EXPLORING THE NON-EQUILIBRIUM EARLY UNIVERSE: FROM GRAVITATIONAL WAVES TO SPECTRAL DISTORTIONS

Pedro Schwaller

Mainz University

Cluster of Excellence PRISMA+

Particle and Astroparticle Physics Colloquium in Hamburg

DESY

January 24, 2023

Overview

Messengers from the early Universe

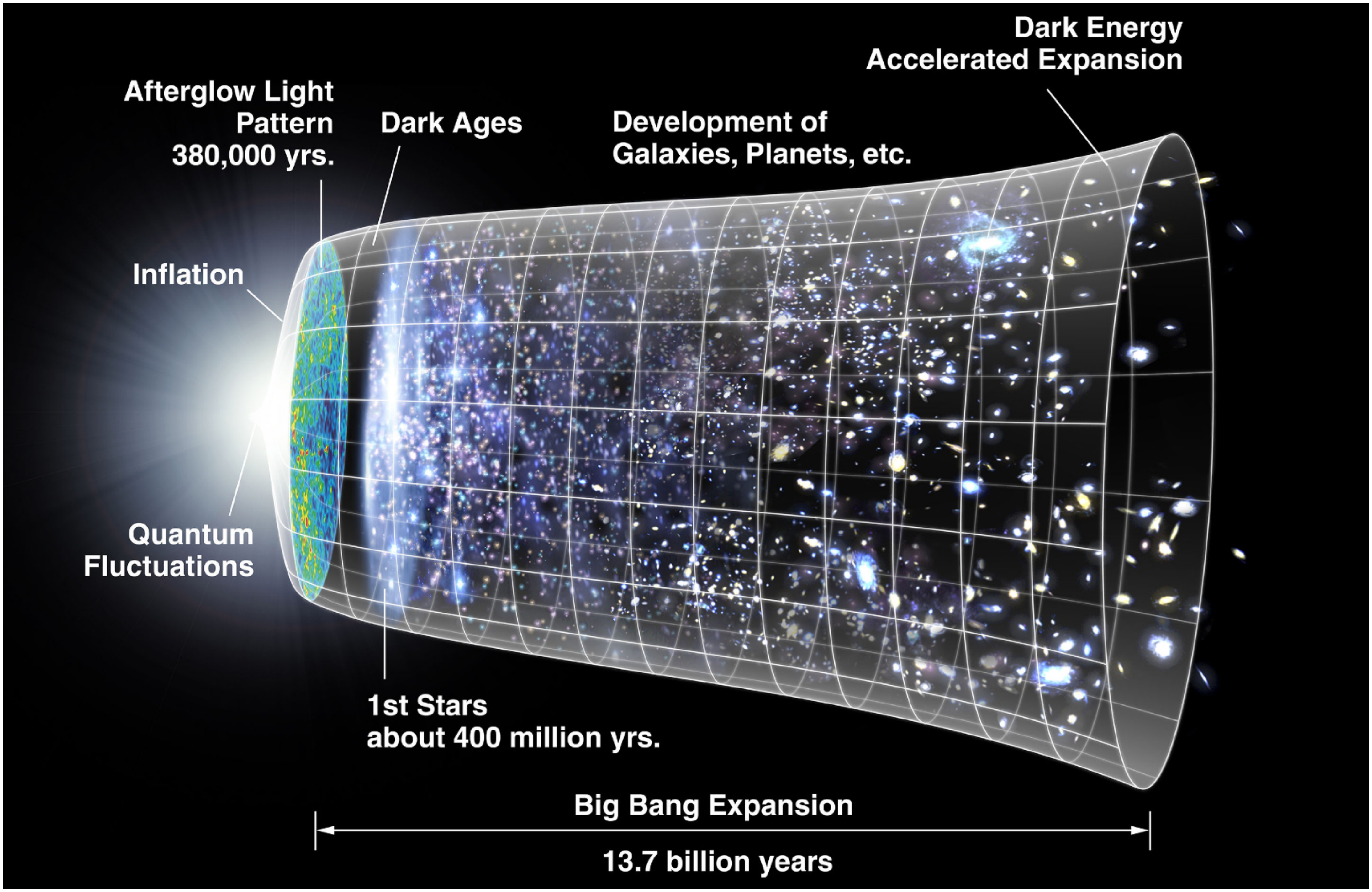
- Gravitational waves
- (Distortions of the) Cosmic microwave background

Messages from non-equilibrium physics

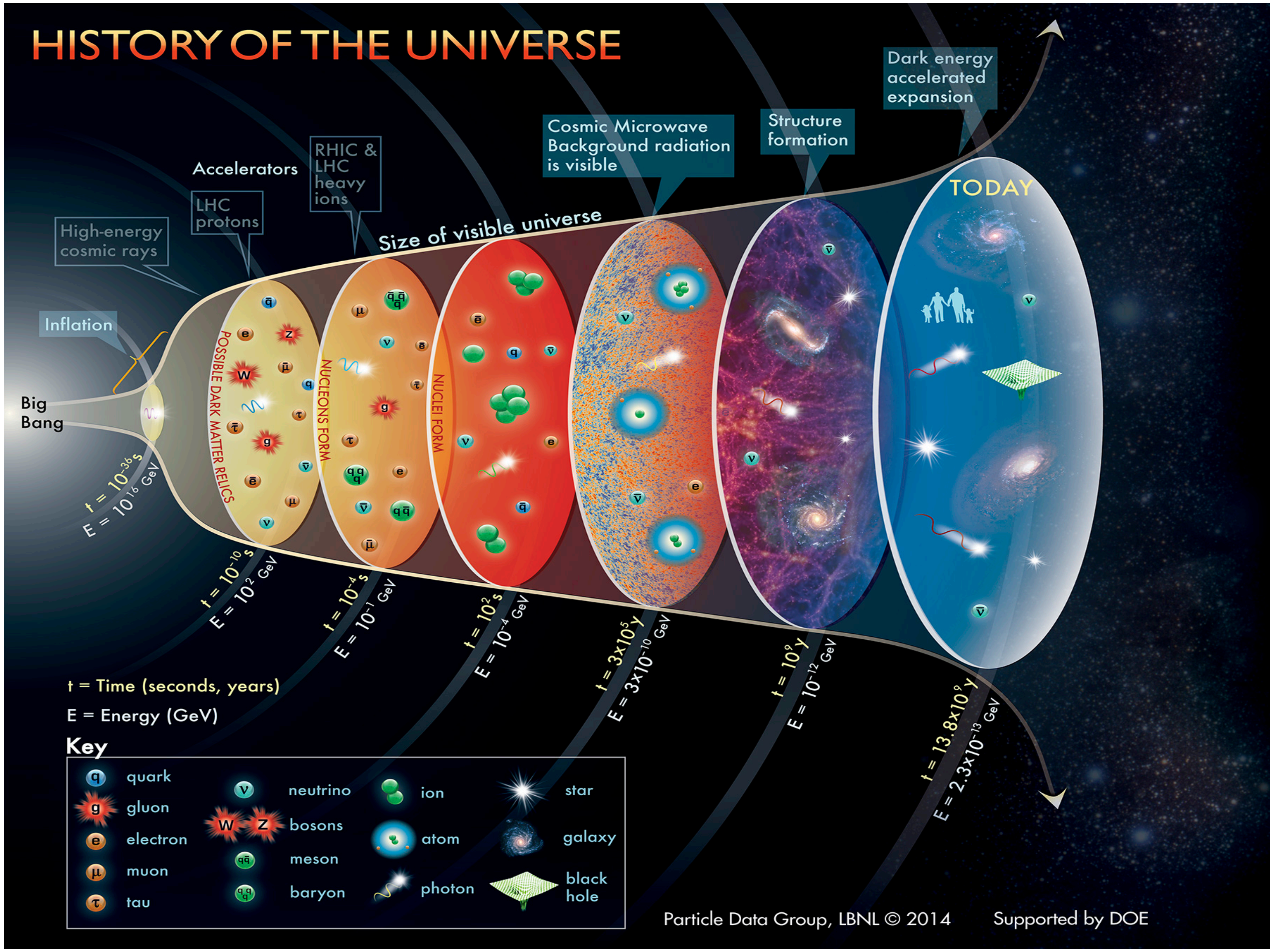
- Phase transitions
- Axion/scalar field dynamics, strings, domain walls, …

What do we know about the early Universe?

Thermal history



Thermal history and particle physics

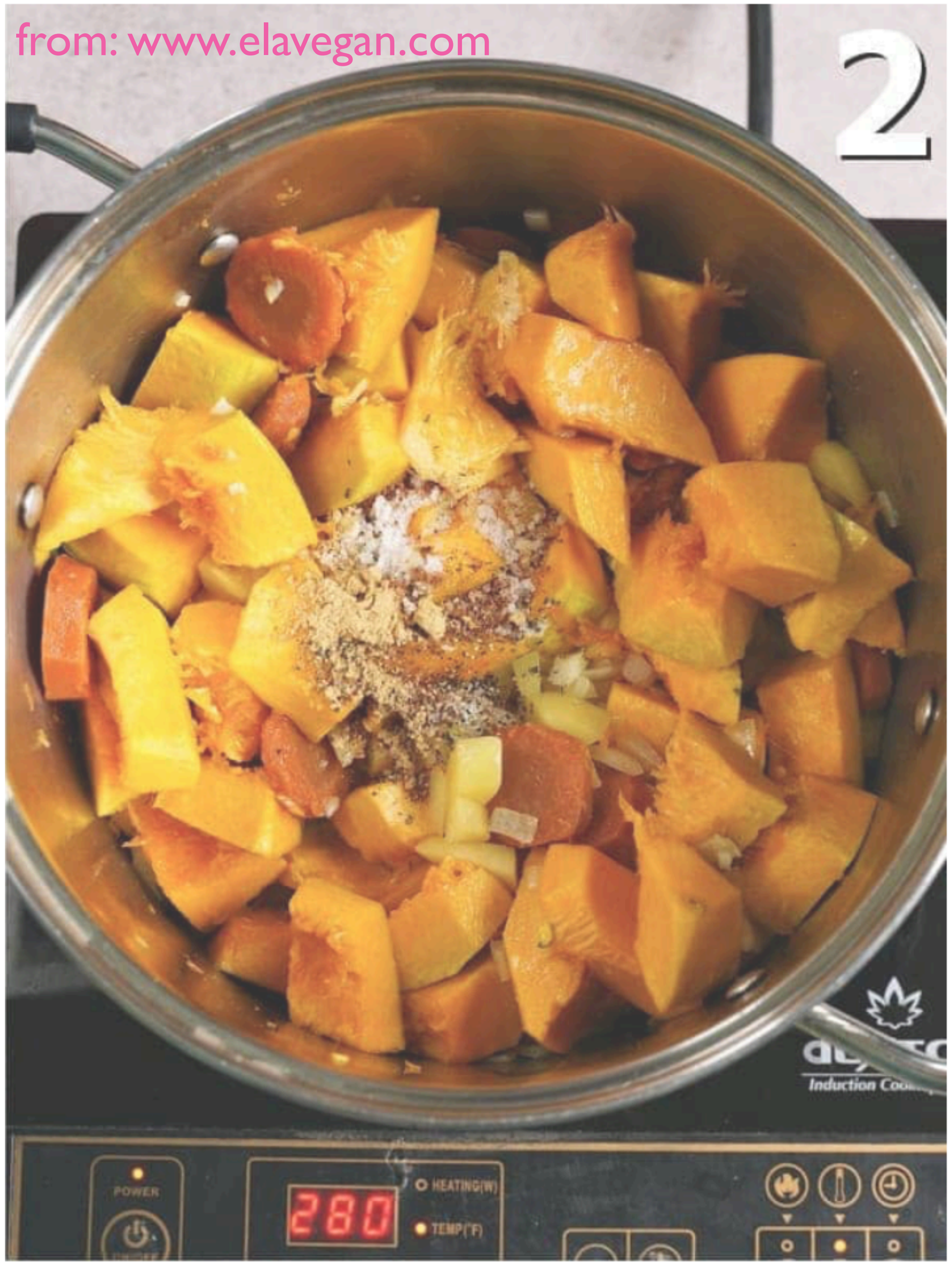


Thermal history and particle physics

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

The early Universe soup



The early Universe soup

The early Universe soup

How to identify ingredients

Taste

- i.e. study Universe today

Smell in kitchen

- Cosmic microwave background

Splashes in kitchen

- Gravitational Waves (from phase transitions)

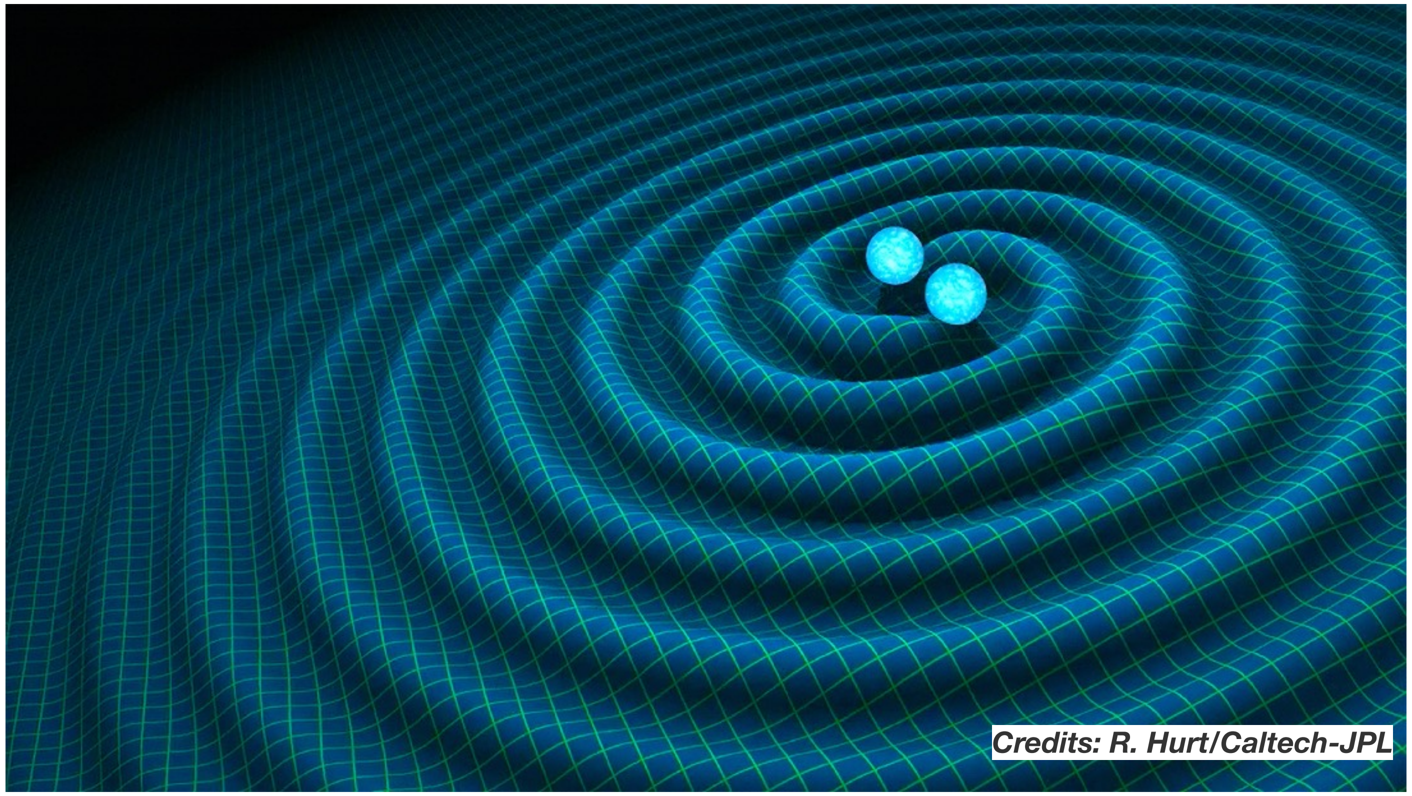
Messengers I: Gravitational waves

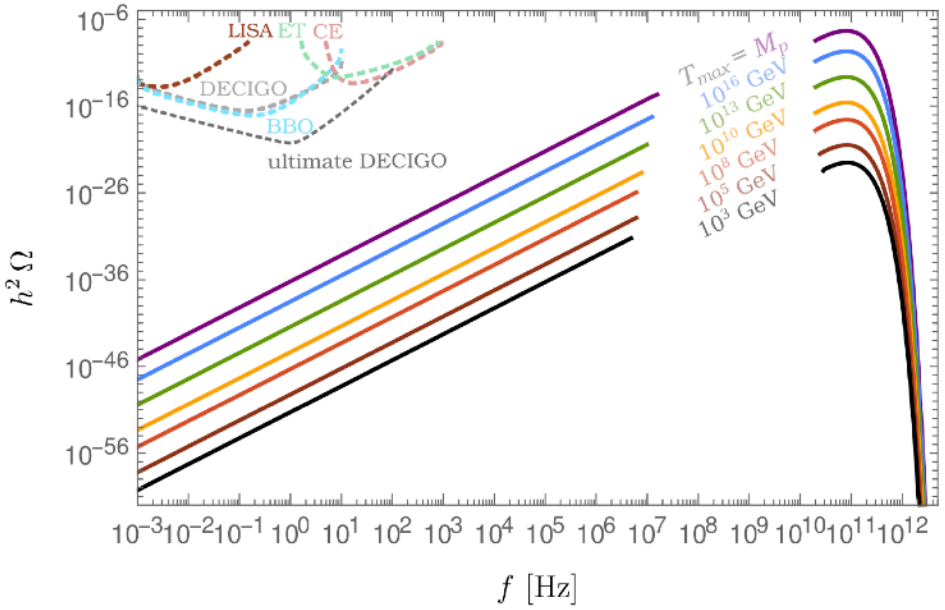
Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background

Or with very very (very!) high temperatures





From Ringwald, Schütte-Engel, Tamarit, 2020

Messengers II: Photons

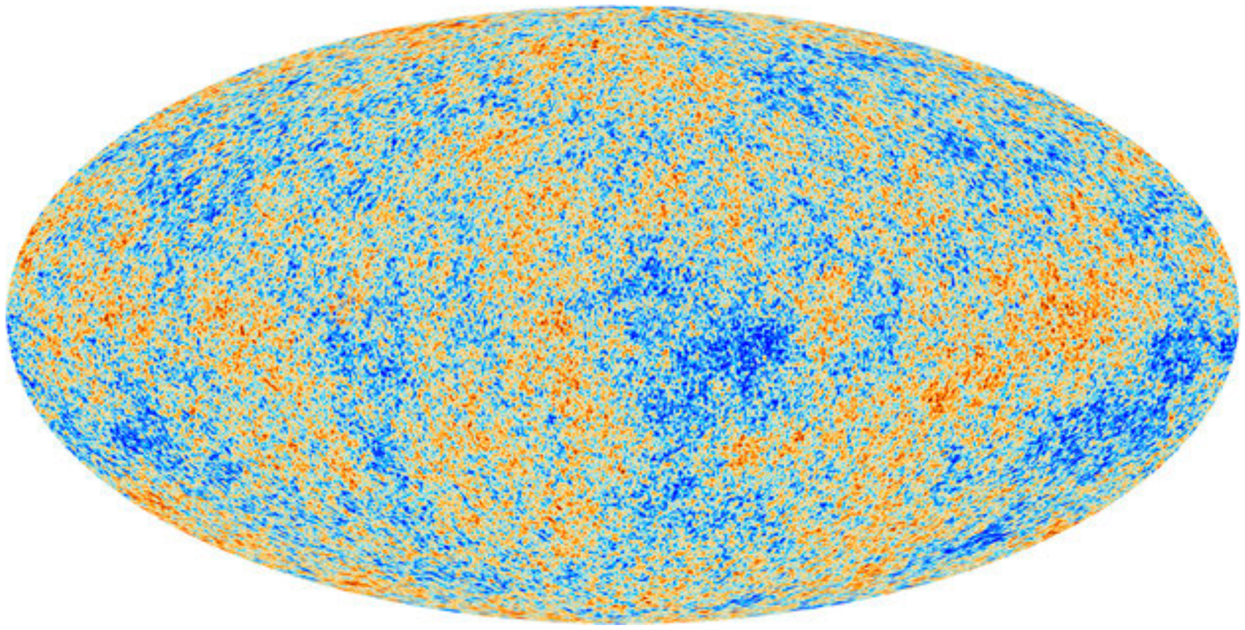
Emitted at $T \sim 1\,\mathrm{eV}$

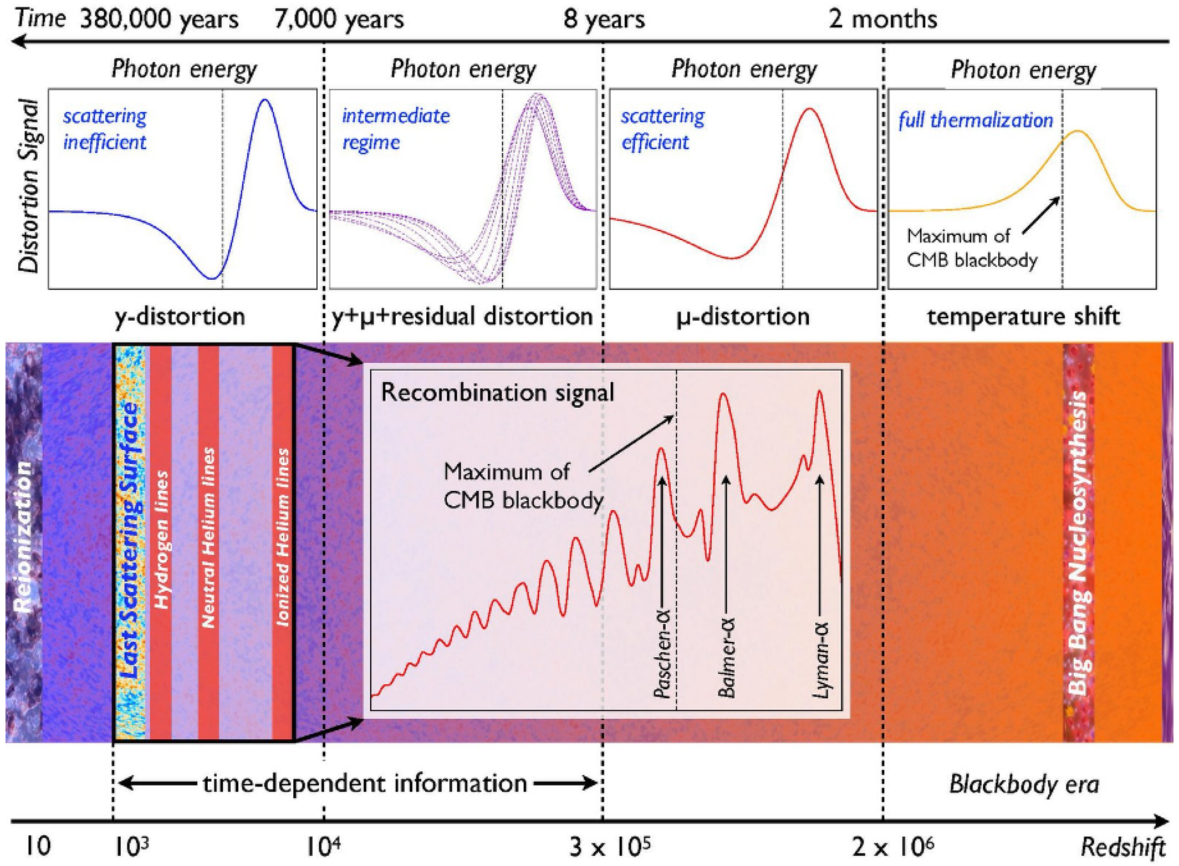
Equilibrium phyiscs

- almost perfect black body spectrum

Non-equilibrium physics can distort the spectrum

- Probe of $\mathrm{keV} - \mathrm{MeV}$ temperatures





Non-equilibrium in the early Universe

GWs from Phase Transitions

QFT at finite temperature ➞ symmetry restoration

For first order PT

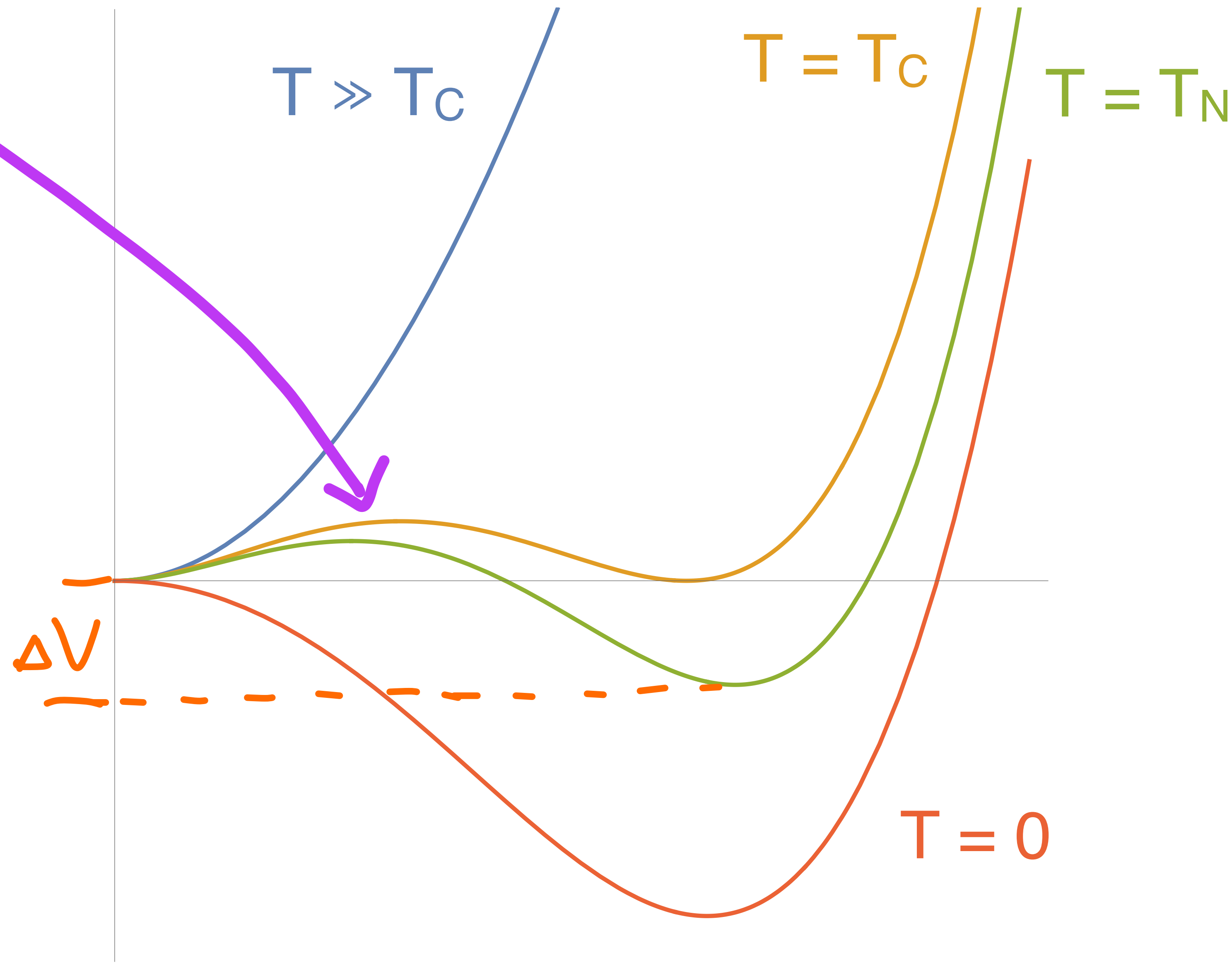
- Need barrier here

PT occurs at T_N

Potential energy

GWs

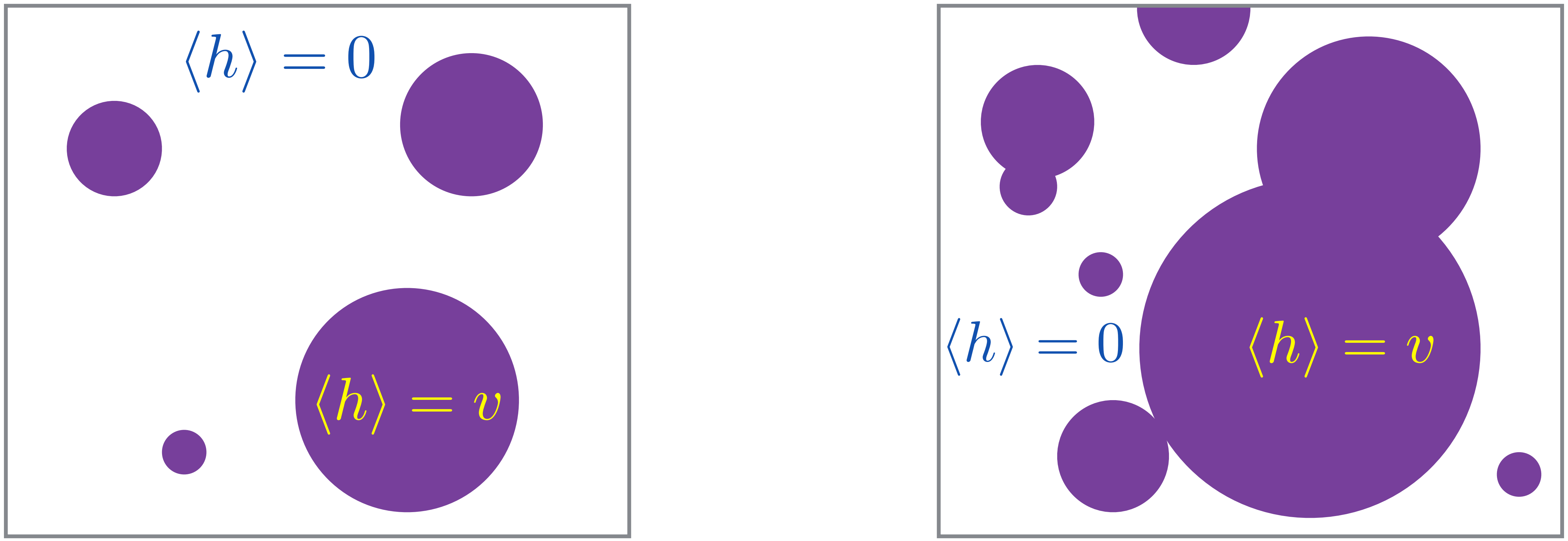
Not in SM! Possible in
 BSM scenarios



GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

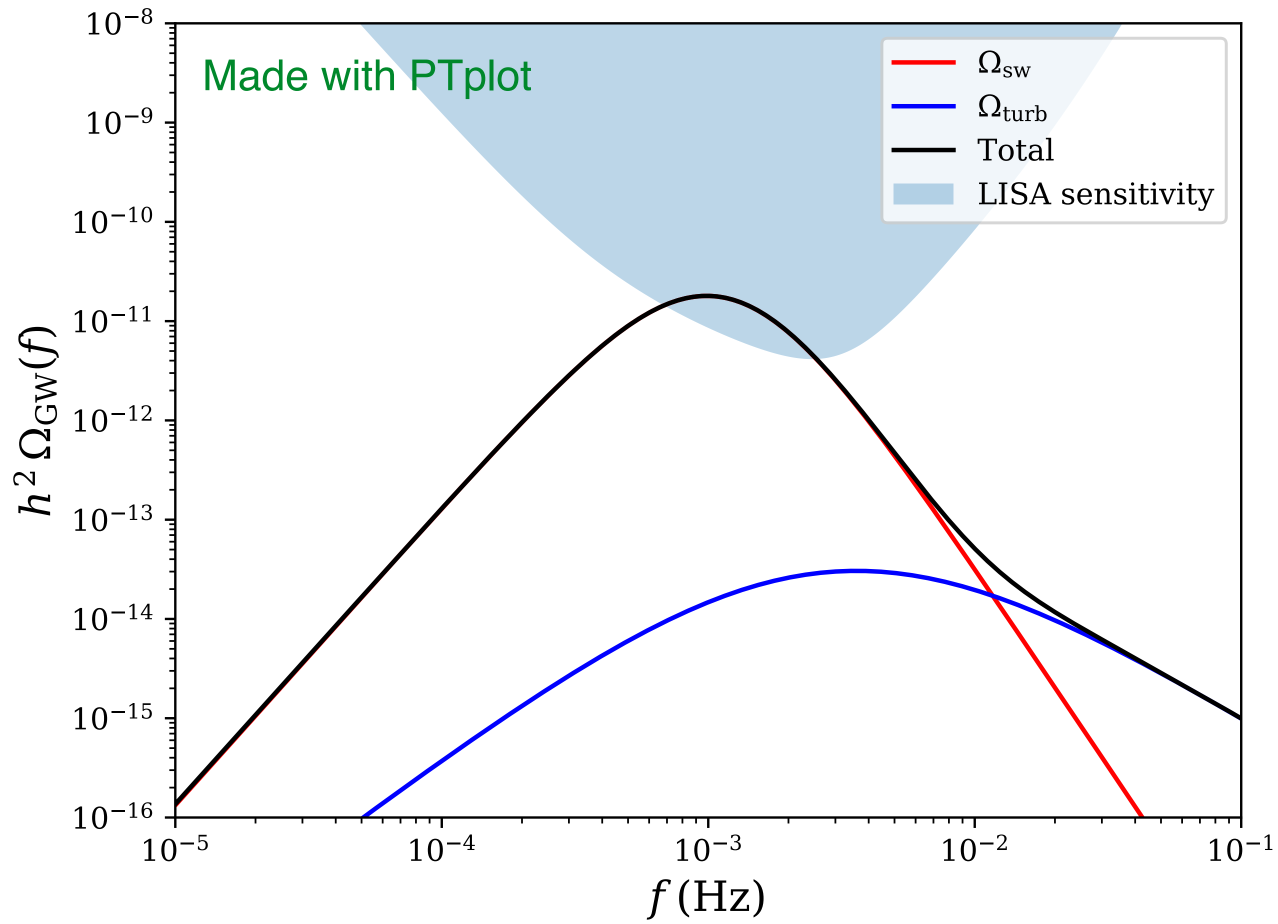
Bubble collisions → Gravitational Waves



PT signal

PT characterised by few parameters:

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

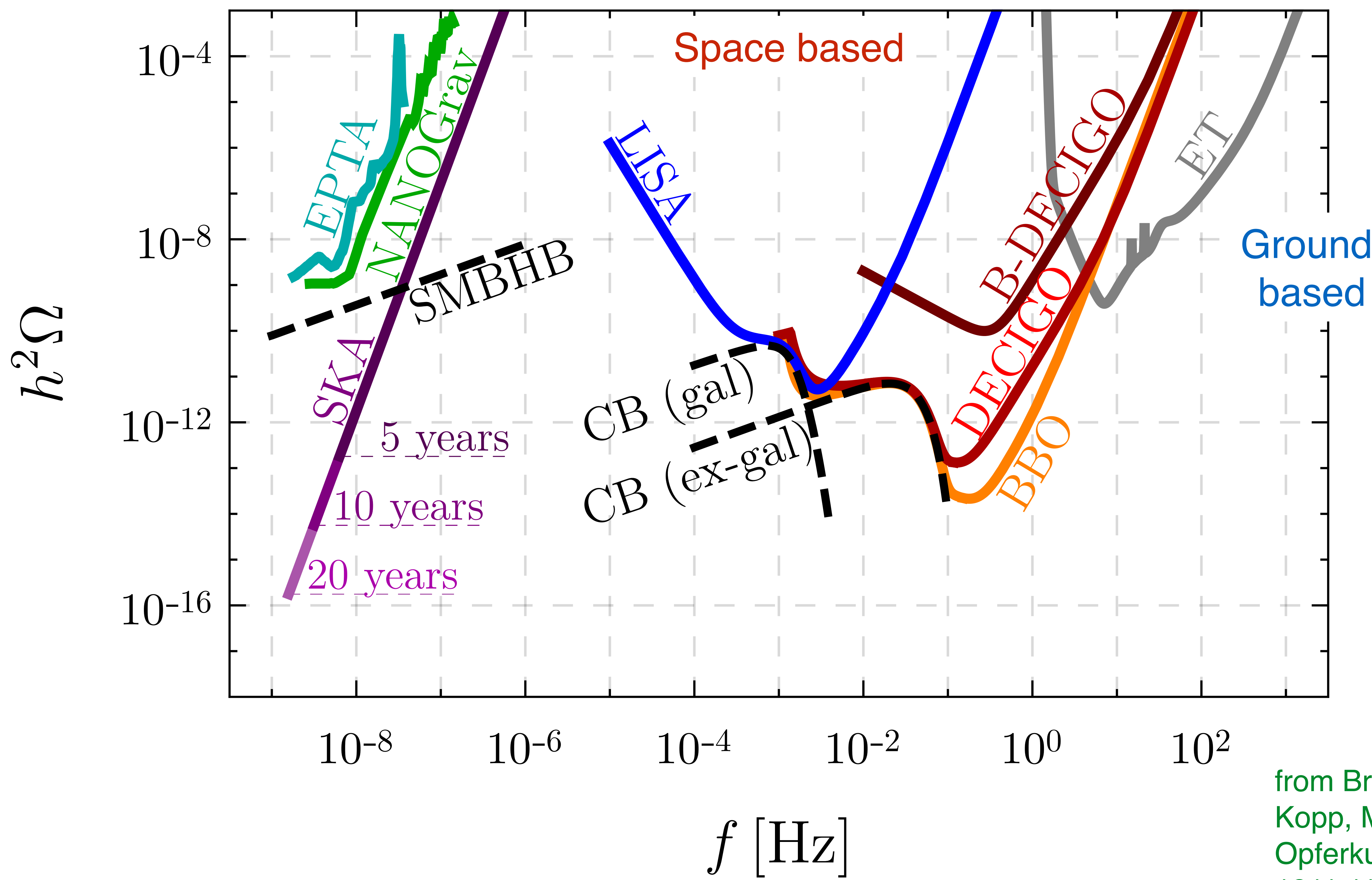


More details, see e.g.:

Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Frequency ranges

New physics scale GeV TeV PeV

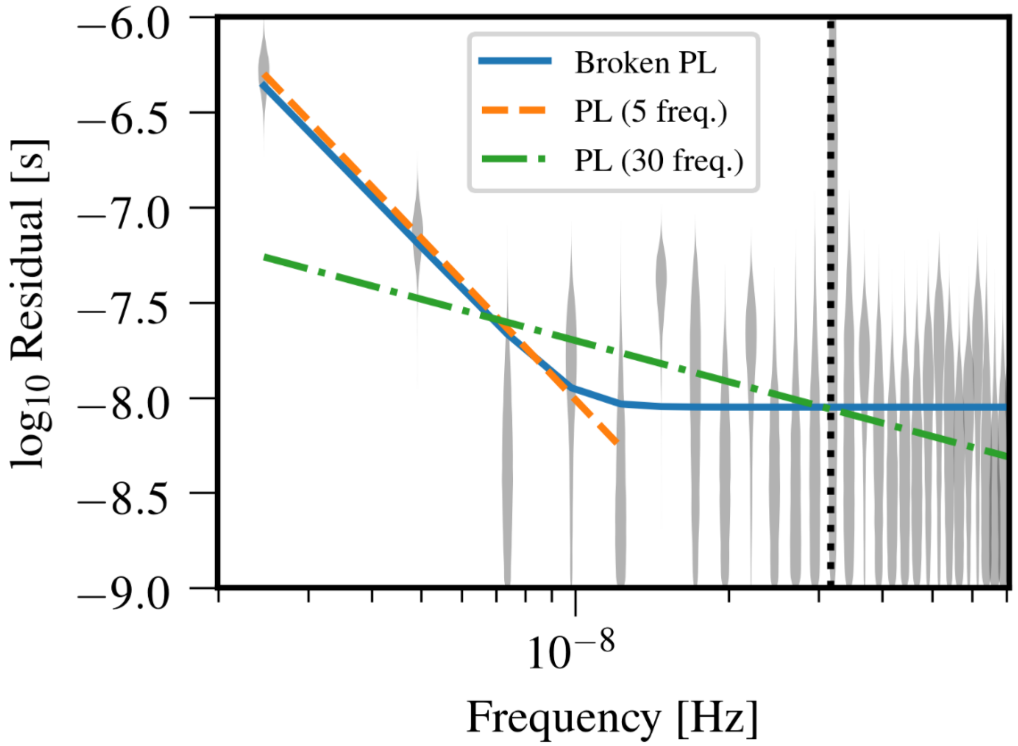


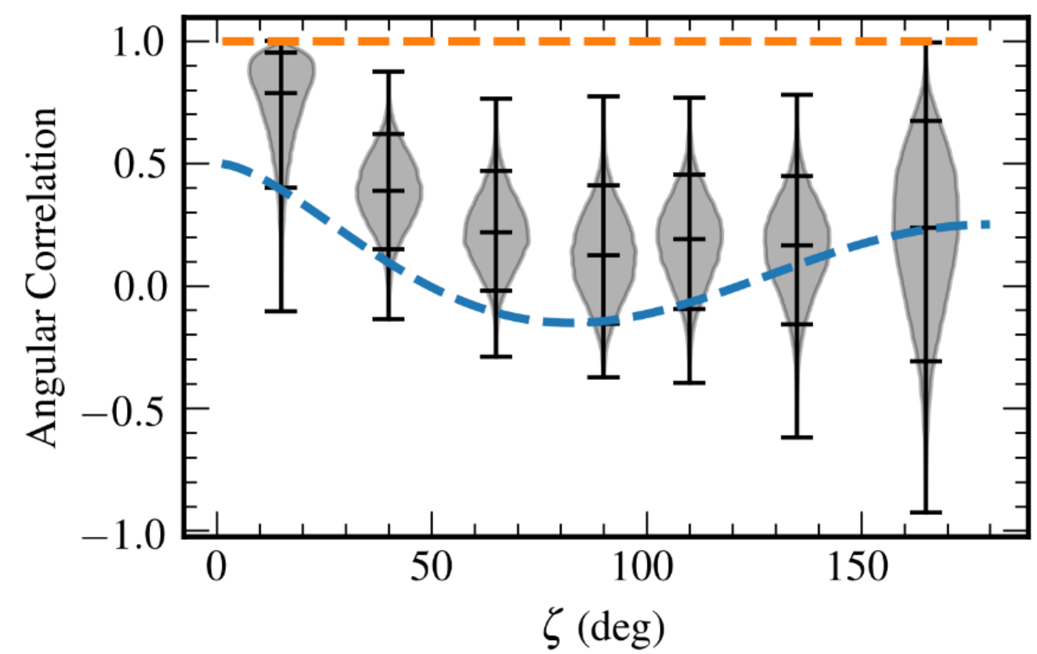
from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

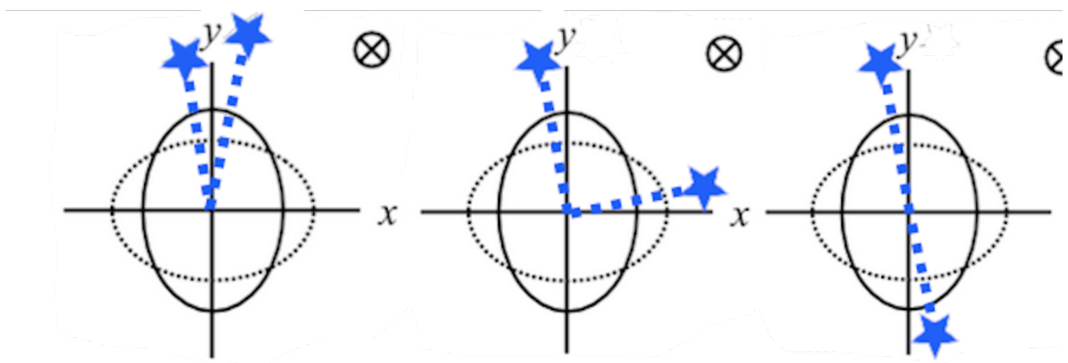
NANOGrav saw something!

No 4σ evidence for Quadrupole

Significant Strain at low frequencies



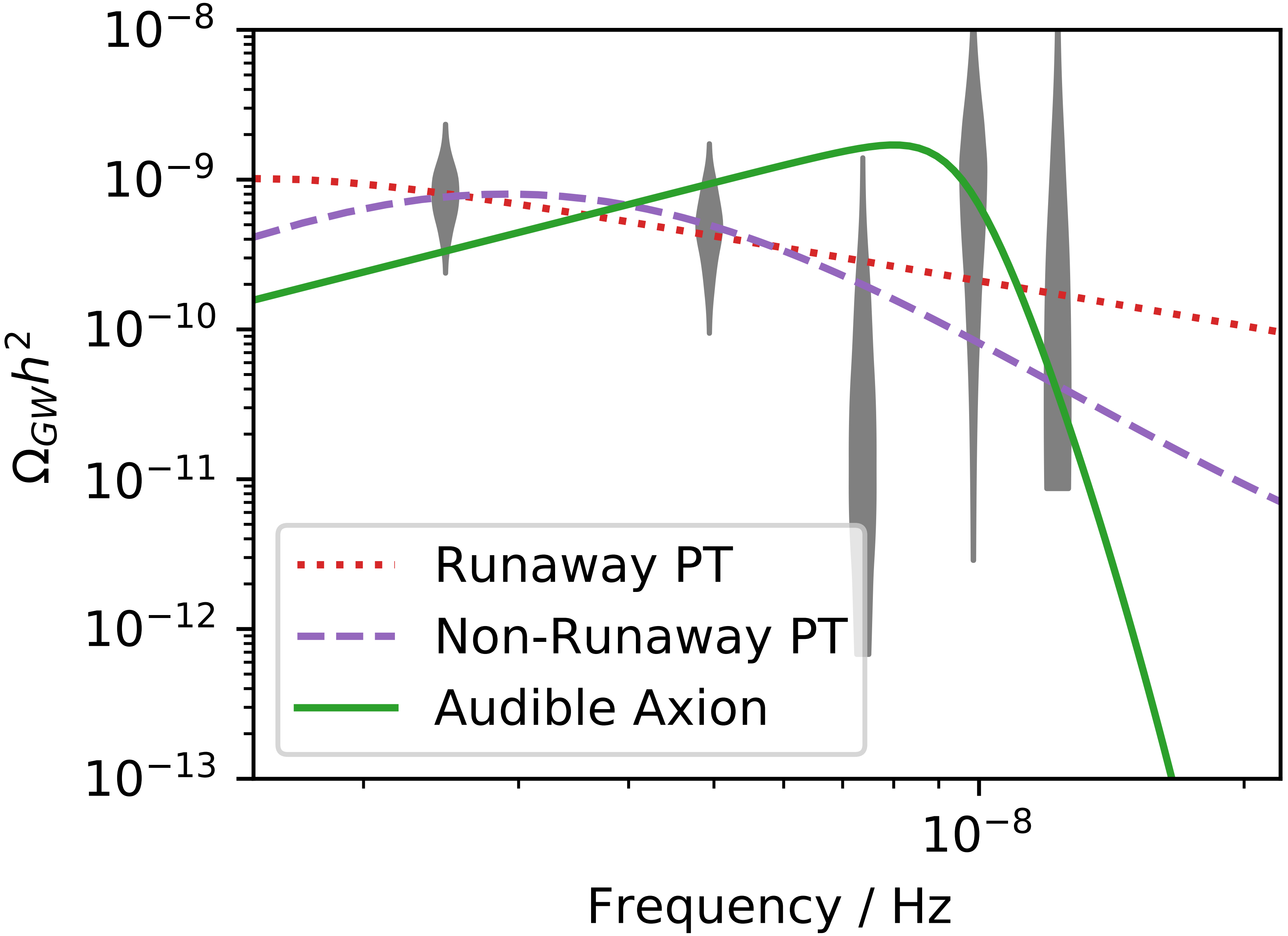




From NANOGrav collaboration, 2009.04496

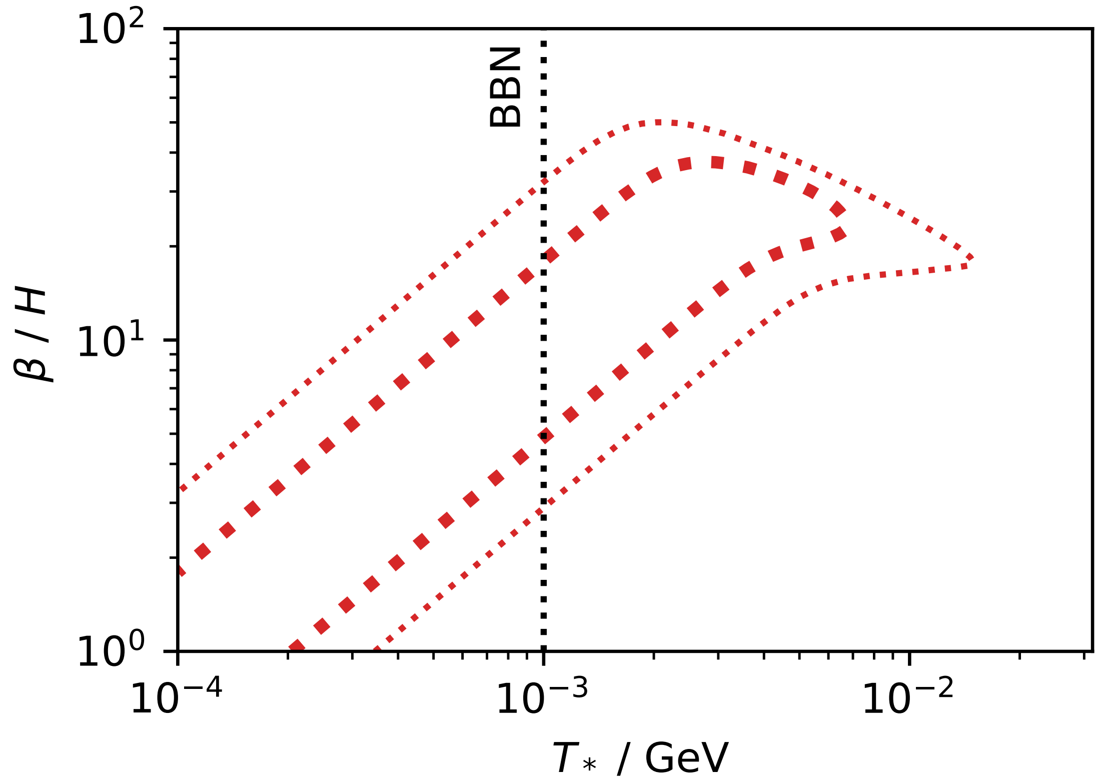
Now also consistent signals in PPTA, EPTA and IPTA - still not fully conclusive though

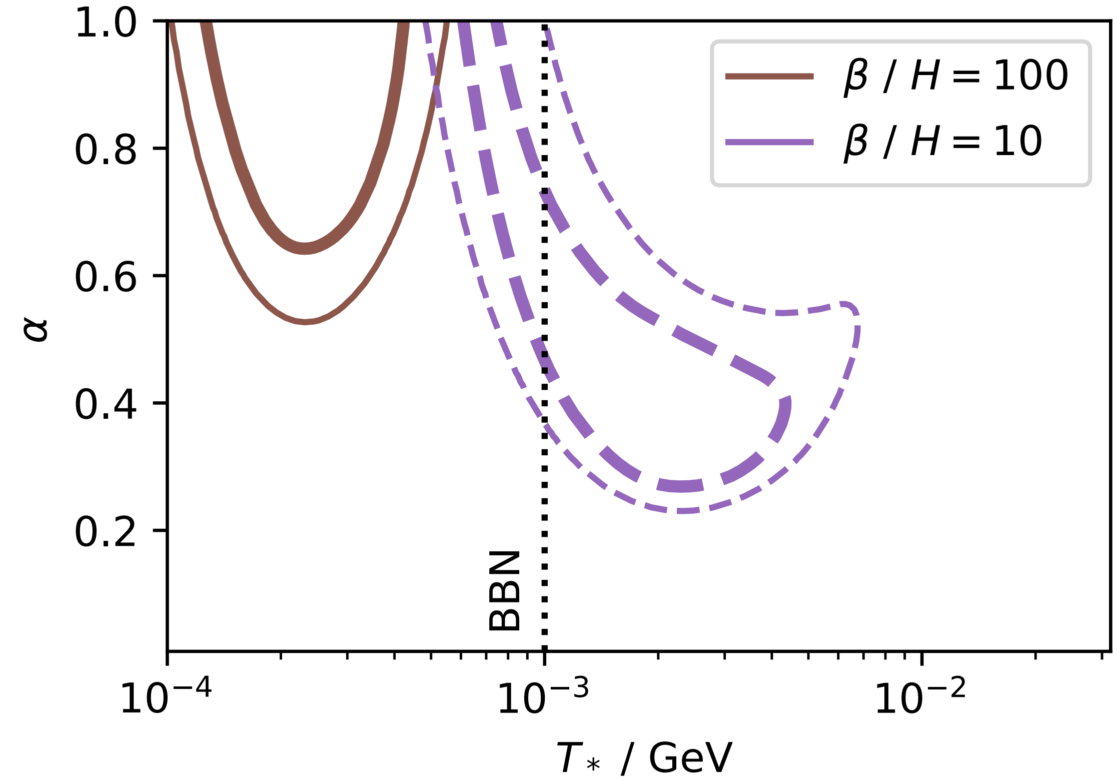
Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



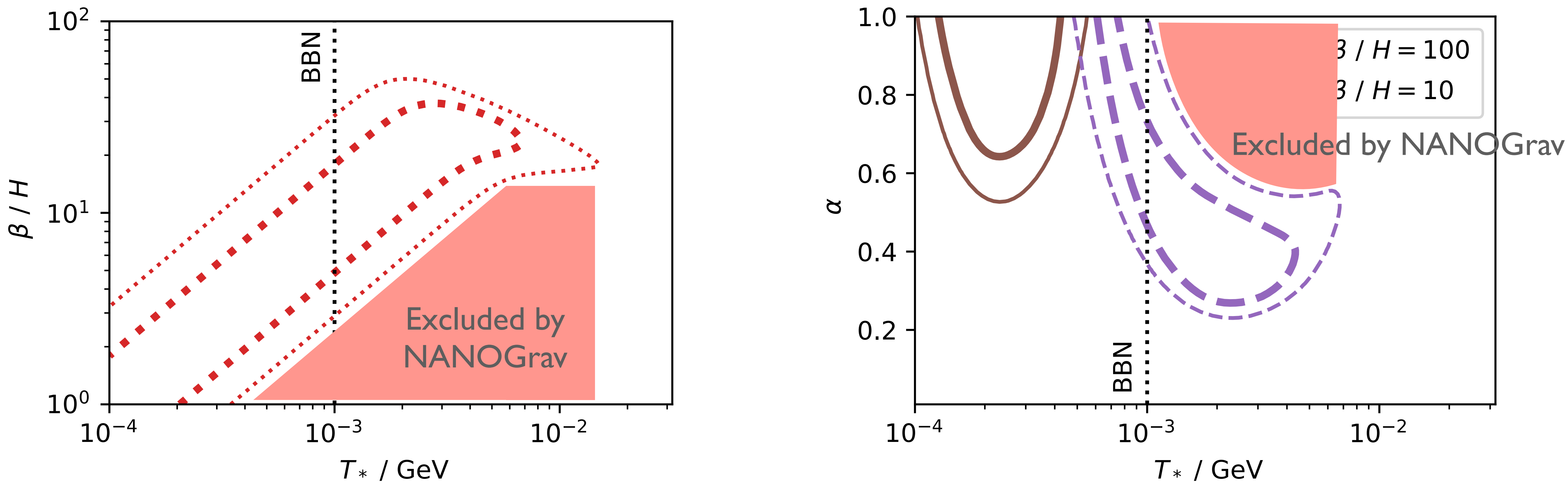


Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Challenge for model building → Hint for dark sector

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

QCD-like dark sectors

The new physics should be light and hidden

QCD-like dark sector can naturally have $\Lambda_d \sim \mathrm{MeV}$

Confinement PT is first order for

- $N_d \geq 3$ and $n_f = 0$
- $N_d \geq 3$ and $3 \leq n_f \lesssim 4N_d$

Can this explain the NANOGrav/PTA data?

- Difficult question in itself due to strong coupling

Combine lattice and holography

Improved holographic QCD

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

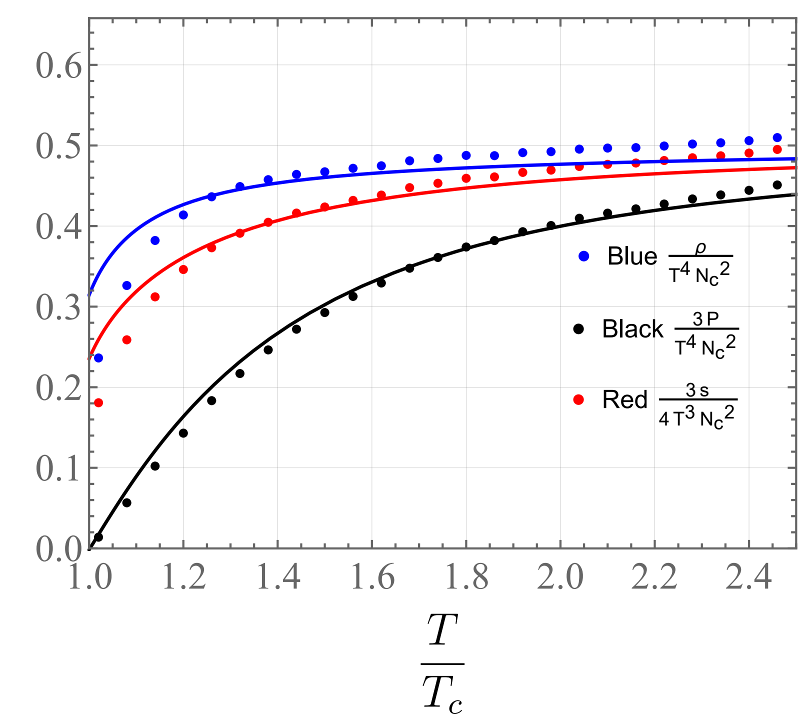
$$\mathcal{S}_5 = -M_P^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3} (\partial\Phi)^2 + V(\Phi) \right] + 2M_P^3 N_c^2 \int_{\partial M} d^4x \sqrt{h} K$$

Want this to reproduce SU(N) theories

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

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

- Parameters fit to match RGE in UV and lattice in IR!



Effective potential and bounce action

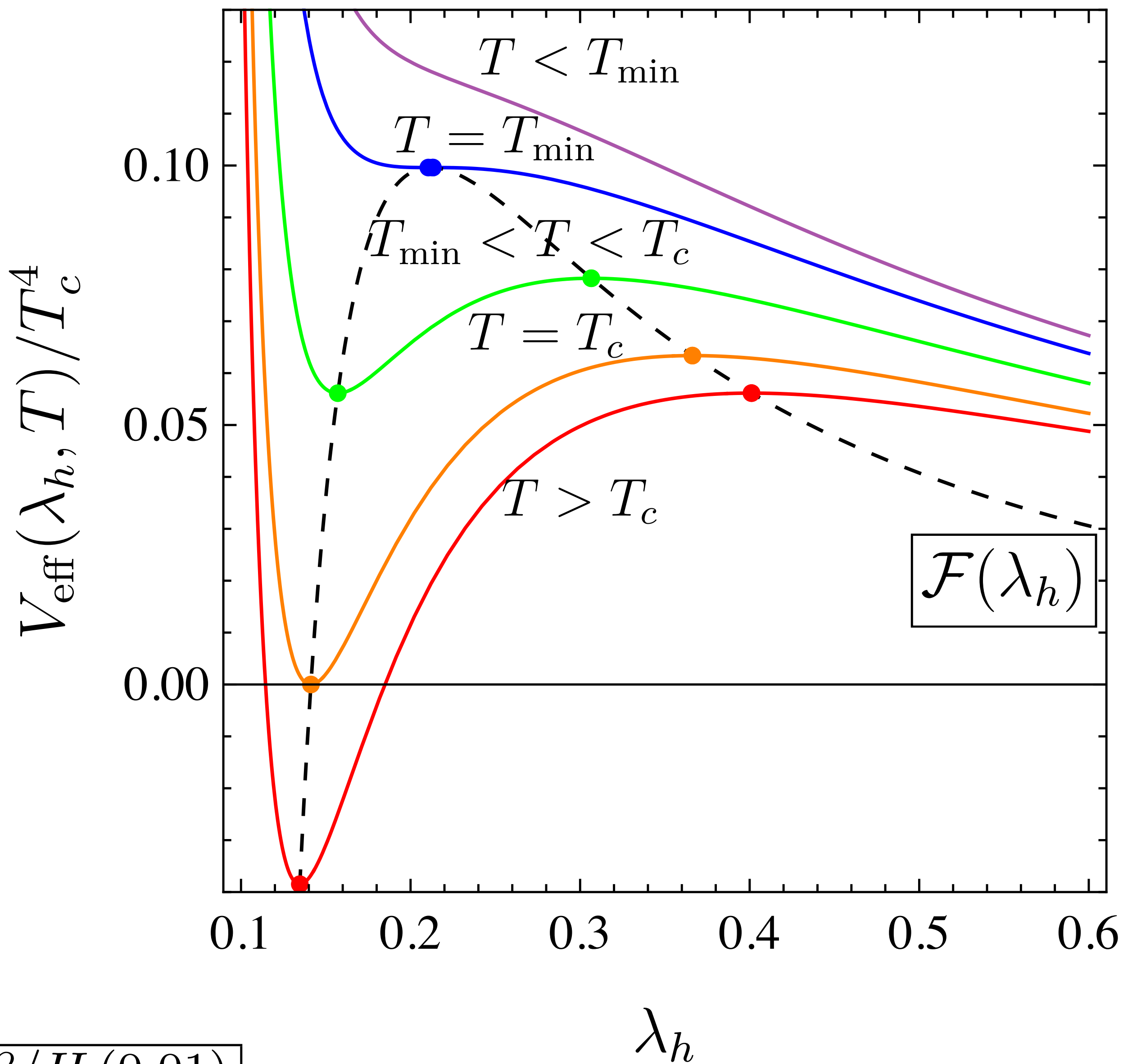
Bounce action

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

Tunneling decay rate

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

Allows us to compute α and β



	α	$\beta/H\ (v_w=1)$	$\beta/H\ (0.1)$	$\beta/H\ (0.01)$
$T_c = 50\,\text{MeV}$	0.343	$9.0\ \times 10^4$	8.6×10^4	8.2×10^4
100 GeV	0.343	6.8×10^4	6.4×10^4	6.1×10^4

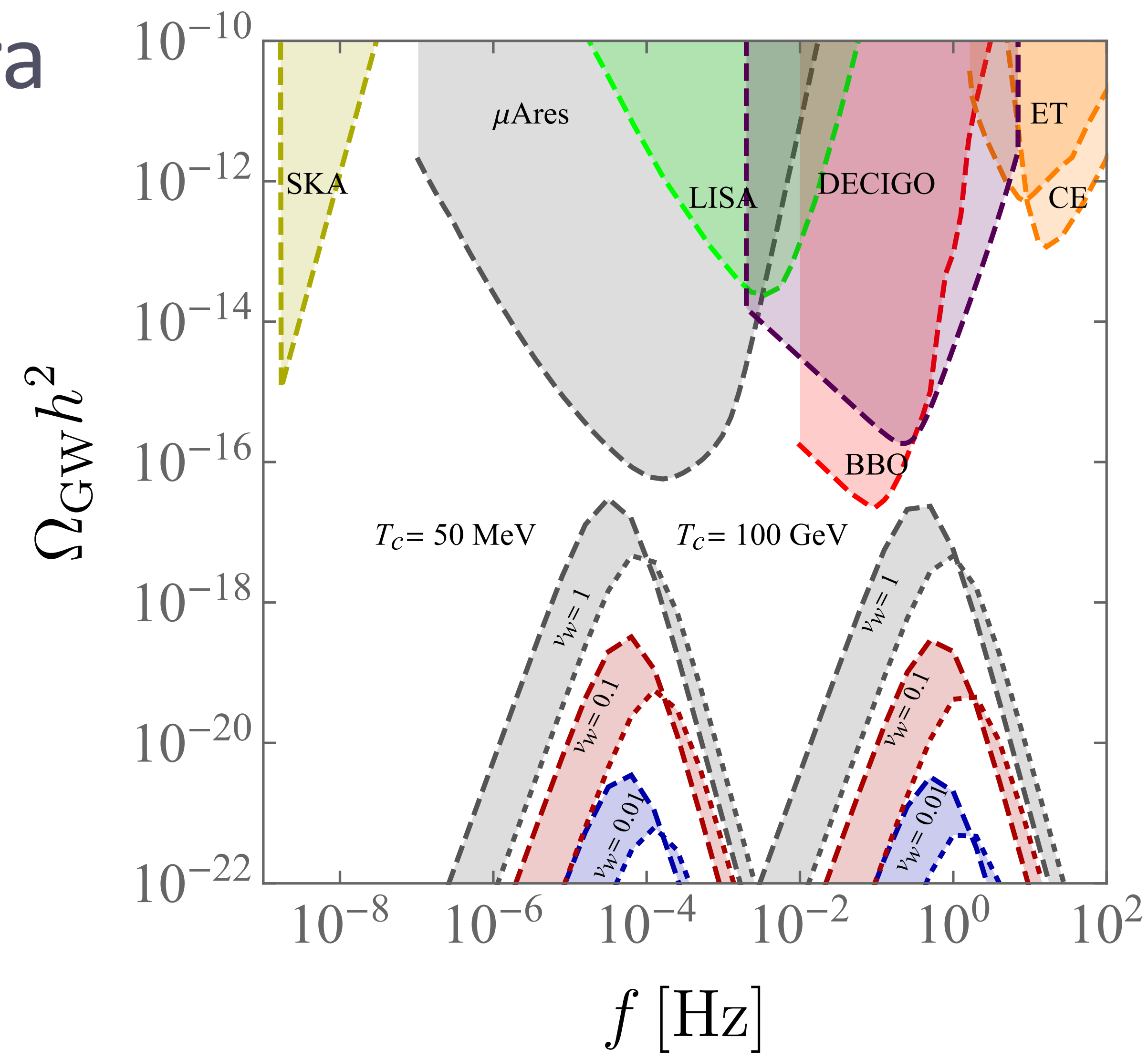
Morgante, Ramberg, PS, 2210.11821

GW spectrum

Morgante, Ramberg, PS, 2210.11821

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

- for $N_c = 3, n_f = 0$
- Some work remains (wall velocity)
- Larger signal possible for larger N_c, n_f
- Agrees with estimates based on effective theories and lattice data (e.g. Halverson+ 2012.04071, Huang+ 2012.11614, March-Russell+ 1505.07109)



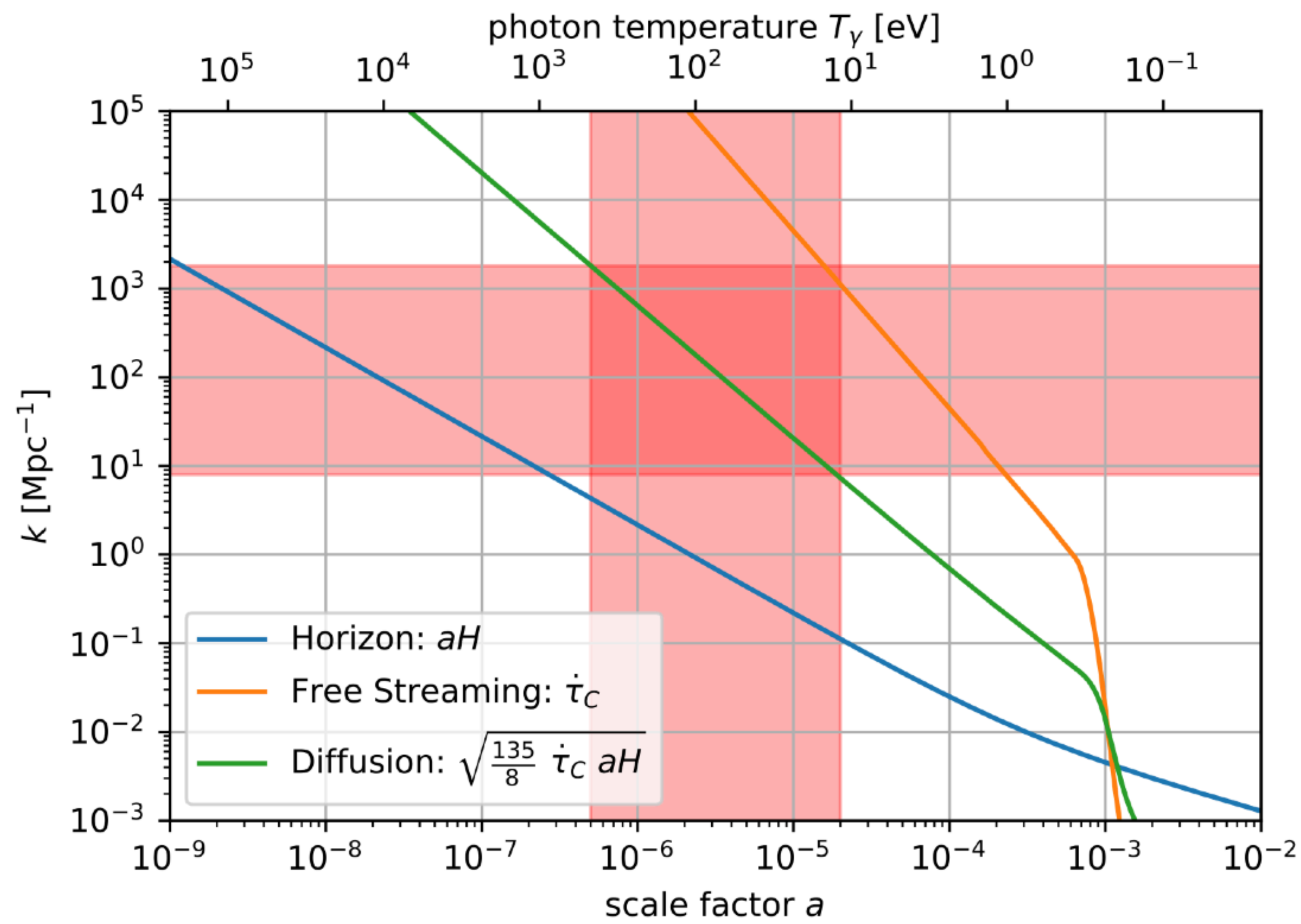
Now what about the spectral distortions?

Spectral distortions?

Around $10^4 \lesssim z \lesssim 10^6$, photon number is frozen

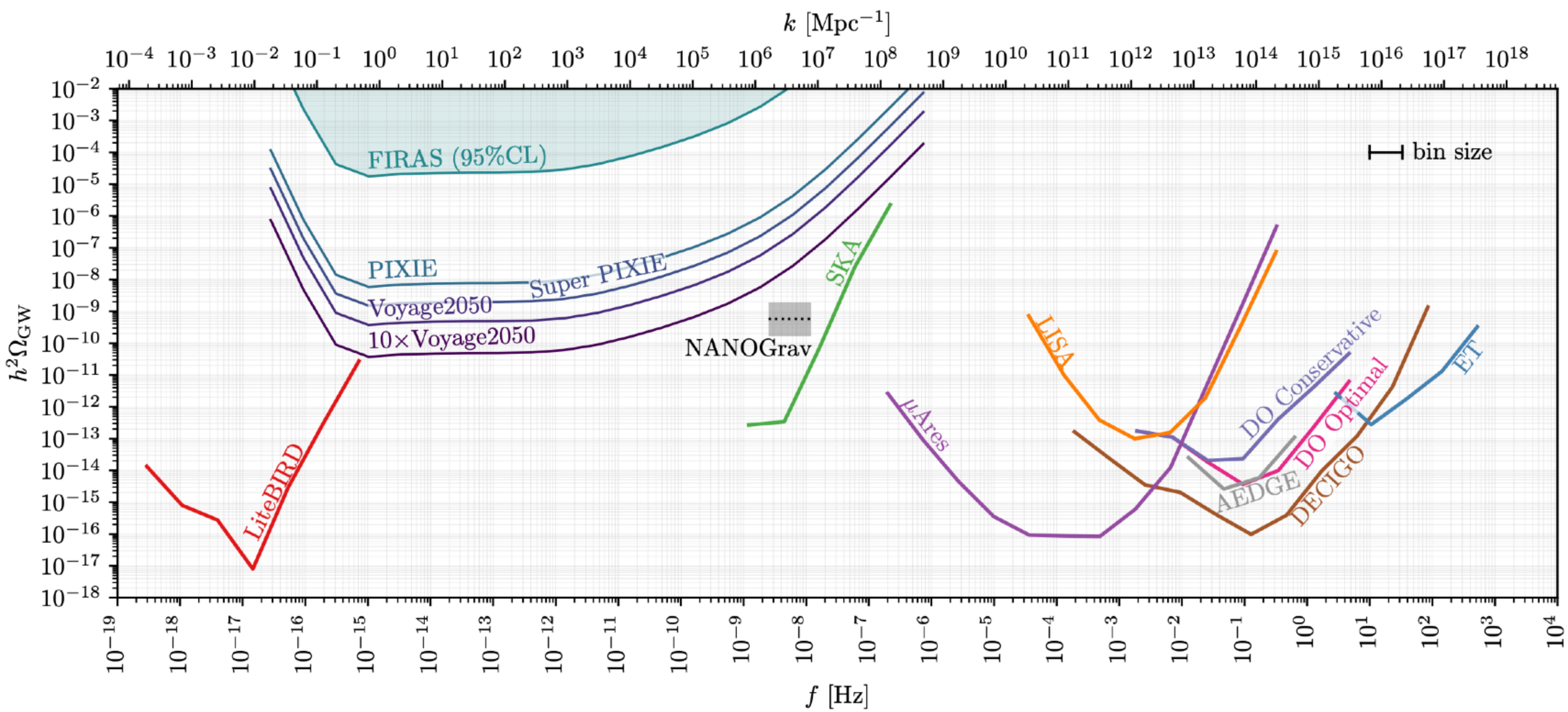
Any energy added to the photons leads to a so called μ distortion

Energy source we consider here: Gravitational damping of dark sector fluctuations



Ramberg, Ratzinger & PS, 2209.14313

Spectral distortions as probes of low scale GWs



From Kite, Ravenni, Patil, Chluba, MNRAS 2021

Tensor fluctuations (GWs) also source μ distortions

- But difficult to test. Better to directly go for the scalar fluctuations (that also source the GWs)

Spectral distortions from dark sector anisotropies

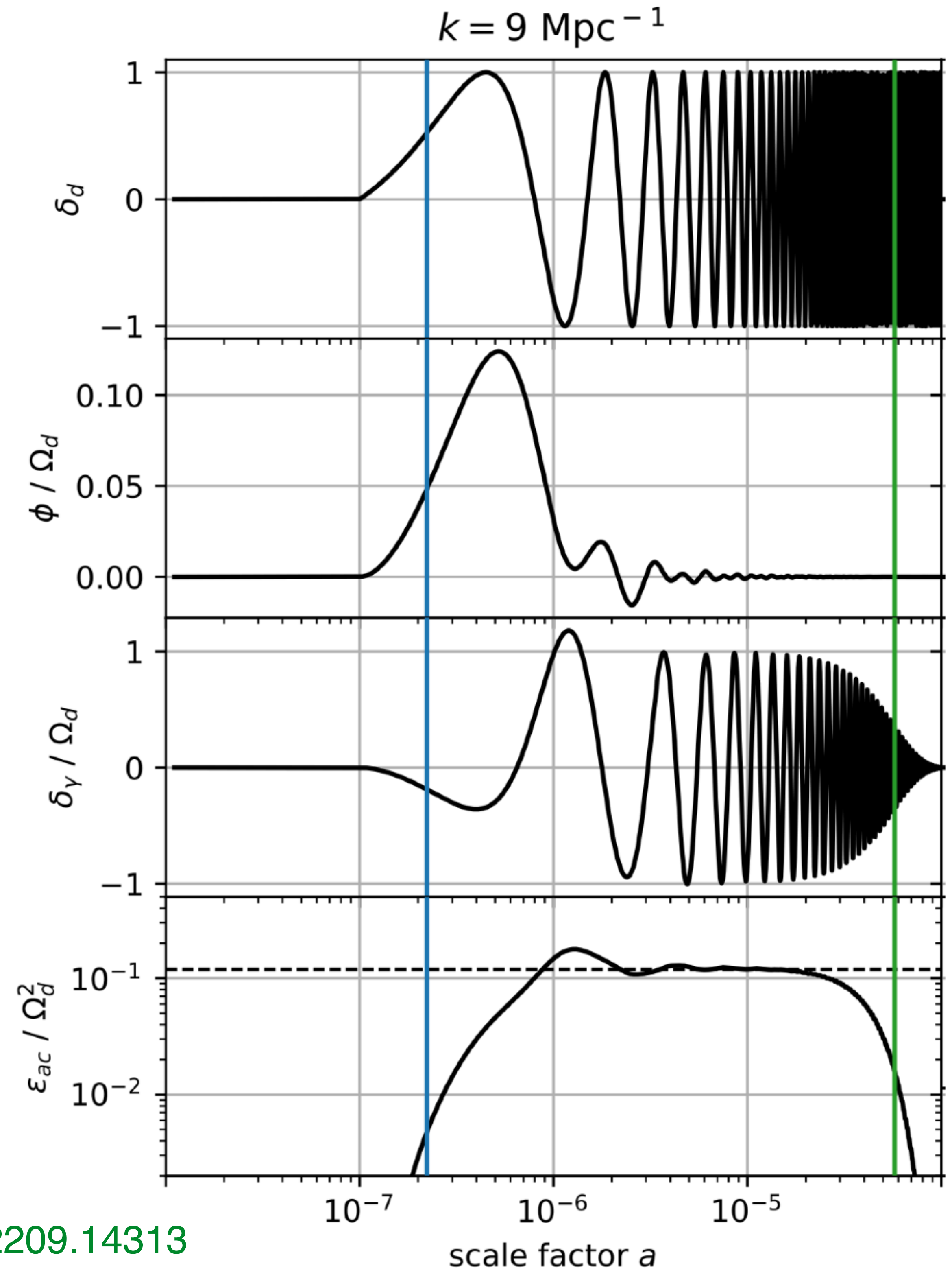
Assume decoupled dark sector, $\Omega_d \ll 1$

Large fluctuations $\delta_d = \delta\rho_d/\rho_d \sim 1$

- Gravitationally induced sound waves in photons $\epsilon_{\rm ac}$

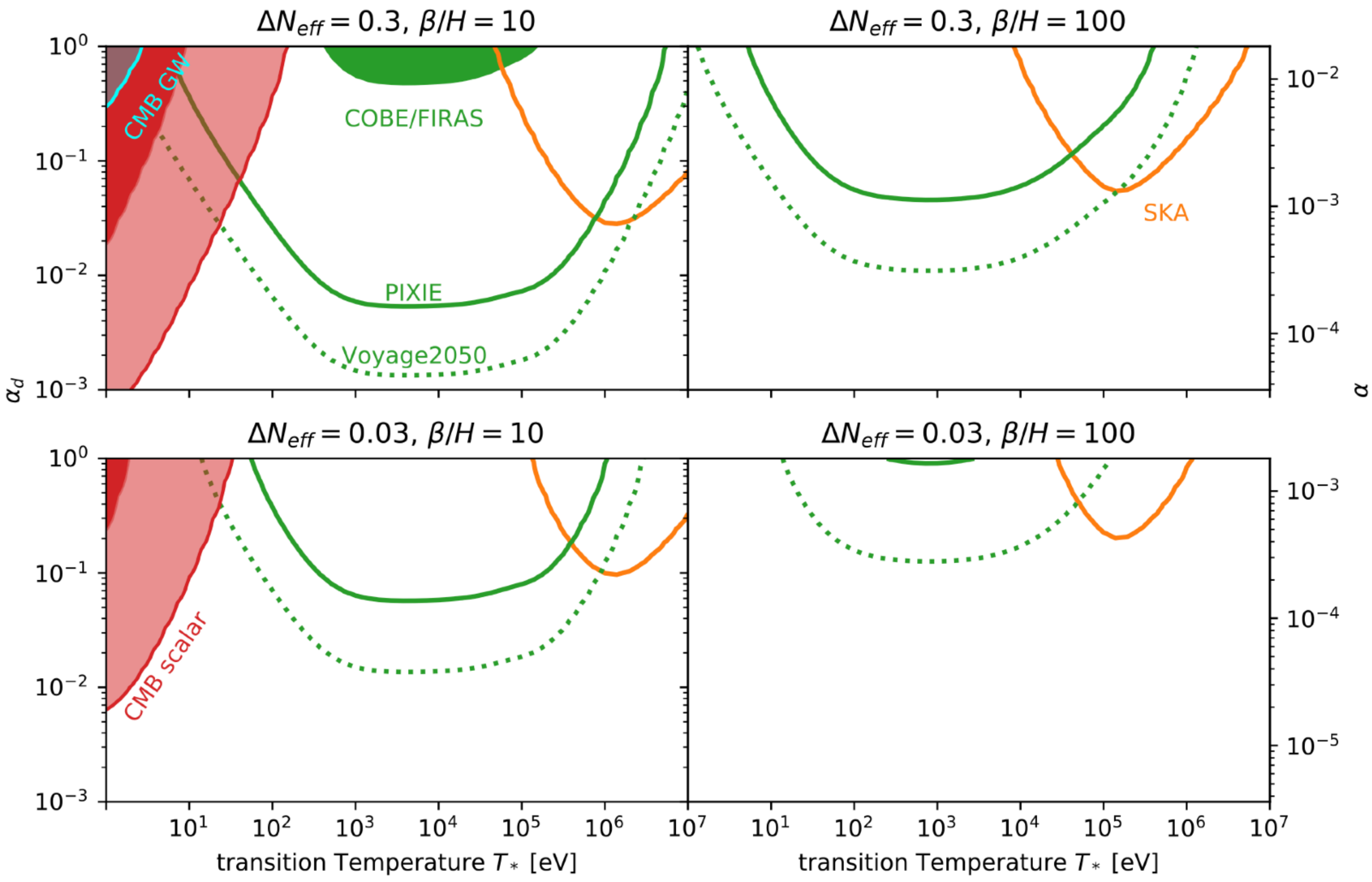
Resulting μ distortions

$$\mu = \int d\log k \ \epsilon_{ac}^{\lim}(k)\mathcal{W}(k),$$



Ramberg, Ratzinger & PS, 2209.14313

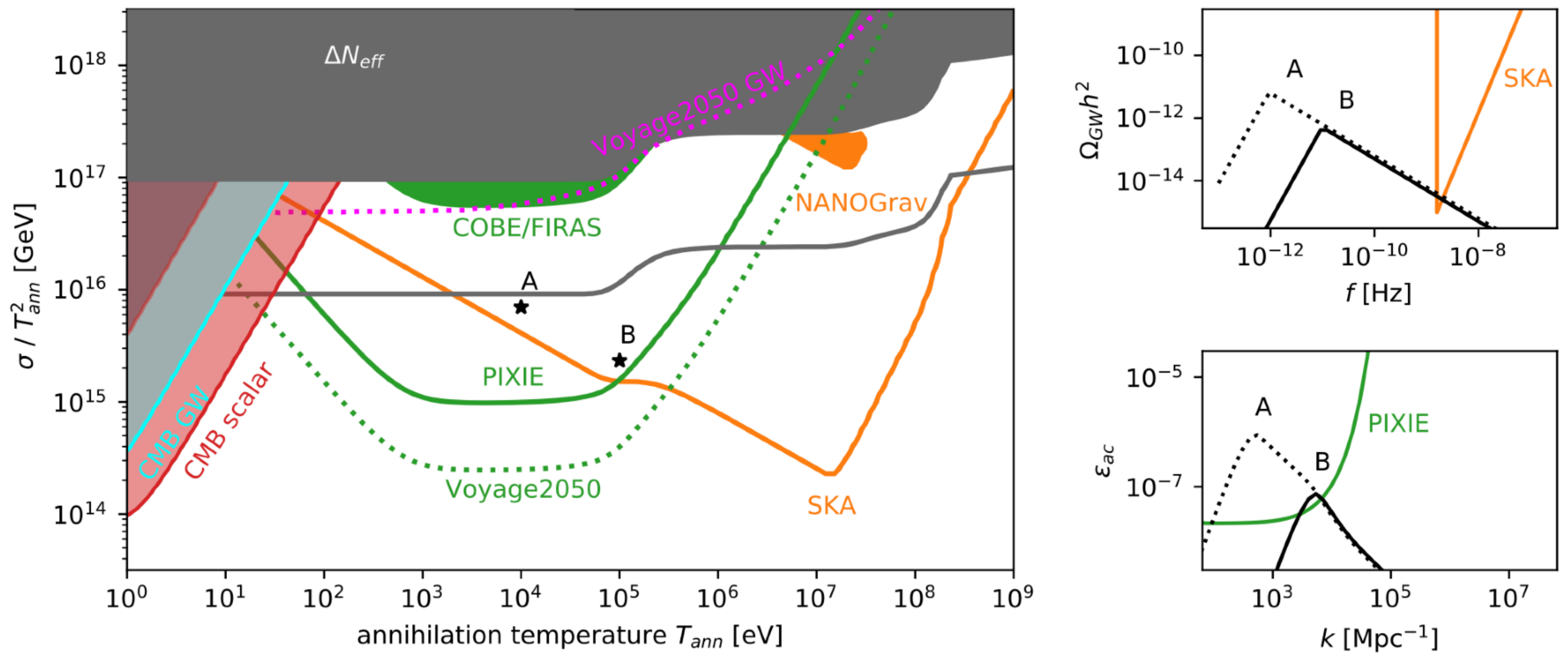
Example source I: Dark sector phase transition



Note: Ω_d fixed to satisfy N_{eff} constraints

Ramberg, Ratzinger & PS, 2209.14313

Example source II: Annihilating domain walls



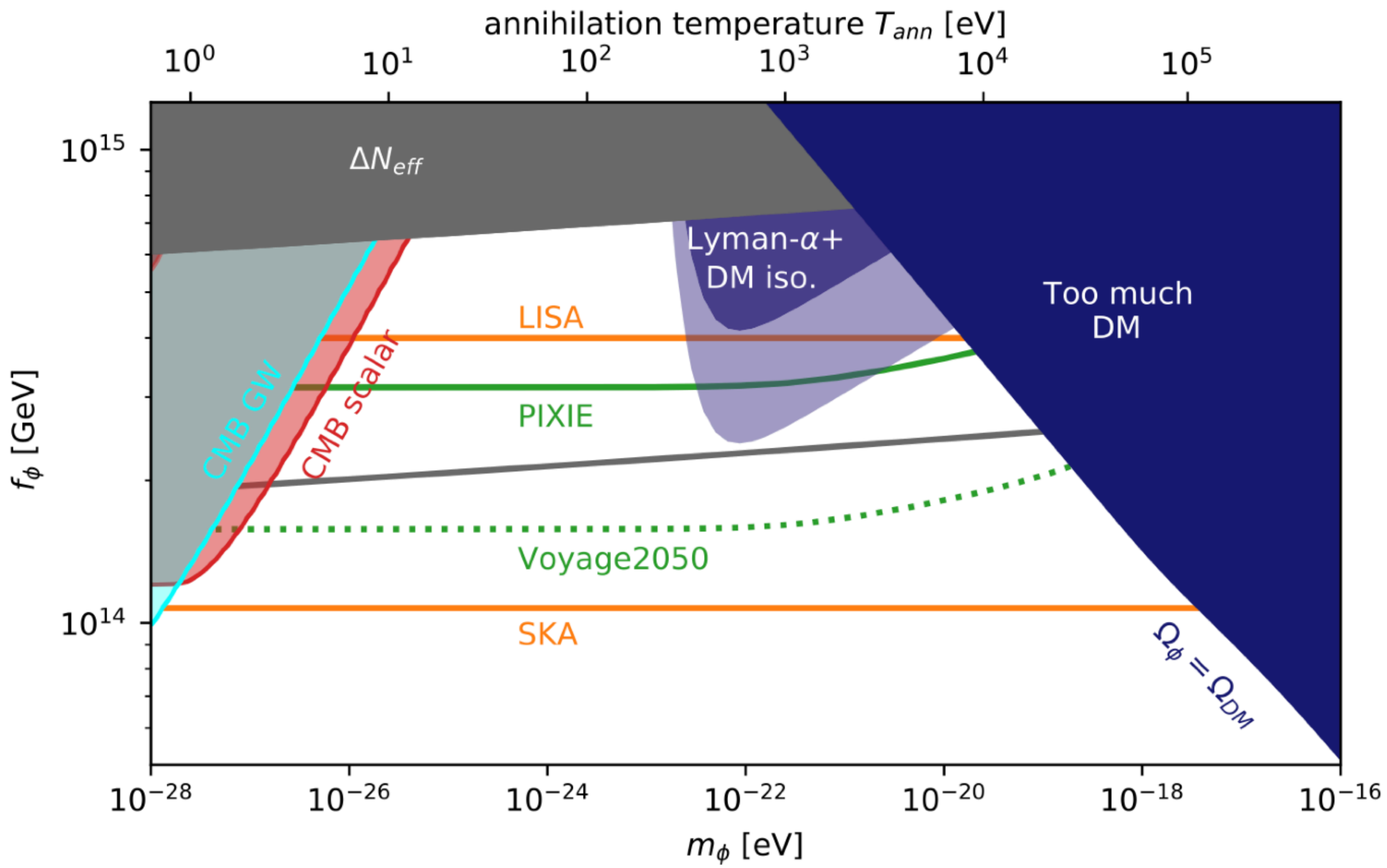
Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



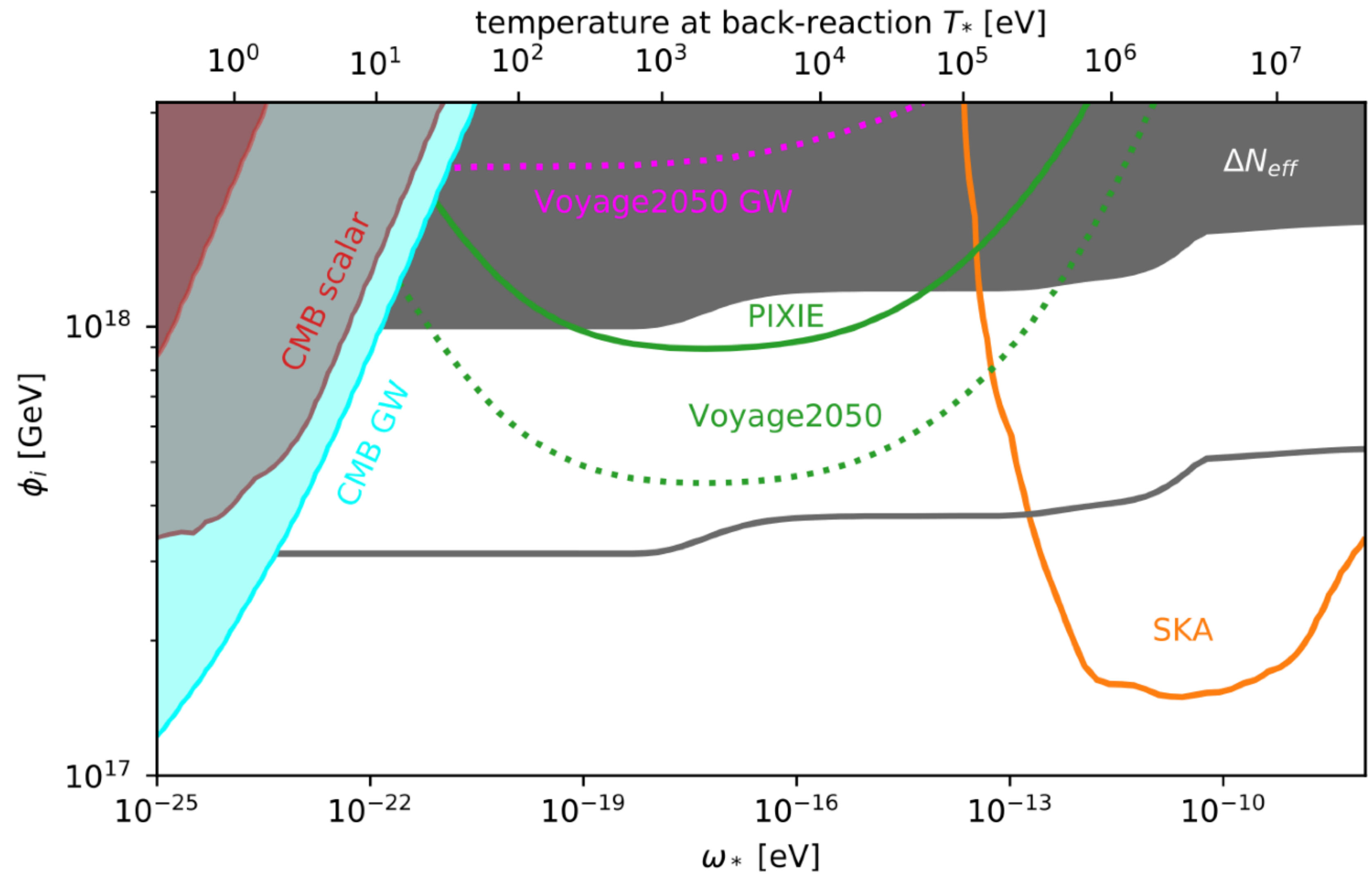
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

Results for scalar toy model

Constraints not as strong since fluctuations are not horizon size



Expect better sensitivity for axion fragmentation

Ramberg, Ratzinger & PS, 2209.14313

Summary

GWs and CMB spectral distortions (SD) probe non-equilibrium physics in the early Universe

- Sensitive to otherwise inaccessible (dark) sectors

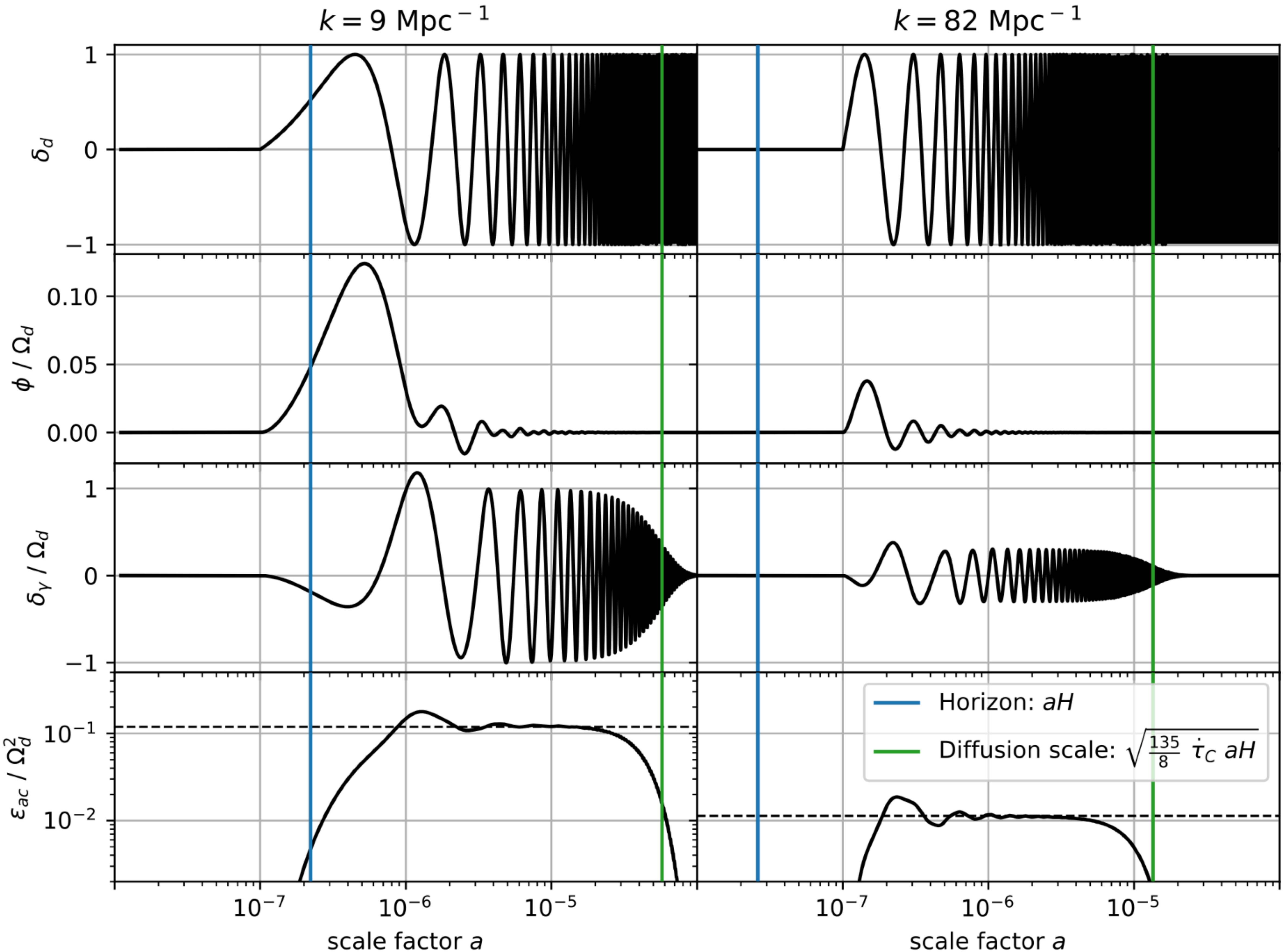
PTA data hints towards a strong first order PT at the MeV scale, potentially in a dark sector

Holography allows computation of PT observables also at strong coupling

Combination of GW and SD

- multi-messenger probes of early Universe anisotropies

Thank you for your attention!

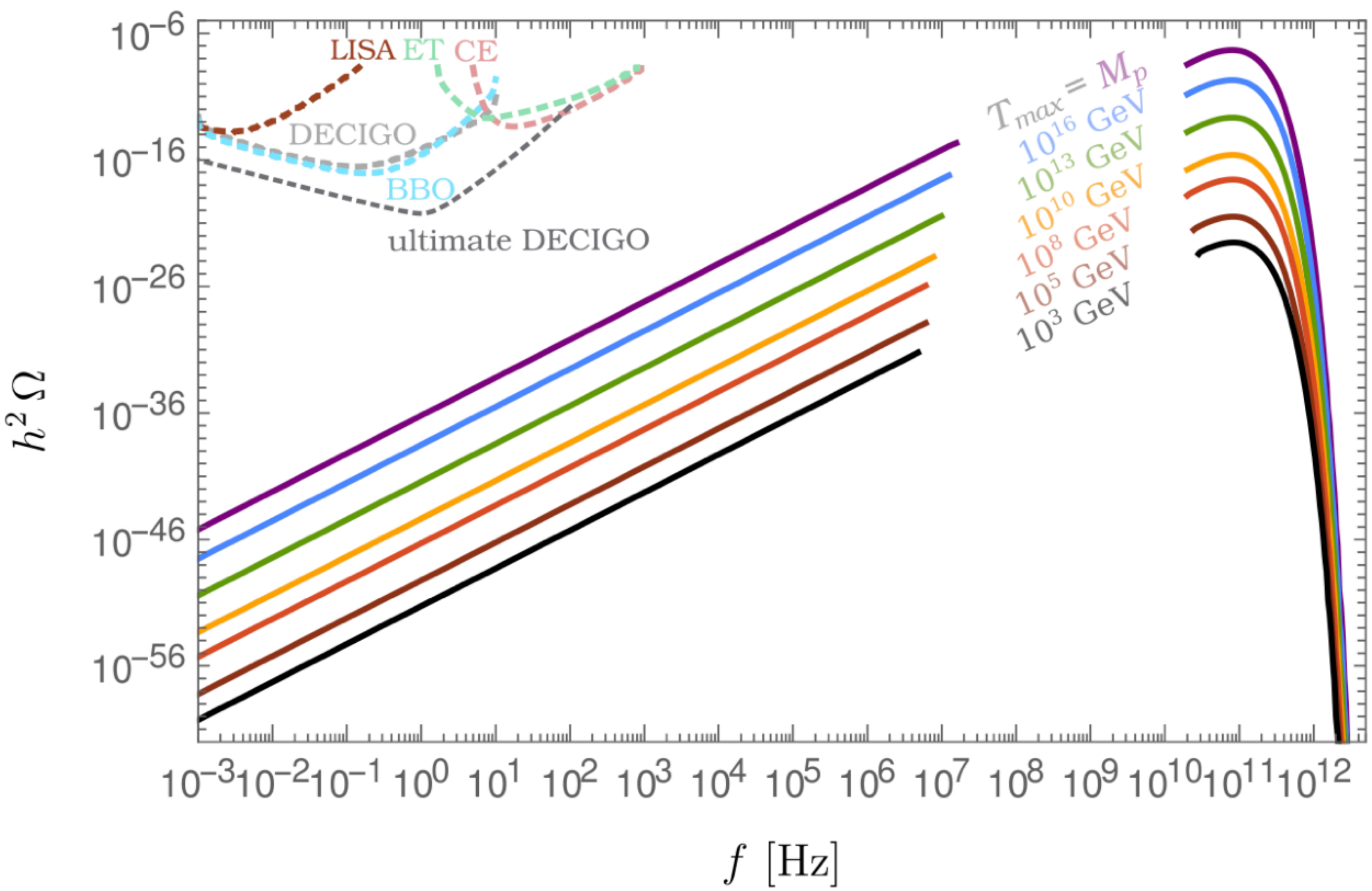


$k = 9\ \mathrm{Mpc}^{-1}$
$k = 82\ \mathrm{Mpc}^{-1}$
δ_d
$\phi\ /\ \Omega_d$
$\delta_\gamma\ /\ \Omega_d$
$\varepsilon_{ac}\ /\ \Omega_d^2$
Horizon: aH
Diffusion scale: $\sqrt{\frac{135}{8}\ \dot{\tau}_C\ aH}$
scale factor a
scale factor a

Standard model

The hot early Universe sources GWs!

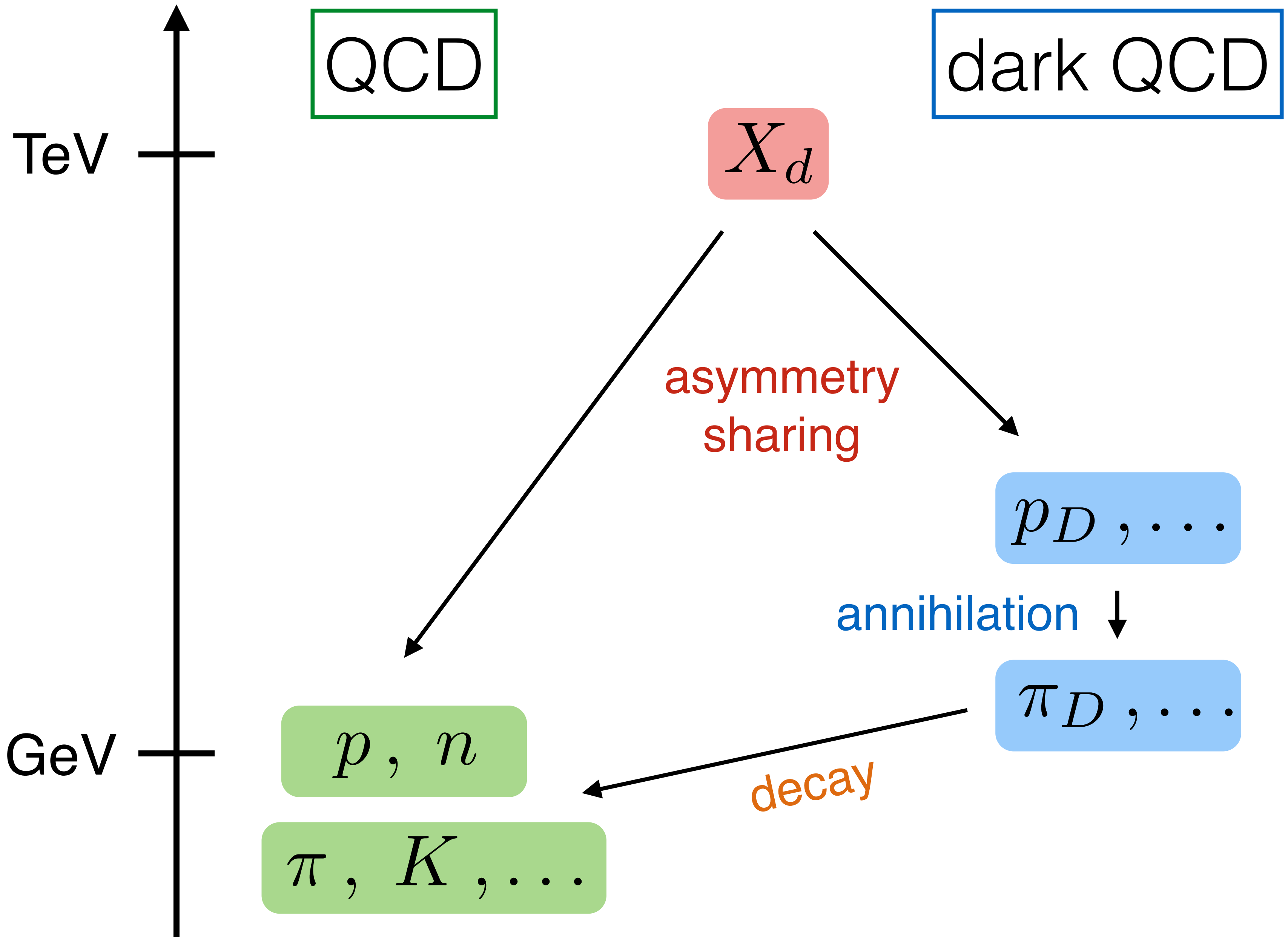
- Classical picture: thermal fluctuations source tensor fluctuations
- Quantum picture: gluon + gluon -> graviton



From Ringwald, Schütte-Engel, Tamarit, 2020

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

Composite DM / Hidden Sector



- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

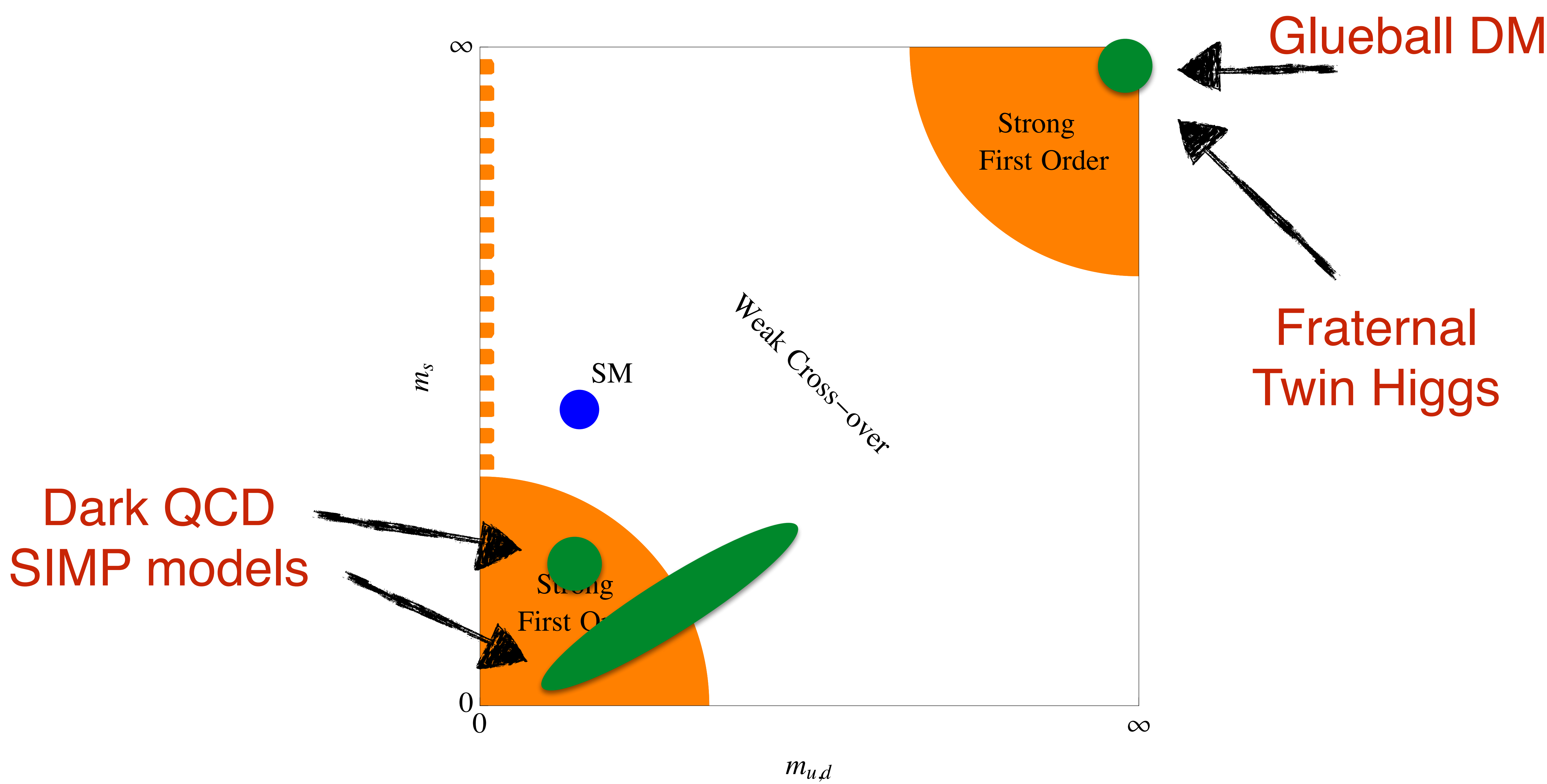
$$\Lambda_{\mathrm{darkQCD}}$$

- DM is composite "dark proton"

Bai, PS, PRD 89, 2014
PS, Stolarski, Weiler, JHEP 2015

many other works!
Similar setup e.g.: Blennow et al; Cohen et al; Frandsen et al;
Hidden Valleys: Strassler, Zurek;…

Phase Diagram II



PS, 2016

SU(N) - PT

Consider. $SU(N_d)$ with n_f massless flavours

PT is first order for

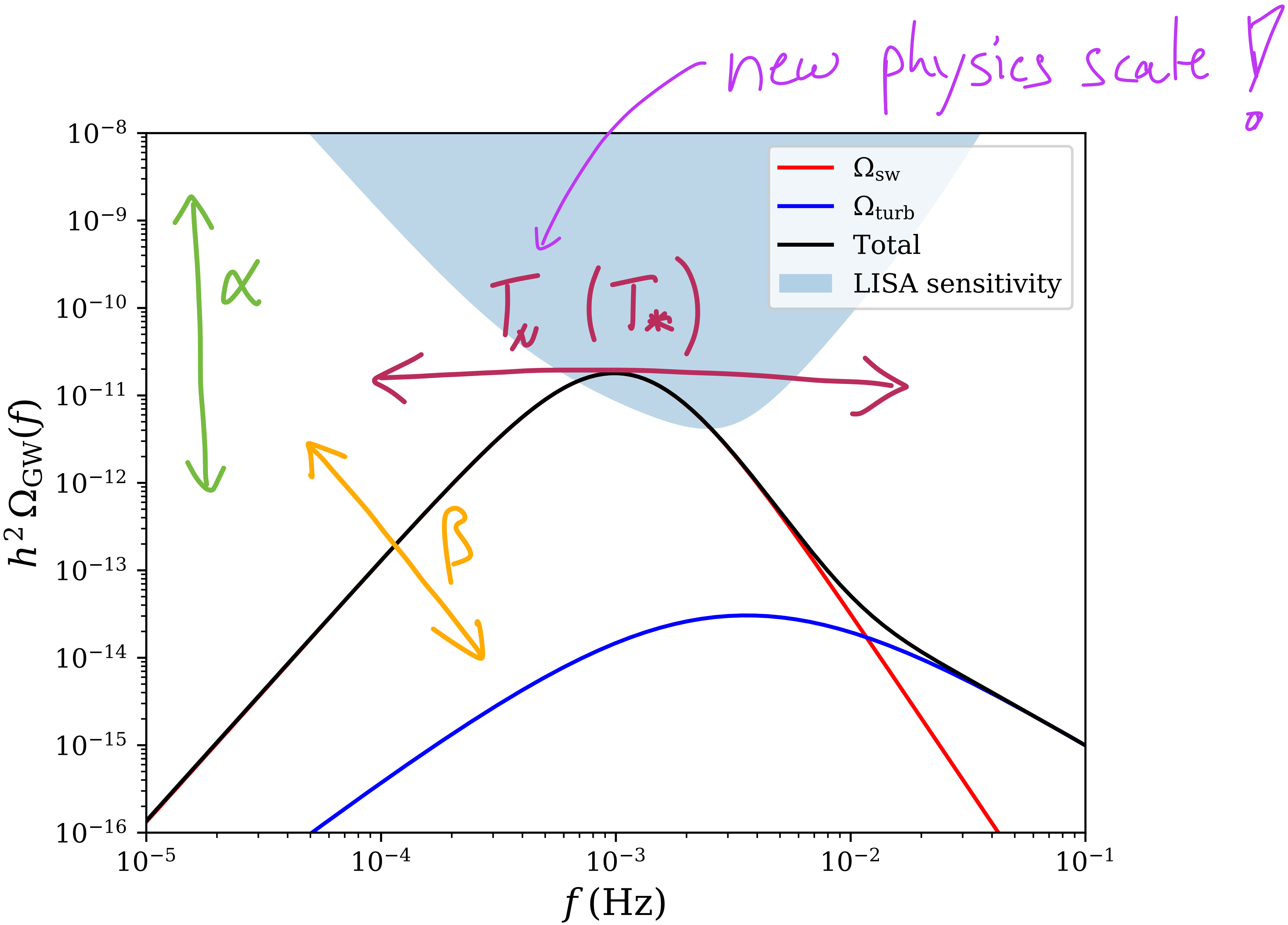
- $N_d \geq 3\,,\quad n_f = 0$ — Svetitsky, Yaffe, 1982; M. Panero, 2009
- $N_d \geq 3\,,\ \ 3 \leq n_f < 4N_d$ — Pisarski, Wilczek, 1983

Not for:

- $n_f = 1$ (no global symmetry, no PT)
- $n_f = 2$ (not yet known)

Note: Nature of the PT does not depend on arbitrary model parameters

Signal properties



Combine lattice and holography

Improved holographic QCD

$$\mathcal{S}_5 = -M_P^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3}(\partial\Phi)^2 + V(\Phi) \right] + 2M_P^3 N_c^2 \int_{\partial M} d^4x \sqrt{h} K$$

- AdS Einstein-dilaton gravity $\leftrightarrow$ 4D CFT
- Dilaton potential $V(\Phi)$
- Dilaton $\lambda = \exp\Phi$ $\leftrightarrow$ 't Hooft coupling $\lambda_t = N_c g_{YM}^2$
- …
- Solutions of EOM $\leftrightarrow$ phases of SU(N)

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

Improved holographic QCD

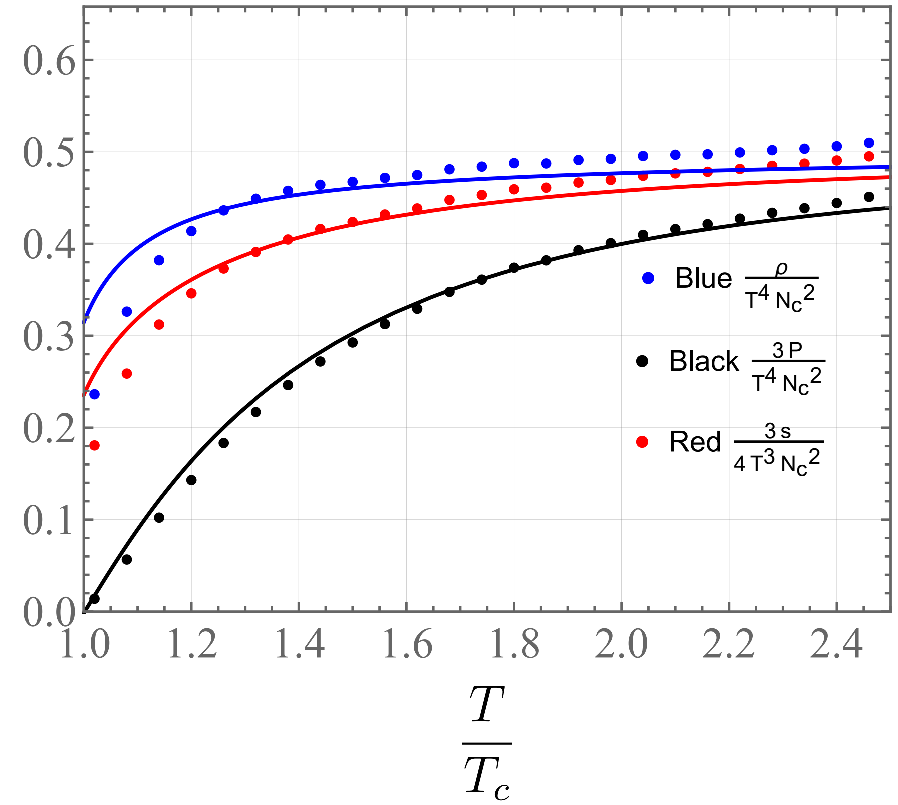
Want this to reproduce SU(N) theories

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

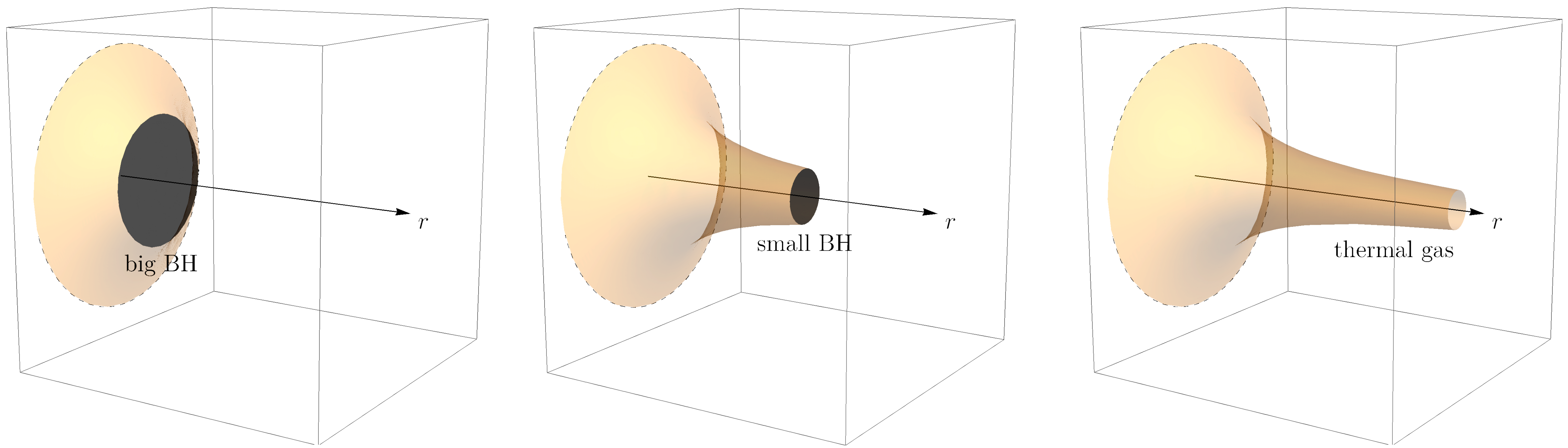
$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

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



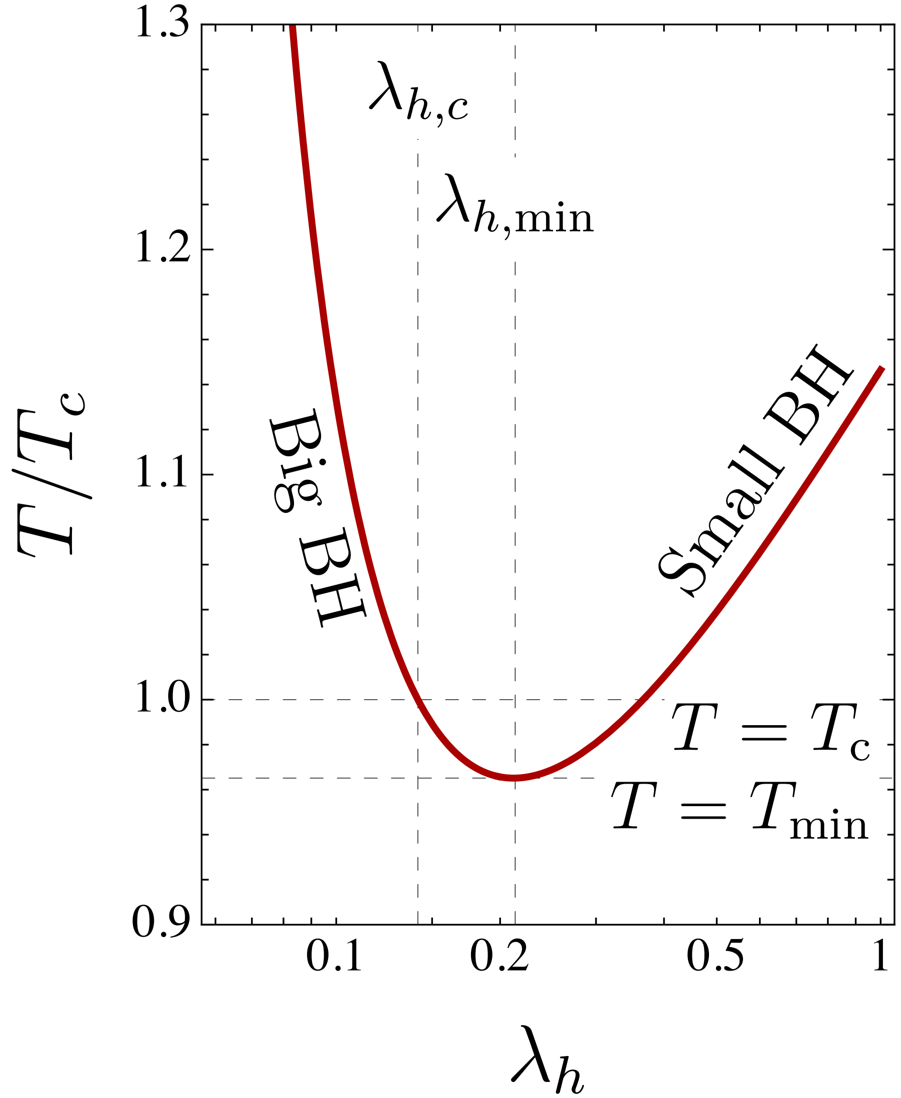
The phase transition in ihQCD

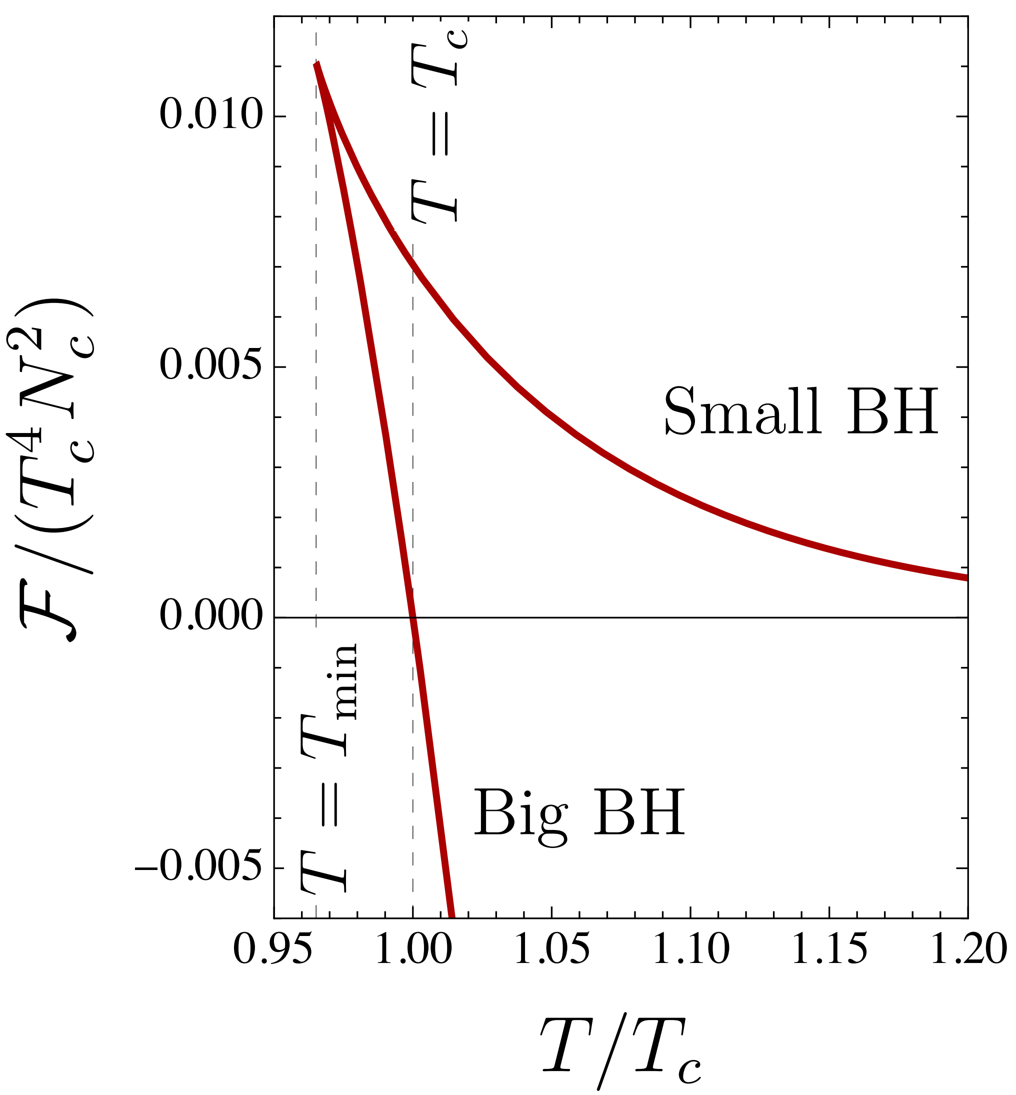


Three solutions

- Big BH: Deconfined phase
- Small BH: Unstable, saddle point
- Thermal gas: Confined phase

The phase transition in ihQCD II





At $T = T_c$, deconfined phase becomes meta-stable

Morgante, Ramberg, PS, 2210.11821

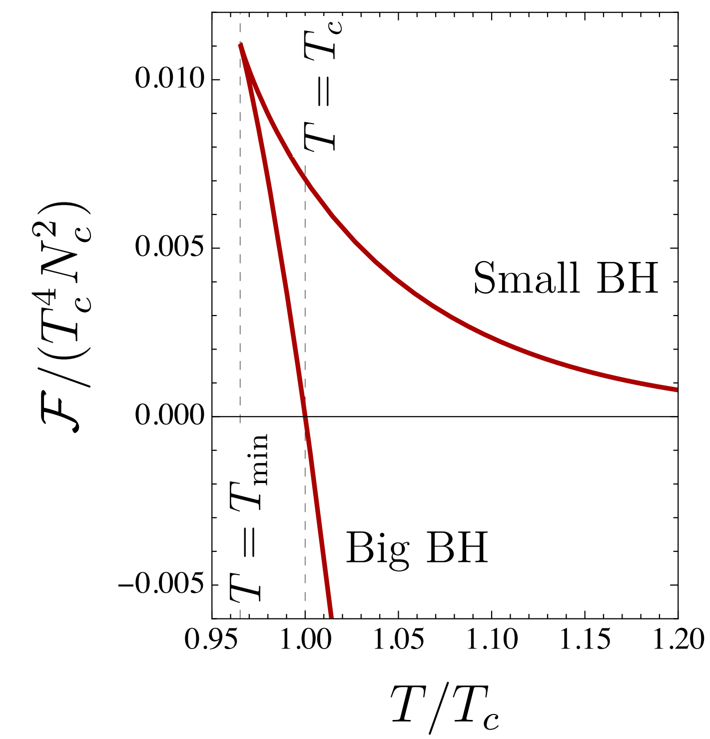
The phase transition in ihQCD III

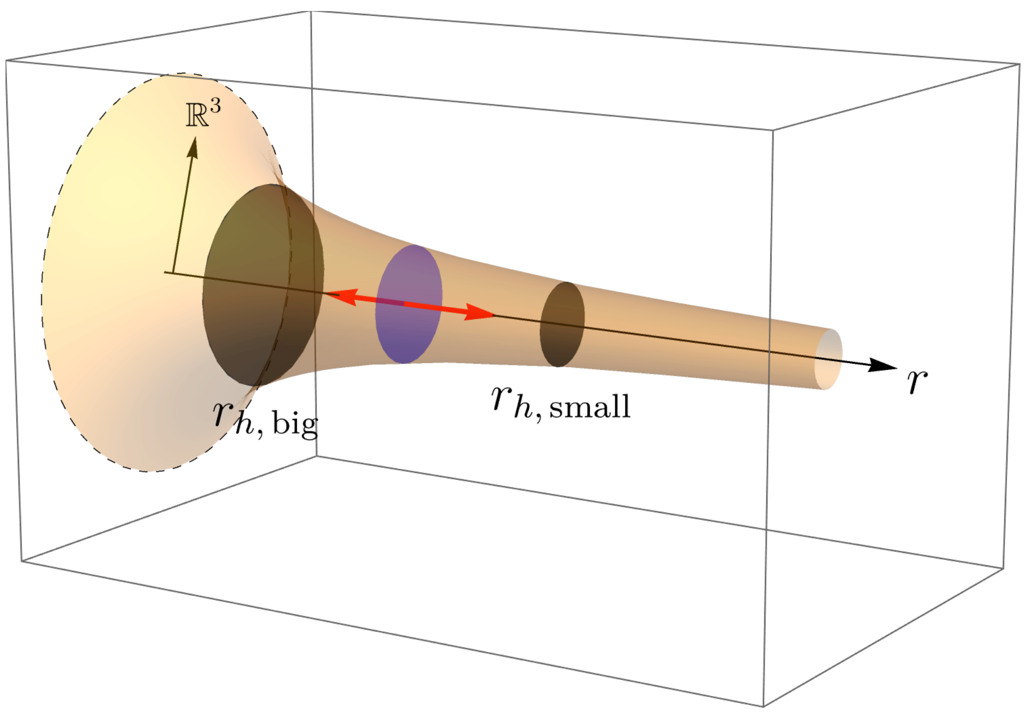
Hawking Page transition, with small BH acting as instanton

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