

# Robust phase transition predictions for PTAs and LISA

## First Granada workshop on phase transitions

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**Institut de física corpuscular (IFIC)**

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

arXiv: 2502.19478, 2602.09092, 2605.15259, 2608.23679, 2x in preparation

UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

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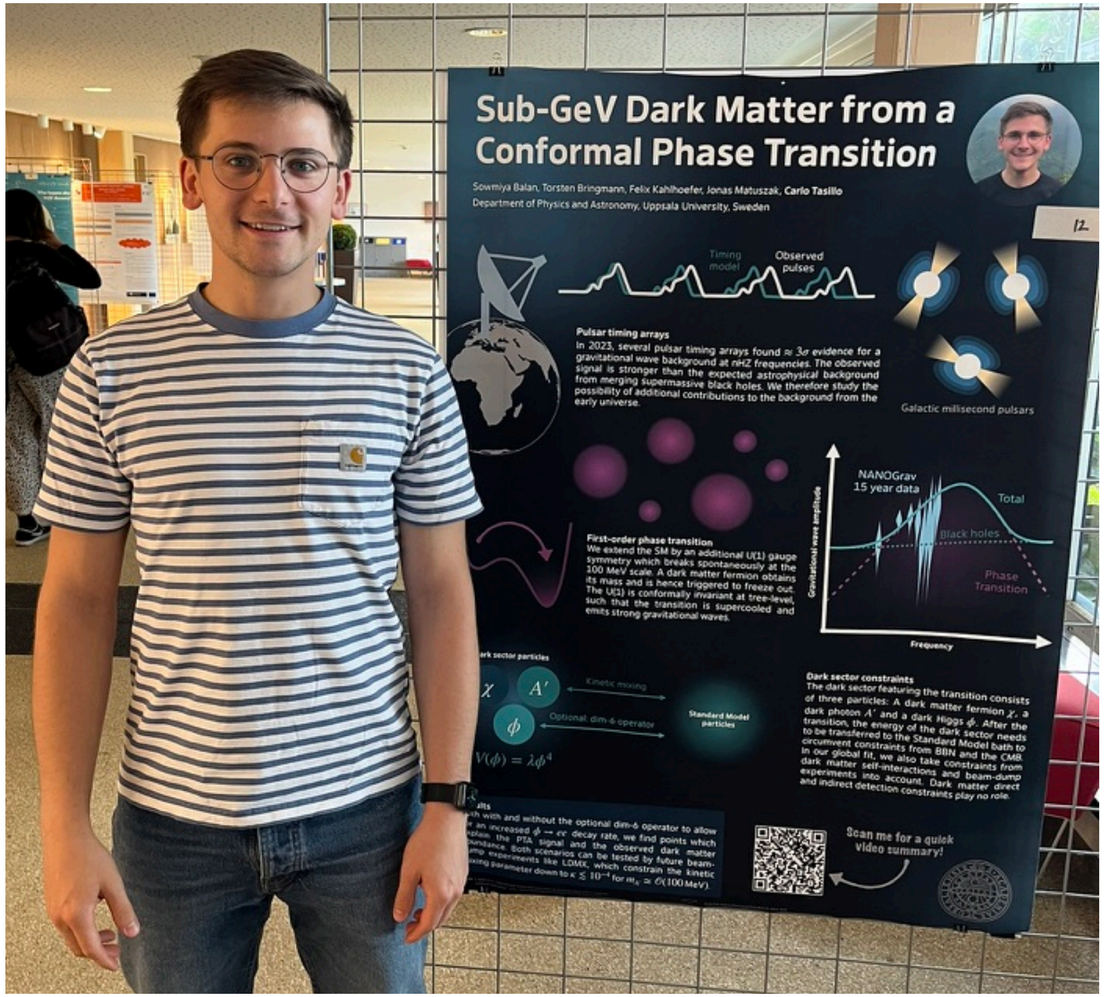
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EXCELENCIA SEVERO OCHOA

# My research since 2023: Phase transitions and PTAs






**It's time to recap what happened since then and what the next challenges will be**

## June 2023

- NANOGrav, EPTA, PPTA, and CPTA find strong evidence for a nHz background
- New physics ambulance chasing
- Astrophysical predictions span orders of magnitude
- No consensus on SMBHBs vs. new physics

## 2023 — 2026

- Meerkat PTA and InPTA. IPTA DR3?
- First global fits
- Conformal models in dimensional reduction
- Errata: no evidence for SMBHBs, broken PTA analysis pipeline
- Still no consensus on SMBHBs vs. new physics

## The future

- IPTA DR3?!
- Global fits with control over modeling uncertainties and astrophysical nuisance
- The absence of PTA discreteness as an argument for phase transitions?
- Preparation for analogous LISA case

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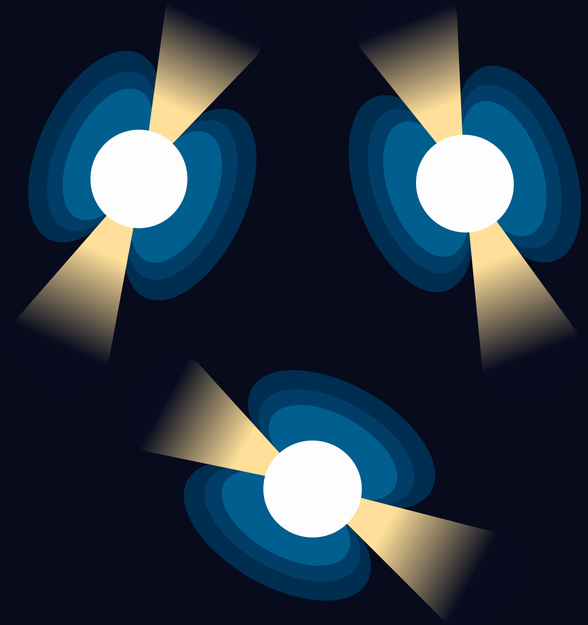
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**But let's start slowly and see what the data tells already**

# The working principle of a pulsar timing array



Galactic millisecond pulsars



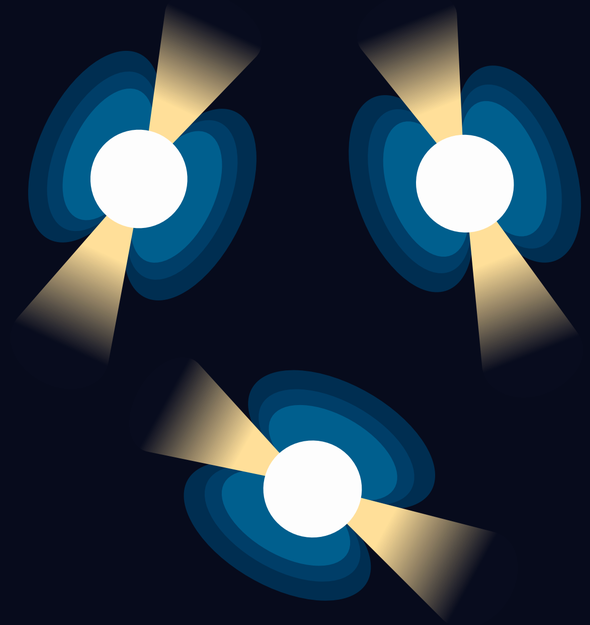
# The working principle of a pulsar timing array





Pulses expected
from timing model

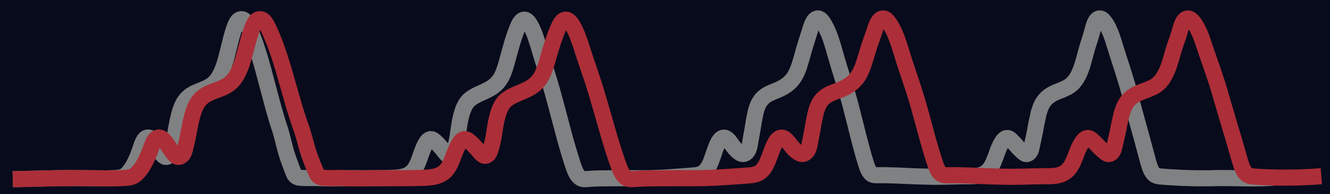
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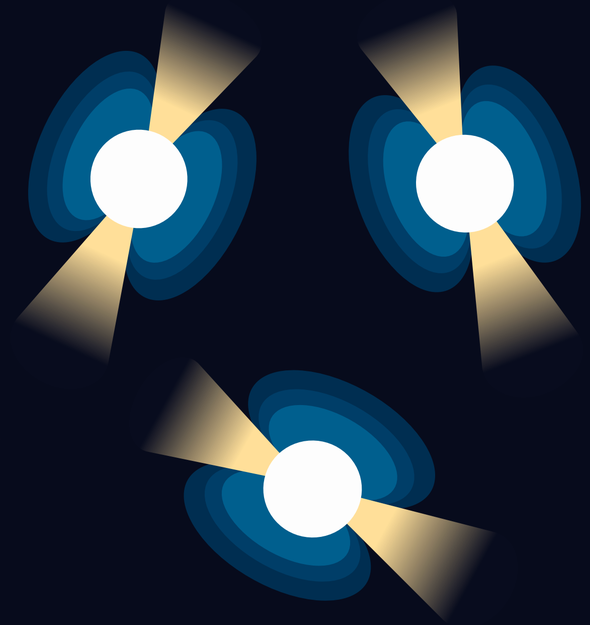
Galactic millisecond pulsars





Pulses expected from timing model

Pulses recorded by radio telescopes

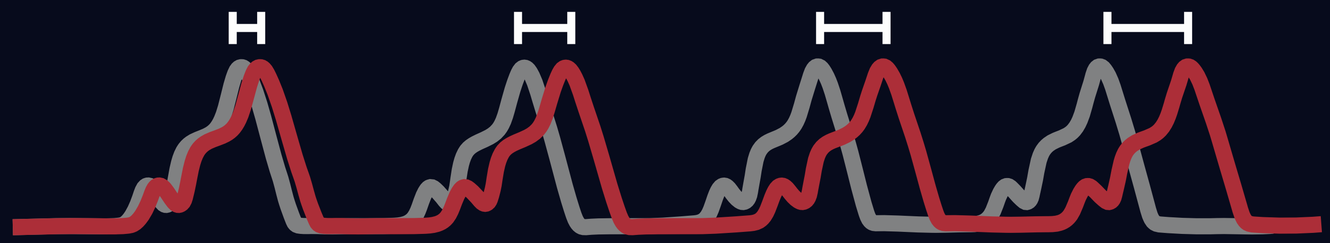


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Galactic millisecond pulsars

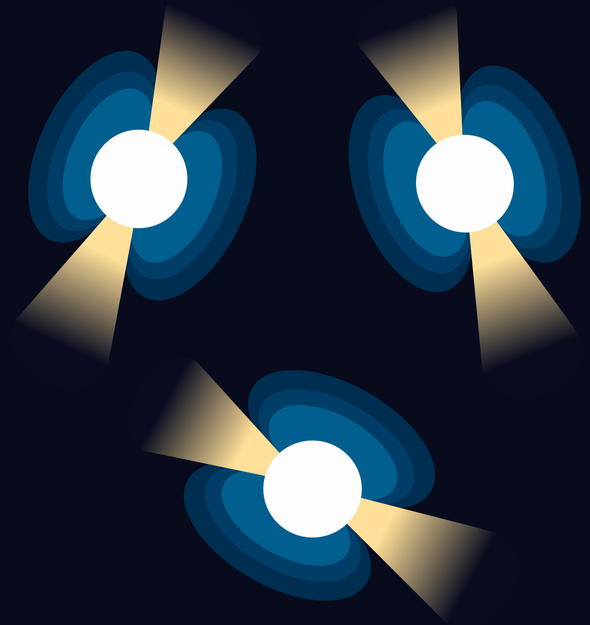


Timing residuals $\delta t$



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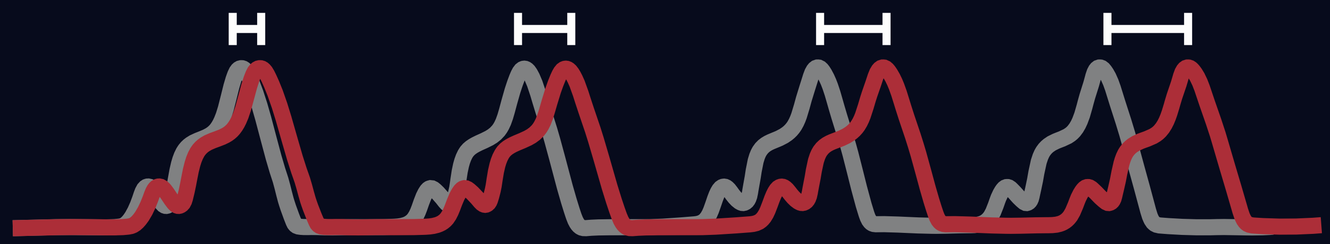


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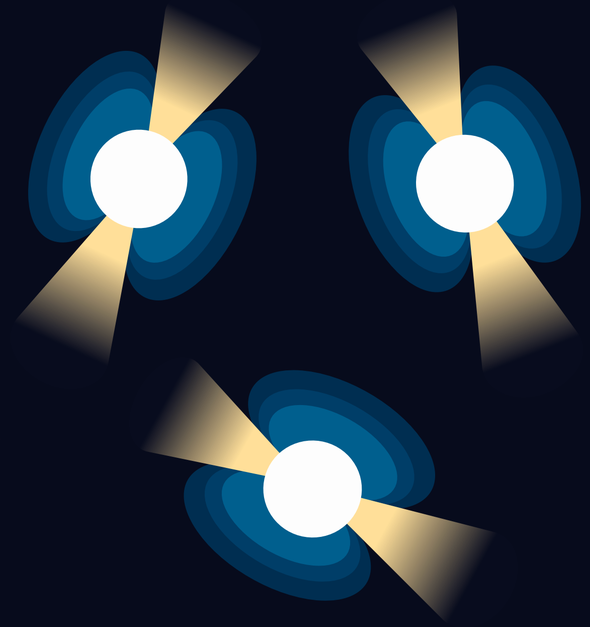


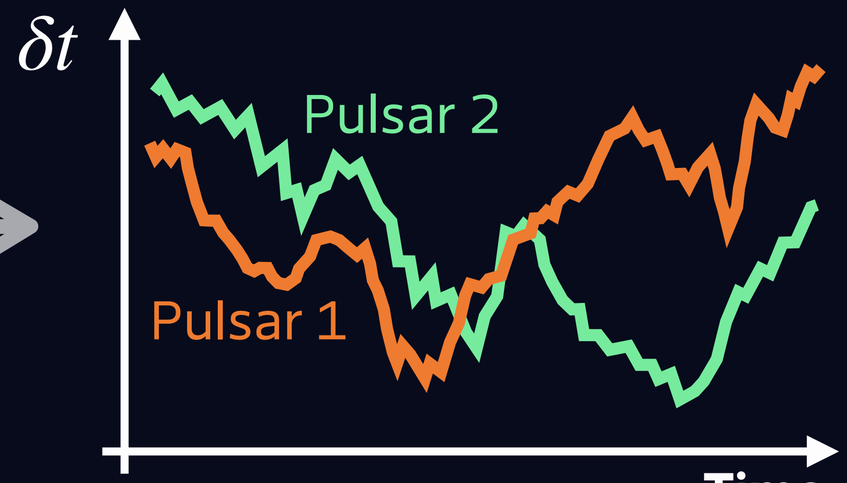
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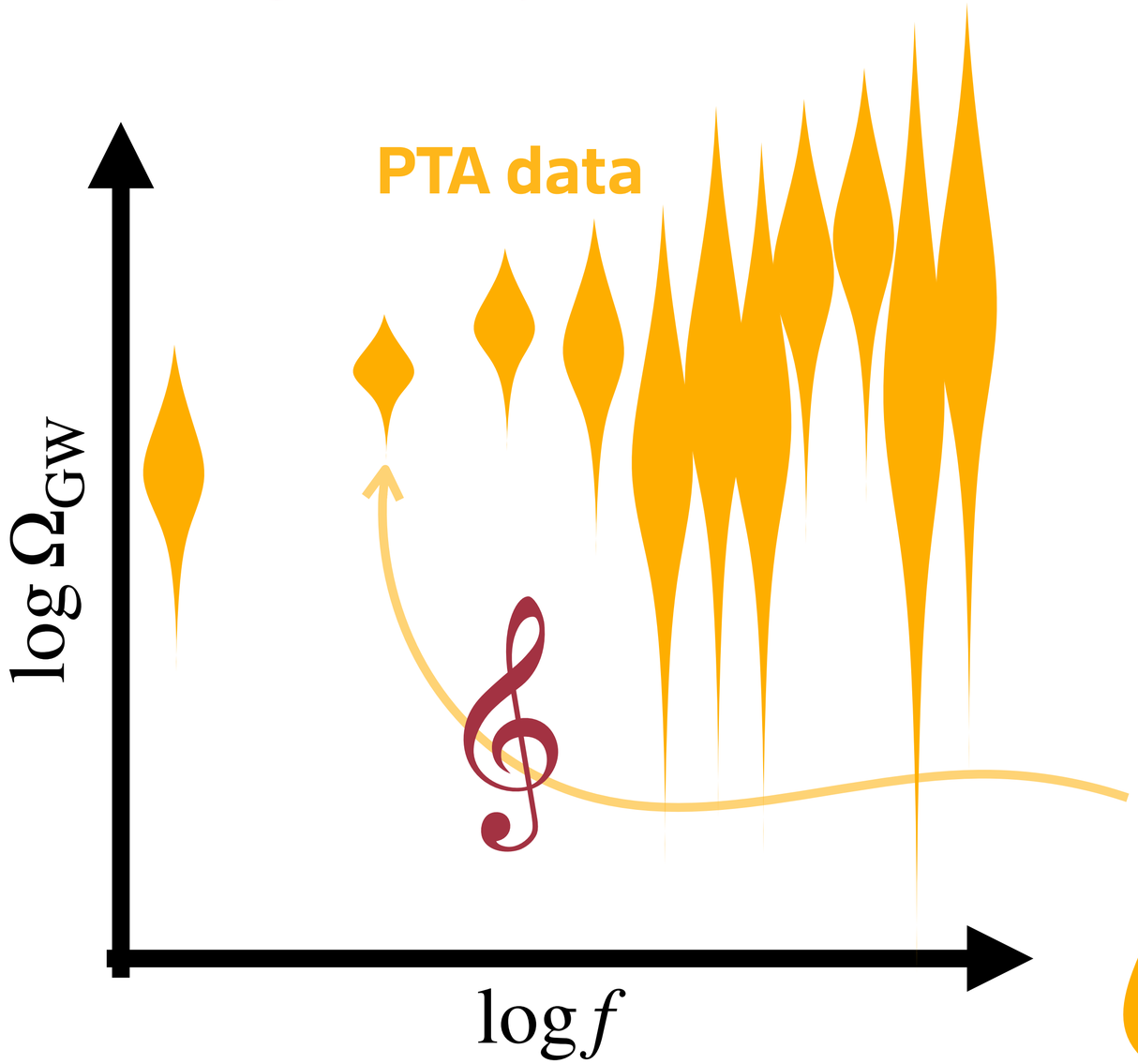
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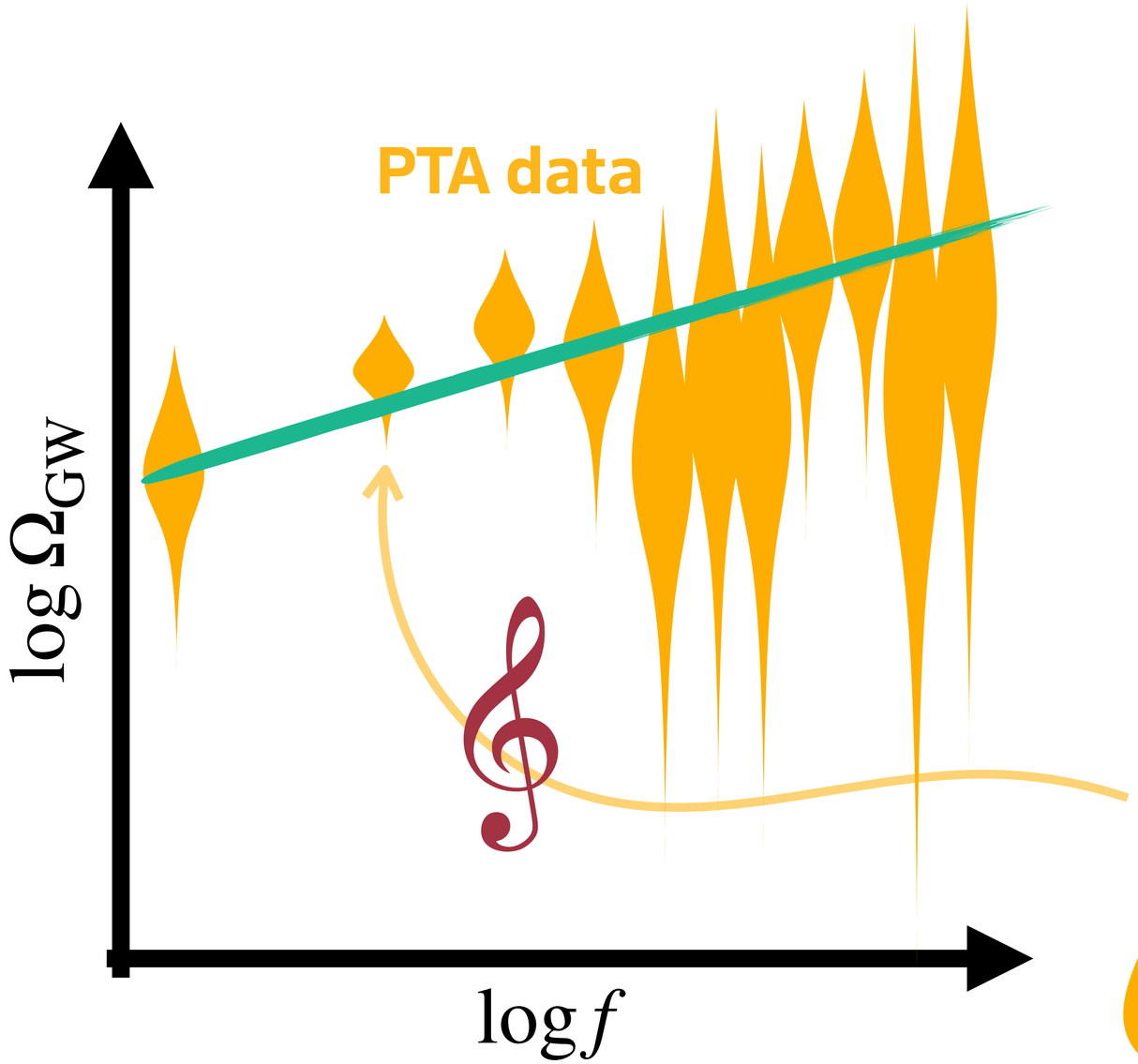

**A gravitational wave backgrounds imprints itself in the common evolution of the timing residuals over time**

# 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 of a given frequency.**

# Learning to play the violin

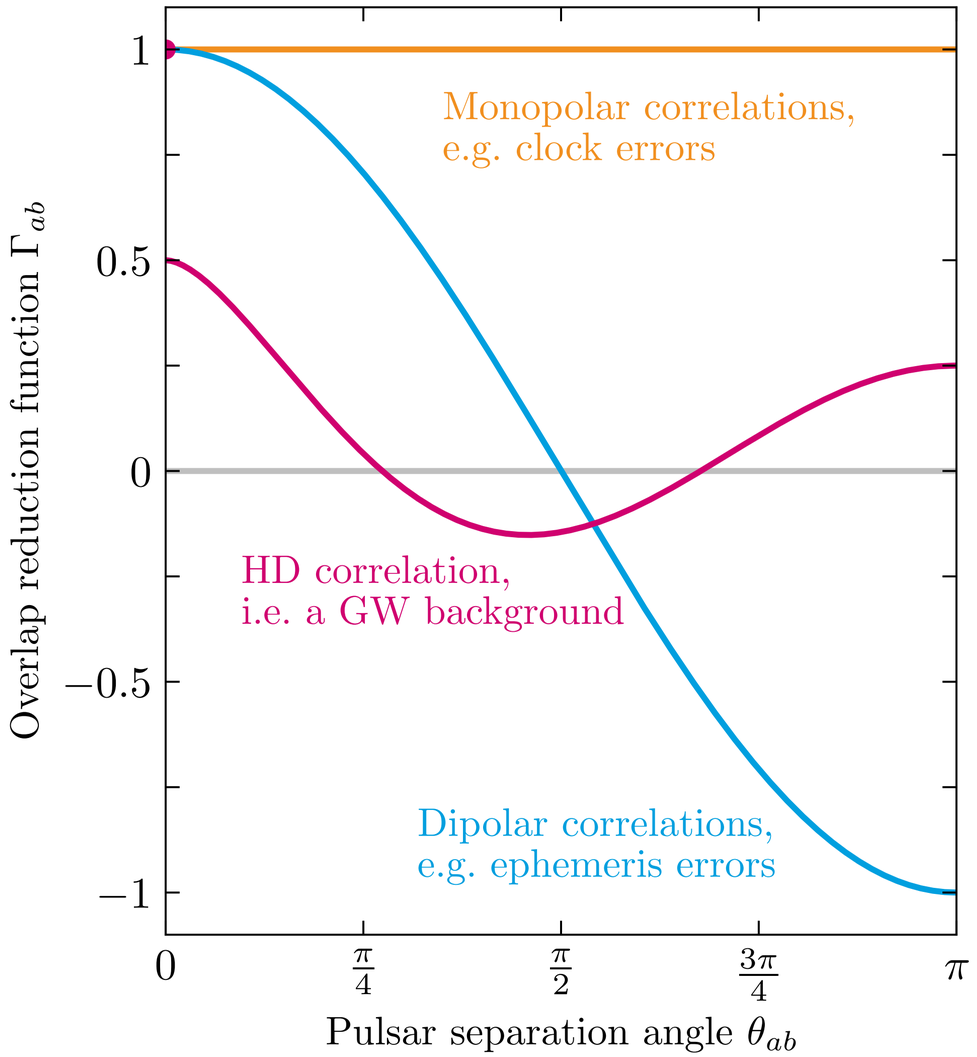



## The inferred spectral shape of the GWB is to first approximation a power law

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

**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.**

# 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]

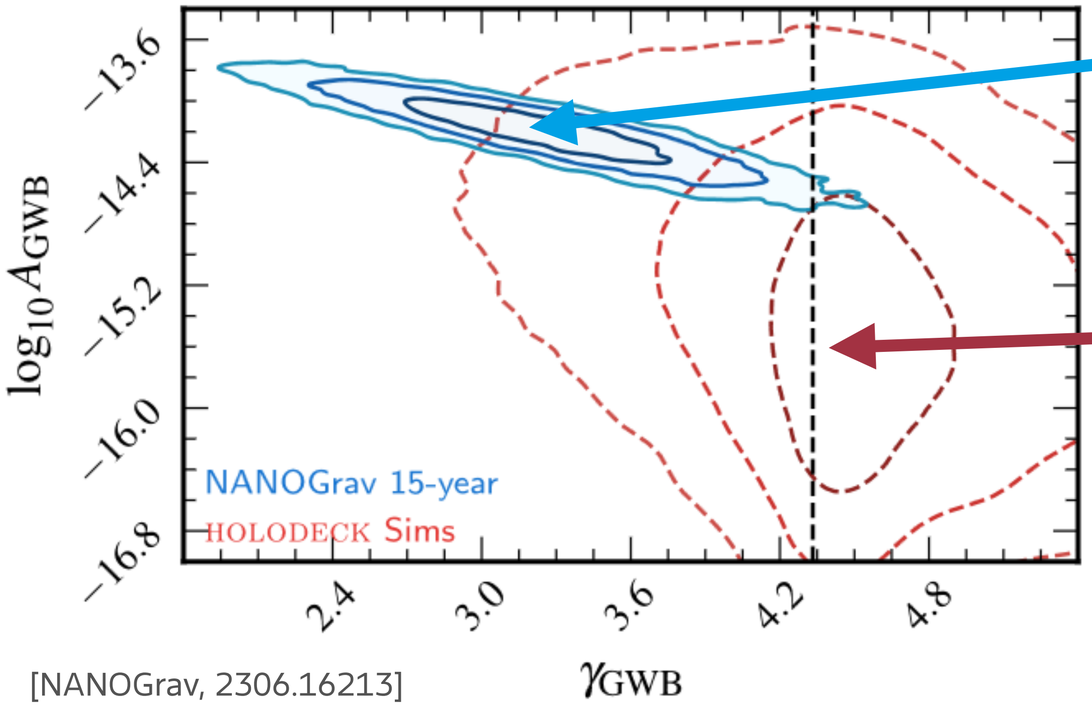


Next IPTA data release should reach $5\sigma$ GW detection!

# What is the source of the PTA signal?



# Merging supermassive black holes



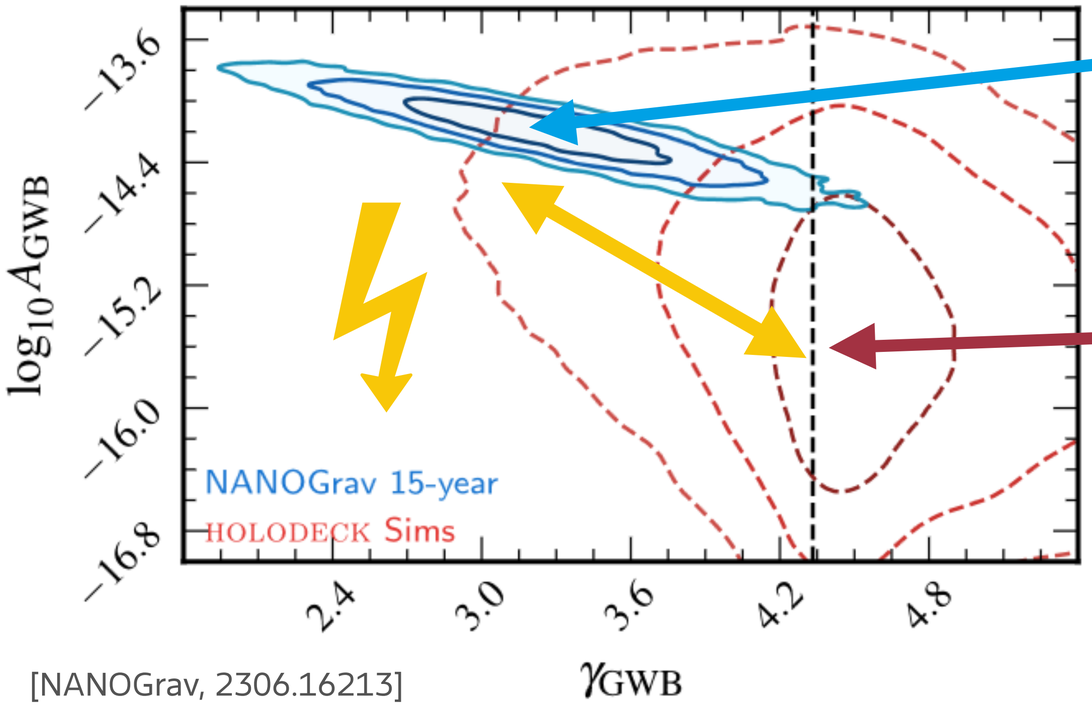

[NANOGrav, 2306.16213]

**Observed signal** roughly follows a power-law spectrum with amplitude $A$ and slope $\gamma$

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

* The shown astro contours are basically an overly optimistic upper bound on the GW amplitude, assuming 1) negligible binary hardening times (whereas naively they should be around the age of the universe) and 2) an artificially widened prior on the observed black hole masses. We'll come back to this...

# Merging supermassive black holes




[NANOGrav, 2306.16213]

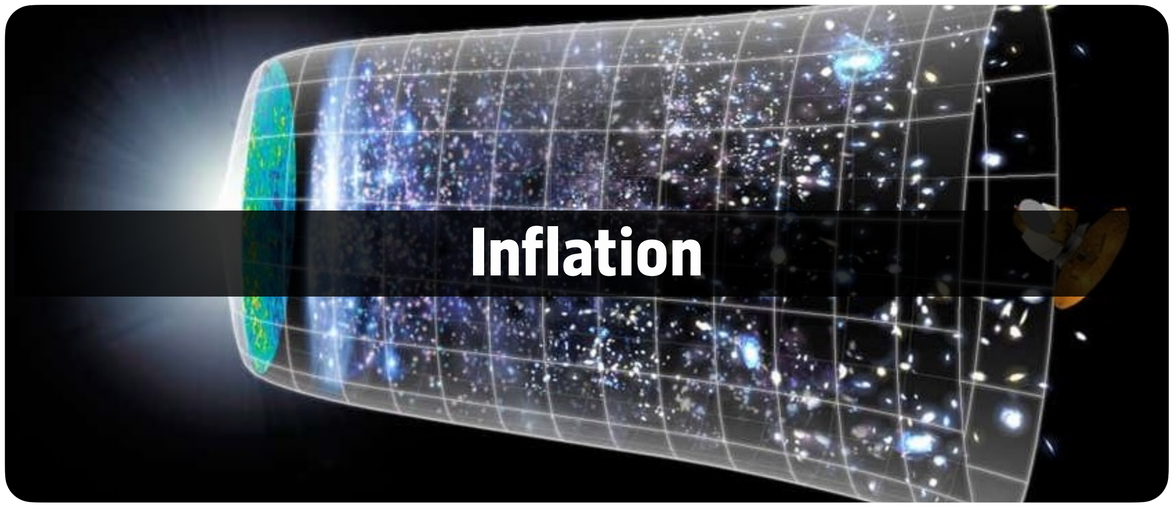
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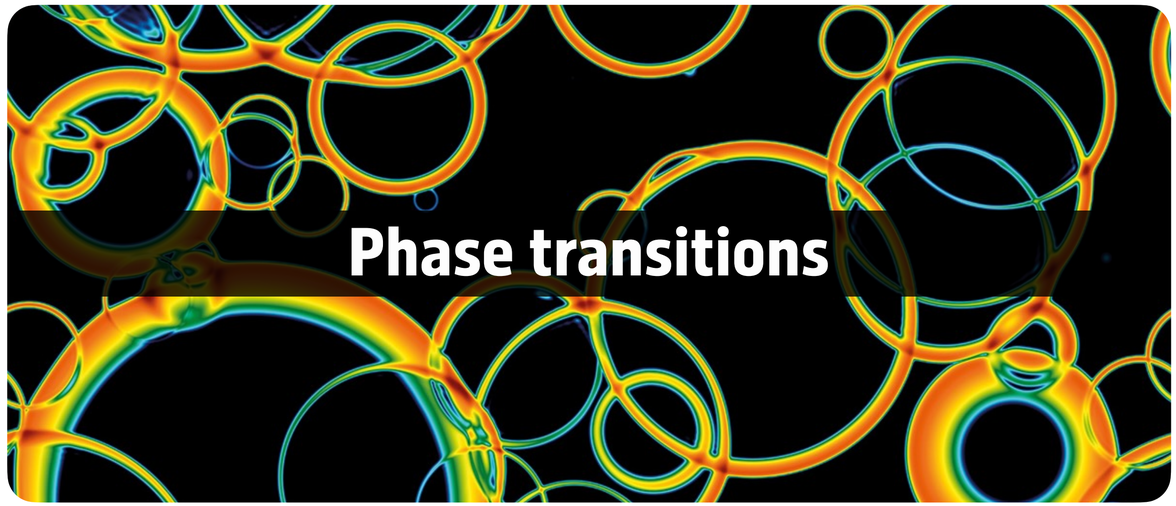
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**Are there other signal sources?**

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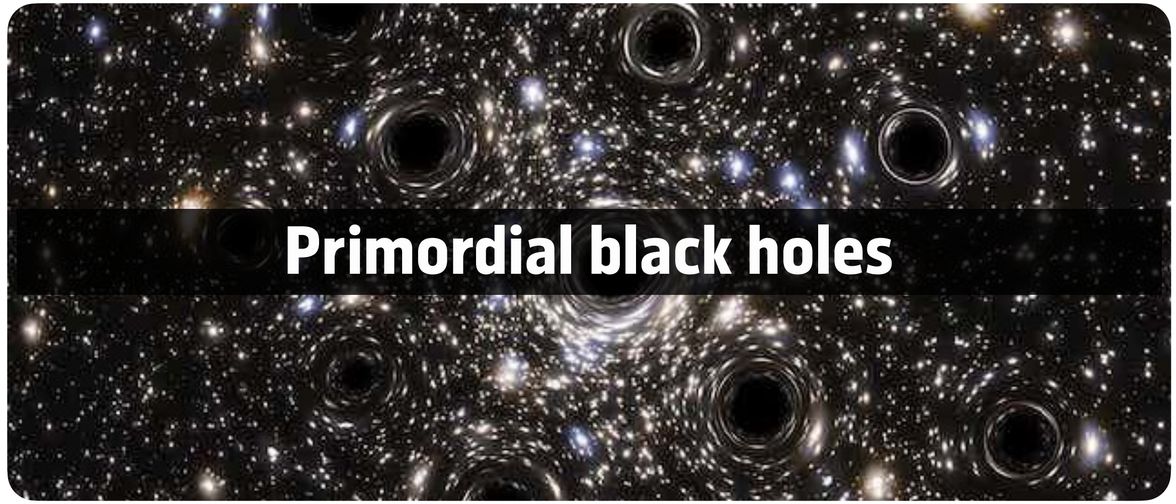
# Possible cosmological sources of the PTA signal



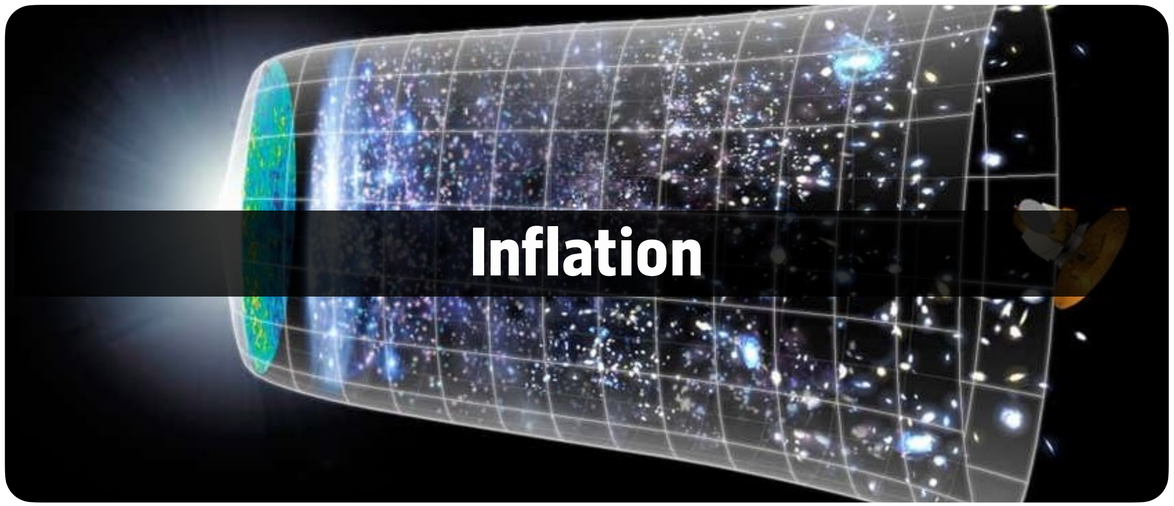



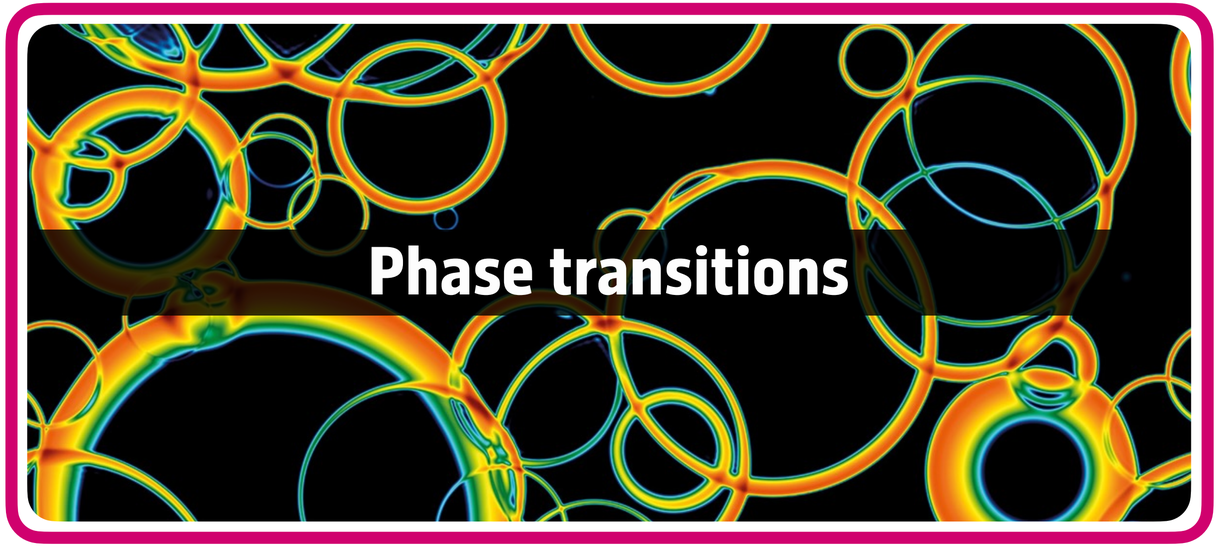






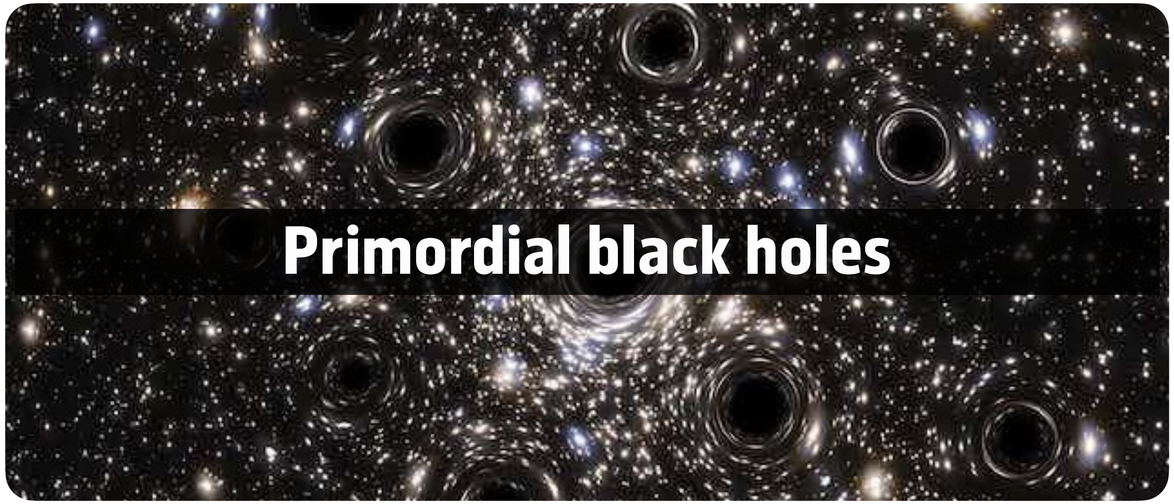
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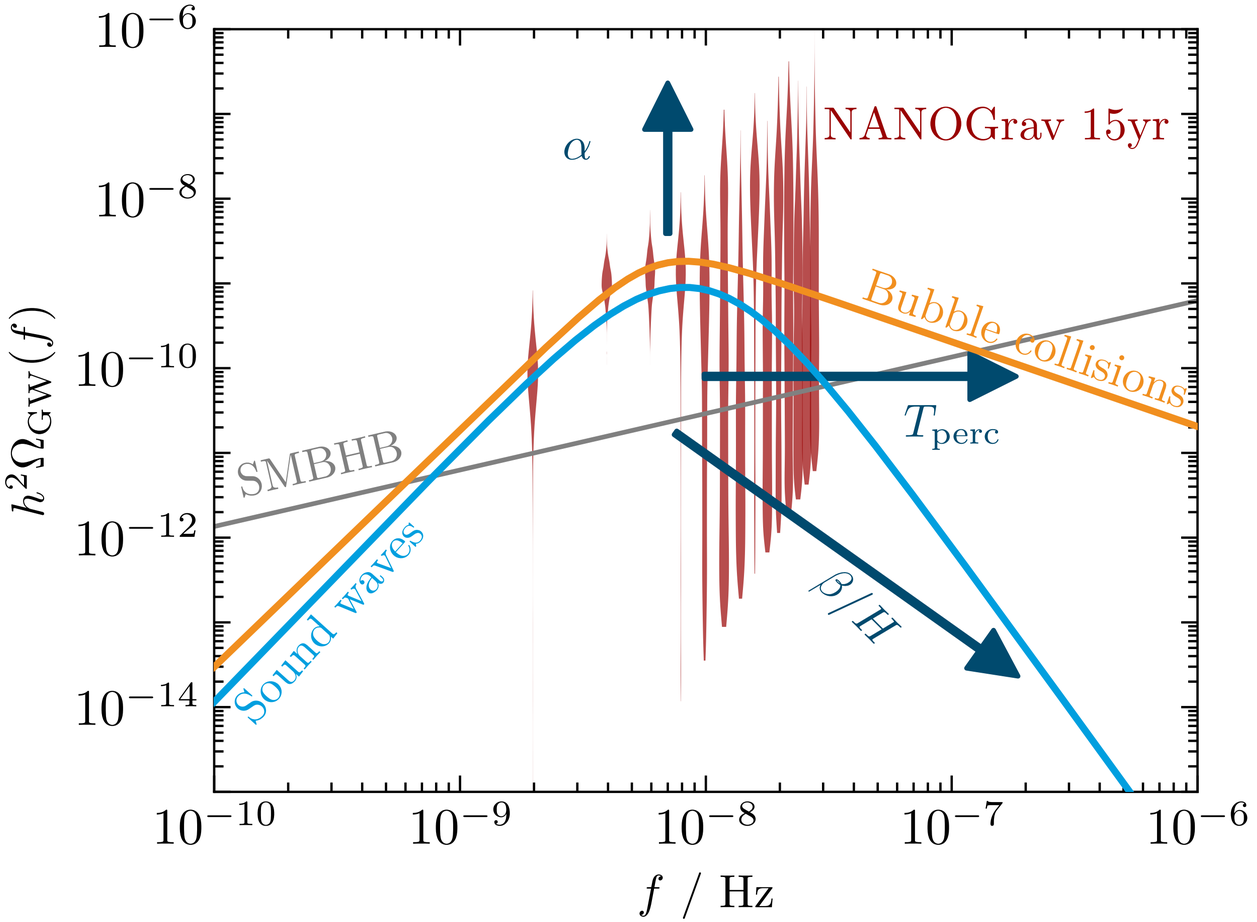









# Parametrization of the GW signal of a phase transition




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

Very roughly (we'll get more precise):

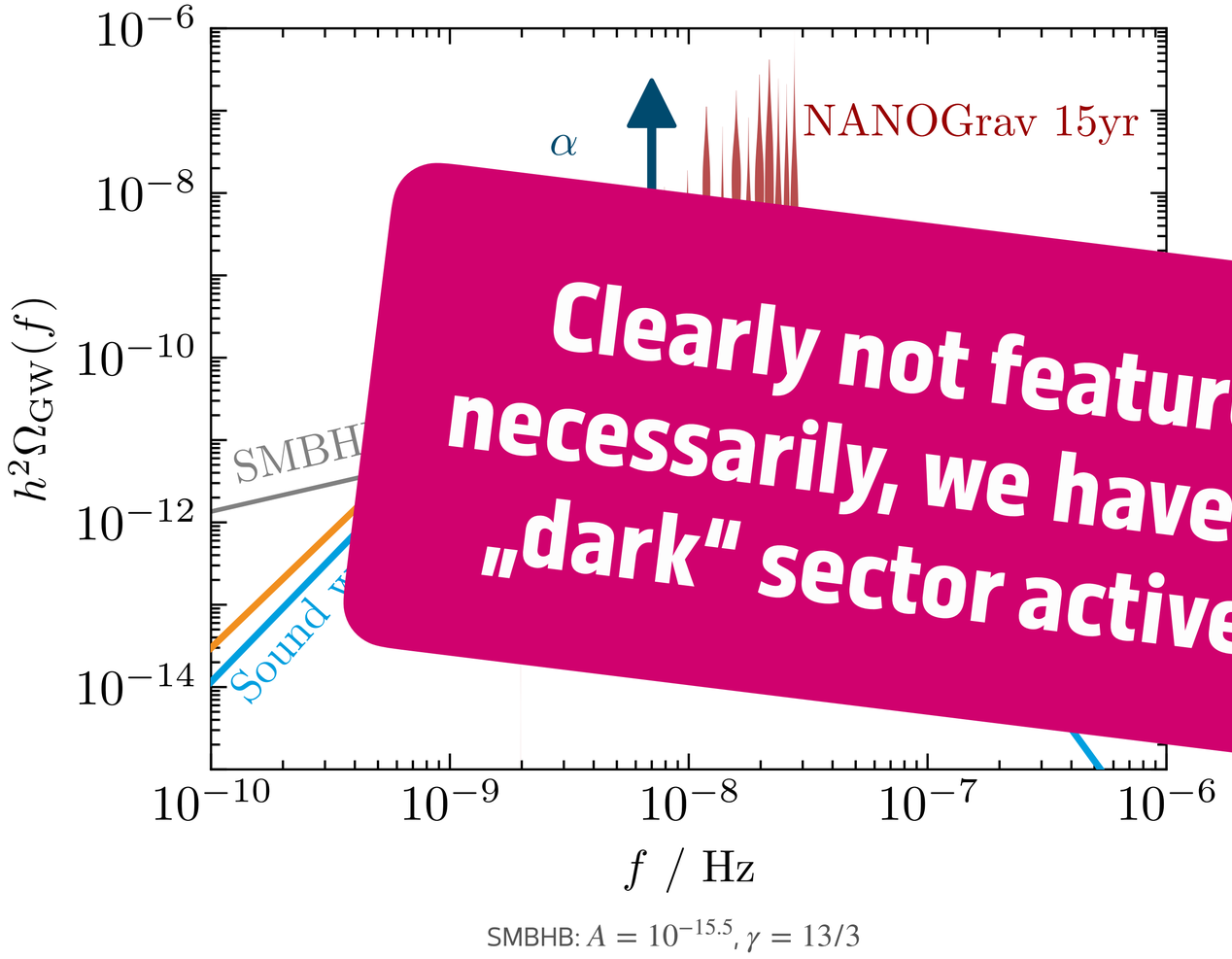
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{H}{\beta}\right)^{1,2} \mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

To fit the new pulsar timing data:

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

# Parametrization of the GW signal of a phase transition




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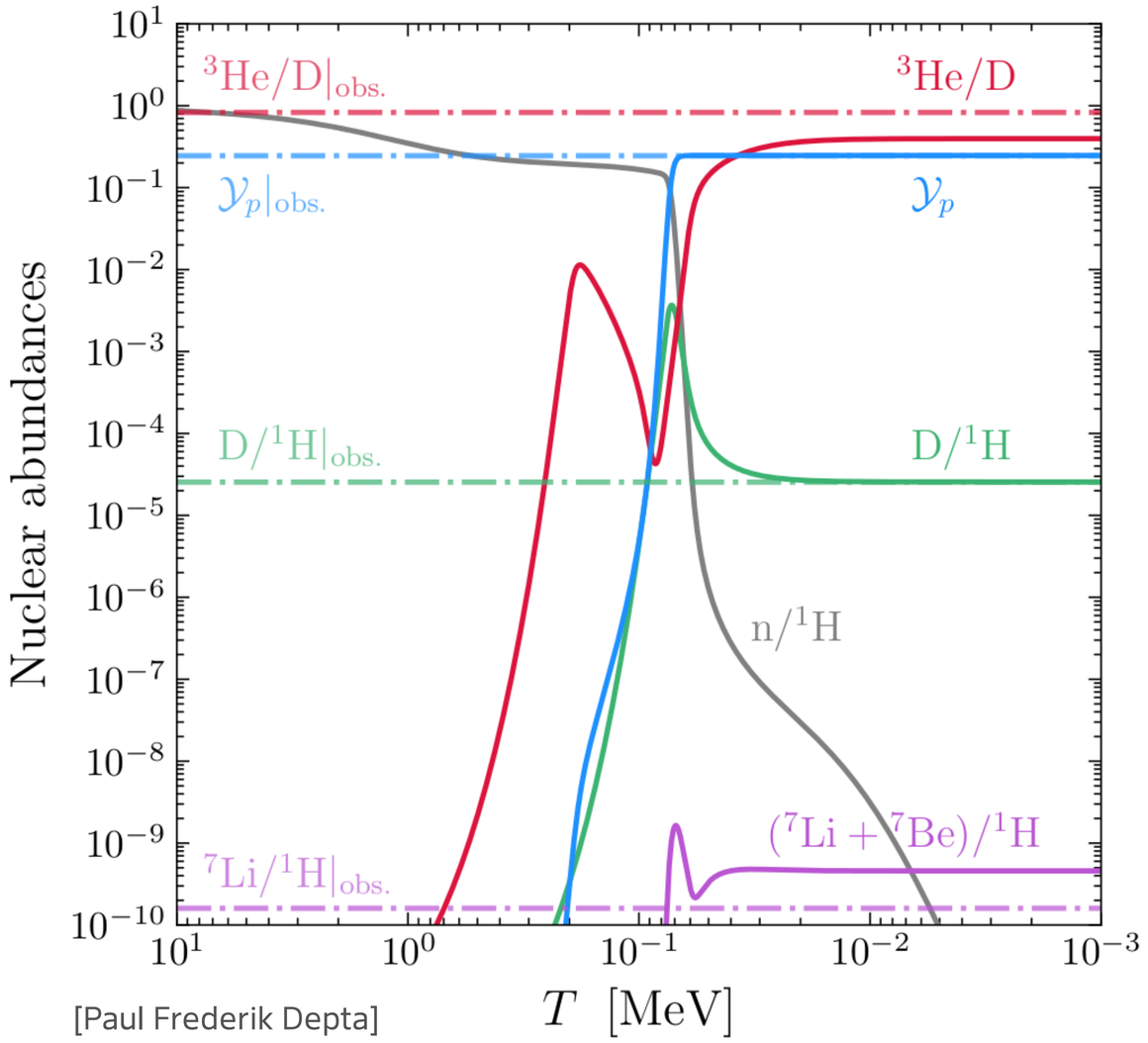
$$\frac{\beta}{} \times \frac{T}{}$$

**Clearly not featured in the SM. So, necessarily, we have to consider a BSM „dark" sector active just before BBN**

data:

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

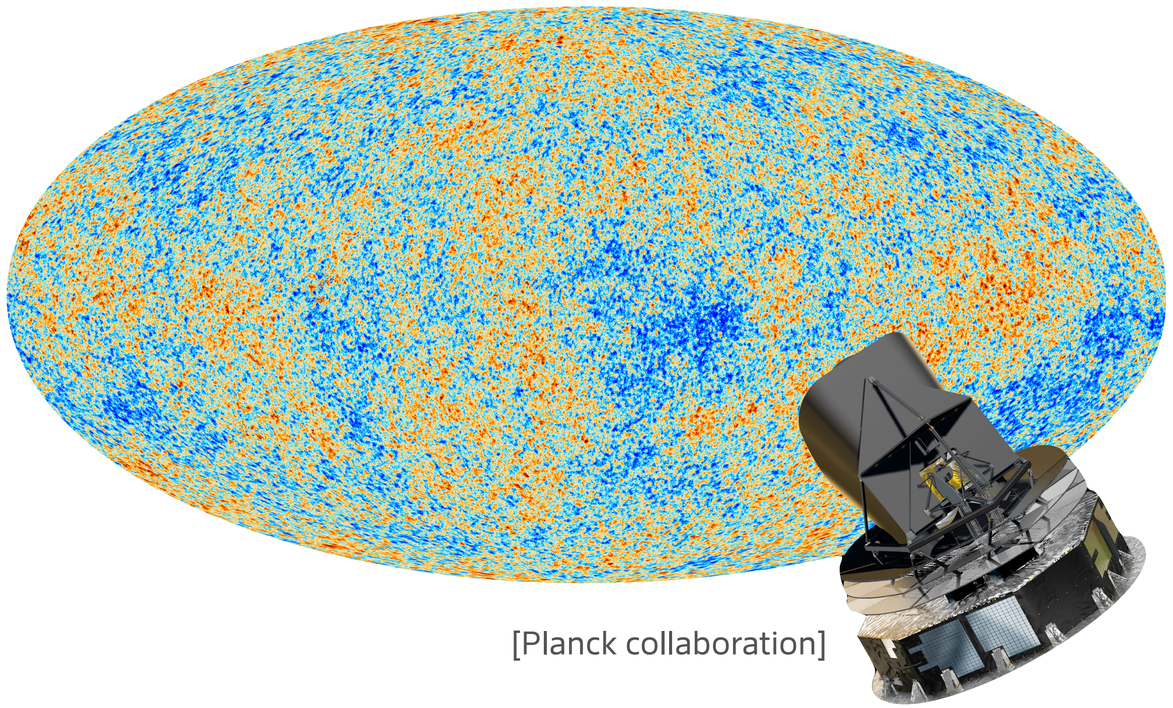
# Big Bang Nucleosynthesis and the CMB




[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

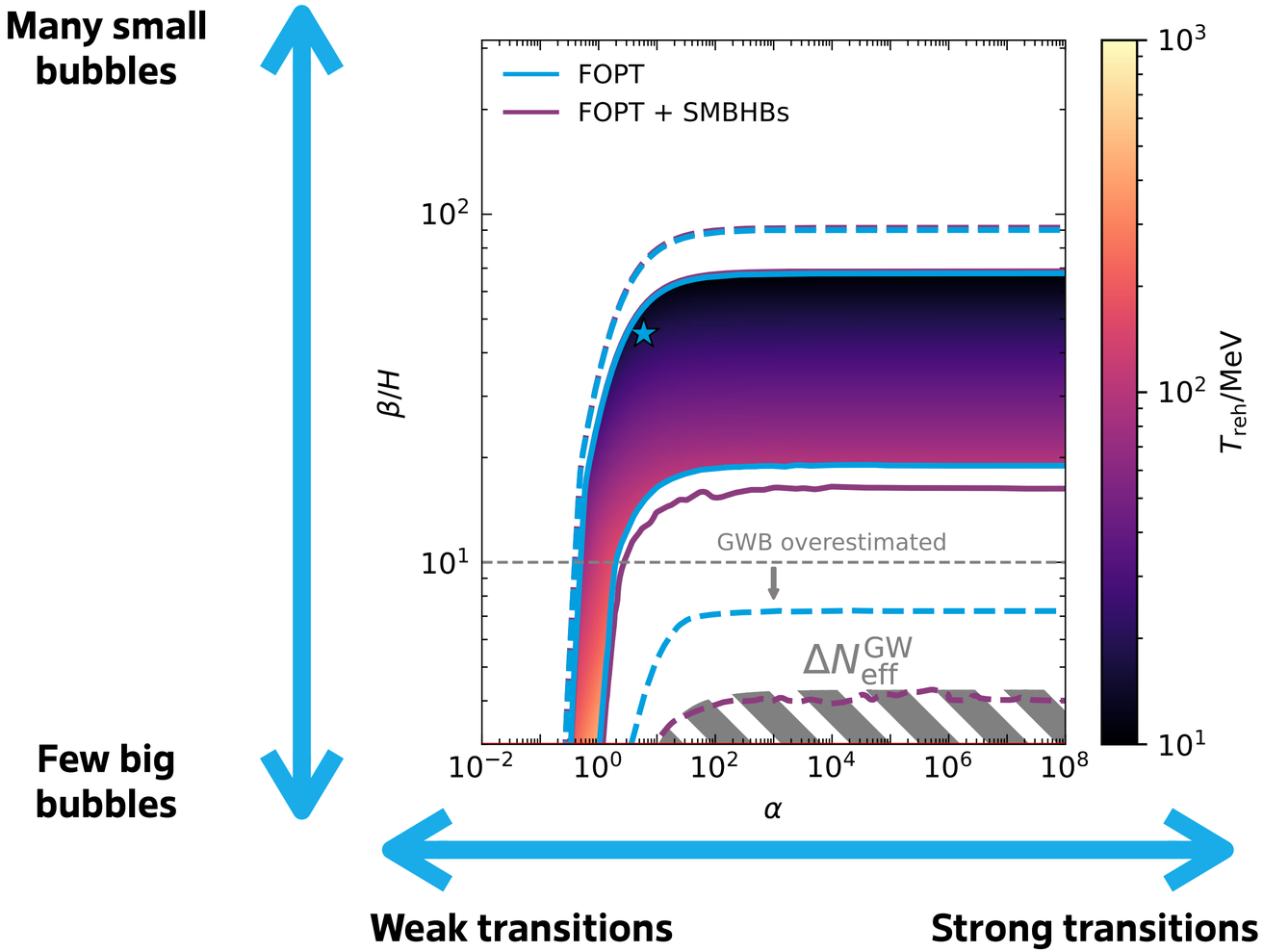
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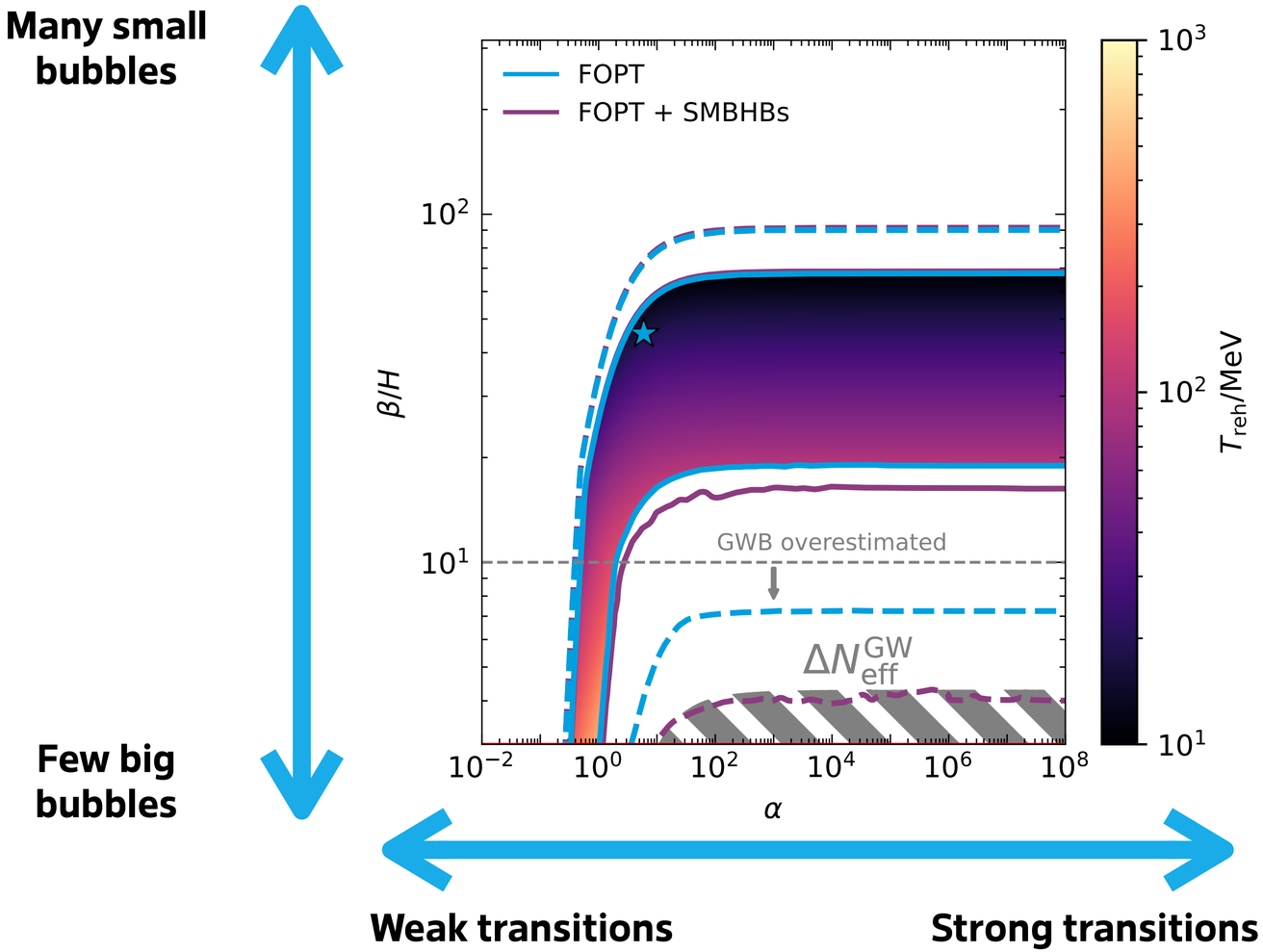
**As long as we reheat to temperatures above some MeV, and there's no abundant dark relics: All good. Time to get more precise.**

# Which phase transitions can fit the PTA data?




**PTA data requires very strong transitions with extremely large bubbles!**

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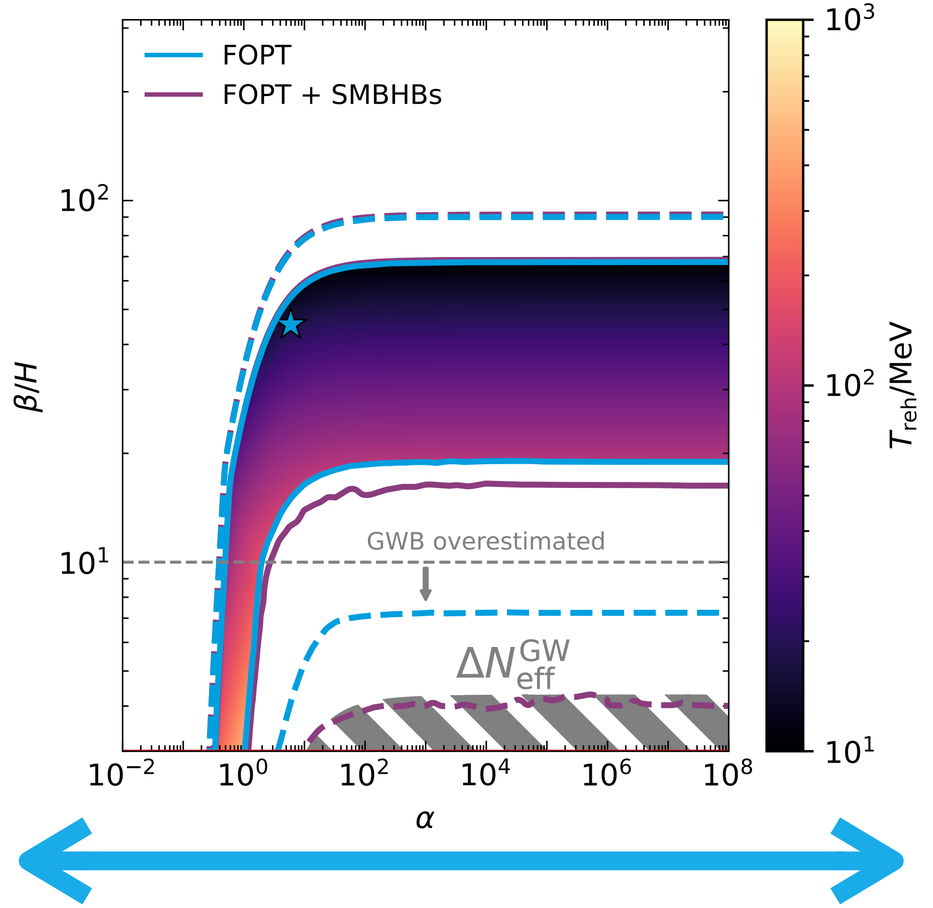
**BSM models typically predict weak transitions with small bubbles…**

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

# Which phase transitions can fit the PTA data?

Many small bubbles

Few big bubbles




Weak transitions

Strong transitions

**PTA data requires very strong transitions with extremely large bubbles!**

**Let's start with this problem**

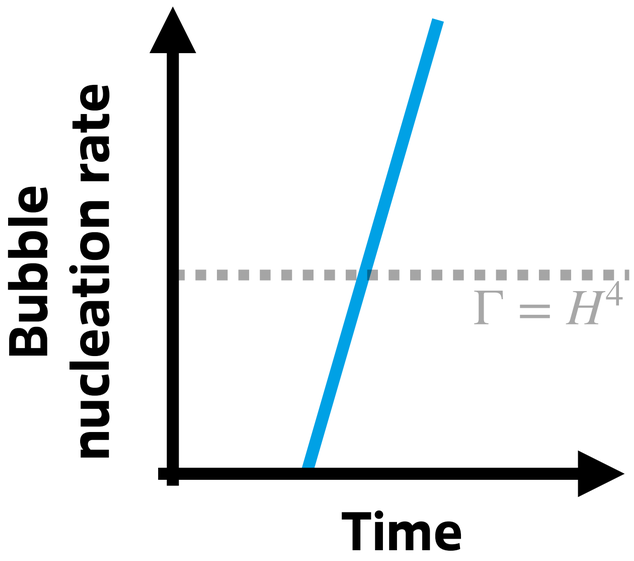


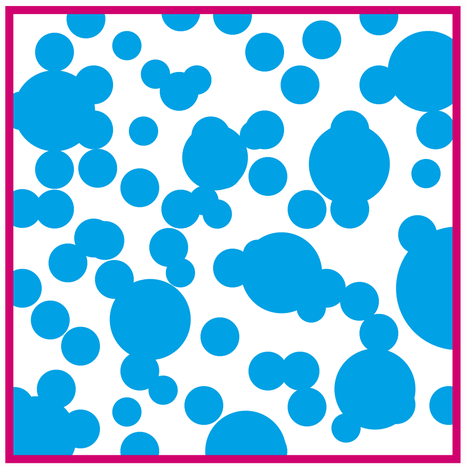
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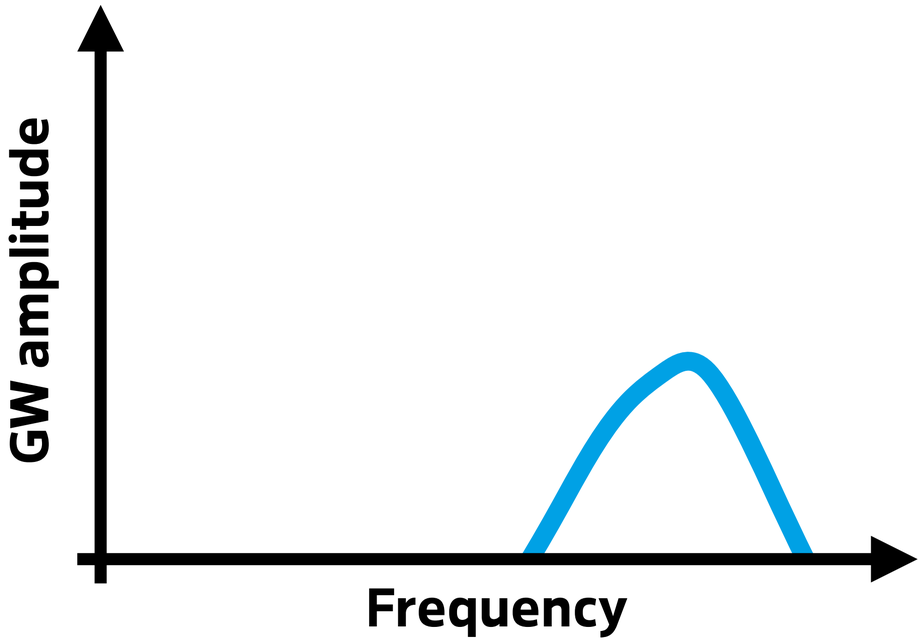


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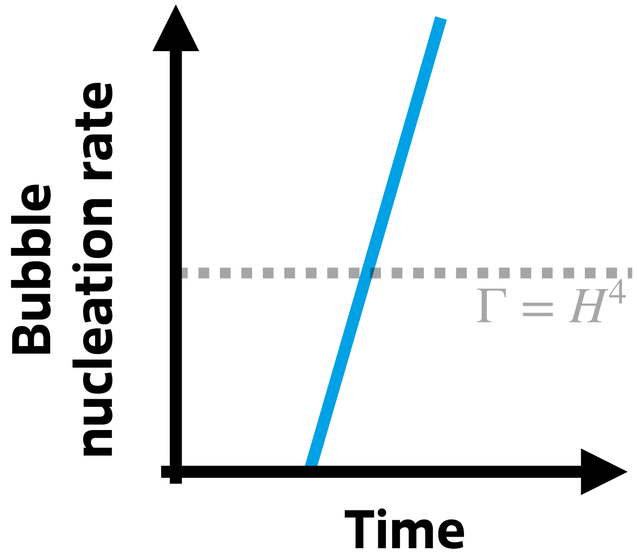
# Why is it so difficult to get big bubbles?

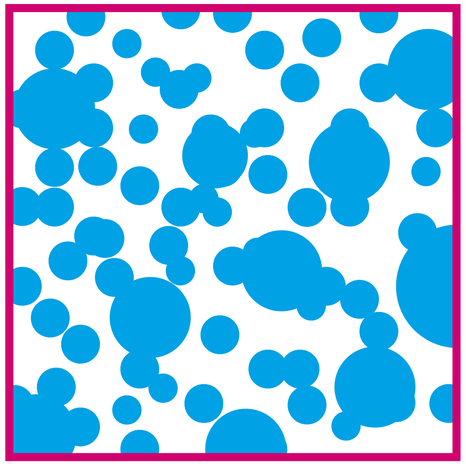


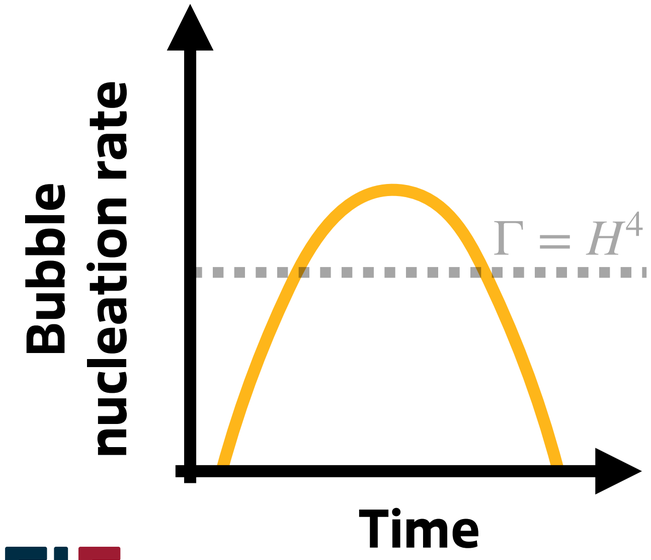



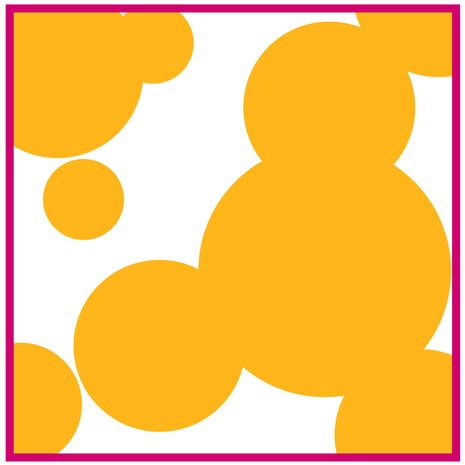


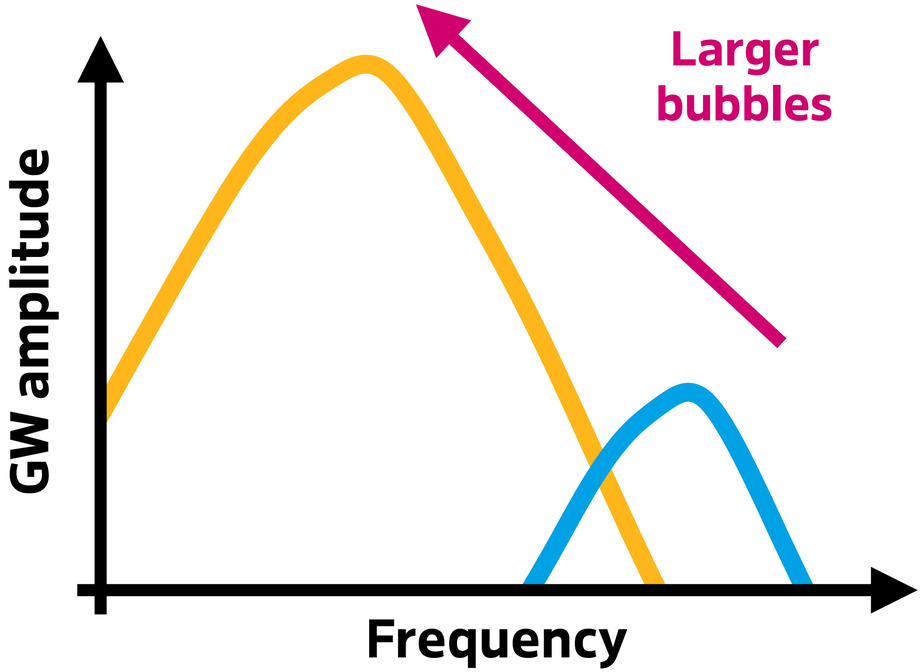
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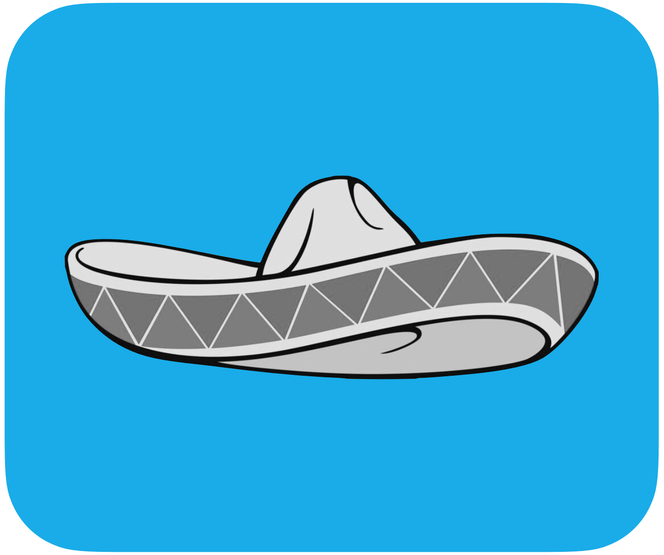



$$\Gamma \propto e^{\beta t - \gamma t^2}$$

**The bubble nucleation rate has to become a Gaussian, i.e. $\beta/H$ has to become small or negative!**

# Model classes for the PTA signal

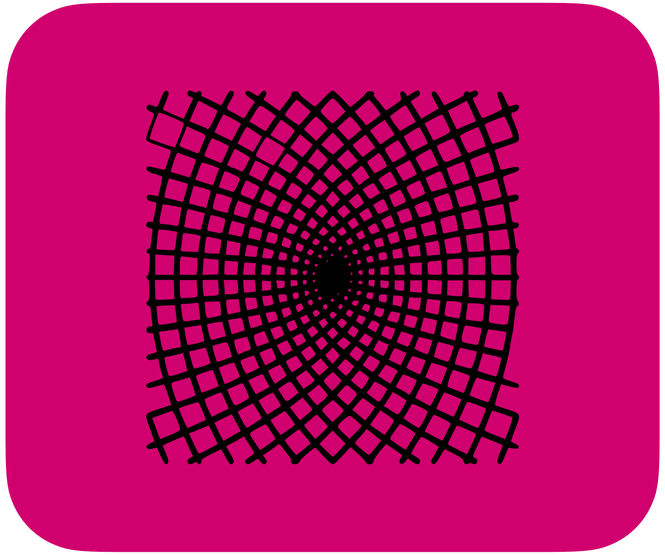
## Abelian dark Higgs



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

Thermally induced barrier

## Conformal dark Higgs



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

Loop-induced barrier

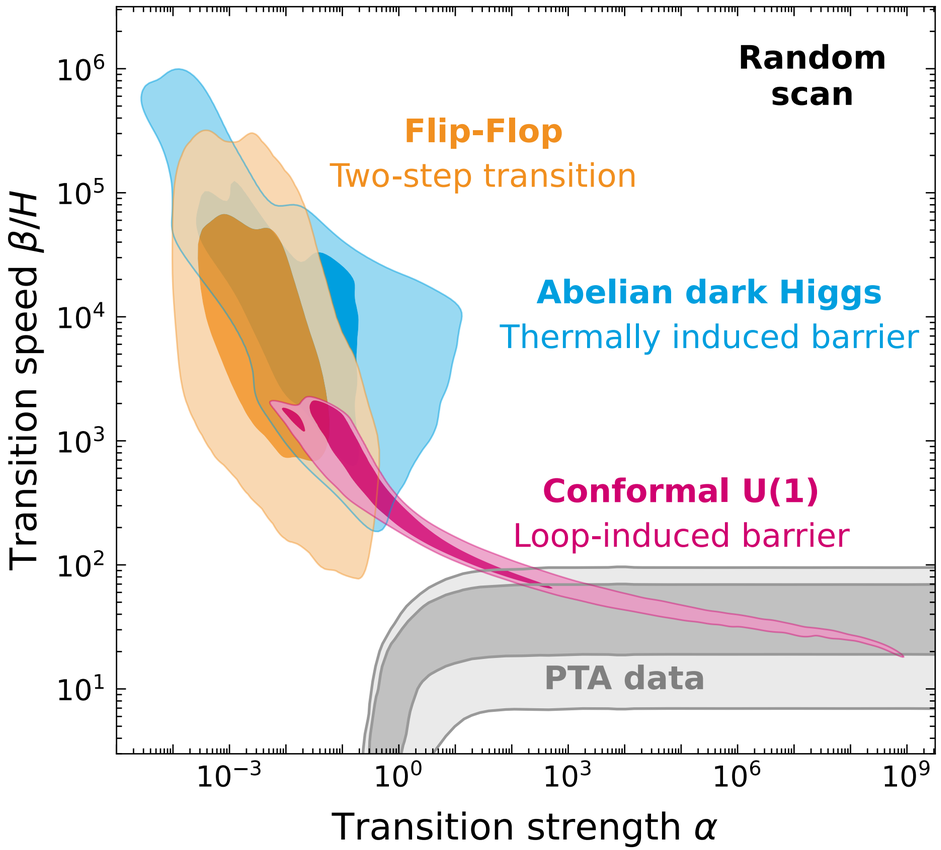
## Dark flipflop

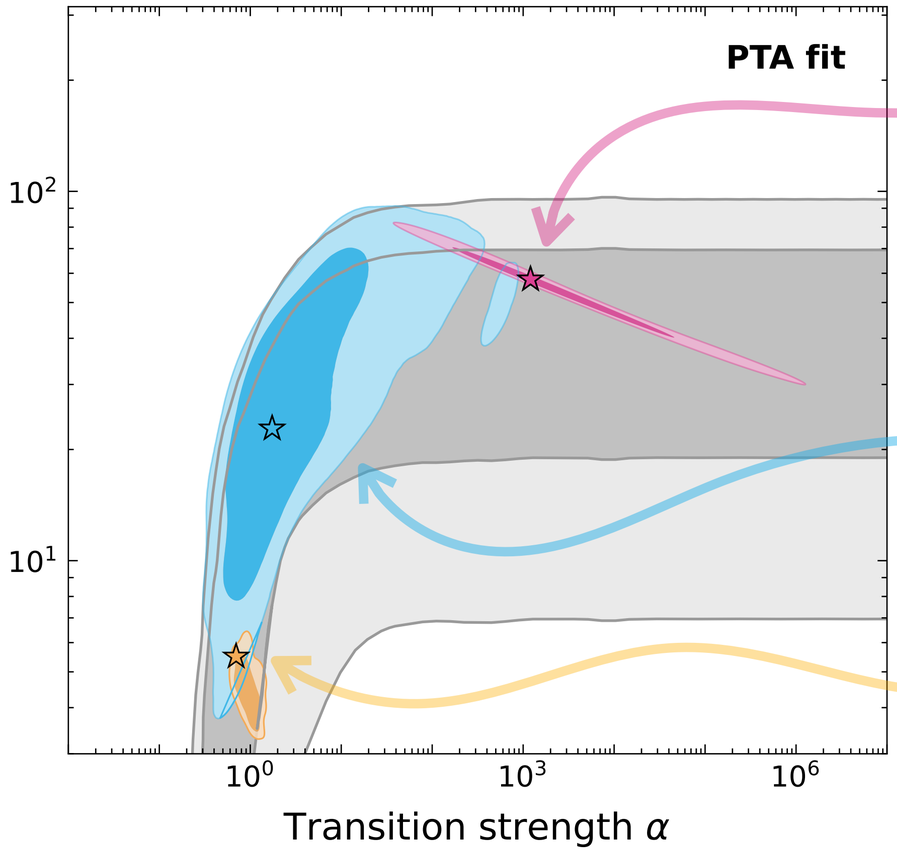


$$V(\phi_1, \phi_2)$$

Transition-induced barrier

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



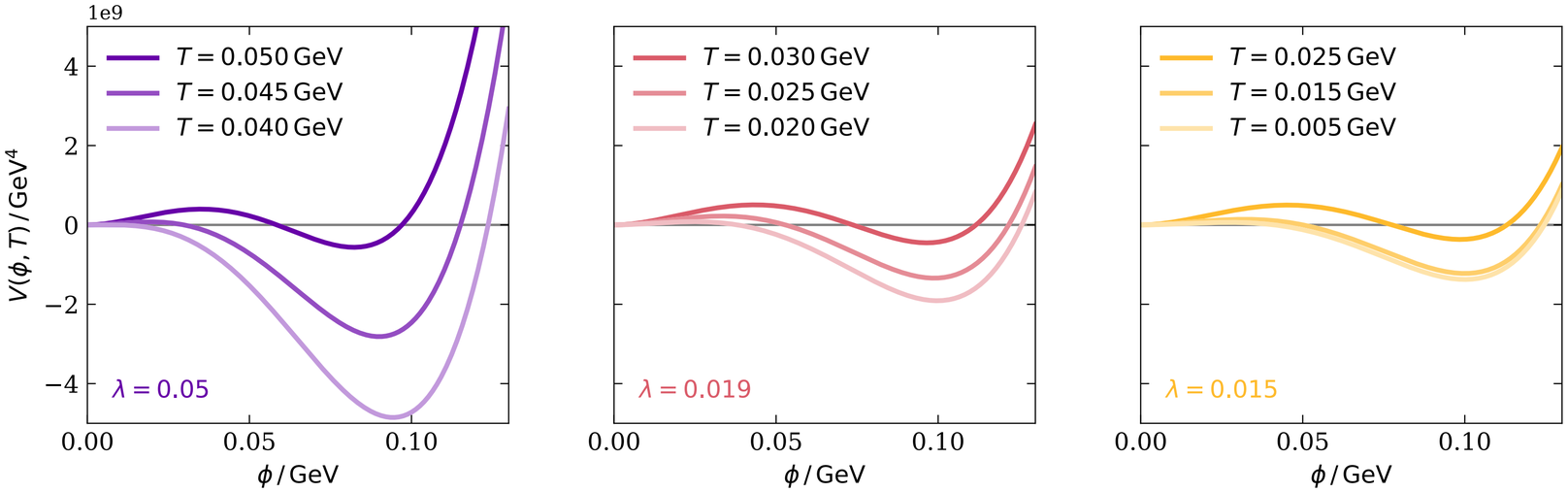

**Required tuning:**
one significant digit in $g$

Two significant digits in $\lambda$

Four significant digits in four couplings...

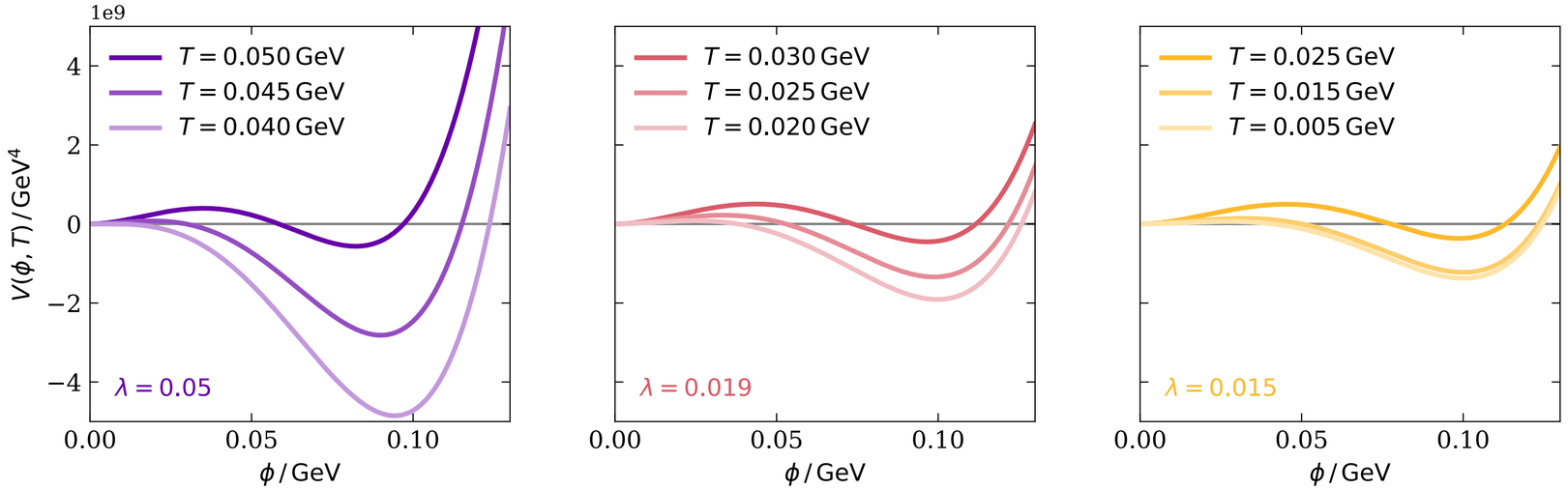
**The goodness of fit is identical (and better than SMBHBs), but the amount of required tuning depends strongly on the mechanism with which the barrier is generated!**

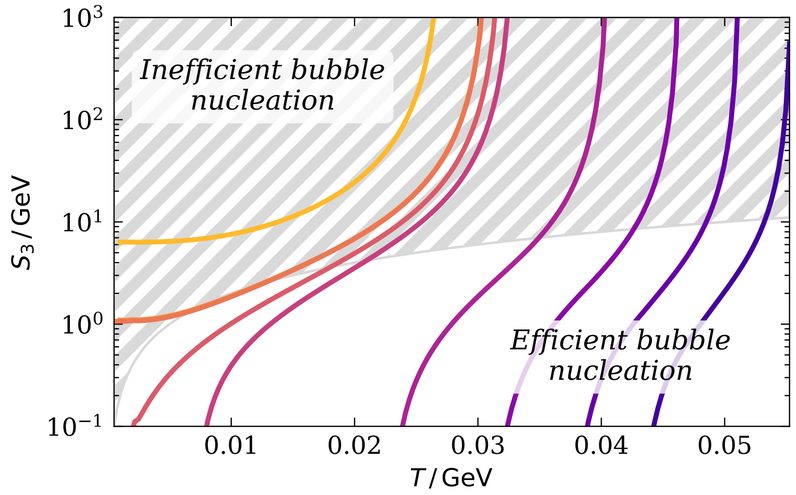
# Large bubbles in the Abelian dark Higgs model




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

# Large bubbles in the Abelian dark Higgs model



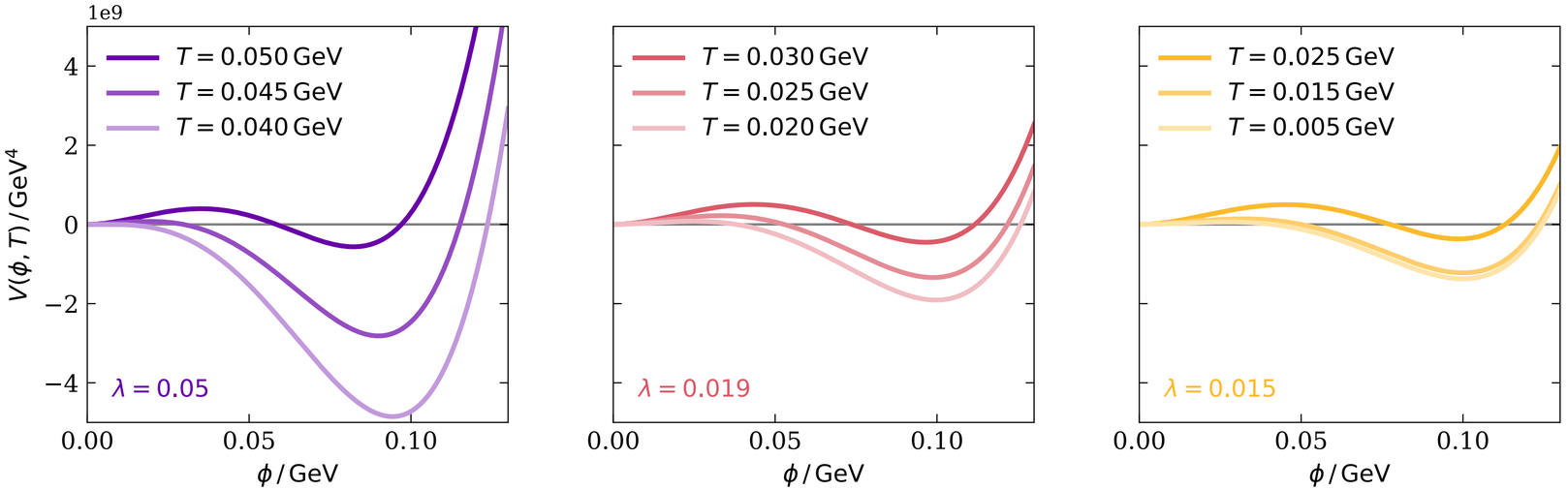



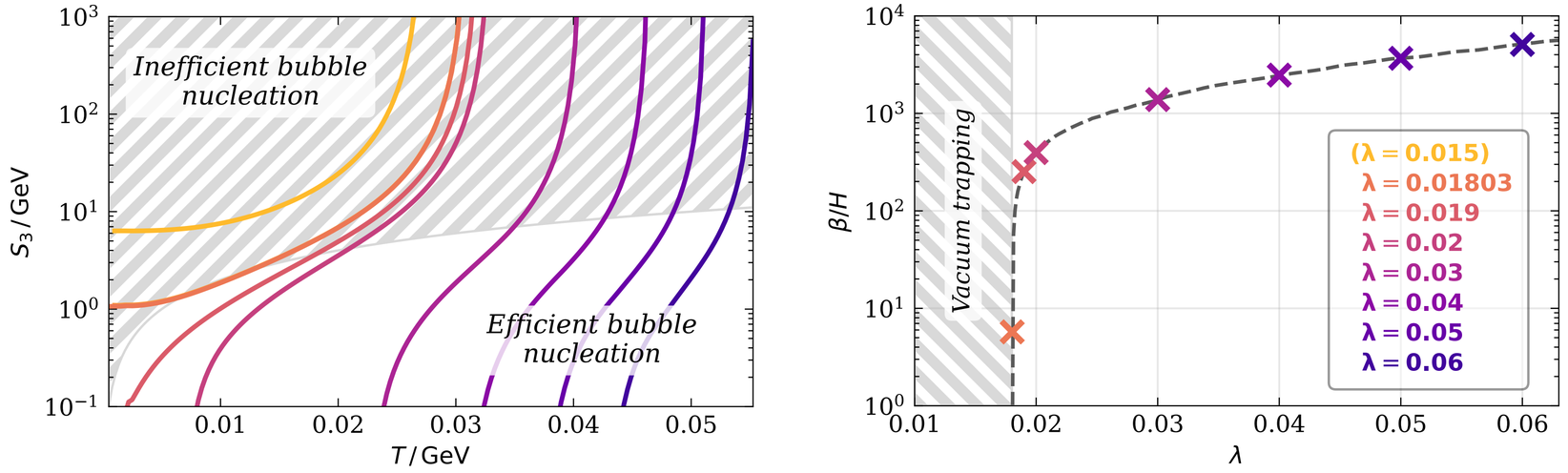

**The transition rate is exponentially dependent on the bounce action**

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

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**

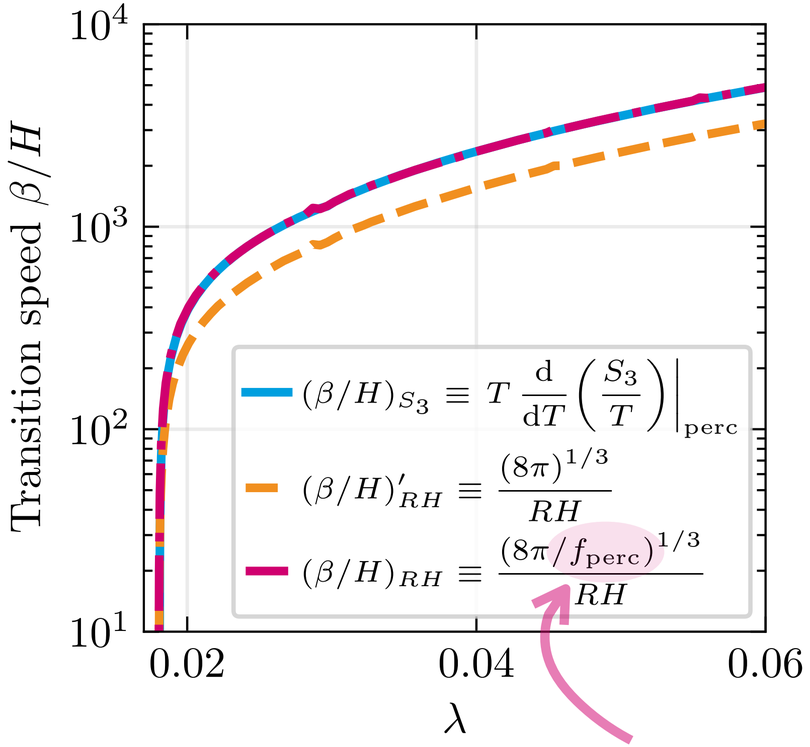
$$\Gamma \propto e^{-S_3/T}$$

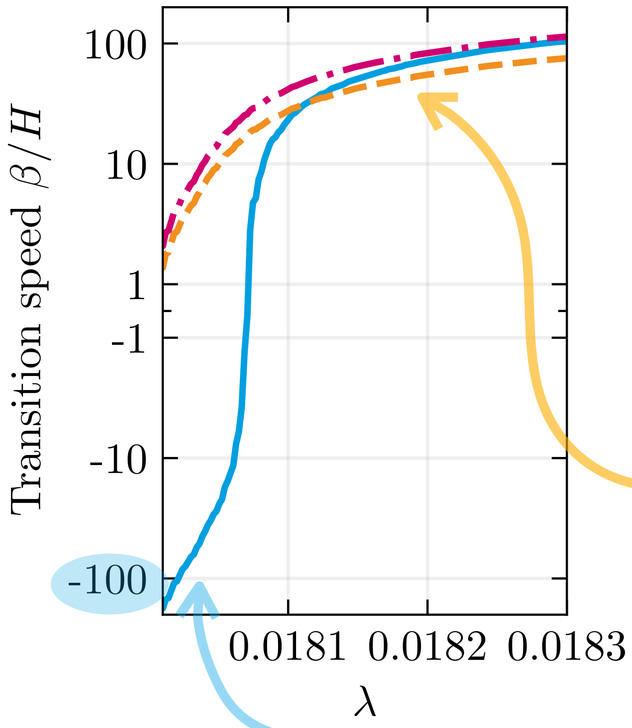
**Only for fine-tuned quartic couplings $\lambda$, large bubbles can be achieved! Generically,**

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

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

# A comment on $\beta/H$ 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**

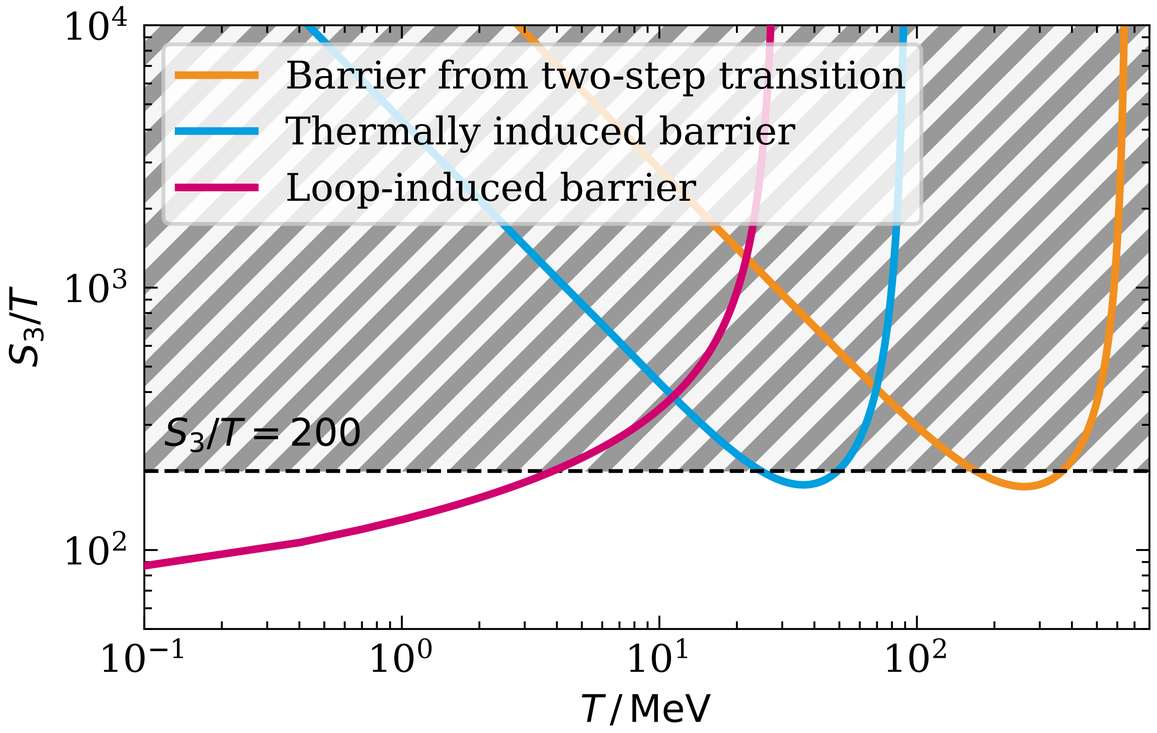
$$\beta/H = (8\pi)^{1/3}/RH$$

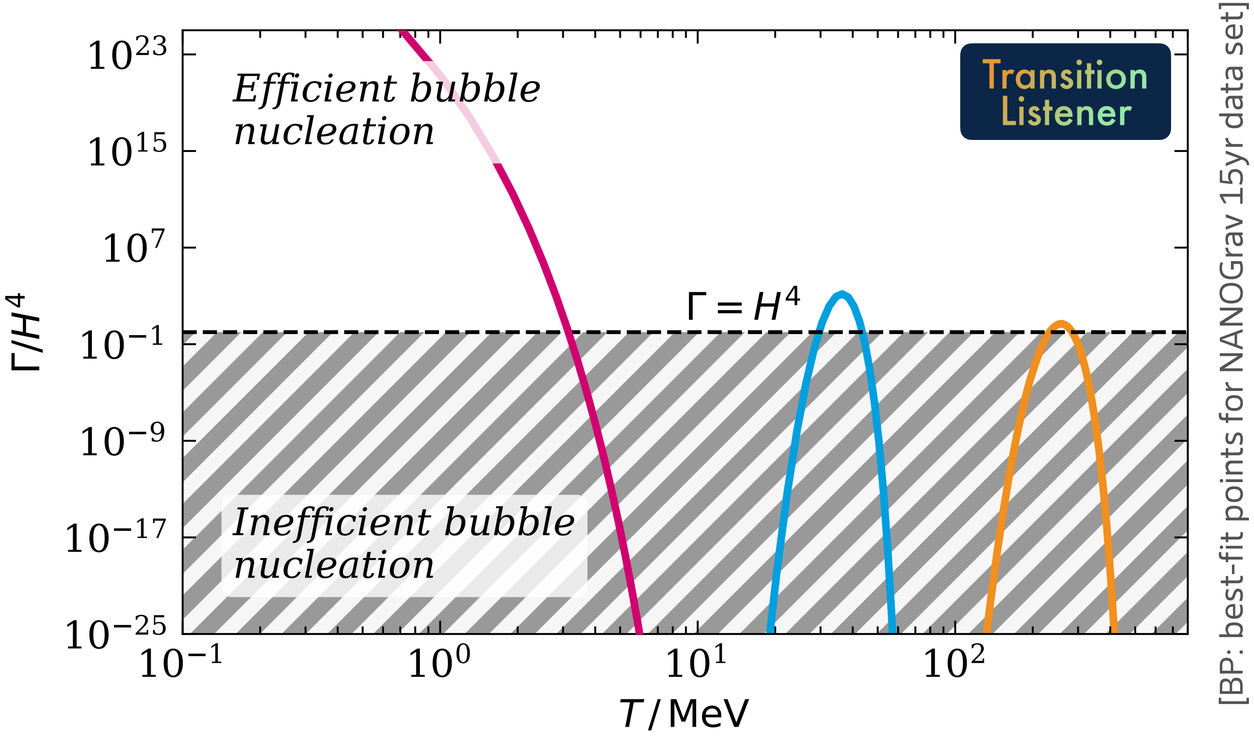
(used in LISA pipeline, Athron review, ...)

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

[Derivation: See appendix of 2605.15259]

# The tuning needed for strong GW signals



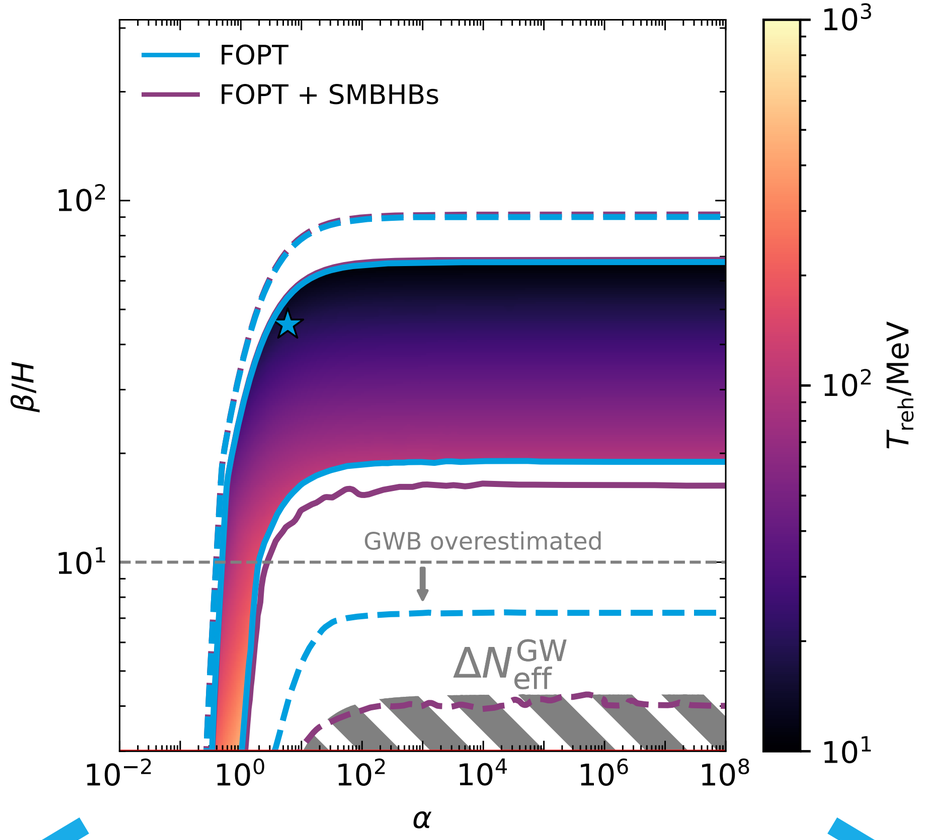

[BP: best-fit points for NANOGrav 15yr data set]

**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

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?**

# What is required for robust phase transition predictions for PTAs?

**Numerical stability**

**Consistent cosmological evolution**

**Perturbative control over bubble nucleation rate**

**GW templates valid for strong supercooling and Hubble-sized bubbles**

# What is required for robust phase transition predictions for PTAs?

Today

Numerical stability

Consistent cosmological evolution




Perturbative control over bubble nucleation rate

GW templates valid for strong supercooling and Hubble-sized bubbles

# What is required for robust phase transition predictions for PTAs?

Today

Numerical stability

Consistent cosmological evolution




Soon

Perturbative control over bubble nucleation rate

GW templates valid for strong supercooling and Hubble-sized bubbles


BROADCAST
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# 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 spectral templates


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]†

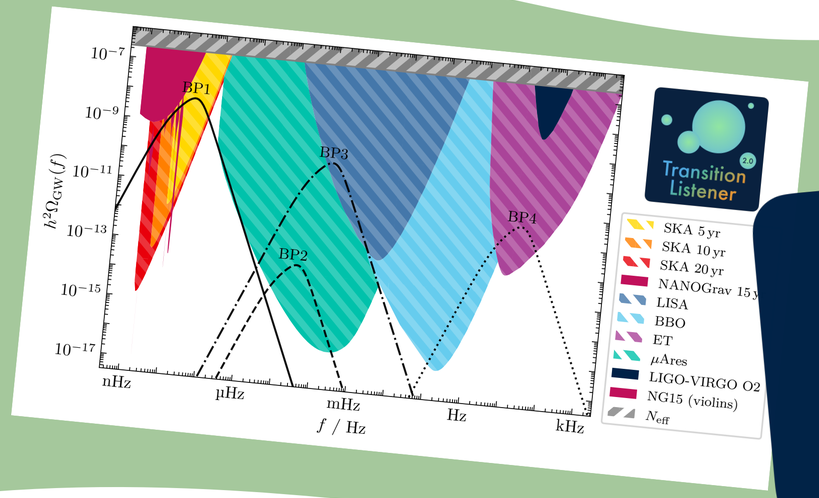
[1] Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany

[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

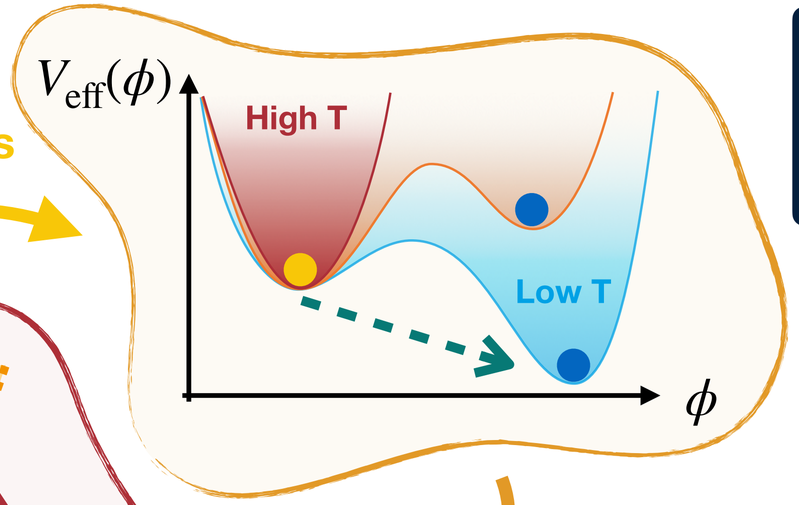
259v1 [hep-ph] 14 May 2026




Transition Listener

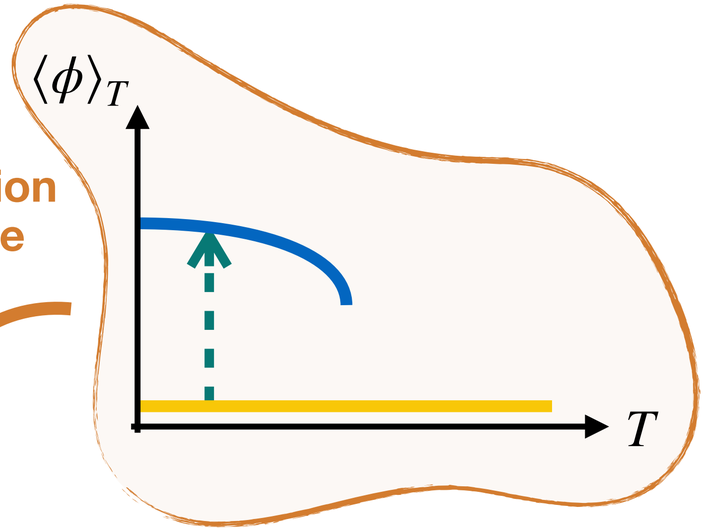
$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

Quantum & finite-temperature corrections

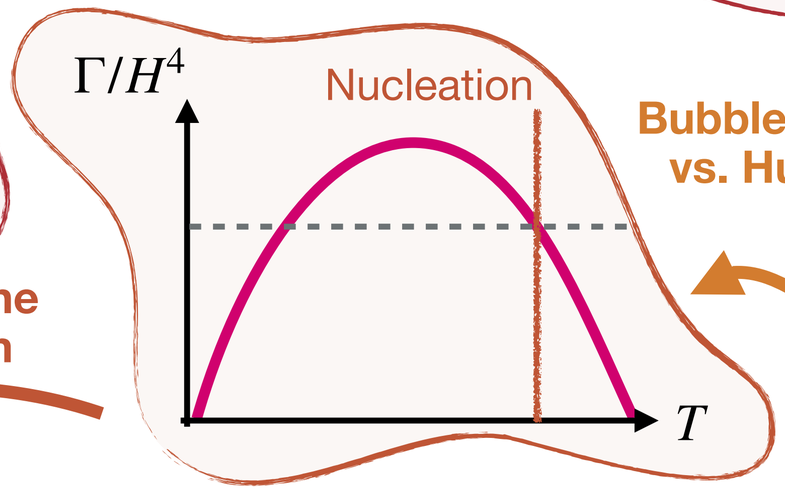



Transition Listener 2.0

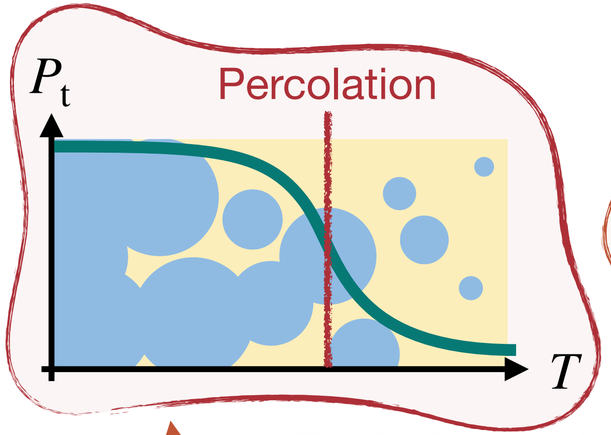
Phase tracing and finding possible transitions




Bubble nucleation vs. Hubble rate

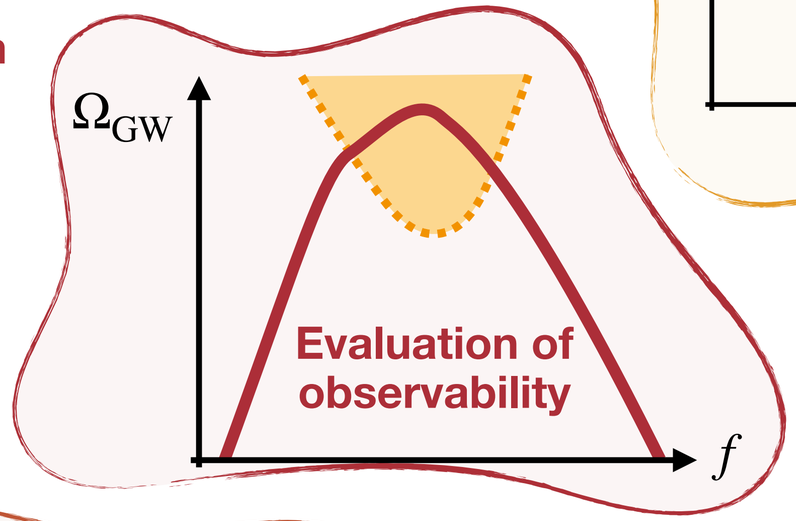



Evolution of the false vacuum




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
```

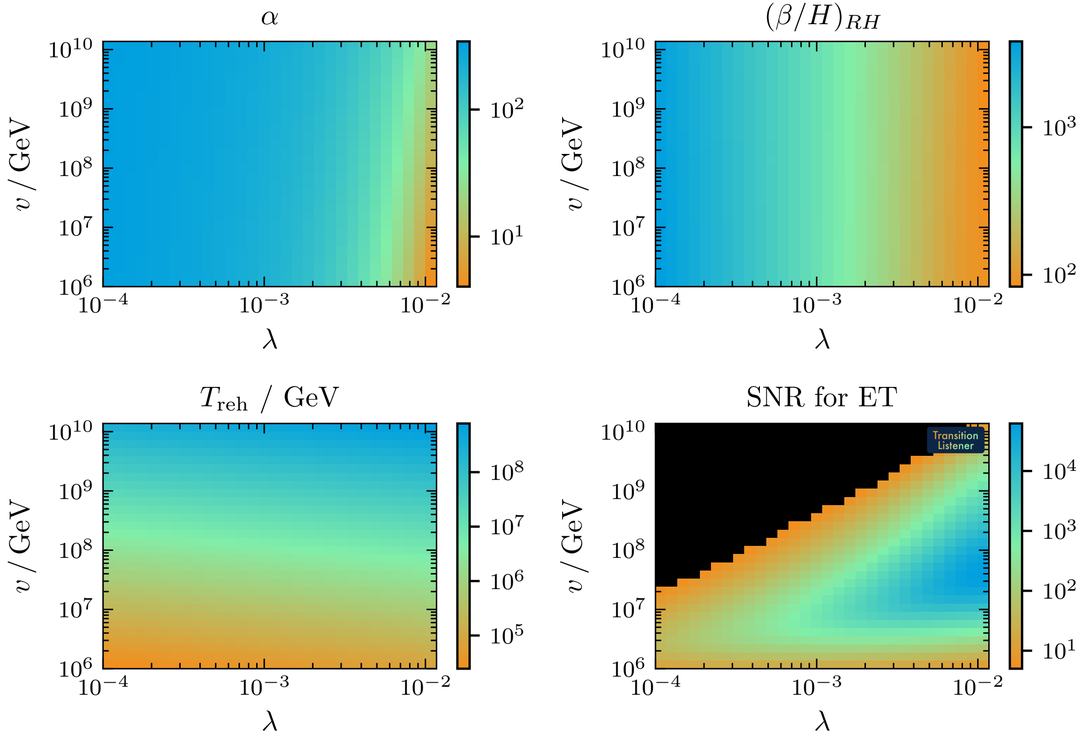
| Parameter | Value |
|---|---|
| g | 7.0000000000e-01 |
| y | 1.0000000000e-02 |
| v_GeV | 1.0000000000e-01 |

*Derived parameters*

| Parameter | Value |
|---|---|
| lambda | 1.6790420728e-02 |

*Zero-temperature mass spectrum*

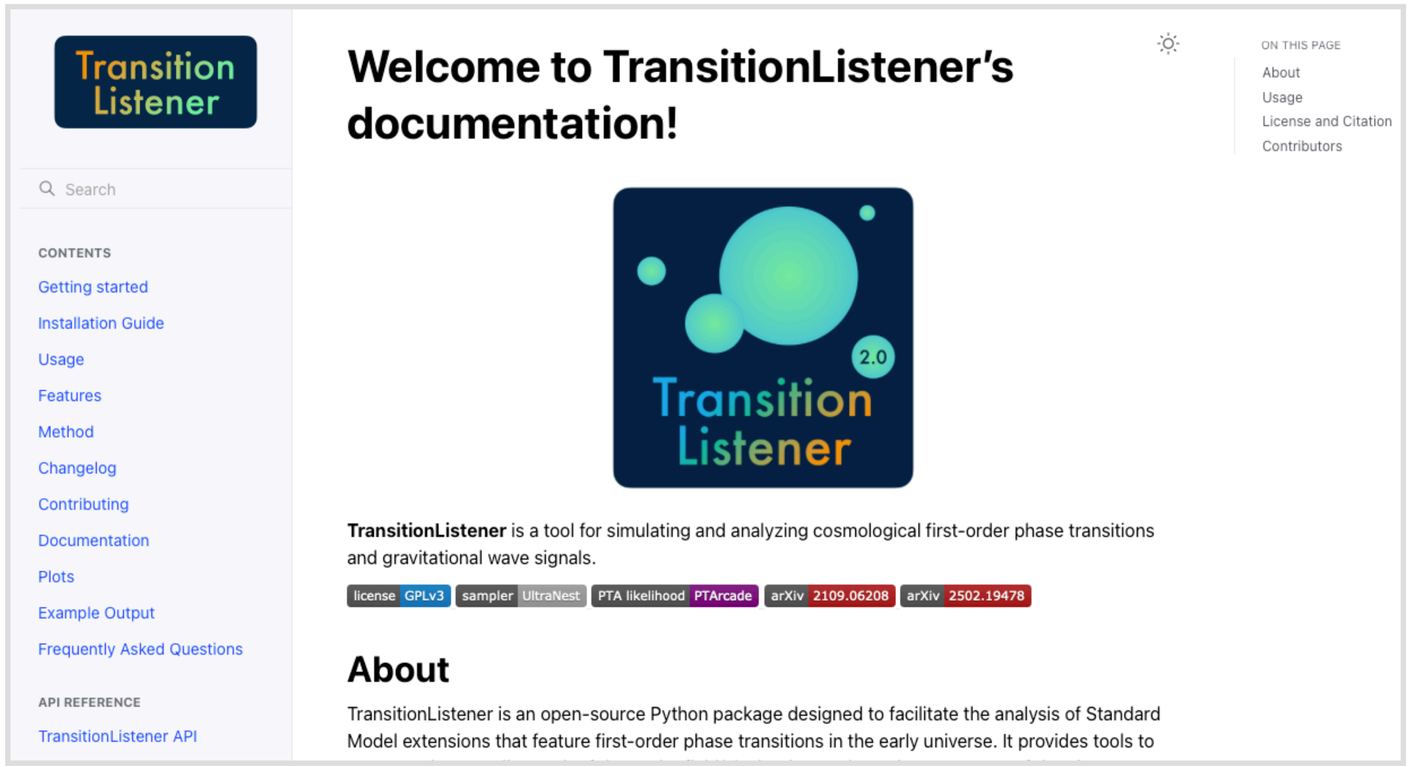
| Particle | Type | Mass [GeV] |
|---|---|---|
| m_phi | boson | 2.2443542988e-02 |
| m_varphi | boson | 1.2957785586e-02 |
| m_A_T | boson | 7.0000000000e-02 |
| m_A_L | boson | 7.0000000000e-02 |
| m_psi1 | fermion | 7.0710678119e-04 |
| m_psi2 | fermion | 7.0710678119e-04 |



Validated against BSMPT!

Comes with dark sector models and 2HDM!

Numerically robust and reliable!




Well-documented and in active use!

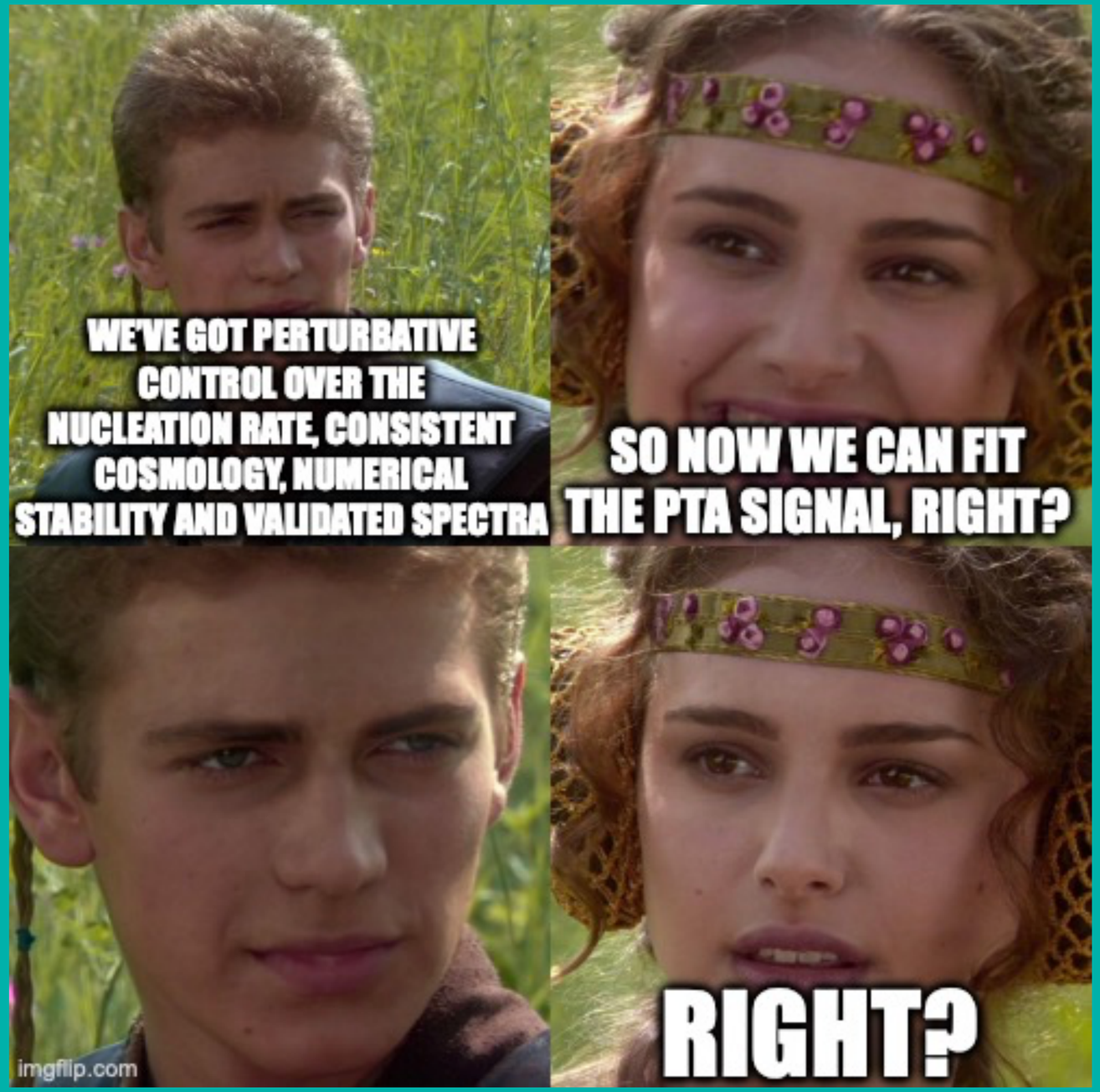
Just try:

```
pip install
transitionlistener
```

Click here!

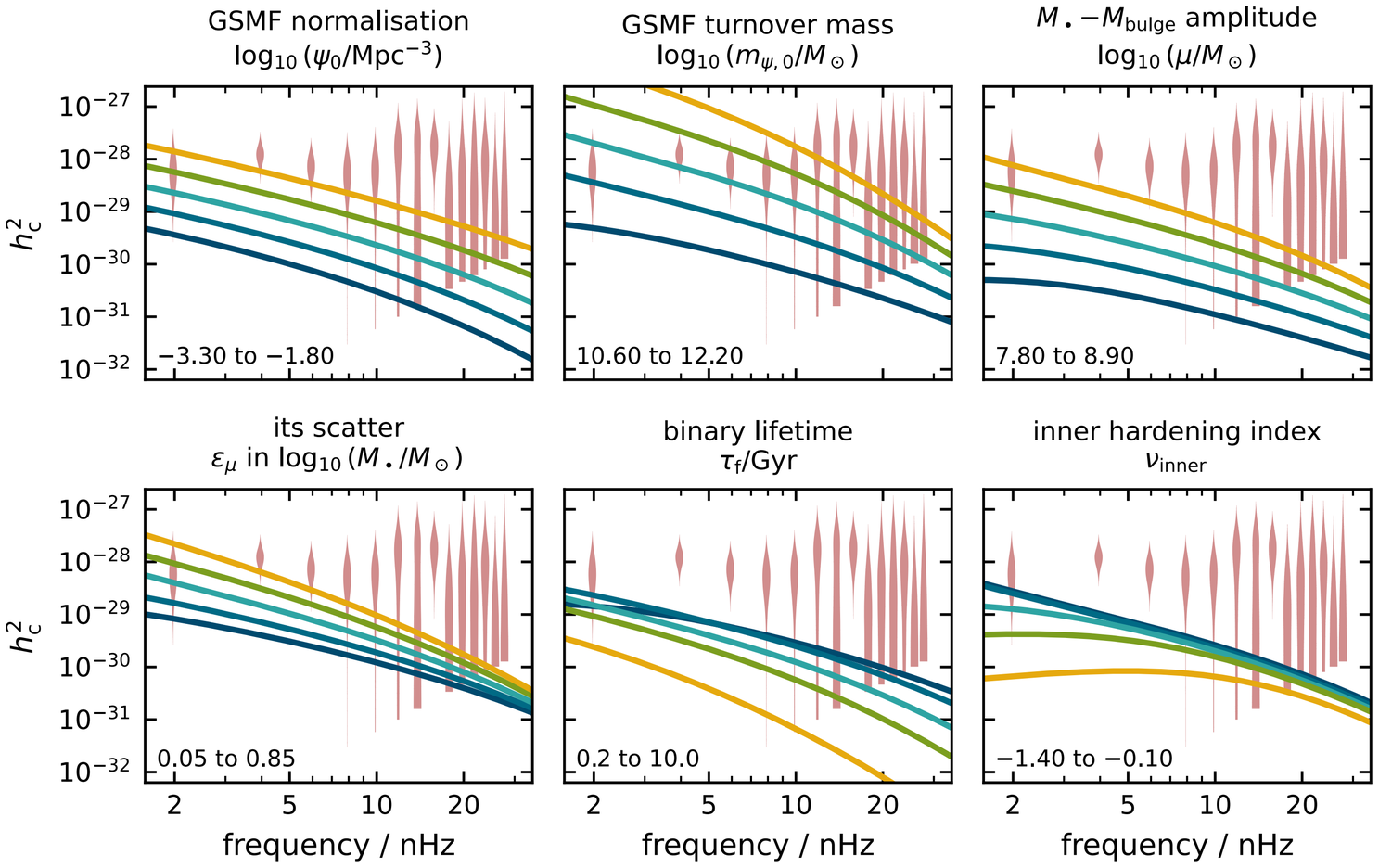
www.tasillo.de/TransitionListener


BROADCAST
INTERRUPTED




# The next challenges

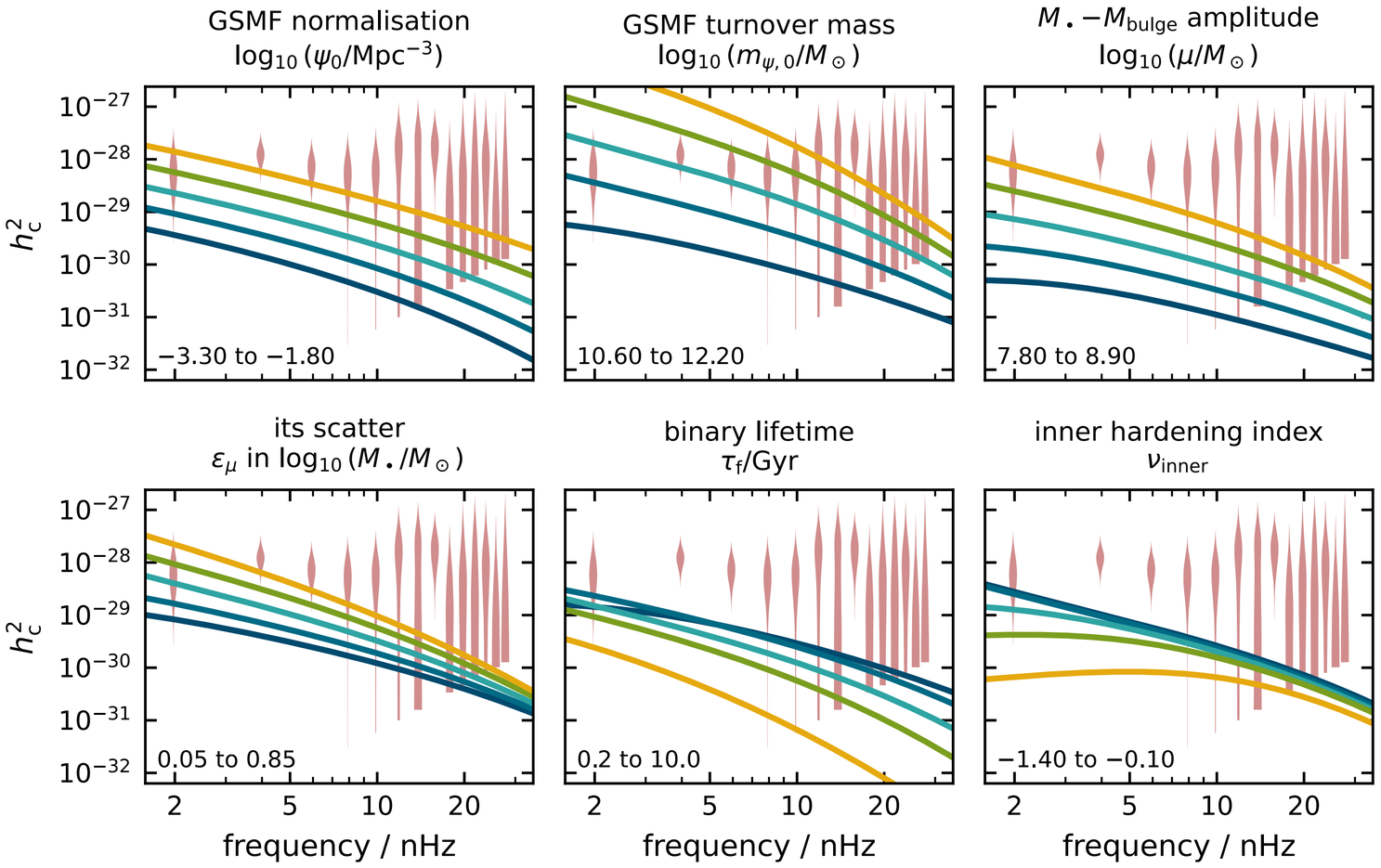
# The return of „the binaries do not really follow a power law…“




***„… the implied GWB amplitude necessitates either a large number of parameters to be at the edges of expected values, or a small number of parameters to be notably different from standard expectations.“***

NANOGrav collaboration, 2306.16220

# The return of „the binaries do not really follow a power law…“

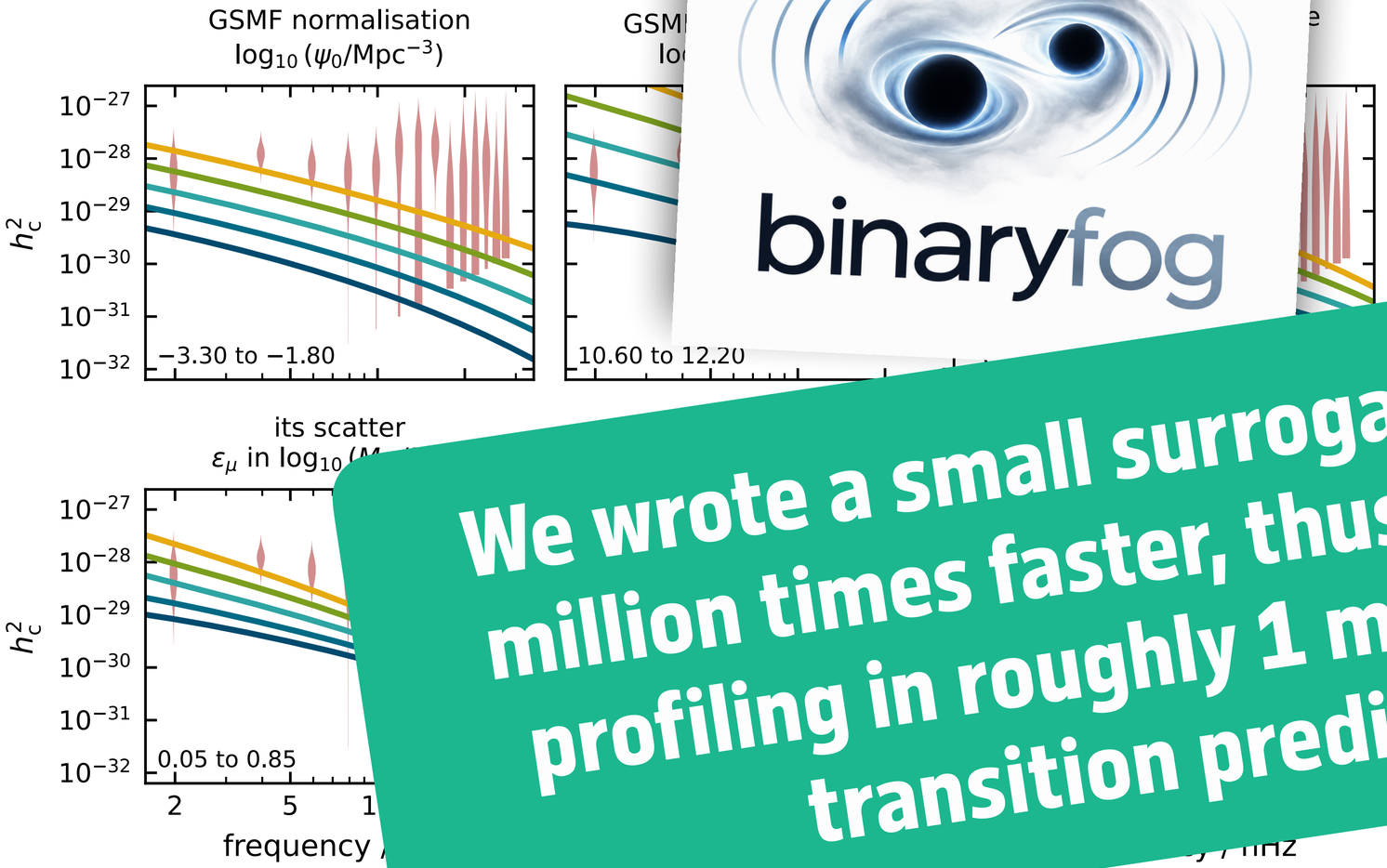



***„… the implied GWB amplitude necessitates either a large number of parameters to be at the edges of expected values, or a small number of parameters to be notably different from standard expectations.“***

NANOGrav collaboration, 2306.16220

**Each binary foreground computation takes about 2 min using `holodeck`. Profiling over the 6D astro nuisance hence takes roughly 1 year per cosmological background. :(**

# The return of „the b lly follow a power law…“




*„… the implied GWB amplitude necessitates either … ber of … t the … values, … of … tably … lard*

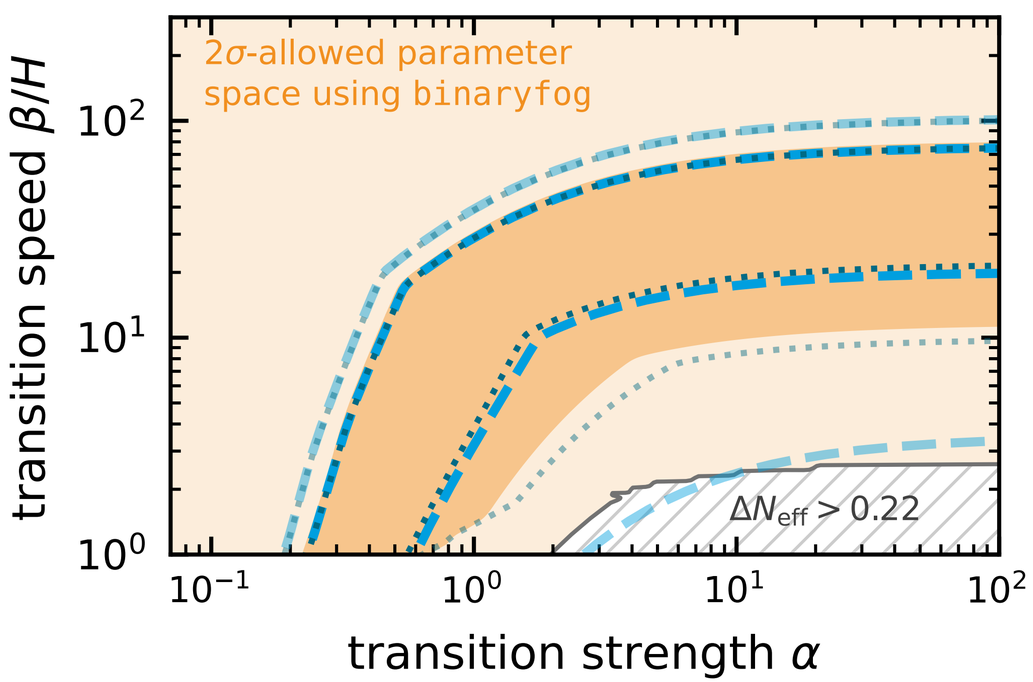
NANOGrav collaboration, 2306.16220

binaryfog

**We wrote a small surrogate which is a million times faster, thus allowing 6D profiling in roughly 1 min per phase transition prediction.**

**Each binary forc… computation takes about 2 min using `holodeck`. Profiling over the 6D astro nuisance hence takes roughly 1 year per cosmological background. :(**

# A binary foreground opens up the FOPT parameter space




Preliminary

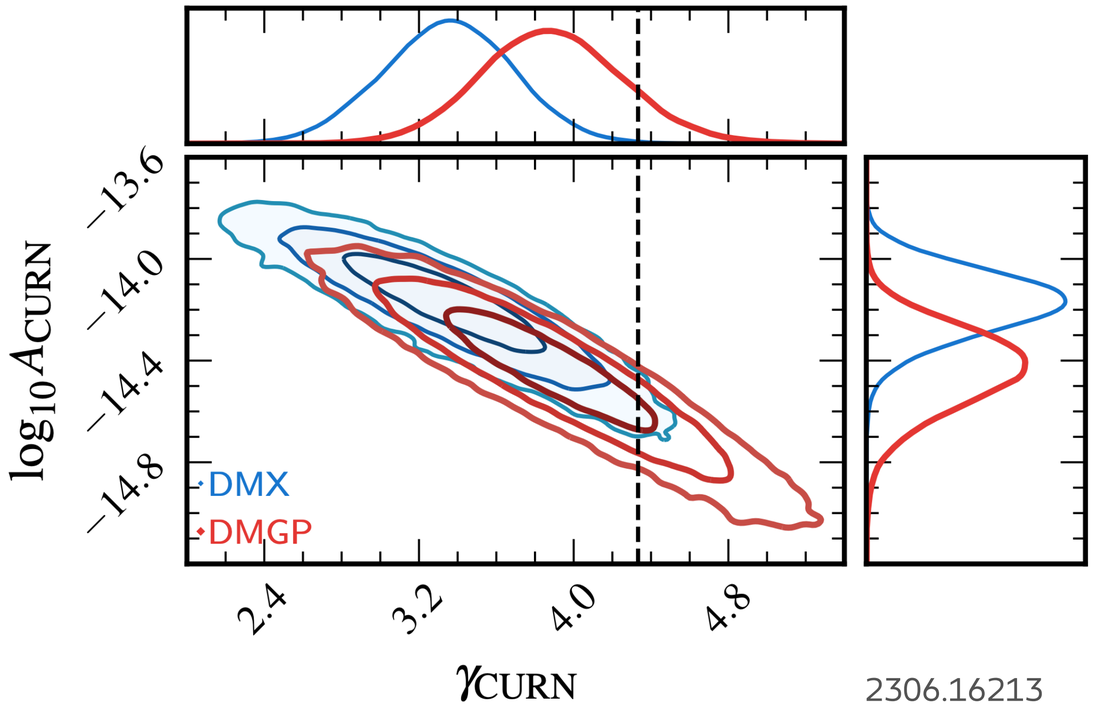
transition alone

+ $(A, \gamma)$ power law, Afzal et al.

+ binaryfog

**With a population-based binary contribution, the preference for a transition drops from $3\sigma$ to below $2\sigma$ and the $2\sigma$ contours become unbounded**

# Two more PTA data analysis issues




2306.16213

**There were errors in the PTA likelihood…**

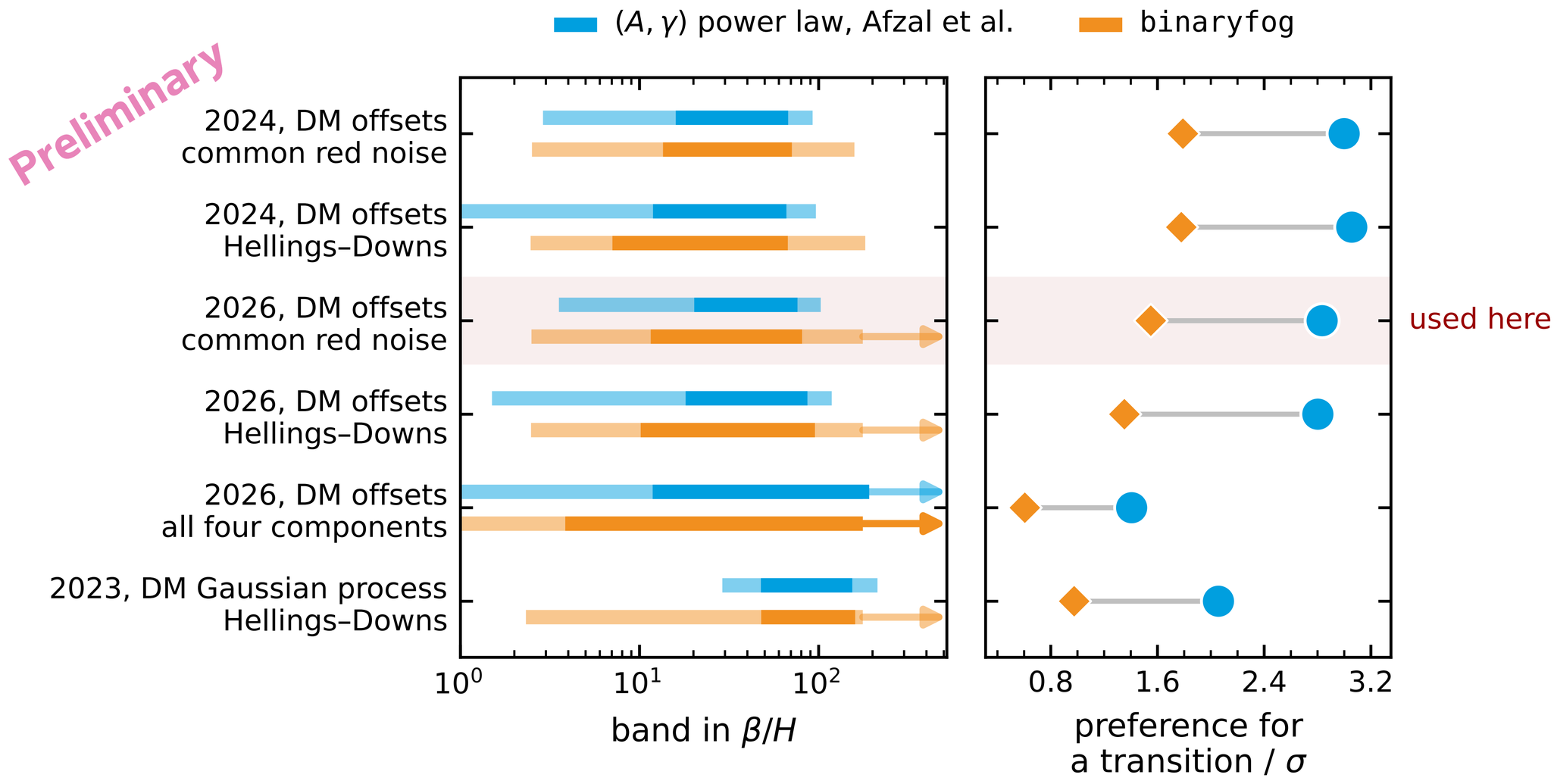
**The dispersion measure variations have a strong effect on the inferred GW signal**

The Astrophysical Journal Letters, 1006:L67 (8pp), 2026 August 1 https://doi.org/10.3847/2041-8213/ae8764
© 2026. The Author(s). Published by the American Astronomical Society.
OPEN ACCESS

**Erratum: "The NANOGrav 15 yr Data Set: Constraints on Supermassive Black Hole Binaries from the Gravitational-wave Background" (2023, ApJL, 952, L37)**

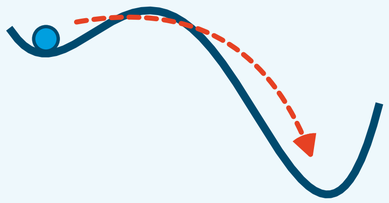
Gabriella Agazie[1], Akash Anumarlapudi[1], Anne M. Archibald[2], Paul T. Baker[3], Bence Bécsy[4], Laura Blecha[5], Alexander Bonilla[6,7], Adam Brazier[8,9], Paul R. Brook[10], Sarah Burke-Spolaor[11,12], Rand Burnette[4], Robin Case[4], J. Andrew Casey-Clyde[13], Maria Charisi[14], Shami Chatterjee[8], Katerina Chatziioannou[15], Belinda D. Cheeseboro[11,12], Siyuan Chen[16], Tyler Cohen[17], James M. Cordes[8], Neil J. Cornish[18], Fronefield Crawford[19], H. Thankful Cromartie[8,70], Kathryn Crowter[20], Curt J. Cutler[15,21], Daniel J. D'Orazio[22], Megan E. DeCesar[23], Dallas DeGan[4], Paul B. Demorest[24], Heling Deng[4], Timothy Dolch[25,26], Brendan Drachler[27,28], Elizabeth C. Ferrara[29,30,31], William Fiore[11,12], Emmanuel Fonseca[11,12], Gabriel E. Freedman[1], Emiko Gardiner[32], Nate Garver-Daniels[11,12], Peter A. Gentile[11,12], Kyle A. Gersbach[14], Joseph Glaser[11,12,73], Deborah C. Good[13,33], Kayhan Gültekin[34], Jeffrey S. Hazboun[4], Sophie Hourihane[15], Kristina Islo[1], Ross J. Jennings[11,12,70], Aaron Johnson[1,35], Megan L. Jones[1], Andrew R. Kaiser[11,12], David L. Kaplan[1], Luke Zoltan Kelley[32], Matthew Kerr[36], Joey S. Key[37], Nima Laal[4], Michael T. Lam[27,28], William G. Lamb[14], T. Joseph W. Lazio[21], Natalia Lewandowska[38], Tyson B. Littenberg[39], Tingting Liu[11,12], Jing Luo[40,72], Ryan S. Lynch[41], Chung-Pei Ma[32,42], Dustin R. Madison[43], Cayenne Matt[34], Alexander McEwen[1], James W. McKee[44,45], Maura A. McLaughlin[11,12], Natasha McMann[14], Bradley W. Meyers[20,46], Patrick M. Meyers[15], Chiara M. F. Mingarelli[13,33,47], Andrea Mitridate[48], Priyamvada Natarajan[49,50], Cherry Ng[51], David J. Nice[52], Stella Koch Ocker[8], Ken D. Olum[53], Timothy T. Pennucci[54], Benetge B. P. Perera[55], Polina Petrov[14], Nihan S. Pol[14], Henri A. Radovan[56], Scott M. Ransom[57], Paul S. Ray[36], Joseph D. Romano[58], Jessie C. Runnoe[14], Shashwat C. Sardesai[1], Ann Schmiedekamp[59], Carl Schmiedekamp[59], Kai Schmitz[60], Levi Schult[14], Brent J. Shapiro-Albert[11,12,74], Xavier Siemens[1,4], Joseph Simon[61,71], Magdalena S. Siwek[62], Ingrid H. Stairs[20], Daniel R. Stinebring[63], Kevin Stovall[24], Jerry P. Sun[4], Abhimanyu Susobhanan[1], Joseph K. Swiggum[52,71], Jacob Taylor[4], Stephen R. Taylor[14], Jacob E. Turner[11,12], Caner Unal[64,65], Michele Vallisneri[21,35], Sarah J. Vigeland[1], Jeremy M. Wachter[66], Haley M. Wahl[11,12], Qiaohong Wang[14], Caitlin A. Witt[12,67,68], David Wright[69], Olivia Young[27,28] The NANOGrav Collaboration

# Effect of the PTA data analysis choices on the preferred phase transition speeds

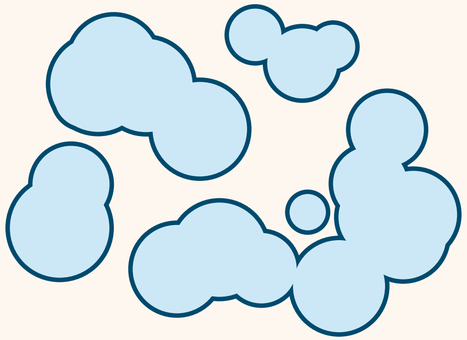


# How do all these modeling choices impact parameter inference?

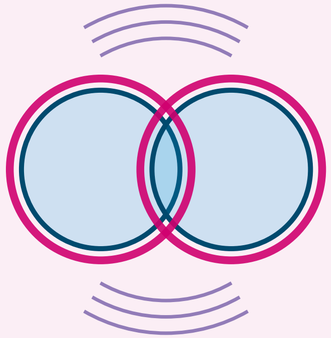
## Nucleation rate



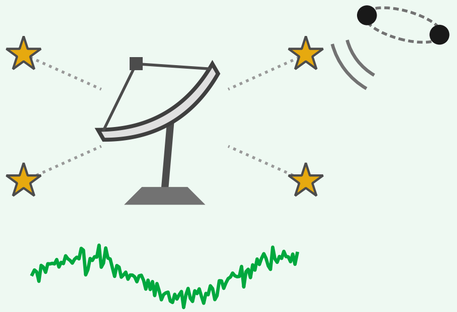
## Percolation and reheating



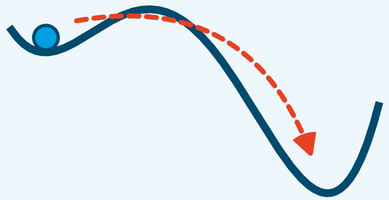
## Gravitational wave source



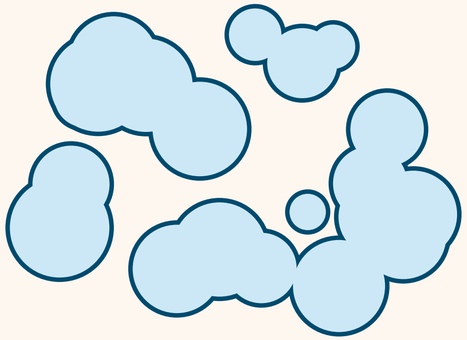
## Binaries and pulsar data



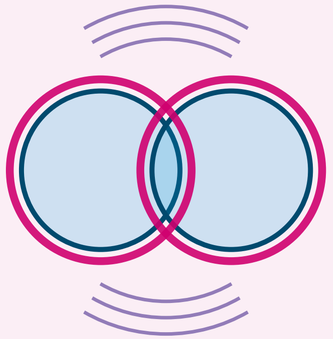
## Nucleation rate



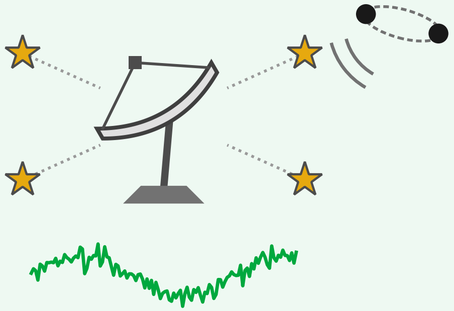
## Percolation and reheating



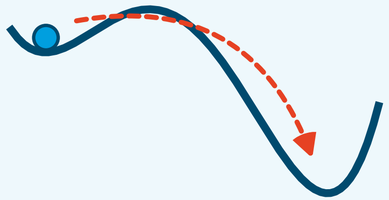
## Gravitational wave source



## Binaries and pulsar data

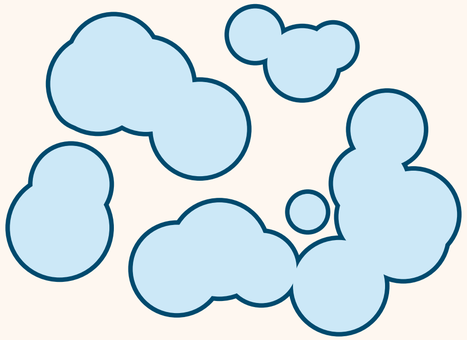


## Nucleation rate

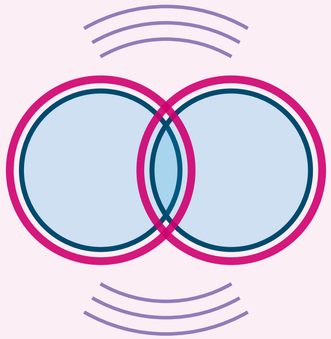


| | |
|---|---|
| N1 | $\mu_4$, $\mu_3$ halved, doubled |
| N2 | Estimate of the next order |
| N3 | Dynamical prefactor ×10, /10 |
| N4 | LO instead of NLO |
| N5 | $V_{4D}$ + Daisy |

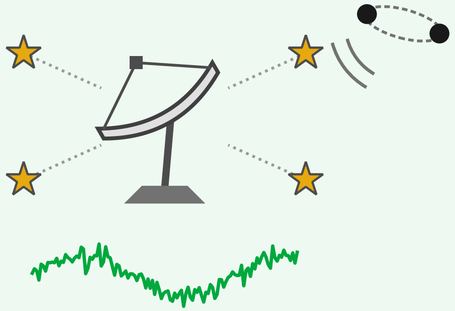
## Percolation and reheating



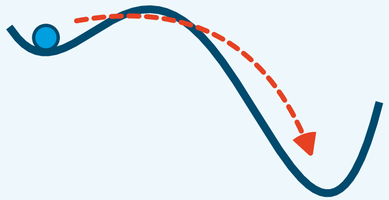
## Gravitational wave source



## Binaries and pulsar data

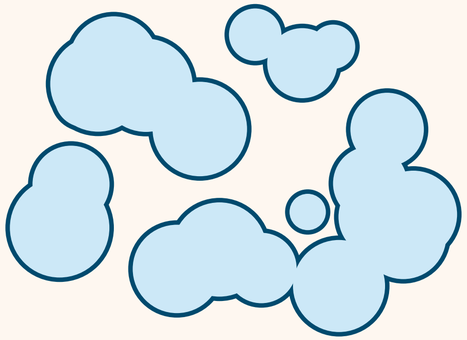


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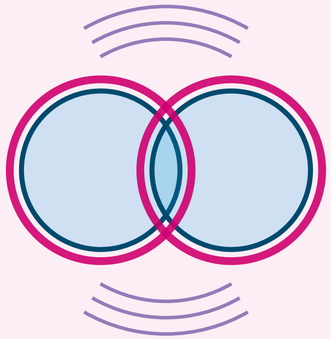
| | |
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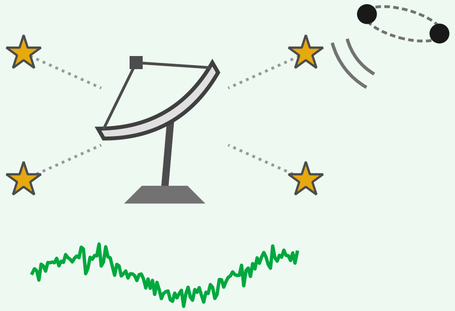


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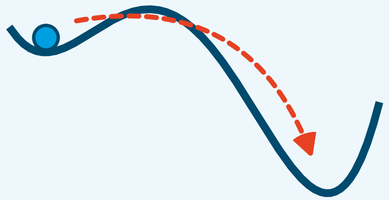
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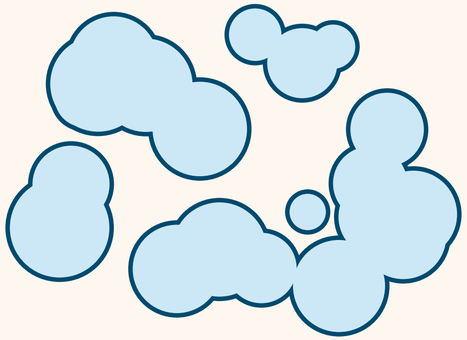


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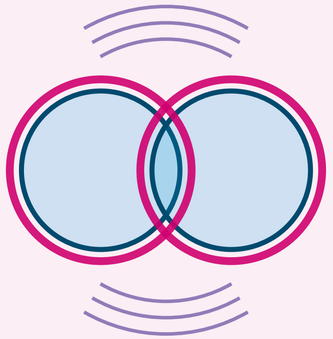
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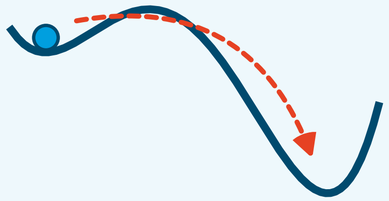


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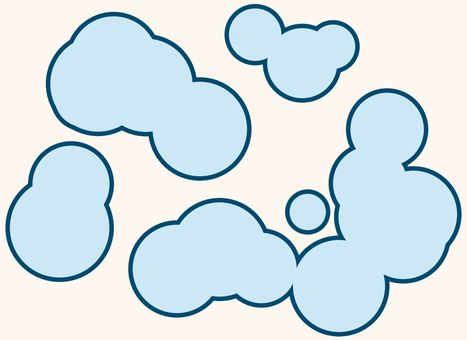


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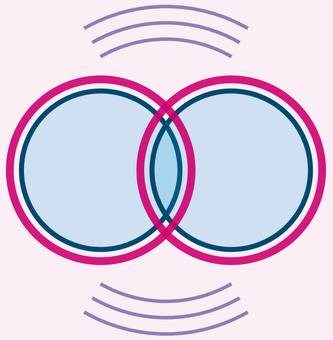
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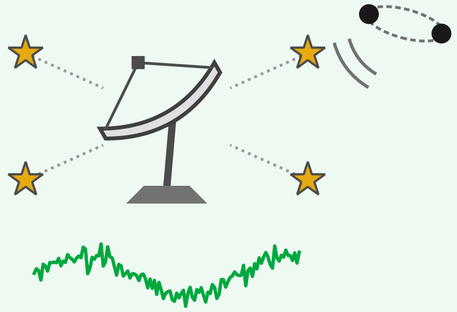
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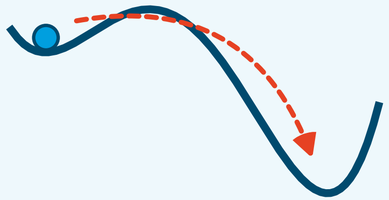
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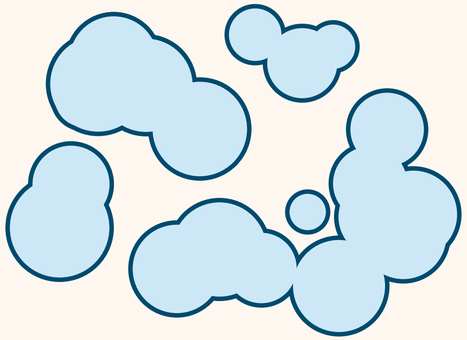
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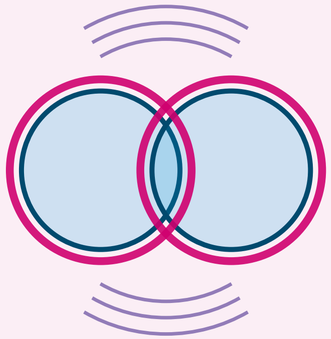
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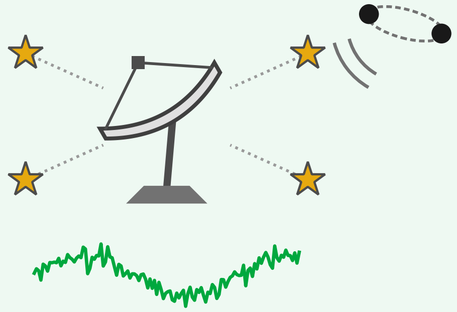
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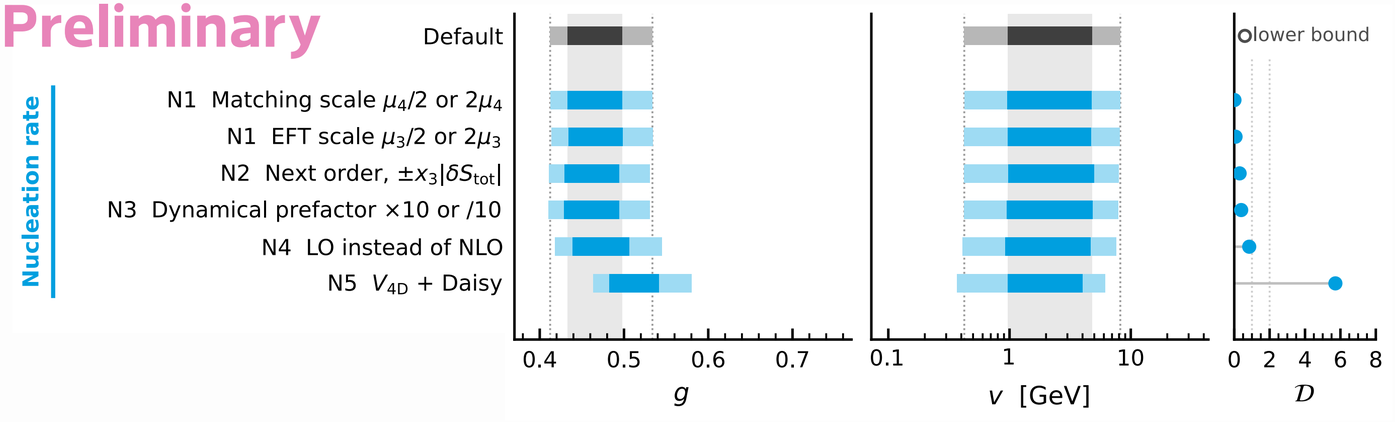
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# Let’s go through the modeling choices one after the other

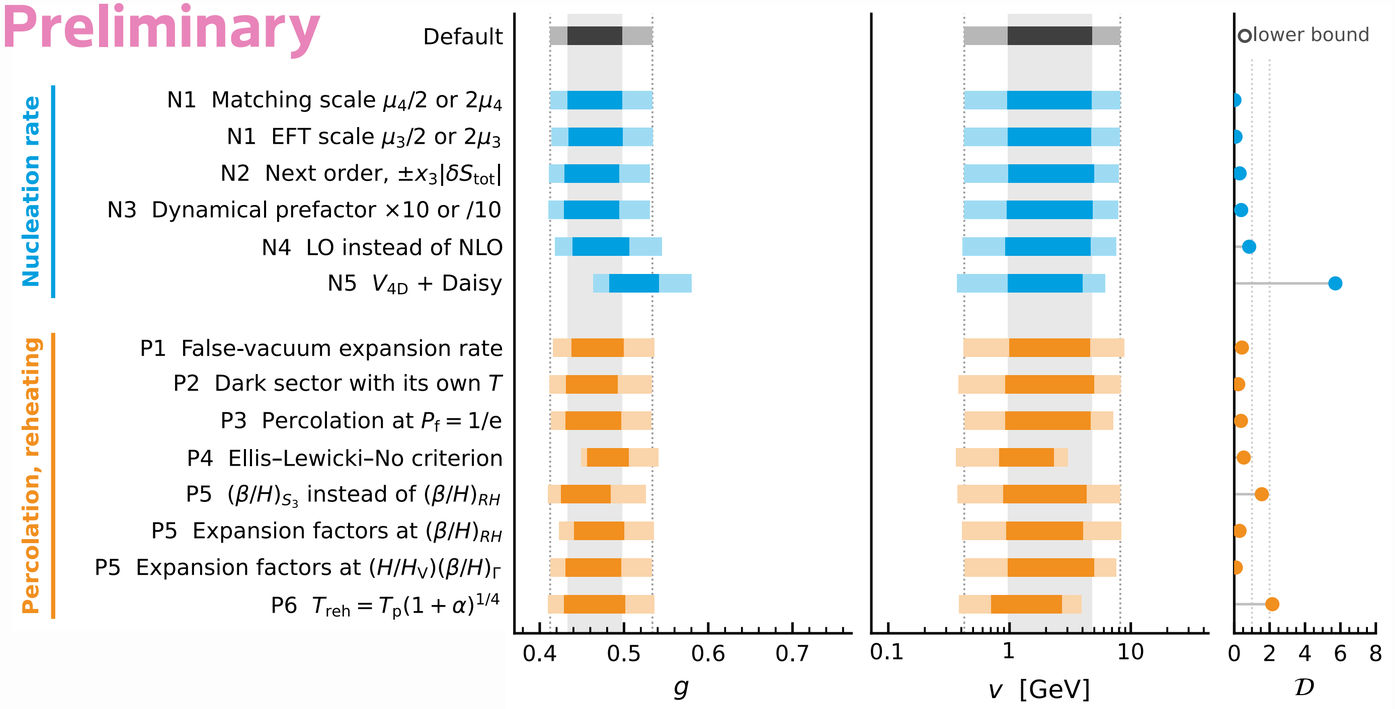
Preliminary




# Use dimensional reduction! LO or NLO or even incl. dim-6 don't impact the results much.

[See also talks by J. Hirvonen, O. Gould, P. Schicho; 2610.12284 by Bernardo+, 2609.12098 by Puchades-Ibáñez+]

Preliminary

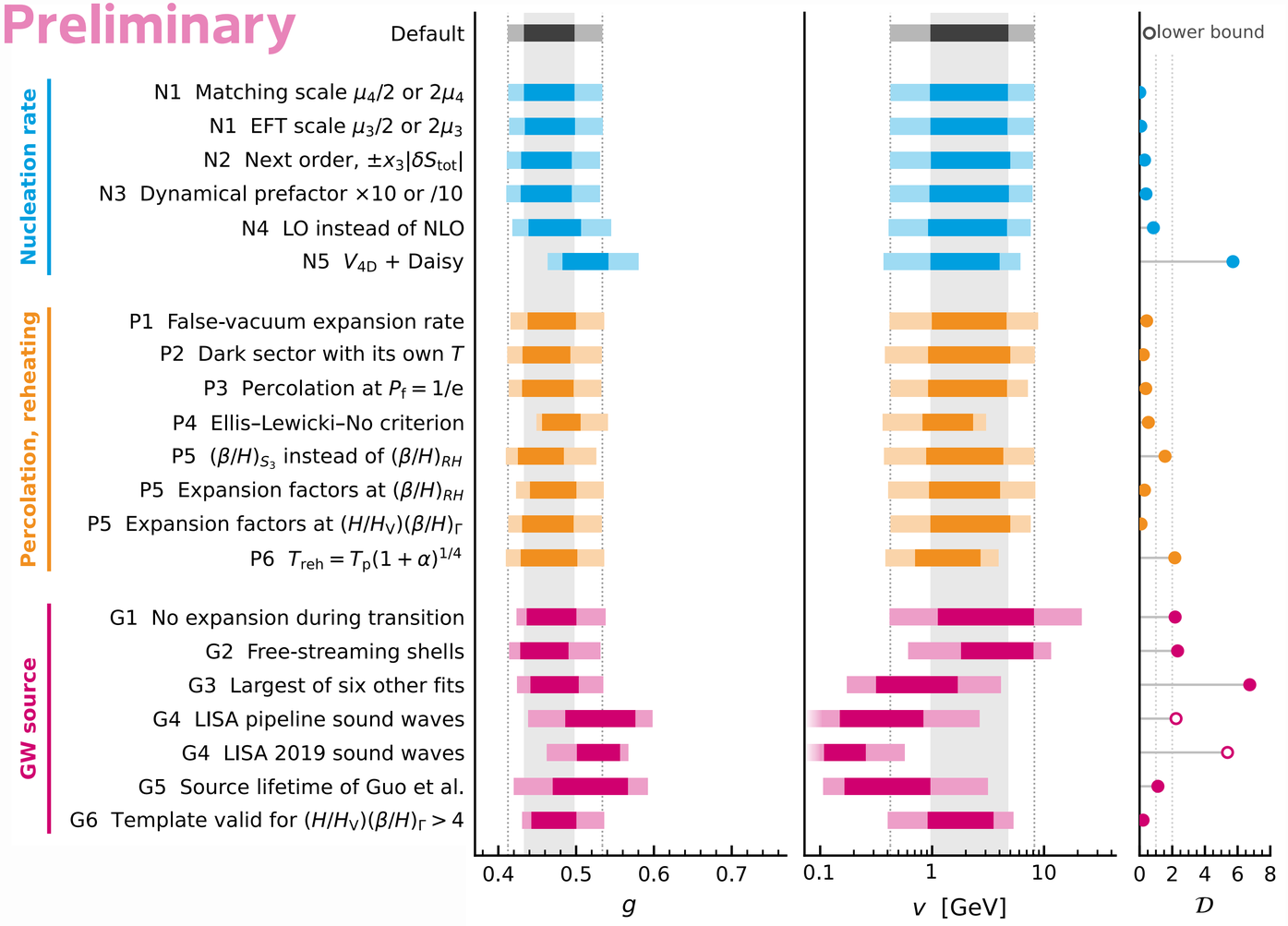



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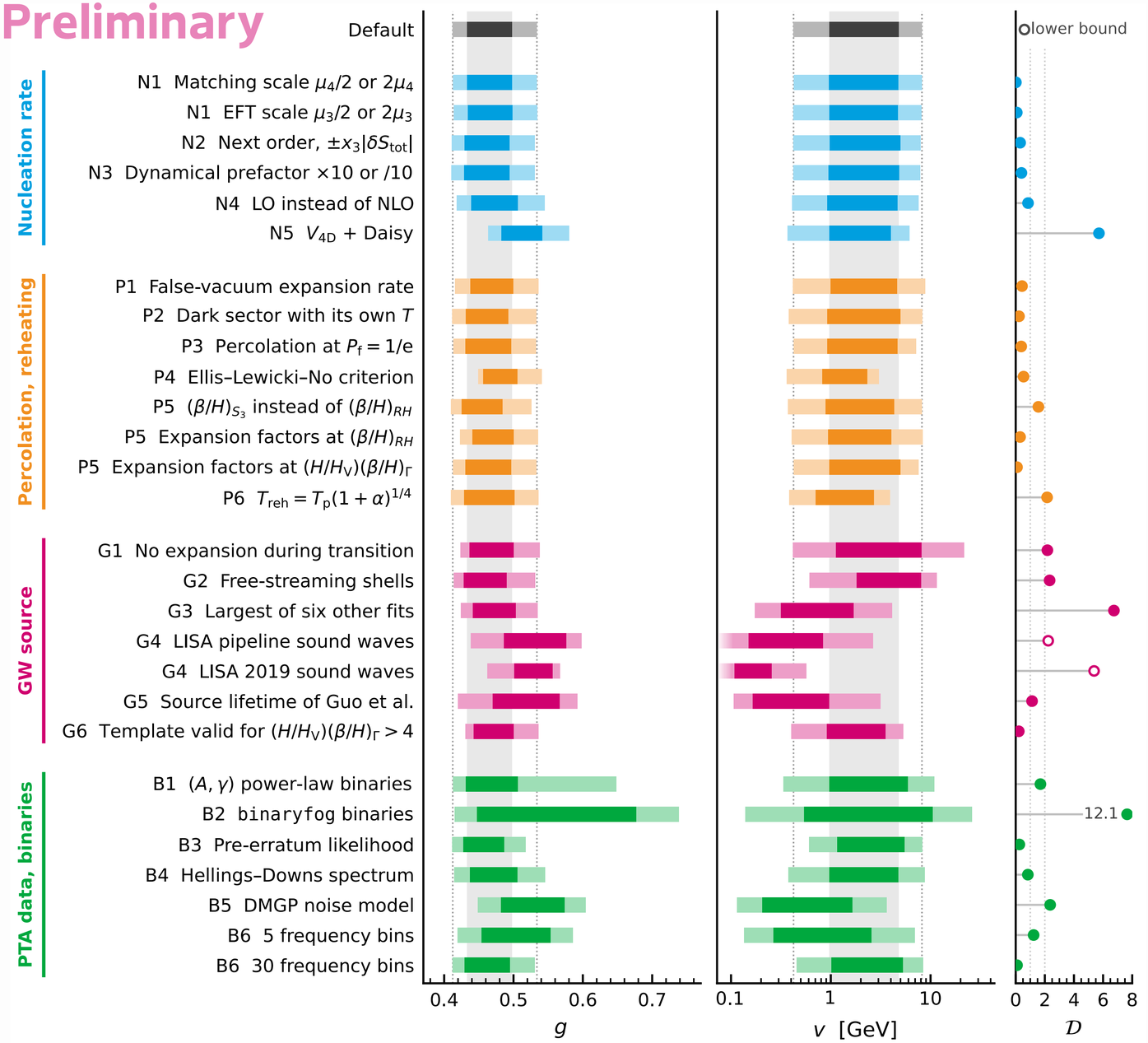

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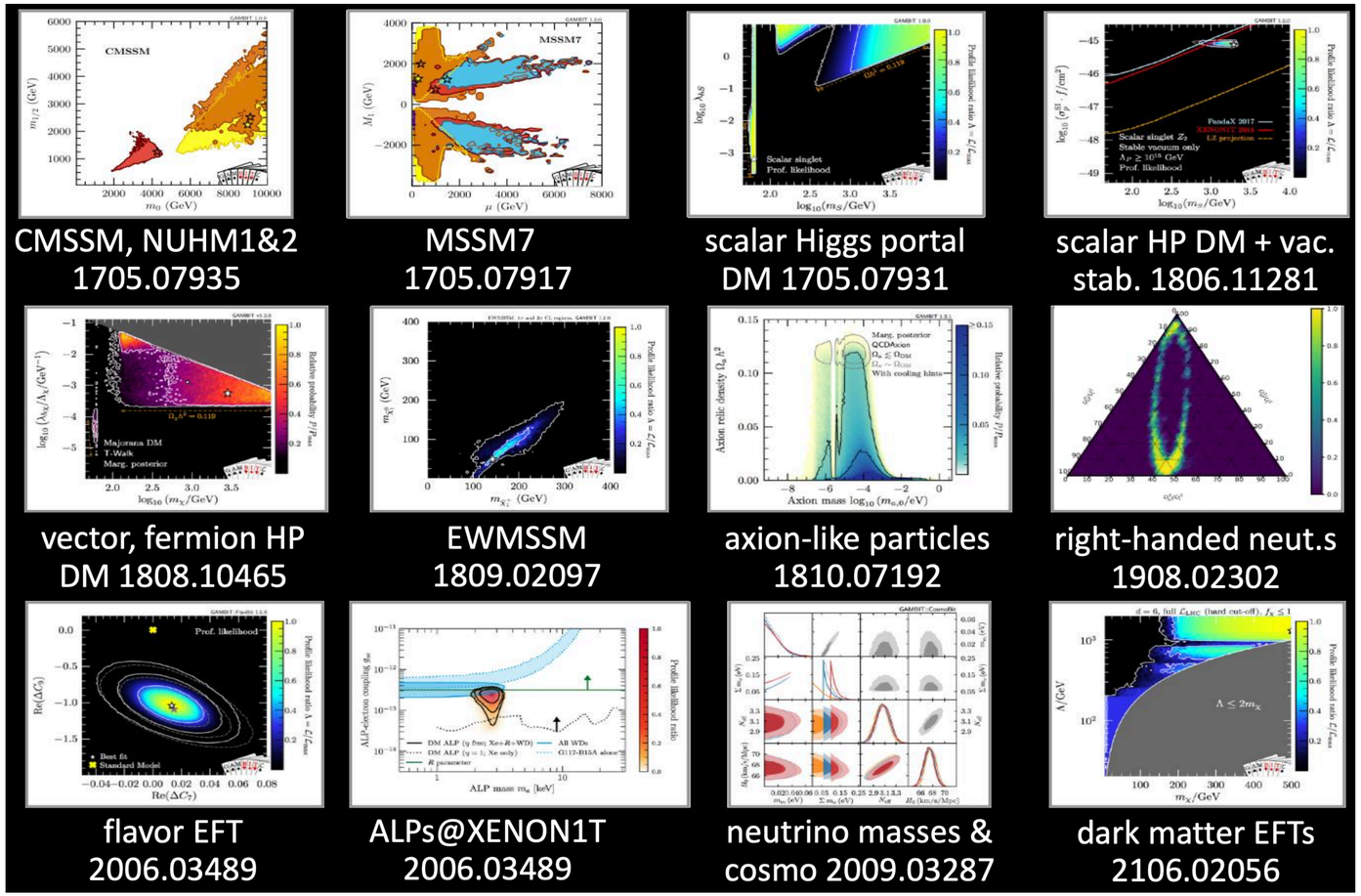
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**Be sure that your transitions actually complete and that you use the right $\beta/H$ definition**

**Use valid GW templates. Clearly more work needed here.**

**Include binaries (!), use the latest likelihoods and state which dispersion measure noise modeling you chose.**

# The next step: Put all of this in a global fit




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

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

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

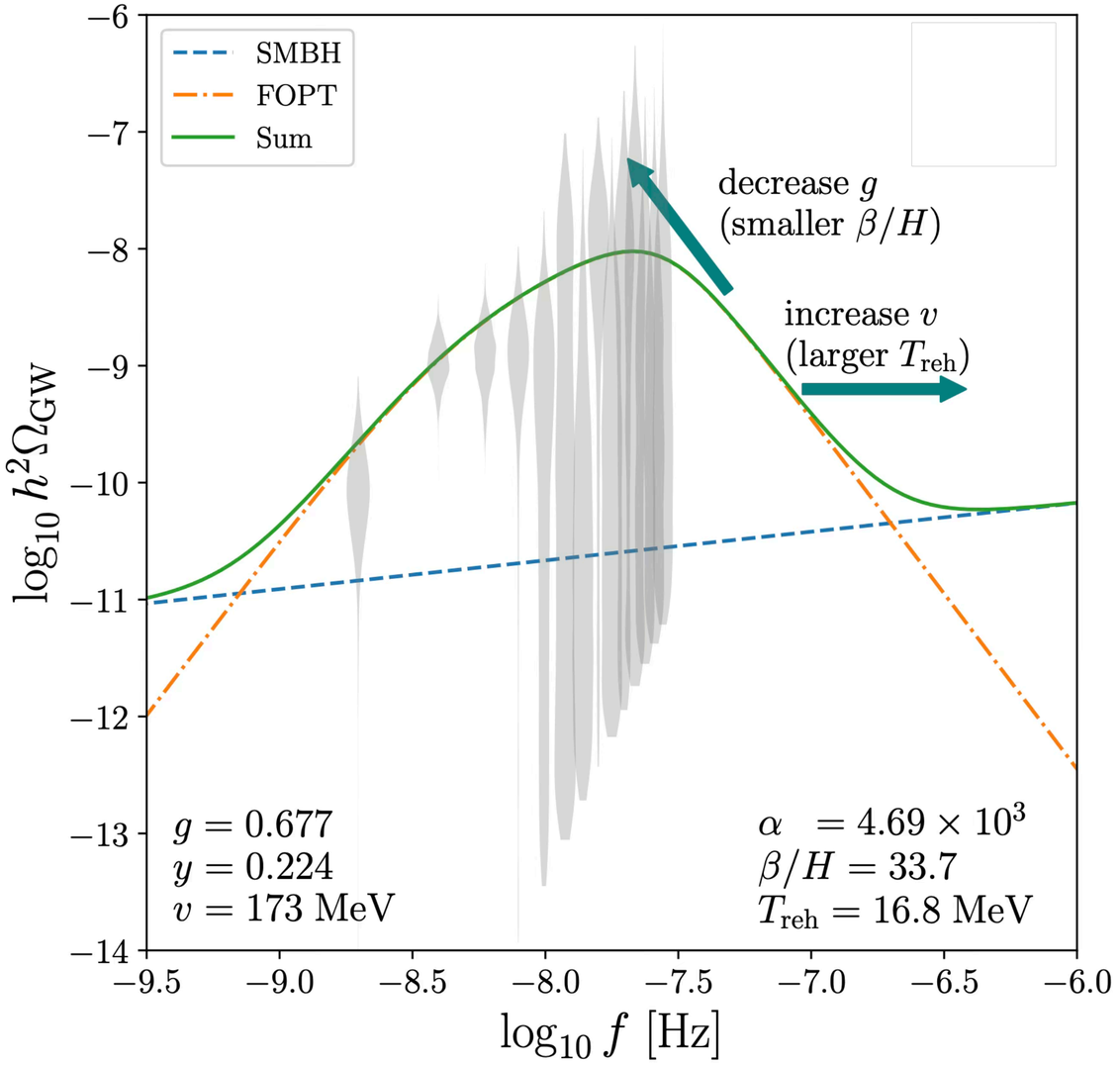
Slide by C. Balázs @ SUSY 2021




**Relevant constraints: BBN and CMB, but also dark matter (in)direct detection, beam dumps, scalar power spectrum, …**

[See also new BBN isocurvature constraints by Elahi et al, 2609.25950]

# Previous global fits: PTA interpretation can be probed in labs!




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

*This fit still used a pre-release version of TransitionListener, binaries following a power law, pre-erratum PTA likelihoods and a 4D+Daisy bubble nucleation rate

# LISA is blind!



# LISA is blind!



# 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]

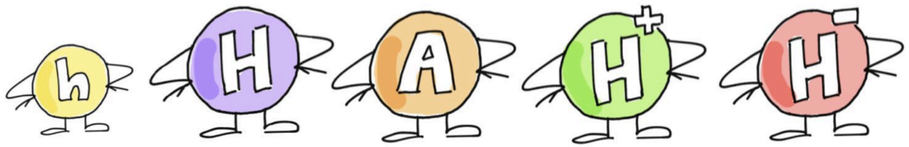
[a] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*

[b] *School of Physics and Astronomy, University of Southampton, Highfield, Southampton SO17 1BJ, United Kingdom*

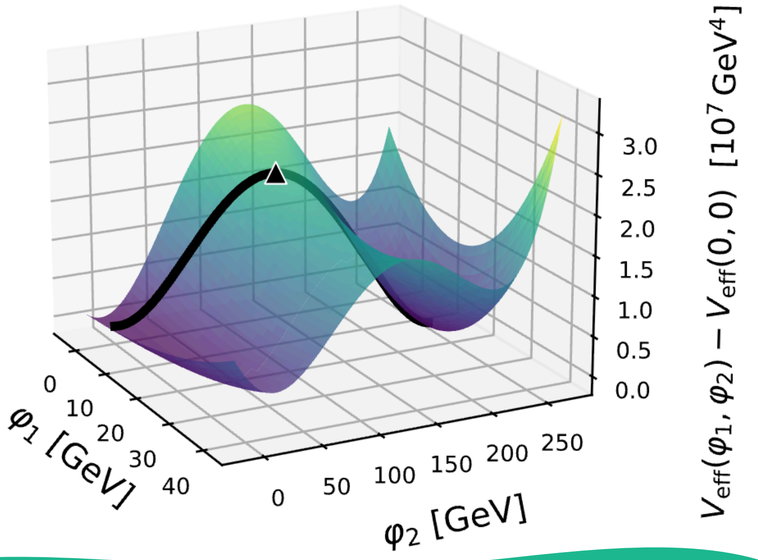
[c] *Instituto de Física orpuscular (IFIC), Universitat de Valéncia-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain*

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

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



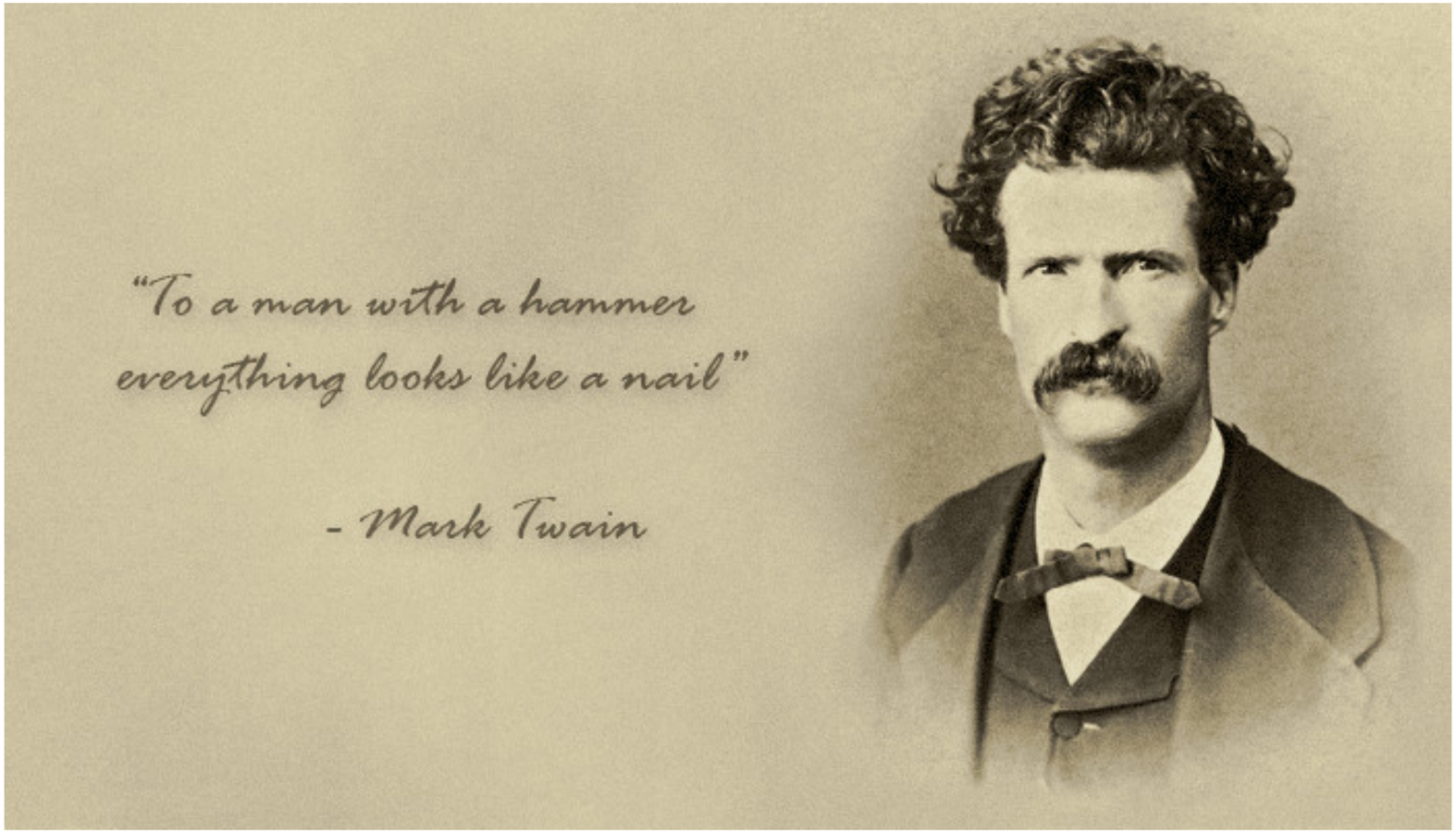

[Image credit: Kateryna Radchenko]



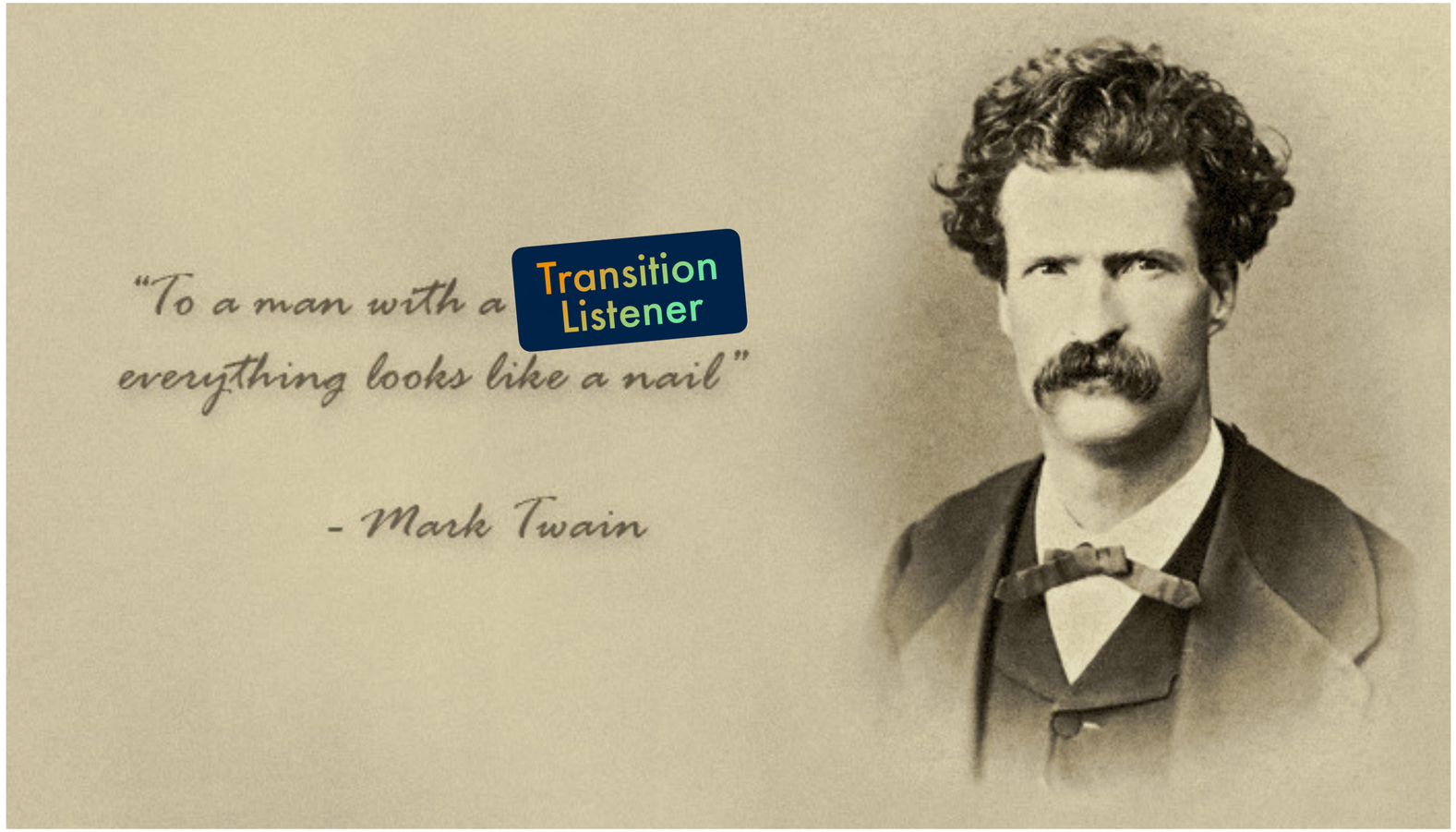

**In the SM the EWPT is a crossover. To get a GW signal and baryogengesis* we need to extend it. One example: 2HDM.**

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

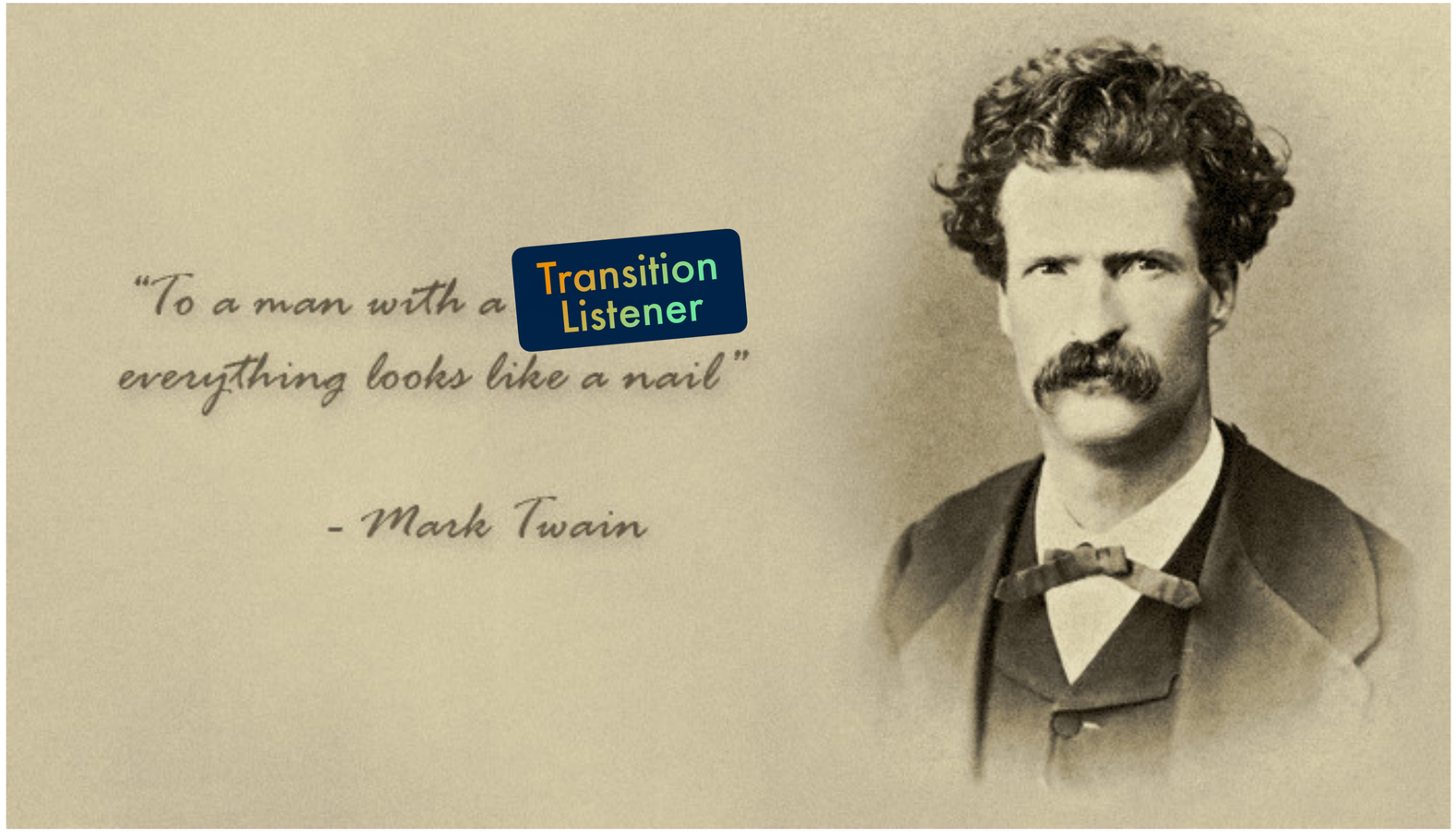
# Why study the 2HDM?



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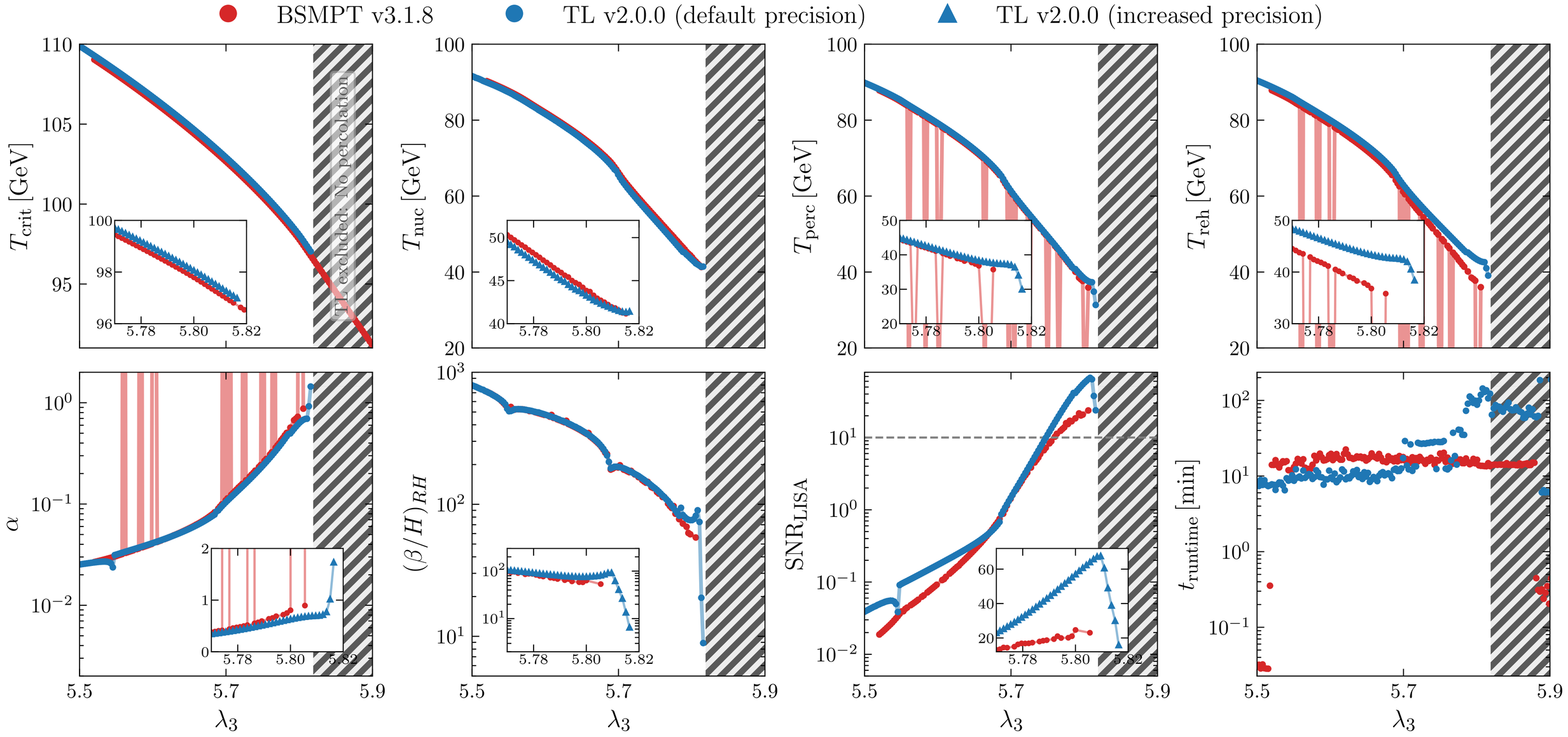


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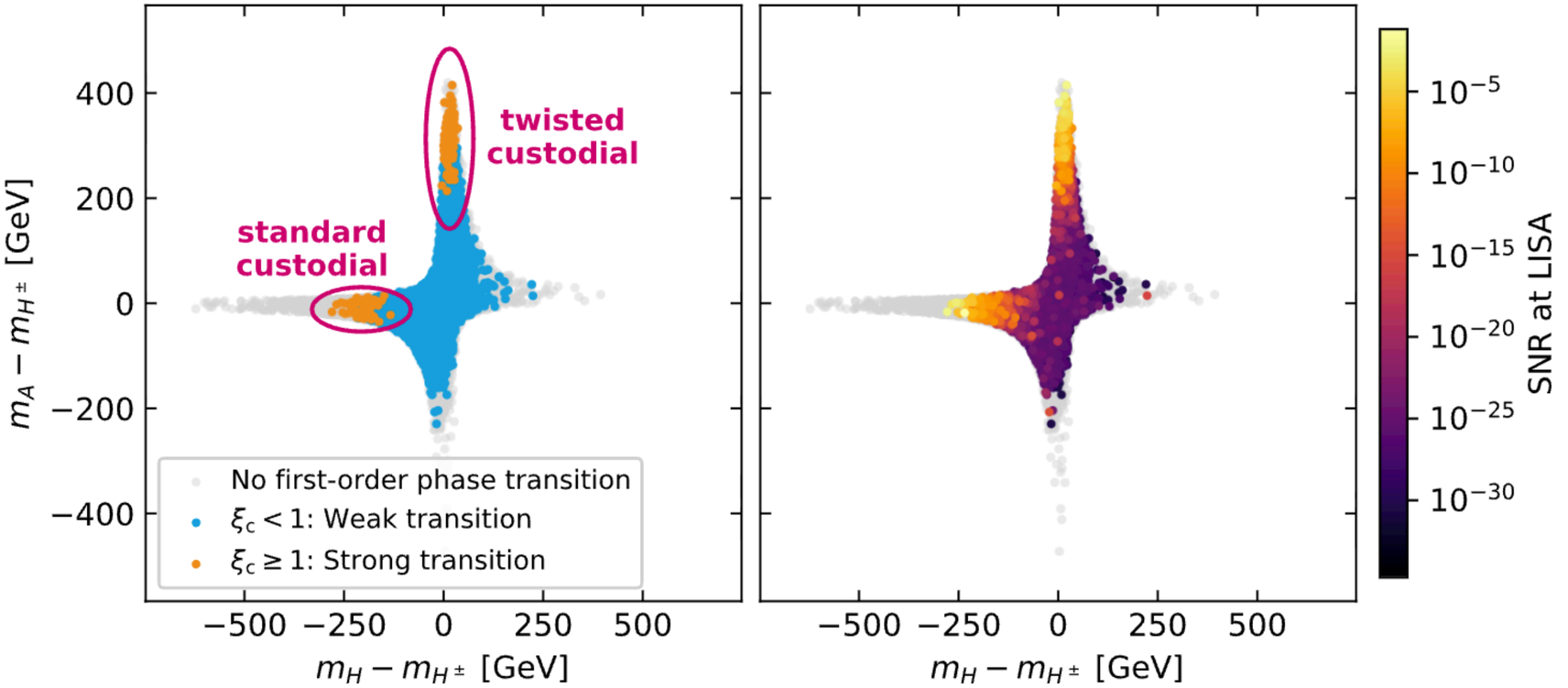



+ the possibility to study large parts of the parameter space at colliders; SUSY and QCD axions also require a second Higgs doublet; the 2HDM features DM candidates itself; ...

# Comparison BSMPT vs. TransitionListener, 2HDM benchmark

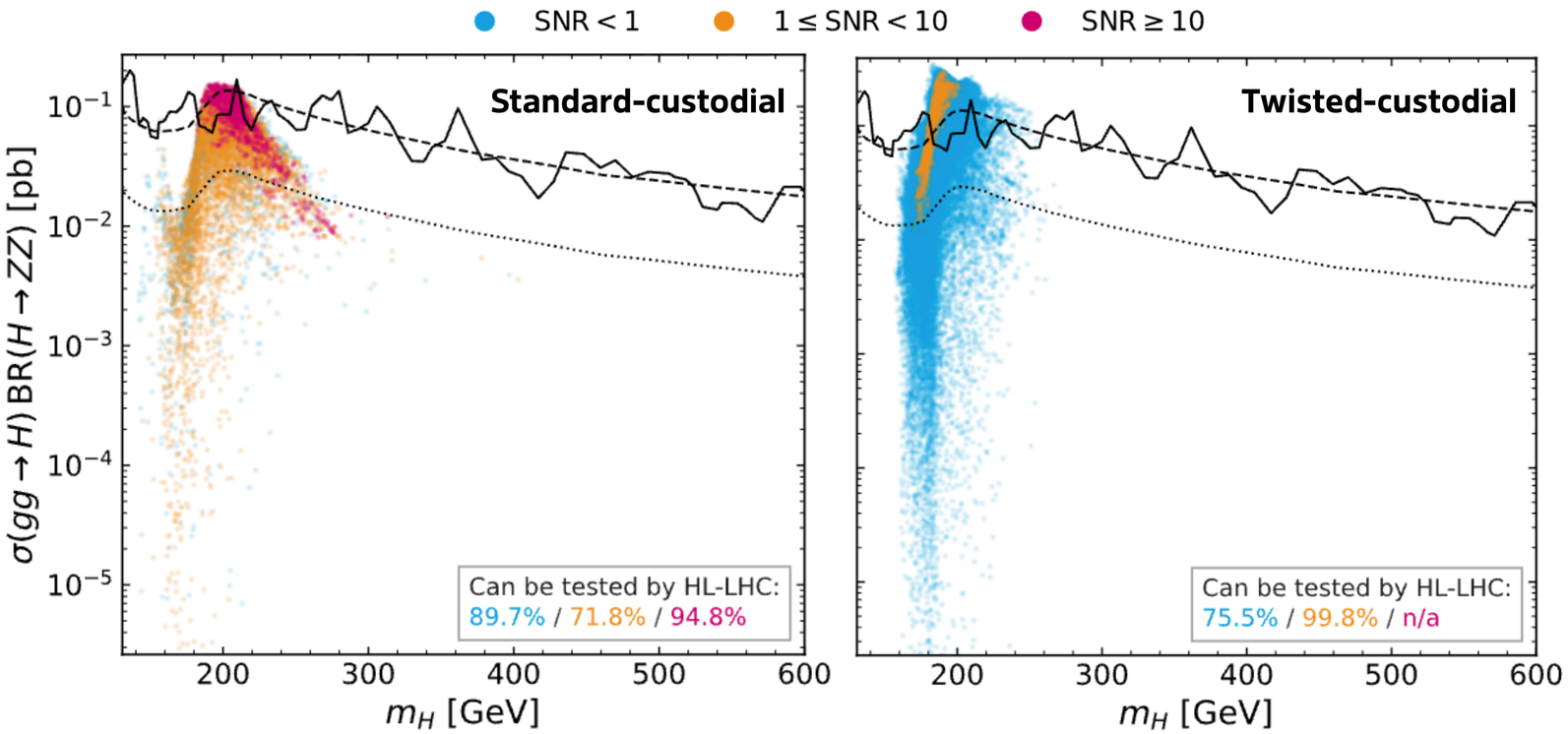


# Observational constraints leave two options for strong LISA signals




**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 wall velocities with WallGo.

We need not only a **controlled perturbative expansion** in the bubble nucleation rate, but also **spectral templates** valid where signals are interesting, **consistent cosmological histories**, and should treat **astrophysical foregrounds** as nuisance.



**TransitionListener v2.0** remains numerically stable and physically accurate under strong supercooling and large bubbles. Soon: NLO rates.

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



**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.

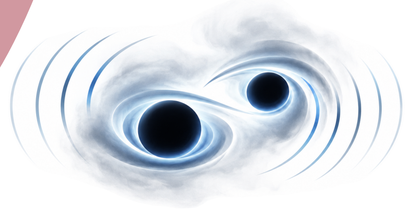




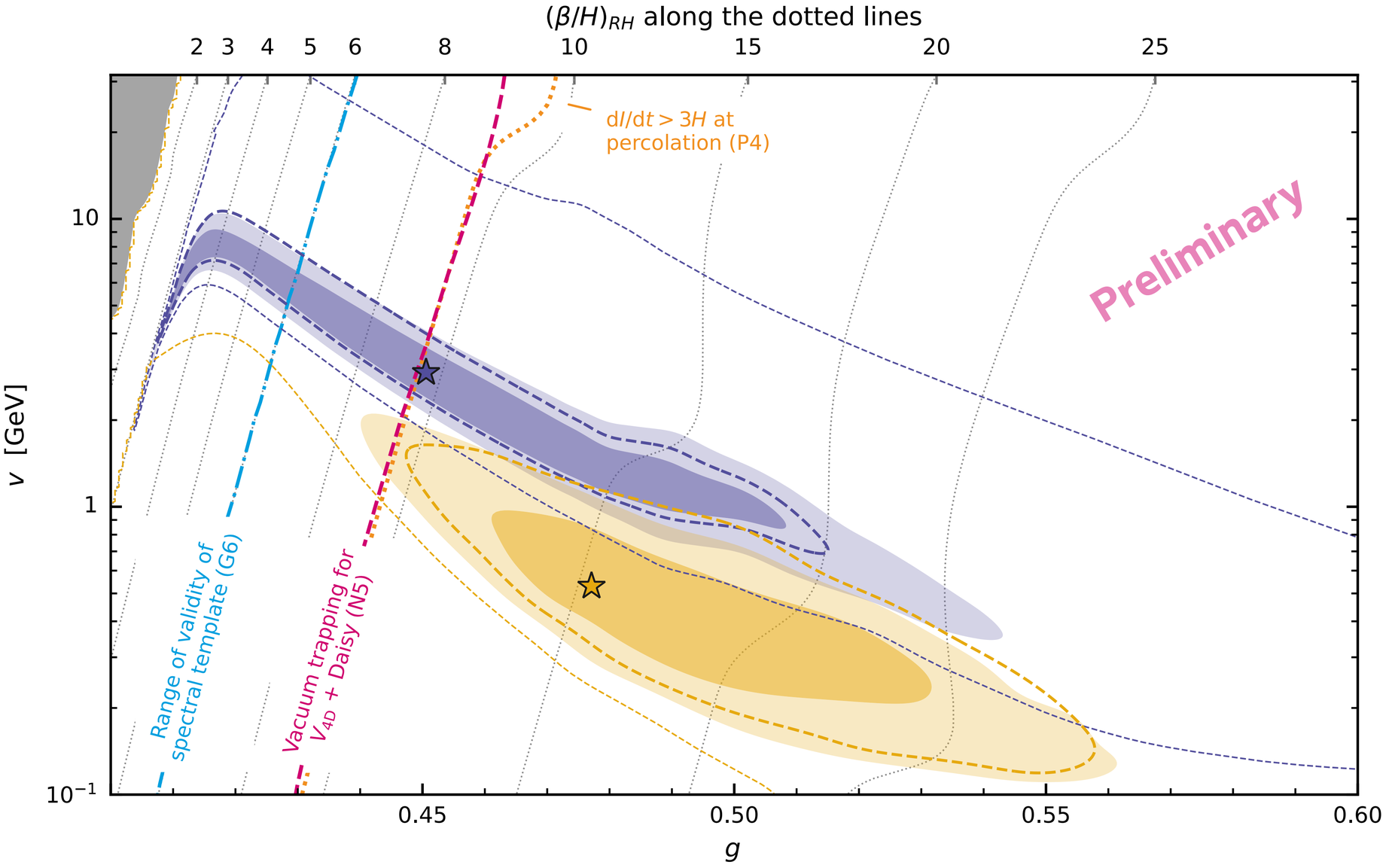
I consider all of the PTA searches for phase transitions also a **big playground for LISA**, since the lessons can be directly transferred there.

**Global fits** are needed to find good transition models which respect additional constrains and don't underestimate the flexibility of astrophysics.

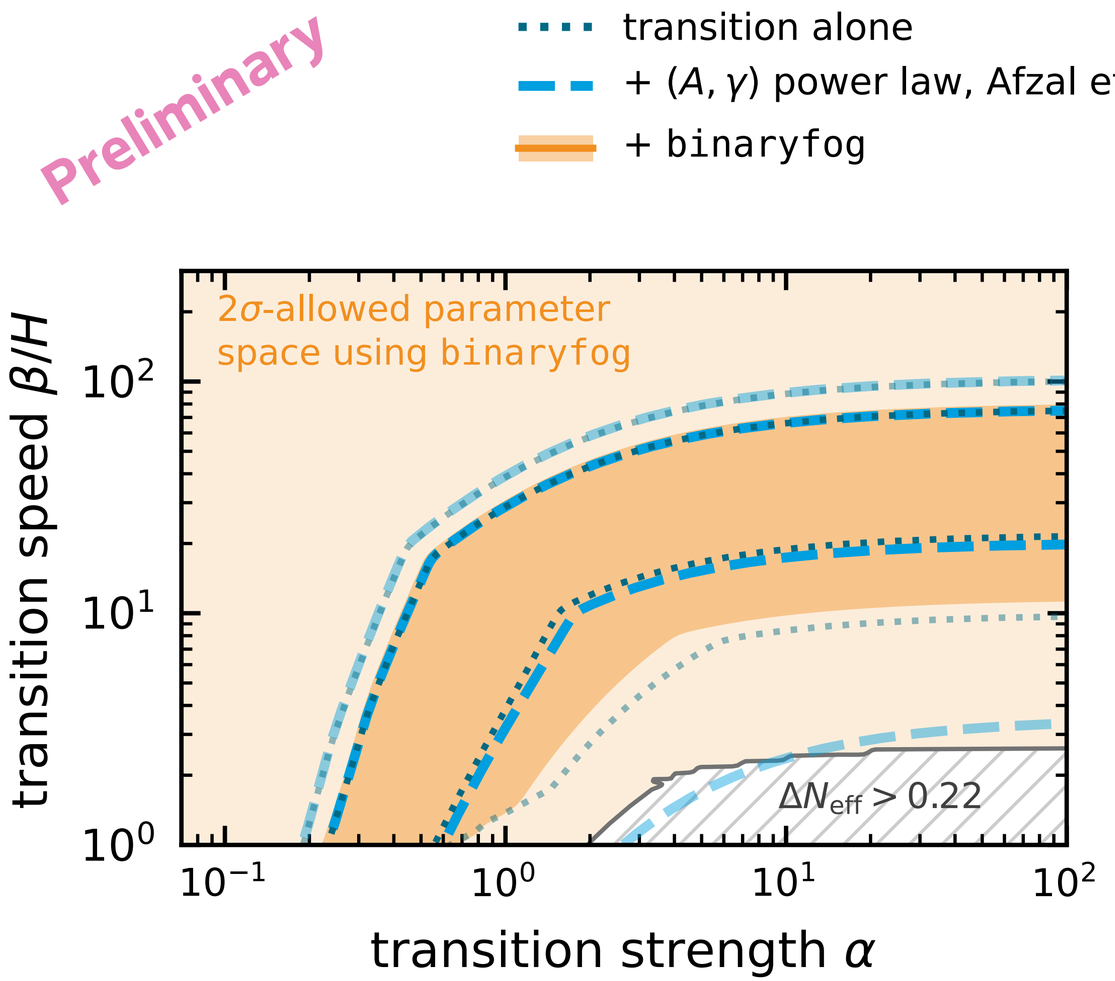


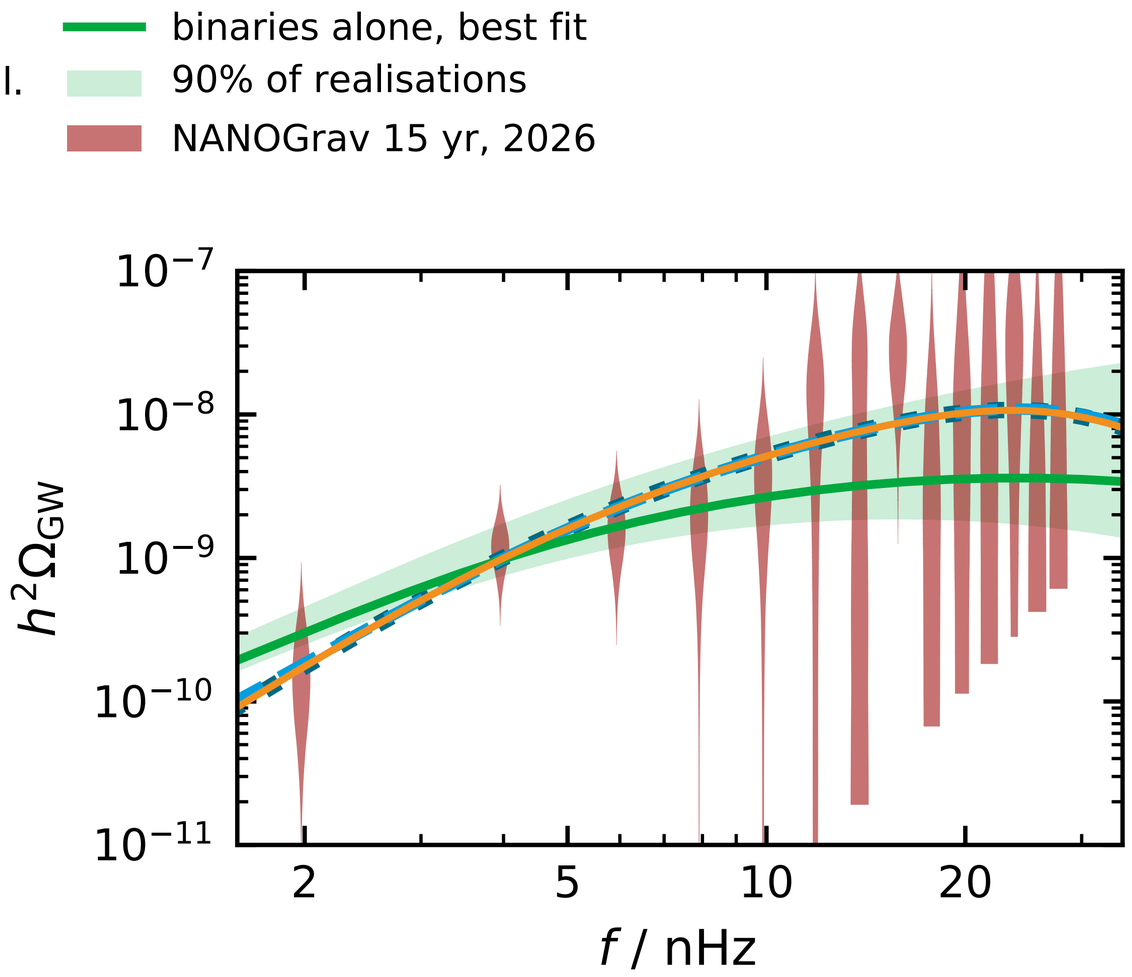



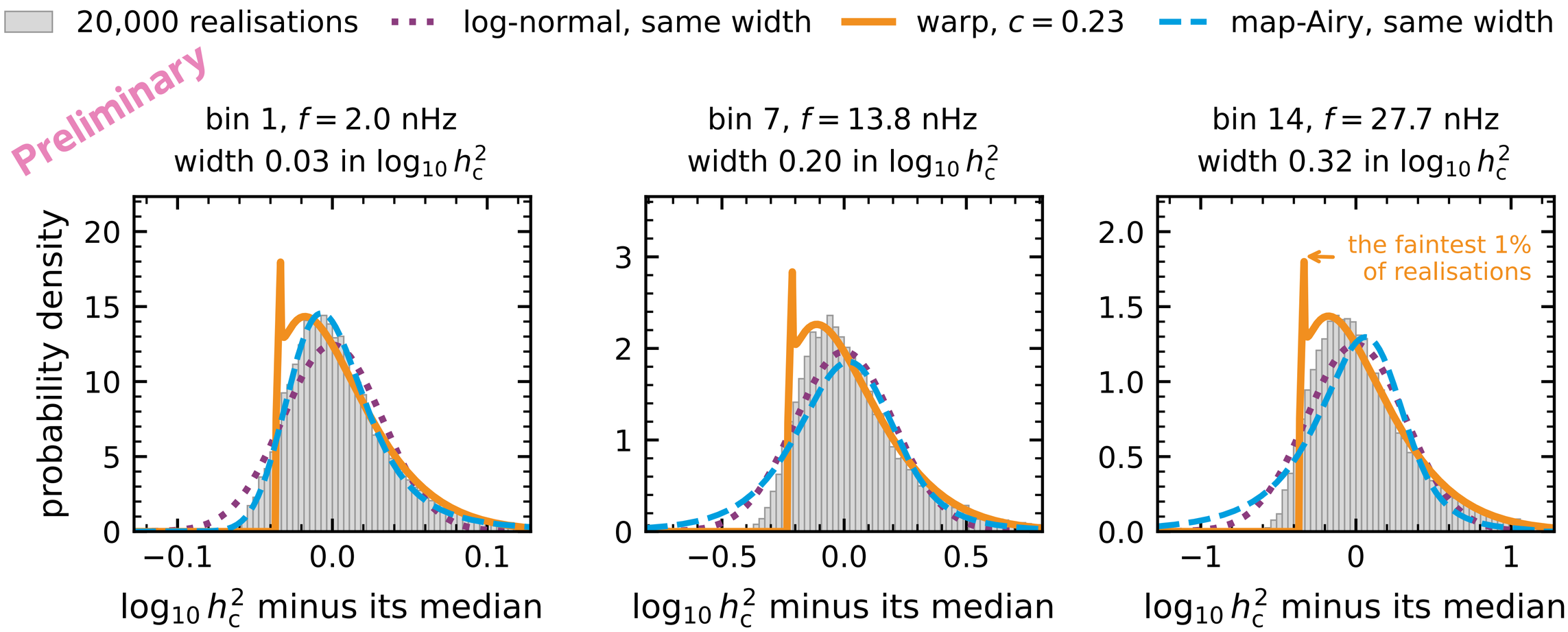
# Backup slides

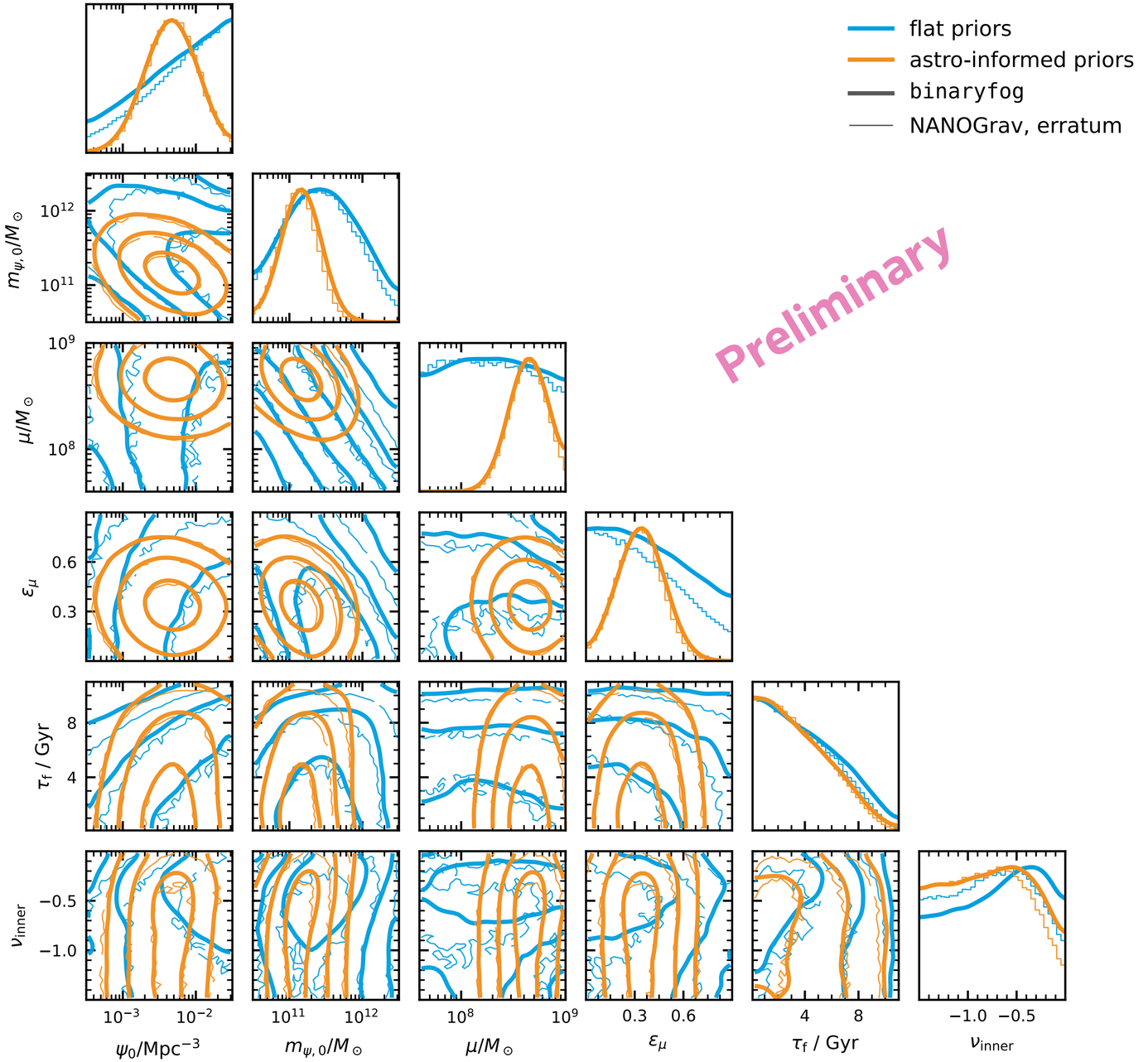

$(\beta/H)_{RH}$ along the dotted lines
2
3
4
5
6
8
10
15
20
25
dl/d$t > 3H$ at percolation (P4)
Preliminary
$v$ [GeV]
10
1
$10^{-1}$
Range of validity of spectral template (G6)
Vacuum trapping for $V_{4D}$ + Daisy (N5)
0.45
0.50
0.55
0.60
$g$
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Vacuum trapping
Best fits

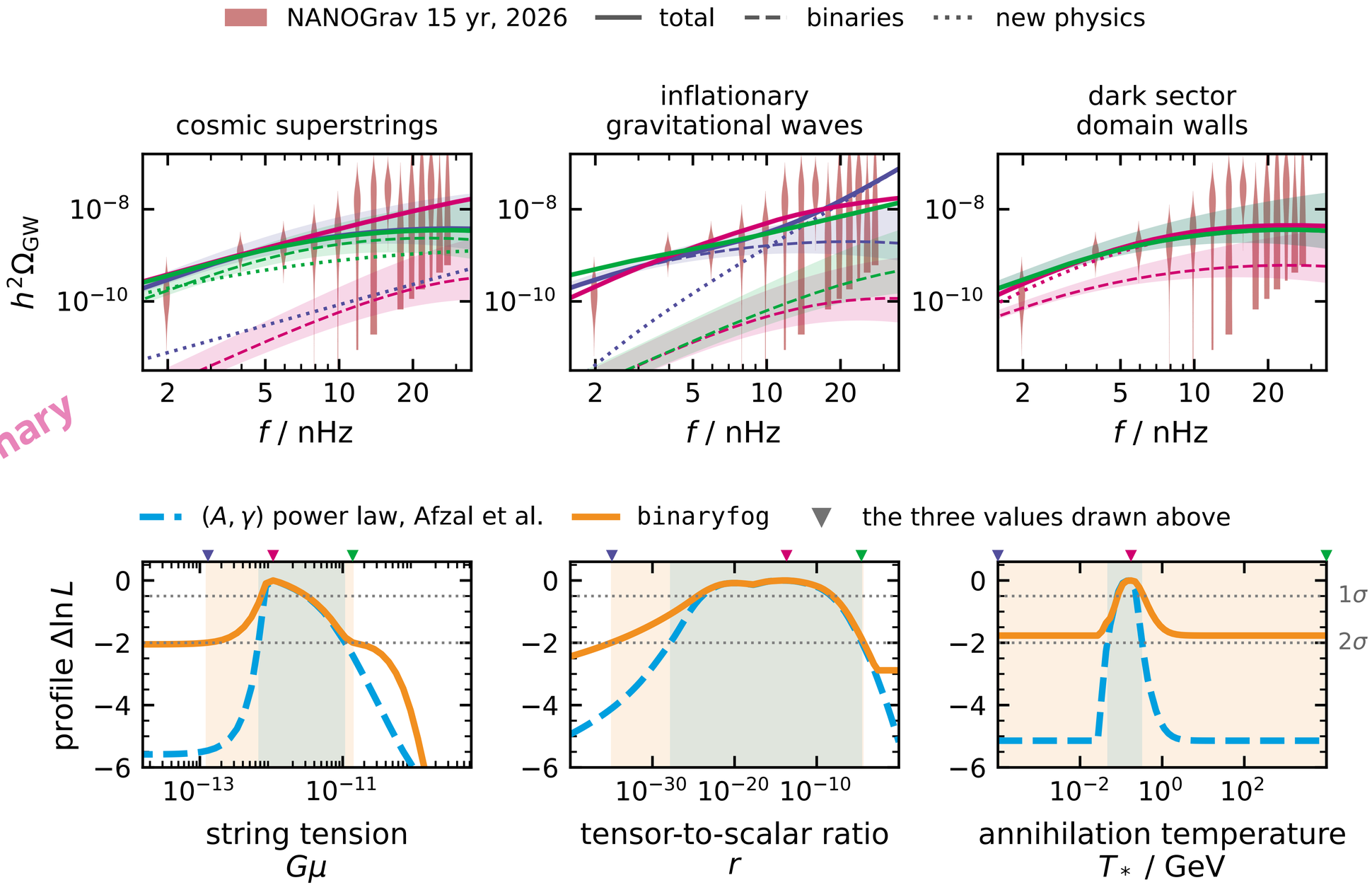
Preliminary

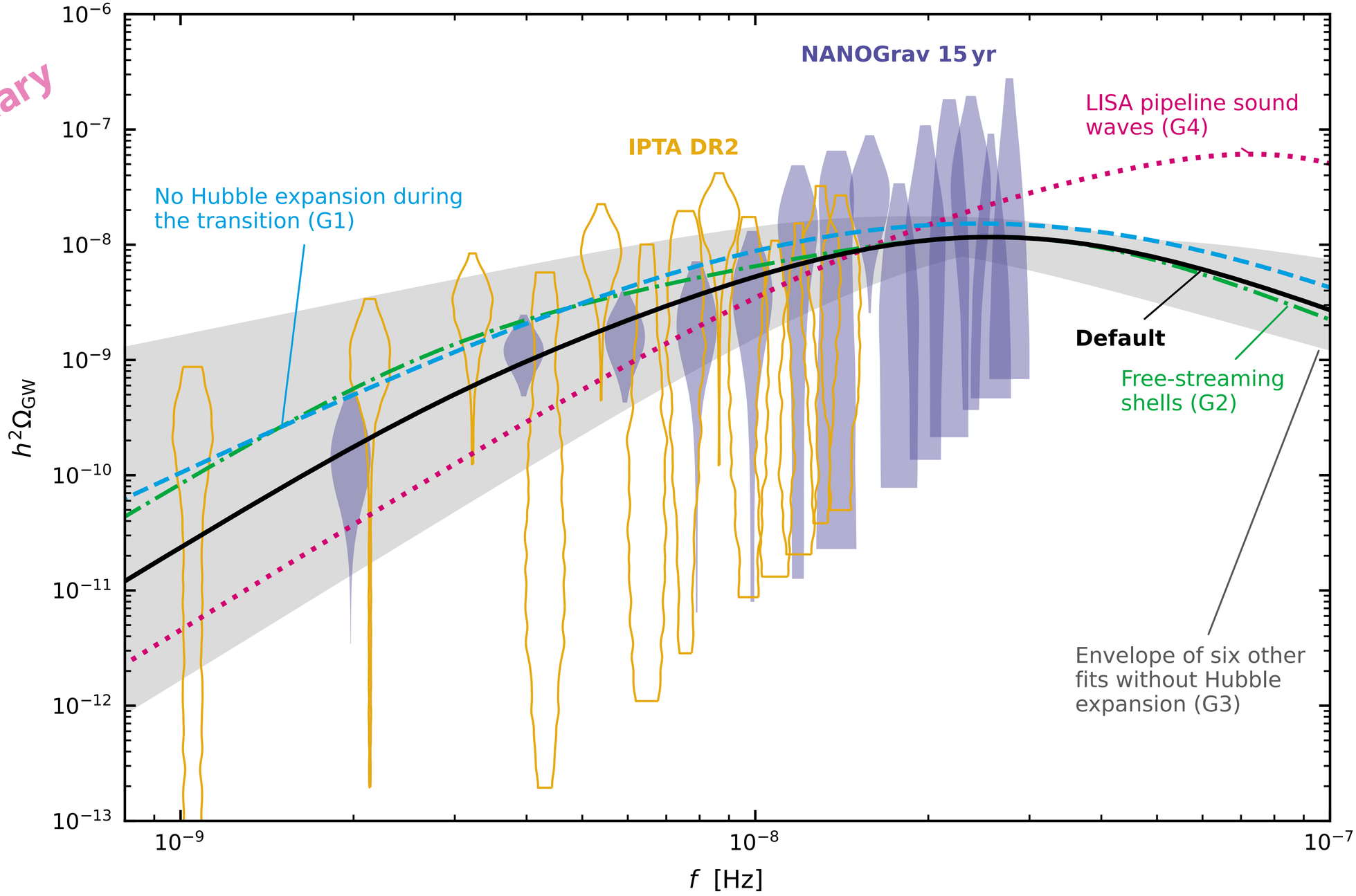


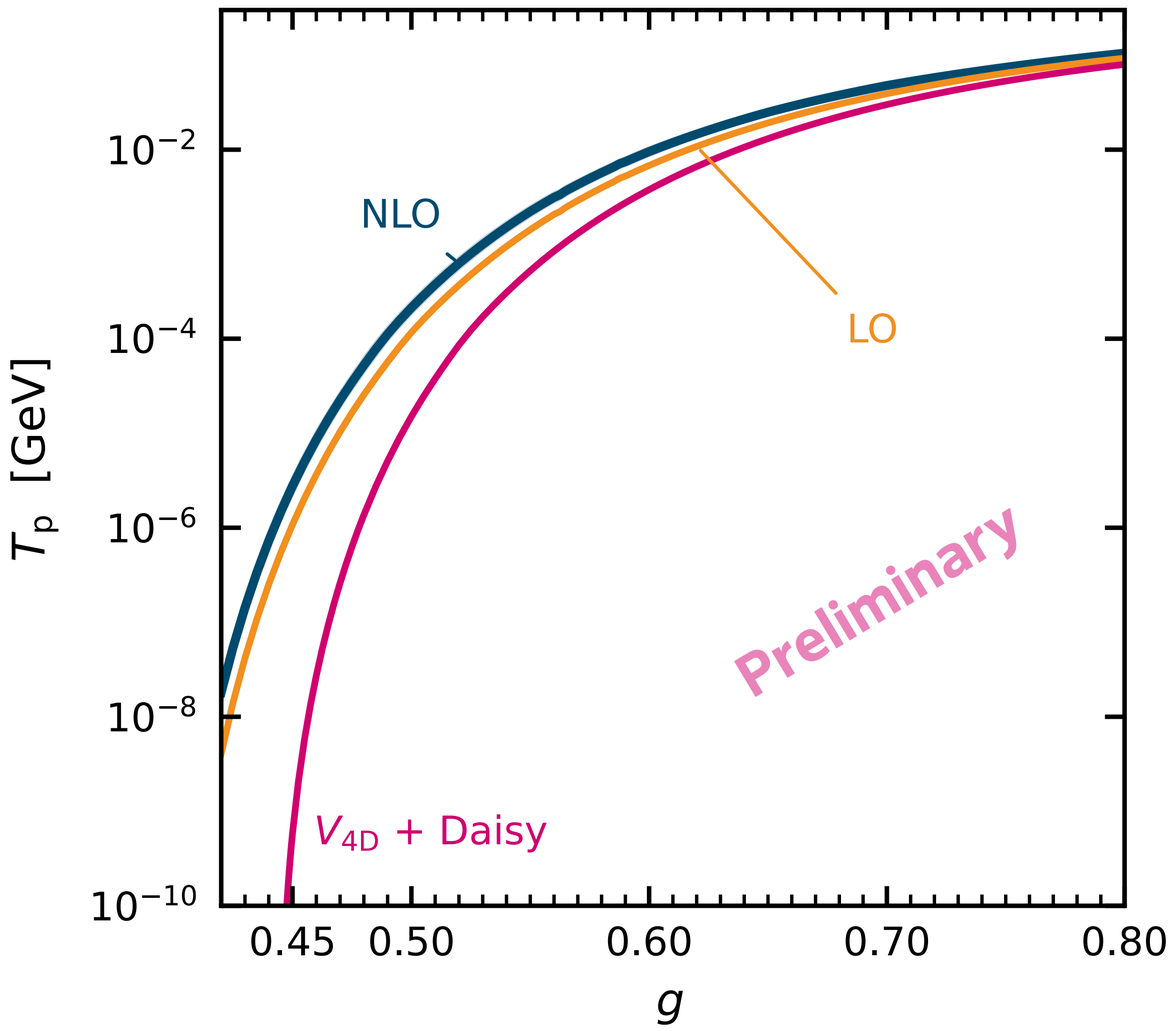



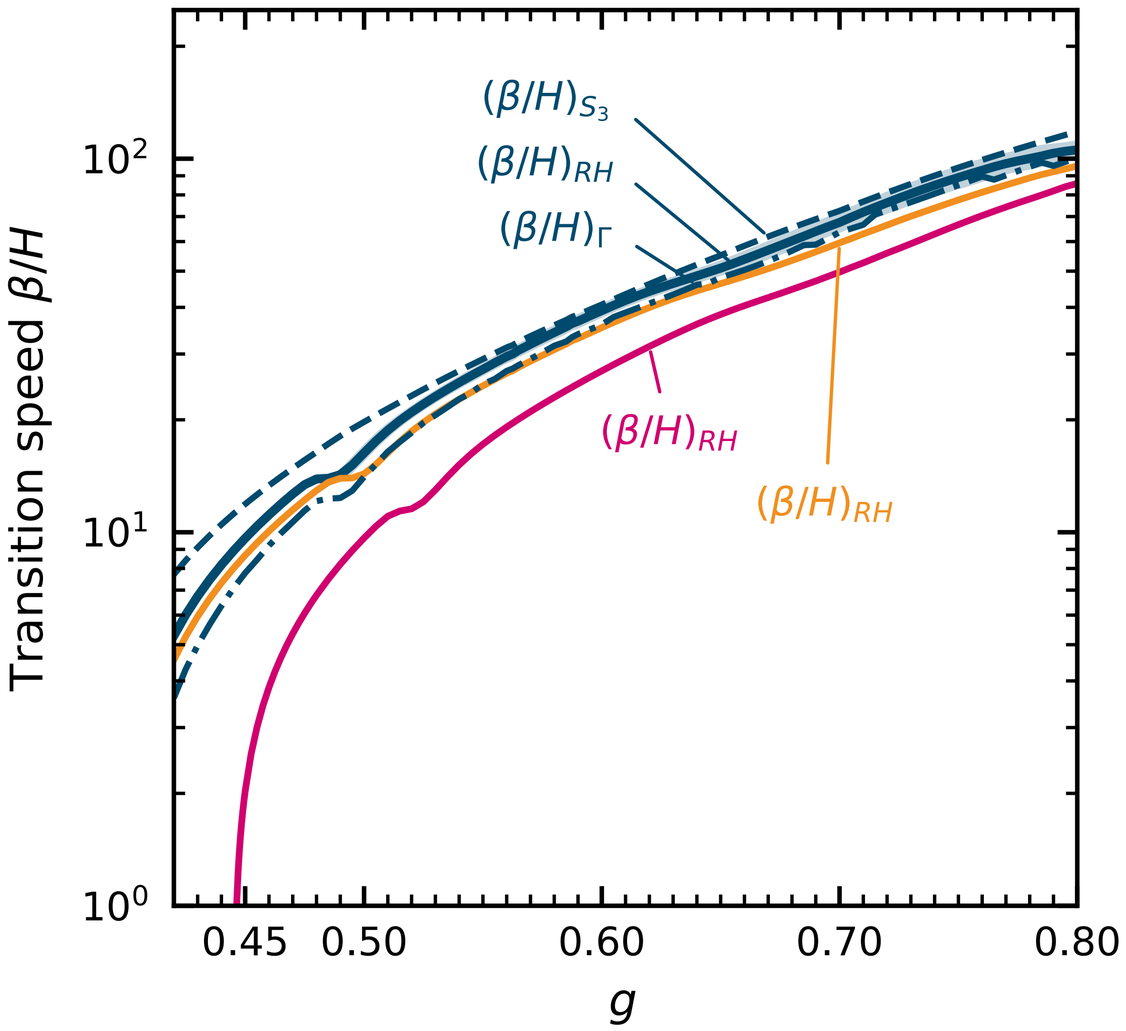

20,000 realisations
log-normal, same width
warp, $c = 0.23$
map-Airy, same width
Preliminary
bin 1, $f = 2.0$ nHz
width 0.03 in $\log_{10} h_c^2$
bin 7, $f = 13.8$ nHz
width 0.20 in $\log_{10} h_c^2$
bin 14, $f = 27.7$ nHz
width 0.32 in $\log_{10} h_c^2$
probability density
the faintest 1%
of realisations
$\log_{10} h_c^2$ minus its median
$\log_{10} h_c^2$ minus its median
$\log_{10} h_c^2$ minus its median


flat priors
astro-informed priors
binaryfog
NANOGrav, erratum
Preliminary
$\psi_0/\mathrm{Mpc}^{-3}$
$m_{\psi,0}/M_\odot$
$\mu/M_\odot$
$\varepsilon_\mu$
$\tau_\mathrm{f}$ / Gyr
$\nu_\mathrm{inner}$

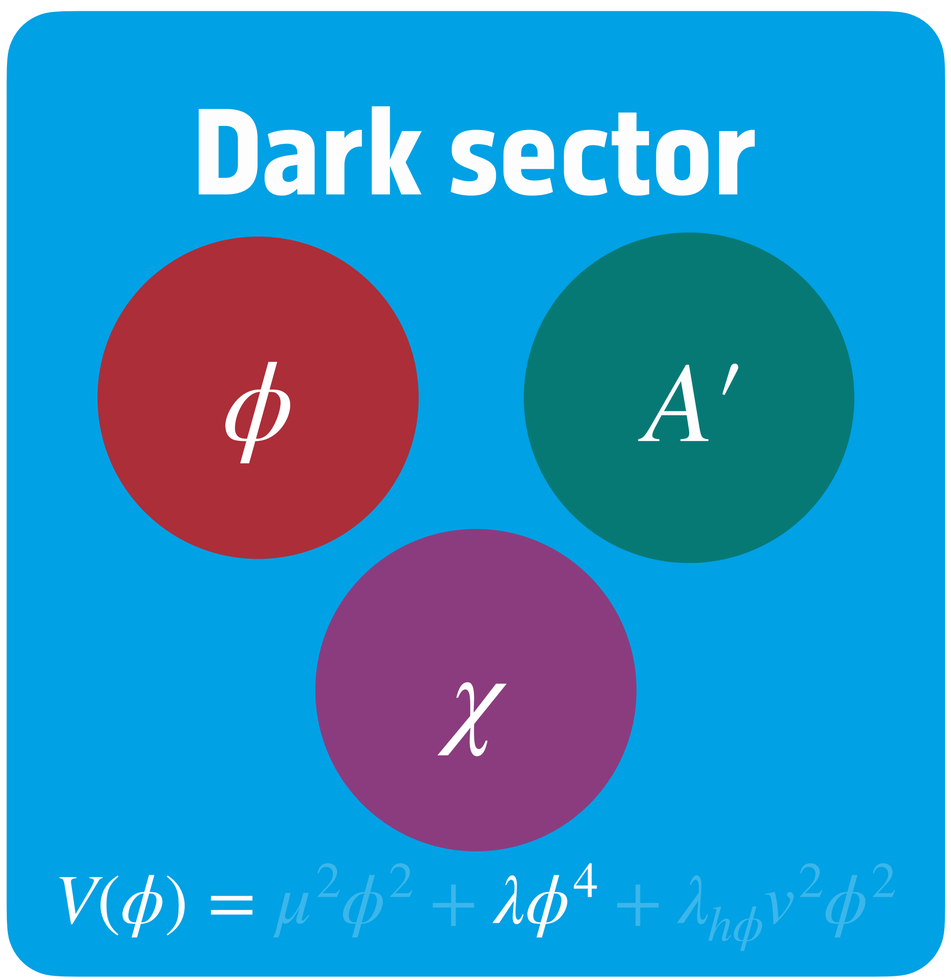

NANOGrav 15 yr, 2026
total
binaries
new physics
cosmic superstrings
inflationary gravitational waves
dark sector domain walls
$h^2\Omega_{\rm GW}$
$10^{-8}$
$10^{-10}$
2
5
10
20
$f$ / nHz
Preliminary
$(A, \gamma)$ power law, Afzal et al.
binaryfog
the three values drawn above
profile $\Delta \ln L$
0
−2
−4
−6
$10^{-13}$
$10^{-11}$
string tension
$G\mu$
$10^{-30}$
$10^{-20}$
$10^{-10}$
tensor-to-scalar ratio
$r$
$10^{-2}$
$10^{0}$
$10^{2}$
annihilation temperature
$T_*$ / GeV
$1\sigma$
$2\sigma$


Preliminary
NANOGrav 15 yr
IPTA DR2
LISA pipeline sound waves (G4)
No Hubble expansion during the transition (G1)
Default
Free-streaming shells (G2)
Envelope of six other fits without Hubble expansion (G3)
$h^2\Omega_{GW}$
$f$ [Hz]
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-9}$
$10^{-8}$
$10^{-7}$

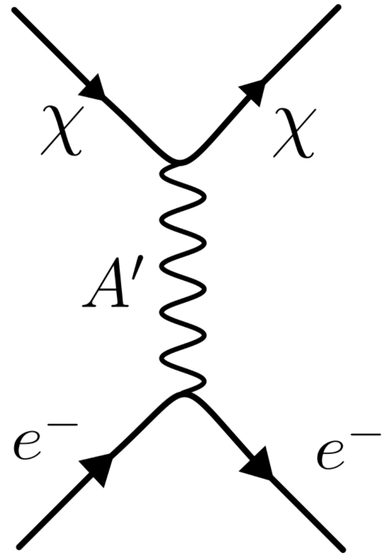

$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$T_p$ [GeV]
NLO
LO
Preliminary
$V_{4D}$ + Daisy
0.45
0.50
0.60
0.70
0.80
$g$


$10^2$
$10^1$
$10^0$
Transition speed $\beta/H$
$(\beta/H)_{S_3}$
$(\beta/H)_{RH}$
$(\beta/H)_\Gamma$
$(\beta/H)_{RH}$
$(\beta/H)_{RH}$
0.45
0.50
0.60
0.70
0.80
$g$

# A conformal dark sector incl. dark matter candidate




Kinetic mixing $\kappa$

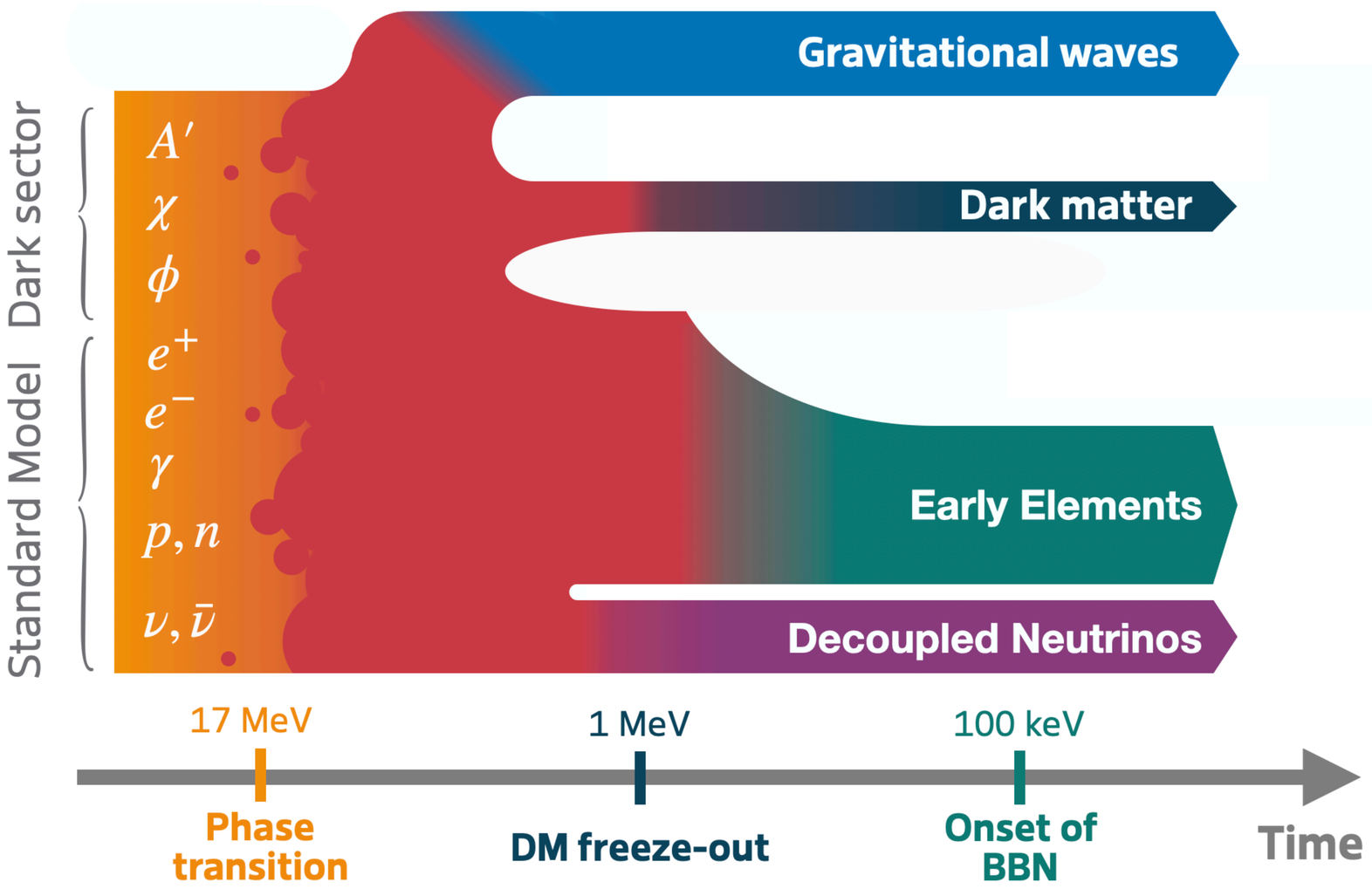


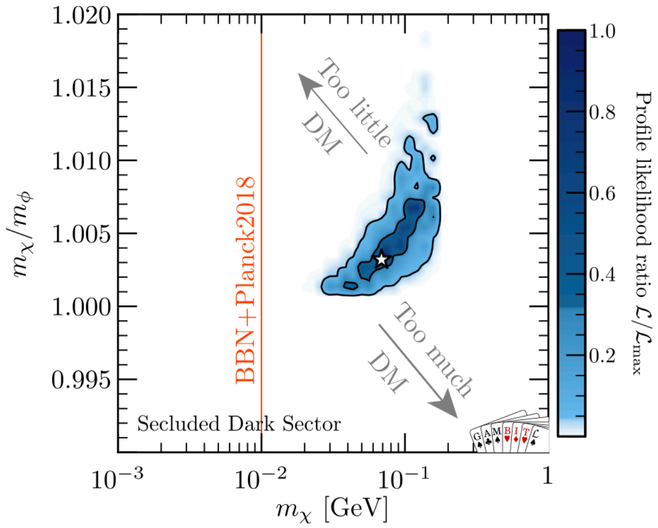

**Thermalization becomes easy!**

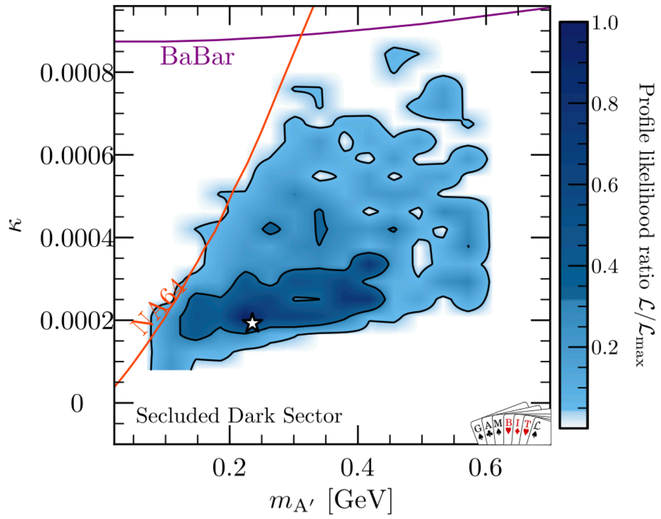
SM

CT+ [JCAP 08 (2025) 062]

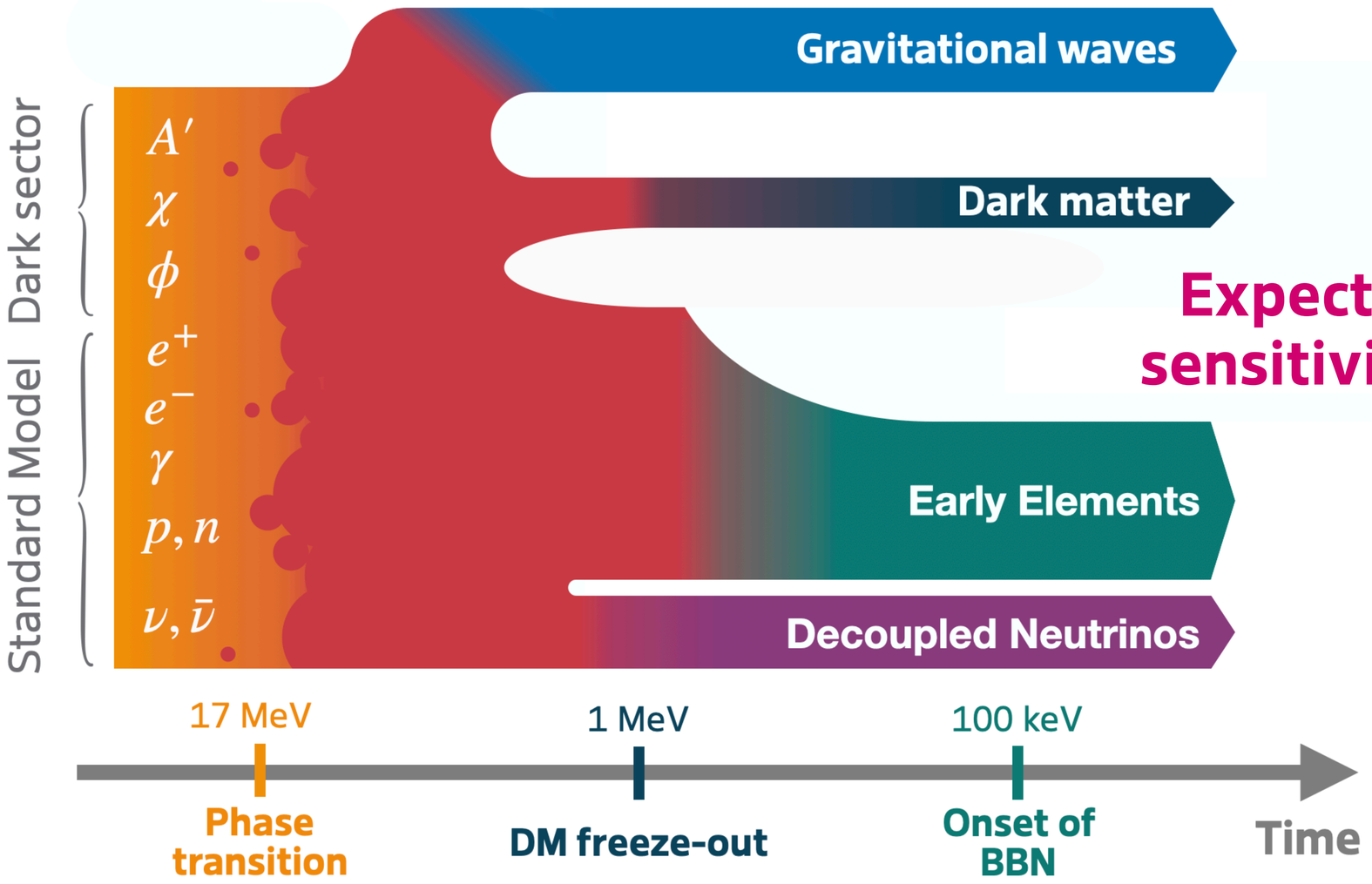
# How does our scenario evade all available constraints?



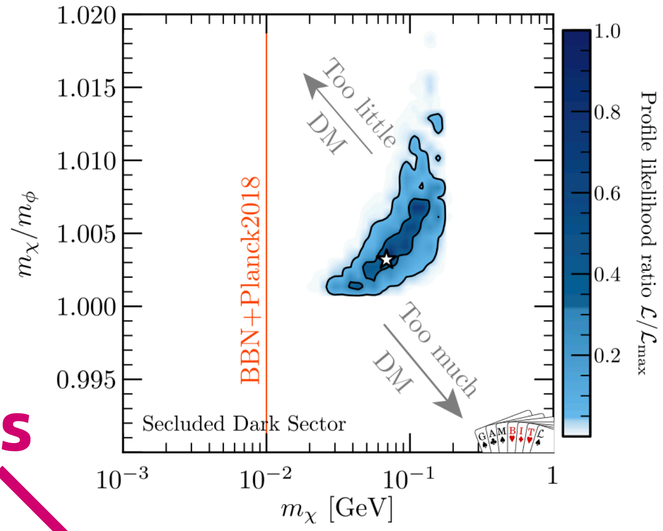



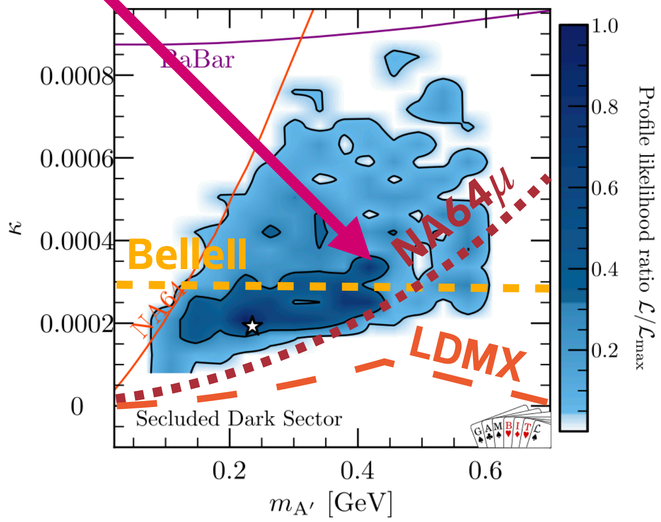



# How does our scenario evade all available constraints?

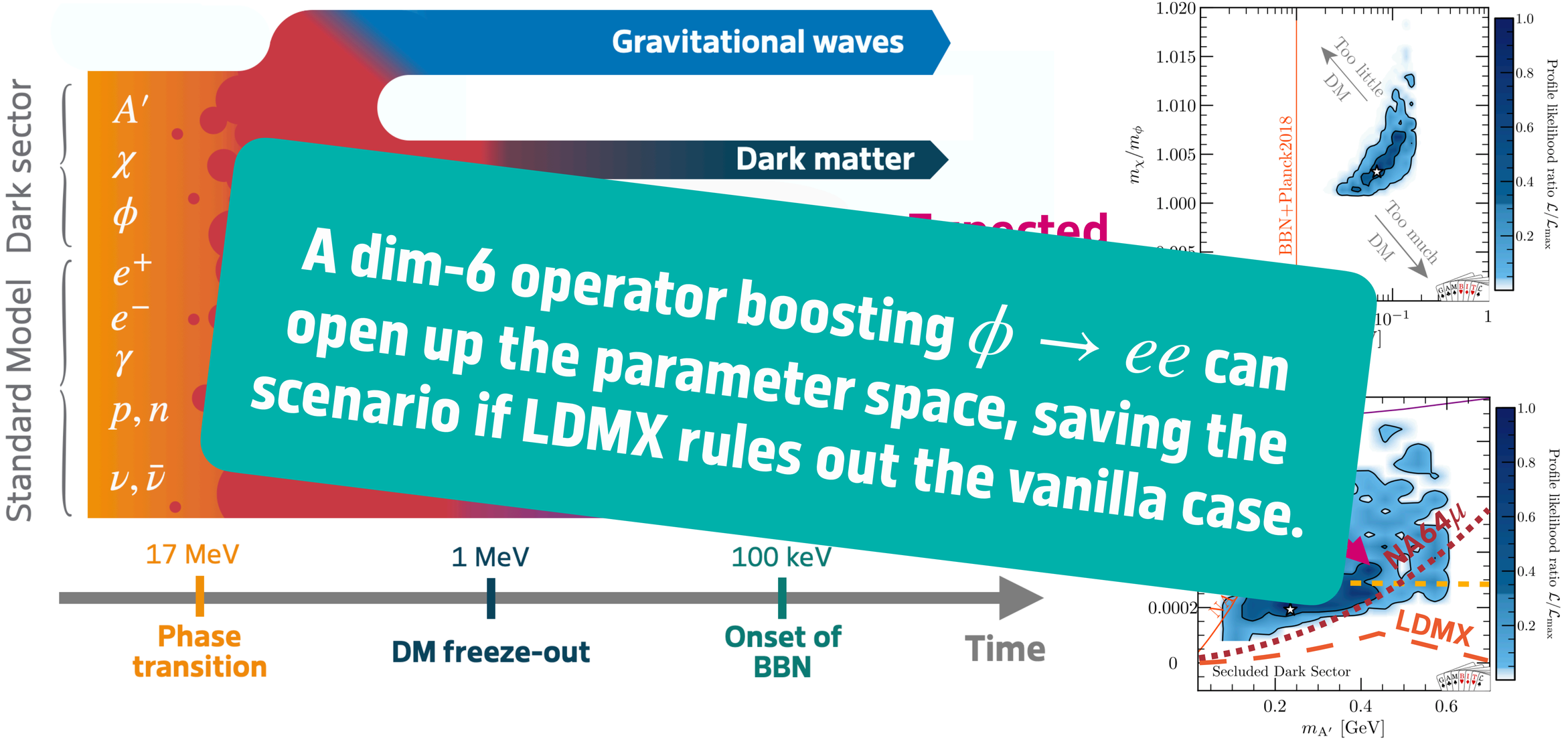



Expected sensitivities

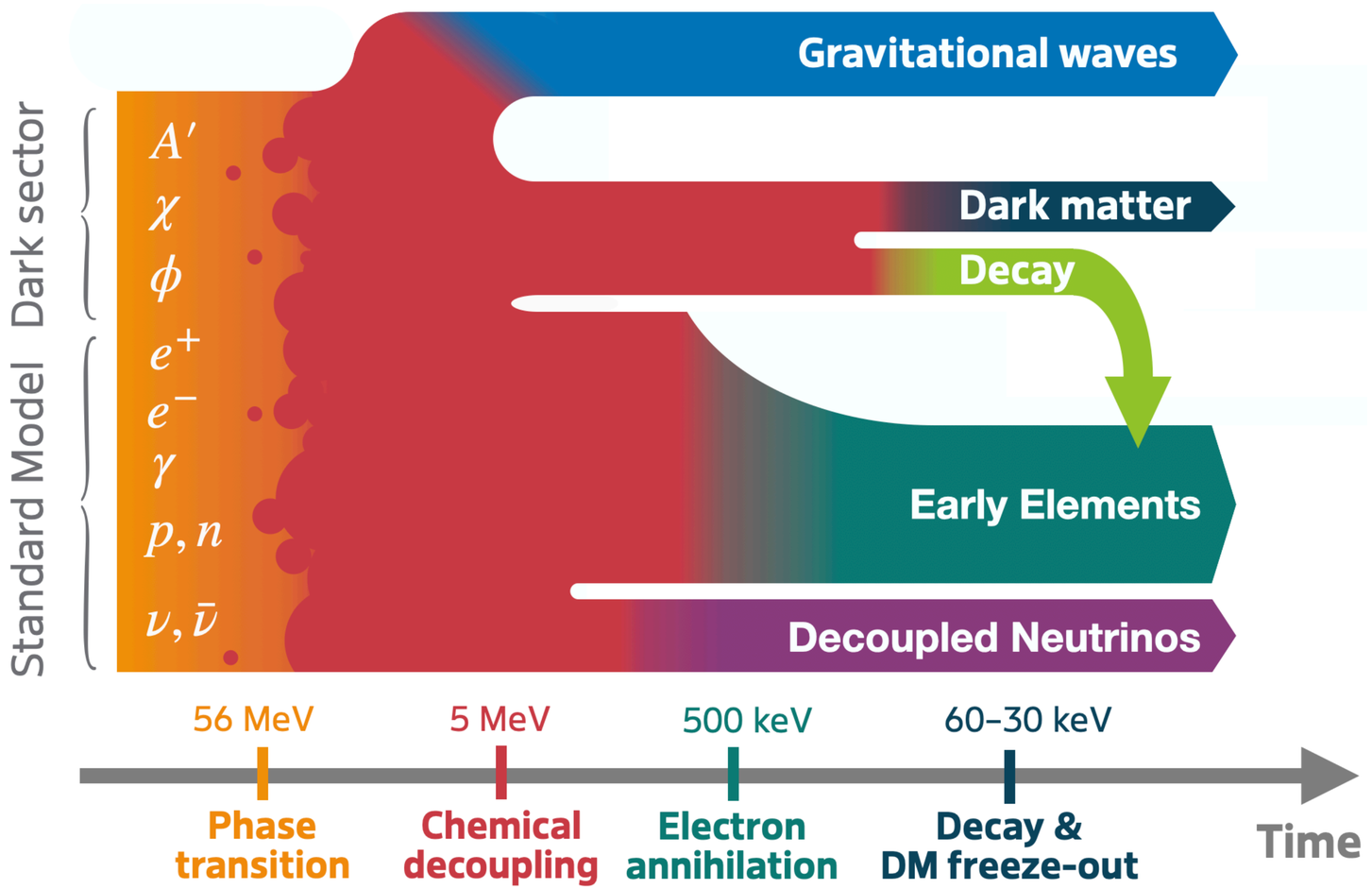


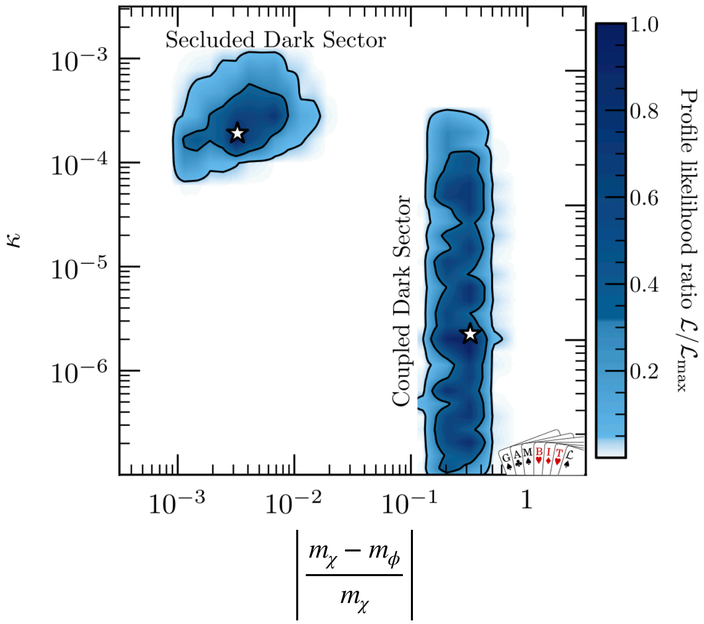



# How does our scenario evade all available constraints?

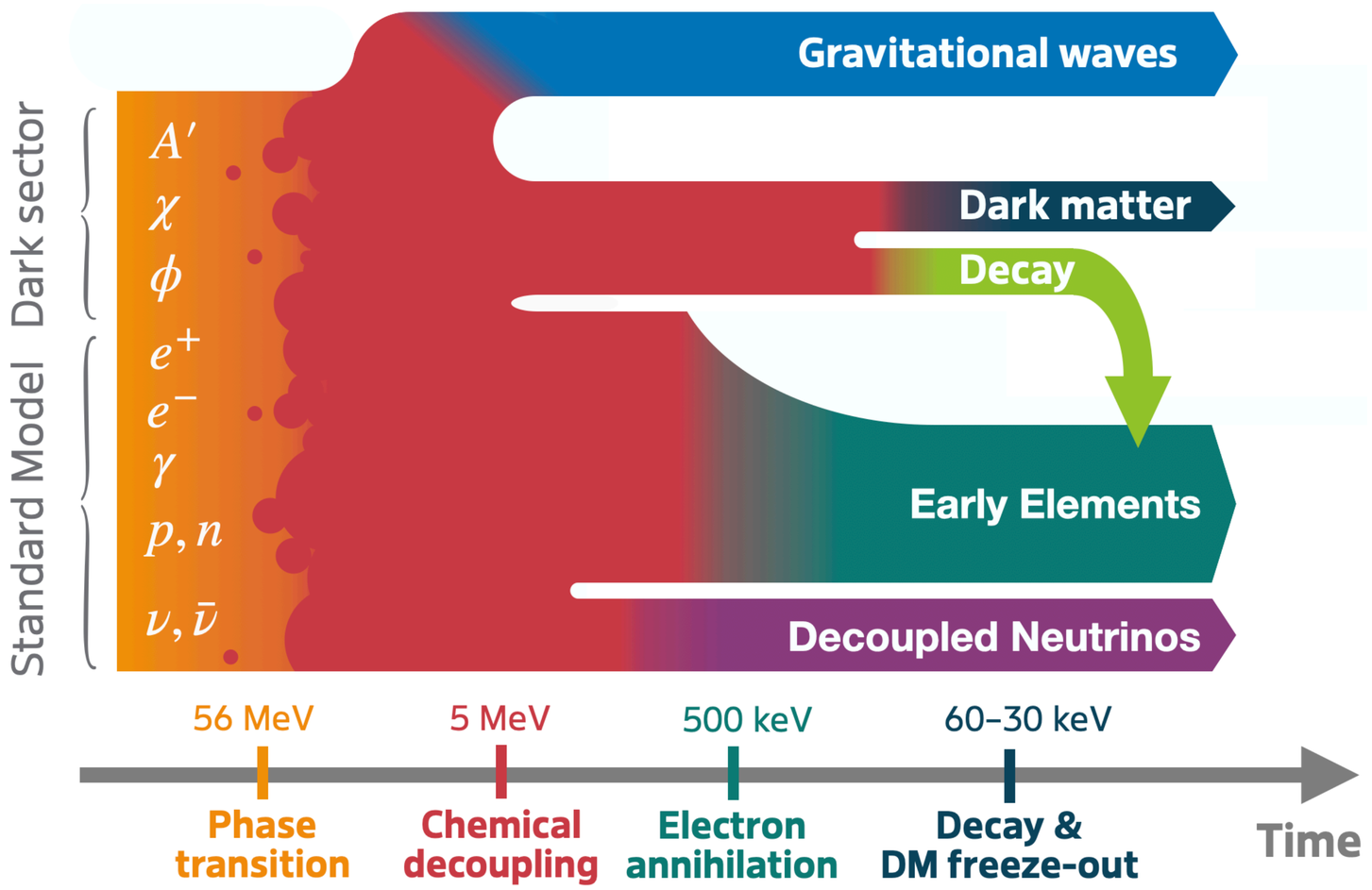


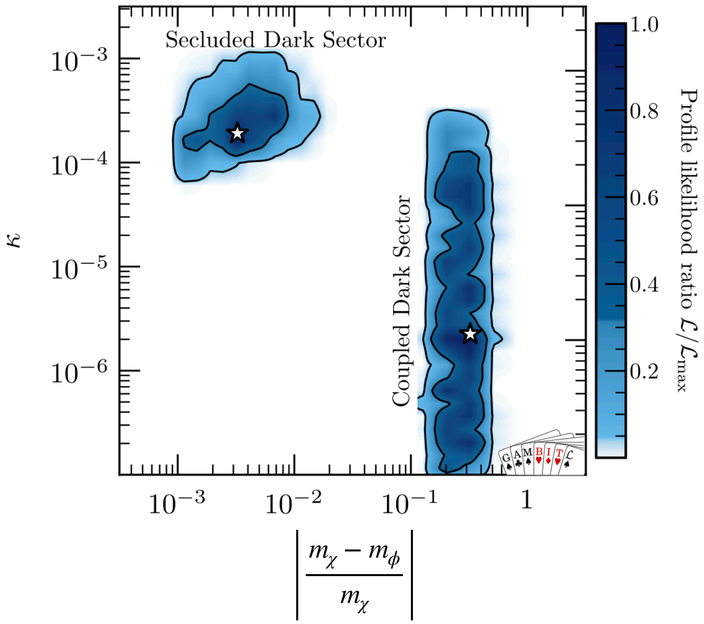
# Coupled DS scenario: incl dim-6 operator for $\phi \to ee$



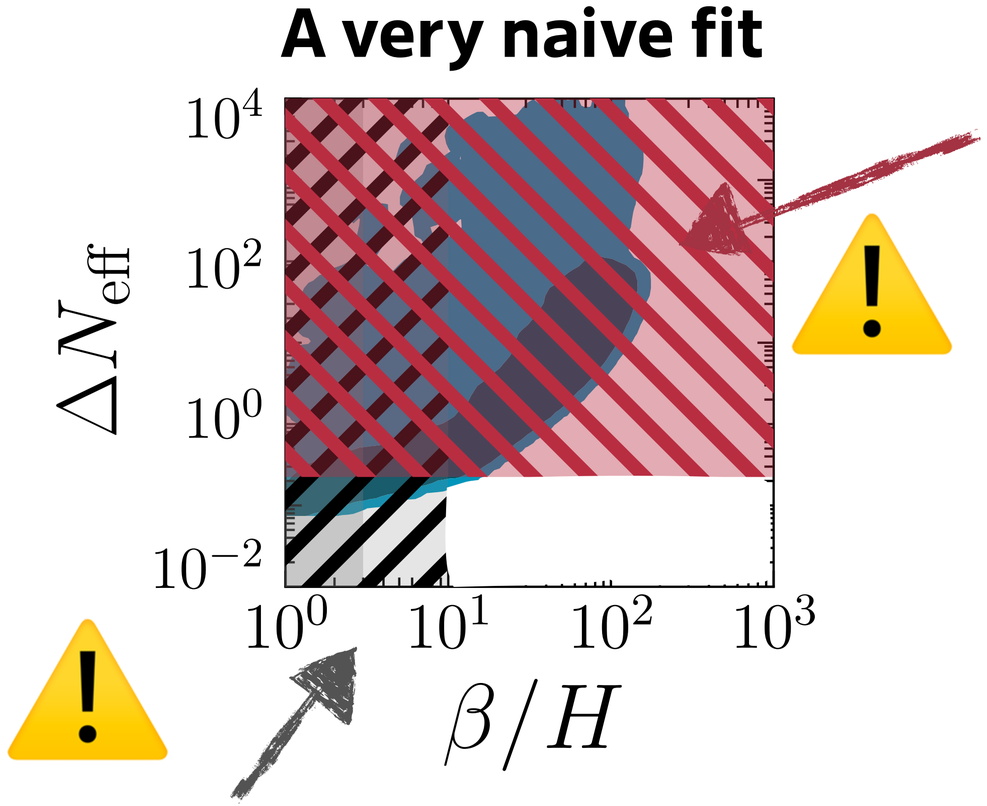
# Coupled DS scenario: incl dim-6 operator for $\phi \to ee$




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

# A dark sector without portal couplings




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

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

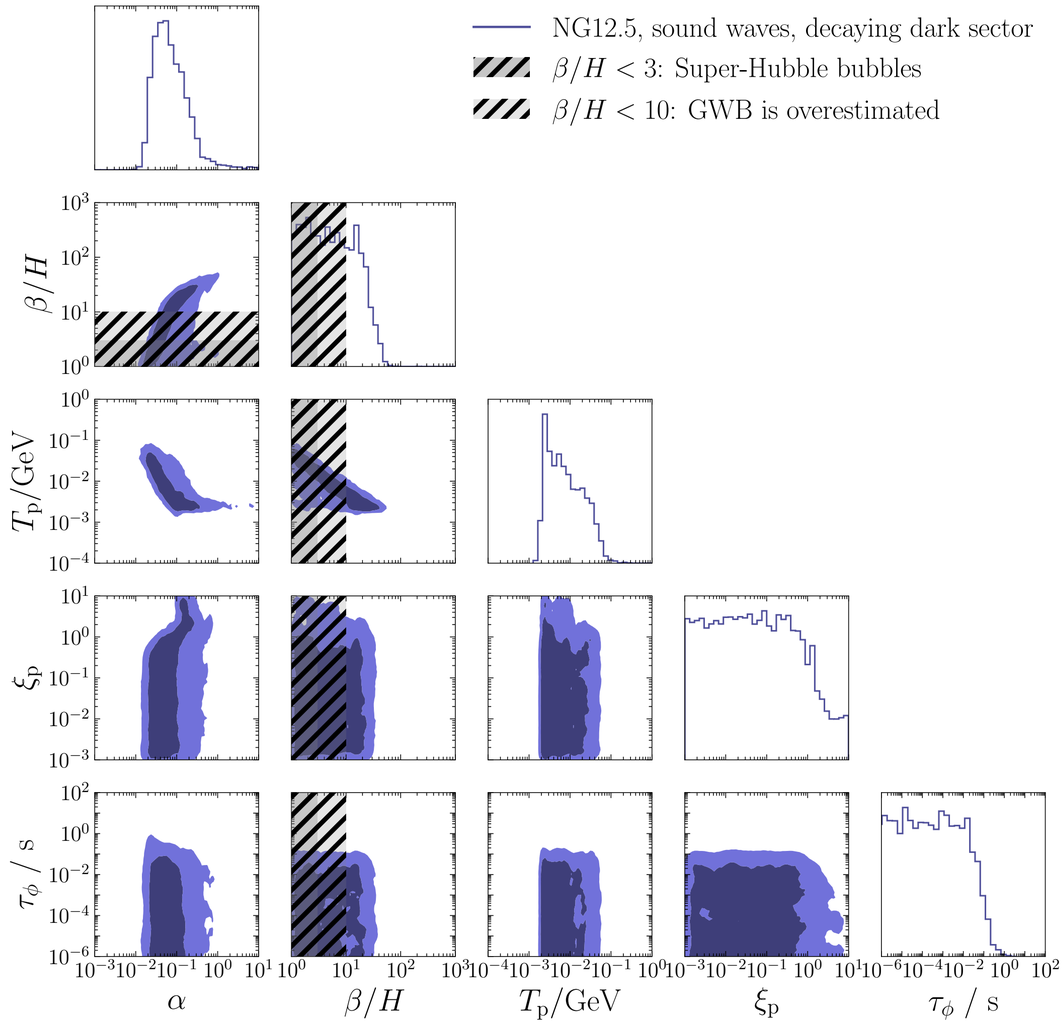
**Giant „Hubble“ bubble sizes would be needed, violating causality & questioning validity of GW predictions**

[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]

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

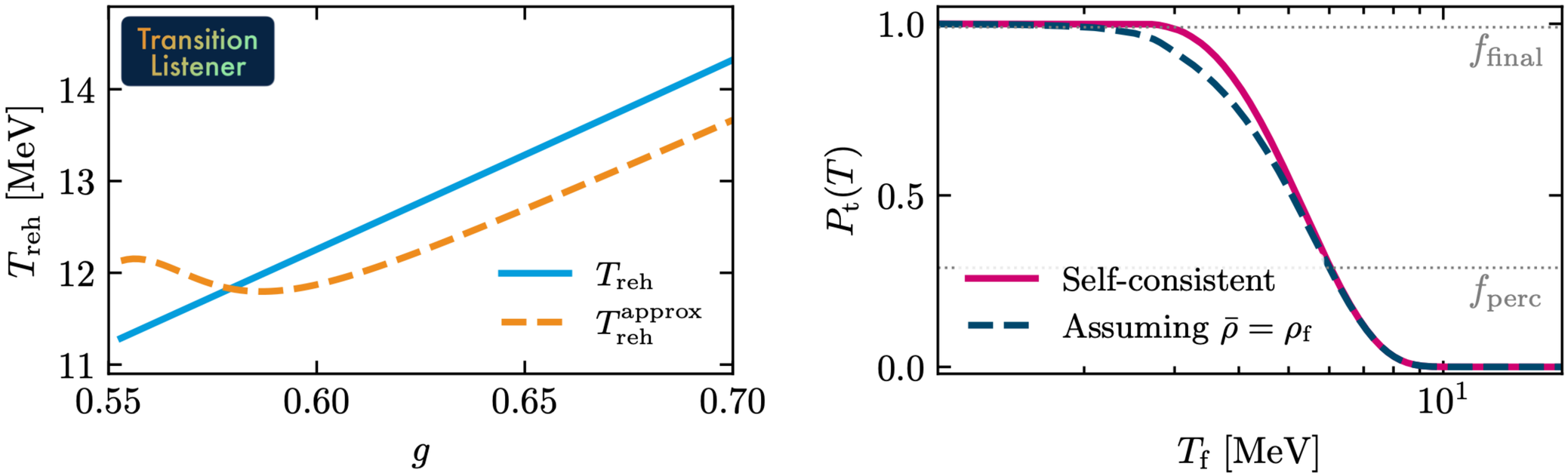
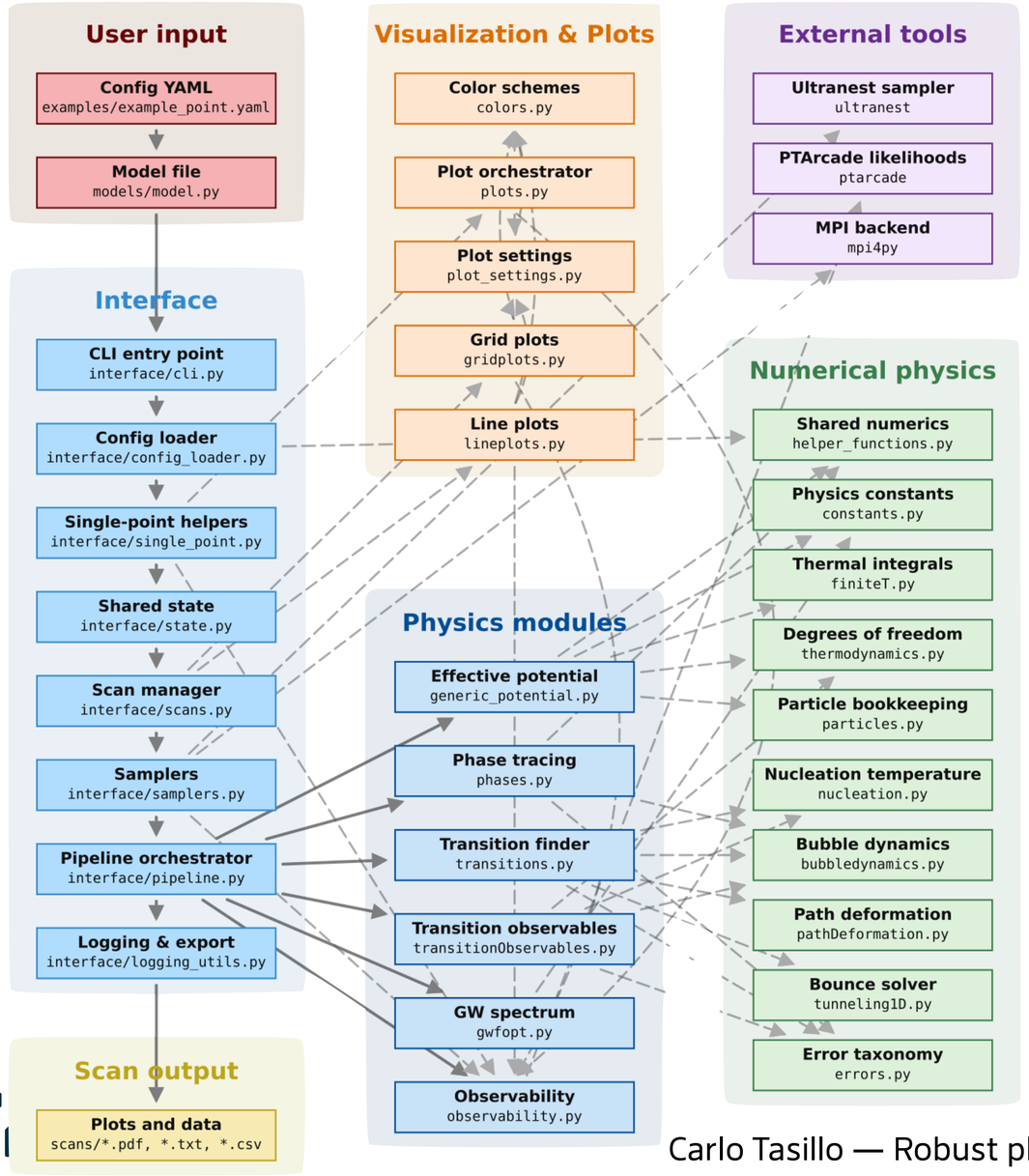
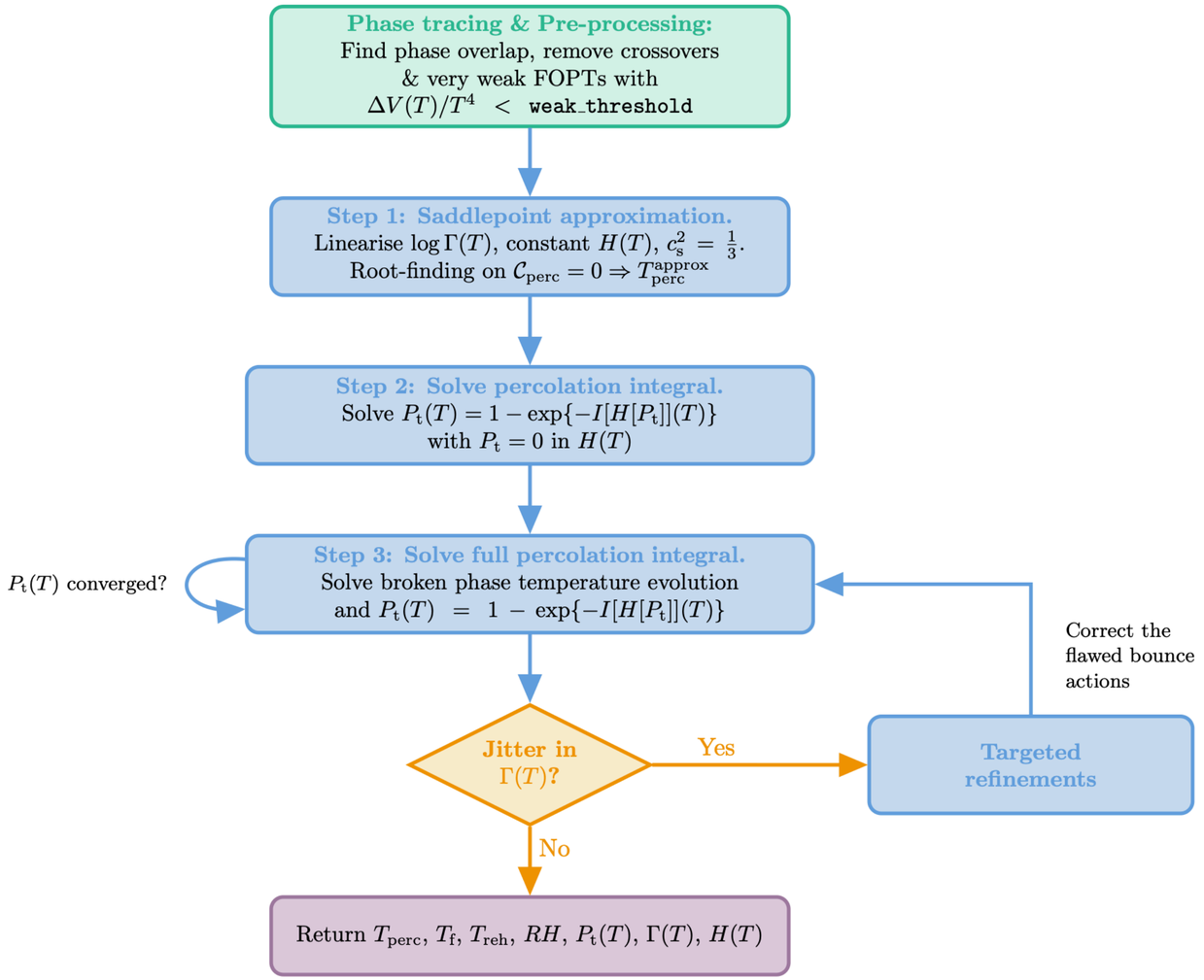



Figure 4: *Left:* Reheating temperature and its approximation $T_{\rm perc}^{\rm approx} = T_{\rm perc}\,(1+\alpha)^{1/4}$ as a function of the gauge coupling $g$ in the conformal $U(1)'$ model ($y = 0.01$, $v = 140\,\text{MeV}$). *Right:* Comparison of the self-consistent and approximate ($\bar{\rho} = \rho_{\rm f}$) 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`

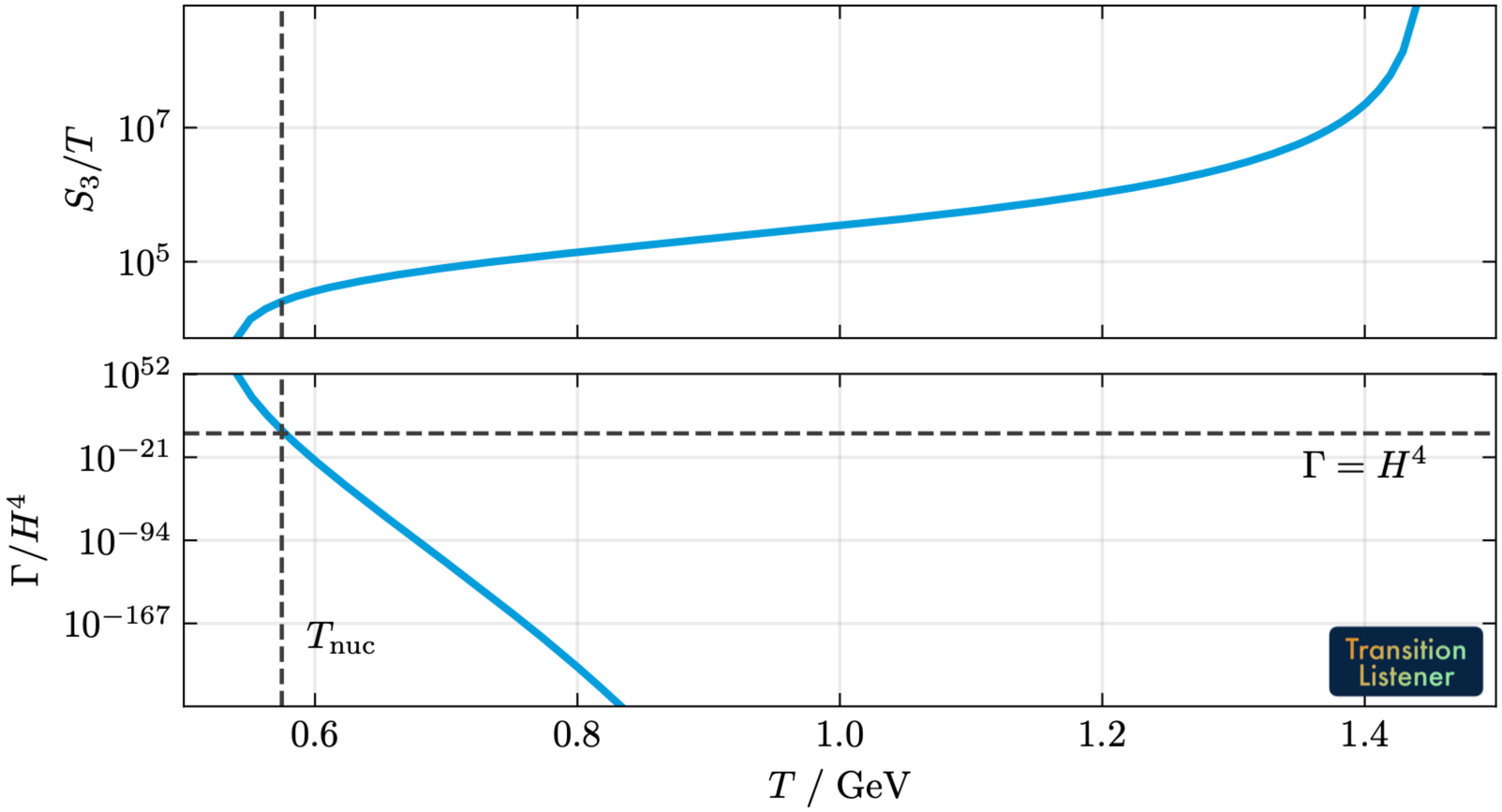



Figure 9: Output of the `action` plot option for the dark flipflop benchmark point 2 from table 1. *Upper panel:* Bounce action $S_3/T$ in dependence of temperature. *Lower panel:* Corresponding bubble nucleation rate $\Gamma$ in units of $H^4$.

# Automated `profile` plot in `TransitionListener`

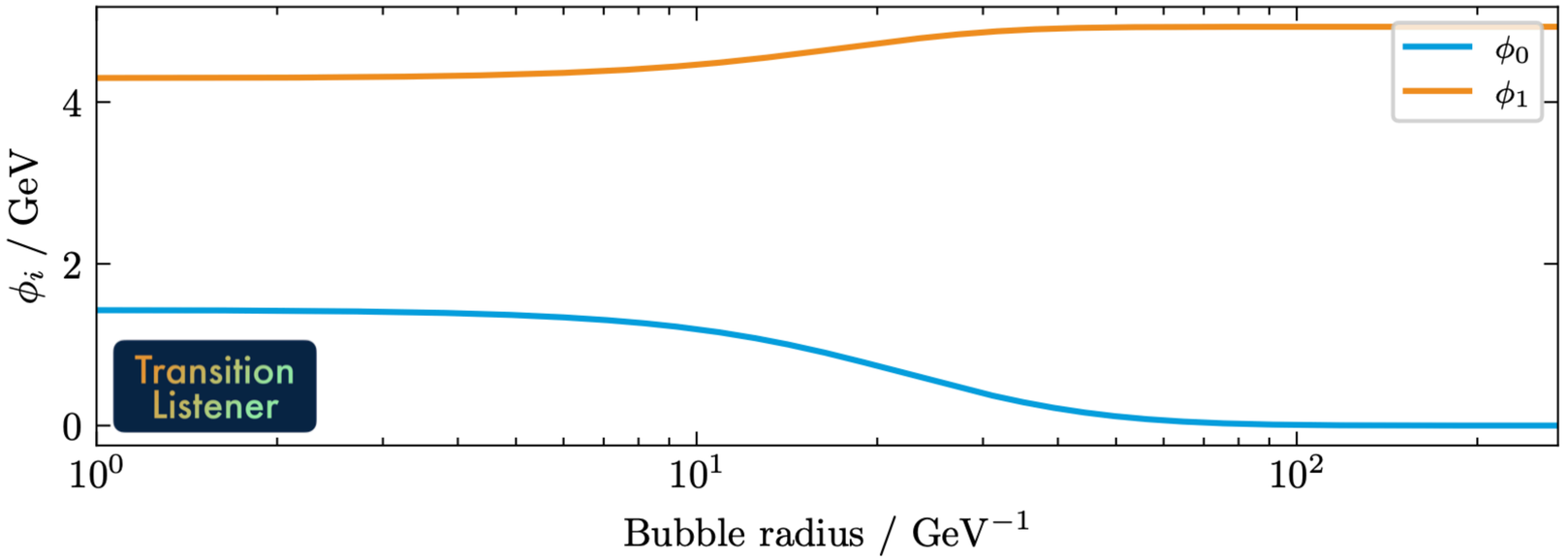



Figure 10: Bubble profile at nucleation for the dark flipflop benchmark point 2 from table 1, generated using the **`profile`** plot option. Inside the bubble, at $r = 0$, the fields approach their release point. At $r \to \infty$ (outside the bubble), the field values approach their false-vacuum values.

# Automated `percolation` plot in `TransitionListener`

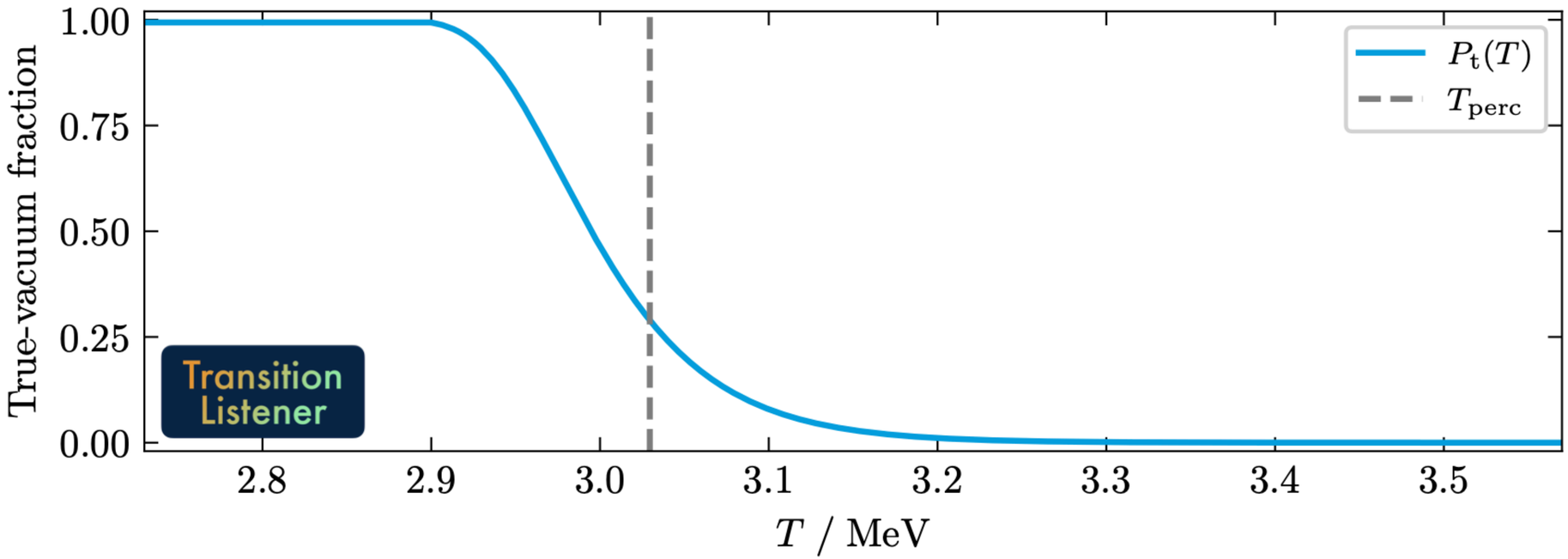



Figure 11: True-vacuum fraction evolution of the conformal dark $U(1)'$ benchmark point 1 from table 1 ($g = 0.7$, $v = 0.14\,\text{GeV}$ and $y = 0.01$), generated using the `percolation` plot option.

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

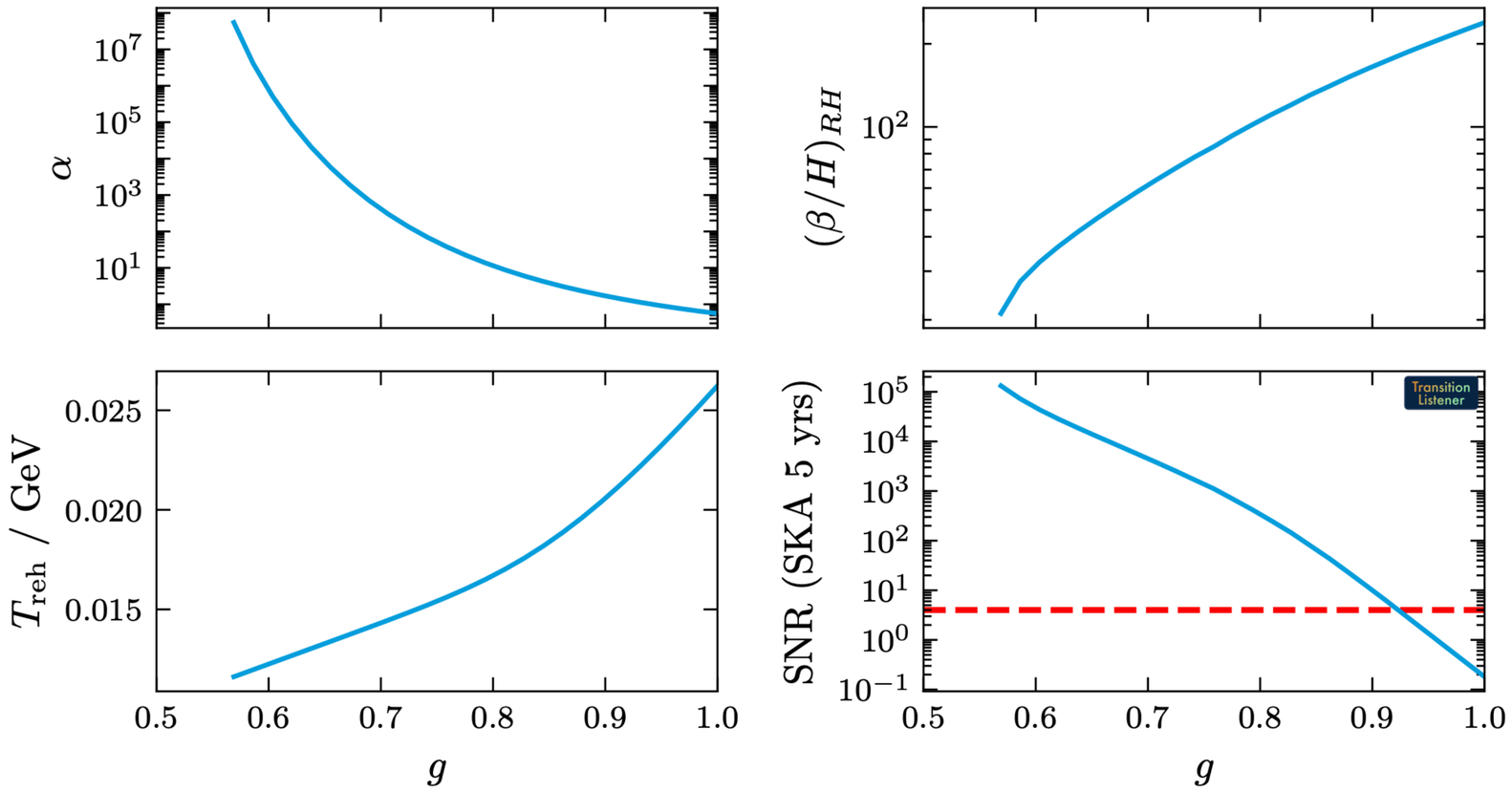
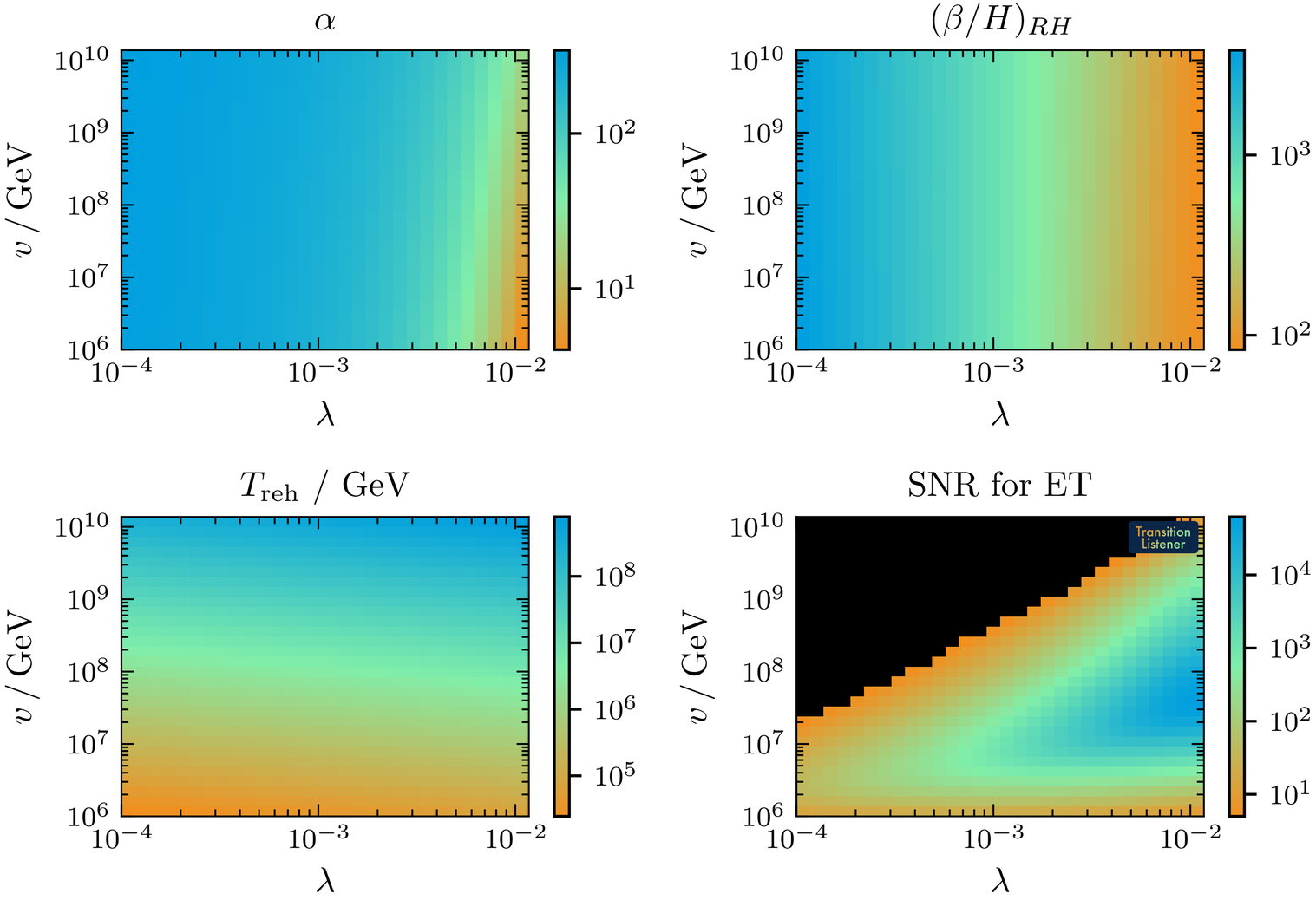



Figure 12: Overview plot of the example line scan based on the conformal model near the benchmark point from table 1, scanning $g$ at fixed $y = 0.01$ and $v = 140\,\text{MeV}$. The fourth panel shows the expected SNR after 5 years of data taking at SKA. The red dashed line indicates the detection threshold.

# 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. | $T_*$ | $T_{\rm reh}$ | $T_{\rm f}$ | $v_{\rm w}$ | $\alpha$ | $(\beta/H)_{S_3}$ | $RH$ |
| `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 $\beta/H$

## C Analytical relation between transition speed and bubble size

Here we derive an analytical relation between $R_{\rm sep}$ and $\beta$ 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

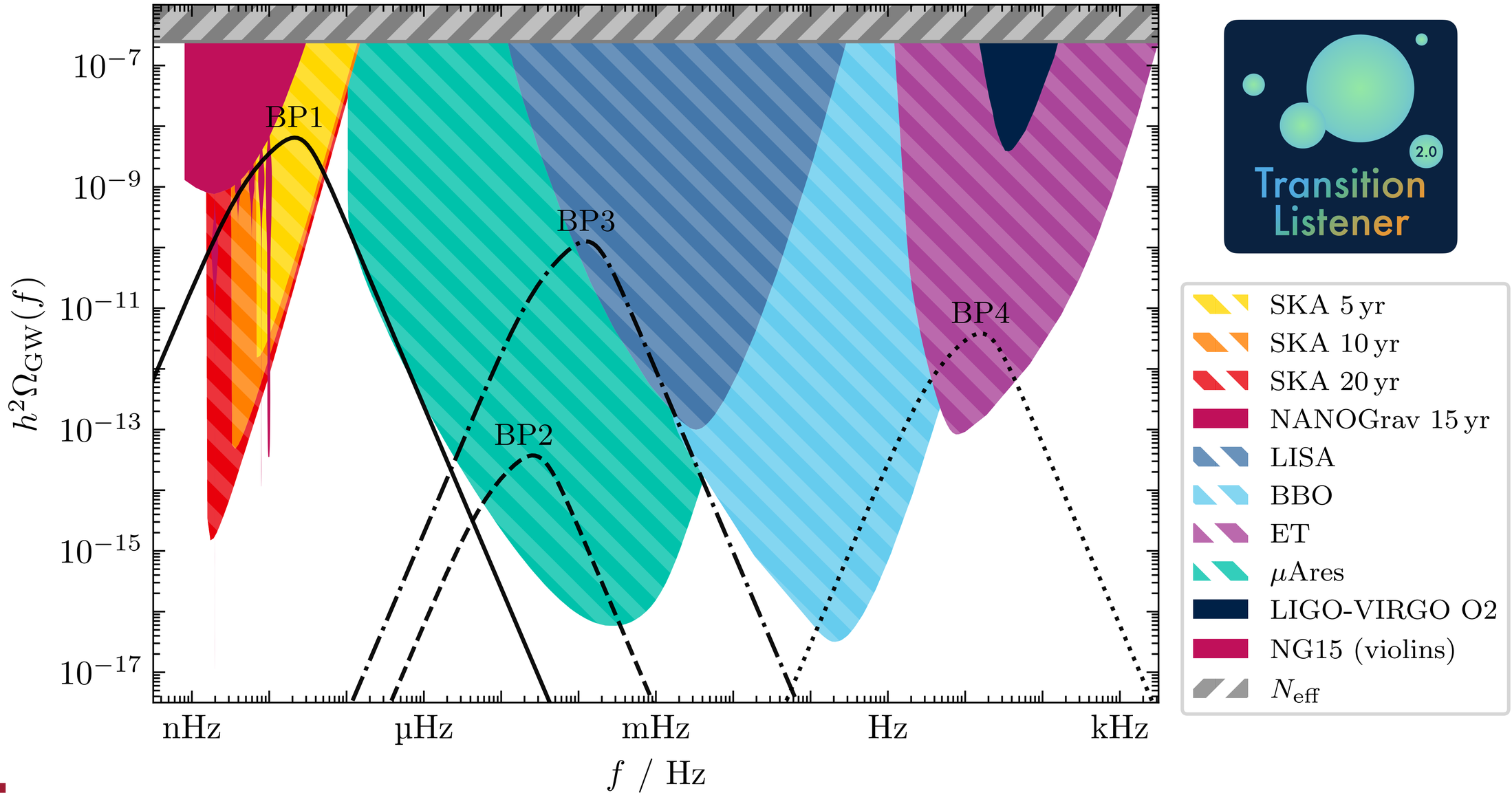
$$R_{\rm sep}(t_{\rm perc}) = \frac{1}{n(t_{\rm perc})^{1/3}} \approx \left(\frac{8\pi}{f_{\rm perc}}\right)^{1/3}\frac{v_{\rm w}}{\beta} \tag{C.3}$$

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

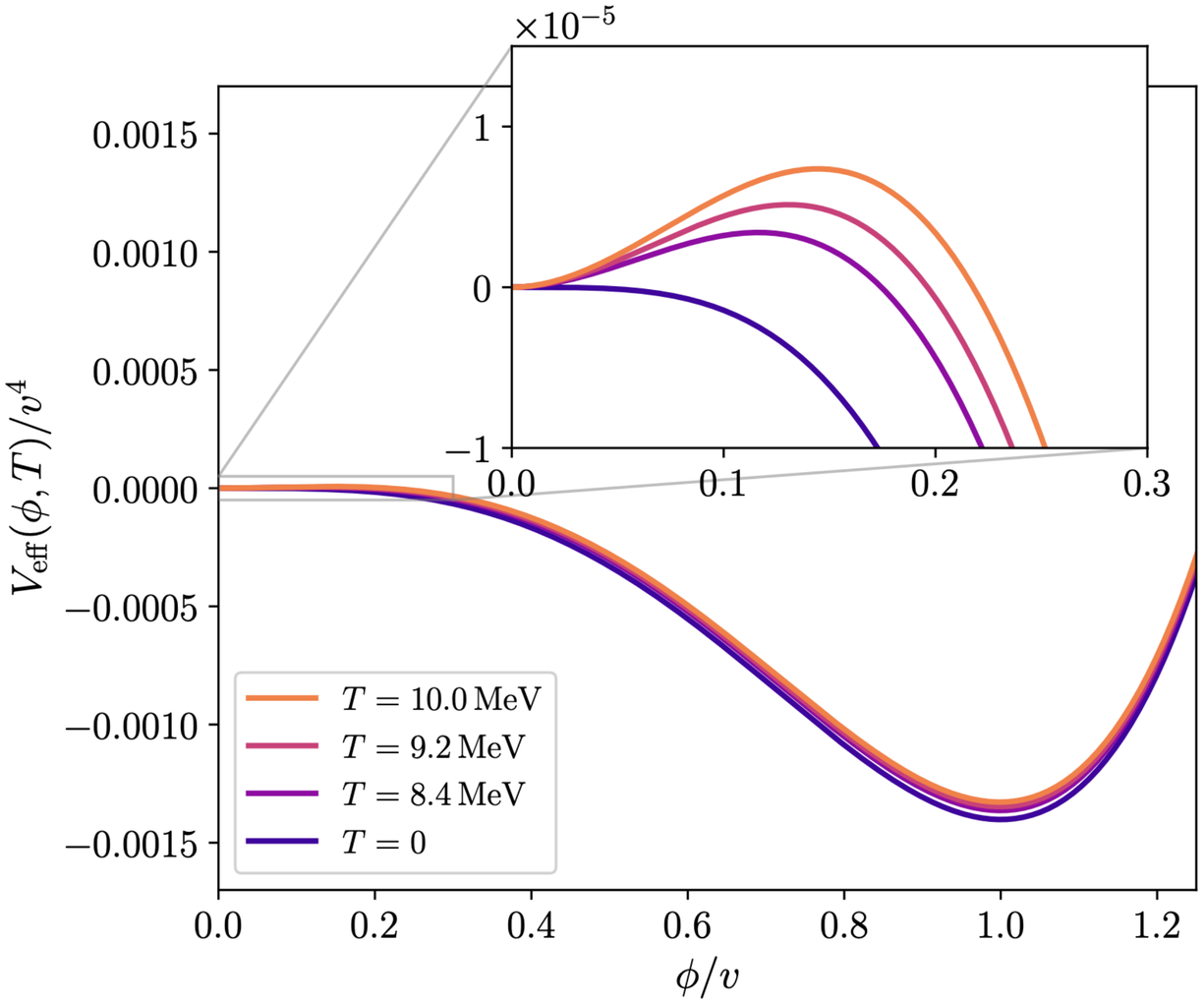
# Error classes in `TLv2`

| 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 $\Gamma/H^4$ 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`



# How to be supercool 😎




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

Quantum and thermal corrections

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

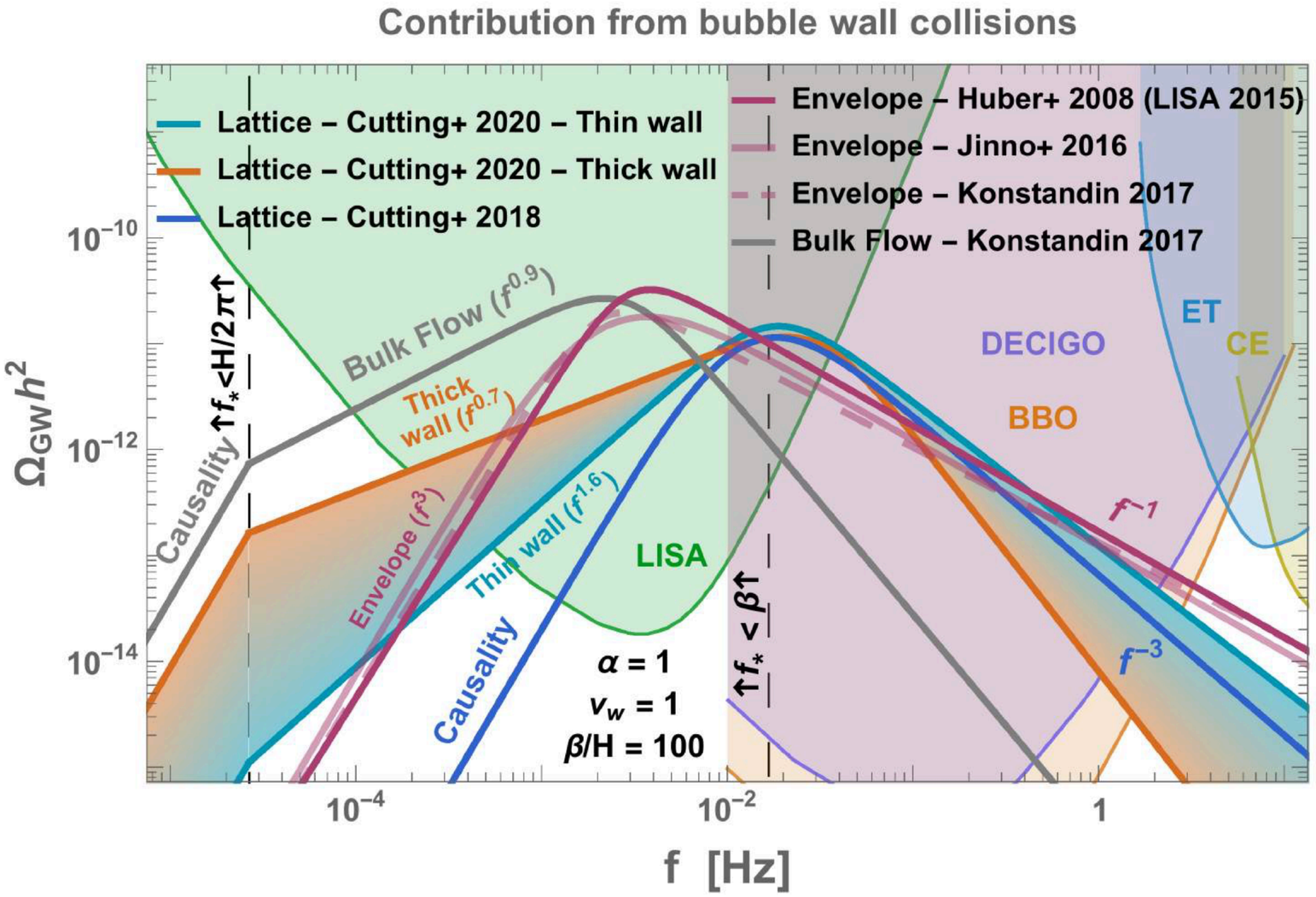
**Loop-induced barrier down until very low temperatures, i.e. strong supercooling**

# 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] |

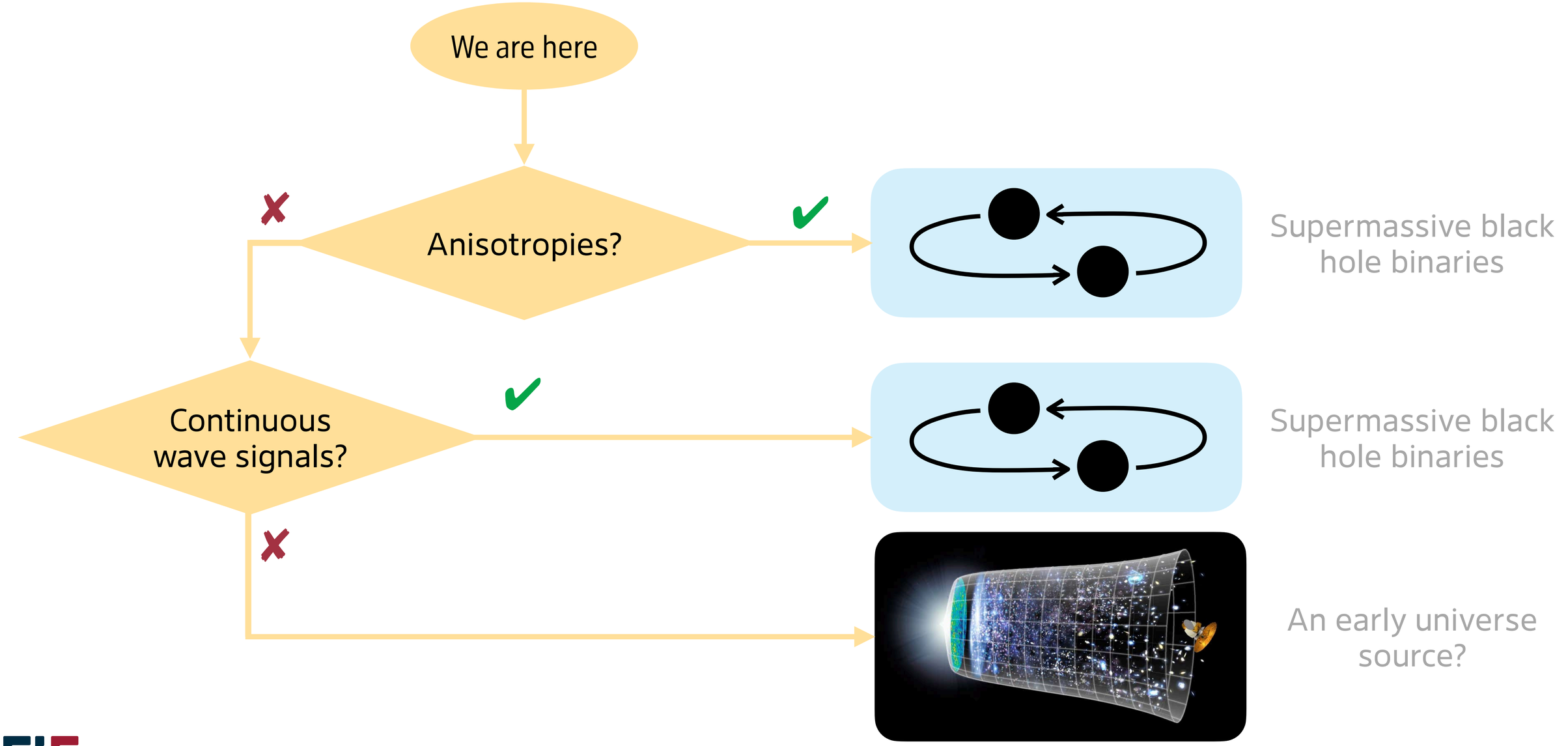
| | IR | Intermediate | UV | References |
|---|---|---|---|---|
| Sound shell | 9 | 1 | −3 | [22, 23] |
| Scalar + fluid lattice | — | 1 | −3 | [18, 20, 21, 29] |
| Hybrid | [2,4] | [−1,0] | [−4,−3] | [30] |
| Higgsless | 3 | 1 | −3 | This work |

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

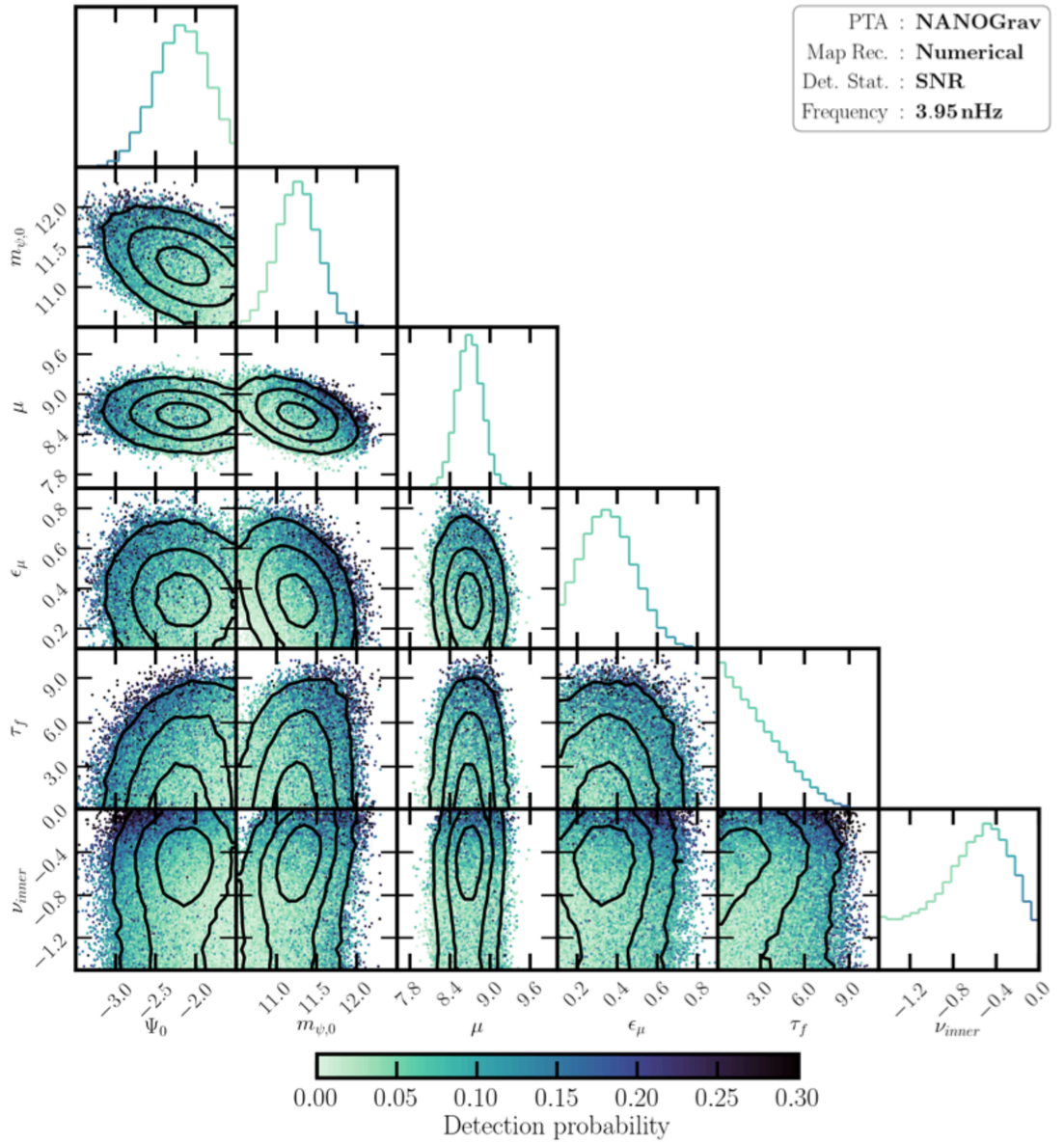



Yann Gouttenoire: Beyond the Standard Model Cocktail

# 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