The (first) LISA miracle

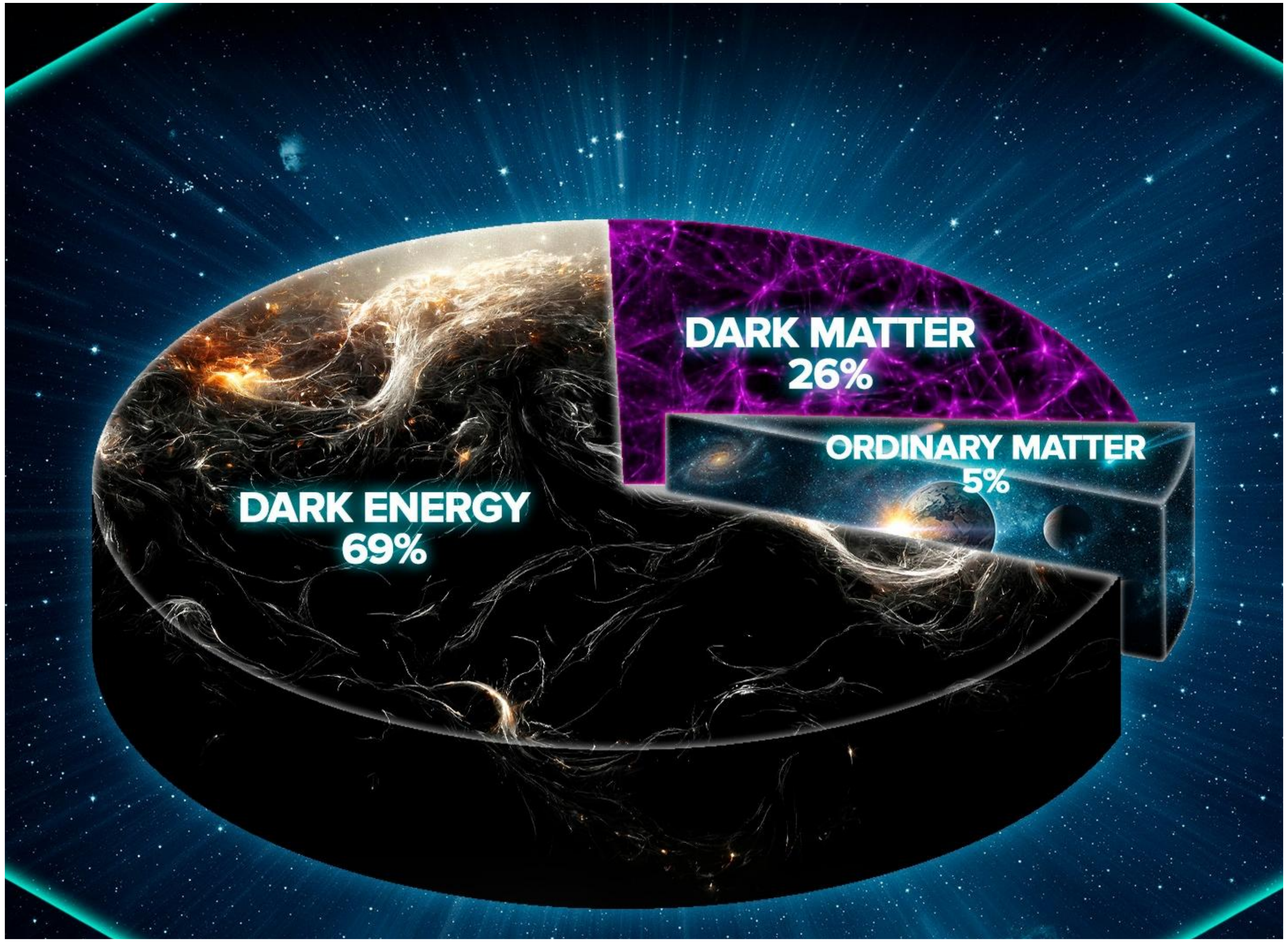
DESY theory workshop 2024
„Whispers from the dark universe“
September 26th, 2024

Carlo Tasillo,
Deutsches Elektronen-Synchrotron (DESY)

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

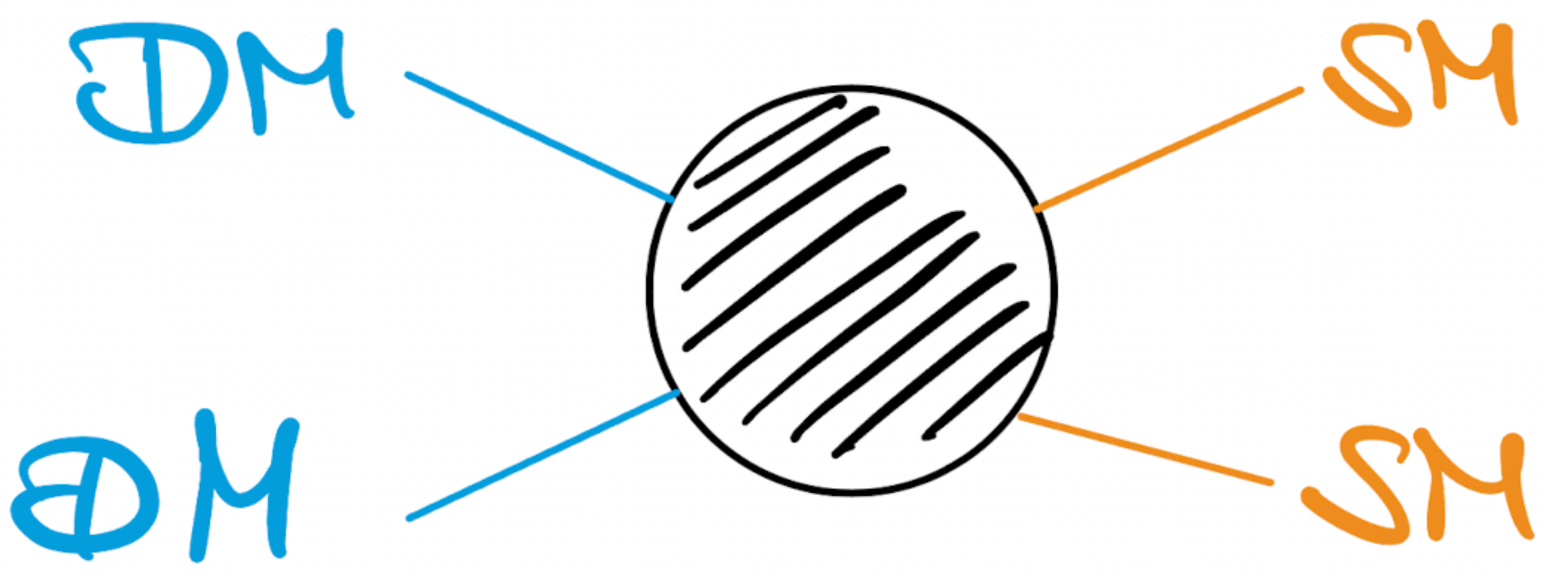
$$\boxed{\Omega_{\rm DM}h^2 = 0.12}$$

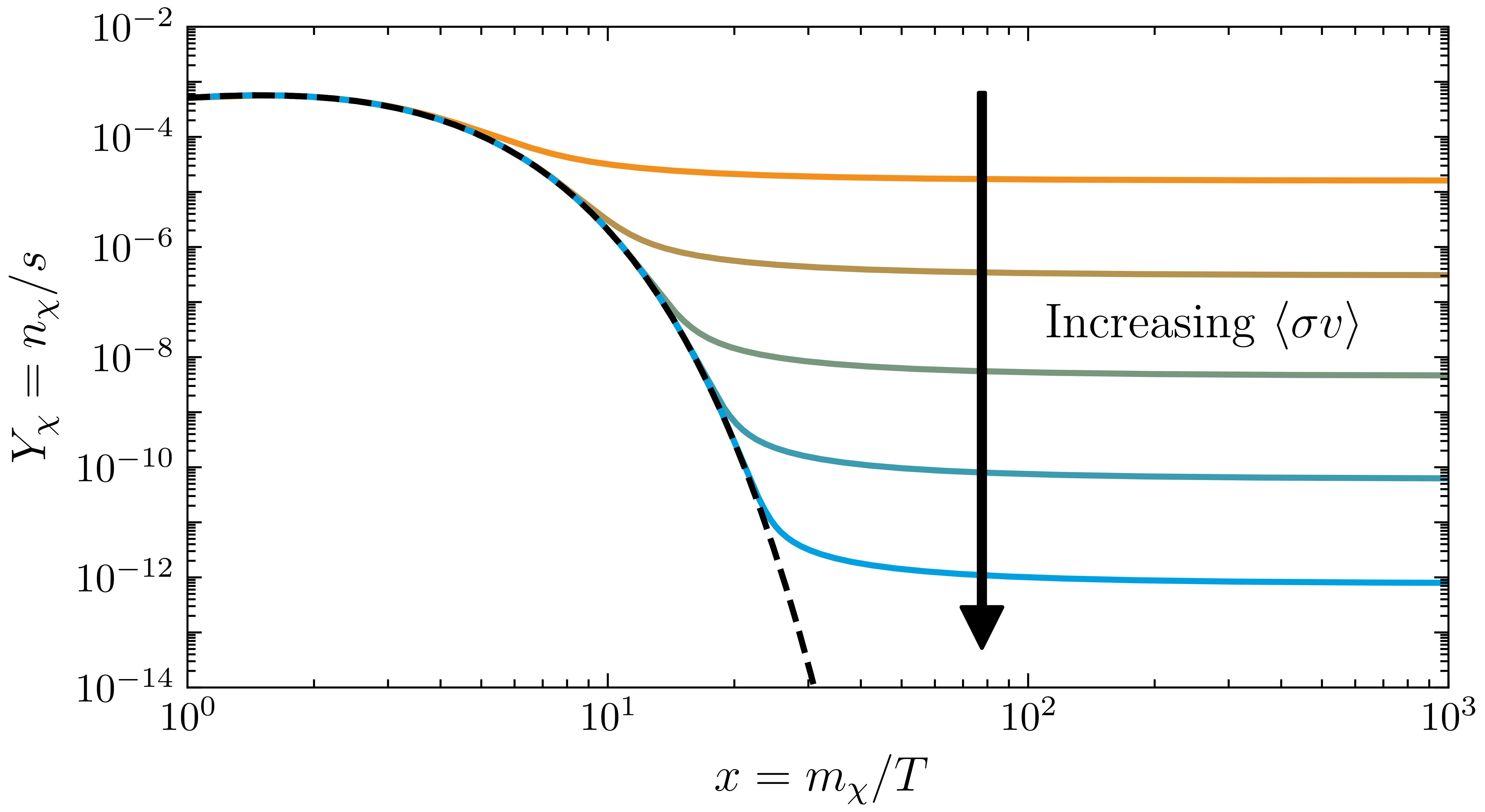
of cold dark matter in order to explain the CMB, galaxy clustering, the bullet cluster, galactic rotation curves, ...

Cirelli+ [2406.01705]

The WIMP miracle.

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



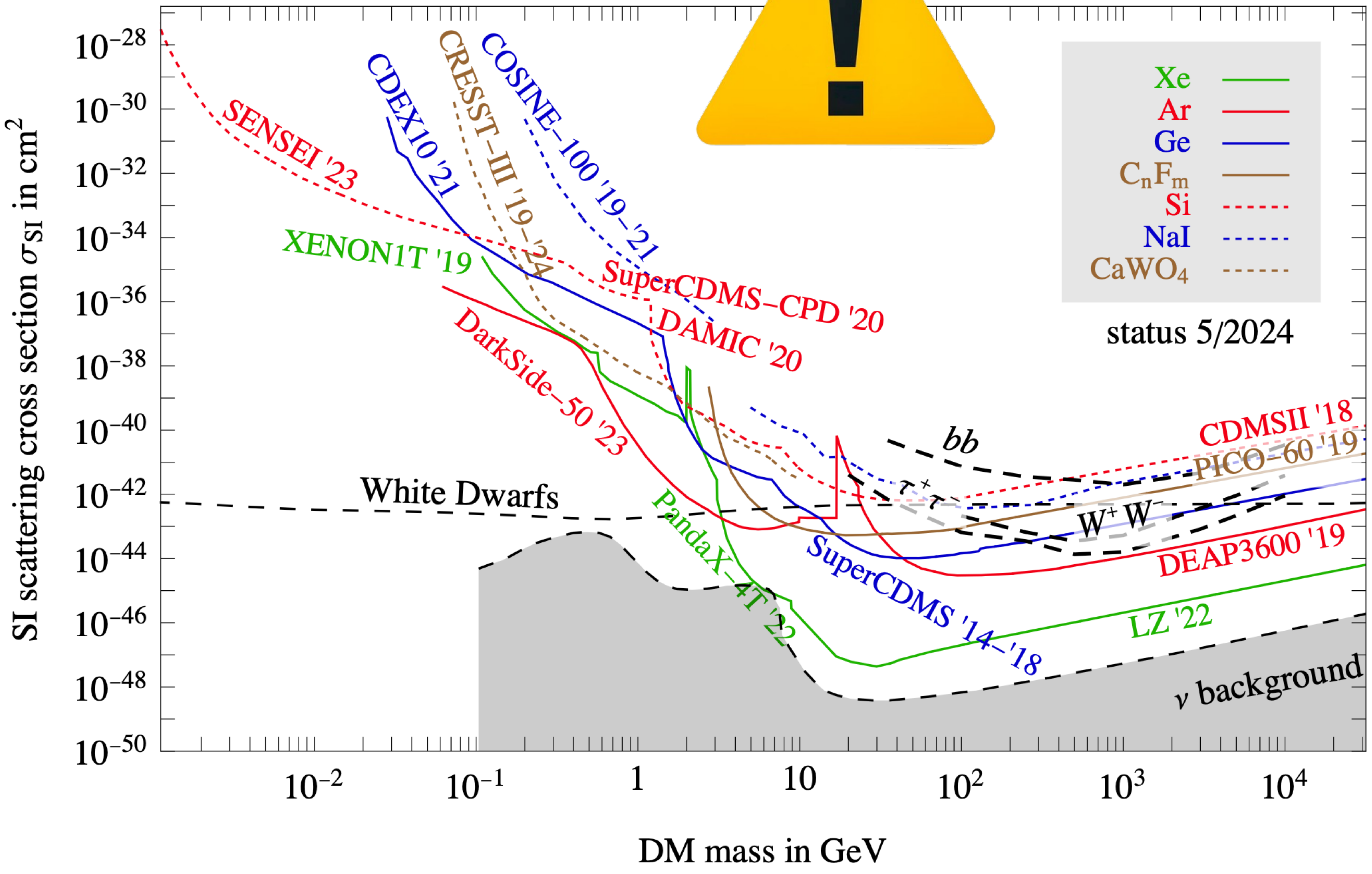


… the DM abundance can freeze out to the observed relic abundance for weak interactions and $m_{\text{DM}} \simeq \mathcal{O}(\text{TeV})$.

Rage, rage against the dying of the WIMP.

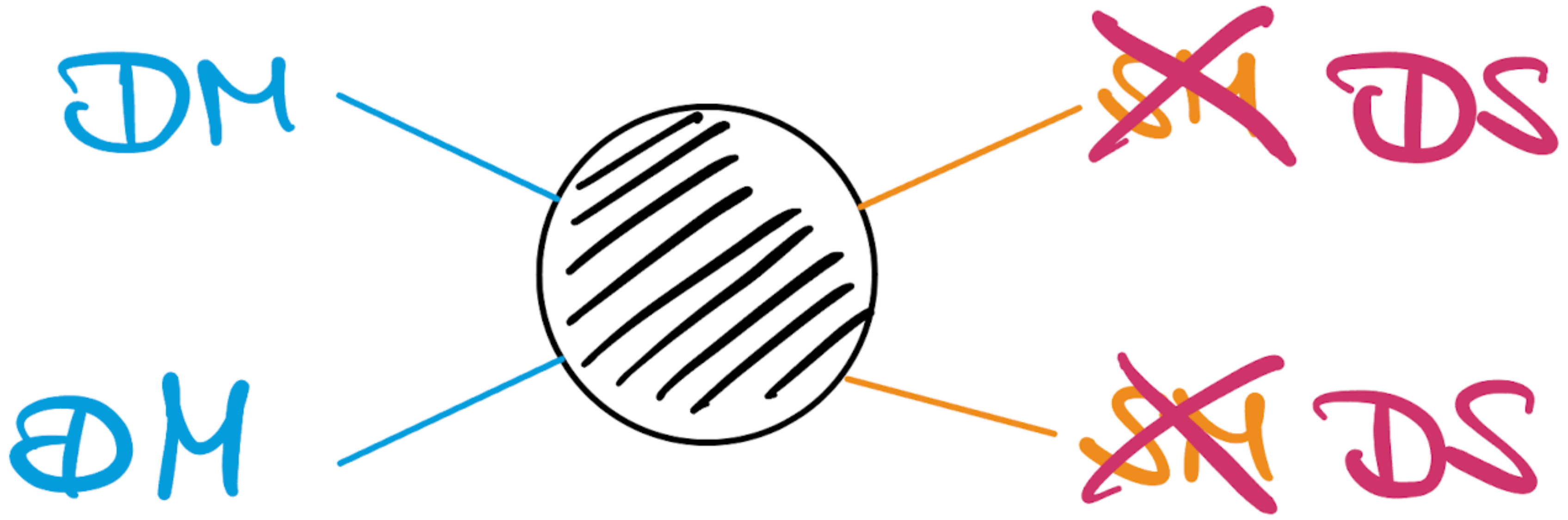
Direct detection experiments put this scenario under pressure, excluding „vanilla“ WIMPs.

[Lindner+ 2403.15860]



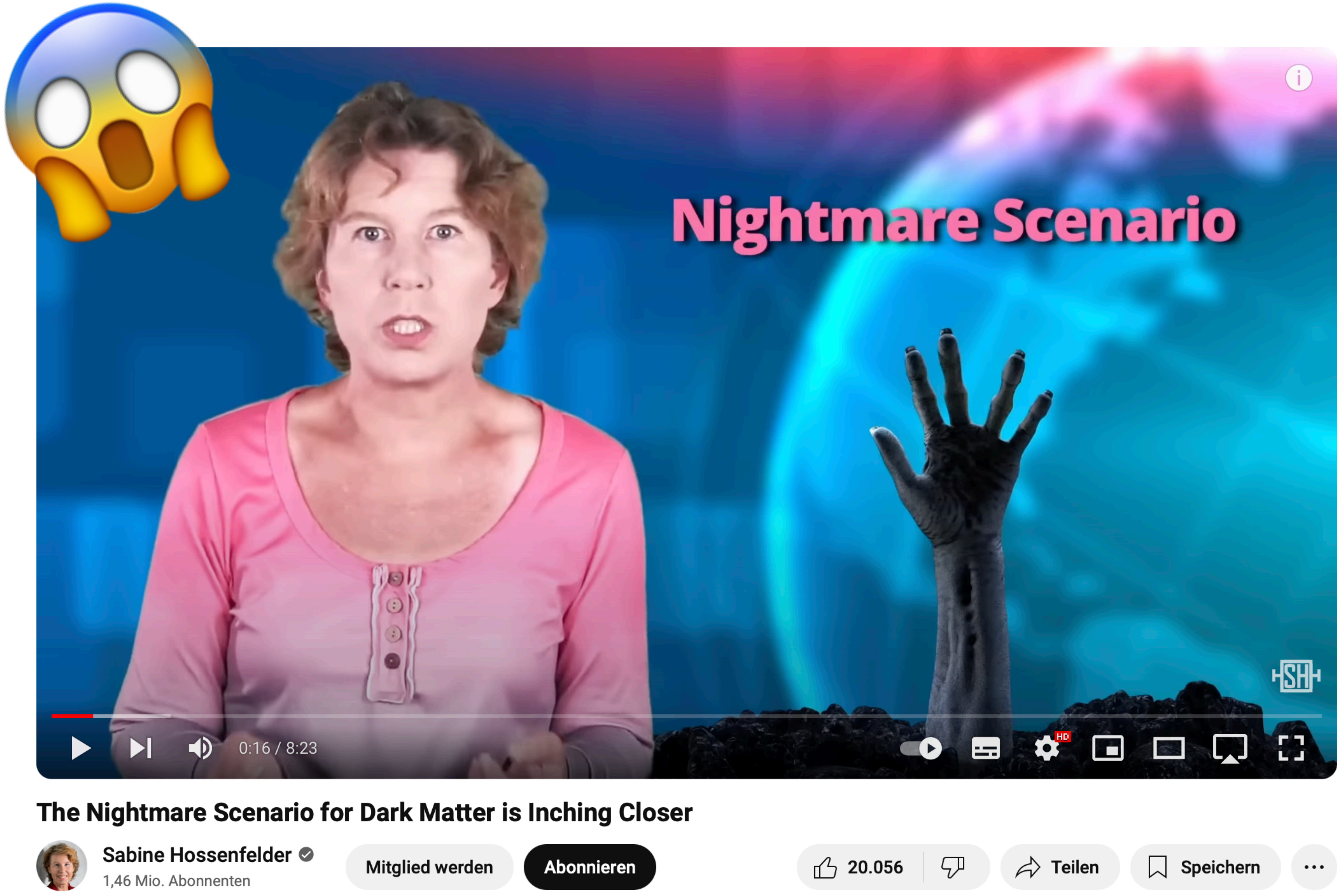
Cirelli+ [2406.01705]

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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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 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

Astro

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

rs used dead stars w form of ripple in

Monster gravitational spotted for first

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 at the center of the M

Scientists r come from c holes

it may assive black

SCIENCE

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

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

The Washington Post

Democracy Dies in Darkness

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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Ground king gravitational wave discov 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

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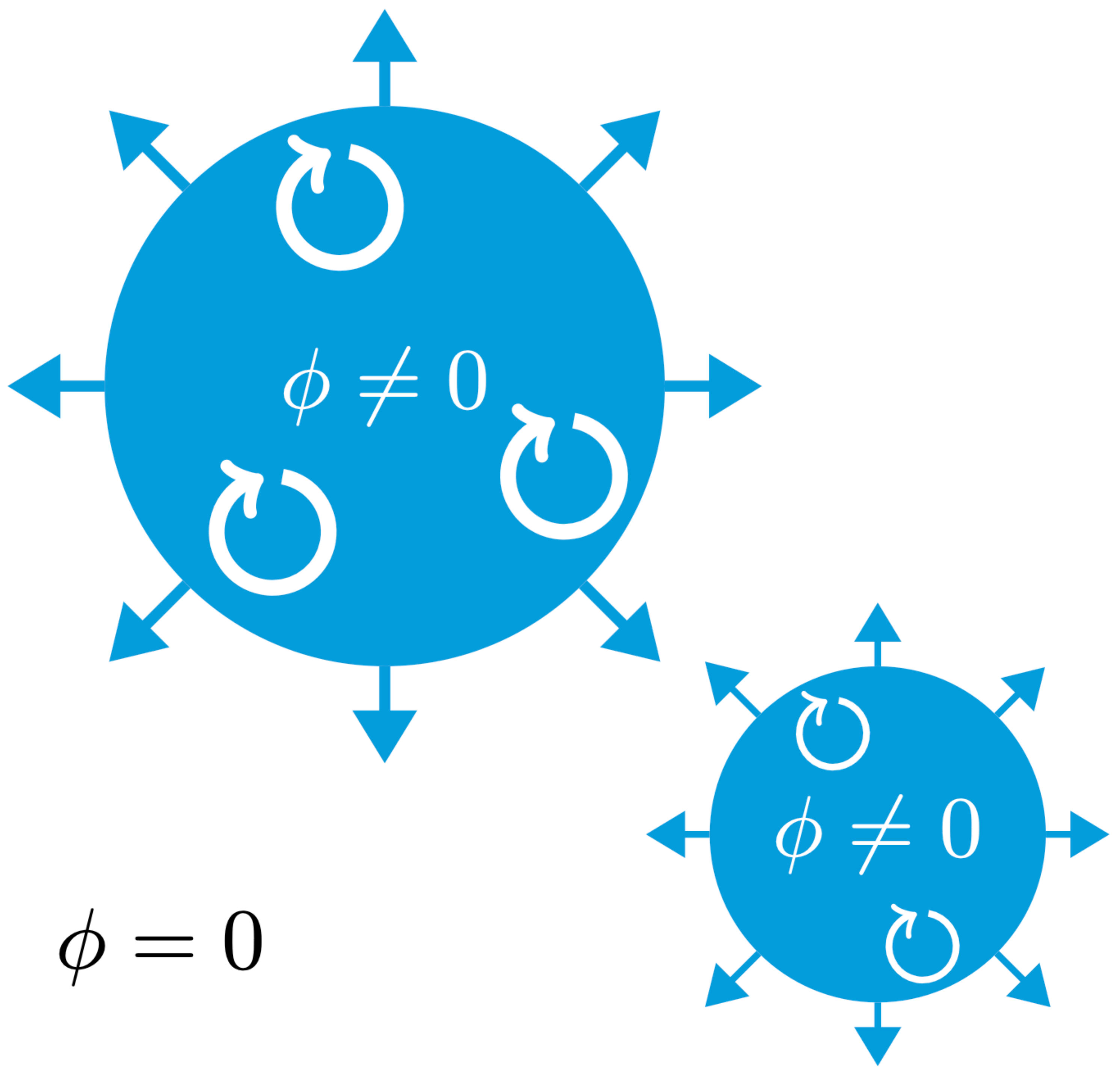
In a major discovery, scientists say space-time churns like a choppy sea

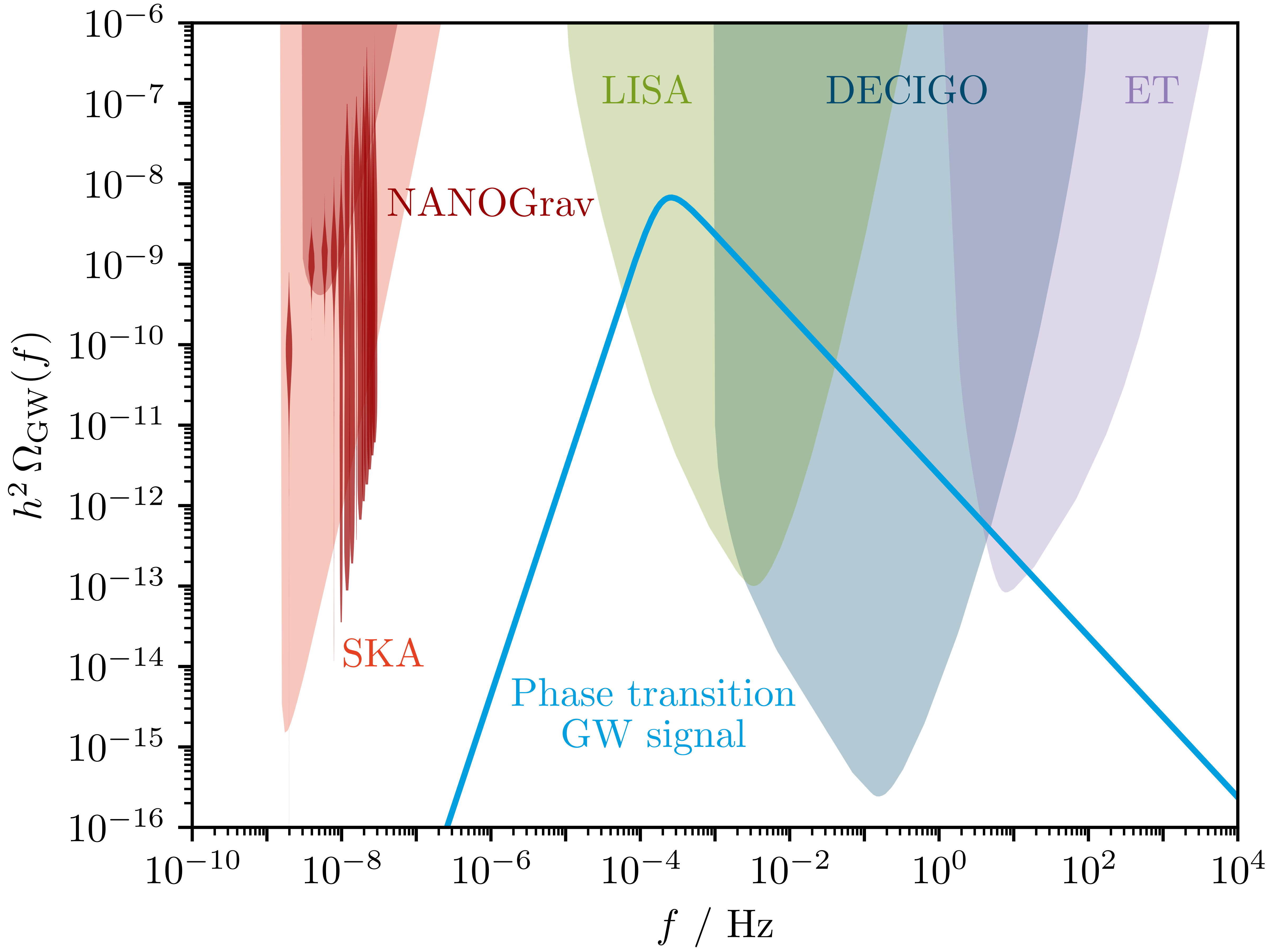
The mind-bending finding suggests that everything around us is constantly being roiled by low-frequency gravit waves

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

First-order phase transitions produce GW backgrounds.

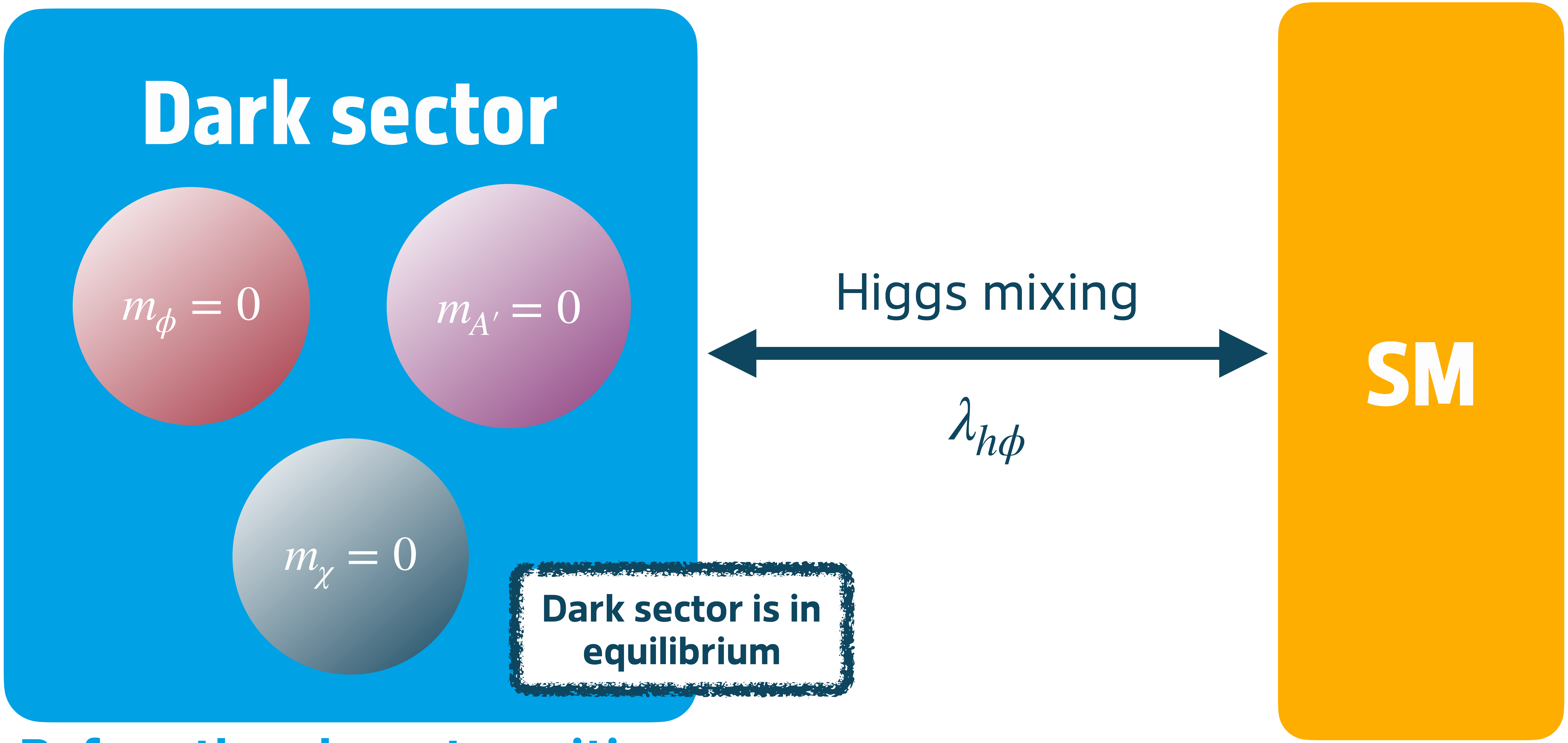
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Our model setup.



Dark sector

$m_\phi = 0$

$m_{A'} = 0$

$m_\chi = 0$

Dark sector is in equilibrium

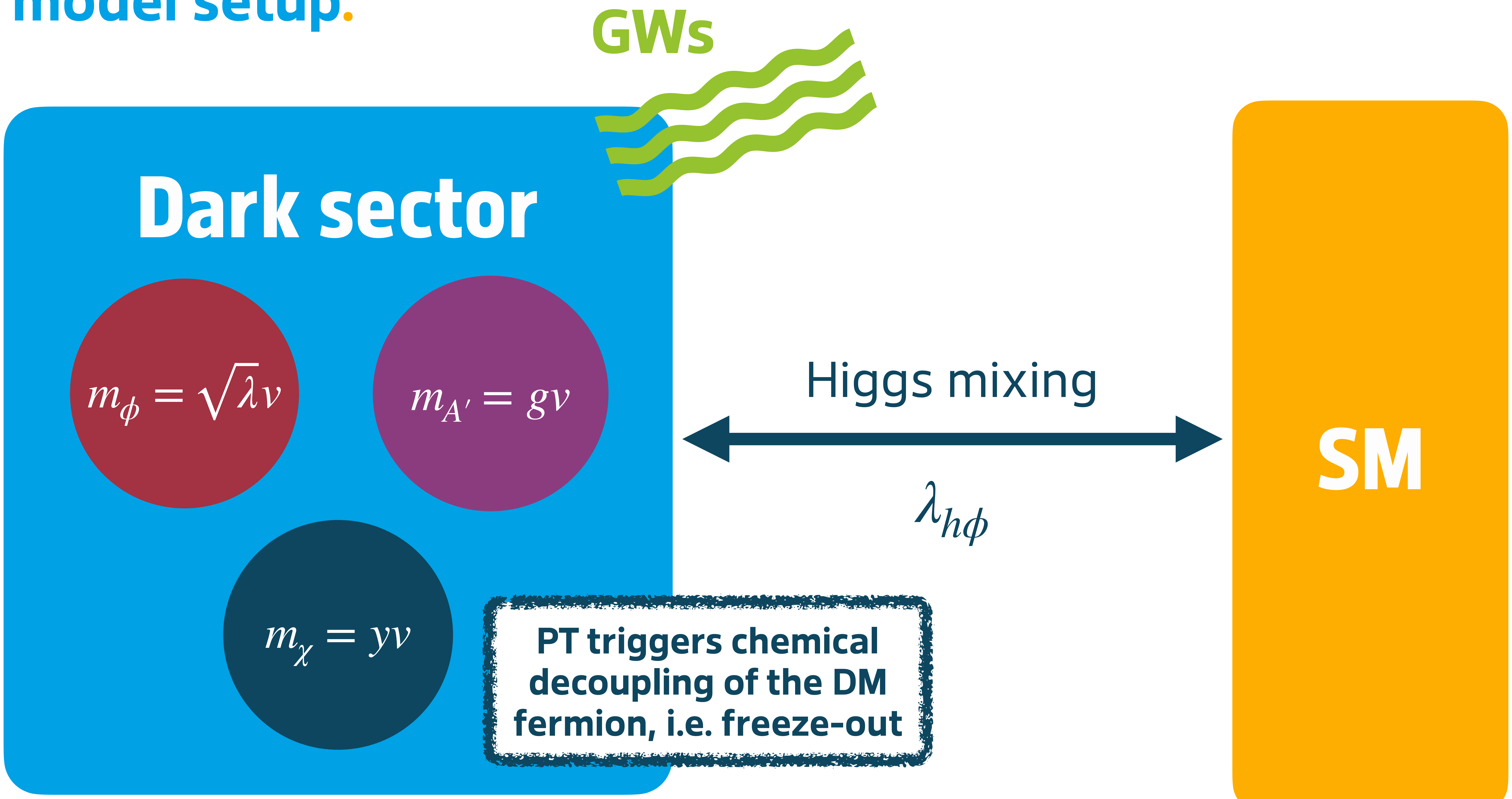
Higgs mixing

$\lambda_{h\phi}$

SM

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

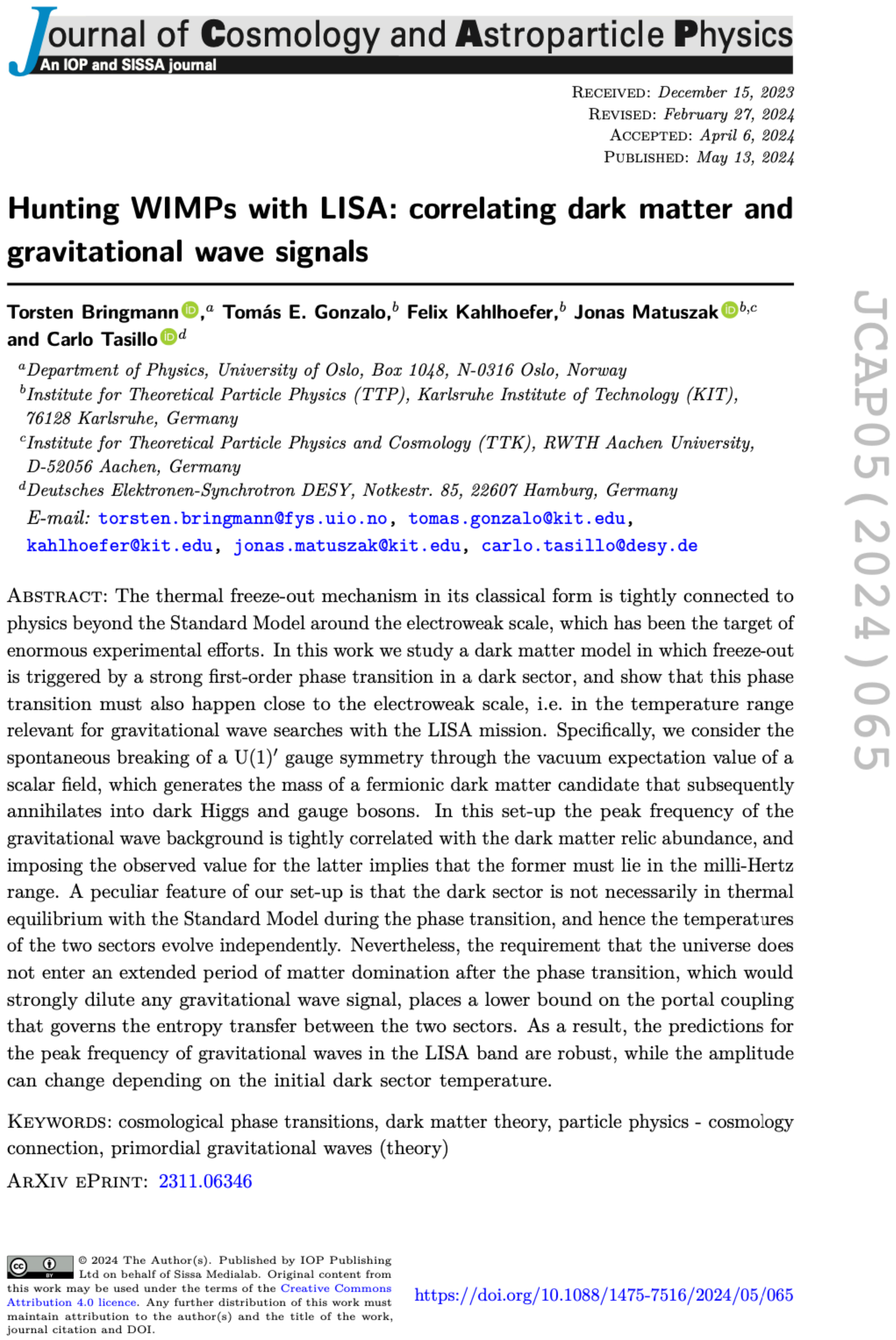
$\lambda_{h\phi}$

SM

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

After the phase transition

A first glance at our punchline.



Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Received: December 15, 2023
Revised: February 27, 2024
Accepted: April 6, 2024
Published: May 13, 2024

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

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

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

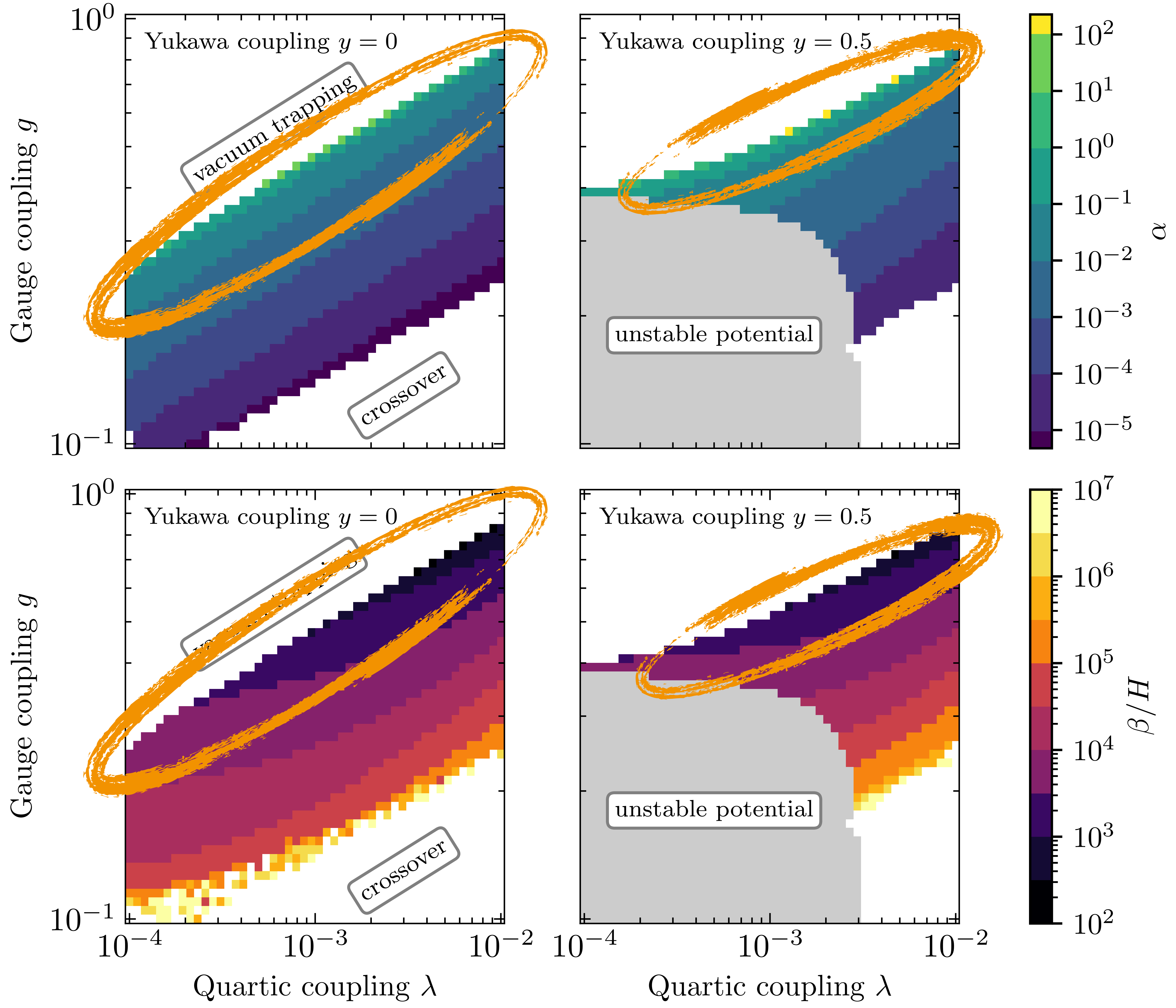
$$\langle\sigma v\rangle \sim \frac{y^4}{m_\chi^2} \sim \frac{y^2}{v^2}$$

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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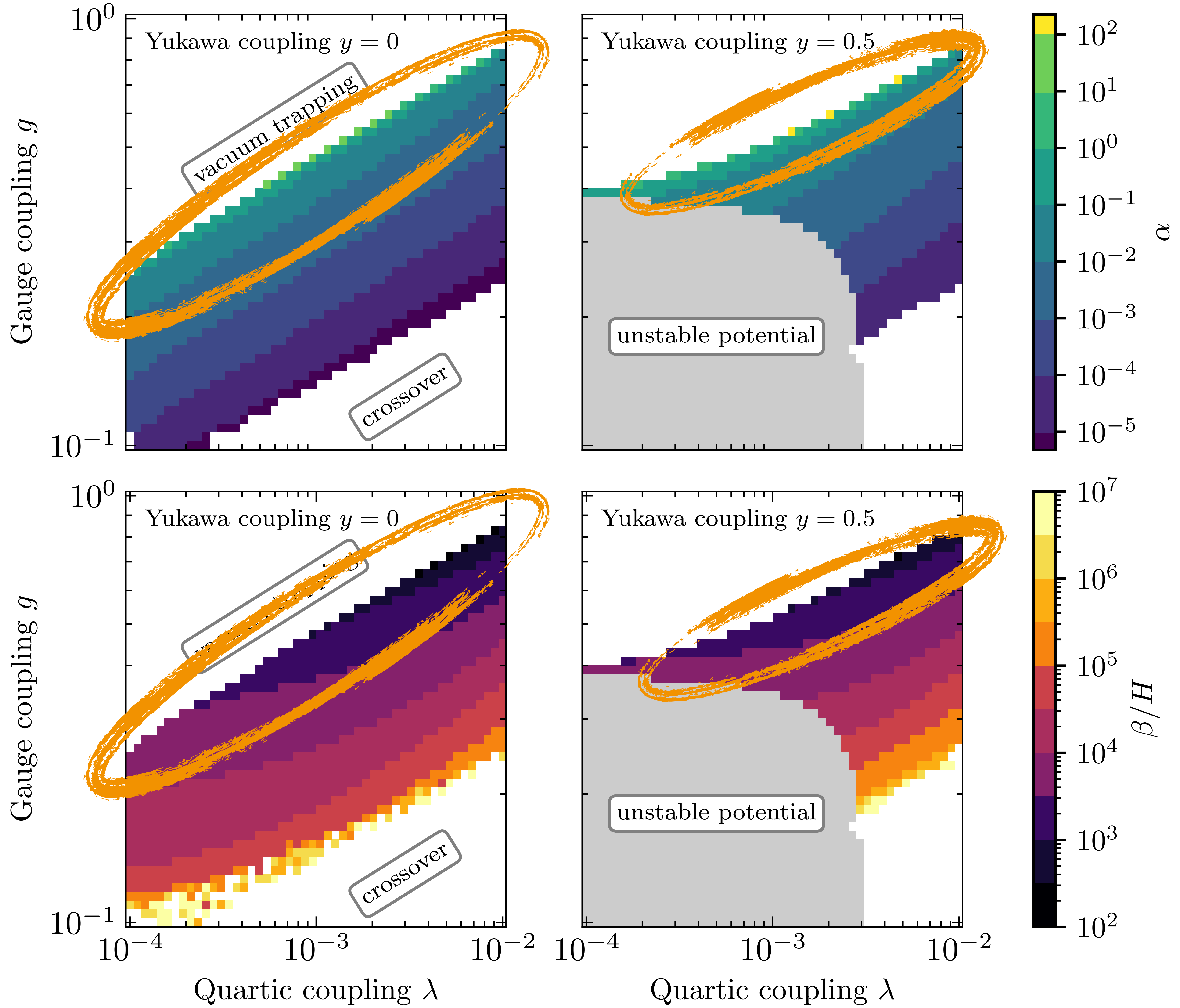
Freeze-out condition:

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



Intermediate Yukawa couplings.

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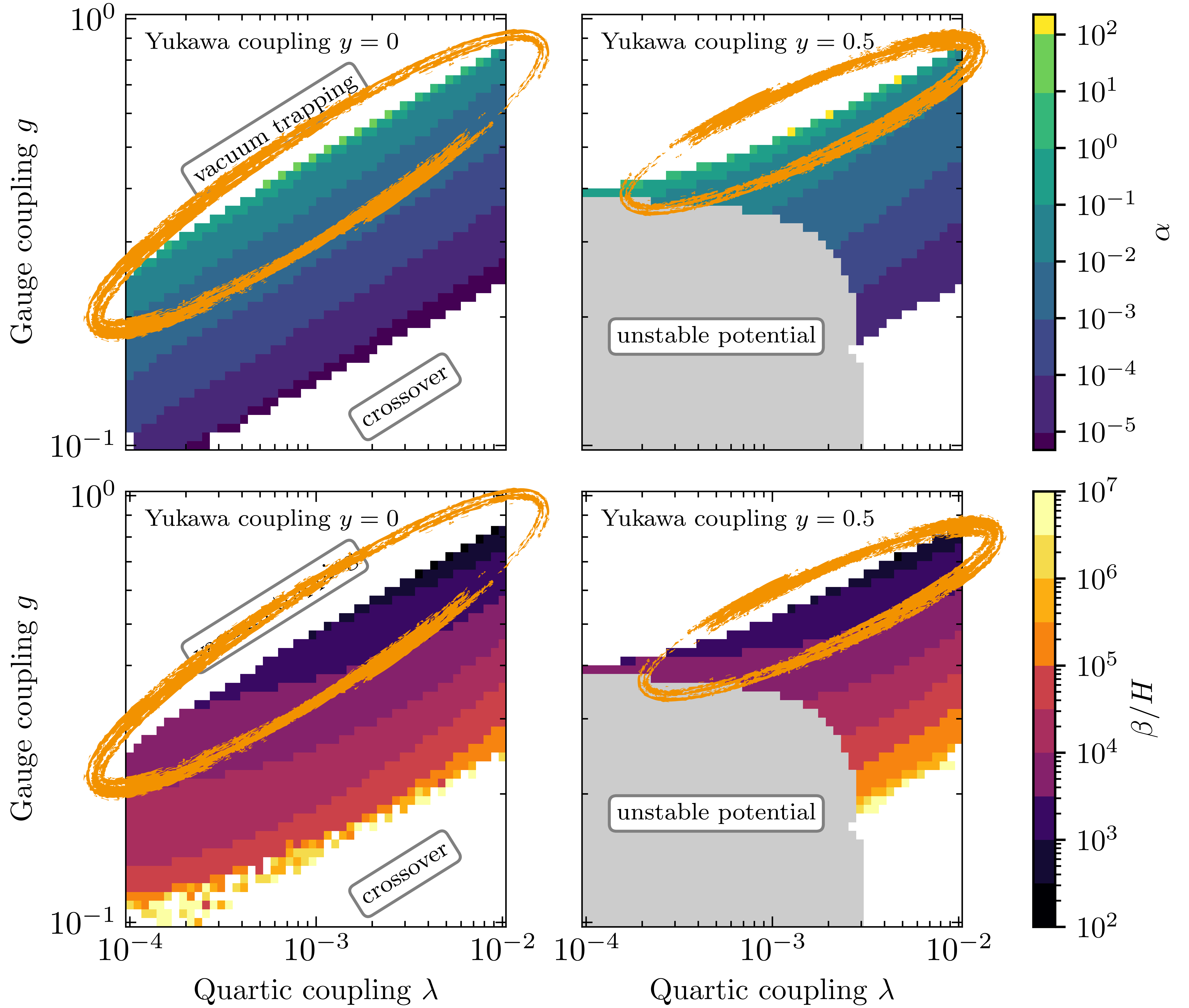
Conclusion:

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

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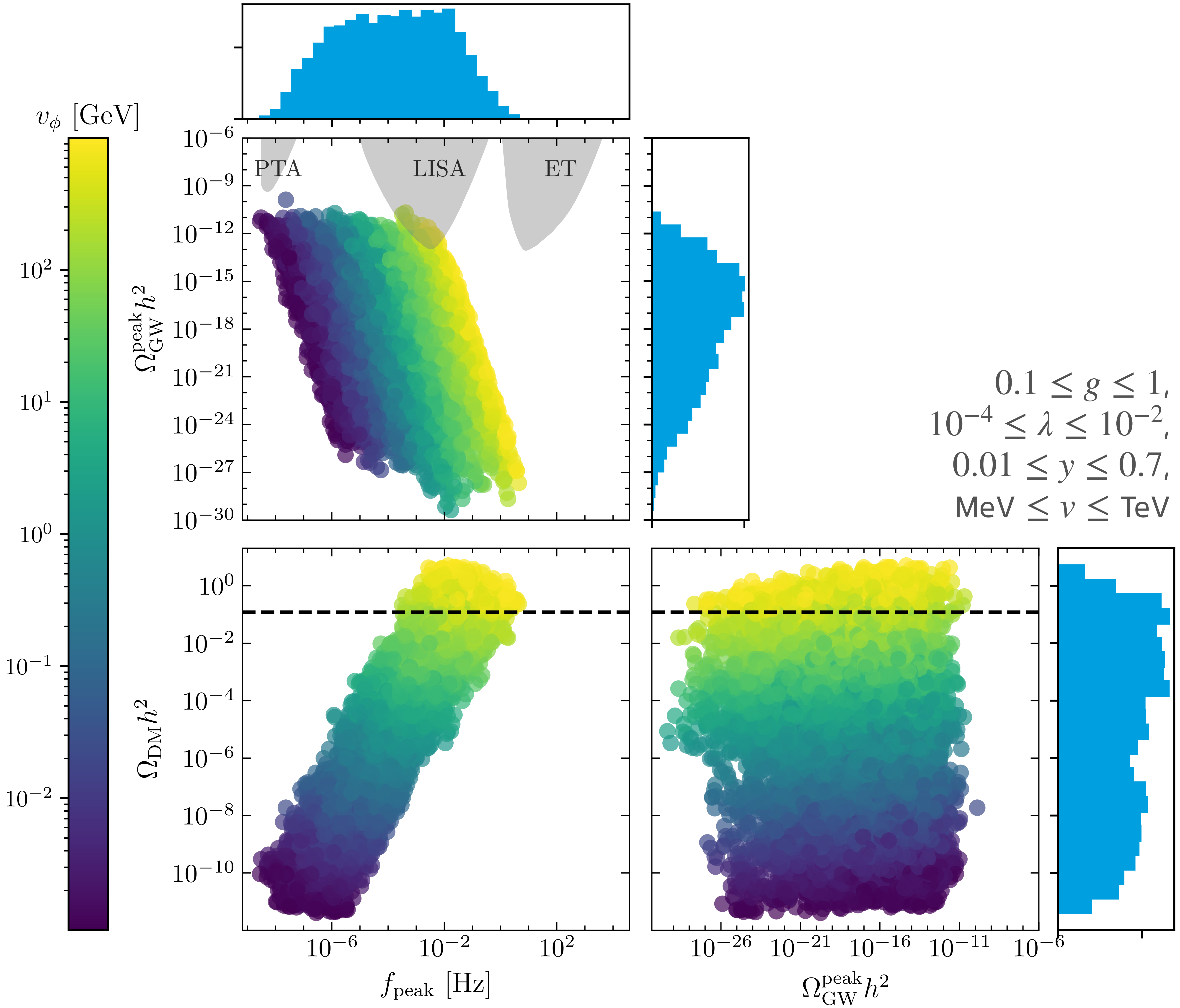
- Influence of temperature ratio $\xi = T_{\text{DS}}/T_{\text{SM}}$ on $\Omega_{\text{GW}}(f)$ and Ω_{DM}?
- $\lambda_{h\phi}$: Collider bounds? Early matter domination?

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

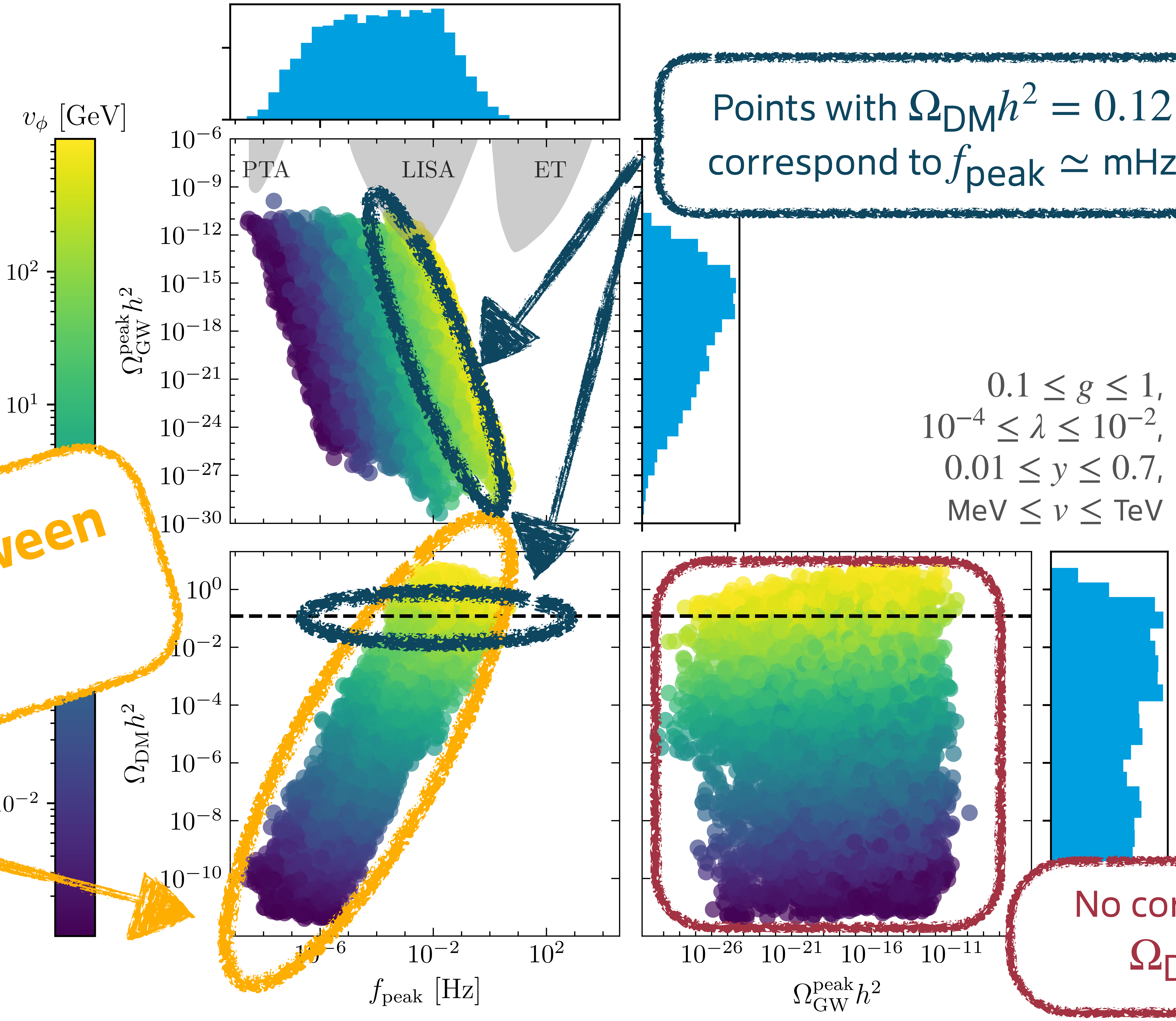
* TransitionListener & DarkSUSY [Ertas+ 2109.06208, Bringmann+ 1802.03399]

Results of our scans.



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

Results of our scans.



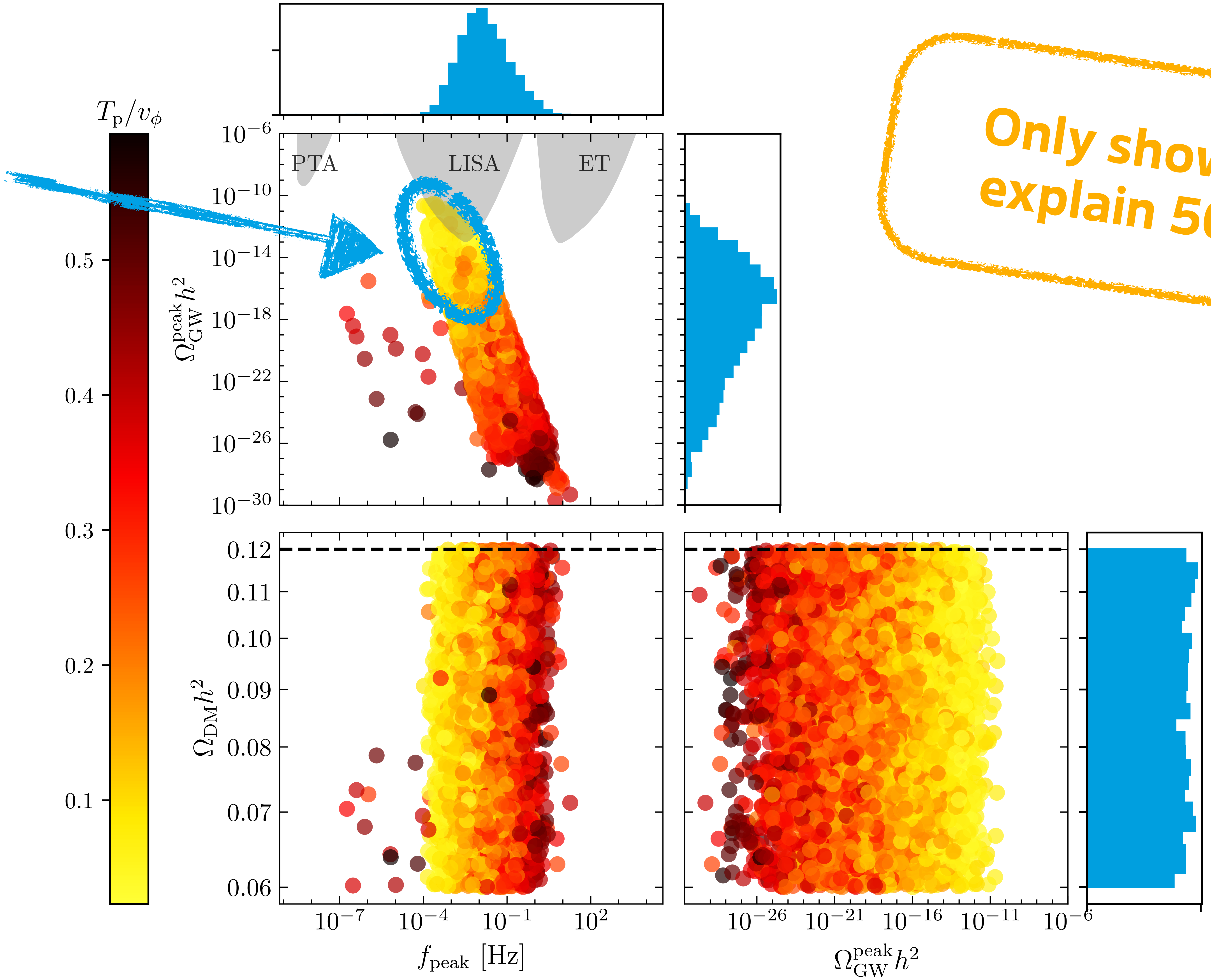
Points with $\Omega_{\rm DM} h^2 = 0.12$ correspond to $f_{\rm peak} \simeq$ mHz

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

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

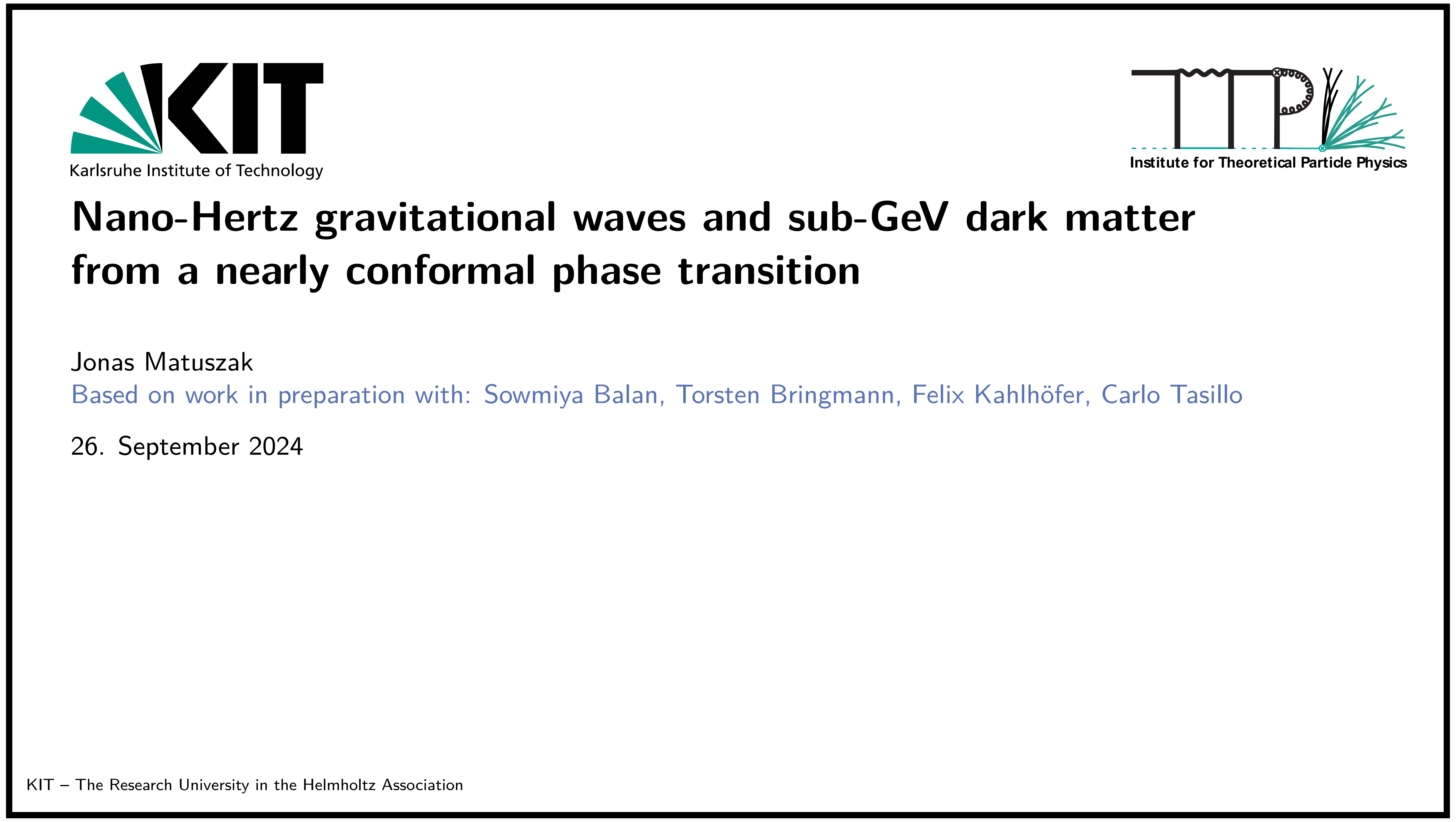
Only show points which explain 50-100% of DM

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

Ongoing work.

Is there a LISA miracle also for other model classes? What about conformal models? Can we explain PTA data?

See Jonas' talk!



Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

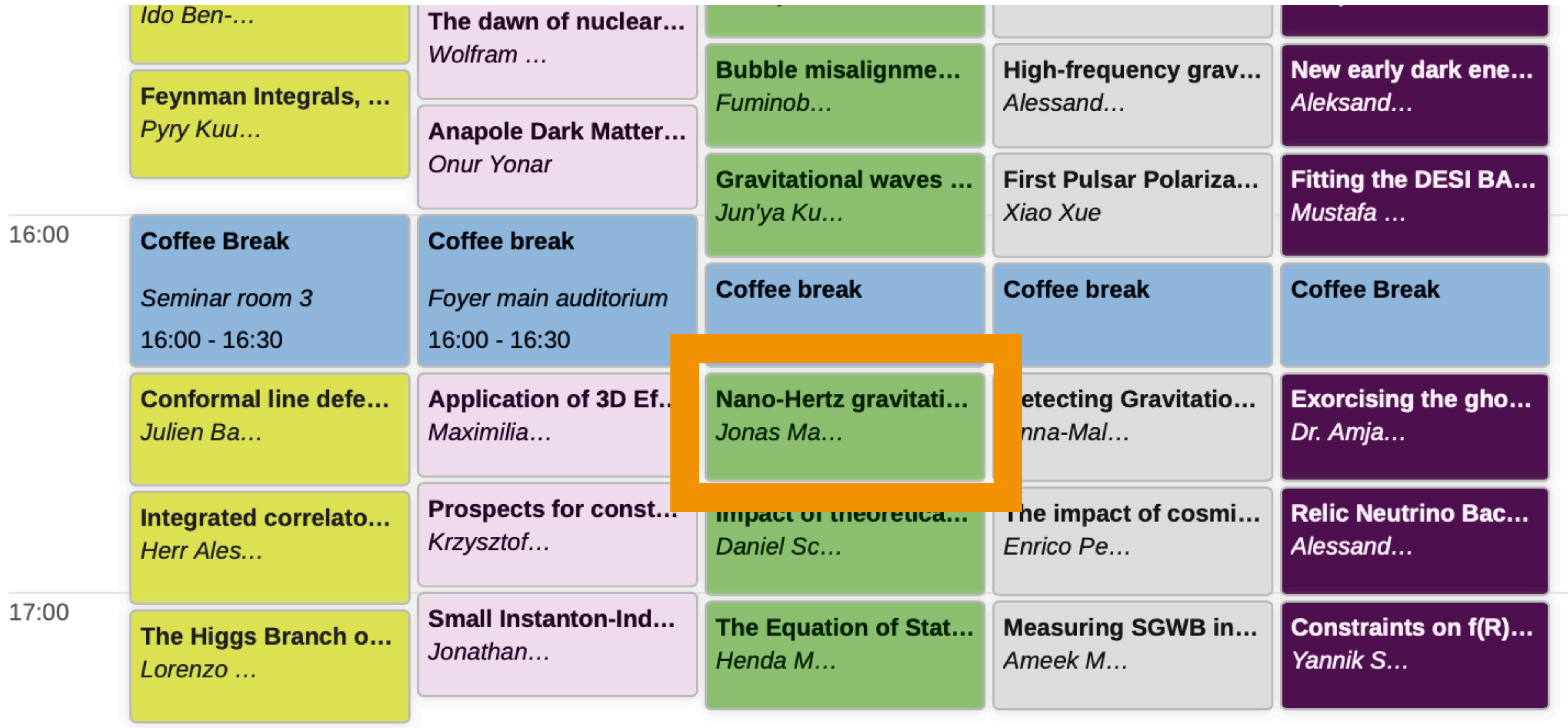
Nano-Hertz gravitational waves and sub-GeV dark matter from a nearly conformal phase transition

Jonas Matuszak

Based on work in preparation with: Sowmiya Balan, Torsten Bringmann, Felix Kahlhöfer, Carlo Tasillo

26. September 2024

KIT – The Research University in the Helmholtz Association



16:00

17:00

Ido Ben-…

Feynman Integrals, …
Pyry Kuu…

Coffee Break
Seminar room 3
16:00 - 16:30

Conformal line defe…
Julien Ba…

Integrated correlato…
Herr Ales…

The Higgs Branch o…
Lorenzo …

The dawn of nuclear…
Wolfram …

Anapole Dark Matter…
Onur Yonar

Coffee break
Foyer main auditorium
16:00 - 16:30

Application of 3D Ef…
Maximilia…

Prospects for const…
Krzysztof…

Small Instanton-Ind…
Jonathan…

Bubble misalignme…
Fuminob…

Gravitational waves …
Jun'ya Ku…

Coffee break

Nano-Hertz gravitati…
Jonas Ma…

Impact of theoretica…
Daniel Sc…

The Equation of Stat…
Henda M…

High-frequency grav…
Alessand…

First Pulsar Polariza…
Xiao Xue

Coffee break

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he impact of cosmi…
Enrico Pe…

Measuring SGWB in…
Ameek M…

New early dark ene…
Aleksand…

Fitting the DESI BA…
Mustafa …

Coffee Break

Exorcising the gho…
Dr. Amja…

Relic Neutrino Bac…
Alessand…

Constraints on f(R)…
Yannik S…

Summary.

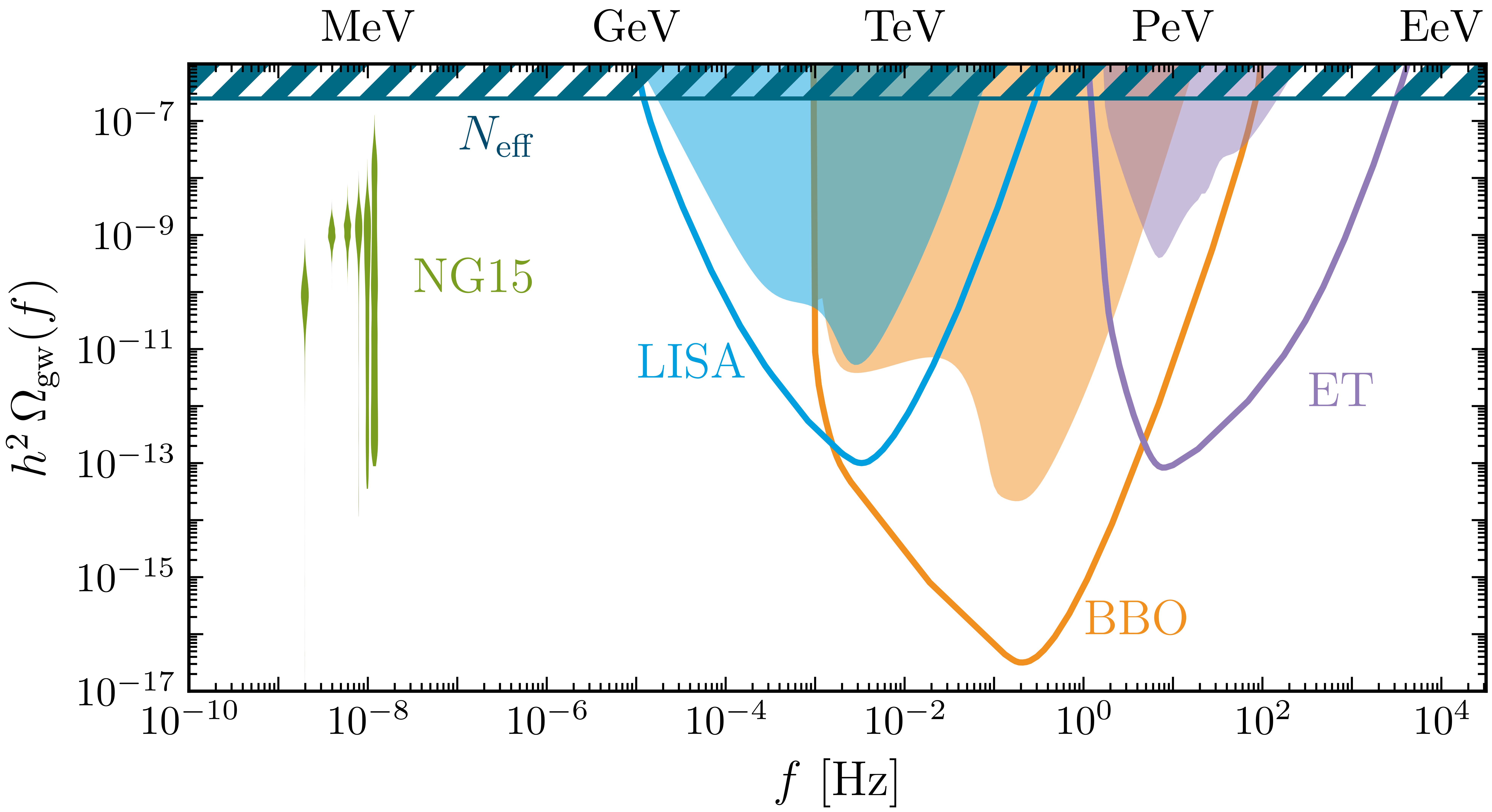
The *first* LISA miracle:

- In our $U(1)'$ model there is a robust correlation between f_{peak} and Ω_{DM}
- $\Omega_{\text{DM}}h^2 = 0.12$ corresponds to mHz frequencies, i.e. the LISA band
- A future LISA detection of a GW background would hint towards secluded DS freeze-out
- Ongoing work on other model setups

Thank you very much for your attention!

Do you have any questions?

Backup: Current bounds on cosmic GW backgrounds.



Backup: 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

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

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

Backup: GWB details.

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

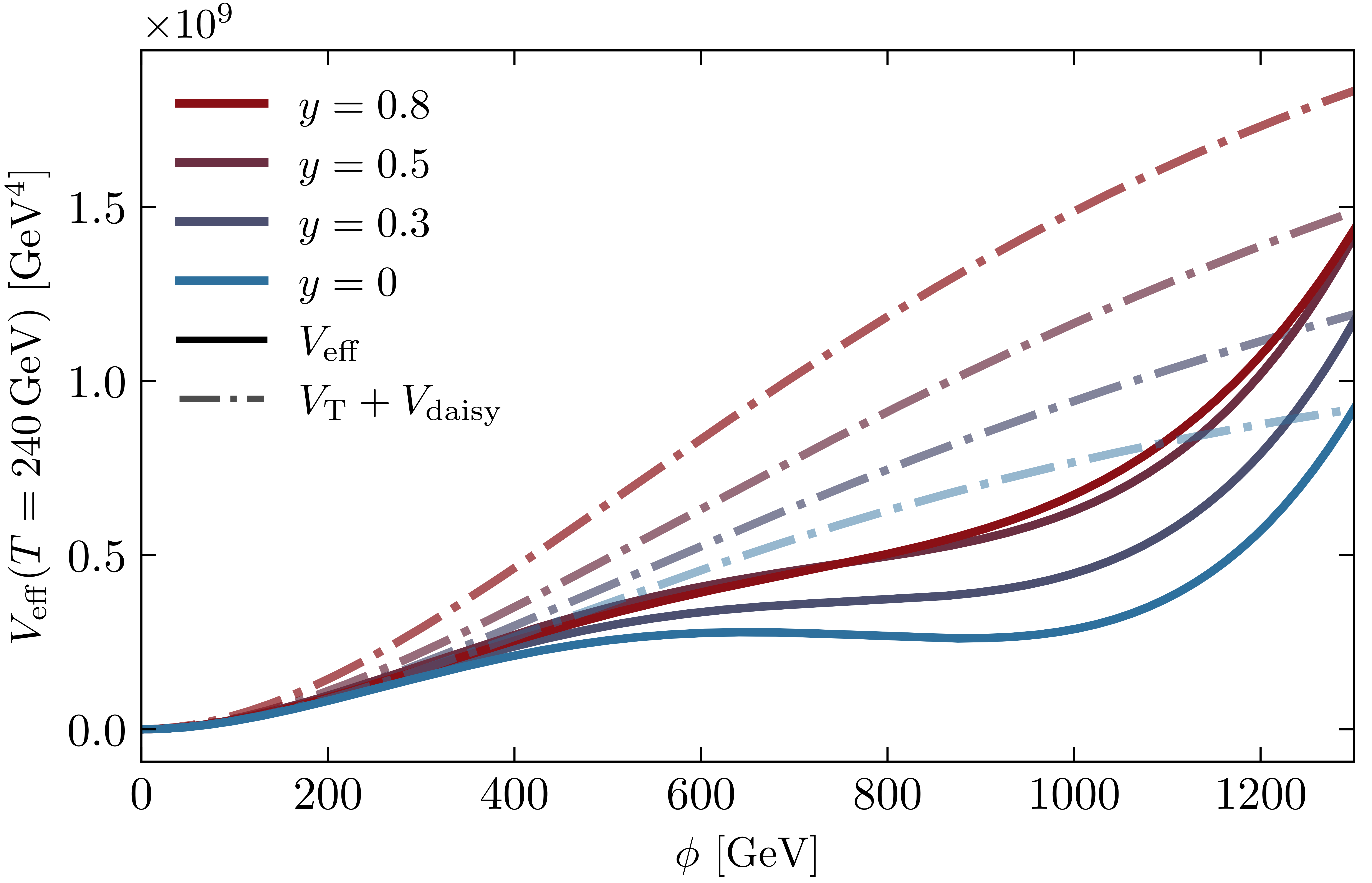
$$\mathcal{R}h^2 = \Omega_\gamma h^2\left(\frac{h_{\rm SM,0}}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{g_{\gamma,0}}\right) = 1.653\cdot 10^{-5}\left(\frac{100}{h_{\rm tot,p}}\right)^{4/3}\left(\frac{g_{\rm tot,p}}{100}\right)$$

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

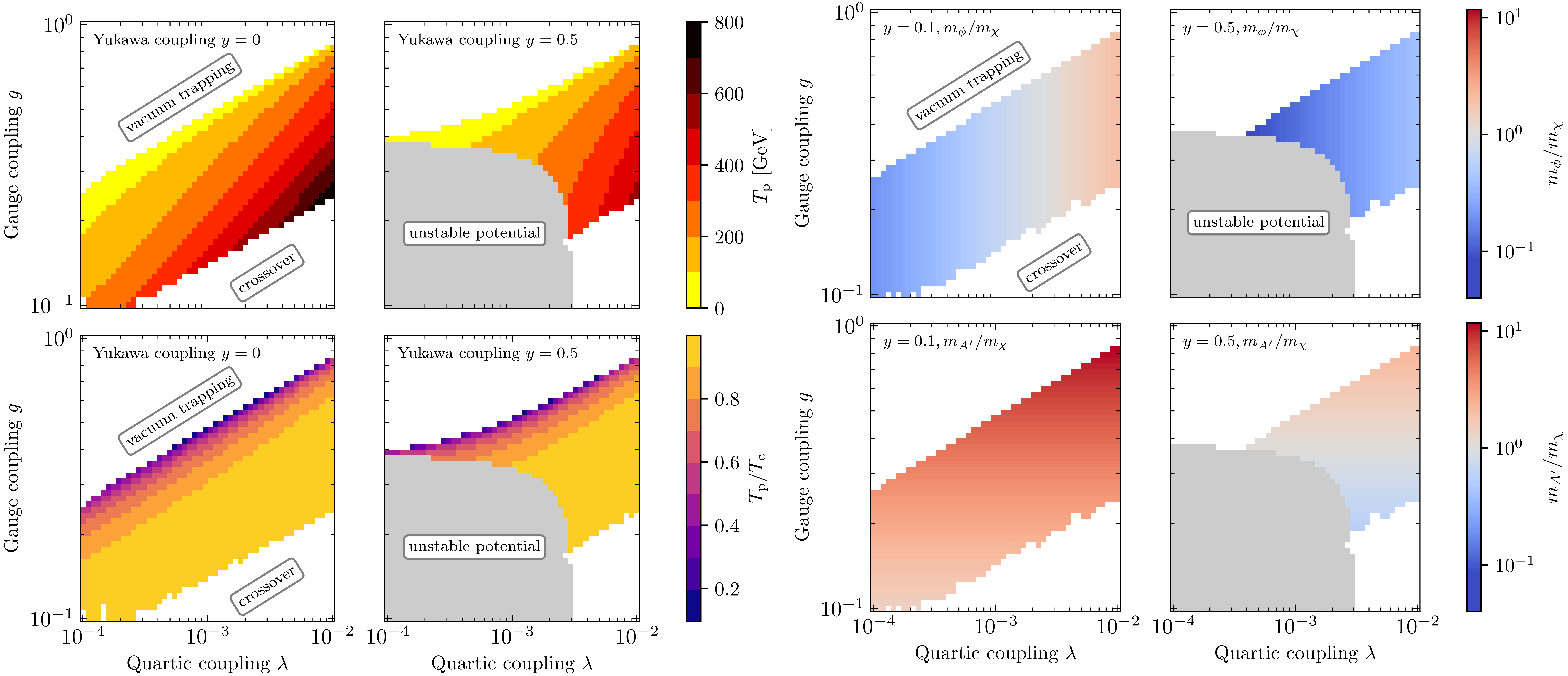
$$S(f) = \left(\frac{f}{f_{\rm peak}}\right)^3\left(\frac{7}{4+3\,(f/f_{\rm peak})^2}\right)^{7/2}$$

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

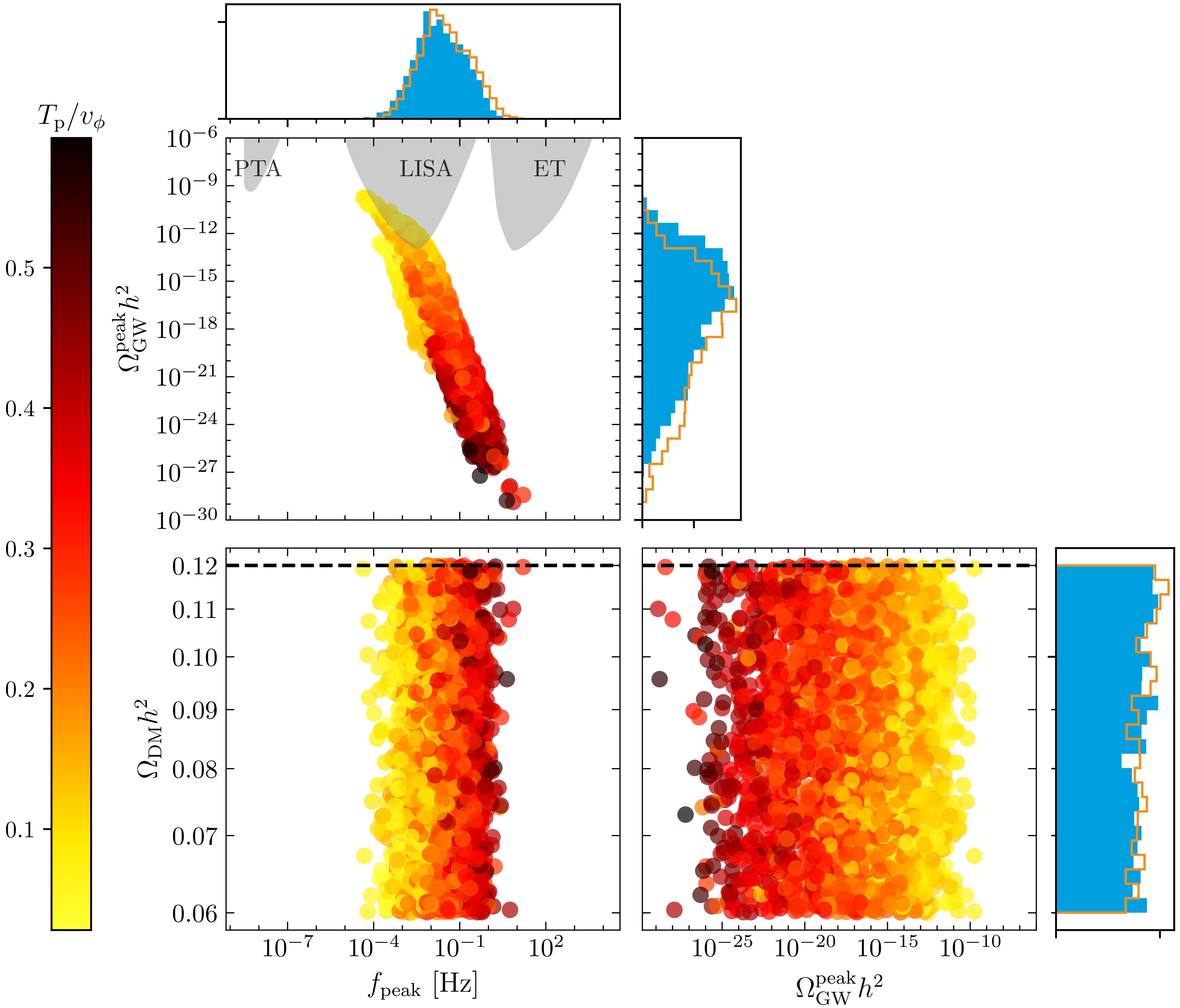
Backup: Effect of Yukawa coupling on effective potential.



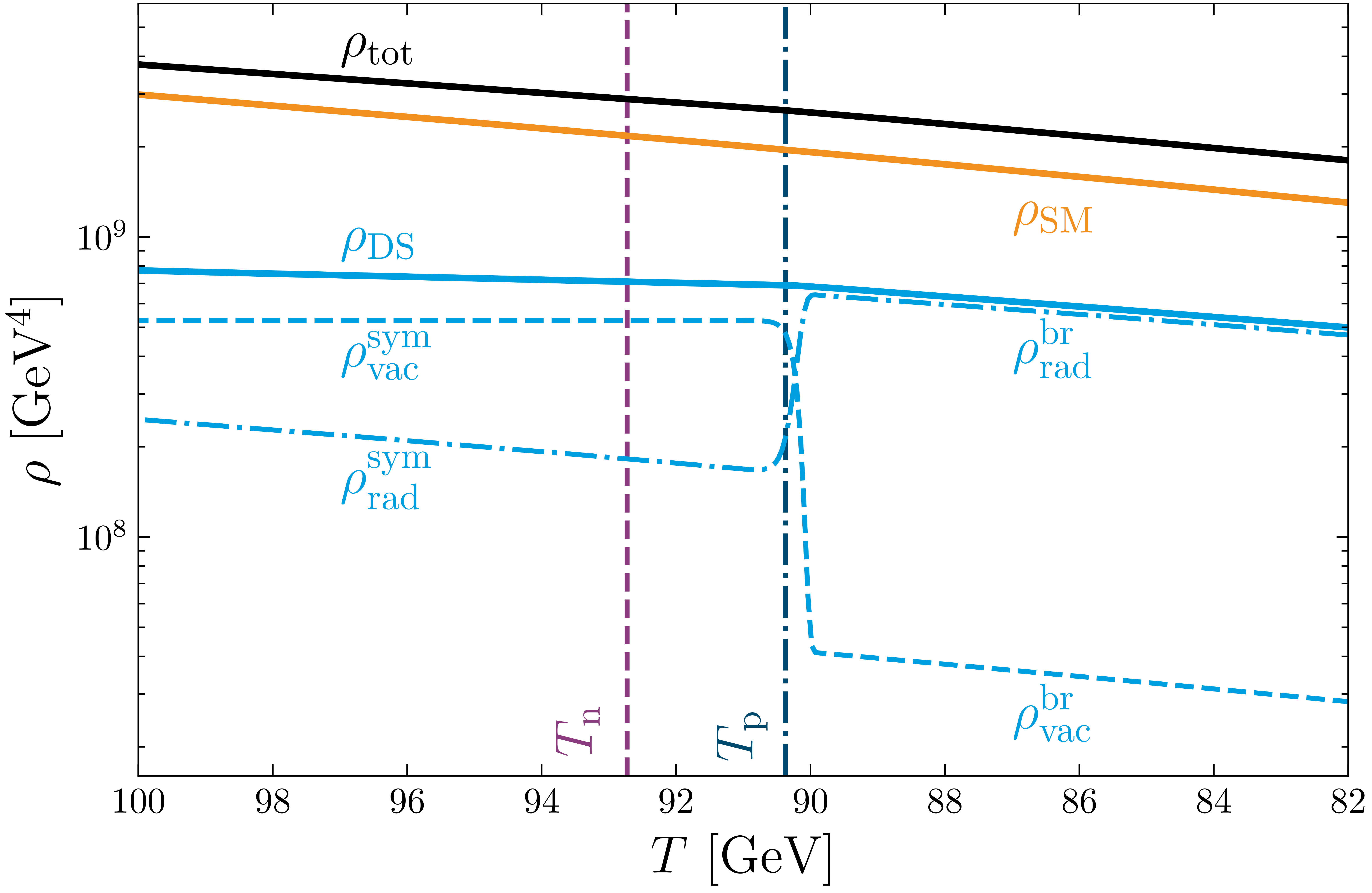
Backup: Grid scans over couplings.



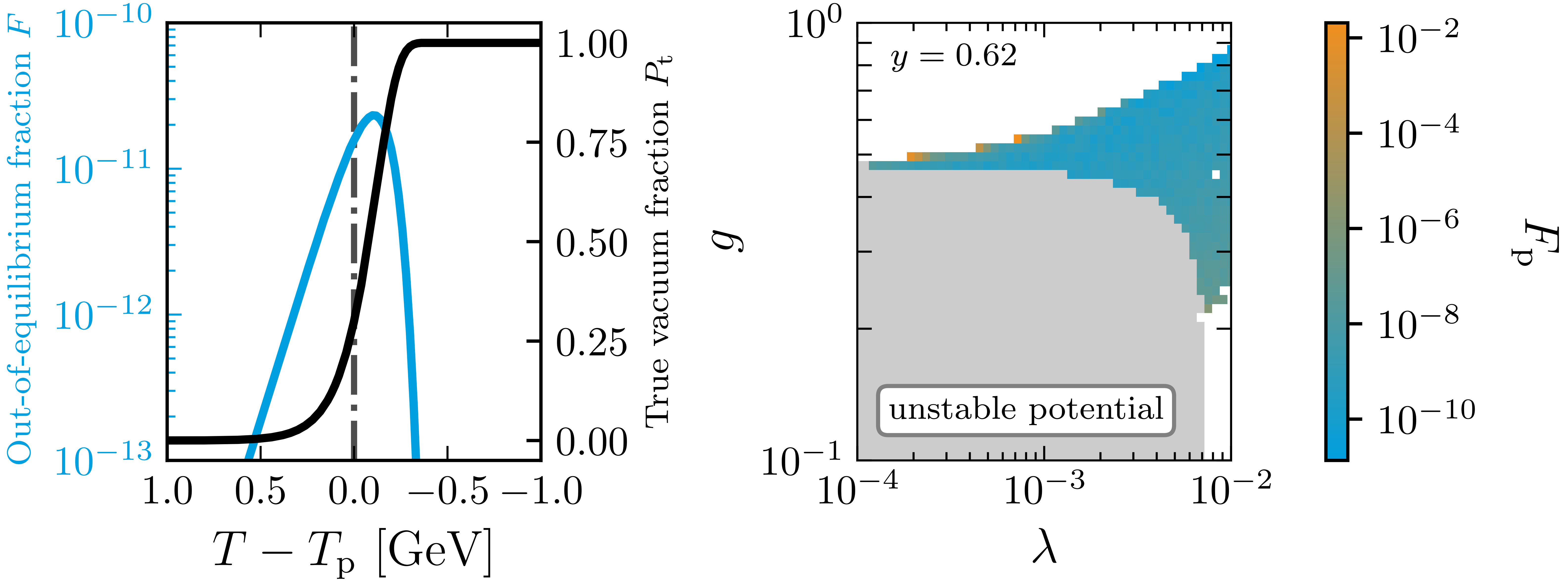
Backup: Comparison with hot dark sector phase transition.



Backup: Evolution of energy densities.



Backup: out-of-equilibrium fraction of the dark sector.

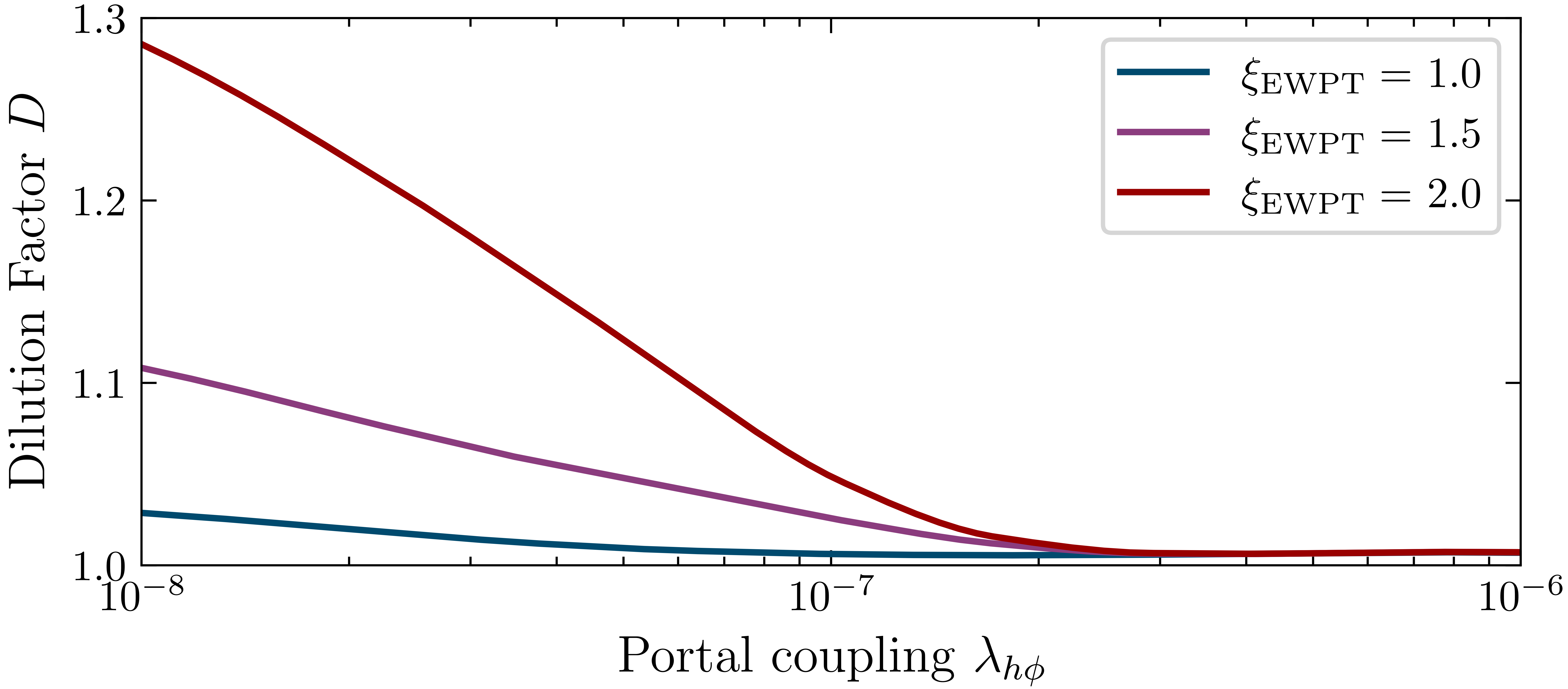


$$F(t) \equiv P(t-\tau) - P(t) > 0$$

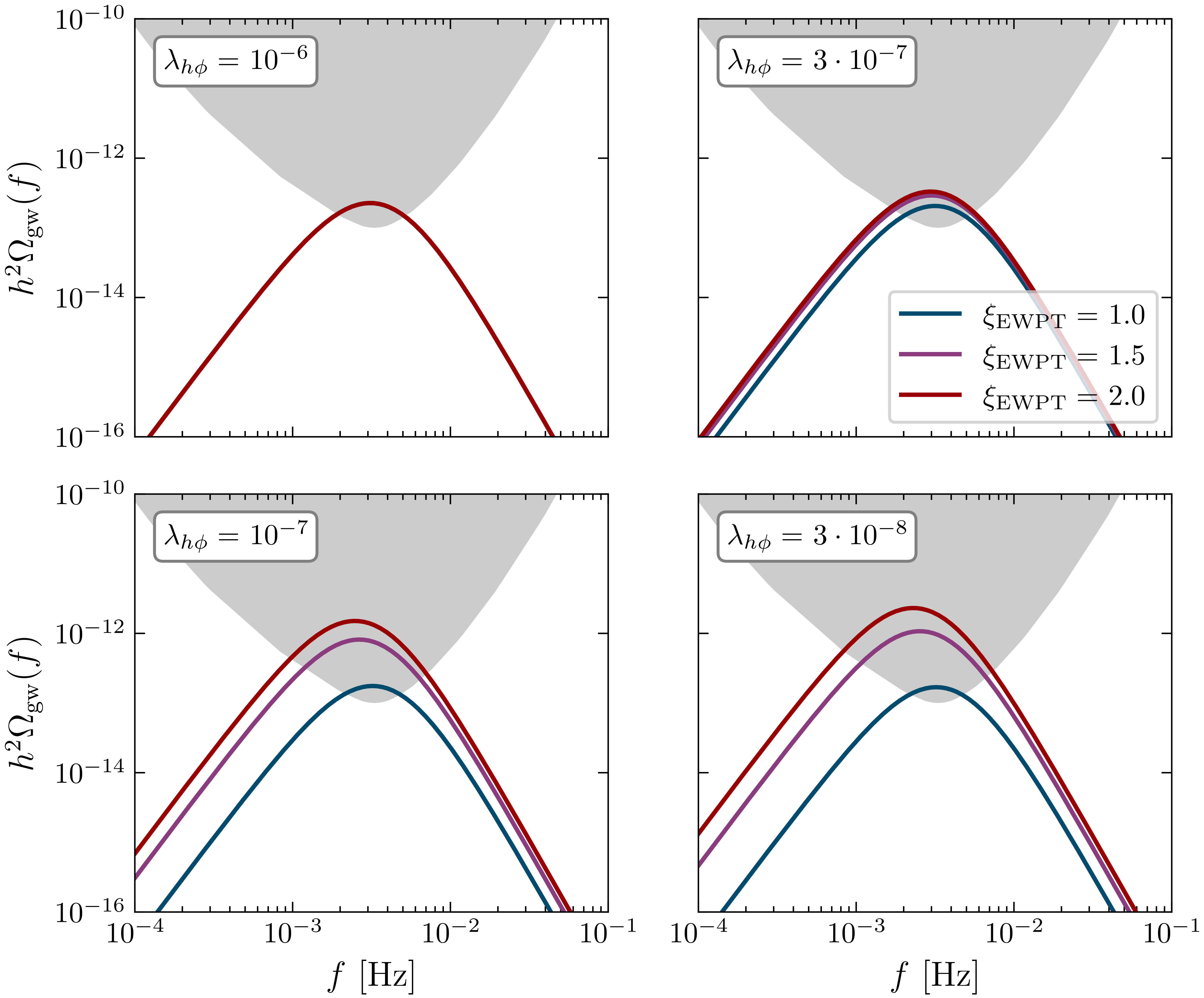
$$\begin{aligned} F(t) &\approx \exp\left(-0.34 e^{\beta(t-t_\mathrm{p}-\tau)}\right) - \exp\left(-0.34 e^{\beta(t-t_\mathrm{p})}\right) \\ &\approx \beta\tau e^{\beta(t-t_\mathrm{p})} \exp\left(-0.34 e^{\beta(t-t_\mathrm{p})}\right) \leq 0.37\beta\tau\,. \end{aligned} \tag{4.6}$$

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.

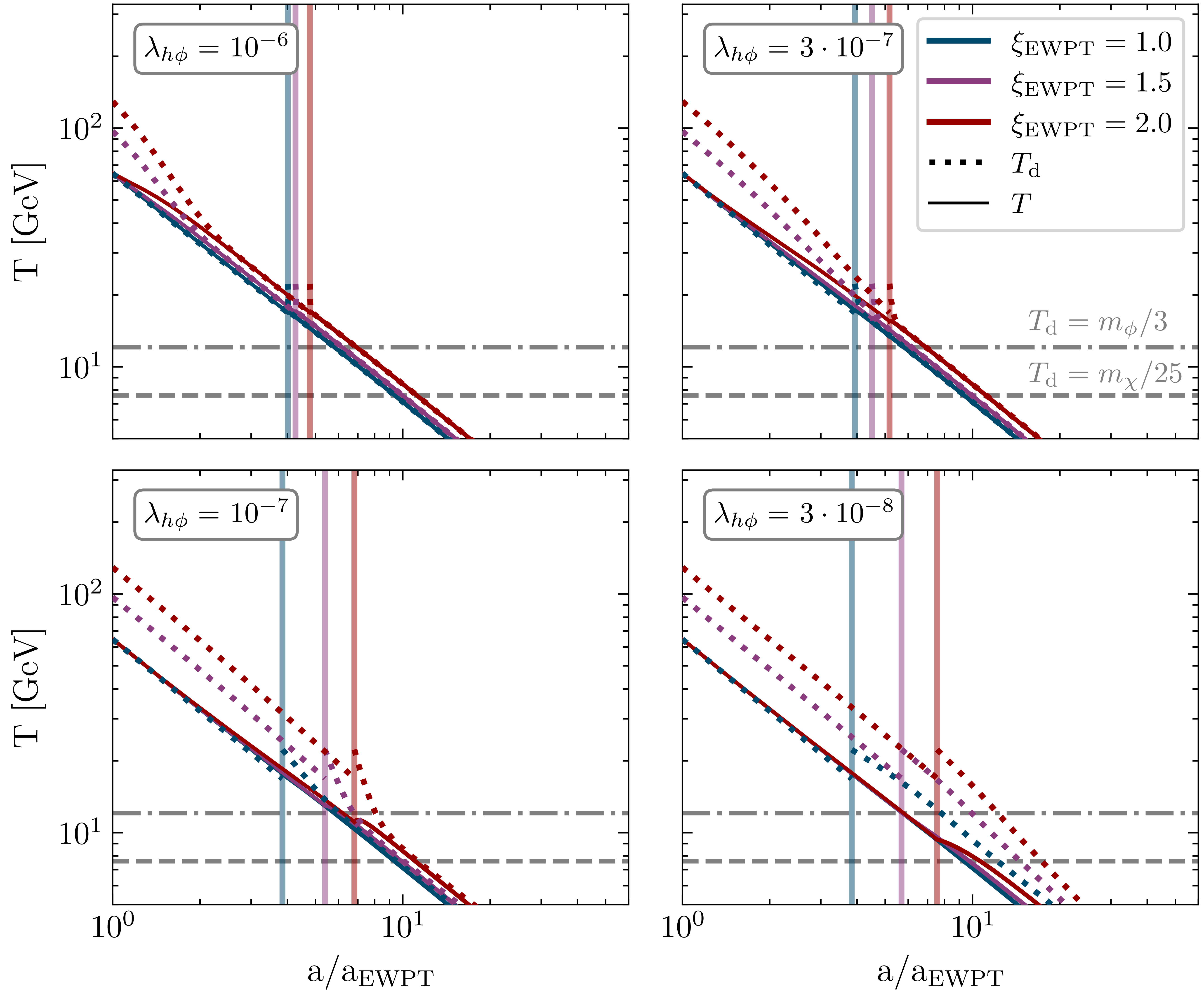
Backup: Dilution effect.



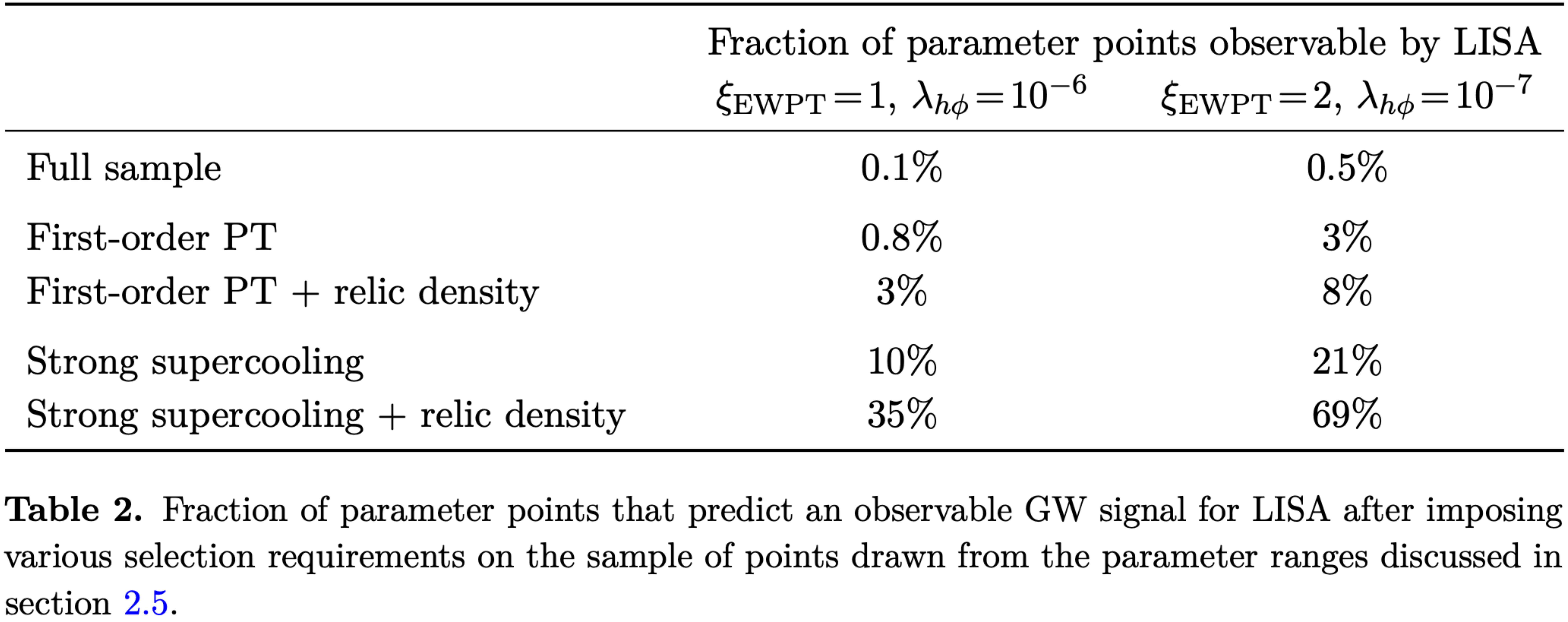
Backup: Effect of $\lambda_{h\phi}$ and ξ.



Backup: temperature evolution in the dark sector.



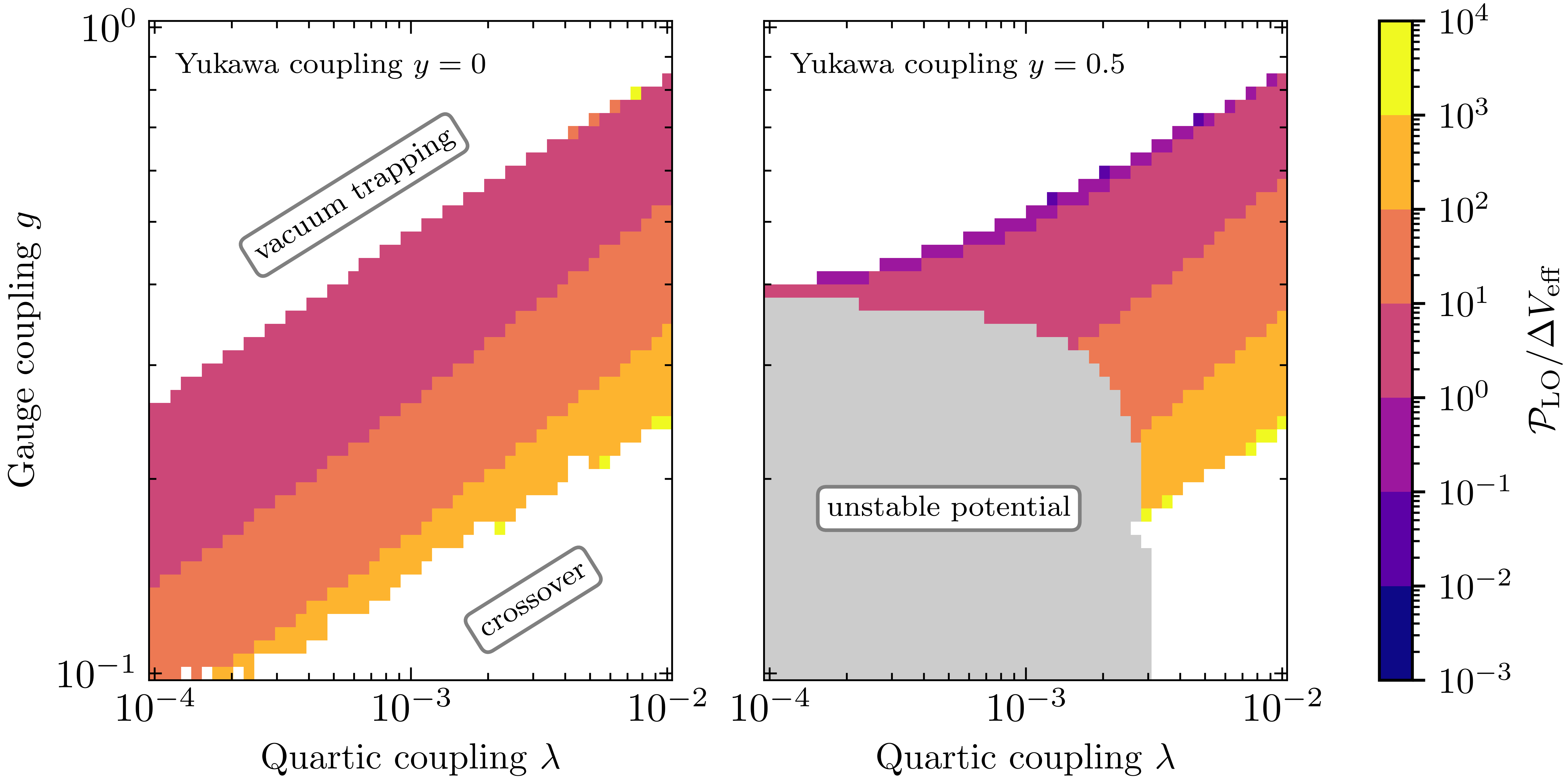
Backup: „Detection probabilities“.



	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.

Backup: Bödeker-Moore criterion.



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