Towards robust gravitational wave predictions for strong phase transitions

UFMG Particle Cosmology group — online colloquium

Carlo Tasillo,
Institut de física corpuscular (IFIC)

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

arXiv: 2502.19478, 2602.09092 and 2605.15259

UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

CSIC Consejo Superior de Investigaciones Científicas

Universitat de València

IFIC Institut de Física Corpuscular

Excelencia Severo Ochoa

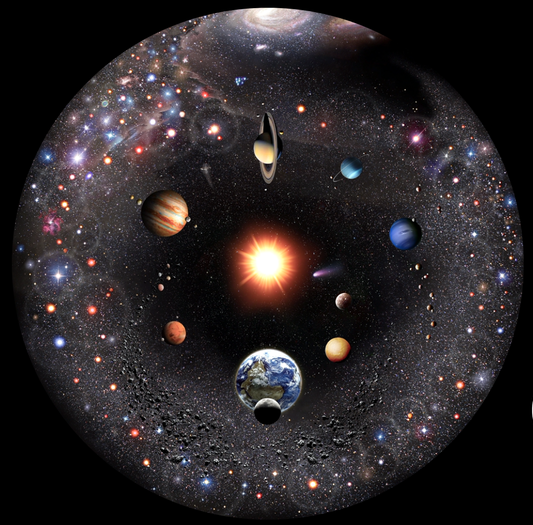
It’s the end of the world as we know it (and I feel fine)



Our Solar System

PABLO
CARLOS
BUDASSI

It’s the end of the world as we know it (and I feel fine)

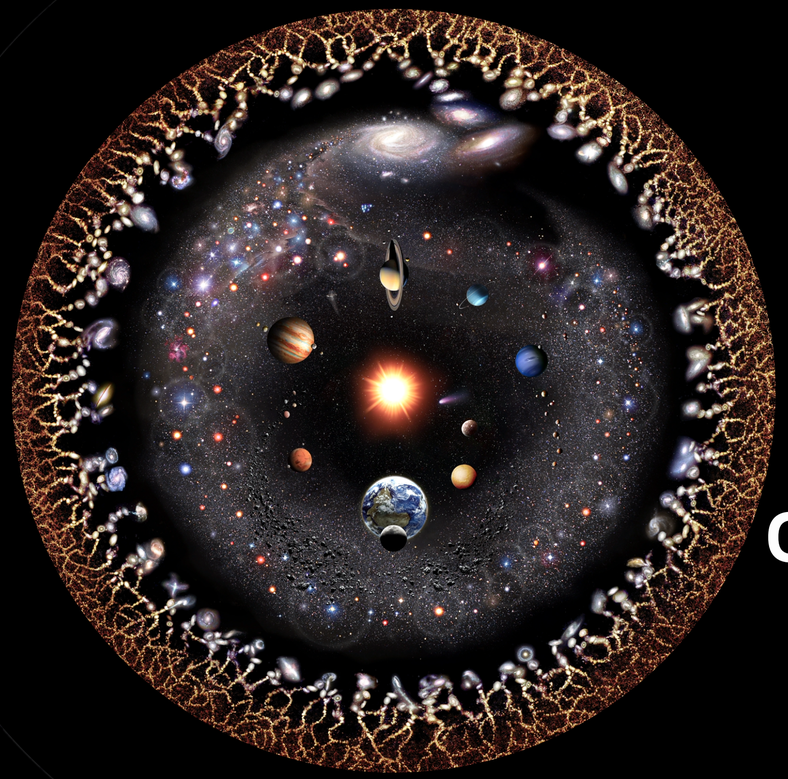


Our galaxy

PABLO
CARLOS
BUDASSI

[Pablo Carlos Budassi]

It’s the end of the world as we know it (and I feel fine)

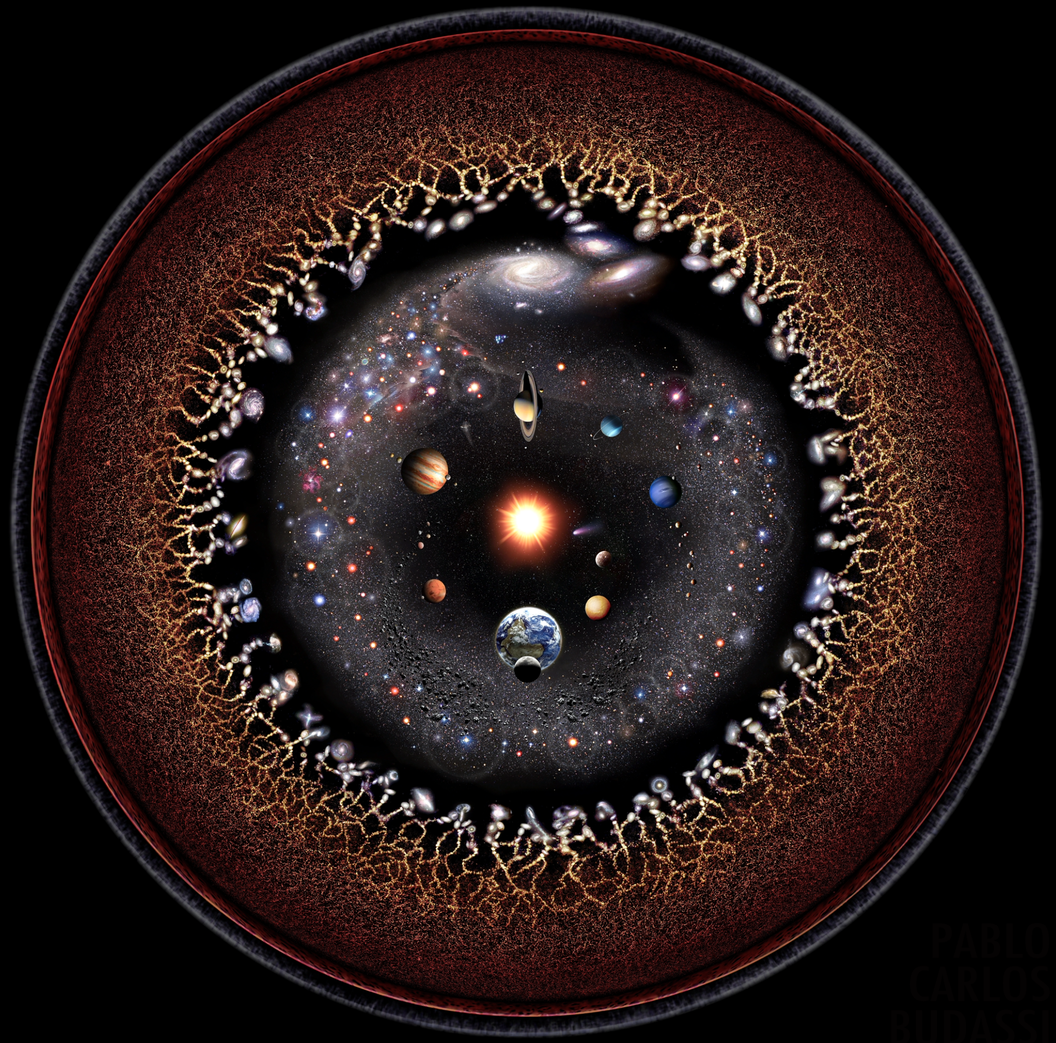


Other galaxies

PABLO CARLOS BUDASSI

[Pablo Carlos Budassi]

It’s the end of the world as we know it (and I feel fine)



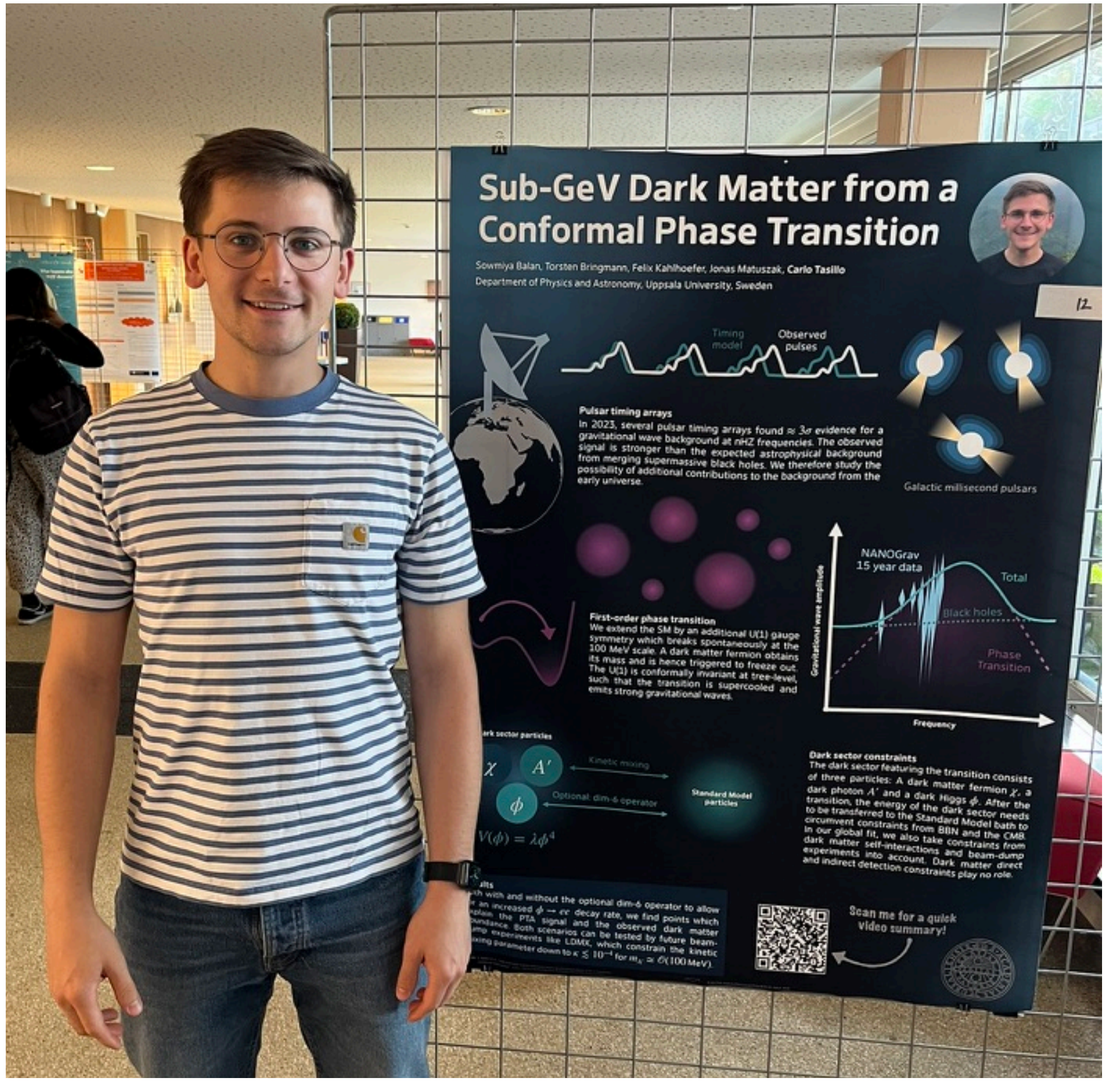
The CMB…
and the CGWB?

[Pablo Carlos Budassi]


At Last, There's
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 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
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.
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
SCIENCE
Colossal gravitational waves—trillions of miles long—found for the first time
The Washington Post
In a major discovery, scientists say space-time churns like a choppy sea
First Evidence of Giant Gravitational Waves Thrills Astronomers
For first time ever, scientists 'hear' gravitational waves rippling through the universe
Monster gravitational
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




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 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
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.
For first time ever, scientists 'hear' gravitational waves rippling through the universe
First Evidence of Giant Gravitational Waves Thrills Astronomers
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
SCIENCE
Colossal gravitational waves—trillions of miles long—found for the first time
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
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 rolled by low-frequency gravitational waves
The Washington Post


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
Timing model
Observed pulses
Pulsar timing arrays
In 2023, several pulsar timing arrays found ≈ 3σ 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.
Galactic millisecond pulsars
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.
NANOGrav 15 year data
Total
Black holes
Phase Transition
Gravitational wave amplitude
Frequency
Kinetic mixing
Optional dim-6 operator
Standard Model particles
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.
Scan me for a quick video summary!

Plan for today:



Pulsar timing arrays discovering nHz GWs



Dark sector phase transitions

The need for robust phase transition predictions



Are the violins tuned?



Is there dark matter in the dark sector?



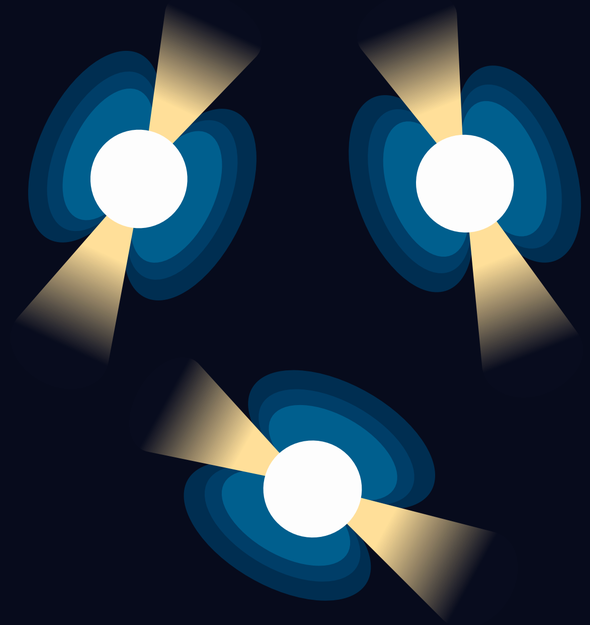
LISA is blind!



The working principle of a pulsar timing array



Galactic millisecond pulsars



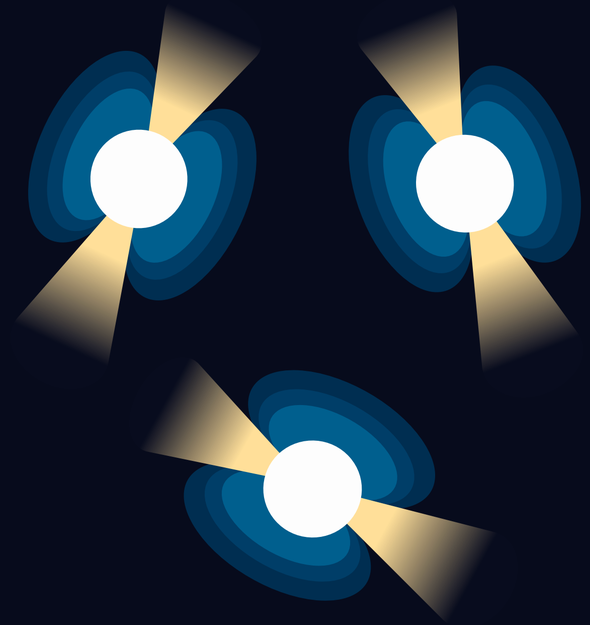
The working principle of a pulsar timing array

Galactic millisecond pulsars



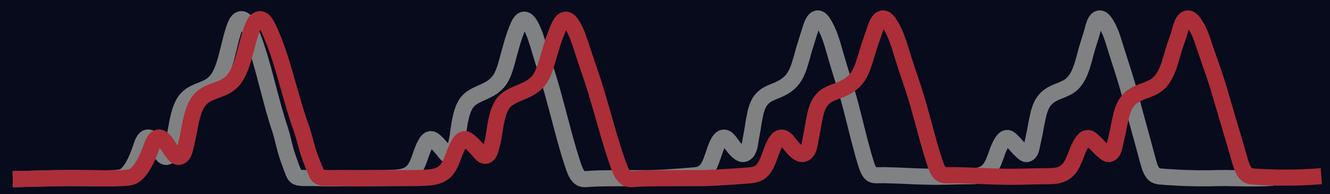


Pulses expected
from timing model



The working principle of a pulsar timing array

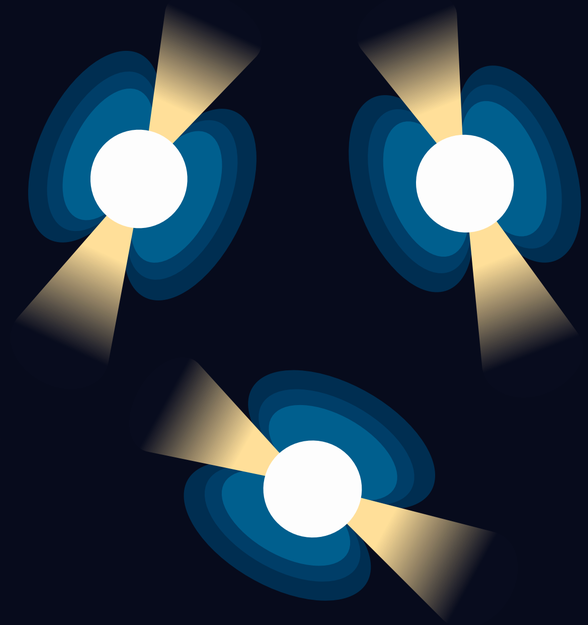




Pulses expected from timing model

Pulses recorded by radio telescopes

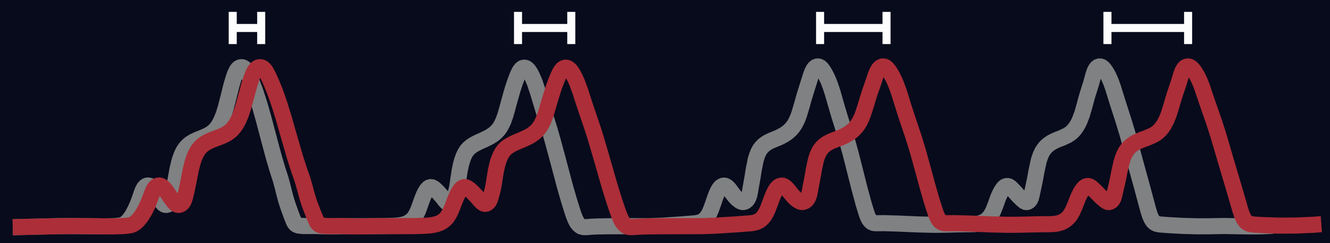
Galactic millisecond pulsars



The working principle of a pulsar timing array



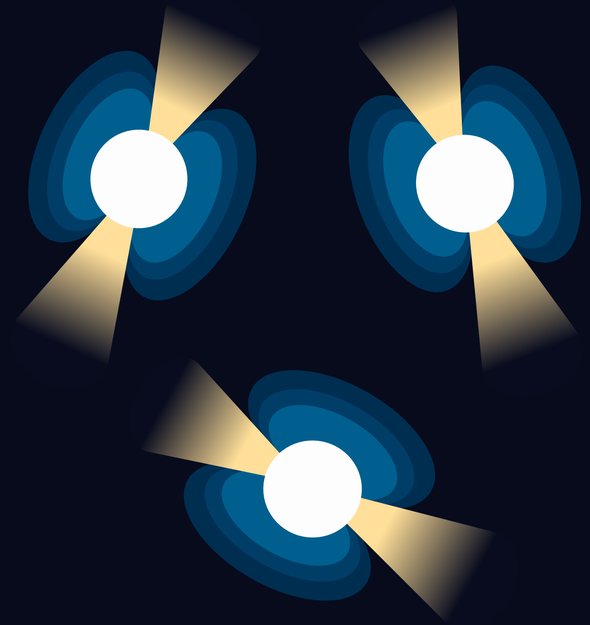
Timing residuals δt



Pulses expected from timing model

Pulses recorded by radio telescopes

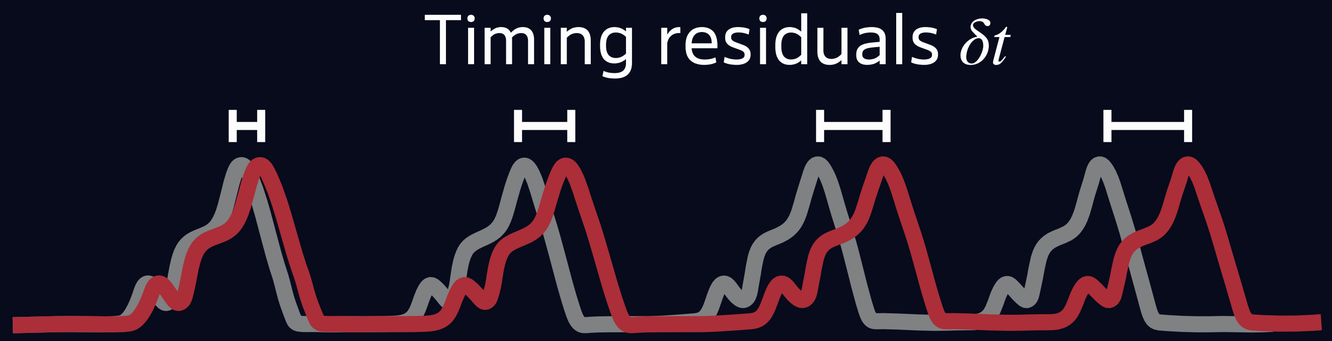
Galactic millisecond pulsars

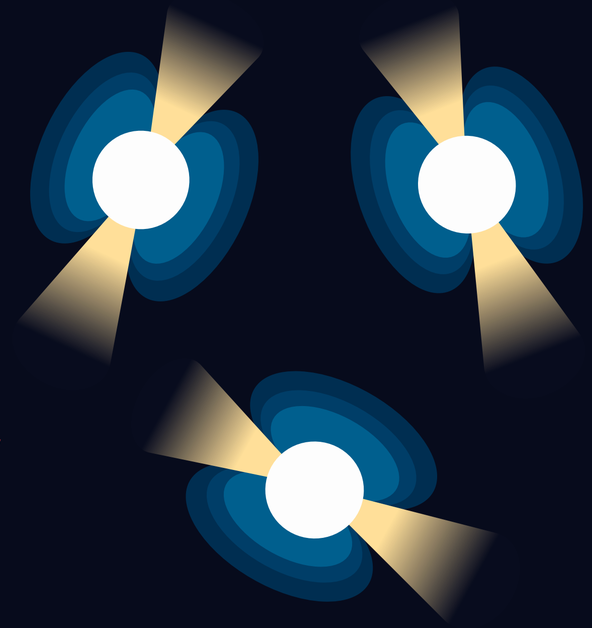


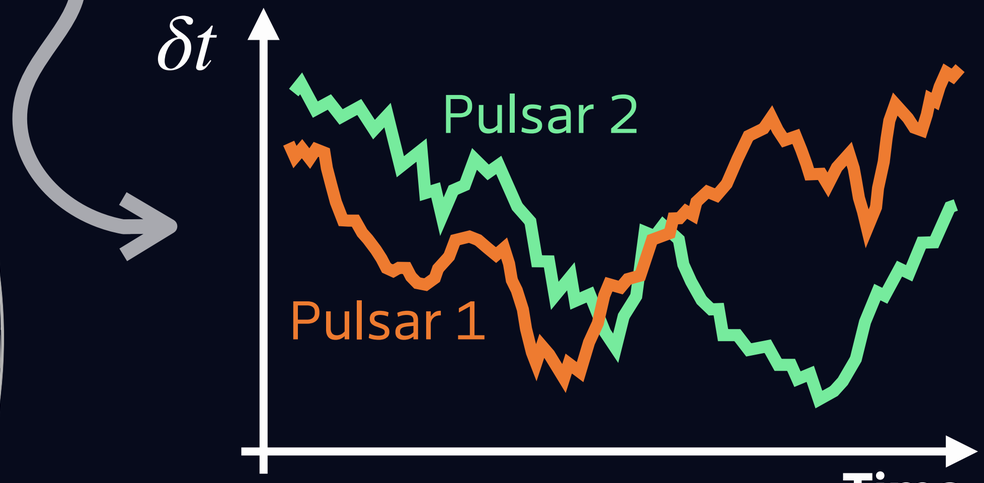
The working principle of a pulsar timing array

Galactic millisecond pulsars



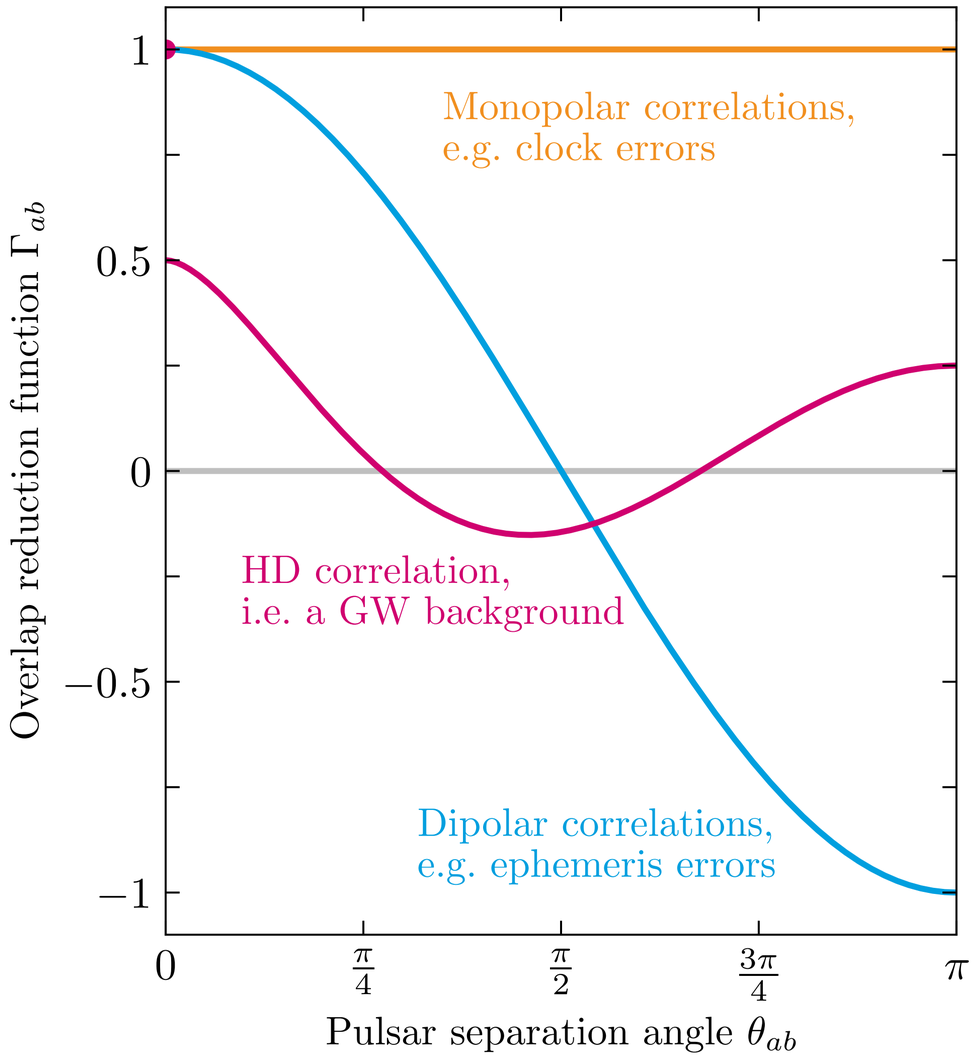






A gravitational wave backgrounds imprints itself in the common evolution of the timing residuals over time

Searching for the Hellings-Downs correlation

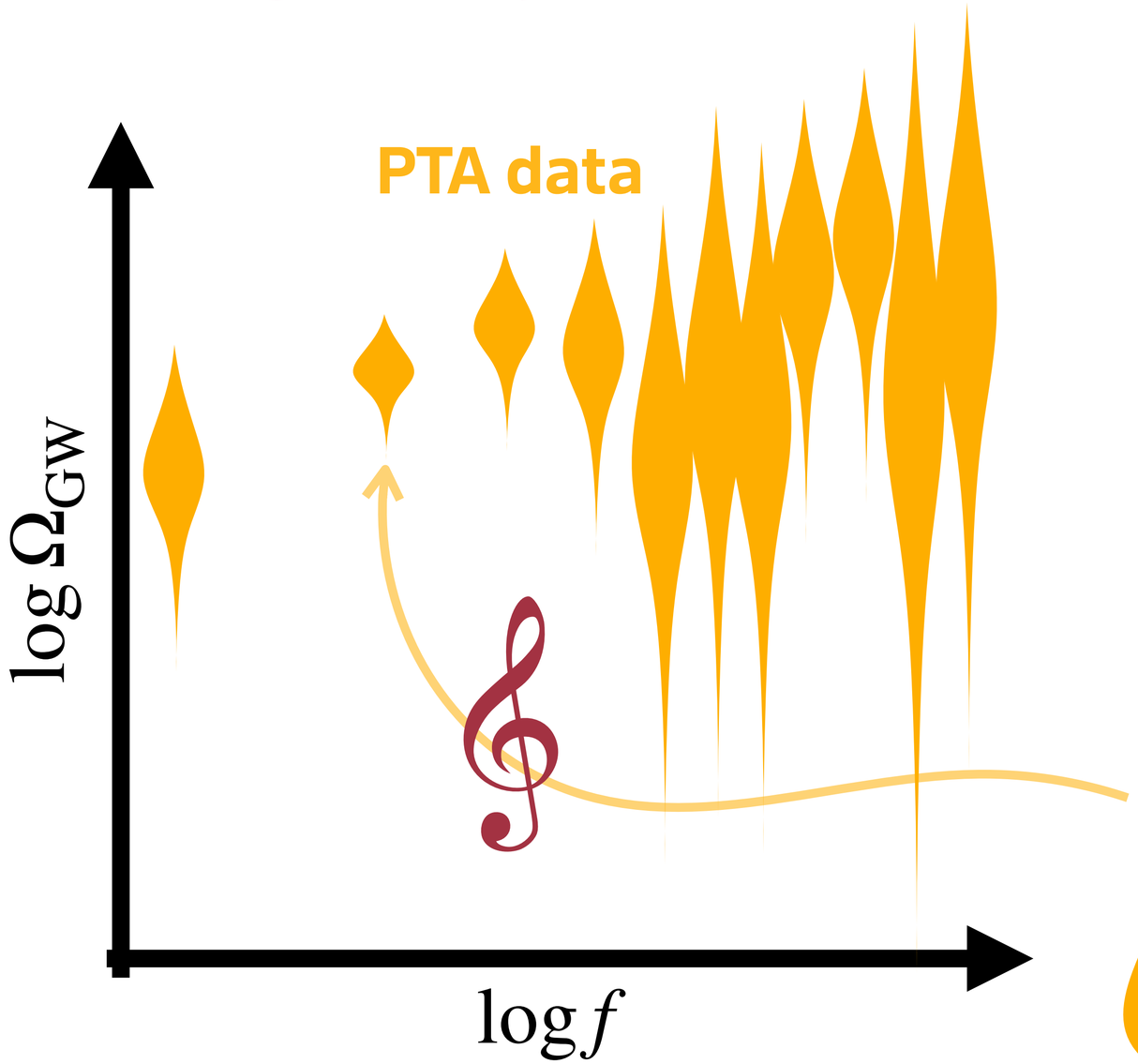


- PTAs found an underlying „common red process“ among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves, Clock errors, Ephemeris errors:
    All ruled out with $>5\sigma$ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]



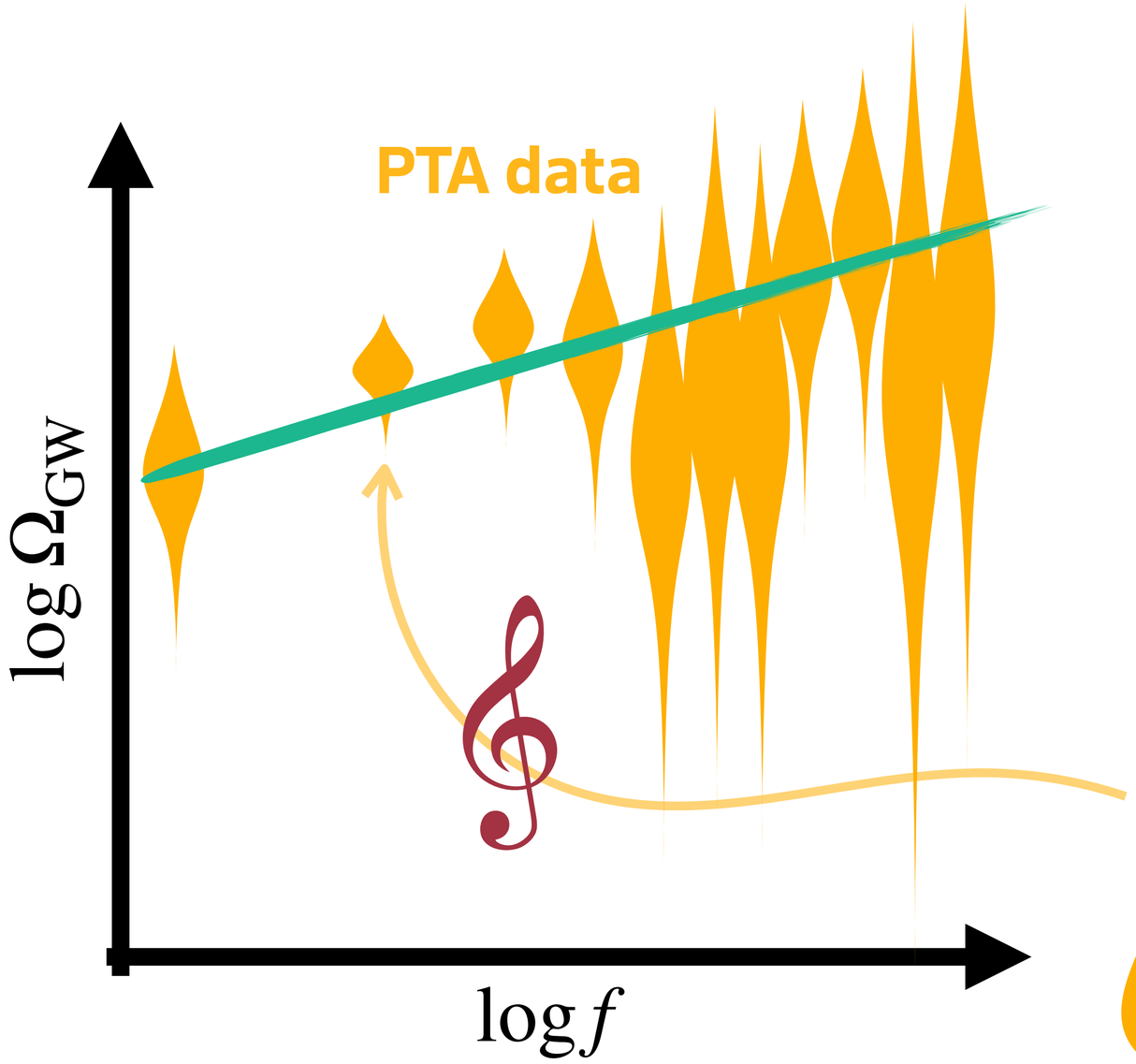
Next IPTA data release should reach 5σ GW detection!

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 of a given frequency.

Learning to play the violin



The inferred spectral shape of the GWB is well-described by a power law

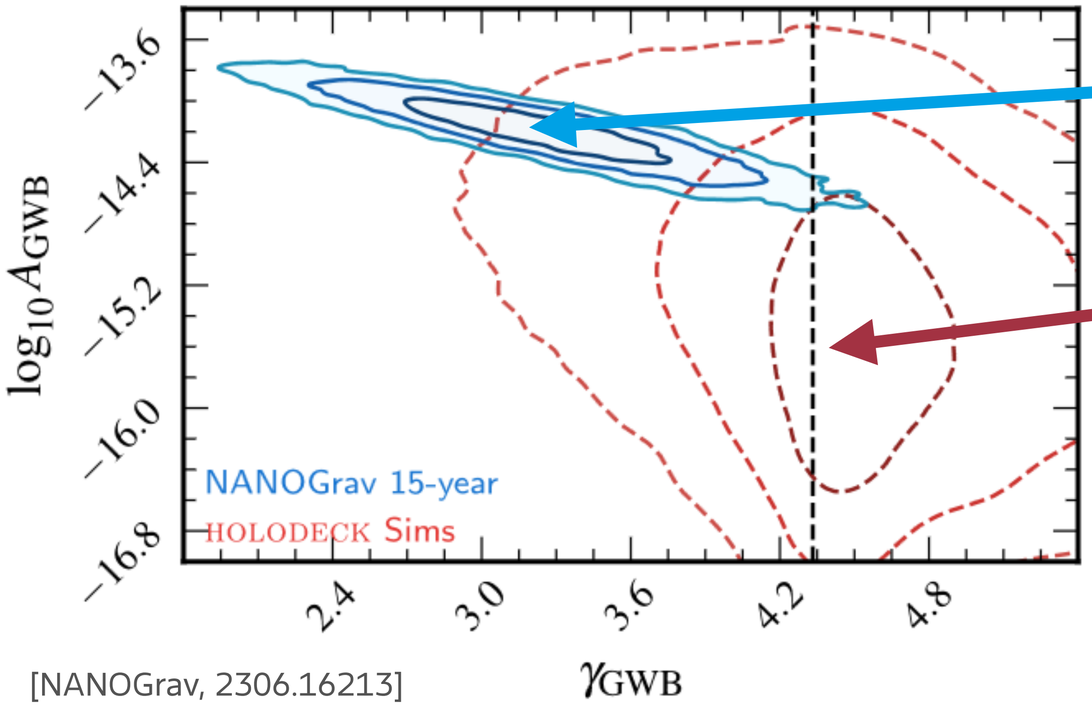
$$\Omega_{\rm GW}(f) = \frac{2\pi^2}{3H_0^2} A^2 \left(\frac{f}{1\,\mathrm{yr}^{-1}}\right)^{5-\gamma} \mathrm{yr}^{-2}$$

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

What is the source of the PTA signal?



Merging supermassive black holes

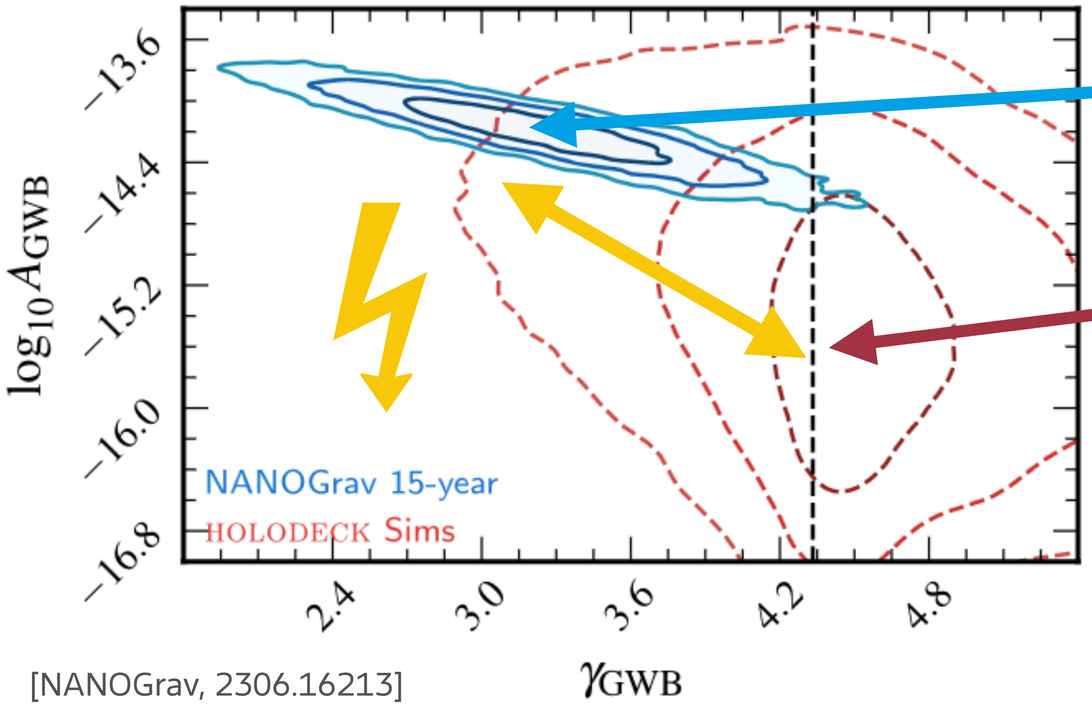


[NANOGrav, 2306.16213]

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)

Merging supermassive black holes



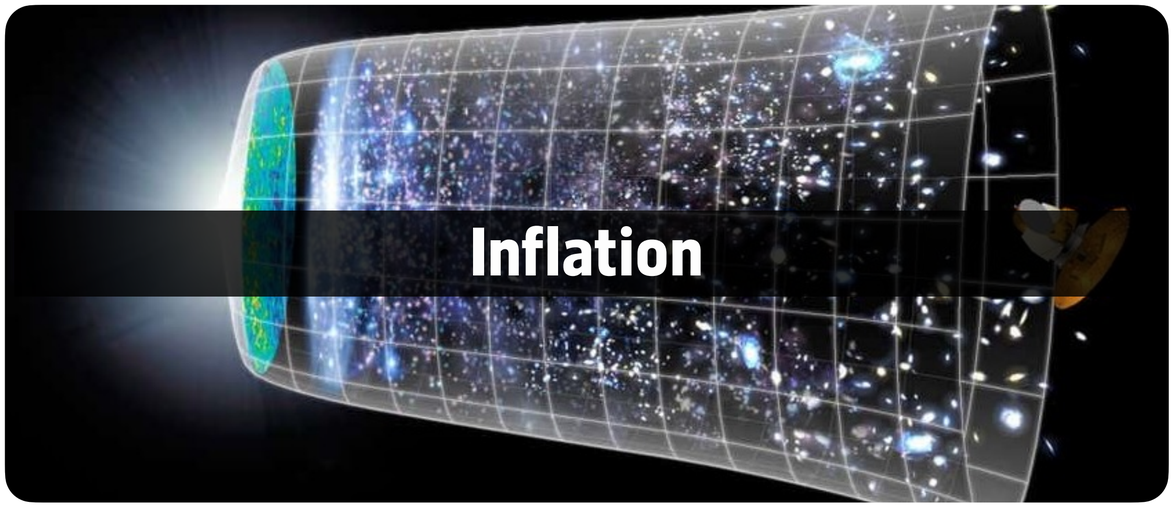
[NANOGrav, 2306.16213]

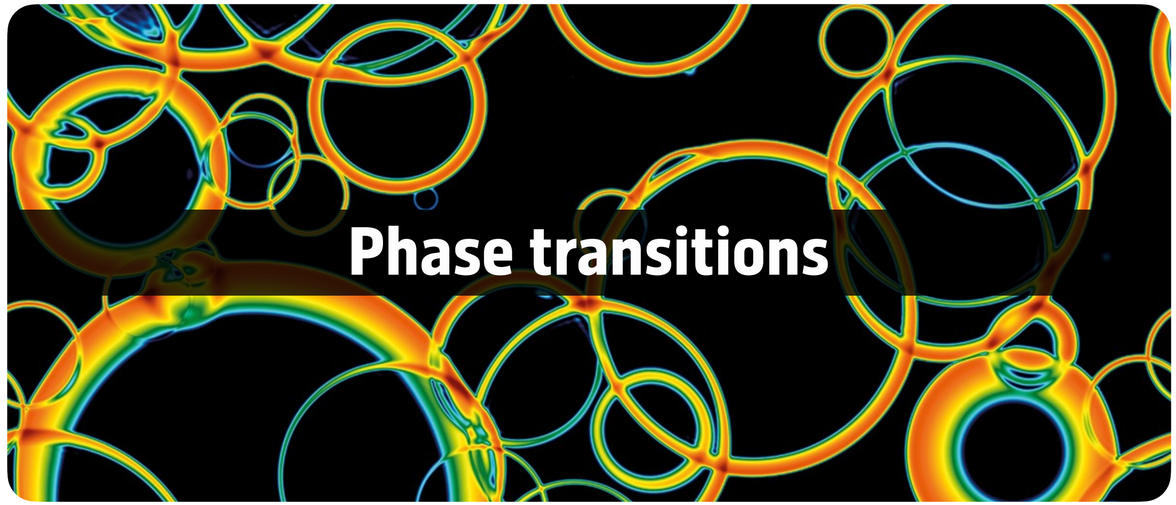
Observed signal follows a power-law spectrum with amplitude A and slope γ

Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ (more power in low frequencies)

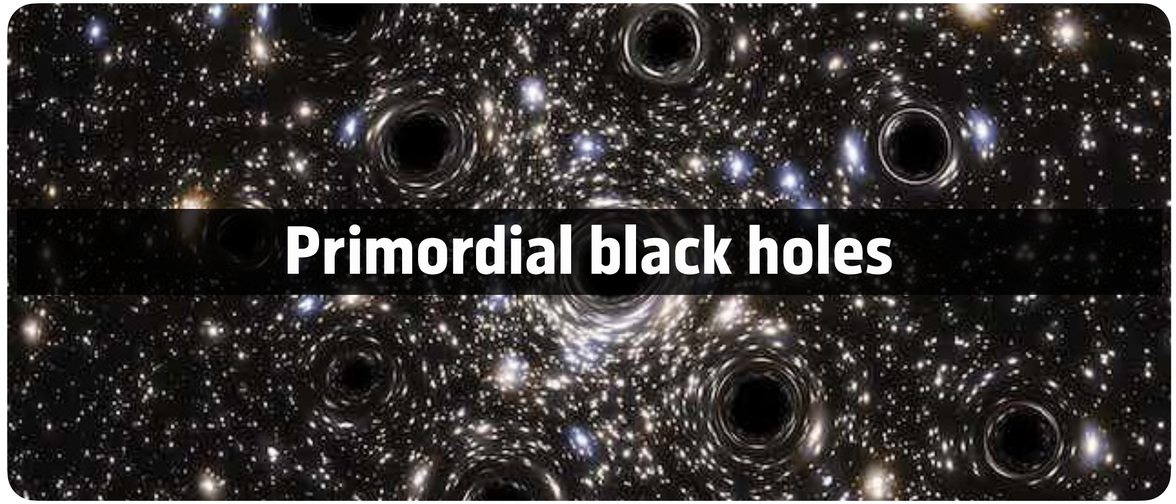
Are there other signal sources?

Possible cosmological sources of the PTA signal

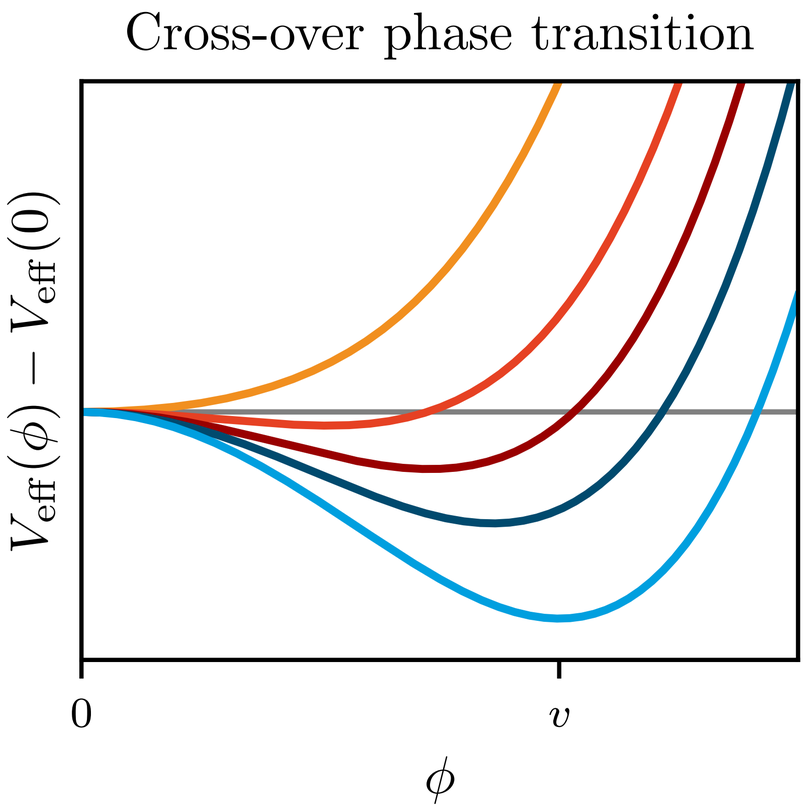




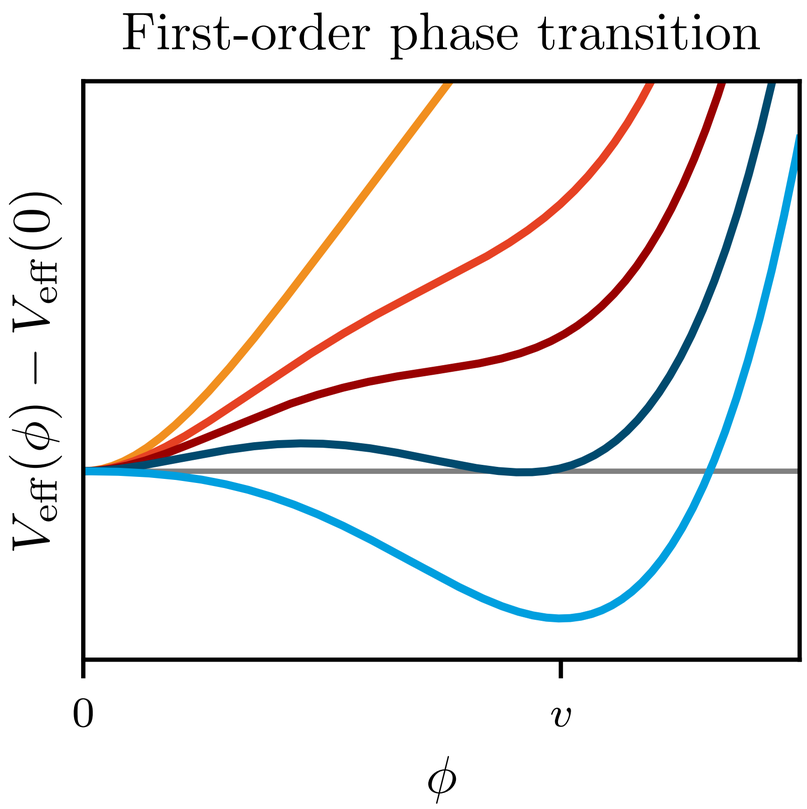




First-order phase transitions vs. cross-overs



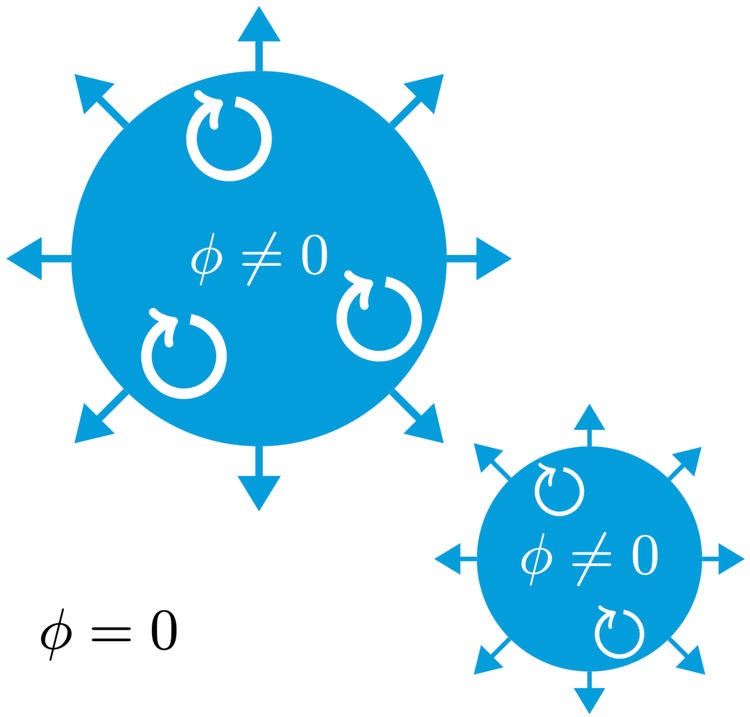
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

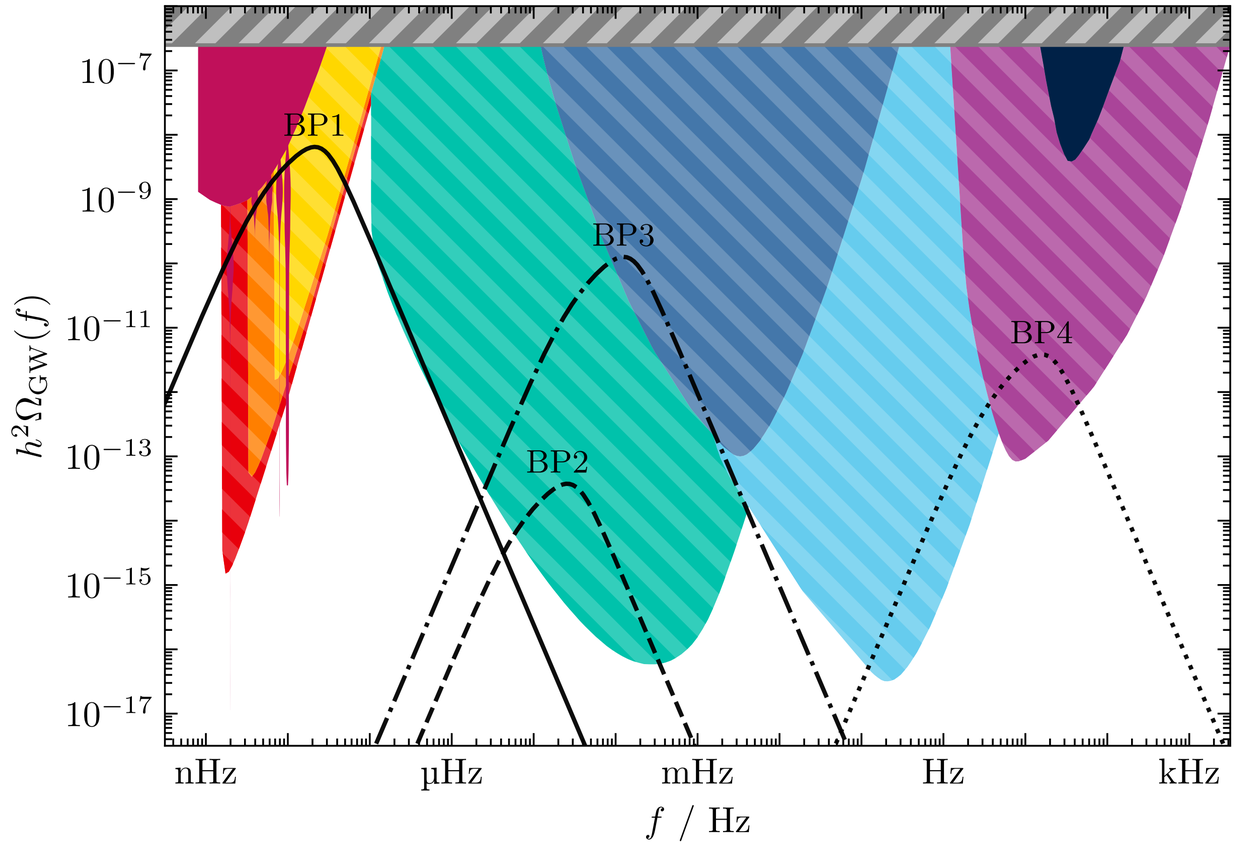


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy.

First-order phase transitions produce GWs

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



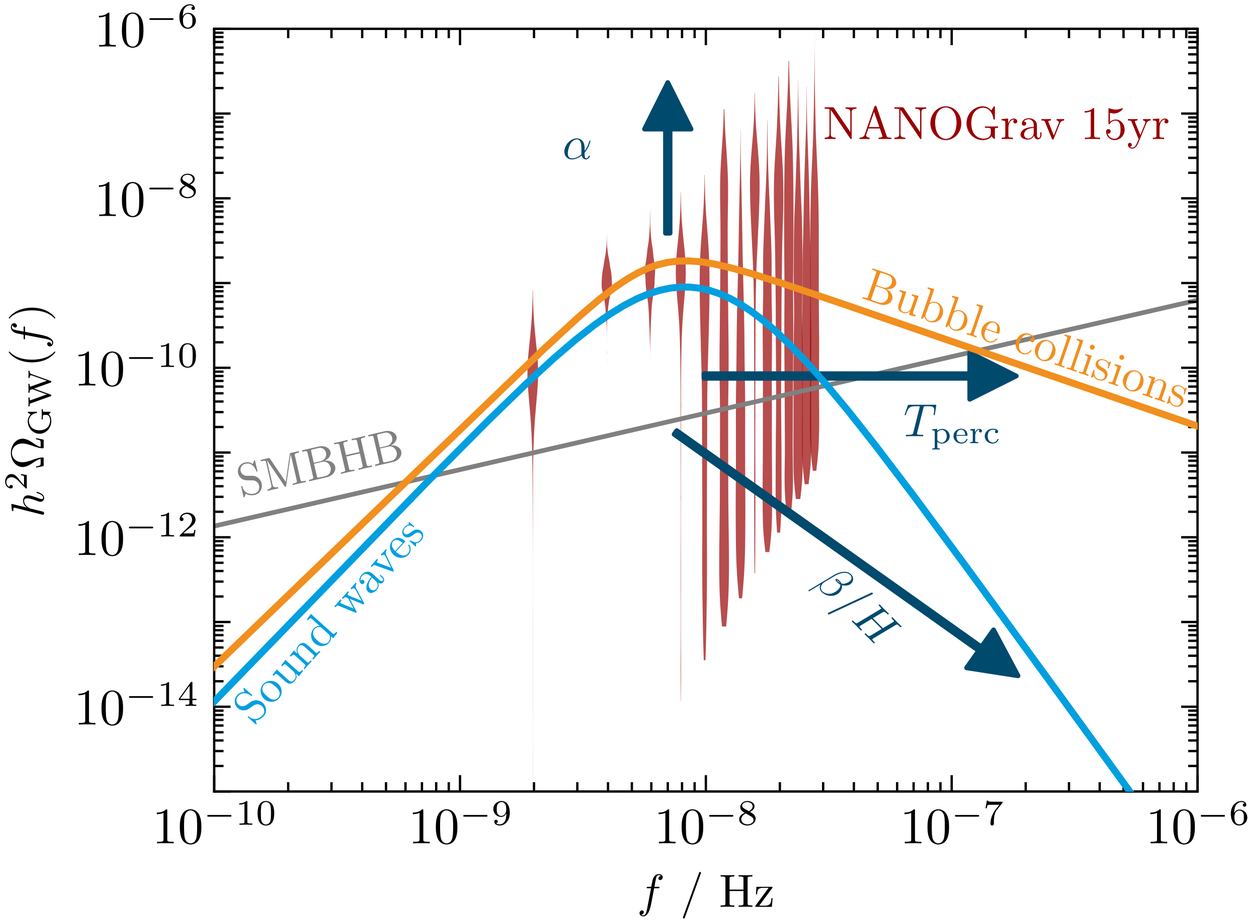






… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

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

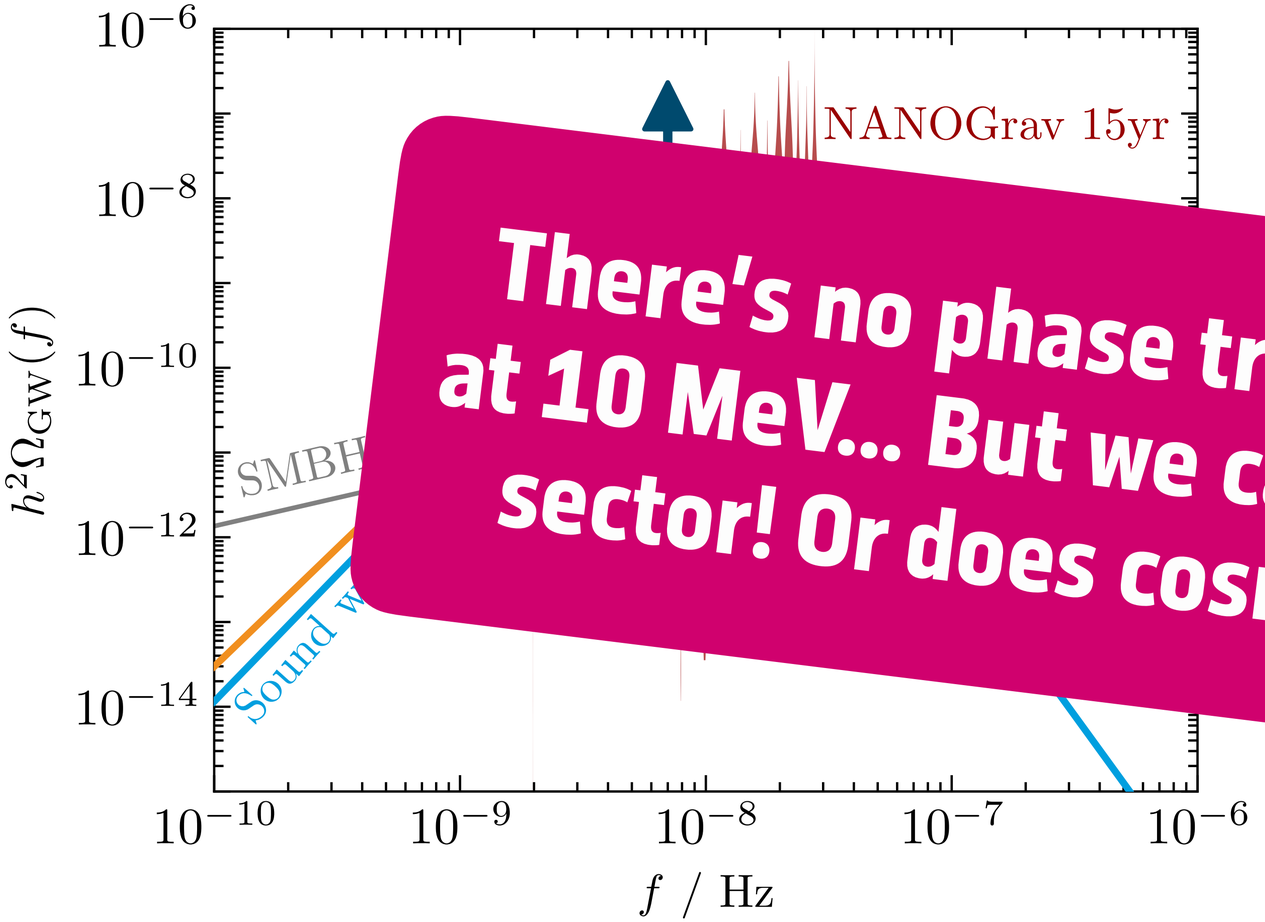
with $\quad f_{\rm peak} \simeq 0.1\,{\rm nHz} \times \frac{\beta}{H} \times \frac{T}{\rm MeV}$

To fit the new pulsar timing data:

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

NB: The actual signal prediction is a more complicated function. This is just to give an intuition.

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

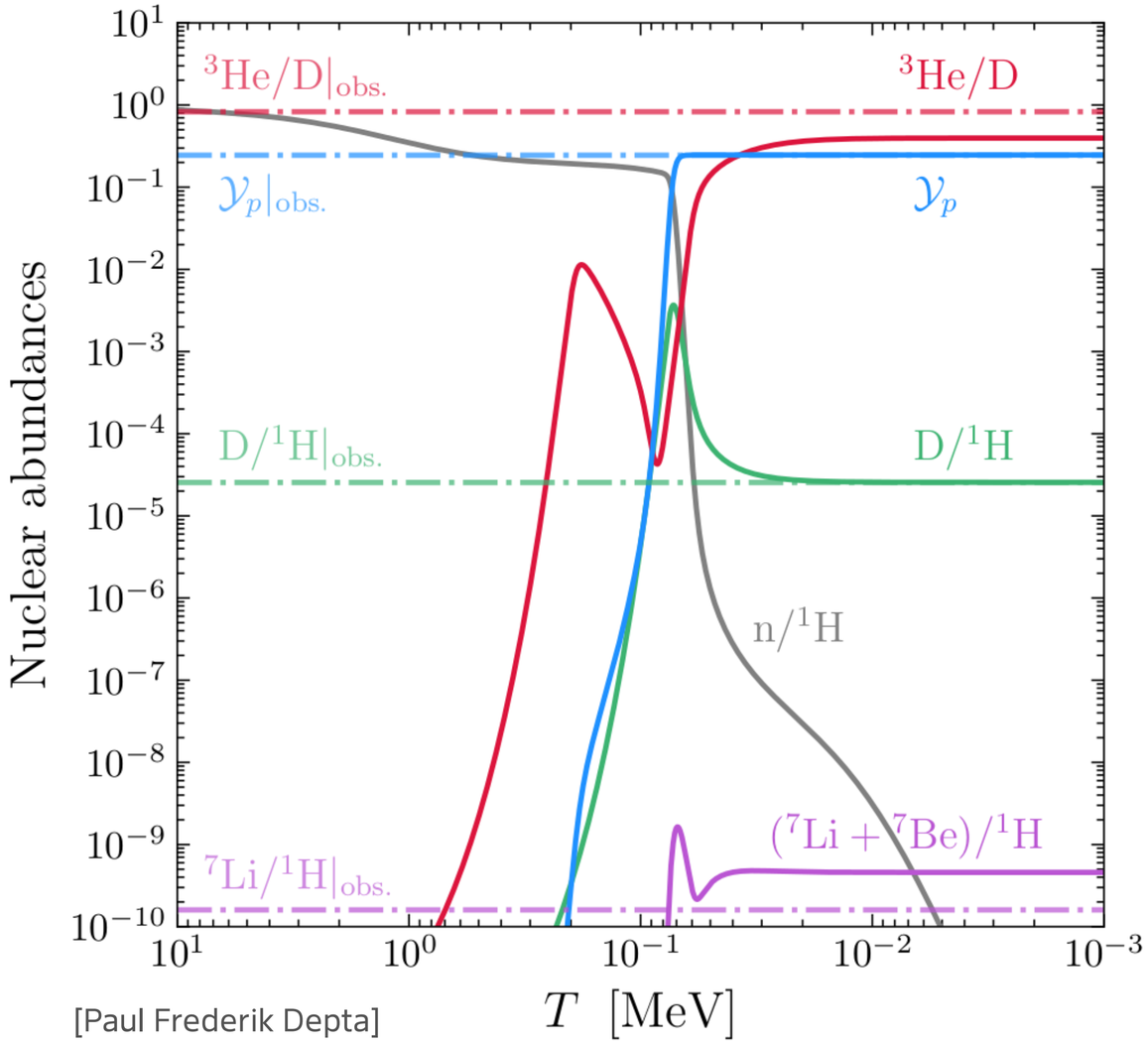
There's no phase transition in the SM at 10 MeV... But we can have it in a dark sector! Or does cosmology forbid it?

data:

- $\lesssim 1$
- ≈ 10
- Percolation around $T \approx 10\,{\rm MeV}$

NB: The actual signal prediction is a more complicated function. This is just to give an intuition.

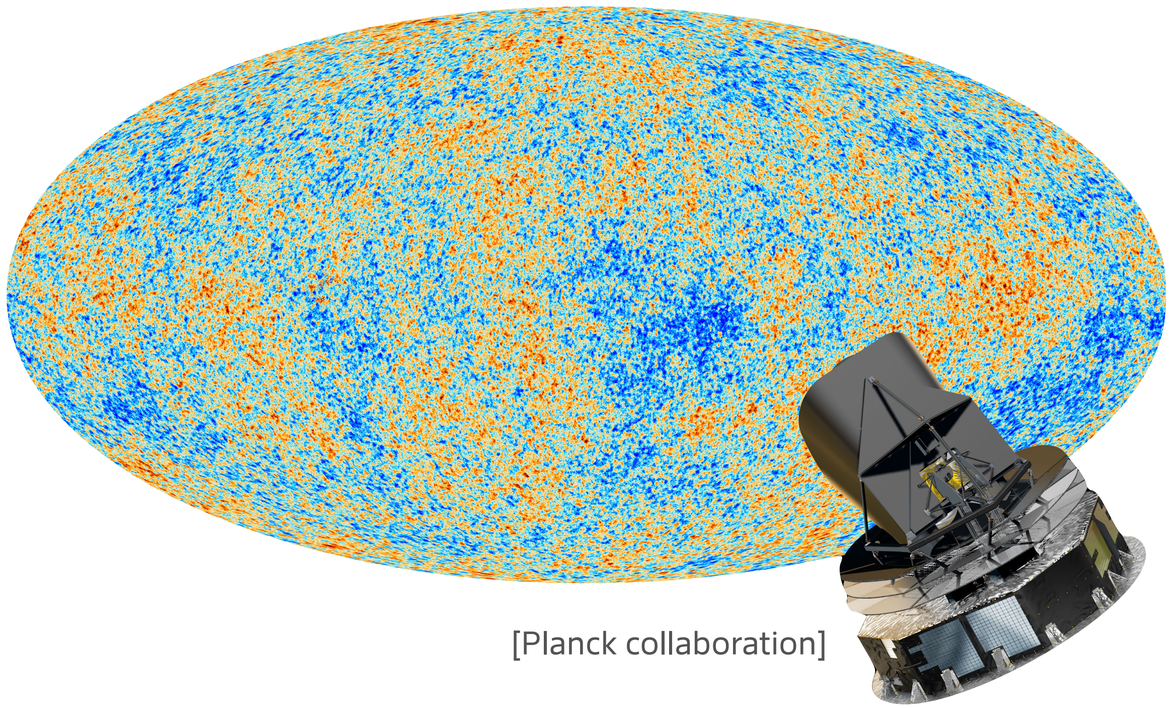
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

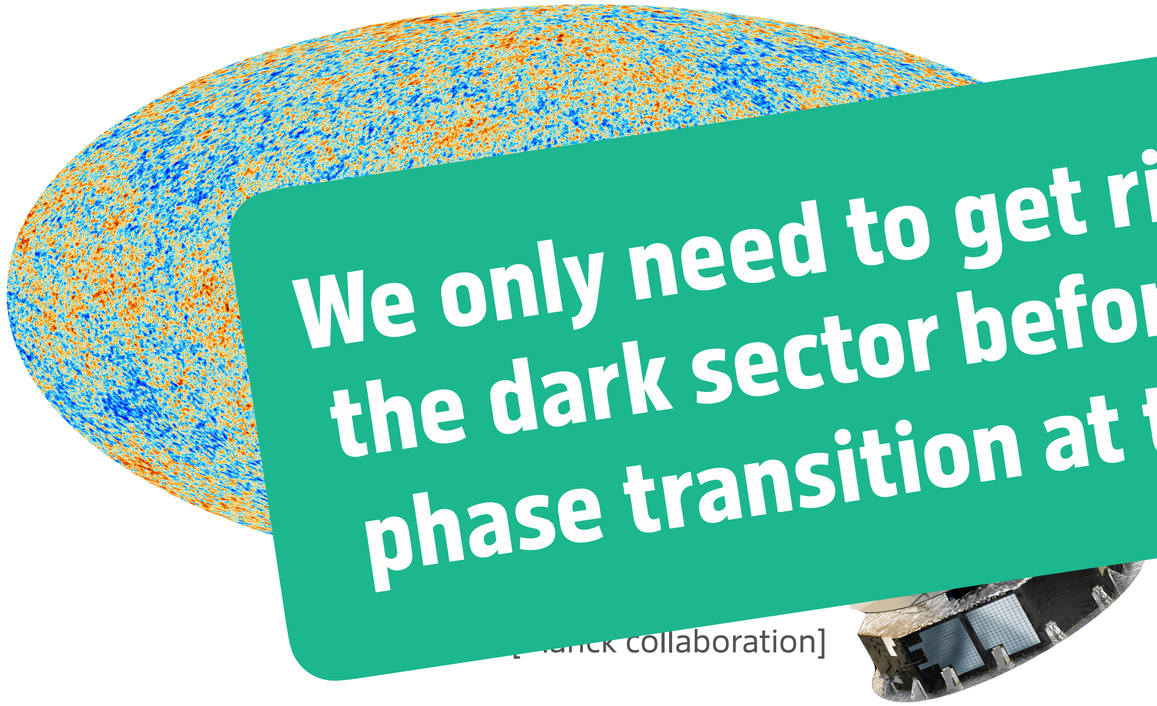
Big Bang Nucleosynthesis and the CMB



[Planck collaboration]

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

Big Bang Nucleosynthesis and the CMB



[Planck collaboration]

We only need to get rid of extra energy in the dark sector before BBN to allow for a phase transition at the 10 MeV scale 😊

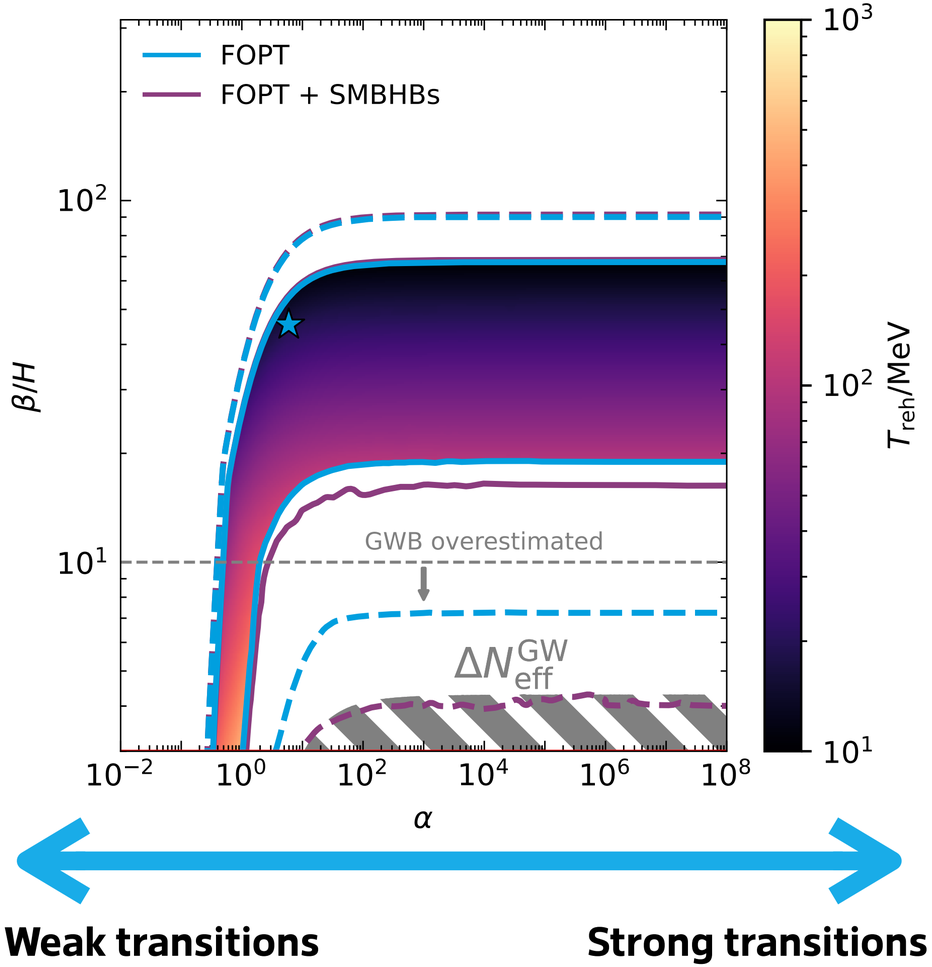
- Observation of primordial abundances in
- $N_{\rm eff} = 2.99 \pm 0.17$
- Consistent with 3 SM neutrinos

Which phase transitions can fit the PTA data?

Many small bubbles

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

Few big bubbles



Weak transitions — **Strong transitions**

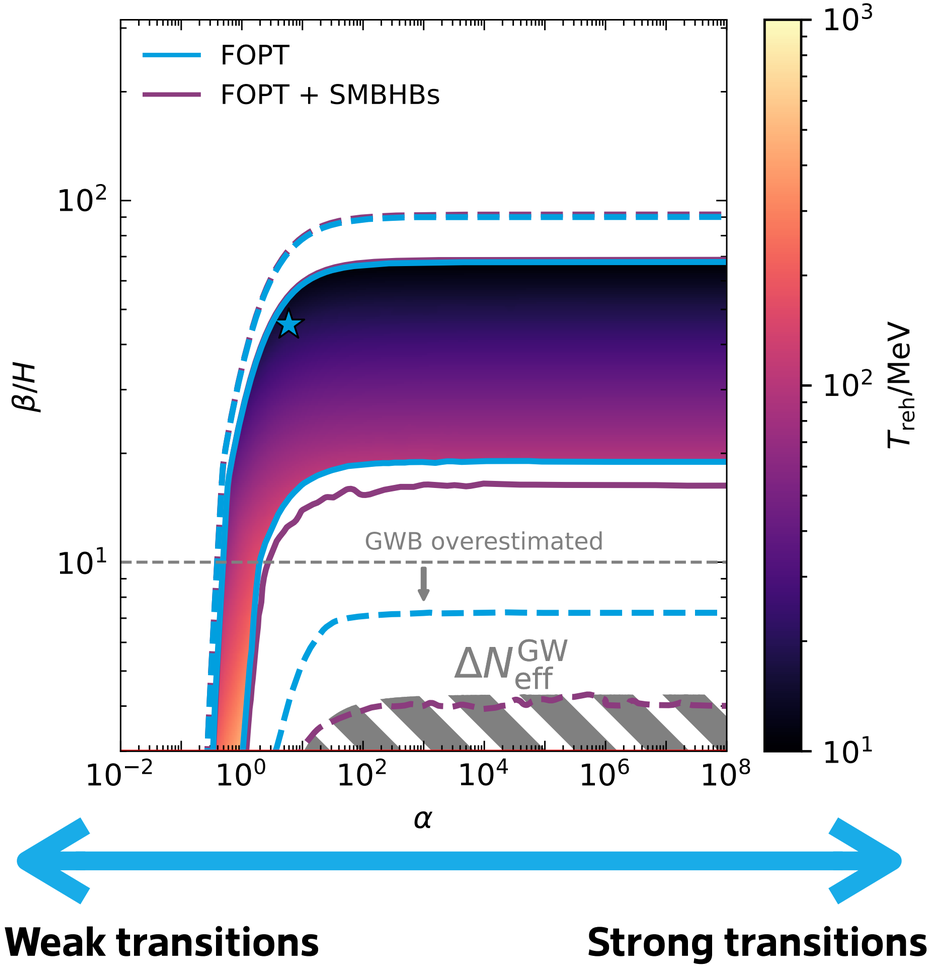
PTA data requires very strong transitions with extremely large bubbles!

Which phase transitions can fit the PTA data?

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…

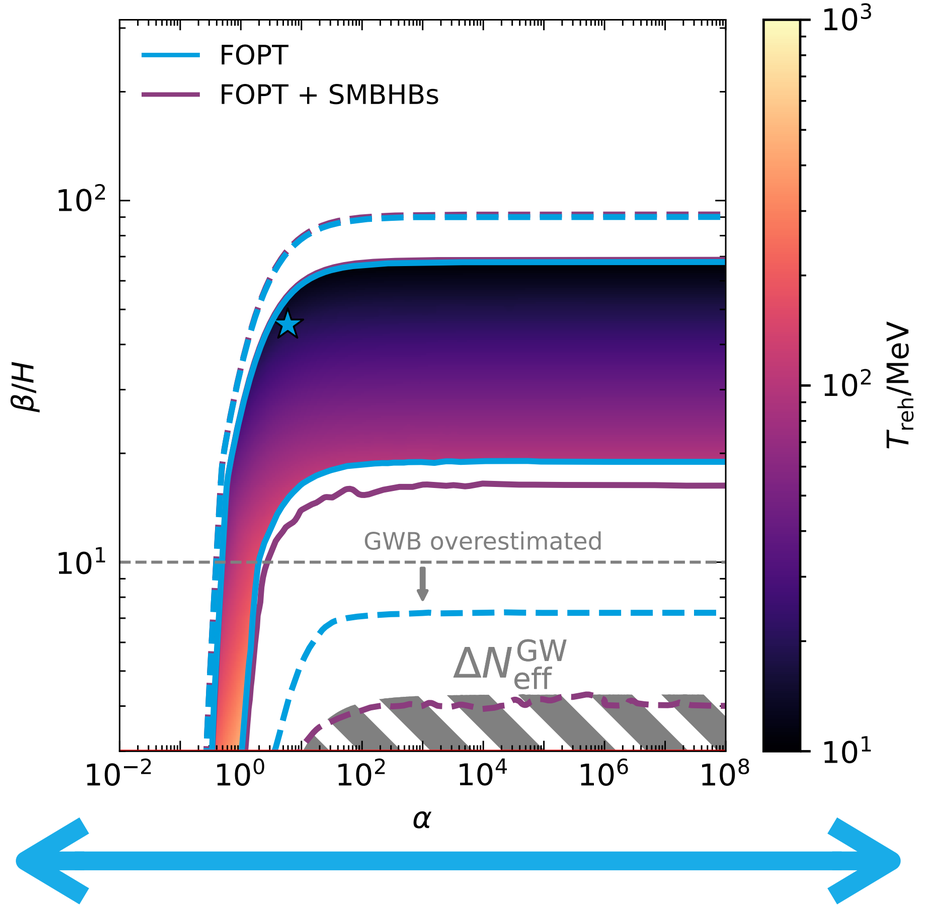
Robust predictions of the GW signal in that regime are difficult…

Which phase transitions can fit the PTA data?

Many small bubbles

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

Few big bubbles



Weak transitions — Strong transitions

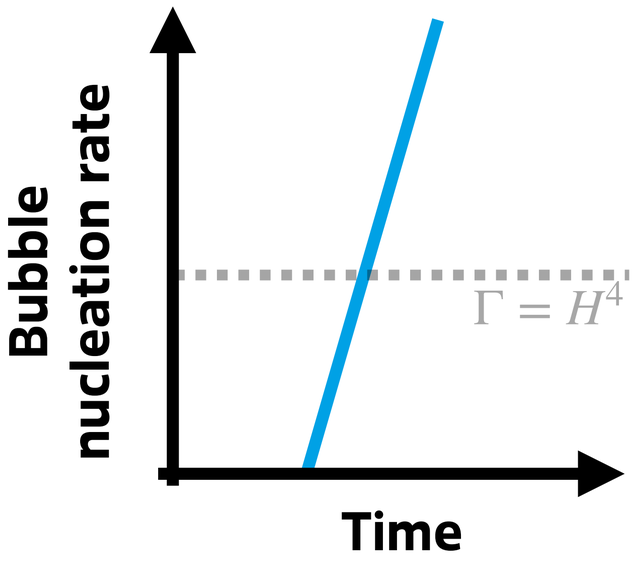
PTA data requires very strong transitions with extremely large bubbles!

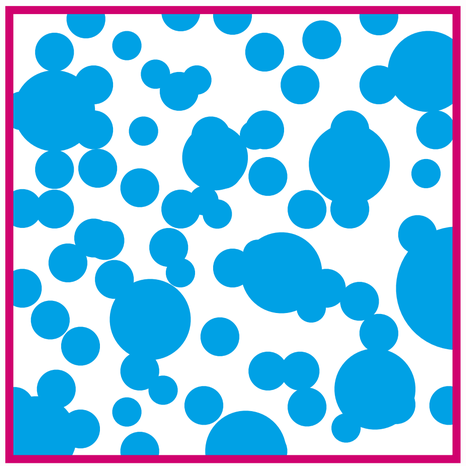
Let's start with this problem

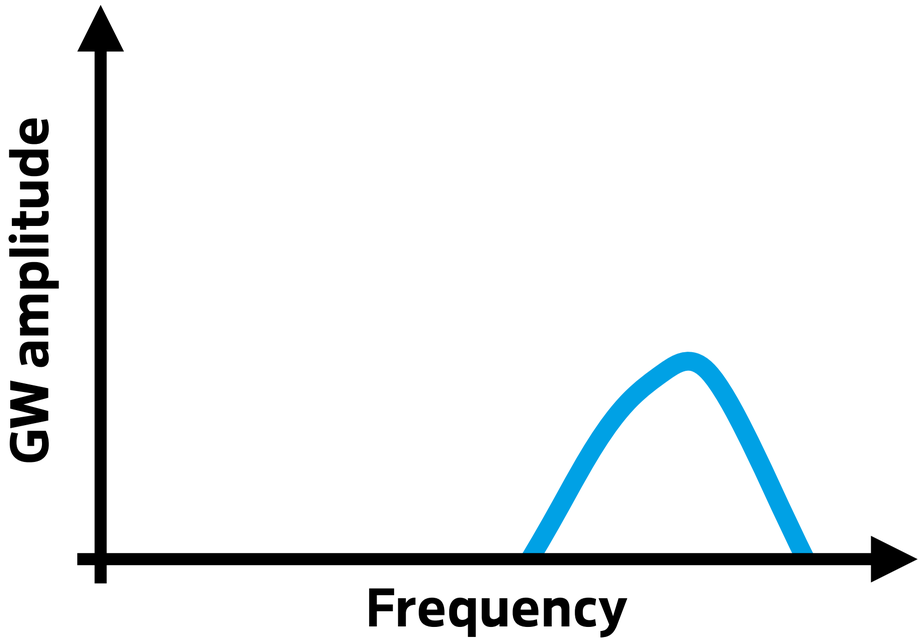
BSM models typically predict weak transitions with small bubbles...

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

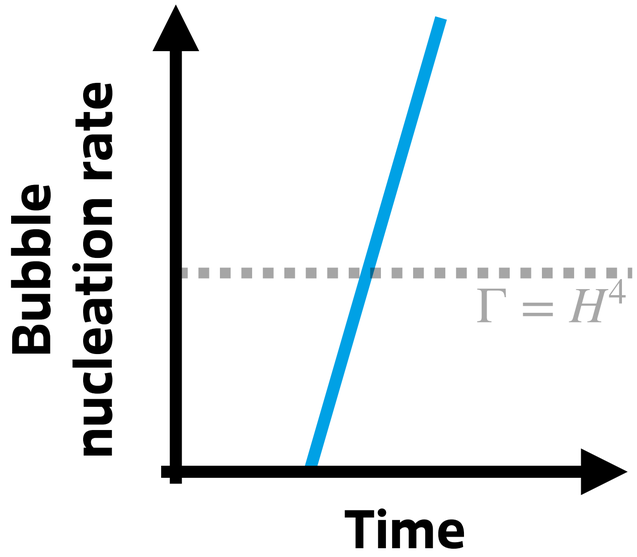
Why is it so difficult to get big bubbles?

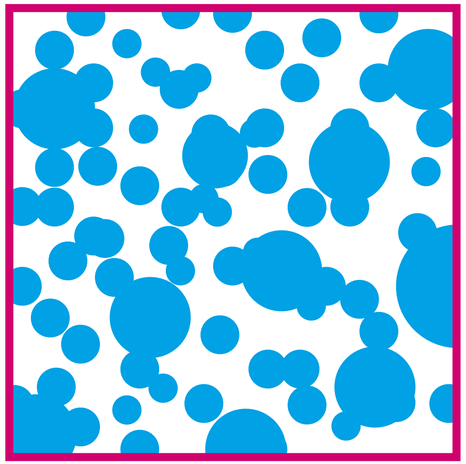


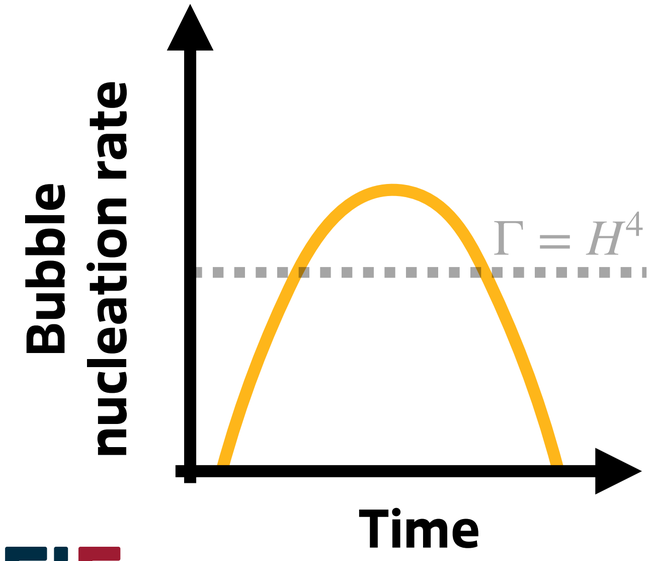


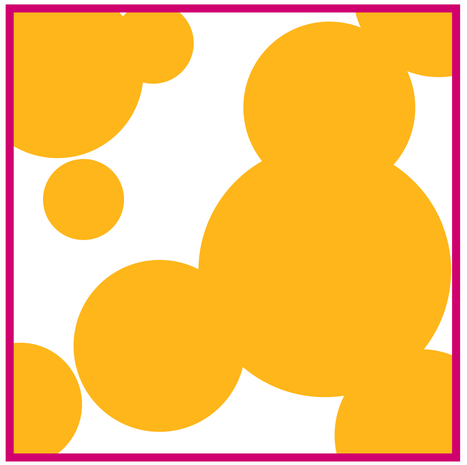


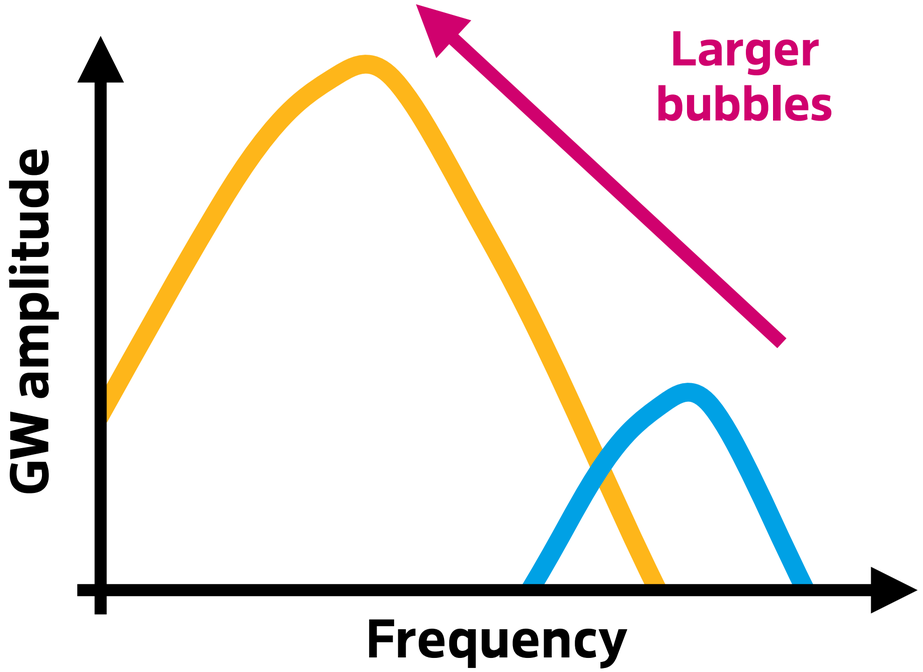
Why is it so difficult to get big bubbles?









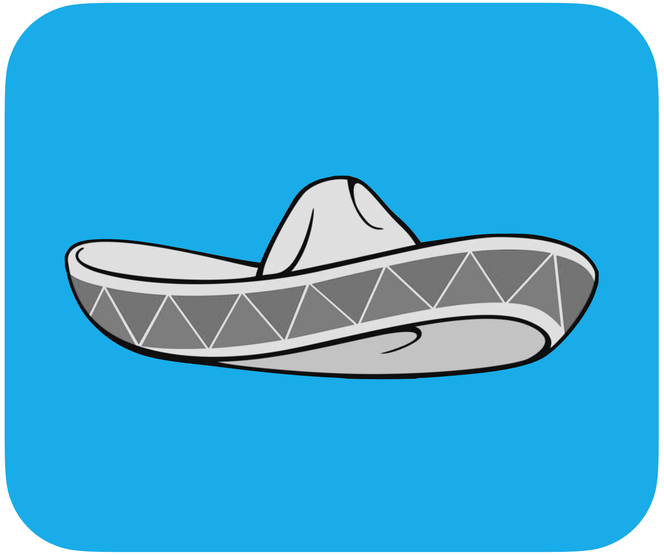


$$\Gamma \propto e^{\beta t - \gamma t^2}$$

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

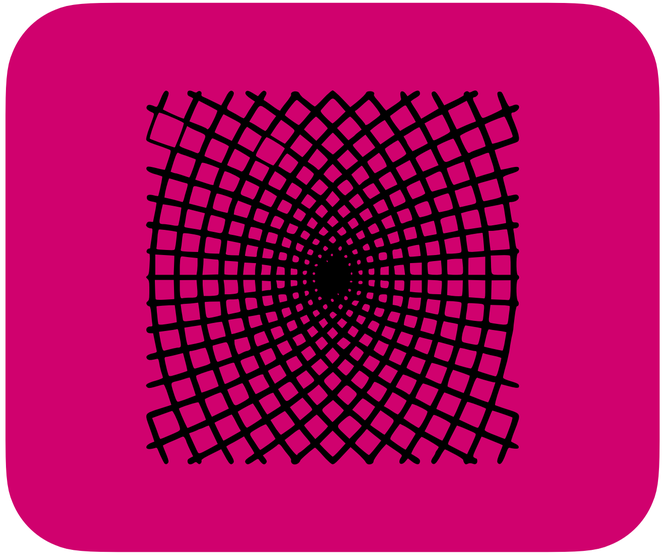
Abelian dark Higgs



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

Thermally induced barrier

Conformal dark Higgs



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

Loop-induced barrier

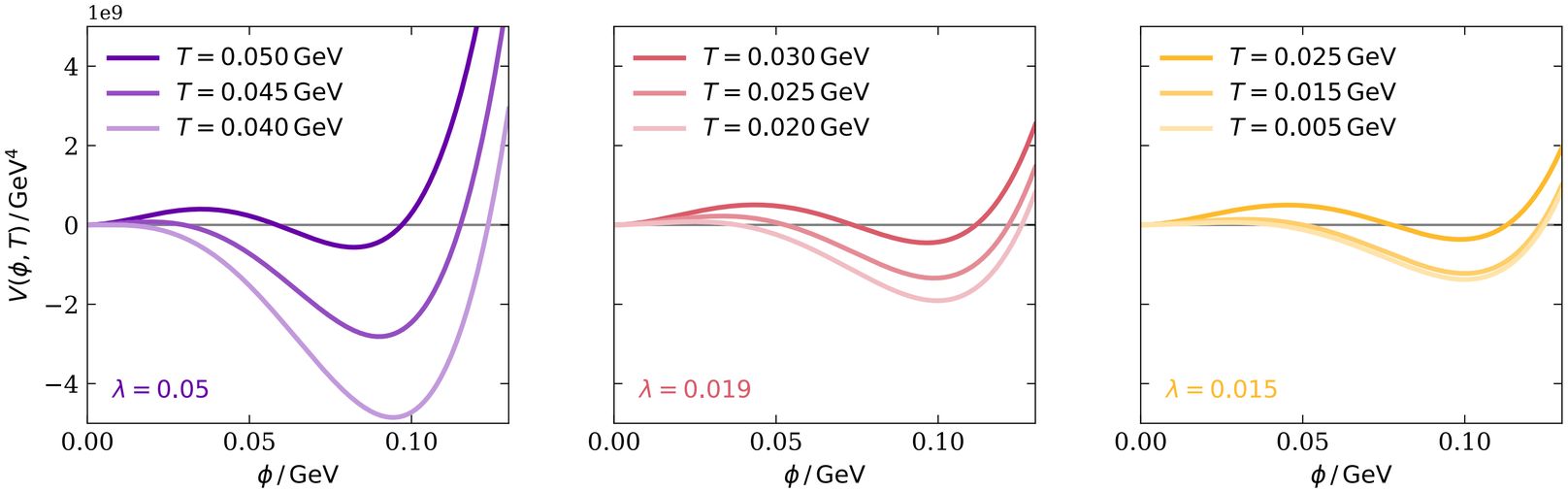
Dark flipflop



$$V(\phi_1, \phi_2)$$

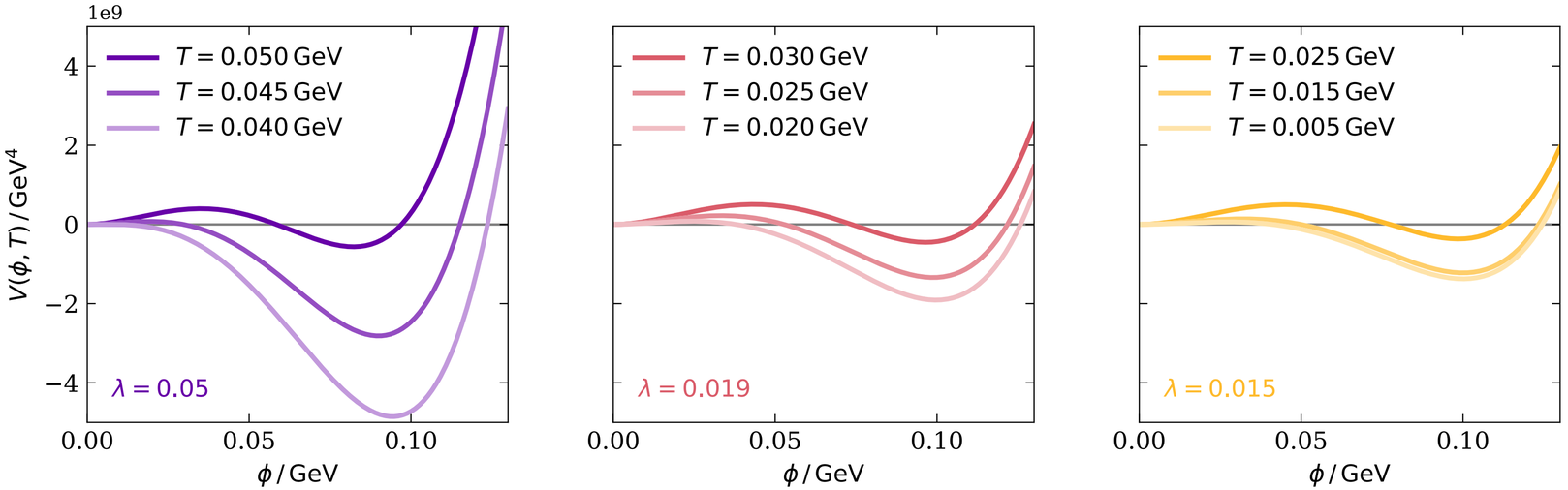
Transition-induced barrier

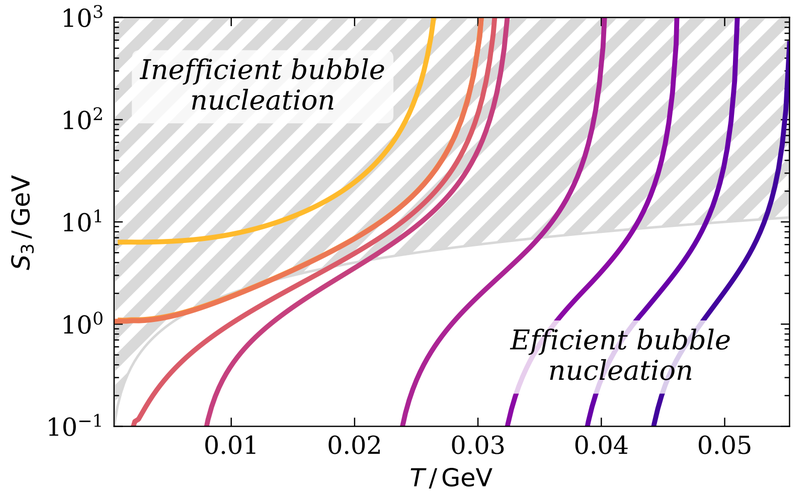
Large bubbles in the Abelian dark Higgs model



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

Large bubbles in the Abelian dark Higgs model



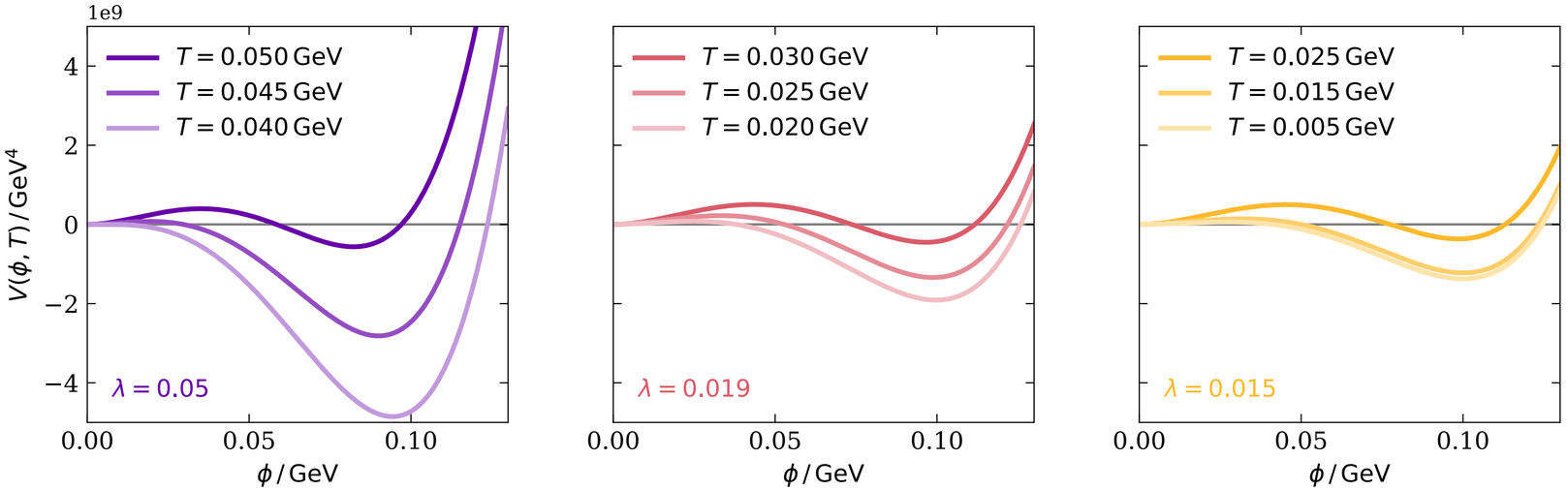


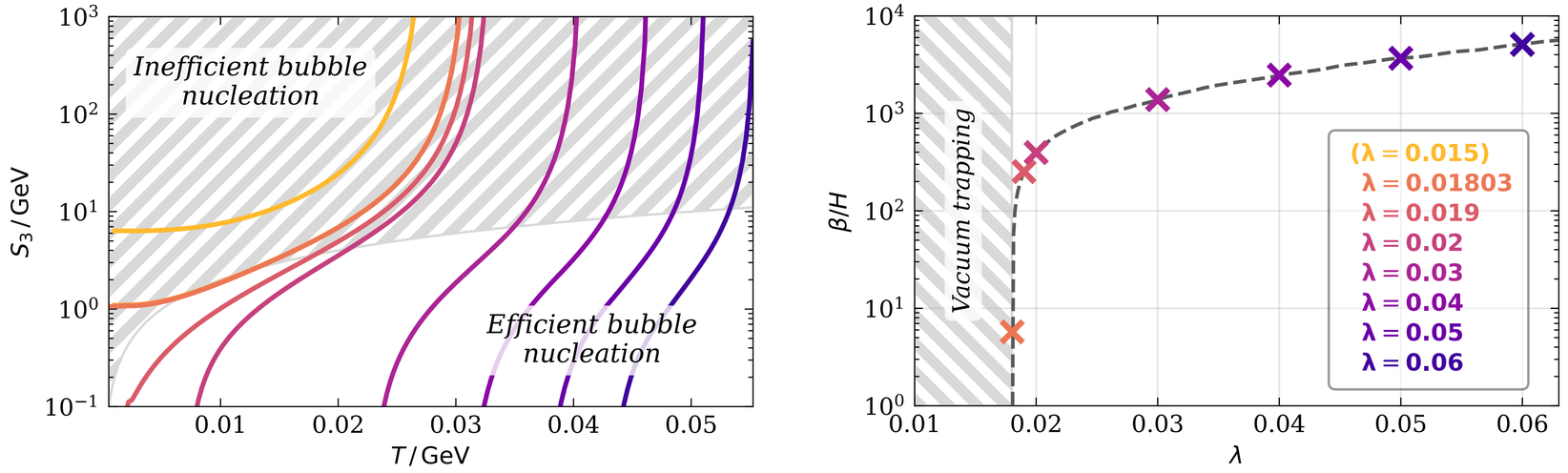
The transition rate is exponentially dependent on the bounce action

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

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

Large bubbles in the Abelian dark Higgs model





The transition rate is exponentially dependent on the bounce action

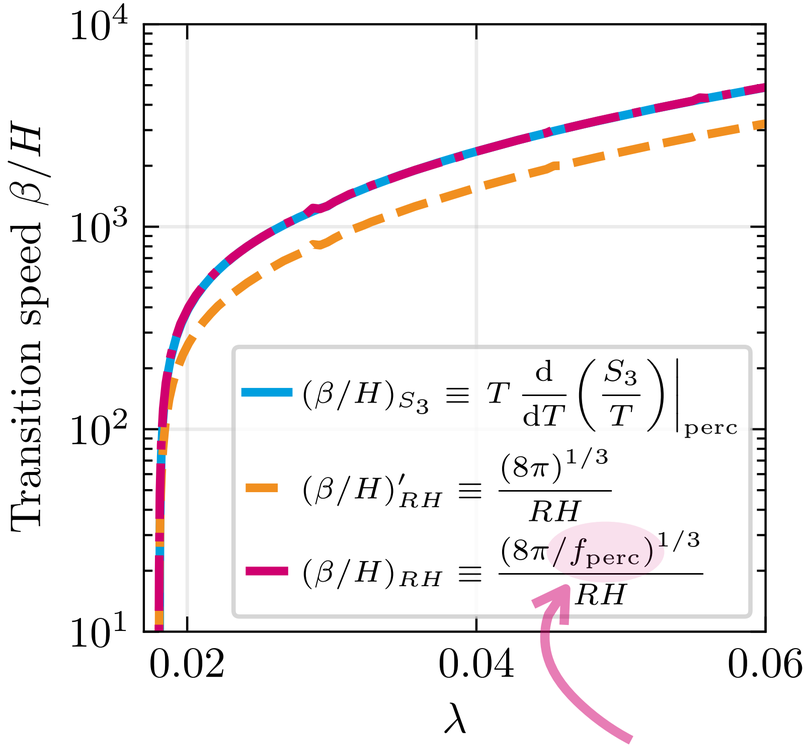
$$\Gamma \propto e^{-S_3/T}$$

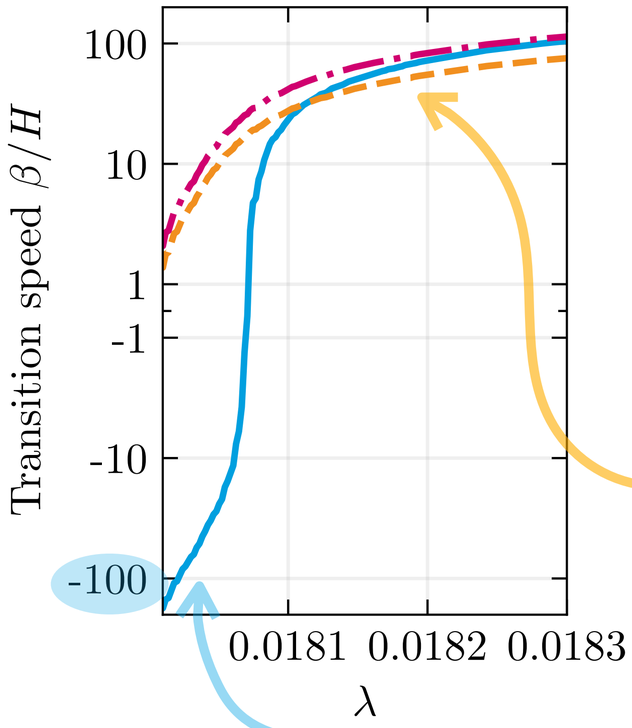
Only for fine-tuned quartic couplings λ, large bubbles can be achieved! Generically,

$$\beta/H > 10^3.$$

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

A comment on β/H and RH





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.

The common relation

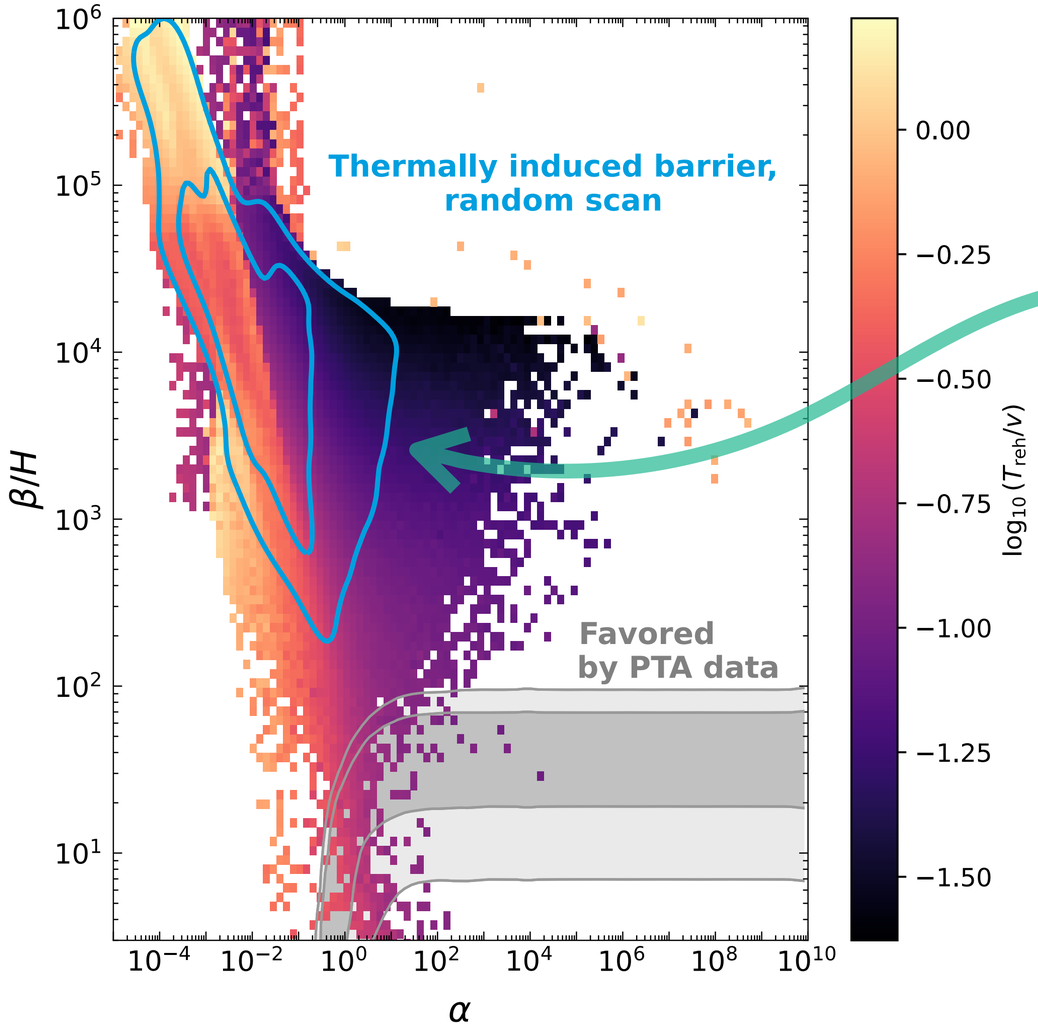
$$\beta/H = (8\pi)^{1/3}/RH$$

(used in LISA pipeline, Athron review, ...)

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

[Derivation: See appendix of 2605.15259]

Generic model predictions for the Abelian dark Higgs



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

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

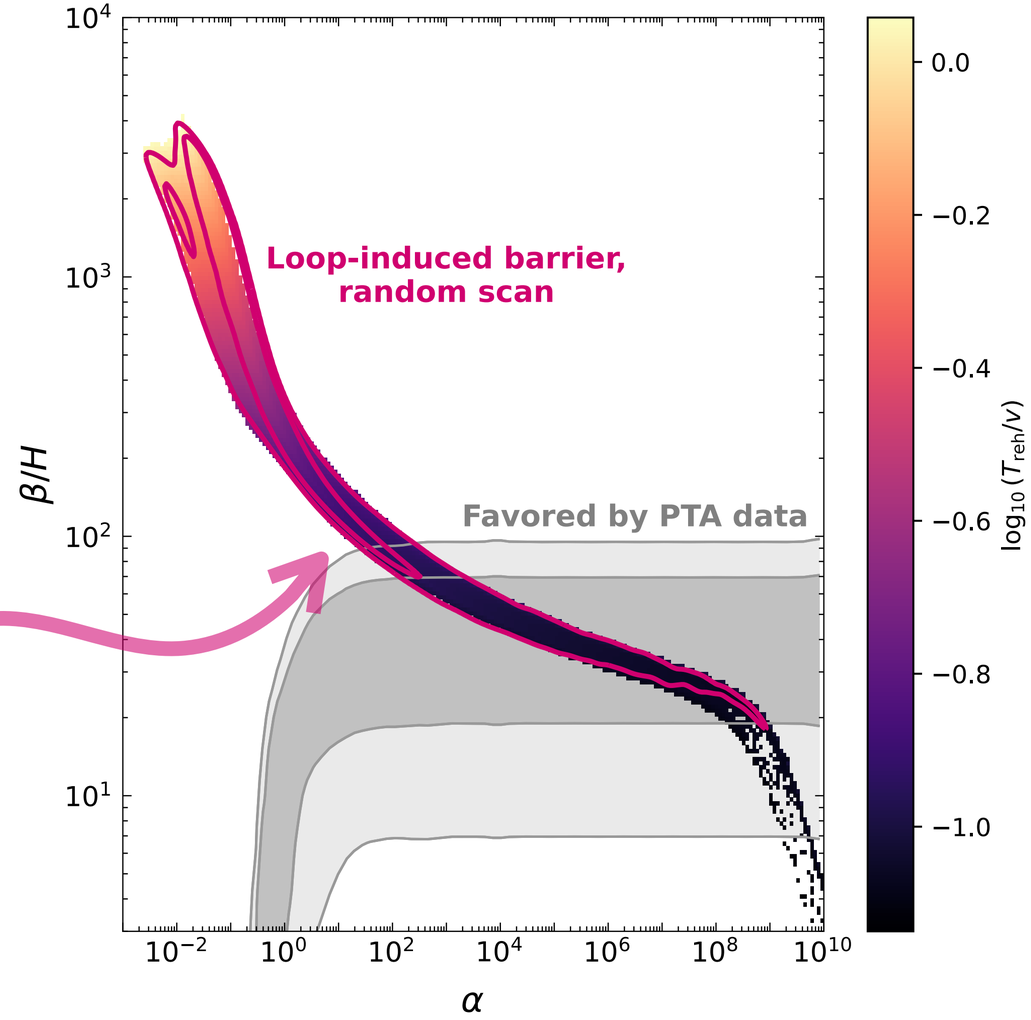
* based on a random scan with flat priors

Generic predictions in the conformal dark Higgs model

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

Ensure conformality at scale $\Lambda = v$ in renormalization:
V_{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



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

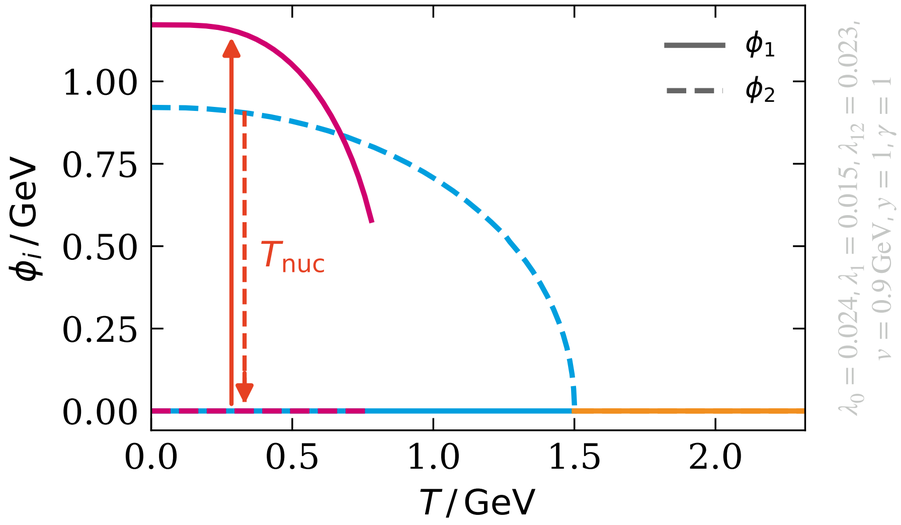
The dark flipflop

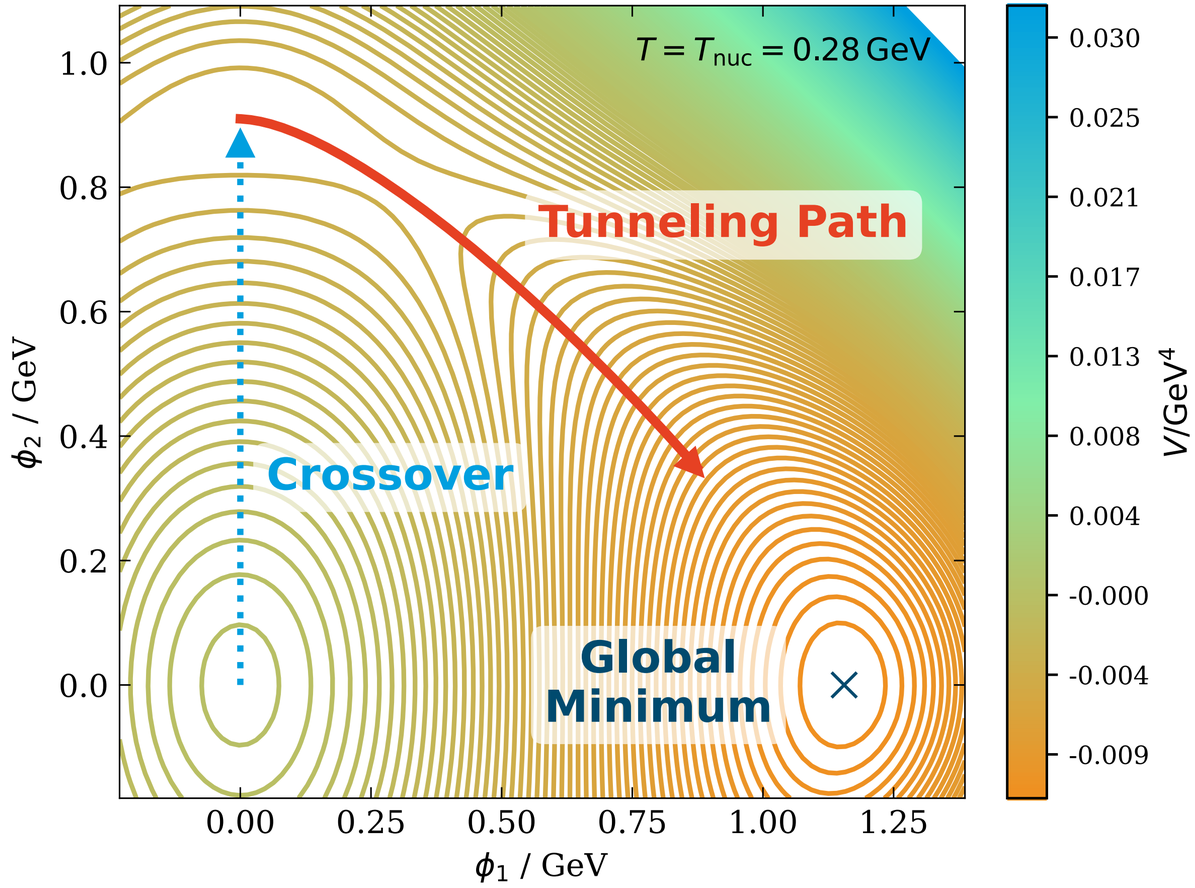


Setup: Two real scalars with a potential

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

and a fermion that only couples to ϕ_1



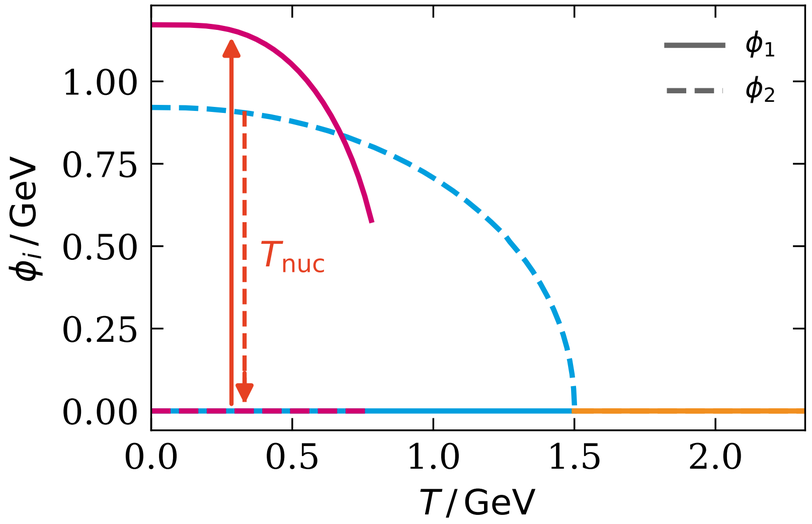


The dark flipflop

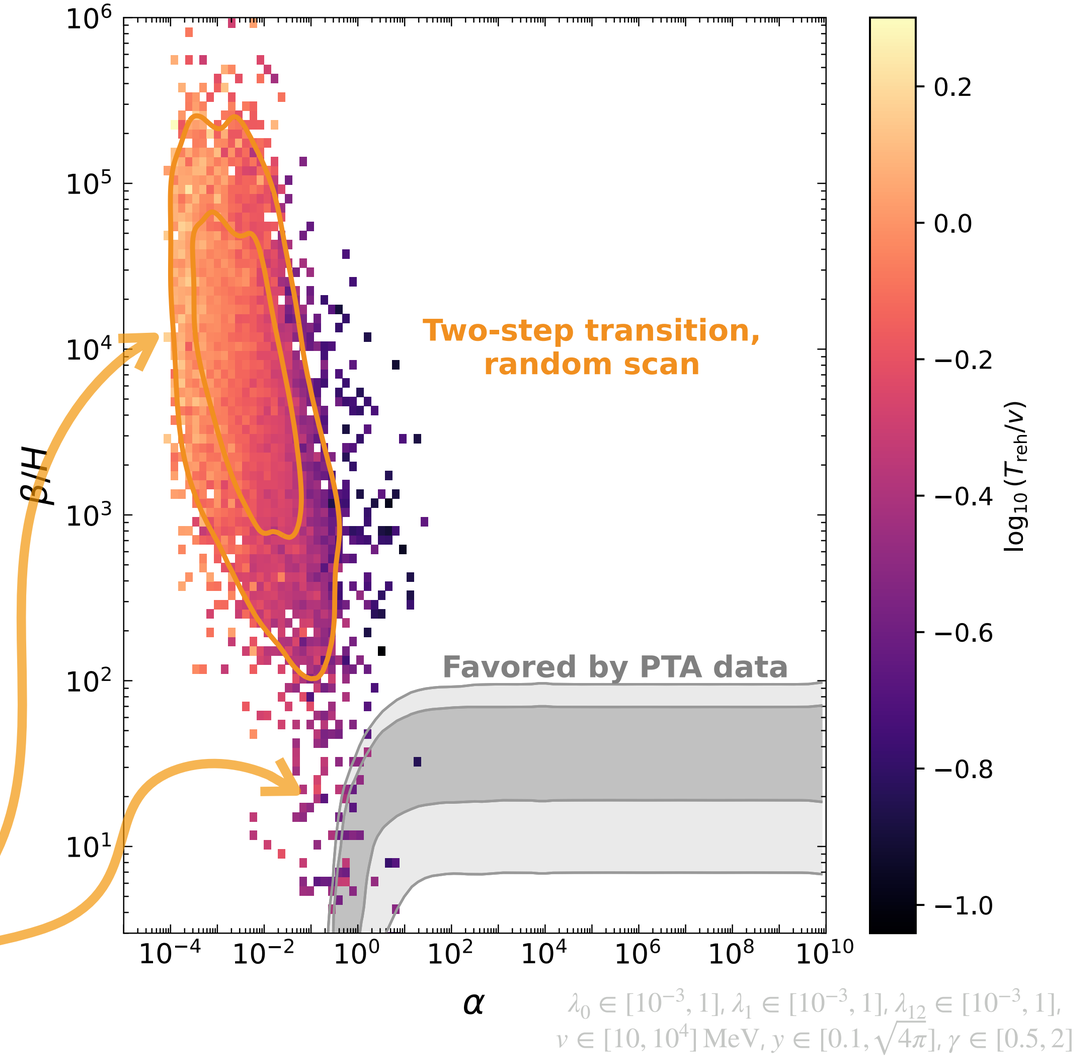
Setup: Two real scalars with a potential

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

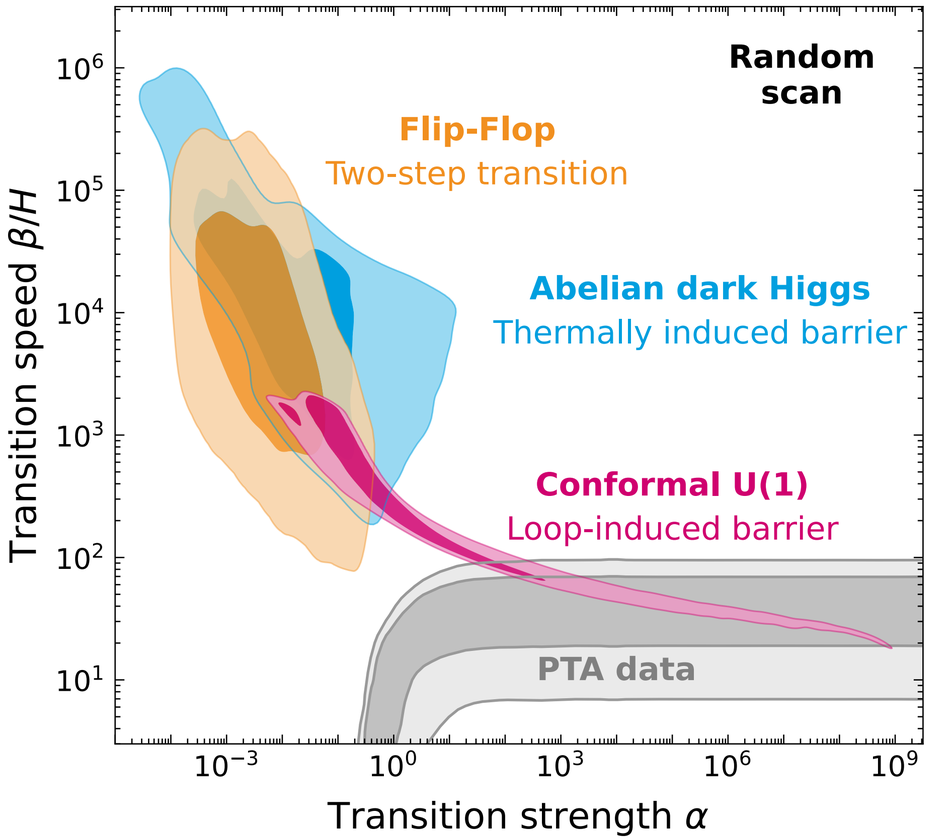
and a fermion that only couples to ϕ_1

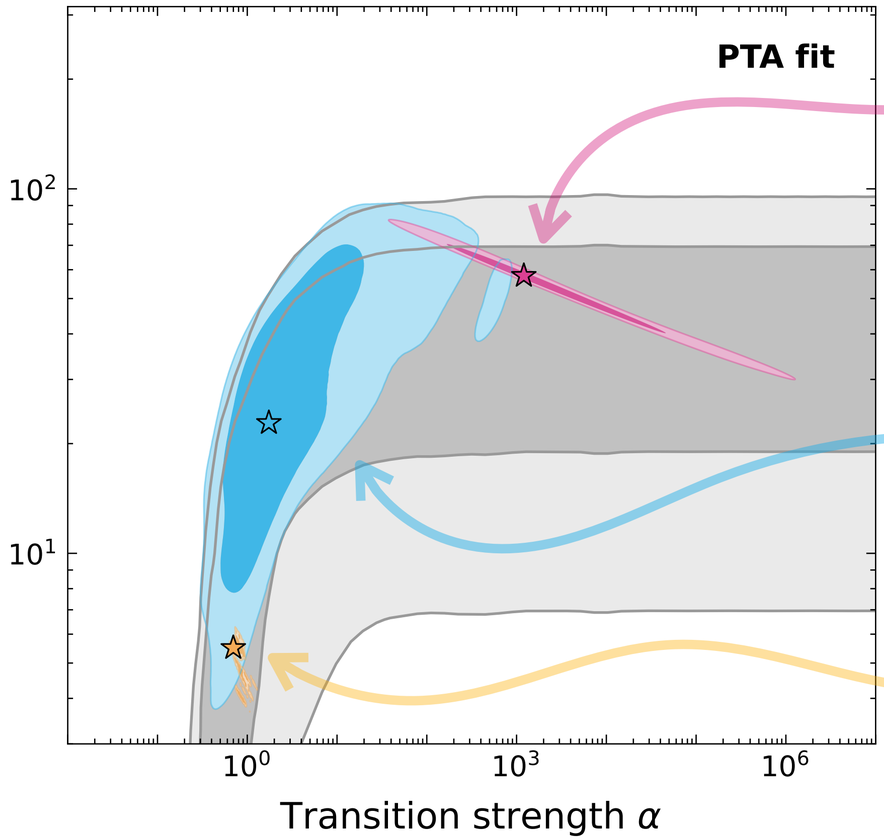


Generally, the bubbles are far too small, but for specific parameter choices, the PTA region can be reached



So... which model explains the PTA data best?





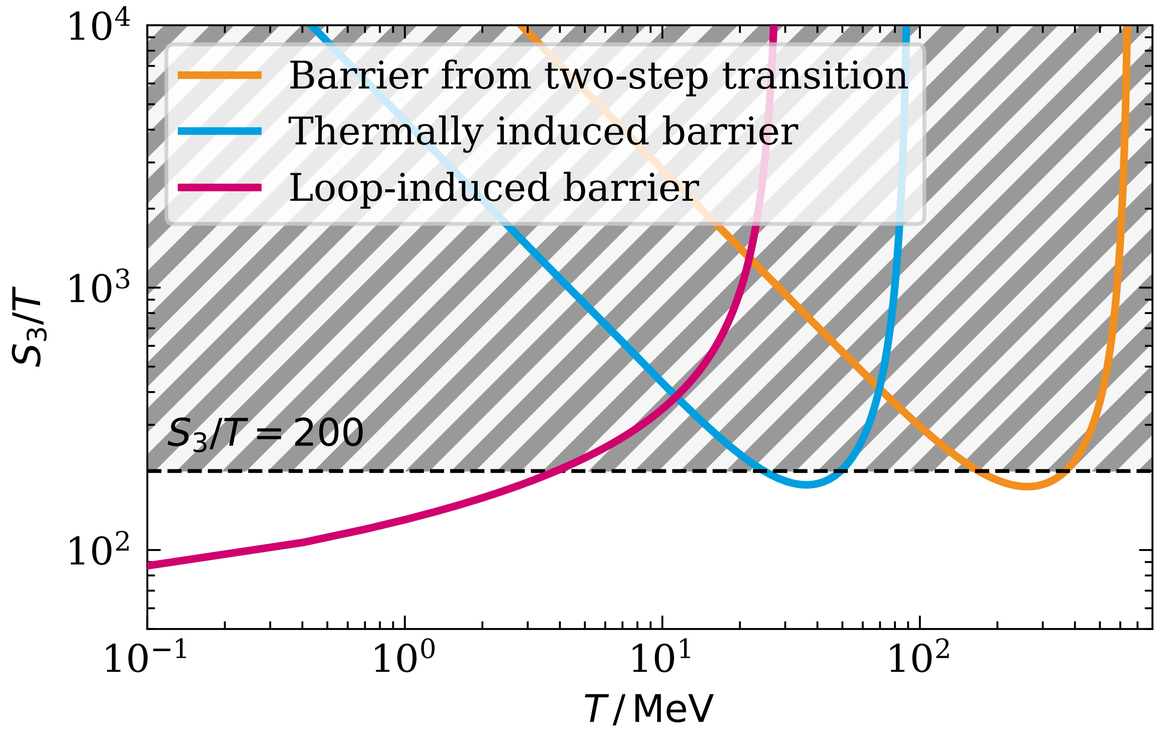
Required tuning:
one significant digit in g

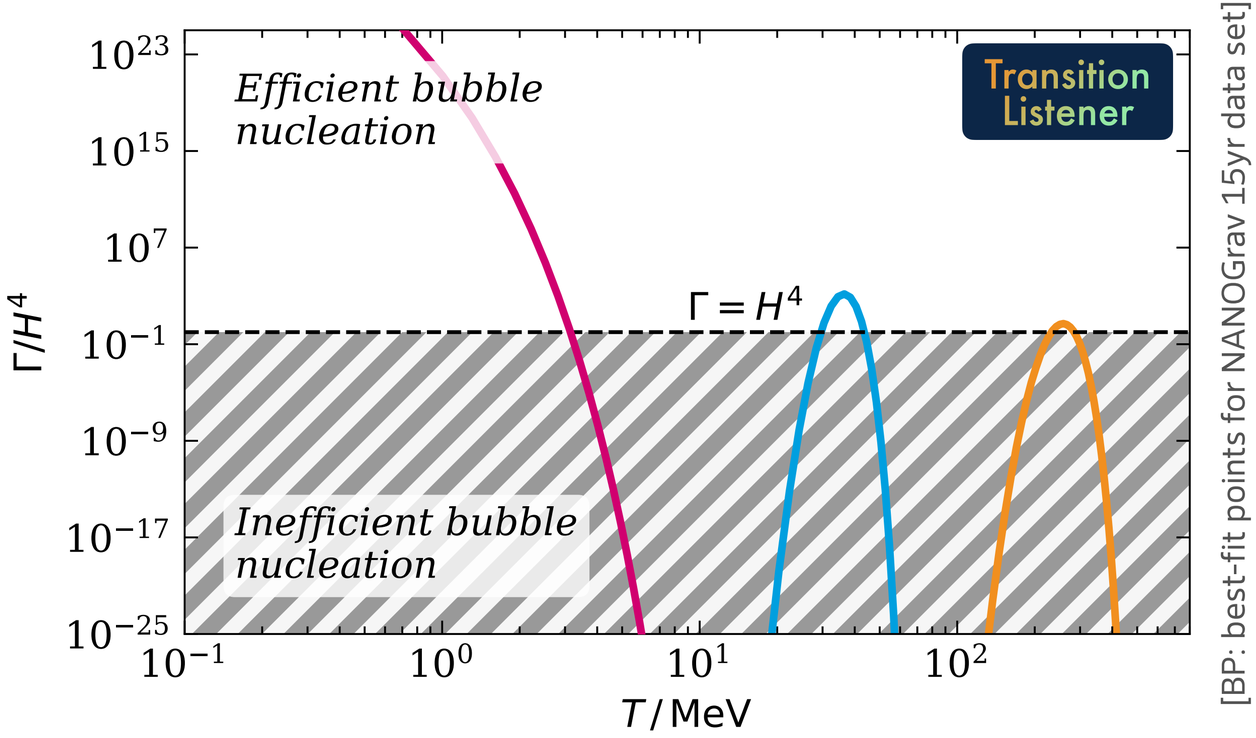
Two significant digits in λ

Four significant digits in four couplings...

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

The origin of tuning to get strong GW signals





[BP: best-fit points for NANOGrav 15yr data set]

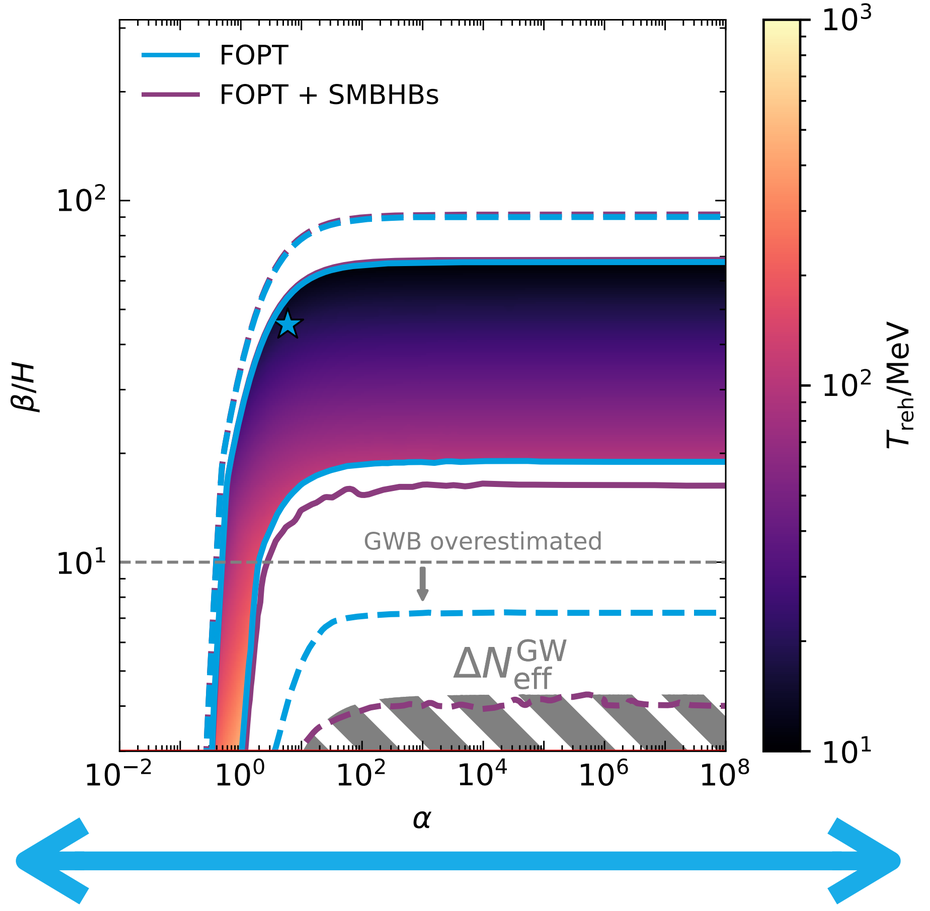
The required amount of tuning comes directly from the typical transition temperature: The higher it is, the larger the bubbles have to be, and the more the bubble nucleation rate has to be tuned.

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...

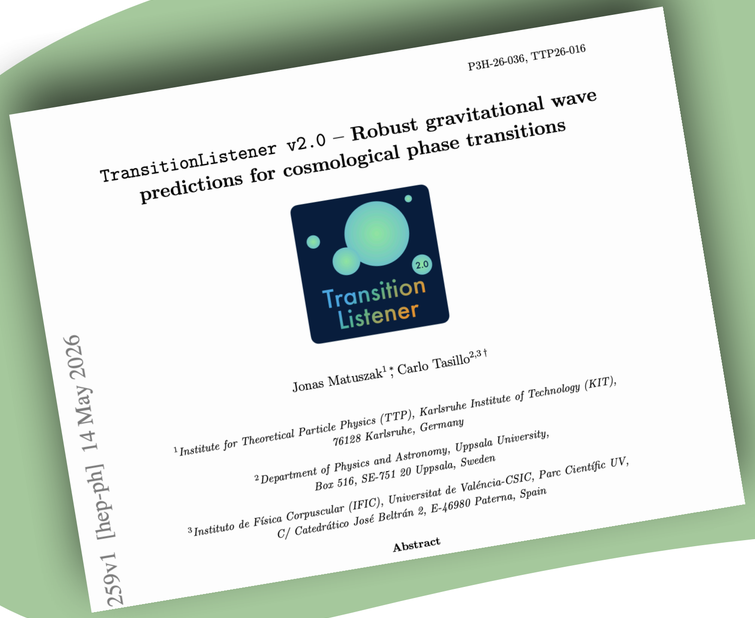
Robust predictions of the GW signal in that regime are difficult...

WHAT ABOUT THIS PROBLEM?


BROADCAST
INTERRUPTED

Commercial break

- $\beta/H \approx (8\pi)^{1/3}/RH$
- $S_3(T_{\rm nuc})/T_{\rm nuc} = 140$
- $T_{\rm reh} \approx T_{\rm perc}(1+\alpha)^{1/4}$
- $\alpha \approx \Delta V/\rho_{\rm rad}$
- $c_{\rm s}^2 = 1/3$
- 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

Jonas Matuszak[1]*, Carlo Tasillo[2,3]†

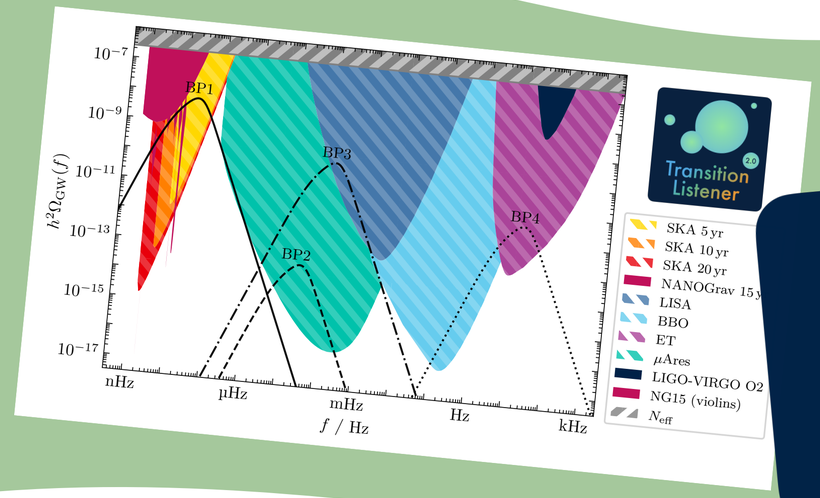
[1] Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany

[2] Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden

[3] Instituto de Física Corpuscular (IFIC), Universitat de València-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain

Abstract

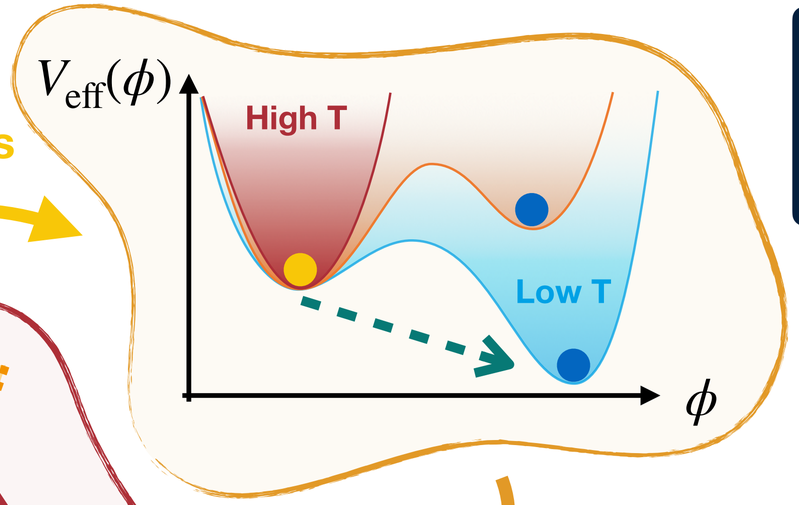
259v1 [hep-ph] 14 May 2026



Transition Listener

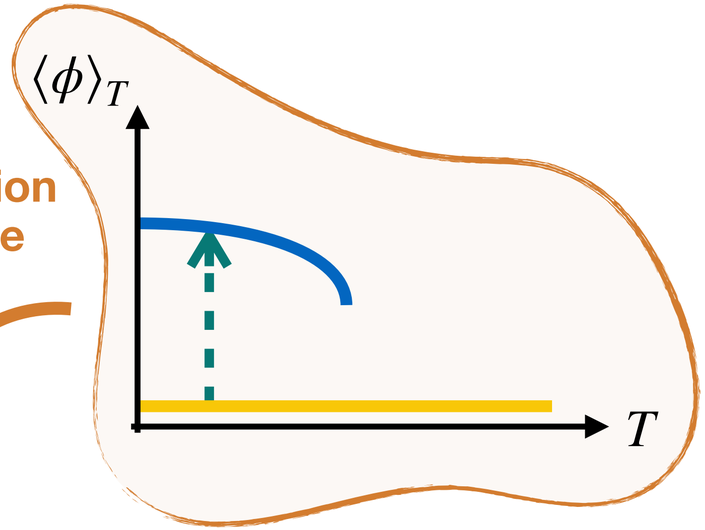
$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

Quantum & finite-temperature corrections

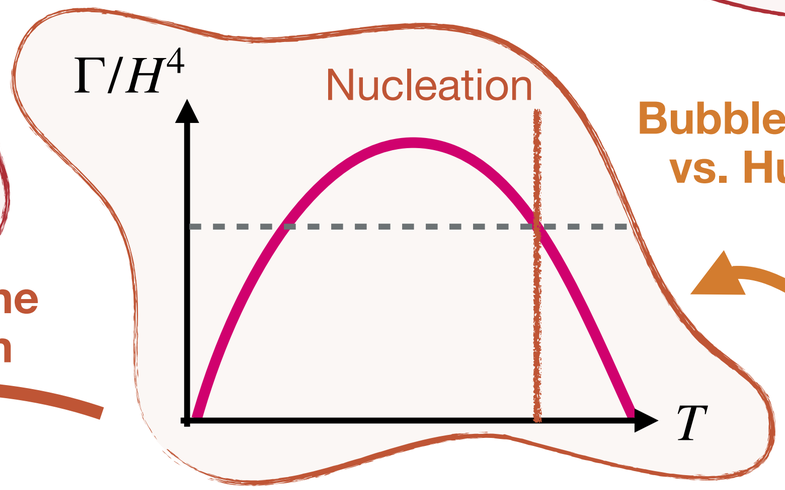


Transition Listener 2.0

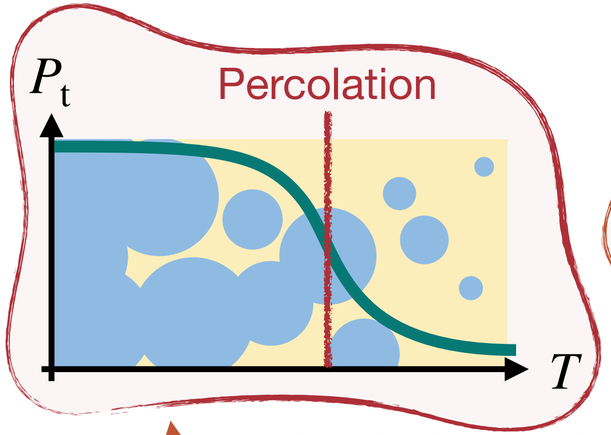
Phase tracing and finding possible transitions



Bubble nucleation vs. Hubble rate

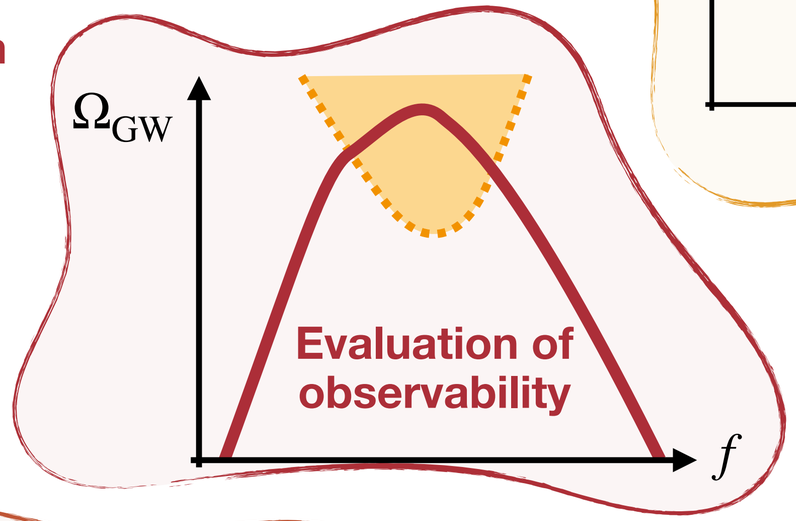


Evolution of the false vacuum



Mapping to GW templates from hydrodynamic simulations via

$\alpha, \beta/H, T_{\rm reh}, v_{\rm w}, \ldots$



Commercial break

Easy to install!

Beautiful 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
```

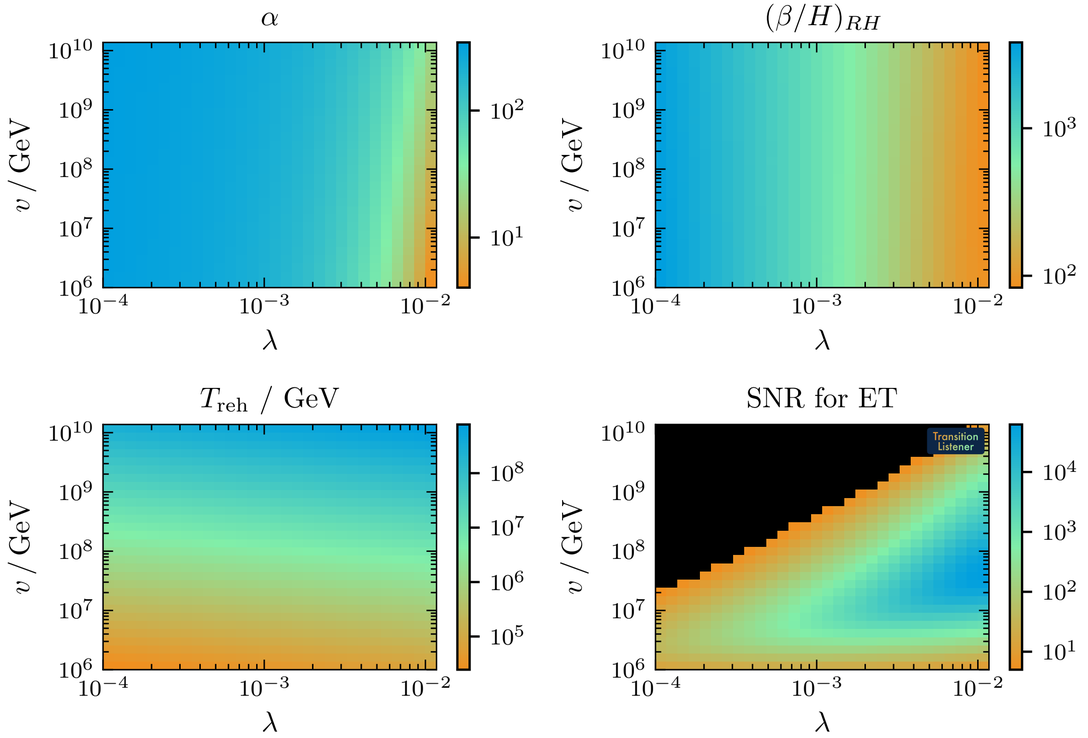
Parameter	Value
g	7.0000000000e-01
y	1.0000000000e-02
v_GeV	1.0000000000e-01

Derived parameters

Parameter	Value
lambda	1.6790420728e-02

Zero-temperature mass spectrum

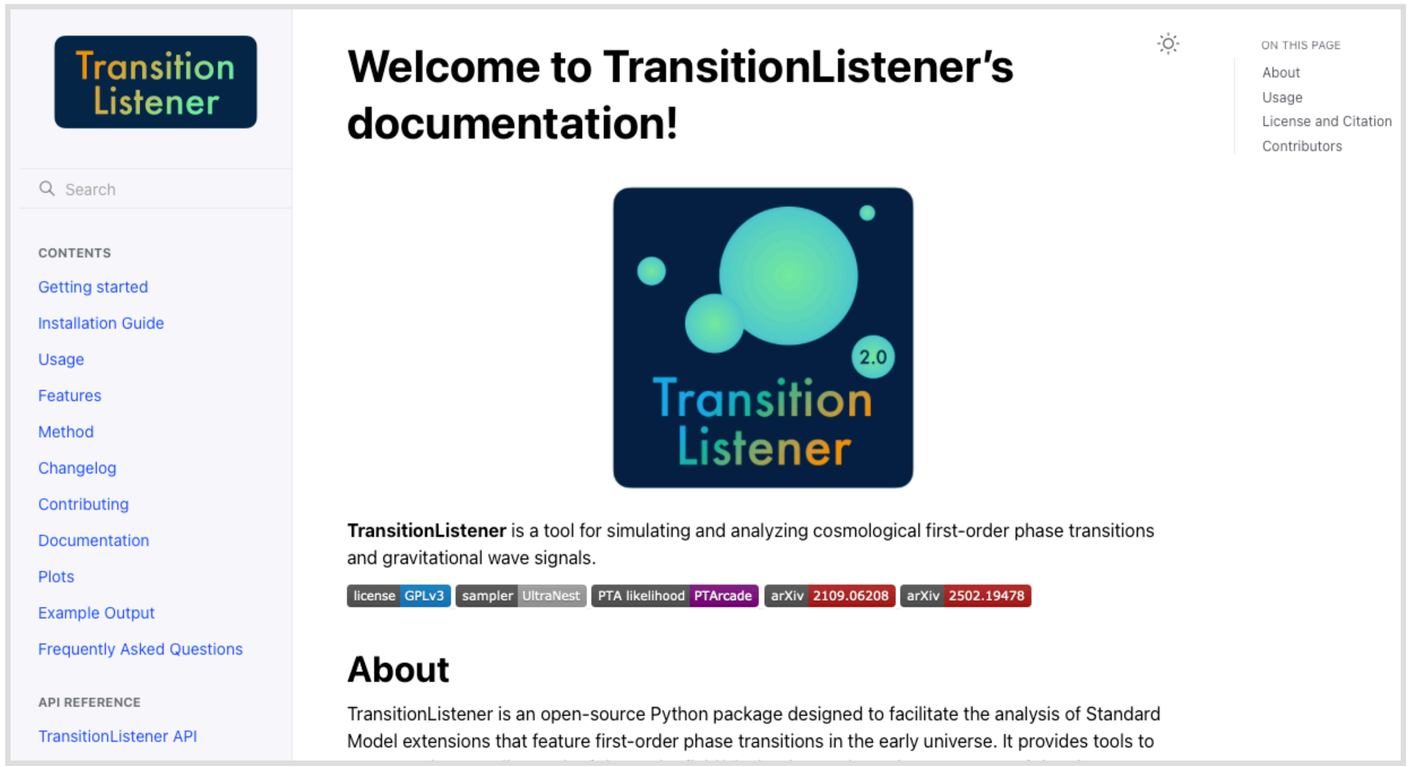
Particle	Type	Mass [GeV]
m_phi	boson	2.2443542988e-02
m_varphi	boson	1.2957785586e-02
m_A_T	boson	7.0000000000e-02
m_A_L	boson	7.0000000000e-02
m_psi1	fermion	7.0710678119e-04
m_psi2	fermion	7.0710678119e-04



Validated against BSMPT!

Comes with dark sector models and 2HDM!

Numerically robust and reliable!



Well-documented and in active use!

Just try:

```
pip install
transitionlistener
```

Click here!

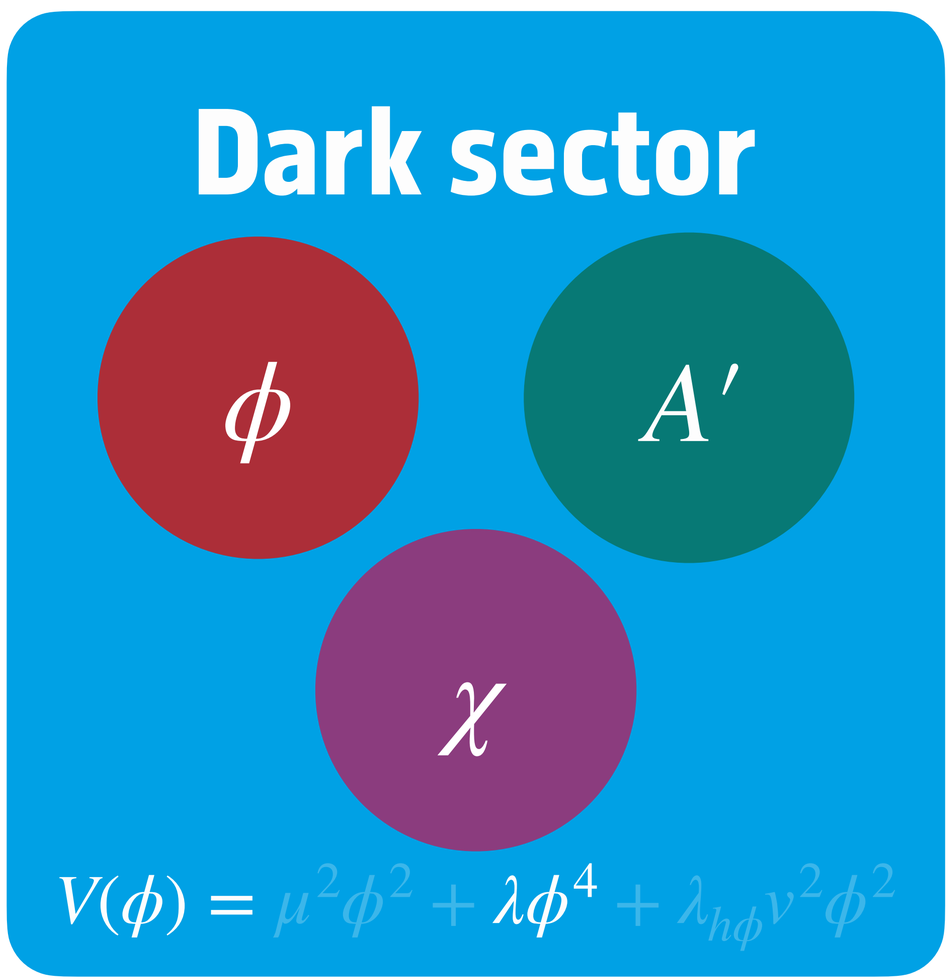
www.tasillo.de/TransitionListener


BROADCAST
INTERRUPTED

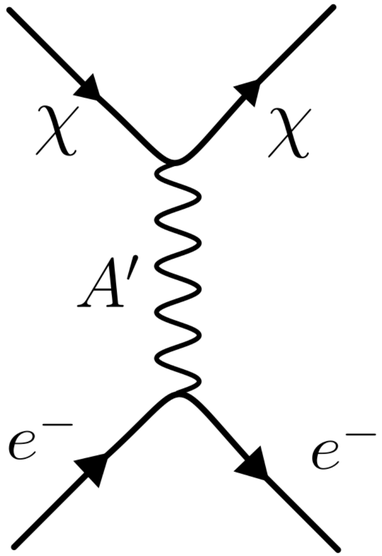


Is there dark matter in the dark sector?

A conformal dark sector incl. dark matter candidate



Kinetic mixing κ

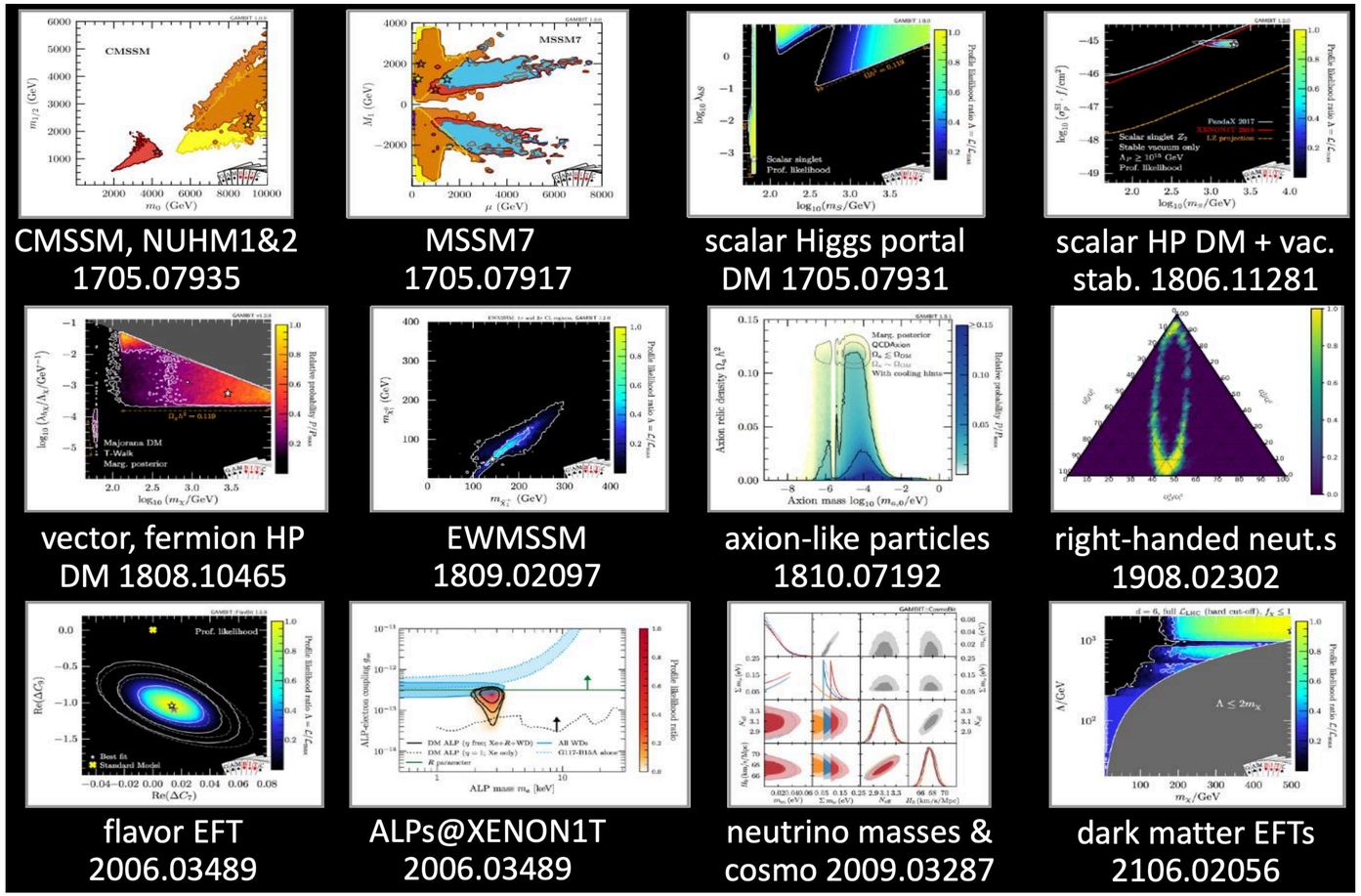


Thermalization becomes easy!

SM

CT+ [JCAP 08 (2025) 062]

GAMBIT: from Lagrangians to Likelihoods



CMSSM, NUHM1&2 1705.07935 | MSSM7 1705.07917 | scalar Higgs portal DM 1705.07931 | scalar HP DM + vac. stab. 1806.11281

vector, fermion HP DM 1808.10465 | EWMSSM 1809.02097 | axion-like particles 1810.07192 | right-handed neut.s 1908.02302

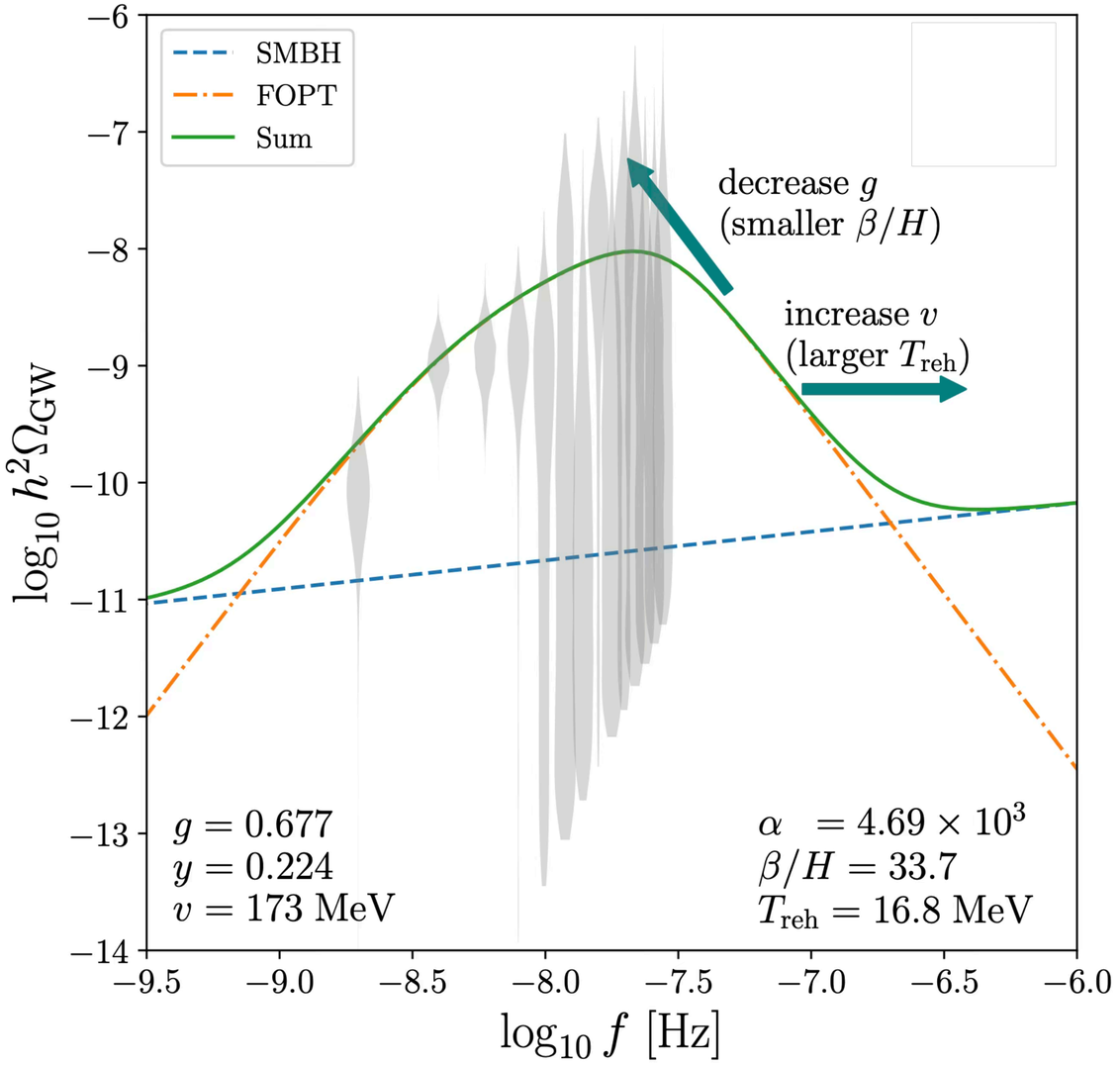
flavor EFT 2006.03489 | ALPs@XENON1T 2006.03489 | neutrino masses & cosmo 2009.03287 | dark matter EFTs 2106.02056



To combine BBN + CMB, direct and indirect DM detection, bullet cluster and beam dump constraints: GAMBIT

Slide by C. Balázs @ SUSY 2021

All constraints can be circumvented

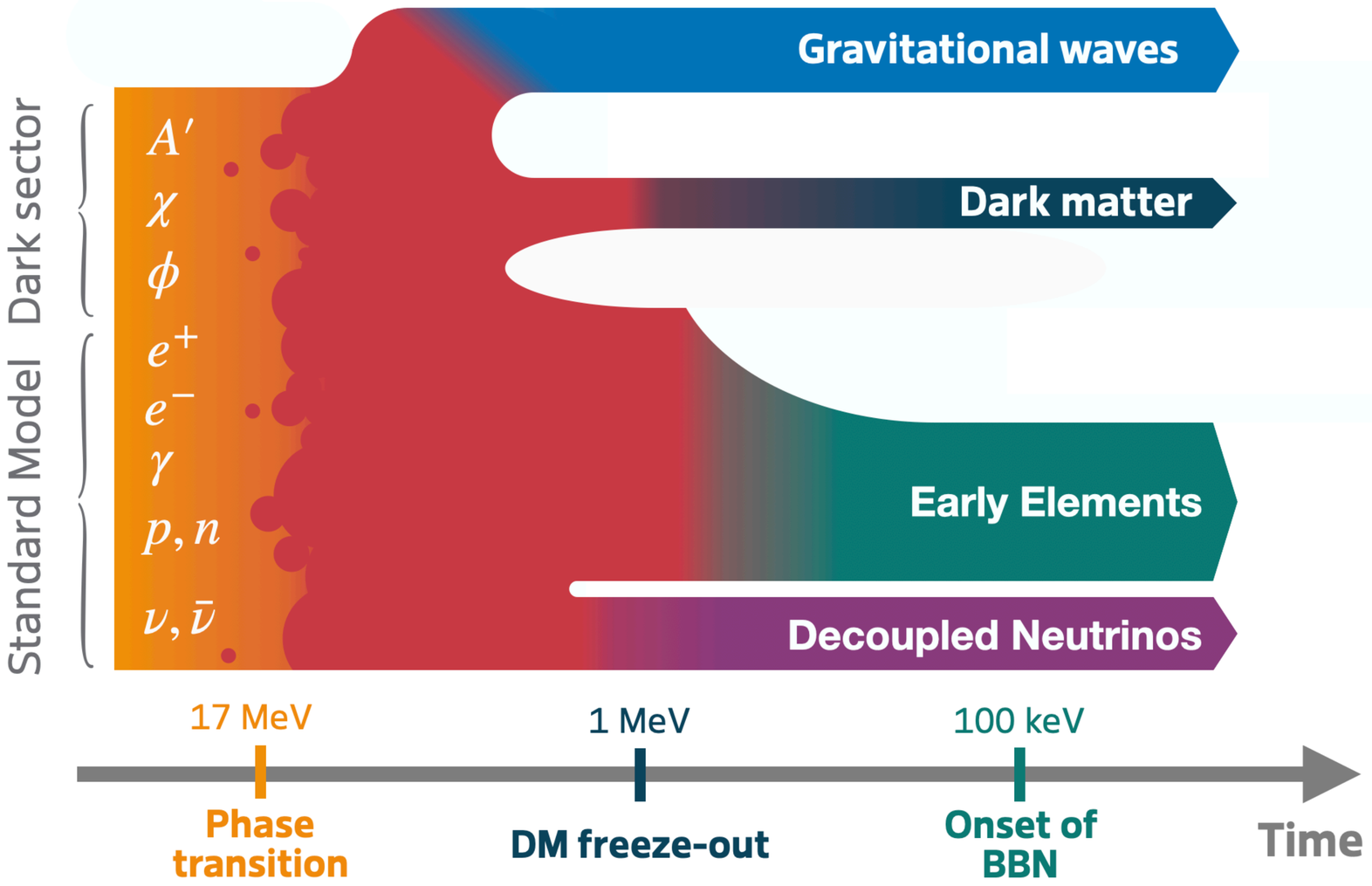


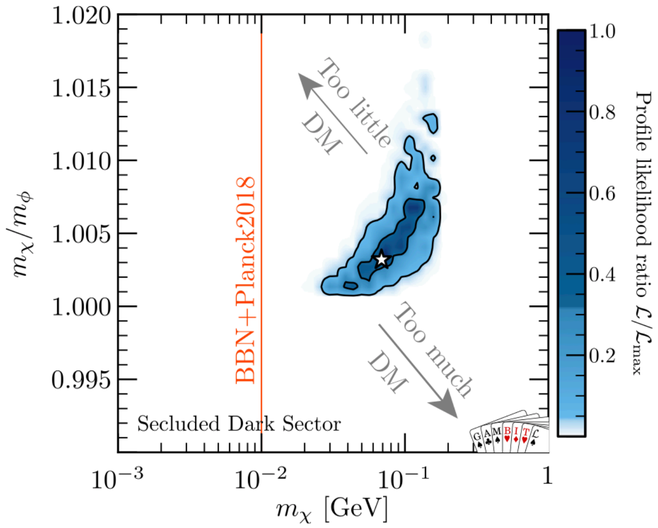
Global fit found parameter space with

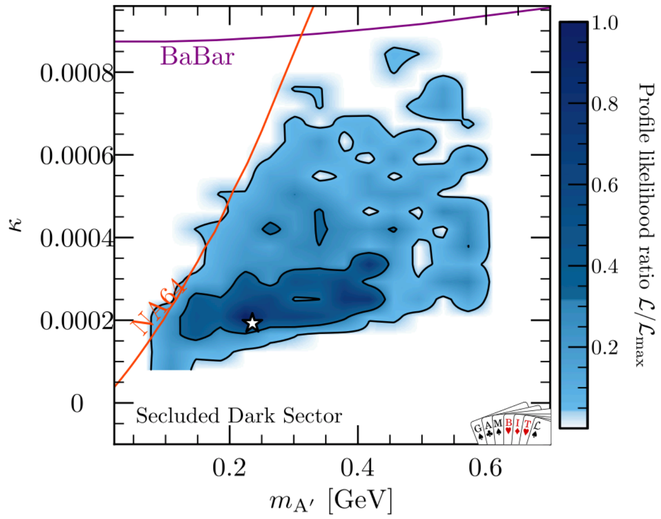
- 100% of observed DM relic density
- Loud phase transition on top of „standard“ SMBH background
- Negligible impact on BBN and CMB
- No relevant direct + indirect detection + bullet cluster constraints
- Testable LDMX/Belle-II/NA64 prediction:

$$m_{A'} = 100 - 200\,\text{MeV},\ \kappa \simeq 10^{-4}$$

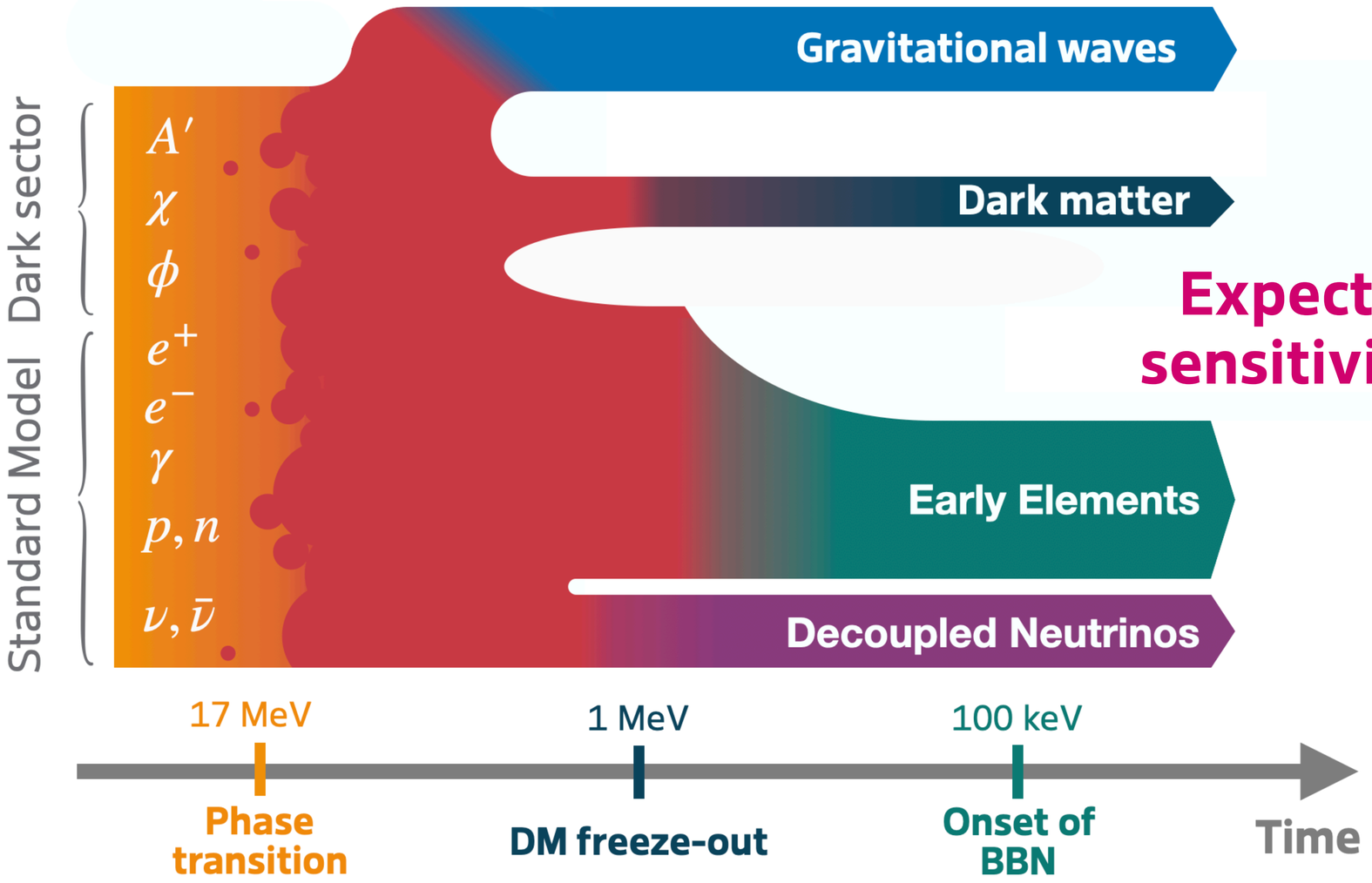
How does our scenario evade all available constraints?



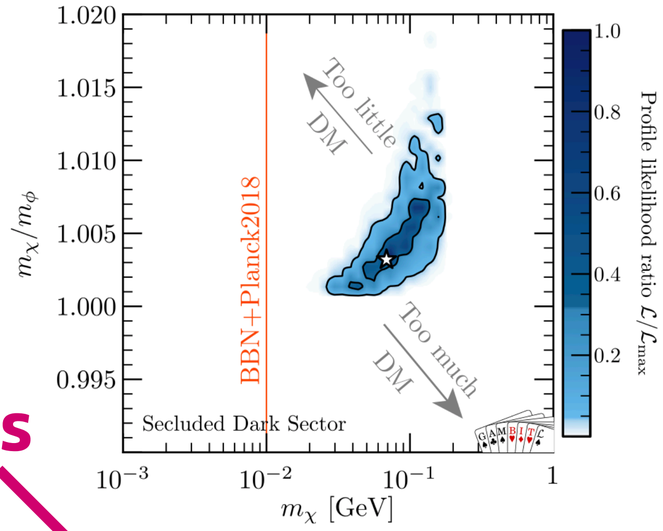


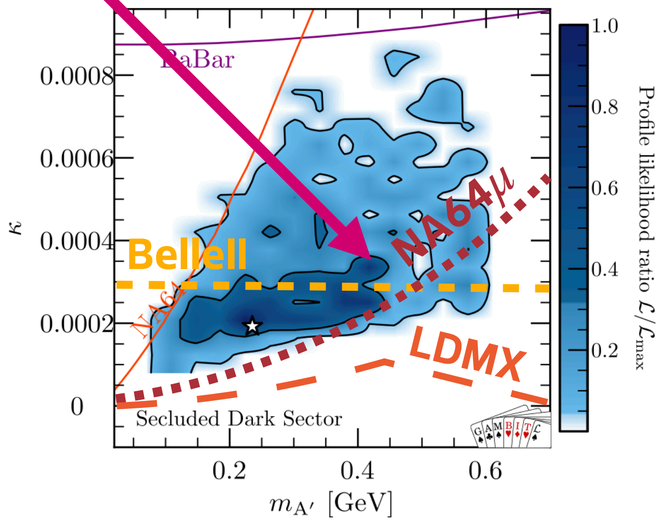


How does our scenario evade all available constraints?

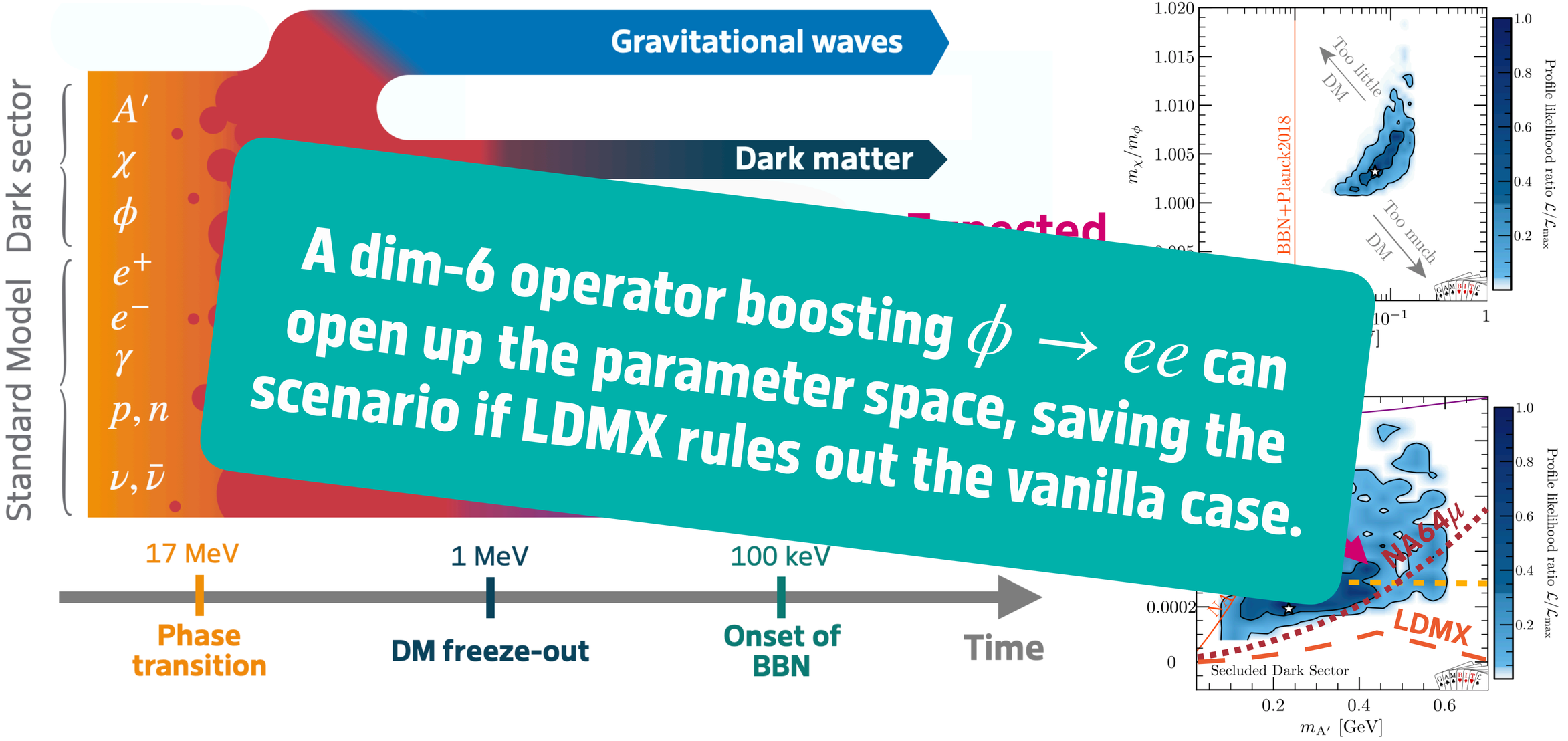


Expected sensitivities





How does our scenario evade all available constraints?



LISA is blind!



LISA is blind!



Sneak peak: Revisiting the 2HDM

When HL-LHC is blind, LISA is deaf (but not vice versa): collider-cosmology synergies in the 2HDM

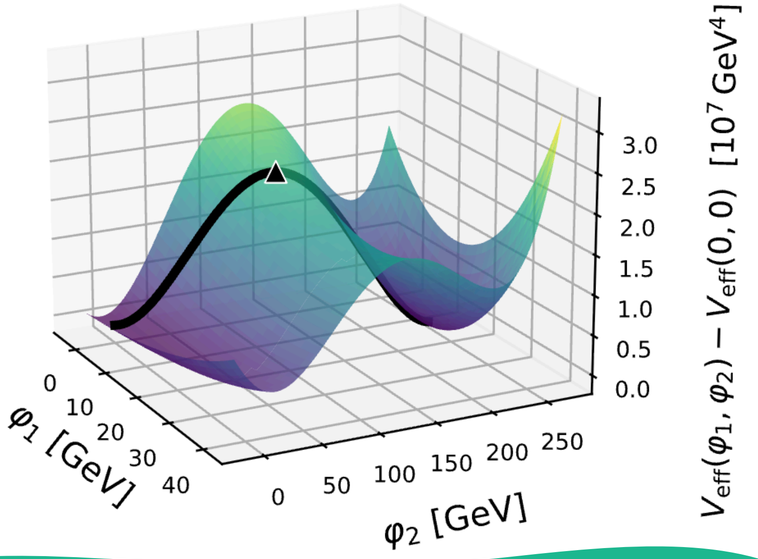
Stefano Moretti,[a,b] André Pousette,[a] and Carlo Tasillo[a,c]

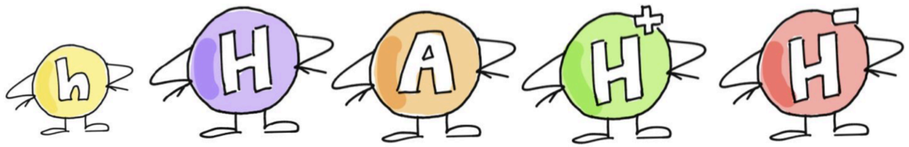
[a] Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden
[b] School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom
[c] Instituto de Física orpuscular (IFIC), Universitat de València-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain

E-mail: stefano.moretti@cern.ch, andre.pousette.0193@student.uu.se, carlo.tasillo@ific.uv.es

PREVIEW

ABSTRACT: Extensions of the Standard Model scalar sector can render the electroweak phase transition first-order and thereby provide the necessary departure from equilibrium for electroweak baryogenesis, while at the same time sourcing a stochastic gravitational



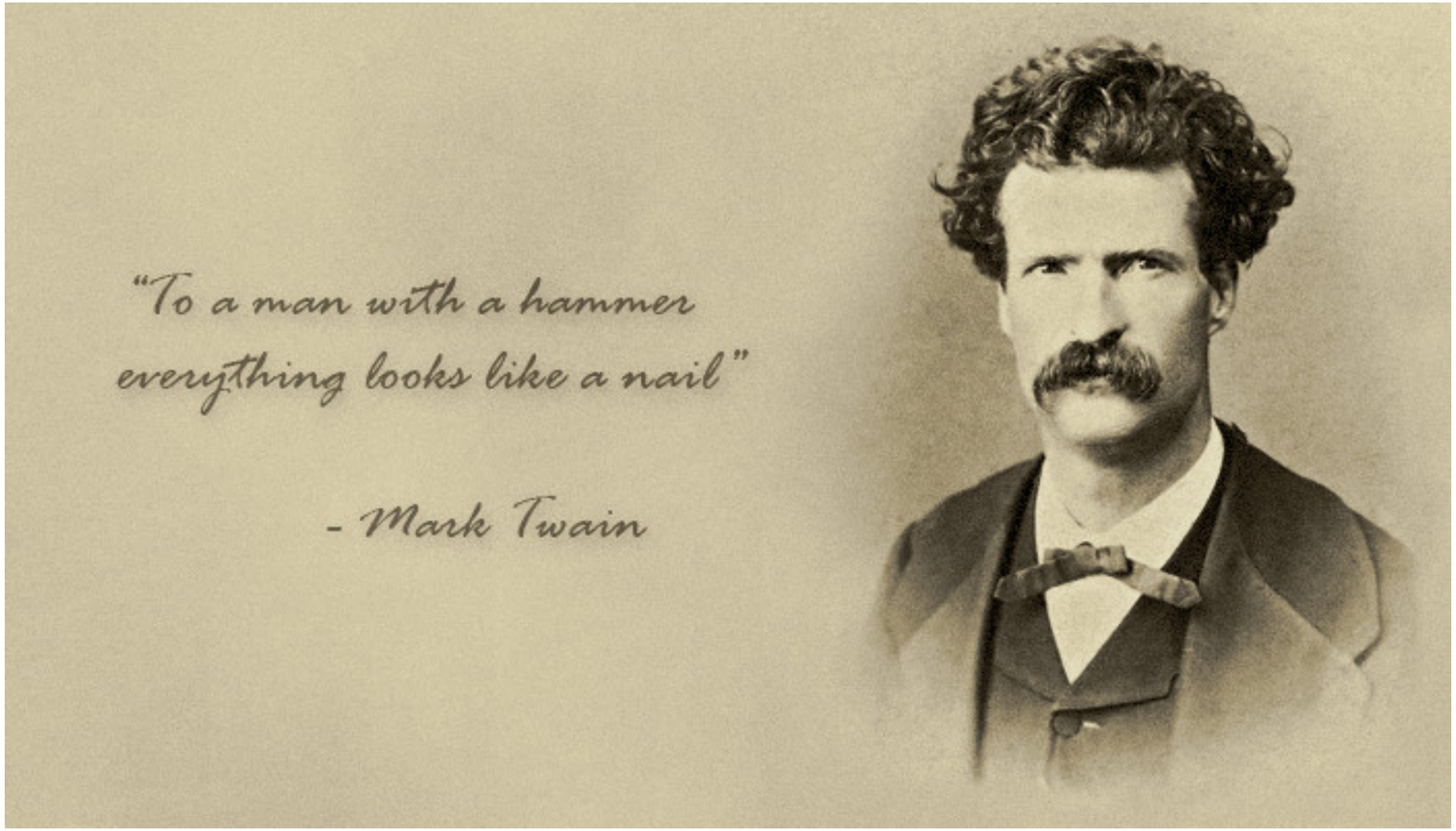


[Image credit: Kateryna Radchenko]

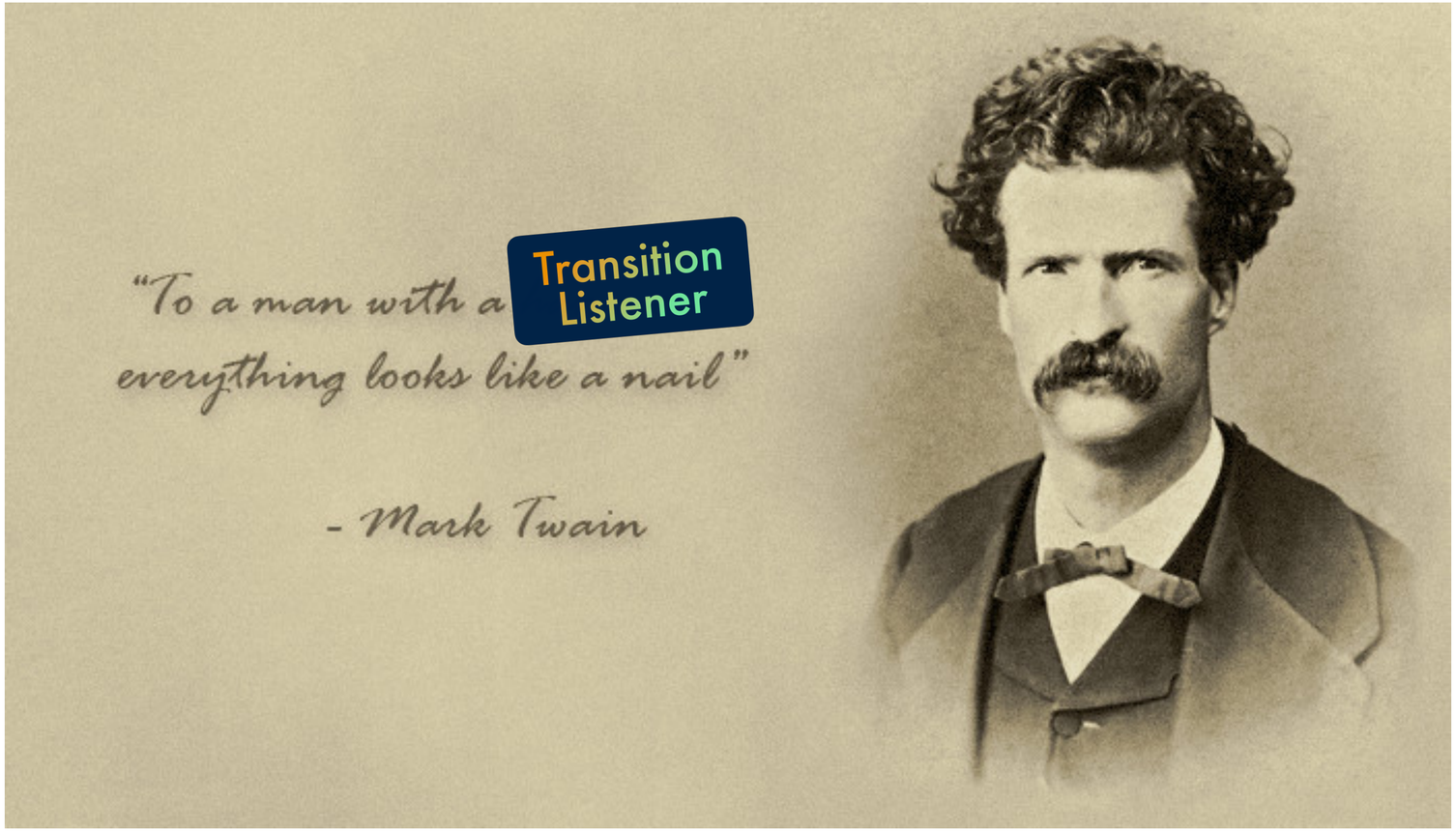
In the SM the EWPT is a crossover. To get a GW signal and baryogengesis* we need to extend it. One example: 2HDM.

* We only care about the GWs in this work. We therefore assume the CP-conserving 2HDM

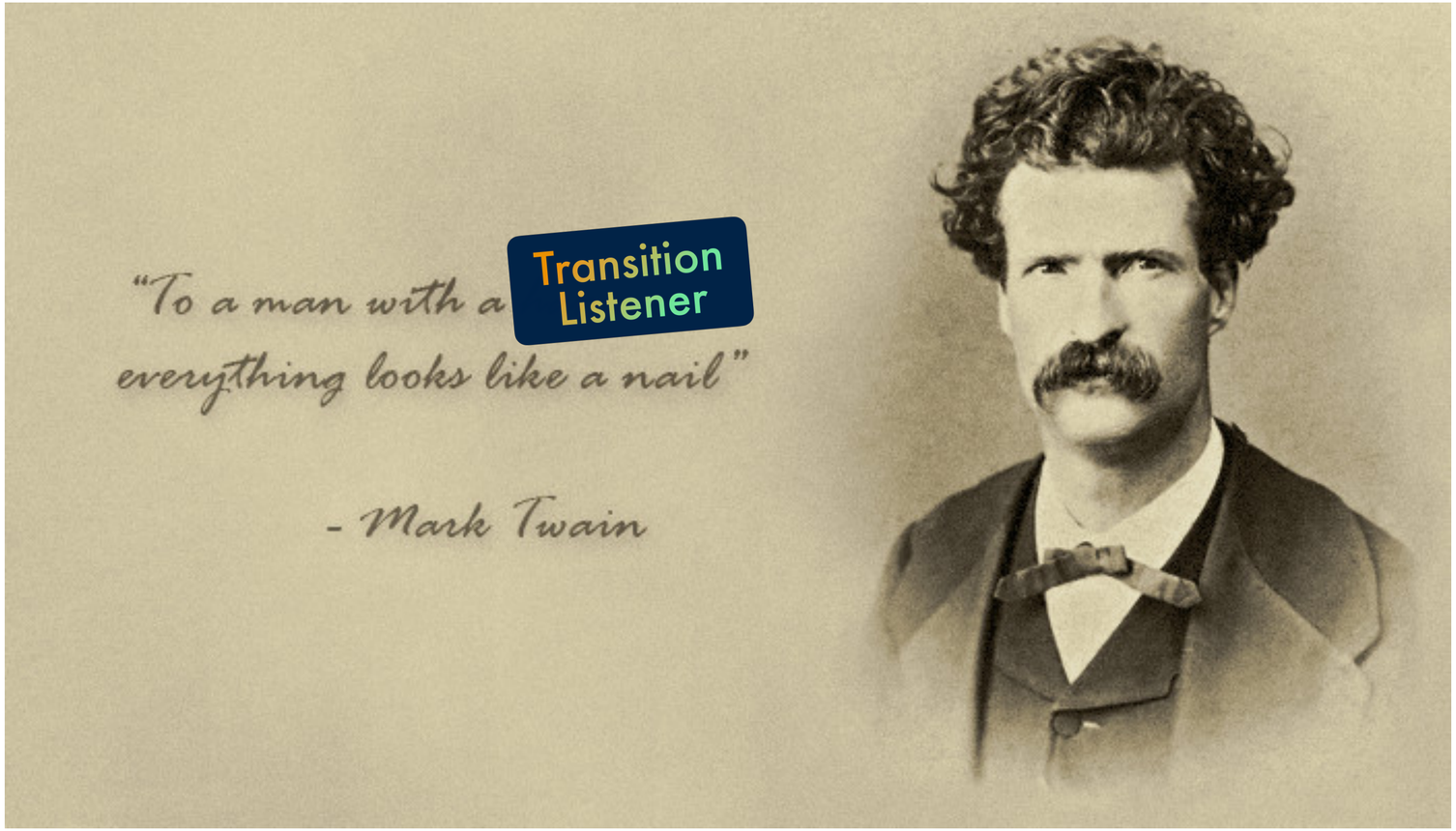
Why study the 2HDM?



Why study the 2HDM?

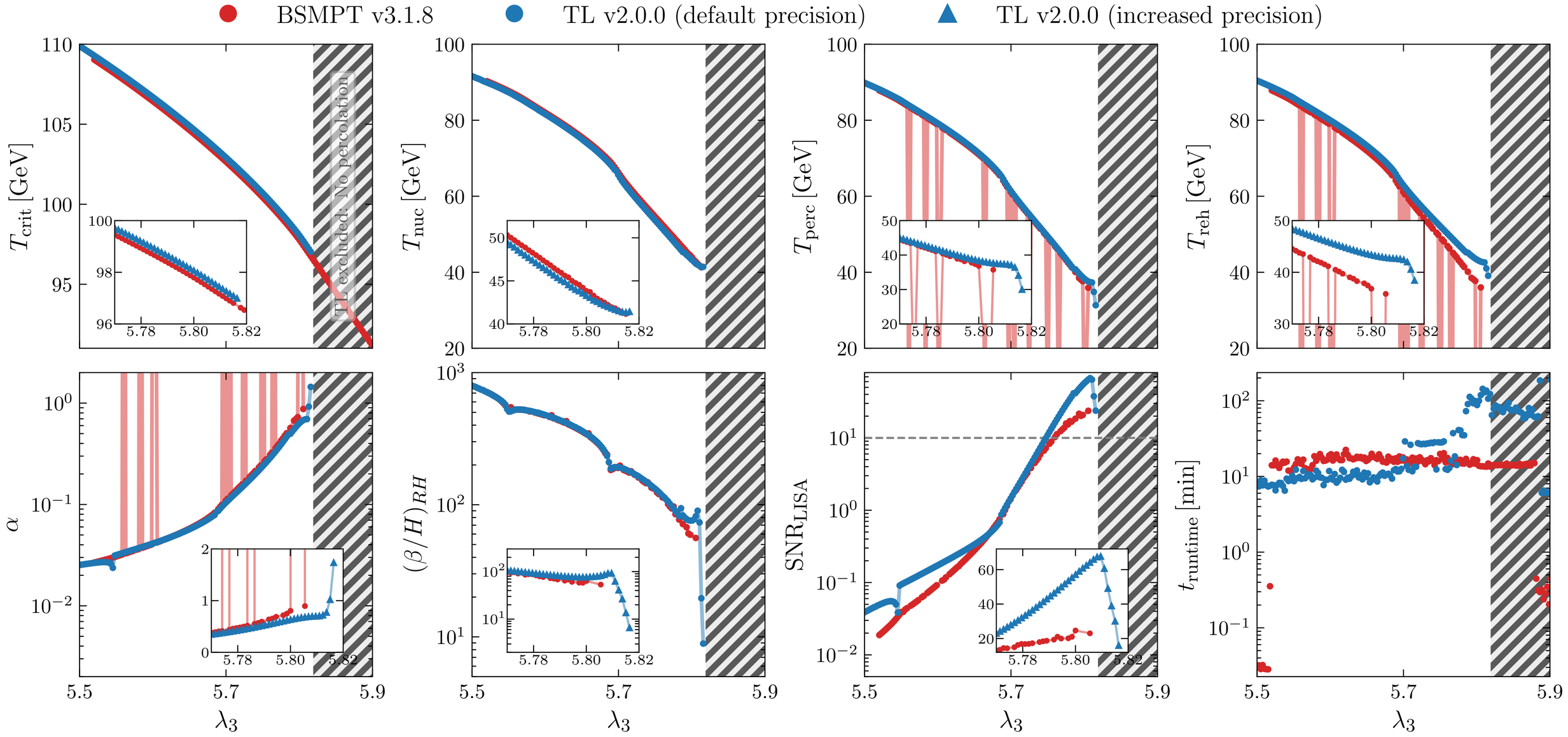


Why study the 2HDM?

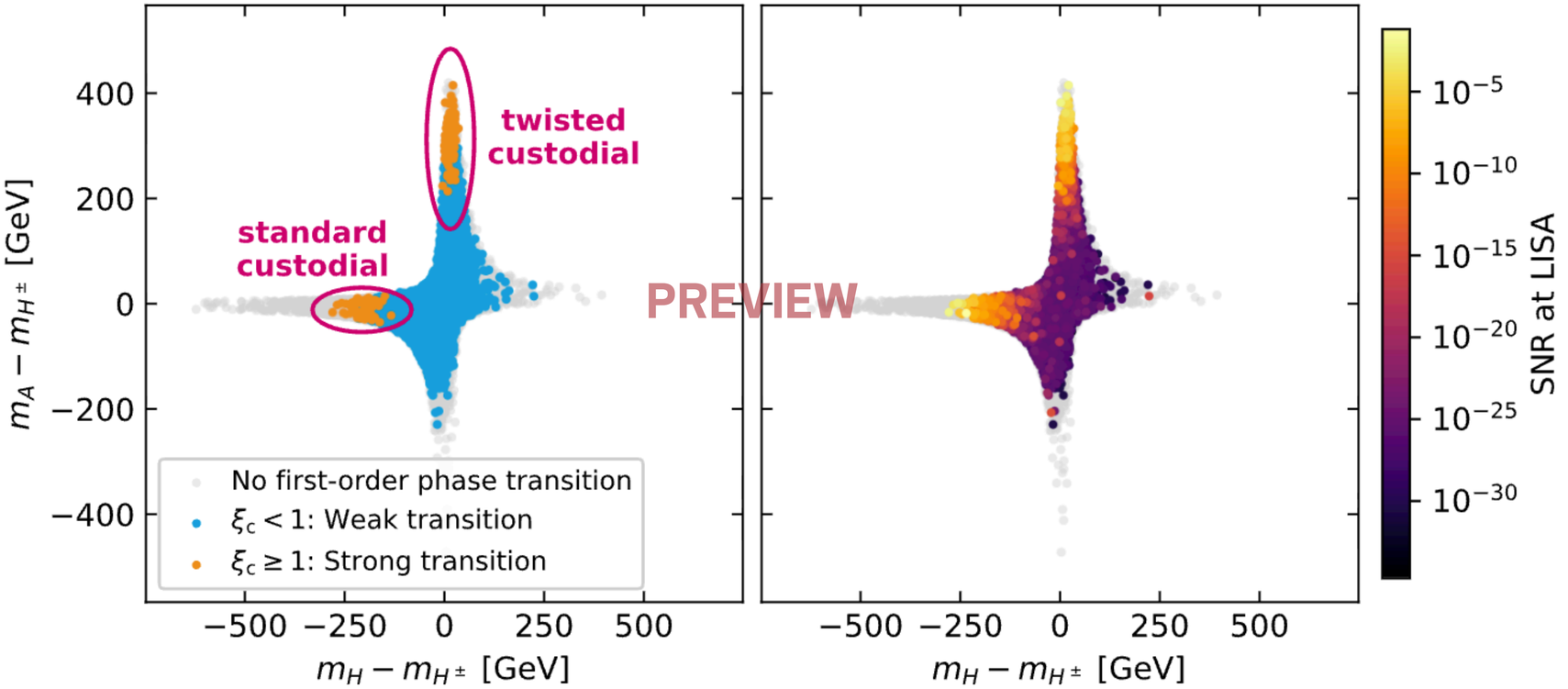


+ the possibility to study large parts of the parameter space at colliders; SUSY and QCD axions also require a second Higgs doublet; the 2HDM features DM candidates itself; ...

Comparison BSMPT vs. TransitionListener, 2HDM benchmark

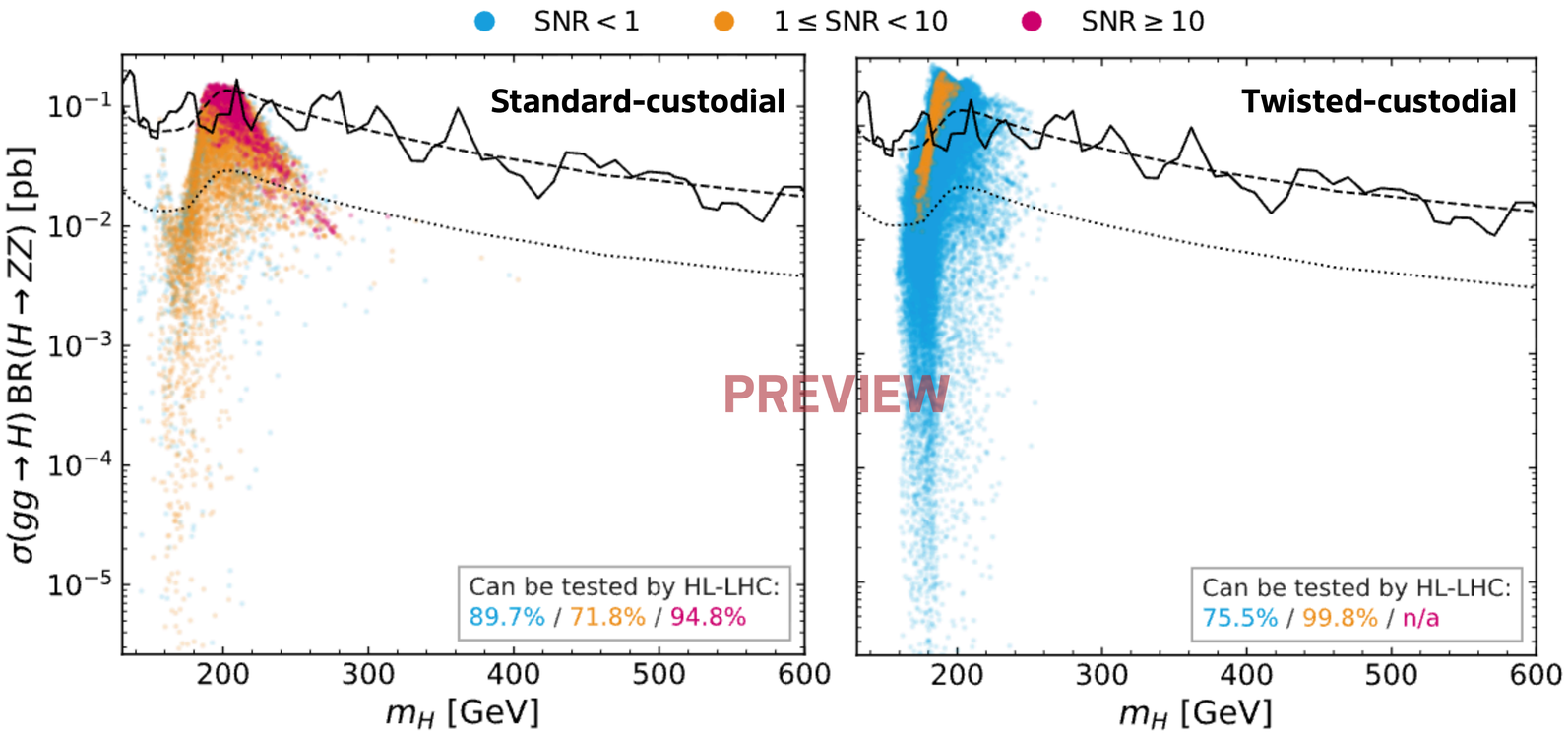


Observational constraints leave two options for strong LISA signals



We find that only two regions can give strong LISA signals and perform MC parameter scans in those.

Decays of the Heavy CP-even Higgs to ZZ



Essentially all LISA-observable type-I 2HDM points can already be excluded by HL-LHC! *

* And given that that's a big claim we reran all BSMPT points with TransitionListener, also allow for electroweak symmetry non-restoration at high-T, and cross-check LTE wall velocities with WallGo.

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.



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

LISA is (> 95%) blind: If the HL-LHC does not find any $H \to ZZ$ events, we should be safe to expect no observable type-I 2HDM GWs.



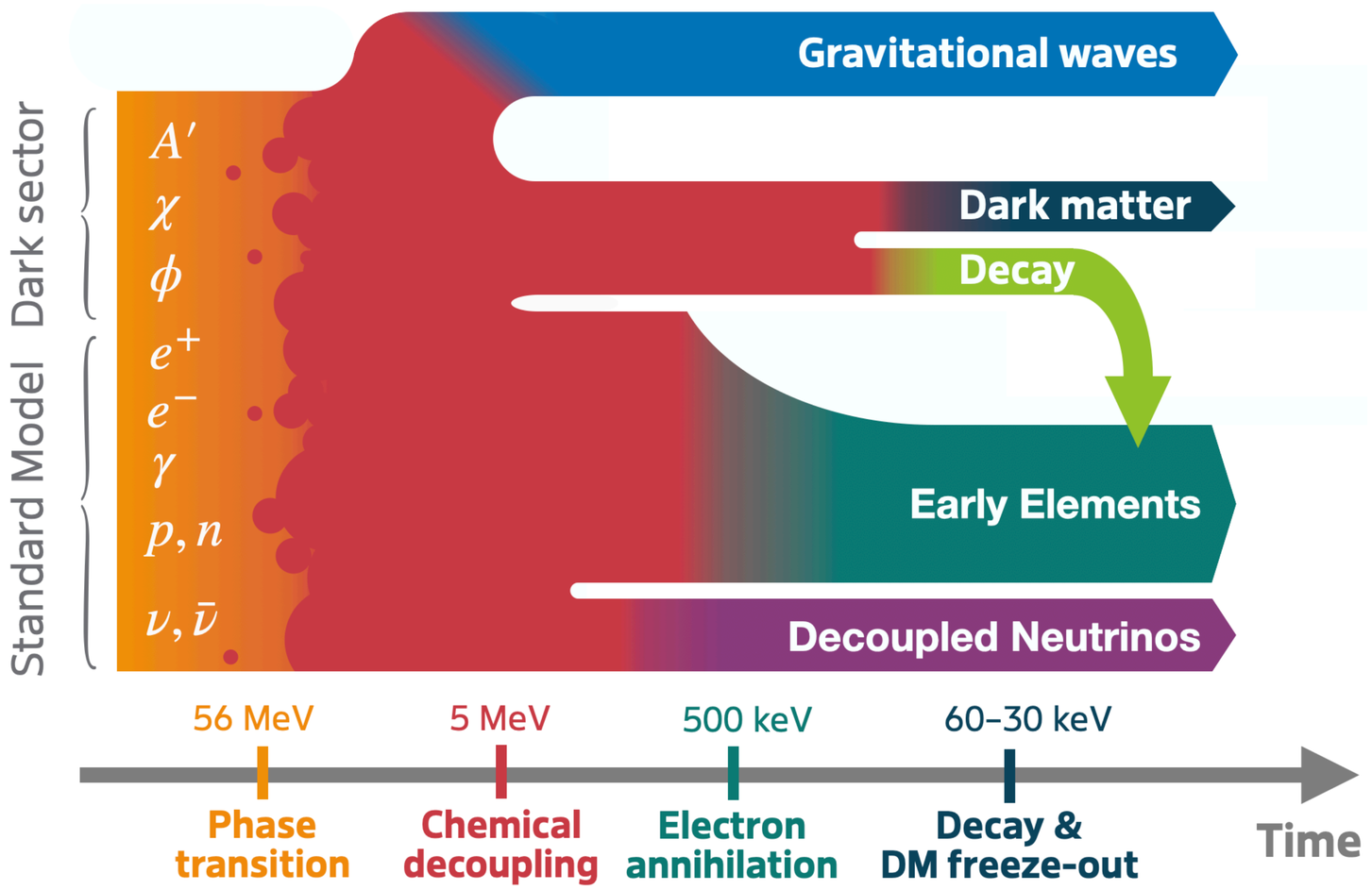
Even if the IPTA DR3 will find an astrophysical origin of the PTA signal, our **tuning arguments will remain** for future GW background studies, e.g. **at LISA**.

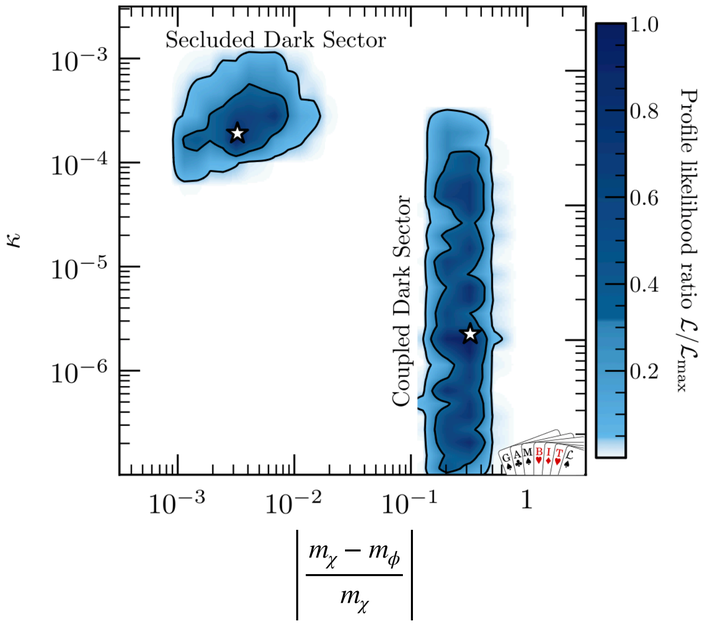
Sub-GeV Dark matter could have also been produced right after the PTA signal was emitted. Beam dump experiments will be able to tell us soon.



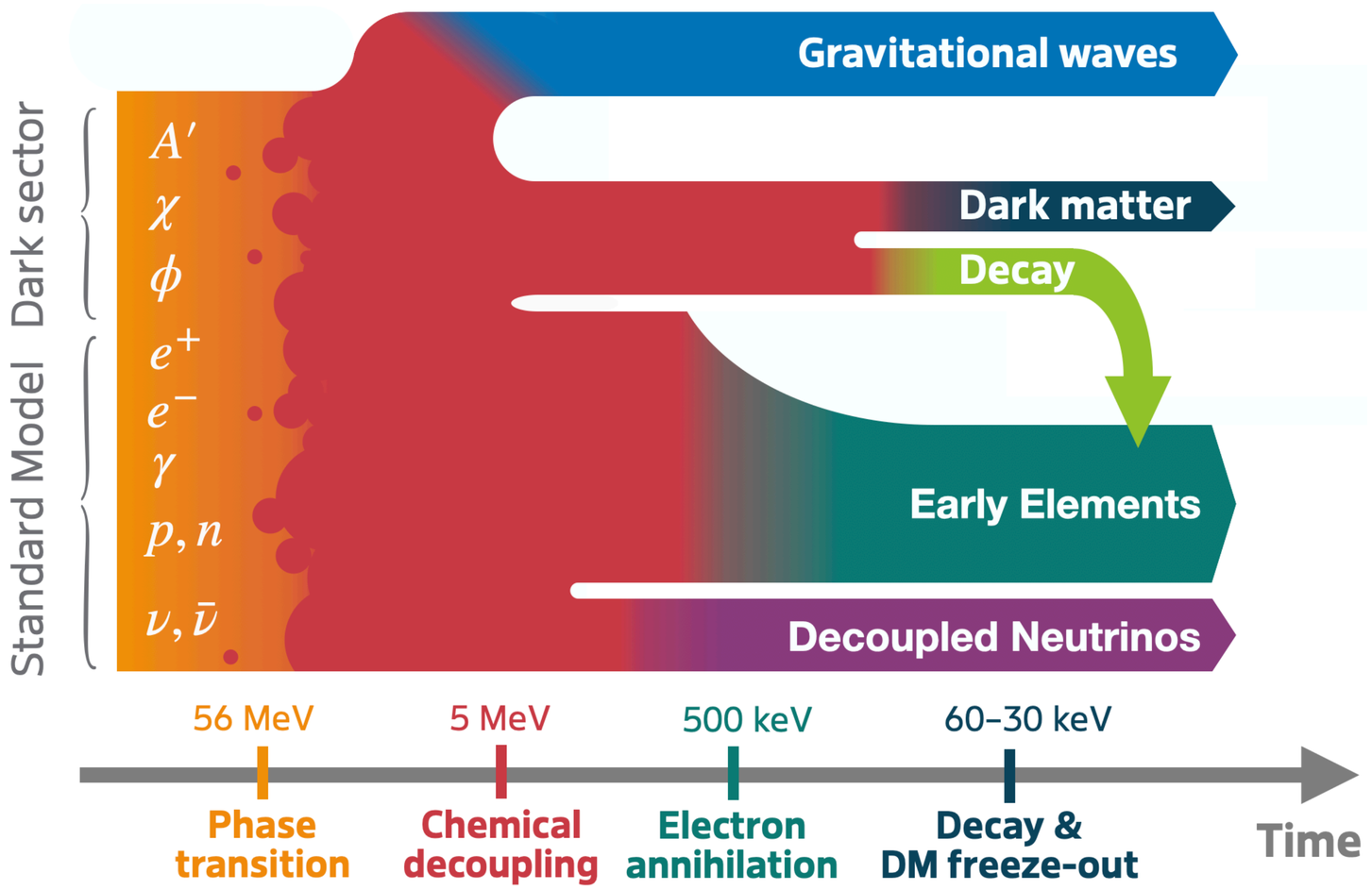
Backup slides

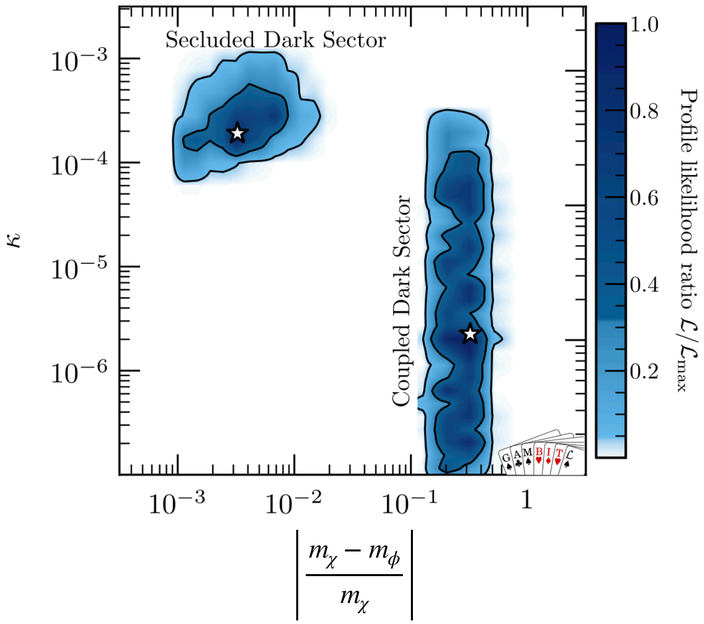
Coupled DS scenario: incl dim-6 operator for $\phi \to ee$





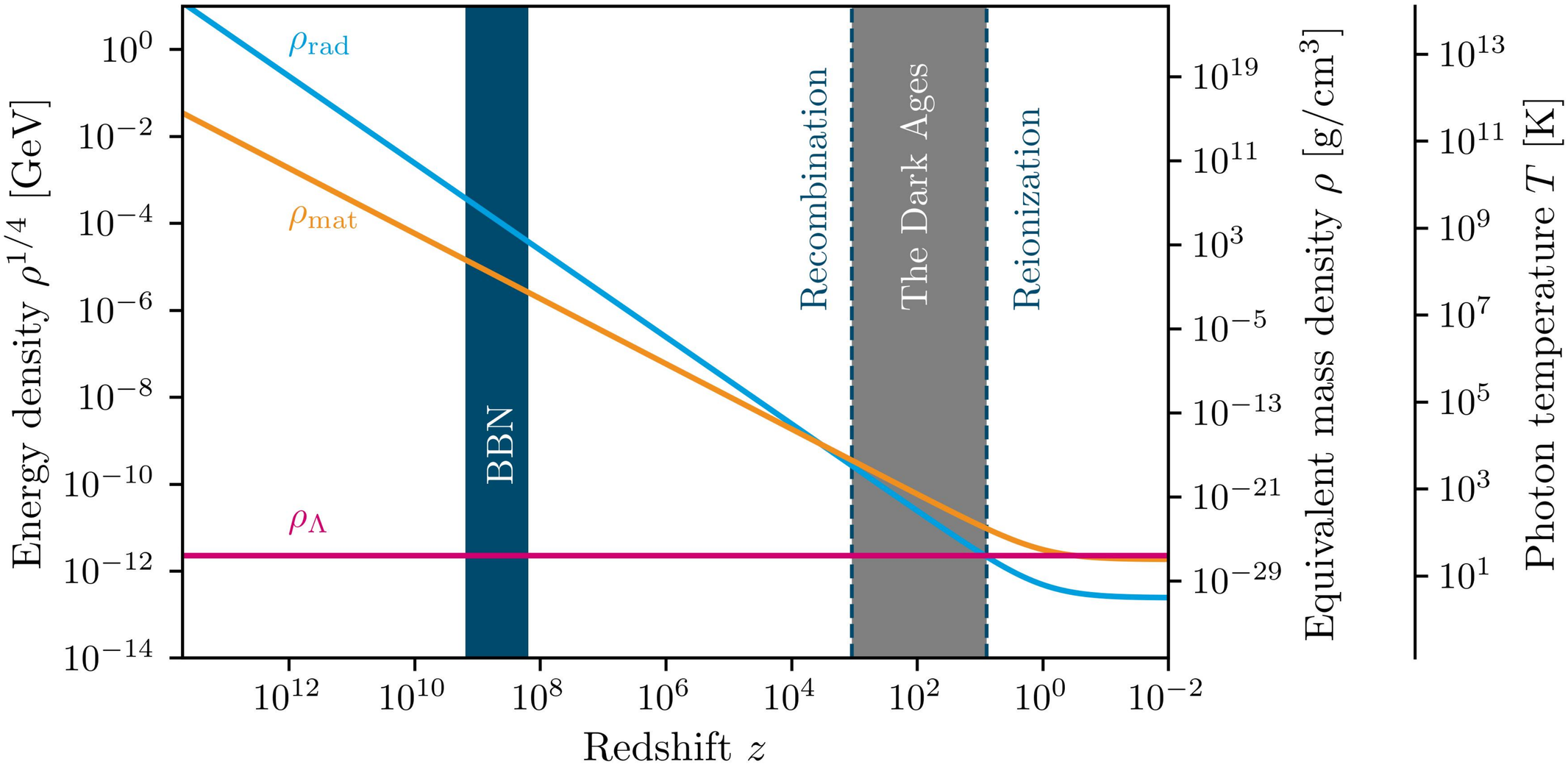
Coupled DS scenario: incl dim-6 operator for $\phi \to ee$



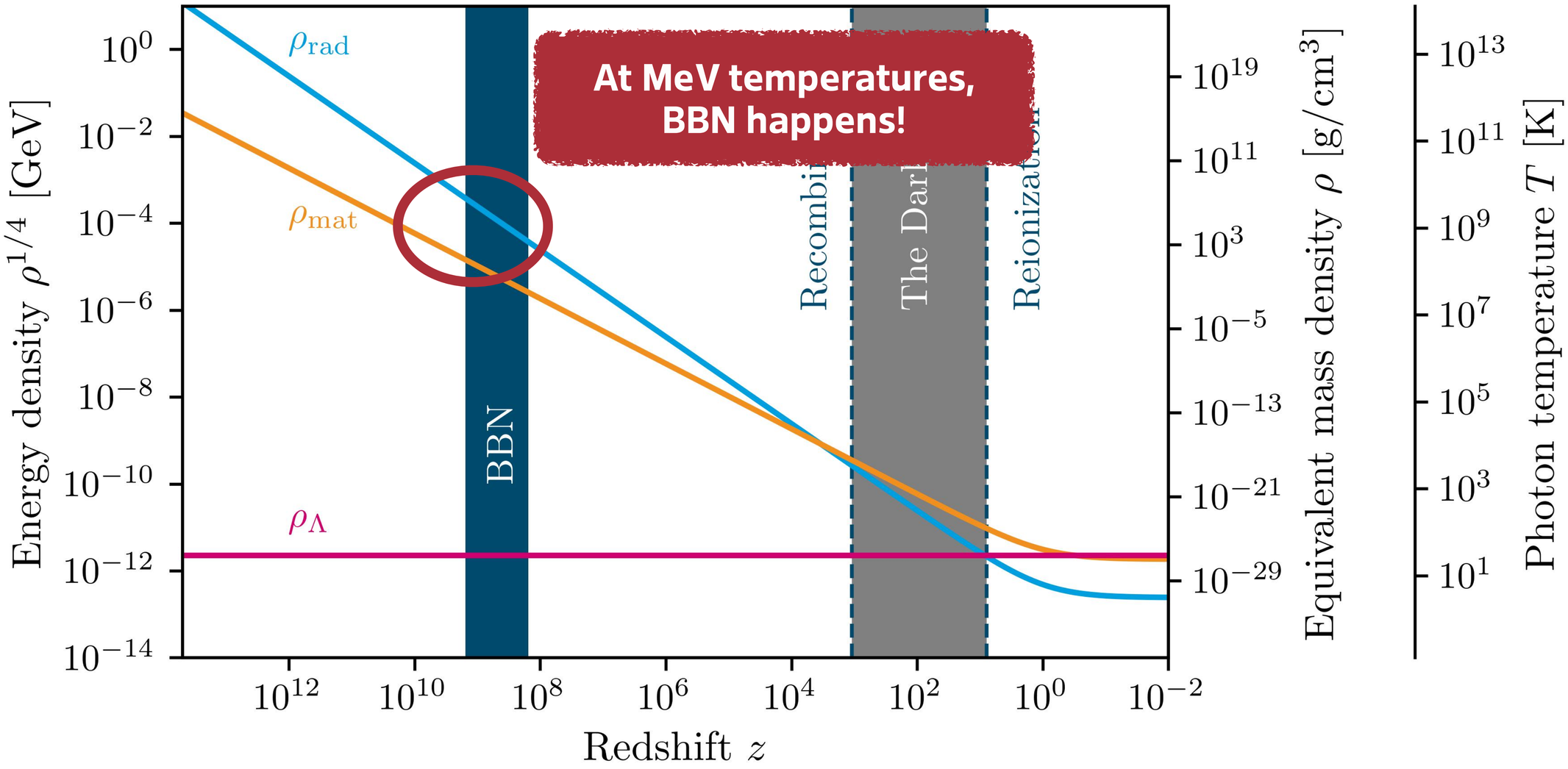


$\phi \to ee$ decays through a dim-6 operator open up the parameter space and save the model from potential future constraints

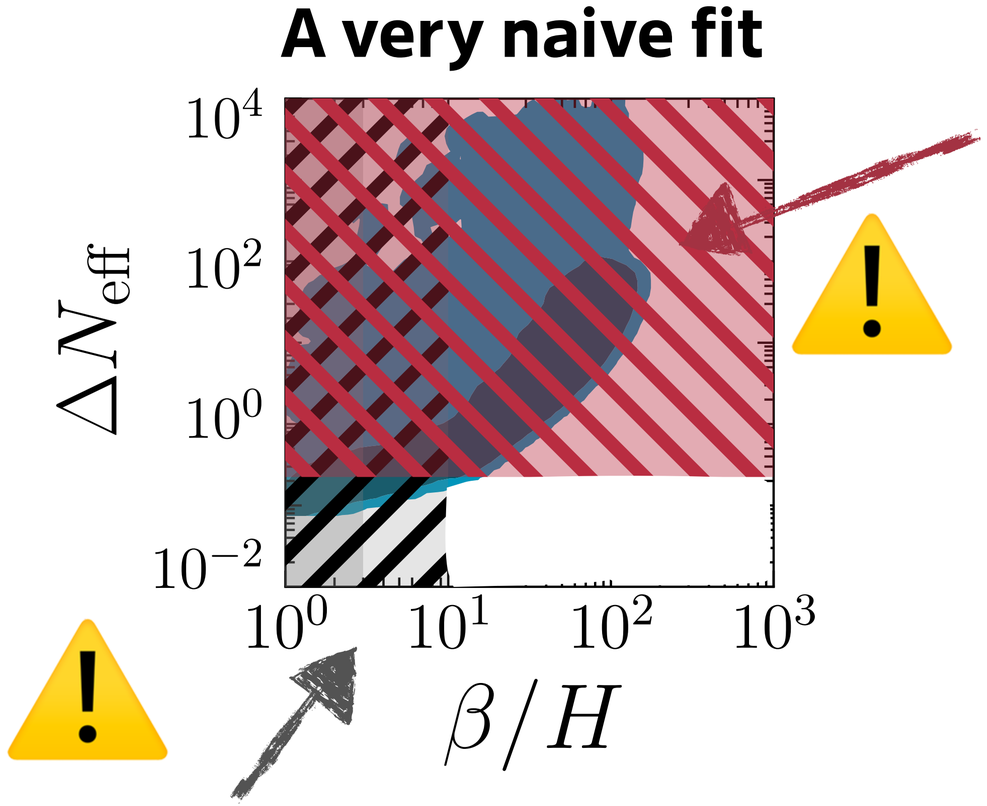
A brief history of time



A brief history of time



A dark sector without portal couplings



The liberated vacuum energy remains in the dark sector. A good fit would require enormous

$$\Delta N_{\rm eff} \gg 0.22$$

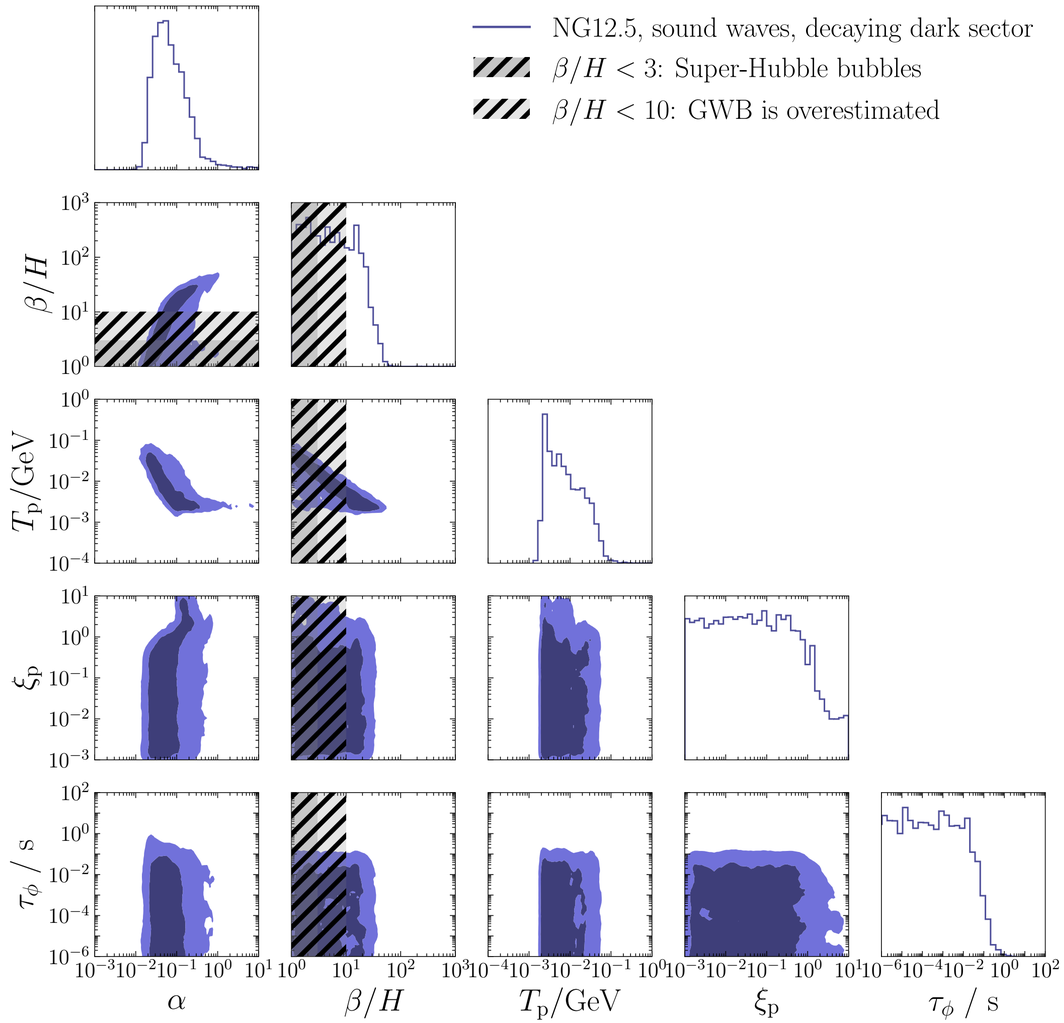
Giant „Hubble“ bubble sizes would be needed, violating causality & questioning validity of GW predictions

[CT et al, JCAP 11 (2023) 053]

The dark sector must die for the GWs to live...



If the dark sector decays before BBN, a great fit to PTA data can be achieved!



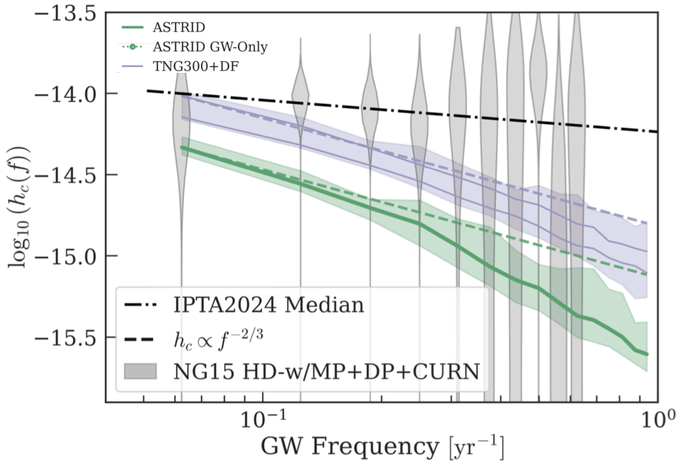
[CT et al, JCAP 11 (2023) 053]

New PTA data: higher peak frequency and slope

[NANOGrav, PPTA, EPTA, CPTA, InPTA, Meerkat]

Solution to the final parsec problem?

[Chiaberge+, 2501.18730]



What happened since July 2023?

Investigation of specific dark sector models

[2412.16282, 2501.11619,2501.14986, 2501.15649, 2502.04108, ...]

N-Body simulations: SMBHB unable to account for full GW signal

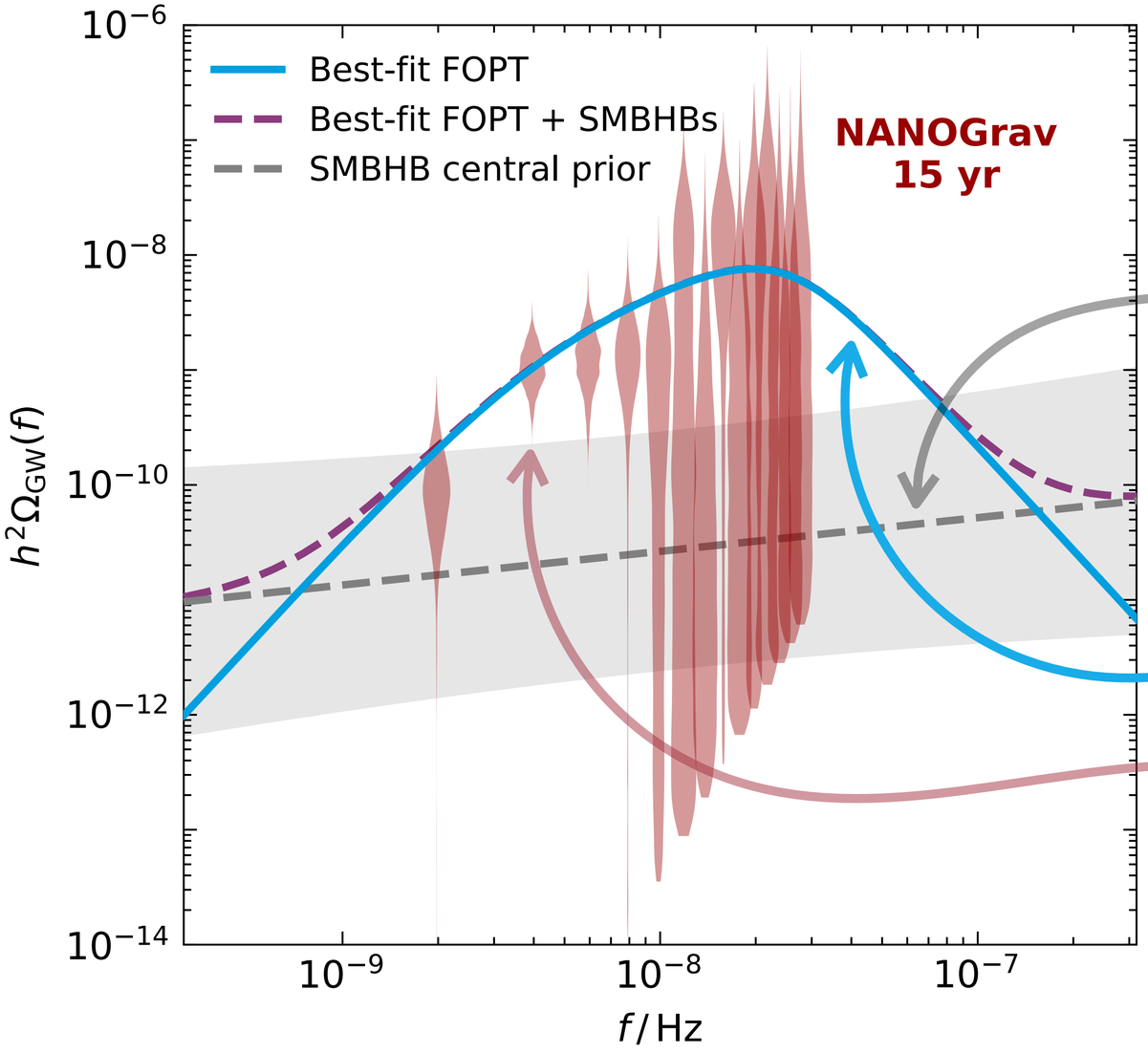
[Chen+, 2502.01024]

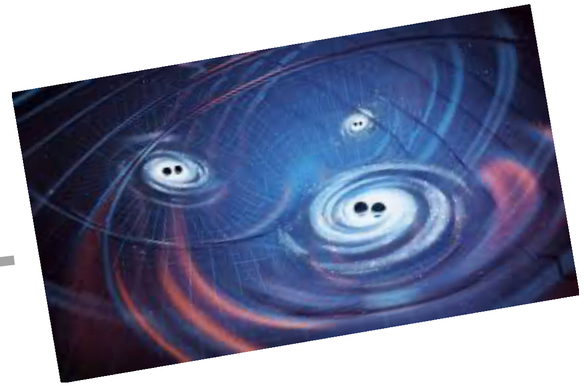
More constraints than just $\Delta N_{\rm eff}$?

CT+ [JCAP 08 (2025) 062]

Rest of this talk and my own focus

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.

Robust and self-consistent predictions for $T_{\rm reh}$

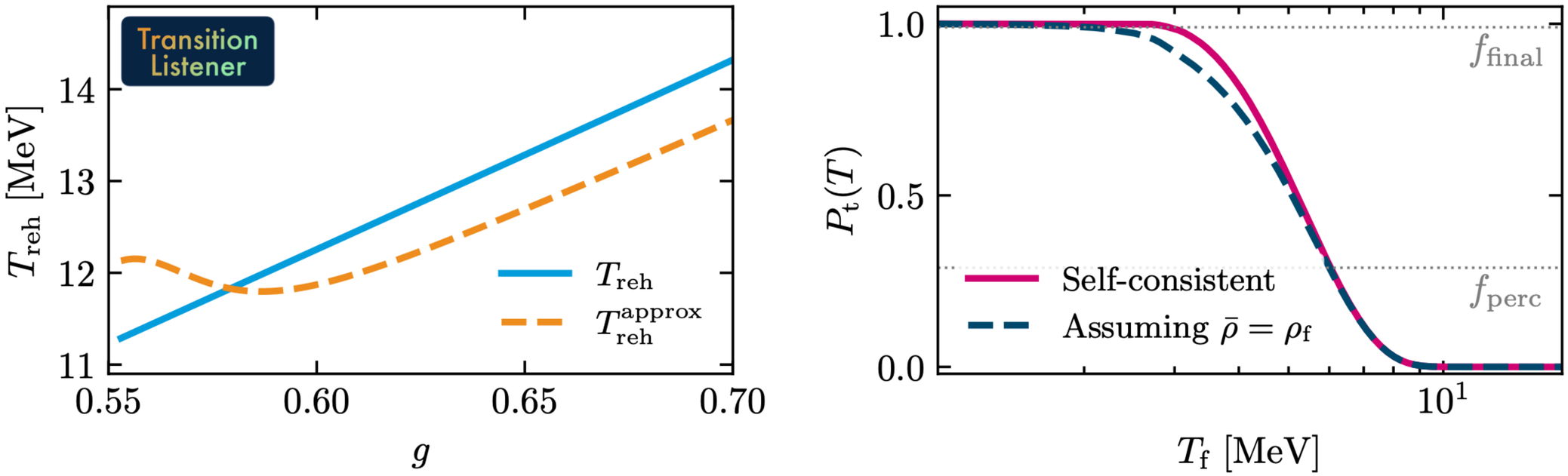
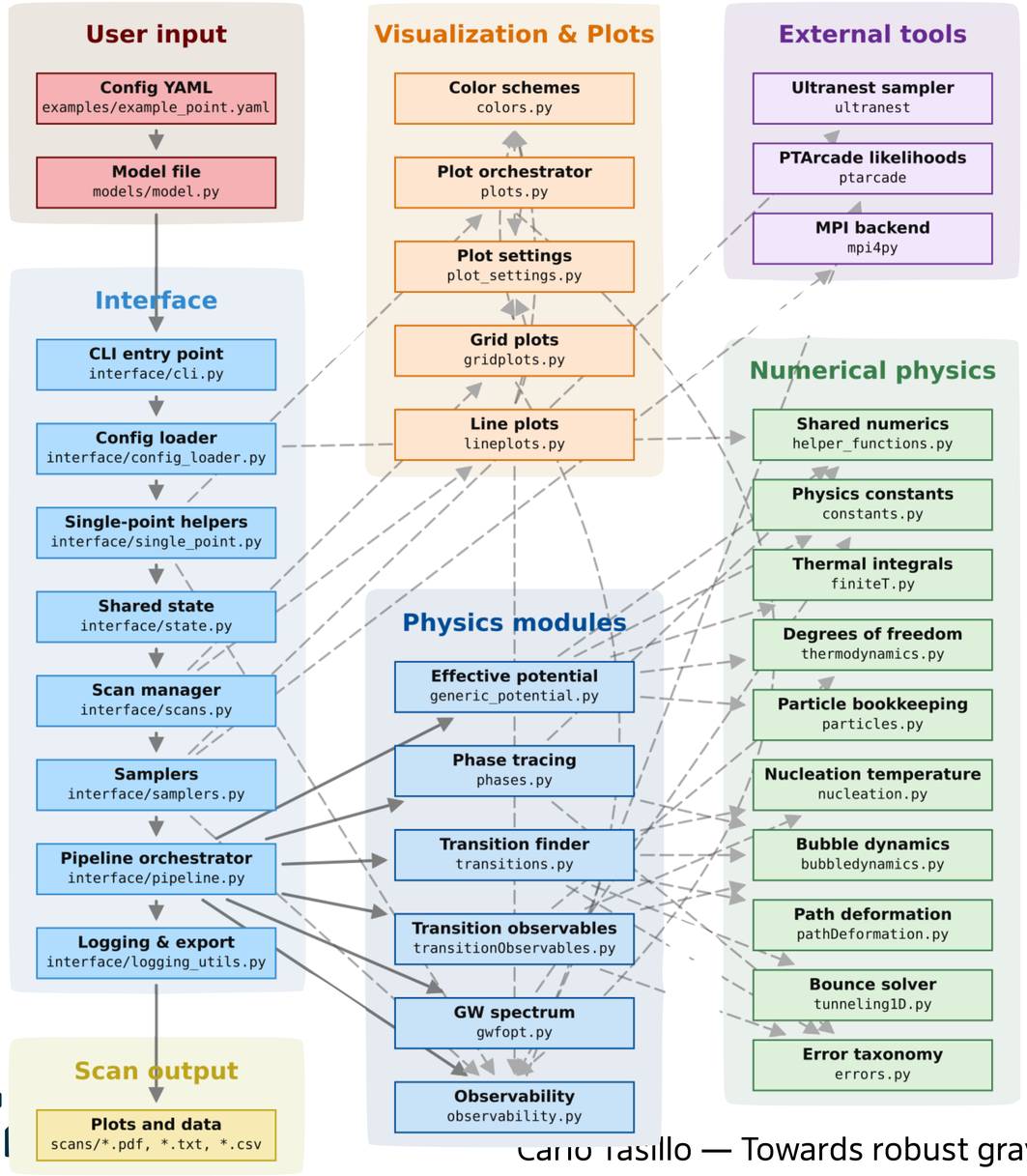
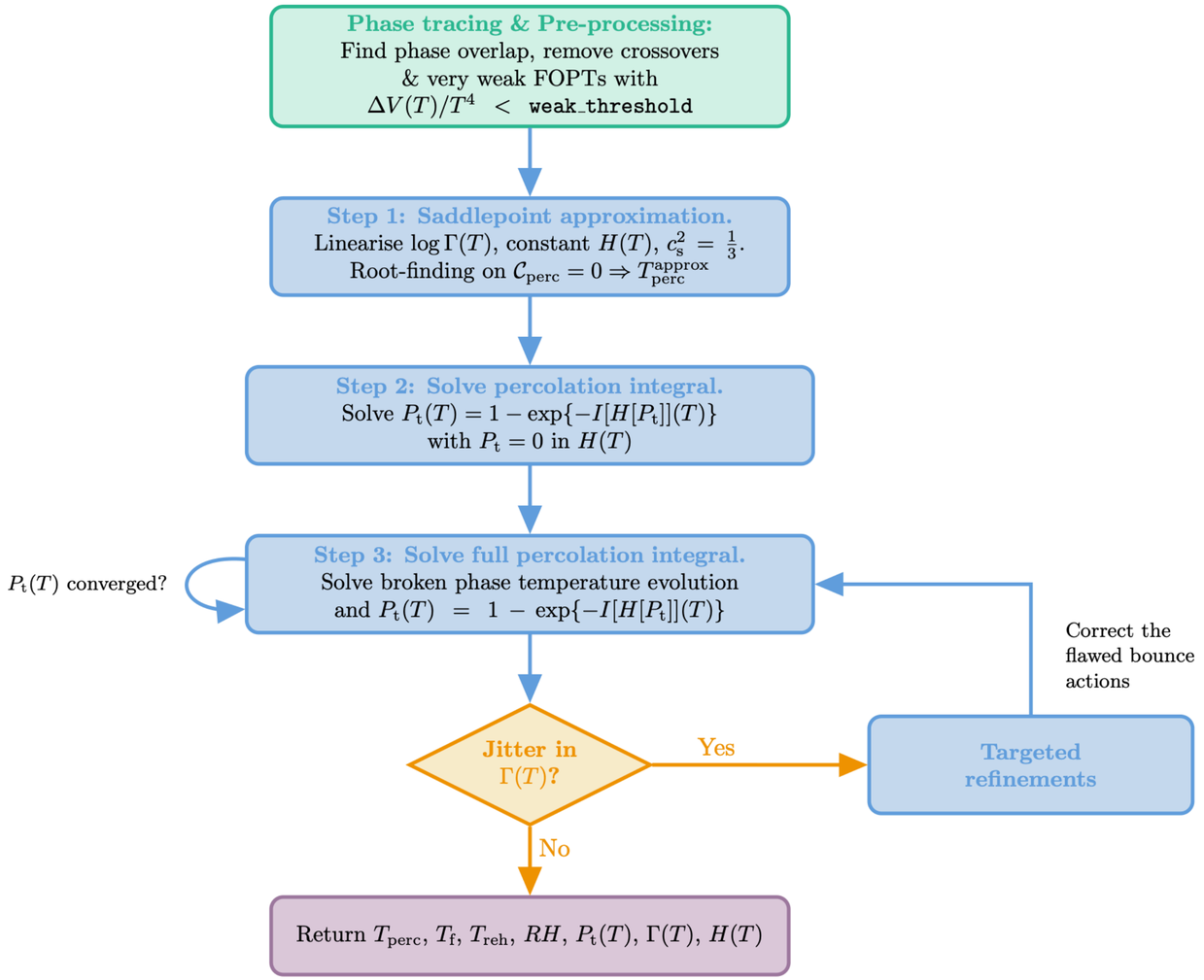


Figure 4: *Left:* Reheating temperature and its approximation $T_{\rm perc}^{\rm approx} = T_{\rm perc}\,(1+\alpha)^{1/4}$ as a function of the gauge coupling g in the conformal $U(1)'$ model ($y = 0.01$, $v = 140\,\text{MeV}$). *Right:* Comparison of the self-consistent and approximate ($\bar{\rho}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

Structure of TransitionListener v2.0





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 $I(T) = \frac{4\pi}{3} v_w^3 J_3(T)$, where

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

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

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.

An example config file for TransitionListener

```yaml
# 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
```

Automated `action` plot in `TransitionListener`

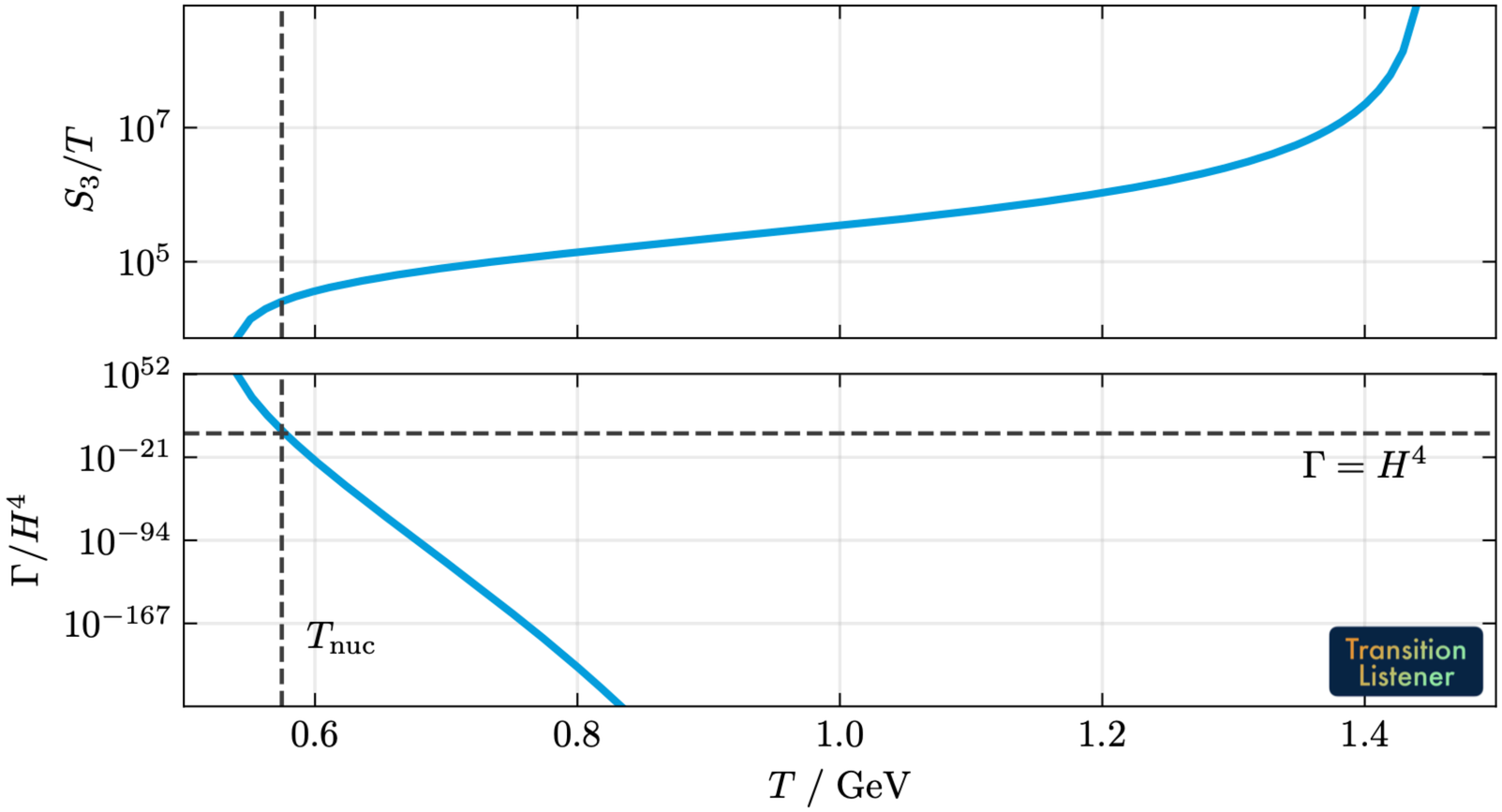


Figure 9: Output of the `action` plot option for the dark flipflop benchmark point 2 from table 1. *Upper panel:* Bounce action S_3/T in dependence of temperature. *Lower panel:* Corresponding bubble nucleation rate Γ in units of H^4.

Automated `profile` plot in `TransitionListener`

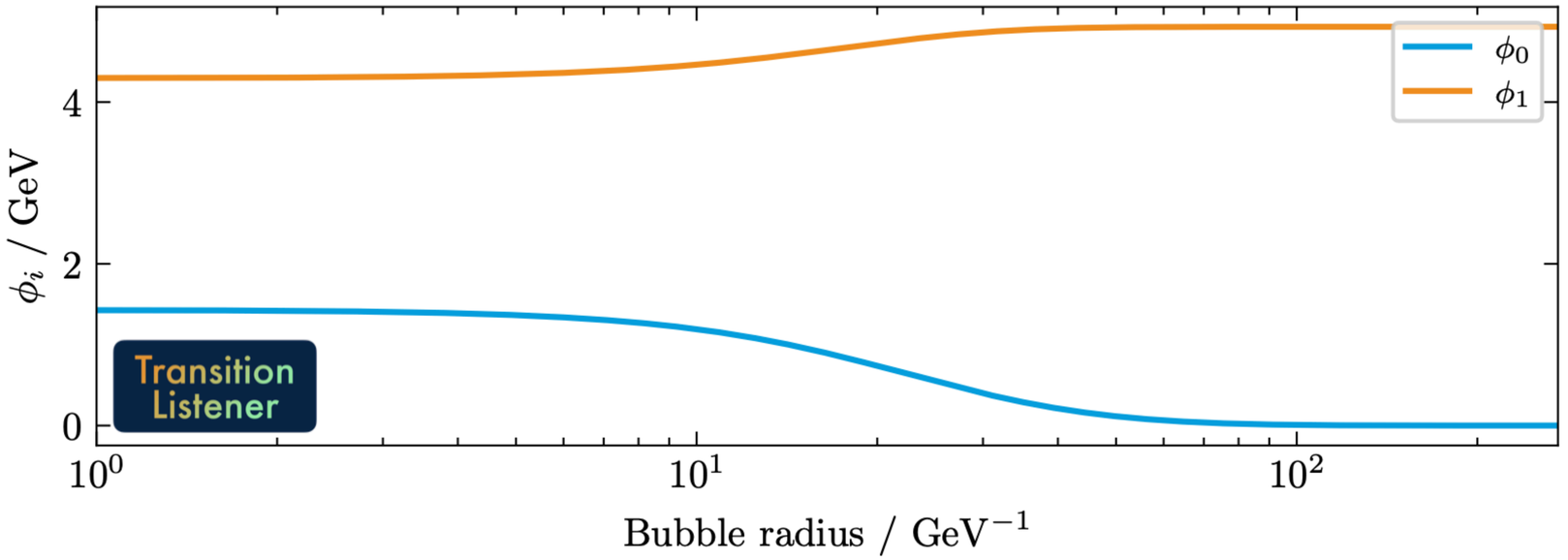


Figure 10: Bubble profile at nucleation for the dark flipflop benchmark point 2 from table 1, generated using the **`profile`** plot option. Inside the bubble, at $r = 0$, the fields approach their release point. At $r \to \infty$ (outside the bubble), the field values approach their false-vacuum values.

Automated `percolation` plot in `TransitionListener`

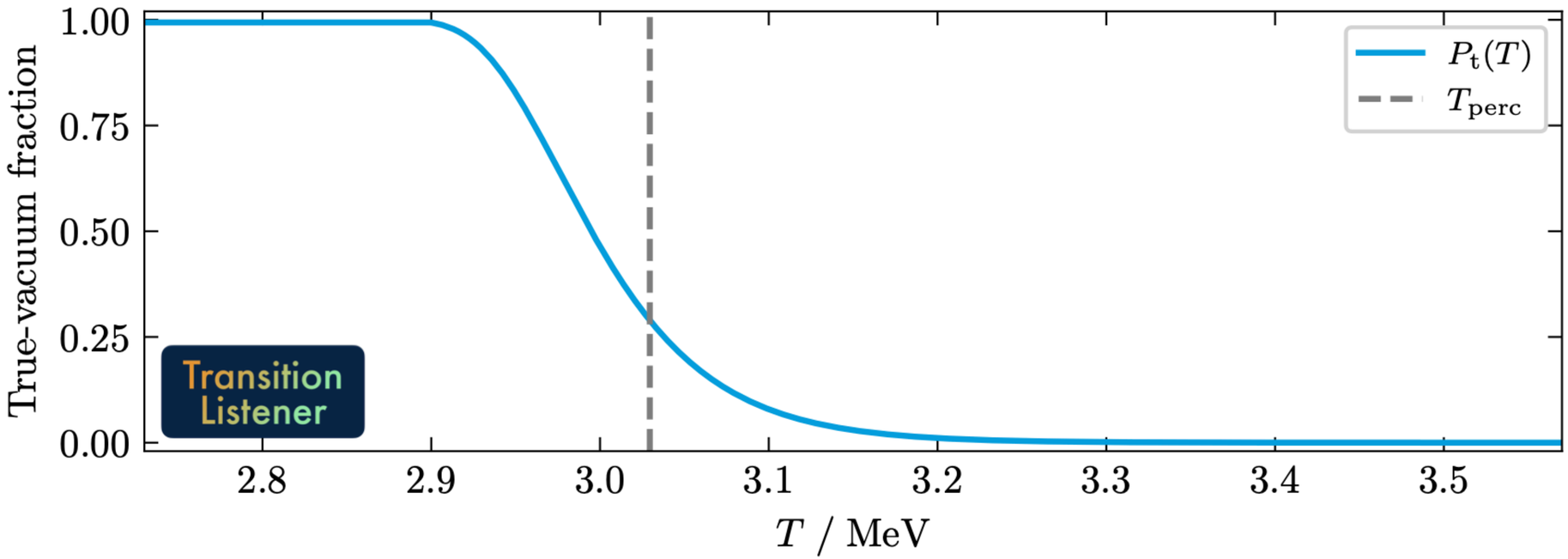


Figure 11: True-vacuum fraction evolution of the conformal dark $U(1)'$ benchmark point 1 from table 1 ($g = 0.7$, $v = 0.14\,\text{GeV}$ and $y = 0.01$), generated using the `percolation` plot option.

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

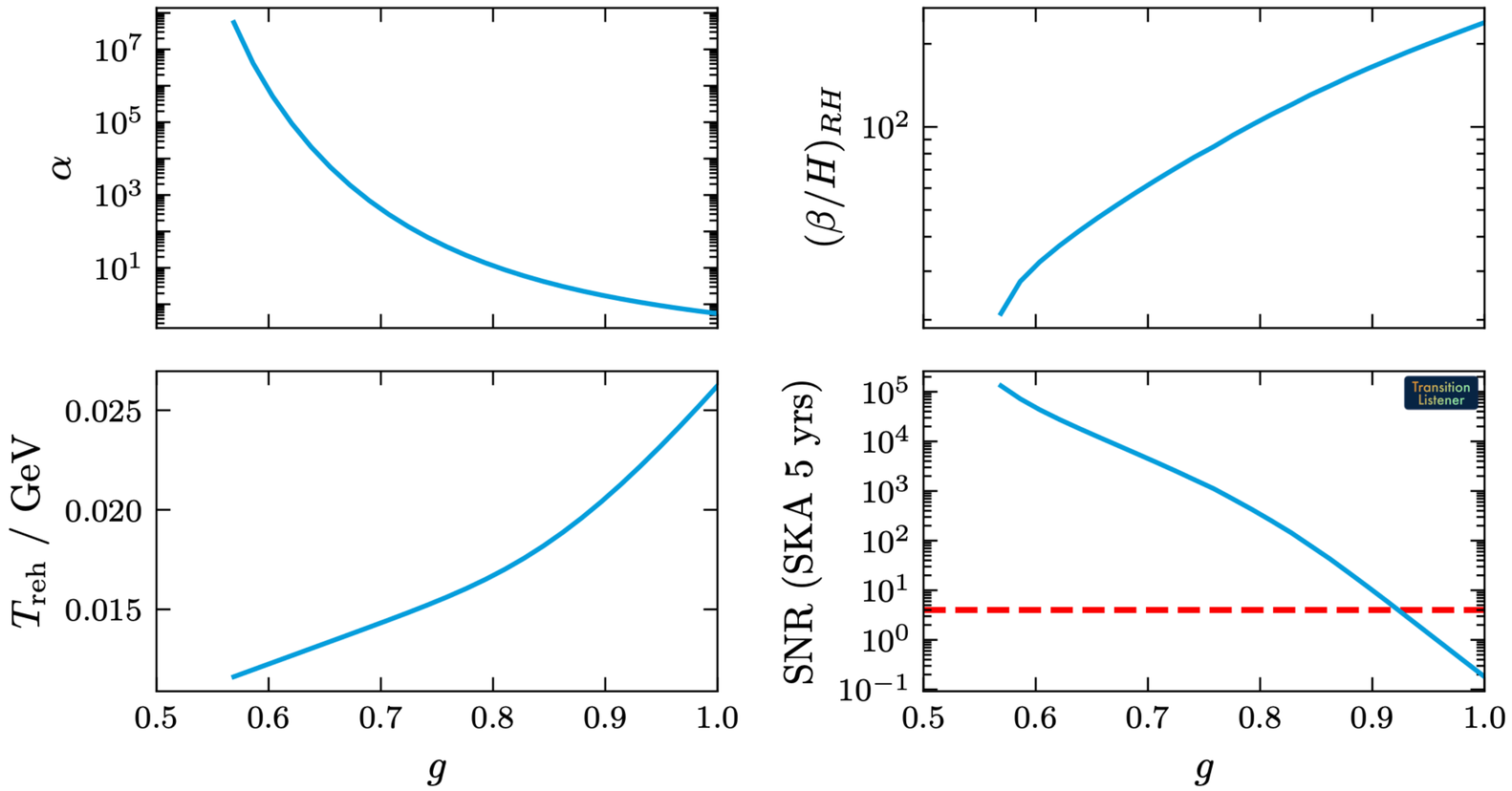
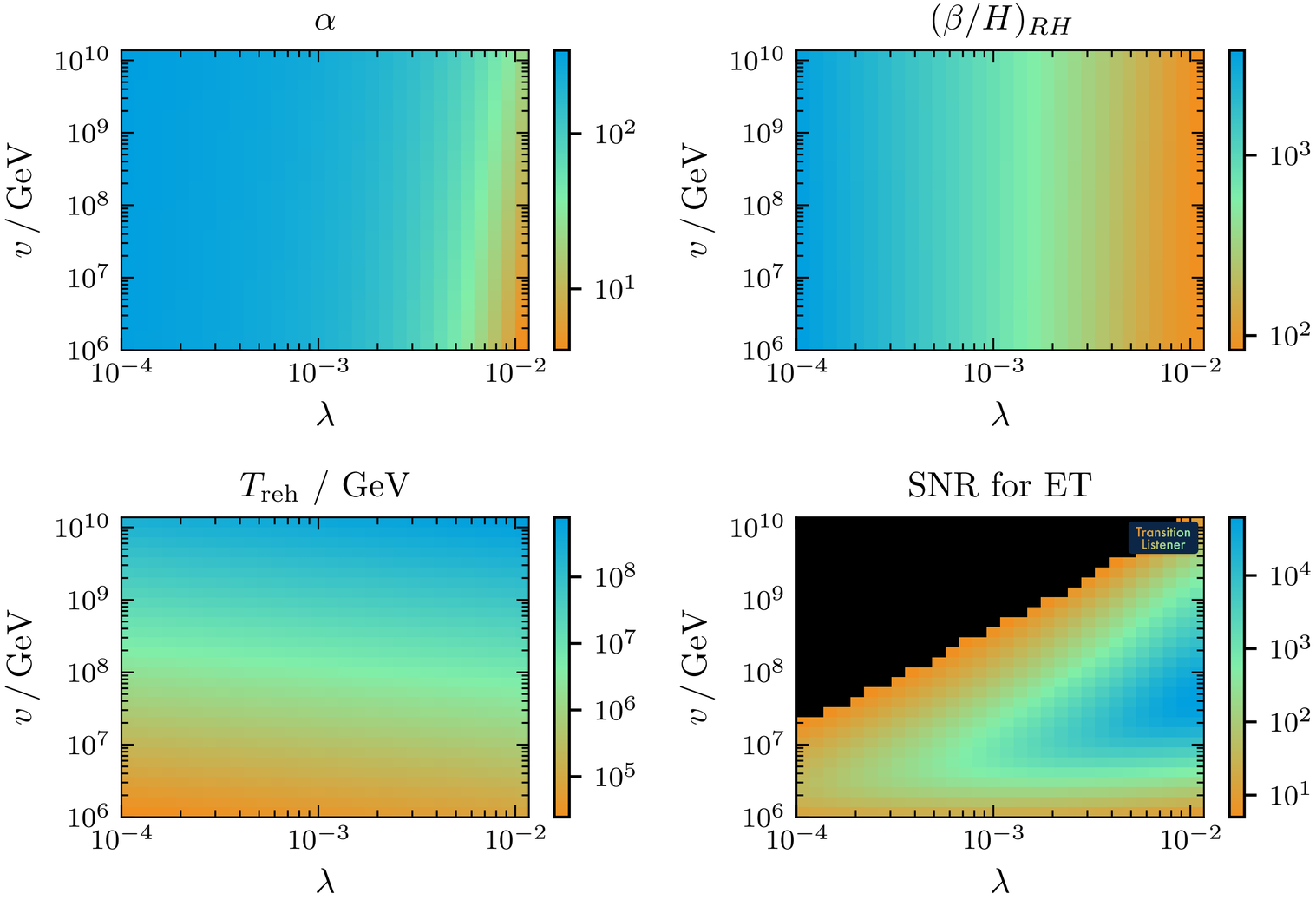


Figure 12: Overview plot of the example line scan based on the conformal model near the benchmark point from table 1, scanning g at fixed $y = 0.01$ and $v = 140\,\text{MeV}$. The fourth panel shows the expected SNR after 5 years of data taking at SKA. The red dashed line indicates the detection threshold.

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



Comparison of `TransitionListener` with other packages

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

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 $P_{\rm t}$. 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 $v_{\rm w} = v_{\rm w}^{\rm LTE}$ and $T_* = T_{\rm perc}$, but also allows other choices.

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

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

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

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

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

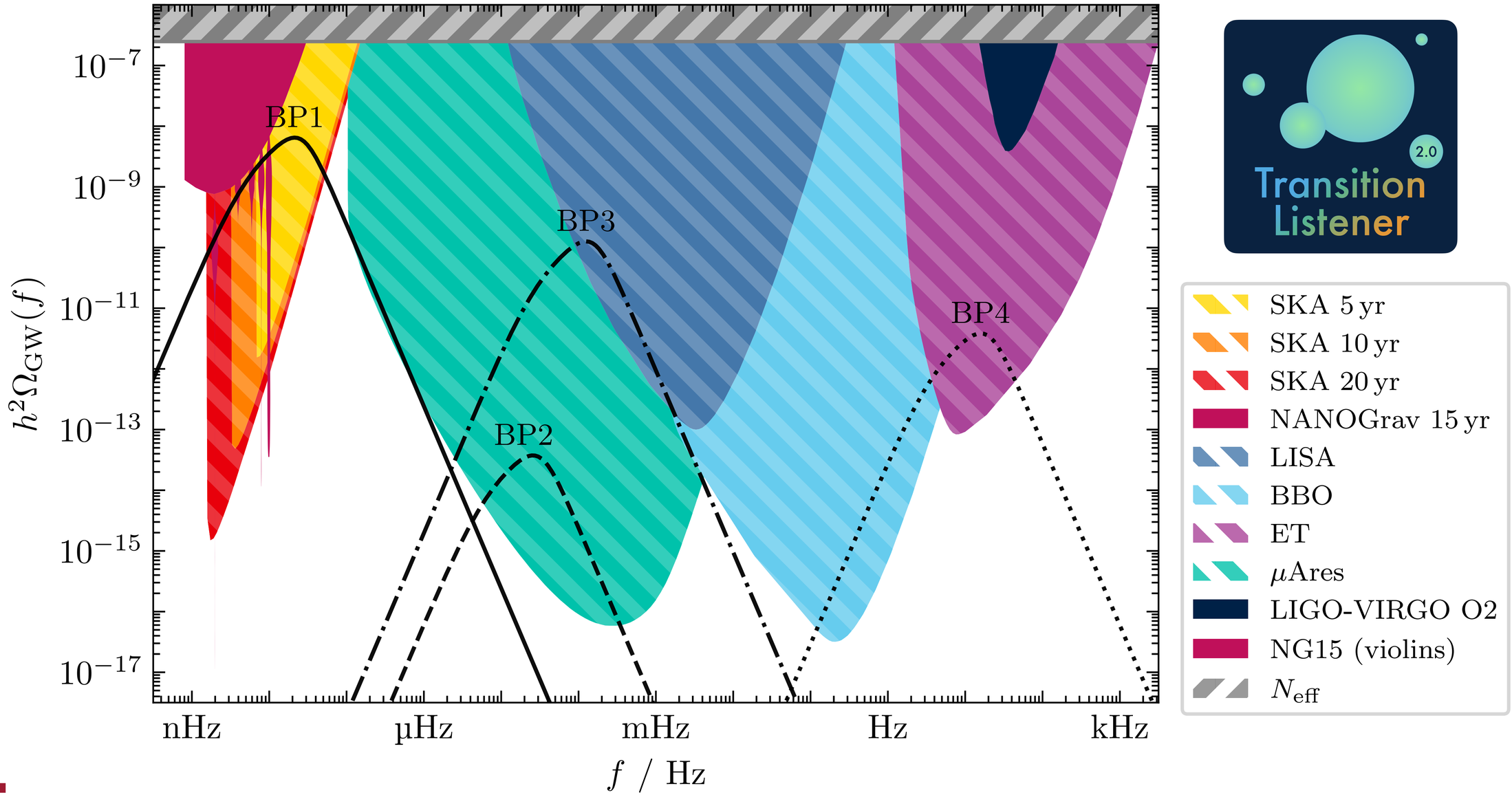
$$R_{\rm sep}(t_{\rm perc}) = \frac{1}{n(t_{\rm perc})^{1/3}} \approx \left(\frac{8\pi}{f_{\rm perc}}\right)^{1/3}\frac{v_{\rm w}}{\beta} \tag{C.3}$$

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

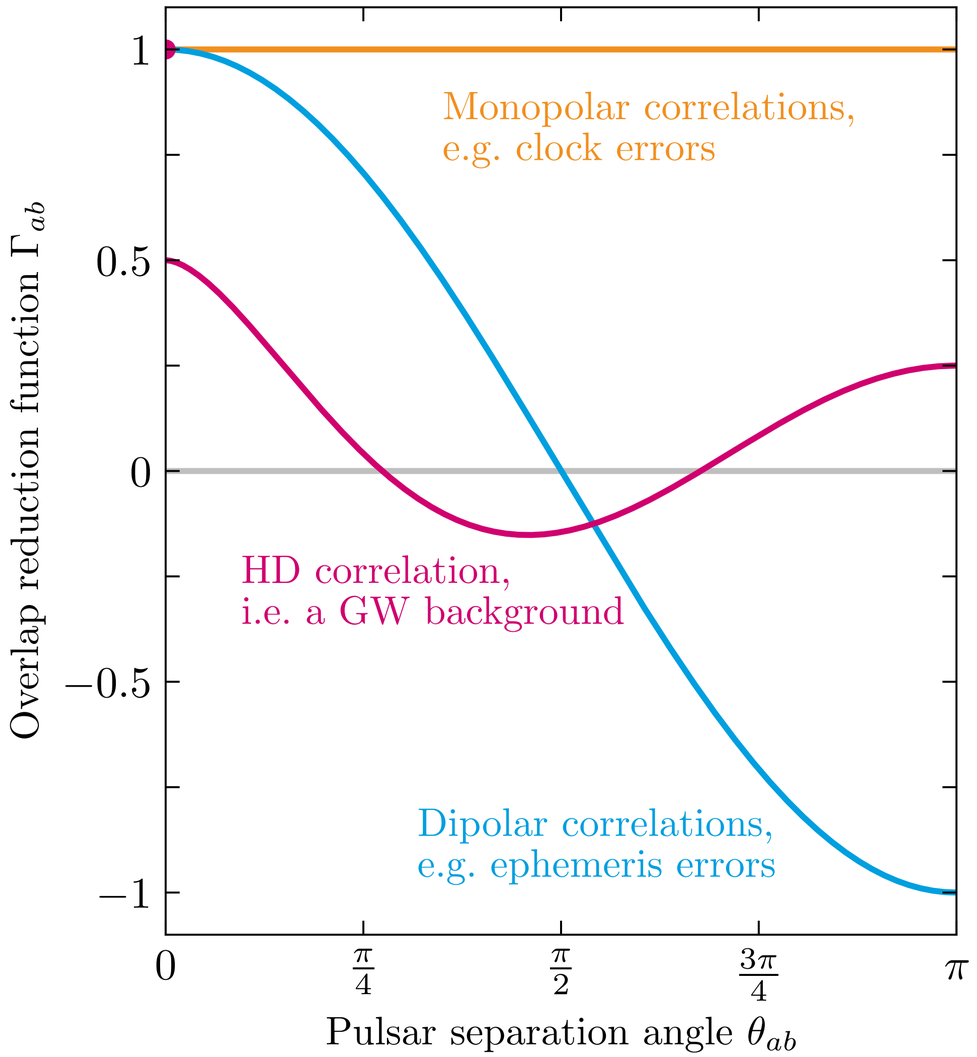
Error classes in `TLv2`

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.

Selection of the implemented sensitivity curves in TLv2



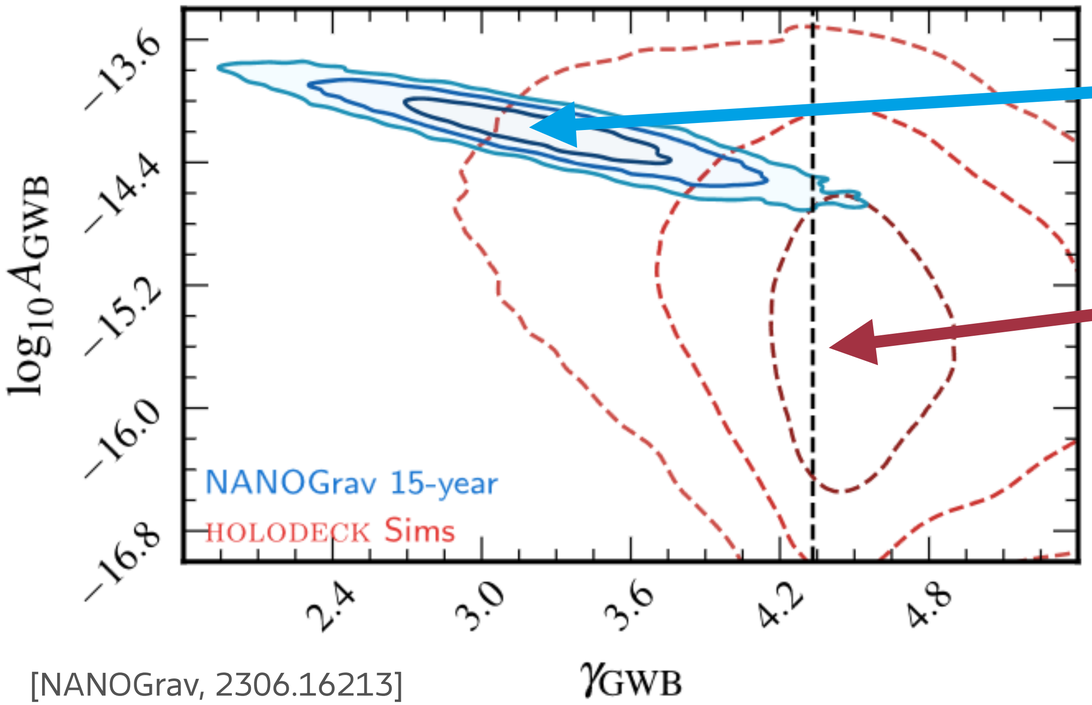
Searching for the Hellings-Downs correlation



- 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 $>5\sigma$ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]



Merging supermassive black holes

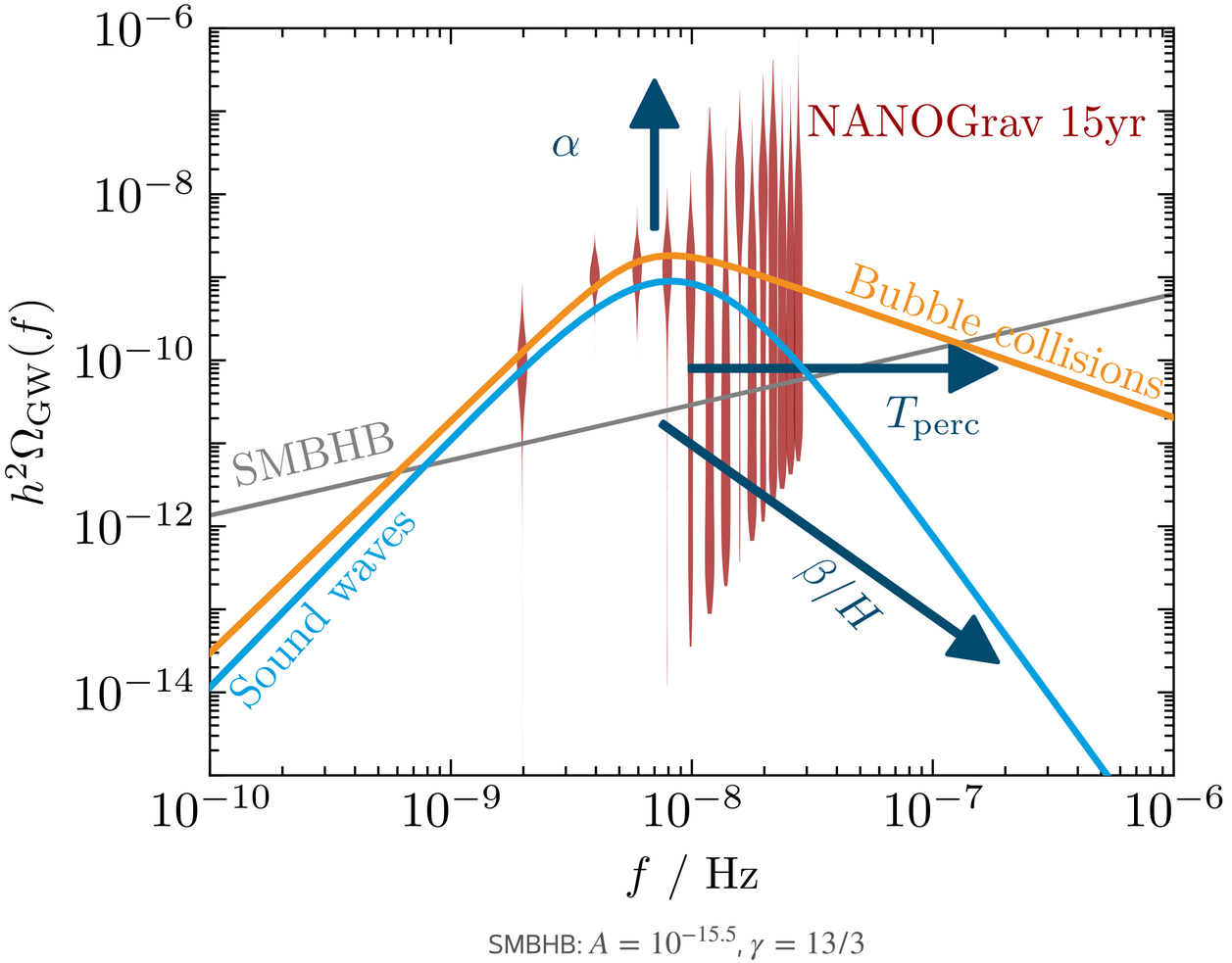


[NANOGrav, 2306.16213]

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

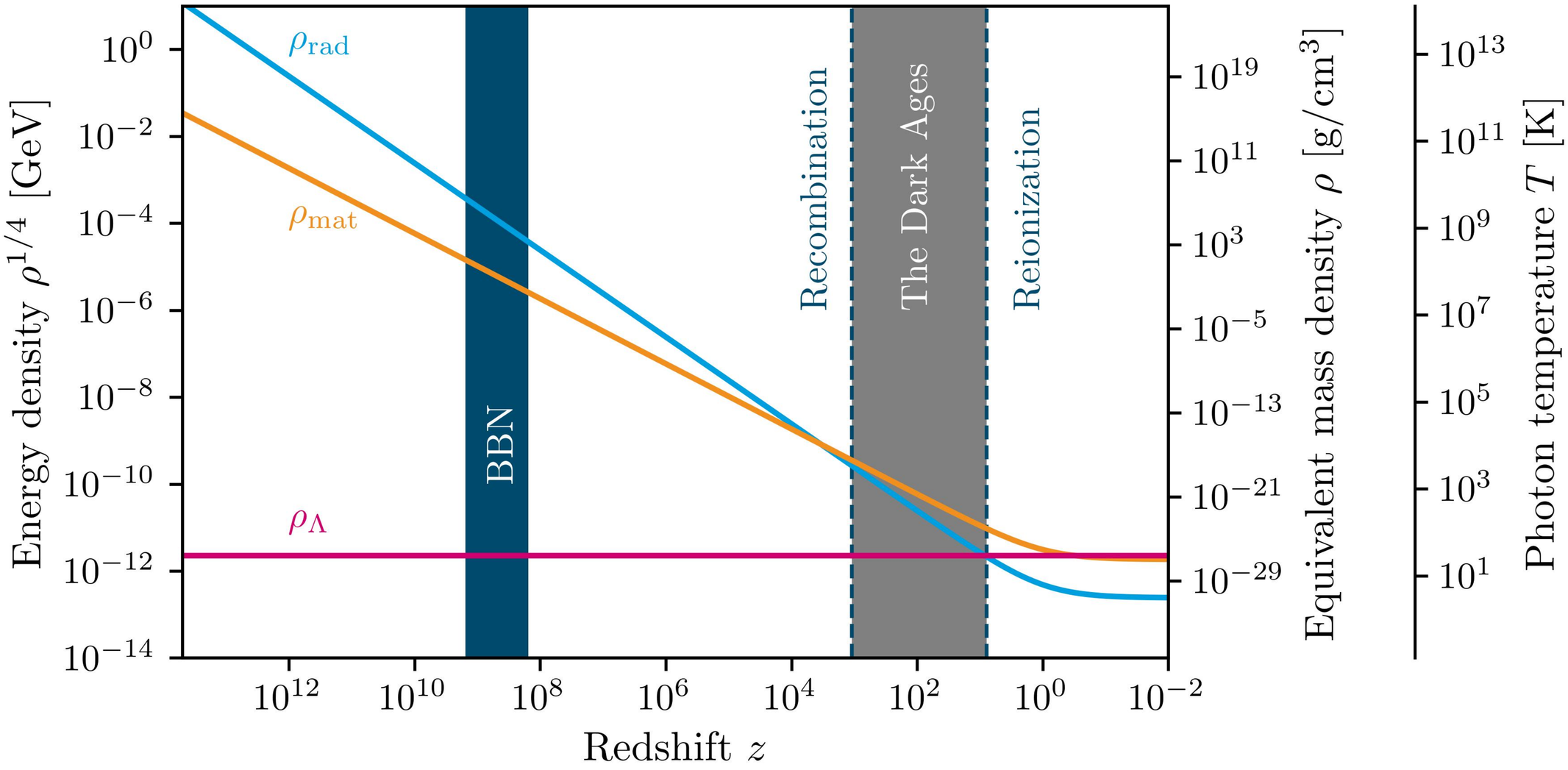
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{H}{\beta}\right)^{1,2} \mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

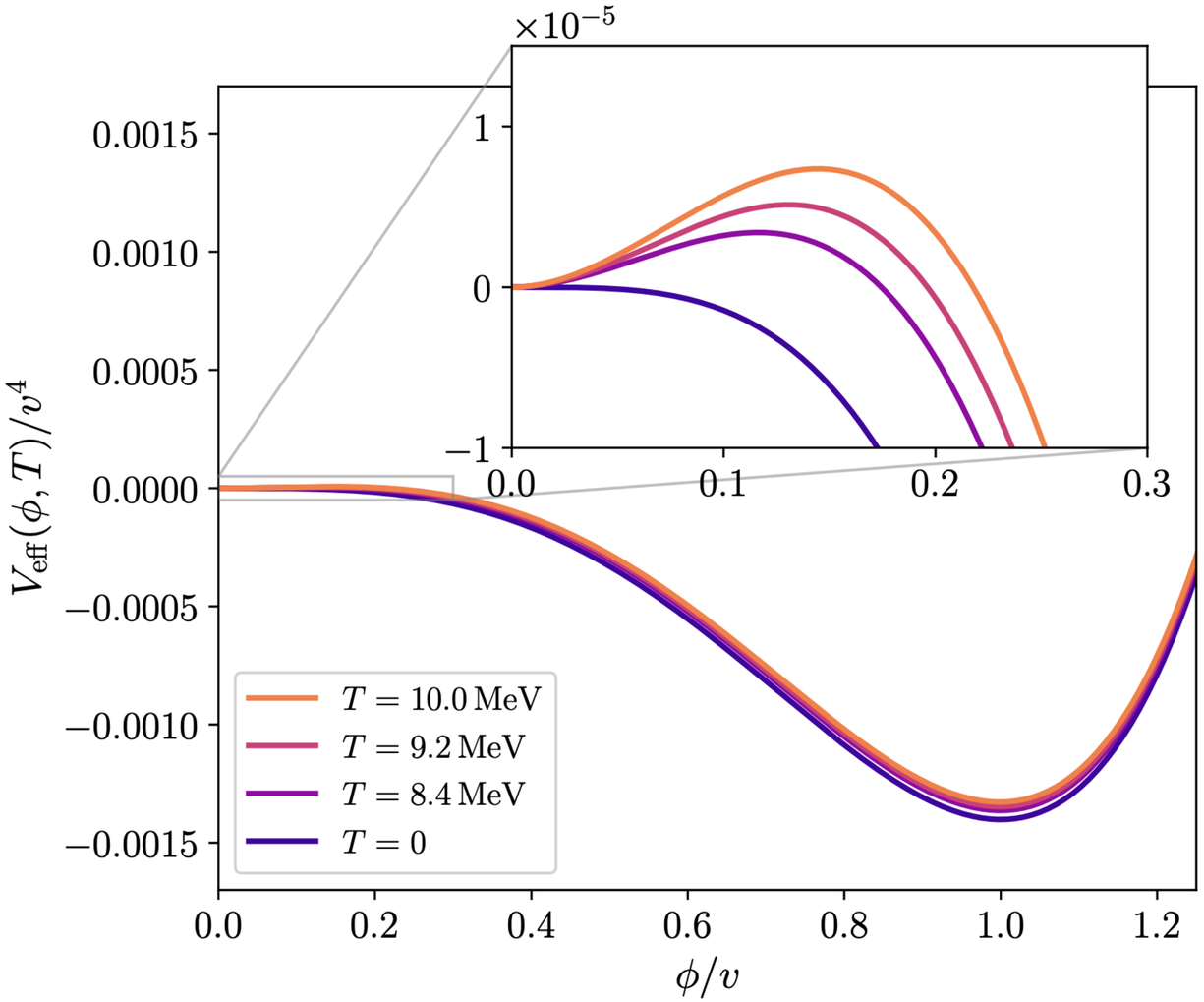
To fit the new pulsar timing data:

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

A brief history of time



How to be supercool 😎



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

Quantum and thermal corrections

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

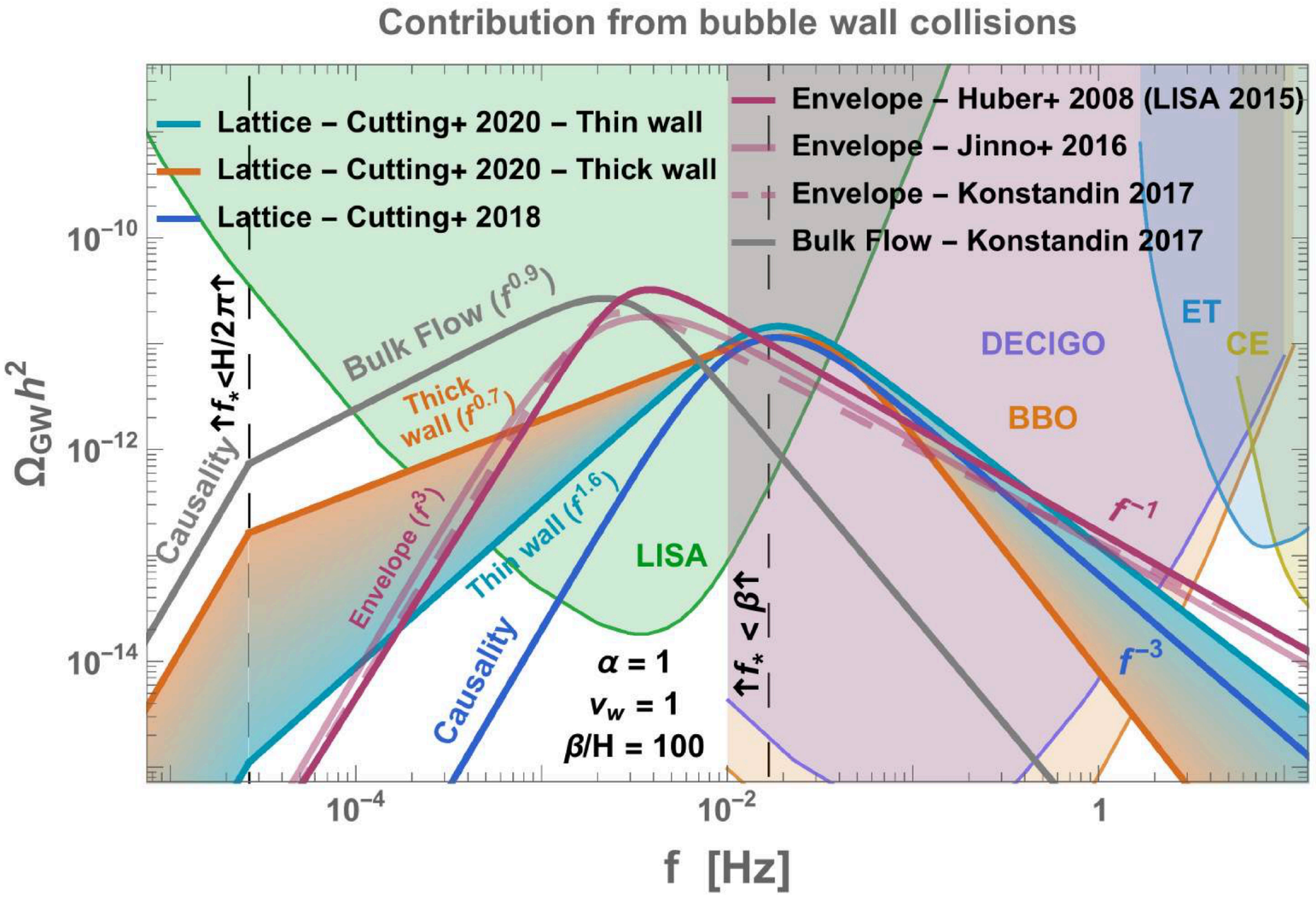
Loop-induced barrier down until very low temperatures, i.e. strong supercooling

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]

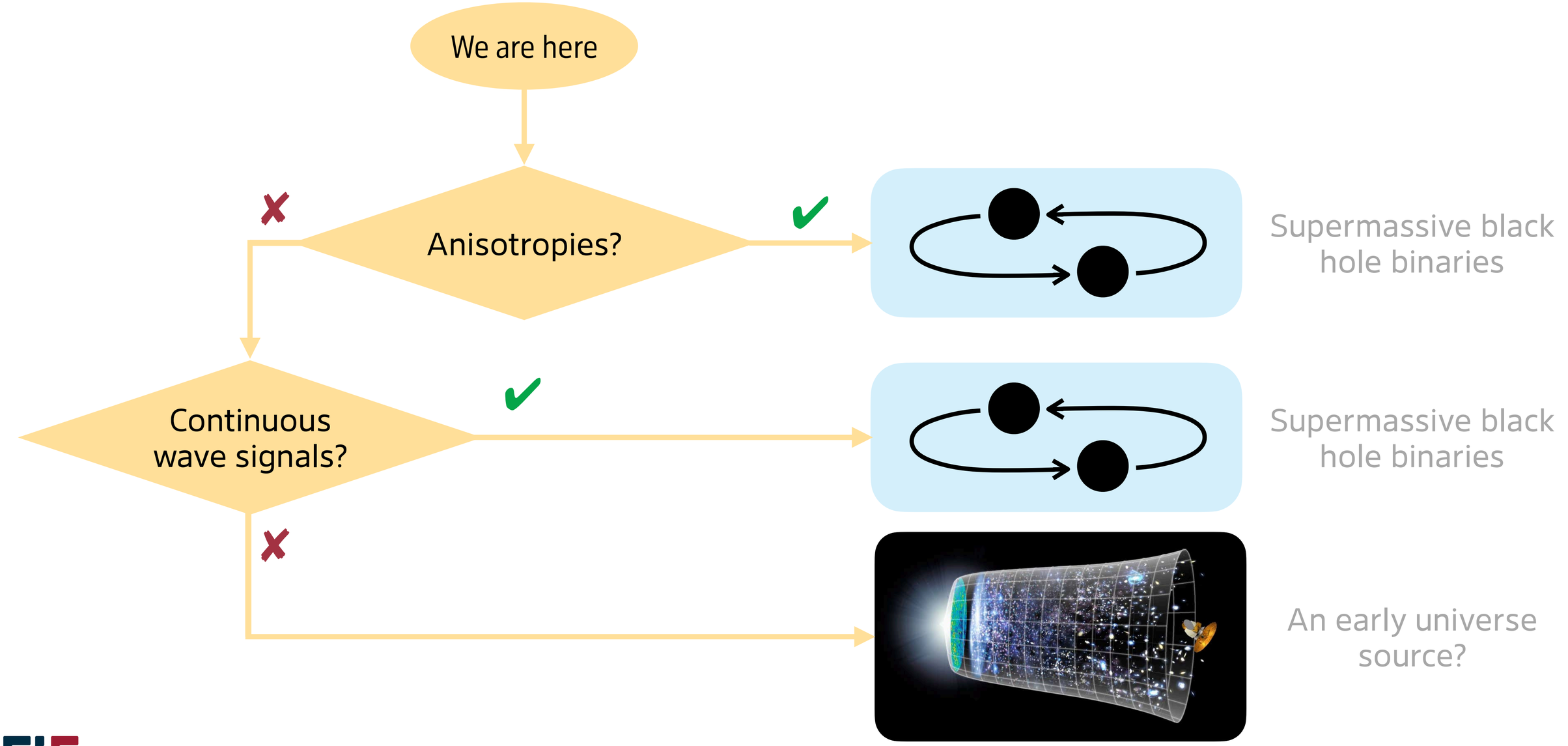
	IR	Intermediate	UV	References
Sound shell	9	1	−3	[22, 23]
Scalar + fluid lattice	—	1	−3	[18, 20, 21, 29]
Hybrid	[2,4]	[−1,0]	[−4,−3]	[30]
Higgsless	3	1	−3	This work

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



Yann Gouttenoire: Beyond the Standard Model Cocktail

Quo vadis pulsar timing?



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

