GRAVITATIONAL WAVES FROM A DARK ~~SU(3)~~ SU(N) PHASE TRANSITION

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Based on work with:
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Cluster of Excellence PRISMA+

The Future of Fundamental Composite Dynamics: Colliders, Cosmology, Tools

MITP Mainz March 13, 2024

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

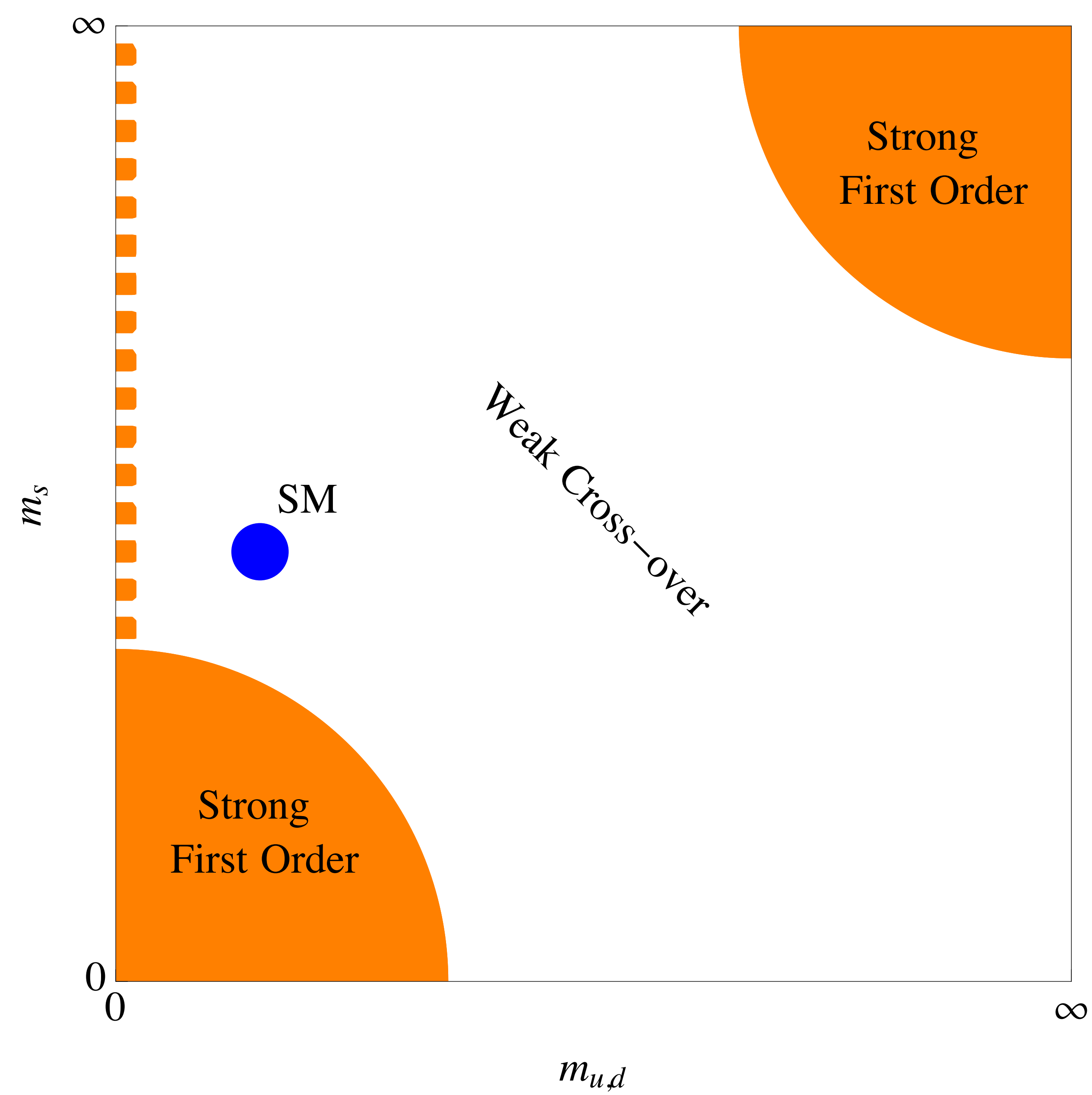
n_f light/massless **dark** quarks

$n_f = 0$	$n_f > 0$
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

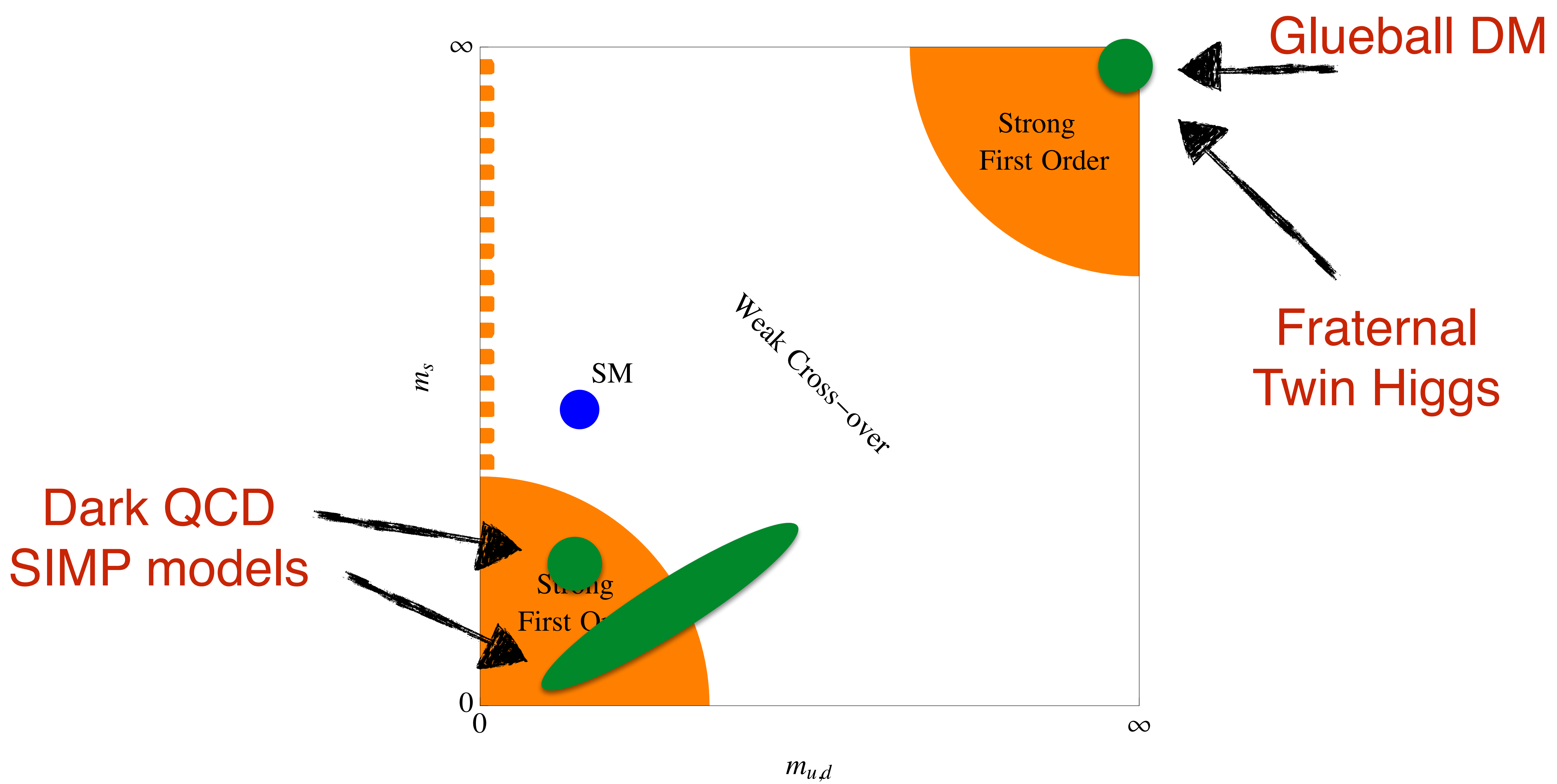
What is the nature of the PT?

QCD phase diagram



PS, 2016

Phase Diagram II



PS, 2016

SU(N) - PT

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

PT is first order for

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

Not for:

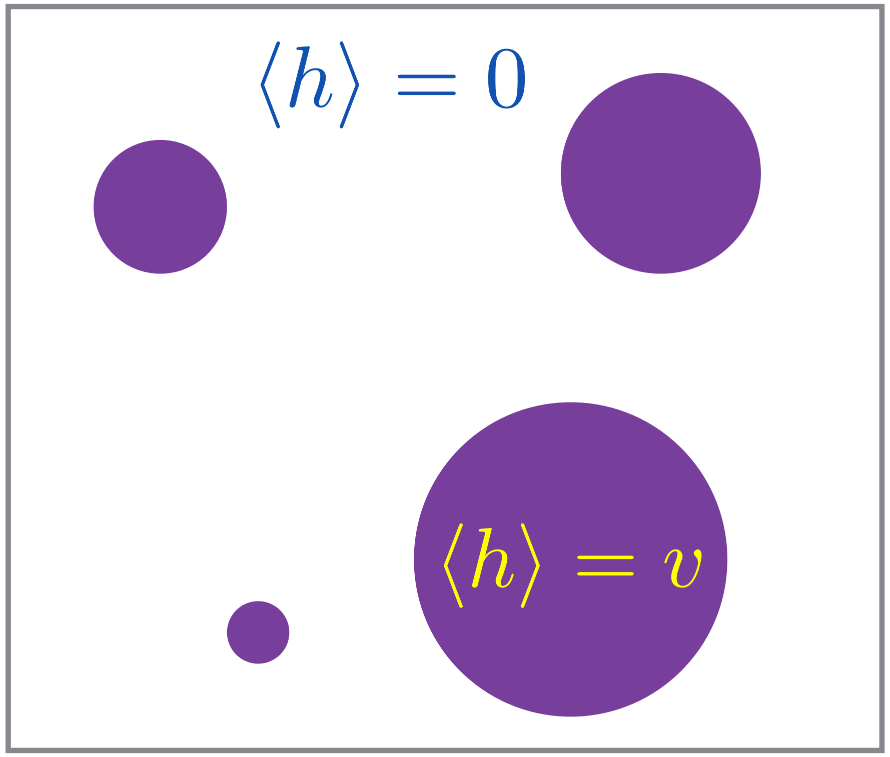
- $n_f = 1$ (no global symmetry, no PT)
- $n_f = 2$ (not yet known)

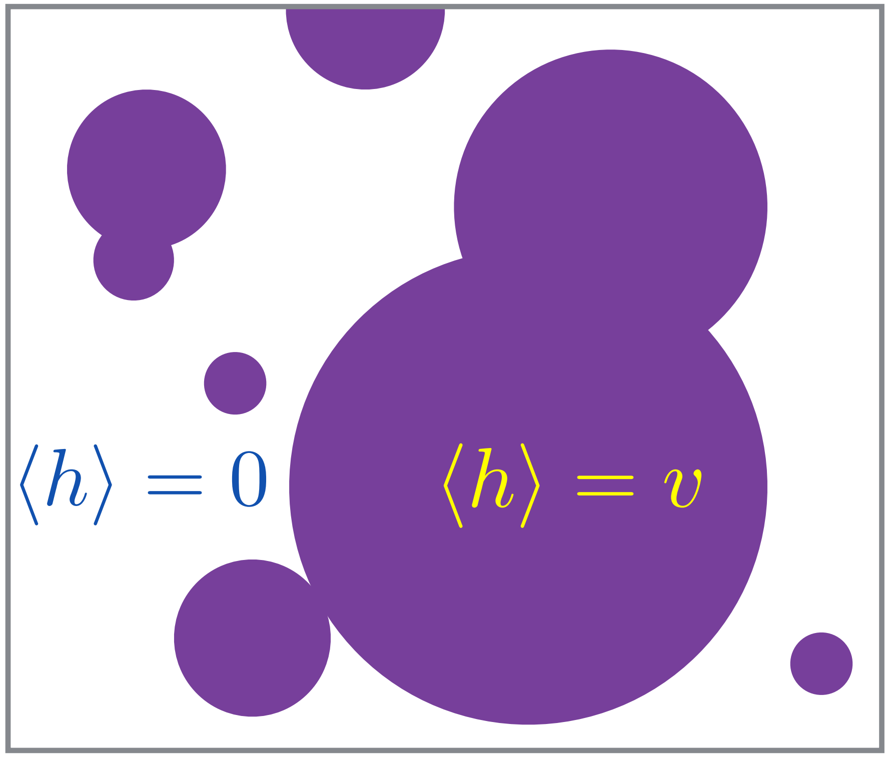
Note: Nature of the PT does not depend on arbitrary model parameters

First order phase transitions produce GWs

First order PT → Bubbles nucleate, expand

Bubble collisions → Gravitational Waves

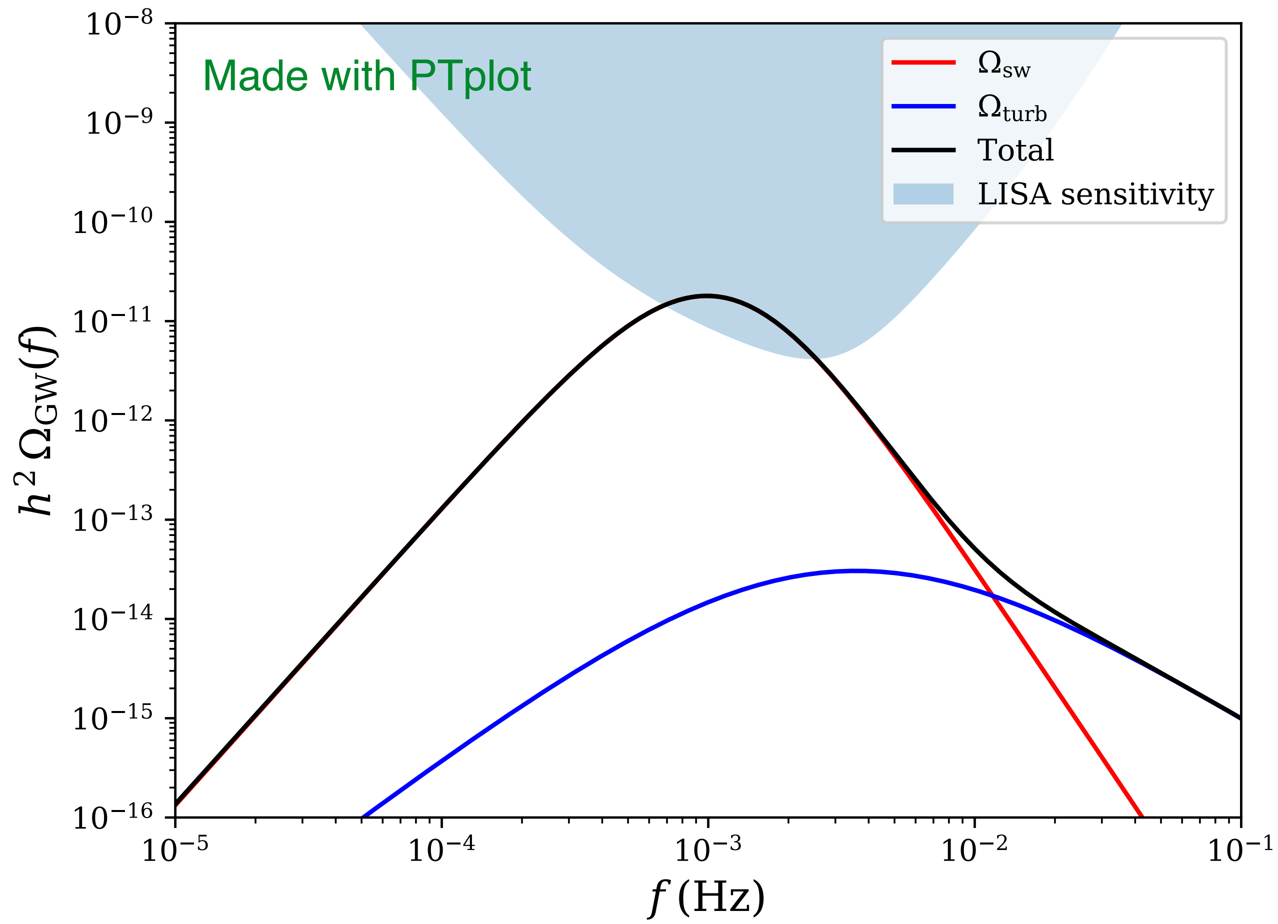




PT signal

PT characterised by few parameters:

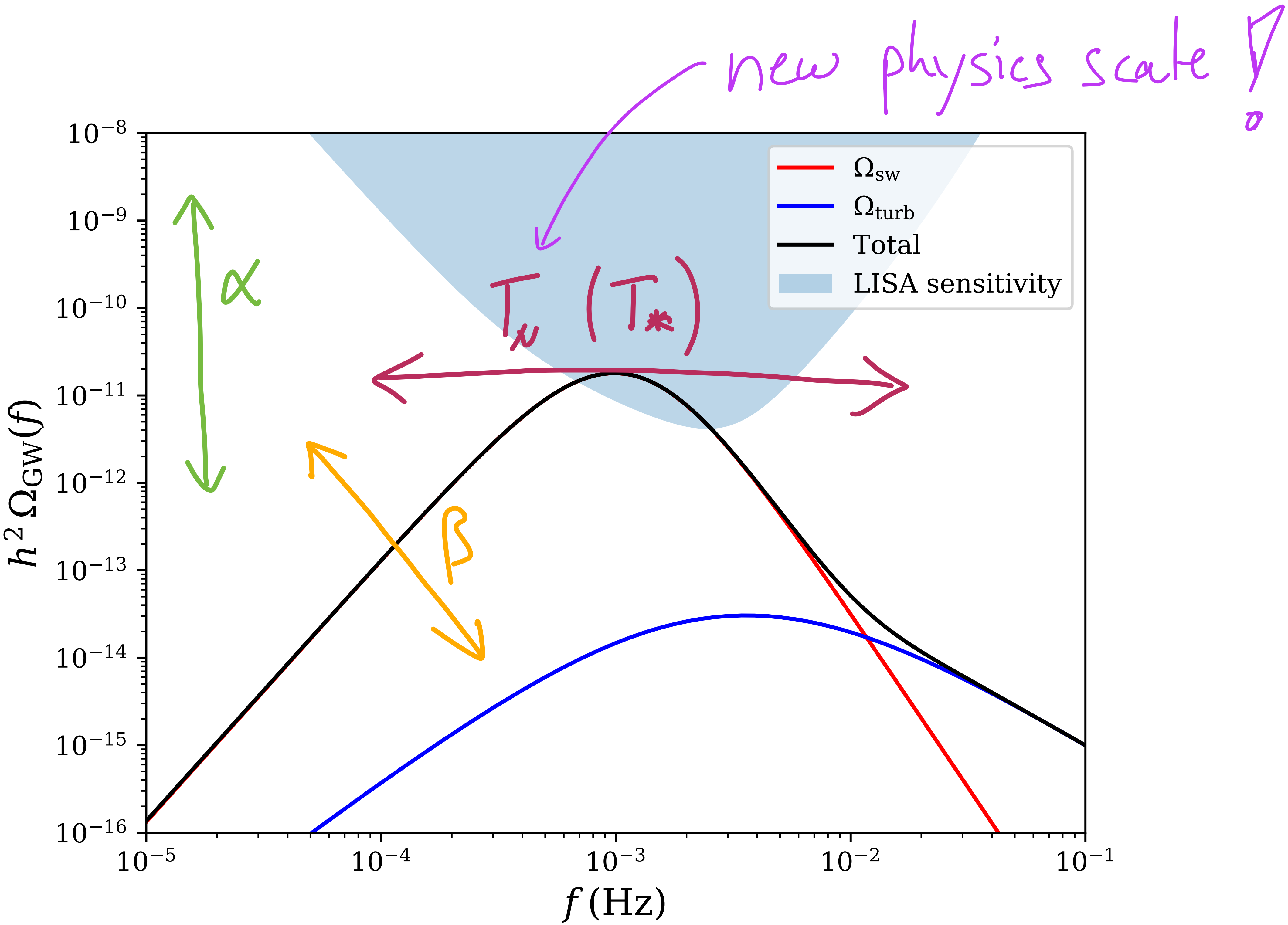
- Latent heat $\alpha \approx \frac{\Omega_{\text{vacuum}}}{\Omega_{\text{rad}}}$
- Bubble wall velocity v
- Bubble nucleation rate β
- PT temperature T_*



More details, see e.g.:

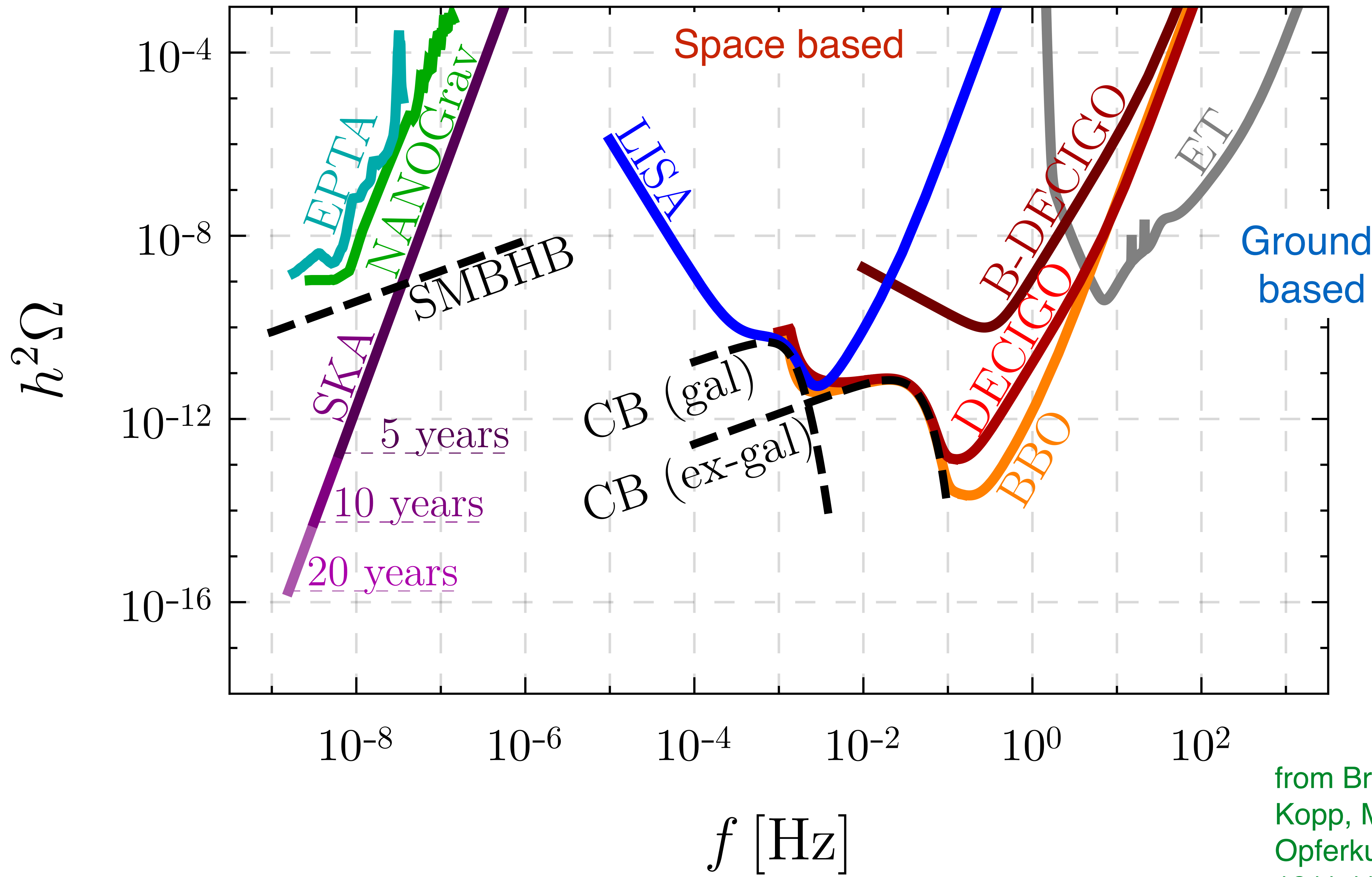
Summary and recommendations:
1910.13125
(LISA Cosmology WG)

Signal properties



There are many (planned) experiments

New physics scale GeV TeV PeV



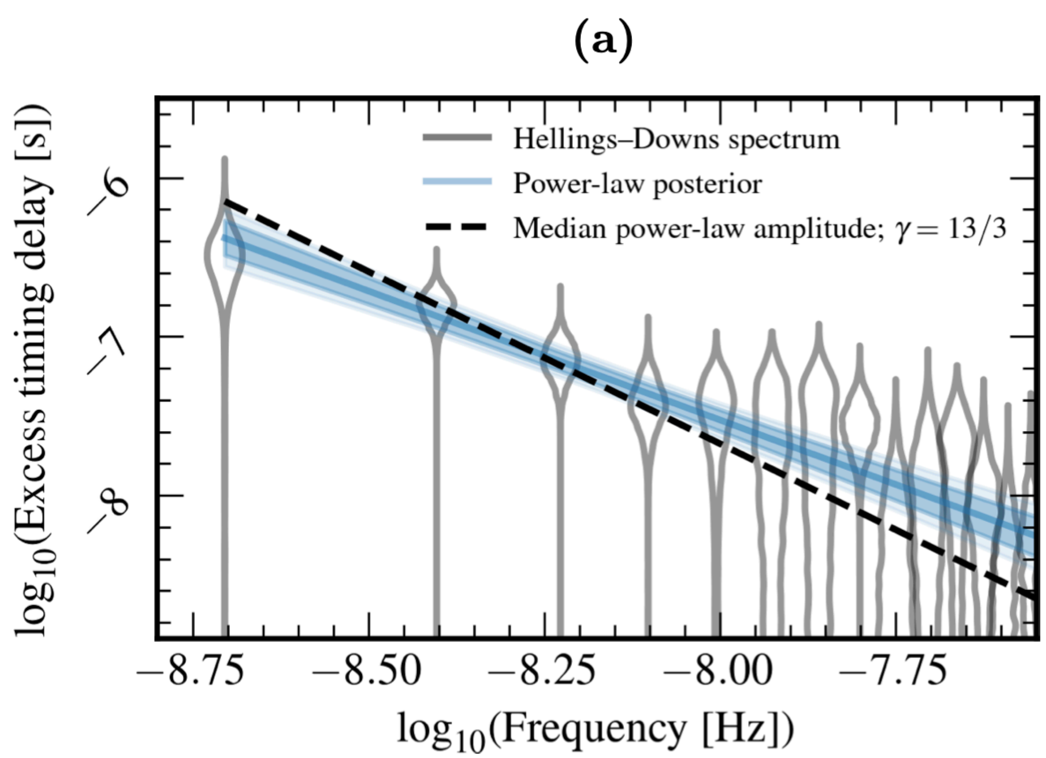
from Breitbach, Kopp, Madge, Opferkuch, PS 1811.11175

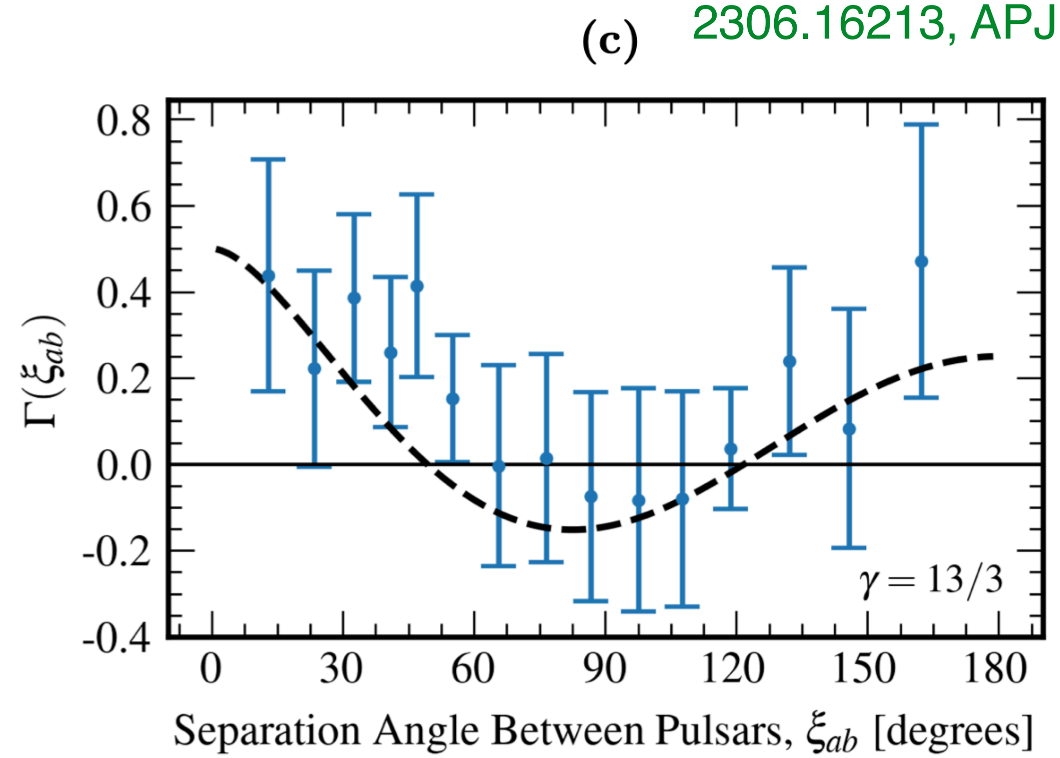
Some recent developments

Pulsar timing arrays

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

NANOGrav Collaboration, 2306.16213, APJL 951

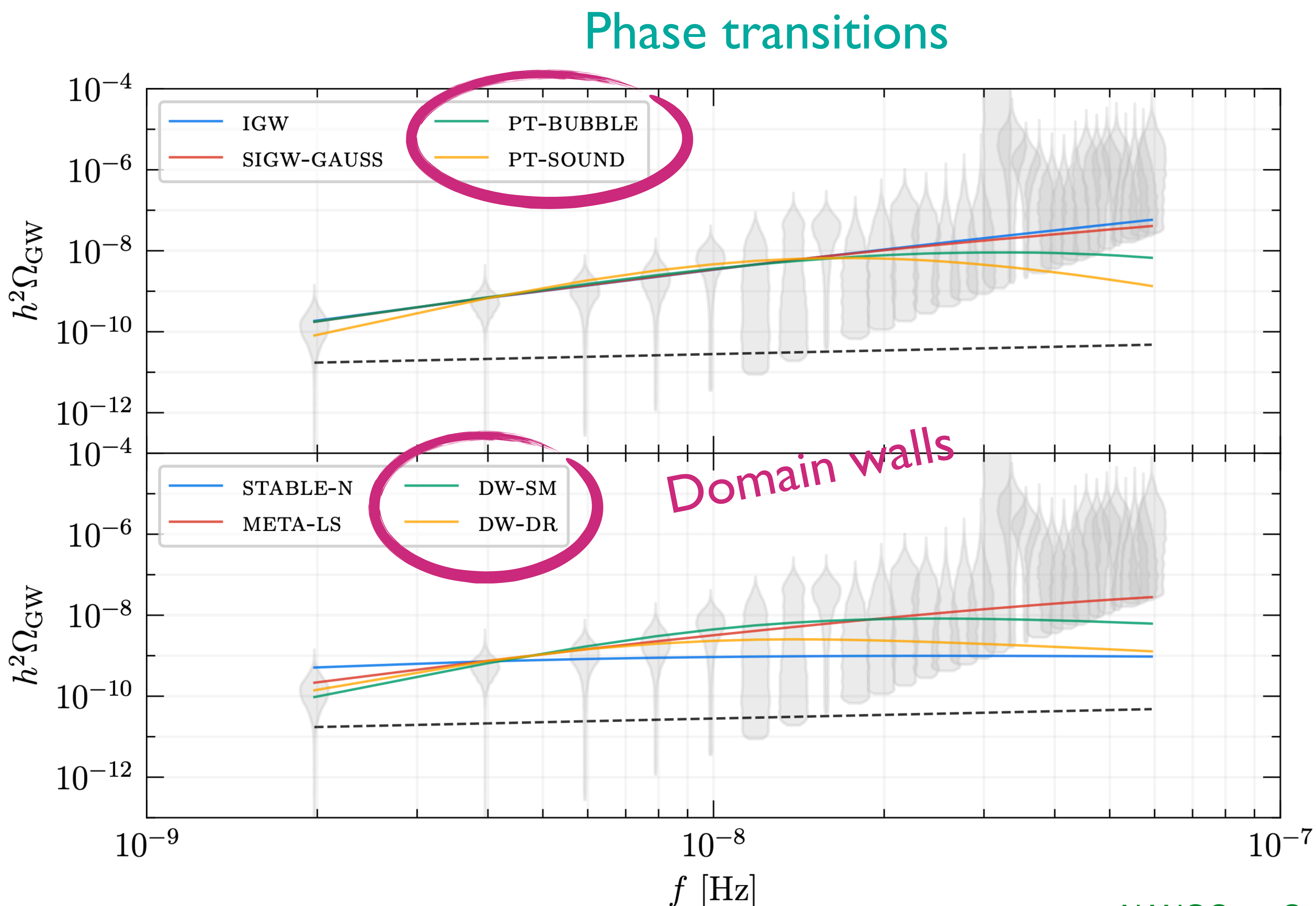




Strong evidence for Hellings-Downs correlation

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:

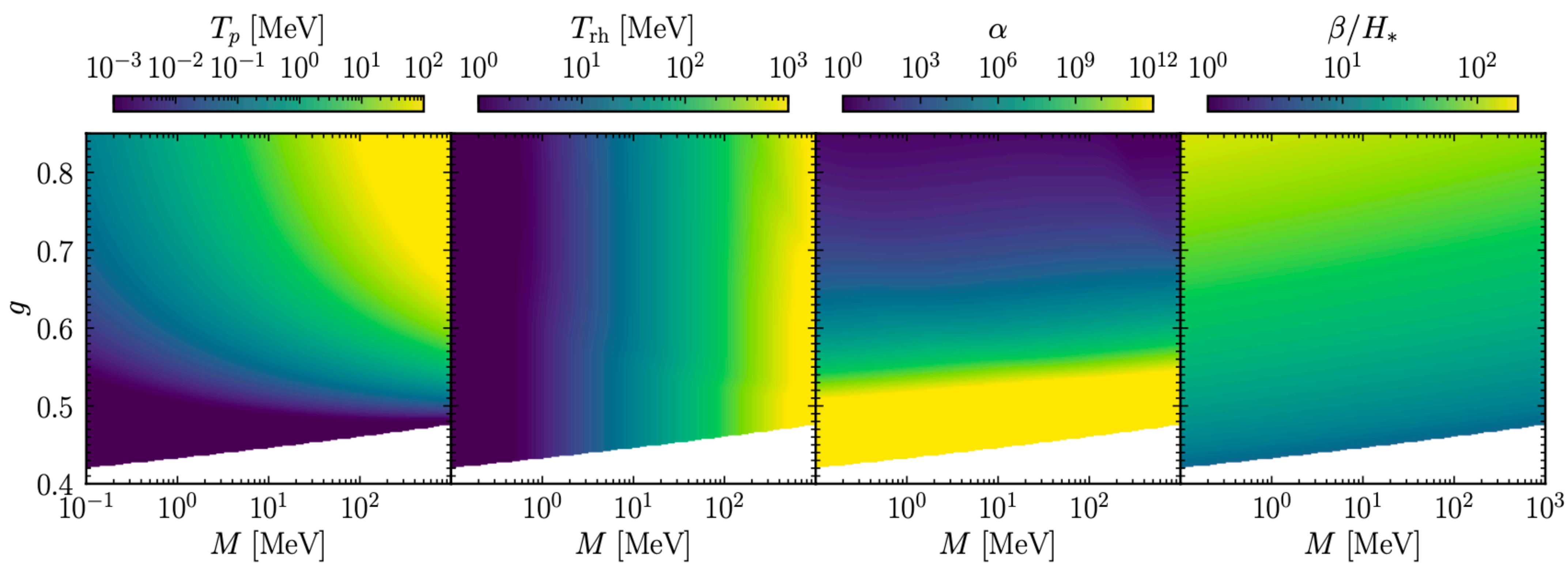
- Represent a significant fraction of the total energy density at the time of production, $T_* \sim (10 - 1000)\,\text{MeV}$
- Be very efficient at converting that energy to GW radiation
- Then disappear before onset of BBN, $T \sim 1\,\text{MeV}$

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

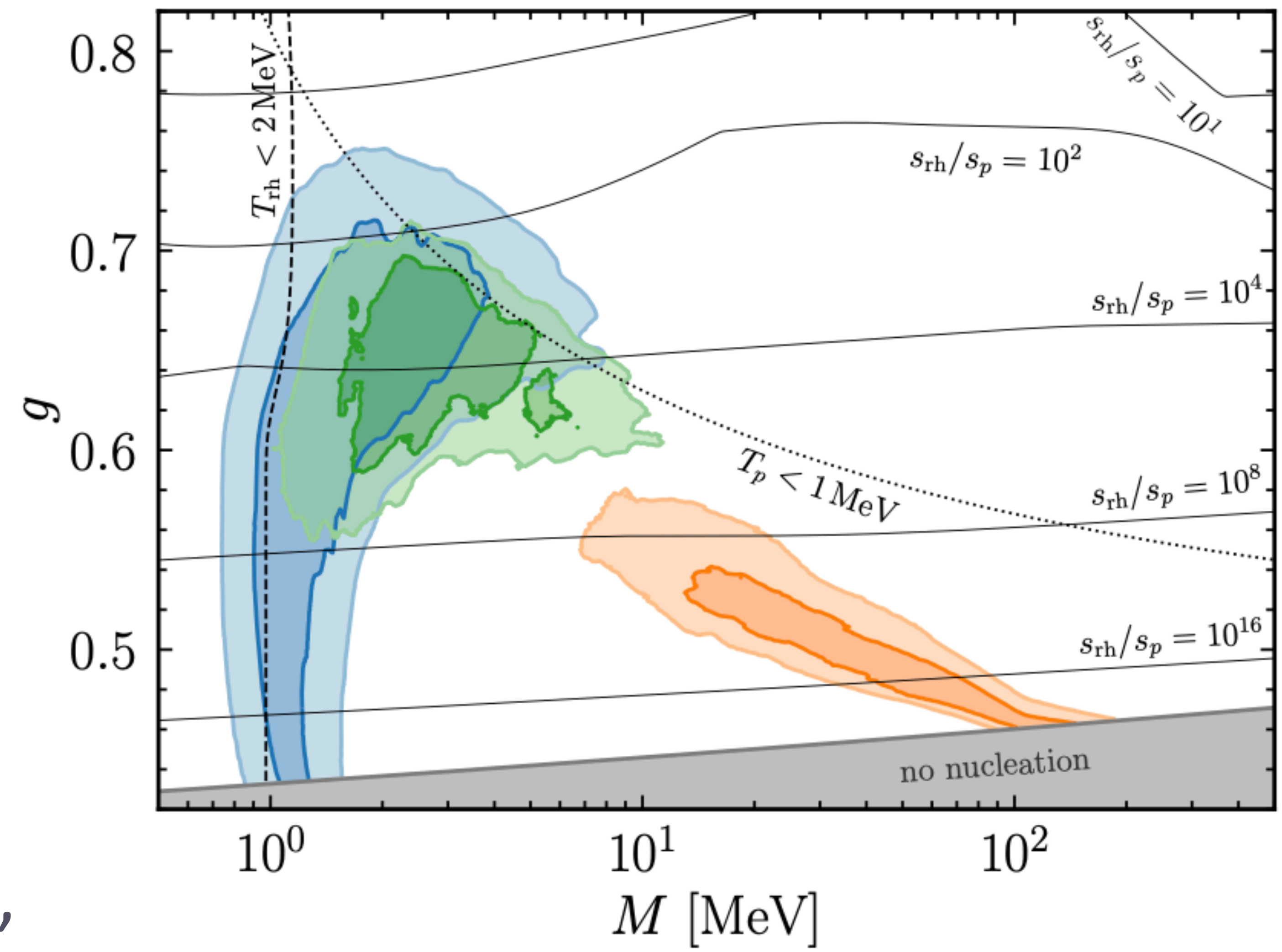
Supercooled phase transitions

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)

Can this be from the (dark) QCD phase transition?

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

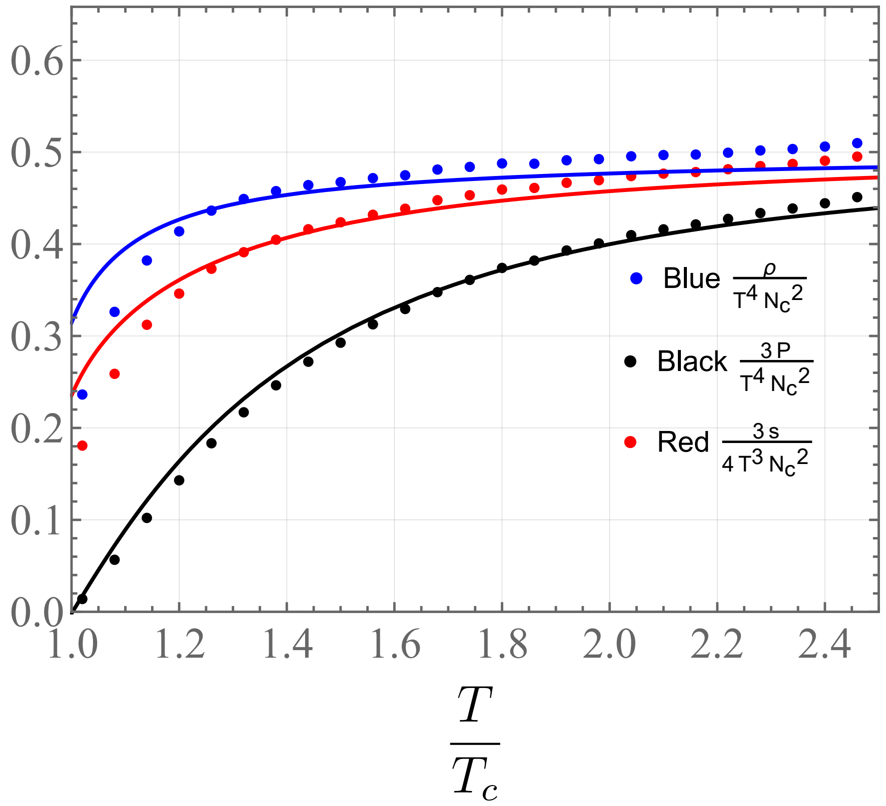
Want this to reproduce SU(N) theories

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

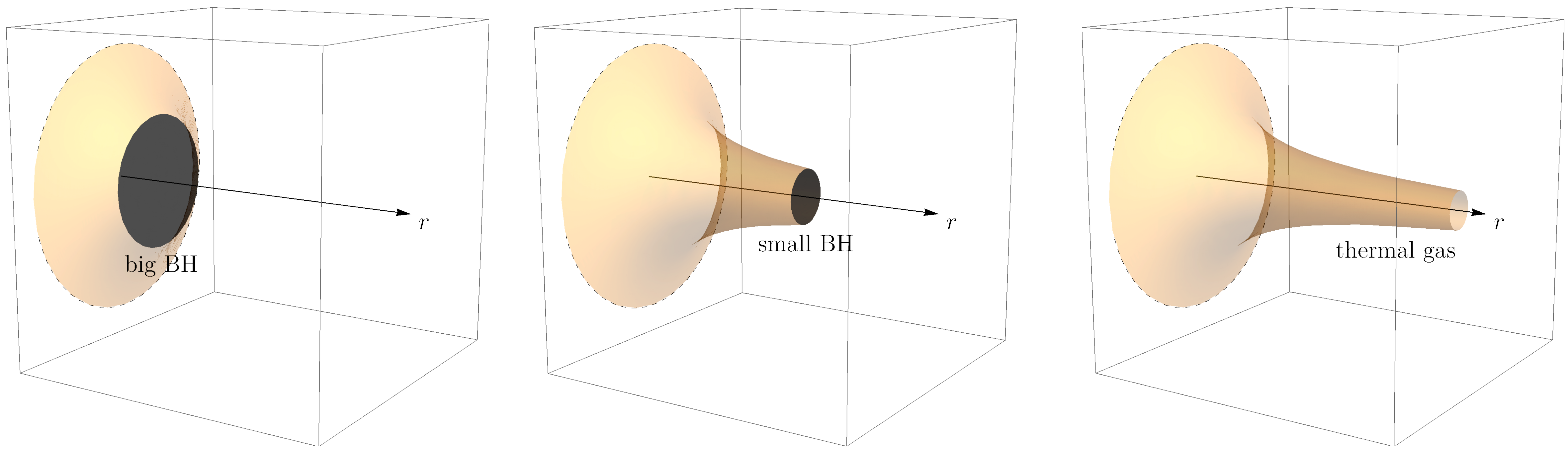
$$V(\lambda) = \frac{12}{\ell^2}\left\{1 + V_0\lambda + V_1\lambda^{4/3}[\log(1 + V_2\lambda^{4/3} + V_3\lambda^2)]^{1/2}\right\}$$

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



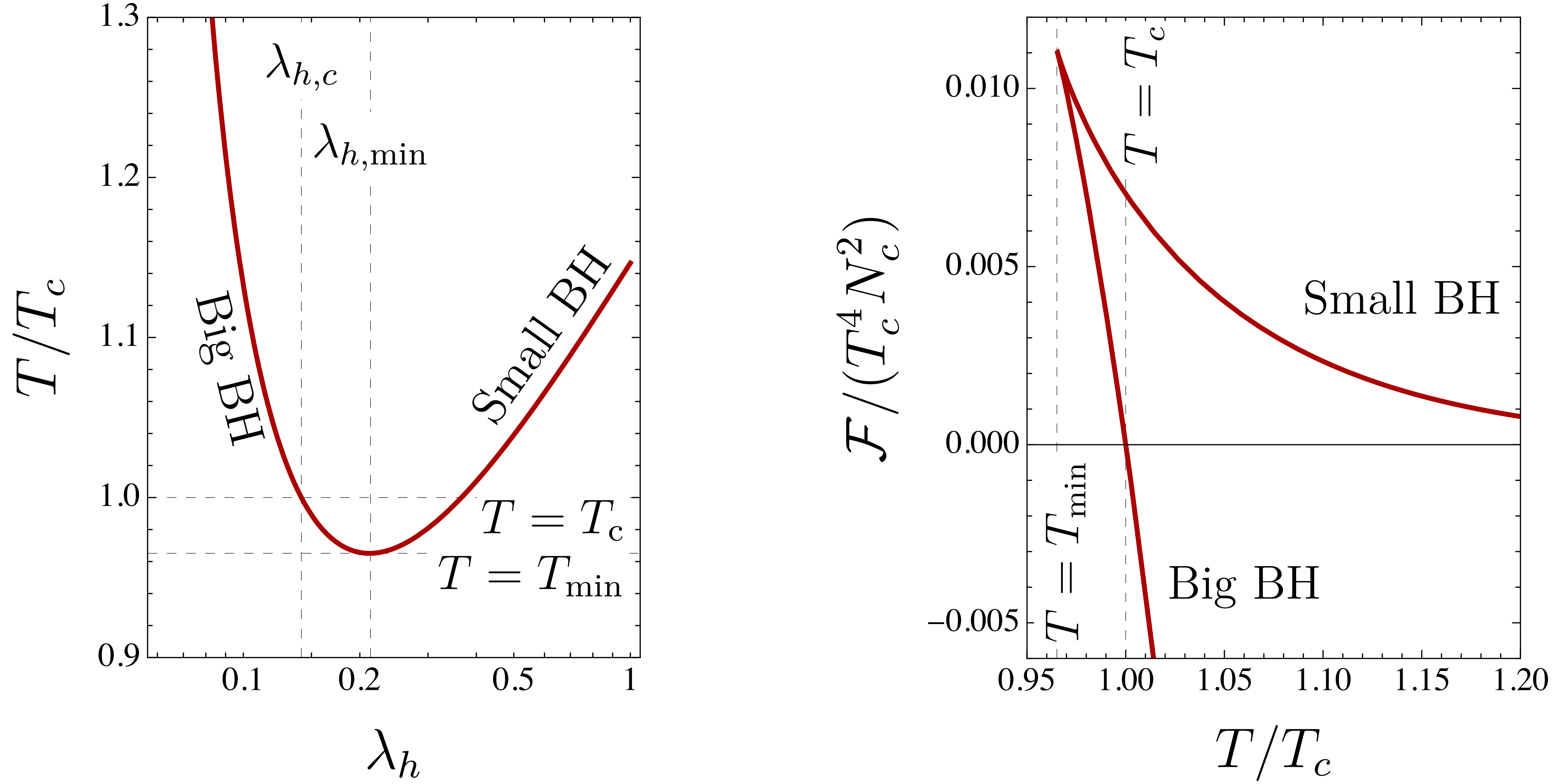
The phase transition in ihQCD



Three solutions

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

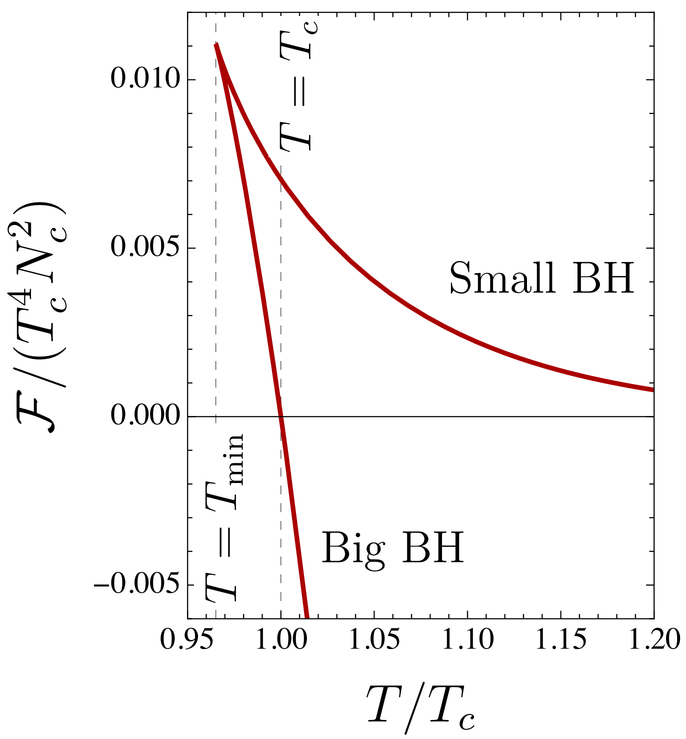
The phase transition in ihQCD II



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

The phase transition in ihQCD III

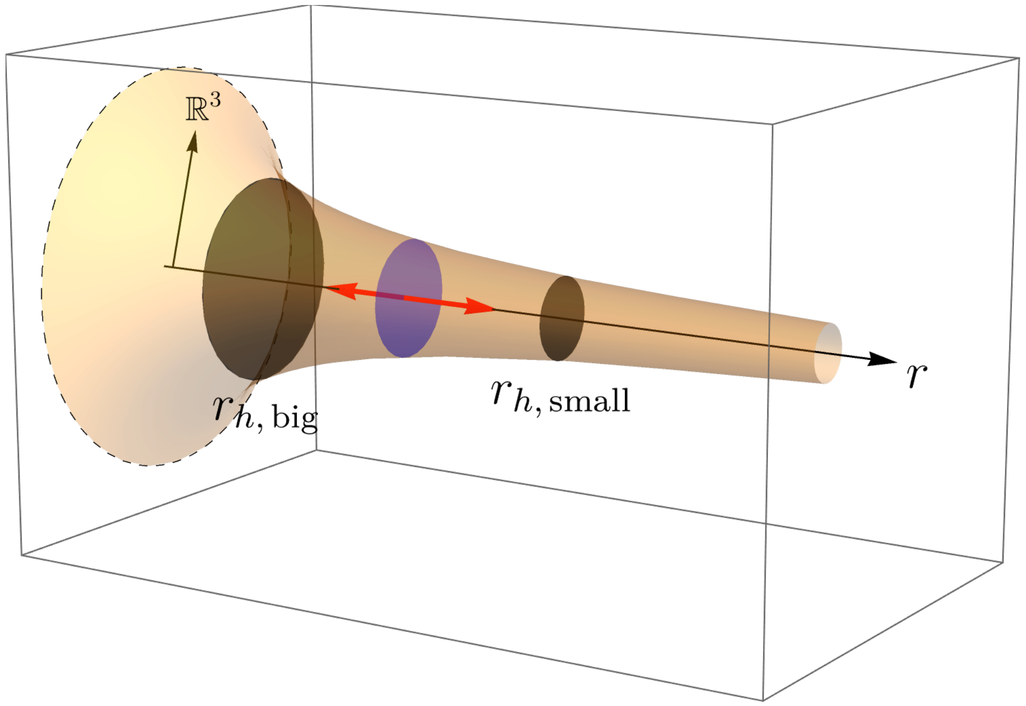
Hawking Page transition, with small BH acting as instanton



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

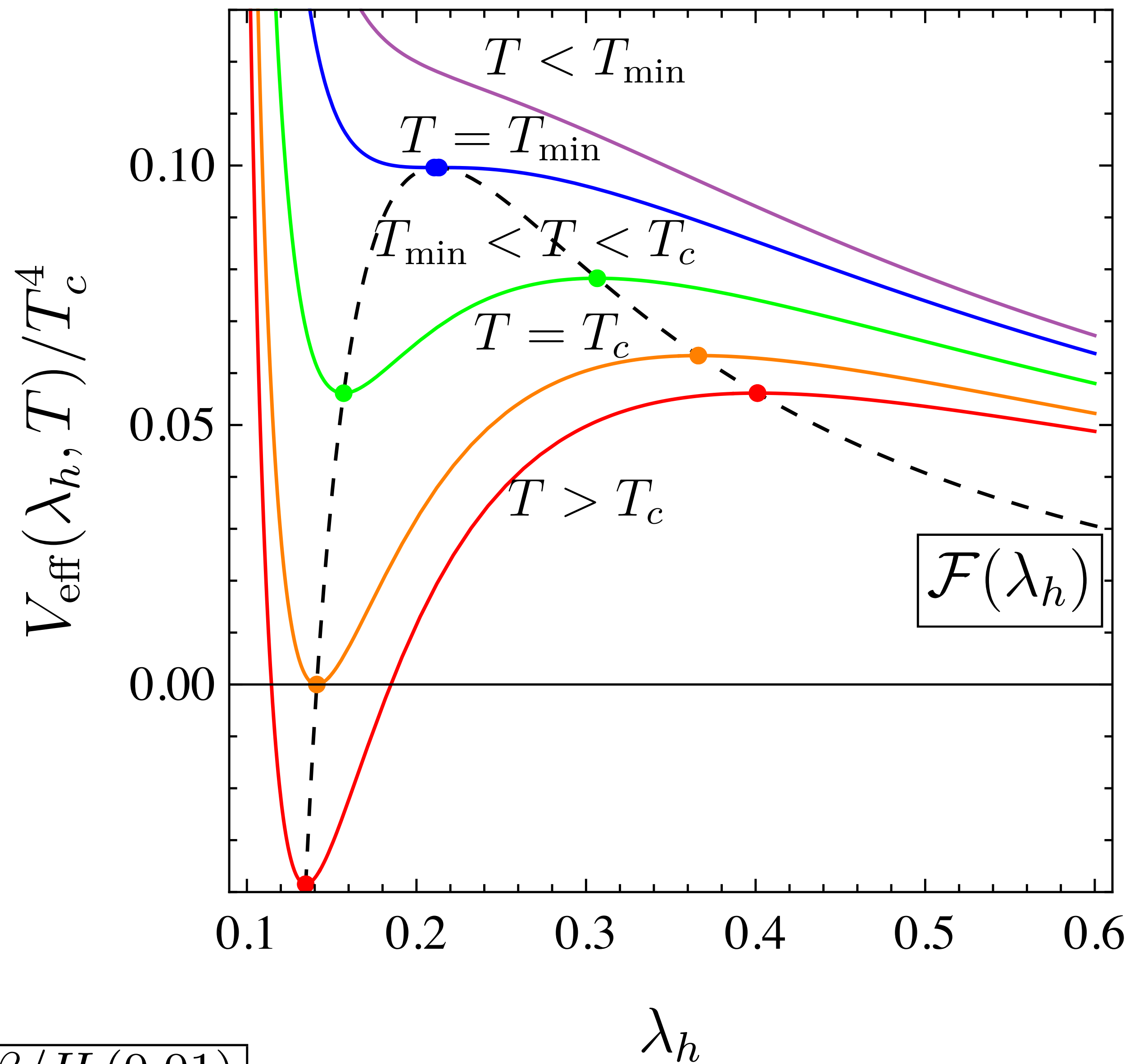
Bounce action

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

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

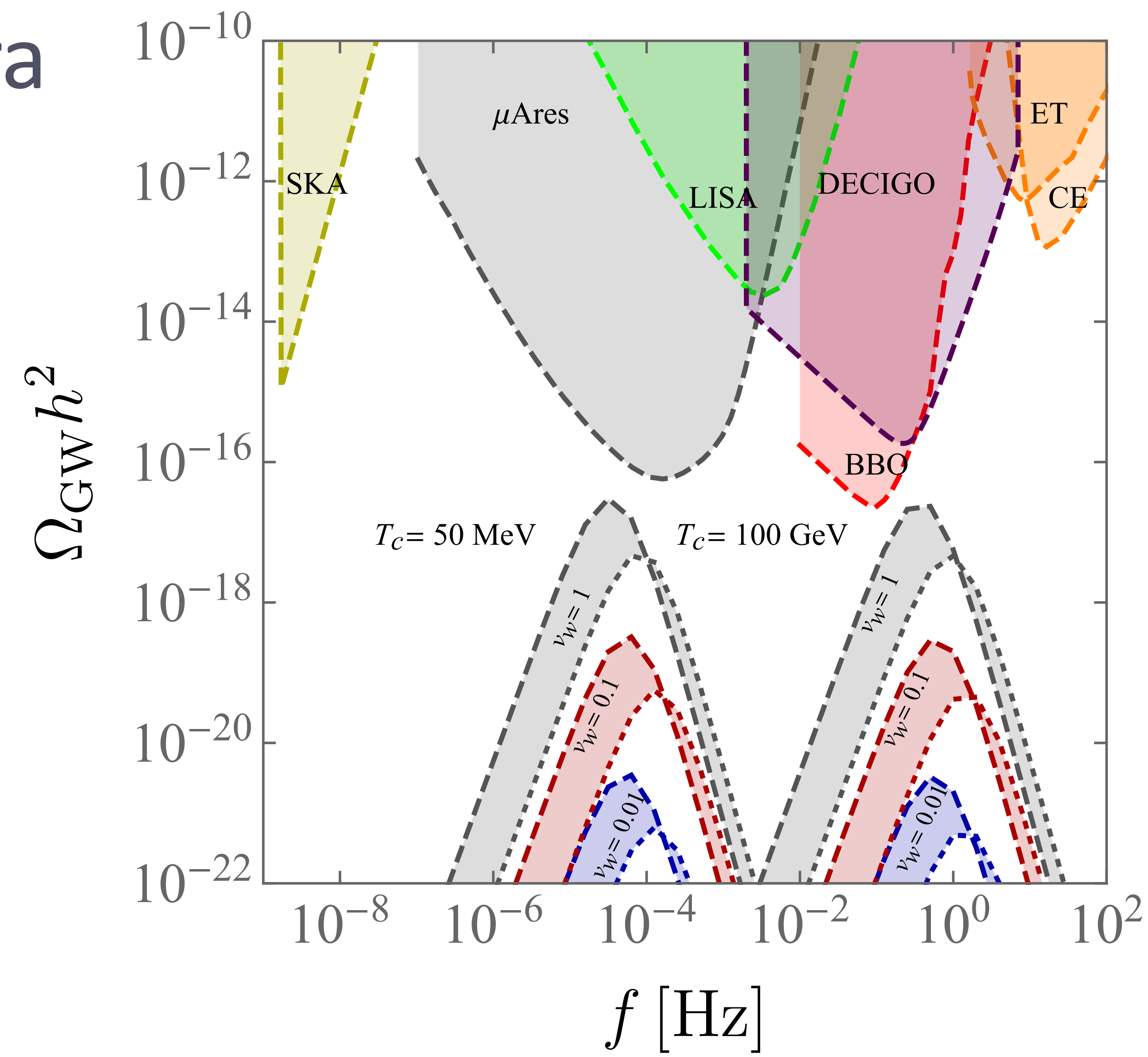
Morgante, Ramberg, PS, 2210.11821

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)



Work in progress

Bounce action

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

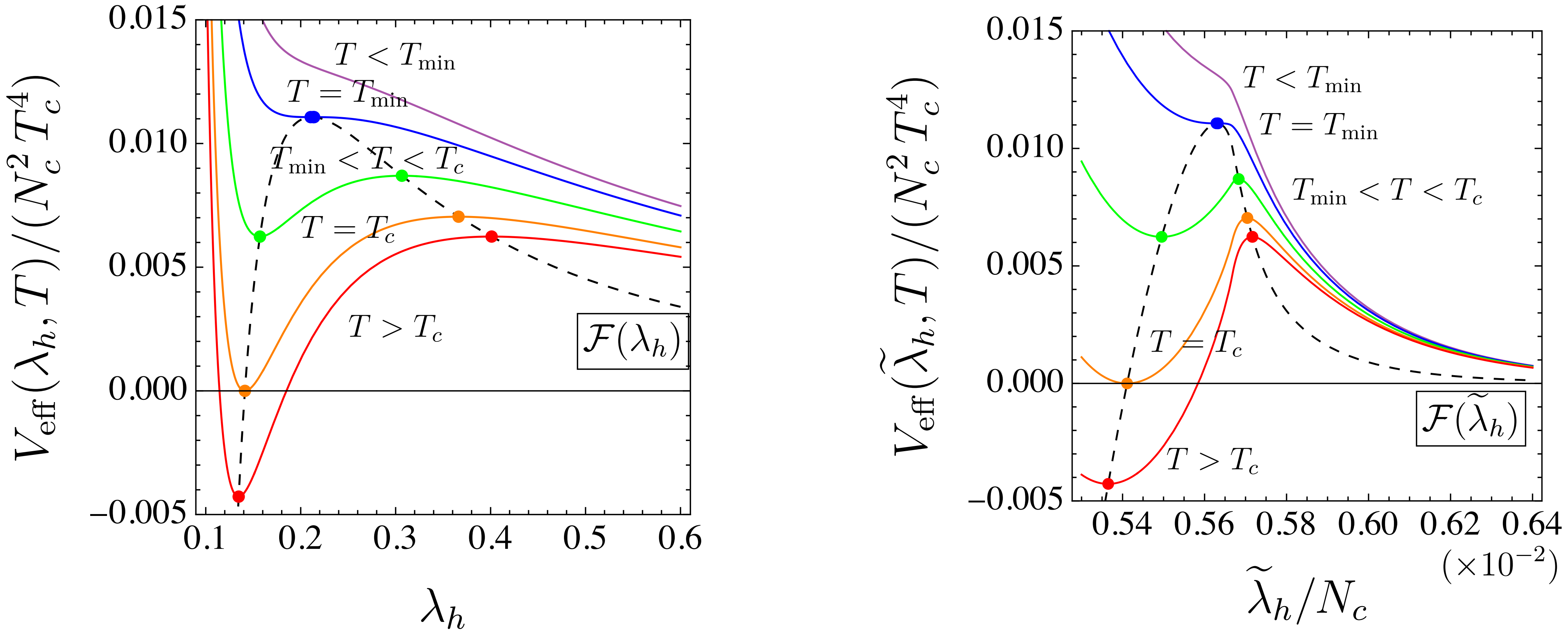
Normalisation “c” of kinetic term unknown

Can be determined for simpler geometries using prescription of Bigazzi et al, 2008.02579

Here: Not so easy. But obtained an estimate that has proper normalisation up to a factor 1-10

Morgante, Ramberg, PS, in preparation

Work in progress



Effective action for canonically normalised field

Unfortunately this seems to further weakens the GW signal

Morgante, Ramberg, PS, in preparation

Work in progress

Furthermore: Redid fit of dilation potential to newer lattice data and for N_c up to 8 - no significant N_c dependence

Extrapolation for large N_c - signal strengthens, but still unobservable

Exploring different methods to estimate wall velocity

Morgante, Ramberg, PS, in preparation

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

Some more details on improved holographic QCD

Thermal gas Ansatz (confined phase):

$$ds^2 = b_0^2(r)(dr^2 - dt^2 + dx^m dx_m).$$

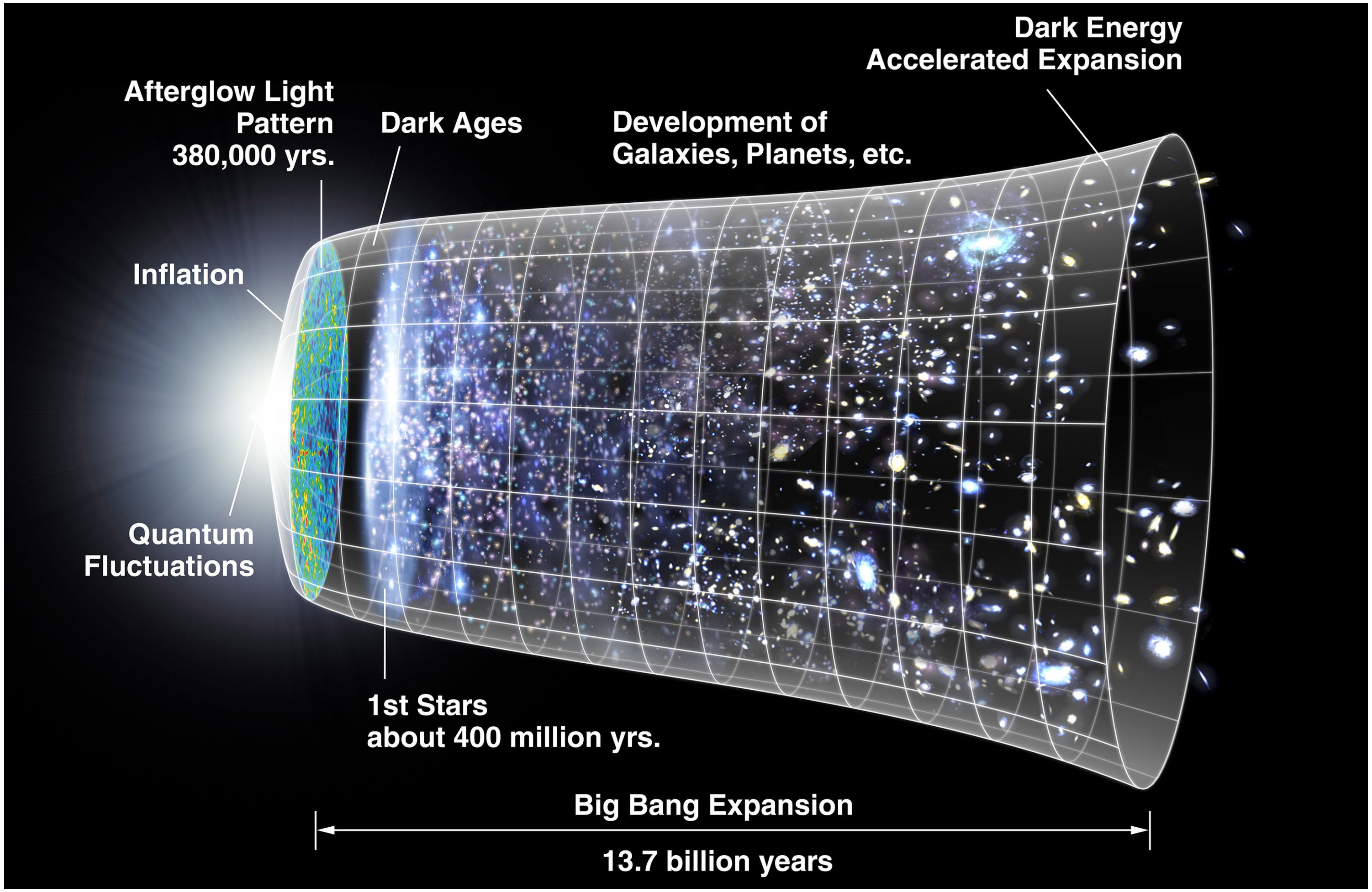
AdS black hole Ansatz (deconfined phase):

$$ds^2 = b^2(r)\left(\frac{dr^2}{f(r)} - f(r)dt^2 + dx^m dx_m\right)$$

Functions $b_0(r), b(r), f(r)$ determined from EOM

Solutions asymptotic to AdS in UV, with log corrections

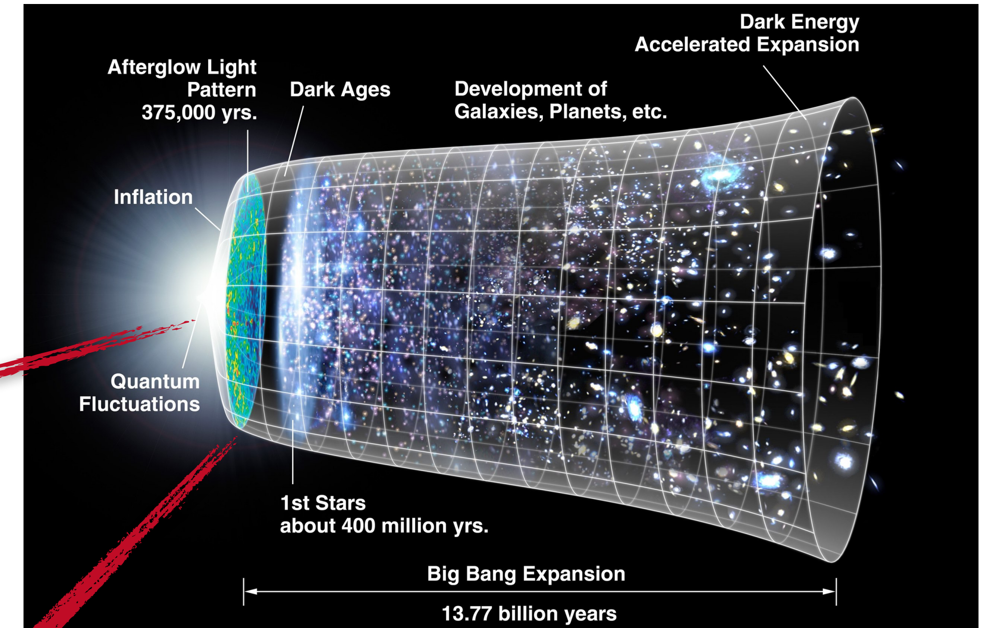
Thermal History

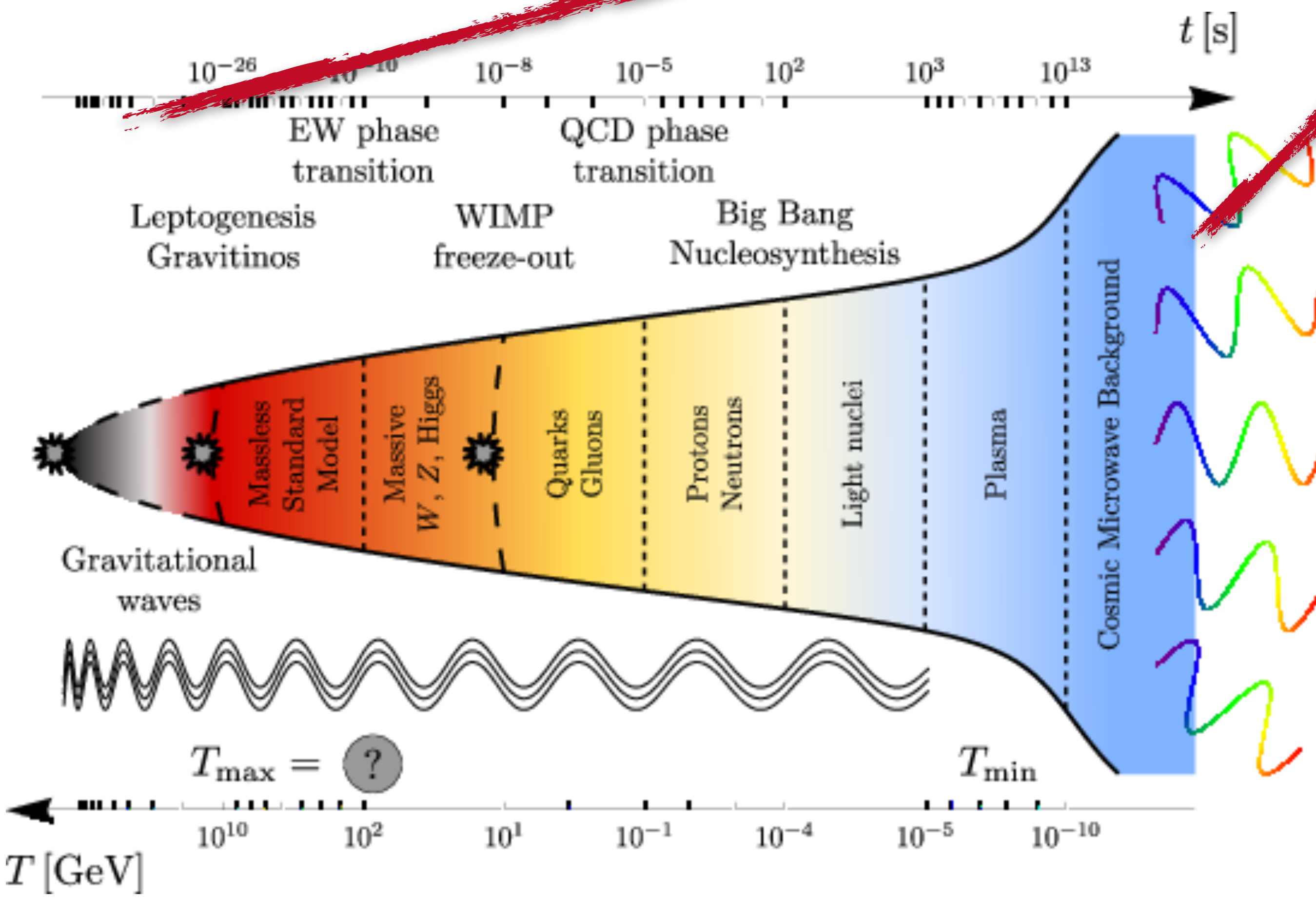


Gravitational Waves?

Zoom into interesting region

New window into early universe





e.g.

Electroweak symmetry breaking

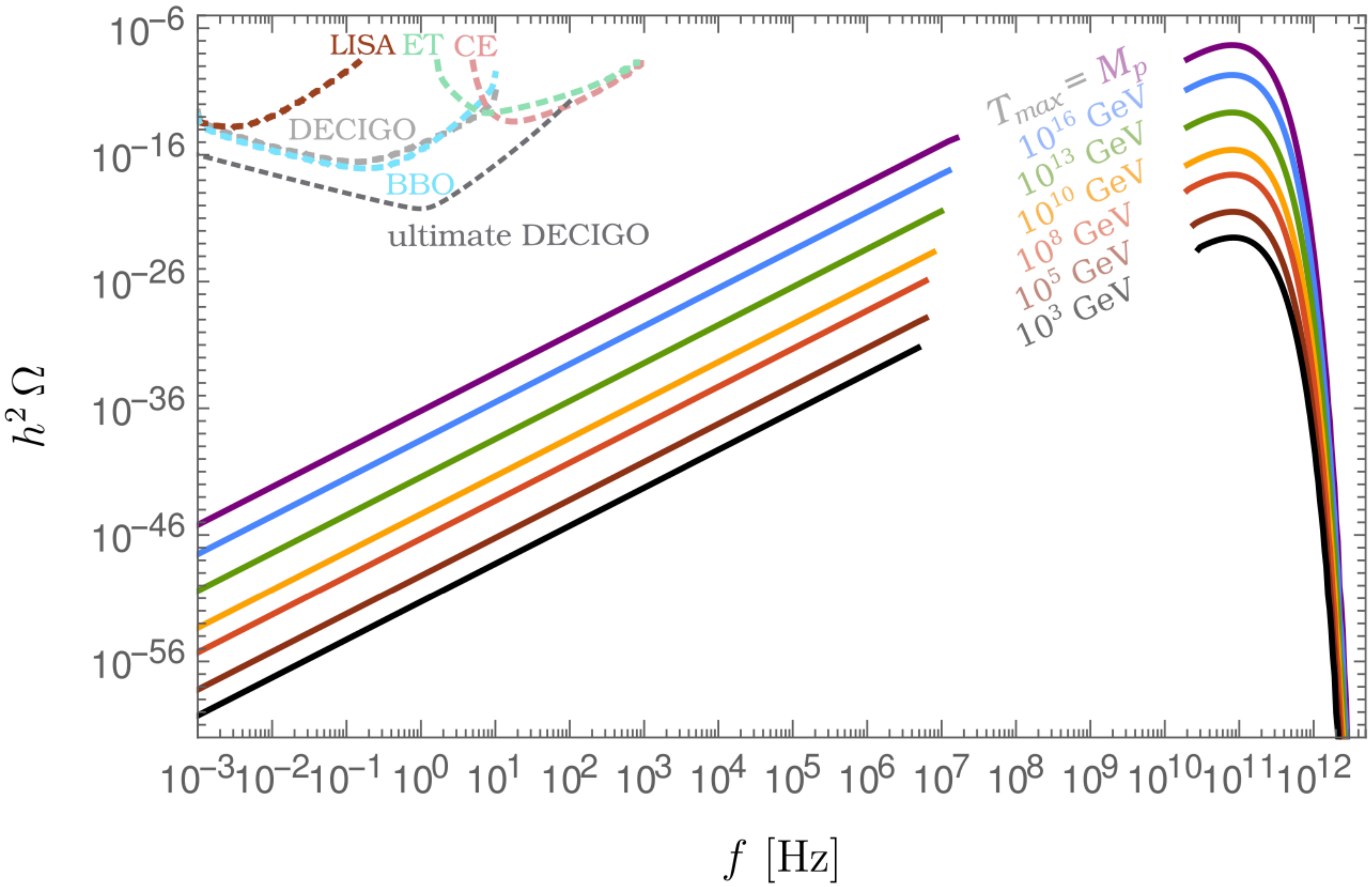
Baryogenesis

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

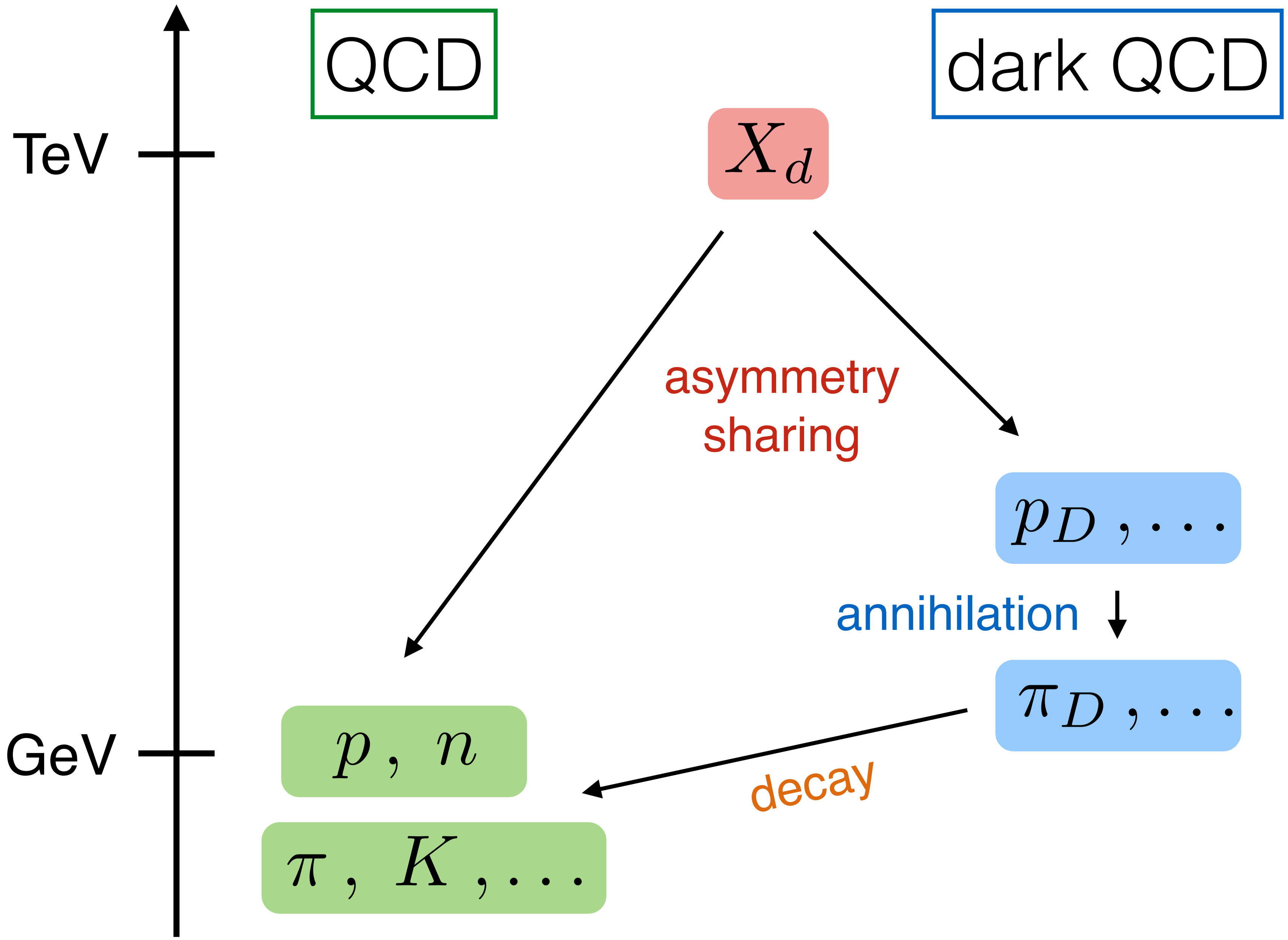
PT from center symmetry restoration

$$n_f > 0$$

Dark Baryons or Dark Pions

Chiral Symmetry Breaking

Composite DM / Hidden Sector



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

$$\Lambda_{\text{darkQCD}}$$

- DM is composite "dark proton"

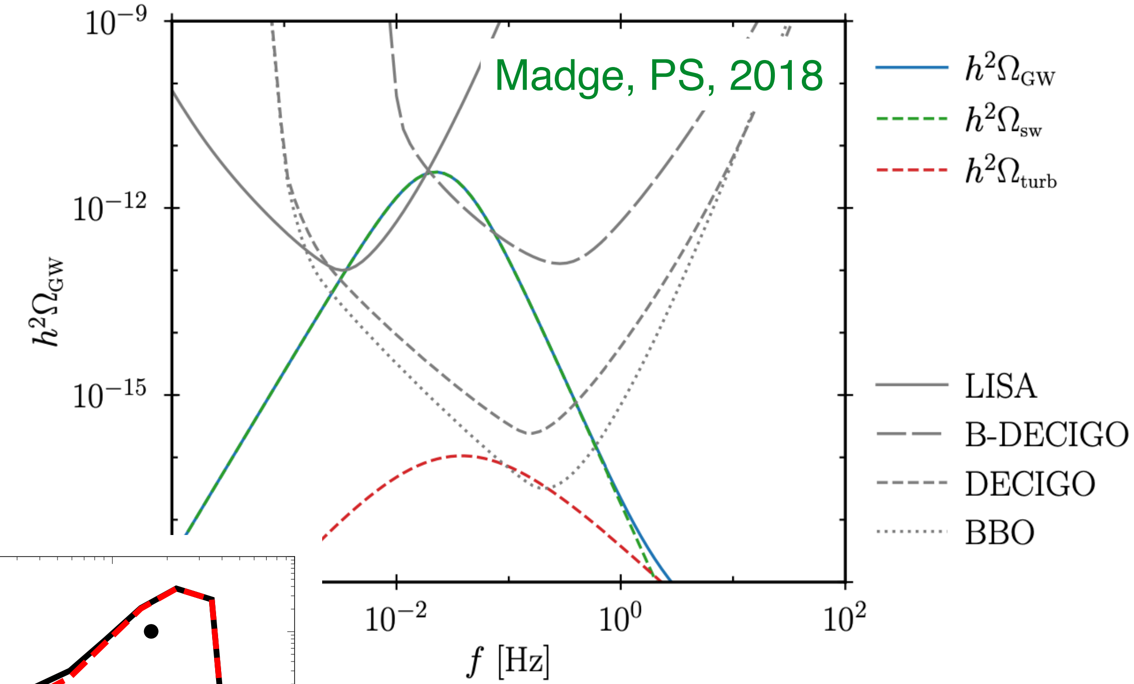
Bai, PS, PRD 89, 2014
PS, Stolarski, Weiler, JHEP 2015

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

New physics mass scales for PTA

Phase transition

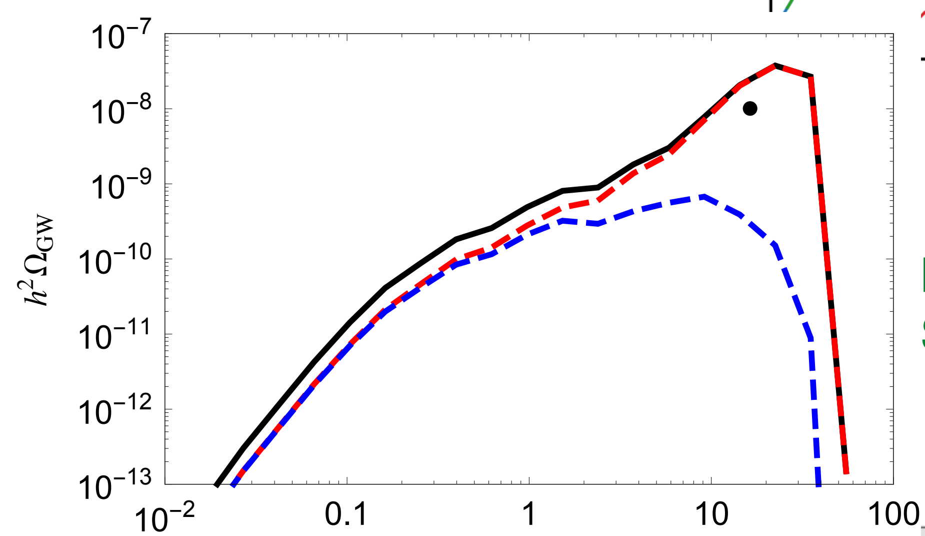
- $T_* = M_{NP} \sim \mathrm{MeV} - \mathrm{GeV}$



Audible axions:

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

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

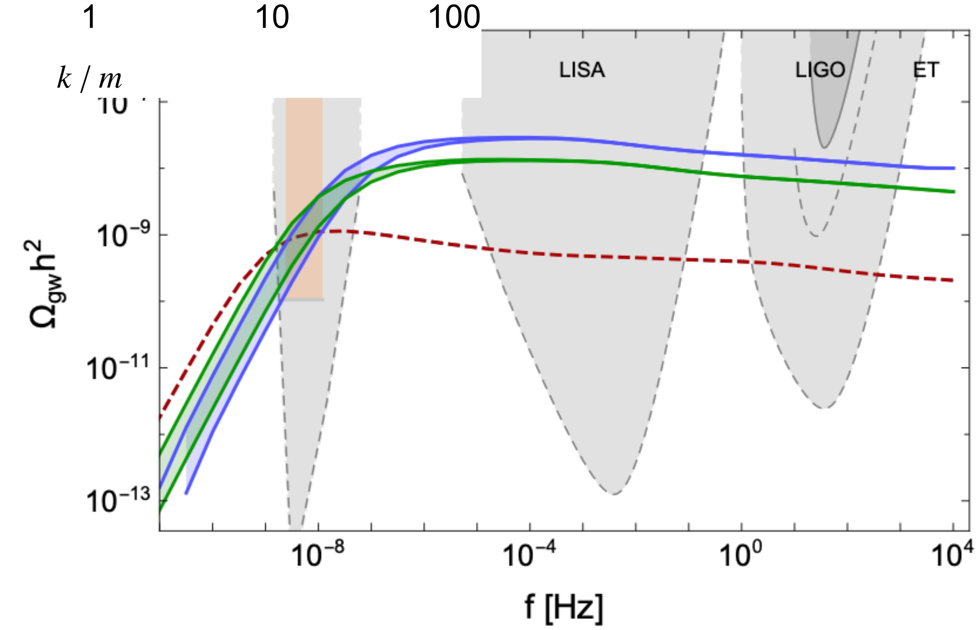


Machado, Ratzinger, Stefanek, PS, 2018/19

Cosmic strings/domain walls

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

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



Buchmuller, Domcke, Schmitz, 2021

Benchmark models with large signals

Madge et al, 2306.14856

Global cosmic strings

- In trouble with N_{eff}

Audible axions

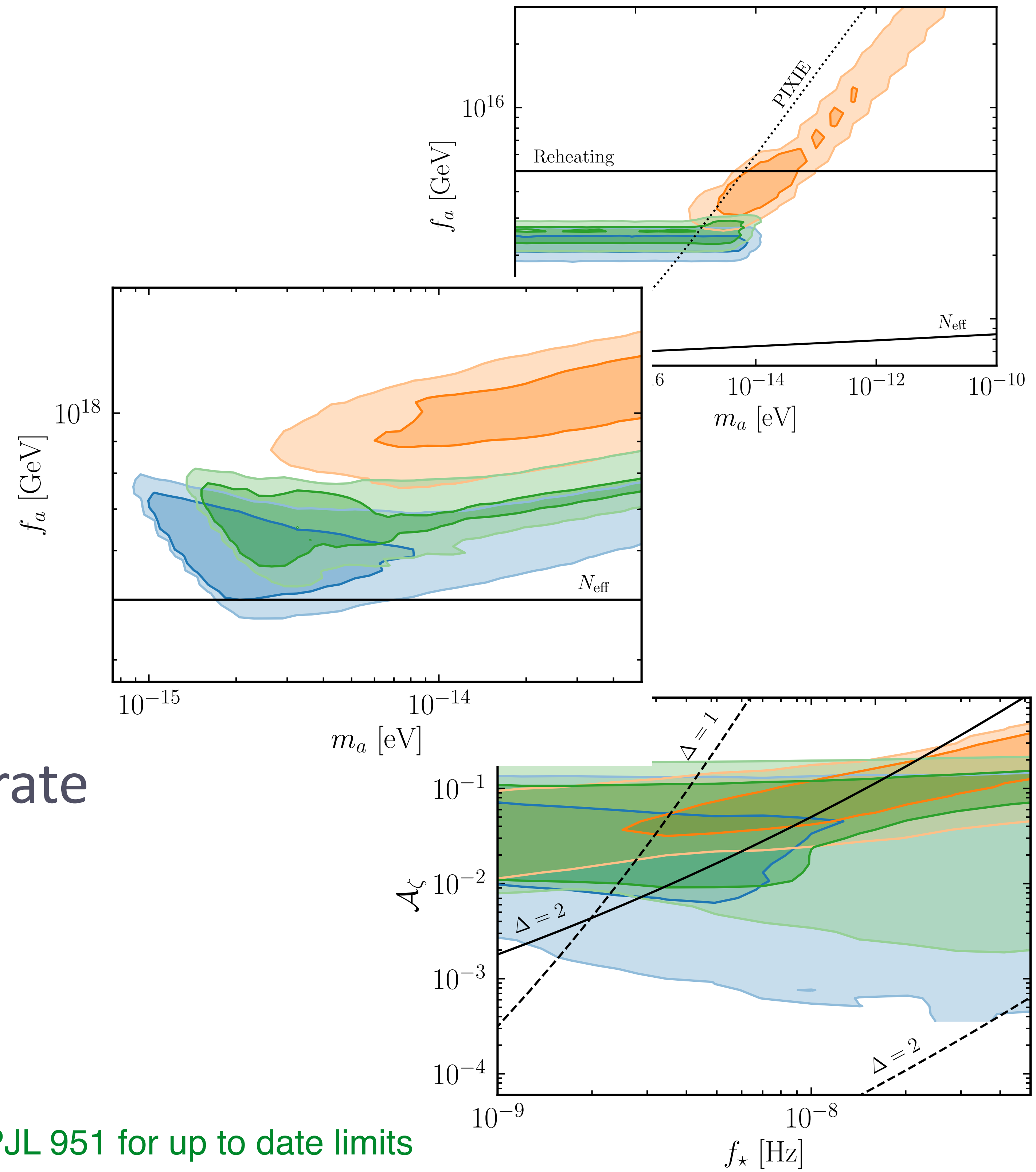
- Barely consistent with N_{eff}

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

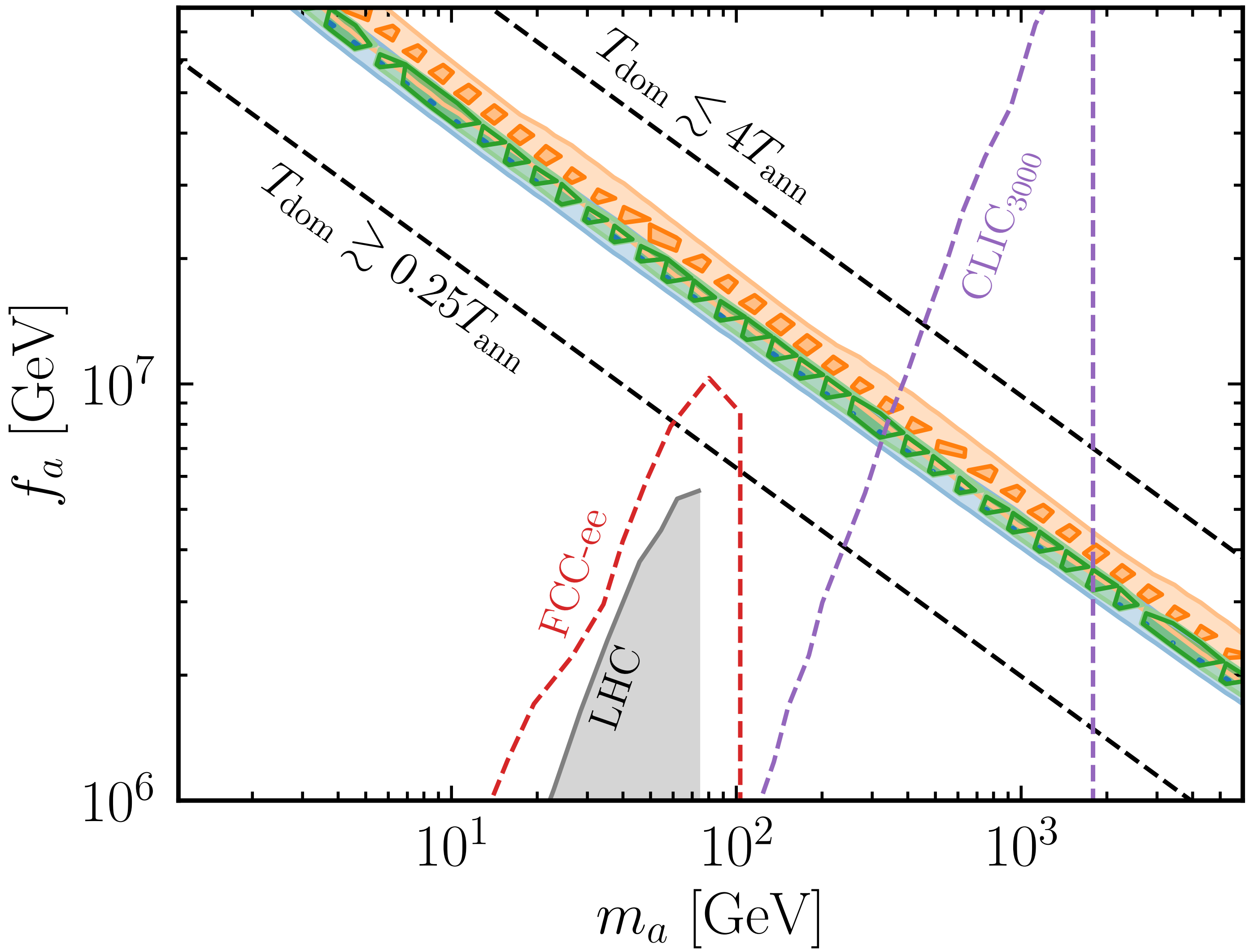
Madge et al, 2306.14856

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

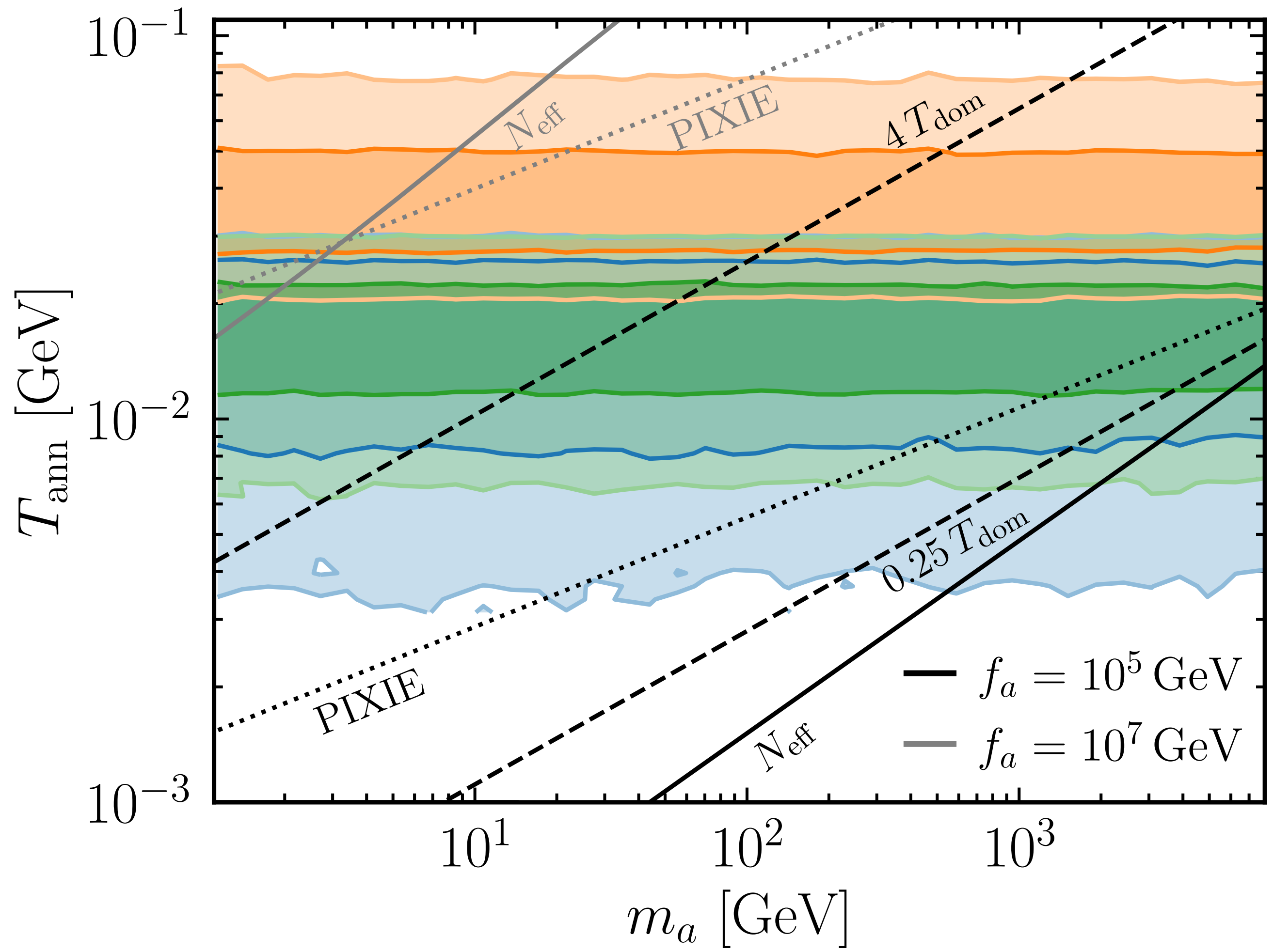
Madge et al, 2306.14856

DWs annihilate to dark radiation

- $N_{\rm eff}$ ok mostly

Dark sector anisotropies induce CMB spectral distortions

- In reach of future experiments (PIXIE)



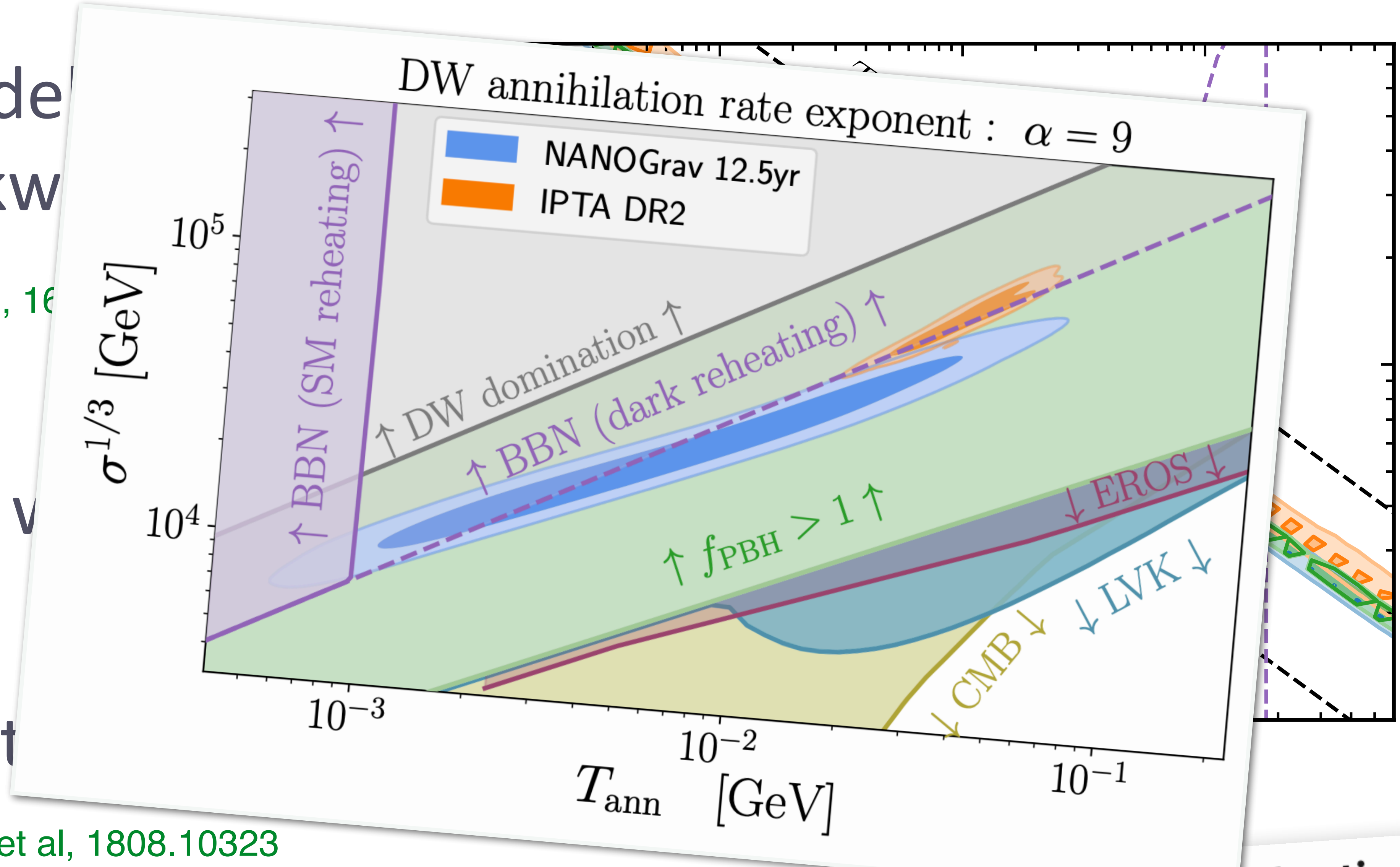
Axion/ALP domain walls

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



Domain wall interpretation of the PTA signal confronting black hole overproduction

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

Jun 30, 2023

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