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

Seminar at Stockholm university, November 13th 2025

Carlo Tasillo,
Uppsala University

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.

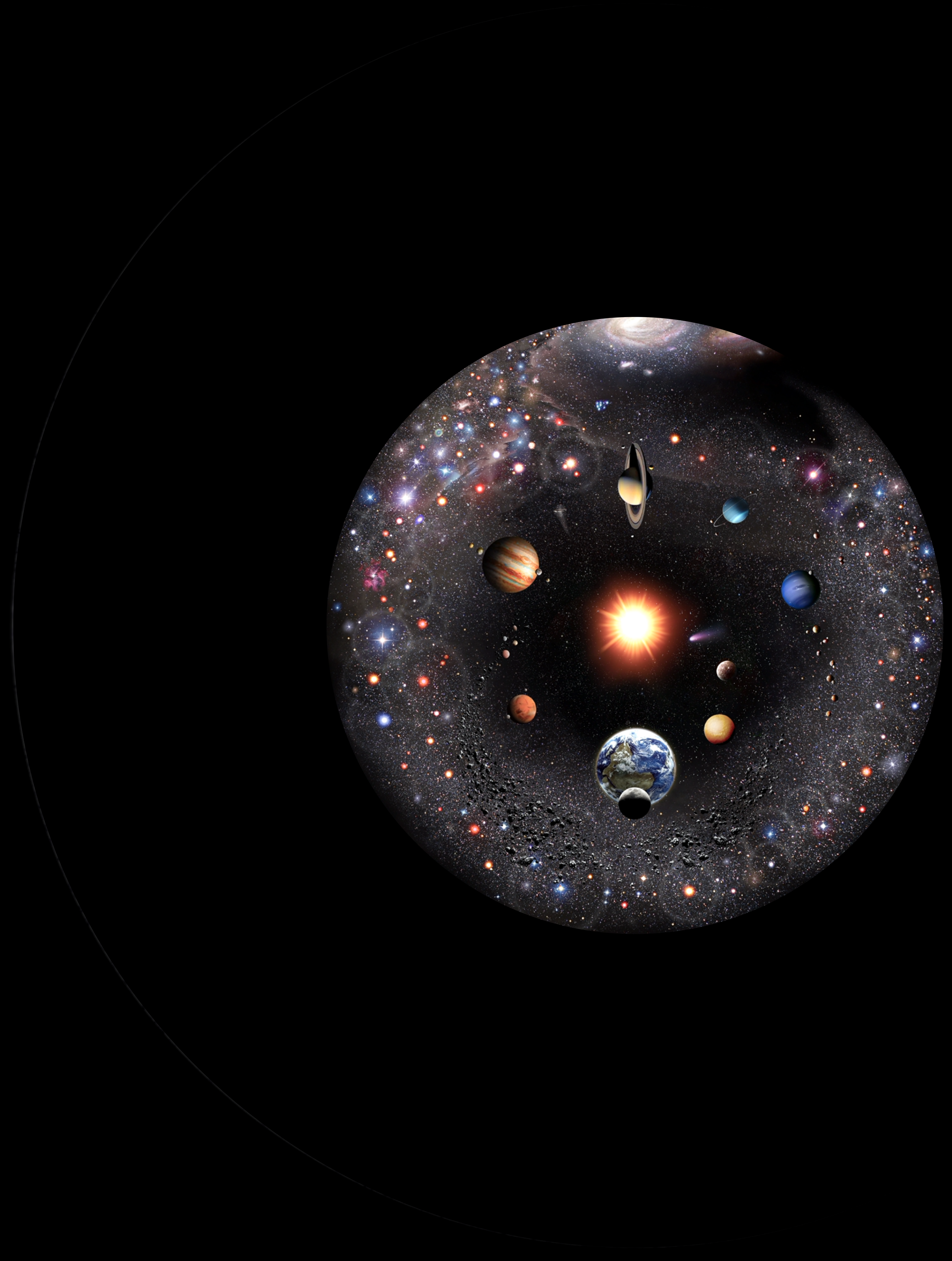
UPPSALA UNIVERSITET

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

Our Solar System

[Pablo Carlos Budassi]

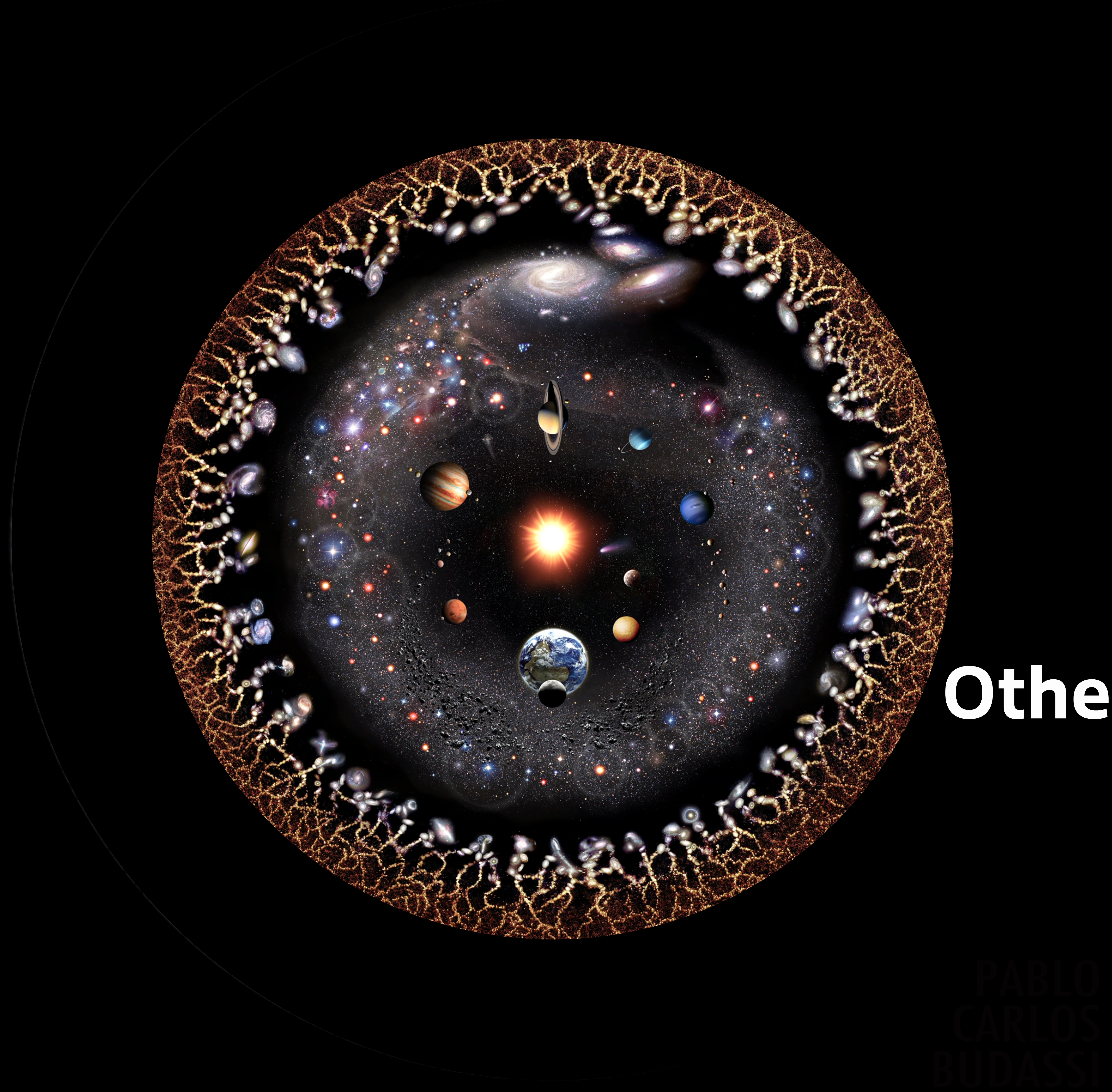
It’s the end of the world as we know it (and I feel fine)



Our galaxy

[Pablo Carlos Budassi]

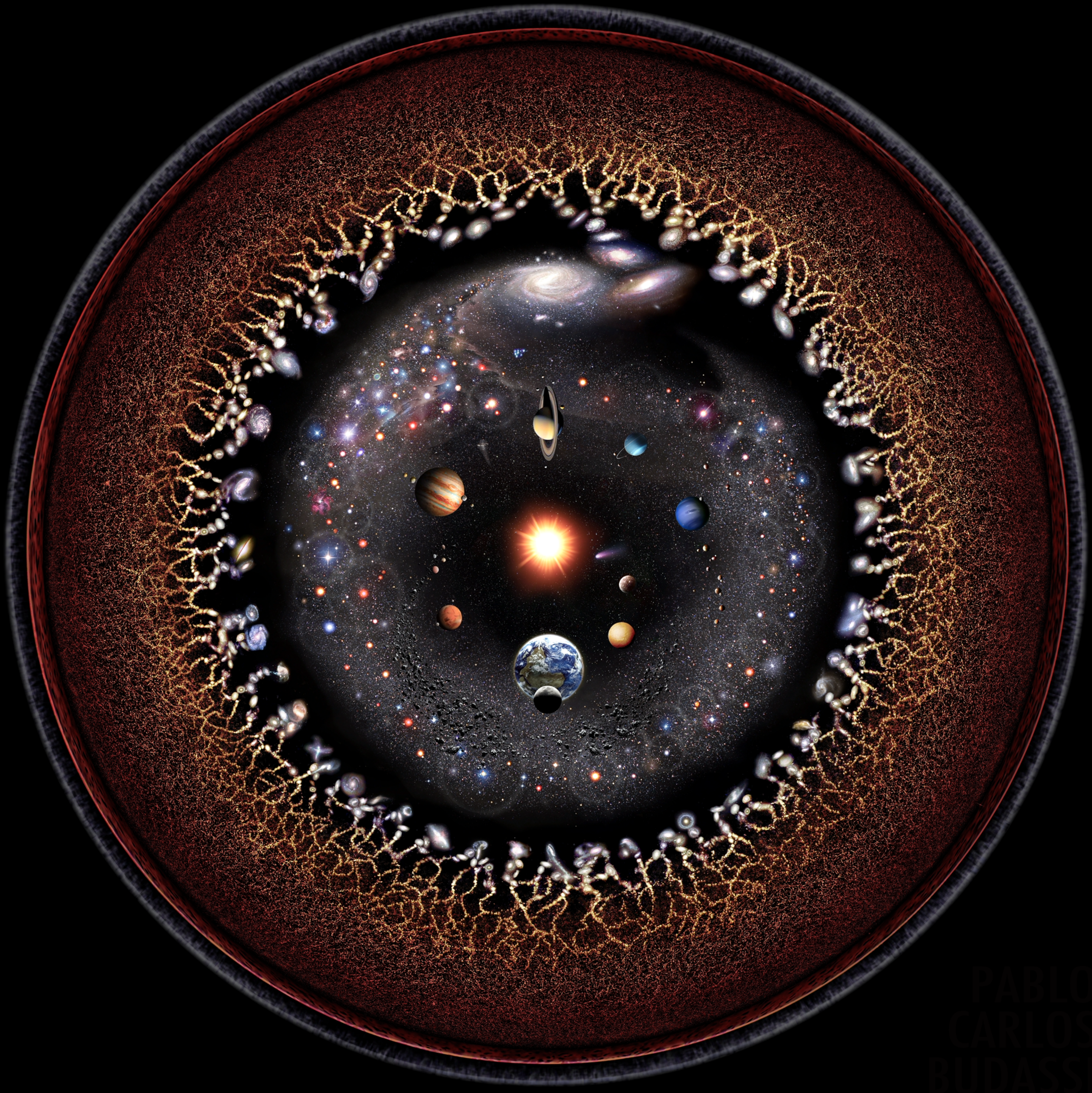
It’s the end of the world as we know it (and I feel fine)



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?

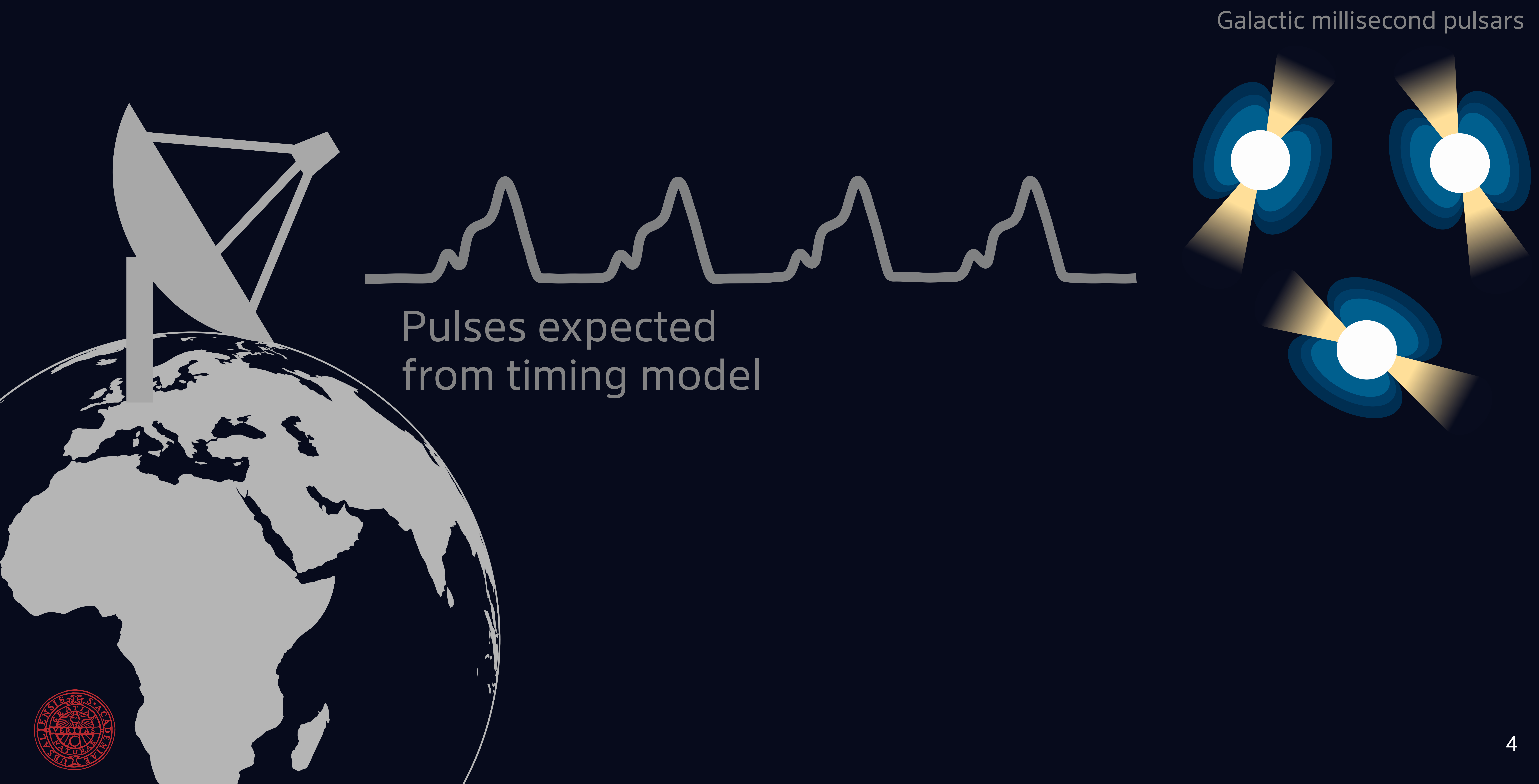
[Pablo Carlos Budassi]


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 Gravit
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
re tuning in to a never-before-seen type of gravitational
pawned by pairs of supermassive black holes
w form of ripple i
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 black holes that are gently stretching and squeezing everything in the universe
Monster gravitational
spotted for first
The New York Times
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
ntists discover that universe is a
gravitational waves
ace-time ripples
Galax
Space
Gravitational wave
at the center of the M
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.
king 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
Scientists r
come from c
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
waves
it may
massive black
The results are
background, a hum o
Universe.

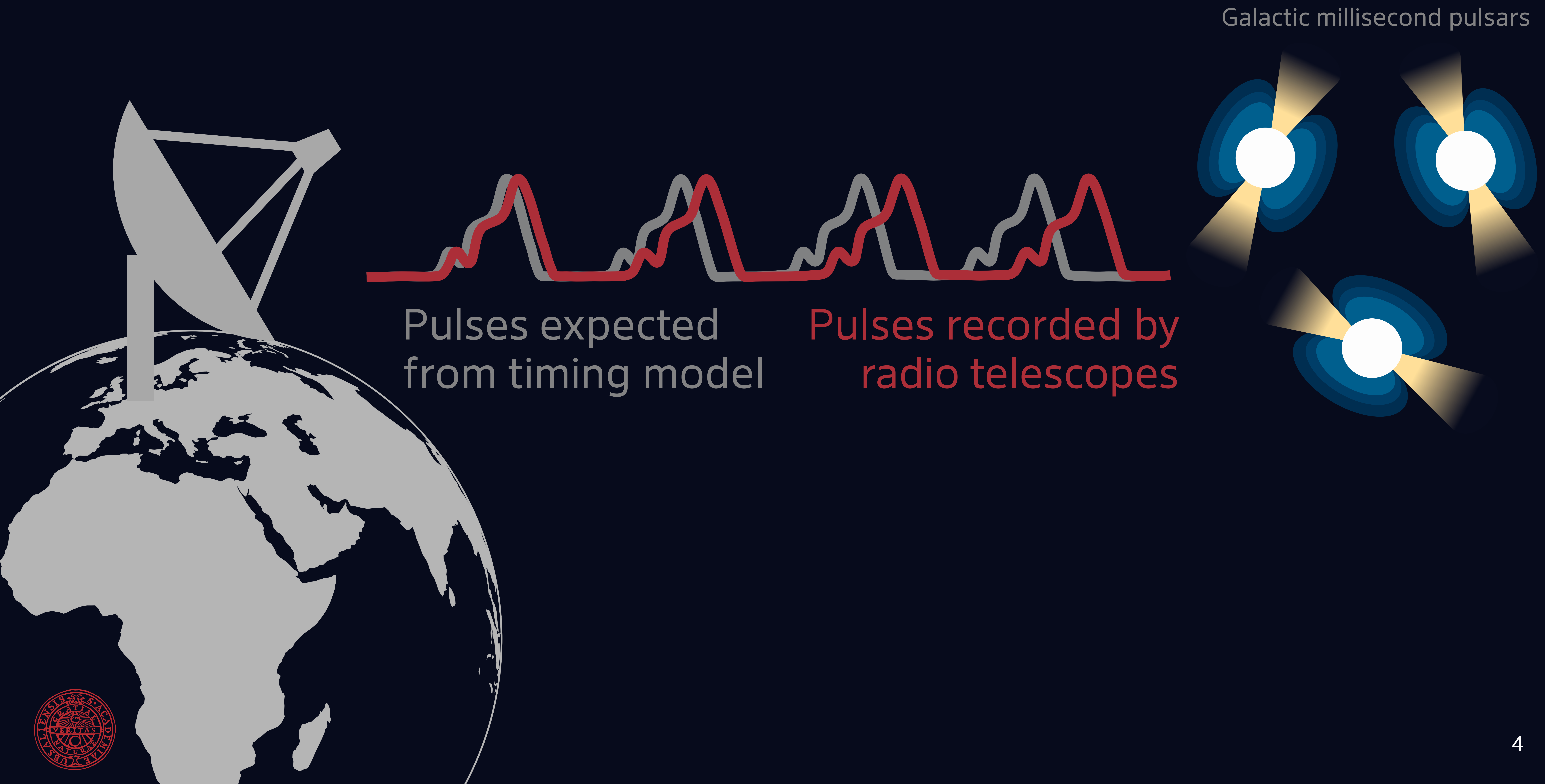

We live in the age of gravitational wave cosmology!
Astronomers detect 'cosmic bass note' of gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists
Scientists 'hear' cosmic hum from gravitational waves
Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe
For first time ever, scientists "hear" gravitational waves rippling through the universe
ASTROPHYSICS
A Background 'Hum' Pervad
Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe
In a major discovery, scientists say space-time churns like a choppy sea
by studying rapidly spinning dead
giant ripples of spacetime likely
from merging supermassive black holes—
The Washington Post
Physics

The working principle of a pulsar timing array

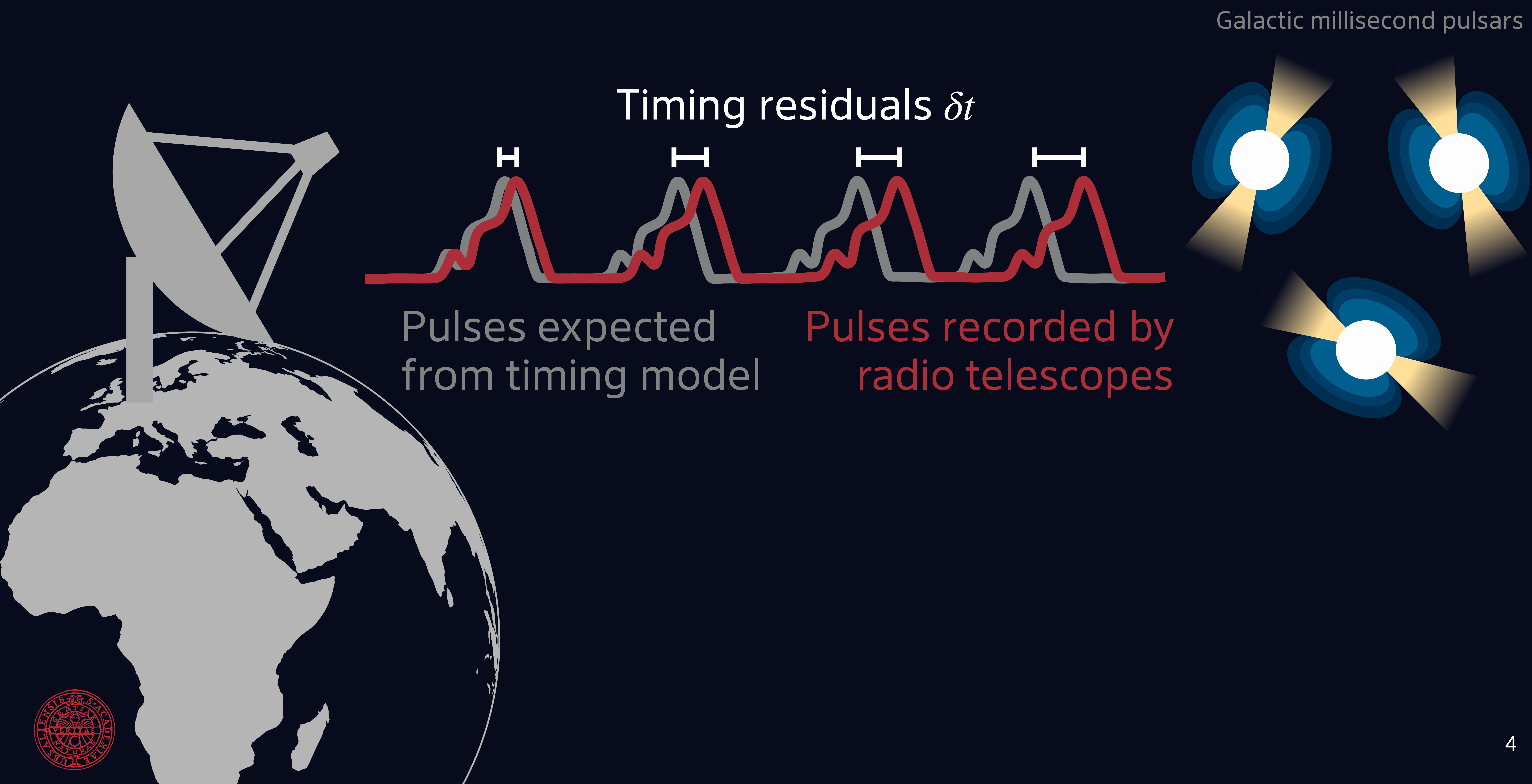
The working principle of a pulsar timing array



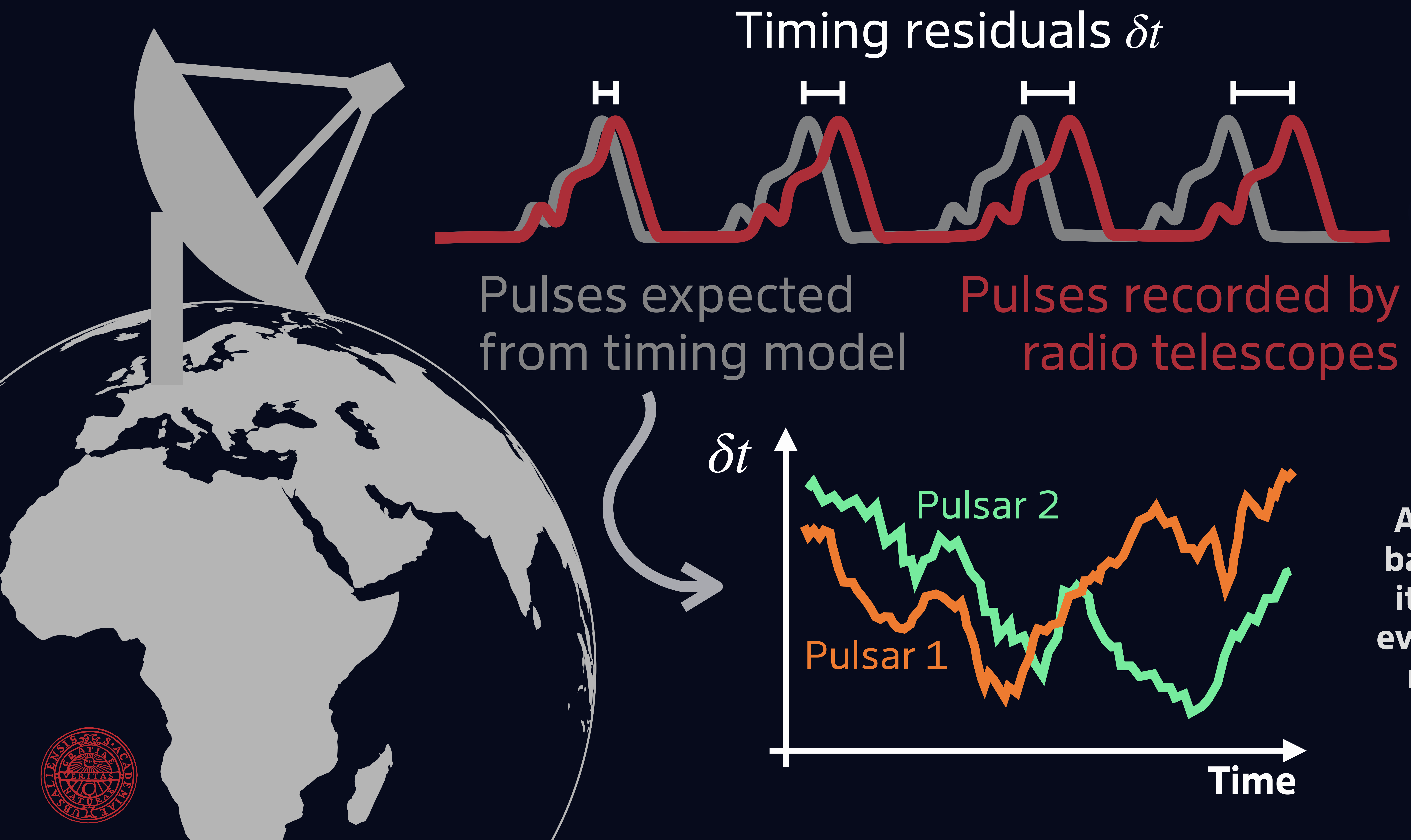
The working principle of a pulsar timing array

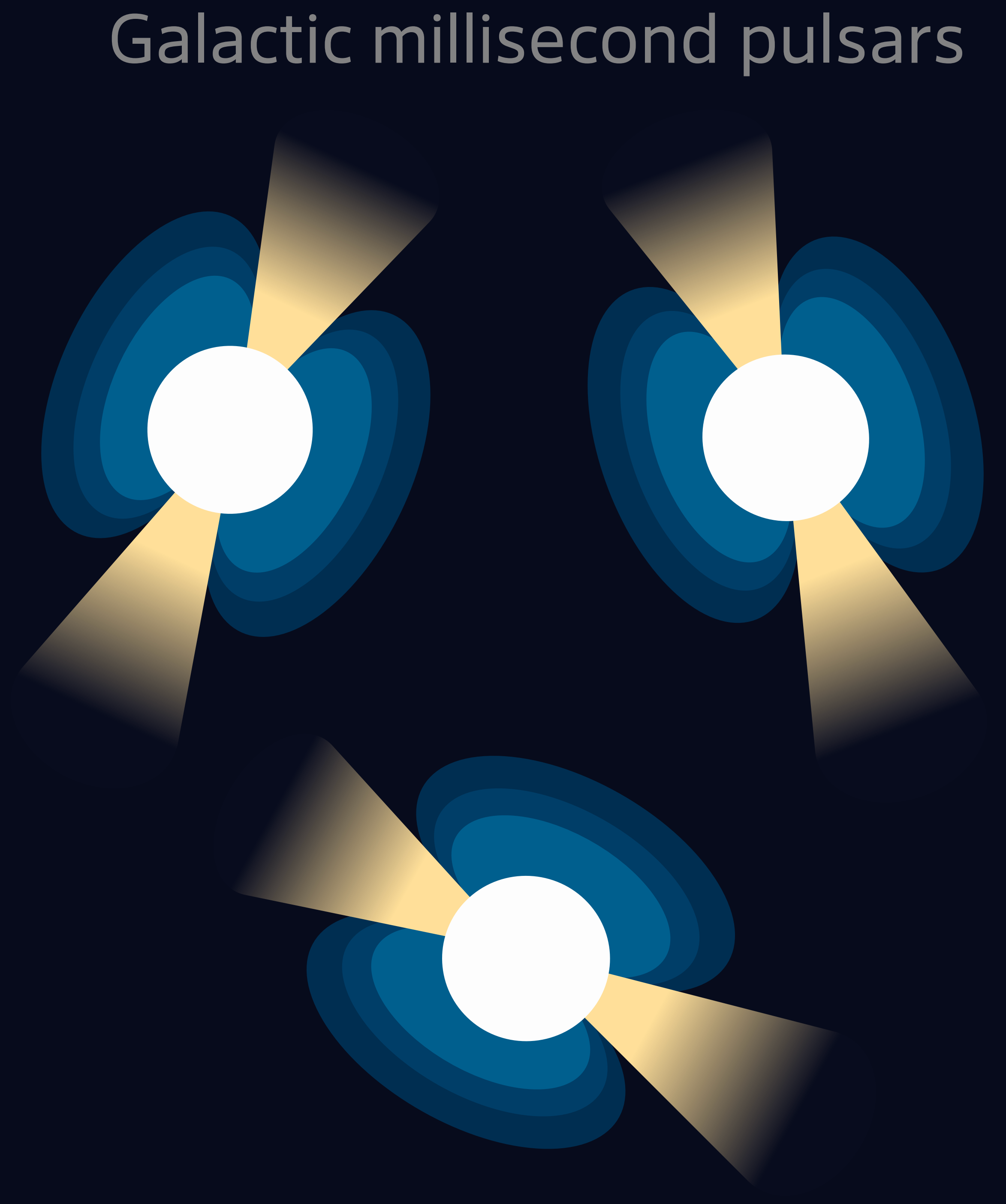


The working principle of a pulsar timing array



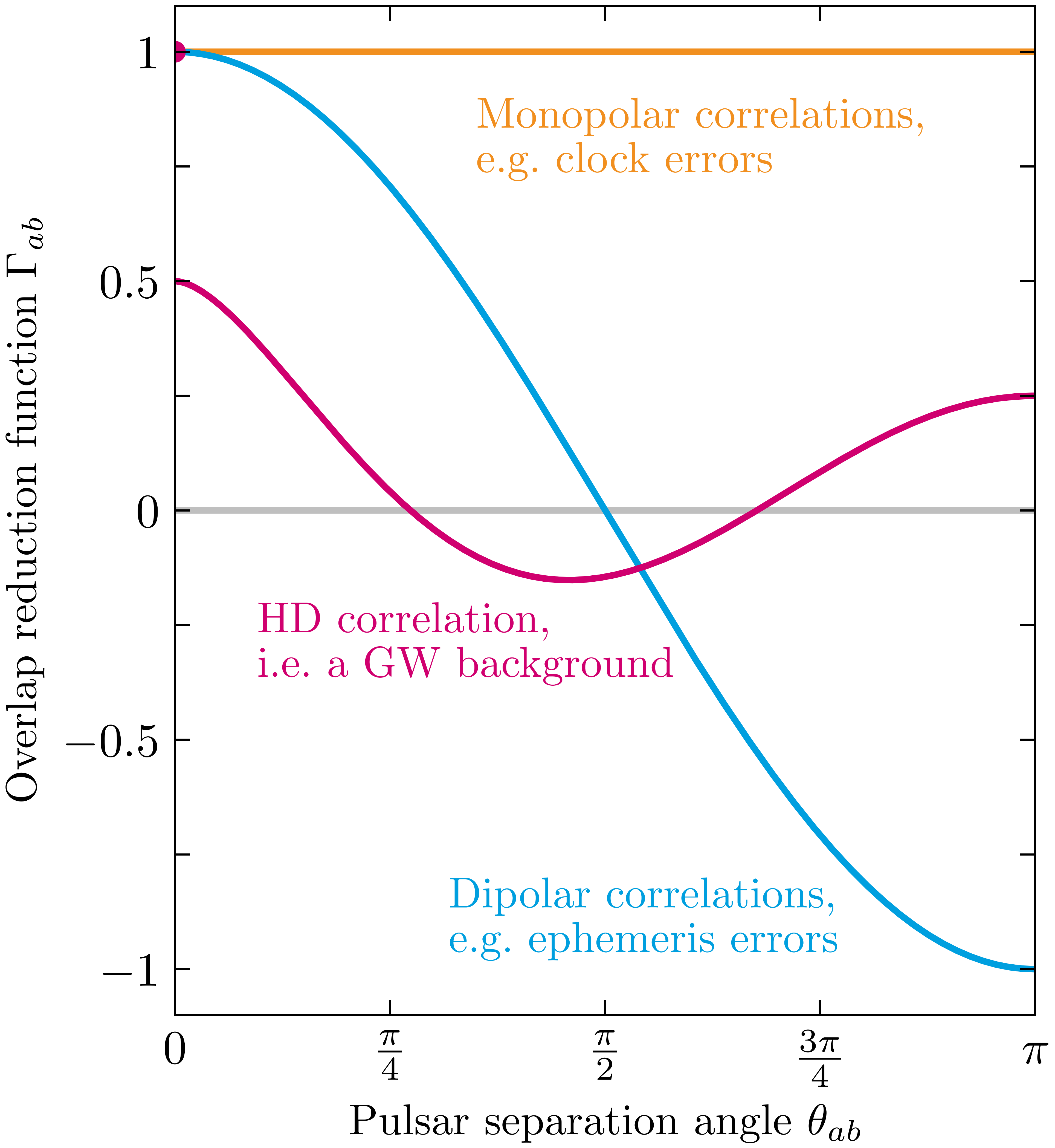
The working principle of a pulsar timing array





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

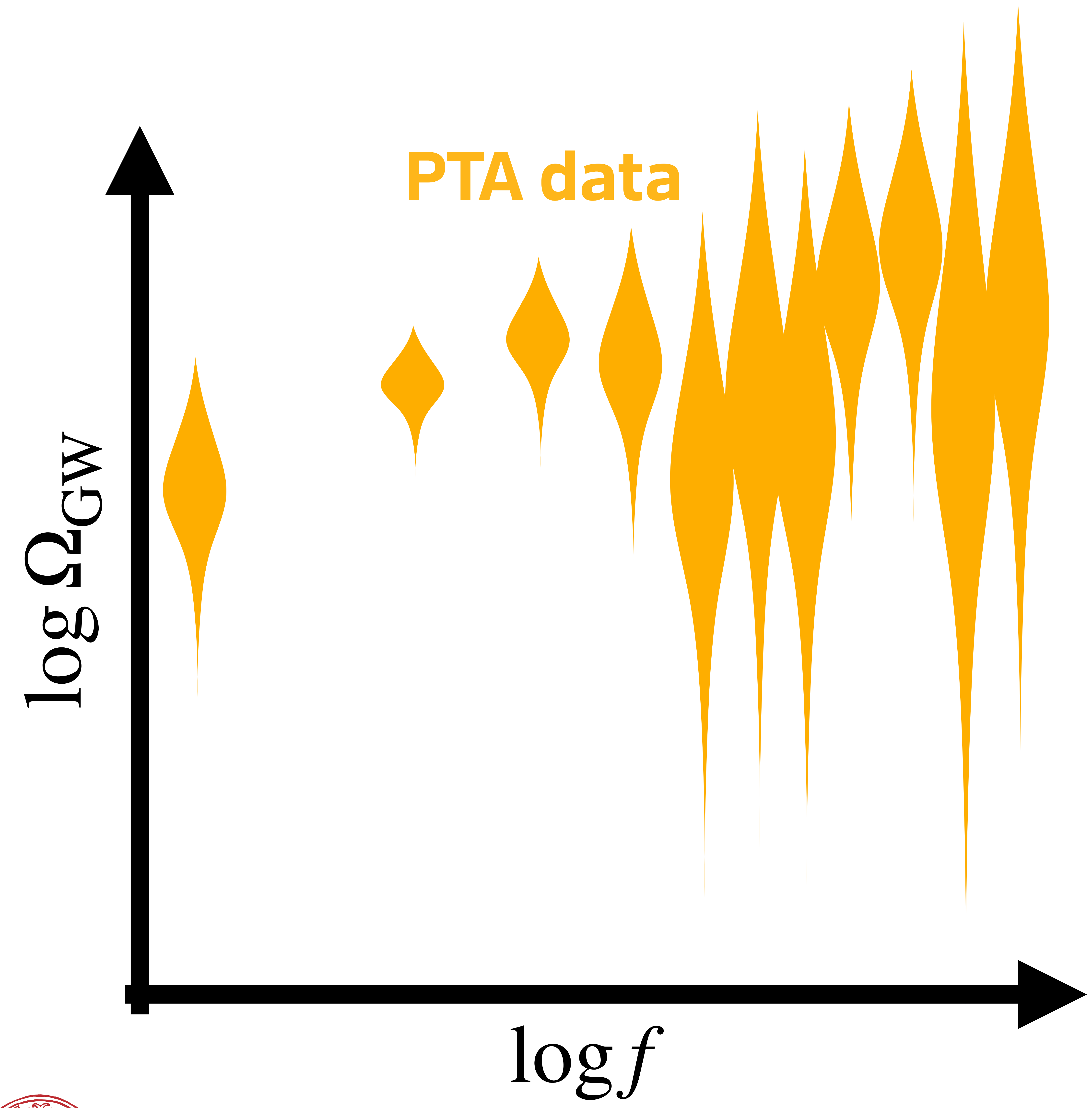
Searching for the Hellings-Downs correlation



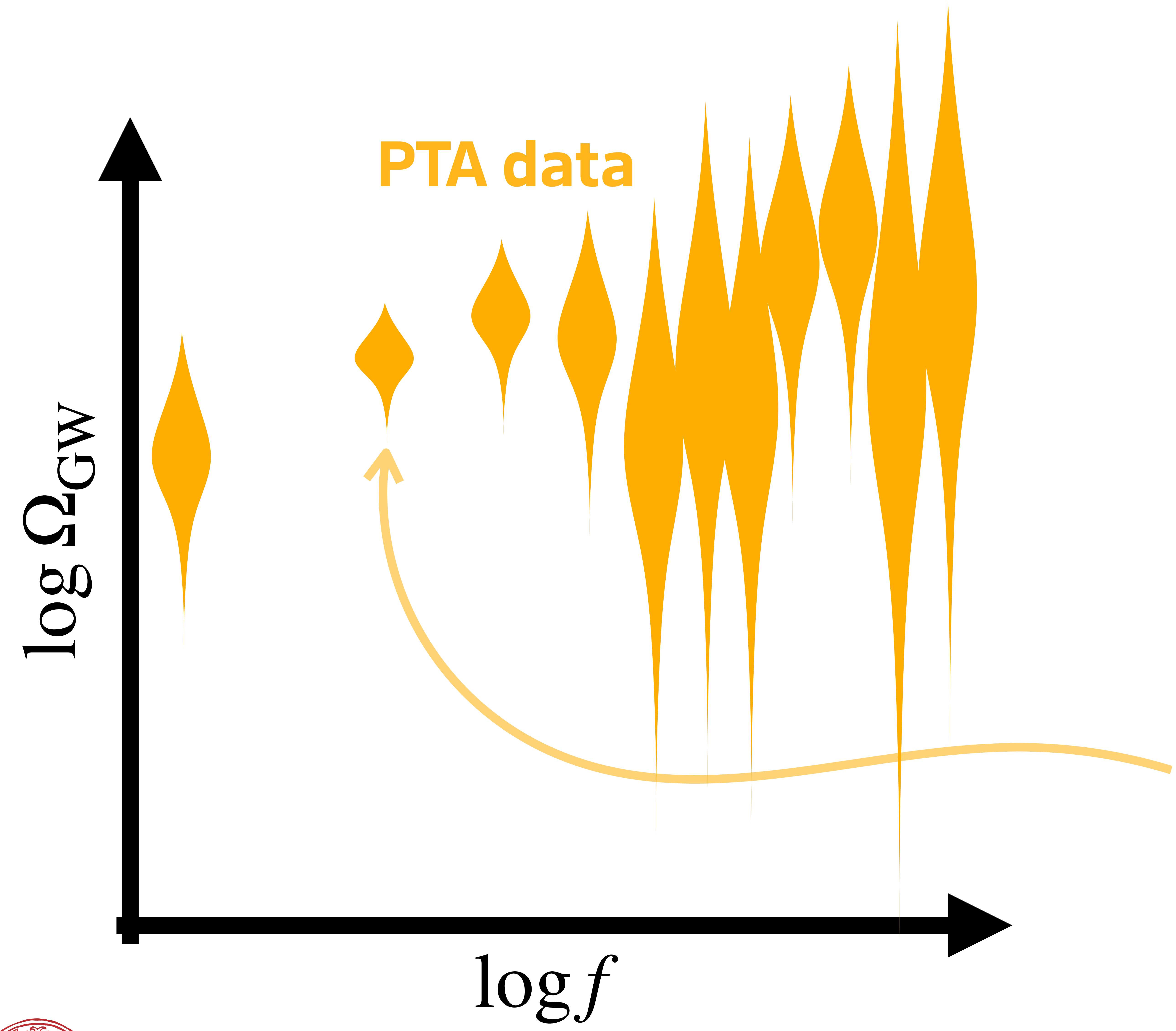
- PTAs found an underlying „common red process" among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves, Clock errors, Ephemeris errors:
    All ruled out with >5σ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]

What is the source?

Learning to play the violin

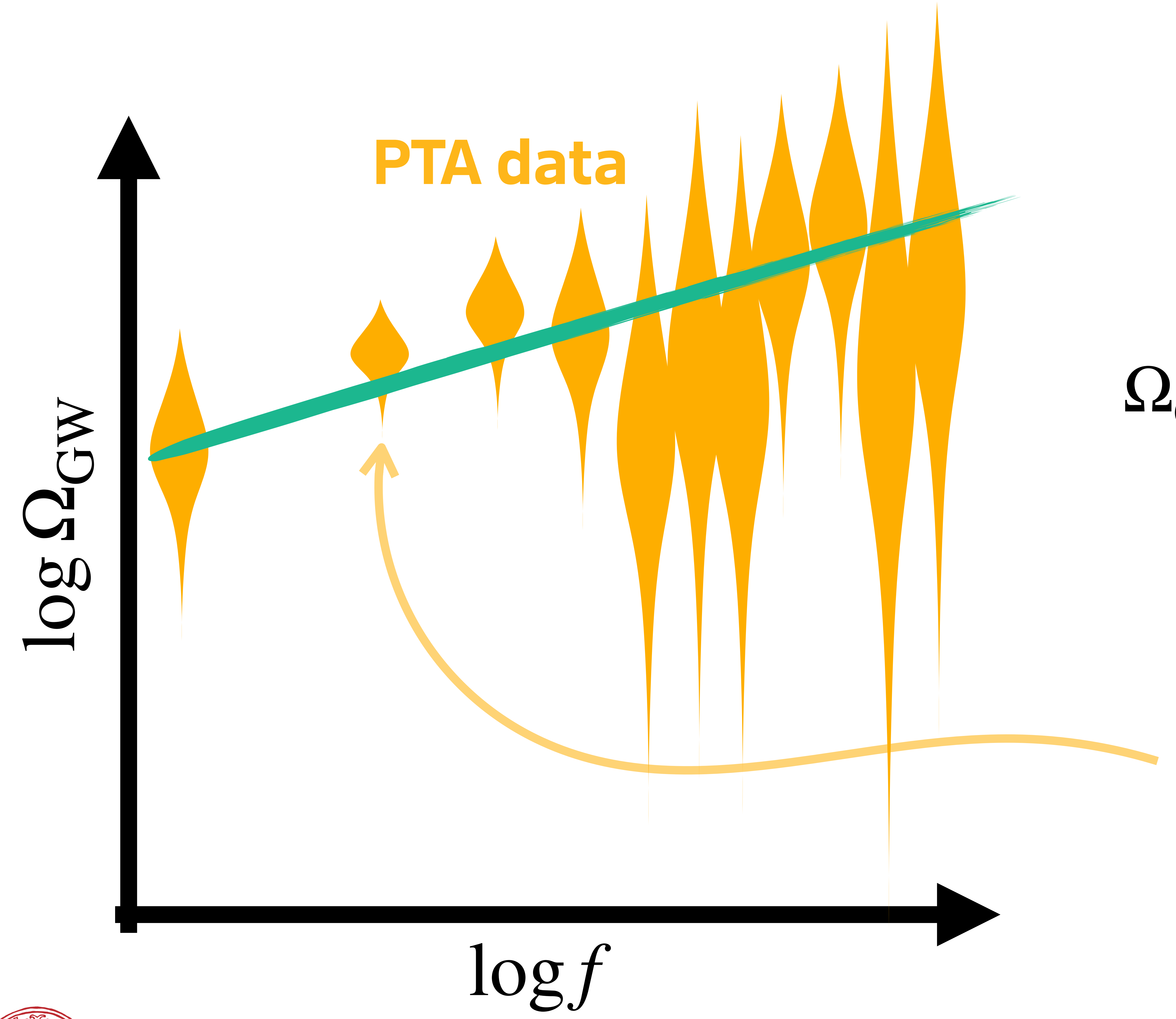


Learning to play the violin



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

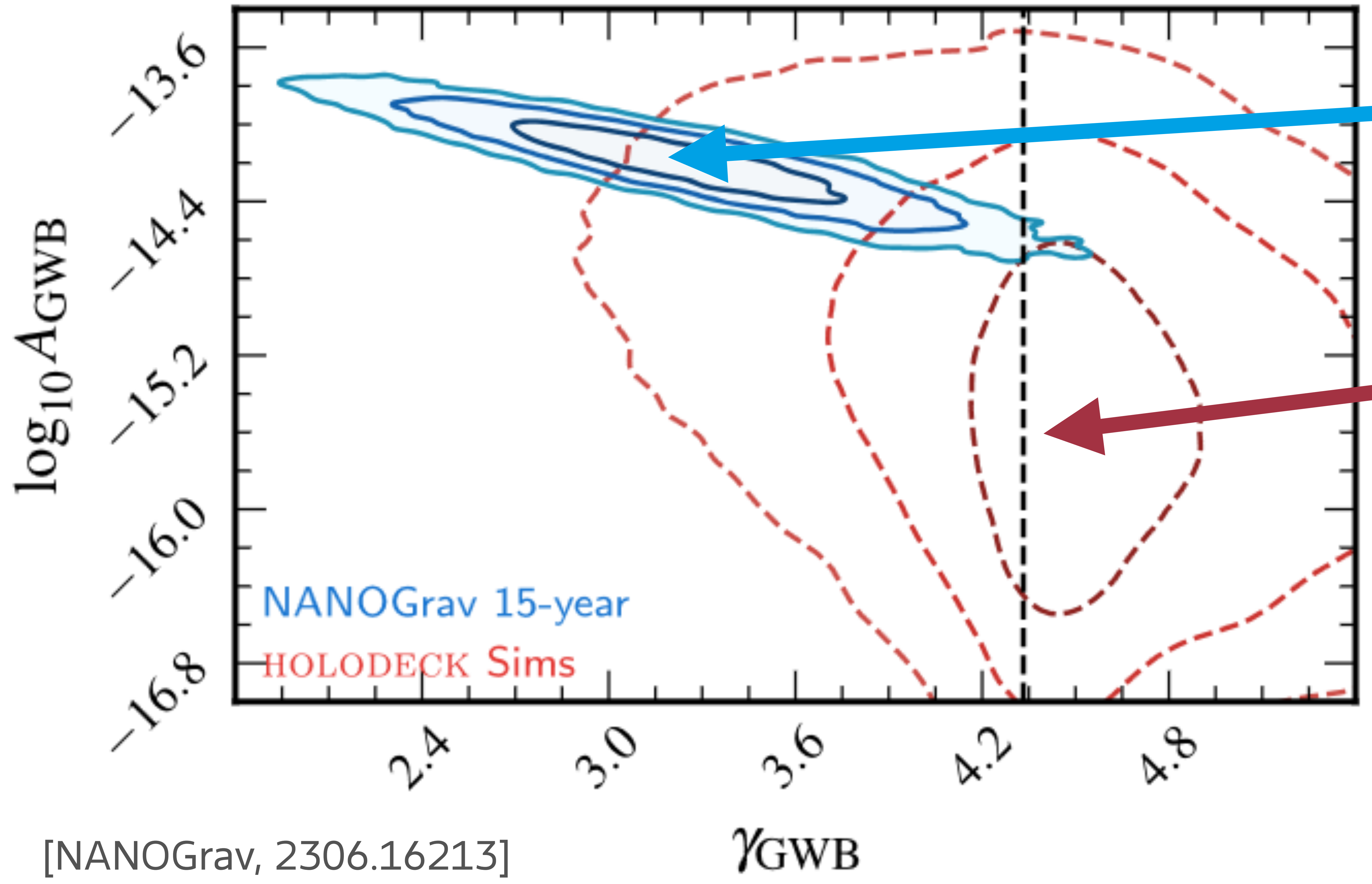


The inferred spectral shape of the GWB is well described by a power law

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

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

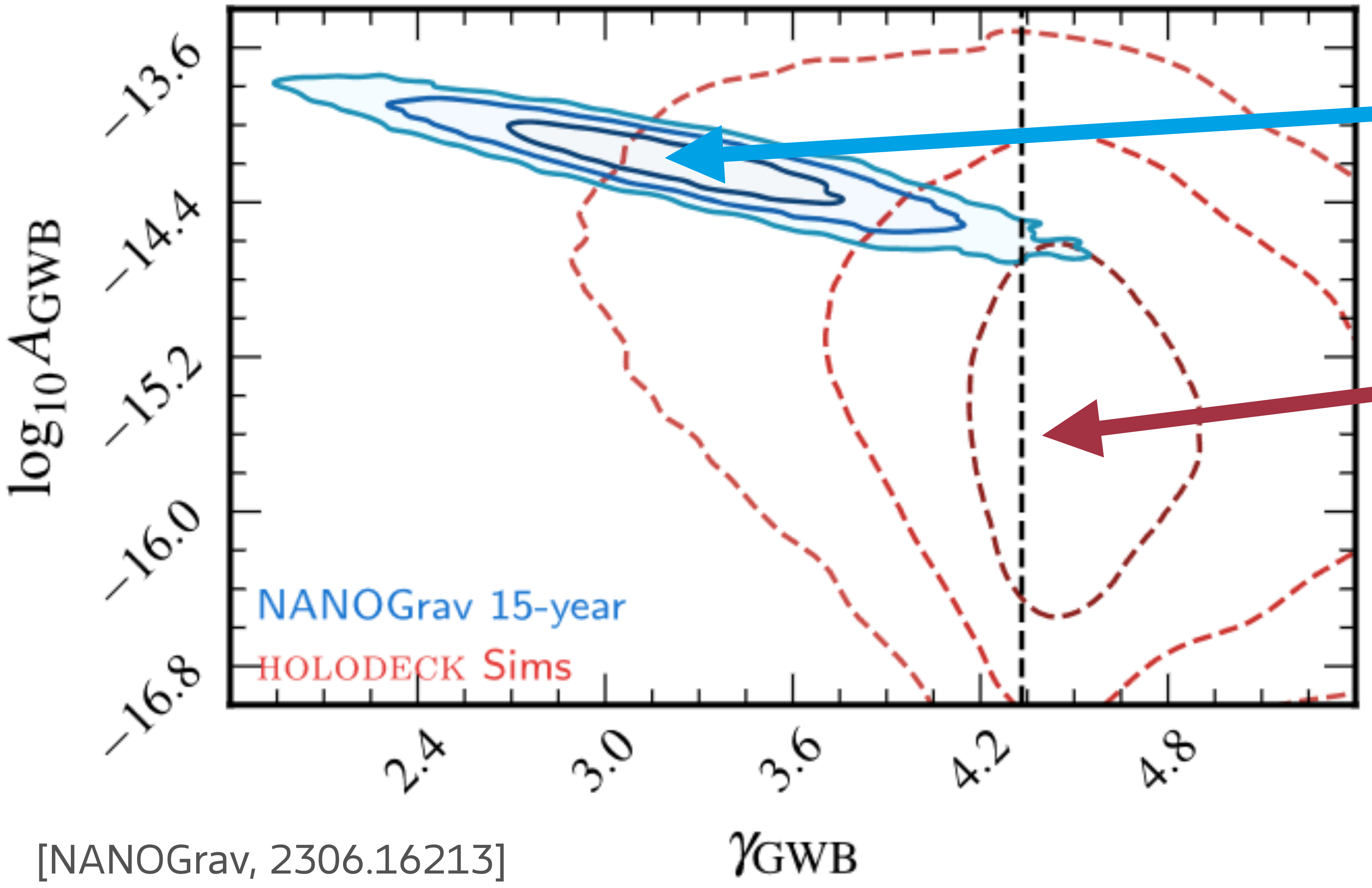


[NANOGrav, 2306.16213]

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



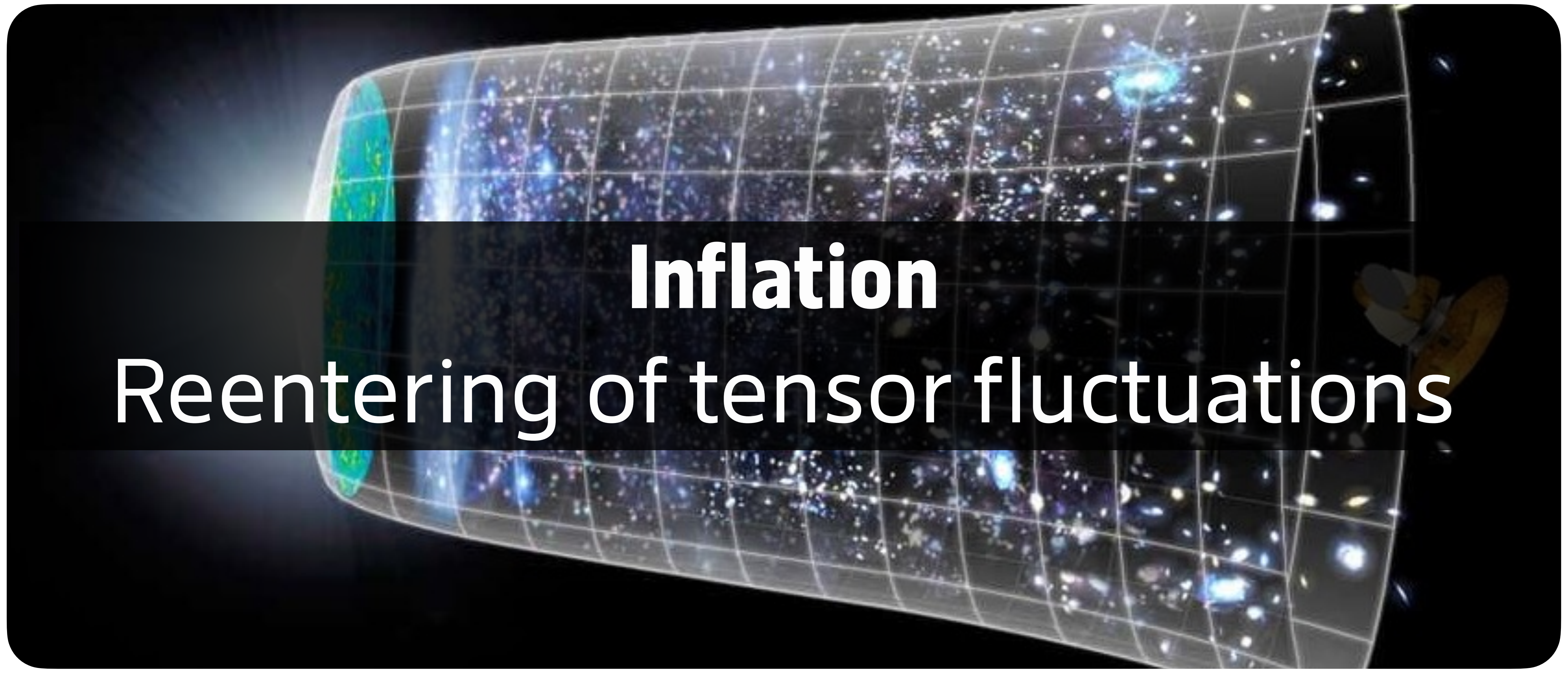
[NANOGrav, 2306.16213]

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

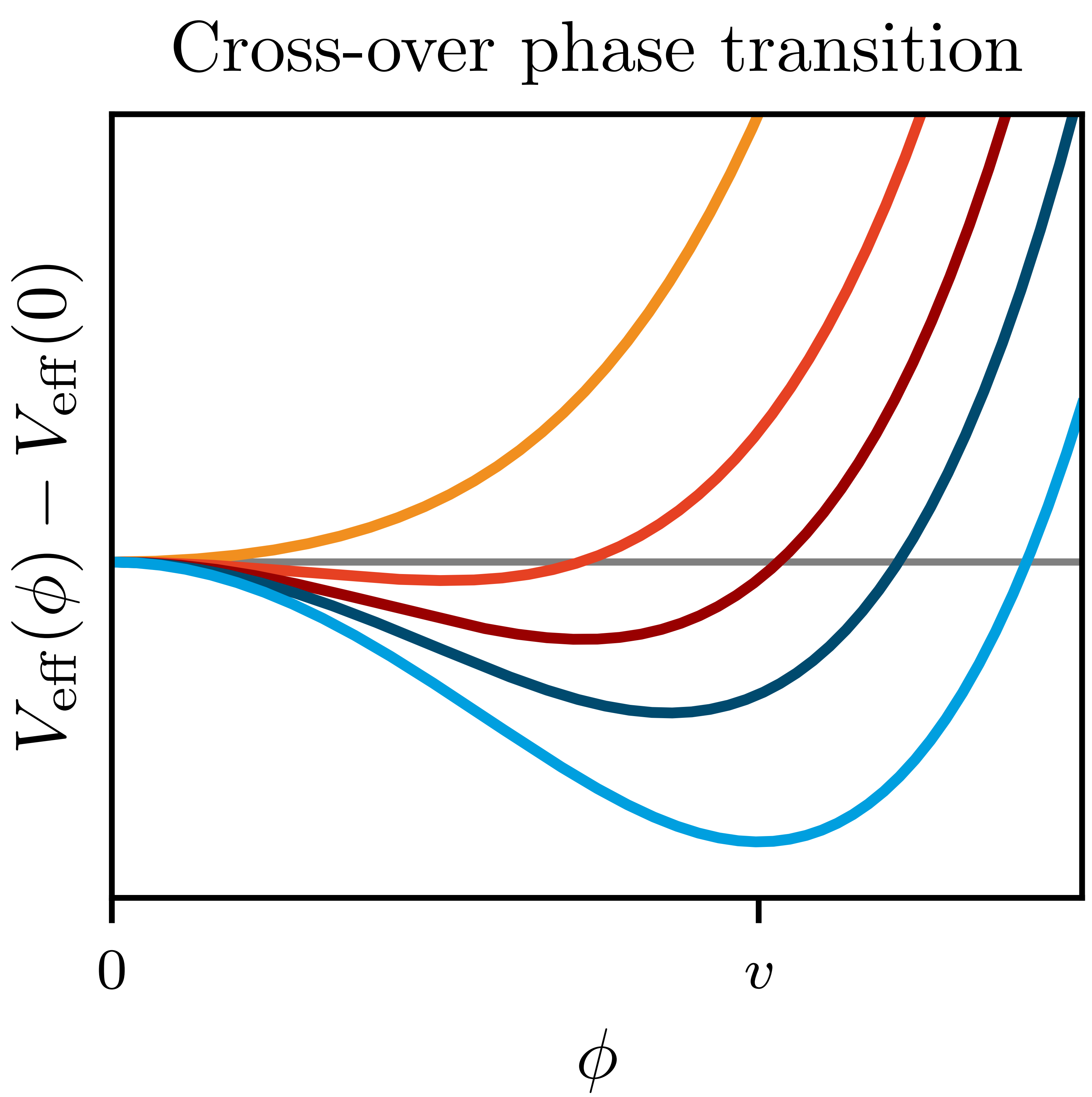
Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ (more power in low frequencies)

Are there other signal sources?

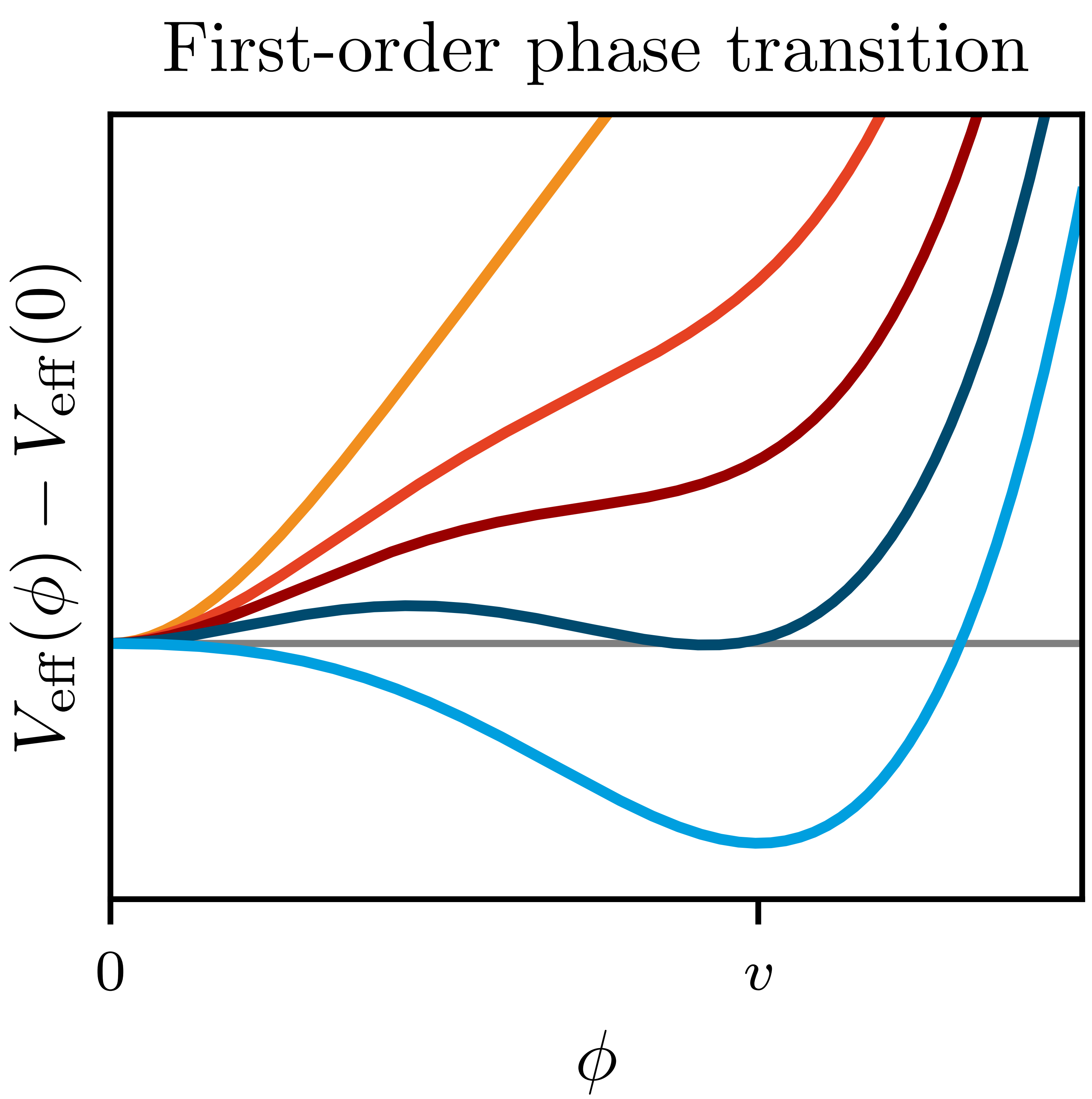
Possible cosmological sources of the PTA signal



First-order phase transitions vs. cross-overs



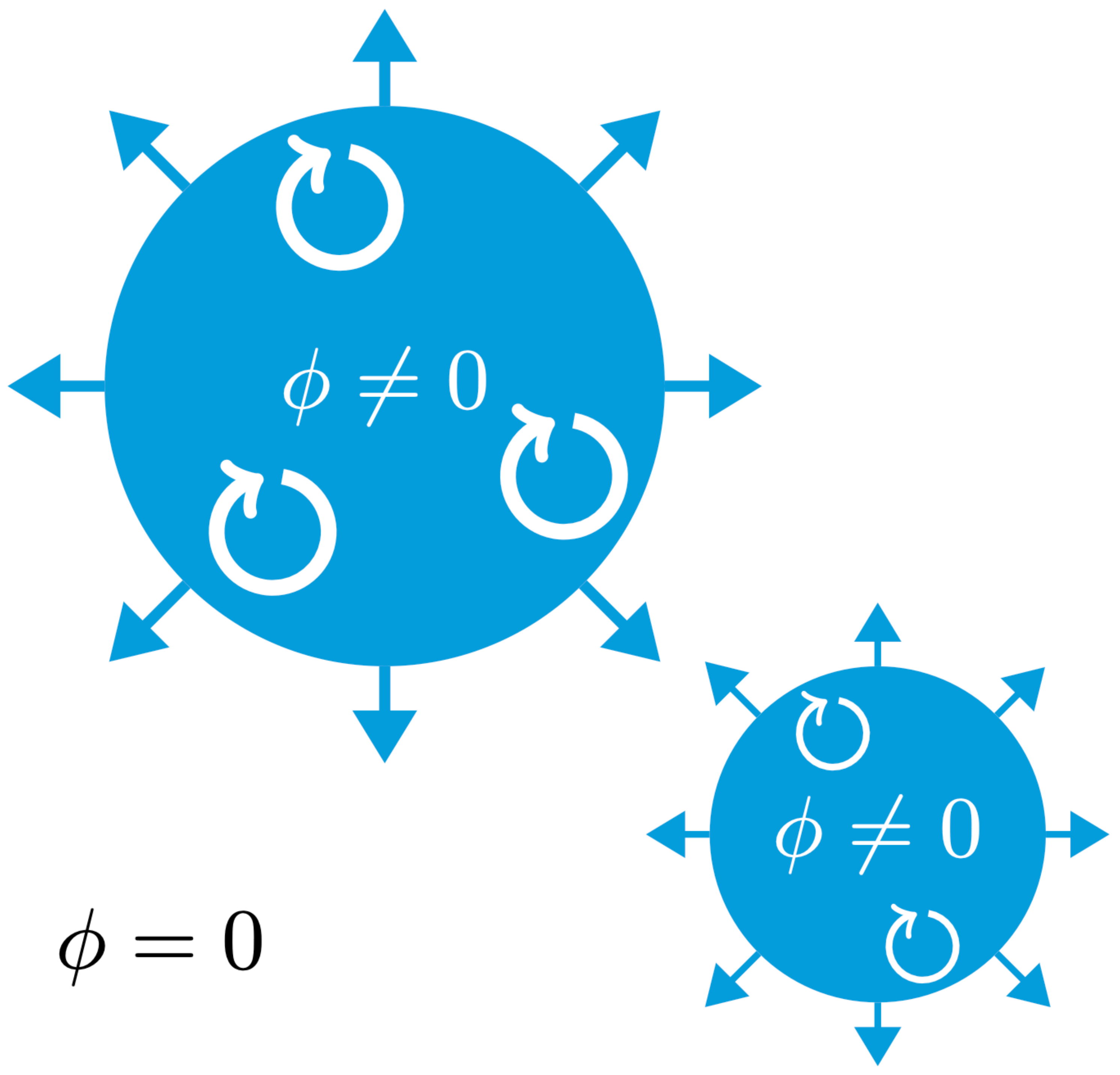
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

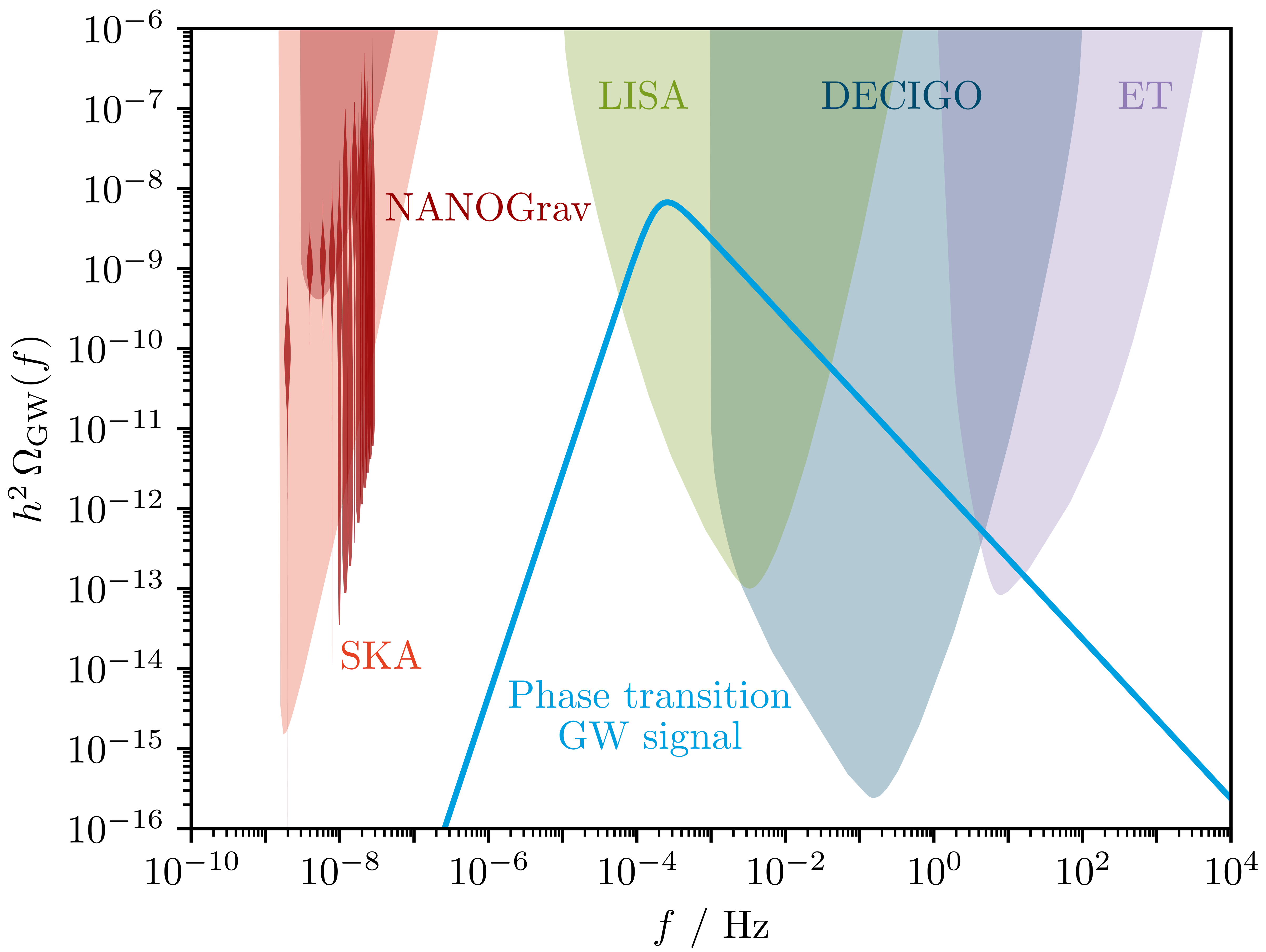


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy.

First-order phase transitions produce GWs

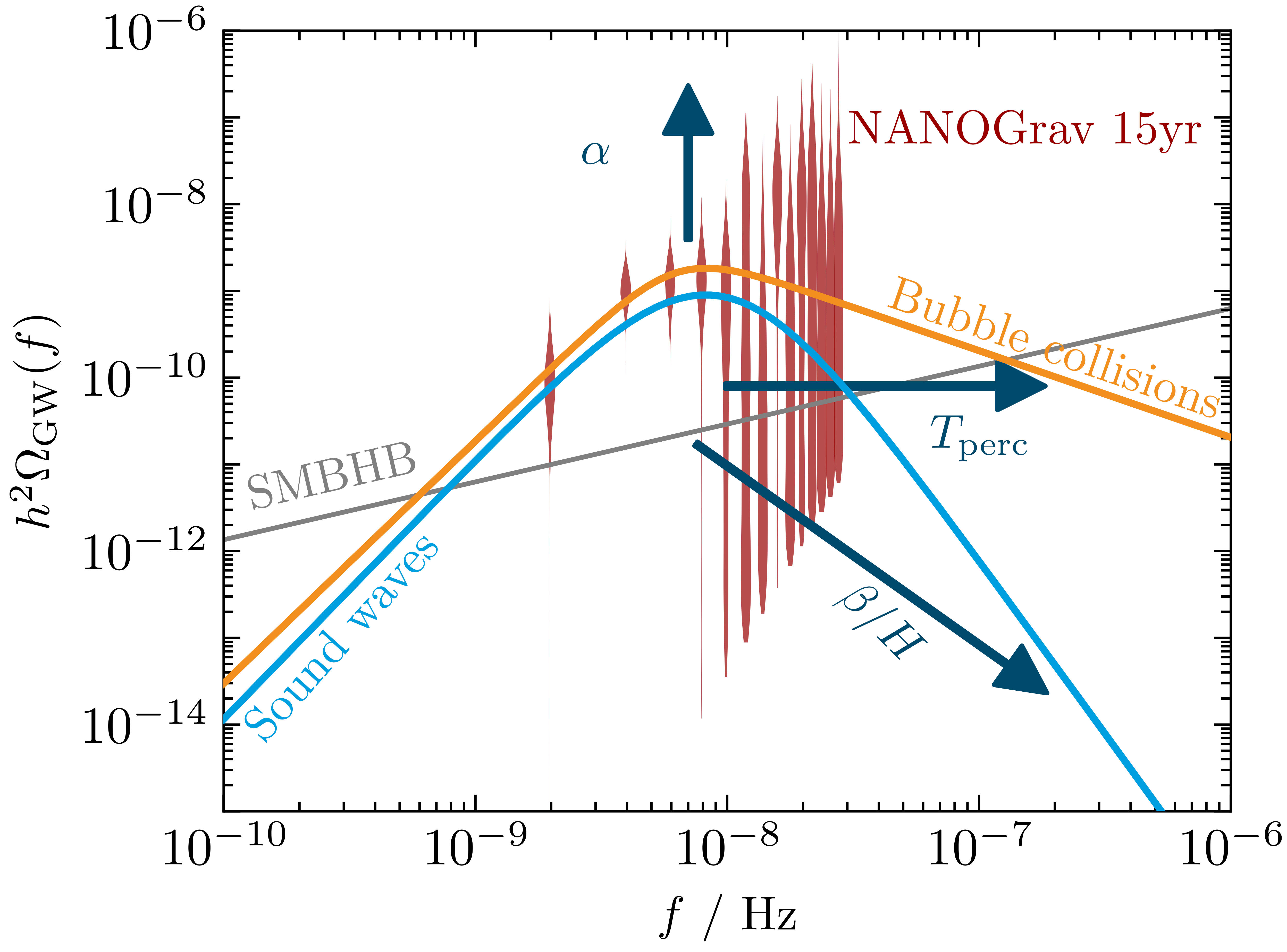
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

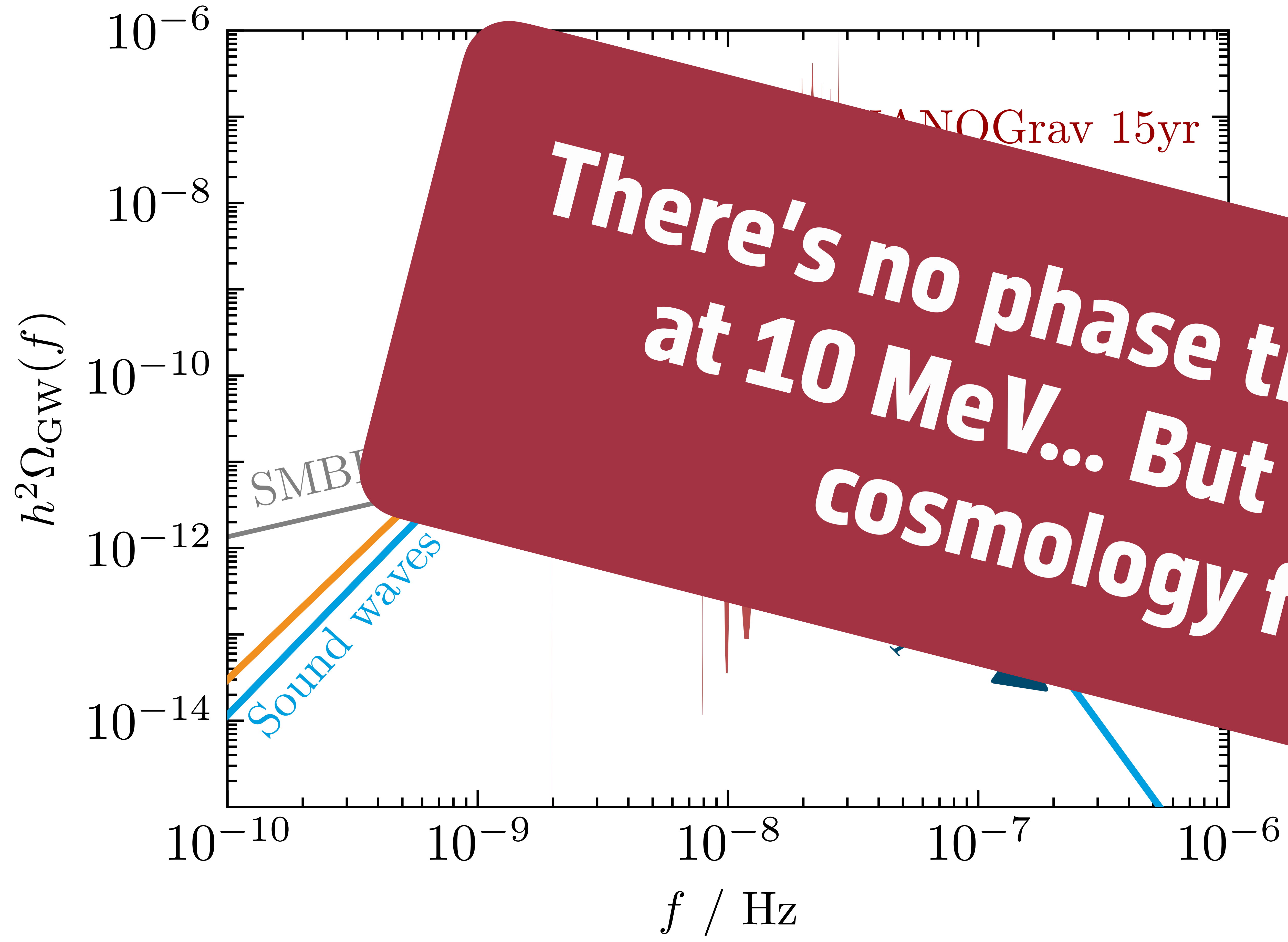
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

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

...ing data:

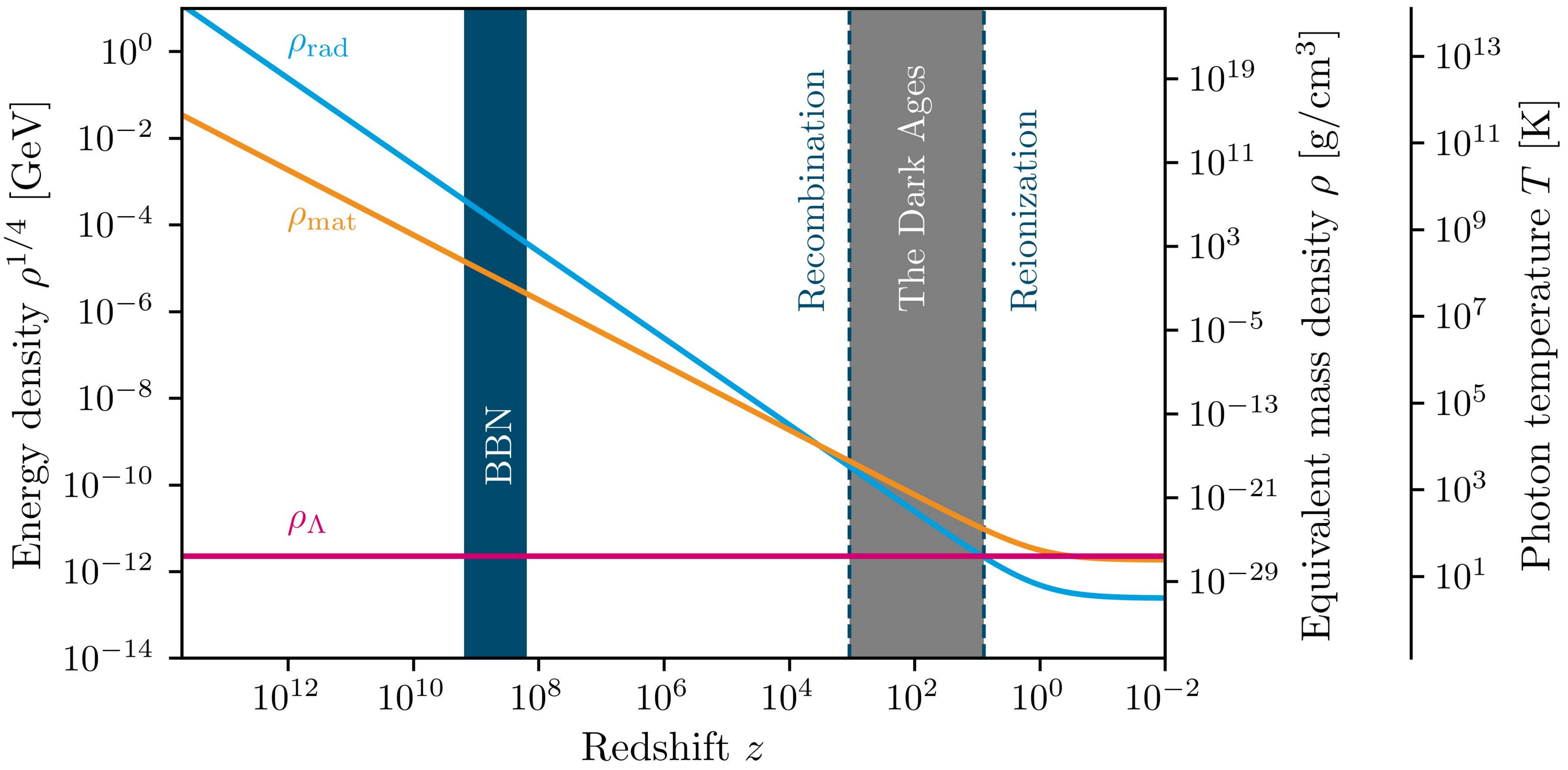
... 1

... ≈ 10

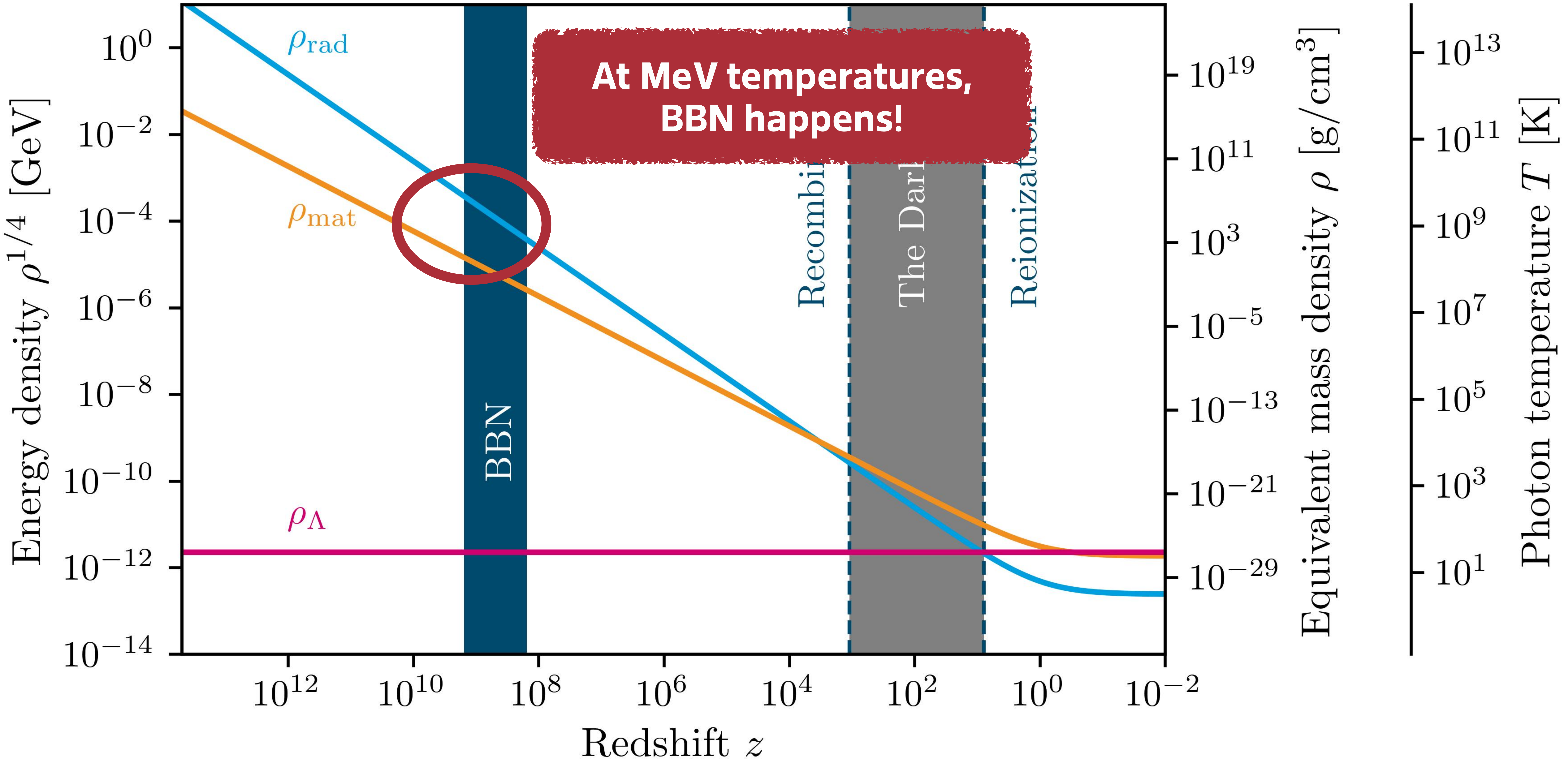
- Percolati... $\approx 10\,\text{MeV}$

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

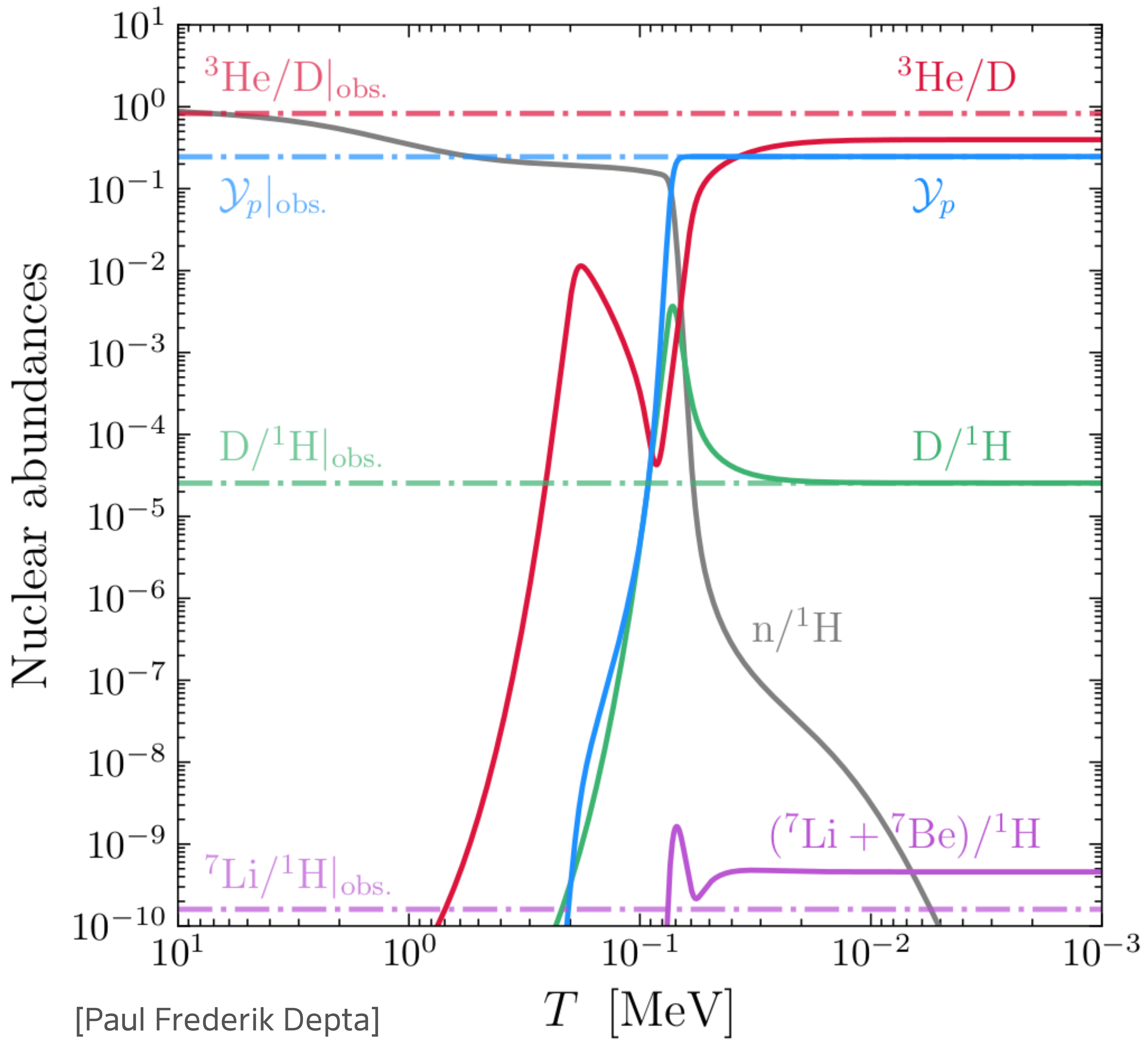
A brief history of time



A brief history of time



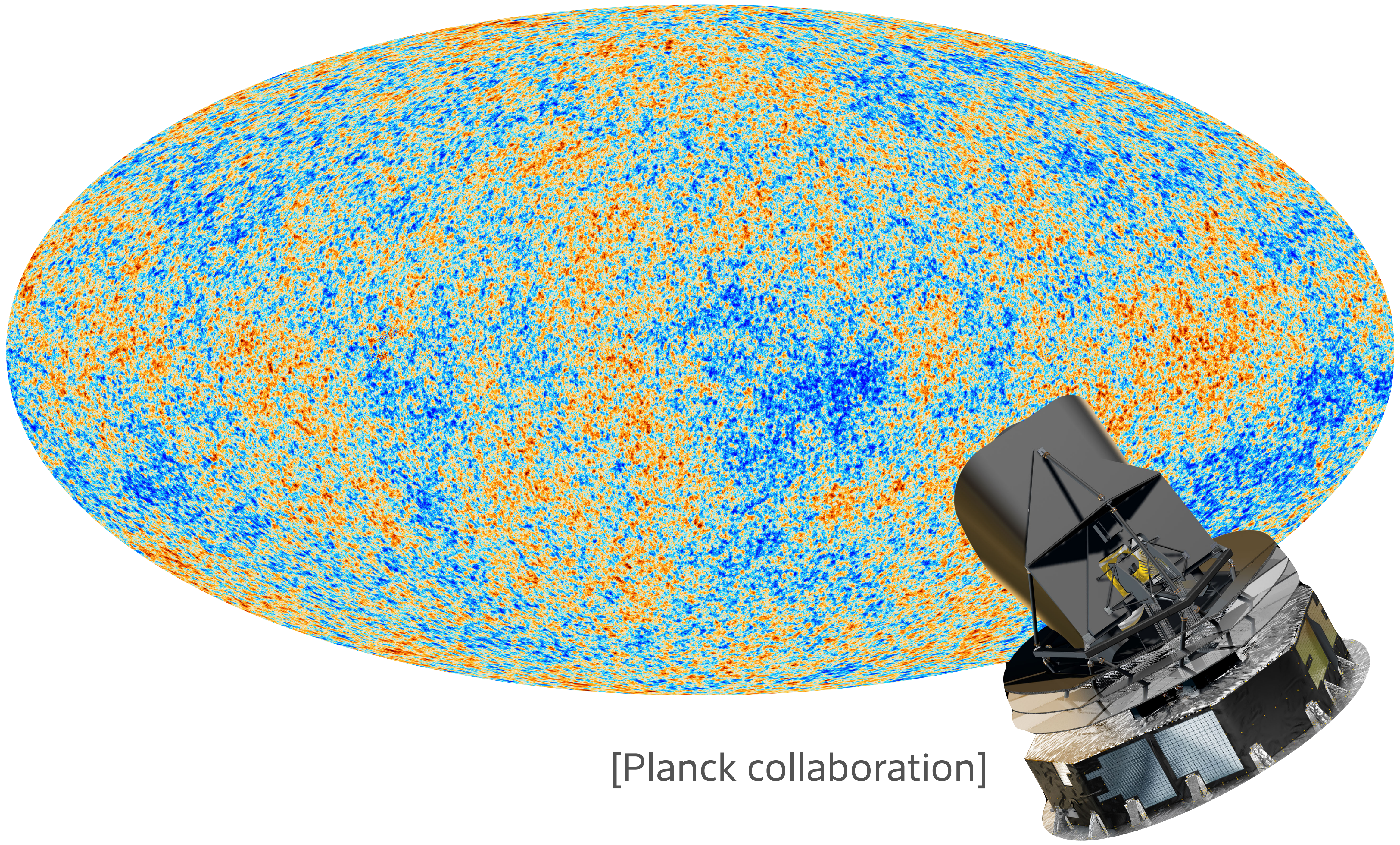
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

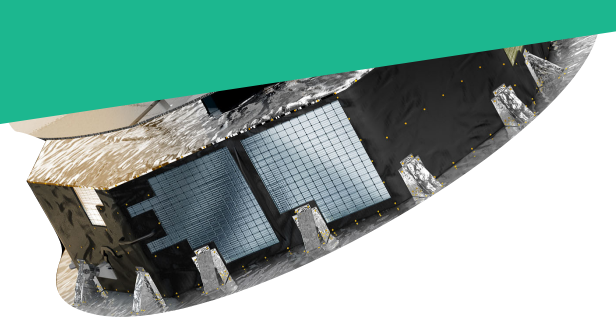
Big Bang Nucleosynthesis and the CMB



[Planck collaboration]

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

Big Bang Nucleosynthesis and the CMB

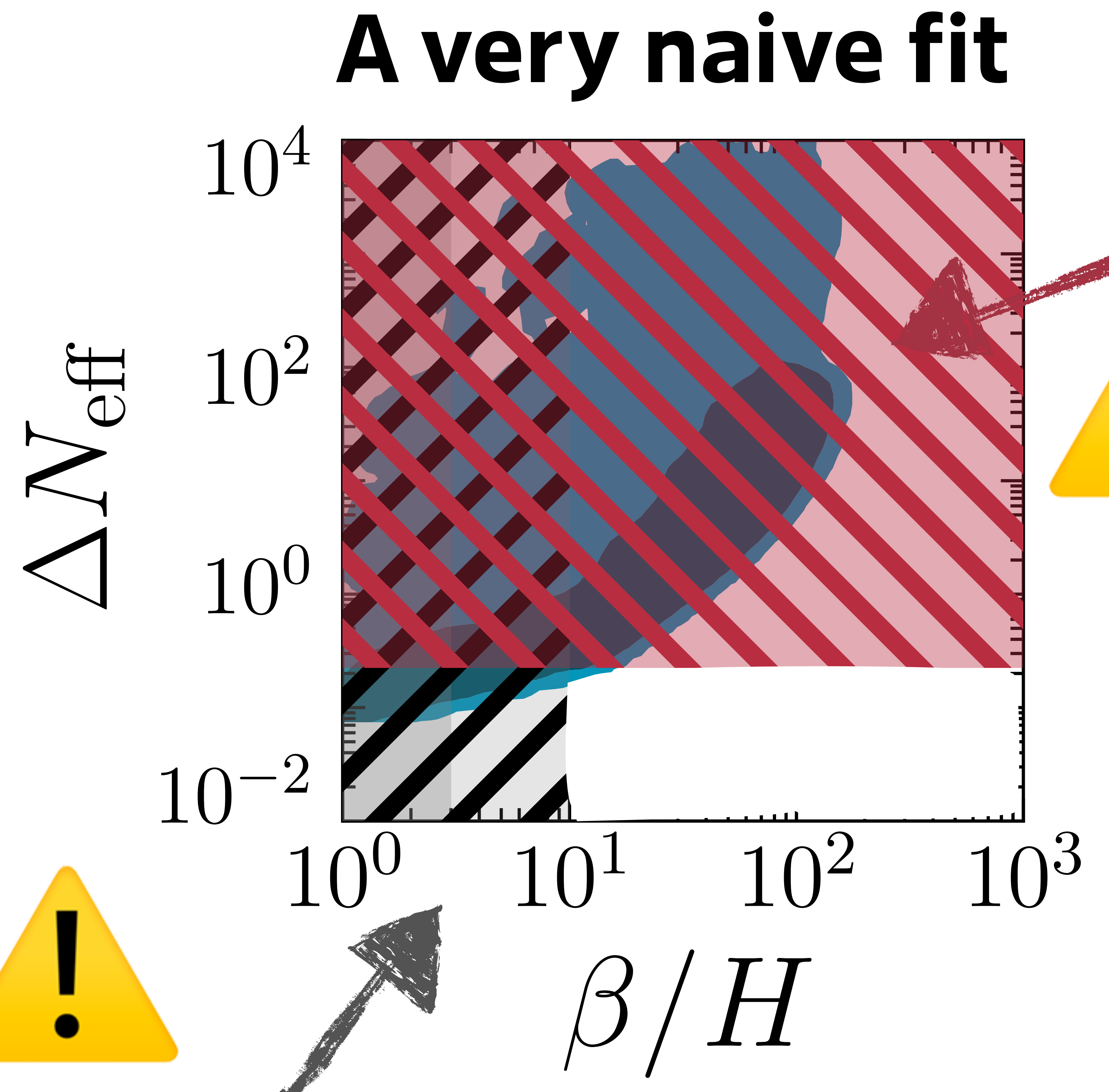


[...ranck collaboration]

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

A dark sector without portal couplings



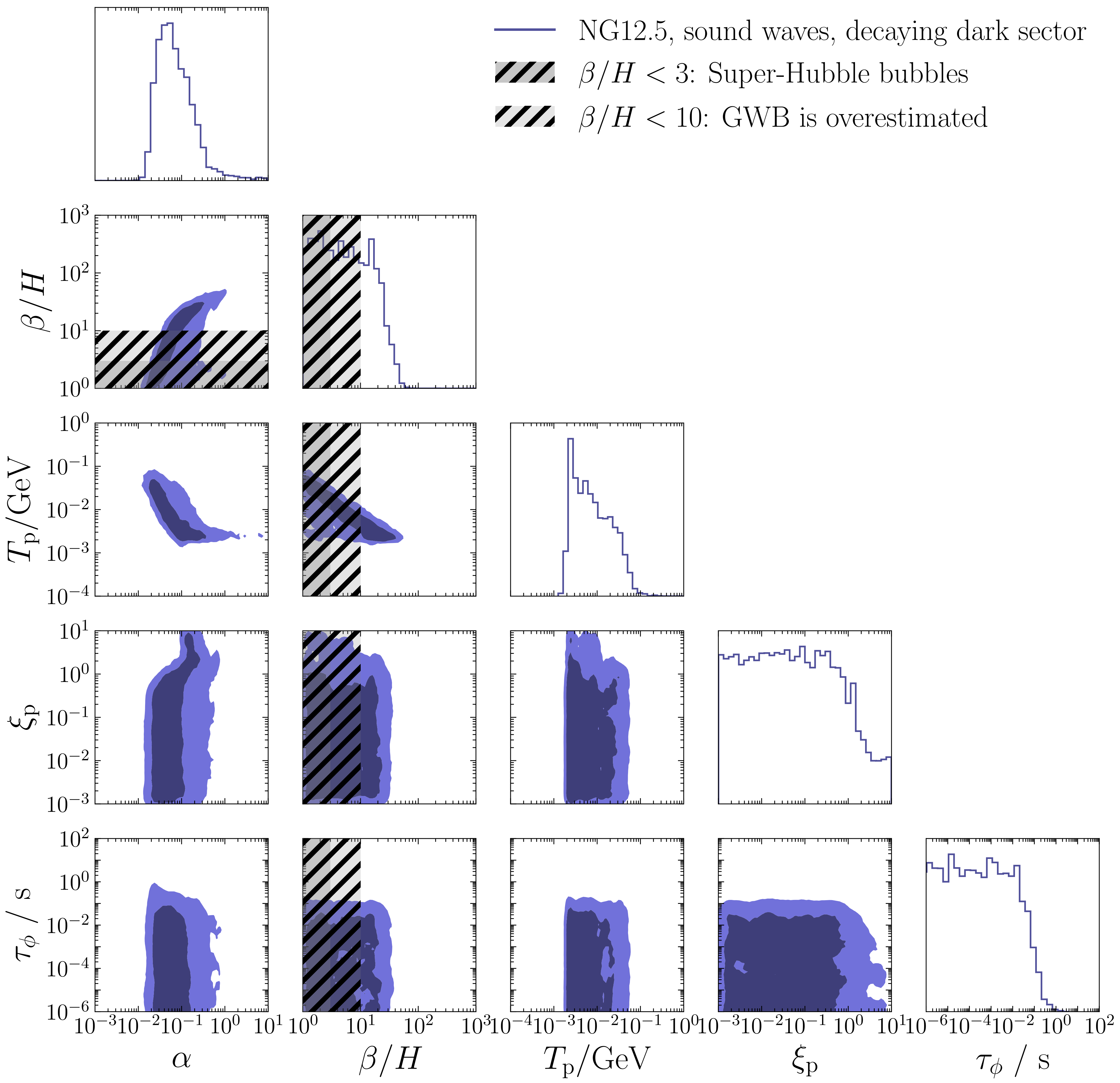
The liberated vacuum energy remains in the dark sector. A good fit would require enormous $\Delta N_{\rm eff} \gg 0.22$

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

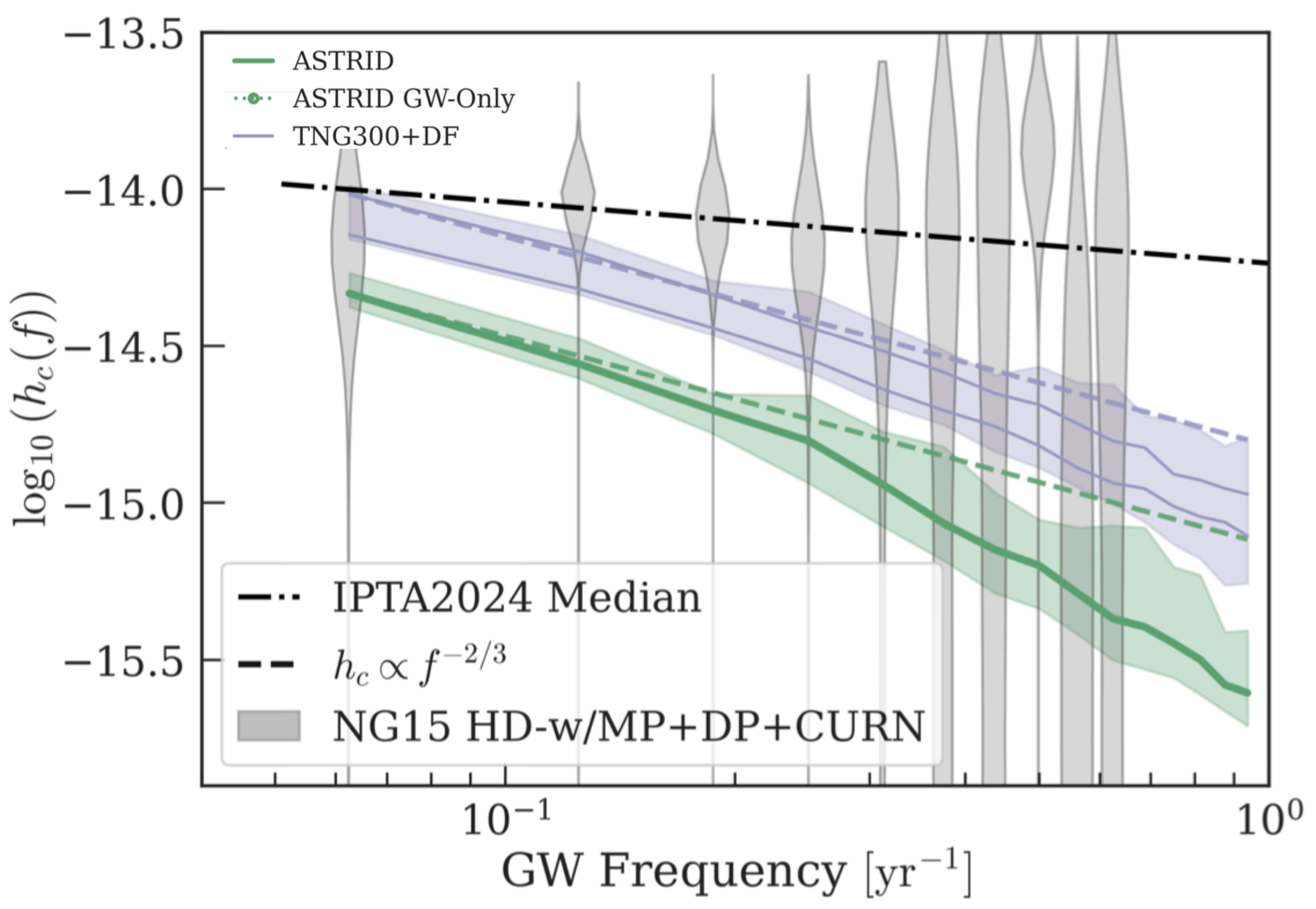
What happened since July 2023?

New PTA data: higher peak frequency and slope

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

Solution to the final parsec problem?

[Chiaberge+, 2501.18730]



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

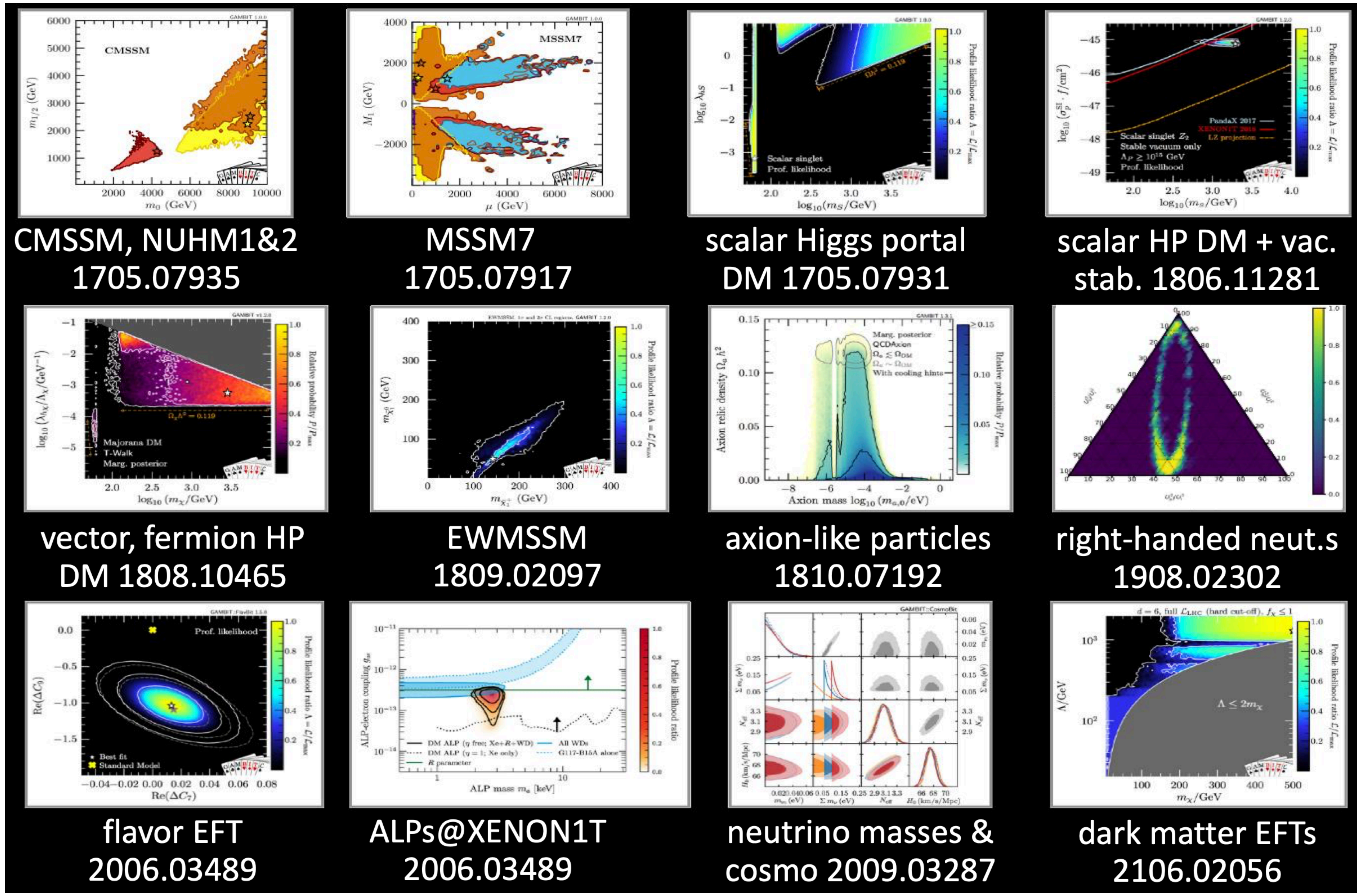
[Chen+, 2502.01024]

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

$V(\phi)$

Higgs mixing

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

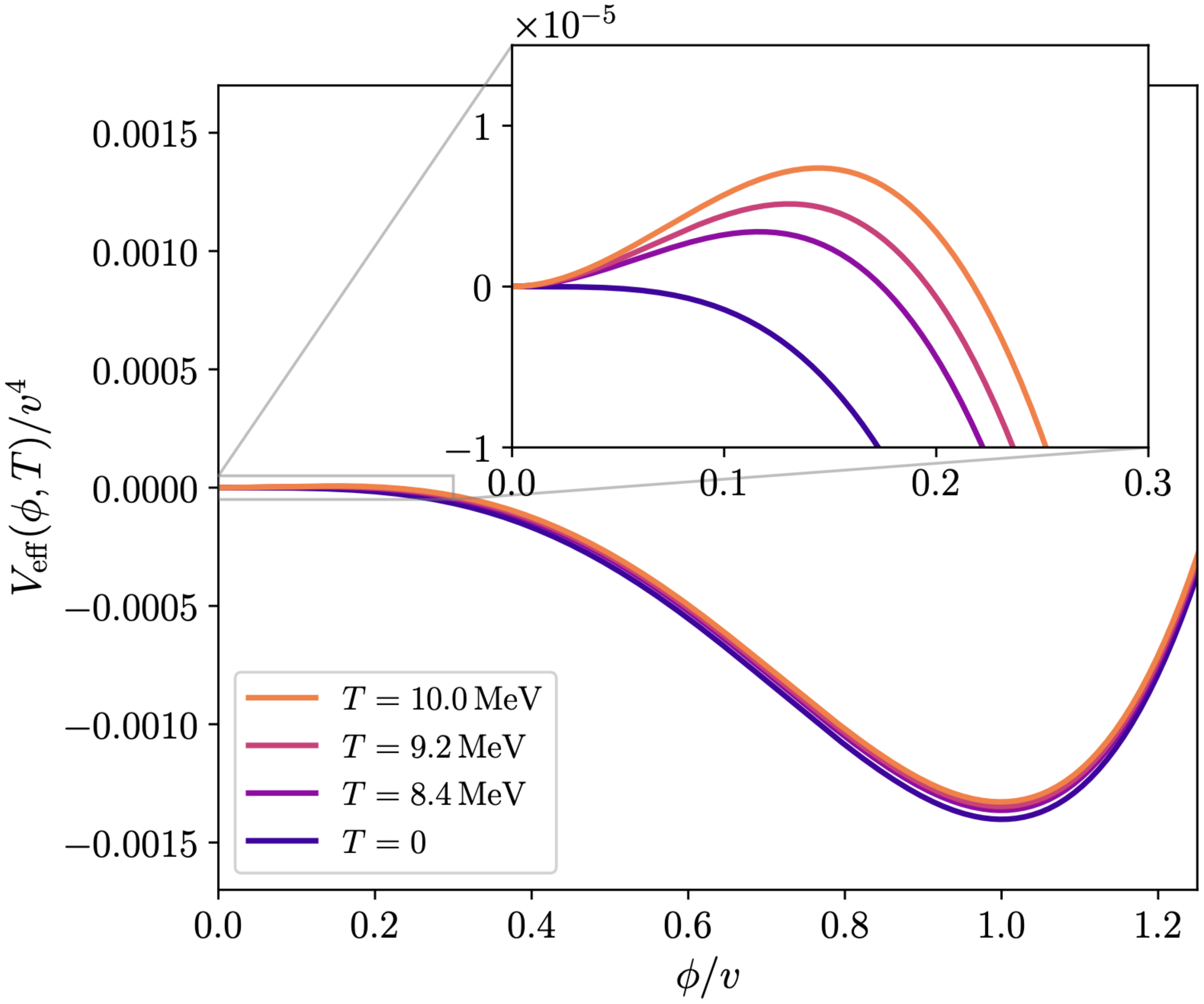
$\phi \to \bar{e}e$ is suppressed by κ^4...

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

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! :)



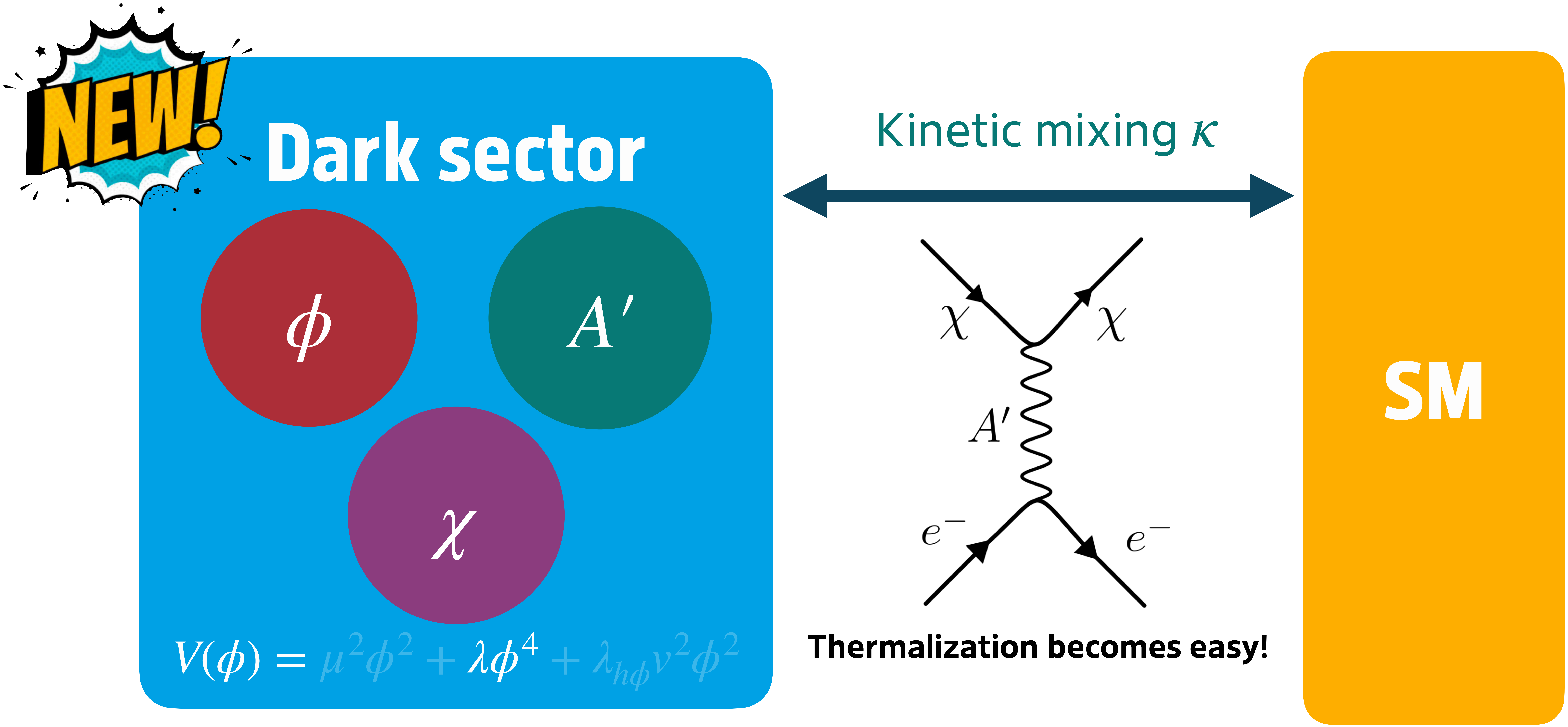
$$V_{\rm tree}(\phi) = \lambda\phi^4$$

Quantum and thermal corrections

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

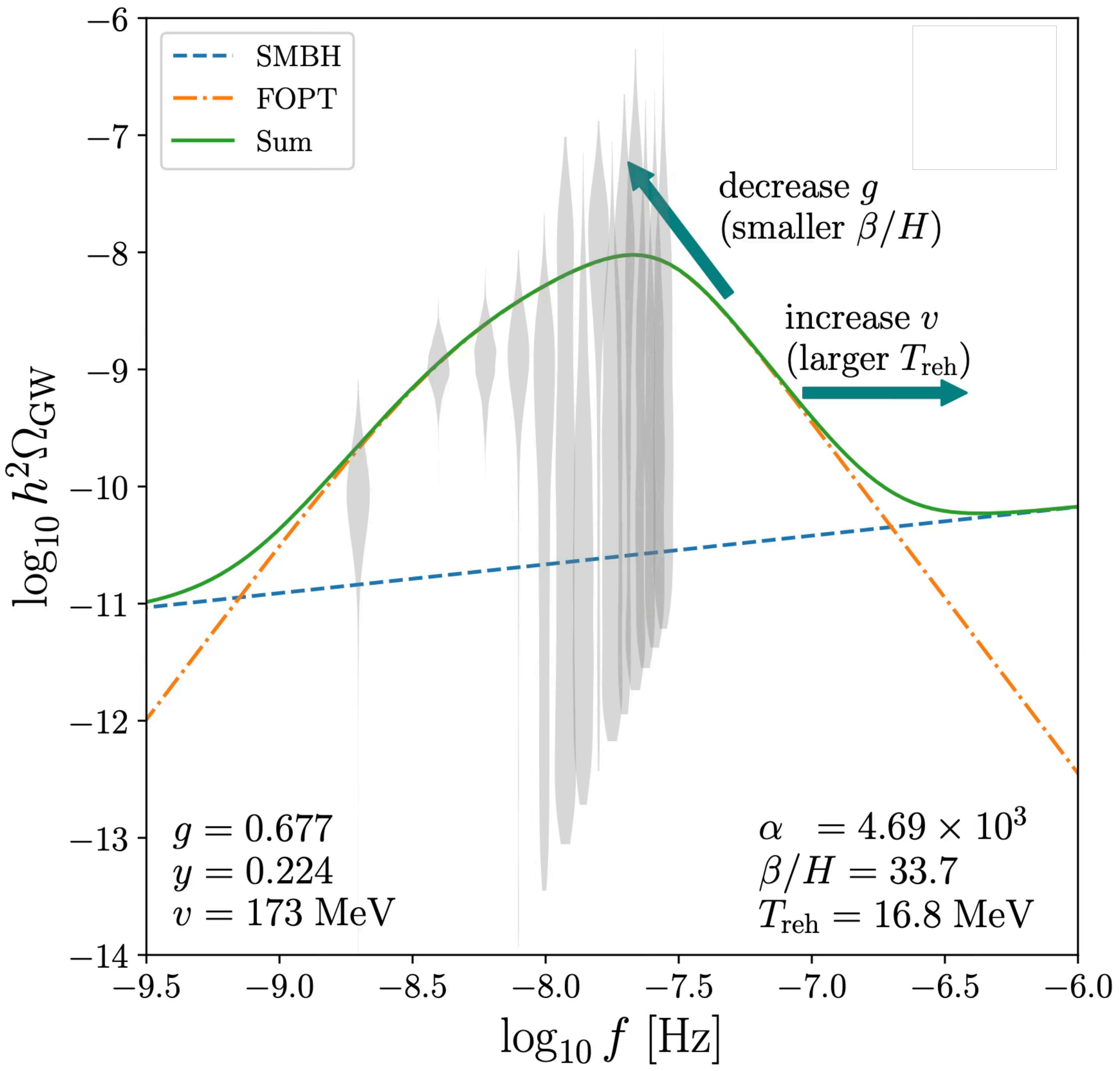
Loop-induced barrier down until very low temperatures, i.e. strong supercooling

A conformal dark sector incl. dark matter candidate



CT+ [JCAP 08 (2025) 062]

All constraints can be circumvented

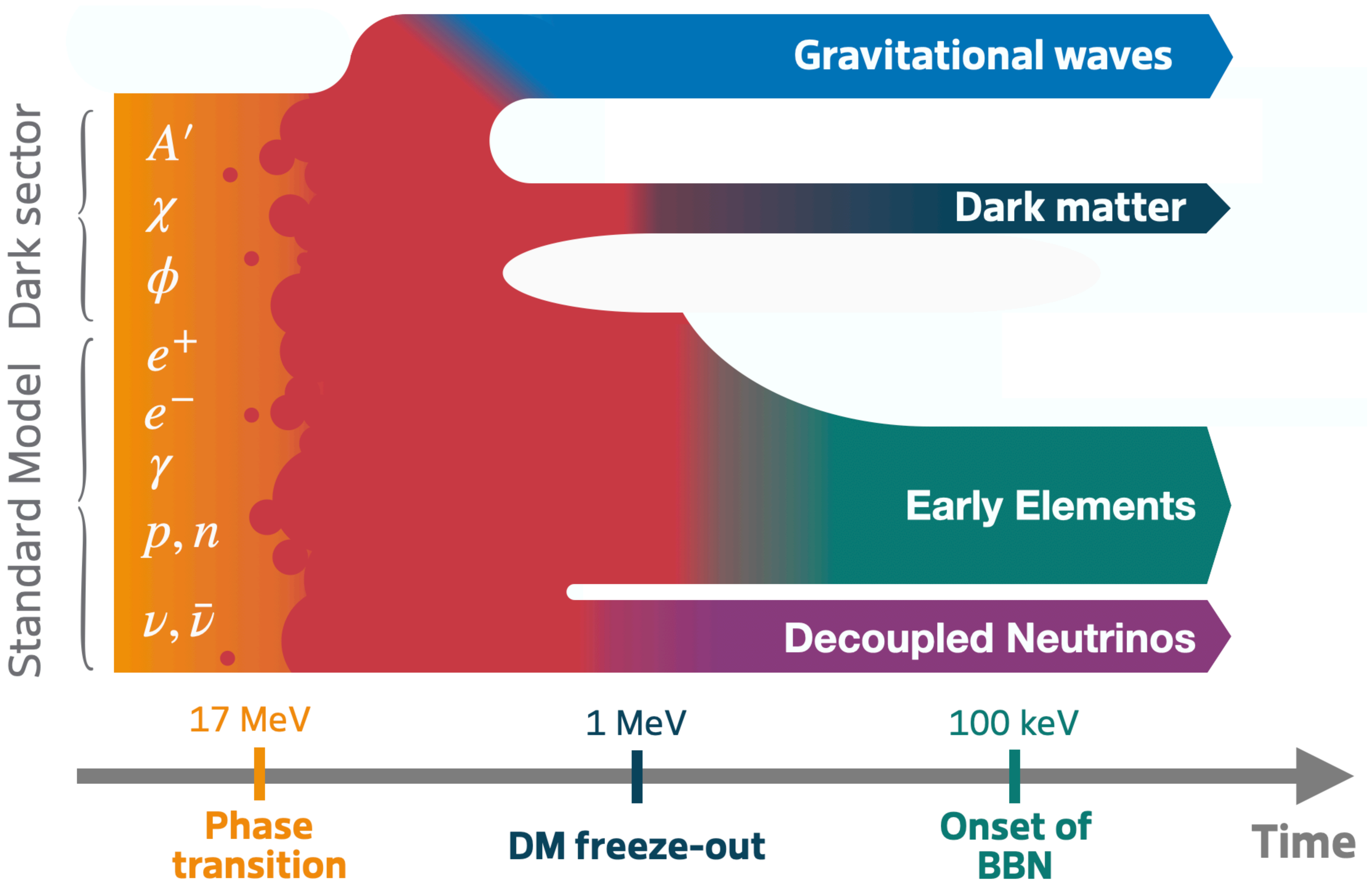


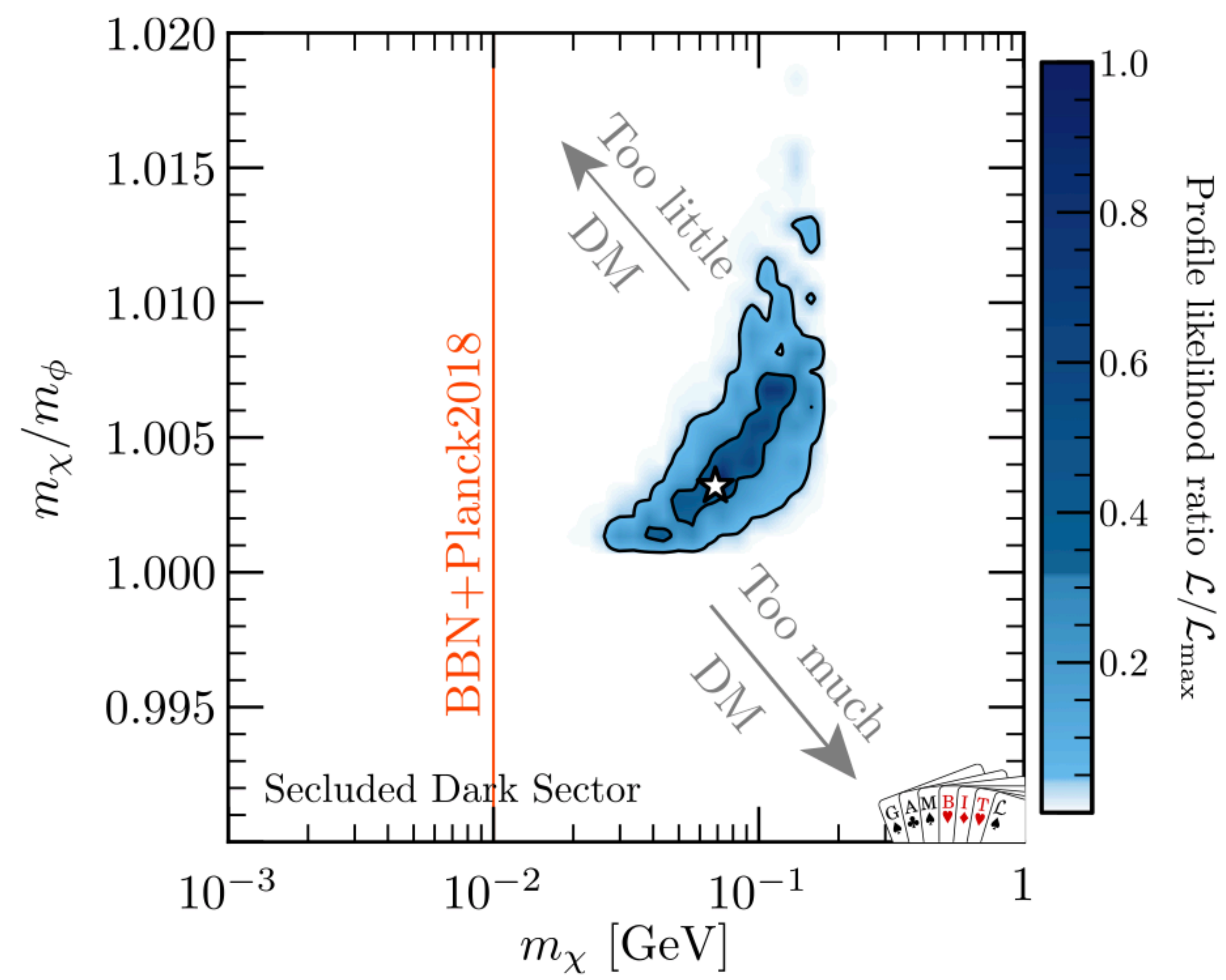
Global fit found parameter space with

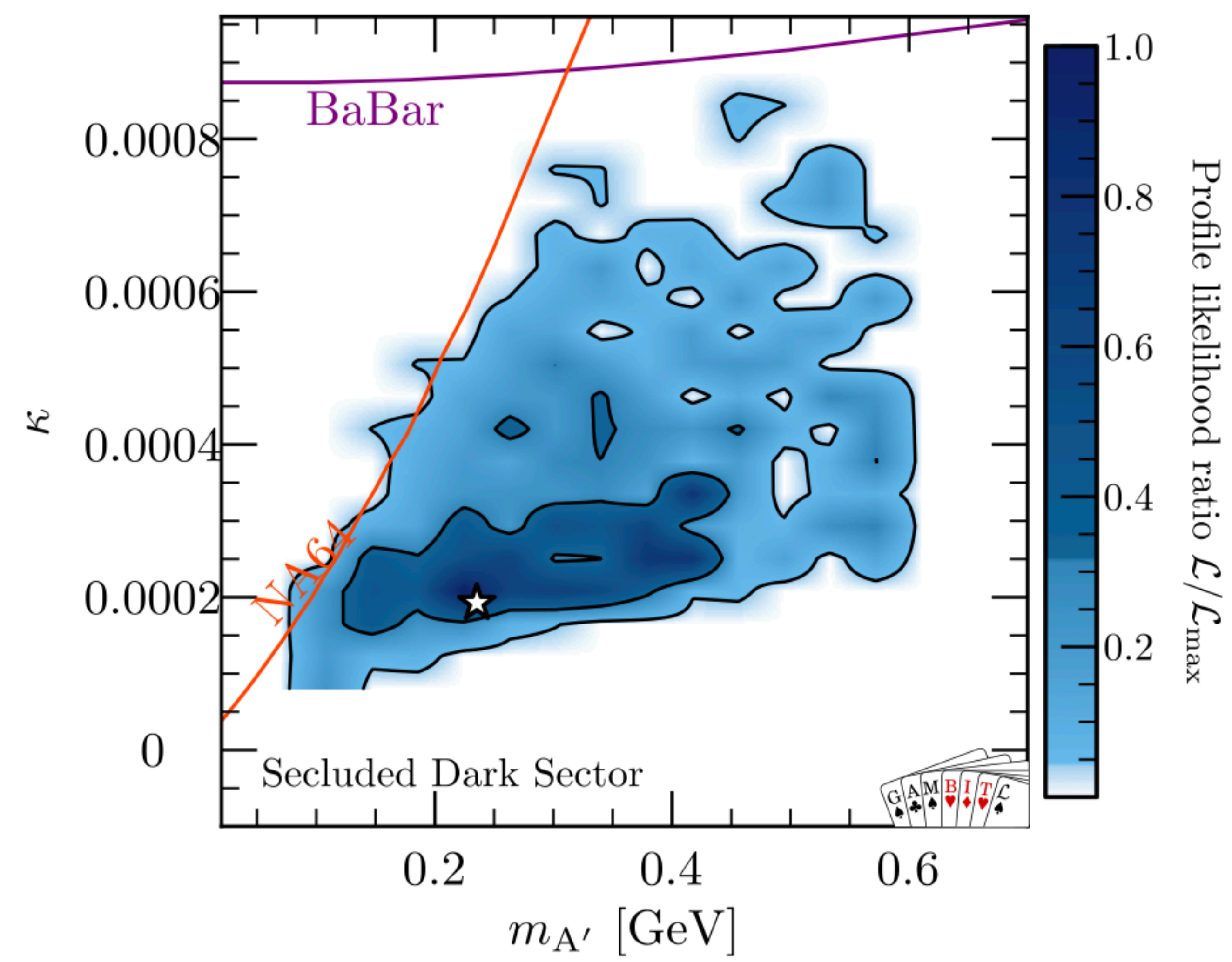
- 100% of observed DM relic density
- Loud phase transition on top of „standard" SMBH background
- Negligible impact on BBN and CMB
- No relevant direct + indirect detection + bullet cluster constraints
- Testable LDMX/Belle-II/NA64 prediction:

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

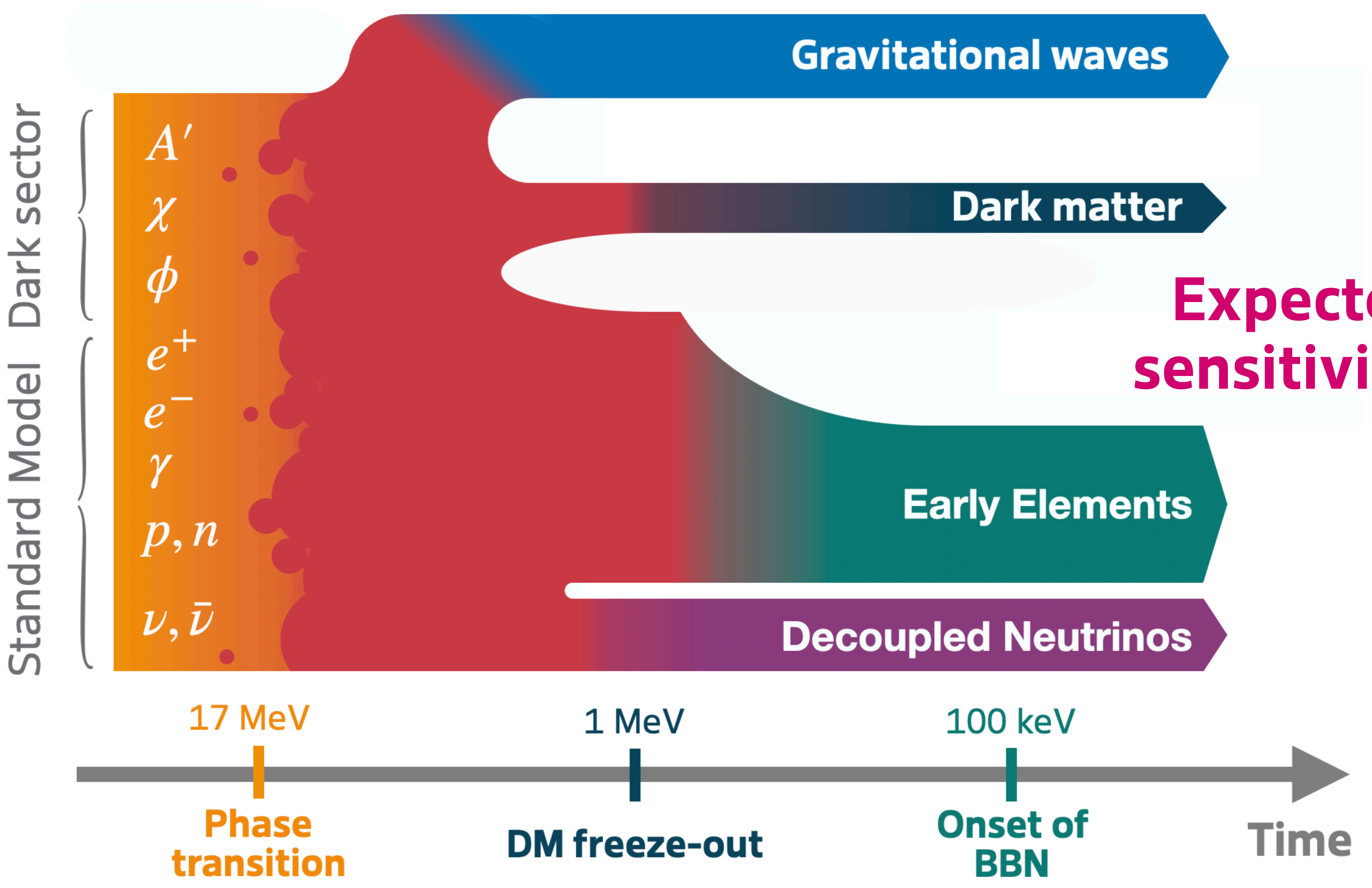
How does our scenario evade all available constraints?



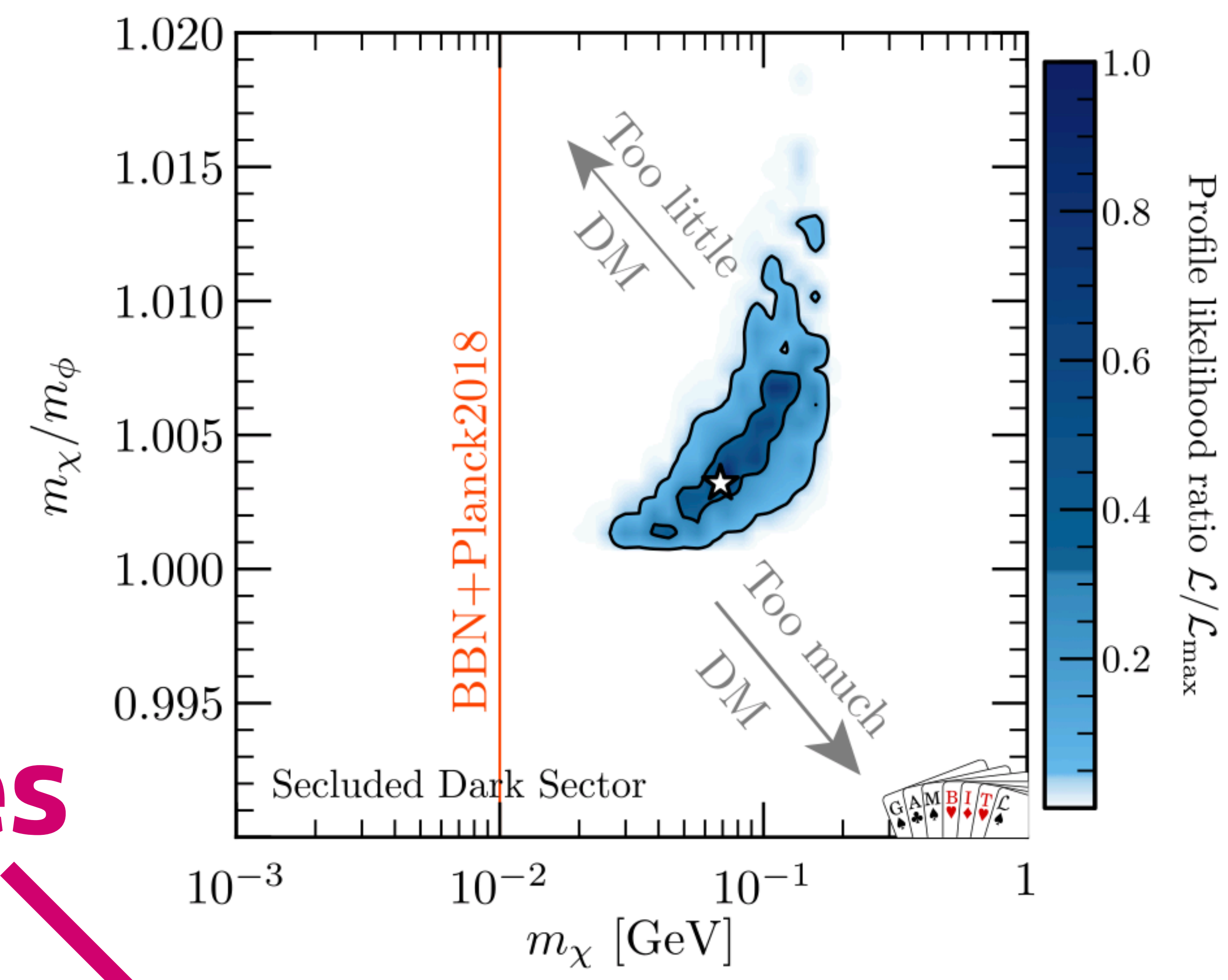


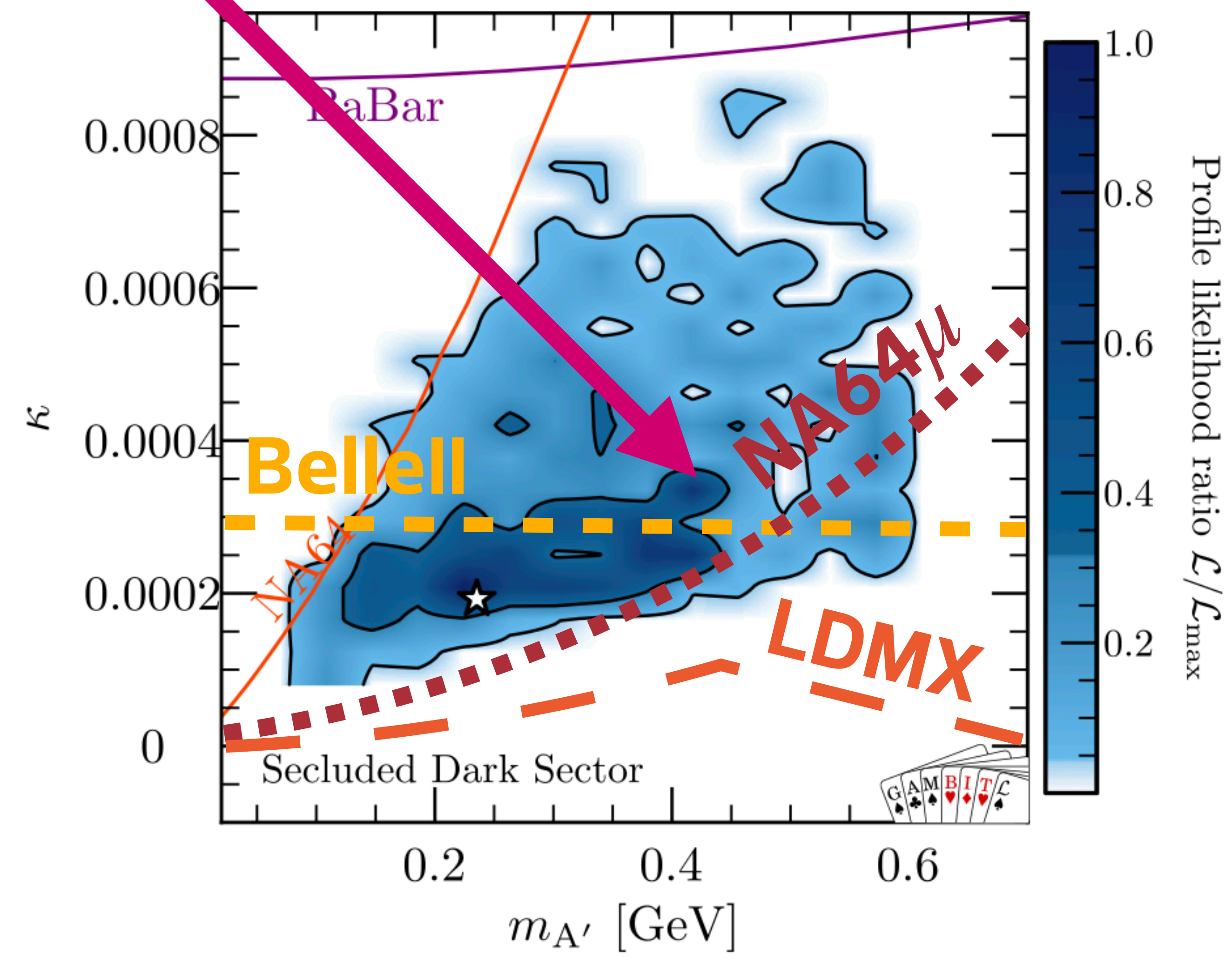


How does our scenario evade all available constraints?

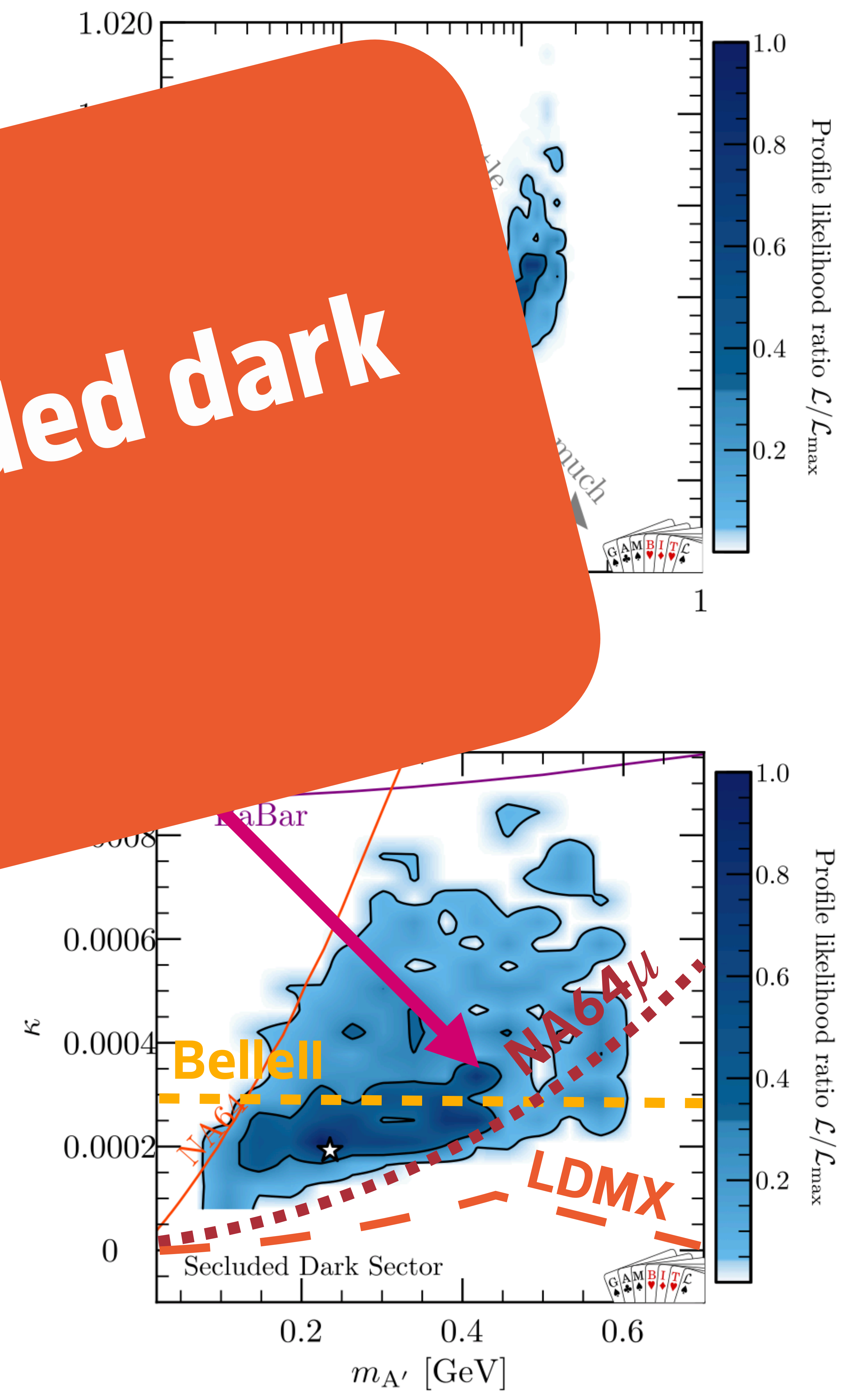


Expected sensitivities



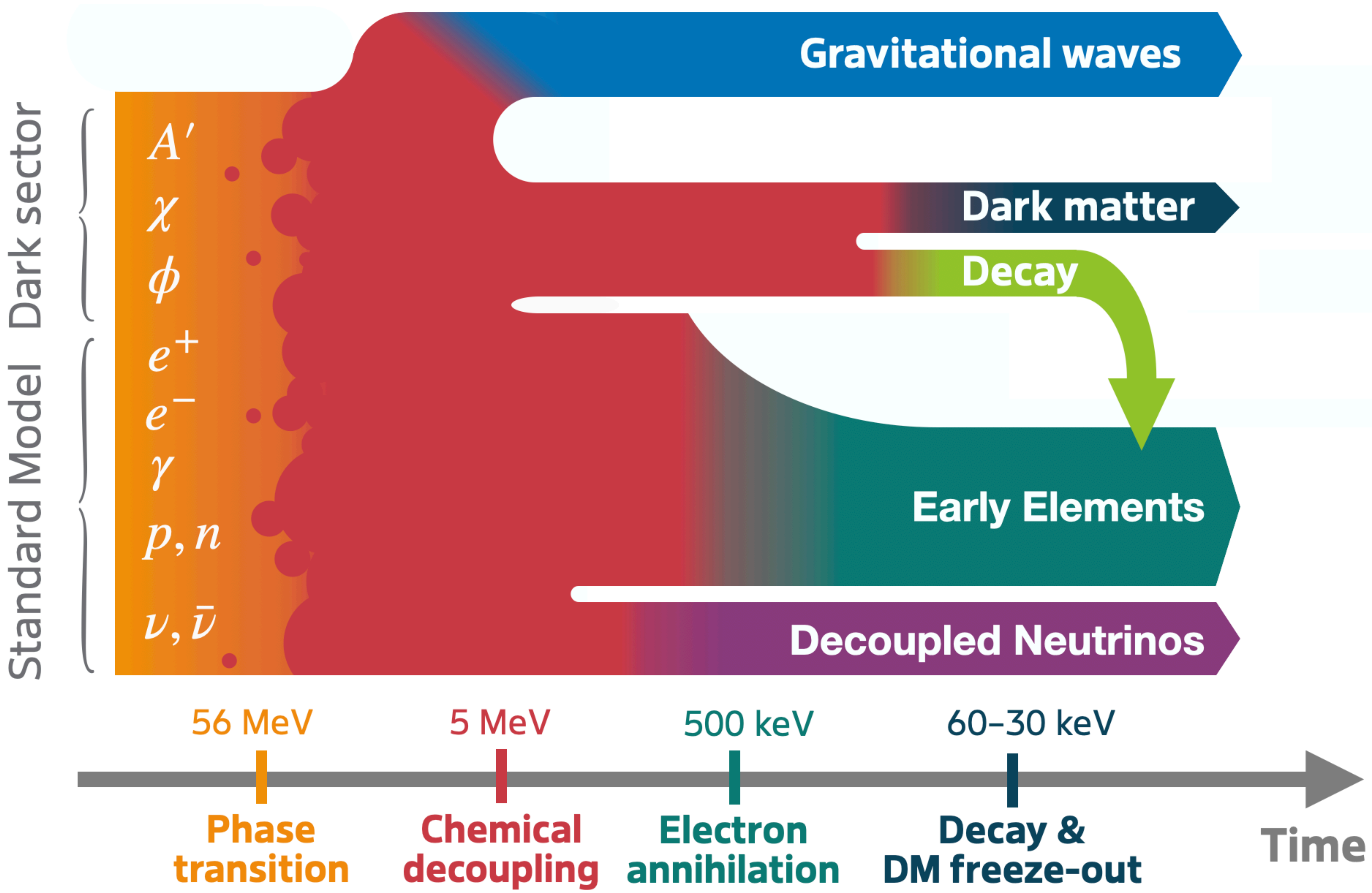


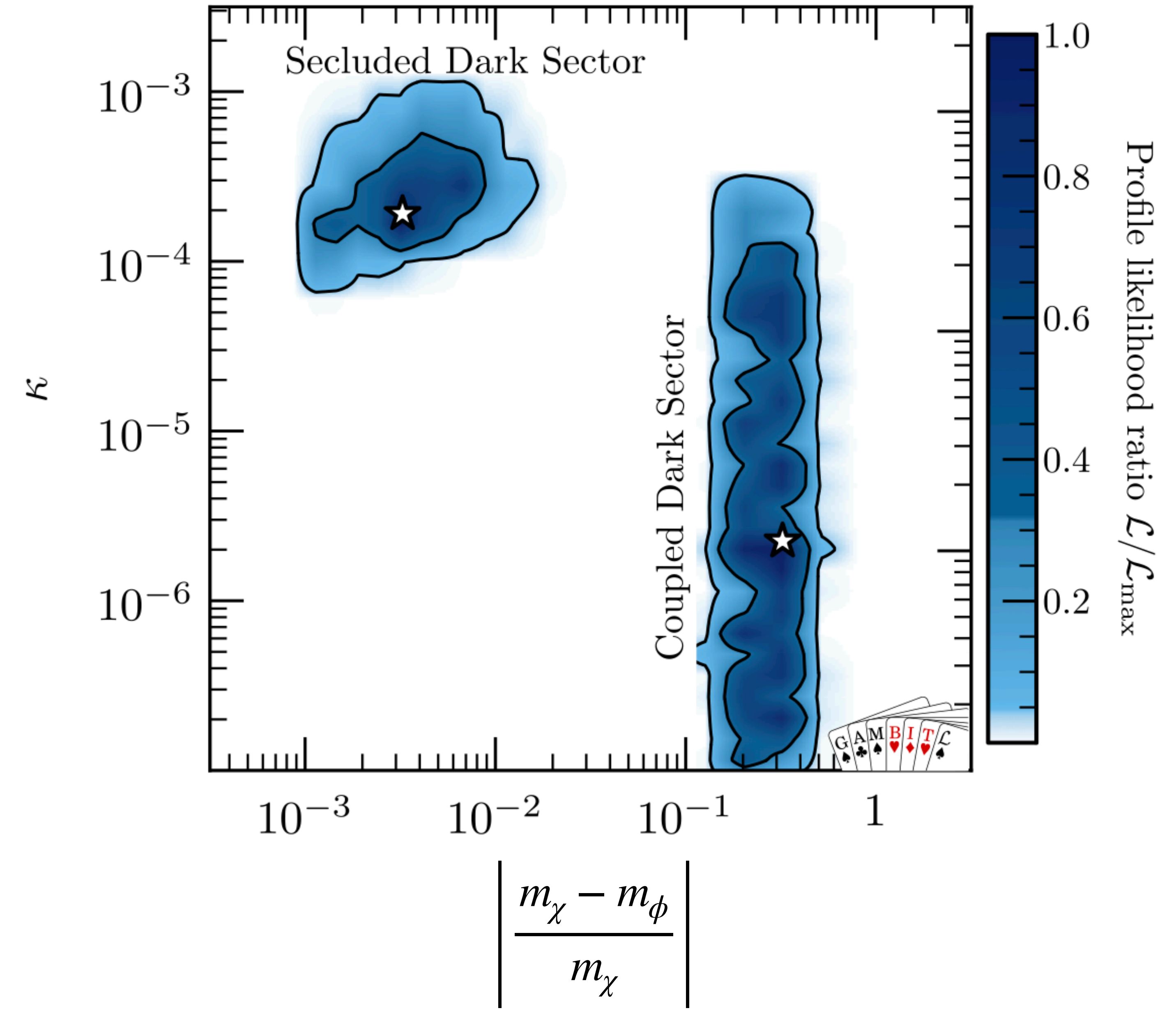
How does our scenario evade all available constraints?



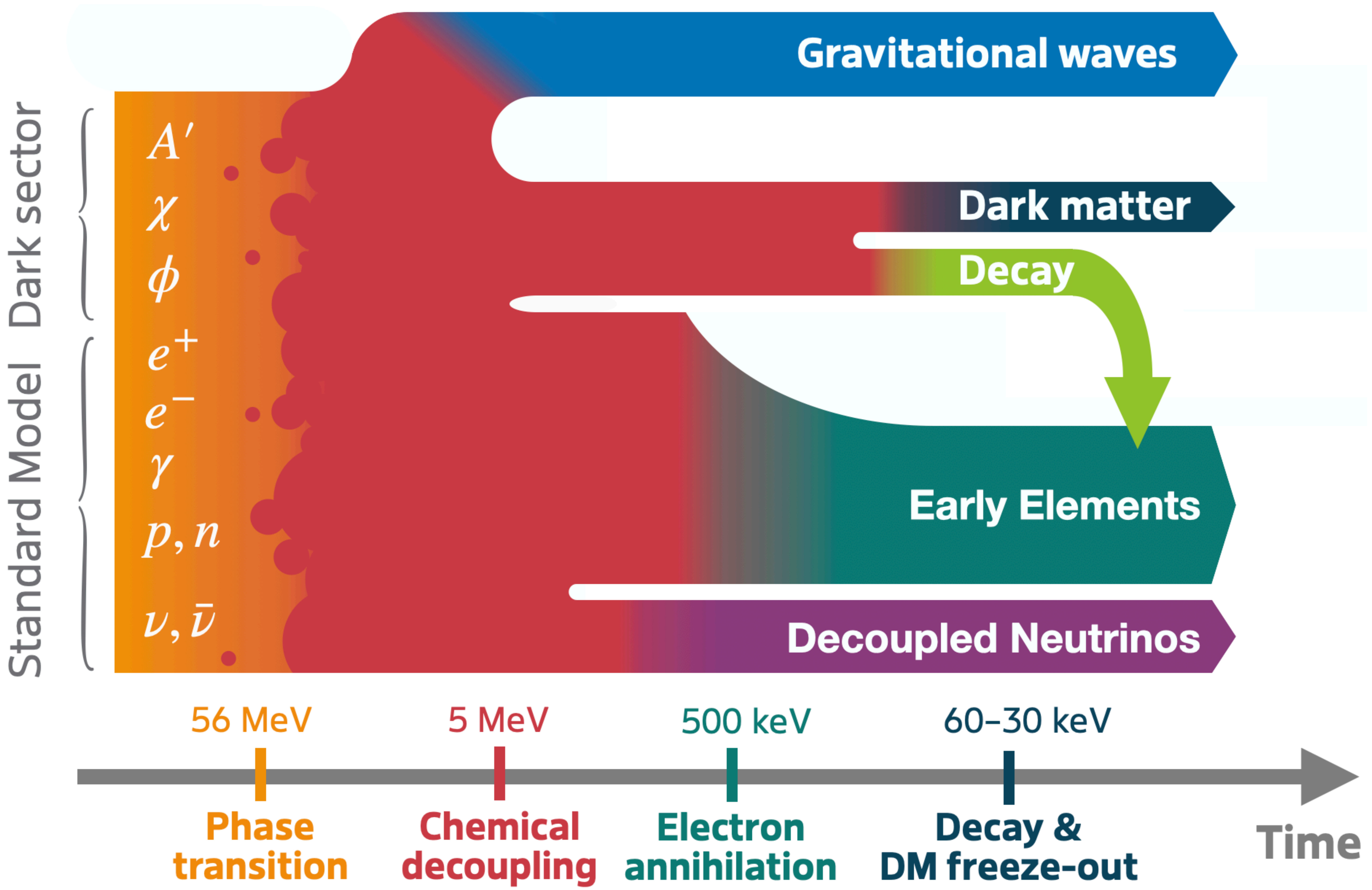
What if LDMX rules out the secluded dark sector scenario?

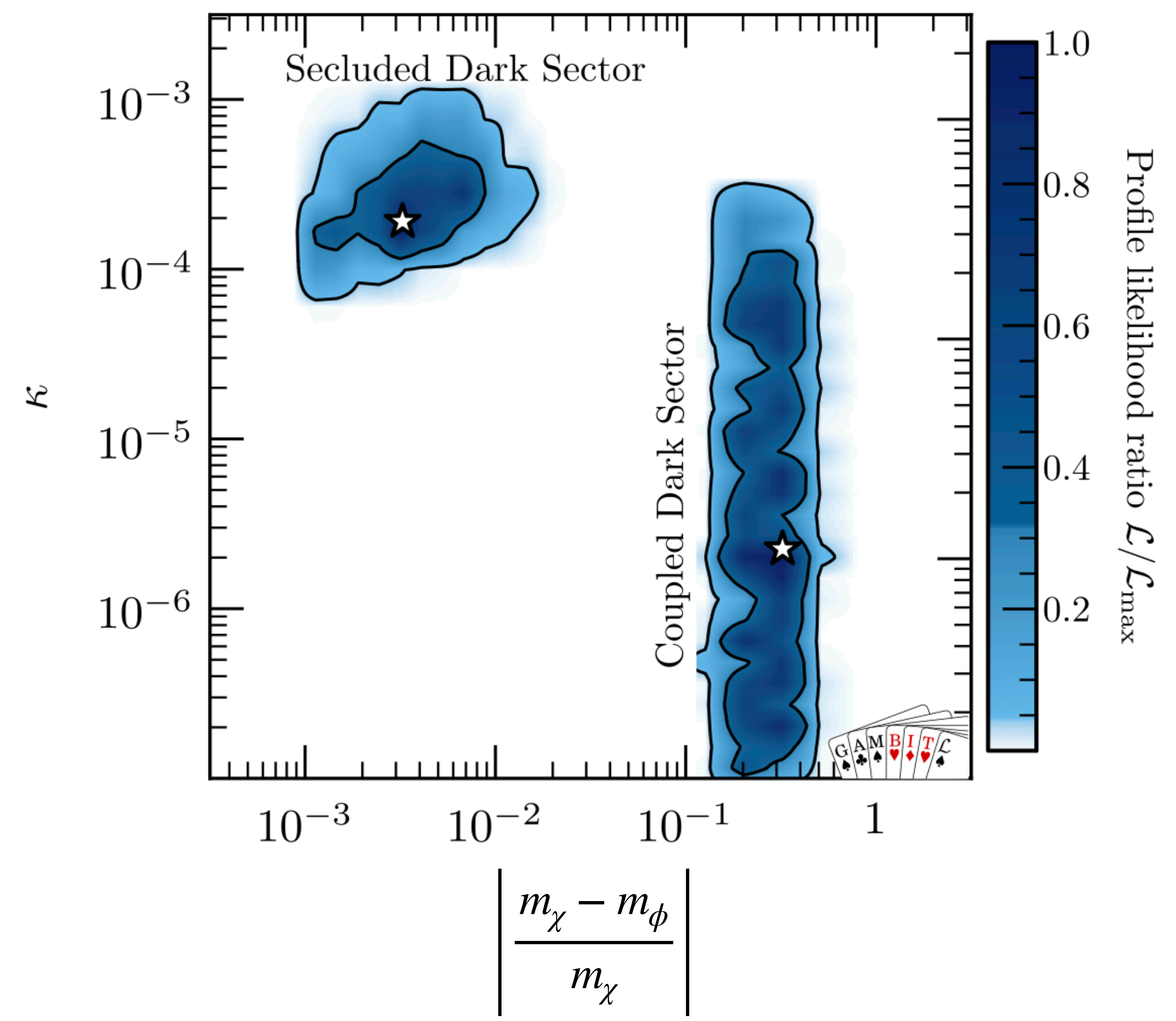
Coupled DS scenario: incl dim-6 operator for $\phi \to ee$





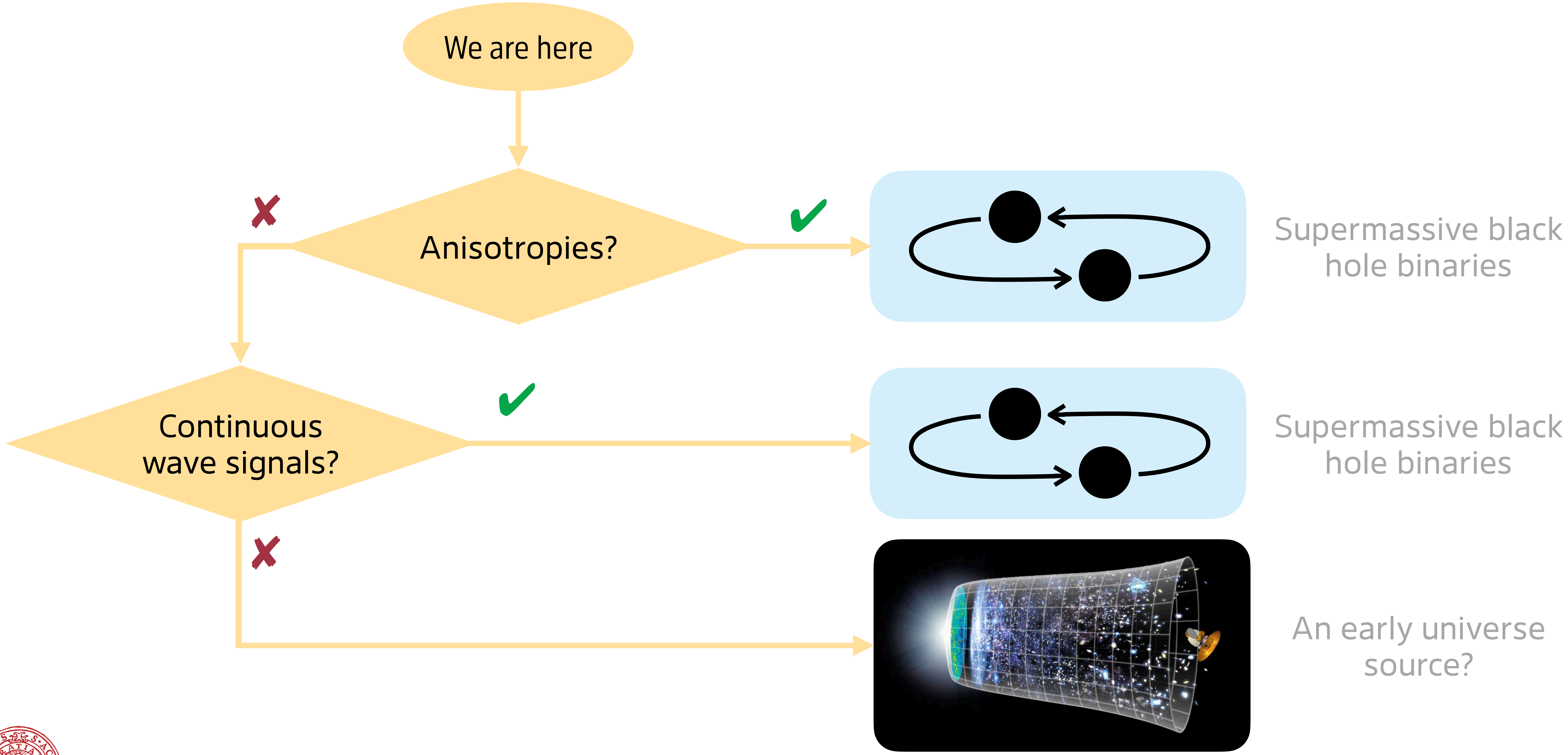
Coupled DS scenario: incl dim-6 operator for $\phi \to ee$





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

Grande finale: Quo vadis pulsar timing?



Time for a commercial break

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


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

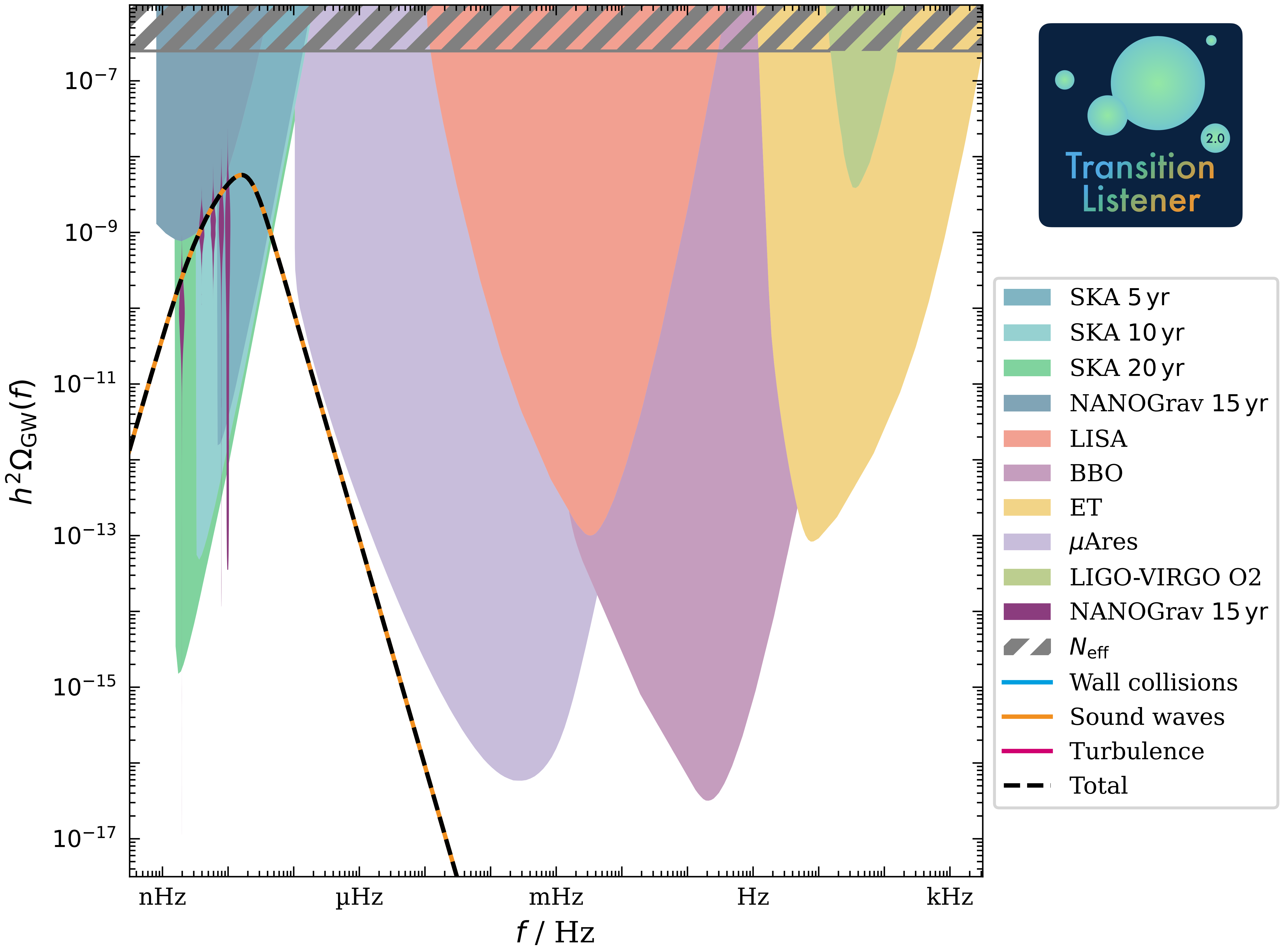
Parameter	Value
g y v_GeV	7.0000000000e-01 1.0000000000e-02 1.0000000000e-01

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



[Ongoing work Jonas Matuszak, code release very soon]

An example for the output of TransitionListener

After removing redundant phases, 2 phases remain.

Found 2 phases:

Phase 0

Parameter	Value
Tmin / GeV	2.35253655e-13
Tmax / GeV	0.025860343165319342
phi(Tmin) / GeV	[0.1]
phi(Tmax) / GeV	[0.07745474]

Phase 1

Parameter	Value
Tmin / GeV	2.35253655e-13
Tmax / GeV	0.25
phi(Tmin) / GeV	[-4.13835065e-10]
phi(Tmax) / GeV	[-2.06018231e-07]

Found 1 possible phase transition(s) ...
First-order phase transition

Parameter	Value
Tnuc / GeV	0.0026767519252717566
high phase	1
low phase	0
high vev / GeV	[-8.4332555e-11]
low vev / GeV	[0.10000133]
action / GeV	0.498614314000584

FULL GW PARAMETERS

Parameter	Value
alpha	5.1244e+02
alpha_e	5.1263e+02
alpha_eq	9.9747e+00
alpha_hyd	5.1244e+02
alpha_inf	1.1566e+00
alpha_p	5.1237e+02
alpha_theta	5.1244e+02
betaH_from_RH	6.2224e+01
betaH_perc	6.3285e+01
c_s	5.8587e-01
c_s_bro	5.8587e-01
c_s_sym	5.7748e-01
coupled_hydrodynamics	True
D	1
g0	2
g_eff_tot_reh	1.4174e+01
h0	3.9100e+00
h_eff_tot_reh	1.4161e+01
kappa_phi	0
kappa_sw	9.9164e-01
kappa_turb	0.0000e+00
RH	7.1120e-02
step	1
Tcrit_SM_GeV	2.1734e-02
Tf_SM_GeV	2.1215e-03
Tnuc_SM_GeV	2.6768e-03
total_steps	1
Tperc	2.2124e+01
Tperc_SM_GeV	2.2124e-03
Treh	101.39173177184342
Treh_SM_GeV	1.0139e-02
v_wall	1
xi_crit	4.3499e+00
Warnings	
betaH_small	False
no_perc_splines	False
not_T0_global_min	False
too_weak_to_compute_perc	False

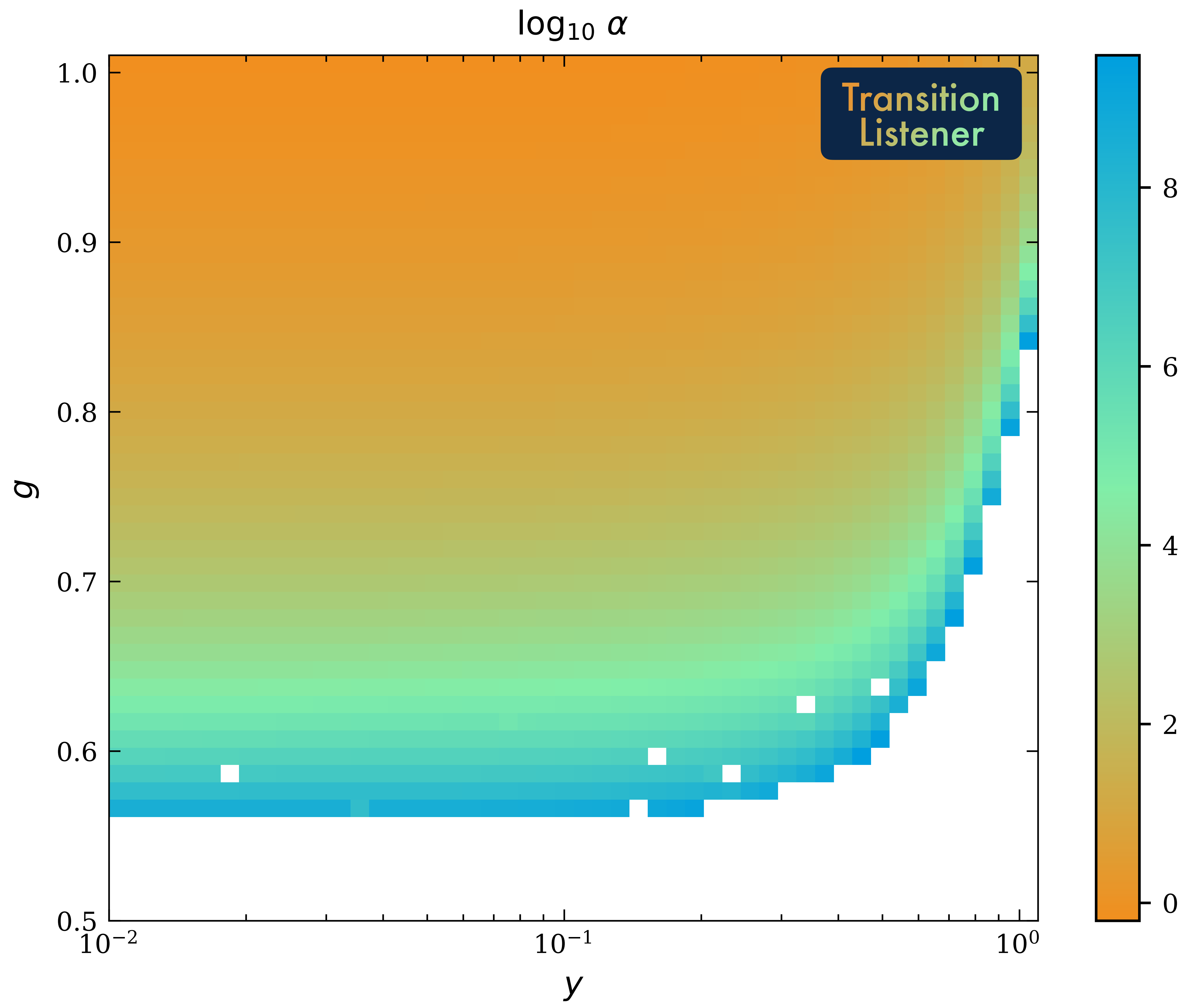
SNR VALUES AND OBSERVABILITY

Detector	SNR	Should have been observed already?	Observable?
SKA_5_yrs	7.0490e+03		✓
SKA_10_yrs	8.6512e+04		✓
SKA_20_yrs	6.5400e+05		✓
EPTA_18_yrs	1.2500e+00	✓	
NANOGrav_11_yrs	3.7351e+00	✓	
NANOGrav_15_yrs	4.7029e+00	✗	
LISA	1.4366e-08		✗
B-DECIGO	8.4122e-09		✗
DECIGO	1.1909e-08		✗
BBO	1.1978e-08		✗
ET	9.4051e-09		✗
muAres	5.8147e+00		✗
HLV_O2	4.8743e-28	✗	
HLVK_design	3.3682e-26		✗

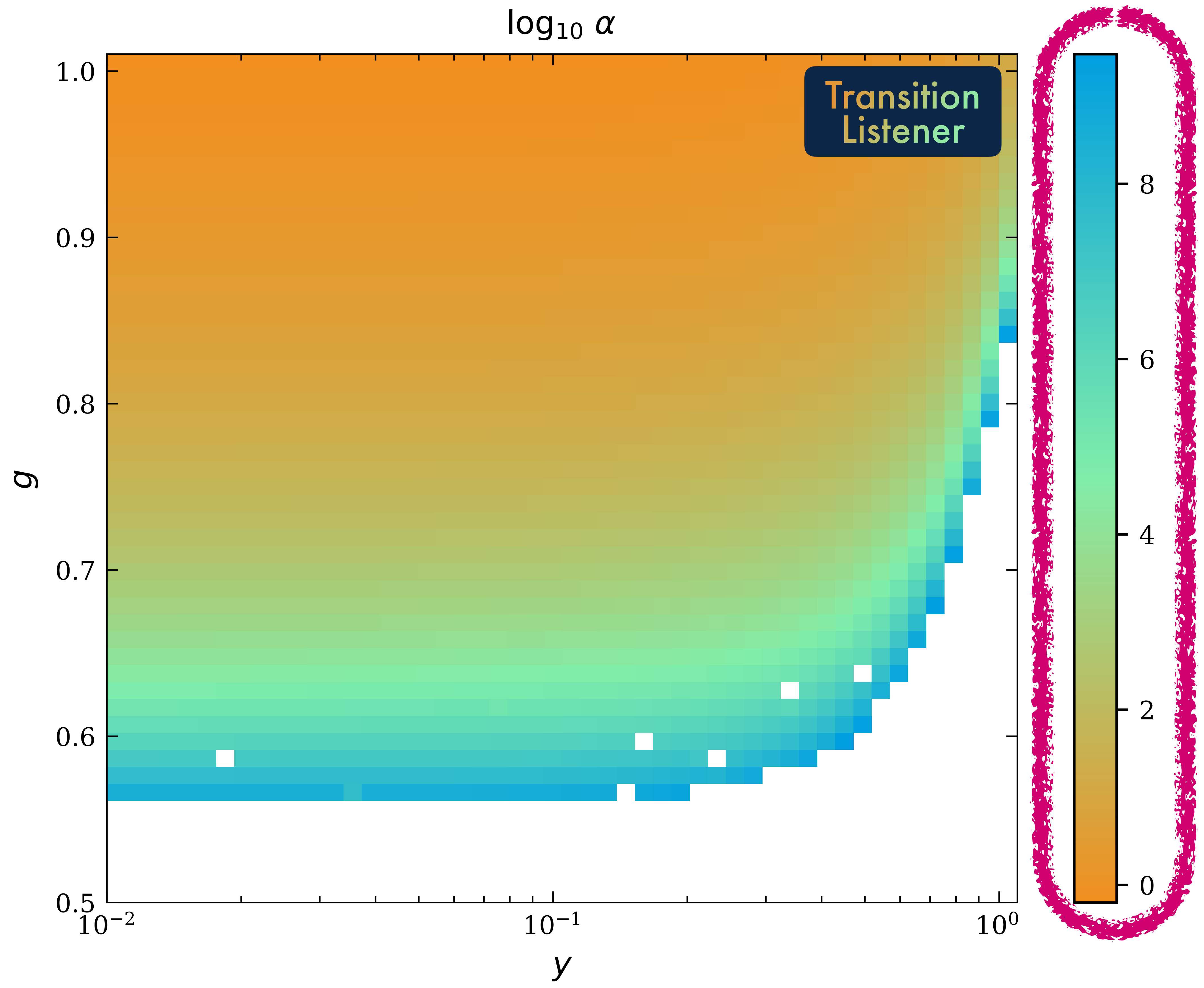
LOG LIKELIHOODS FOR PULSAR TIMING ARRAYS

PTA	Bins	Variant	lnL	Δ lnL	σ	Within 3σ?
NANOGrav 15yr	14	PTArcade	-47.19	-55.94	0.00	✓
	14	mock	-110.02	6.89	3.71	
	14	smooth	-47.19	-55.94	0.00	
NANOGrav 15yr	5	PTArcade	-52.95	23.40	6.84	✗
	5	mock	-35.02	5.47	3.31	
	5	smooth	-35.02	5.47	3.31	
NANOGrav 12.5yr	5	PTArcade	-69.00	32.11	8.01	✗
	5	mock	-45.02	8.13	4.03	
	5	smooth	-45.02	8.13	4.03	
IPTA DR2	13	PTArcade	-31.93	-73.74	0.00	✓
	13	mock	-115.02	9.35	4.32	
	13	smooth	-31.93	-73.74	0.00	

If you're not convinced yet…

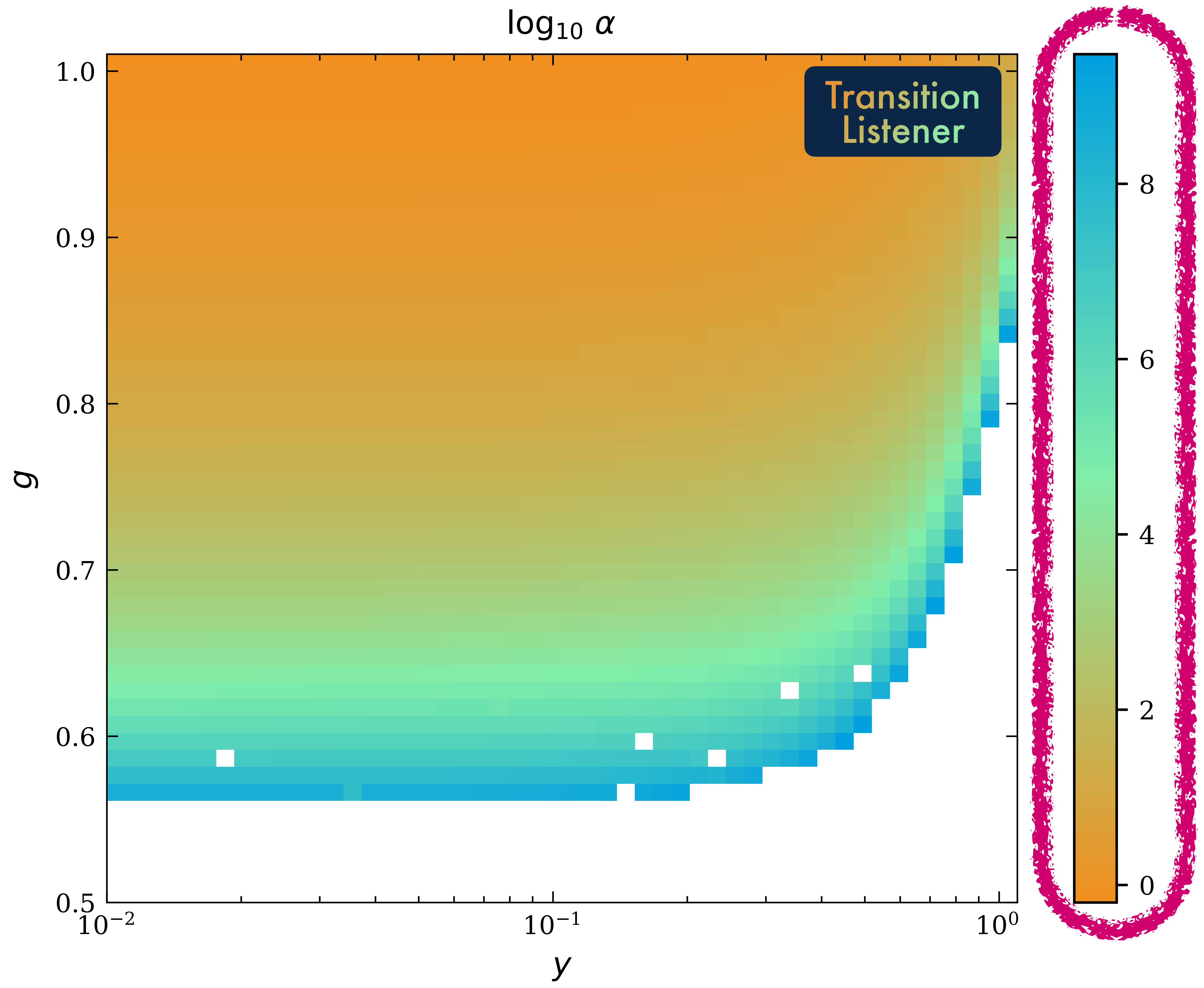


If you're not convinced yet…



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

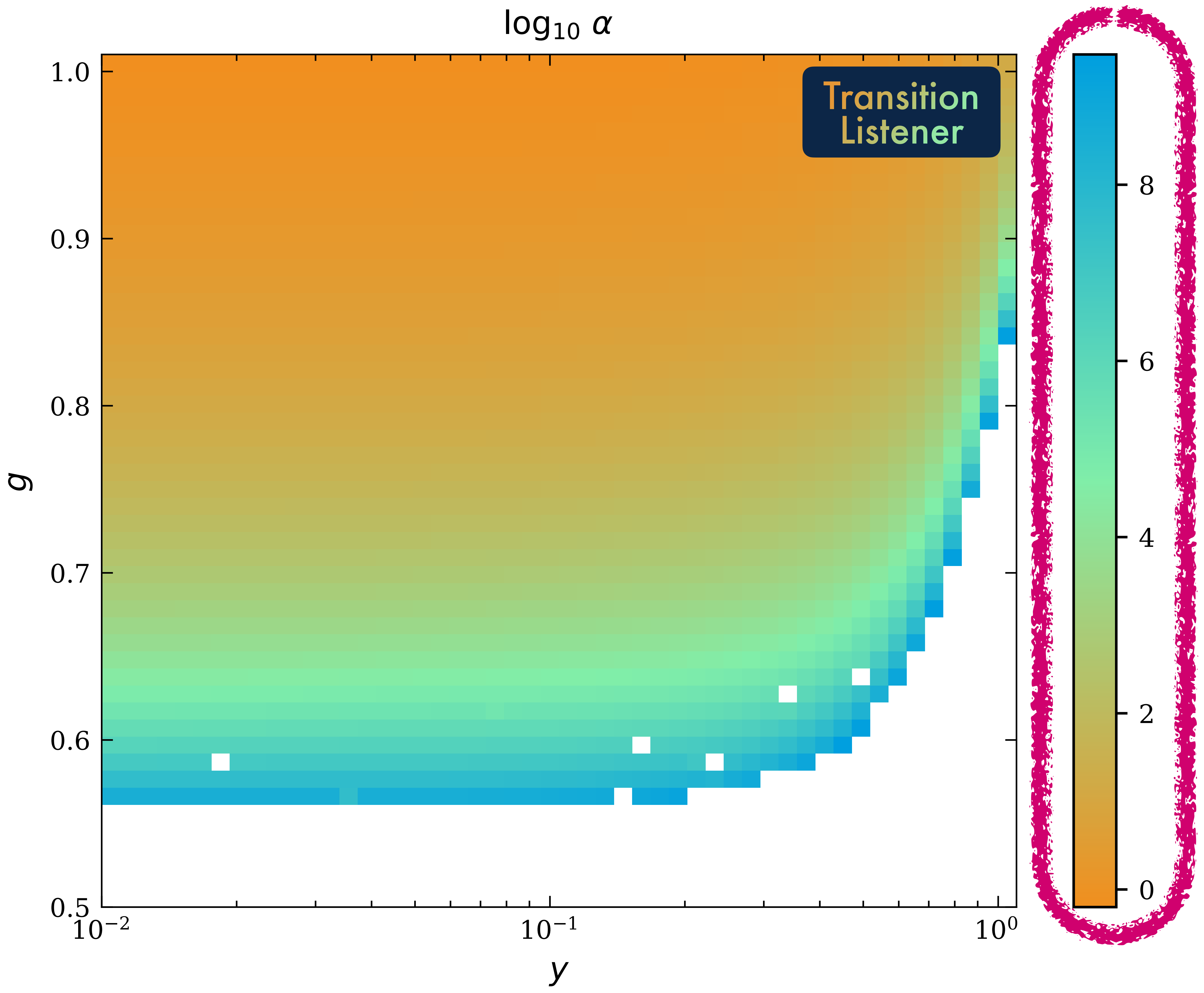
If you're not convinced yet…



$T_{\rm perc}$ & $T_{\rm reh}$

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

If you're not convinced yet…

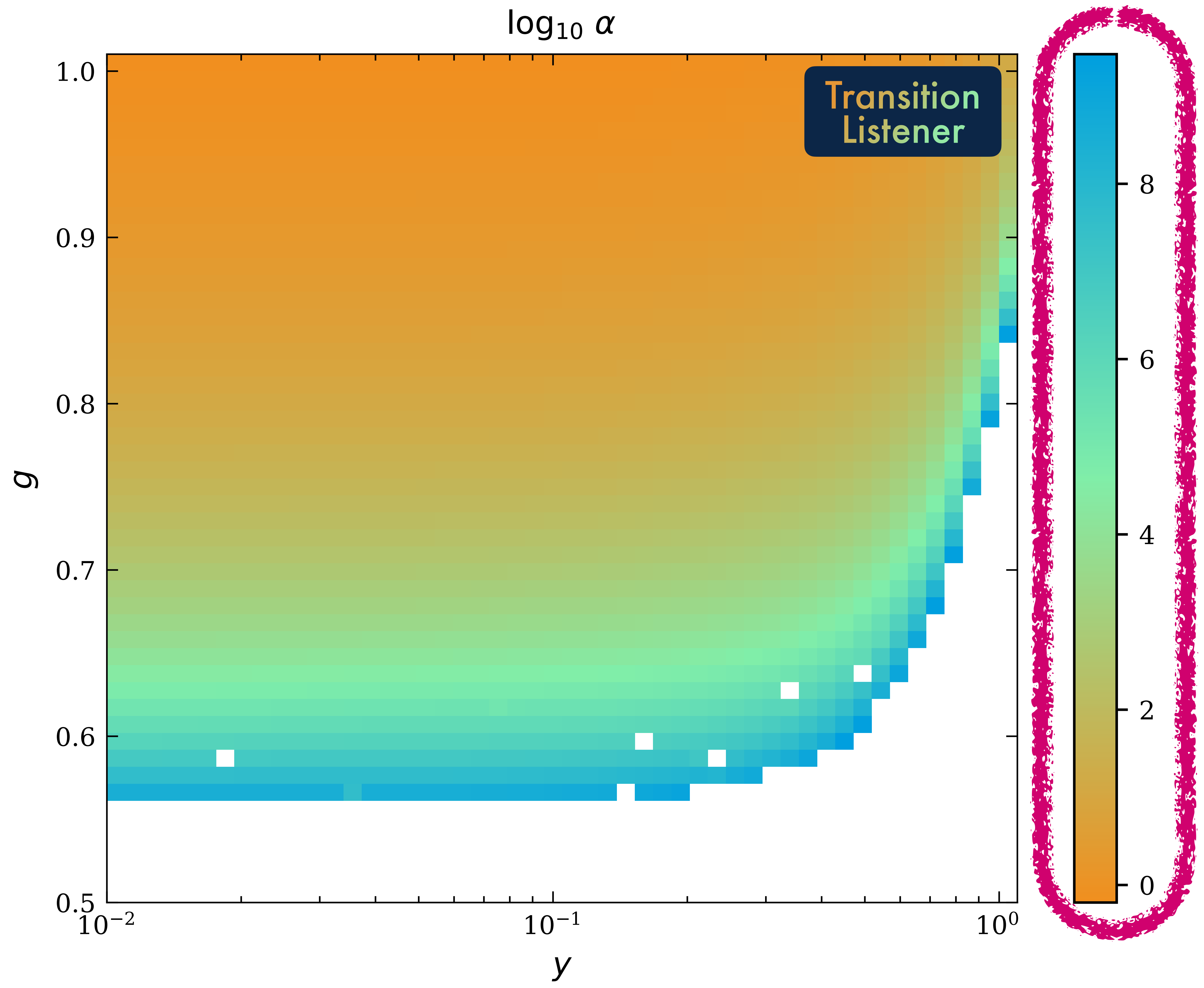


$T_{\rm perc}$ & $T_{\rm reh}$

Incl.
SM, SMEFT, dark sectors, …

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

If you're not convinced yet…



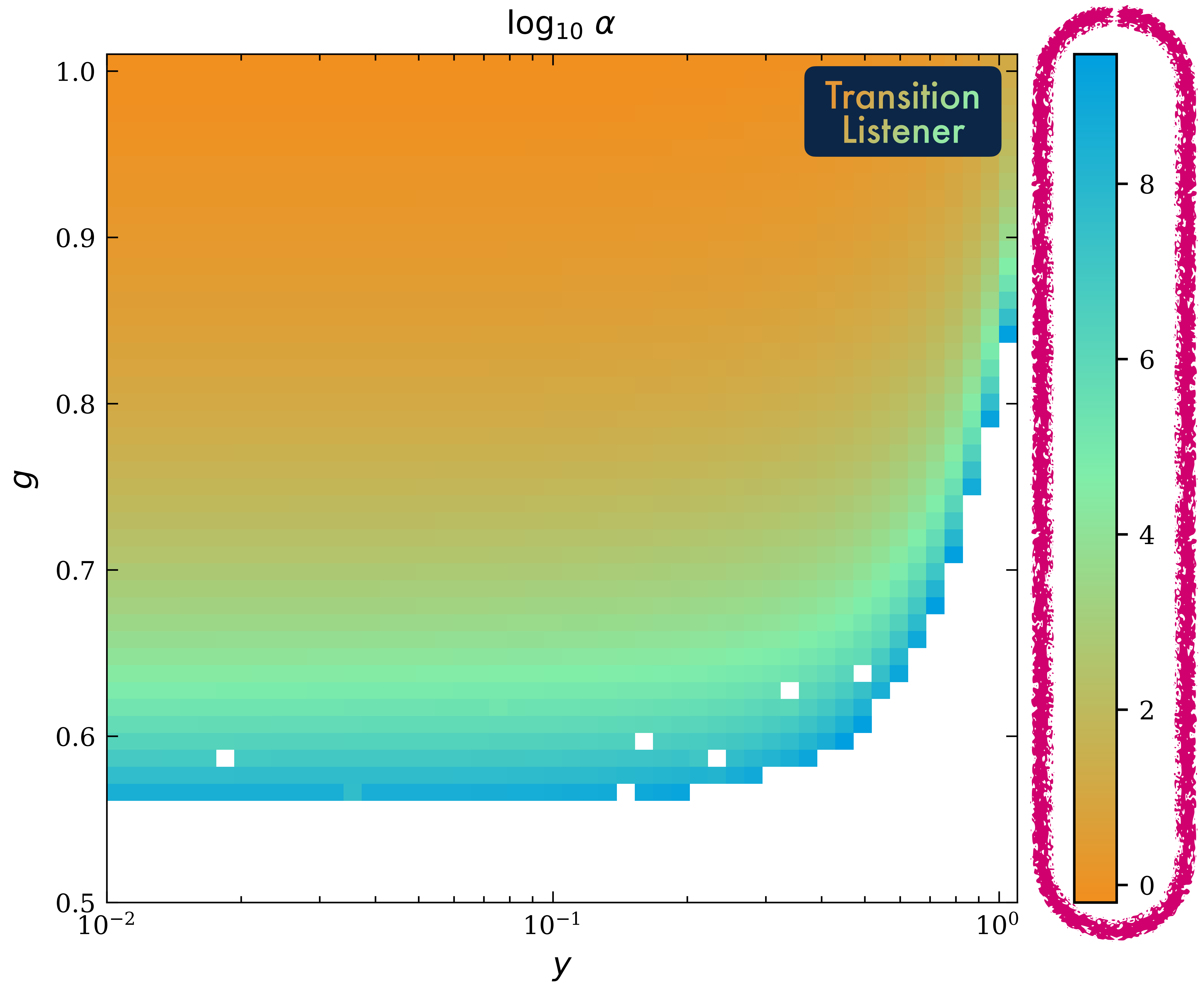
$T_{\rm perc}$ & $T_{\rm reh}$

$v_{\rm wall}$

Incl.
SM, SMEFT, dark sectors, …

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

If you're not convinced yet…



Documentation

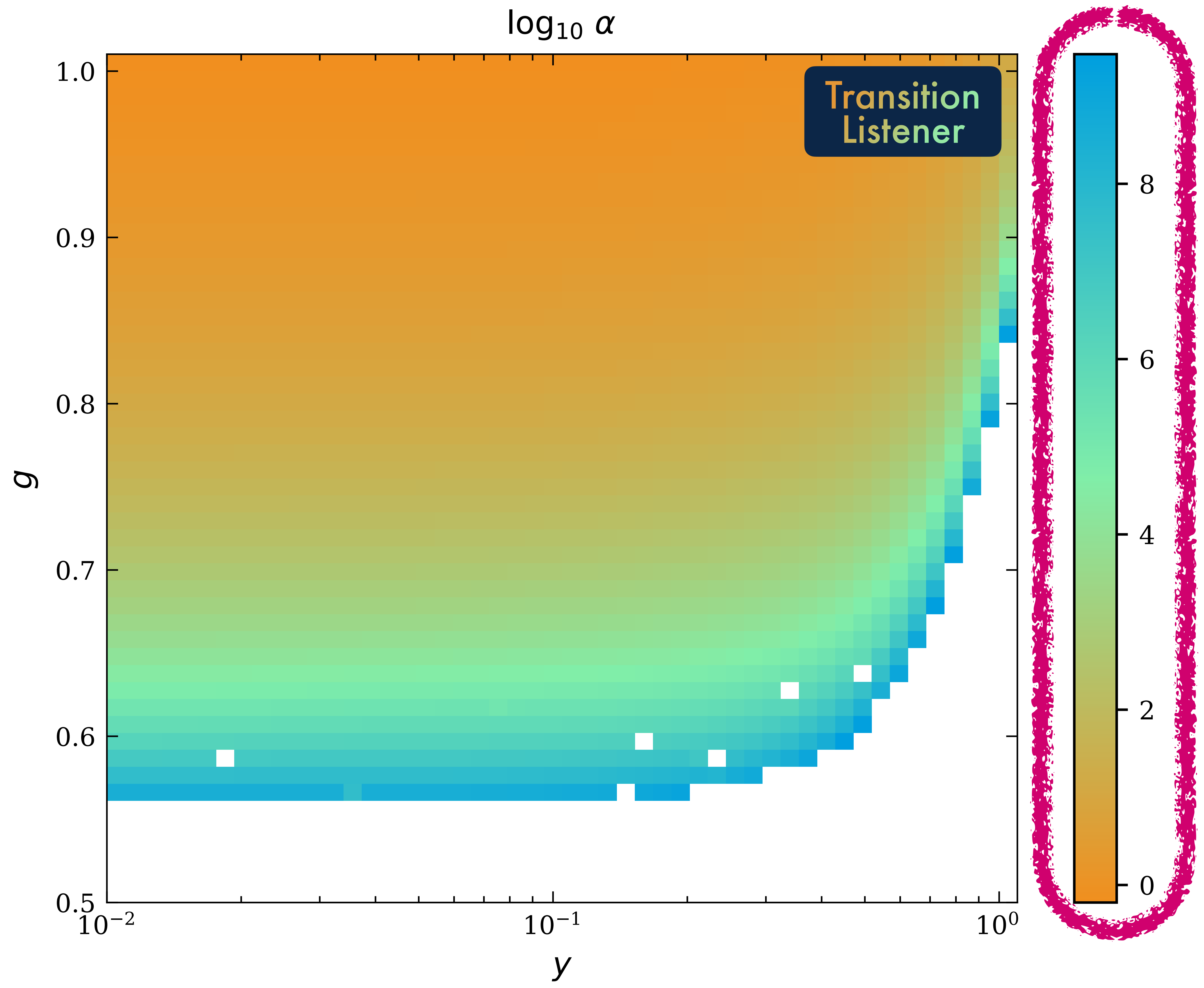
$T_{\rm perc}$ & $T_{\rm reh}$

$v_{\rm wall}$

Incl.
SM, SMEFT, dark sectors, …

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

If you're not convinced yet…



T_{perc} & T_{reh}

Documentation

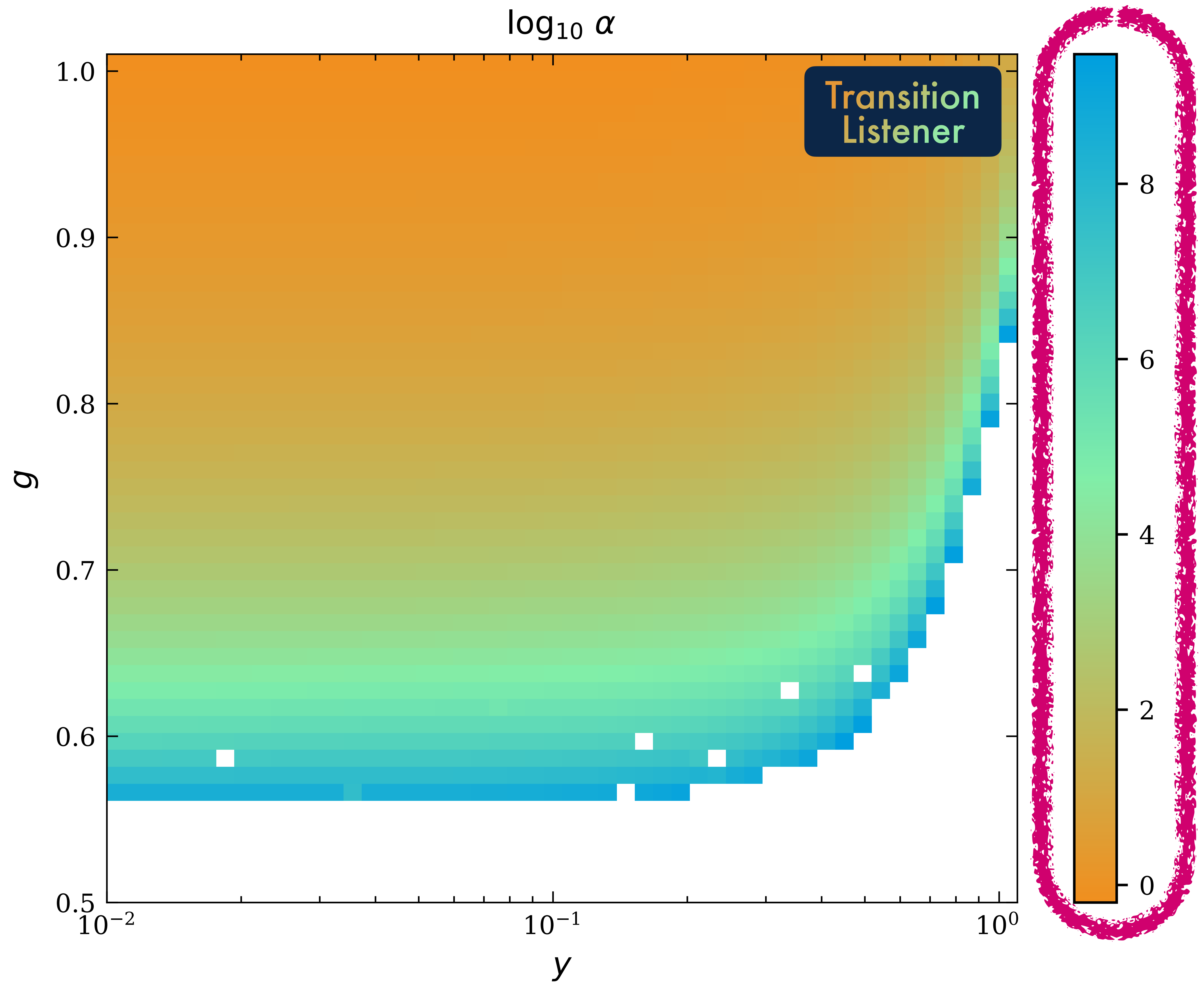
Proper error handling

v_{wall}

Incl. SM, SMEFT, dark sectors, …

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

If you're not convinced yet...



$T_{\rm perc}$ & $T_{\rm reh}$

Documentation

Proper error handling

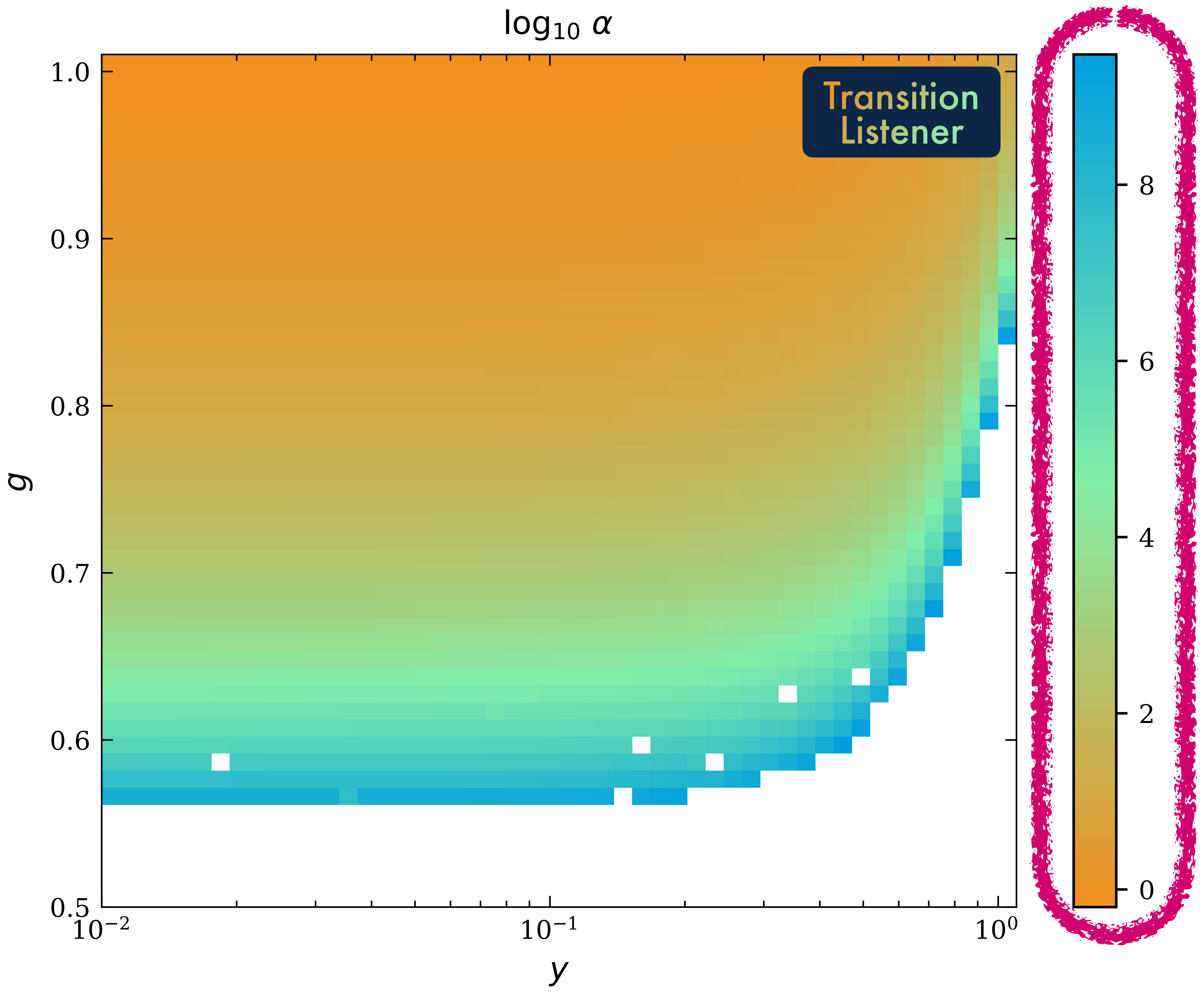
Not just EWSB

$v_{\rm wall}$

Incl. SM, SMEFT, dark sectors, ...

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

If you're not convinced yet…



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

T_{perc} & T_{reh}

Documentation

Proper error handling

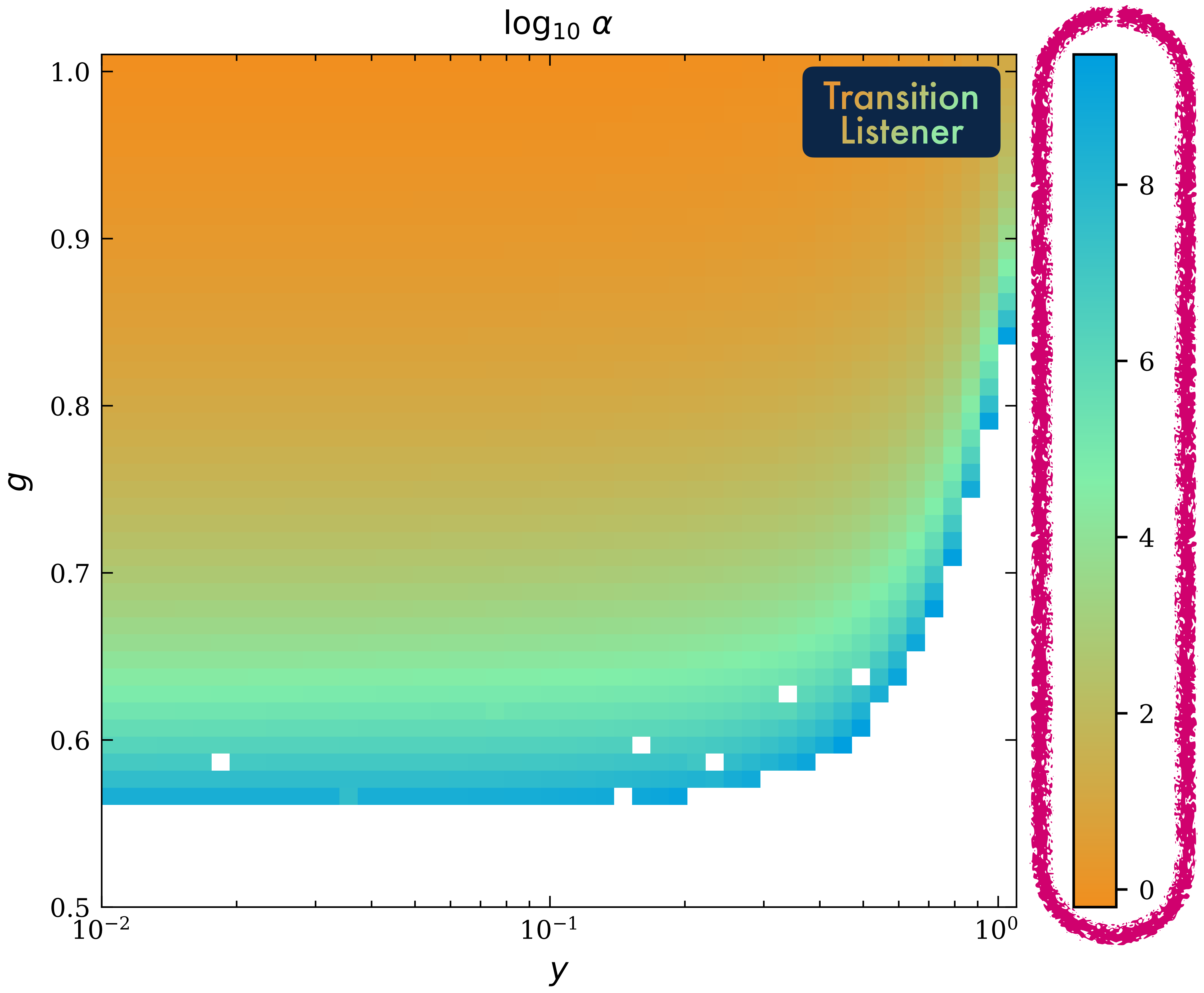
Not just EWSB

Several Higgs fields

v_{wall}

Incl. SM, SMEFT, dark sectors, …

If you're not convinced yet...



$T_{\rm perc}$ & $T_{\rm reh}$

Documentation

Proper error handling

Not just EWSB

PTA likelihoods

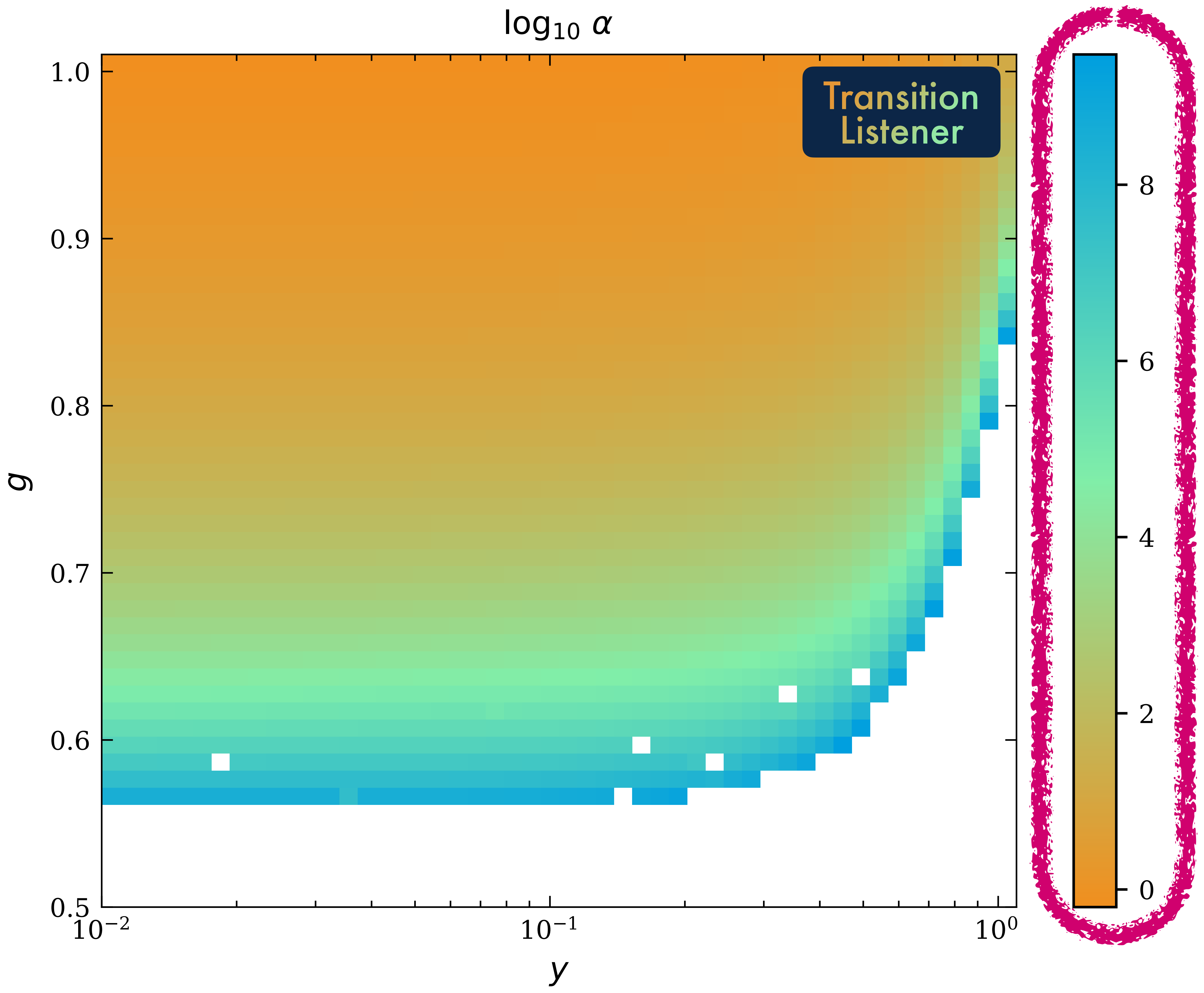
Several Higgs fields

$v_{\rm wall}$

Incl. SM, SMEFT, dark sectors, ...

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

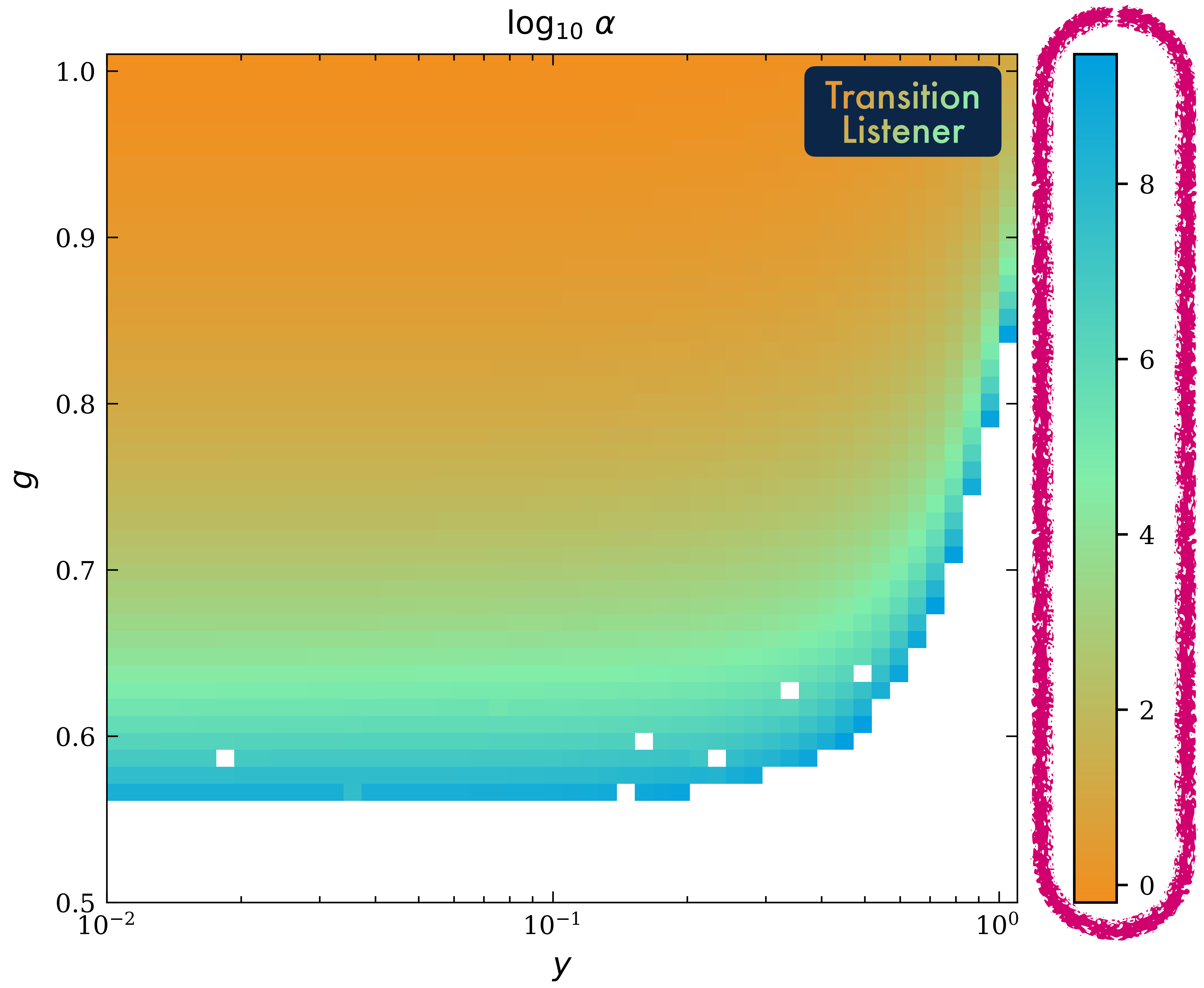
If you're not convinced yet…



- T_{perc} & T_{reh}
- Documentation
- Proper error handling
- PTA likelihoods
- Not just EWSB
- Incl. Nested sampler
- Several Higgs fields
- v_{wall}
- Incl. SM, SMEFT, dark sectors, …

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

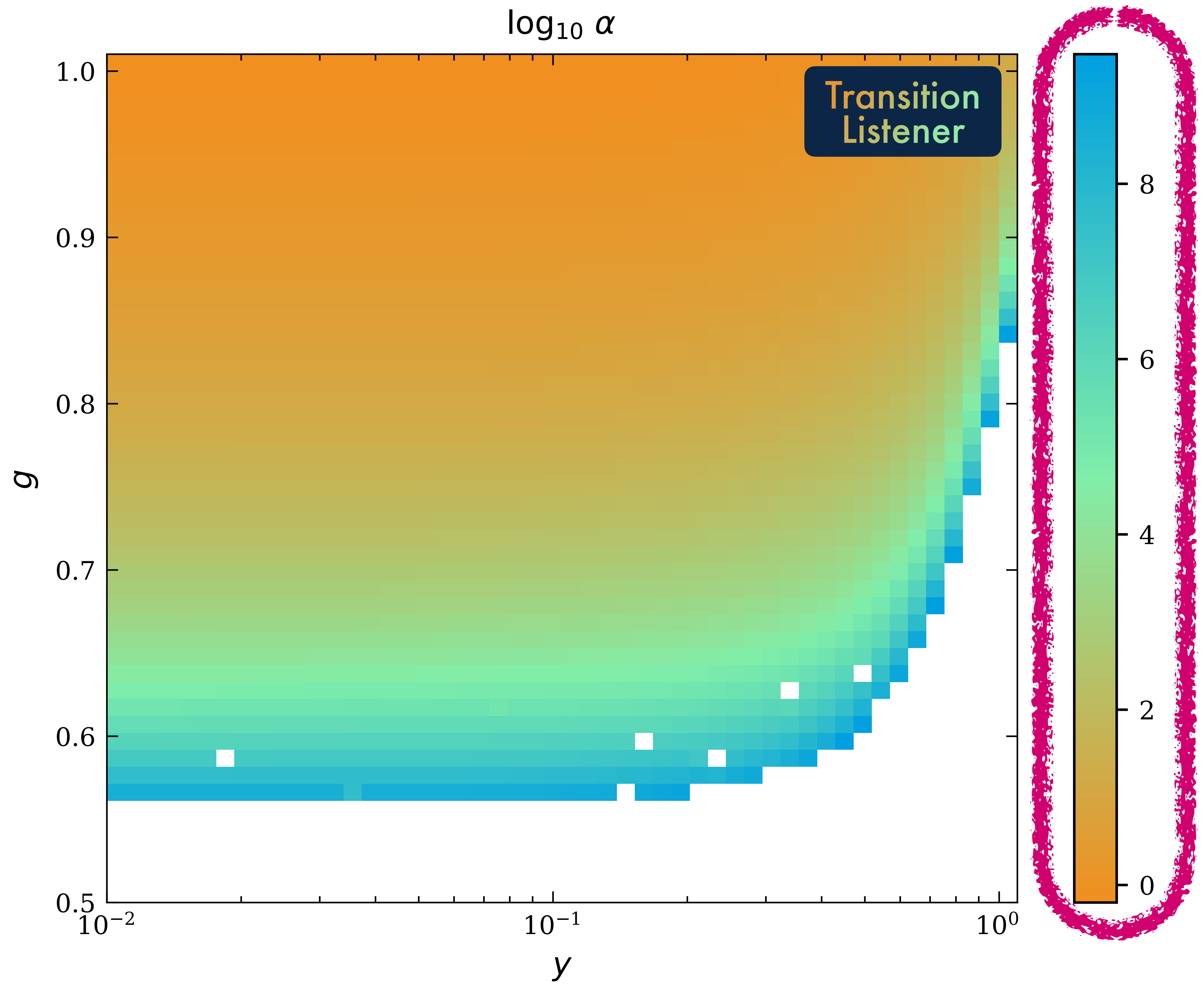
If you're not convinced yet…



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

- $T_{\rm perc}$ & $T_{\rm reh}$
- Documentation
- Proper error handling
- Integration into GAMBIT
- Not just EWSB
- PTA likelihoods
- Incl. Nested sampler
- Several Higgs fields
- $v_{\rm wall}$
- Incl. SM, SMEFT, dark sectors, …

If you're not convinced yet…



$T_{\rm perc}$ & $T_{\rm reh}$

Documentation

Proper error handling

Integration into GAMBIT

Not just EWSB

PTA likelihoods

Incl. Nested sampler

Several Higgs fields

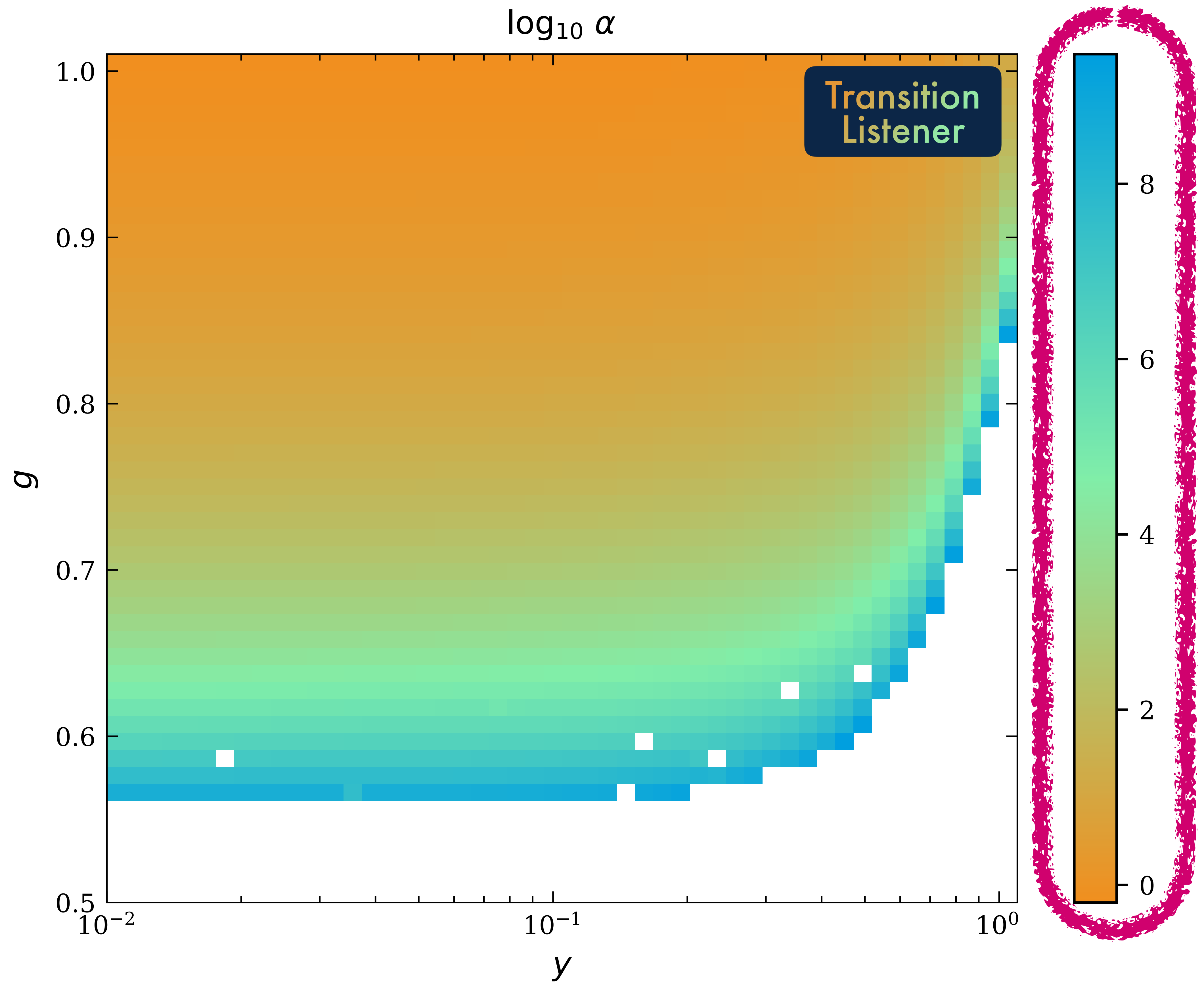
$v_{\rm wall}$

Incl. SM, SMEFT, dark sectors, …

SNR for LISA, ET, …

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

If you're not convinced yet…



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

- T_{perc} & T_{reh}
- Documentation
- Proper error handling
- Integration into GAMBIT
- Not just EWSB
- PTA likelihoods
- Incl. Nested sampler
- Several Higgs fields
- v_{wall}
- Fully modular
- Incl. SM, SMEFT, dark sectors, …
- SNR for LISA, ET, …

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**

Transition Listener

Thank you very much for your attention!

Do you have any questions?