Did we hear the sound of the Universe boiling?

Analysis using the full fluid velocity profiles and NANOGrav 15-year data

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STRING THEORY
- \> 3 spatial dimensions
- Curled up? Size scale?
- Deviations from Newton's *law*

ELECTROWEAK BARYOGENSIS
- Baryon number violation (sphaleron)
- CP violation (e.g. *EDM neutron*)
- Thermal non-equilibrium

Big Bang

Inflation

BARYOGENESIS (E.G. GUT)
- Baryon number violation
- CP violation
- Thermal non-equilibrium

PRIMORDIAL NUCLEOSYNTHESIS
How many neutrons available for nucleosynthesis
- *Coupling constants*
- *Lifetime*

PRODUCTION OF HEAVY ELEMENTS
- Supernova explosions
- *Nuclear physics in neutron rich stars*

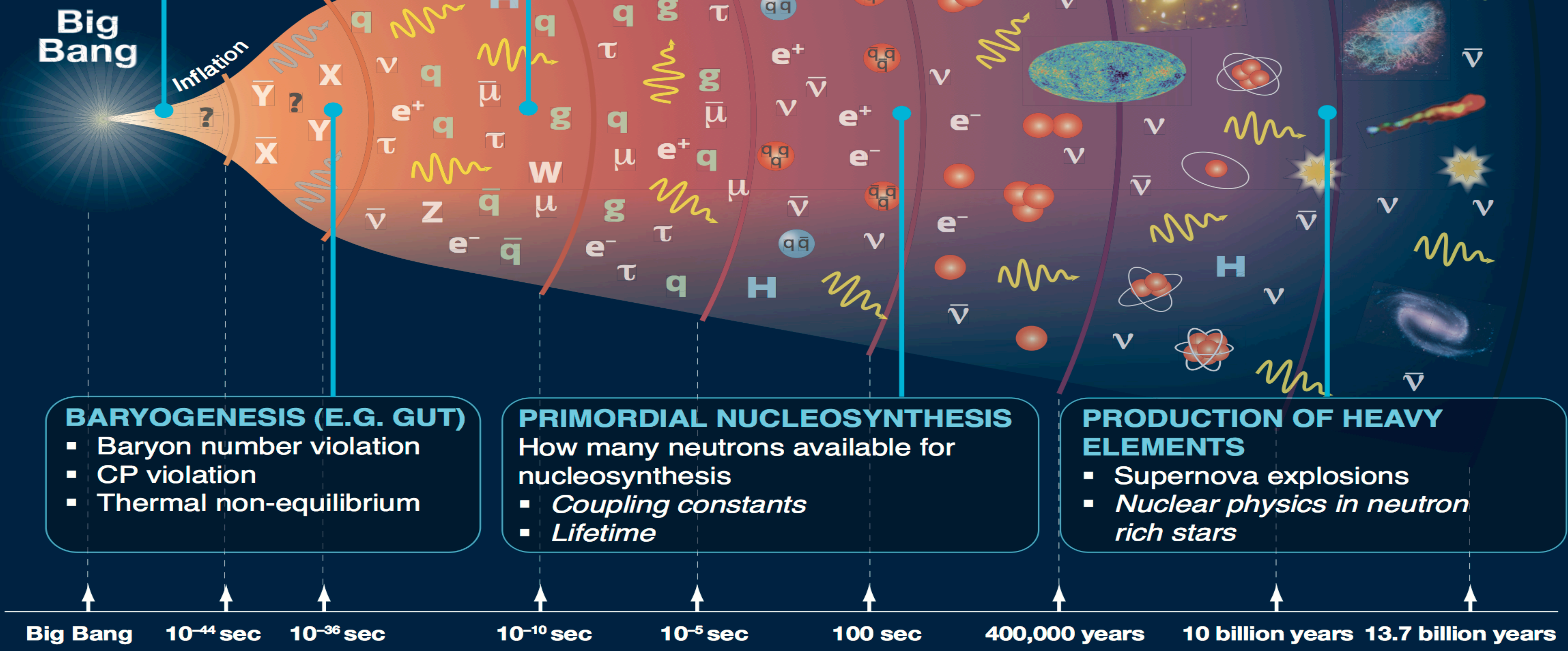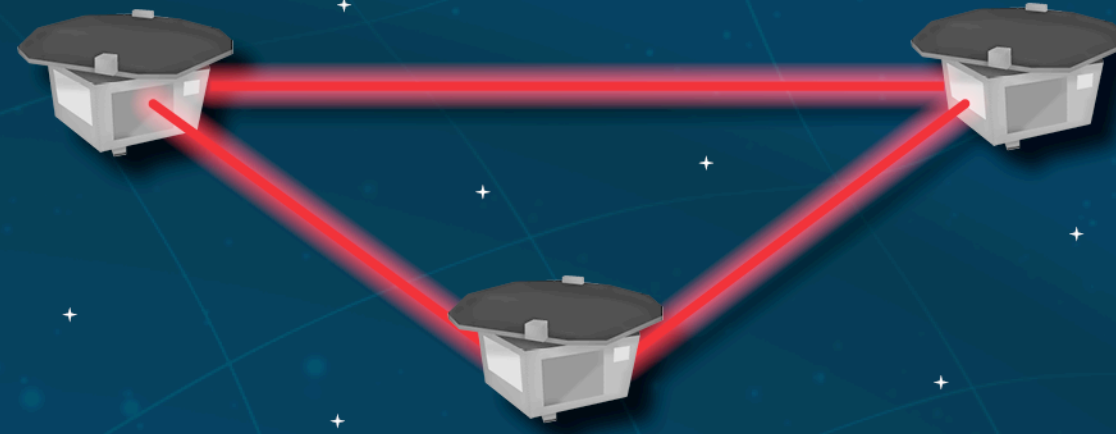| Big Bang | 10^{-44} sec | 10^{-36} sec | 10^{-10} sec | 10^{-5} sec | 100 sec | 400,000 years | 10 billion years | 13.7 billion years |

THE SPECTRUM OF GRAVITATIONAL WAVES

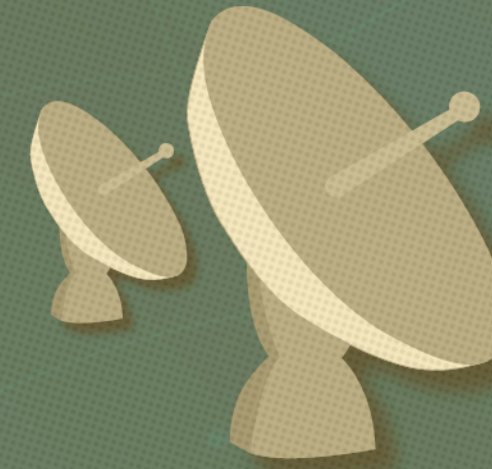**Observatories & experiments**

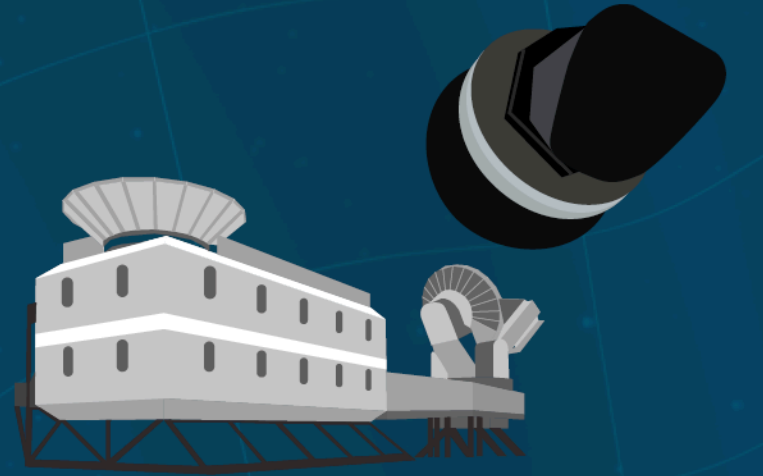Ground-based experiment

Space-based observatory

Pulsar timing array

Cosmic microwave background polarisation

Timescales

milliseconds   seconds   hours   years   billions of years

Frequency (Hz)
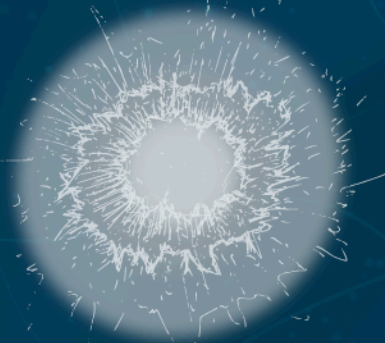
100 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-16}

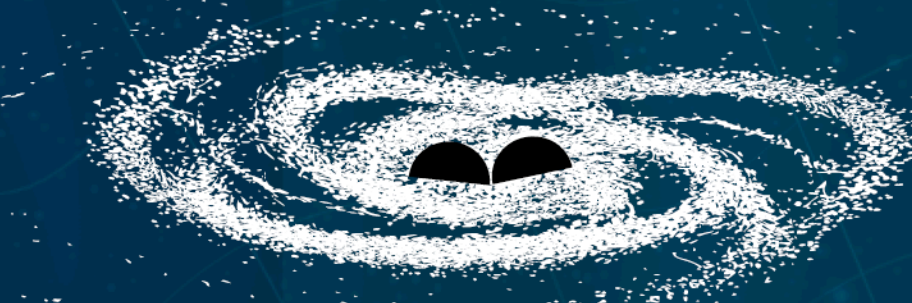Cosmic fluctuations in the early Universe

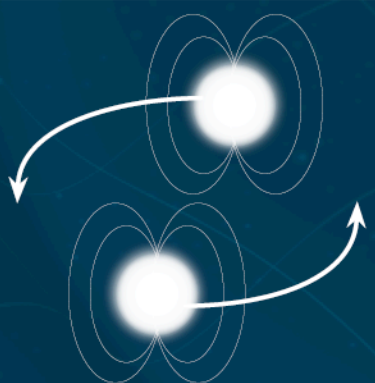**Cosmic sources**

Supernova

Pulsar

Compact object falling onto a supermassive black hole

Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

ESA | NASA
lisa

#lisa

North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

Detecting gravitational waves via regular observations of an ensemble of millisecond pulsars using the Green Bank Telescope, Arecibo Observatory, and the Very Large Array —>

In collaboration with international partners in the Parkes Pulsar Timing Array (PPTA) in Australia, the European Pulsar Timing Array (EPTA), and the Indian Pulsar Timing Array as part of the International Pulsar Timing Array (IPTA).

EARTH

TIMING ARRAY

GRAVITATIONAL WAVES

SUPERMASSIVE
BLACK HOLE BINARY

NANOGrav Observation - 15 Years
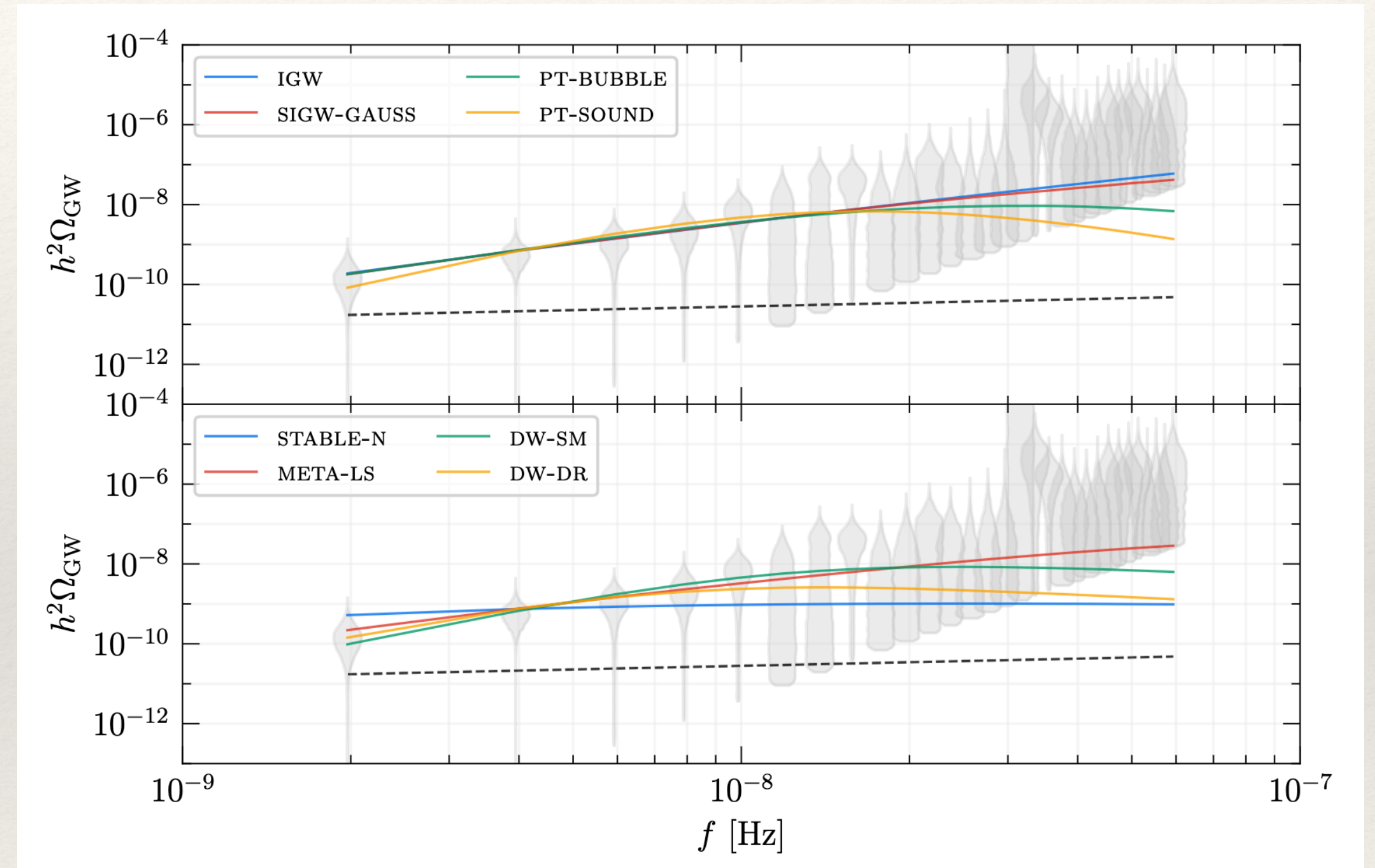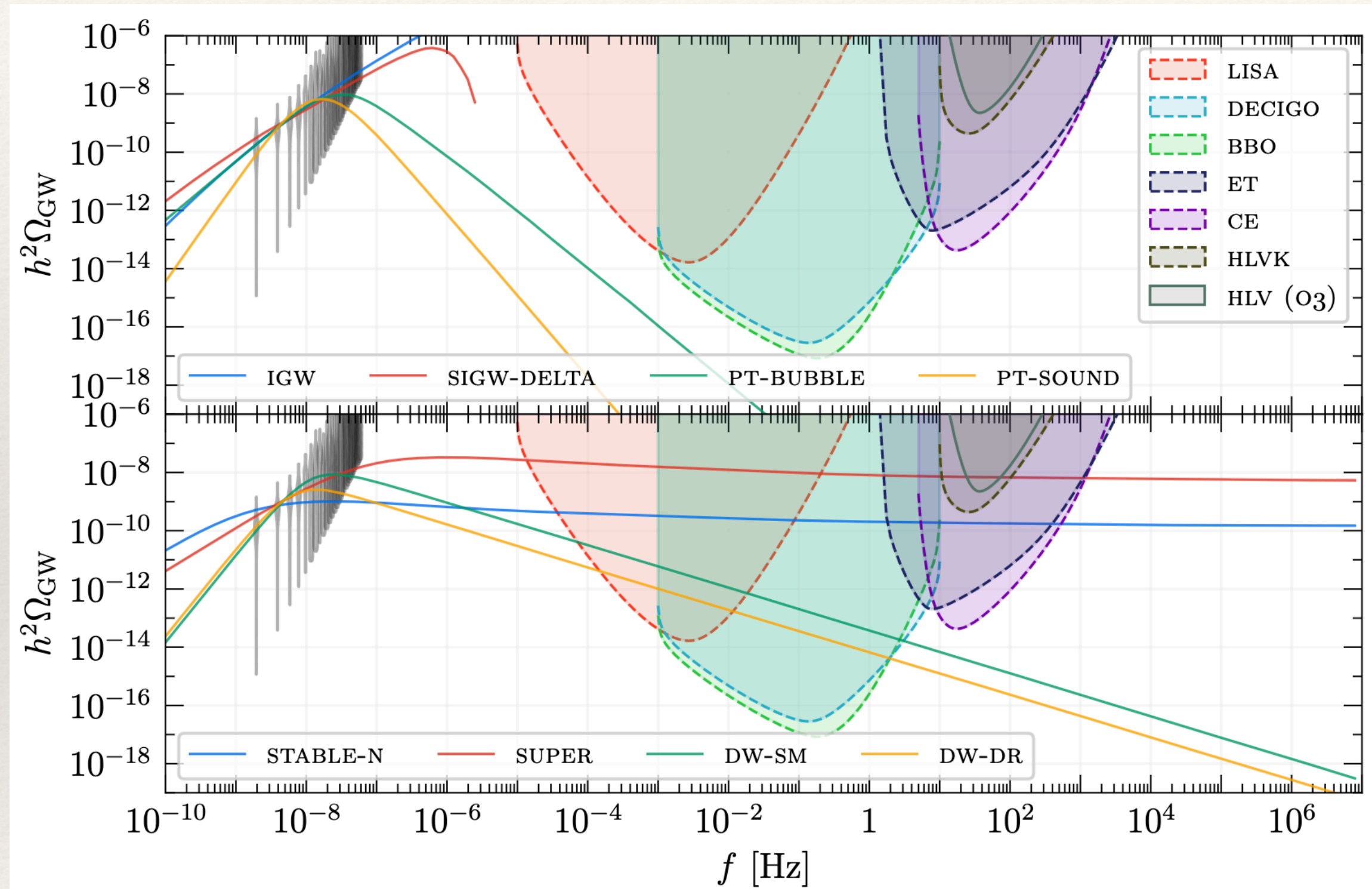
It can be explained with different possible scenarios: background from supermassive black holes binaries (SMBHB), induced GW, phase transitions, domain walls, etc.

First Order Phase Transitions

Starting from the unbroken phase, as the Universe cools, the potential energy undergoes a transformation, leading to the emergence of a new minimum that is distinct from the original one. This newly formed minimum is separated from the original by a potential energy barrier.
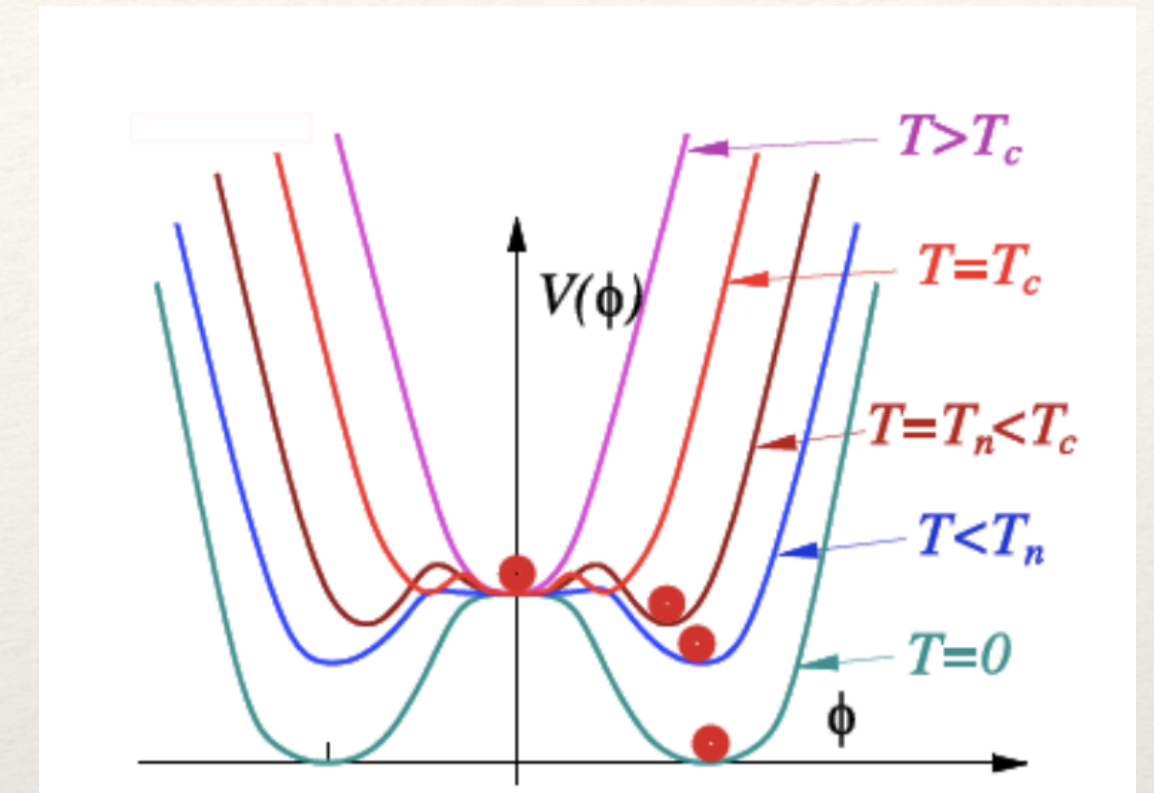
The phase transition proceeds through a process known as bubble nucleation. In this process, tiny regions within the Universe spontaneously transition from the old phase to the new one, forming bubbles of the new phase within the surrounding unbroken phase. These bubbles of the new phase then grow and expand, eventually dominating the Universe's state as it continues to cool.

Nucleation temperature: T_n
Hubble rate at Nucleation: H_n
Strength of the FOPT: α_n
Bubble nucleation rate: β
Bubble wall velocity: v_w

$$S_3(\vec{\phi}, T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\vec{\phi}(t)}{dr}\right)^2 + V_{\text{eff}}(\vec{\phi}, T) \right] \longrightarrow \frac{S_3(T_n)}{T_n} \approx 140$$

$$\alpha(T_n) = \frac{1}{\rho_{\text{rad}}}\left(\Delta V_{\text{eff}} - \frac{1}{4}\frac{d\Delta V_{\text{eff}}}{dT} \right)\bigg|_{T_n}$$

$$\beta = H_n T_n \frac{d(S_3/T)}{dT}$$

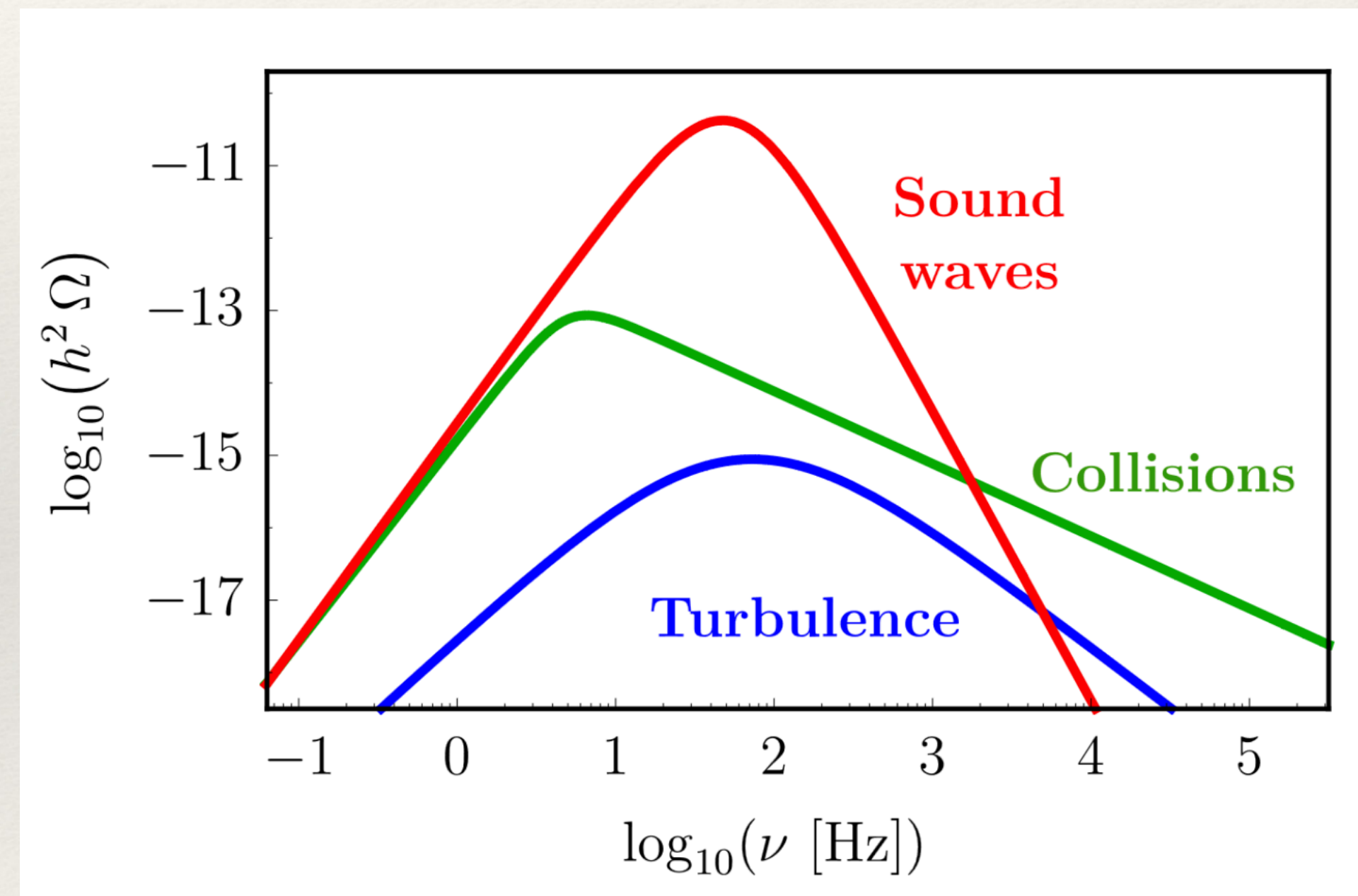$$H_n^2 = \frac{8\pi G}{3}\rho_{\text{rad}}(T_n)$$

First Order Phase Transitions and Gravitational Waves

First Order Phase Transition (FOPT) can give three sources for GW:

- Bubble Collision
- Sound Waves
- Turbulence

FOPT gravitational waves from sound waves:
- Stirred Plasma as Source for GW
- Long-lasting after phase transition
- Much larger than bubble collisions

arXiv:1304.2433   arXiv:2006.08802

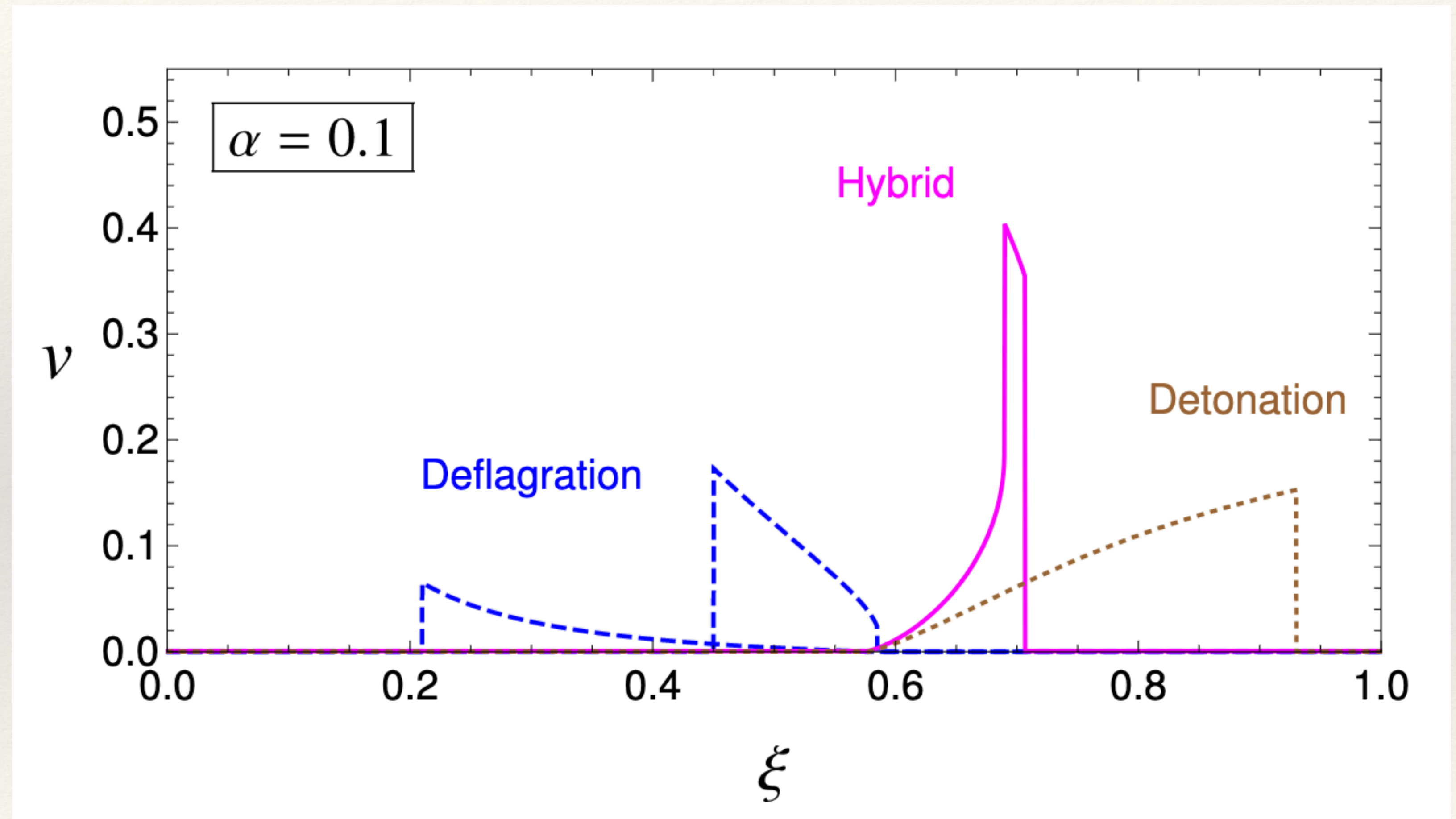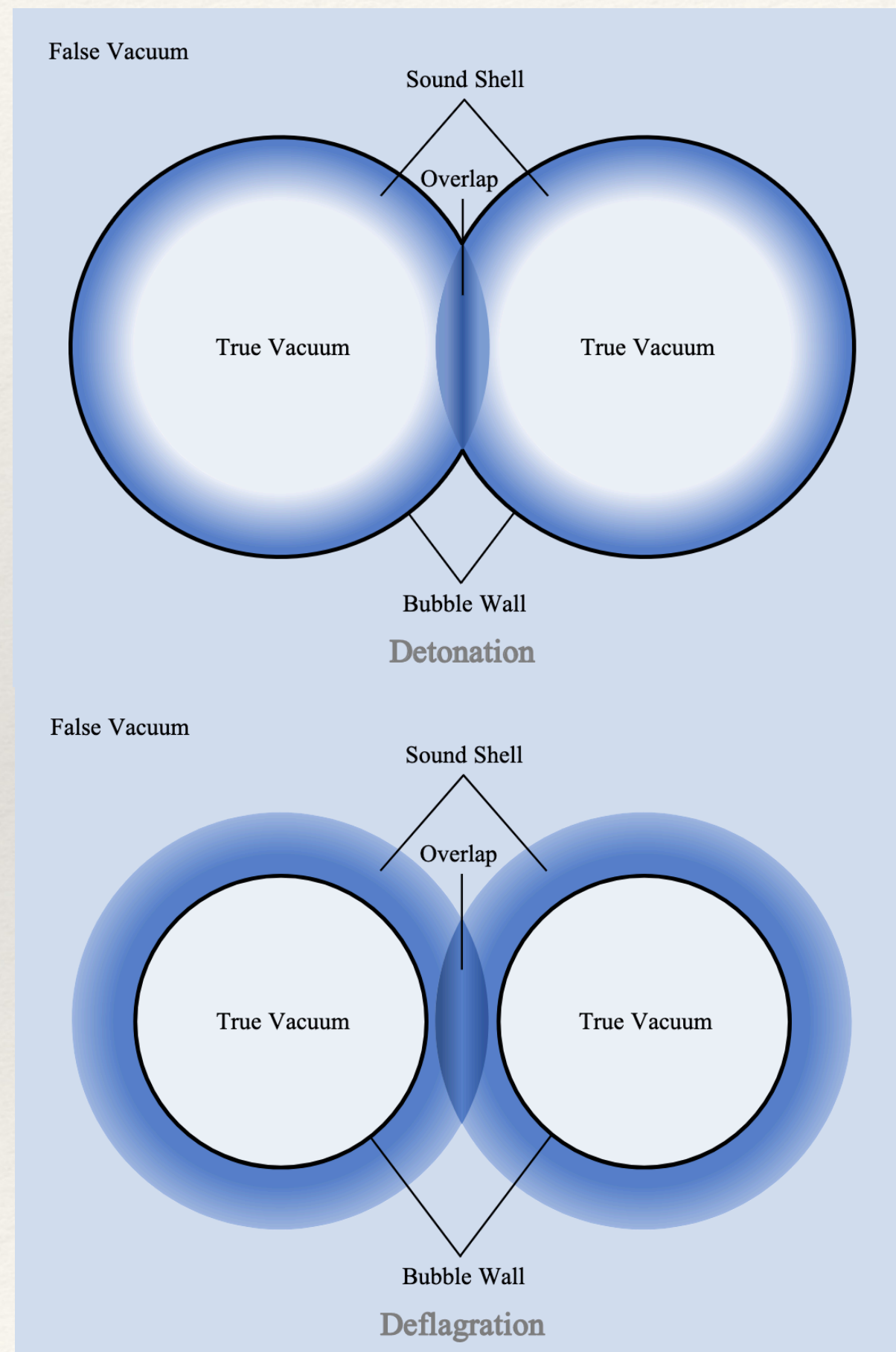# Gravitational Waves from FOPT: Sound Shell Model

During the Universe's cooling process, a new energy minimum forms, separated from the original by a potential energy barrier. Bubble nucleation happens, with small regions transitioning to the new phase, forming bubbles of the new phase within the old phase. These bubbles grow due to the lower energy of the new phase, converting more of the old phase. Gravitational waves result from the motion of the expanding bubble walls, generating spacetime ripples that carry away energy and momentum, creating a burst of gravitational waves.

Constructing the velocity field involves superimposing self-similar velocity and enthalpy density profiles, originating from randomly nucleated, expanding bubbles. These profiles, based on $\xi = R/T$ - R (distance from the bubble's center) and T (time since nucleation), dynamically evolve. When these bubbles collide, the scalar field driving the self-similar profile vanishes, turning it into the initial condition for unfettered sound wave propagation.

Computing the velocity field a convolution of the single-bubble velocity field with the distribution of bubble lifetimes —> Getting the velocity power spectrum —> Calculating the GW power spectrum using the velocity power spectrum!

arXiv:1909.10040

Velocity Profile of Colliding Bubble Walls

Gravitational Waves from FOPT: Full Sound Shell Model

Relic density of GW from FOPT:

$$\Omega_{\mathrm{GW}}h^2 = 8.5 \times 10^{-6} \left(\frac{100}{g_*(T_n)}\right)^{1/3} \Gamma^2 \bar{U}_f^4 \left[\frac{H_n}{\beta(v_w)}\right] v_w \times \Upsilon \times S(f)$$

$$\Upsilon = 1 - \frac{1}{\sqrt{1 + 2\tau_{\mathrm{sh}}H_s}}$$

Single broken power-law spectral form:

$$S(f) = \left(\frac{f}{f_p}\right)^3 \left(\frac{7}{4 + 3(f/f_p)^2}\right)^{7/2}$$

$$f_p = 8.9 \times 10^{-6} \frac{1}{v_w} \left(\frac{\beta}{H_n}\right) \left(\frac{z_p}{10}\right) \left(\frac{T_n}{100\mathrm{GeV}}\right) \left(\frac{g_*(T_n)}{100}\right)^{1/6} \mathrm{Hz}$$

Nucleation temperature: T_n
Strength of the FOPT: α_n
Bubble nucleation rate: β
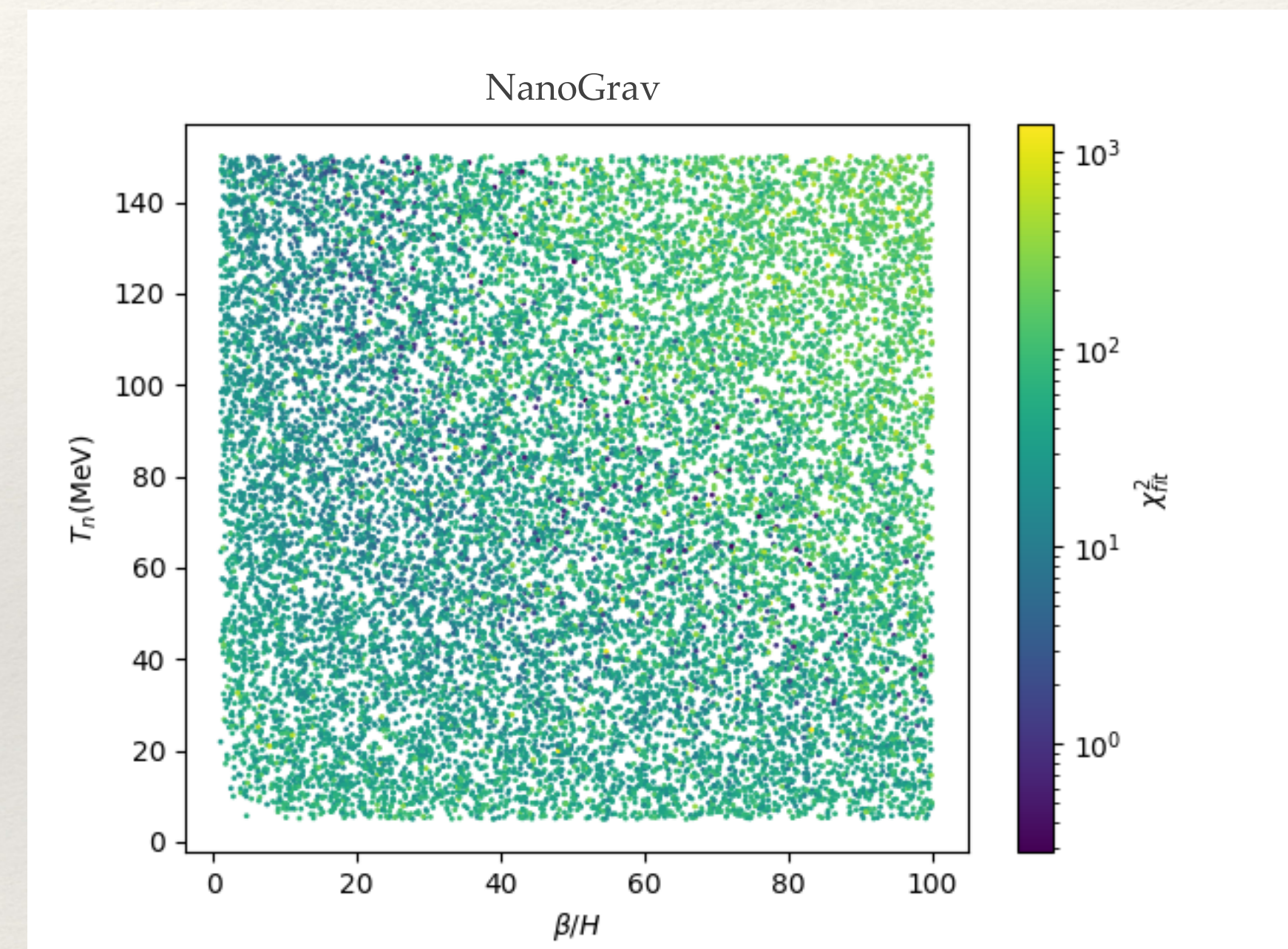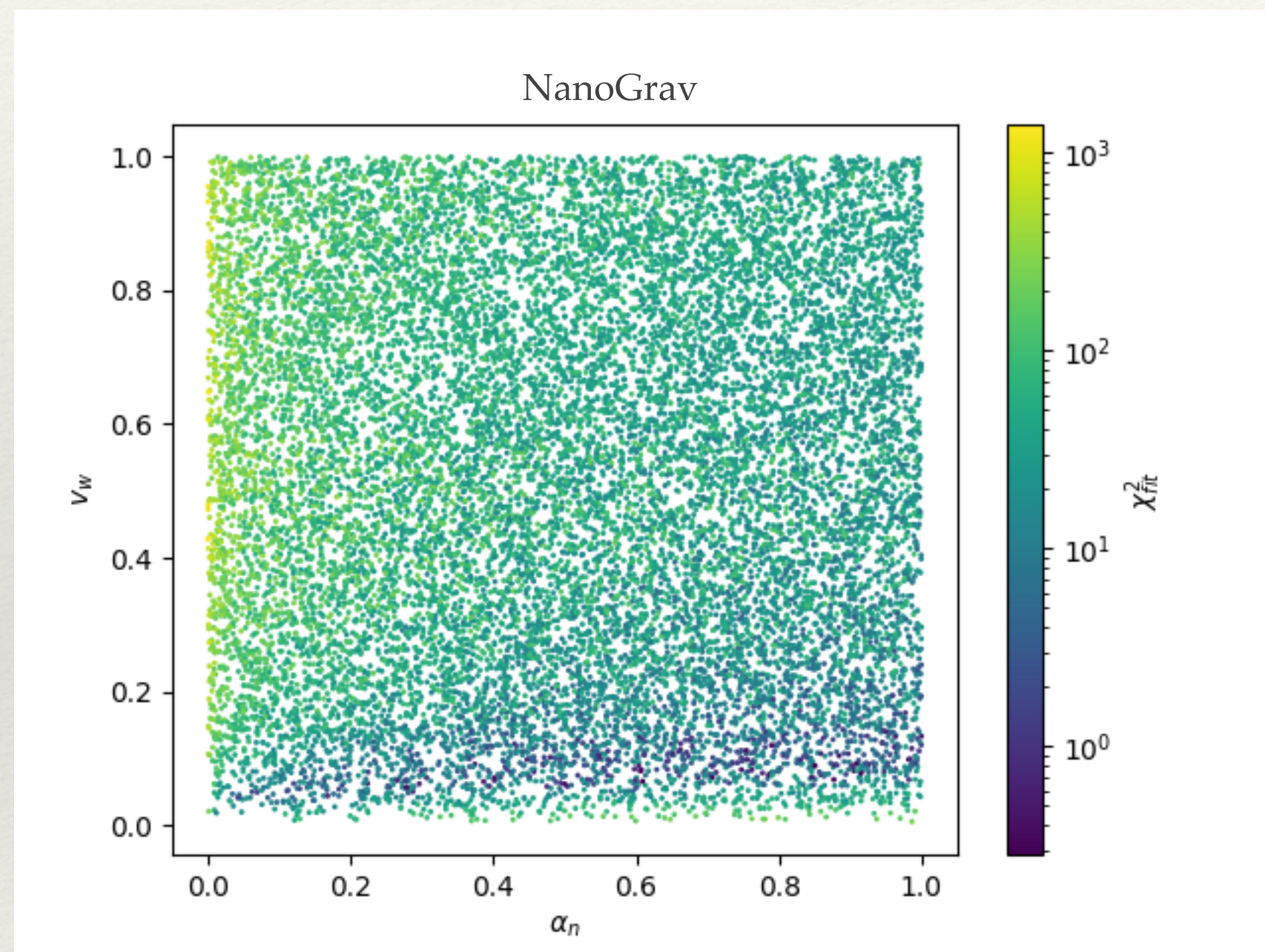Bubble wall velocity: v_w
Root mean square fluid velocity: $\bar{U}_f$
Adiabatic index: $\Gamma \sim 4/3$
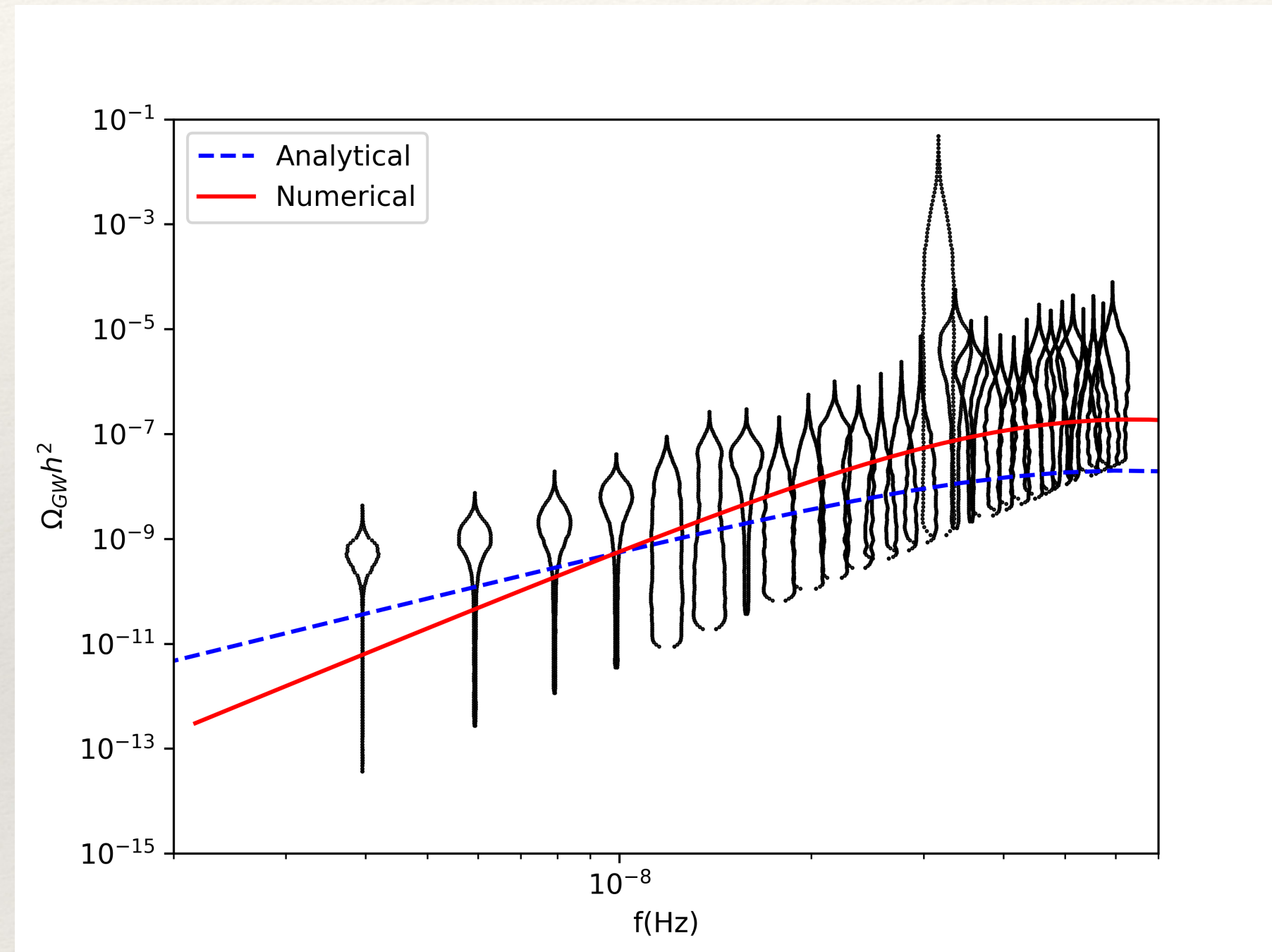Suppression factor from the finite lifetime (τ_{sh}) of the sound waves: Υ

Fitting FOPT to NANOGrav Data

Scanning over the parameter space of v_w, β/H_n, α, T_n from numerical estimation of GW using full velocity profile:

$$\chi_{\text{fit}}^2 = \sum_{i=1}^{N} \frac{\left(\log_{10} \Omega_{\text{th}} h^2 - \log_{10} \Omega_{\text{exp}} h^2 \right)^2}{2\bar{\sigma}_i^2}$$

Best Fit - NANOGrav

Full Sound shell		Broken power law fit	
Parameter	Best fit value	Parameter	Best fit value
α_n	0.85	α_n	0.89
β/H_*	42	β/H_*	5.17
T_n	133 MeV	T_n	142 MeV
v_w	0.09	v_w	0.67
χ_{fit}	1.4	χ_{fit}	1.59

A possible (dark) phase transition at low temperatures!
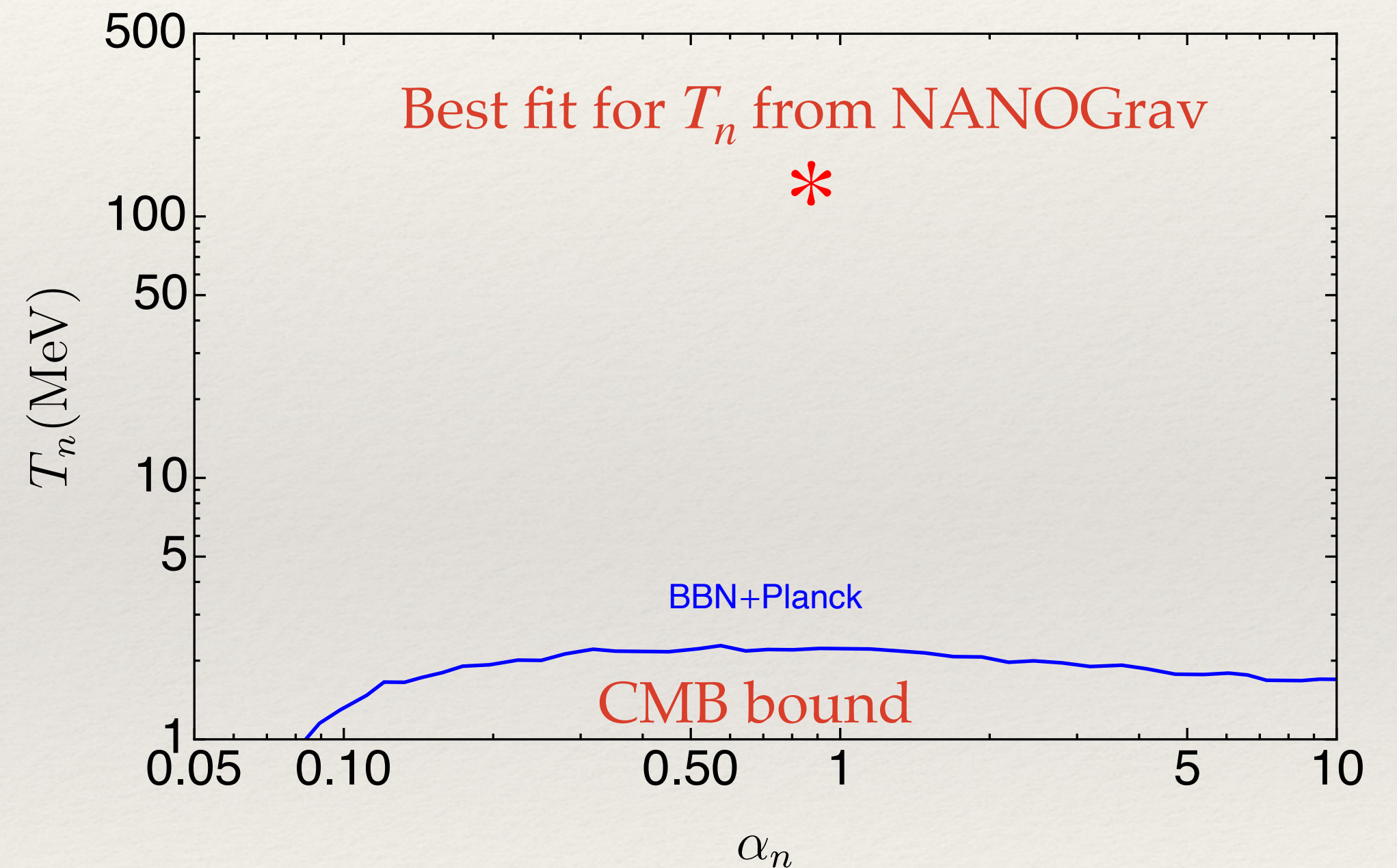
FOPT at low temperature and BSM Physics

Complementarity approach to probe phase transitions via GW and CMB detectors —>
To distinguish the SMBHB and phase transition explanations to the observed GW
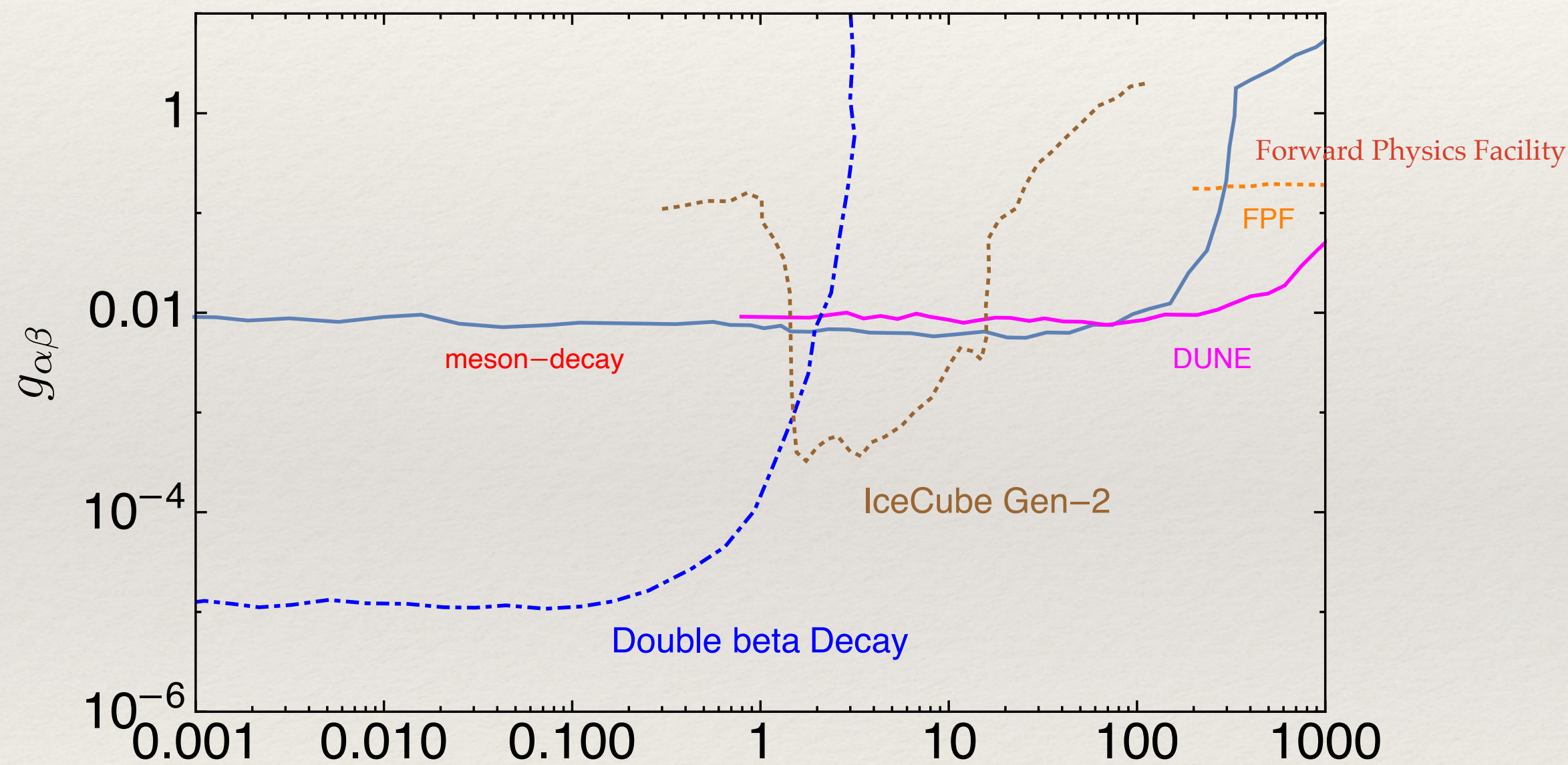
Dark scalar m_ϕ(MeV)

$$\mathcal{O} = \lambda_{\alpha\beta} \frac{(L_\alpha^T i\sigma_2 H)(H^T i\sigma_2 L_\beta)\phi}{\Lambda^2} \qquad g_{\alpha\beta} = \lambda_{\alpha\beta} v^2/\Lambda^2$$

Source for dark phase transition

$$T_{\rm rh}^\nu = \left[1 + \alpha_n + \alpha_n \frac{g_*^\gamma(t_{\rm rh})}{g_*^\nu(t_{\rm rh})}\left(\frac{T_n^\gamma}{T_n^\nu}\right)^4\right]^{1/4} T_n^\nu$$

Thanks for your attention!