The Nano-Hertz Gravitational Wave Background: Connection to sub-GeV dark matter

Seminar at IFIC, October 16th 2025

Carlo Tasillo,
Uppsala University (Soon: IFIC! 🥳)

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

JCAP 11 (2023) 053,
JCAP 08 (2025) 062,
and **Phys.Rev.Res. 7 (2025)**

DESY.

UPPSALA UNIVERSITET

UNTERSTÜTZT VON / SUPPORTED BY
Alexander von HUMBOLDT STIFTUNG

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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

Our Solar System

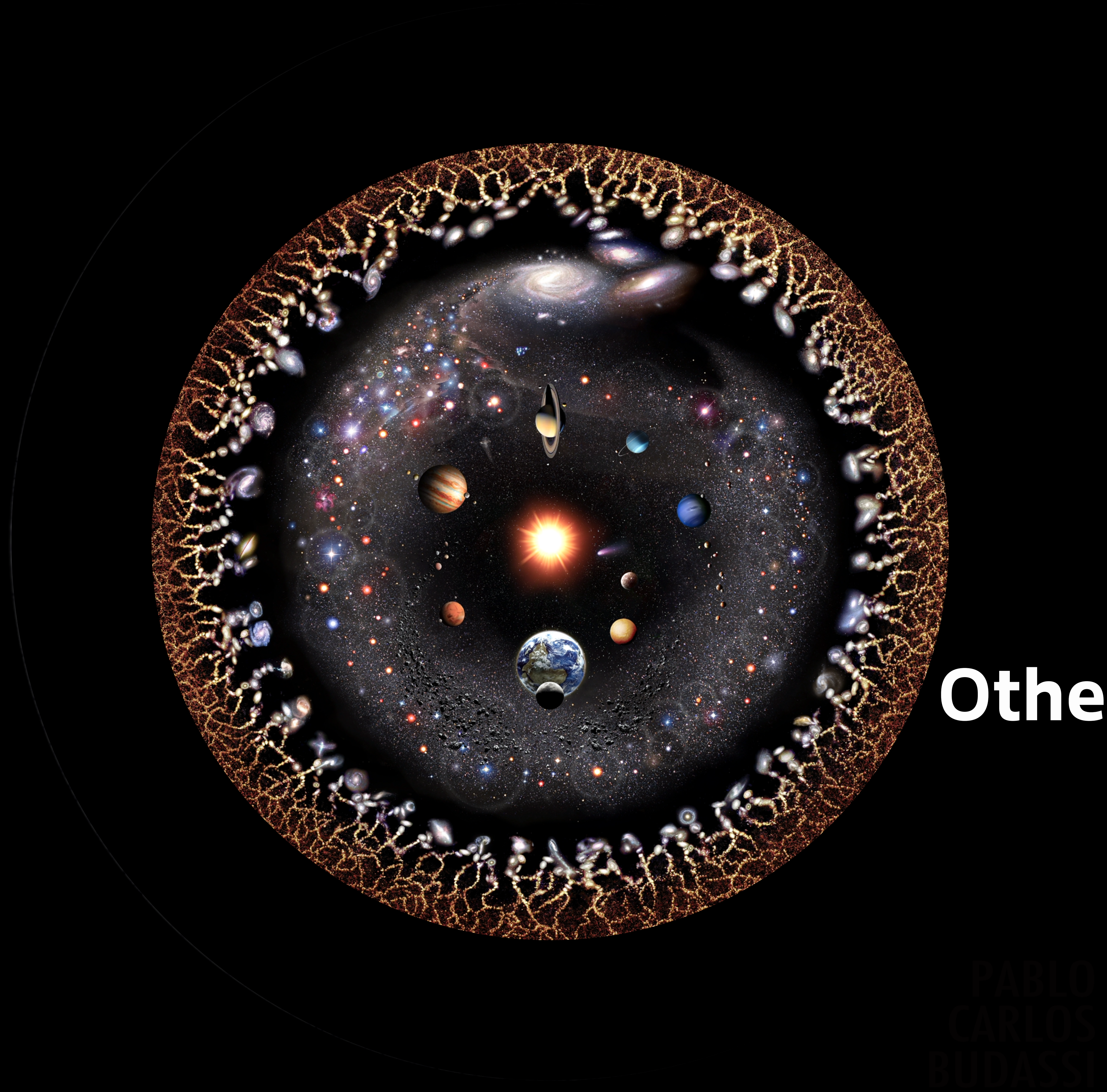
[Pablo Carlos Budassi]

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

Our galaxy

[Pablo Carlos Budassi]

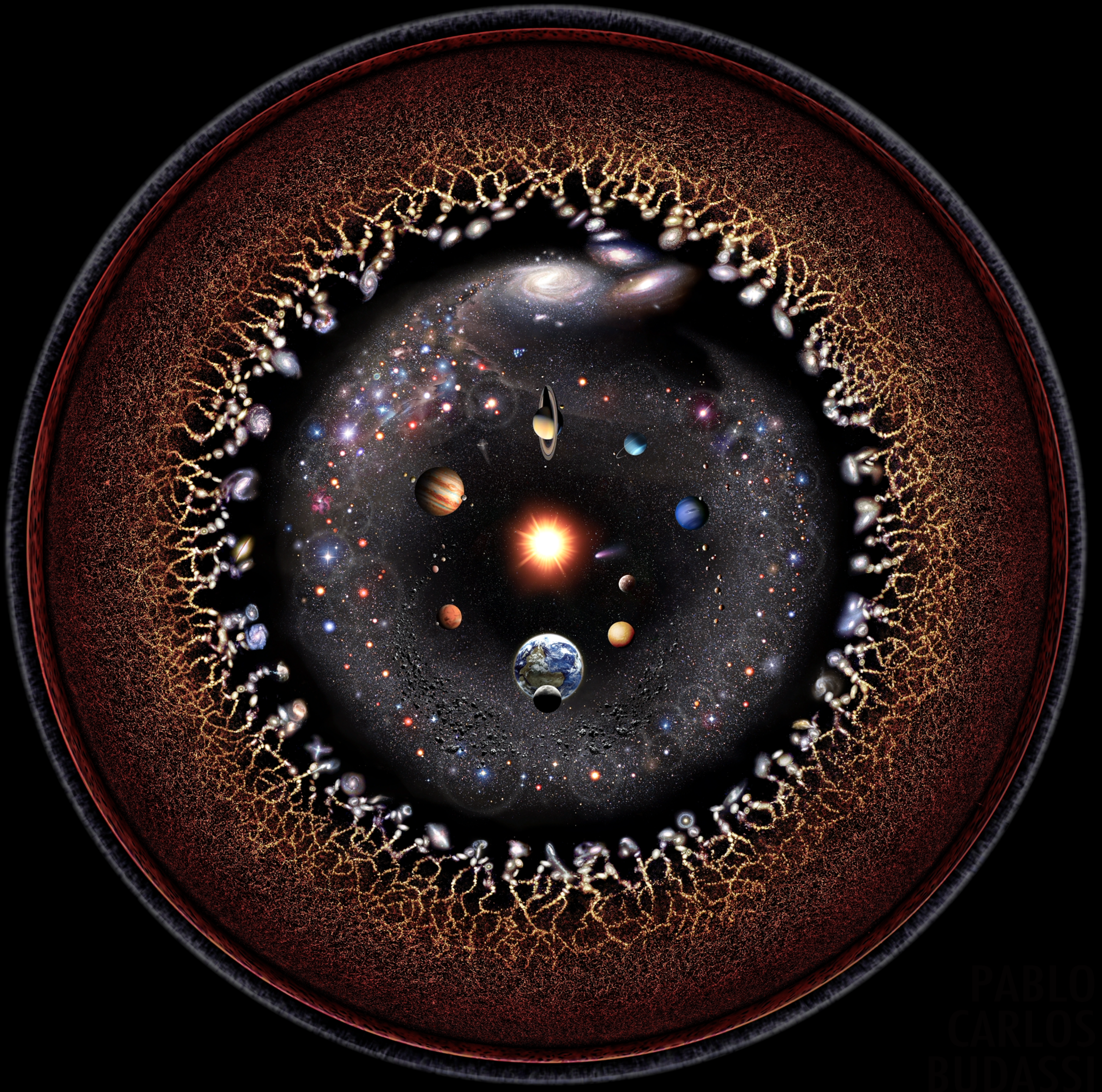
It’s the end of the world as we know it (and I feel fine)



Other galaxies

[Pablo Carlos Budassi]

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



The CMB...
and the CGWB?

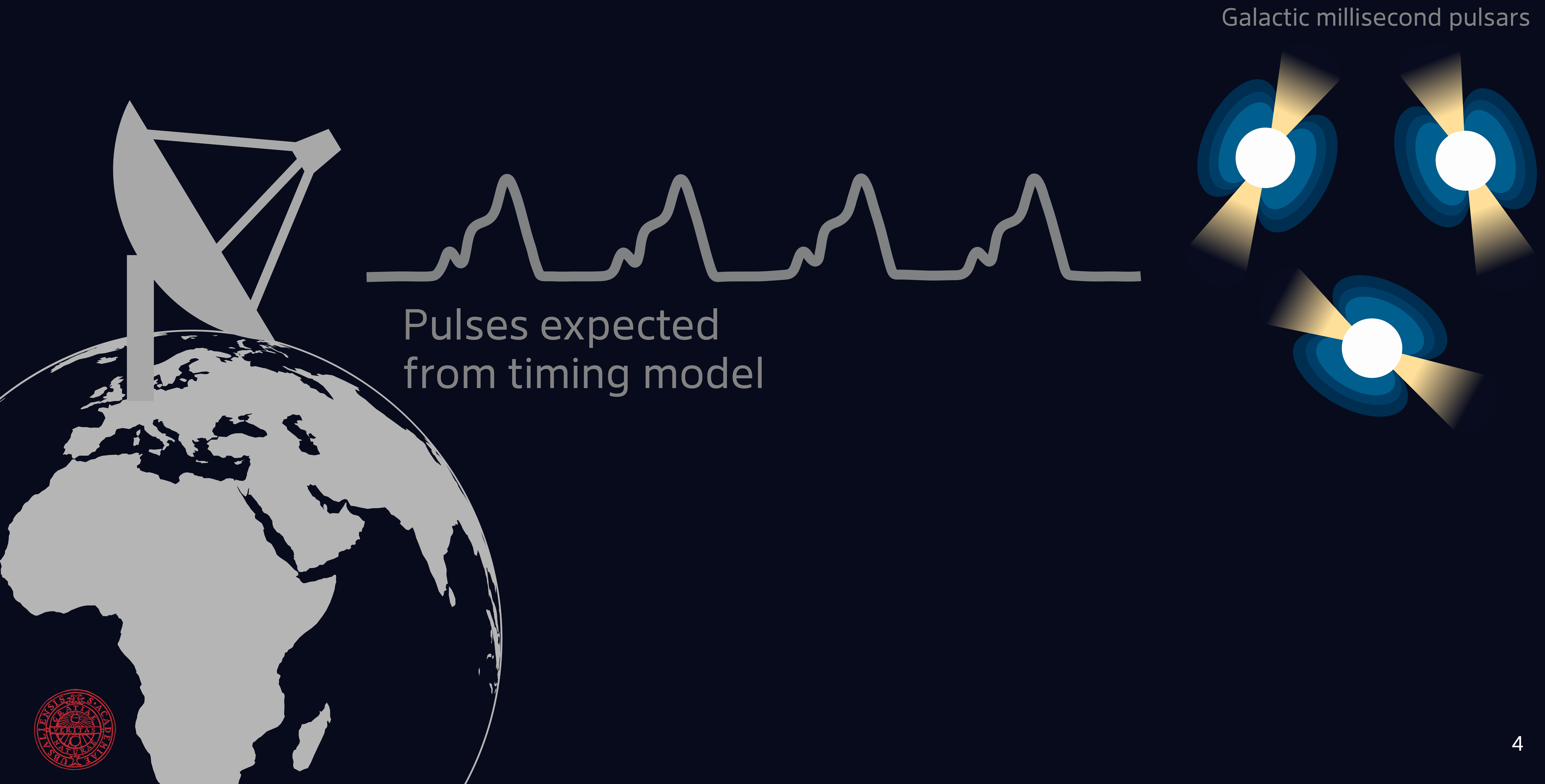
[Pablo Carlos Budassi]

At Last, There's
Astronomers detect 'cosmic bass note' of gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists
of Low-Frequency Gravitational Wa
For first time ever, scientists "hear" gravitational waves rippling through the universe
First Evidence of Giant Gravitational Waves Thrills Astronomers
Scientists 'hear' cosmic hum from gravitational waves
Scientists observed for the first time faint ripples caused by the motion of black
ing everything in the universe.
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
are tuning in to a never-before-seen type of gravitational
spawned by pairs of supermassive black holes
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
Monster gravitational
spotted for first
The New York Times
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find
Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.
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
ntists discover that universe is
gravitational waves
Galaxy
Space
Gravitational wave
at the center of the M
Scientists r
come from
holes
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 gravit
gravitational wave
lock our
teries
Physics
Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe
The results are
background, a hum
Universe.

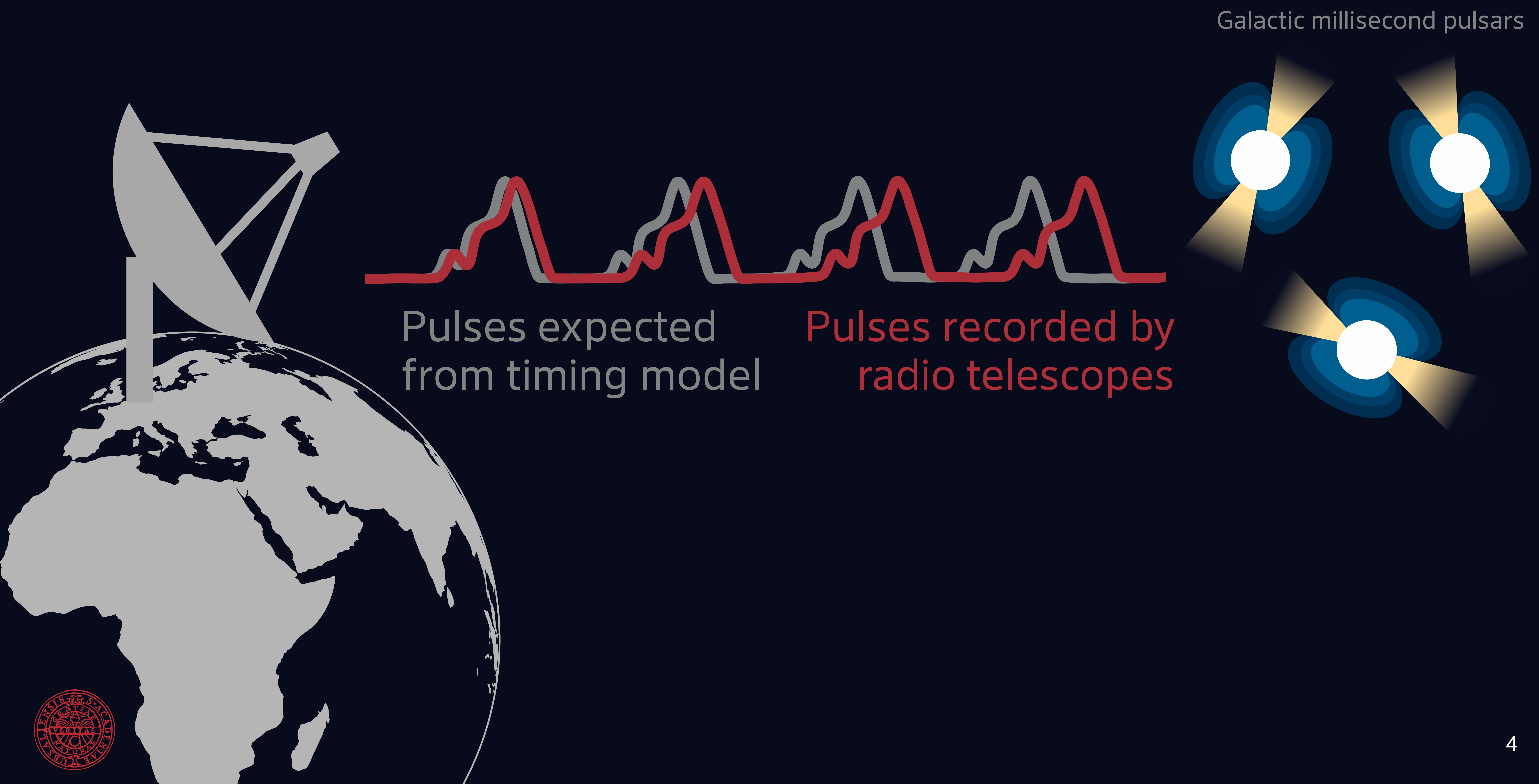
We live in the age of gravitational wave cosmology!

The working principle of a pulsar timing array

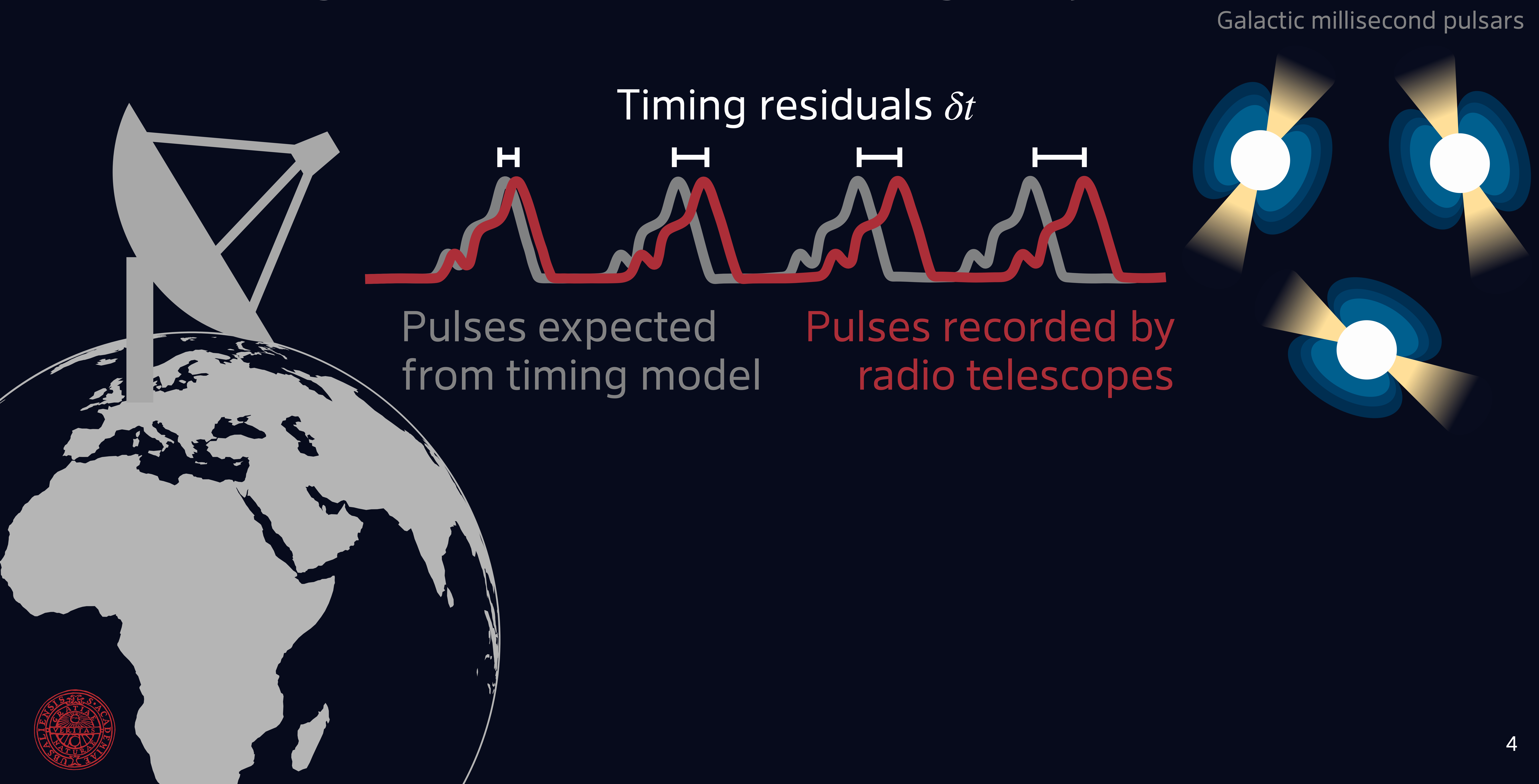
The working principle of a pulsar timing array



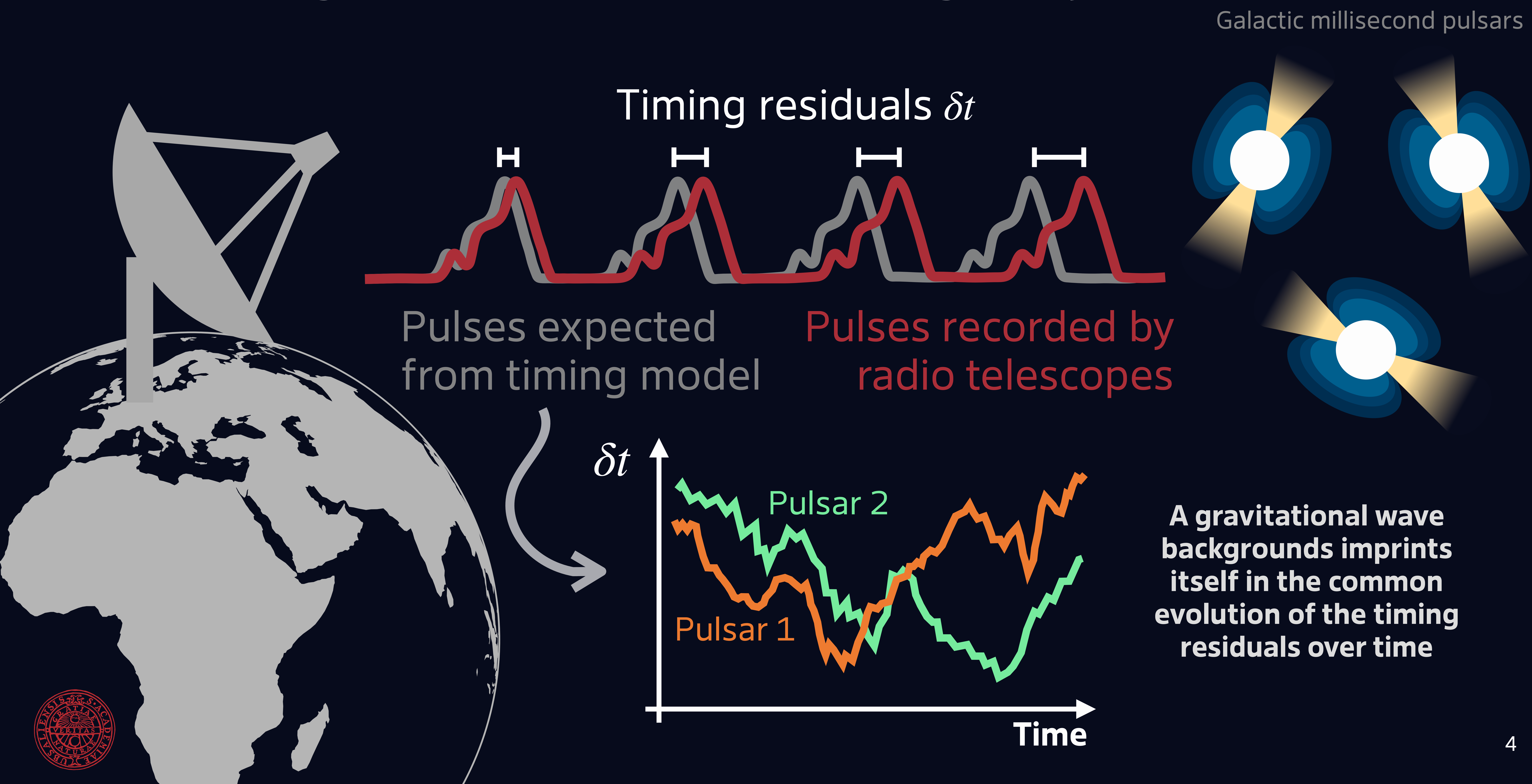
The working principle of a pulsar timing array



The working principle of a pulsar timing array

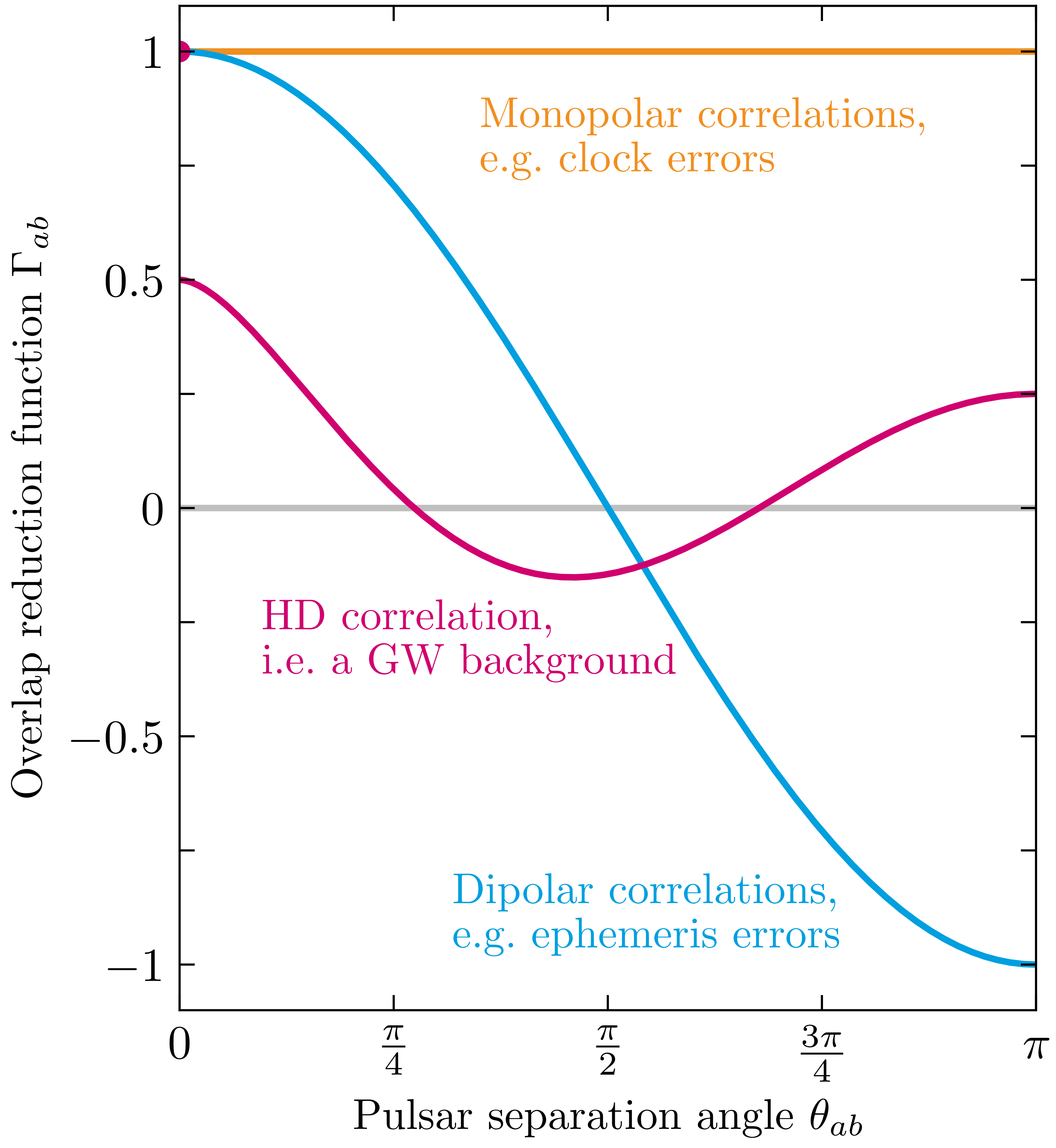


The working principle of a pulsar timing array



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

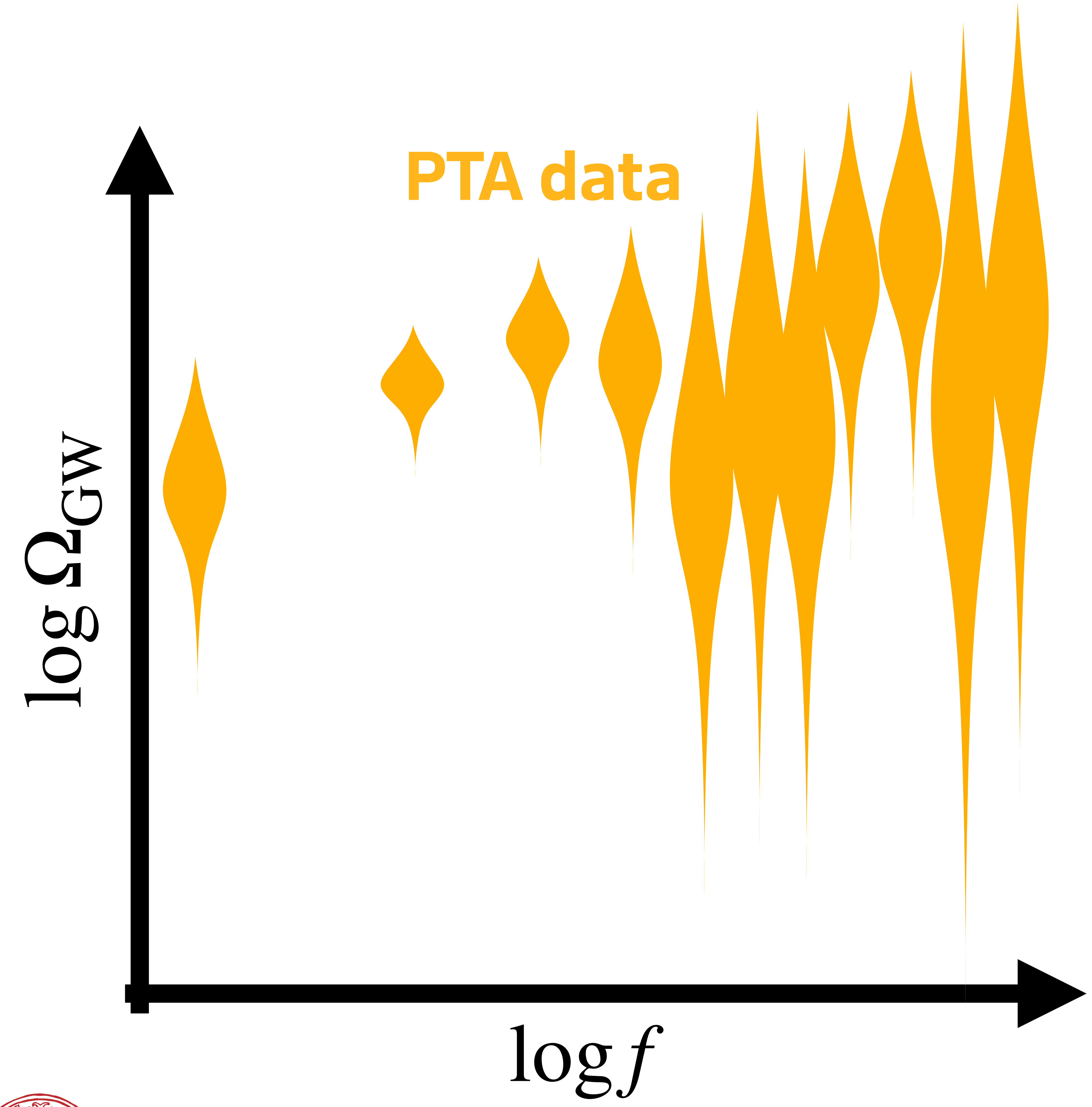
Searching for the Hellings-Downs correlation



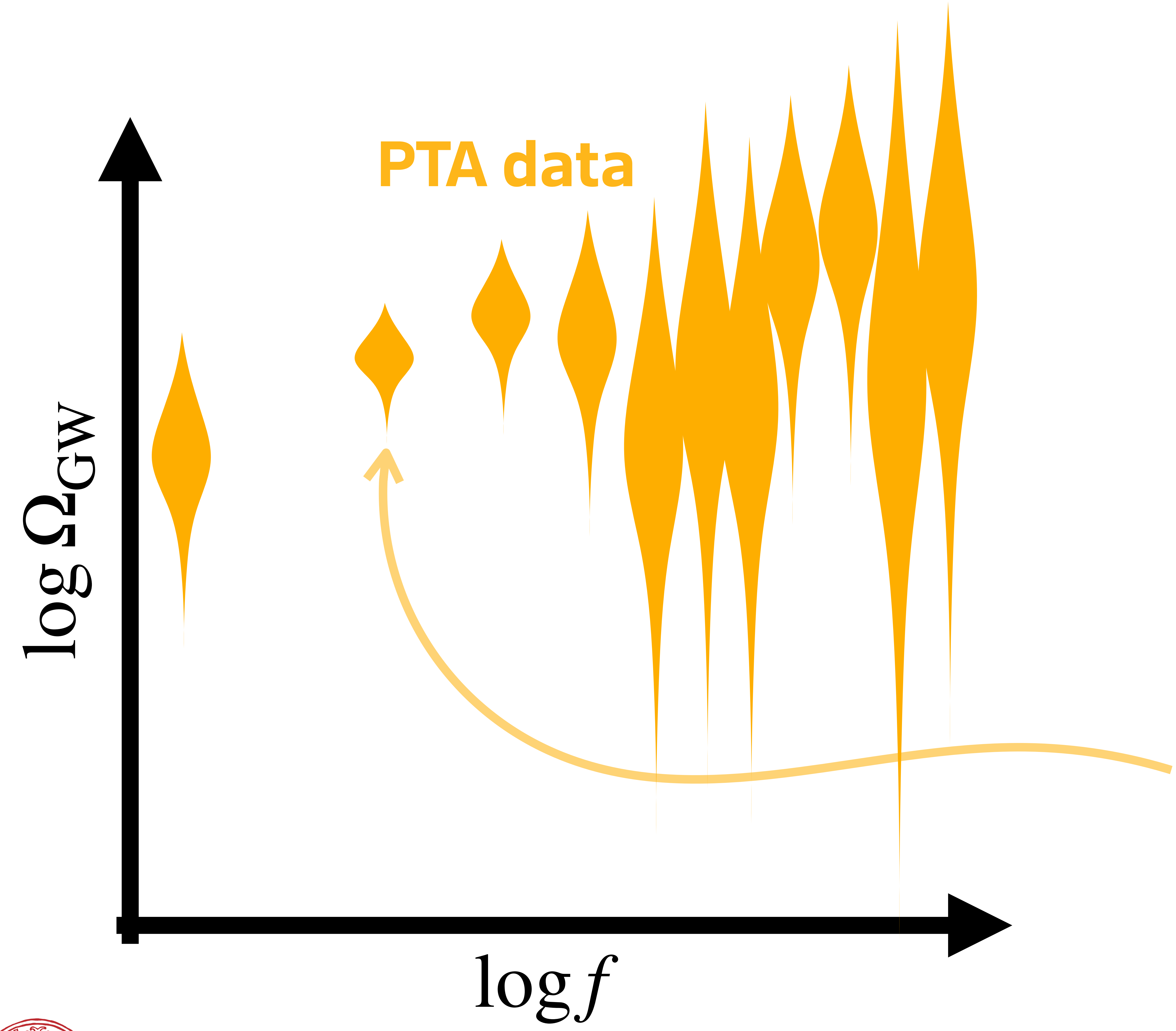
- PTAs found an underlying „common red process" among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves, Clock errors, Ephemeris errors:
    All ruled at with >5σ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]

What is the source?

Learning to play the violin

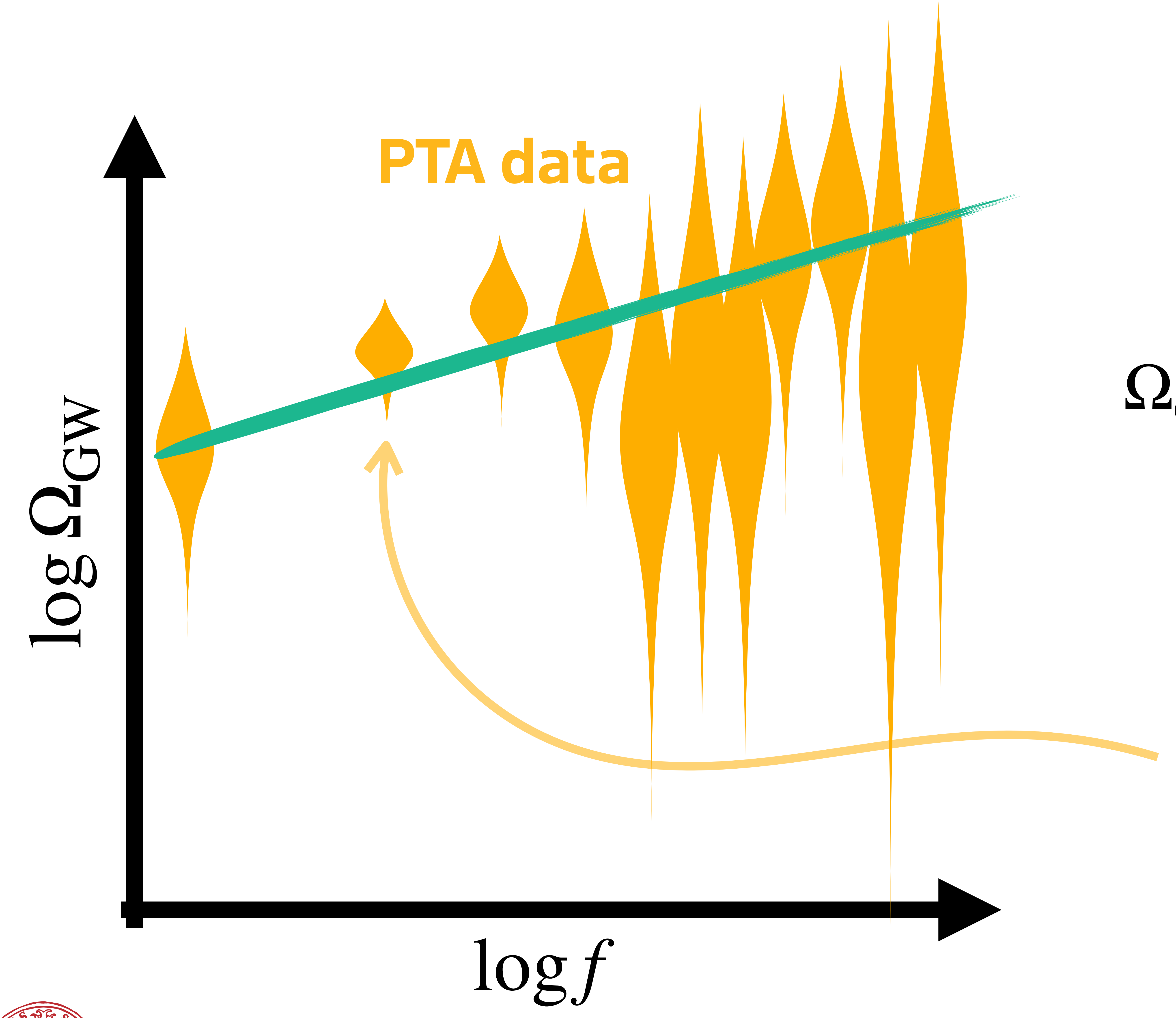


Learning to play the violin



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

Learning to play the violin

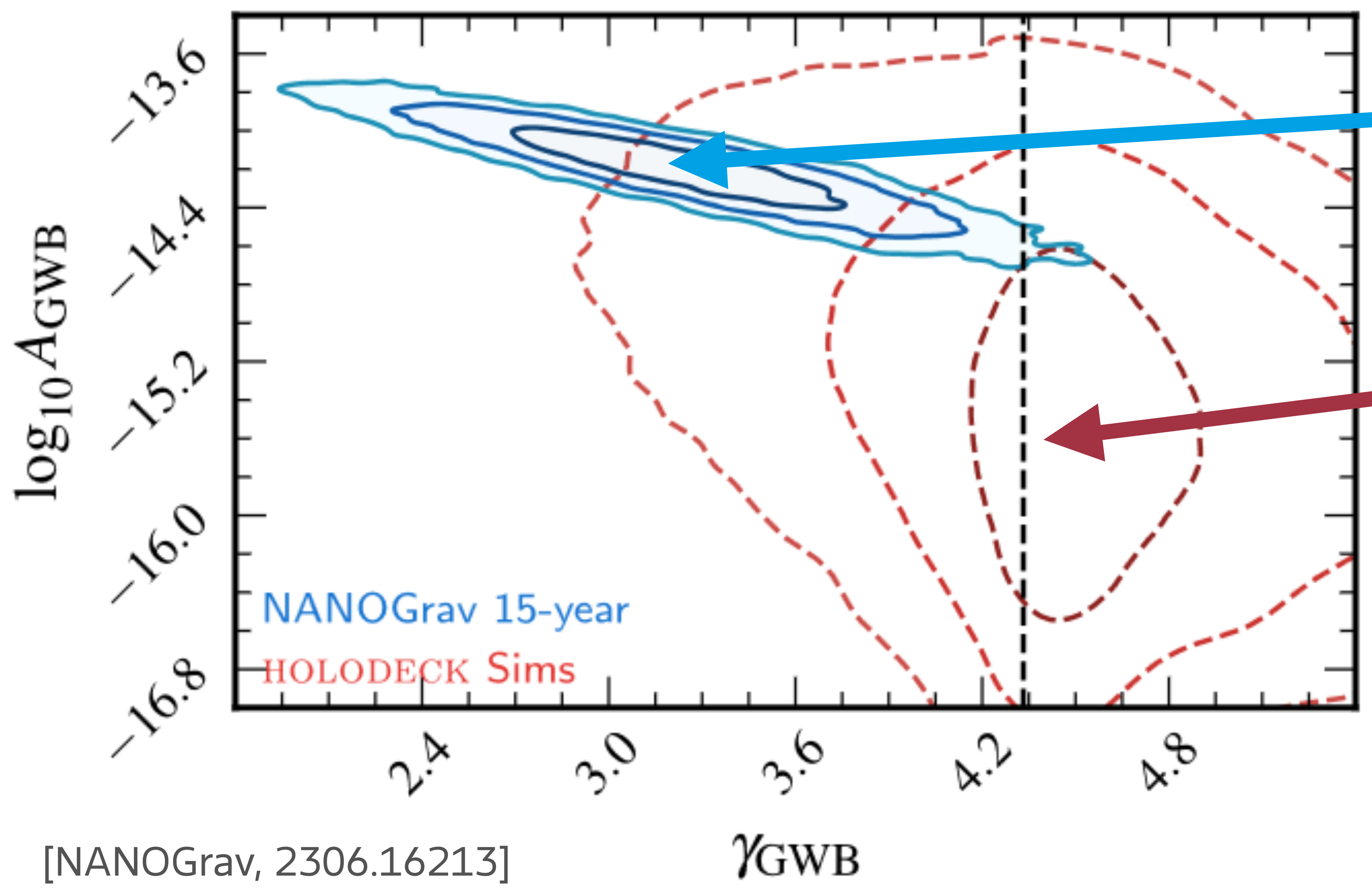


The inferred spectral shape of the GWB is well described by a power law

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

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.

Merging supermassive black holes

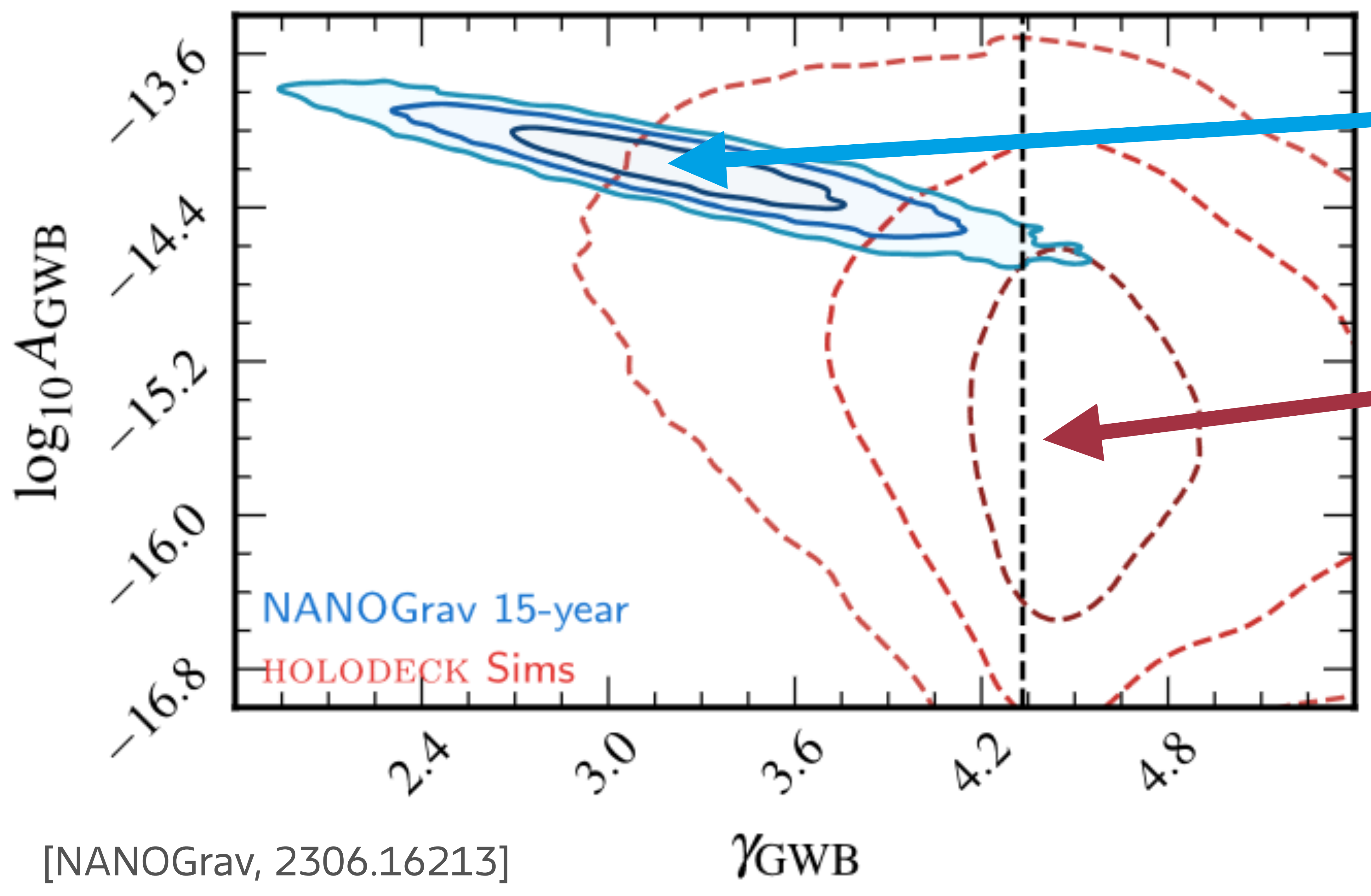


[NANOGrav, 2306.16213]

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

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

Merging supermassive black holes



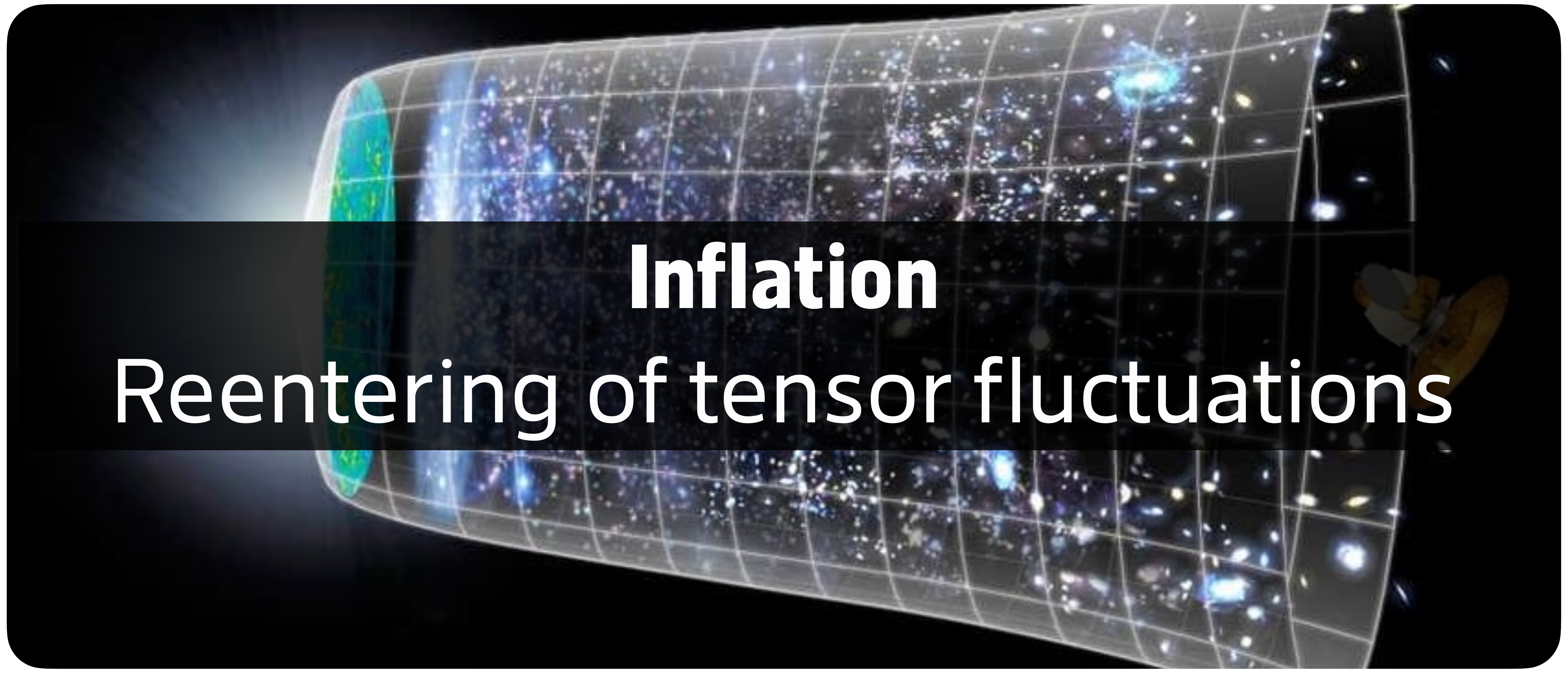
[NANOGrav, 2306.16213]

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

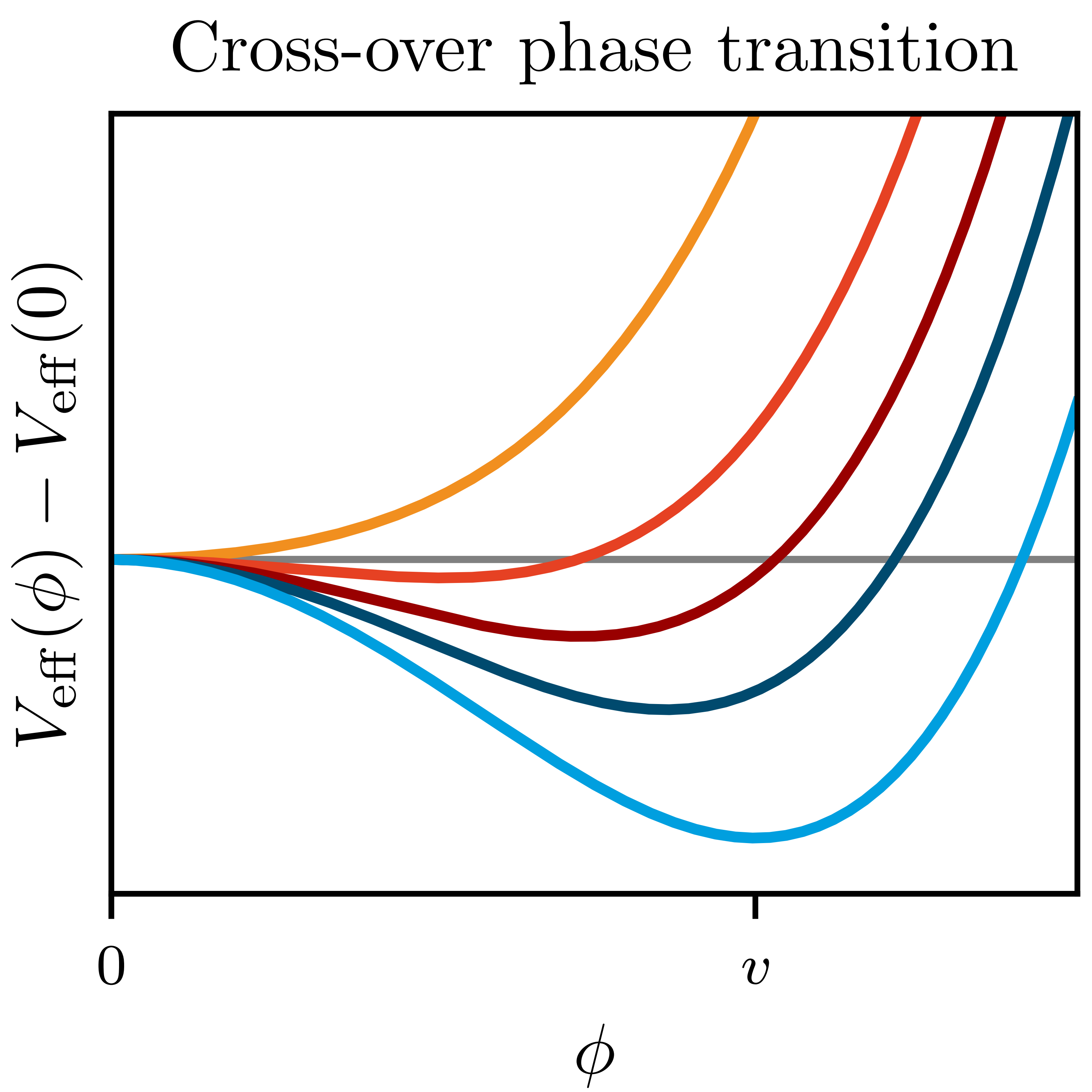
Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ (more power in low frequencies)

Are there other signal sources?

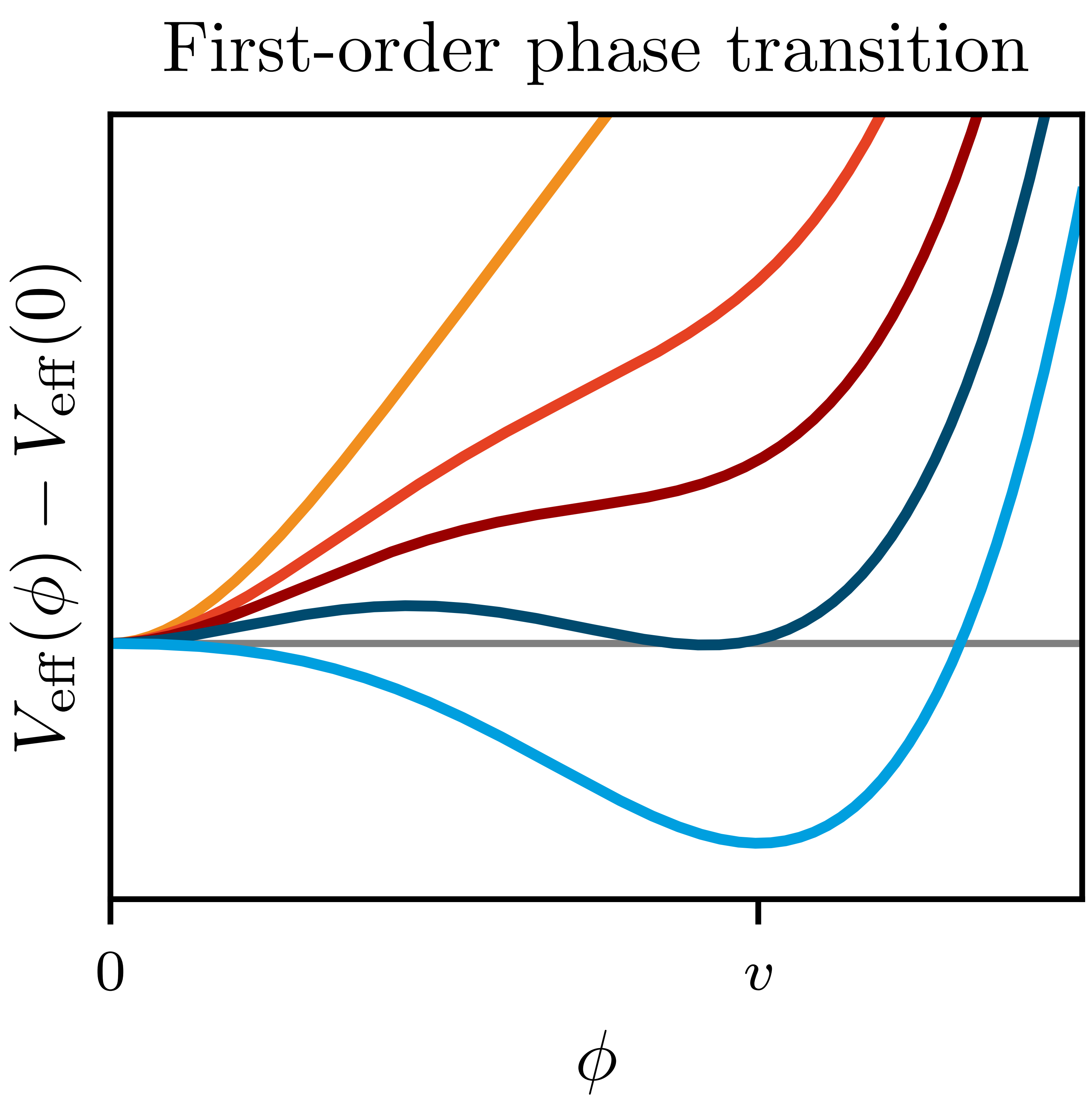
Possible cosmological sources of the PTA signal



First-order phase transitions vs. cross-overs



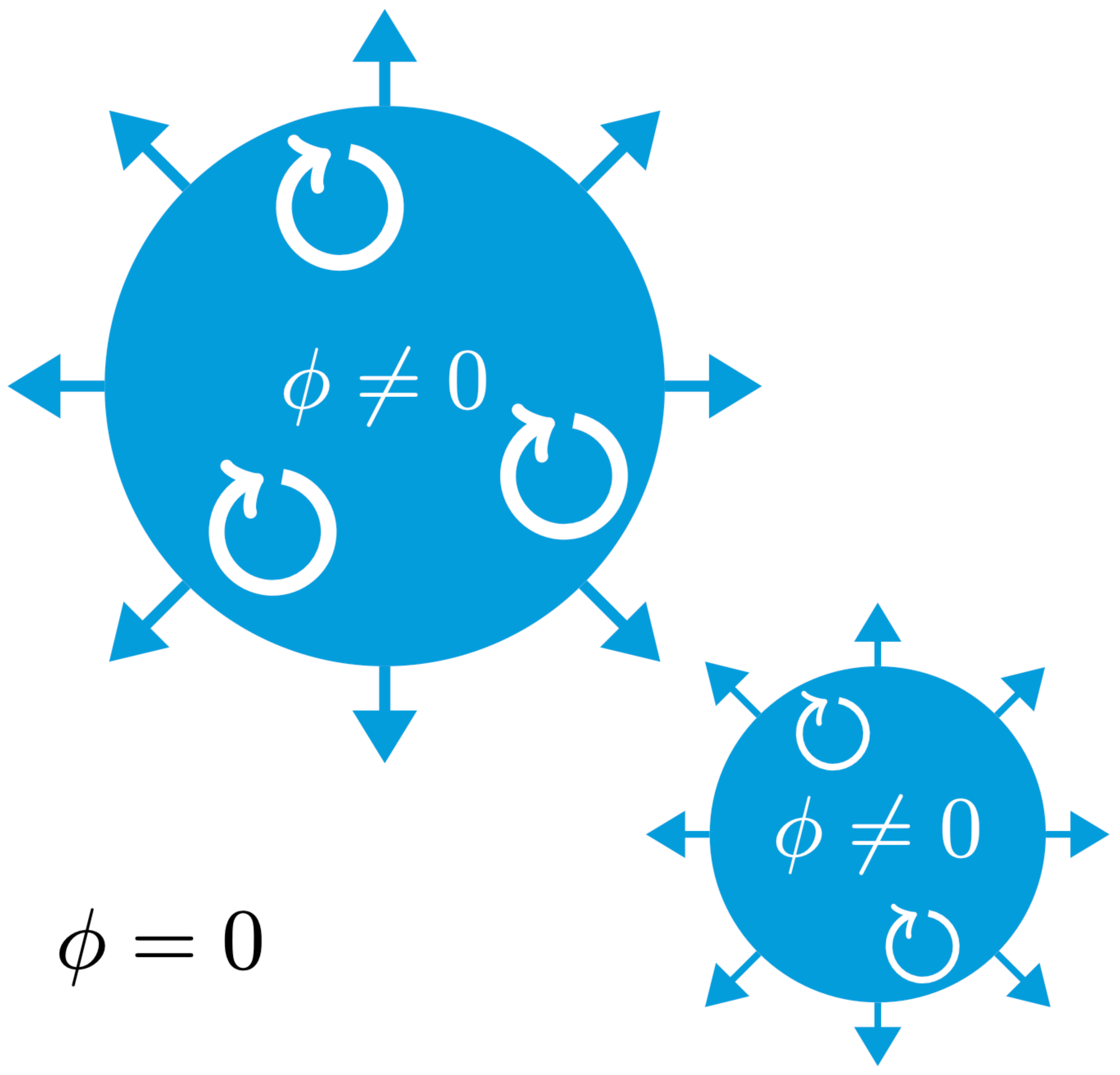
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

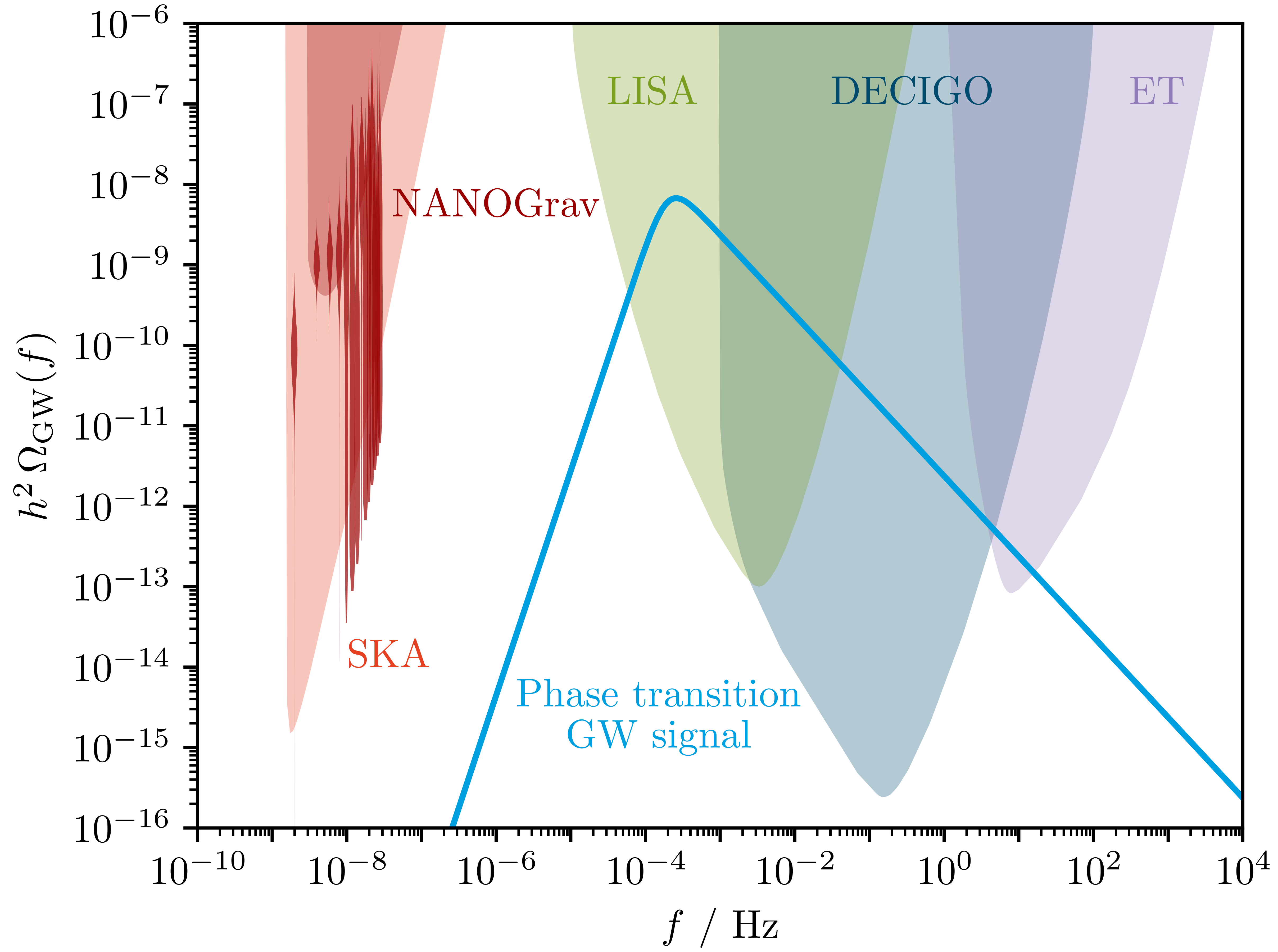


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy.

First-order phase transitions produce GWs

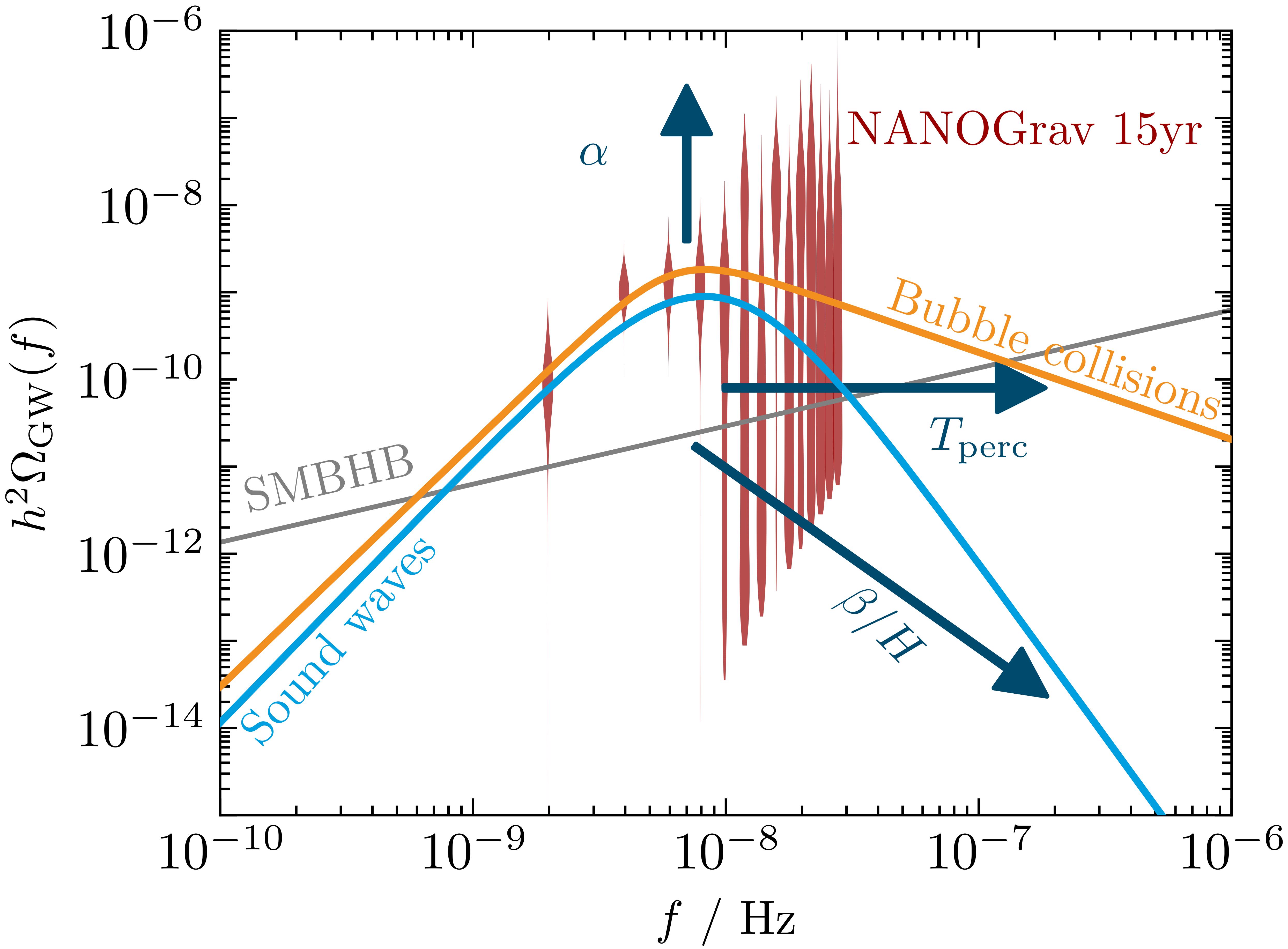
Bubbles of the new phase nucleate, collide and perturb the plasma...





... giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

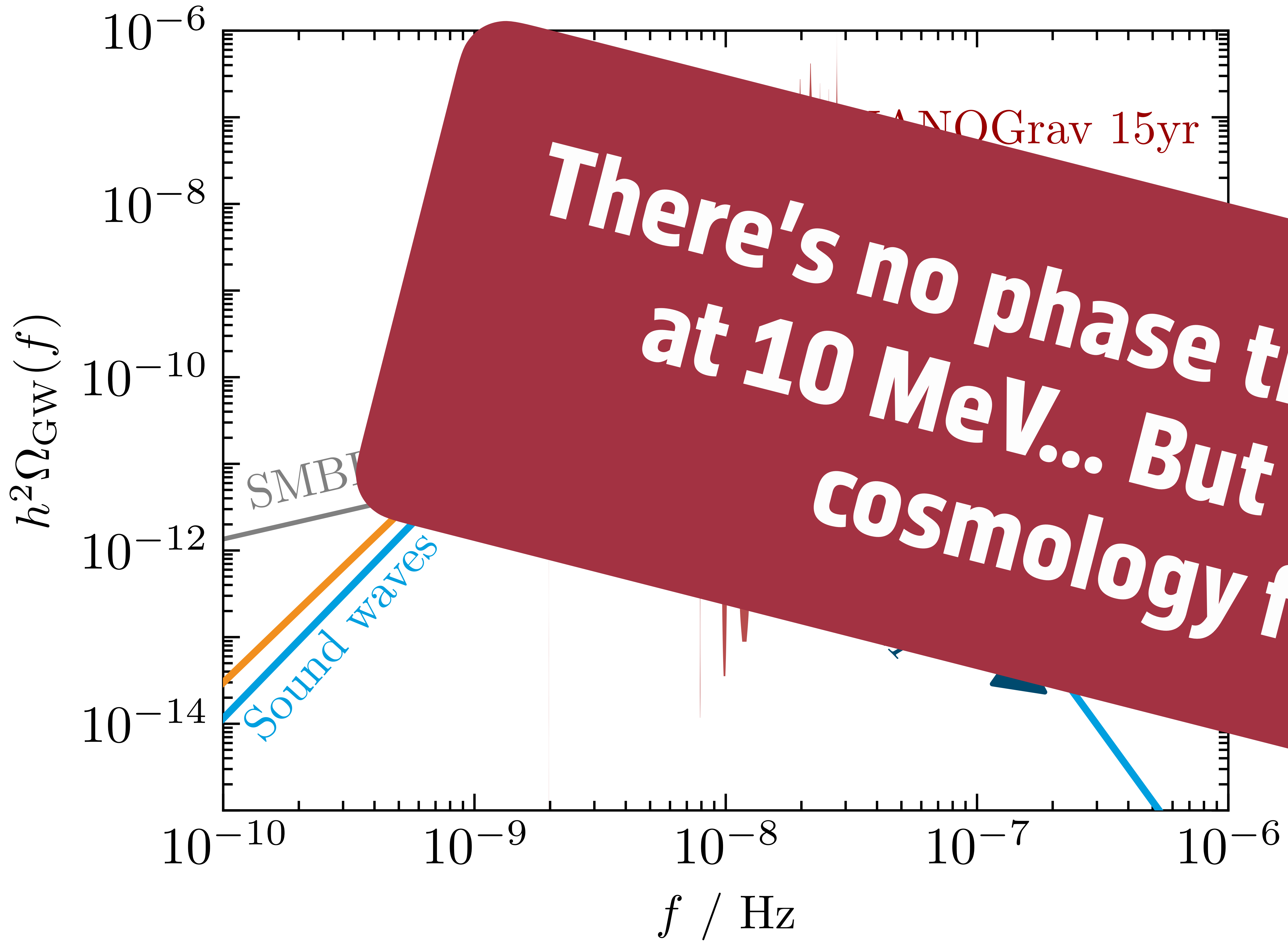
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal



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

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

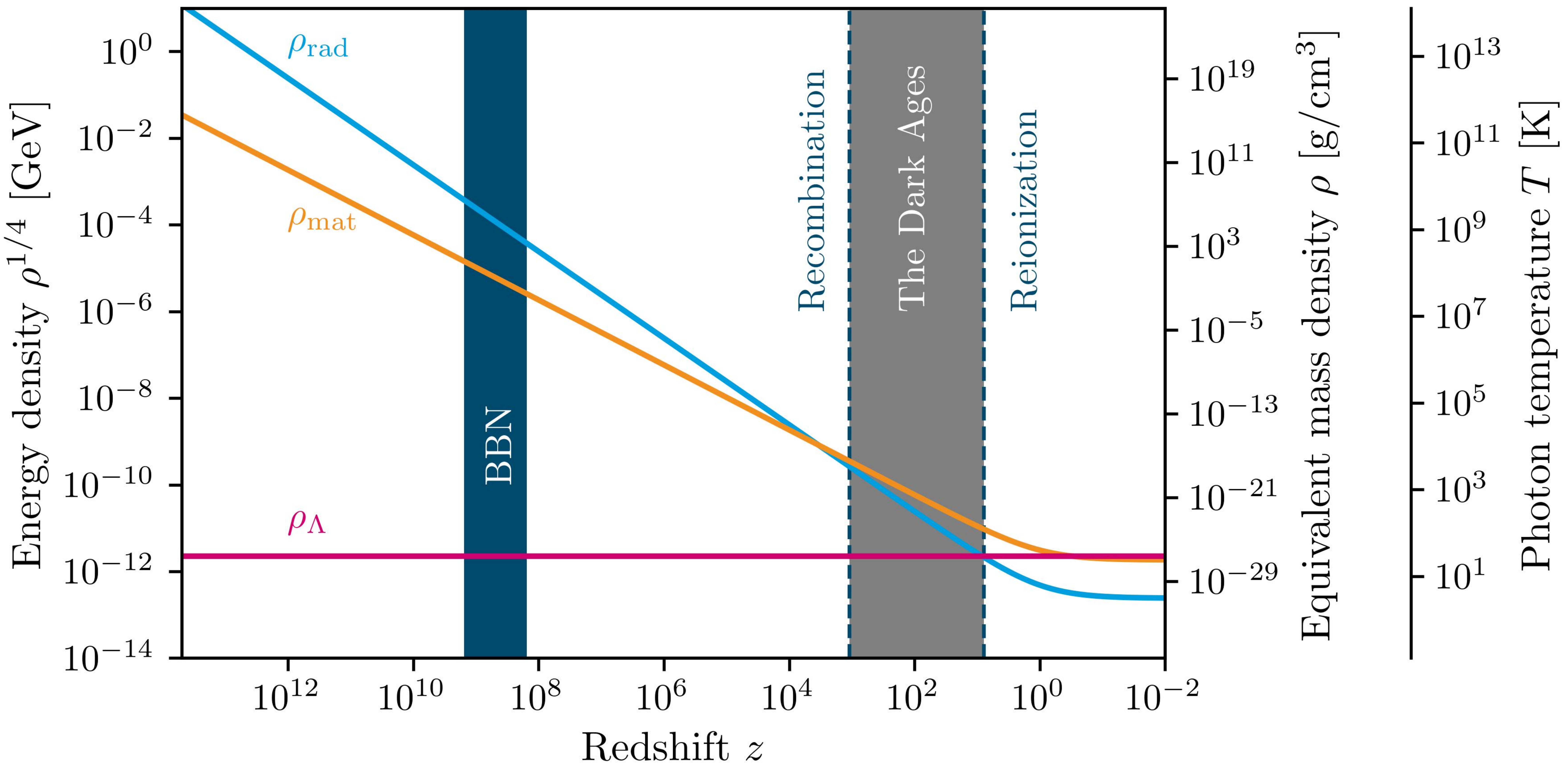
with $\quad f_{\rm peak} \simeq 0.1\,{\rm nHz} \times \frac{\beta}{H} \times \frac{T}{\rm MeV}$

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

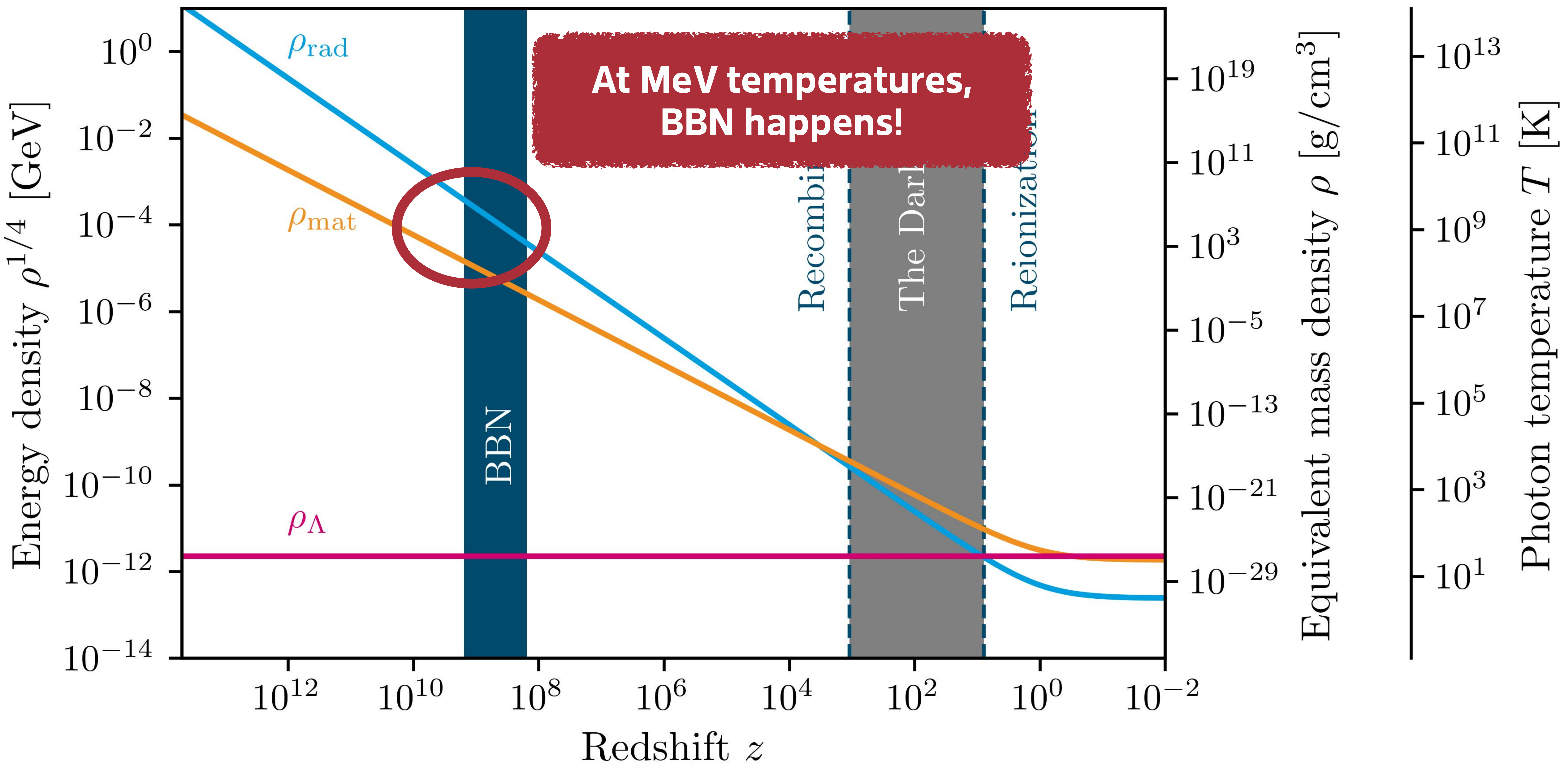
...ing data:

- ... 1
- ... ≈ 10
- Percolati... $\approx 10\,{\rm MeV}$

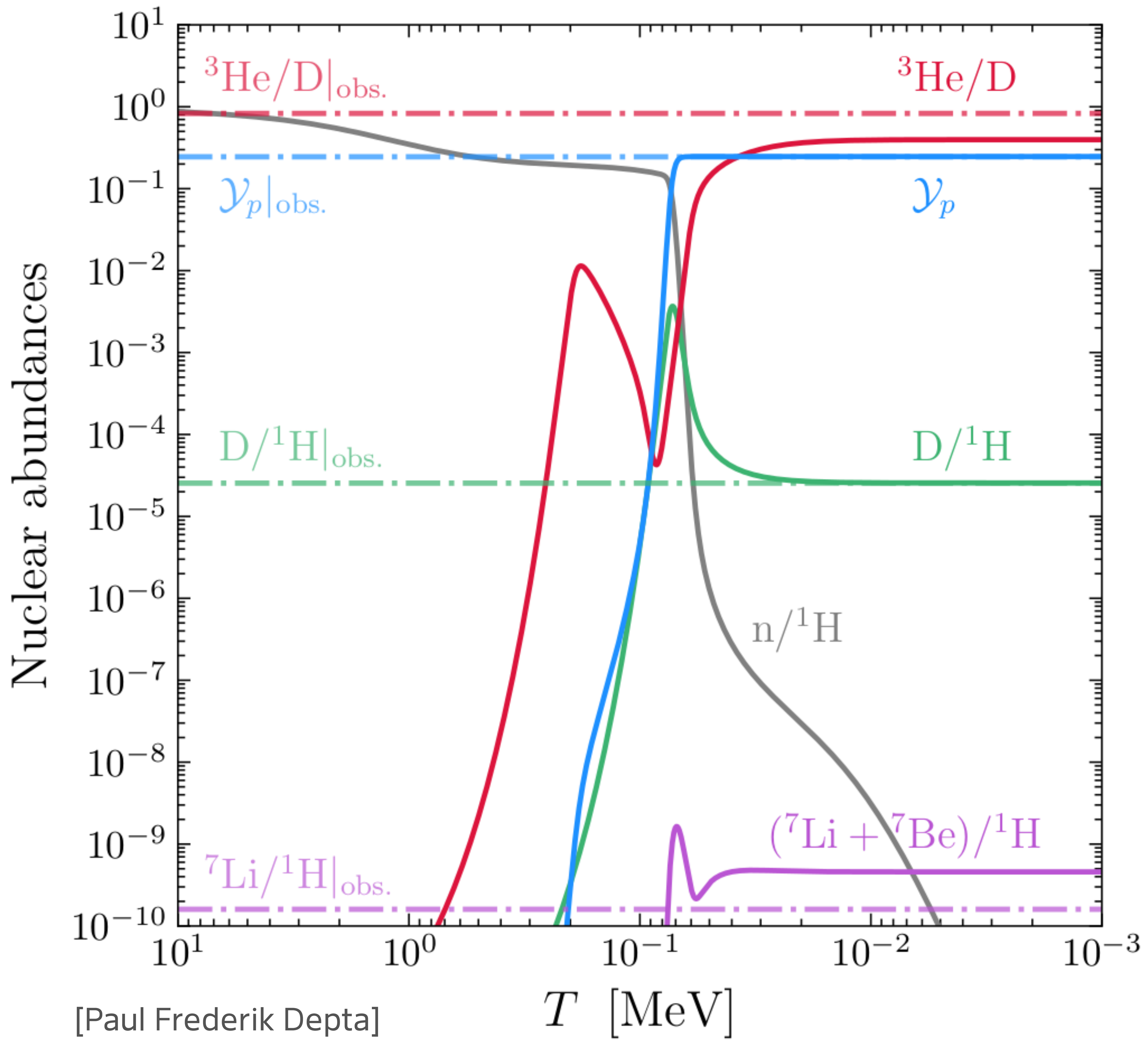
A brief history of time



A brief history of time



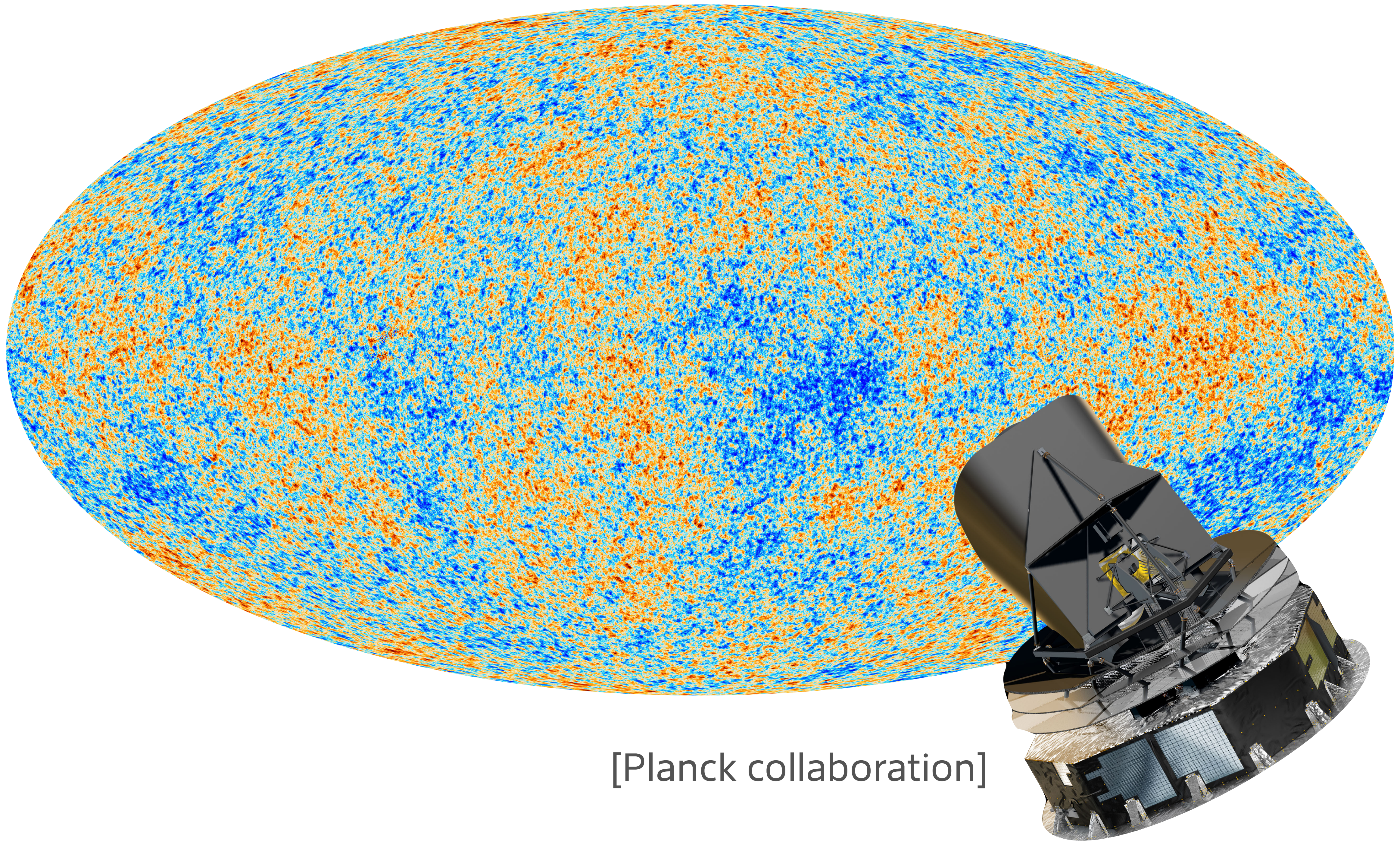
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

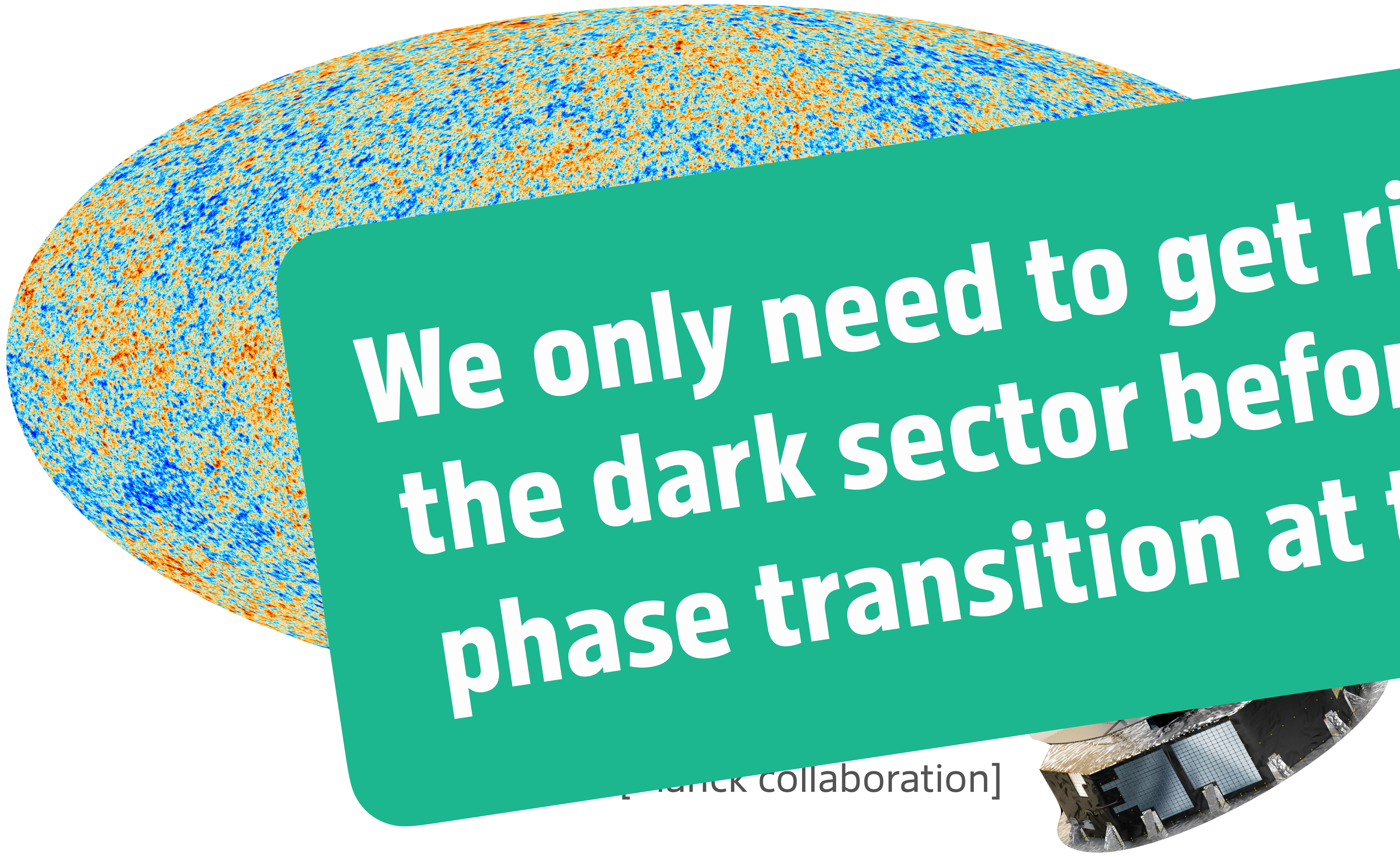
Big Bang Nucleosynthesis and the CMB



[Planck collaboration]

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

Big Bang Nucleosynthesis and the CMB

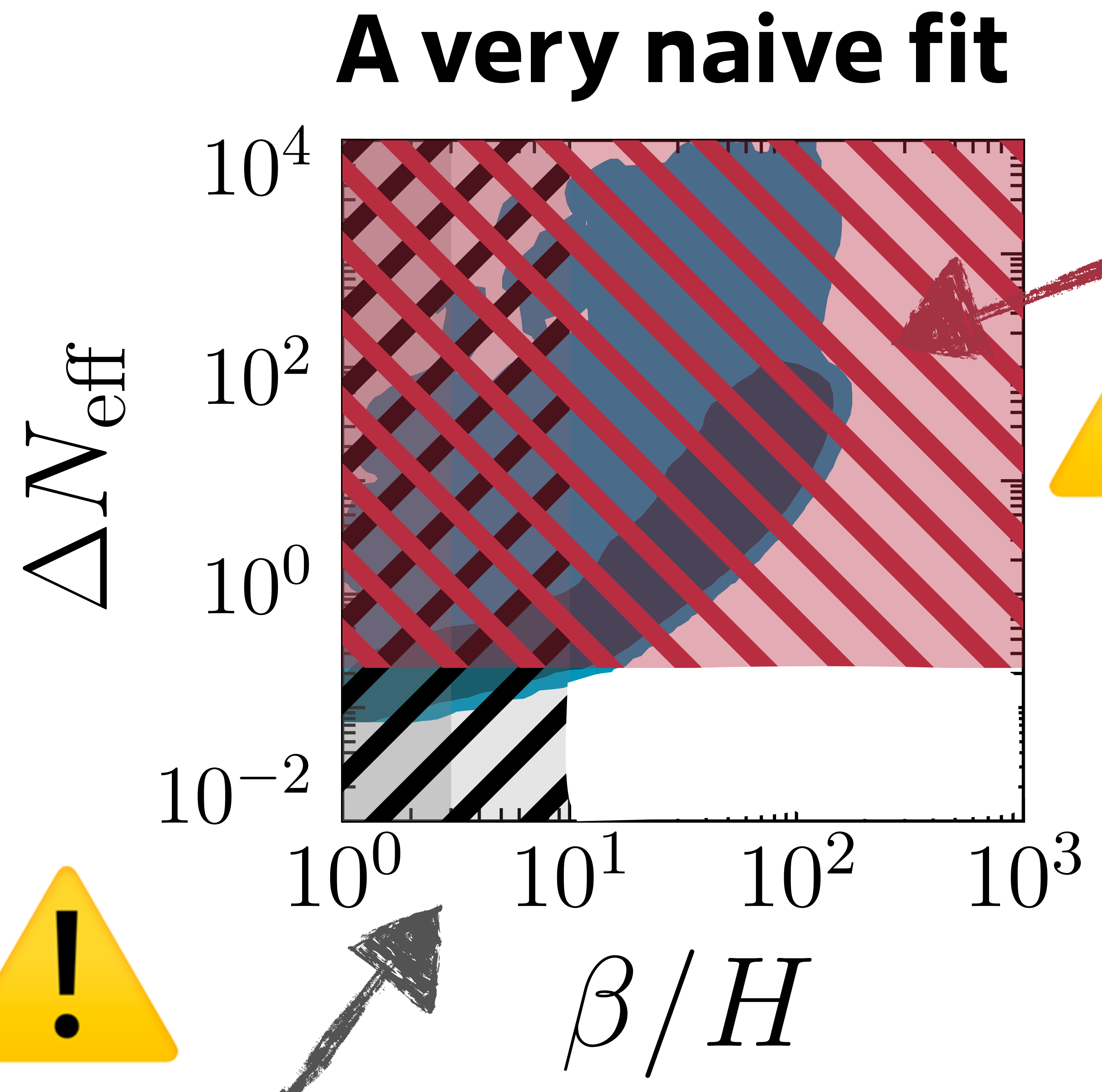


[...anck collaboration]

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 ... mordial
  ... ances in
  ... h
  ... 41
  ... eff ... 2.99 ± 0.17
- Consistent with 3 SM neutrinos

A dark sector without portal couplings



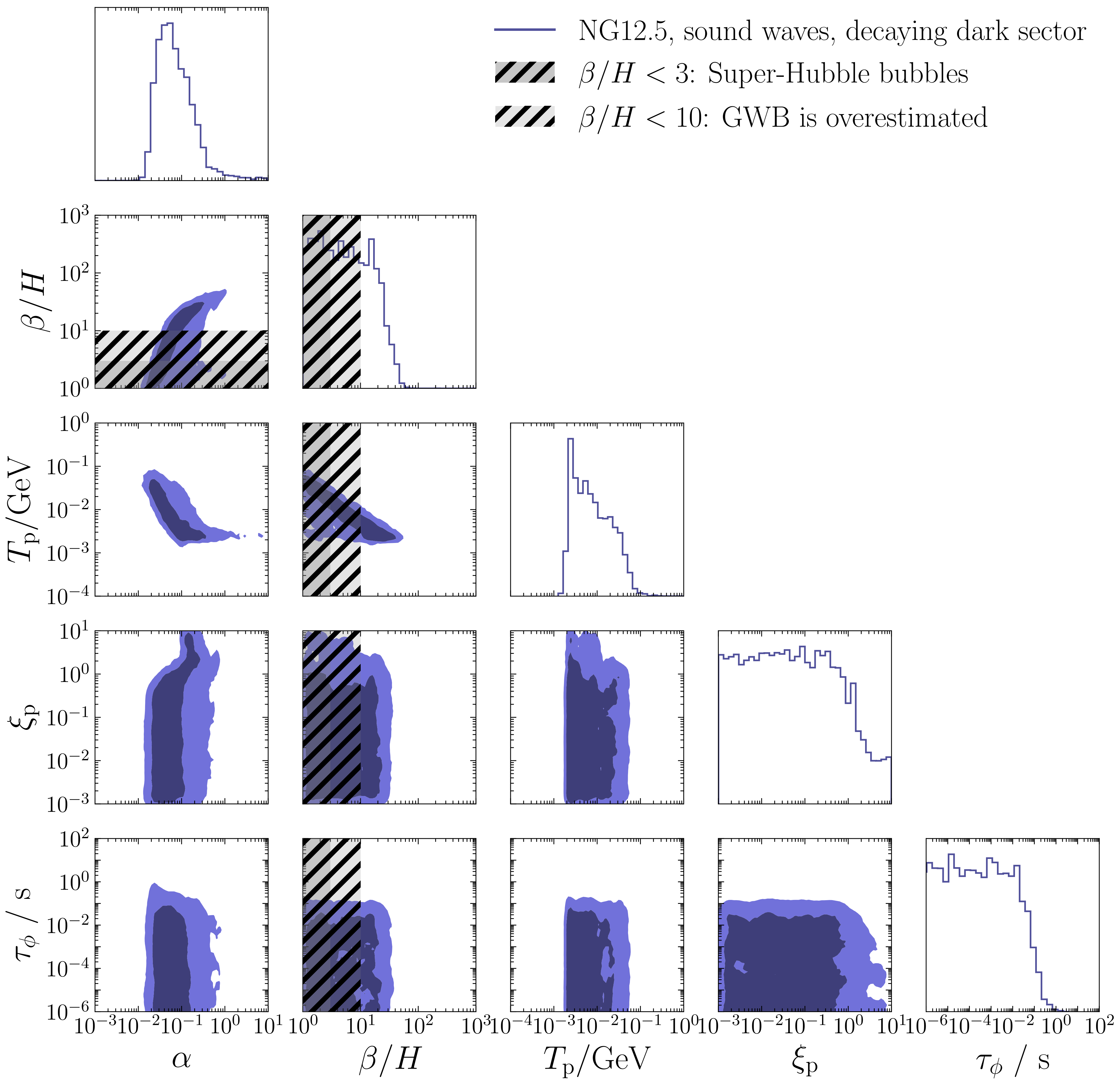
The liberated vacuum energy remains in the dark sector. A good fit would require enormous $\Delta N_{\rm eff} \gg 0.22$

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

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

The dark sector must die for the GWs to live…

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



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

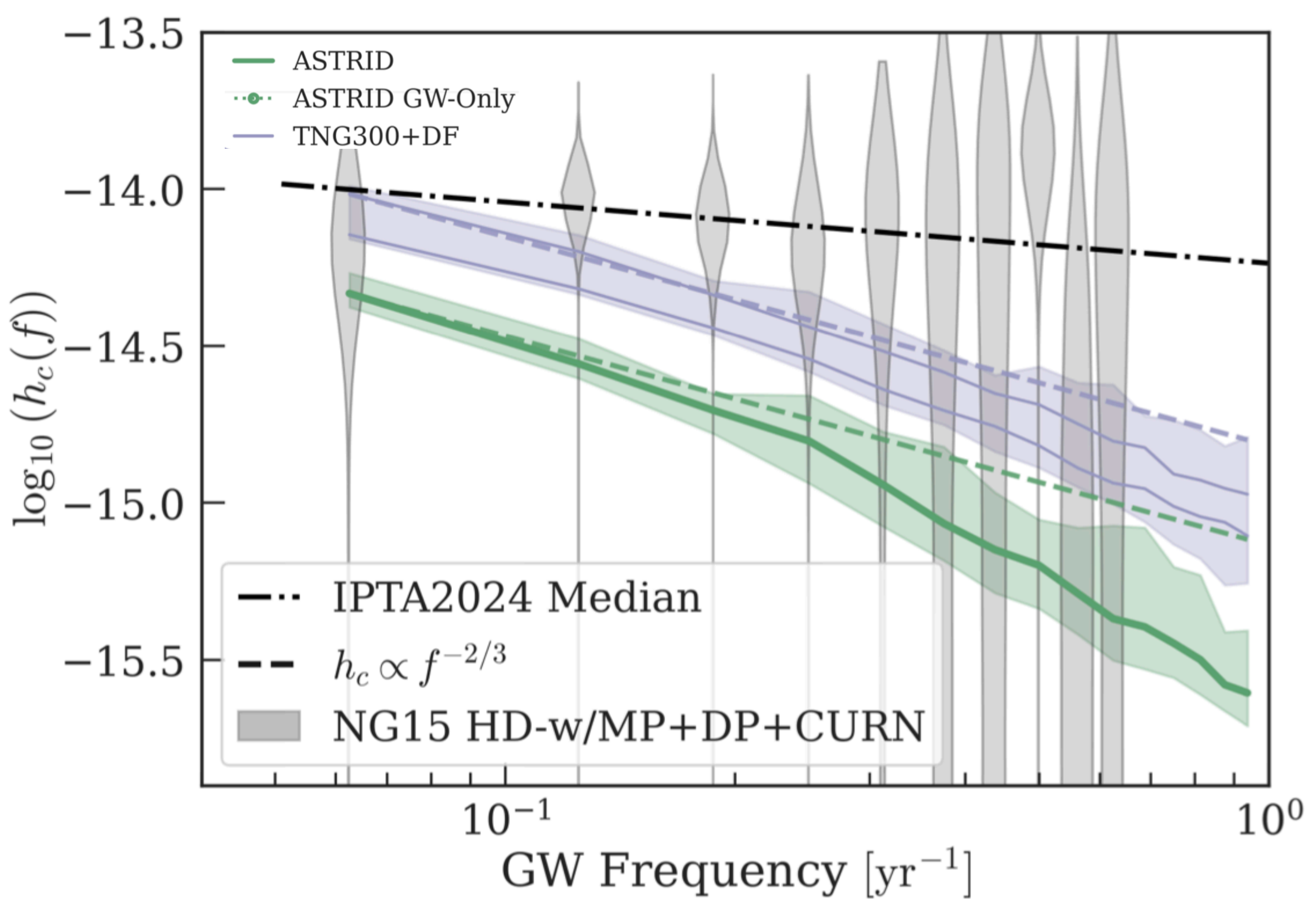
New PTA data: higher peak frequency and slope

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

Solution to the final parsec problem?

[Chiaberge+, 2501.18730]

What happened since July 2023?



Investigation of specific dark sector models

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

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

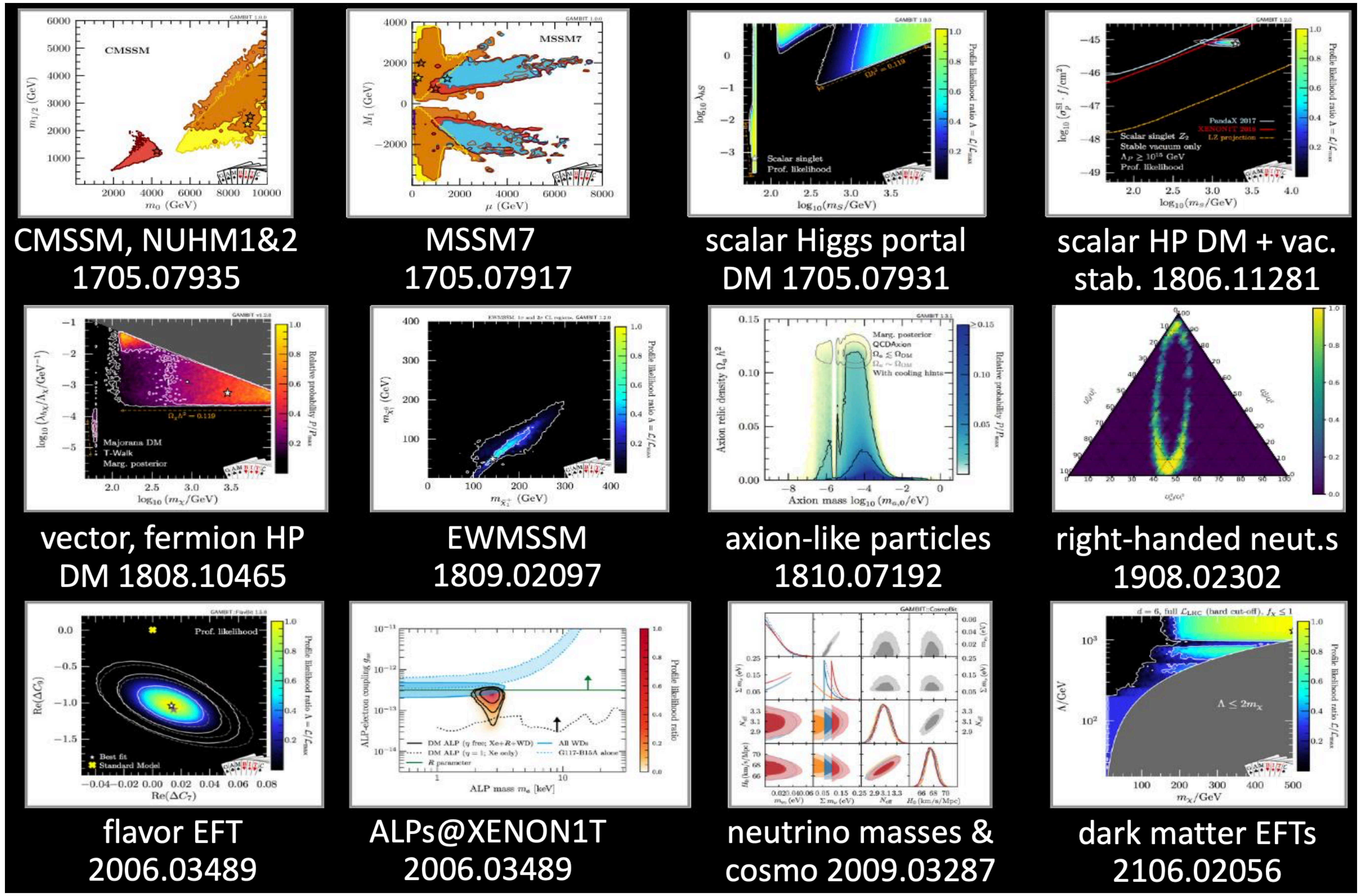
[Chen+, 2502.01024]

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

CT+ [JCAP 08 (2025) 062]

Rest of this talk and my own focus

GAMBIT: from Lagrangians to Likelihoods



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

Dark sector

ϕ A'

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

Higgs mixing $\lambda_{h\phi}$

Changes the dark Higgs potential…

Portal couplings

Kinetic mixing κ

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

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

SM

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

A minimal dark sector setup

Dark sector

Higgs mixing

$V(\phi)$

This model is flawed. Hard (impossible?) to avoid cosmological constraints and fine-tuning...

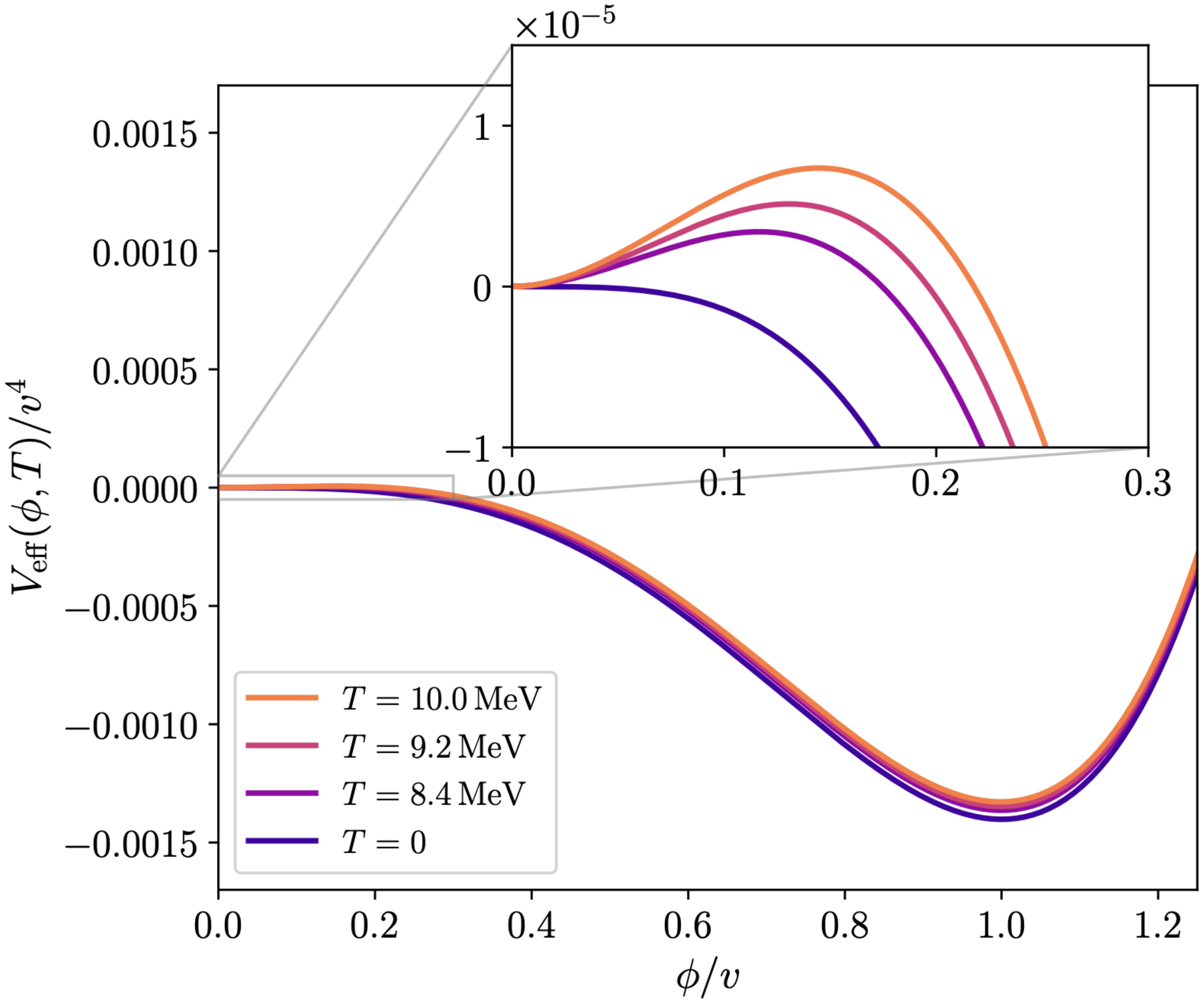
…xing κ

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

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

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

Interlude: How to be supercool 😎



Note: This is not the *only* way to achieve strong supercooling. Watch out for my upcoming paper together with Jonas, Kai, Thomas and Torsten! :)

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

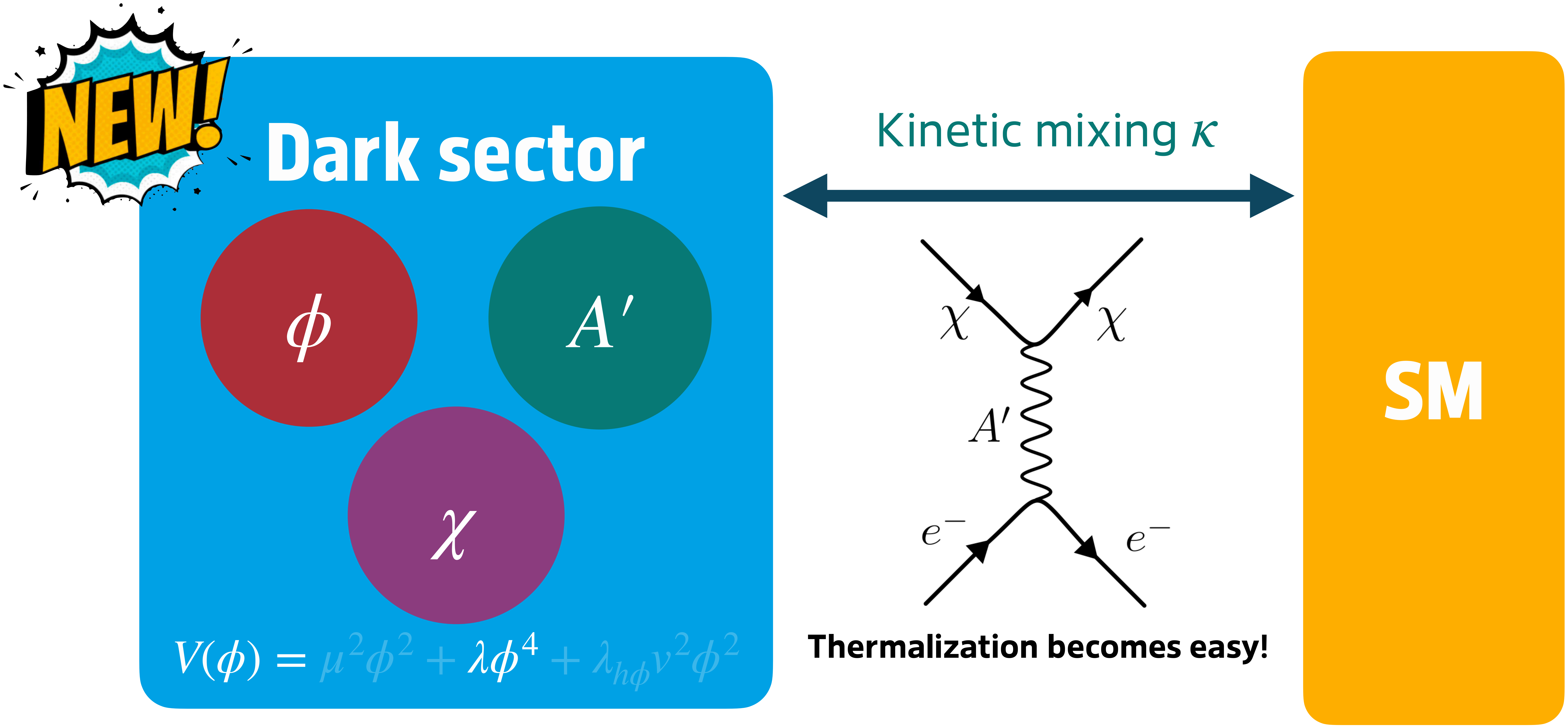
↓ Quantum and thermal corrections

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

↓

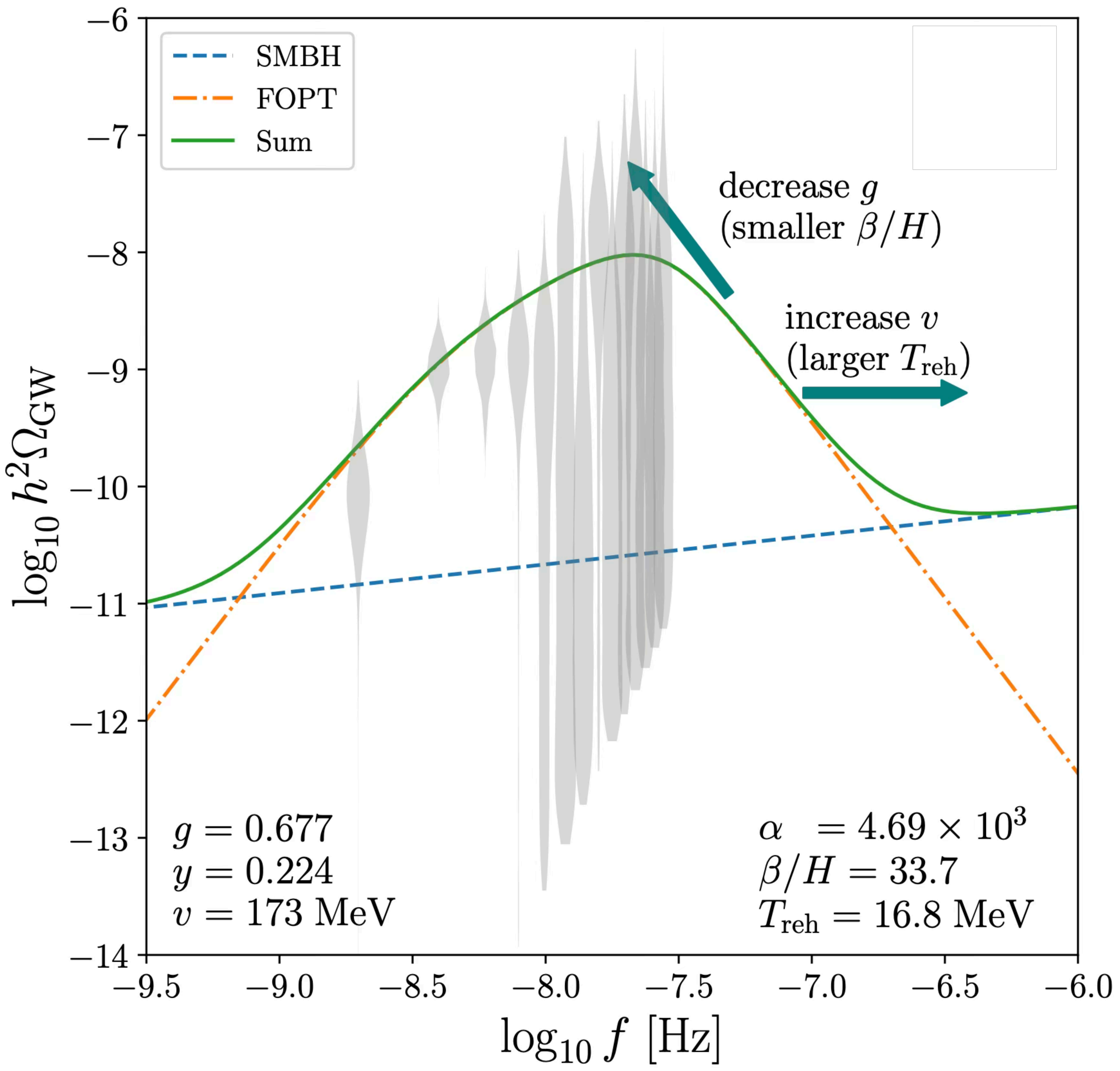
Loop-induced barrier down until very low temperatures, i.e. strong supercooling

A conformal dark sector incl. dark matter candidate



CT+ [JCAP 08 (2025) 062]

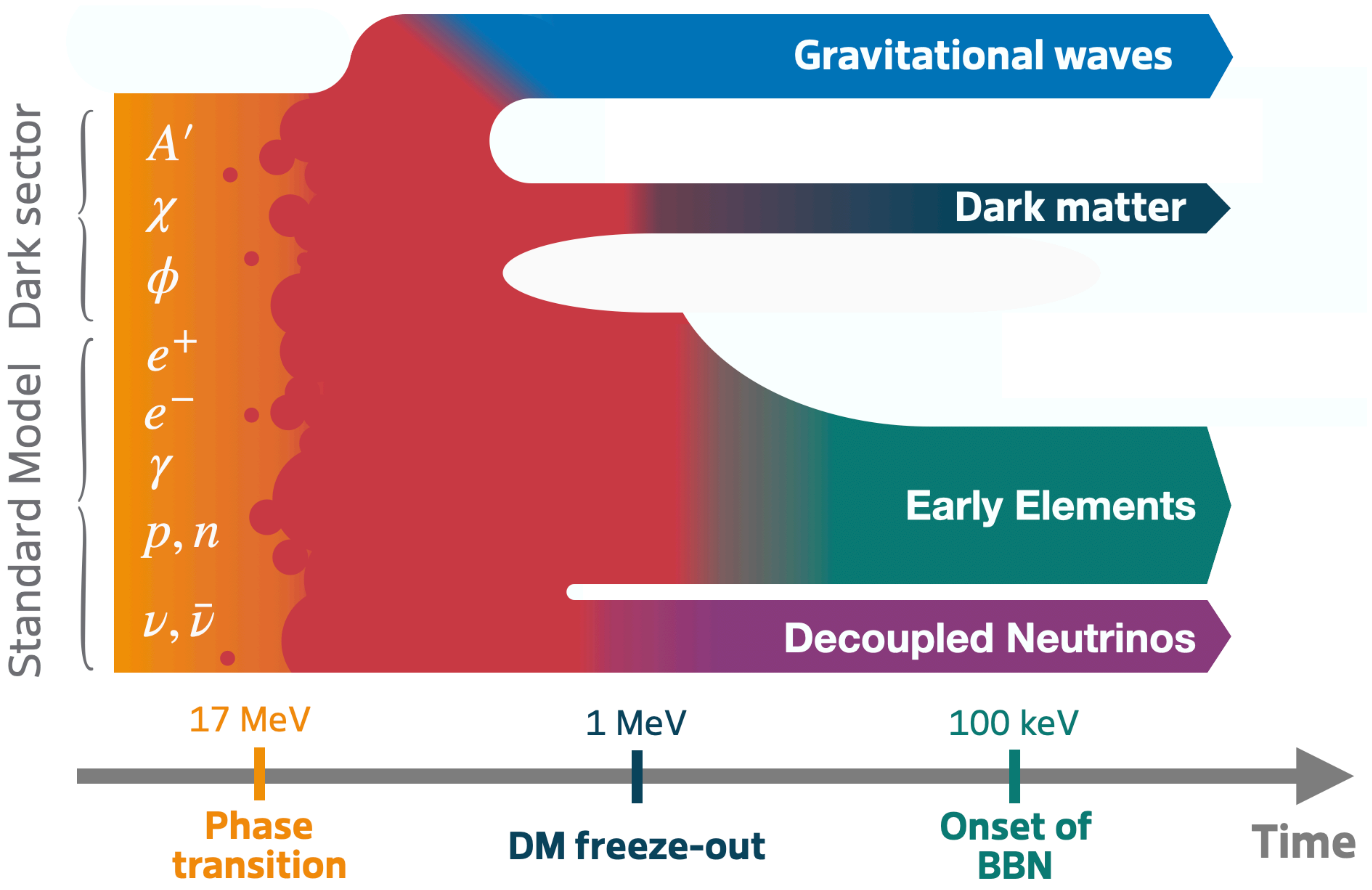
All constraints can be circumvented

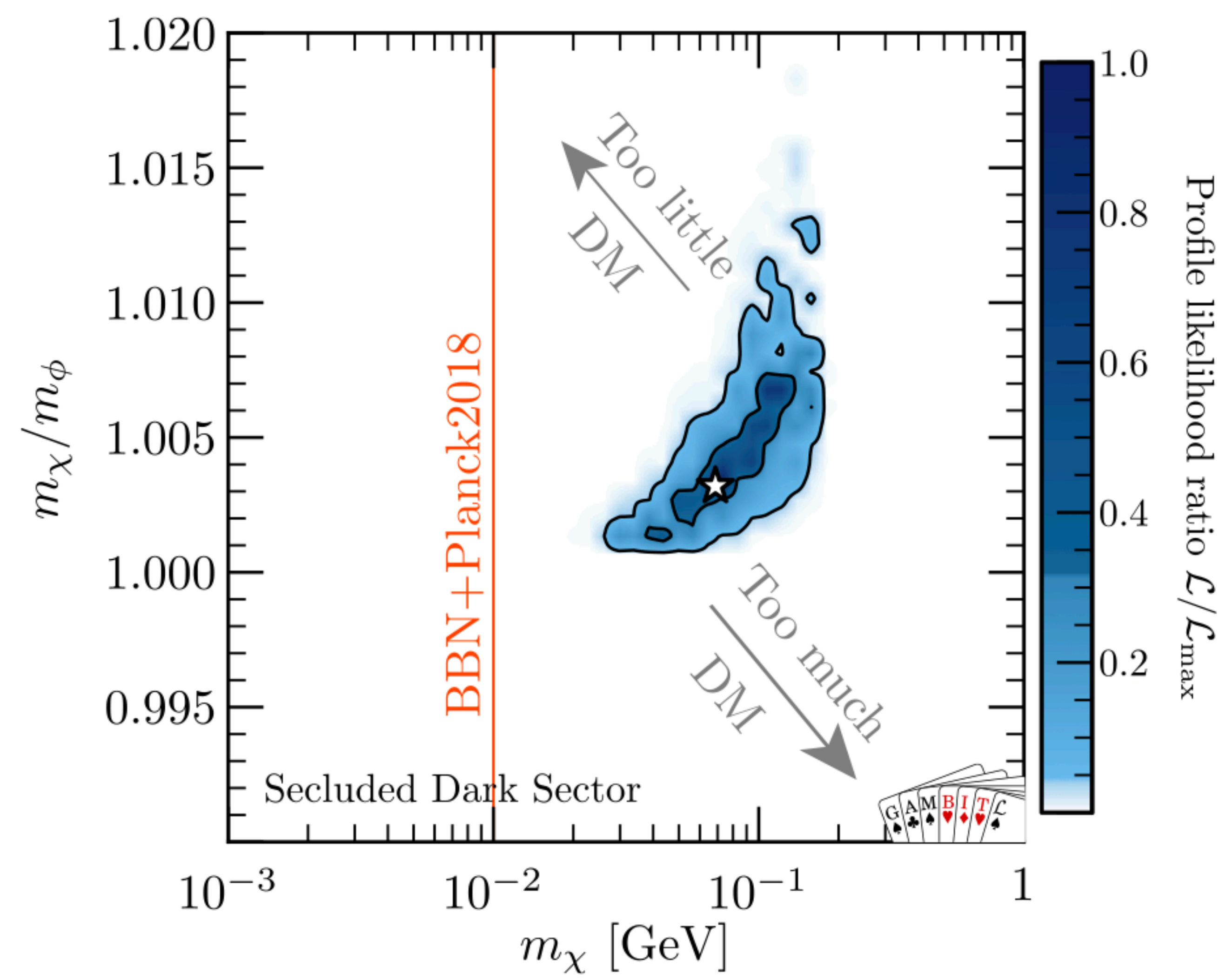


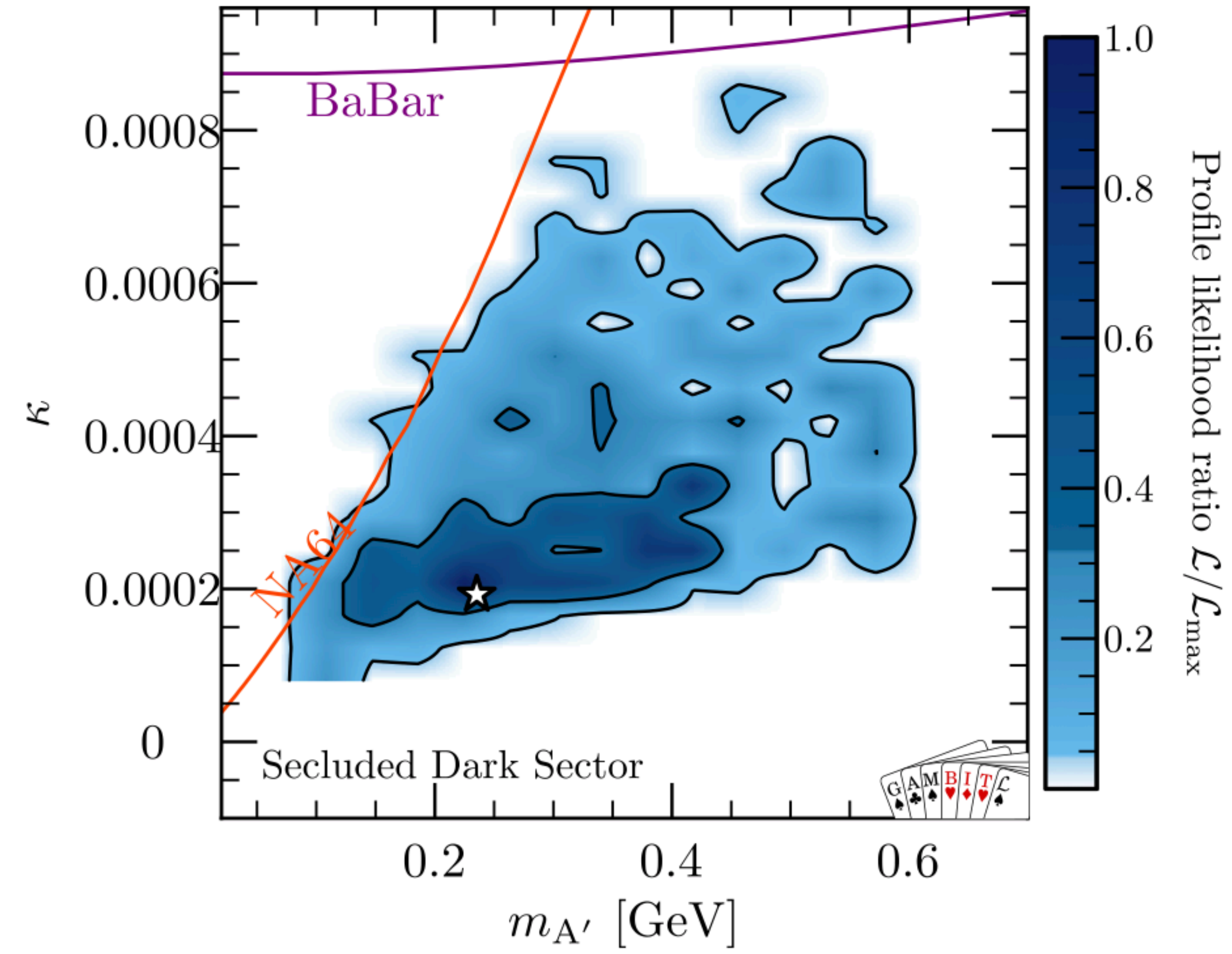
Global fit found parameter space with

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

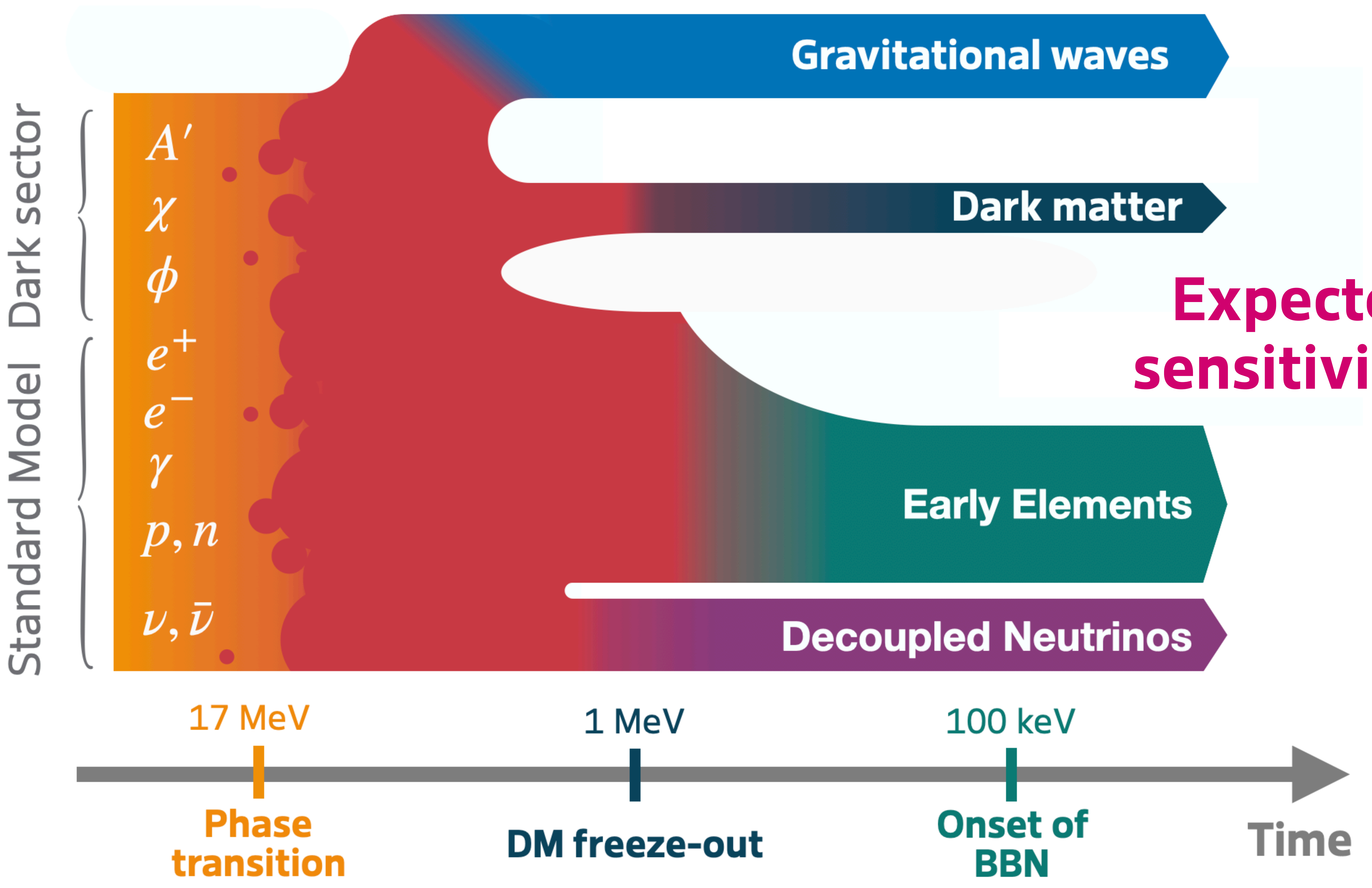
How does our scenario evade all available constraints?



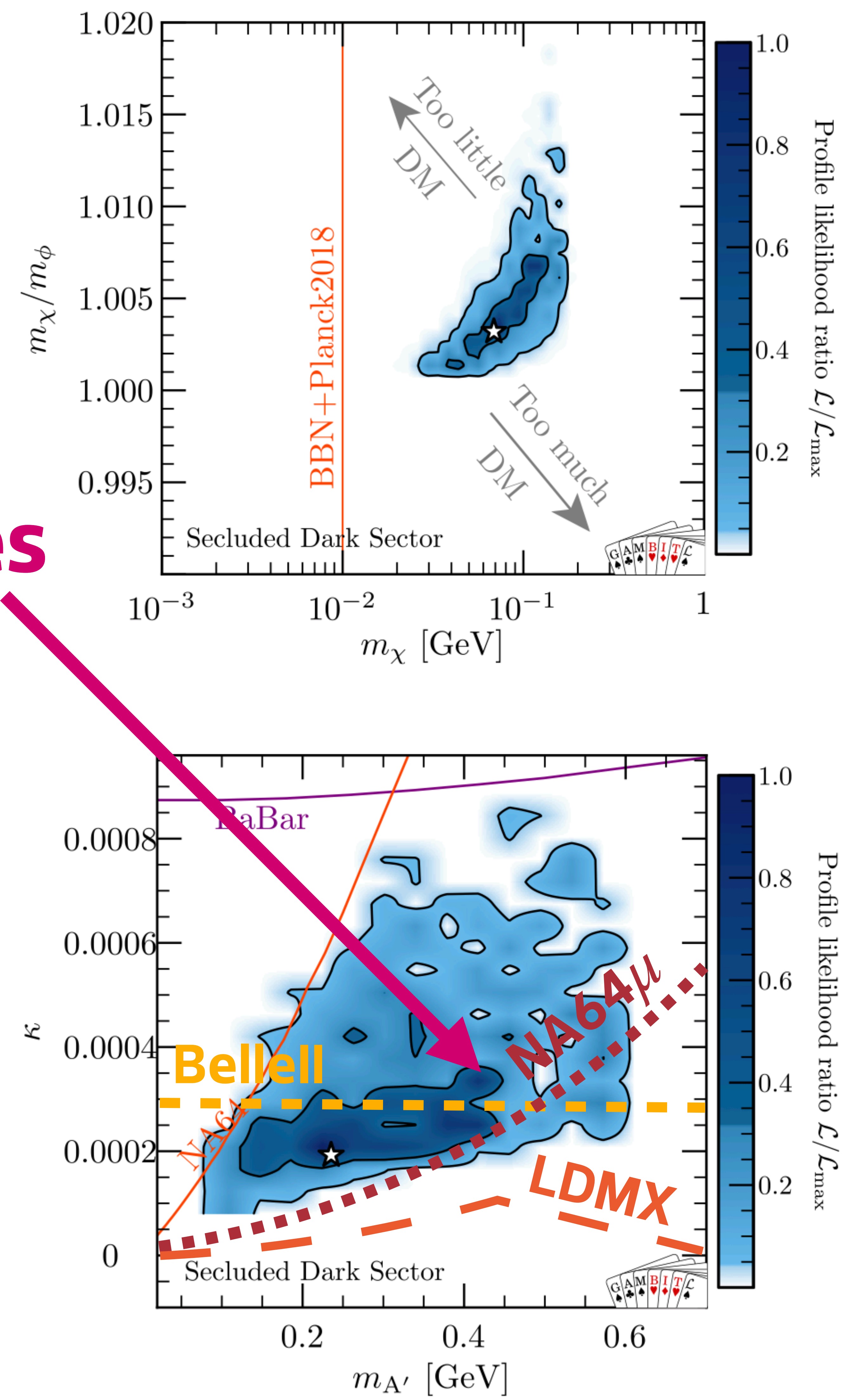




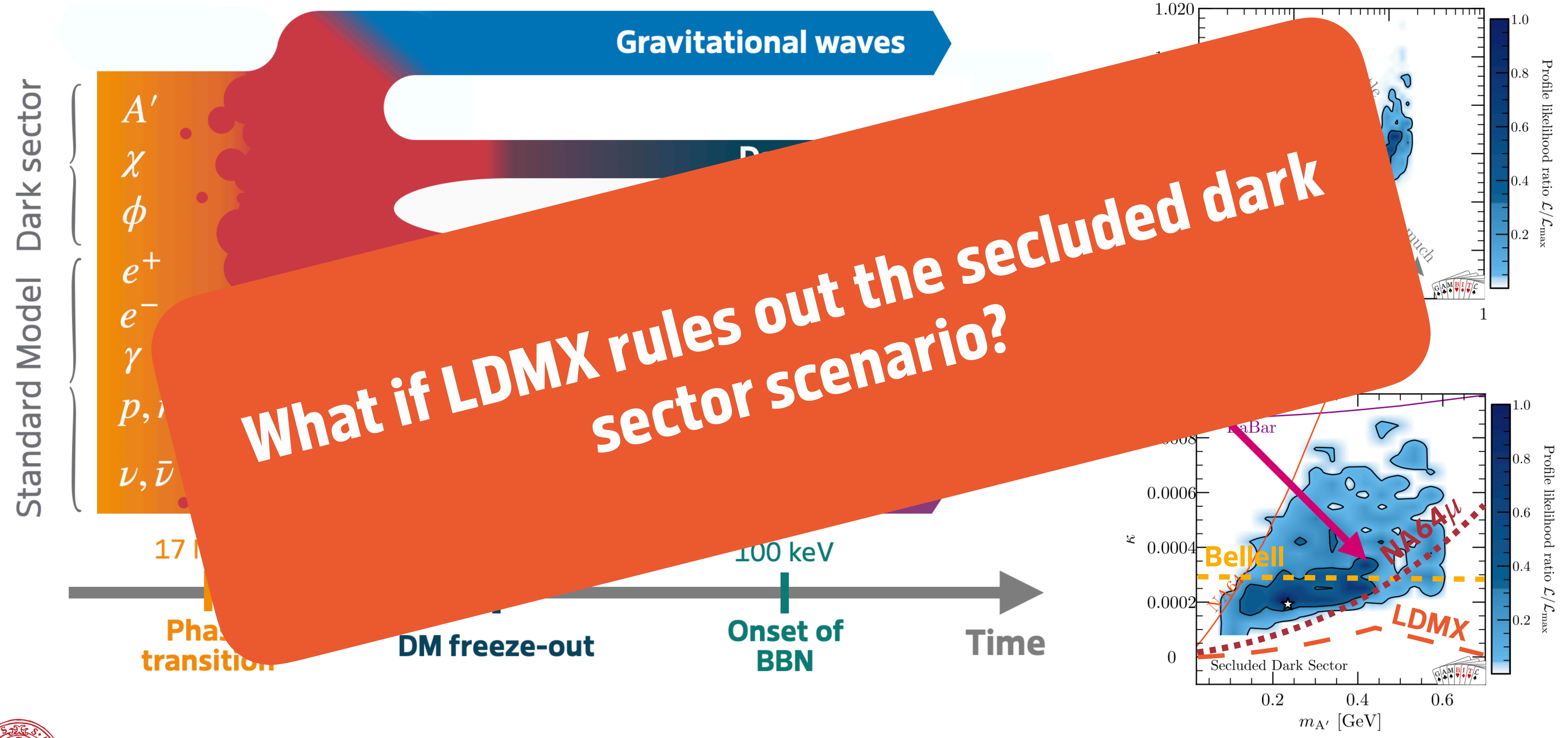
How does our scenario evade all available constraints?



Expected sensitivities

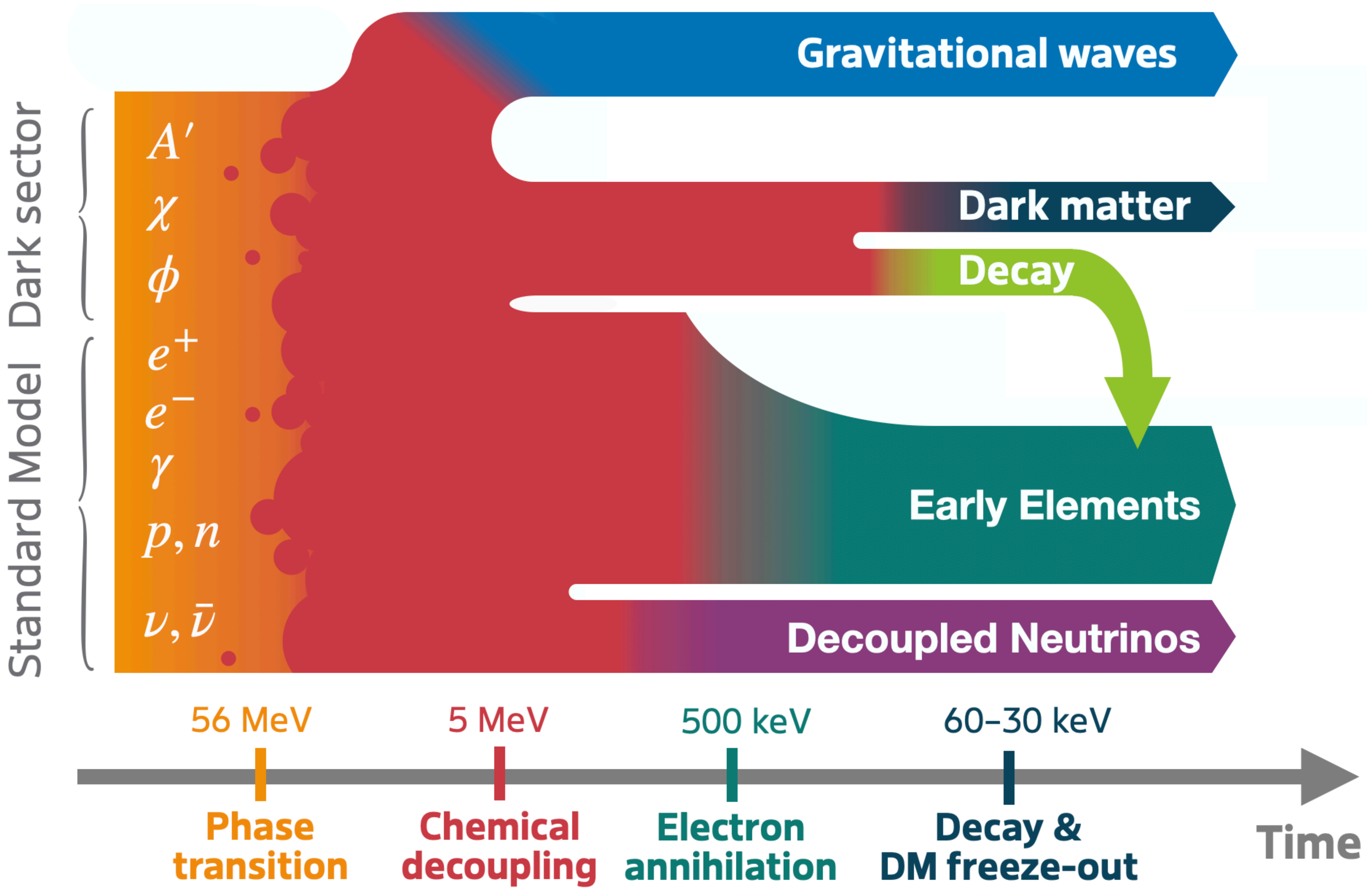


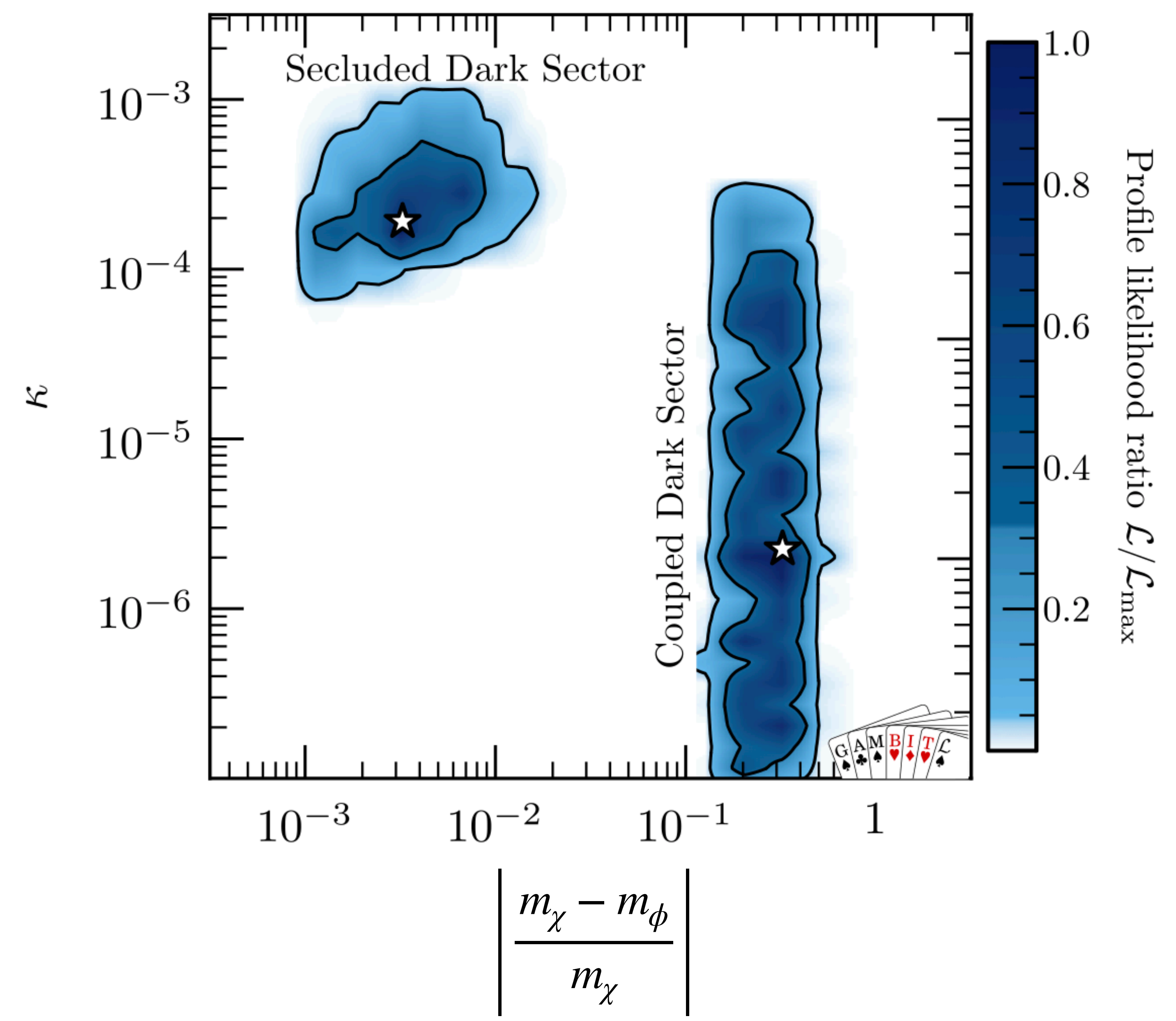
How does our scenario evade all available constraints?



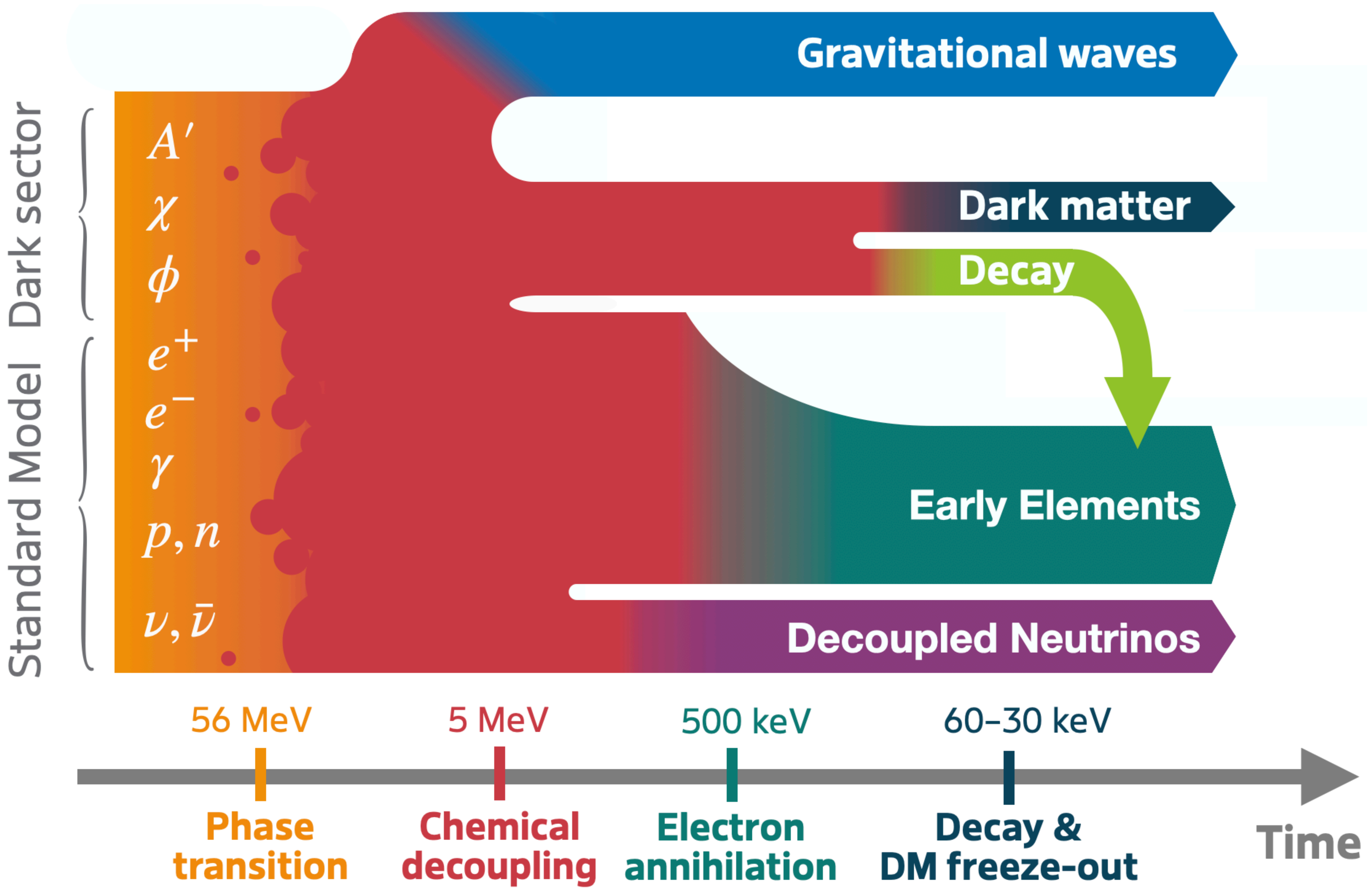
What if LDMX rules out the secluded dark sector scenario?

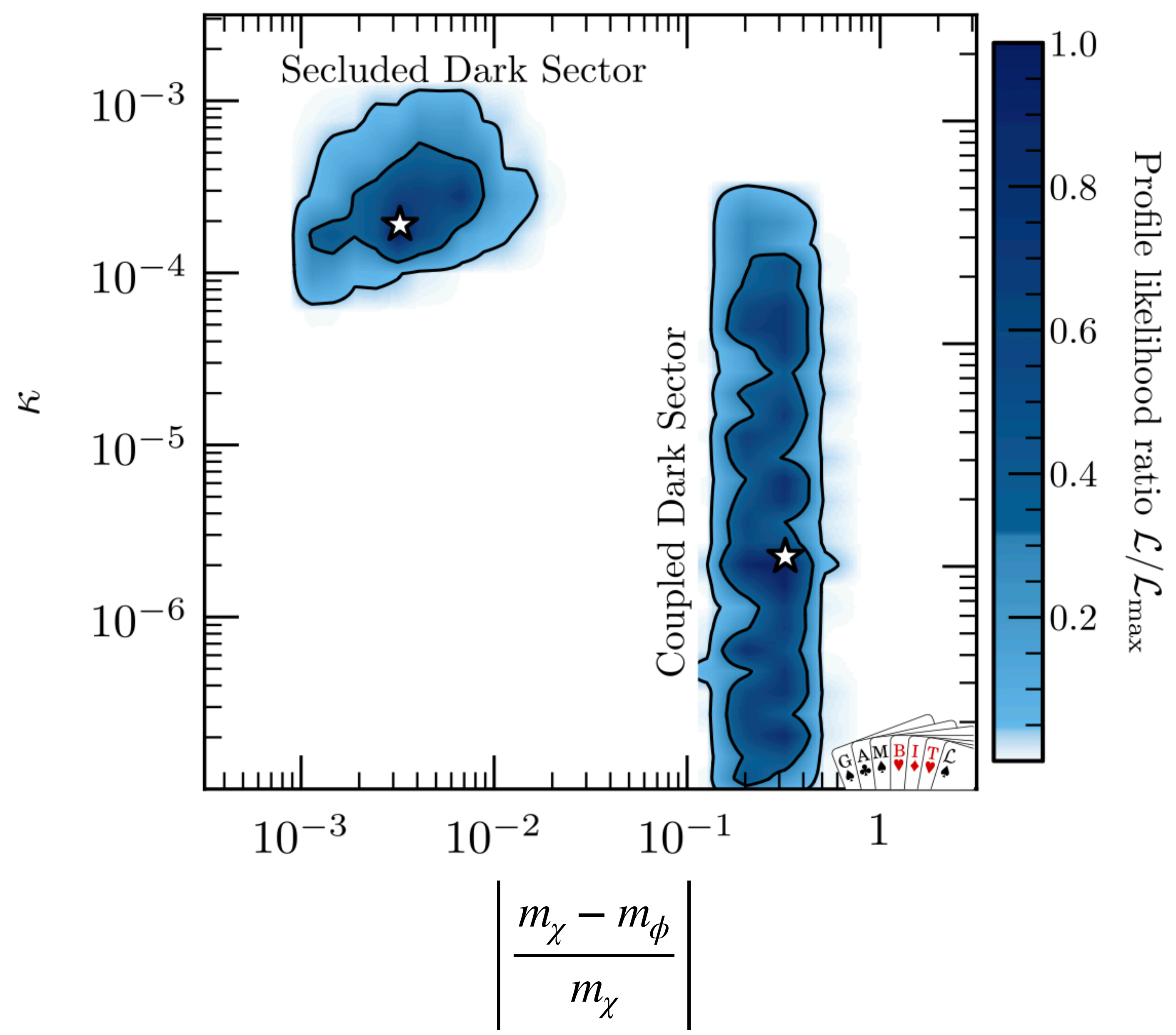
Coupled DS scenario: incl dim-6 operator for $\phi \to ee$





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





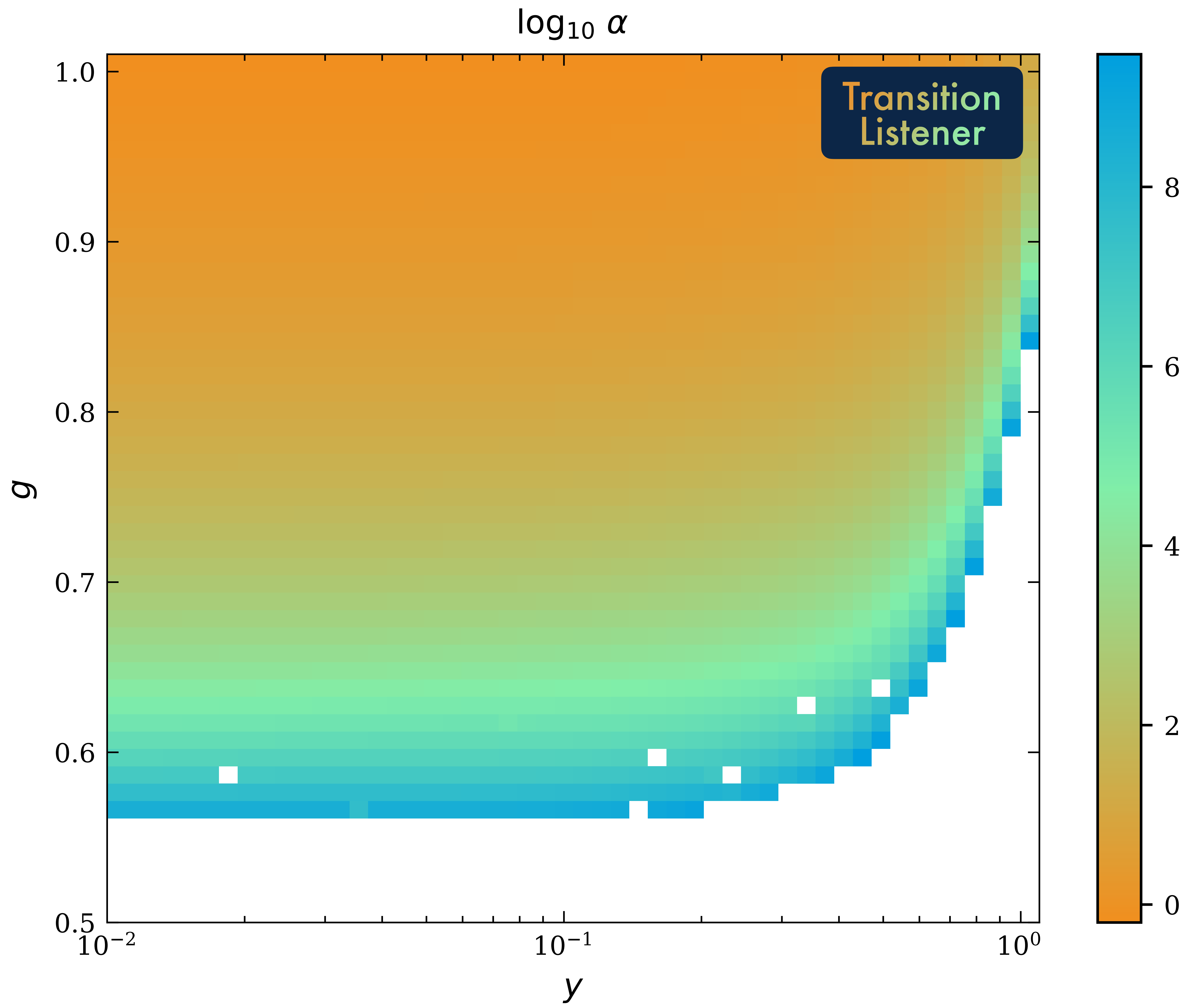
$\phi \to ee$ **decays through a dim-6 operator open up the parameter space and save the model from potential future constraints**

Some open ends:

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

Transition Listener 2.0

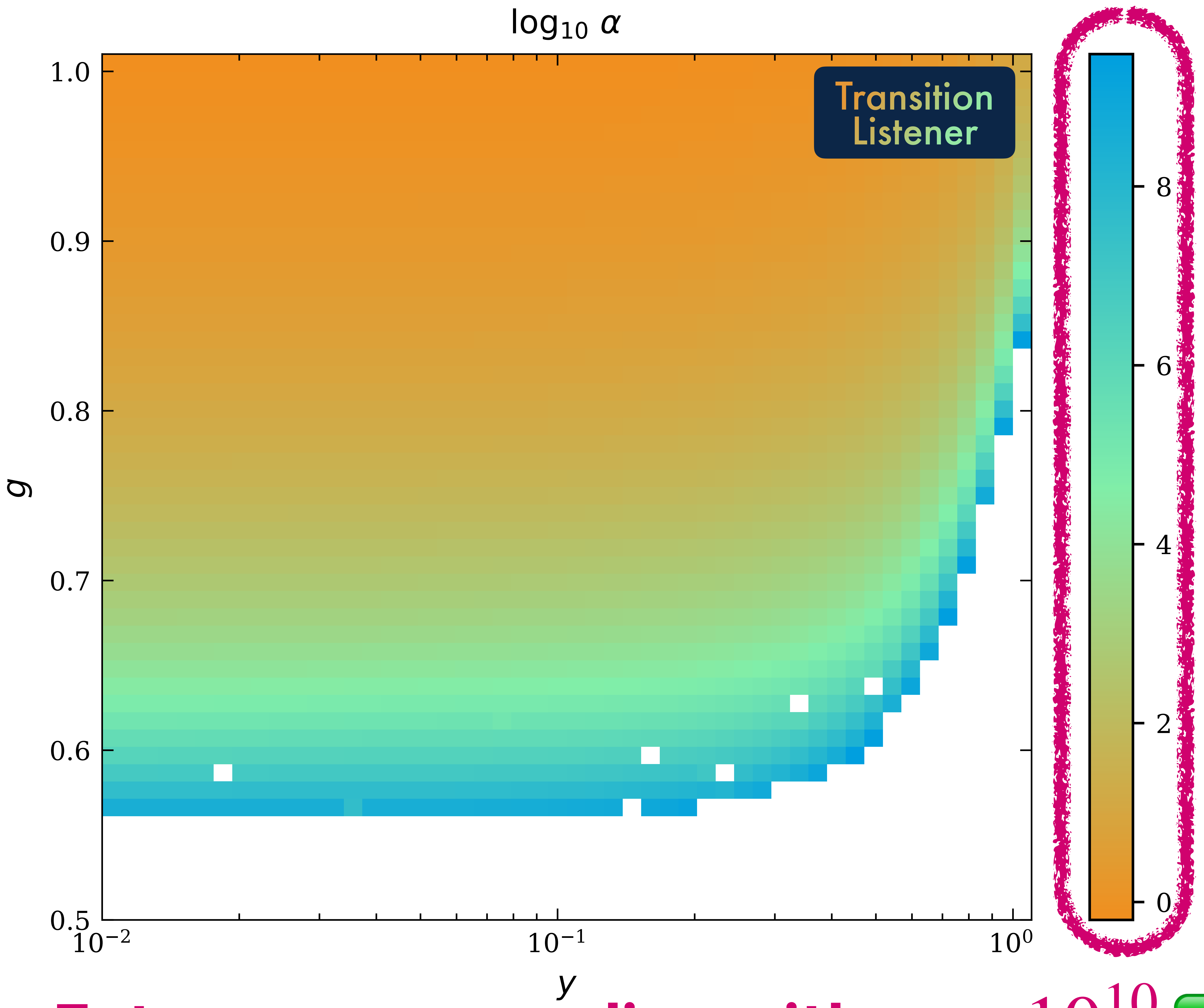
[Ongoing work Jonas Matuszak,
code release very soon]



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

2.0
Transition Listener

[Ongoing work Jonas Matuszak, code release very soon]

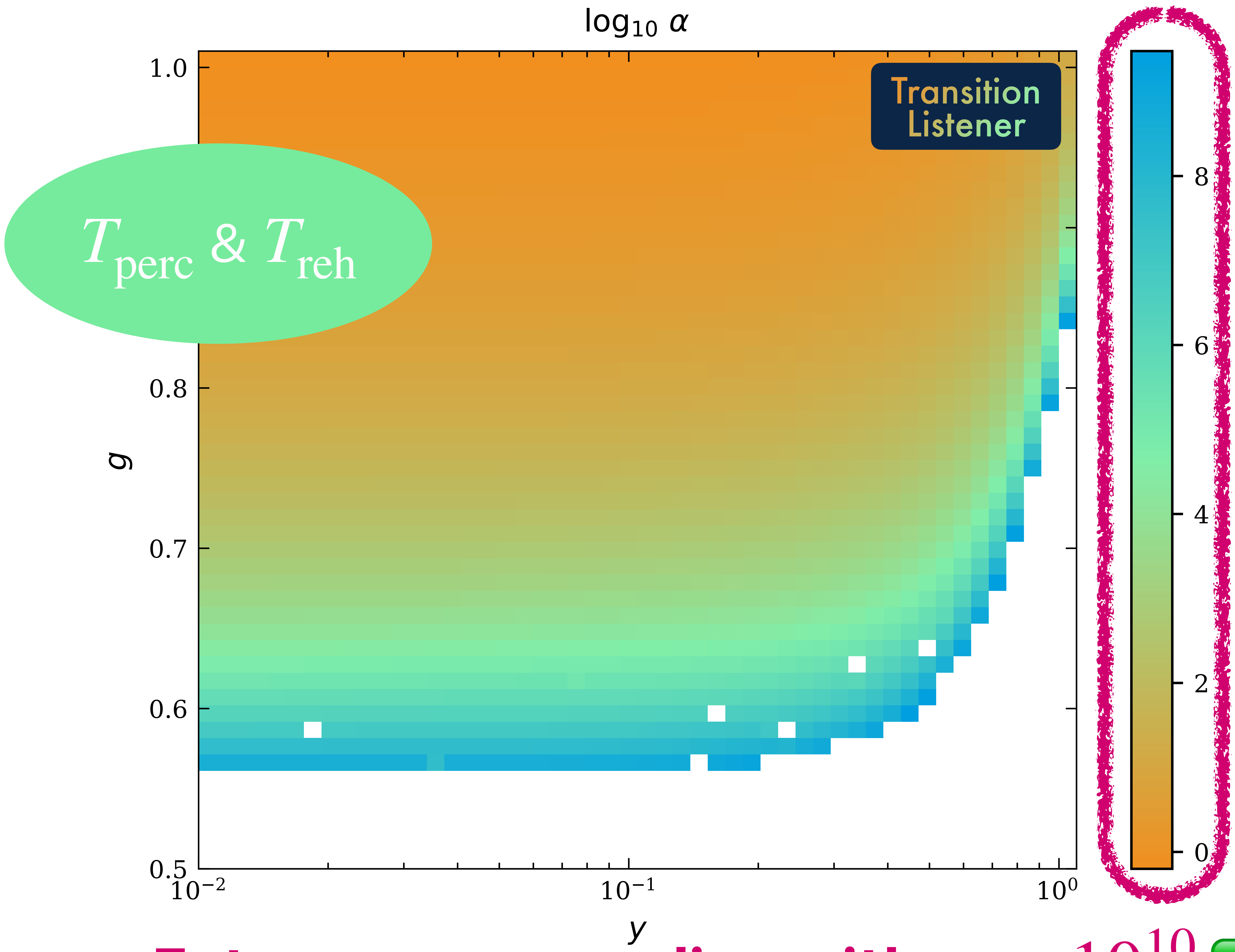


Extreme supercooling with $\alpha = 10^{10}$ ✅

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

Transition Listener 2.0

[Ongoing work Jonas Matuszak, code release very soon]

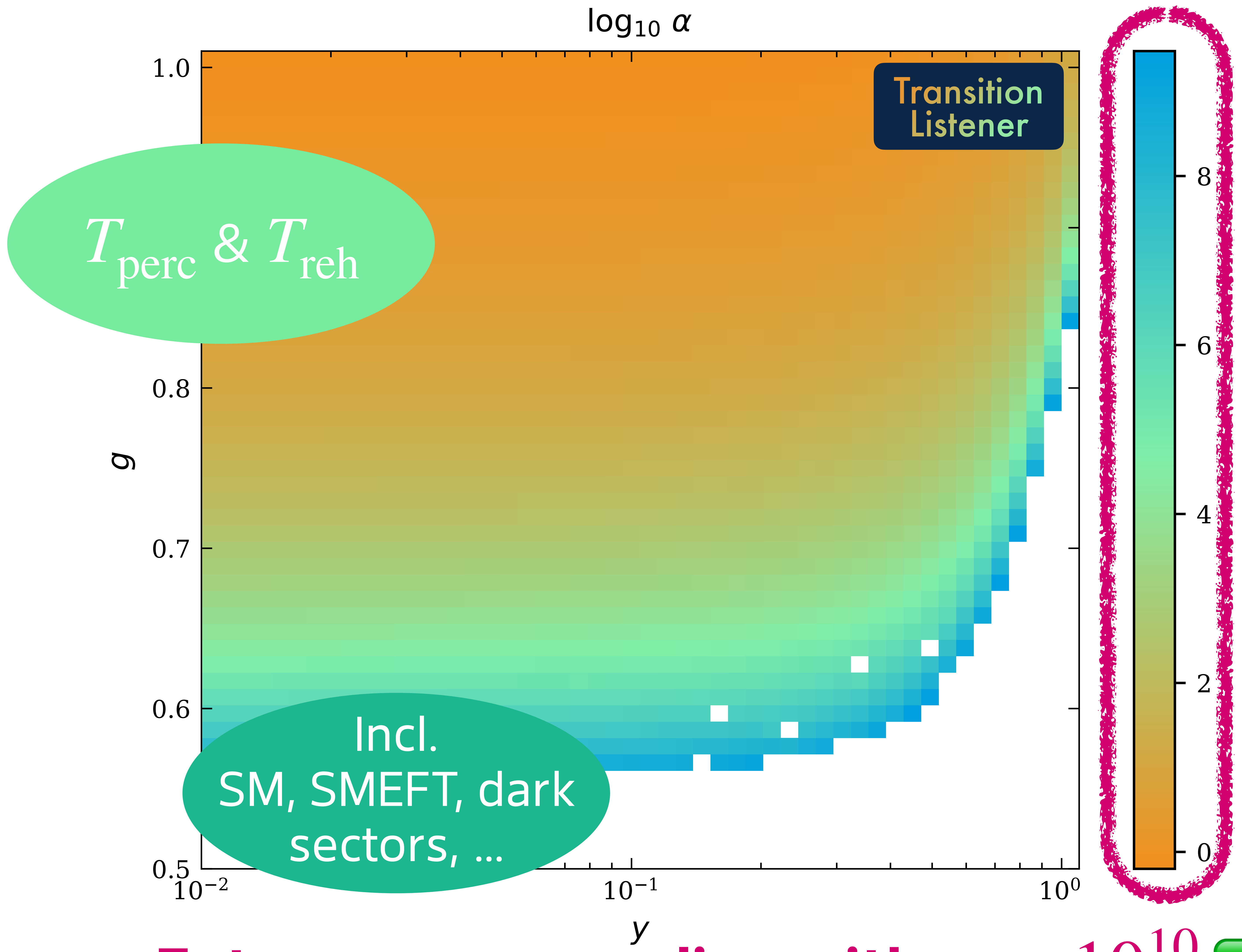


Extreme supercooling with $\alpha = 10^{10}$ ✅

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

Transition Listener 2.0

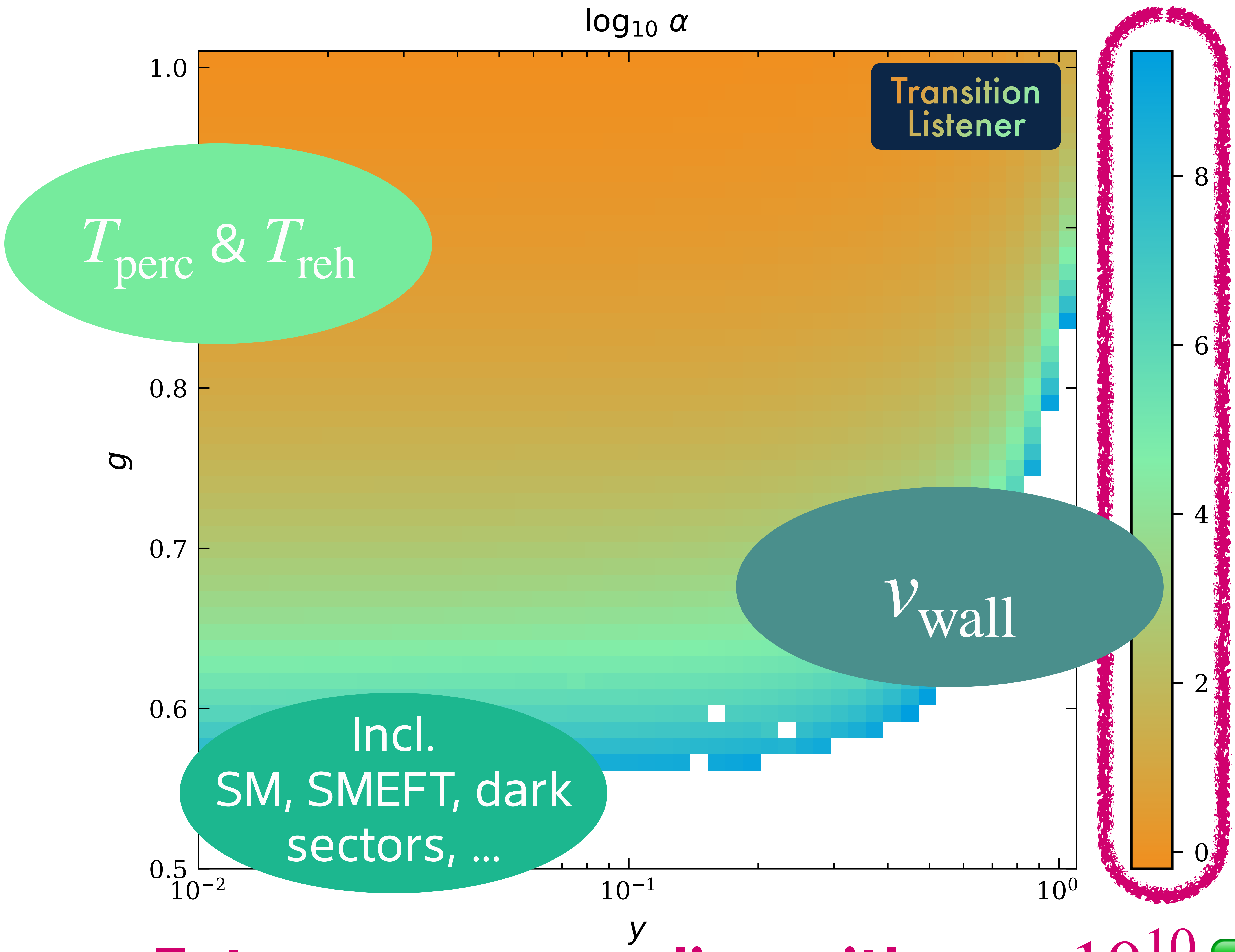
[Ongoing work Jonas Matuszak, code release very soon]



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

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

[Ongoing work Jonas Matuszak,
code release very soon]

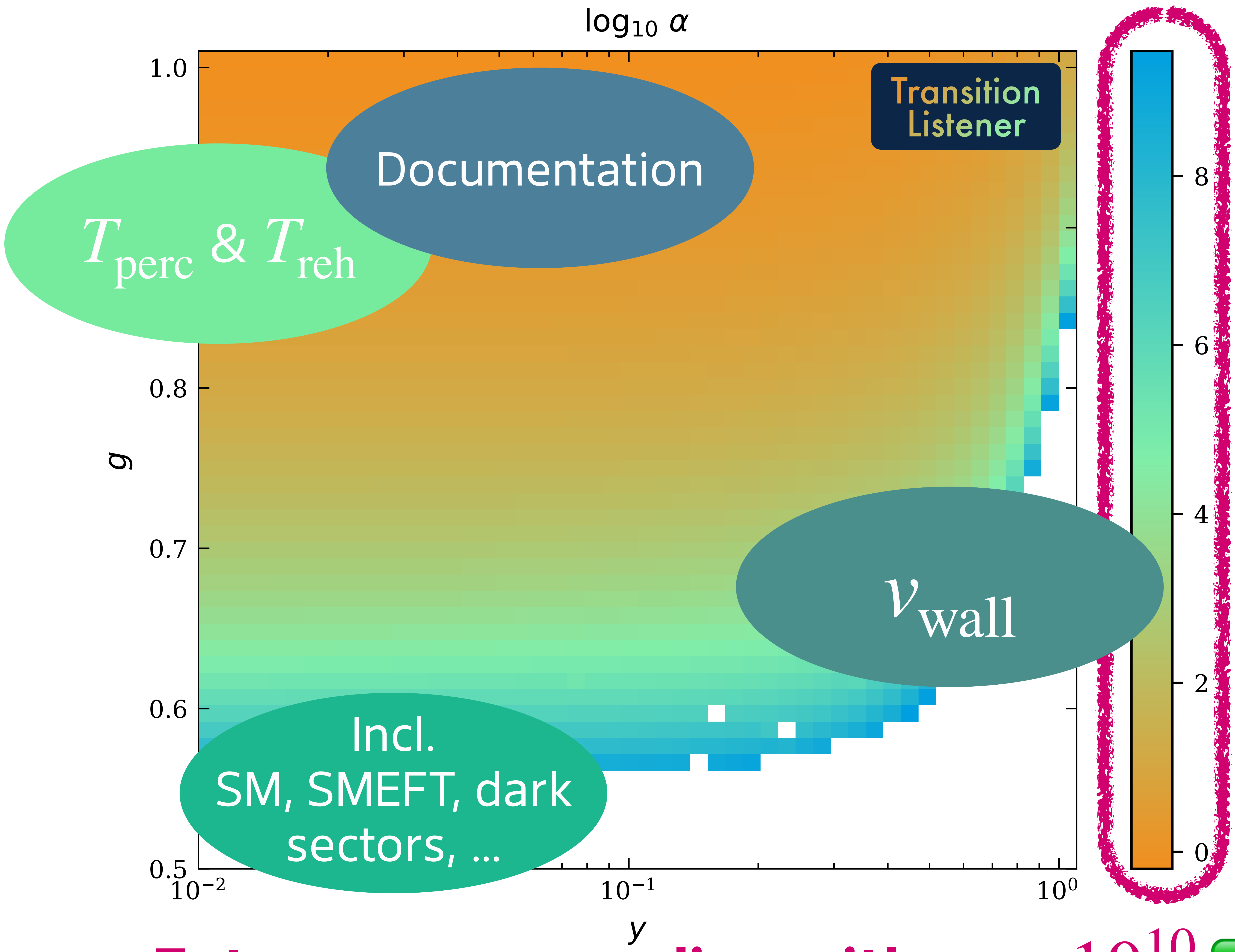


Extreme supercooling with $\alpha = 10^{10}$ ✅

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

Transition Listener 2.0

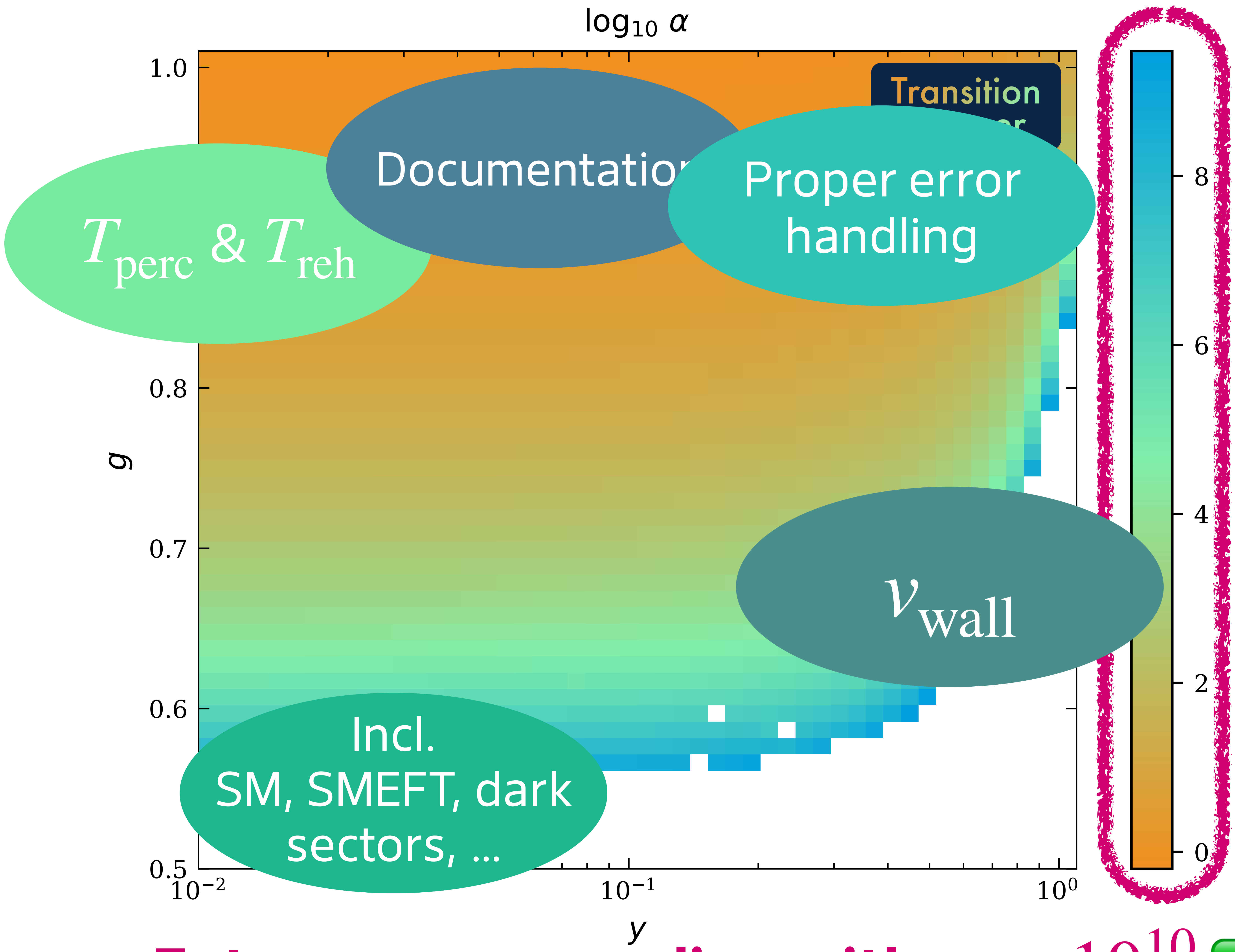
[Ongoing work Jonas Matuszak, code release very soon]



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

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

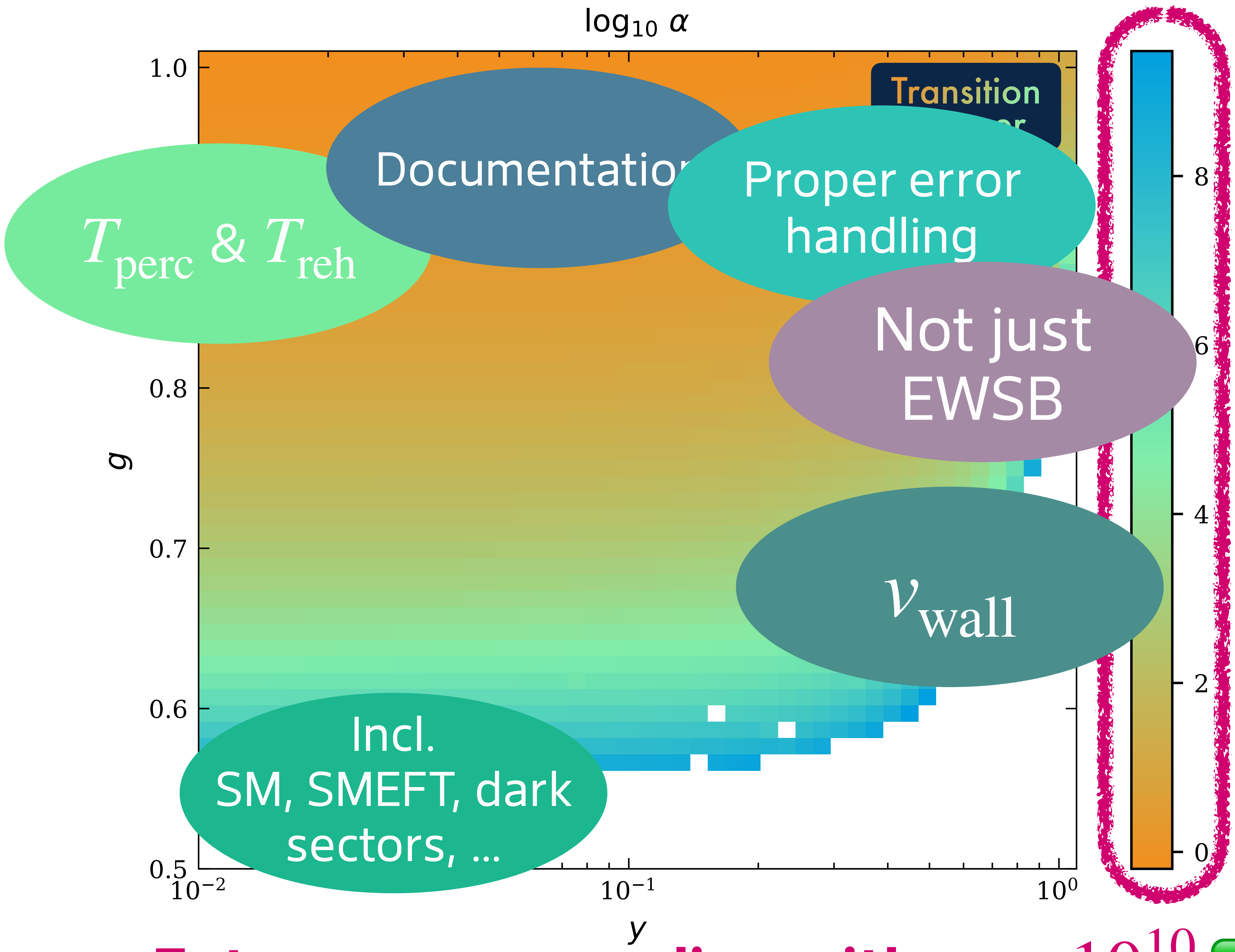
[Ongoing work Jonas Matuszak, code release very soon]



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

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

[Ongoing work Jonas Matuszak,
code release very soon]

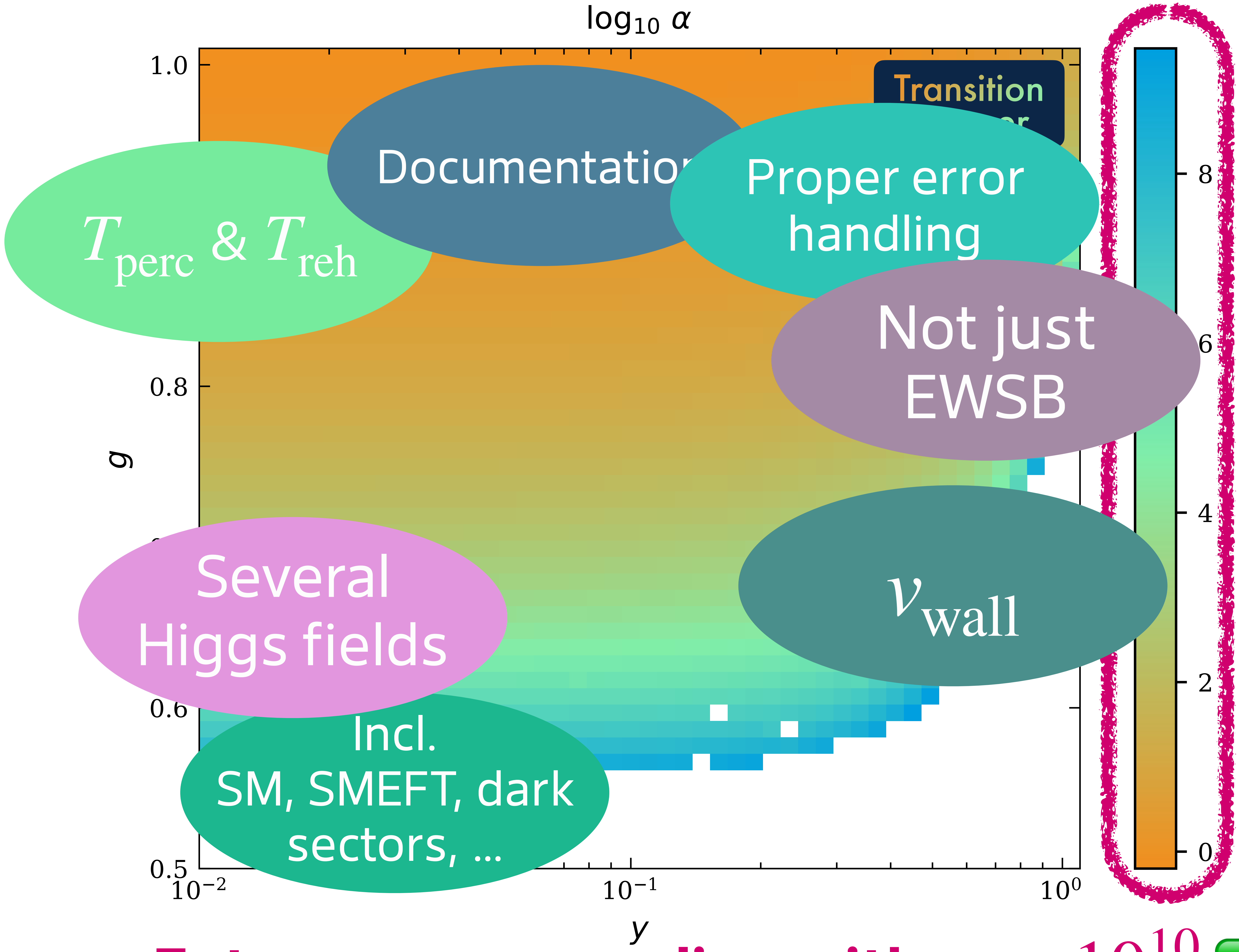


Extreme supercooling with $\alpha = 10^{10}$ ✅

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

Transition Listener 2.0

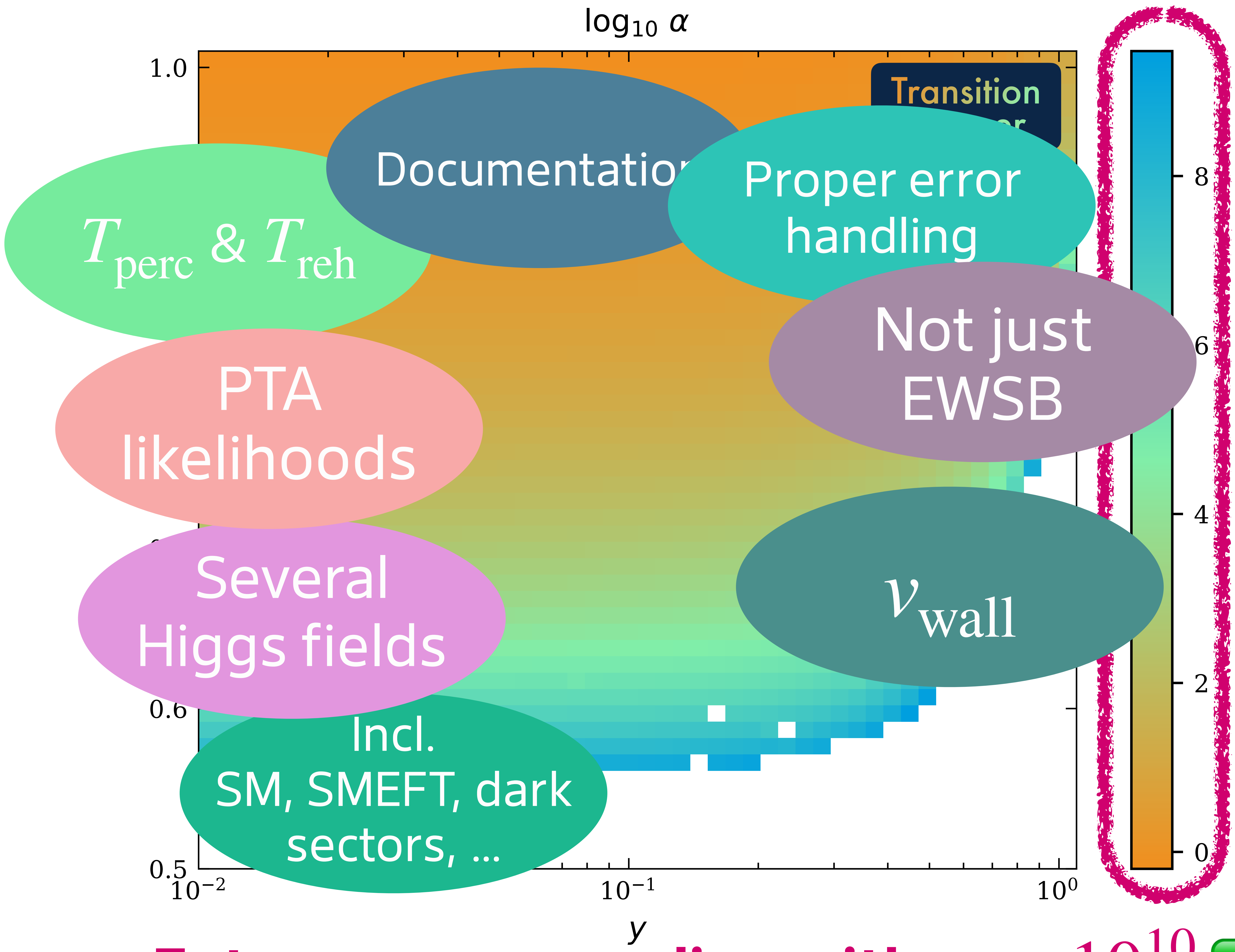
[Ongoing work Jonas Matuszak,
code release very soon]



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

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

[Ongoing work Jonas Matuszak, code release very soon]

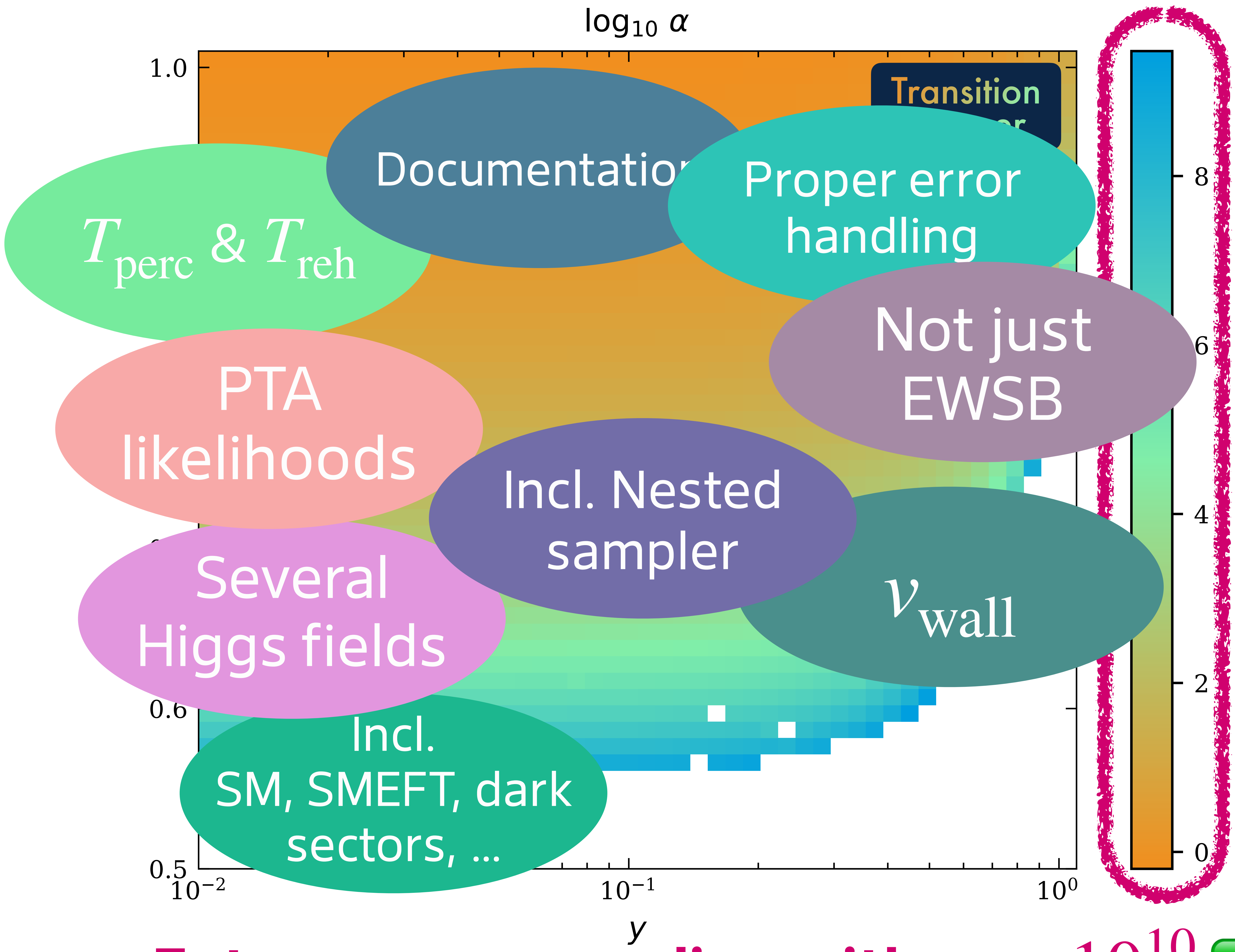


Extreme supercooling with $\alpha = 10^{10}$ ✅

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

Transition Listener 2.0

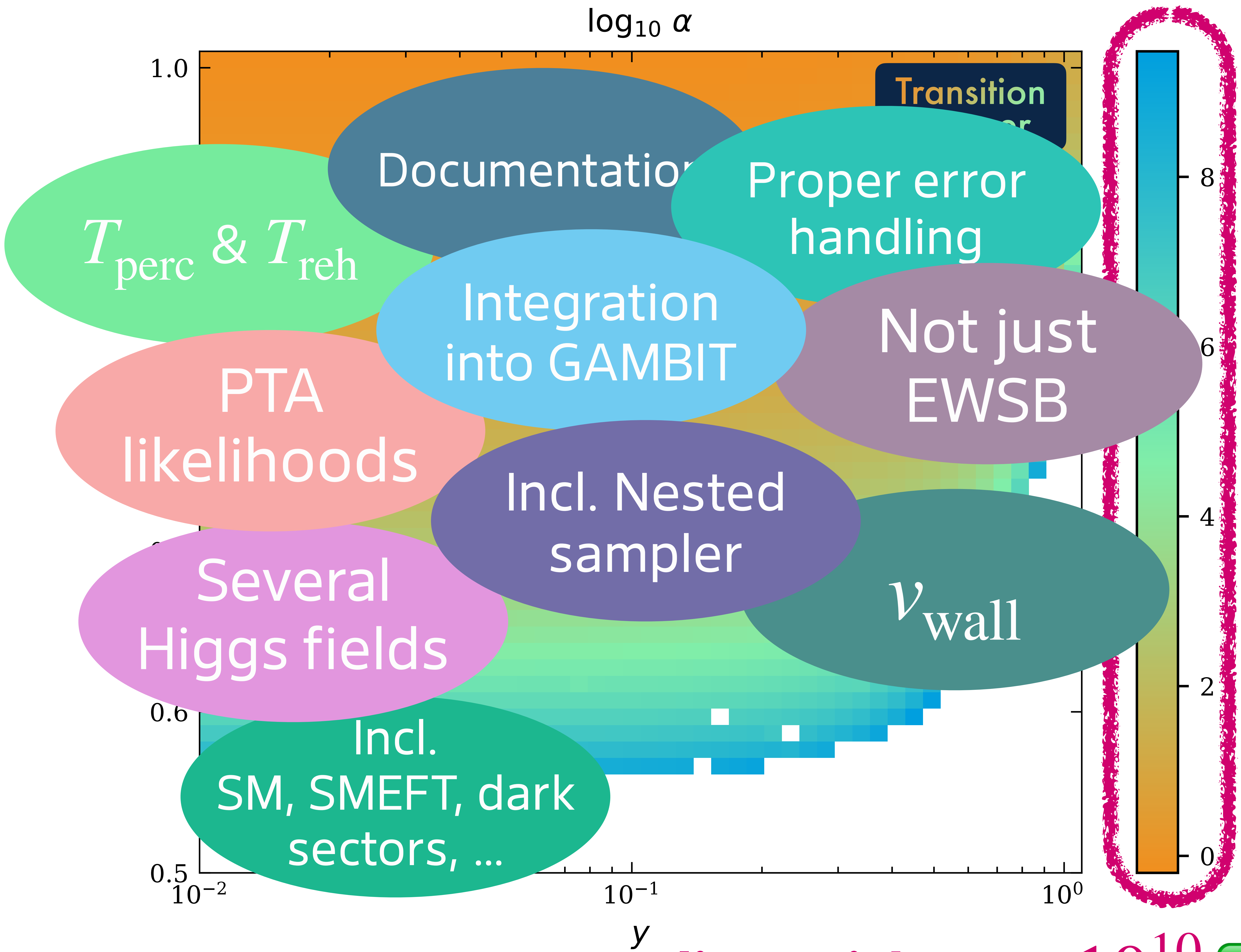
[Ongoing work Jonas Matuszak, code release very soon]



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

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

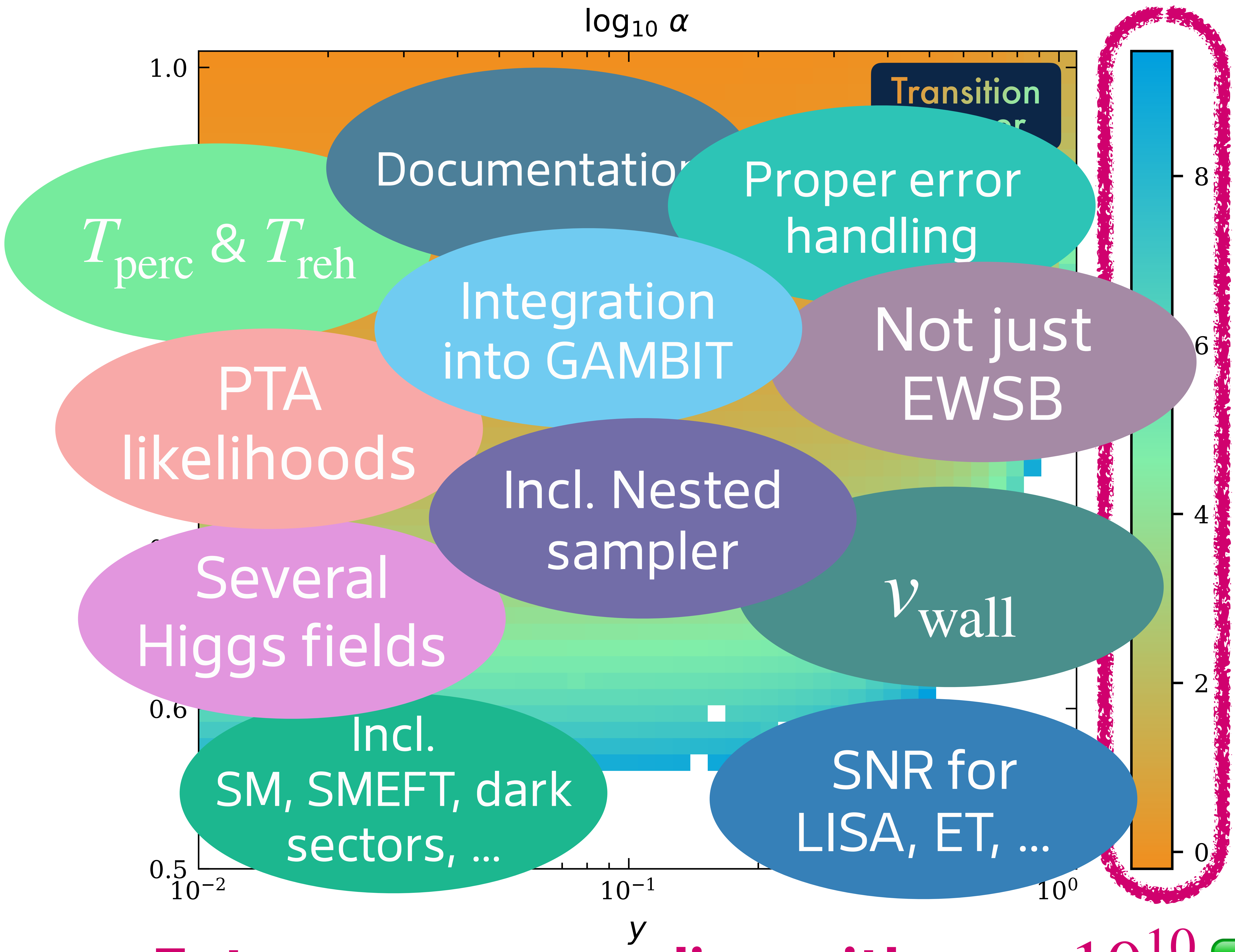
[Ongoing work Jonas Matuszak, code release very soon]



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

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

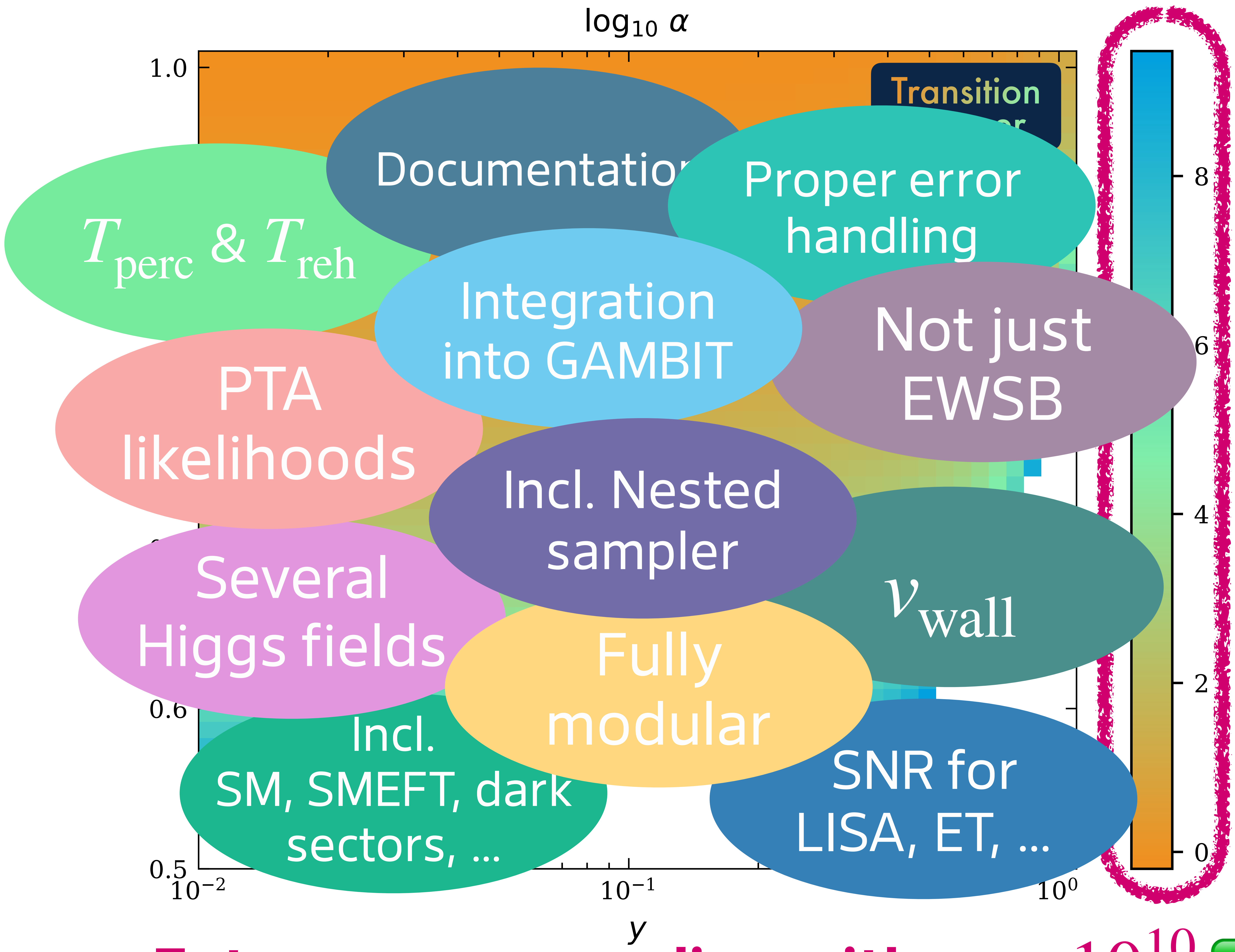
[Ongoing work Jonas Matuszak, code release very soon]



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

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

[Ongoing work Jonas Matuszak, code release very soon]



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

Is anyone interested in looking into this with me?

Preprint 3 September 2025

A direct black hole mass measurement in a Little Red Dot at the Epoch of Reionization

Ignas Juodžbalis[1,2★], Cosimo Marconcini[3,4], Francesco D'Eugenio[1,2], Roberto Maiolino[1,2,5], Alessandro Marconi[3,4], Hannah Übler[6], Jan Scholtz[1,2], Xihan Ji[1,2], Santiago Arribas[7], Jake S. Bennett[8], Volker Bromm[9], Andrew J. Bunker[10], Stefano Carniani[11], Stéphane Charlot[12], Giovanni Cresci[4], Pratika Dayal[13,14], Eiichi Egami[15], Andrew Fabian[16], Kohei Inayoshi[17], Yuki Isobe[1,2,18], Lucy R. Ivey[1,2], Gareth C. Jones[1,2], Sophie Koudmani[19,20], Nicolas Laporte[21], Boyuan Liu[22], Jianwei Lyu[15], Giovanni Mazzolari[6], Stephanie Monty[16], Eleonora Parlanti[11], Pablo G. Pérez-González[7], Michele Perna[7], Brant Robertson[23], Raffaella Schneider[24], Debora Sijacki[1,16], Sandro Tacchella[1,2], Alessandro Trinca[25], Rosa Valiante[26], Marta Volonteri[12], Joris Witstok[27,28], Saiyang Zhang[29,30]

Recent discoveries of faint active galactic nuclei (AGN) at the redshift frontier have revealed a plethora of broad Hα emitters with optically red continua, named Little Red Dots (LRDs)[1], which comprise 15-30% of the high redshift broad line AGN population[2]. Due to their peculiar spectral properties[3–5] and X-ray weakness[6], modeling LRDs with standard AGN templates has proven challenging. In particular, the validity of single-epoch virial mass estimates in determining the black hole (BH) masses of LRDs has been called into question, with some models claiming that masses might be overestimated by up to 2 orders of magnitude[7–10], and other models claiming that LRDs may be entirely stellar in nature[11]. We report the direct, dynamical BH mass measurement in a strongly lensed LRD at $z = 7.04$. The combination of lensing with deep spectroscopic data reveals a rotation curve that is inconsistent with a nuclear star cluster, yet can be well explained by Keplerian rotation around a point mass of 50 million Solar masses, consistent with virial BH mass estimates from the Balmer lines. The Keplerian rotation leaves little room for any stellar component in a host galaxy, as we conservatively infer $M_{\rm BH}/M_* > 2$. Such a "naked" black hole, together with its near-pristine environment[12], indicates that this LRD is a massive black hole seed caught in its earliest accretion phase.

Is this the first detection of a PBH with $M = 5 \cdot 10^7\, M_\odot$ at $z = 7$?

If so, it might as well be a tempting hint at a new explanation for the PTA data!

Signals of merging supermassive primordial black holes in pulsar timing arrays

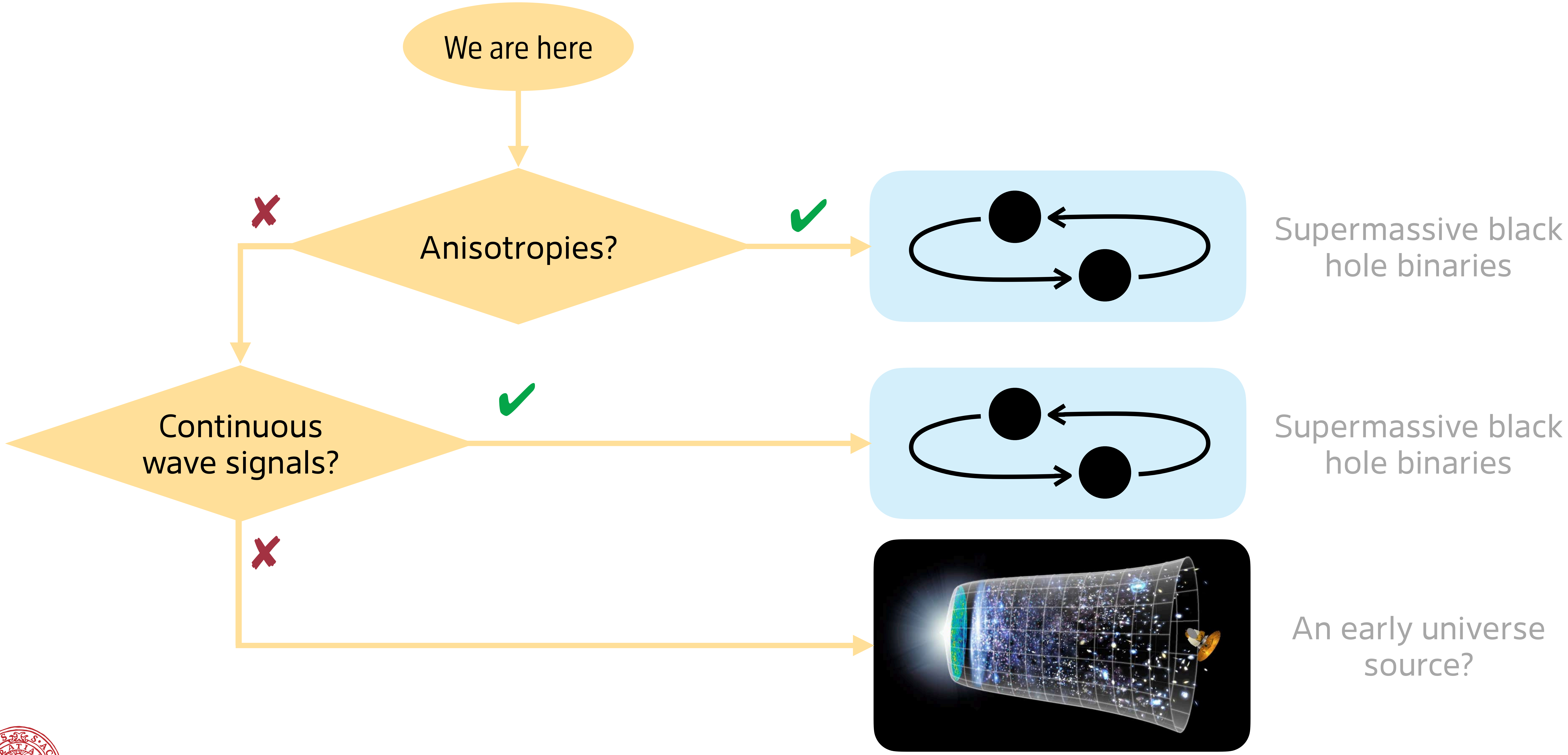
Paul Frederik Depta,[1,*] Kai Schmidt-Hoberg,[2,†] Pedro Schwaller,[3,‡] and Carlo Tasillo[2,§]

[1] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[3] *PRISMA+ Cluster of Excellence and Mainz Institute for Theoretical Physics, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

(Dated: July 25, 2023)

In this work we evaluate whether the gravitational wave background recently observed by a number of different pulsar timing arrays could be due to merging *primordial* supermassive black hole binaries. We find that for homogeneously distributed primordial black holes this possibility is inconsistent with strong cosmological and astrophysical constraints on their total abundance. If the distribution exhibits some clustering, however, the merger rate will in general be enhanced, opening the window for a consistent interpretation of the pulsar timing array data in terms of merging primordial black holes, if μ-distortion constraints associated with the formation mechanism can be evaded.

Grande finale: Quo vadis pulsar timing?



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 & collider experiments**

➡ **Soon: TransitionListener v2 and me moving to VLC!**

Thank you very much for your attention!

Do you have any questions?

Backup slides