Explaining the PTA signal and dark matter with a conformal dark sector

DESY theory workshop, September 24th 2025

Carlo Tasillo,
Uppsala University

Based on work with Sowmiya Balan, Torsten Bringmann, Frederik Depta, Felix Kahlhöfer, Thomas Konstandin, Jonas Matuszak, and Kai Schmidt-Hoberg

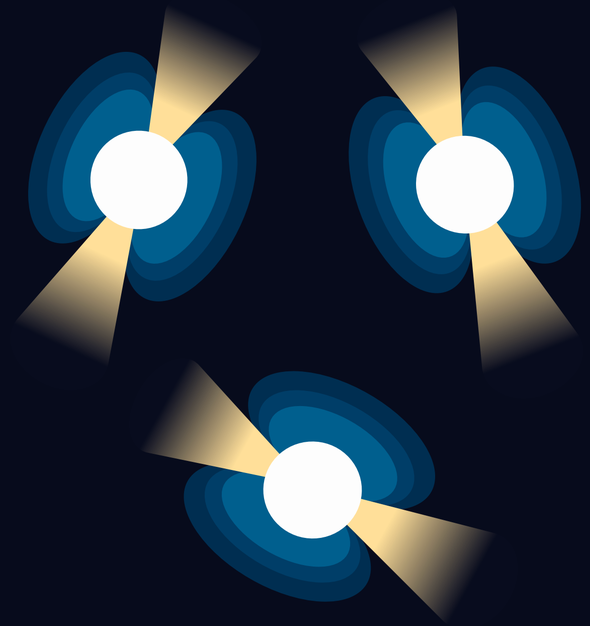
JCAP 11 (2023) 053 and
JCAP 08 (2025) 062

UPPSALA UNIVERSITET

At Last, There's
A globe-spa
Astronomers detect 'cosmic bass note' of gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists
Scientists 'hear' cosmic hum from gravitational waves
Gravitational
Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe
Scientists have observed for the first time the faint ripples caused by the motion of holes that are gently stretching and squeezing everything in the universe
The New York Times
ack H
Galax
Space
Gravitational wave
at the center of the M
Scientists r
come from c
holes
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find
Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.
t may
massive black
of Low-Frequen
e the waves, wh
Scientists observed for the first time faint ripples caused by the motion of black
ing everything in the universe.
ASTROPHYSICS
A Background 'Hum' Pervades the Universe. Scientists Are Racing to Find Its Source
Astronomers are now seeking to pinpoint the origins of an exciting new form of gravitational waves that was announced earlier this year
Gravi
d from pai
Astro
vitationa
SCIENCE
Colossal gravitational waves—trillions of miles long—found for the first time
by studying rapidly spinning dead
giant ripples of spacetime likely
from merging supermassive black holes—
The Washington Post
Democracy Dies in Darkness
In a major discovery, scientists say space-time churns like a choppy sea
The mind-bending finding suggests that everything around us is constantly being roiled by low-frequency gravita
waves
For first time ever, scientists "hear" gravitational waves rippling through the universe
First Evidence of Giant Gravitational Waves Thrills Astronomers
re tuning in to a never-before-seen type of gravitational
pawned by pairs of supermassive black holes
rs used dead stars to
w form of ripple in
Monster gravitational
spotted for first
ntists discover that universe is a
gravitational waves
-time ripples
king gravitational wave
lock our
teries
Ground
disco
Univ
The results are
background, a hum o
Universe.
Physics
Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe

The working principle of a pulsar timing array

Galactic millisecond pulsars



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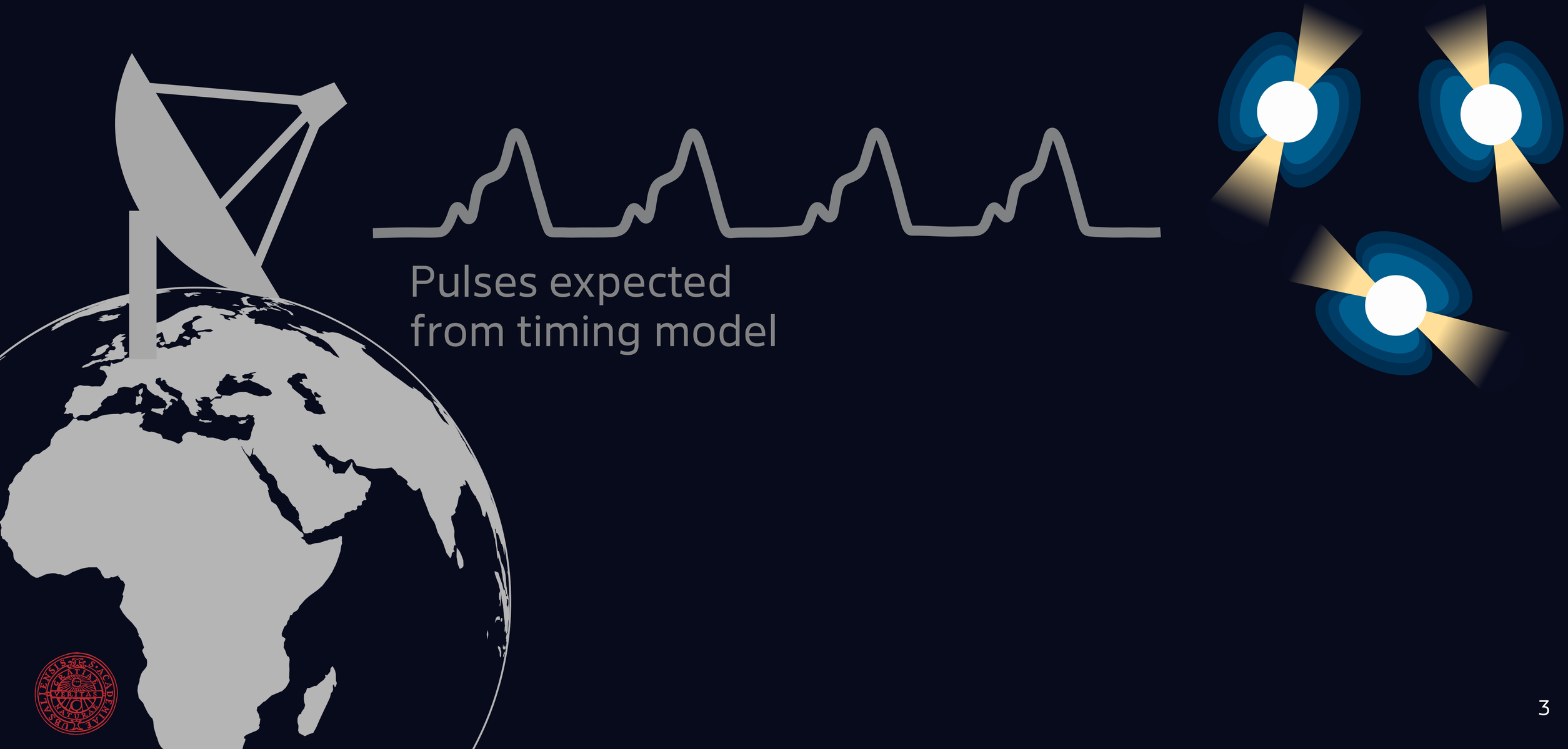

Pulses expected
from timing model

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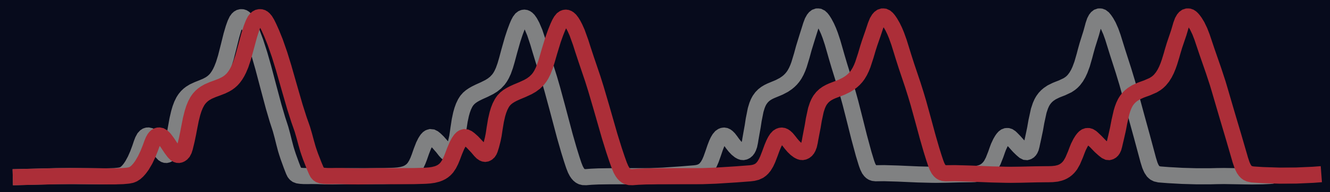
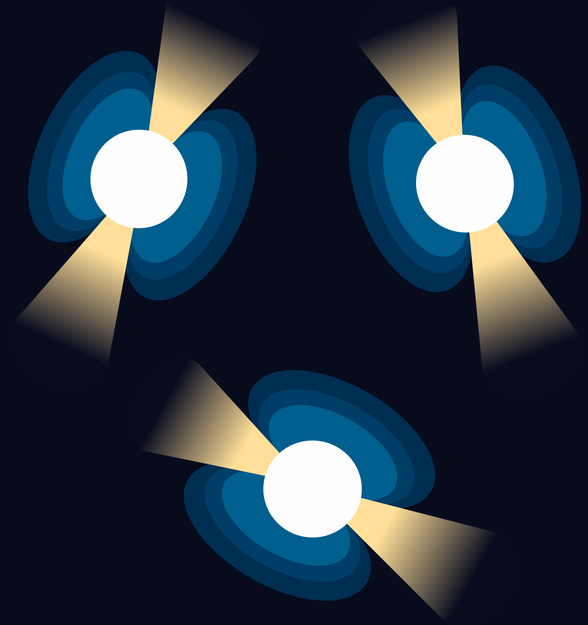


Pulses expected from timing model

Pulses recorded by radio telescopes



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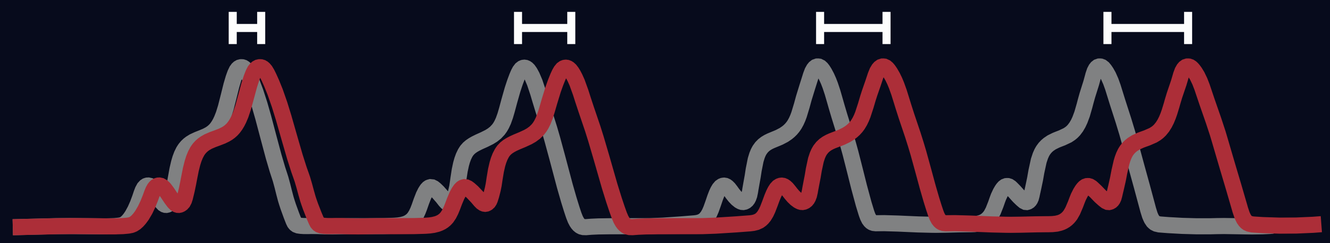
Timing residuals δt



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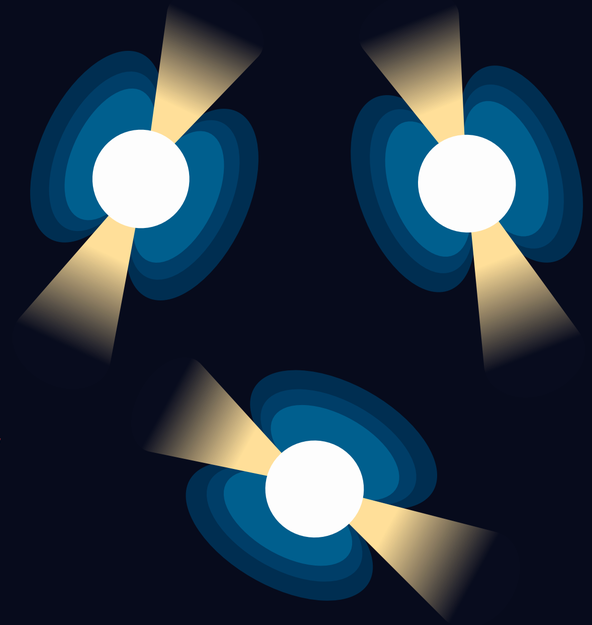

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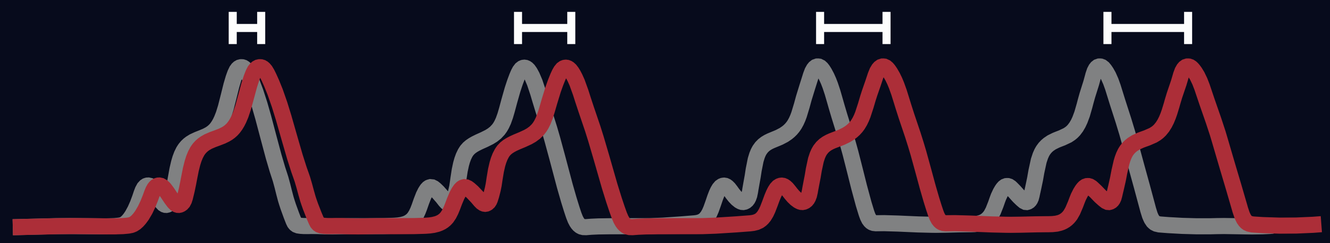

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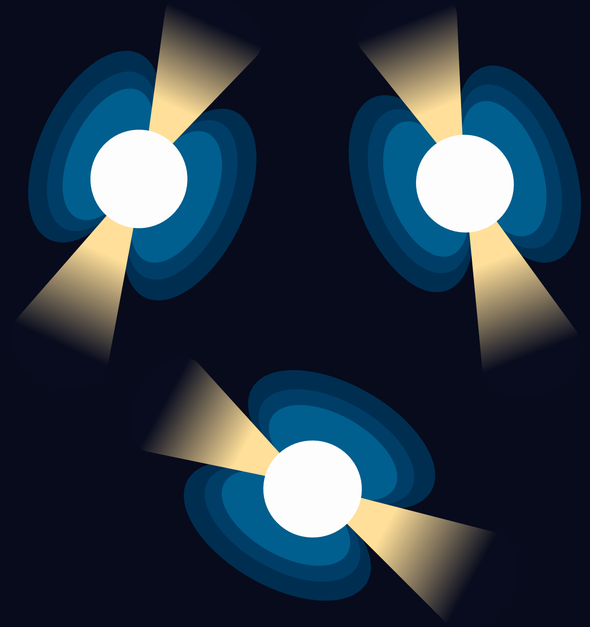
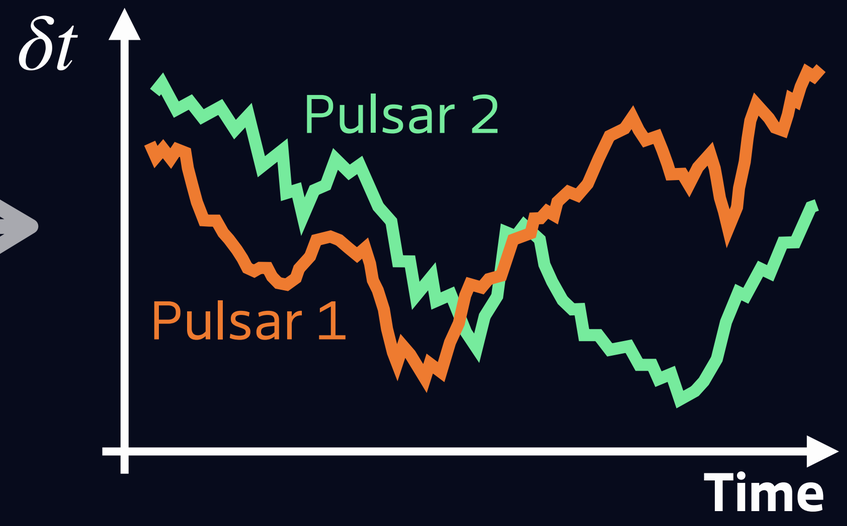
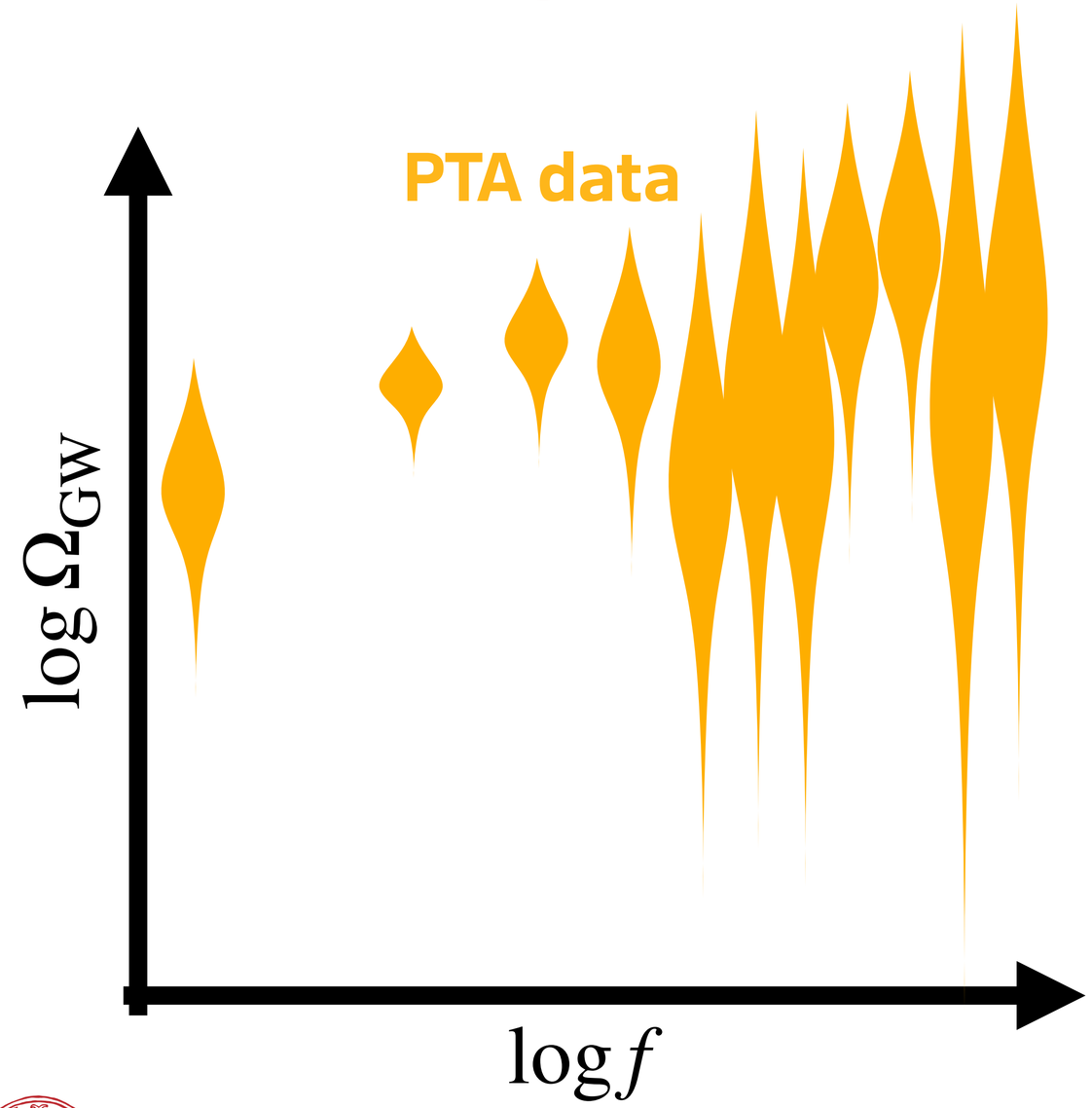




A gravitational wave backgrounds imprints itself in the common evolution of the timing residuals over time

The observed gravitational wave spectrum



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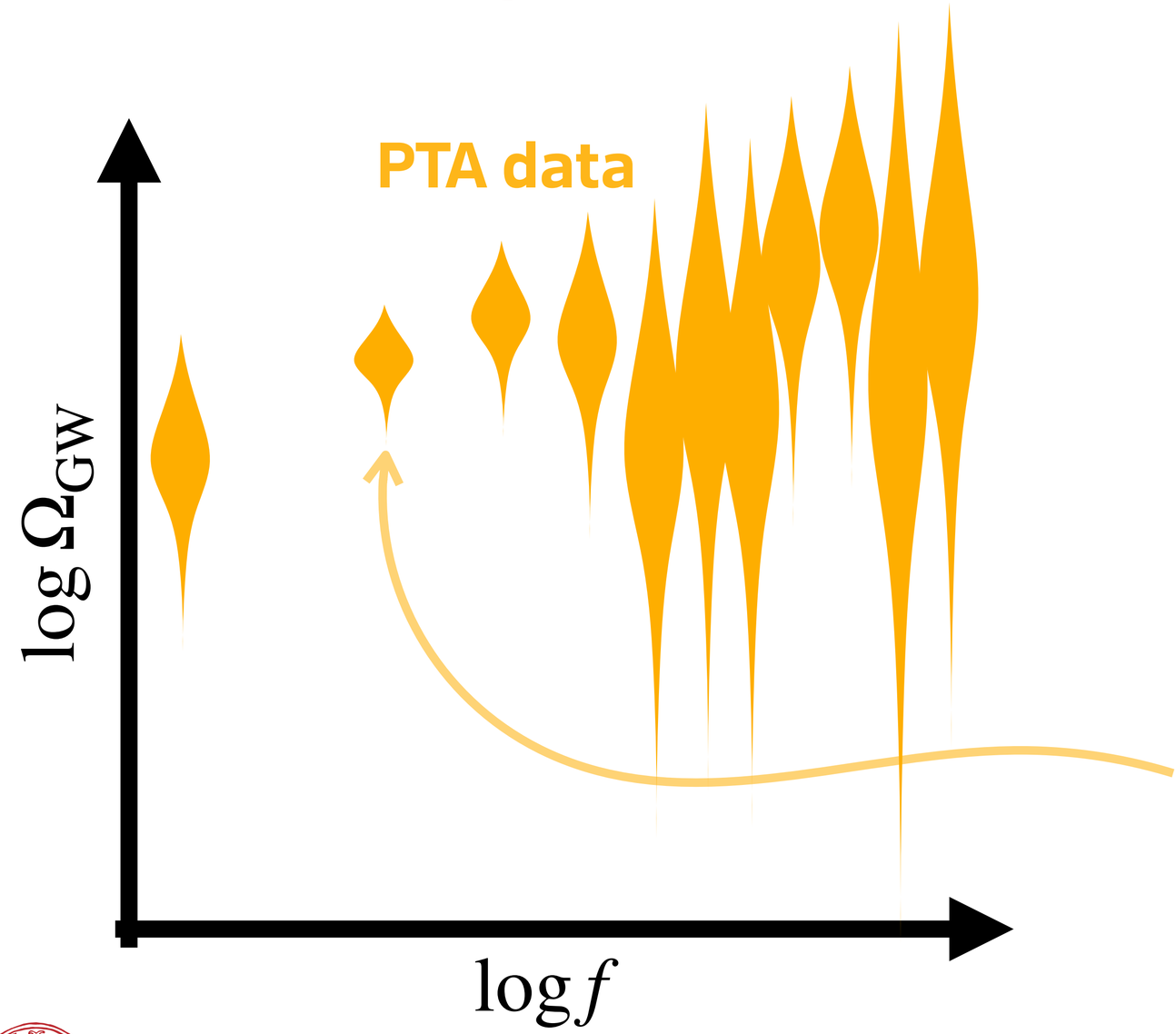

Each „violin“ in the Bayesian spectrogram can be understood as a data point with non-Gaussian error bar, describing the Fourier amplitude of a given frequency.

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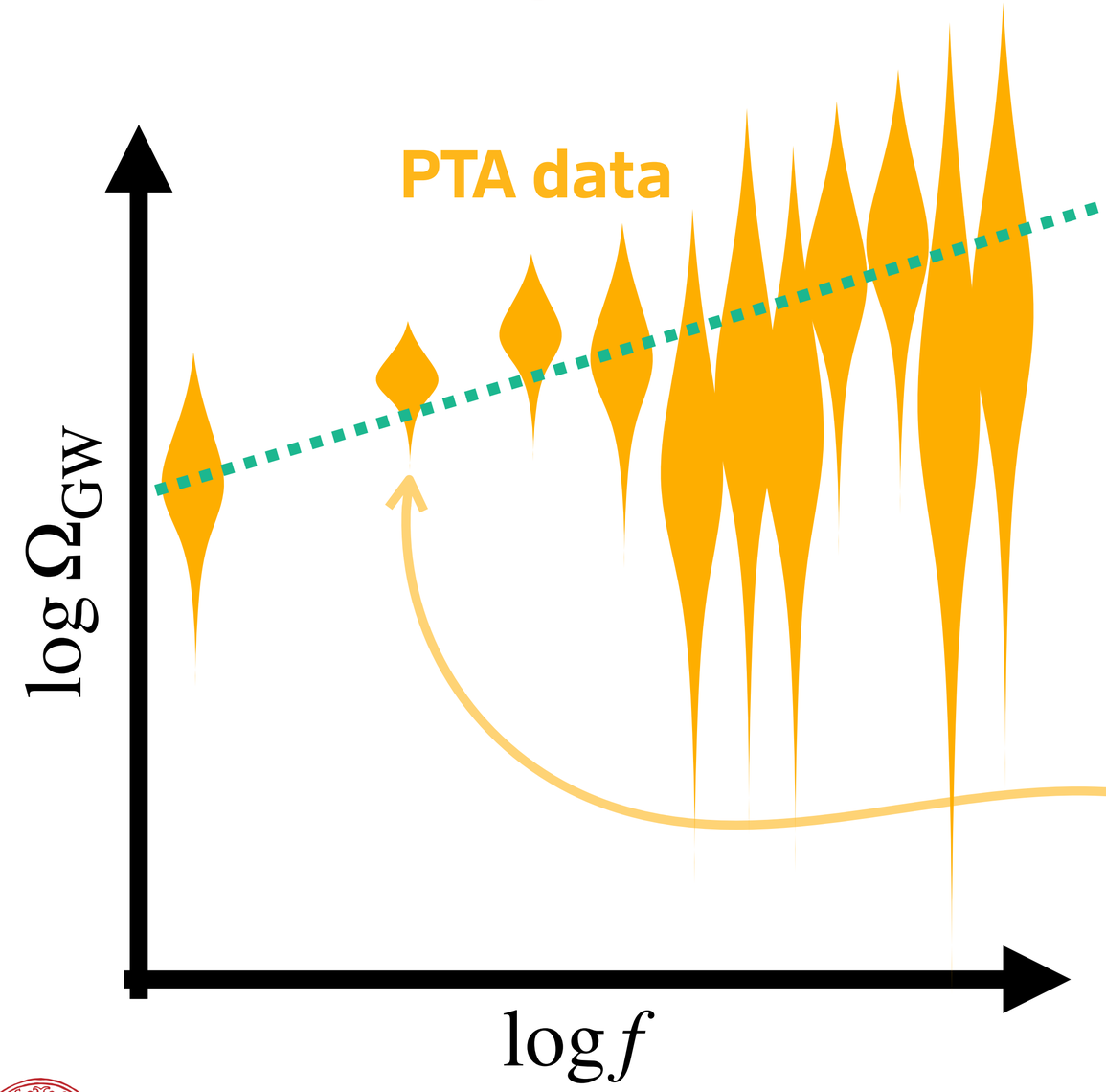

The inferred spectral shape of the GWB is well-described by a power law

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

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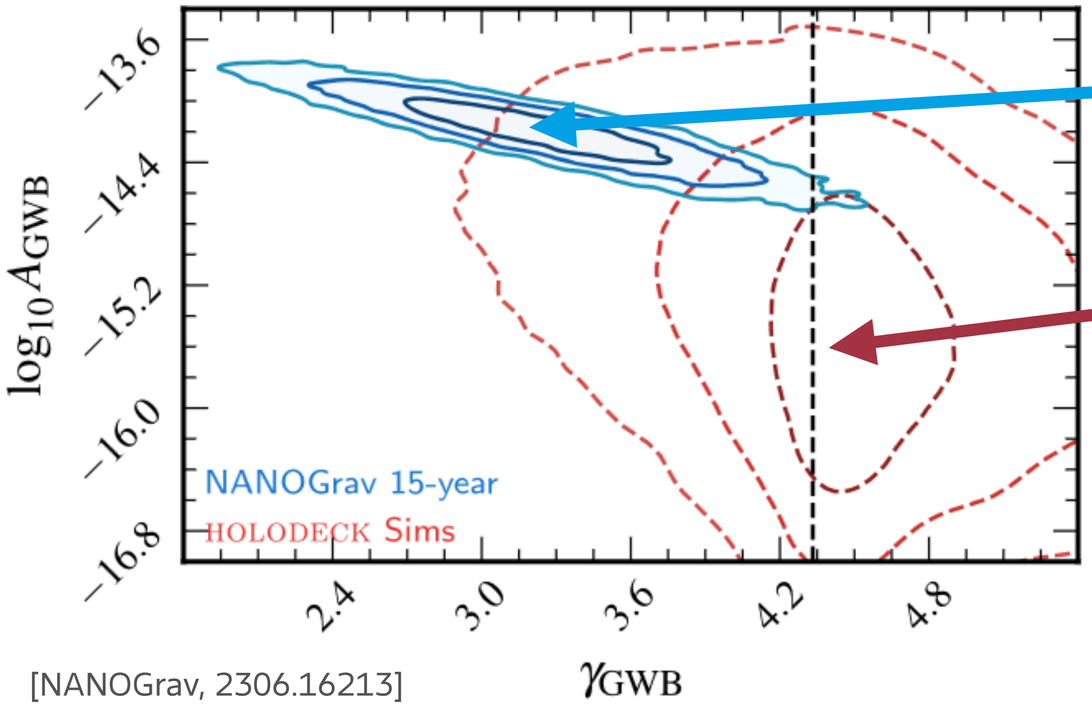
Merging supermassive black holes?



[NANOGrav, 2306.16213]

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

Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ

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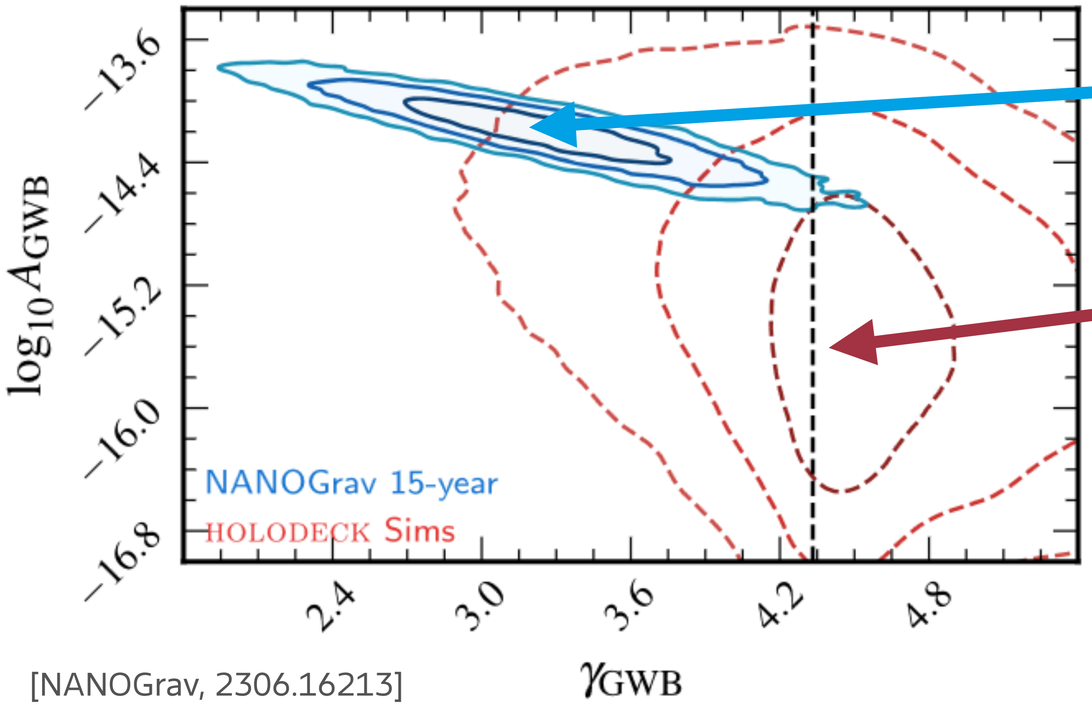

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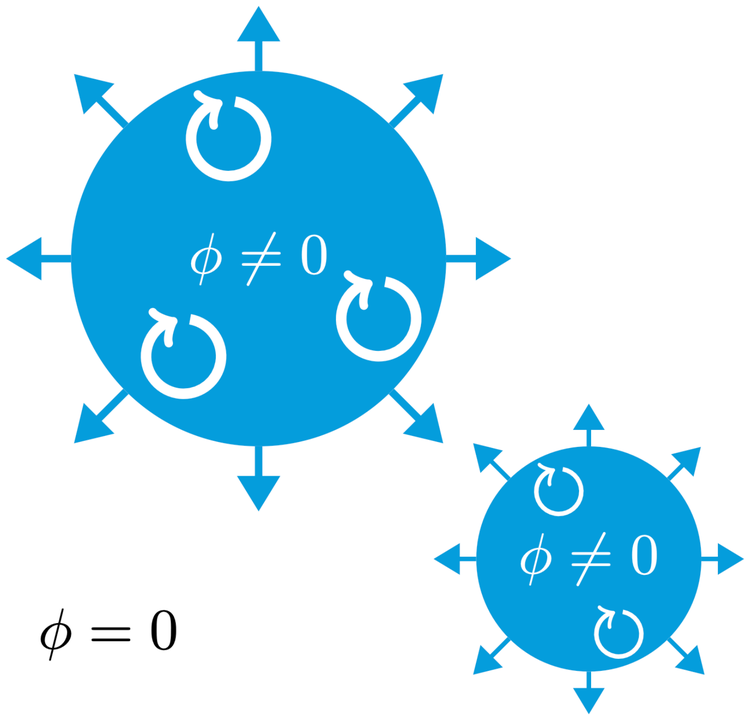
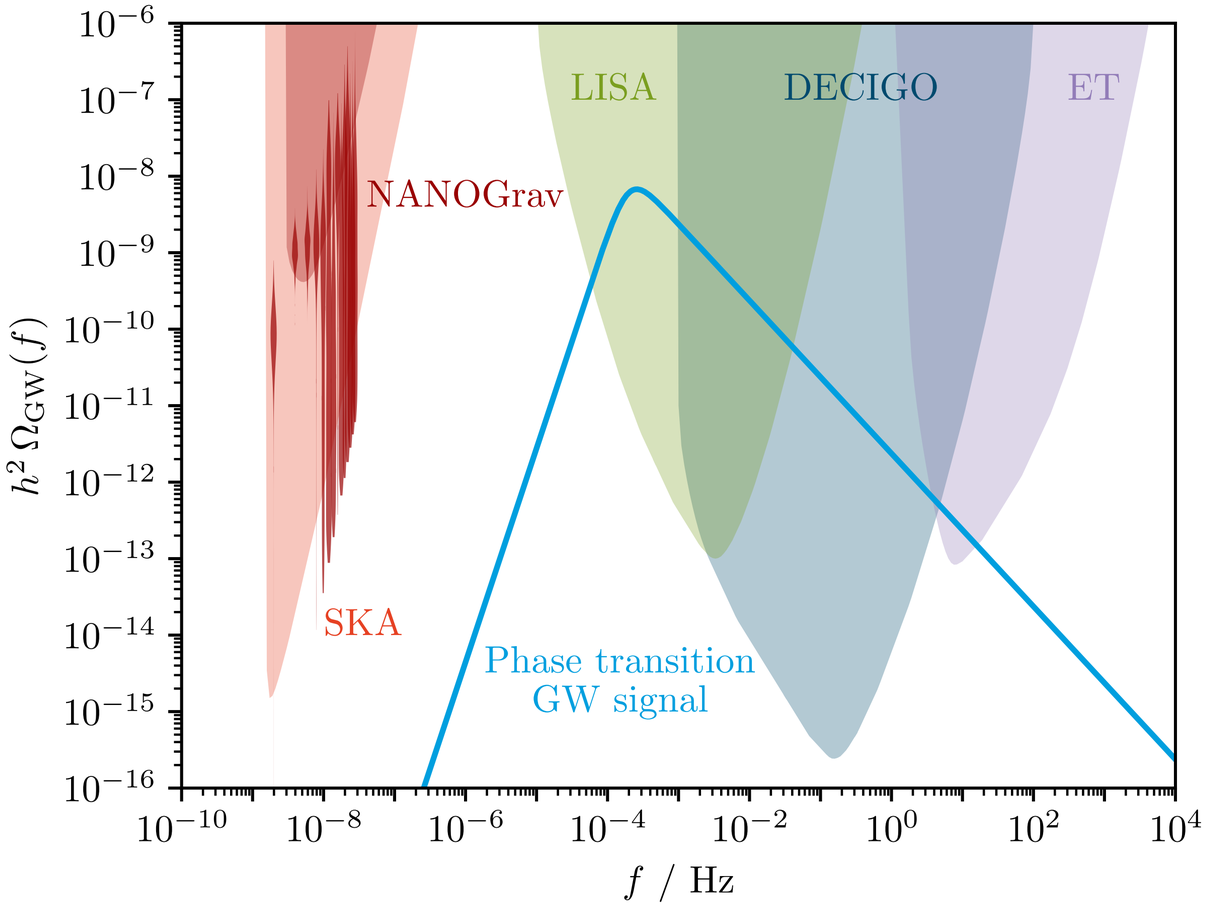
Are there other signal sources?

First-order phase transitions produce GWs

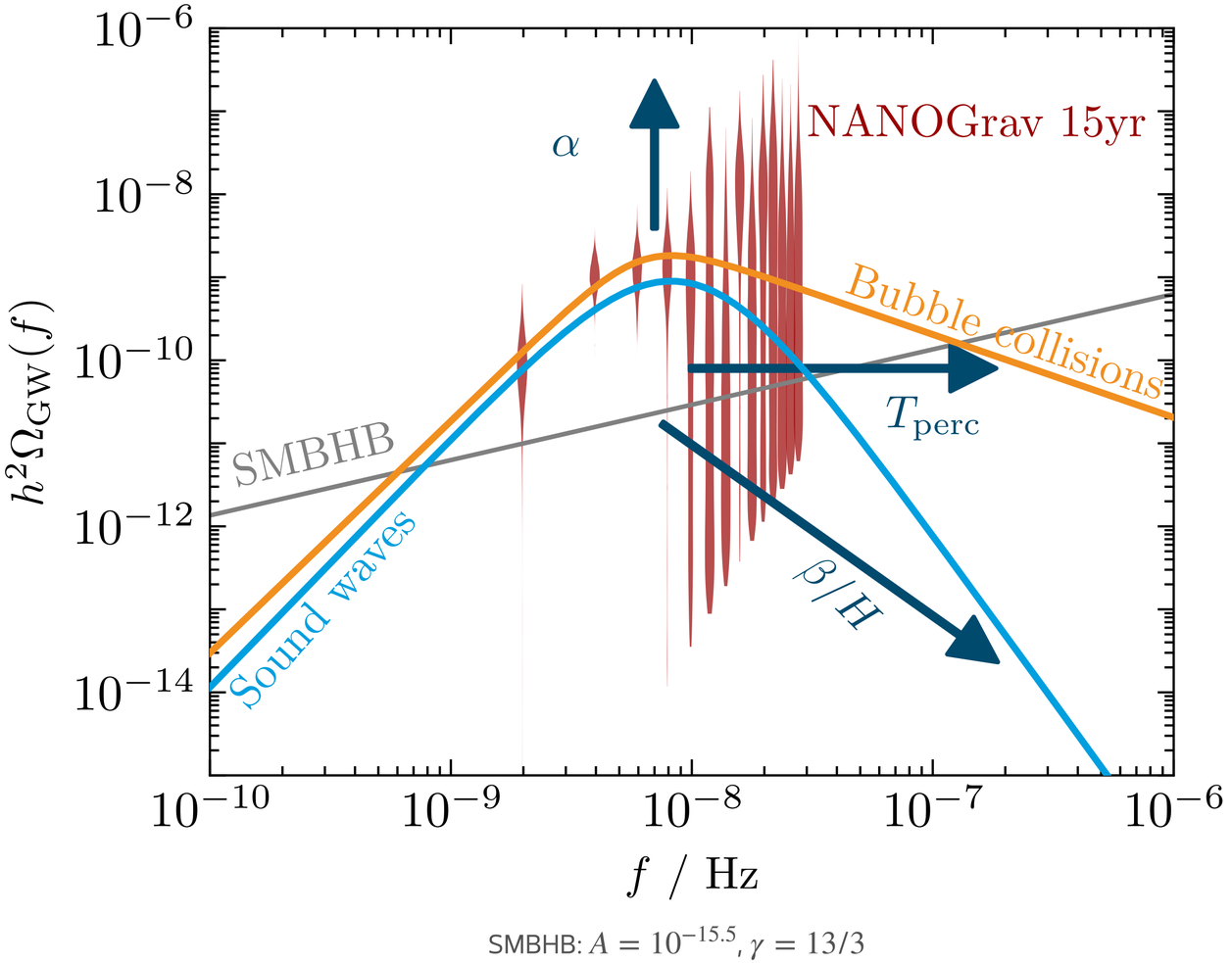
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

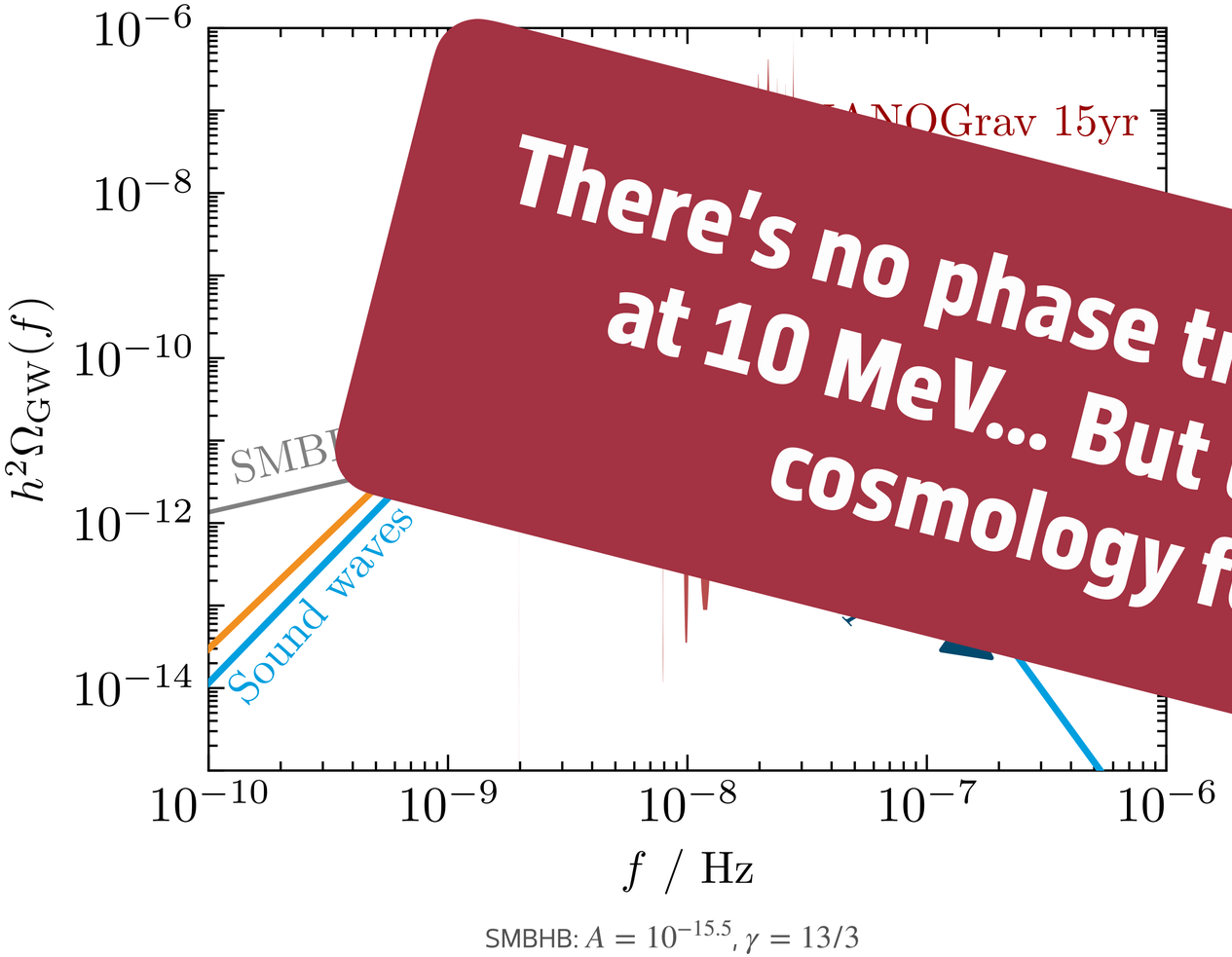
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{H}{\beta}\right)^{1,2} \mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal



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There's no phase transition in the SM at 10 MeV... But does precision cosmology forbid it?!

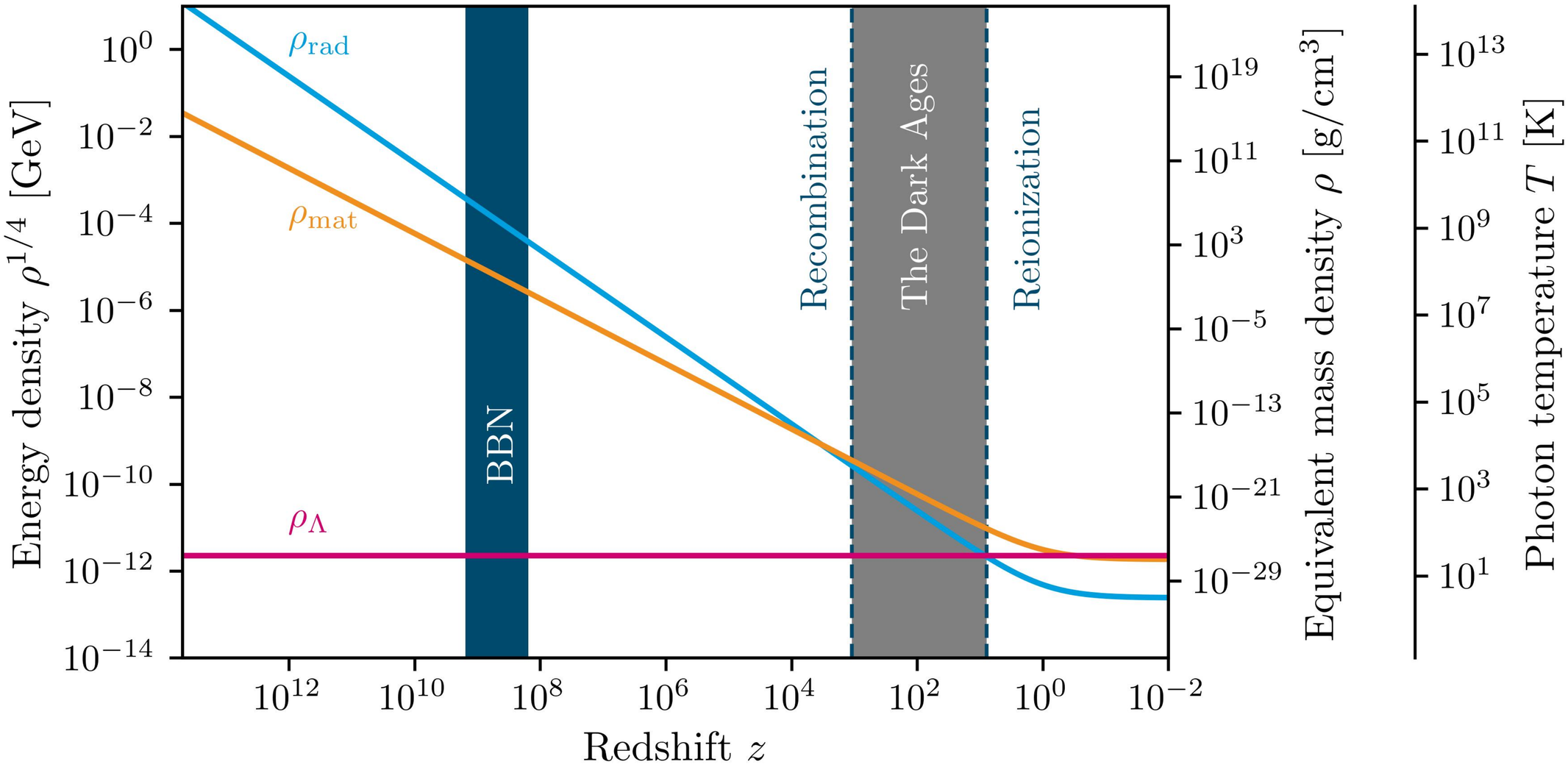
ing data:

≈ 1

≈ 10

- Percolat… $\approx 10\,{\rm MeV}$

A brief history of time



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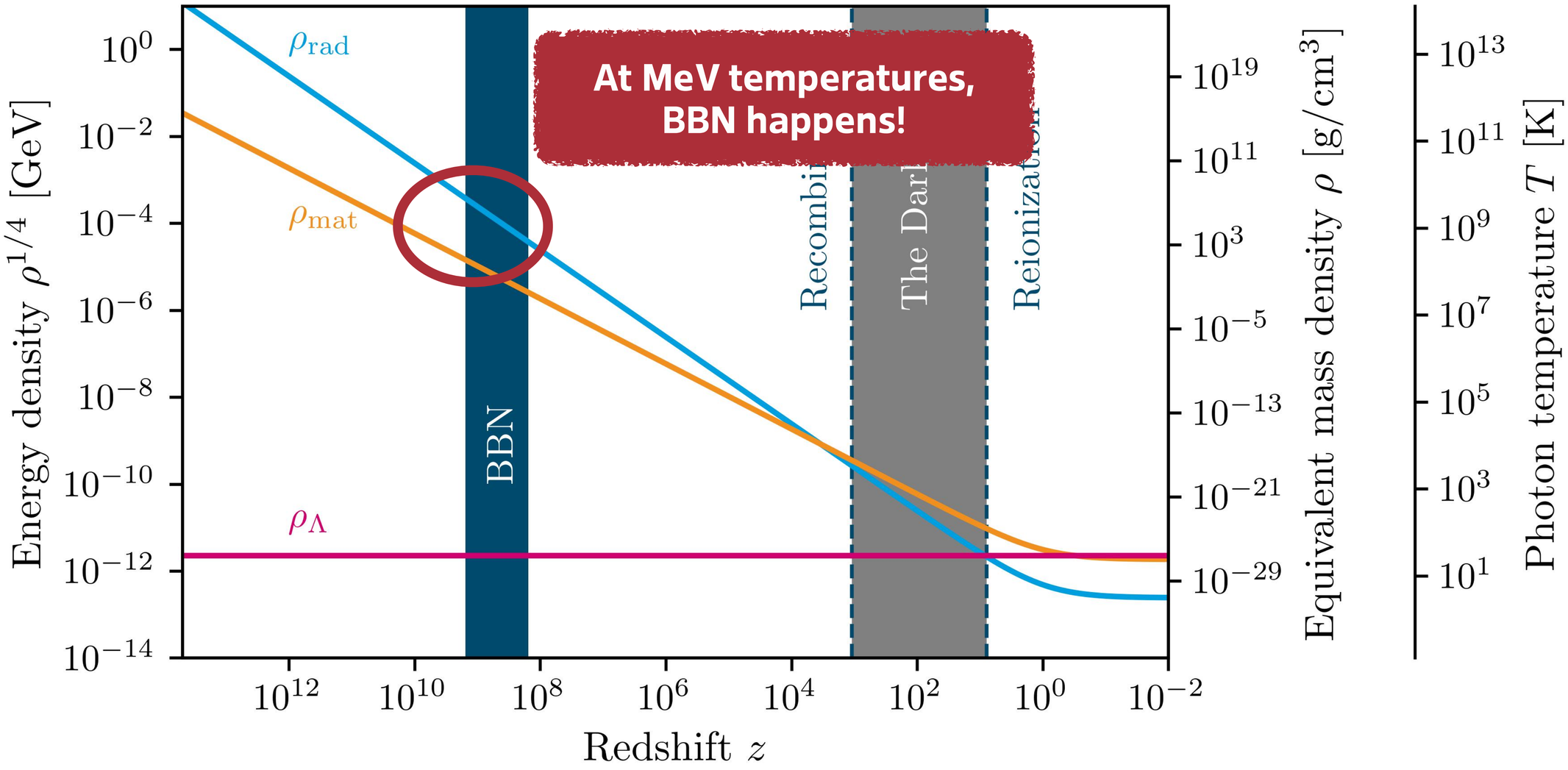
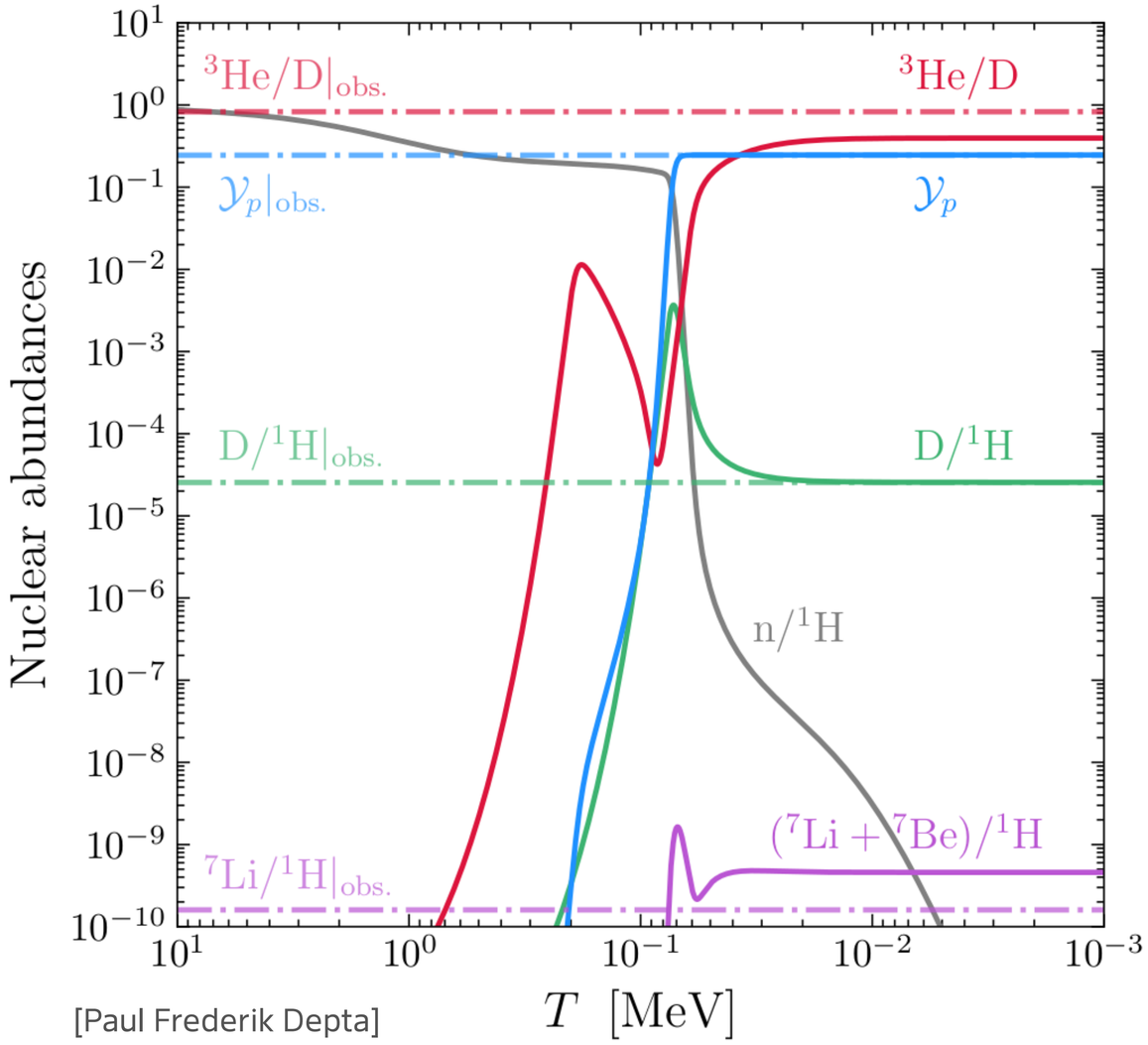


Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

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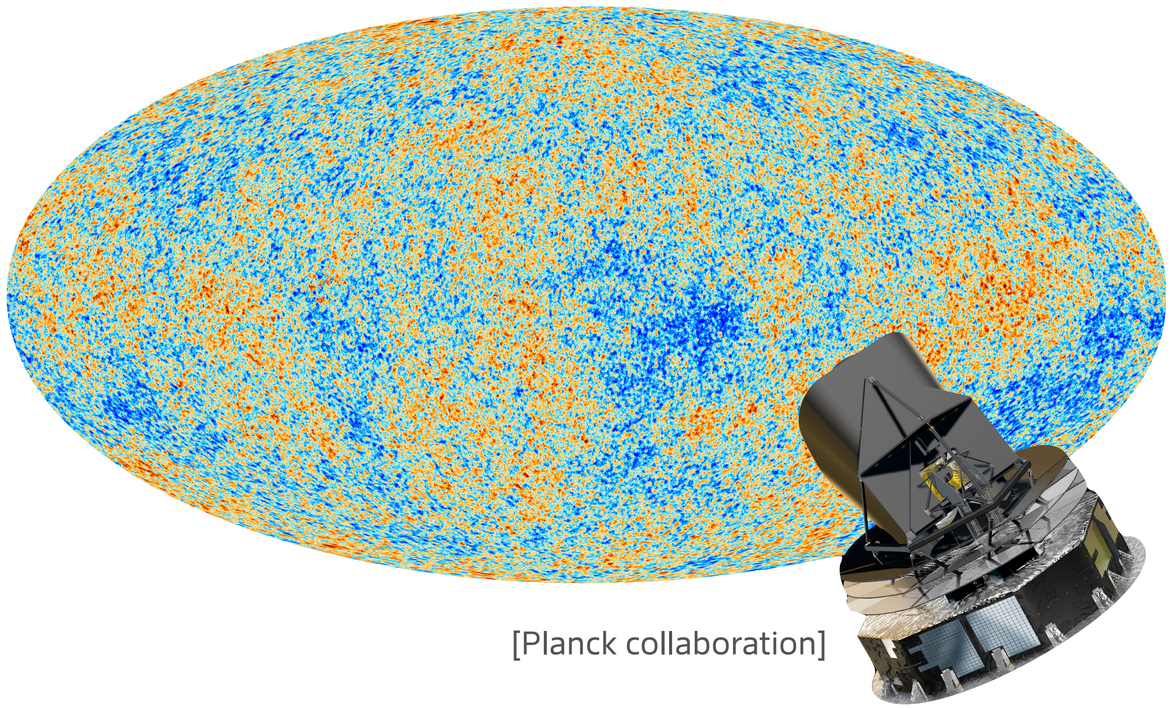
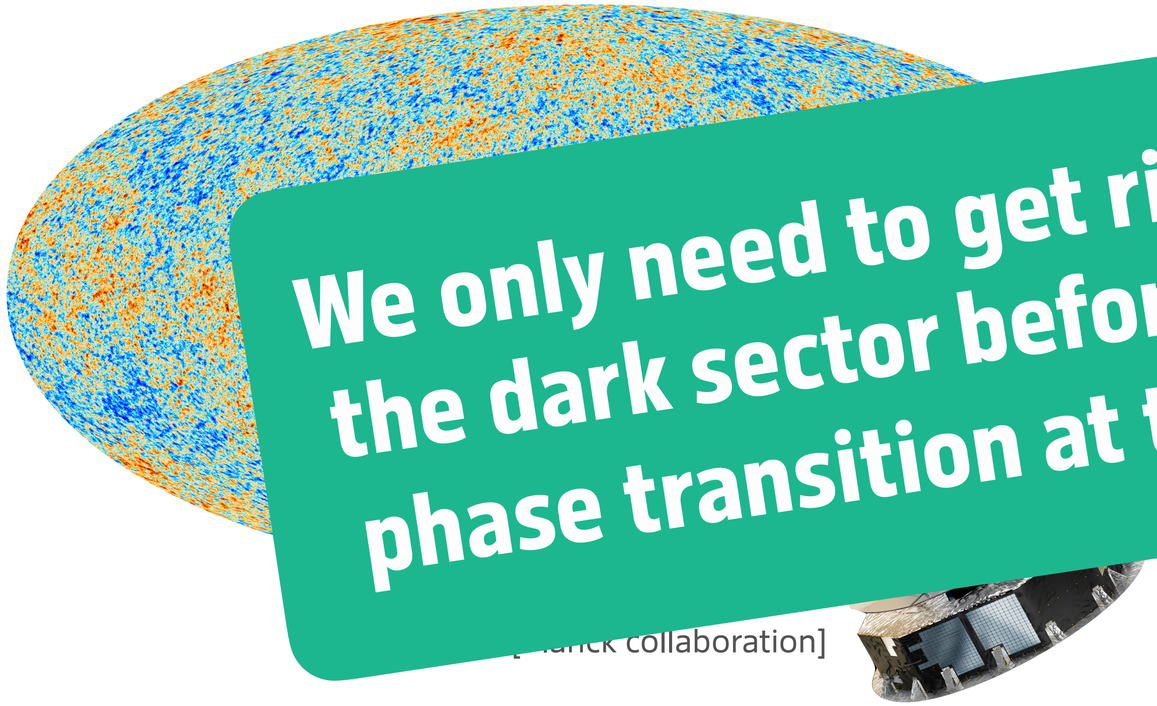


[Planck collaboration]

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

Big Bang Nucleosynthesis and the CMB

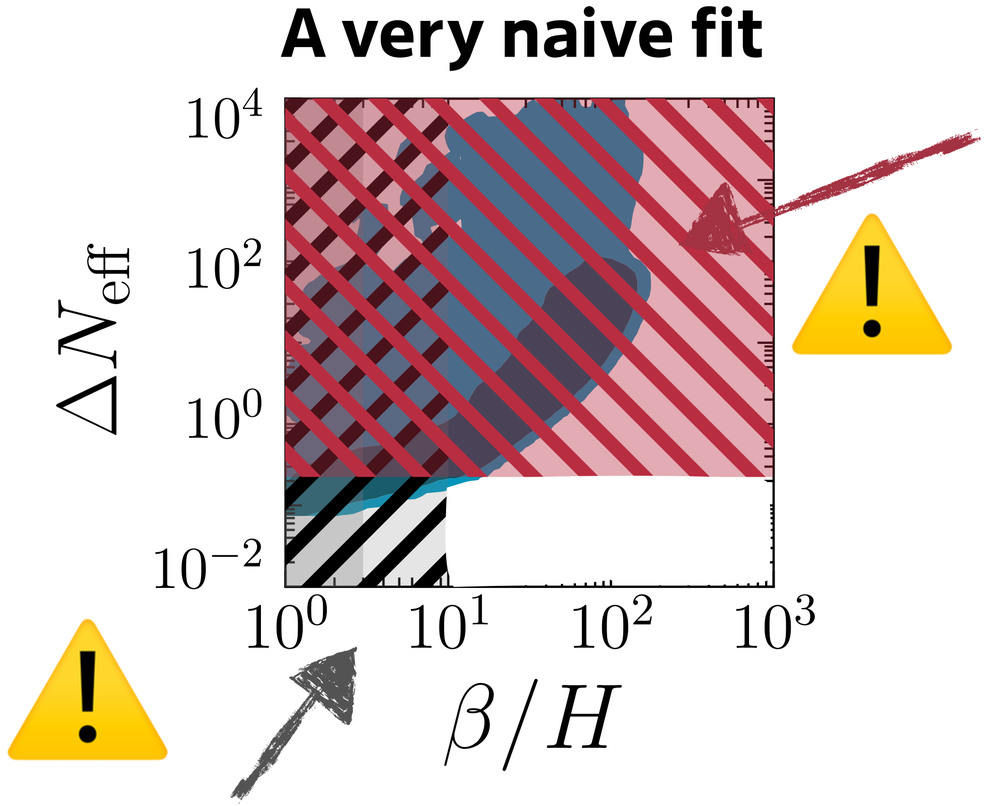


[Planck collaboration]

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

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

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, questioning validity of GW predictions & very difficult to get in a model

[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]

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

But how?!

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

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

New PTA data: higher peak frequency and slope

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

Solution to the final parsec problem?

[Chiaberge+, 2501.18730]

What happened since July 2023?

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

[Chen+, 2502.01024]

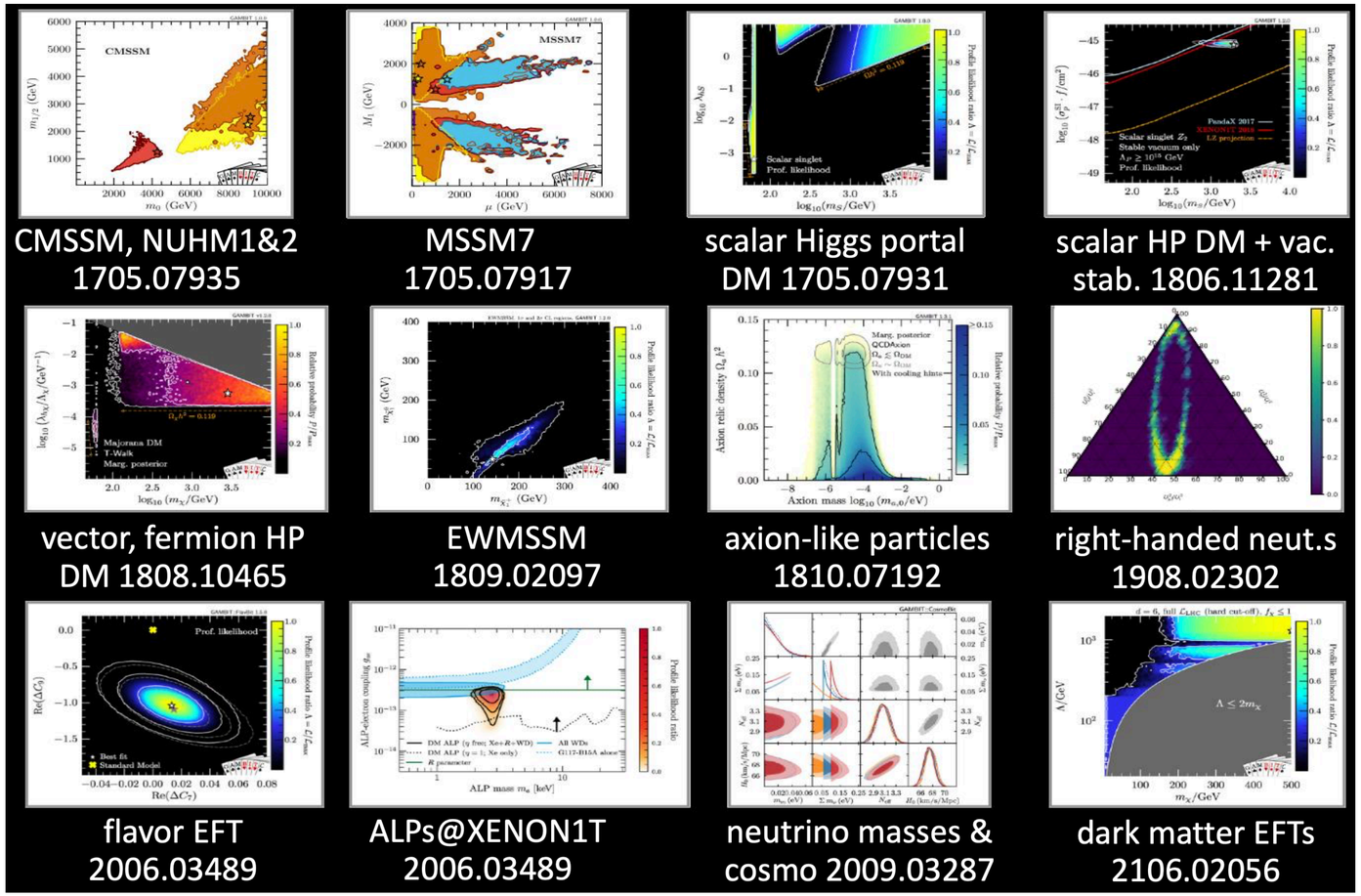
Investigation of specific dark sector models

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

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

Our latest work

GAMBIT: from Lagrangians to Likelihoods



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

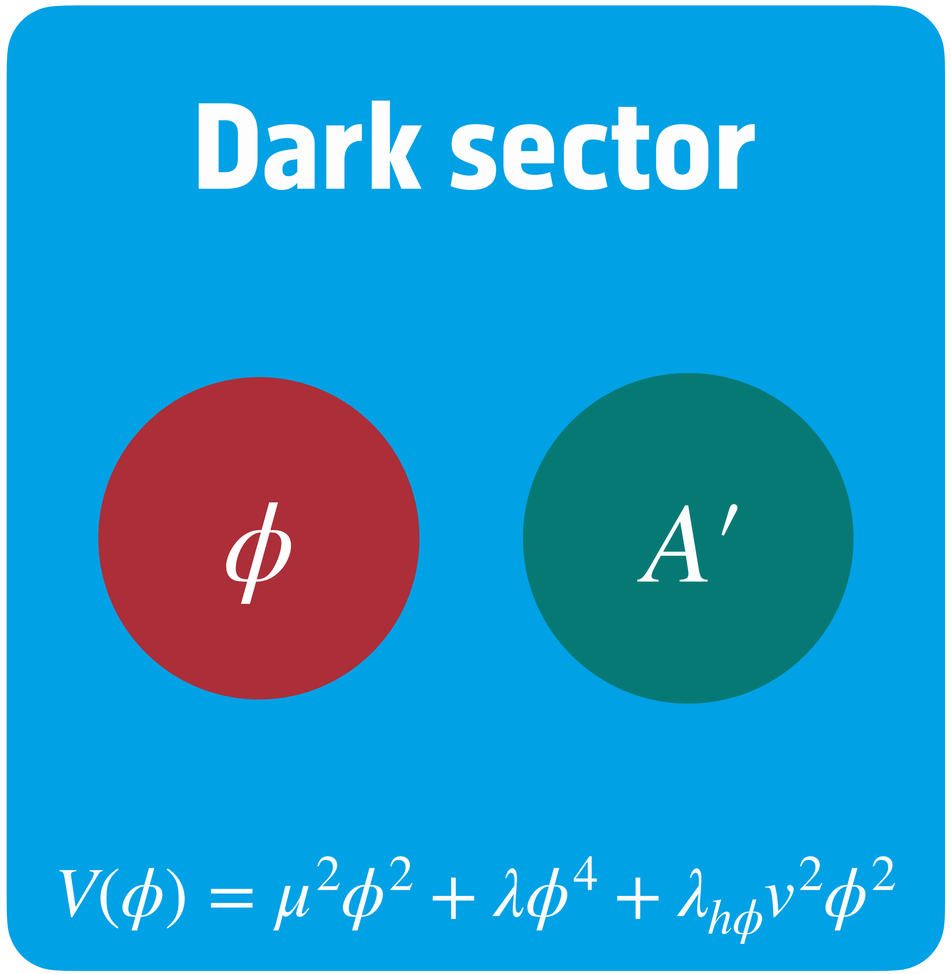
vector, fermion HP DM 1808.10465 | EWMSSM 1809.02097 | axion-like particles 1810.07192 | right-handed neut.s 1908.02302

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

Slide by C. Balázs @ SUSY 2021

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

A minimal dark sector setup



Higgs mixing $\lambda_{h\phi}$

Changes the dark Higgs potential...

Portal couplings

Kinetic mixing κ

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

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

SM

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

A minimal dark sector setup

Dark sector

$V(\phi)$ $+ \lambda_{h\phi} v^2 \phi^2$

Higgs mixing λ

mixing κ

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

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

Model building is complicated!
Hard to avoid cosmological constraints
and fine-tuning...

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

A conformal dark sector incl. dark matter candidate

Dark sector

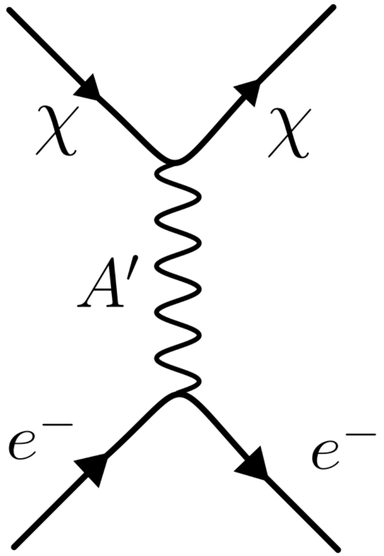
ϕ

A'

χ

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

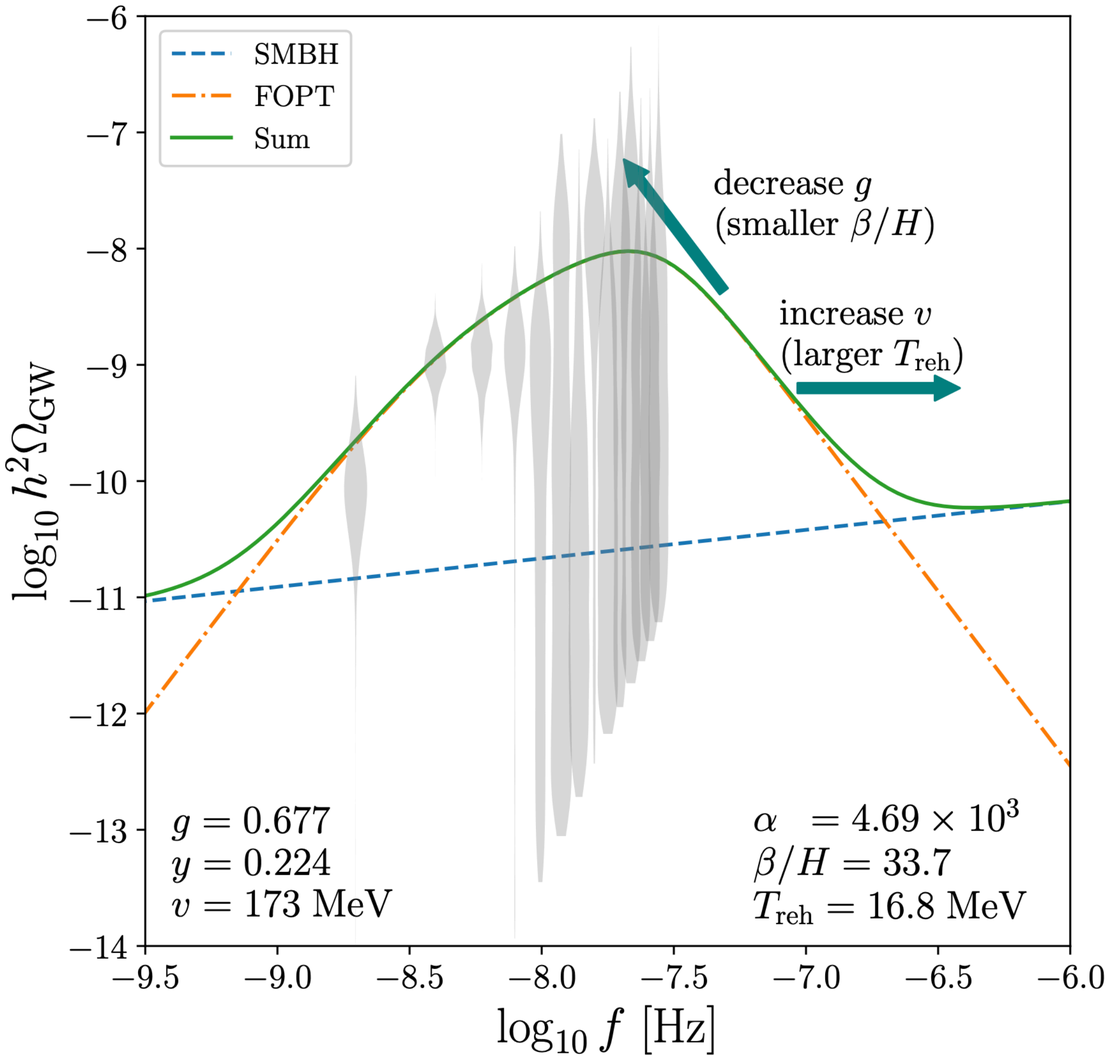
Kinetic mixing κ



Thermalization becomes easy!

SM

All constraints can be circumvented

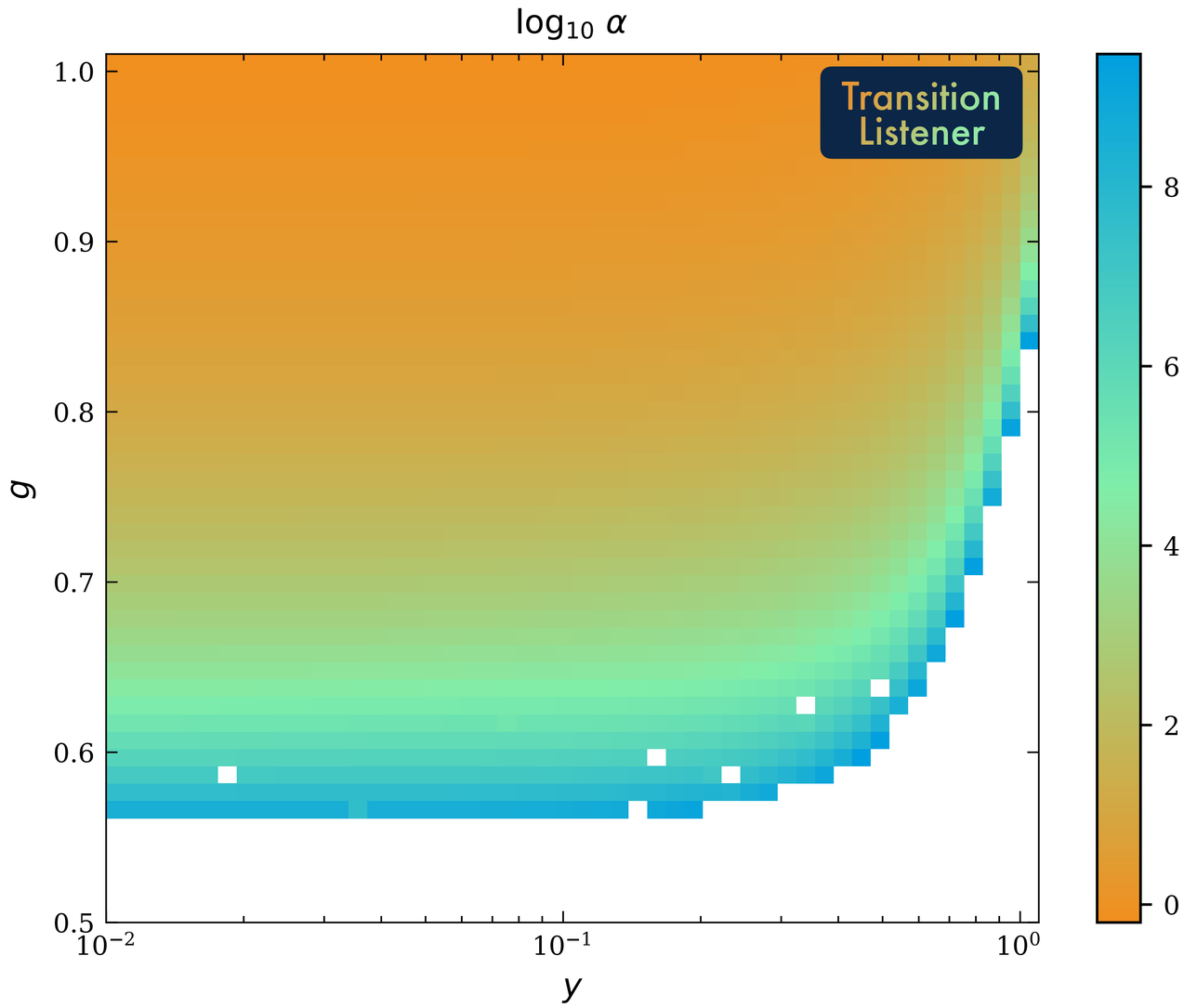


Global fit found parameter space with

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

In case you want to test your own phase transition models…

[Ongoing work Jonas Matuszak,
code release in fall 2025]



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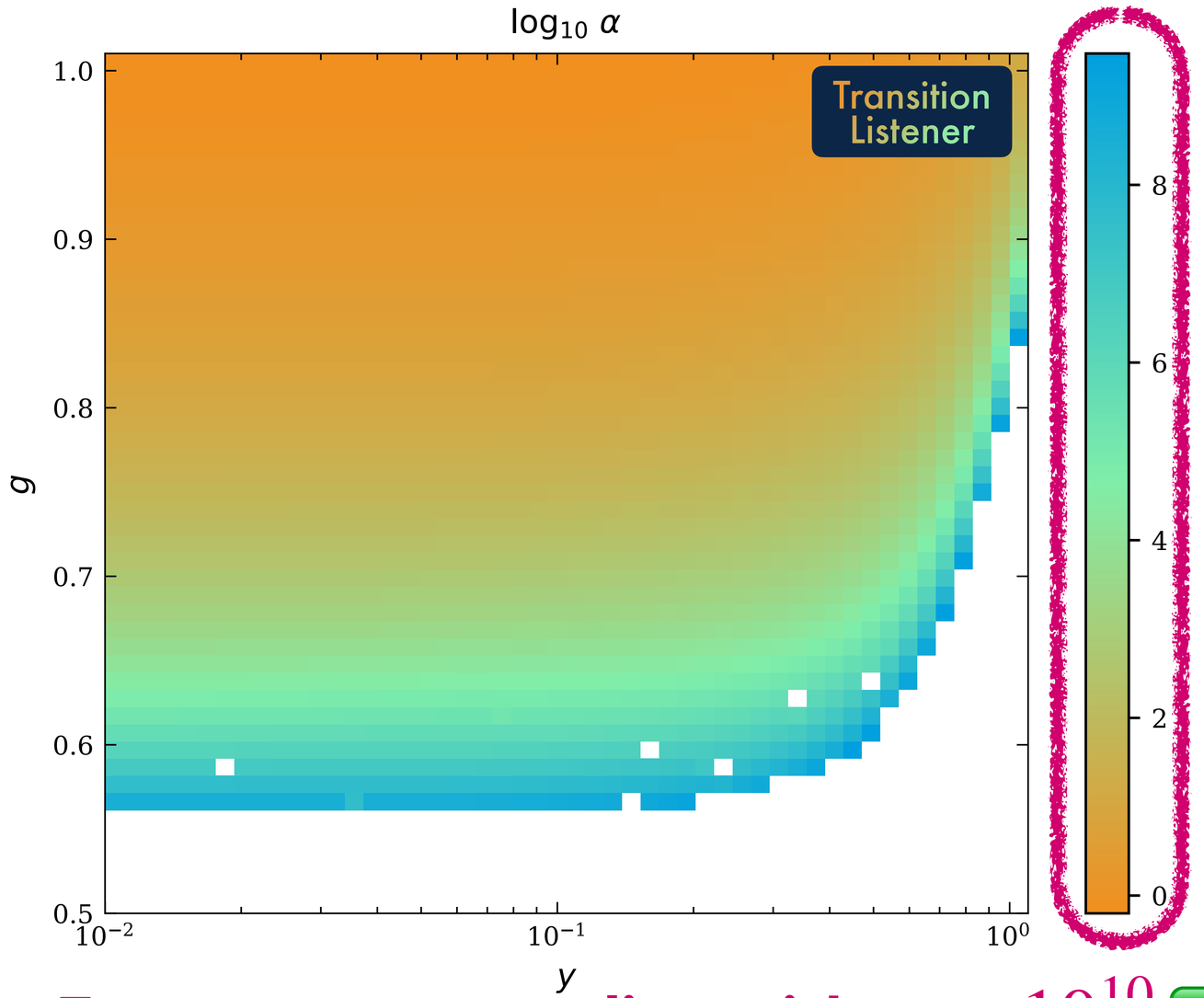
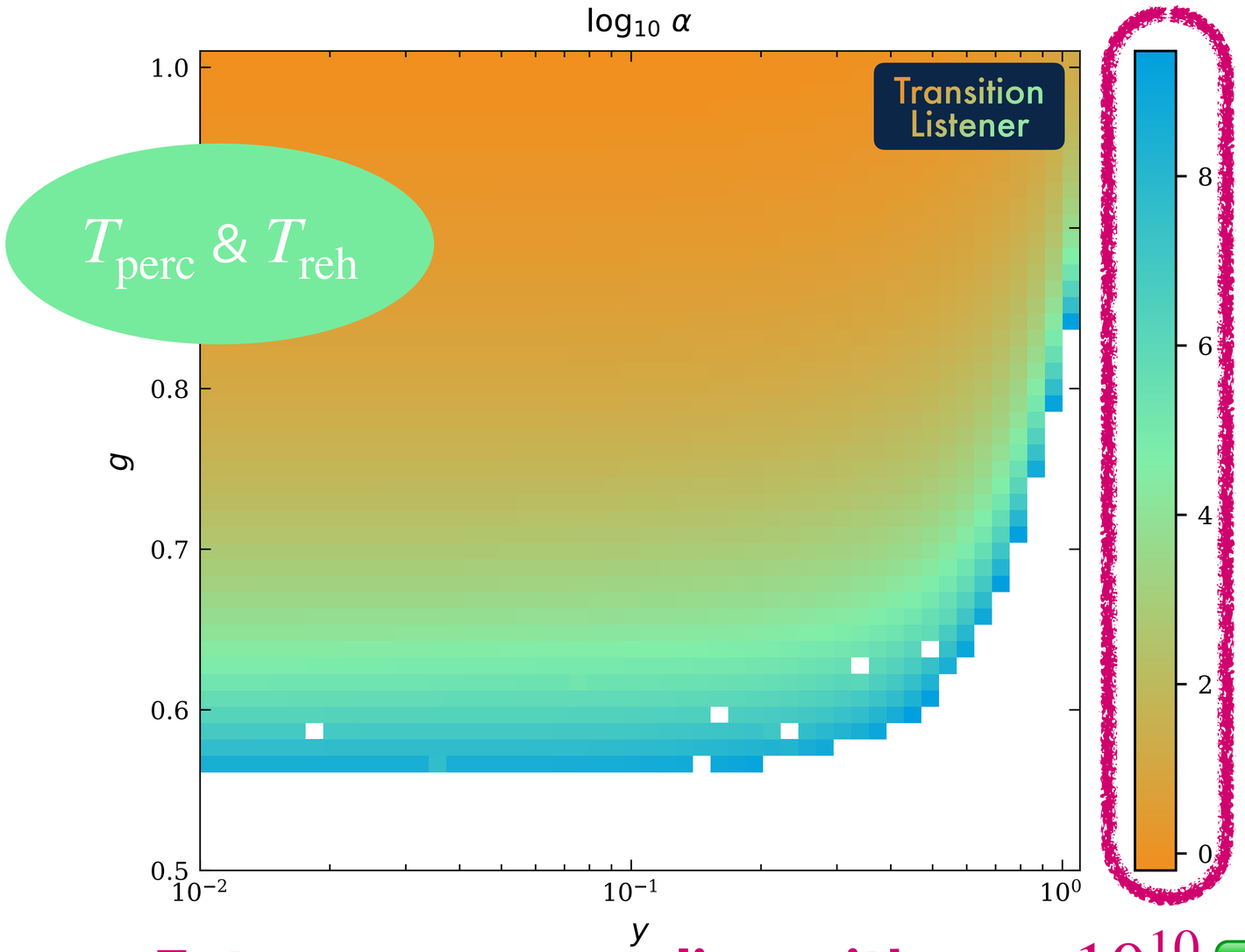


Extreme supercooling with $\alpha = 10^{10}$ ✅

In case you want to test your own phase transition models…

Transition Listener 2.0

[Ongoing work Jonas Matuszak, code release in fall 2025]



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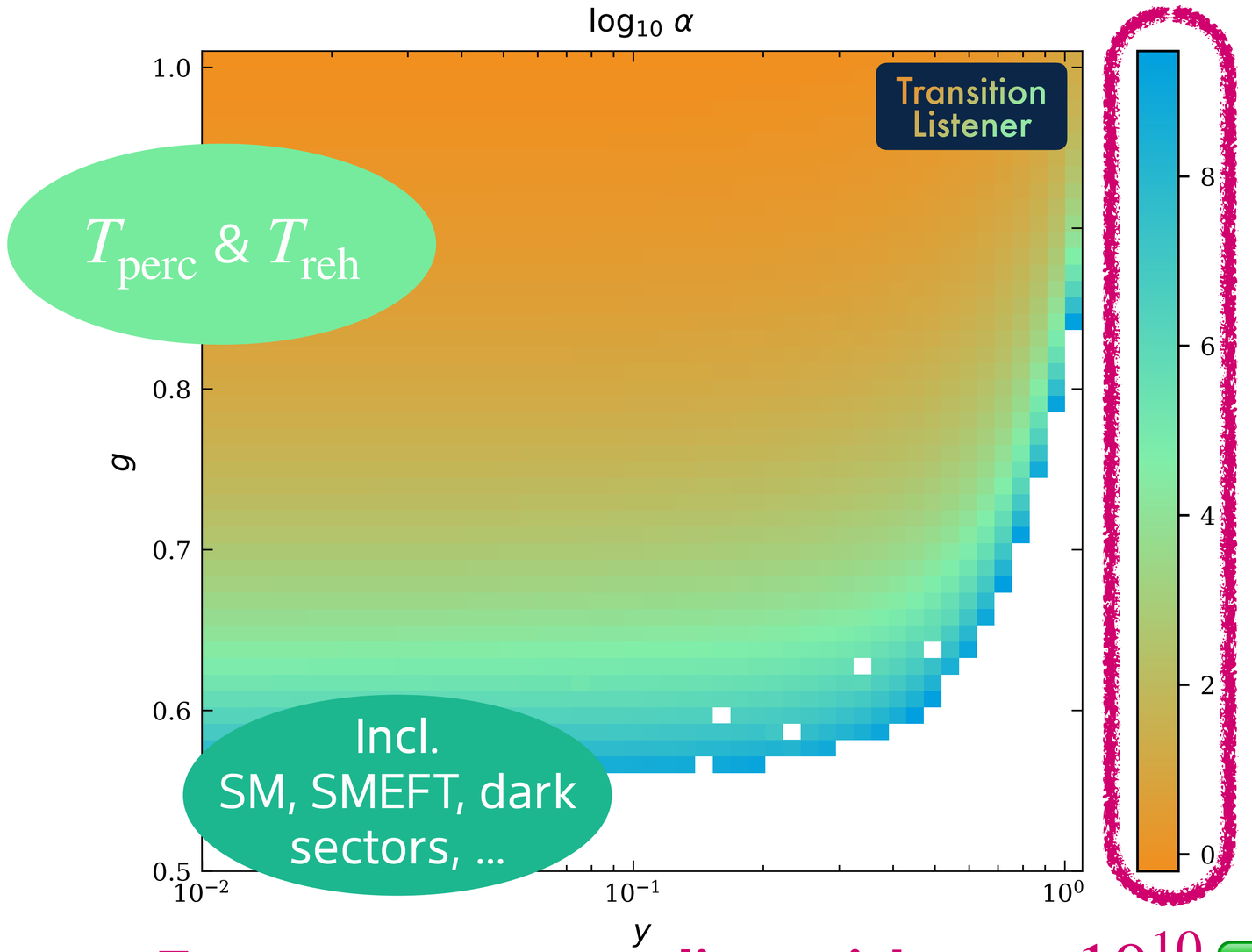

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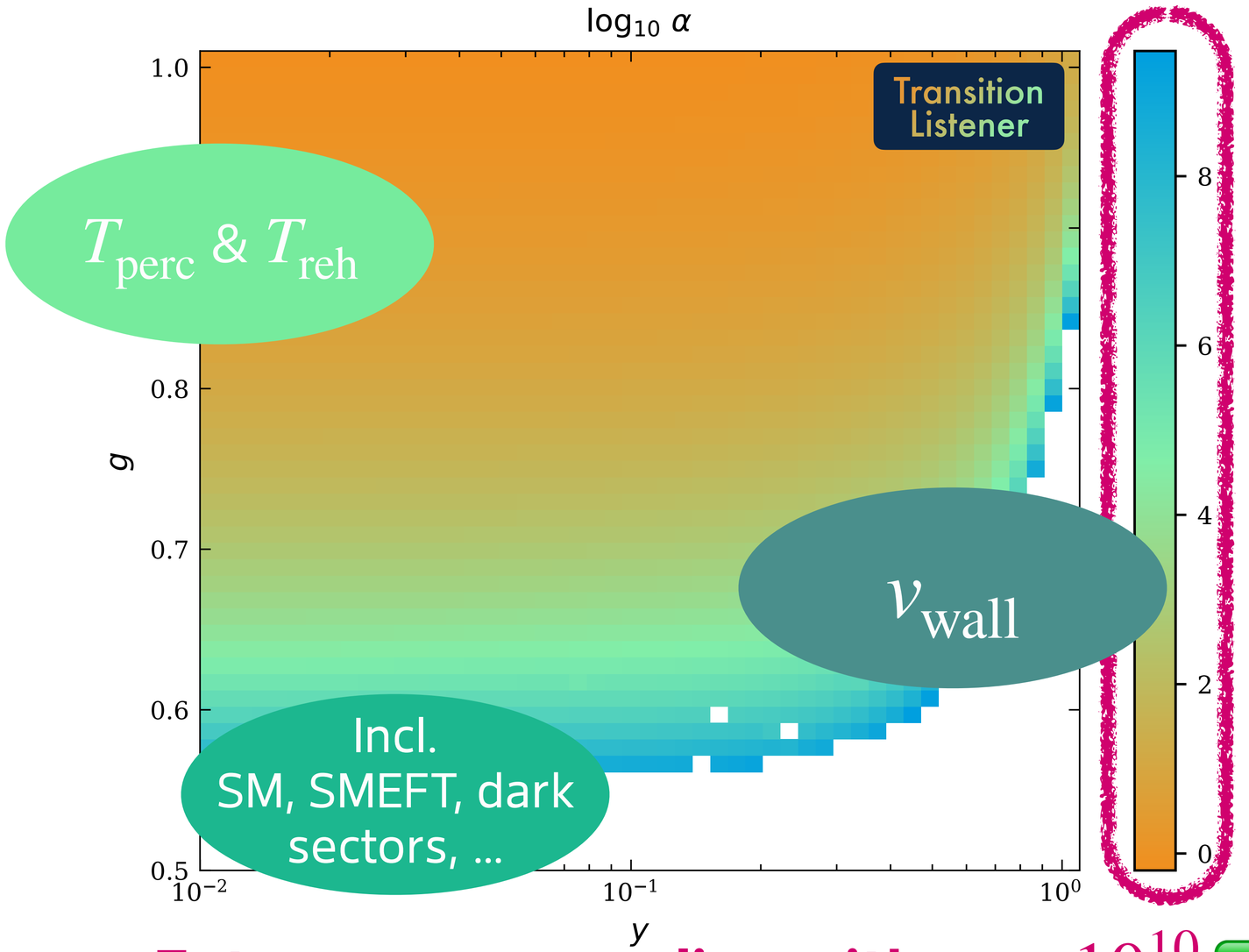

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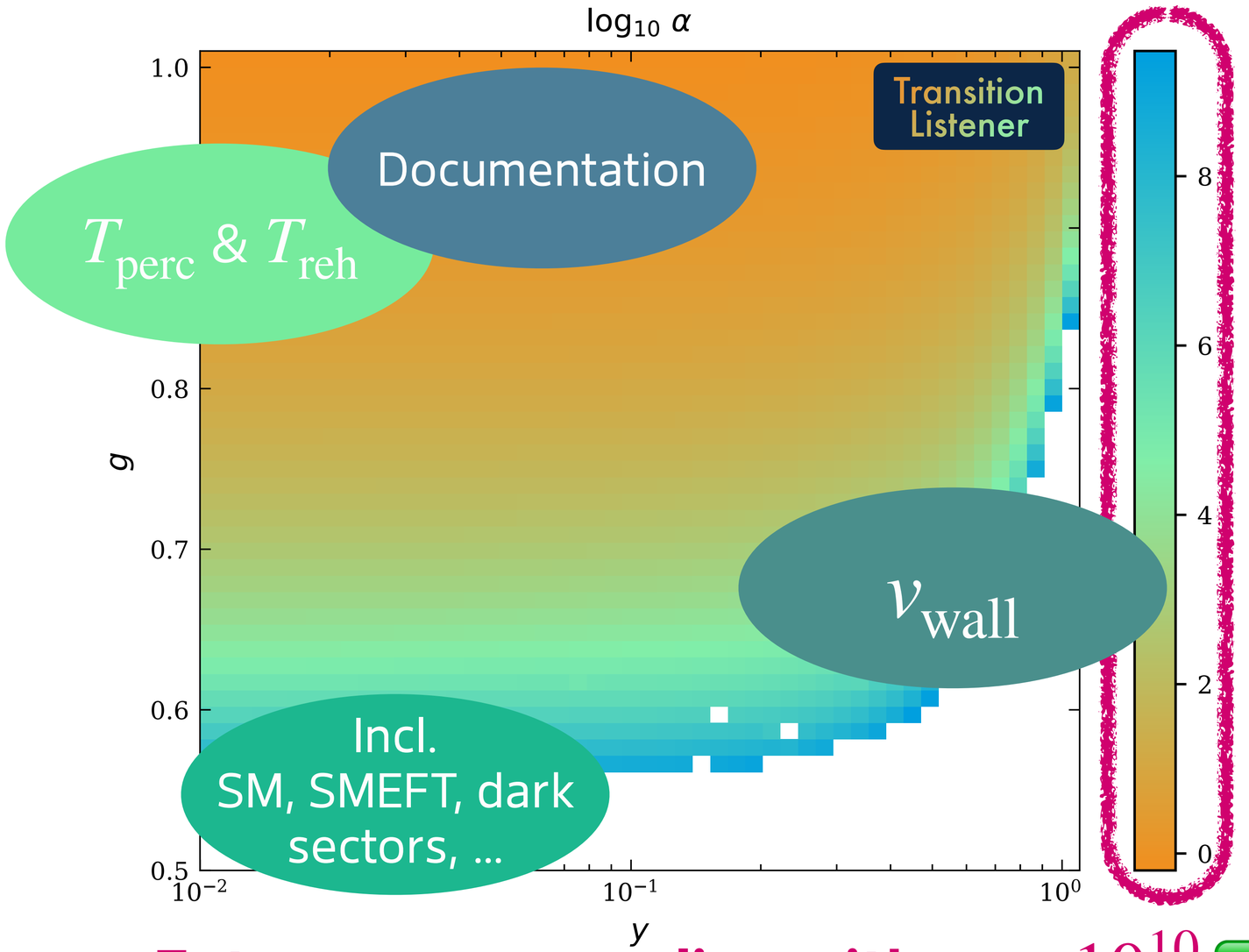

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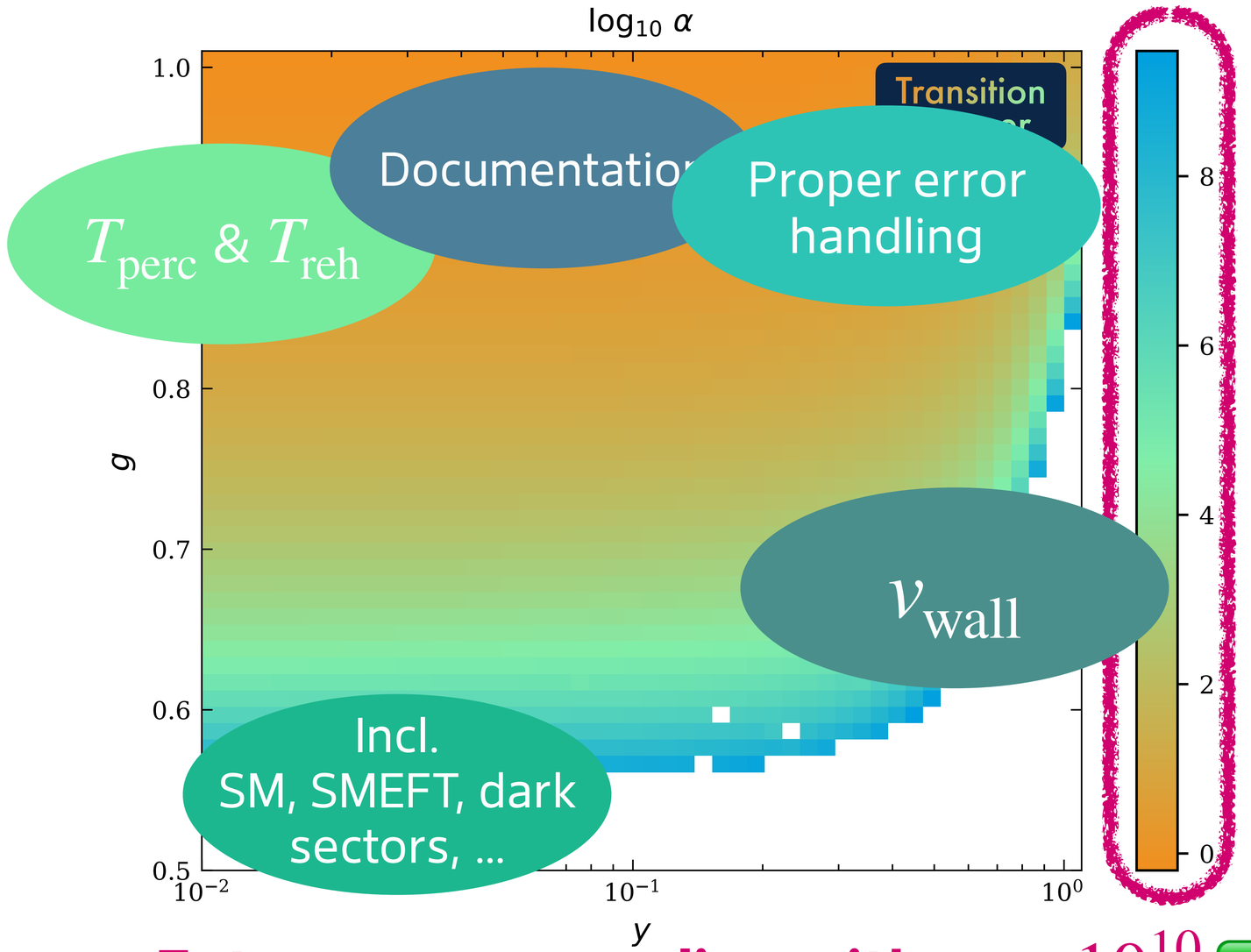

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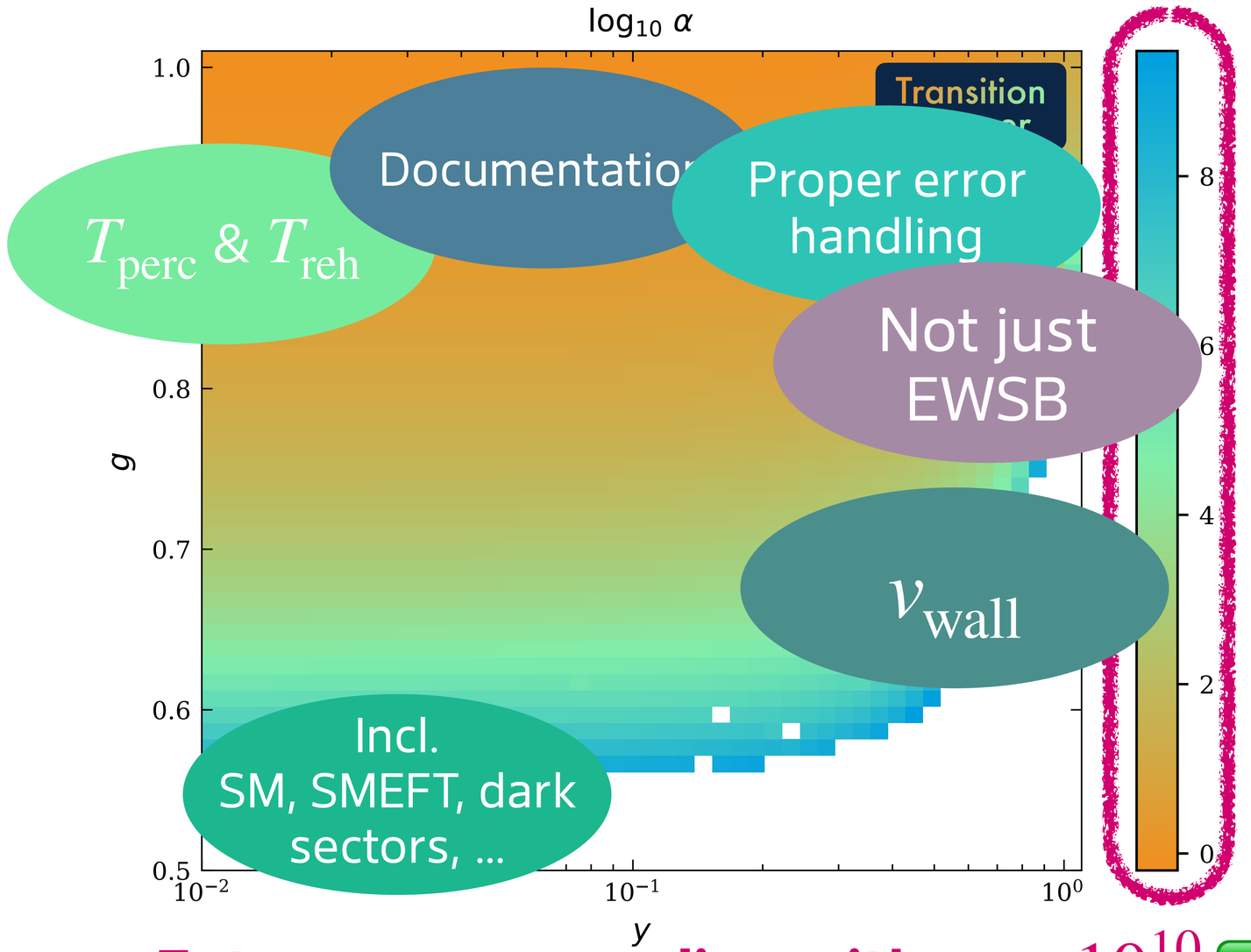

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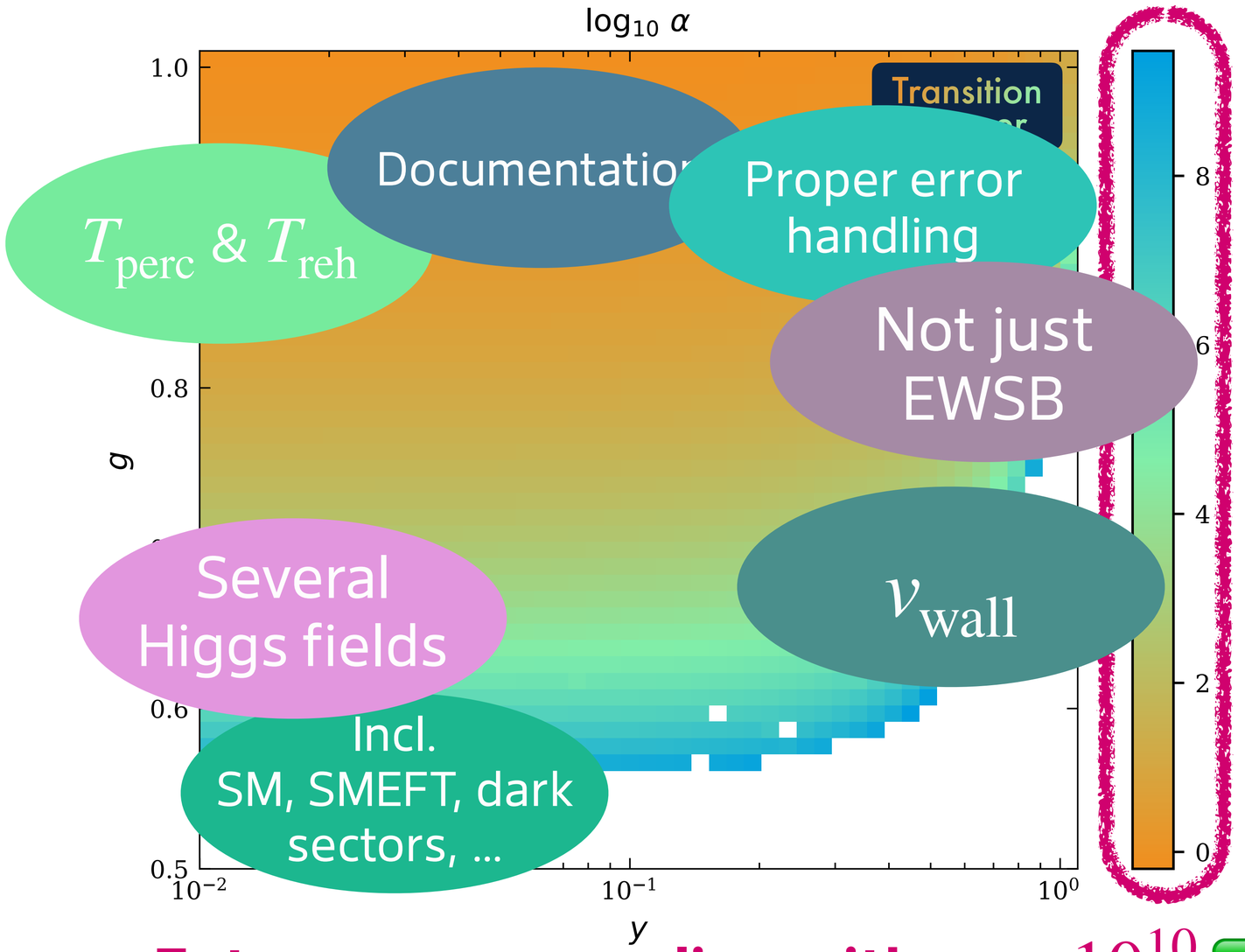
Transition Listener

[Ongoing work Jonas Matuszak, code release in fall 2025]



Extreme supercooling with $\alpha = 10^{10}$ ✅

In case you want to test your own phase transition models…

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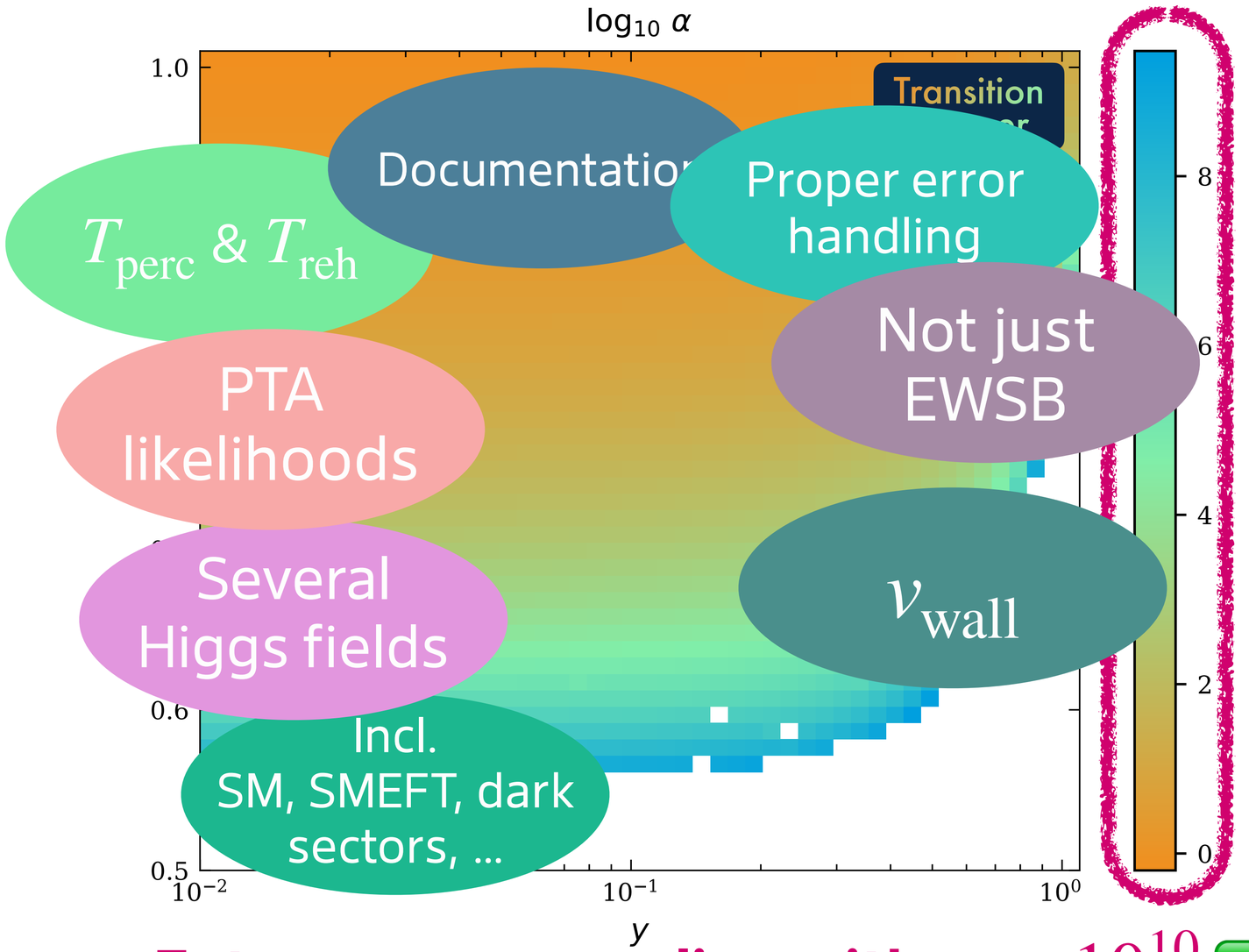

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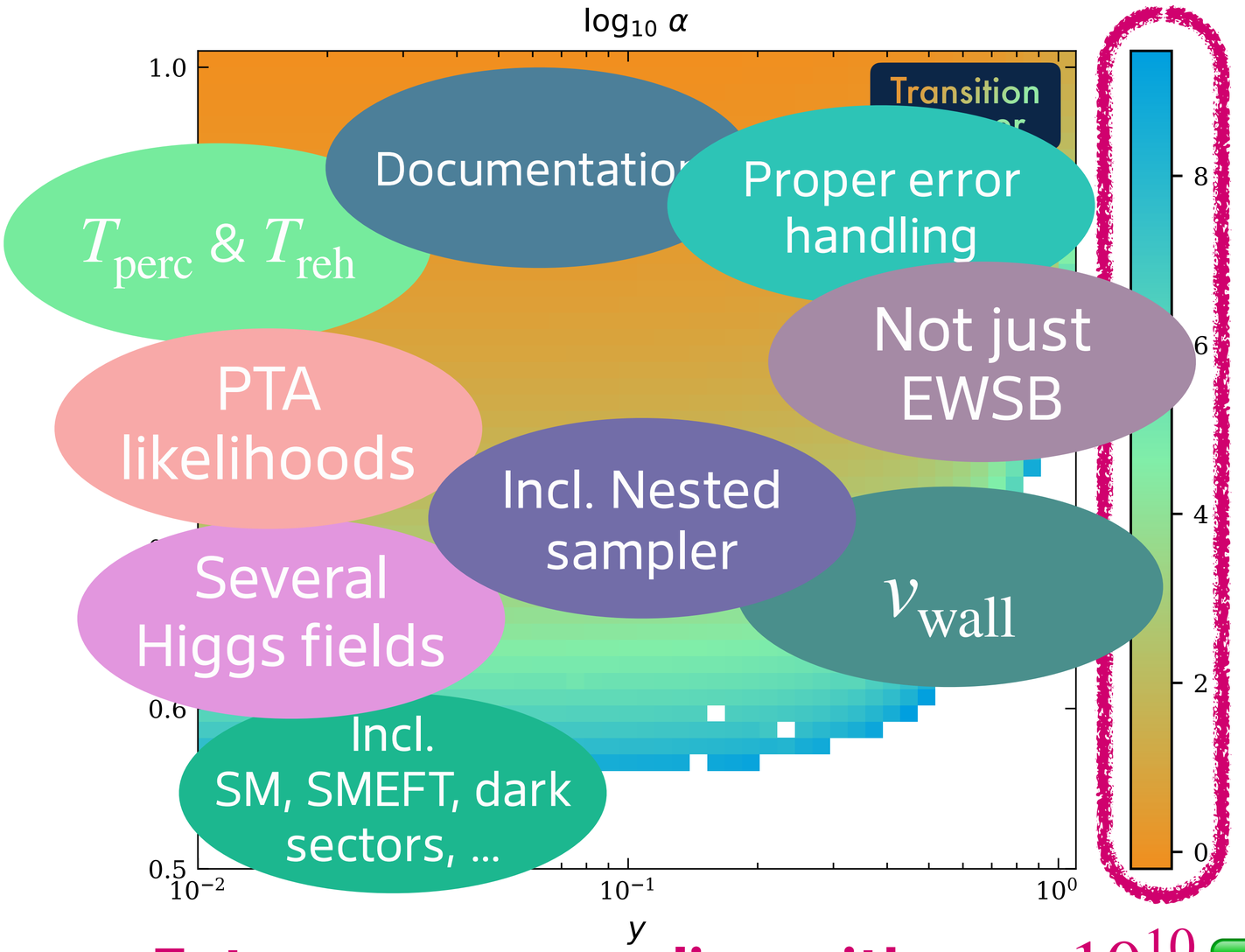

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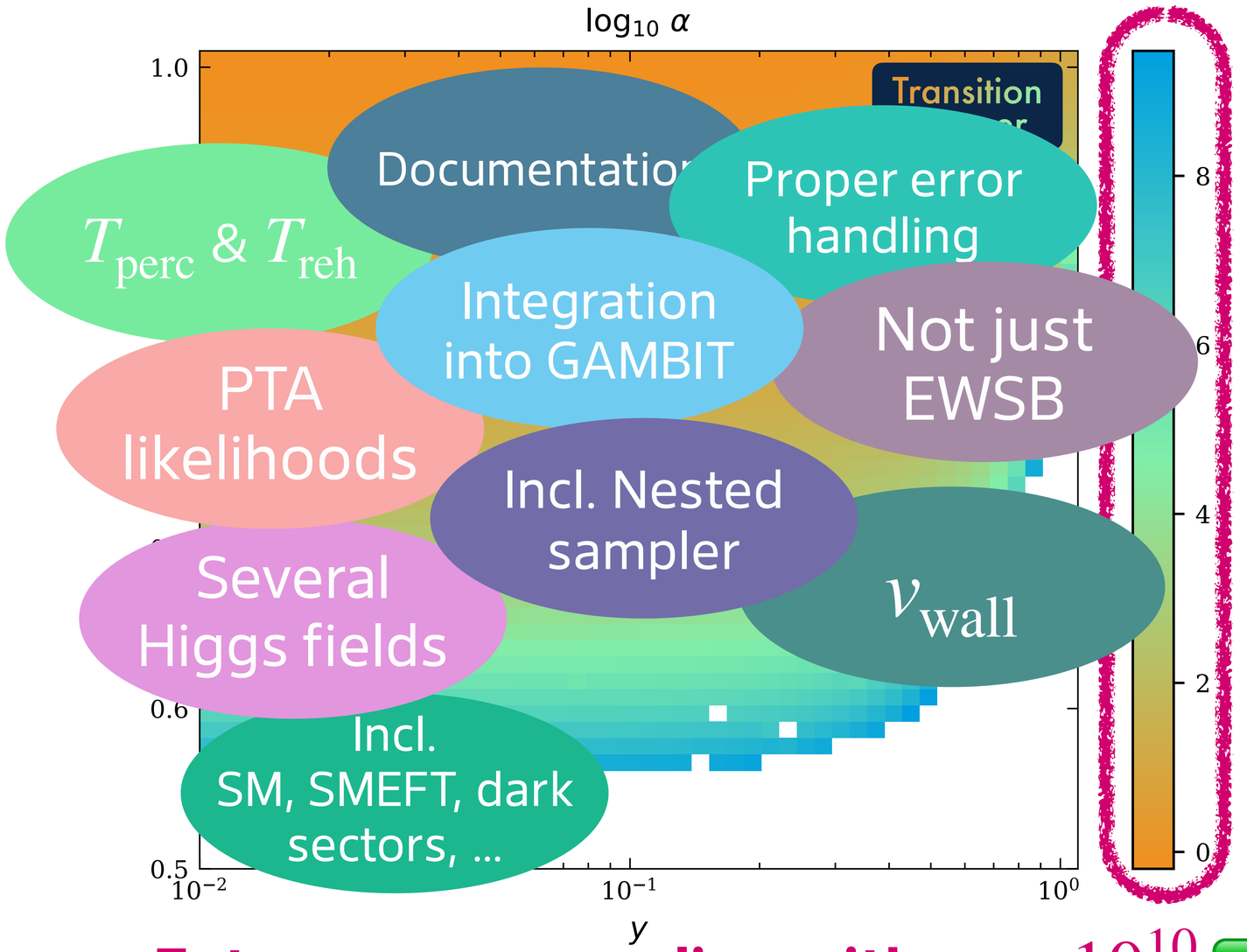

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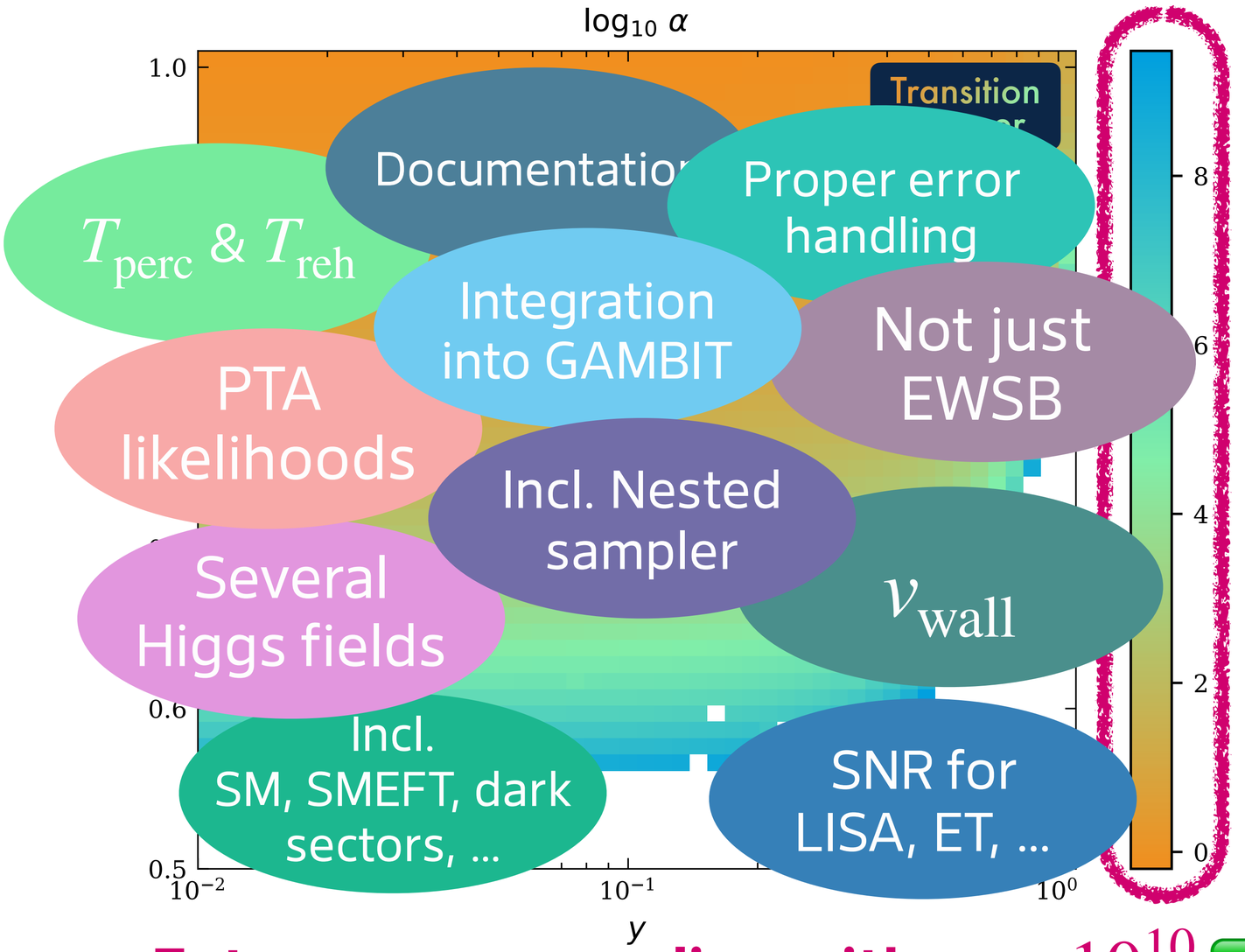

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2.0

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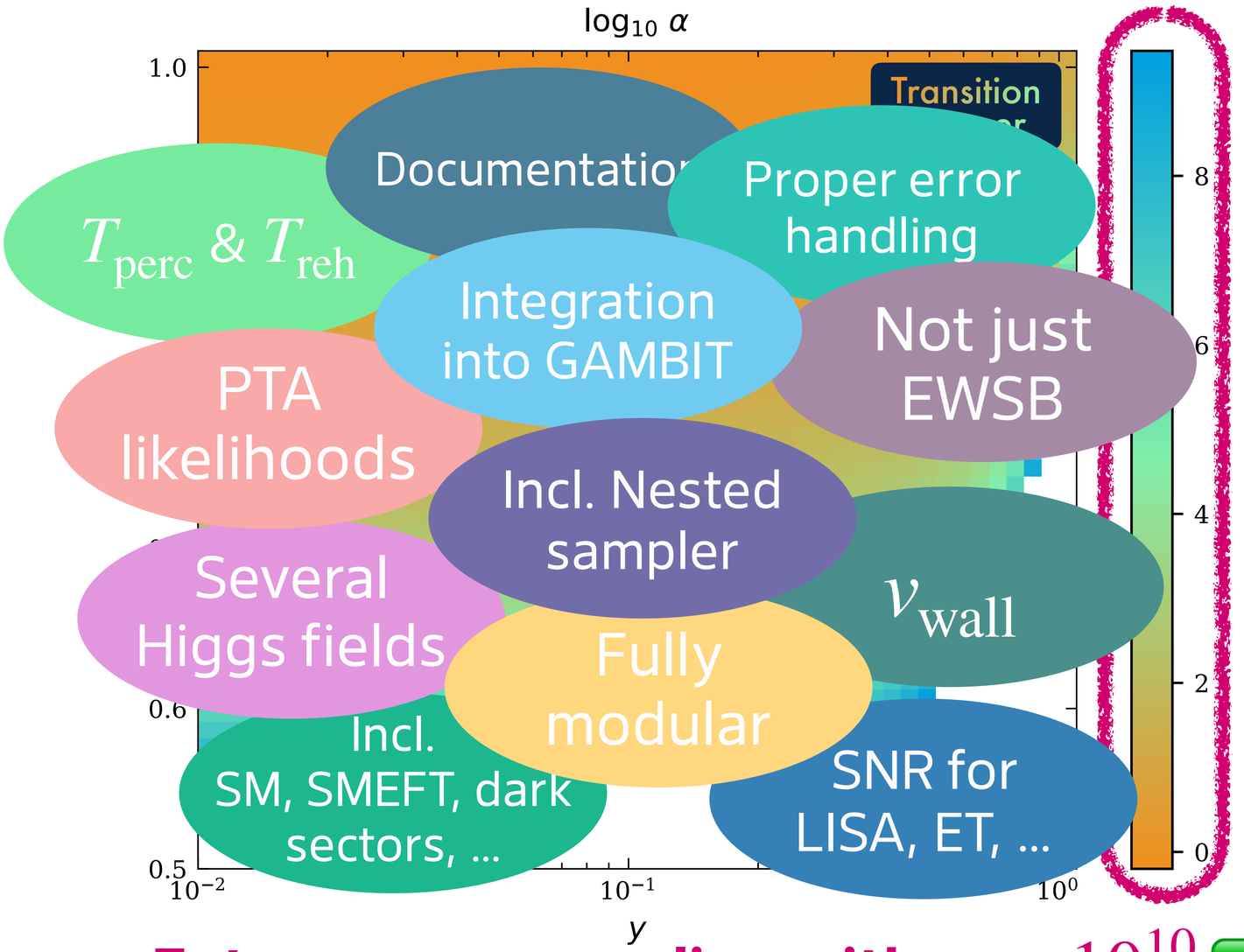

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Summary

- PTAs could have observed a dark sector phase transition on top of the black hole background
  - ➡ Dark sector phase transition can explain the PTA signal **better than only SMBHBs**
  - ➡ Performed global fit with PTA, BBN, CMB, bullet cluster, and beam dump likelihoods
  - ➡ Best-fit scenarios **can be tested by upcoming beam-dump experiments**
- ➡ **Soon: TransitionListener v2!**

Transition Listener

Thank you very much for your attention!

Do you have any questions?

Backup slides