LIGHT DARK SECTORS AND NANO-HZ GRAVIATIONAL WAVES

Pedro Schwaller
Mainz University

Based on work with:
Eric Madge
Enrico Morgante
Cristina Puchades-Ibanez
Nicklas Ramberg
Wolfram Ratzinger
Sebastian Schenk

Cluster of Excellence PRISMA+

PADUA 2023: Light Dark Sectors

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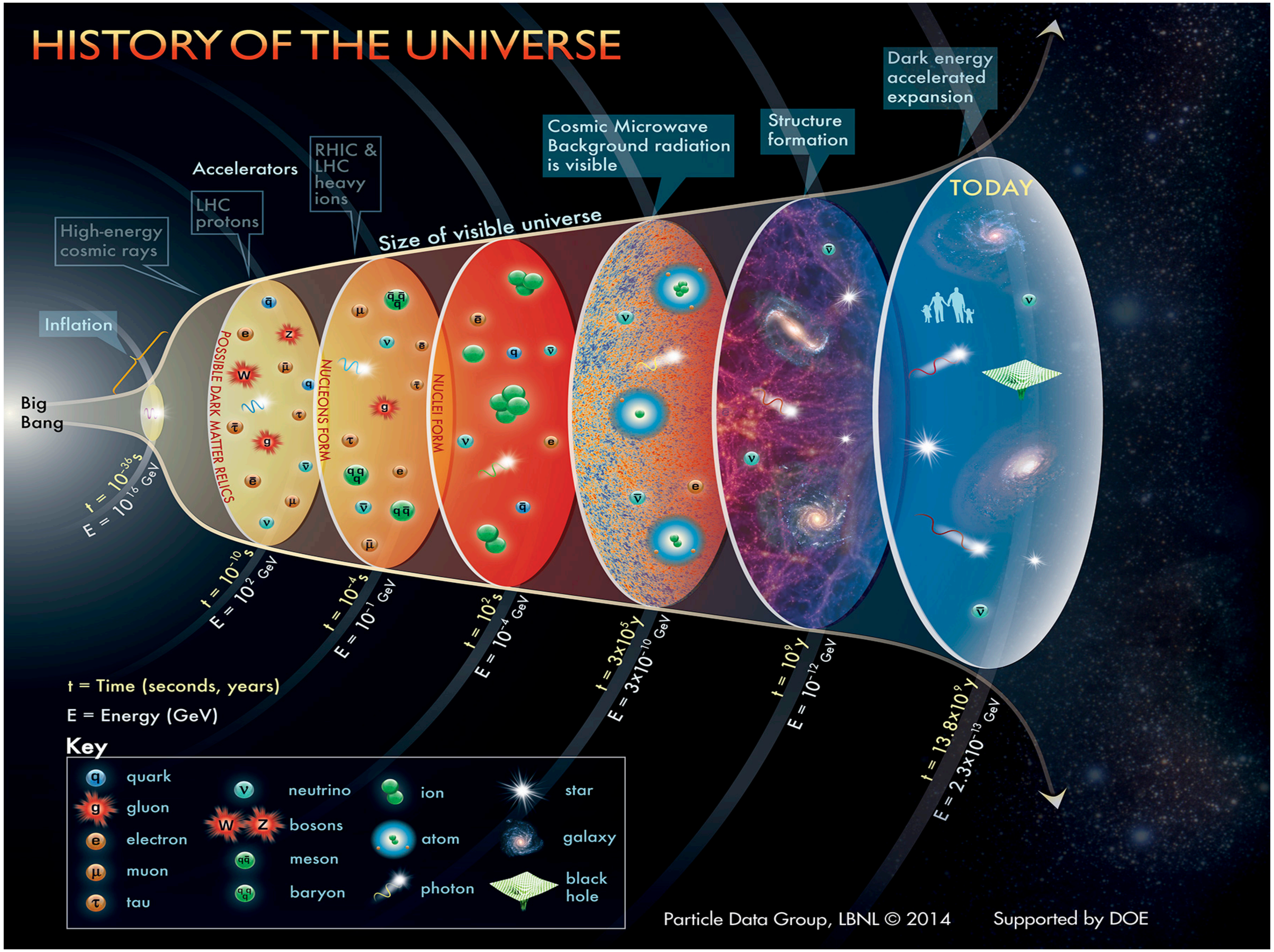
Gravitational waves as windows into the early Universe

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

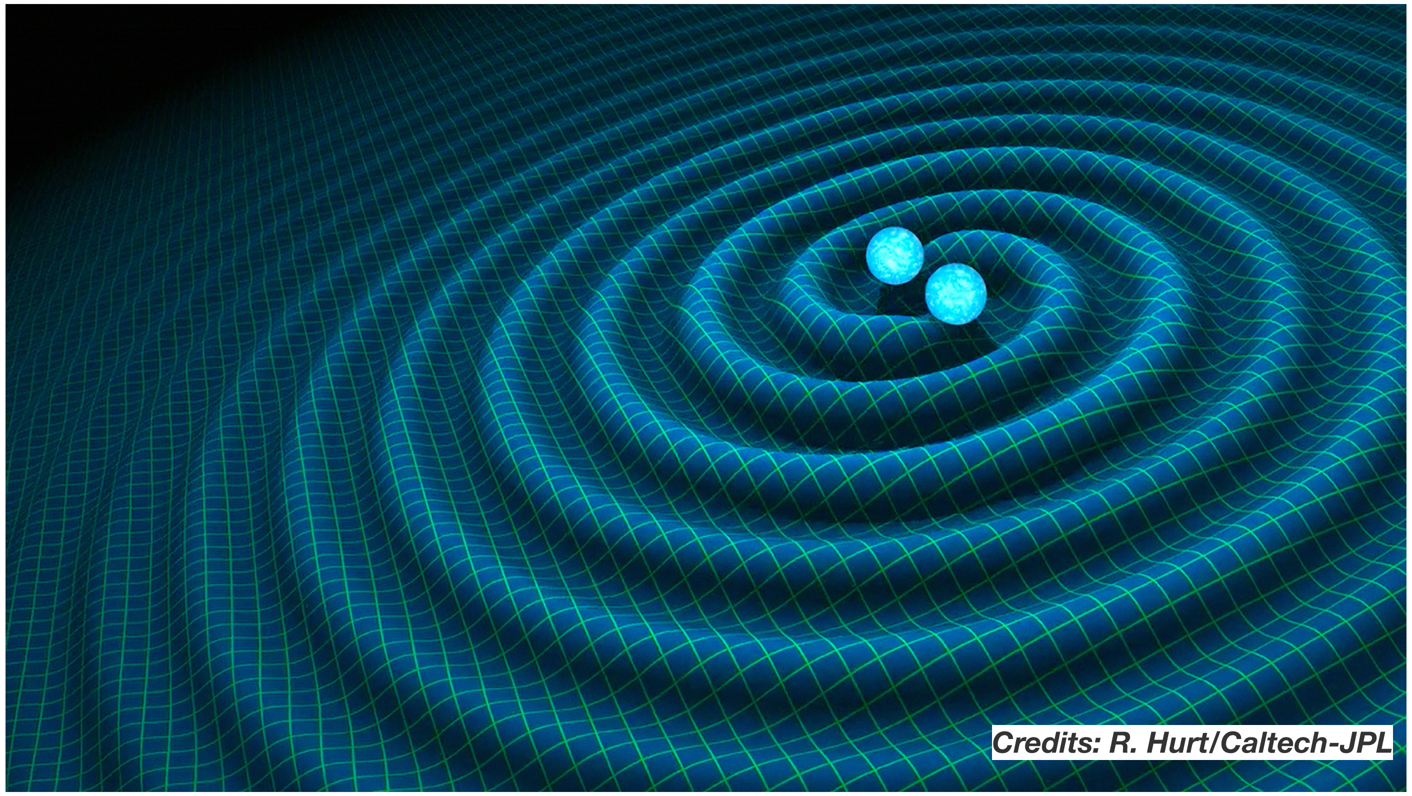
- What is dark matter, and how is it made
- What is the origin of matter
- What is the dynamics of inflation and reheating

Gravitational waves as messengers from the early Universe

Travel undisturbed from earliest times

Only produced by violent, non-equilibrium physics

- Stochastic GW background



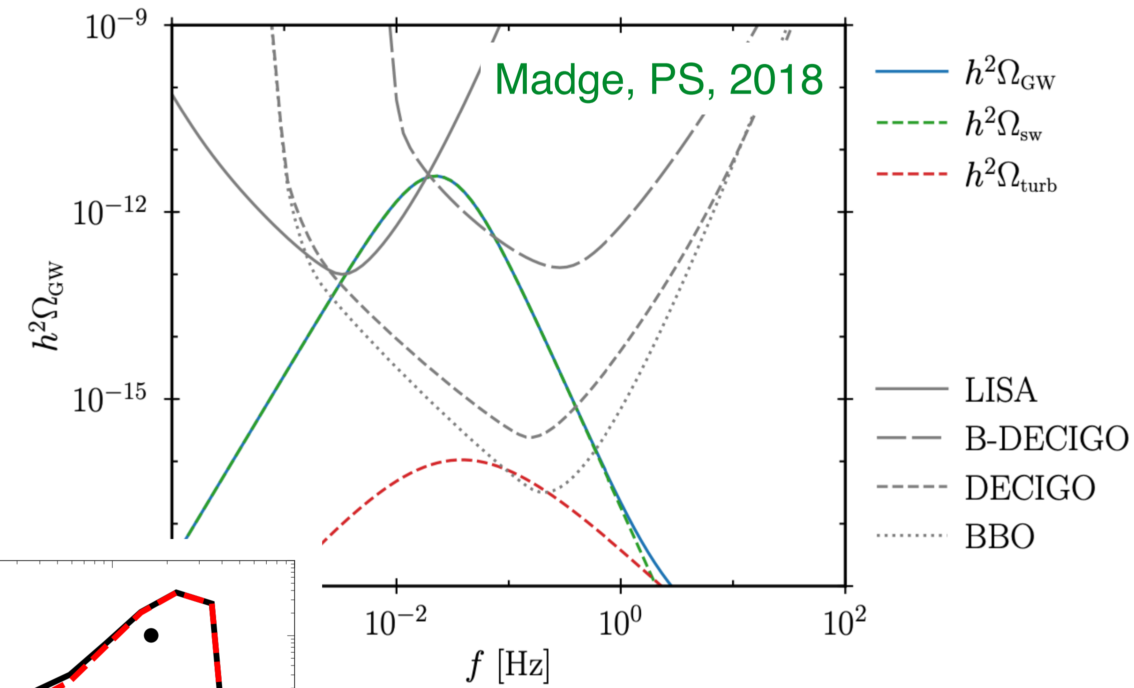
Relevant scale: Hubble radius ↔ GW wavelength

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

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

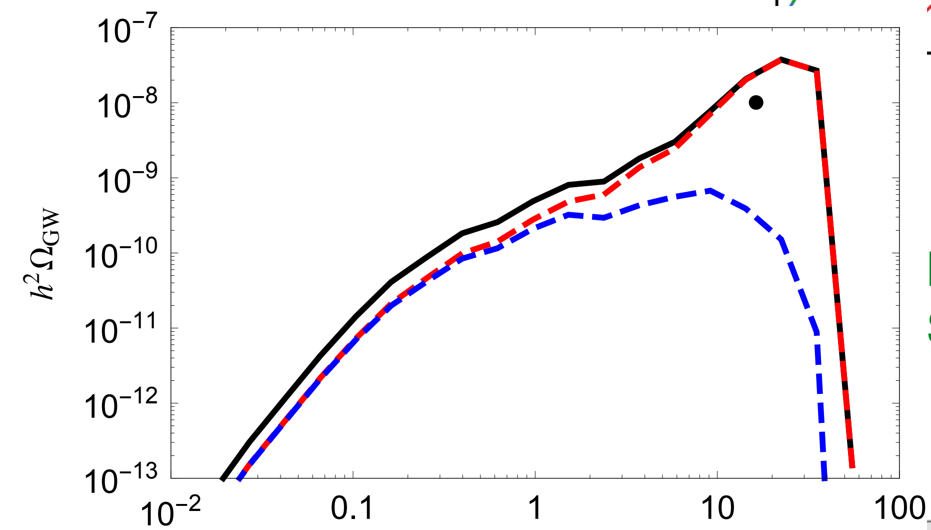
Phase transition

- Peak position depends on critical temperature



Audible axions:

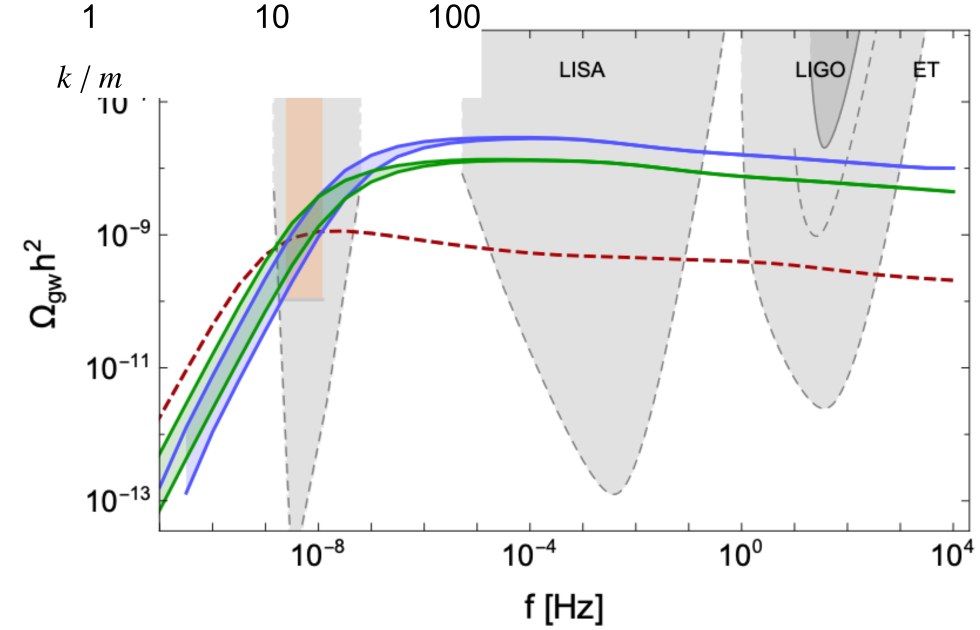
- Peaked but chiral



Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings

- Flatter spectrum

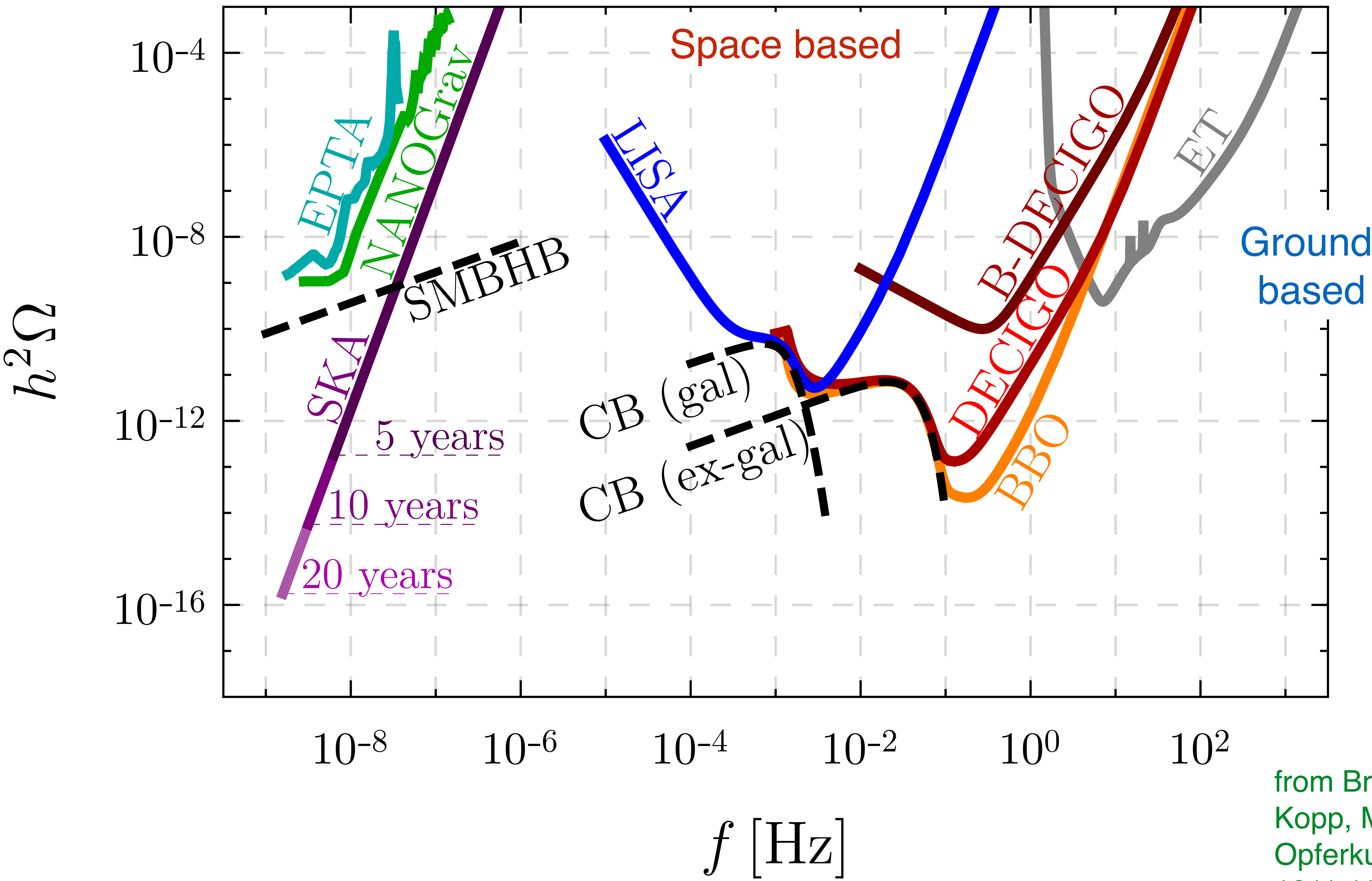


Buchmuller, Domcke, Schmitz, 2021

Frequency ranges

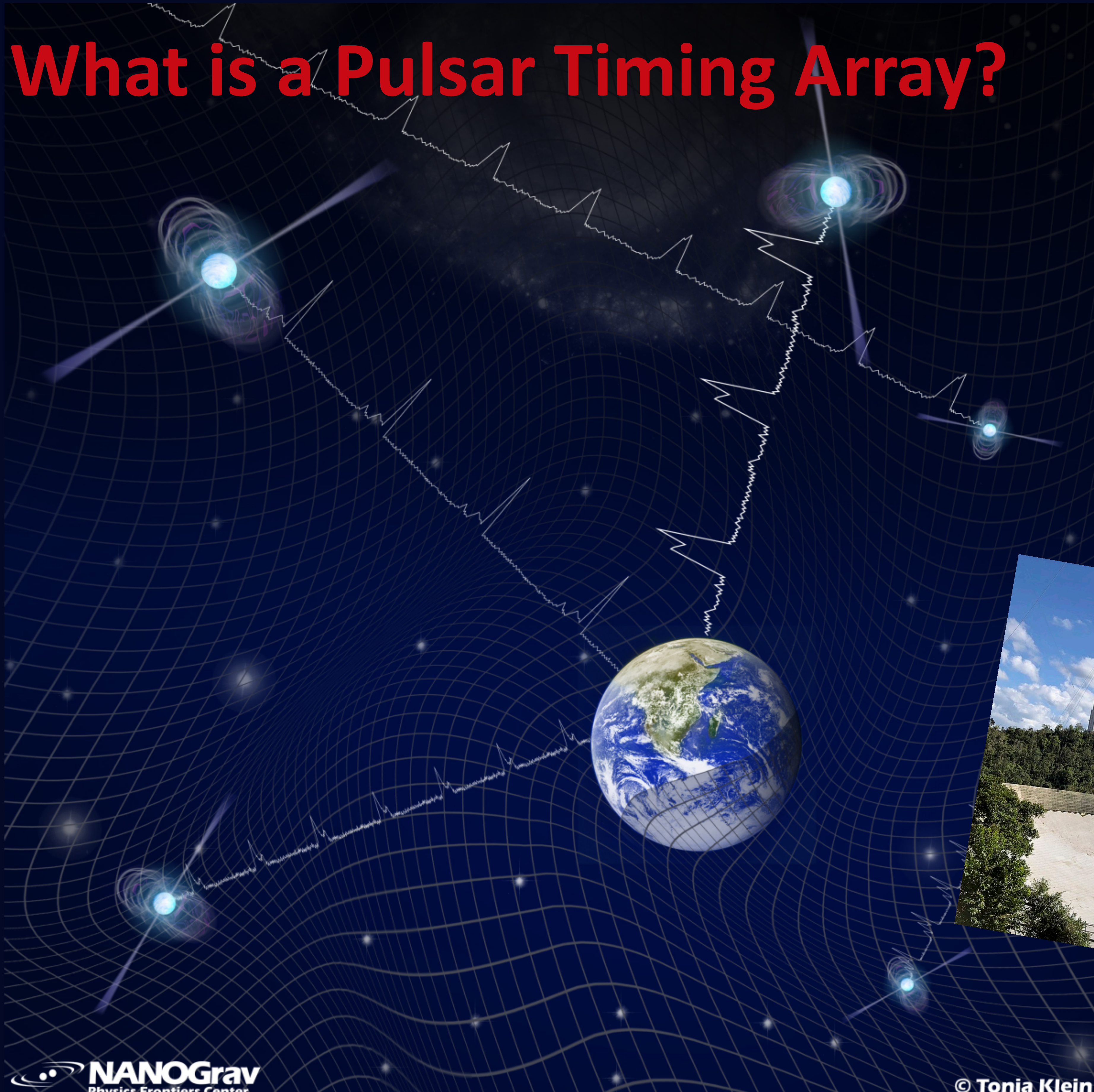
New physics scale

MeV GeV TeV PeV



from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

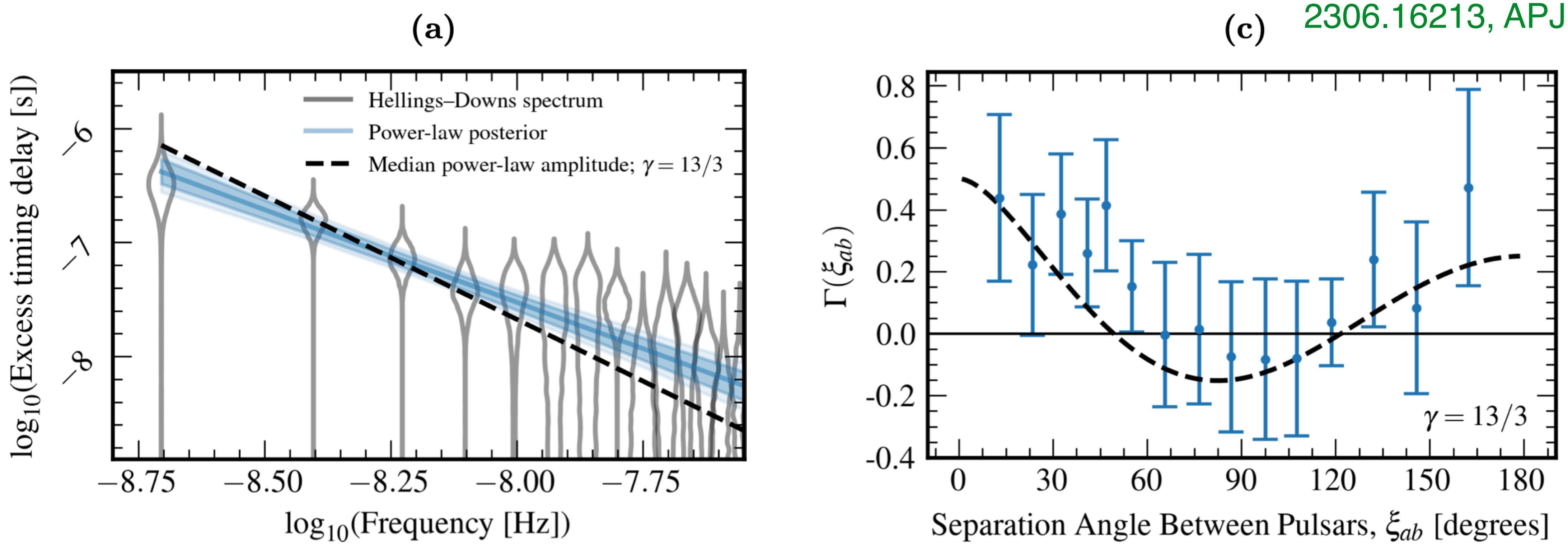
What is a Pulsar Timing Array?



Pulsar timing arrays

NANOGrav has observed evidence for a stochastic GW background at nano-Hz frequencies:

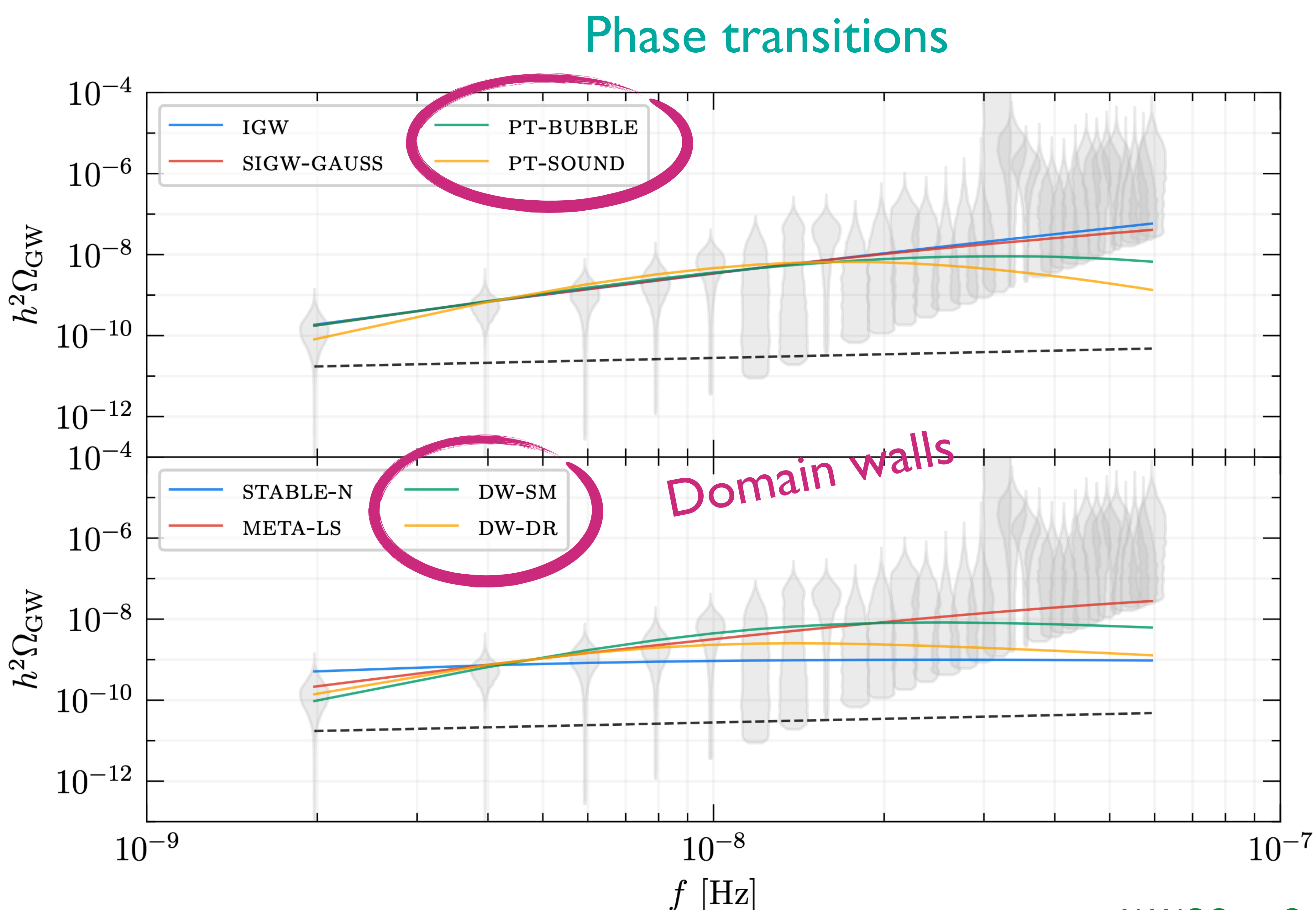
NANOGrav Collaboration, 2306.16213, APJL 951



Strong evidence for Hellings-Downs correlation

Also supported by new EPTA+InPTA, CPTA data (PPTA less)

Compatible with primordial GWs from new physics



NANOGrav Collaboration, 2306.16219, APJL 951

Thoughts:

This is a very strong signal!

$$\Omega_{\text{GW, today}} \sim 10^{-9}$$

Comparison: The photon density today is $\Omega_\gamma \sim 10^{-5}$, but photons were in thermal equilibrium in early Universe

Any source that can explain this must:

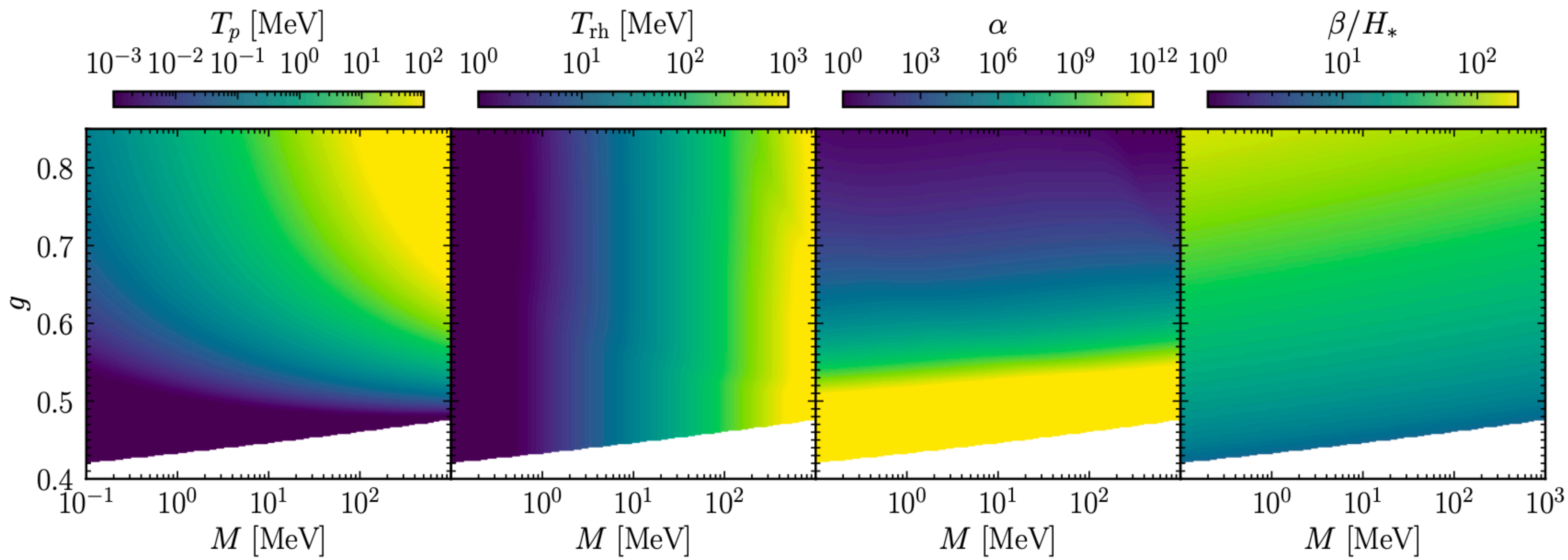
- Represent a significant fraction of the total energy density at the time of production, $T_* \sim (10 - 1000)\,\text{MeV}$
- Be very efficient at converting that energy to GW radiation
- Then disappear before onset of BBN, $T \sim 1\,\text{MeV}$

Supercooled phase transitions

Benchmark model: Coleman-Weinberg model with vanishing tree level potential

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, T)$$

Two parameter model: Mass scale M and coupling g



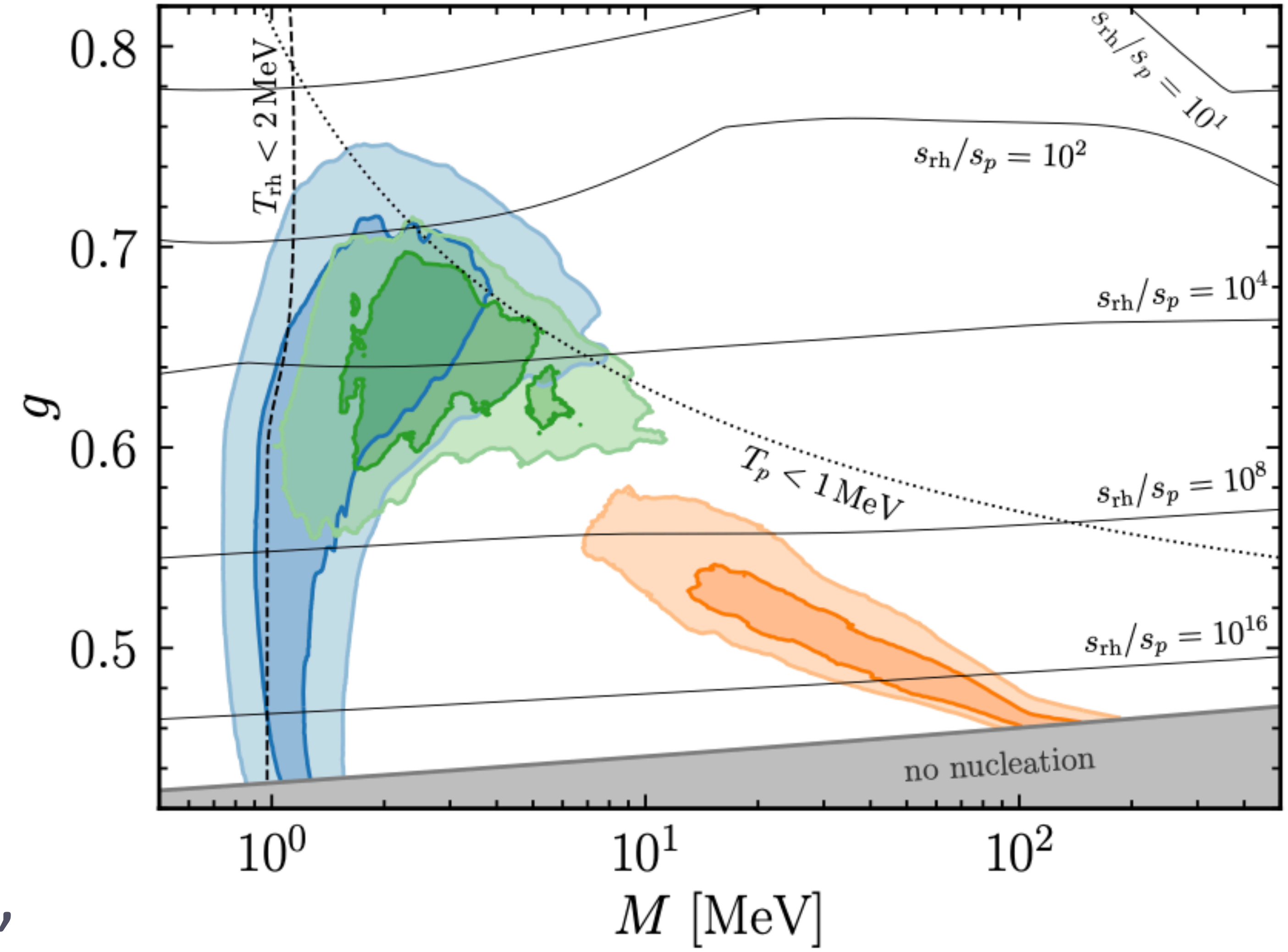
Madge et al, 2306.14856

Signal dominated by colliding bubbles and sound shells

Simulated by Lewicki and Vaskonen, 2208.11697

Supercooled phase transitions

Madge et al, 2306.14856



Comparison with 12 year data

Large supercooling and reheating

- Dilution of baryons, dark matter
- Two BBNs

Pheno: Light scalar $m_\phi \approx M$, decay to electrons and photons

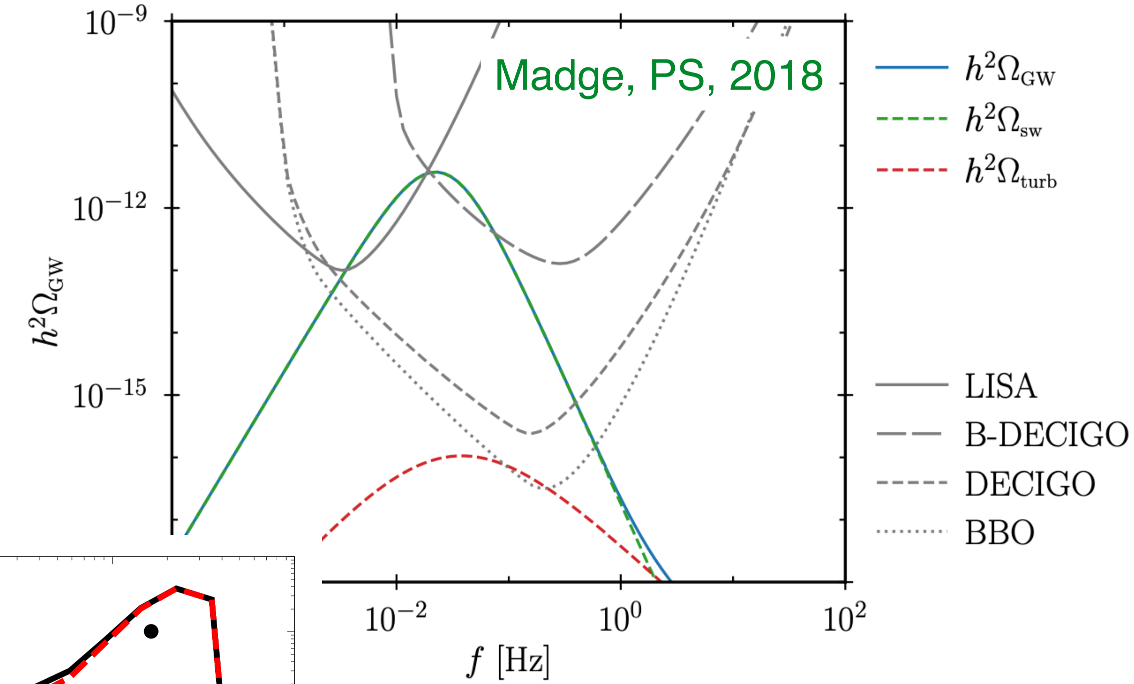
Higgs portal not viable, instead

$$\mathcal{L} \supset c_{ee}\frac{|\Phi|^2}{\Lambda^2} L H \bar{e} + c_{\gamma\gamma}\frac{|\Phi|^2}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}$$

FCC? Or low energy e+e- machine (e.g. MESA in Mainz)

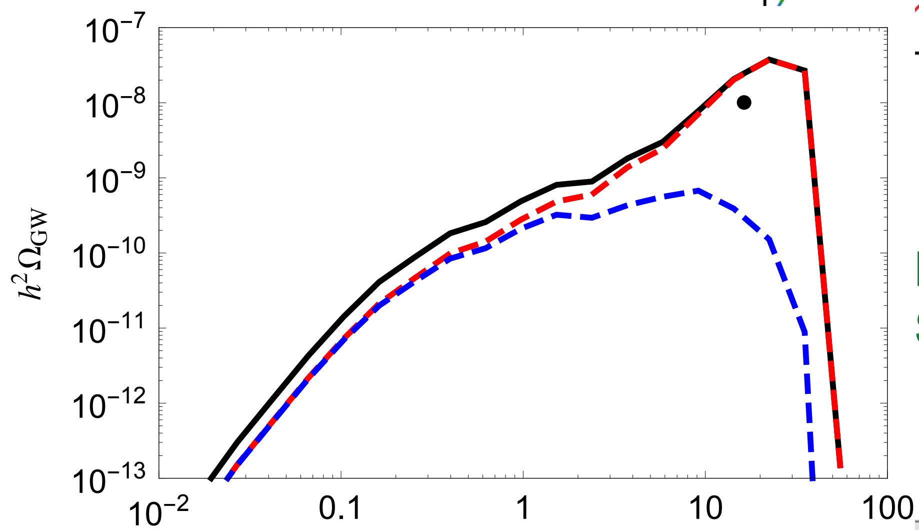
How about the other sources?

New physics mass scales for PTA



Phase transition

- $T_* = M_{NP} \sim \text{MeV} - \text{GeV}$

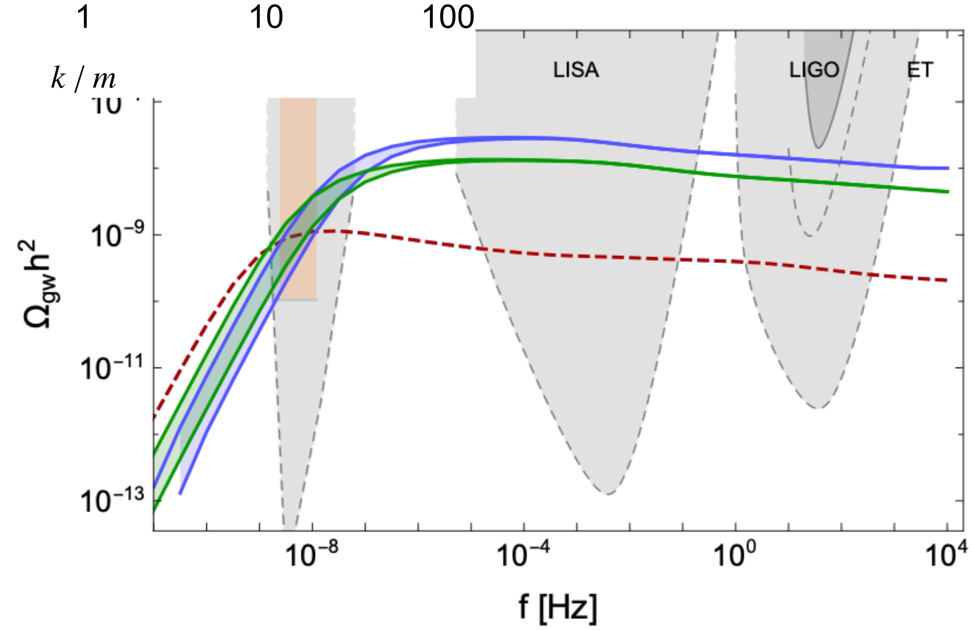


Machado, Ratzinger, Stefanek, PS, 2018/19

Audible axions:

- $T_*^2 / M_{Pl} = M_{NP}$

$\rightarrow M_{NP} \sim 10^{-14}$ eV



Buchmuller, Domcke, Schmitz, 2021

Cosmic strings/domain walls

- $T_* \sim \Gamma_{decay}$

  $M_{NP} \gg \text{MeV}$

Benchmark models with large signals

Madge et al, [2306.14856](https://arxiv.org/abs/2306.14856)

Global cosmic strings

- In trouble with N_{eff}

Audible axions

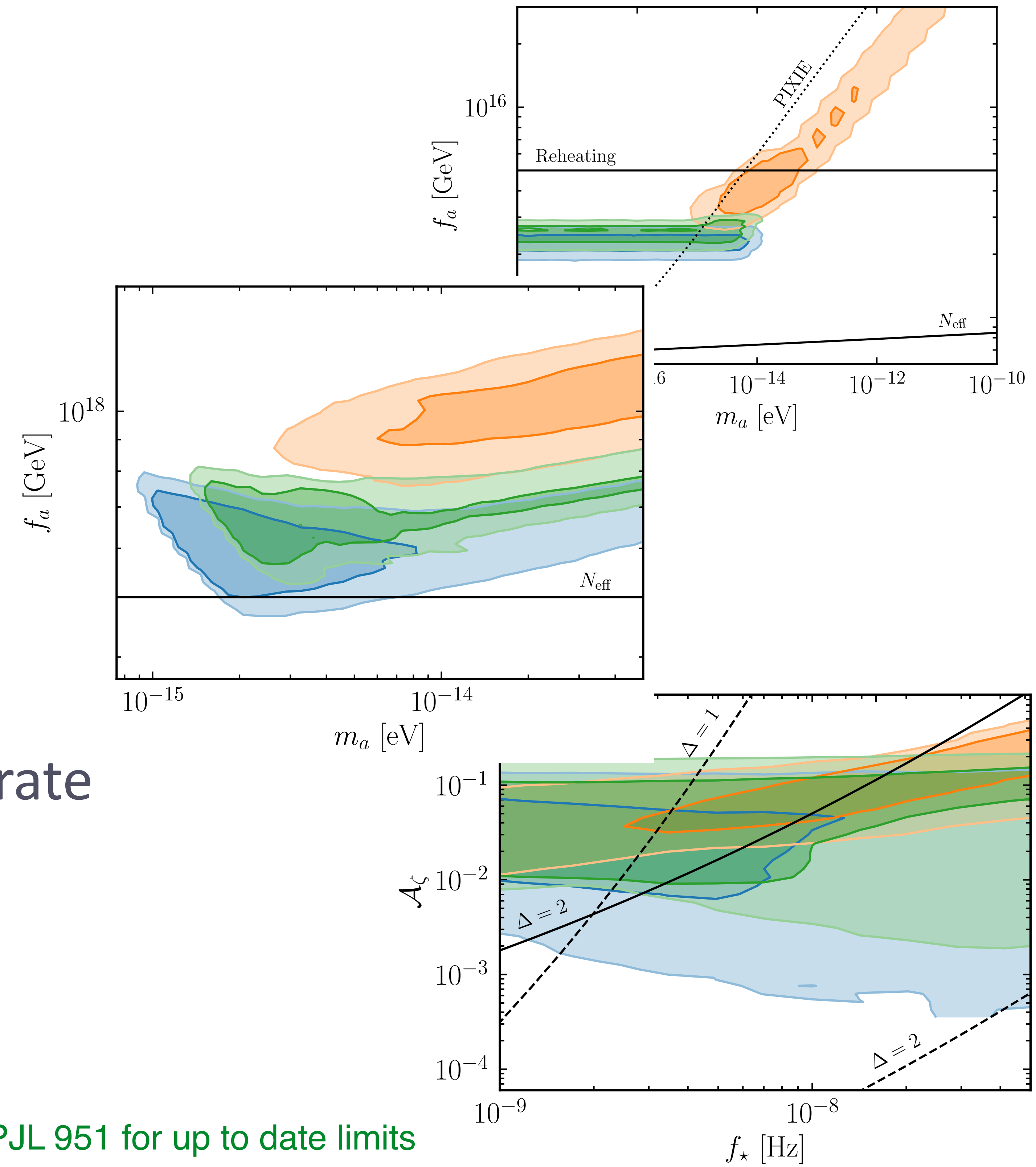
- Barely consistent with N_{eff}

Scalar induced GWs

- OK, but difficult to generate

Domain walls

- Better :)



See also NANOGrav Collaboration, 2306.16219, APJL 951 for up to date limits

Axion/ALP domain walls

Domain walls appear when discrete symmetries are spontaneously broken to degenerate ground states

Long lasting GW source, until DWs annihilate, before dominating the Universe ideally

Review: Saikawa, 1703.02576

Axion DW: $U(1)_{\rm PQ} \to Z_N$

Surface tension $\sigma = 8 m_a f_a^2$

Annihilation triggered by QCD instantons

$$T_{\rm ann} \sim 1\,{\rm GeV} \left(\frac{g_*(T_{\rm ann})}{80}\right)^{-\frac{1}{4}} \left(\frac{\Lambda_{\rm QCD}}{400\,{\rm MeV}}\right)^2 \left(\frac{10^7\,{\rm GeV}}{f_a}\right) \sqrt{\frac{10\,{\rm GeV}}{m_a}}$$

Madge et al, 2306.14856

Axion/ALP domain walls

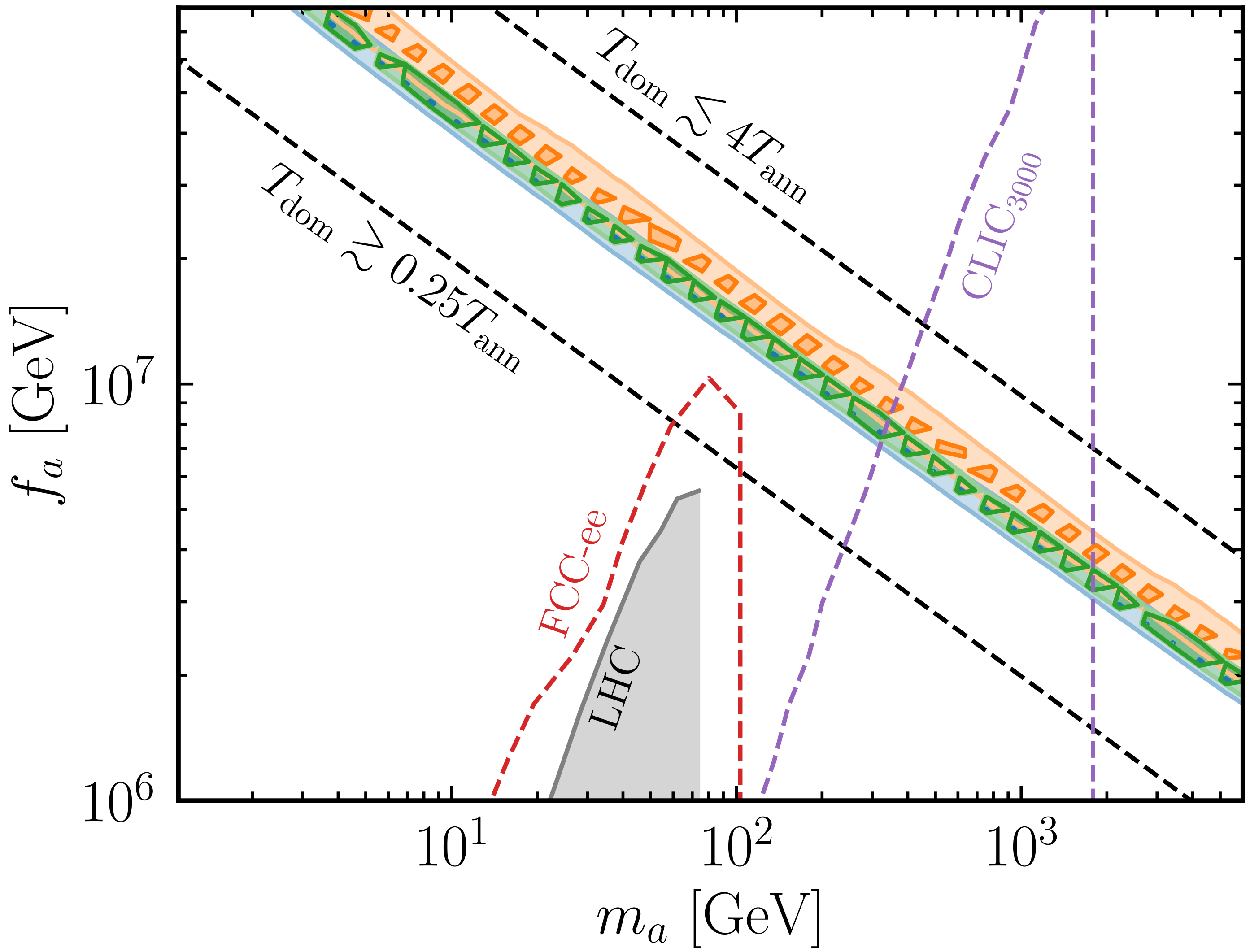
Madge et al, 2306.14856

Concrete model: Aligned/clockwork Axions Higaki et al, 1606.05552

Heavy axion "partners" at weak scale

In reach of future colliders Bauer et al, 1808.10323

- Maybe room for improvement (FCC-hh?)



Invisibly decaying DWs

Madge et al, 2306.14856

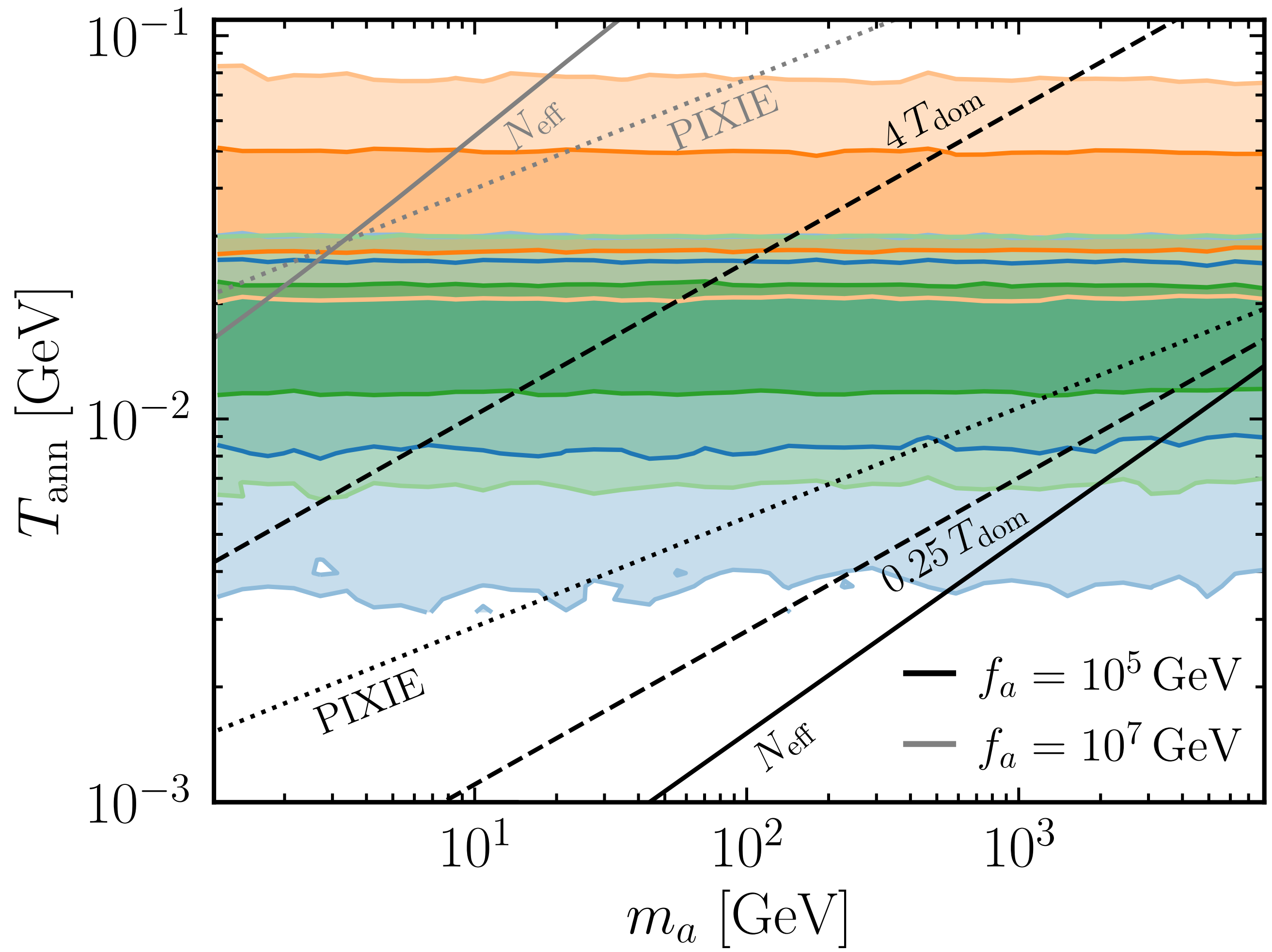
DWs annihilate to dark radiation

- N_{eff} ok mostly

Dark sector anisotropies induce CMB spectral distortions

Ramberg, Ratzinger, PS, 2022

- In reach of future experiments (PIXIE)



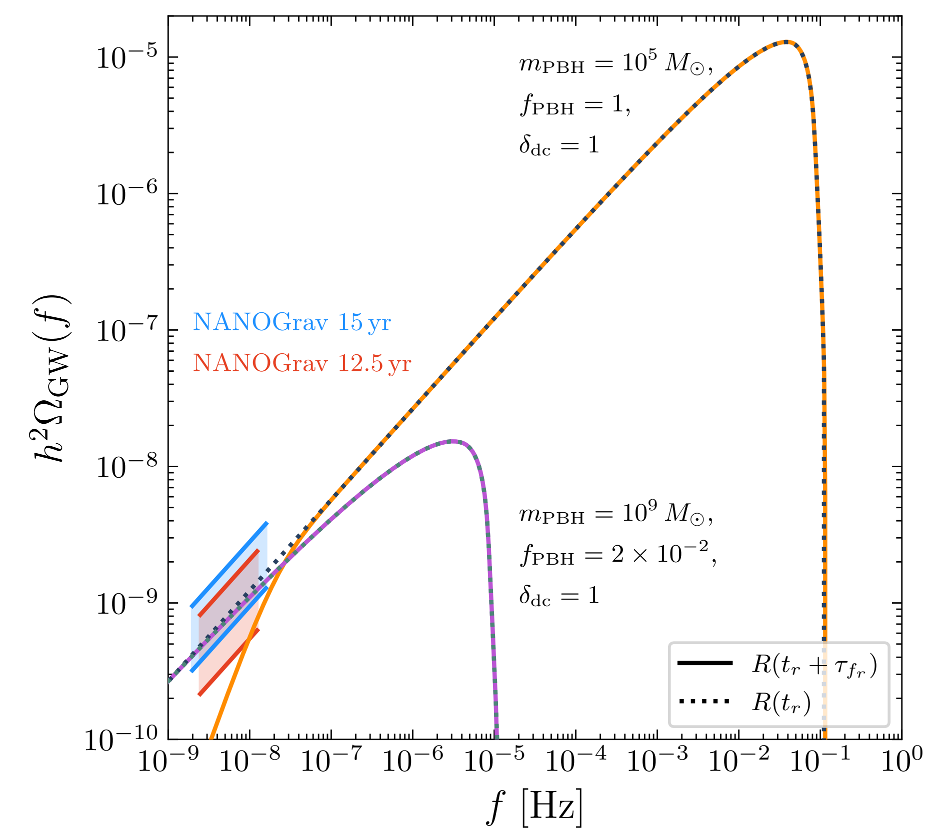
One more: Primordial black holes

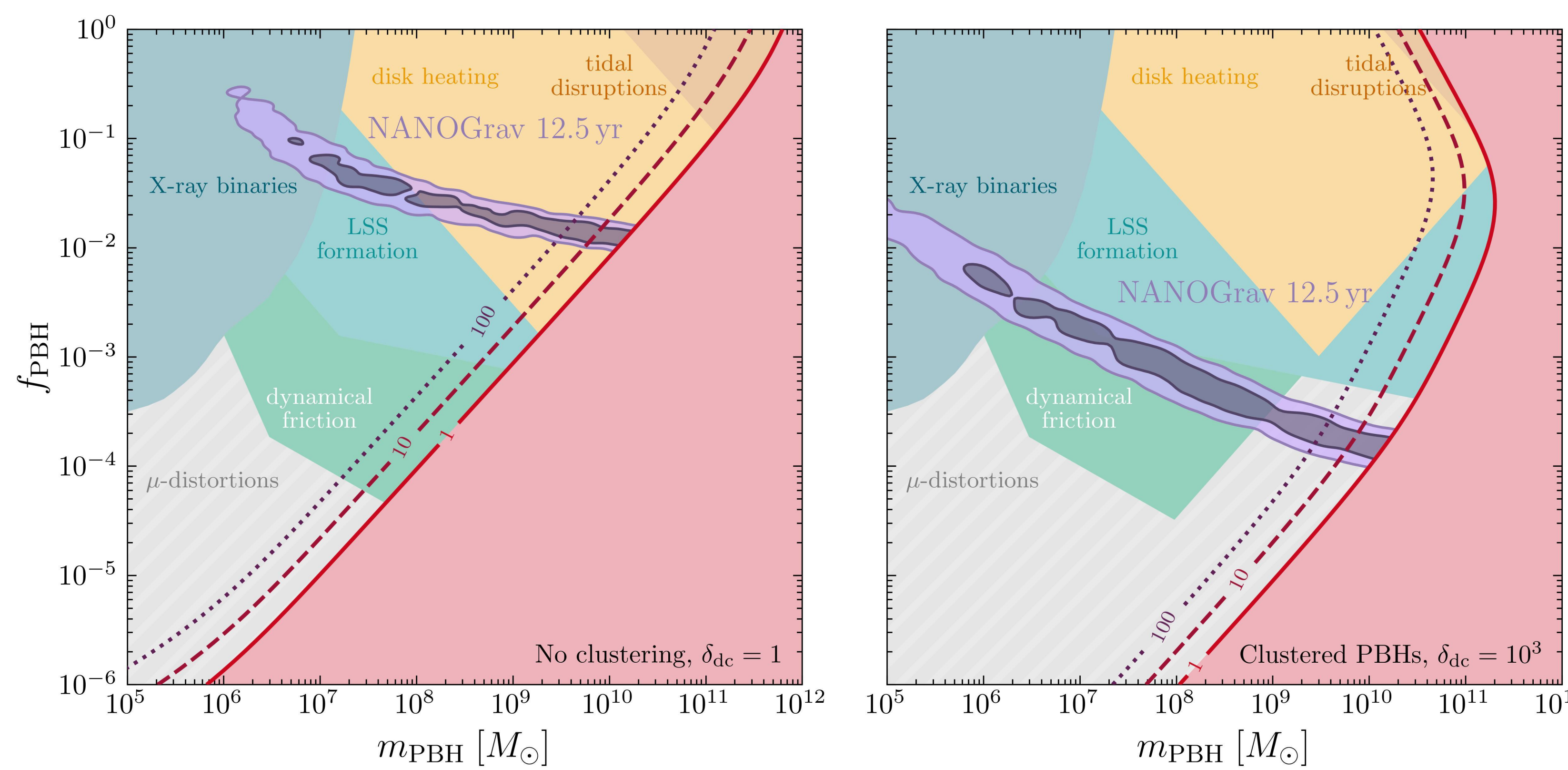
Depta et al, 2306.17836

pBH mergers can explain the data

Clustering needed to evade most stringent bounds

Expect larger anisotropies than from primordial sources





Summary

GWs probe non-equilibrium physics in the early Universe

PTA experiments made first observation of a stochastic GW background

Consistent with SMBHB, but also can be (partially) explained by new physics

- Dark (but not decoupled) sector phase transition
- Domain walls
- …

Combination of laboratory, GW and astro/cosmo measurements required to identify source

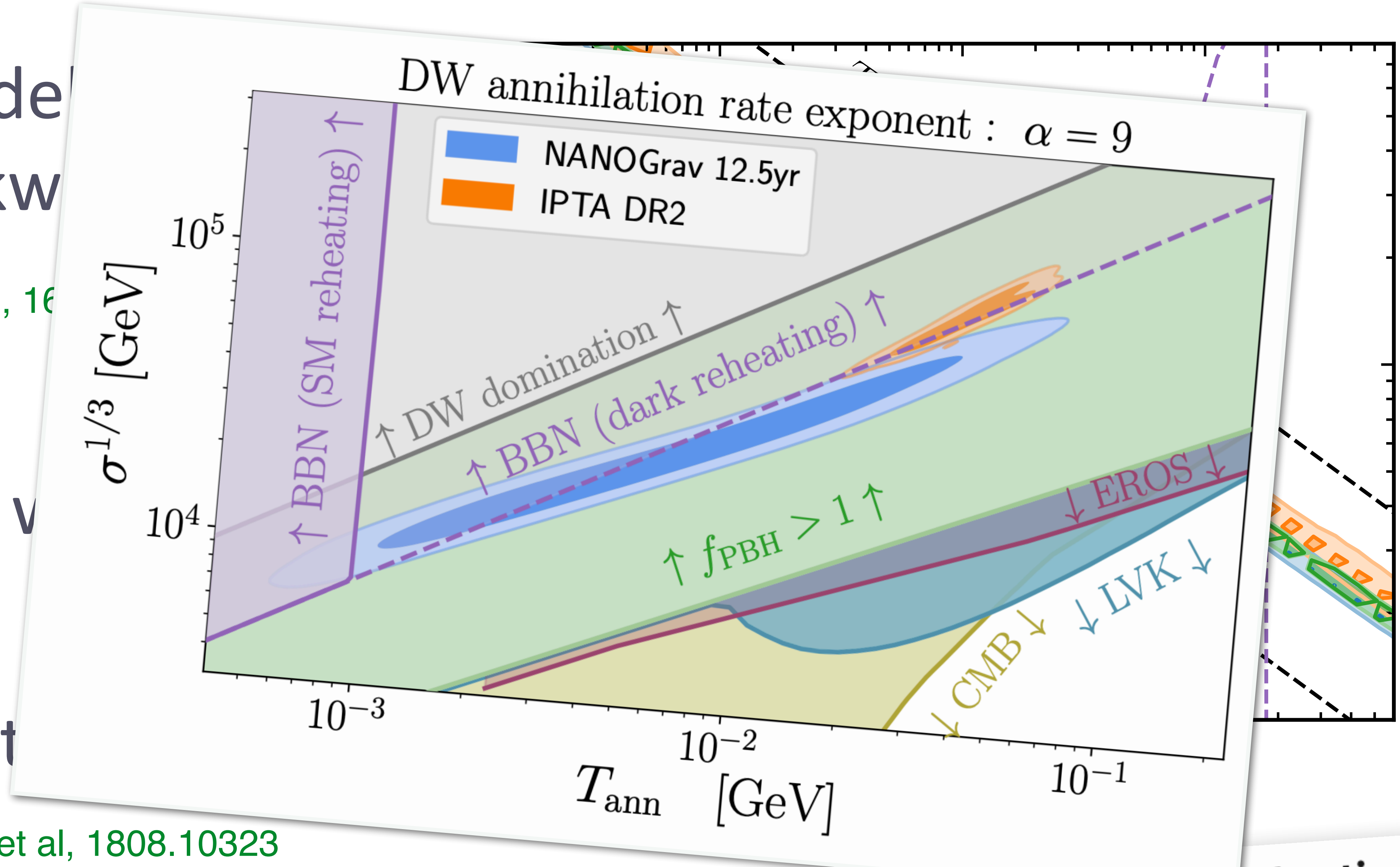
Exciting times :)

Extra slides :)

Axion/ALP domain walls

Madge et al, [2306.14856]

Concrete mode
Aligned/clockw
Axions Higaki et al, 16



Heavy axion
"partners" at v
scale

In reach of fut
colliders Bauer et al, 1808.10323

► Maybe ...

Domain wall interpretation of the PTA signal confronting black hole overproduction

Yann Gouttenoire (Tel Aviv U.), Edoardo Vitagliano (Hebrew U.)

Jun 30, 2023

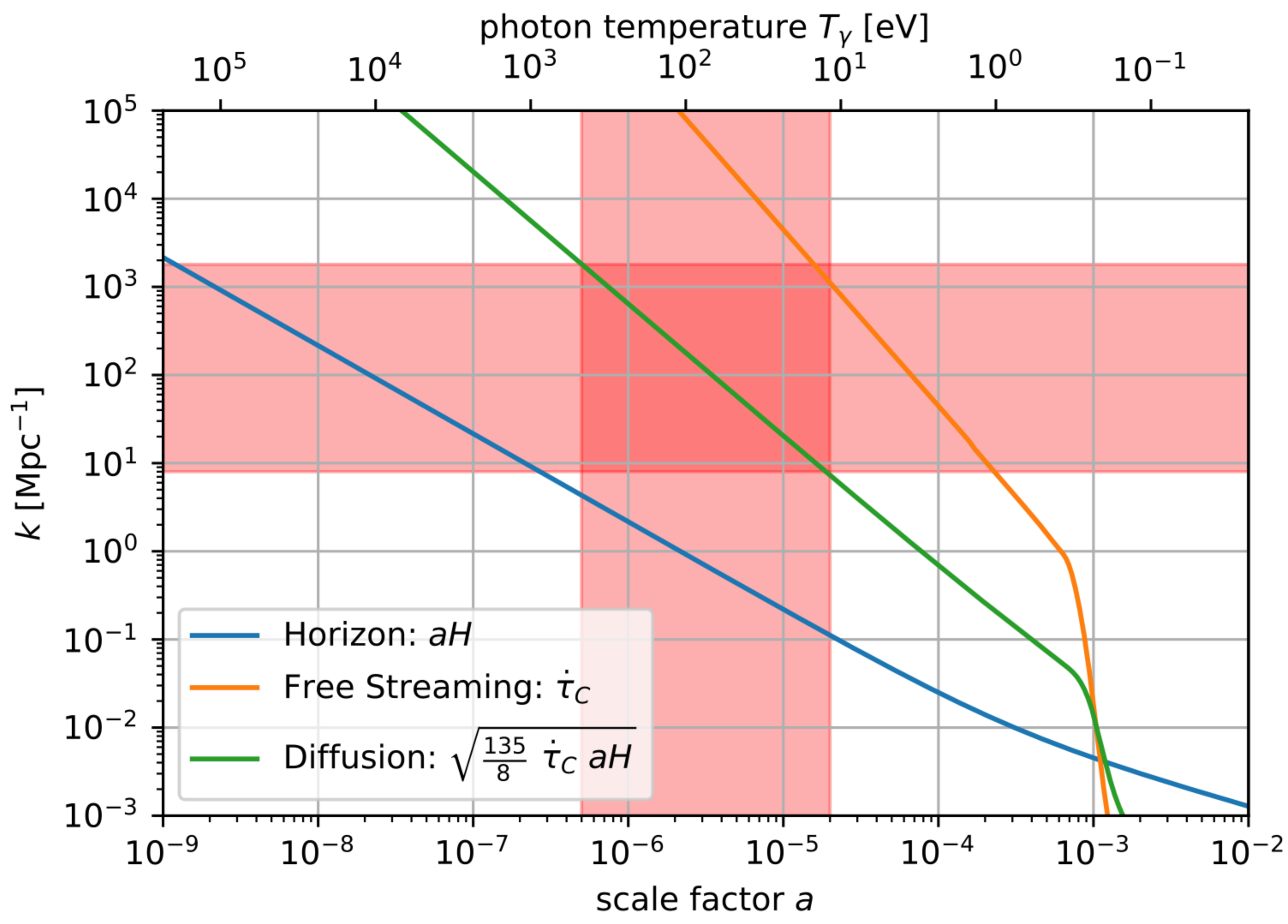
Now what about the spectral distortions?

Spectral distortions?

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

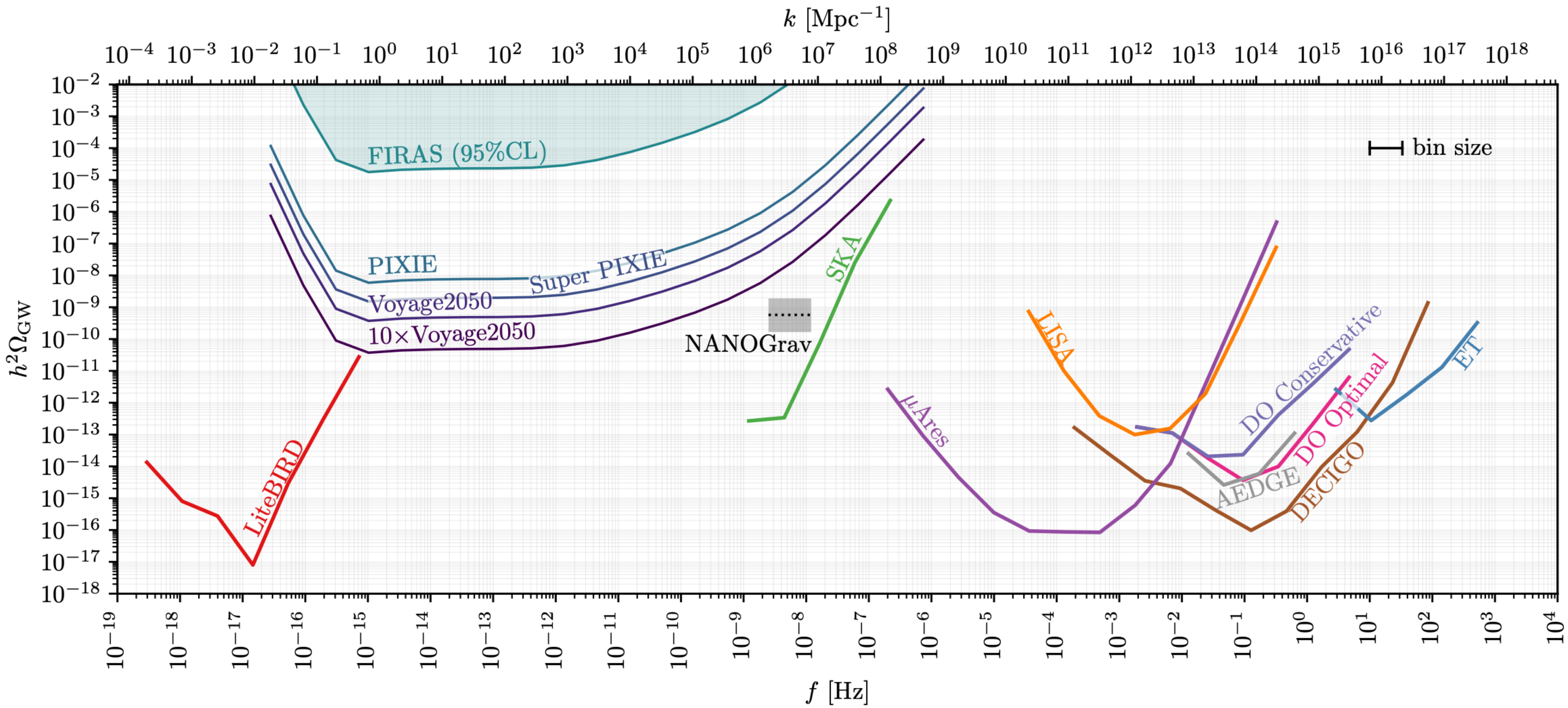
Any energy added to the photons leads to a so called μ distortion

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

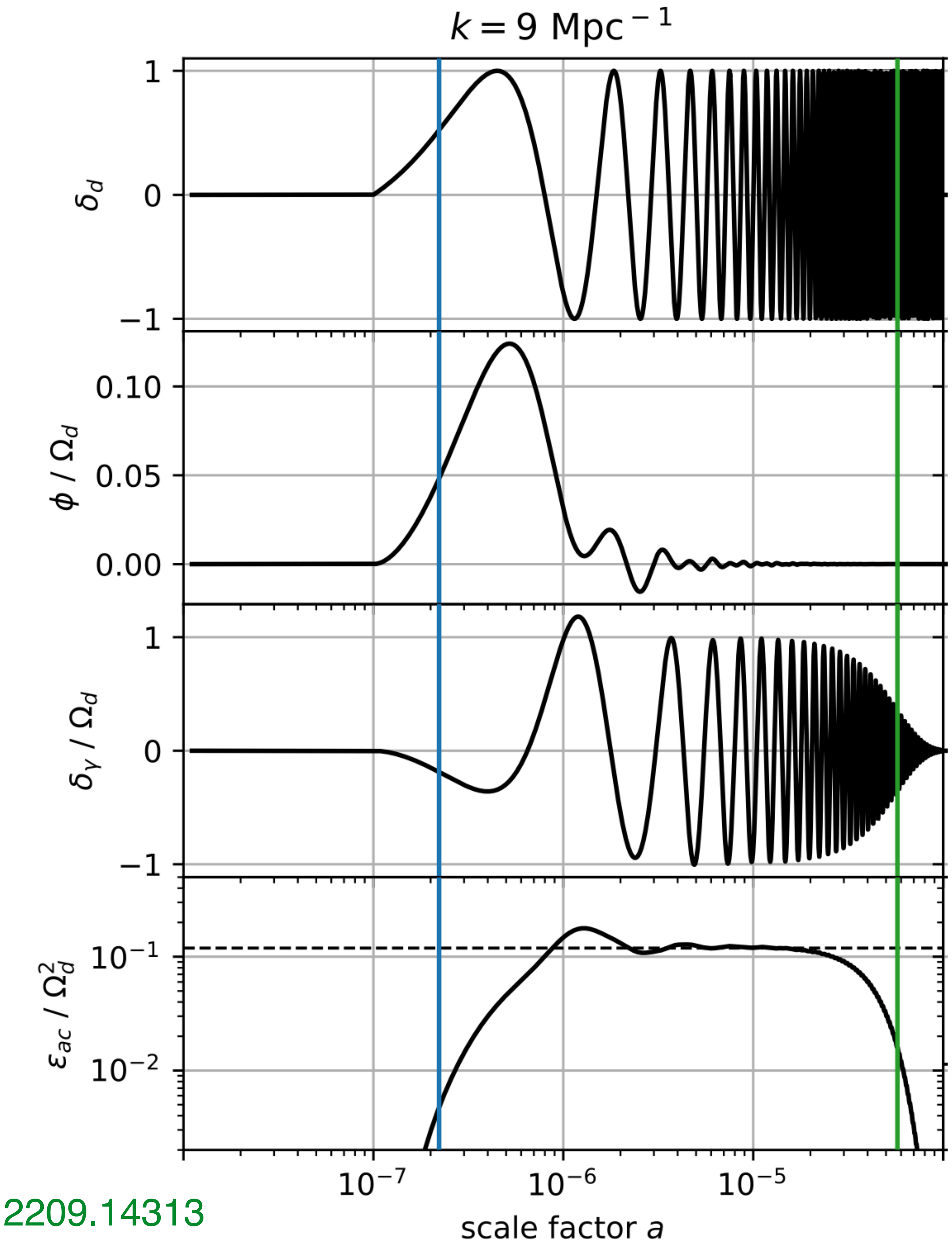
Assume decoupled dark sector, $\Omega_d \ll 1$

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

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

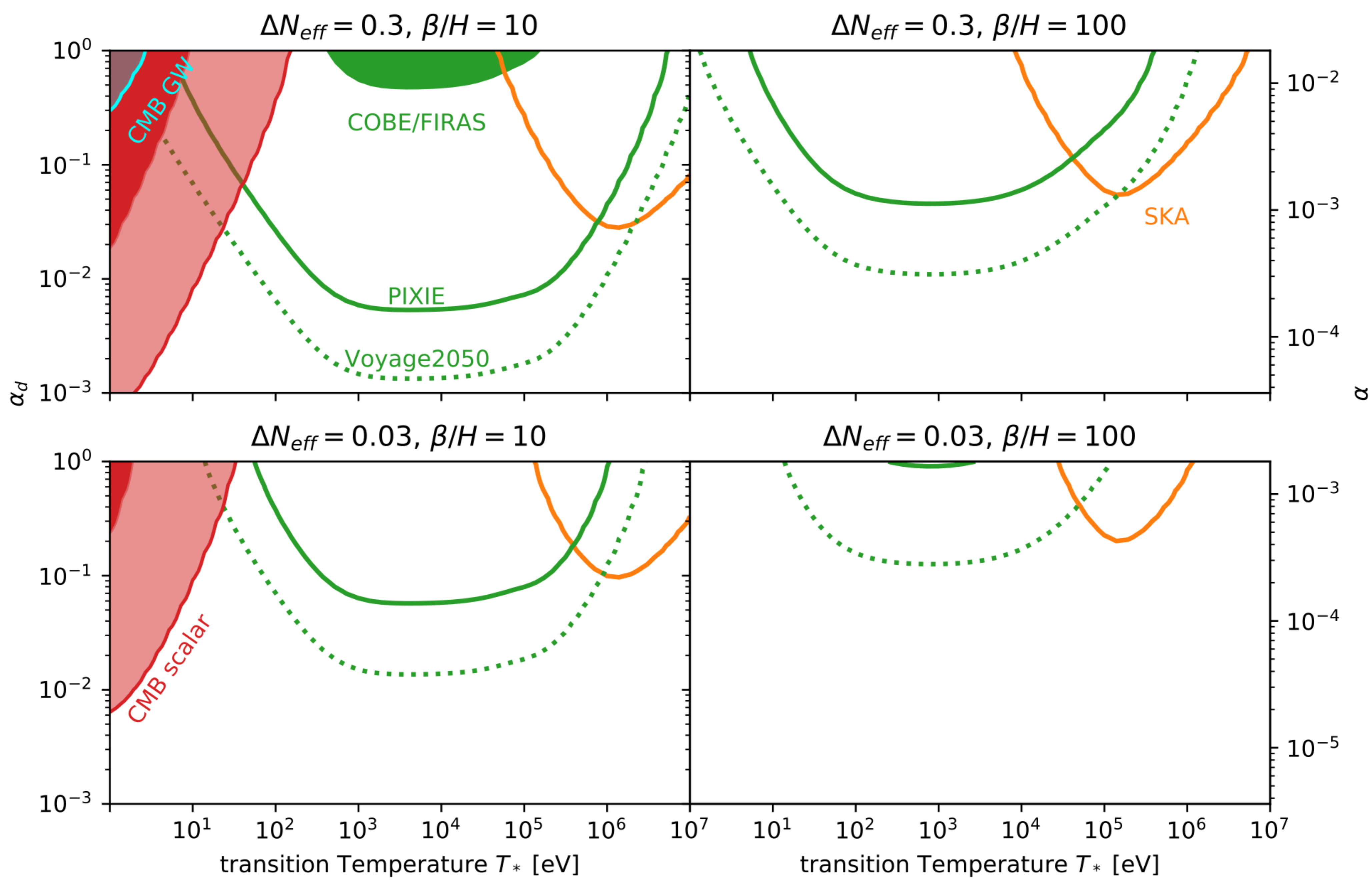
Resulting μ distortions

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



Ramberg, Ratzinger & PS, 2209.14313

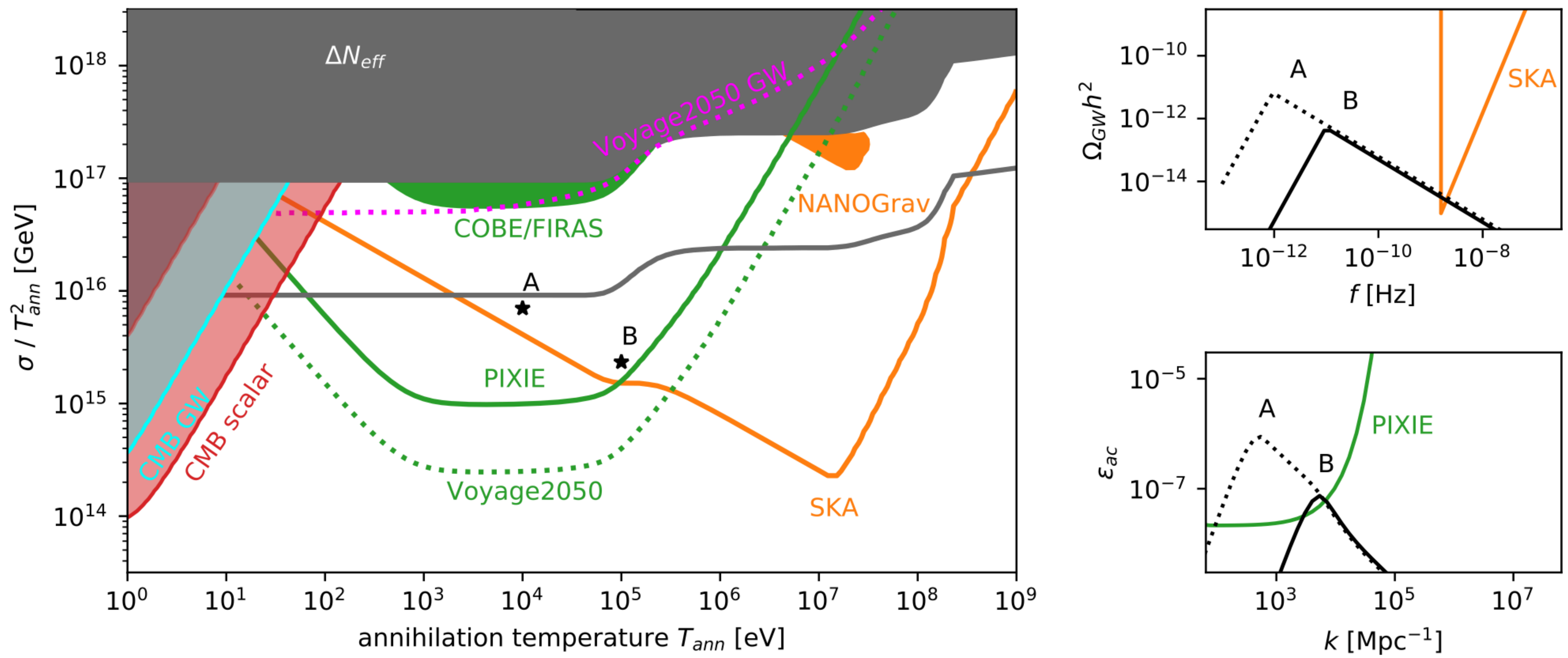
Example source I: Dark sector phase transition



Note: Ω_d fixed to satisfy $N_{\rm eff}$ constraints

Ramberg, Ratzinger & PS, 2209.14313

Example source II: Annihilating domain walls



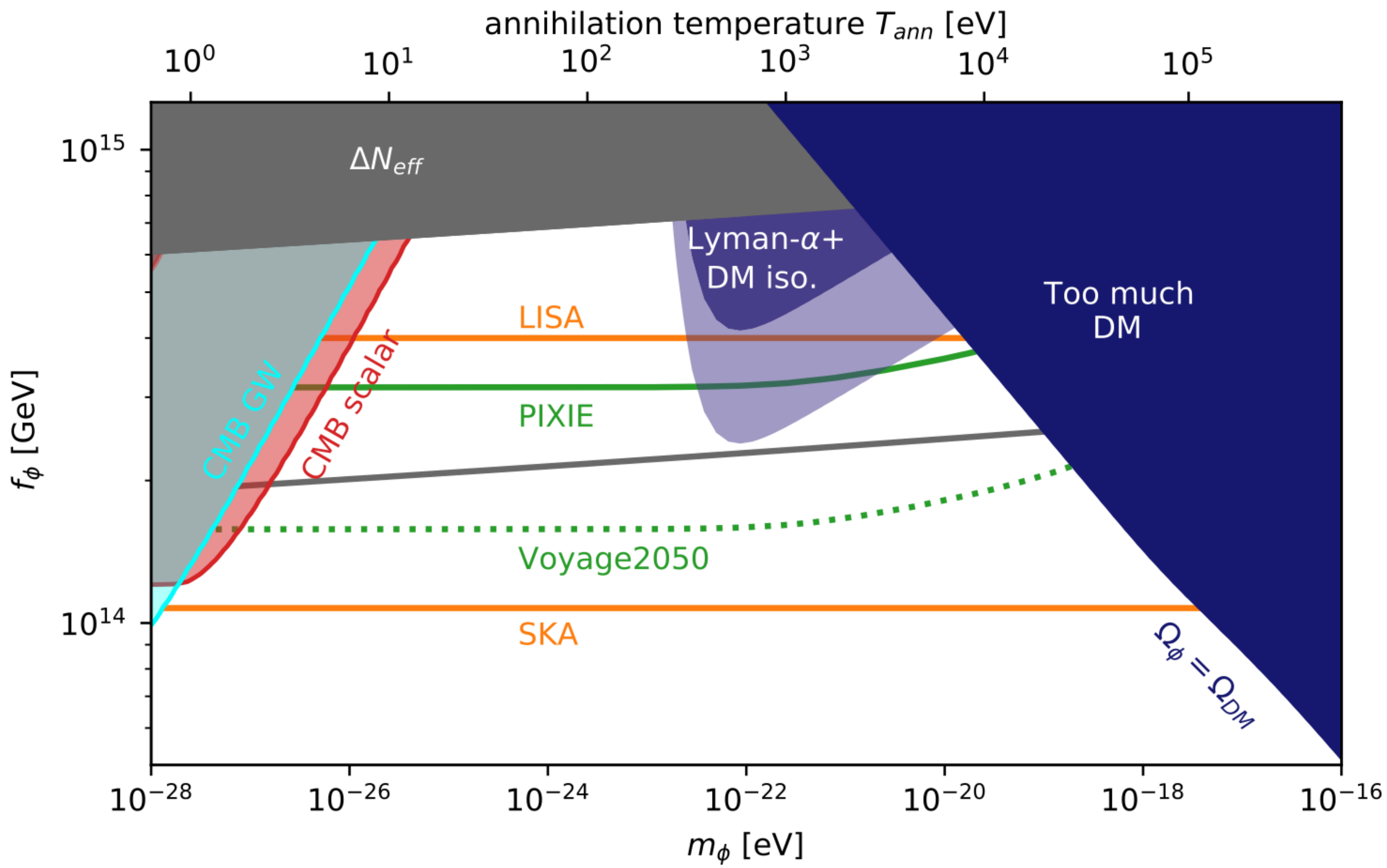
Already probes allowed parameter space

Complementary to GW probes, can break degeneracy

- Multi-messenger cosmology

Ramberg, Ratzinger & PS, 2209.14313

Source III: (global) cosmic strings



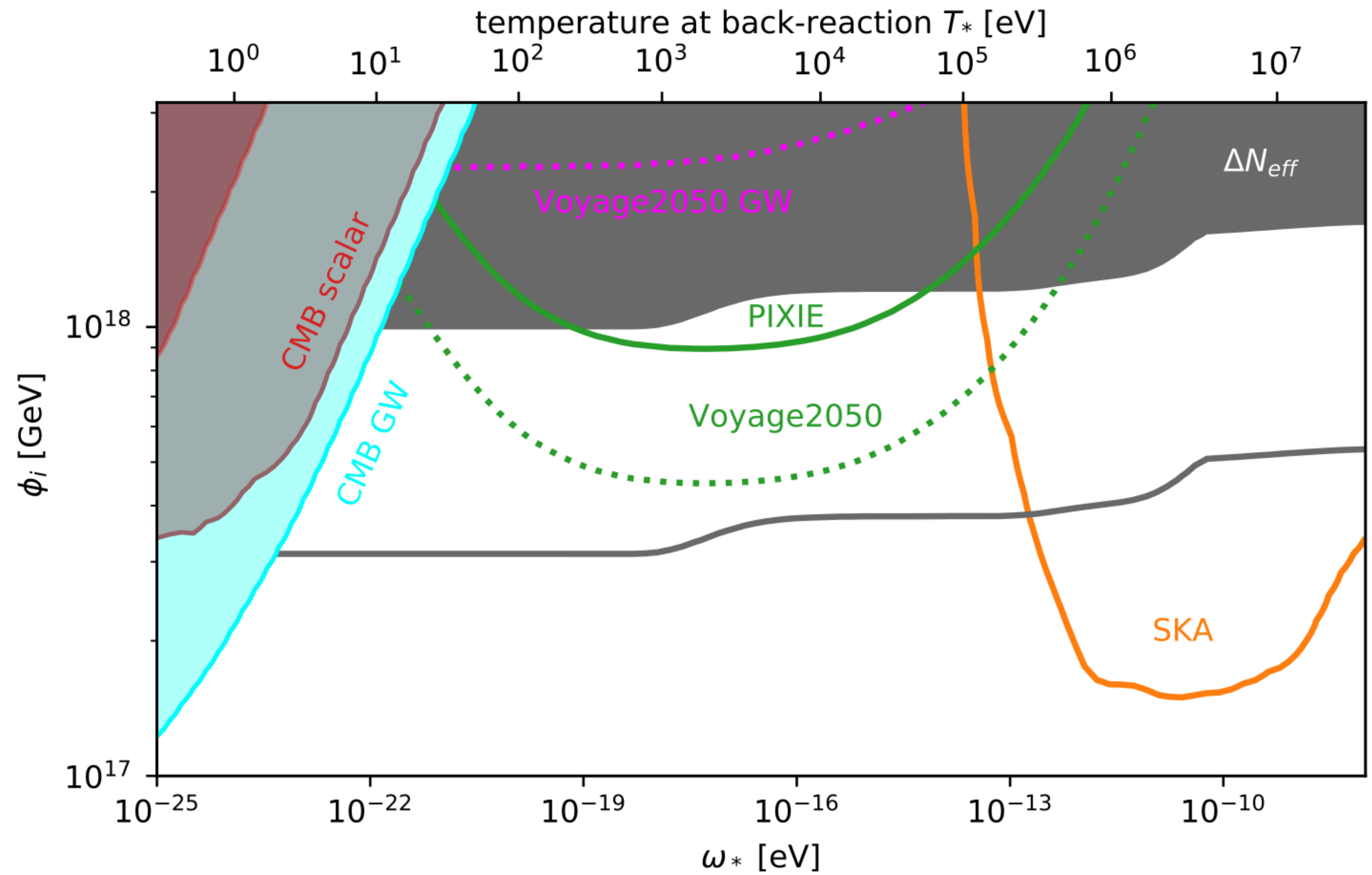
Note: Local strings mainly radiate from small loops and are thus NOT an efficient source of spectral distortions

Example source IV: Audible axions…

Not yet…

Results for scalar toy model

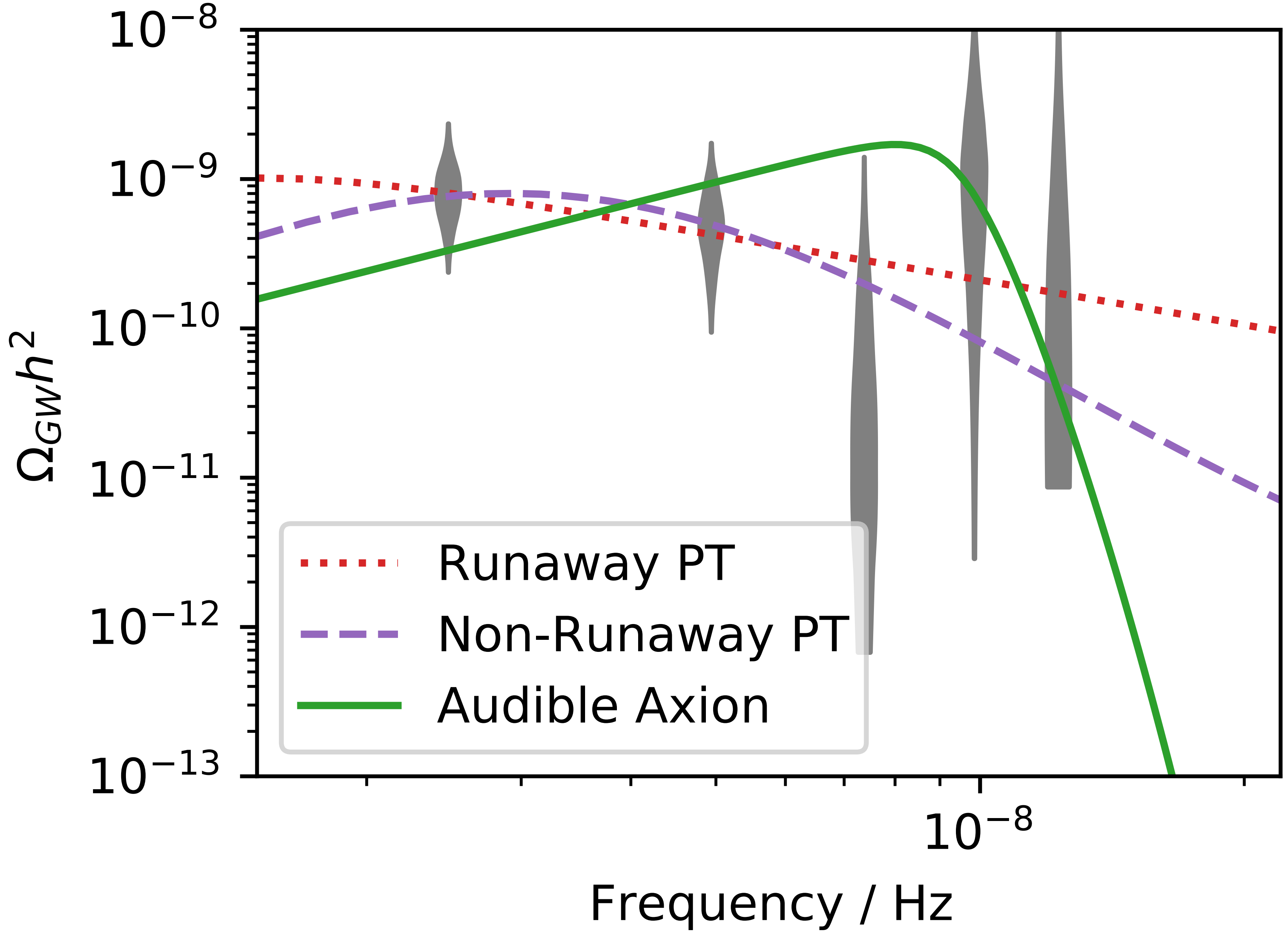
Constraints not as strong since fluctuations are not horizon size



Expect better sensitivity for axion fragmentation

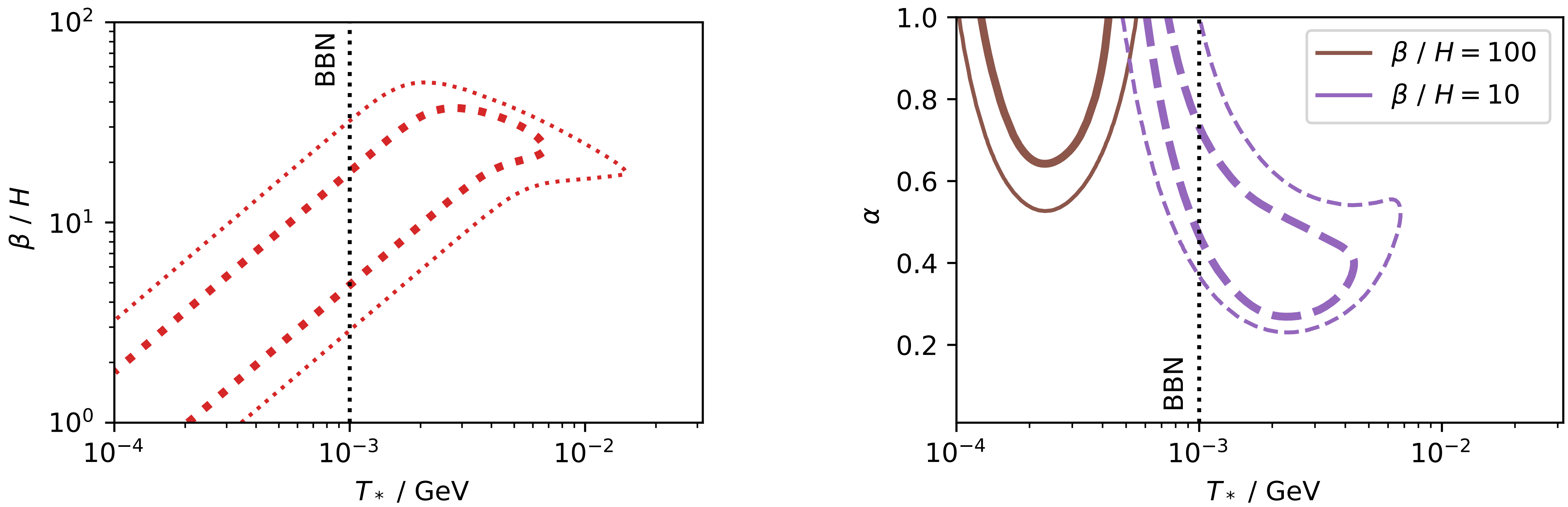
Ramberg, Ratzinger & PS, 2209.14313

Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition

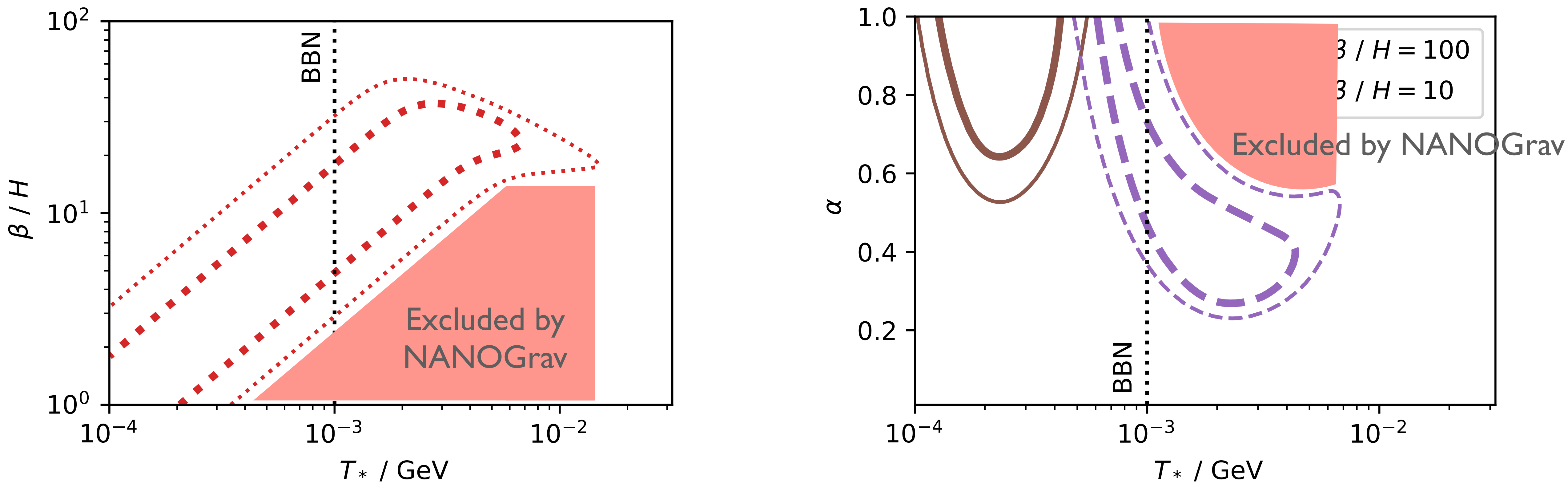


Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Challenge for model building → Hint for dark sector

Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



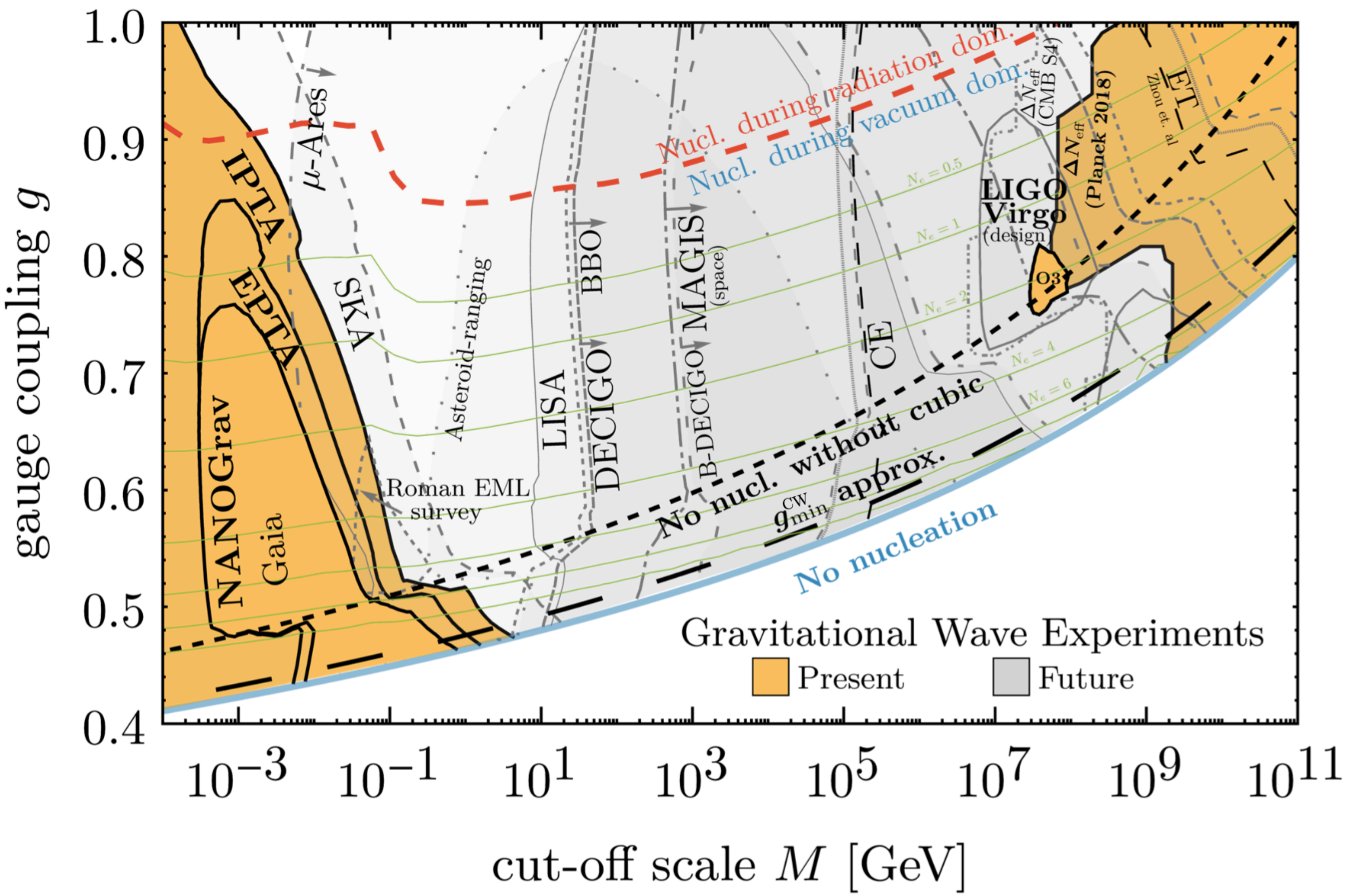
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

Some model parameters excluded by PTA data now!

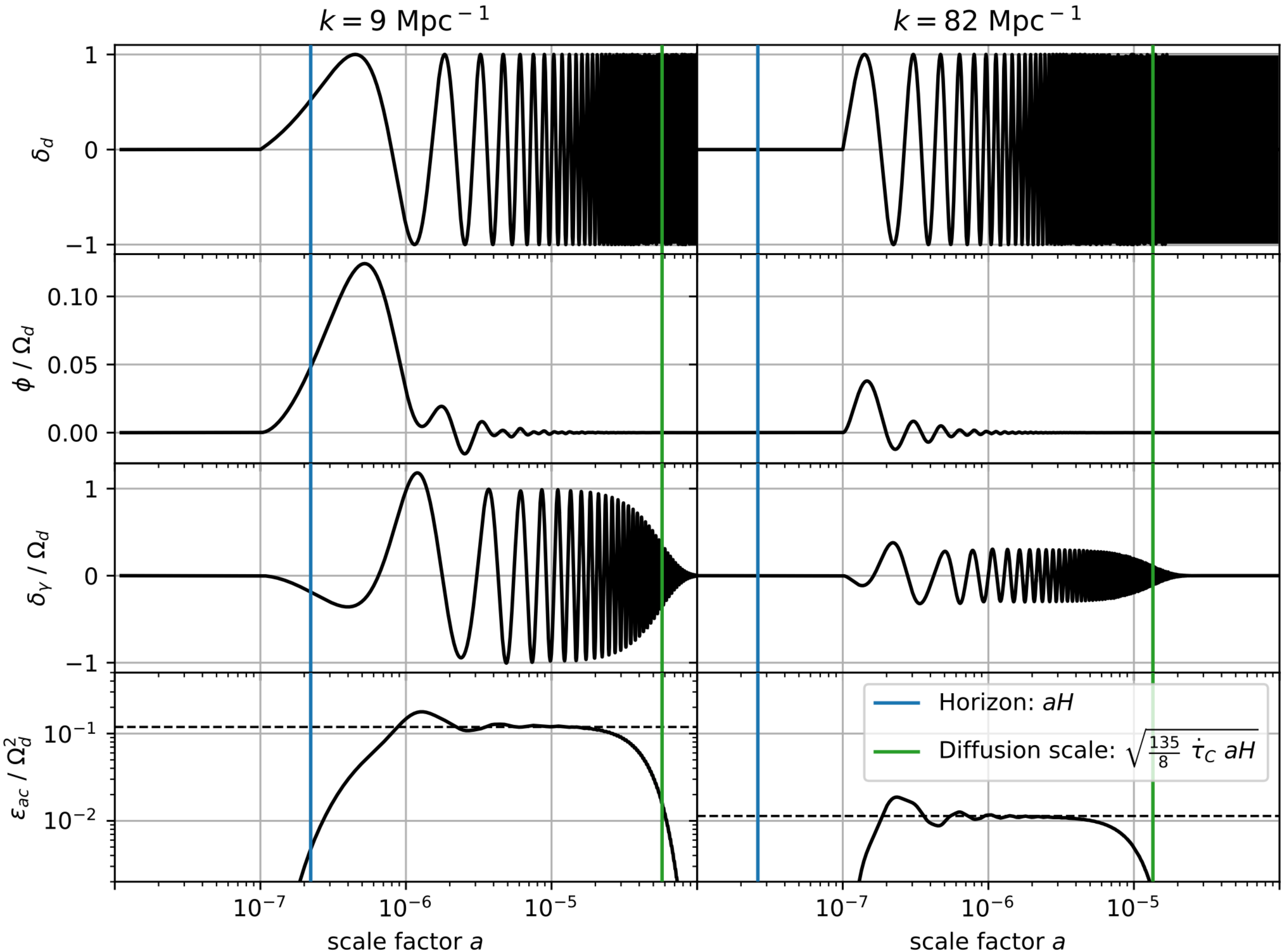
Wolfram Ratzinger & PS, 2009.11875

At higher frequencies

Levi, Opferkuch, Redigolo, 2212.08085



LISA will probe above 10 GeV, colliders could fill gap

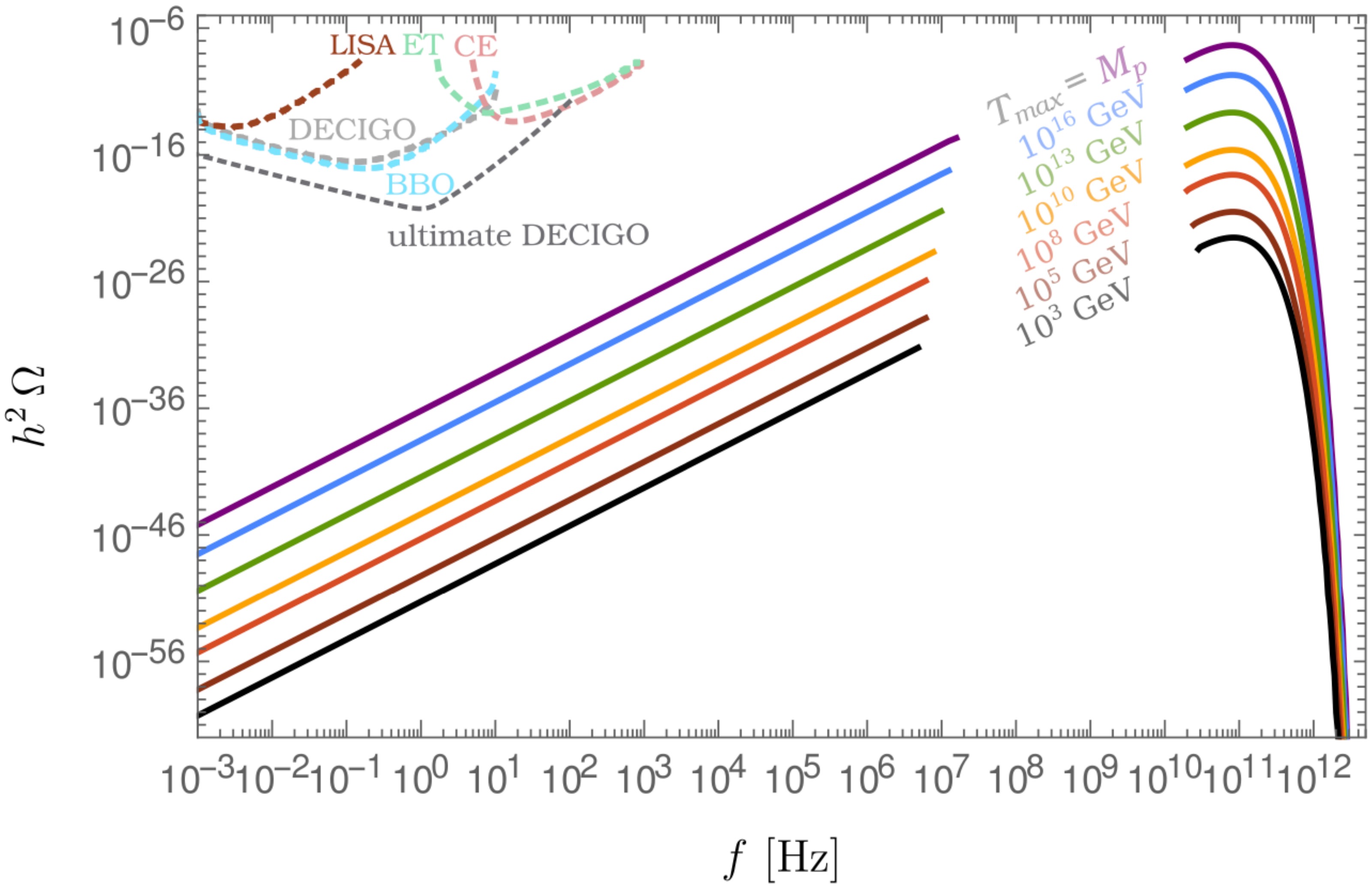


$k = 9$ Mpc^{-1}
$k = 82$ Mpc^{-1}
δ_d
ϕ / Ω_d
δ_γ / Ω_d
ϵ_{ac} / Ω_d^2
Horizon: aH
Diffusion scale: $\sqrt{\frac{135}{8}\ \dot{\tau}_C\ aH}$
scale factor a

Standard model

The hot early Universe sources GWs!

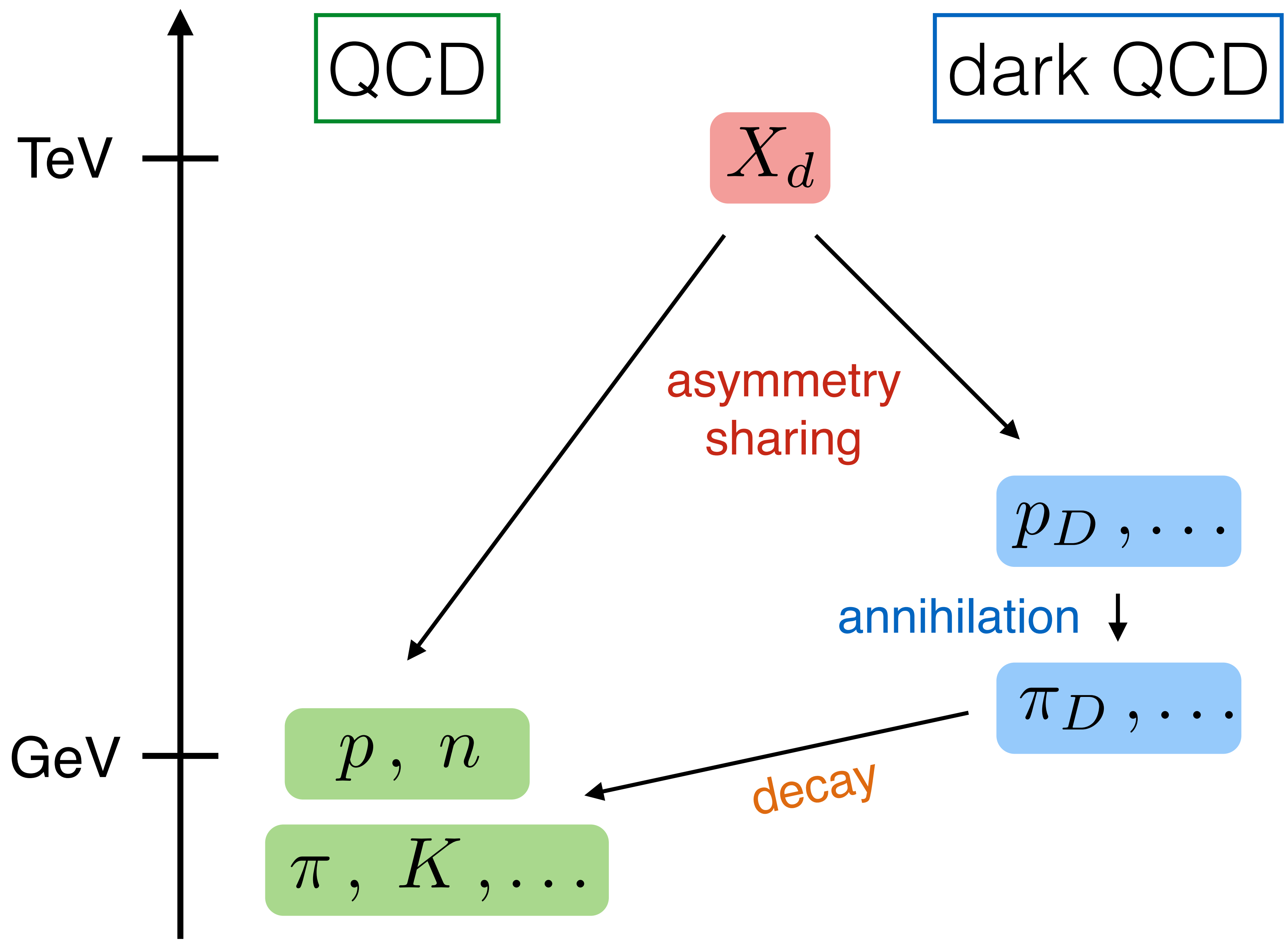
- Classical picture: thermal fluctuations source tensor fluctuations
- Quantum picture: gluon + gluon -> graviton



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;…

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

- $N_d \geq 3\,,\quad 3 \leq n_f < 4N_d$

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

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

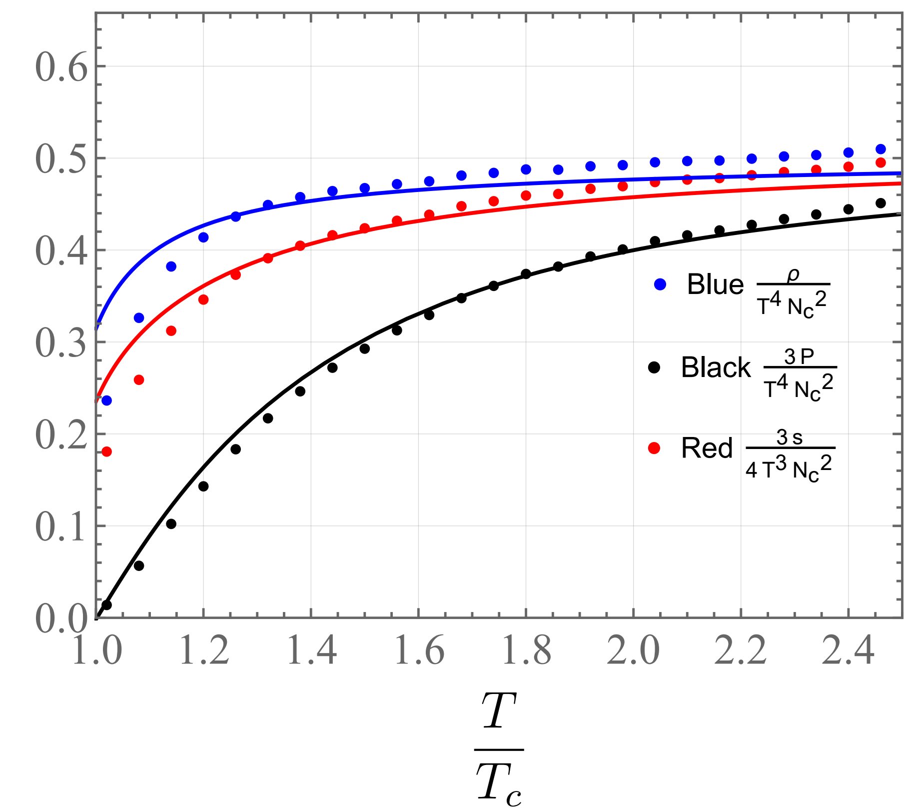
Want this to reproduce SU(N) theories

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

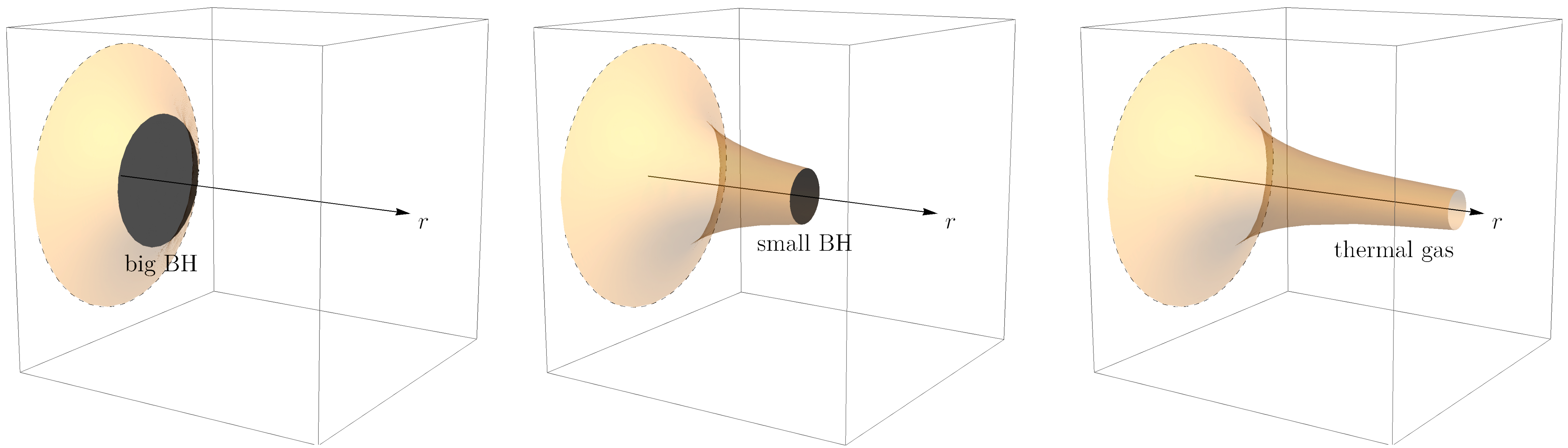
$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

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



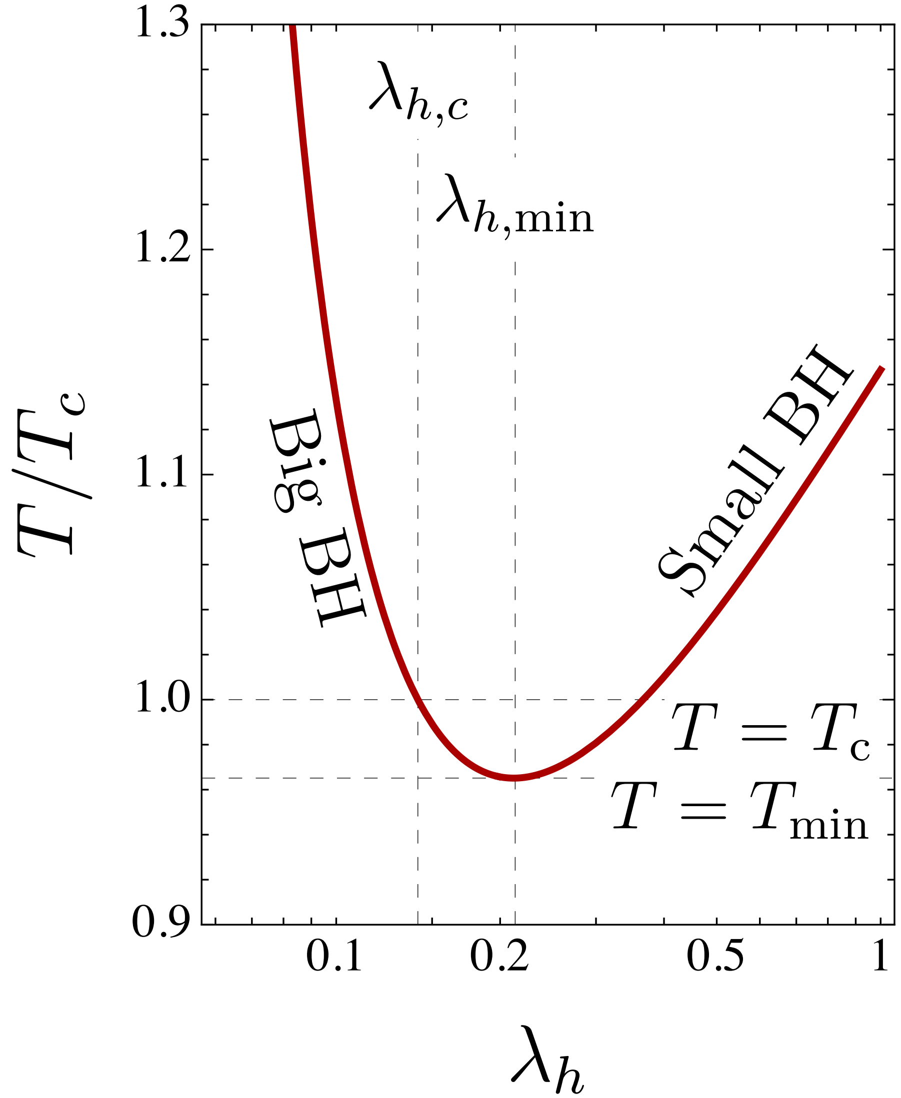
The phase transition in ihQCD

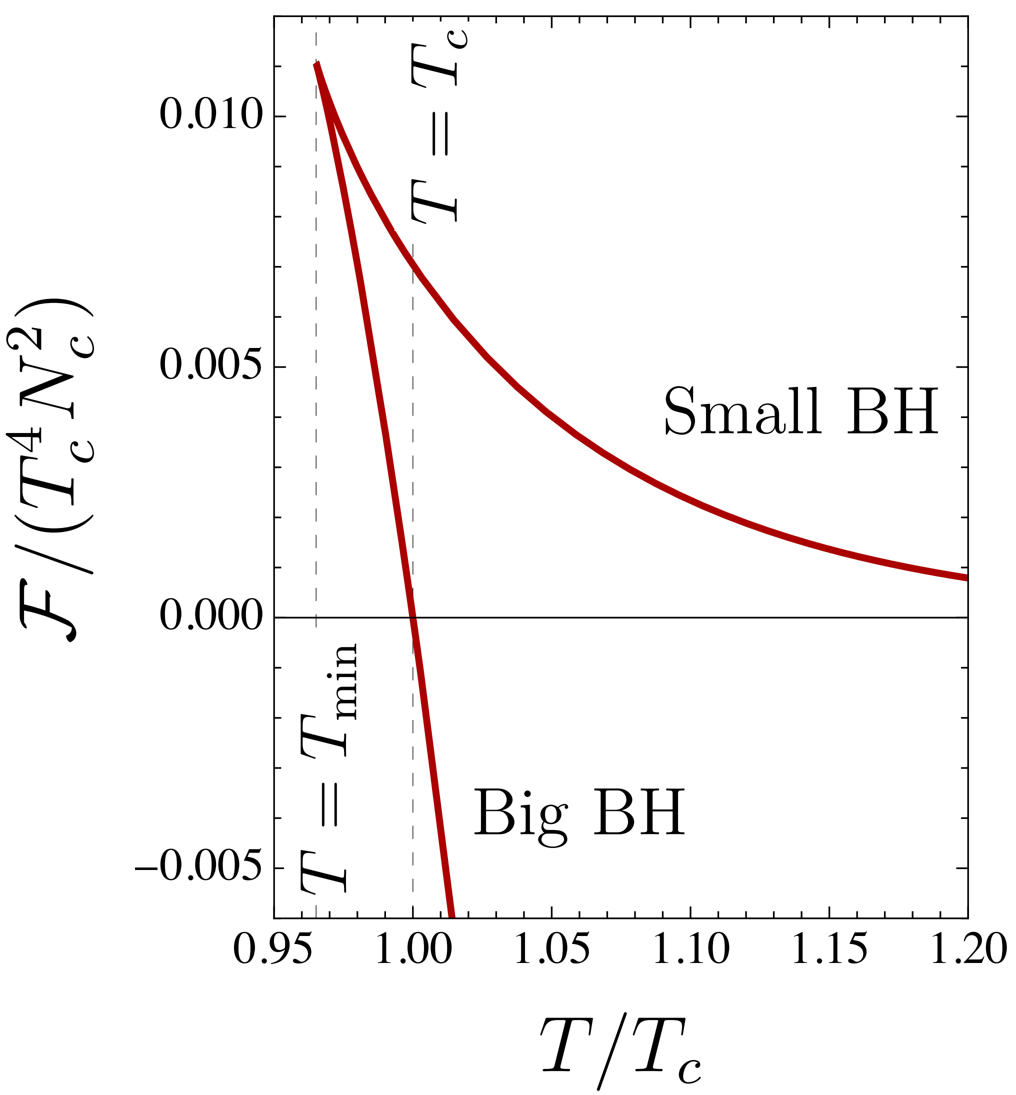


Three solutions

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

The phase transition in ihQCD II



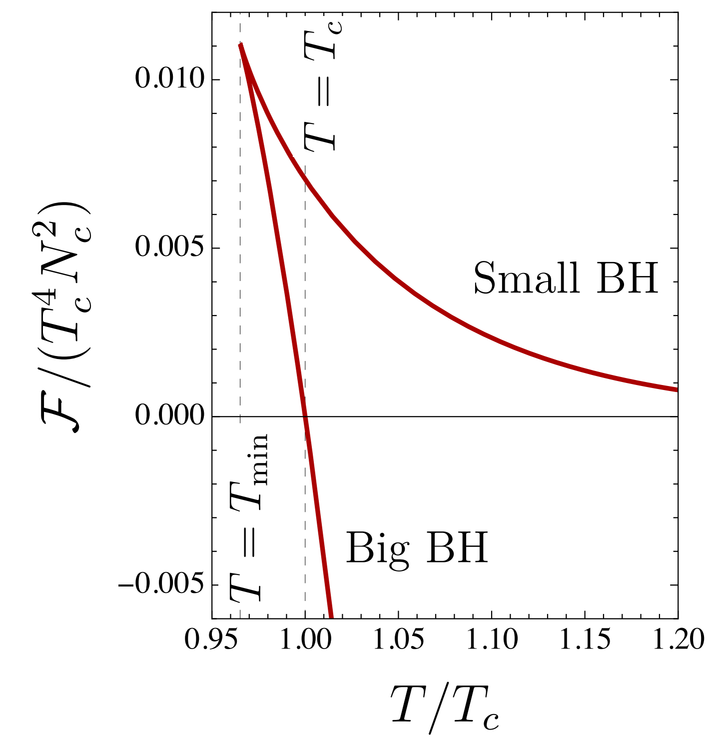


At $T = T_c$, deconfined phase becomes meta-stable

Morgante, Ramberg, PS, 2210.11821

The phase transition in ihQCD III

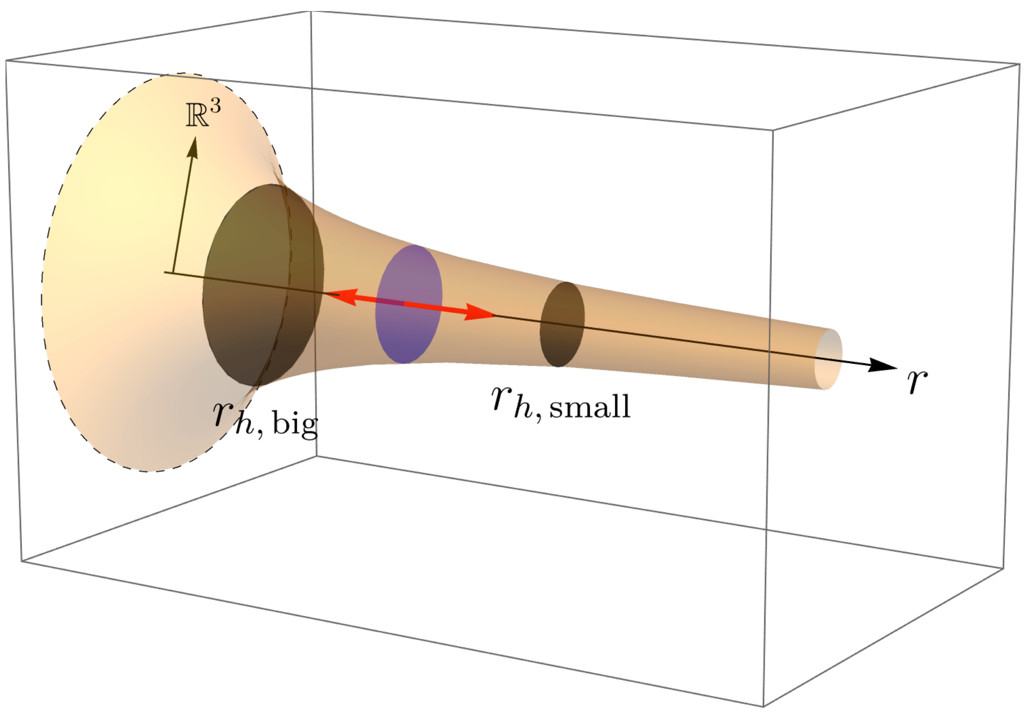
Hawking Page transition, with small BH acting as instanton



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

GWs from Phase Transitions

QFT at finite temperature ➞ symmetry restoration

For first order PT

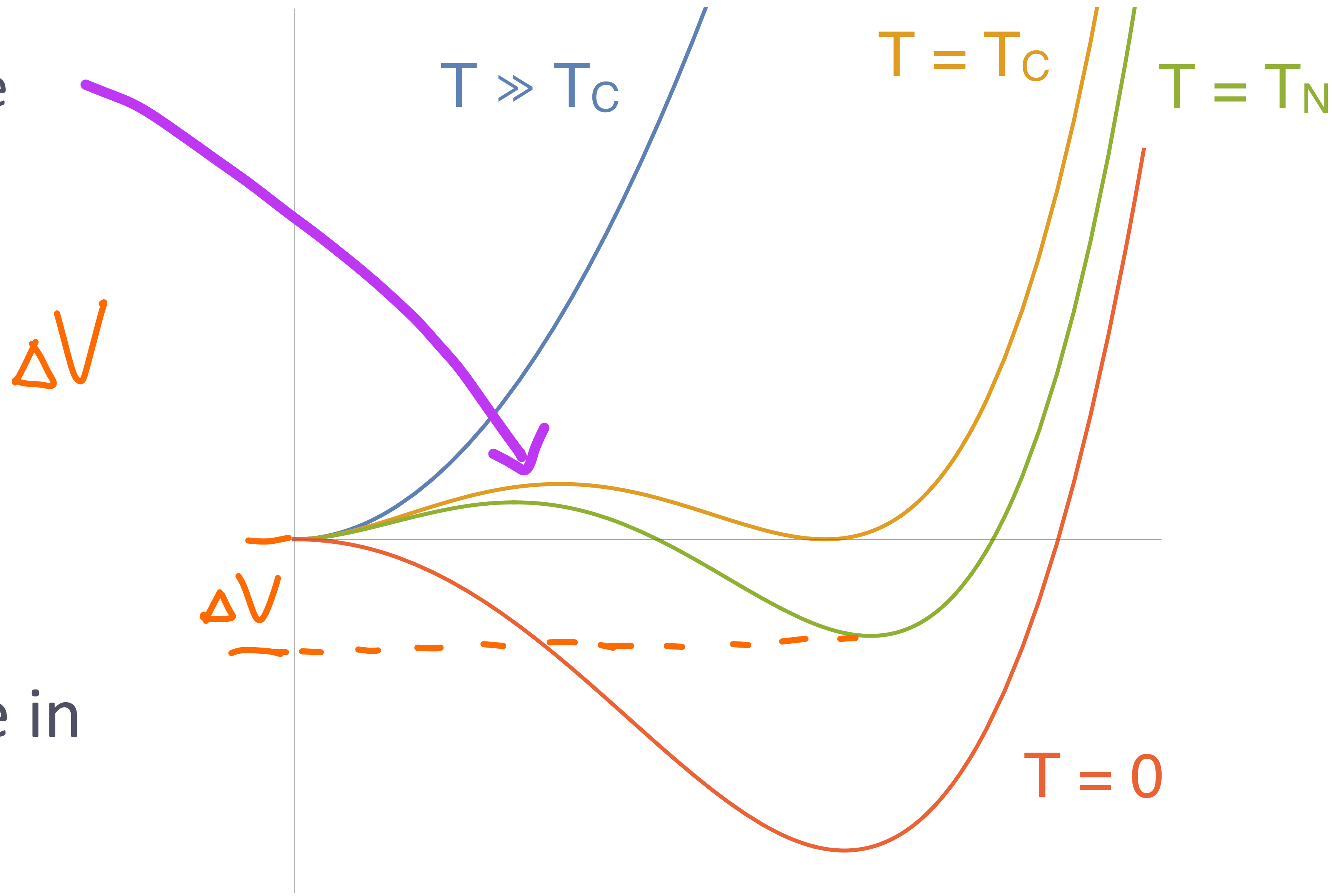
- Need barrier here

PT occurs at T_N

Potential energy

GWs

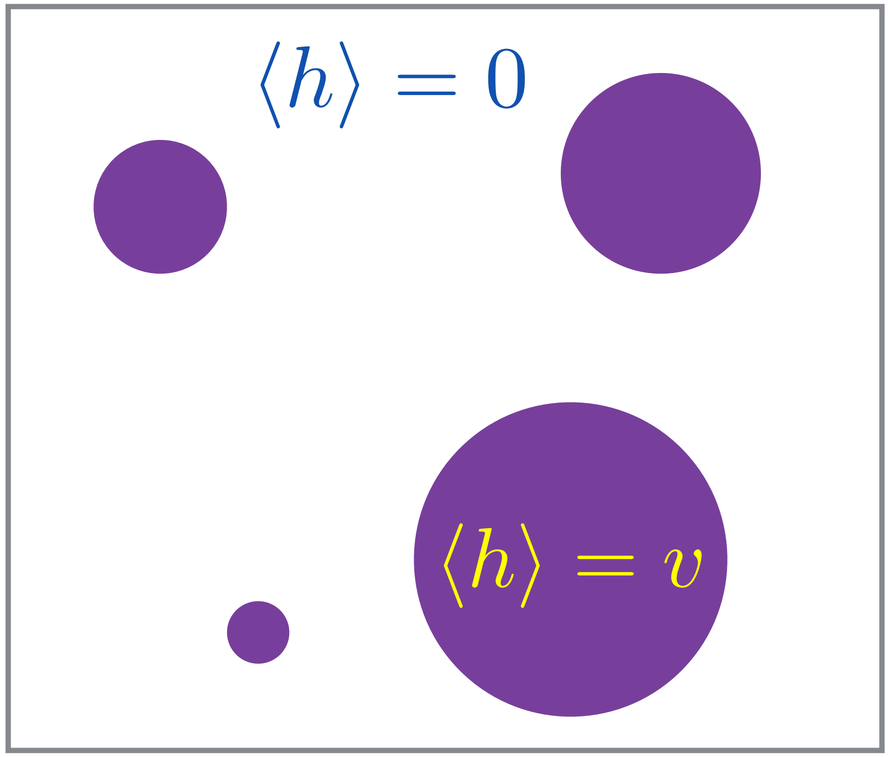
Not in SM! Possible in
 BSM scenarios

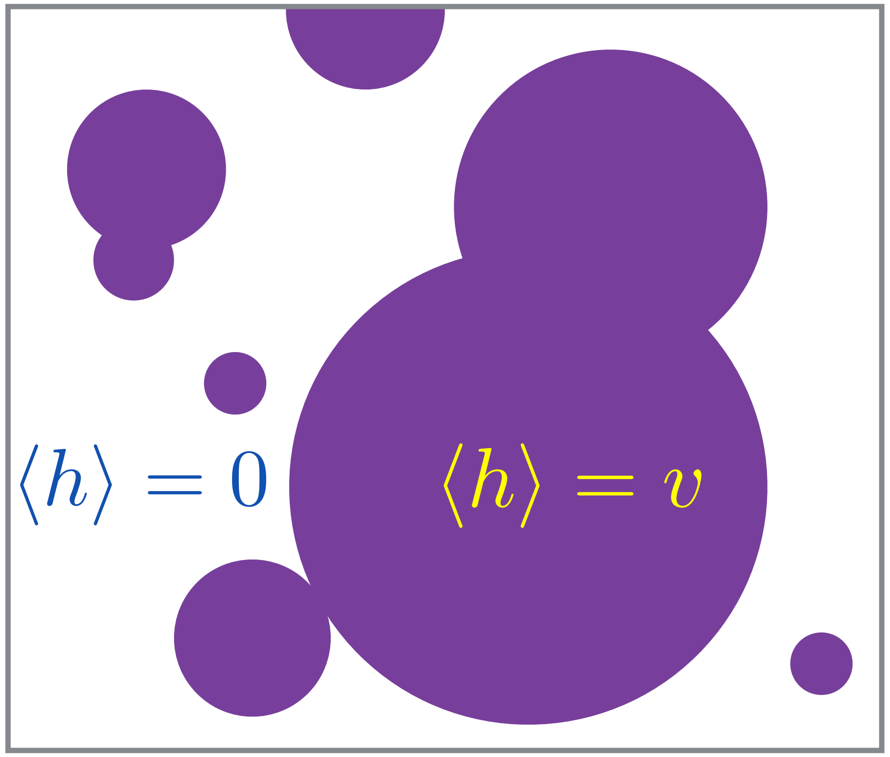


GWs from Phase Transitions

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves

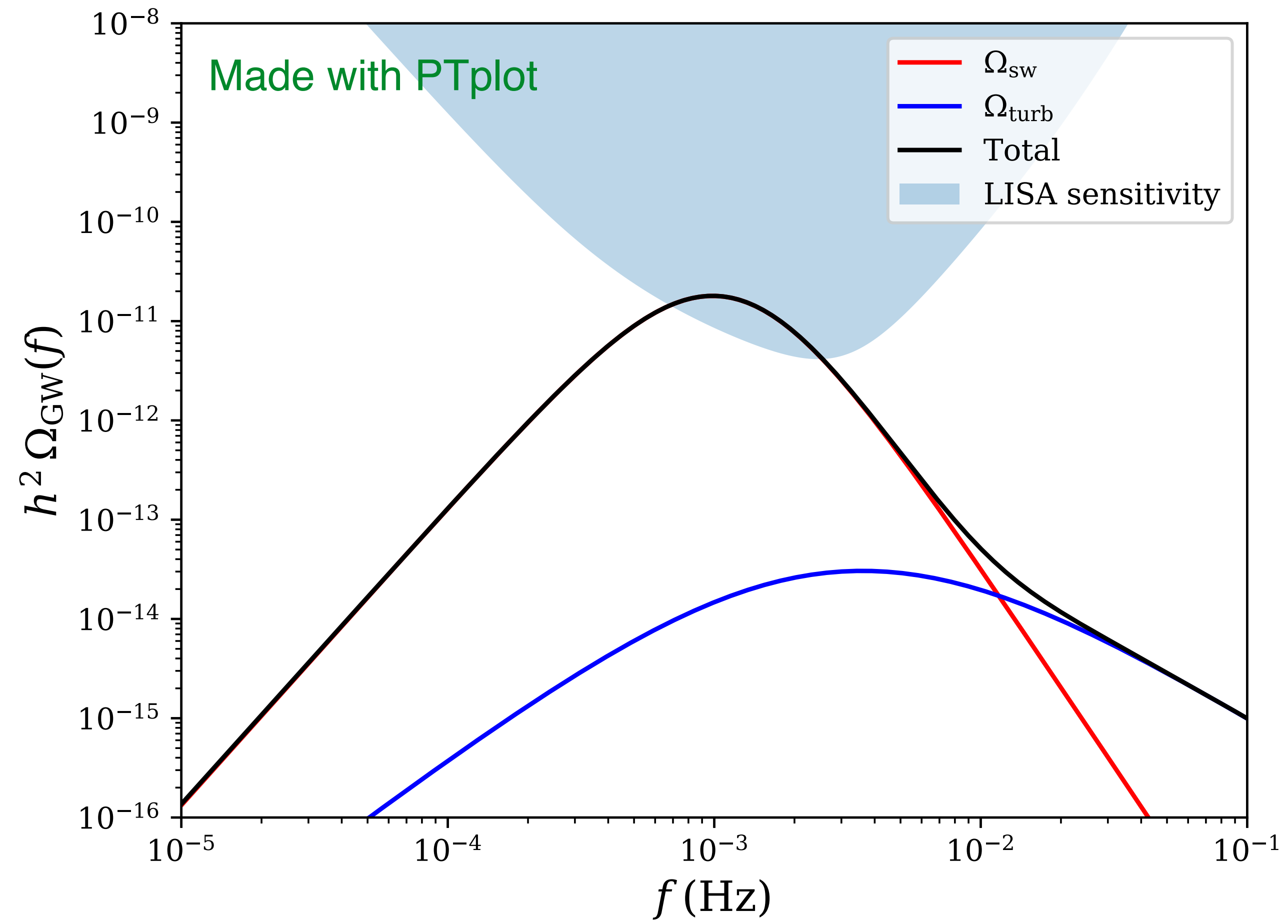




PT signal

PT characterised by few parameters:

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



More details, see e.g.:

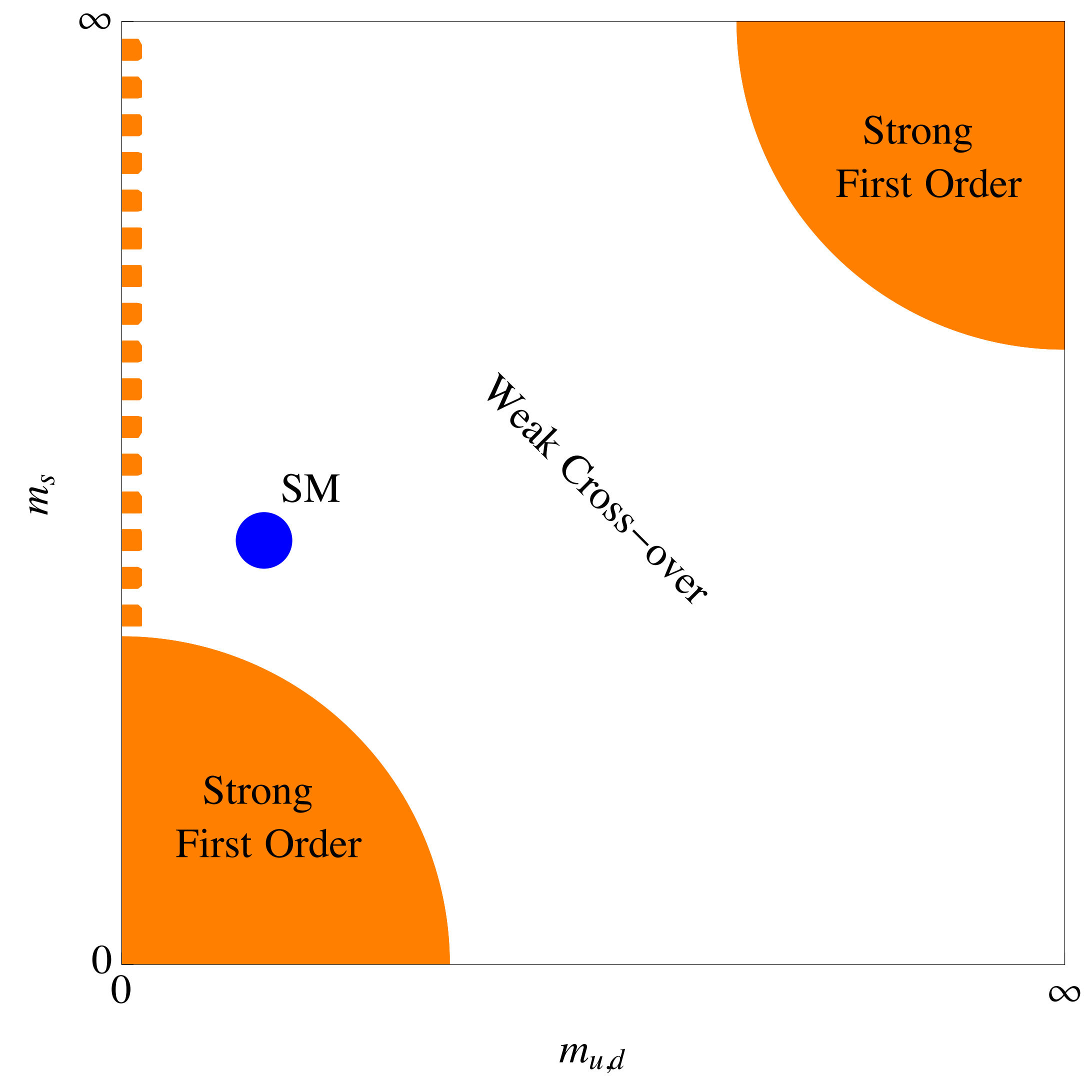
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Can this be from the QCD phase transition?

QCD phase transition?

The short answer is NO

- QCD PT is a smooth cross-over



PS, 2016

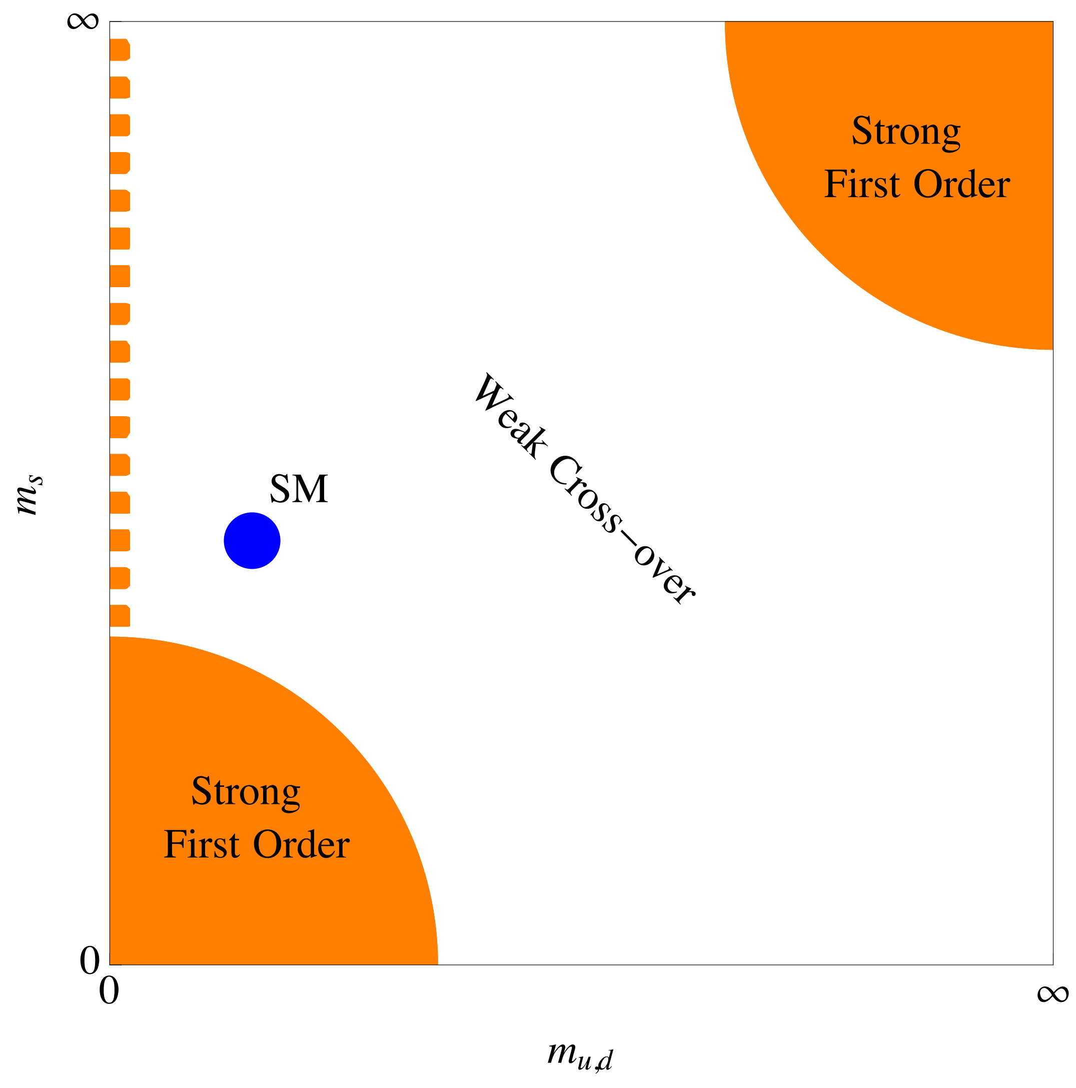
QCD phase transition?

The short answer is NO

- QCD PT is a smooth cross-over

The longer answer:

- QCD PT can be first order in presence of large lepton asymmetry
- Or if EWPT is delayed
- Or if it is not QCD but a QCD-like dark sector



PS, 2016

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, ...

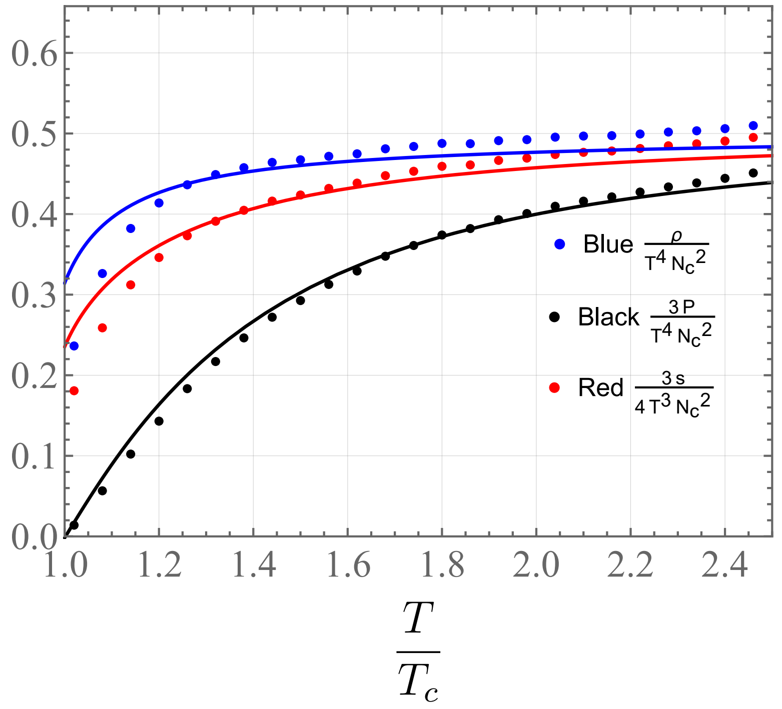
$$\mathcal{S}_5 = -M_P^3 N_c^2 \int d^5x \sqrt{g} \left[R - \frac{4}{3}(\partial\Phi)^2 + V(\Phi) \right] + 2M_P^3 N_c^2 \int_{\partial M} d^4x \sqrt{h} K$$

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

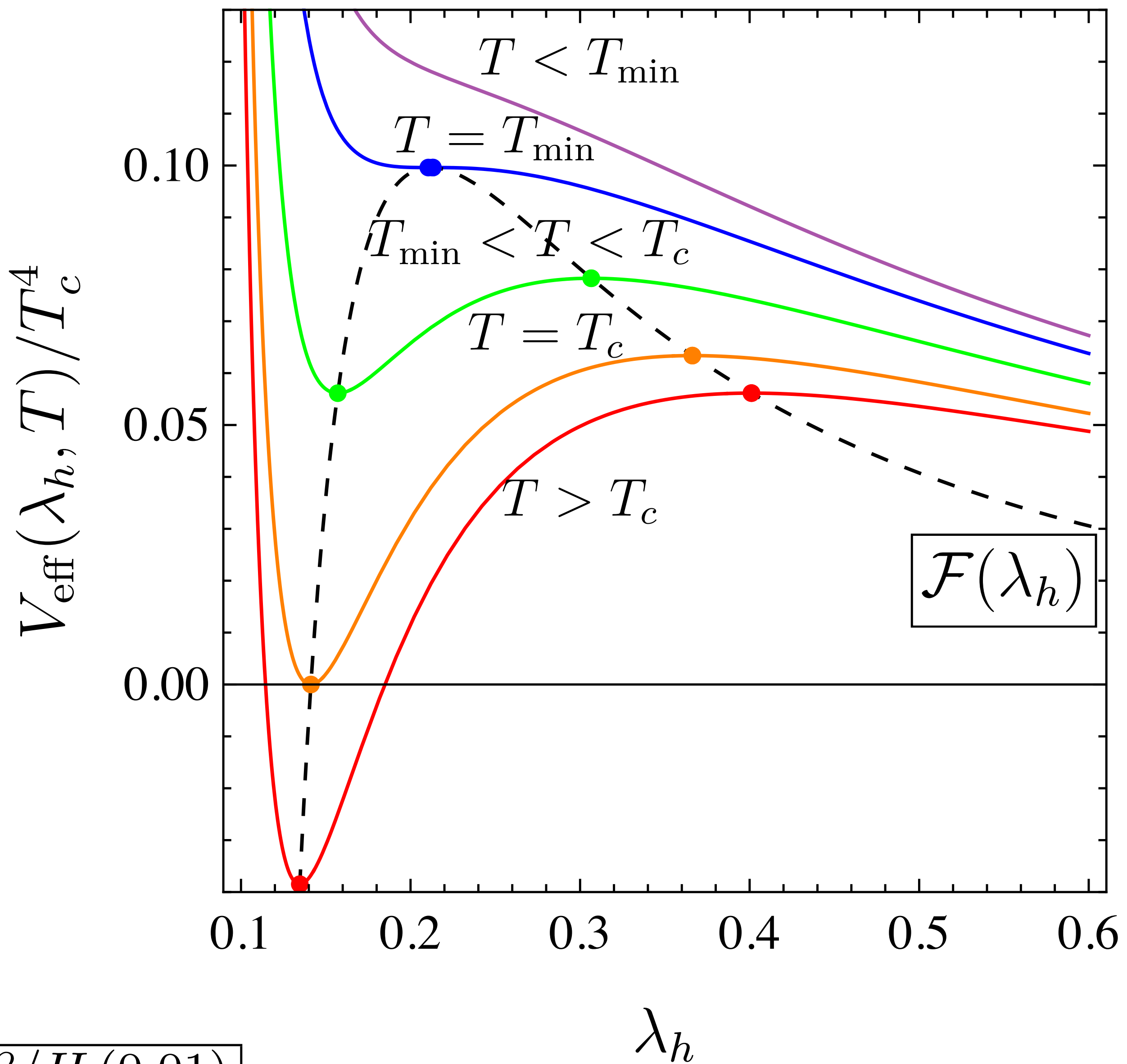
Bounce action

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

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
$100\,\text{GeV}$	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)