Do PTAs observe a dark sector phase transition?

Early Universe from Home, February 2025

Carlo Tasillo,
Uppsala University

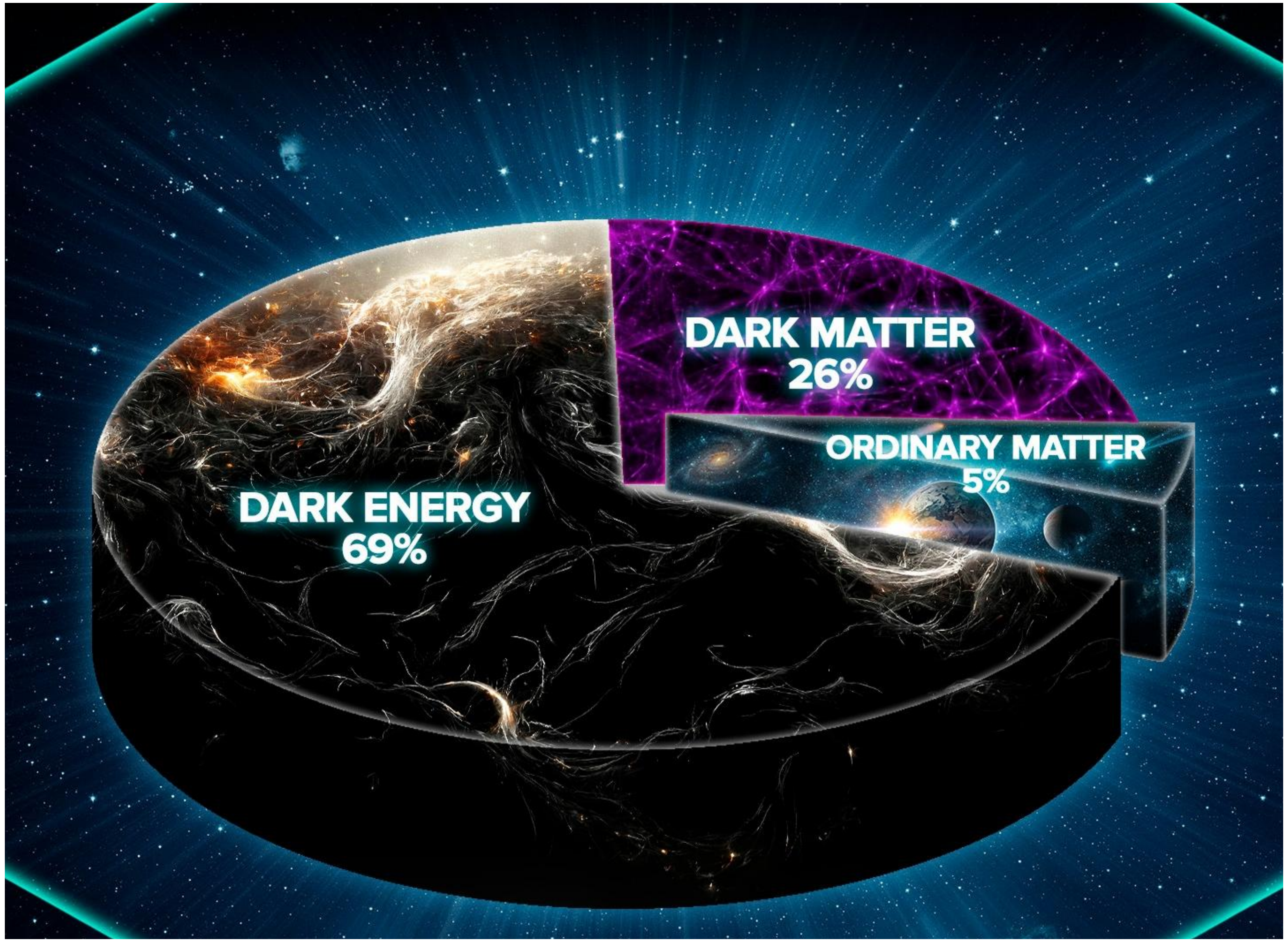
Based on work with Sowmiya Balan, Torsten Bringmann, Frederik Depta, Felix Kahlhöfer, Thomas Konstandin, Jonas Matuszak, and Kai Schmidt-Hoberg

JCAP 11 (2023) 053 and **2502.soon**

DESY.

UPPSALA UNIVERSITET

We only understand 5%



[PBS spacetime]

We need

26% of dark matter

of cold dark matter in order to explain the CMB, galaxy clustering, the bullet cluster, galactic rotation curves, …

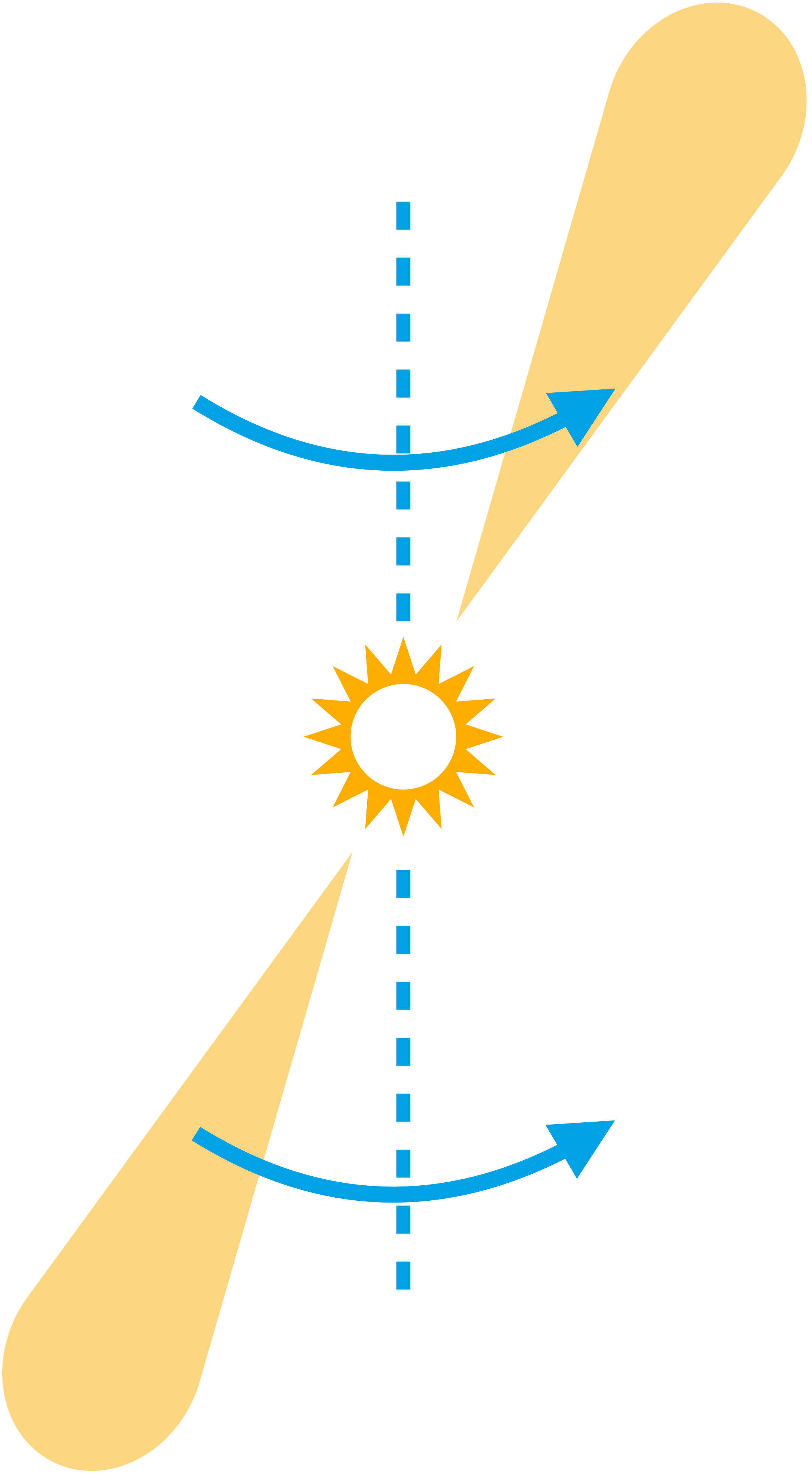
Still, dark matter searches only had null results so far ☹️

Cirelli+ [2406.01705]


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
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
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
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.
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
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.

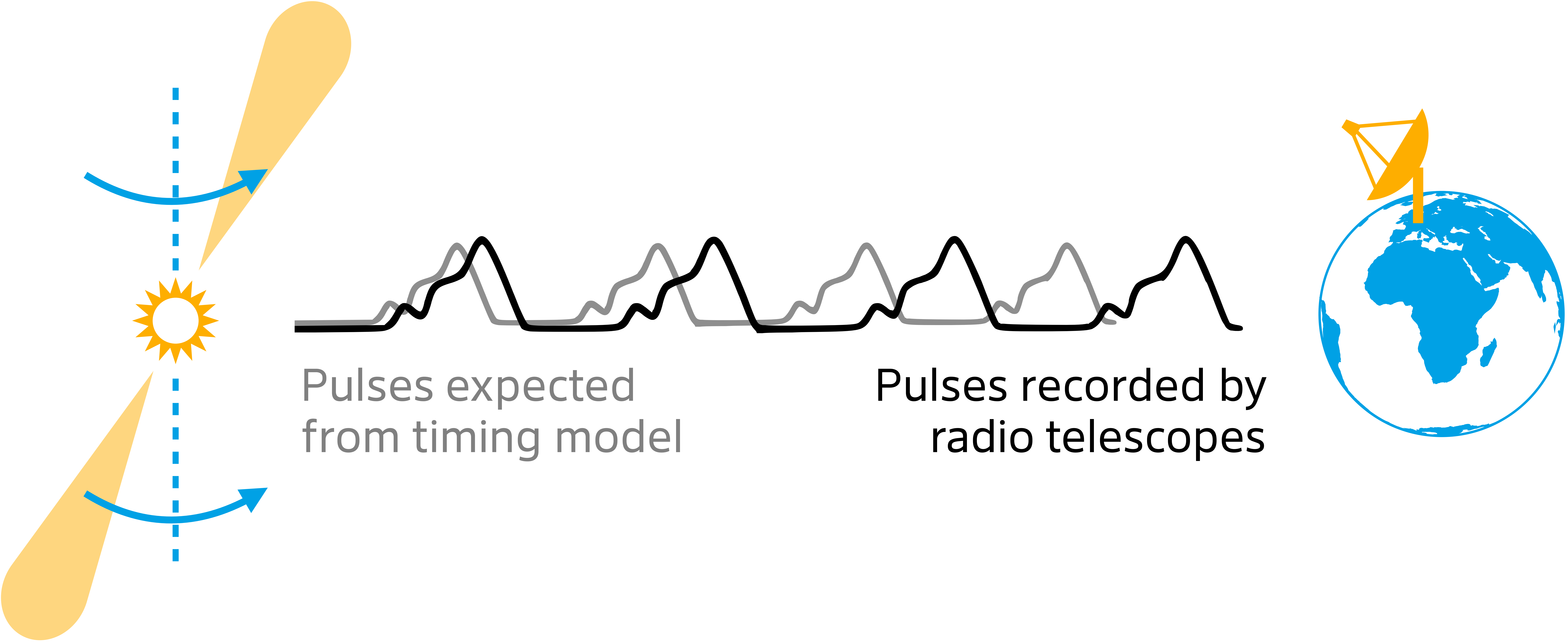
Luckily, we now live in the age of gravitational wave cosmology!

Pulsar timing arrays

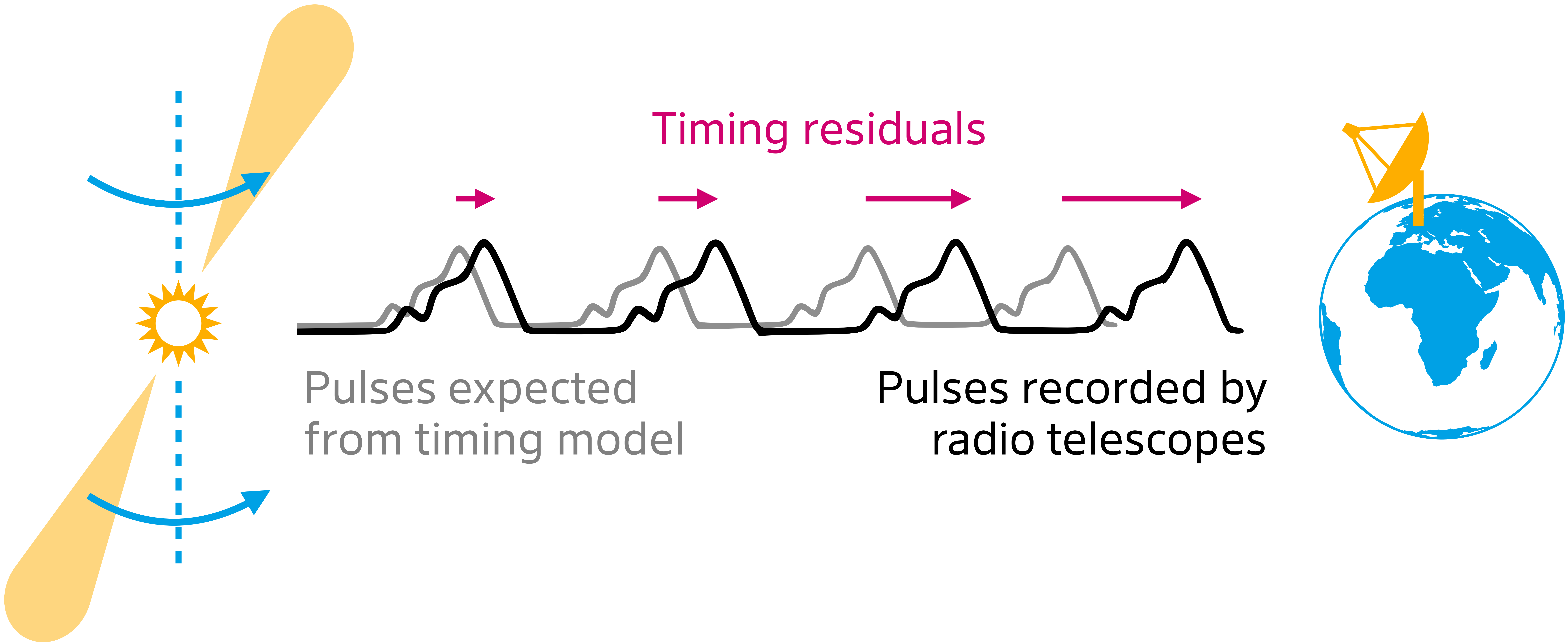


Pulsar timing arrays

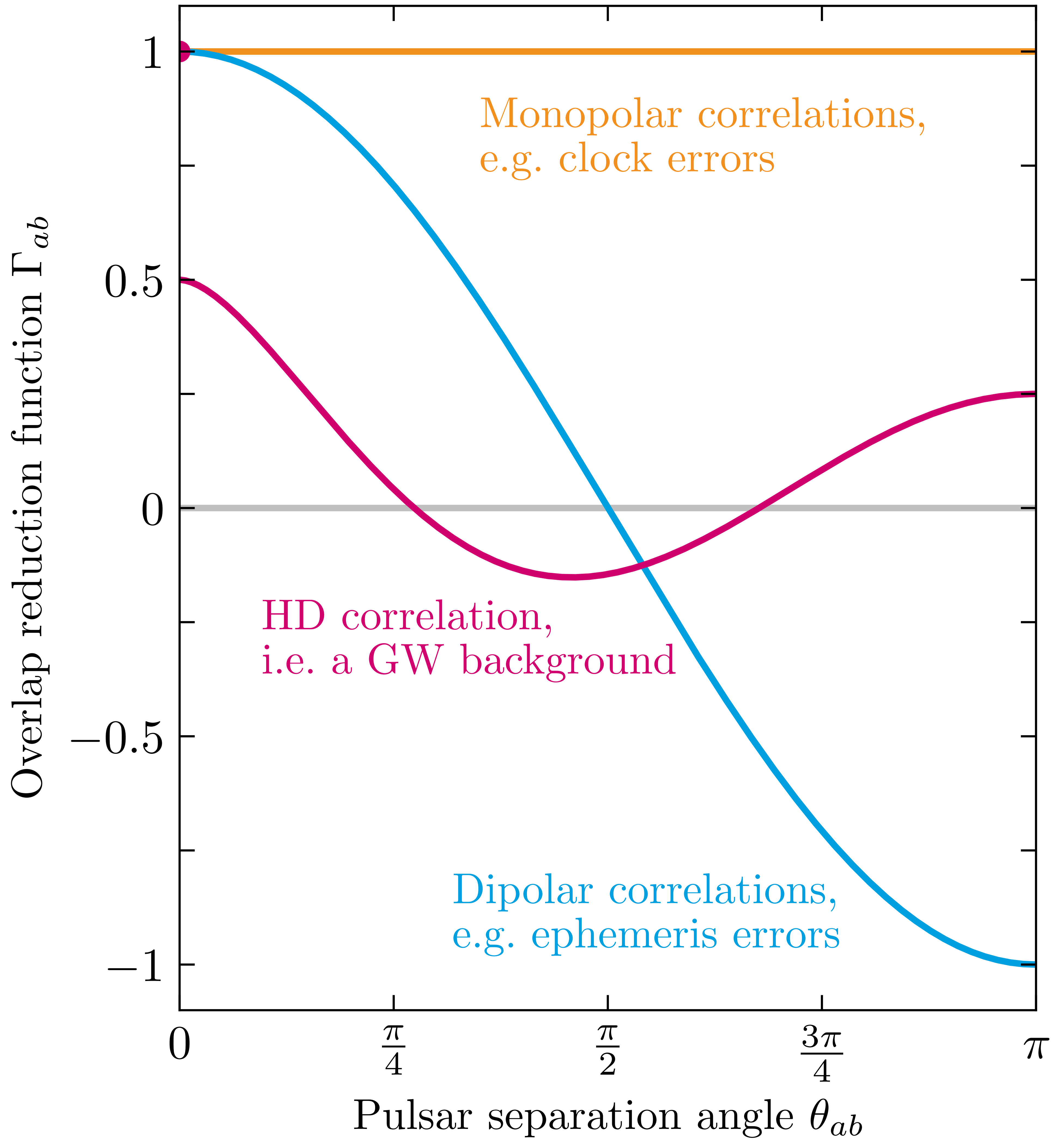
Pulsar timing arrays



Pulsar timing arrays

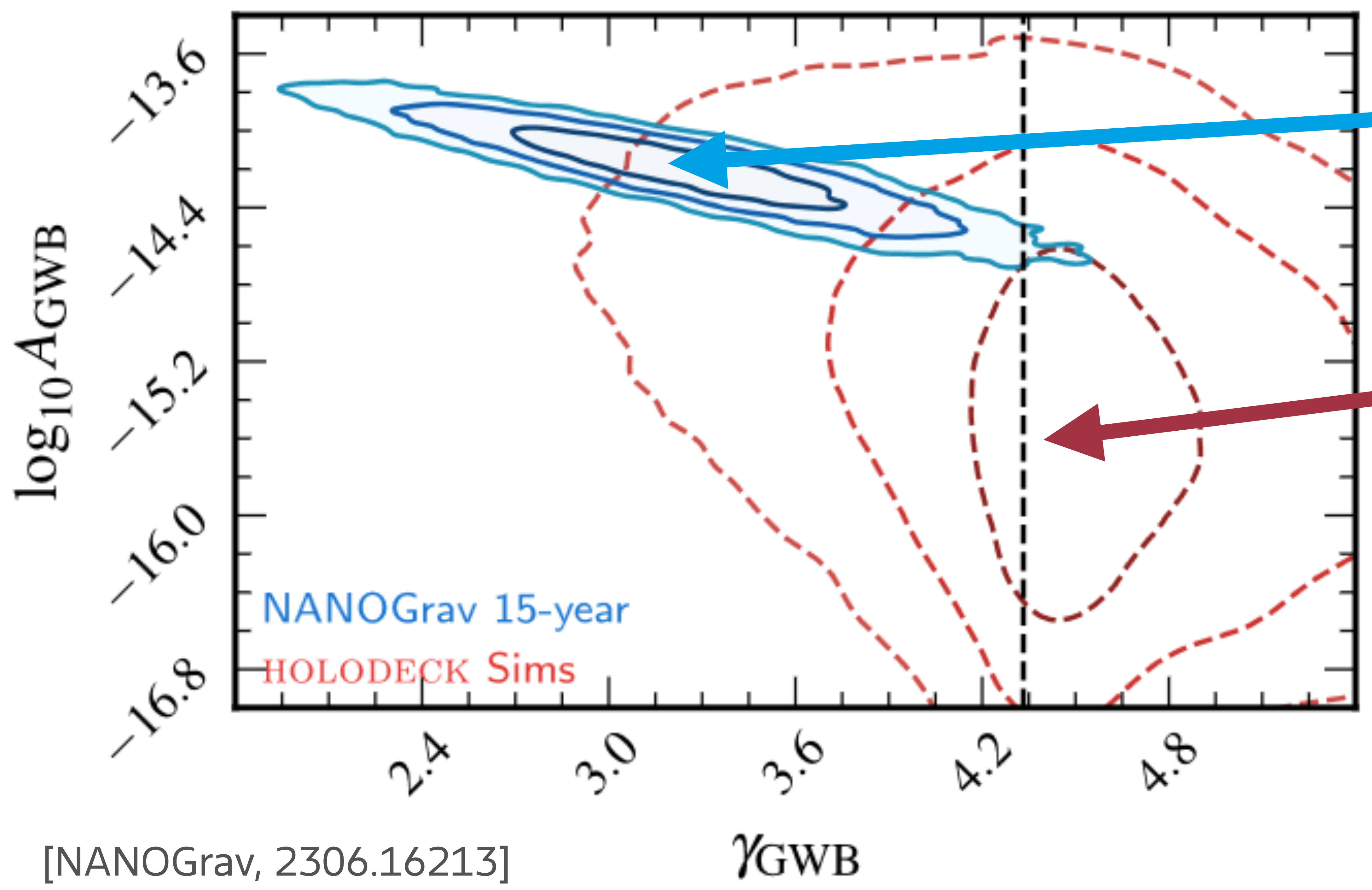


Searching for the Hellings-Downs correlation



- 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 $>5\sigma$ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]

Merging supermassive black holes

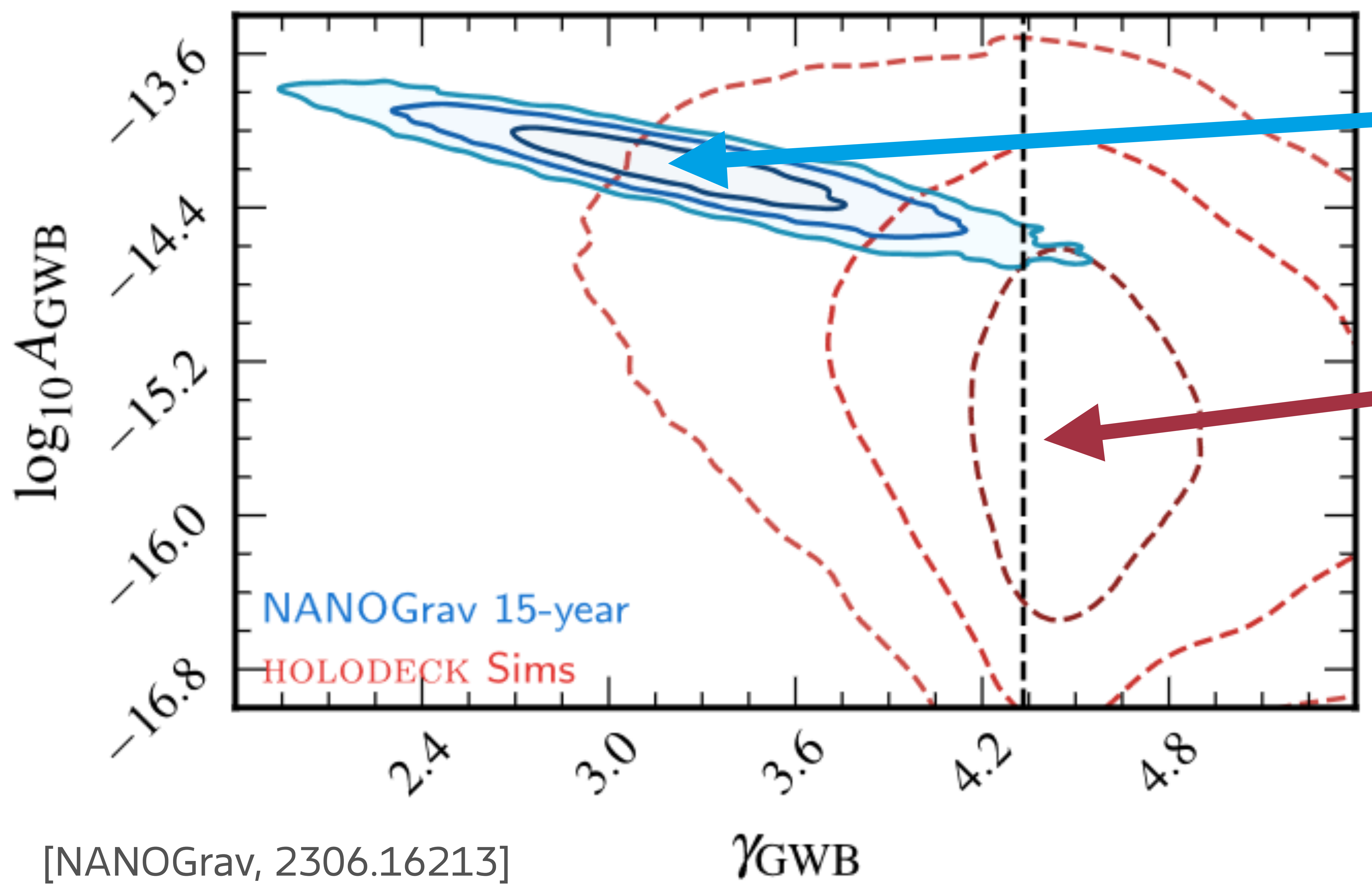


[NANOGrav, 2306.16213]

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

Merging supermassive black holes



[NANOGrav, 2306.16213]

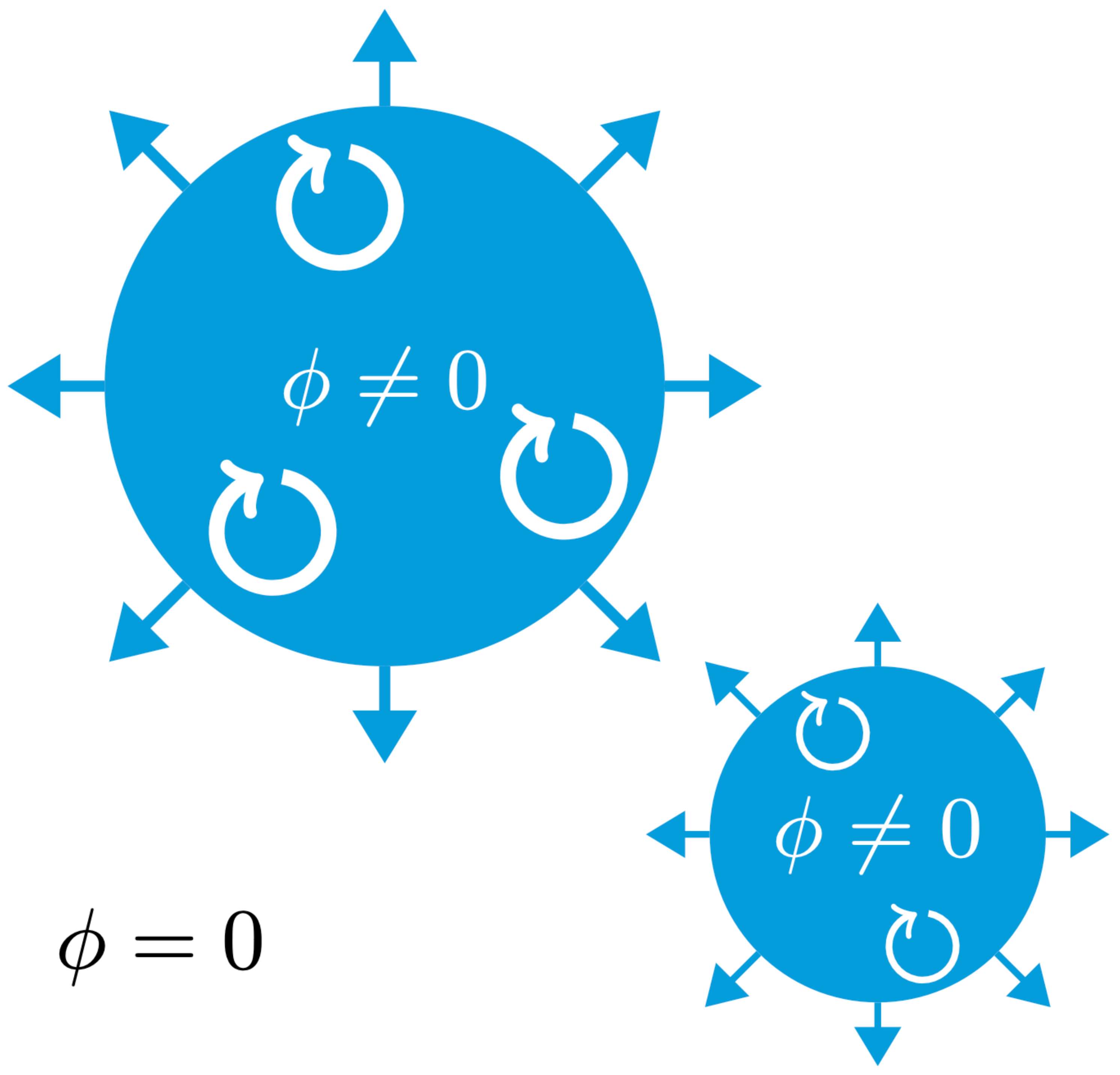
Observed signal follows a power-law spectrum with amplitude A and slope γ

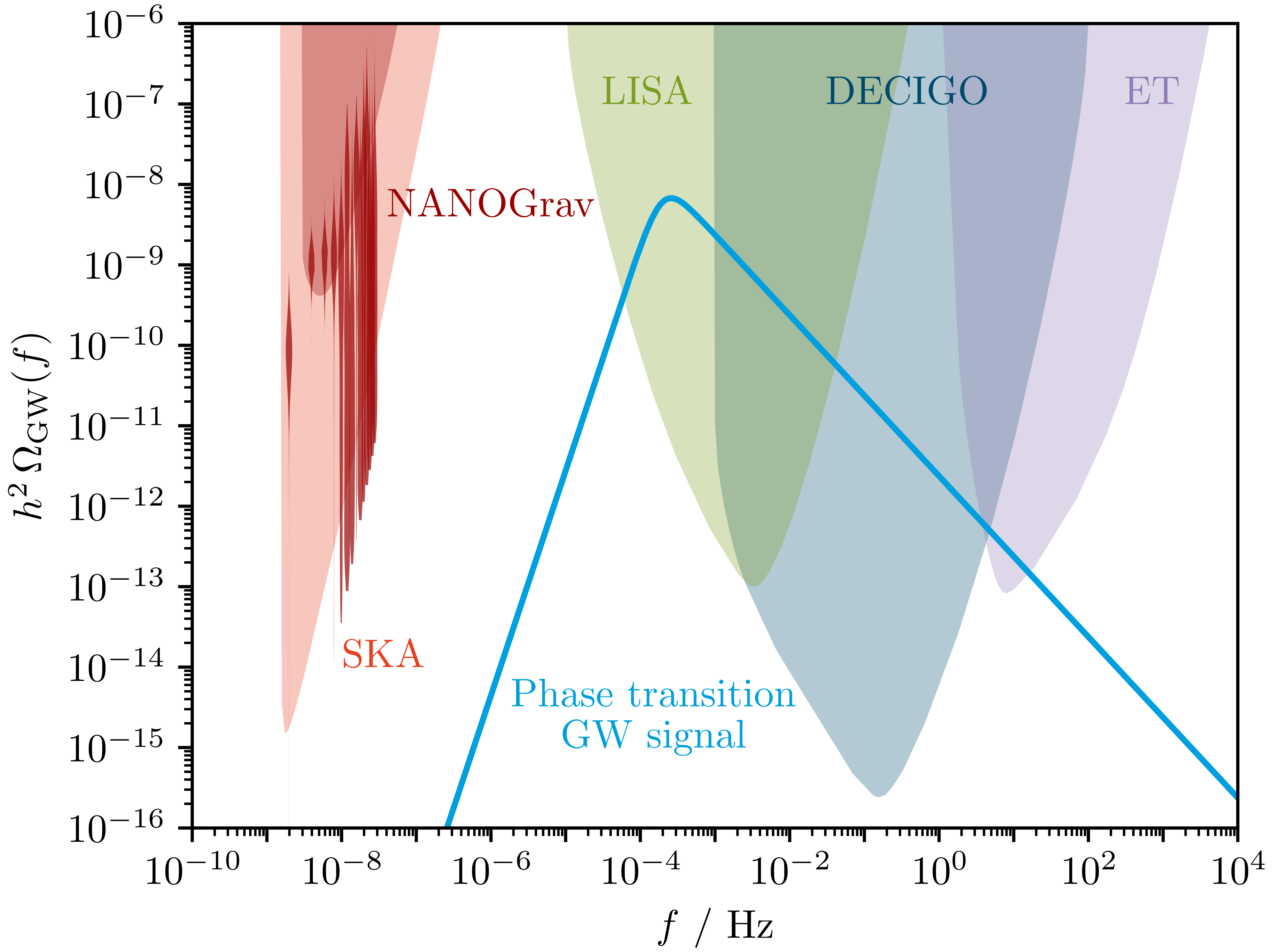
Astrophysical simulations based on realistic BH populations predict much weaker signals with higher γ

Are there other signal sources?

First-order phase transitions produce GWs

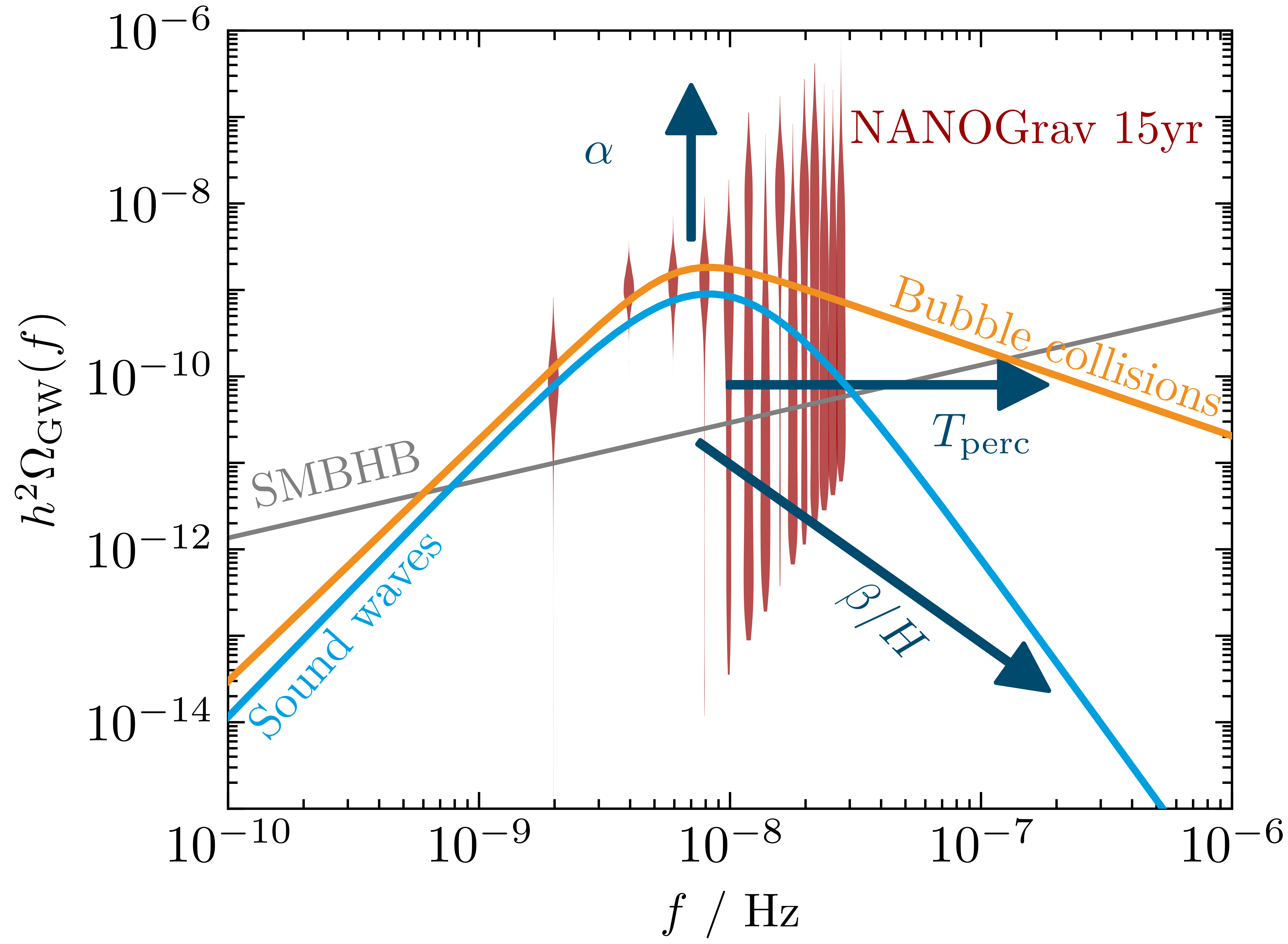
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

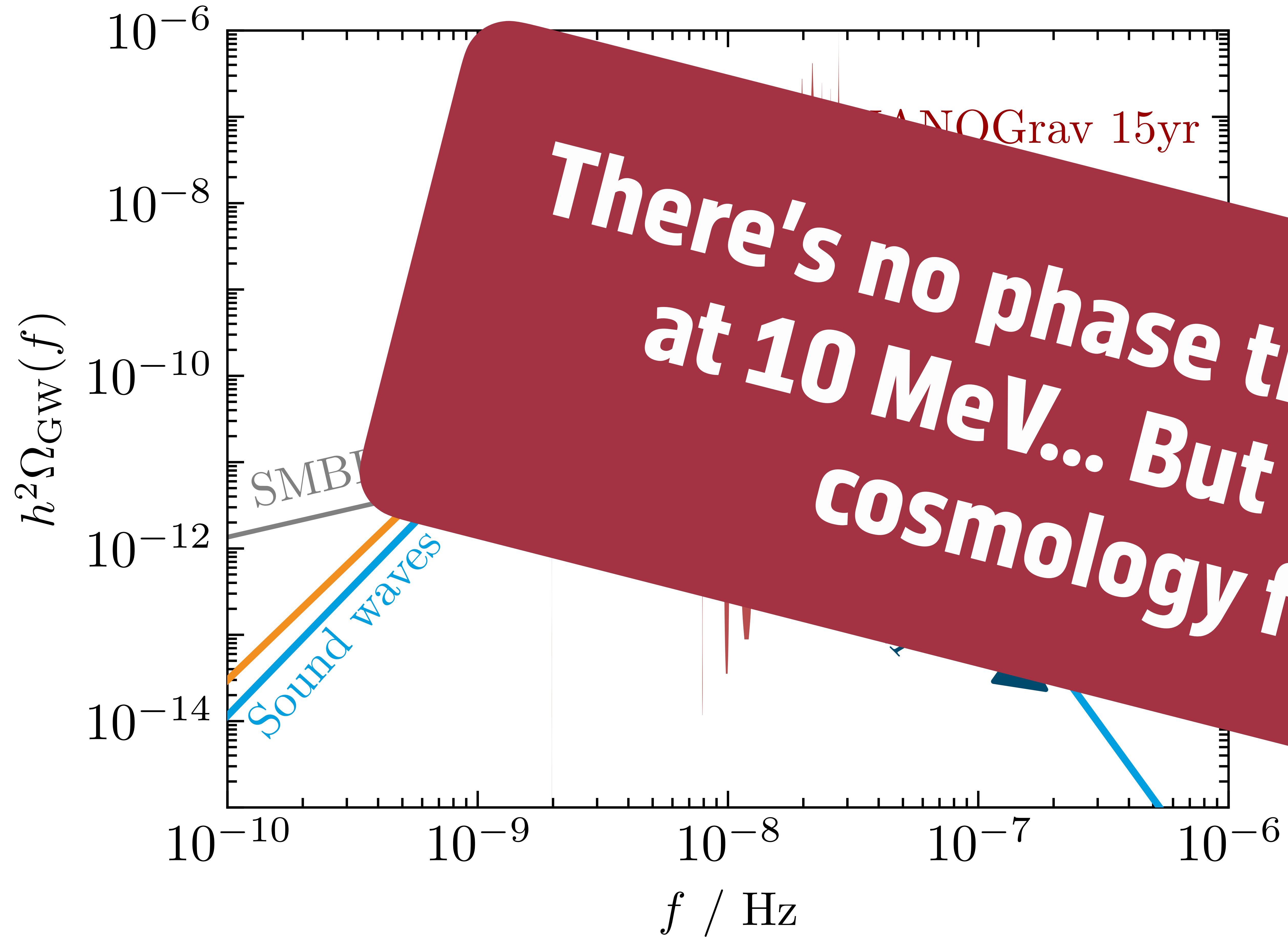
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

To fit the new pulsar timing data:

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

Parametrization of the GW signal



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

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

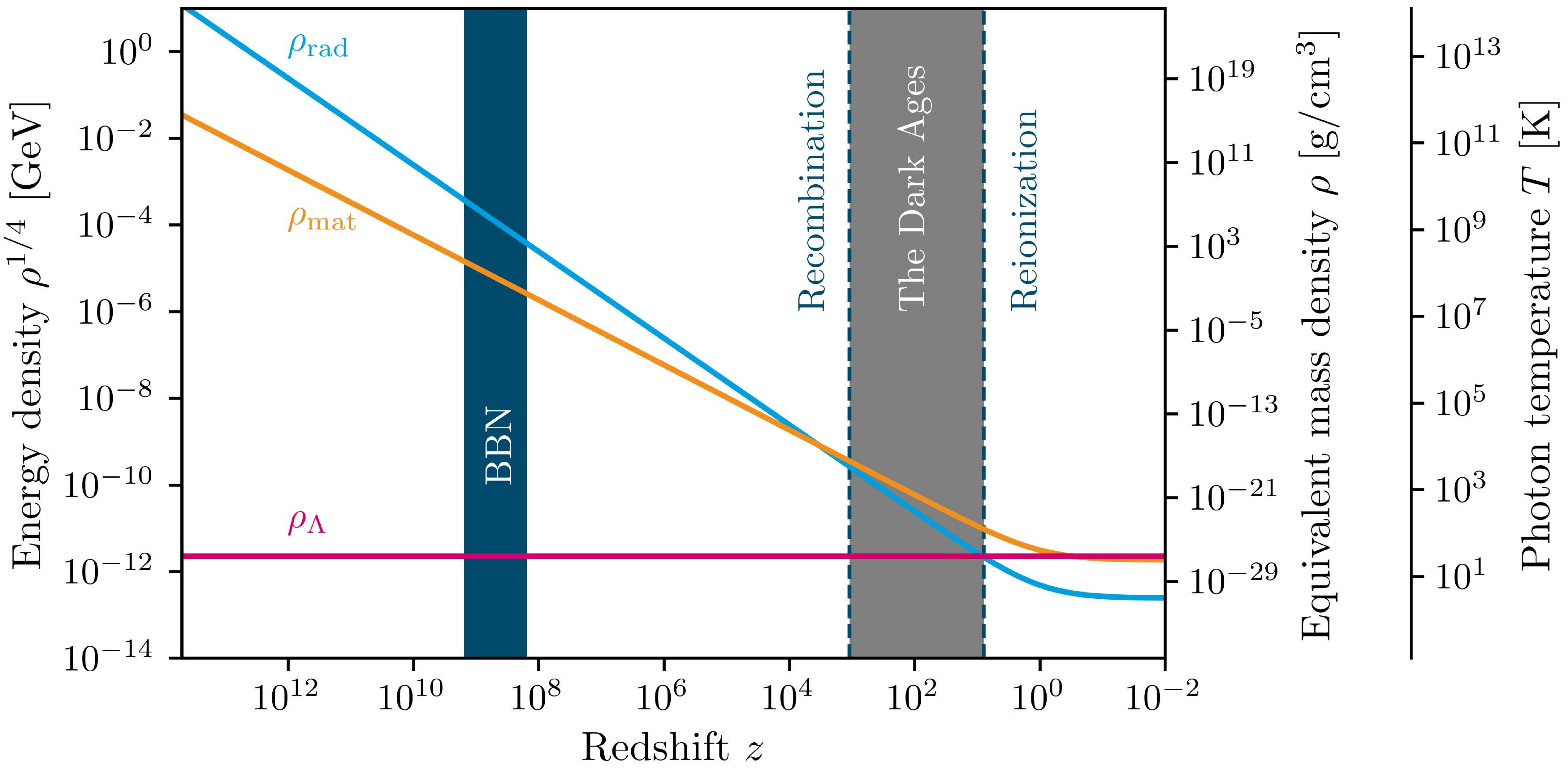
with $\quad f_{\mathrm{peak}} \simeq 0.1\,\mathrm{nHz} \times \frac{\beta}{H} \times \frac{T}{\mathrm{MeV}}$

...ing data:

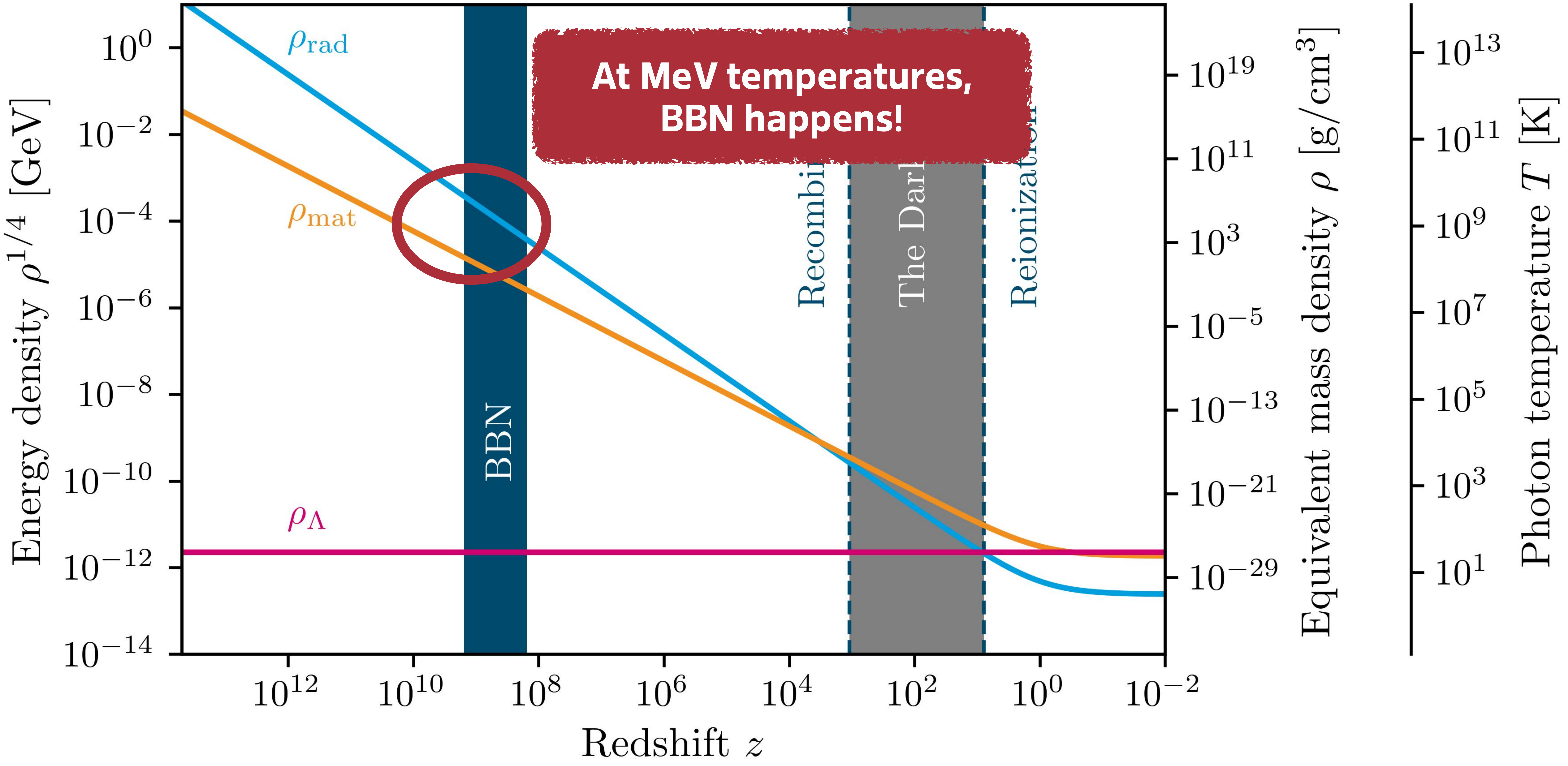
- ... 1
- ... ≈ 10
- Percolati... $\approx 10\,\mathrm{MeV}$

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

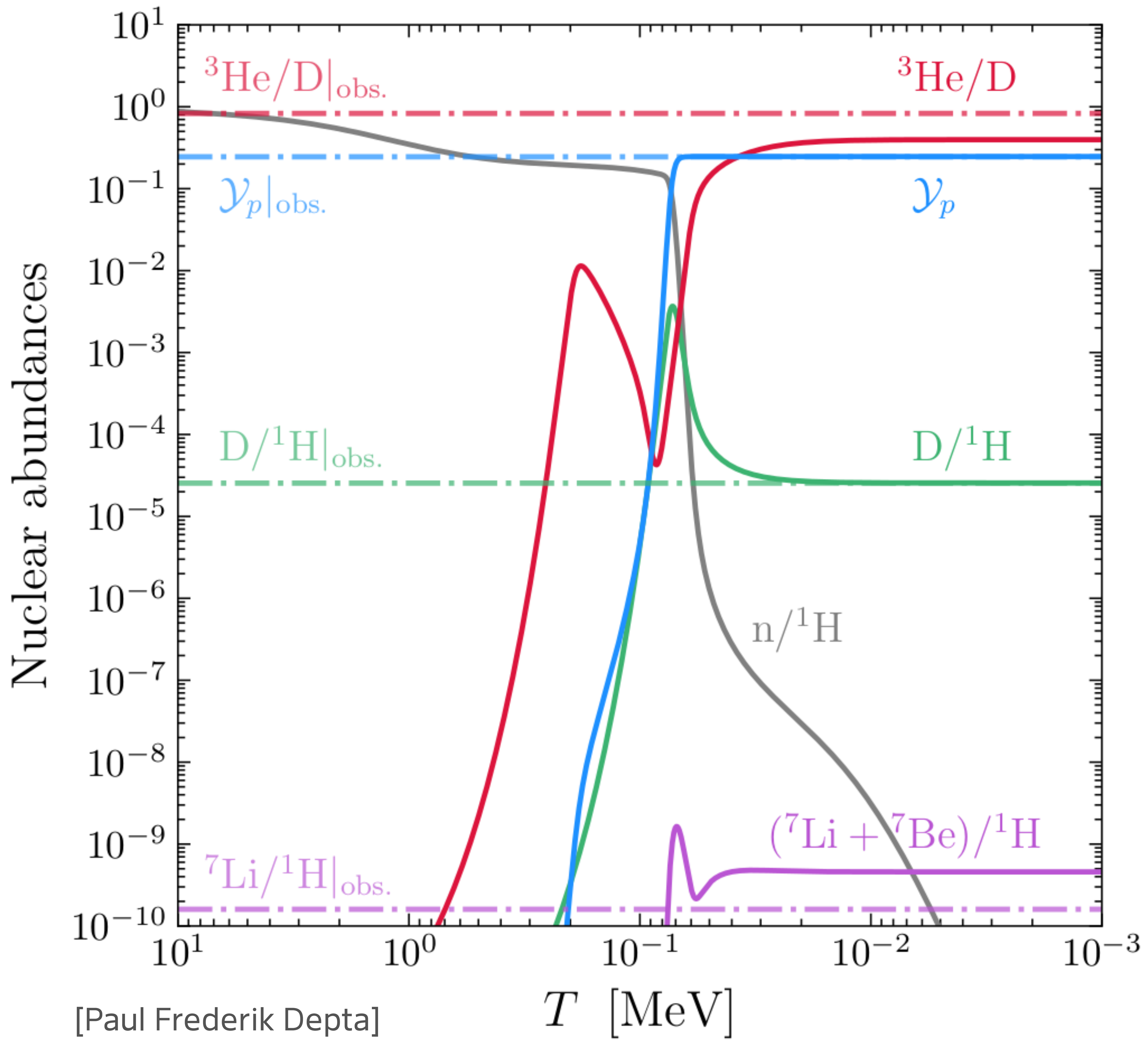
A brief history of time



A brief history of time



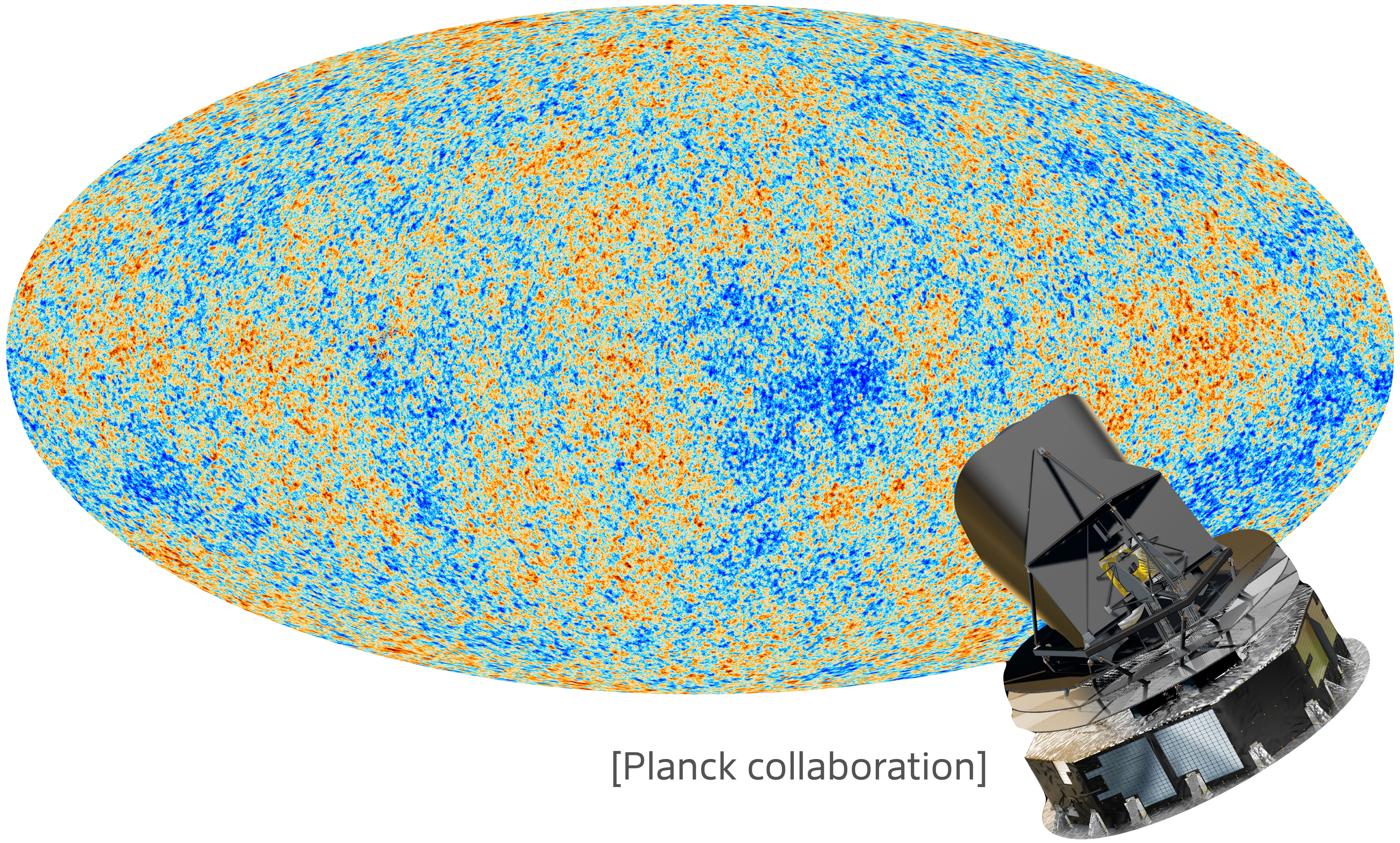
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

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

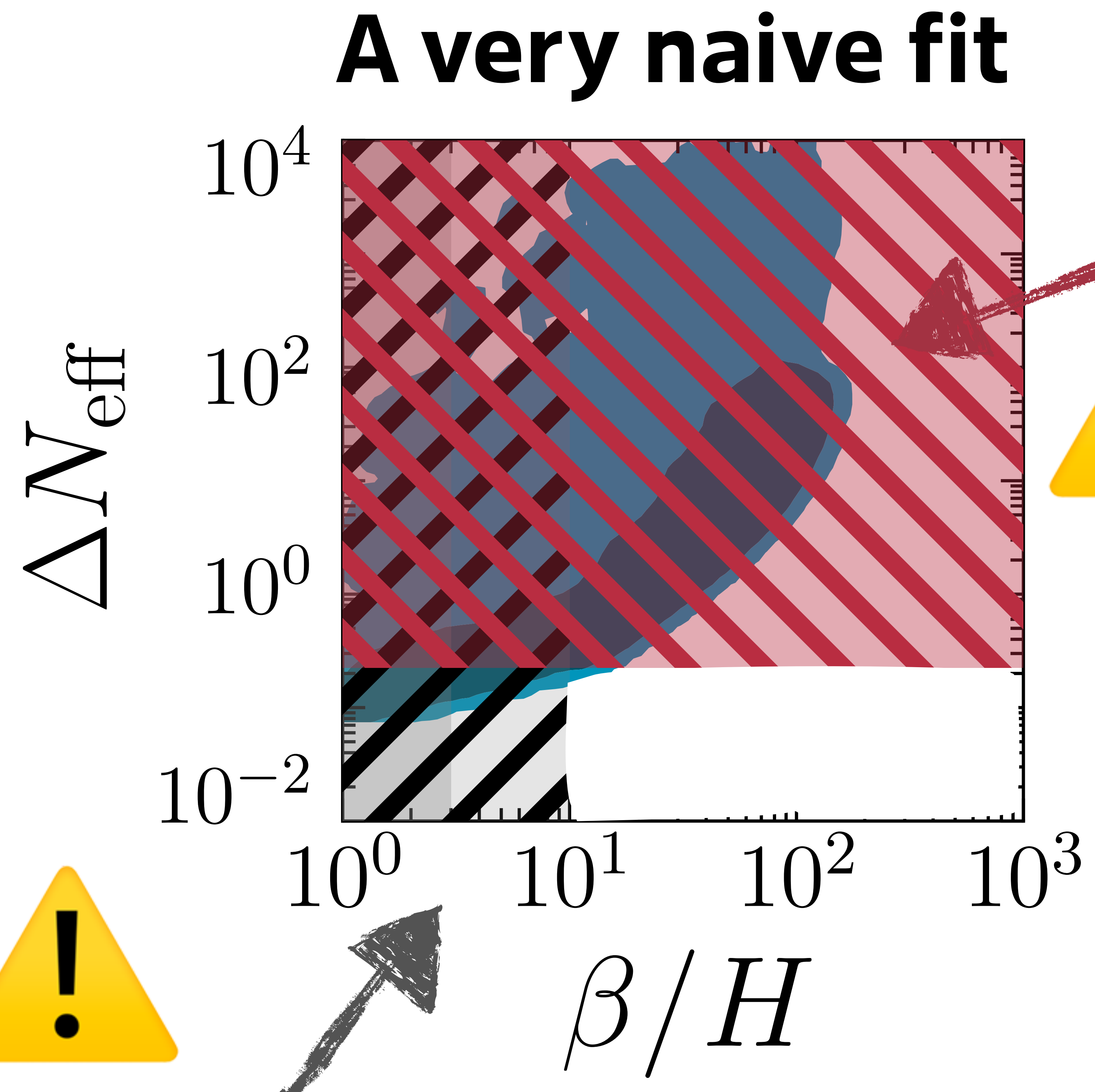
Big Bang Nucleosynthesis and the CMB

anck collaboration]

We only need to get rid of extra energy in the dark sector before BBN 😊

- Observation of … ordial … ances in … h
- … 41
- … $_{\text{eff}}$ … 2.99 ± 0.17
- Consistent with 3 SM neutrinos

A dark sector without portal couplings



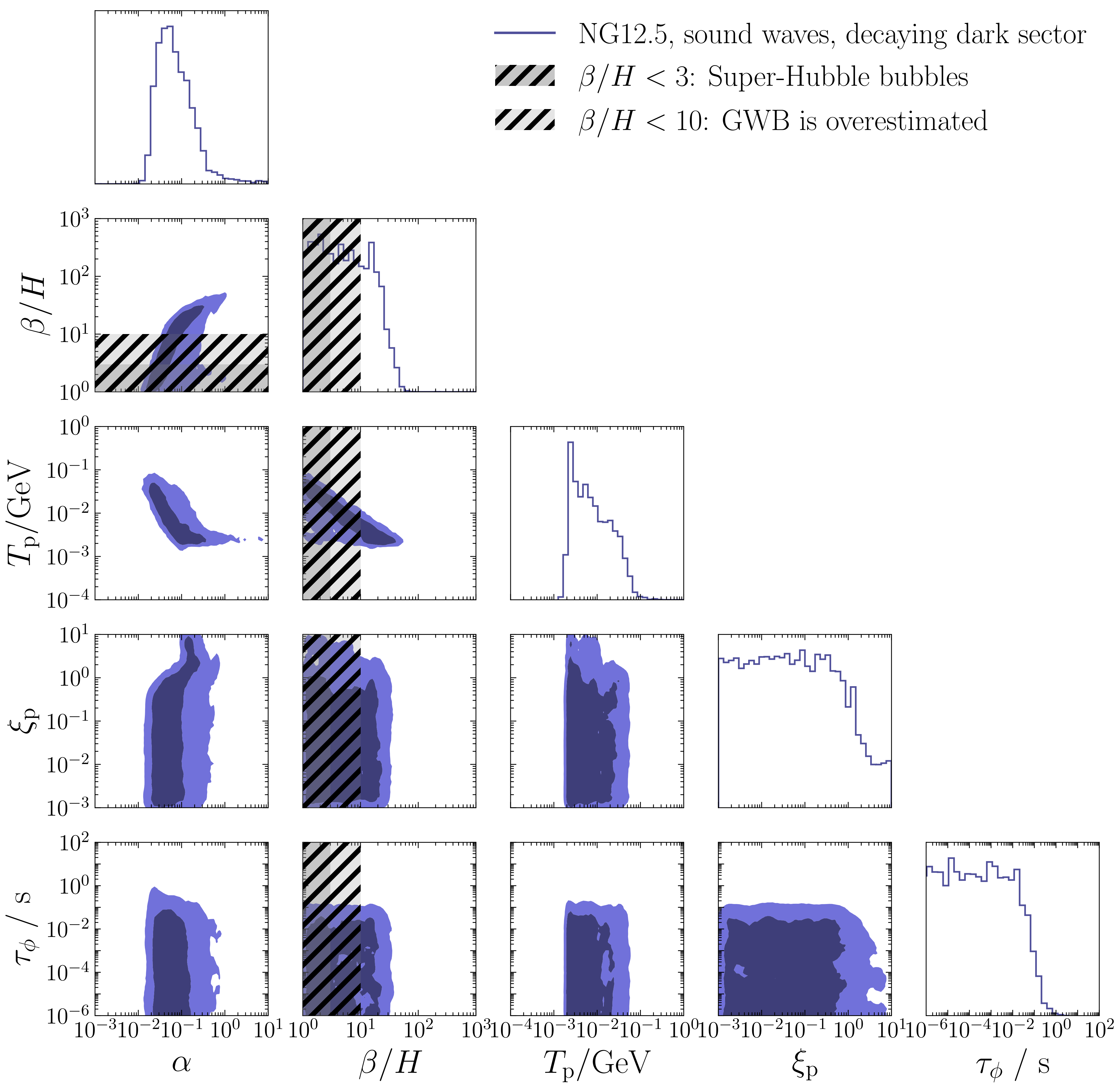
The liberated vacuum energy remains in the dark sector. A good fit would require enormous $\Delta N_{\rm eff} \gg 0.22$

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]

What happened after 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?

SMBH remain unable to account for full GW signal

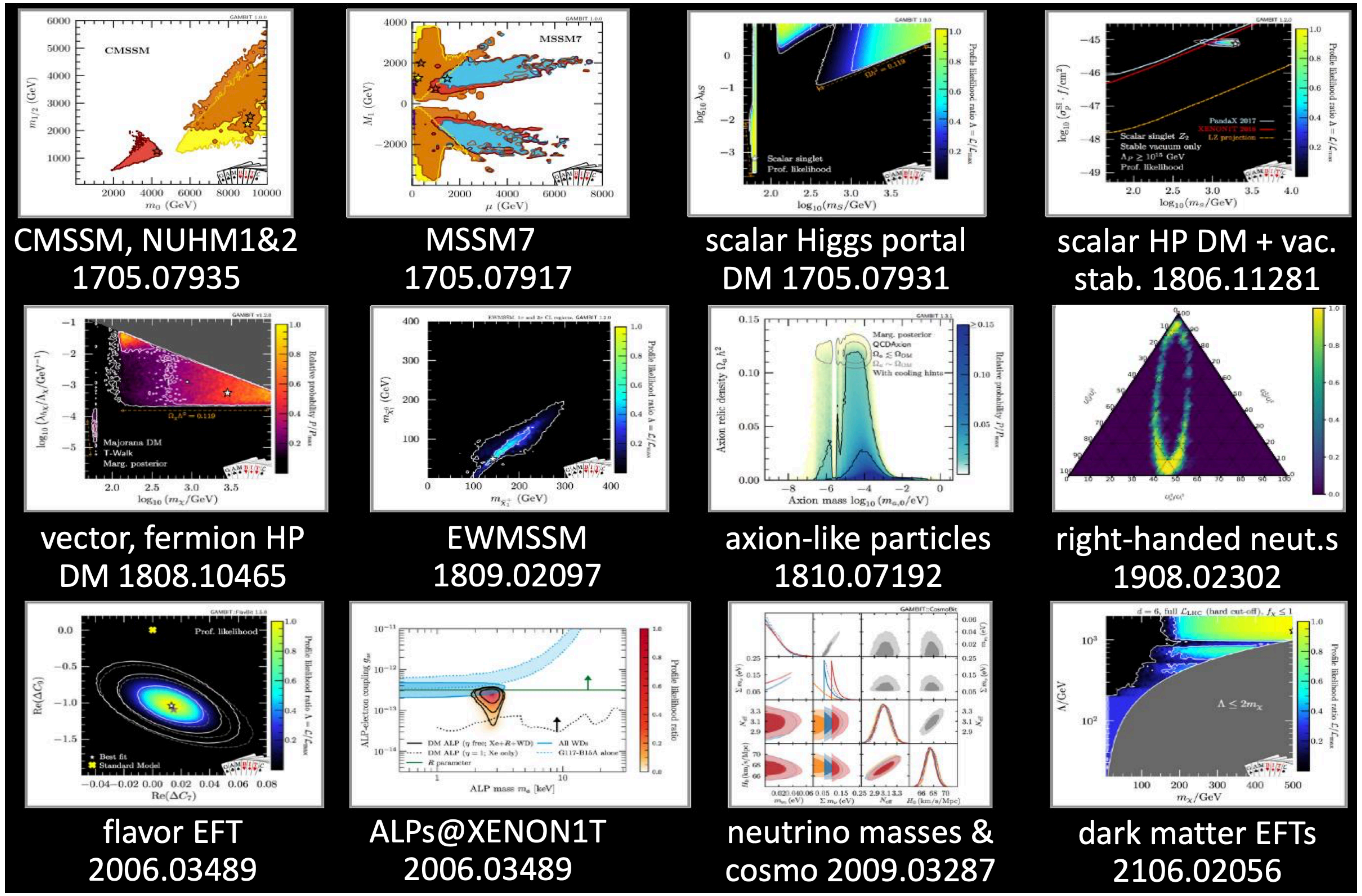
[Chen+, 2502.01024]

Investigation of specific dark sector models

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

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

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 λ

$V(\phi)$ ... ϕ

...xing κ

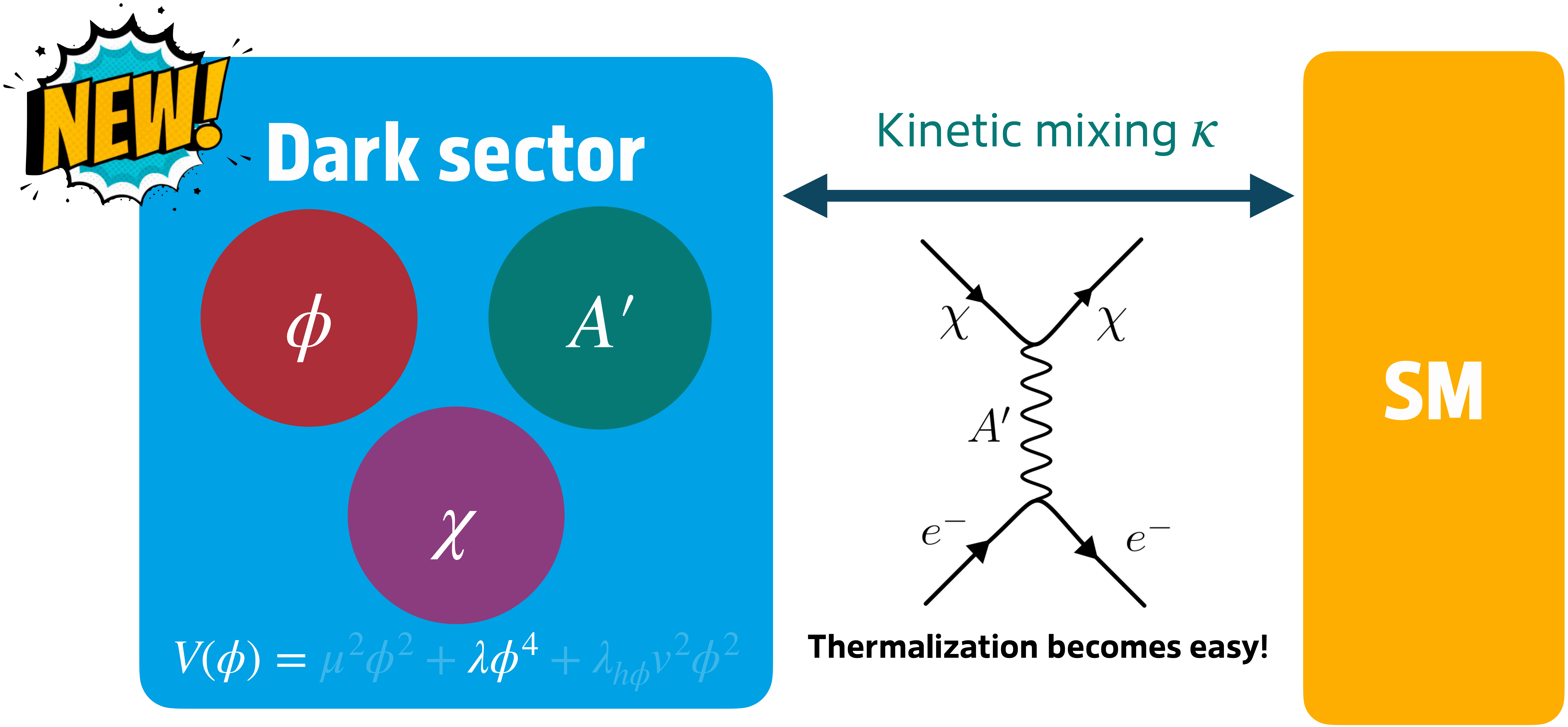
$$\mathscr{L} \supset \kappa F'_{\mu\nu} F^{\mu\nu}$$

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

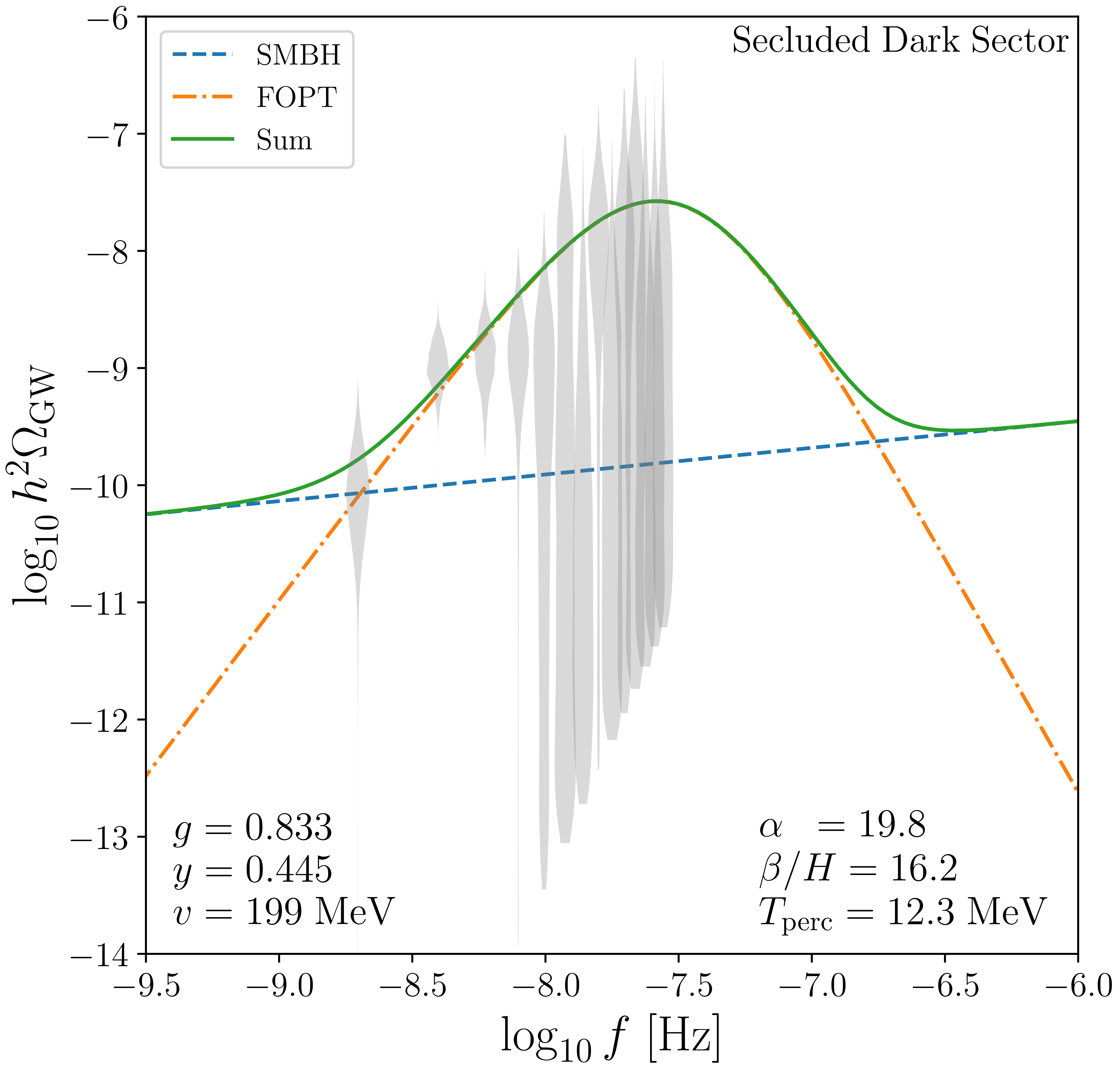
Model building is complicated!
Hard to avoid cosmological constraints and fine-tuning...

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

A conformal dark sector incl. dark matter candidate



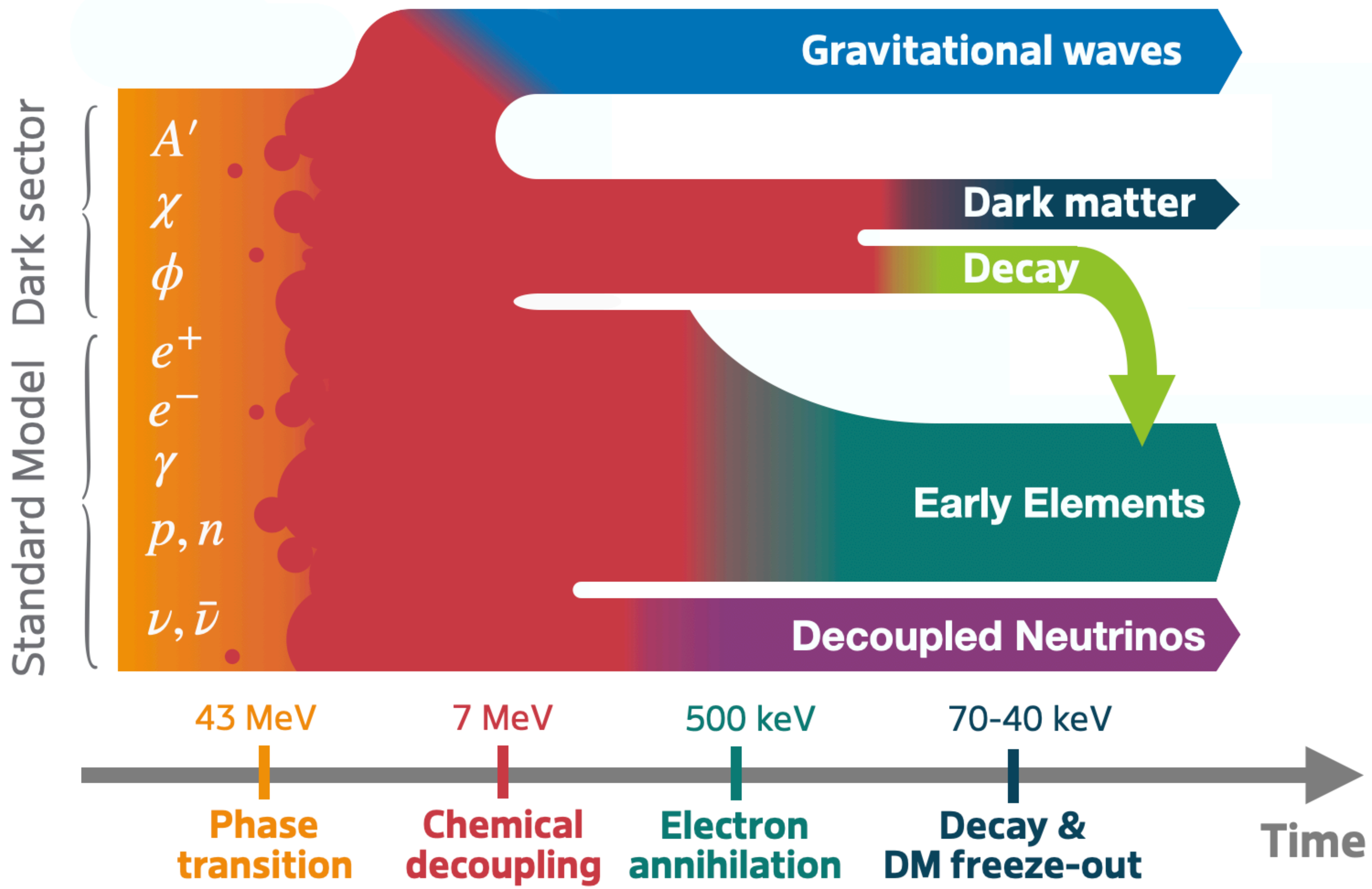
All constraints can be circumvented



Global fit found parameter space with

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

What needs to happen before BBN?

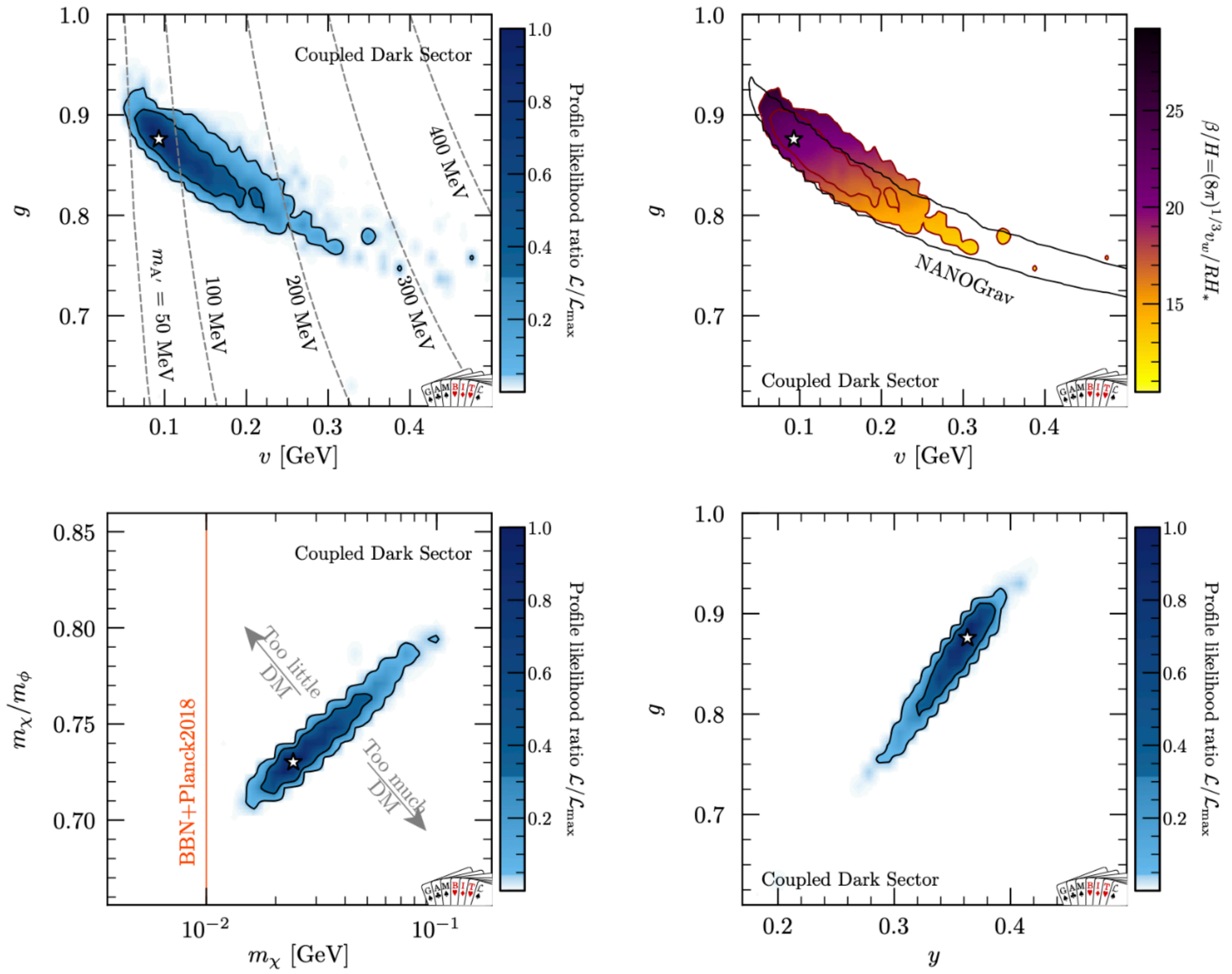


What if κ is not enough for thermalization?

The found parameter region around $\kappa \simeq 10^{-4}$ is small and could be ruled out soon!

Separate analysis incl. dimension-six operator allowing $\phi \to \bar{e}e$ decays before BBN shows: Even $\kappa = 0$ is viable!

$\longrightarrow$ **Possible supernova constraints?**



Summary

- We are only at the dawn of GW cosmology, but can already probe the pre-BBN universe!
- 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 SMBH**
  - ➡ Performed global fit with PTA, BBN, CMB, direct detection, indirect detection, bullet cluster, and beam dump likelihoods
  - ➡ Best-fit scenarios **can be tested by LDMX**!

Thank you very much for your attention!

Do you have any questions?