Exploring the Dark Universe with Gravitational Wave Cosmology

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.

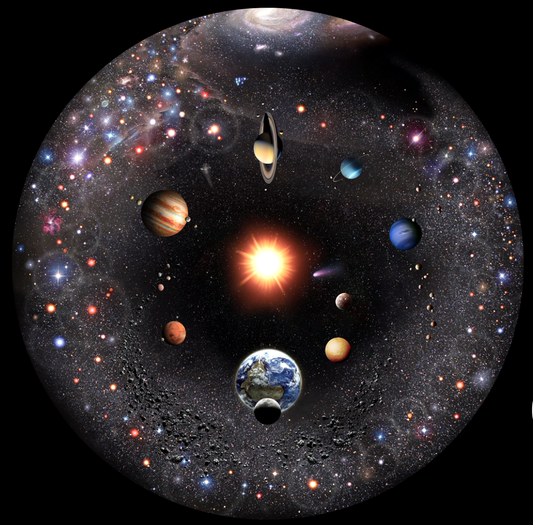
UPPSALA UNIVERSITET

The observable universe

Our Solar System

PABLO
CARLOS
BUDASSI

The observable universe



Our galaxy

PABLO CARLOS BUDASSI

[Pablo Carlos Budassi]

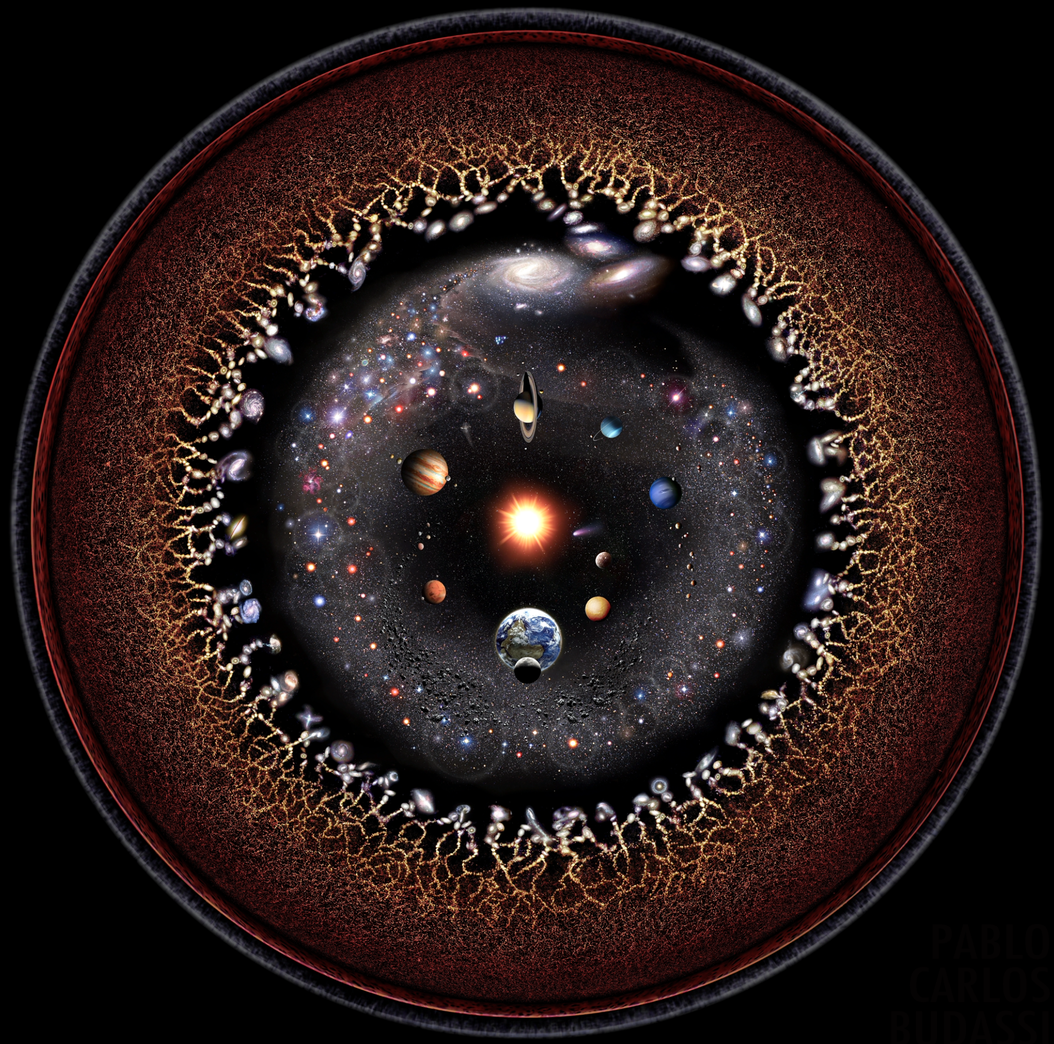
The observable universe

Other galaxies

PABLO CARLOS BUDASSI

[Pablo Carlos Budassi]

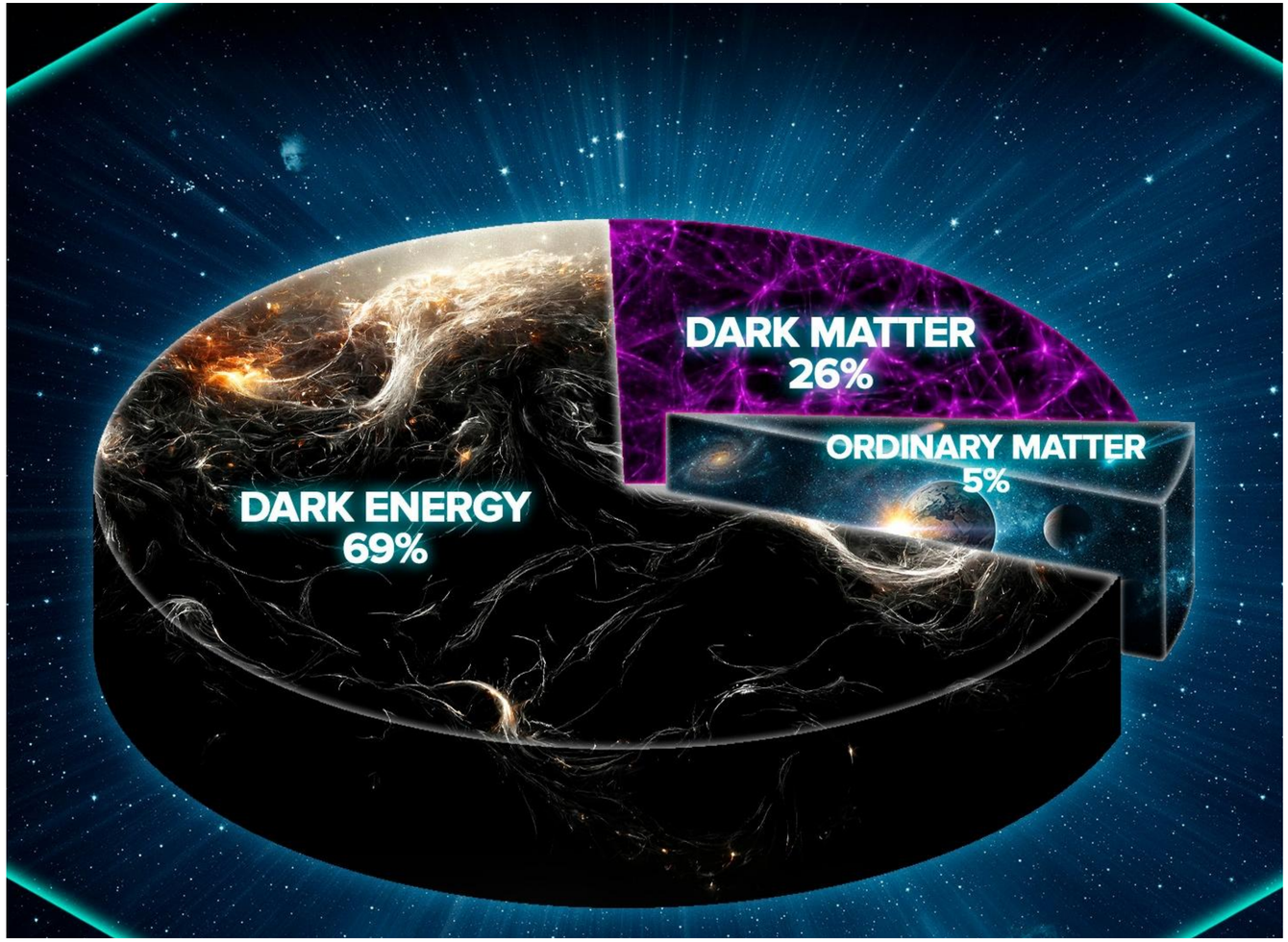
The observable universe



The CMB…
and the CGWB?

[Pablo Carlos Budassi]

We only understand 5%



[PBS spacetime]

We need

26% of cold dark matter

in order to explain seemingly independent phenomena: 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
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
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Galax
Space
Gravitational wave
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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.
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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
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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
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Monster gravitational
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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


Luckily, we now live in the age of gravitational wave cosmology!
At Last, There's
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Sound comes from the merging of supermassive black holes across the universe, according to scientists
Scientists 'hear' cosmic hum from gravitational waves
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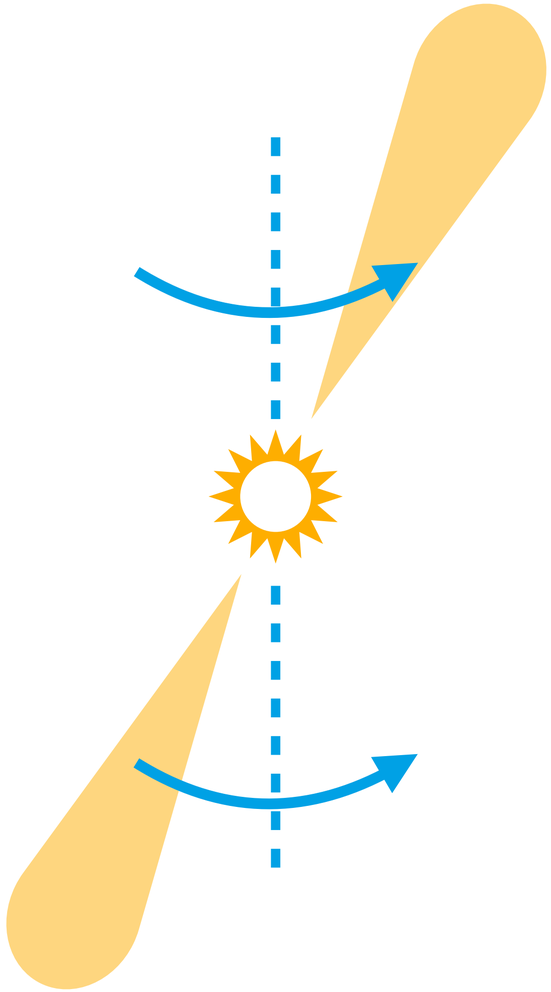
Pulsar timing arrays



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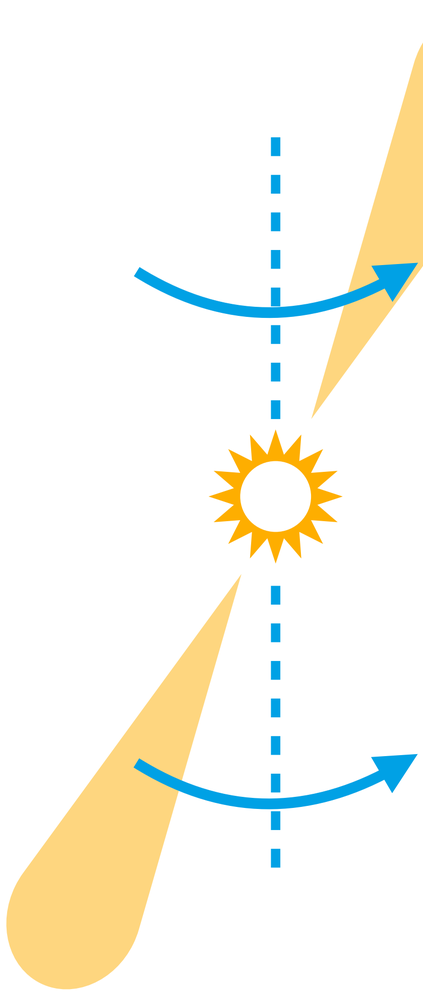
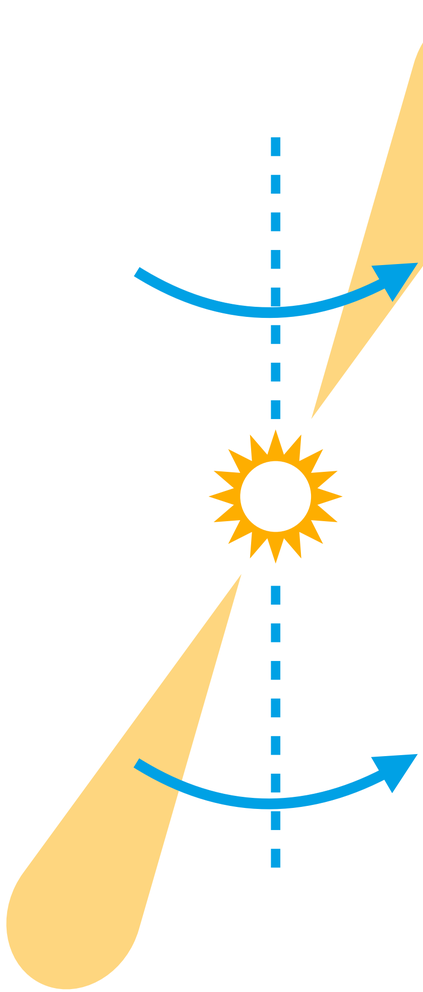
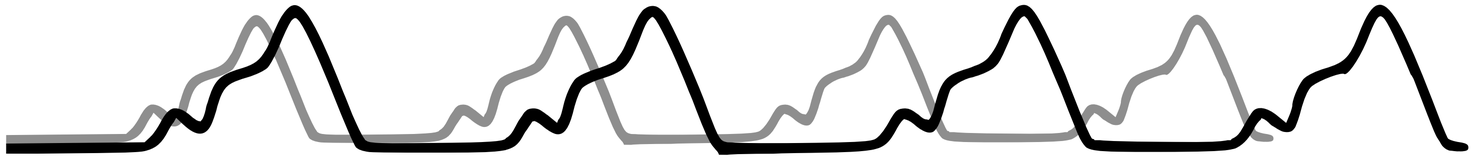


Pulses expected
from timing model

Pulsar timing arrays





Pulses expected
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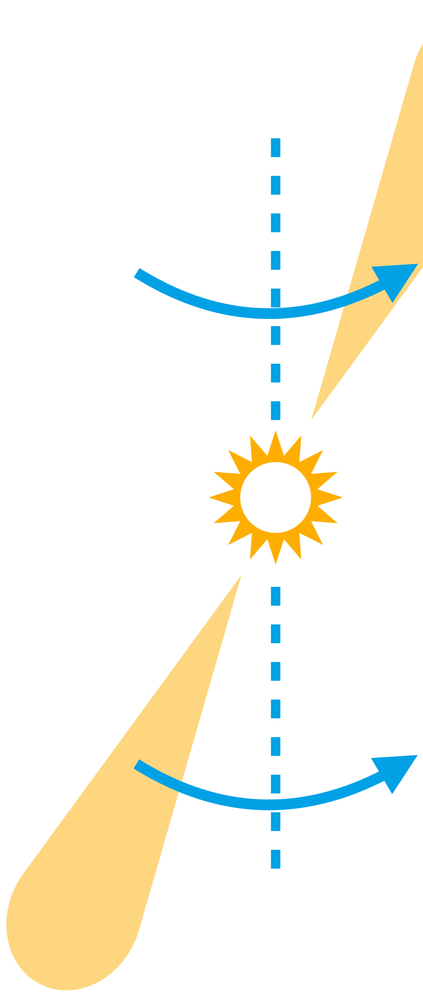
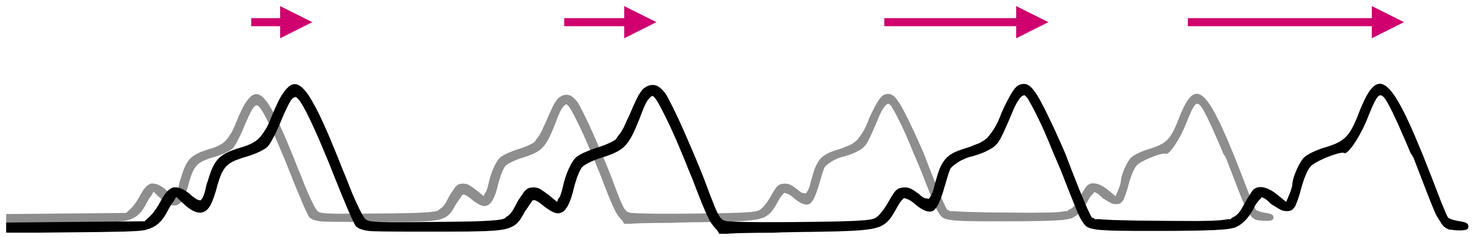
Pulses recorded by
radio telescopes

Pulsar timing arrays



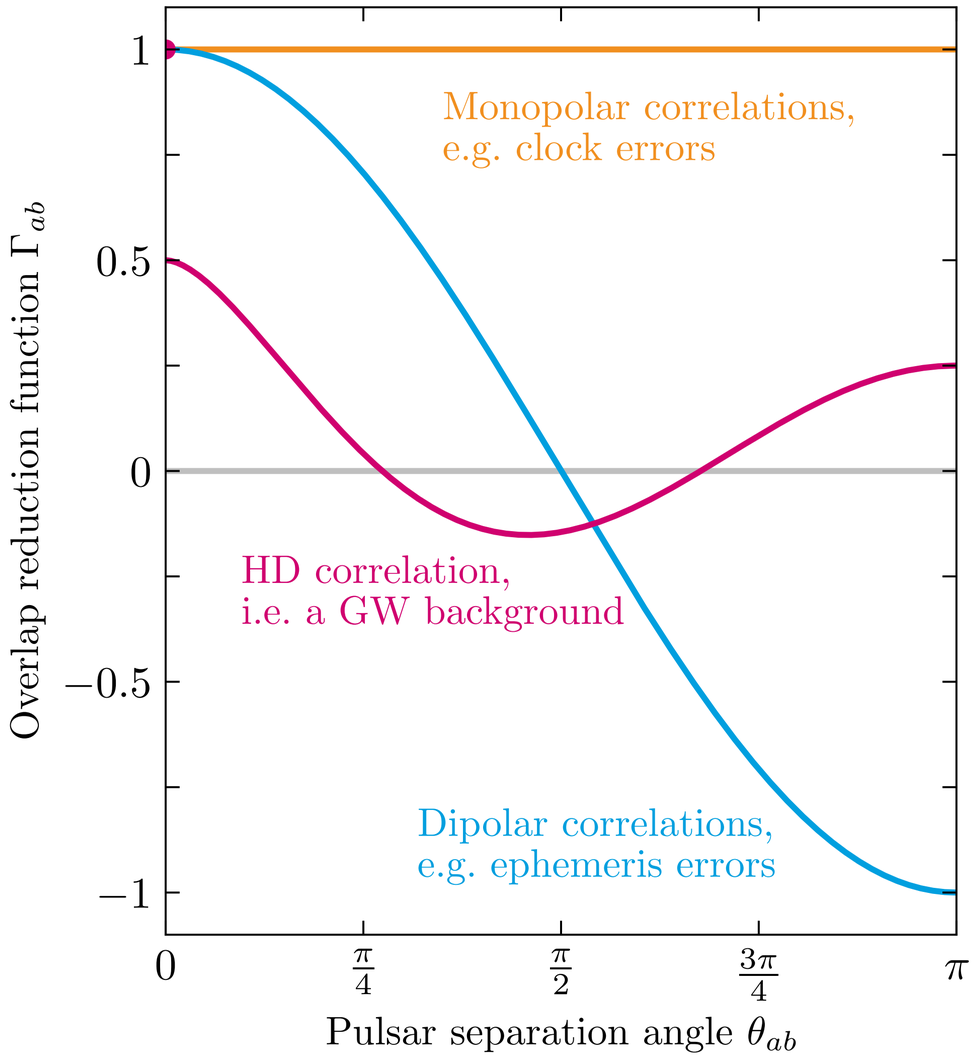
Timing residuals



Pulses expected from timing model

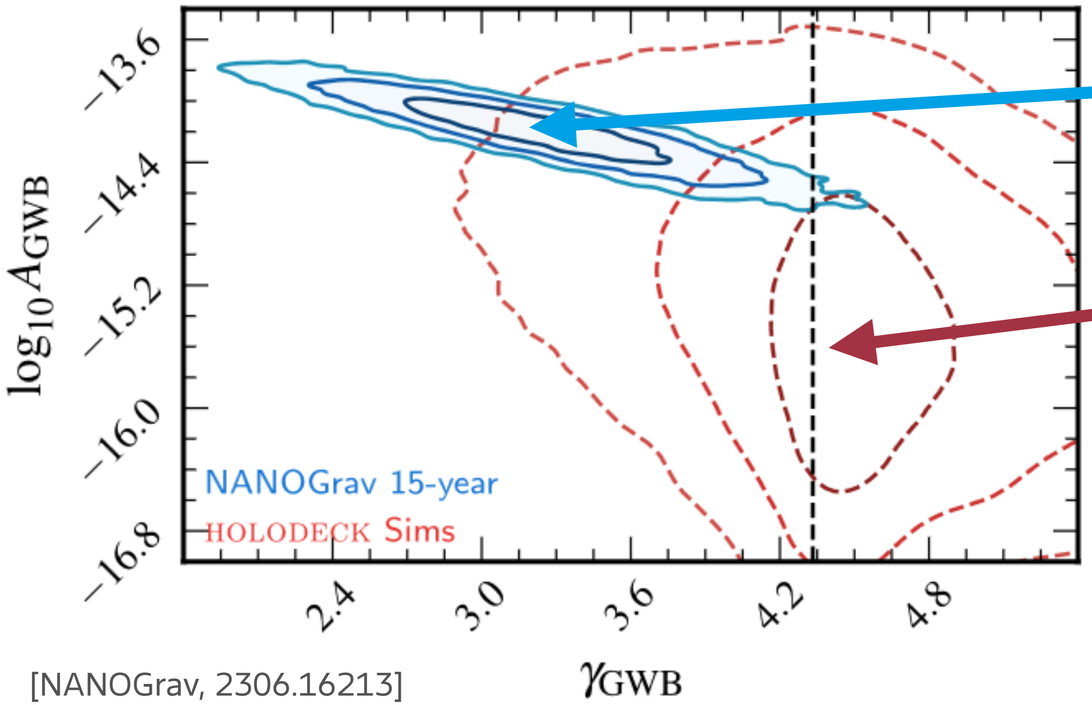
Pulses recorded by radio telescopes

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

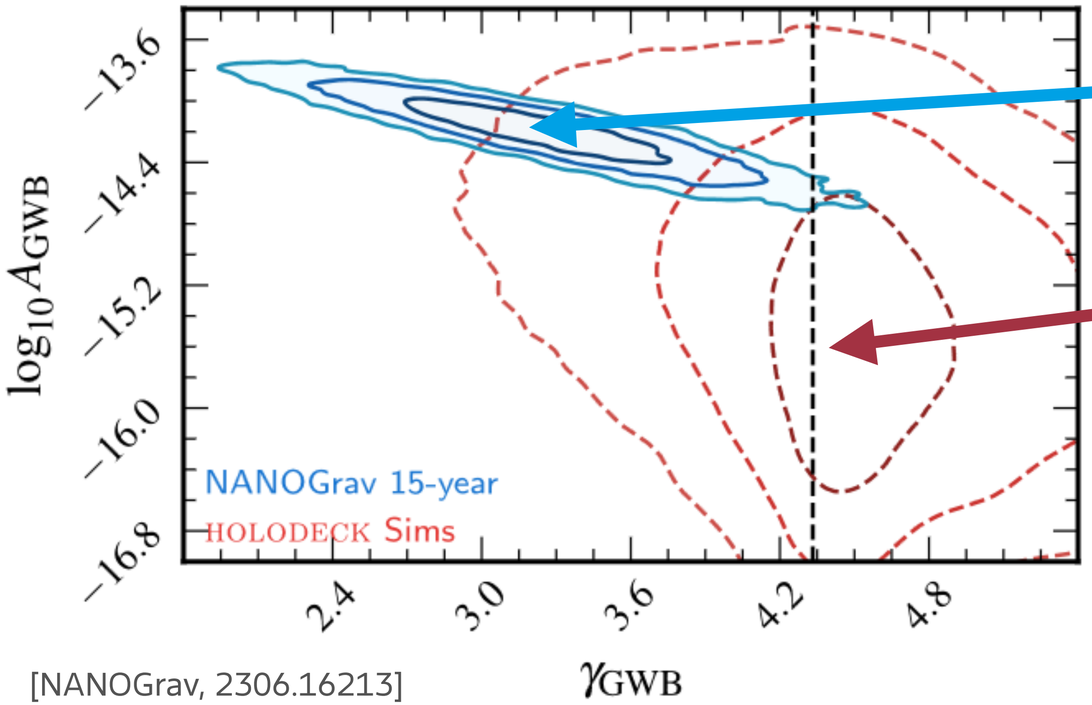


[NANOGrav, 2306.16213]

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



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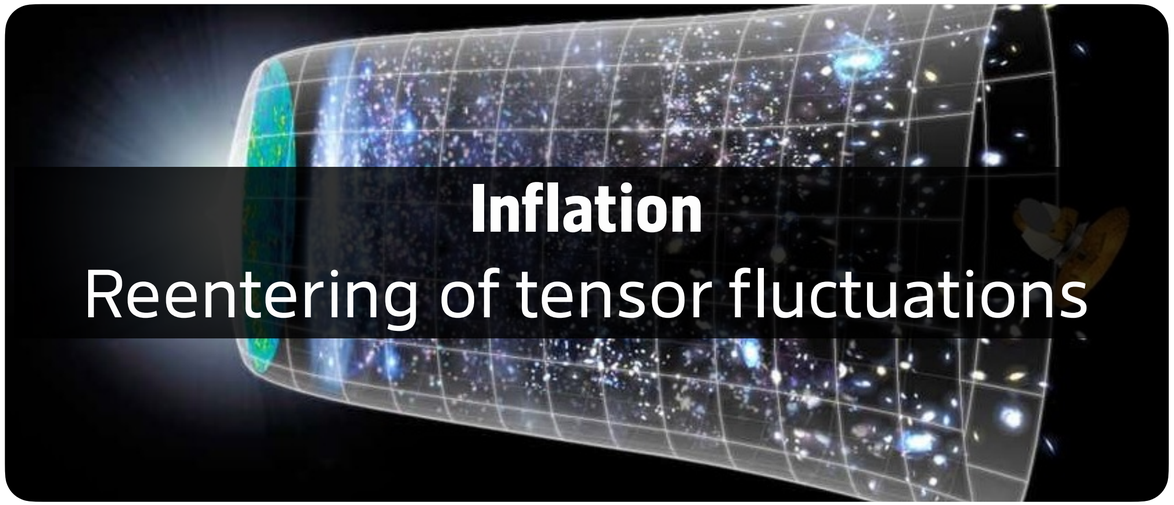
Are there other signal sources?

Possible cosmological sources of the PTA signal



Inflation

Reentering of tensor fluctuations

Phase transitions

Connection to dark matter?

Topological defects

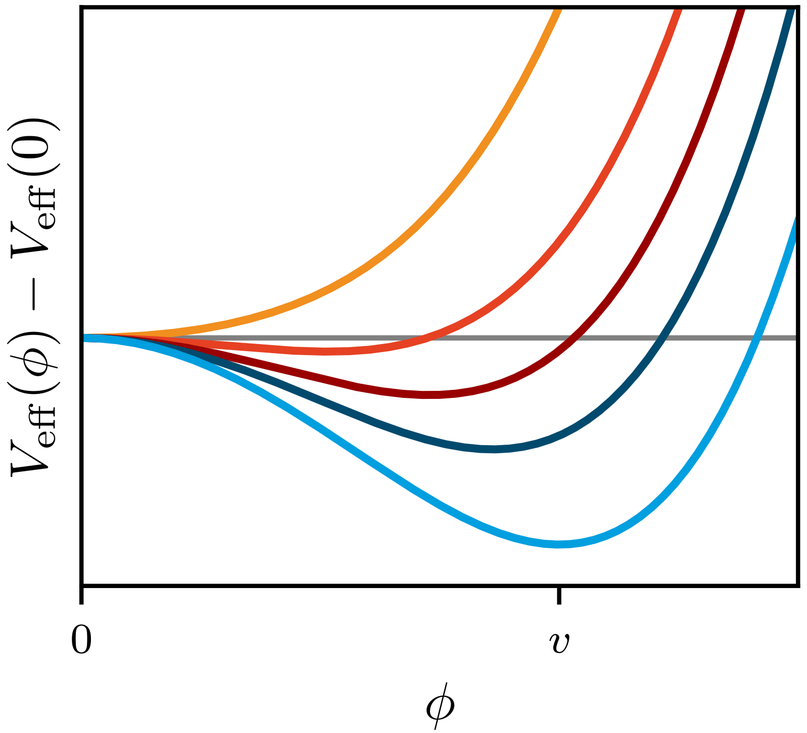
Cosmic strings and domain walls

Primordial black holes

But only if they are clustered

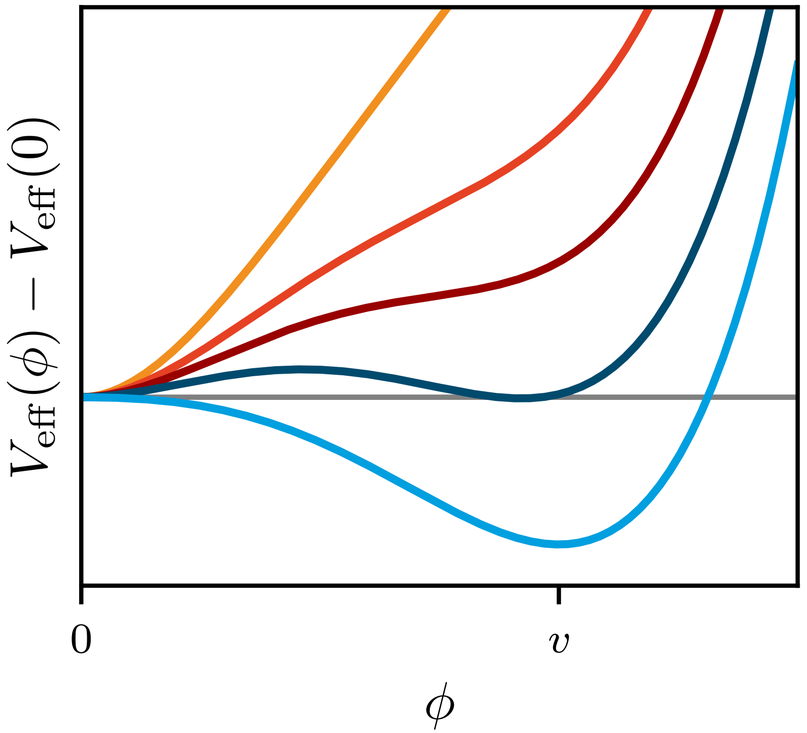
First-order phase transitions vs. cross-overs

Cross-over phase transition



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

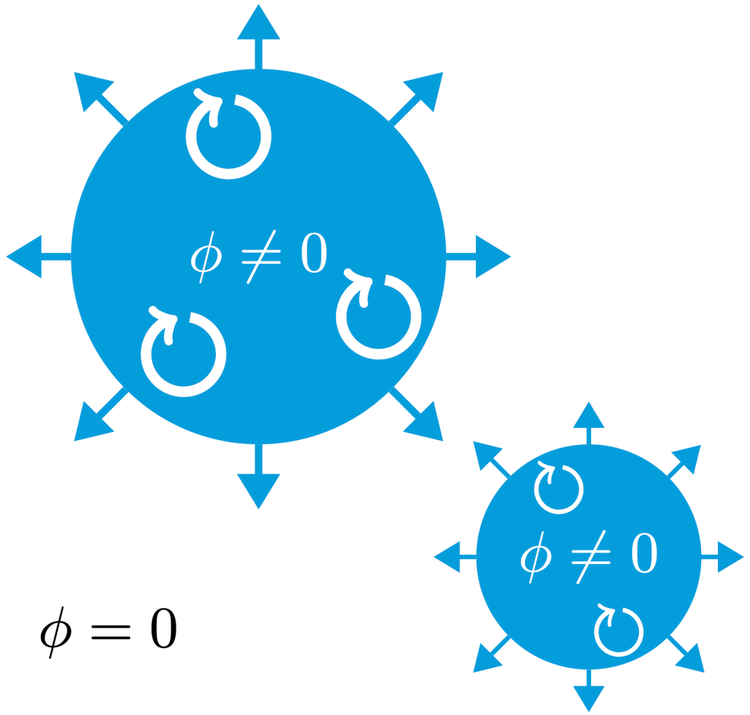
First-order phase transition

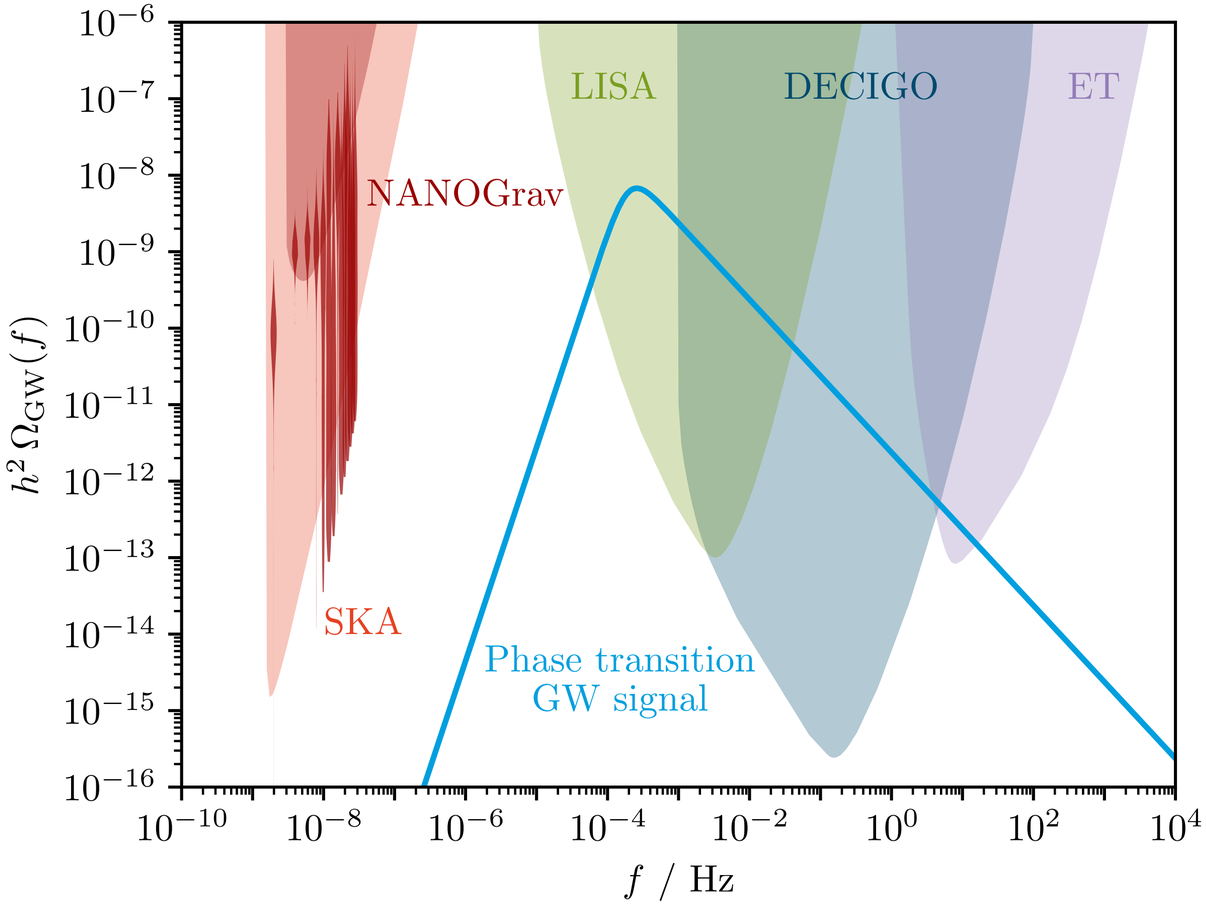


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy / its action.

First-order phase transitions produce GWs

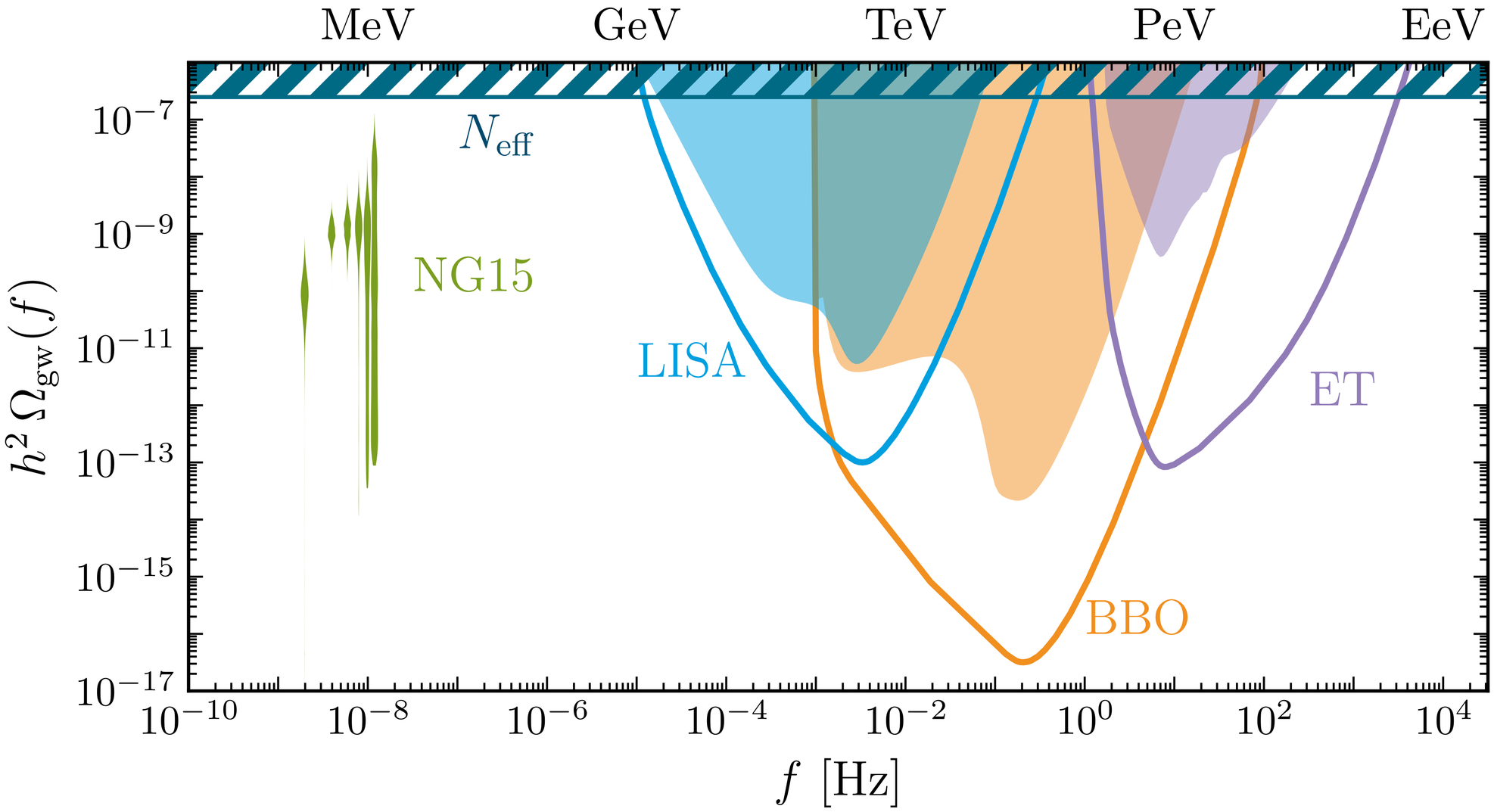
Bubbles of the new phase nucleate, collide and perturb the plasma…



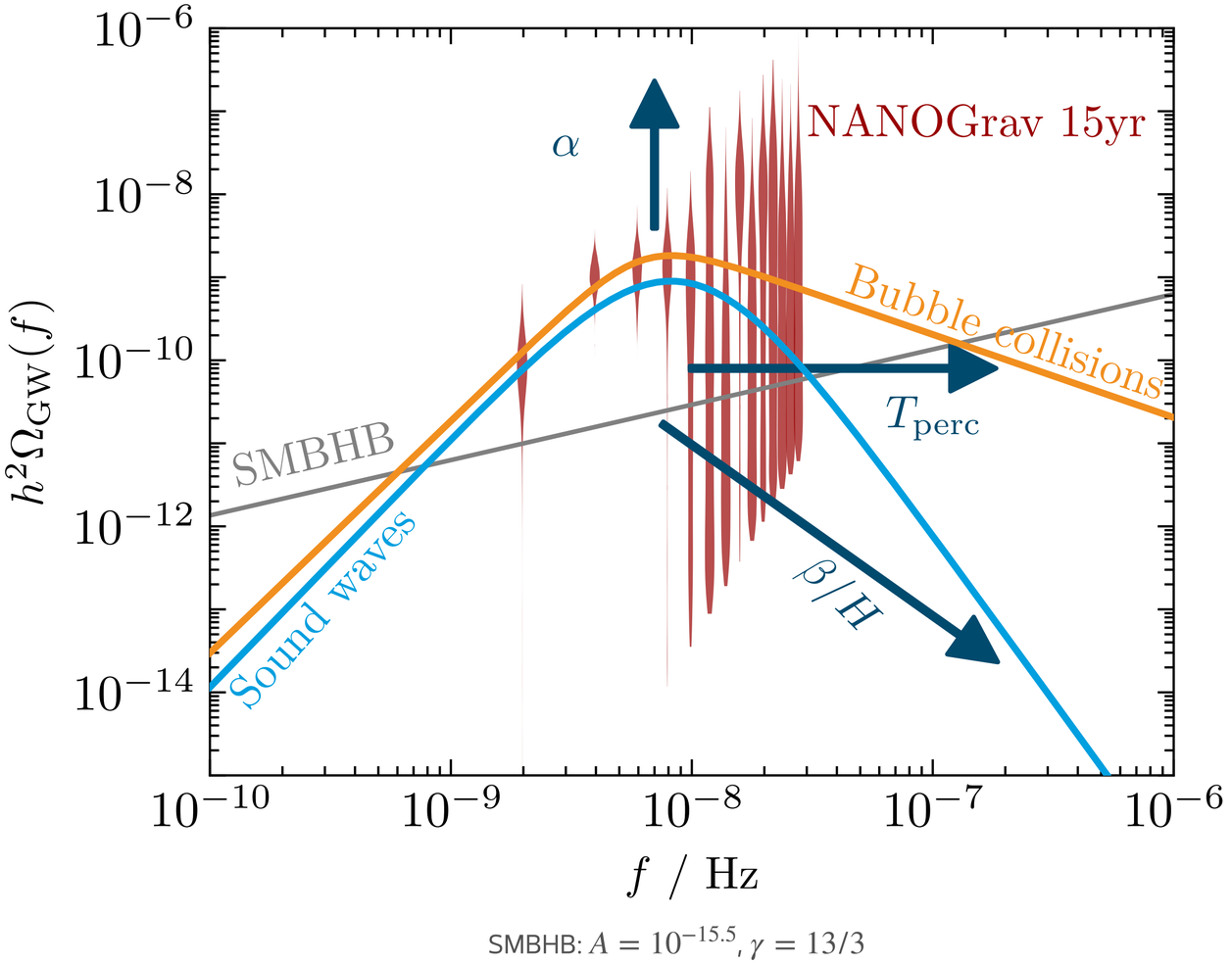


… giving rise to an observable stochastic gravitational wave background.

Sensitivity for cosmic GW backgrounds



Parametrization of the GW signal



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

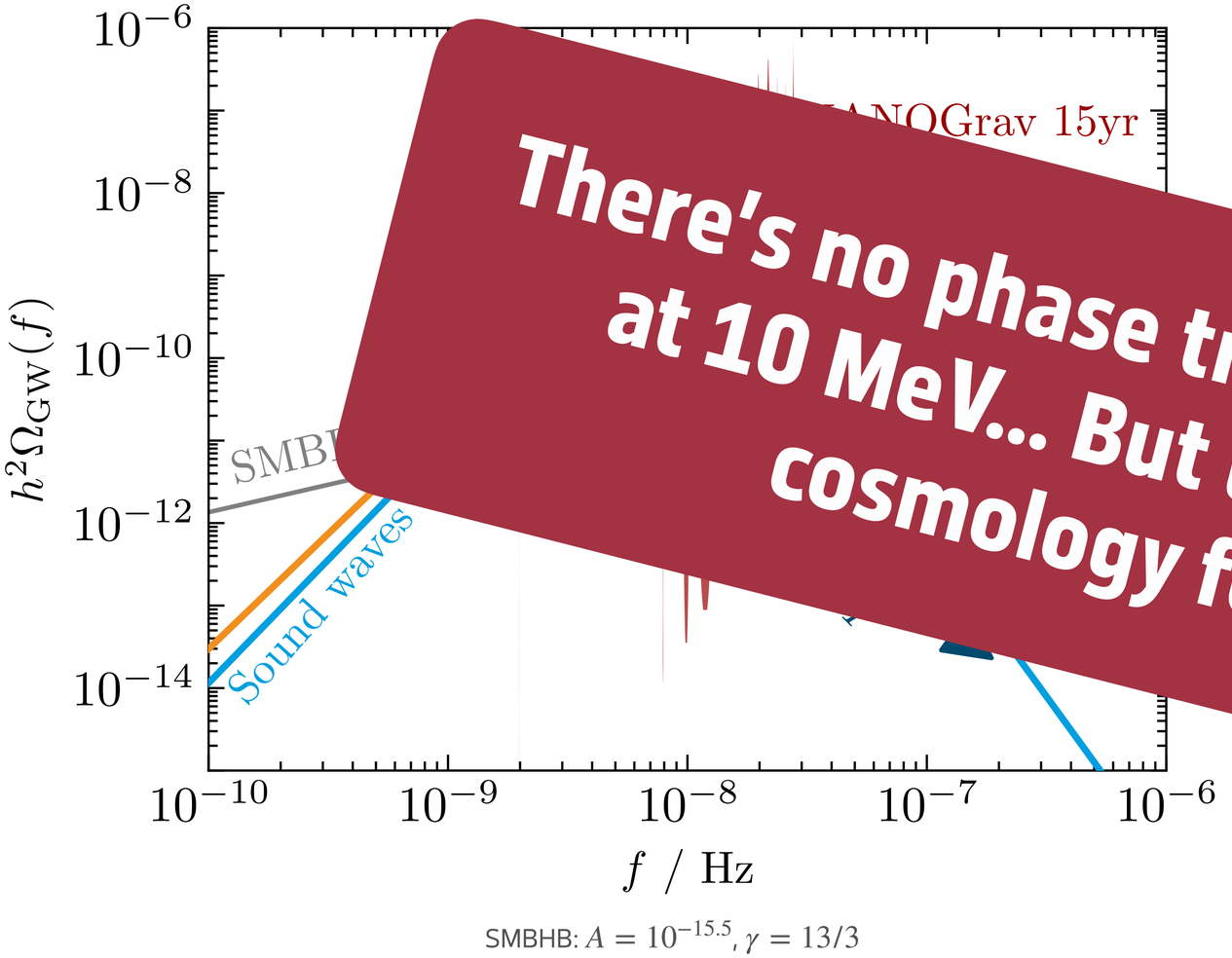
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6} \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{H}{\beta}\right)^{1,2} \mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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



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

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

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

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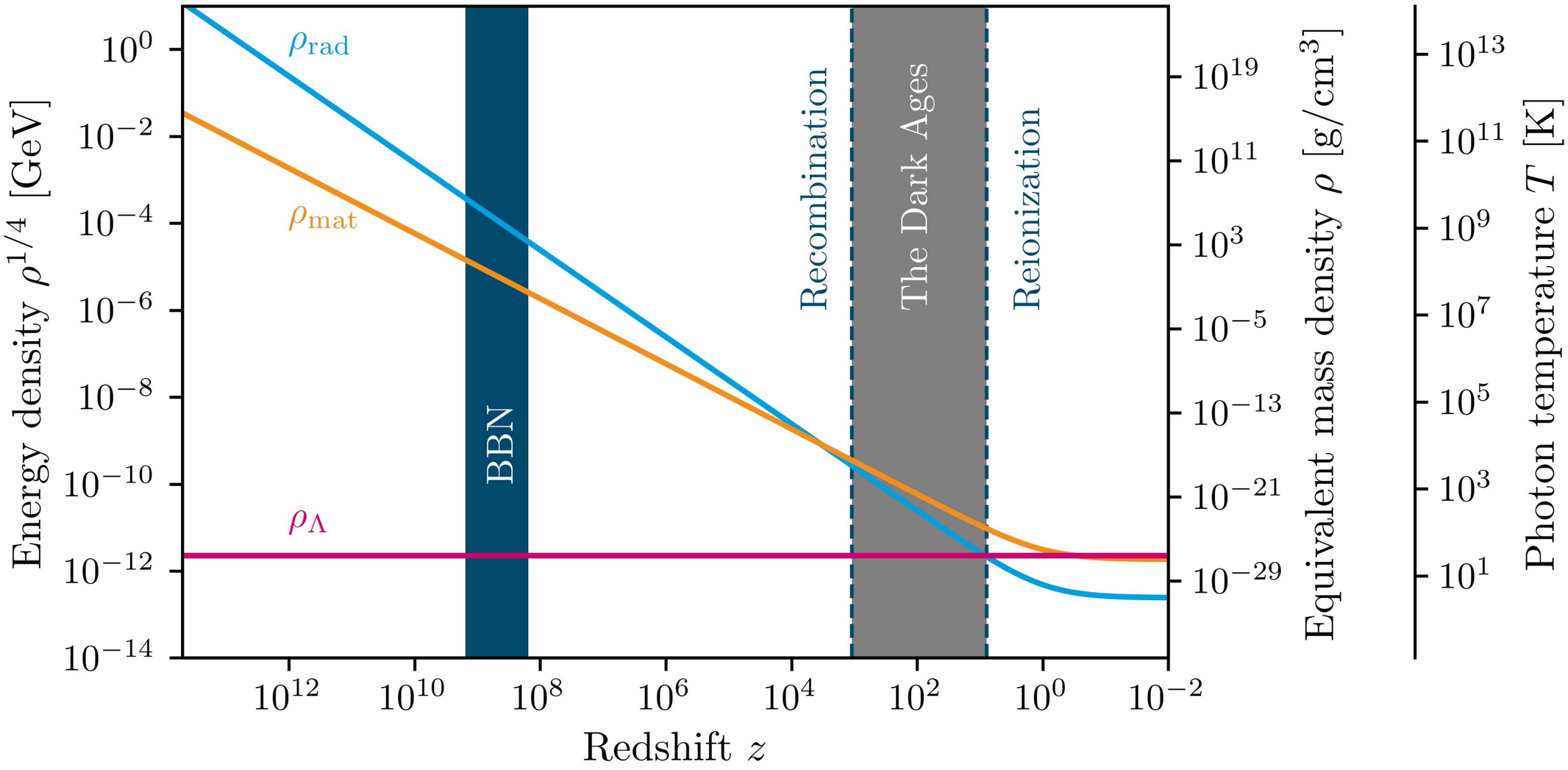
$\alpha \gtrsim 1$

$\frac{\beta}{H} \gtrsim 10$

- Percolat… $T \approx 10\,{\rm MeV}$

A brief history of time



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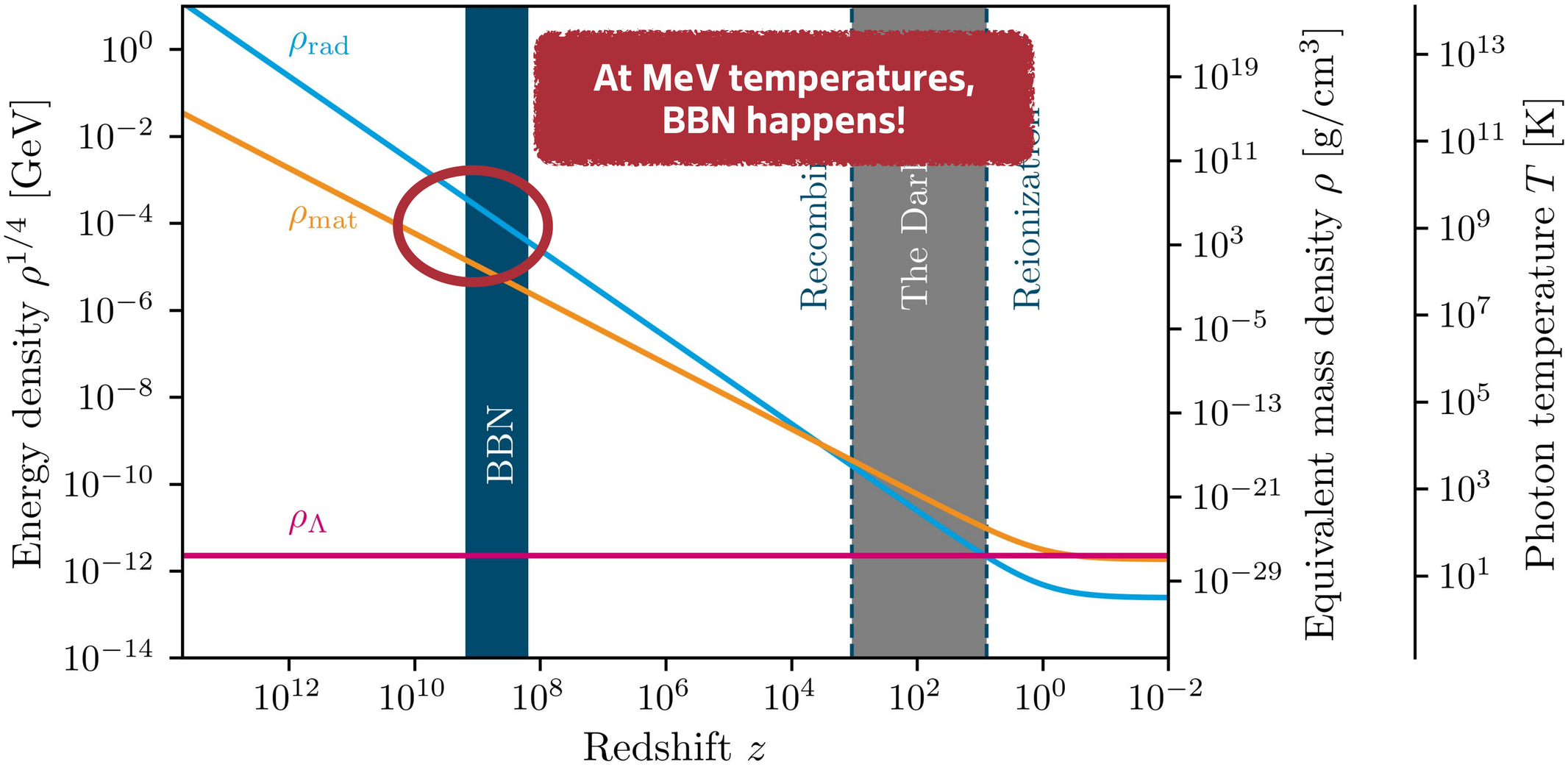
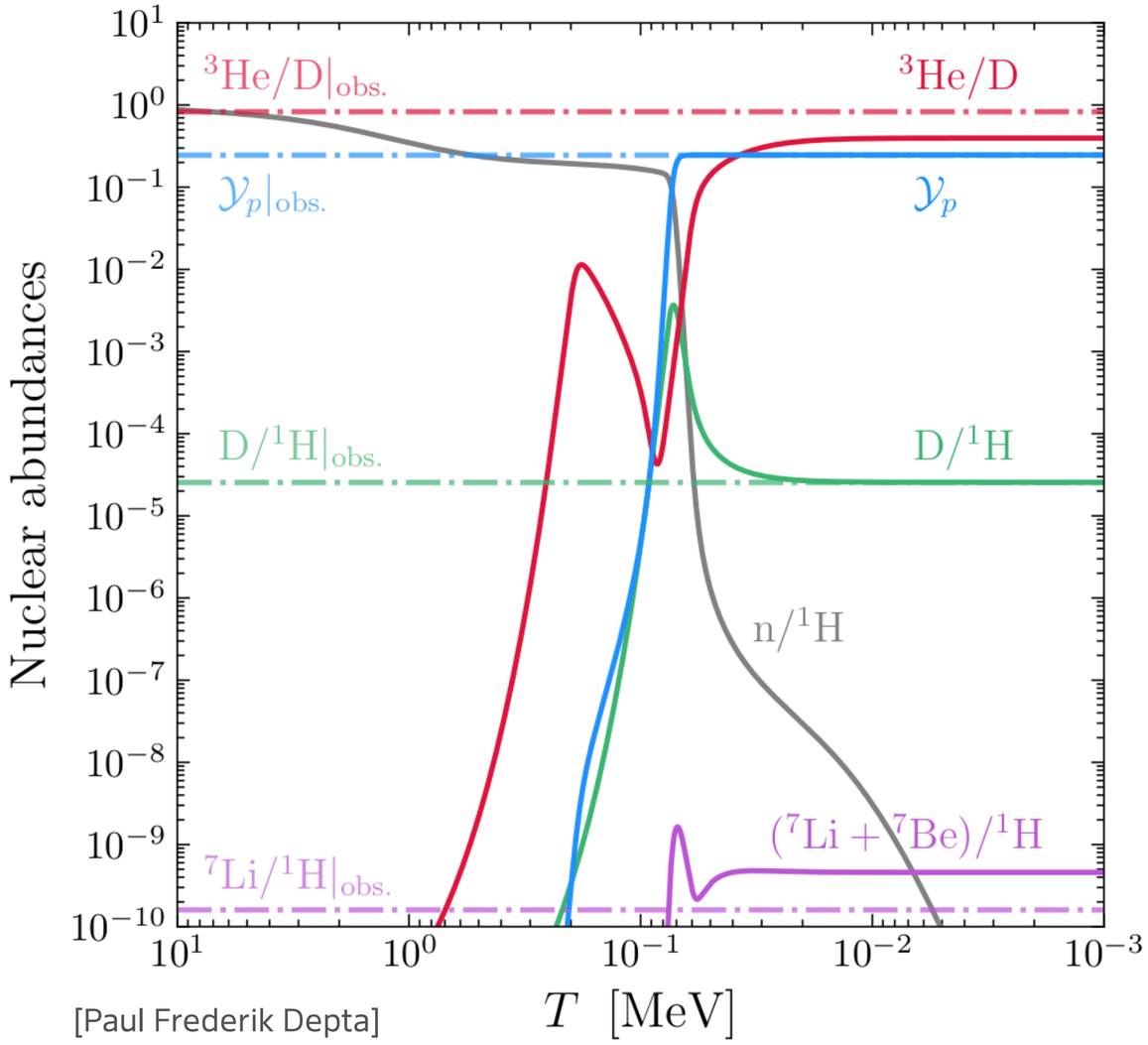


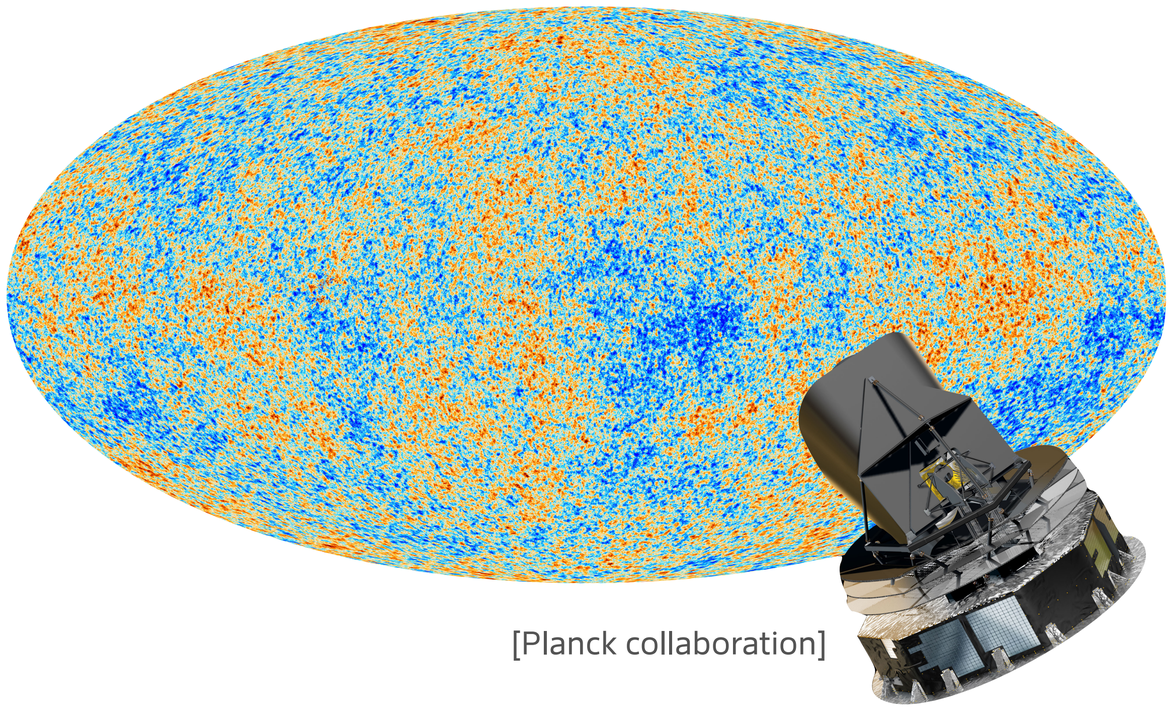
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

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

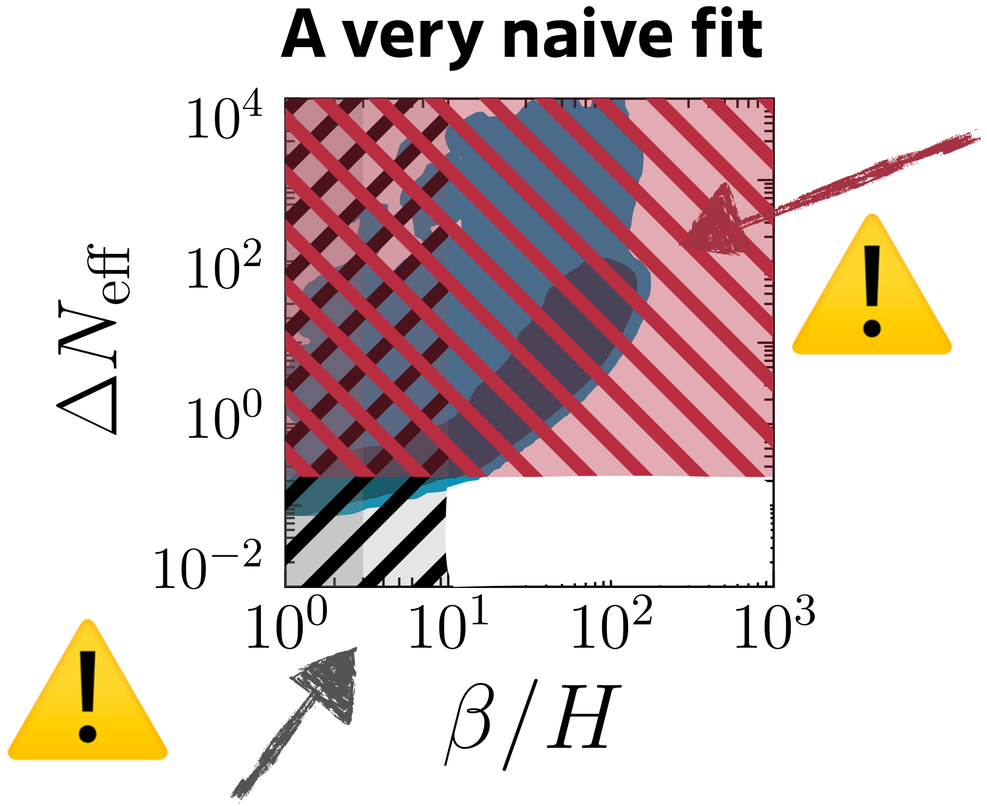
Big Bang Nucleosynthesis and the CMB

[Planck collaboration]

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

- Observation of primordial
- ances in
- h
- 41
- $N_{\rm eff} = 2.99 \pm 0.17$
- 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

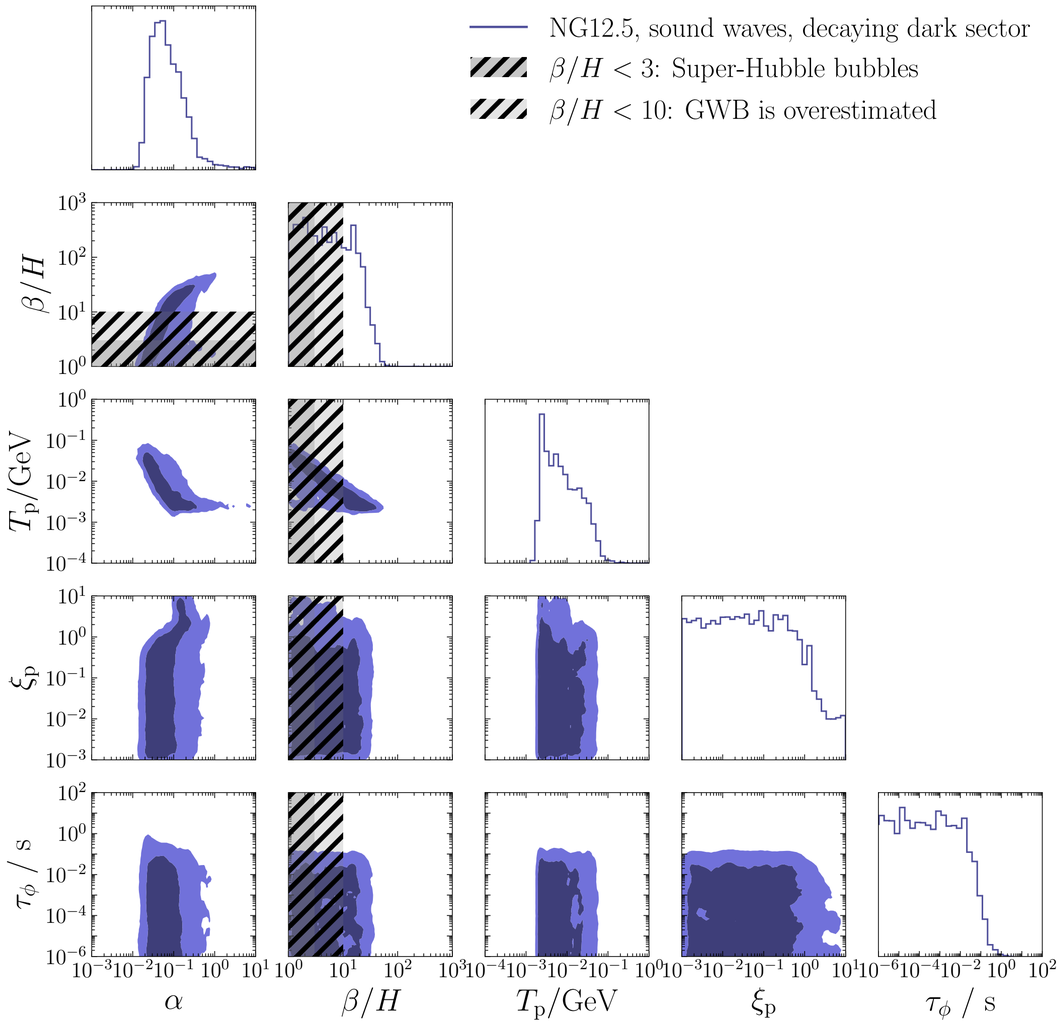
$$\Delta N_{\rm eff} \gg 0.22$$

Giant „Hubble“ bubble sizes would be needed, 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

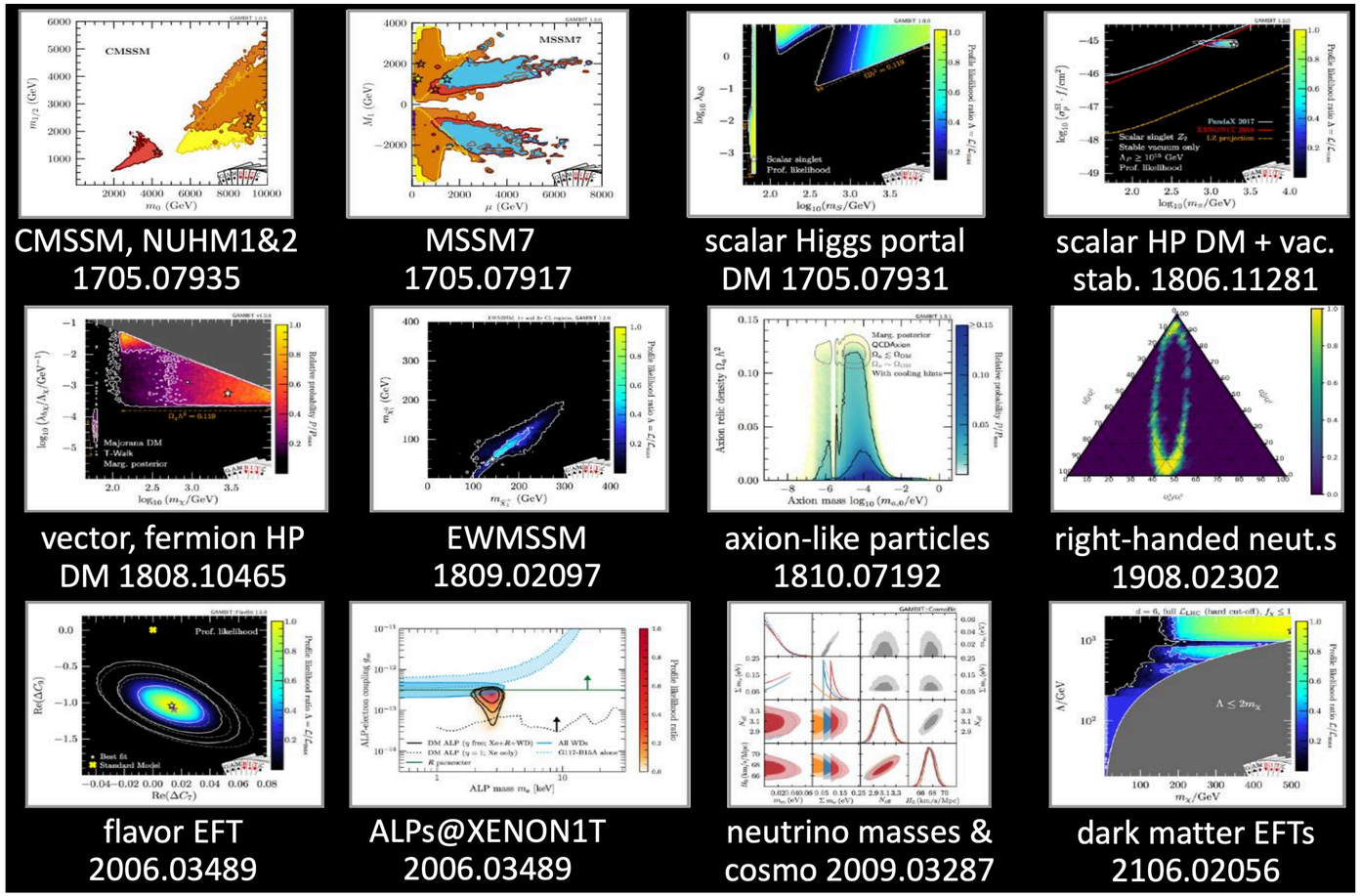
[Chen+, 2502.01024]

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



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

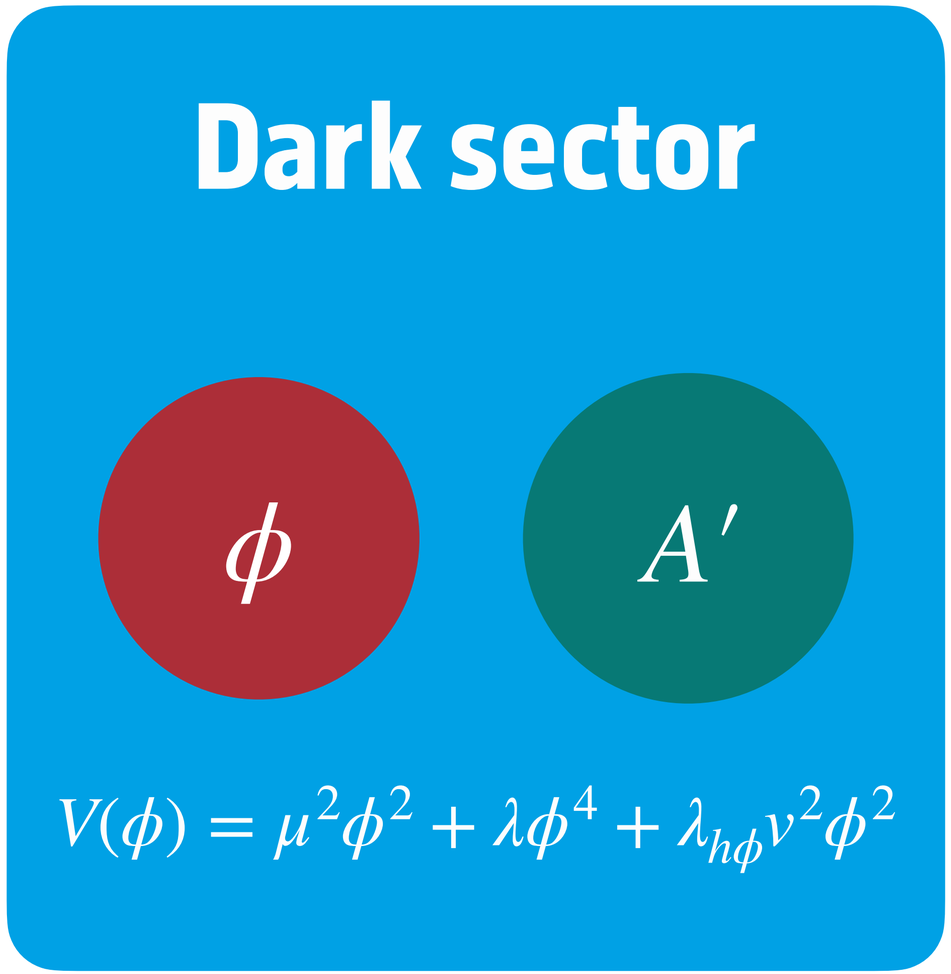
vector, fermion HP DM 1808.10465 | EWMSSM 1809.02097 | axion-like particles 1810.07192 | right-handed neut.s 1908.02302

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

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

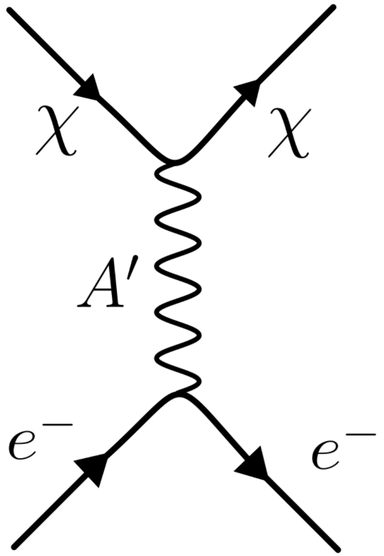
ϕ

A'

χ

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

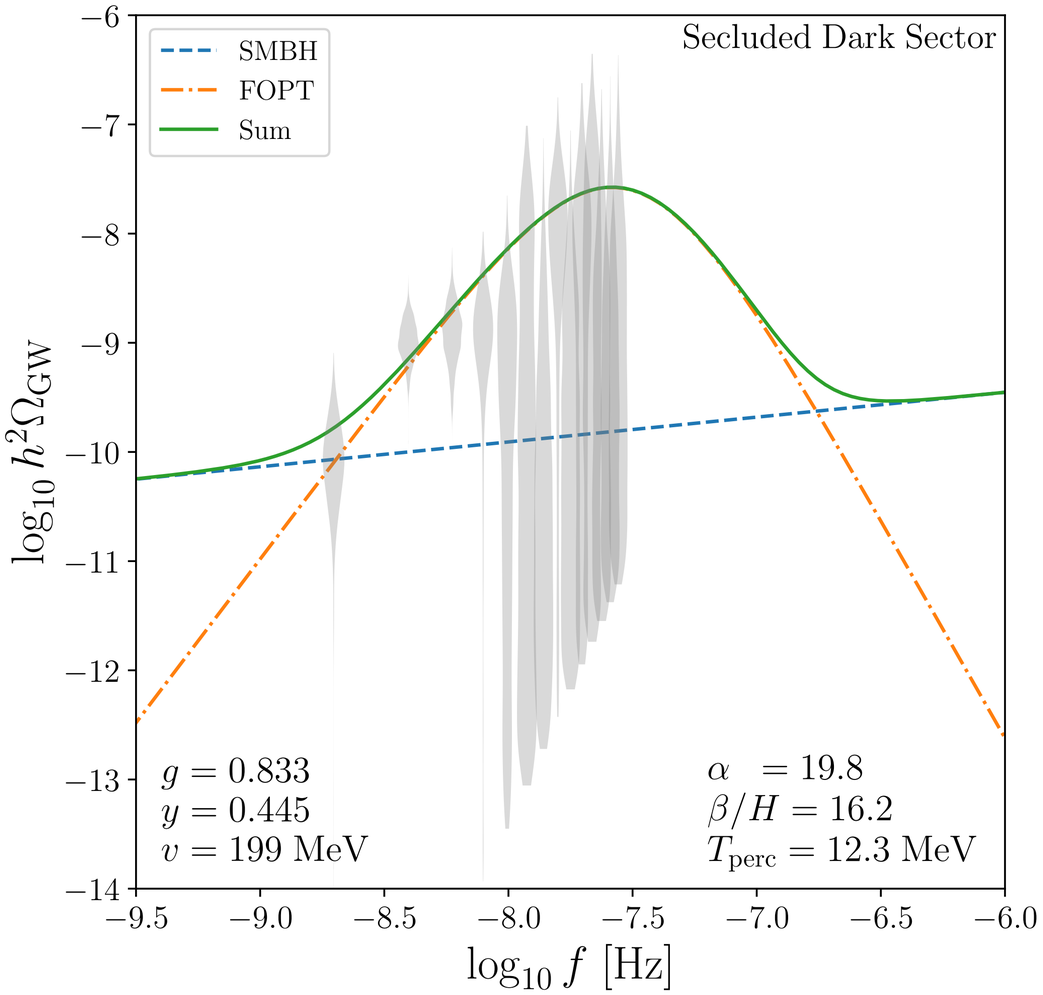
Kinetic mixing κ



Thermalization becomes easy!

SM

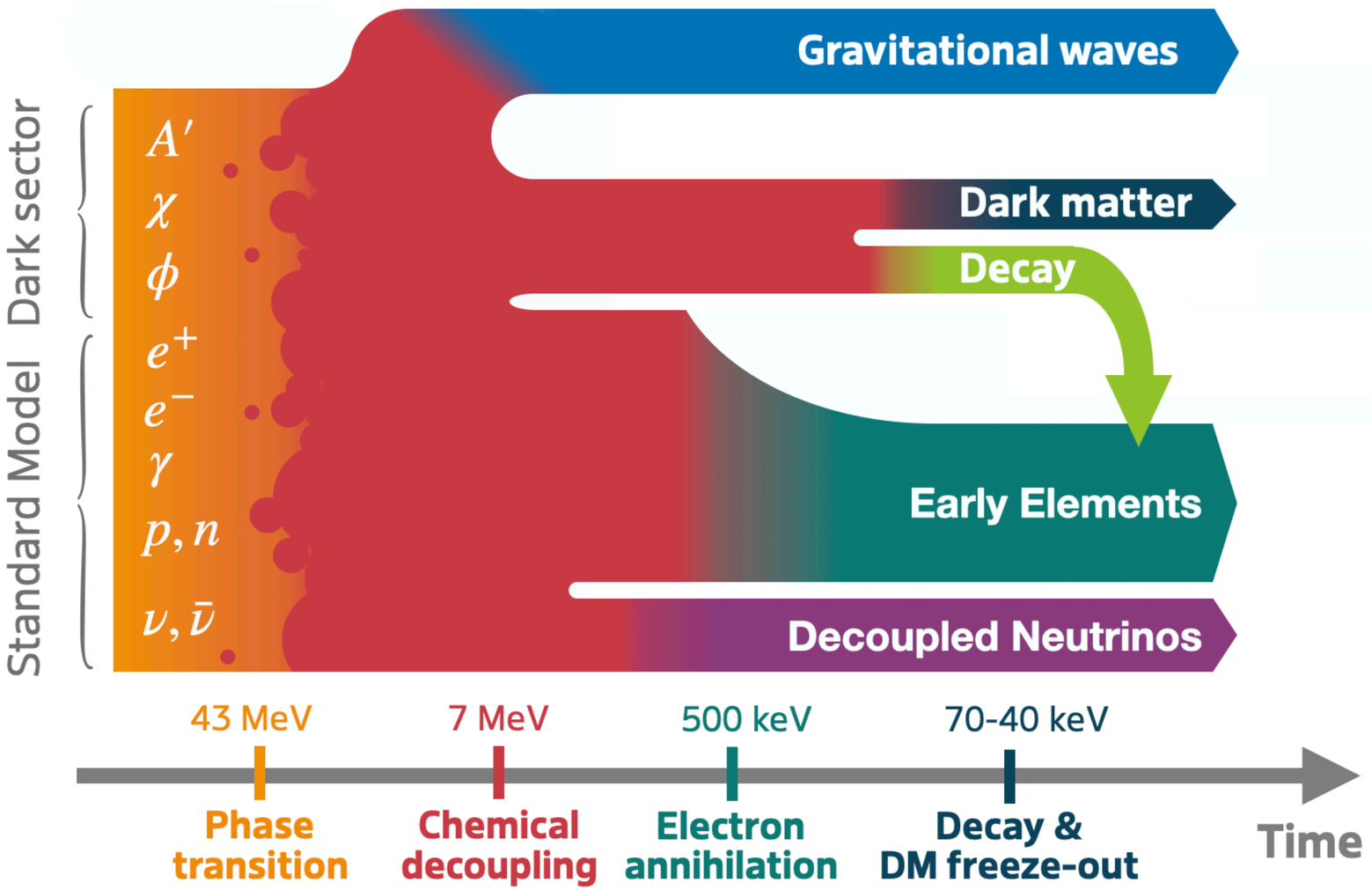
All constraints can be circumvented



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

What needs to happen before BBN?

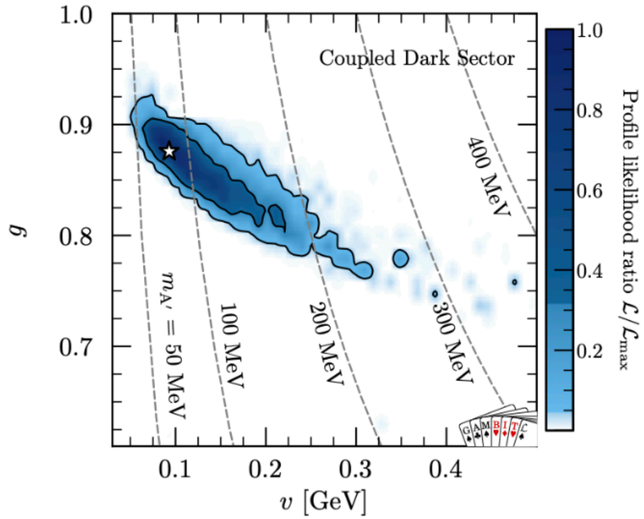


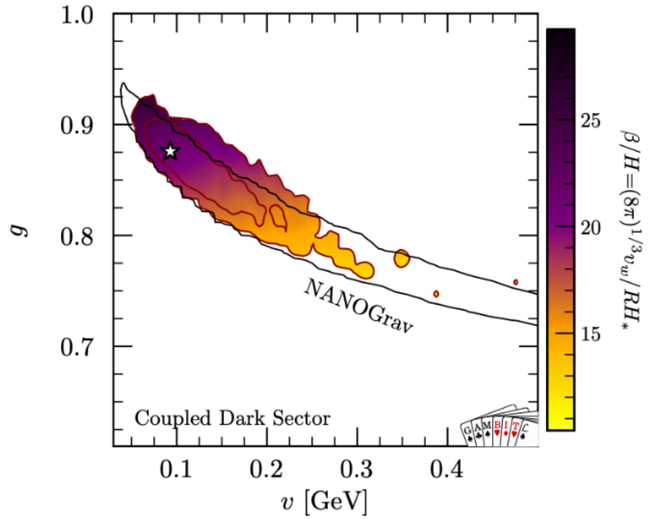
What if κ is not enough for thermalization?

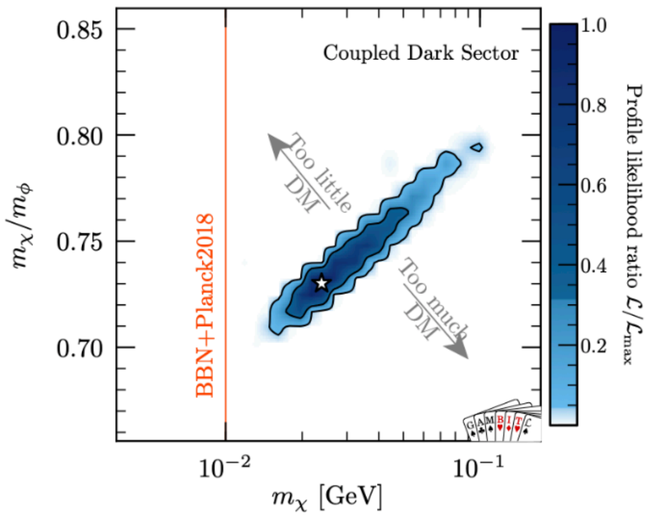
The found parameter region around $\kappa \simeq 10^{-4}$ is small and could be ruled out soon!

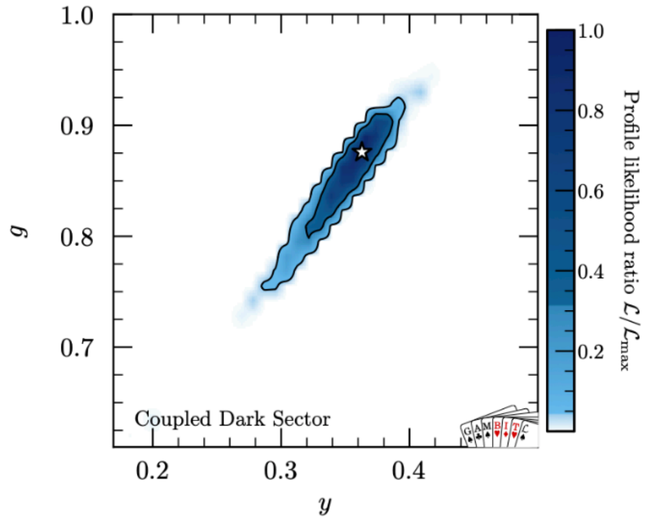
Separate analysis incl. dimension-six operator allowing $\phi \to \bar{e}e$ decays before BBN shows: Even $\kappa = 0$ is viable!

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

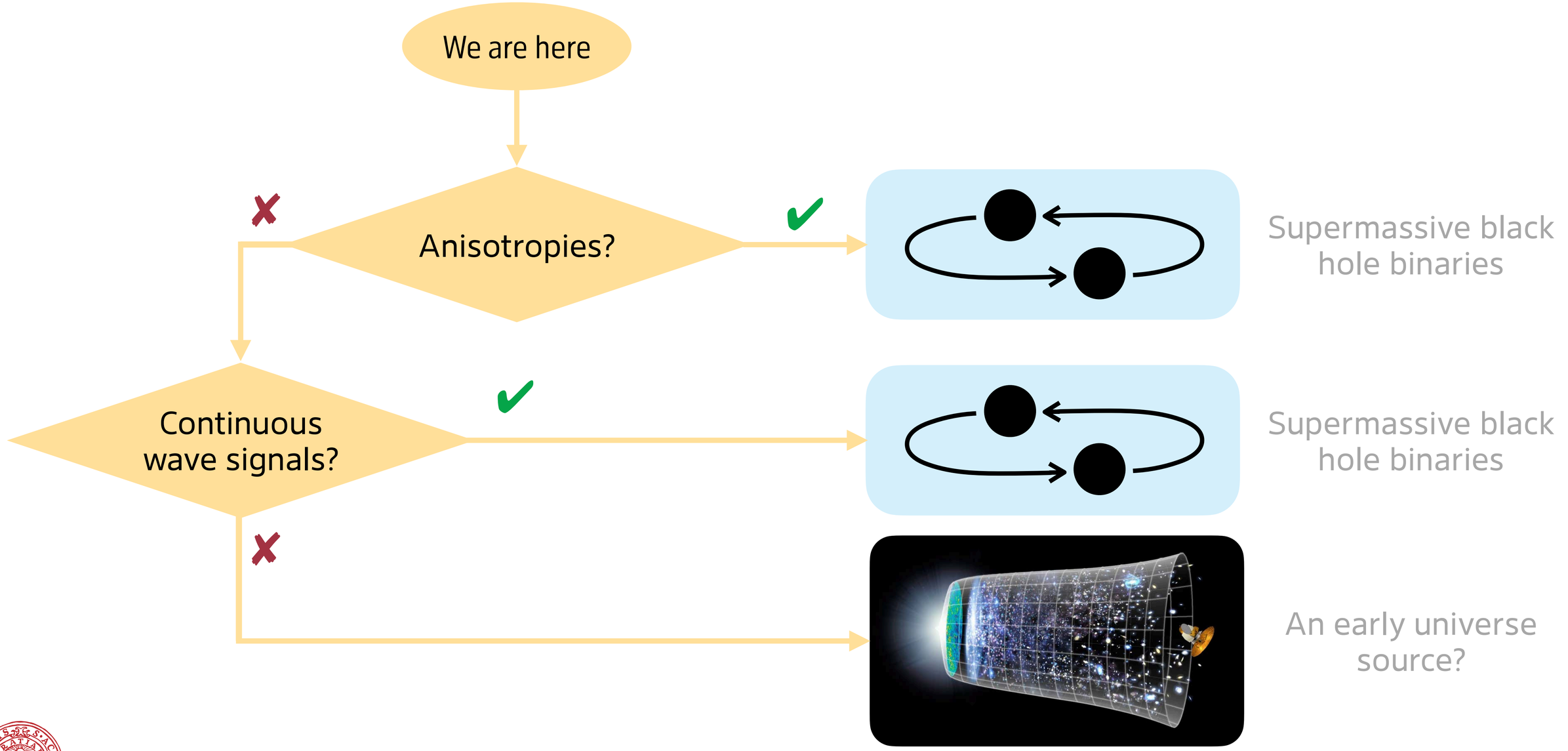








Quo vadis pulsar timing?



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?

Backup slides