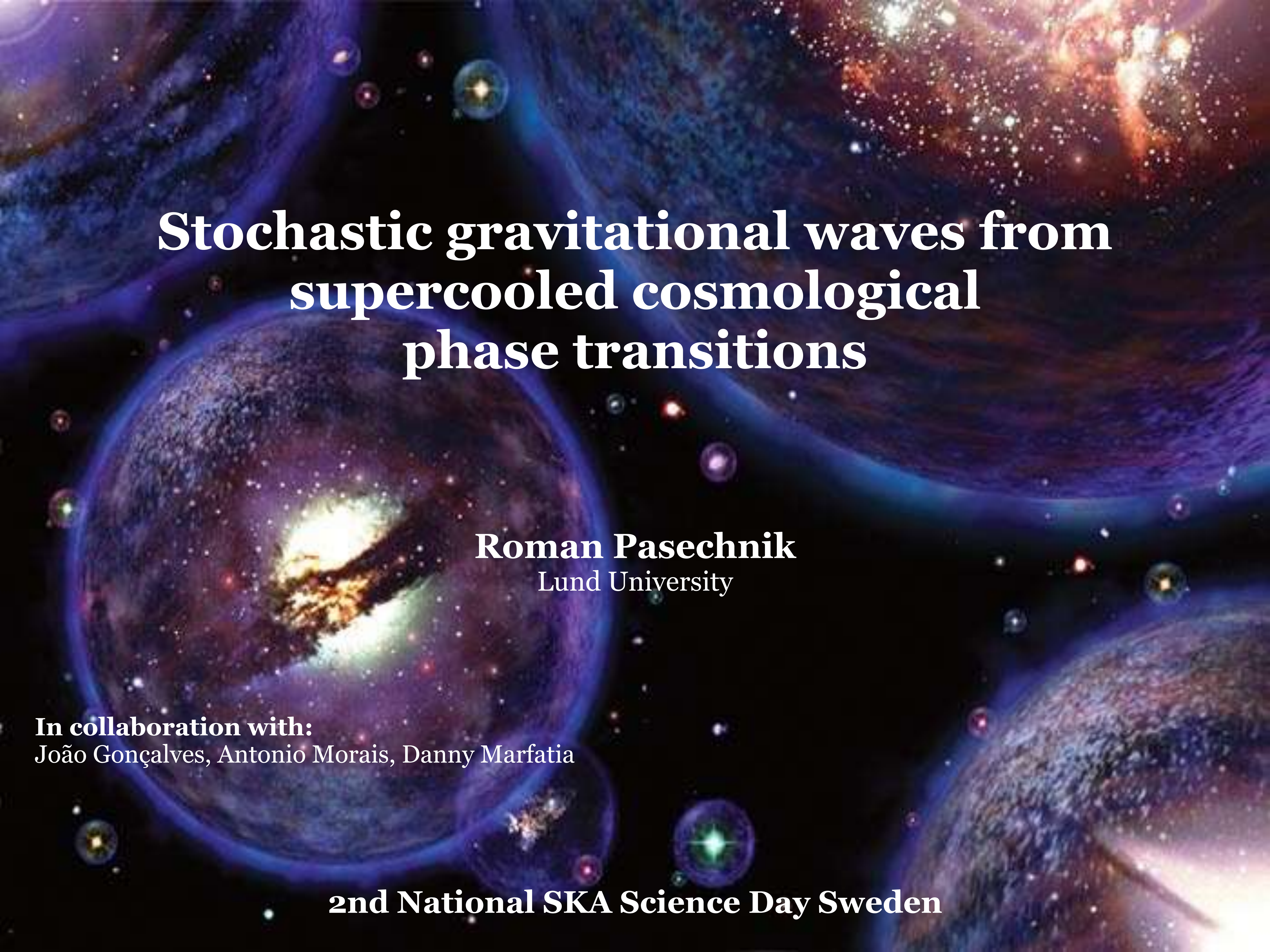


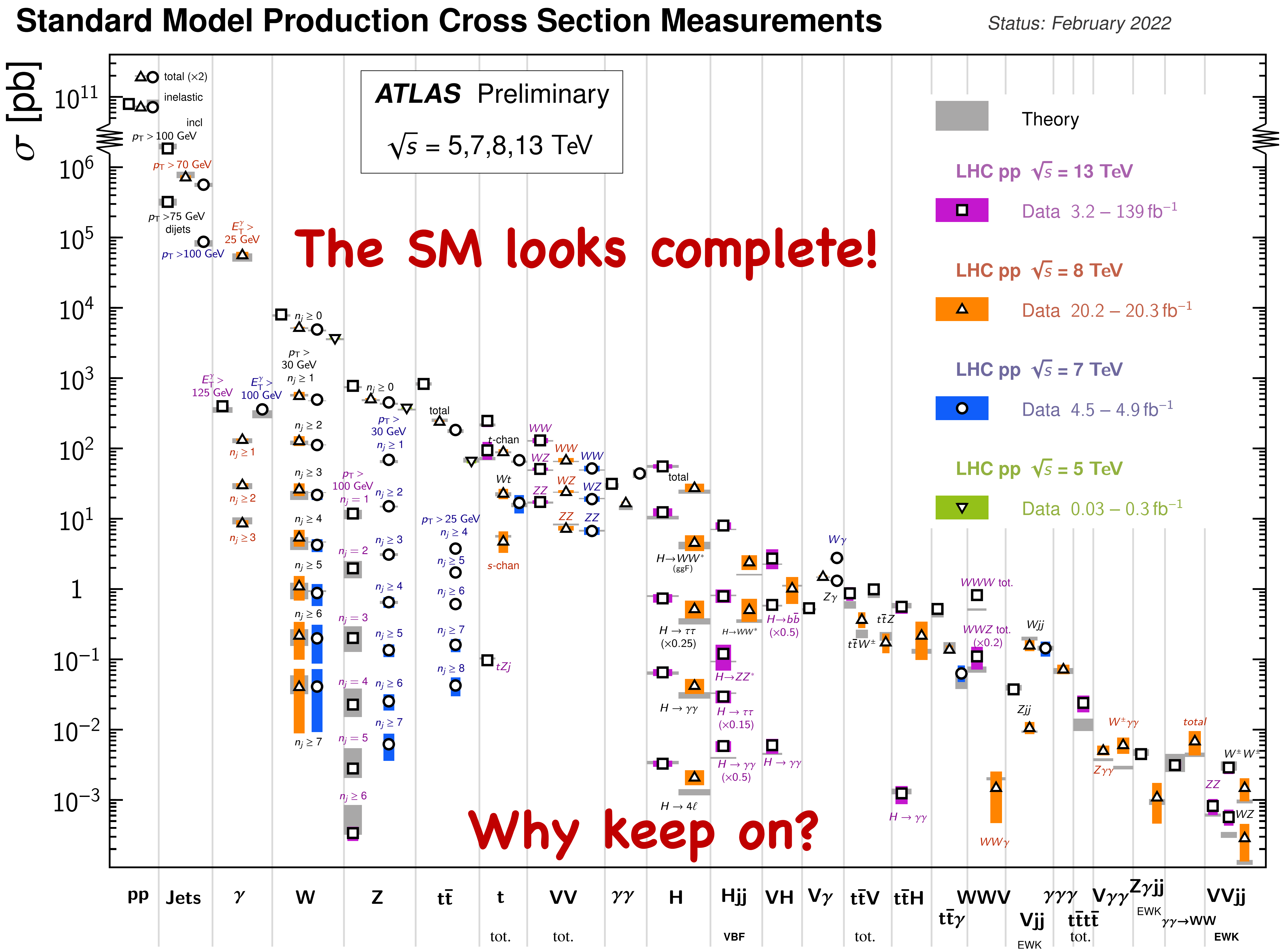
# Stochastic gravitational waves from supercooled cosmological phase transitions

**Roman Pasechnik**
Lund University

**In collaboration with:**
João Gonçalves, Antonio Morais, Danny Marfatia

**2nd National SKA Science Day Sweden**

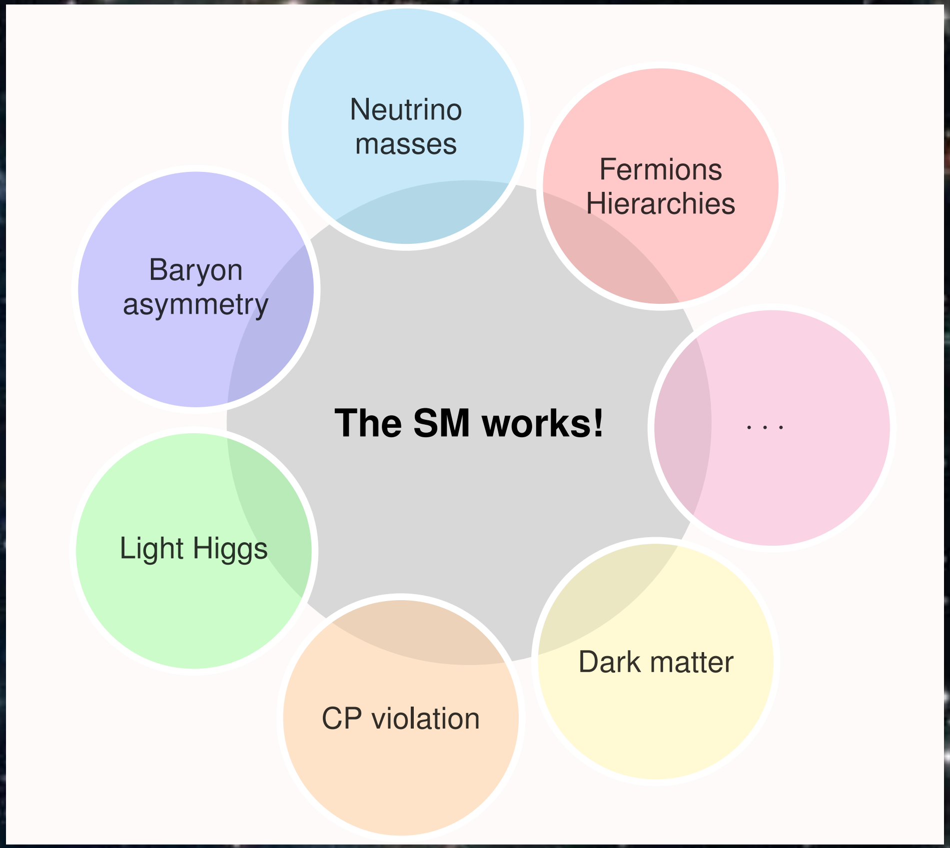
# Impressive performance of the Standard Model



## The SM looks complete!

## Why keep on?

# Open questions



Neutrino masses

Fermions Hierarchies

Baryon asymmetry

**The SM works!**

. . .

Light Higgs

Dark matter

CP violation

Unexplained phenomena:

- Dark Matter
- Matter-antimatter asymmetry
- Dark Energy

Unsatisfactory structure of the SM:

- Hierarchy problems (Higgs, flavour)
- Naturalness
- Quantum Gravity etc

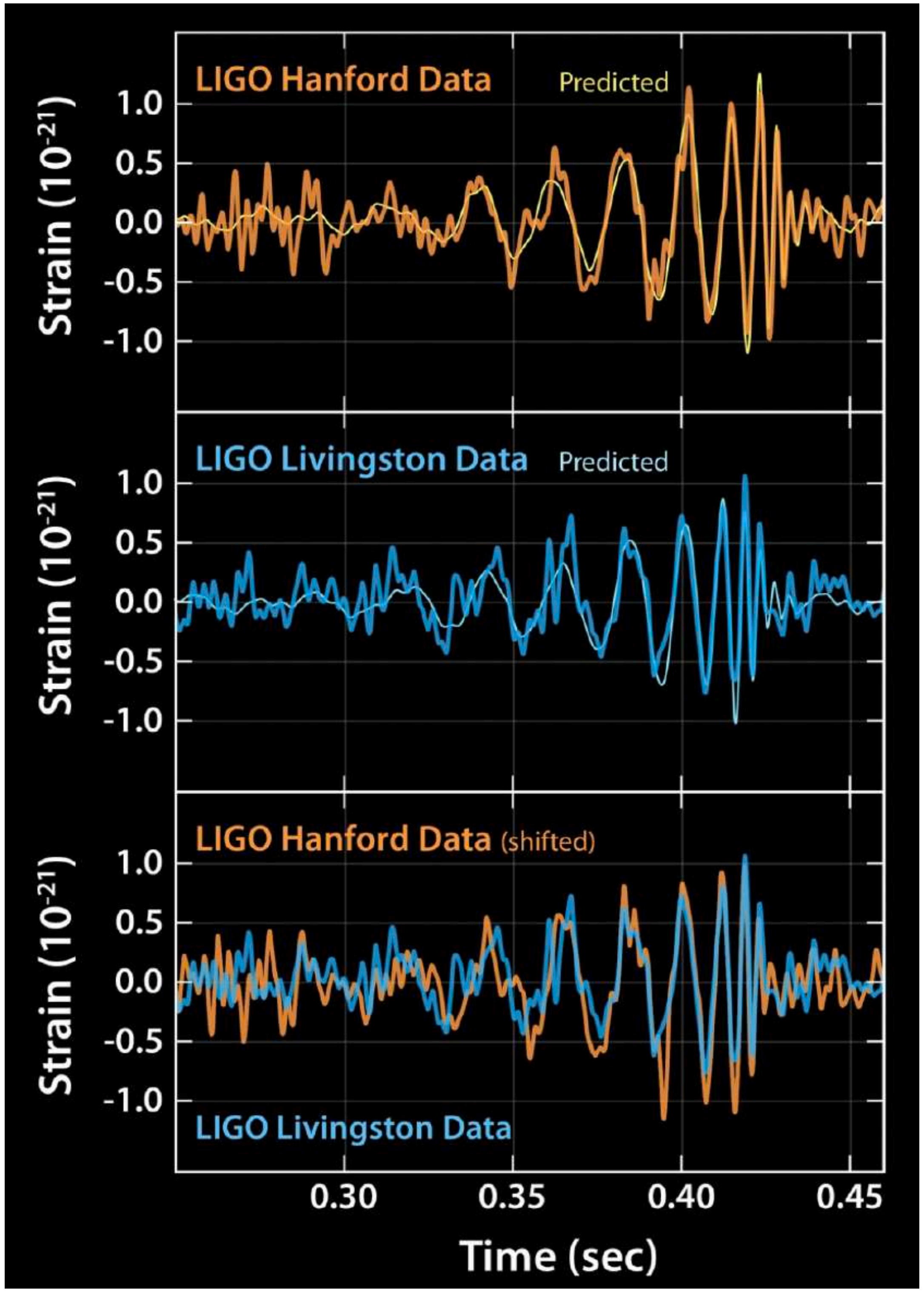
What are the alternative ways to probe New Physics?

NASA, ESA, AND THE HUBBLE HERITAGE TEAM (STSCI/AURA)

# New Era of gravitational-wave astrophysics

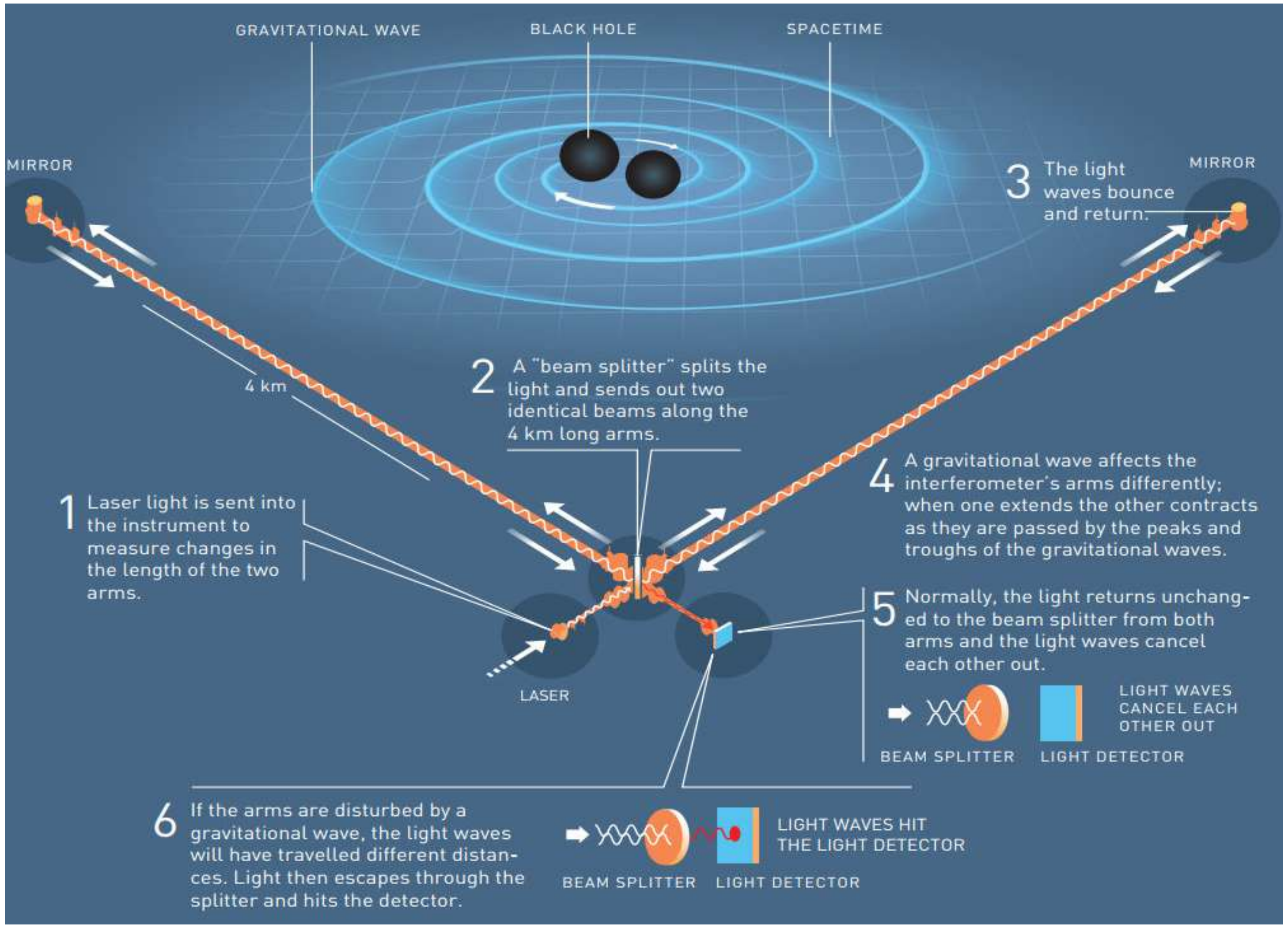
The first ever detection of gravitational waves

**Event GW150914**



Credit: LIGO

**LIGO spectrometer**



1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

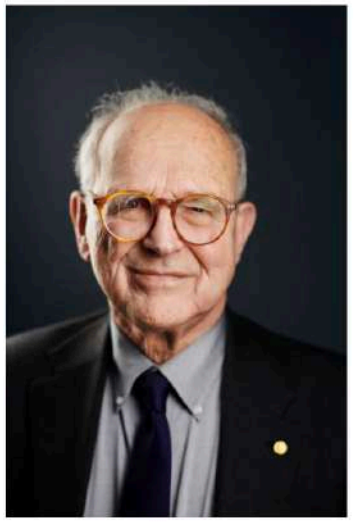
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently; when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

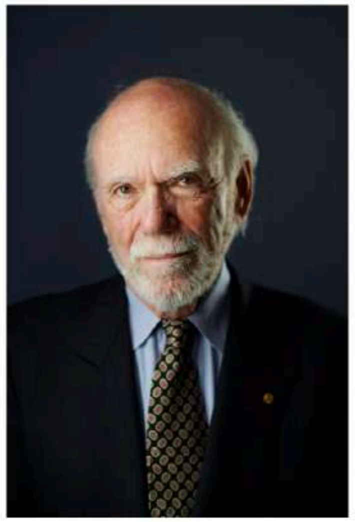
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

## The Nobel Prize in Physics 2017



© Nobel Media AB. Photo: A. Mahmoud

Rainer Weiss



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Barry C. Barish

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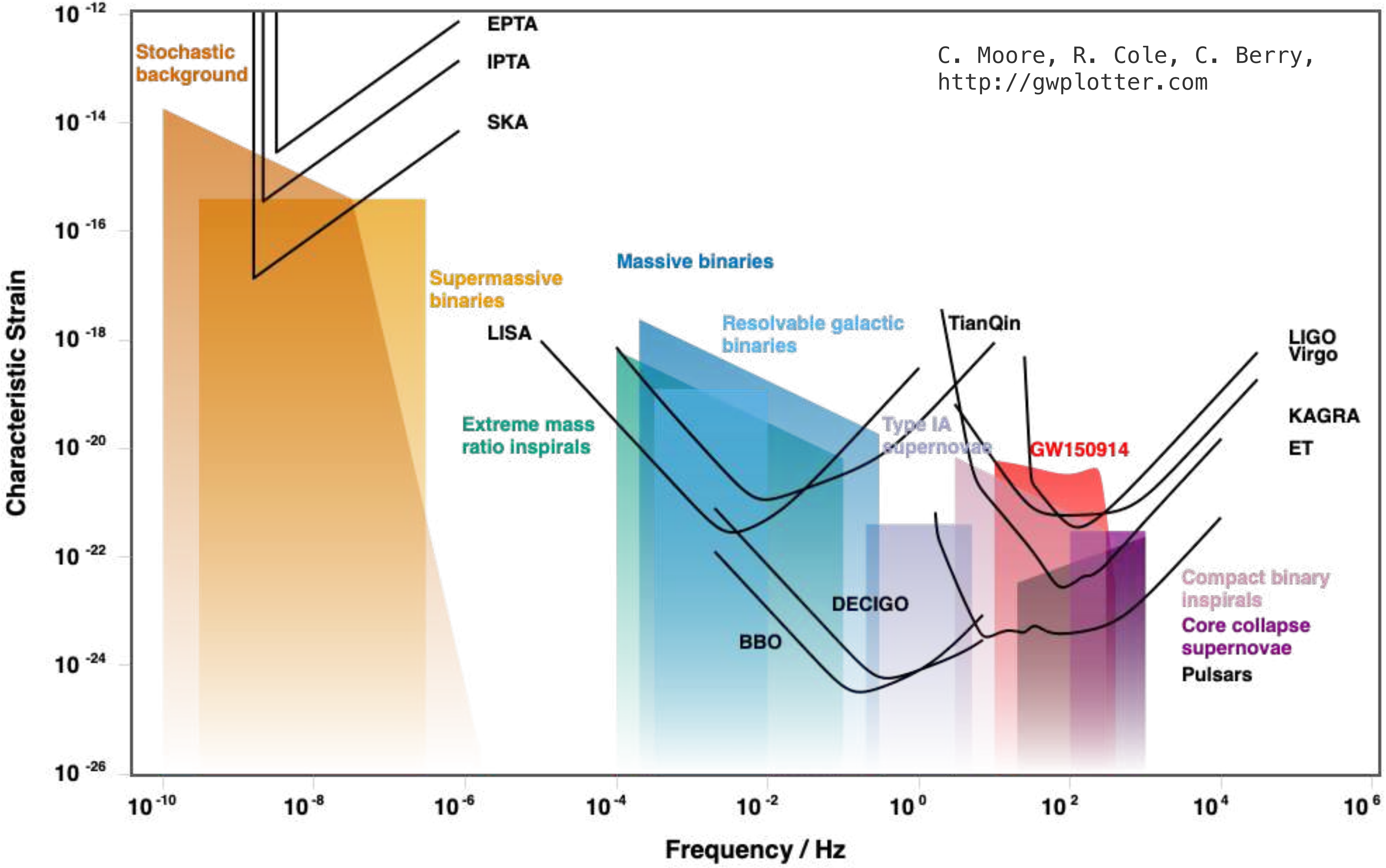
Kip S. Thorne

# Why do Gravitational Waves matter?

**Quick answer: GWs, in the form of a stochastic cosmological background, allow to probe physics not at the reach of collider experiments .**

- Cosmological events
  - (i) Inflation
  - (ii) Cosmic strings
  - (iii) **Strong cosmological phase transitions (PTs)** → by expanding vacuum bubbles of a broken phase in a universe filled with a symmetric phase

# Gravitational wave detectors and sources

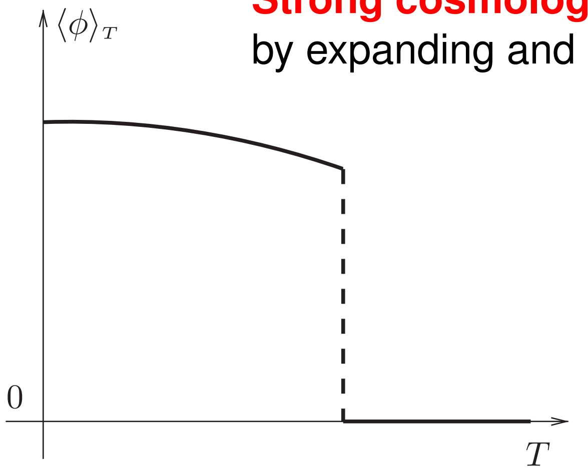


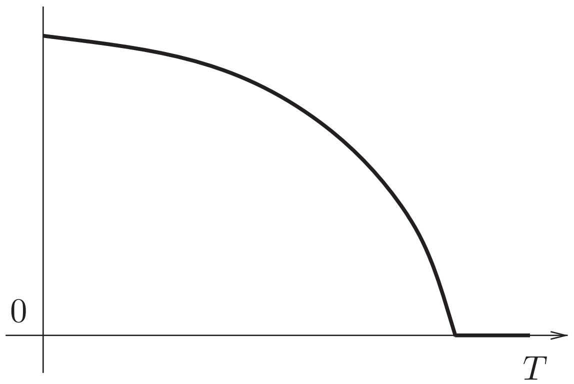
C. Moore, R. Cole, C. Berry, http://gwplotter.com

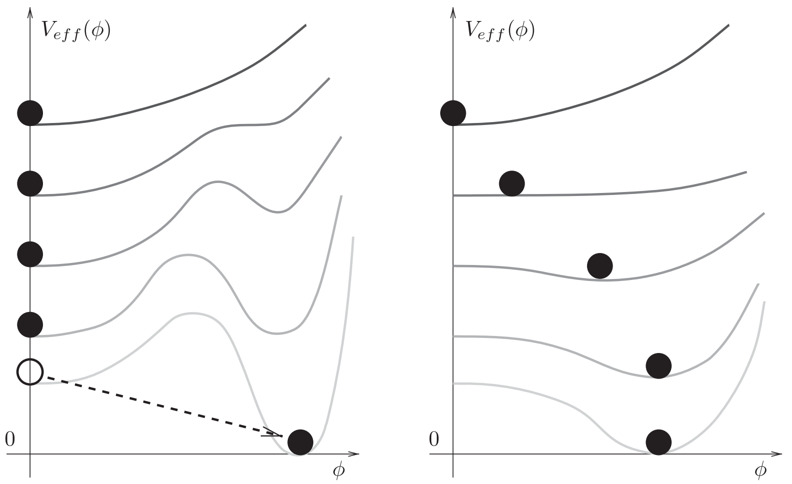
**Wide coverage of amplitudes/frequencies in a number of GW facilities!**

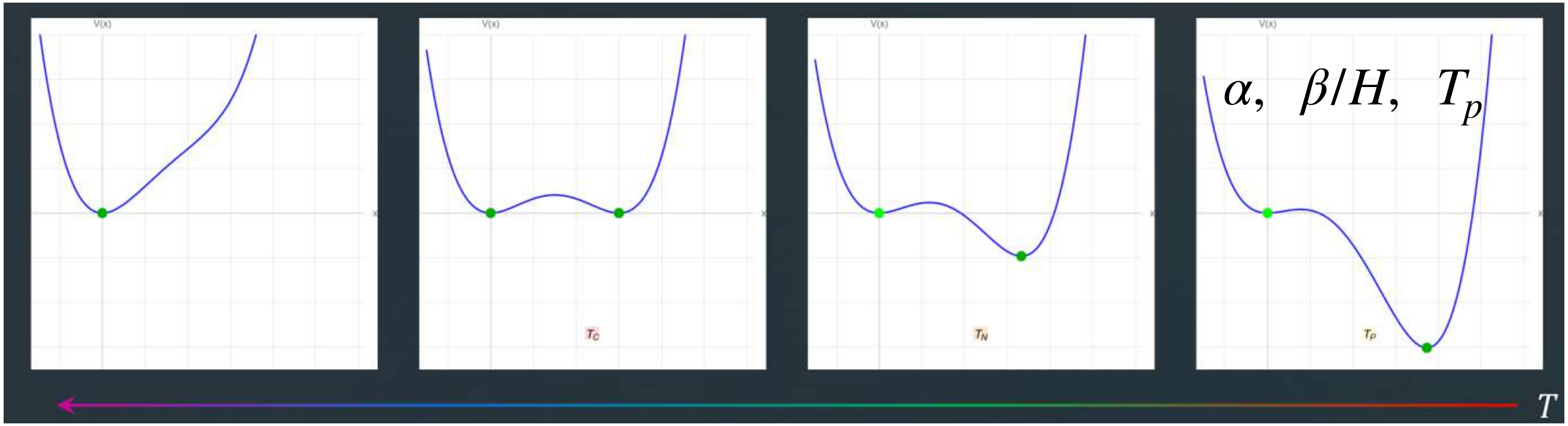
# Phase transitions in the early Universe

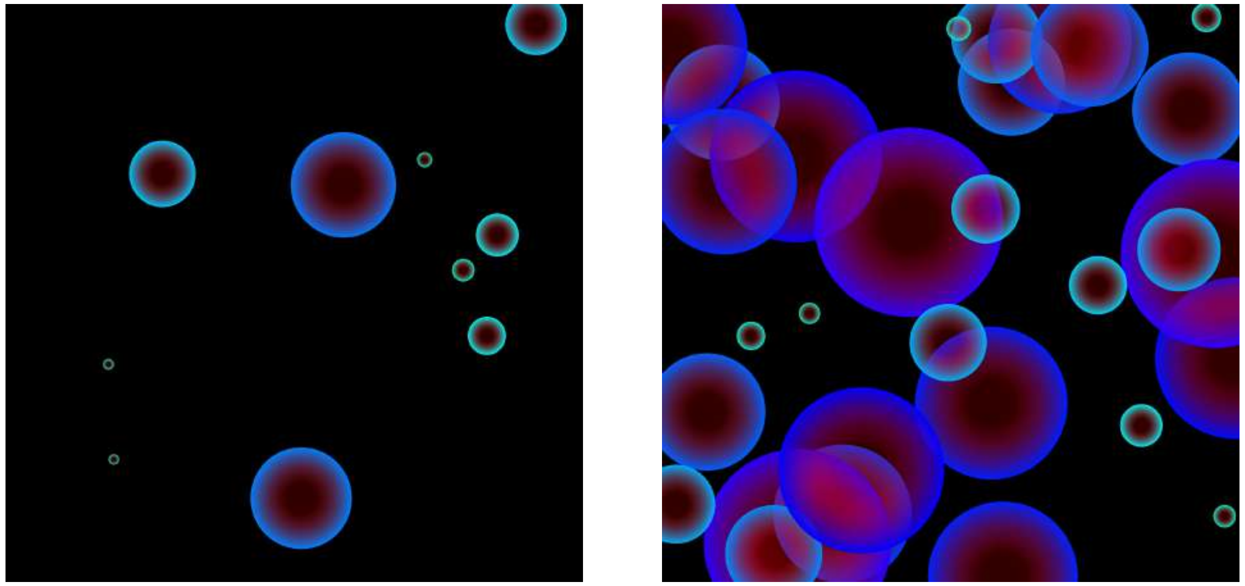
**Strong cosmological phase transitions (PTs)** →
by expanding and colliding vacuum bubbles of new phase











Stochastic Gravitational Wave (GW) background as a gravitational probe for New Physics

Credit: Marco Finetti

# Gravitational-wave power spectrum

- GW energy density per logarithmic frequency

$$h^2\Omega_{\rm GW} \equiv \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW}}{d\log f} \simeq h^2\Omega_{\rm col} + h^2\Omega_{\rm sw} + h^2\Omega_{\rm MHD}$$

**Strength**
$\alpha$

**Inverse duration**
$\beta/H$

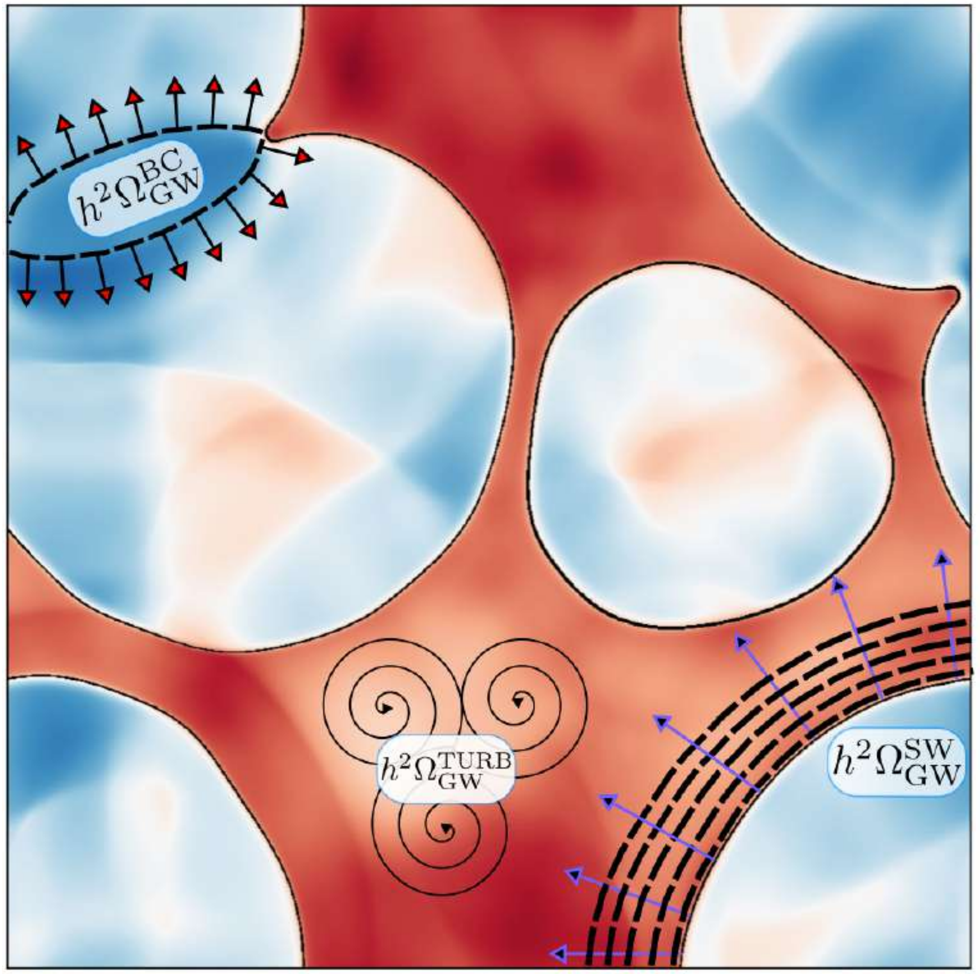
**Percolation temperature**
$T_p$

**Latest SGWB templates can be found in:**

`LISA Cosmology Working Group, C. Caprini et al, 2403.03723`

$$\boxed{\text{signal} \sim \text{amplitude} \times \text{spectral shape}\,(f/f_{\rm peak})}$$

*Phys.Rev.Lett. 125 (2020) 2, 021302*



**Primordial GWs power spectrum:**

$$h^2\Omega_{\rm GW} = h^2\Omega_{\rm GW}^{\rm peak}\left(\frac{4}{7}\right)^{-\frac{7}{2}}\left(\frac{f}{f_{\rm peak}}\right)^3\left[1+\frac{3}{4}\left(\frac{f}{f_{\rm peak}}\right)\right]^{-\frac{7}{2}}$$

Peak amplitude

Spectral function

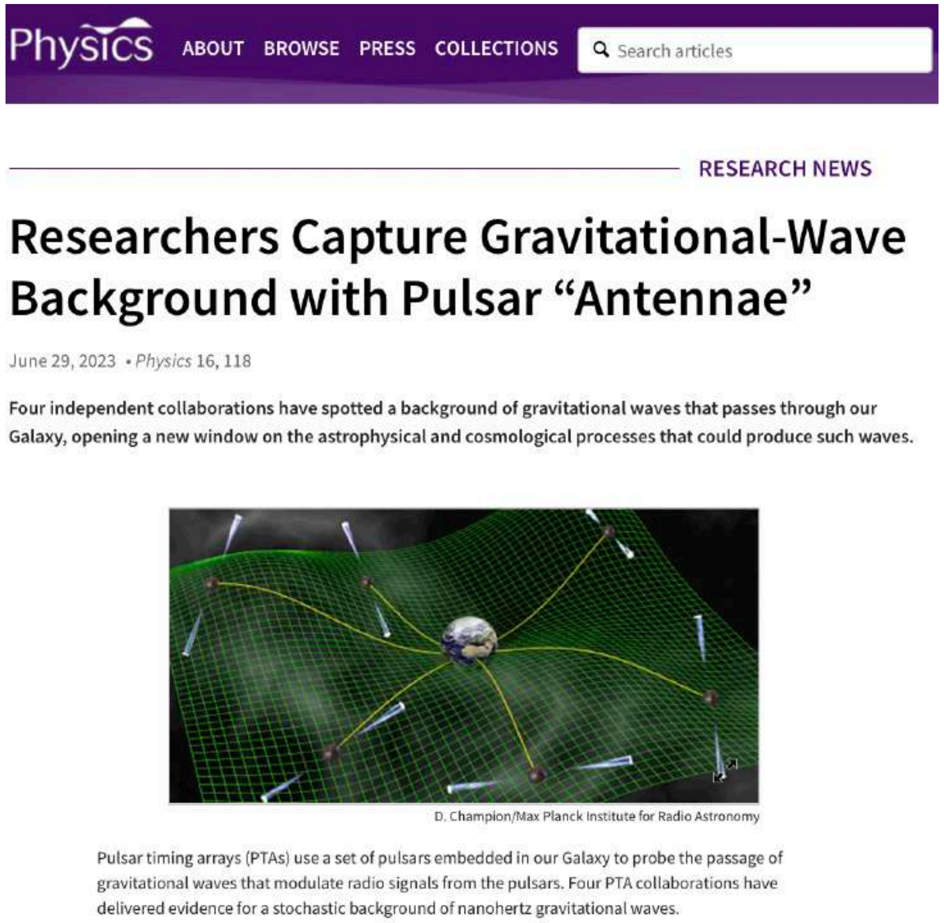
**peak frequency**

$$f_{\rm peak} \propto (\beta/H)T_*$$

$$h^2\Omega_{\rm GW}^{\rm peak} \propto T_*^2 K(\alpha) f_{\rm peak}^{-2}$$

**Highly sensitive to details of FOPTs and to underlined particle physics model**

# Evidence of the stochastic GW background



RESEARCH NEWS

## Researchers Capture Gravitational-Wave Background with Pulsar “Antennae”

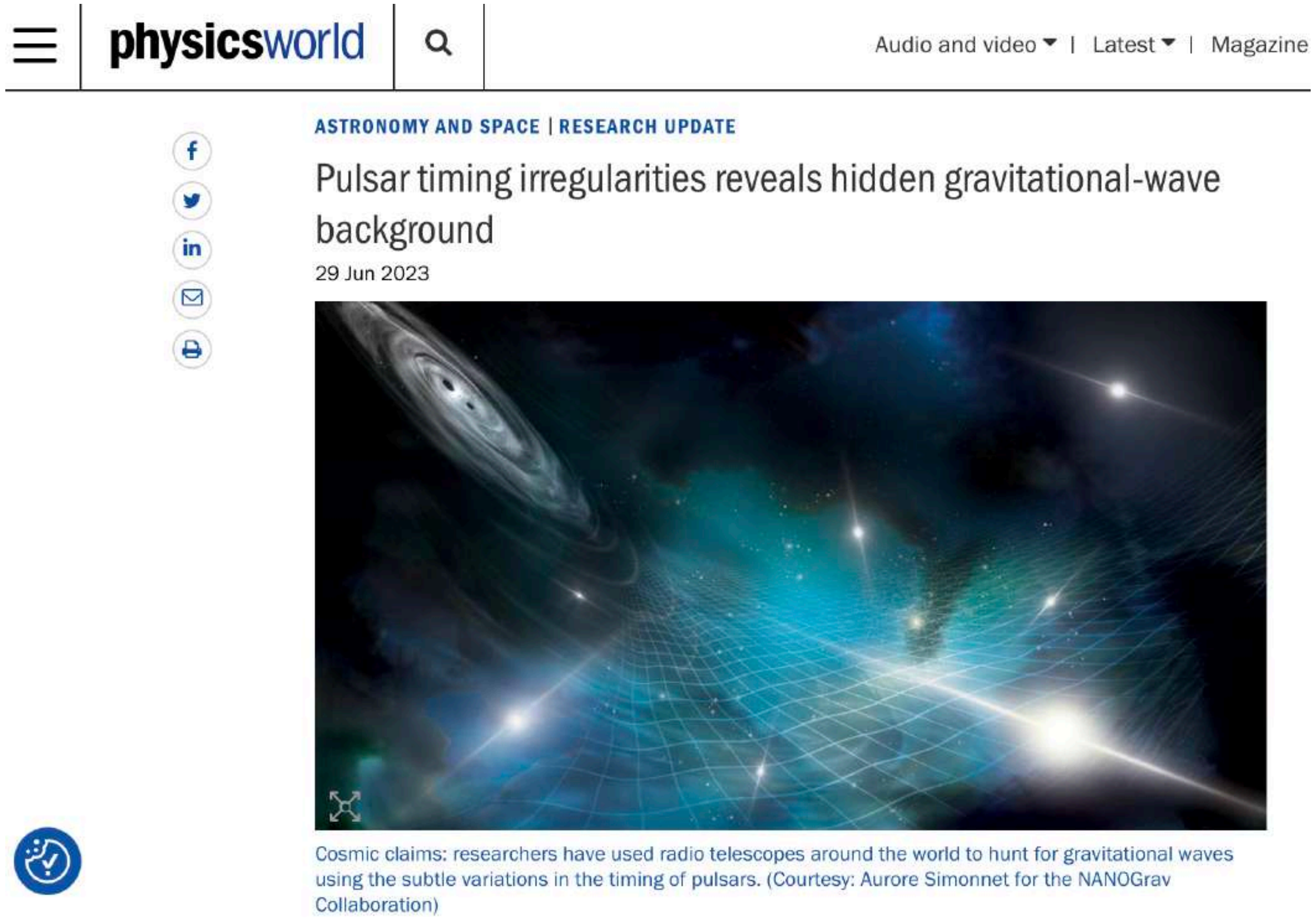
June 29, 2023 • *Physics* 16, 118

Four independent collaborations have spotted a background of gravitational waves that passes through our Galaxy, opening a new window on the astrophysical and cosmological processes that could produce such waves.

D. Champion/Max Planck Institute for Radio Astronomy

Pulsar timing arrays (PTAs) use a set of pulsars embedded in our Galaxy to probe the passage of gravitational waves that modulate radio signals from the pulsars. Four PTA collaborations have delivered evidence for a stochastic background of nanohertz gravitational waves.

`NANOGrav Collaboration,`
`Astrophys. J. Lett. 951 (2023) 1, L8; 2306.16213`



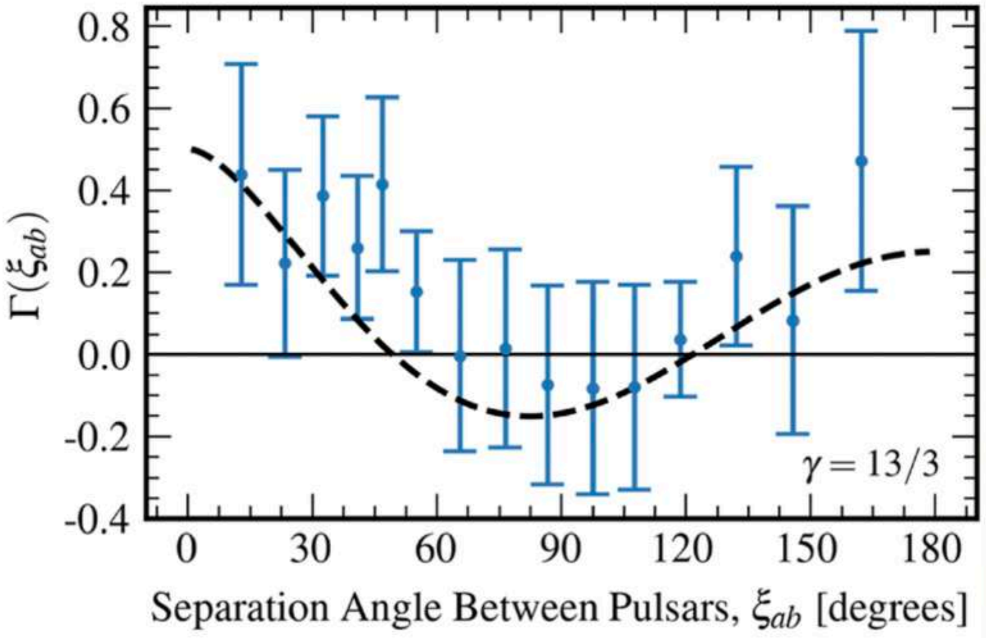
ASTRONOMY AND SPACE | RESEARCH UPDATE

## Pulsar timing irregularities reveals hidden gravitational-wave background

29 Jun 2023

Cosmic claims: researchers have used radio telescopes around the world to hunt for gravitational waves using the subtle variations in the timing of pulsars. (Courtesy: Aurore Simonnet for the NANOGrav Collaboration)

NANOGrav data vs expected correlation for SGWB



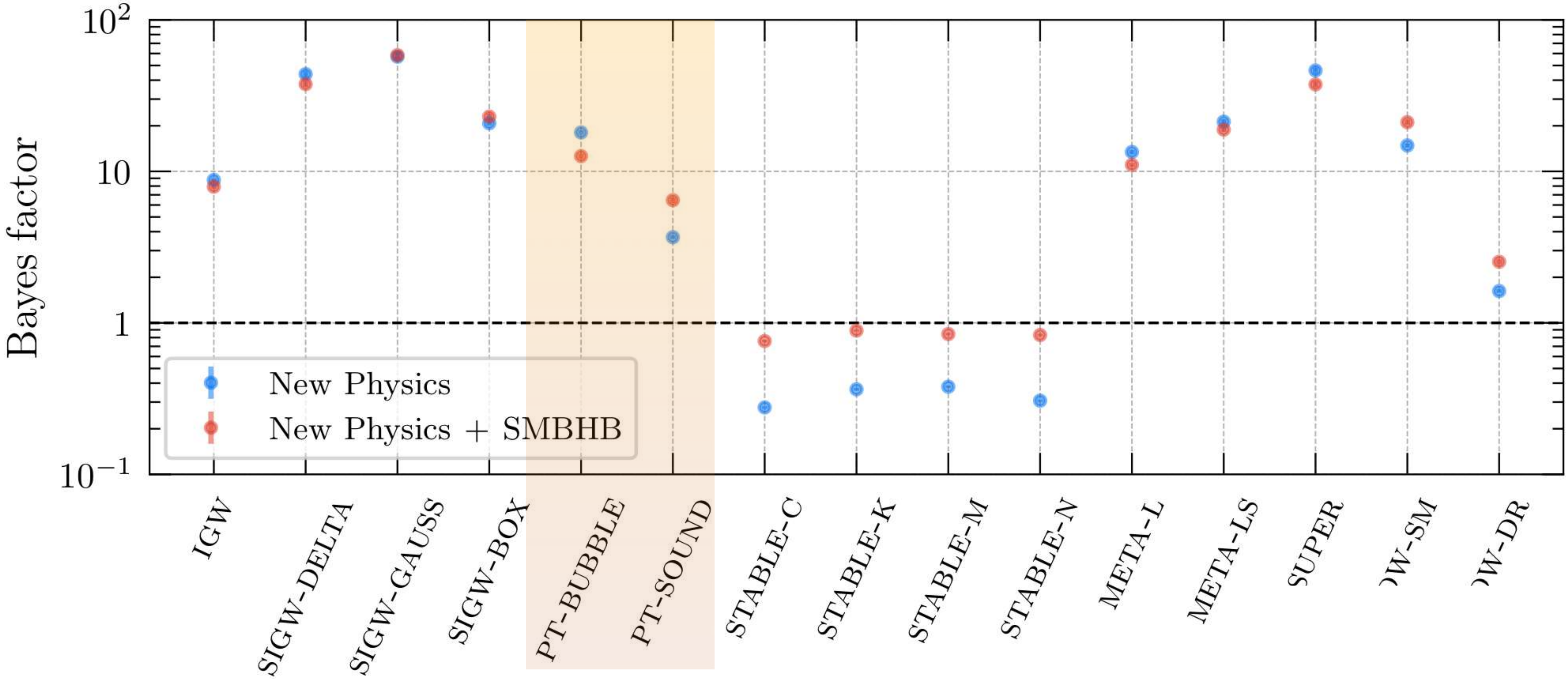
**The correlation between two pulsars depends on the separation of the pulsars in the sky, measured in degrees.**

**A conservative explanation: supermassive BH binaries**

**Can such an observation become a window into “New Physics”?**

# Probing New Physics at NANOGrav

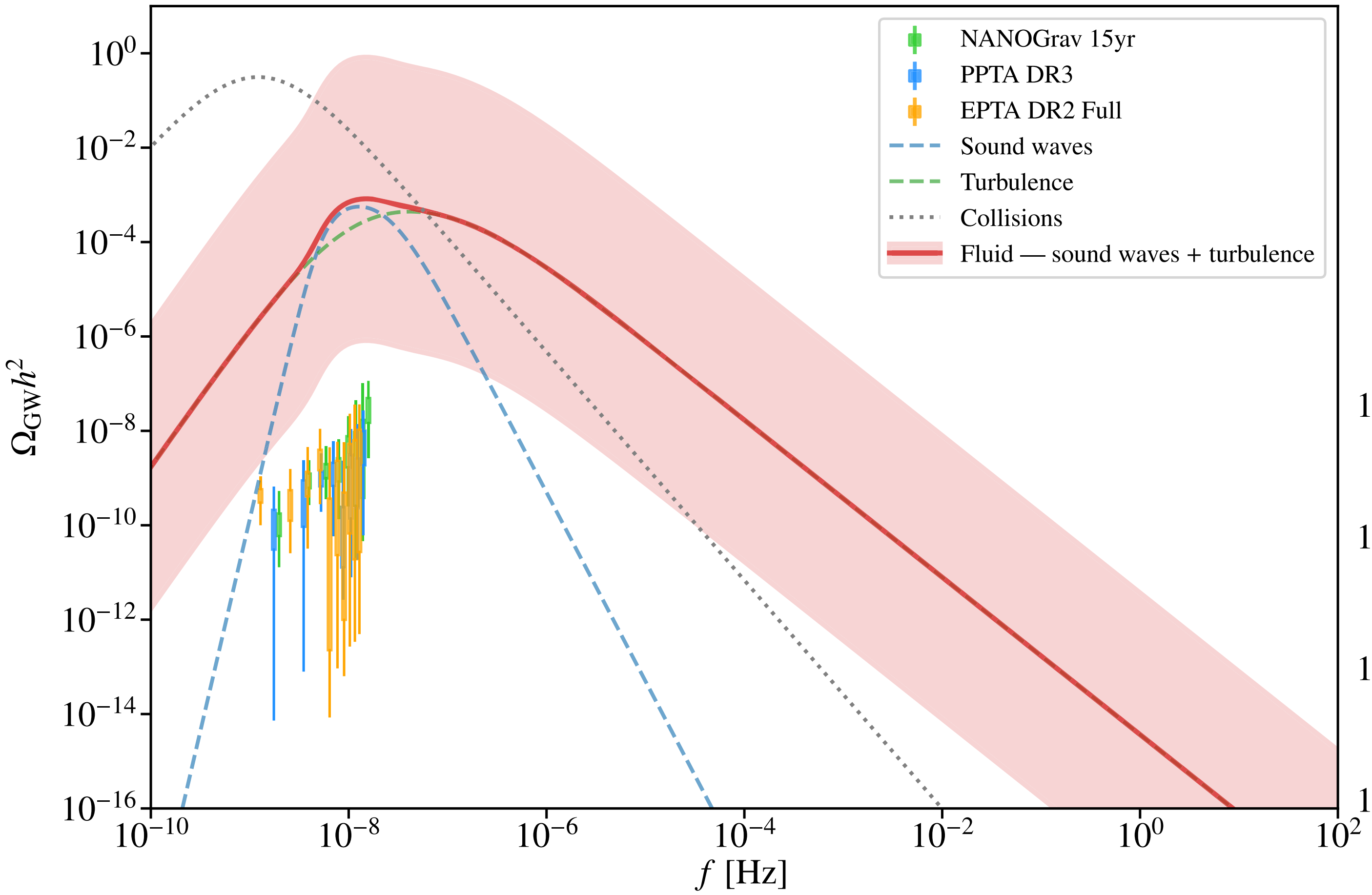
NANOGrav Collaboration,
Astrophys. J. Lett. 951 (2023) 1, L11; 2306.16219



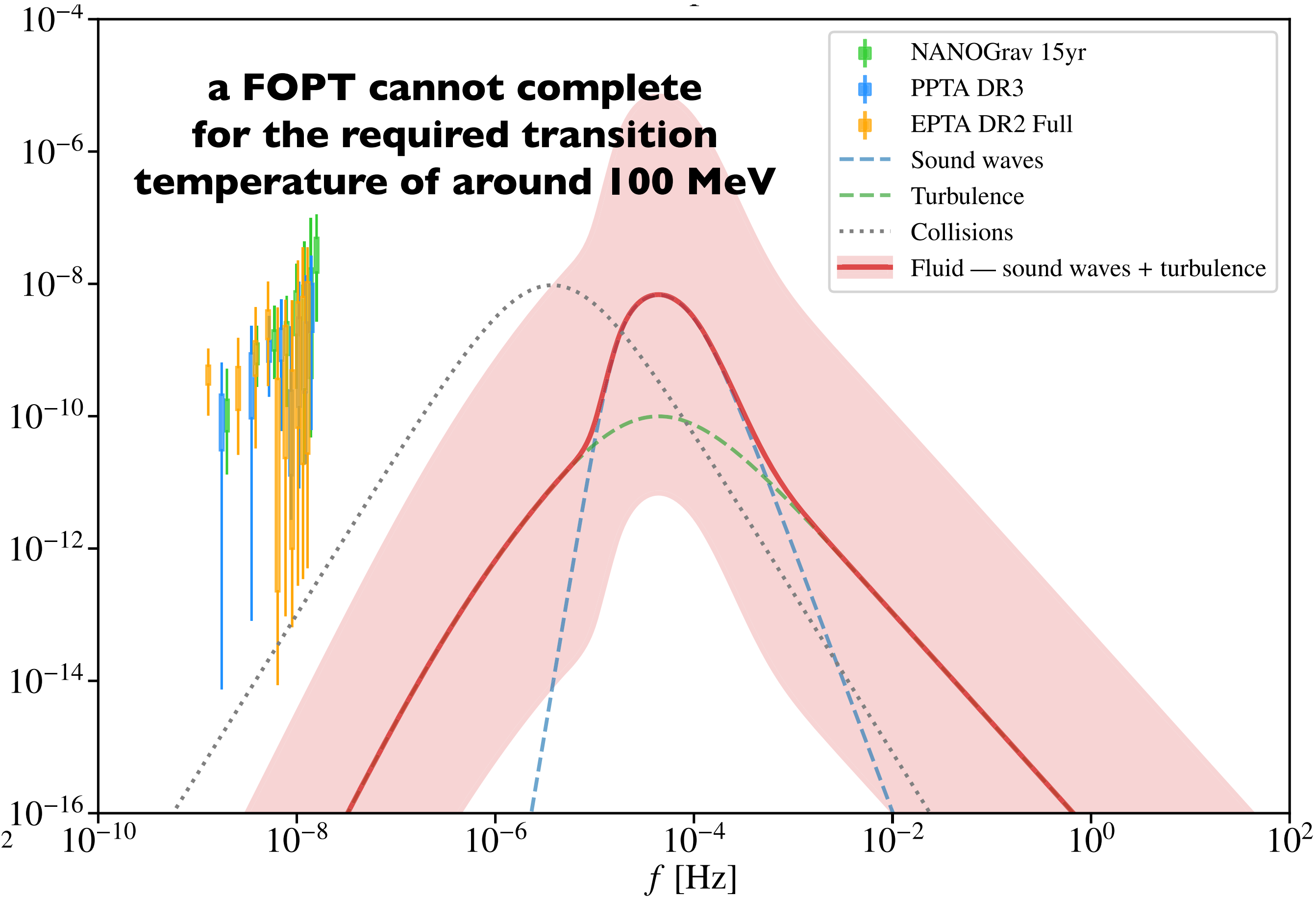
- many models provide a better fit resulting in Bayes factors from 10 to 100
- strongly depend on modelling assumptions about the cosmic SMBHB population
- considered by many theorists as a constraint on scenarios of New Physics
- for specific models, however, making predictions requires a great care!

# Call for caution in NANOGrav data interpretations

P. Athron et al, PRL 132 (2024) 22, 221001; 2306.17239



strongest supercooling for which the FOPT is NOT completed and percolation may not occur


**a FOPT cannot complete for the required transition temperature of around 100 MeV**

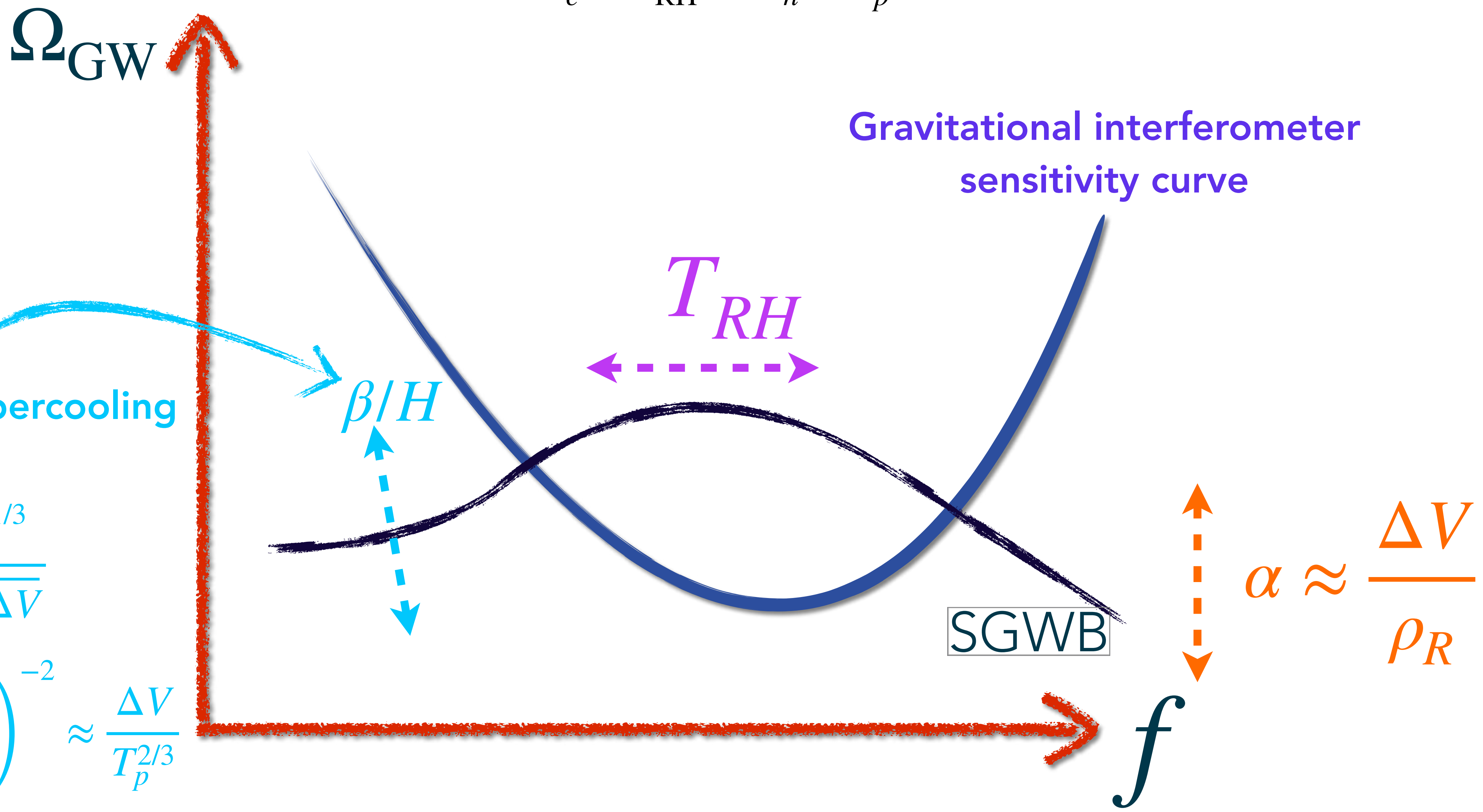
strongest supercooling for which the FOPT is completed

period of vacuum domination hinders bubble percolation and transition completion preventing a consistent interpretation of NANOGrav signal through supercooled transitions

# Stochastic GWs from supercooling

$$h^2\Omega_{\rm GW}^{\rm peak} \propto \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{\beta}{H(T_p)}\right)^{-2} \qquad f_{\rm peak} \propto \left(\frac{\beta}{H(T_p)}\right)\left(\frac{T_{\rm RH}}{\rm GeV}\right) \qquad T_{\rm RH} \propto T_p\,(1+\alpha)^{1/4}$$

$$T_c > T_{\rm RH} \gg T_n > T_p$$



With strong supercooling

$$\alpha \gg 1$$

$$\frac{\beta}{H(T_p)} \approx \frac{T_p^{1/3}}{\sqrt{\Delta V}}$$

$$\Omega_{\rm GW} \approx \left(\frac{\beta}{H(T_p)}\right)^{-2} \approx \frac{\Delta V}{T_p^{2/3}}$$

$$\alpha \approx \frac{\Delta V}{\rho_R}$$

Credit: Antonio Morais

# Supercooling in conformal U(1)′ models

generic charge assignments

| **Field** | **U(1)′** |
|---|---|
| $Q$ | $\frac{1}{3}x_{\mathcal{H}} + \frac{1}{6}x_\sigma$ |
| $u_R$ | $\frac{4}{3}x_{\mathcal{H}} + \frac{1}{6}x_\sigma$ |
| $d_R$ | $-\frac{2}{3}x_{\mathcal{H}} + \frac{1}{6}x_\sigma$ |
| $L$ | $-x_{\mathcal{H}} - \frac{1}{2}x_\sigma$ |
| $e_R$ | $-2x_{\mathcal{H}} - \frac{1}{2}x_\sigma$ |
| $\mathcal{H}$ | $x_{\mathcal{H}}$ |
| $\nu_R$ | $-\frac{1}{2}x_\sigma$ |
| $\sigma$ | $x_\sigma$ |

scale invariant scalar potential

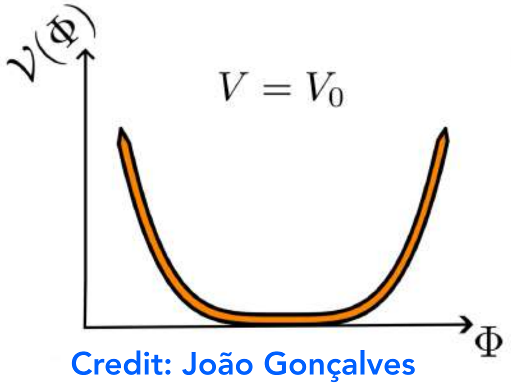
$$V_0(\mathcal{H},\sigma) = \lambda_h(\mathcal{H}^\dagger\mathcal{H})^2 + \lambda_\sigma(\sigma^\dagger\sigma)^2 + \lambda_{\sigma h}(\mathcal{H}^\dagger\mathcal{H})(\sigma^\dagger\sigma)$$

Tree level CP-even scalar masses

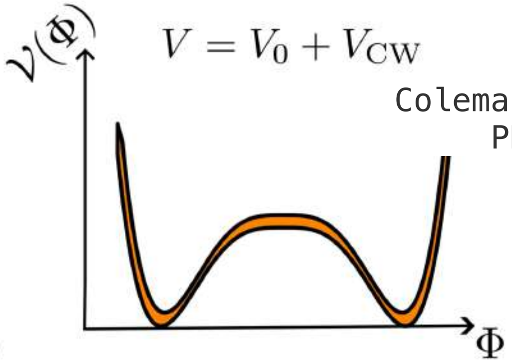
$M_{h_1}^{(0)} = 0$ $\quad$ $M_{h_2}^{(0)} \neq 0$

▼

Goldstone "scalon" → Higgs boson as pseudo-Goldstone "scalon"



Credit: João Gonçalves



Coleman, Weinberg, PRD7 (1973) 1888

$M_{h_1} \neq 0$ $\quad$ $M_{h_2} \neq 0$

[Gildener, Weinberg, PRD13 (1976) 3333]

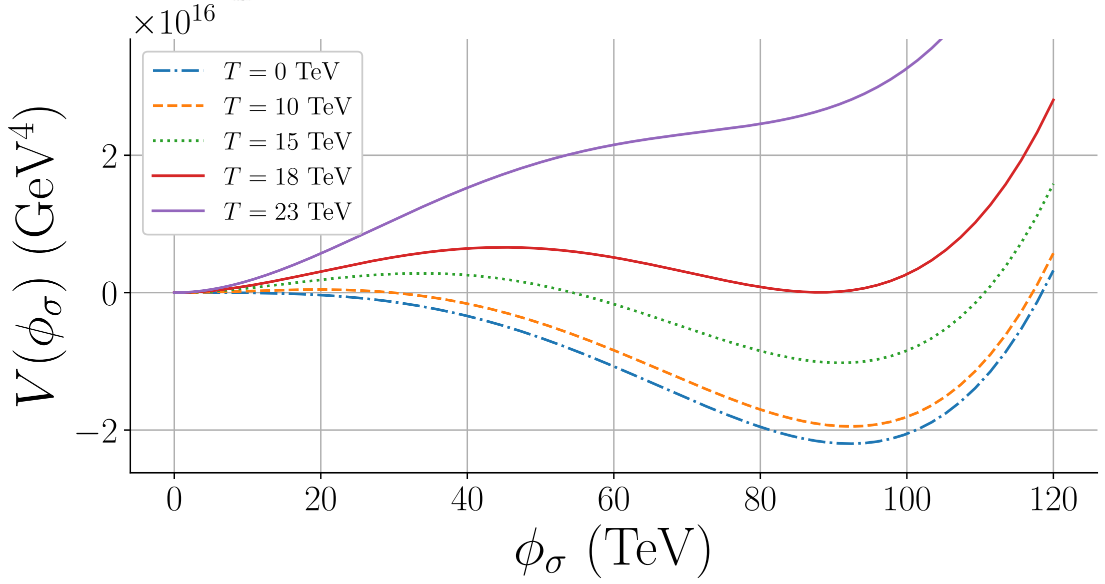
**Neutrino masses/mixing via Type-I seesaw mechanism**

$$\mathcal{L}_\nu = y_\nu^{ij}\overline{L}_i\tilde{\mathcal{H}}\nu_{\mathrm{R}j} + y_\sigma^{ij}\bar{\nu}^c_{\mathrm{R}i}\nu_{\mathrm{R}j}\sigma + \mathrm{h.c.}$$

High-temperature EFT potential

$$V_{\rm eff}^{\rm HT} = \phi_\sigma^4\left(-\frac{g_L^4}{2\pi^2} - \frac{g_L^3}{2\sqrt{2}\pi} + \frac{\lambda_\sigma}{4} + \frac{\ln 2\left([\sum_{i=1}^3[\boldsymbol{y_\sigma^4}]_{ii}\right)}{32\pi^2}\right)\boxed{-\,\phi_\sigma^3\frac{4g_L^3T}{3\pi}} + \phi_\sigma^2\left(\frac{g_L^2T^2}{2} - \frac{g_L^3T^2}{\sqrt{2}\pi} + \frac{T^2}{48}\sum_{i=1}^3[\boldsymbol{y_\sigma^2}]_{ii}\right)$$

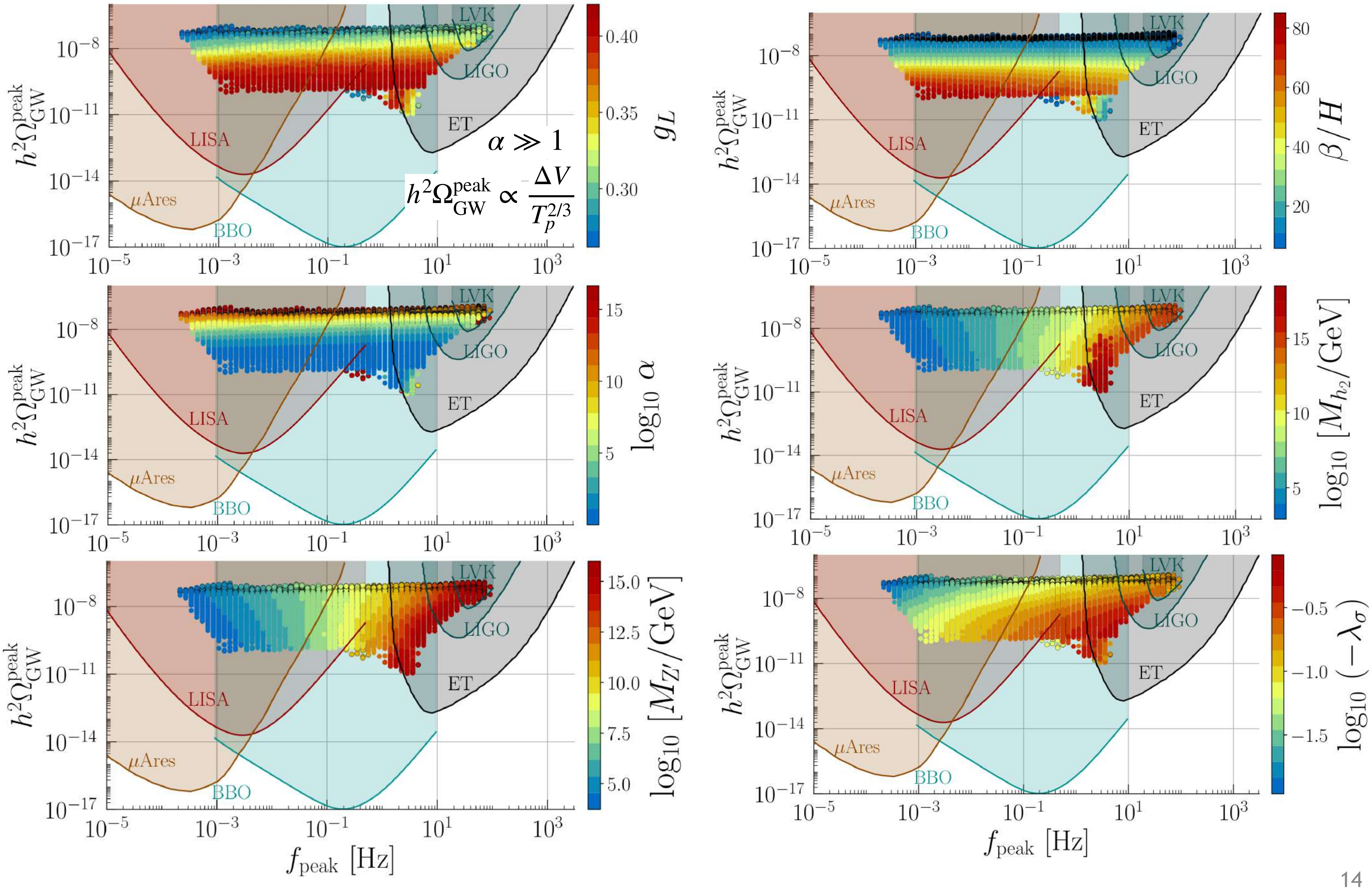
negative cubic term is generated!



- ⇒ dynamical symmetry breaking
- ⇒ potential barrier persists till very low T
- ⇒ long-lasting FOPT $\beta/H \sim \mathcal{O}(10-100)$
- ⇒ $\Delta V$ is maximised leading to $\alpha \approx \dfrac{\Delta V}{\rho_R} \gg 1$

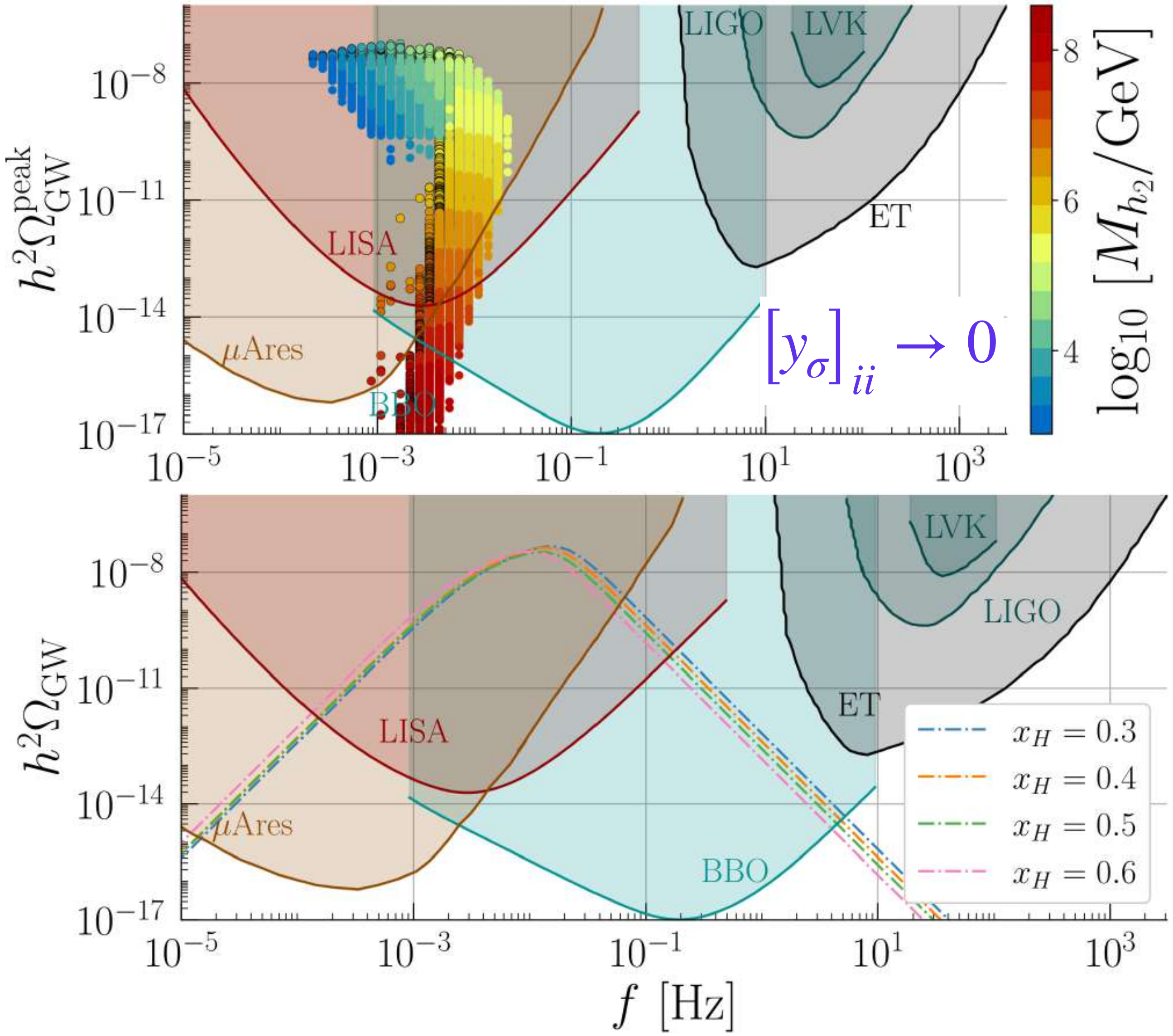
# SGWB predictions in conformal B-L theory

$x_\sigma = 2$ and $x_H = 0$ $\beta/H \gtrsim 8$ from PBH constraints [Y. Gouttenoire, T. Volanski, 2305.04942]



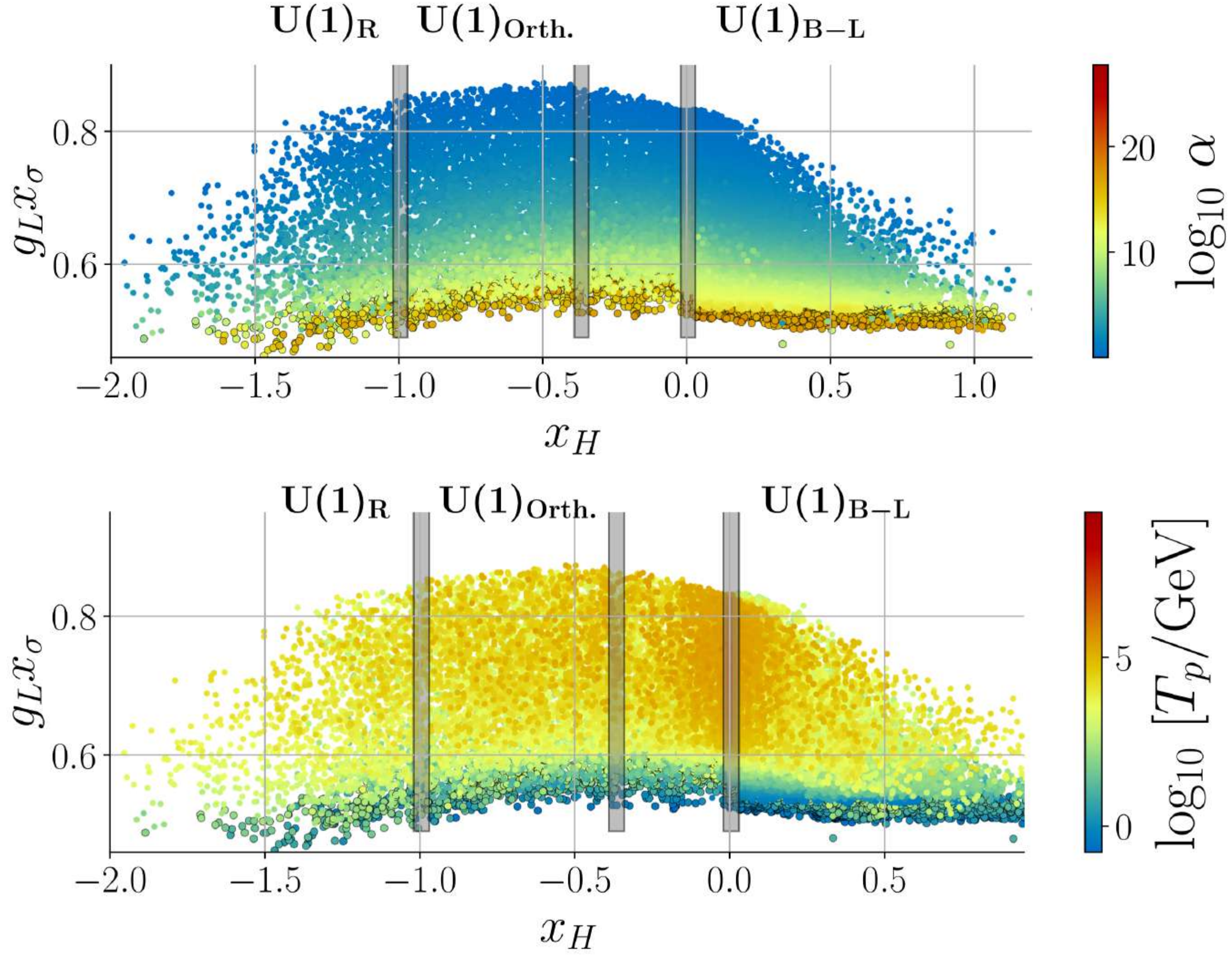
# SGWB predictions: role of neutrinos and charges

**LIGO/ET signal <=> neutrino mass generation**

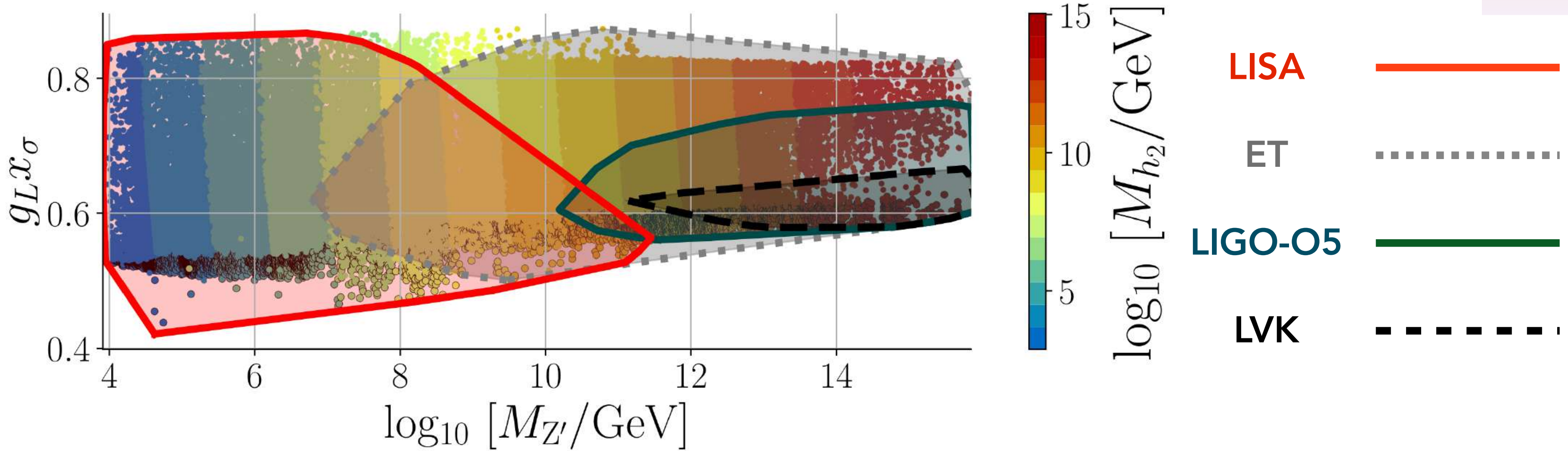


$[y_\sigma]_{ii} \to 0$

$(-1,2)$ $\left(-\frac{16}{41},2\right)$ $(0,2)$ $(x_H, x_\sigma)$



SNR > 10 for observable SGWB



**LISA**

**ET**

**LIGO-O5**

**LVK**

**LIGO+Virgo+KAGRA (LVK) excluded:**

$10^{12}\ \mathrm{GeV} < M_{h_2} \sim M_{Z'} < 10^{16}\ \mathrm{GeV}$

$g_L x_\sigma \sim 0.6$

**LISA+ET+LIGO will probe:**

$M_{h_2} > 1\mathrm{TeV}\,, M_{Z'} > 10\ \mathrm{TeV}$

$0.55 \lesssim g_L x_\sigma \lesssim 0.8$

# Conclusions

- Vacuum domination hinders bubble percolation in the frequency domain of PTAs making it difficult to interpret NANOGrav data due to supercooled phase transitions
- SGWB detection at LISA+ET+LIGO probes supercooling at higher temperatures (hence, larger frequencies) setting bounds on parameters of conformal models with new gauge symmetries
- Simultaneous explanation of neutrino masses in the U(1)′ conformal model is crucial for high-frequency SGWB searches
- LISA+ET+LIGO can either rule out most of the parameter space challenging the hypothesis of supercooling and scale invariance, or lead to a ground-breaking discovery