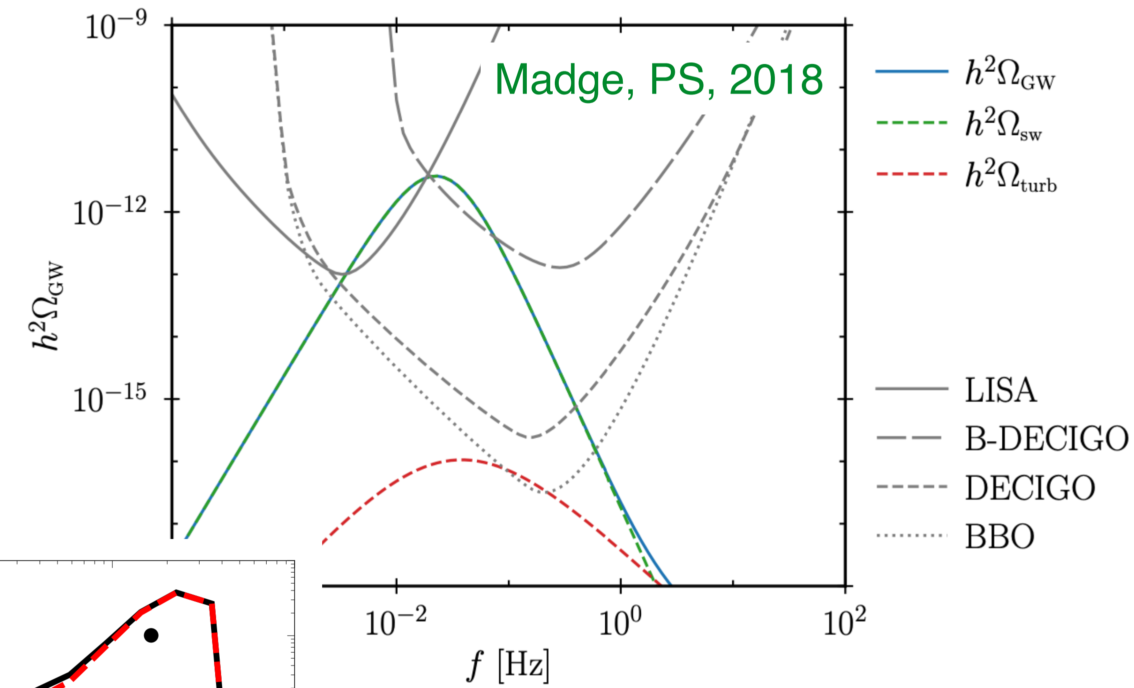
Relevant scale: Hubble radius ↔ GW wavelength

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

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

Phase transition

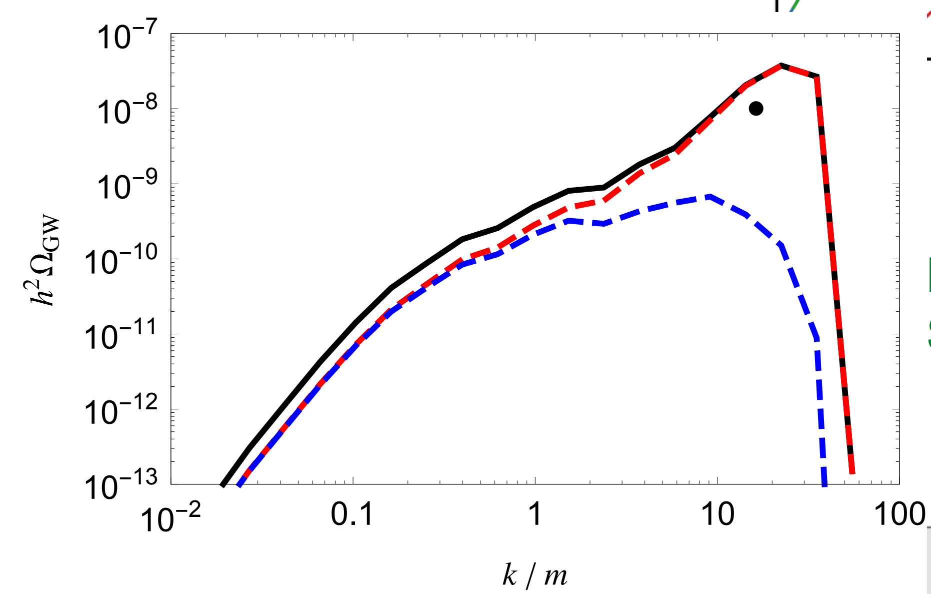
- Peak position depends on critical temperature



Madge, PS, 2018

Audible axions:

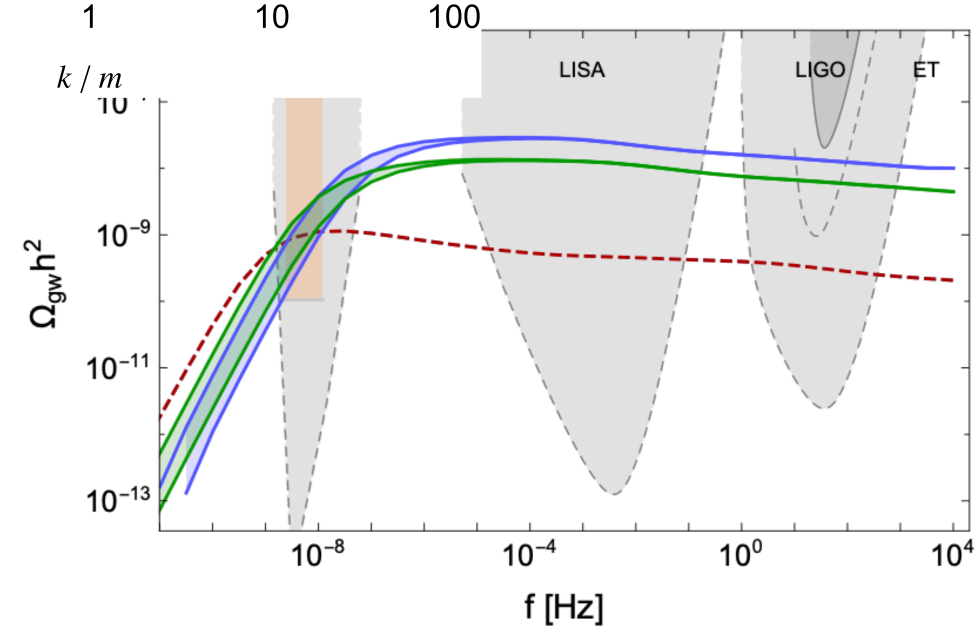
- Peaked
  but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

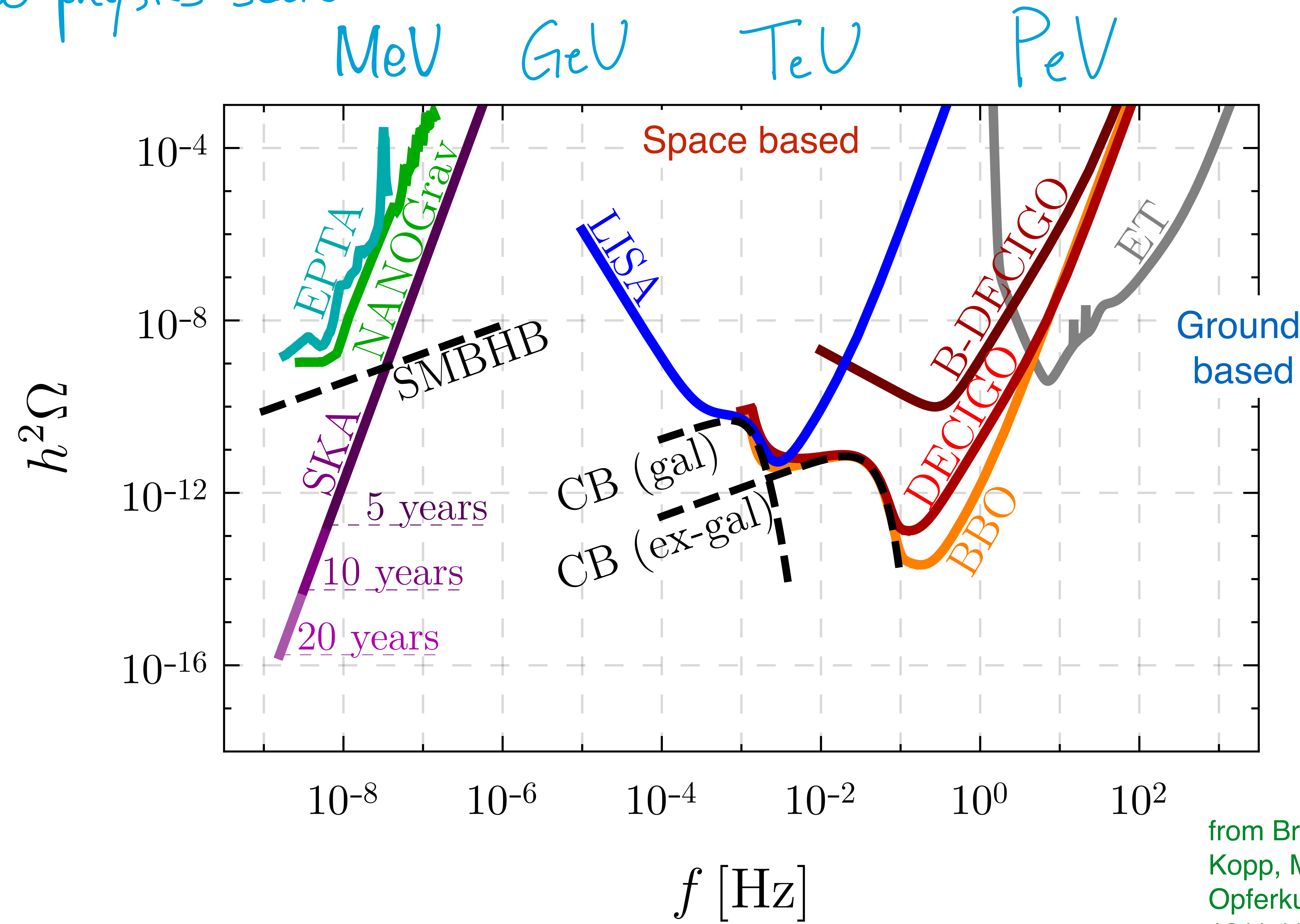
- Flatter spectrum



Buchmuller, Domcke, Schmitz, 2021

Frequency ranges

New physics scale



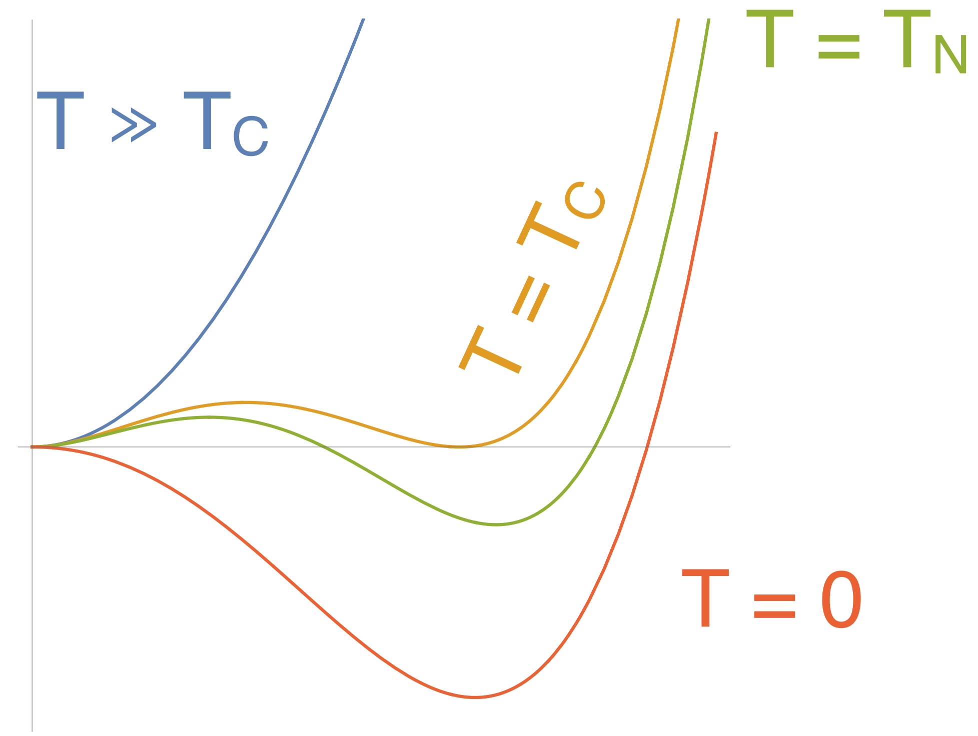
from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

Example: Gravitational waves from phase transitions

Broken symmetries are restored at high T

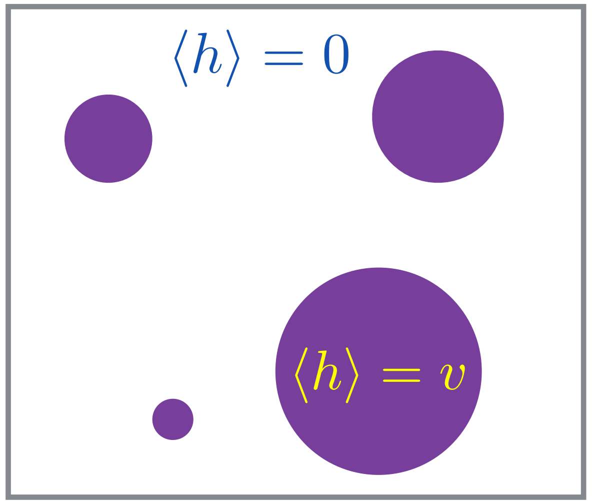
Symmetry breaking phase transitions

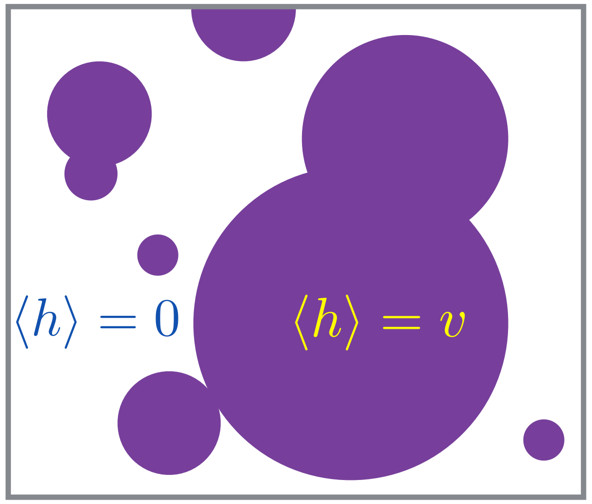
- Cross-over in SM
- First order possible in BSM



FOPT source GWs

Cosmological GW background observable today!

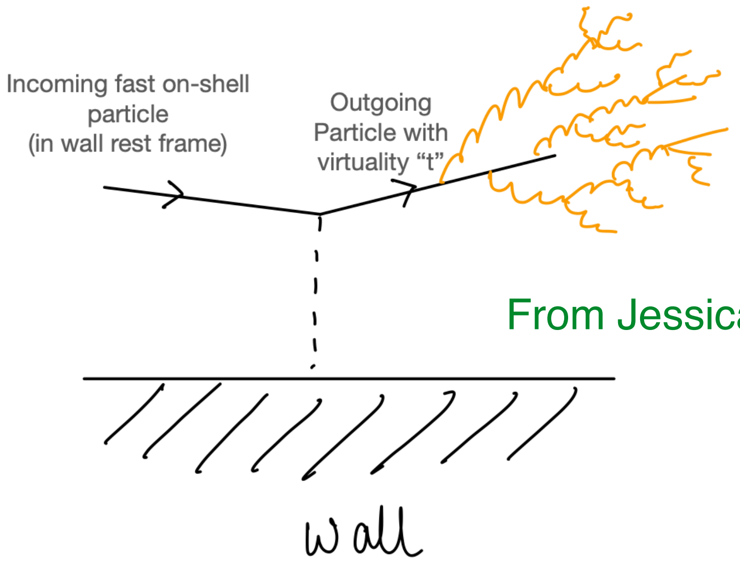




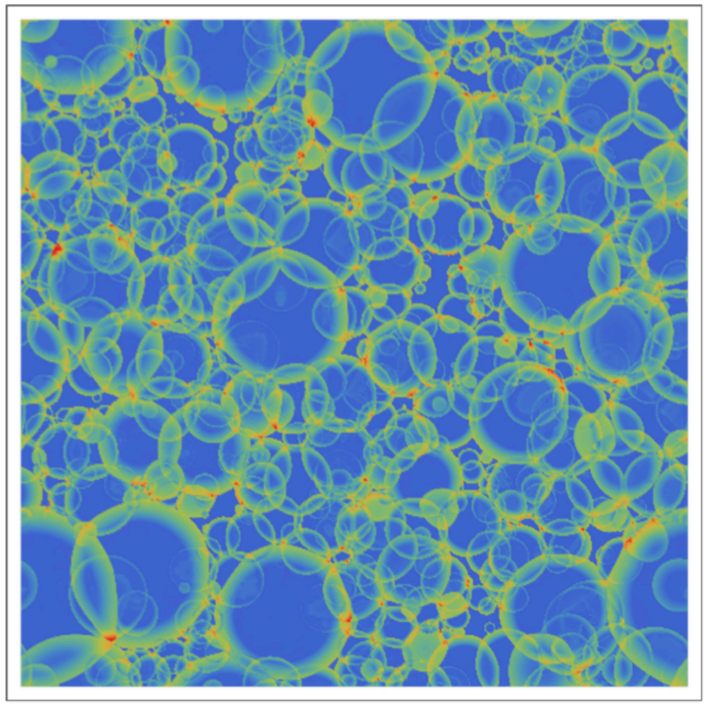
Gravitational waves from phase transitions

Hard work to get precise predictions

- Finite T QFT to high orders
- Simulations of bubble collisions
- Bubble wall dynamics



From Jessica Turner, 2021



Jinno, Konstandin, Rubira, 2021

Many new results discussed at MITP workshops

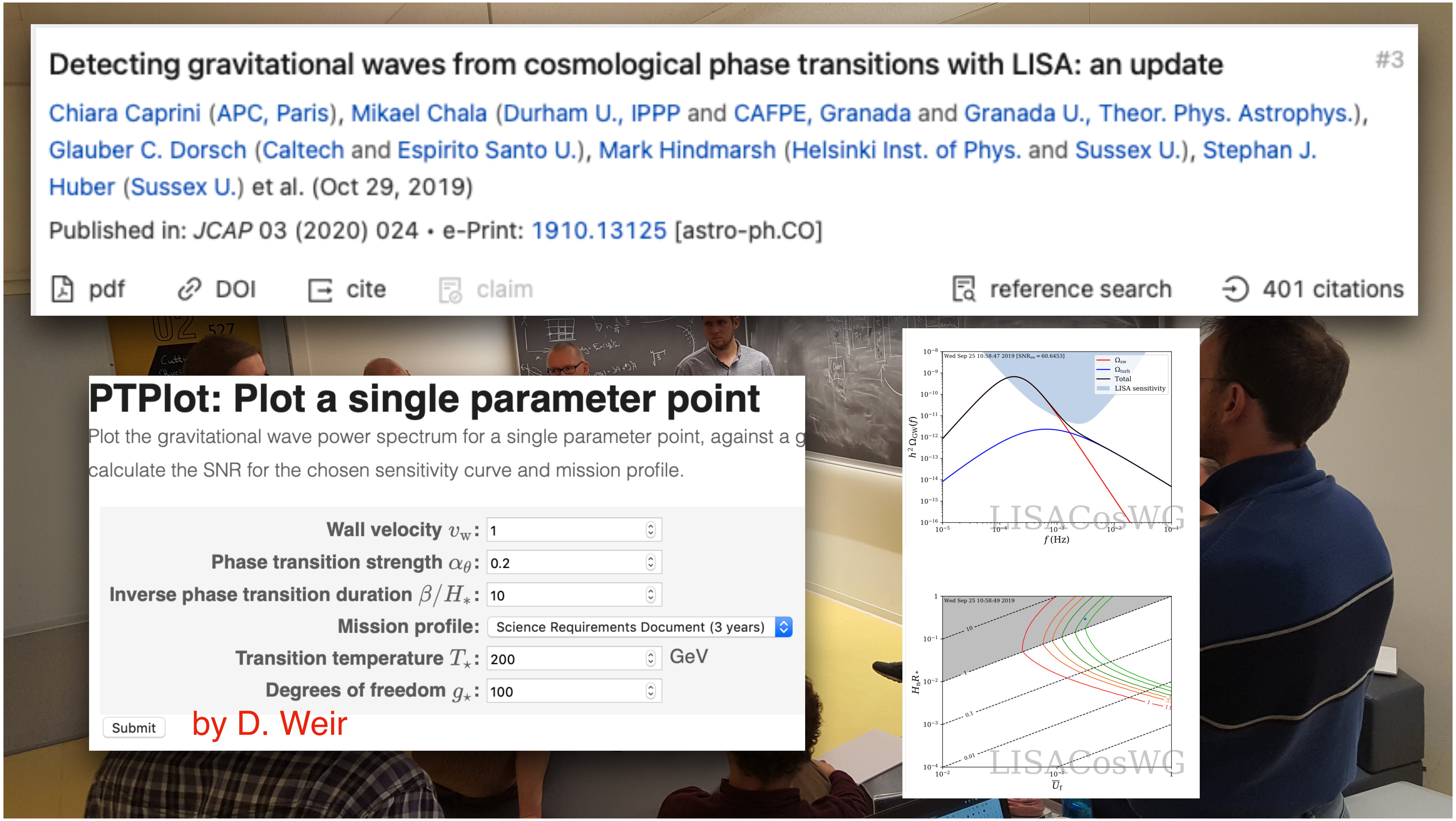
Gravitational waves from phase transitions

Review status every few years

4th CosWG @ MITP Mainz

Gravitational waves from phase transitions

Review status every few years



Pushing the limits

(aka some recent results)

GWs from QCD like dark sectors

Nonabelian $SU(N)$ dark sector, confinement scale Λ_d

n_f light/massless **dark** quarks

$n_f = 0$	$n_f > 0$
Glueball DM	Dark Baryons or Dark Pions
PT from center symmetry restoration	Chiral Symmetry Breaking
First order	First order for $n_f \geq 3$

Quantitative predictions?

Neither lattice nor holography alone suitable

We use improved holographic QCD

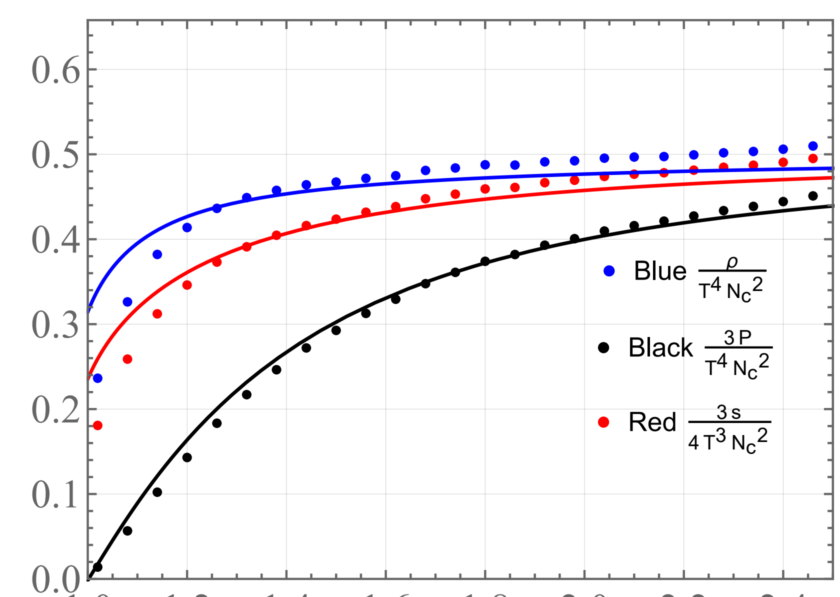
Gürsoy, Kiritsis, Mazzanti, Nitti
0707.1324, 0707.1349, 0812.0792, 0903.2859, ...

- Confinement in IR ($\lambda \to \infty$)
- Yang Mills beta function in UV ($\lambda \to 0$)

$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

Fix parameters:

- V_0, V_2 to reproduce 2 loop YM running in UV
- V_1, V_3 fit to reproduce SU(3) lattice thermodynamics in IR



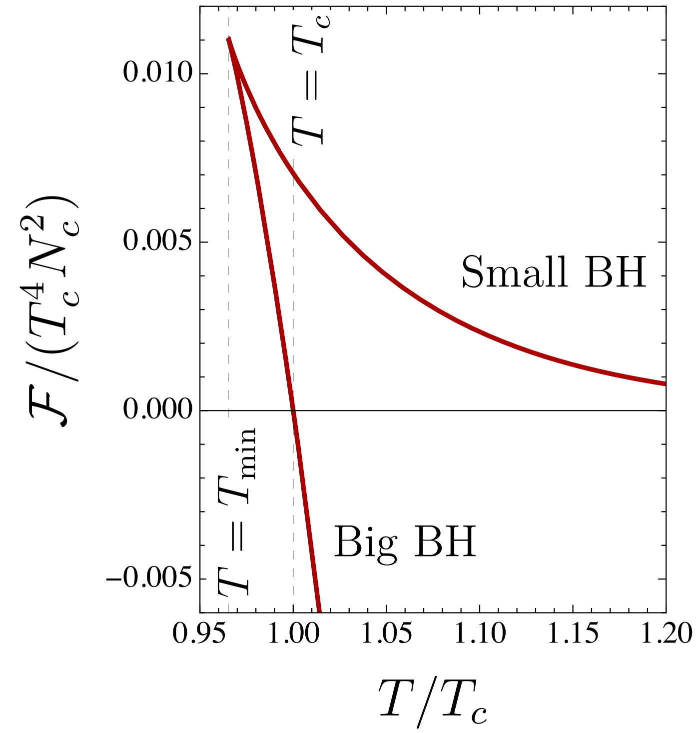
The phase transition in ihQCD

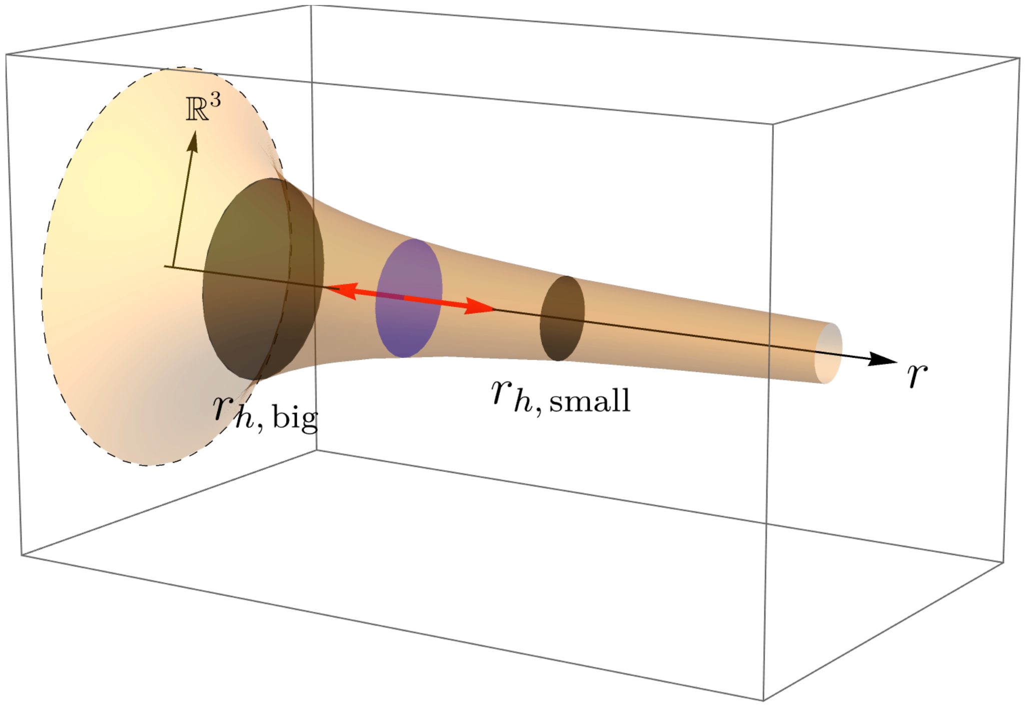
Hawking Page transition, with small BH acting as instanton

To compute bounce action, need effective action (or free energy) along the full path

Interpolate between big and small BH solutions

- Do some hard work...
- Win :)





Morgante, Ramberg, PS, 2210.11821

Effective potential and GW spectrum

Morgante, Ramberg, PS, 2210.11821

Bounce action

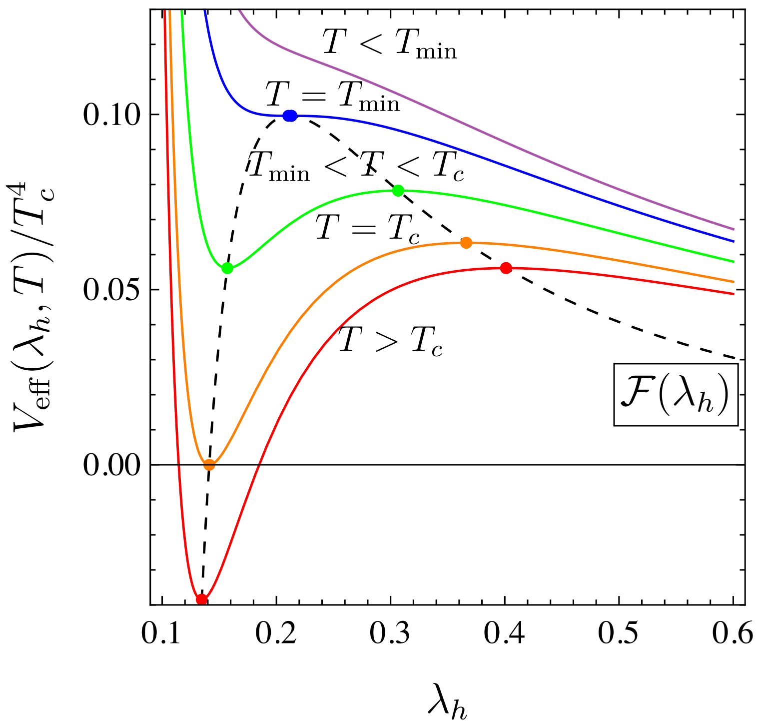
$$\mathcal{S}_{\rm eff} = \frac{4\pi}{T}\int d\rho\rho^2\left[c\frac{N_c^2}{16\pi^2}(\partial_r\lambda_h(r))^2 + V_{\rm eff}(\lambda_h(r))\right]$$

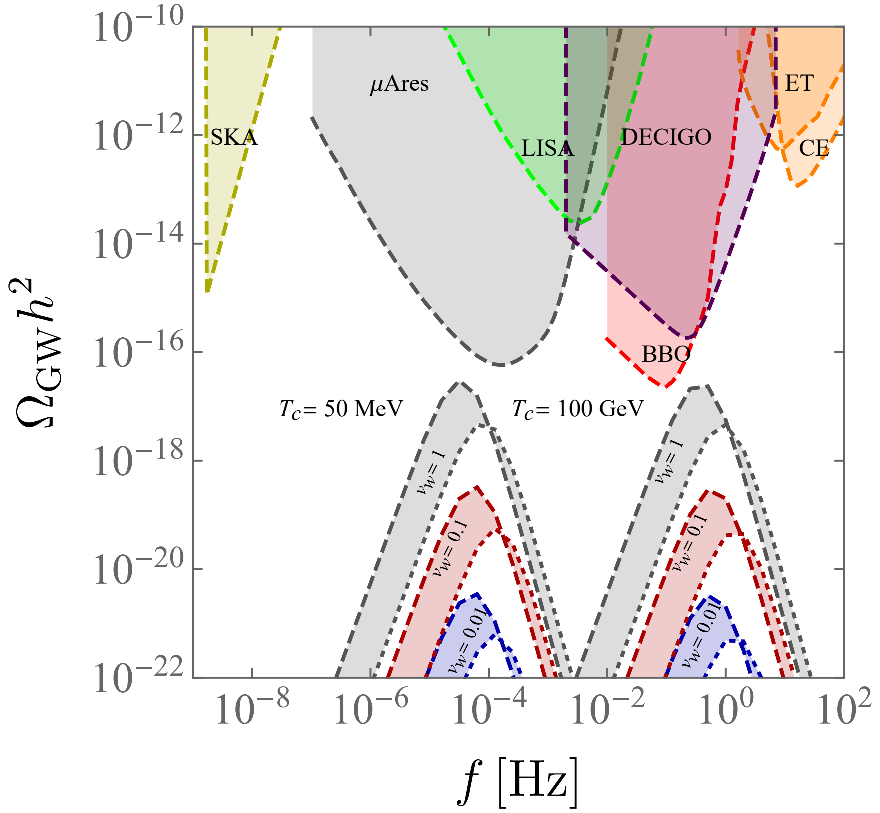
Tunneling rate

$$\Gamma = T^4\left(\frac{\mathcal{S}_B}{2\pi}\right)^{3/2} e^{-\mathcal{S}_B}$$

Allows us to compute GW parameters

- So far: $N_c = 3$, $n_f = 0$
- Agrees with estimates based on effective theories and lattice data
  (e.g. Halverson+ 2012.04071, Huang+ 2012.11614, March-Russell+ 1505.07109)



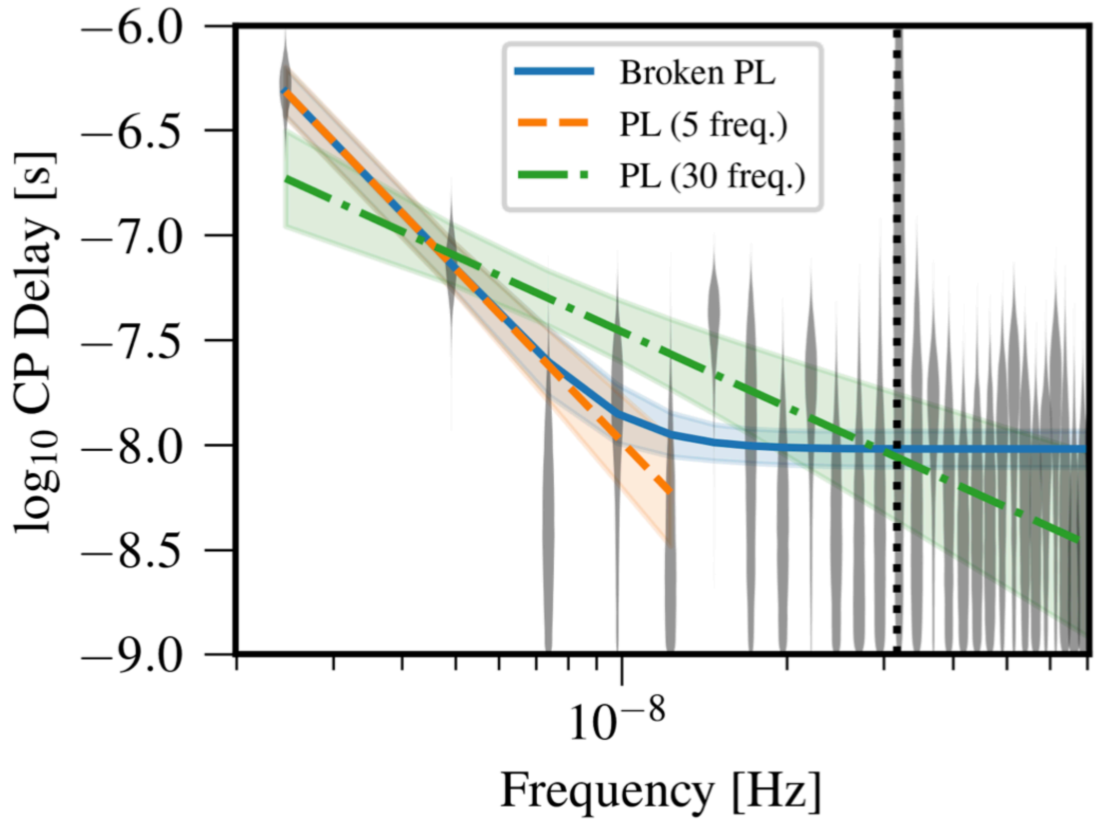


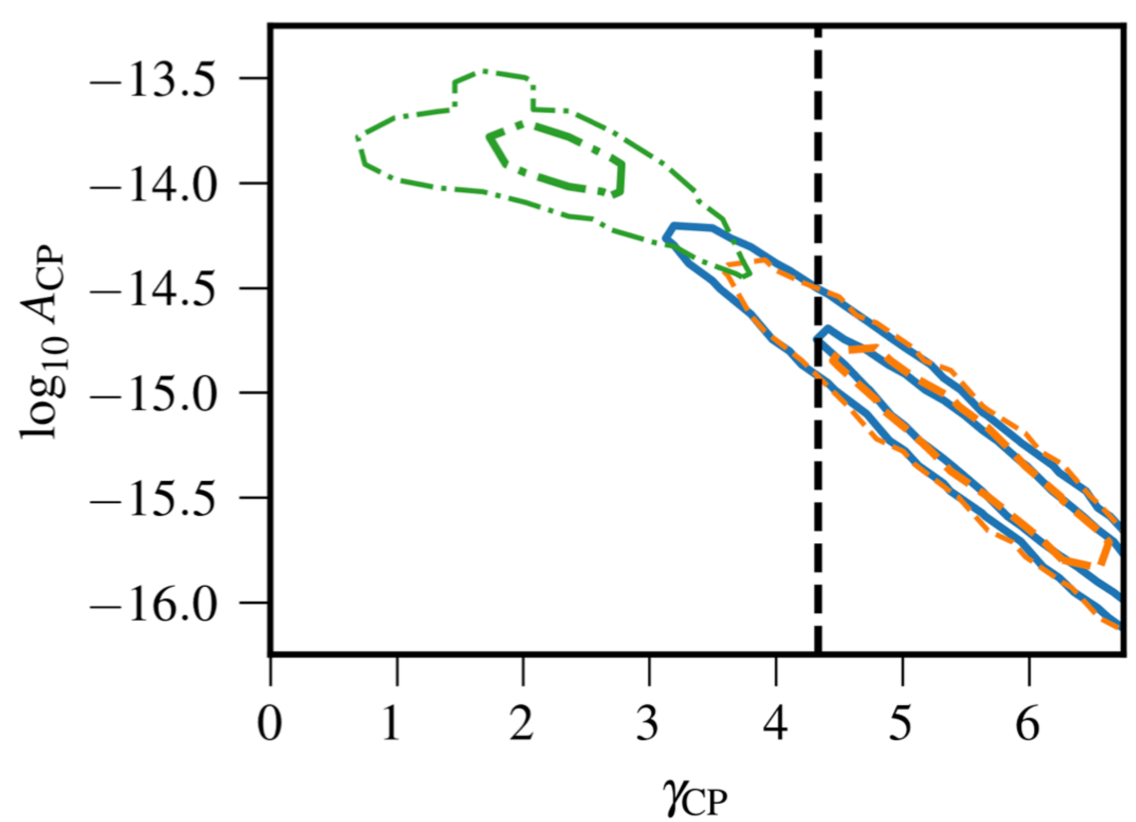
Pushing the limits

(and some recent hints)

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

arXiv:2009.04496





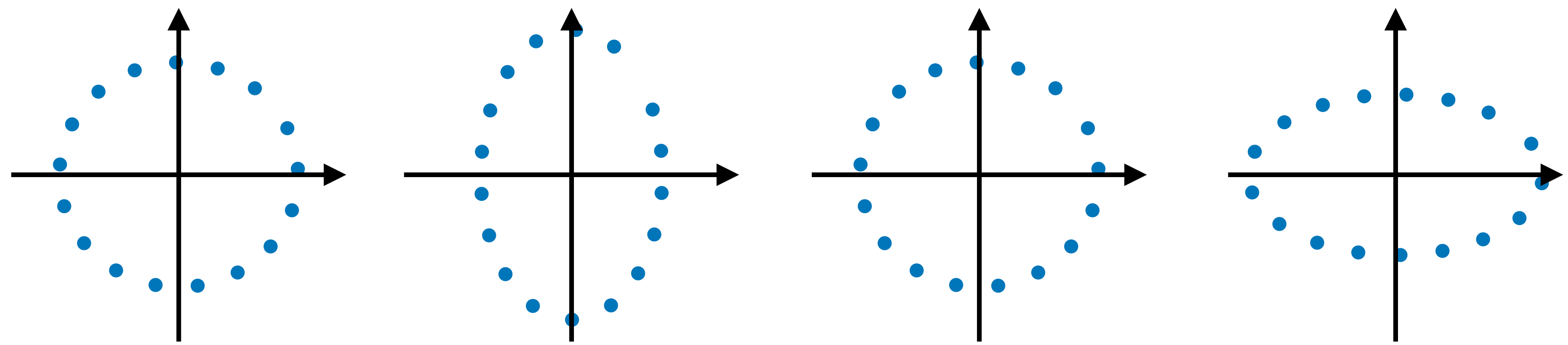
Fit with free spectrum (violins) or simple power law signals

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

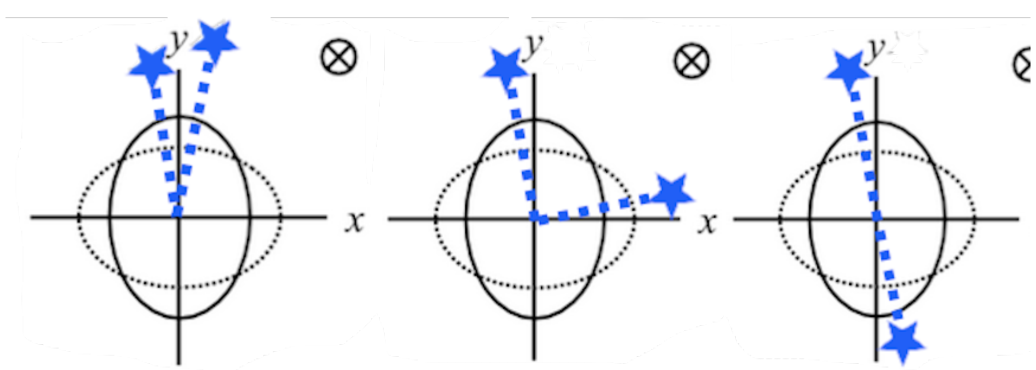
$$h_c(f) = A_{\mathrm{GWB}}\left(\frac{f}{f_{\mathrm{year}}}\right)^{\alpha}$$

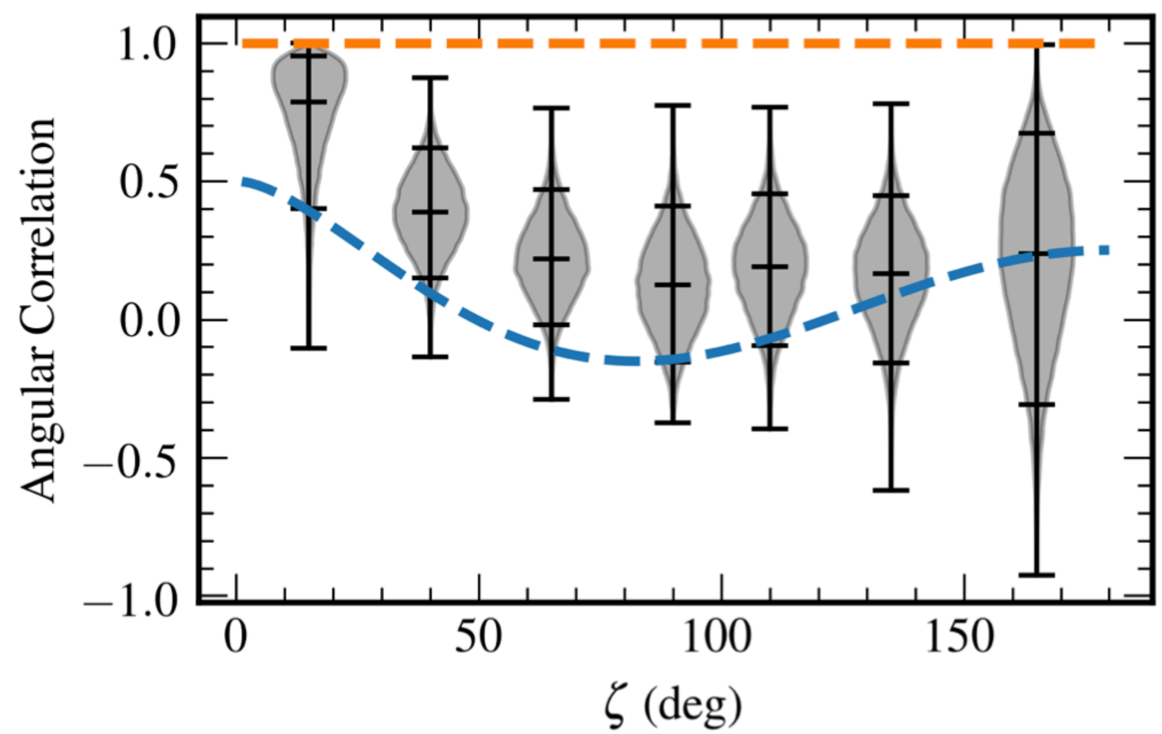
$$\gamma = 3 - 2\alpha$$

GWs are quadrupole radiation



Angular correlation in pulsar response (Helling Downs)





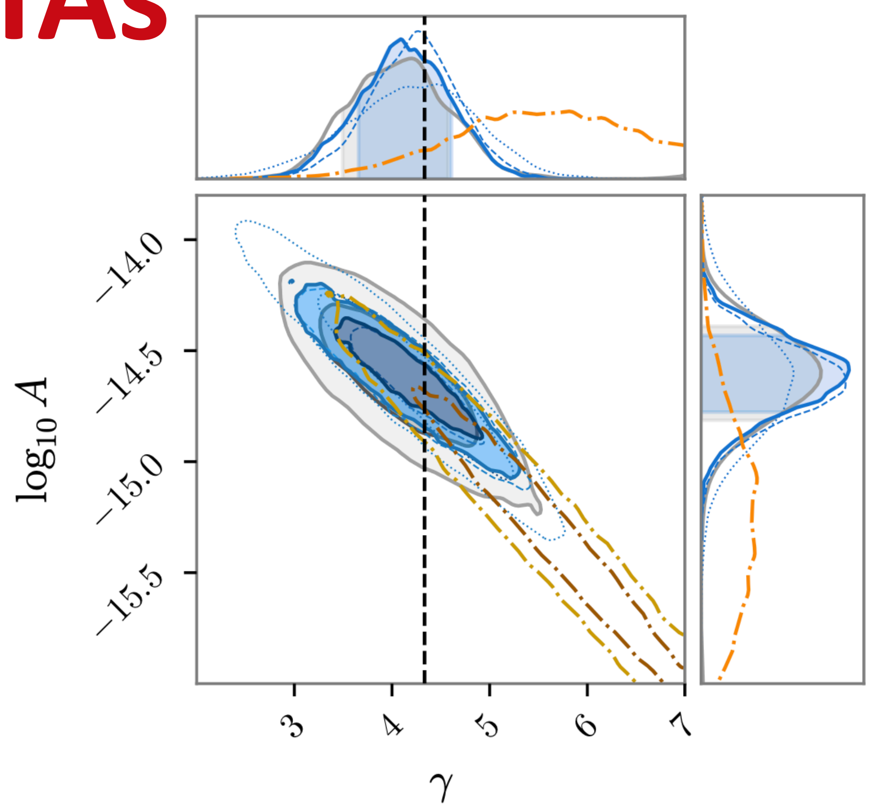
No conclusive evidence for HD correlation (yet)

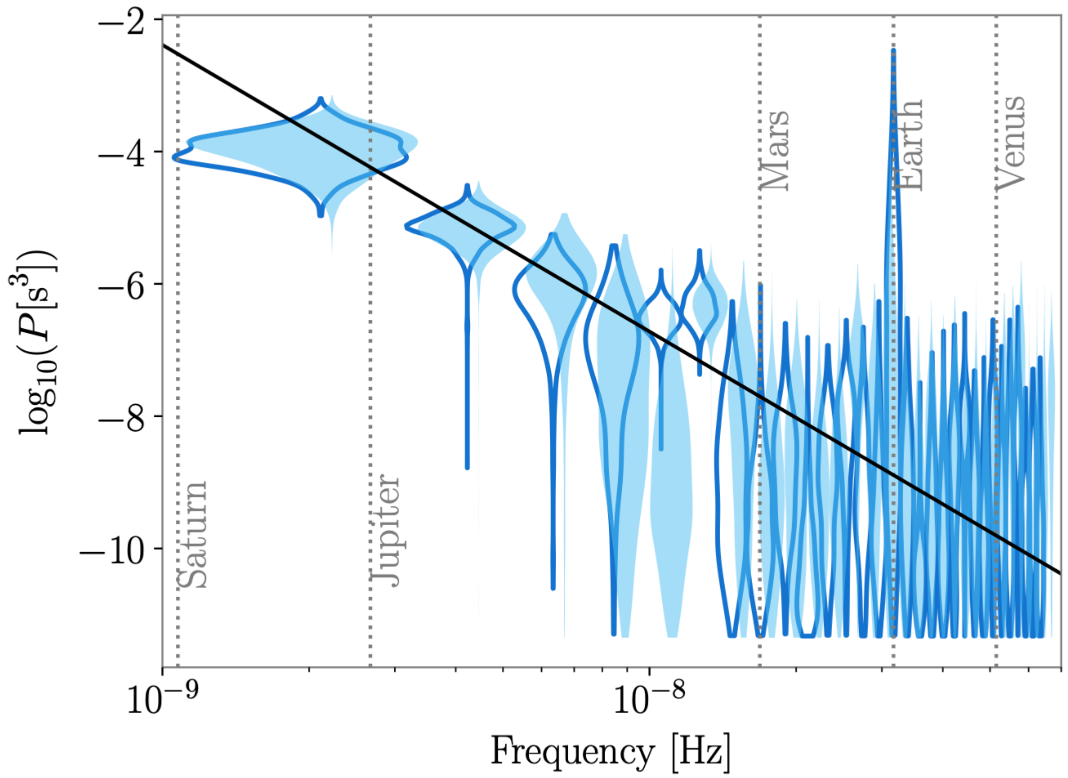
arXiv:2009.04496

Other PTAs

Parkes PTA (Australia)

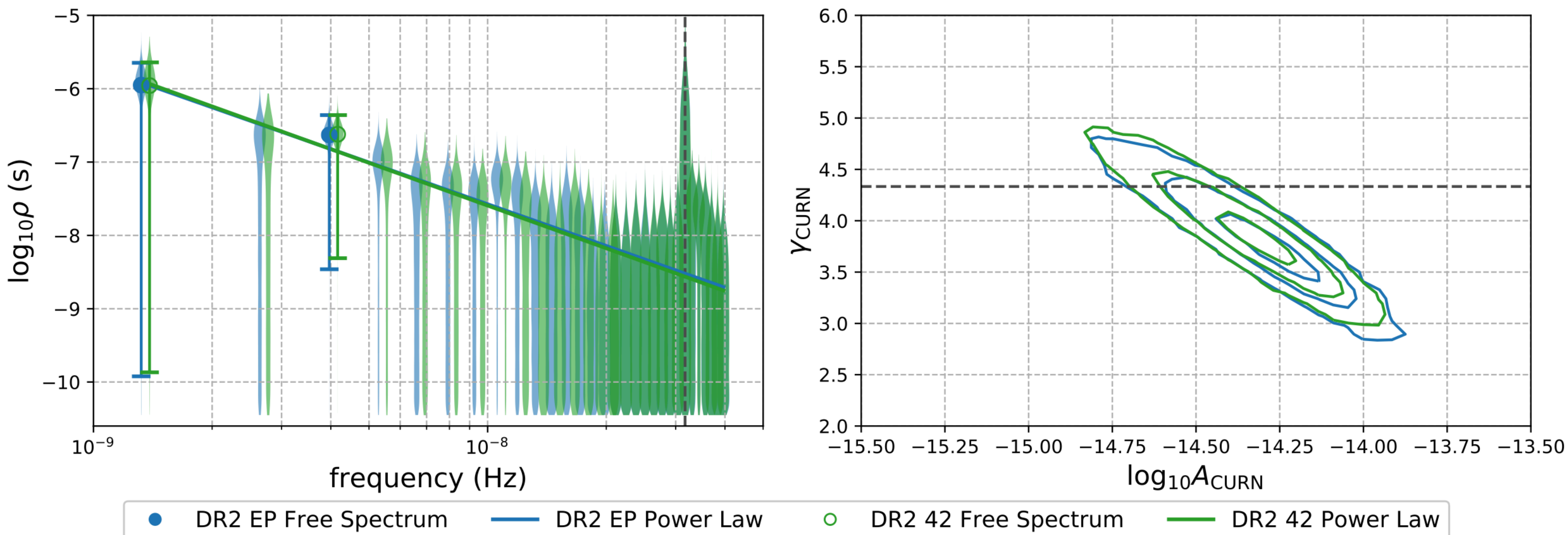
arXiv:2107.12112



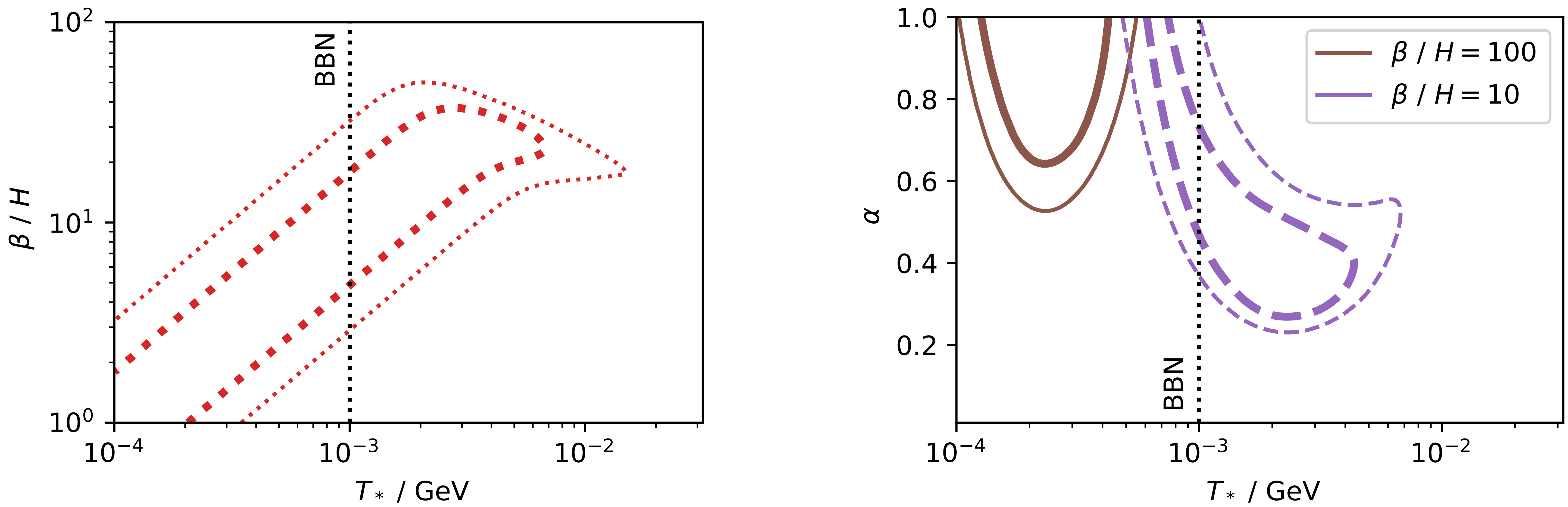


European PTA

arXiv:2110.13184



Fit with Phase Transition



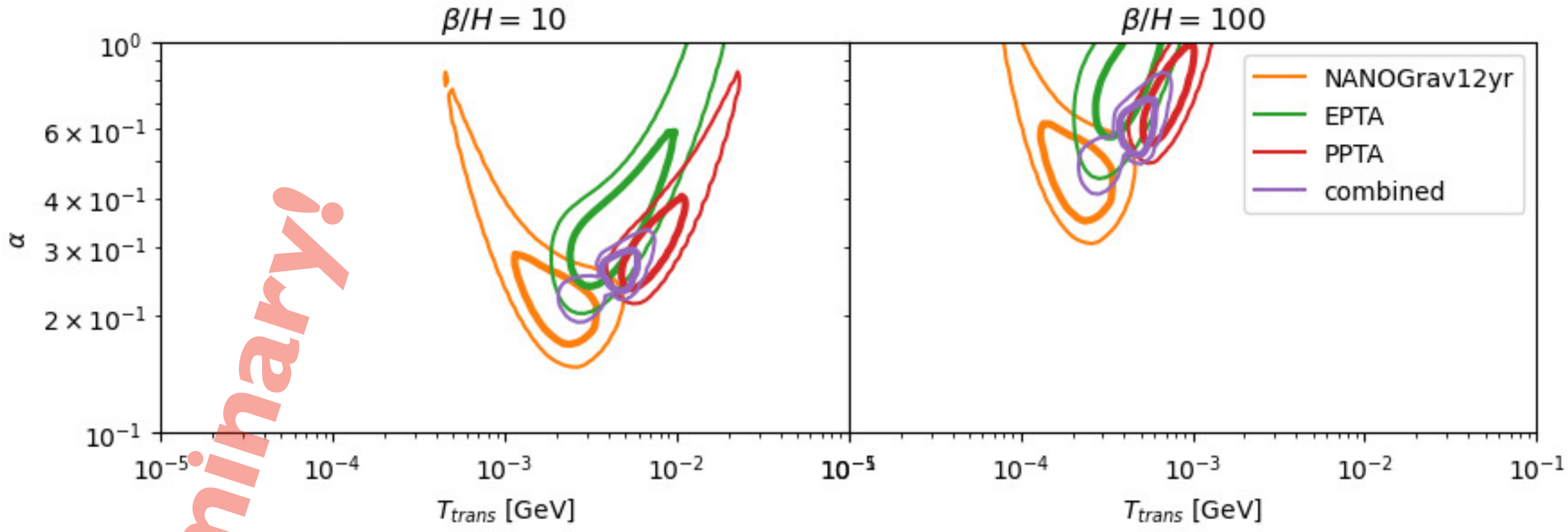
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

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

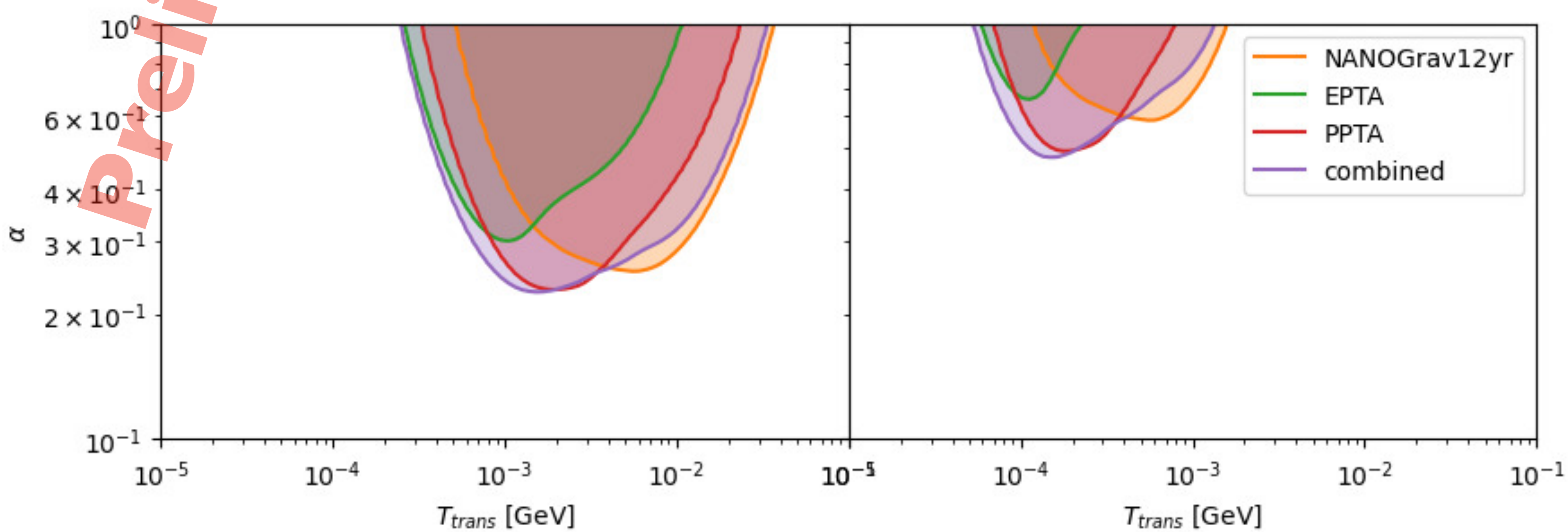
Wolfram Ratzinger & PS, 2009.11875

Phase transitions revisited

Fit to all PTA data



Also: Model exclusion



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

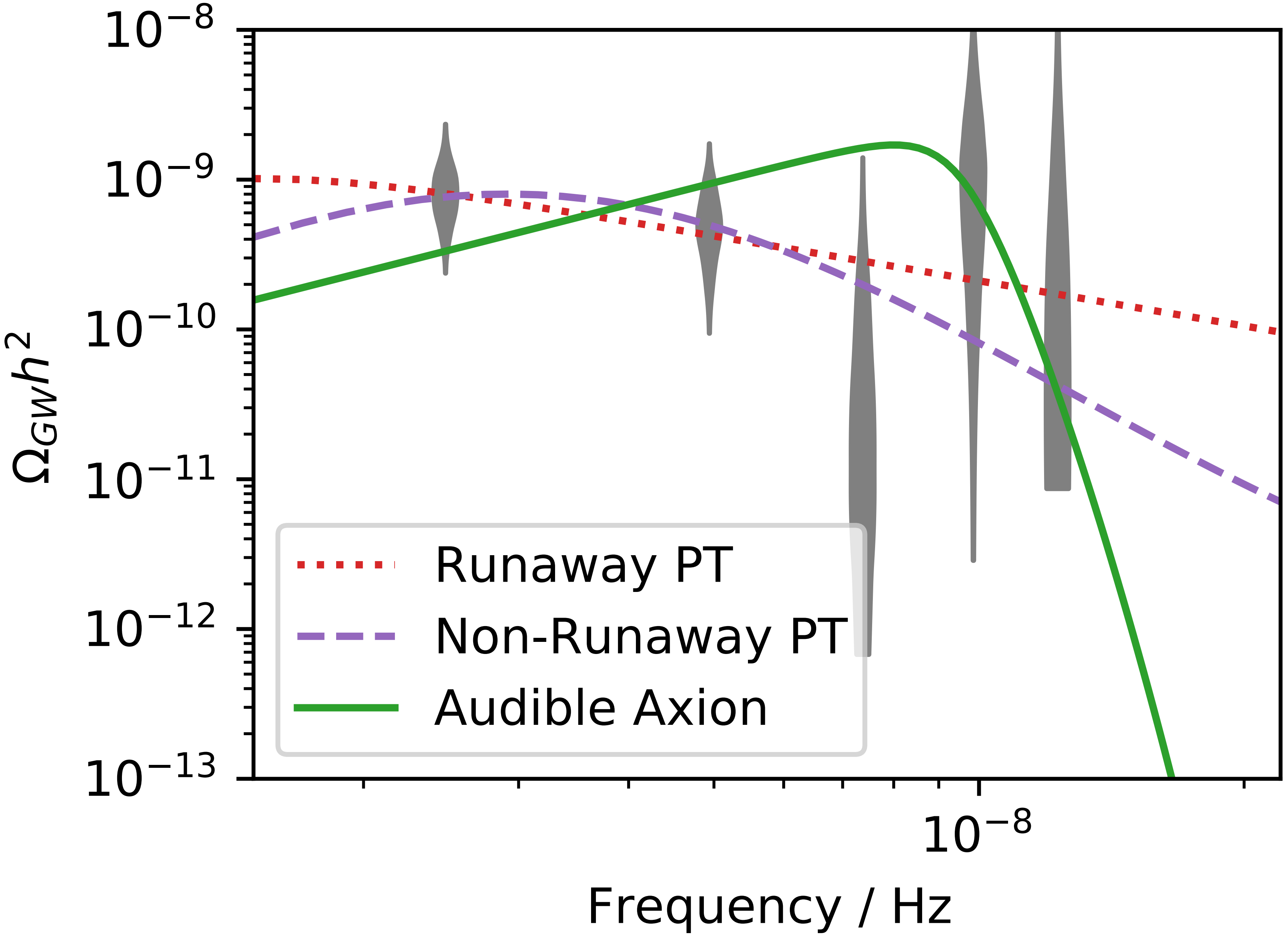
Waiting for next data release

And we will hopefully be able to discuss the implications at the next GW themed MITP workshop

Looking forward to the next 10 years!
And many more nice memories
Thank you Matthias!!!

Stuff :)

Broken power laws: PTs and axions



Wolfram Ratzinger & PS, 2009.11875

GW source discrimination

Many possible sources of primordial GWs

- Phase transitions, cosmic strings, audible axions, inflation,…

Cosmological probes

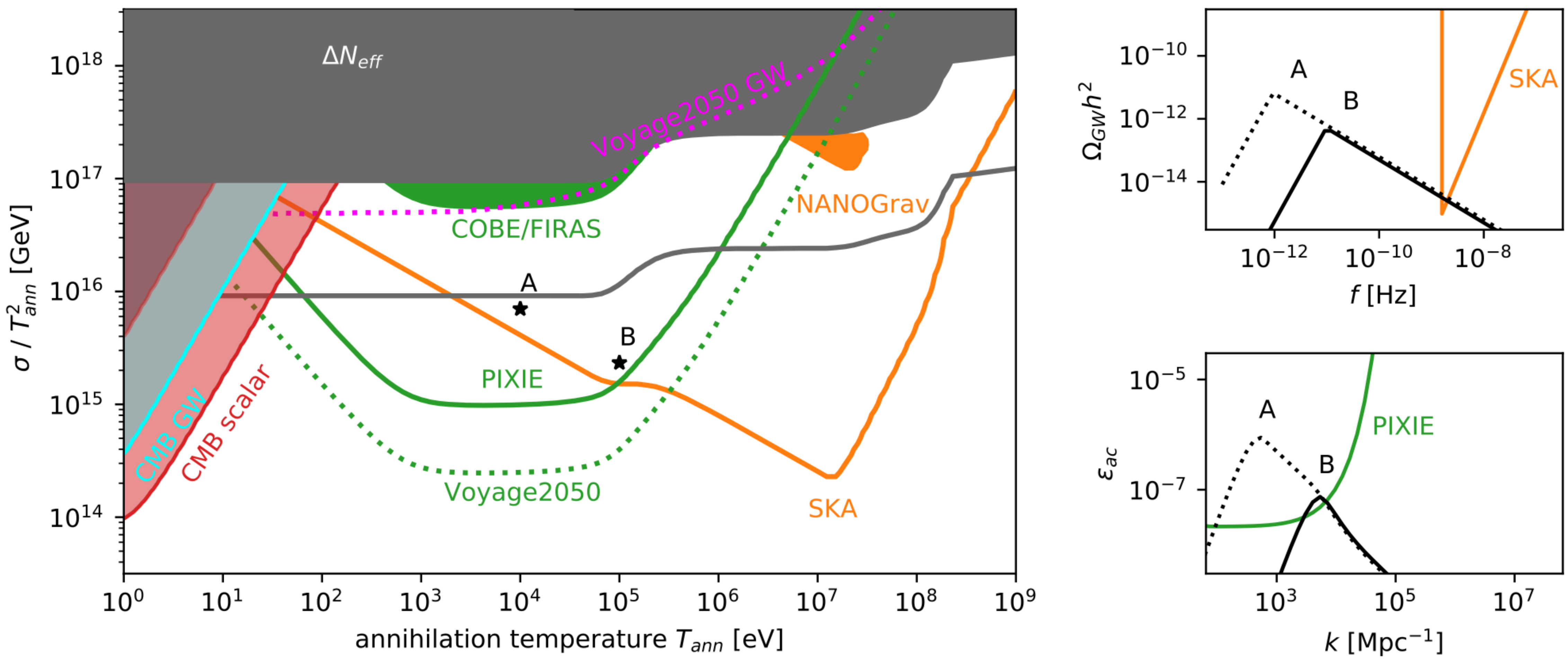
- Many sources contribute to N_{eff} , should not upset BBN
- Requires concrete models

CMB spectral distortions

Ramberg, Ratzinger & PS, 2209.14313

- Strong GW sources imply large anisotropies "somewhere"
- Anisotropies couple at least gravitationally to SM plasma
- If close to CMB decoupling → spectral distortions

Example GW source: Annihilating domain walls



Spectral distortions already probe parameter space

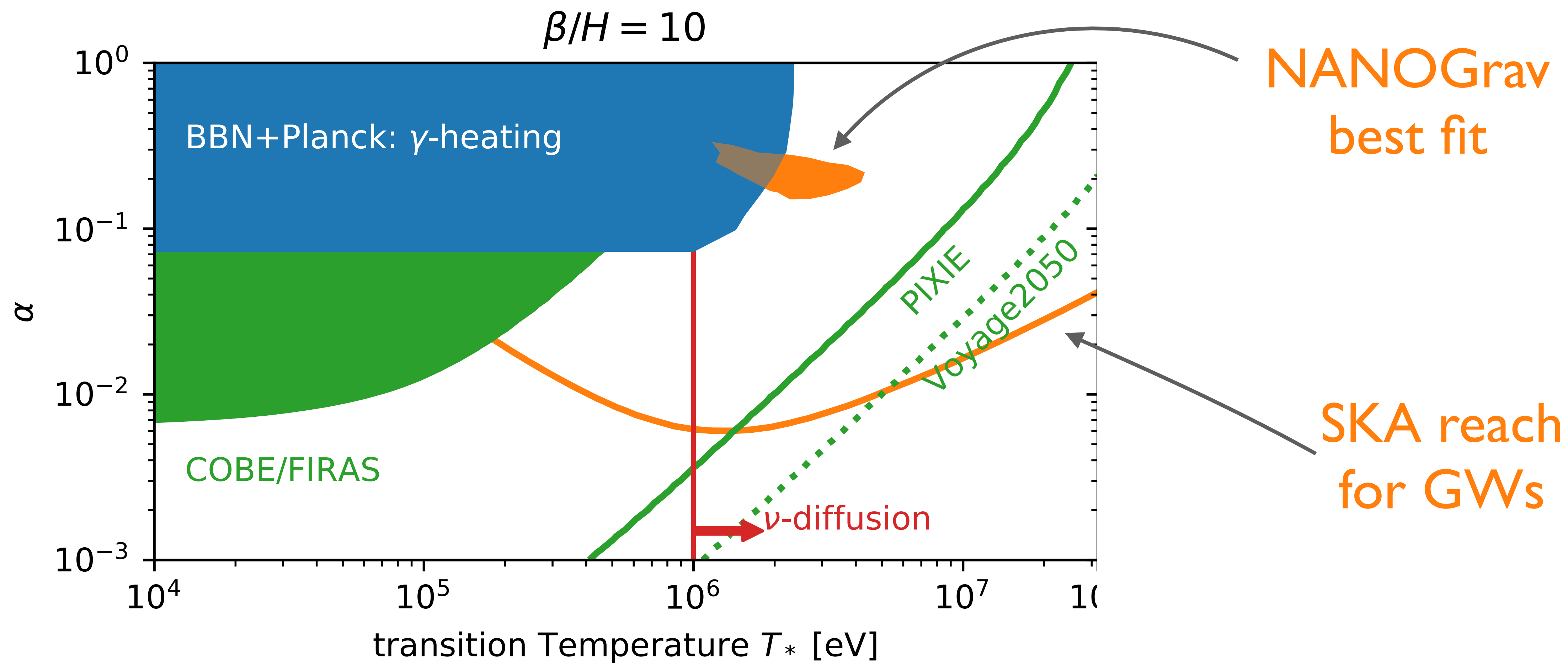
Complementary to GW probes, can break degeneracy

- 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

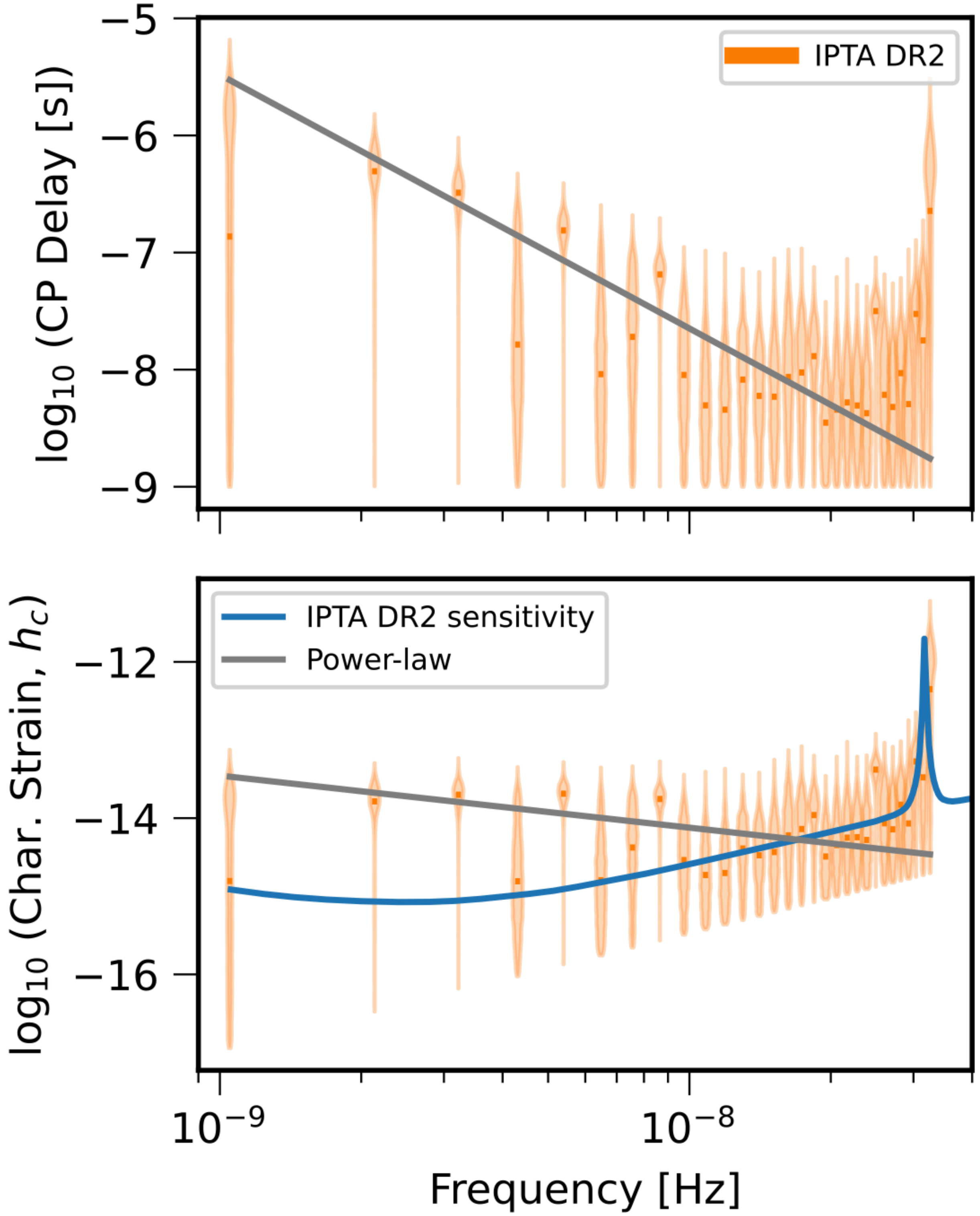
International PTA

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

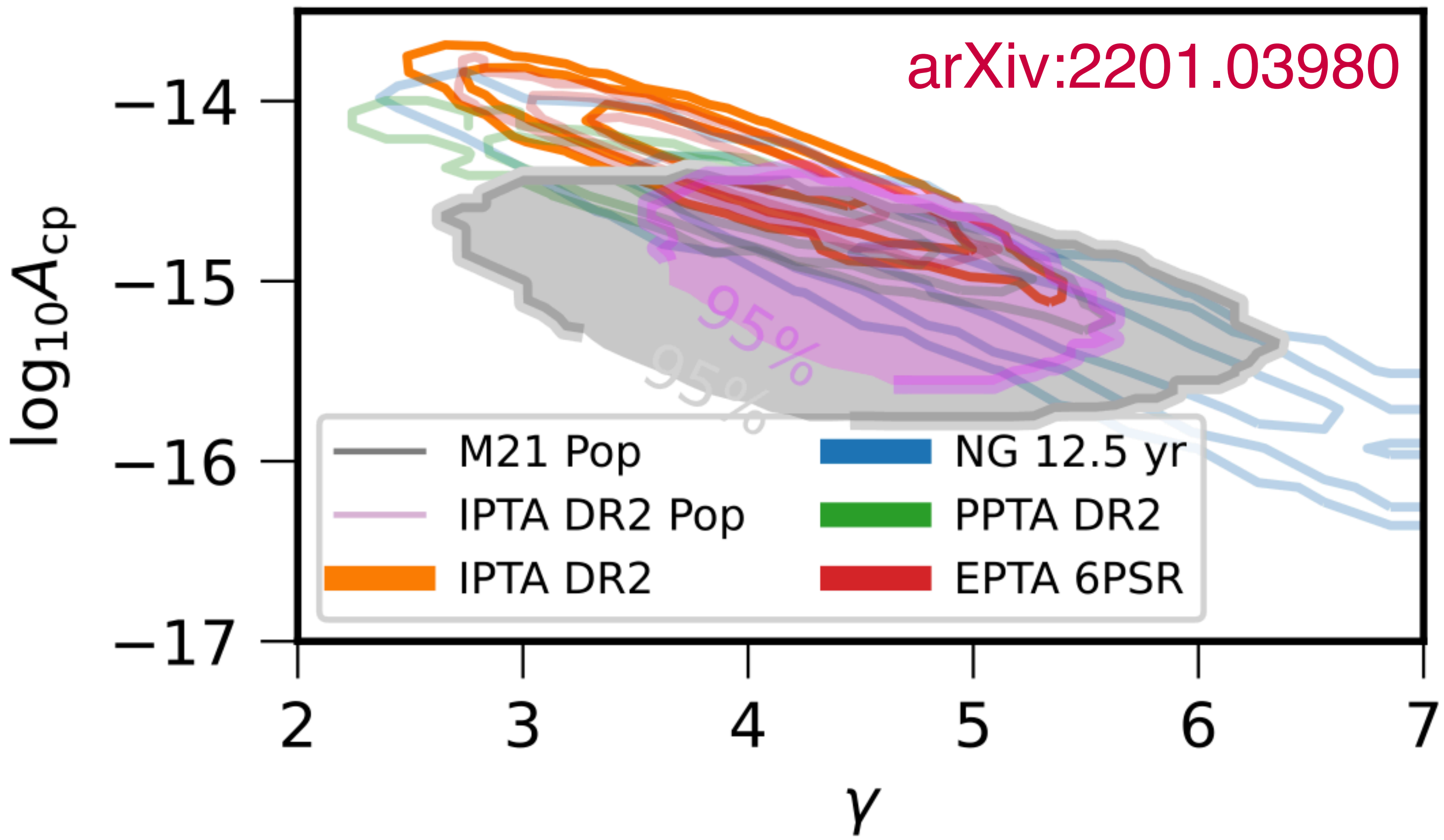


Not an anomaly?

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

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

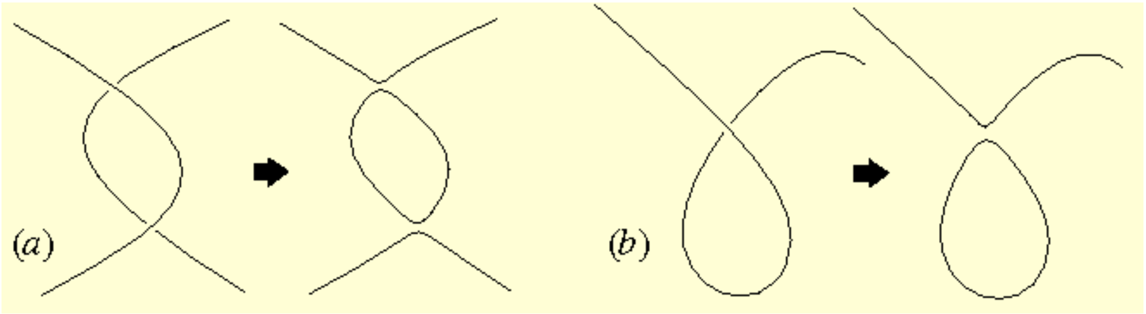
Amplitude a bit high for pure Astro signal

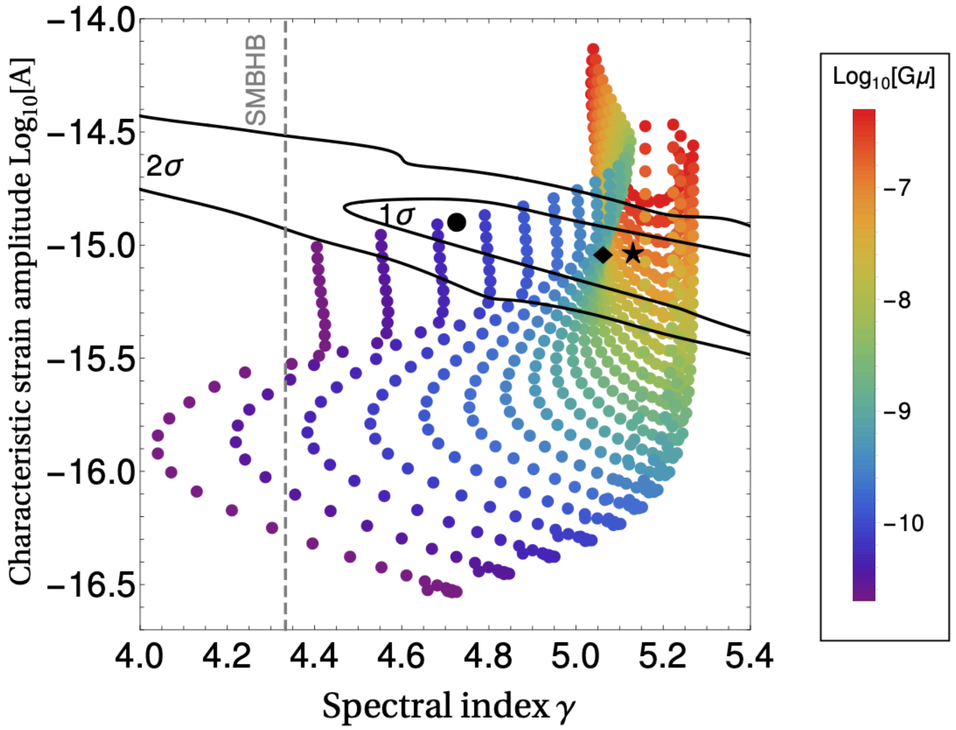


- Room for new physics contribution!

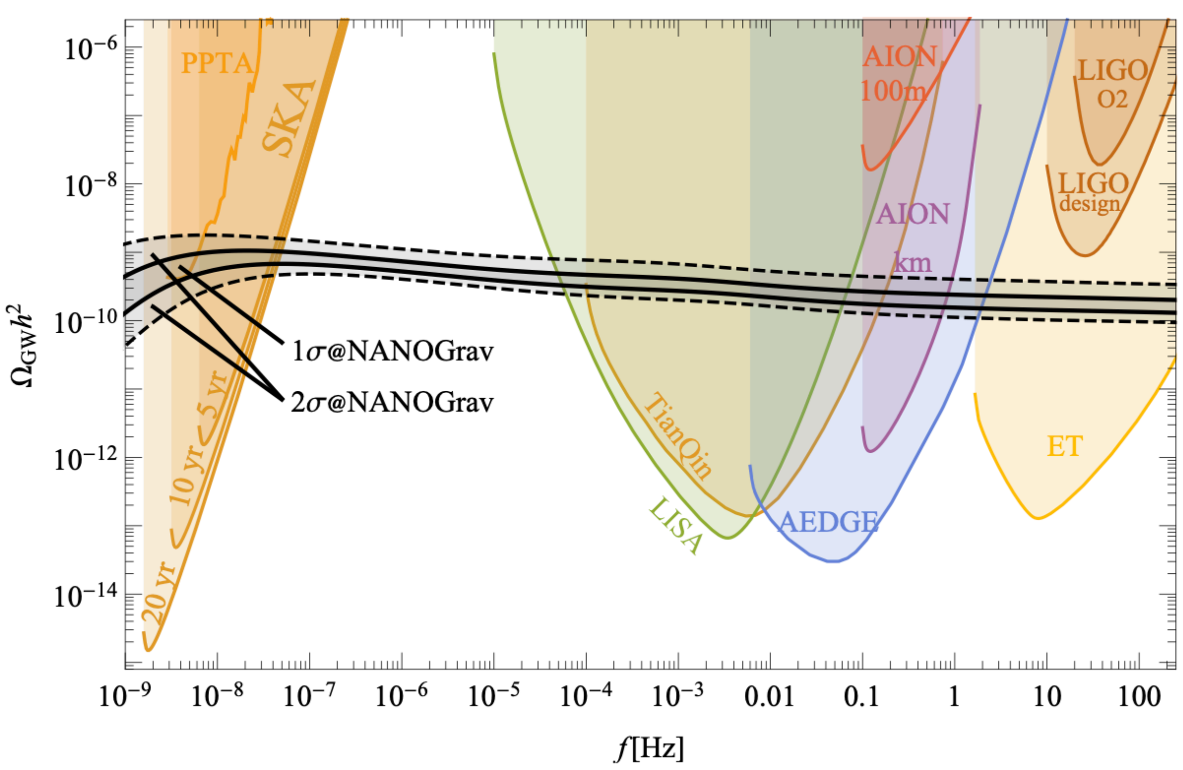
Simple power laws: Inflation or cosmic strings

Strings work better though!





Blasi, Brdar, Schmitz, 2009.06607



Ellis, Lewicki, 2009.06555

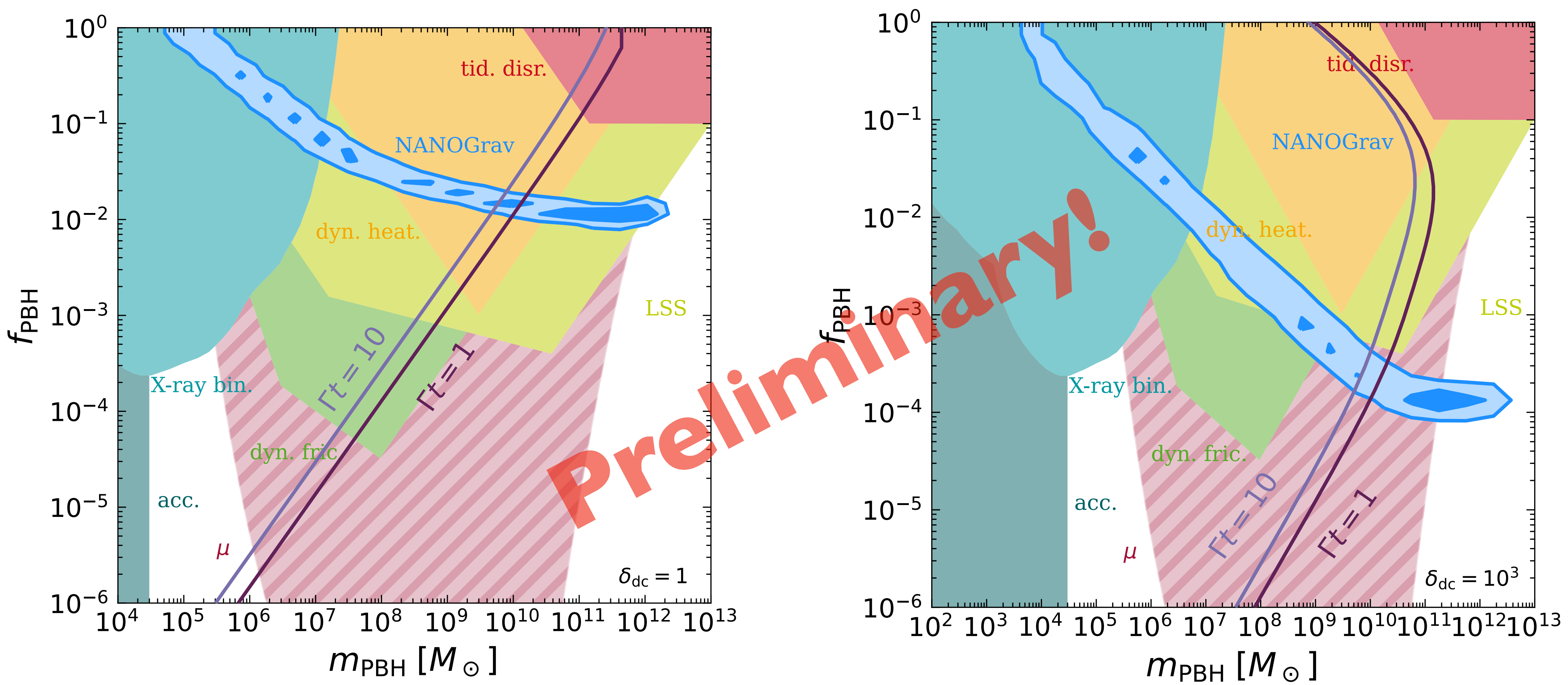
More BHs?

Signal from mergers "stupendously" large primordial BH?

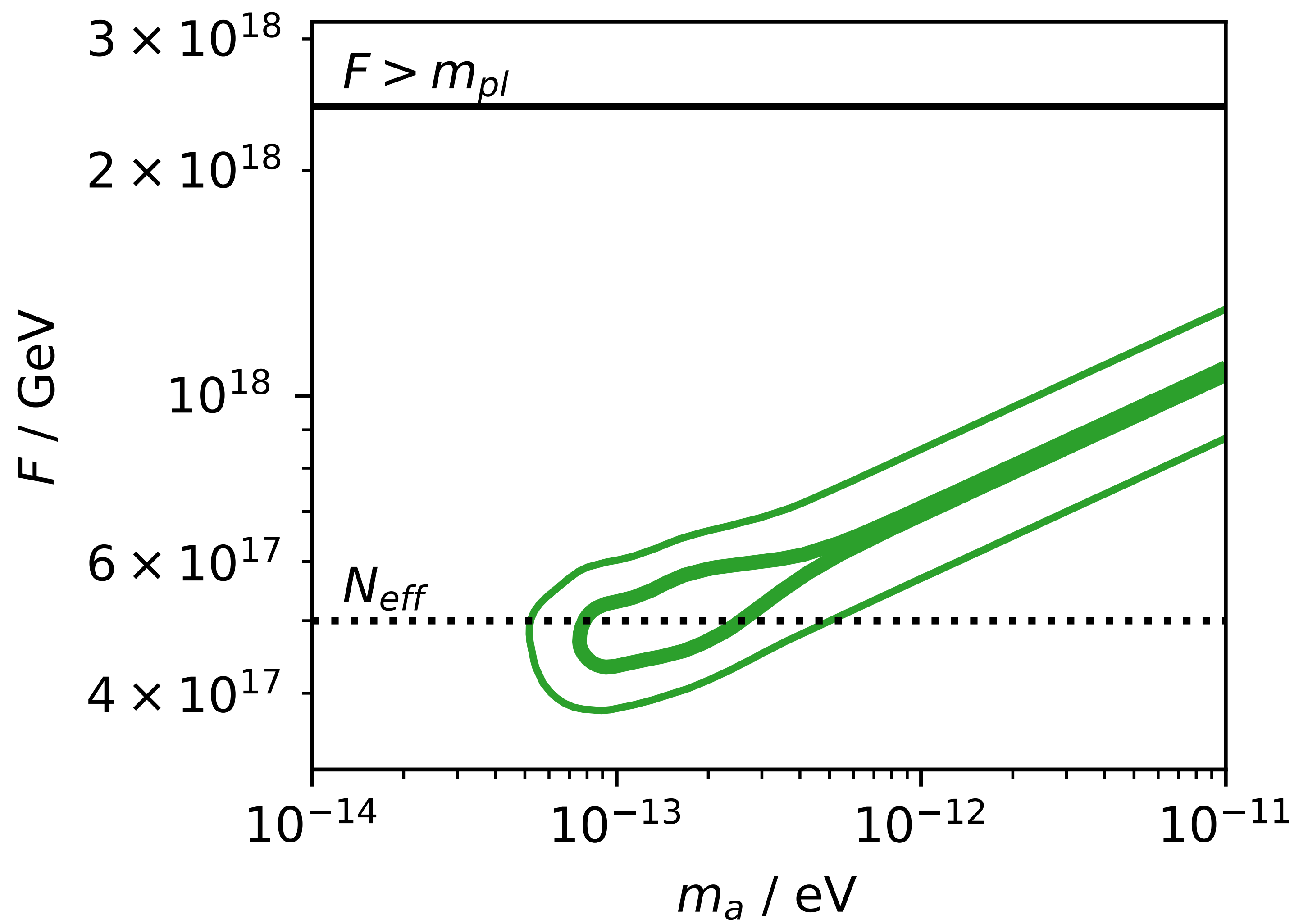
Atal, Sanglas, Triantafyllou, 2012.14721

Only possible with large clustering!

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



Example: Audible Axion



Parameter reconstruction already possible

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

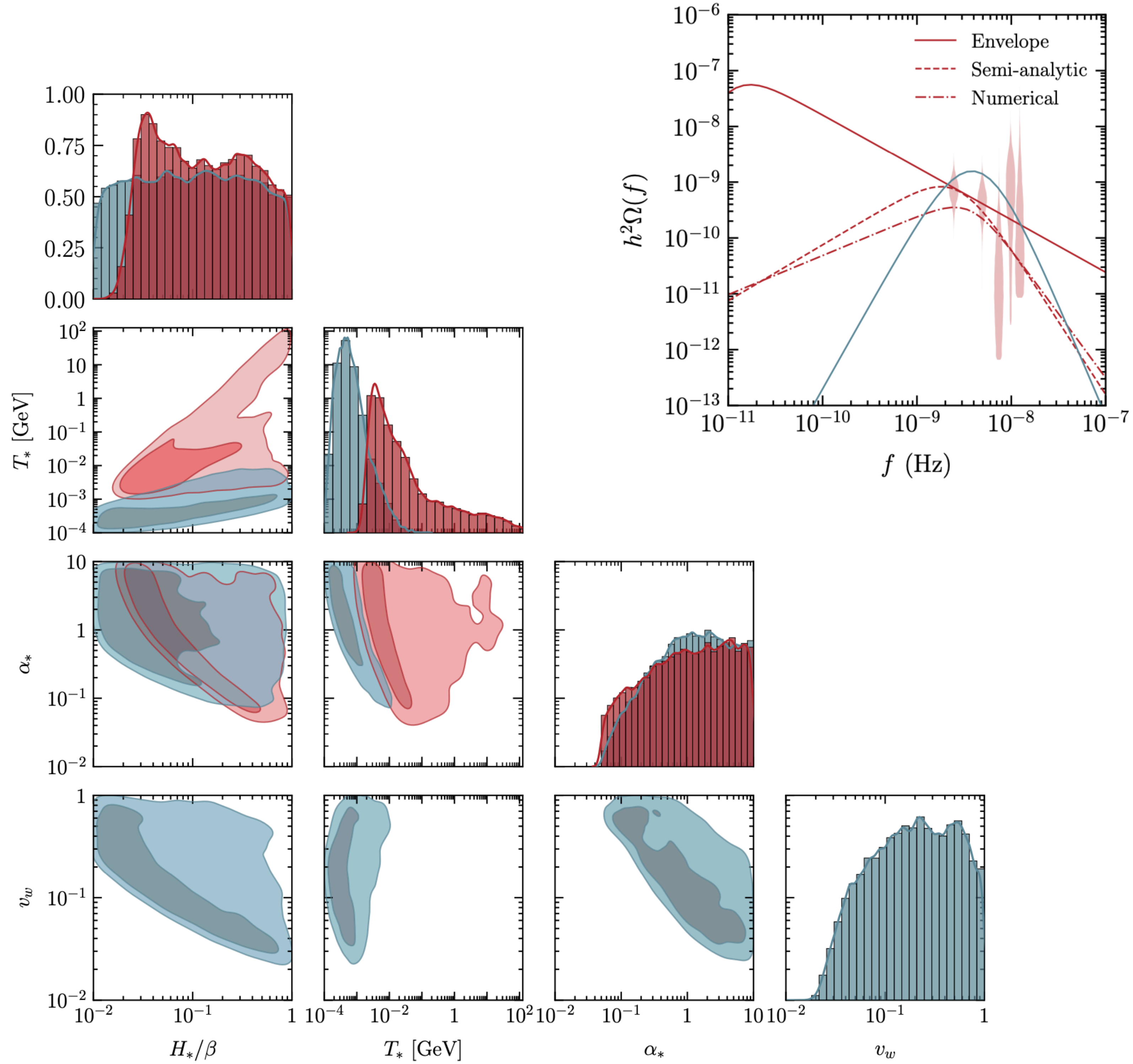
Wolfram Ratzinger & PS, 2009.11875

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

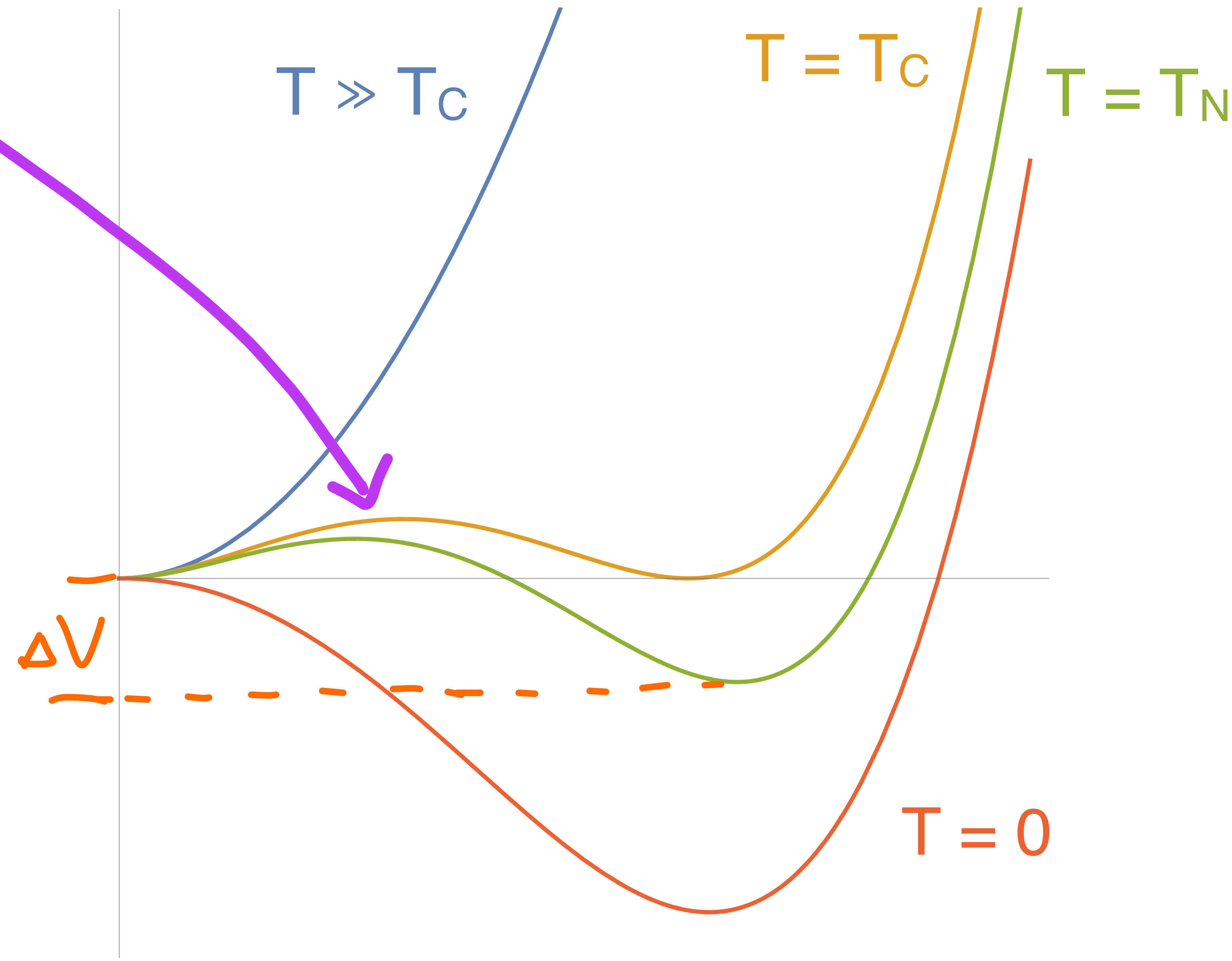
- Need barrier here

PT occurs at T_N

Potential energy ΔV

GWs

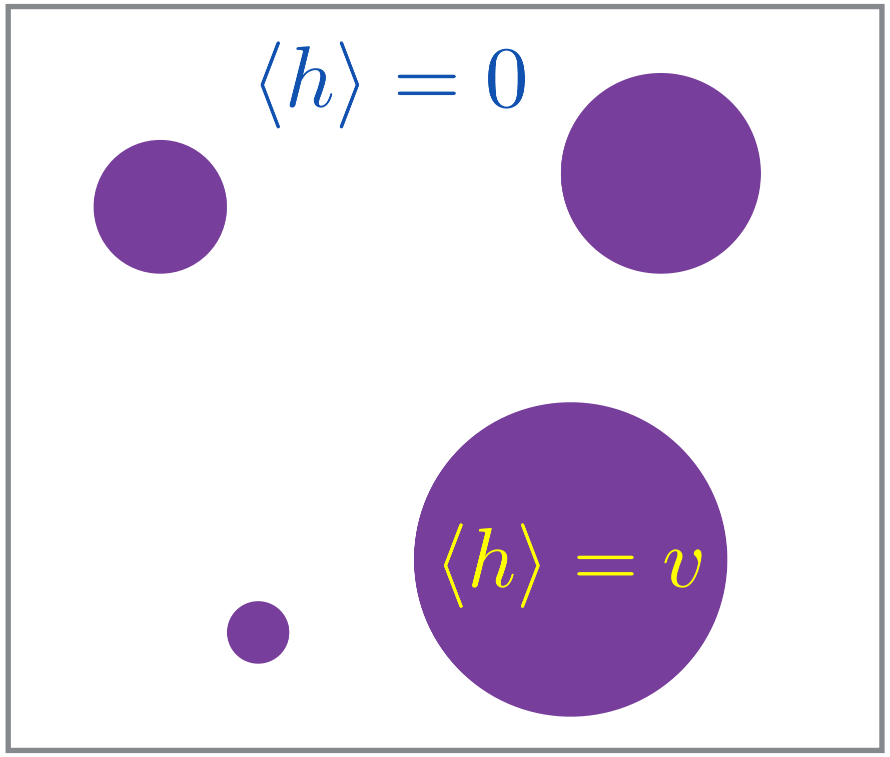
Not in SM! Possible in
BSM scenarios

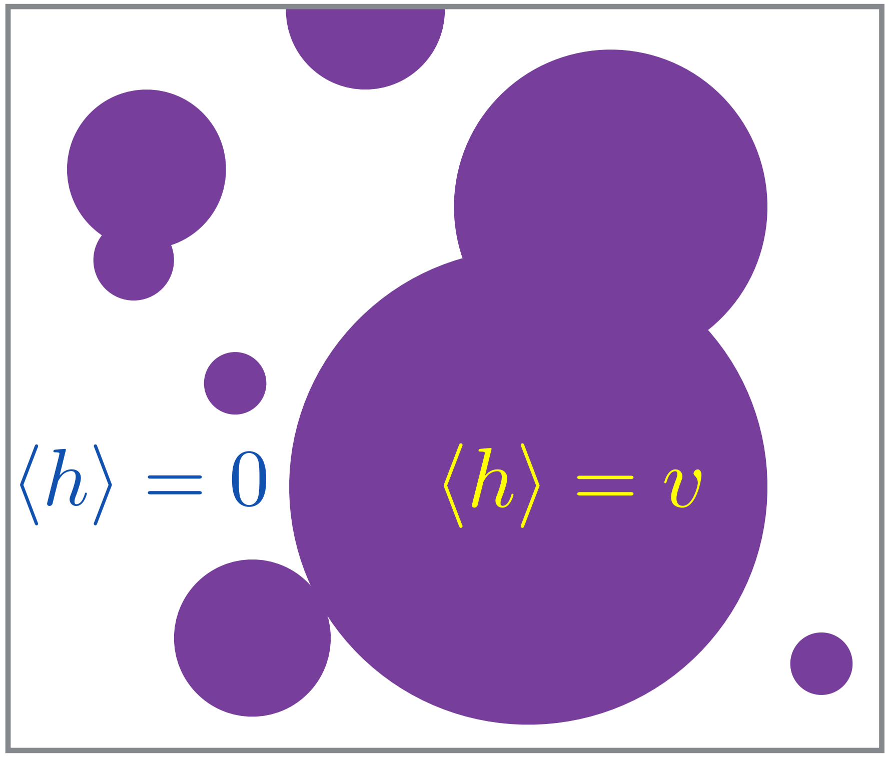


GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves





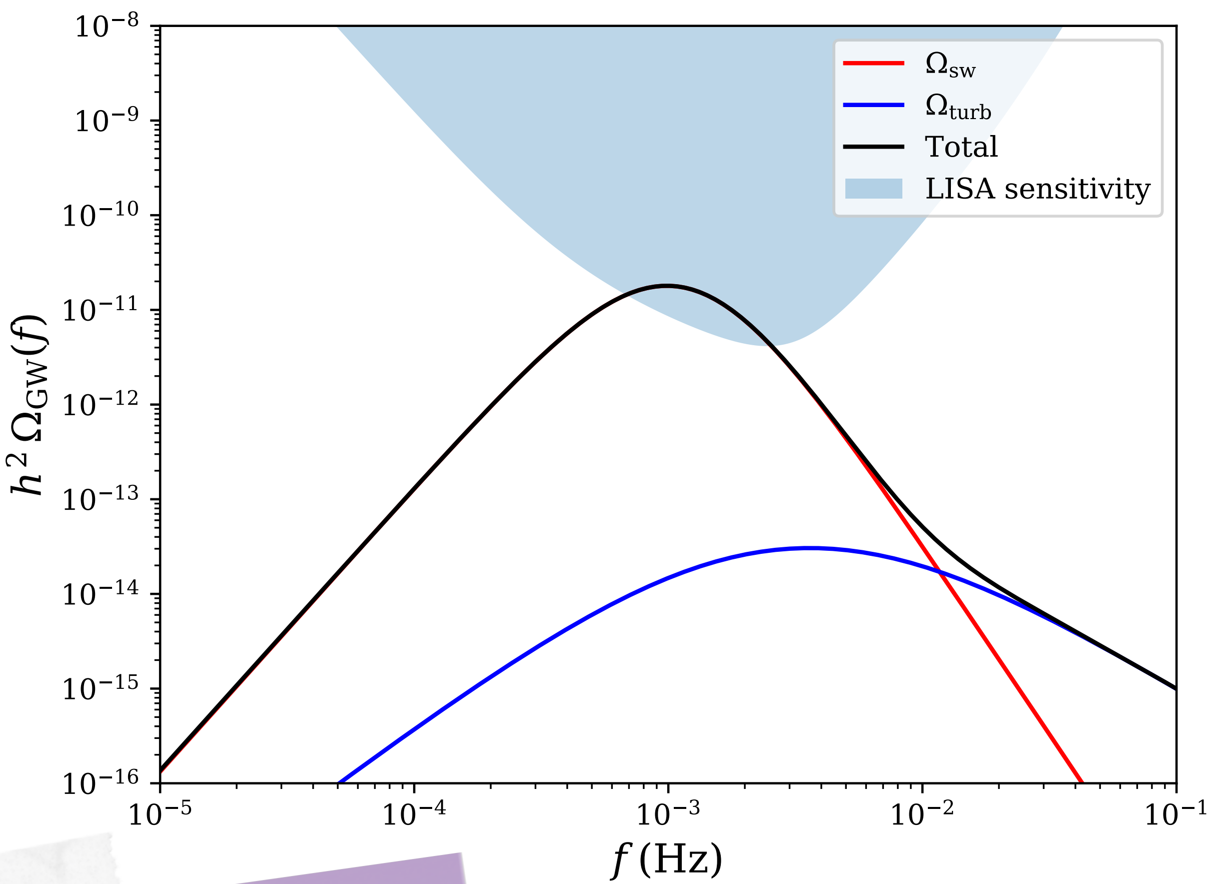
PT signal

PT characterised by few parameters:

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

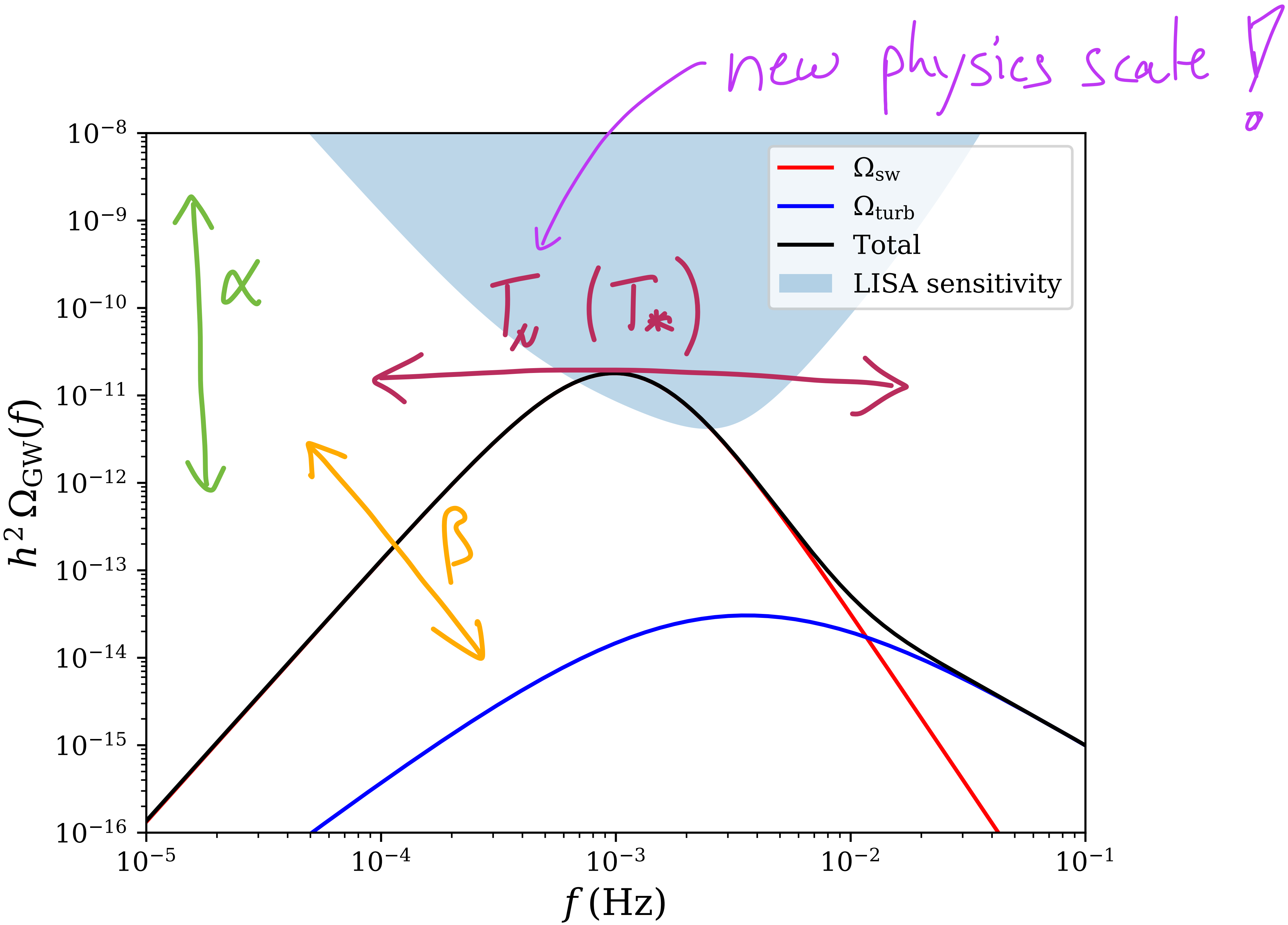
Three physical contributions

- Bubble wall collisions
- Turbulence
- Sound waves



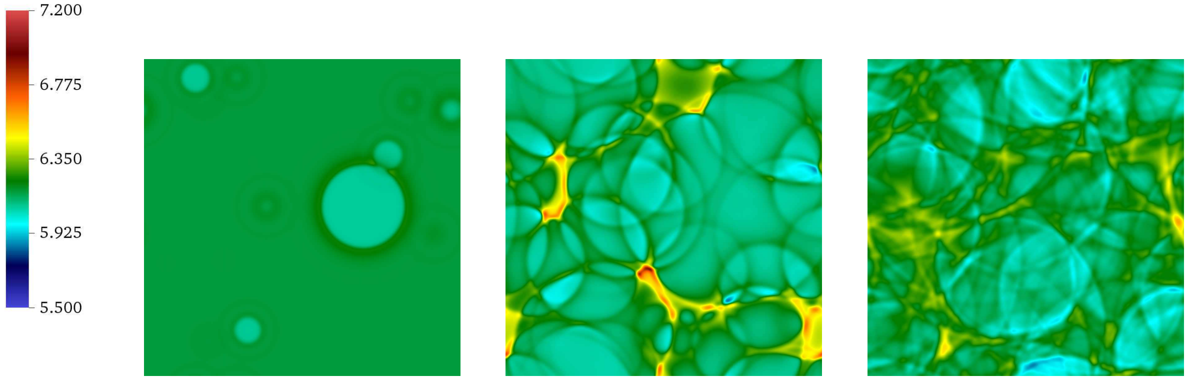
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Signal properties



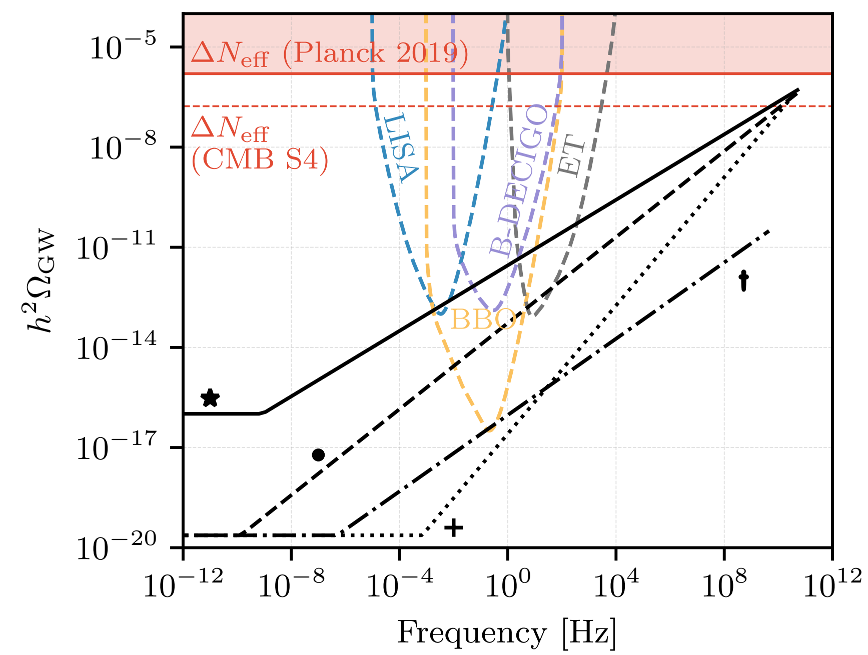
Primordial sources of GWs

First order phase transitions (symmetry breaking)



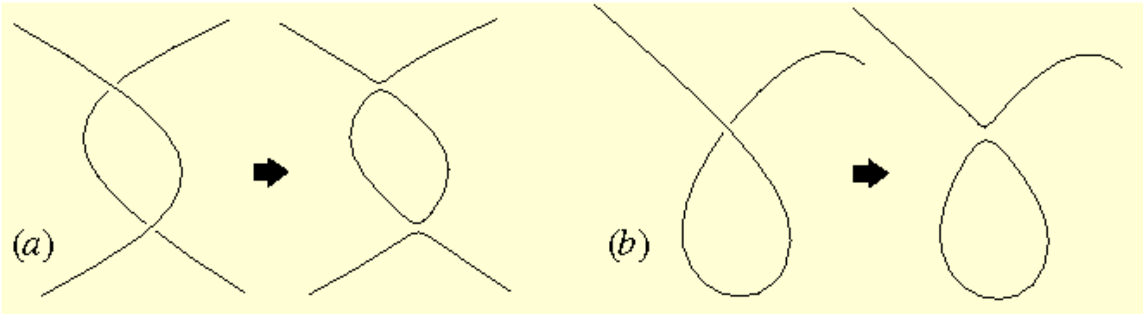
from Hindmarsh et al

Inflation/Reheating



Opferkuch, PS, Stefanek, 2019

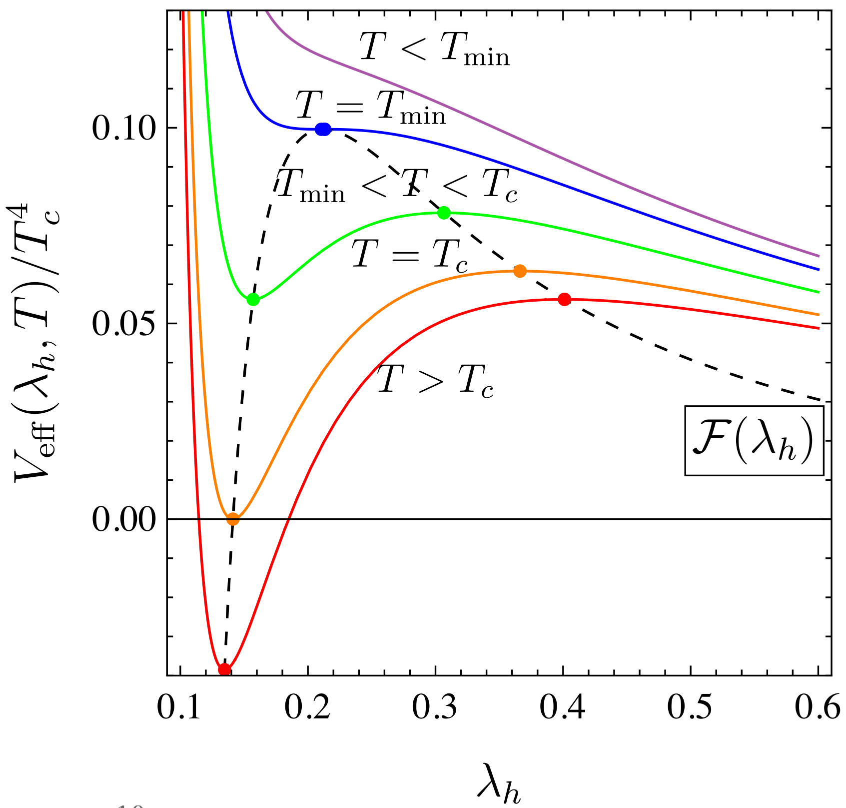
Cosmic strings



Strongly coupled PTs are also difficult

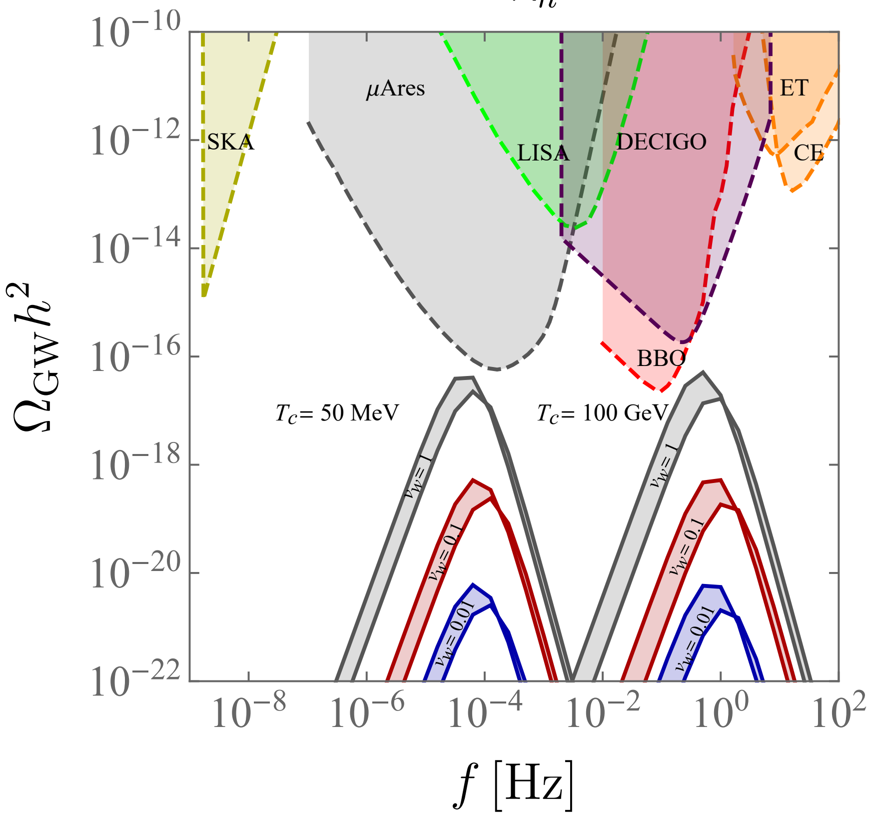
Computed thermal effective potential in improved holographic QCD

- Fit to reproduce finite T lattice data



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

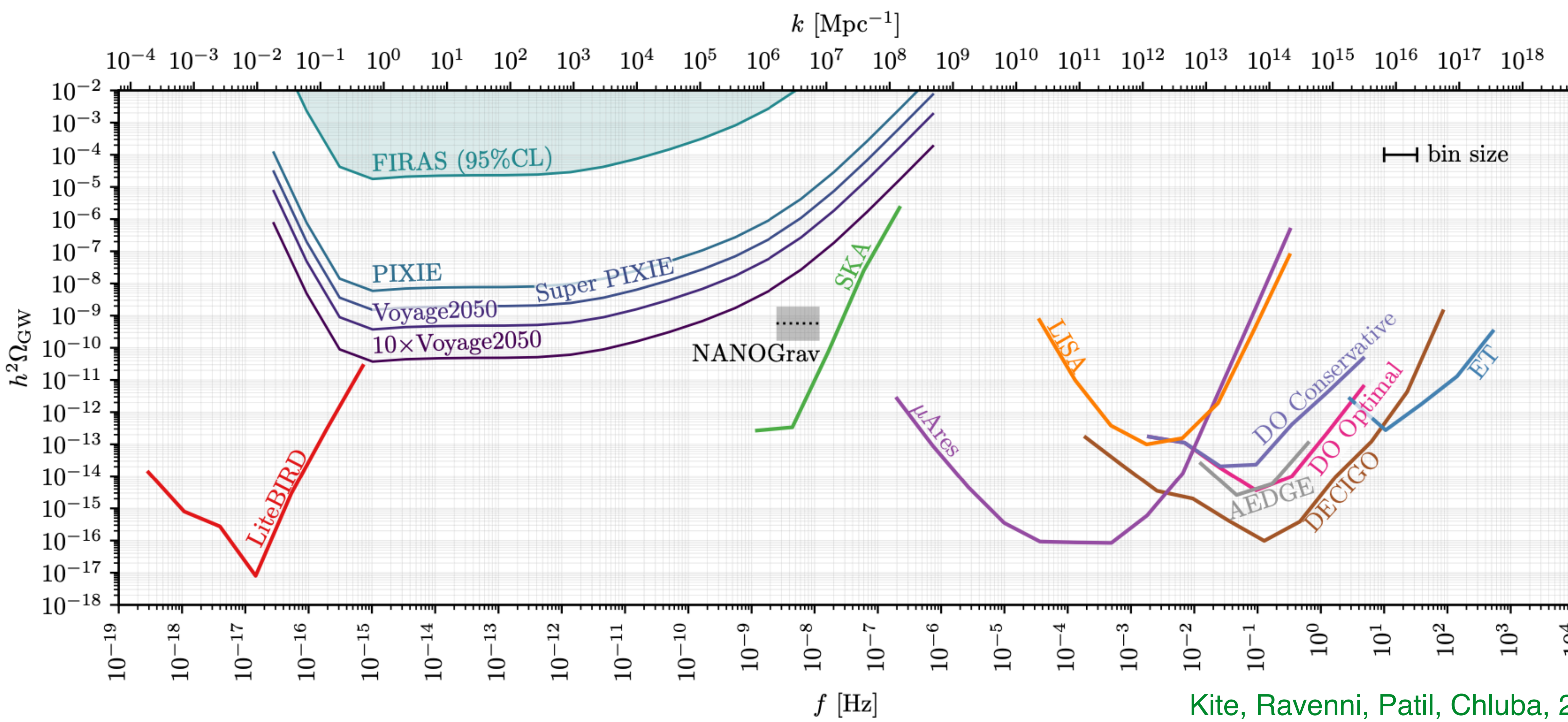
Enrico Morgante, Nicklas Ramberg, PS, in preparation



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)

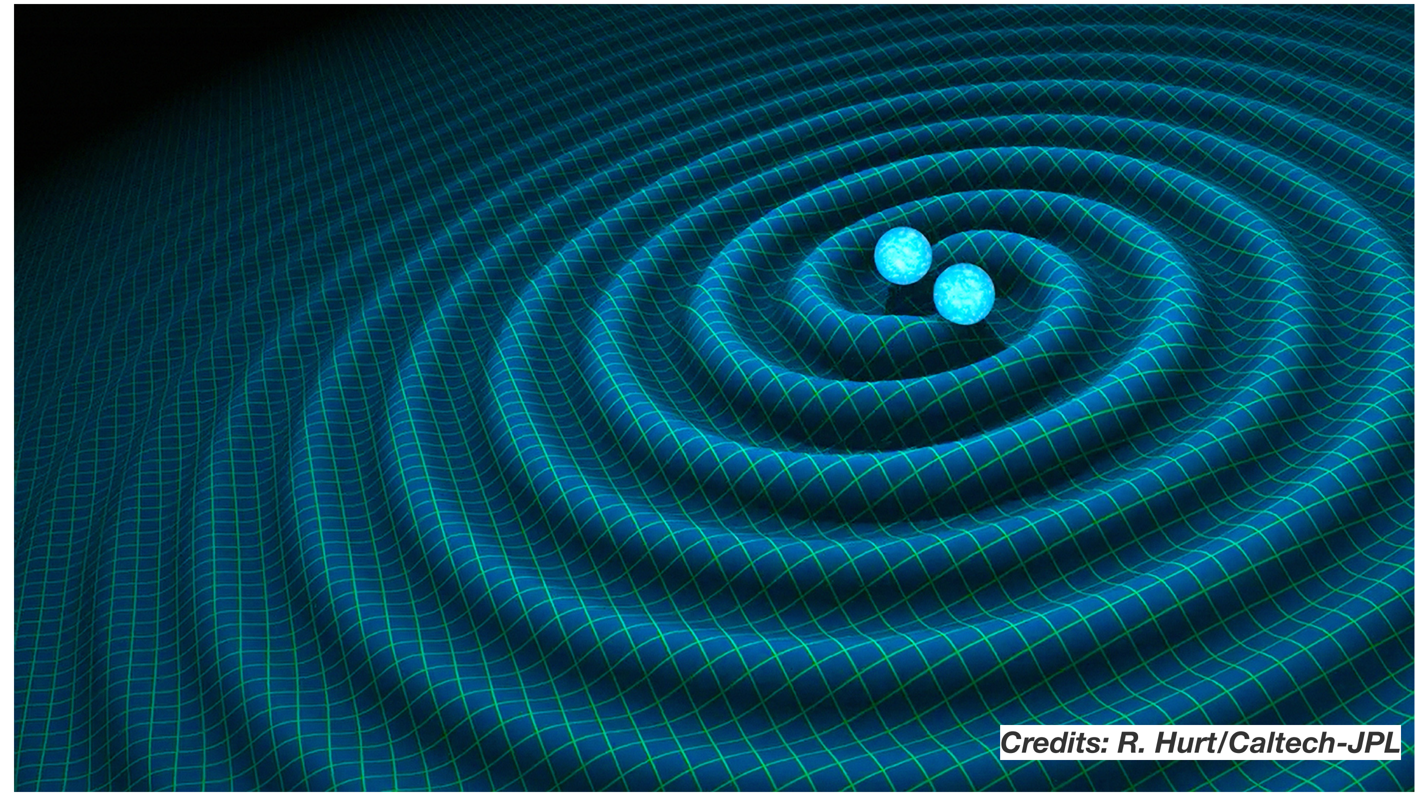
Gravitational waves as messengers from the early Universe

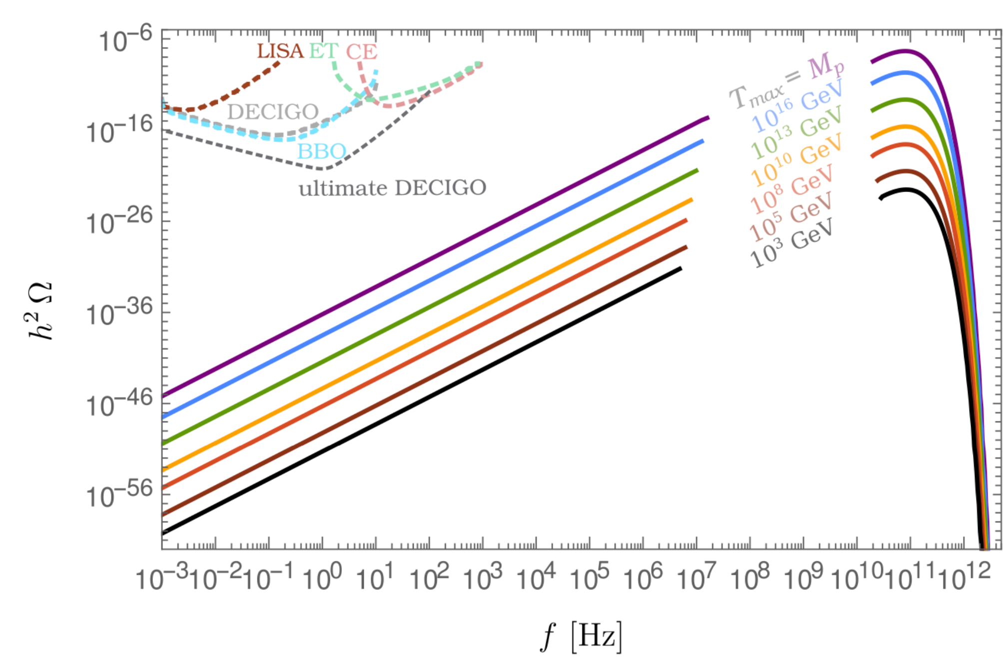
Travel undisturbed from earliest times

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