When the HL-LHC is blind, LISA is deaf (but not vice versa)



VAST 2026, Madrid

Carlo Tasillo,
Institut de física corpuscular (IFIC)

Based on work with Jonas Matuszak,
Stefano Moretti and André Pousette

arXiv: 2605.15259, 2608.23679

UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

CSIC Consejo Superior de Investigaciones Científicas

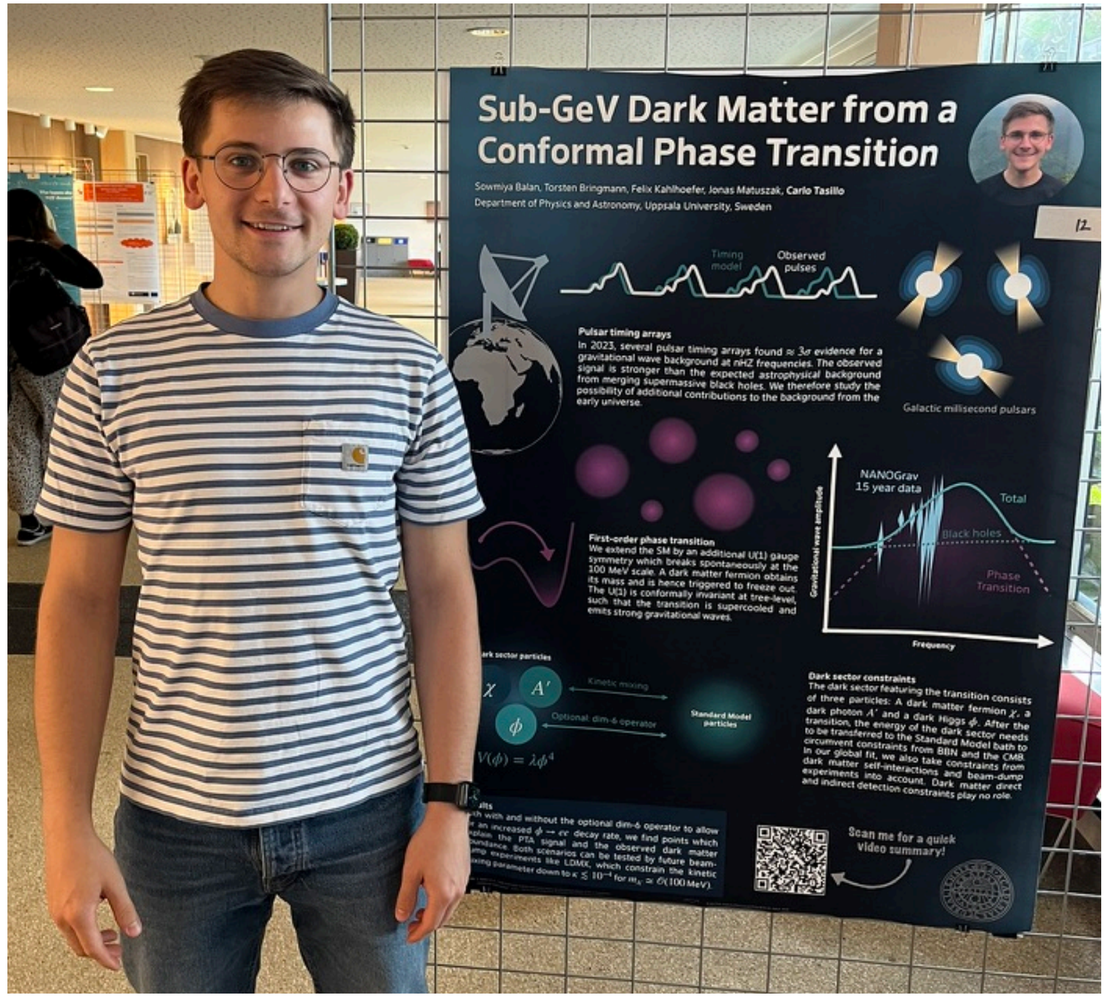
Universitat de València

IFIC Institut de Física Corpuscular

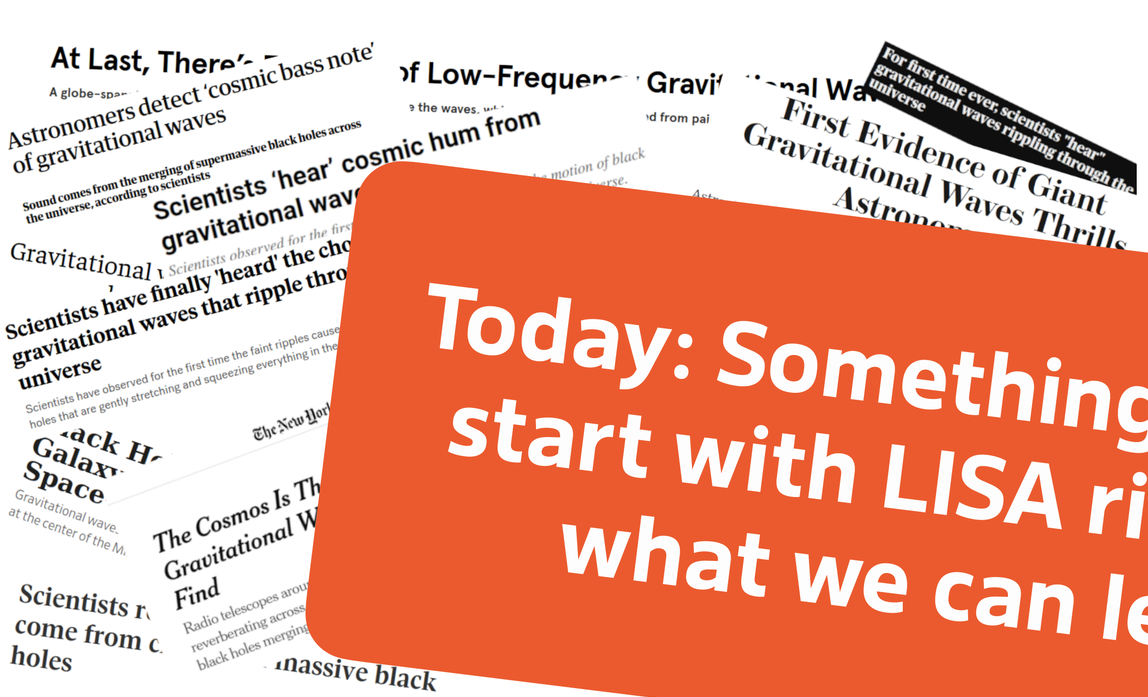
Excelencia Severo Ochoa

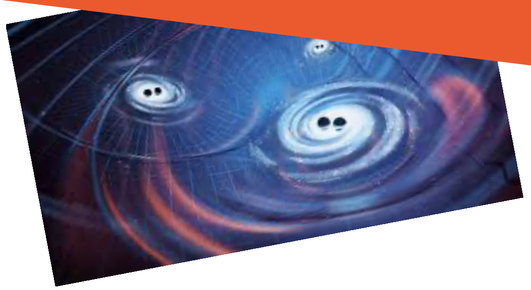
My main focus: Phase transitions and PTAs





My main focus: Phase transitions and PTAs

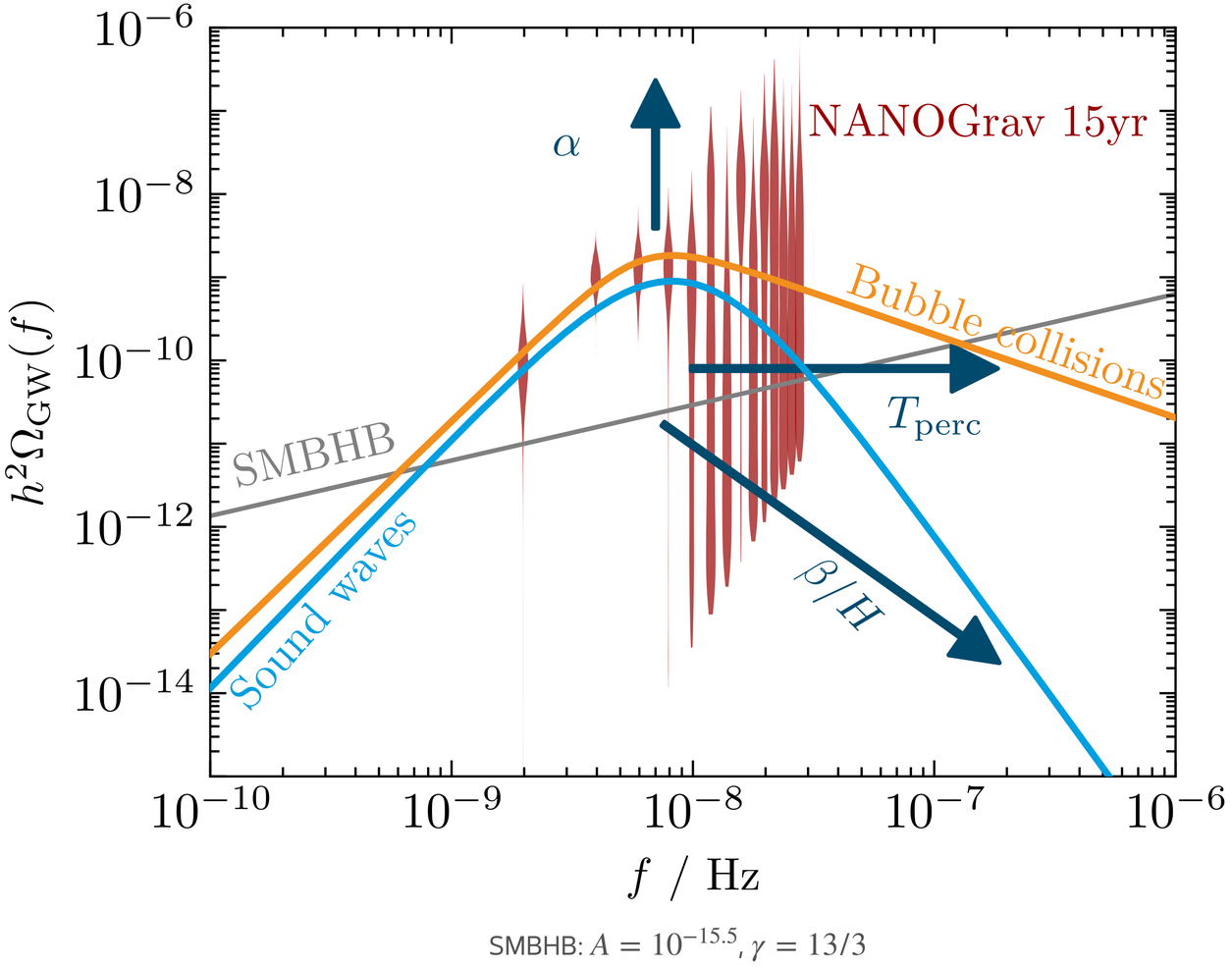






Today: Something different. Let's *not* start with LISA right away, but with what we can learn from PTAs.

Parametrization of the GW signal of a phase transition



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

Very roughly:

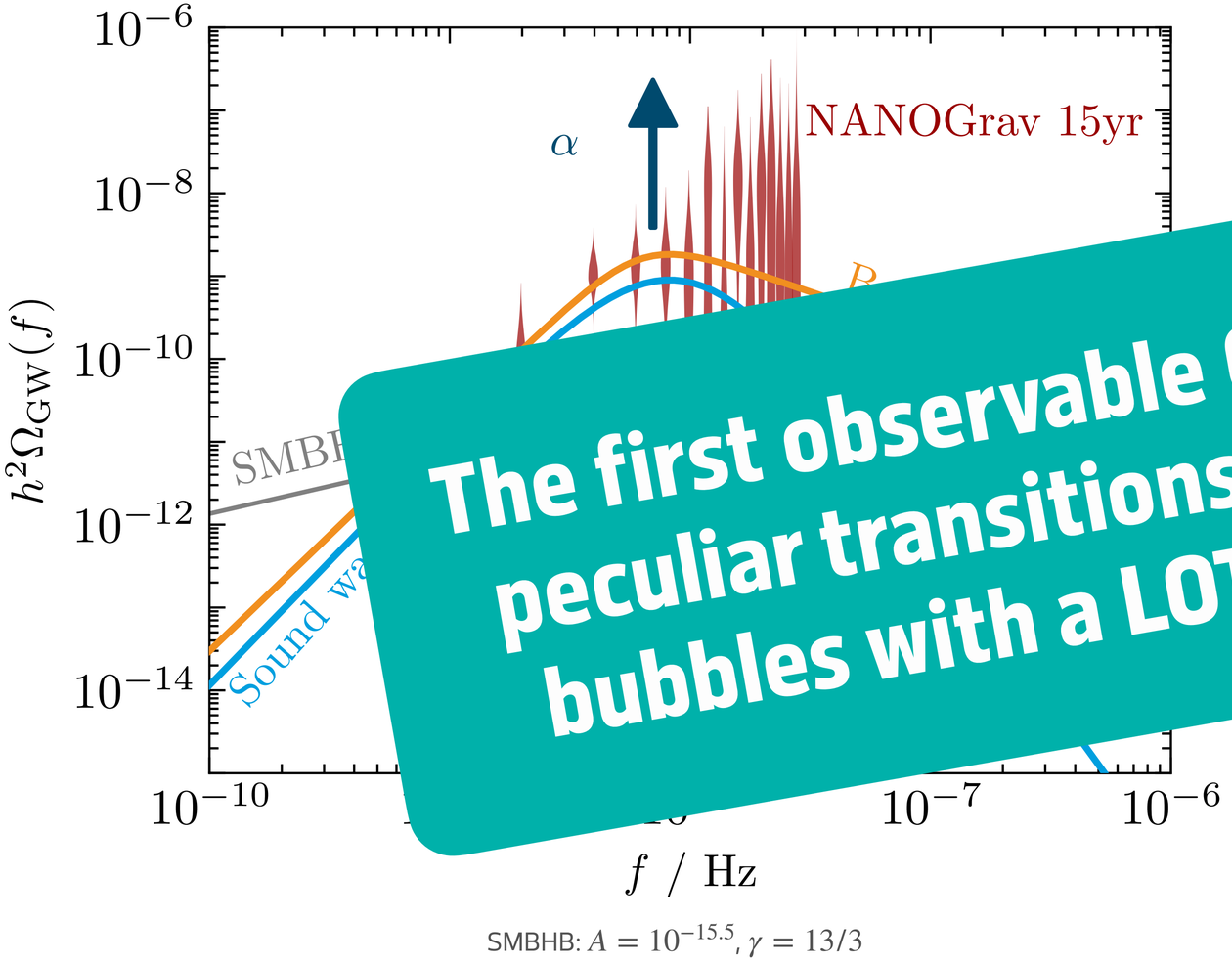
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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, $\beta/H \approx 10$
- Reheating around $T \approx 10\,{\rm MeV}$

Parametrization of the GW signal of a phase transition



Very roughly:

$$h^2\Omega^{\rm sw,bw} \dots \left(\frac{H}{\beta}\right)^{1,2} \mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

The first observable GW signals require peculiar transitions: EXTREMLY large bubbles with a LOT of supercooling.

data:

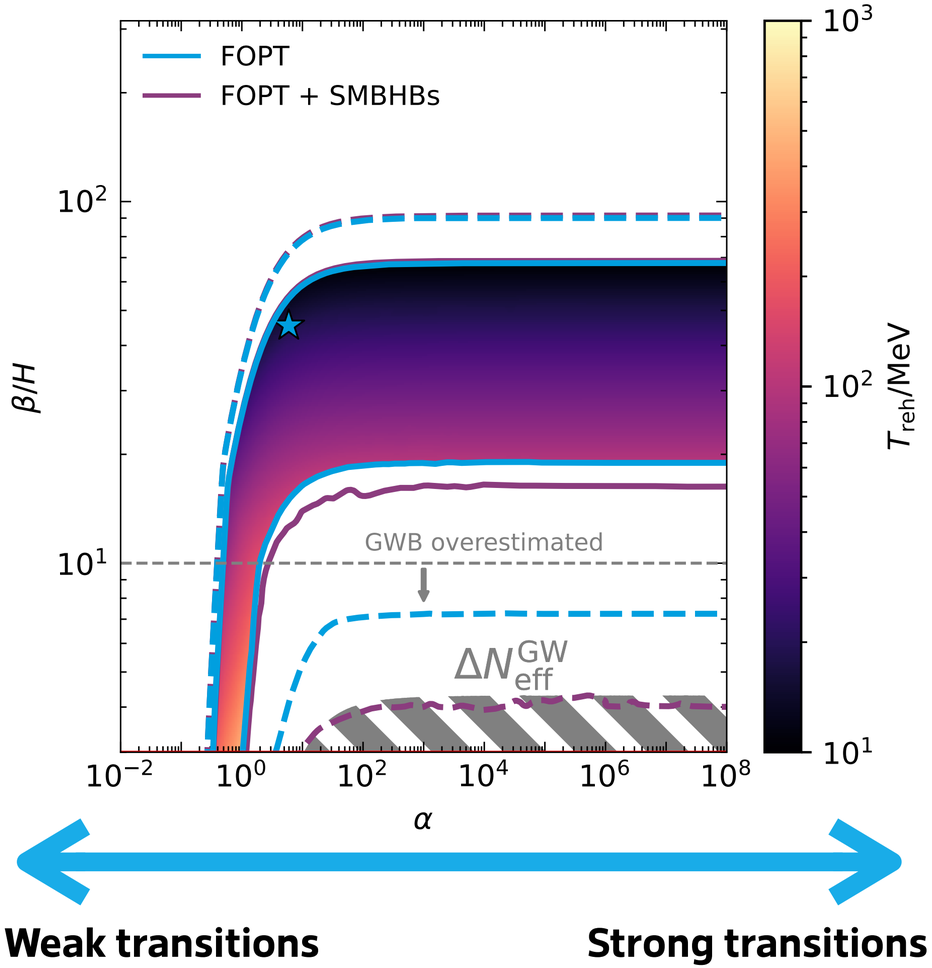
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Which phase transitions can fit the PTA data?

Many small bubbles

$$\beta/H \simeq \frac{(8\pi)^{1/3}}{RH_*}$$

Few big bubbles



Weak transitions — Strong transitions

CT+ [2602.09092]

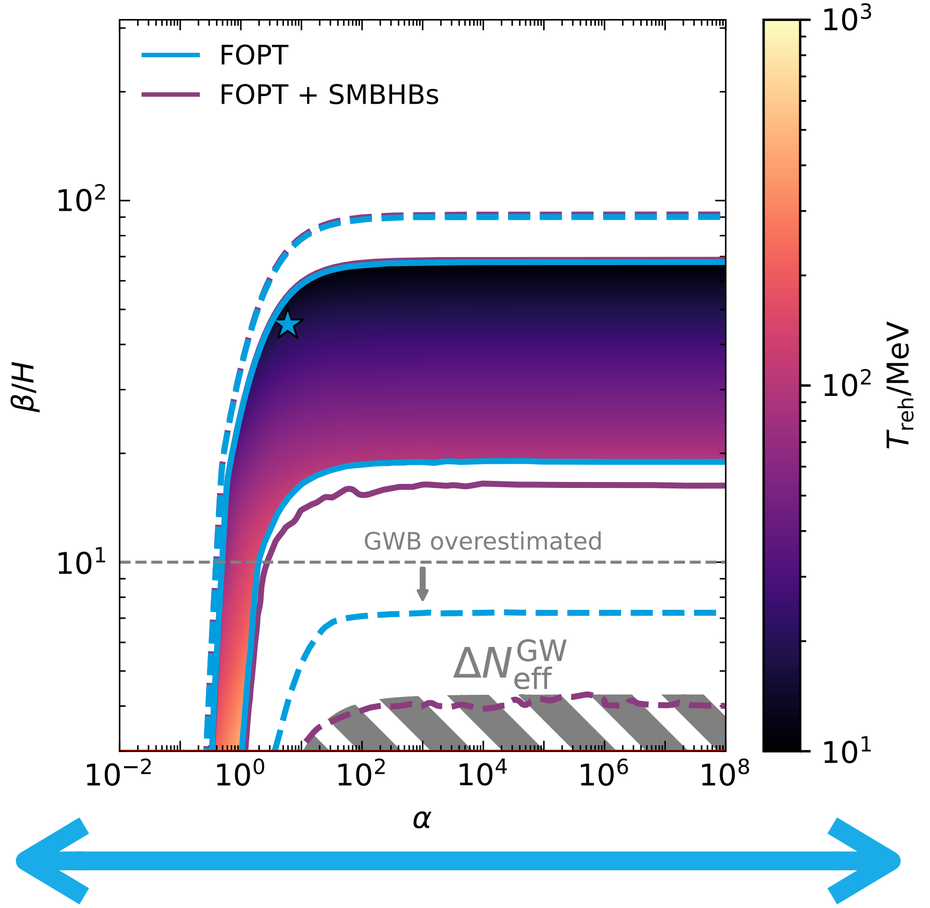
PTA data requires very strong transitions with extremely large bubbles!

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CT+ [2602.09092]

PTA data requires very strong transitions with extremely large bubbles!

That relationship is wrong, by the way… (you can ask me over coffee about it)

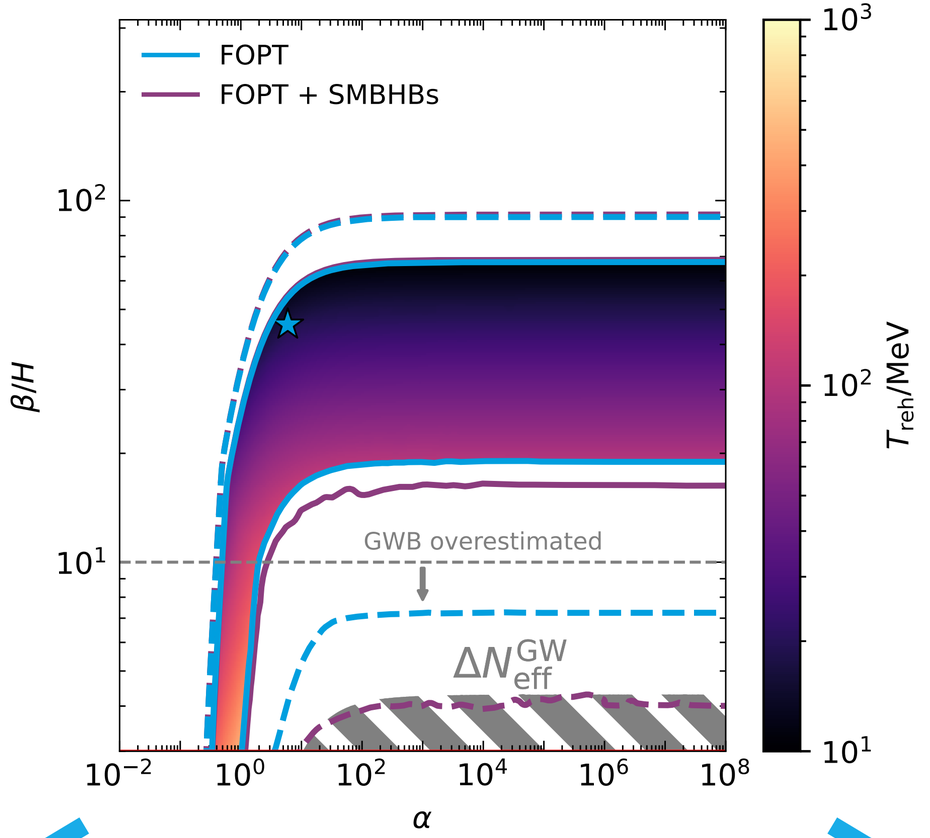
CT+ [2605.15259]

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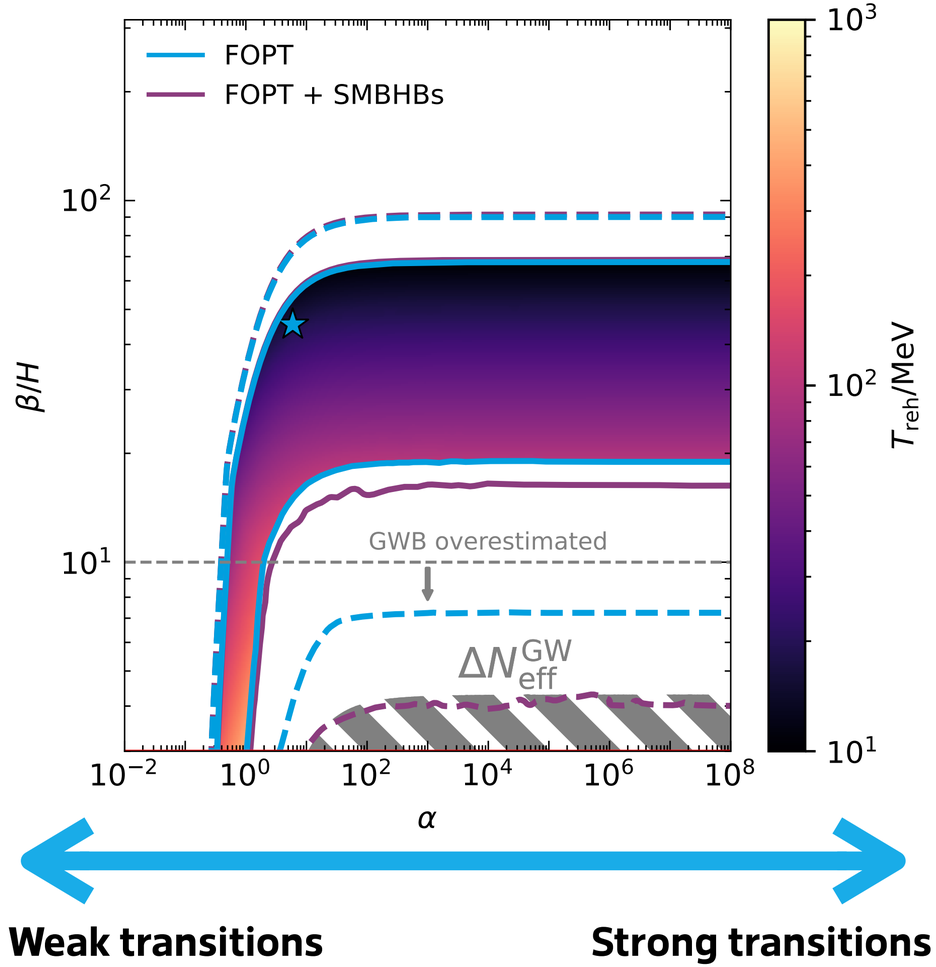
Robust predictions of the GW signal in that regime are difficult…

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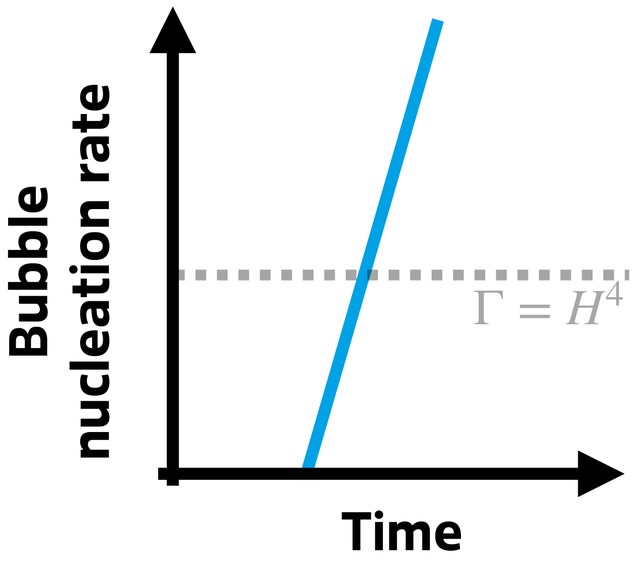
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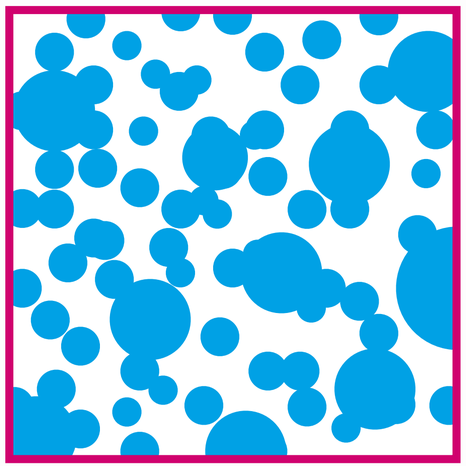
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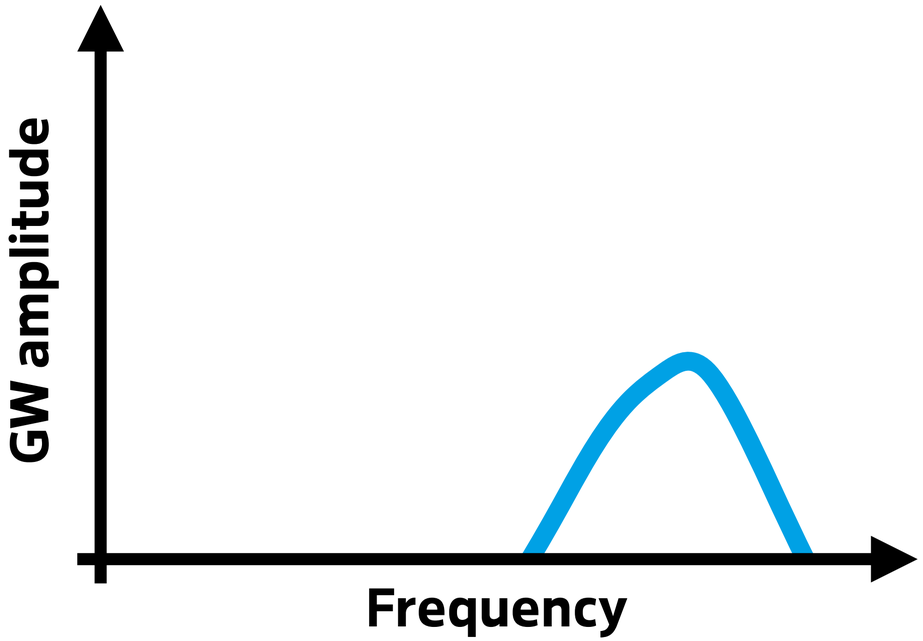
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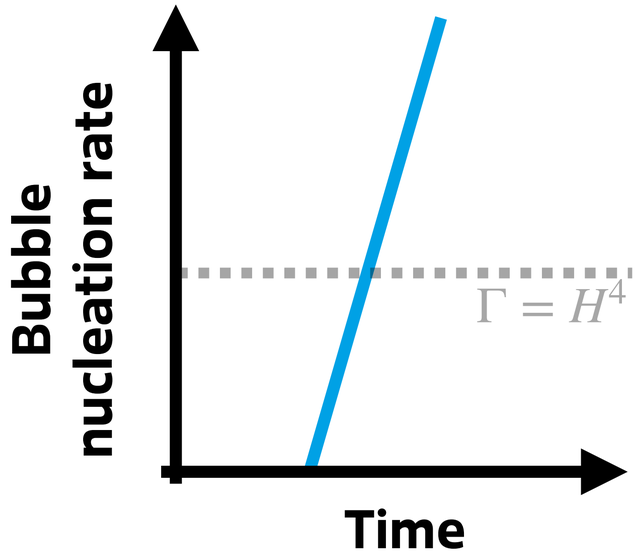
Why is it so difficult to get big bubbles?

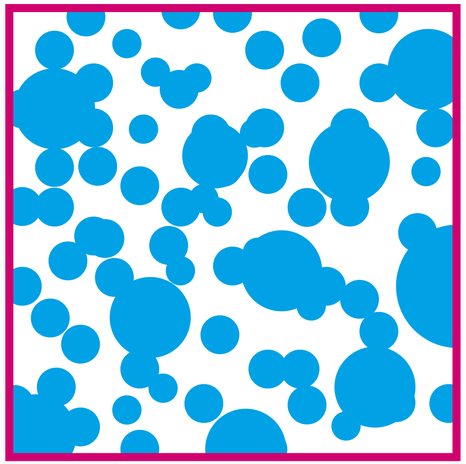


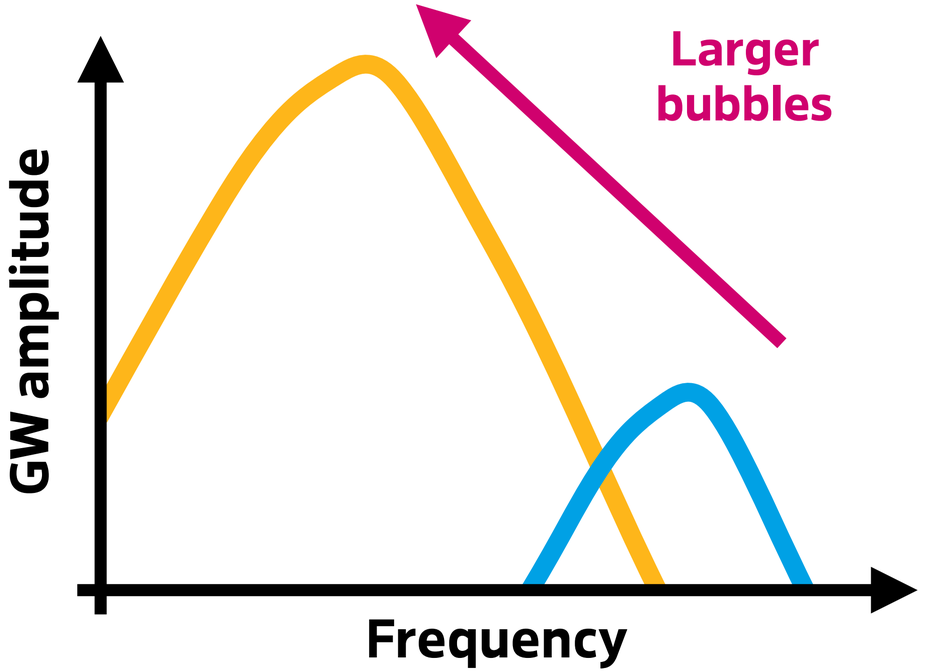


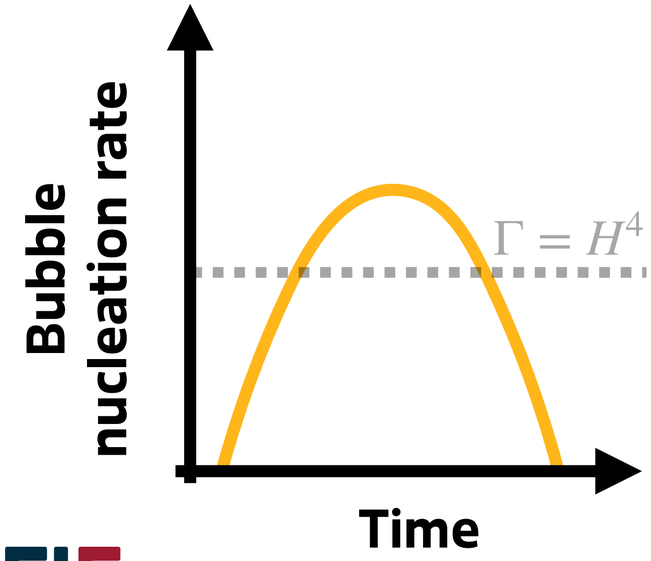


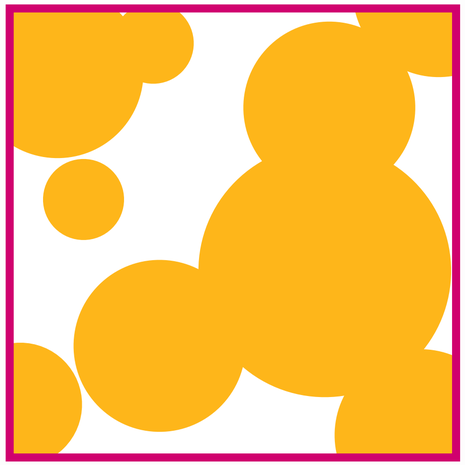
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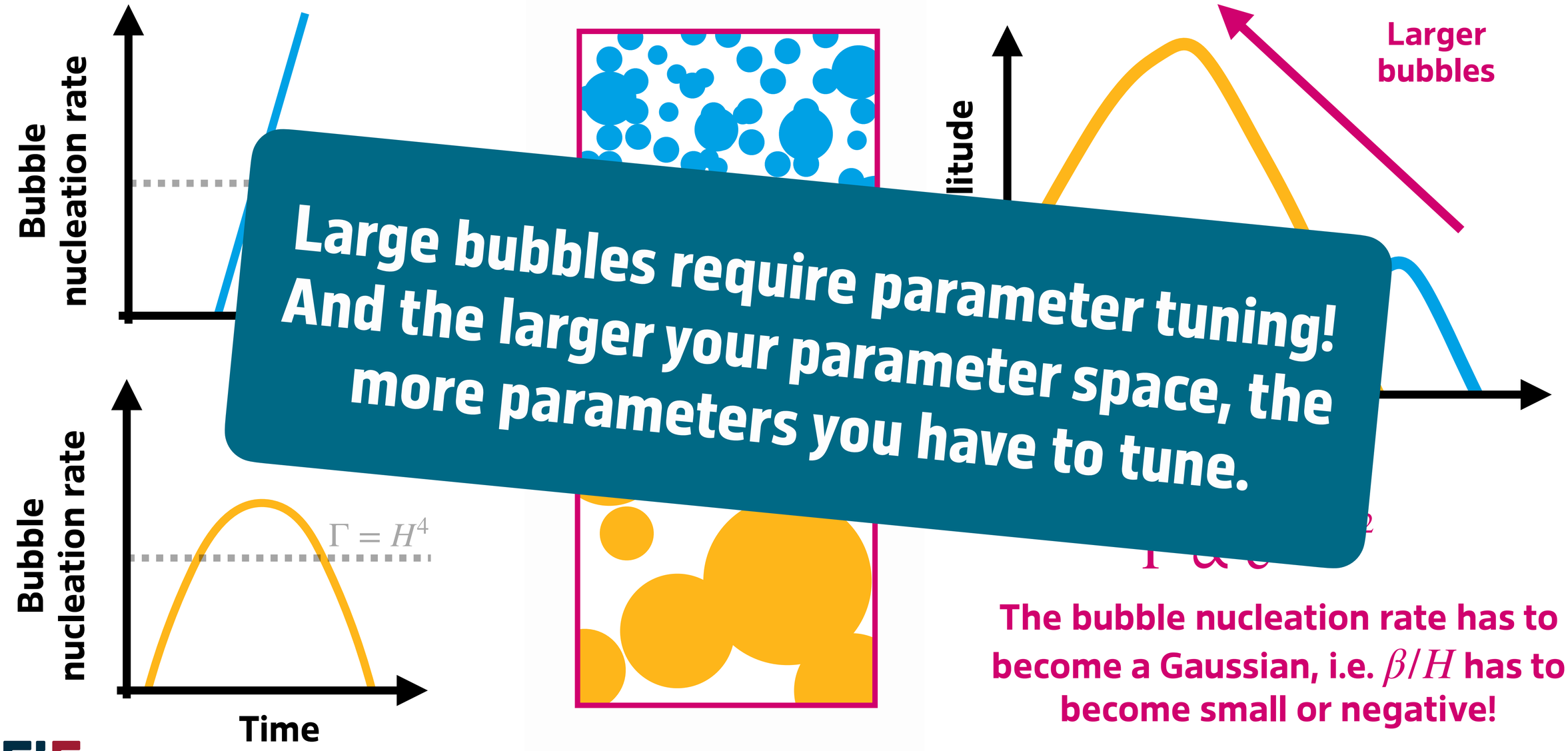




$$\Gamma \propto e^{\beta t - \gamma t^2}$$

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

Why is it so difficult to get big bubbles?

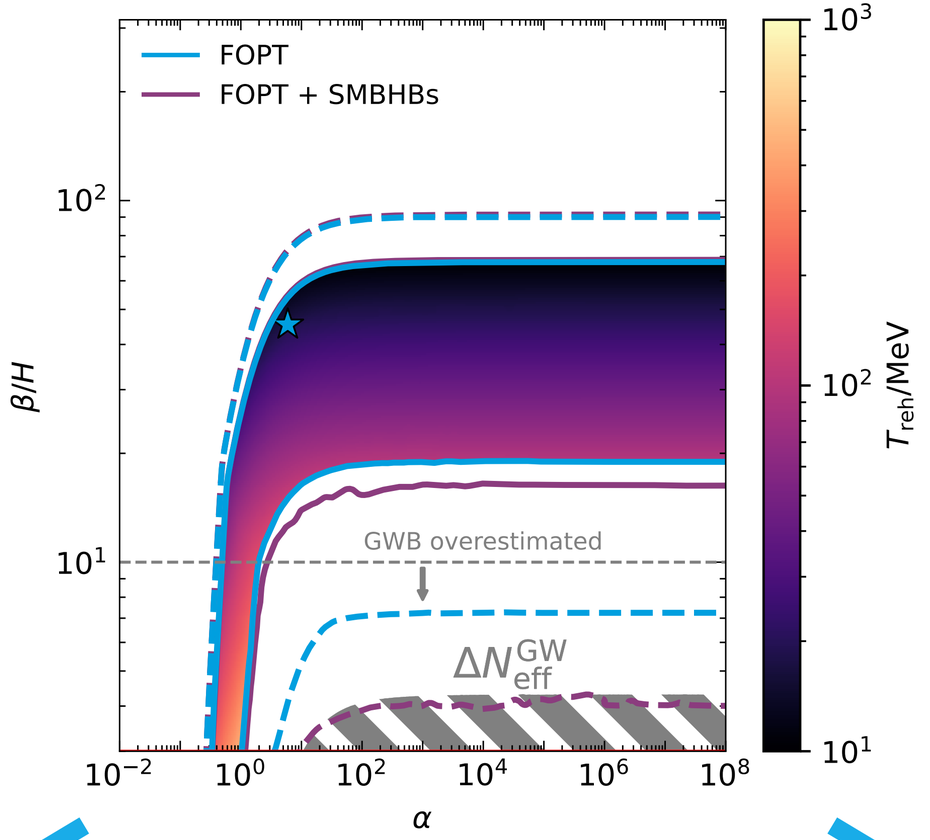


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Weak transitions

Strong transitions

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What is required for robust phase transition predictions?

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?

Today

Numerical stability

Consistent cosmological evolution



Perturbative control over bubble nucleation rate

GW templates valid for strong supercooling and Hubble-sized bubbles

[2605.15259]

What is required for robust phase transition predictions?

Today

Numerical stability

Consistent cosmological evolution

[2605.15259]



Soon

Perturbative control over bubble nucleation rate

GW templates valid for strong supercooling and Hubble-sized bubbles

[2611.XXXXX]


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 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]†

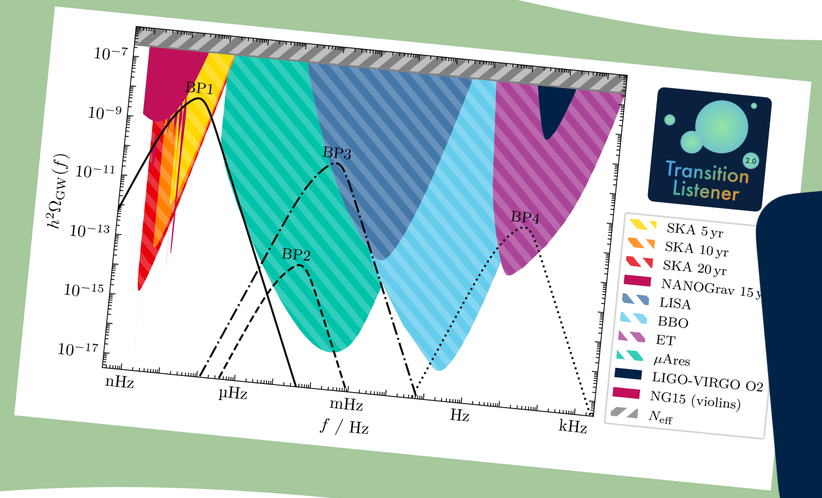
[1] Institute for Theoretical Particle Physics (TTP), Karlsruhe Institute of Technology (KIT), 76128 Karlsruhe, Germany

[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

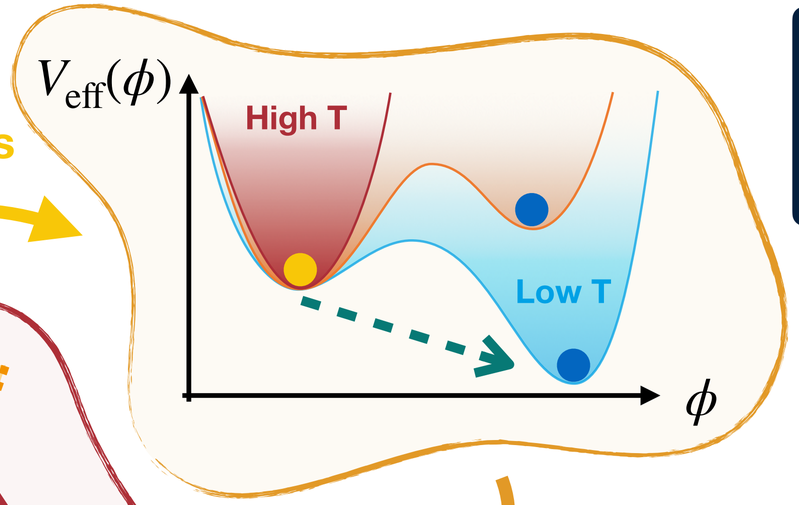
259v1 [hep-ph] 14 May 2026



Transition Listener

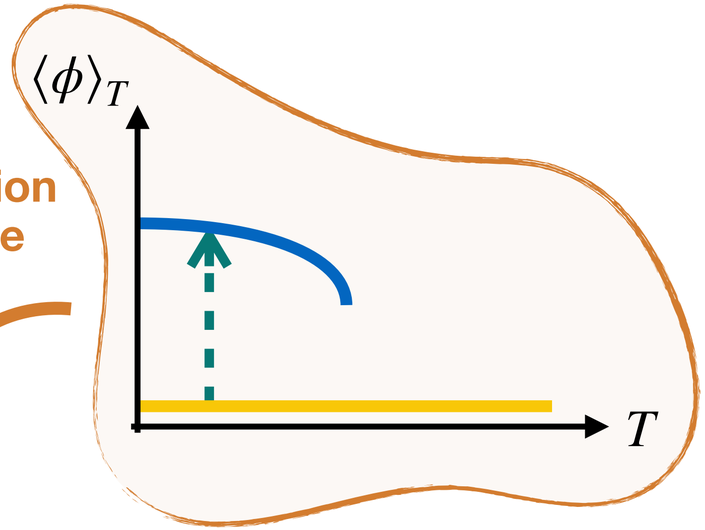
$$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

Quantum & finite-temperature corrections

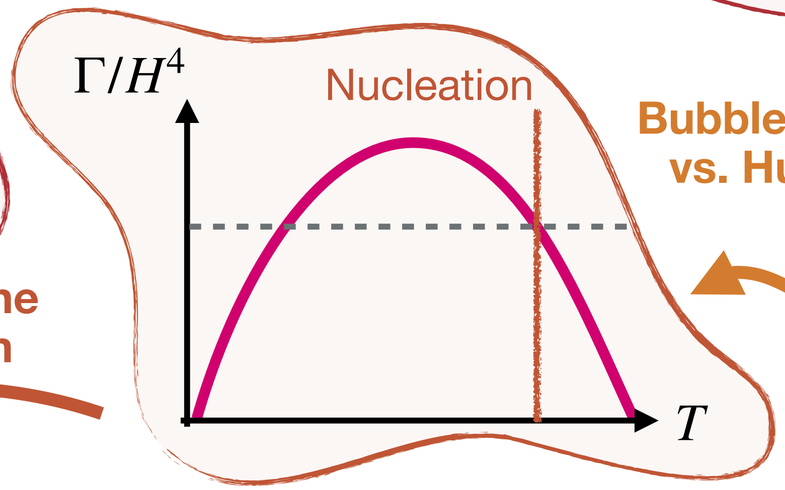


Transition Listener 2.0

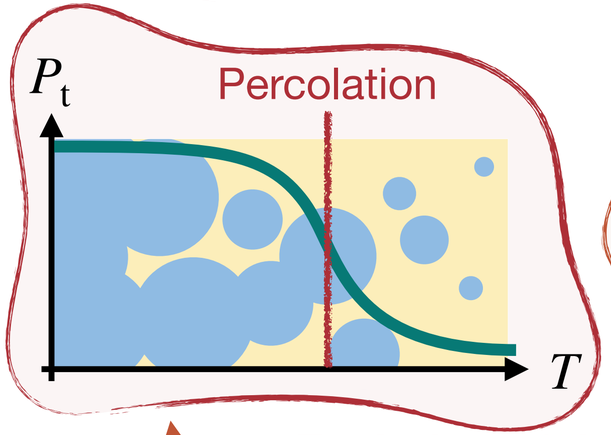
Phase tracing and finding possible transitions



Bubble nucleation vs. Hubble rate

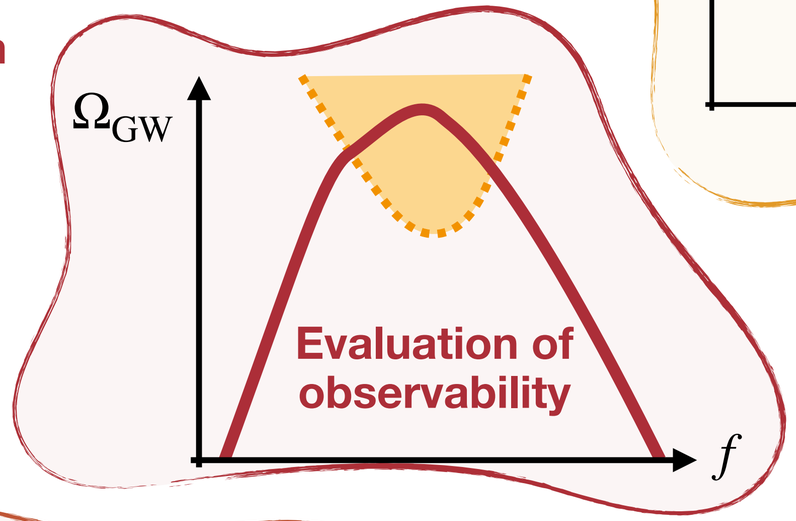


Evolution of the false vacuum



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

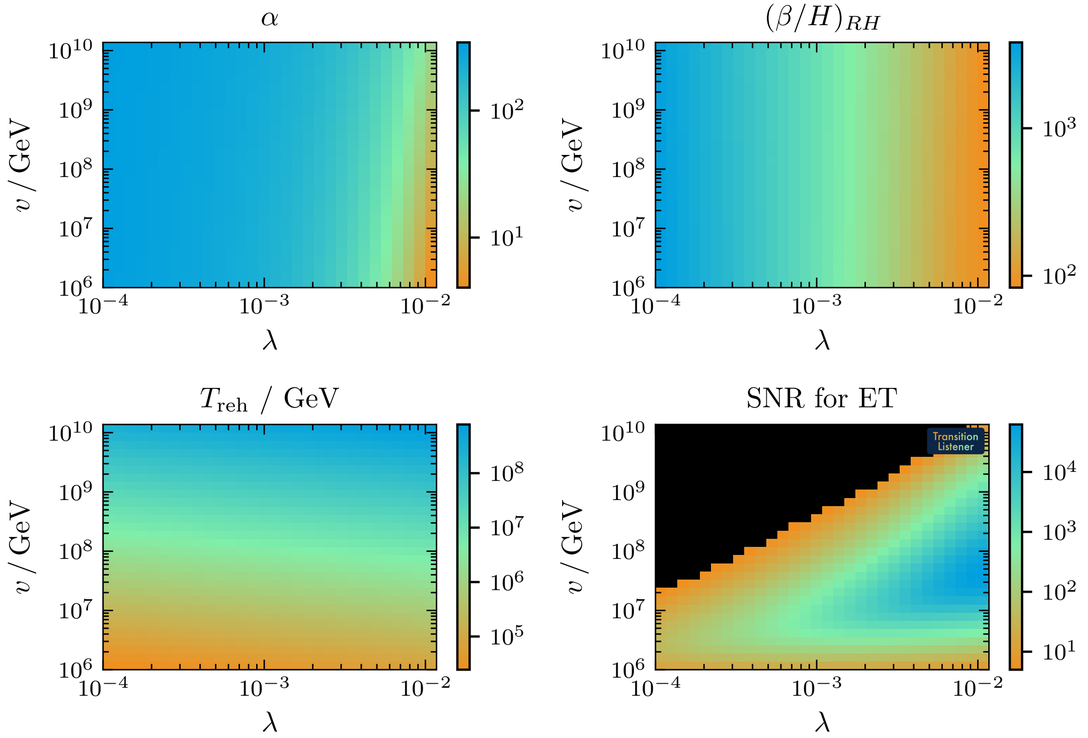
Scan parameters
Parameter  Value
g          0.7
v_GeV      0.1
y          0.01

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

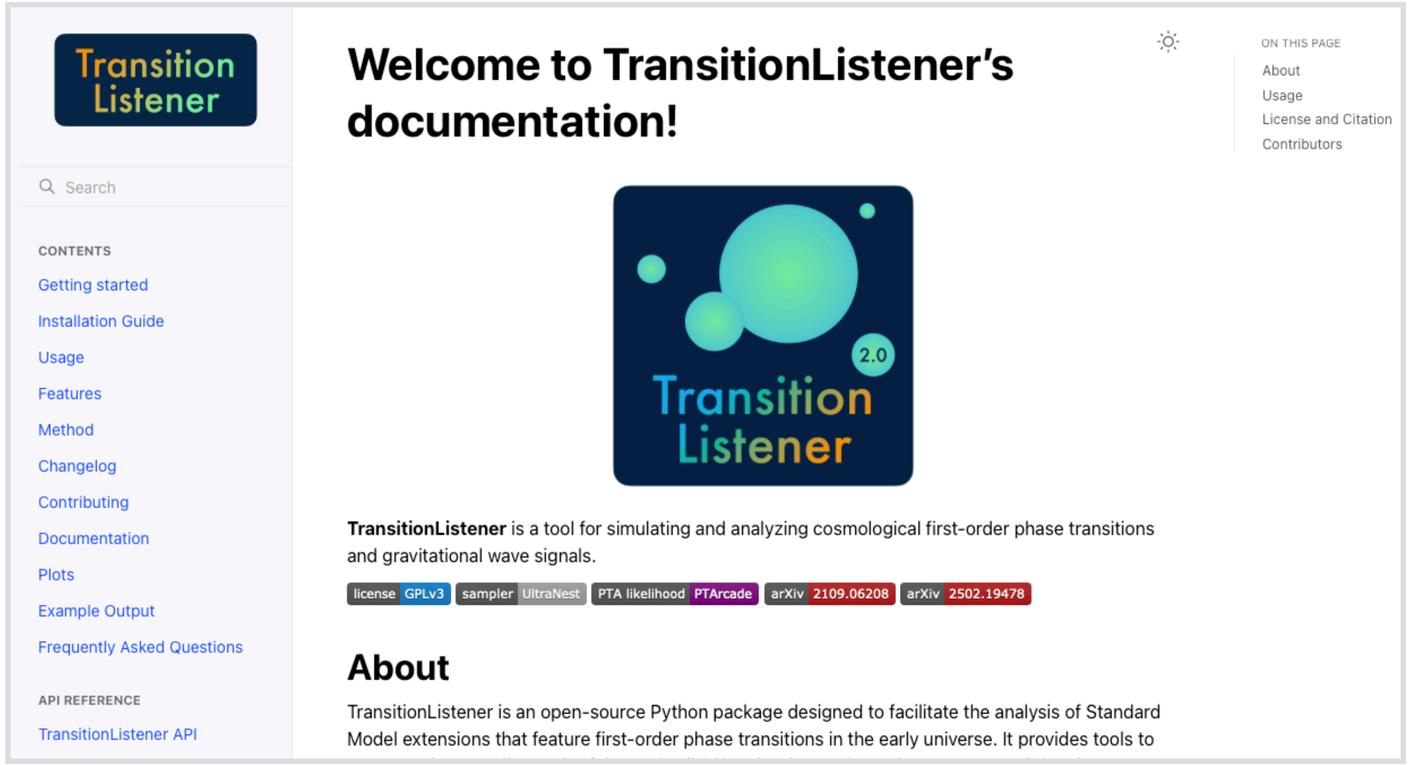
Zero-temperature mass spectrum
Particle  Type     Mass [GeV]
m_phi     boson    2.2443542988e-02
m_varphi  boson    1.2957785586e-02
m_A_T     boson    7.0000000000e-02
m_A_L     boson    7.0000000000e-02
m_psi1    fermion  7.0710678119e-04
m_psi2    fermion  7.0710678119e-04
```



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!

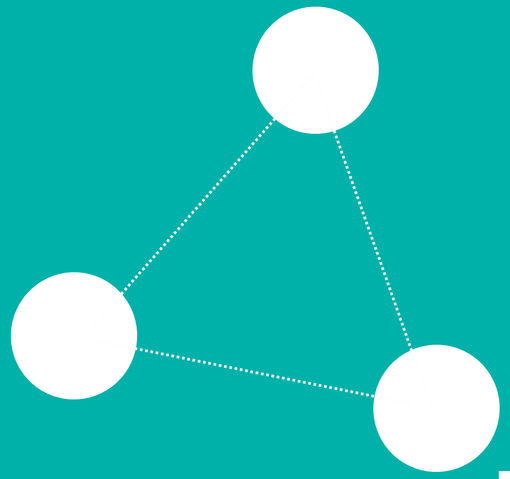
www.tasillo.de/TransitionListener


BROADCAST
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Back to the main topic today:

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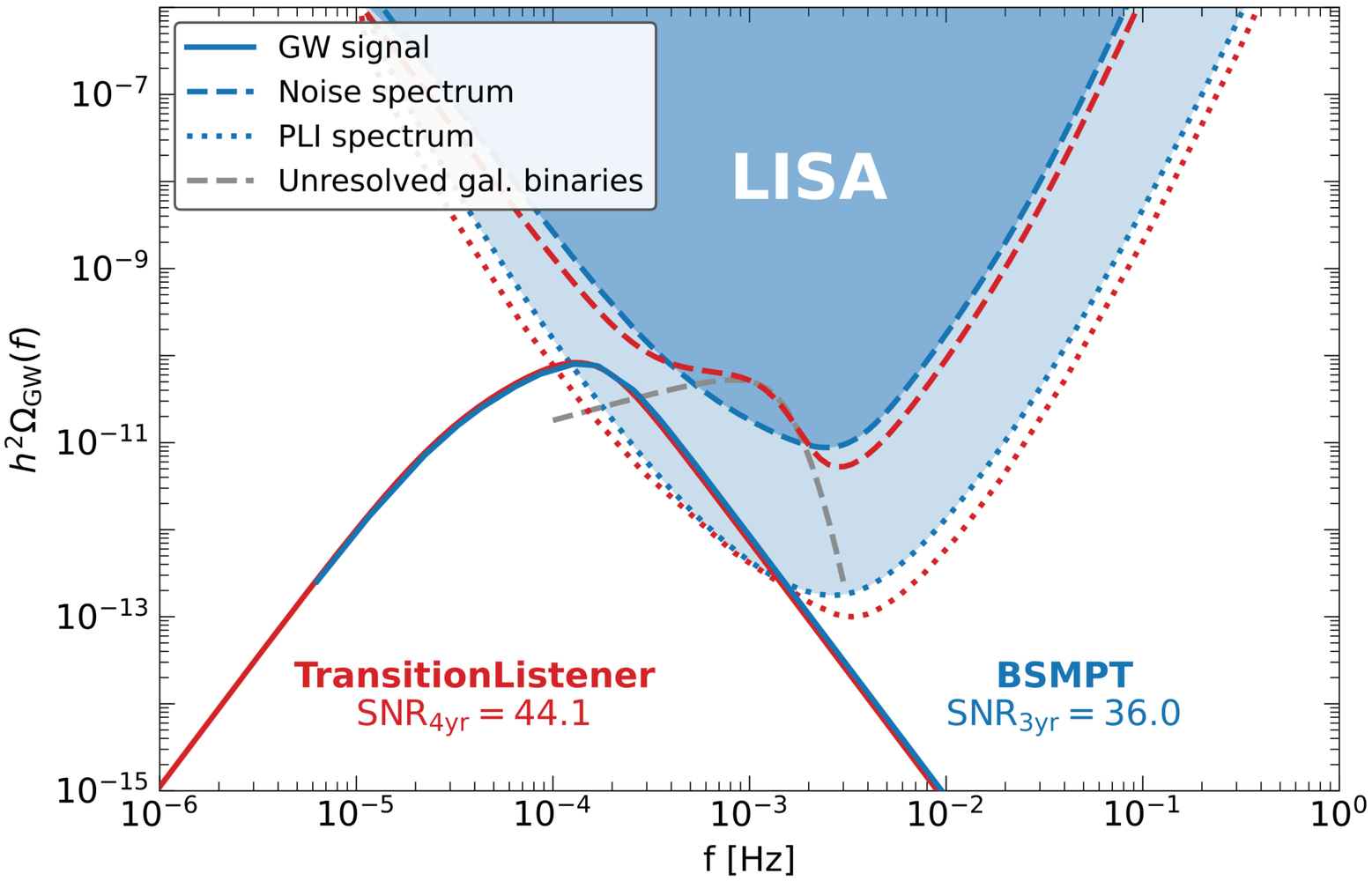




LISA



The LISA spectrum



LISA can detect GWs in the mHz band, directly related to **cosmological sources at** $\mathcal{O}(100\,\mathrm{GeV})$ **temperatures.**

There's **hope to find a background** stronger than an astrophysical background, potentially from the **electroweak phase transition**.

Some motivation for 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]

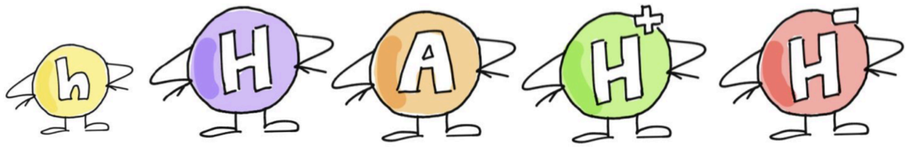
[a] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*

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

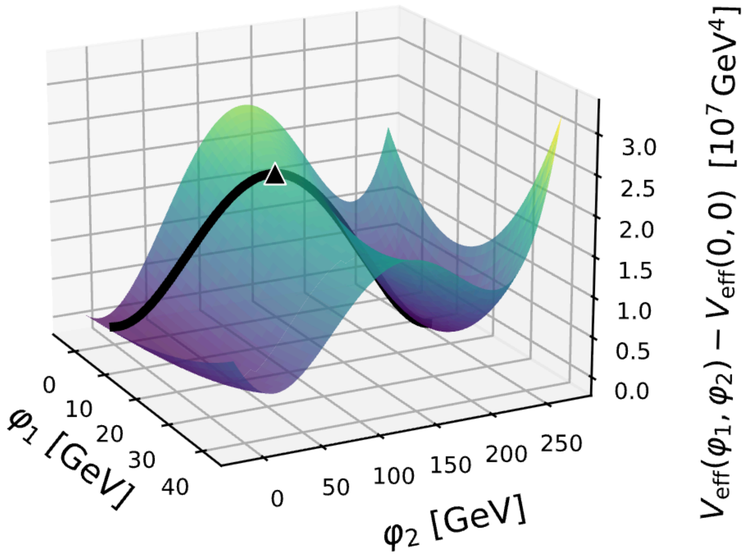
[c] *Instituto de Física orpuscular (IFIC), Universitat de Valéncia-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain*

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

Which parts of the 2HDM are still allowed?

$$V_{\text{tree}}(\mathbf{\Phi}) = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4$$
$$+ \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2\right.$$
$$\left. + \lambda_6\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1^\dagger\Phi_2\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right],$$

Complicated potential structure with many parameters and constraints...

Peturbative unitarity

Boundedness from below at zero temperature

Flavor constraints

SM-like Higgs state matching the observations

Additional Higgs states not excluded from LHC searches

Vacuum stability at zero temperature

Boundedness from below at finite temperature

Electroweak precision constraints (S, T, U)

We use a combination of ScannerS, BSMPT, HiggsSignals and HiggsBounds for these constraints

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$$+ \lambda_3|\Phi$$

$$+ \lambda$$

$$\left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2$$

Complicated potential structure with many parameters and
ints...

Sounds complicated... Let's get a more intuitive understanding of the viable parameter space.

Peturbative unitarity

SM-like
tate matching
bservations

Additional Higgs states not excluded from LHC searches

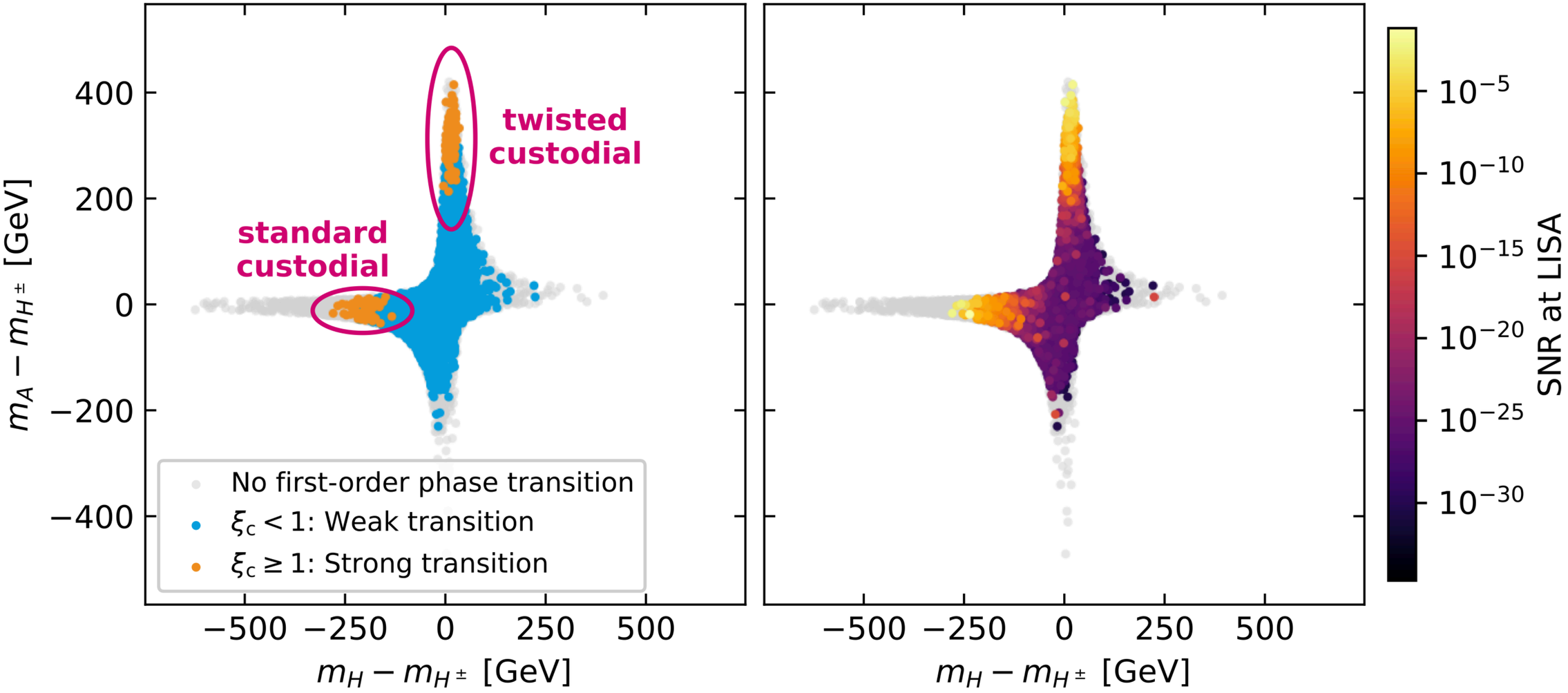
Vacuum stability at zero temperature

from below a
temperature

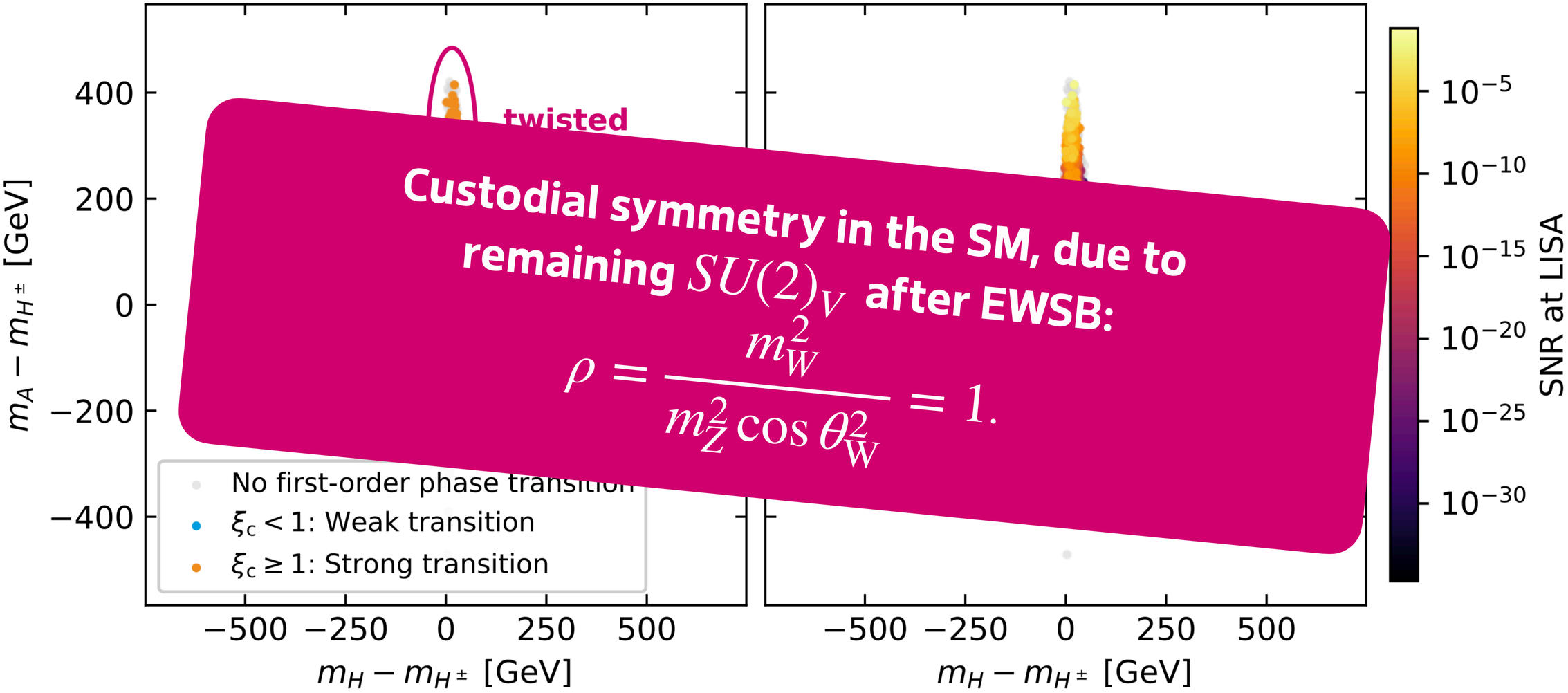
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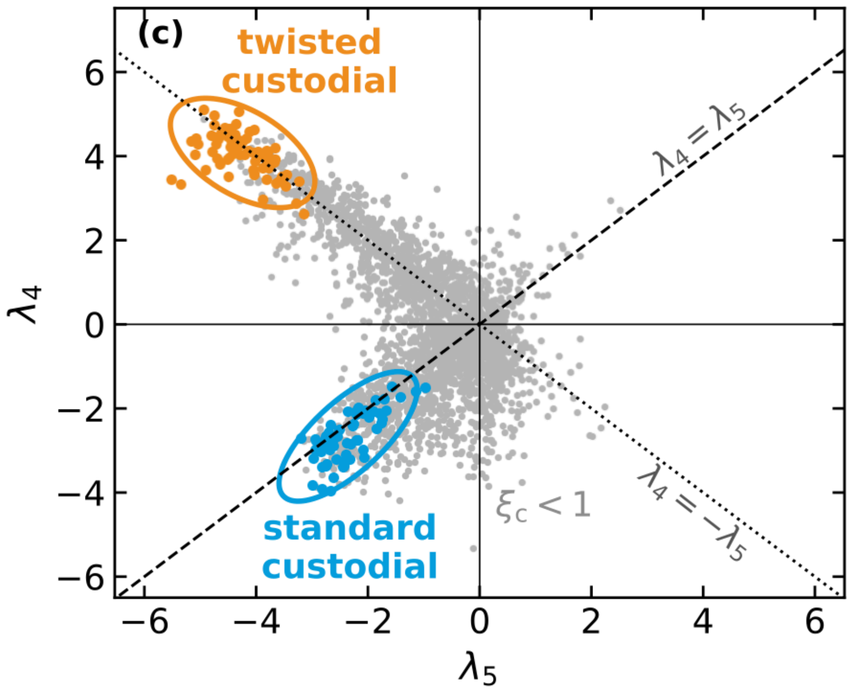
A random scan of the viable 2HDM parameter space shows 2 hotspots



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Custodial symmetry is conserved in these two spots



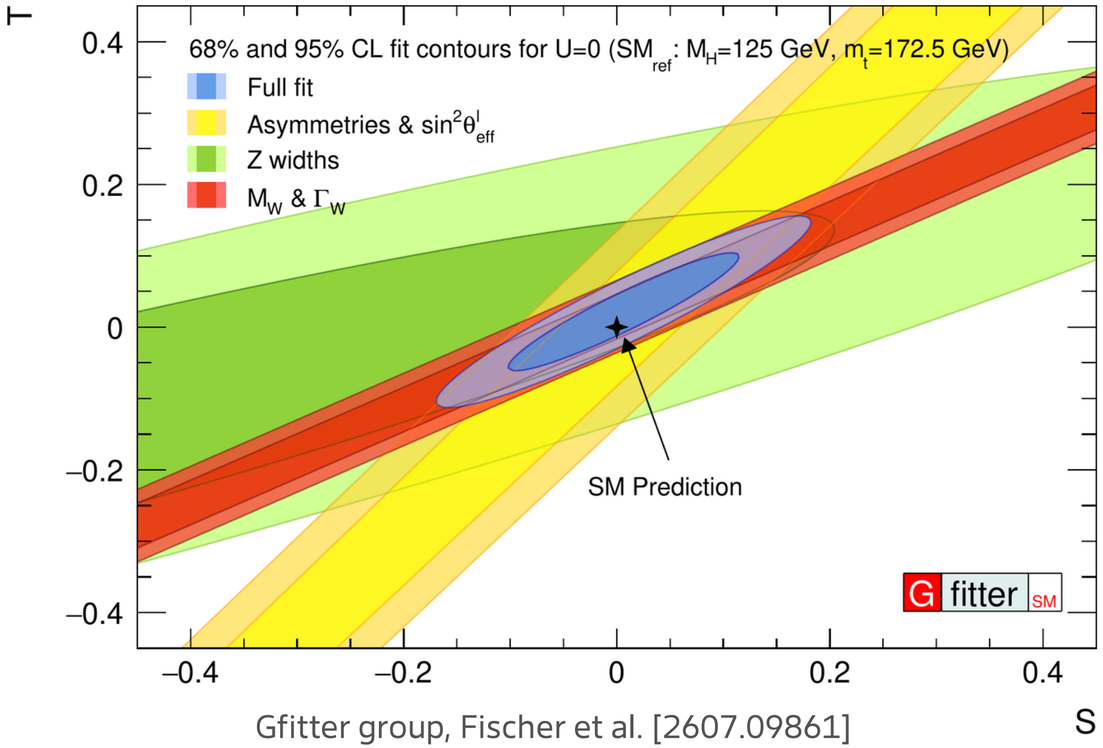
The strong transitions sit on the diagonals $\lambda_4 = \pm\lambda_5$, where $m_{H^\pm} = m_A$ or $m_{H^\pm} = m_H$

In the 2HDM: $\Delta\rho = \dfrac{1}{32\pi^2 v^2}(F_{H^\pm,A} + F_{H^\pm,H} - F_{A,H})$

with $F_{x,y} = \dfrac{m_x^2 + m_y^2}{2} - \dfrac{m_x^2 m_y^2}{m_x^2 - m_y^2}\log\dfrac{m_x^2}{m_y^2}$

$\Delta\rho = \alpha_{em} T \lesssim 10^{-3}$ since $|T| \lesssim 0.1$, i.e. mass splittings of up to $\mathcal{O}(10\,\text{GeV})$

Custodial symmetry is conserved in these two spots



Gfitter group, Fischer et al. [2607.09861]

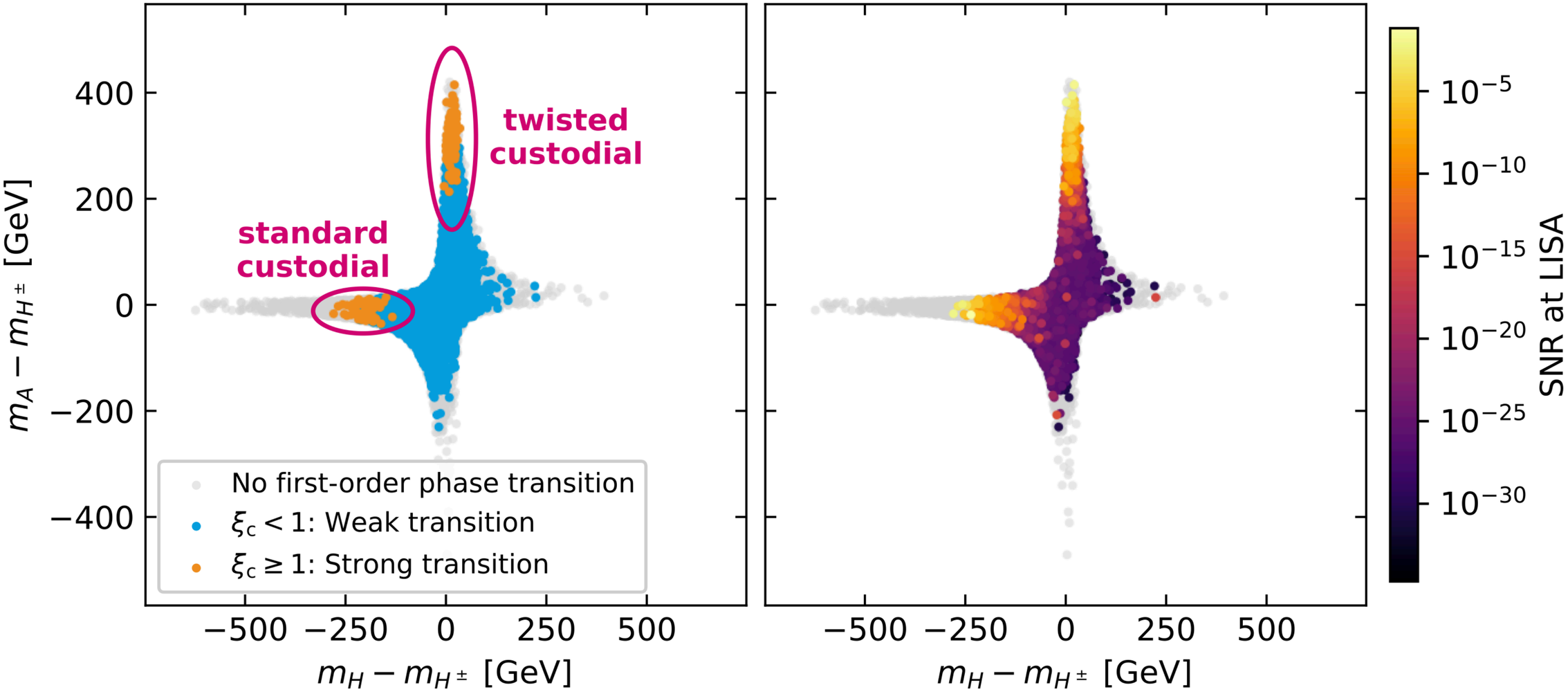
The strong transitions sit on the diagonals $\lambda_4 = \pm\lambda_5$, where $m_{H^\pm} = m_A$ or $m_{H^\pm} = m_H$

In the 2HDM: $\Delta\rho = \dfrac{1}{32\pi^2 v^2}(F_{H^\pm,A} + F_{H^\pm,H} - F_{A,H})$

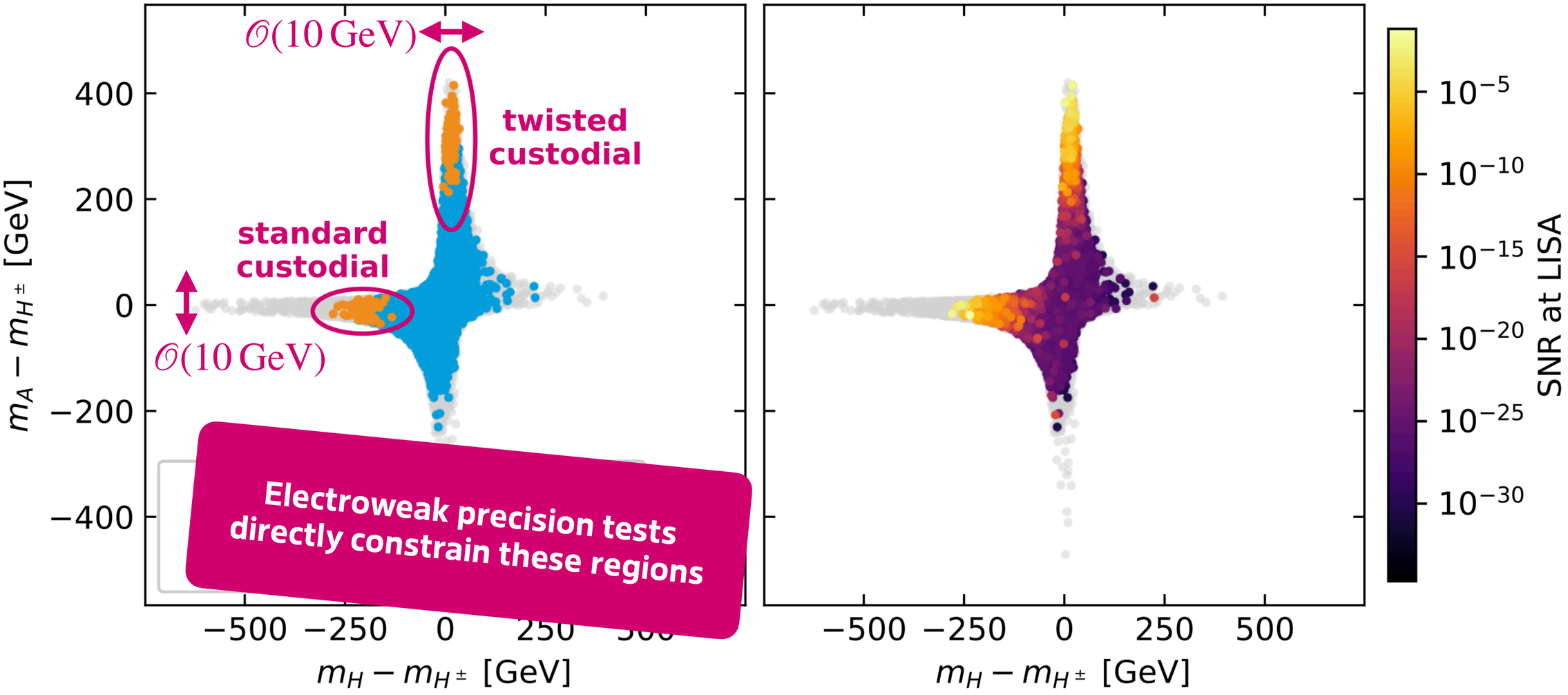
with $F_{x,y} = \dfrac{m_x^2 + m_y^2}{2} - \dfrac{m_x^2 m_y^2}{m_x^2 - m_y^2}\log\dfrac{m_x^2}{m_y^2}$

$\Delta\rho = \alpha_{\rm em} T \lesssim 10^{-3}$ since $|T| \lesssim 0.1$, i.e. mass splittings of up to $\mathcal{O}(10\,\text{GeV})$

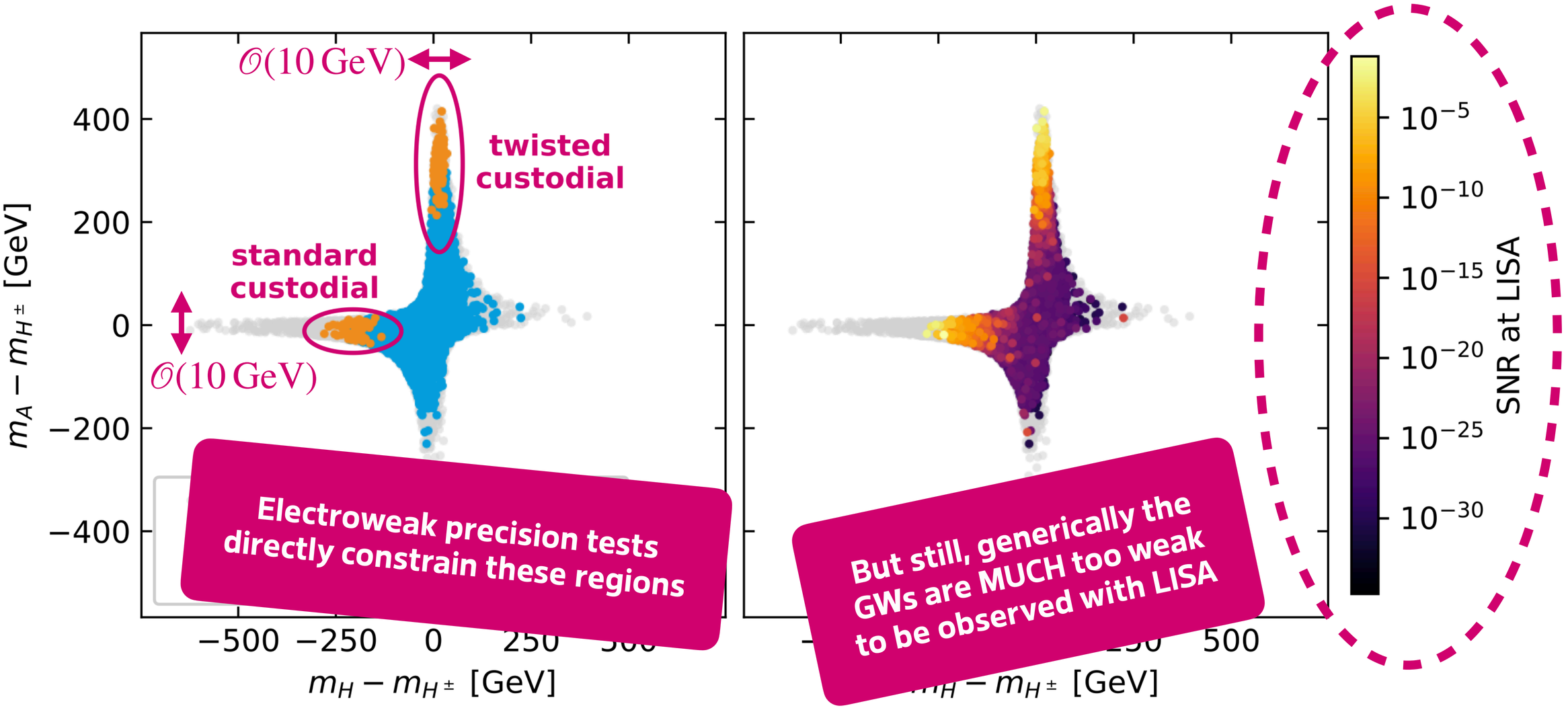
A random scan of the viable 2HDM parameter space shows 2 hotspots



A random scan of the viable 2HDM parameter space shows 2 hotspots



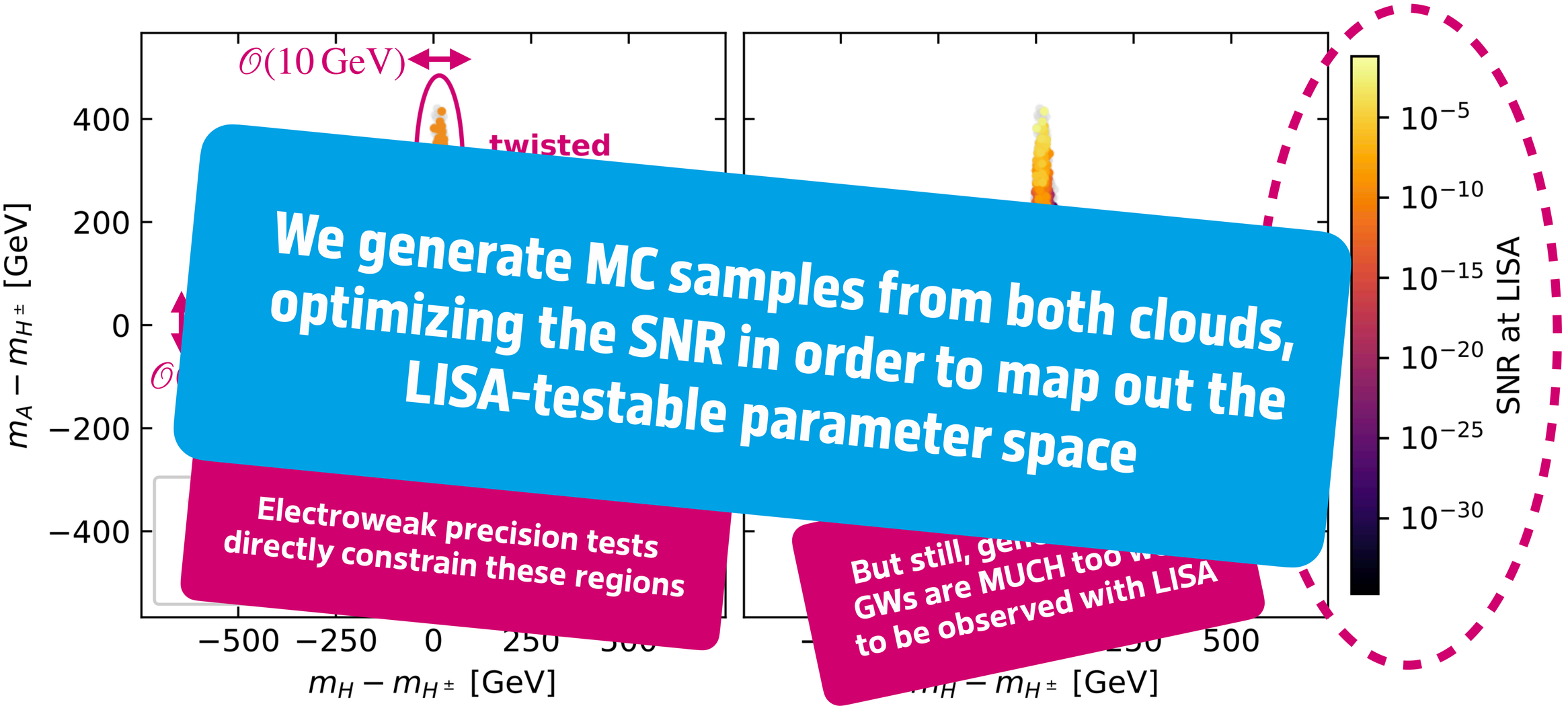
A random scan of the viable 2HDM parameter space shows 2 hotspots



Electroweak precision tests directly constrain these regions

But still, generically the GWs are MUCH too weak to be observed with LISA

A random scan of the viable 2HDM parameter space shows 2 hotspots



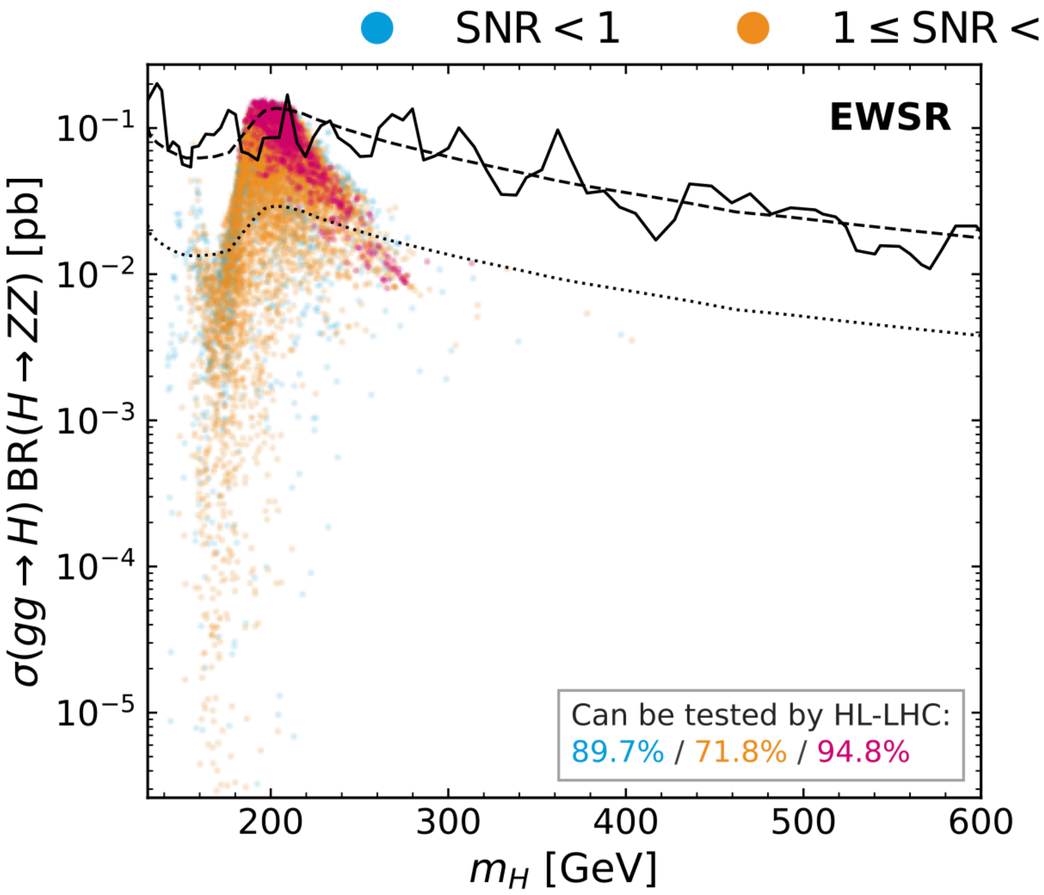
We generate MC samples from both clouds, optimizing the SNR in order to map out the LISA-testable parameter space

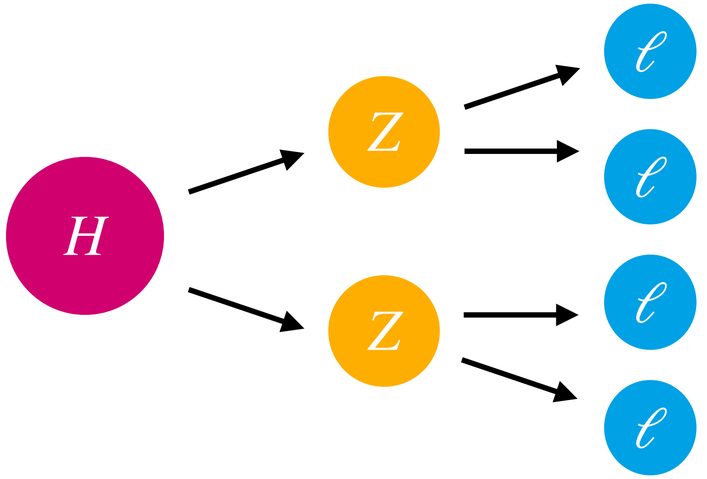
Electroweak precision tests directly constrain these regions

But still, ge… GWs are MUCH too … to be observed with LISA

$H \to ZZ$ remains a great channel to find Higgses!

Collider testability of the points in the standard custodial cloud ($m_A \simeq m_{H^\pm}$)

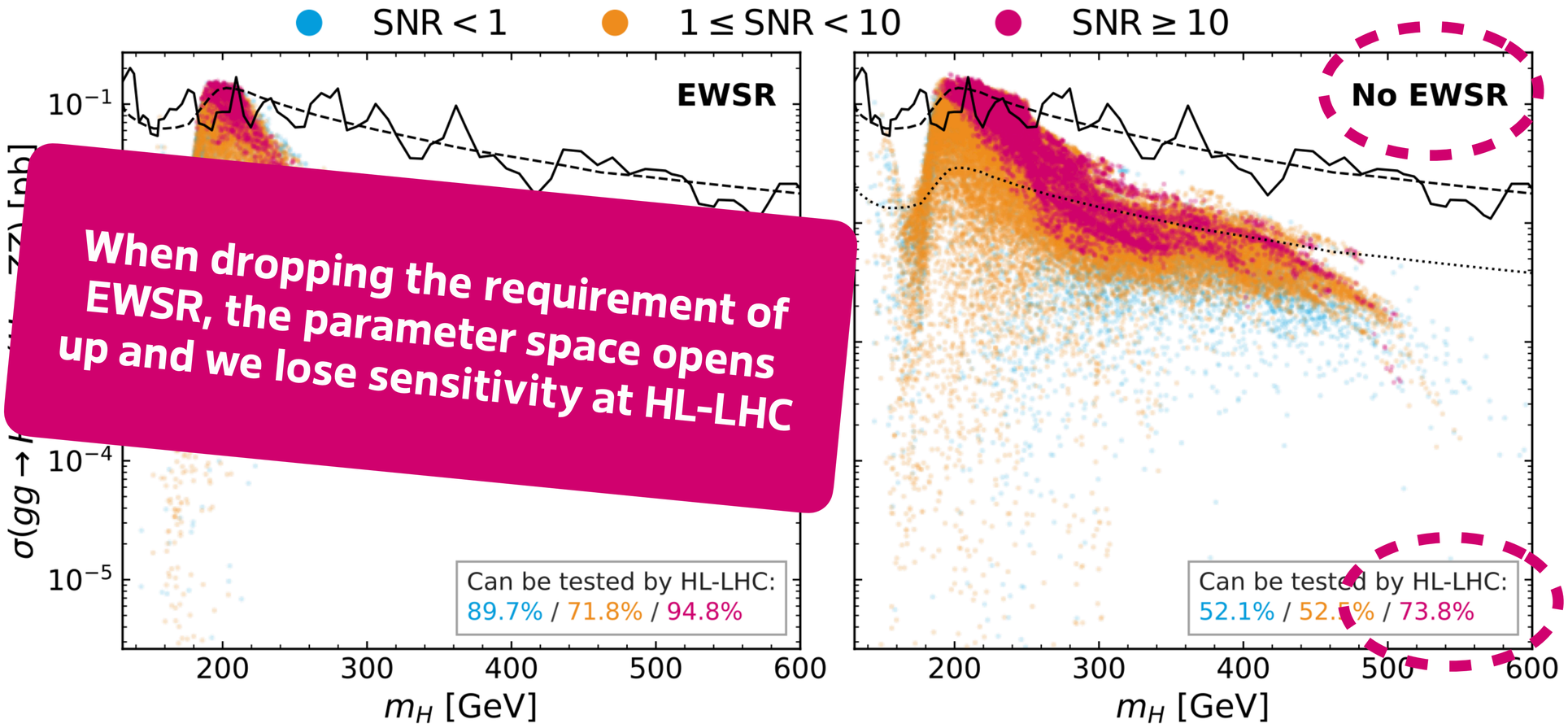




95% of all SNR > 10 cases can be tested by the HL-LHC!

$H \to ZZ$ remains a great channel to find Higgses!

Collider testability of the points in the standard custodial cloud ($m_A \simeq m_{H^\pm}$)

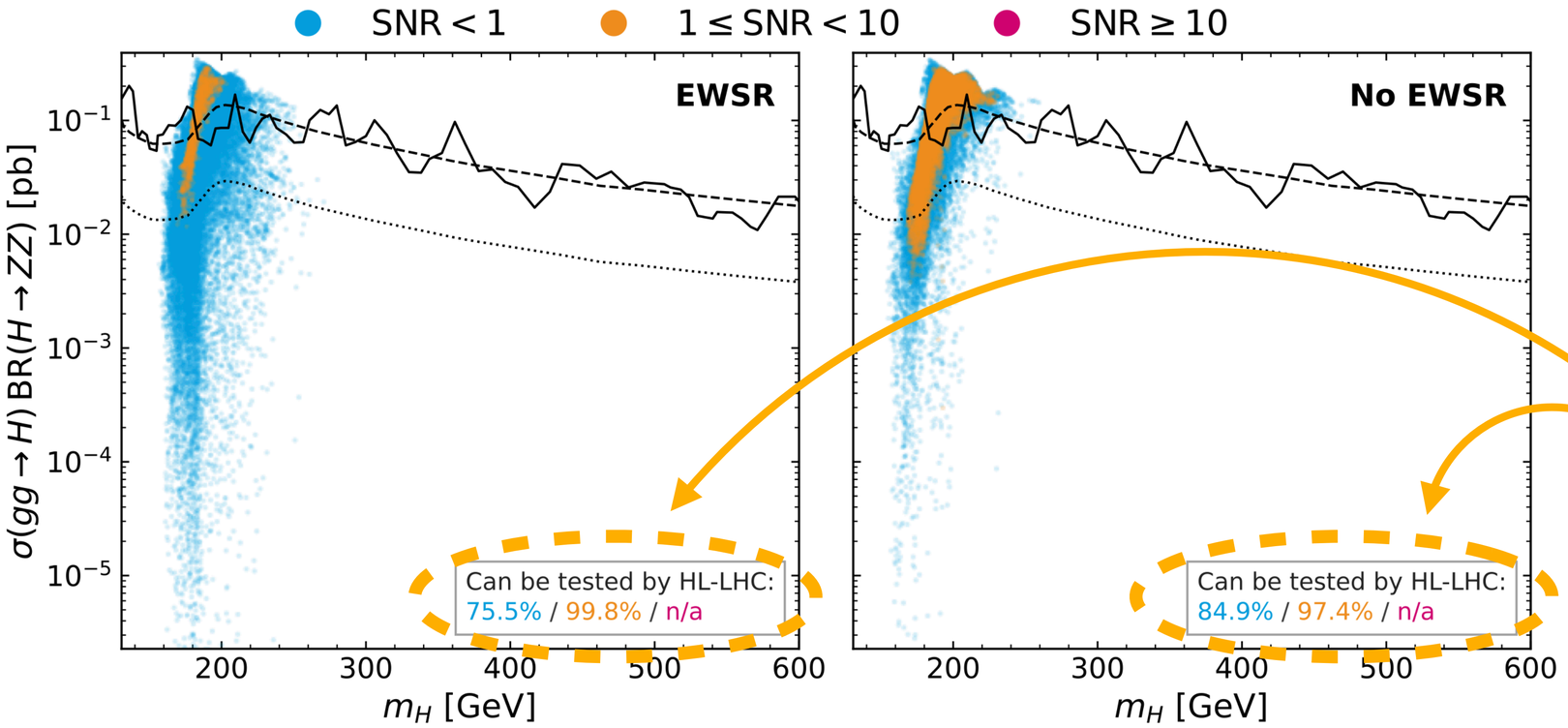


When dropping the requirement of EWSR, the parameter space opens up and we lose sensitivity at HL-LHC

* I strongly assume that the non-EWSR is a feature of the way we resum daisies (AE prescription). It would be great to look into this again in some formalism which is less awkward at large gauge couplings, allows for large-scale parameter scans, does not rely on high-T and is validated on lattice...

We did not manage to find LISA-visible points in the twisted cloud…

Collider testability of the points in the twisted custodial cloud ($m_H \simeq m_{H^\pm}$)

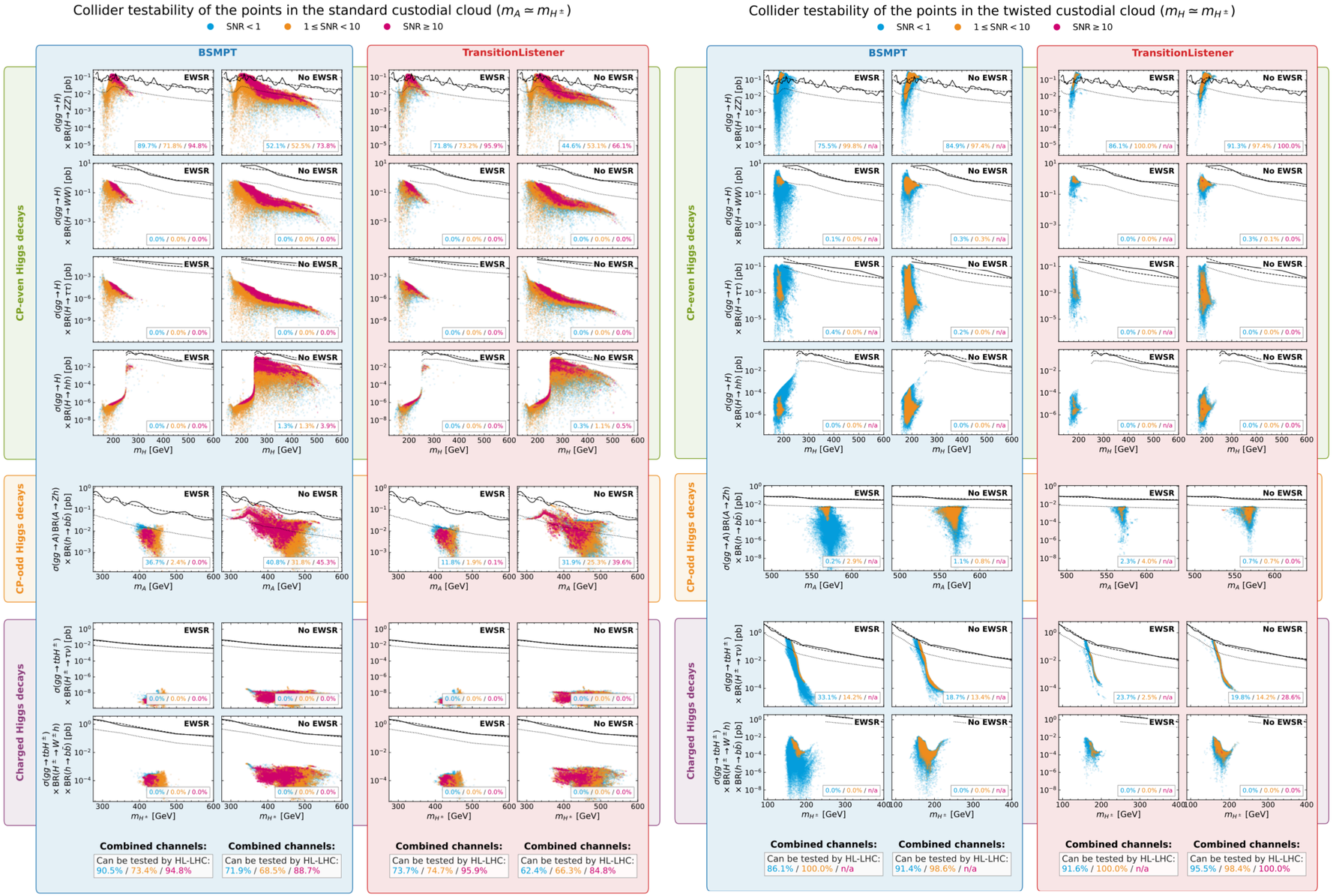


Almost all of the 1 < SNR < 10 points can be tested by HL-LHC!

The twisted cloud in general is more silent. Our *LISA is deaf* statement is trivially true.

In case you are interested in other collider signatures, the comparison of BSMPT with TransitionListener, or the wall velocity computation with WallGo check out our paper:

2608.23679



Holy grail of phase transition searches: solving the ***inverse problem*** requires precise nucleation rate predictions, robust numerics, fast samplers, understanding of astrophysics, valid GW templates, ...



TransitionListener v2.0 remains numerically stable and physically accurate under strong supercooling and large bubbles.

Strong gravitational waves from phase transitions almost always **require strong parameter tuning**, corresponding to narrow strips in model parameter space



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





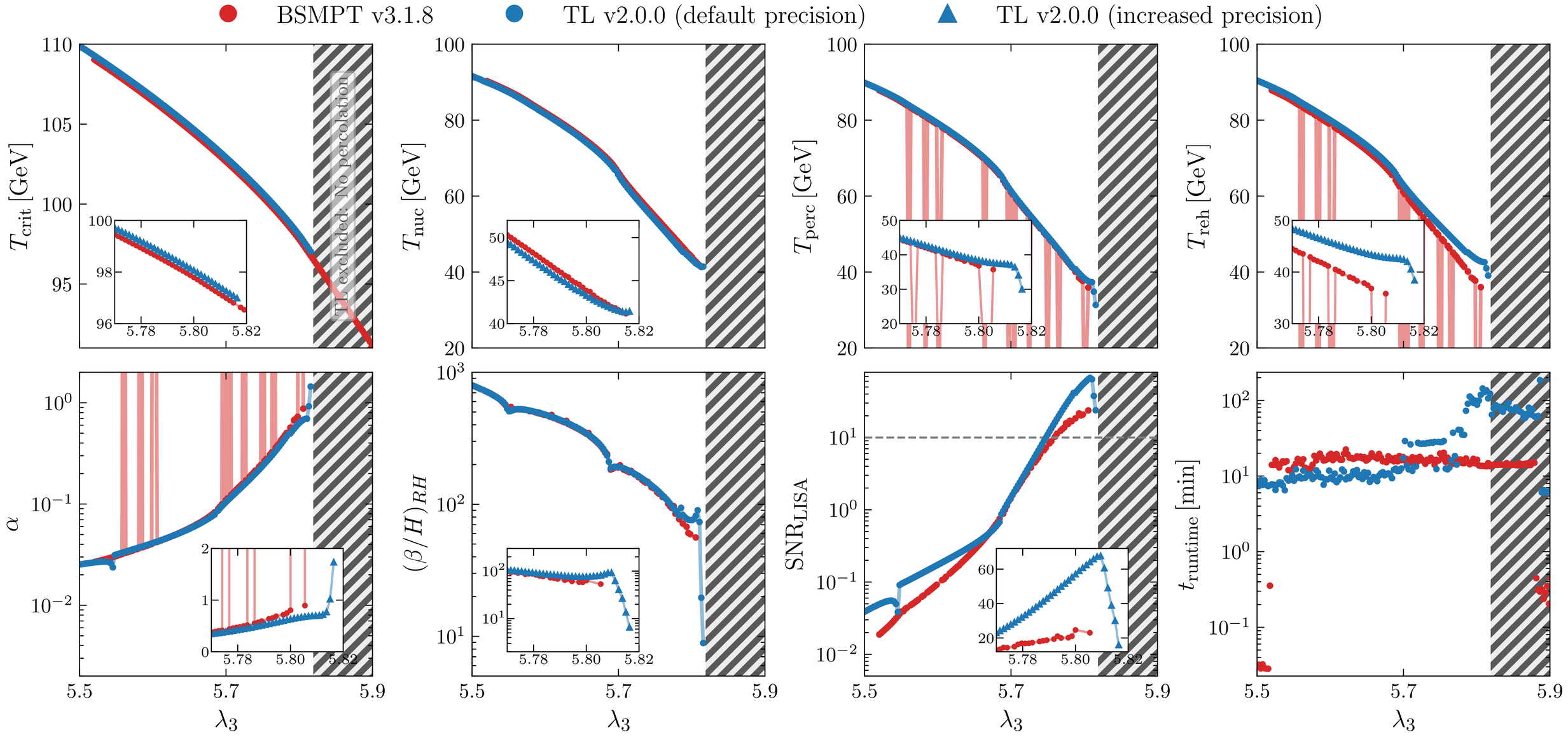
I consider the PTA searches for phase transitions also a **big playground for LISA**, since many lessons can be directly transferred there.

More work is needed on many ends: **Collider searches** around $m_H \simeq 200\,\mathrm{GeV}$, **LISA data analysis** pipeline, pheno-ready **3D EFT** for the 2HDM, understanding of **large quartics**, varying **prior choices** (e.g. $\tan\beta$), ...

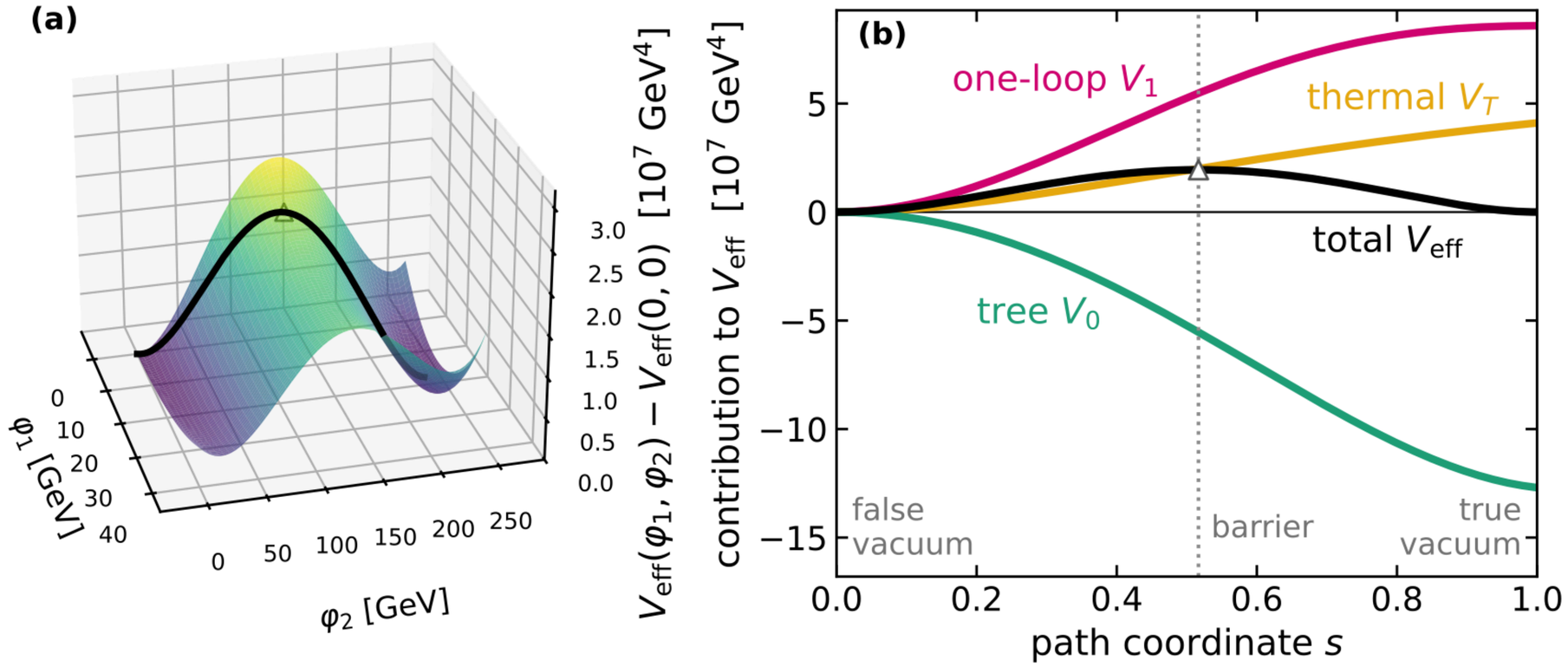


Backup slides

Comparison BSMPT vs. TransitionListener, 2HDM benchmark

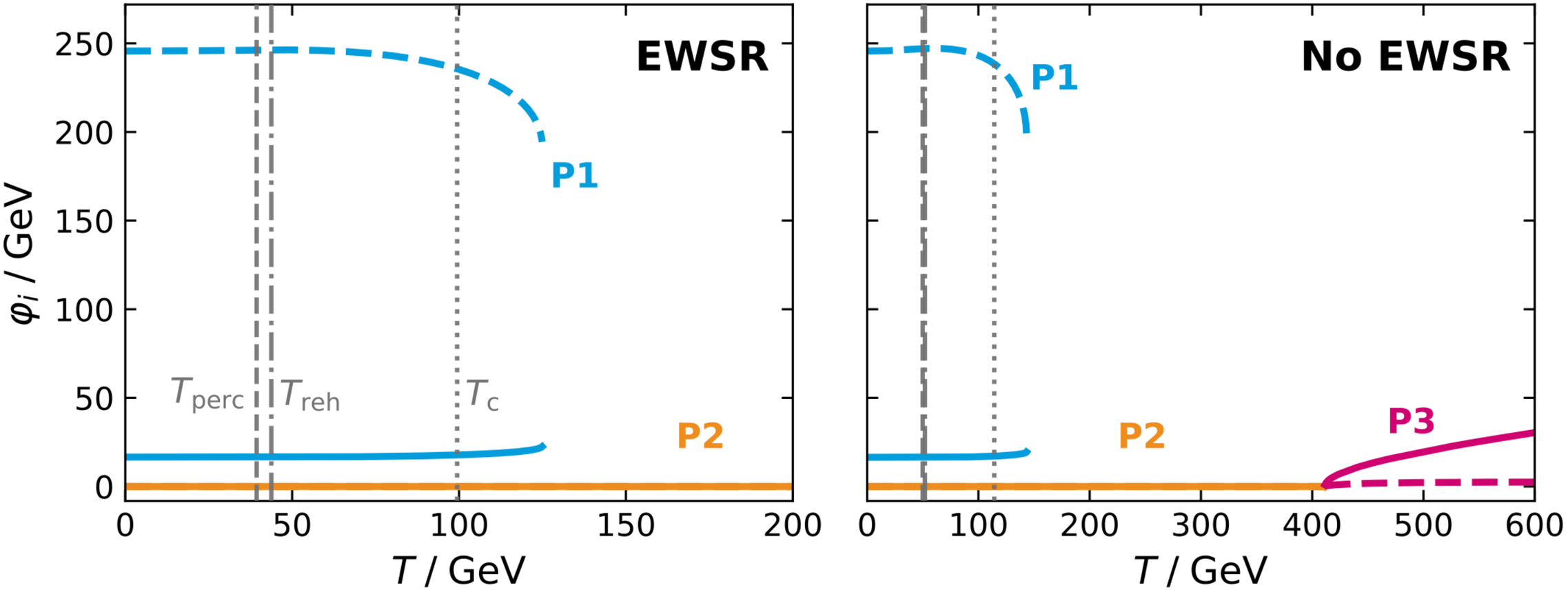


Large loop corrections are required...



Not clear yet how to treat those properly, would also persist in 3D EFT

EWSR and non-EWSR

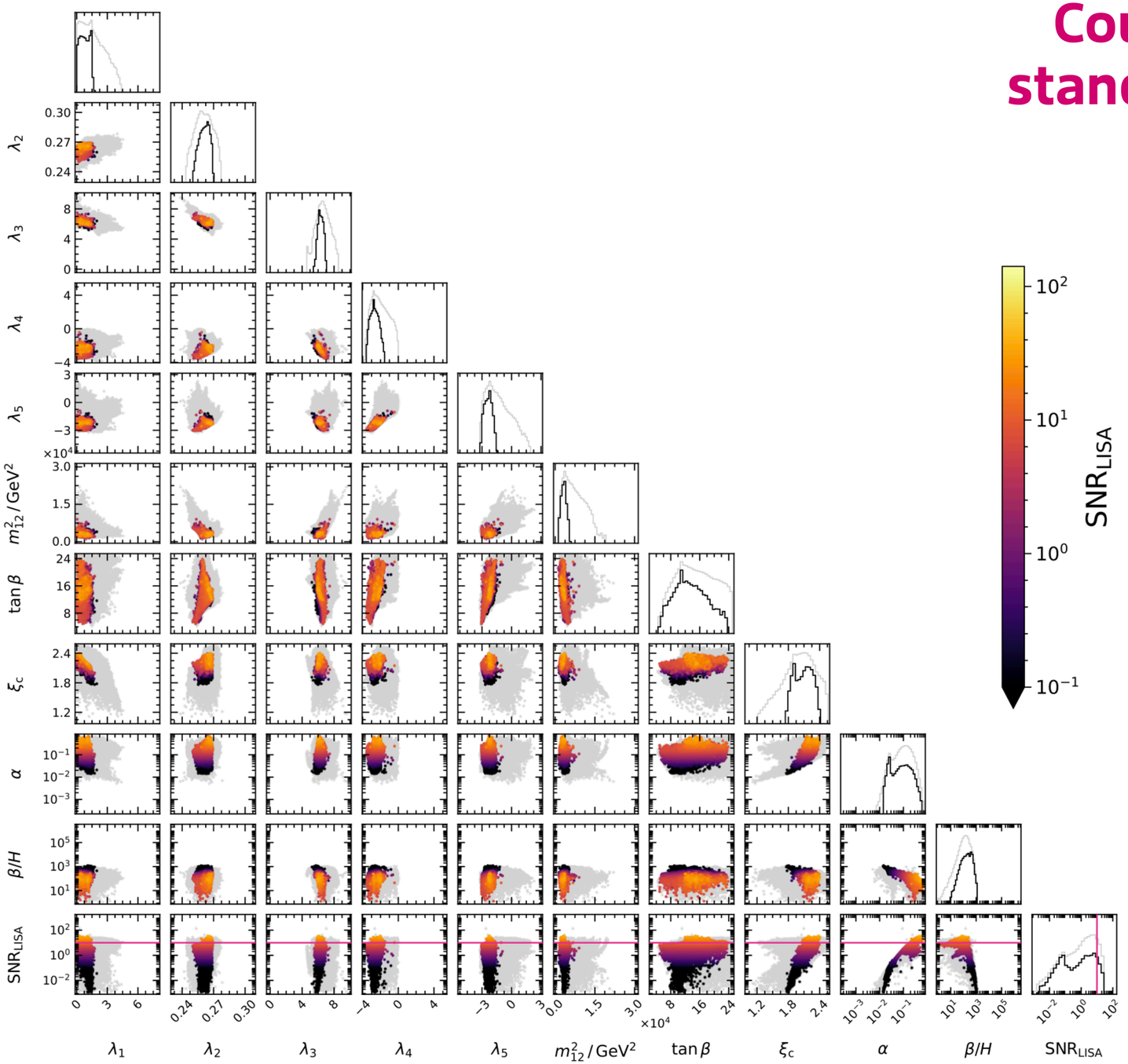


Prior choices

$$
\begin{aligned}
m_{H_a} &= 125.20\,\mathrm{GeV}, \\
m_{H_b} &\in [60,\ 1500]\,\mathrm{GeV}, \\
m_{A} &\in [60,\ 1500]\,\mathrm{GeV}, \\
m_{H^\pm} &\in [60,\ 1500]\,\mathrm{GeV}, \\
c_{HbVV} &\in [-0.3,\ 0.3], \\
\tan\beta &\in [0.8,\ 25], \\
m_{12}^2 &\in [10^{-3},\ 10^{5}]\,(\mathrm{GeV})^2
\end{aligned}
$$

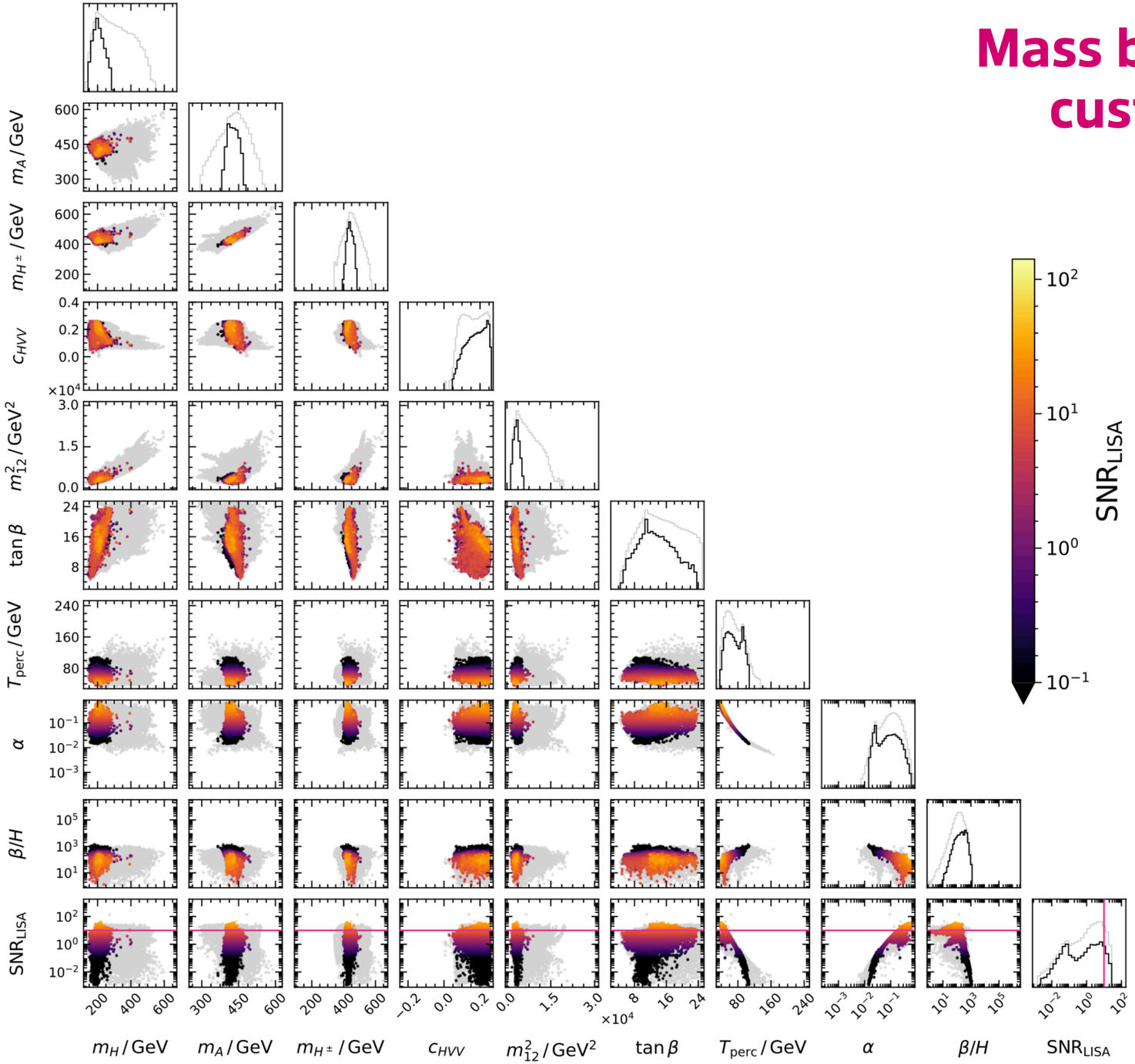
Corner plots

Coupling basis, standard custodial cloud



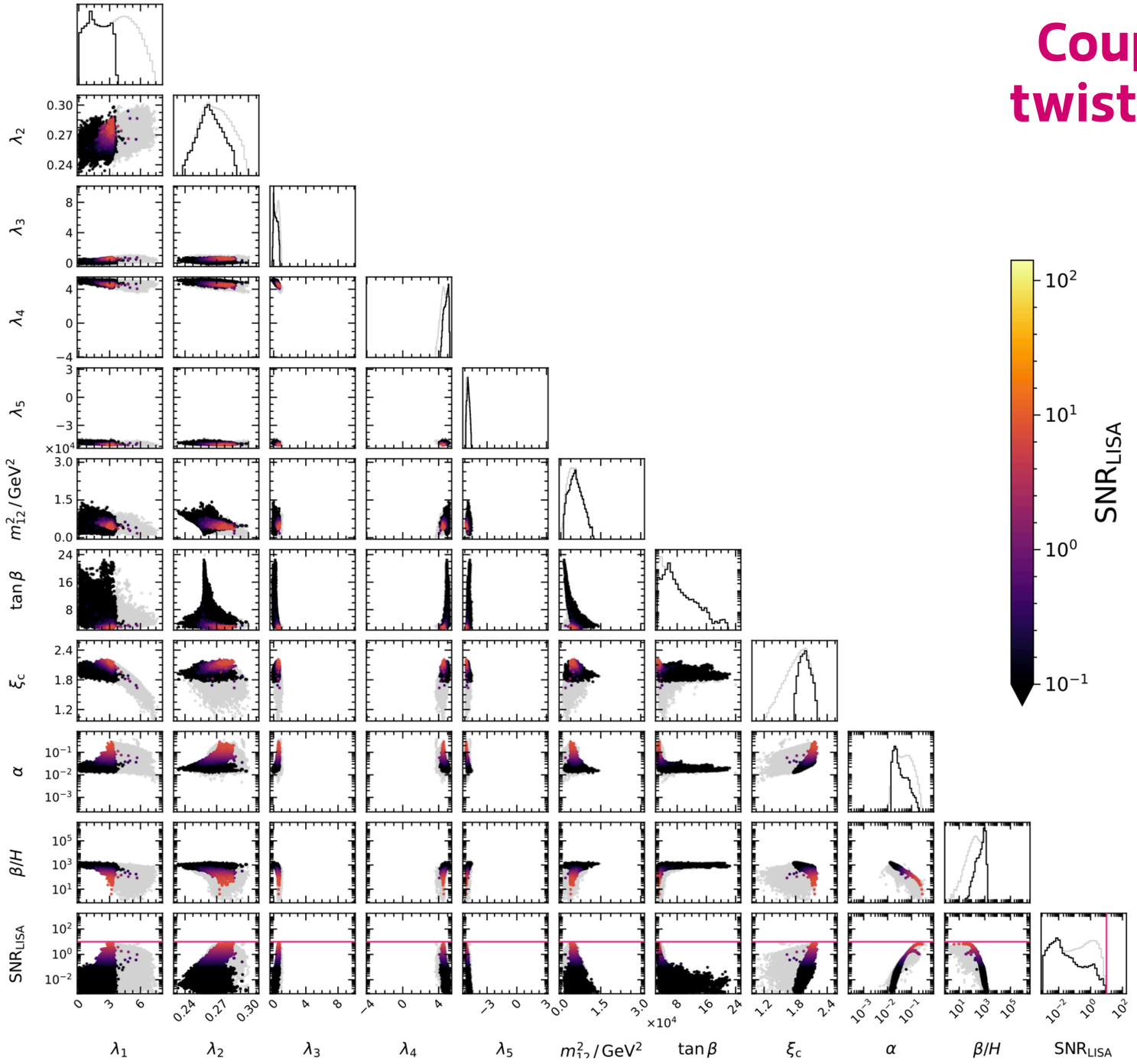
Corner plots

Mass basis, standard custodial cloud



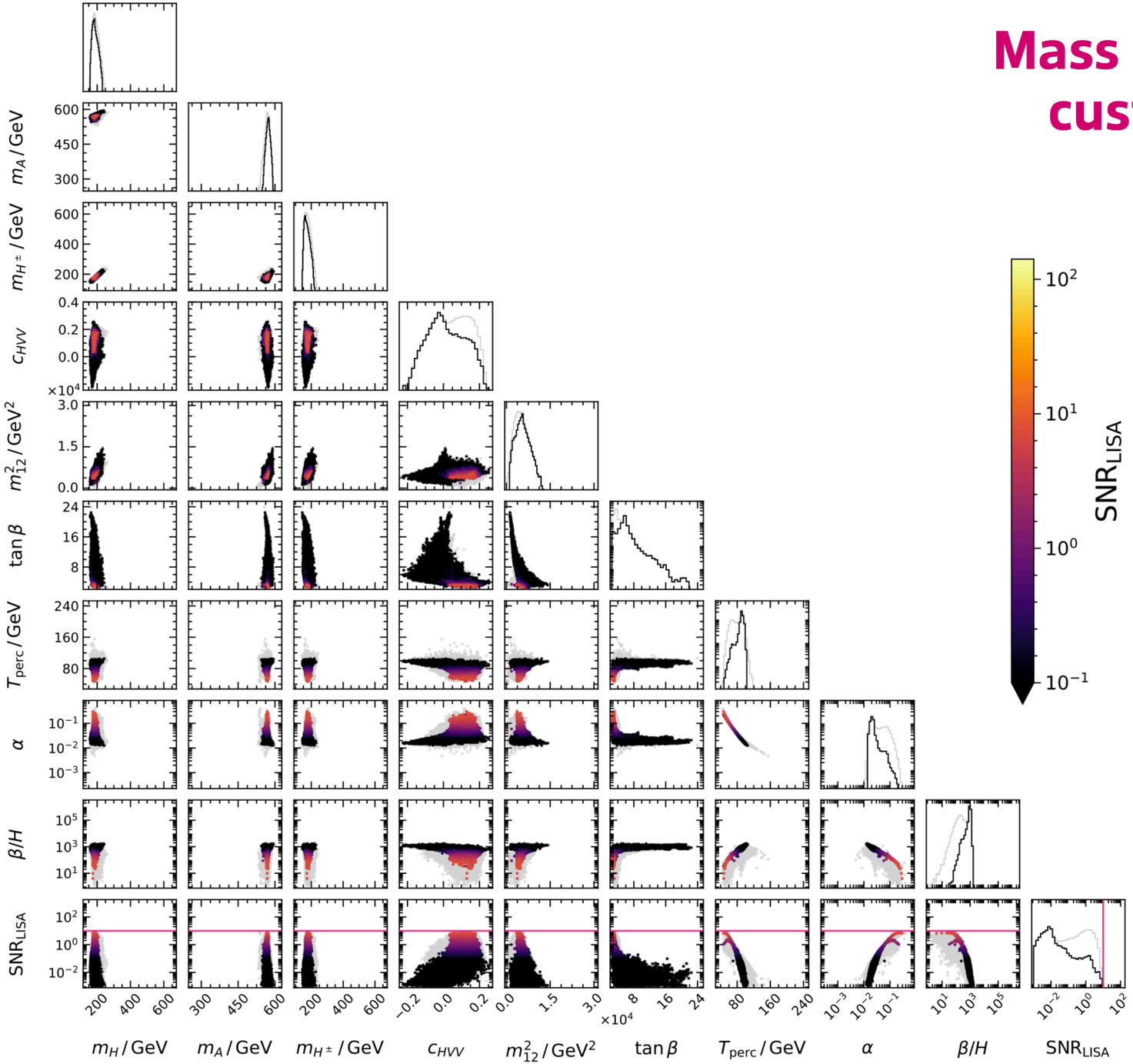
Corner plots

Coupling basis, twisted custodial cloud



Corner plots

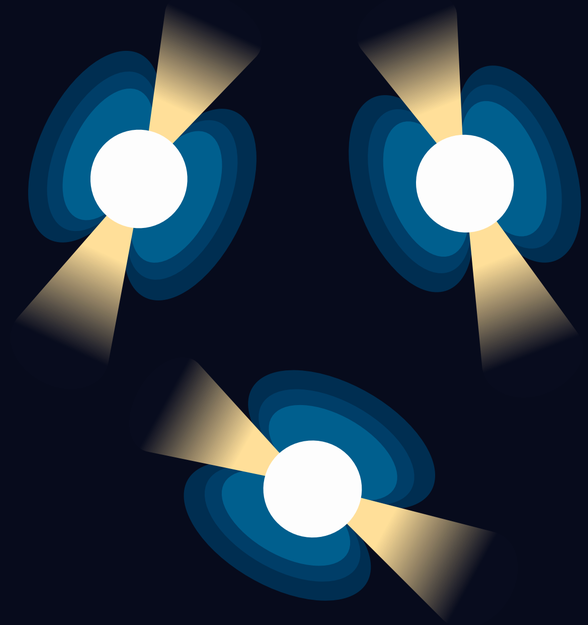
Mass basis, twisted custodial cloud



The working principle of a pulsar timing array



Galactic millisecond pulsars



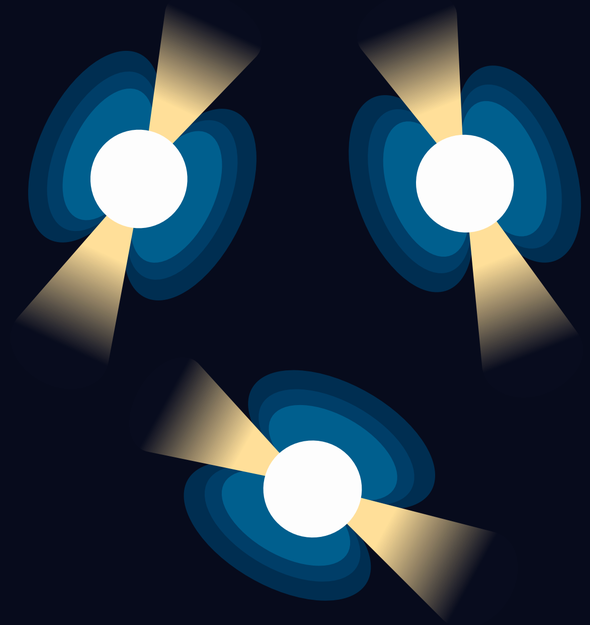
The working principle of a pulsar timing array

Galactic millisecond pulsars



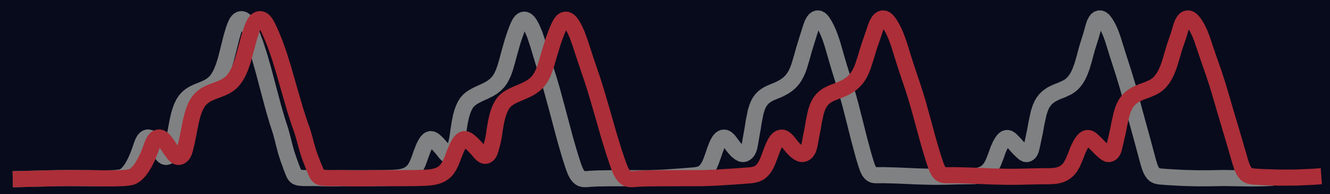


Pulses expected
from timing model



The working principle of a pulsar timing array

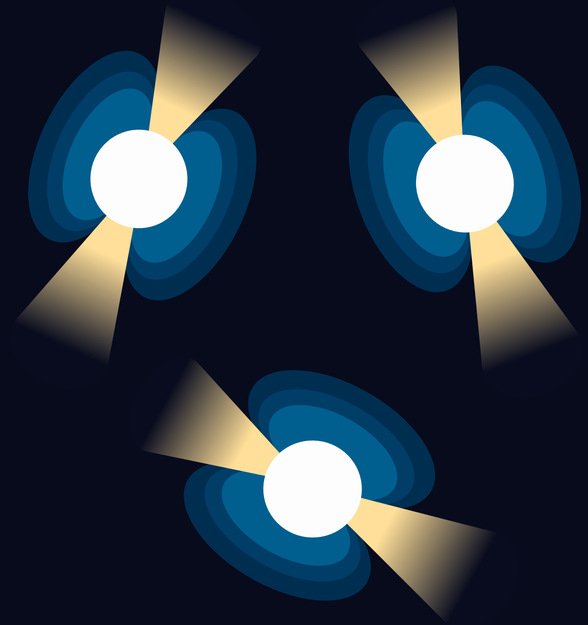




Pulses expected from timing model

Pulses recorded by radio telescopes

Galactic millisecond pulsars

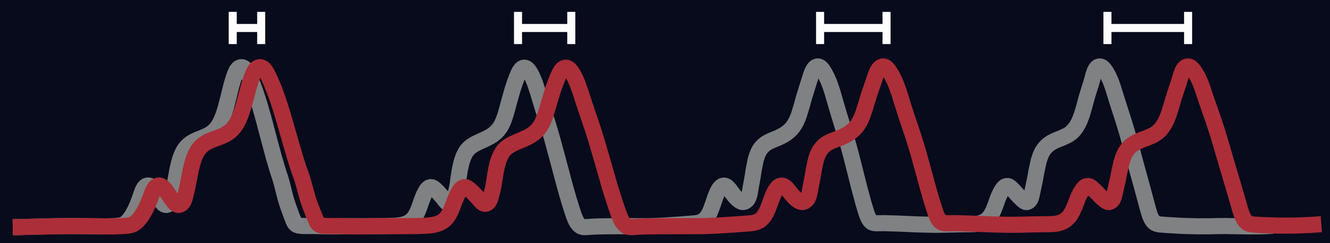


The working principle of a pulsar timing array

Galactic millisecond pulsars

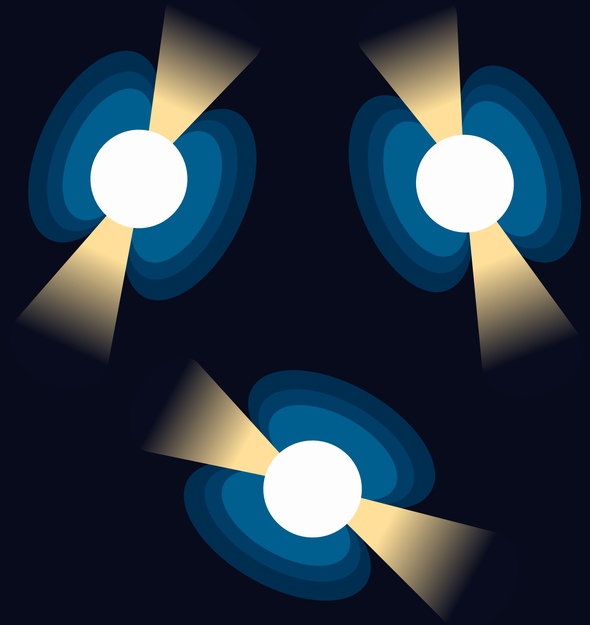


Timing residuals δt



Pulses expected from timing model

Pulses recorded by radio telescopes

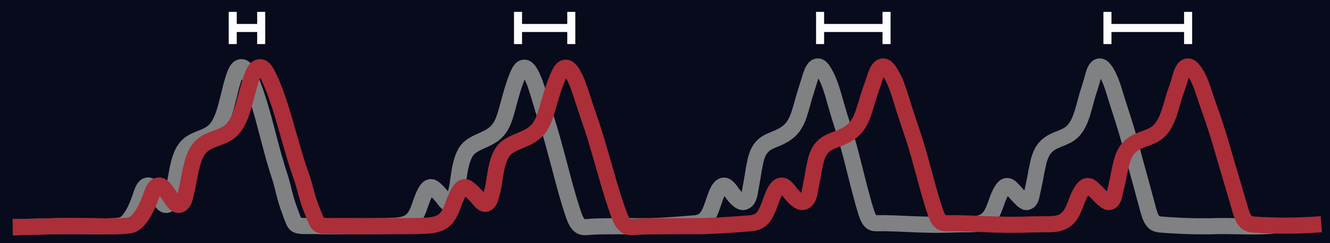


The working principle of a pulsar timing array

Galactic millisecond pulsars

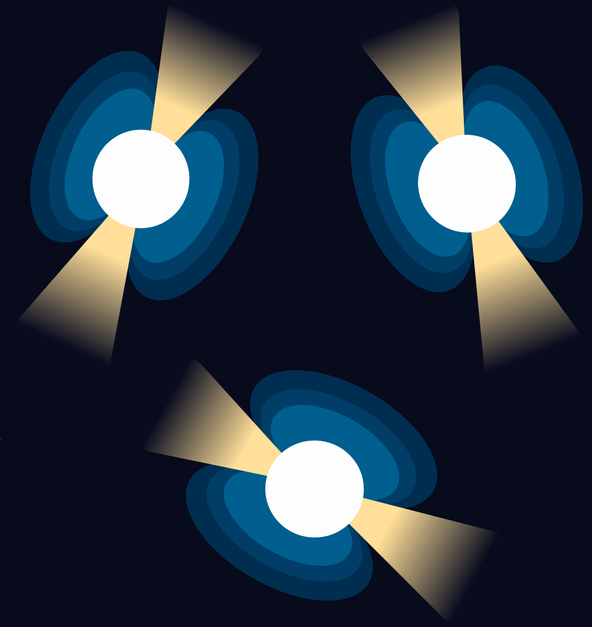


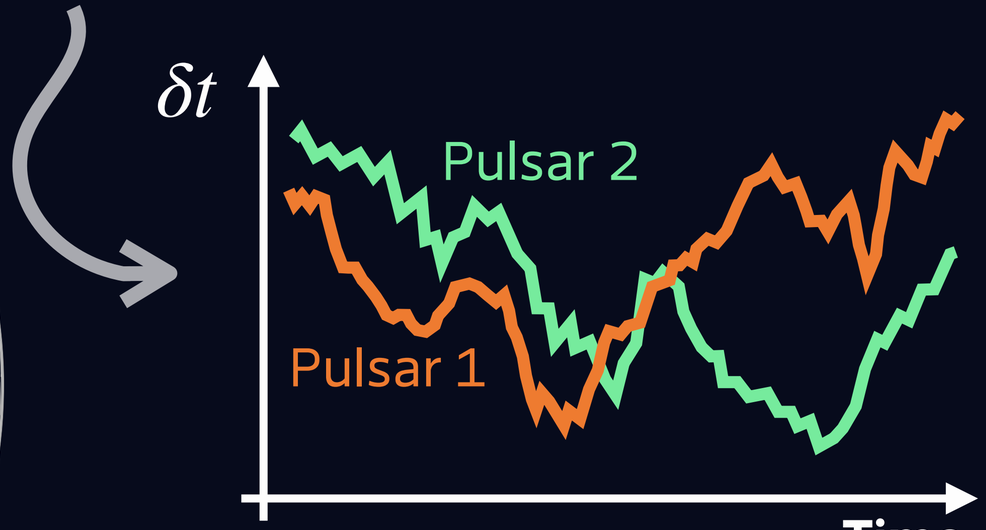
Timing residuals δt



Pulses expected from timing model

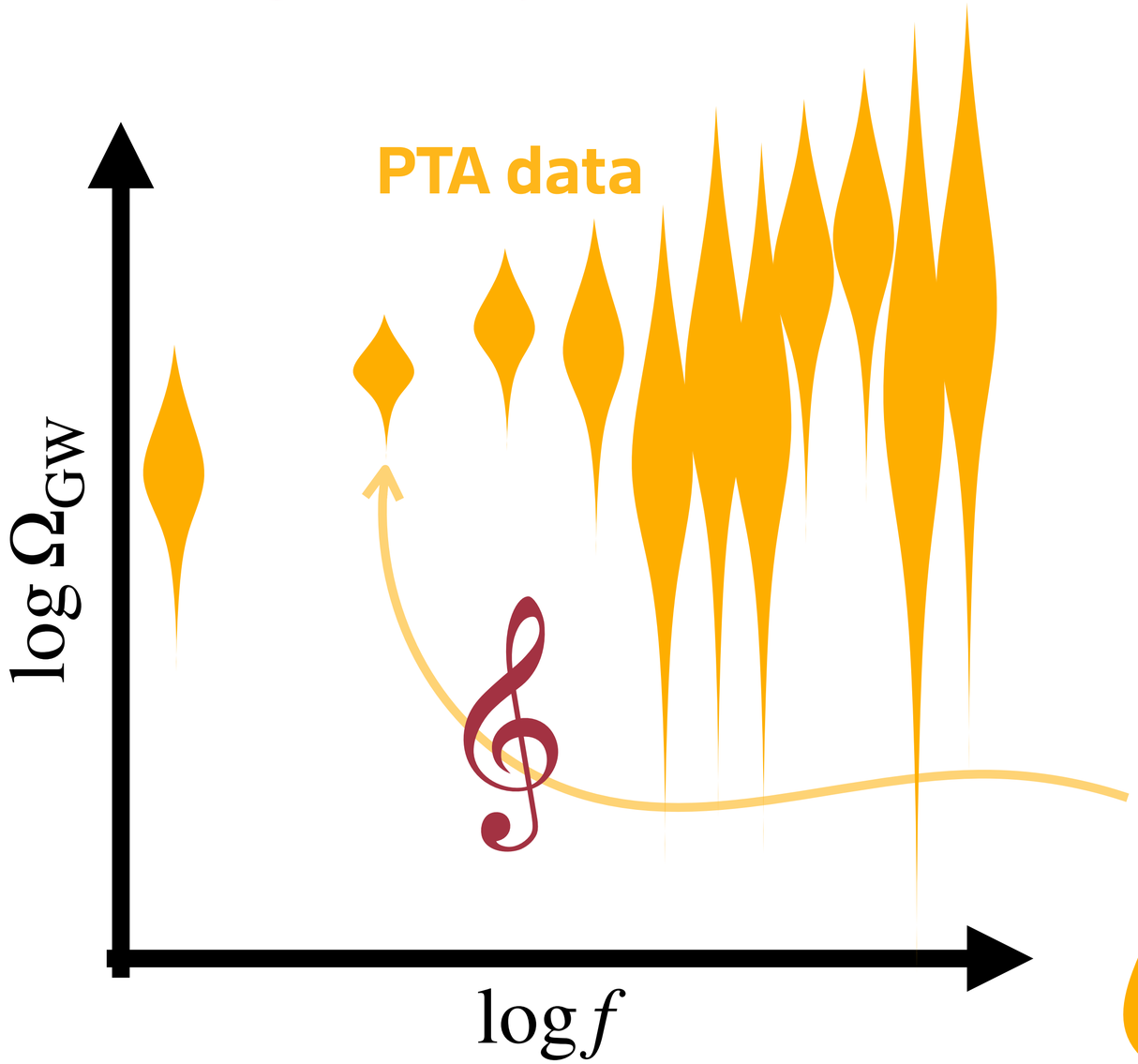
Pulses recorded by radio telescopes





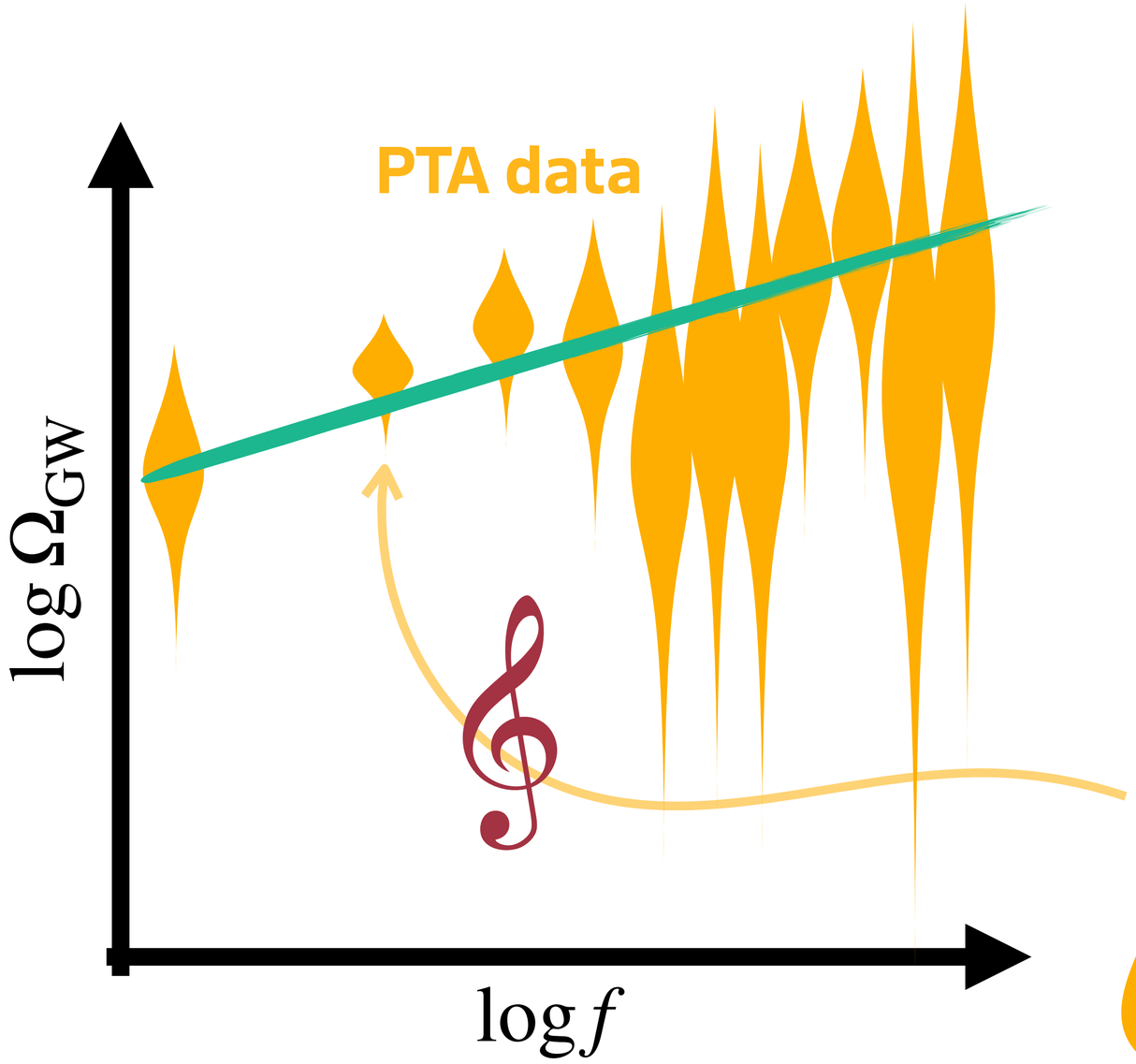
A gravitational wave backgrounds imprints itself in the common evolution of the timing residuals over time

Learning to play the violin



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

Learning to play the violin

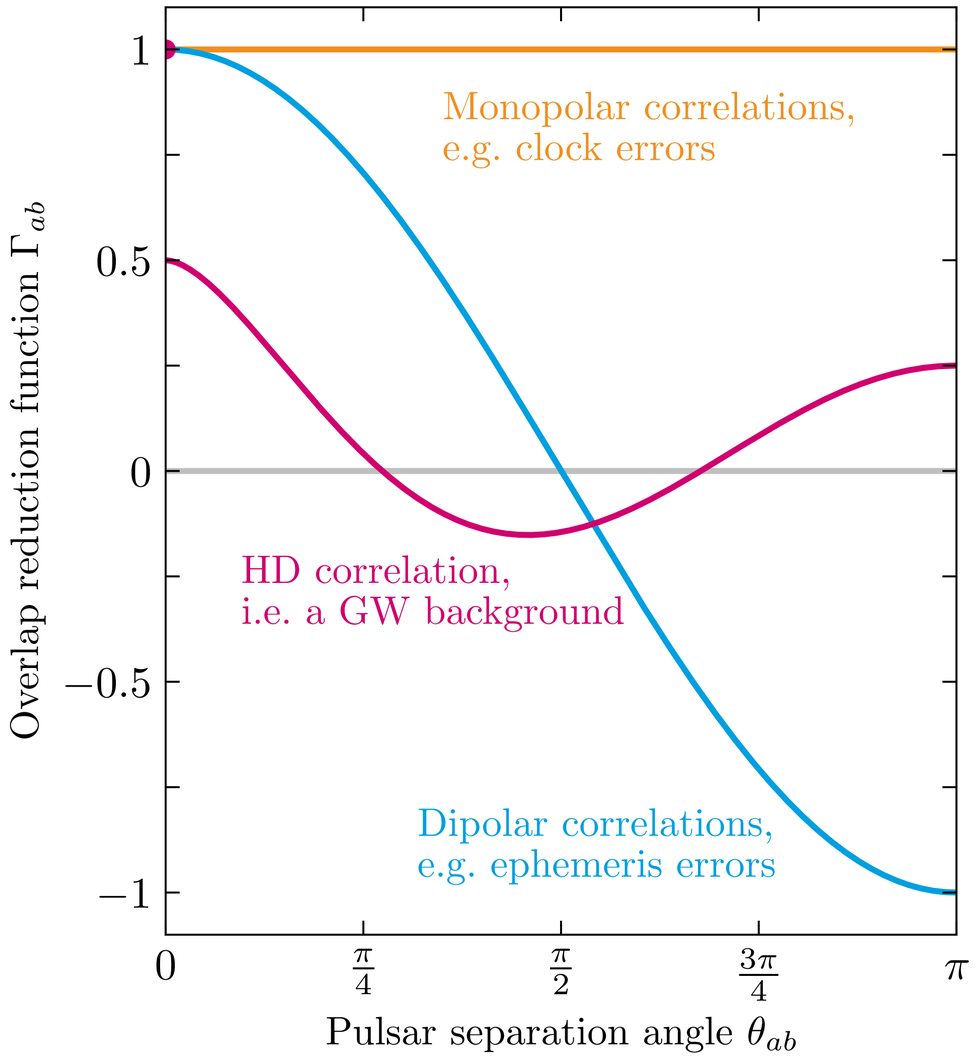


The inferred spectral shape of the GWB is to first approximation a power law

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

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

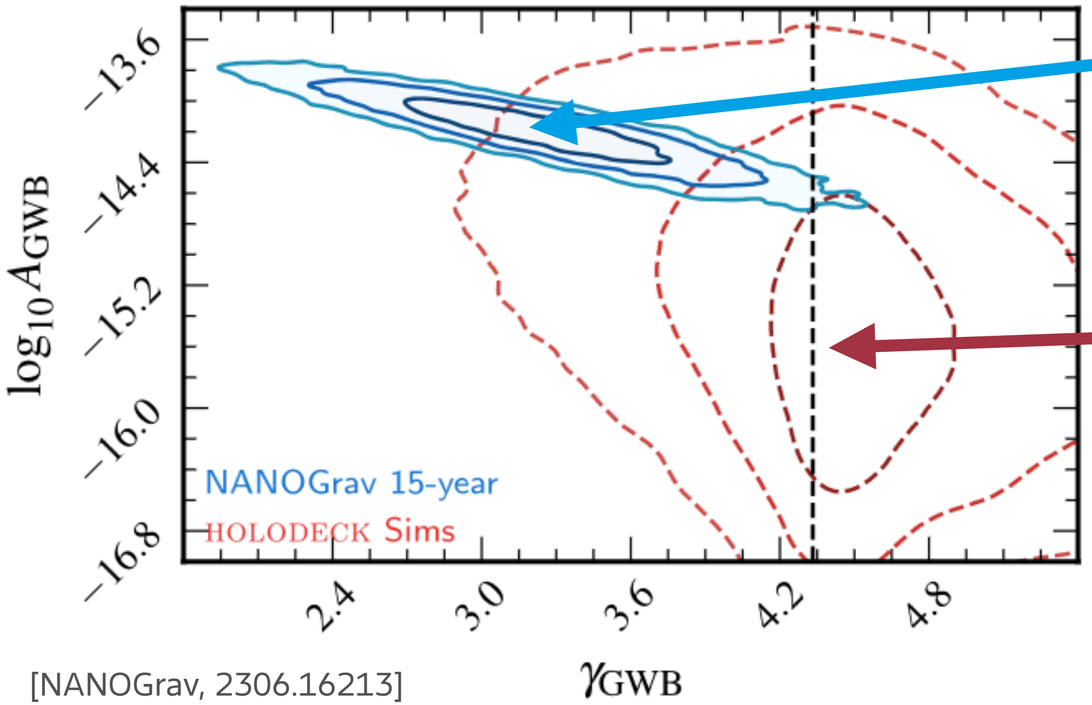


- PTAs found an underlying „common red process“ among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves, Clock errors, Ephemeris errors:
    All ruled out with $>5\sigma$ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]



Next IPTA data release should reach 5σ GW detection!

Merging supermassive black holes



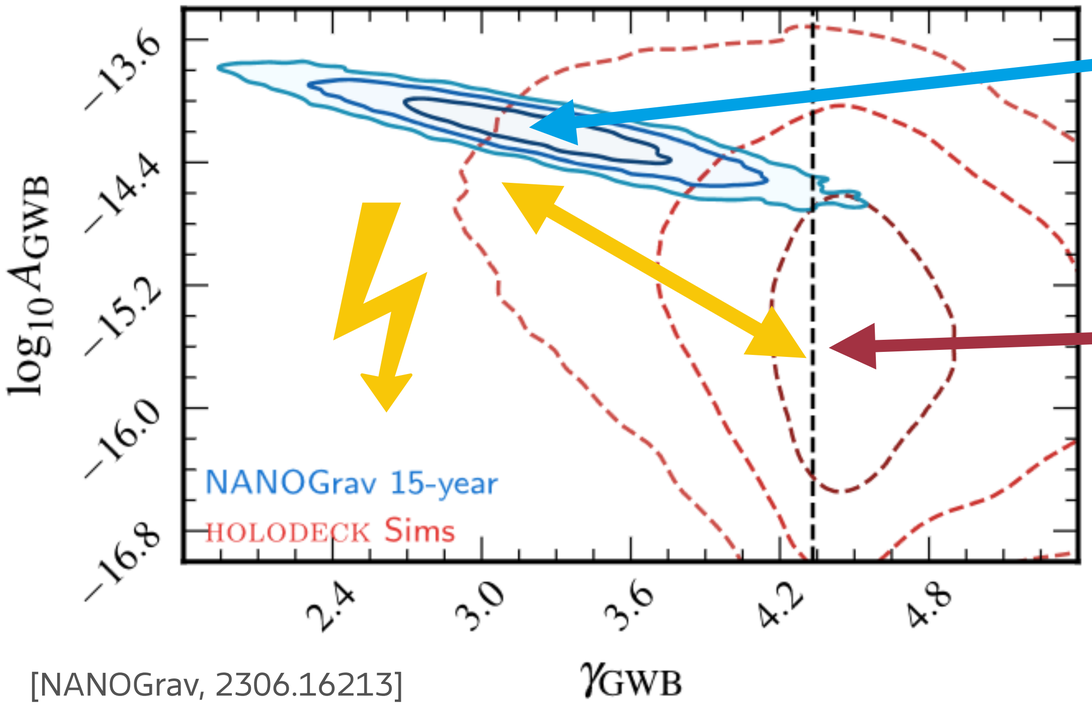
[NANOGrav, 2306.16213]

Observed signal roughly 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)

* 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]

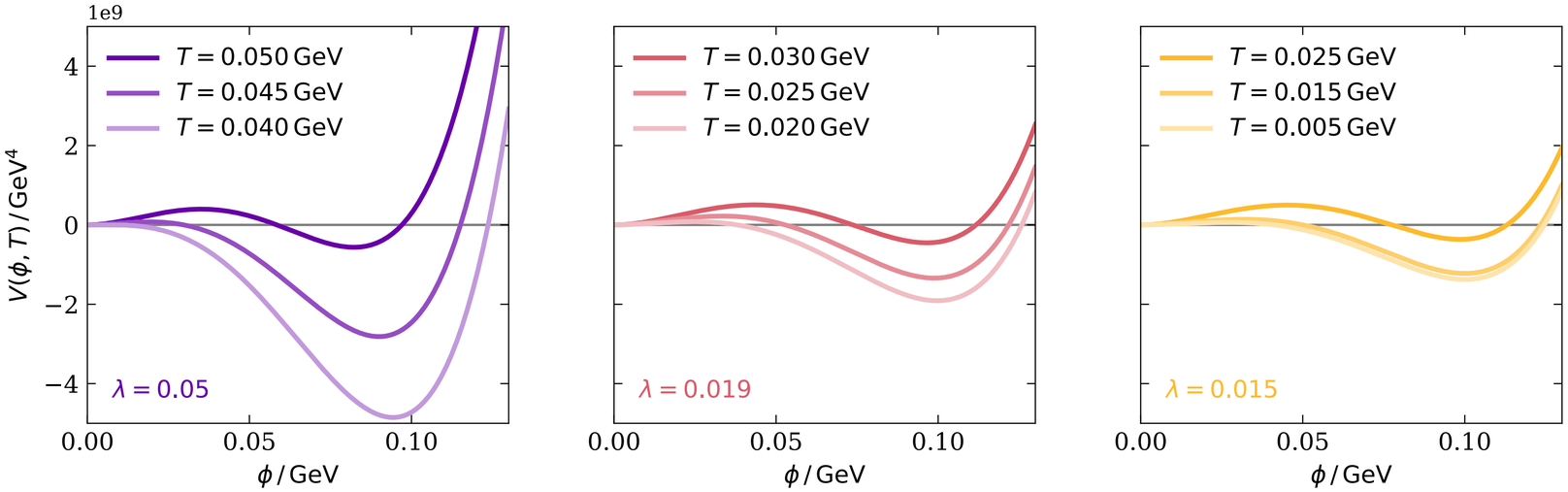
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Are there other signal sources?

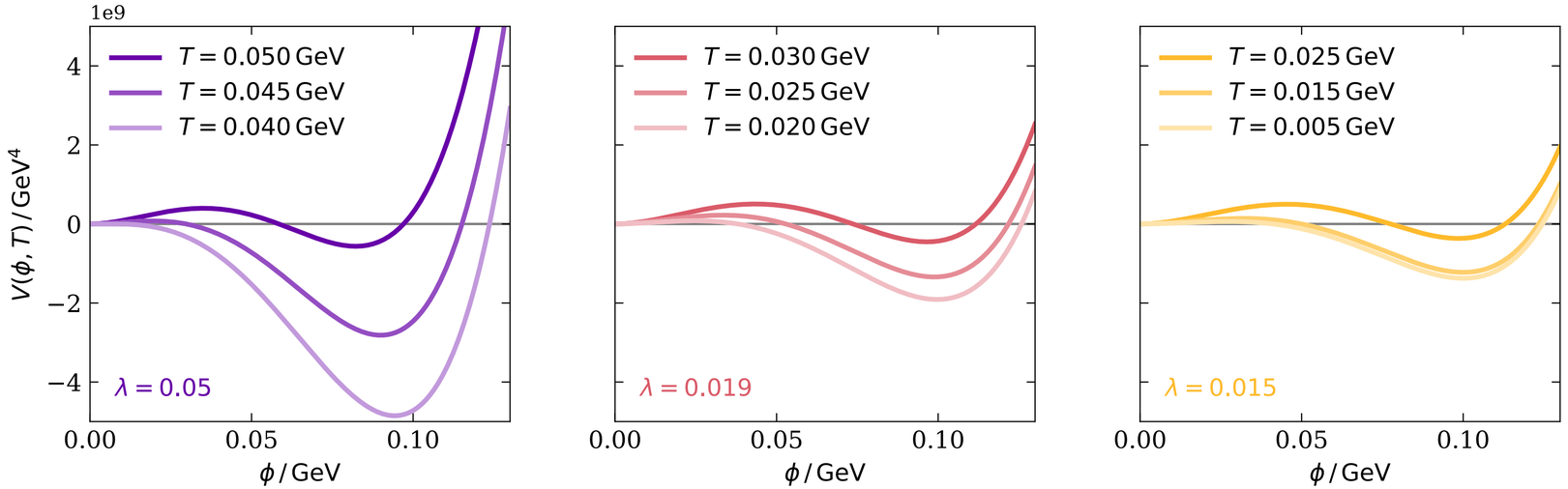
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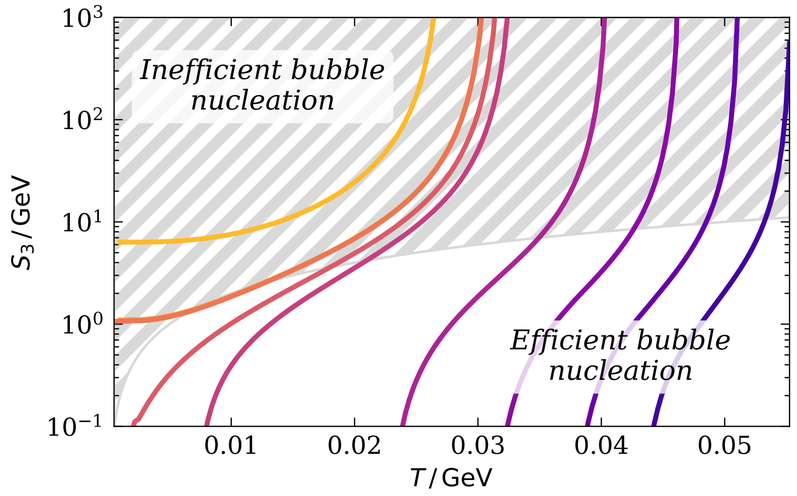
Large bubbles in the Abelian dark Higgs model



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

Large bubbles in the Abelian dark Higgs model



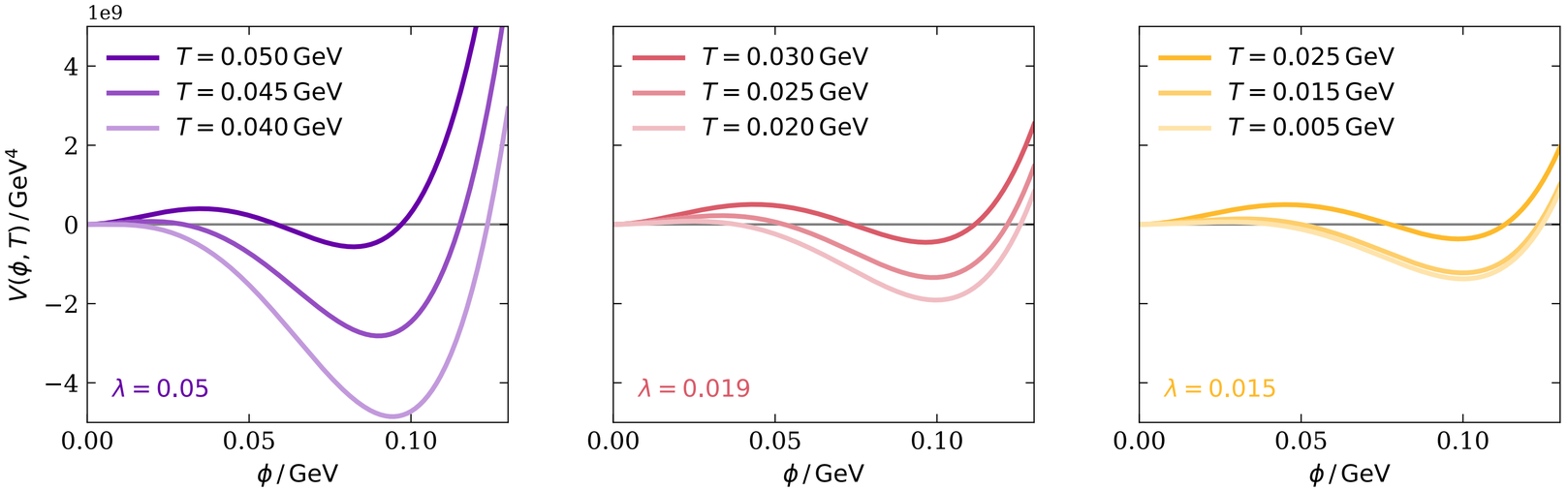


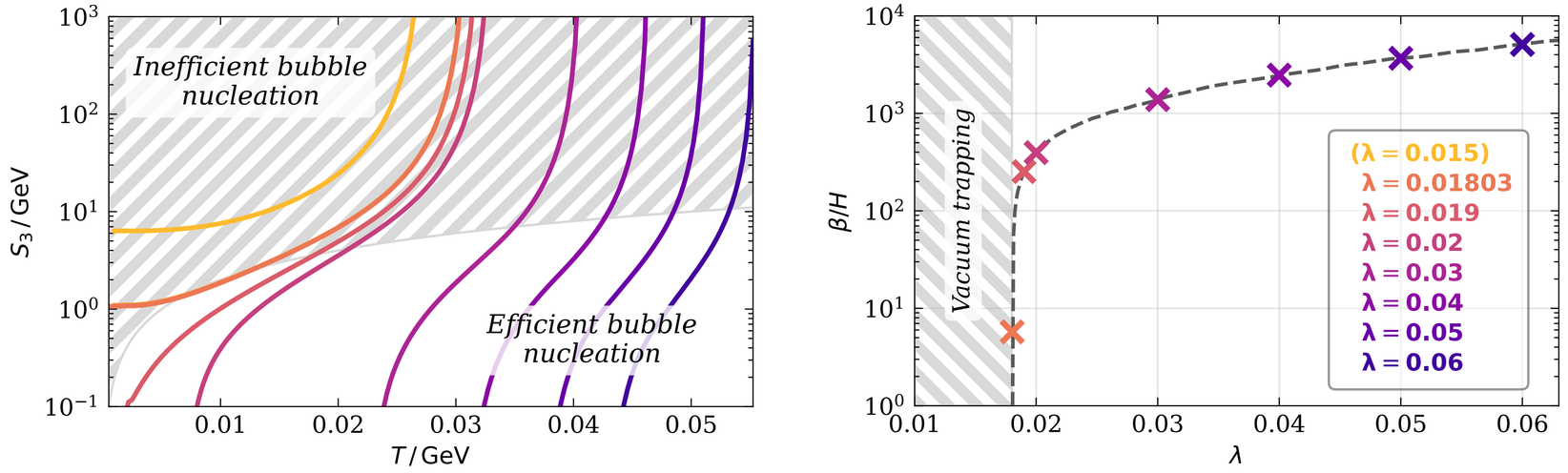
Benchmark point: $g = 1$, $v = 100\,\mathrm{MeV}$

The transition rate is exponentially dependent on the bounce action

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

Large bubbles in the Abelian dark Higgs model





The transition rate is exponentially dependent on the bounce action

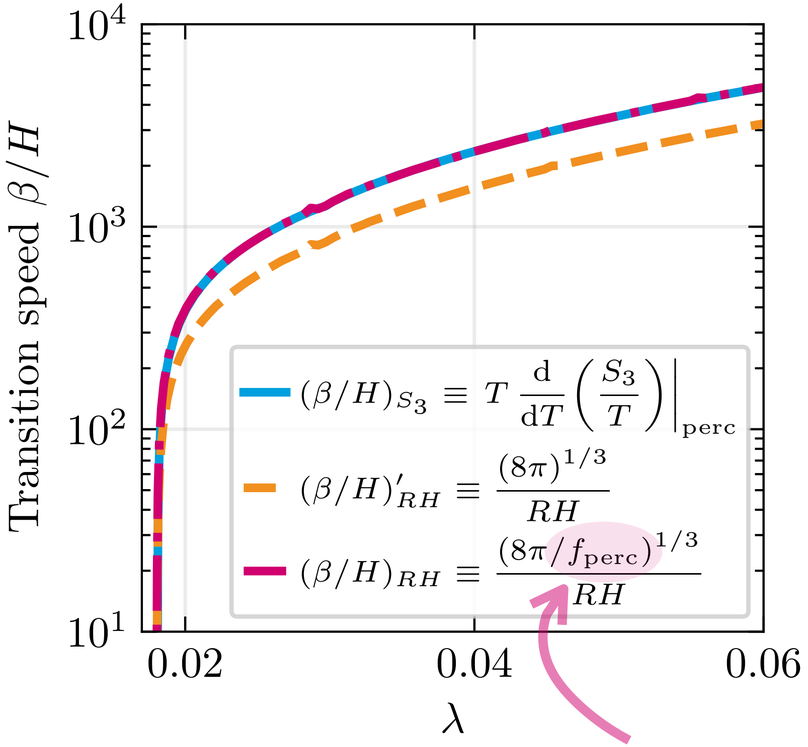
$$\Gamma \propto e^{-S_3/T}$$

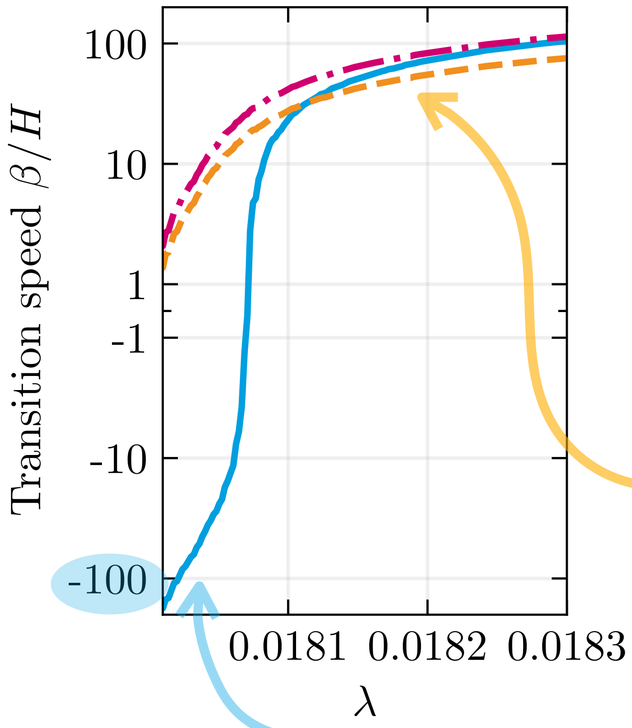
Only for fine-tuned quartic couplings λ, large bubbles can be achieved! Generically,

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

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]