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

PLANCK conference, 28.05.2025

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 **2502.19478**

UPPSALA UNIVERSITET

At Last, There's
A globe-spa
Astronomers detect 'cosmic bass note' of gravitational waves
Sound comes from the merging of supermassive black holes across the universe, according to scientists
Scientists 'hear' cosmic hum from gravitational waves
Gravitational
Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe
Scientists have observed for the first time the faint ripples caused by the motion of holes that are gently stretching and squeezing everything in the universe
The New York Times
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Galax
Space
Gravitational wave
at the center of the M
Scientists r
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holes
The Cosmos Is Thrumming With Gravitational Waves, Astronomers Find
Radio telescopes around the world picked up a telltale hum reverberating across the cosmos, most likely from supermassive black holes merging in the early universe.
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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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Astro
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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
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Monster gravitational
spotted for first
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The results are
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Universe.
Physics
Gravitational waves produce a background hum across the whole universe
After decades of searching, astronomers have found a distinctive pattern of light, from spinning stars called pulsars, that suggests huge gravitational waves are creating gentle ripples in space-time across the universe


There's a new signal to explain!
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Physics
Gravitational waves produce a background hum across the whole universe
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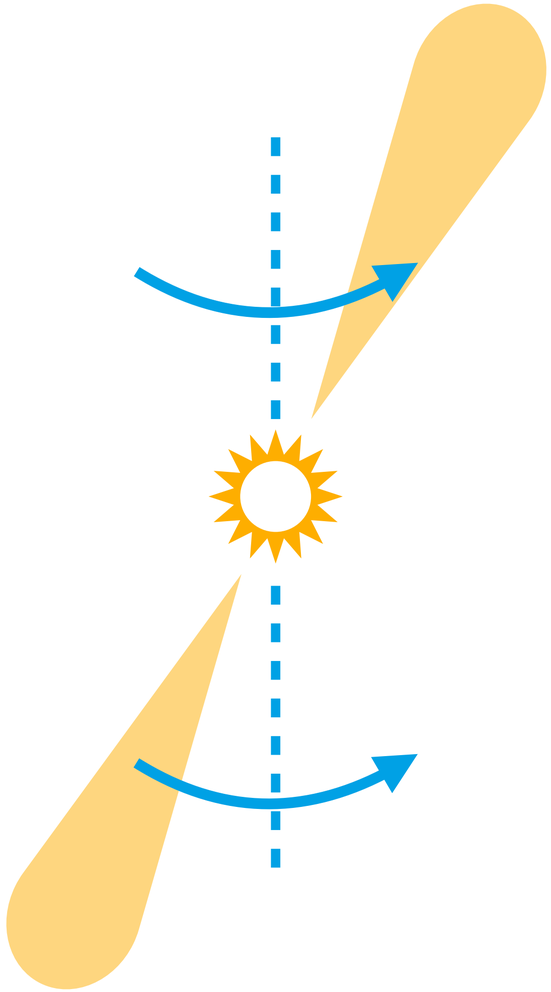
Pulsar timing arrays



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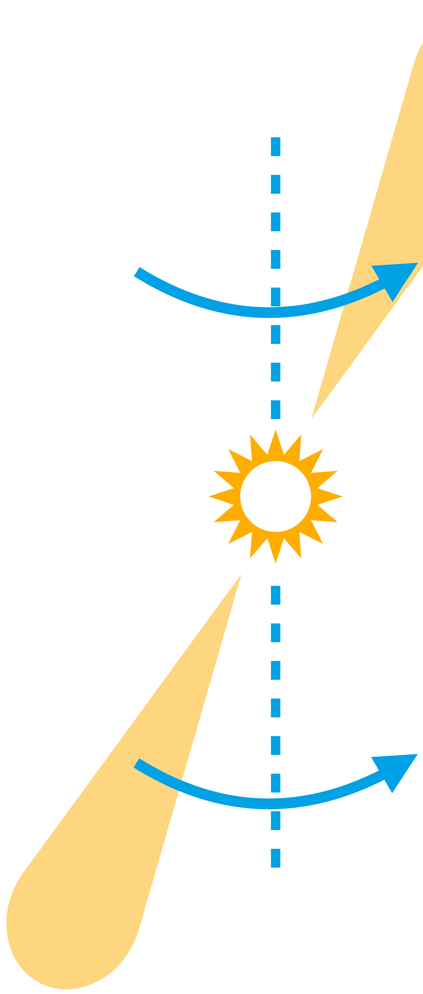
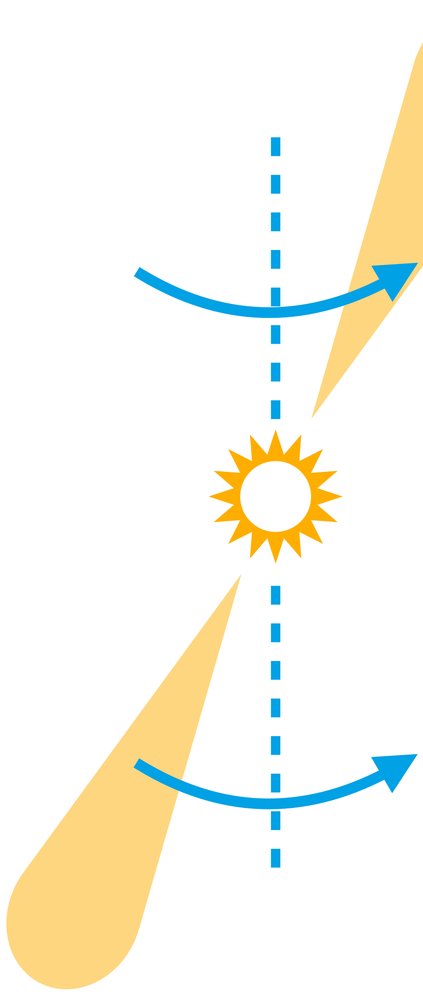
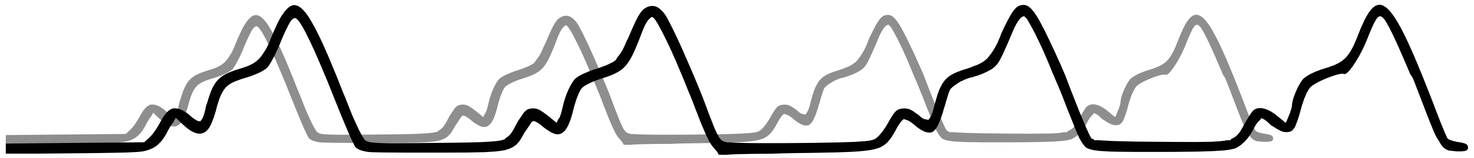


Pulses expected
from timing model

Pulsar timing arrays





Pulses expected
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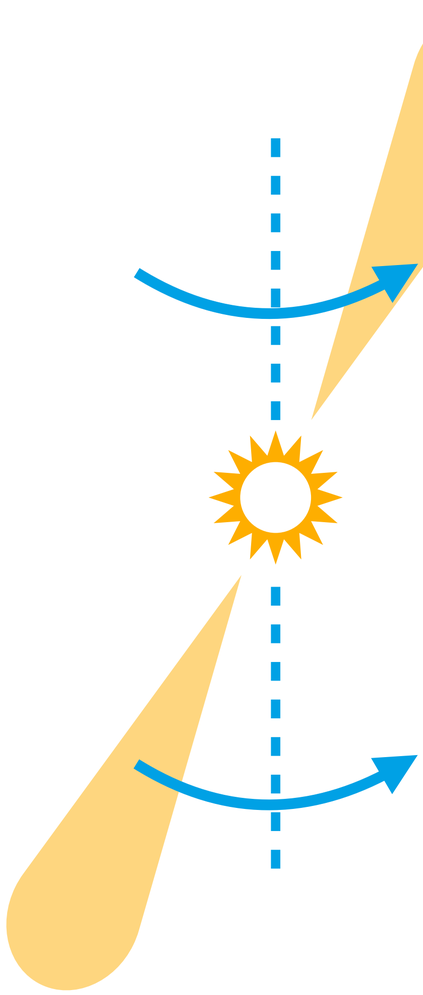
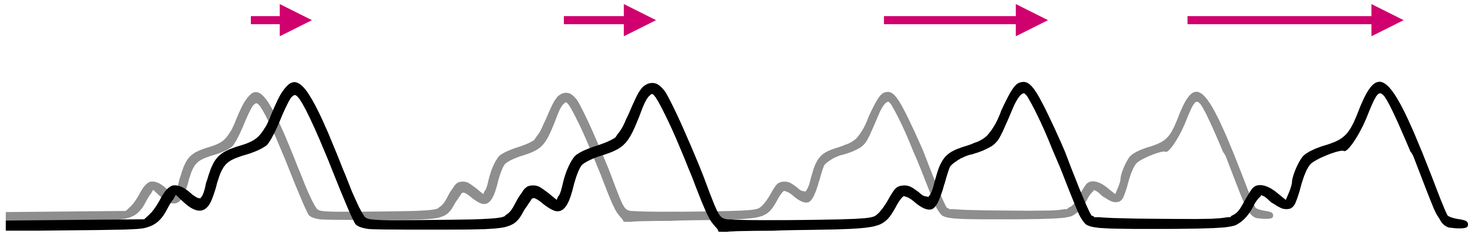
Pulses recorded by
radio telescopes

Pulsar timing arrays



Timing residuals



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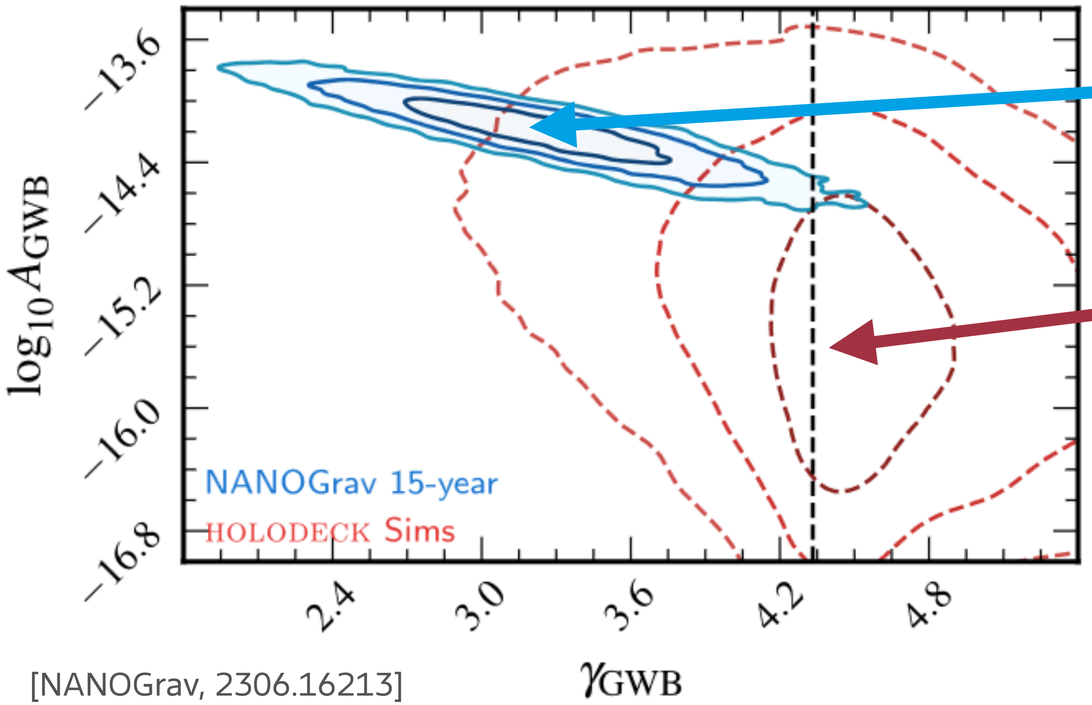
Pulses recorded by radio telescopes

Merging supermassive black holes



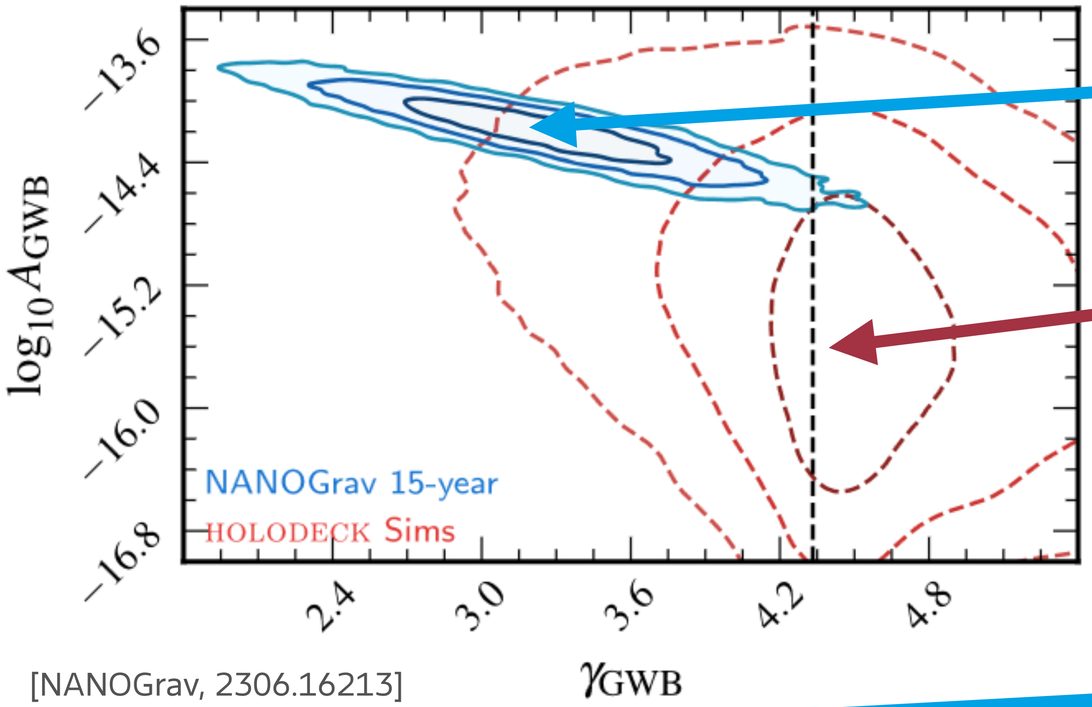
[NANOGrav, 2306.16213]

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. Recently backed up by N-Body simulations.

Chen+ [2502.01024]

Merging supermassive black holes



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

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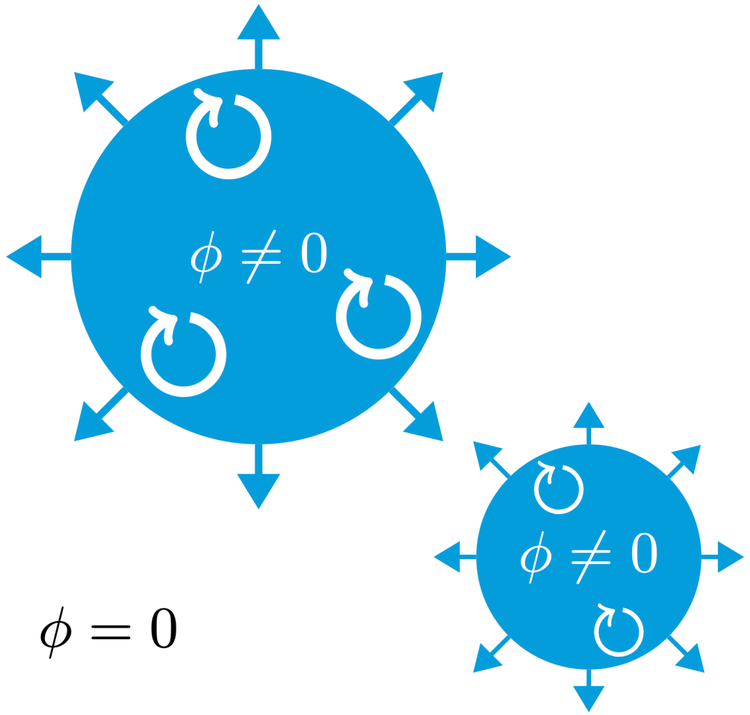
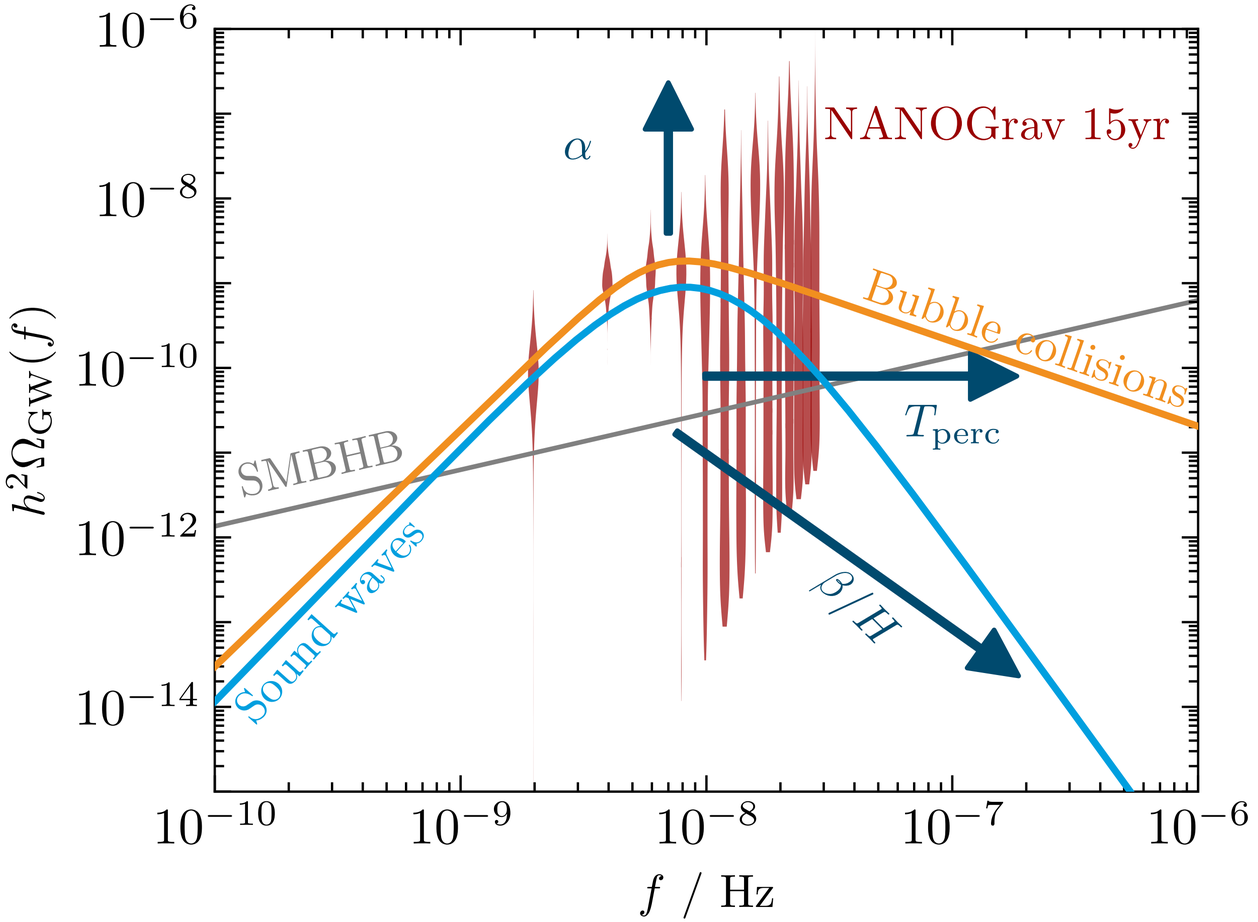
Chen+ [2502.01024]

The observed PTA background is probably not only due to black hole mergers!
Are there other signal sources?

First-order phase transitions produce GWs

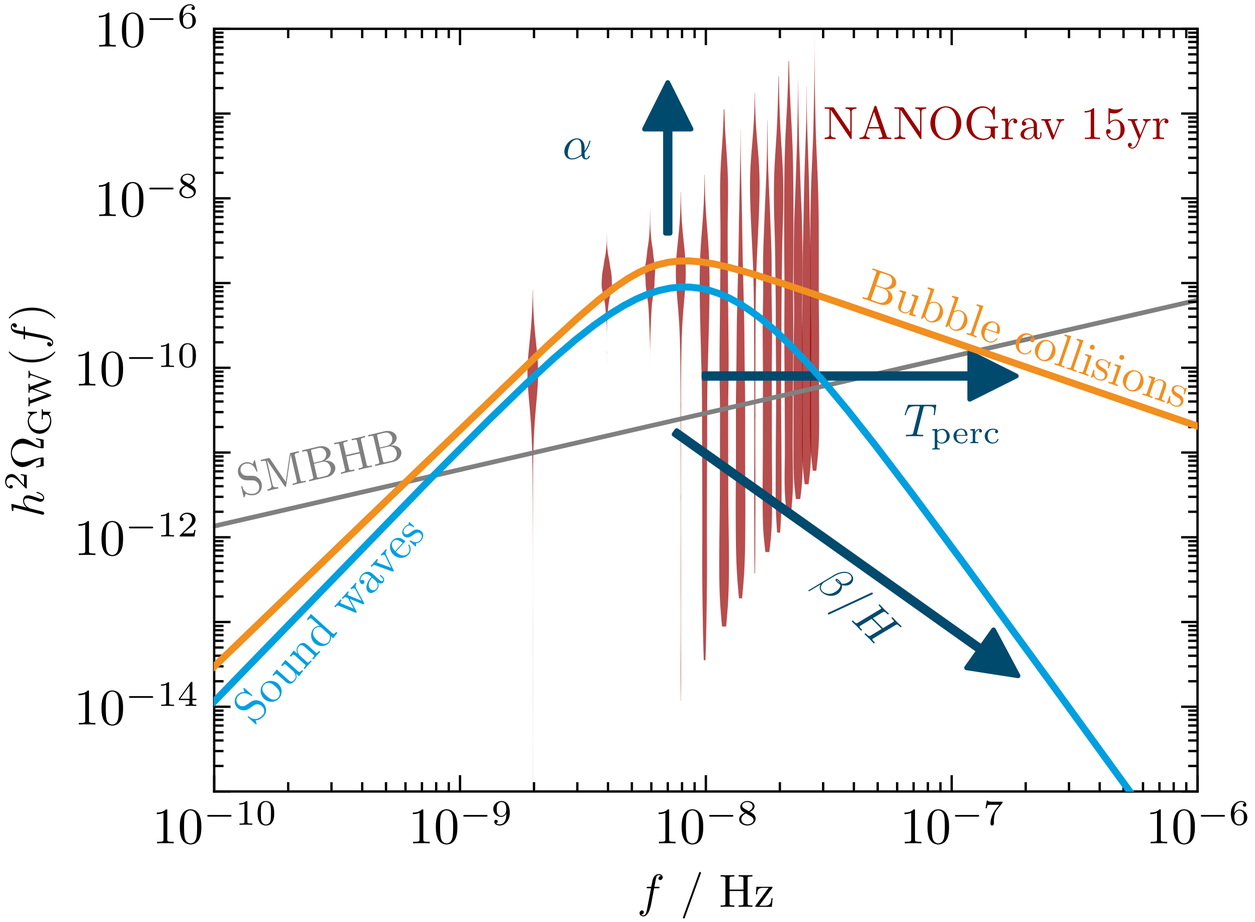
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

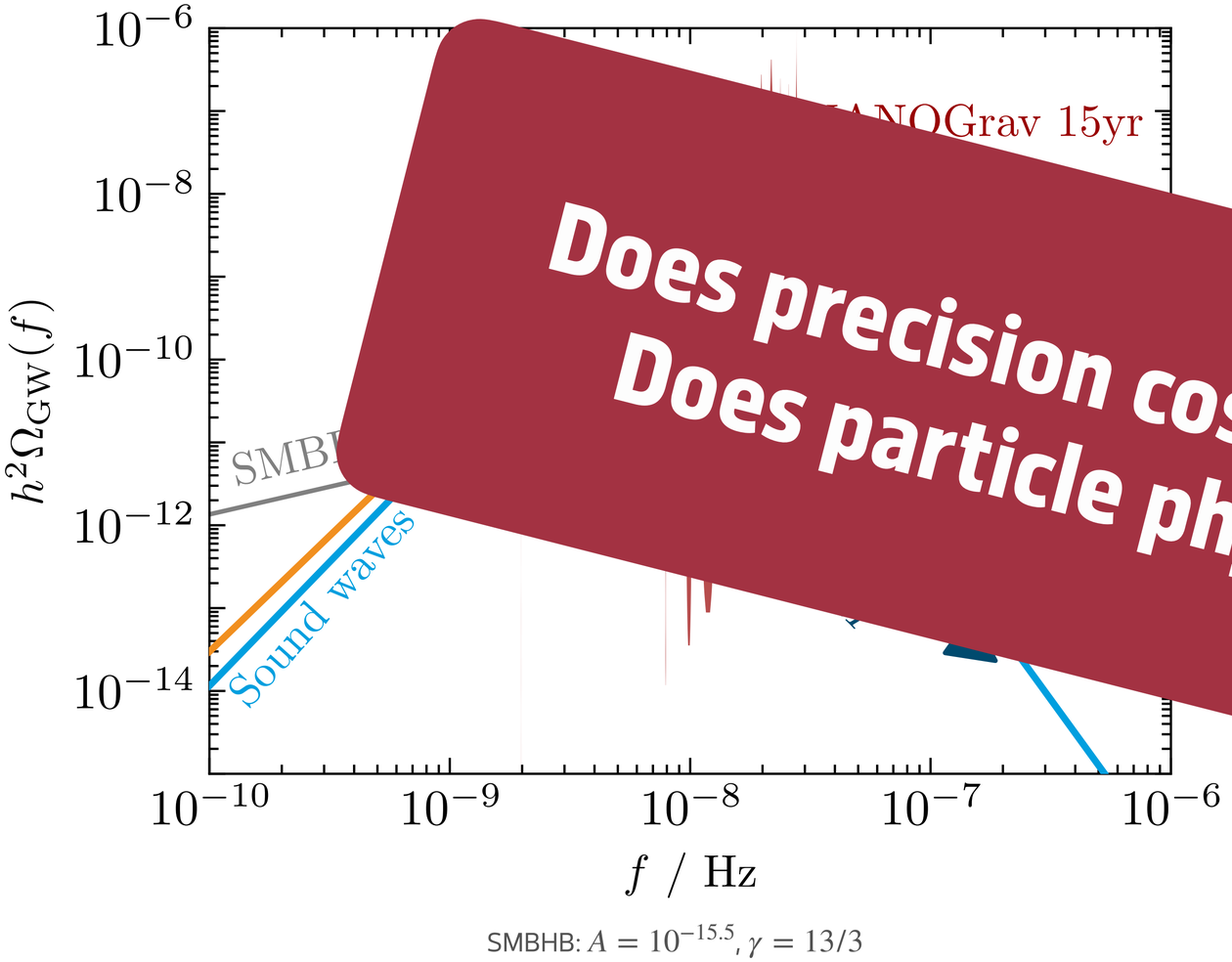
To fit the new pulsar timing data:

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

But: There's no strong first-order phase transition in the SM at 10 MeV… So:

A transition in a dark sector? Is it related to the origin of dark matter?

Parametrization of the GW signal



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

Does precision cosmology allow it?
Does particle physics allow it?

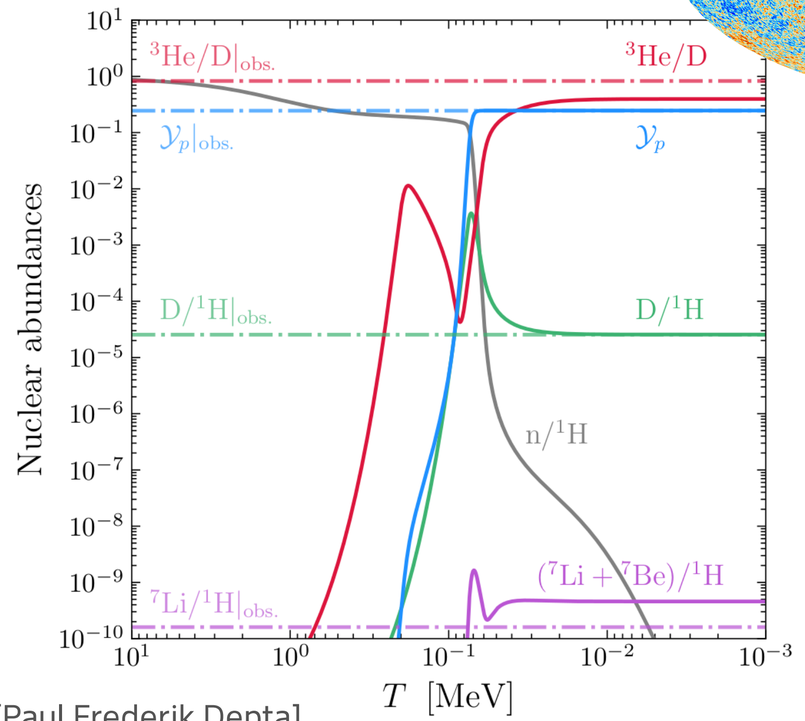
To fit the new pulsar timing data:

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

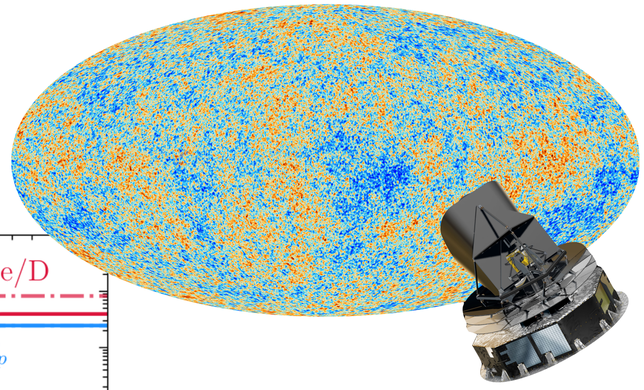
-order
at 10 MeV...

A transition in a d sector? Is it related to the origin of dark matter?

Big Bang Nucleosynthesis and the CMB



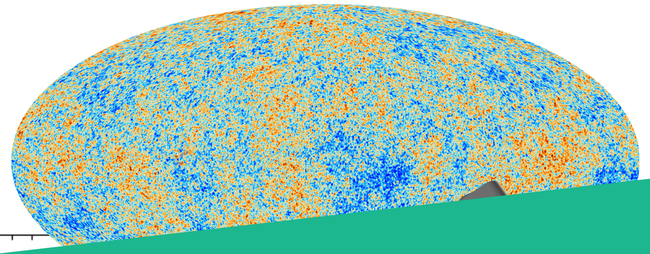
[Paul Frederik Depta]

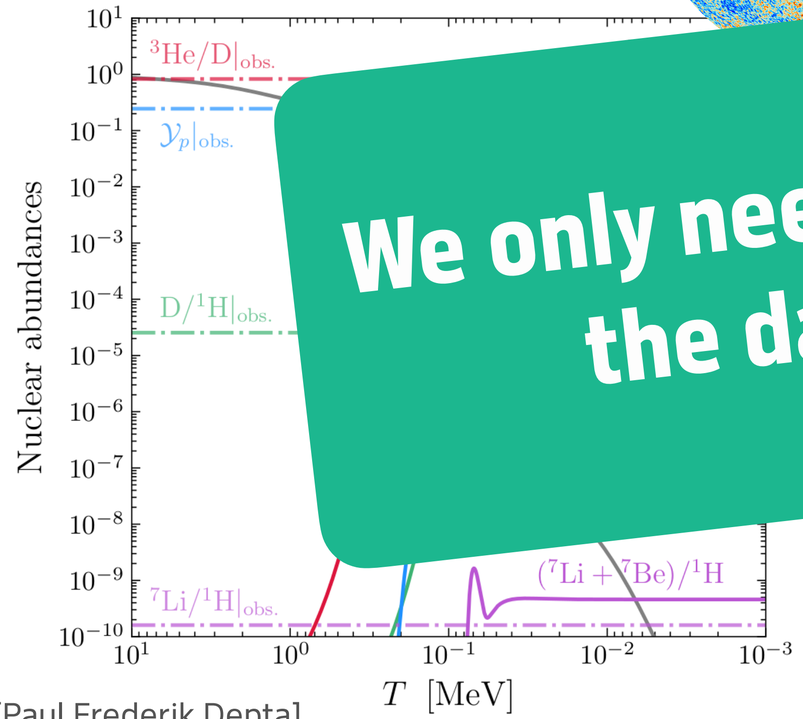


[Planck collaboration]

- 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





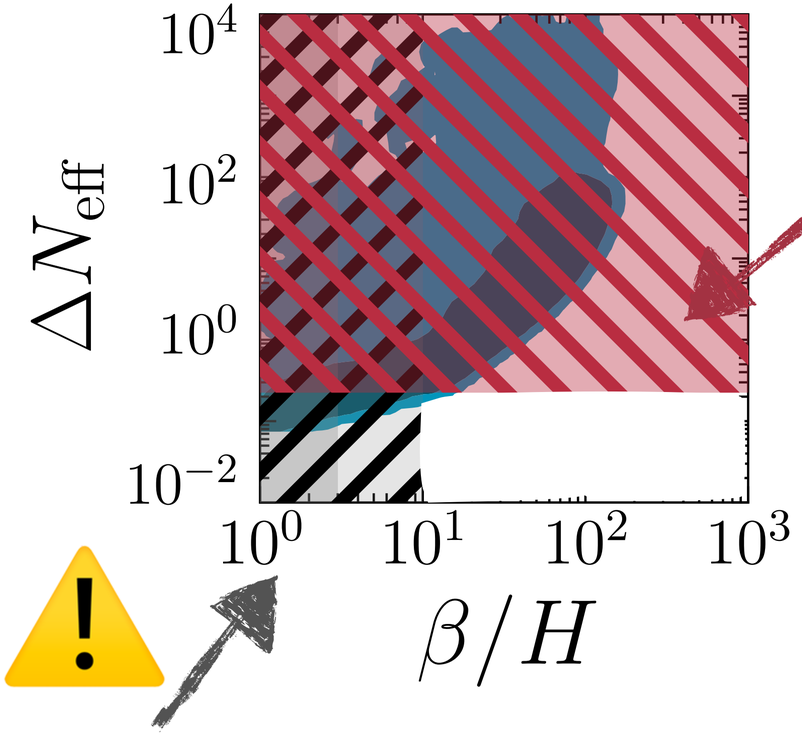
[Paul Frederik Depta]

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

- Oh… …ordial
- …ances in
- …h
- …41
- $N_{\mathrm{eff}}^{\mathrm{CMB}} = 2.99 \pm 0.17$
- Consistent with 3 SM neutrinos

Cosmological constraints: ✅

A very naive fit



If 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. PBHs?

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

CT+ [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

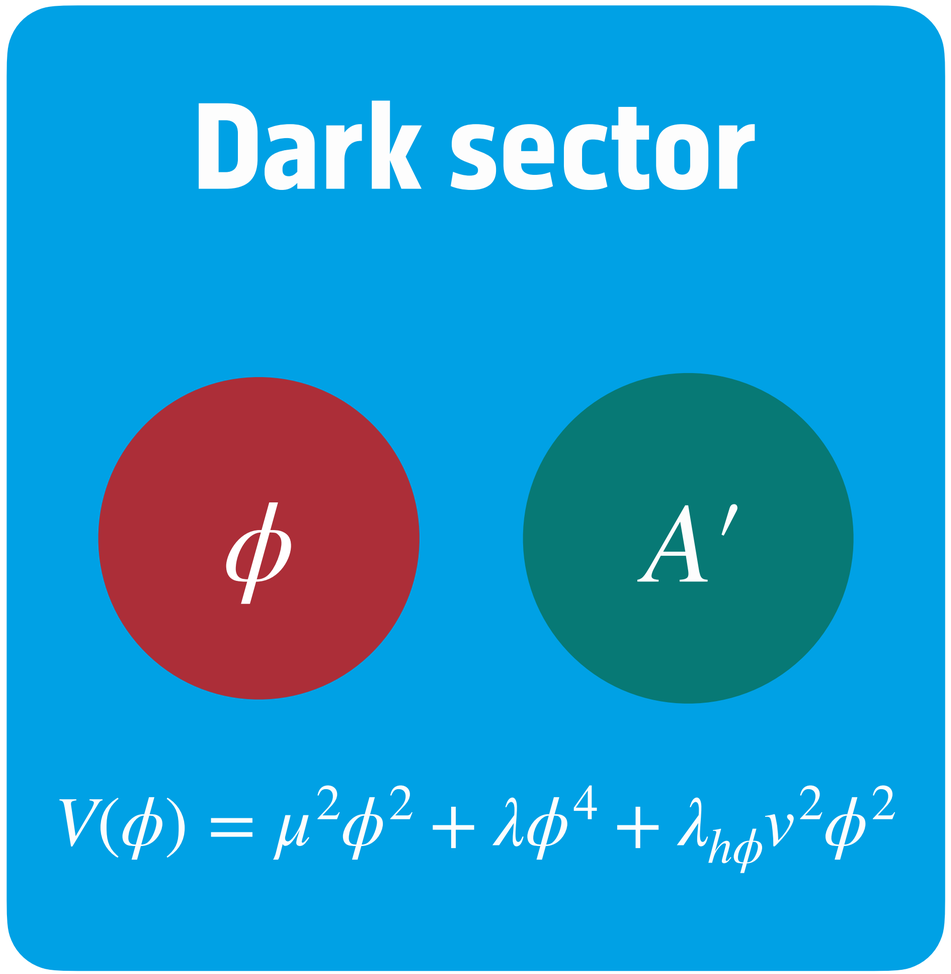
[Chen+, 2502.01024]

Investigation of specific dark sector models

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

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

A minimal dark sector setup



Higgs mixing $\lambda_{h\phi}$

Changes the dark Higgs potential...

Portal couplings

Kinetic mixing κ

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

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

SM

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

A minimal dark sector setup

Dark sector

Higgs mixing $\lambda_{h\phi}$

Changes the dark Hi

$V(\phi$ $\eta\phi^2\phi$

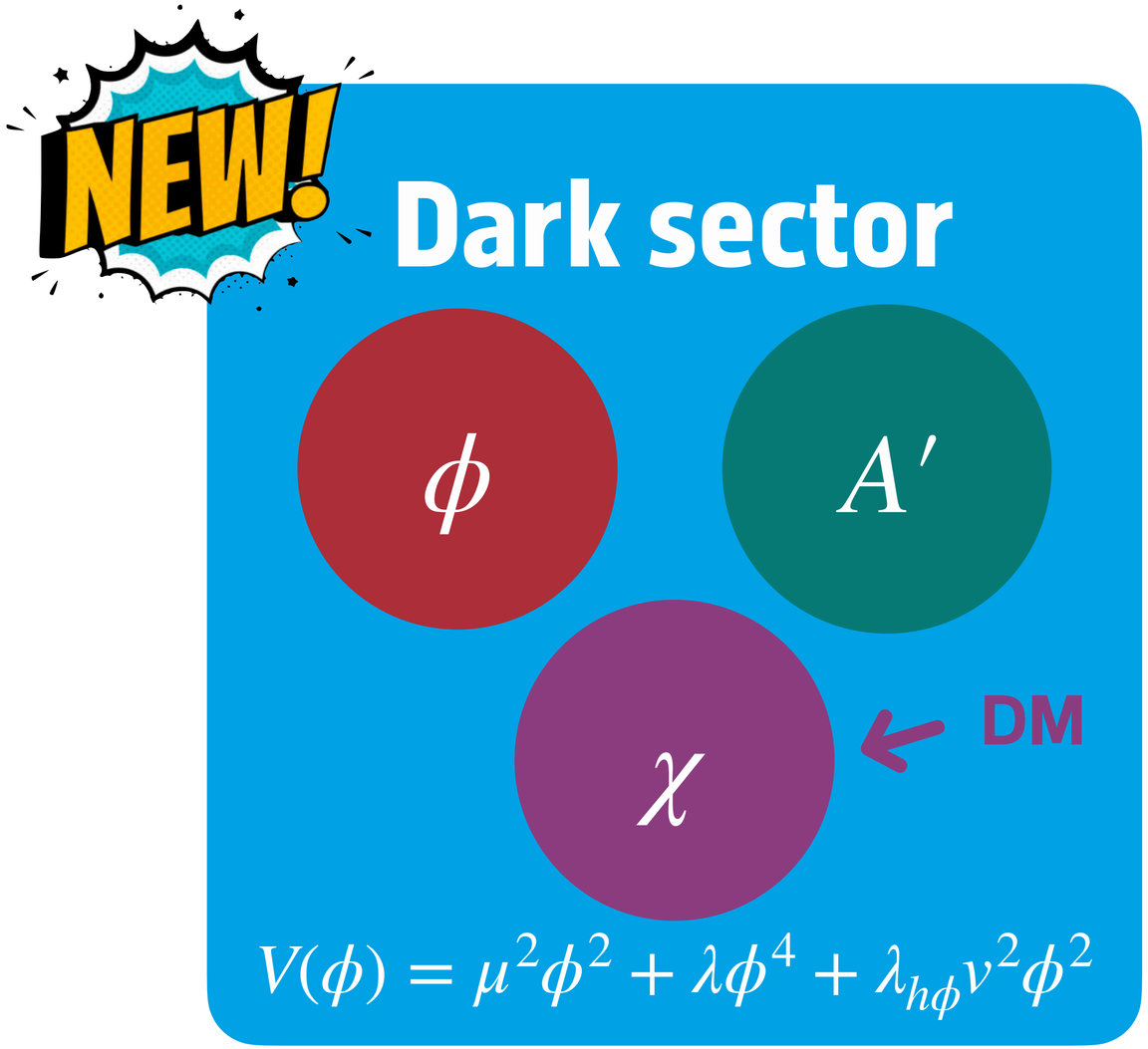
$\mathcal{L} \supset \kappa F'_{\mu\nu} F^{\mu\nu}$

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

Hard to make dark sector decay quick enough, to avoid cosmological constraints & 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



A conformal dark sector incl. dark matter candidate

Dark sector

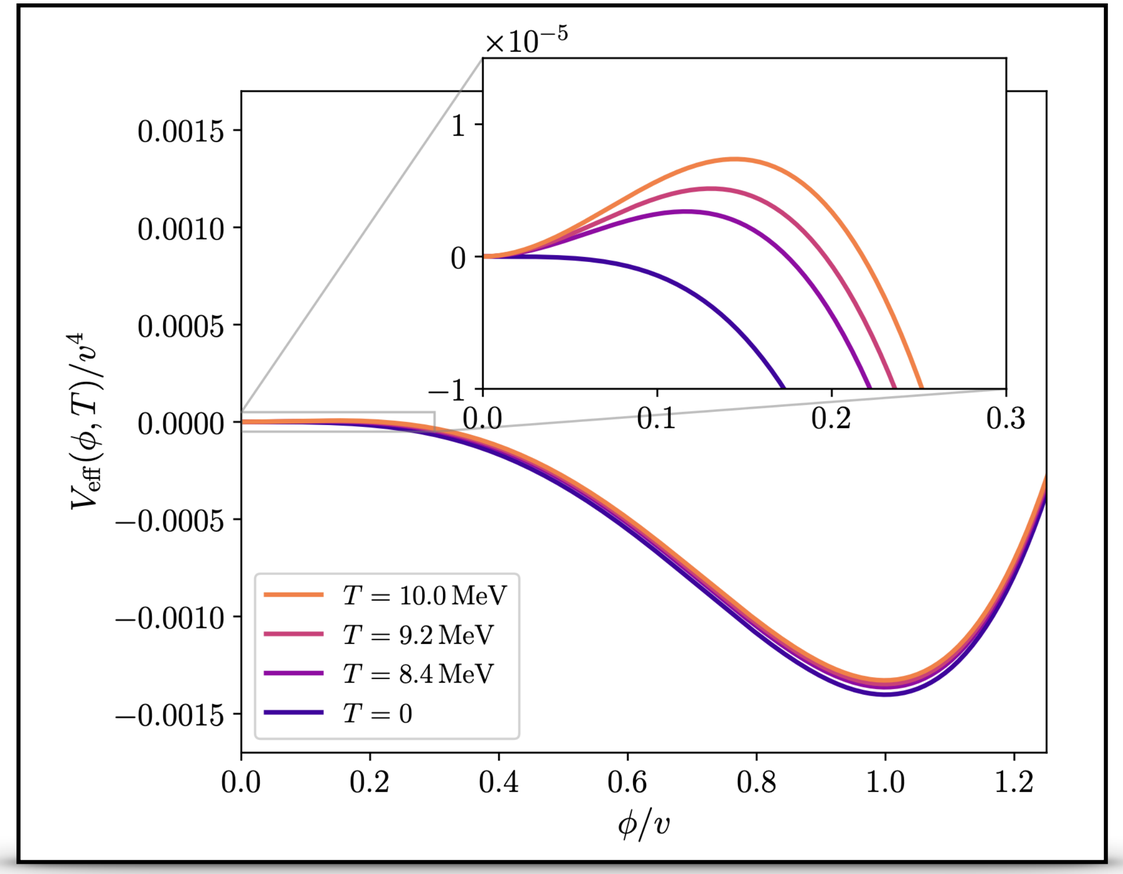
ϕ

A'

χ

DM

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



Strong supercooling throughout the whole parameter space!

A conformal dark sector incl. dark matter candidate

Dark sector

ϕ

A'

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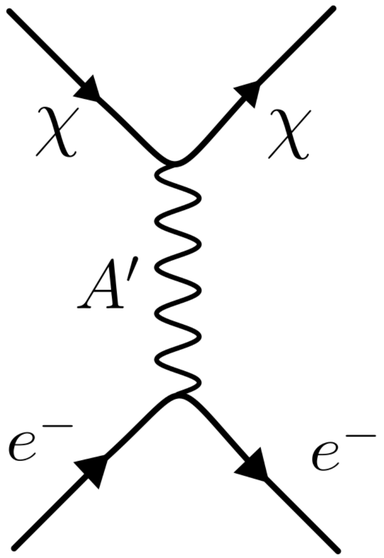
DM

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

Kinetic mixing κ

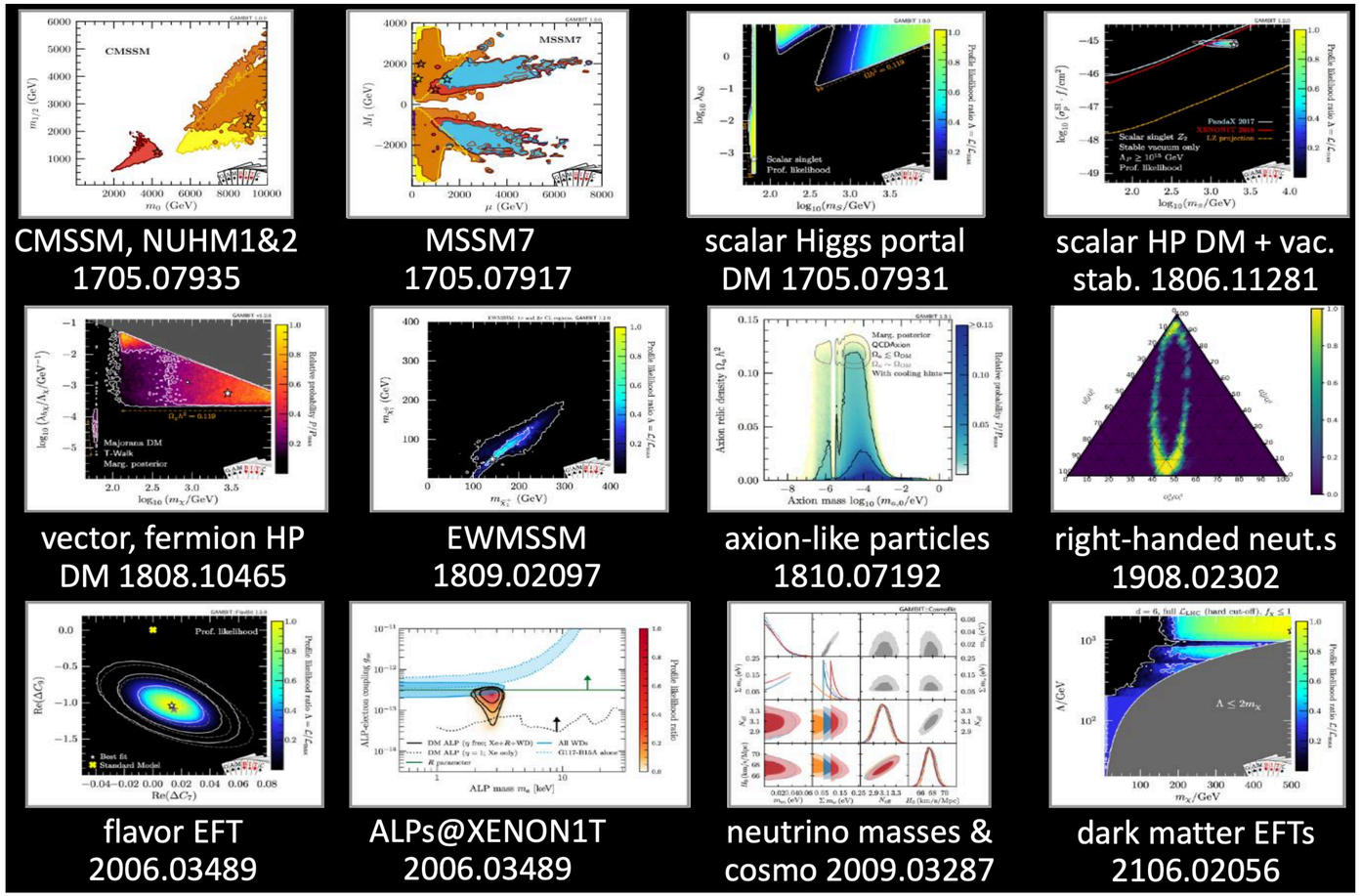


Thermalization becomes easy!

SM

CT+ [2502.19478]

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

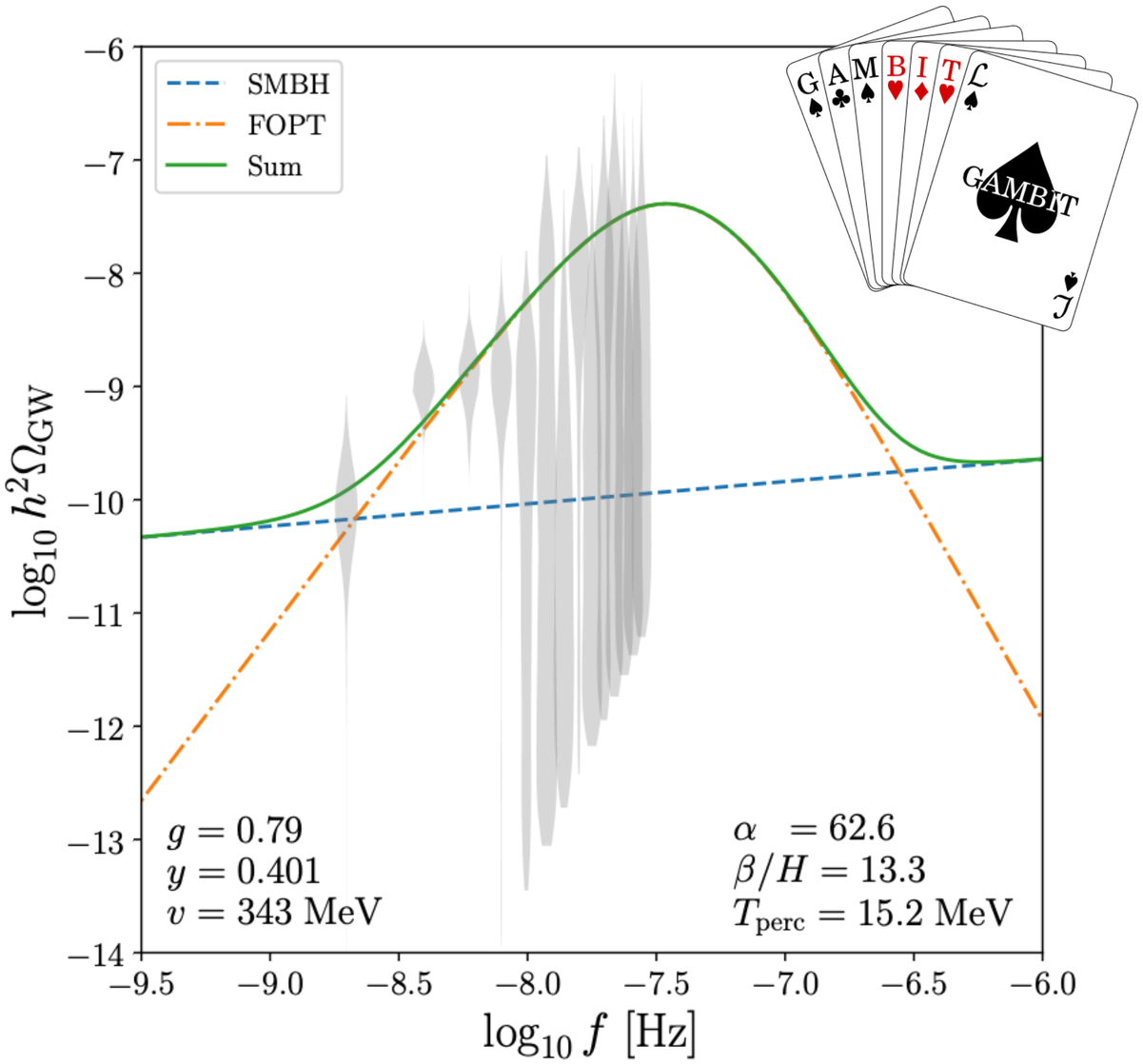
vector, fermion HP DM 1808.10465 | EWMSSM 1809.02097 | axion-like particles 1810.07192 | right-handed neut.s 1908.02302

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

All constraints can be circumvented



Global fit found parameter space with

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

Reliable computation of the GW spectra for strong supercooling?

No public code that can deal with strong supercooling

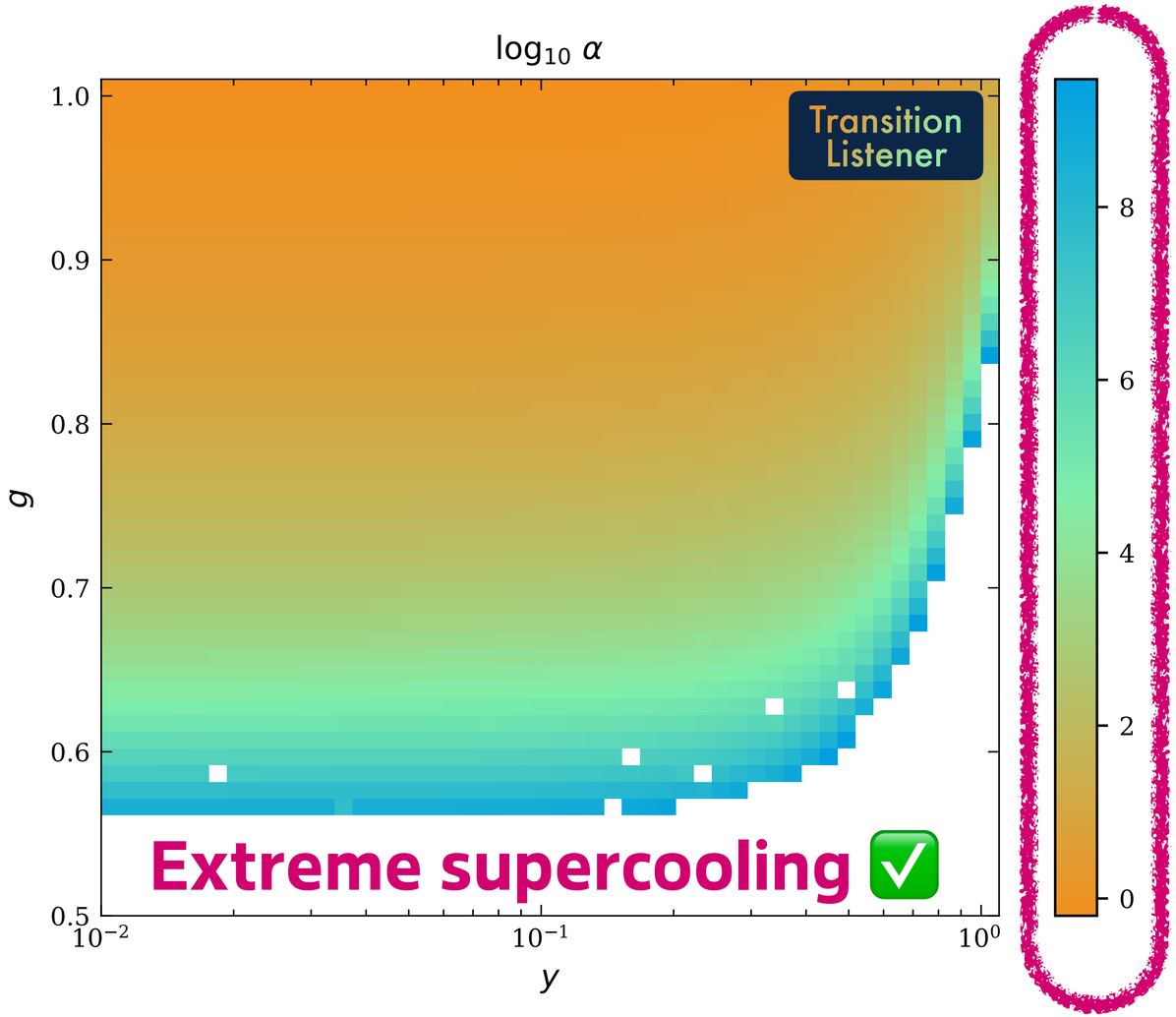
Available codes are specific to the Electroweak symmetry breaking

Available codes are specialized on specific sub-tasks like phase tracing, the bounce action, the bubble nucleation rate, the wall velocity…

They are not integrated into the ecosystem of global fits, i.e. GAMBIT

[Ongoing work Jonas Matuszak]

We're on it!



[Ongoing work with Jonas Matuszak]

RH_*

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

$v_{\rm wall}^{\rm LTE}$

Arbitrary number of scalars

Warnings & error handling

~10s per point

User-friendly

Not just EWSB

PTA likelihoods

Written in python

SNR for LISA, ET, …

Integration into GAMBIT

Summary

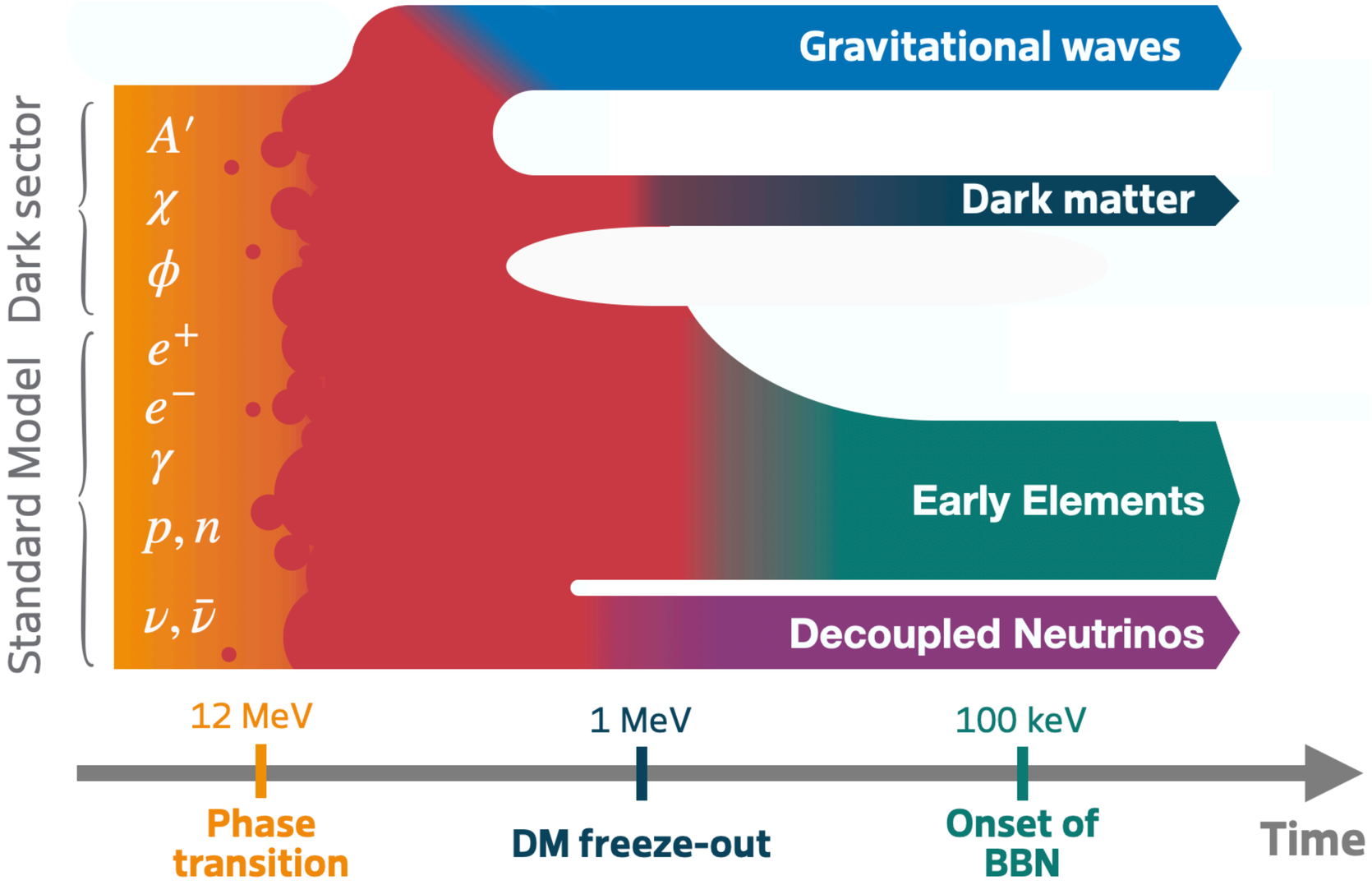
- **PTAs can probe the pre-BBN universe!**
- Dark sector phase transition can explain the PTA signal **better than only SMBHs**
- **Performed global fit** with PTA, BBN, CMB, direct detection, indirect detection, bullet cluster, and beam dump likelihoods
- Best-fit scenario explains PTA data & dark matter and **can be tested by LDMX!**
- Soon: **TransitionListener v2** for studying phase transition models and comparing them with actual data

Thank you very much for your attention!

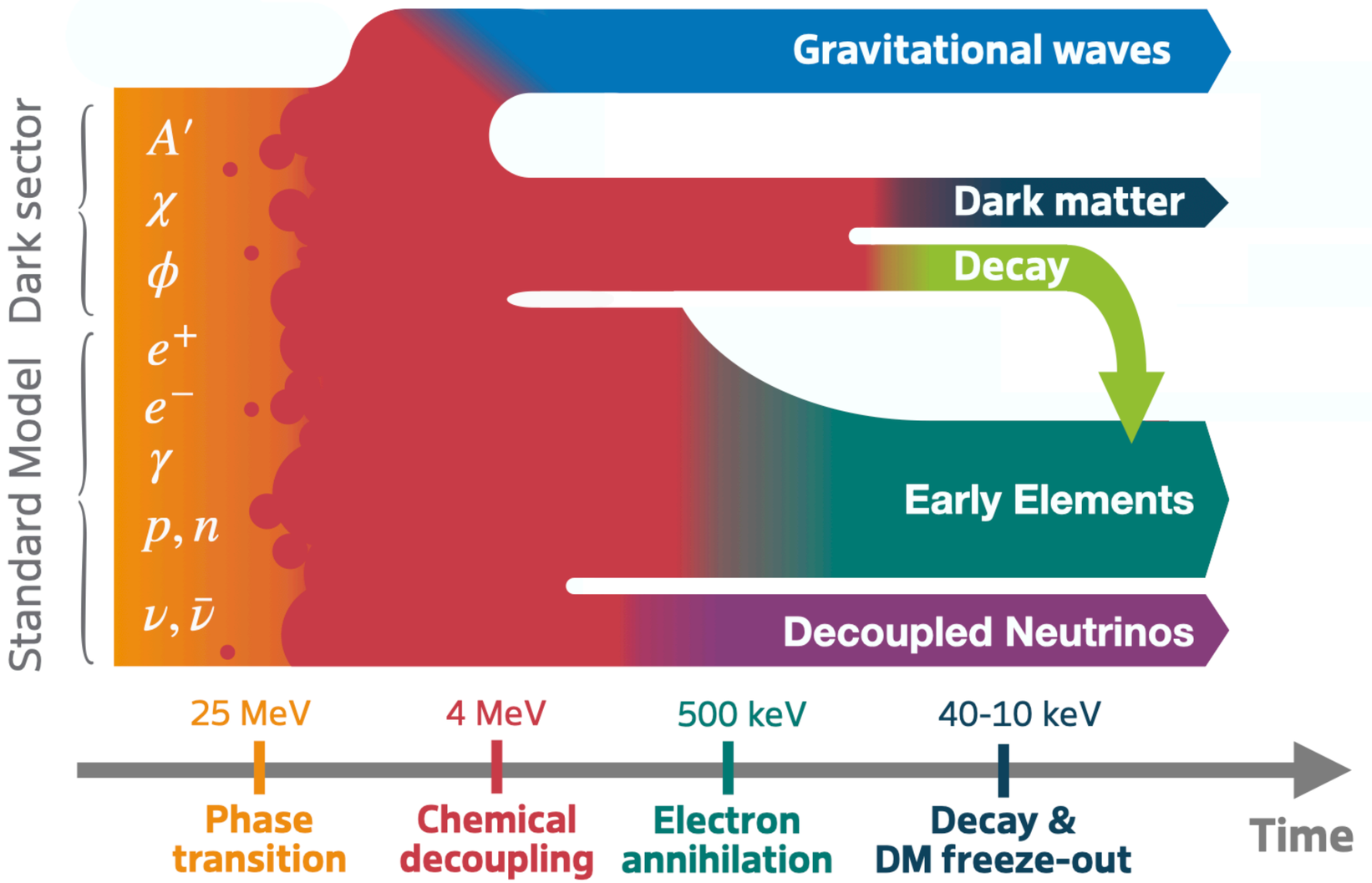
Do you have any questions?

Backup slides

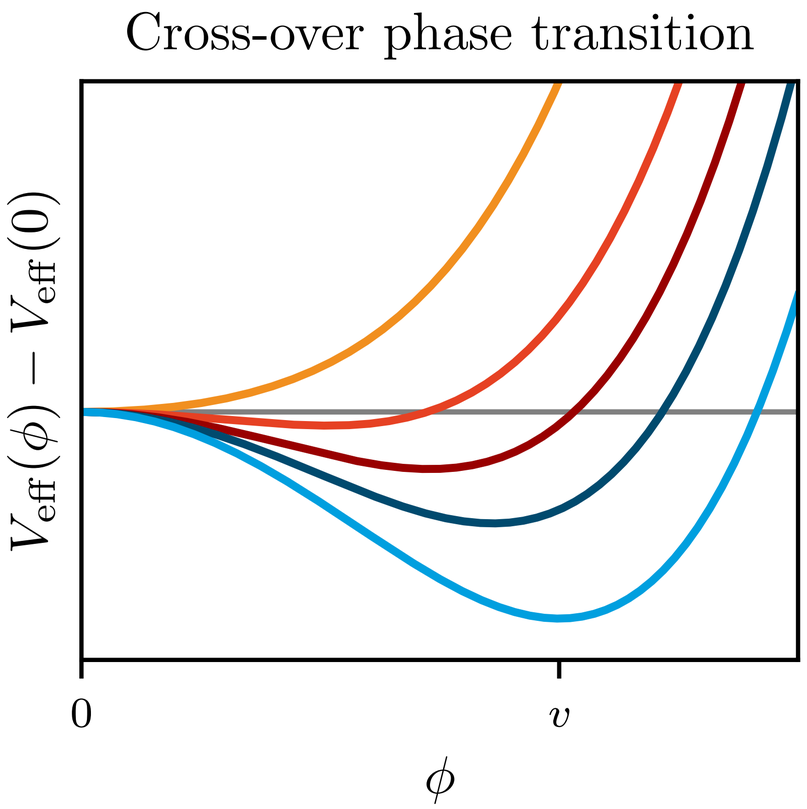
Coupled dark sector scenario



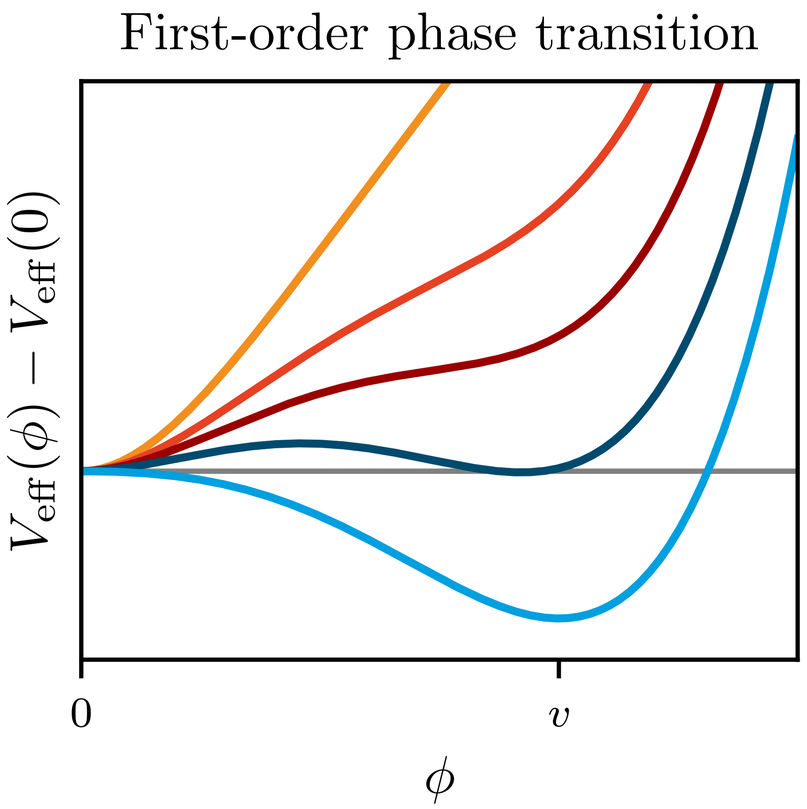
What needs to happen before BBN?



First-order phase transitions vs. cross-overs

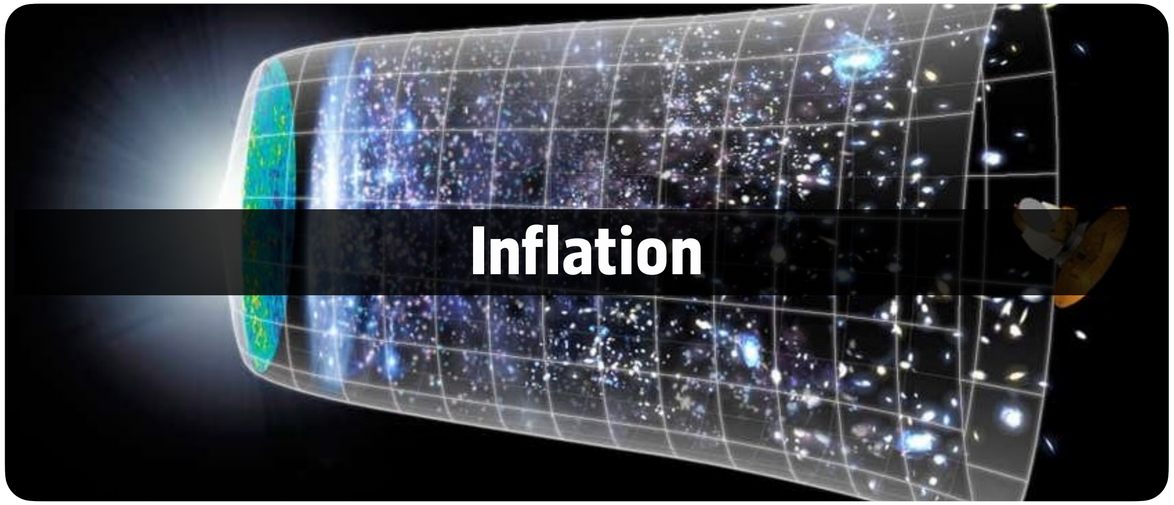


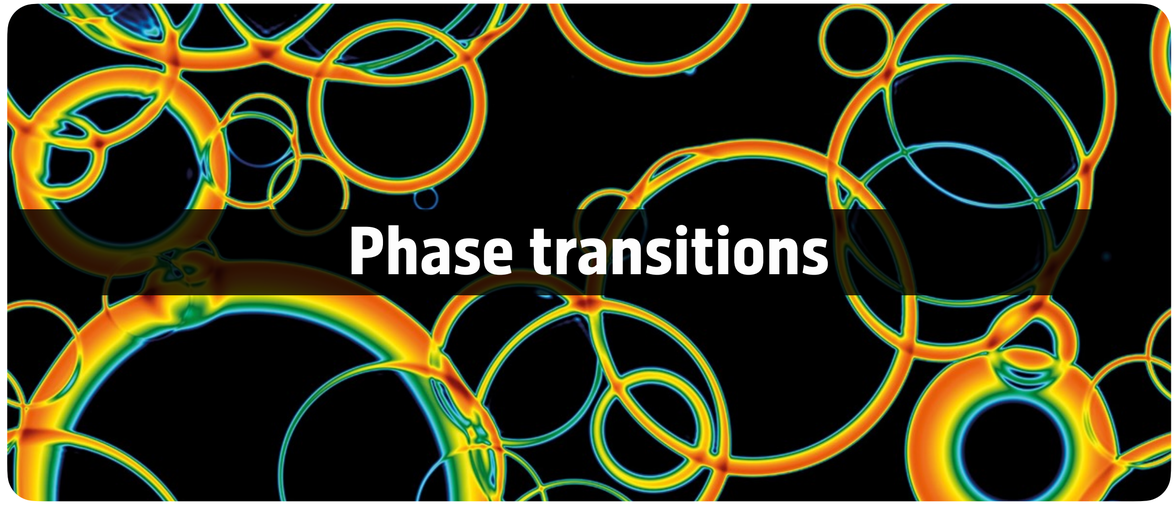
A scalar field "rolls down" from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

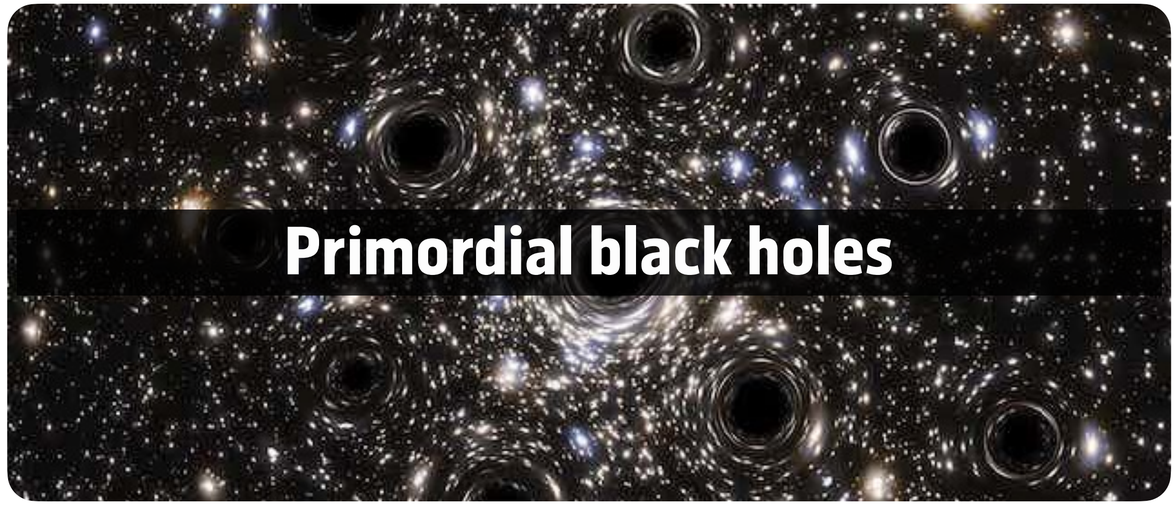


A scalar field tunnels to the true potential minimum $\phi \neq 0$ to minimize its free energy / maximize its action.

Possible sources of a loud CGWB

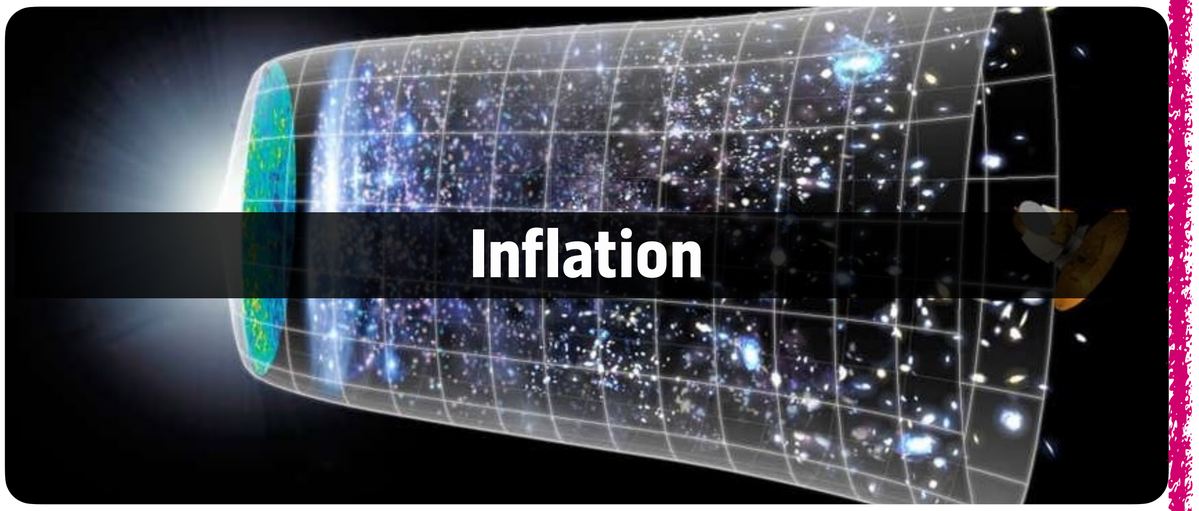


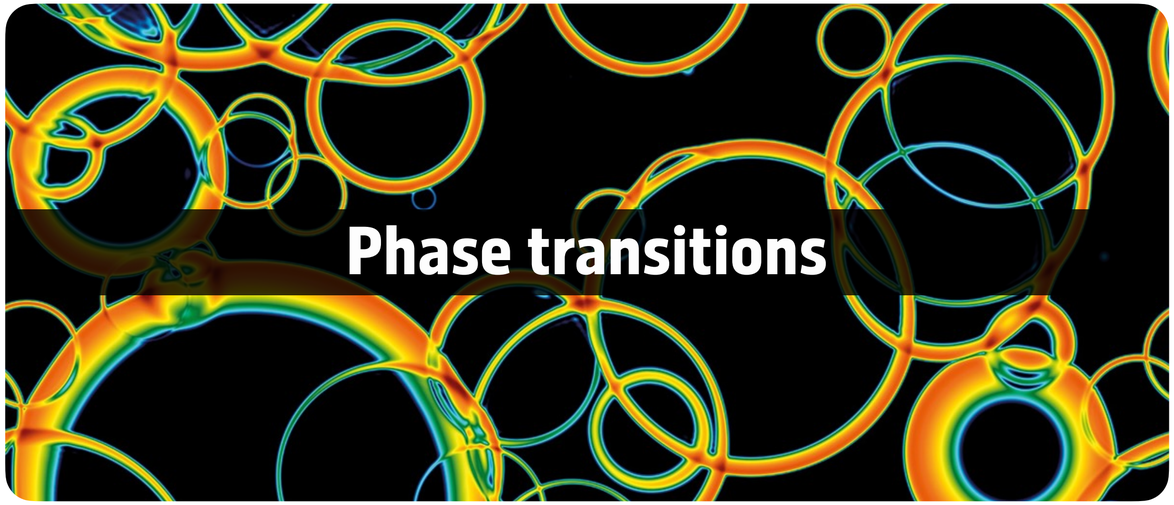




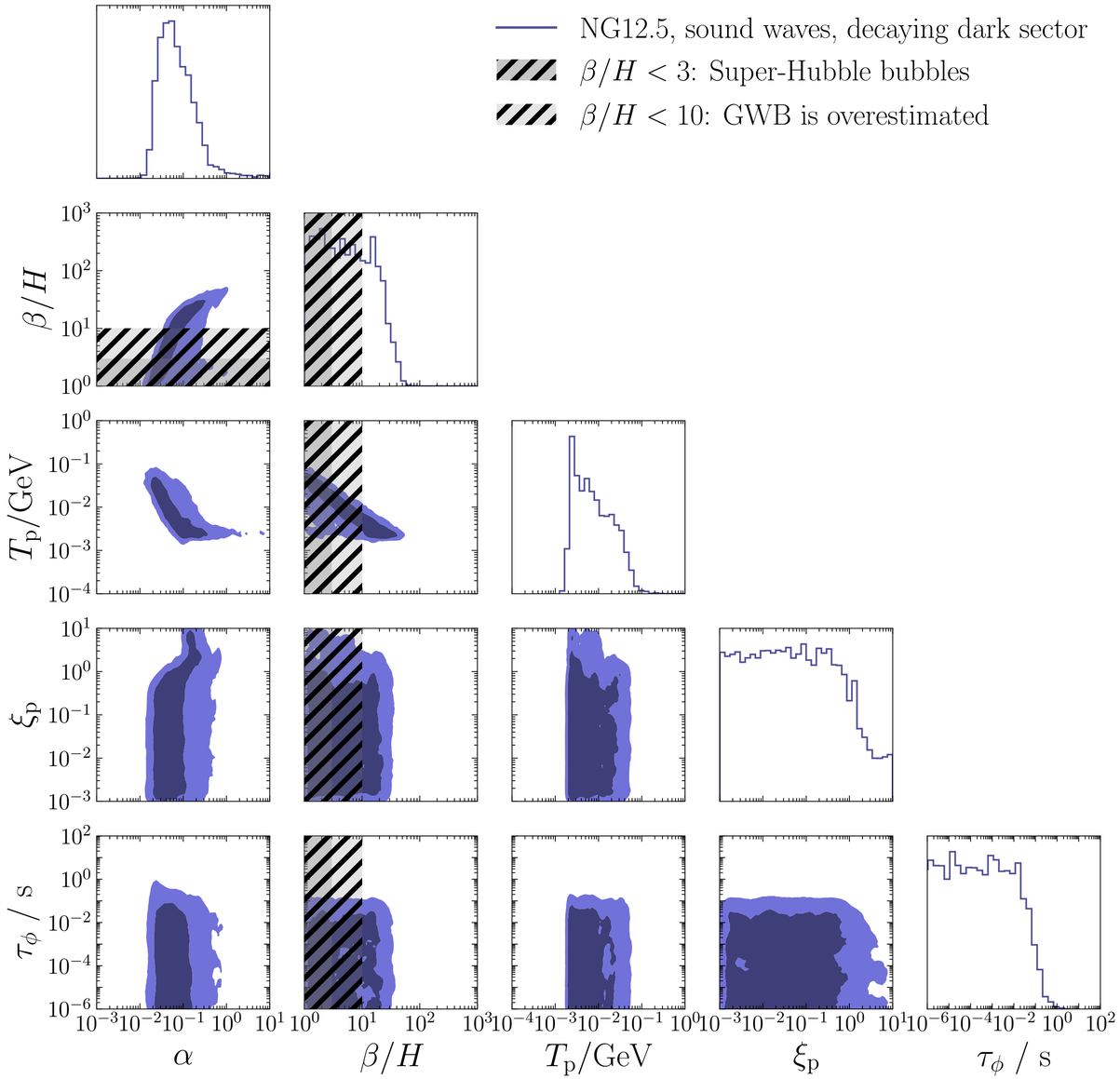
Possible sources of a loud CGWB

Today's focus



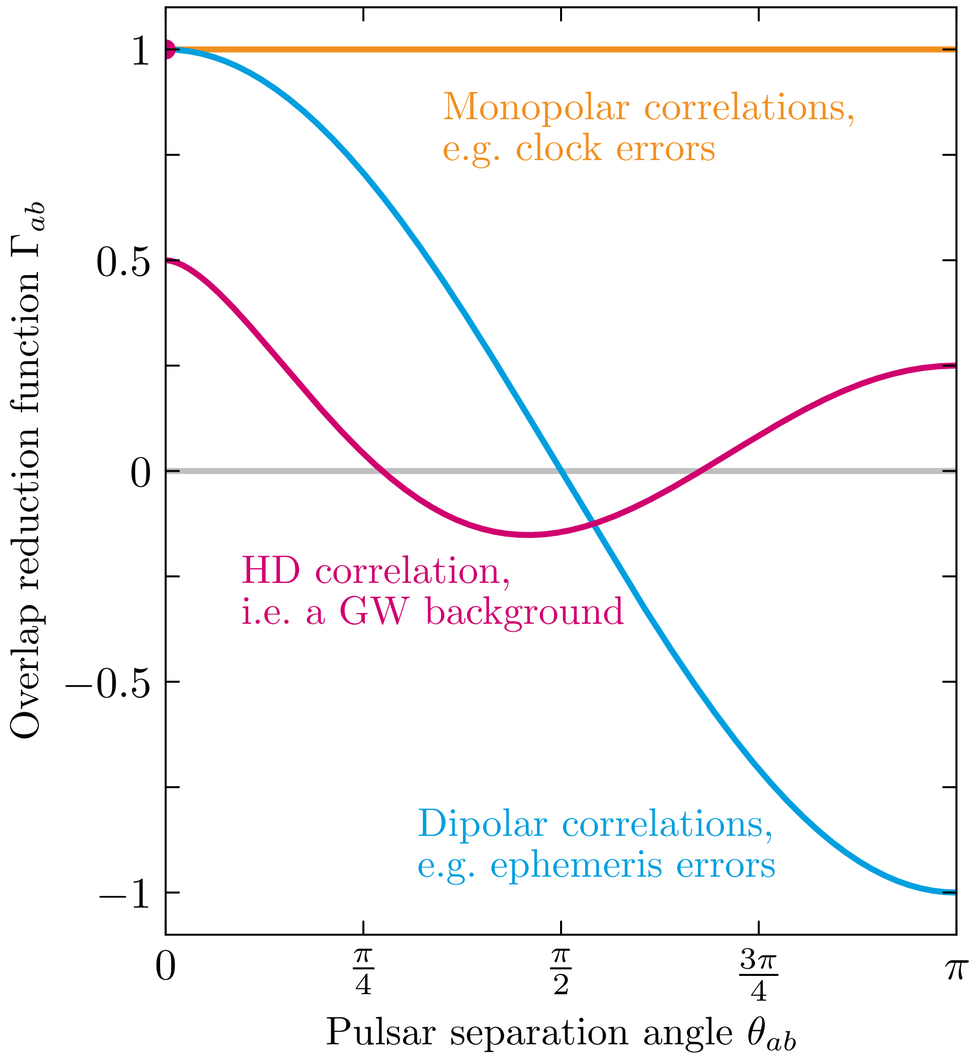


The dark sector must die for the GWs to live...



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

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]

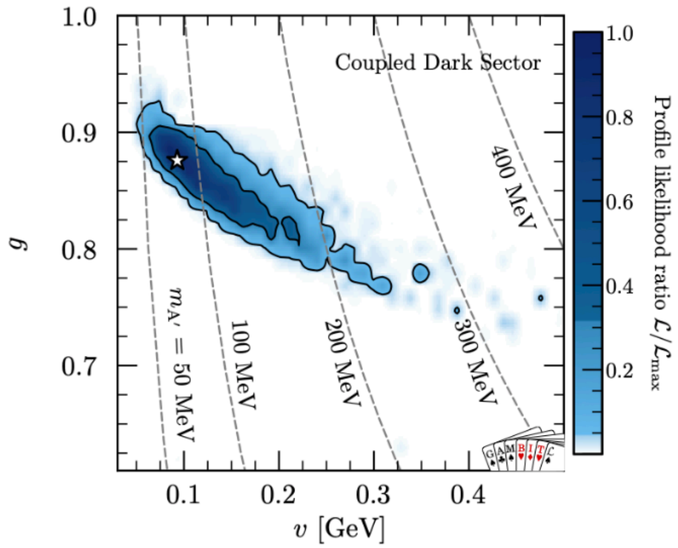
What if κ is not enough for thermalization?

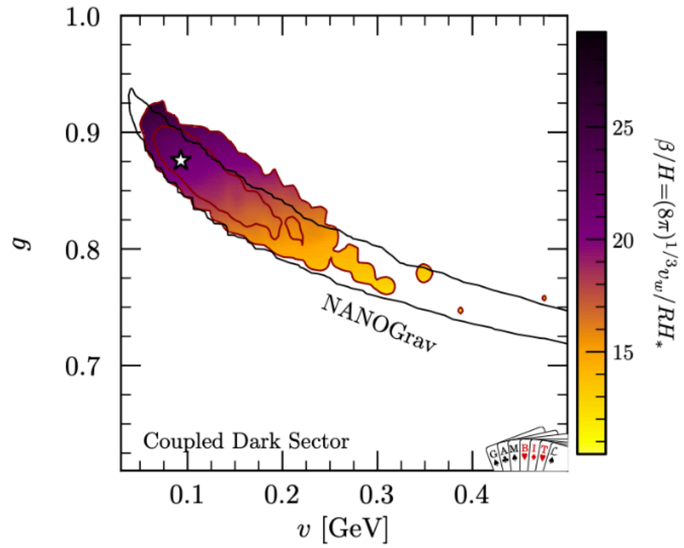
The found parameter region around $\kappa \simeq 10^{-4}$ is small and could be ruled out soon!

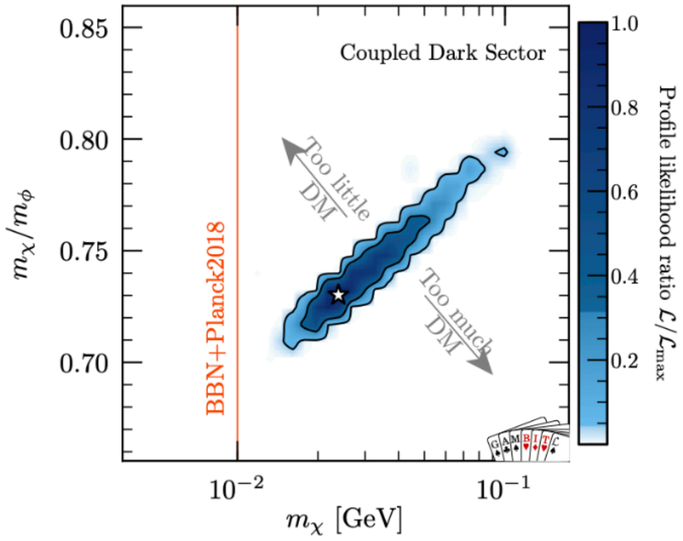
Separate analysis incl. dimension-six operator allowing $\phi \to \bar{e}e$ decays before BBN shows: Even $\kappa = 0$ is viable!

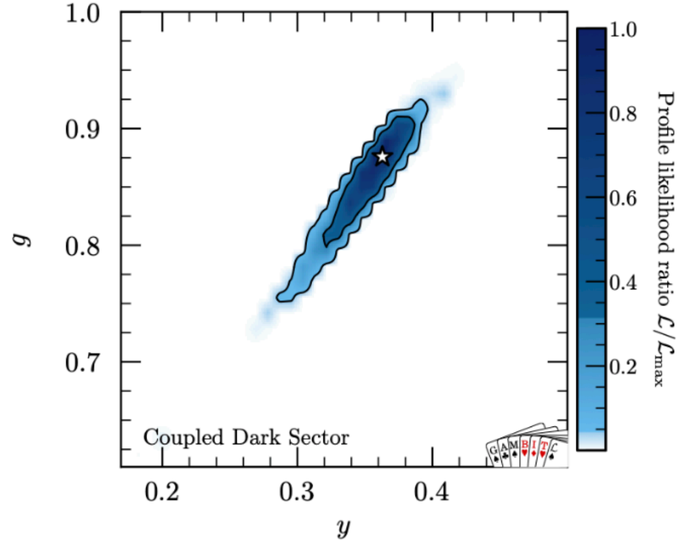
⟶ **Possible supernova constraints?**

See Fiorillo+ [2503.15630]

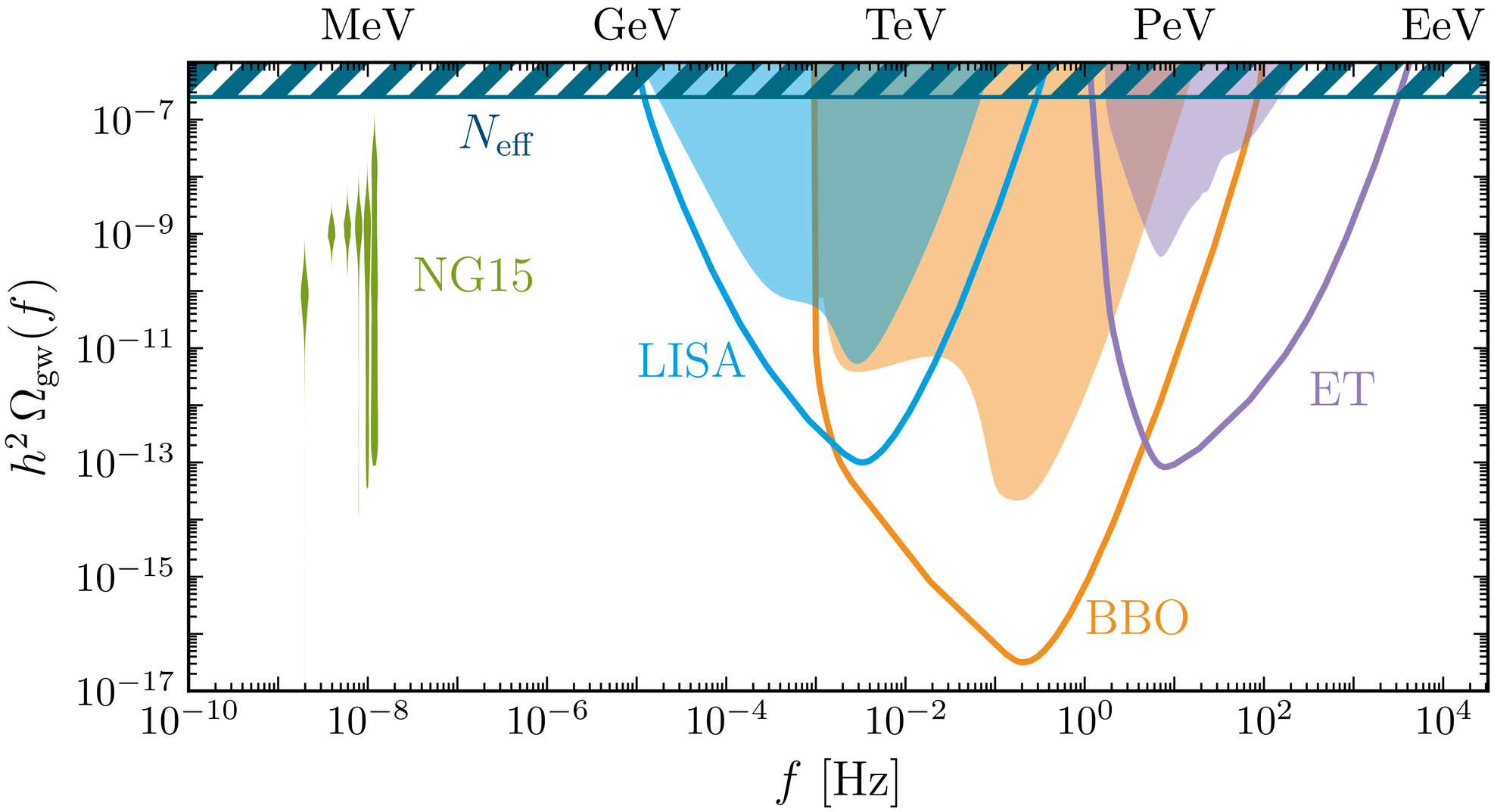




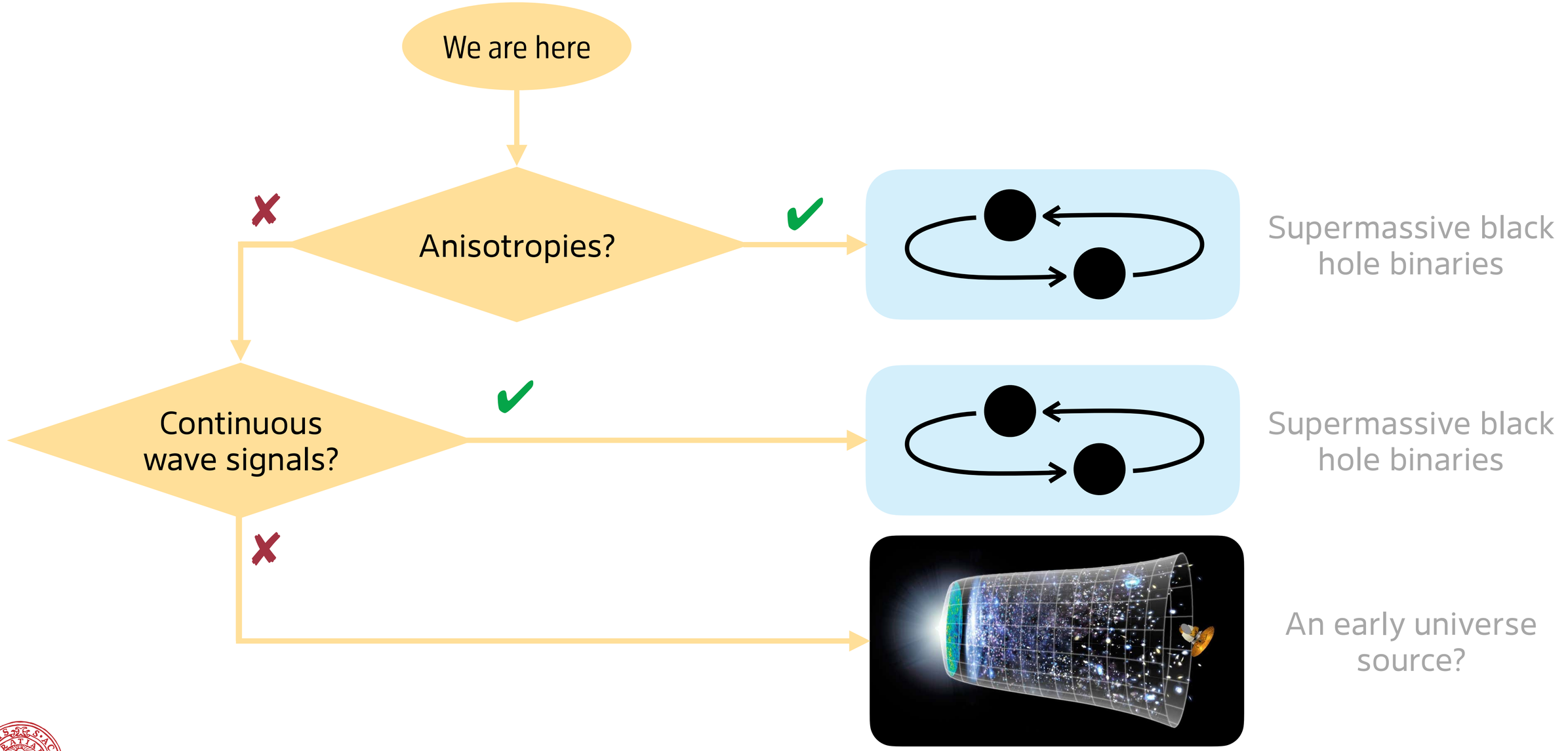


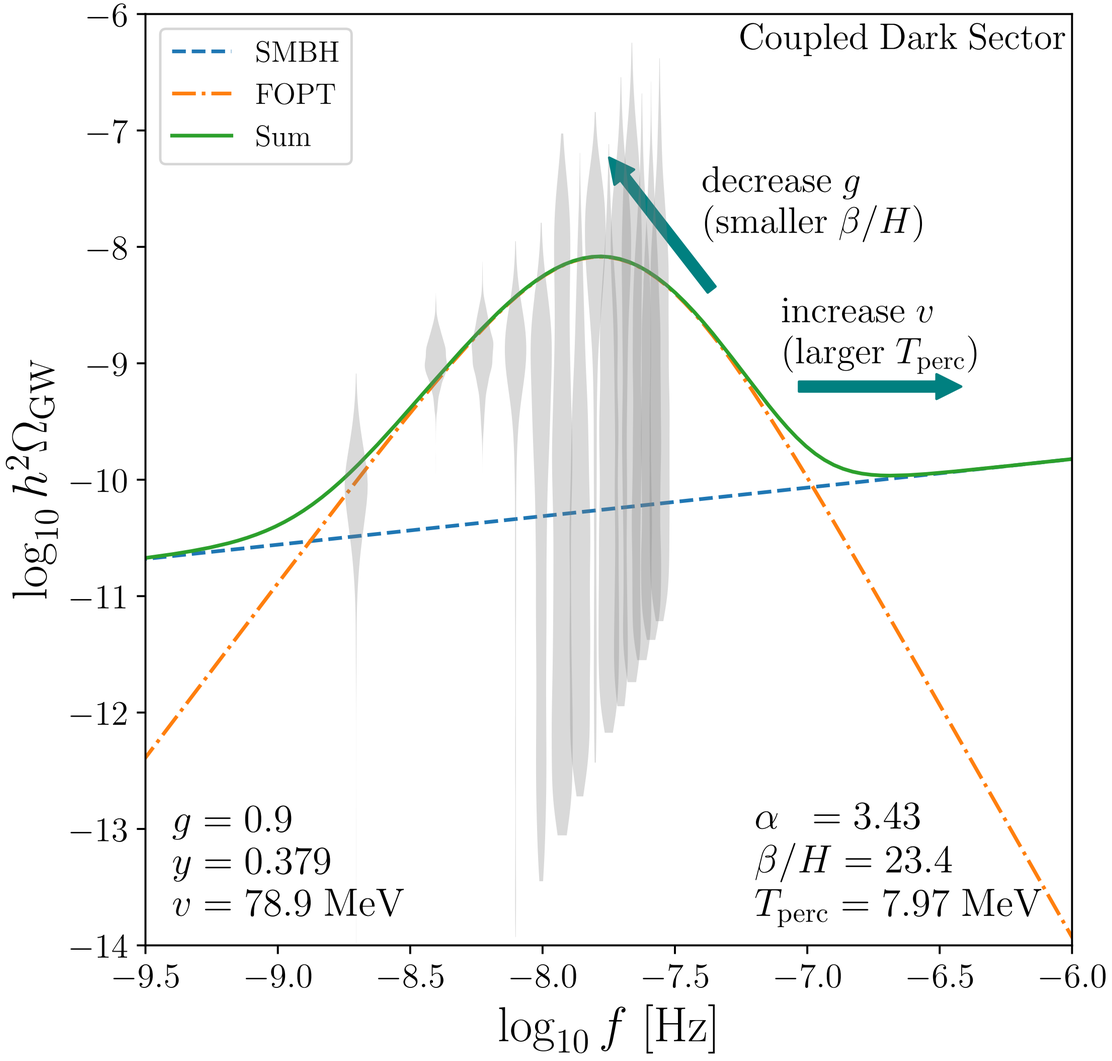


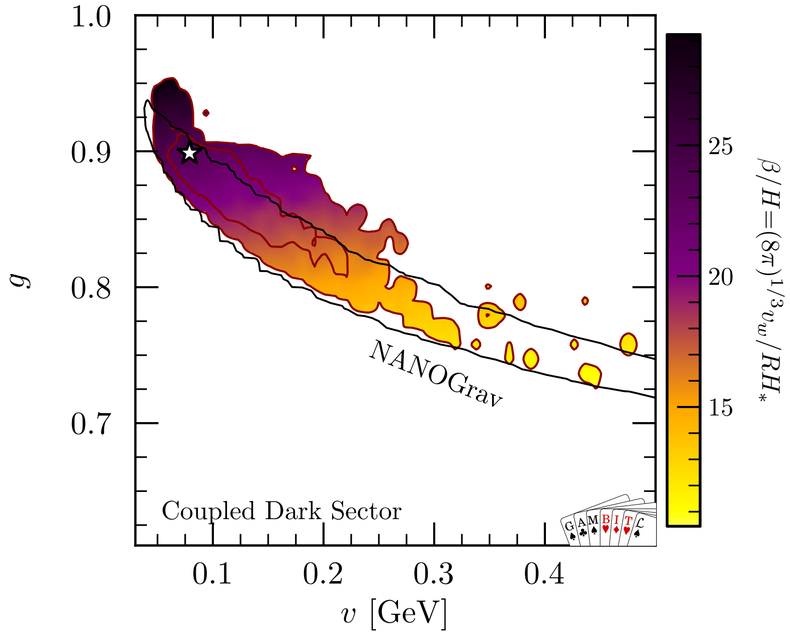
Sensitivity for cosmic GW backgrounds

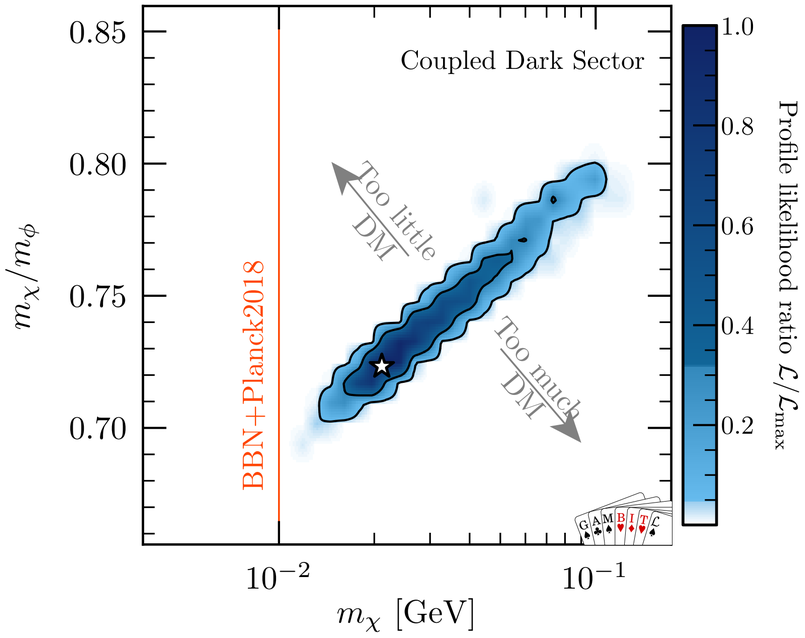


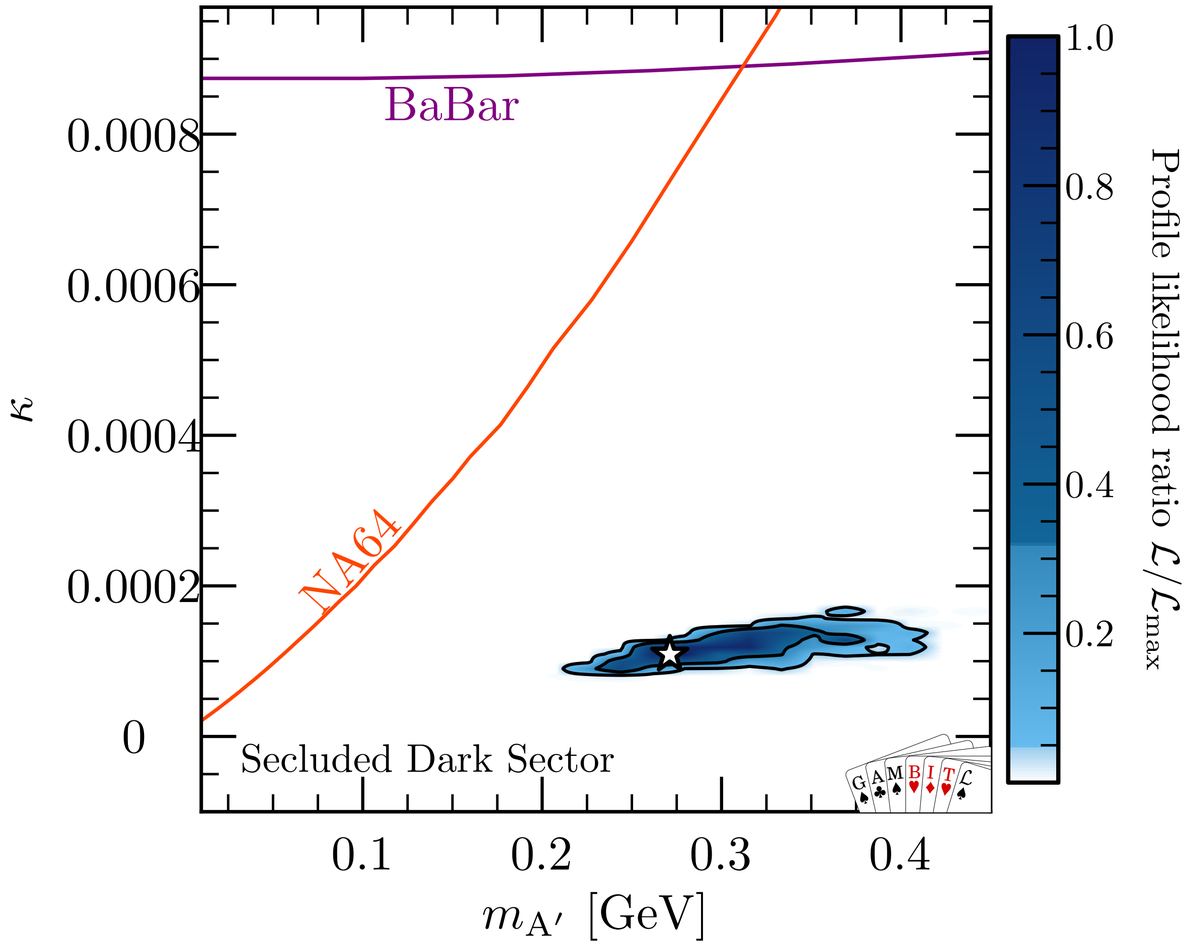
Quo vadis pulsar timing?

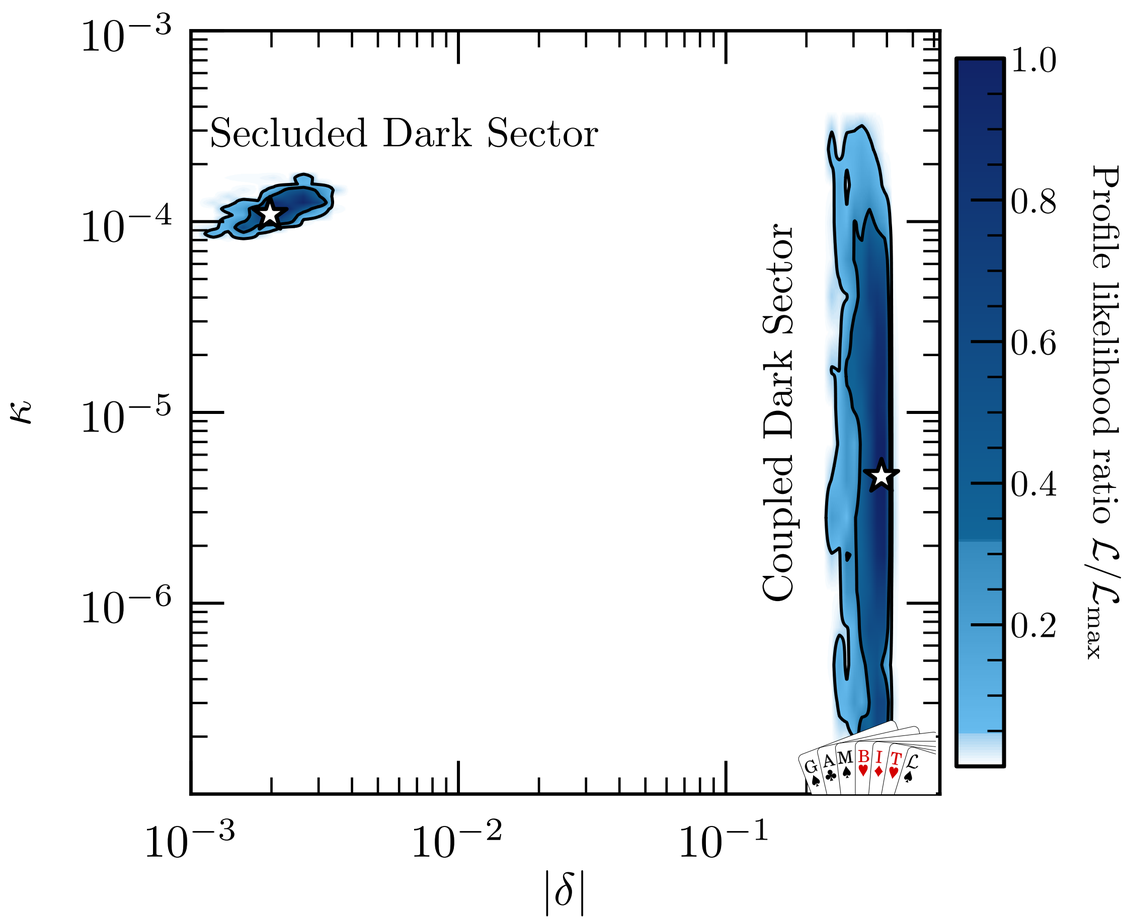



Coupled Dark Sector
SMBH
FOPT
Sum
decrease g
(smaller β/H)
increase v
(larger $T_{\rm perc}$)
$g = 0.9$
$y = 0.379$
$v = 78.9$ MeV
$\alpha = 3.43$
$\beta/H = 23.4$
$T_{\rm perc} = 7.97$ MeV
$\log_{10} h^2\Omega_{\rm GW}$
$\log_{10} f$ [Hz]

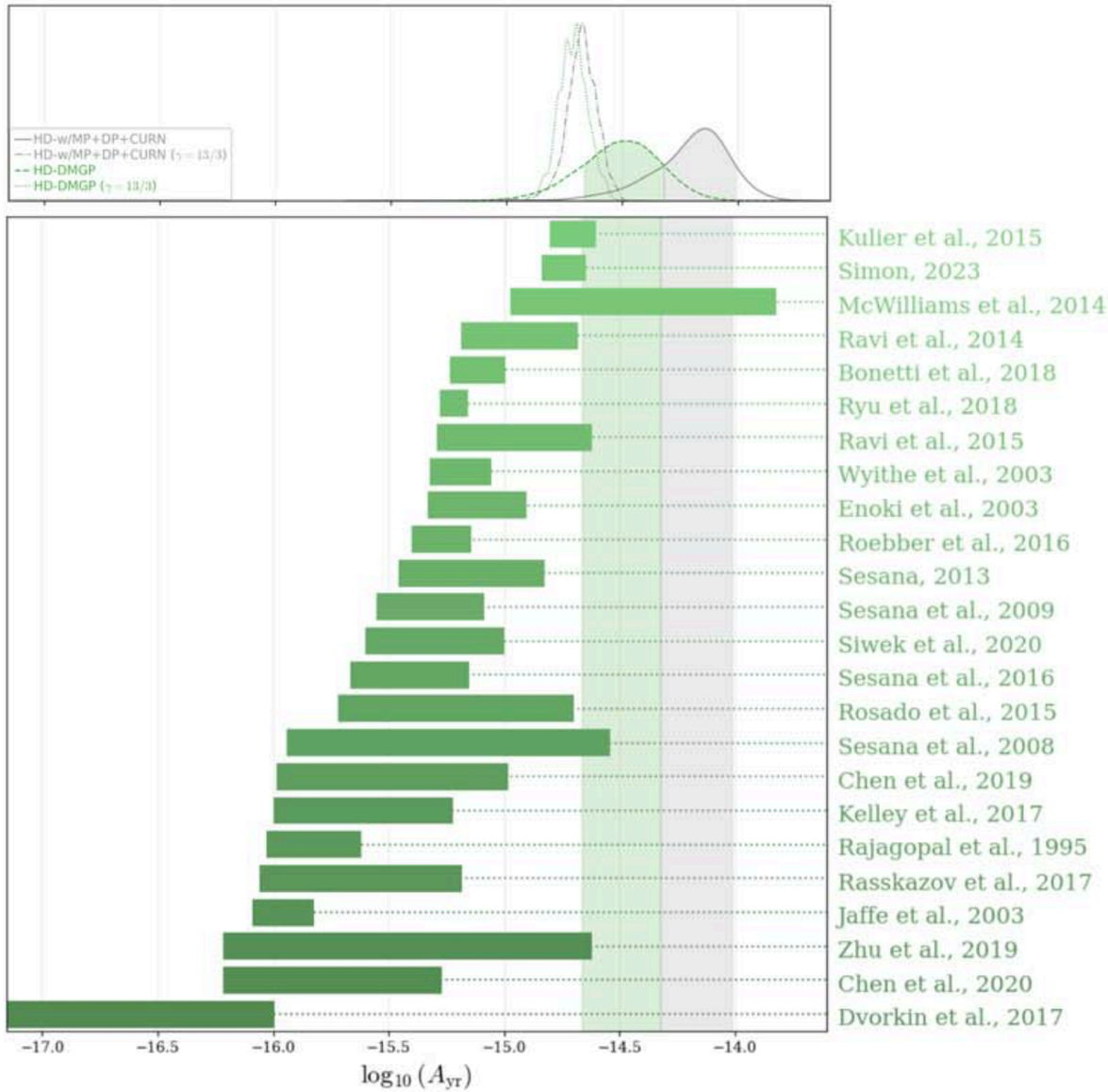

Coupled Dark Sector
NANOGrav
g
v [GeV]
$\beta/H=(8\pi)^{1/3}v_w/RH_*$


Coupled Dark Sector
BBN+Planck2018
Too little DM
Too much DM
m_χ/m_ϕ
m_χ [GeV]
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{\rm max}$


BaBar
NA64
Secluded Dark Sector
κ
$m_{A'}$ [GeV]
0.0008
0.0006
0.0004
0.0002
0
0.1
0.2
0.3
0.4
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{\max}$
1.0
0.8
0.6
0.4
0.2


Secluded Dark Sector
Coupled Dark Sector
κ
$|\delta|$
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-3}
10^{-2}
10^{-1}
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{\max}$
1.0
0.8
0.6
0.4
0.2

Uncertainties of the GWB amplitude from SMBHBs



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Continuous waves in the NANOGrav 15yr data set

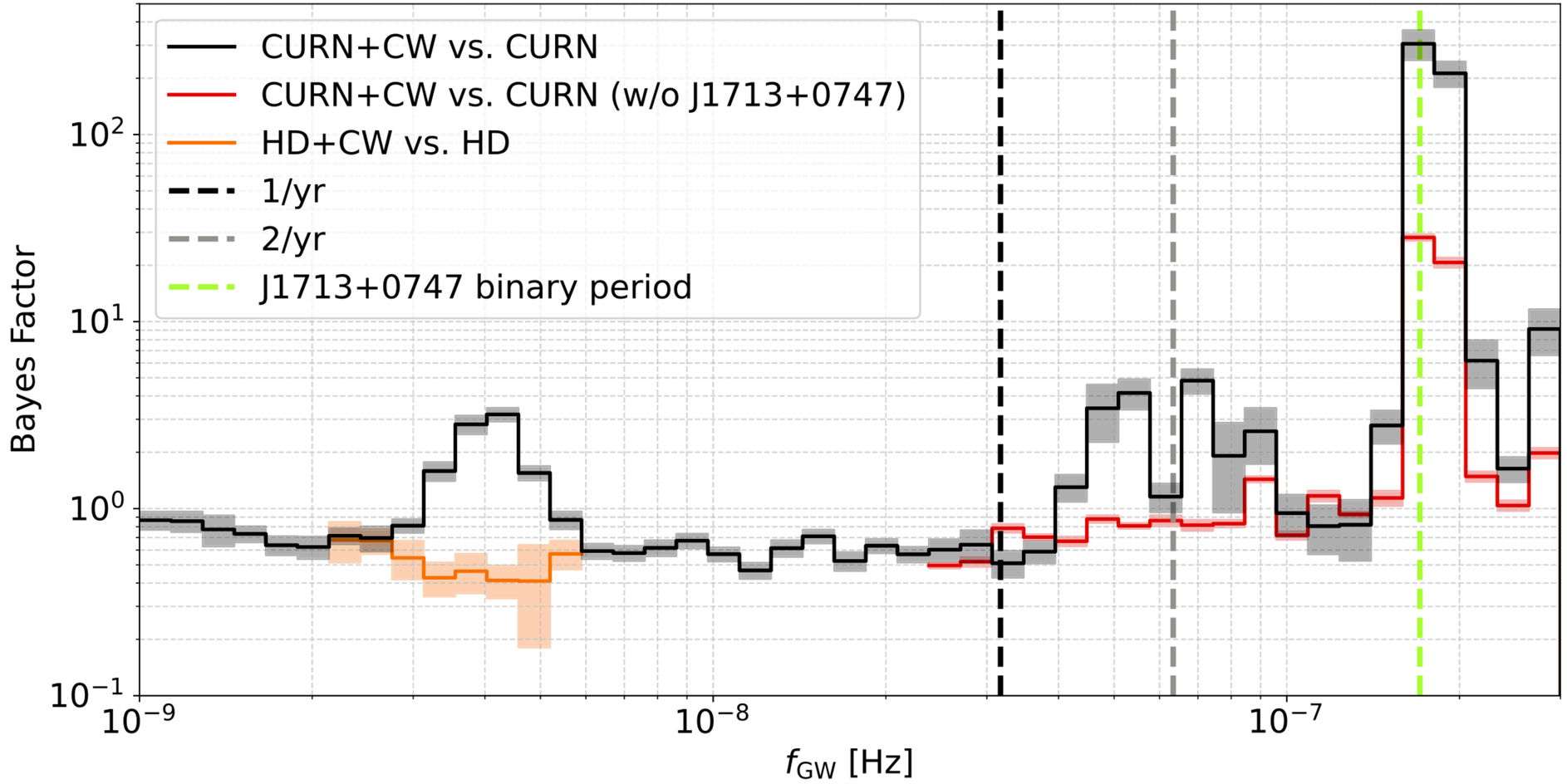

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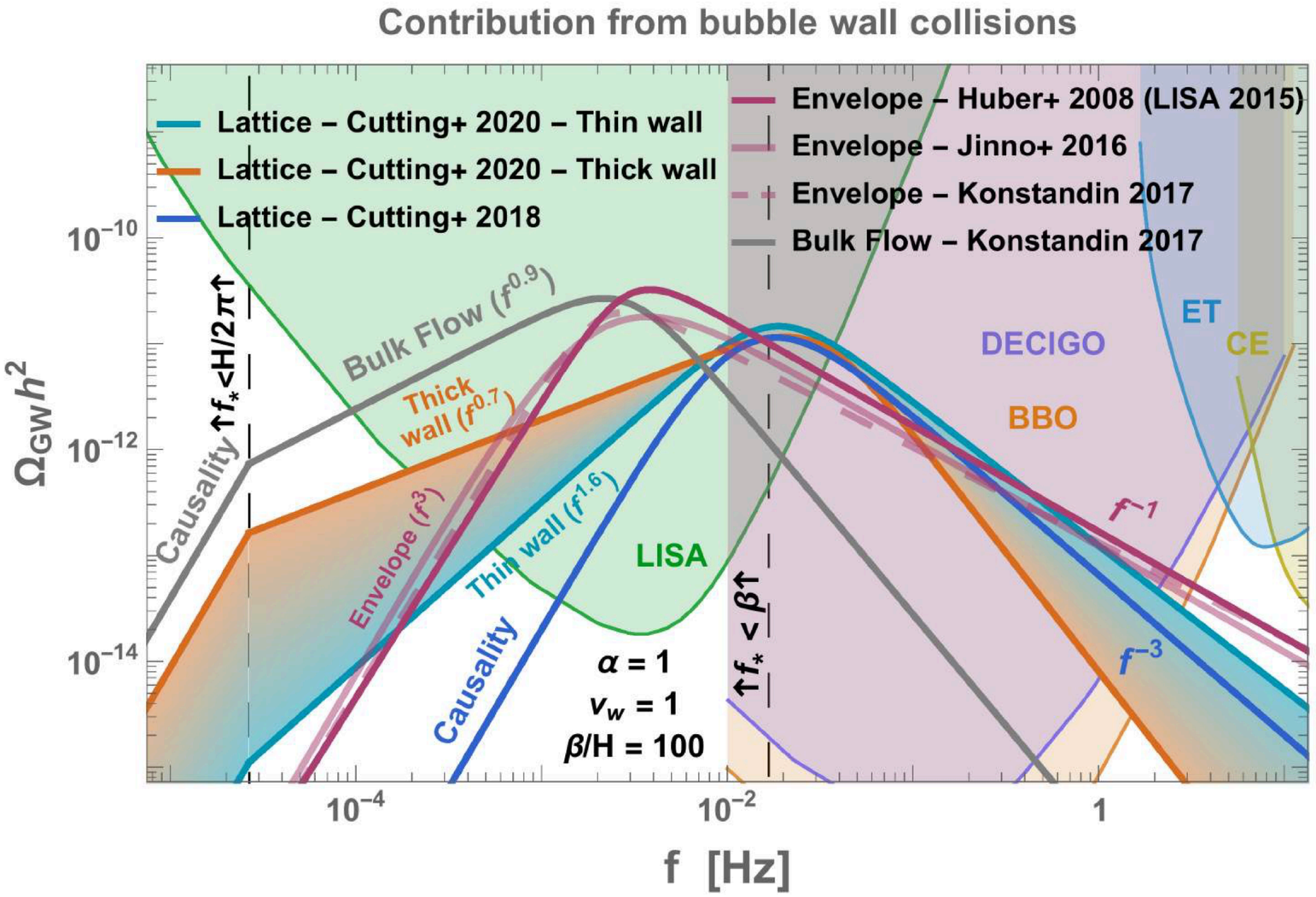
Figure 1. Savage-Dickey Bayes factors for the CW+CURN model vs. the CURN model as a function of frequency (black). Also shown are Bayes factors when excluding PSR J1713+0747 (red, only computed for $f_{GW} > 24$ nHz) and Bayes factors based on a resampled posterior that takes into account the presence of HD correlations in the common red noise process, i.e., CW+HD vs. HD (orange, only computed for 2.1 nHz $< f_{GW} <$ 5.9 nHz). Shaded regions show the 1σ uncertainties.

Different models for the GW spectrum from a FOPT

	IR	UV	References
Envelope	3	−1	[16, 27]
Bulk flow	1	−3	[17, 28]
Scalar lattice	3	−1.5	[38]

	IR	Intermediate	UV	References
Sound shell	9	1	−3	[22, 23]
Scalar + fluid lattice	—	1	−3	[18, 20, 21, 29]
Hybrid	[2,4]	[−1,0]	[−4,−3]	[30]
Higgsless	3	1	−3	This work

JCAP02(2023)011, Jinno, Konstandin, Rubira, Stomberg



Yann Gouttenoire: Beyond the Standard Model Cocktail