GRAVITATIONAL WAVES FROM A DARK SU(3) PHASE TRANSITION

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UZH & ETH

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Overview

Motivation for confining/QCD-like dark sectors

The confinement/deconfinement phase transition (PT)

- Gravitational waves from a first order PT
- The NANOGrav GW hint for a low scale PT

Towards quantitative predictions of GWs in strongly coupled PTs

With Enrico Morgante, Nicklas Ramberg, 2210.11821

Why should you care about dark SU(N)

Top down perspective:

- Many string compactifications contain hidden sectors with new gauge symmetries
- Straightforward extension of SM

Useful for model building

- LHC-safe solutions to the hierarchy problem (twin Higgs…)
- Axion models and composite axions, relaxion

Interesting (&new) phenomenology

- DM with self-interactions, SIMP mechanism
- Unique collider signatures…

Composite/QCD-like DM

Alternative to elementary WIMP models

Phenomenologically viable, “generic” possibility in presence of hidden sectors

Some nice features:

- DM stability, mass scale
- Self interactions, unique collider pheno
- Natural implementation of SIMP mechanism (3->2 annihilation)
- Glueball dark matter

e.g. Bai, PS, 2014
PS, Stolarski, Weiler, JHEP 2015

Hochberg, Kuflik, Murayama, Volansky, Wacker, 2014
…

e.g. Soni, Zhang, 2016
Asadi, Kramer, Kuflik, Slatyer, Smirnov, 2022
Carenza, Pasechnik, Salinas, Wang, 2022

Models I'm interested here

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

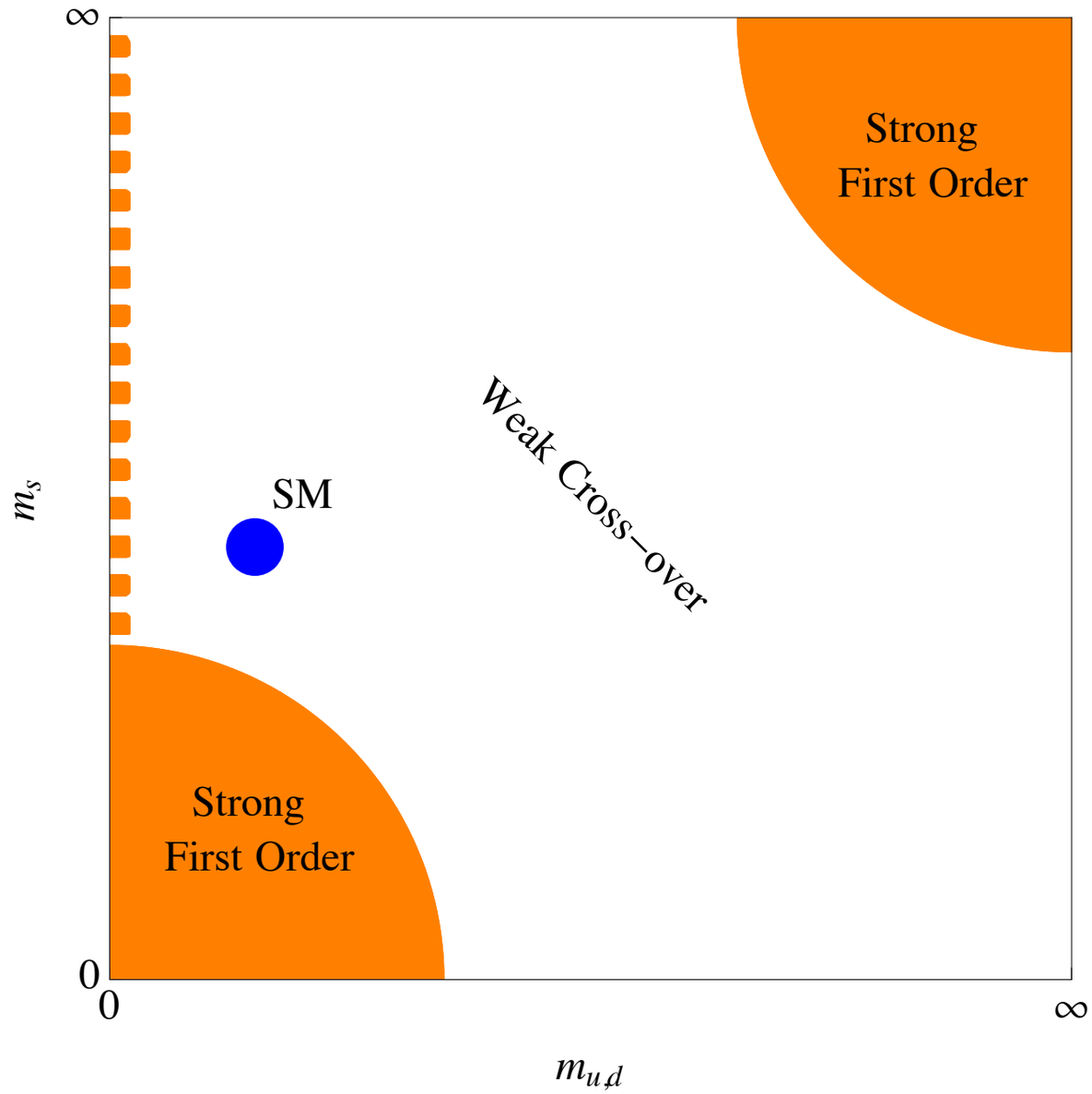
n_f light/massless **dark** quarks

$n_f = 0$	$n_f > 0$
Glueball DM	Dark Baryons or Dark Pions
PT from center symmetry restoration	Chiral Symmetry Breaking

A new PT is a robust prediction of these scenarios

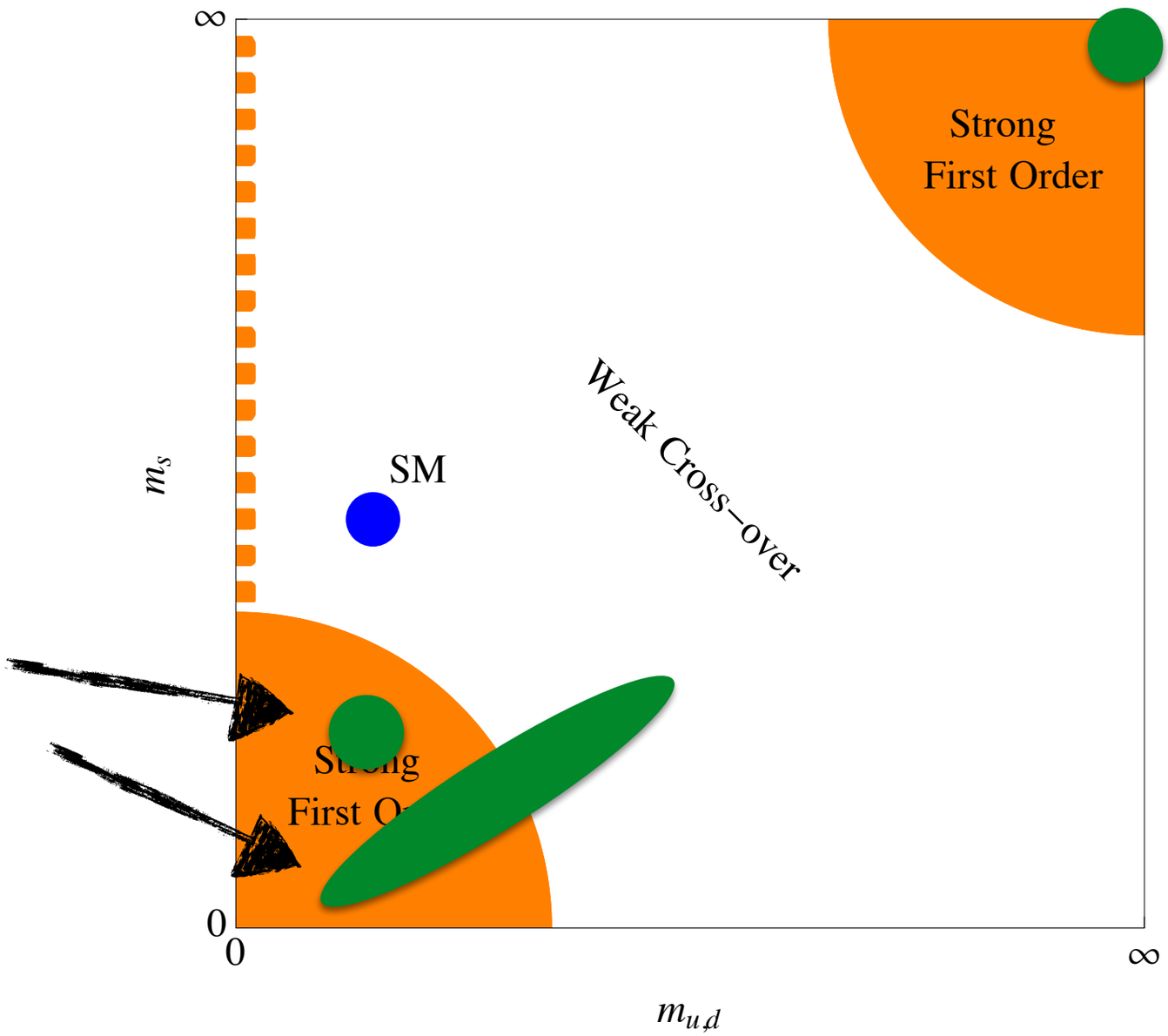
What is the nature of the PT?

QCD phase diagram



PS, 2016

Phase Diagram II



Glueball DM

Fraternal
Twin Higgs

Dark QCD
SIMP models

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

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

Pisarski, Wilczek, 1983

Not for:

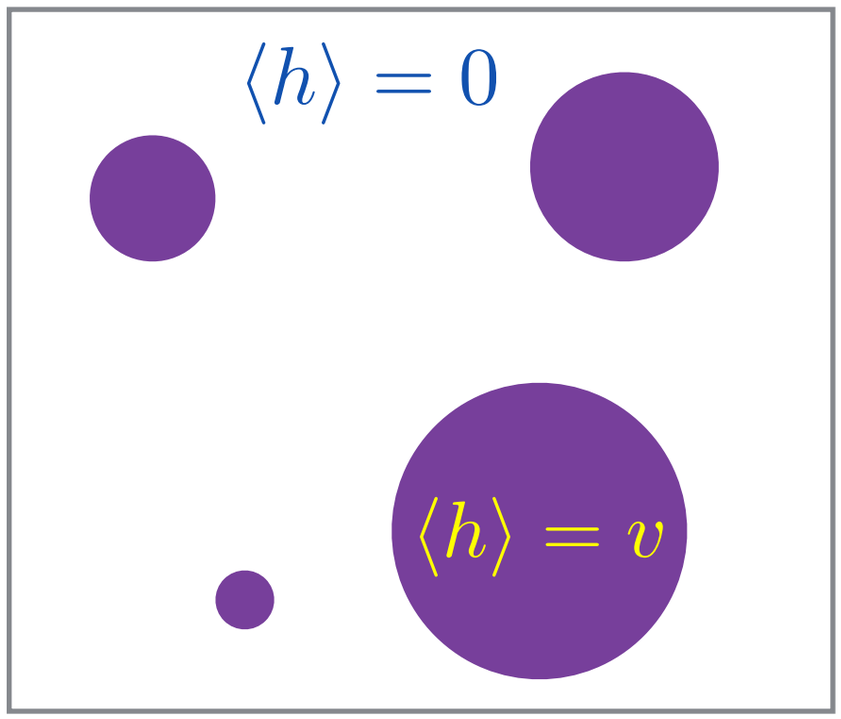
- $n_f = 1$ (no global symmetry, no PT)
- $n_f = 2$ (not yet known)

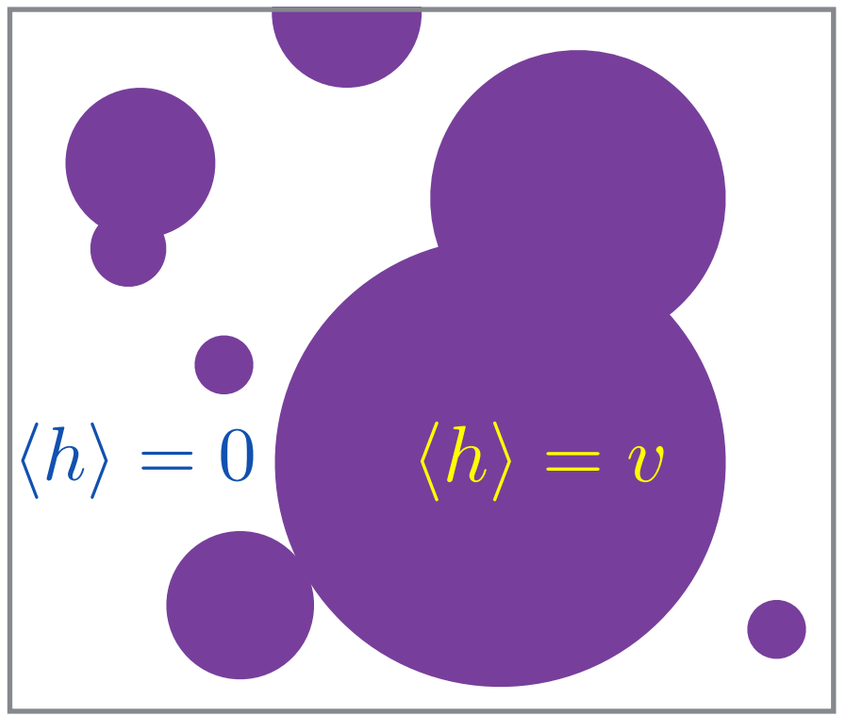
Note: Nature of the PT does not depend on arbitrary model parameters

First order phase transitions produce GWs

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves

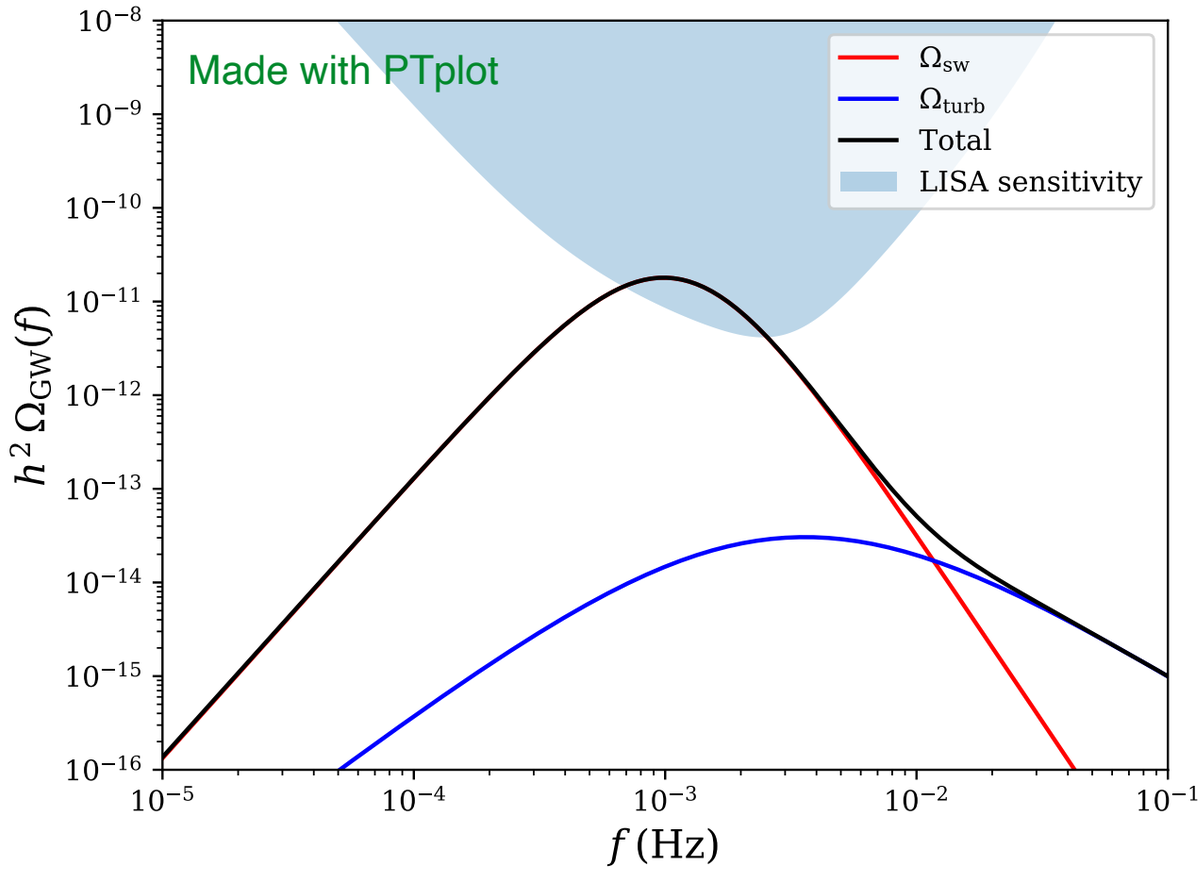




PT signal

PT characterised by few parameters:

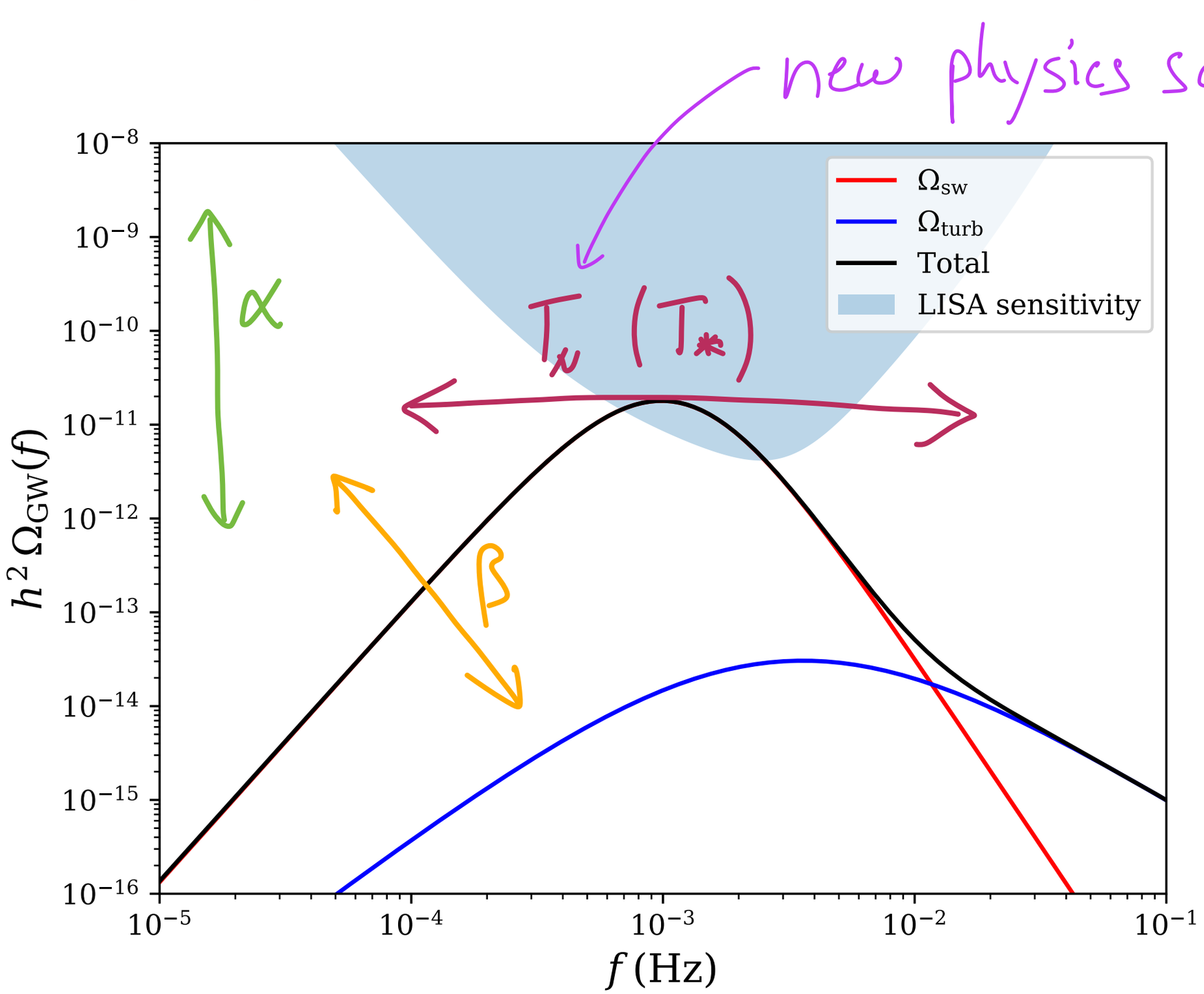
- Latent heat $\alpha \approx \dfrac{\Omega_{\rm vacuum}}{\Omega_{\rm rad}}$
- Bubble wall velocity v
- Bubble nucleation rate β
- PT temperature T_*



More details, see e.g.:

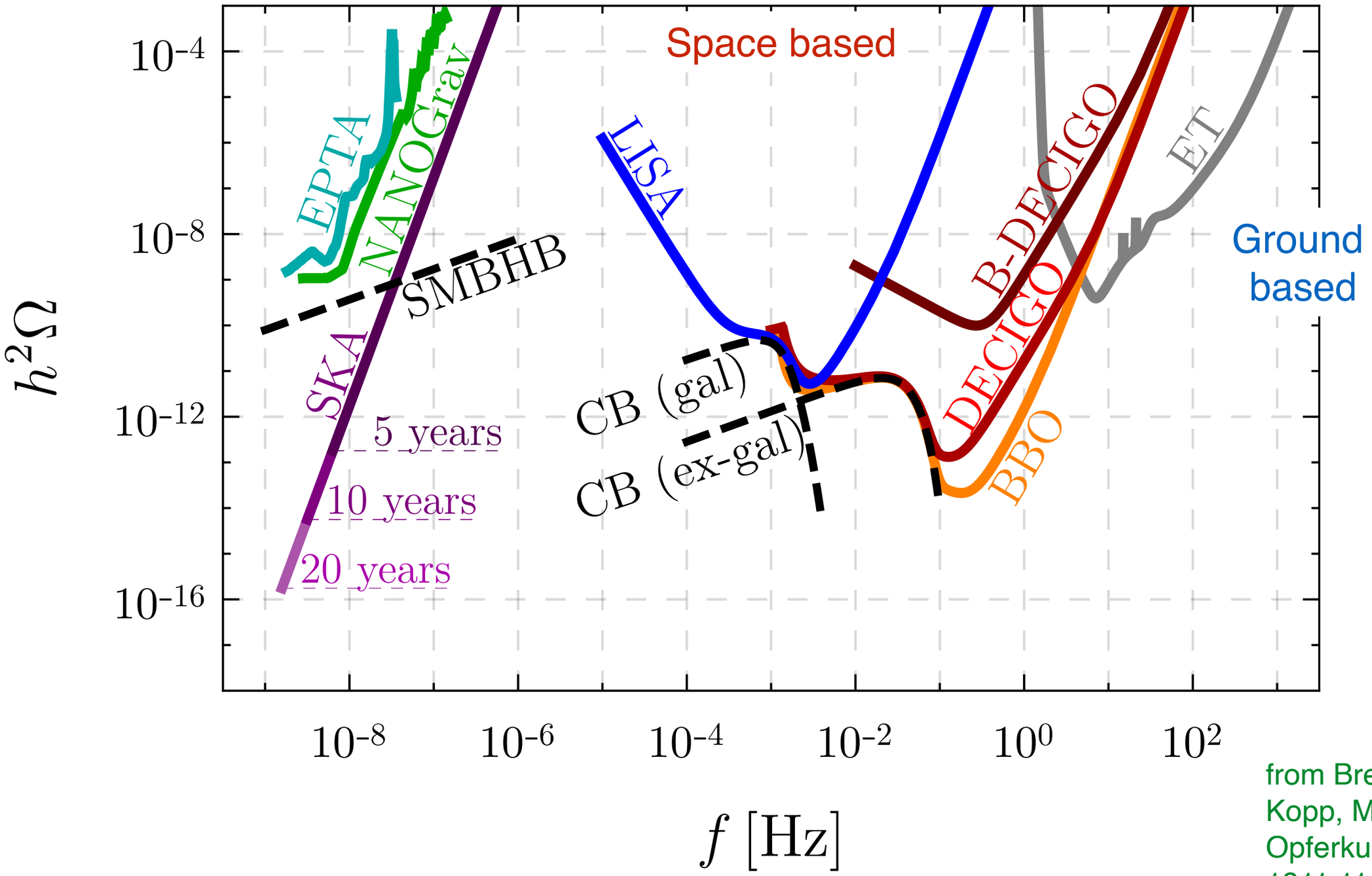
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Signal properties



There are many (planned) experiments

New physics scale GeV TeV PeV

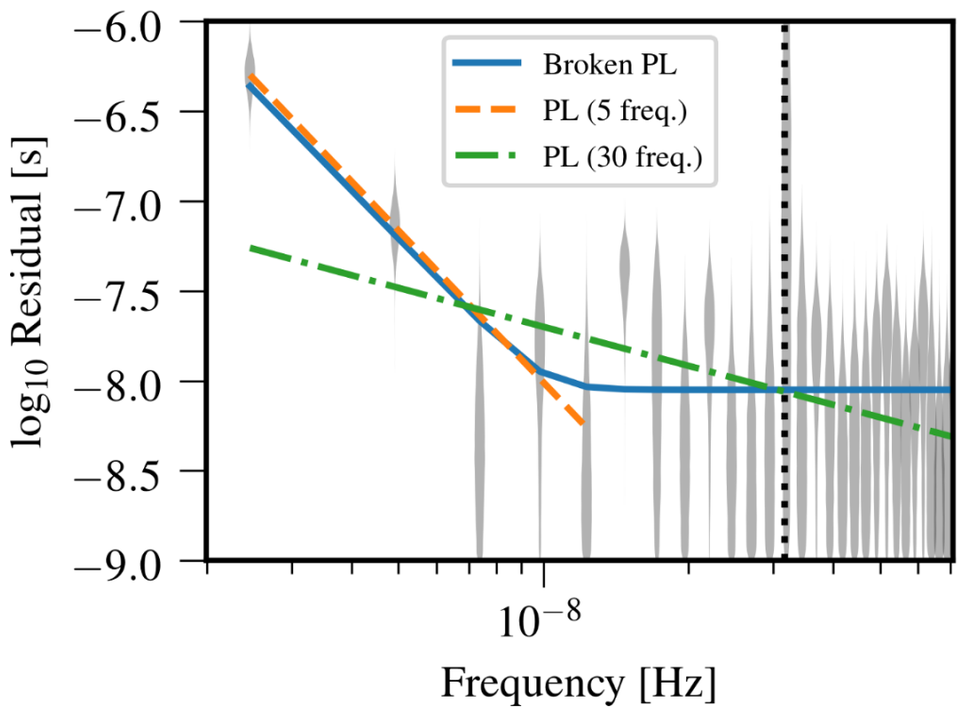


from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

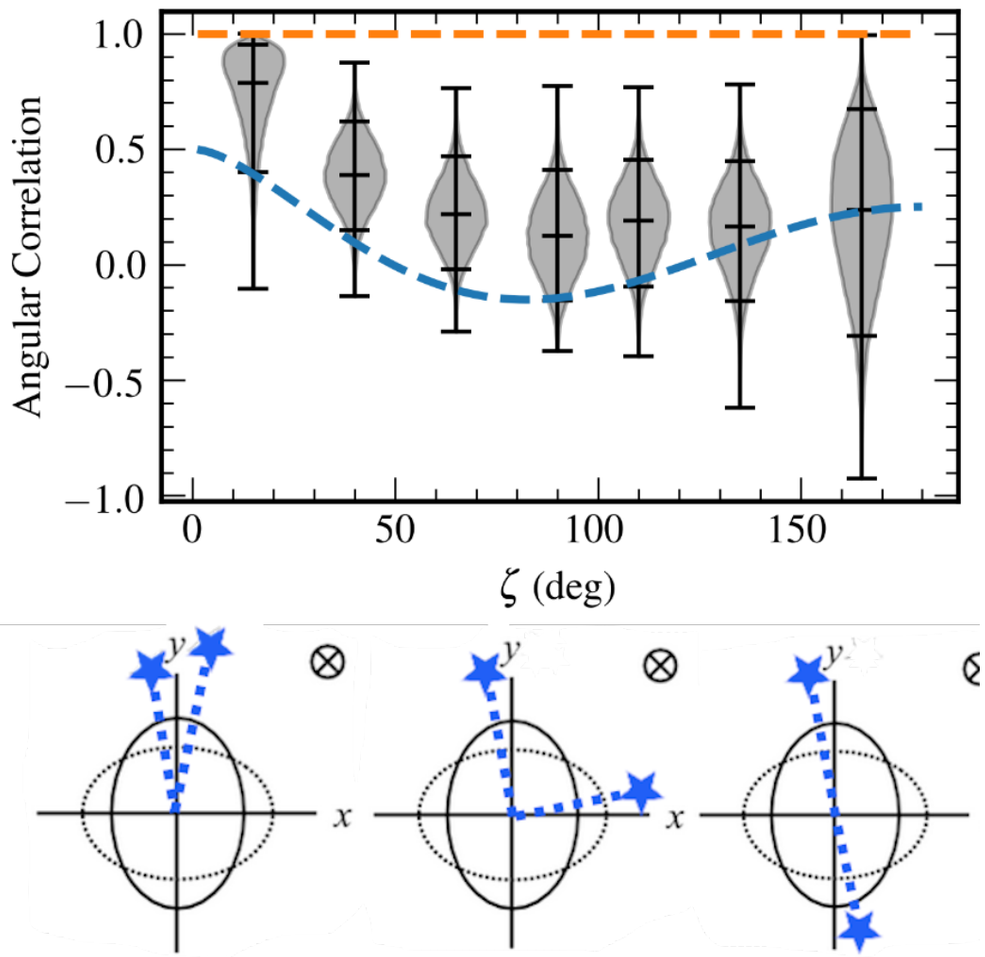
Some recent developments

NANOGrav saw something!

Significant Strain at low frequencies



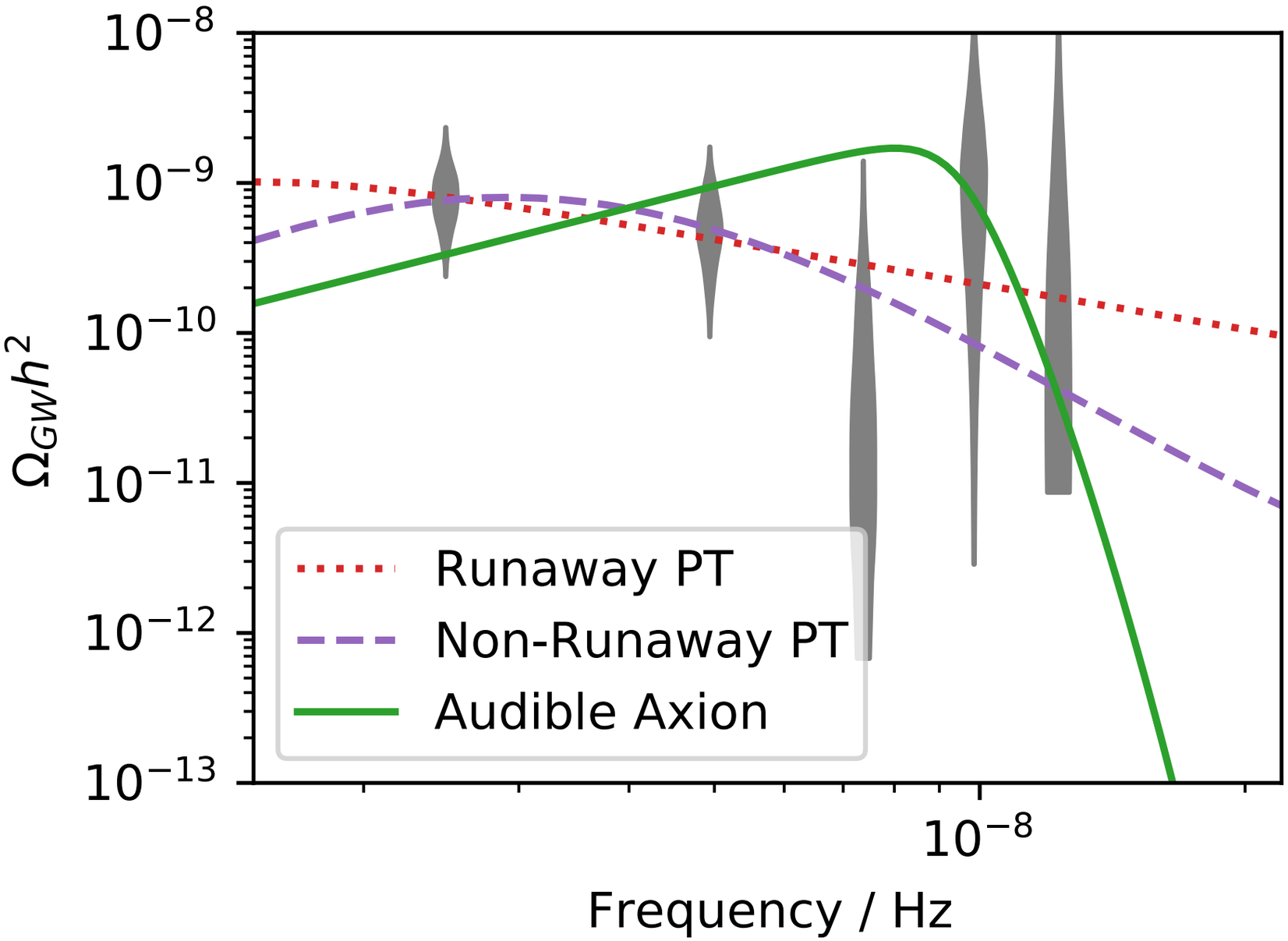
No 4σ evidence for Quadrupole



From NANOGrav collaboration, 2009.04496

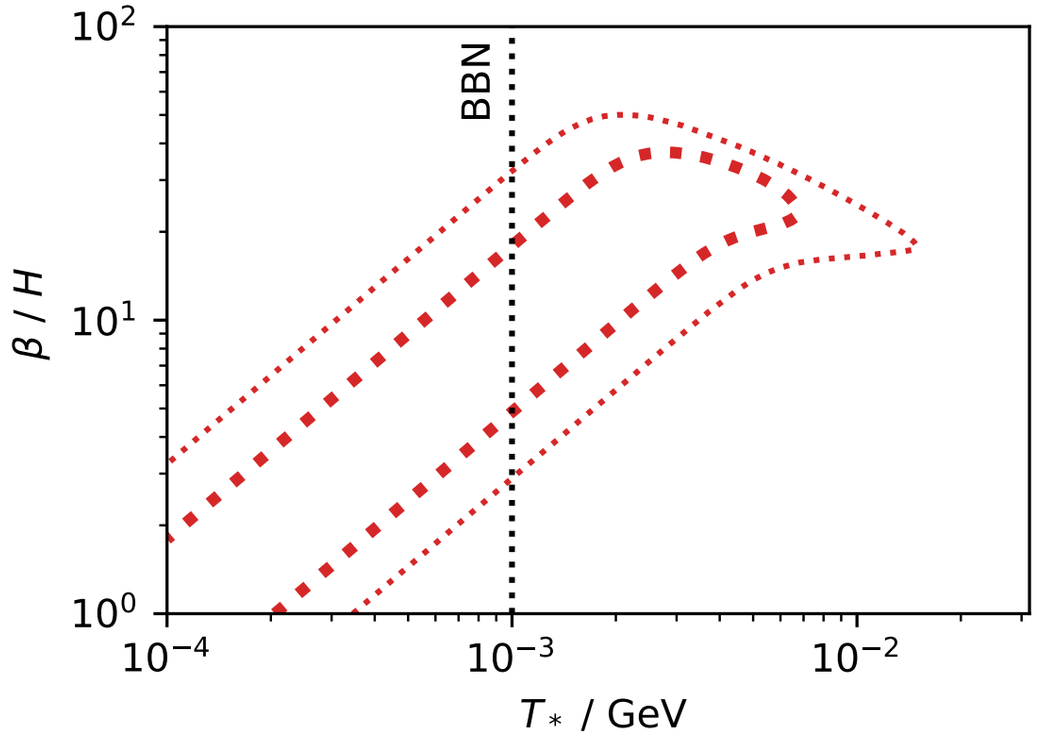
Now also consistent signals in PPTA, EPTA and IPTA - still not fully conclusive though

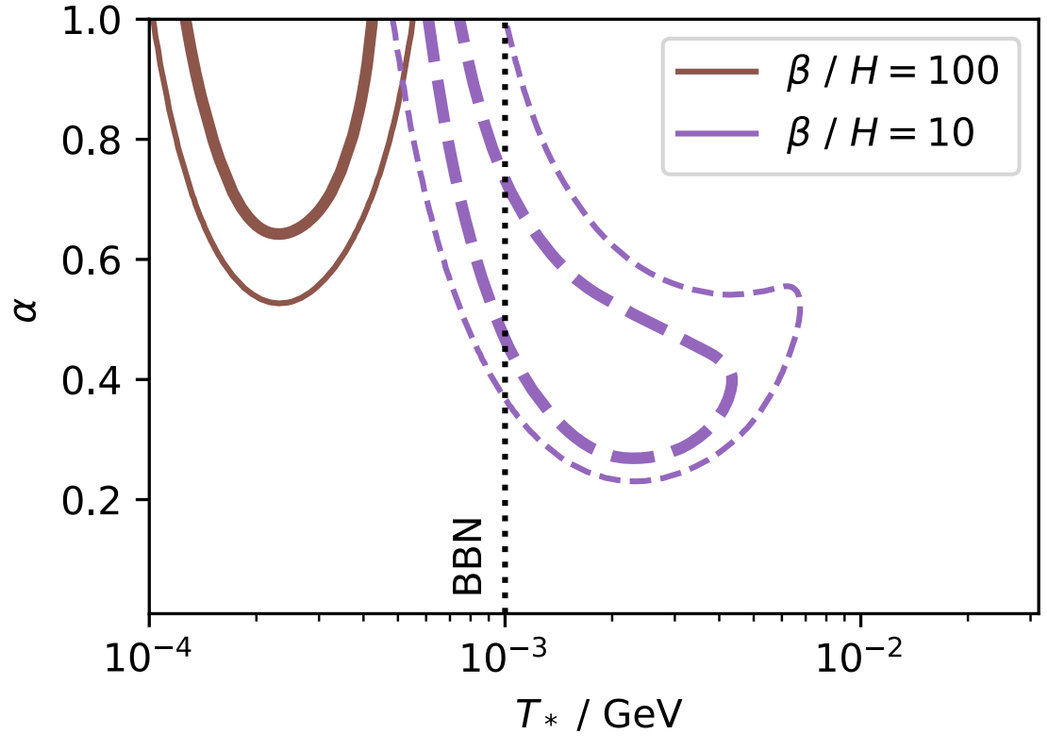
Fit with broken power law signals



Wolfram Ratzinger & PS, 2009.11875

Fit with Phase Transition



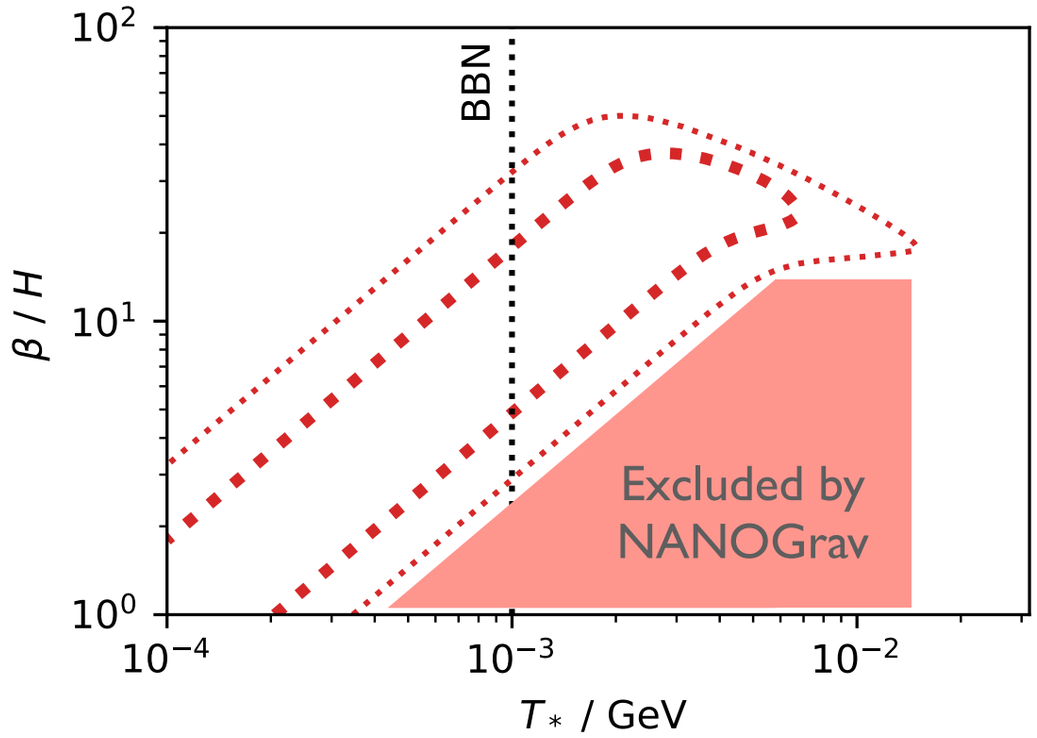


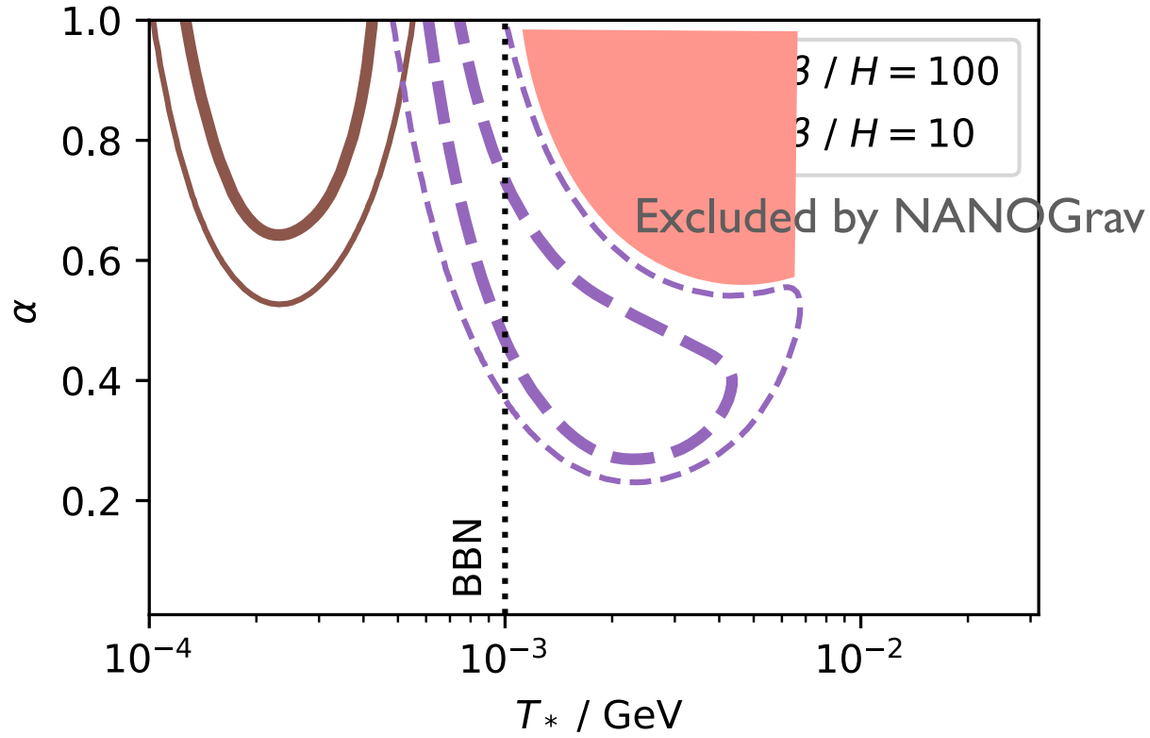
Generic PT parameterisation, best fit with PT at temperatures in few MeV range

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

Towards quantitative predictions for SU(N) PTs

Strong coupling → Non-perturbative methods required

Lattice?

- Good for equilibrium thermodynamics (free energy, pressure…)
- Easier for $n_f = 0$, lots of data for $N_c = 3$
- No real time dynamics

Holography (AdS/CFT)

- Allows perturbative calculations
- Works best for large N_c and in CFT limit

e.g. Hindmarsh et al, Cotrone et al, …

Combine both approaches

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

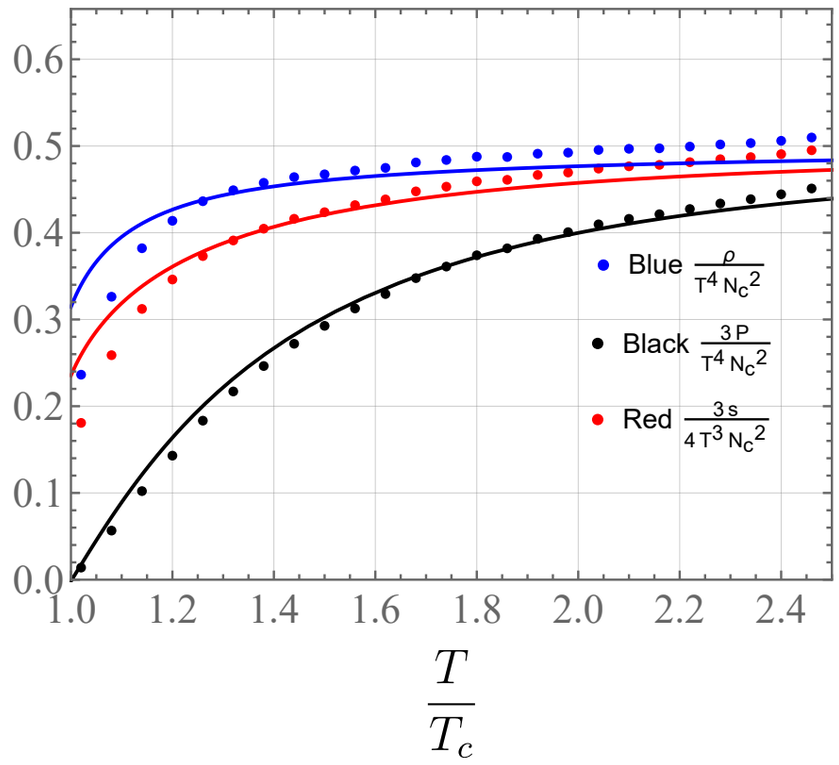
Want this to reproduce SU(N) theories

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

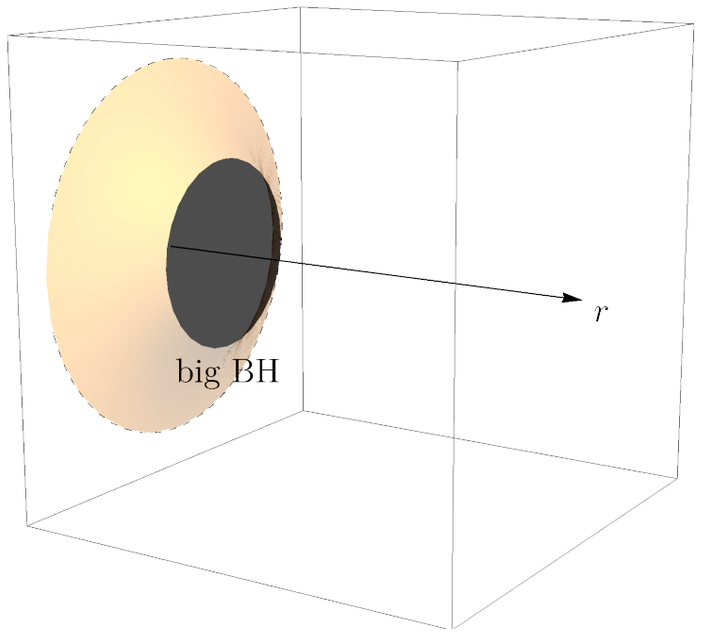
$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

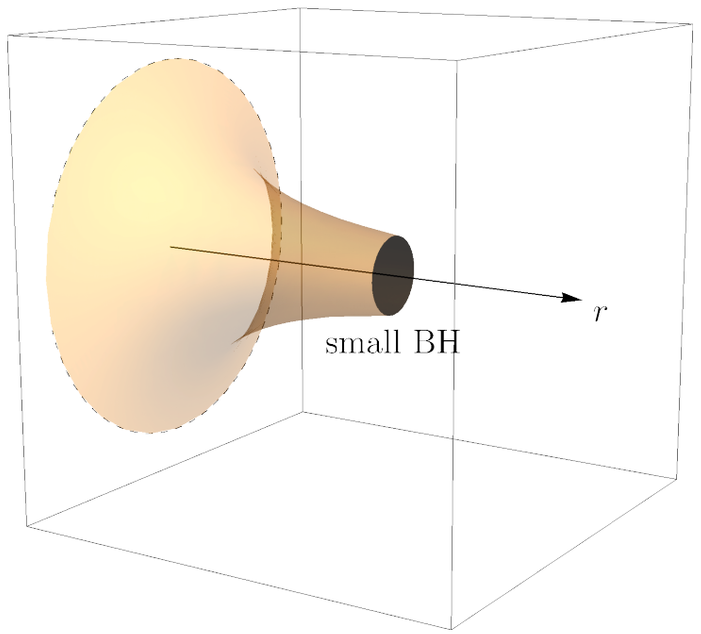
Fix parameters:

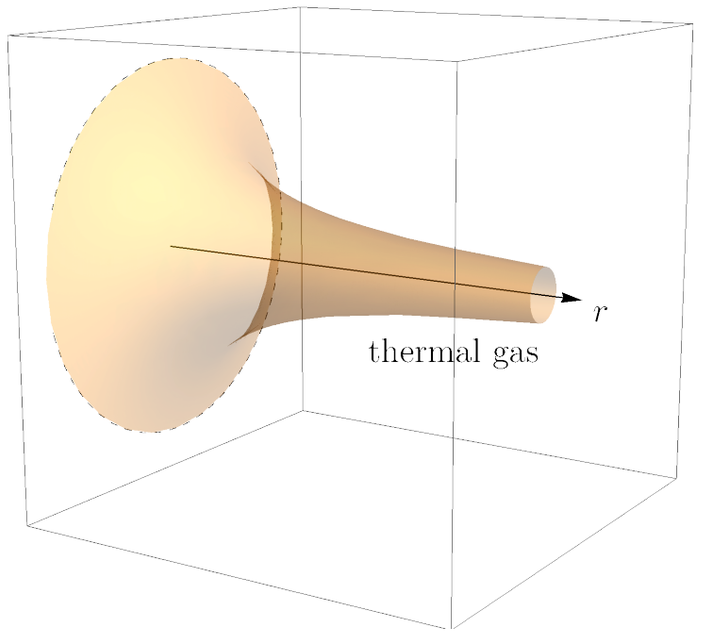
- V_0, V_2 to reproduce 2 loop YM running in UV
- V_1, V_3 fit to reproduce SU(3) lattice thermodynamics in IR



The phase transition in ihQCD



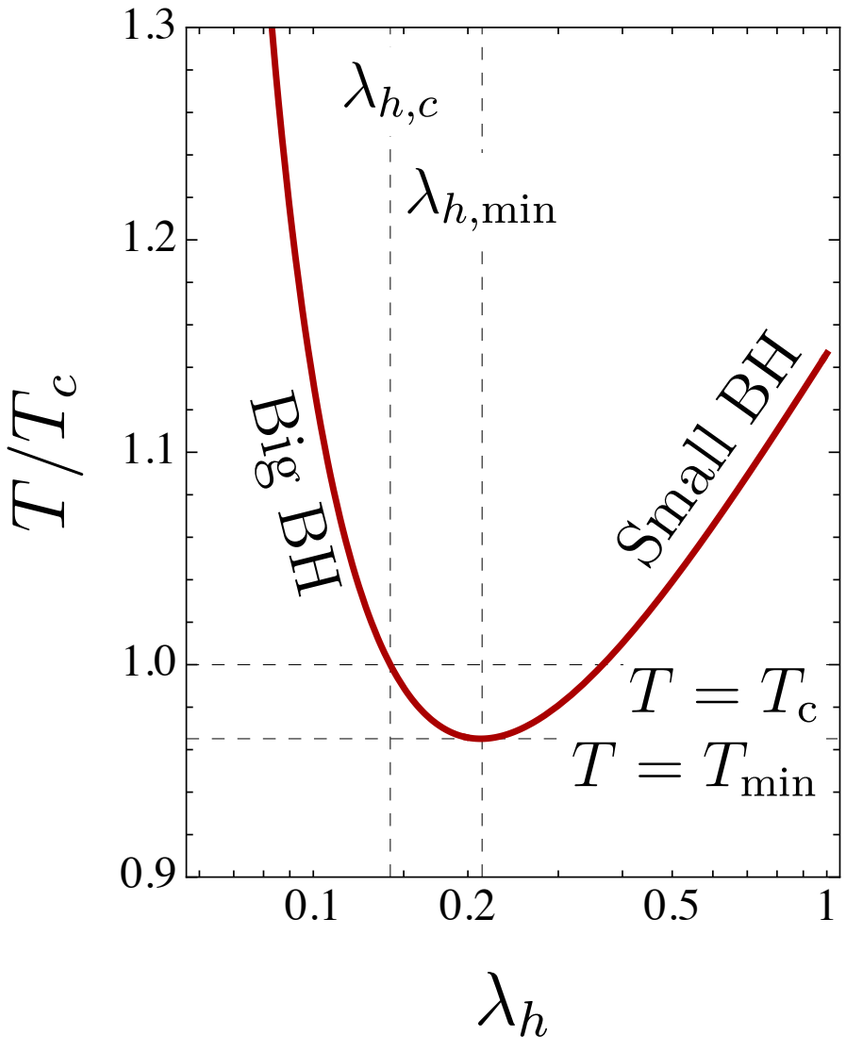


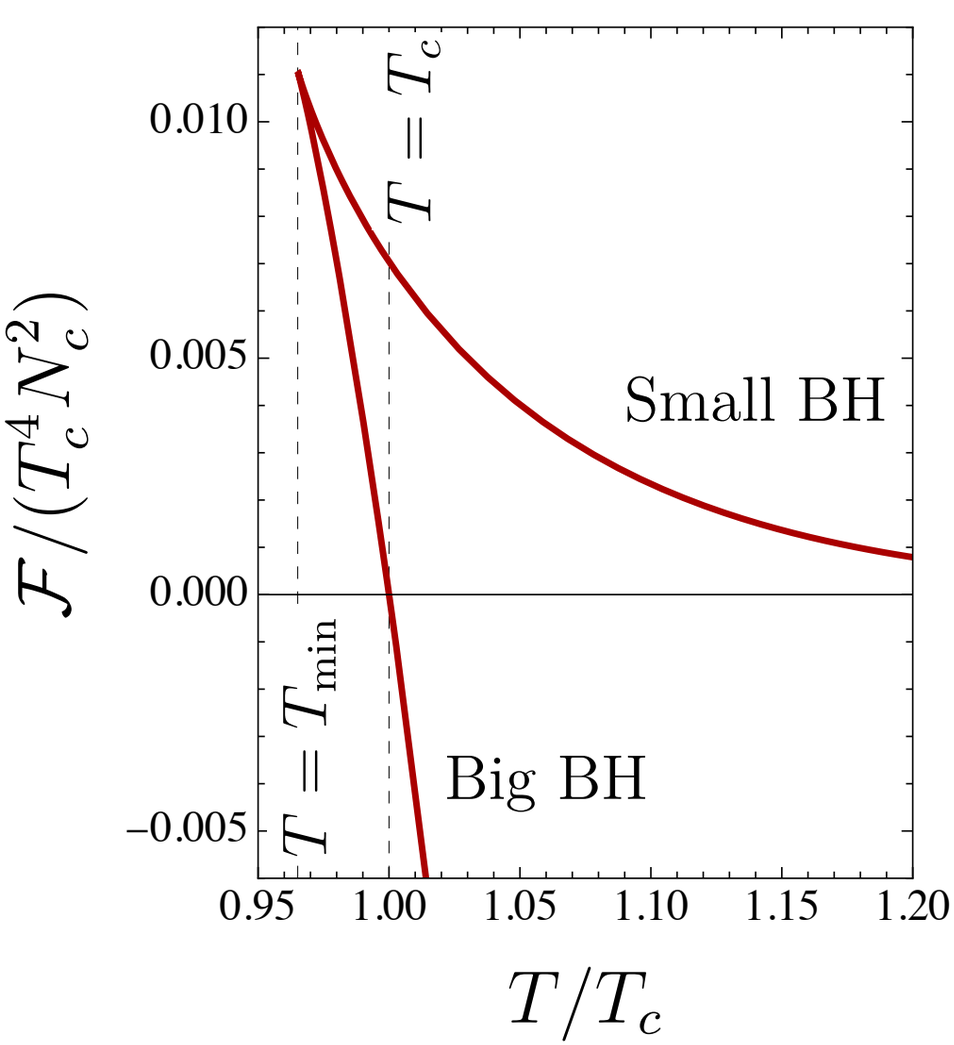


Three solutions

- 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

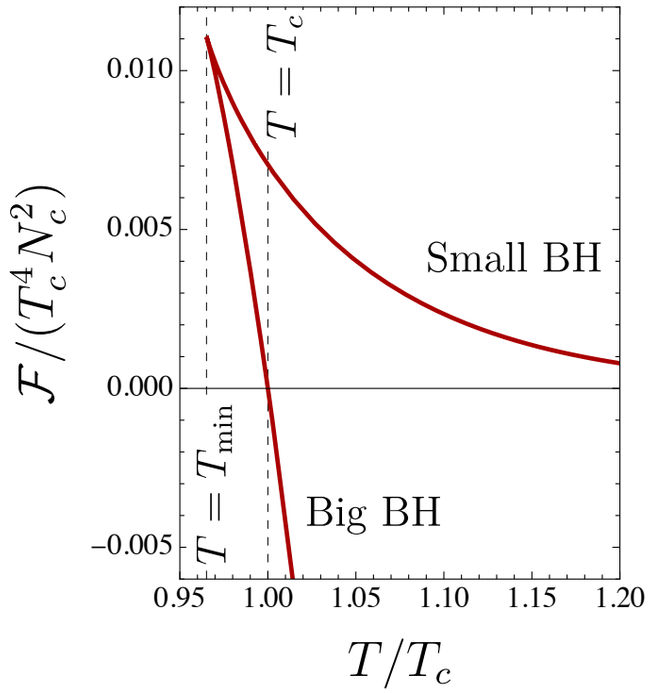
The phase transition in ihQCD III

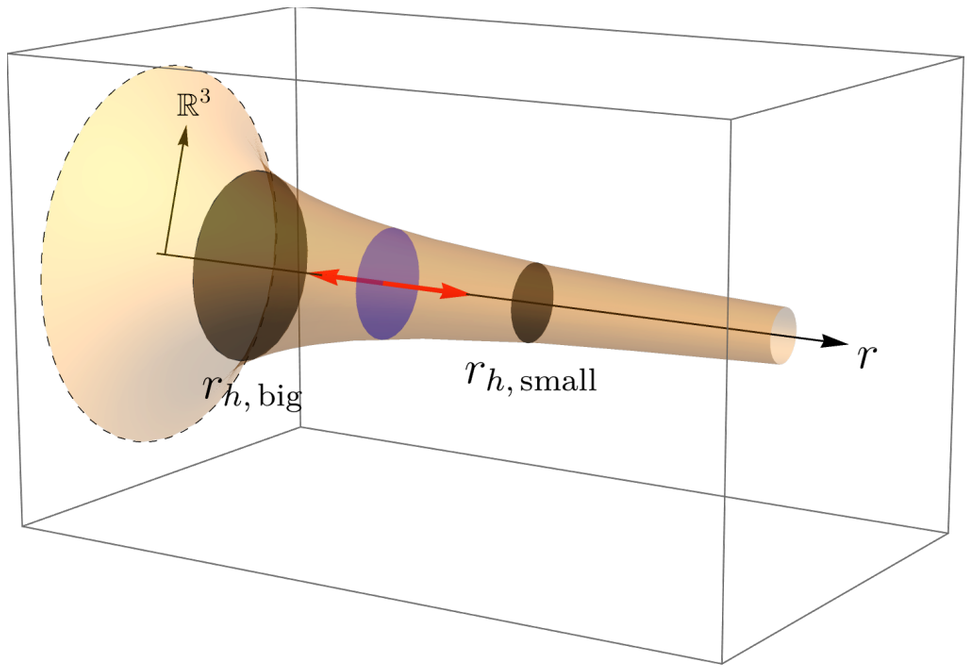
Hawking Page transition, with small BH acting as instanton

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

Effective potential and bounce action

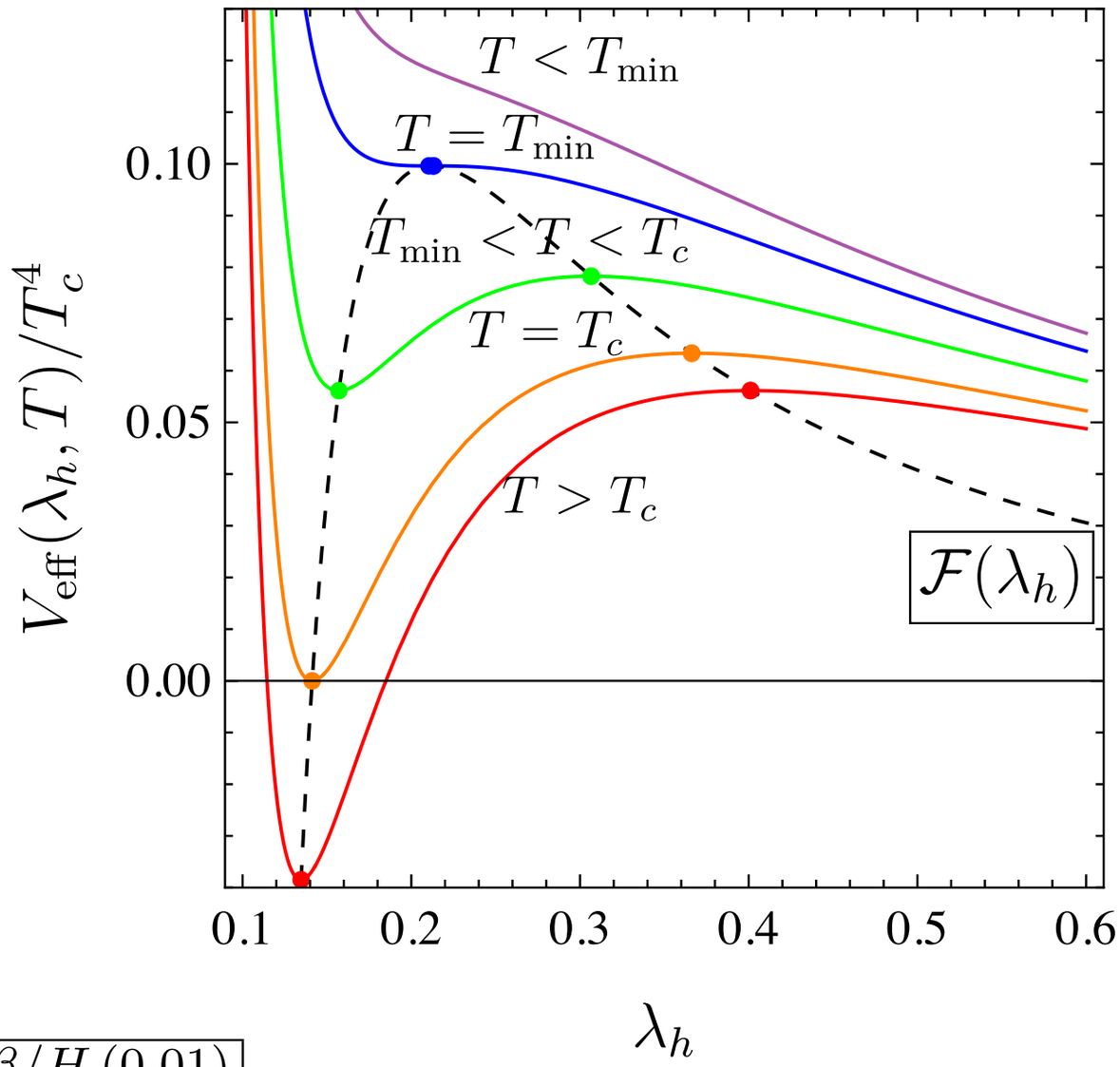
Bounce action

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

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	9.0×10^4	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

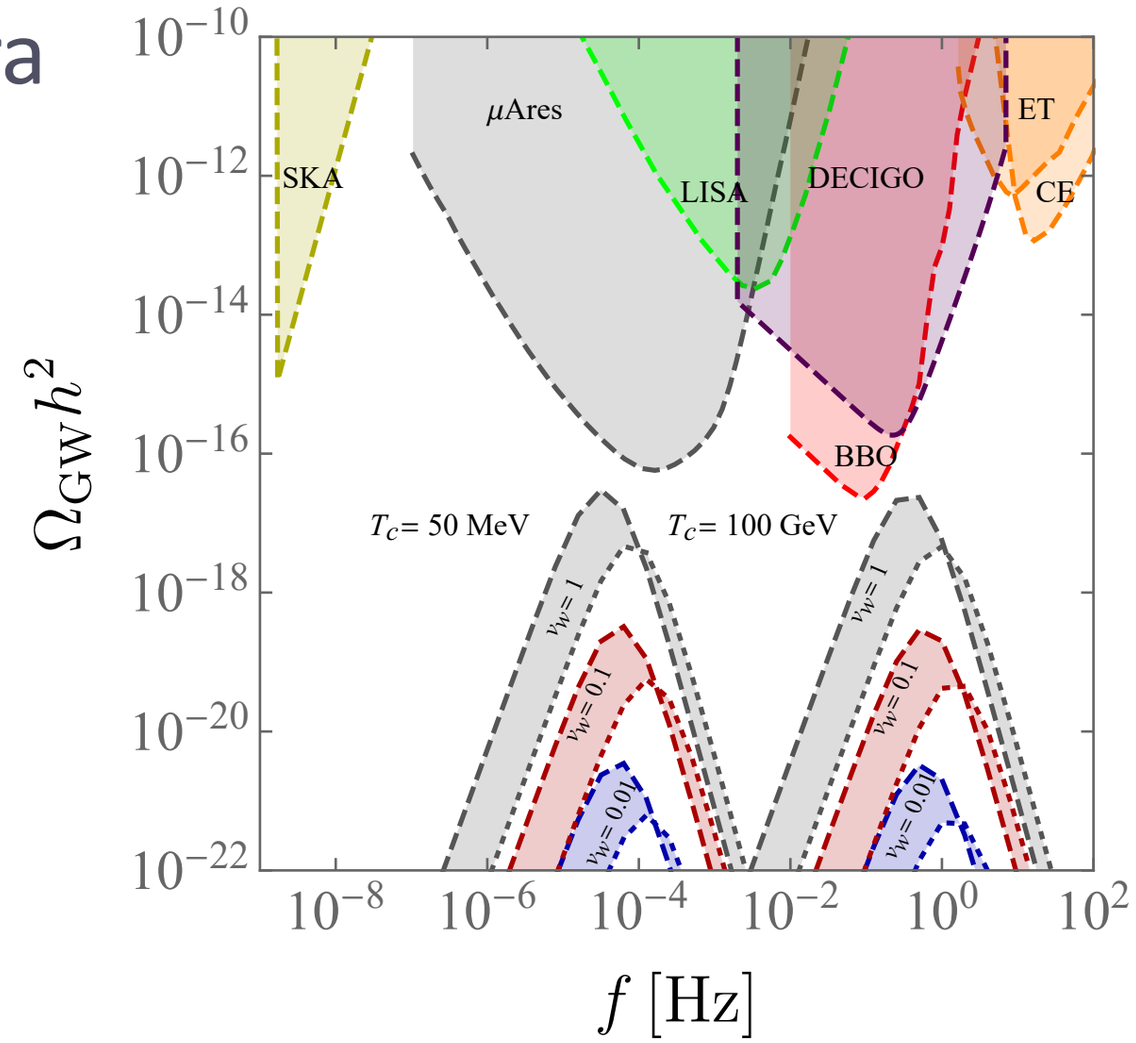
GW spectrum

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)

Morgante, Ramberg, PS, 2210.11821



Summary

Confining dark sectors are interesting

Predict additional phase transition in the early Universe

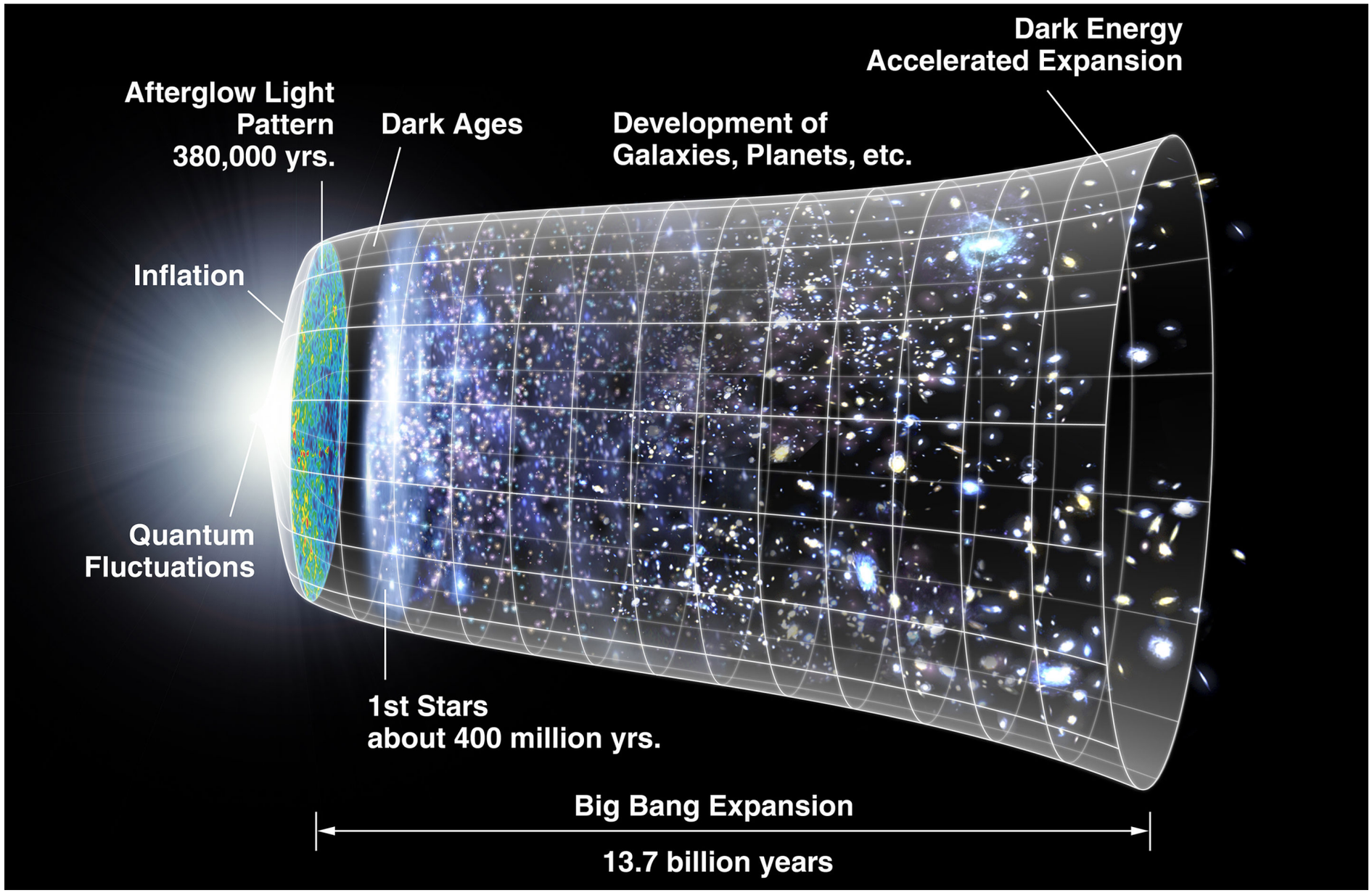
- First order for many scenarios, without tuning of parameters

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

In general: GWs are a new window into the early Universe, with lots of data expected in near (PTAs) and far (LISA, ET) future

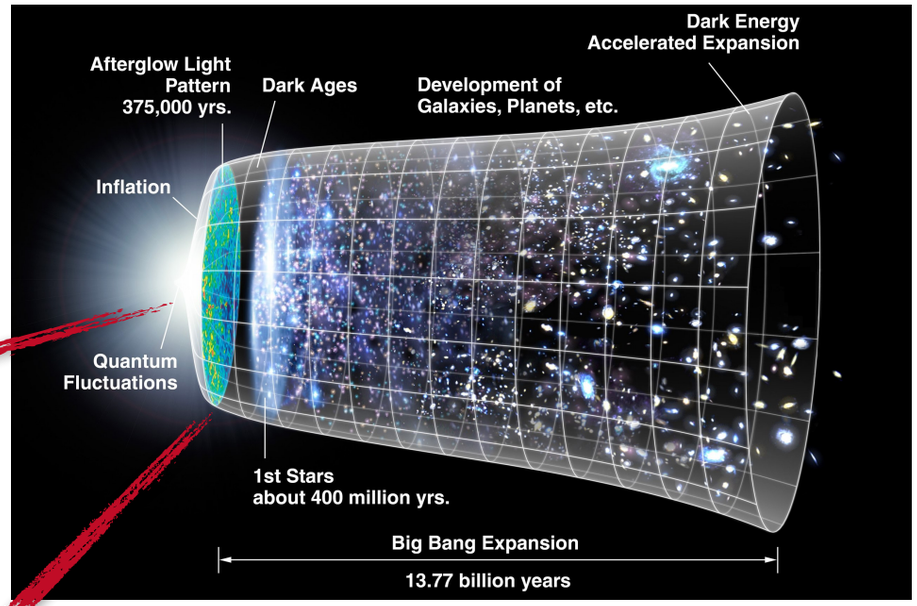
Thermal History

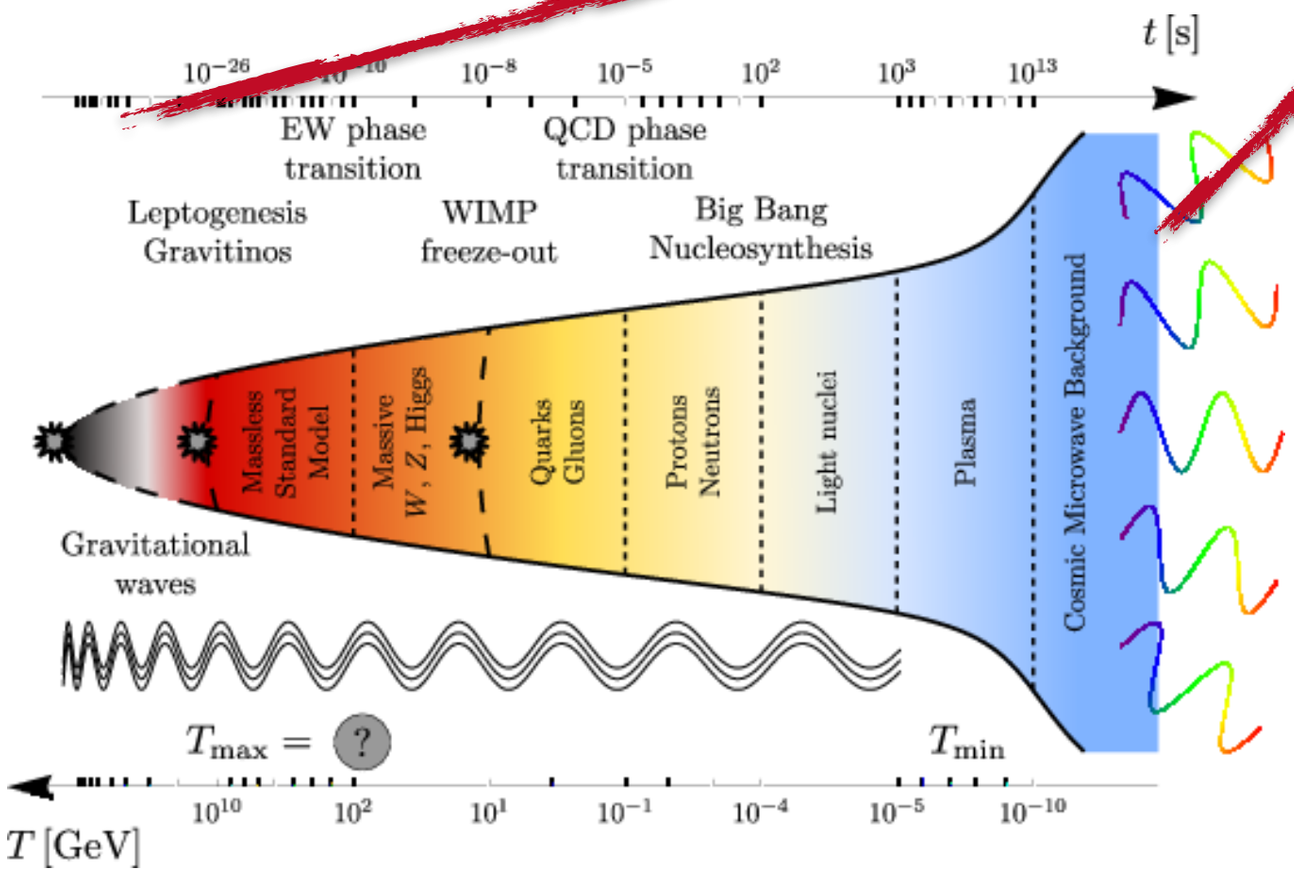


Gravitational Waves?

Zoom into interesting region

New window into early universe





e.g.

Electroweak symmetry breaking

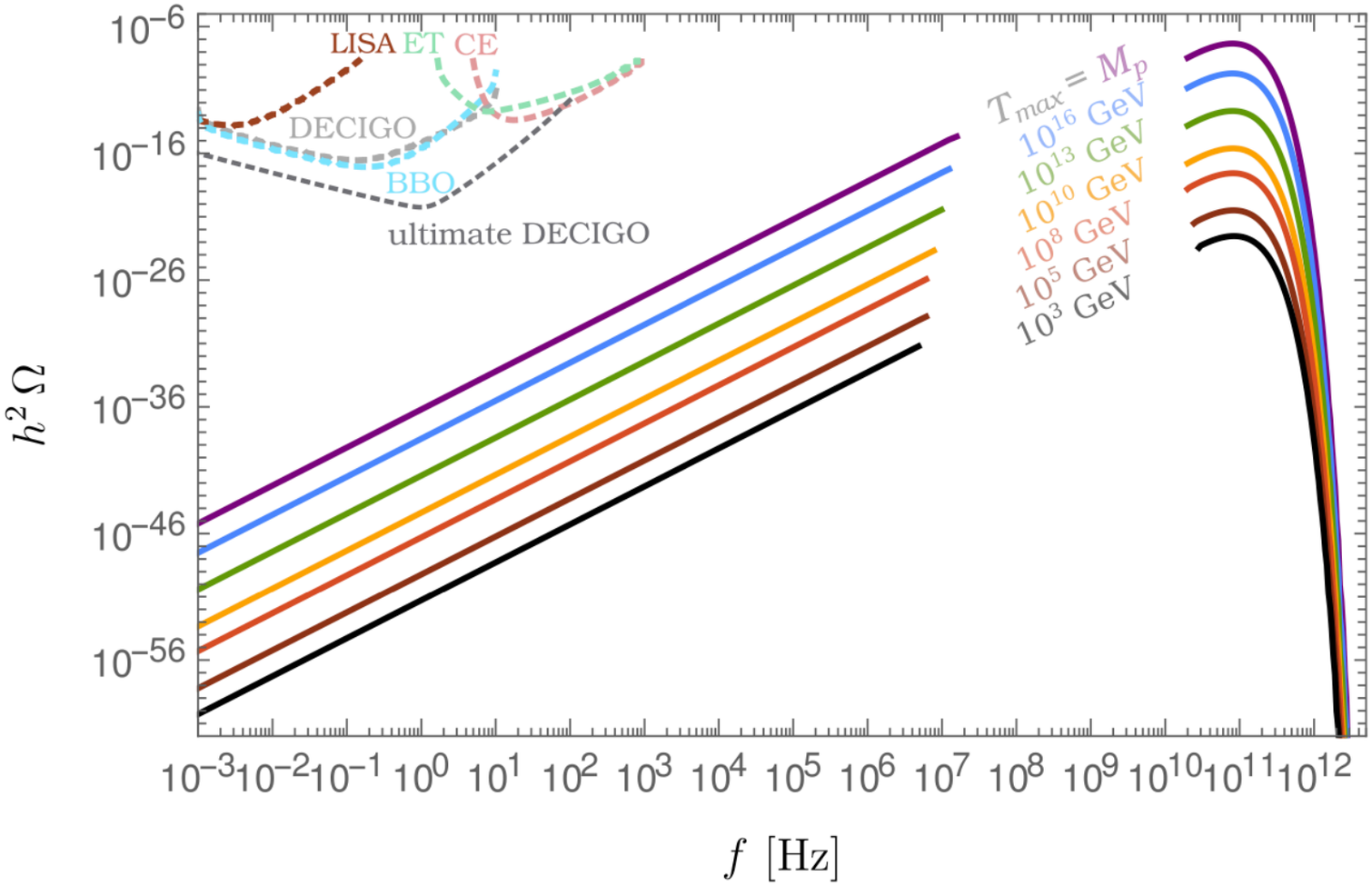
Baryogenesis

Dark matter production

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

Dark QCD

Models I'm interested in here:

Nonabelian SU(N) dark sector, confinement scale Λ_d

n_f light/massless flavours

$n_f = 0$

Glueball DM

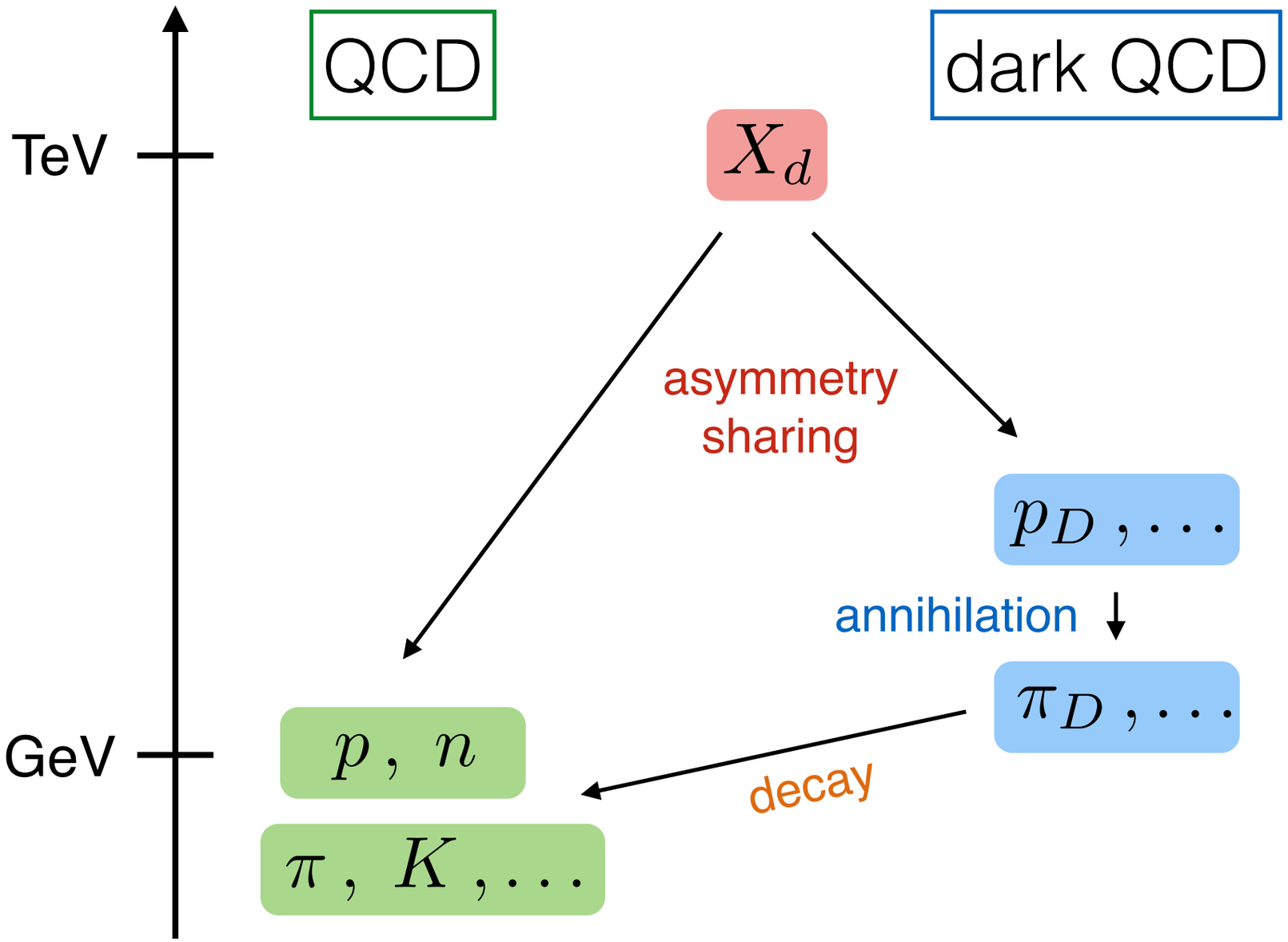
PT from center symmetry restoration

$n_f > 0$

Dark Baryons or Dark Pions

Chiral Symmetry Breaking

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;…

Confinement

Assuming asymptotic freedom, dark sector becomes strongly coupled at some scale Λ

This implies a phase transition in the early universe at $T \sim \Lambda$

Transition from deconfined (dark)quark - (dark)gluon plasma to confined hadron or glueball gas

Robust prediction of the scenario, with the details depending on few, often discrete, parameters!