Exploring the dark universe with gravitational wave backgrounds

Seminar talk at IPNP Prague, 04.12.2024

Carlo Tasillo,
Uppsala University

Based on work with Sowmiya Balan, Torsten Bringmann, Paul Frederik Depta, Tomás Gonzalo, Felix Kahlhöfer, Thomas Konstandin, Jonas Matuszak, Kai Schmidt-Hoberg and Pedro Schwaller

JCAP 05 (2024) 065, 2306.17836, and JCAP 11 (2023) 053

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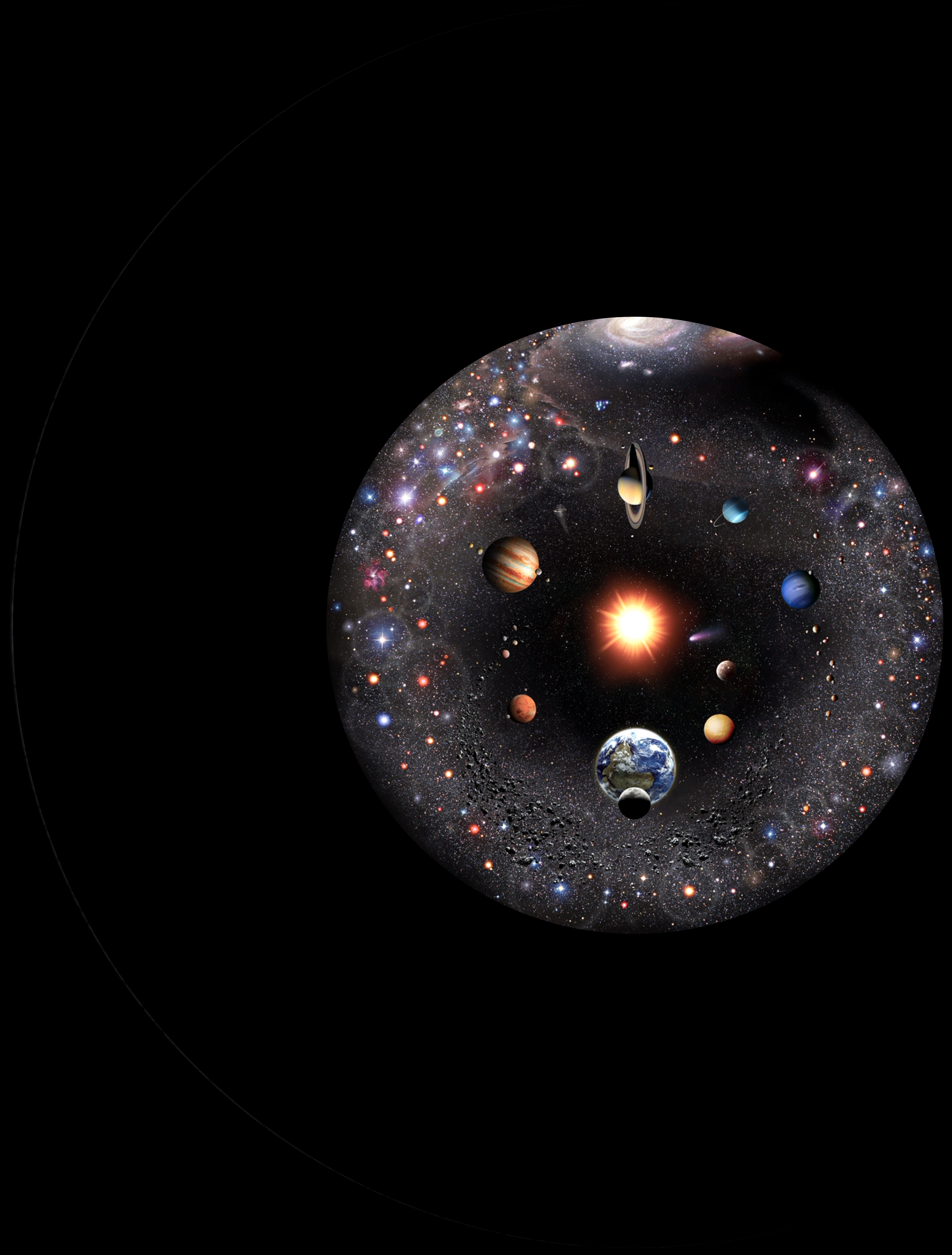
The observable universe

Our Solar System

[Pablo Carlos Budassi]

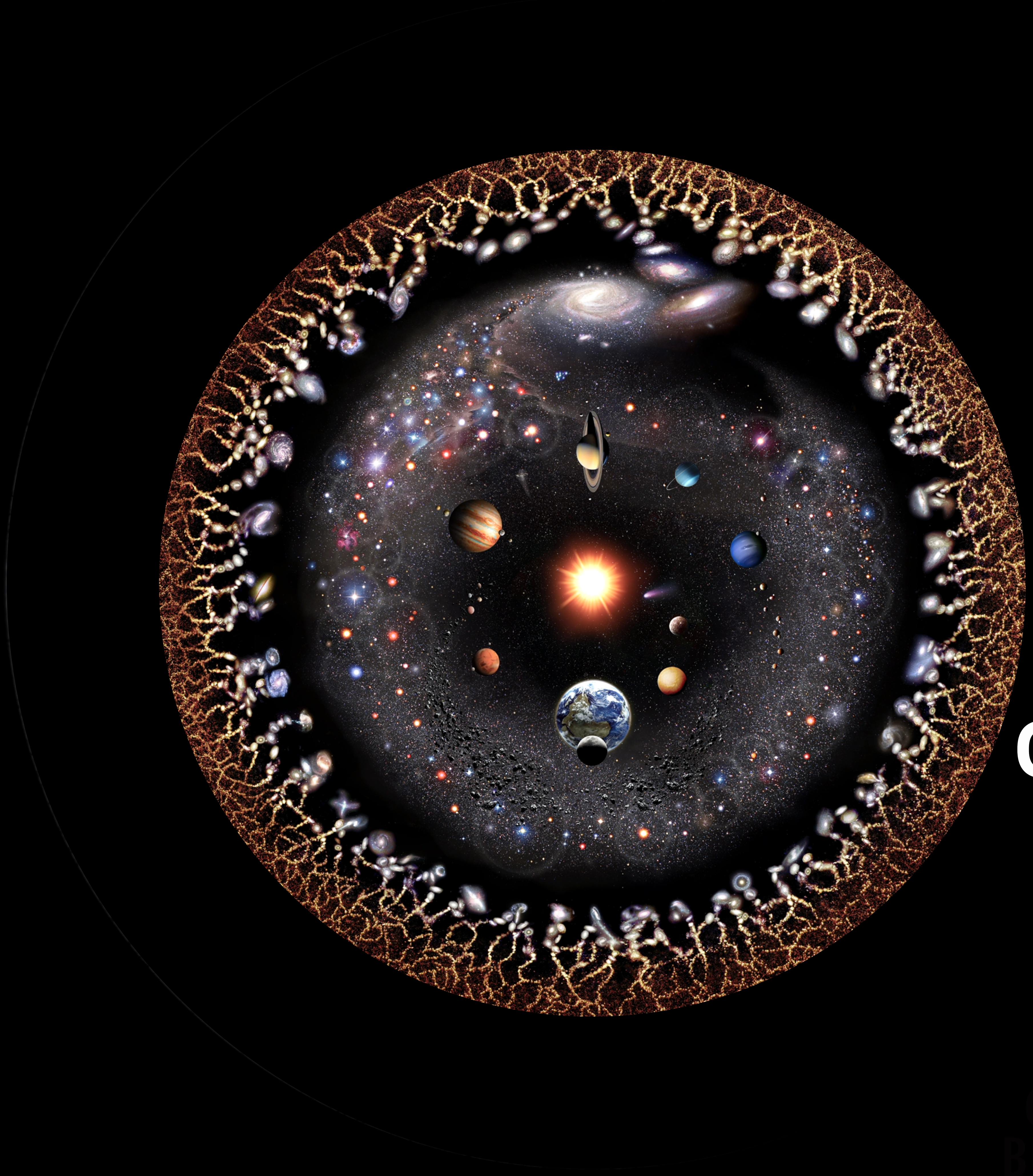
The observable universe



Our galaxy

[Pablo Carlos Budassi]

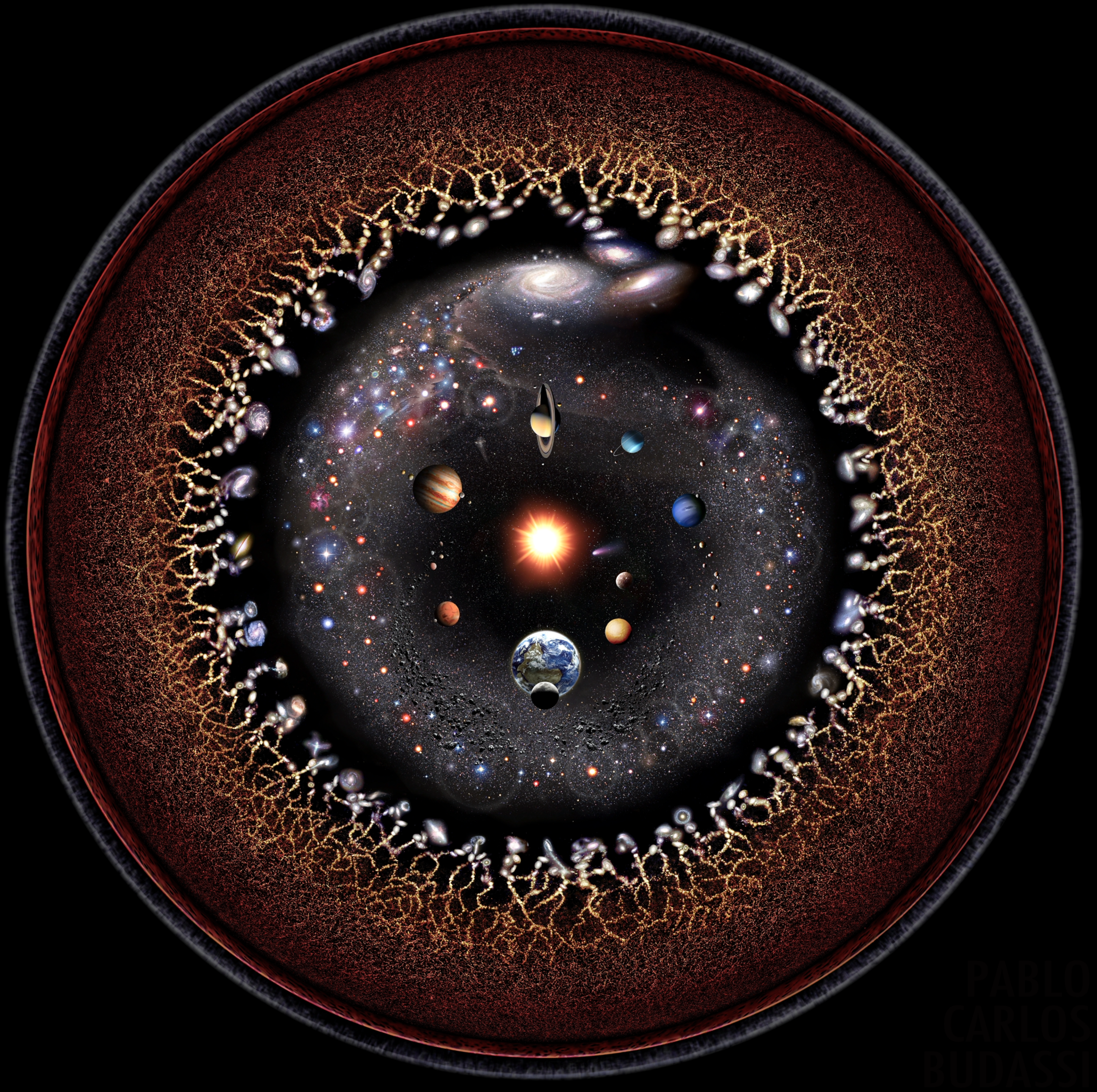
The observable universe



Other galaxies

[Pablo Carlos Budassi]

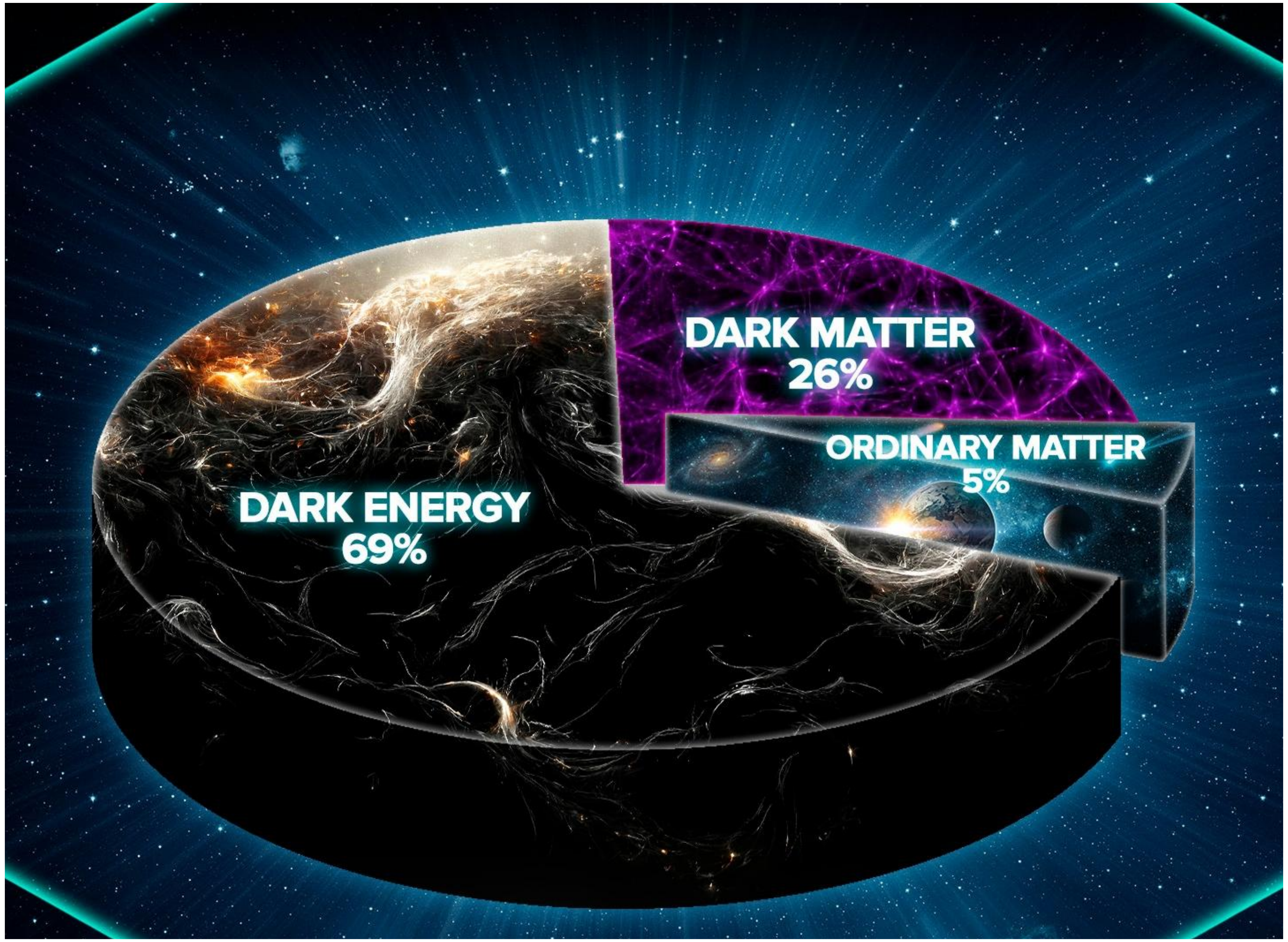
The observable universe



The CMB…
and the CGWB?

[Pablo Carlos Budassi]

We only understand 5%



[PBS spacetime]

We need

$$\boxed{\Omega_{\mathrm{DM}}h^2 = 0.12}$$

of cold dark matter in order to explain the CMB, galaxy clustering, the bullet cluster, galactic rotation curves, …

Cirelli+ [2406.01705]

At Last, There’

A globe-span

Astronomers detect ‘cosmic bass note’ of gravitational waves

Sound comes from the merging of supermassive black holes across the universe, according to scientists

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Scientists ‘hear’ cosmic hum from gravitational waves

Scientists observed for the first time faint ripples caused by the motion of black ing everything in the universe.

Gravitational

Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe

Scientists have observed for the first time the faint ripples caused by the motion of black holes that are gently stretching and squeezing everything in the universe

ASTROPHYSICS

A Background ‘Hum’ Pervades the Universe. Scientists Are Racing to Find Its Source

Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year

For first time ever, scientists "hear" gravitational waves rippling through the universe

First Evidence of Giant Gravitational Waves Thrills Astronomers

re tuning in to a never-before-seen type of gravitational pawned by pairs of supermassive black holes

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gravitational waves

ace-time ripples

The New York Times

The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find

Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.

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Galax

Space

Gravitational wave

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SCIENCE

Colossal gravitational waves—trillions of miles long—found for the first time

d by studying rapidly spinning dead e giant ripples of spacetime likely e from merging supermassive black holes—

The Washington Post

Democracy Dies in Darkness

Ground king gravitational wave disco lock our Univ teries

The results are background, a hum o Universe.

Physics

Gravitational waves produce a background hum across the whole universe

After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe

Scientists r come from c holes

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In a major discovery, scientists say space-time churns like a choppy sea

The mind-bending finding suggests that everything around us is constantly being roiled by low-frequency gravit waves

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Physics
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After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe

The results are background, a hum of Universe.

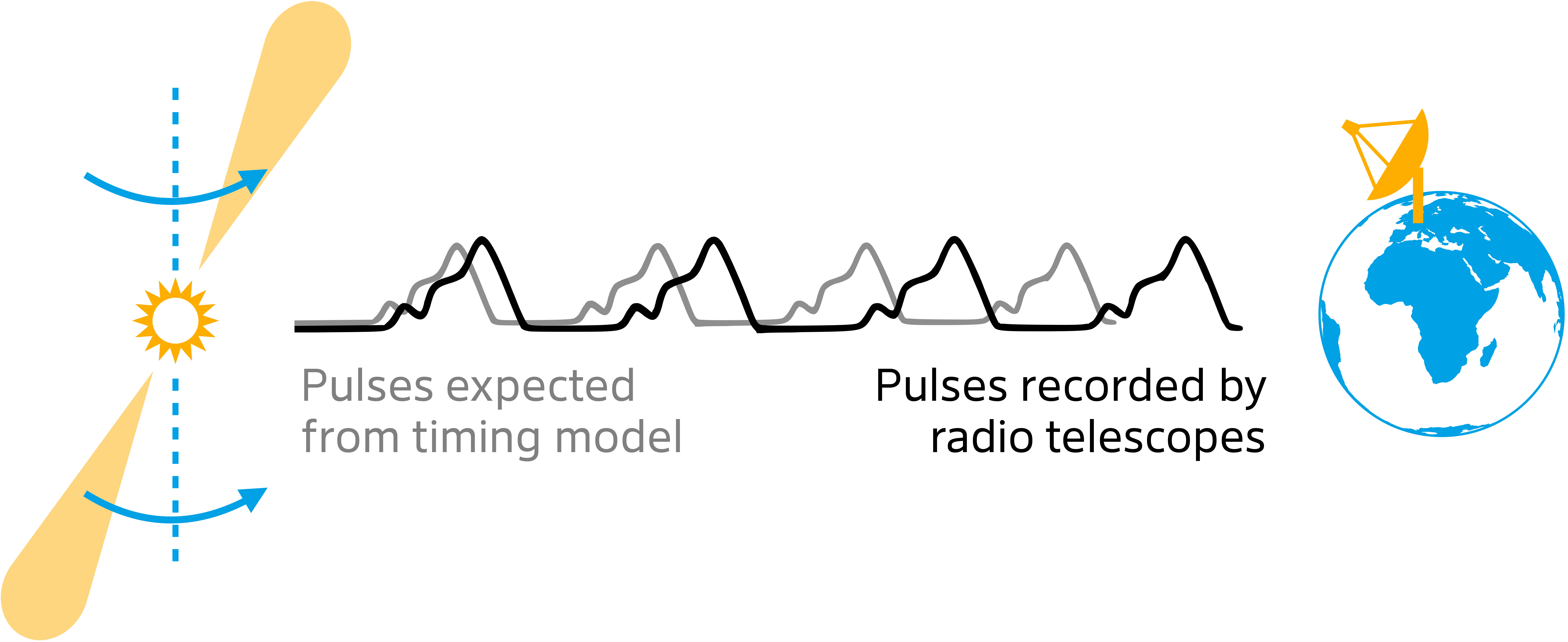
Luckily, we live in the age of gravitational wave cosmology!

Pulsar timing arrays

Pulsar timing arrays

Pulses expected
from timing model

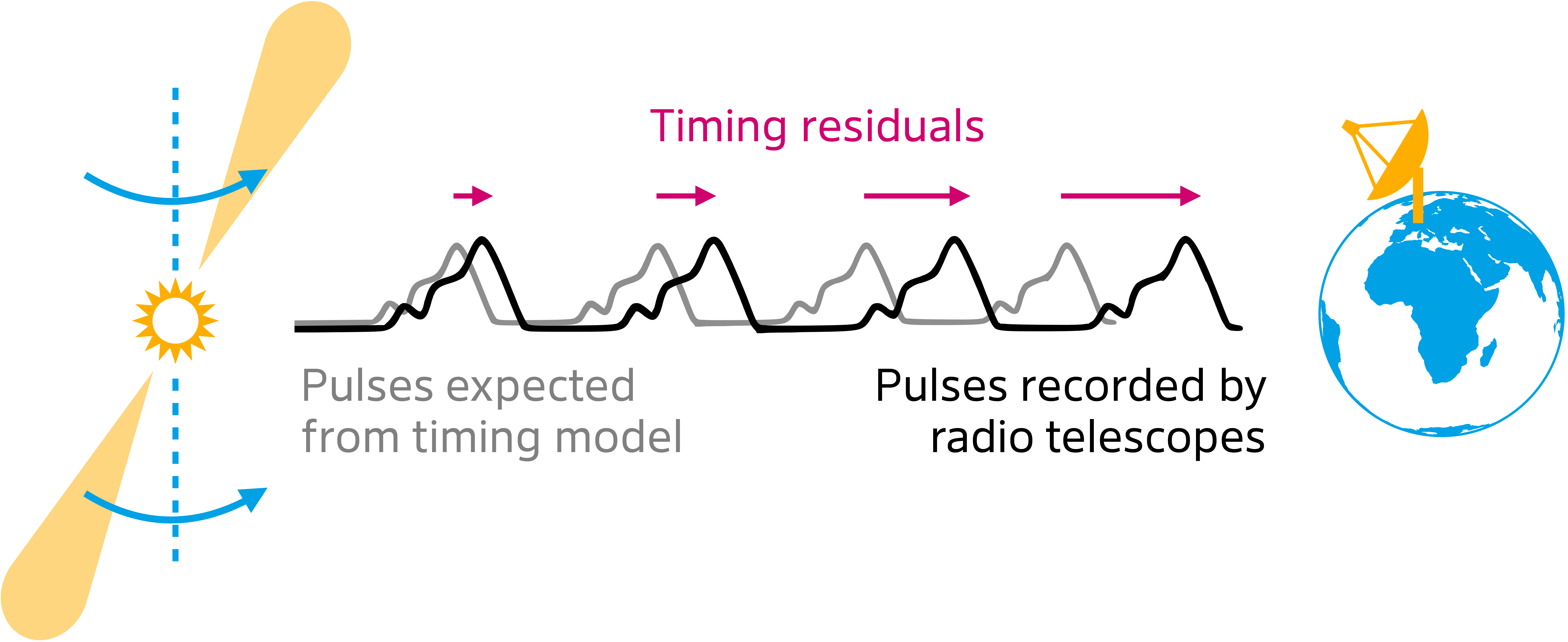
Pulsar timing arrays



Pulses expected
from timing model

Pulses recorded by
radio telescopes

Pulsar timing arrays



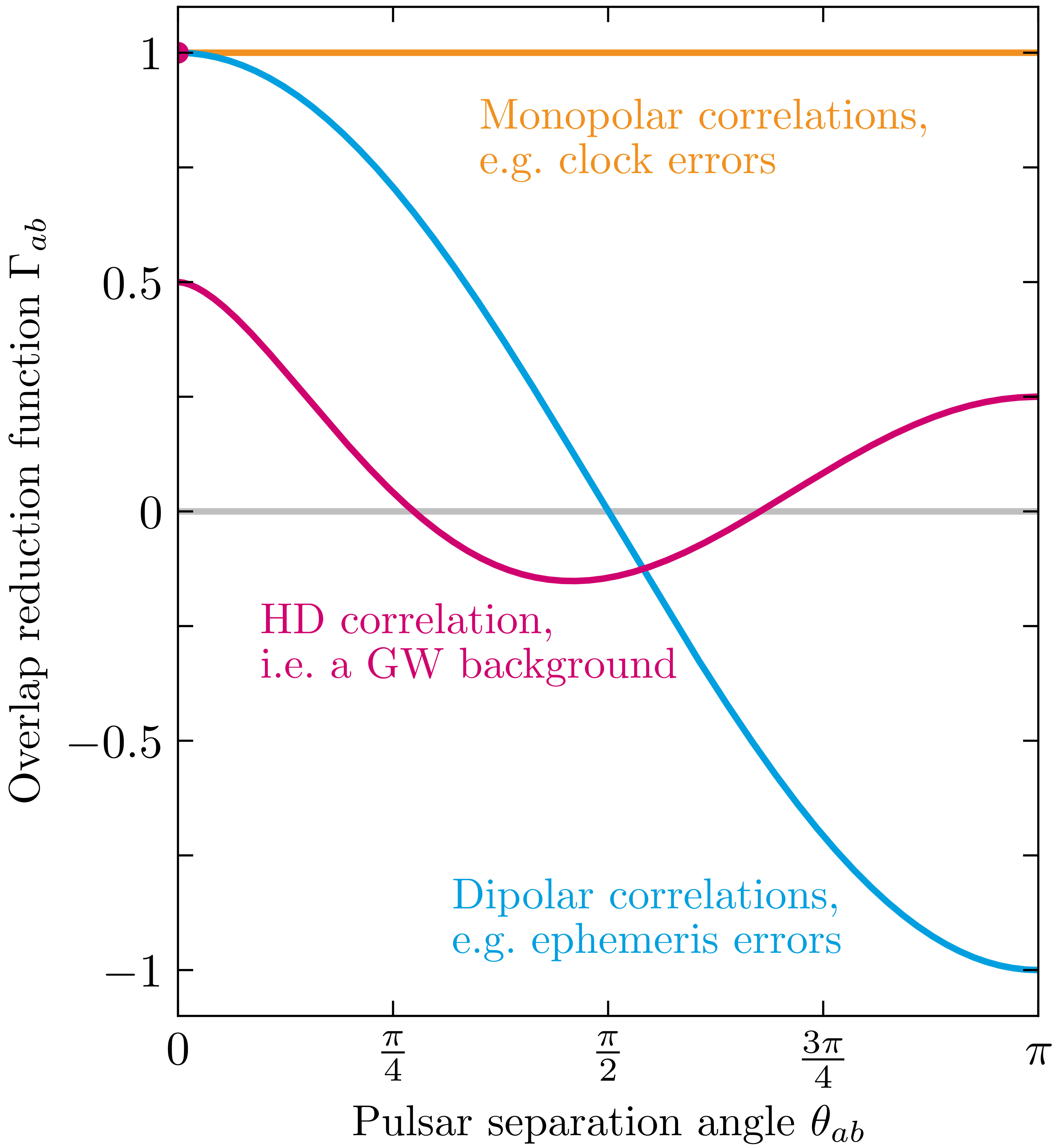
Timing residuals

Pulses expected from timing model

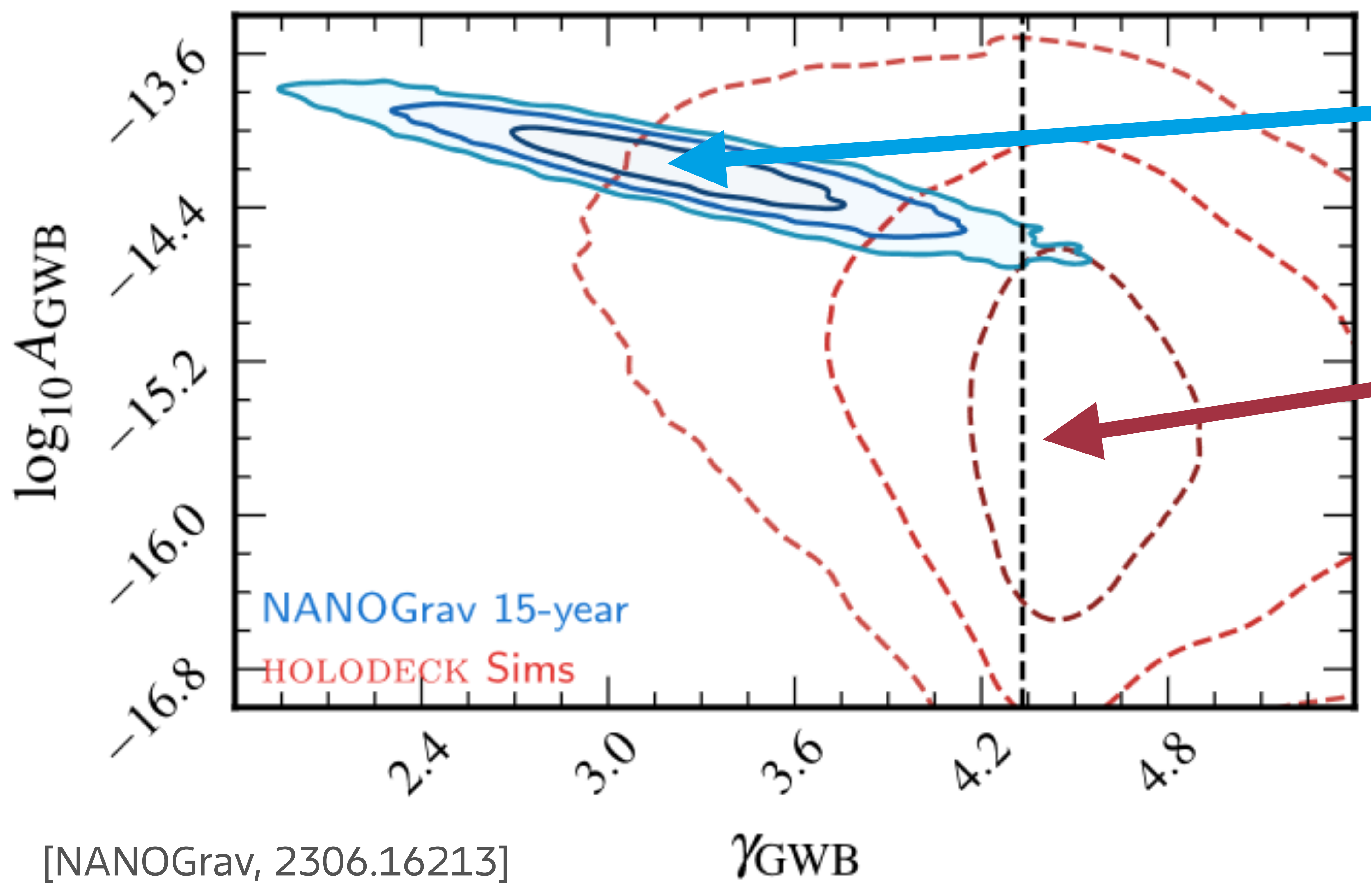
Pulses recorded by radio telescopes

Searching for the Hellings-Downs correlation

- PTAs found an underlying „common red process“ among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves: $\mathscr{B} < 10^{-12}$
  - Clock errors: $\mathscr{B} < 10^{-8}$
  - Ephemeris errors: $\mathscr{B} < 10^{-7}$
  - GWs: $\mathscr{B} = 200 - 1000$ 🥳



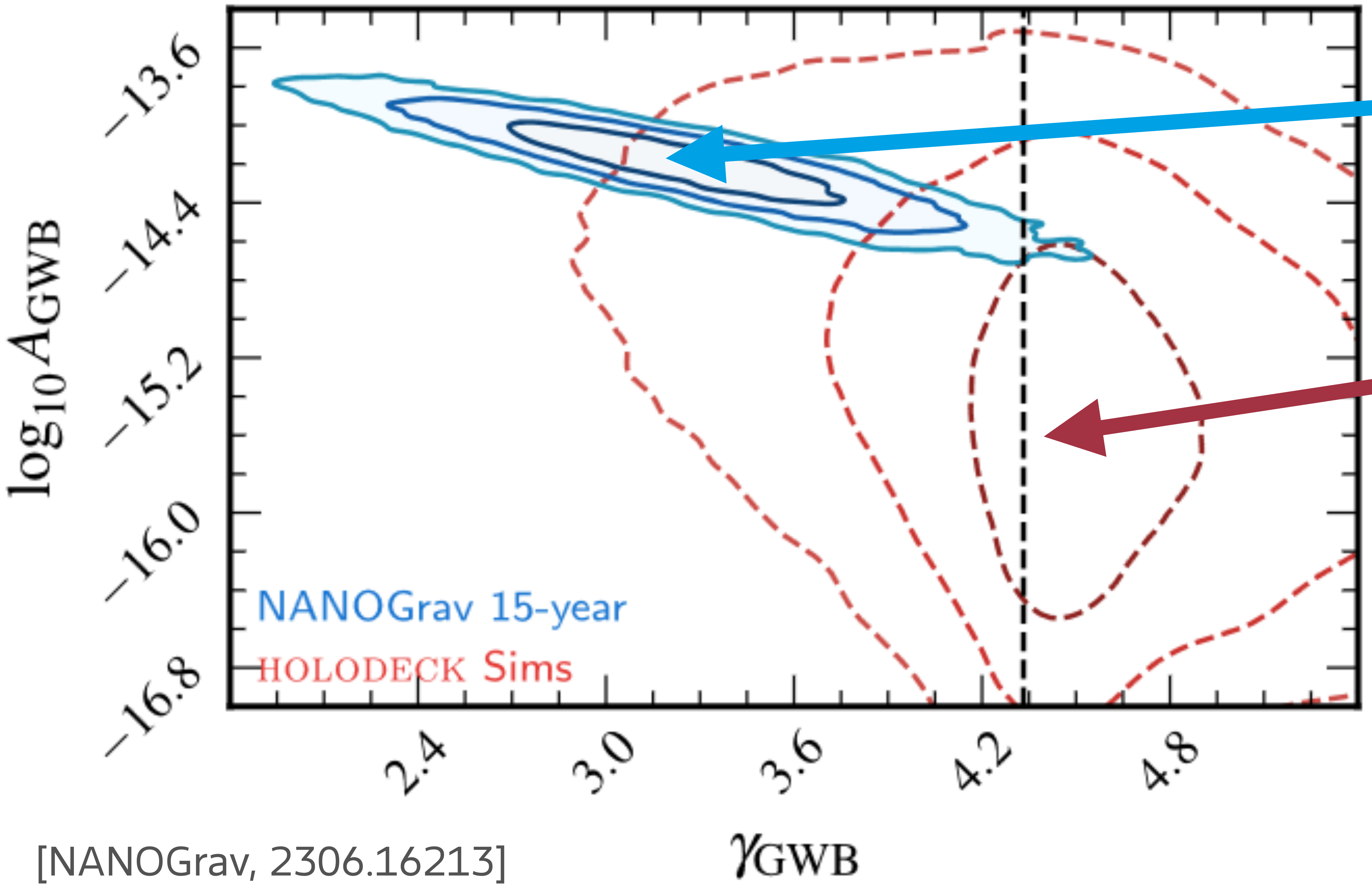
Merging supermassive black holes



[NANOGrav, 2306.16213]

- Observed signal follows a power-law spectrum with amplitude A and slope γ
- Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ

Merging supermassive black holes



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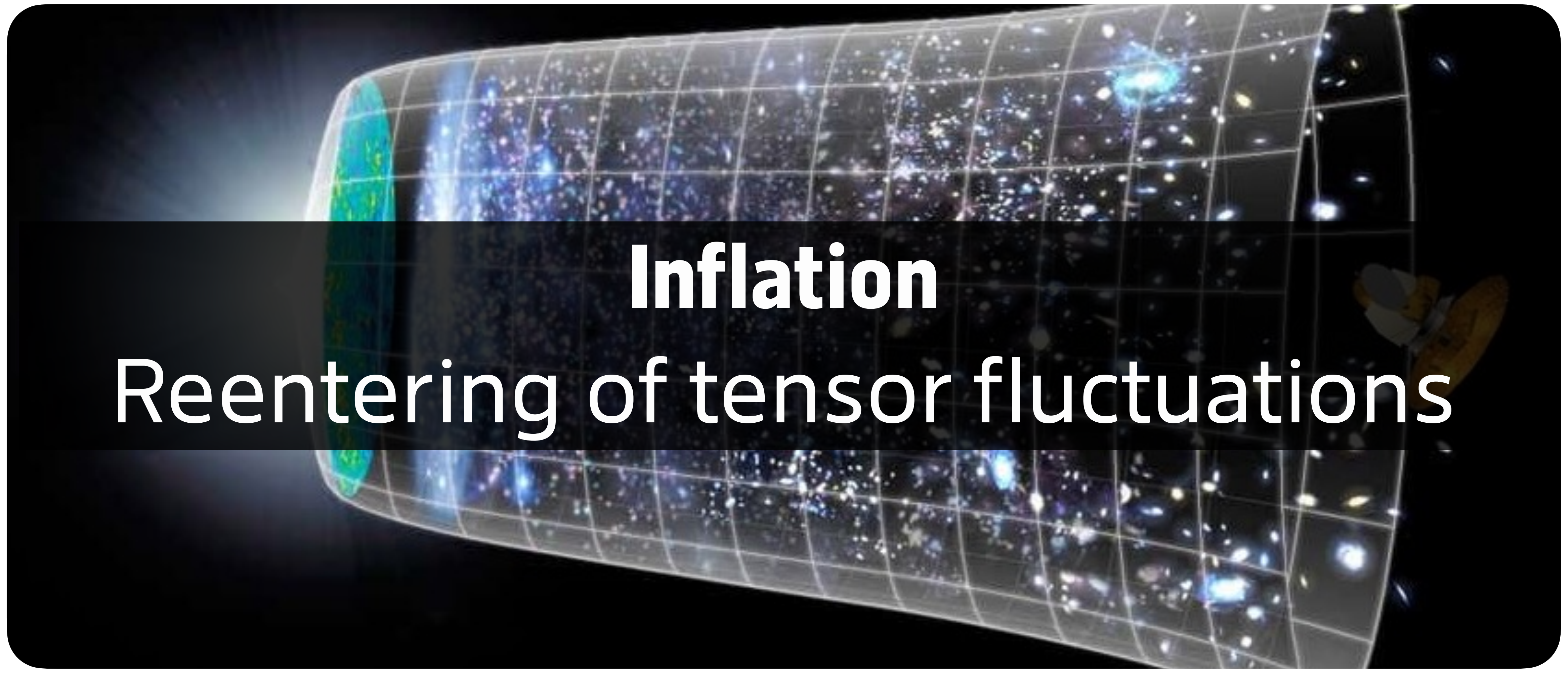
- Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ

Are there other signal sources?

Possible cosmological sources of the PTA signal



Inflation

Reentering of tensor fluctuations

Phase transitions

Connection to dark matter?

Topological defects

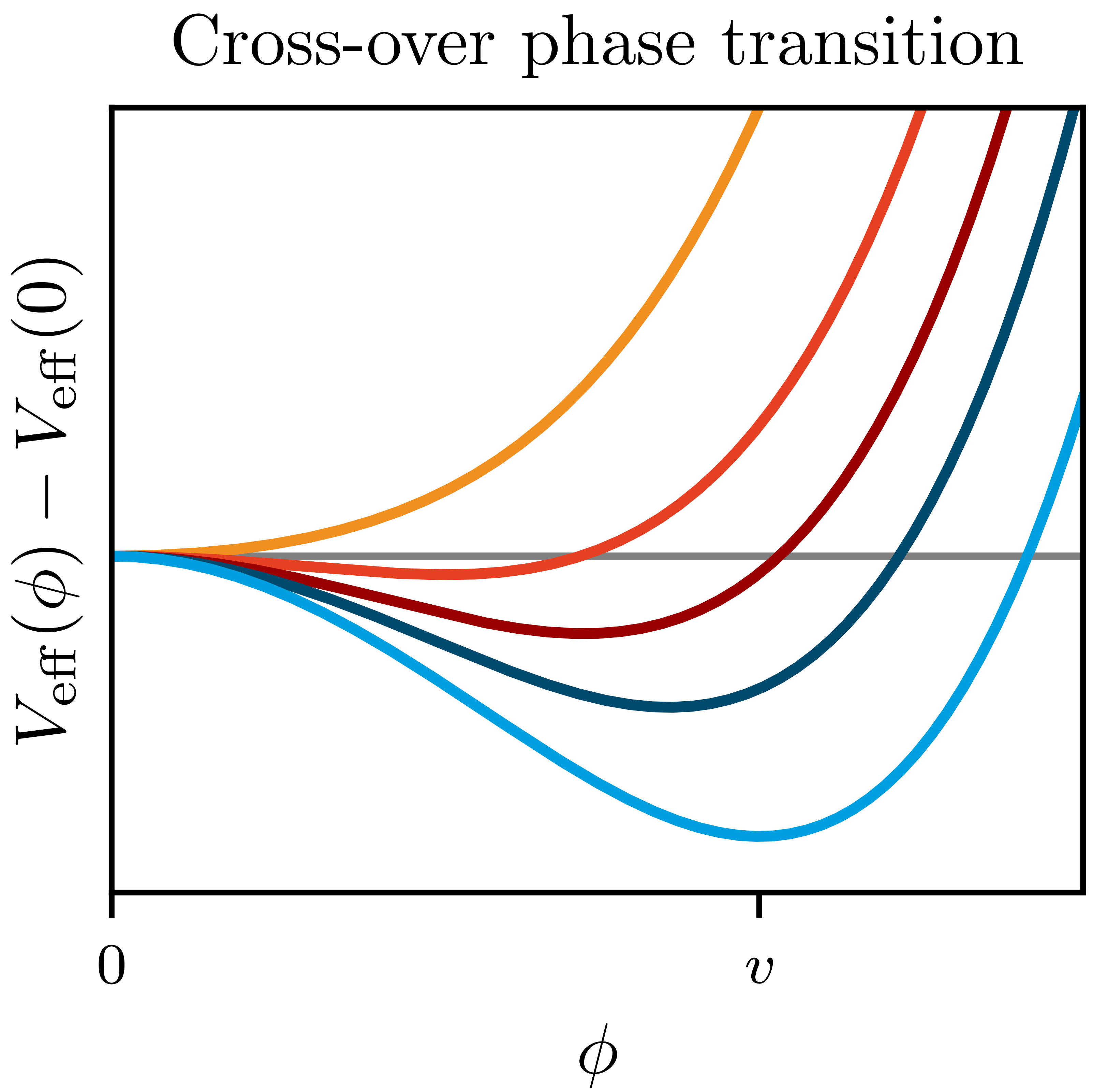
Cosmic strings and domain walls

Primordial black holes

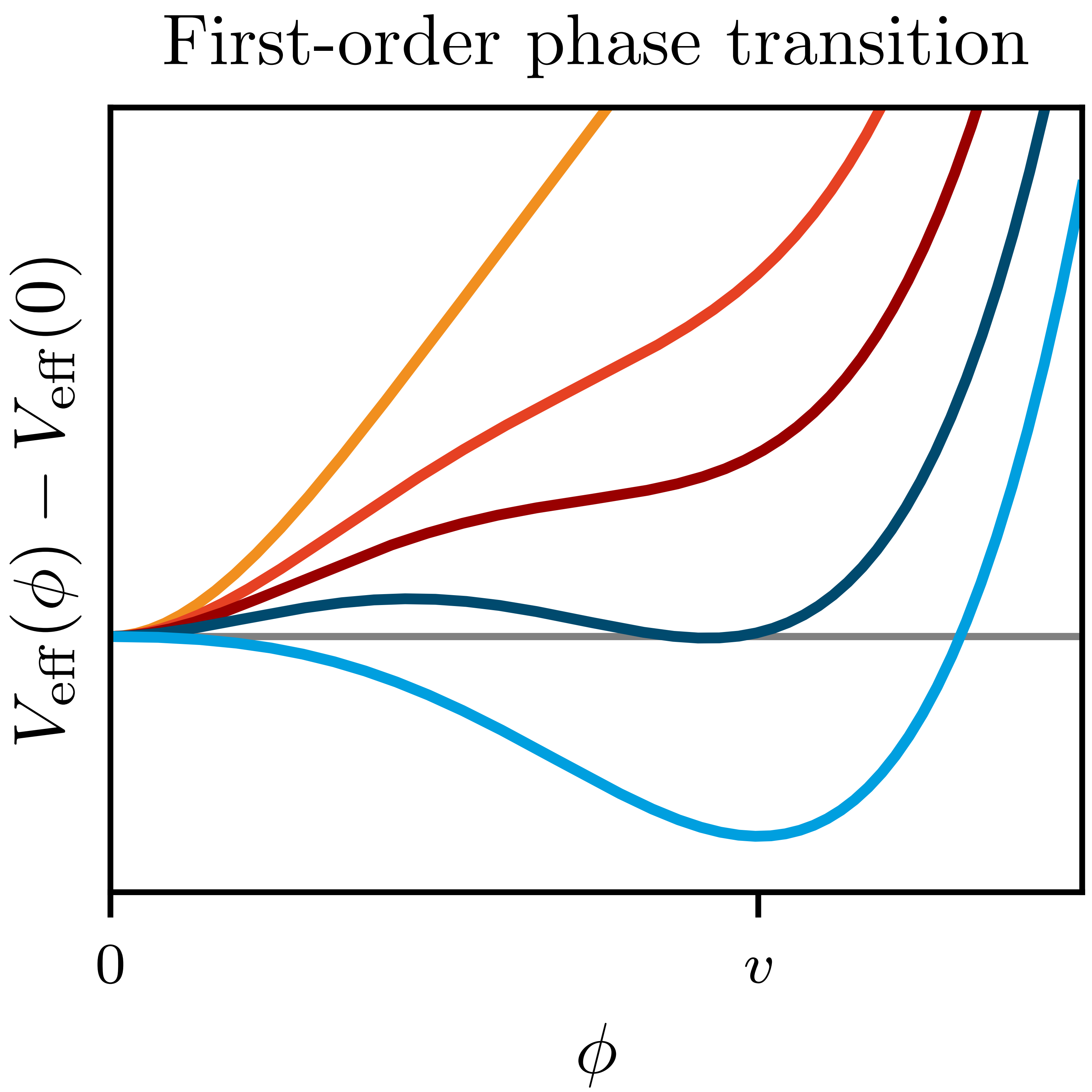
But only if they are clustered

Do PTAs observe a dark sector phase transition?

First-order phase transitions vs. cross-overs



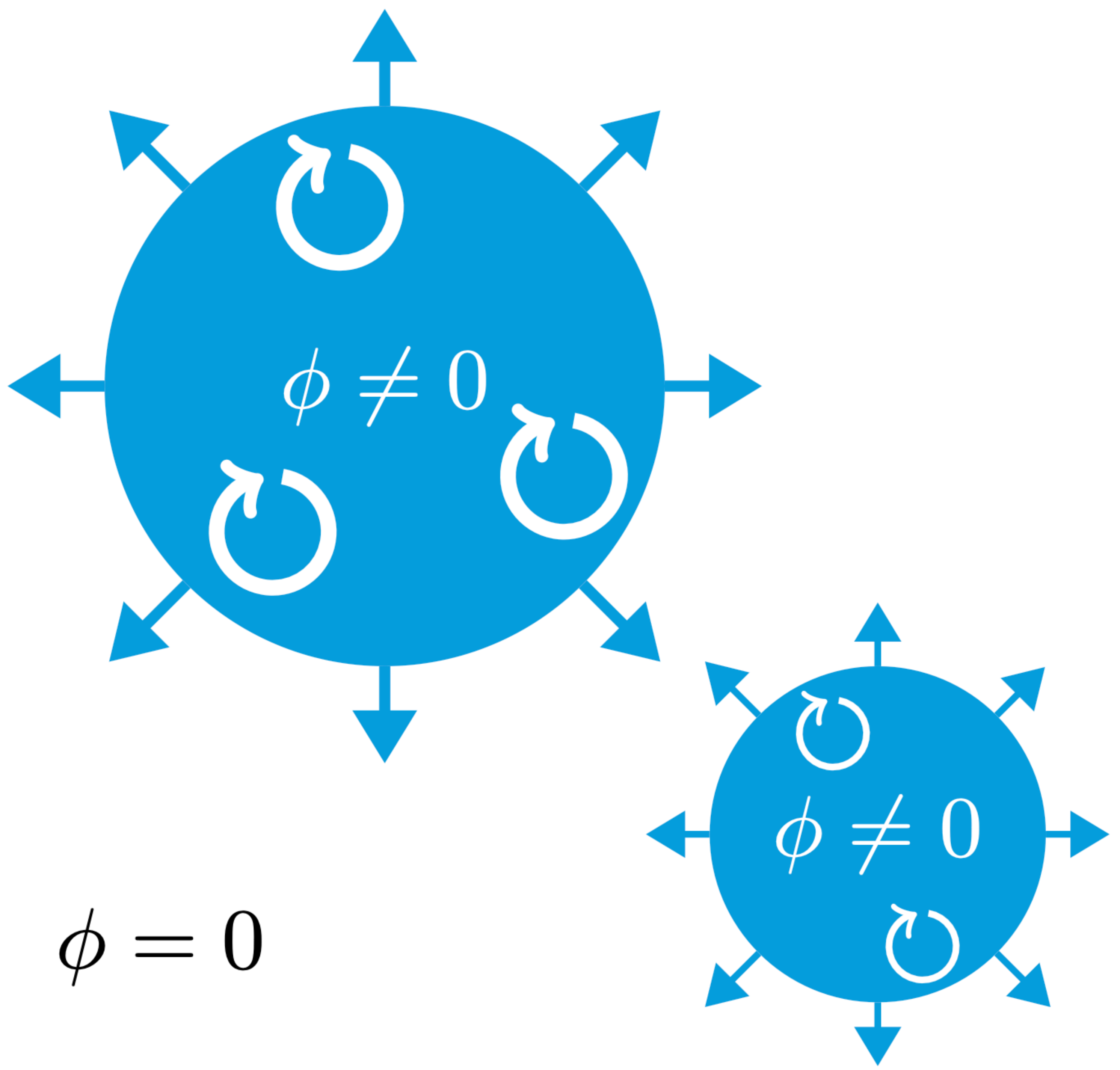
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

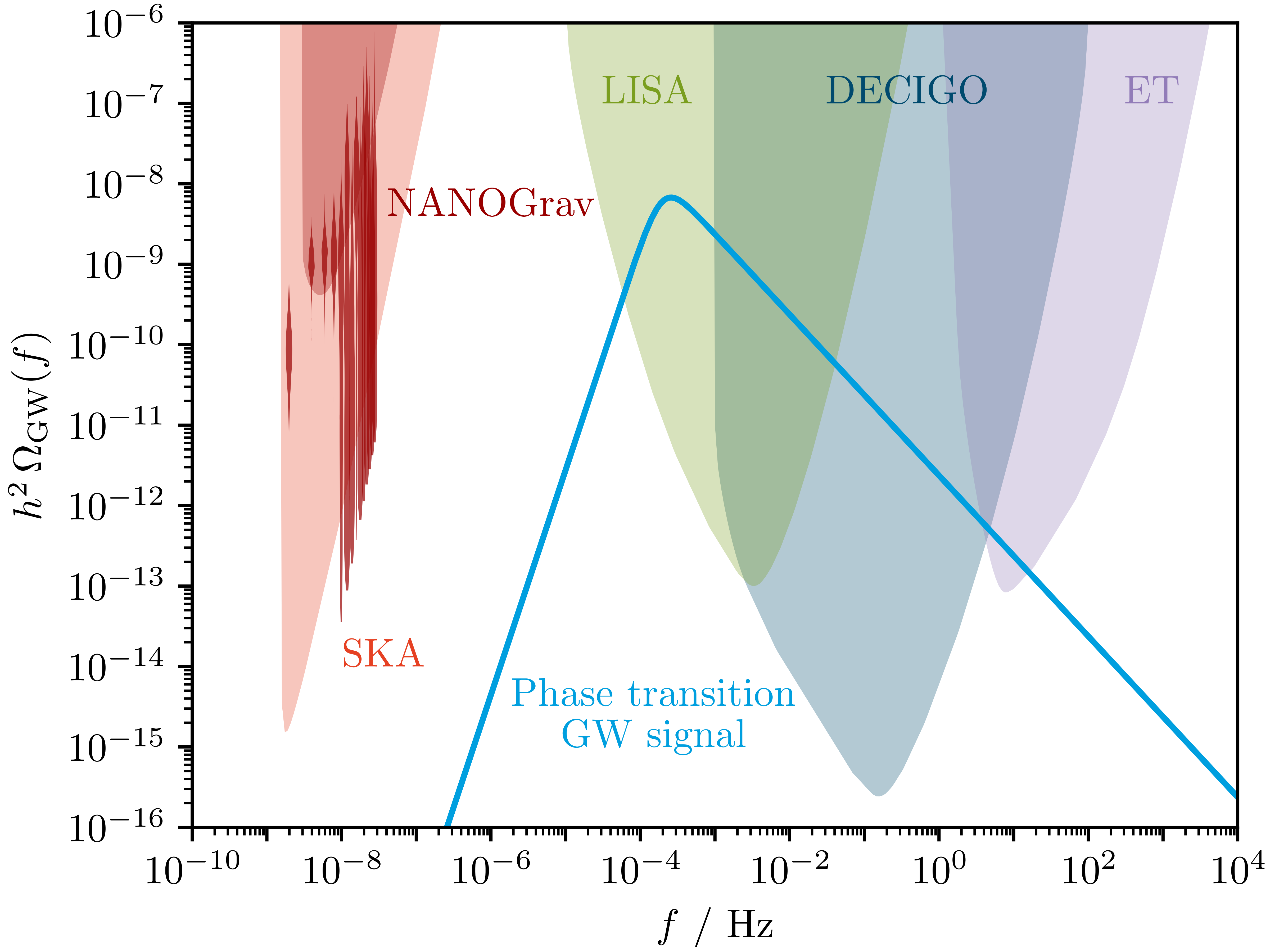


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy / its action.

First-order phase transitions produce GW backgrounds

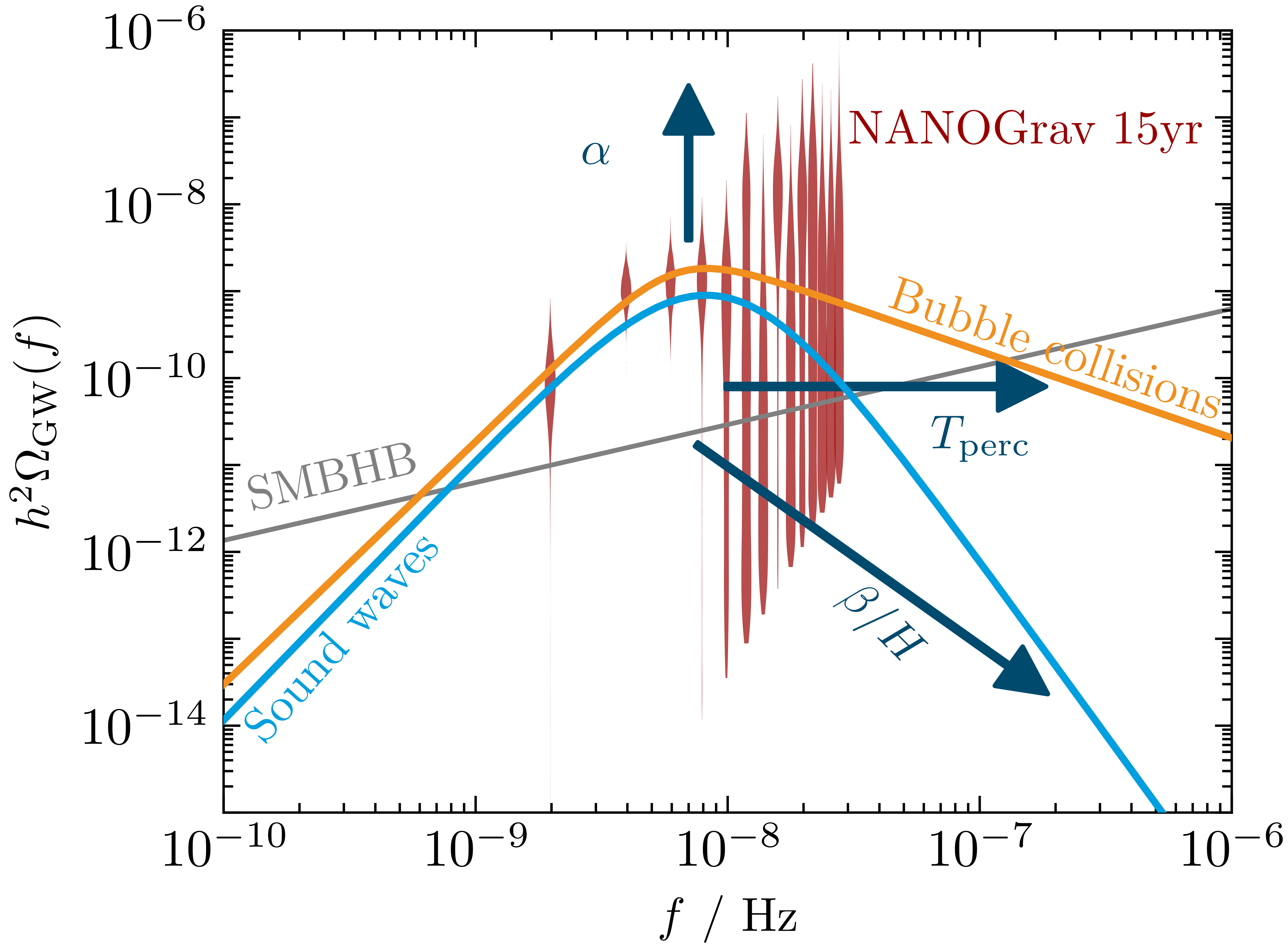
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



SMBHB: $A = 10^{-15.5}$, $\gamma = 13/3$

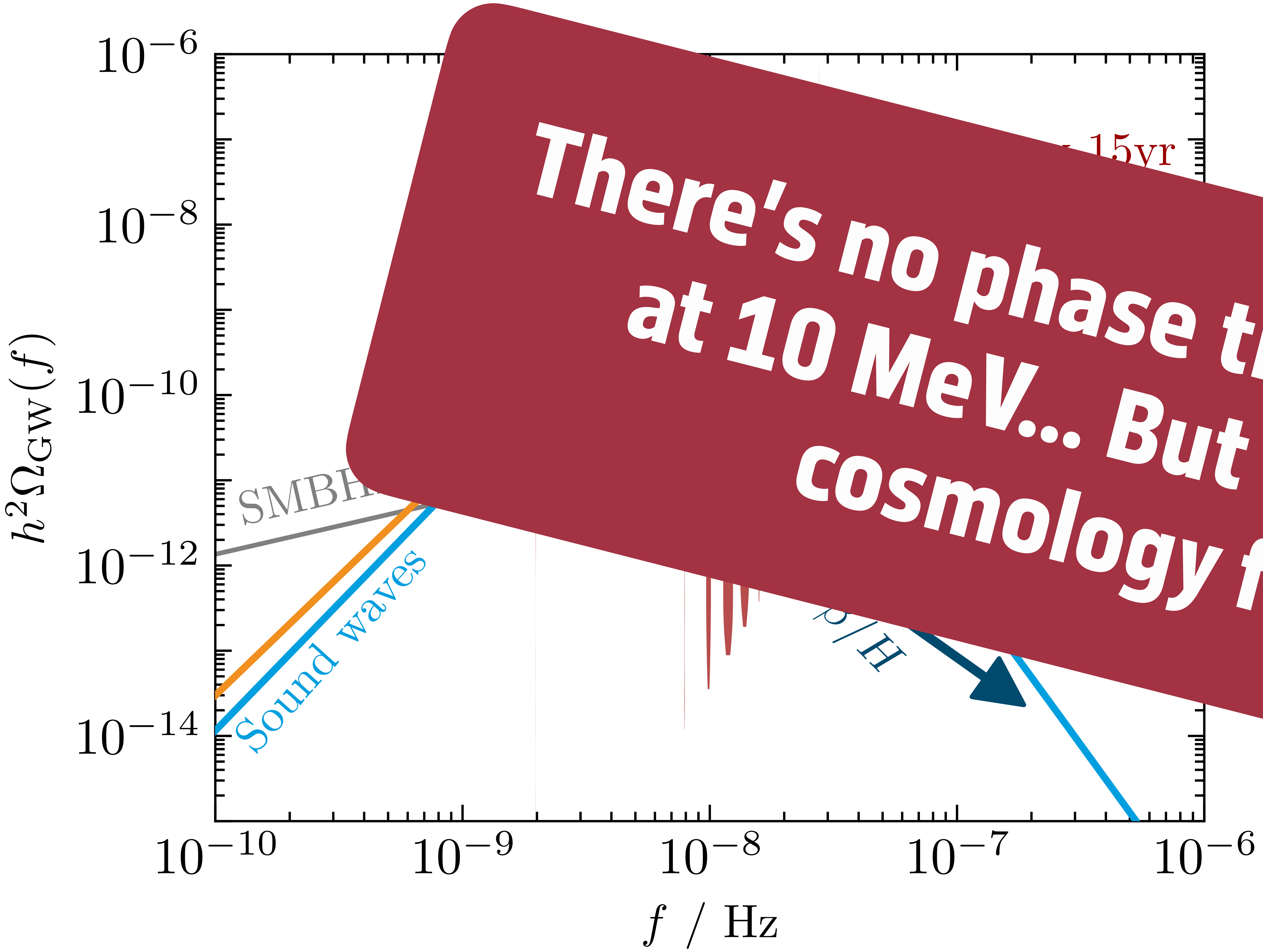
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

with $f_{\rm peak} \simeq 0.1\,{\rm nHz} \times \frac{\beta}{H} \times \frac{T}{\rm MeV}$

To fit the new pulsar timing data:

- Strong transitions, $\alpha \approx 1$
- Slow transitions, $\beta/H \approx 10$
- Percolation around $T \approx 10\,{\rm MeV}$

Parametrization of the GW signal



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$$f_{\rm peak} \simeq 0.1\,{\rm nHz}\times\frac{\beta}{H}\times\frac{T}{\rm MeV}$$

There's no phase transition in the SM at 10 MeV… But does precision cosmology forbid it?!

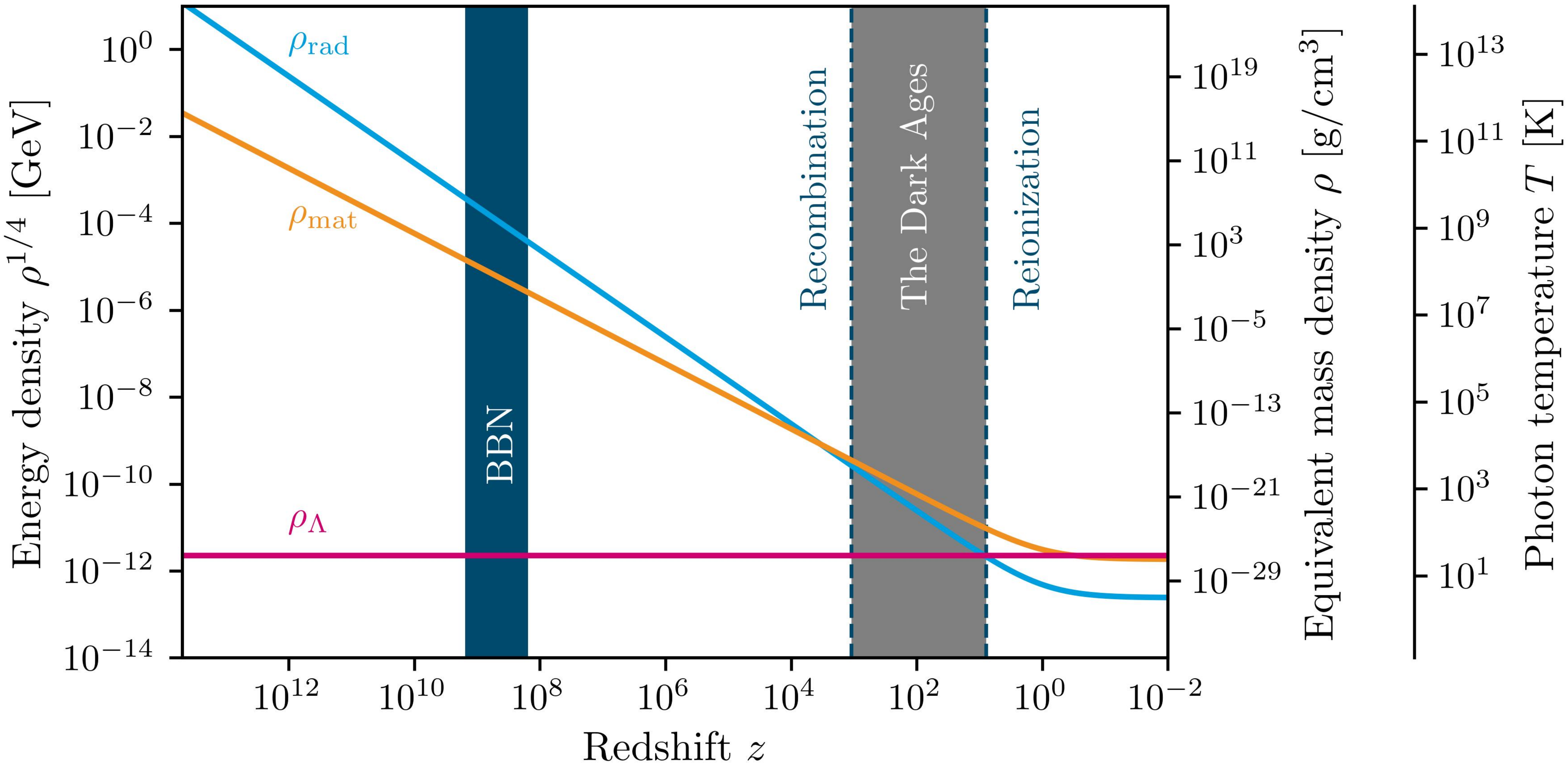
data:

1

≈ 10

- Percolation a $T \approx 10\,$MeV

A brief history of time



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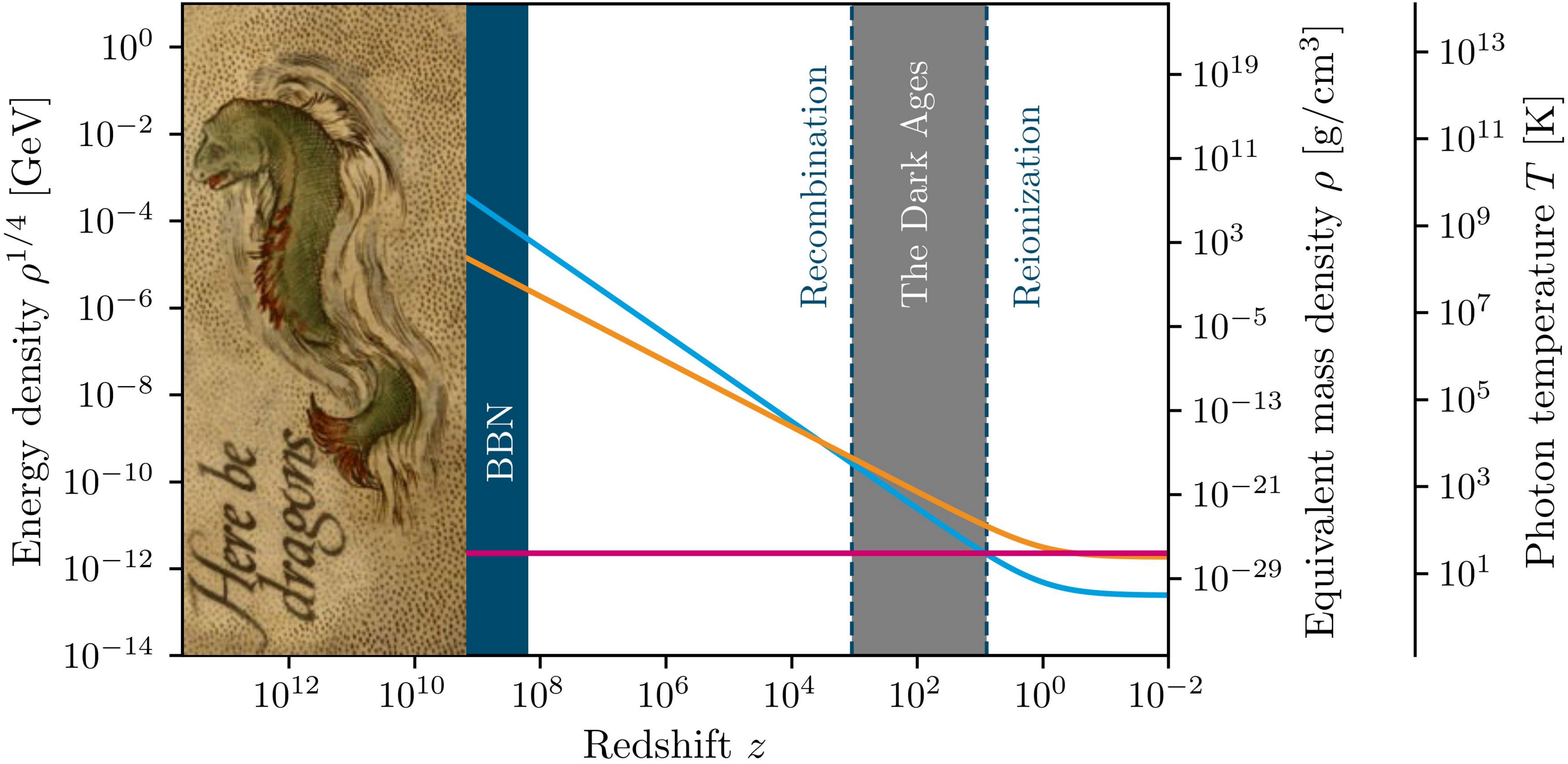
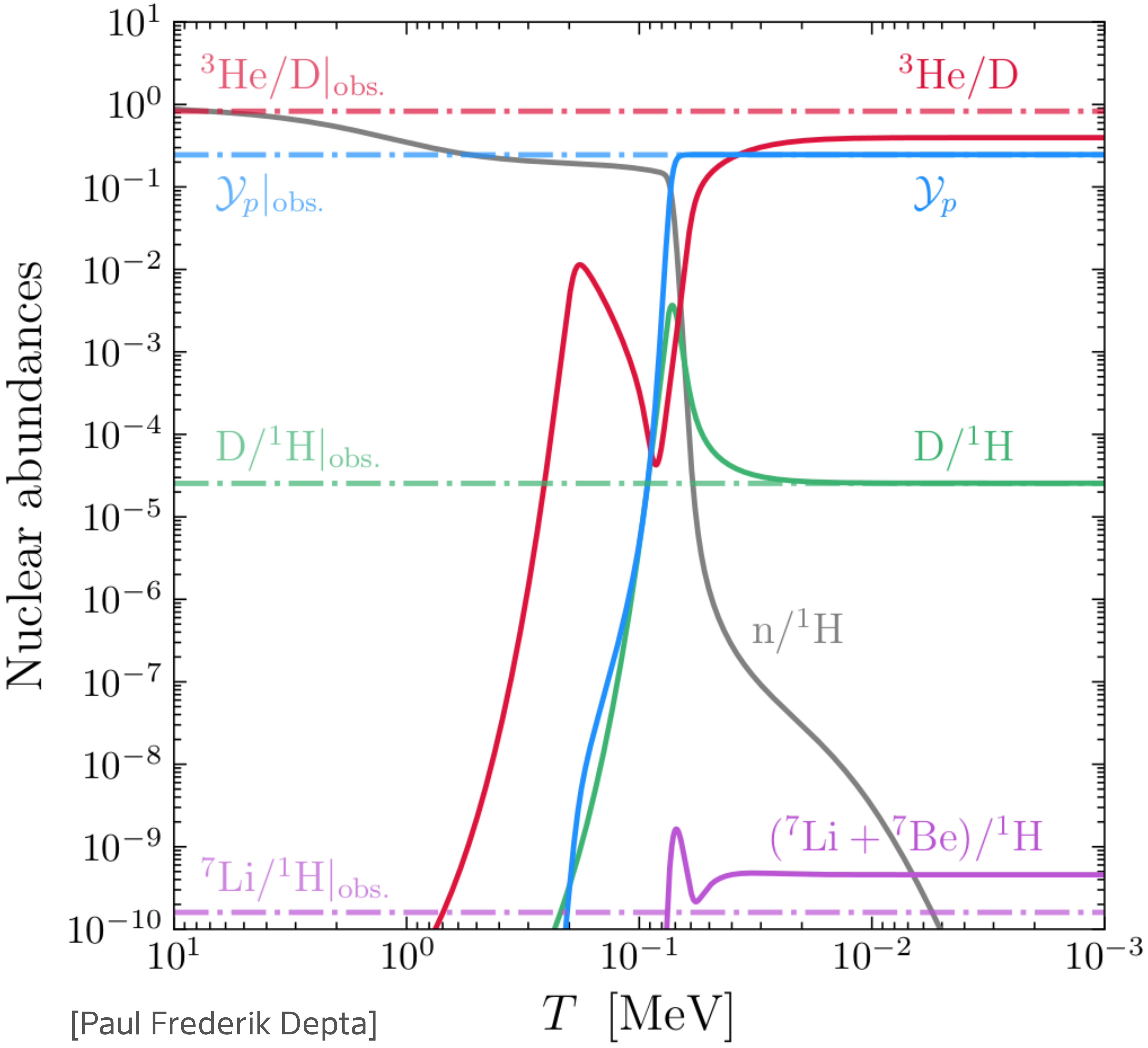


Big Bang Nucleosynthesis and the Cosmic Microwave Background



[Paul Frederik Depta]

- Observation of primordial light element abundances in good agreement with standard BBN
- $N_{\mathrm{eff}}^{\mathrm{BBN}} = 2.898 \pm 0.141$

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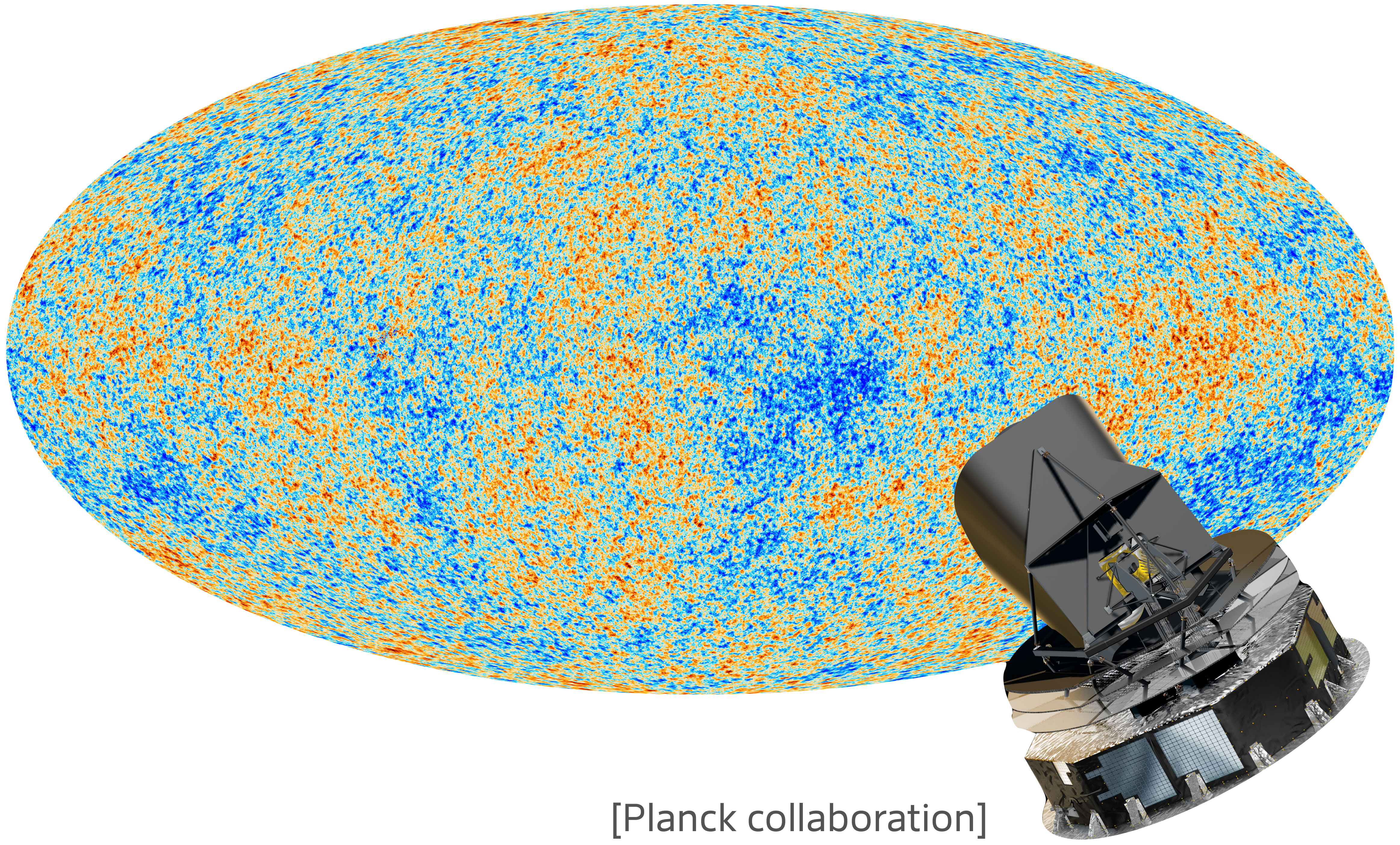


[Planck collaboration]

- Observation of primordial light element abundances in good agreement with standard BBN
- $N_{\text{eff}}^{\text{BBN}} = 2.898 \pm 0.141$
- $N_{\text{eff}}^{\text{CMB}} = 2.99 \pm 0.17$
- Consistent with $N_{\text{eff}}^{\text{SM}} = 3.044$ from 3 ν generations

Big Bang Nucleosynthesis and the Cosmic Microwave Background

anck collaboration]

Thermalized BSM species at T < 1 MeV are ruled out. Before: no constraints. 😊

- Observation of primordial light el ances in th

141

0.17

- Consistent with $N_{\text{eff}}^{\text{SM}} = 3.044$ from 3 ν generations

Adding more Higgs bosons to the Standard model

There's no strong first-order phase transition at 10 MeV in the Standard Model. :(

Don't worry, just put it in a dark sector! :)

Turning on the light in a dark sector

Stable dark sector

Additional DS energy density accelerates Hubble expansion via

$$\Delta N_{\text{eff}} \gtrsim 6 \times \alpha$$

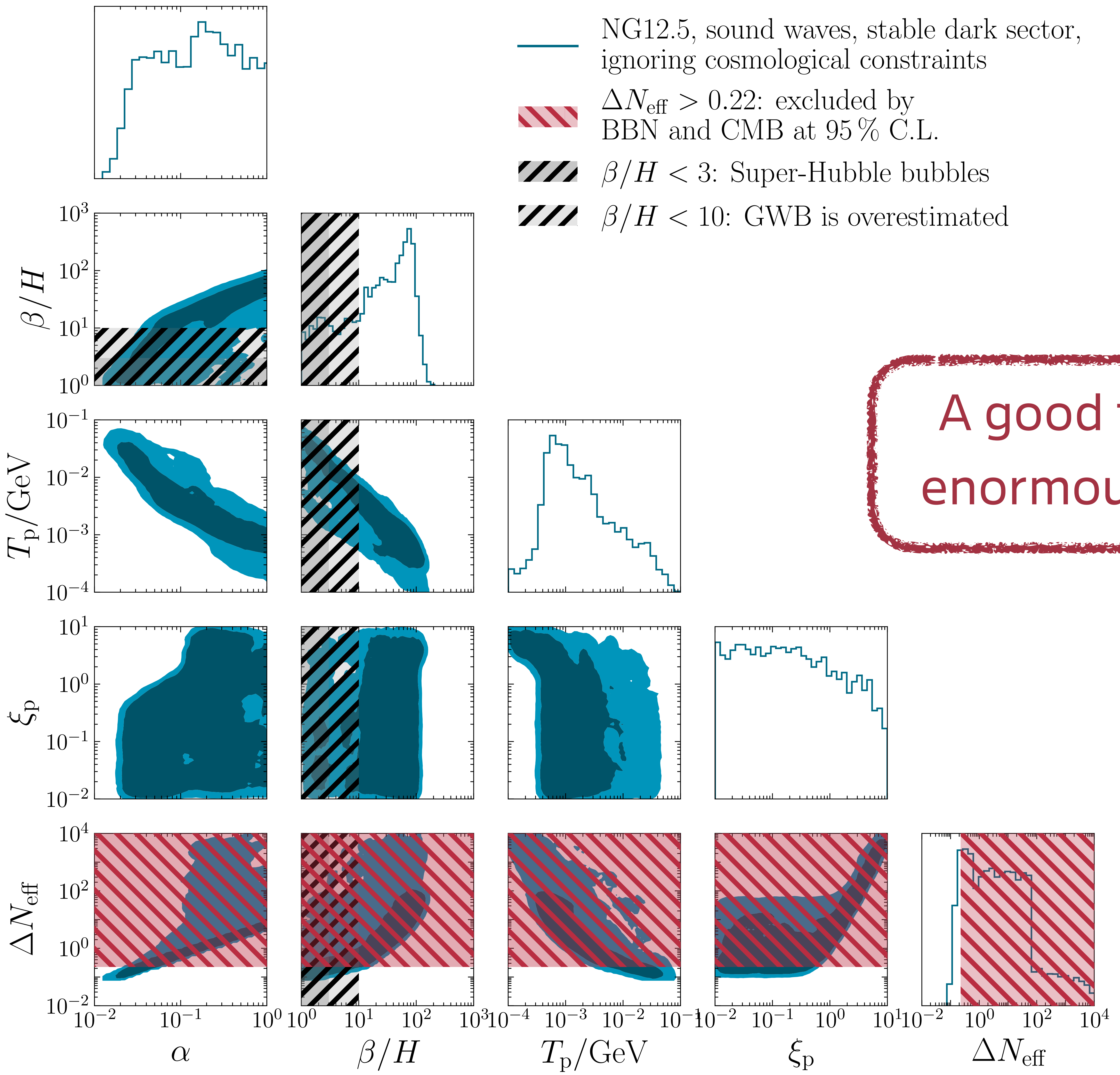
But we need $\alpha \simeq 1$…

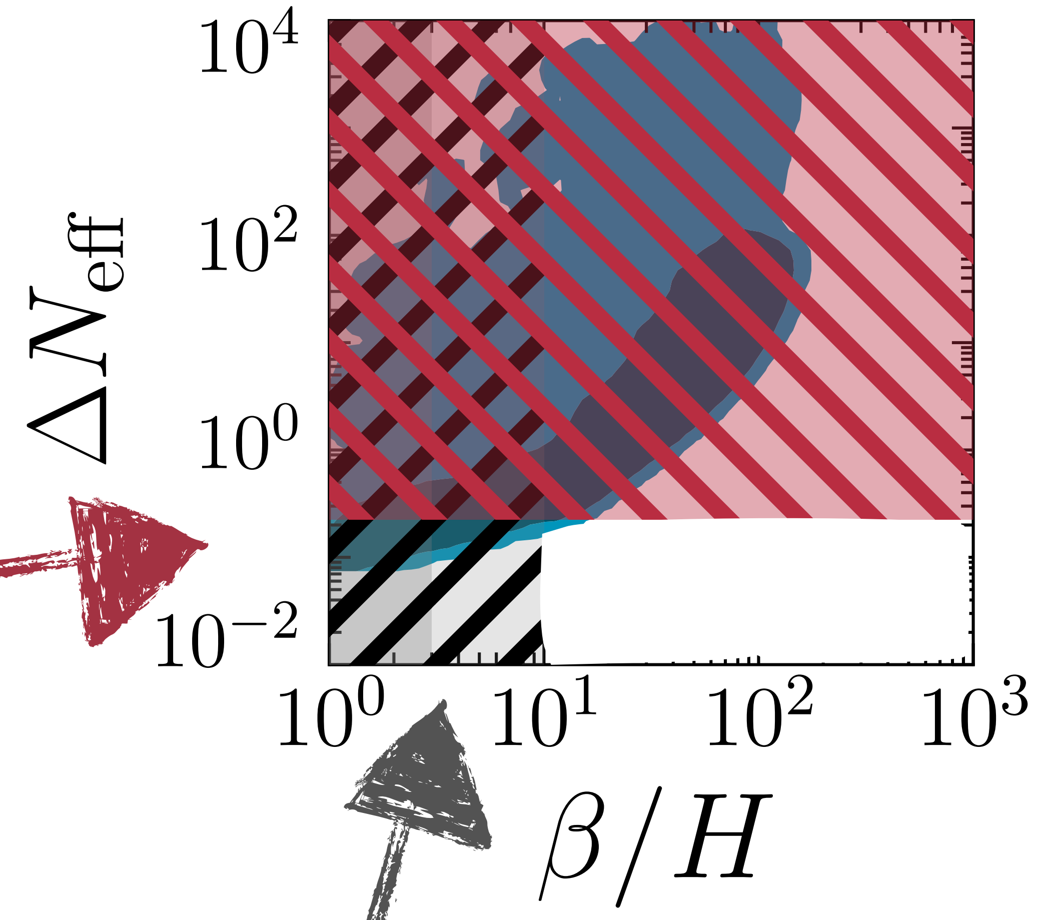
$\Delta N_{\text{eff}} < 0.22\,@\,95\,\%$ C.L. ⚡

Decaying dark sector

Can the dark sector decay quickly enough to the SM to circumvent BBN and CMB constraints?

Stable dark sector phase transition: A naive fit



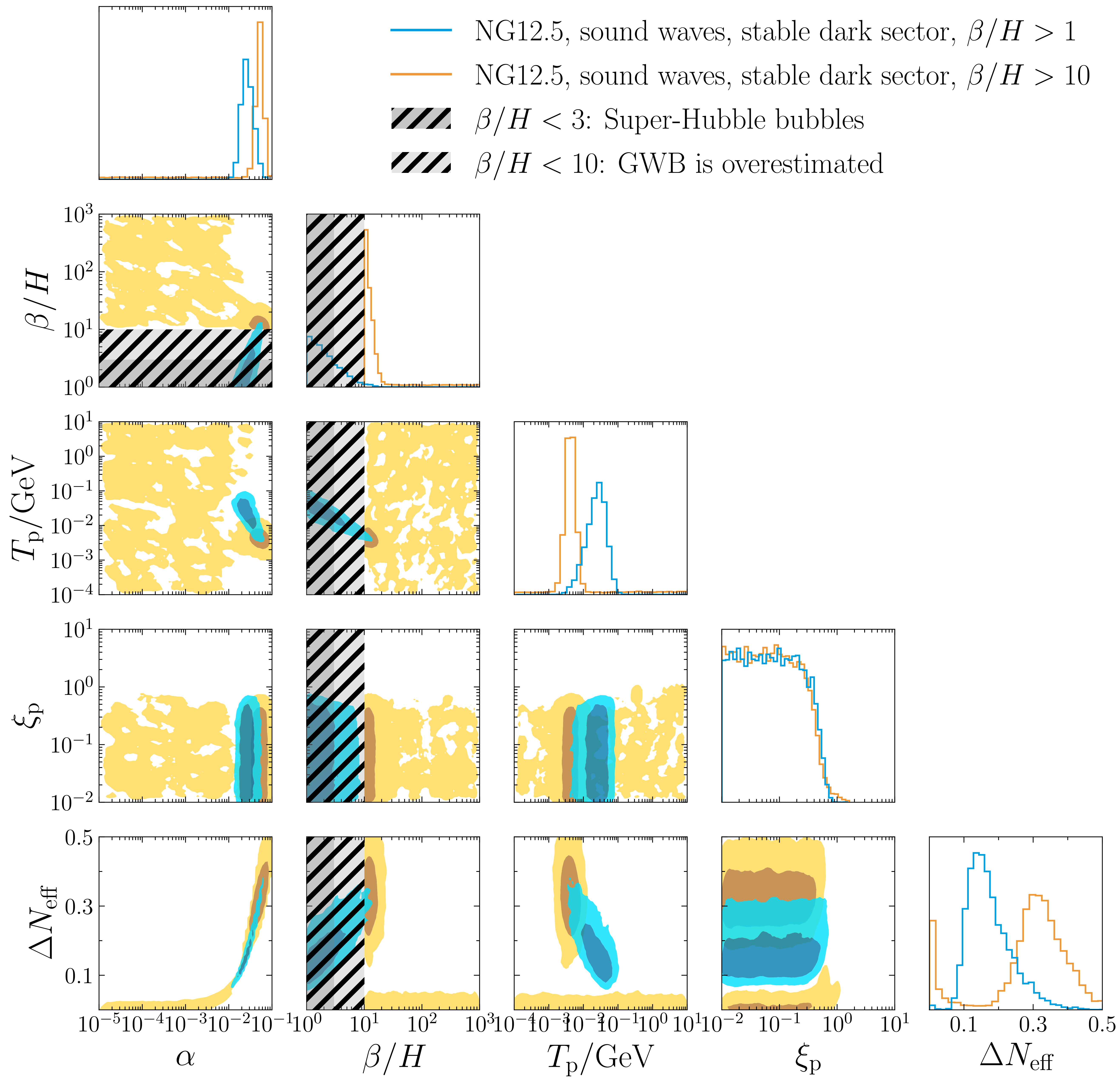


A good fit would require enormous $\Delta N_{\text{eff}} \gg 0.22$

Giant bubble sizes would be needed, violating causality & questioning validity of GW predictions

Global fits

- Combined PTA and BBN/CMB likelihoods in `enterprise`
- $\beta/H > 1$: Would fit the data if GW spectrum were reliable
- $\beta/H > 10$: Shot noise because not explaining PTA data is better than messing up BBN + CMB



Global fits

- Combined PTA and BBN/CMB likelihoods in `enterprise`
- $\beta/H > 1$: Would f
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- $\beta/H >$
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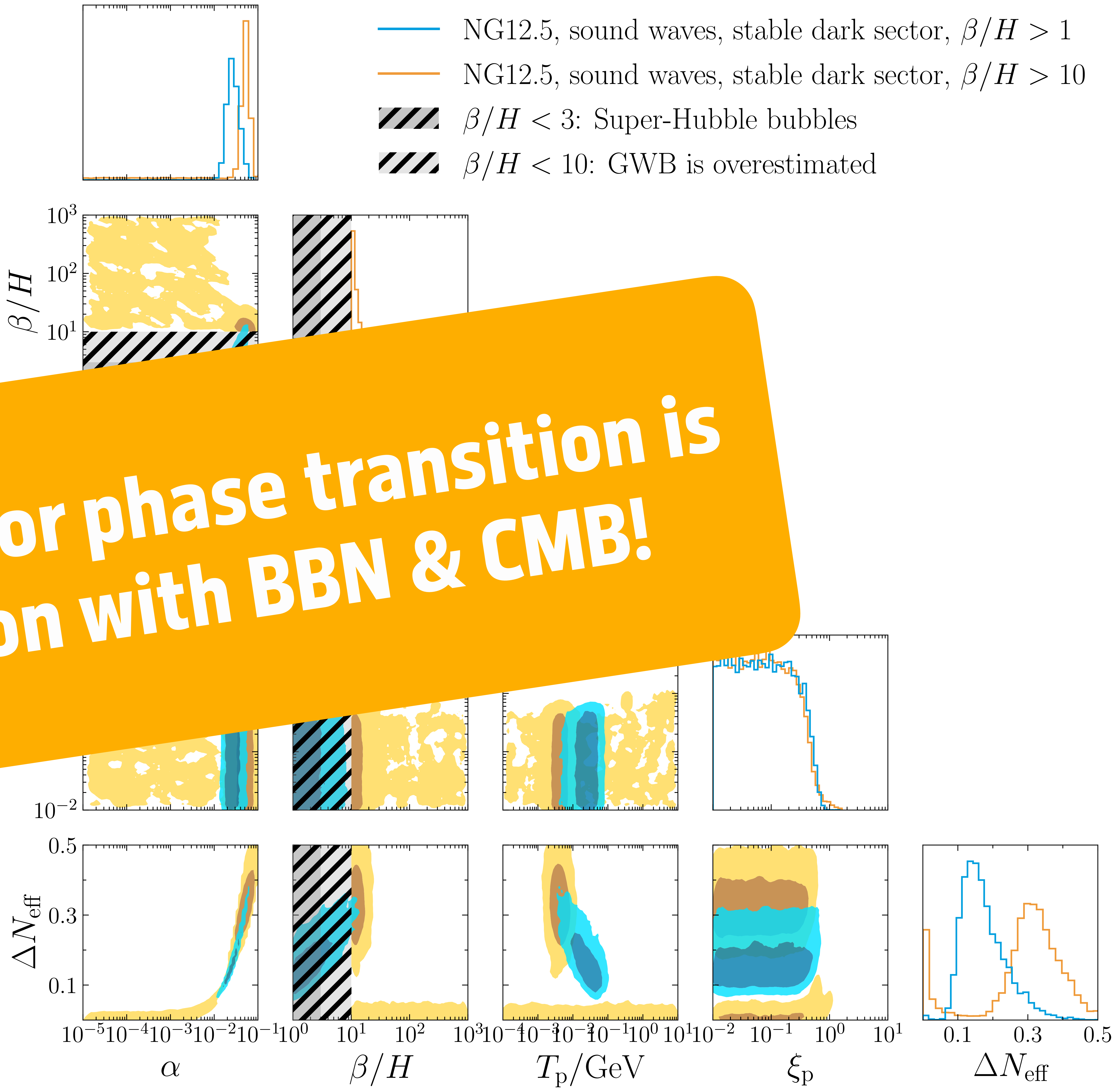
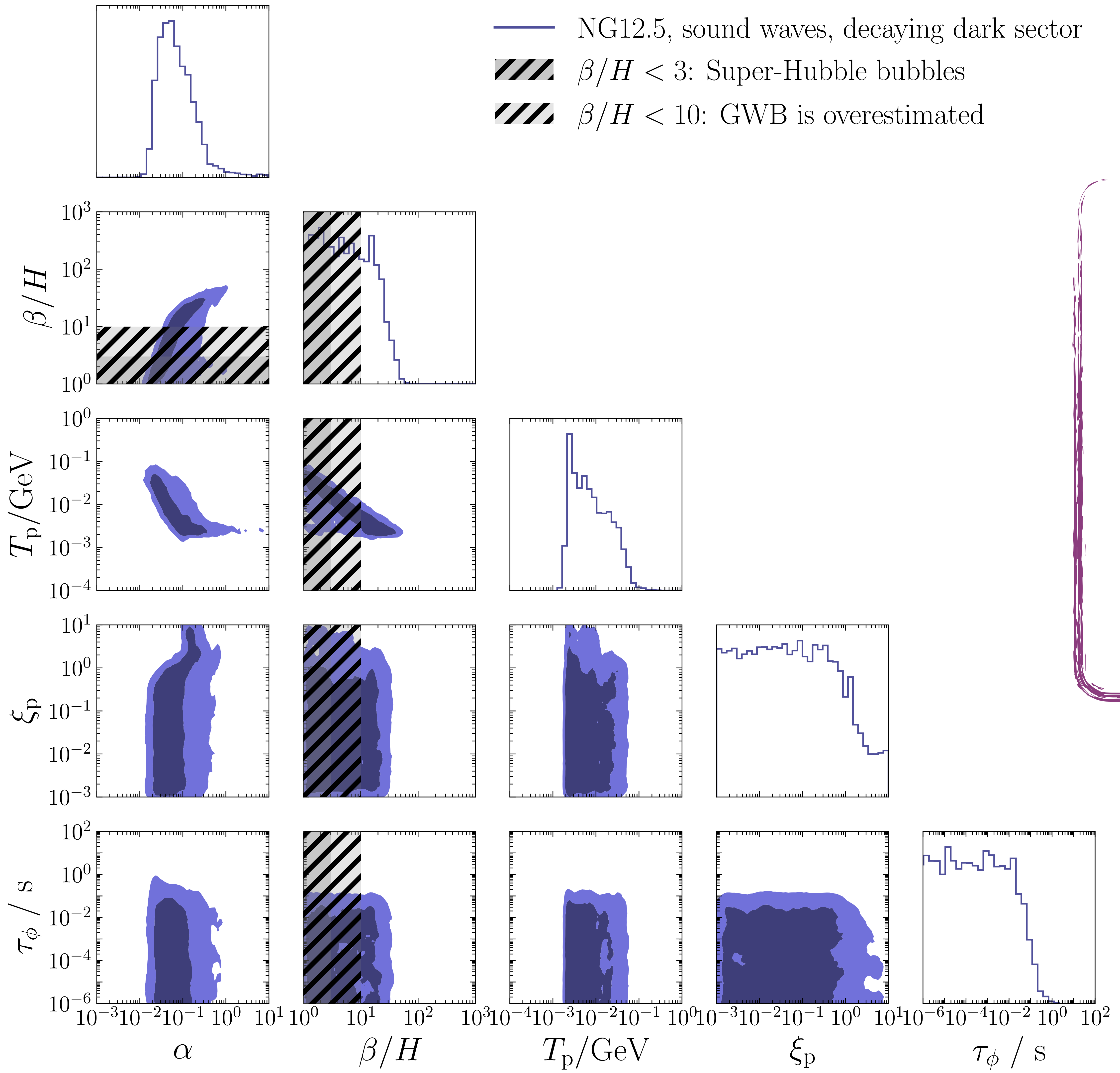
A stable dark sector phase transition is in strong tension with BBN & CMB!



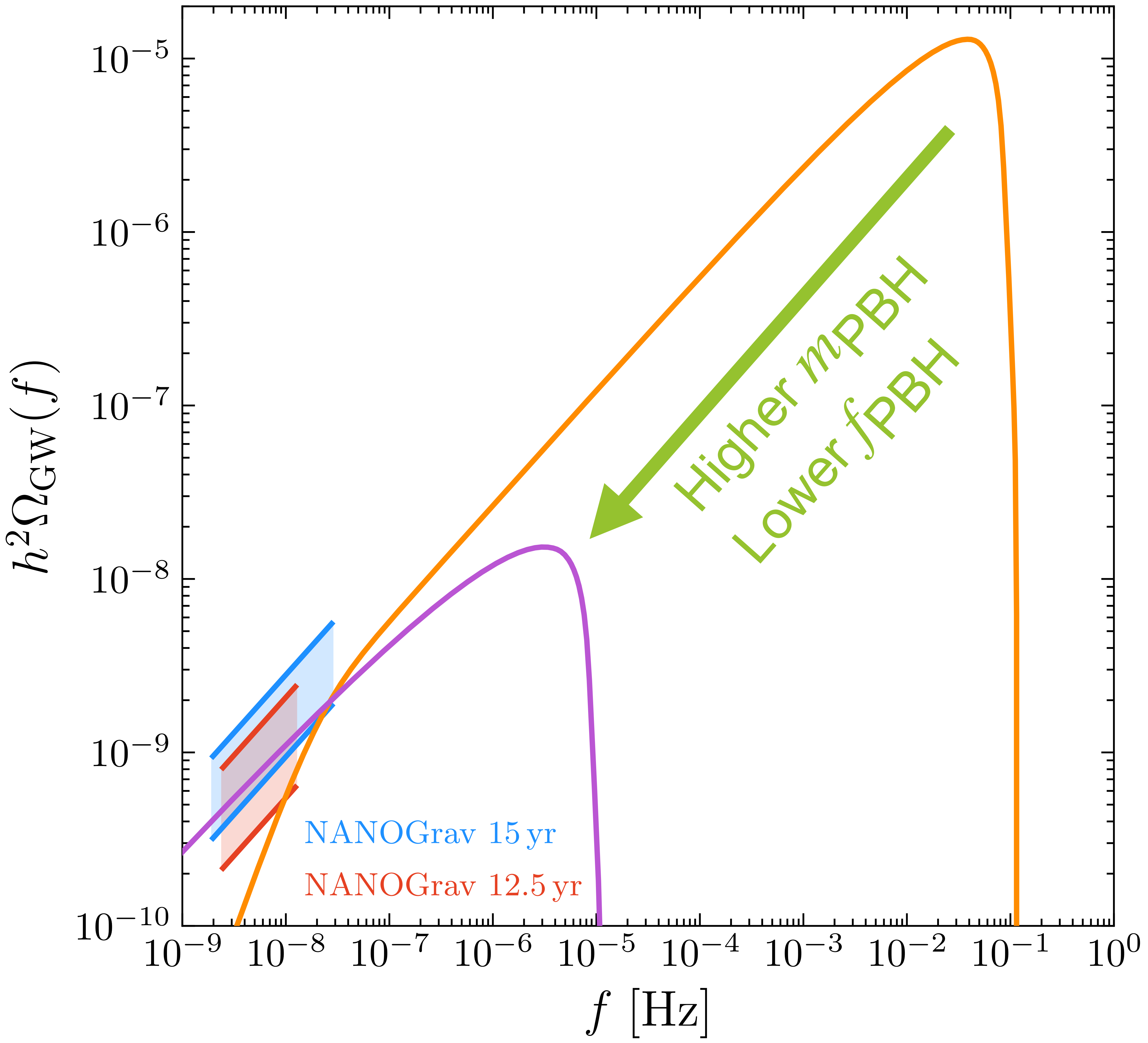
Decays to the rescue



If the dark sector decays quickly ($\tau_\phi \lesssim 0.1$ s) before neutrino decoupling ($T \gtrsim 2$ MeV), a great fit to PTA data can be achieved!

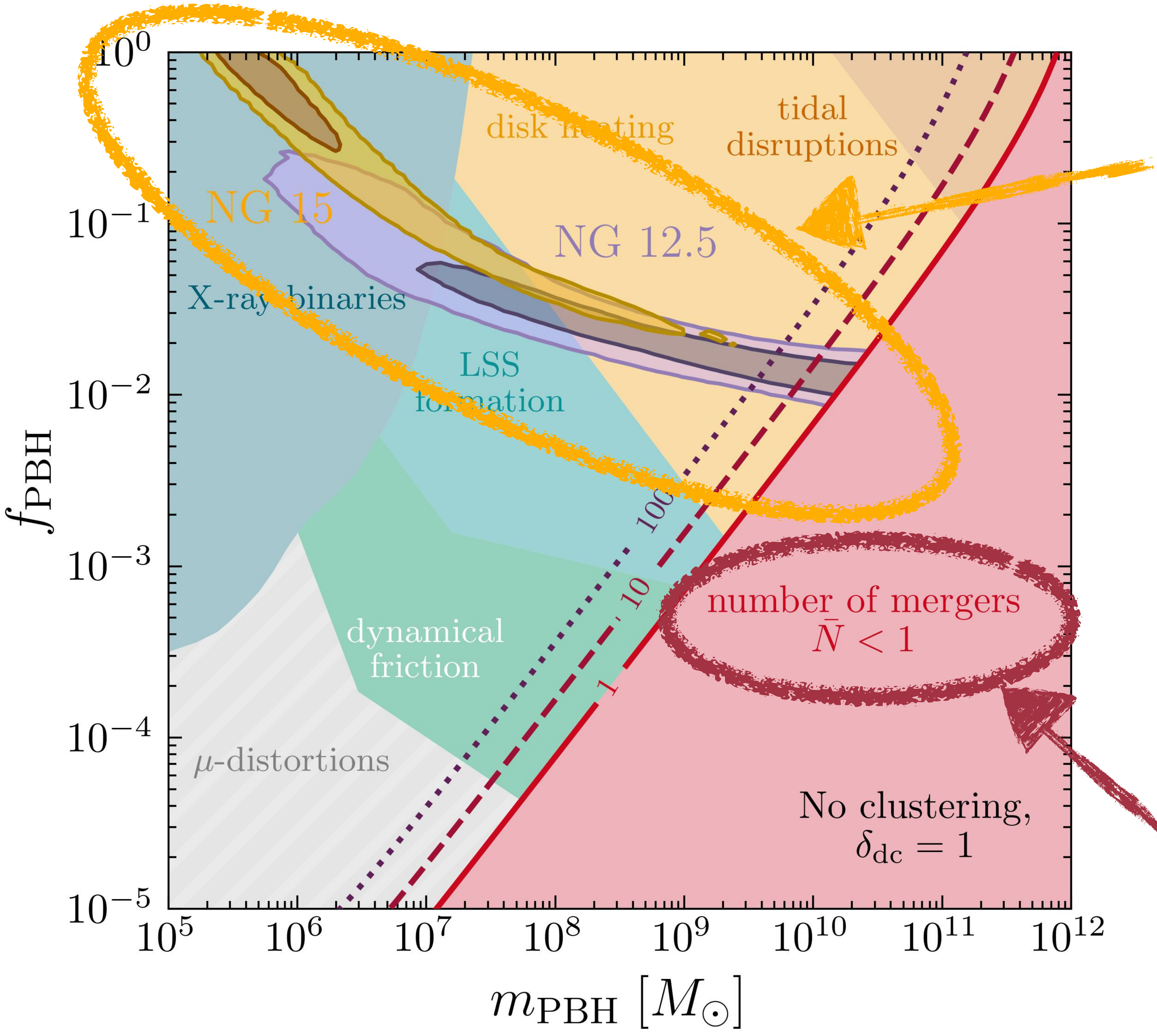
Do PTAs observe primordial black hole mergers?

Supermassive primordial black holes



- Inflation leaves large super-Hubble density perturbations
- BHs form when these come into causal contact again, long before first stars form
- Described by mass $m_{\rm PBH}$ and DM fraction $f_{\rm PBH}$

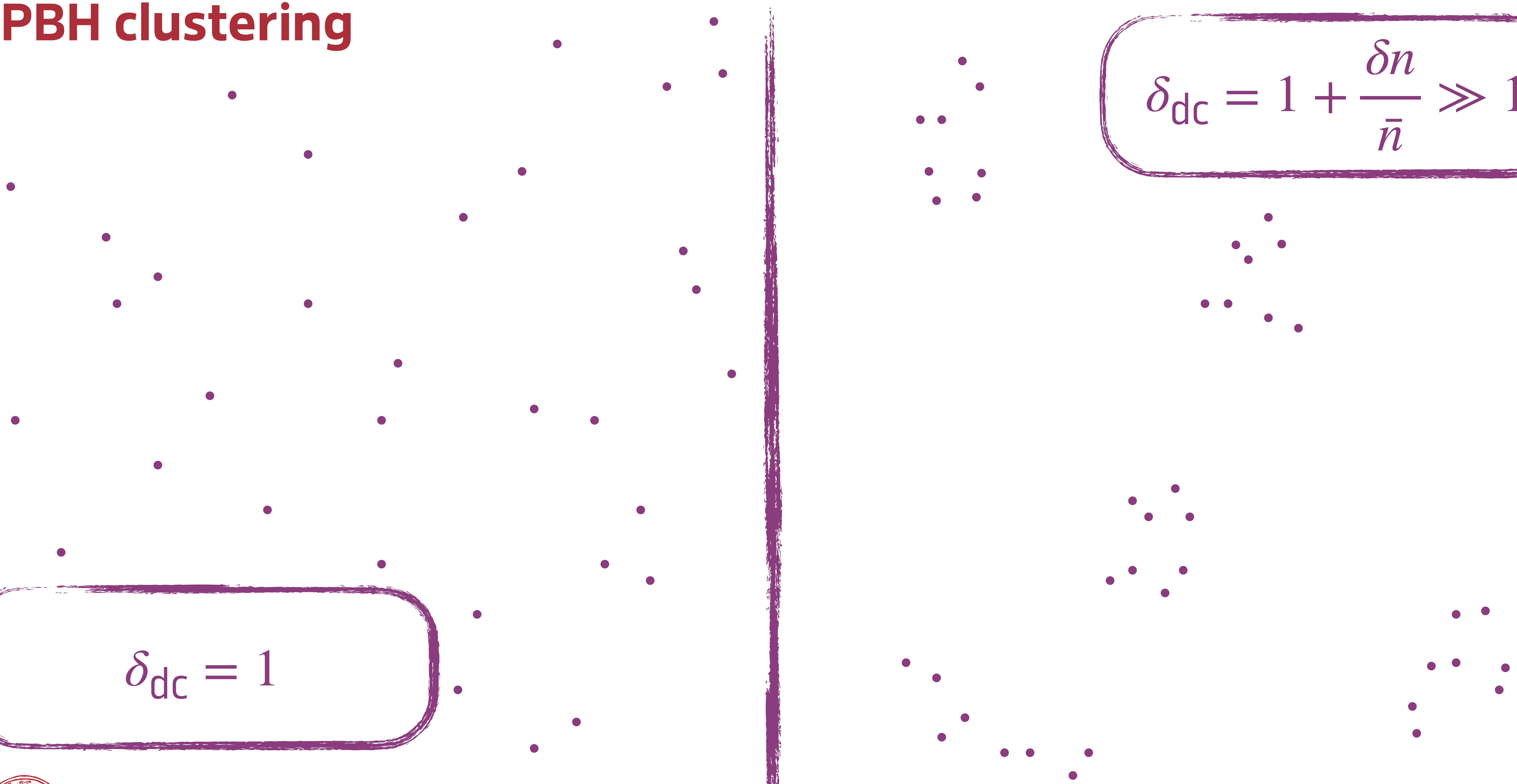
Homogeneously distributed PBHs cannot explain PTA data



Parameter space favored by PTAs is excluded by astrophysical bounds

Crucial: excluded regions with small merger numbers. Atal et al. came to the wrong conclusion.

PBH clustering

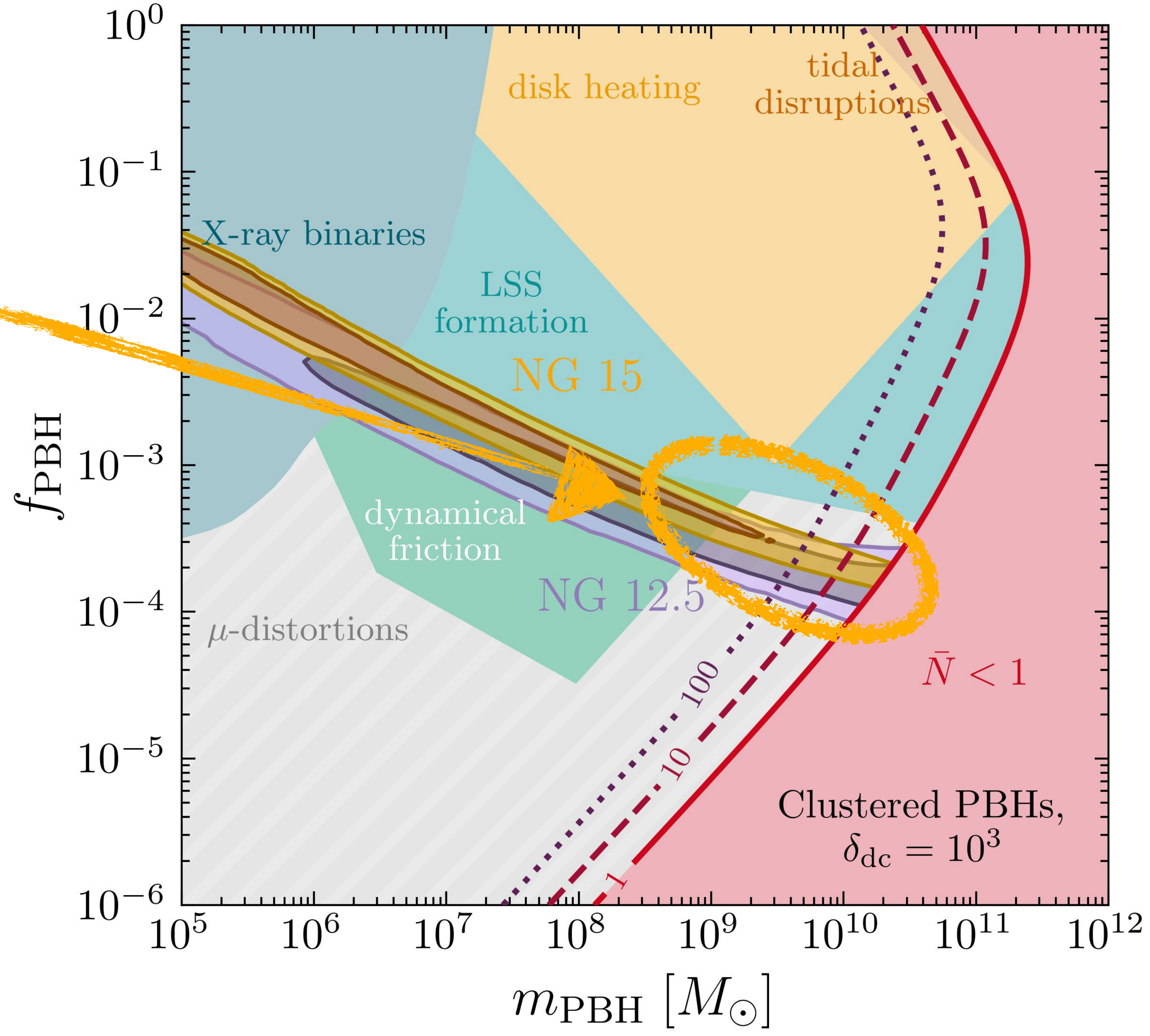


$$\delta_{\mathrm{dc}} = 1$$

$$\delta_{\mathrm{dc}} = 1 + \frac{\delta n}{\bar{n}} \gg 1$$

Clustered PBHs can explain the PTA data

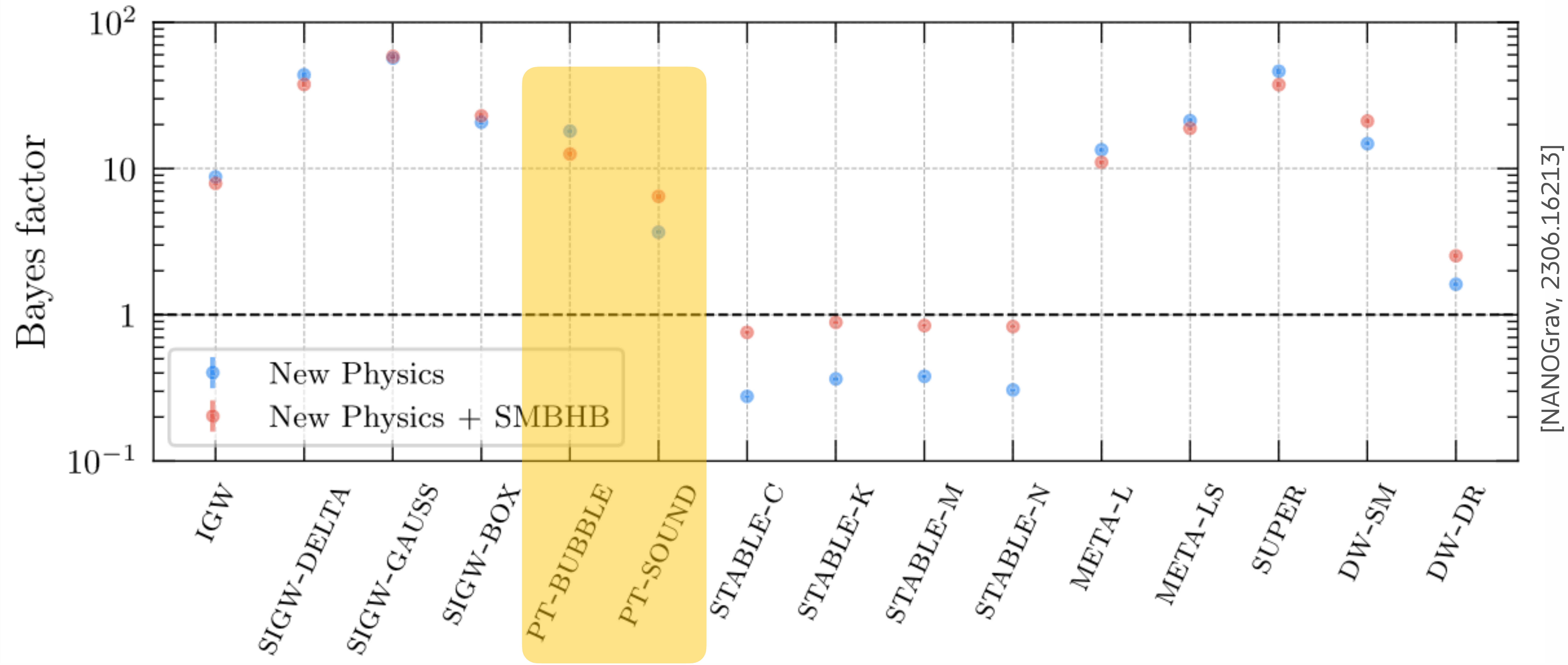
Clustering increases merger rate and shifts the best fit region below constraints: Good fit is possible! *



* Caveats: μ-distortion constraints from PBH production need to be circumvented & astrophysical constraints are expected to weaken/shift with clustering

Soooo… what is the source of the PTA signal?

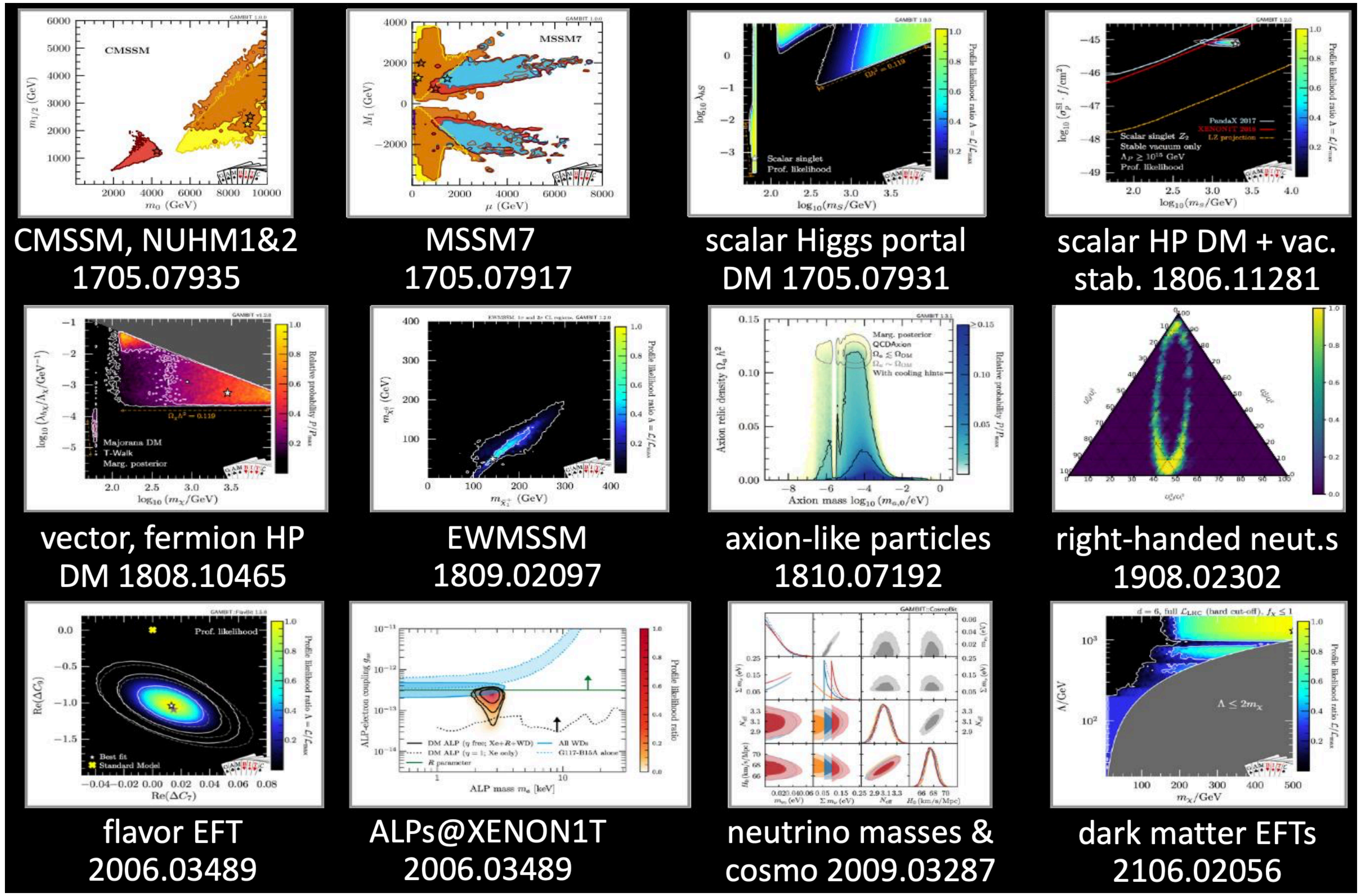
New physics interpretation of the NANOGrav 15yr data



[NANOGrav, 2306.16213]

Cosmological constraints have not been included in the analysis.

GAMBIT: from Lagrangians to Likelihoods



CMSSM, NUHM1&2 1705.07935

MSSM7 1705.07917

scalar Higgs portal DM 1705.07931

scalar HP DM + vac. stab. 1806.11281

vector, fermion HP DM 1808.10465

EWMSSM 1809.02097

axion-like particles 1810.07192

right-handed neut.s 1908.02302

flavor EFT 2006.03489

ALPs@XENON1T 2006.03489

neutrino masses & cosmo 2009.03287

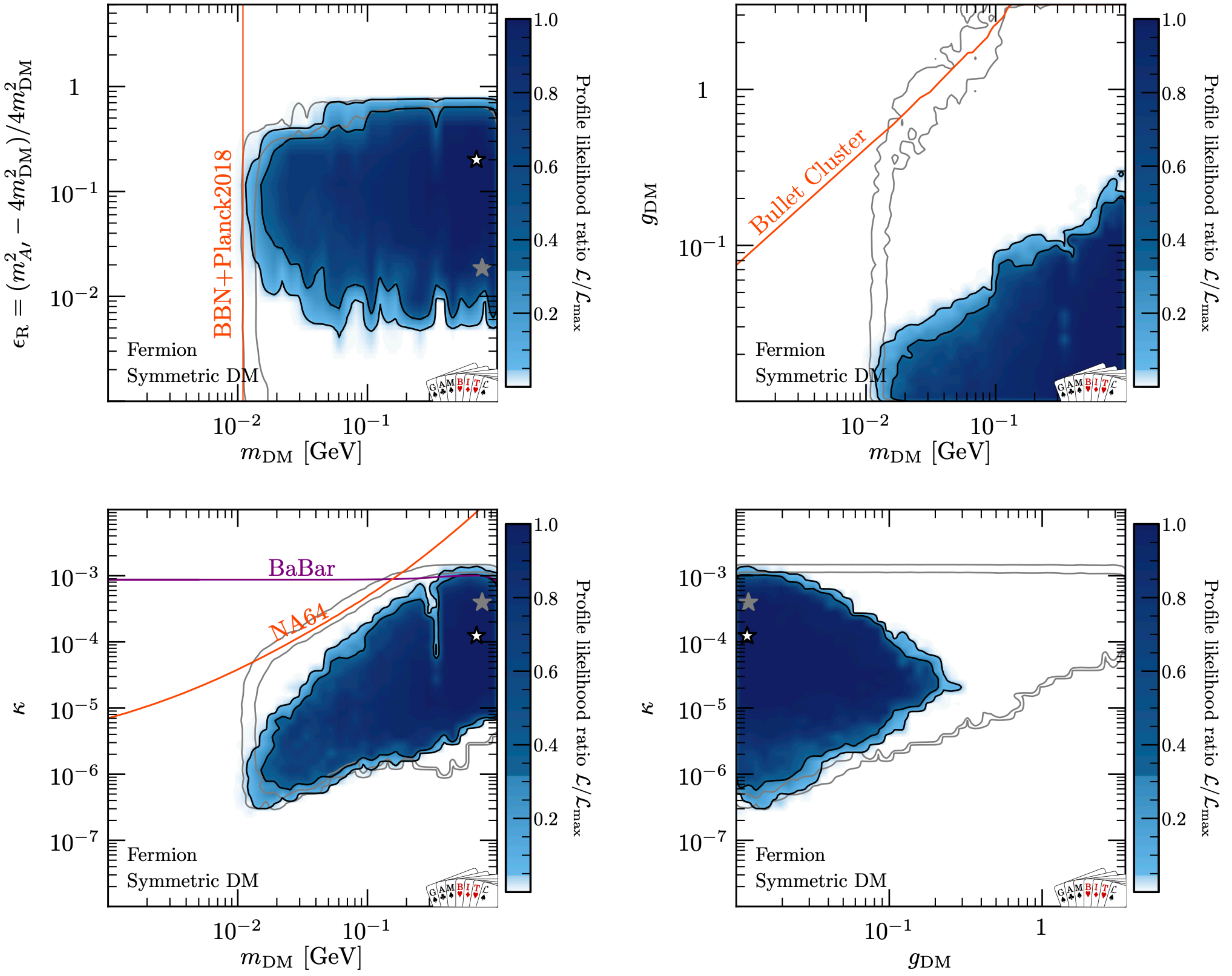
dark matter EFTs 2106.02056

Slide by C. Balázs @ SUSY 2021

Today's models and experiments are too complicated to keep track of all constraints. The solution: GAMBIT

Global fits: work in progress

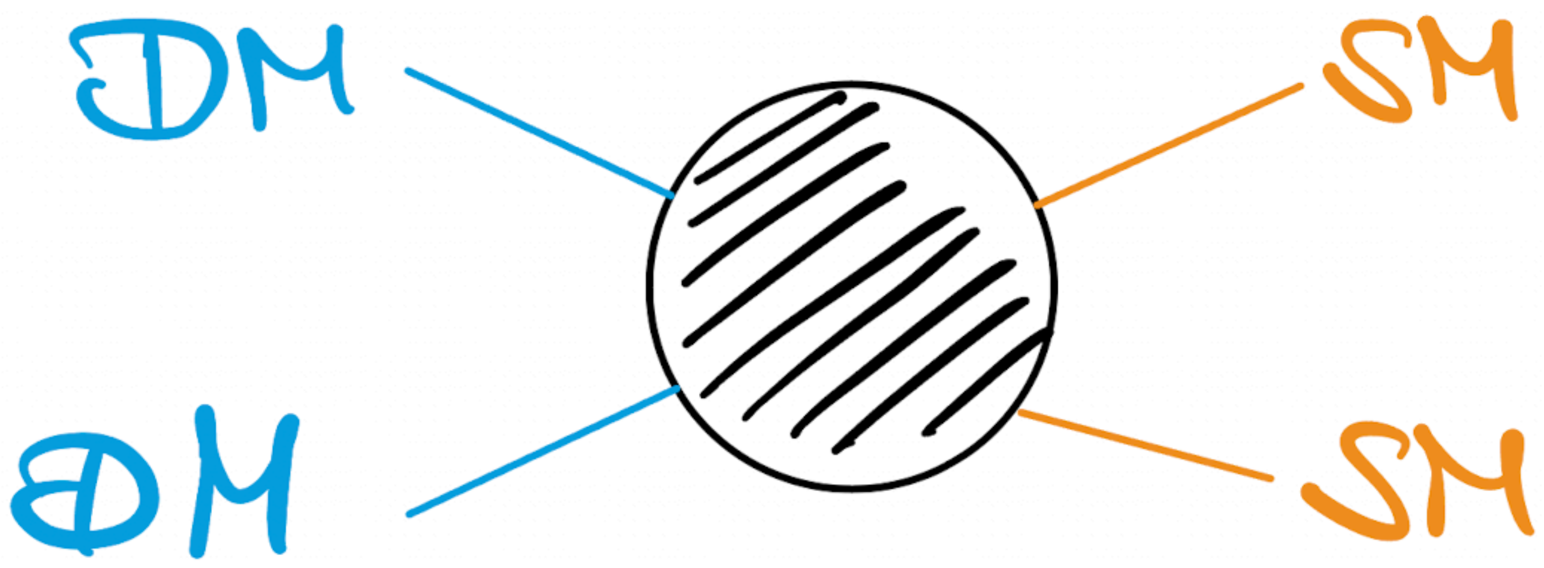
- 2405.17548 studied sub-GeV dark matter in a $U(1)$ setup
- We break that conformal $U(1)$ and generate very strong GWs
- **Best fit point explains both PTA data and dark matter!**
- Exciting: Best-fit point might be in reach for tests with Belle II, LDMX, SuperCDMS, …

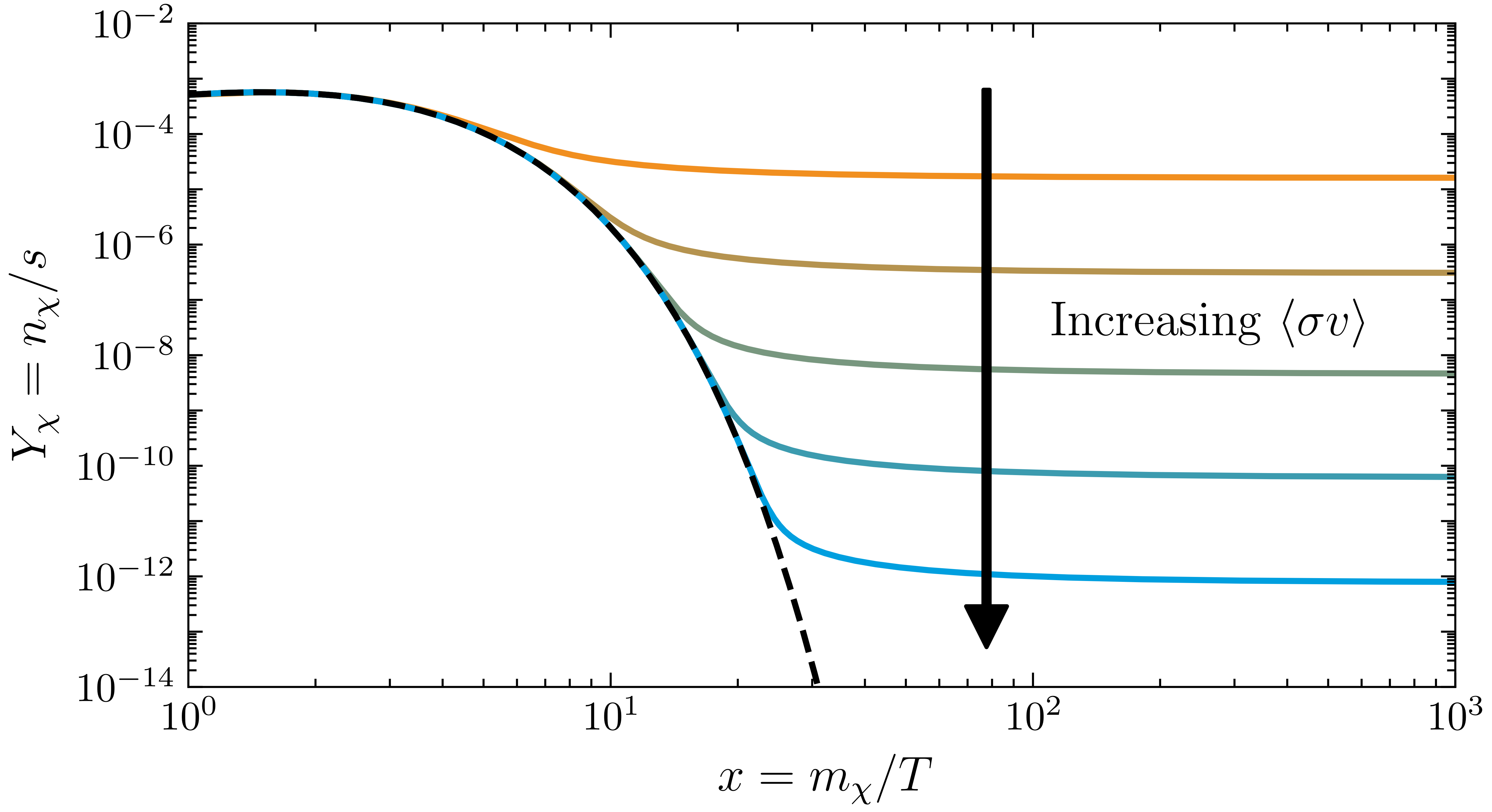


The (first) LISA miracle.

The WIMP miracle

If DM can annihilate into SM particles with a cross section $\langle \sigma v \rangle$ …



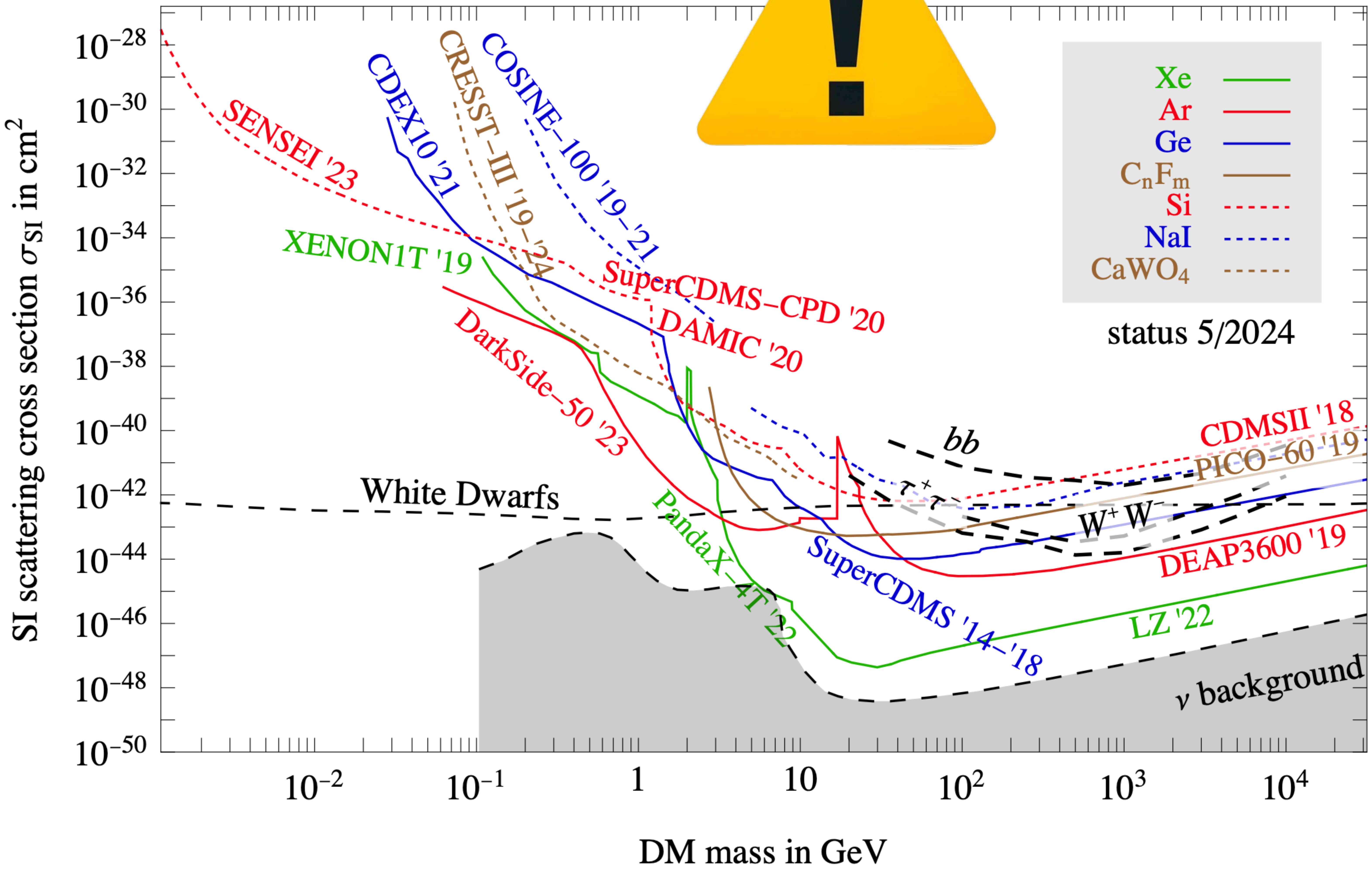


… the DM abundance can freeze out to the observed relic abundance for weak interactions and $m_{\mathrm{DM}} \simeq \mathcal{O}(\mathrm{TeV})$.

Rage, rage against the dying of the WIMP

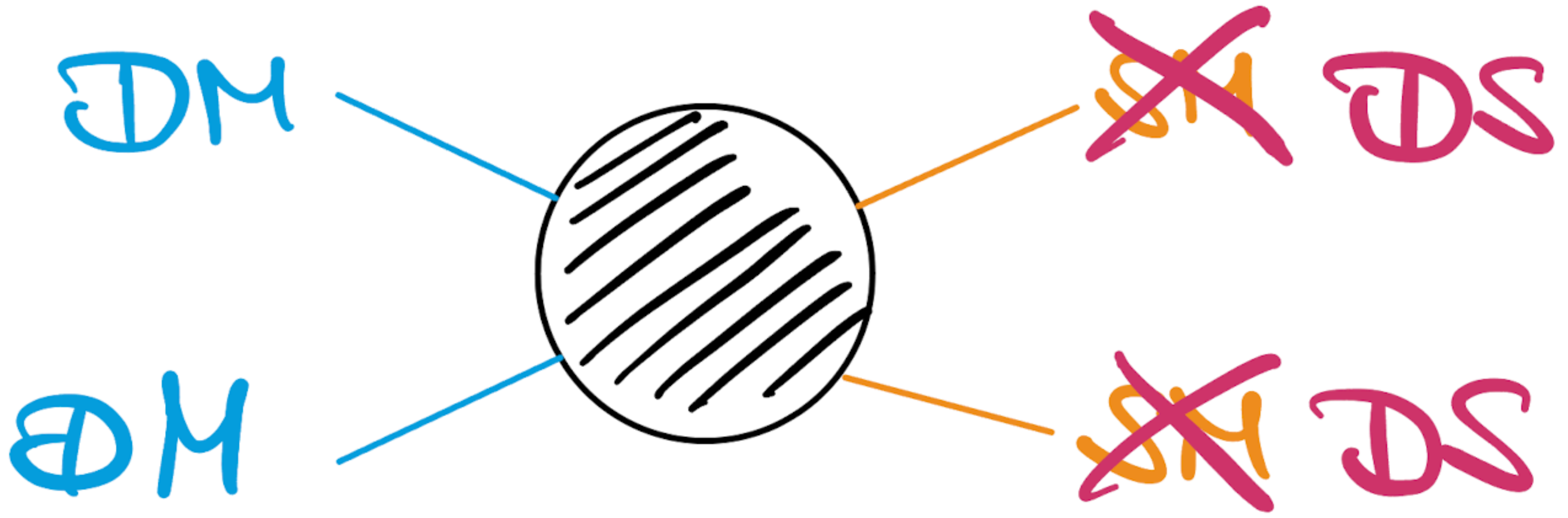
Direct detection experiments put this scenario under pressure, excluding „vanilla“ WIMPs.

[Lindner+ 2403.15860]



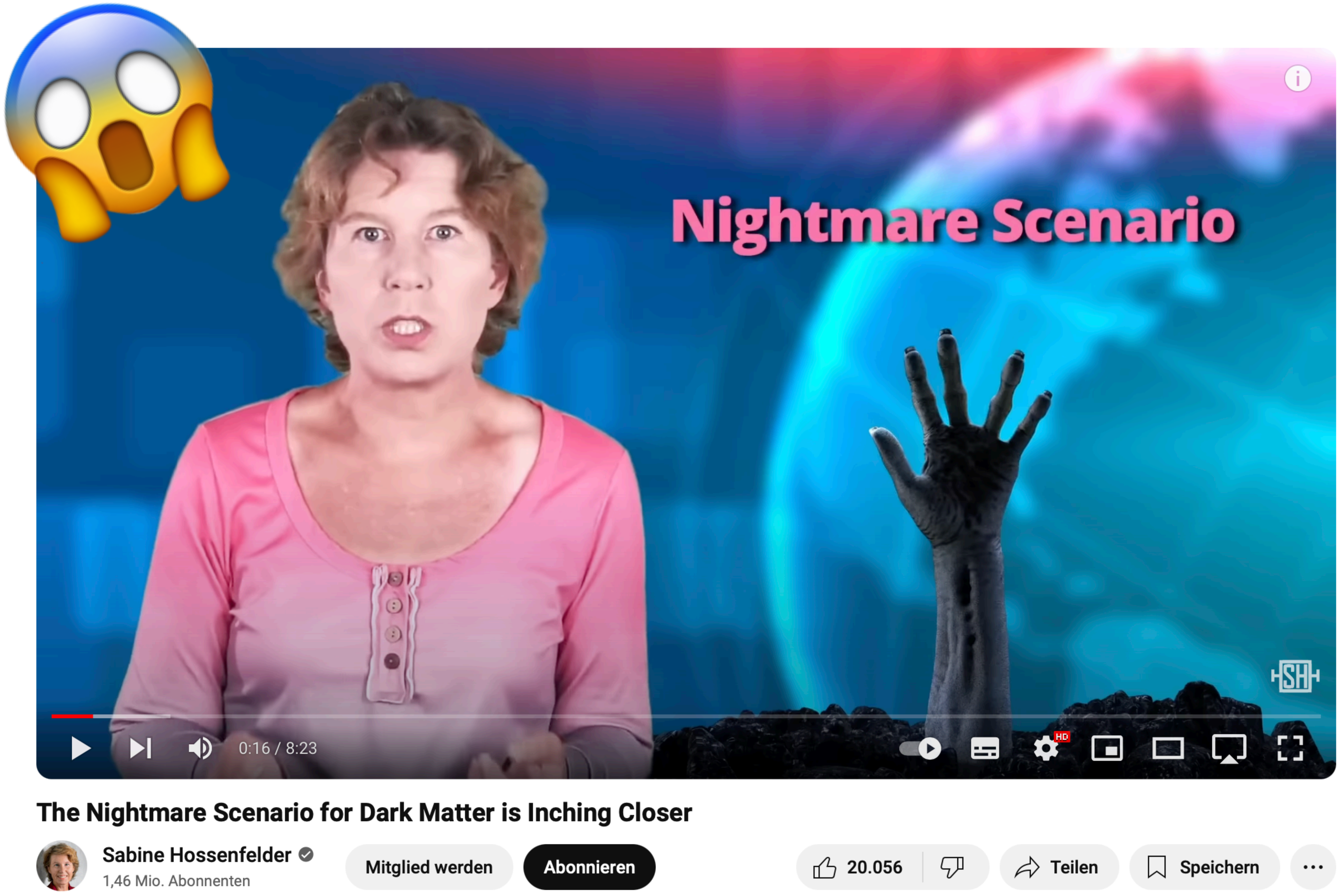
Cirelli+ [2406.01705]

The nightmare scenario



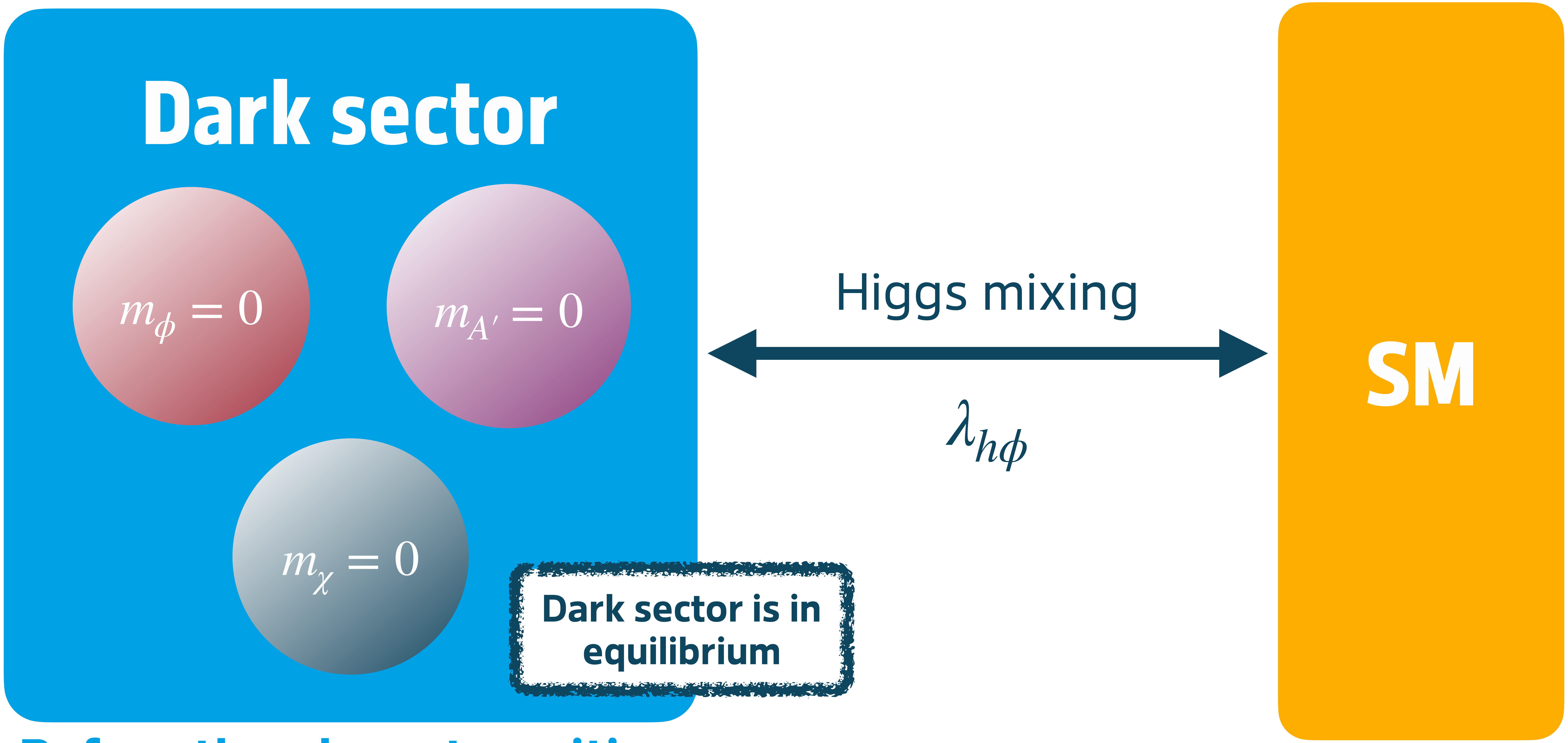
What if WIMPs evade our detection because they never were in contact with the SM and froze out of a secluded dark sector?

Pospelov+ [0711.4866]



The Nightmare Scenario for Dark Matter is Inching Closer

Our model setup



Dark sector

$m_\phi = 0$

$m_{A'} = 0$

$m_\chi = 0$

Higgs mixing

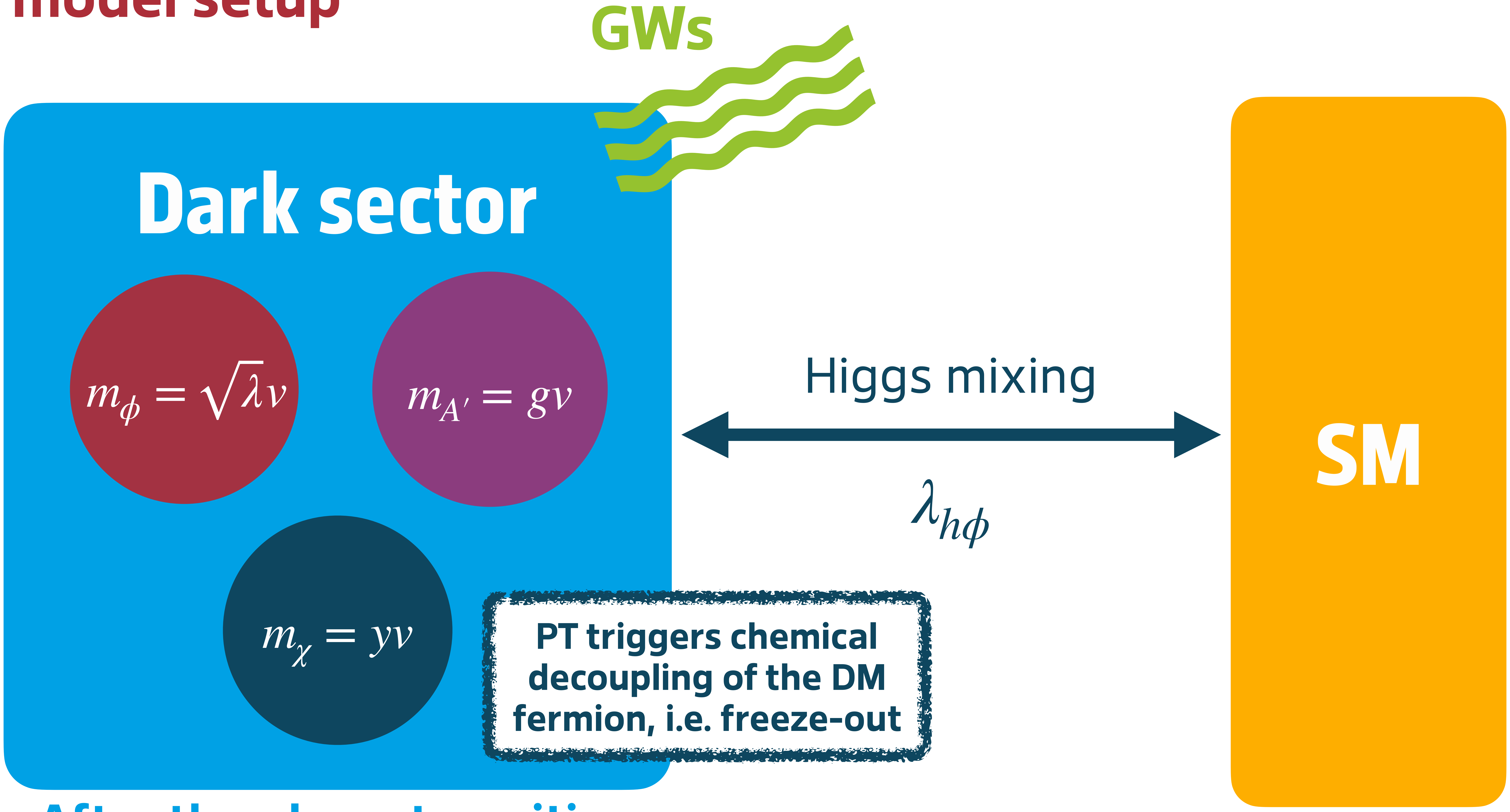
$\lambda_{h\phi}$

SM

Dark sector is in equilibrium

Before the phase transition

Our model setup



GWs

Dark sector

$m_\phi = \sqrt{\lambda} v$

$m_{A'} = gv$

$m_\chi = yv$

Higgs mixing

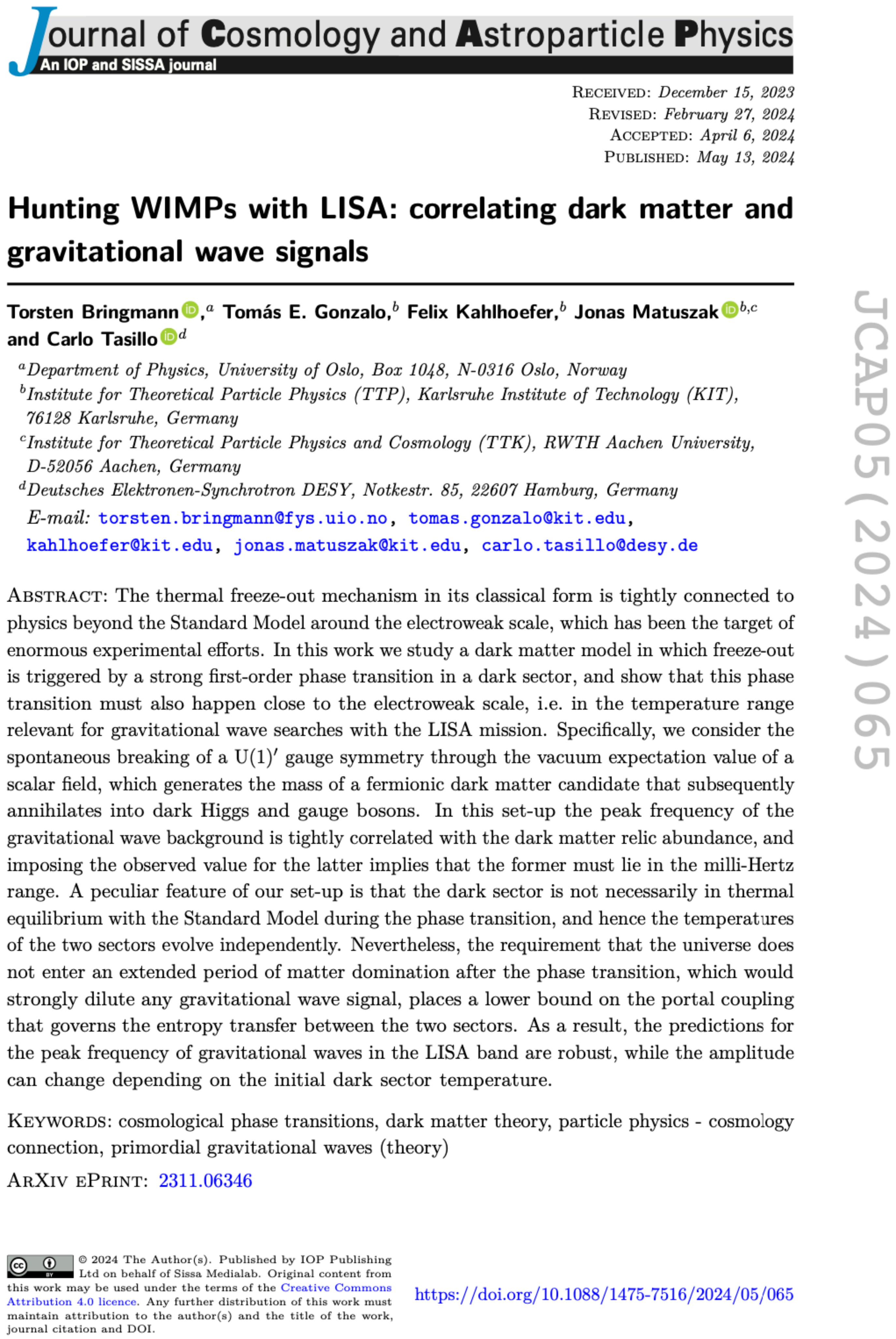
$\lambda_{h\phi}$

SM

PT triggers chemical decoupling of the DM fermion, i.e. freeze-out

After the phase transition

A first glance at our punchline



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Hunting WIMPs with LISA: correlating dark matter and gravitational wave signals

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ABSTRACT: The thermal freeze-out mechanism in its classical form is tightly connected to physics beyond the Standard Model around the electroweak scale, which has been the target of enormous experimental efforts. In this work we study a dark matter model in which freeze-out is triggered by a strong first-order phase transition in a dark sector, and show that this phase transition must also happen close to the electroweak scale, i.e. in the temperature range relevant for gravitational wave searches with the LISA mission. Specifically, we consider the spontaneous breaking of a U(1)′ gauge symmetry through the vacuum expectation value of a scalar field, which generates the mass of a fermionic dark matter candidate that subsequently annihilates into dark Higgs and gauge bosons. In this set-up the peak frequency of the gravitational wave background is tightly correlated with the dark matter relic abundance, and imposing the observed value for the latter implies that the former must lie in the milli-Hertz range. A peculiar feature of our set-up is that the dark sector is not necessarily in thermal equilibrium with the Standard Model during the phase transition, and hence the temperatures of the two sectors evolve independently. Nevertheless, the requirement that the universe does not enter an extended period of matter domination after the phase transition, which would strongly dilute any gravitational wave signal, places a lower bound on the portal coupling that governs the entropy transfer between the two sectors. As a result, the predictions for the peak frequency of gravitational waves in the LISA band are robust, while the amplitude can change depending on the initial dark sector temperature.

KEYWORDS: cosmological phase transitions, dark matter theory, particle physics - cosmology connection, primordial gravitational waves (theory)

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Theorem:

There is a correlation between the GW peak frequency and the DM abundance.

Proof:

$f_\mathrm{peak} \propto v$ and $\Omega_\mathrm{DM} \propto v^2$ for a transition with vacuum expectation value v.

Lemma:

$\Omega_\mathrm{DM} h^2 = 0.12 \quad \Longrightarrow \quad f_\mathrm{peak} \simeq \mathcal{O}(\mathrm{mHz})$. If DM freeze-out is triggered by a strong phase transition, it is observable by LISA.

The miracle at work

Peak frequency: $$f_{\rm peak} \simeq 10\,{\rm mHz}\left(\cancel{\frac{\beta/H}{100}}\right)\left(\frac{\cancel{T}\ v}{1\,{\rm TeV}}\right) \simeq 10\,{\rm mHz}\left(\frac{v}{1\,{\rm TeV}}\right)$$

DM abundance: $$\Omega_{\rm DM}h^2 \simeq 0.1\frac{10^{-8}\,{\rm GeV}^{-2}}{\langle\sigma v\rangle} \propto \frac{v^2}{y^2}$$

Assuming that dominant annihilation channel is $\chi\chi \to \phi\phi$:

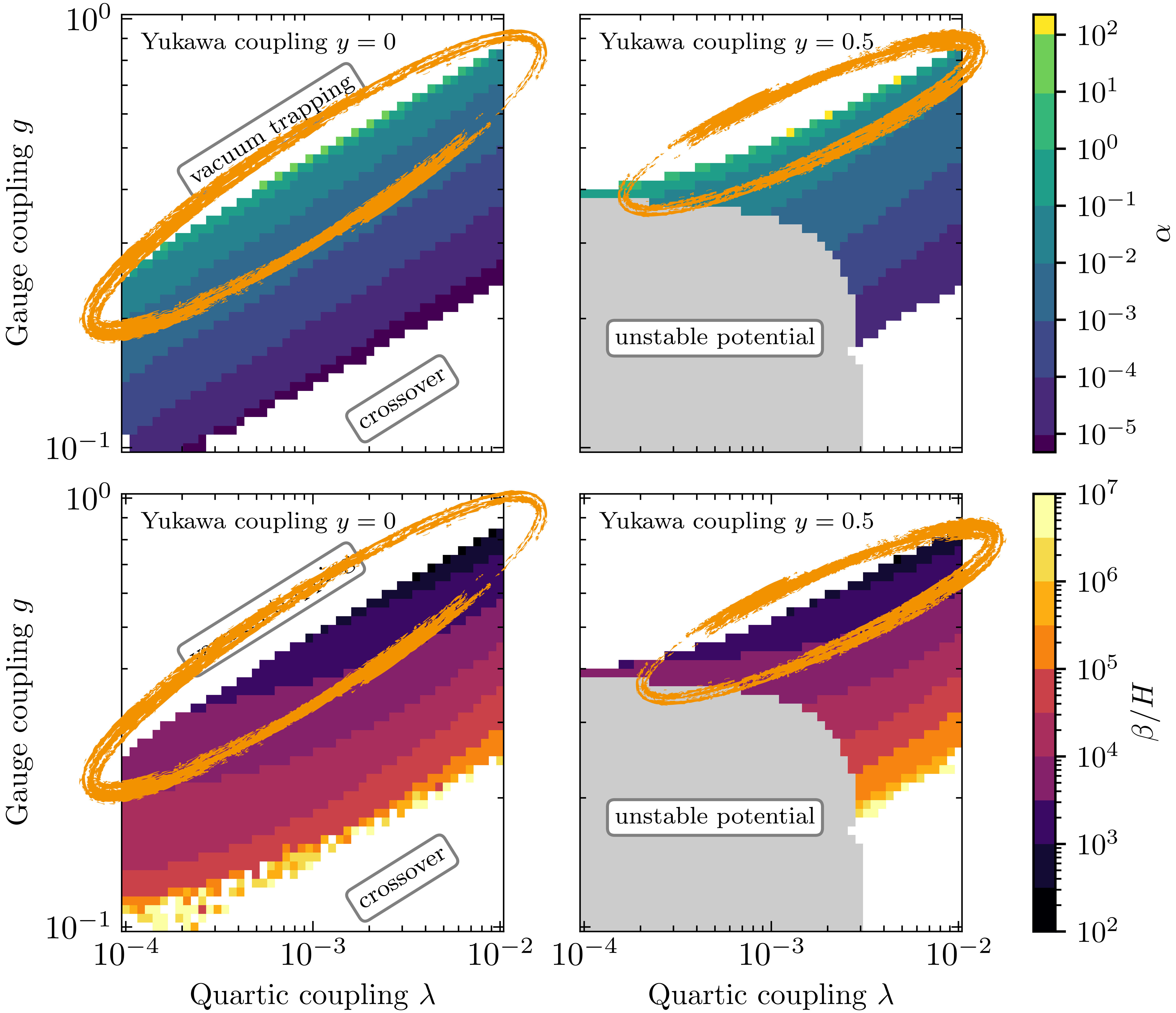
$$\langle\sigma v\rangle \sim \frac{y^4}{m_\chi^2} \sim \frac{y^2}{v^2}$$

Since Yukawa coupling y is **a-priori** arbitrary: **no correlation expected...**

Intermediate Yukawa couplings

Strong-GW condition:

Sizable couplings and $m_\phi \lesssim m_{A'}$



Intermediate Yukawa couplings

Strong-GW condition:

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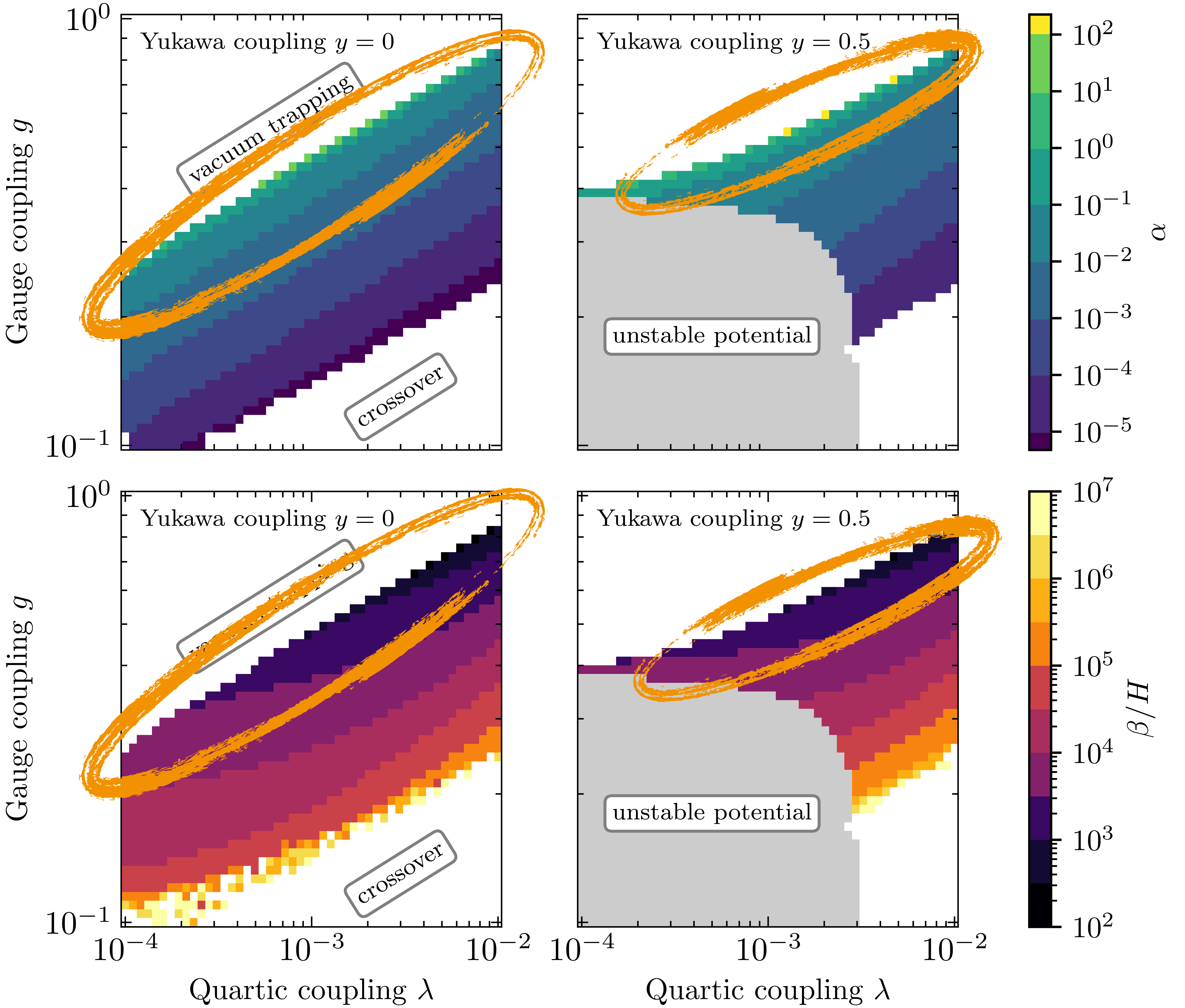
Freeze-out condition:

DM cannot be lightest dark sector state: $m_\phi < m_\chi$ or $m_{A'} < m_\chi$



Intermediate Yukawa couplings

Strong-GW condition:

Sizable couplings and $m_\phi \lesssim m_{A'}$

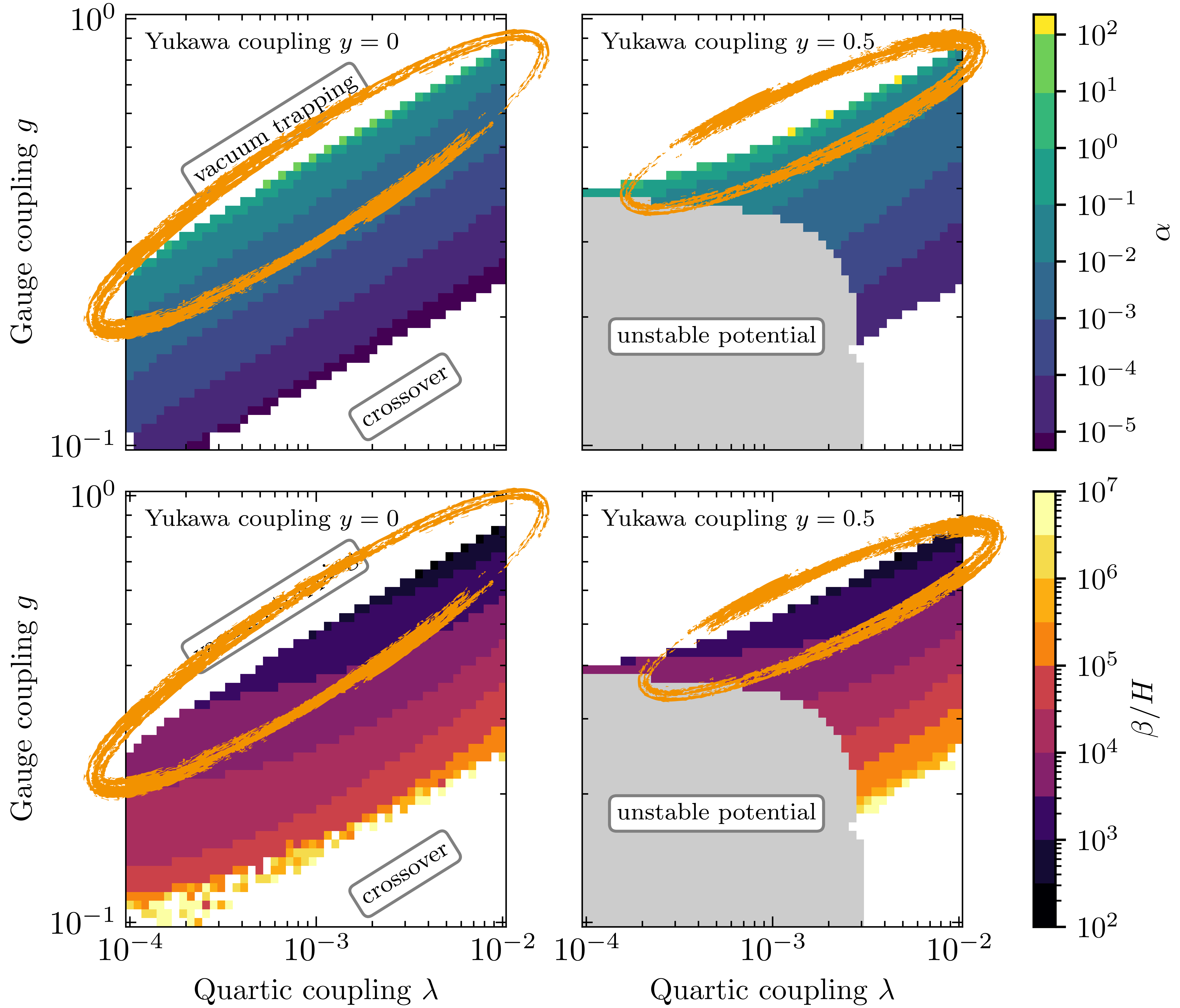
Freeze-out condition:

DM cannot be lightest dark sector state: $m_\phi < m_\chi$ or $m_{A'} < m_\chi$

Conclusion:

$m_\phi \lesssim m_\chi \lesssim m_{A'}$

Yukawa couplings are bounded and $\mathcal{O}(0.1)$. Miracles can happen! 🤩



You shouldn’t be convinced

So far we skipped over several potential issues:

- Sizable Yukawa couplings vs. vacuum stability
- What about the $\chi\chi \to A'A'$ and $\chi\chi \to \phi A'$ annihilations?
- Influence of temperature ratio $\xi = T_{\mathrm{DS}}/T_{\mathrm{SM}}$ on $\Omega_{\mathrm{GW}}(f)$ and Ω_{DM}?
- $\lambda_{h\phi}$: Collider bounds? Early matter domination?

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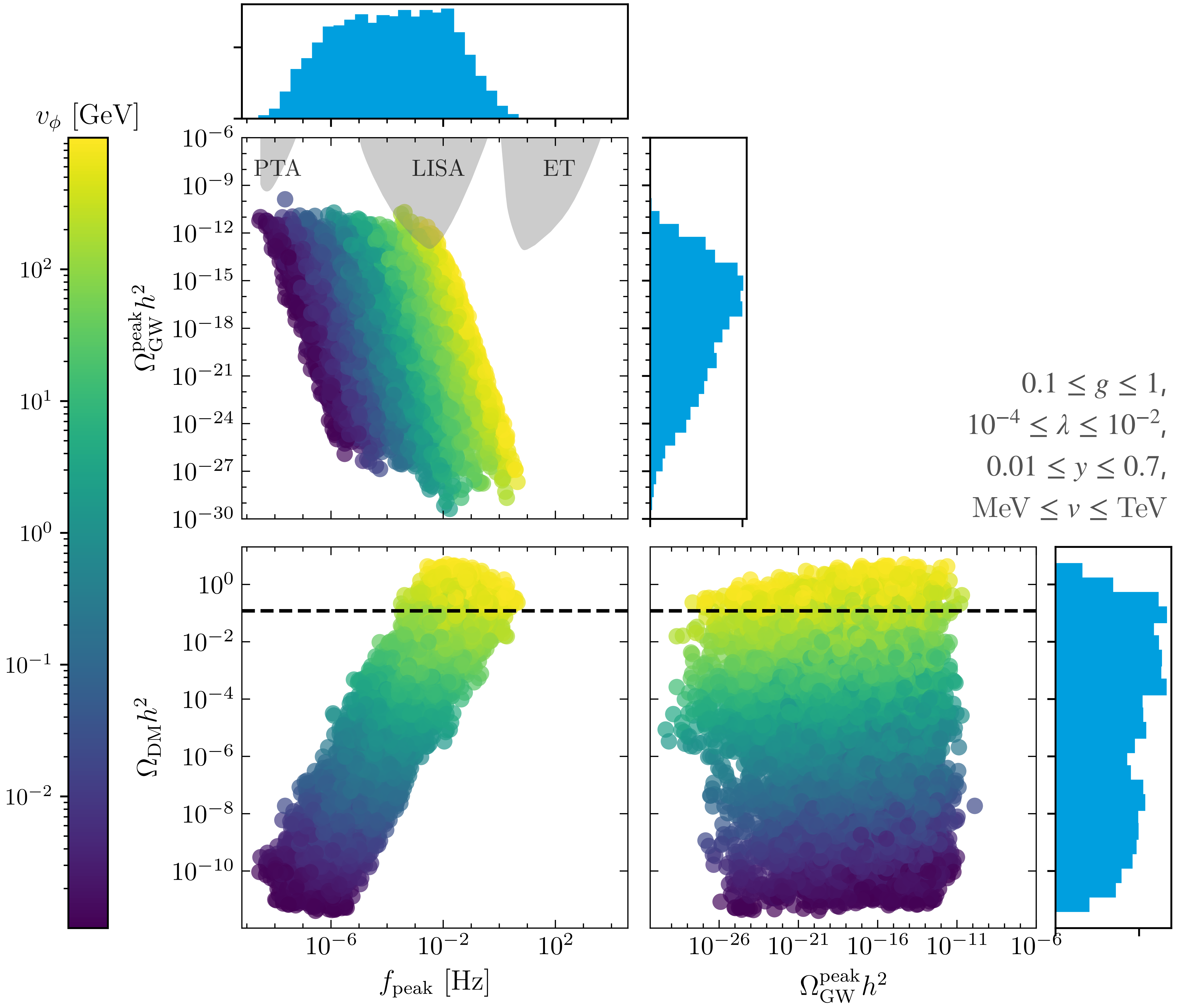
- $\lambda_{h\phi}$: Collider bounds? Early matter domination?

We performed full model scans* over $\lambda, g, y, v, \xi, \lambda_{h\phi}$ and confirmed the LISA miracle!

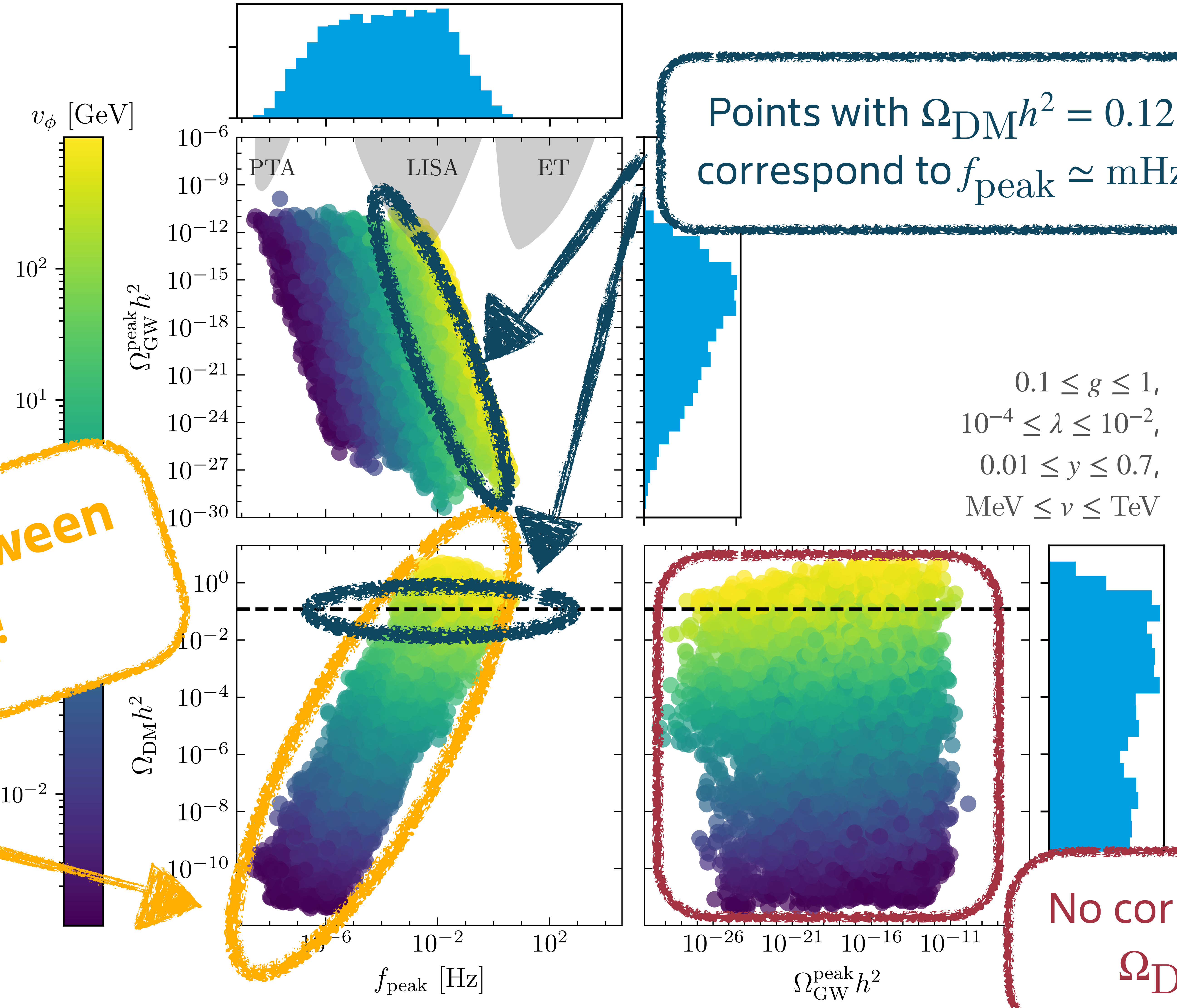
* TransitionListener & DarkSUSY [Ertas+ 2109.06208, Bringmann+ 1802.03399]

Results of our scans



$0.1 \leq g \leq 1,$
$10^{-4} \leq \lambda \leq 10^{-2},$
$0.01 \leq y \leq 0.7,$
$\text{MeV} \leq v \leq \text{TeV}$

Results of our scans



Points with $\Omega_{\rm DM}h^2 = 0.12$ correspond to $f_{\rm peak} \simeq \text{mHz}$

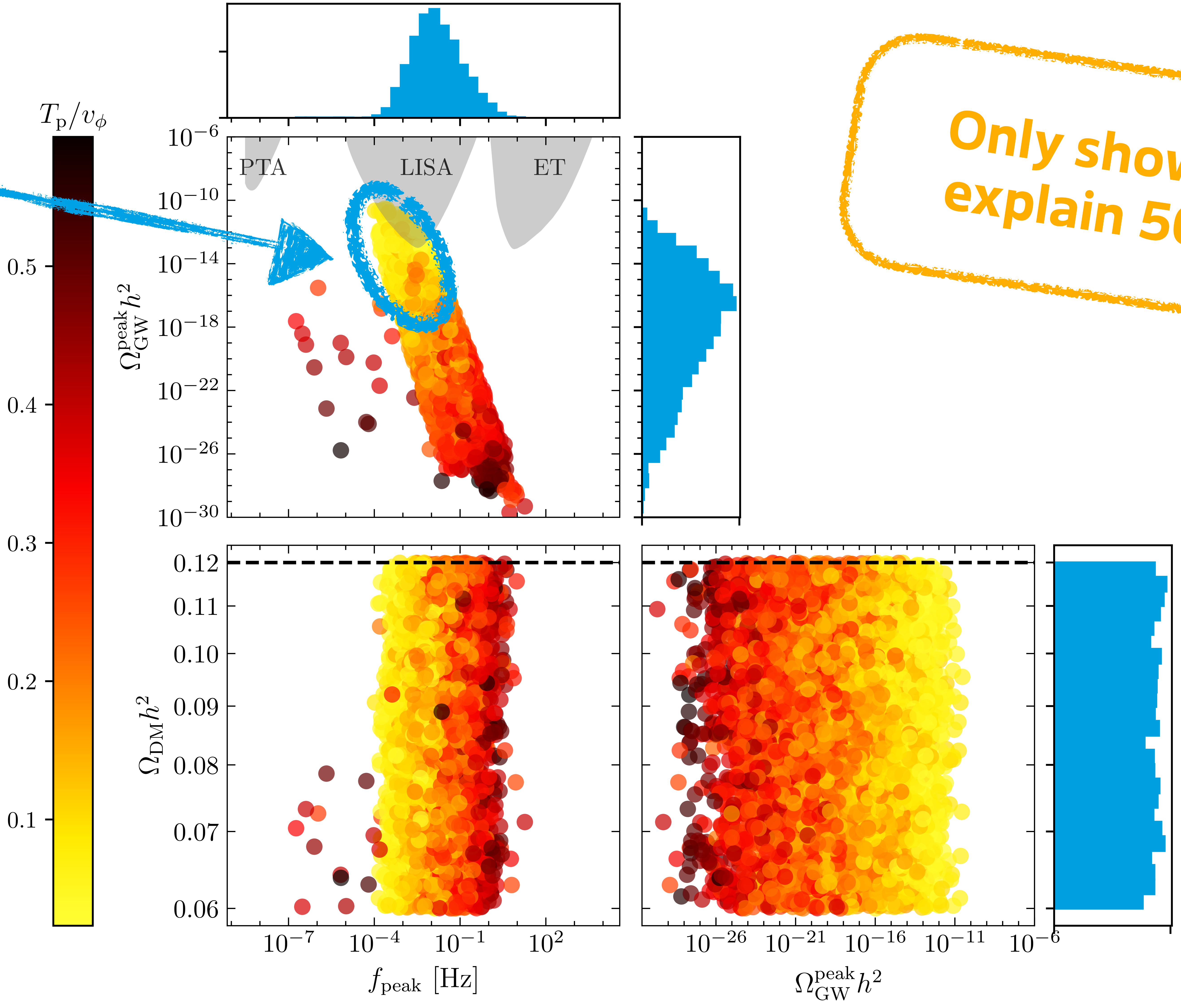
Strong correlation between $f_{\rm peak}$ and $\Omega_{\rm DM}$!

No correlation between $\Omega_{\rm DM}$ and $\Omega_{\rm GW}^{\rm peak}$

Selection: observed DM abundance is explained

Strong supercooling

35% of points with strong supercooling and correct DM abundance are observable



Only show points which explain 50-100% of DM

Summary

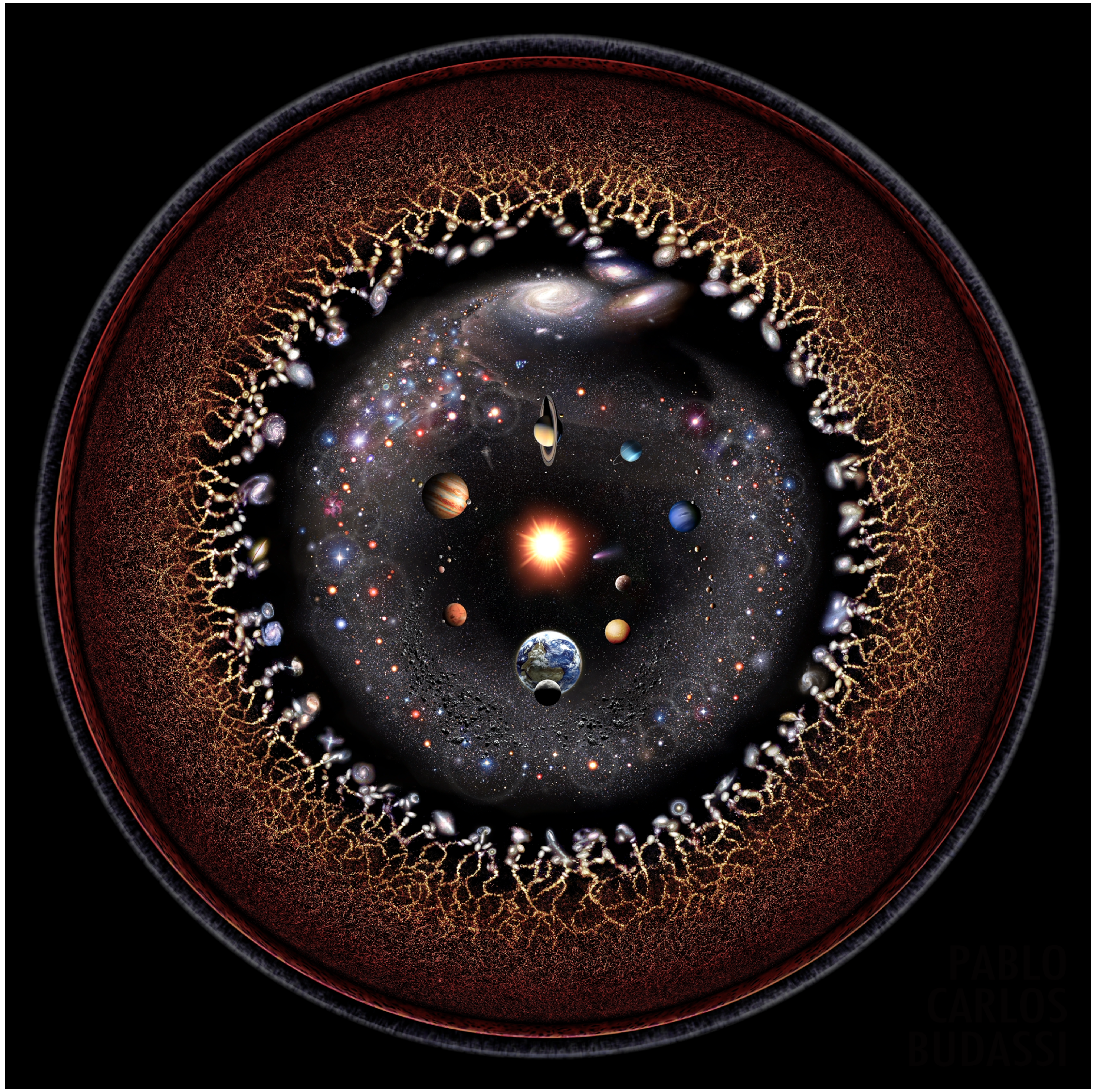
- We are only at the dawn of GW cosmology, but can already probe the pre-BBN universe!
- PTAs could have observed a dark sector phase transition or merging supermassive PBHs
  - ➡ Dark sector phase transitions cannot be too strong & quick: Need $\alpha \lesssim 0.1$ and $\beta/H \lesssim 10$ or (better) quick decays ($\tau_\phi \lesssim 0.1$ s)
  - ➡ PBHs need to be clustered, no μ-distortions at production
  - ➡ Look out for our next GAMBIT results
- A future LISA detection of a GW background would hint towards secluded DS freeze-out

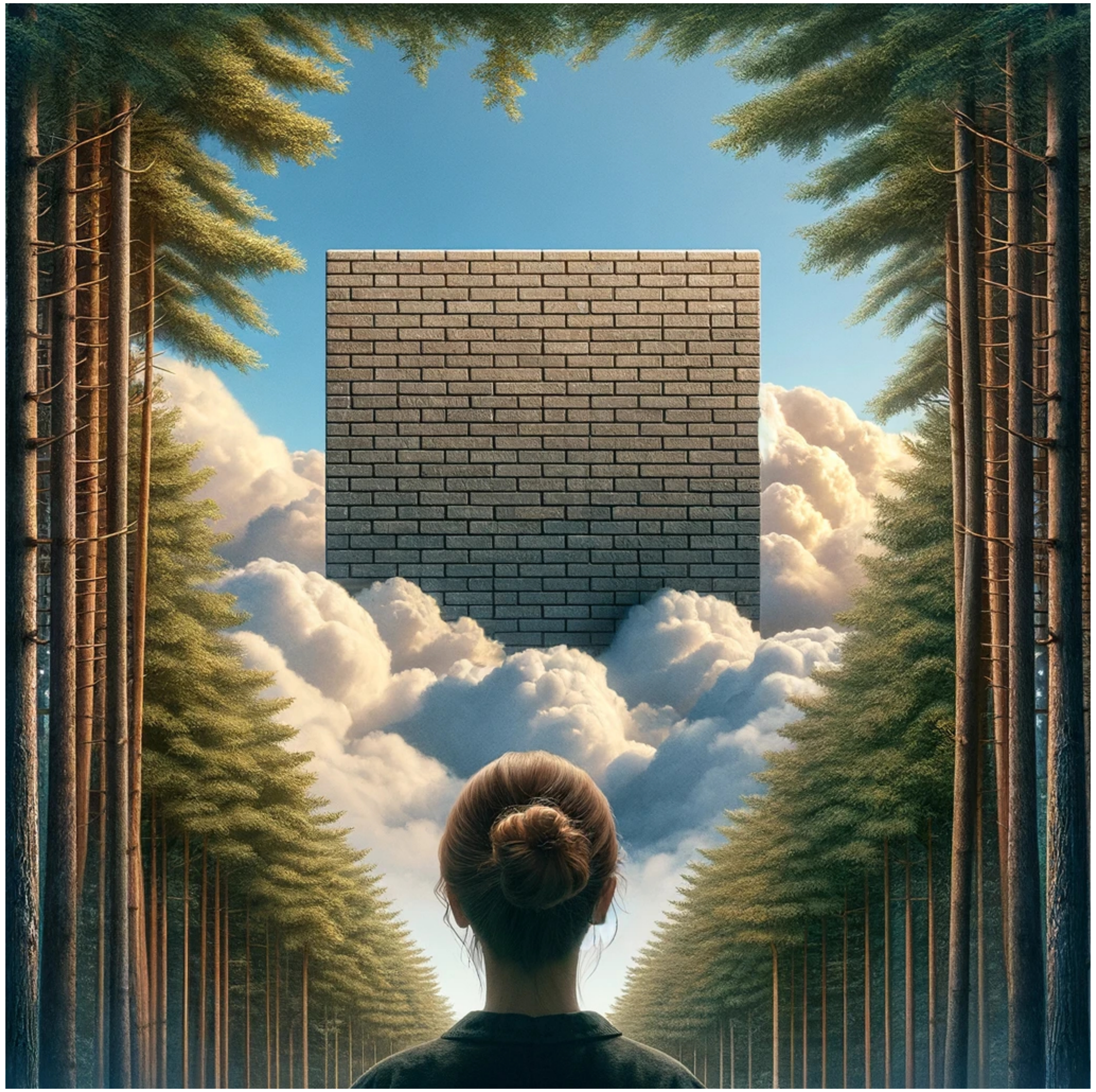
Thank you very much for your attention!

Do you have any questions?

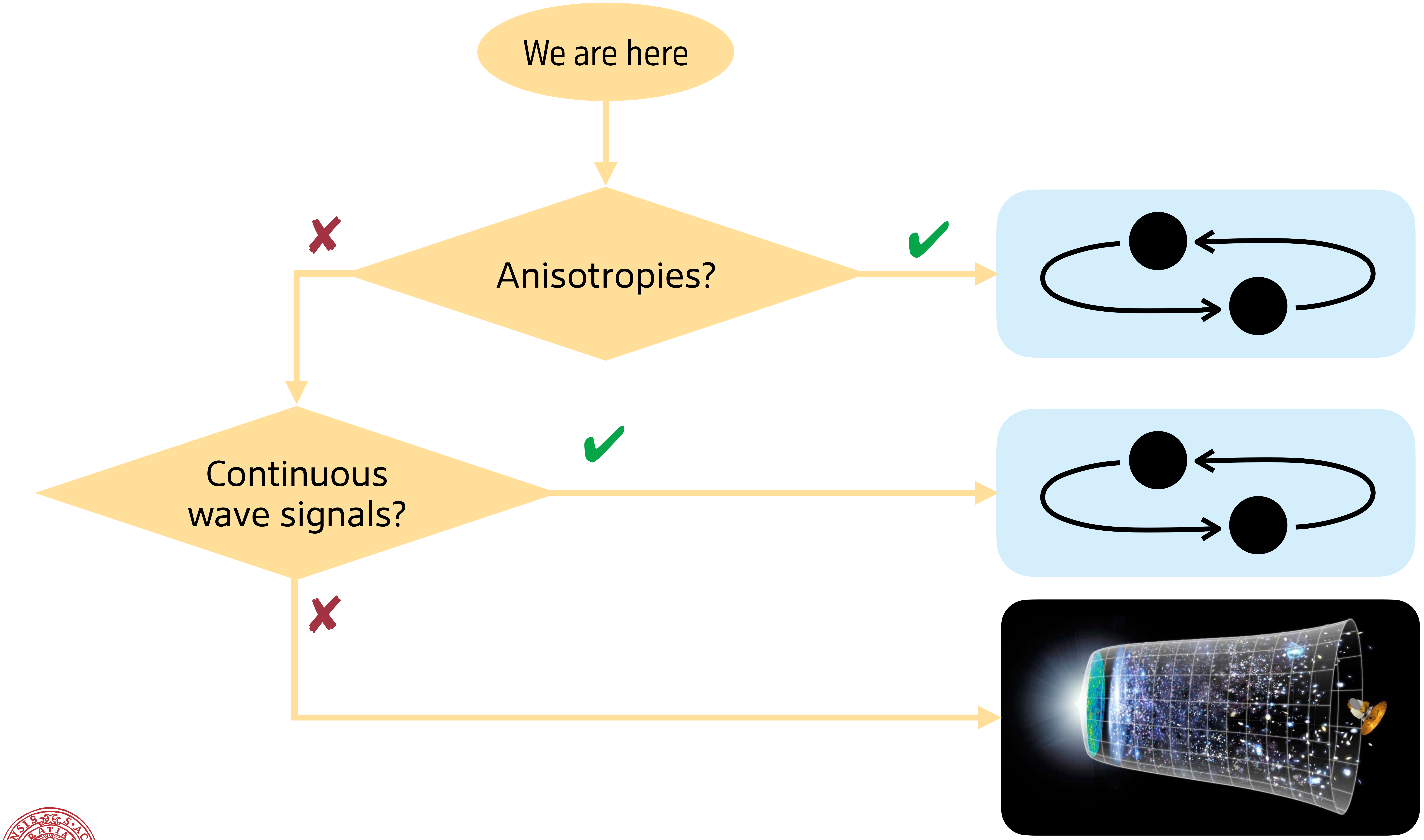
Backup slides

What do we know about the early universe?





Quo vadis pulsar timing?



We are here

Anisotropies?

✓

✗

Continuous wave signals?

✓

✗

Supermassive black hole binaries

Supermassive black hole binaries

An early universe source?

GWB details

$$h^2\Omega_{\rm GW}(f) = \mathcal{R}h^2\,\tilde{\Omega}\left(\frac{\kappa_{\rm sw}\,\alpha}{\alpha+1}\right)^2\left(\frac{\beta}{H}\right)^{-1}\mathcal{Y}\,S(f)$$

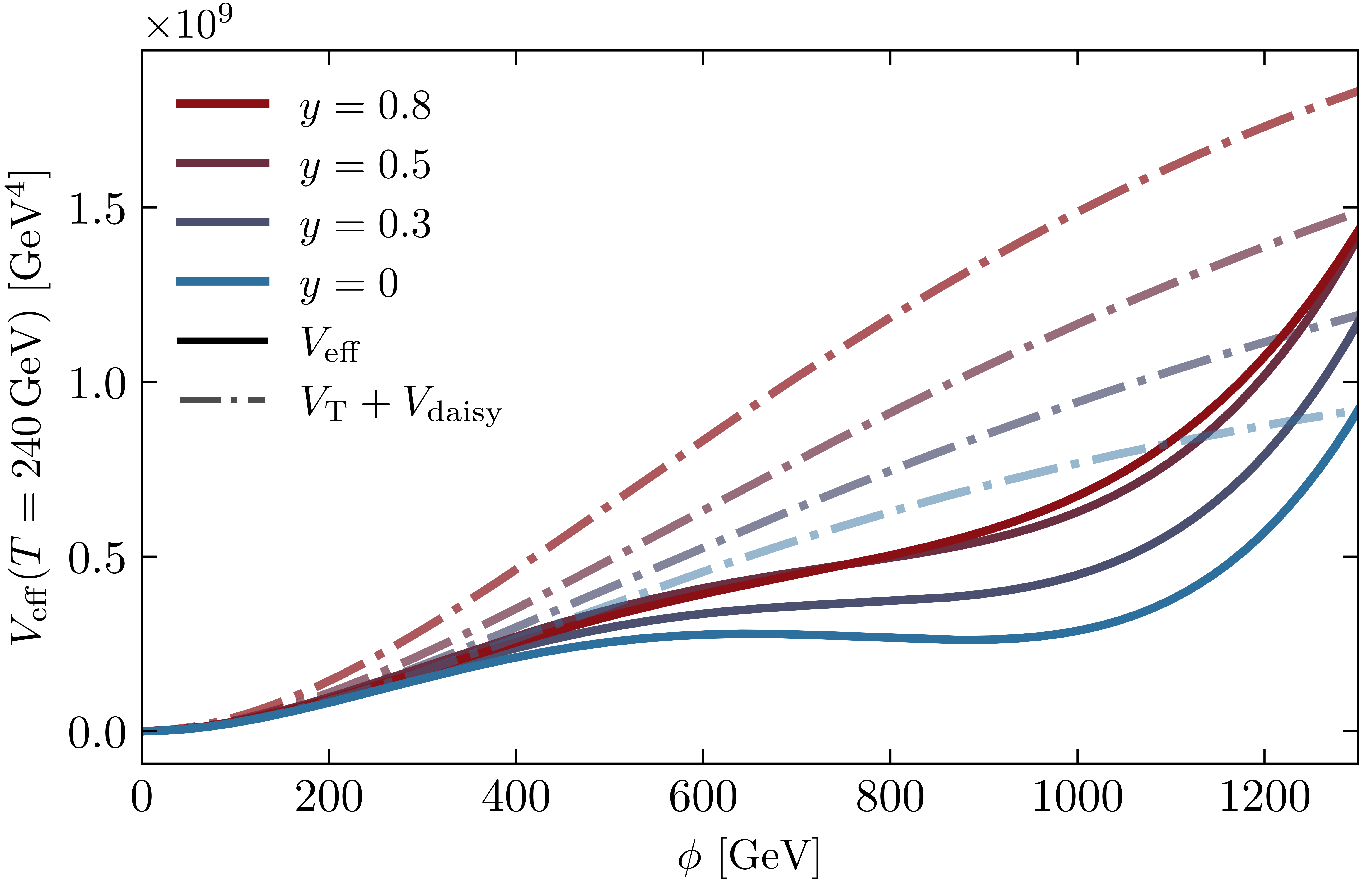
$$\mathcal{R}h^2 = \Omega_\gamma h^2\left(\frac{h_{\rm SM,0}}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{g_{\gamma,0}}\right) = 1.653\cdot 10^{-5}\left(\frac{100}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{100}\right)$$

$$\mathcal{Y} = \min\left[1, \tau_{\rm sh}H\right] \simeq \min\left[1, \frac{3.38}{\beta/H}\sqrt{\frac{1+\alpha}{\kappa_{\rm sw}\,\alpha}}\right]$$

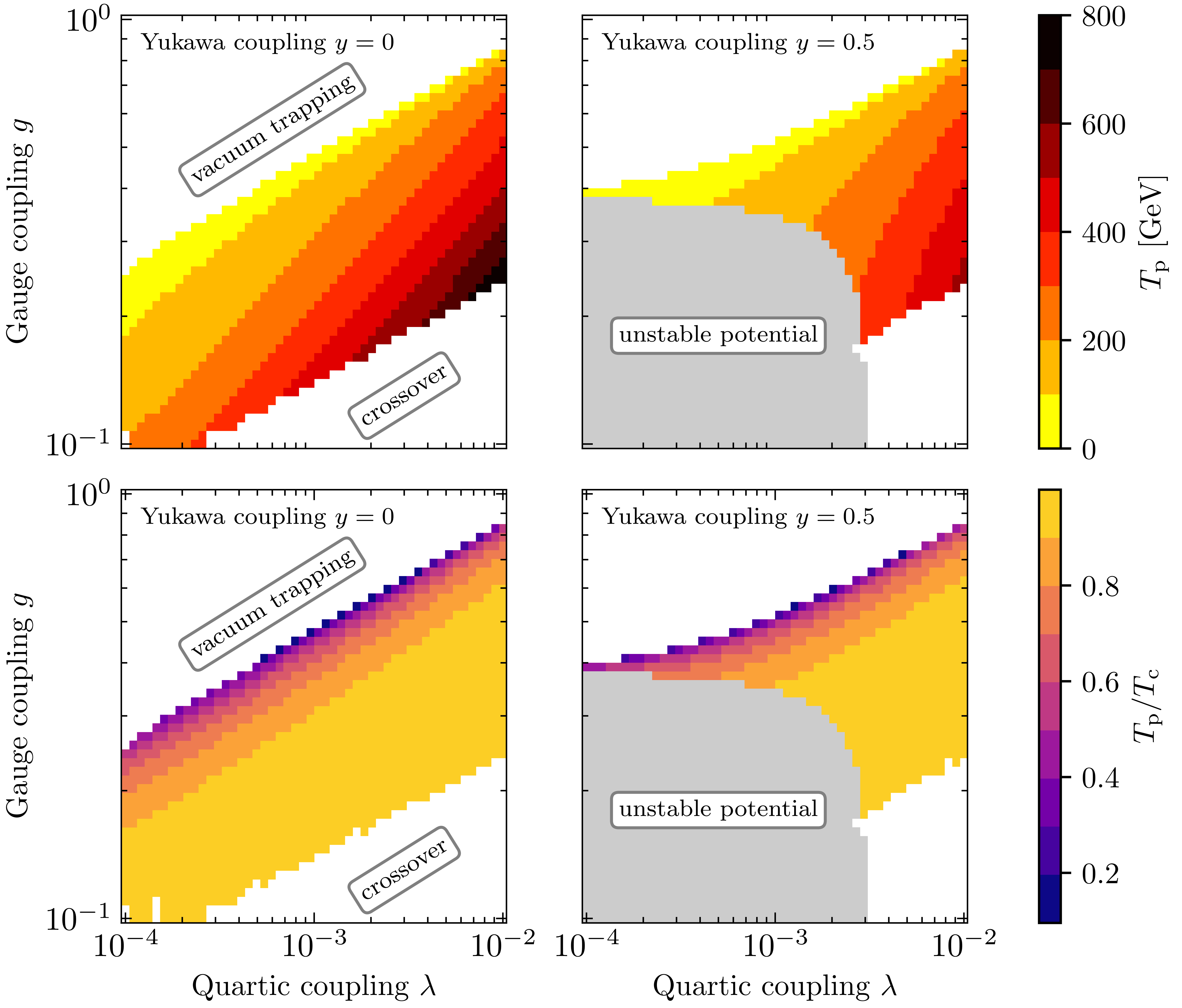
$$S(f) = \left(\frac{f}{f_{\rm peak}}\right)^3\left(\frac{7}{4+3\,(f/f_{\rm peak})^2}\right)^{7/2}$$

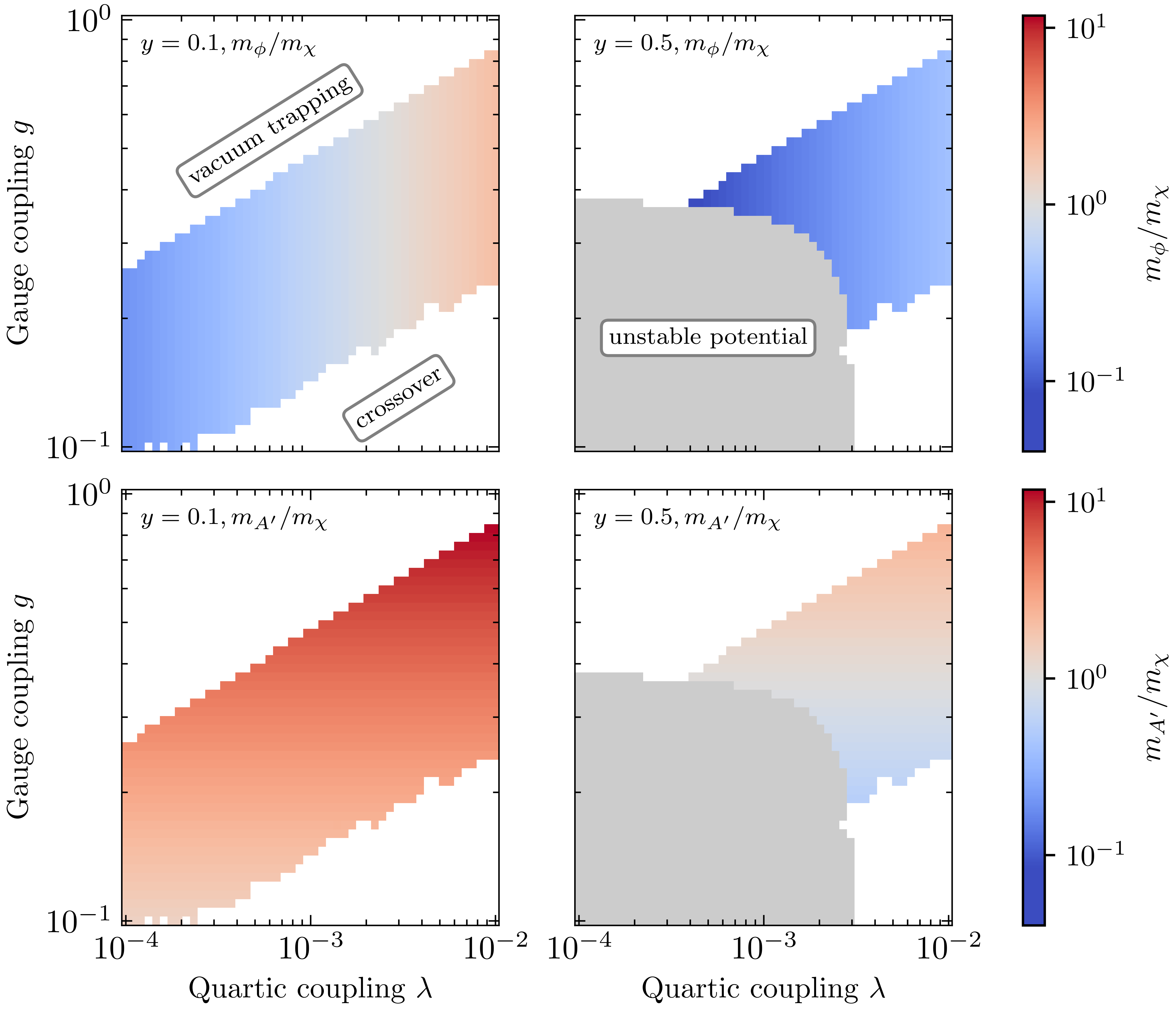
$$f_{\rm peak} = 8.9\,{\rm mHz}\left(\frac{T_{\rm p}}{100\ {\rm GeV}}\right)\left(\frac{\beta/H}{1000}\right)\left(\frac{g_{\rm tot,p}}{100}\right)^{1/2}\left(\frac{100}{h_{\rm tot,p}}\right)^{1/3}$$

Effect of Yukawa coupling on effective potential

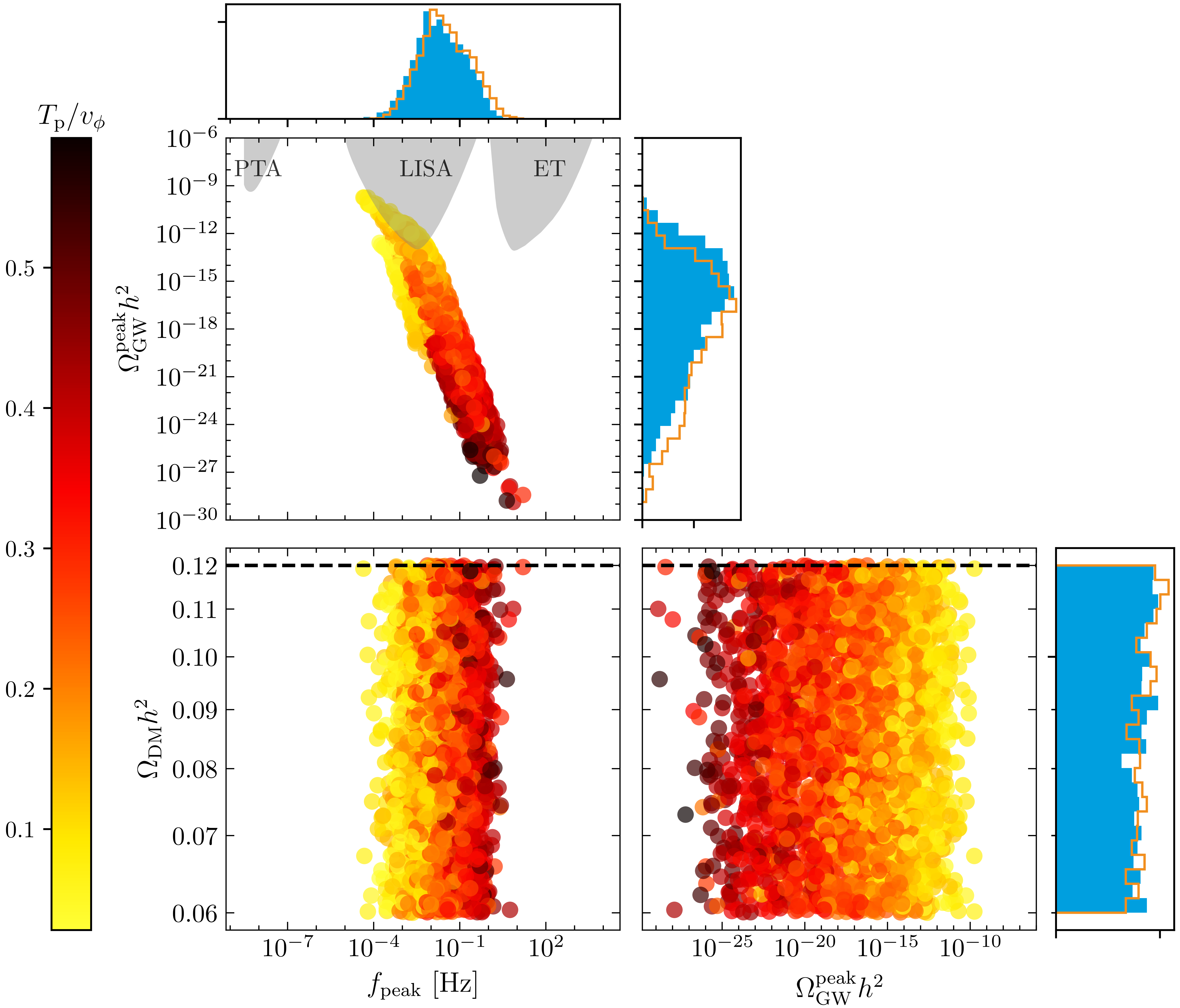


Grid scans over couplings

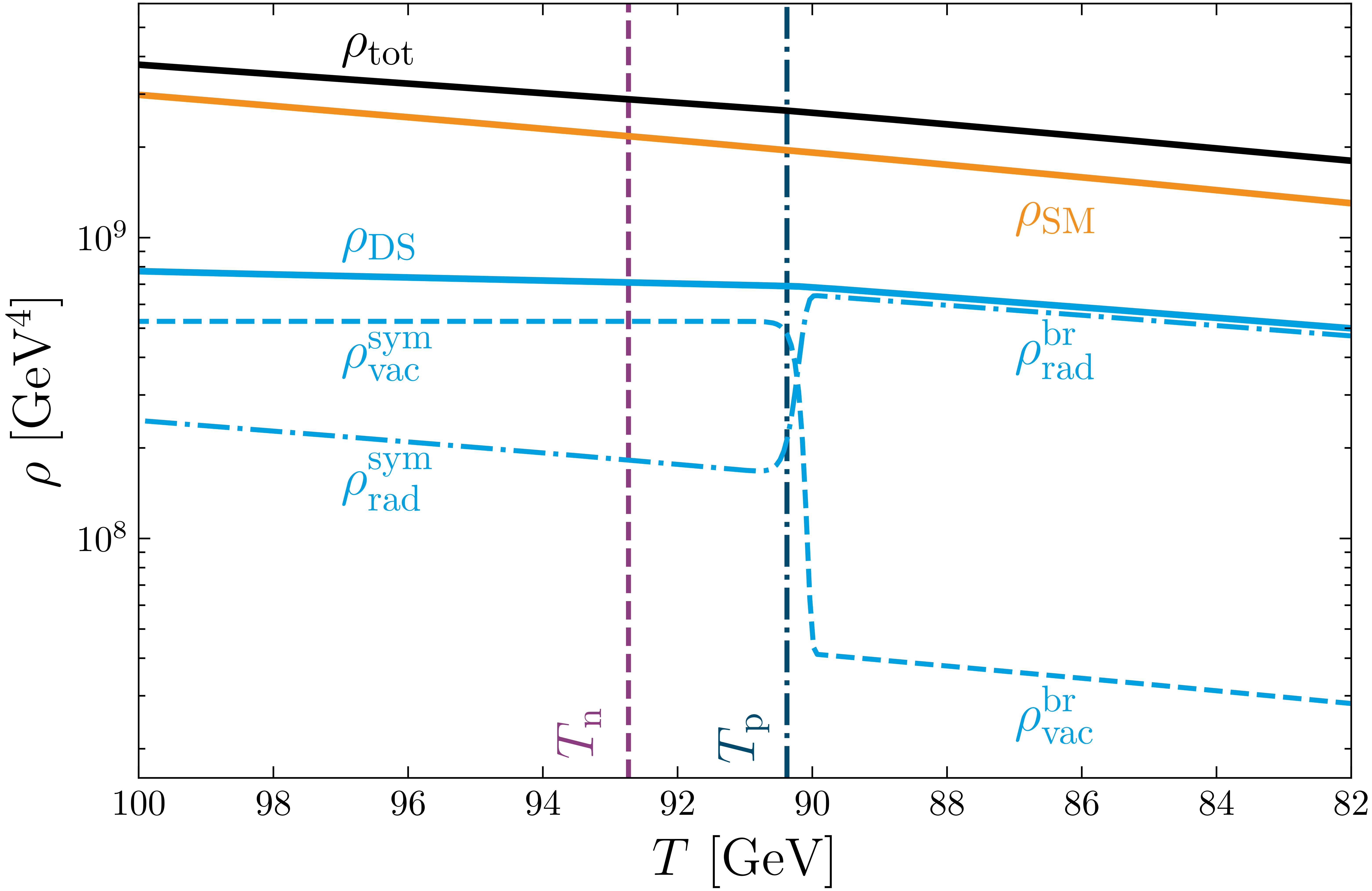




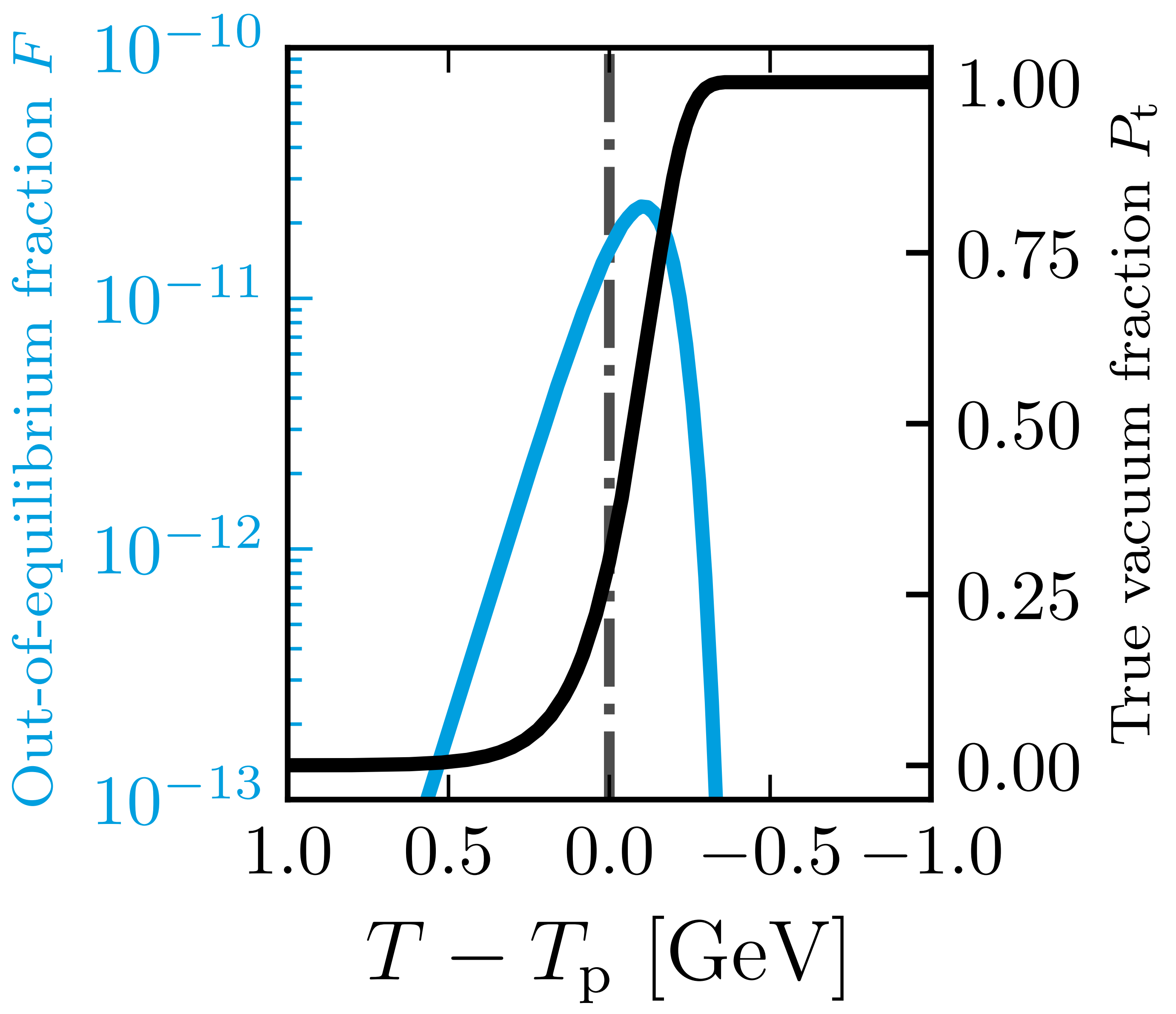
Comparison with hot dark sector phase transition

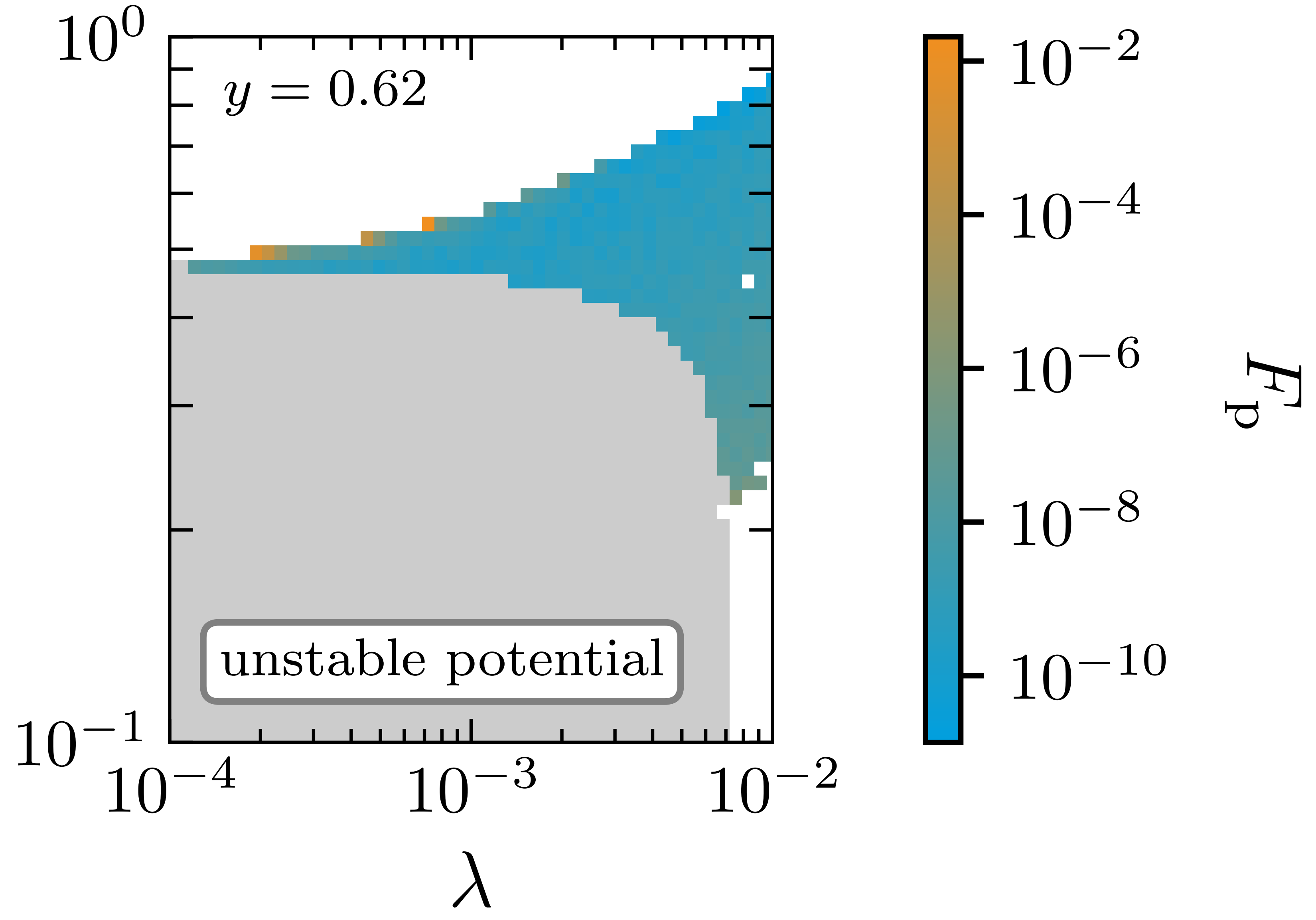


Evolution of energy densities



Out-of-equilibrium fraction of the dark sector



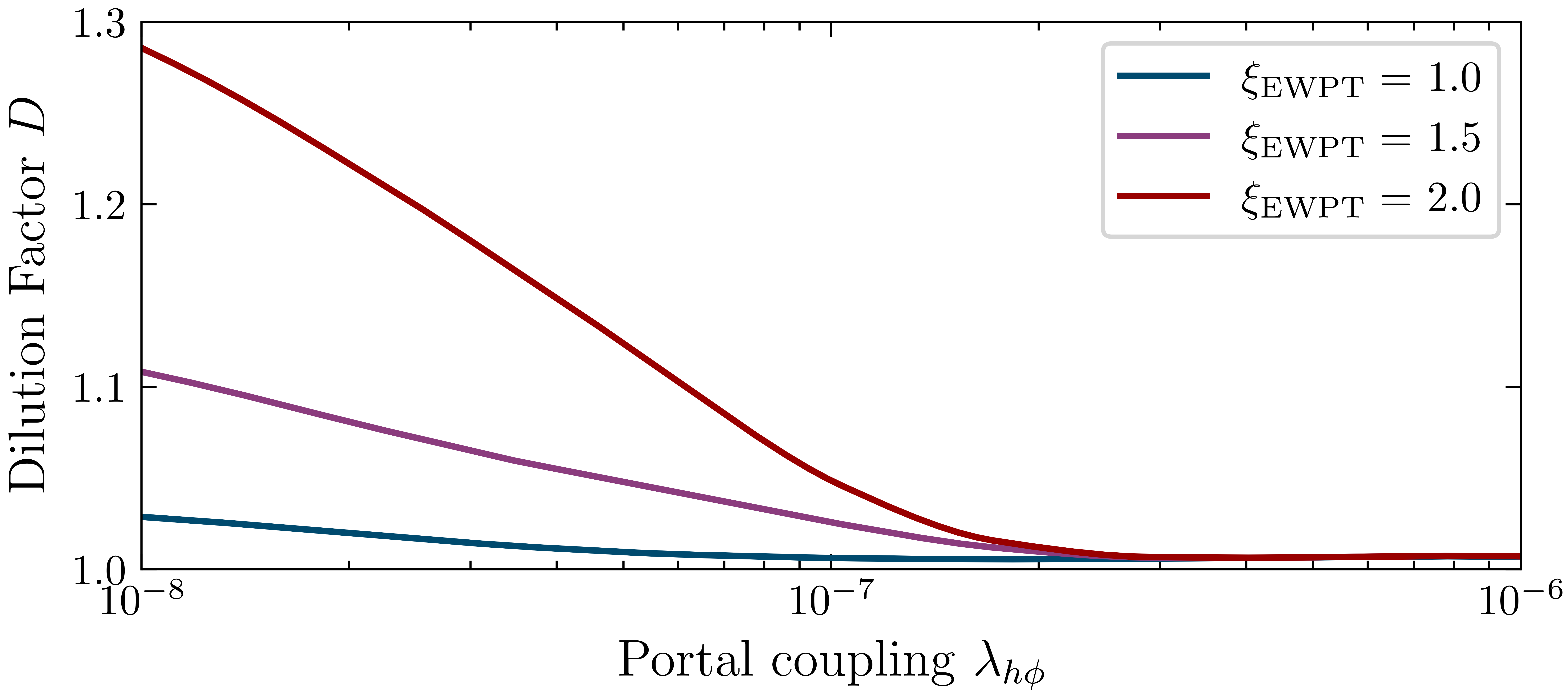


$$F(t) \equiv P(t-\tau) - P(t) > 0$$

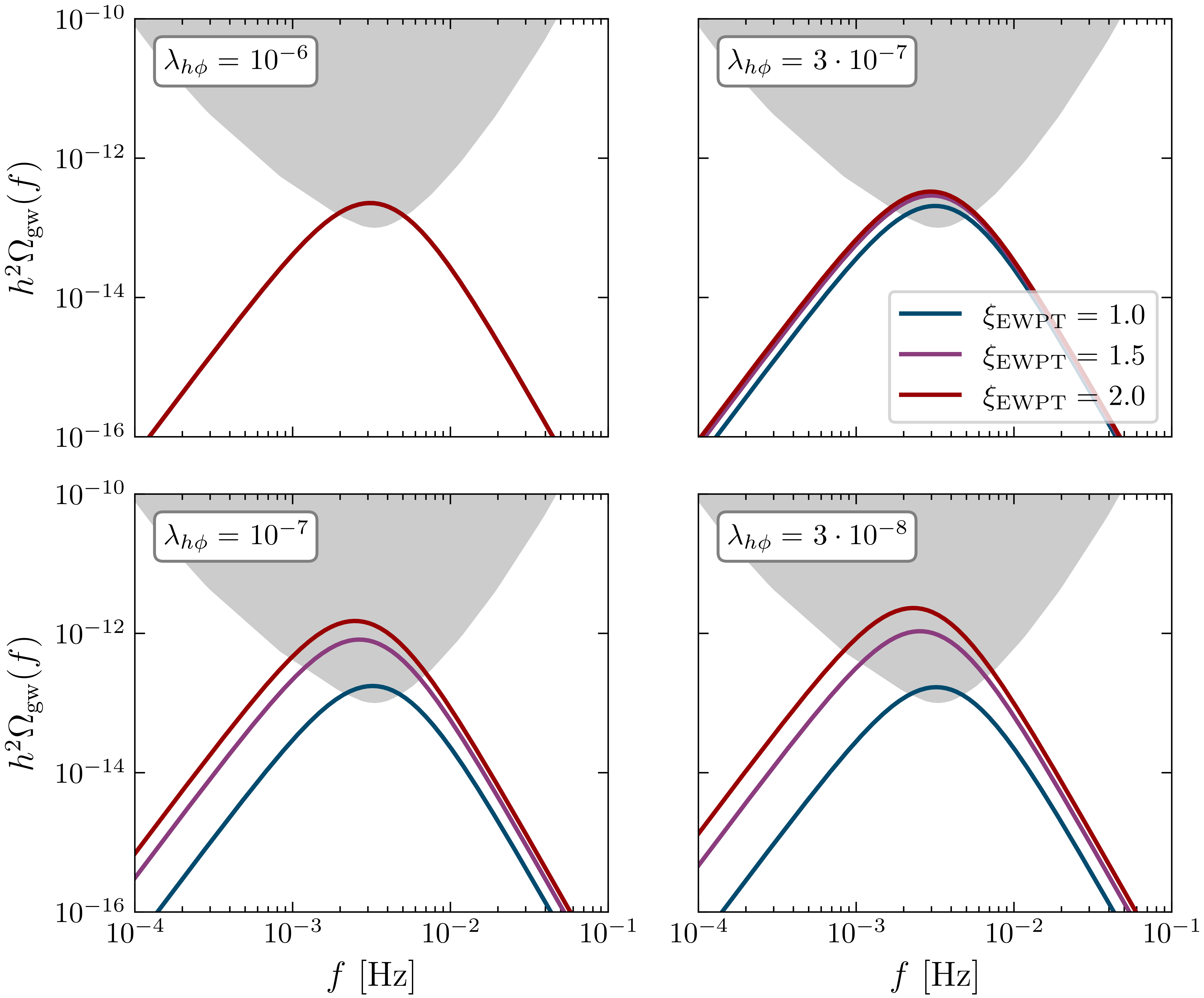
$$\begin{aligned} F(t) &\approx \exp\left(-0.34 e^{\beta(t-t_\mathrm{p}-\tau)}\right) - \exp\left(-0.34 e^{\beta(t-t_\mathrm{p})}\right) \\ &\approx \beta\tau e^{\beta(t-t_\mathrm{p})} \exp\left(-0.34 e^{\beta(t-t_\mathrm{p})}\right) \leq 0.37\beta\tau\,. \end{aligned} \tag{4.6}$$

Here, the last term follows by inserting the time at which $F(t)$ peaks, which is found to be $t \approx t_\mathrm{p} - 1.08/\beta$. Alternatively, one can interpret F as the volume fraction of a shell around the bubbles with the width of the mean free path of the particles that just entered the bubbles.

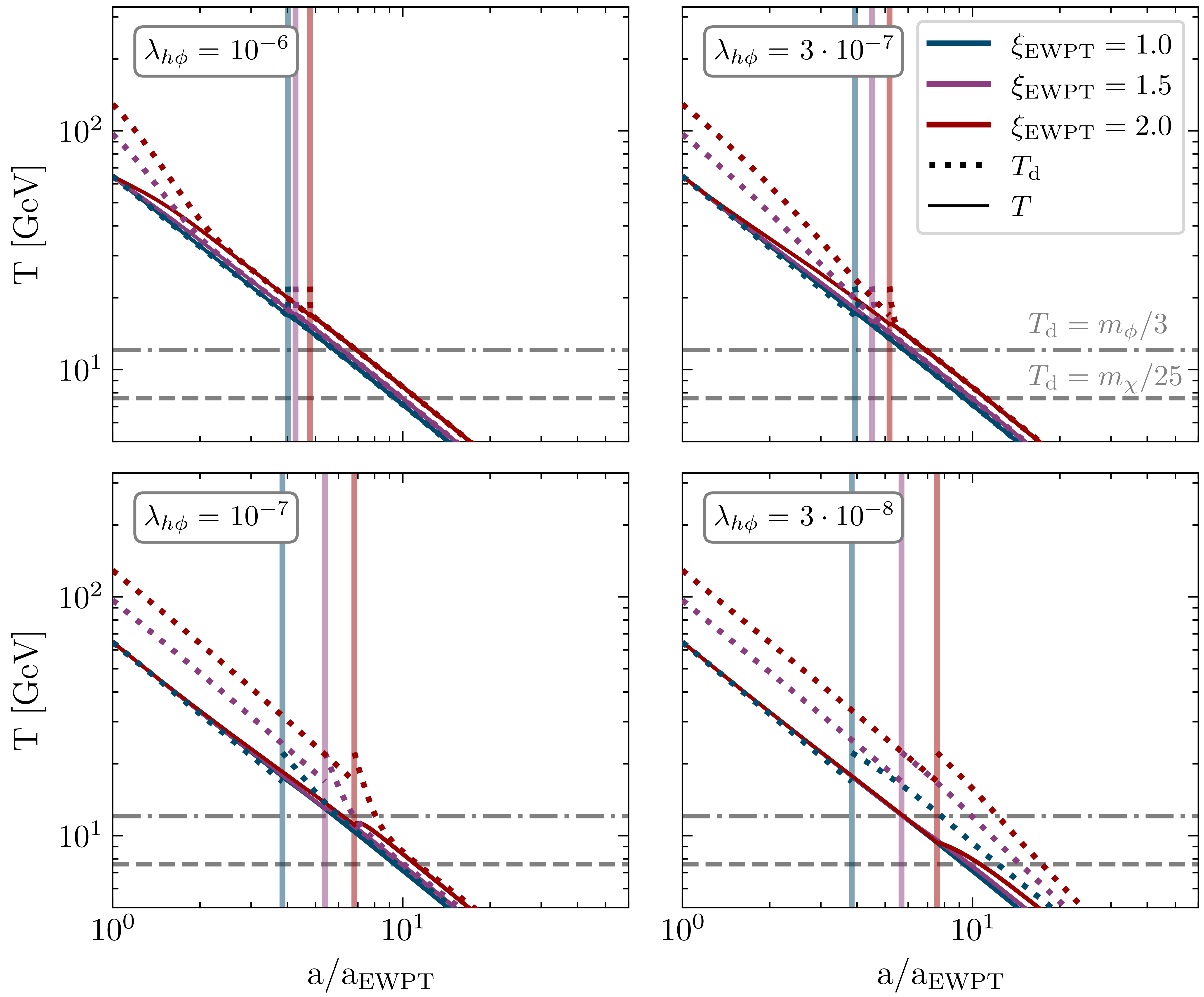
Dilution effect



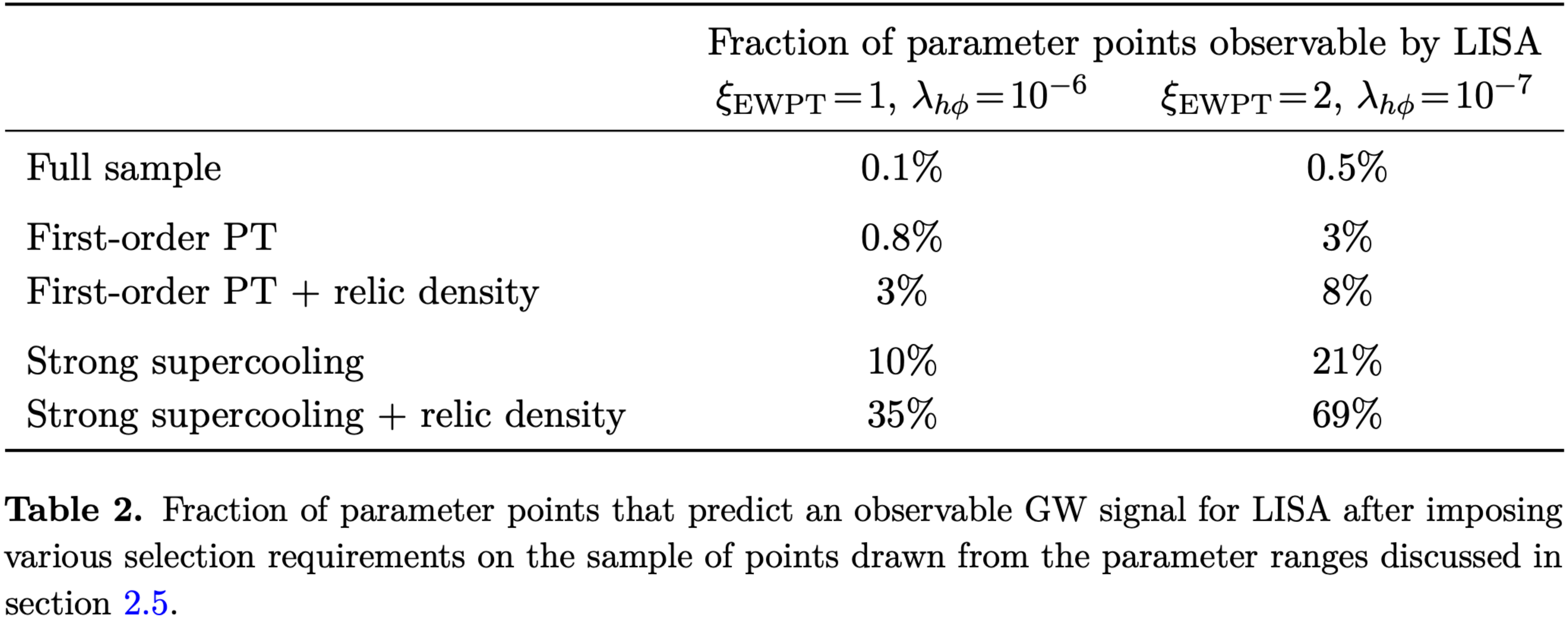
Effect of $\lambda_{h\phi}$ and ξ



Temperature evolution in the dark sector



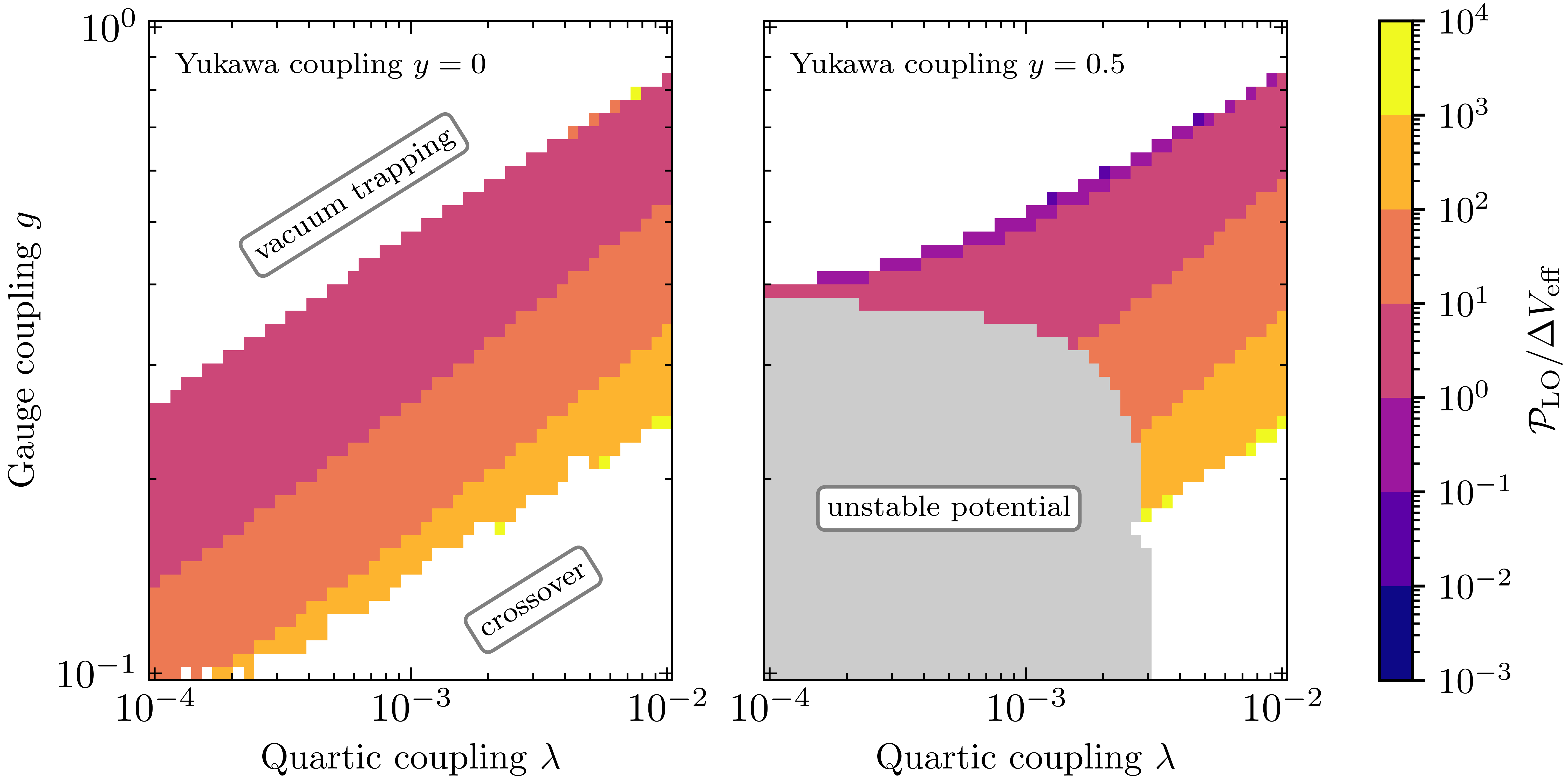
Detection probabilities



	Fraction of parameter points observable by LISA	
	$\xi_{\rm EWPT}=1,\ \lambda_{h\phi}=10^{-6}$	$\xi_{\rm EWPT}=2,\ \lambda_{h\phi}=10^{-7}$
Full sample	0.1%	0.5%
First-order PT	0.8%	3%
First-order PT + relic density	3%	8%
Strong supercooling	10%	21%
Strong supercooling + relic density	35%	69%

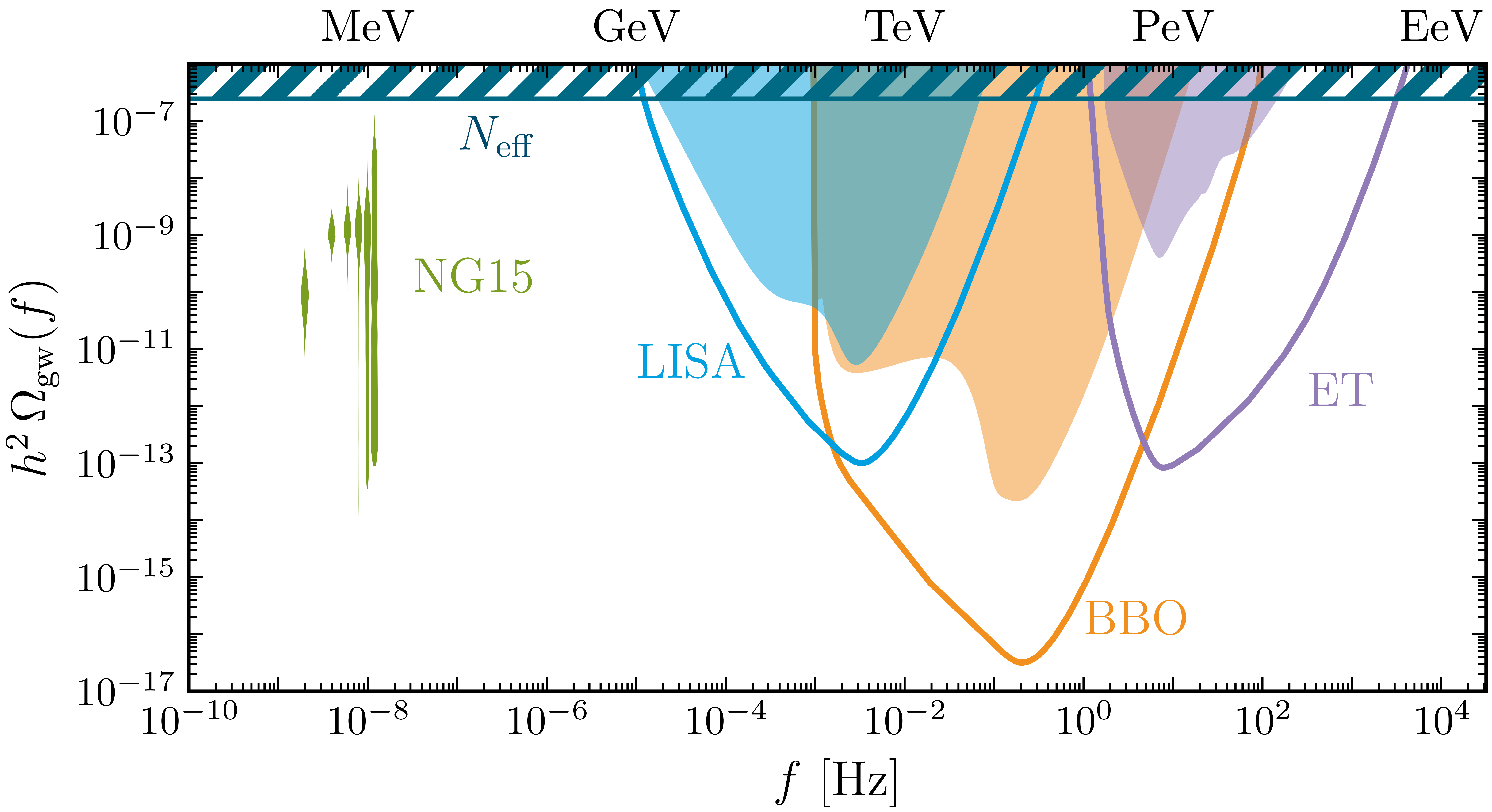
Table 2. Fraction of parameter points that predict an observable GW signal for LISA after imposing various selection requirements on the sample of points drawn from the parameter ranges discussed in section 2.5.

Bödeker-Moore criterion



$$\text{Bödeker-Moore criterion:} \quad \begin{cases} \Delta V_{\rm eff} > \mathcal{P}_{\rm LO} & \text{Relativistic bubble walls} \\ \Delta V_{\rm eff} < \mathcal{P}_{\rm LO} & \text{Non-relativistic bubble walls} \end{cases}$$

Sensitivity for cosmic GW backgrounds



Model details

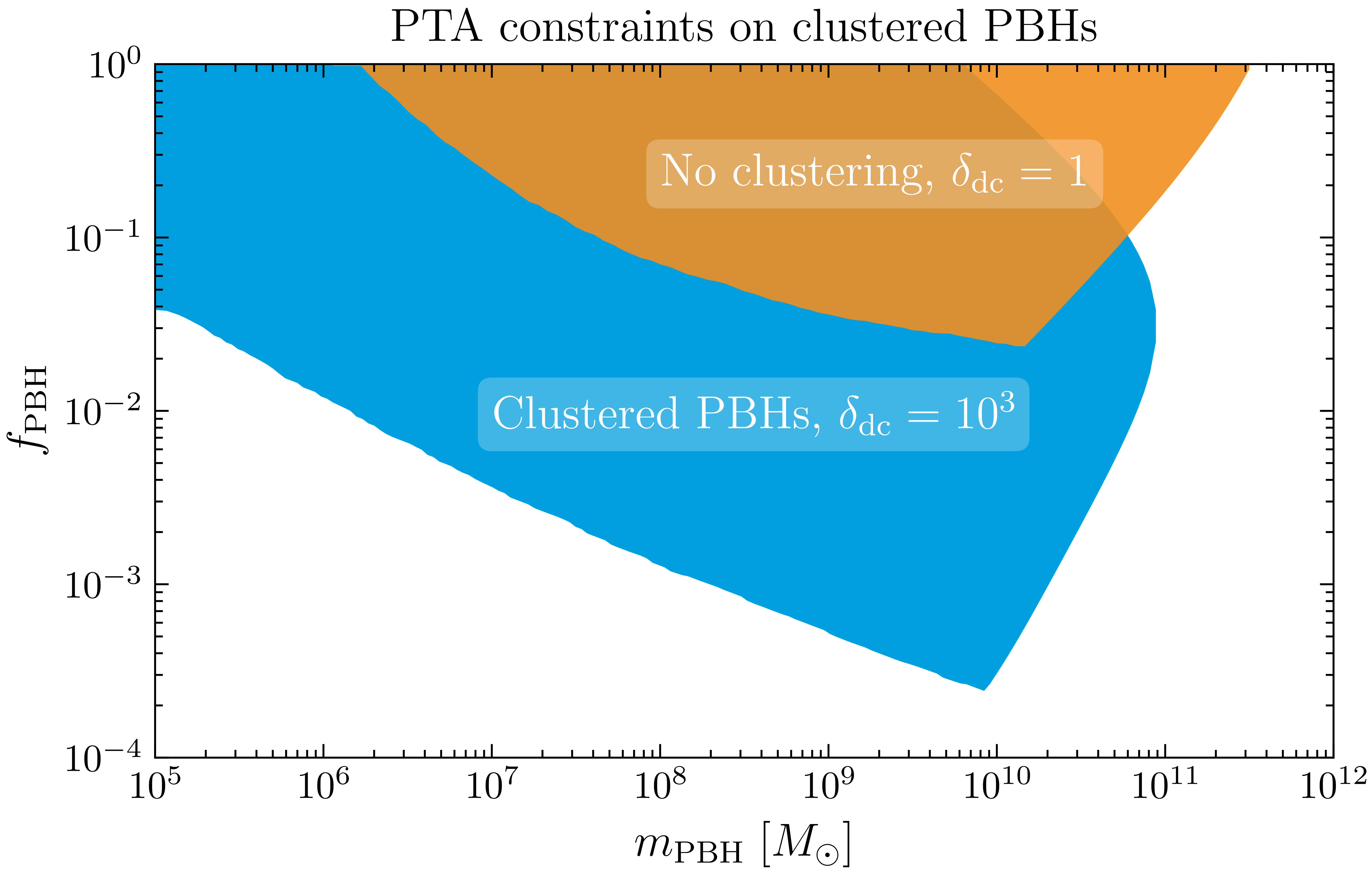
$$\begin{aligned}\mathcal{L} =& |D_\mu \Phi|^2 - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 \\ &+ \chi_L^\dagger i \not{D} \chi_L + \chi_R^\dagger i \not{D} \chi_R - y \Phi \chi_L^\dagger \chi_R - y \Phi^* \chi_R^\dagger \chi_L\end{aligned}$$

The tree-level scalar potential of our model has a minimum at $v_\phi = \pm\sqrt{\mu^2/\lambda}$. One can hence expand the complex field as $\Phi = (v_\phi + \phi + i\varphi)/\sqrt{2}$, where ϕ and φ are real scalar fields. In addition, the chiral fermions χ_L and χ_R can be written as a Dirac fermion χ. The Lagragian in eq. (2.1) can thus be re-written as

$$\begin{aligned}\mathcal{L} =& \frac{1}{2}\partial_\mu \phi \partial^\mu \phi + \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} - \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_{A'}^2 A'^2_\mu \\ & - g A'_\mu [\varphi \partial^\mu \phi - \phi \partial^\mu \varphi - v_\phi \partial^\mu \varphi] + \frac{g^2}{2} \phi^2 A'^2_\mu + \frac{g^2}{2} \varphi^2 A'^2_\mu + g^2 v_\phi \phi A'^2_\mu \\ & - \lambda v_\phi \phi^3 - \lambda v_\phi \varphi^2 \phi - \frac{\lambda}{4} \phi^2 \varphi^2 - \frac{\lambda}{4} \phi^4 - \frac{\lambda}{4} \varphi^4 \\ & + i \bar{\chi} \not{\partial} \chi - m_\chi \bar{\chi} \chi + \frac{g}{2} \bar{\chi} \not{A}' \gamma^5 \chi - \frac{y}{\sqrt{2}} \phi \bar{\chi} \chi + i \frac{y}{\sqrt{2}} \varphi \bar{\chi} \gamma^5 \chi \,,\end{aligned}$$

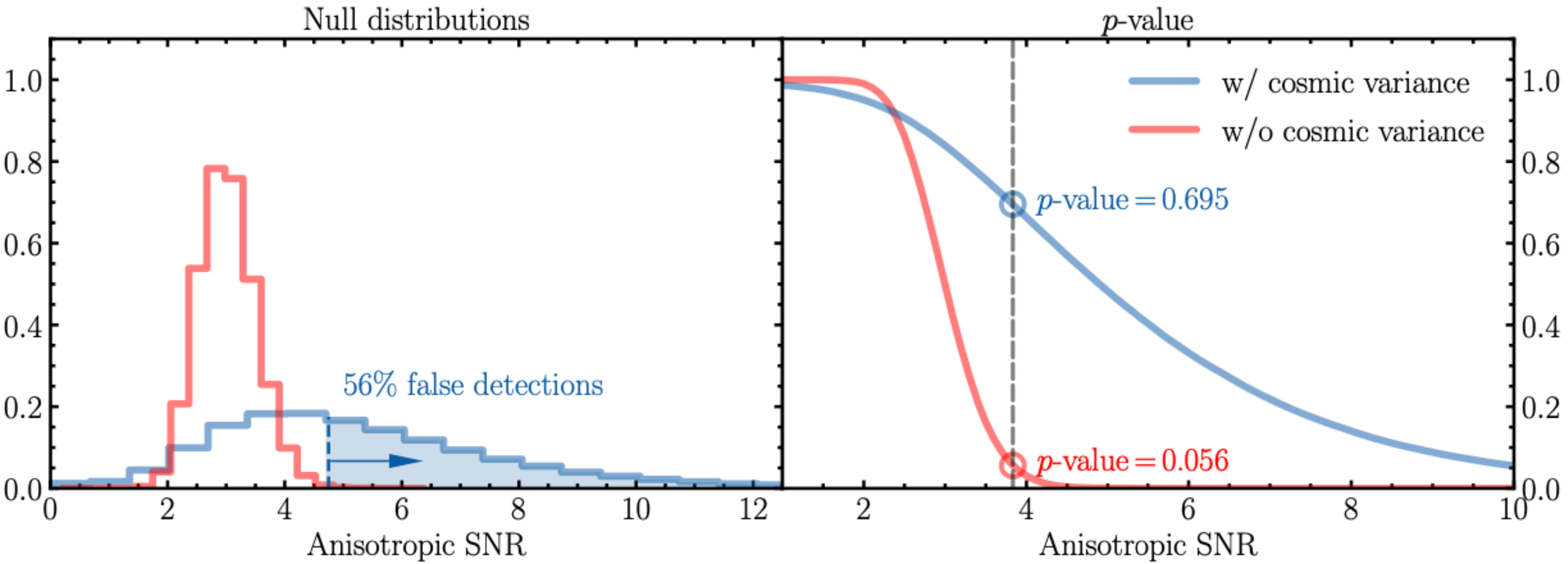
$$m_\phi^2 = -\mu^2 + 3\lambda v_\phi^2 = 2\lambda v_\phi^2, \quad m_\varphi^2 = 0, \quad m_{A'}^2 = g^2 v_\phi^2, \quad m_\chi^2 = \frac{y^2}{2} v_\phi^2.$$

In any case: Novel PBH bounds



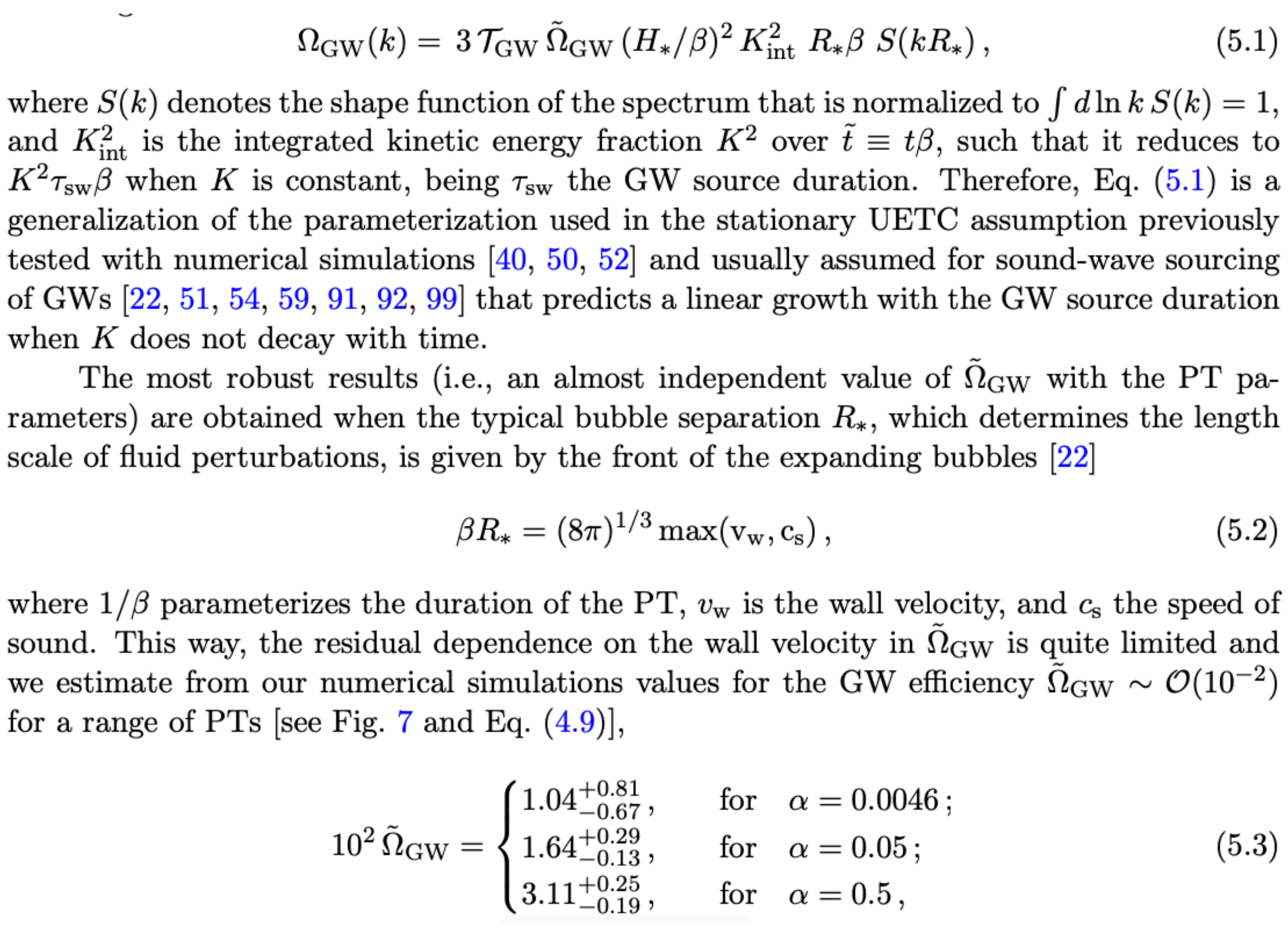
In the shaded regions, the GW signal exceeds the measured PTA signal.

The impact of cosmic variance on PTA anisotropy searches



2408.07741, Konstandin, Lemke, Mitridate, Perboni

Gravitational waves from decaying sources in strong PTs



$$\Omega_{\rm GW}(k) = 3\,\mathcal{T}_{\rm GW}\,\tilde{\Omega}_{\rm GW}\,(H_*/\beta)^2\,K^2_{\rm int}\;R_*\beta\;S(kR_*)\,, \tag{5.1}$$

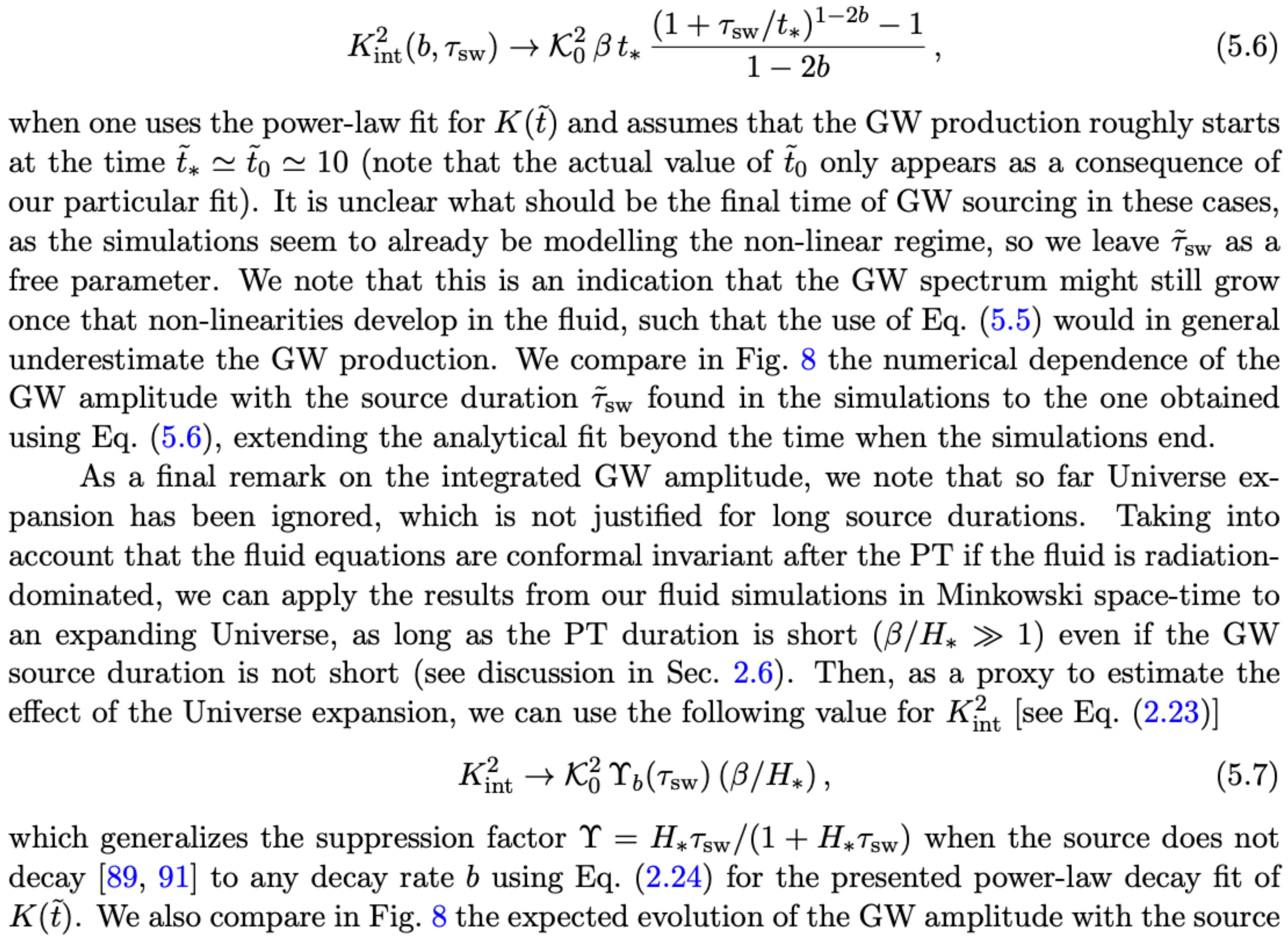
where $S(k)$ denotes the shape function of the spectrum that is normalized to $\int d\ln k\,S(k) = 1$, and $K^2_{\rm int}$ is the integrated kinetic energy fraction K^2 over $\tilde{t} \equiv t\beta$, such that it reduces to $K^2\tau_{\rm sw}\beta$ when K is constant, being $\tau_{\rm sw}$ the GW source duration. Therefore, Eq. (5.1) is a generalization of the parameterization used in the stationary UETC assumption previously tested with numerical simulations [40, 50, 52] and usually assumed for sound-wave sourcing of GWs [22, 51, 54, 59, 91, 92, 99] that predicts a linear growth with the GW source duration when K does not decay with time.

The most robust results (i.e., an almost independent value of $\tilde{\Omega}_{\rm GW}$ with the PT parameters) are obtained when the typical bubble separation R_*, which determines the length scale of fluid perturbations, is given by the front of the expanding bubbles [22]

$$\beta R_* = (8\pi)^{1/3}\,\max({\rm v_w}, {\rm c_s})\,, \tag{5.2}$$

where $1/\beta$ parameterizes the duration of the PT, $v_{\rm w}$ is the wall velocity, and $c_{\rm s}$ the speed of sound. This way, the residual dependence on the wall velocity in $\tilde{\Omega}_{\rm GW}$ is quite limited and we estimate from our numerical simulations values for the GW efficiency $\tilde{\Omega}_{\rm GW} \sim \mathcal{O}(10^{-2})$ for a range of PTs [see Fig. 7 and Eq. (4.9)],

$$10^2\,\tilde{\Omega}_{\rm GW} = \begin{cases} 1.04^{+0.81}_{-0.67}\,, & \text{for} \quad \alpha = 0.0046\,; \\ 1.64^{+0.29}_{-0.13}\,, & \text{for} \quad \alpha = 0.05\,; \\ 3.11^{+0.25}_{-0.19}\,, & \text{for} \quad \alpha = 0.5\,, \end{cases} \tag{5.3}$$



$$K^2_{\rm int}(b, \tau_{\rm sw}) \to \mathcal{K}^2_0\,\beta\,t_*\,\frac{(1+\tau_{\rm sw}/t_*)^{1-2b} - 1}{1-2b}\,, \tag{5.6}$$

when one uses the power-law fit for $K(\tilde{t})$ and assumes that the GW production roughly starts at the time $\tilde{t}_* \simeq \tilde{t}_0 \simeq 10$ (note that the actual value of $\tilde{t}_0$ only appears as a consequence of our particular fit). It is unclear what should be the final time of GW sourcing in these cases, as the simulations seem to already be modelling the non-linear regime, so we leave $\tilde{\tau}_{\rm sw}$ as a free parameter. We note that this is an indication that the GW spectrum might still grow once that non-linearities develop in the fluid, such that the use of Eq. (5.5) would in general underestimate the GW production. We compare in Fig. 8 the numerical dependence of the GW amplitude with the source duration $\tilde{\tau}_{\rm sw}$ found in the simulations to the one obtained using Eq. (5.6), extending the analytical fit beyond the time when the simulations end.

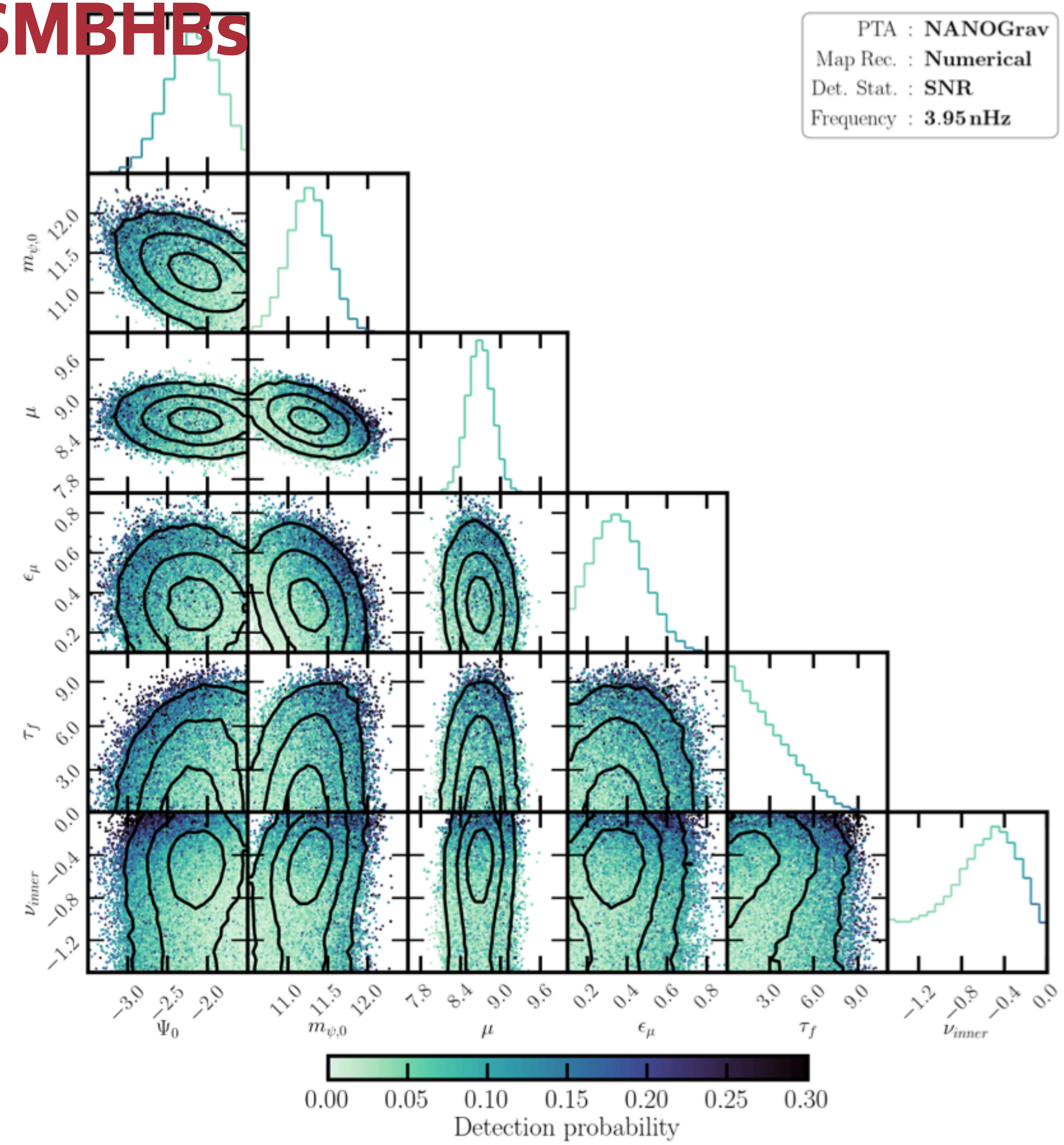
As a final remark on the integrated GW amplitude, we note that so far Universe expansion has been ignored, which is not justified for long source durations. Taking into account that the fluid equations are conformal invariant after the PT if the fluid is radiation-dominated, we can apply the results from our fluid simulations in Minkowski space-time to an expanding Universe, as long as the PT duration is short ($\beta/H_* \gg 1$) even if the GW source duration is not short (see discussion in Sec. 2.6). Then, as a proxy to estimate the effect of the Universe expansion, we can use the following value for $K^2_{\rm int}$ [see Eq. (2.23)]

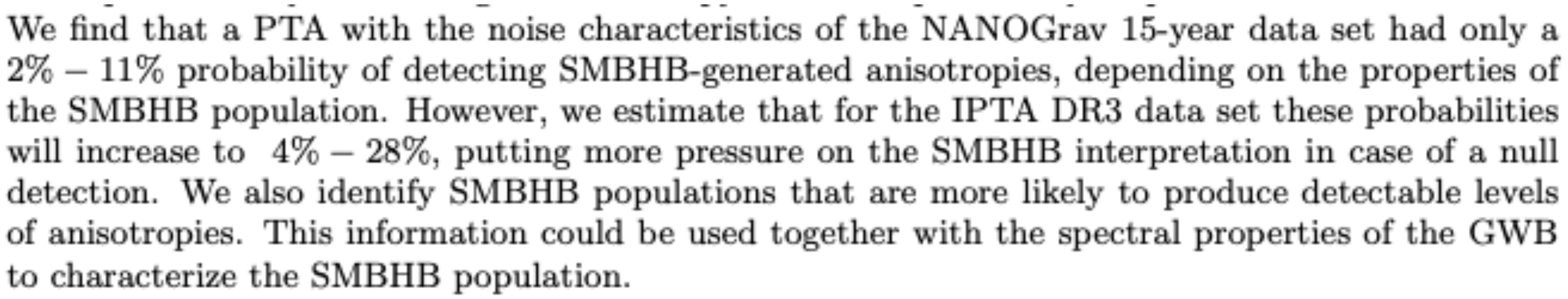
$$K^2_{\rm int} \to \mathcal{K}^2_0\,\Upsilon_b(\tau_{\rm sw})\,(\beta/H_*)\,, \tag{5.7}$$

which generalizes the suppression factor $\Upsilon = H_*\tau_{\rm sw}/(1 + H_*\tau_{\rm sw})$ when the source does not decay [89, 91] to any decay rate b using Eq. (2.24) for the presented power-law decay fit of $K(\tilde{t})$. We also compare in Fig. 8 the expected evolution of the GW amplitude with the source

2409.03651, Caprini, Jinno, Konstandin, Roper Pol, Rubira, Stomberg

Detecting GW anisotropies from SMBHBs

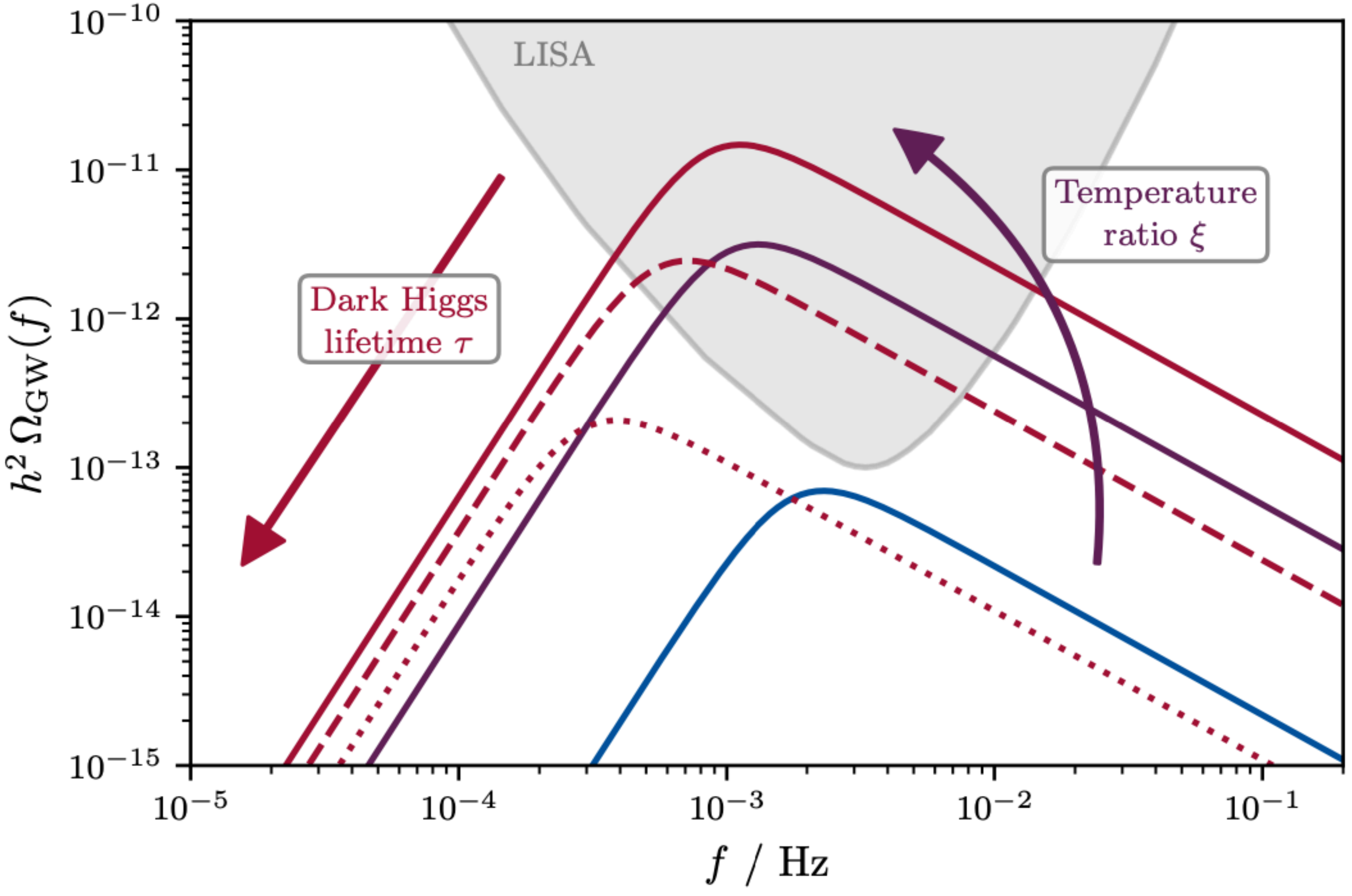




We find that a PTA with the noise characteristics of the NANOGrav 15-year data set had only a 2% – 11% probability of detecting SMBHB-generated anisotropies, depending on the properties of the SMBHB population. However, we estimate that for the IPTA DR3 data set these probabilities will increase to 4% – 28%, putting more pressure on the SMBHB interpretation in case of a null detection. We also identify SMBHB populations that are more likely to produce detectable levels of anisotropies. This information could be used together with the spectral properties of the GWB to characterize the SMBHB population.

2407.08705, Lemke, Mitridate, Gersbach

Turn up the volume



2109.06208, Ertas, Kahlhöfer, CT

Turn up the volume

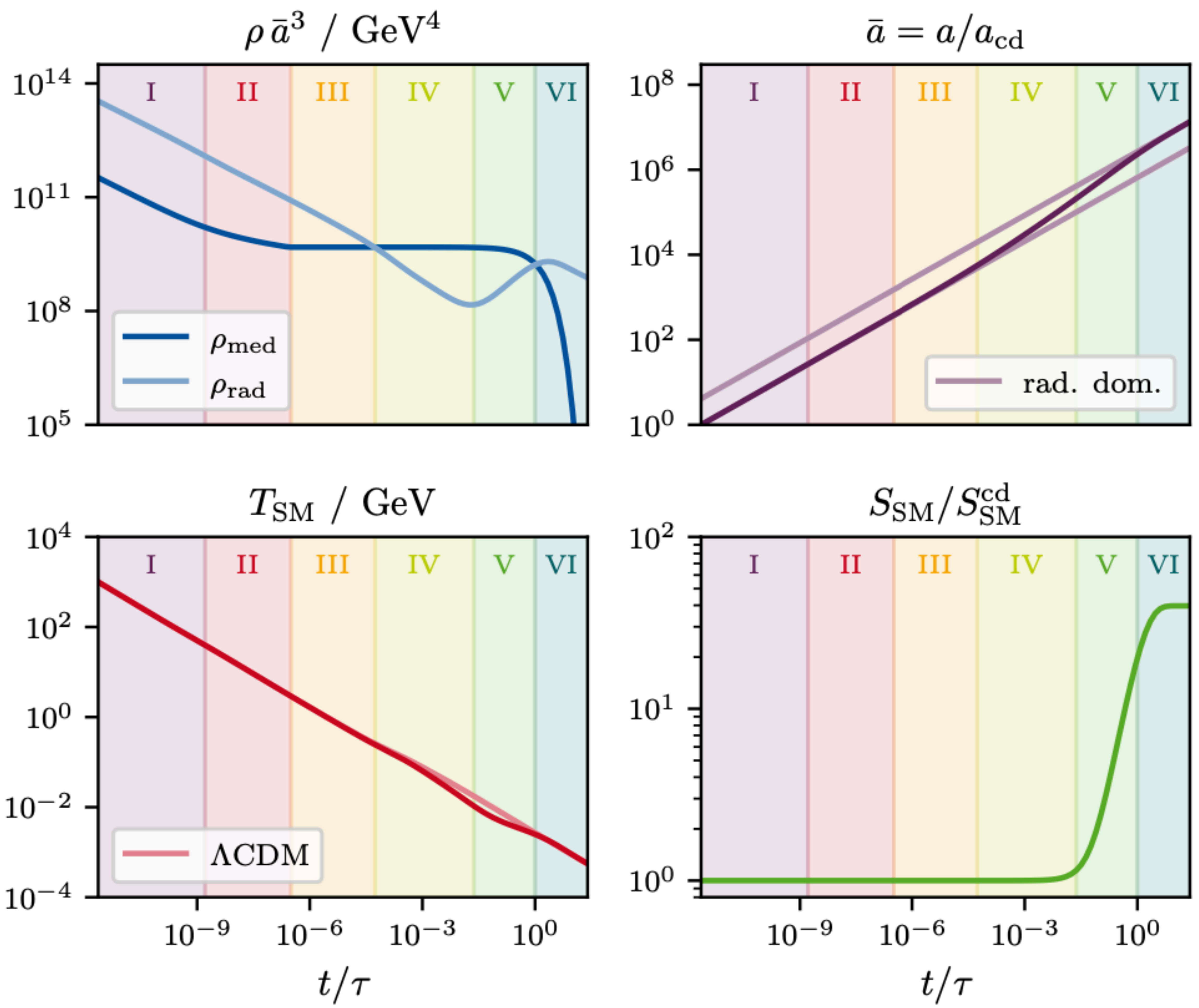
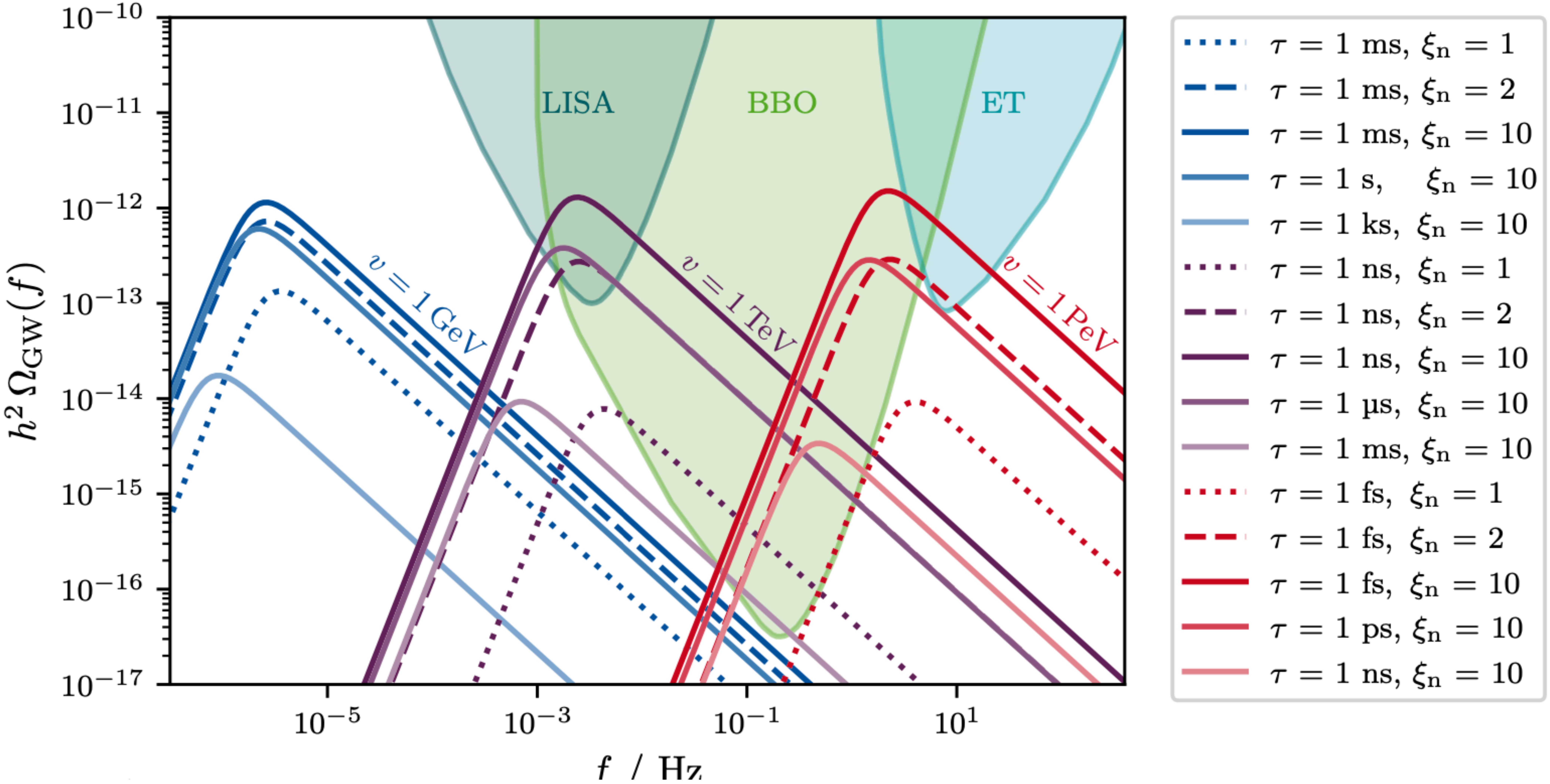


Figure 5. Time evolution of the comoving energy densities $\rho\,\bar{a}^3$ of the mediator species and the SM radiation (top-left), the normalized scale factor $\bar{a}$ (top-right), the temperature T_{SM} of the SM bath (bottom-left), as well as its entropy $S_{\mathrm{SM}}/S_{\mathrm{SM}}^{\mathrm{cd}}$ (bottom-right). The evolution can be divided into the following phases: relativistic mediator (I), cannibalism (II), non-relativistic mediator (III), early matter domination (IV), entropy injection (V), and decay (VI). See text for details.

2109.06208, Ertas, Kahlhöfer, CT

Turn up the volume



2109.06208, Ertas, Kahlhöfer, CT

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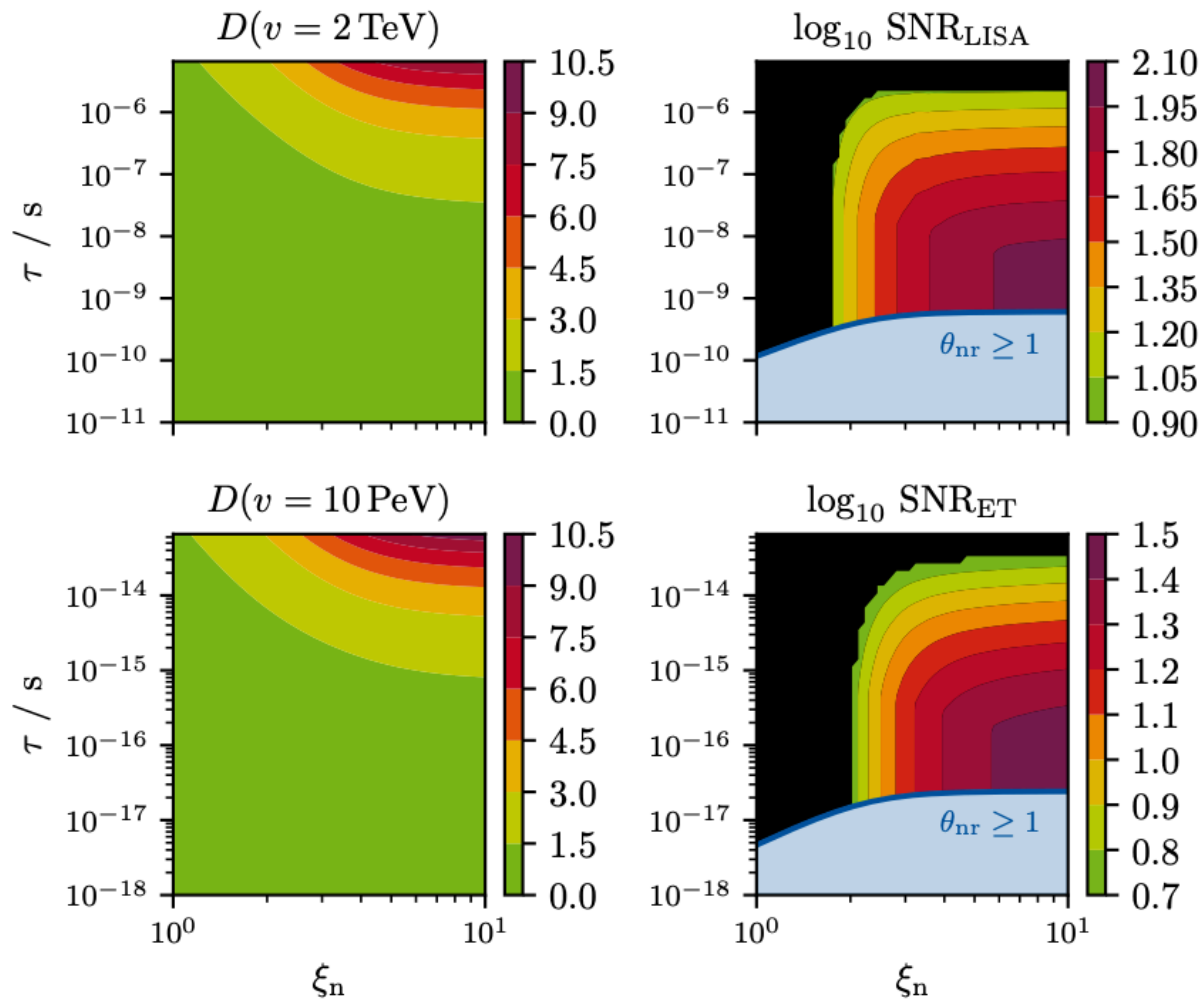
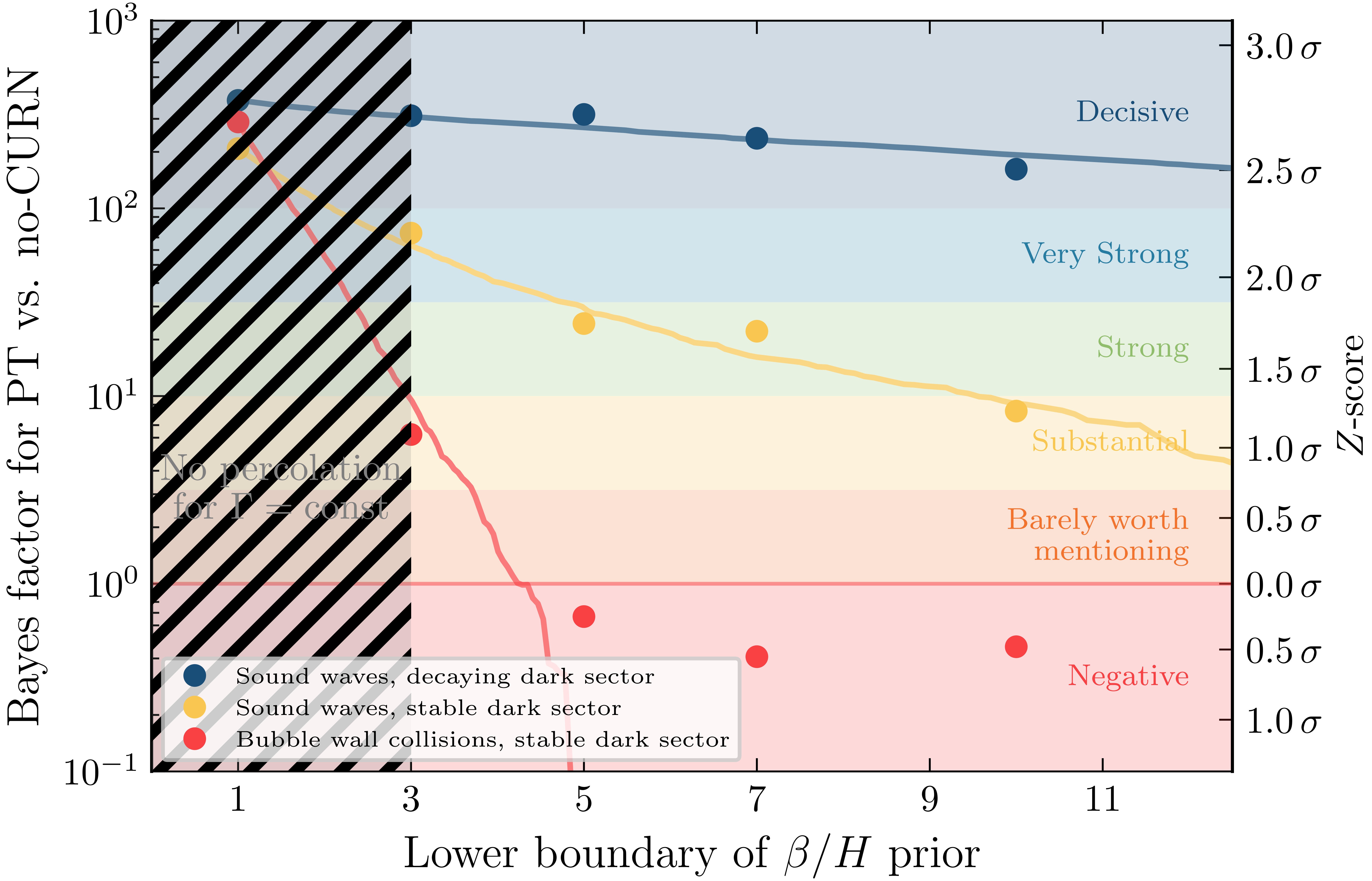


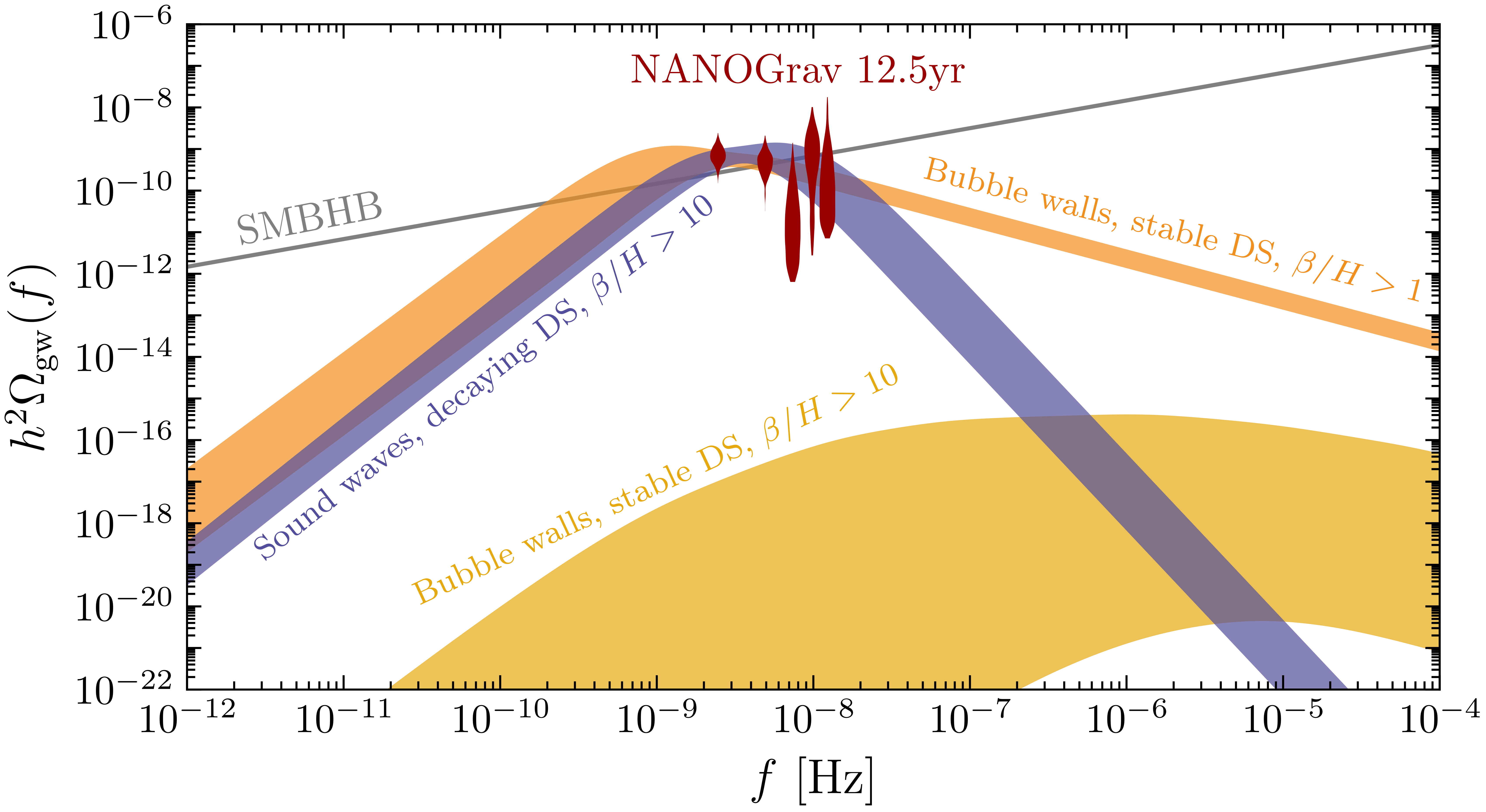
2109.06208, Ertas, Kahlhöfer, CT

Do PTAs observe a dark sector phase transition?



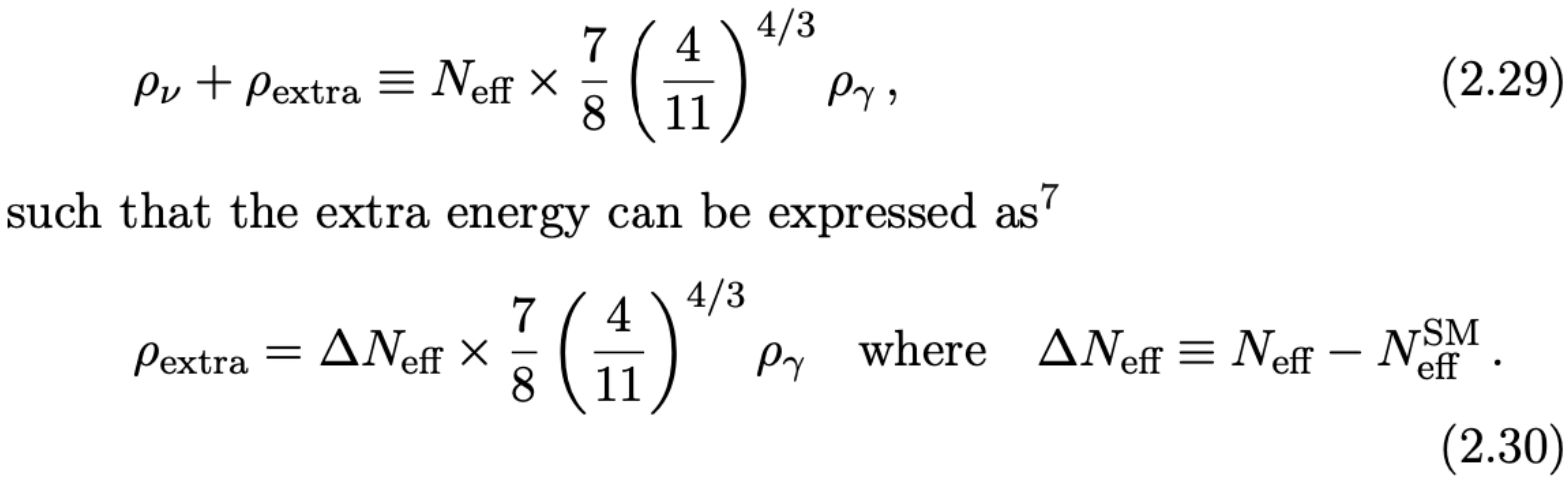
2306.09411, Bringmann, Depta, Konstandin, Schmidt-Hoberg, CT

Do PTAs observe a dark sector phase transition?



2306.09411, Bringmann, Depta, Konstandin, Schmidt-Hoberg, CT

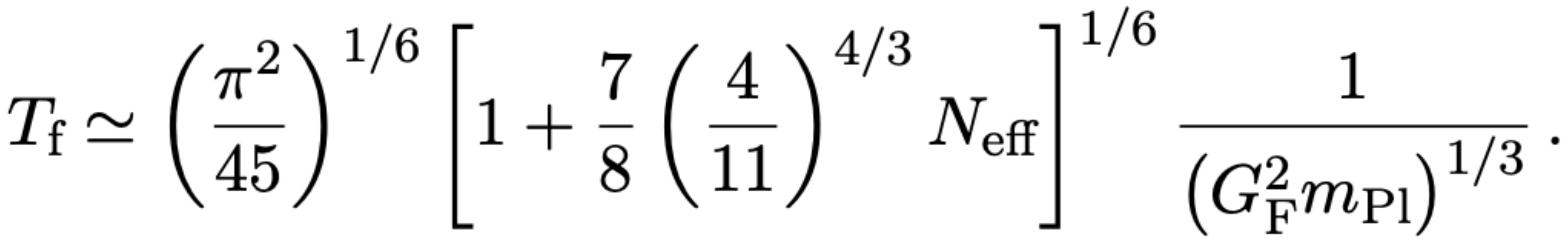
Number of effective degrees of freedom at BBN



$$\rho_\nu + \rho_{\rm extra} \equiv N_{\rm eff} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma \,, \tag{2.29}$$

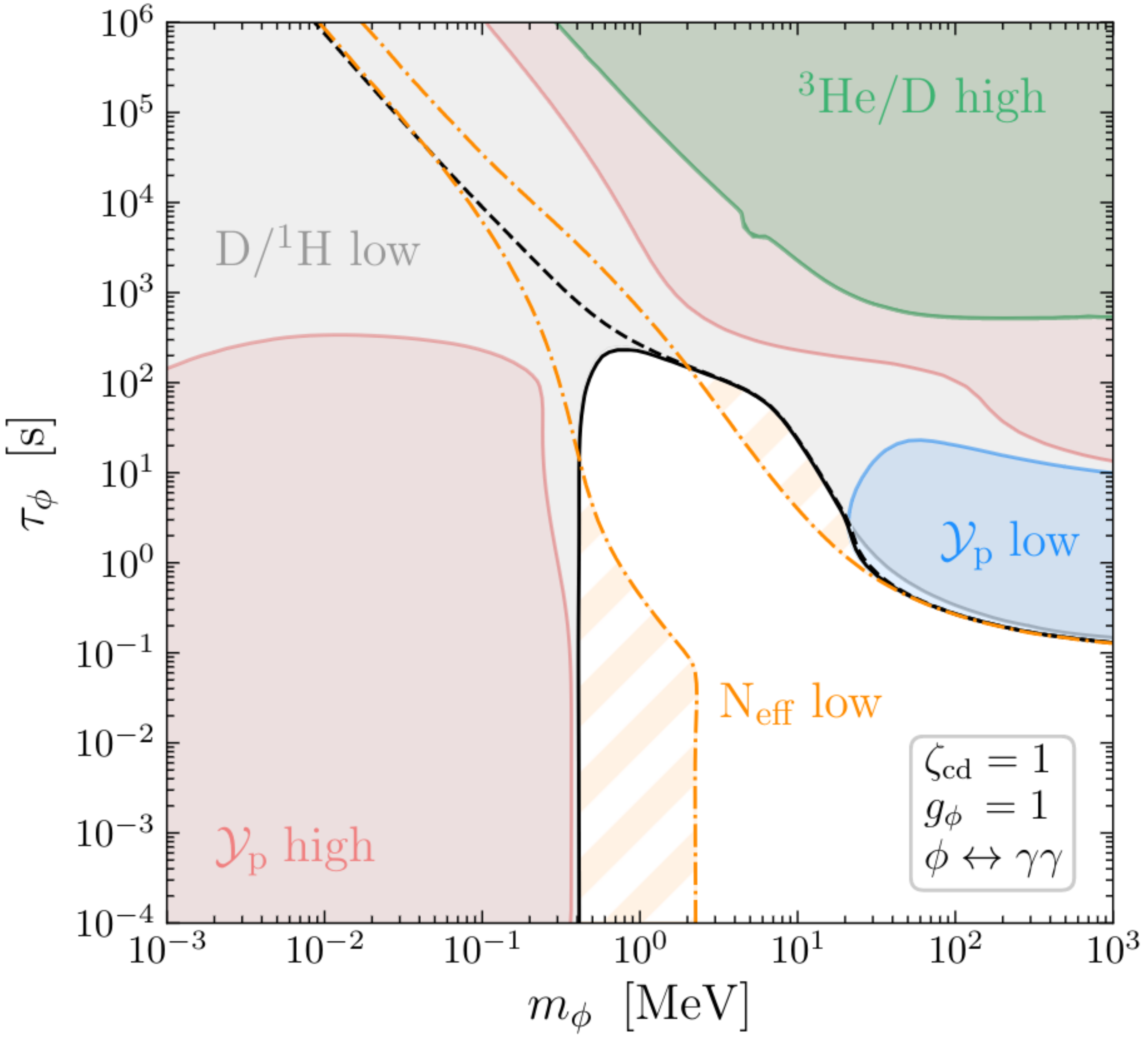
such that the extra energy can be expressed as[7]

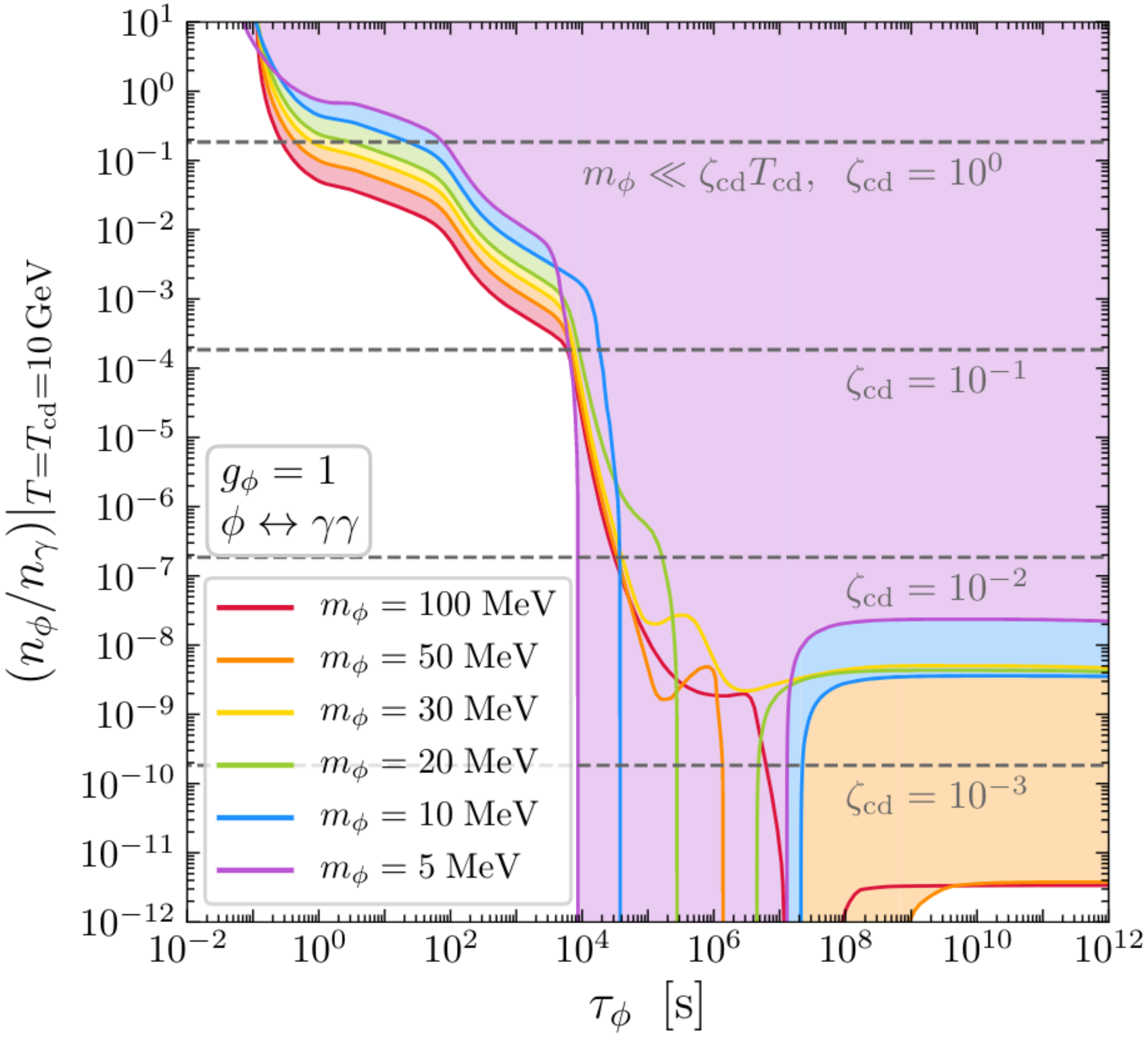
$$\rho_{\rm extra} = \Delta N_{\rm eff} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma \quad \text{where} \quad \Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM} \,. \tag{2.30}$$



$$T_{\rm f} \simeq \left(\frac{\pi^2}{45}\right)^{1/6} \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]^{1/6} \frac{1}{(G_{\rm F}^2 m_{\rm Pl})^{1/3}} \,.$$

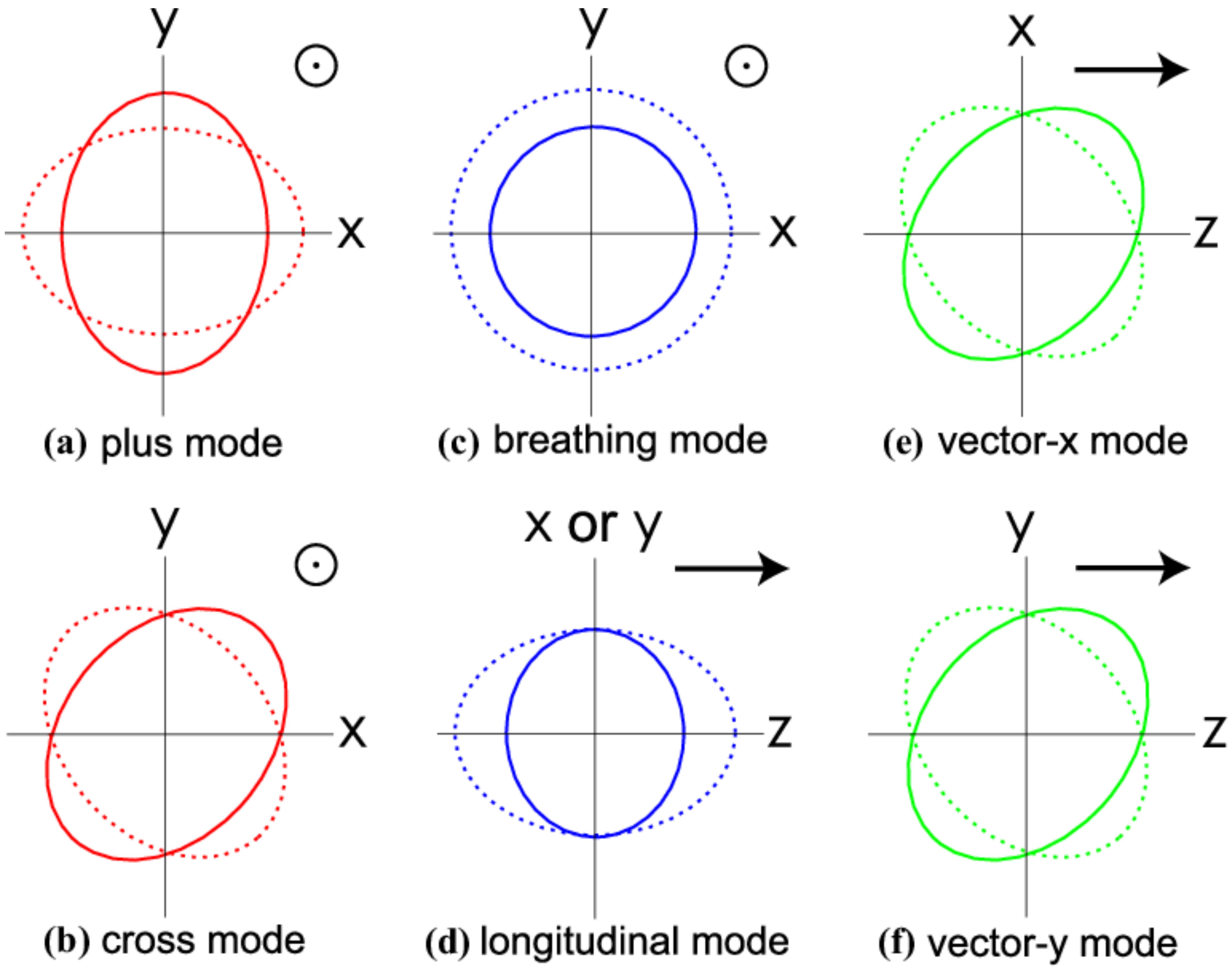
BBN limits on MeV-scale electromagnetic scalar decays





[Paul Frederik Depta]

Polarization of a GW



(a) plus mode (c) breathing mode (e) vector-x mode

(b) cross mode (d) longitudinal mode (f) vector-y mode

[Stephen Taylor et al., 2019]

Cosmological perturbation theory

$$\Delta\Phi - 3\mathcal{H}\left(\Phi' - \mathcal{H}\Psi\right) = -2\frac{a^2\delta\rho}{m_{\mathrm{Pl}}^2}\,, \quad \Delta\left(\Phi + \Psi\right) = -\frac{a^2\Delta\sigma}{m_{\mathrm{Pl}}^2}\,,$$

$$\Delta\Xi_i = -\frac{2a^2 S_i}{m_{\mathrm{Pl}}^2} \quad \text{and} \quad \left(h_{ij}^{\mathrm{TT}}\right)'' + 2\mathcal{H}\left(h_{ij}^{\mathrm{TT}}\right)' - \Delta h_{ij}^{\mathrm{TT}} = \frac{2a^2\sigma_{ij}^{\mathrm{TT}}}{m_{\mathrm{Pl}}^2}\,.$$

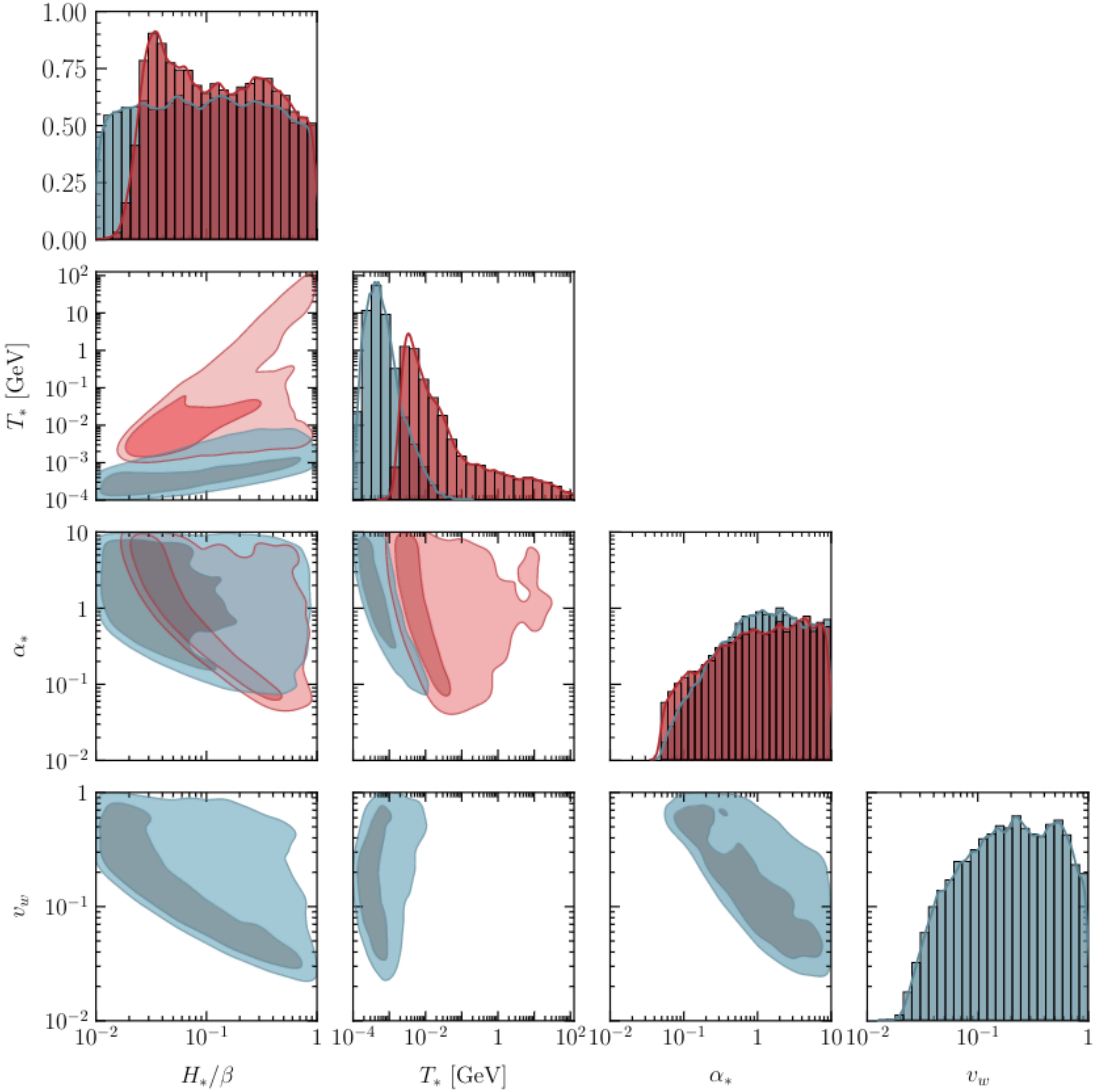
Conversion of different GW spectra

$$h^2\Omega_{\rm gw}(f) = \frac{4\pi^2}{3H_{100}^2} f^3 S_h(f) = \frac{2\pi^2}{3H_{100}^2} f^2 h_{\rm c}^2(f)$$

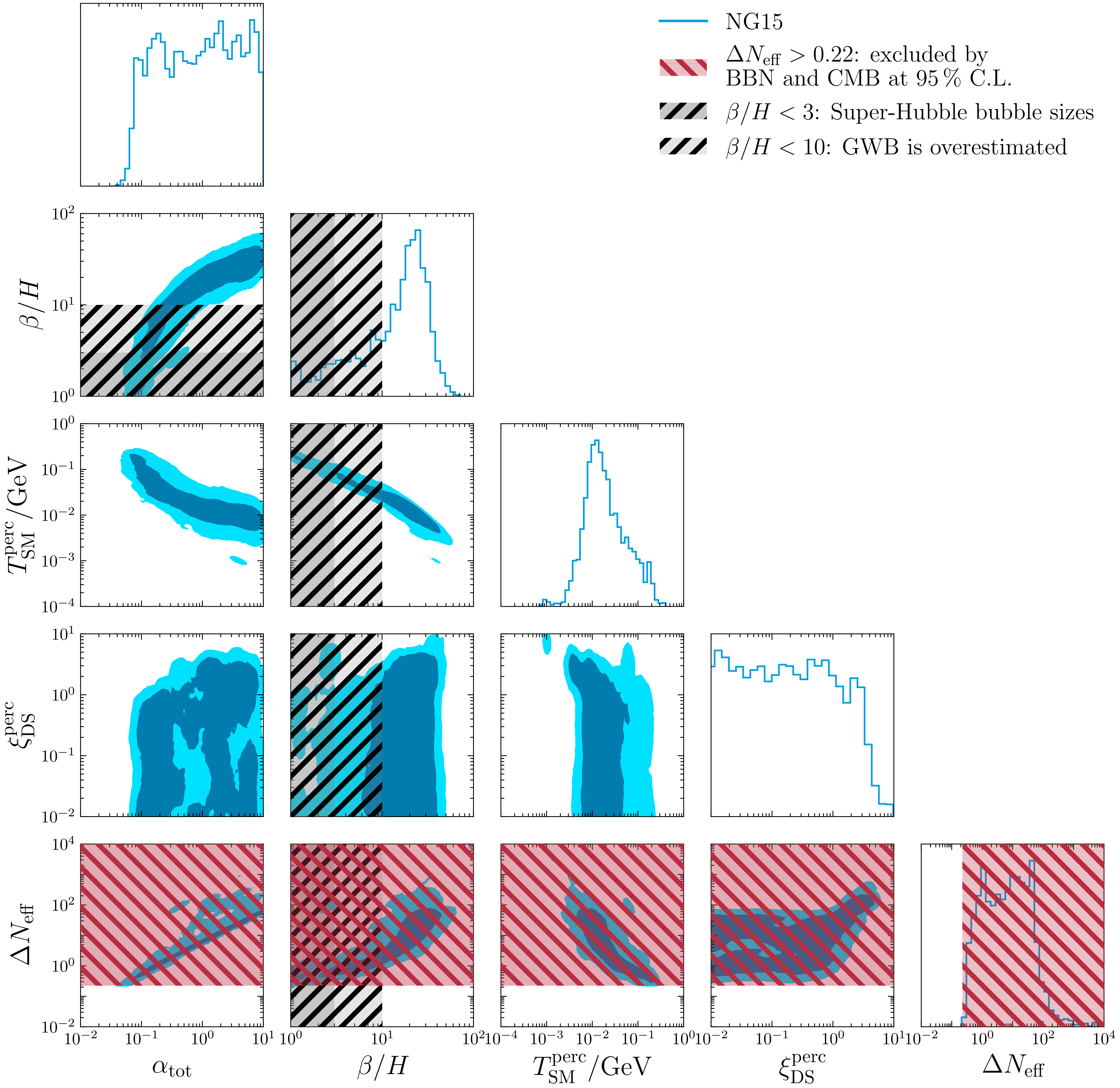
$$S_h(f) \simeq 10^{-36} \left(\frac{\rm Hz}{f}\right)^3 \frac{h^2\Omega_{\rm gw}(f)}{\rm Hz}$$

$$h_{\rm c}(f) \simeq 10^{-18} \left(\frac{\rm Hz}{f}\right) \sqrt{h^2\Omega_{\rm gw}(f)}$$

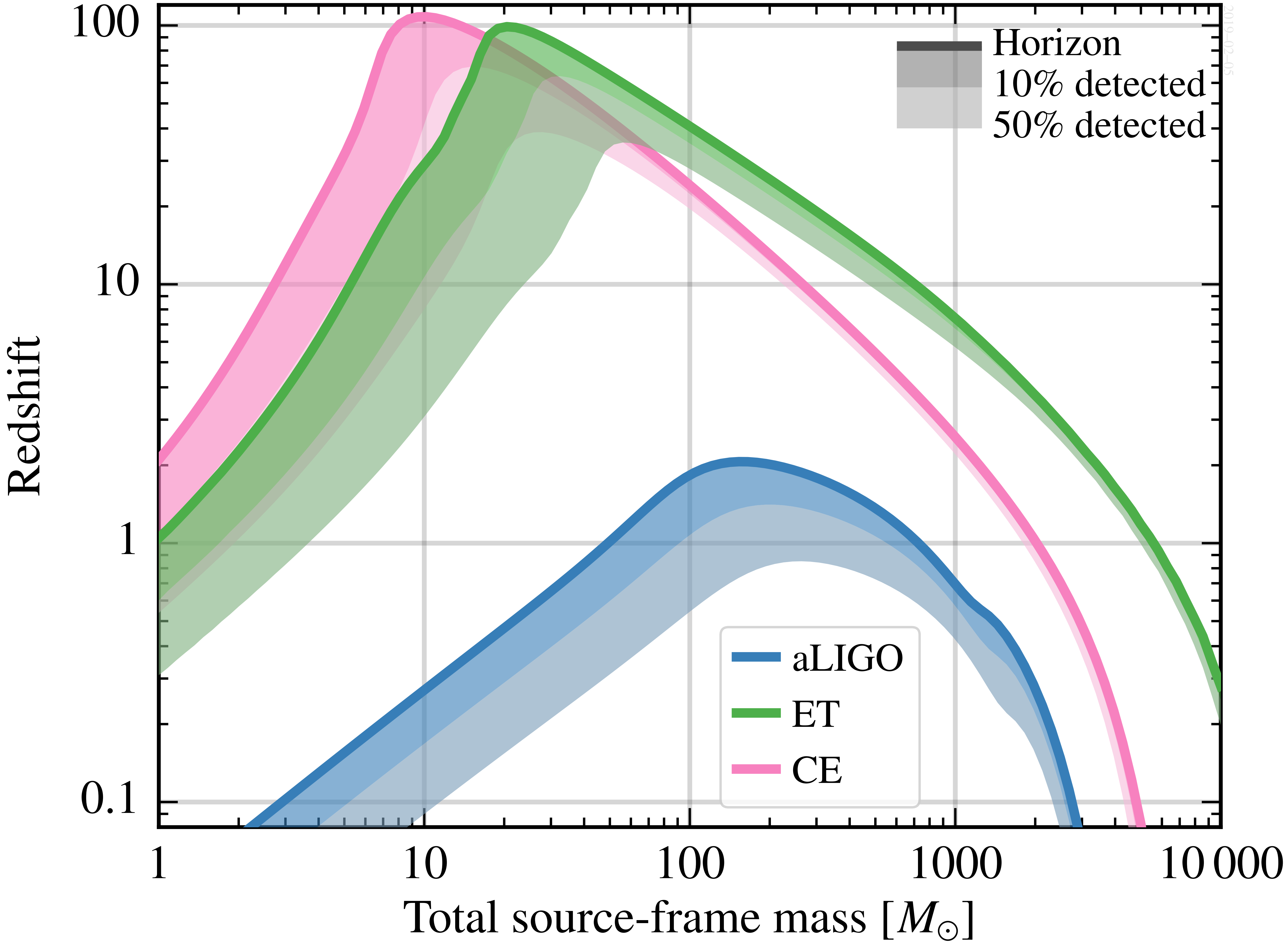
NANOGrav 15yr new physics analysis



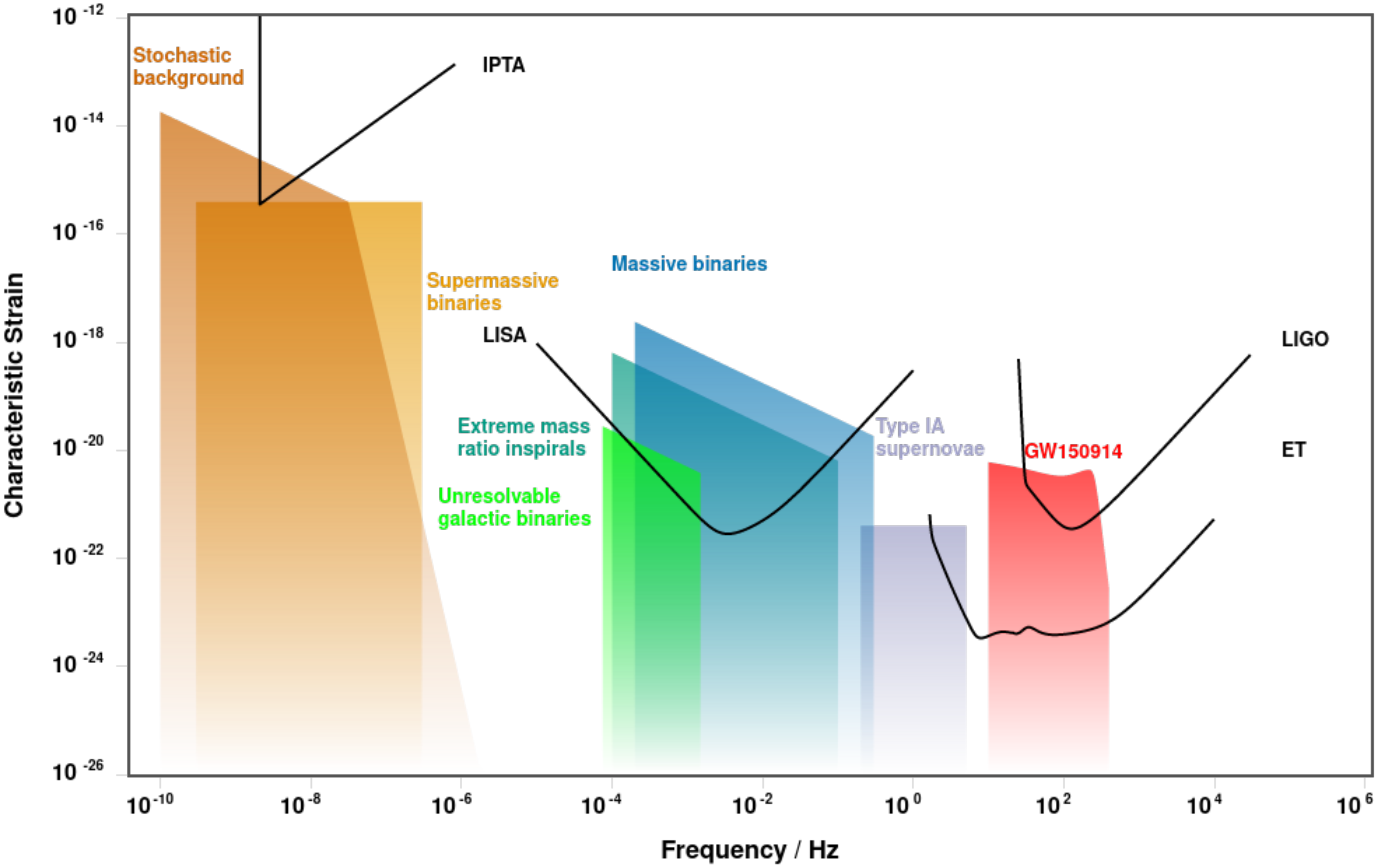
NANOGrav 15yr with BBN and CMB limits



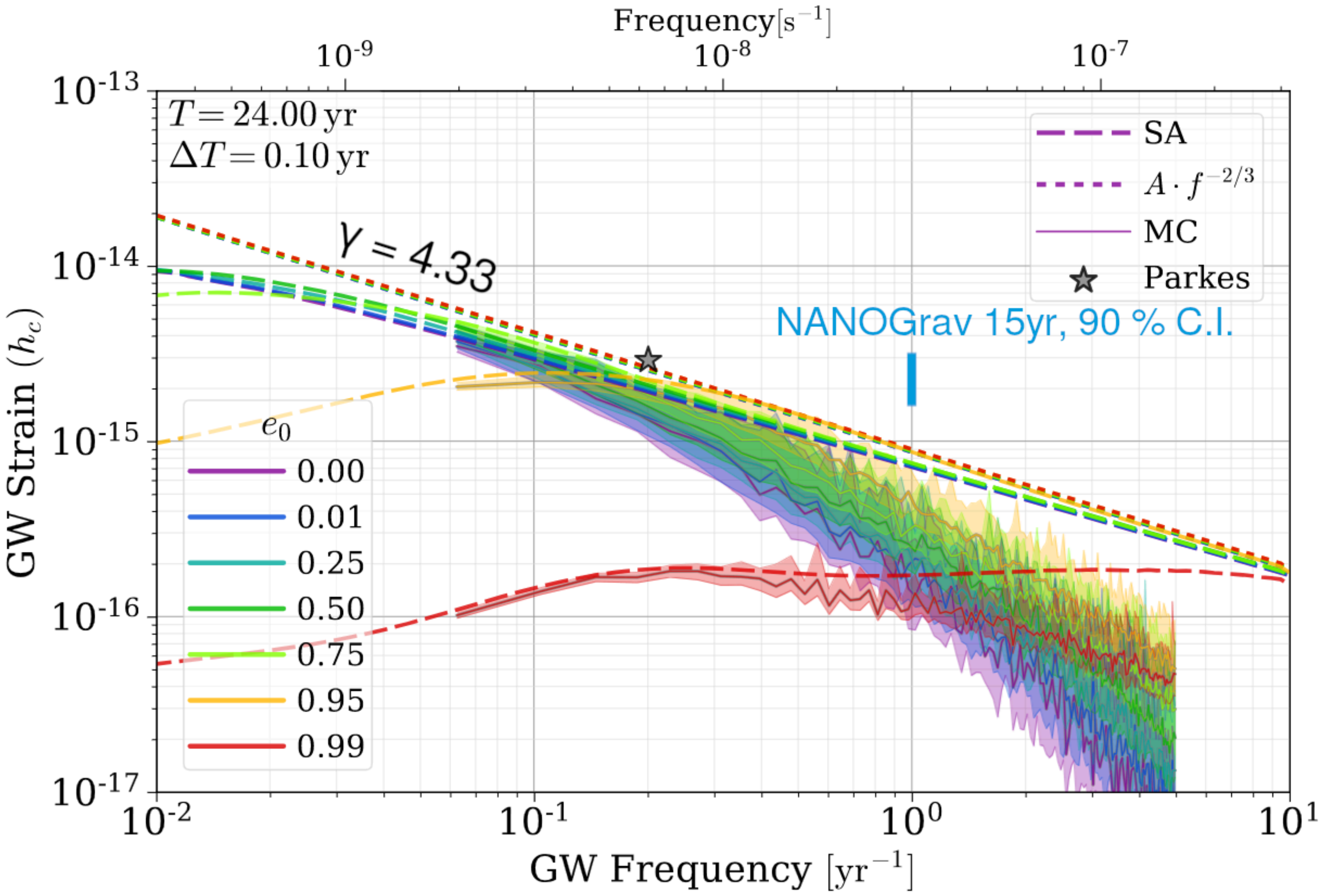
Einstein Telescope science case



GW spectrum in characteristic strain

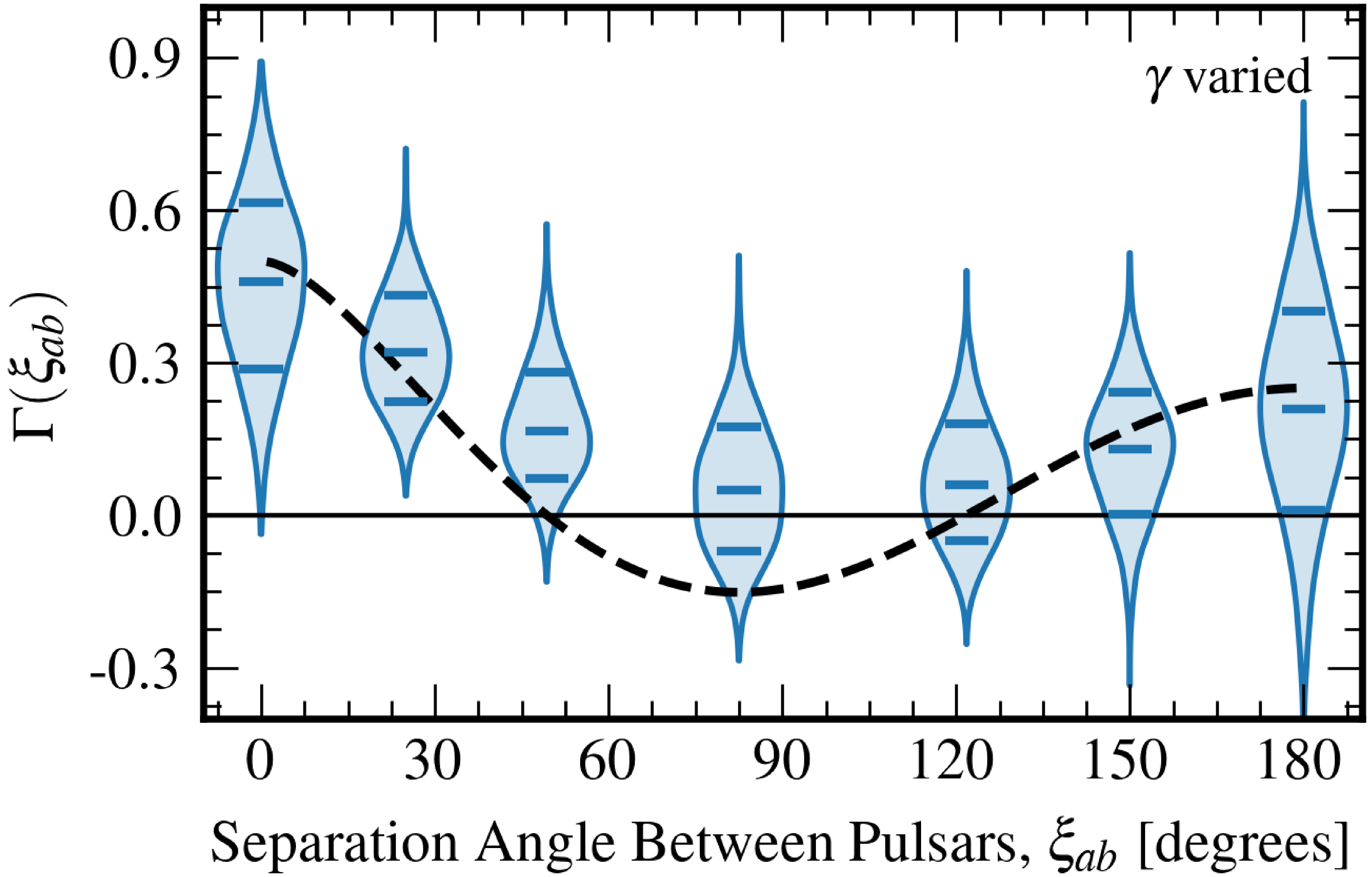


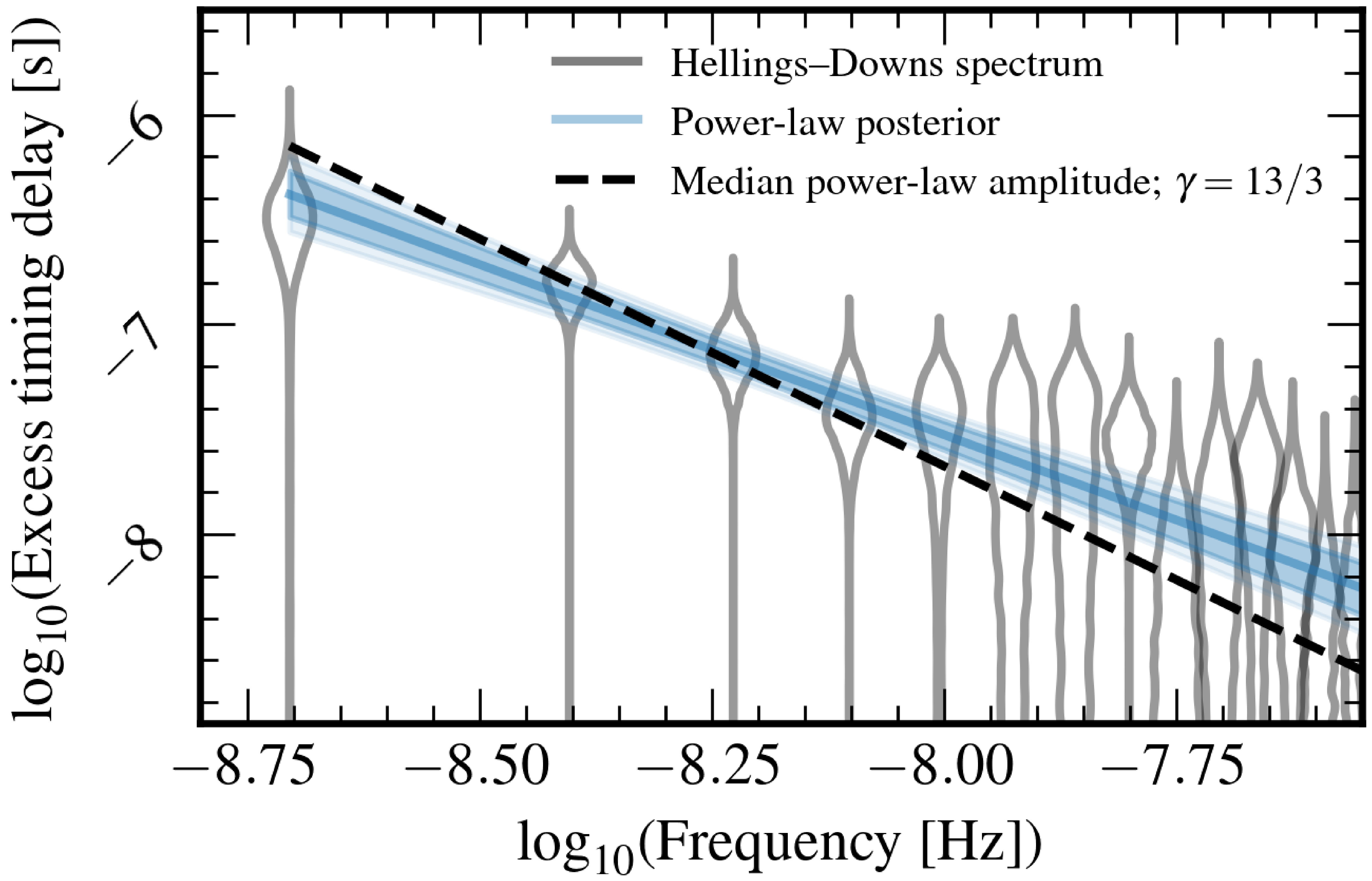
Influence of eccentricity on SMBHB signals



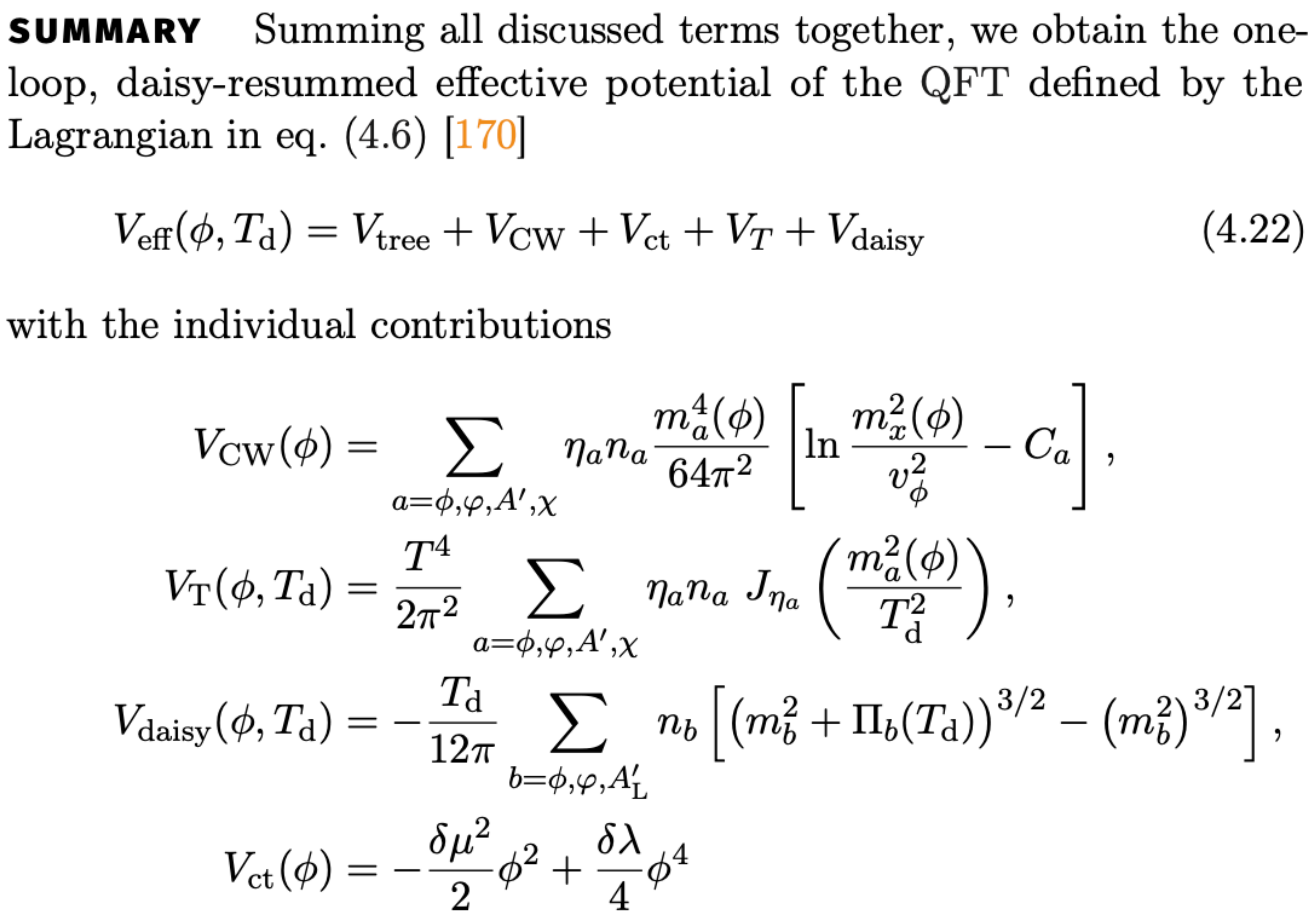
[Adapted from: Kelley+, 1702.02180]

NANOGrav 15yr data analysis





Daisy-improved effective potential

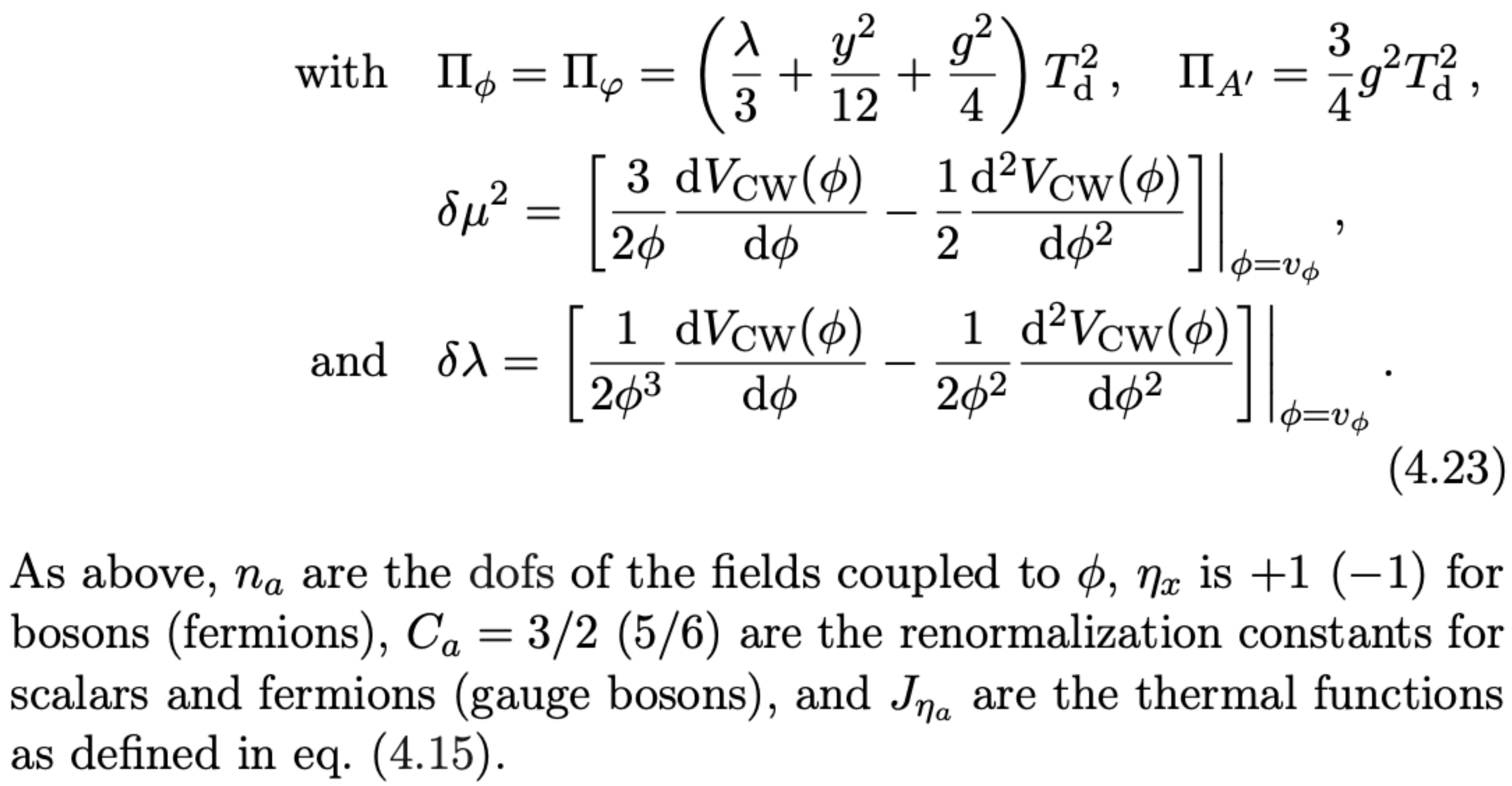


SUMMARY Summing all discussed terms together, we obtain the one-loop, daisy-resummed effective potential of the QFT defined by the Lagrangian in eq. (4.6) [170]

$$V_{\text{eff}}(\phi, T_{\text{d}}) = V_{\text{tree}} + V_{\text{CW}} + V_{\text{ct}} + V_T + V_{\text{daisy}} \tag{4.22}$$

with the individual contributions

$$\begin{aligned} V_{\text{CW}}(\phi) &= \sum_{a=\phi,\varphi,A',\chi} \eta_a n_a \frac{m_a^4(\phi)}{64\pi^2} \left[\ln \frac{m_x^2(\phi)}{v_\phi^2} - C_a \right], \\ V_{\text{T}}(\phi, T_{\text{d}}) &= \frac{T^4}{2\pi^2} \sum_{a=\phi,\varphi,A',\chi} \eta_a n_a \; J_{\eta_a} \left(\frac{m_a^2(\phi)}{T_{\text{d}}^2} \right), \\ V_{\text{daisy}}(\phi, T_{\text{d}}) &= -\frac{T_{\text{d}}}{12\pi} \sum_{b=\phi,\varphi,A'_{\text{L}}} n_b \left[\left(m_b^2 + \Pi_b(T_{\text{d}}) \right)^{3/2} - \left(m_b^2 \right)^{3/2} \right], \\ V_{\text{ct}}(\phi) &= -\frac{\delta\mu^2}{2}\phi^2 + \frac{\delta\lambda}{4}\phi^4 \end{aligned}$$



$$\begin{aligned} \text{with} \quad \Pi_\phi = \Pi_\varphi &= \left(\frac{\lambda}{3} + \frac{y^2}{12} + \frac{g^2}{4} \right) T_{\text{d}}^2 , \quad \Pi_{A'} = \frac{3}{4} g^2 T_{\text{d}}^2 , \\ \delta\mu^2 &= \left[\frac{3}{2\phi} \frac{\text{d}V_{\text{CW}}(\phi)}{\text{d}\phi} - \frac{1}{2} \frac{\text{d}^2 V_{\text{CW}}(\phi)}{\text{d}\phi^2} \right] \Bigg|_{\phi=v_\phi} , \\ \text{and} \quad \delta\lambda &= \left[\frac{1}{2\phi^3} \frac{\text{d}V_{\text{CW}}(\phi)}{\text{d}\phi} - \frac{1}{2\phi^2} \frac{\text{d}^2 V_{\text{CW}}(\phi)}{\text{d}\phi^2} \right] \Bigg|_{\phi=v_\phi} . \end{aligned} \tag{4.23}$$

As above, n_a are the dofs of the fields coupled to ϕ, η_x is $+1$ (-1) for bosons (fermions), $C_a = 3/2$ ($5/6$) are the renormalization constants for scalars and fermions (gauge bosons), and J_{η_a} are the thermal functions as defined in eq. (4.15).

Computation of the bounce

$$\Gamma(t) = A(T_{\mathrm{d}}) \exp\left[-\frac{S_3(T_{\mathrm{d}})}{T_{\mathrm{d}}}\right]$$

$$S_3\left(T_{\mathrm{d}}\right) \equiv S_3\left[\phi_{\mathrm{b}}(\boldsymbol{x}; T_{\mathrm{d}})\right] = \int \mathrm{d}^3 x \left[\frac{\left(\nabla\phi_{\mathrm{b}}\right)^2}{2} + V_{\mathrm{eff}}(\phi_{\mathrm{b}}, T_{\mathrm{d}})\right]$$

$$\frac{\partial^2\phi}{\partial r^2} + \frac{2}{r}\frac{\partial\phi}{\partial r} = \frac{\mathrm{d}V_{\mathrm{eff}}(\phi, T_{\mathrm{d}})}{\mathrm{d}\phi} \equiv V'_{\mathrm{eff}}(\phi, T_{\mathrm{d}})\,.$$

$$\left.\frac{S_3(T_{\mathrm{d}})}{T_{\mathrm{d}}}\right|_{T_{\mathrm{d,n}}=\xi_{\mathrm{n}}T_{\mathrm{n}}} \simeq 146 - 2\ln\left(\frac{g_*(T_{\mathrm{n}})}{100}\right) - 4\ln\left(\frac{T_{\mathrm{n}}}{100\,\mathrm{GeV}}\right)$$

$$I(T) = \frac{4\pi}{3} v_{\mathrm{w}}^3 \int_T^{T_{\mathrm{c}}} \mathrm{d}T' \frac{\Gamma(T')}{T'^4\, H(T')} \left(\int_T^{T'} \frac{\mathrm{d}T''}{H(T'')}\right)^3$$

GWs from PBH mergers

$$\Omega_{\rm gw}(f) = \frac{f}{\rho_{\rm crit}} \int_0^{t_0} {\rm d}t_{\rm r} \left(R(t_{\rm r} + \tau_{f_{\rm r}}) \frac{{\rm d}E^{\rm r}_{\rm gw}}{{\rm d}f_{\rm r}} \right)_{f_{\rm r}=(1+z)f}$$

$$\frac{{\rm d}E^{\rm r}_{\rm gw}}{{\rm d}f_{\rm r}} \simeq \frac{(\pi G)^{2/3} m_{\rm PBH}^{5/3}}{3 \times 2^{1/3}} \begin{cases} f_{\rm r}^{-1/3} & f_{\rm r} < f_1 \\ \frac{f_{\rm r}^{2/3}}{f_1} & f_1 \leq f_{\rm r} < f_2 \\ \frac{f_{\rm r}^2 f_4^4}{f_1 f_2^{4/3} [4(f_{\rm r} - f_2)^2 + f_4^2]^2} & f_2 \leq f_{\rm r} < f_3 \\ 0 & f_3 \leq f_{\rm r} \,. \end{cases} \quad (7.3)$$

$${\rm d}n_3(x,y) = \frac{n_{\rm PBH}}{2} \, {\rm e}^{-N_{\rm PBH}(y)} \, (4\pi n_{\rm PBH} \delta_{\rm dc})^2 \, x^2 \, y^2 \, {\rm d}x \, {\rm d}y$$

$$\begin{aligned} R(t_{\rm r}) &= \int_0^{\tilde{x}} {\rm d}x \int_x^{\infty} {\rm d}y \, \frac{\partial^2 n_3}{\partial x \, \partial y} \, \delta(t_{\rm r} - \tau(x,y)) \\ &= \frac{9 \, \tilde{N}_{\rm PBH}^{53/37}}{296\pi \, \delta_{\rm dc} \, \tilde{x}^3 \, \tilde{\tau}} \left(\frac{t_{\rm r}}{\tilde{\tau}} \right)^{-34/37} \\ &\times \left(\Gamma \left[\frac{58}{37}, \tilde{N}_{\rm PBH} \left(\frac{t_{\rm r}}{\tilde{\tau}} \right)^{3/16} \right] - \Gamma \left[\frac{58}{37}, \tilde{N}_{\rm PBH} \left(\frac{t_{\rm r}}{\tilde{\tau}} \right)^{-1/7} \right] \right) \end{aligned}$$

Expected number of PBH pairs contributing to GWB

$$\bar{N}(f_-, f_+) = \int_{f_-}^{f_+} \frac{\mathrm{d}f}{f} \int_0^{\infty} \mathrm{d}z \, \frac{8}{3} \, \tau_{f_\mathrm{r}} \, \frac{4\pi \, [d_c(z)]^2}{H(z)} \, R(t_\mathrm{r}(z) - \tau_{f_\mathrm{r}})$$

Evidence in favor of a stochastic GW background

The Astrophysical Journal Letters, 951:L8 (24pp), 2023 July 1 Agazie et al.

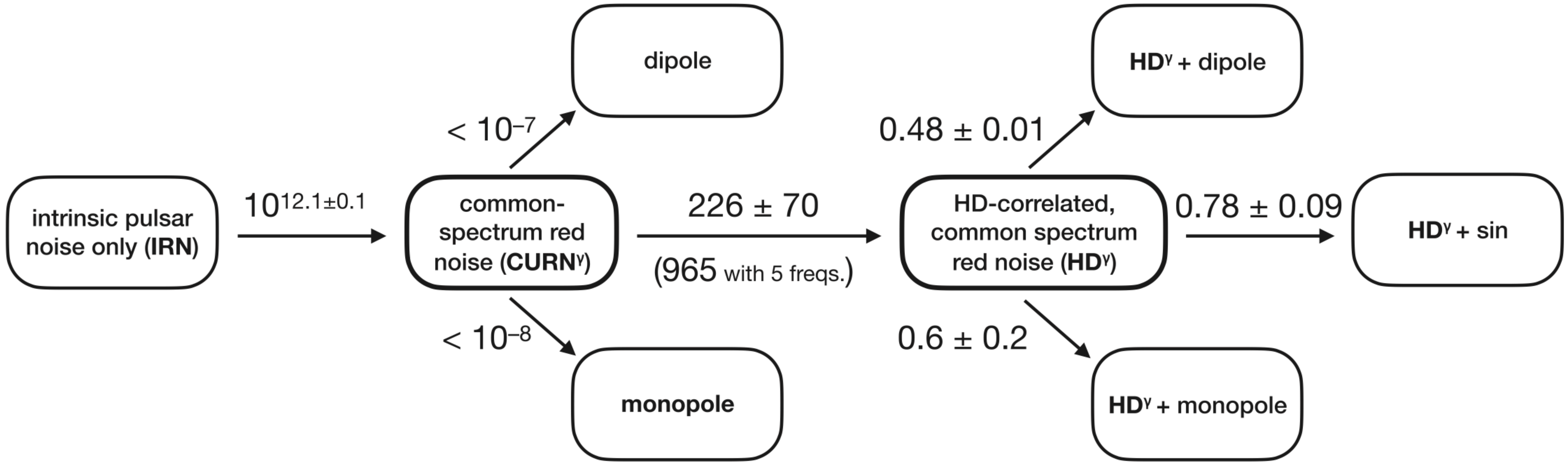
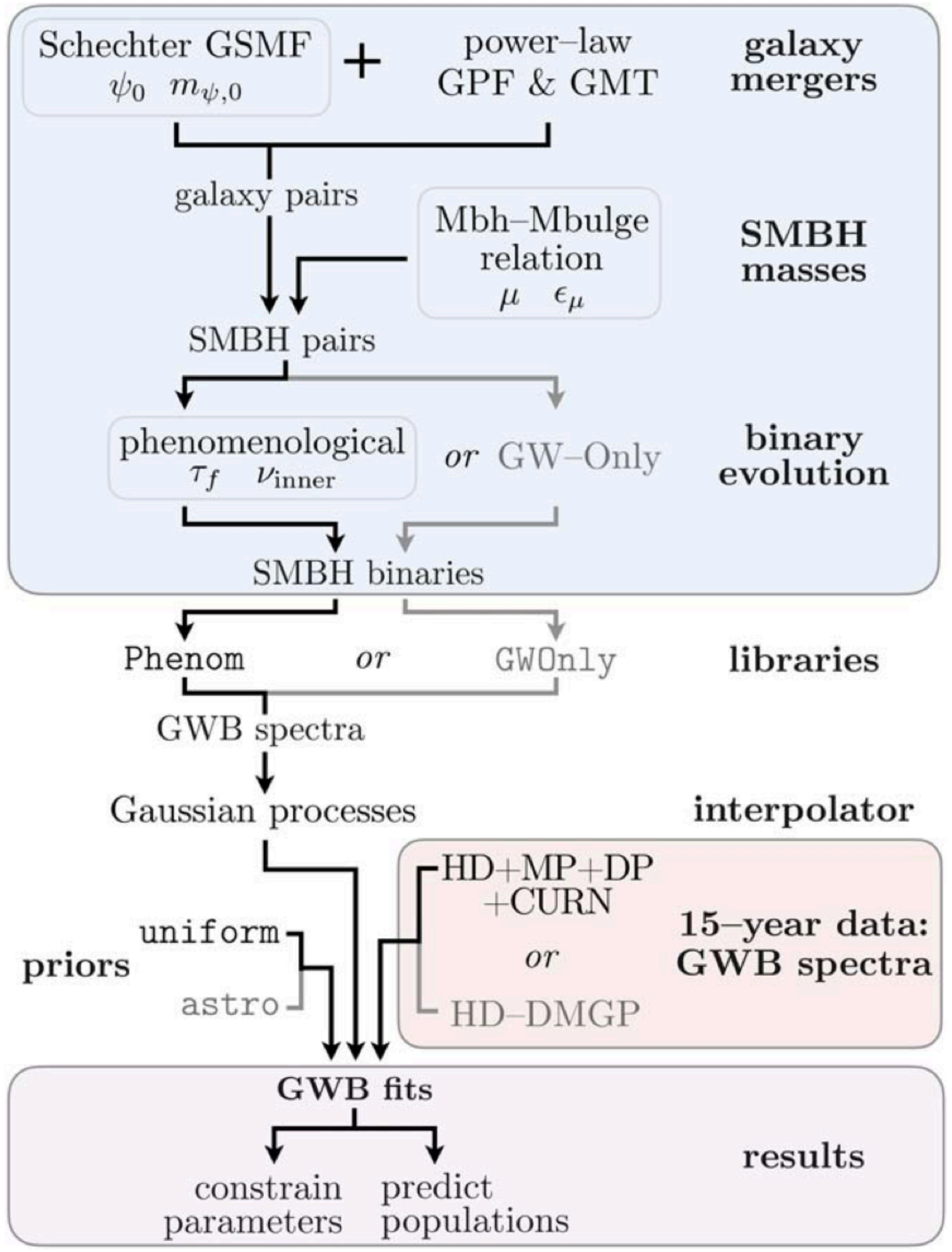
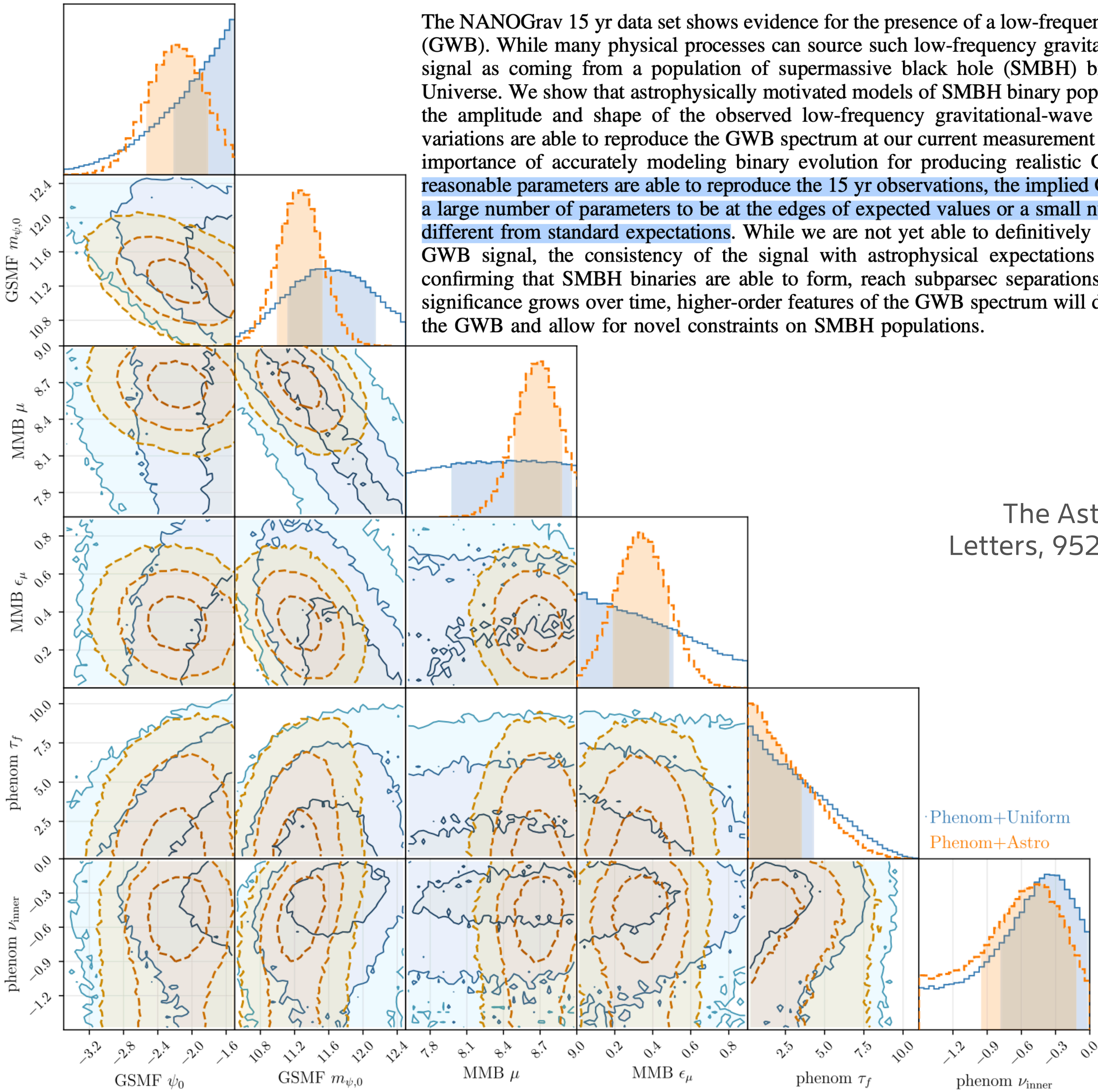


Figure 2. Bayes factors between models of correlated red noise in the NANOGrav 15 yr data set (see Section 5.3 and Appendix B). All models feature variable-γ power laws. CURN$^\gamma$ is vastly favored over IRN (i.e., we find very strong evidence for common-spectrum excess noise over pulsar intrinsic red noise alone); HD$^\gamma$ is favored over CURN$^\gamma$ (i.e., we find evidence for Hellings–Downs correlations in the common-spectrum process); dipole and monopole processes are strongly disfavored with respect to CURN$^\gamma$; adding correlated processes to HD$^\gamma$ is disfavored. While the interpretation of "raw" Bayes factors is somewhat subjective, they can be given a statistical significance within the hypothesis-testing framework by computing their background distributions and deriving the p-values of the observed factors, e.g., Figure 3.

Modeling SMBHBs



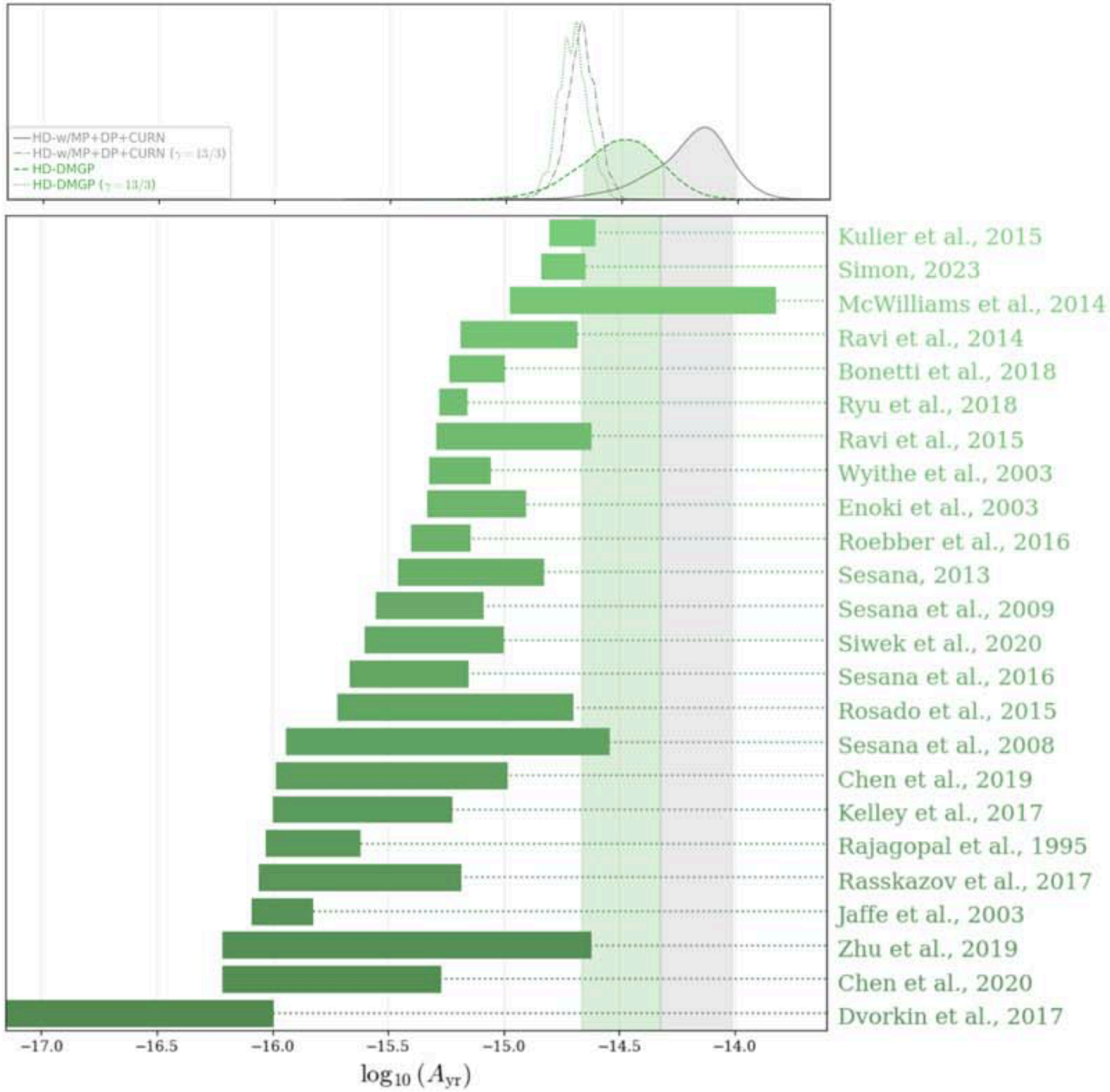


Abstract

The NANOGrav 15 yr data set shows evidence for the presence of a low-frequency gravitational-wave background (GWB). While many physical processes can source such low-frequency gravitational waves, here we analyze the signal as coming from a population of supermassive black hole (SMBH) binaries distributed throughout the Universe. We show that astrophysically motivated models of SMBH binary populations are able to reproduce both the amplitude and shape of the observed low-frequency gravitational-wave spectrum. While multiple model variations are able to reproduce the GWB spectrum at our current measurement precision, our results highlight the importance of accurately modeling binary evolution for producing realistic GWB spectra. Additionally, while reasonable parameters are able to reproduce the 15 yr observations, the implied GWB amplitude necessitates either a large number of parameters to be at the edges of expected values or a small number of parameters to be notably different from standard expectations. While we are not yet able to definitively establish the origin of the inferred GWB signal, the consistency of the signal with astrophysical expectations offers a tantalizing prospect for confirming that SMBH binaries are able to form, reach subparsec separations, and eventually coalesce. As the significance grows over time, higher-order features of the GWB spectrum will definitively determine the nature of the GWB and allow for novel constraints on SMBH populations.

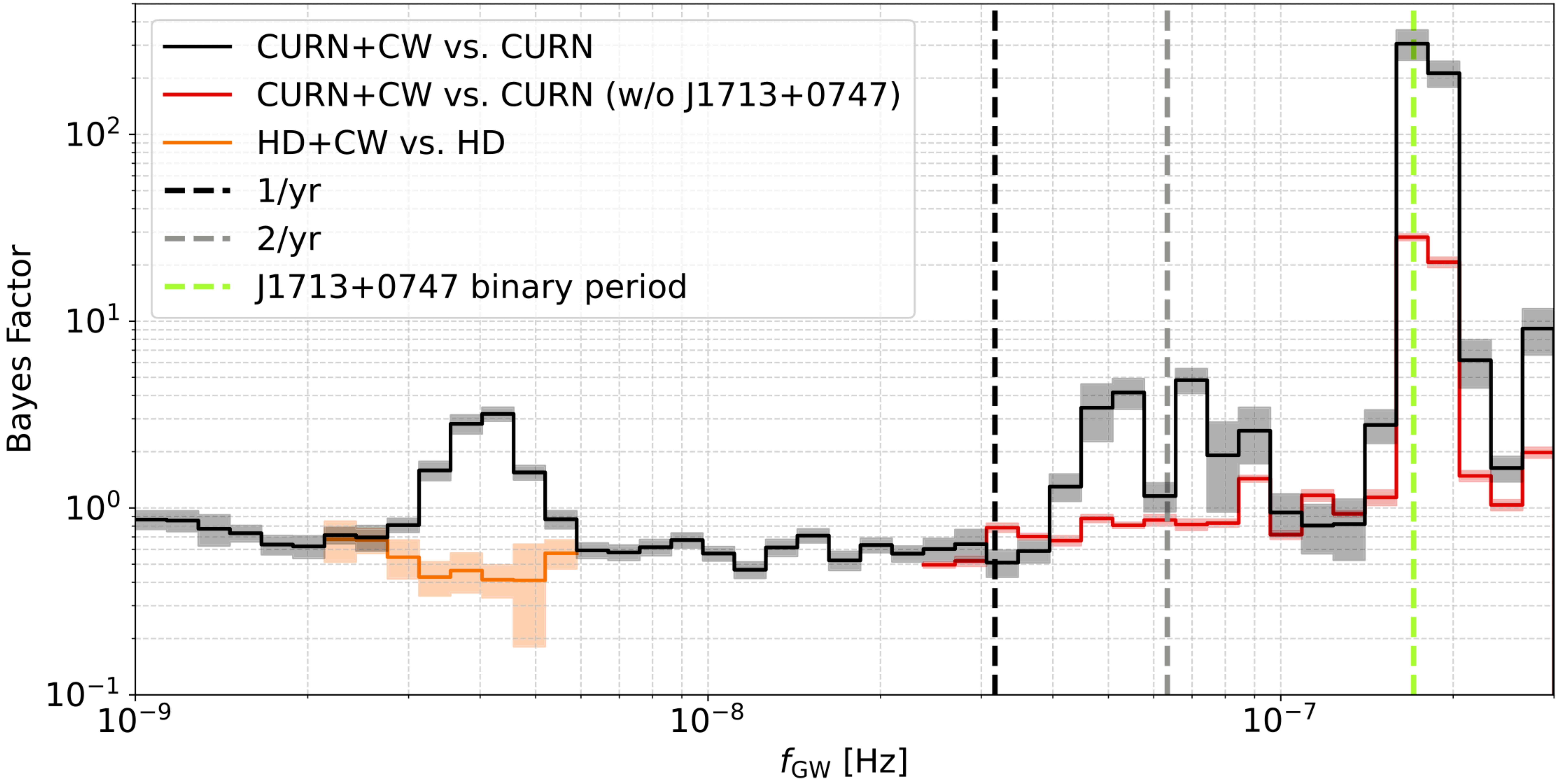
The Astrophysical Journal
Letters, 952:L37 (30pp), 2023
August 1

Uncertainties of the GWB amplitude from SMBHBs



The Astrophysical Journal Letters, 952:L37 (30pp), 2023 August 1

Continuous waves in the NANOGrav 15yr data set



Astrophys.J.Lett. 951 (2023) 2, L50

Figure 1. Savage-Dickey Bayes factors for the CW+CURN model vs. the CURN model as a function of frequency (black). Also shown are Bayes factors when excluding PSR J1713+0747 (red, only computed for $f_{\mathrm{GW}} > 24$ nHz) and Bayes factors based on a resampled posterior that takes into account the presence of HD correlations in the common red noise process, i.e., CW+HD vs. HD (orange, only computed for $2.1\ \mathrm{nHz} < f_{\mathrm{GW}} < 5.9$ nHz). Shaded regions show the 1σ uncertainties.

NANOGrav 15yr data limits on anisotropy

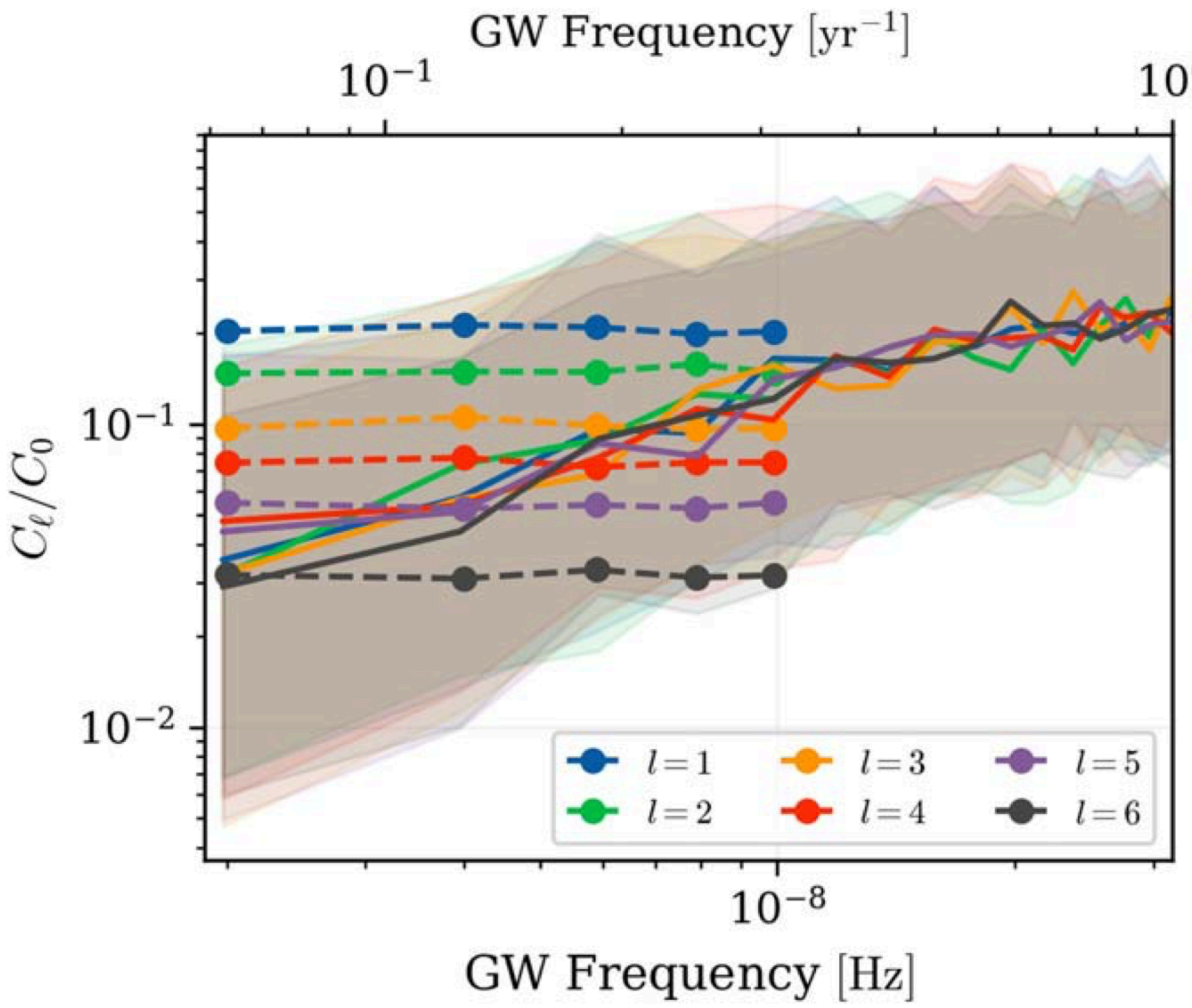
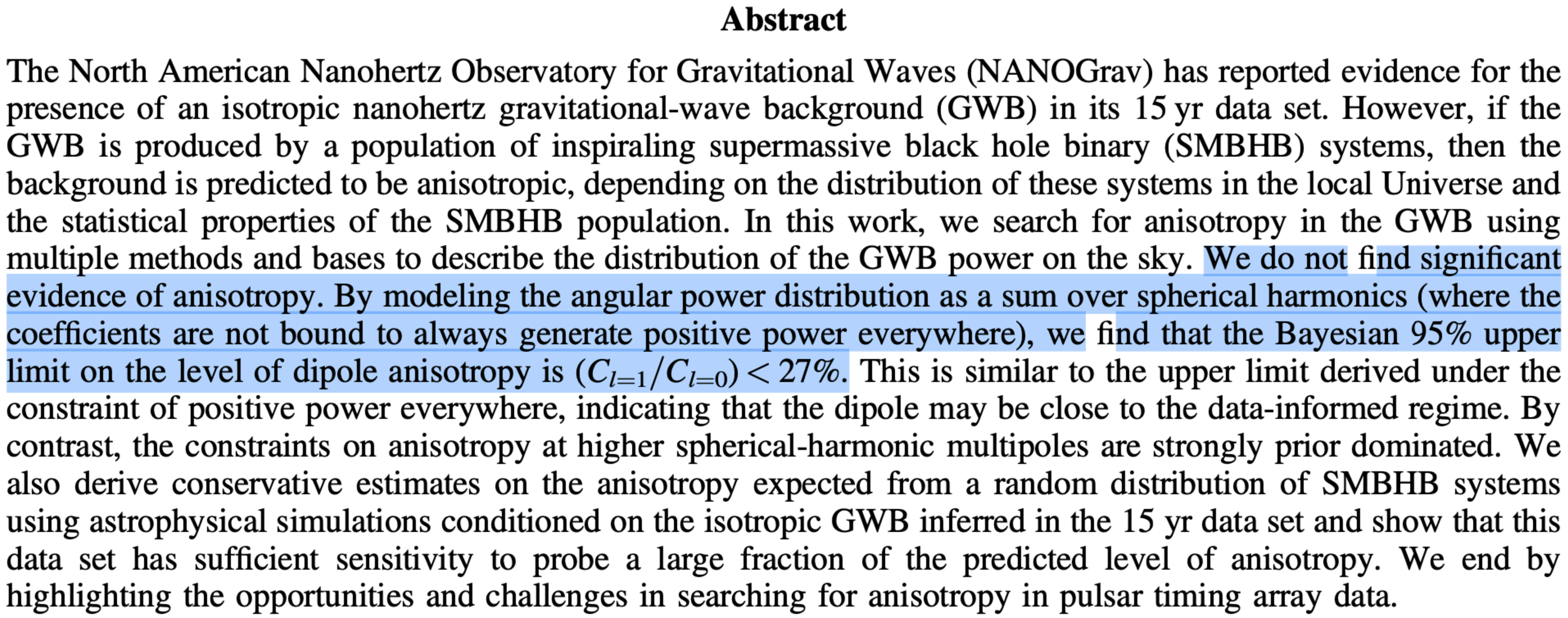


Figure 11. Normalized spherical-harmonic coefficients C_l/C_0 of the gravitational-wave sky as produced by simulated populations of SMBHBs, filtered by consistency with the 15 yr isotropic gravitational-wave background estimation (Agazie et al. 2023b). The different colors correspond to individual harmonics from $l=1$ to $l=6$. The solid lines represent the median realization of the median samples, and the shaded regions represent the 68% confidence intervals across all samples' median realizations. The circles connected by dashed lines represent the Bayesian upper limits as in Figure 5.



Abstract

The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has reported evidence for the presence of an isotropic nanohertz gravitational-wave background (GWB) in its 15 yr data set. However, if the GWB is produced by a population of inspiraling supermassive black hole binary (SMBHB) systems, then the background is predicted to be anisotropic, depending on the distribution of these systems in the local Universe and the statistical properties of the SMBHB population. In this work, we search for anisotropy in the GWB using multiple methods and bases to describe the distribution of the GWB power on the sky. We do not find significant evidence of anisotropy. By modeling the angular power distribution as a sum over spherical harmonics (where the coefficients are not bound to always generate positive power everywhere), we find that the Bayesian 95% upper limit on the level of dipole anisotropy is $(C_{l=1}/C_{l=0}) < 27\%$. This is similar to the upper limit derived under the constraint of positive power everywhere, indicating that the dipole may be close to the data-informed regime. By contrast, the constraints on anisotropy at higher spherical-harmonic multipoles are strongly prior dominated. We also derive conservative estimates on the anisotropy expected from a random distribution of SMBHB systems using astrophysical simulations conditioned on the isotropic GWB inferred in the 15 yr data set and show that this data set has sufficient sensitivity to probe a large fraction of the predicted level of anisotropy. We end by highlighting the opportunities and challenges in searching for anisotropy in pulsar timing array data.

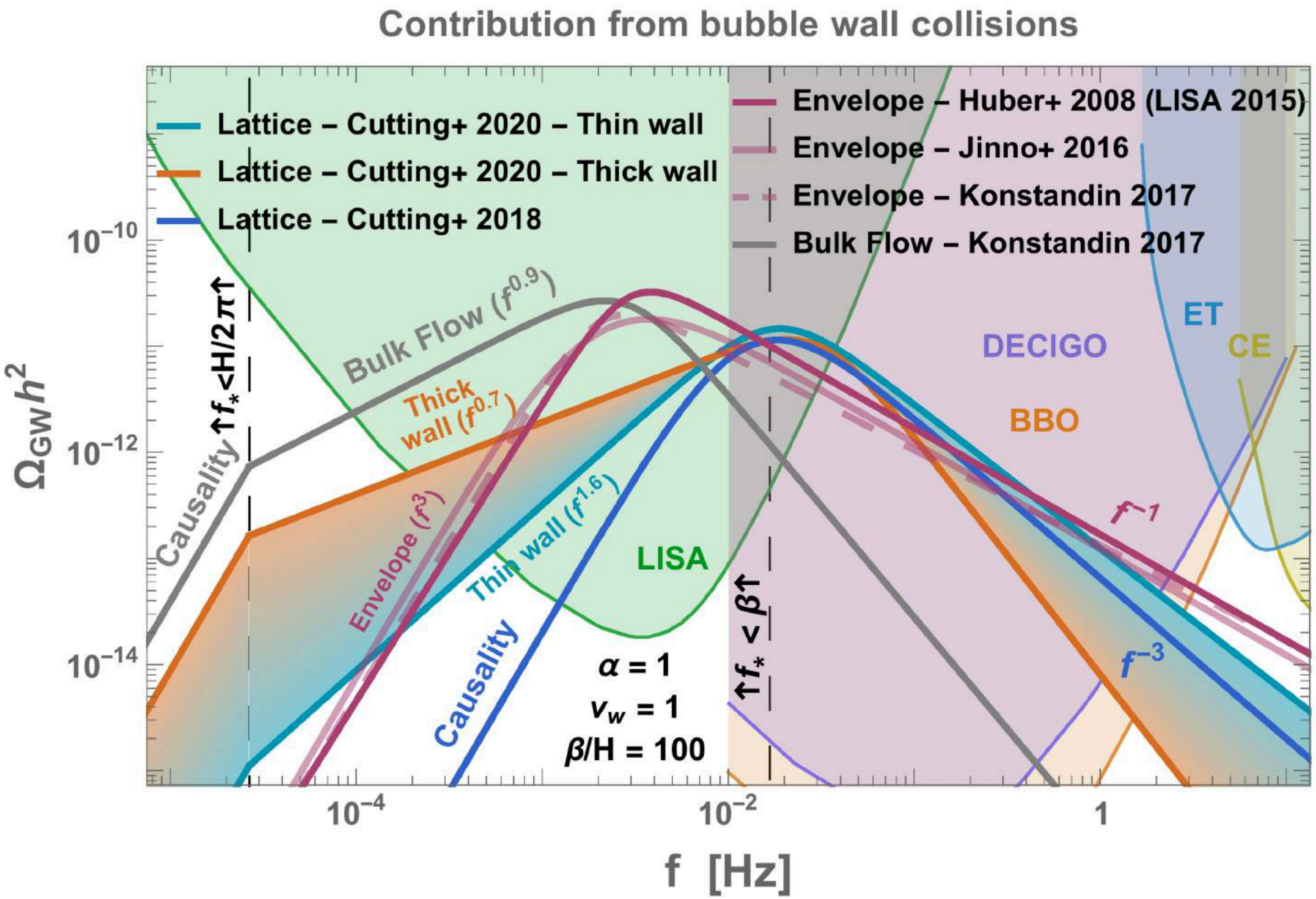
The Astrophysical Journal Letters, 956:L3 (15pp), 2023 October 10

Different models for the GW spectrum from a FOPT

	IR	UV	References
Envelope	3	-1	[16, 27]
Bulk flow	1	-3	[17, 28]
Scalar lattice	3	-1.5	[38]

	IR	Intermediate	UV	References
Sound shell	9	1	-3	[22, 23]
Scalar + fluid lattice	—	1	-3	[18, 20, 21, 29]
Hybrid	[2,4]	[−1,0]	[−4,−3]	[30]
Higgsless	3	1	-3	This work

JCAP02(2023)011, Jinno, Konstandin, Rubira, Stomberg


Contribution from bubble wall collisions

Yann Gouttenoire: Beyond the Standard Model Cocktail