The Nano-Hertz GW Background: Black holes or Phase Transitions?

Astronomy and Space Physics Seminar at UU, September 18th 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 and ongoing discussions at UU

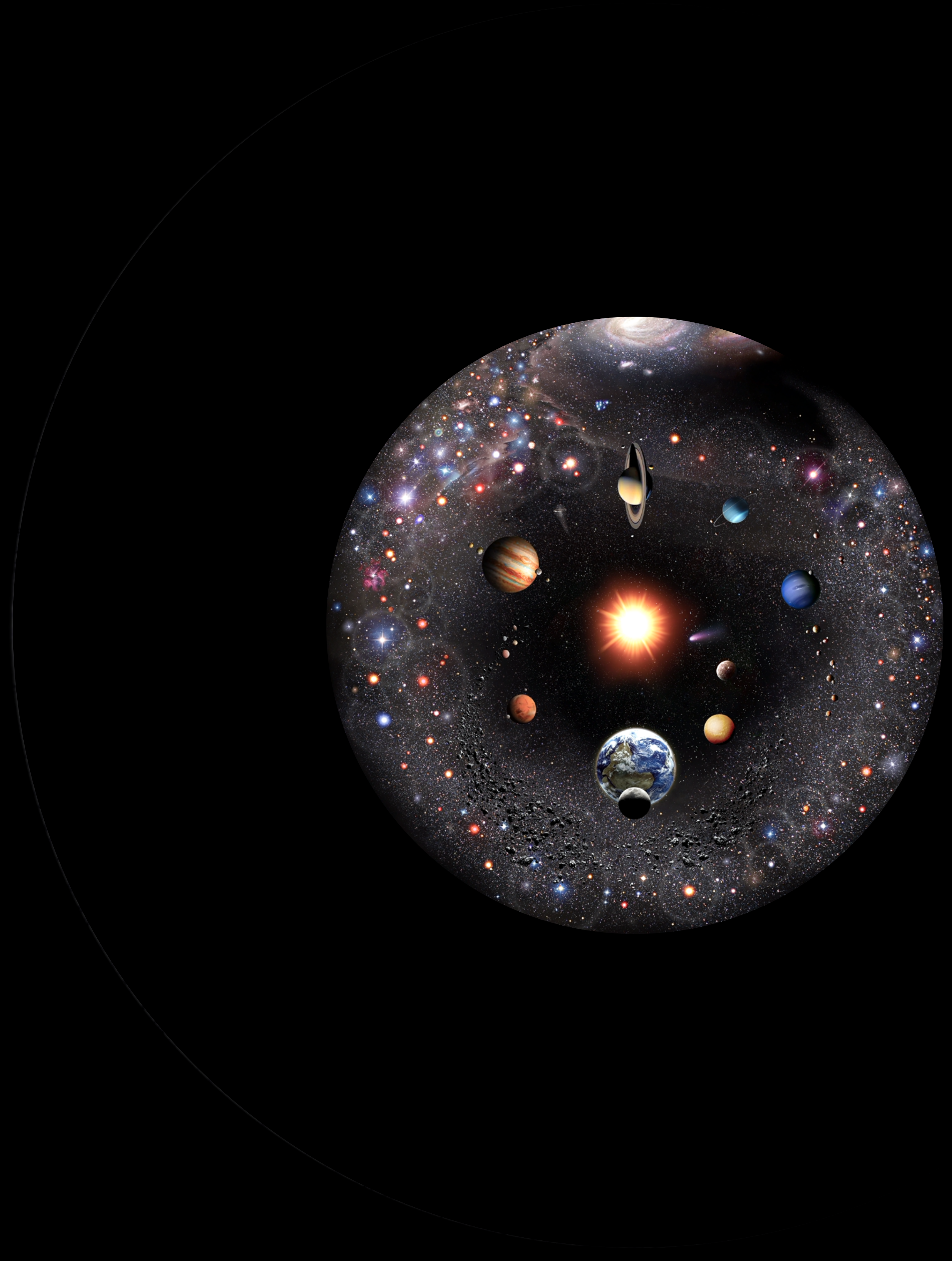
JCAP 11 (2023) 053,
JCAP 08 (2025) 062,
and **Phys.Rev.Res. 7 (2025)**

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

Our Solar System

[Pablo Carlos Budassi]

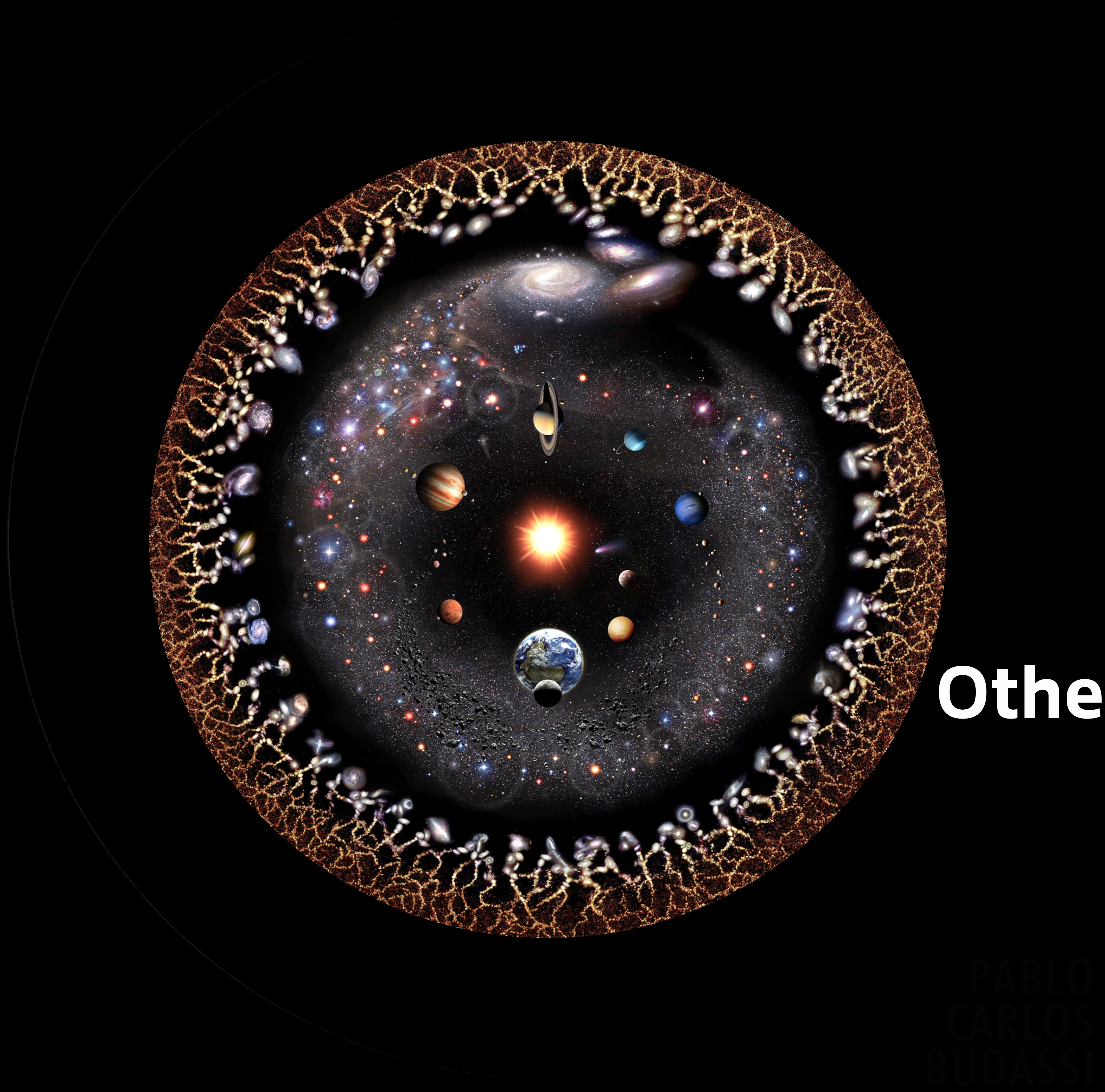
It’s the end of the world as we know it (and I feel fine)



Our galaxy

[Pablo Carlos Budassi]

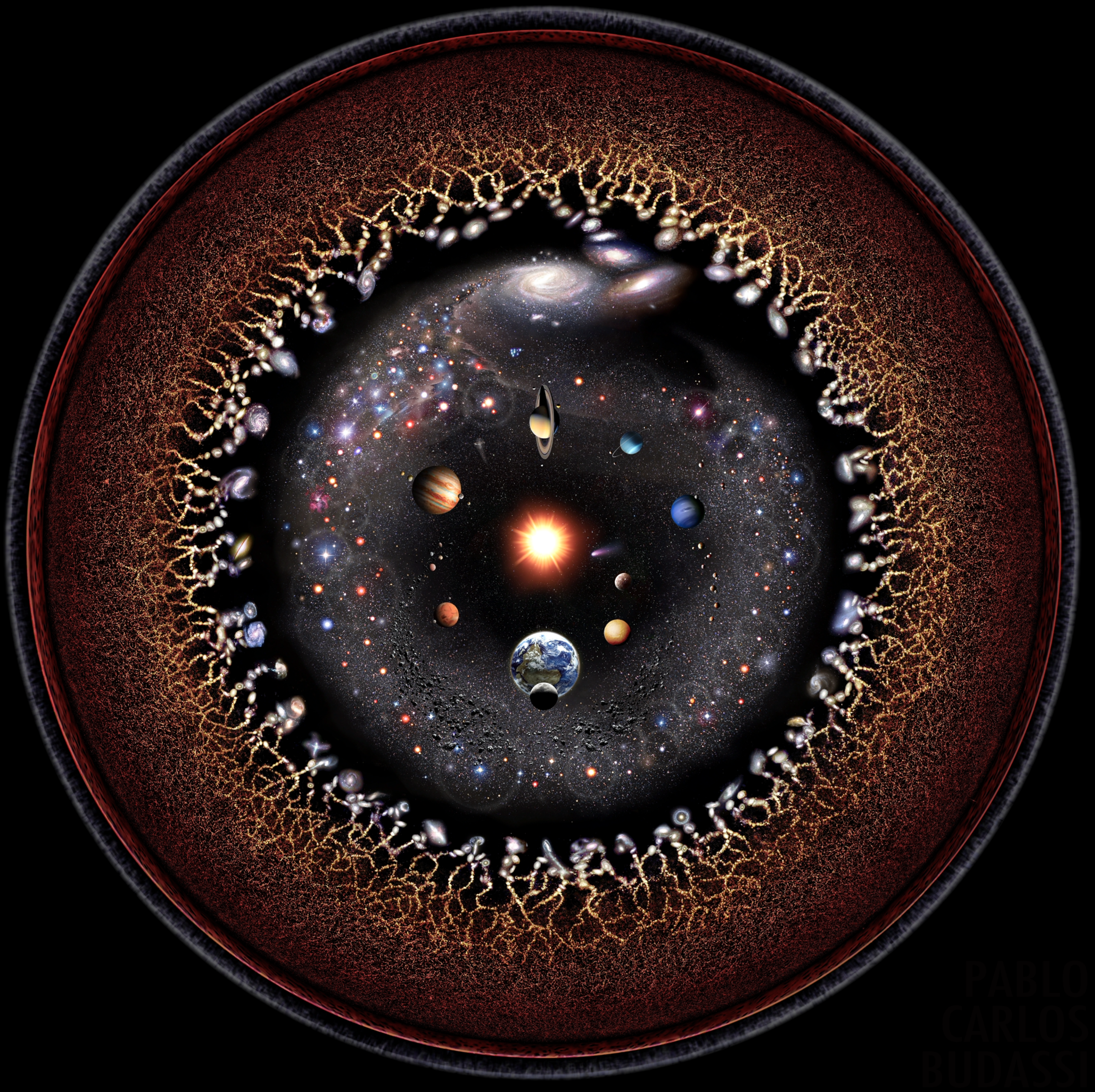
It’s the end of the world as we know it (and I feel fine)



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

A globe-span

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-Frequen Gravit nal Wa

the waves, wh

d from pai

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.

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

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

Astro

re tuning in to a never-before-seen type of gravitational pawned by pairs of supermassive black holes

rs used dead stars t w form of ripple i

vitationa

Monster gravitational spotted for first

SCIENCE

Colossal gravitational waves—trillions of miles long—found for the first time

d by studying rapidly spinning dead e giant ripples of spacetime likely e from merging supermassive black holes—

The Washington Post
Democracy Dies in Darkness

ntists discover that universe is a gravitational waves

ace-time ripples

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.

ack H
Galax
Space

Gravitational wave at the center of the M

Scientists r come from c holes

t may nassive black

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

Ground king gravitational wave discov lock our Univ teries

The results are background, a hum o 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

At Last, There'…

A globe-span…

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-Frequen… Gravit…onal Wa…

…e the waves, wh…

…d from pai

For first time ever, scientists "hear" gravitational waves rippling through the universe

First Evidence of Giant Gravitation… …es Thrills

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.

Gravitational …

Scientists have finally 'heard' the chorus of gravitational waves that ripple through the universe

Scientists have observed for th… holes that are gently stretchi…

ASTROPHYSICS

A Background 'Hum' Perva… Universe, S…

Astro…

…pe of gravitational …k holes

…universe is a

…ravitational waves

…ace-time ripples

…ack H… Galax… Space

Gravitational wave… at the center of the M…

The C… Grav… Find…

Radio teles… reverberating across the cosmos, most … black holes merging in the early universe.

Scientists r… come from c… holes

…it may …massive black

…nd for …ime

…by studying rapidly spinning dead …e giant ripples of spacetime likely …e 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 gravit… waves

Ground… discov… Univ…

…king gravitational wave… …nlock our …teries

The results are … background, a hum o… Universe.

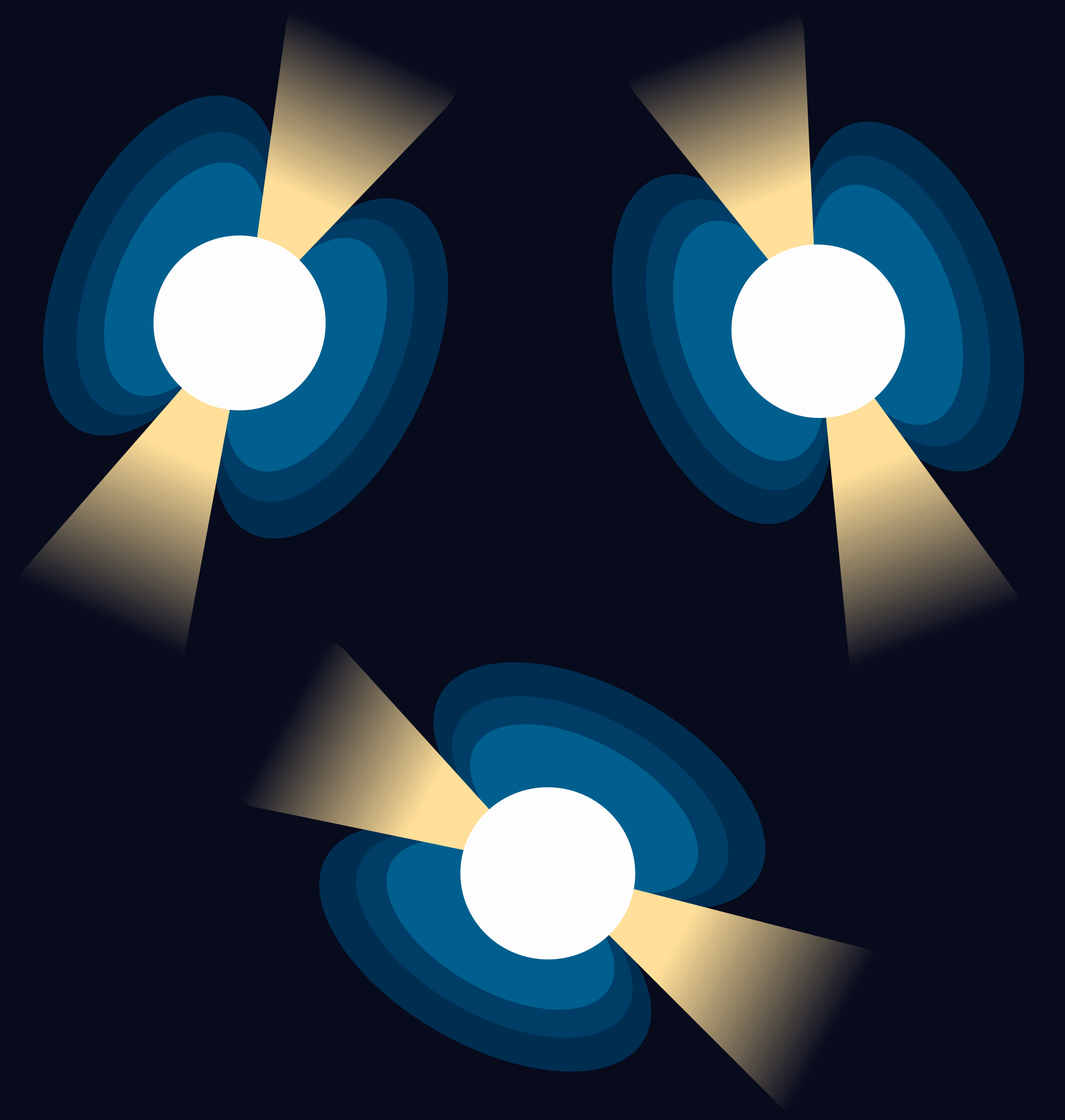
Physics

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

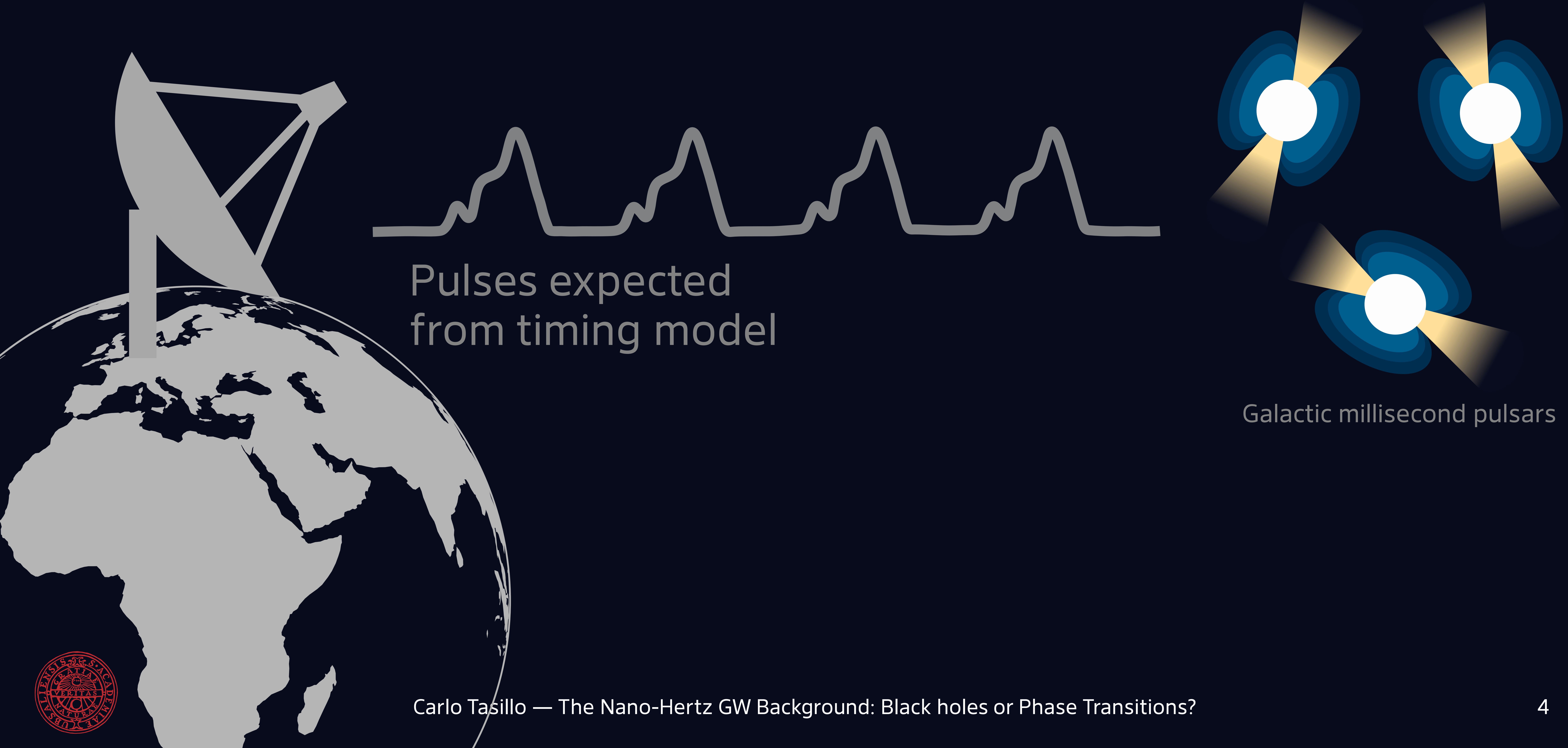
We live in the age of gravitational wave cosmology!

The working principle of a pulsar timing array



Galactic millisecond pulsars

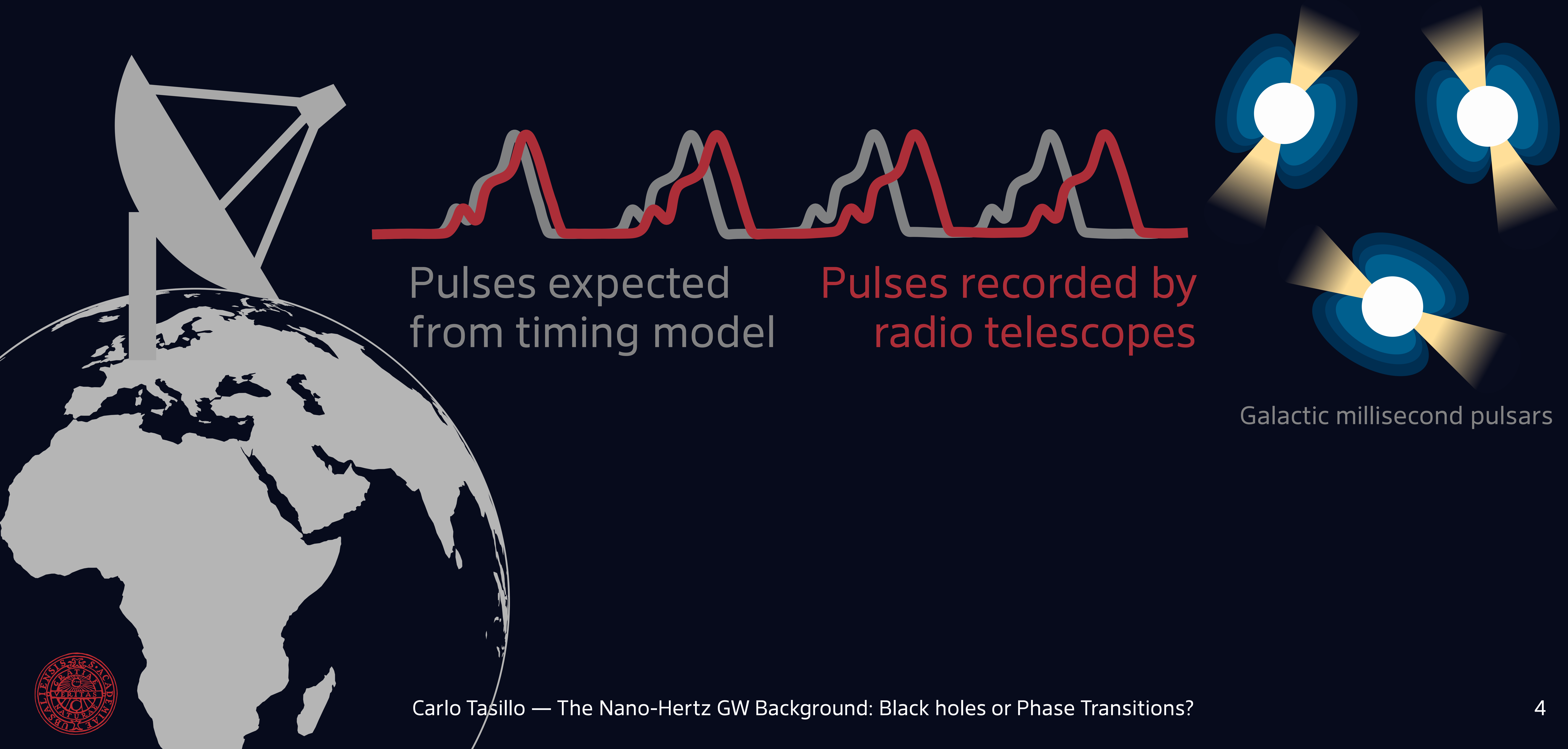
The working principle of a pulsar timing array



Pulses expected from timing model

Galactic millisecond pulsars

The working principle of a pulsar timing array

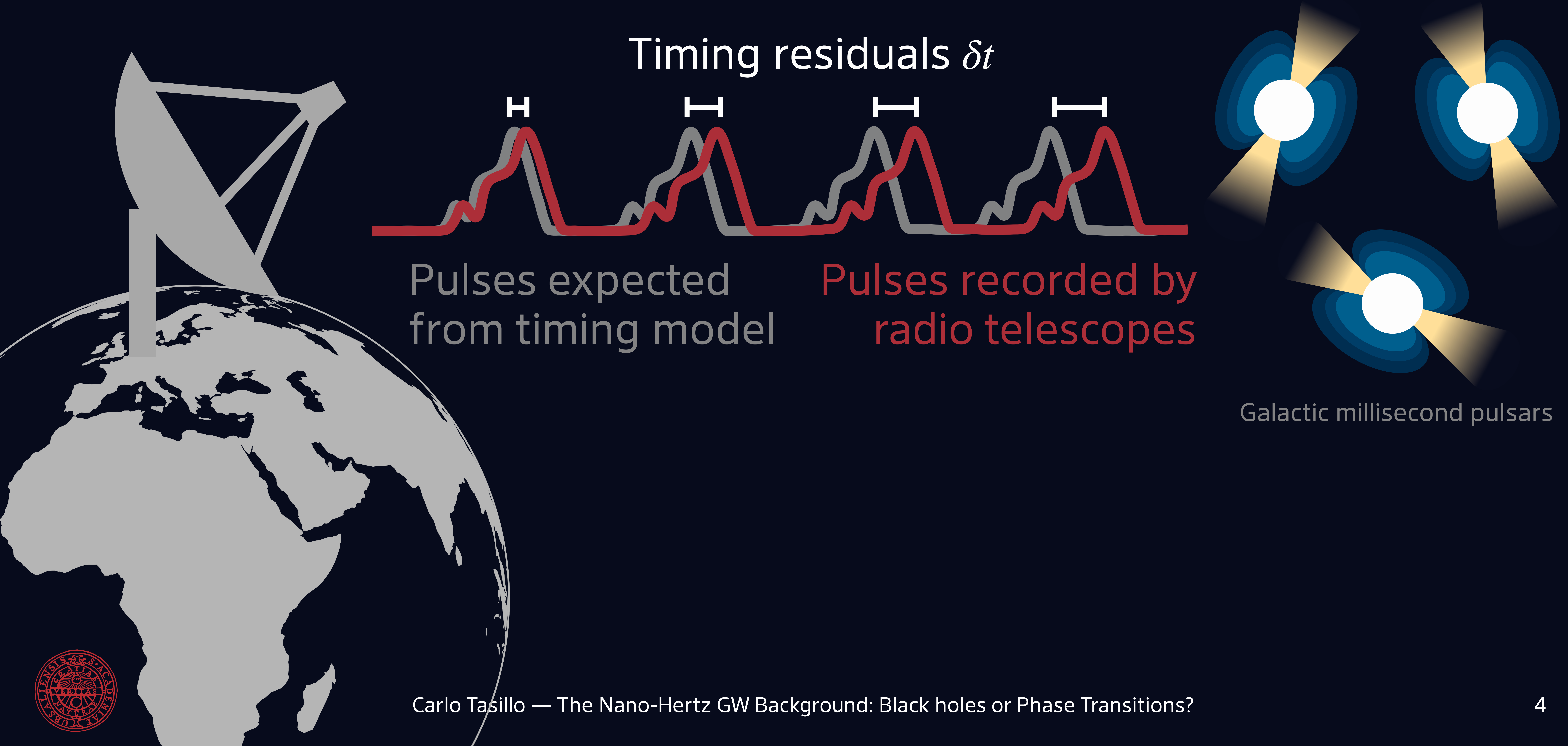


Pulses expected from timing model

Pulses recorded by radio telescopes

Galactic millisecond pulsars

The working principle of a pulsar timing array



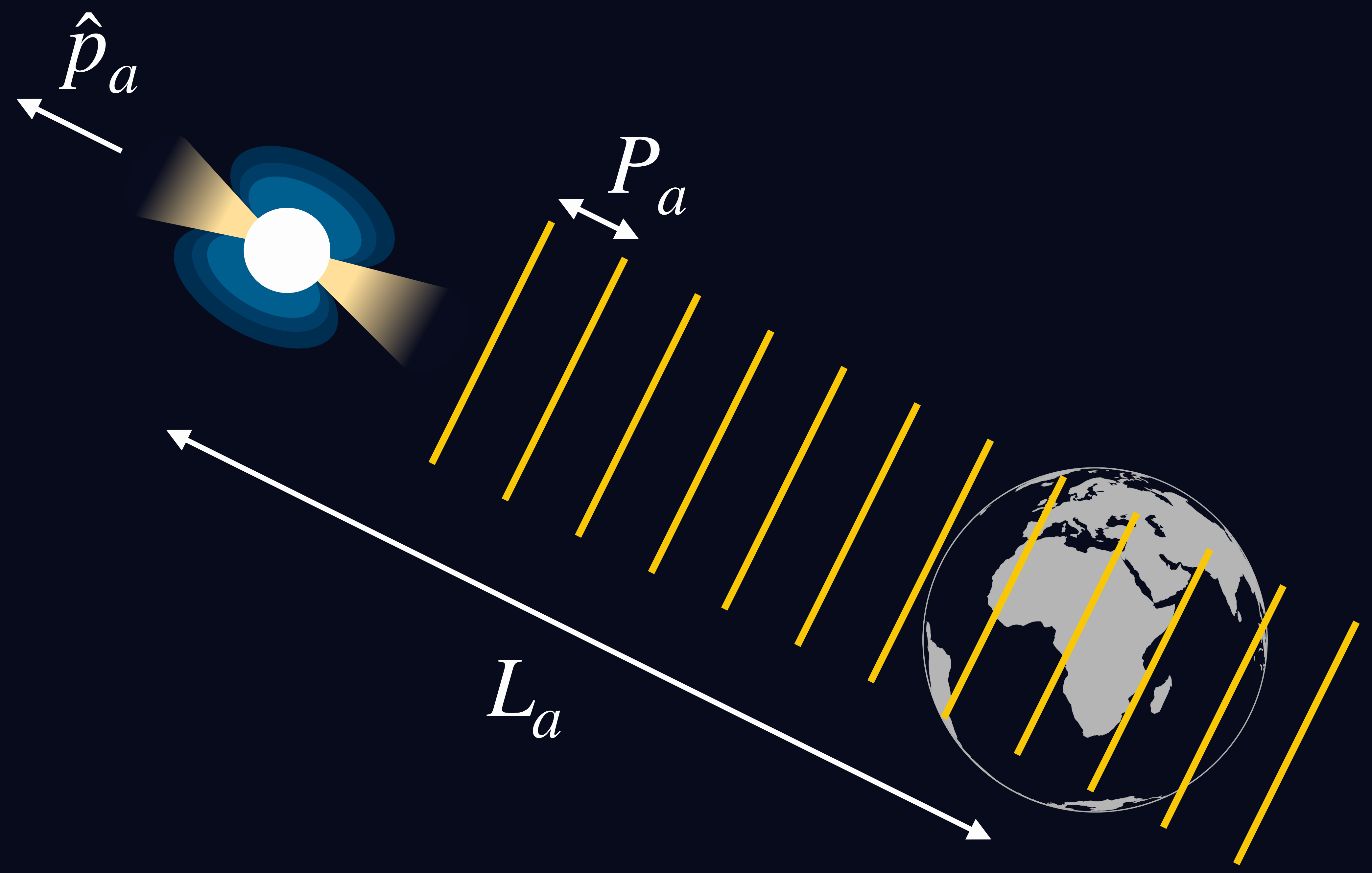
Timing residuals δt

Pulses expected from timing model

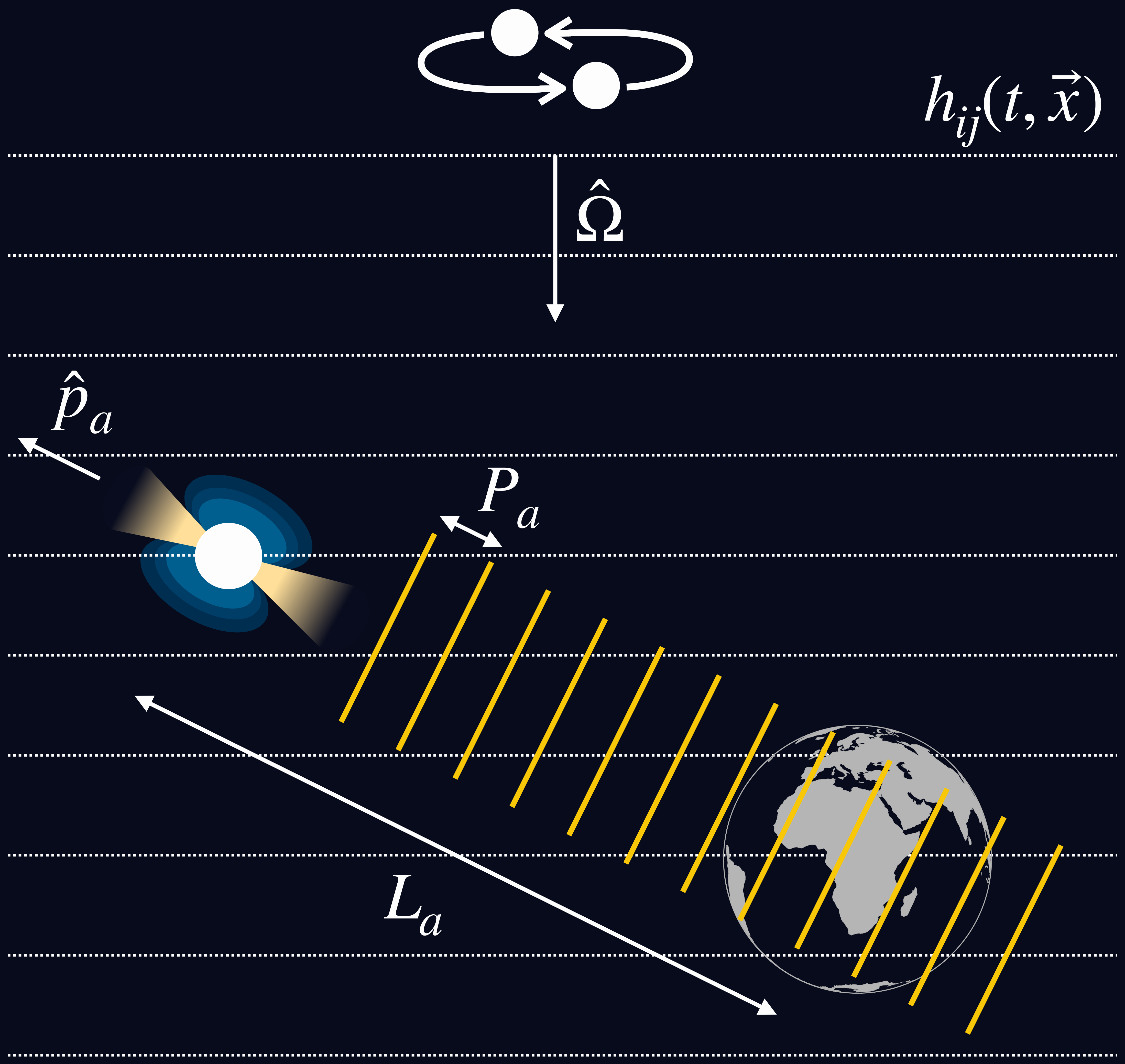
Pulses recorded by radio telescopes

Galactic millisecond pulsars

Single-pulsar response to a monochromatic GW



Single-pulsar response to a monochromatic GW



Single-pulsar response to a monochromatic GW

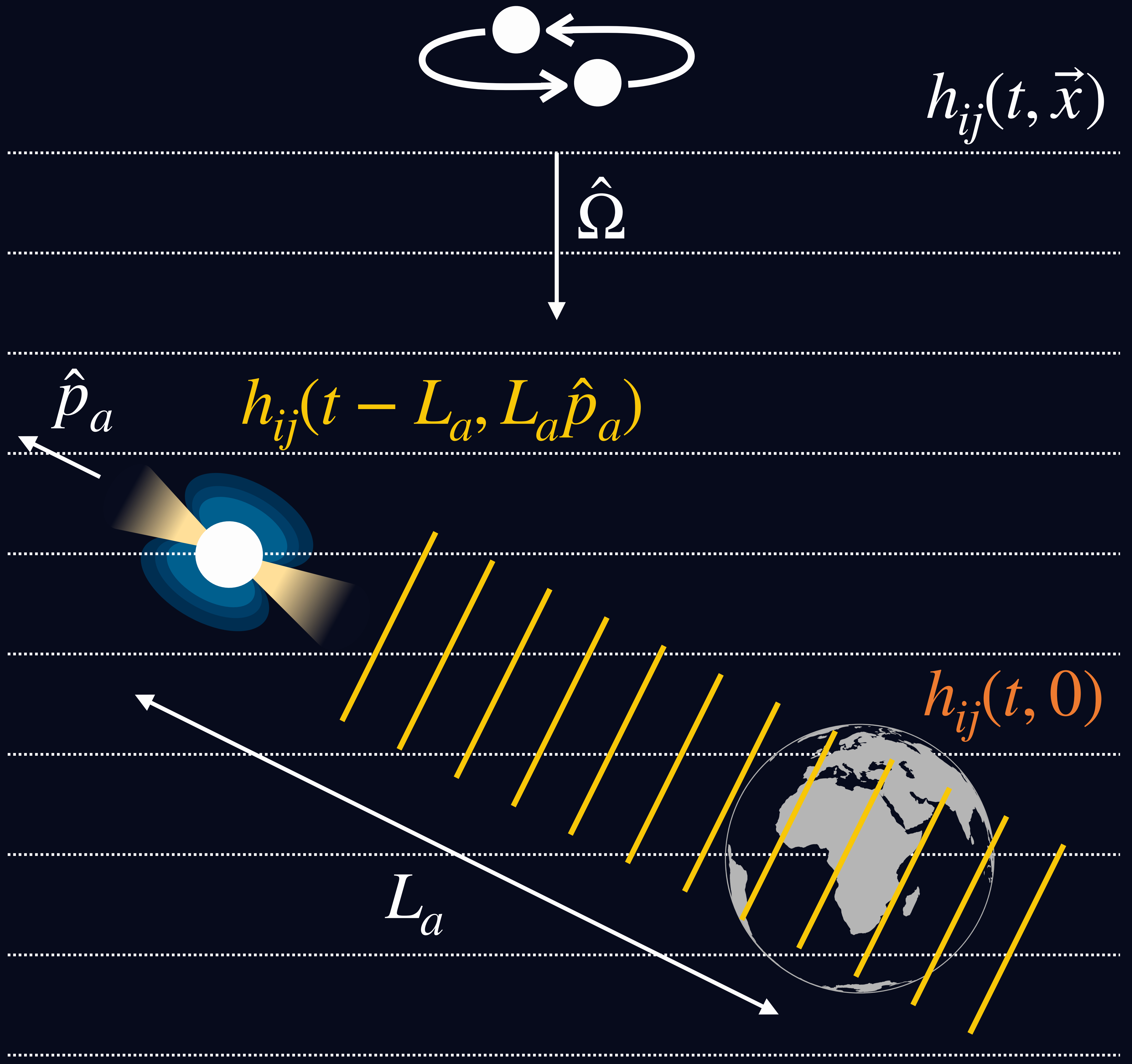
Timing residual

„Earth term"

$$\frac{\delta P_a(t)}{P_a} = \frac{\hat{p}^i_a \hat{p}^j_a}{2(1+\hat{\Omega}\cdot\hat{p}_a)}\left[h_{ij}(t,0) - h_{ij}(t-L_a, L_a\hat{p}_a)\right]$$

Geometric response function

„Pulsar term"



[Penelope Cowley]

GW backgrounds

$$h_{ij}(t,\vec{x}) = \sum_A \int \mathrm{d}f \int \mathrm{d}\hat{\Omega}\, \tilde{h}_A(f,\hat{\Omega})\, e^A_{ij}(\hat{\Omega})\, \mathrm{e}^{-2\pi \mathrm{i} f\,(t-\hat{\Omega}\cdot\vec{x})}$$

GW backgrounds

$$h_{ij}(t,\vec{x}) = \sum_{A} \int \mathrm{d}f \int \mathrm{d}\hat{\Omega}\, \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\substack{\text{„Fourier“ amplitudes,} \\ \text{Treated as random variables}}} \overbrace{e_{ij}^{A}(\hat{\Omega})}^{\text{Polarization tensors}} \underbrace{\mathrm{e}^{-2\pi \mathrm{i} f\,(t-\hat{\Omega}\cdot\vec{x})}}_{\text{Plane waves}}$$

GW backgrounds

$$h_{ij}(t,\vec{x}) = \sum_A \int \mathrm{d}f \int \mathrm{d}\hat{\Omega}\, \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\text{„Fourier" amplitudes, Treated as random variables}}\, \overbrace{e^A_{ij}(\hat{\Omega})}^{\text{Polarization tensors}}\, \underbrace{\mathrm{e}^{-2\pi \mathrm{i} f(t-\hat{\Omega}\cdot\vec{x})}}_{\text{Plane waves}}$$

Isotropy, gaussianity,
stationarity, no polarization

$$\langle \tilde{h}_A(f,\hat{\Omega})^* \tilde{h}_A(f',\hat{\Omega}') \rangle \propto \delta(f-f')\, H(f)$$

GW backgrounds

$$h_{ij}(t,\vec{x}) = \sum_A \int \mathrm{d}f \int \mathrm{d}\hat{\Omega}\, \underbrace{\tilde{h}_A(f,\hat{\Omega})}_{\substack{\text{„Fourier“ amplitudes,} \\ \text{Treated as random variables}}}\, \overbrace{e^A_{ij}(\hat{\Omega})}^{\text{Polarization tensors}}\, \underbrace{\mathrm{e}^{-2\pi \mathrm{i} f\,(t-\hat{\Omega}\cdot\vec{x})}}_{\text{Plane waves}}$$

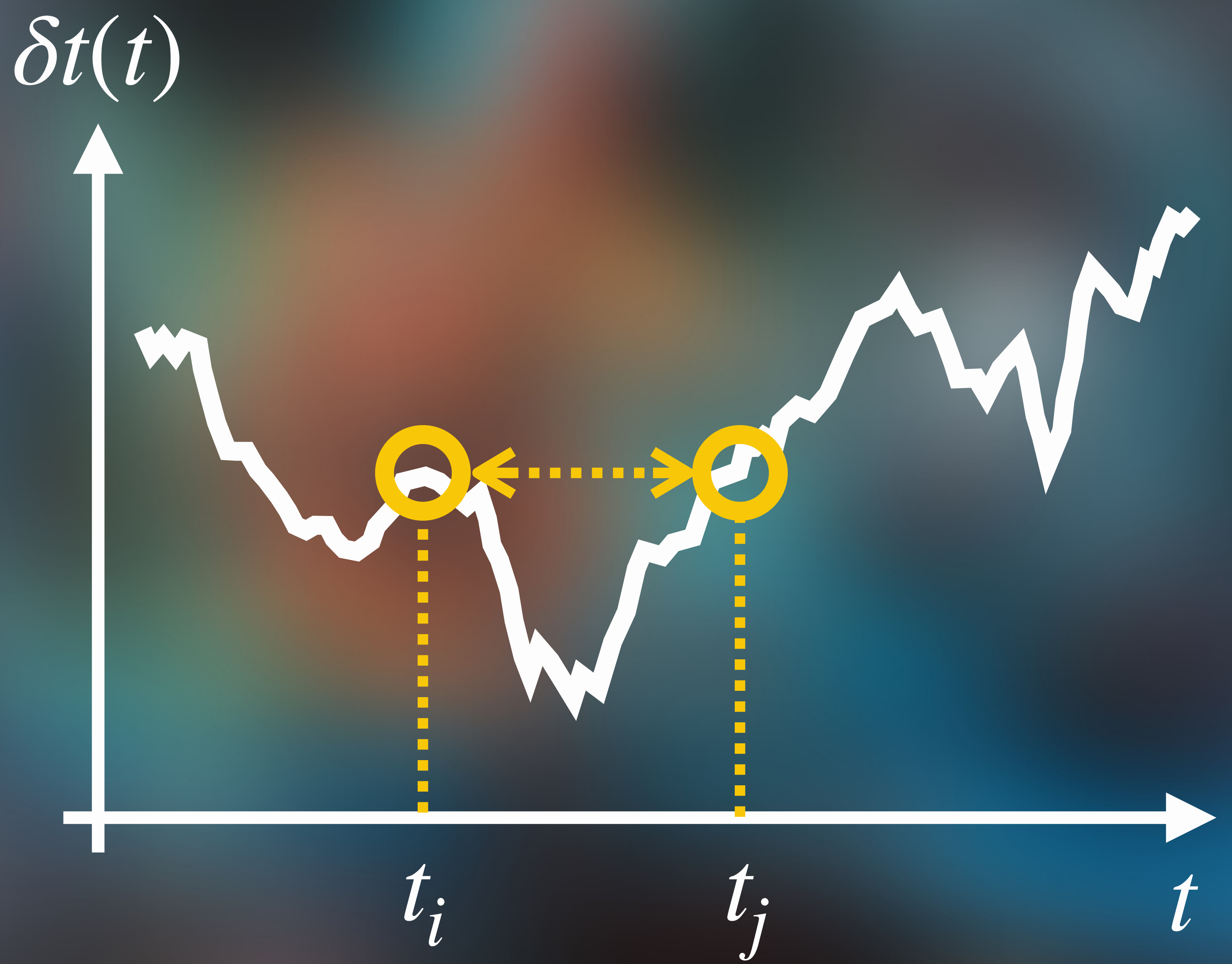
Isotropy, gaussianity,
stationarity, no polarization

$$\langle \tilde{h}_A(f,\hat{\Omega})^*\, \tilde{h}_A(f',\hat{\Omega}')\rangle \propto \delta(f-f')\boxed{H(f)}$$

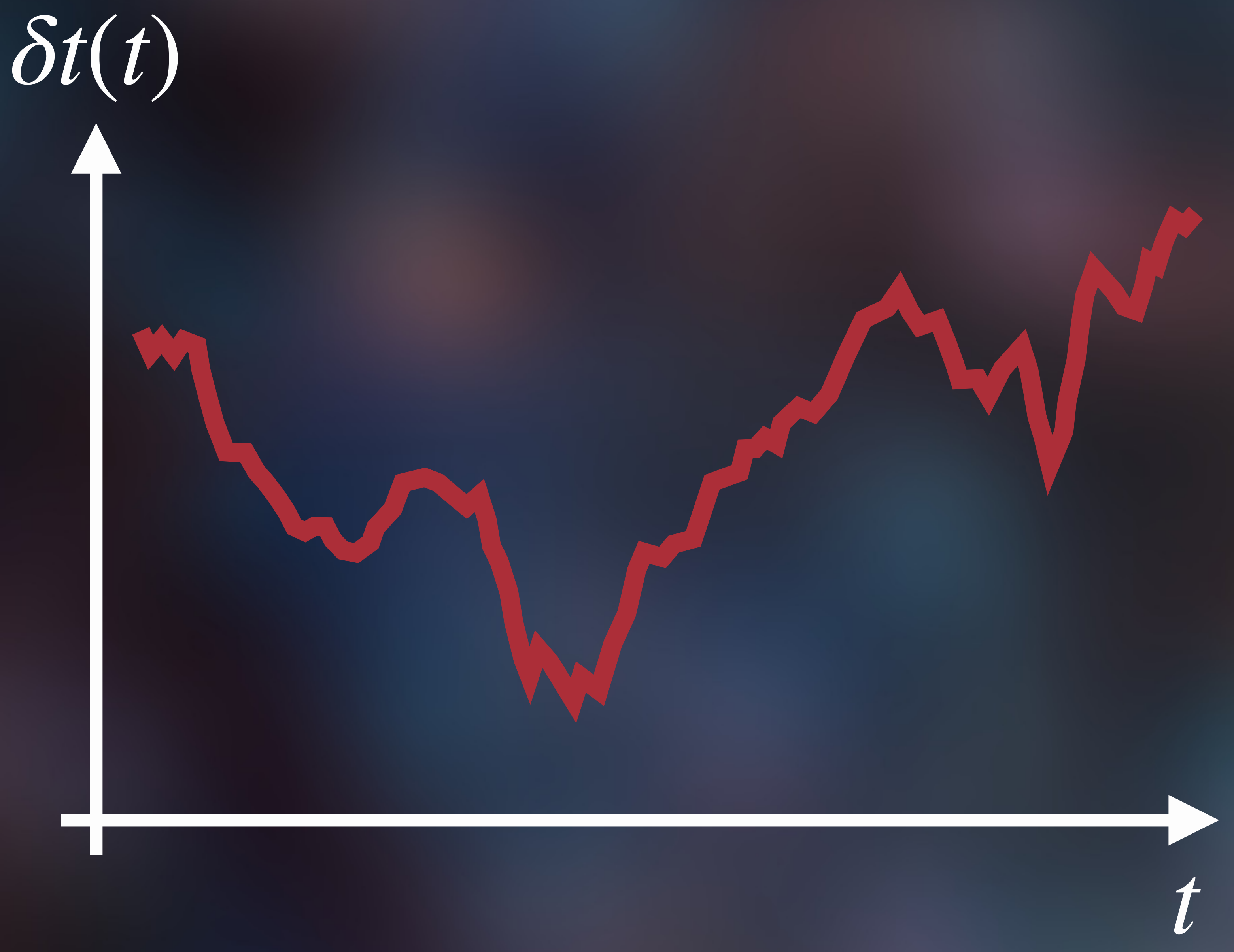
The GWB is fully described by its spectrum!

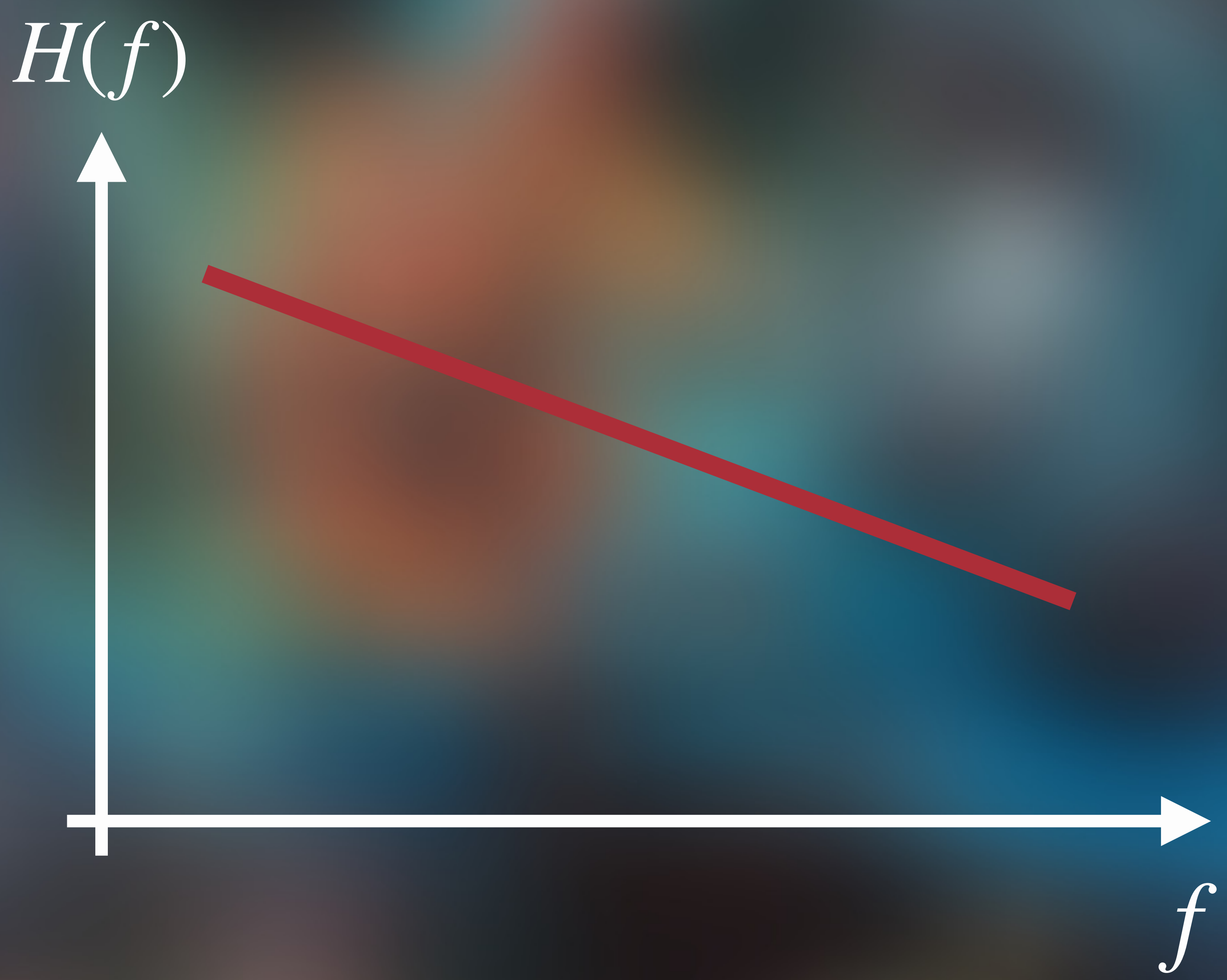
Correlations between timing residuals

$$\langle \delta t(t_i)\, \delta t(t_j) \rangle \propto \int \mathrm{d}f\, \boxed{H(f)}\, \mathrm{e}^{2\pi i f (t_i - t_j)}$$

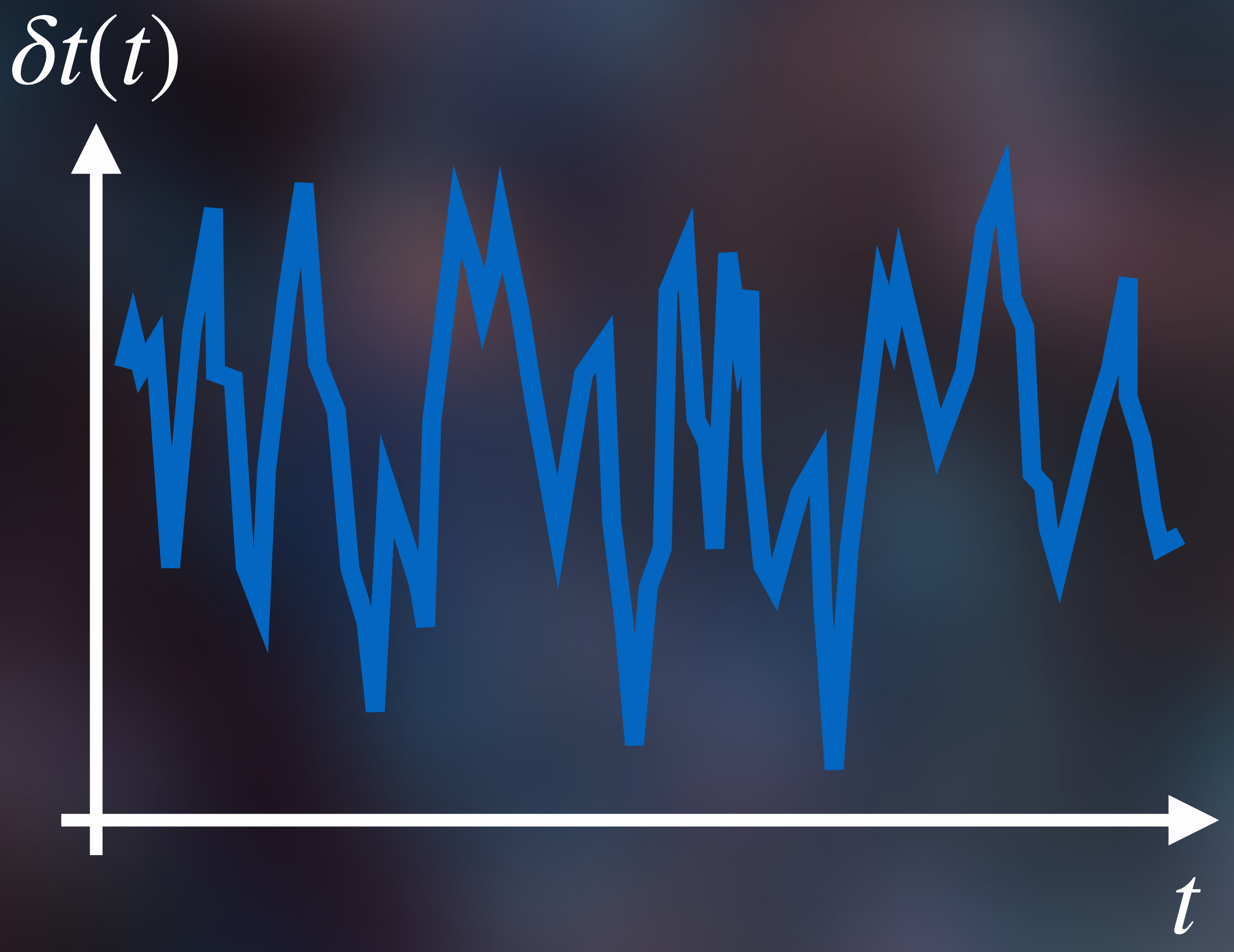


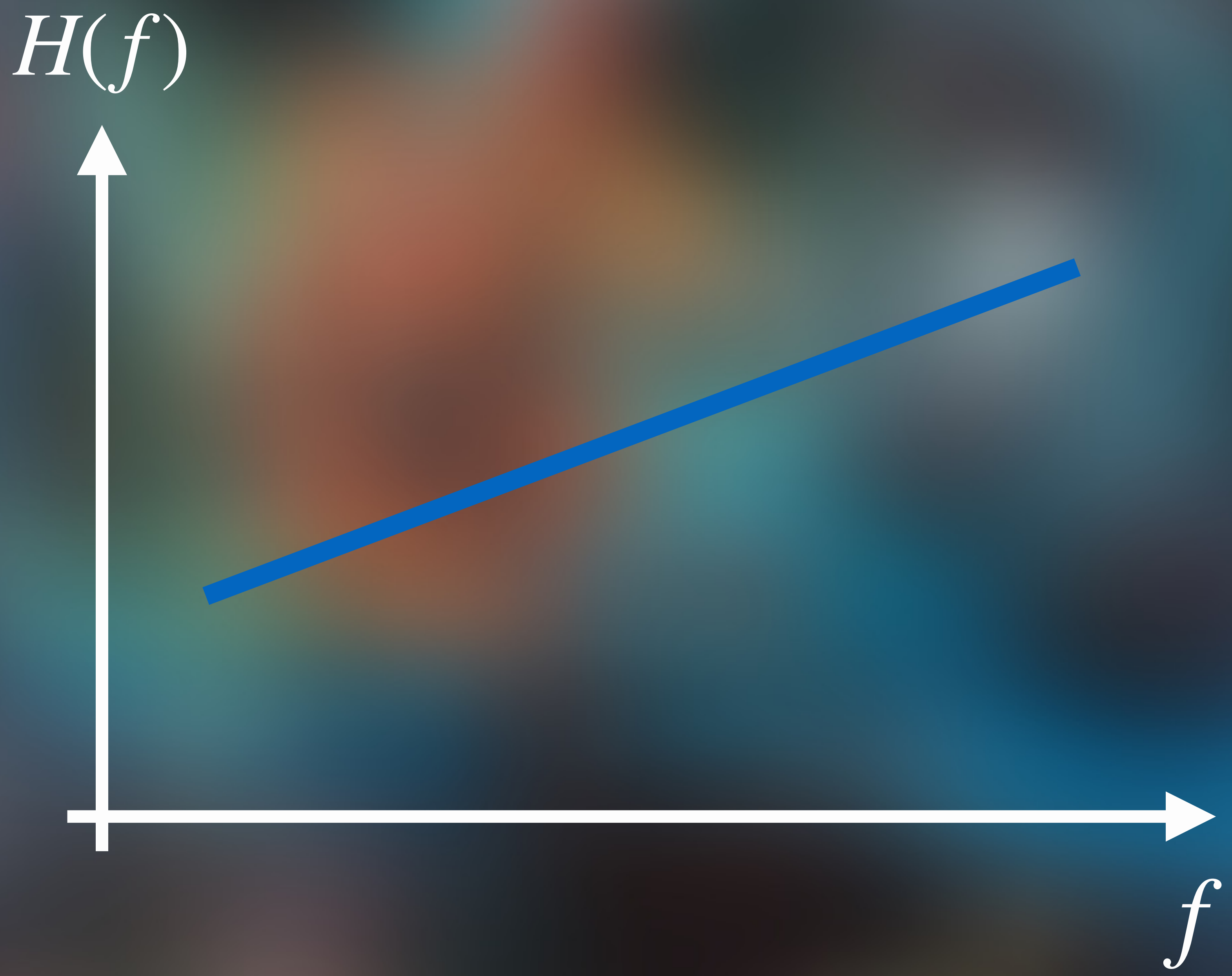
Correlations between timing residuals



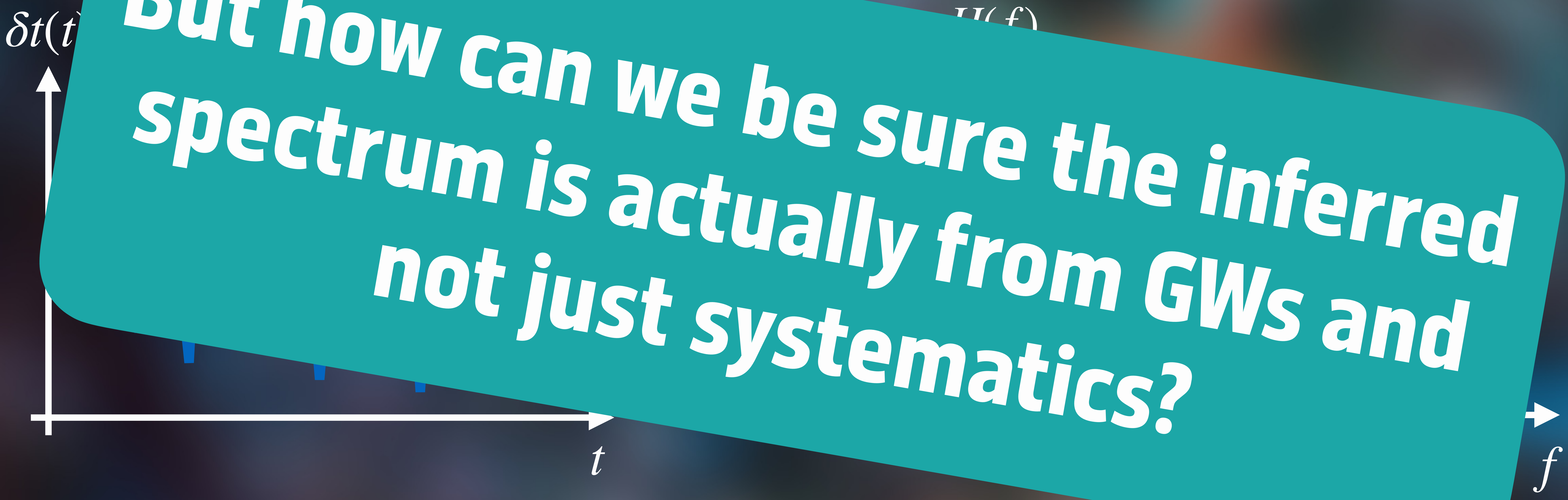


Correlations between timing residuals





Correlations between timing residuals

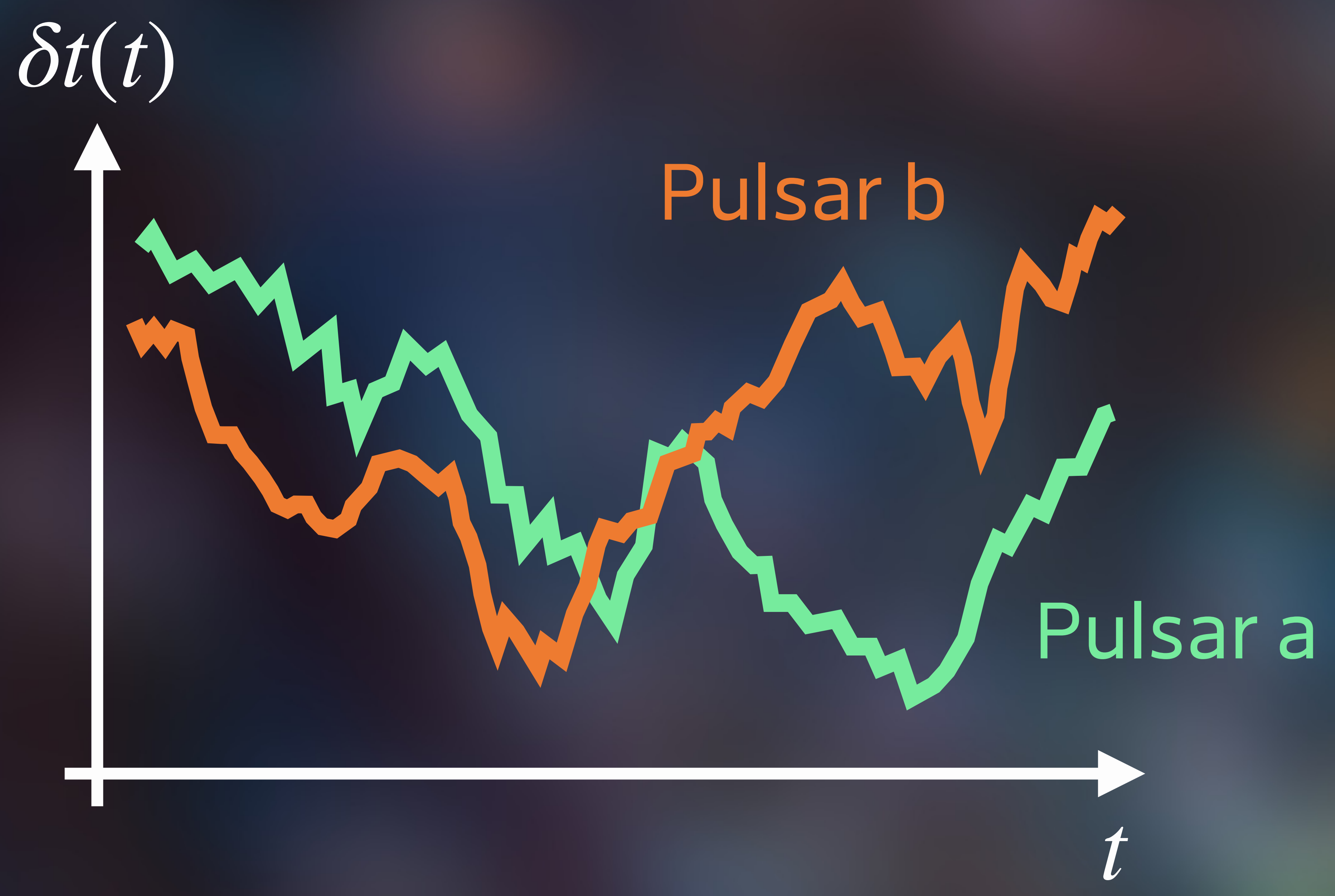


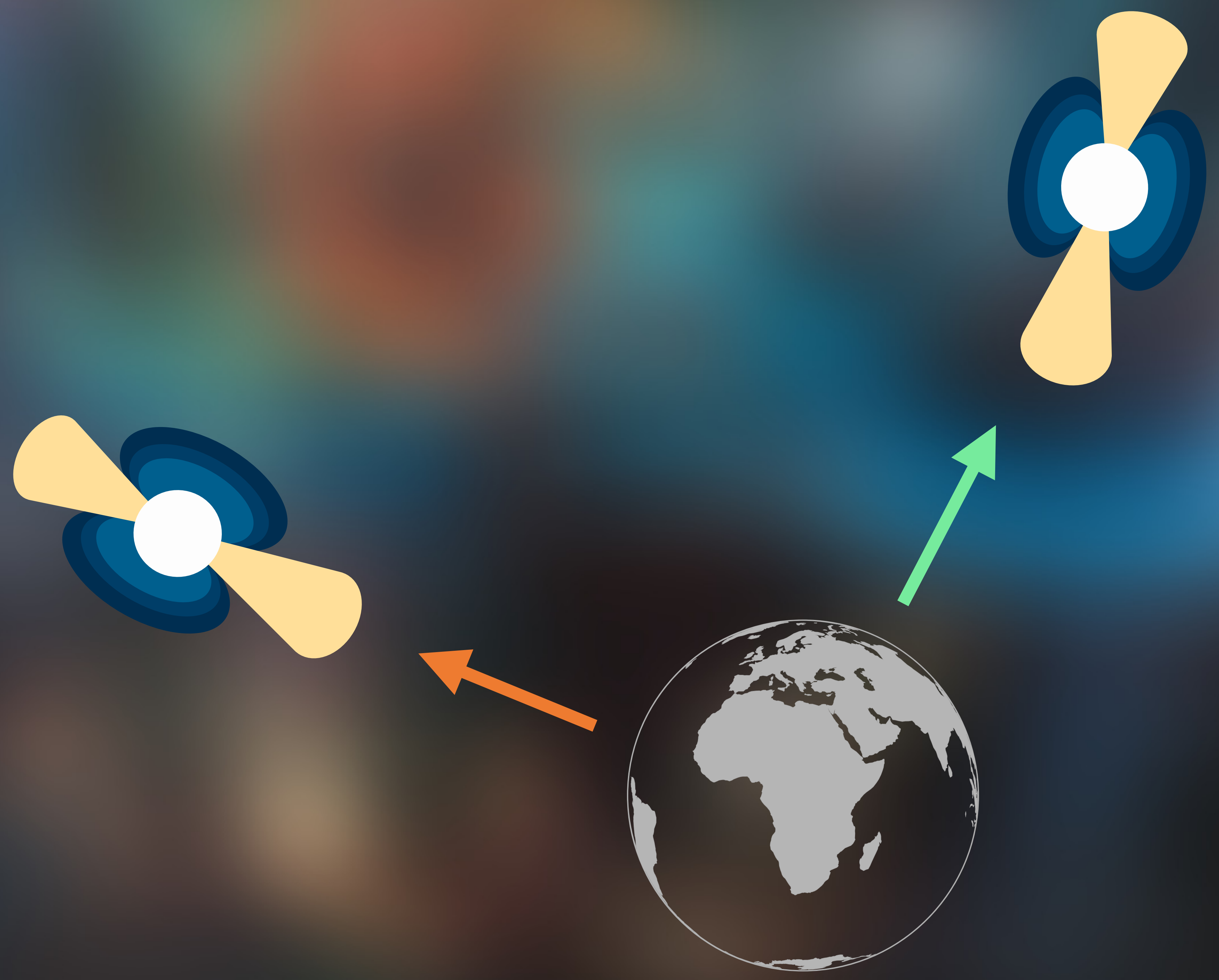
But how can we be sure the inferred spectrum is actually from GWs and not just systematics?

Correlations between timing residuals

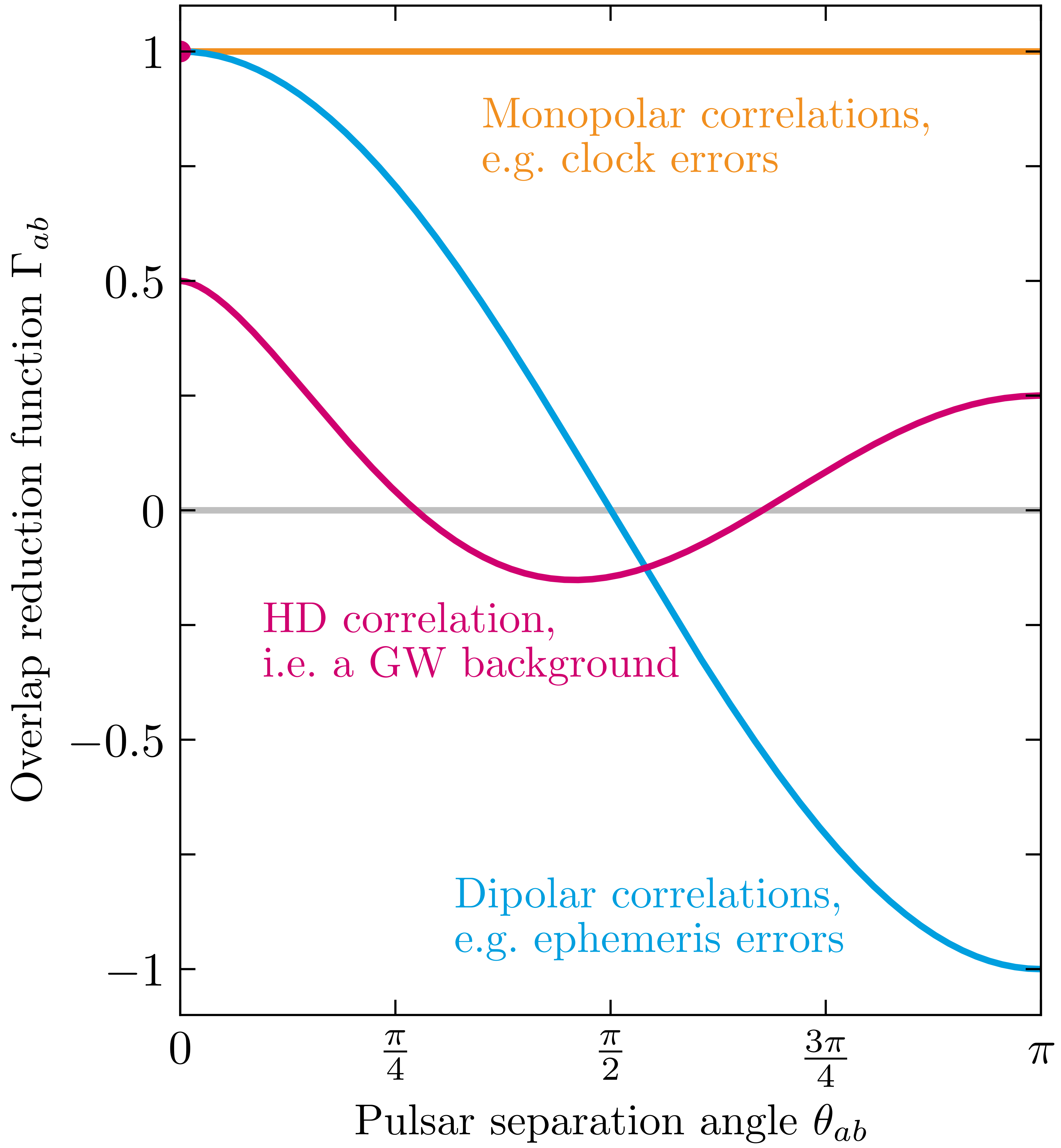
If the source of the common spectrum among pulsars is GWs, there is a characteristic correlation between different pulsars

$$\langle \delta t_a \, \delta t_b \rangle \propto \Gamma_{ab}$$





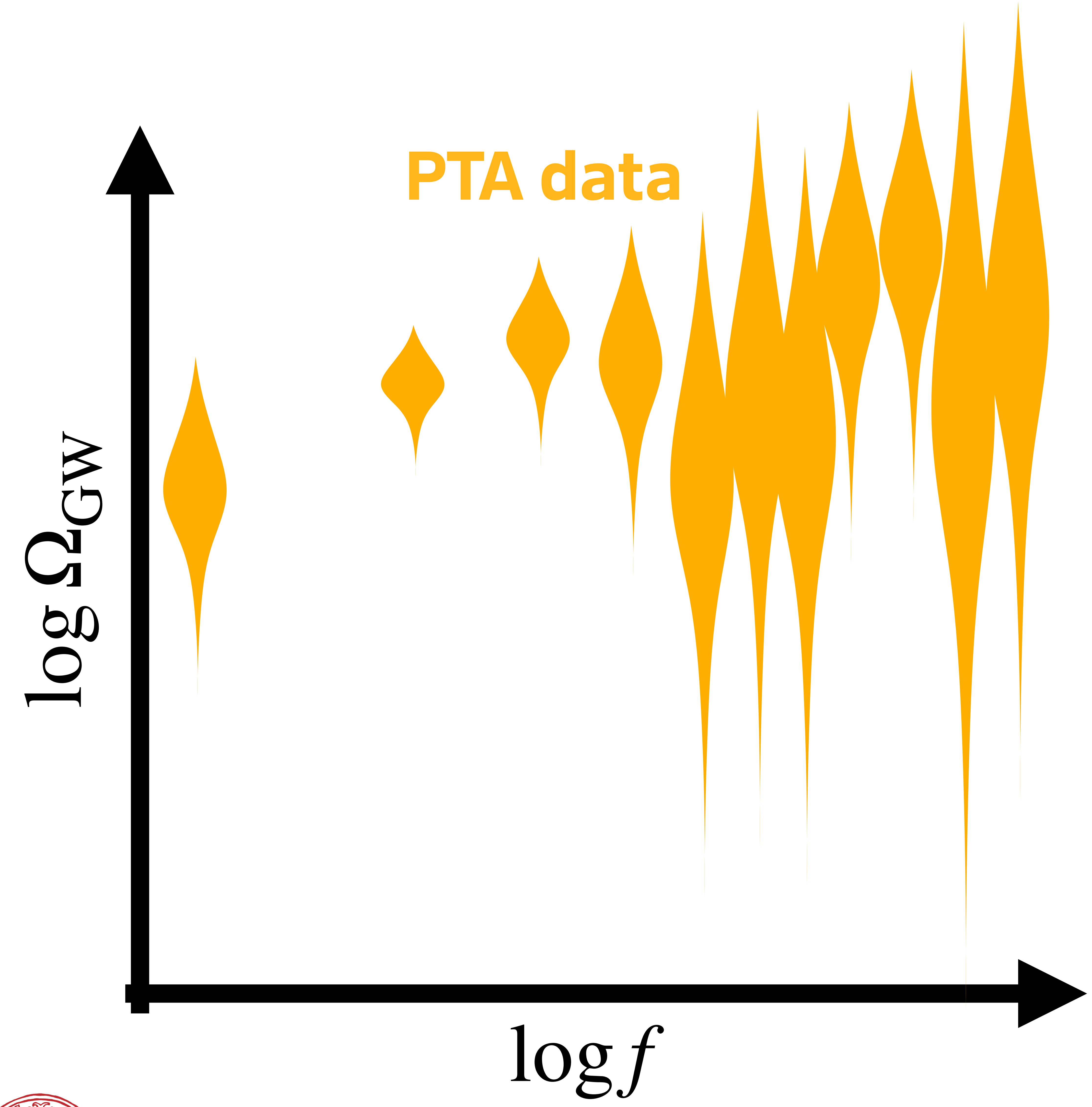
Searching for the Hellings-Downs correlation



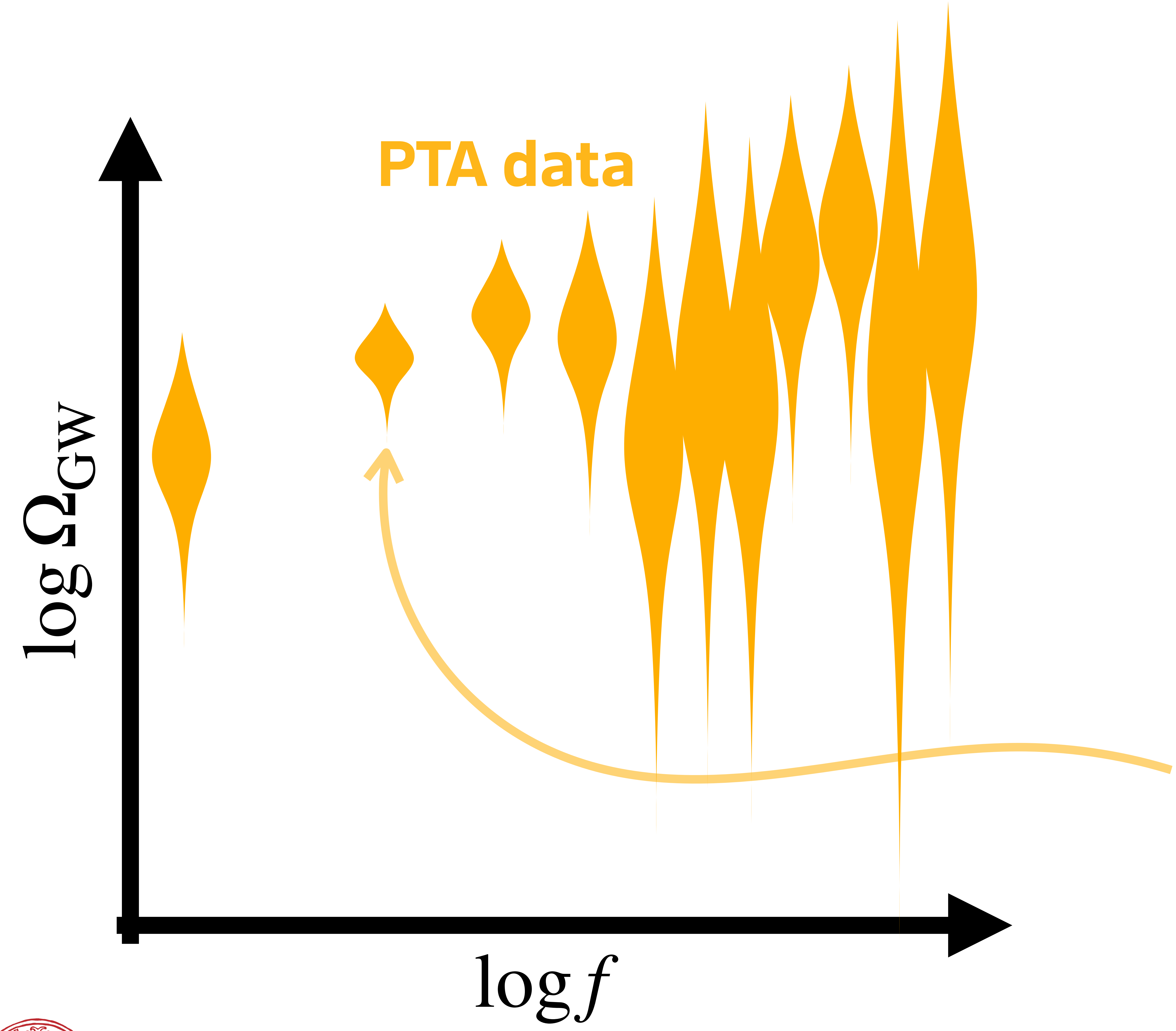
- PTAs found an underlying „common red process" among $\mathcal{O}(70)$ pulsars
- Signal could have many sources:
  - Pulsars themselves, Clock errors, Ephemeris errors:
    All ruled at with $>5\sigma$ significance
  - Gravitational wave background:
    $3-4\sigma$ evidence [NANOGrav, 2023]

What is the source?

Learning to play the violin

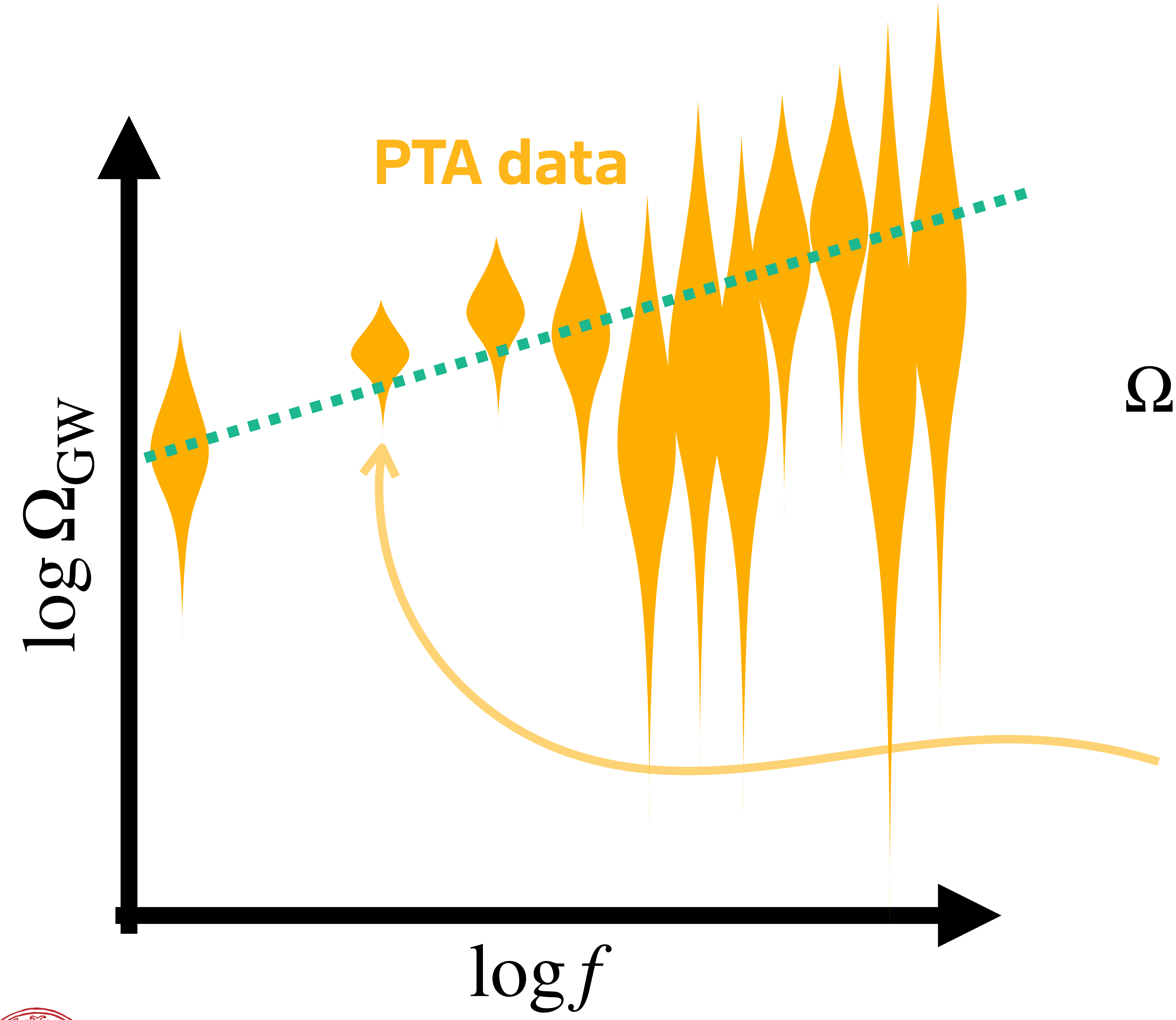


Learning to play the violin



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

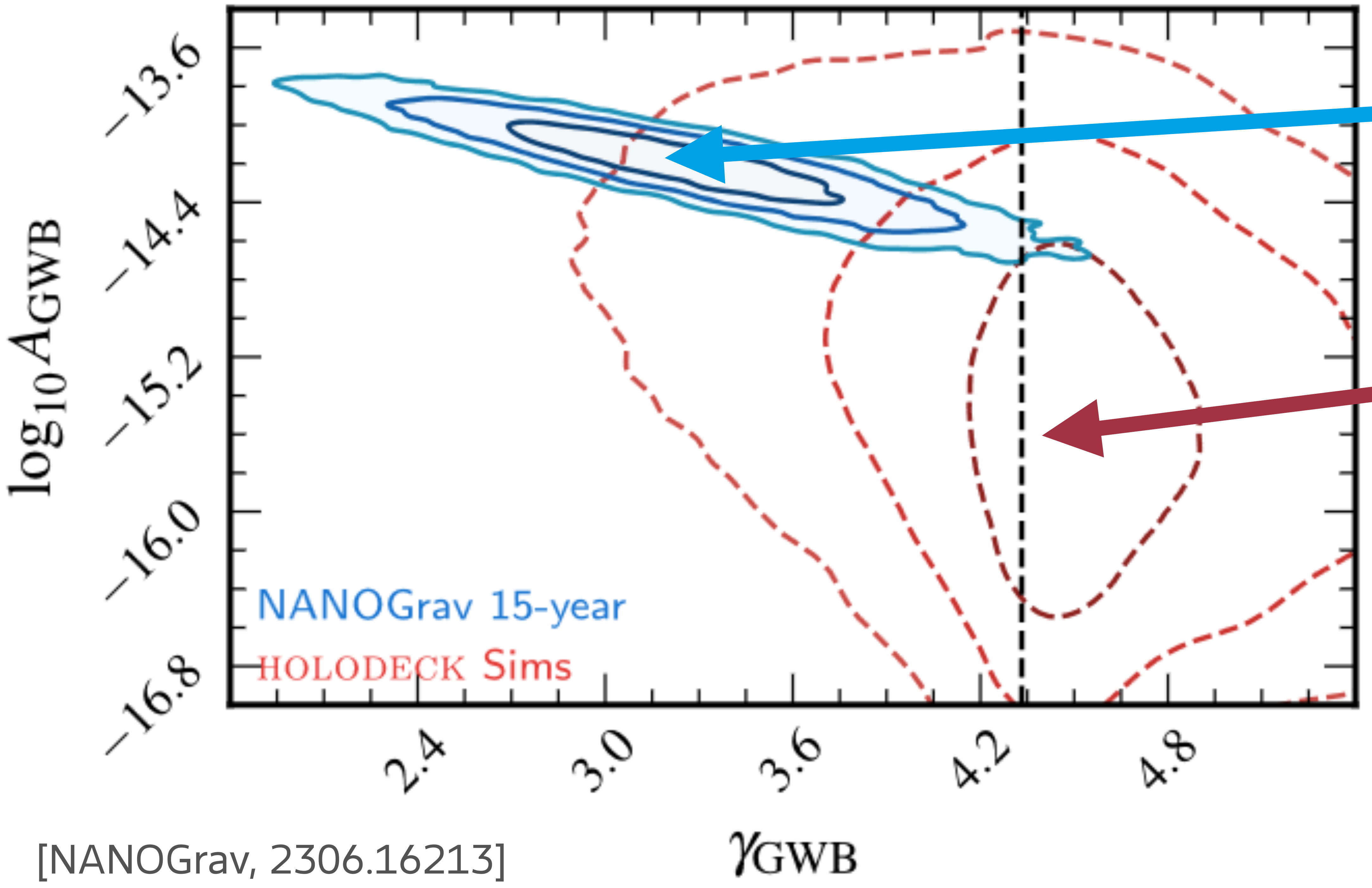


The inferred spectral shape of the GWB is well described by a power law

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

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

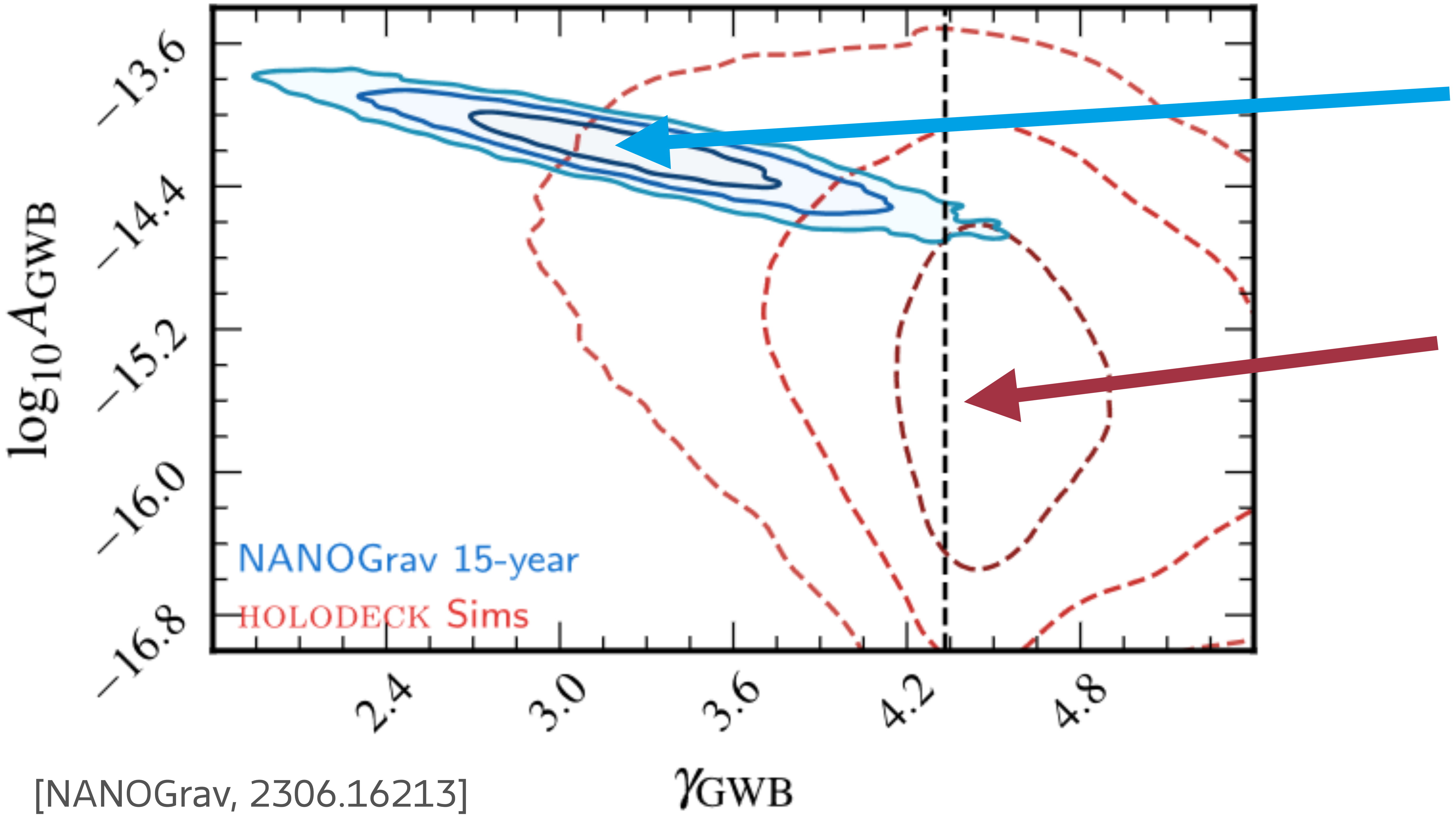


[NANOGrav, 2306.16213]

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



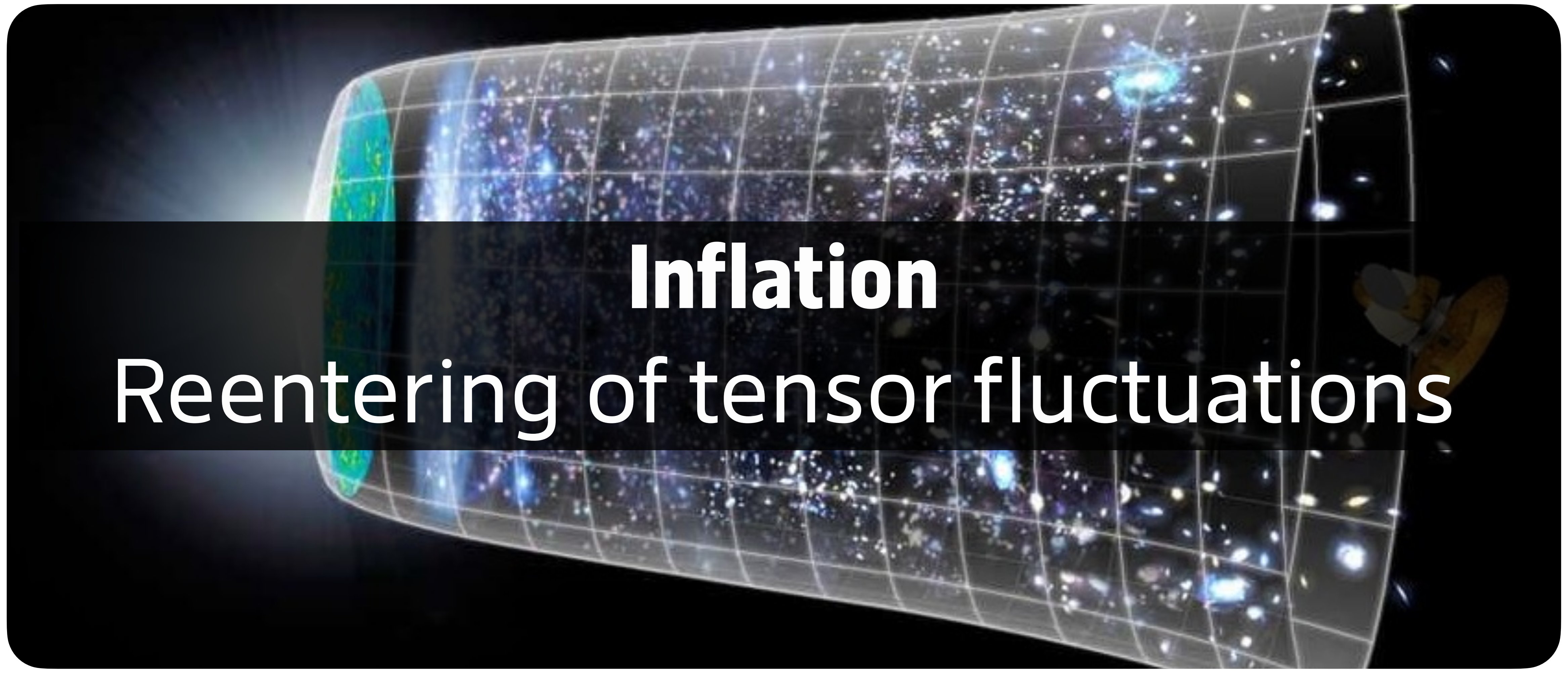
[NANOGrav, 2306.16213]

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



Inflation

Reentering of tensor fluctuations

Phase transitions

Connection to dark matter?

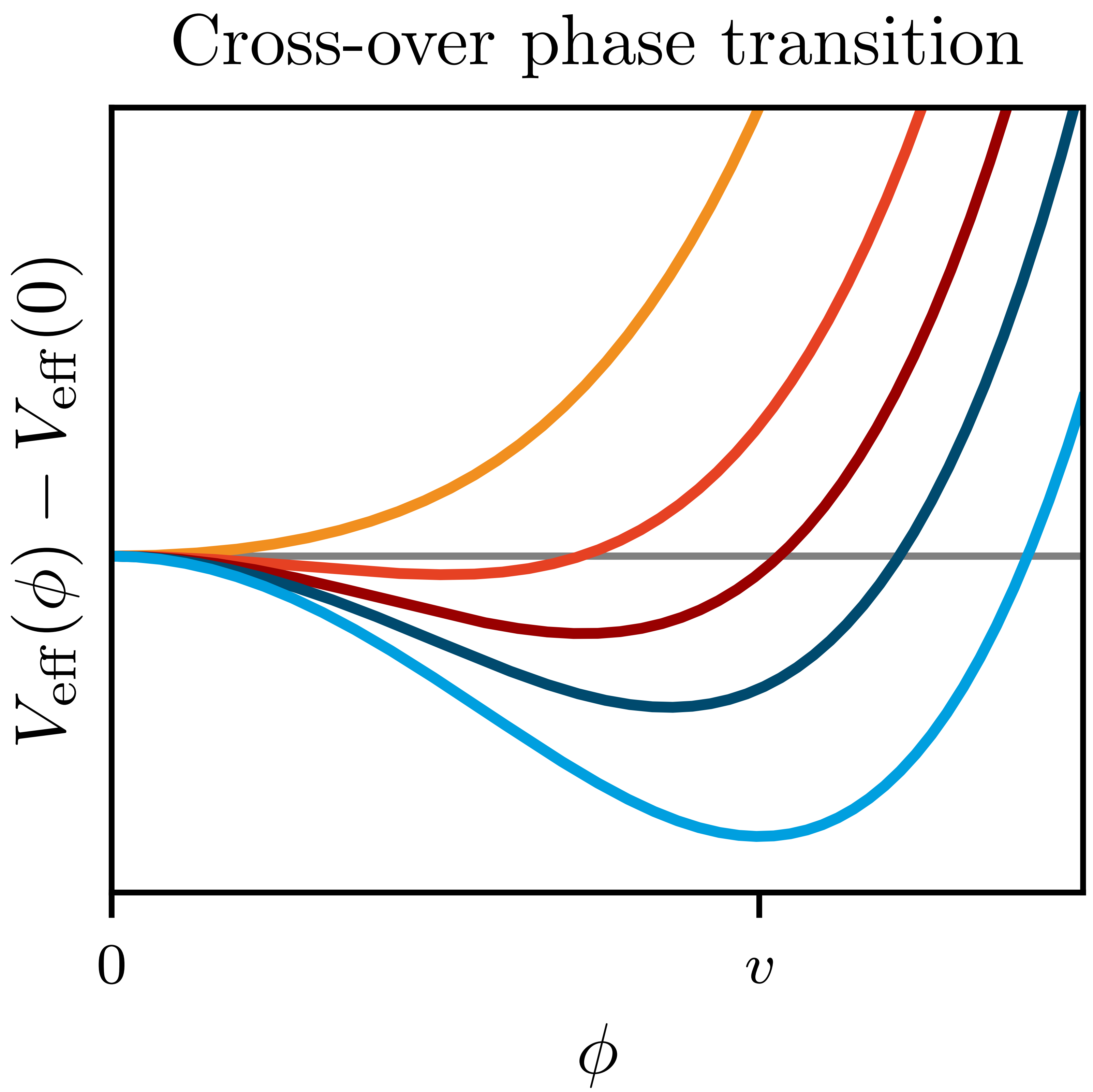
Topological defects

Cosmic strings and domain walls

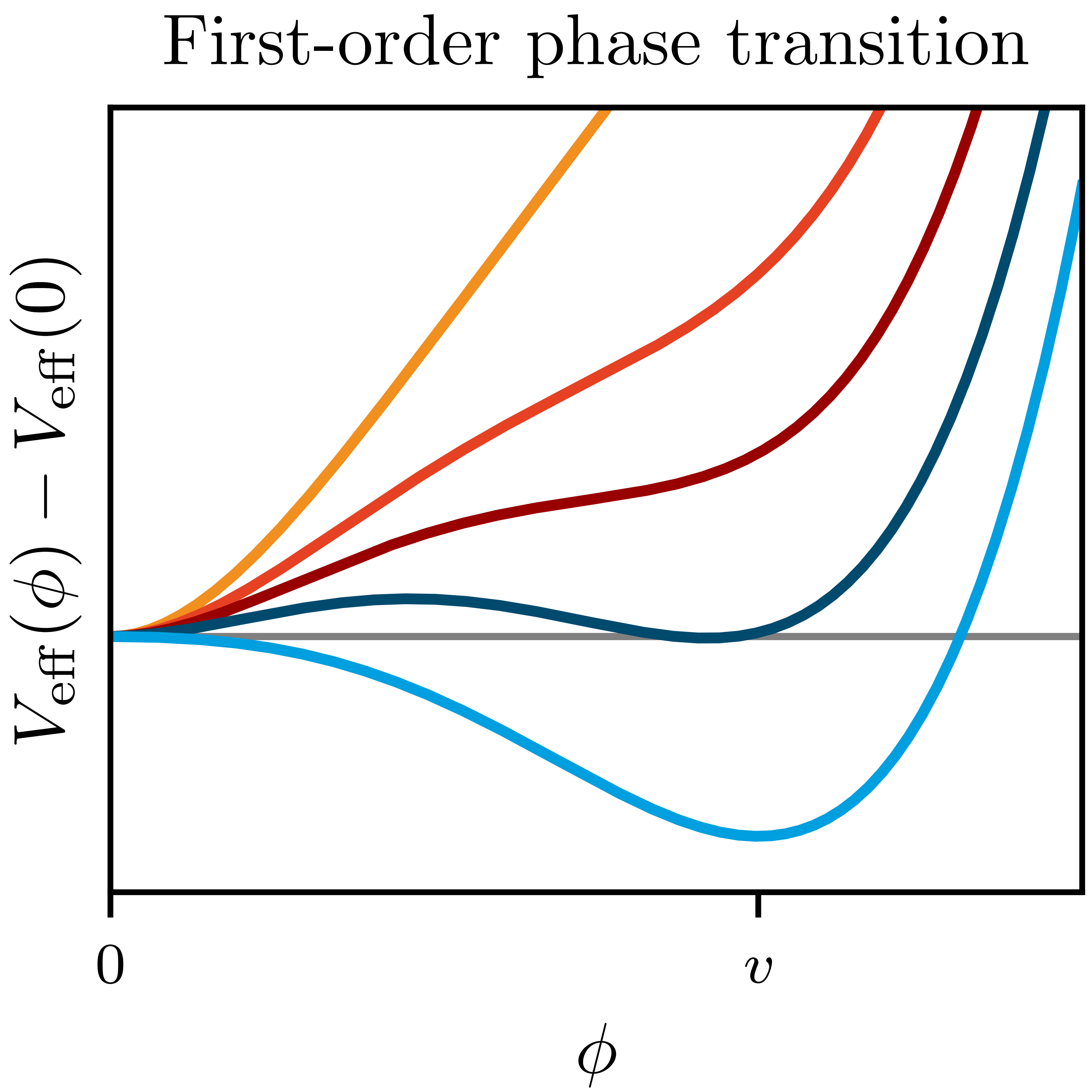
Primordial black holes

But only if they are clustered

First-order phase transitions vs. cross-overs


Cross-over phase transition

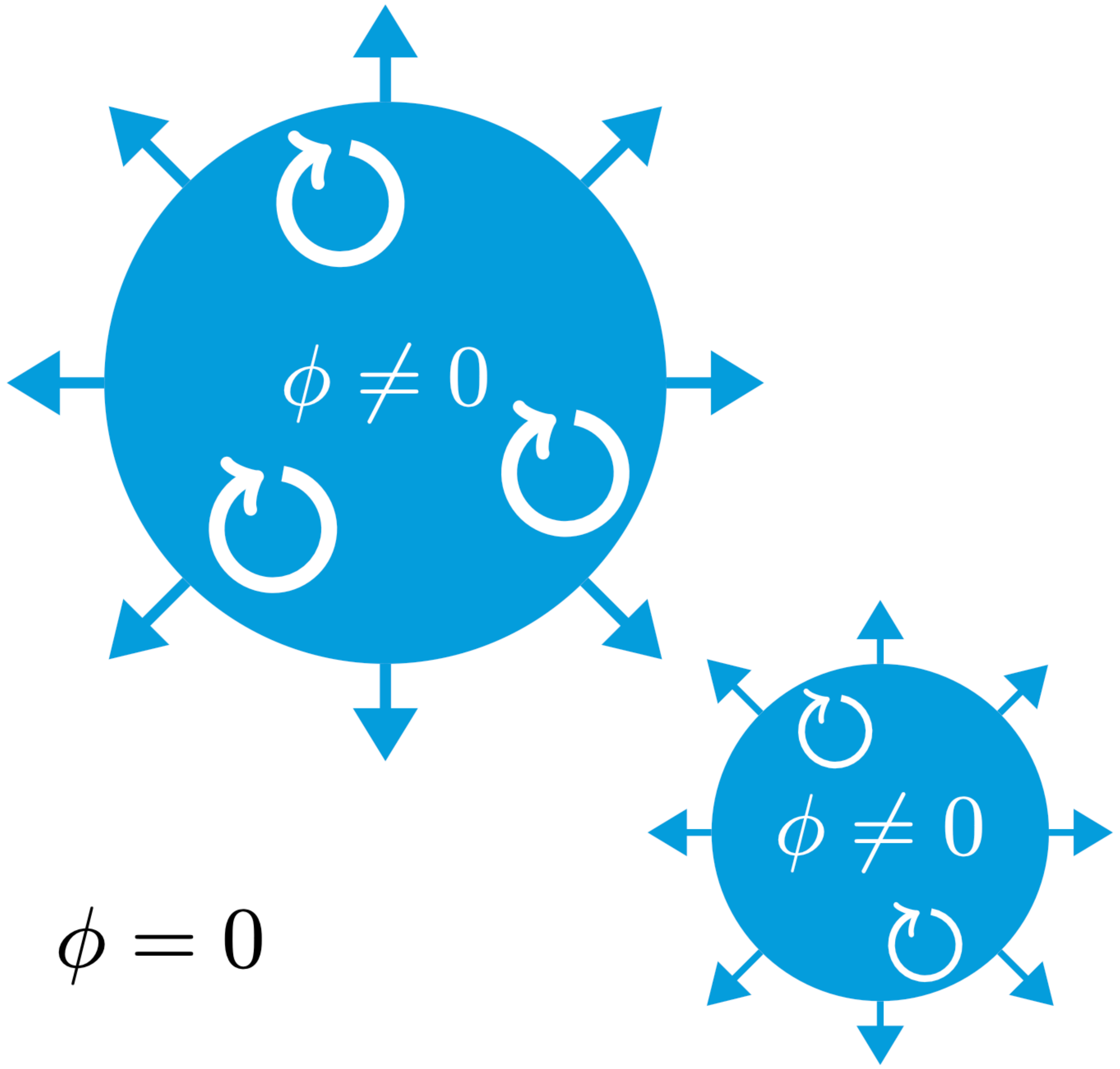
A scalar field “rolls down” from $\phi = 0$ to $\phi = v$, when the plasma cools from high temperatures to low temperatures.

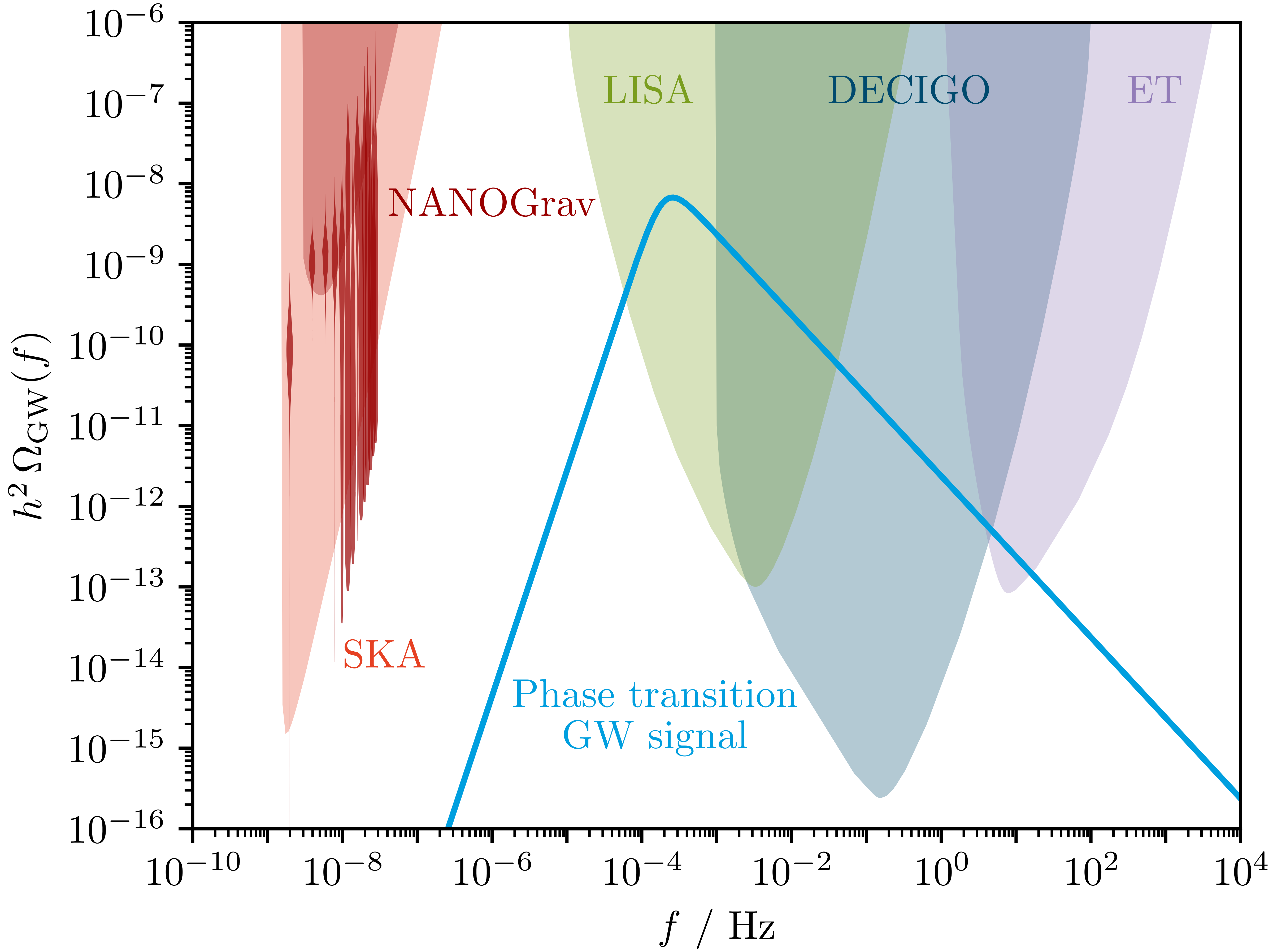

First-order phase transition

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

First-order phase transitions produce GWs

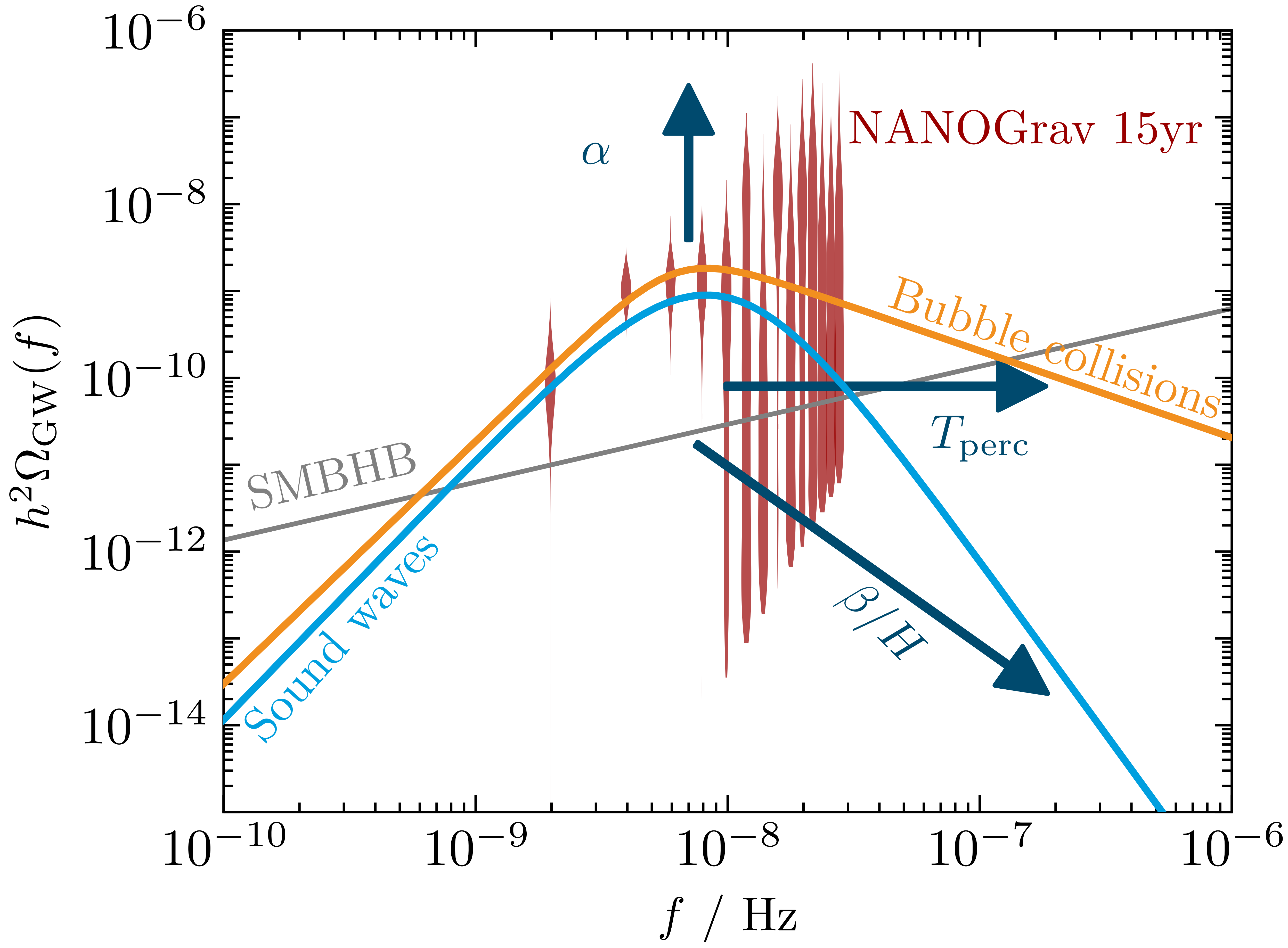
Bubbles of the new phase nucleate, collide and perturb the plasma…





… giving rise to an observable stochastic gravitational wave background.

Parametrization of the GW signal



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

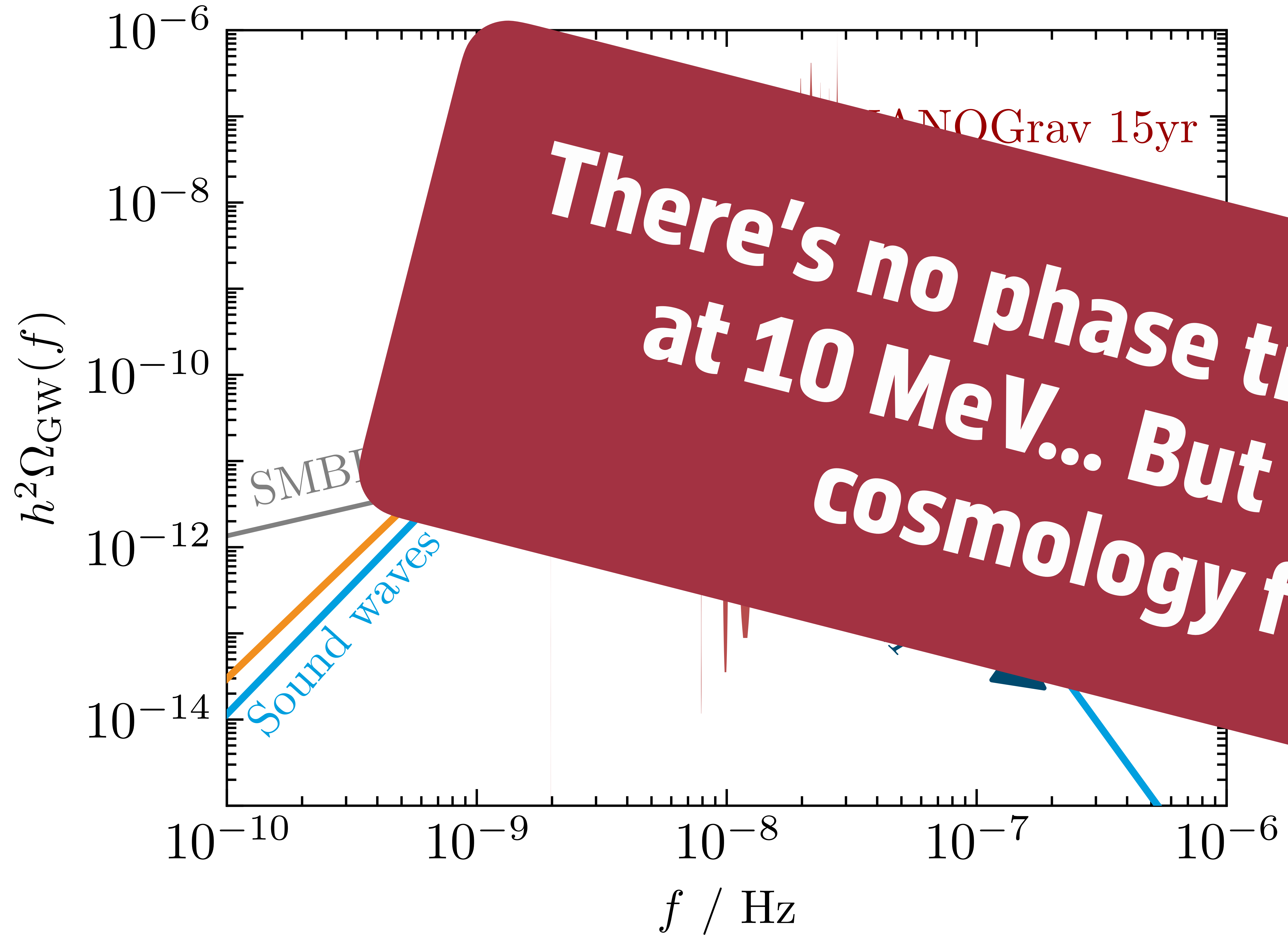
$$h^2\Omega_{\rm GW}^{\rm sw,bw}(f) \simeq 10^{-6}\left(\frac{\alpha}{\alpha+1}\right)^2\left(\frac{H}{\beta}\right)^{1,2}\mathcal{S}\left(\frac{f}{f_{\rm peak}}\right)$$

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

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:

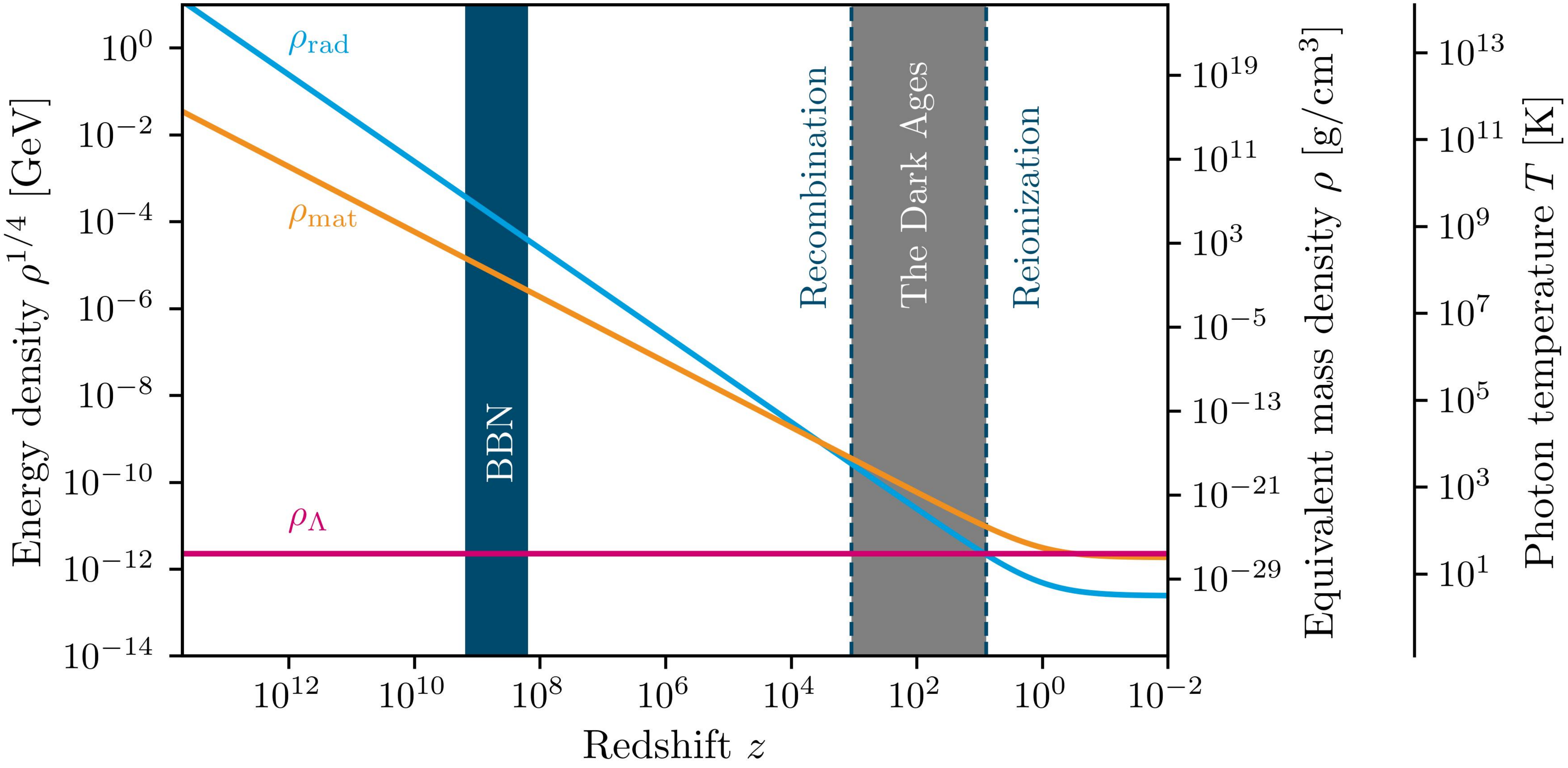
1

≈ 10

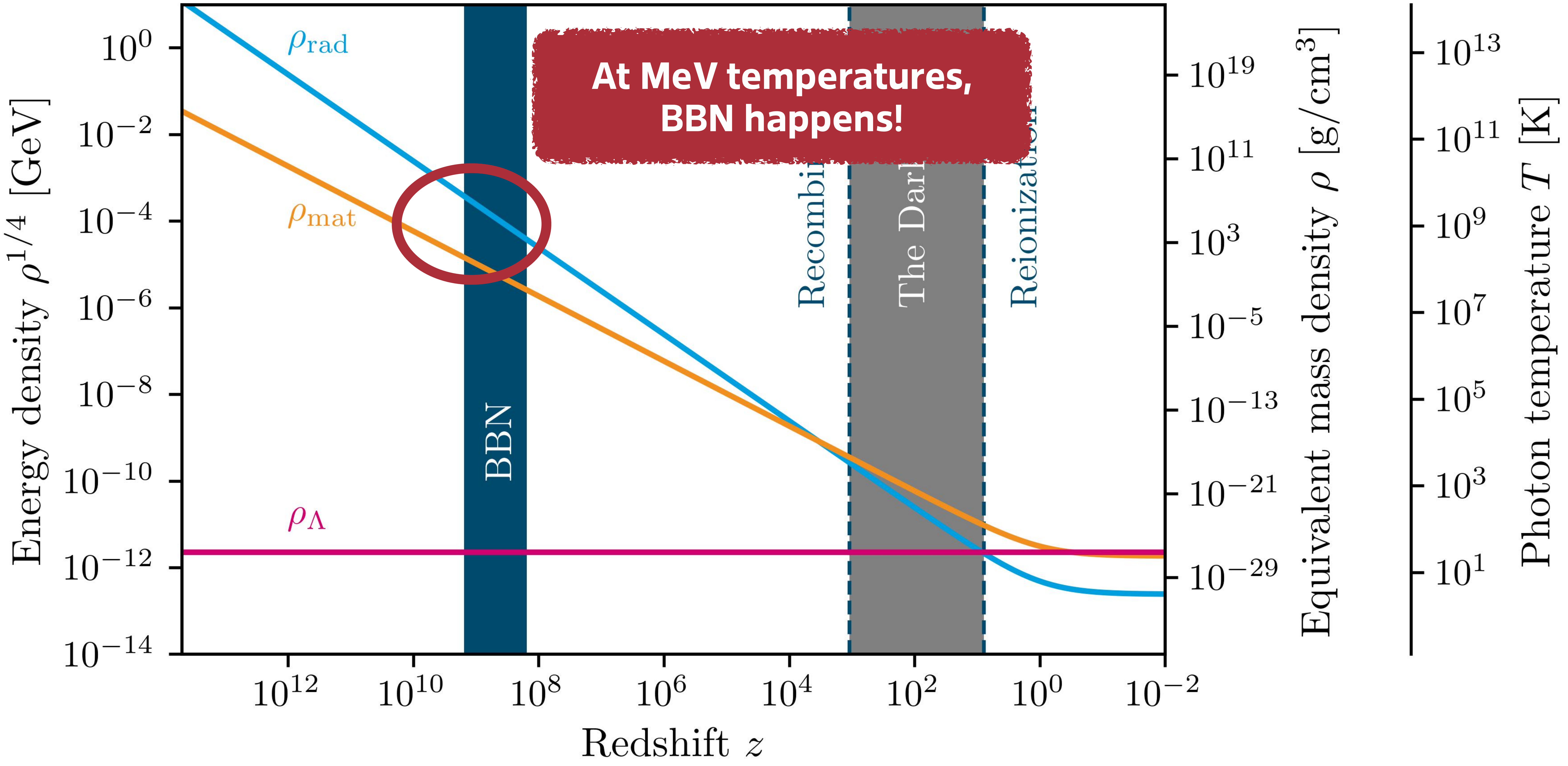
- Percolat $\approx 10\,\text{MeV}$

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

A brief history of time

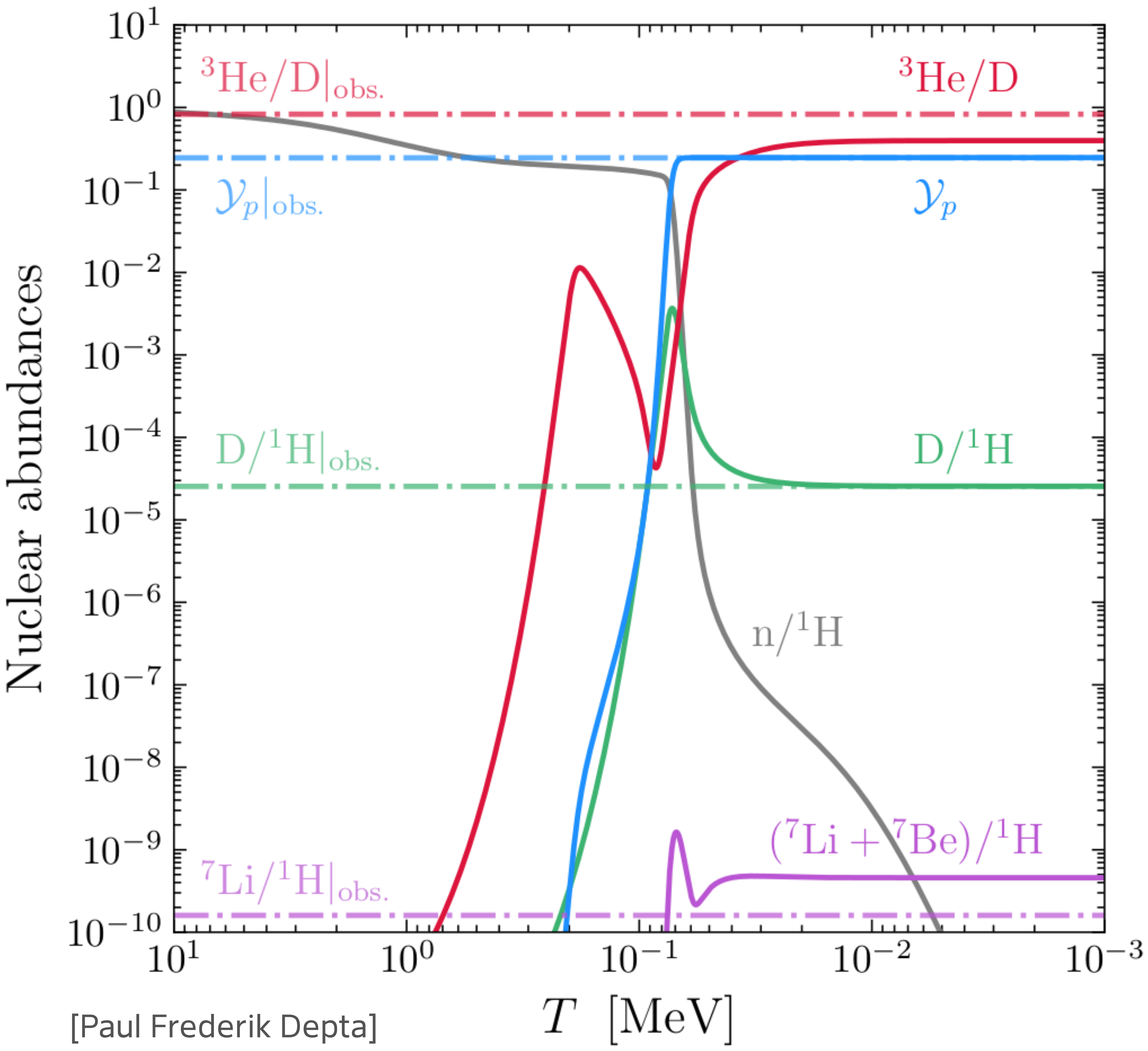


A brief history of time



At MeV temperatures, BBN happens!

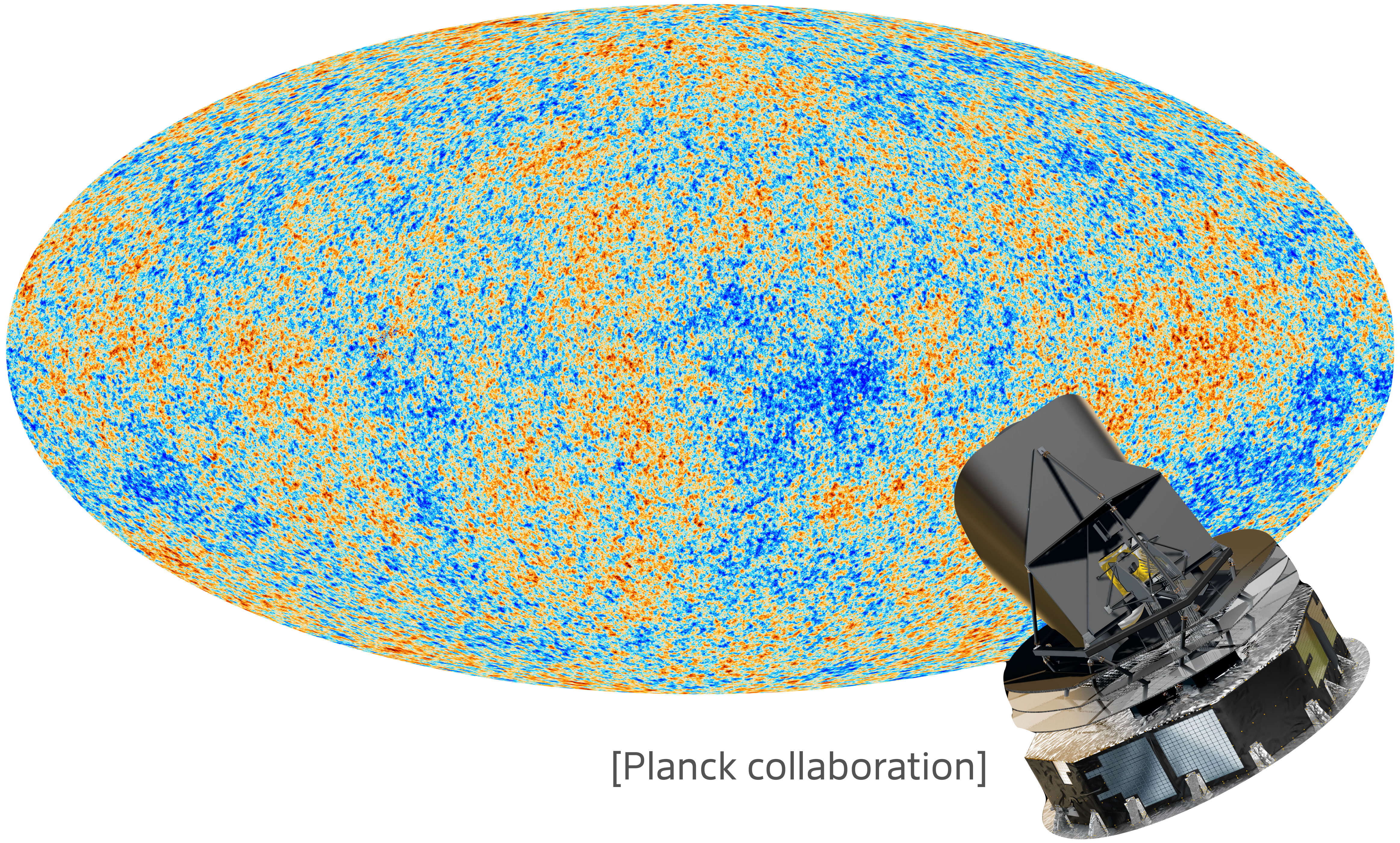
Big Bang Nucleosynthesis and the CMB



[Paul Frederik Depta]

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

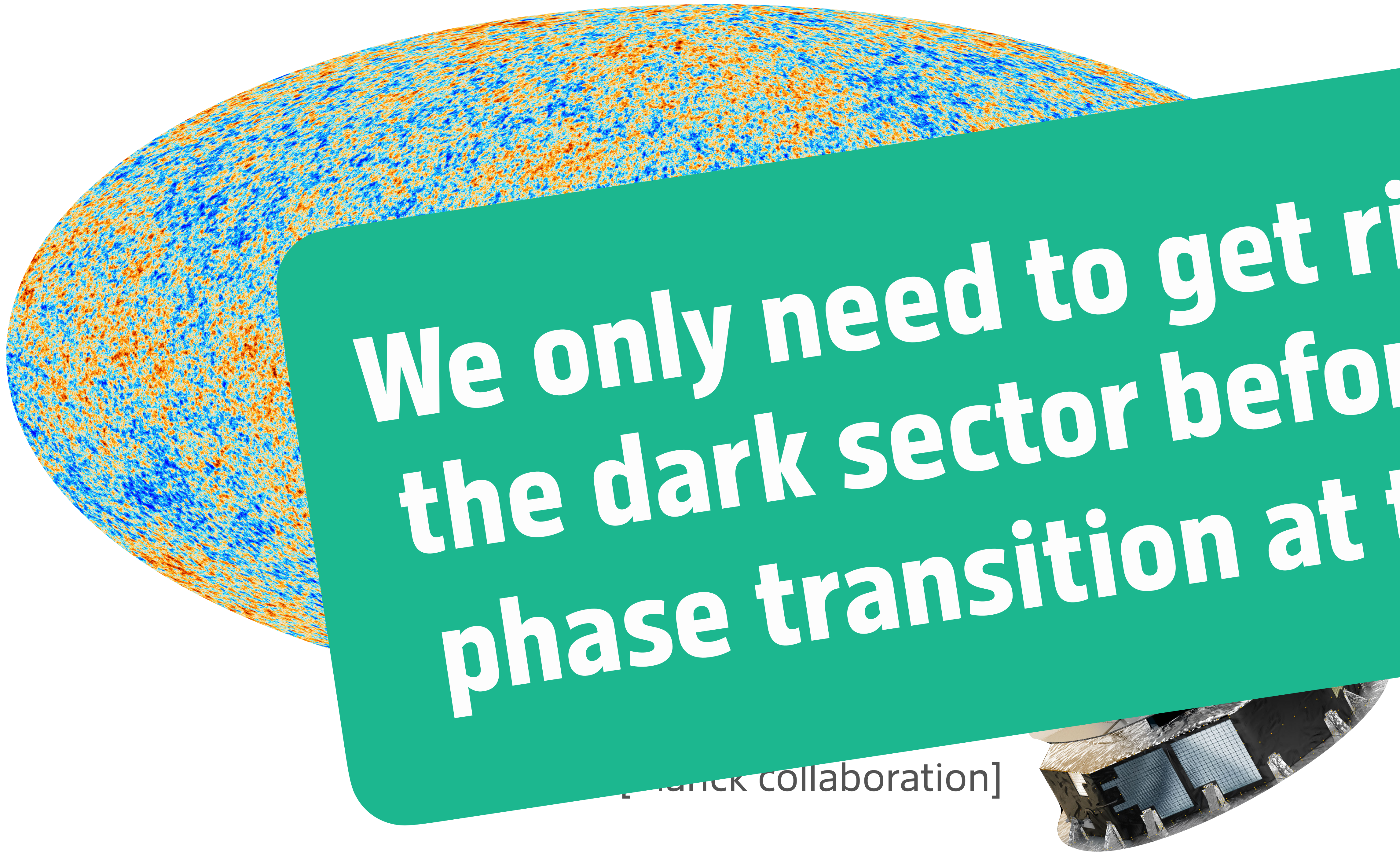
Big Bang Nucleosynthesis and the CMB



[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

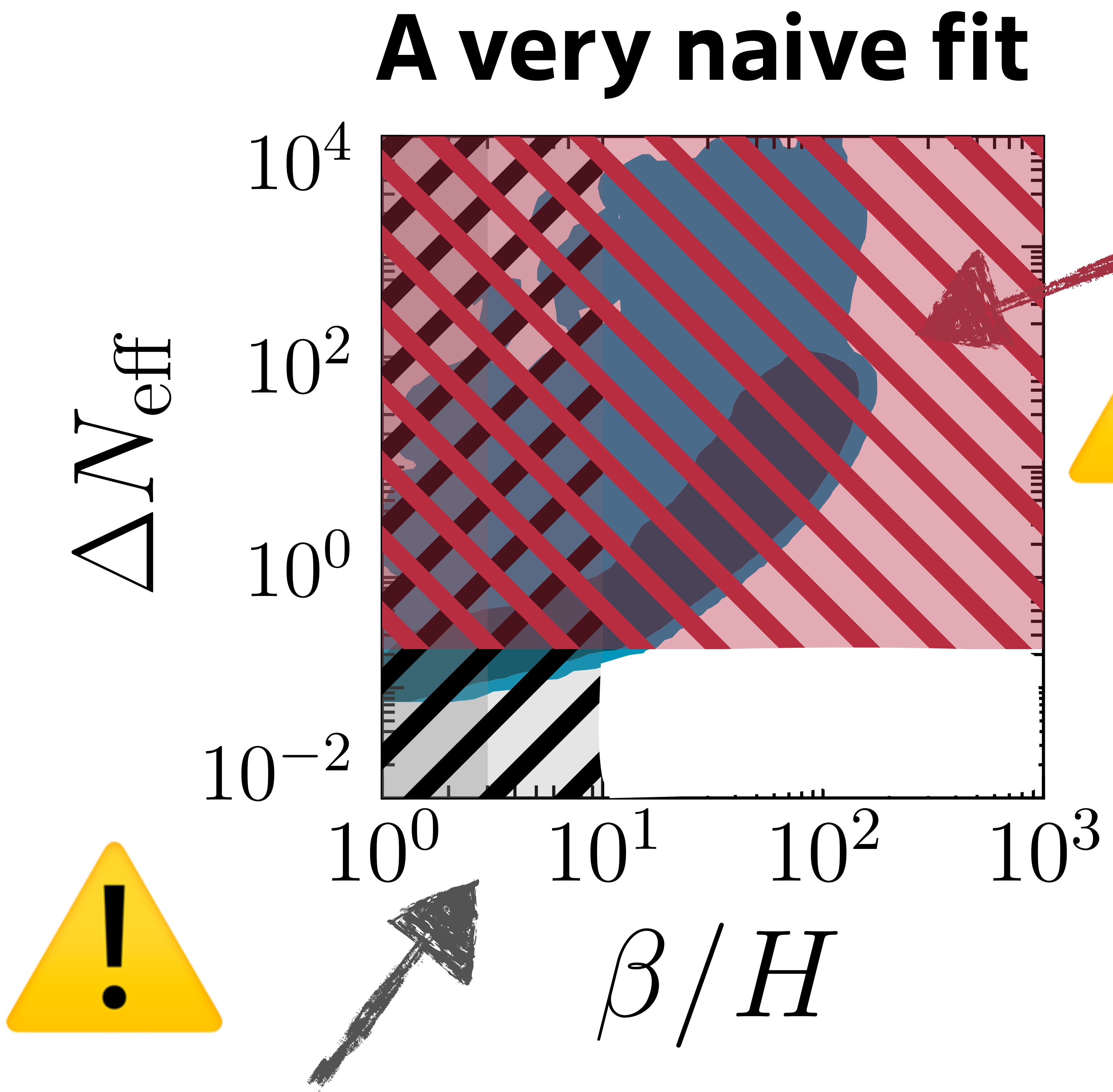


[anck collaboration]

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 nordial
  ances in
  h
  41
  eff = 2.99 ± 0.17
- Consistent with 3 SM neutrinos

A dark sector without portal couplings



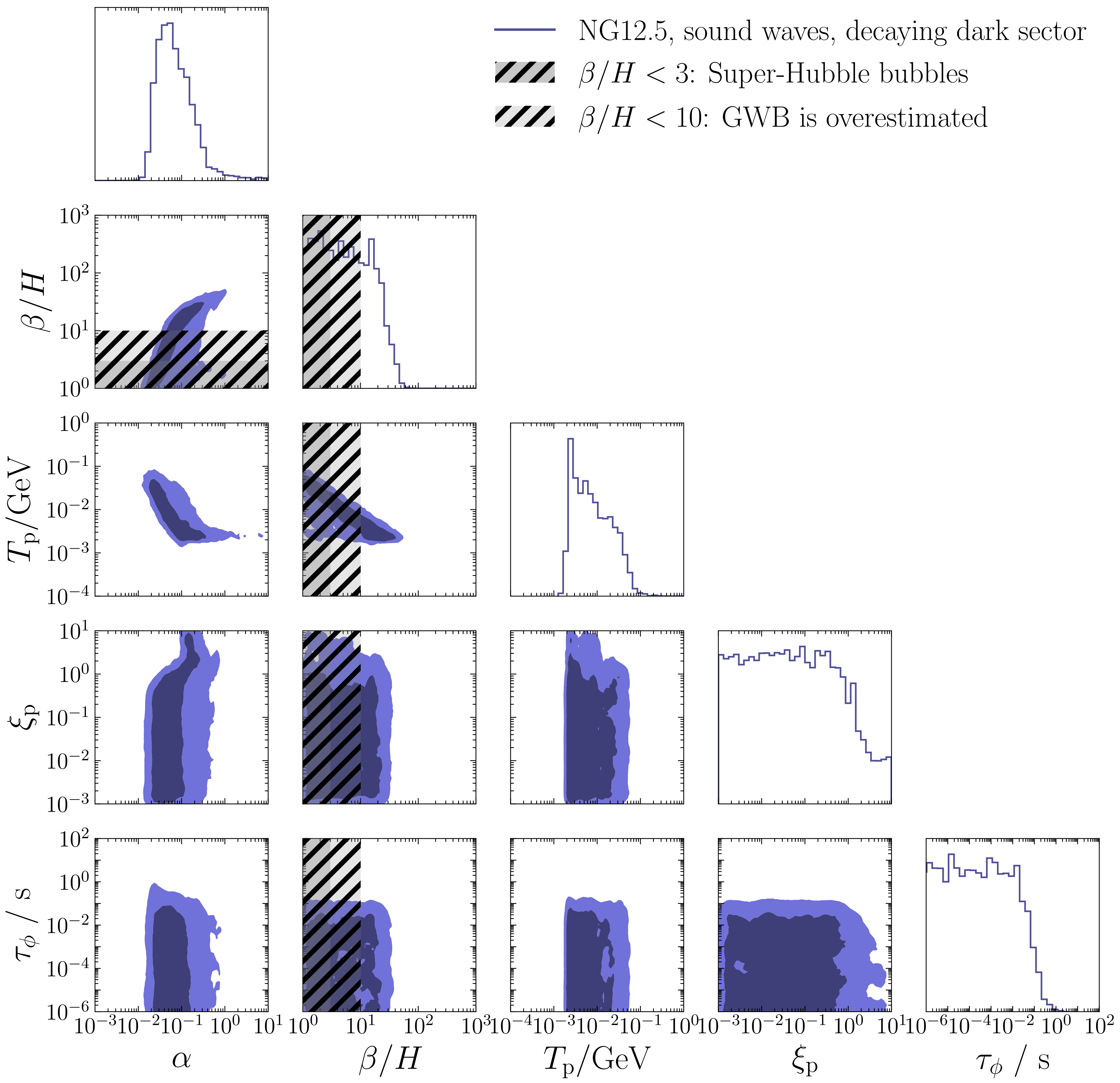
The liberated vacuum energy remains in the dark sector. A good fit would require enormous $\Delta N_{\text{eff}} \gg 0.22$

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

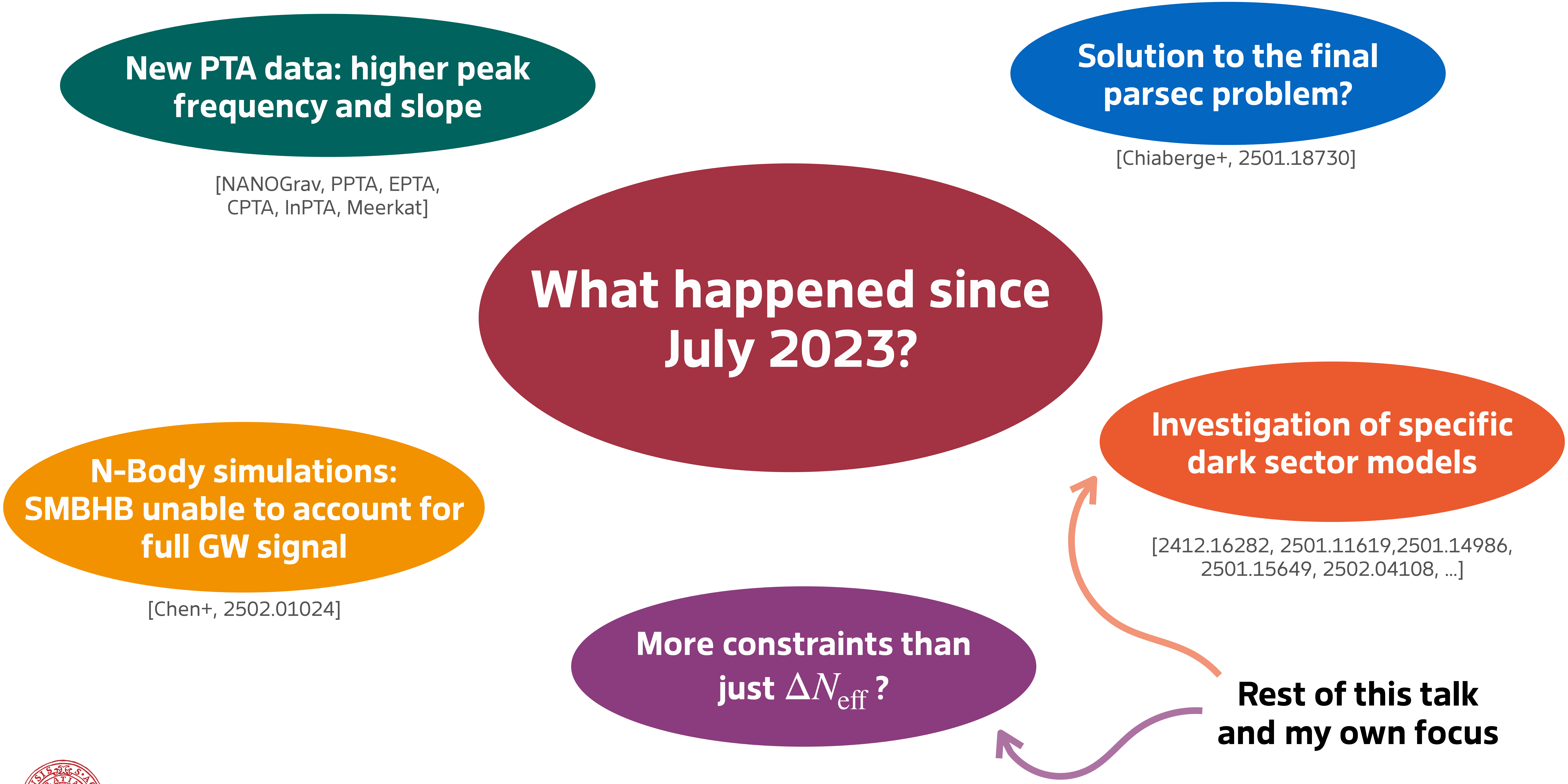
[CT et al, JCAP 11 (2023) 053]

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 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]

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

[Chen+, 2502.01024]

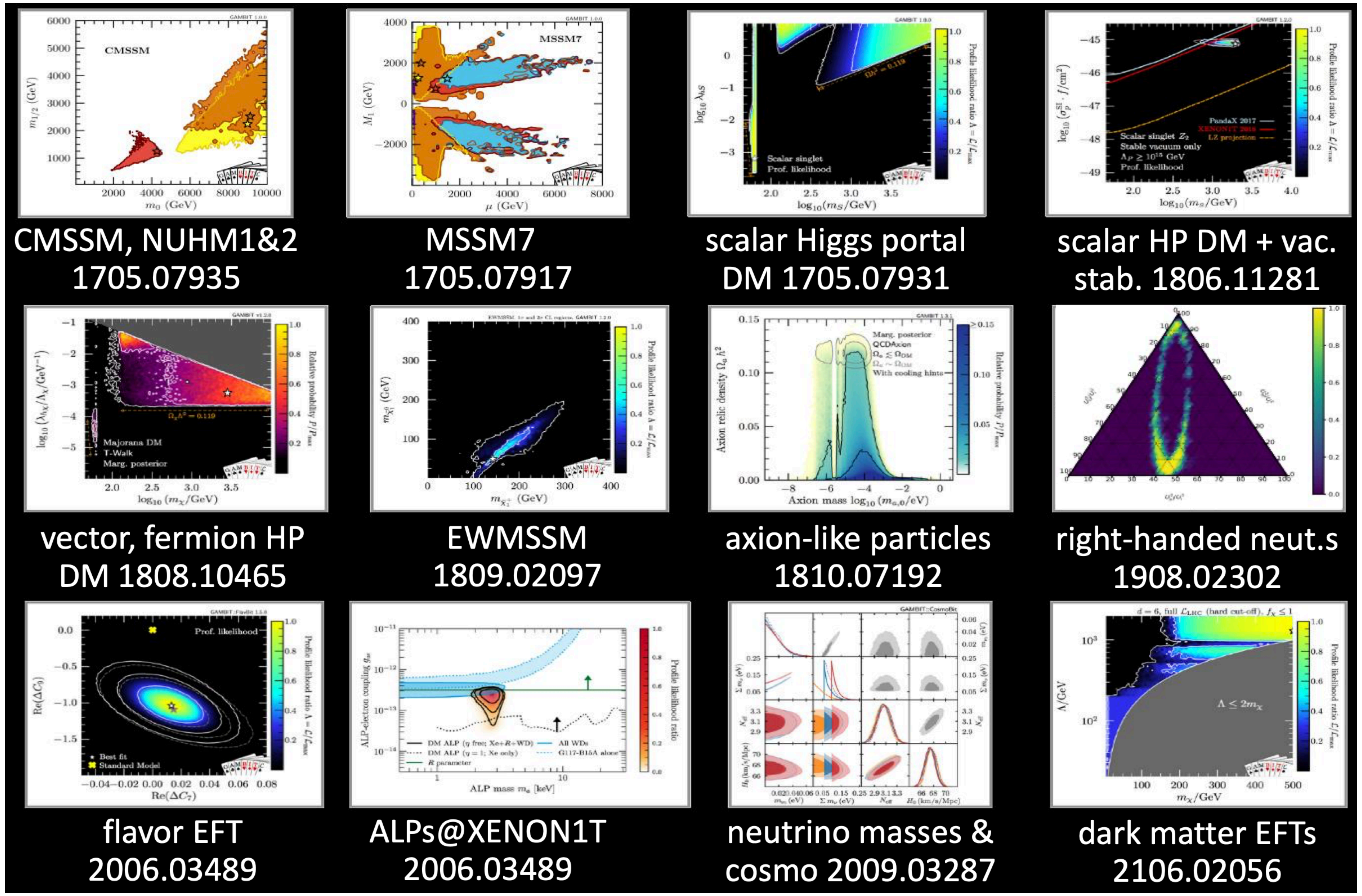
Investigation of specific dark sector models

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

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

Rest of this talk and my own focus

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

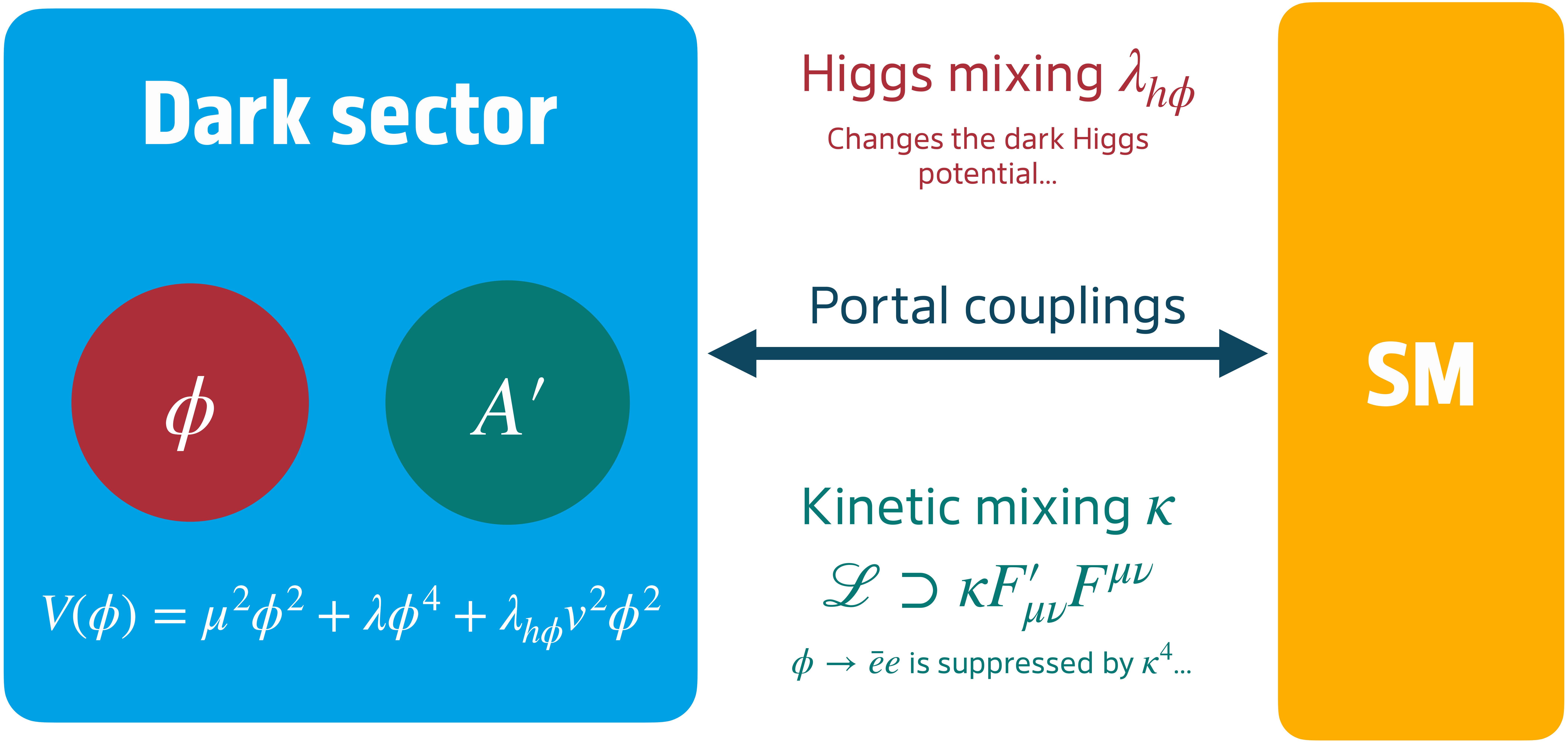
neutrino masses & cosmo 2009.03287

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



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

$V(\phi)$

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

Higgs mixin

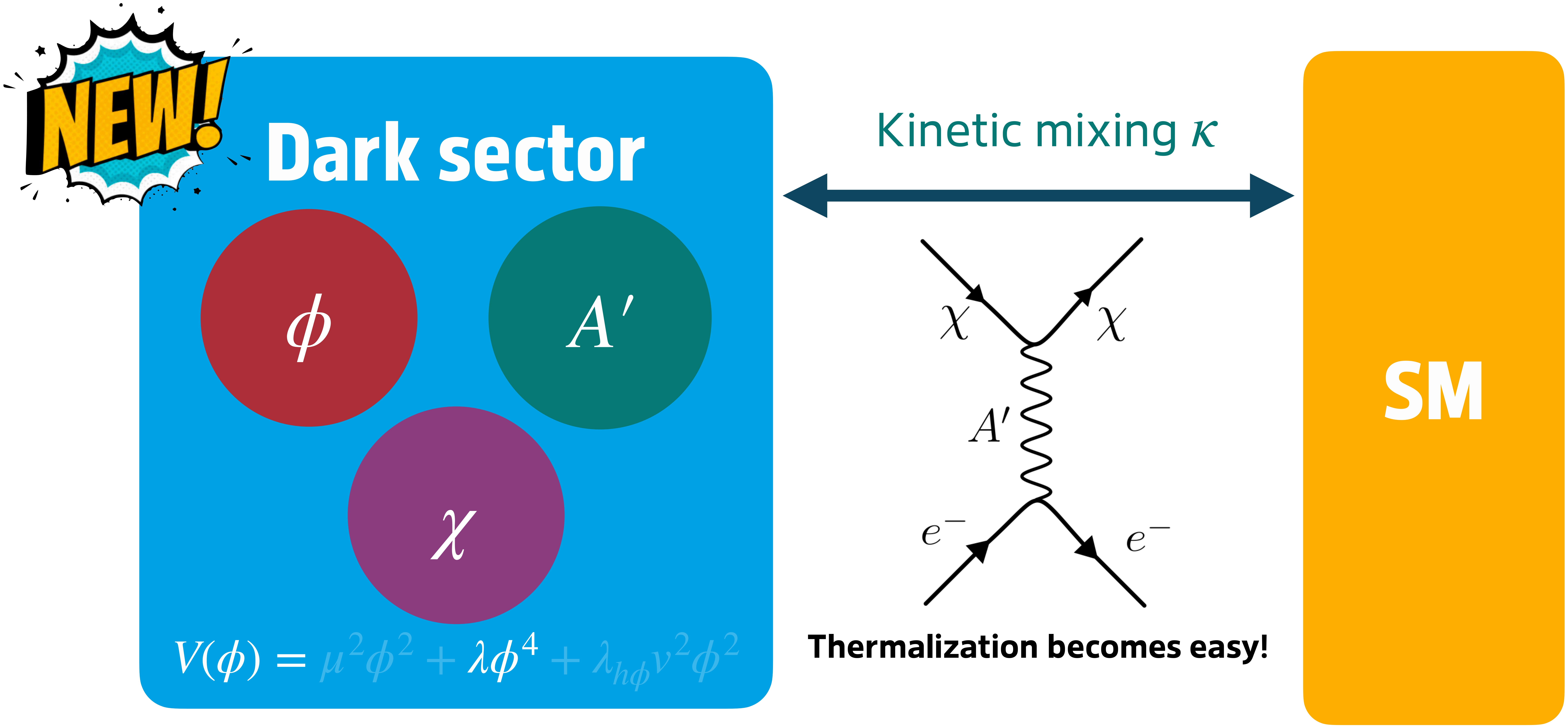
xing κ

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

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

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

A conformal dark sector incl. dark matter candidate



Dark sector

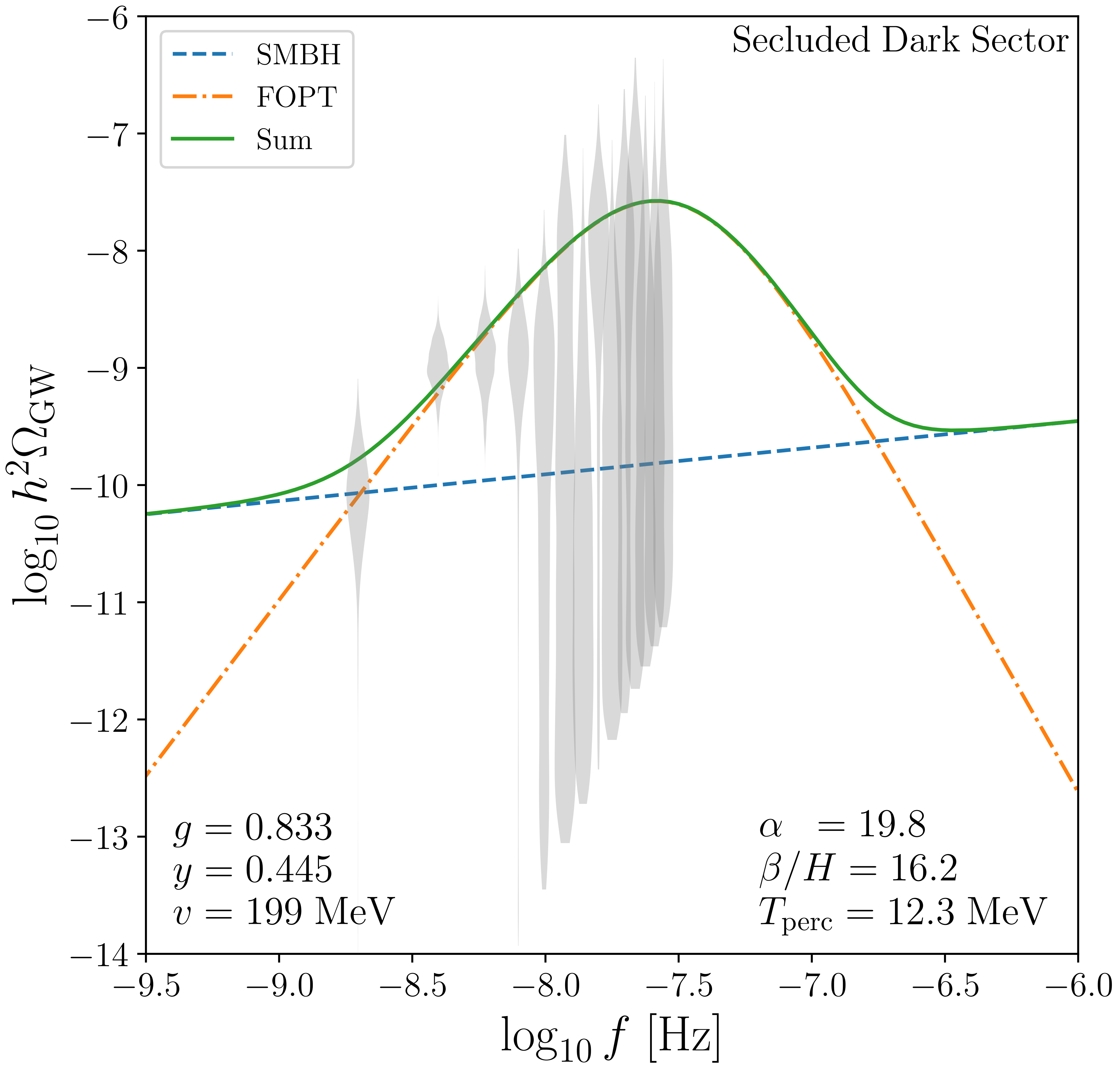
$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4 + \lambda_{h\phi}v^2\phi^2$$

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

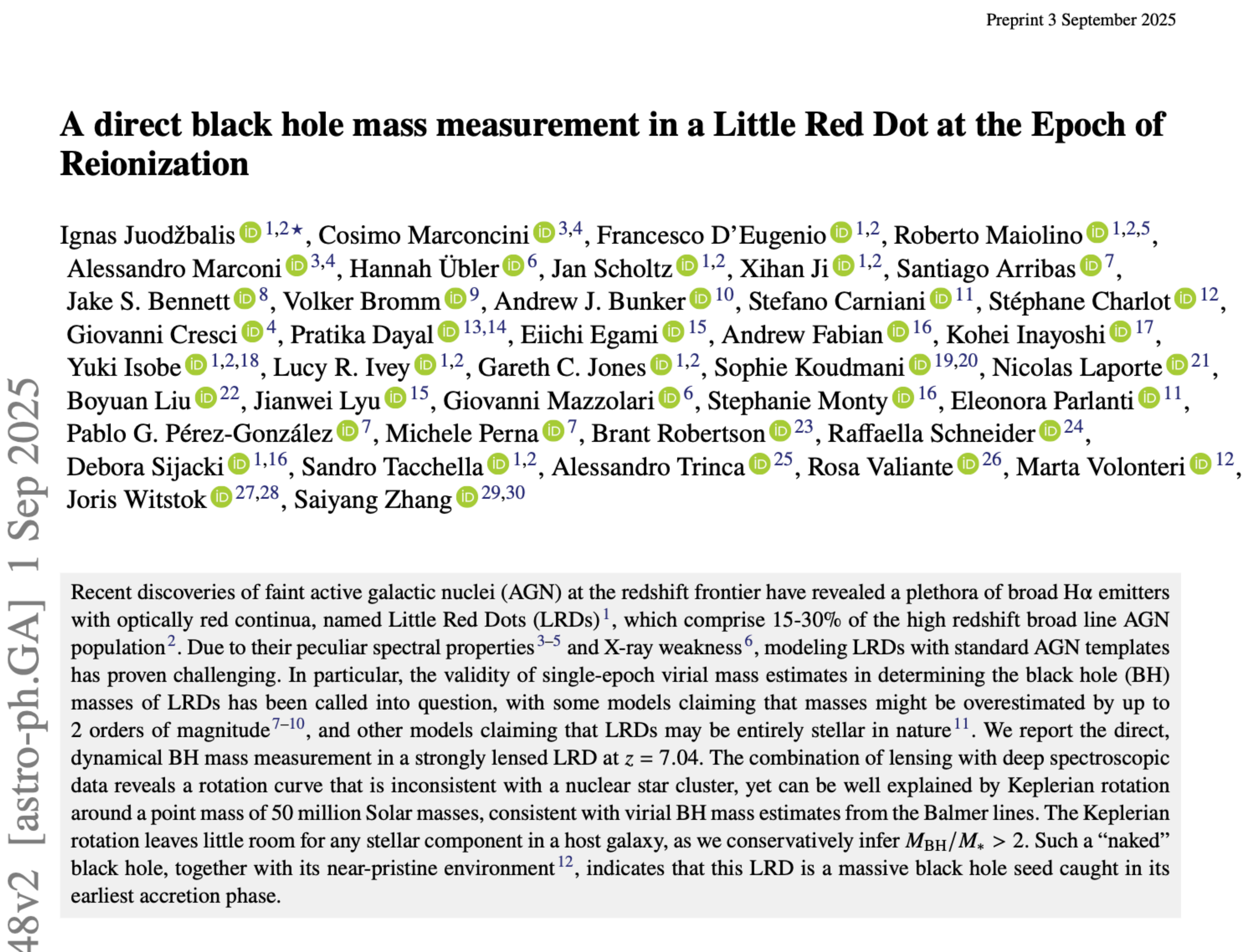
Some open ends:

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

Transition Listener 2.0

[Ongoing work Jonas Matuszak]

Can you explain this to us?



Preprint 3 September 2025

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

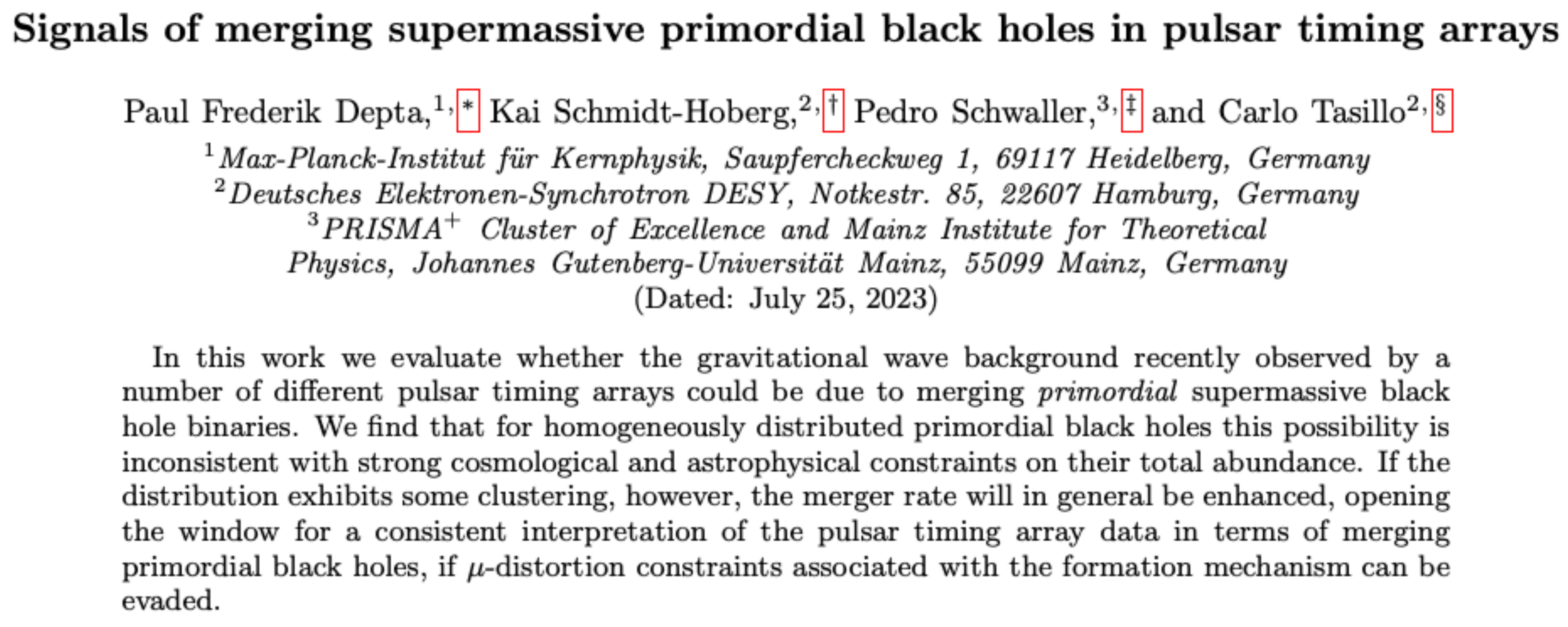
Ignas Juodžbalis [1,2★], Cosimo Marconcini [3,4], Francesco D'Eugenio [1,2], Roberto Maiolino [1,2,5], Alessandro Marconi [3,4], Hannah Übler [6], Jan Scholtz [1,2], Xihan Ji [1,2], Santiago Arribas [7], Jake S. Bennett [8], Volker Bromm [9], Andrew J. Bunker [10], Stefano Carniani [11], Stéphane Charlot [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 $M_{\mathrm{BH}}/M_* > 2$. 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.

48v2 [astro-ph.GA] 1 Sep 2025

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!

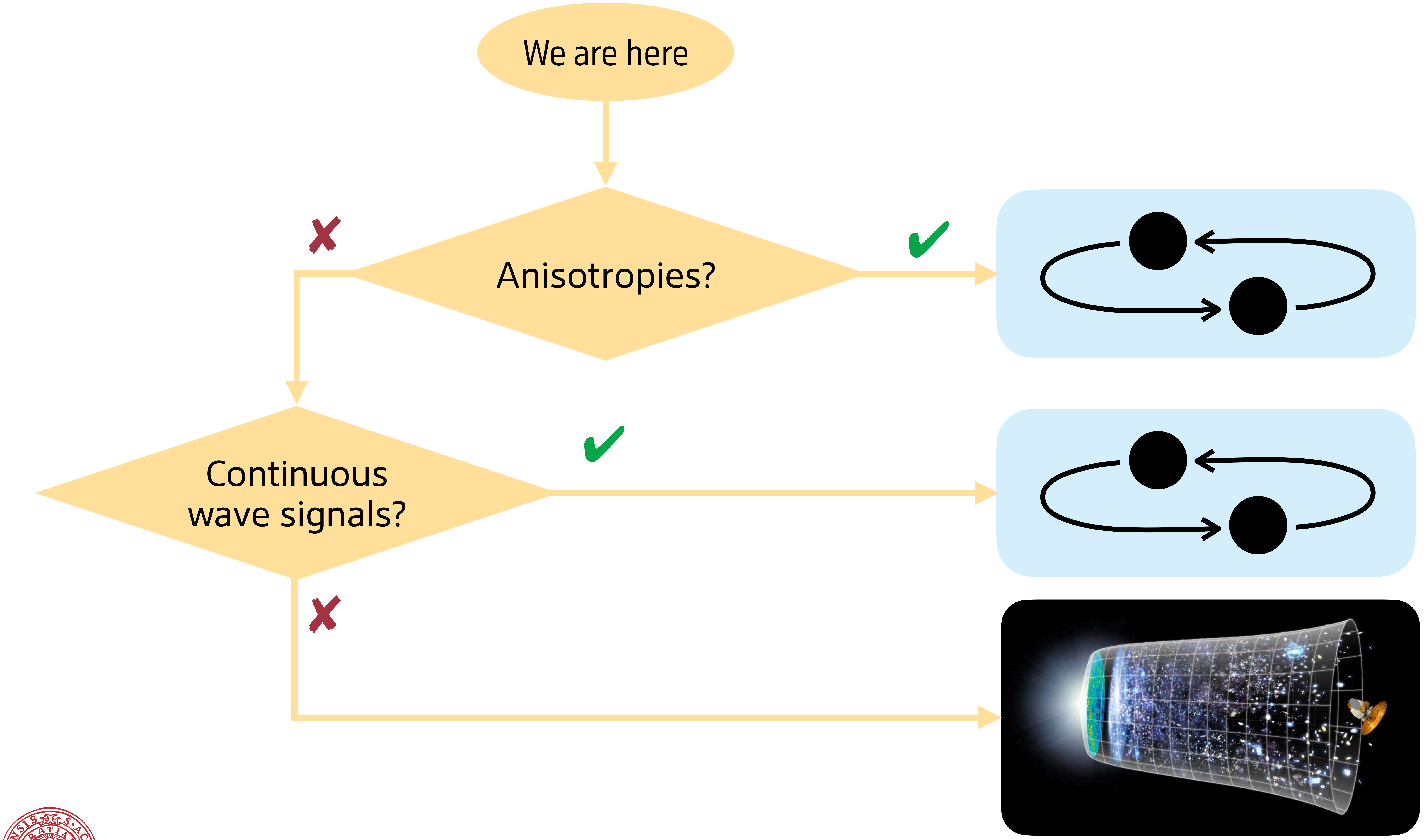


Signals of merging supermassive primordial black holes in pulsar timing arrays

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.

Quo vadis pulsar timing?



We are here

Anisotropies?

✓

✗

Supermassive black hole binaries

Continuous wave signals?

✓

✗

Supermassive black hole binaries

An early universe source?

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 SMBHBs**
  - ➡ Performed global fit with PTA, BBN, CMB, direct detection, indirect detection, bullet cluster, and beam dump likelihoods
  - ➡ Best-fit scenarios **can be tested by upcoming beam-dump experiments**

Thank you very much for your attention!

Do you have any questions?

Backup slides