Are the violins tuned?

Dark sector phase transition explanations for the PTA signal

PLANCK 2026 + 6th EuCAPT Symposium

Carlo Tasillo,
Institut de física corpuscular (IFIC)

Based on work with Torsten Bringmann, Thomas Konstandin, Jonas Matuszak, and Kai Schmidt-Hoberg

arXiv: 2602.09092 and 2605.15259

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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

…of Low-Frequen… Gravit…onal Wa…

…e the waves, wh…

…d from pai…

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

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 i…

…ack H… Galaxy… Space

Gravitational wave… at the center of the M…

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.

Scientists r… come from c… holes

…it may …massive black

SCIENCE

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

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

Monster gravitational … spotted for first …

…ntists discover that universe i… gravitational waves

…ce-time ripples

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 gravitational waves

The Washington Post

Ground…king gravitational wa… disco…lock our Univ…teries

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

The results are … background, a hum of … Universe.

NANOGrav

[See talk by Kai Schmitz]

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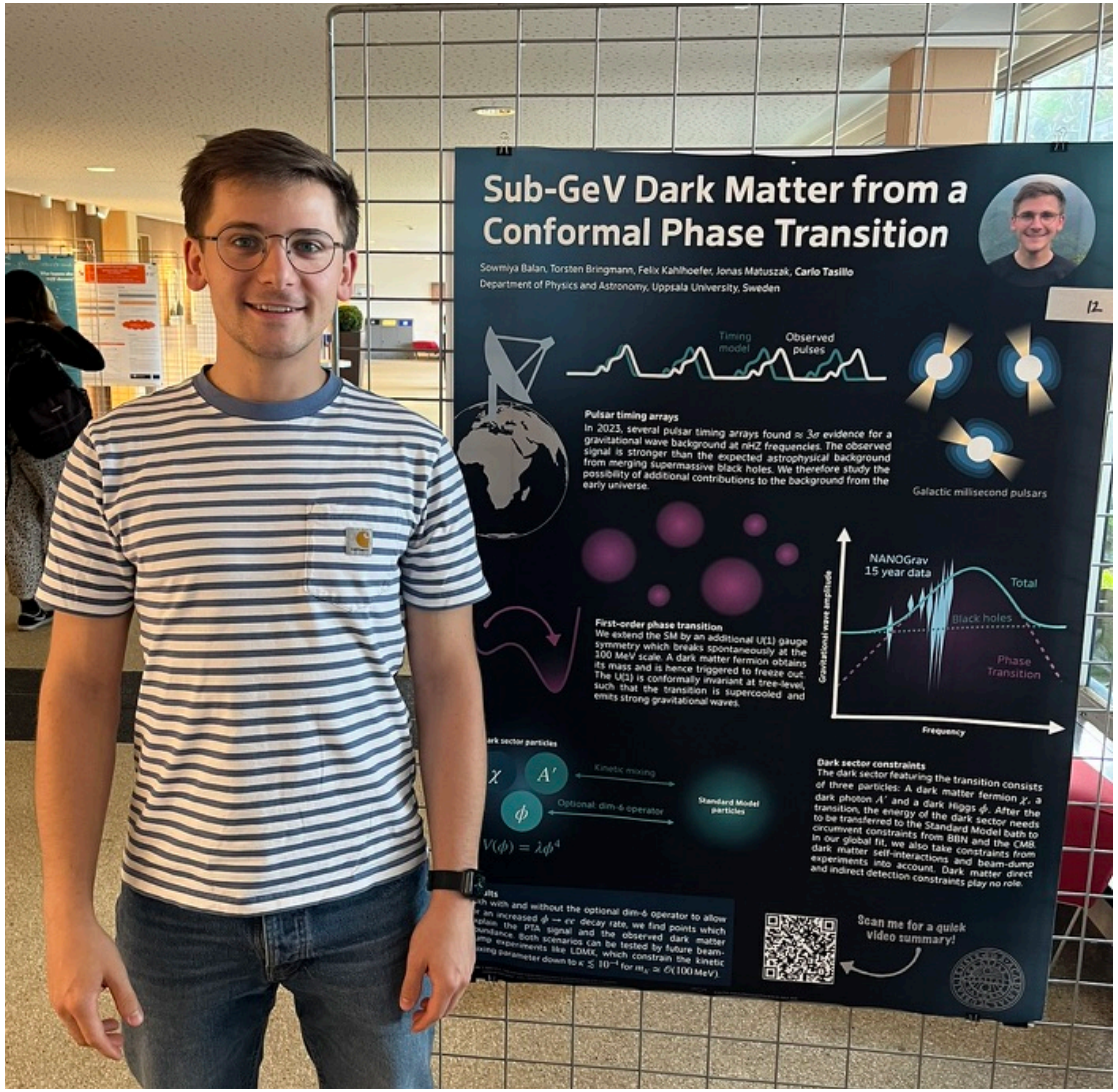

Sub-GeV Dark Matter from a Conformal Phase Transition

Sowmiya Balan, Torsten Bringmann, Felix Kahlhoefer, Jonas Matuszak, **Carlo Tasillo**

Department of Physics and Astronomy, Uppsala University, Sweden

12

Pulsar timing arrays

In 2023, several pulsar timing arrays found $\approx 3\sigma$ evidence for a gravitational wave background at nHZ frequencies. The observed signal is stronger than the expected astrophysical background from merging supermassive black holes. We therefore study the possibility of additional contributions to the background from the early universe.

First-order phase transition

We extend the SM by an additional U(1) gauge symmetry which breaks spontaneously at the 100 MeV scale. A dark matter fermion obtains its mass and is hence triggered to freeze out. The U(1) is conformally invariant at tree-level, such that the transition is supercooled and emits strong gravitational waves.

–rk sector particles

$V(\phi) = \lambda\phi^4$

Dark sector constraints

The dark sector featuring the transition consists of three particles: A dark matter fermion χ, a dark photon A' and a dark Higgs ϕ. After the transition, the energy of the dark sector needs to be transferred to the Standard Model bath to circumvent constraints from BBN and the CMB. In our global fit, we also take constraints from dark matter self-interactions and beam-dump experiments into account. Dark matter direct and indirect detection constraints play no role.

–lts

–th with and without the optional dim-6 operator to allow –r an increased $\phi \to ee$ decay rate, we find points which –plain the PTA signal and the observed dark matter –undance. Both scenarios can be tested by future beam-–ump experiments like LDMX, which constrain the kinetic –ixing parameter down to $\kappa \lesssim 10^{-4}$ for $m_\chi \simeq \mathcal{O}(100\,\text{MeV})$.

Scan me for a quick video summary!

[See talk by Felix Kahlhoefer]

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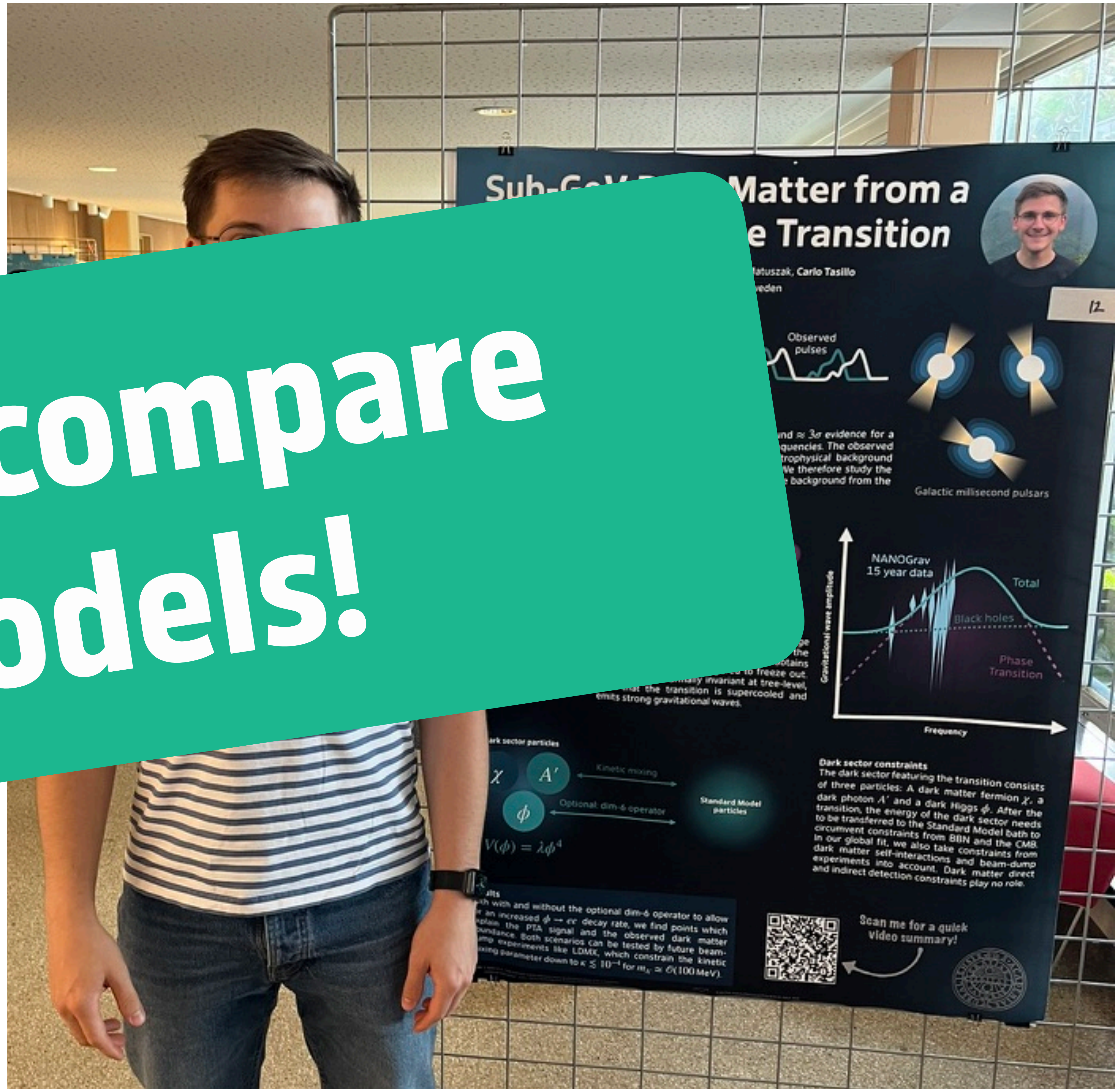
It's time to compare some models!

NANOGrav

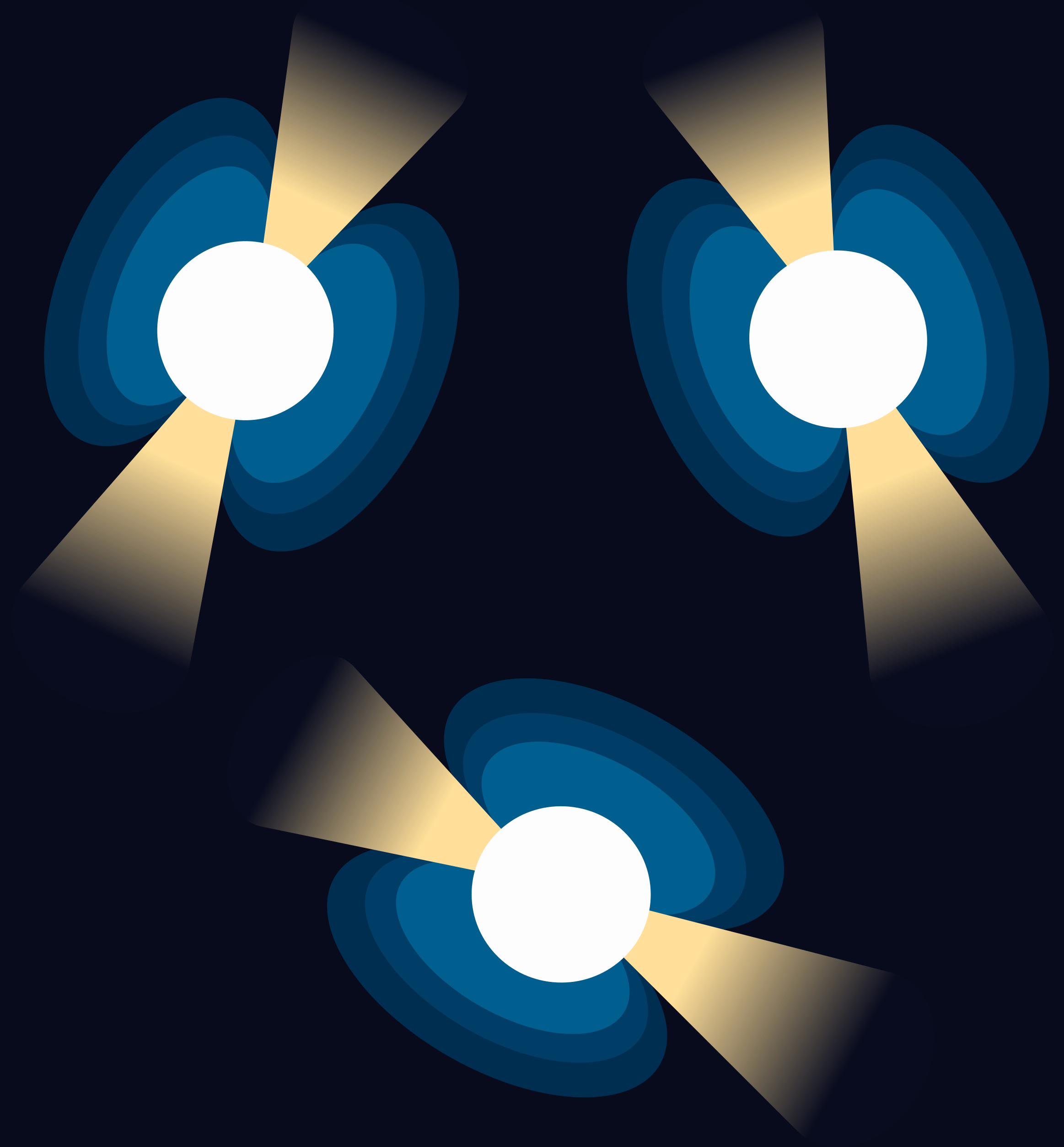
[See talk by Kai Schmitz]



[See talk by Felix Kahlhoefer]

The working principle of a pulsar timing array

Galactic millisecond pulsars



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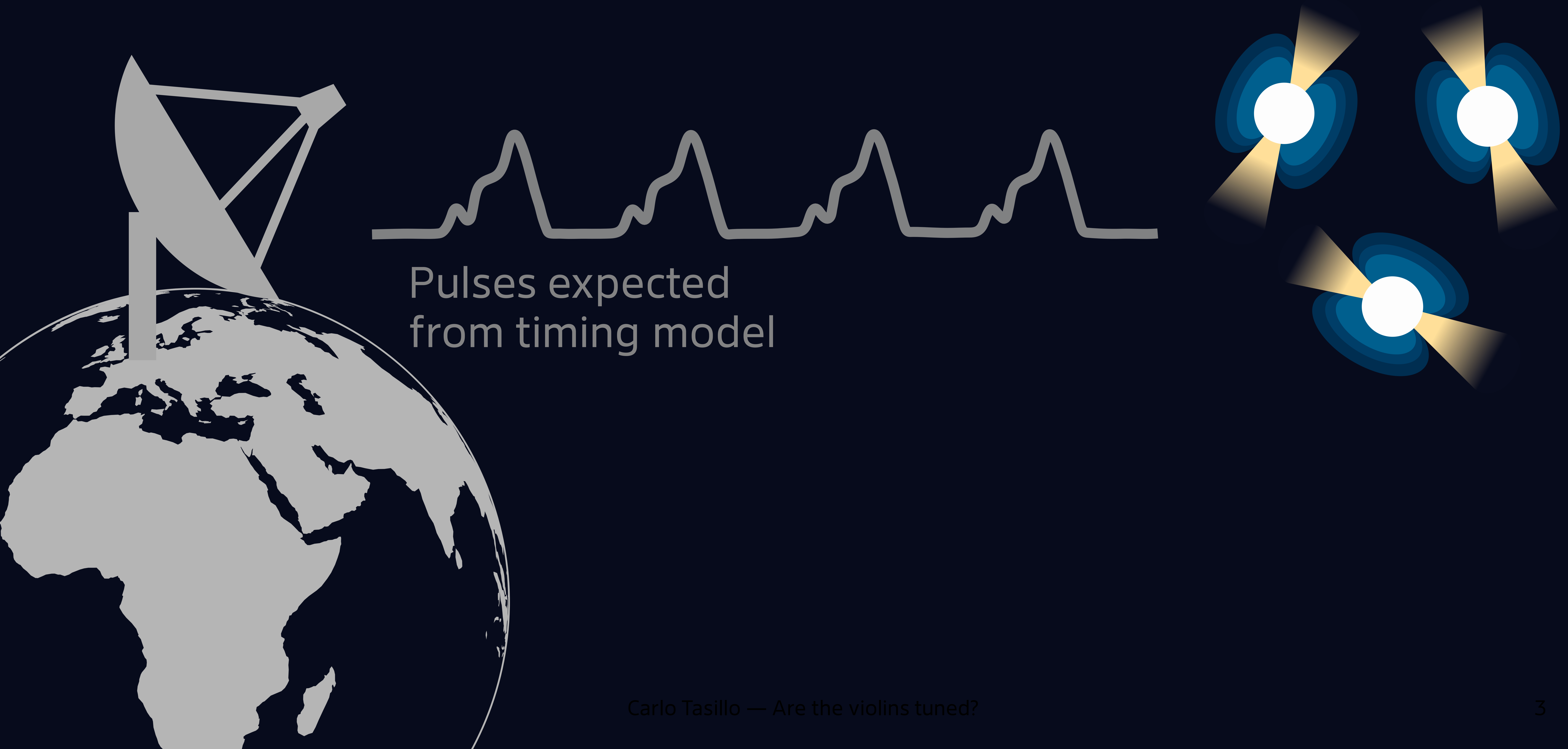
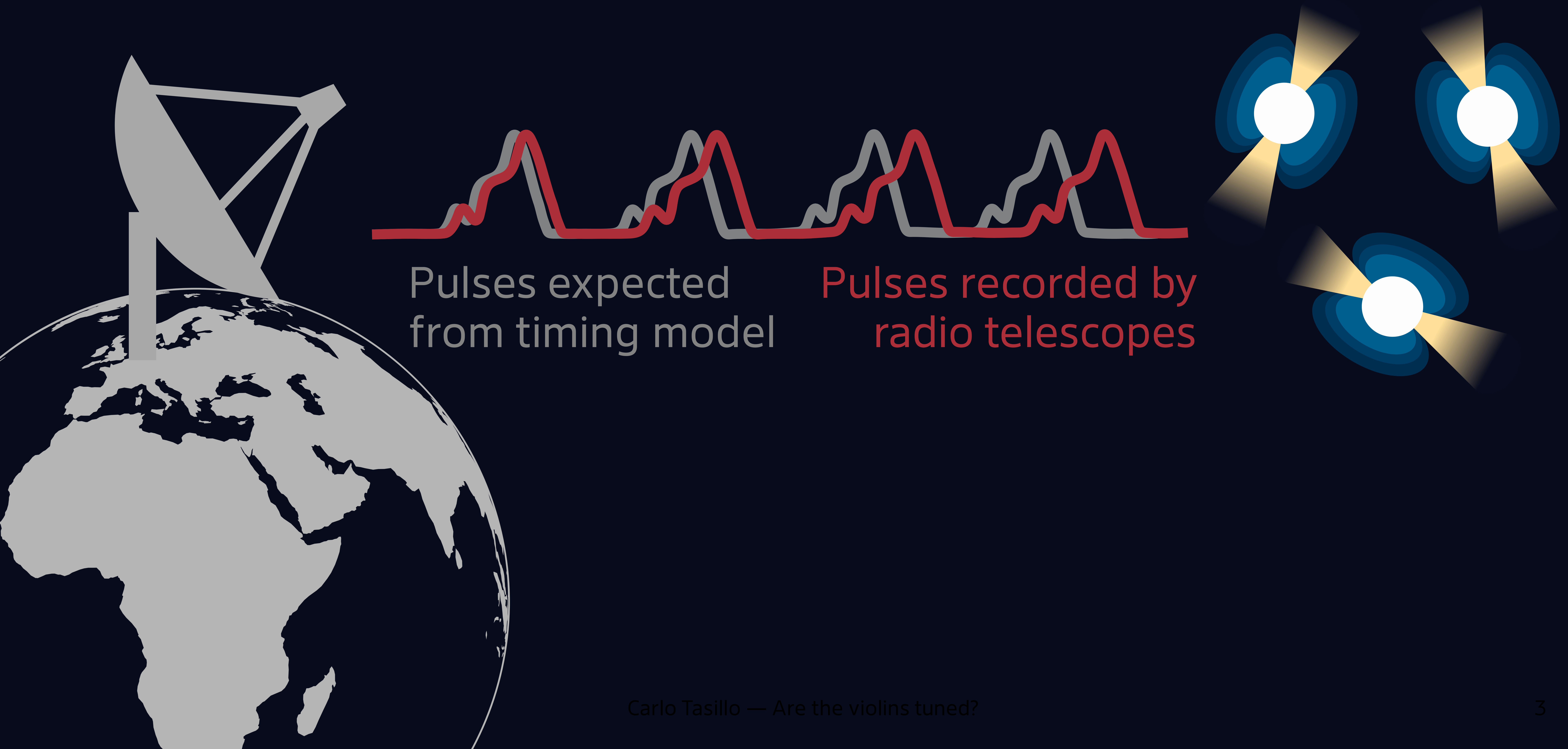


Galactic millisecond pulsars

Pulses expected
from timing model

The working principle of a pulsar timing array



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Pulses recorded by
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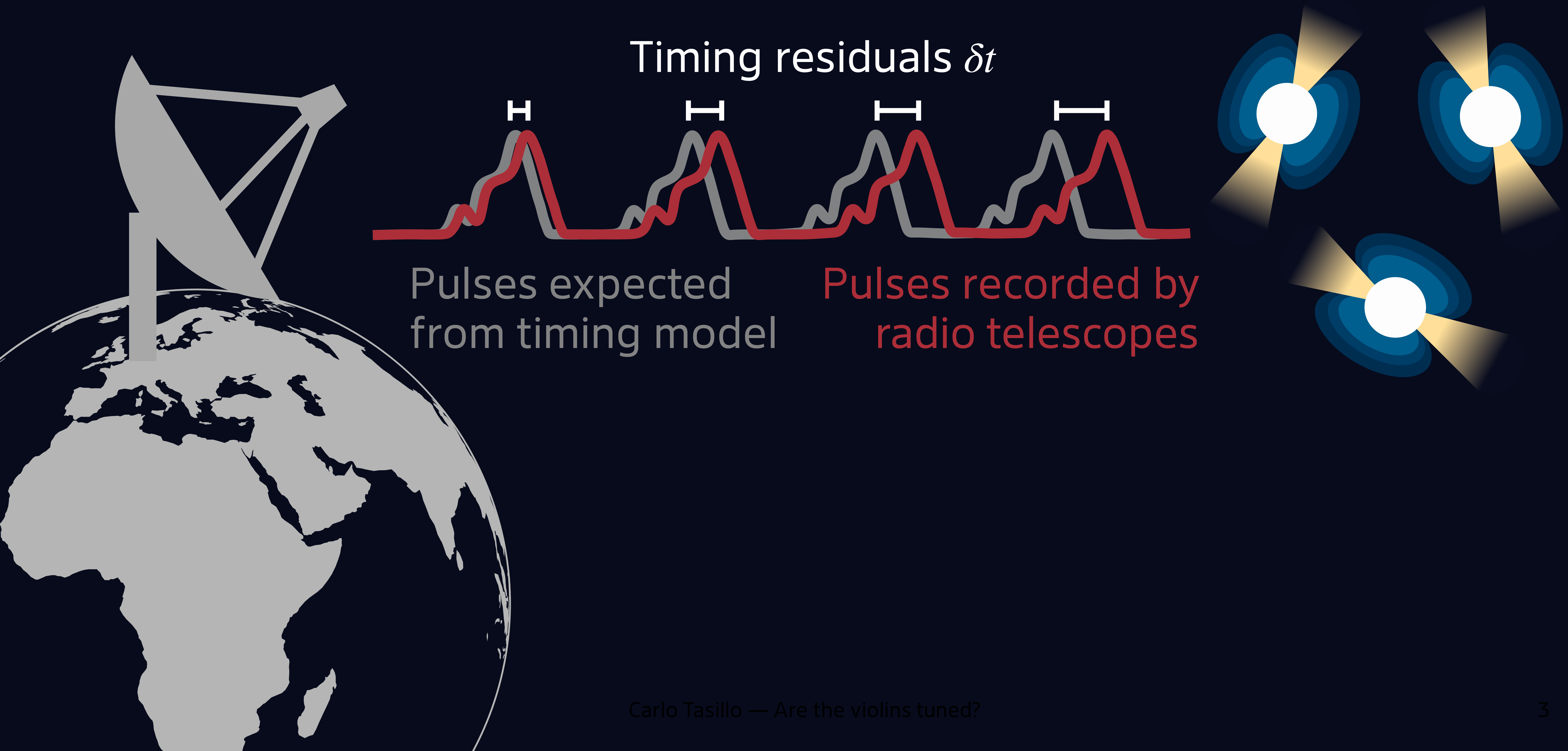


Galactic millisecond pulsars

Timing residuals δt

Pulses expected from timing model

Pulses recorded by radio telescopes

The working principle of a pulsar timing array

Galactic millisecond pulsars

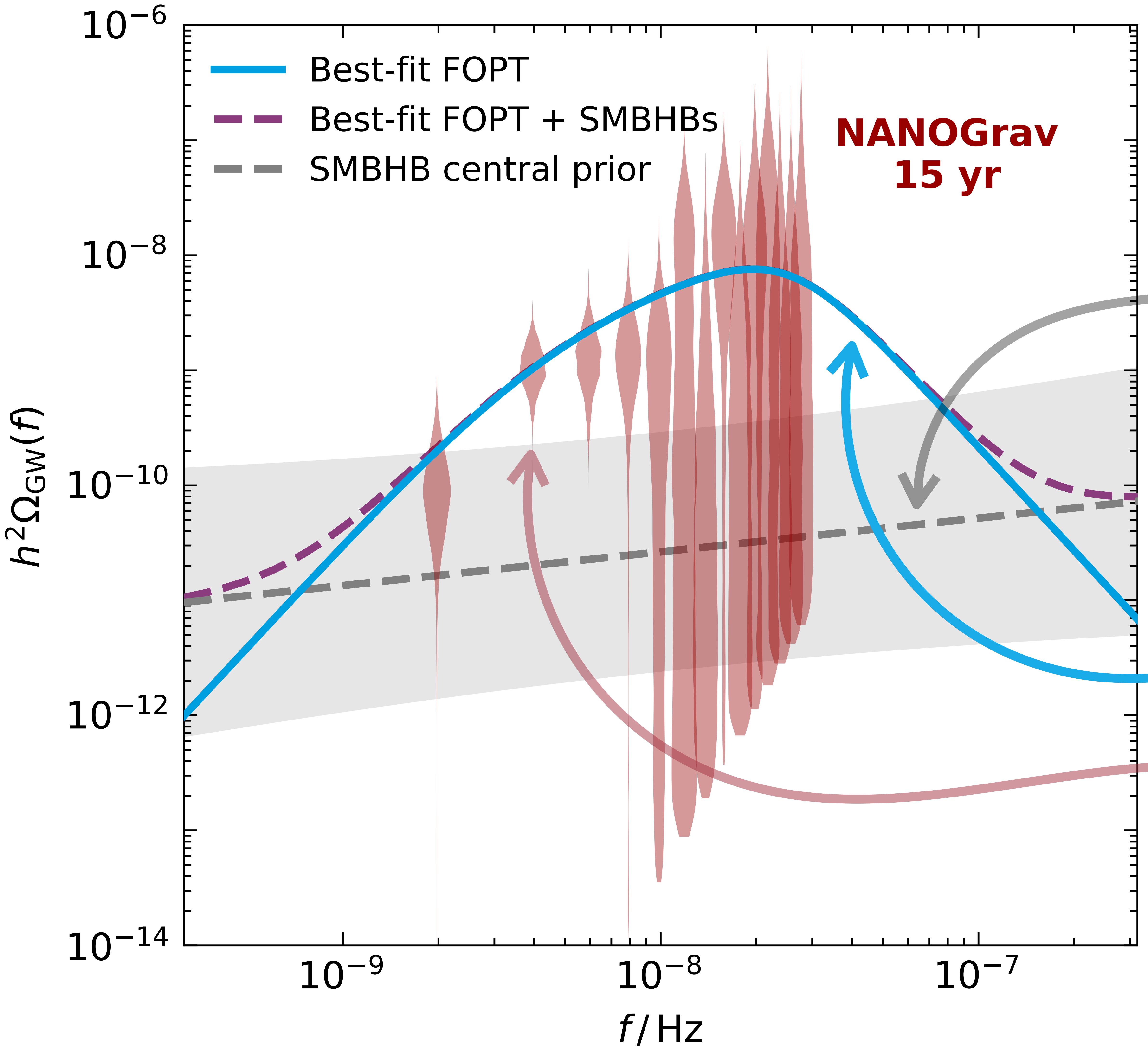
Timing residuals δt

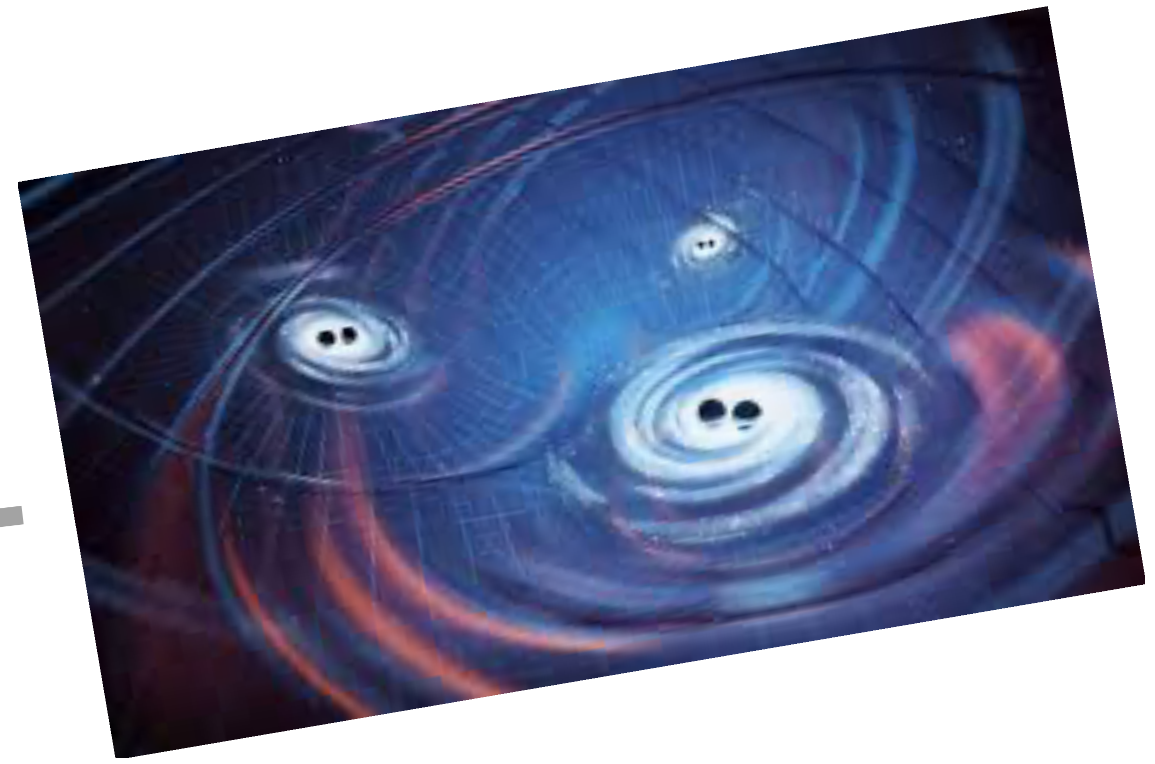
Pulses expected from timing model

Pulses recorded by radio telescopes

A gravitational wave backgrounds imprints itself in the common evolution of the timing residuals over time

Learning to play the violin





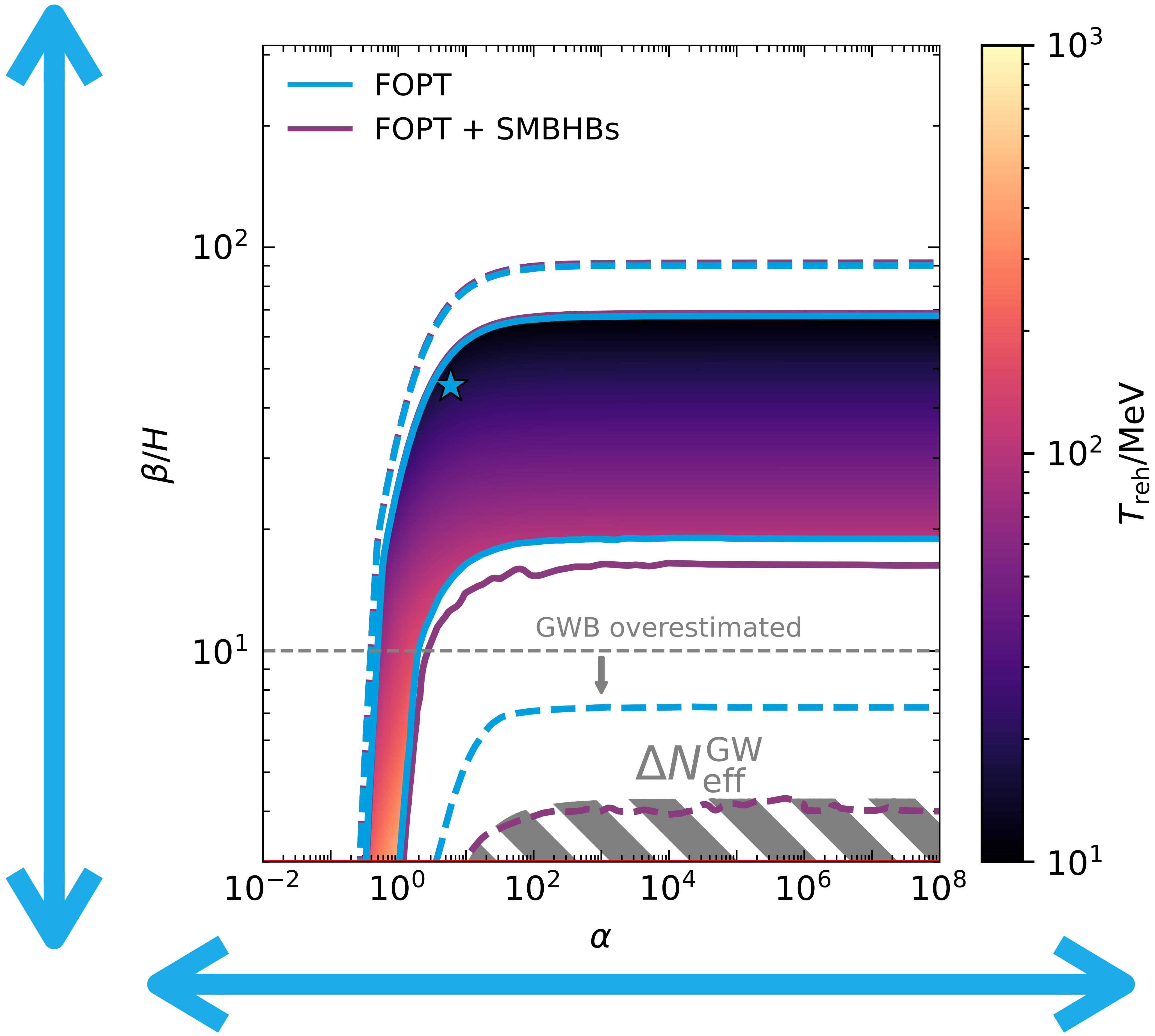
Each „violin“ in the Bayesian spectrogram can be understood as a data point with non-Gaussian error bar, describing the Fourier amplitude at a given frequency.

Which phase transitions can fit the PTA data?

Many small bubbles

$$RH \sim \frac{1}{\beta/H}$$

Few big bubbles



Weak transitions

Strong transitions

PTA data requires very strong transitions with extremely large bubbles!

Which phase transitions can fit the PTA data?

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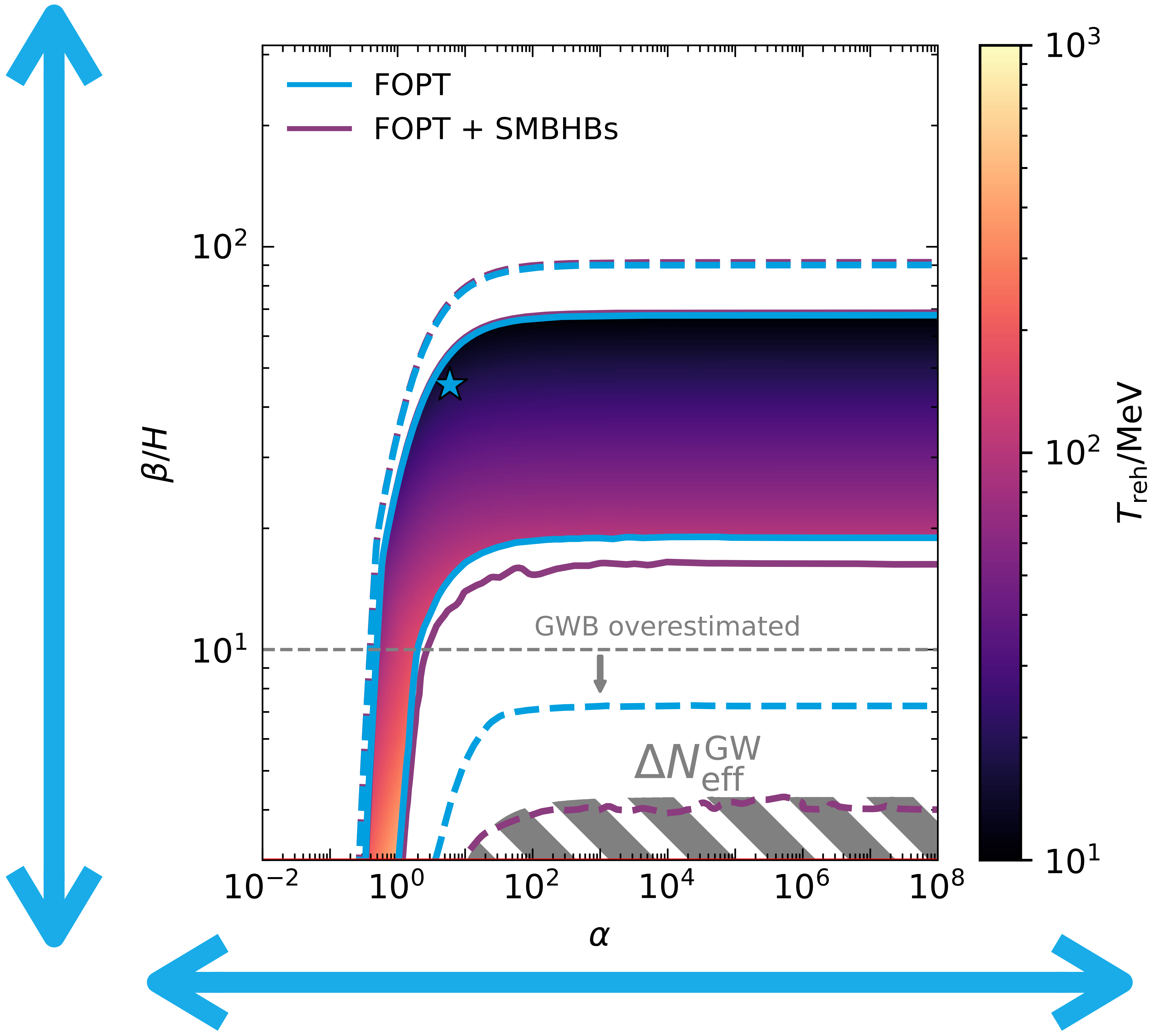


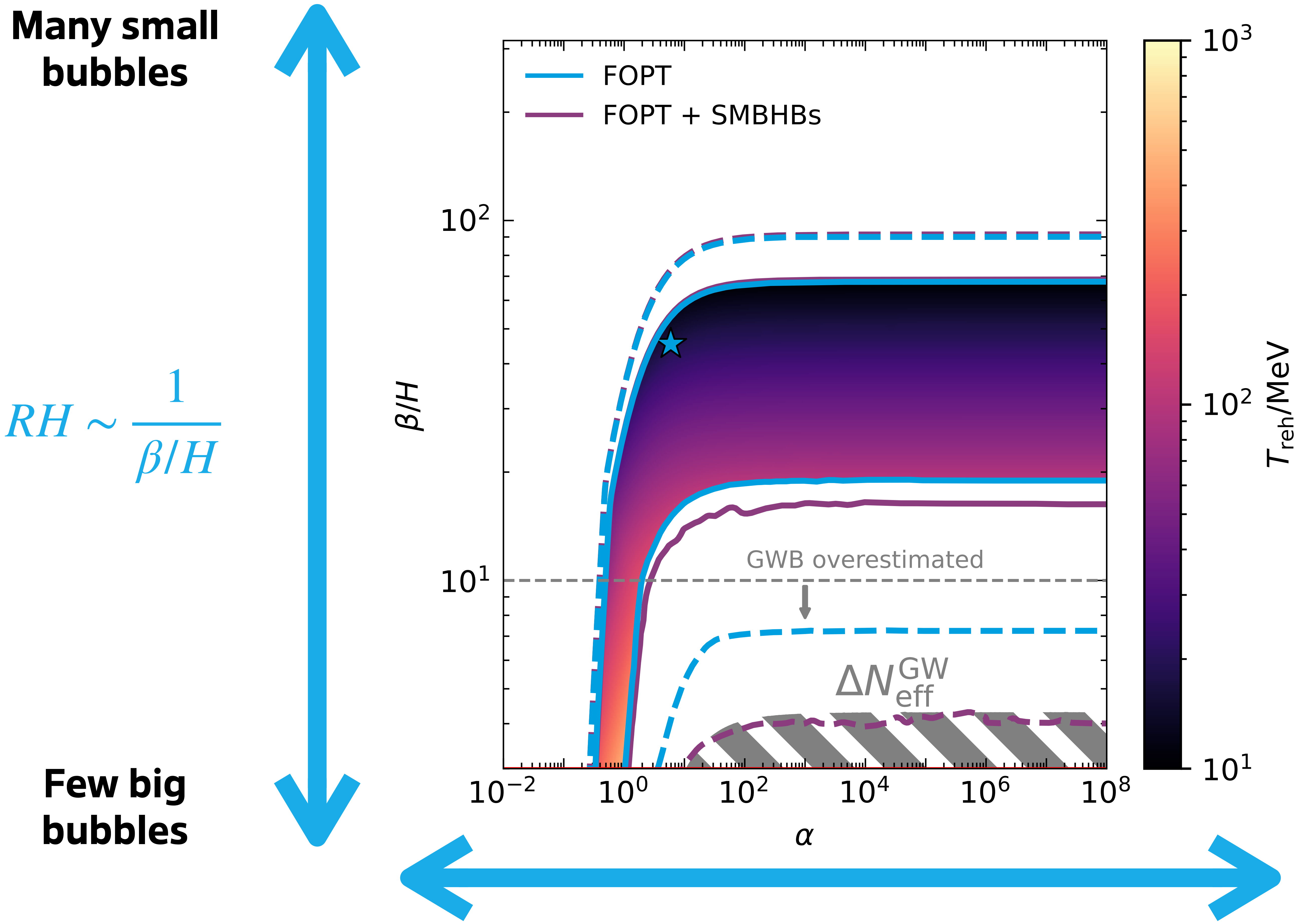
Weak transitions **Strong transitions**

PTA data requires very strong transitions with extremely large bubbles!

BSM models typically predict weak transitions with small bubbles…

Robust predictions of the GW signal in that regime are difficult…

Which phase transitions can fit the PTA data?



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$$RH \sim \frac{1}{\beta/H}$$

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Weak transitions

Strong transitions

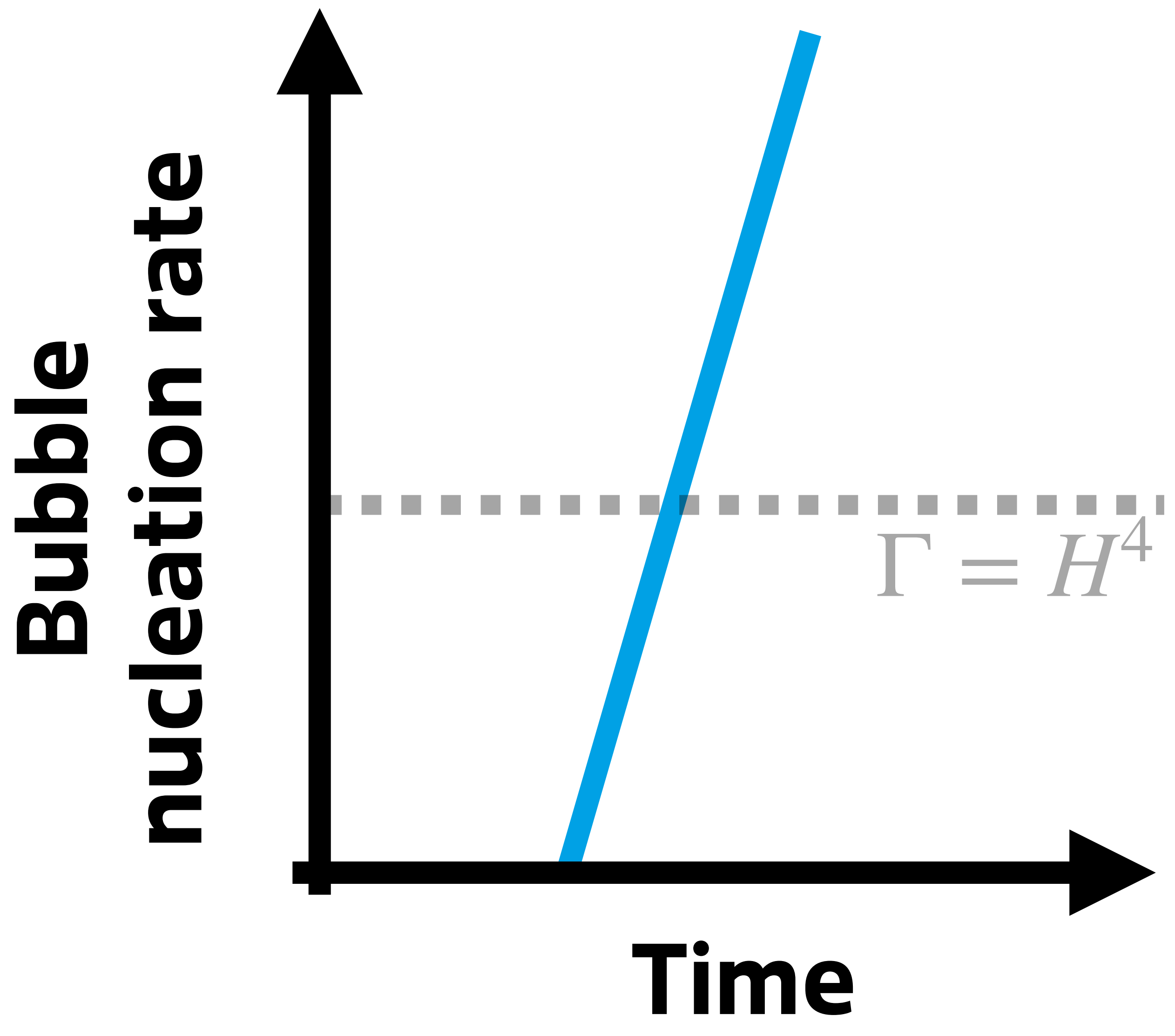
PTA data requires very strong transitions with extremely large bubbles!

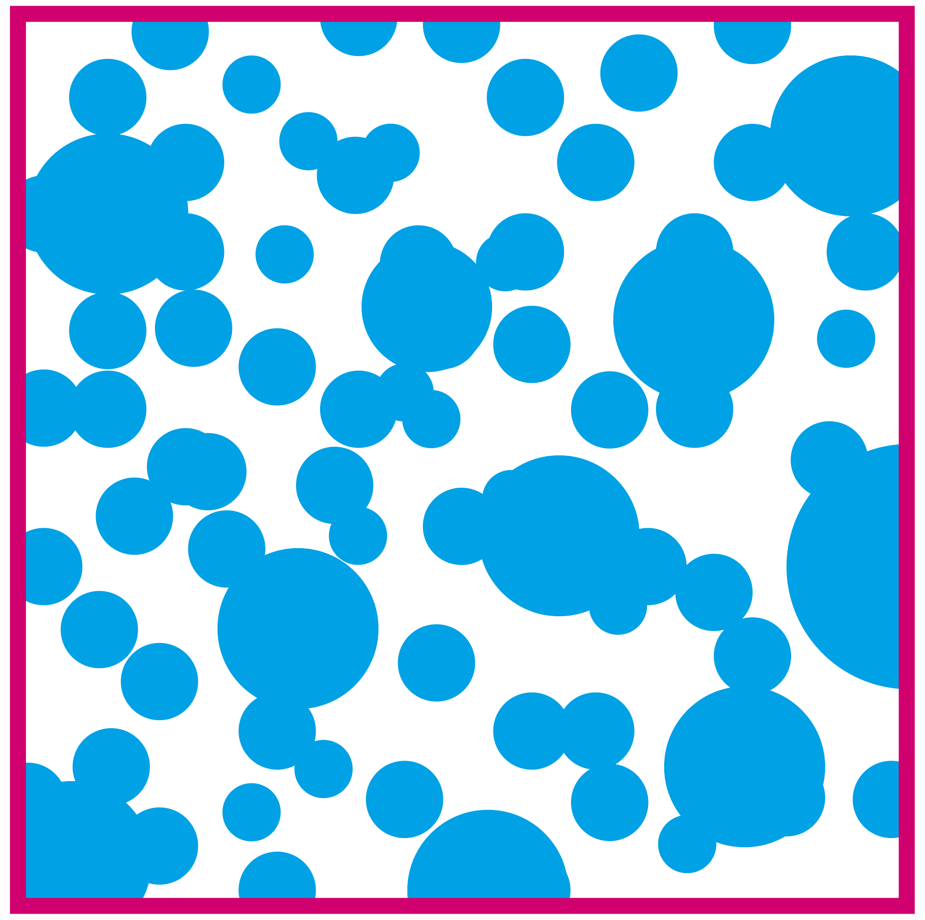
Let's start with this problem

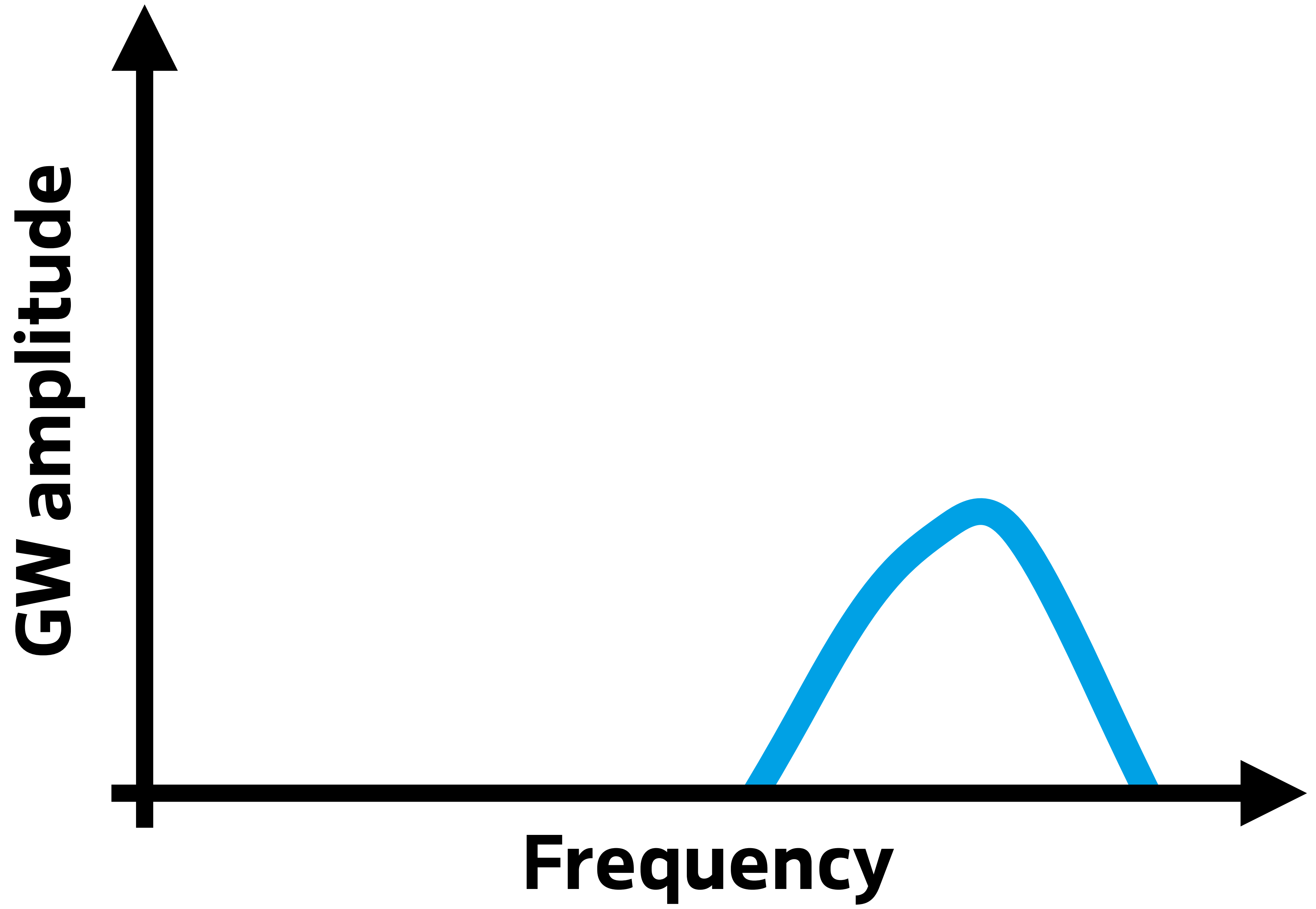
⚠ **BSM models typically predict weak transitions with small bubbles…**

⚠ **Robust predictions of the GW signal in that regime are difficult…**

Why is it so difficult to get big bubbles?







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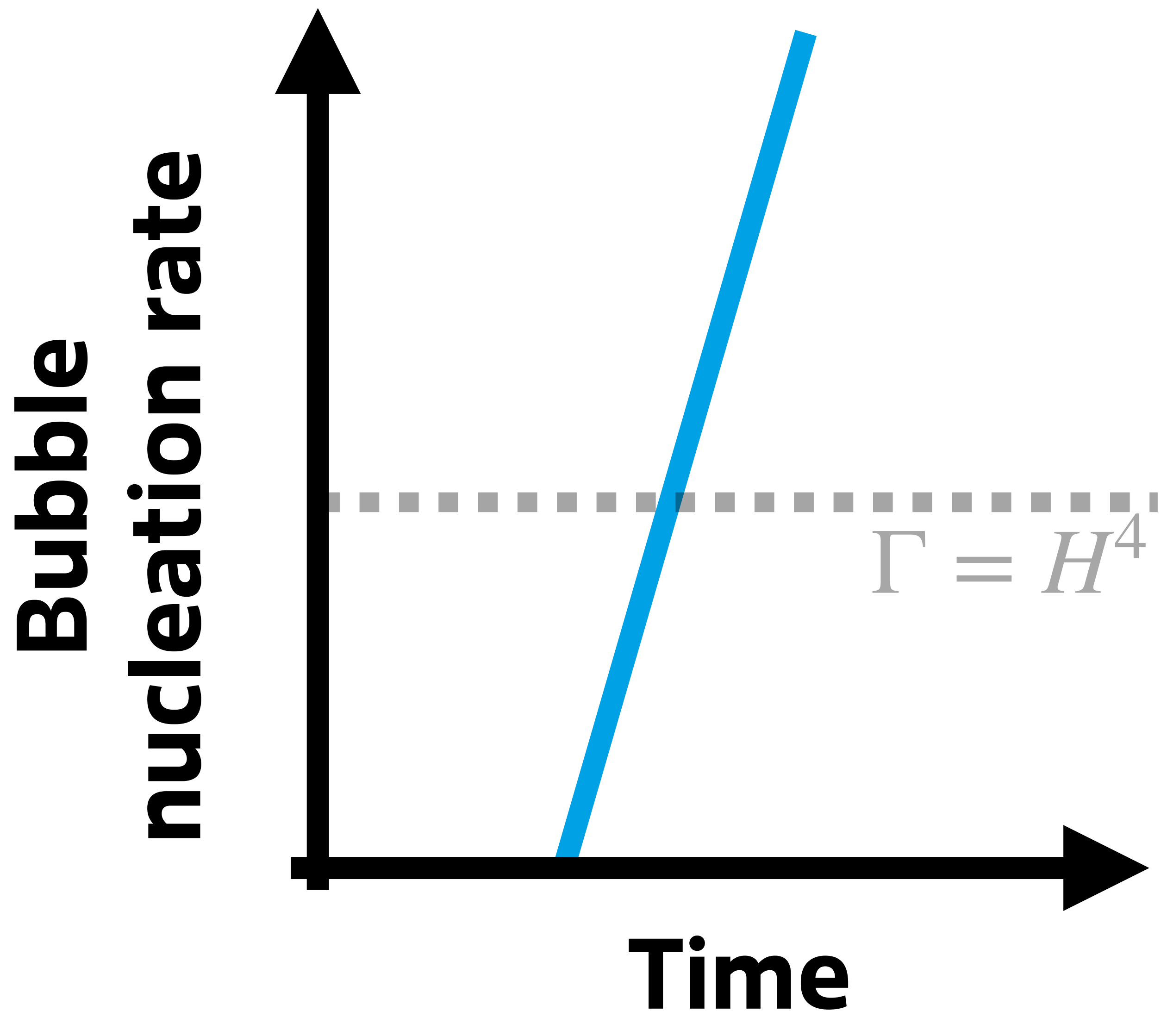
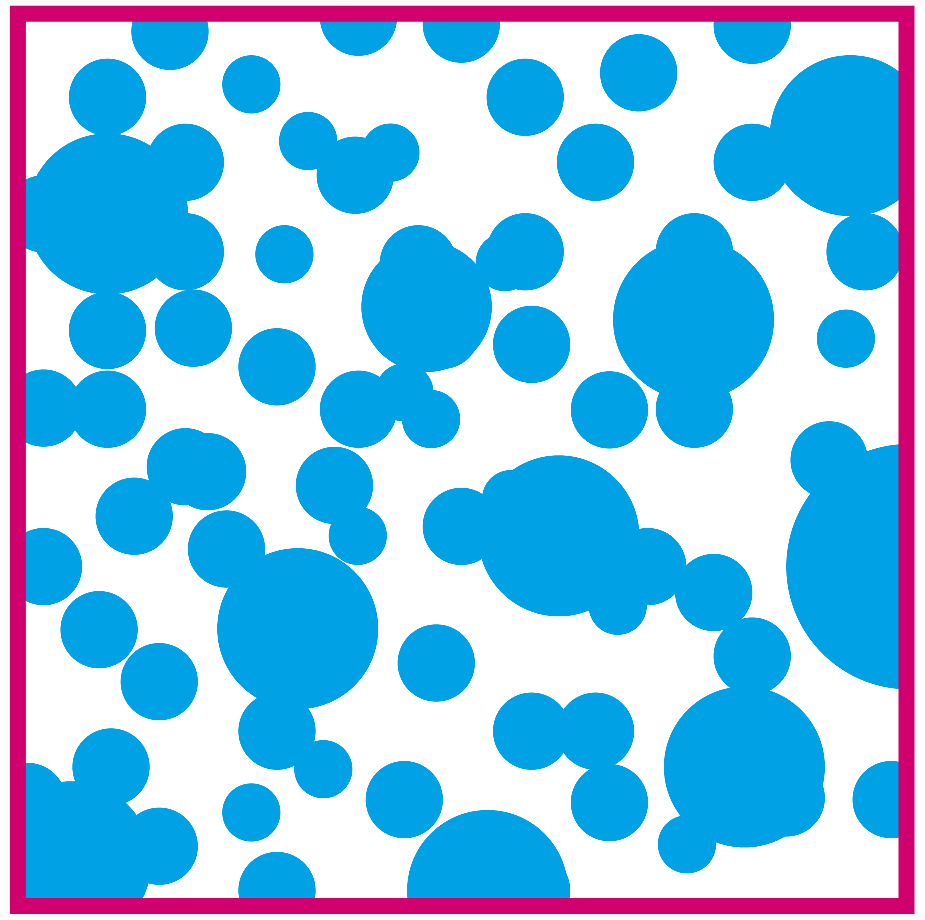
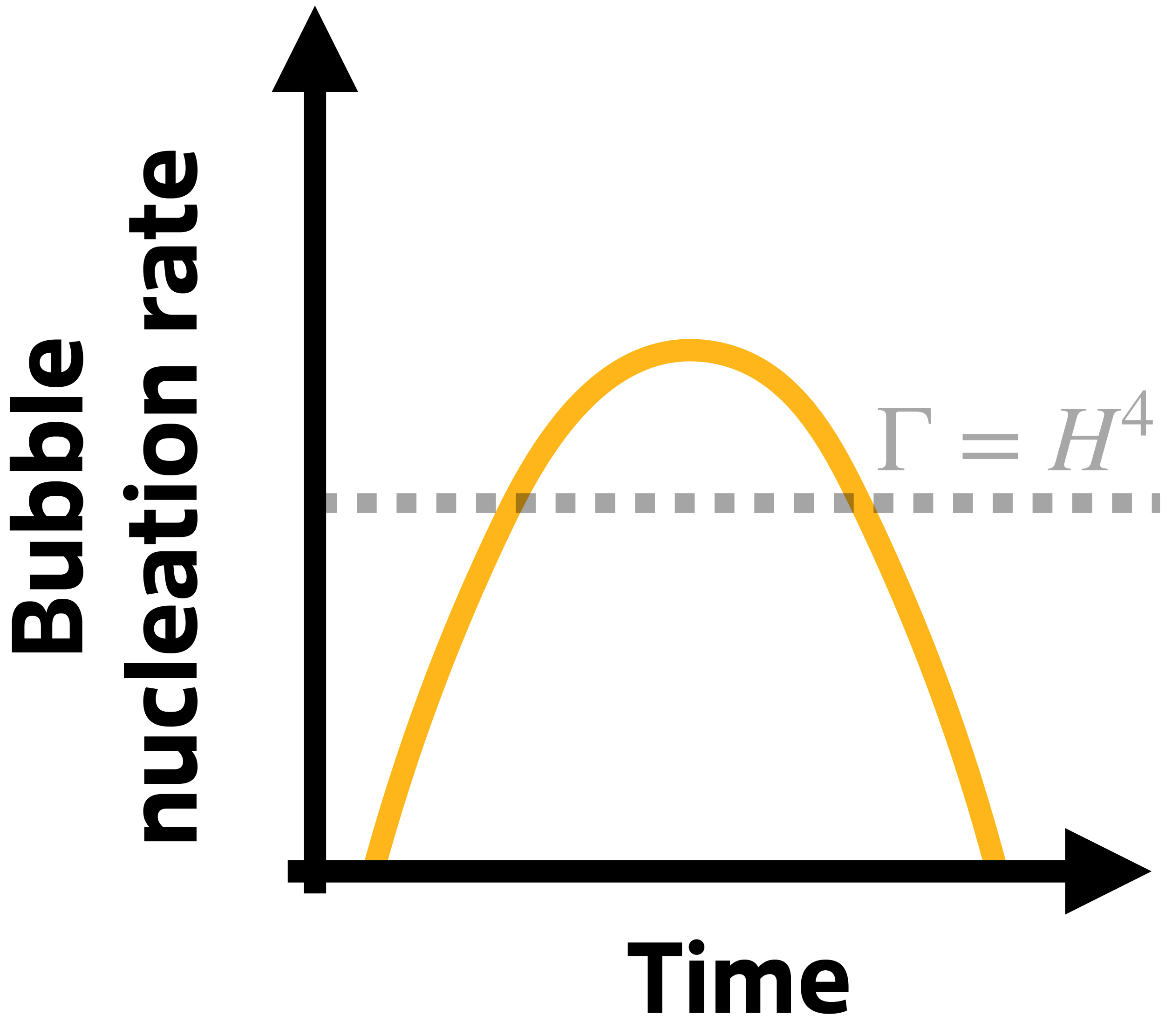
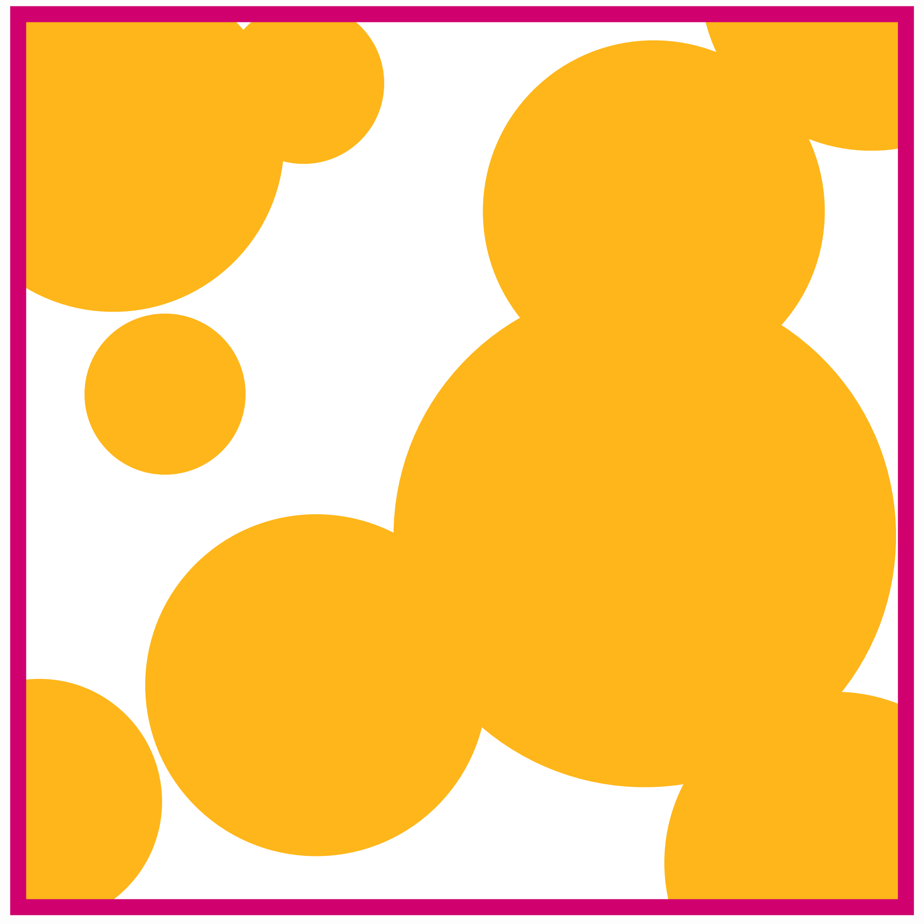
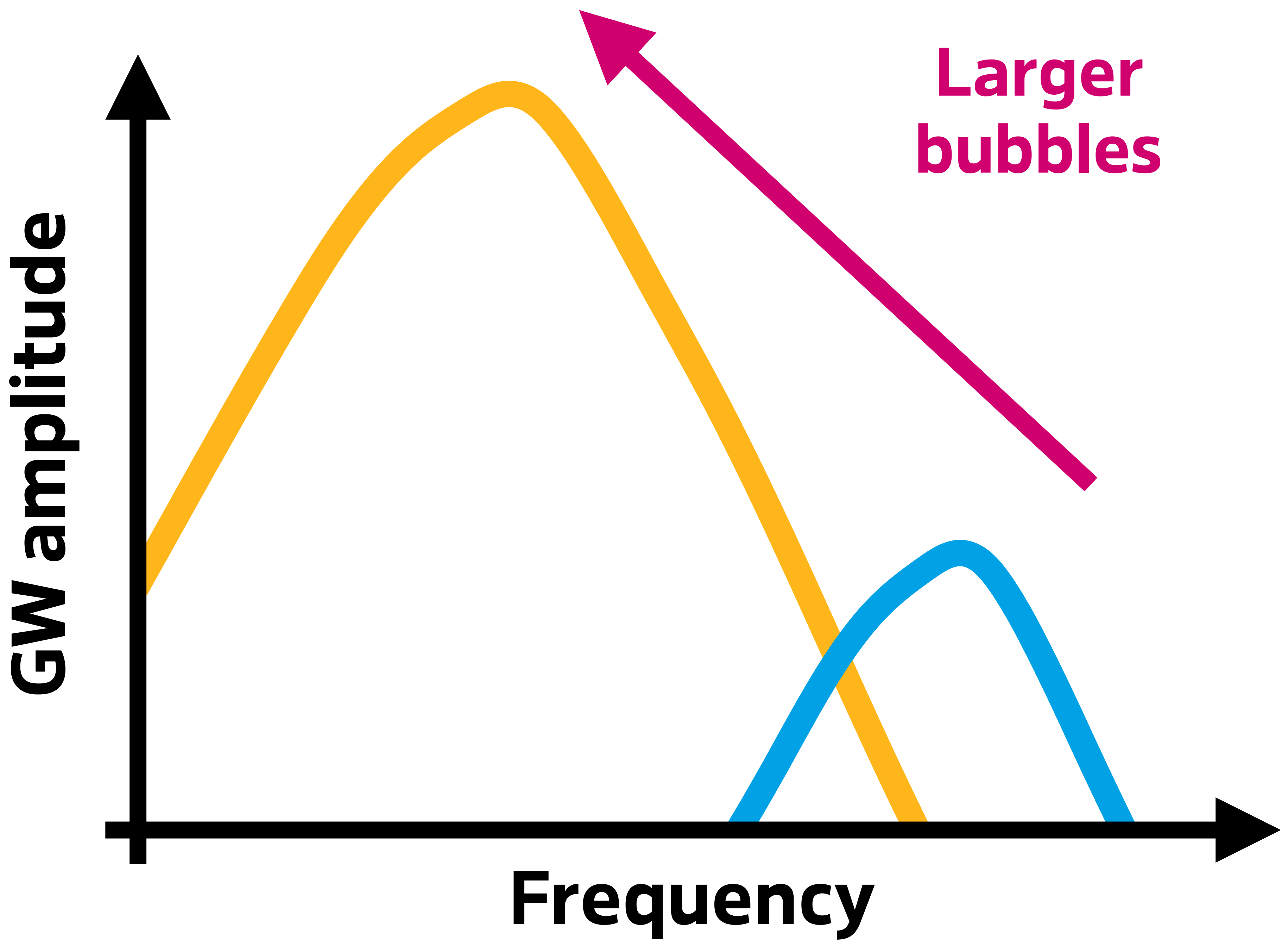








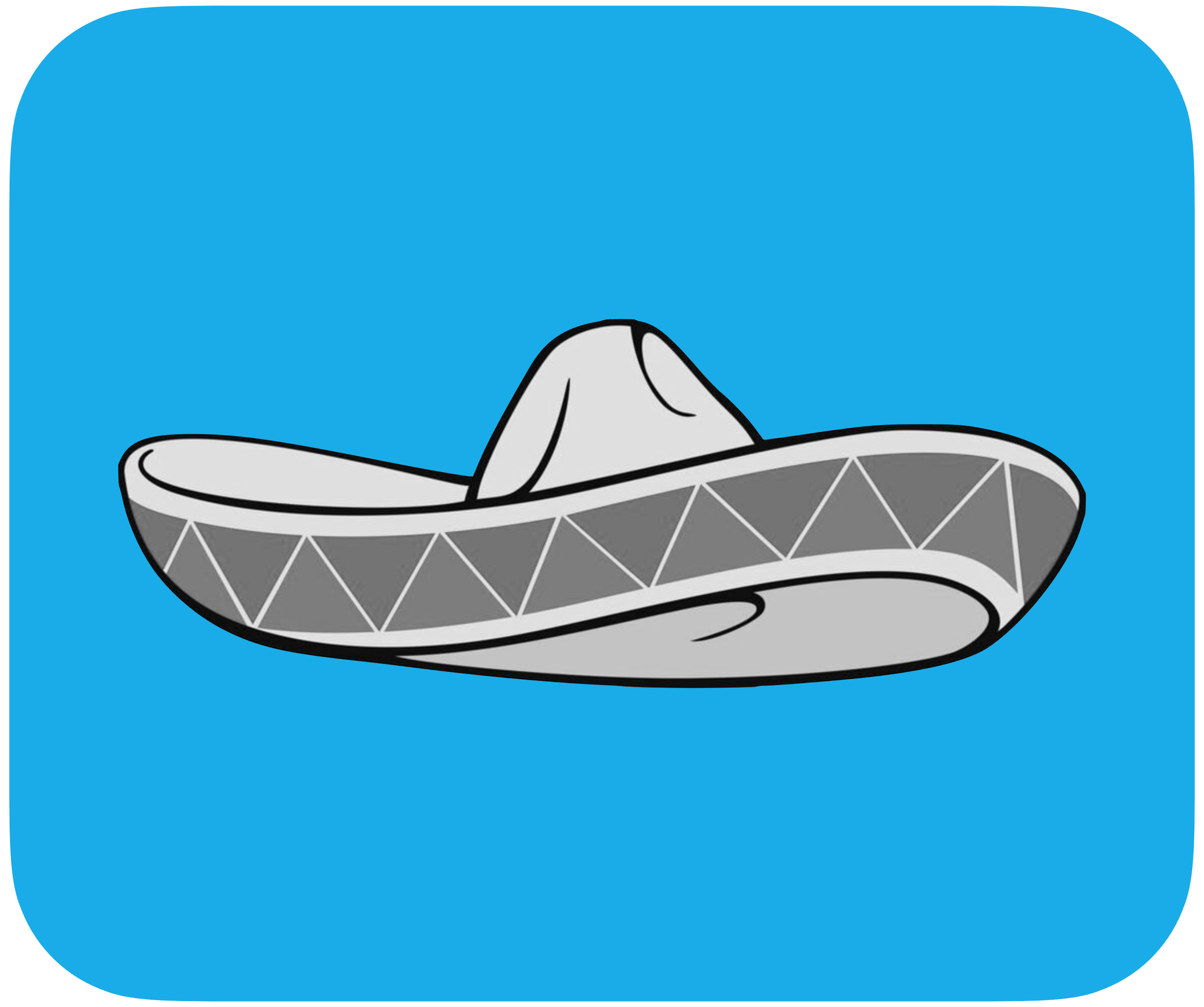


$$\Gamma \propto e^{\beta t - \gamma t^2}$$

The bubble nucleation rate has to become a Gaussian, i.e. β/H has to become small or negative!

Model classes for the PTA signal

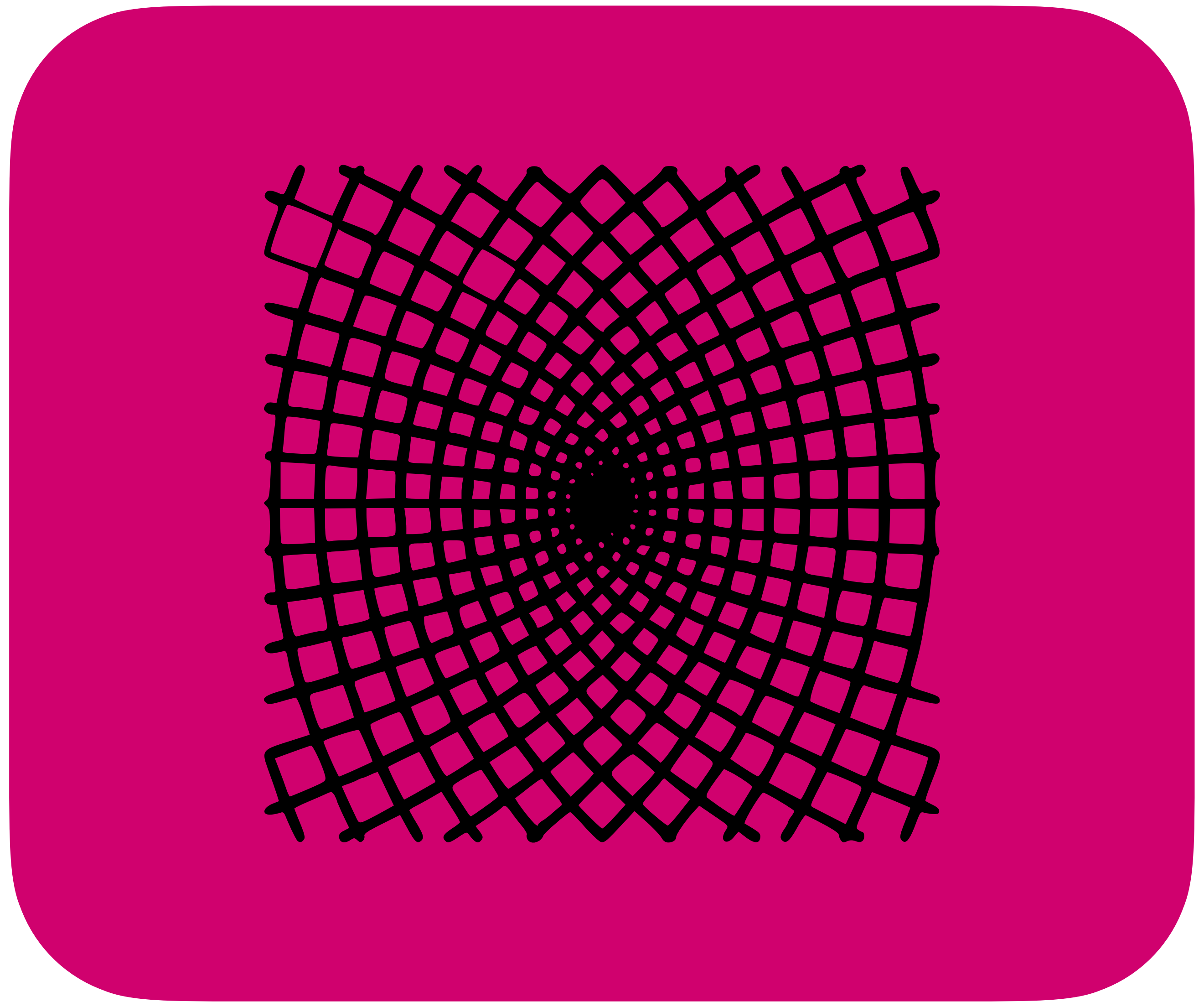
Abelian dark Higgs



$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$

Thermally induced barrier

Conformal dark Higgs



$V(\phi) = \lambda\phi^4$

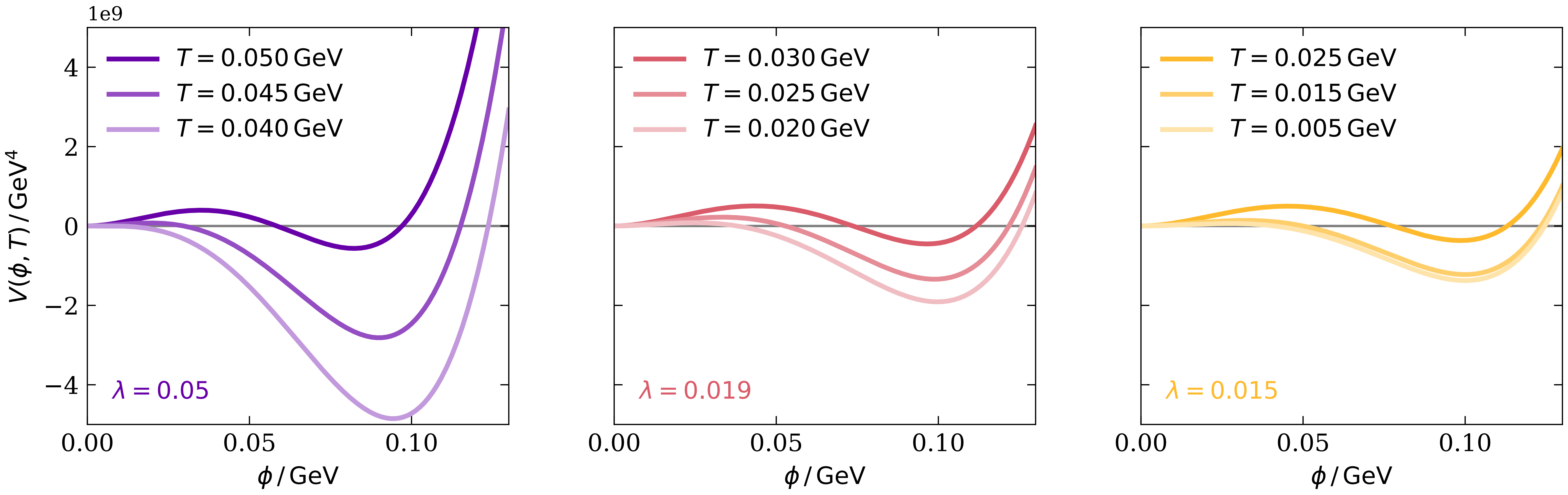
Loop-induced barrier

Dark flipflop

$V(\phi_1, \phi_2)$

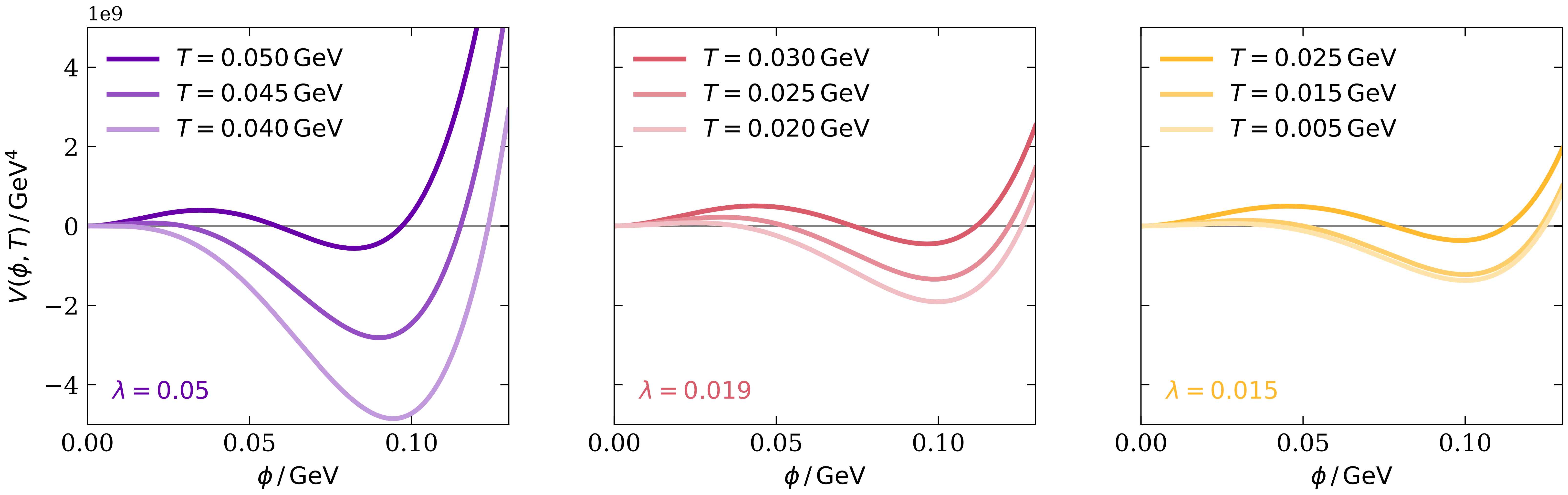
Transition-induced barrier

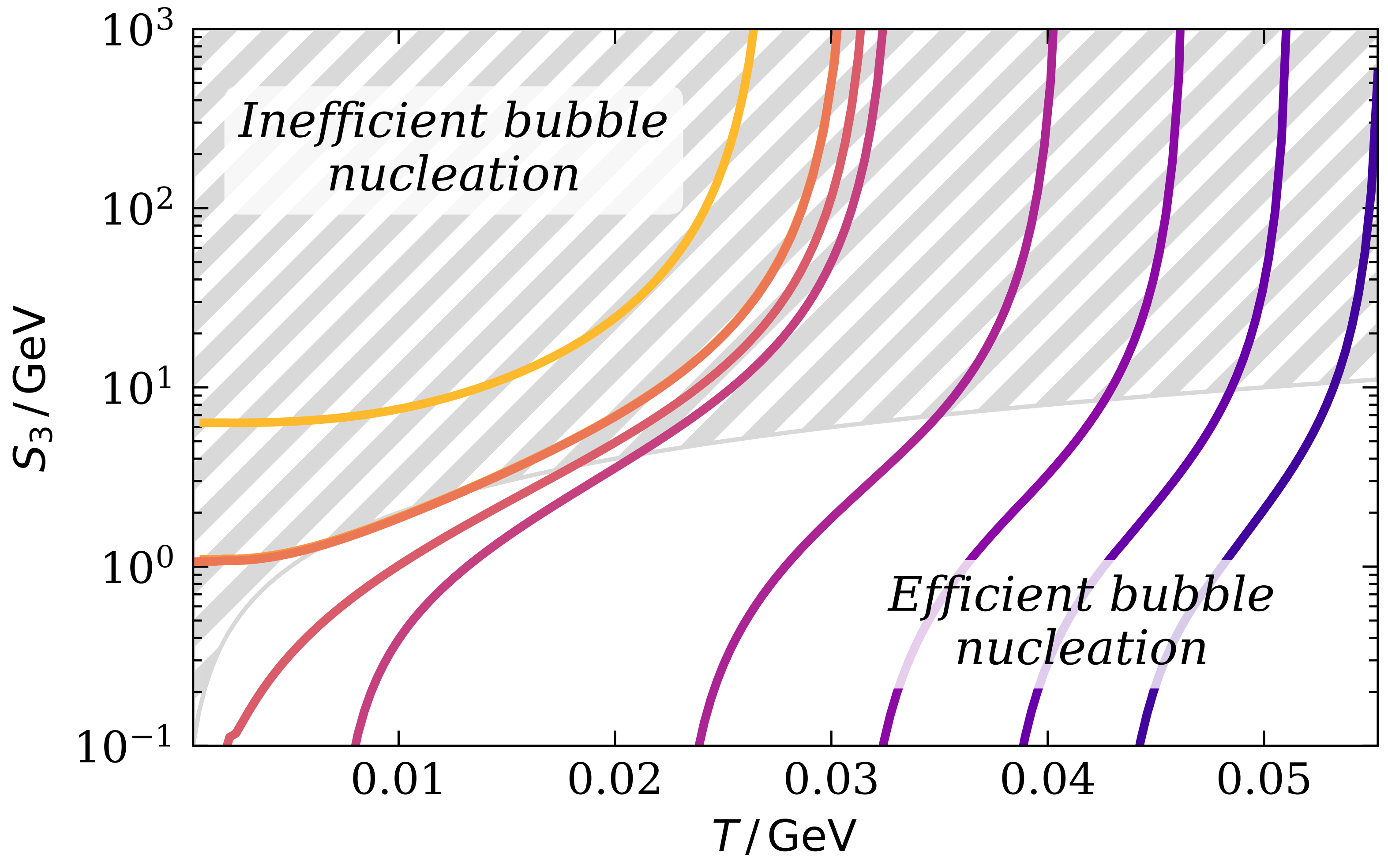
Large bubbles in the Abelian dark Higgs model



Benchmark point: $g = 1$, $v = 100\,\mathrm{MeV}$

Large bubbles in the Abelian dark Higgs model



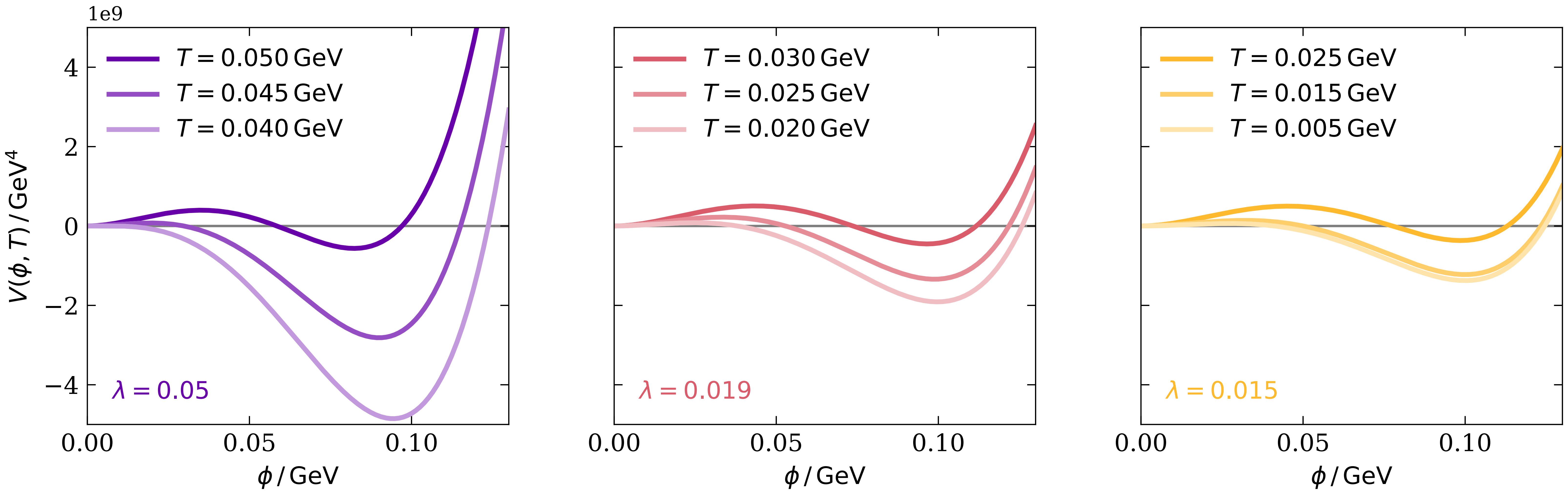


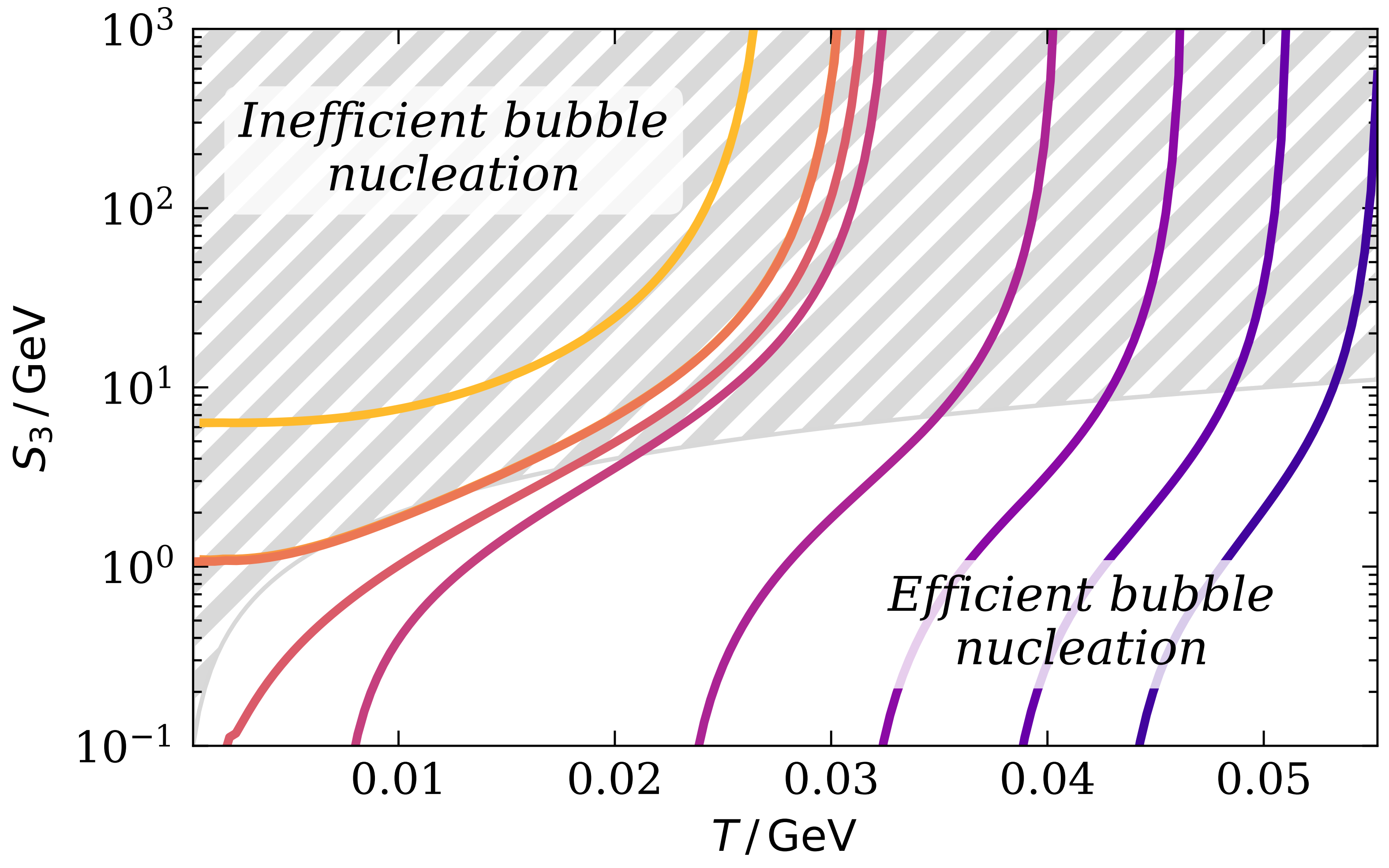
Benchmark point: $g = 1$, $v = 100\,\mathrm{MeV}$

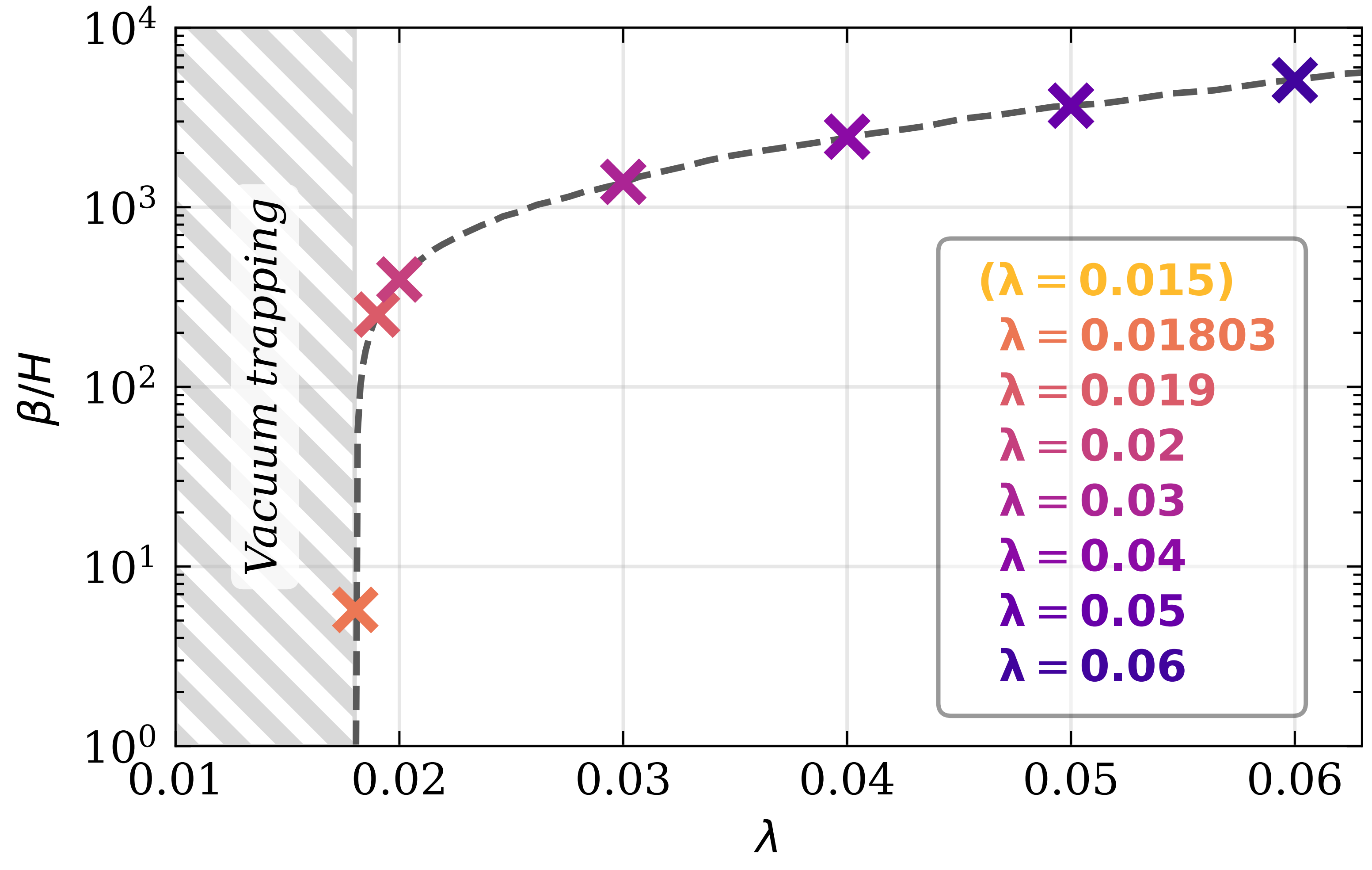
The transition rate is exponentially dependent on the bounce action

$$\Gamma \propto \mathrm{e}^{-S_3/T}$$

Large bubbles in the Abelian dark Higgs model







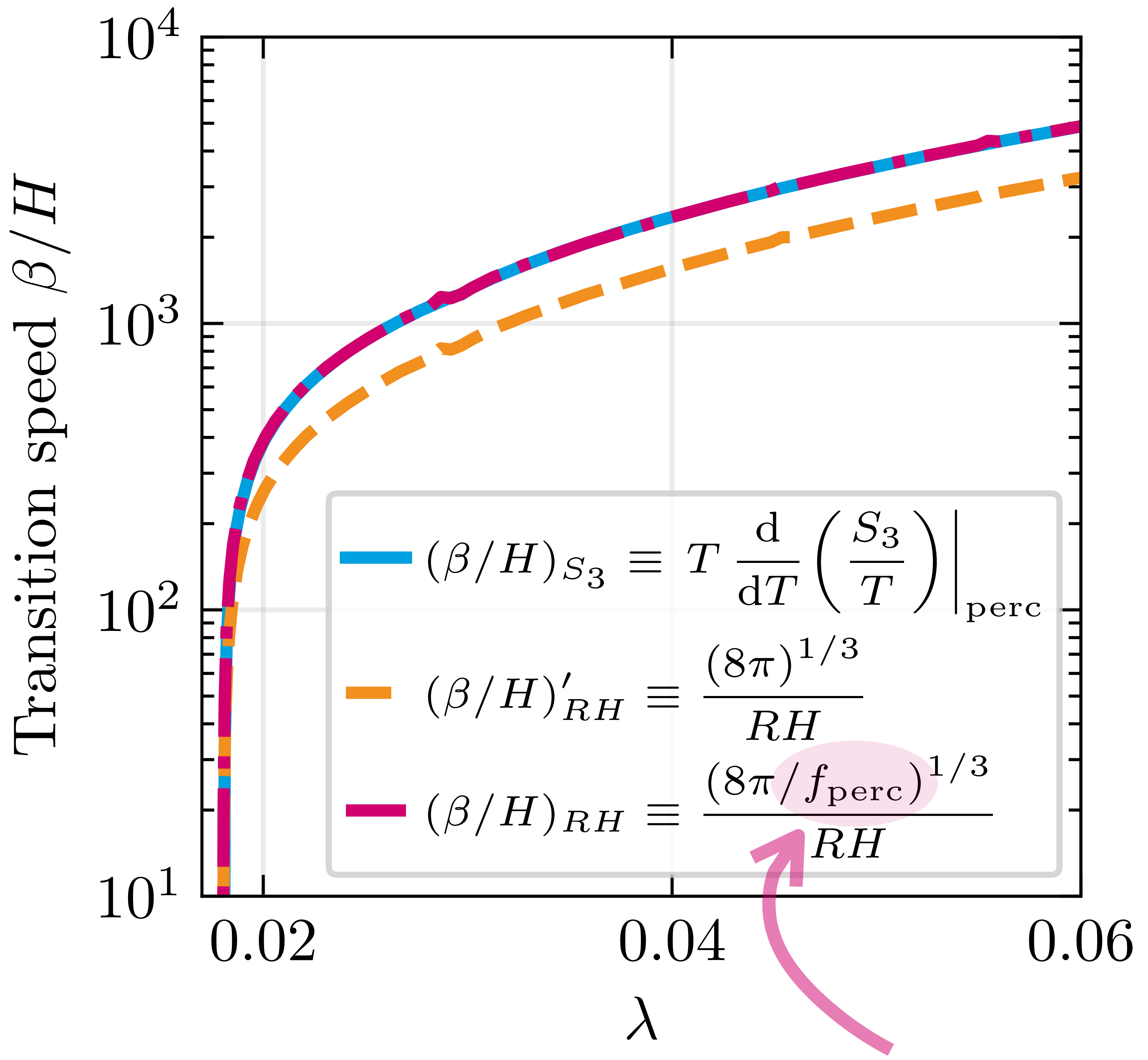
Benchmark point: $g = 1$, $v = 100\,\mathrm{MeV}$

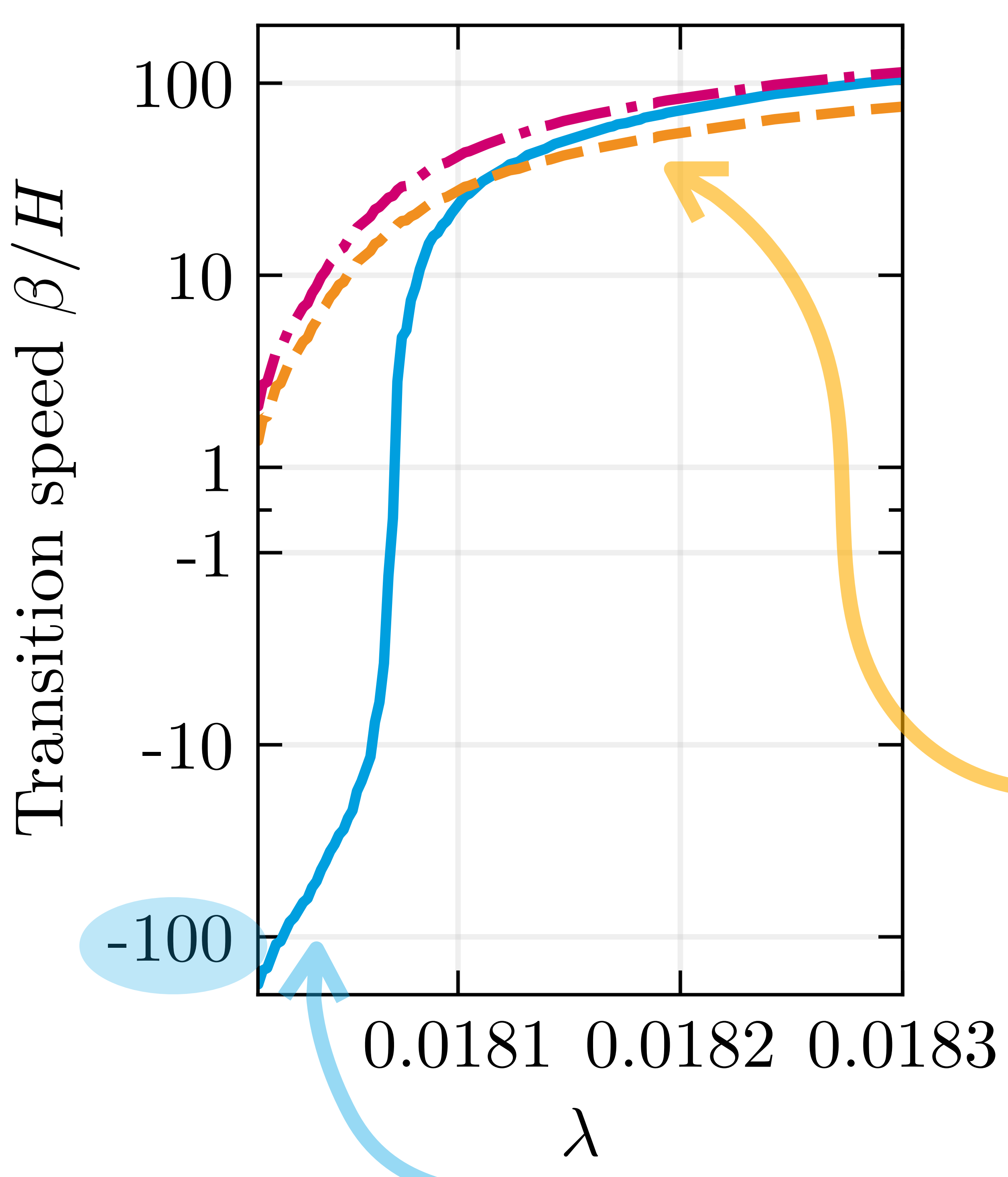
The transition rate is exponentially dependent on the bounce action

$$\Gamma \propto \mathrm{e}^{-S_3/T}$$

Only for fine-tuned quartic couplings λ, large bubbles can be achieved! Generically, $\beta/H > 10^3$.

A comment on β/H and RH





The common relation

$$\beta/H = (8\pi)^{1/3}/RH$$

(used in LISA pipeline, Athron review, …)

is off by 51% and only holds where signals are typically unobservable!

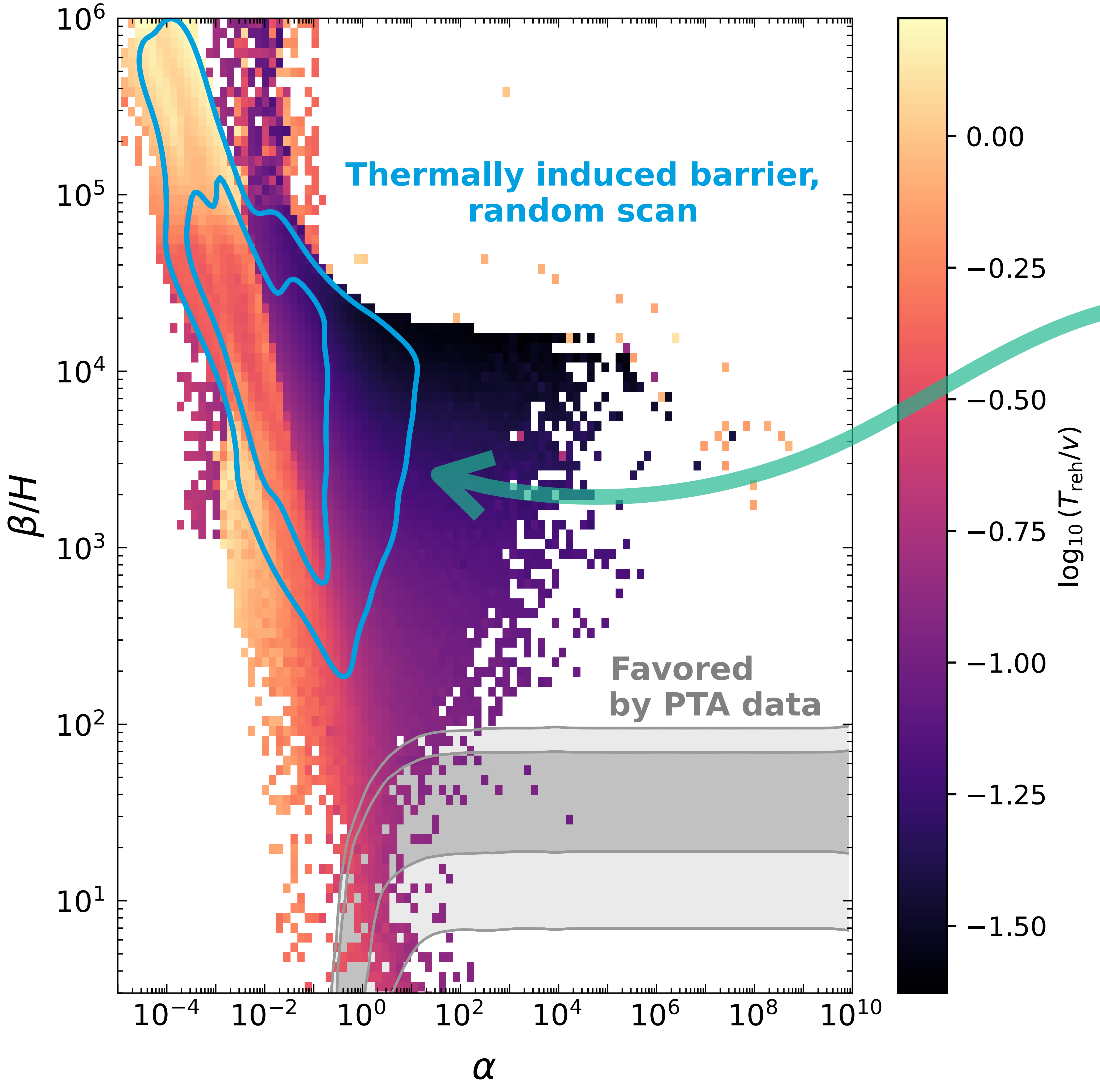
Benchmark point: $g = 1$, $v = 100\,\mathrm{MeV}$

$f_{\mathrm{perc}} = 0.29$ is the true-vacuum fraction at percolation

$T\,\frac{\mathrm{d}}{\mathrm{d}T}\frac{S_3}{T}$ can become *very* negative! This is where the strongest GW signals are.

[Derivation: See appendix of 2605.15259]

Generic model predictions for the Abelian dark Higgs



$g/\lambda^{1/4} \in [0.8, 3.2]$, $\lambda \in [10^{-5}, 1]$, $v \in [1\,\mathrm{MeV}, 1\,\mathrm{GeV}]$

Typically, the phase transitions in the Abelian dark Higgs model are too weak and too fast to explain the PTA data*

* based on a random scan with flat priors

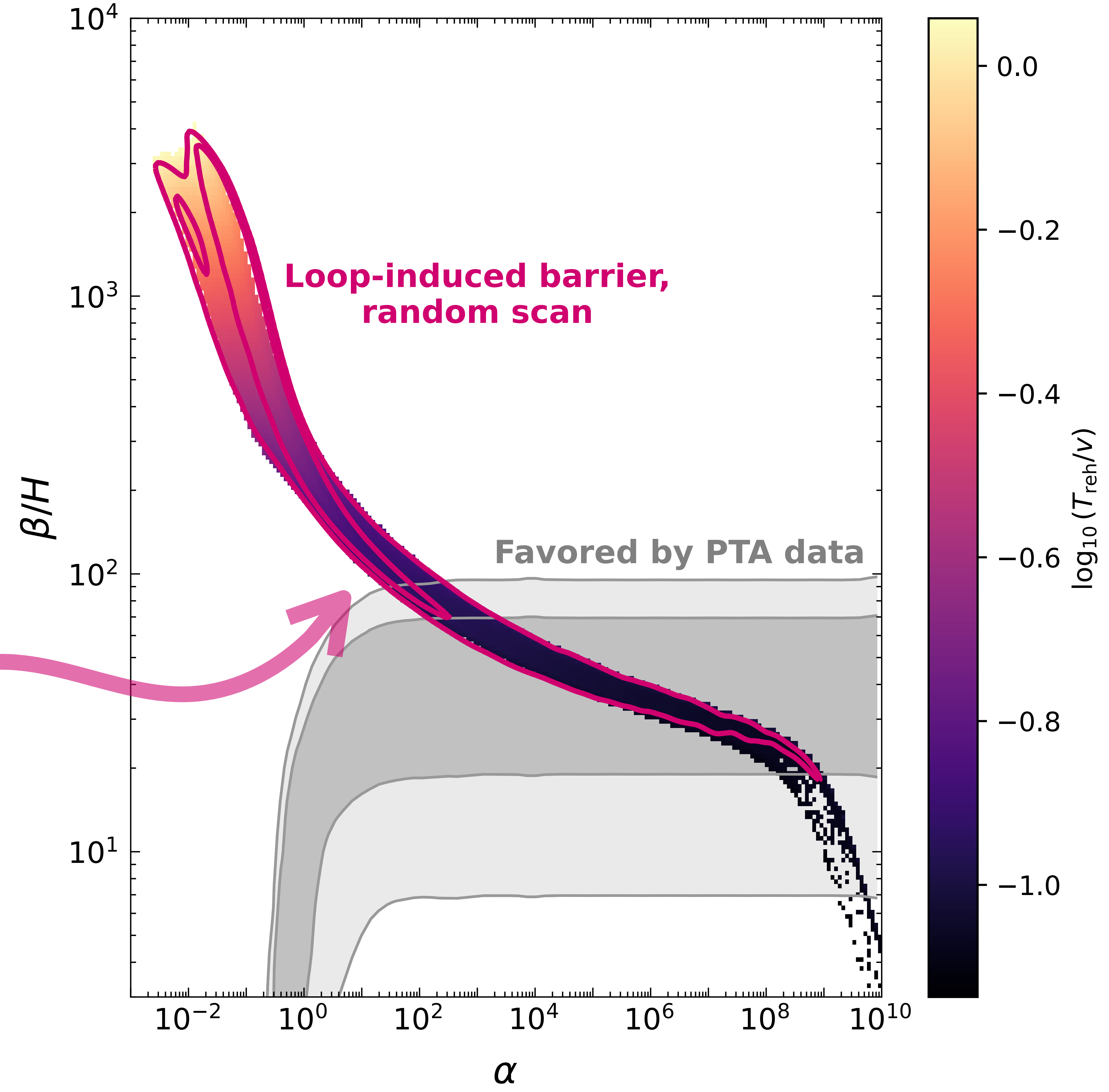
Generic predictions in the conformal dark Higgs model

$$V_{\rm eff} = V_{\rm tree} + V_{\rm CW} + V_{\rm thermal} + \dots$$

Ensure conformality at scale $\Lambda = v$ in renormalization:
$V_{\rm eff}$ picks up a logarithmic temperature dependence!

If the potential barrier is loop-generated, the bounce action becomes log T-dependent, such that α is huge and β/H small by default

[See talk by Cristina Puchades Ibáñez]



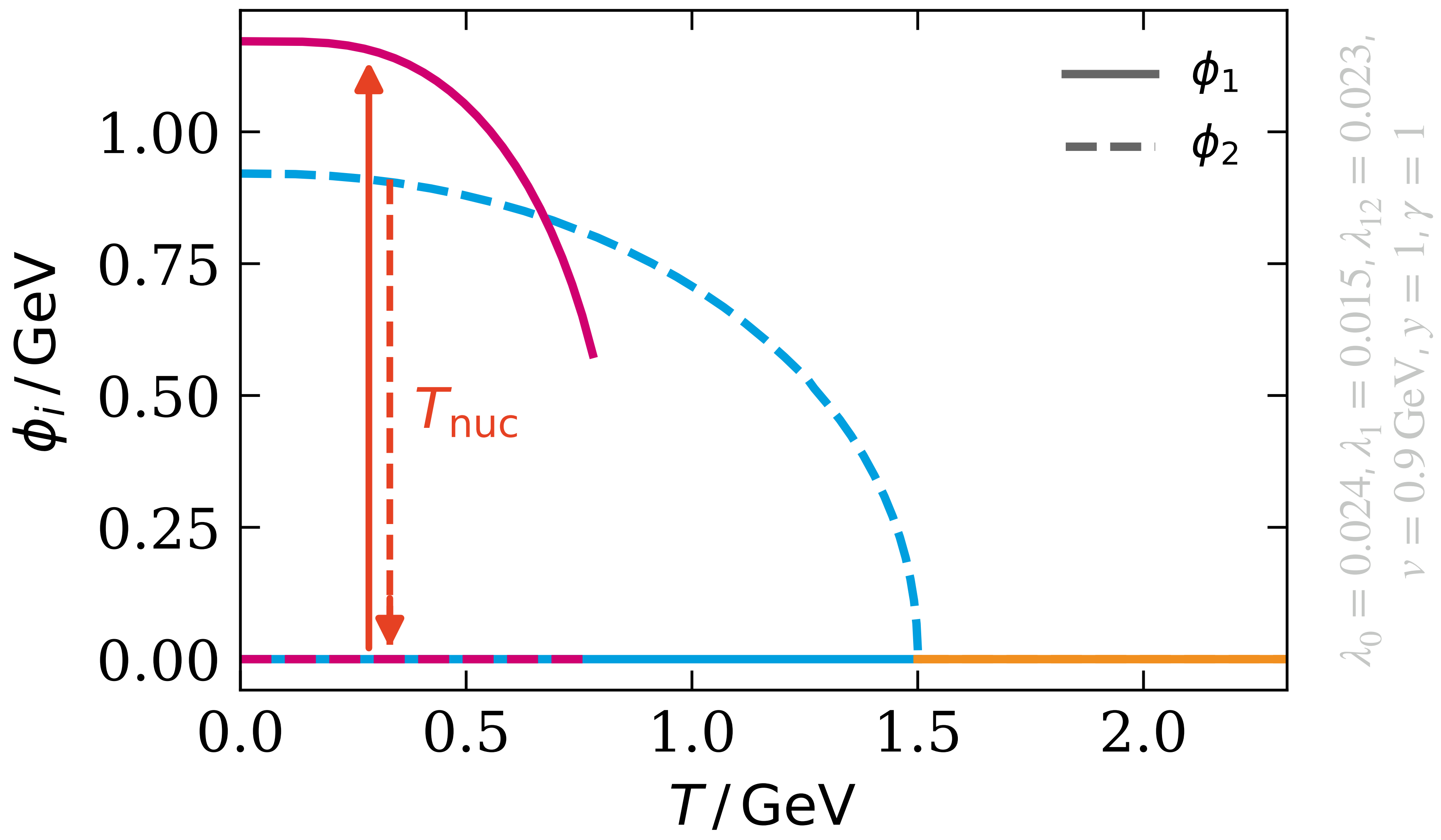
$g \in [0.5, 2]$, $v \in [1\,\mathrm{MeV}, 1\,\mathrm{GeV}]$

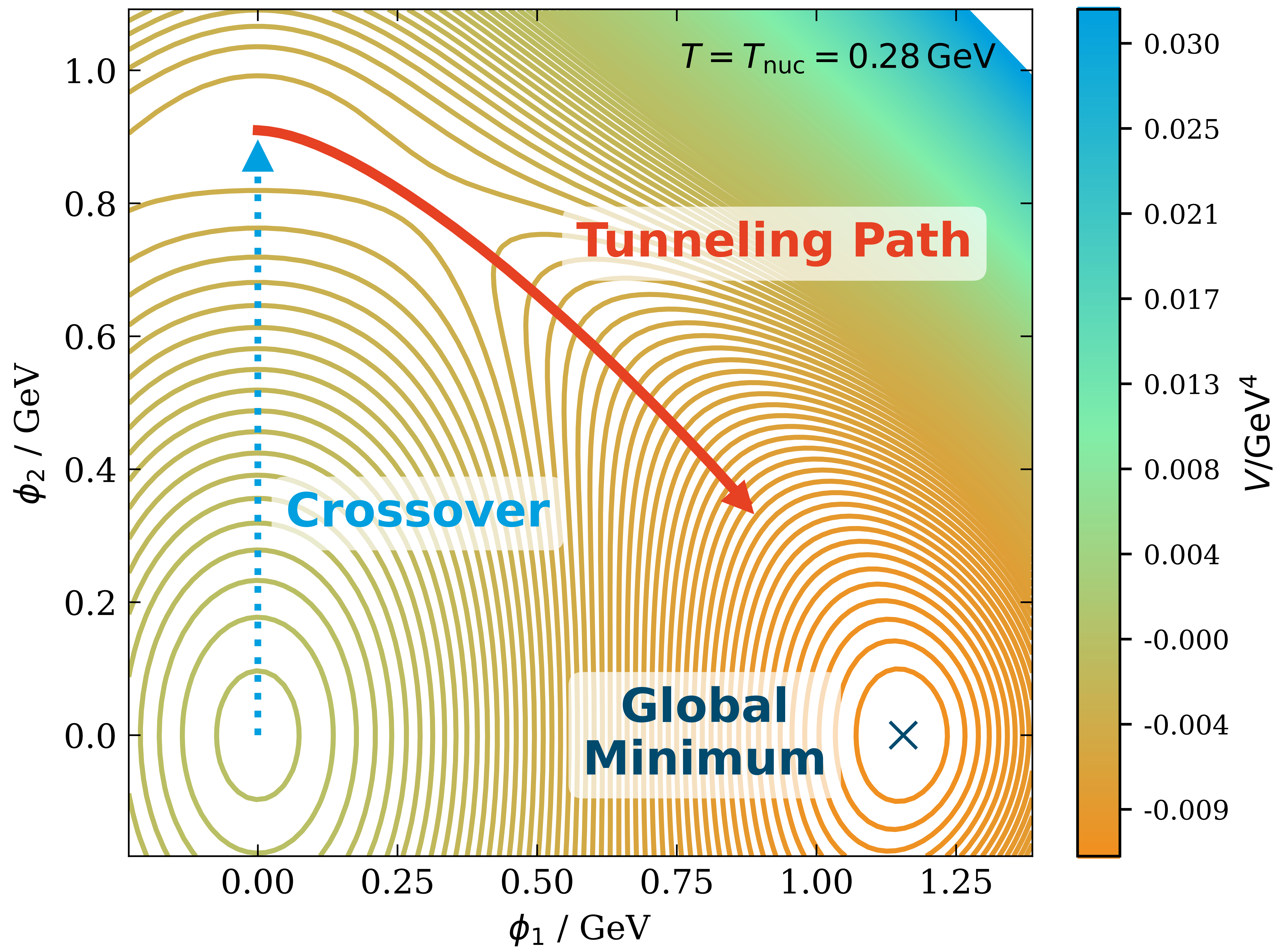
The dark flipflop

Setup: Two real scalars with a potential

$$V(\phi_1, \phi_2) = \frac{\lambda_0}{4}\left(\phi_1^2 + \gamma^2\phi_2^2 - v^2\right)^2 - \frac{\lambda_1}{2}v^2\phi_1^2 + \frac{\lambda_{12}}{2}\phi_1^2\phi_2^2$$

and a fermion that only couples to ϕ_1





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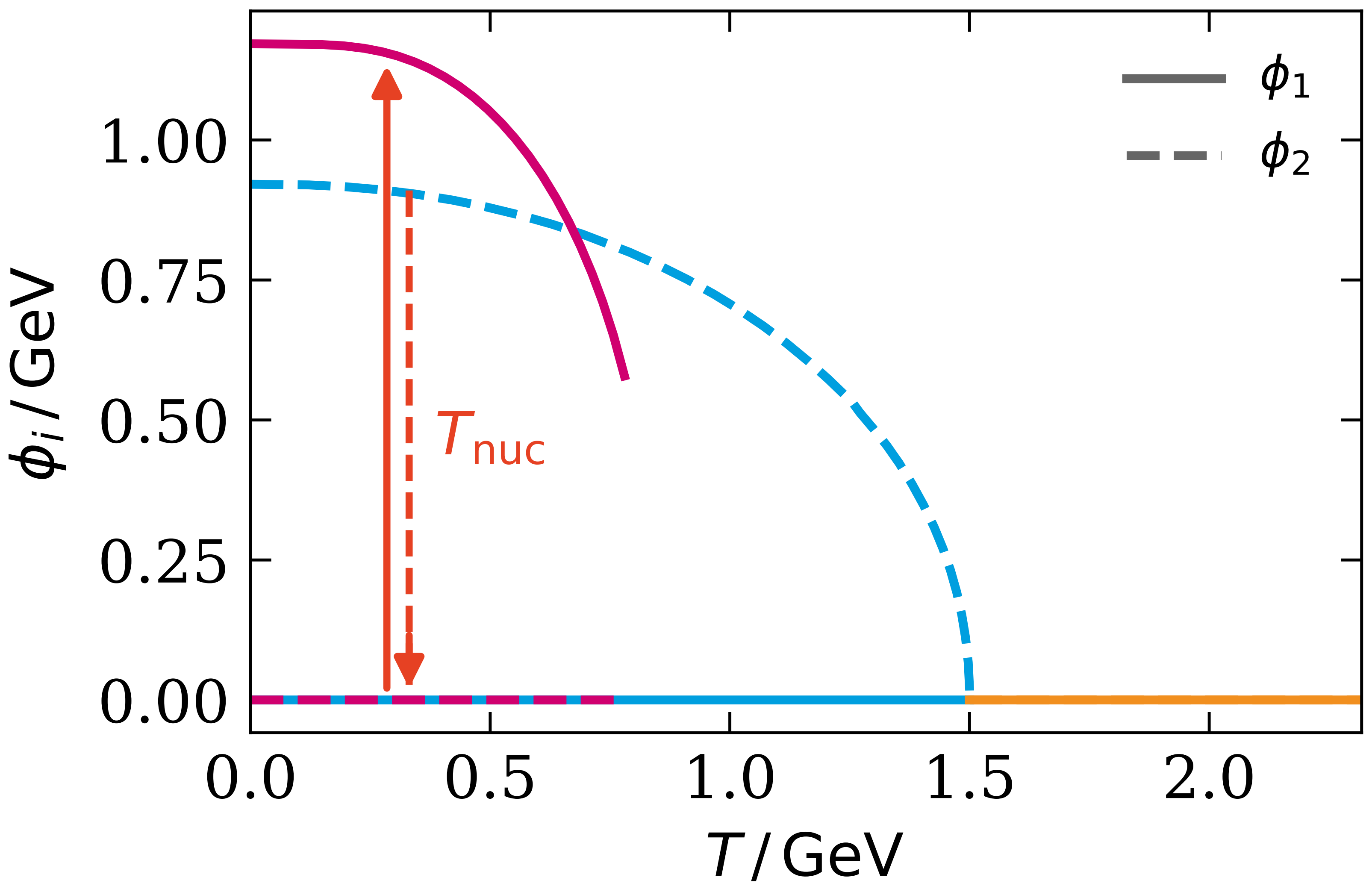
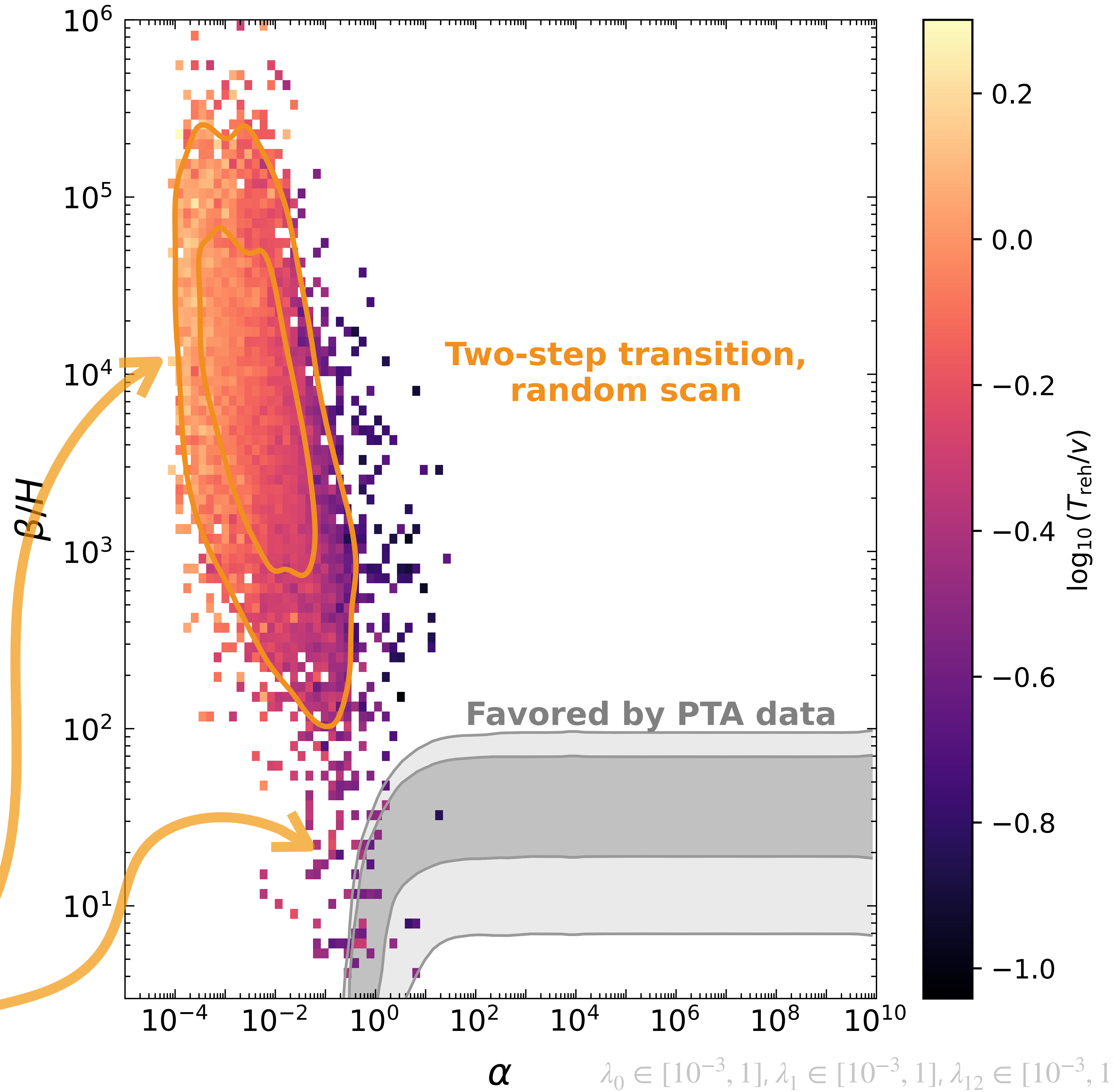


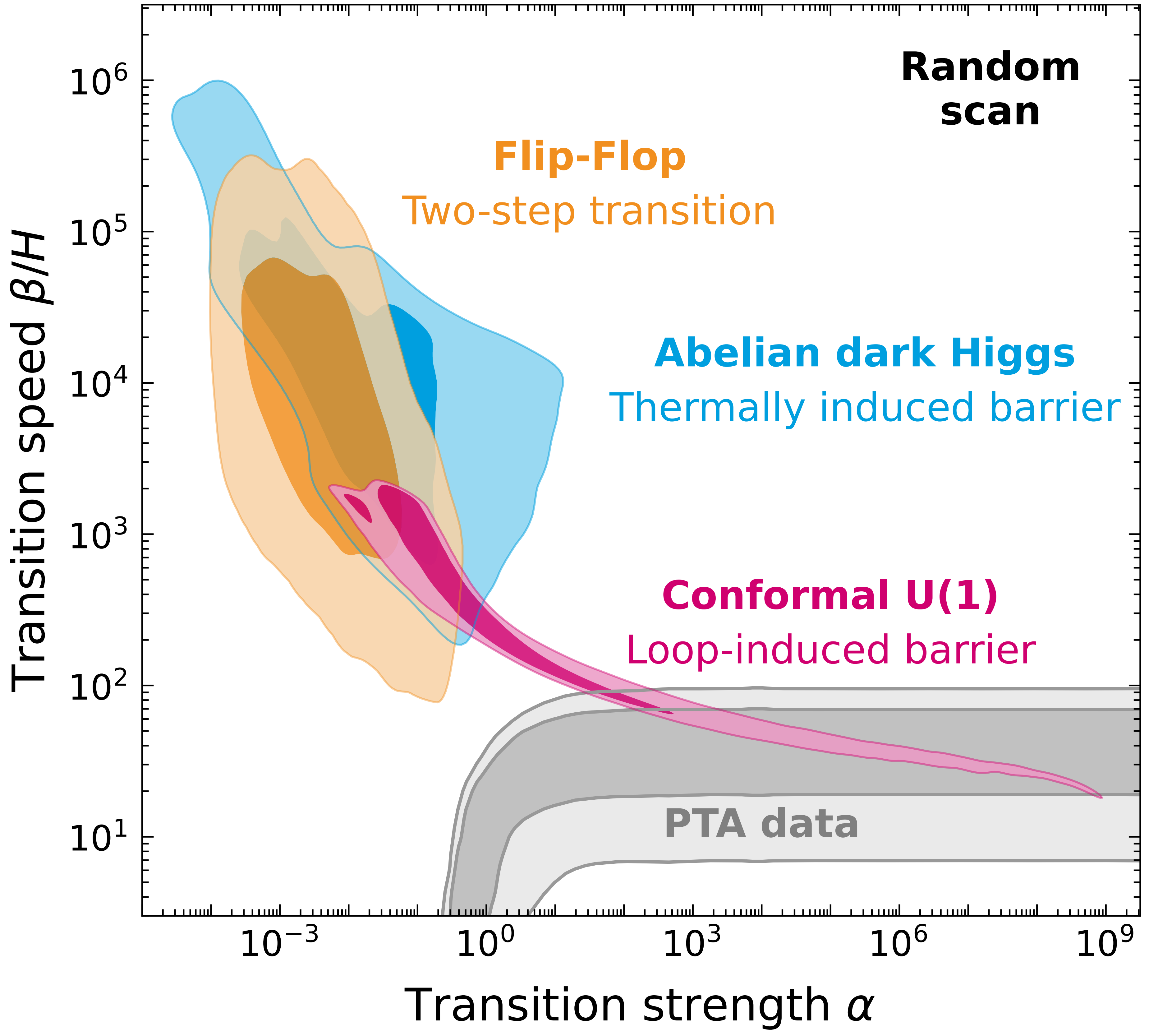
$\lambda_0 = 0.024, \lambda_1 = 0.015, \lambda_{12} = 0.023,$
$v = 0.9\,\text{GeV}, y = 1, \gamma = 1$

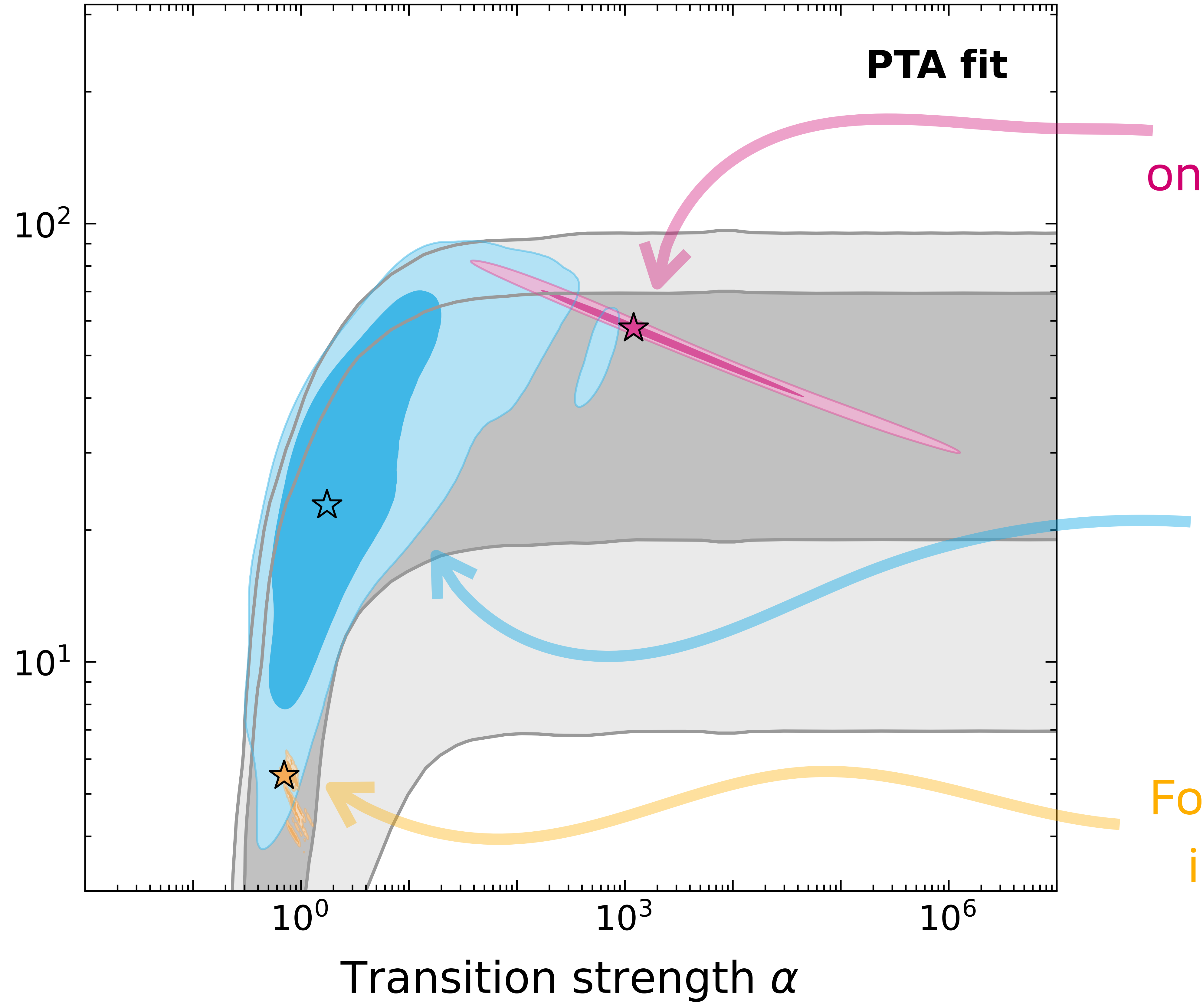
Generally, the bubbles are far too small, but for specific parameter choices, the PTA-favored region can be reached.



$\lambda_0 \in [10^{-3}, 1], \lambda_1 \in [10^{-3}, 1], \lambda_{12} \in [10^{-3}, 1],$
$v \in [10, 10^4]\,\text{MeV}, y \in [0.1, \sqrt{4\pi}], \gamma \in [0.5, 2]$

So… which model explains the PTA data best?





Required tuning:
one significant digit in g

Two significant
digits in λ

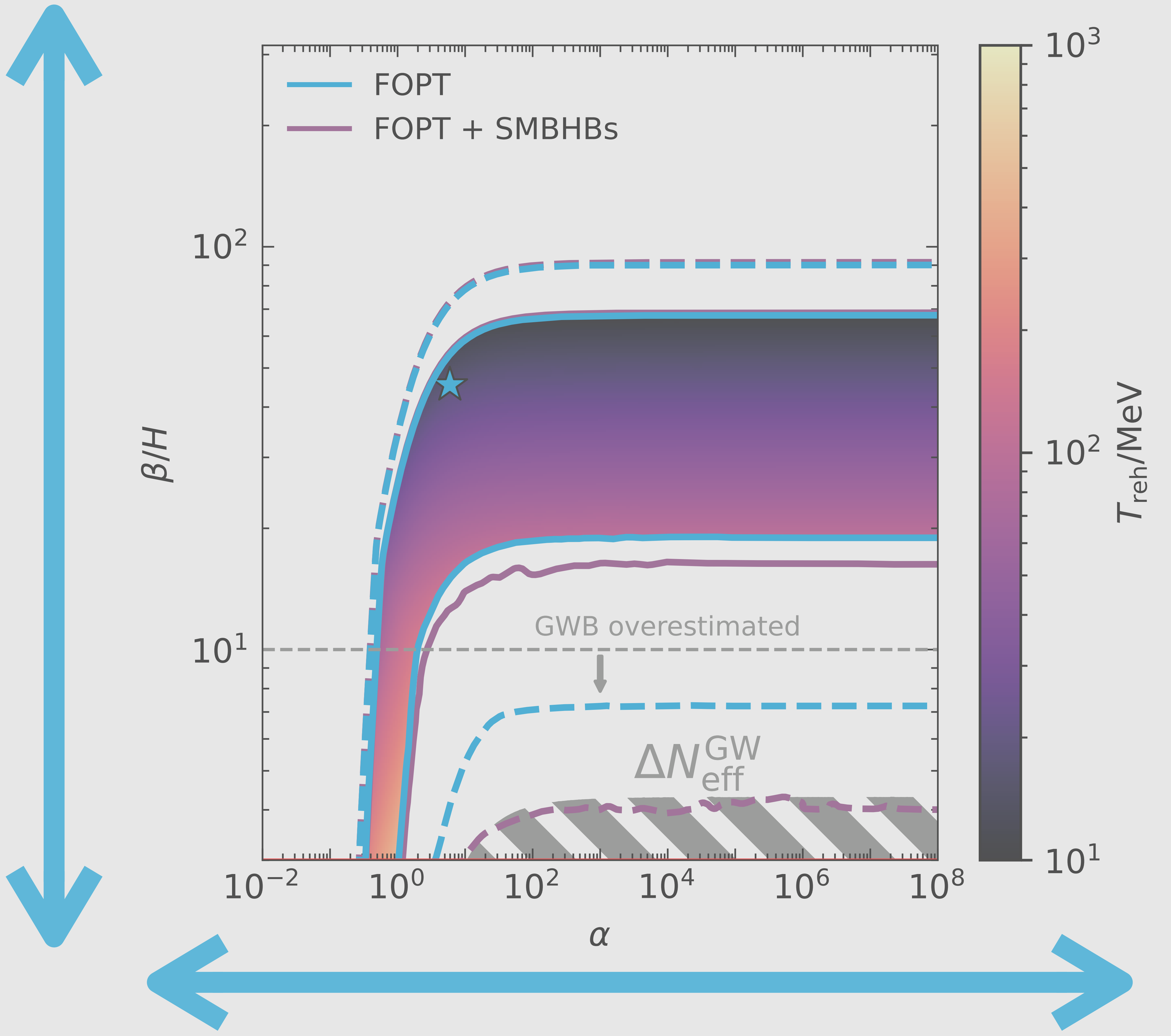
Four significant digits
in four couplings…

The goodness of fit is identical for all model classes (and better than SMBHBs), but the amount of required tuning depends strongly on the mechanism with which the potential barrier is generated!

Which phase transitions can fit the PTA data?

Many small bubbles

$$RH \sim \frac{1}{\beta/H}$$



Few big bubbles

Weak transitions

Strong transitions

PTA data requires very strong transitions with extremely large bubbles!

BSM models typically predict weak transitions with small bubbles…

Robust predictions of the GW signal in that regime are difficult…

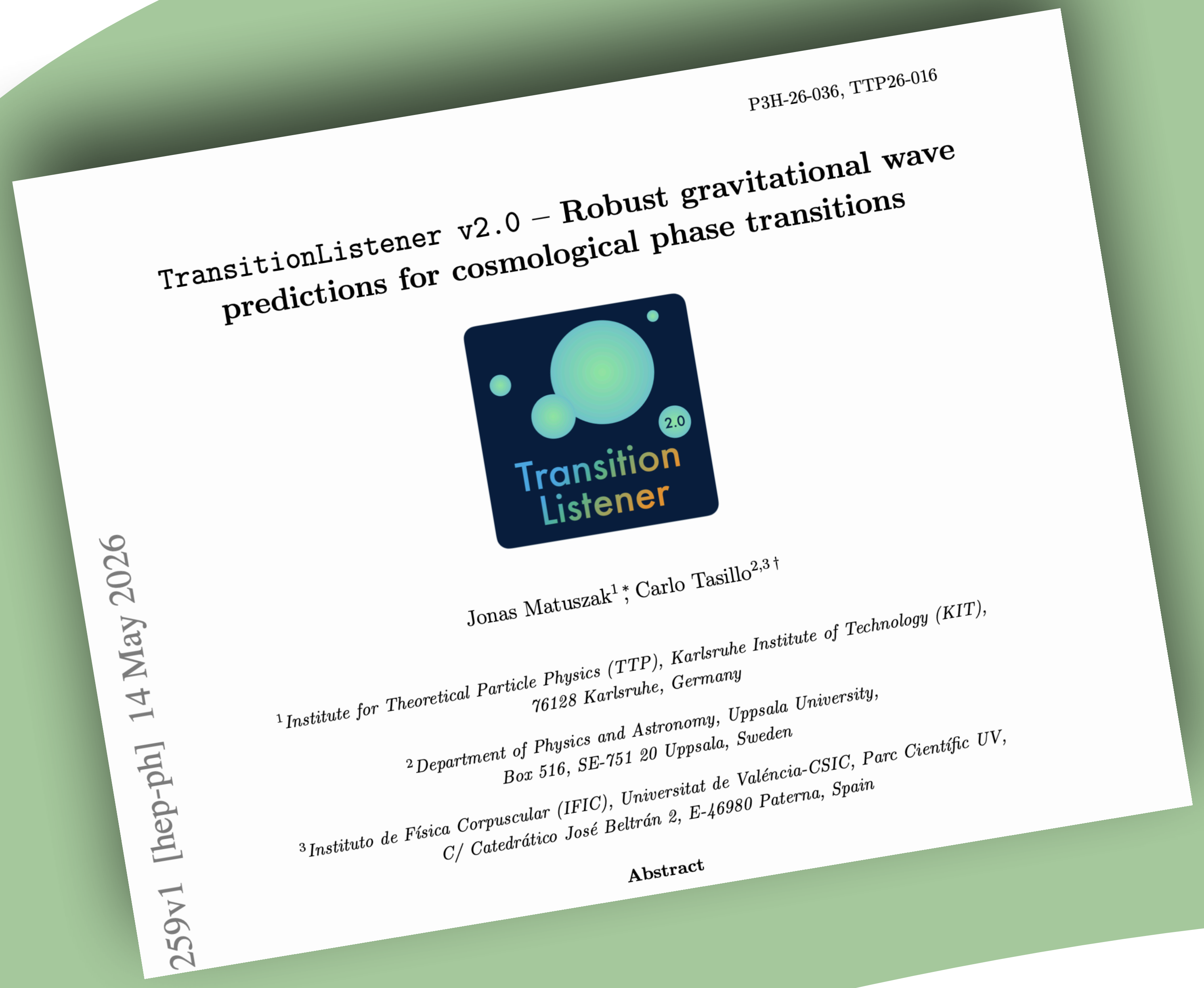
WHAT ABOUT THIS PROBLEM?

BROADCAST INTERRUPTED

Commercial break

- $\beta/H \approx (8\pi)^{1/3}/RH$
- $S_3(T_\text{nuc})/T_\text{nuc} = 140$
- $T_\text{reh} \approx T_\text{perc}(1+\alpha)^{1/4}$
- $\alpha \approx \Delta V/\rho_\text{rad}$

- $c_\text{s}^2 = 1/3$
- Permanent radiation domination
- No false-vacuum fraction feedback on Hubble rate
- Outdated GW spectra



P3H-26-036, TTP26-016

`TransitionListener v2.0` – Robust gravitational wave predictions for cosmological phase transitions

Transition Listener 2.0

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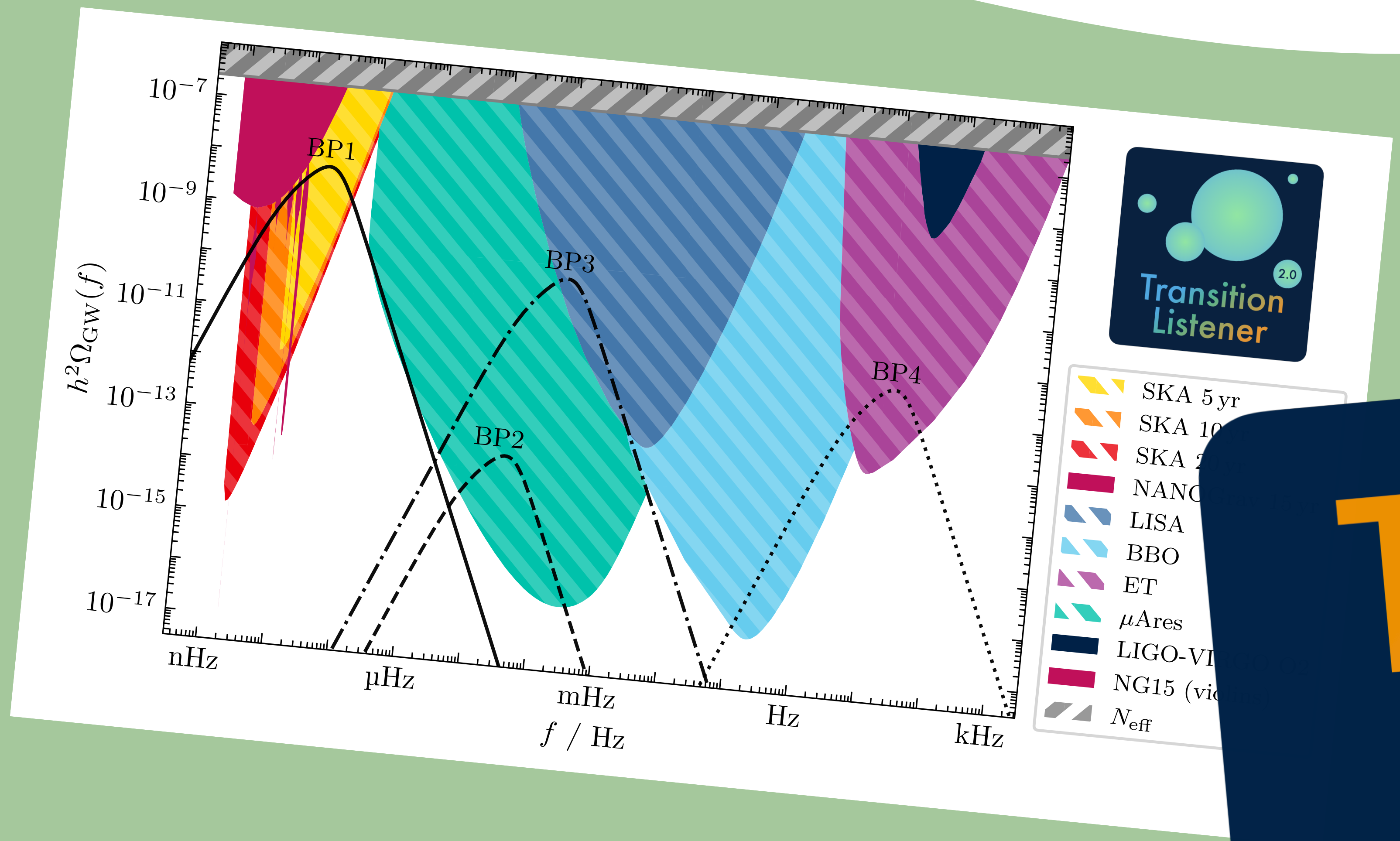
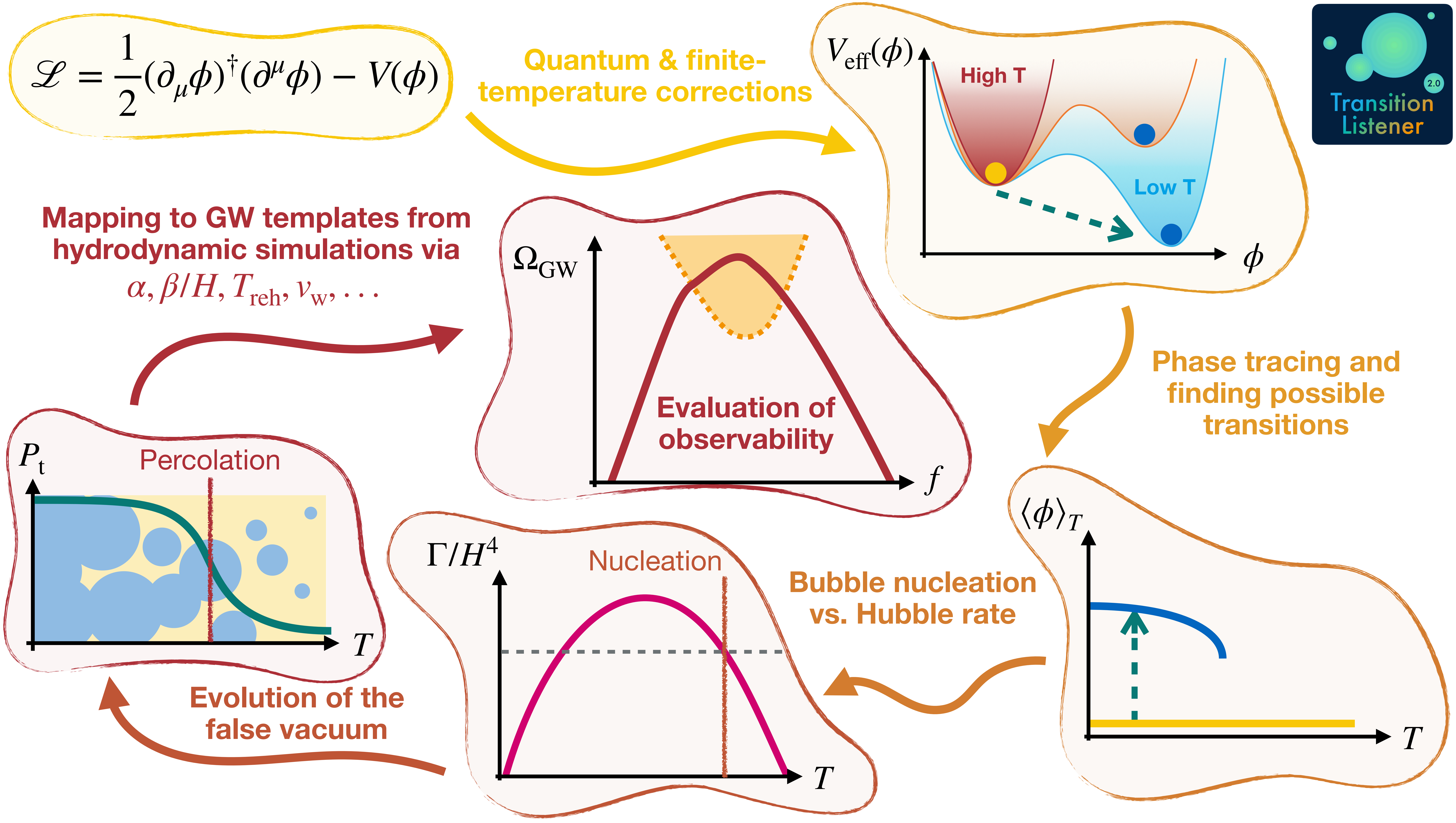
Abstract

259v1 [hep-ph] 14 May 2026



Transition Listener



$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^\dagger(\partial^\mu \phi) - V(\phi)$$

Quantum & finite-temperature corrections

Phase tracing and finding possible transitions

Bubble nucleation vs. Hubble rate

Evolution of the false vacuum

Mapping to GW templates from hydrodynamic simulations via $\alpha, \beta/H, T_{\rm reh}, v_{\rm w}, \ldots$

Evaluation of observability

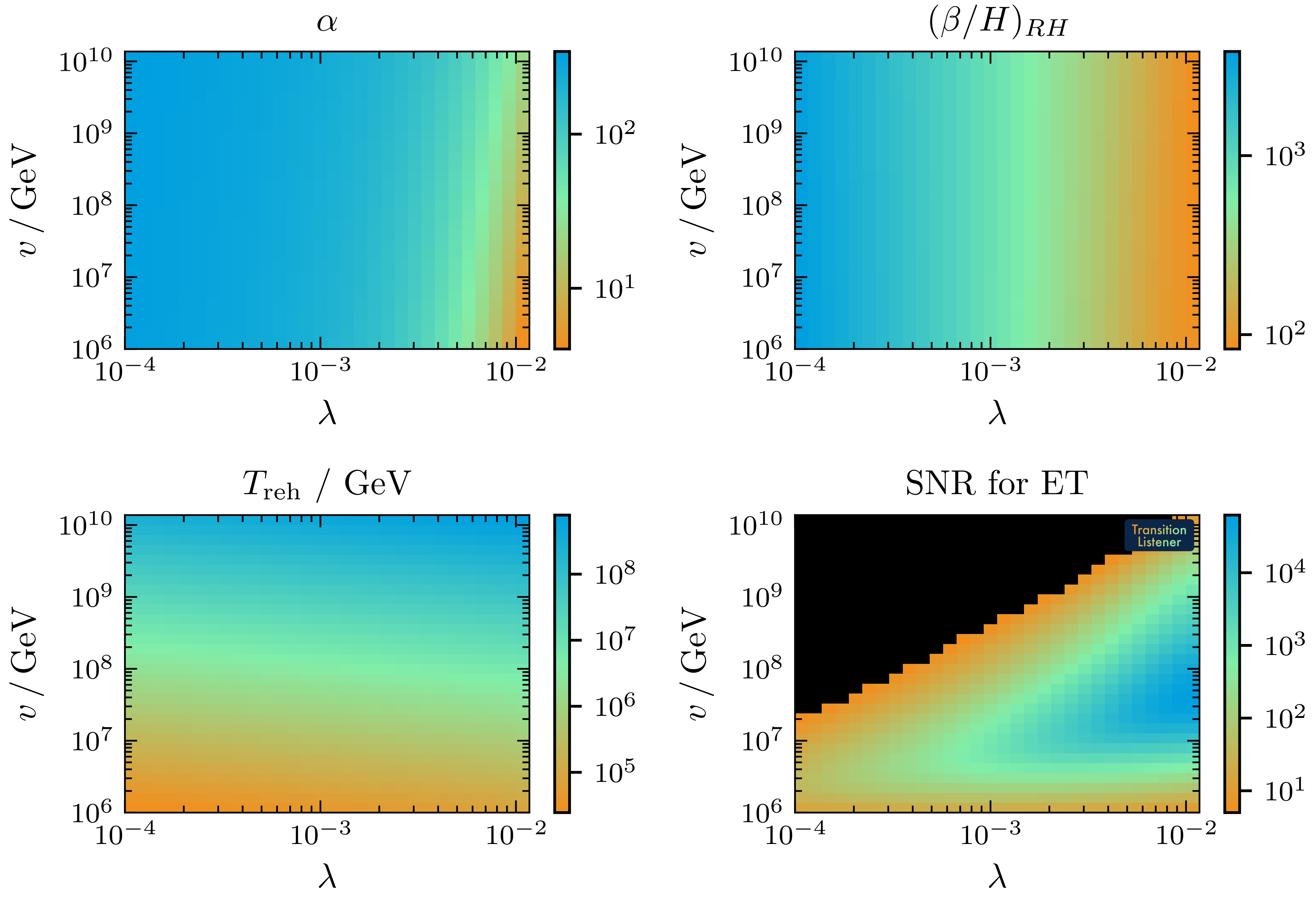
Commercial break

Easy to install!

Pretty plots!

Interfaced with PTArcade!

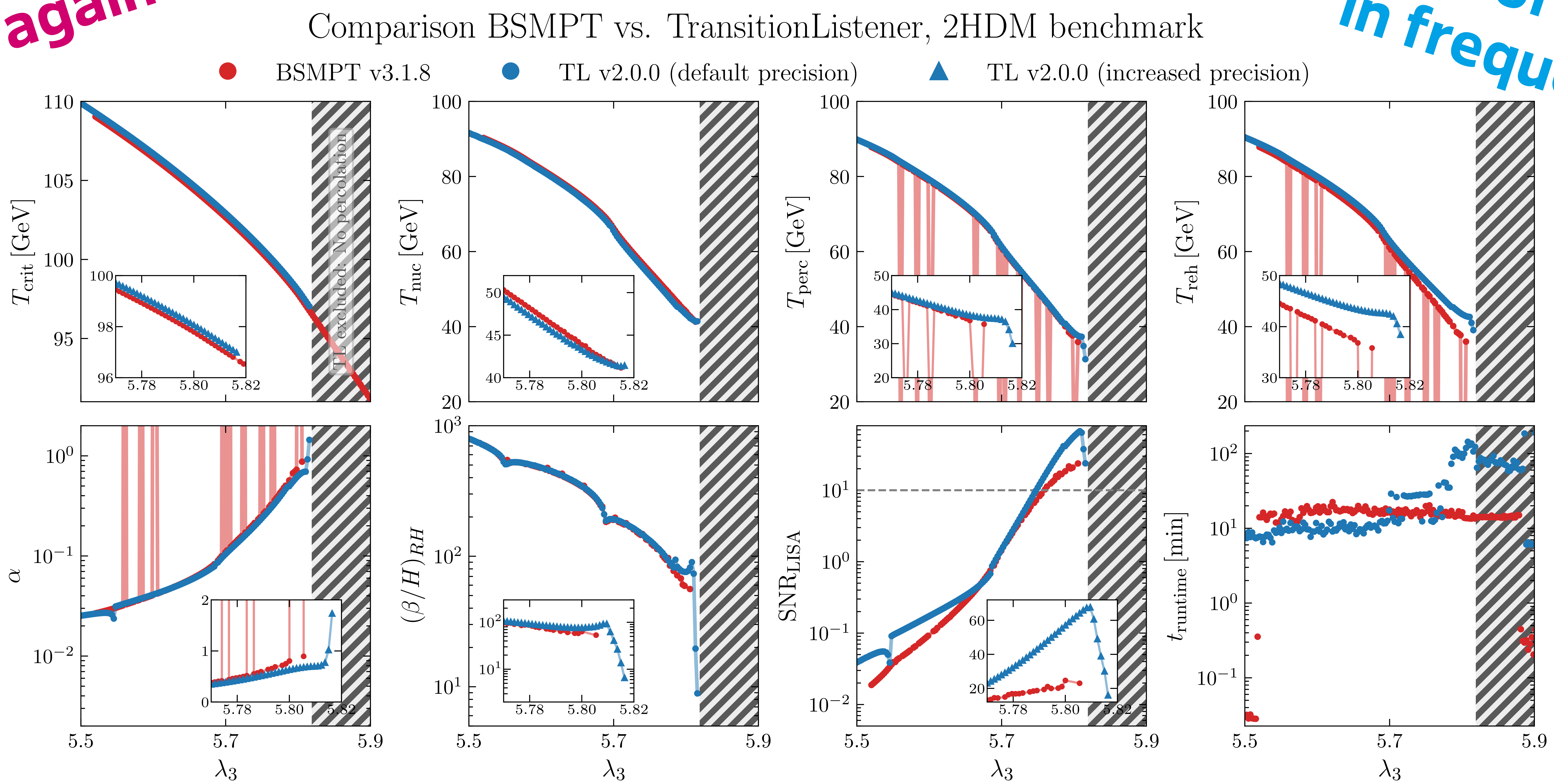
```
Welcome to TransitionListener v2.0!

──────────────────────────── Config ────────────────────────────
Type          SinglePoint
Model         models/TL_conformal_dark_u1.py
Output        scans/example_point/
Format        txt
Description   example point, conformal U(1) model

──────────────────────── Scan parameters ───────────────────────
Parameter  Value
g          0.7
v_GeV      0.1
y          0.01

Starting analysis of example point, conformal U(1) model

Input parameters
┌───────────┬──────────────────┐
│ Parameter │ Value            │
├───────────┼──────────────────┤
│ g         │ 7.0000000000e-01 │
│ y         │ 1.0000000000e-02 │
│ v_GeV     │ 1.0000000000e-01 │
└───────────┴──────────────────┘
Derived parameters
┌───────────┬──────────────────┐
│ Parameter │ Value            │
├───────────┼──────────────────┤
│ lambda    │ 1.6790420728e-02 │
└───────────┴──────────────────┘
Zero-temperature mass spectrum
┌──────────┬─────────┬──────────────────┐
│ Particle │ Type    │ Mass [GeV]       │
├──────────┼─────────┼──────────────────┤
│ m_phi    │ boson   │ 2.2443542988e-02 │
│ m_varphi │ boson   │ 1.2957785586e-02 │
│ m_A_T    │ boson   │ 7.0000000000e-02 │
│ m_A_L    │ boson   │ 7.0000000000e-02 │
│ m_psi1   │ fermion │ 7.0710678119e-04 │
│ m_psi2   │ fermion │ 7.0710678119e-04 │
└──────────┴─────────┴──────────────────┘
```



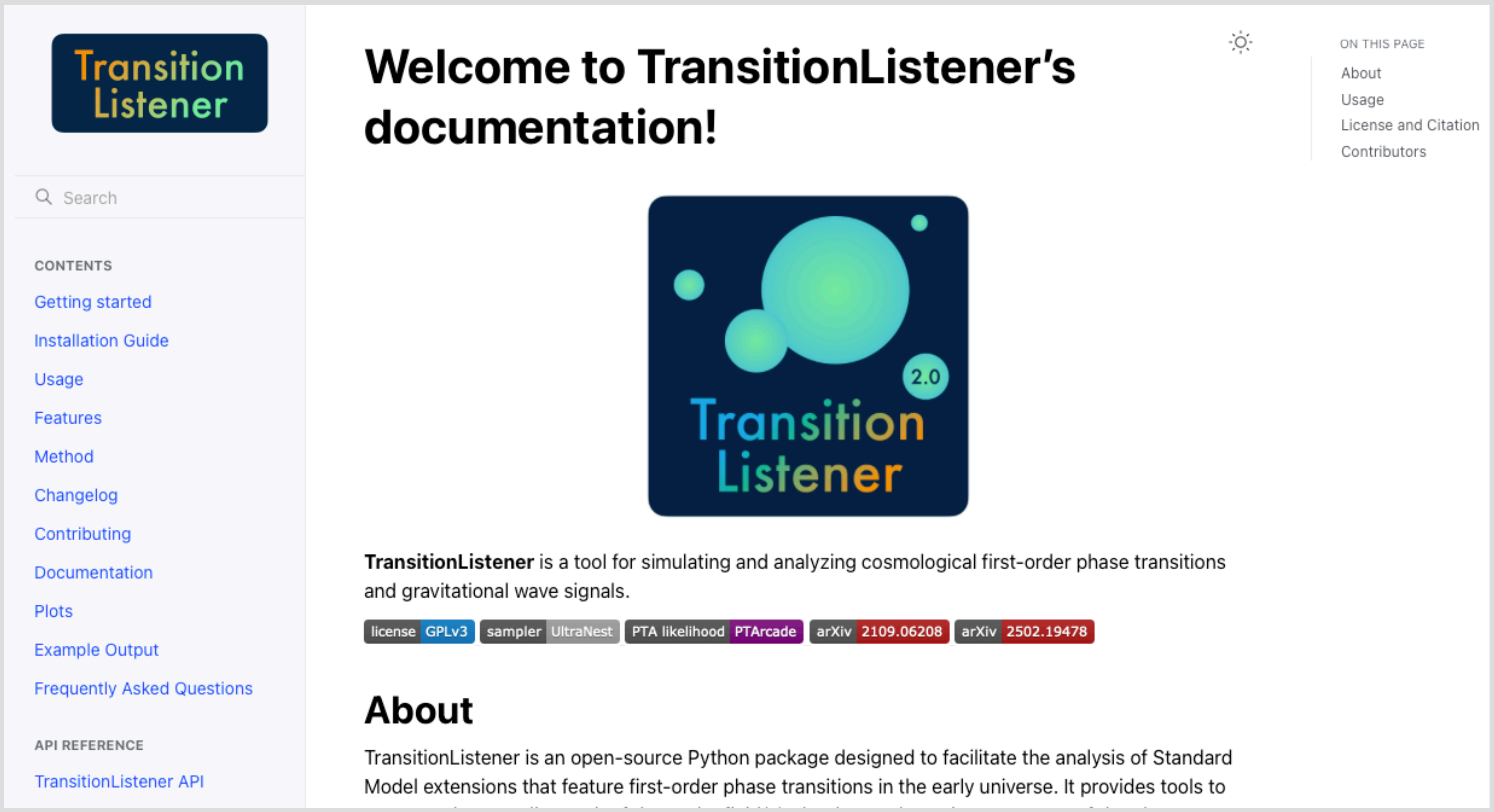
Carlo Tasillo — Are the violins tuned?

Validated against BSMPT!

Numerically stable over 12 orders of magnitude in frequency!


Comparison BSMPT vs. TransitionListener, 2HDM benchmark

Comes with dark sector models and 2HDM!



CONTENTS

- Getting started
- Installation Guide
- Usage
- Features
- Method
- Changelog
- Contributing
- Documentation
- Plots
- Example Output
- Frequently Asked Questions

API REFERENCE

- TransitionListener API

Welcome to TransitionListener's documentation!

ON THIS PAGE

- About
- Usage
- License and Citation
- Contributors

TransitionListener is a tool for simulating and analyzing cosmological first-order phase transitions and gravitational wave signals.

license GPLv3 | sampler UltraNest | PTA likelihood PTArcade | arXiv 2109.06208 | arXiv 2502.19478

About

TransitionListener is an open-source Python package designed to facilitate the analysis of Standard Model extensions that feature first-order phase transitions in the early universe. It provides tools to

Well-documented and in active use!

Just try:

`pip install transitionlistener`

Click here!

www.tasillo.de/TransitionListener

BROADCAST INTERRUPTED

Summary and outlook

The violins are tuned (at least a bit)! Without tuning, thermally & transition-induced barriers don't produce strong GW signals. Radiative symmetry breaking: 👑 All models can fit the PTA data better than SMBHBs.

$$RH_{\mathrm{perc}} = \left(\frac{8\pi}{f_{\mathrm{perc}}}\right)^{1/3} \frac{\max(v_{\mathrm{w}}, c_{\mathrm{s}})}{\beta/H}$$

only holds for $\beta/H \gg 100$.

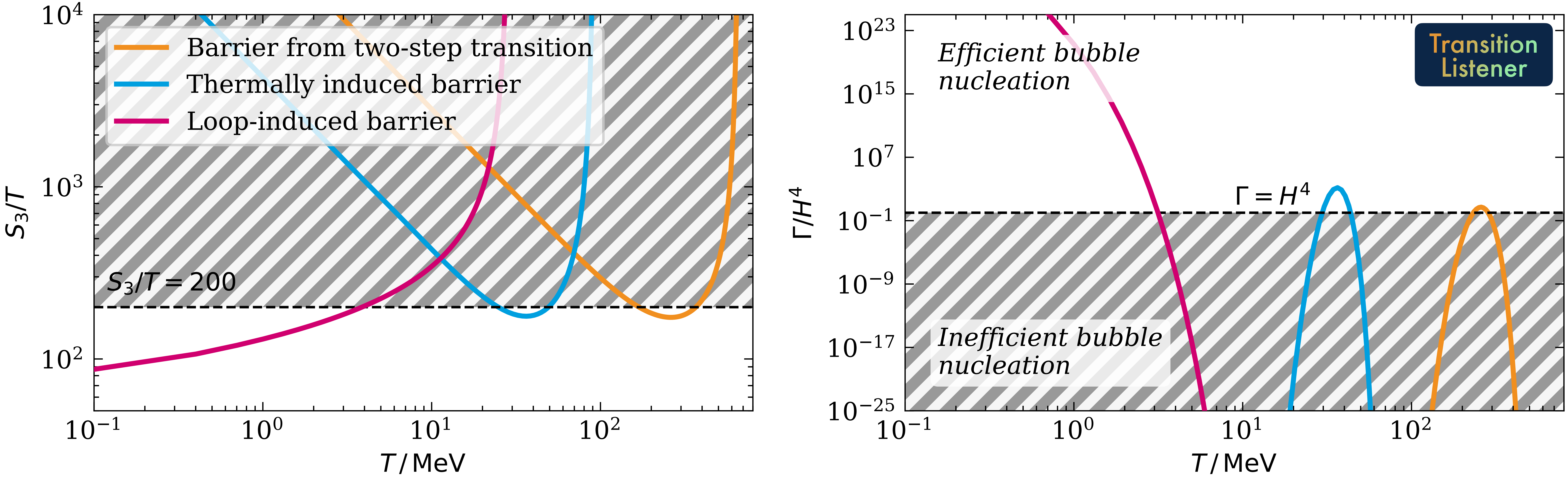
Presented **TransitionListener v2.0,** which remains numerically stable and physically accurate for $\alpha \gg 1$ and $\beta/H \ll 100$.

Even if the IPTA DR3 will find an astrophysical origin of the PTA signal, our **tuning arguments will remain** for future GW background studies, e.g. at LISA.

What about dark matter and the collider complementarity? Check 2606.09092 and Felix Kahlhoefer's talk or just ask me!

Backup slides.

Bubble nucleation rates for the three model classes



[BP: best-fit points for NANOGrav 15yr data set, 2602.09092, CT+]

Robust and self-consistent predictions for T_{reh}

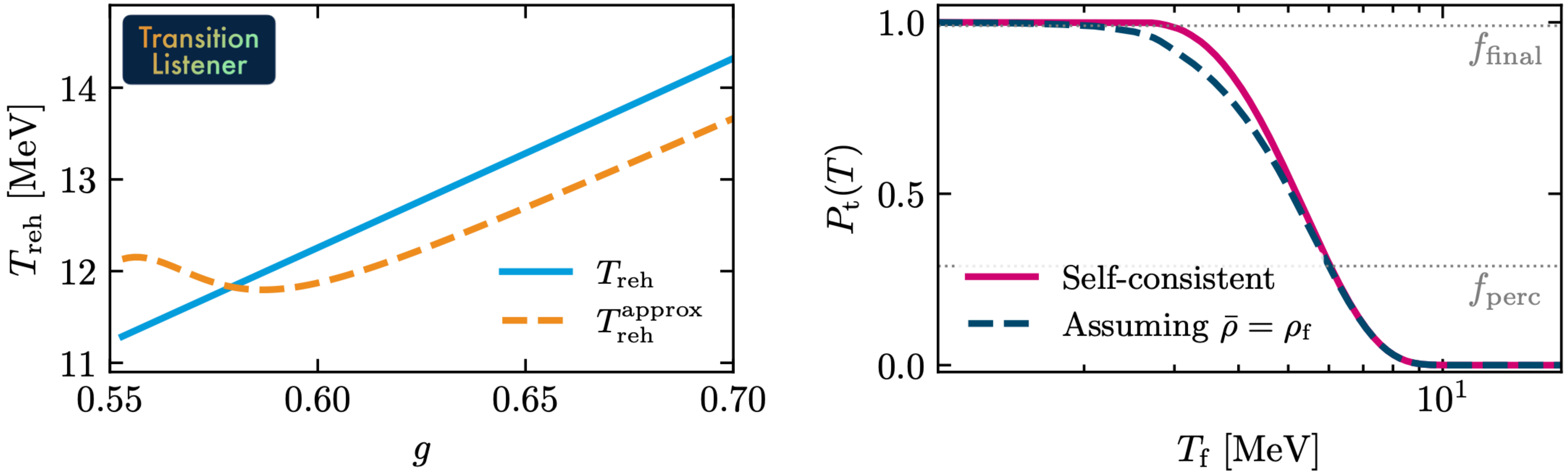
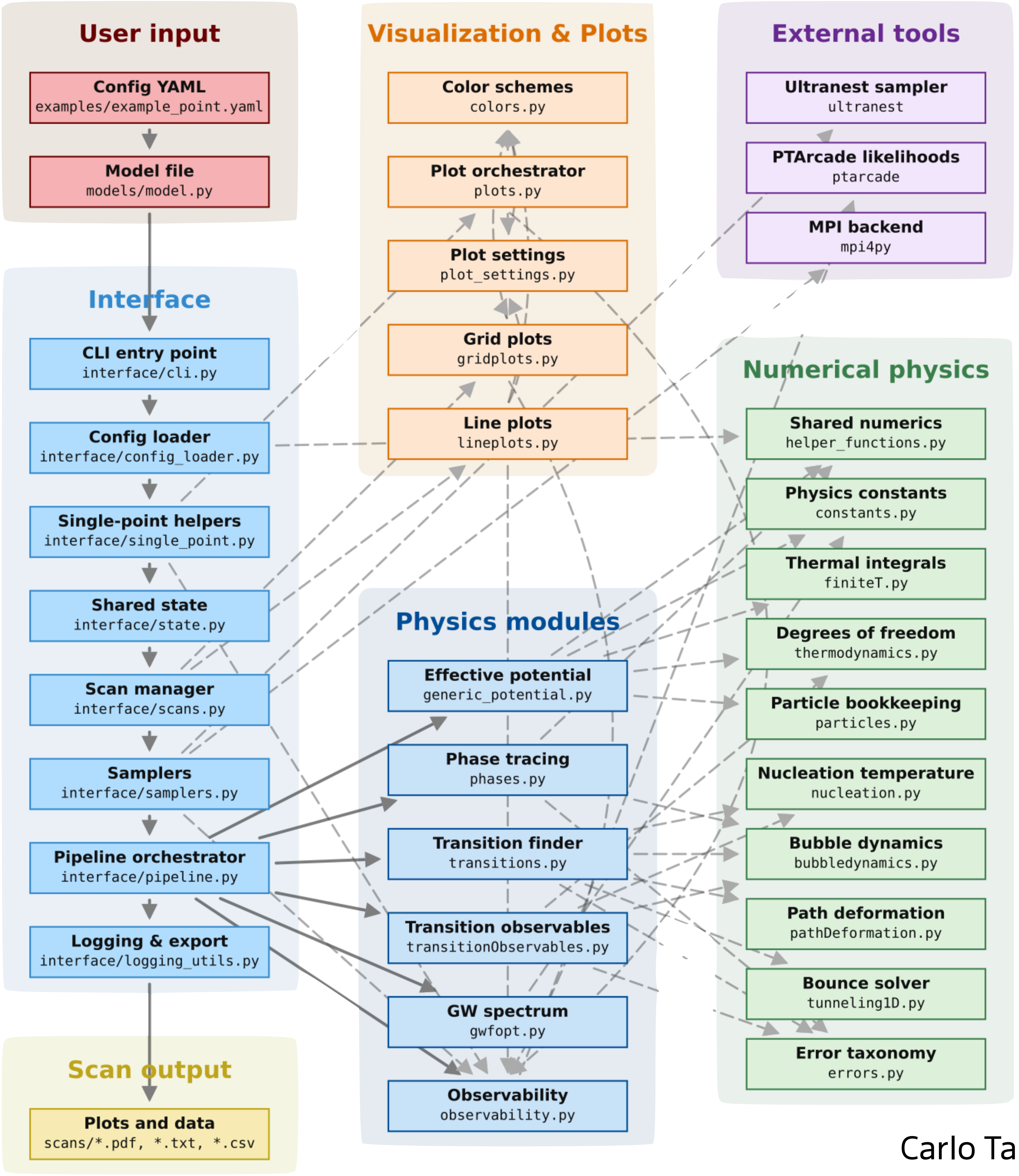


Figure 4: *Left:* Reheating temperature and its approximation $T_{\mathrm{perc}}^{\mathrm{approx}} = T_{\mathrm{perc}}\,(1+\alpha)^{1/4}$ as a function of the gauge coupling g in the conformal $U(1)'$ model ($y = 0.01$, $v = 140\,\mathrm{MeV}$). *Right:* Comparison of the self-consistent and approximate ($\bar{\rho} = \rho_{\mathrm{f}}$) solution of the percolation integral $P_{\mathrm{t}}(T) = 1 - \exp\{-I[H[P_{\mathrm{t}}]](T)\}$ for an ultraslow transition with $(\beta/H)_{RH} = 3.5$ featured in the dark Abelian Higgs model ($\lambda = 0.018$, $g = 1$, $v = 100\,\mathrm{MeV}$).

[2605.15259, CT+]

Structure of TransitionListener v2.0



User input

Config YAML
`examples/example_point.yaml`

Model file
`models/model.py`

Interface

CLI entry point
`interface/cli.py`

Config loader
`interface/config_loader.py`

Single-point helpers
`interface/single_point.py`

Shared state
`interface/state.py`

Scan manager
`interface/scans.py`

Samplers
`interface/samplers.py`

Pipeline orchestrator
`interface/pipeline.py`

Logging & export
`interface/logging_utils.py`

Scan output

Plots and data
`scans/*.pdf, *.txt, *.csv`

Visualization & Plots

Color schemes
`colors.py`

Plot orchestrator
`plots.py`

Plot settings
`plot_settings.py`

Grid plots
`gridplots.py`

Line plots
`lineplots.py`

Physics modules

Effective potential
`generic_potential.py`

Phase tracing
`phases.py`

Transition finder
`transitions.py`

Transition observables
`transitionObservables.py`

GW spectrum
`gwfopt.py`

Observability
`observability.py`

External tools

Ultranest sampler
`ultranest`

PTArcade likelihoods
`ptarcade`

MPI backend
`mpi4py`

Numerical physics

Shared numerics
`helper_functions.py`

Physics constants
`constants.py`

Thermal integrals
`finiteT.py`

Degrees of freedom
`thermodynamics.py`

Particle bookkeeping
`particles.py`

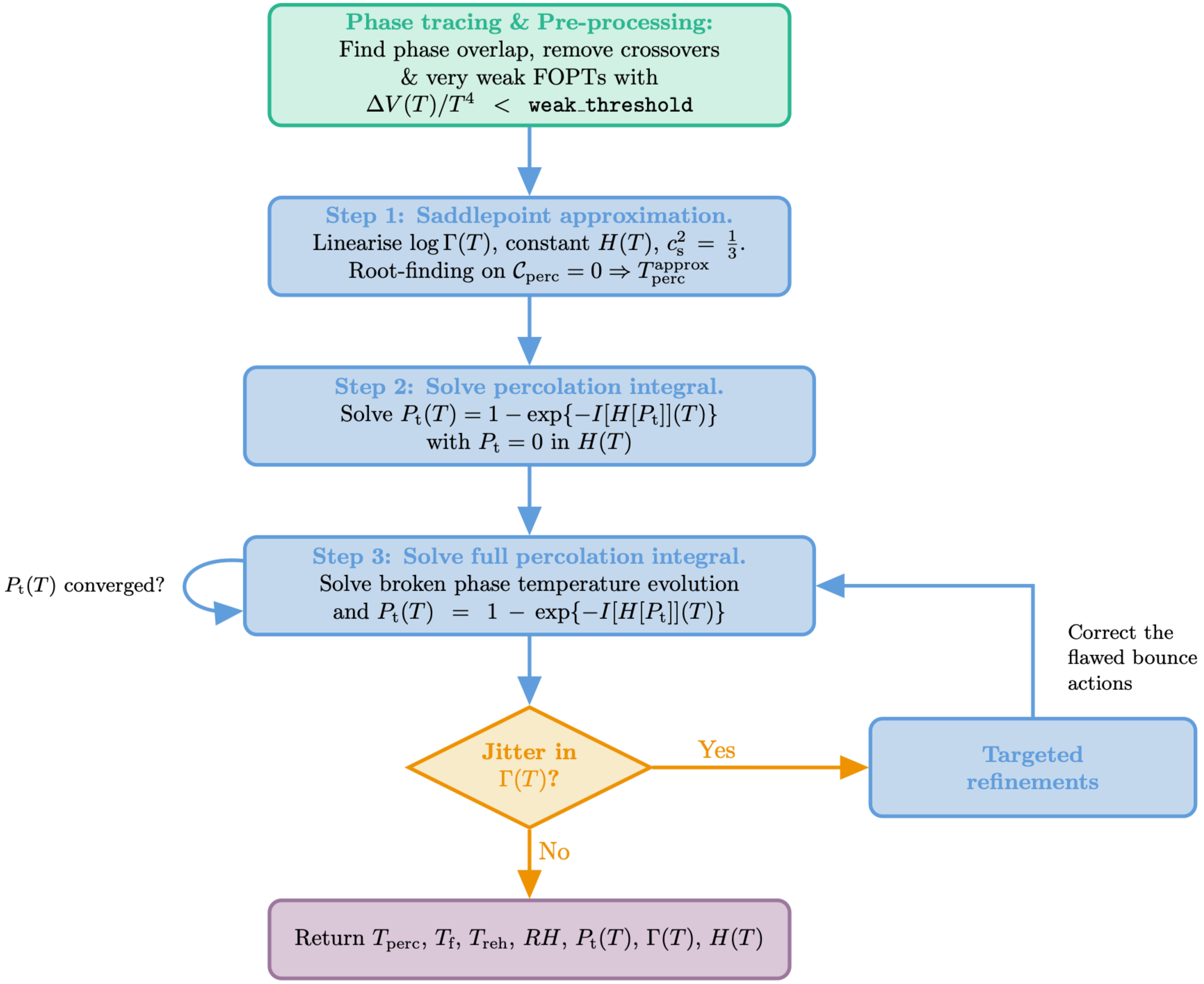
Nucleation temperature
`nucleation.py`

Bubble dynamics
`bubbledynamics.py`

Path deformation
`pathDeformation.py`

Bounce solver
`tunneling1D.py`

Error taxonomy
`errors.py`



Phase tracing & Pre-processing:
Find phase overlap, remove crossovers
& very weak FOPTs with
$\Delta V(T)/T^4 \ < \ \texttt{weak\_threshold}$

Step 1: Saddlepoint approximation.
Linearise $\log\Gamma(T)$, constant $H(T)$, $c_\mathrm{s}^2 \ = \ \frac{1}{3}$.
Root-finding on $\mathcal{C}_\mathrm{perc} = 0 \Rightarrow T_\mathrm{perc}^\mathrm{approx}$

Step 2: Solve percolation integral.
Solve $P_\mathrm{t}(T) = 1 - \exp\{-I[H[P_\mathrm{t}]](T)\}$
with $P_\mathrm{t} = 0$ in $H(T)$

Step 3: Solve full percolation integral.
Solve broken phase temperature evolution
and $P_\mathrm{t}(T) \ = \ 1 \ - \ \exp\{-I[H[P_\mathrm{t}]](T)\}$

$P_\mathrm{t}(T)$ converged?

Jitter in $\Gamma(T)$?

Yes

No

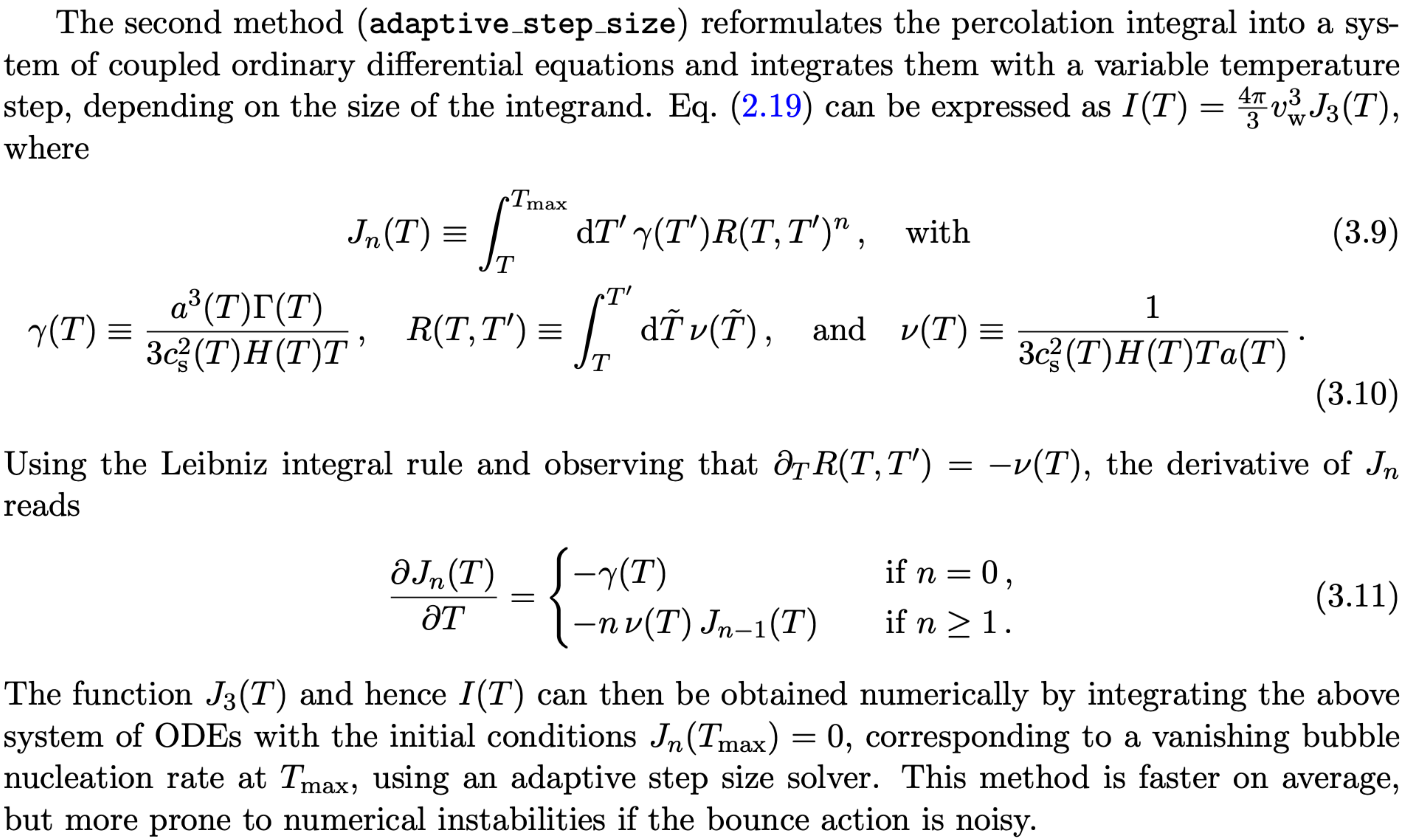
Targeted refinements

Correct the
flawed bounce
actions

Return T_perc, T_f, T_reh, RH, $P_\mathrm{t}(T)$, $\Gamma(T)$, $H(T)$

[2605.15259, CT+]

An elegant trick to compute the percolation integral



The second method (`adaptive_step_size`) reformulates the percolation integral into a system of coupled ordinary differential equations and integrates them with a variable temperature step, depending on the size of the integrand. Eq. (2.19) can be expressed as $I(T) = \frac{4\pi}{3} v_{\mathrm{w}}^3 J_3(T)$, where

$$J_n(T) \equiv \int_T^{T_{\max}} \mathrm{d}T'\, \gamma(T') R(T,T')^n\,, \quad \text{with} \tag{3.9}$$

$$\gamma(T) \equiv \frac{a^3(T)\Gamma(T)}{3c_{\mathrm{s}}^2(T)H(T)T}\,, \quad R(T,T') \equiv \int_T^{T'} \mathrm{d}\tilde{T}\, \nu(\tilde{T})\,, \quad \text{and} \quad \nu(T) \equiv \frac{1}{3c_{\mathrm{s}}^2(T)H(T)T a(T)}\,. \tag{3.10}$$

Using the Leibniz integral rule and observing that $\partial_T R(T,T') = -\nu(T)$, the derivative of J_n reads

$$\frac{\partial J_n(T)}{\partial T} = \begin{cases} -\gamma(T) & \text{if } n = 0\,, \\ -n\,\nu(T)\,J_{n-1}(T) & \text{if } n \geq 1\,. \end{cases} \tag{3.11}$$

The function $J_3(T)$ and hence $I(T)$ can then be obtained numerically by integrating the above system of ODEs with the initial conditions $J_n(T_{\max}) = 0$, corresponding to a vanishing bubble nucleation rate at $T_{\max}$, using an adaptive step size solver. This method is faster on average, but more prone to numerical instabilities if the bounce action is noisy.

[2605.15259, CT+]

An example config file for TransitionListener

```
# Scan settings ====================================
Modelfile:
  models/TL_dark_flipflop.py

Potential:
  DarkFlipFlop

Scan:
  SinglePoint

Parameters:
  lambda0: 0.005098
  lambda1: 0.002144
  lambda12: 0.003078
  v_GeV: 3.728330741601088
  y: 0.972319
  gamma: 0.7532

# ==================================================
# output configuration
# ==================================================
timeout: 300  # Timeout in seconds for the individual TL run, -1 for no timeout
format: txt  # either "txt" or "hdf5"
output_path: scans/exampleScan
description: Example
plot_description: Flipflop benchmark point

additional_plots:
  # Create additional plots
```

[2605.15259, CT+]

Automated `action` plot in `TransitionListener`

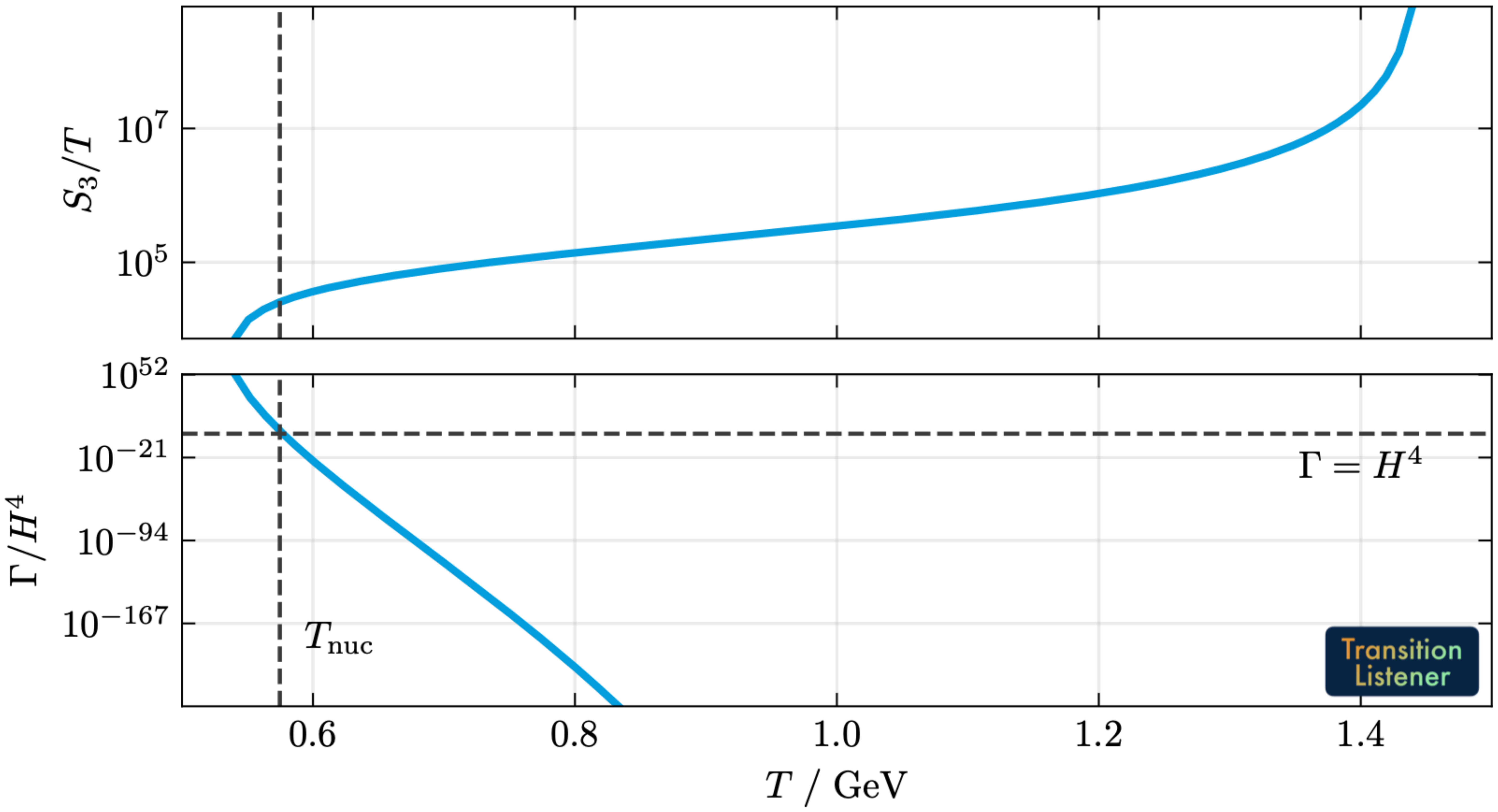


Figure 9: Output of the `action` plot option for the dark flipflop benchmark point 2 from table 1. *Upper panel:* Bounce action S_3/T in dependence of temperature. *Lower panel:* Corresponding bubble nucleation rate Γ in units of H^4.

[2605.15259, CT+]

Automated `profile` plot in `TransitionListener`

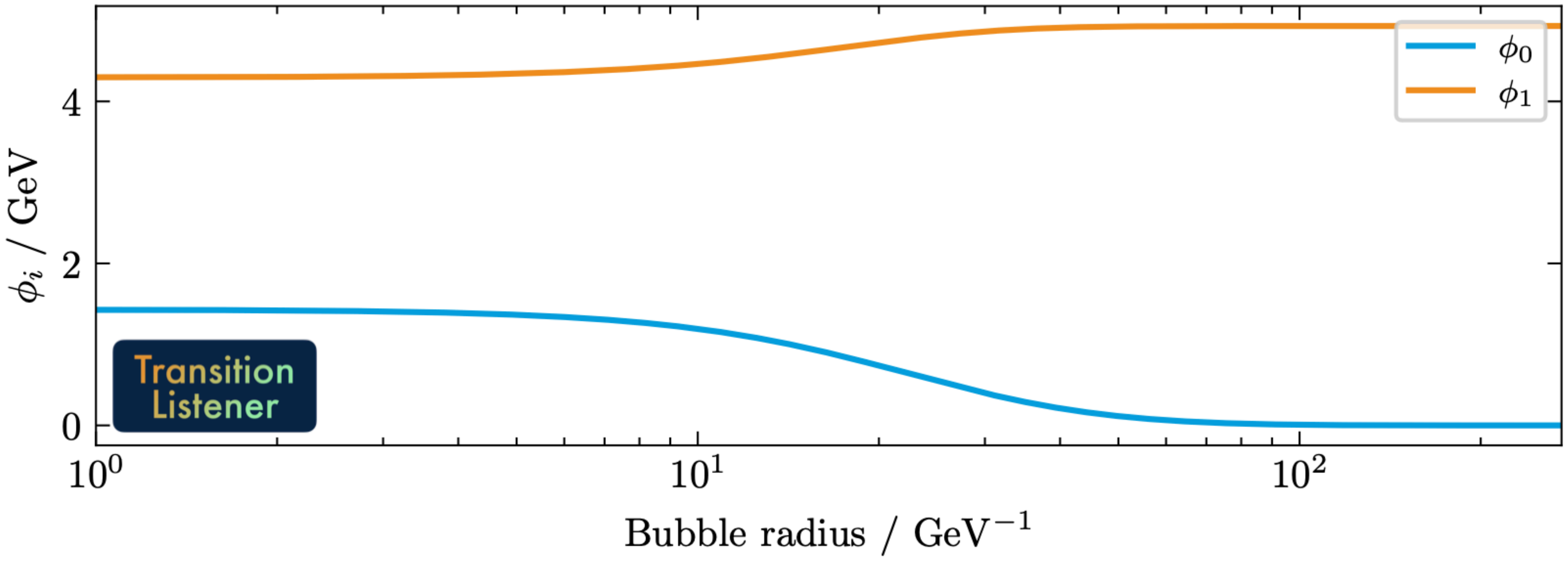


Figure 10: Bubble profile at nucleation for the dark flipflop benchmark point 2 from table 1, generated using the **`profile`** plot option. Inside the bubble, at $r = 0$, the fields approach their release point. At $r \to \infty$ (outside the bubble), the field values approach their false-vacuum values.

[2605.15259, CT+]

Automated `percolation` plot in `TransitionListener`

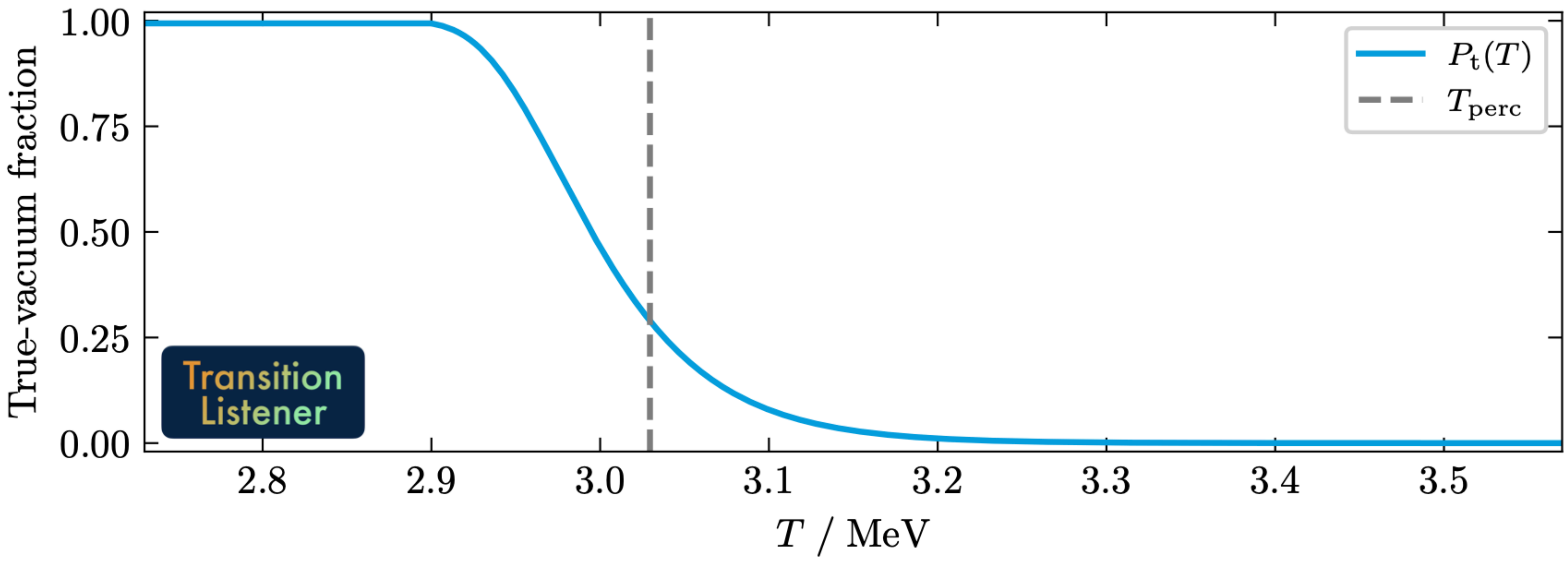


Figure 11: True-vacuum fraction evolution of the conformal dark $U(1)'$ benchmark point 1 from table 1 ($g = 0.7$, $v = 0.14\,\mathrm{GeV}$ and $y = 0.01$), generated using the **`percolation`** plot option.

[2605.15259, CT+]

Automated `overview` plot for line scans in `TransitionListener`

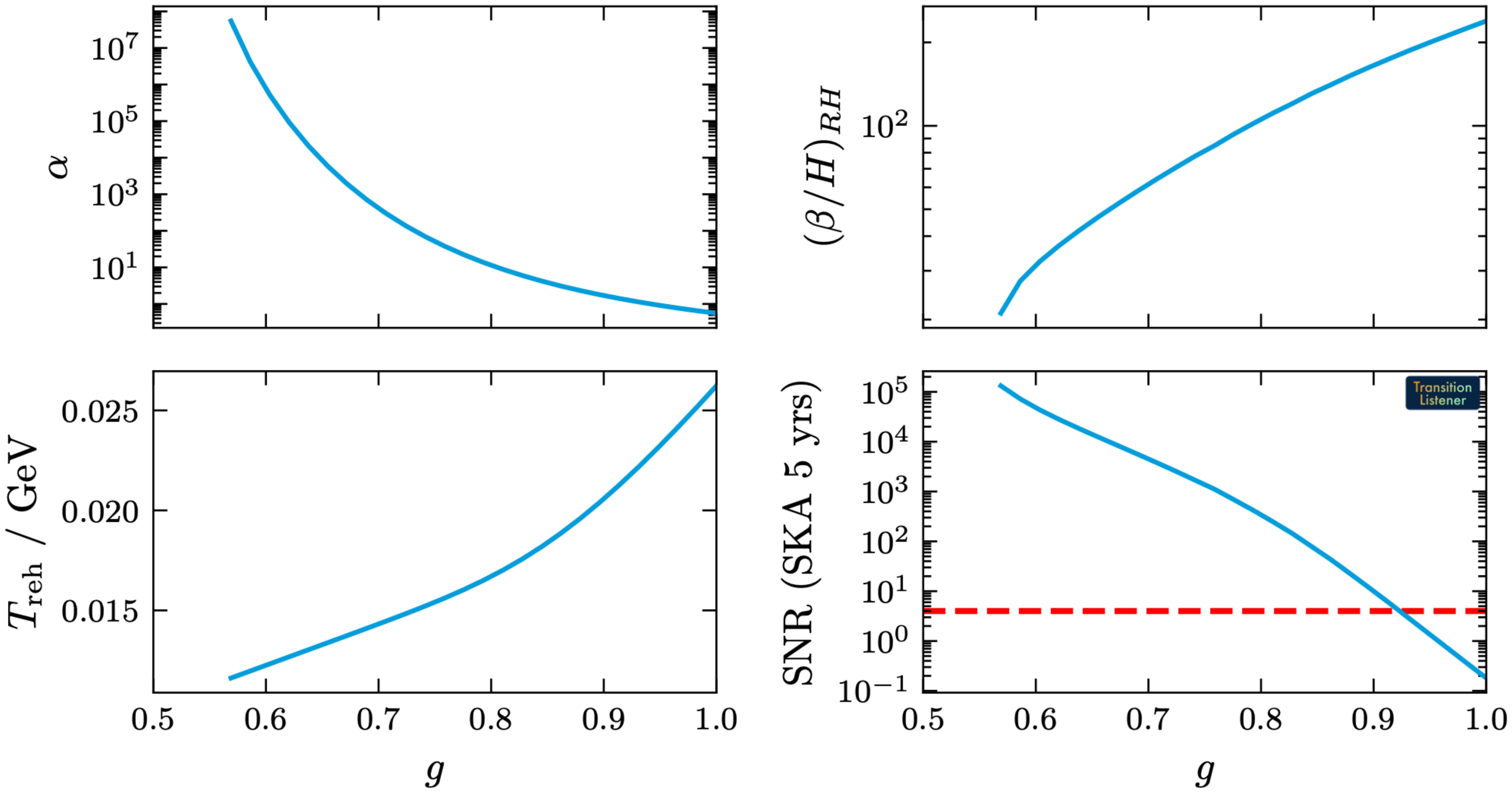
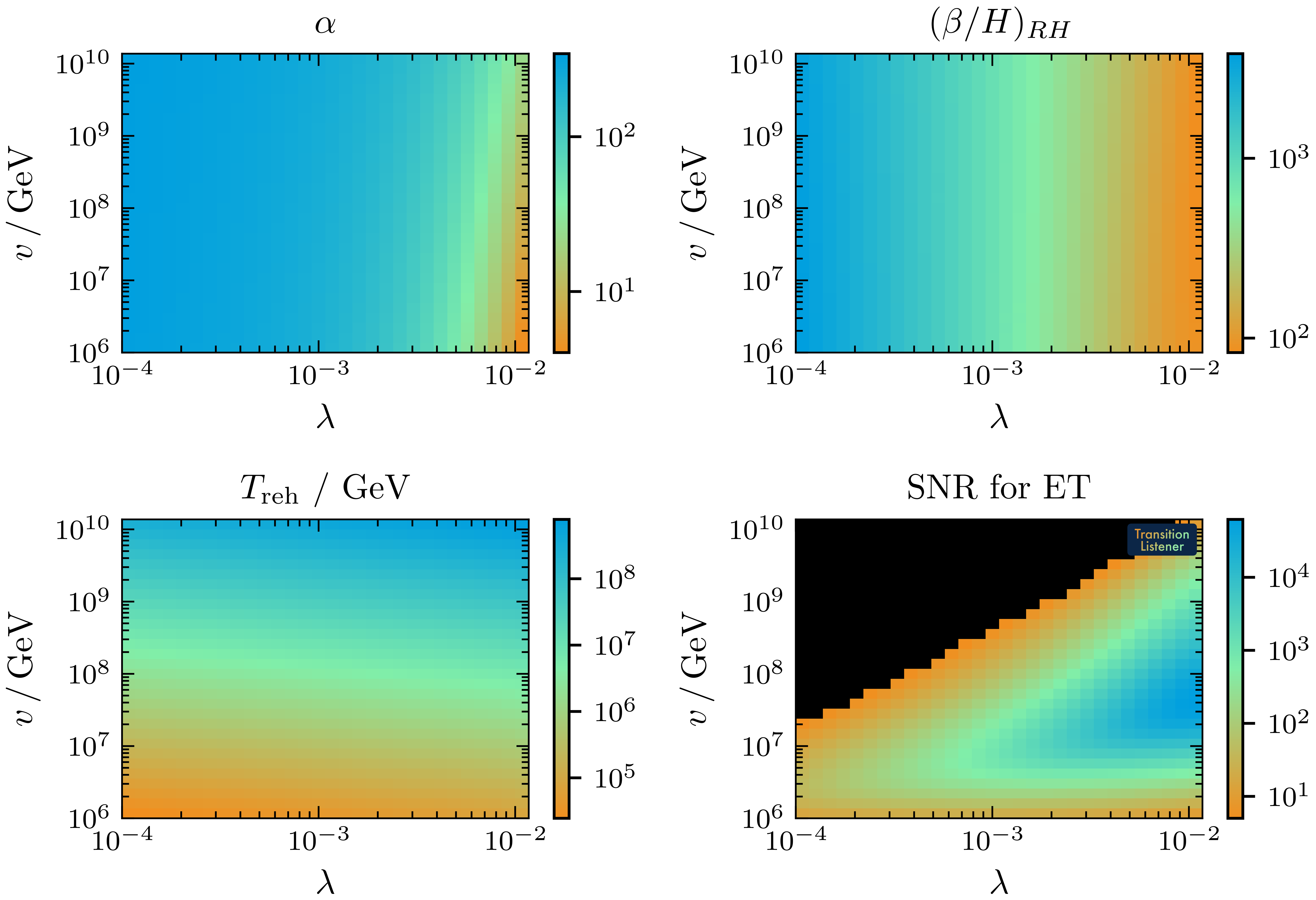


Figure 12: Overview plot of the example line scan based on the conformal model near the benchmark point from table 1, scanning g at fixed $y = 0.01$ and $v = 140\,\text{MeV}$. The fourth panel shows the expected SNR after 5 years of data taking at SKA. The red dashed line indicates the detection threshold.

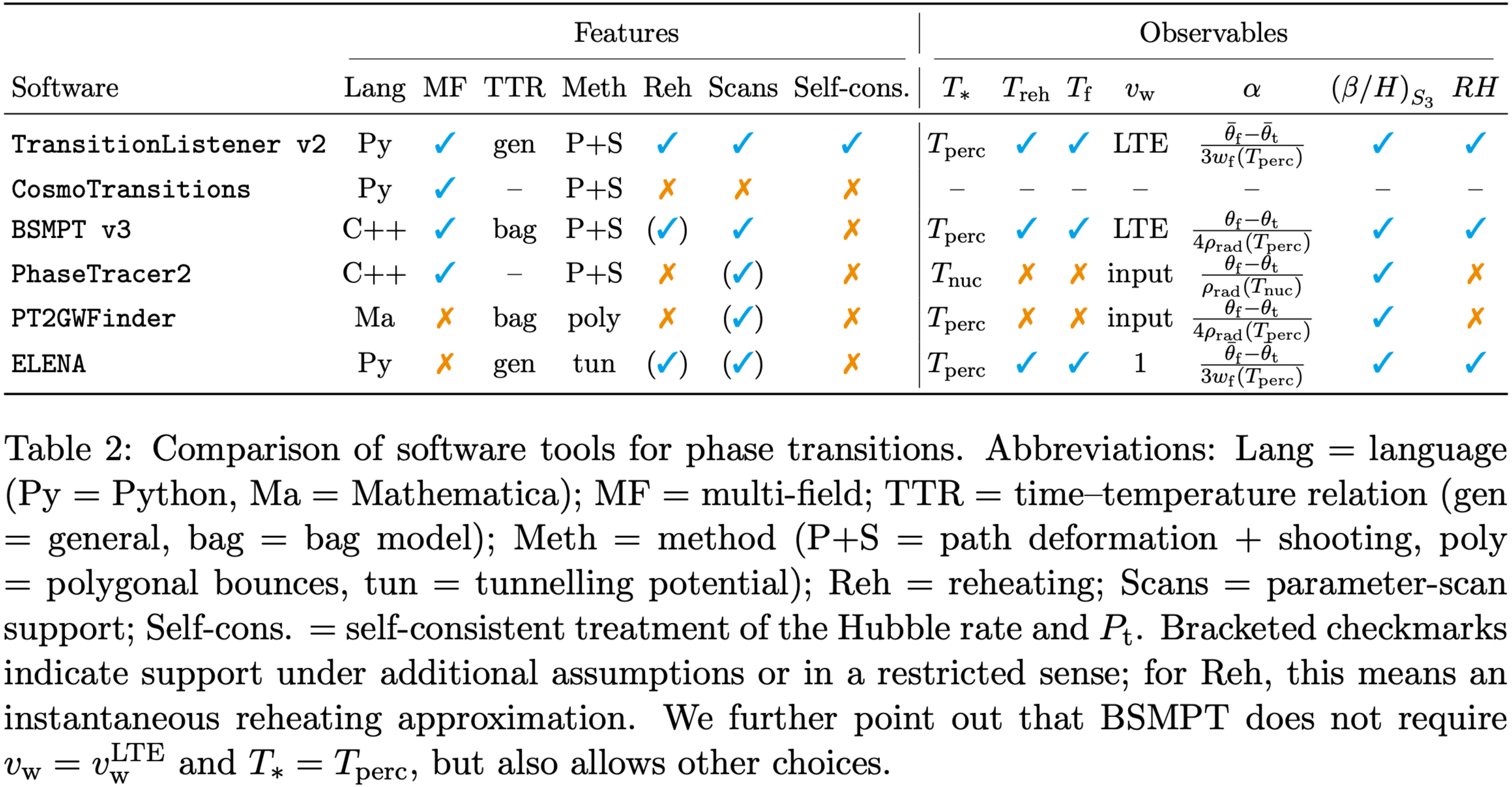
[2605.15259, CT+]

Automated `overview` plot for grid scans in `TransitionListener`



[2605.15259, CT+]

Comparison of `TransitionListener` with other packages

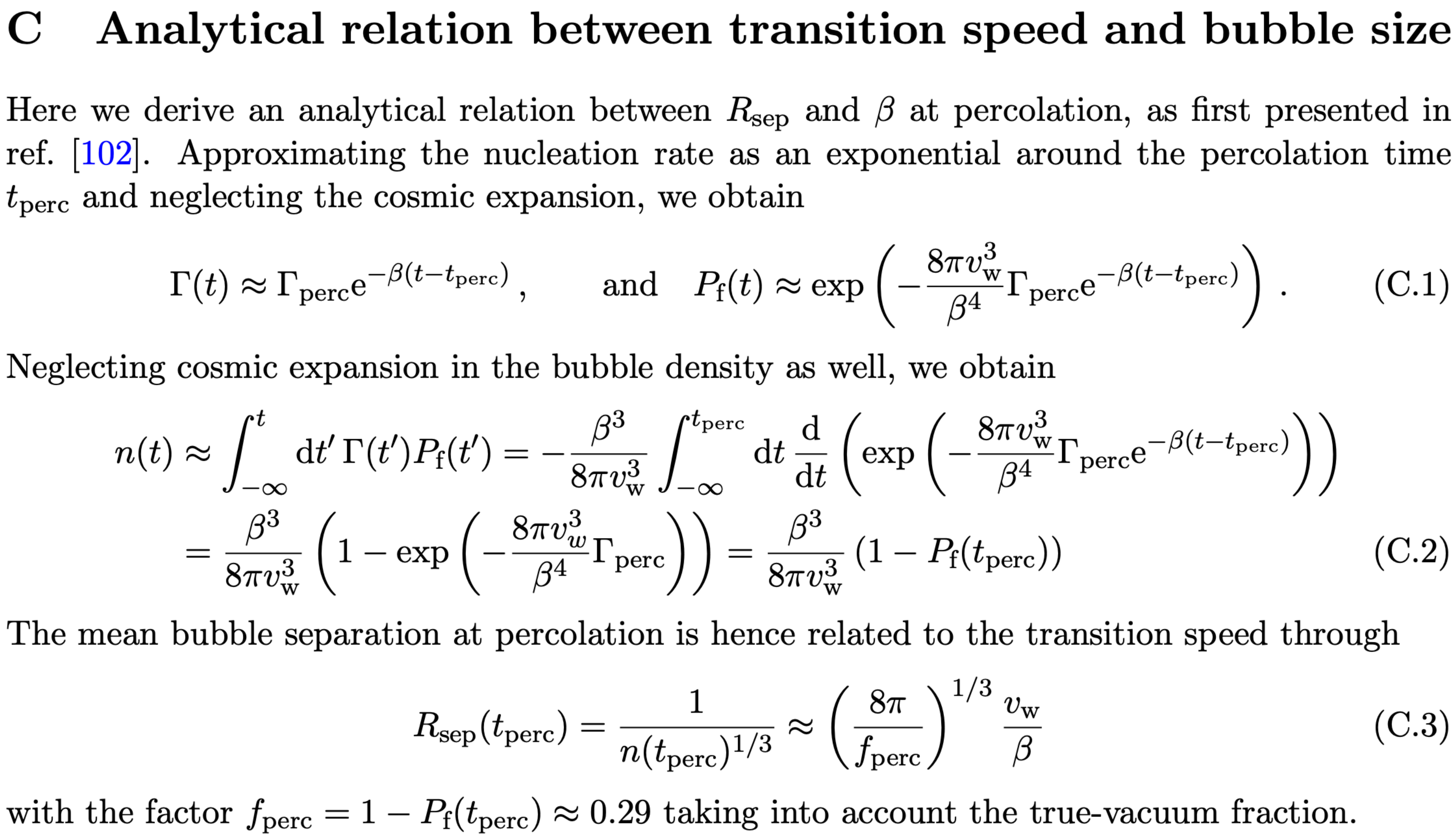


	Features							Observables						
Software	Lang	MF	TTR	Meth	Reh	Scans	Self-cons.	T_*	T_{reh}	T_{f}	v_{w}	α	$(\beta/H)_{S_3}$	RH
`TransitionListener v2`	Py	✓	gen	P+S	✓	✓	✓	T_{perc}	✓	✓	LTE	$\frac{\bar{\theta}_{\mathrm{f}}-\bar{\theta}_{\mathrm{t}}}{3w_{\mathrm{f}}(T_{\mathrm{perc}})}$	✓	✓
`CosmoTransitions`	Py	✓	–	P+S	✗	✗	✗	–	–	–	–	–	–	–
`BSMPT v3`	C++	✓	bag	P+S	(✓)	✓	✗	T_{perc}	✓	✓	LTE	$\frac{\theta_{\mathrm{f}}-\theta_{\mathrm{t}}}{4\rho_{\mathrm{rad}}(T_{\mathrm{perc}})}$	✓	✓
`PhaseTracer2`	C++	✓	–	P+S	✗	(✓)	✗	T_{nuc}	✗	✗	input	$\frac{\theta_{\mathrm{f}}-\theta_{\mathrm{t}}}{\rho_{\mathrm{rad}}(T_{\mathrm{nuc}})}$	✓	✗
`PT2GWFinder`	Ma	✗	bag	poly	✗	(✓)	✗	T_{perc}	✗	✗	input	$\frac{\theta_{\mathrm{f}}-\theta_{\mathrm{t}}}{4\rho_{\mathrm{rad}}(T_{\mathrm{perc}})}$	✓	✗
`ELENA`	Py	✗	gen	tun	(✓)	(✓)	✗	T_{perc}	✓	✓	1	$\frac{\bar{\theta}_{\mathrm{f}}-\bar{\theta}_{\mathrm{t}}}{3w_{\mathrm{f}}(T_{\mathrm{perc}})}$	✓	✓

Table 2: Comparison of software tools for phase transitions. Abbreviations: Lang = language (Py = Python, Ma = Mathematica); MF = multi-field; TTR = time–temperature relation (gen = general, bag = bag model); Meth = method (P+S = path deformation + shooting, poly = polygonal bounces, tun = tunnelling potential); Reh = reheating; Scans = parameter-scan support; Self-cons. = self-consistent treatment of the Hubble rate and P_{t}. Bracketed checkmarks indicate support under additional assumptions or in a restricted sense; for Reh, this means an instantaneous reheating approximation. We further point out that BSMPT does not require $v_{\mathrm{w}} = v_{\mathrm{w}}^{\mathrm{LTE}}$ and $T_* = T_{\mathrm{perc}}$, but also allows other choices.

[2605.15259, CT+]

Derivation of the relationship between RH and β/H



C Analytical relation between transition speed and bubble size

Here we derive an analytical relation between R_{sep} and β at percolation, as first presented in ref. [102]. Approximating the nucleation rate as an exponential around the percolation time t_{perc} and neglecting the cosmic expansion, we obtain

$$\Gamma(t) \approx \Gamma_{\mathrm{perc}} \mathrm{e}^{-\beta(t-t_{\mathrm{perc}})}\,, \qquad \text{and} \quad P_{\mathrm{f}}(t) \approx \exp\left(-\frac{8\pi v_{\mathrm{w}}^3}{\beta^4}\Gamma_{\mathrm{perc}}\mathrm{e}^{-\beta(t-t_{\mathrm{perc}})}\right)\,. \tag{C.1}$$

Neglecting cosmic expansion in the bubble density as well, we obtain

$$\begin{aligned} n(t) &\approx \int_{-\infty}^{t} \mathrm{d}t'\,\Gamma(t')P_{\mathrm{f}}(t') = -\frac{\beta^3}{8\pi v_{\mathrm{w}}^3}\int_{-\infty}^{t_{\mathrm{perc}}} \mathrm{d}t\,\frac{\mathrm{d}}{\mathrm{d}t}\left(\exp\left(-\frac{8\pi v_{\mathrm{w}}^3}{\beta^4}\Gamma_{\mathrm{perc}}\mathrm{e}^{-\beta(t-t_{\mathrm{perc}})}\right)\right) \\ &= \frac{\beta^3}{8\pi v_{\mathrm{w}}^3}\left(1-\exp\left(-\frac{8\pi v_w^3}{\beta^4}\Gamma_{\mathrm{perc}}\right)\right) = \frac{\beta^3}{8\pi v_{\mathrm{w}}^3}\left(1-P_{\mathrm{f}}(t_{\mathrm{perc}})\right) \end{aligned} \tag{C.2}$$

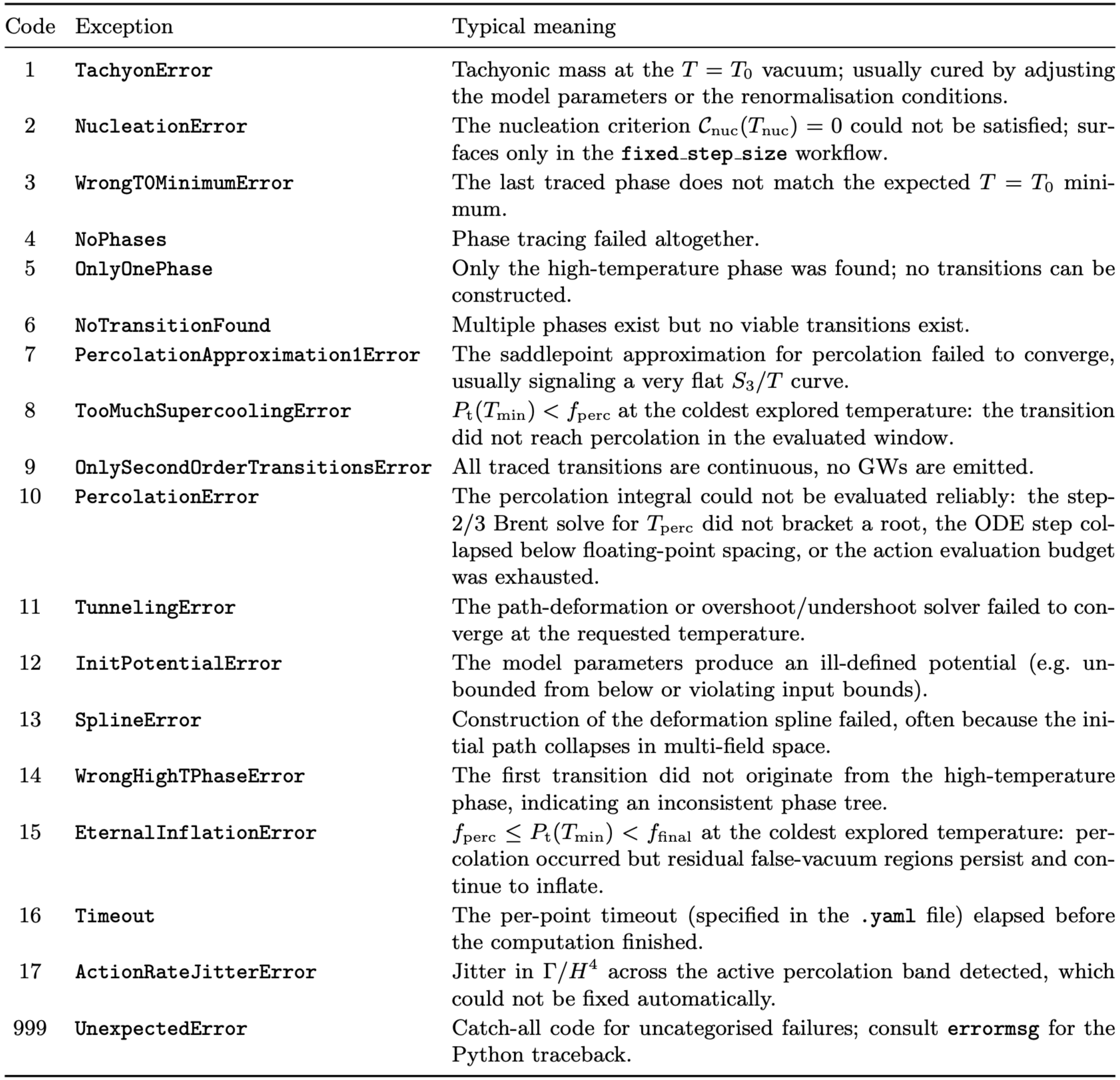
The mean bubble separation at percolation is hence related to the transition speed through

$$R_{\mathrm{sep}}(t_{\mathrm{perc}}) = \frac{1}{n(t_{\mathrm{perc}})^{1/3}} \approx \left(\frac{8\pi}{f_{\mathrm{perc}}}\right)^{1/3}\frac{v_{\mathrm{w}}}{\beta} \tag{C.3}$$

with the factor $f_{\mathrm{perc}} = 1 - P_{\mathrm{f}}(t_{\mathrm{perc}}) \approx 0.29$ taking into account the true-vacuum fraction.

[2605.15259, CT+]

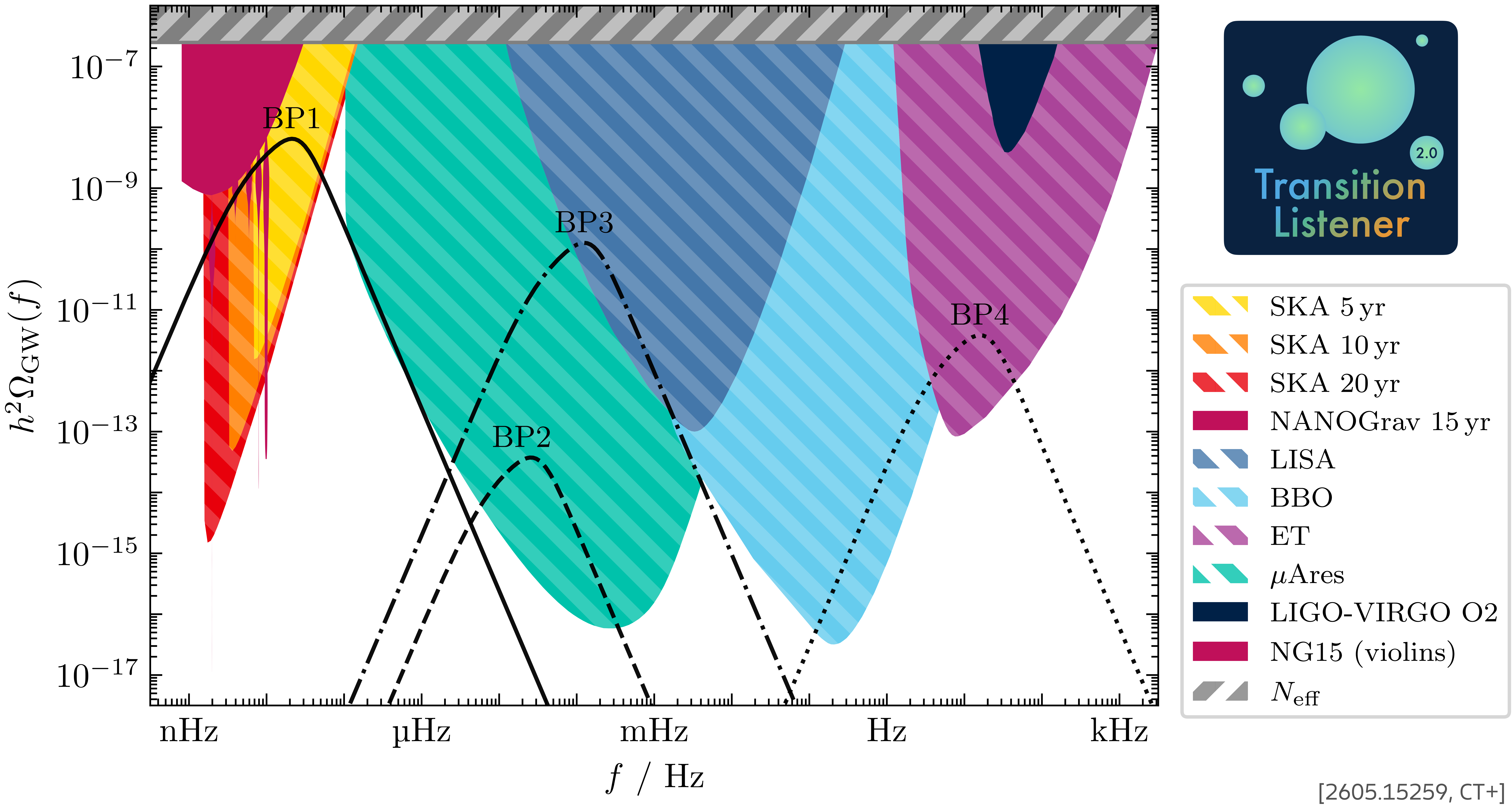
Error classes in `TLv2`



Code	Exception	Typical meaning
1	`TachyonError`	Tachyonic mass at the $T = T_0$ vacuum; usually cured by adjusting the model parameters or the renormalisation conditions.
2	`NucleationError`	The nucleation criterion $\mathcal{C}_{\rm nuc}(T_{\rm nuc}) = 0$ could not be satisfied; surfaces only in the **`fixed_step_size`** workflow.
3	`WrongT0MinimumError`	The last traced phase does not match the expected $T = T_0$ minimum.
4	`NoPhases`	Phase tracing failed altogether.
5	`OnlyOnePhase`	Only the high-temperature phase was found; no transitions can be constructed.
6	`NoTransitionFound`	Multiple phases exist but no viable transitions exist.
7	`PercolationApproximation1Error`	The saddlepoint approximation for percolation failed to converge, usually signaling a very flat S_3/T curve.
8	`TooMuchSupercoolingError`	$P_{\rm t}(T_{\rm min}) < f_{\rm perc}$ at the coldest explored temperature: the transition did not reach percolation in the evaluated window.
9	`OnlySecondOrderTransitionsError`	All traced transitions are continuous, no GWs are emitted.
10	`PercolationError`	The percolation integral could not be evaluated reliably: the step-2/3 Brent solve for $T_{\rm perc}$ did not bracket a root, the ODE step collapsed below floating-point spacing, or the action evaluation budget was exhausted.
11	`TunnelingError`	The path-deformation or overshoot/undershoot solver failed to converge at the requested temperature.
12	`InitPotentialError`	The model parameters produce an ill-defined potential (e.g. unbounded from below or violating input bounds).
13	`SplineError`	Construction of the deformation spline failed, often because the initial path collapses in multi-field space.
14	`WrongHighTPhaseError`	The first transition did not originate from the high-temperature phase, indicating an inconsistent phase tree.
15	`EternalInflationError`	$f_{\rm perc} \leq P_{\rm t}(T_{\rm min}) < f_{\rm final}$ at the coldest explored temperature: percolation occurred but residual false-vacuum regions persist and continue to inflate.
16	`Timeout`	The per-point timeout (specified in the `.yaml` file) elapsed before the computation finished.
17	`ActionRateJitterError`	Jitter in Γ/H^4 across the active percolation band detected, which could not be fixed automatically.
999	`UnexpectedError`	Catch-all code for uncategorised failures; consult **`errormsg`** for the Python traceback.

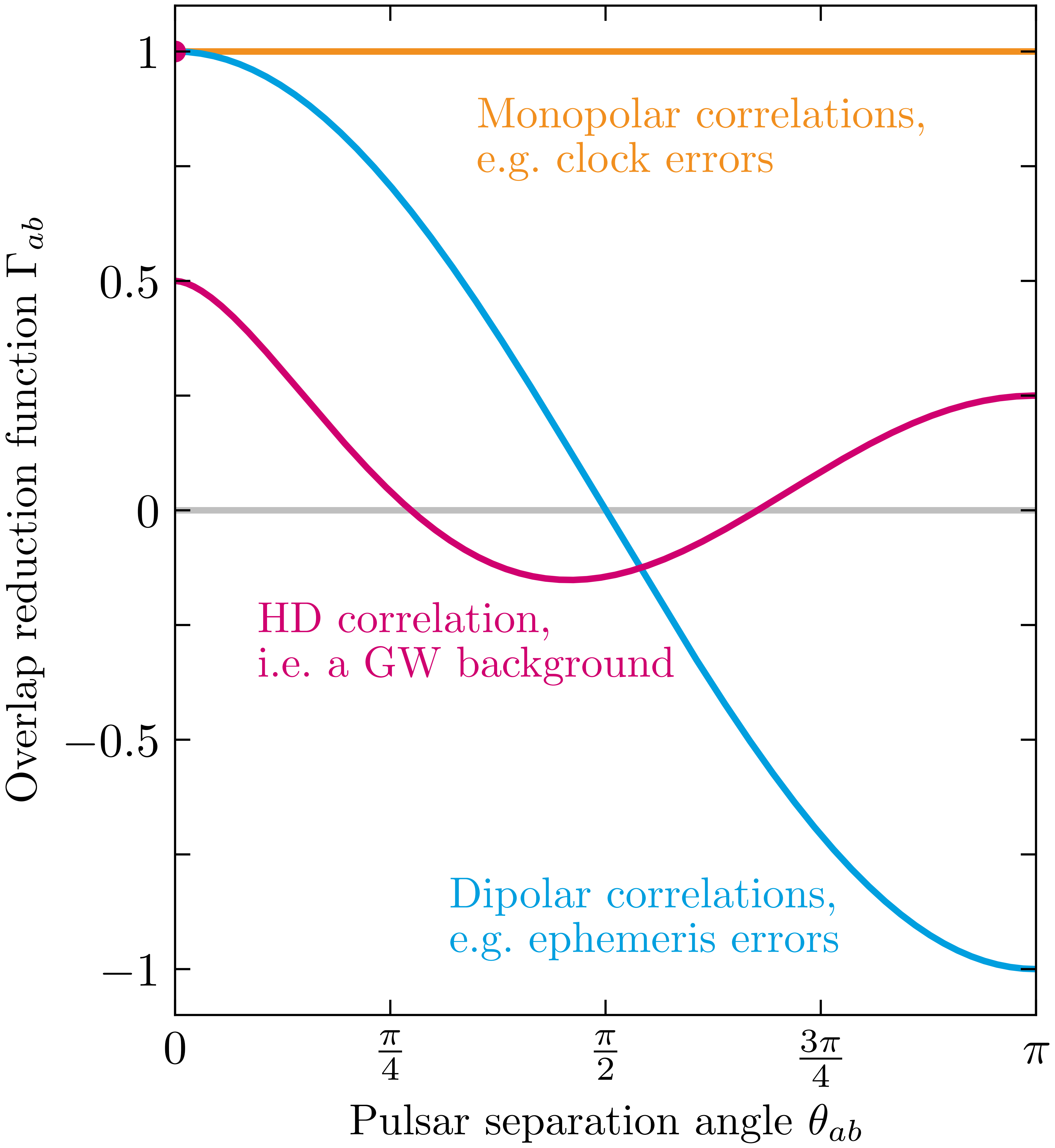
[2605.15259, CT+]

Selection of the implemented sensitivity curves in `TLv2`



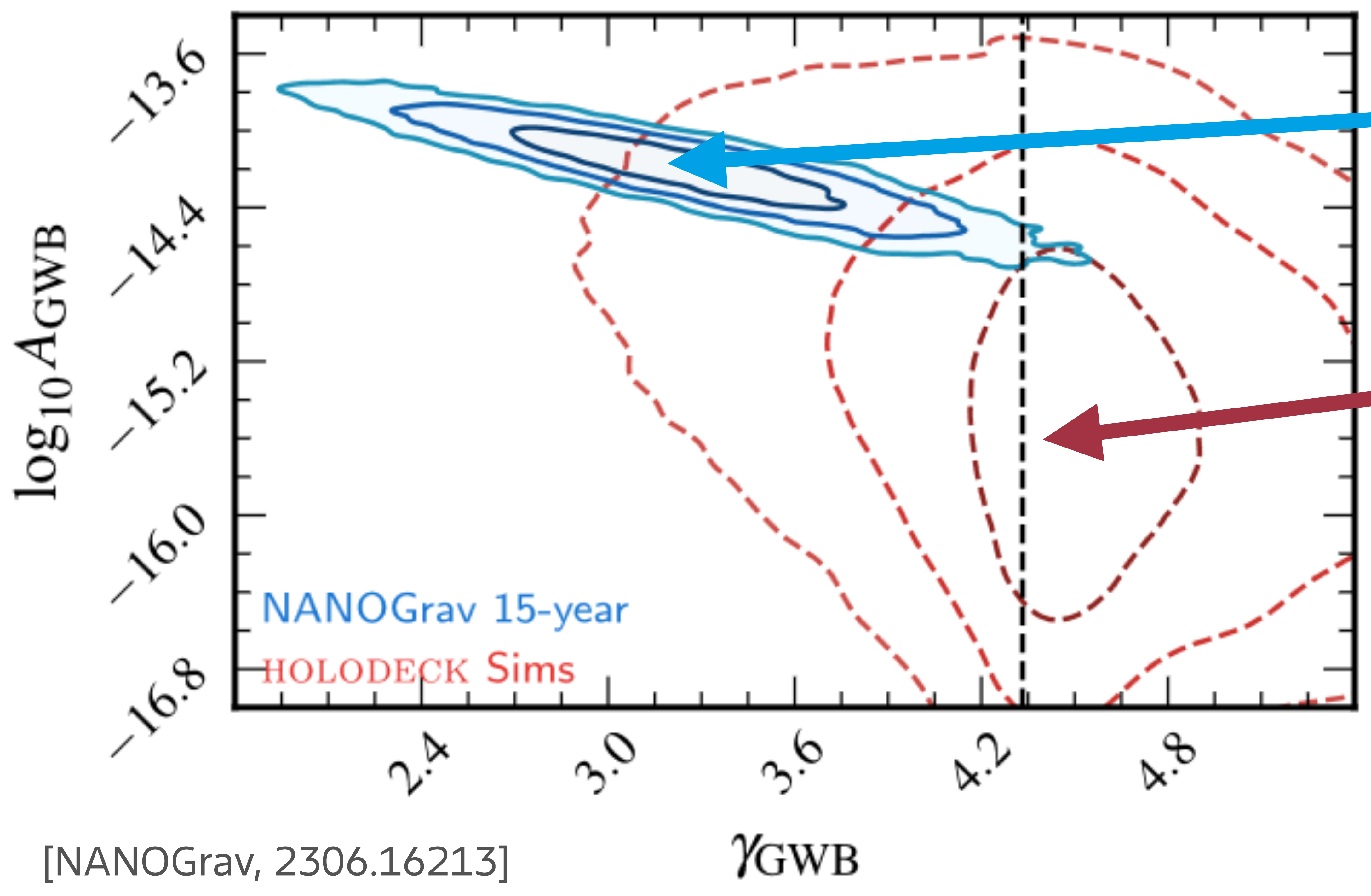
[2605.15259, CT+]

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, Clock errors, Ephemeris errors:
    All ruled out with >5σ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]

Merging supermassive black holes

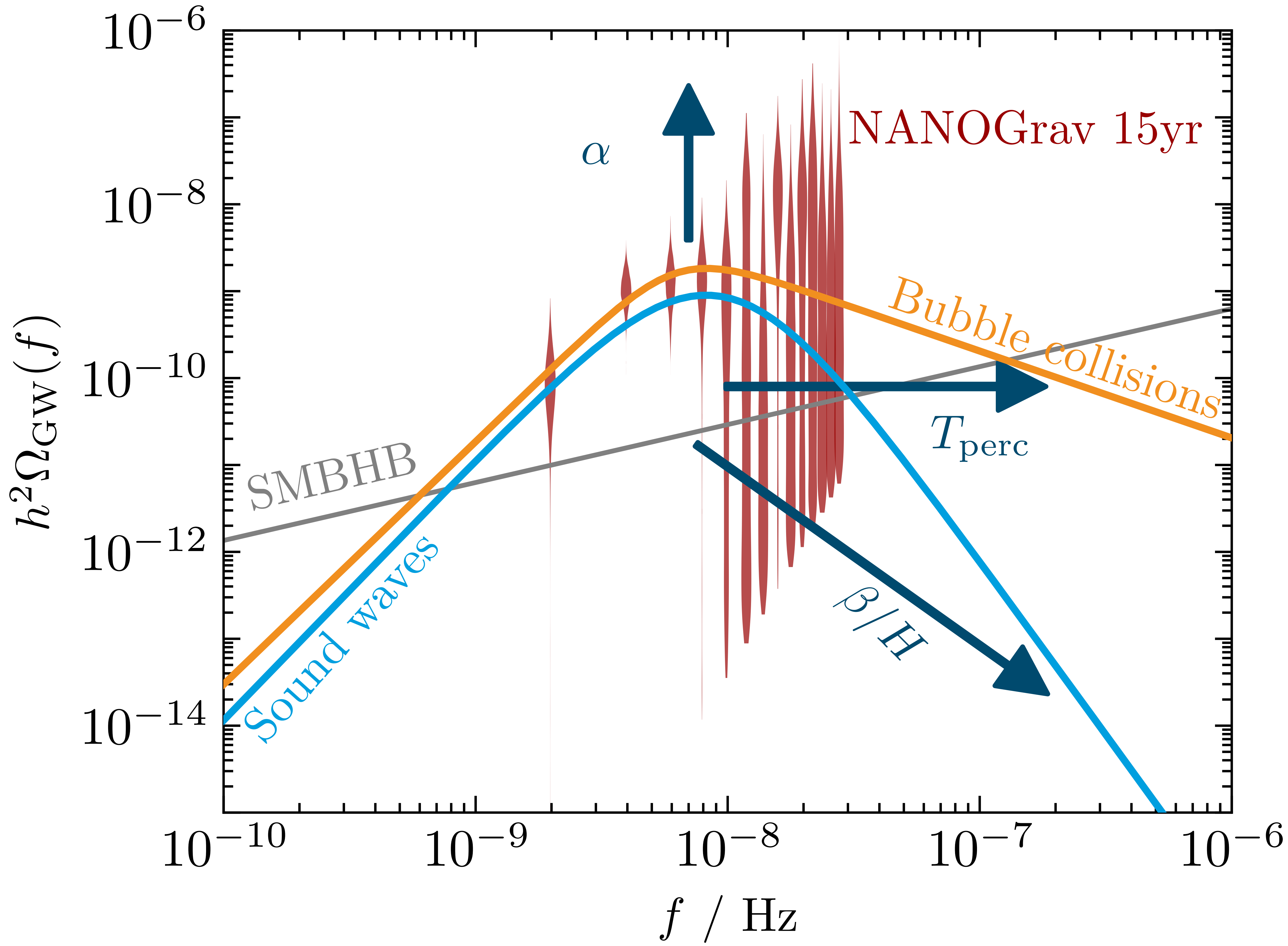


[NANOGrav, 2306.16213]

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 (more power in low frequencies)

Parametrization of the GW signal



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

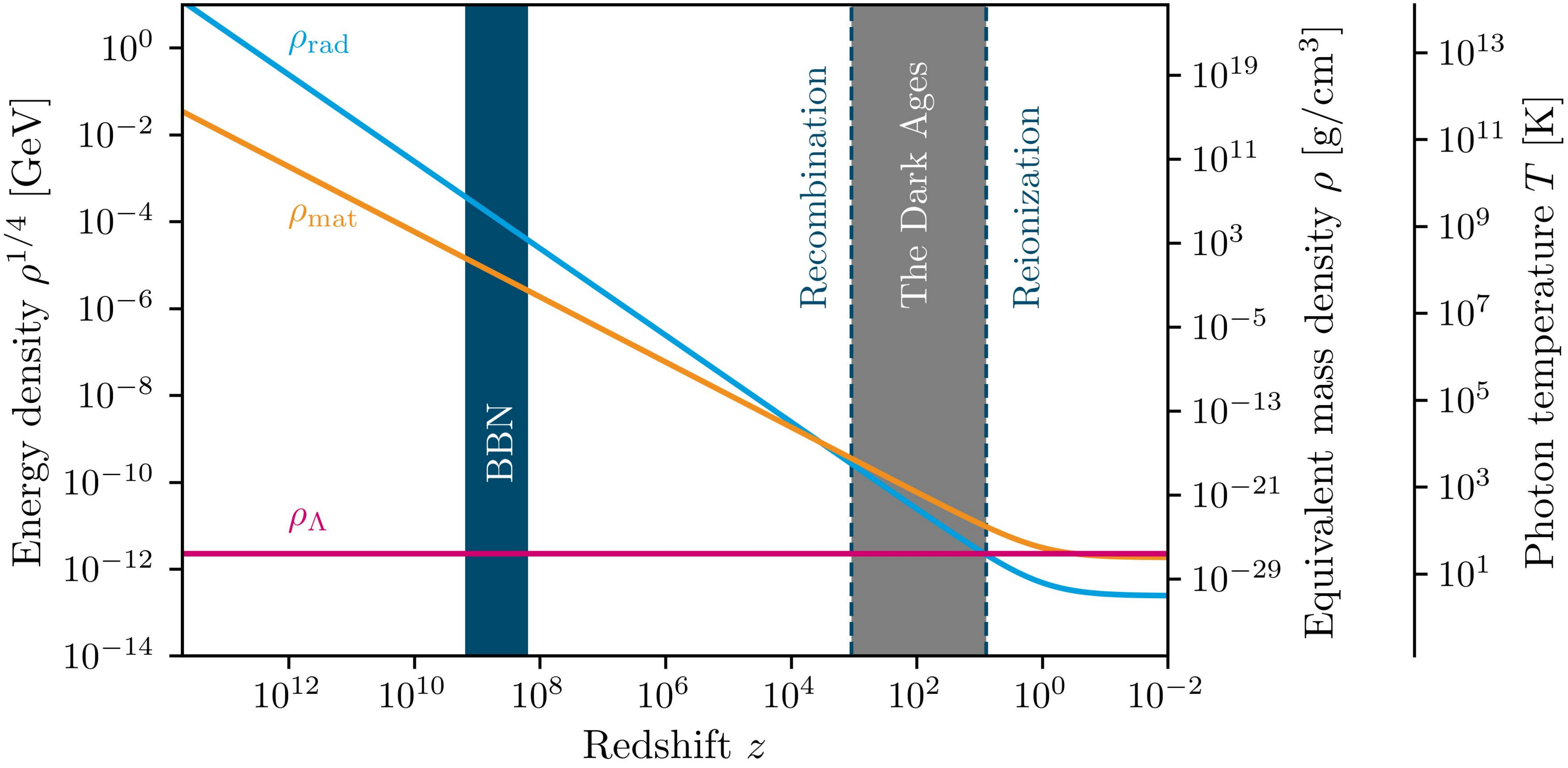
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

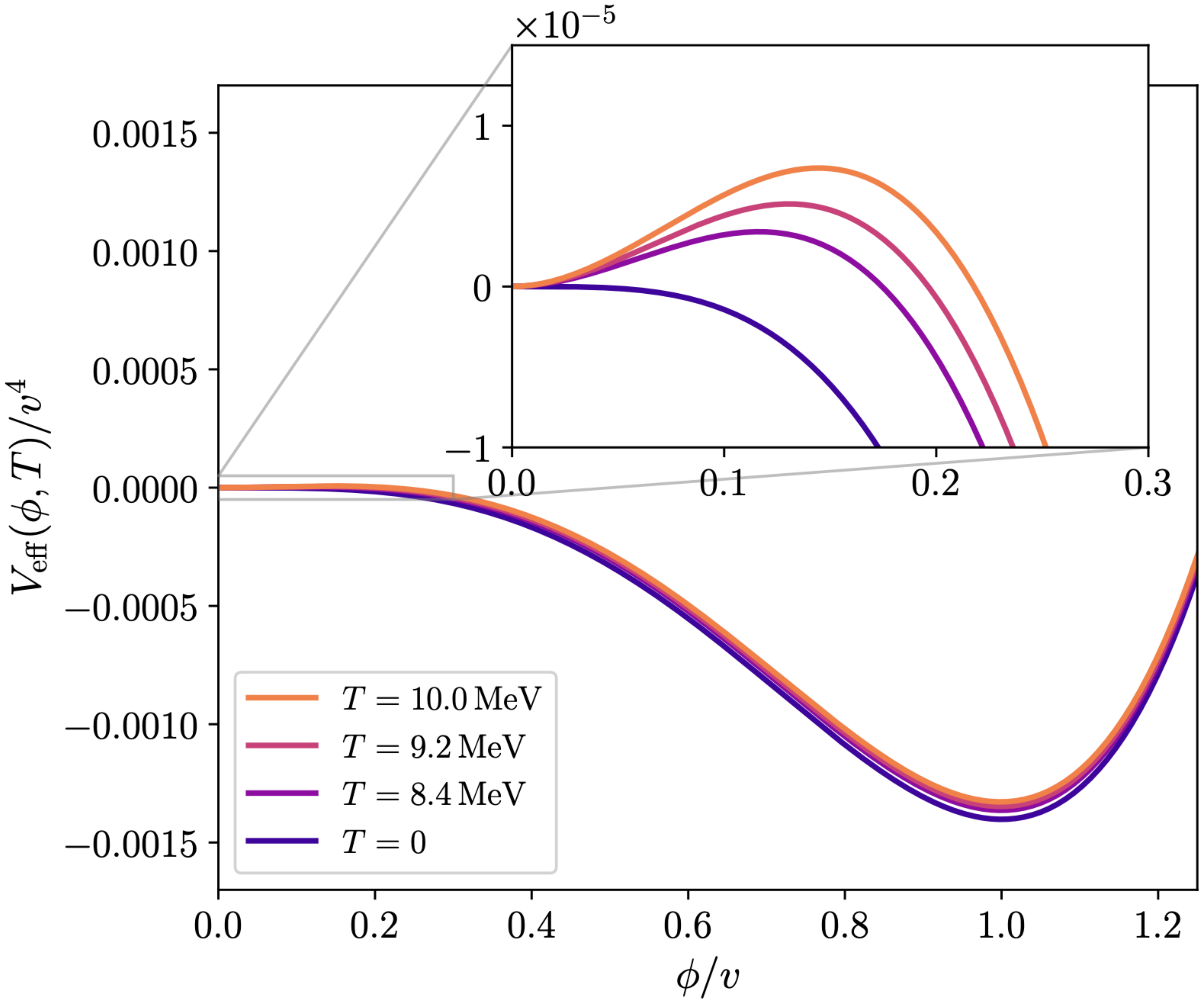
To fit the new pulsar timing data:

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

A brief history of time



How to be supercool 😎



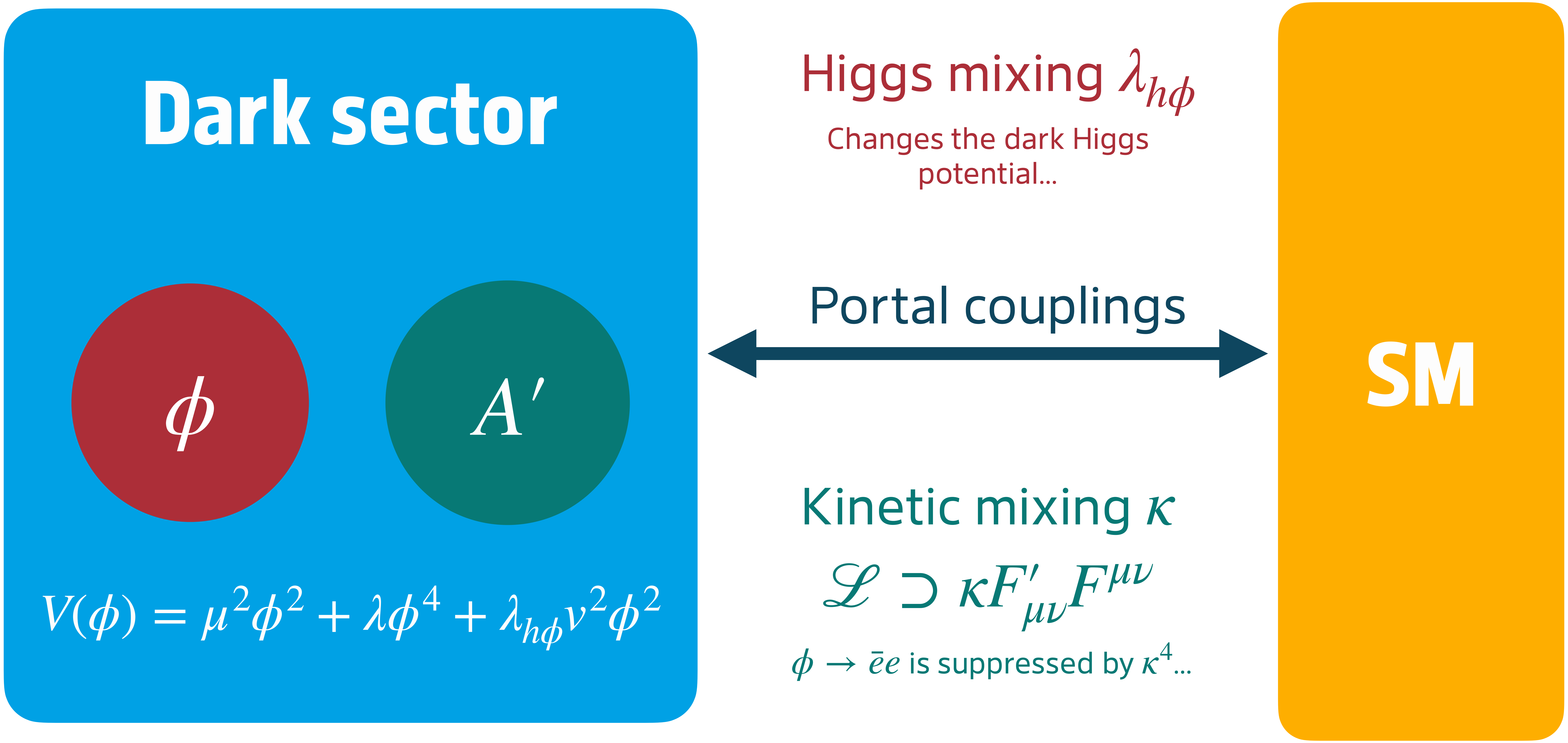
$$V_{\text{tree}}(\phi) = \lambda\phi^4$$

Quantum and thermal corrections

$$V_{\text{eff}}(\phi, T) \supset \lambda\phi^4 \log\left(\frac{T}{v}\right)$$

Loop-induced barrier down until very low temperatures, i.e. strong supercooling

A minimal dark sector setup



Dark sector

ϕ

A'

$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4 + \lambda_{h\phi}v^2\phi^2$$

Higgs mixing $\lambda_{h\phi}$

Changes the dark Higgs potential…

Portal couplings

Kinetic mixing κ

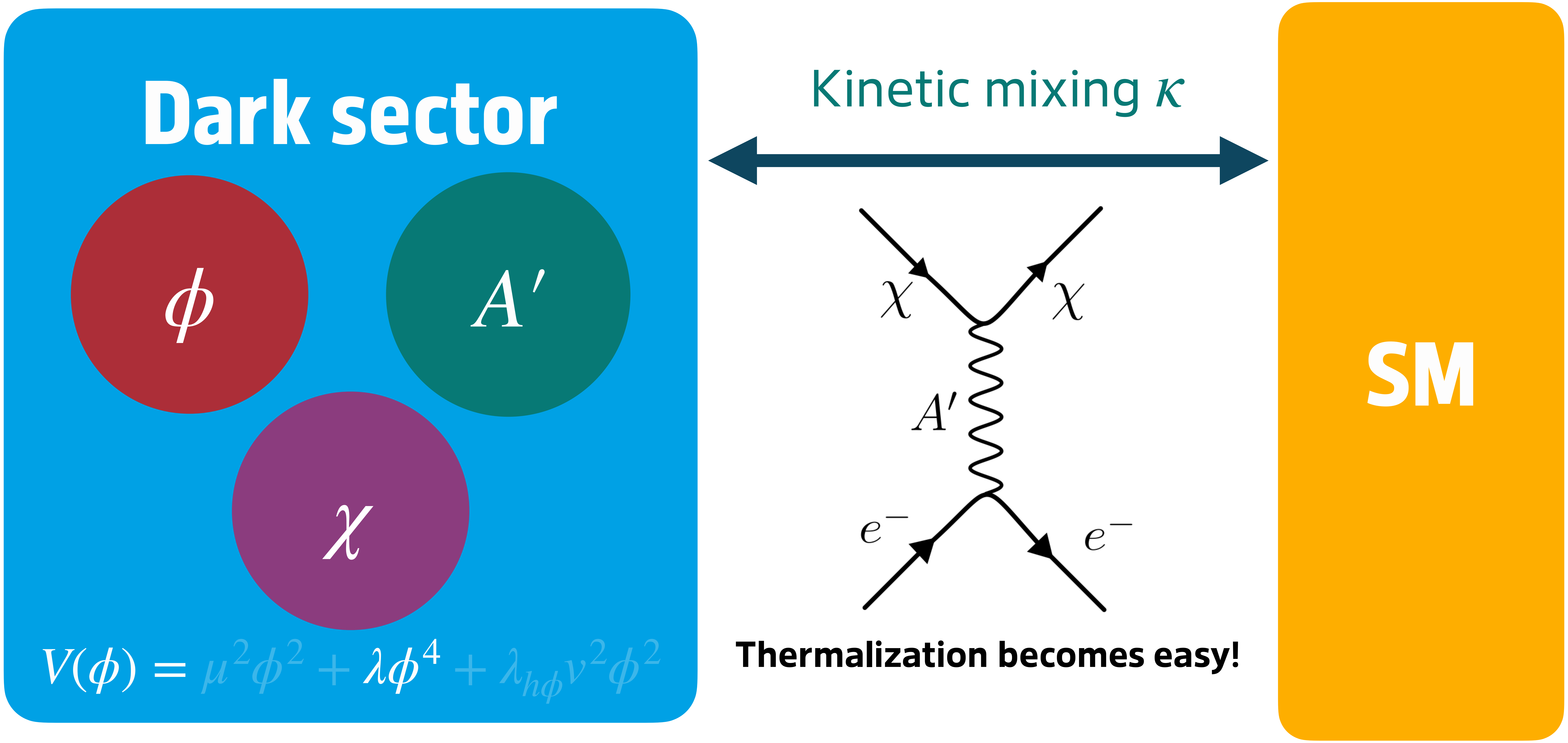
$$\mathscr{L} \supset \kappa F'_{\mu\nu}F^{\mu\nu}$$

$\phi \to \bar{e}e$ is suppressed by κ^4…

SM

See 2412.16282, 2501.11619, 2501.15649, 2501.14986 by Banik, Gonçalves, Costa, Li et al.

A conformal dark sector incl. dark matter candidate

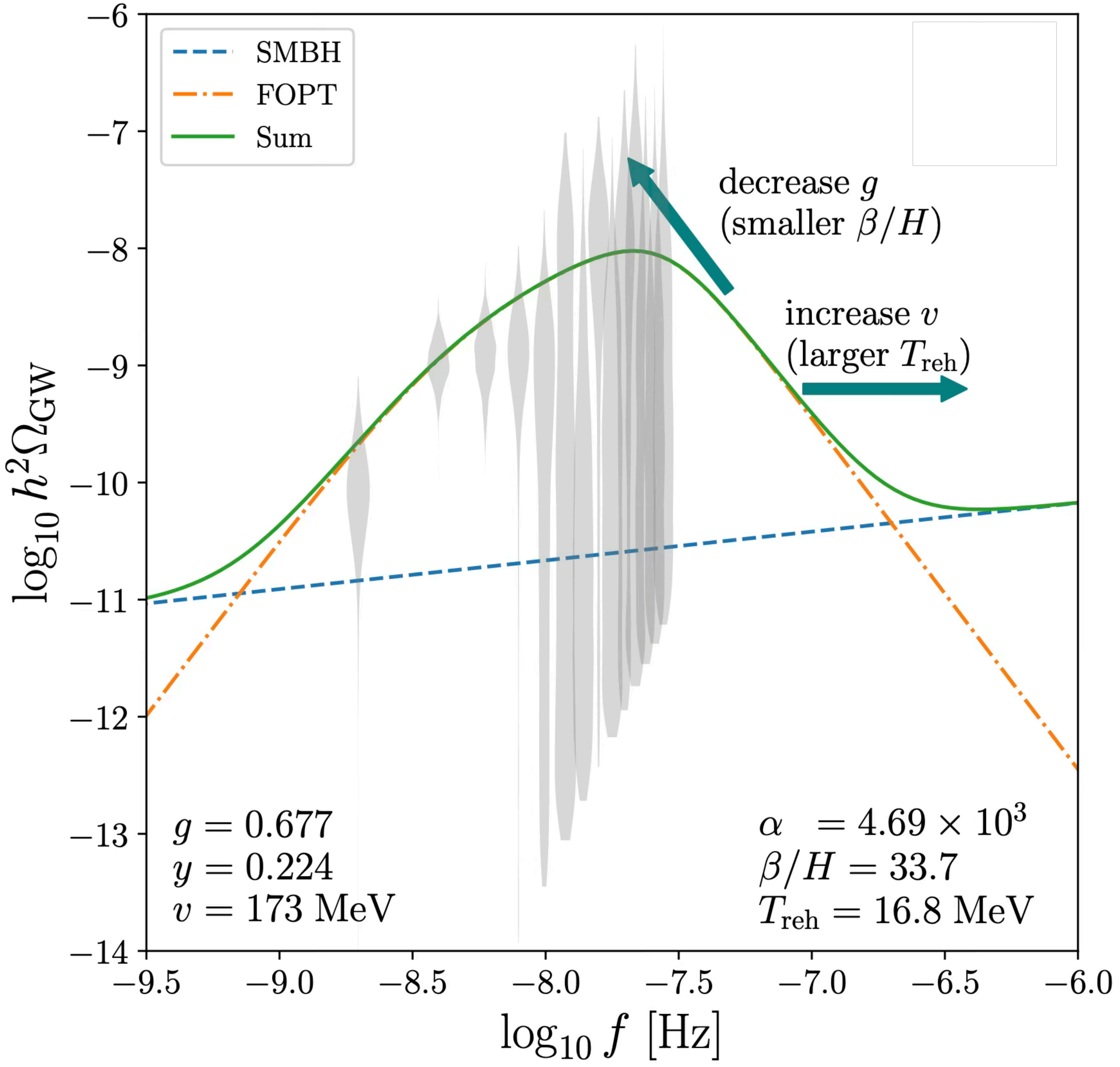


$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4 + \lambda_{h\phi}v^2\phi^2$$

Thermalization becomes easy!

CT+ [JCAP 08 (2025) 062]

All constraints can be circumvented

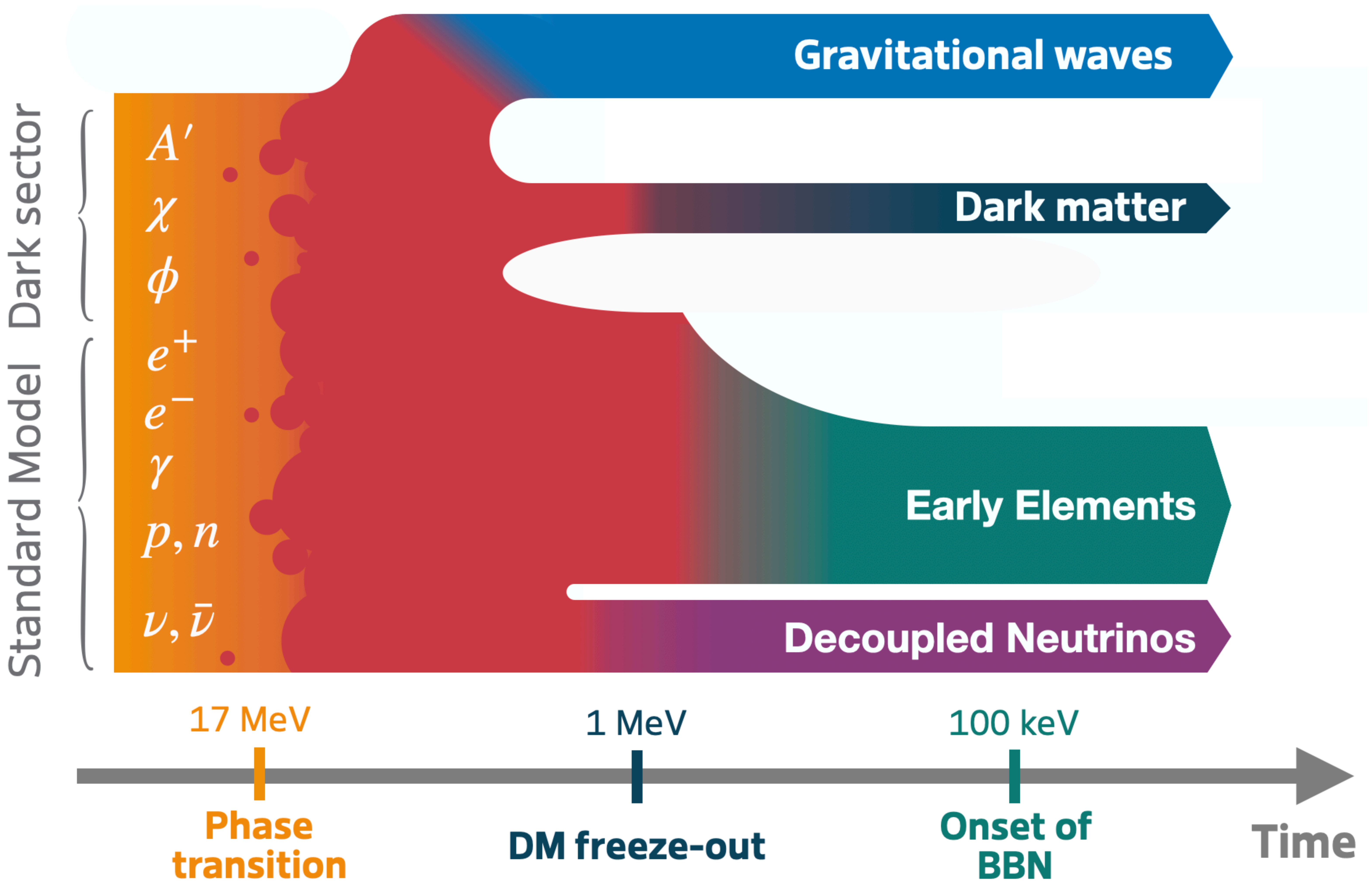


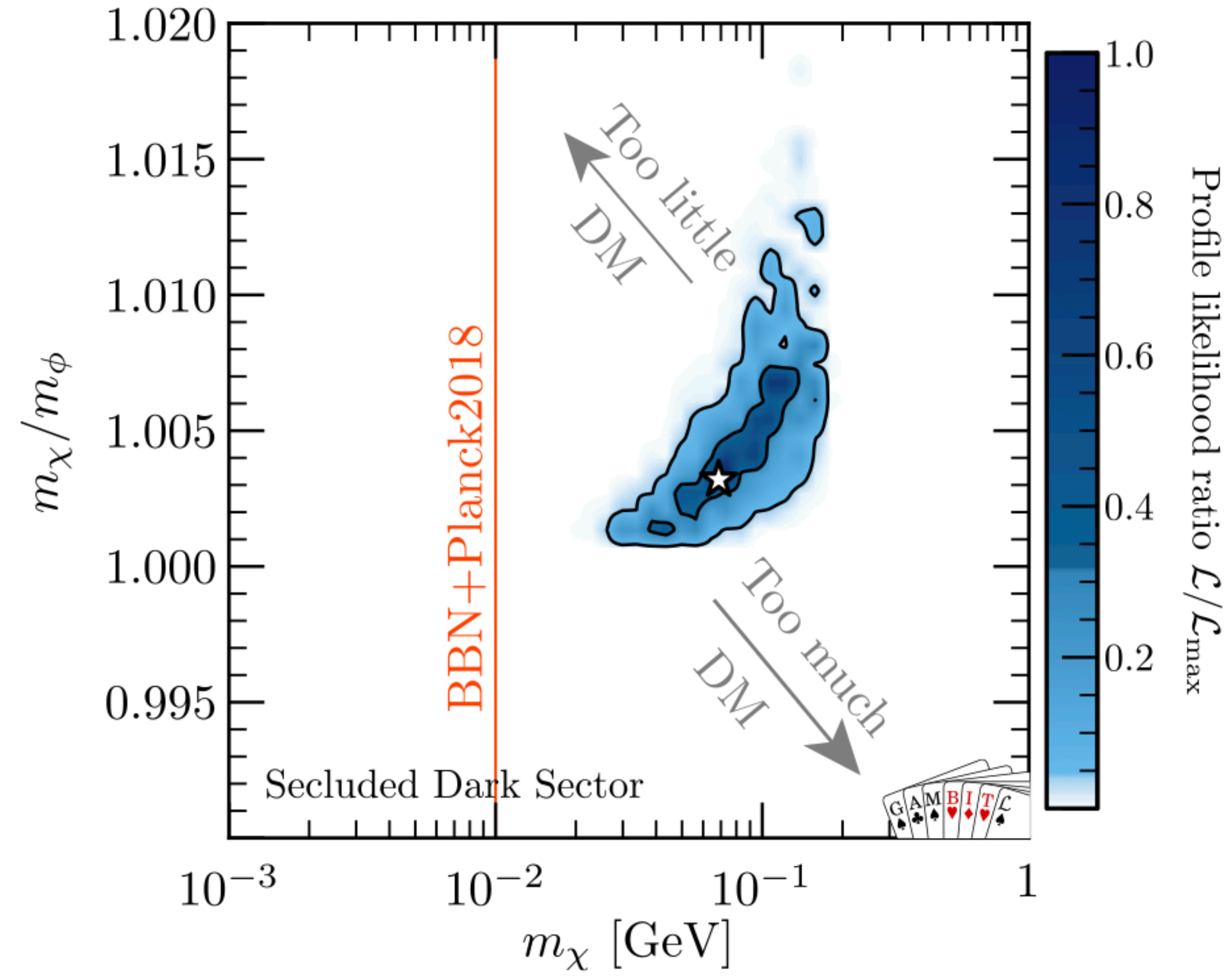
Global fit found parameter space with

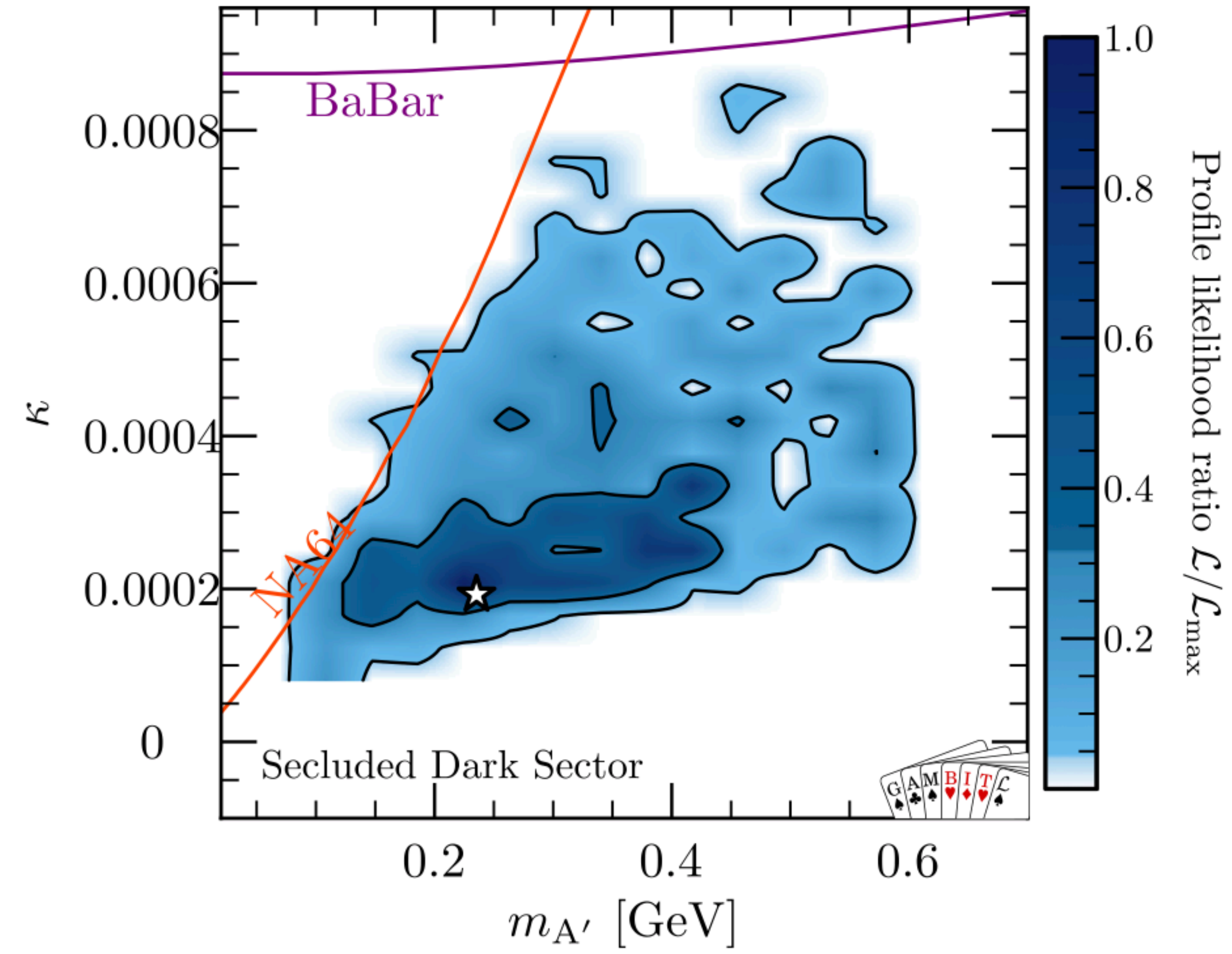
- 100% of observed DM relic density
- Loud phase transition on top of „standard" SMBH background
- Negligible impact on BBN and CMB
- No relevant direct + indirect detection + bullet cluster constraints
- Testable LDMX/Belle-II/NA64 prediction:
  $m_{A'} = 100 - 200\,\mathrm{MeV}, \kappa \simeq 10^{-4}$

CT+ [JCAP 08 (2025) 062]

How does our scenario evade all available constraints?

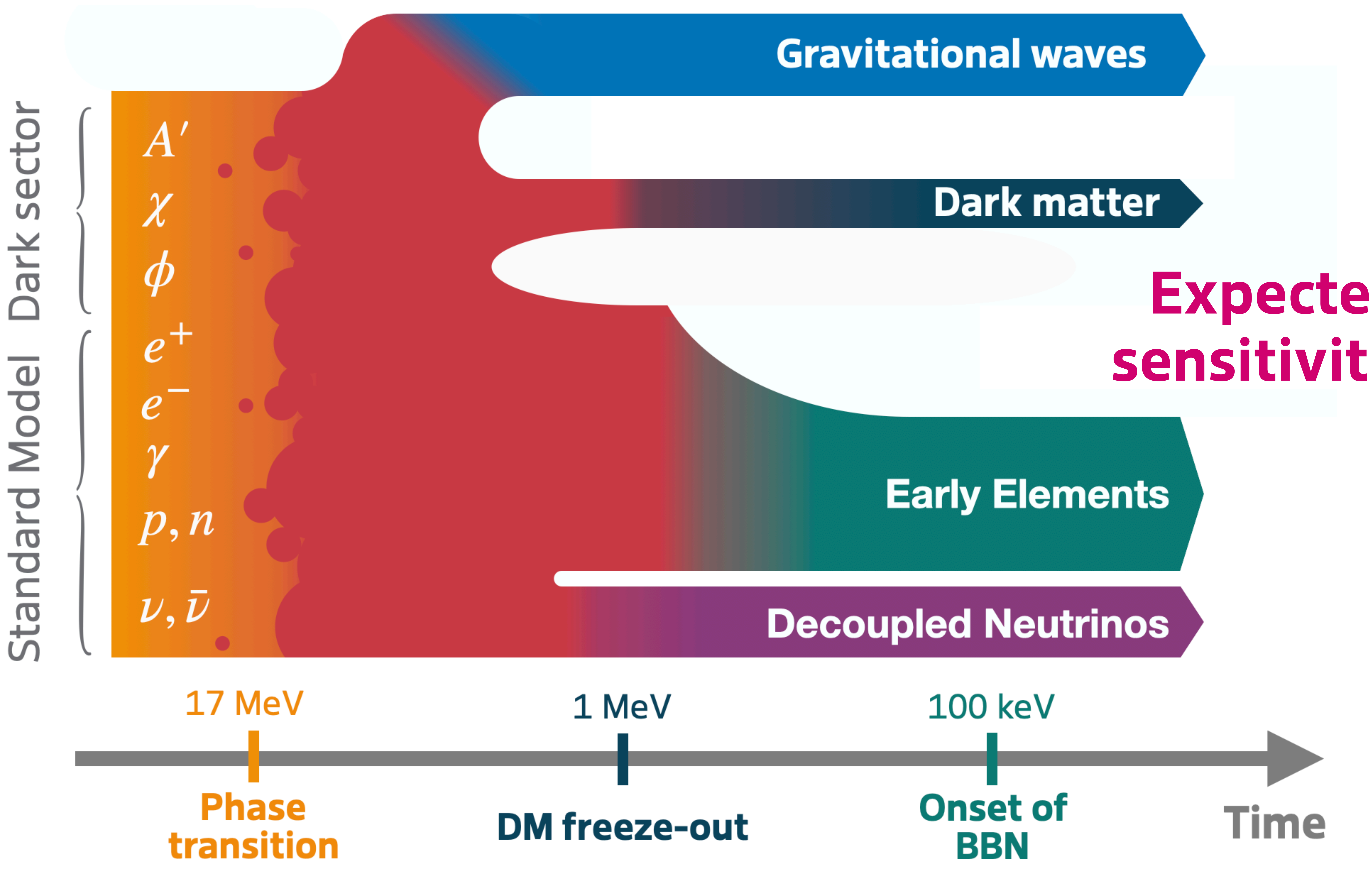




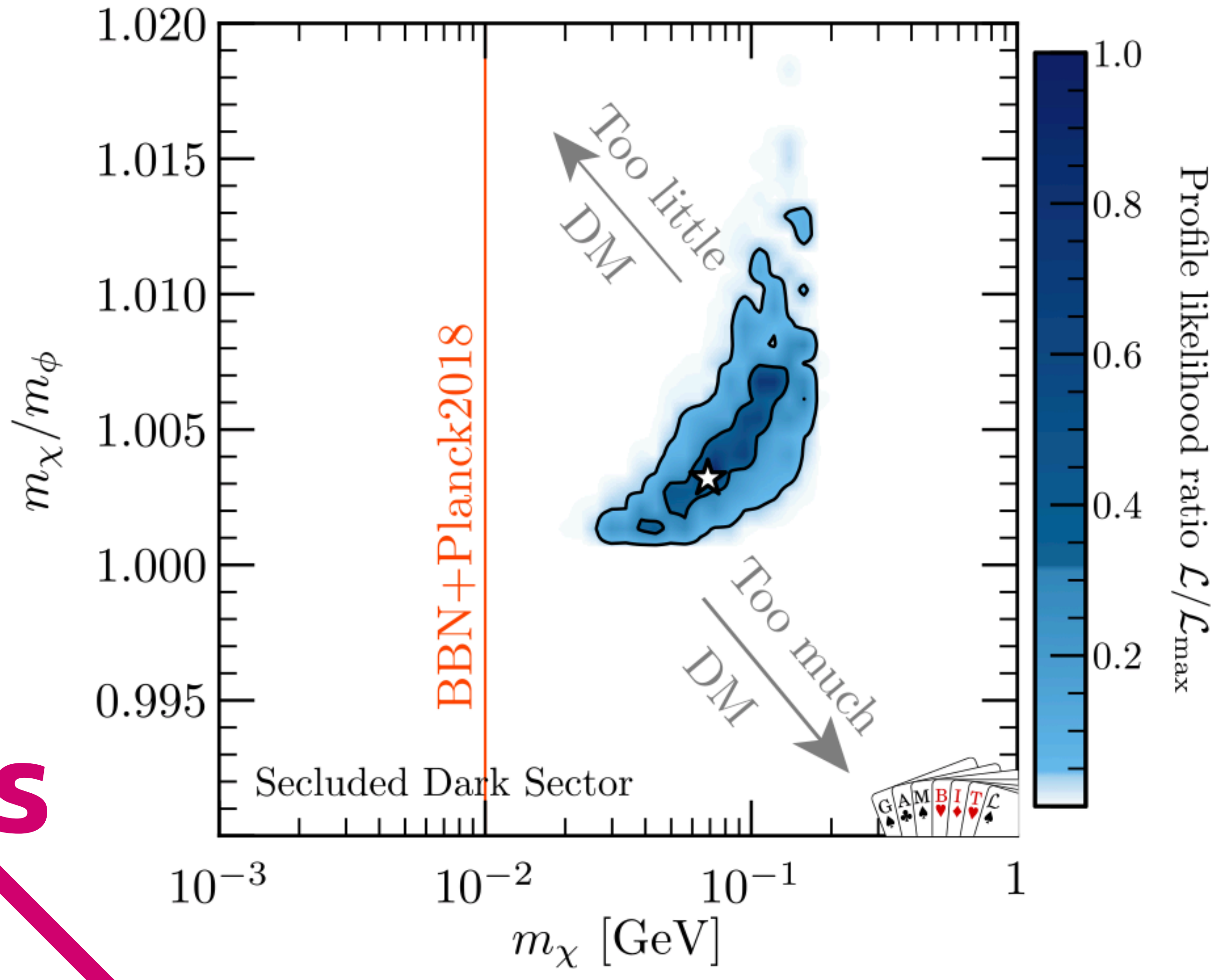


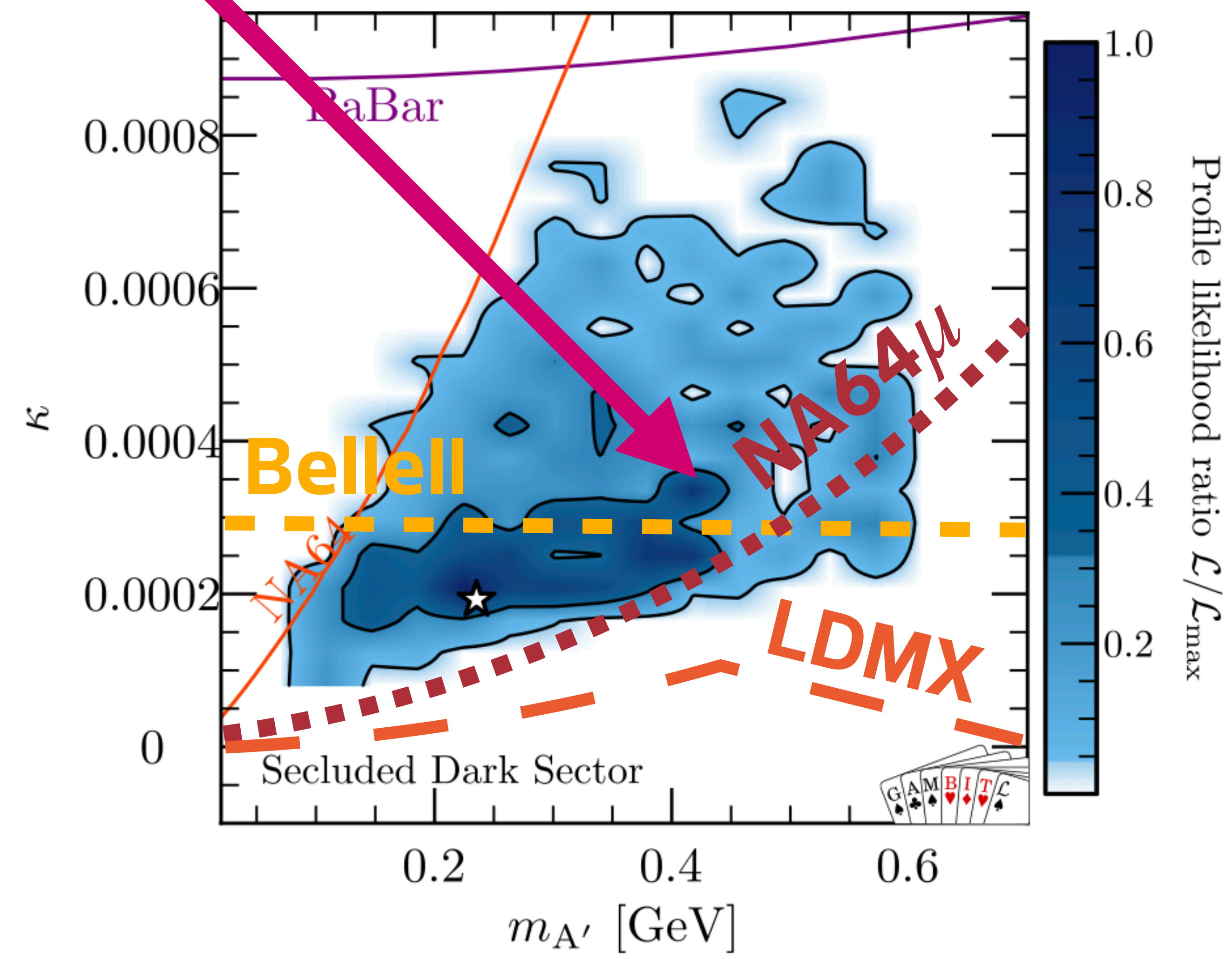
CT+ [JCAP 08 (2025) 062]

How does our scenario evade all available constraints?



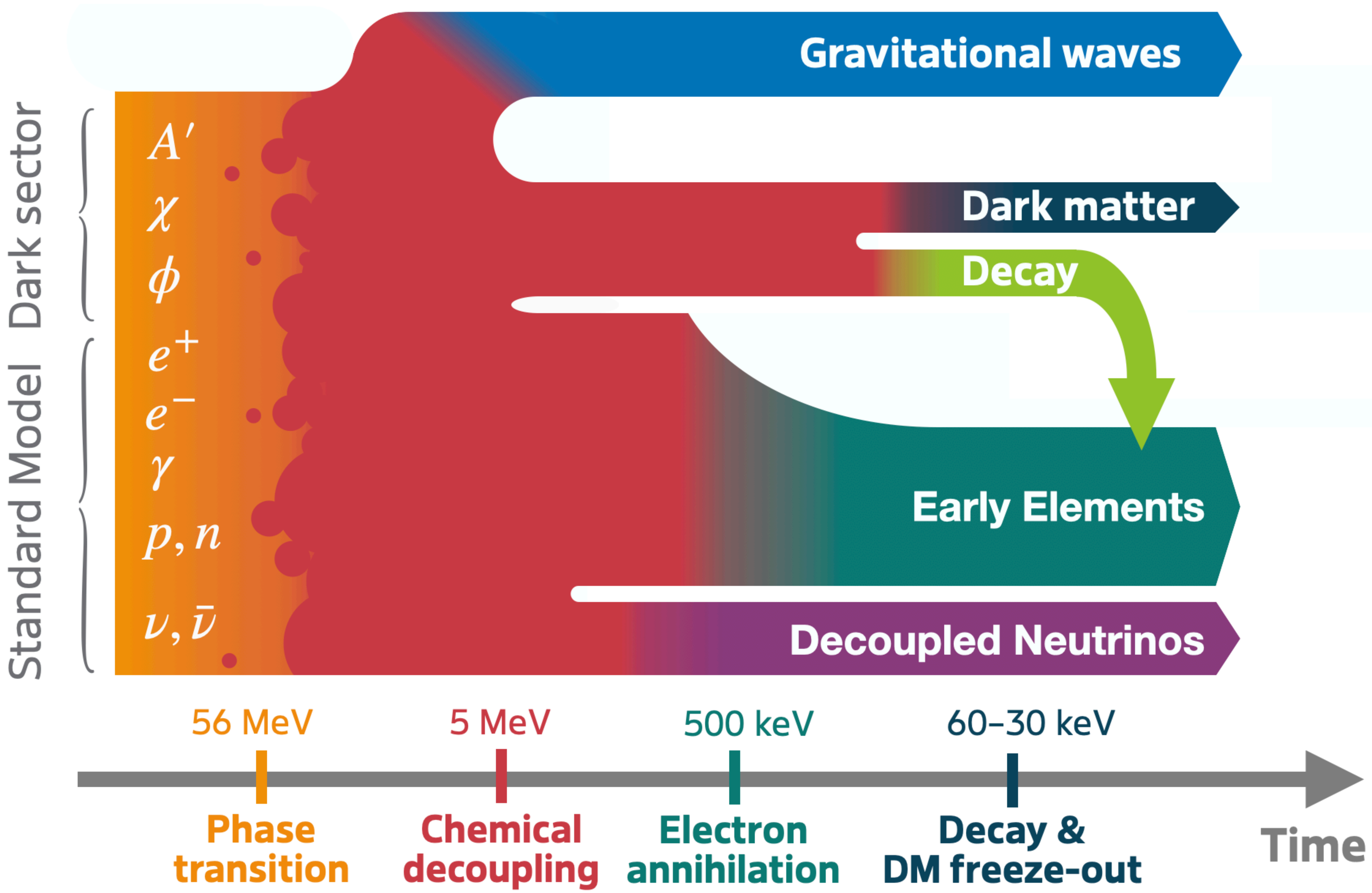
Expected sensitivities





CT+ [JCAP 08 (2025) 062]

Coupled DS scenario: incl dim-6 operator for $\phi \to ee$


Dark sector

Standard Model

A'
χ
ϕ
e^+
e^-
γ
p, n
$\nu, \bar{\nu}$

Gravitational waves

Dark matter

Decay

Early Elements

Decoupled Neutrinos

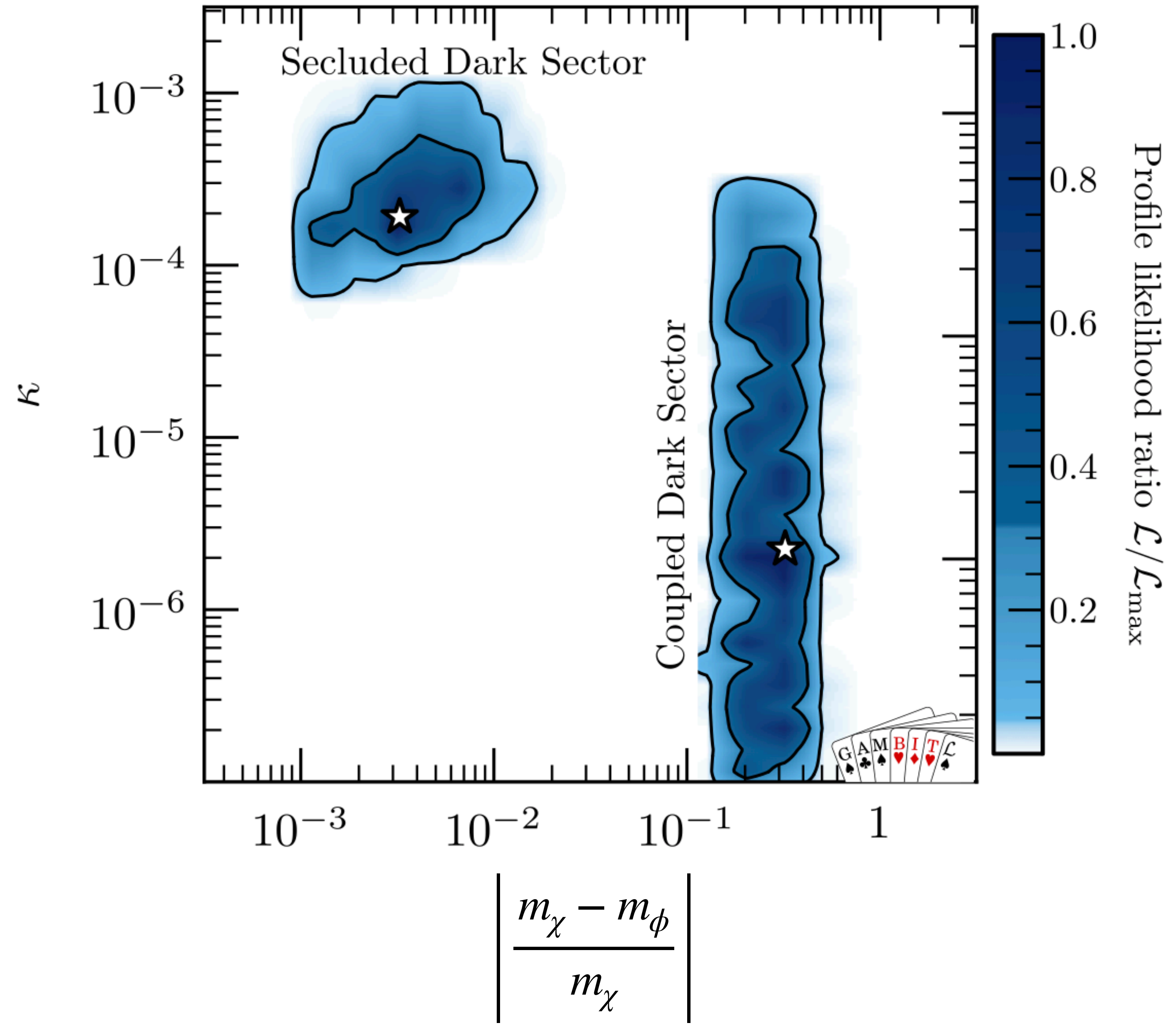
56 MeV — Phase transition

5 MeV — Chemical decoupling

500 keV — Electron annihilation

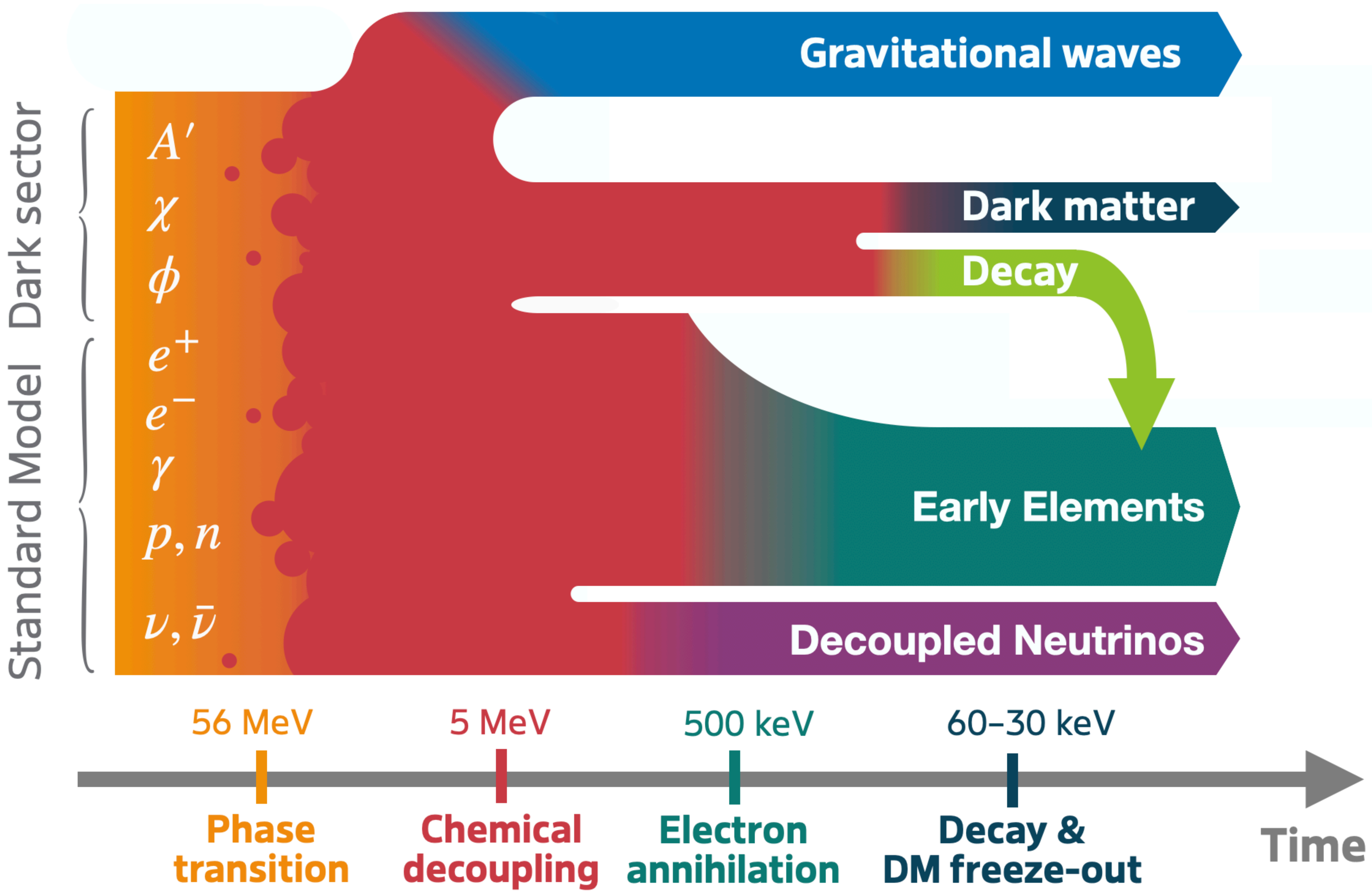
60–30 keV — Decay & DM freeze-out

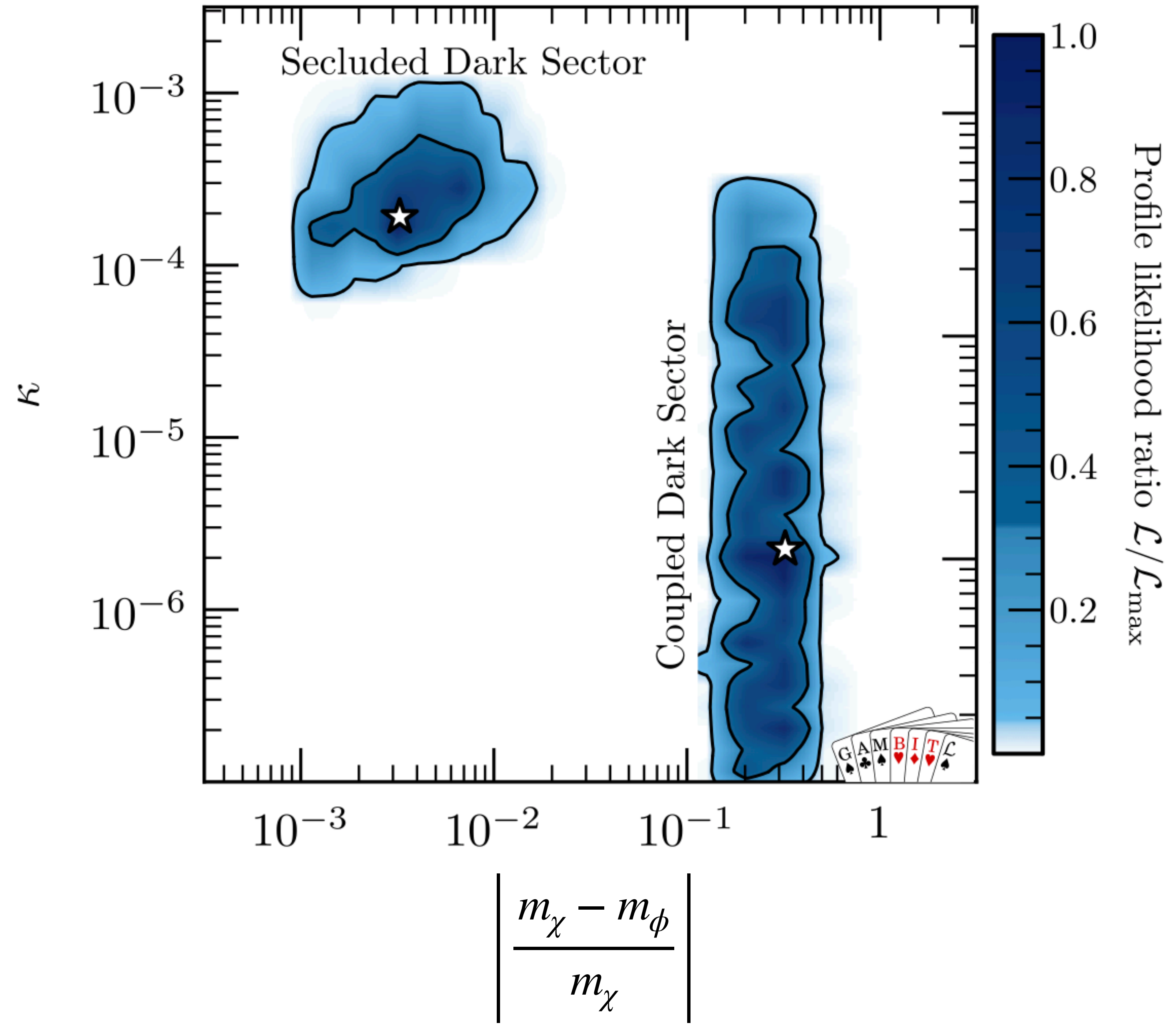
Time



CT+ [JCAP 08 (2025) 062]

Coupled DS scenario: incl dim-6 operator for $\phi \to ee$





$\phi \to ee$ decays through a dim-6 operator open up the parameter space and save the model from potential future constraints

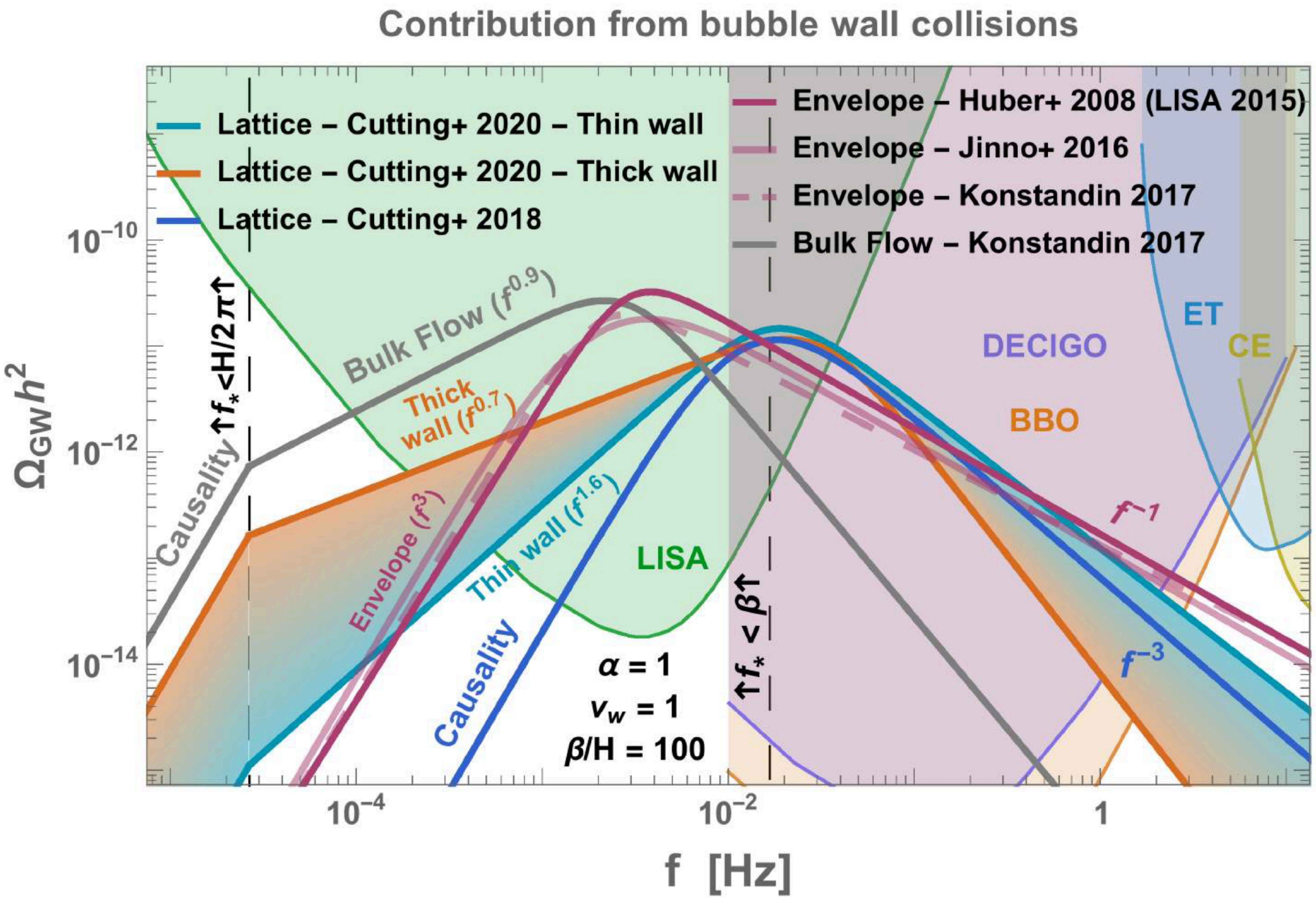
CT+ [JCAP 08 (2025) 062]

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]

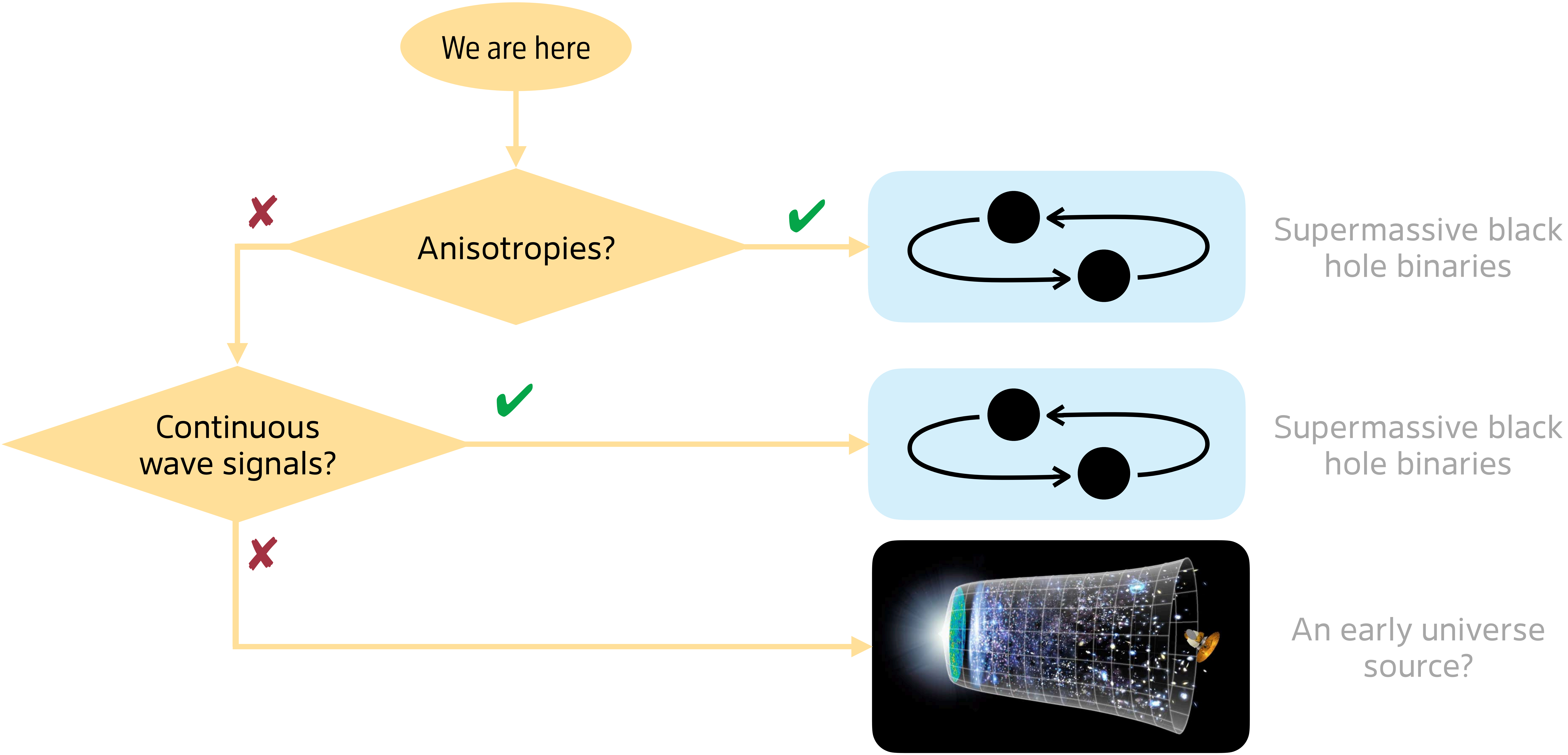
	IR	Intermediate	UV	References
Sound shell	9	1	-3	[22, 23]
Scalar + fluid lattice	—	1	-3	[18, 20, 21, 29]
Hybrid	[2,4]	[-1,0]	[-4,-3]	[30]
Higgsless	3	1	-3	This work

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



[Yann Gouttenoire: Beyond the Standard Model Cocktail]

Quo vadis pulsar timing?



We are here

Anisotropies?

✗

✓

Supermassive black hole binaries

Continuous wave signals?

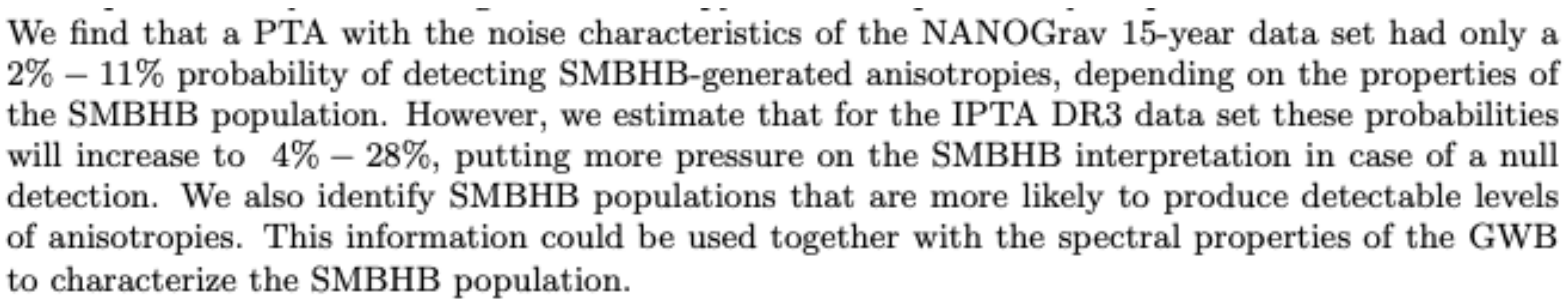
✓

Supermassive black hole binaries

✗

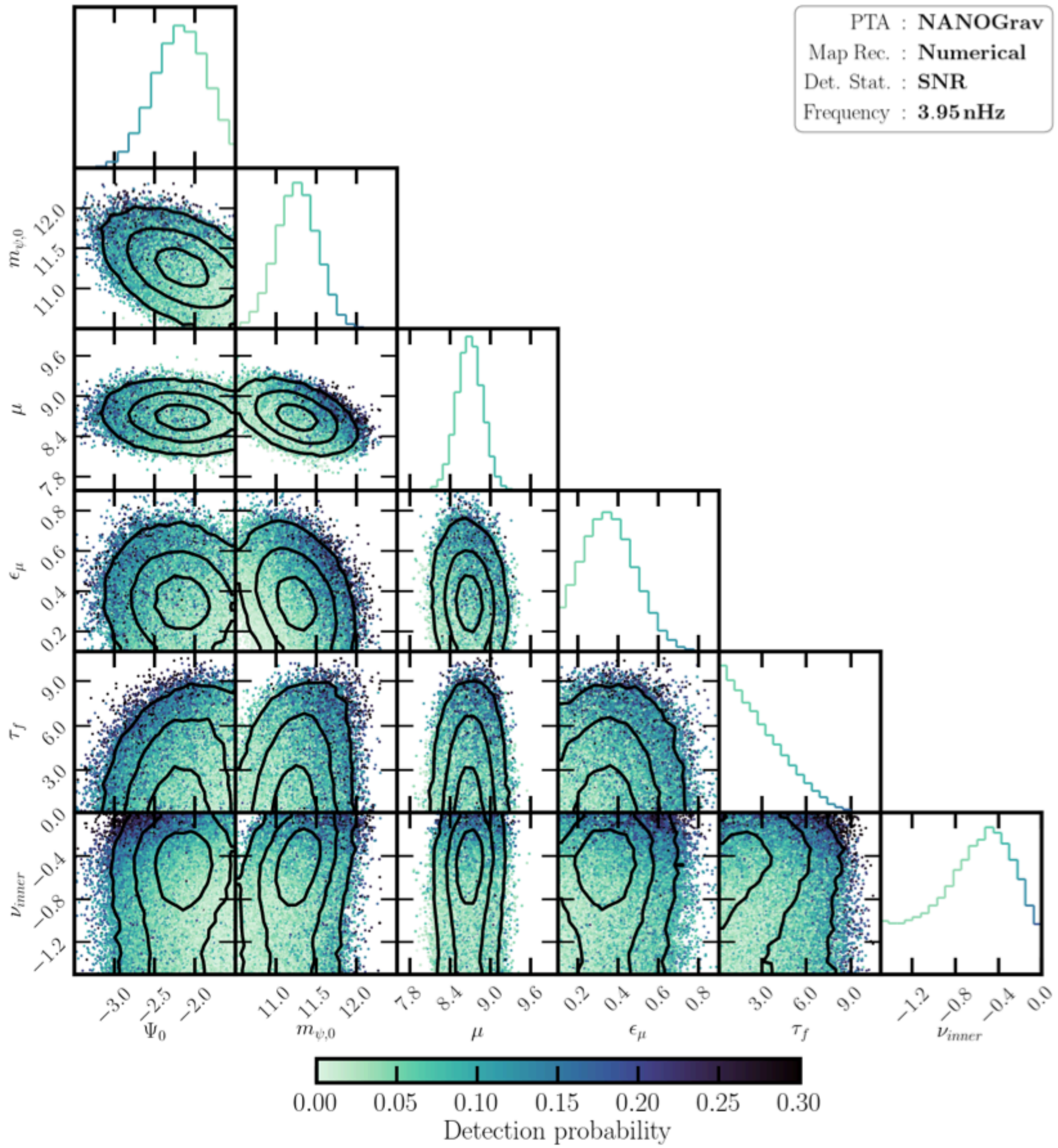
An early universe source?

Detecting GW anisotropies from SMBHBs

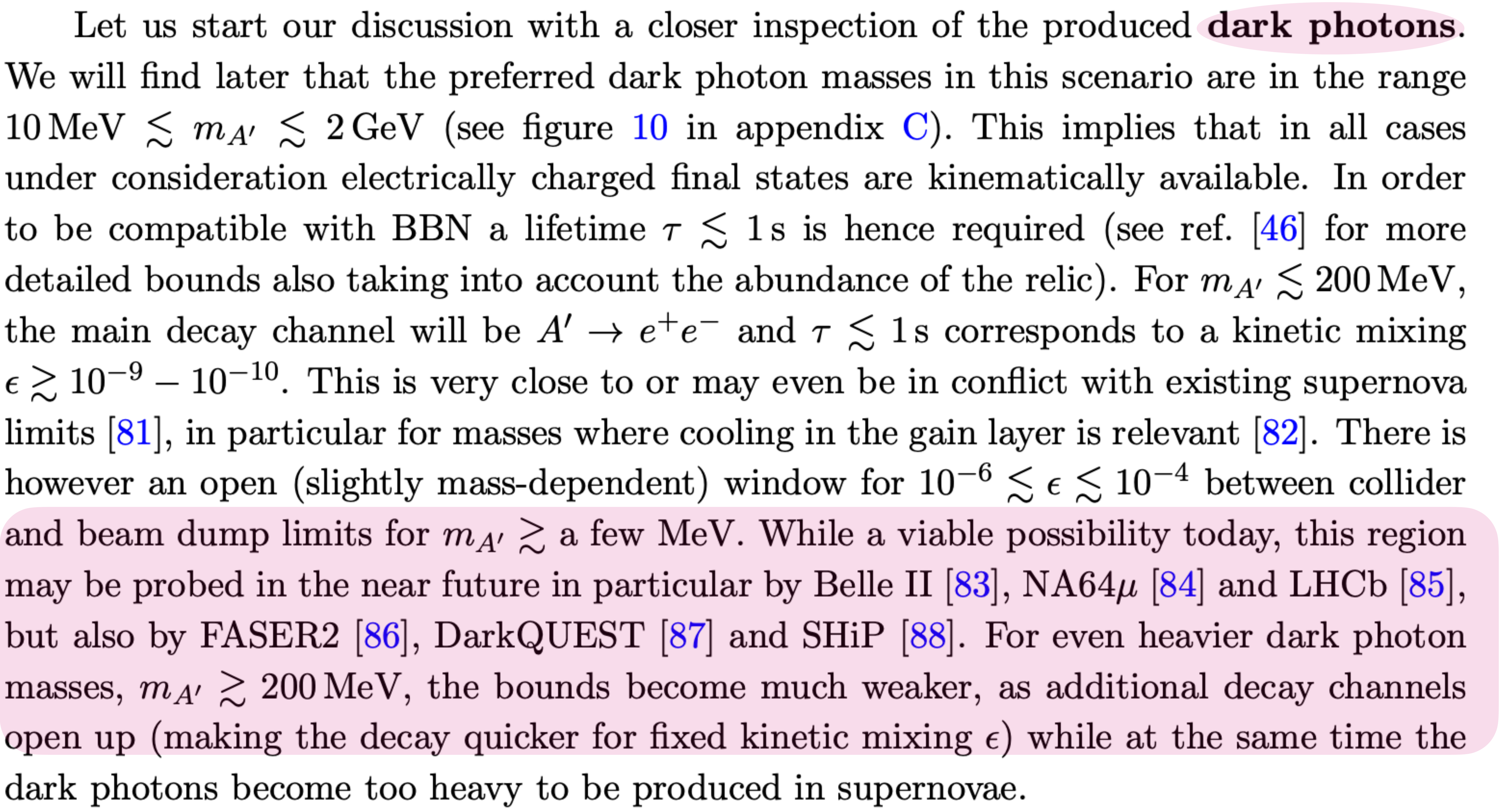


We find that a PTA with the noise characteristics of the NANOGrav 15-year data set had only a 2% – 11% probability of detecting SMBHB-generated anisotropies, depending on the properties of the SMBHB population. However, we estimate that for the IPTA DR3 data set these probabilities will increase to 4% – 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]



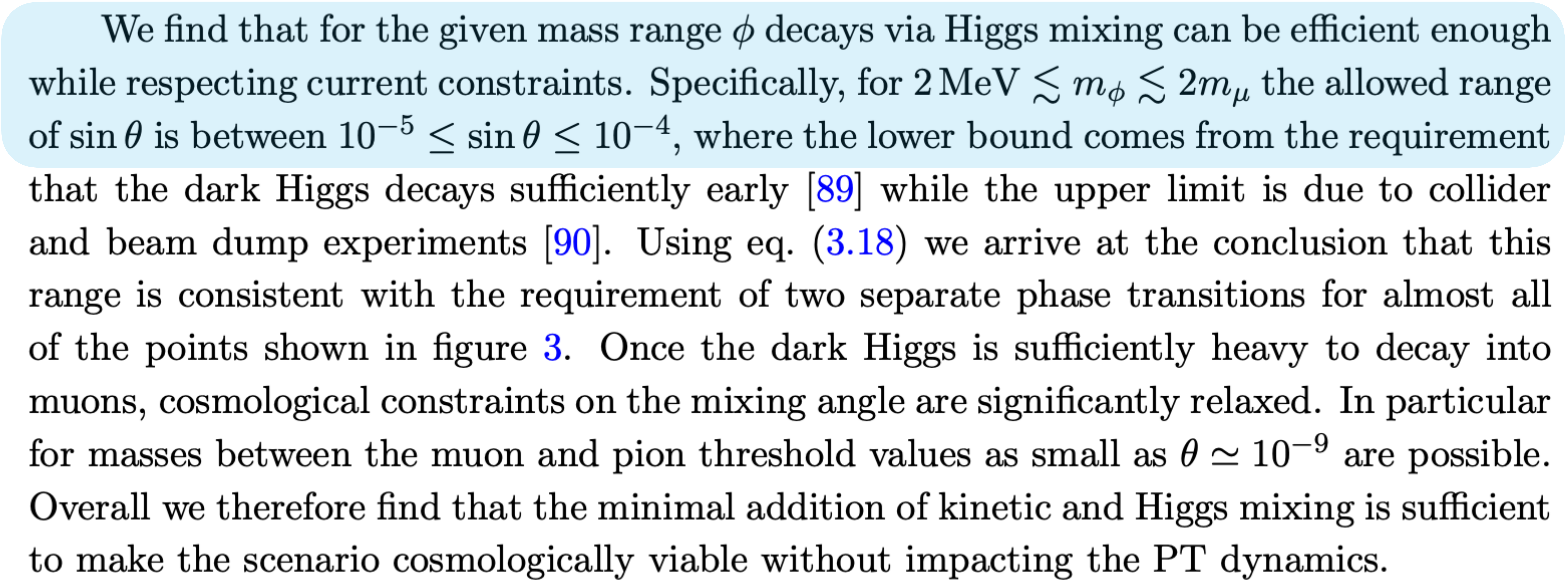
How to make the dark sector models viable: dark photons



Let us start our discussion with a closer inspection of the produced **dark photons**. We will find later that the preferred dark photon masses in this scenario are in the range $10\,\mathrm{MeV} \lesssim m_{A'} \lesssim 2\,\mathrm{GeV}$ (see figure 10 in appendix C). This implies that in all cases under consideration electrically charged final states are kinematically available. In order to be compatible with BBN a lifetime $\tau \lesssim 1\,\mathrm{s}$ is hence required (see ref. [46] for more detailed bounds also taking into account the abundance of the relic). For $m_{A'} \lesssim 200\,\mathrm{MeV}$, the main decay channel will be $A' \to e^+e^-$ and $\tau \lesssim 1\,\mathrm{s}$ corresponds to a kinetic mixing $\epsilon \gtrsim 10^{-9} - 10^{-10}$. This is very close to or may even be in conflict with existing supernova limits [81], in particular for masses where cooling in the gain layer is relevant [82]. There is however an open (slightly mass-dependent) window for $10^{-6} \lesssim \epsilon \lesssim 10^{-4}$ between collider and beam dump limits for $m_{A'} \gtrsim$ a few MeV. While a viable possibility today, this region may be probed in the near future in particular by Belle II [83], NA64μ [84] and LHCb [85], but also by FASER2 [86], DarkQUEST [87] and SHiP [88]. For even heavier dark photon masses, $m_{A'} \gtrsim 200\,\mathrm{MeV}$, the bounds become much weaker, as additional decay channels open up (making the decay quicker for fixed kinetic mixing ϵ) while at the same time the dark photons become too heavy to be produced in supernovae.

[2602.09092, CT+]

How to make the dark sector models viable: dark Higgs



We find that for the given mass range ϕ decays via Higgs mixing can be efficient enough while respecting current constraints. Specifically, for $2\,\mathrm{MeV} \lesssim m_\phi \lesssim 2m_\mu$ the allowed range of $\sin\theta$ is between $10^{-5} \leq \sin\theta \leq 10^{-4}$, where the lower bound comes from the requirement that the dark Higgs decays sufficiently early [89] while the upper limit is due to collider and beam dump experiments [90]. Using eq. (3.18) we arrive at the conclusion that this range is consistent with the requirement of two separate phase transitions for almost all of the points shown in figure 3. Once the dark Higgs is sufficiently heavy to decay into muons, cosmological constraints on the mixing angle are significantly relaxed. In particular for masses between the muon and pion threshold values as small as $\theta \simeq 10^{-9}$ are possible. Overall we therefore find that the minimal addition of kinetic and Higgs mixing is sufficient to make the scenario cosmologically viable without impacting the PT dynamics.

[2602.09092, CT+]