The (first) LISA miracle

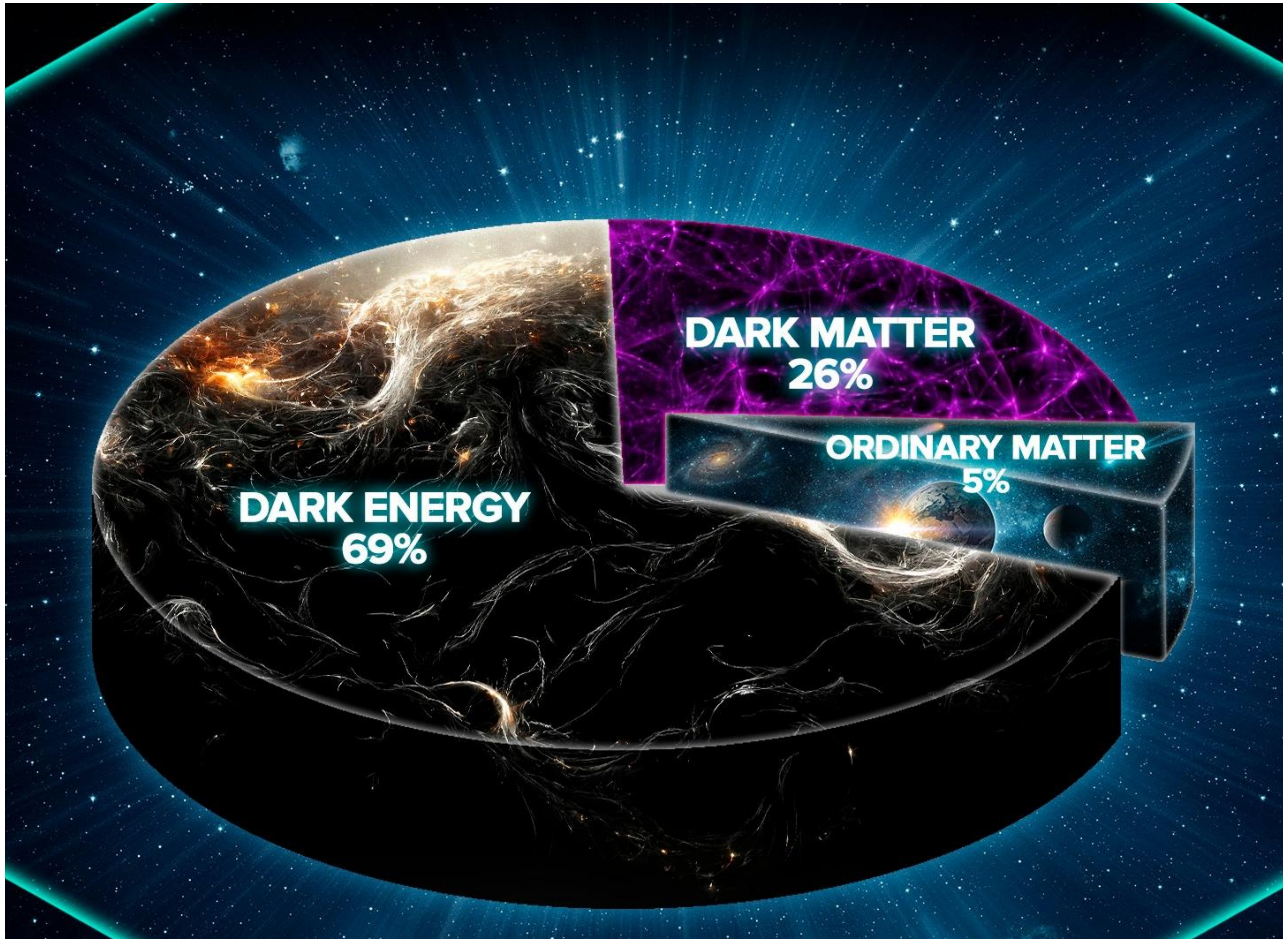
HIGGS 2024 conference,
Uppsala University
06.11.2024

Carlo Tasillo,
Uppsala University

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

JCAP 05 (2024) 065, arXiv: [2311.06346]

We only understand 5%



[PBS spacetime]

We need

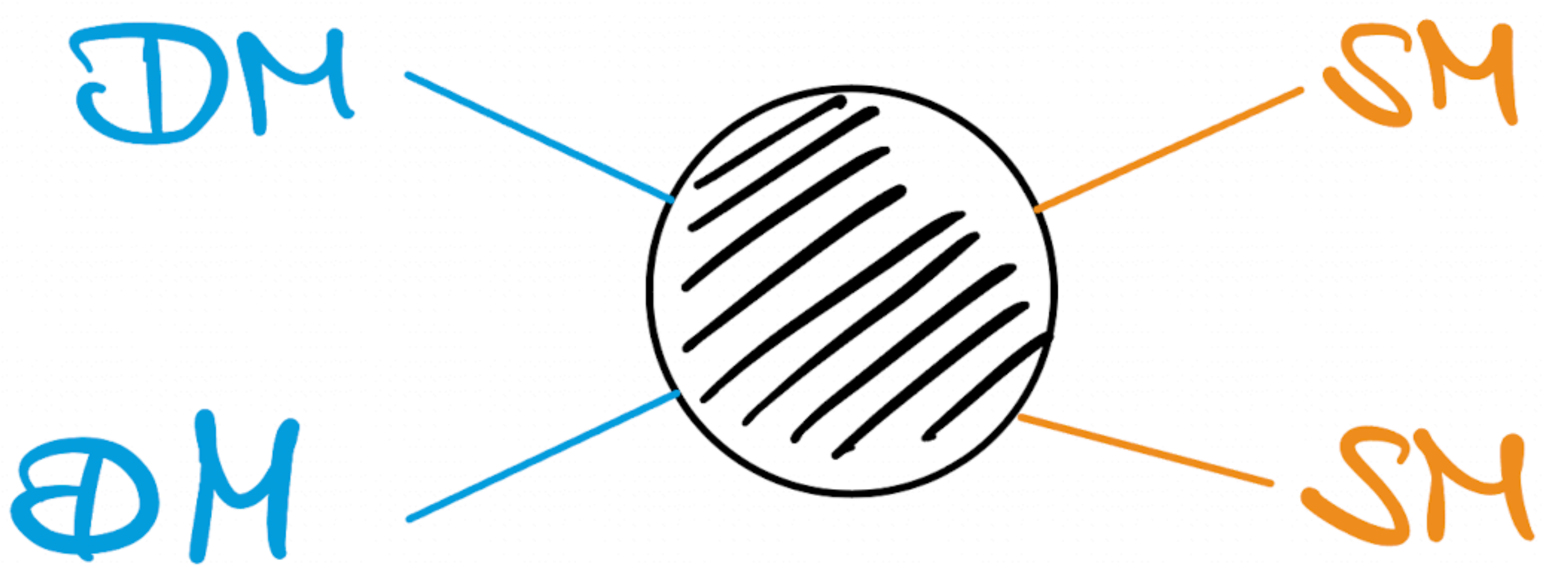
$$\boxed{\Omega_{\rm DM}h^2 = 0.12}$$

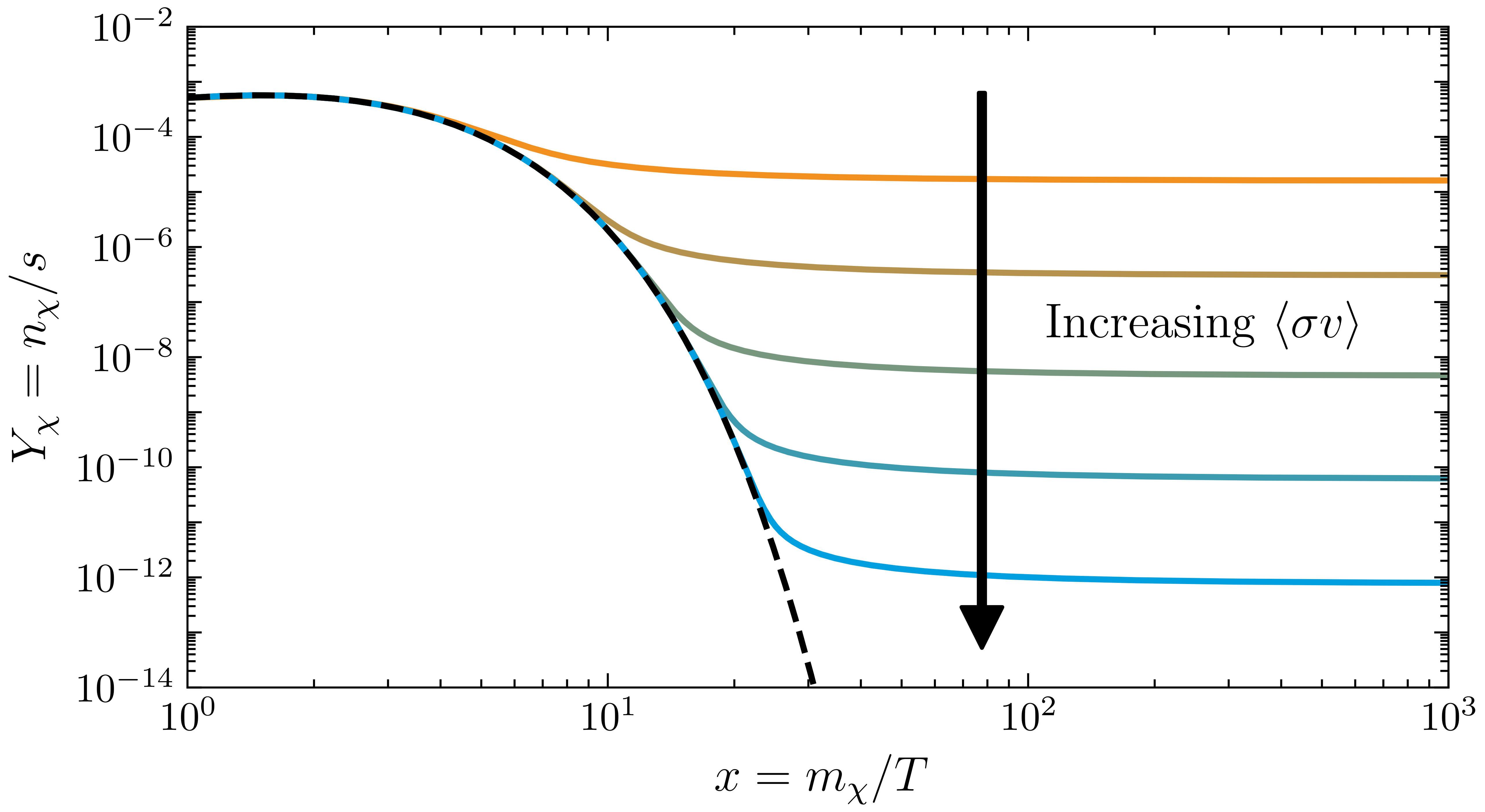
of cold dark matter in order to explain the CMB, galaxy clustering, the bullet cluster, galactic rotation curves, …

Cirelli+ [2406.01705]

The WIMP miracle

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



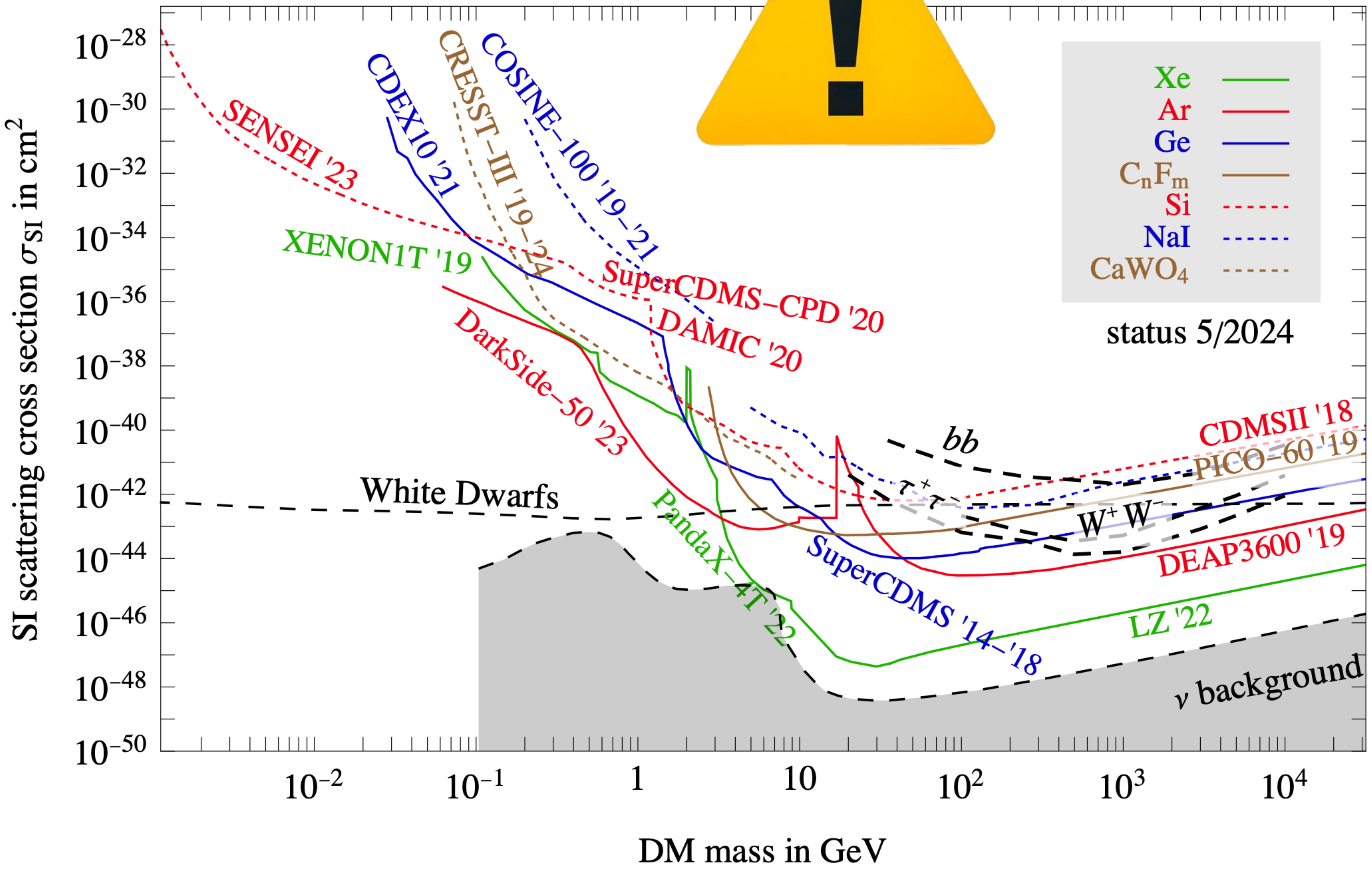


… the DM abundance can freeze out to the observed relic abundance for weak interactions and $m_{\mathrm{DM}} \simeq \mathcal{O}(\mathrm{TeV})$.

Rage, rage against the dying of the WIMP

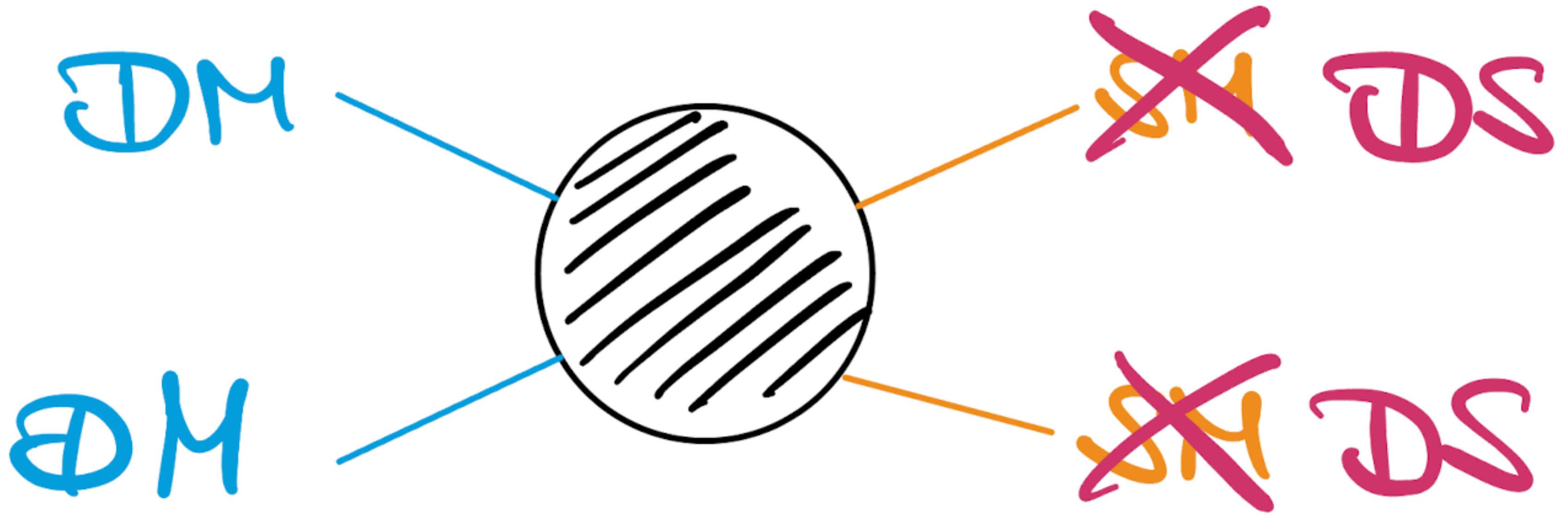
Direct detection experiments put this scenario under pressure, excluding „vanilla“ WIMPs.

[Lindner+ 2403.15860]



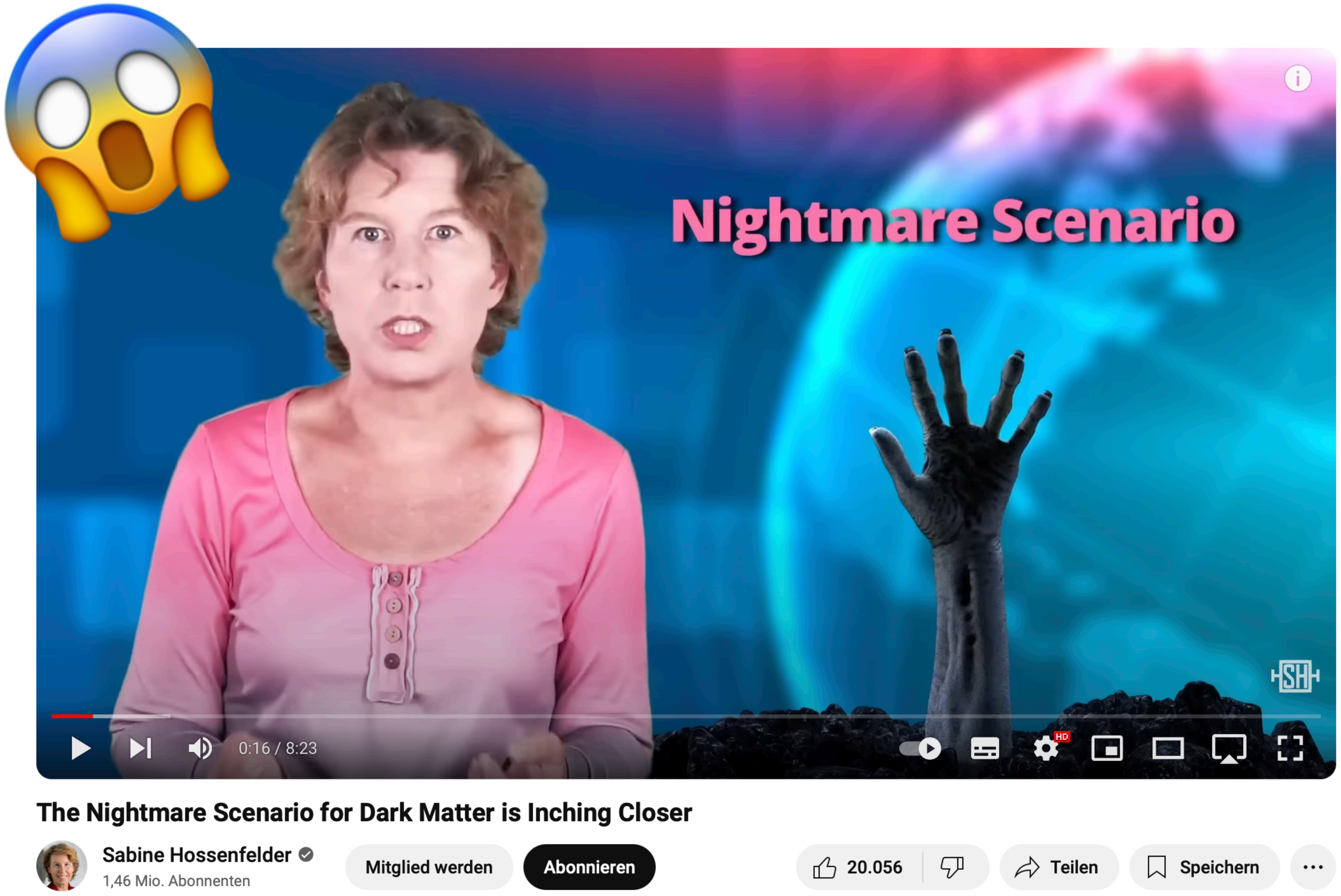
Cirelli+ [2406.01705]

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

Sabine Hossenfelder

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Astronomers detect 'cosmic bass note' of gravitational waves

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

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.

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

First Evidence of Giant Gravitational Waves Thrills Astronomers

Astro

re tuning in to a never-before-seen type of gravitational

pawned by pairs of supermassive black holes

rs used dead stars to

w form of ripple i

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

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Monster gravitational

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ntists discover that universe is a

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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Gravitational wave

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SCIENCE

Colossal gravitational waves—trillions of iles long—found for e first time

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The Washington Post

Democracy Dies in Darkness

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The results are

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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

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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

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

At Last, There’

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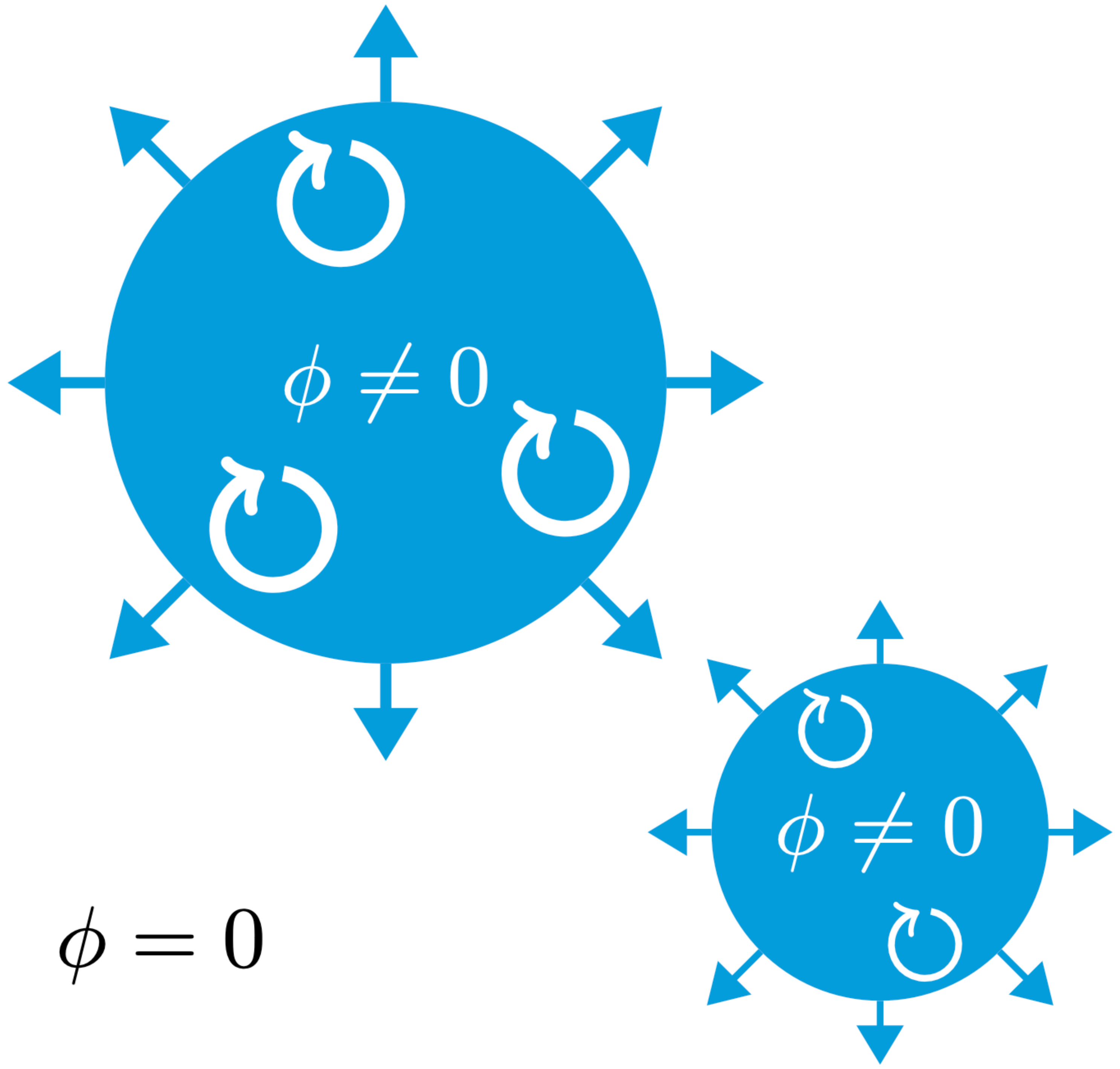
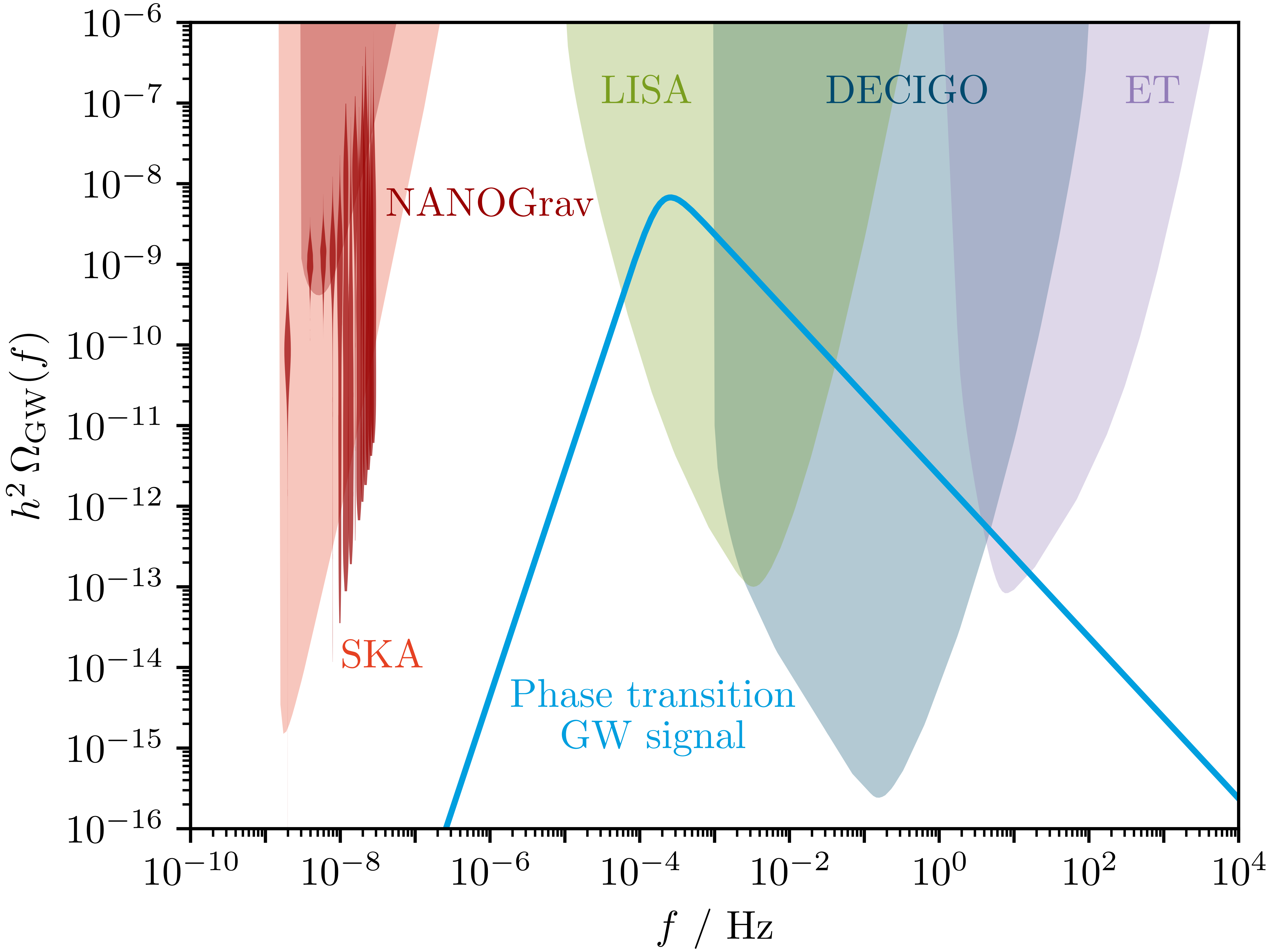
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe

First-order phase transitions produce GW backgrounds

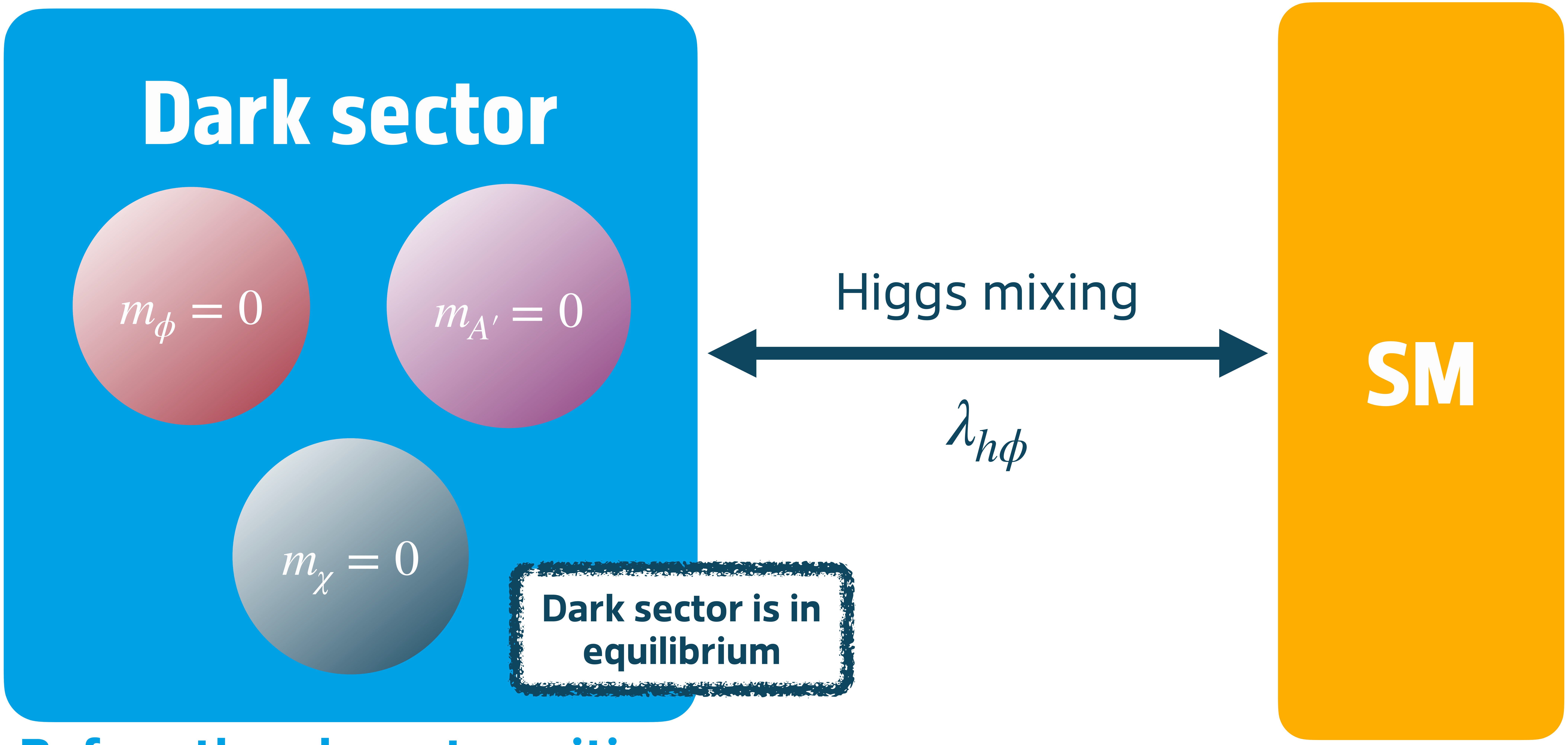
Bubbles of the new phase nucleate, collide and perturb the plasma...





... giving rise to an observable stochastic gravitational wave background.

Our model setup



Dark sector

$m_\phi = 0$

$m_{A'} = 0$

$m_\chi = 0$

Higgs mixing

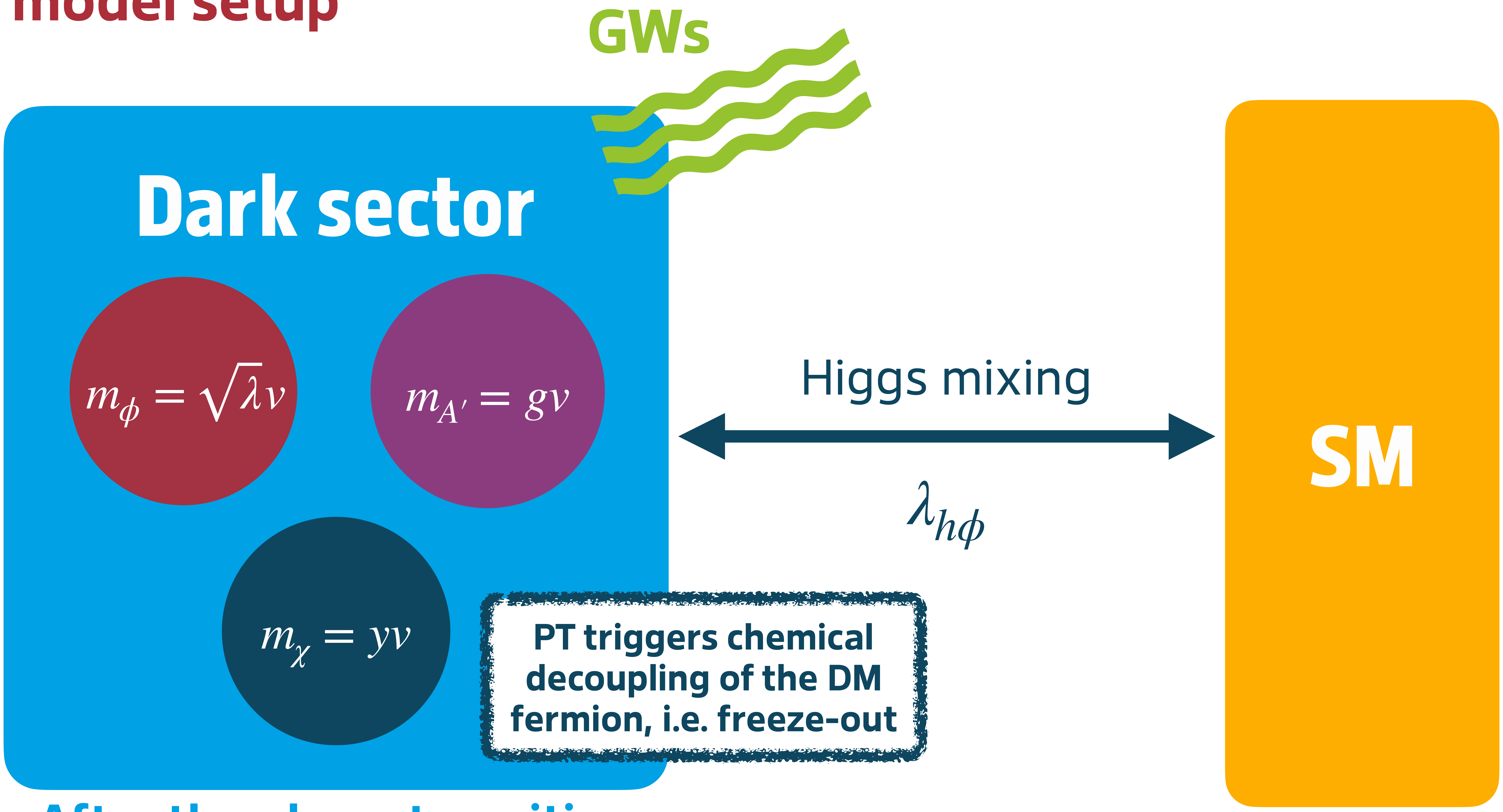
$\lambda_{h\phi}$

SM

Dark sector is in equilibrium

Before the phase transition

Our model setup



GWs

Dark sector

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

$m_{A'} = g v$

$m_\chi = y v$

Higgs mixing

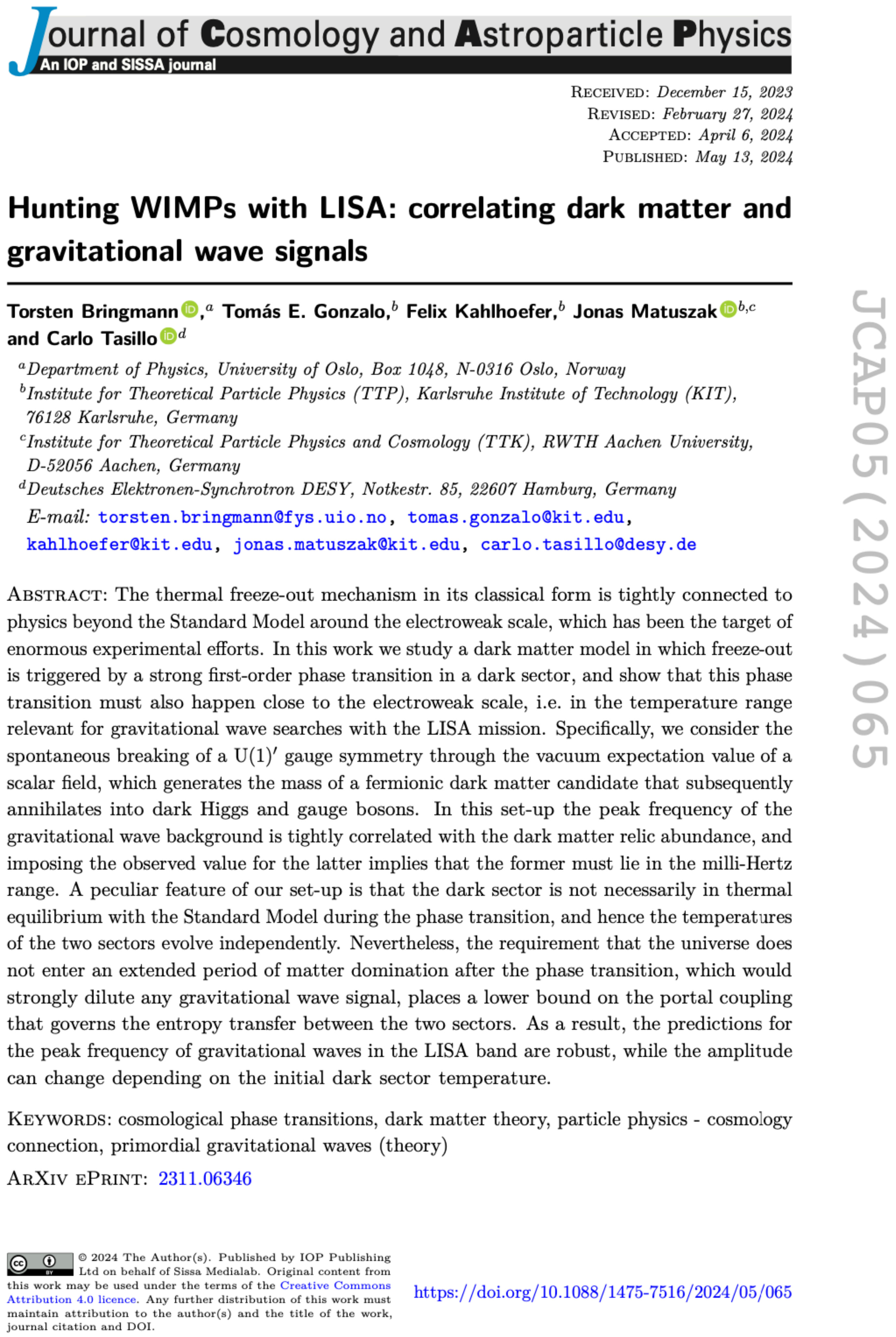
$\lambda_{h\phi}$

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)

ARXIV EPRINT: 2311.06346

https://doi.org/10.1088/1475-7516/2024/05/065

JCAP05(2024)065

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

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

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

The miracle at work

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

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

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

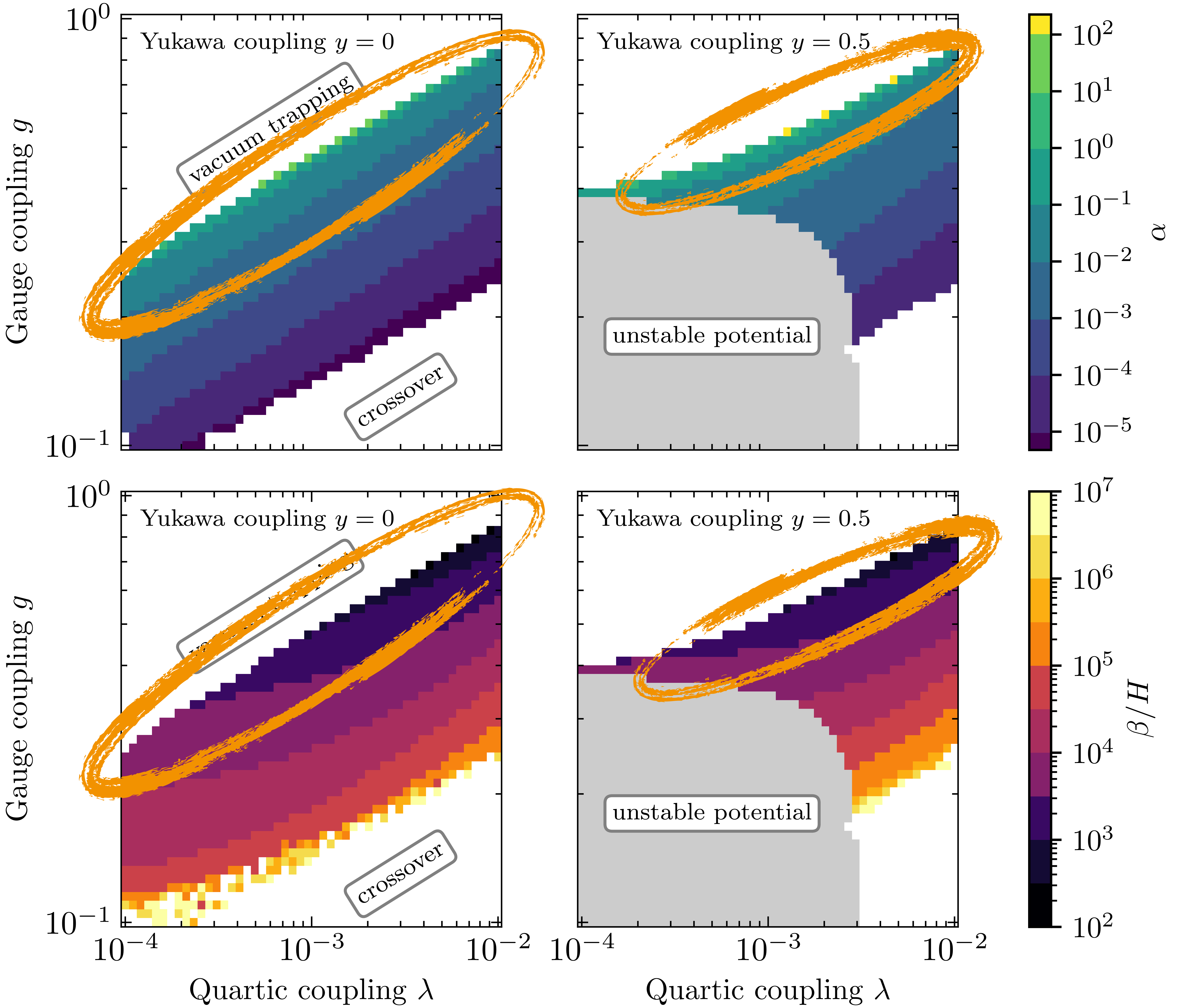
$$\langle\sigma v\rangle \sim \frac{y^4}{m_\chi^2} \sim \frac{y^2}{v^2}$$

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

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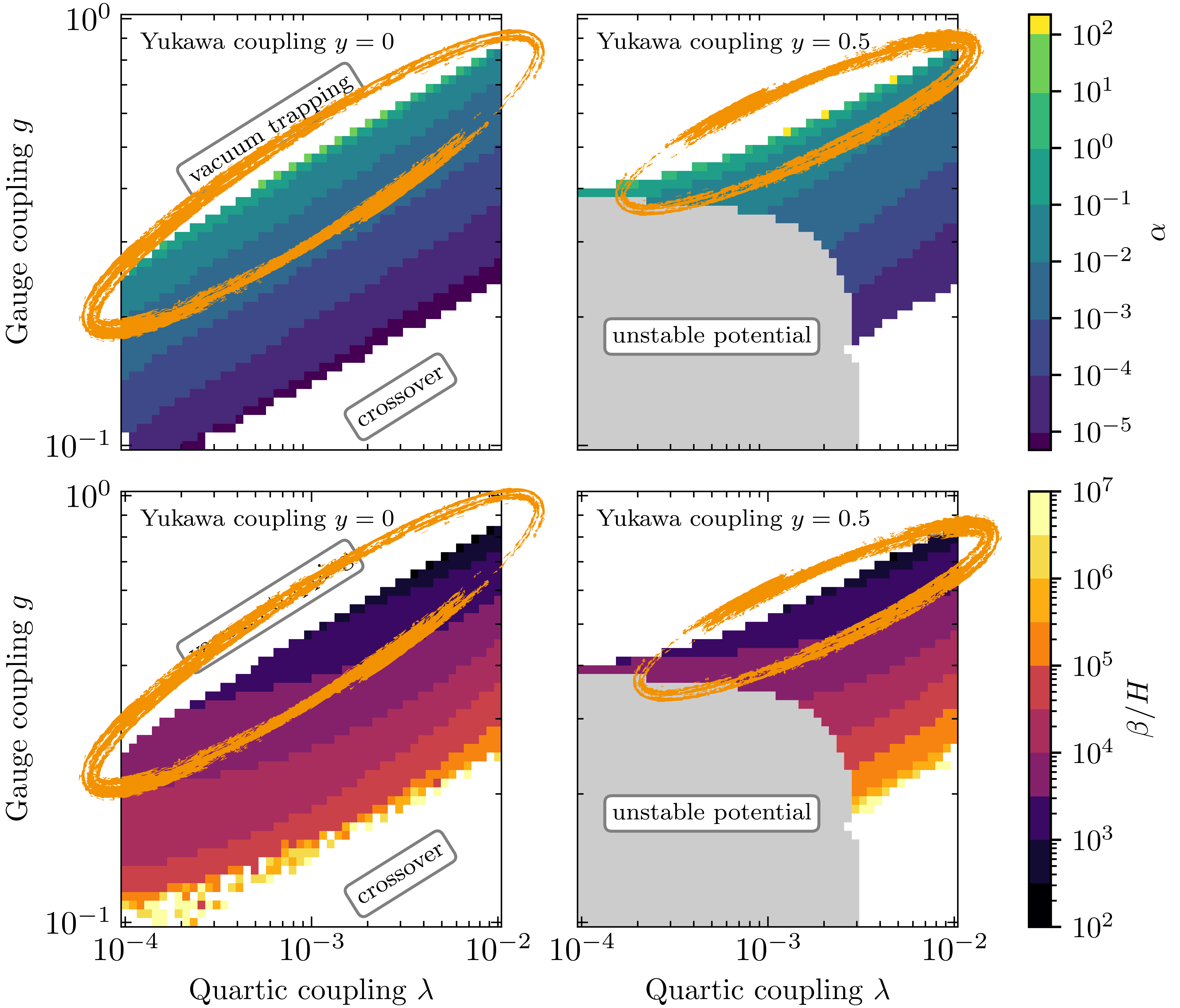
Sizable couplings and $m_\phi \lesssim m_{A'}$

Freeze-out condition:

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



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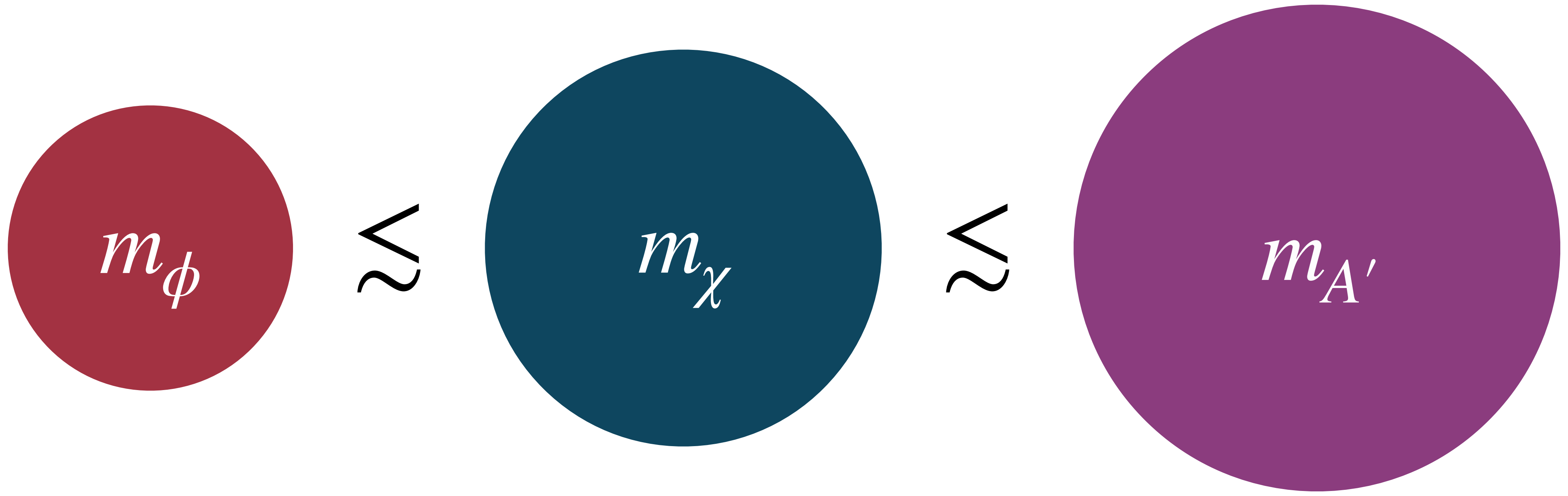
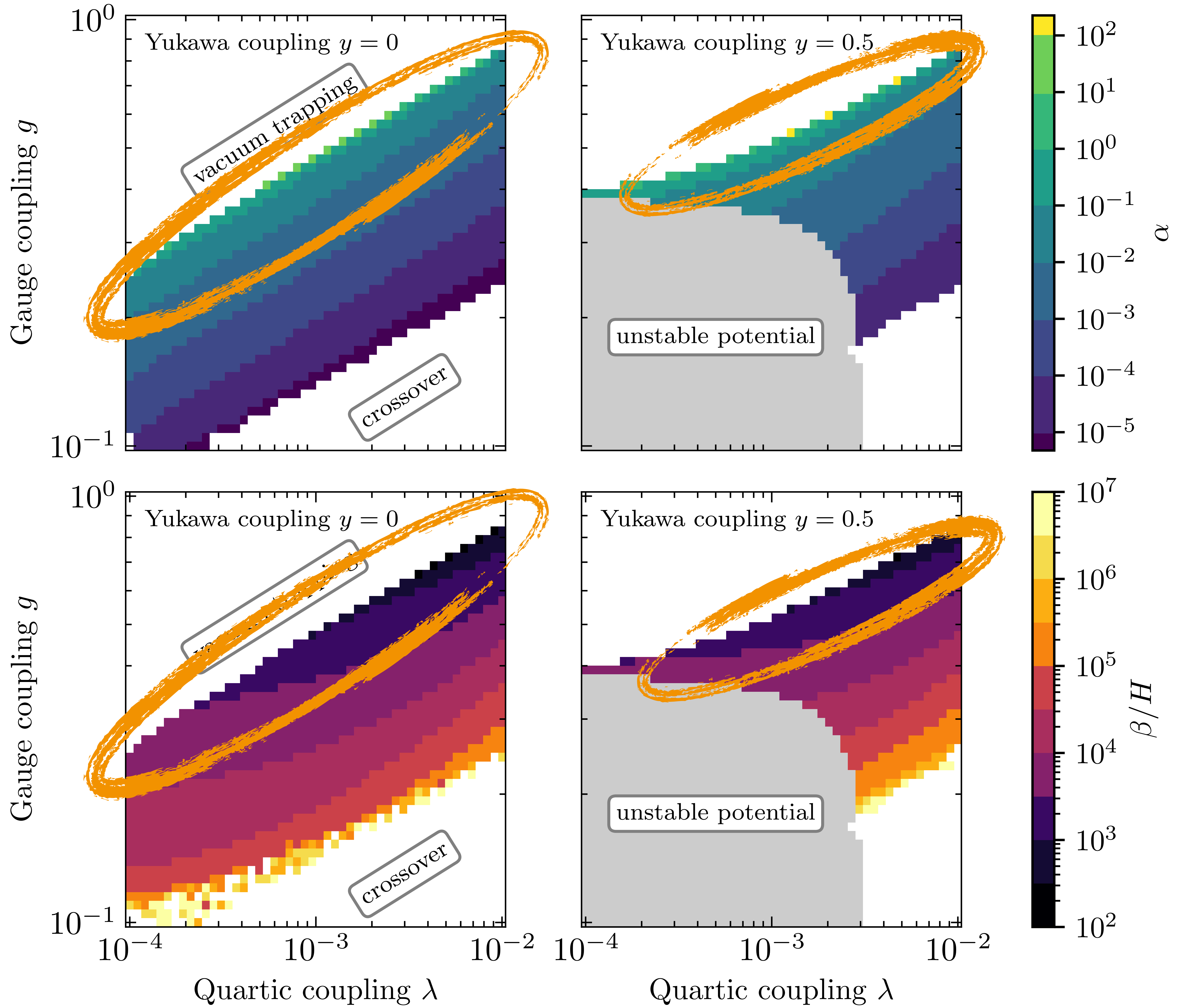
Conclusion:



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

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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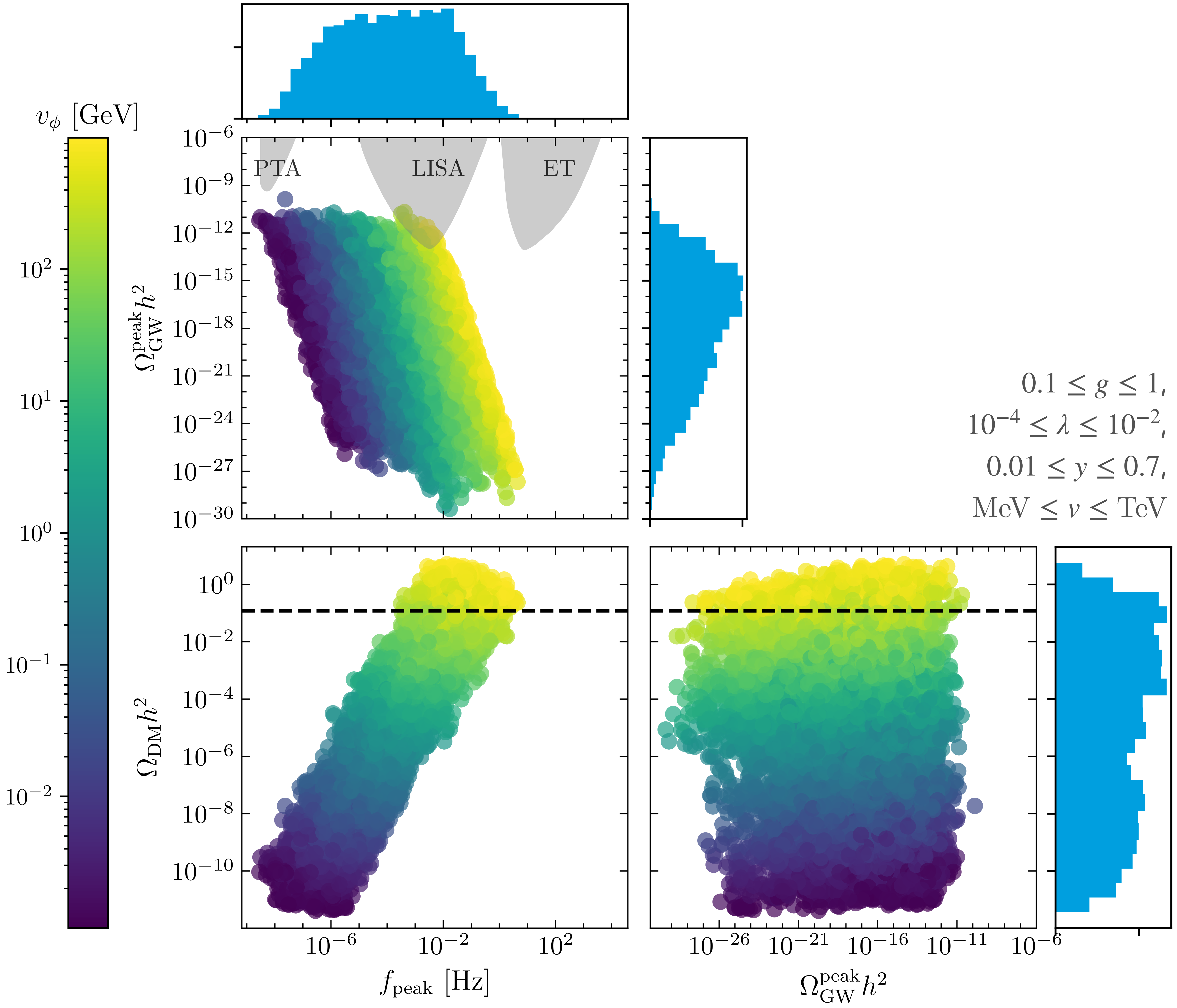
- Influence of temperature ratio $\xi = T_{\mathrm{DS}}/T_{\mathrm{SM}}$ on $\Omega_{\mathrm{GW}}(f)$ and Ω_{DM}?
- $\lambda_{h\phi}$: Collider bounds? Early matter domination?

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

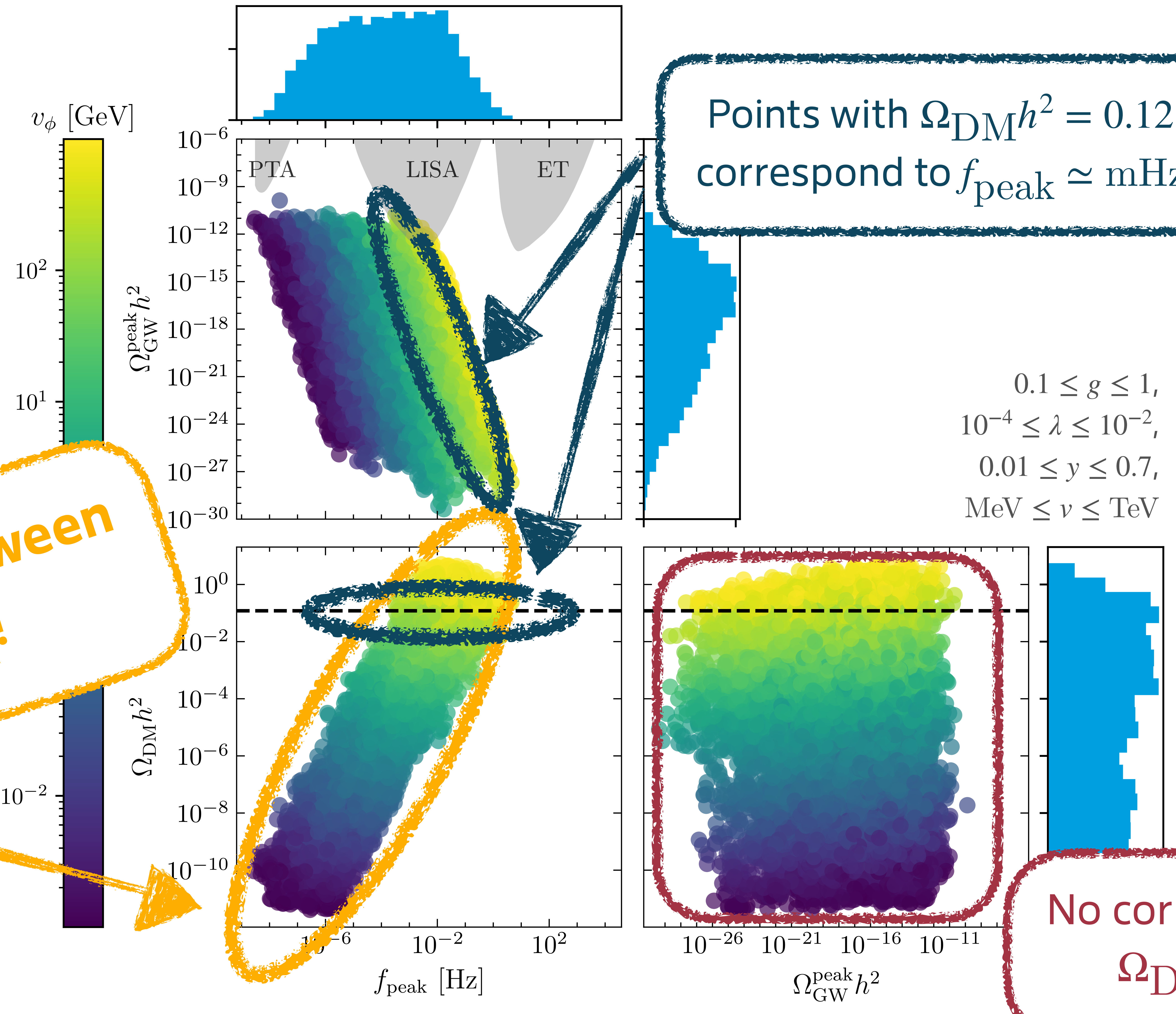
* TransitionListener & DarkSUSY [Ertas+ 2109.06208, Bringmann+ 1802.03399]

Results of our scans



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

Results of our scans



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

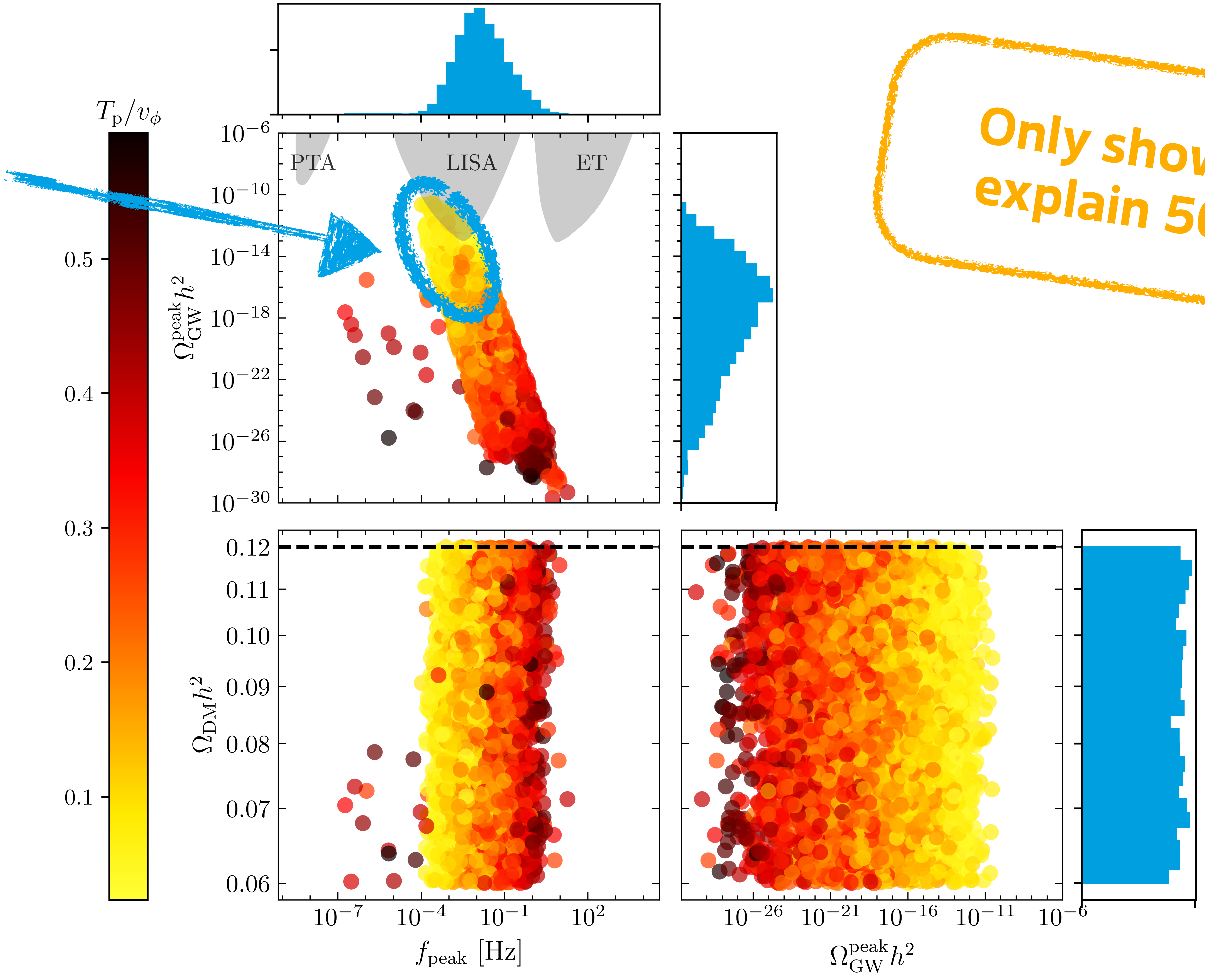
Points with $\Omega_{\rm DM} h^2 = 0.12$ correspond to $f_{\rm peak} \simeq \text{mHz}$

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



Only show points which explain 50-100% of DM

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

Summary

The *first* LISA miracle:

- In our $U(1)'$ model there is a robust correlation between f_{peak} and Ω_{DM}
- $\Omega_{\mathrm{DM}}h^2 = 0.12$ corresponds to mHz frequencies, i.e. the LISA band
- A future LISA detection of a GW background would hint towards secluded DS freeze-out (and not just a first-order EWPT)
- Ongoing work on other model setups

Thank you very much for your attention!

Do you have any questions?

Backup slides

GWB details

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

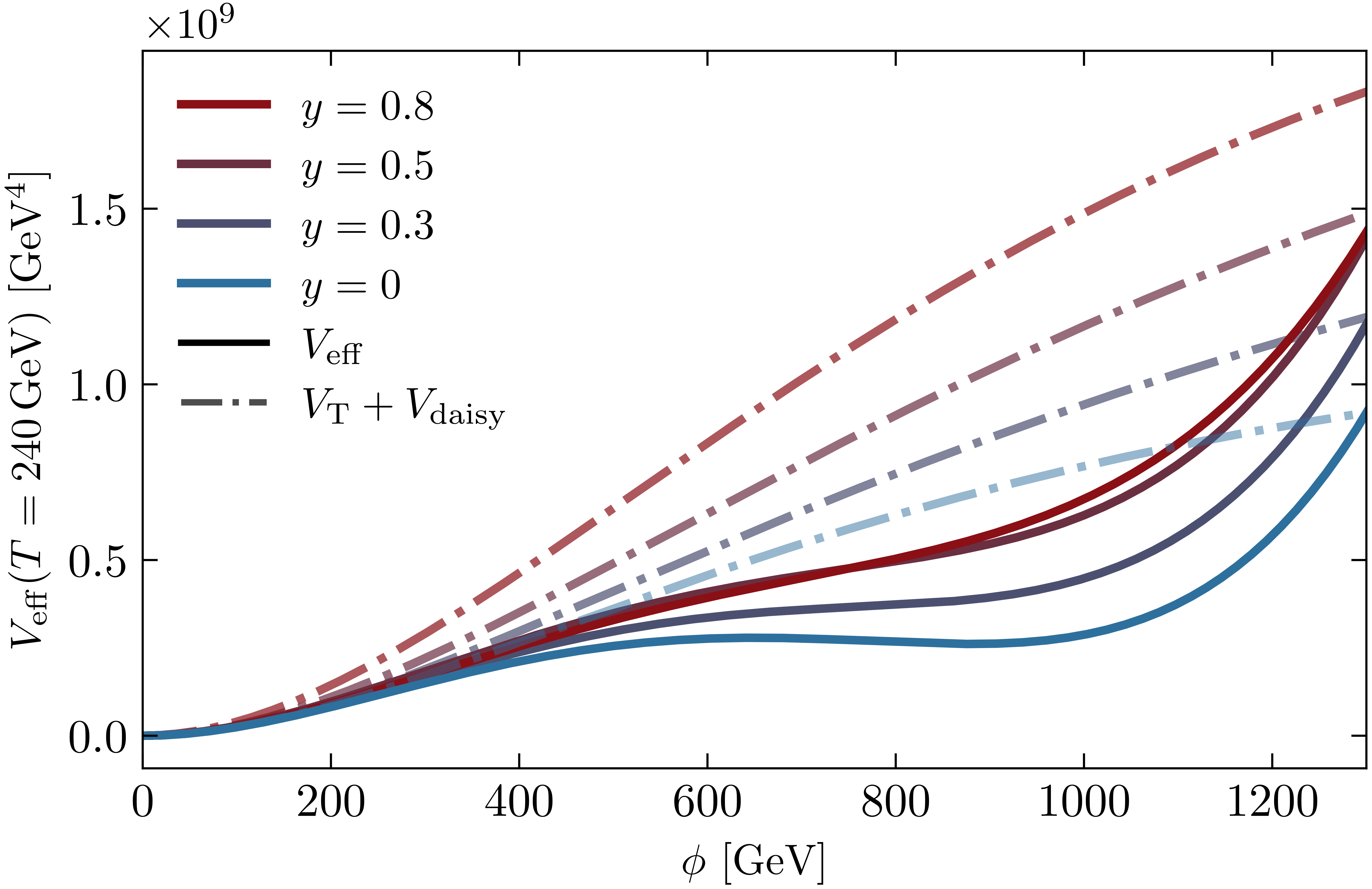
$$\mathcal{R}h^2 = \Omega_\gamma h^2\left(\frac{h_{\rm SM,0}}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{g_{\gamma,0}}\right) = 1.653\cdot10^{-5}\left(\frac{100}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{100}\right)$$

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

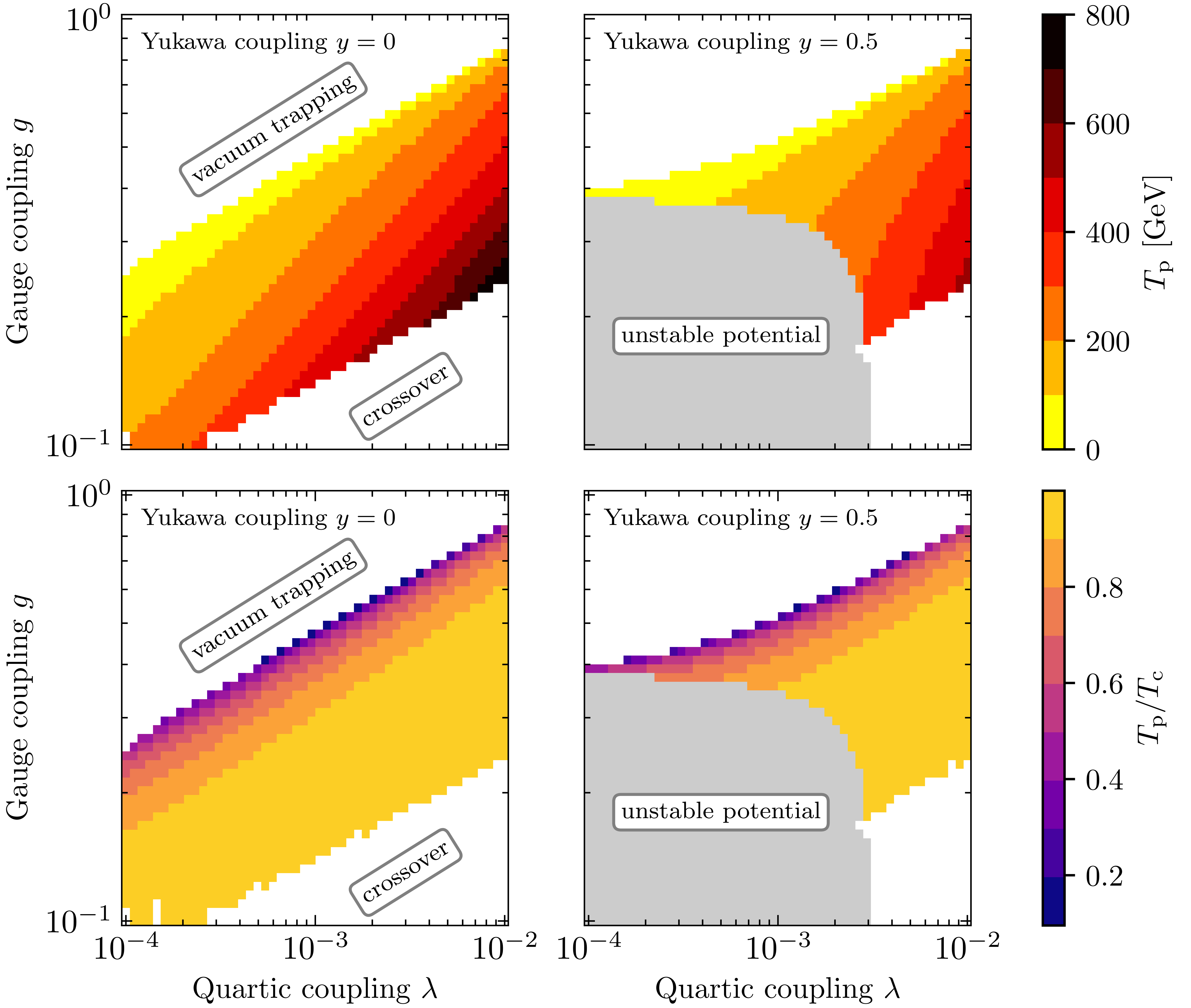
$$S(f) = \left(\frac{f}{f_{\rm peak}}\right)^3\left(\frac{7}{4+3\,(f/f_{\rm peak})^2}\right)^{7/2}$$

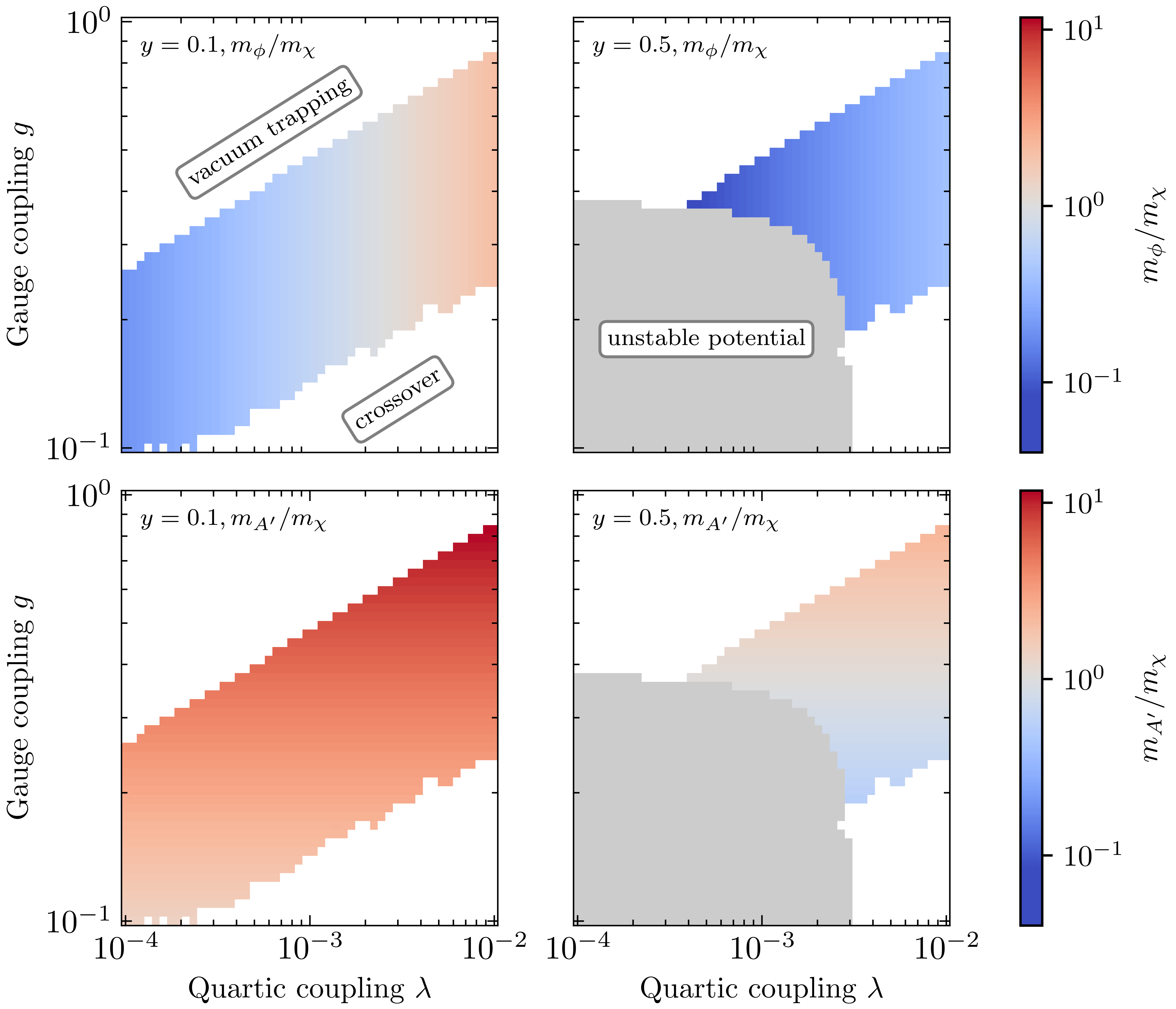
$$f_{\rm peak} = 8.9\,{\rm mHz}\left(\frac{T_{\rm p}}{100\ {\rm GeV}}\right)\left(\frac{\beta/H}{1000}\right)\left(\frac{g_{\rm tot,p}}{100}\right)^{1/2}\left(\frac{100}{h_{\rm tot,p}}\right)^{1/3}$$

Effect of Yukawa coupling on effective potential

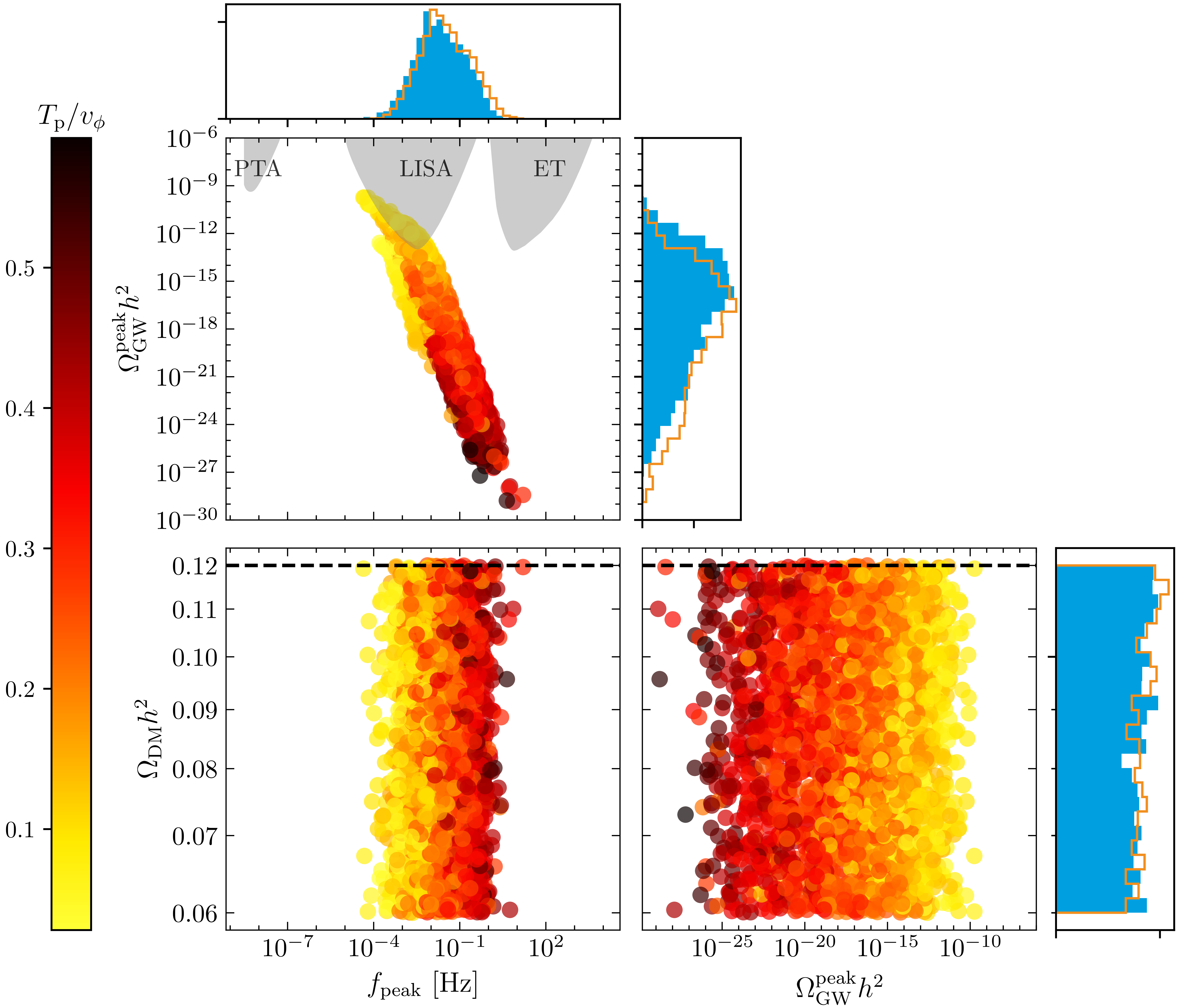


Grid scans over couplings

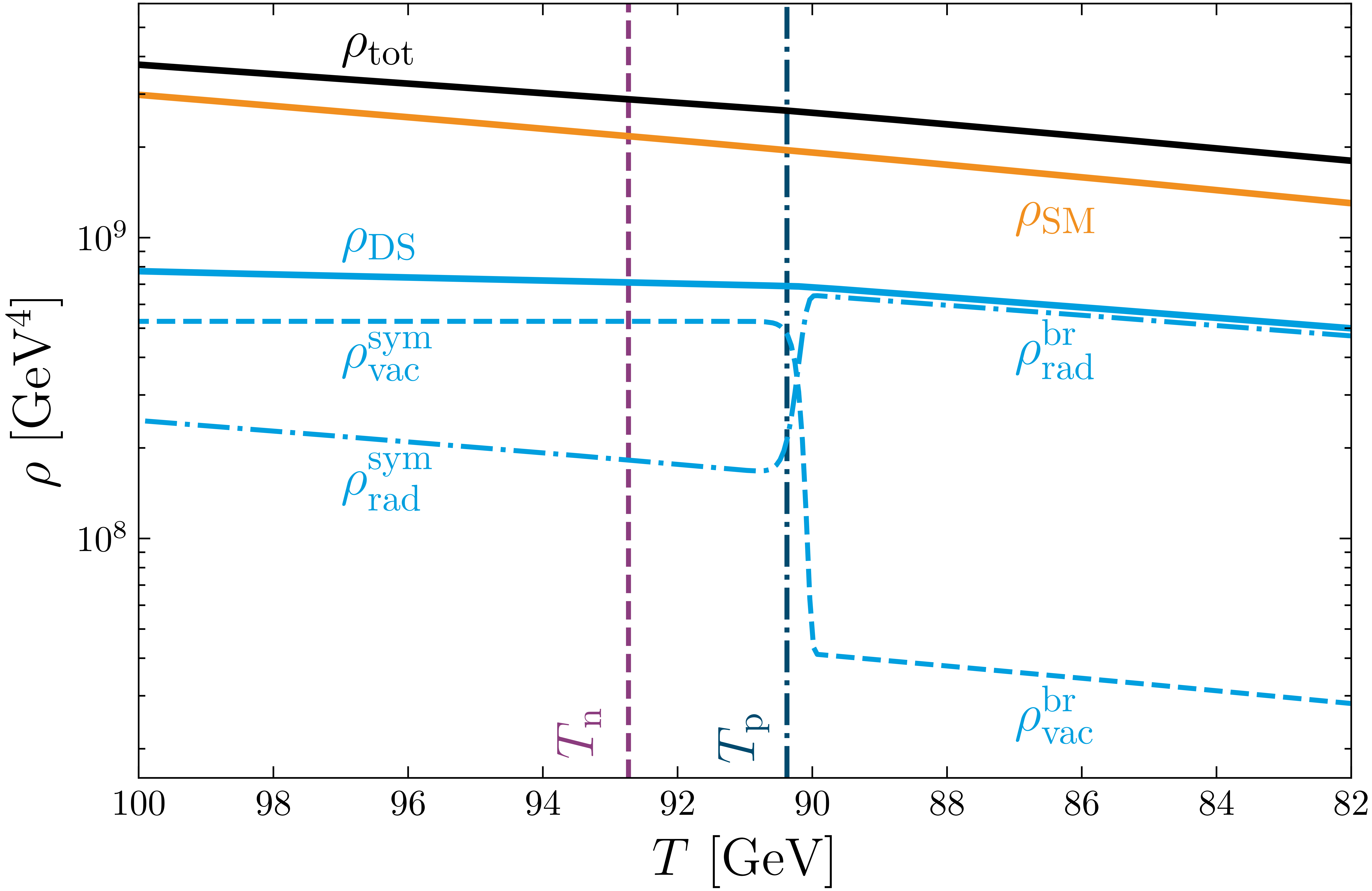




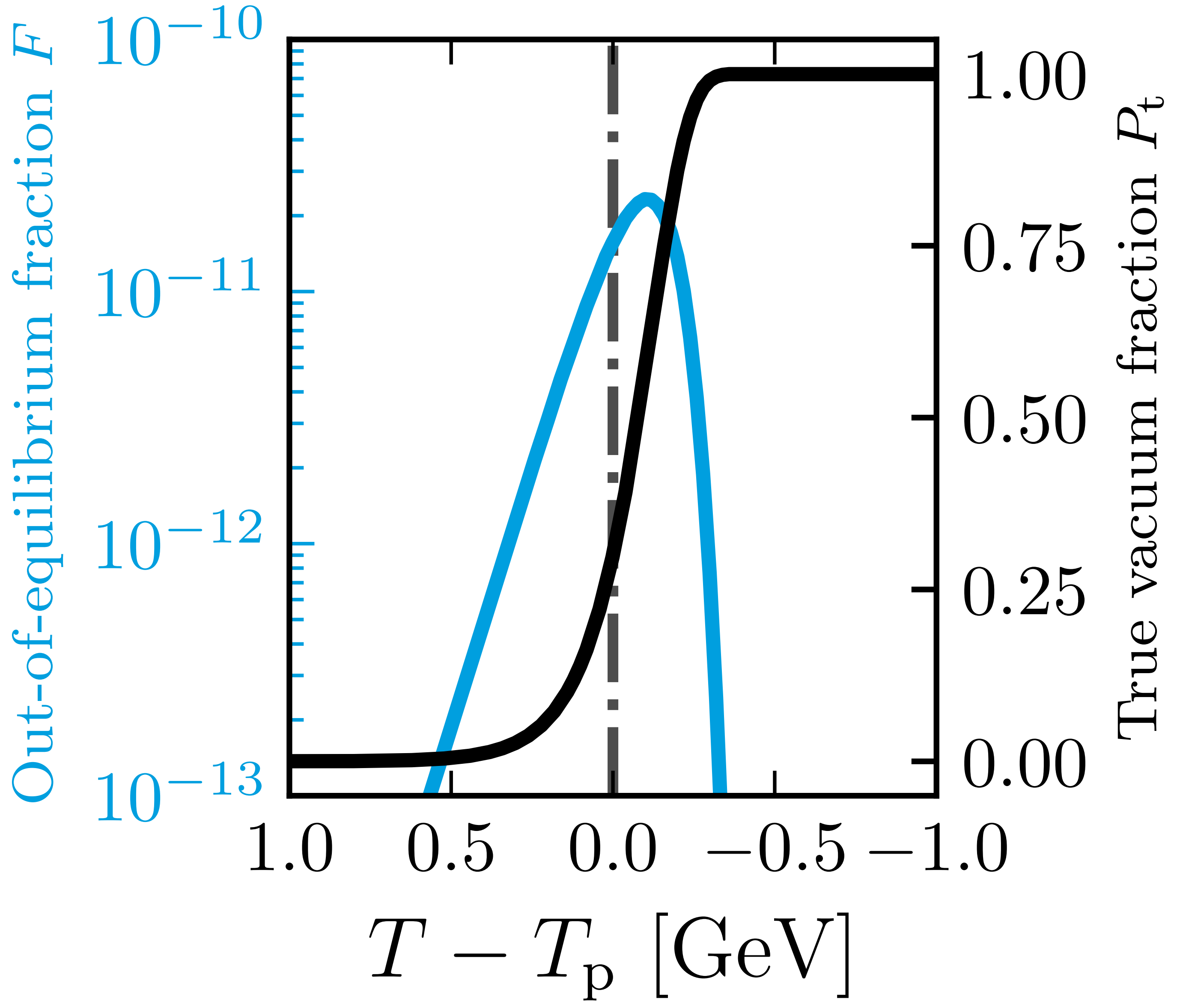
Comparison with hot dark sector phase transition

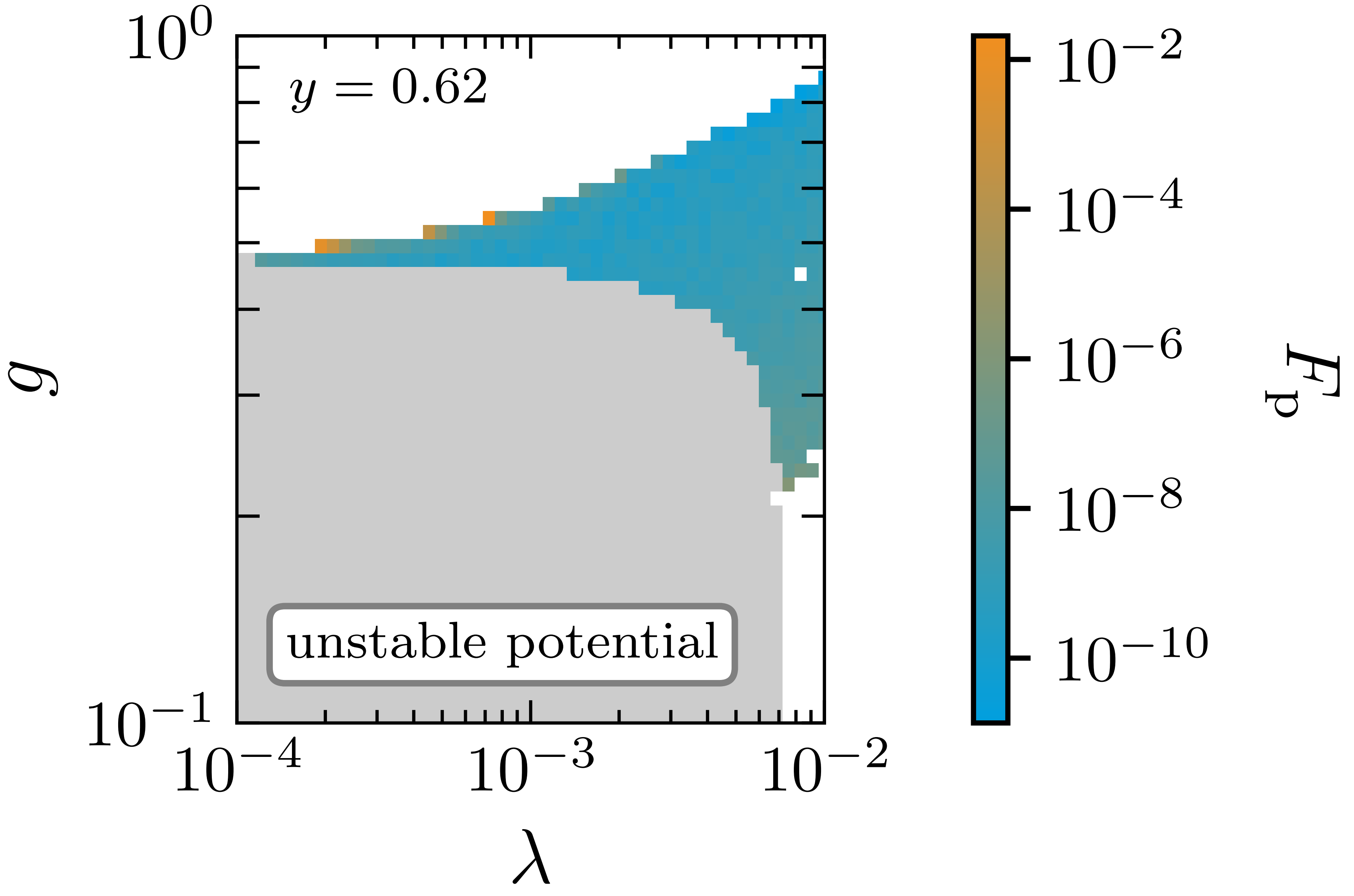


Evolution of energy densities



Out-of-equilibrium fraction of the dark sector



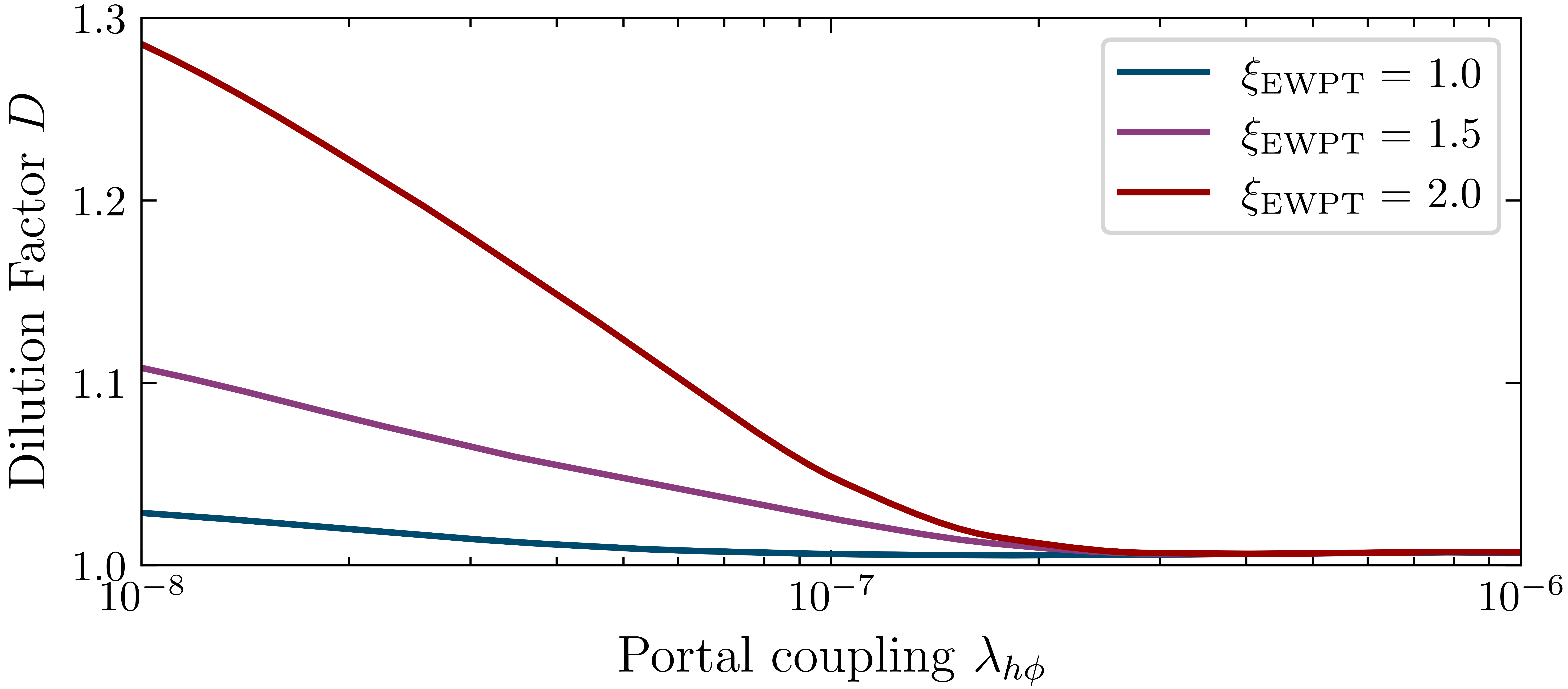


$$F(t) \equiv P(t-\tau) - P(t) > 0$$

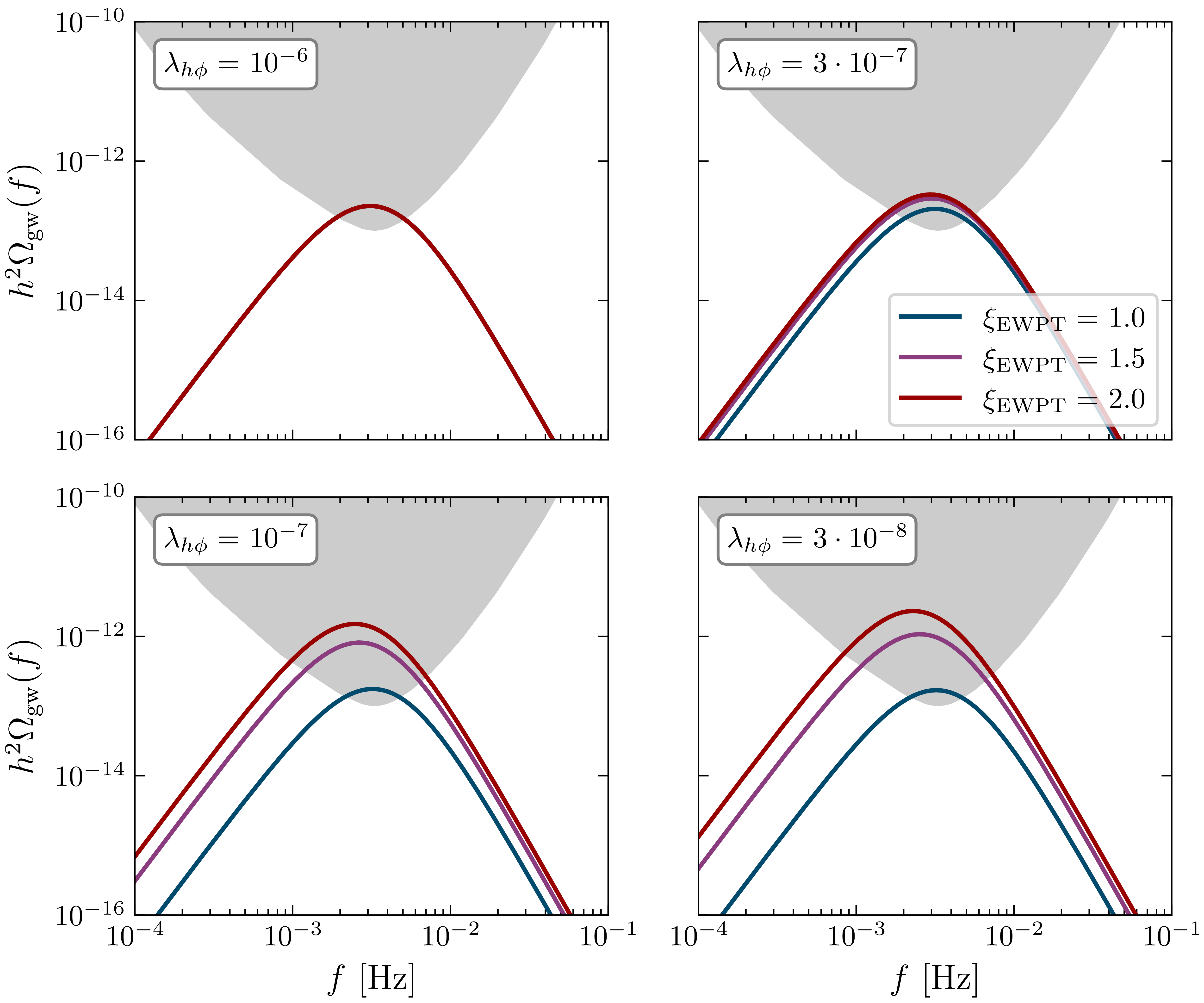
$$\begin{aligned} F(t) &\approx \exp\left(-0.34 e^{\beta(t-t_p-\tau)}\right) - \exp\left(-0.34 e^{\beta(t-t_p)}\right) \\ &\approx \beta\tau e^{\beta(t-t_p)} \exp\left(-0.34 e^{\beta(t-t_p)}\right) \leq 0.37\beta\tau\,. \end{aligned} \tag{4.6}$$

Here, the last term follows by inserting the time at which $F(t)$ peaks, which is found to be $t \approx t_p - 1.08/\beta$. 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.

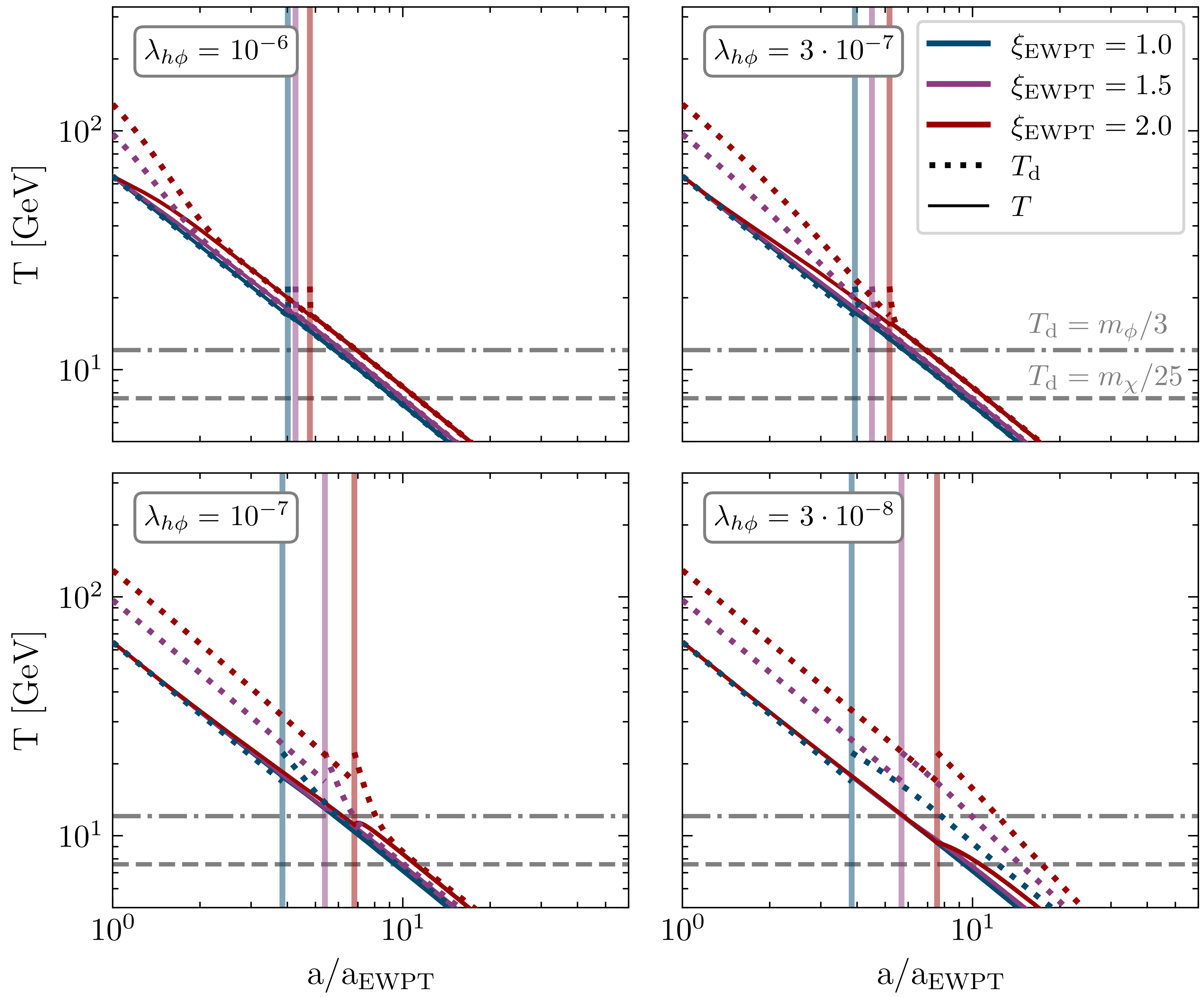
Dilution effect



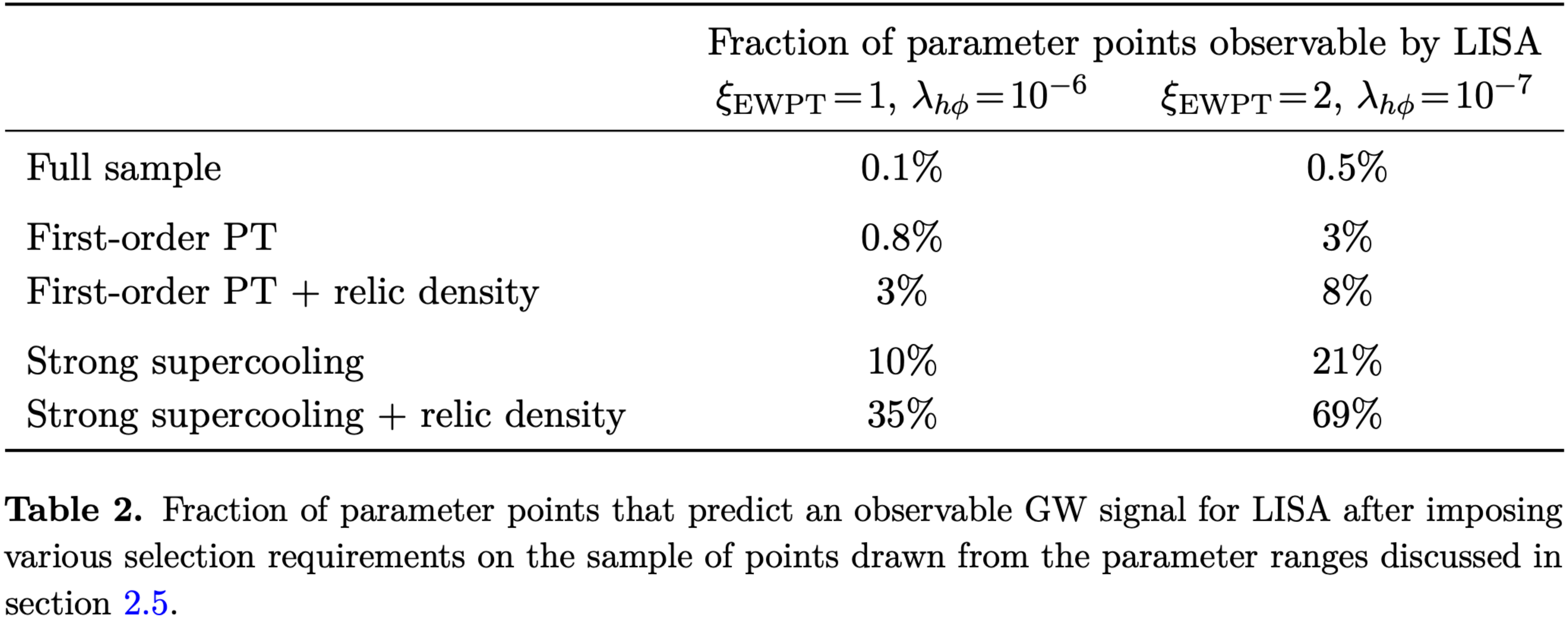
Effect of $\lambda_{h\phi}$ and ξ



Temperature evolution in the dark sector



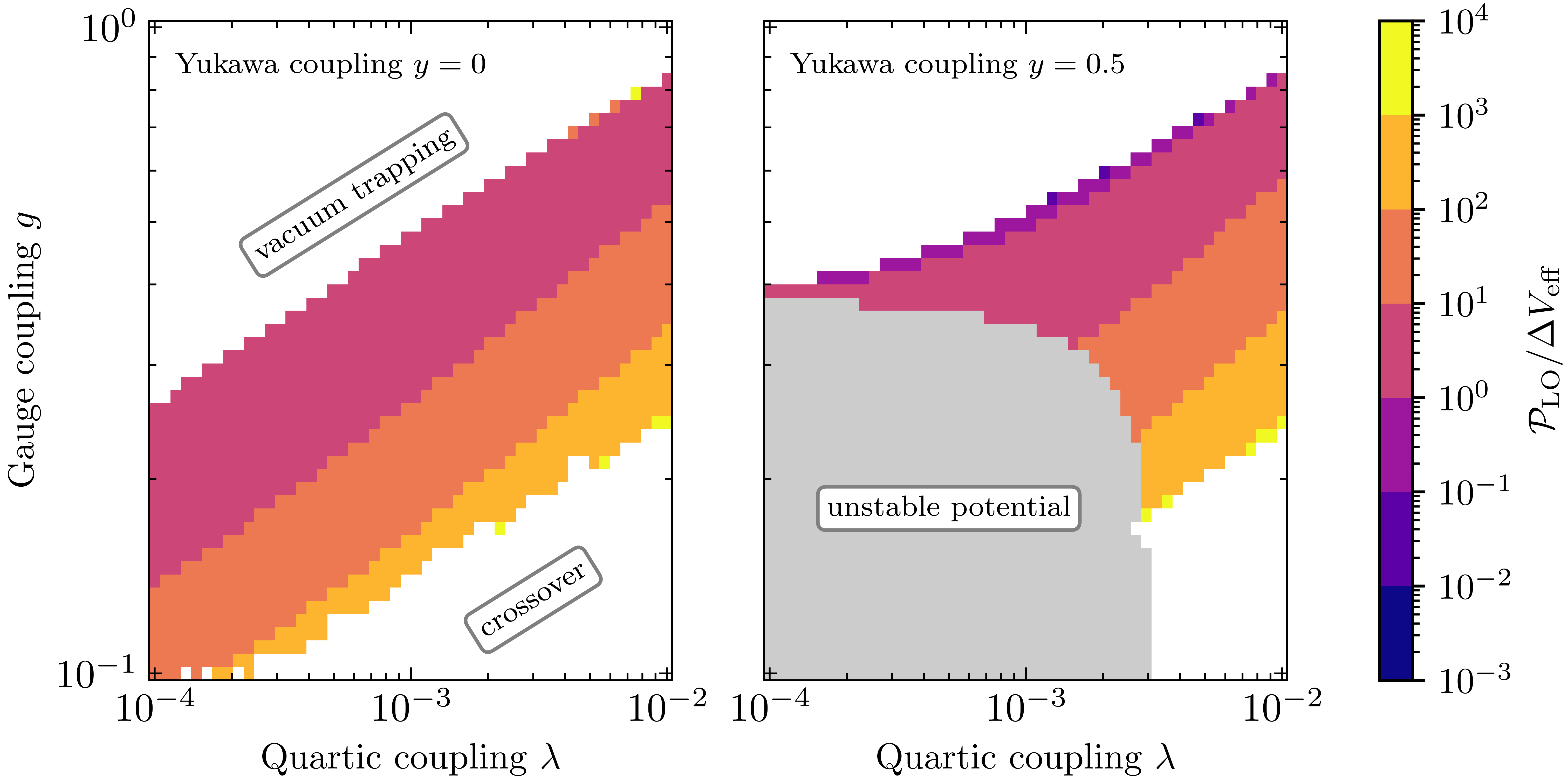
Detection probabilities



	Fraction of parameter points observable by LISA	
	$\xi_{\mathrm{EWPT}}=1,\ \lambda_{h\phi}=10^{-6}$	$\xi_{\mathrm{EWPT}}=2,\ \lambda_{h\phi}=10^{-7}$
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



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