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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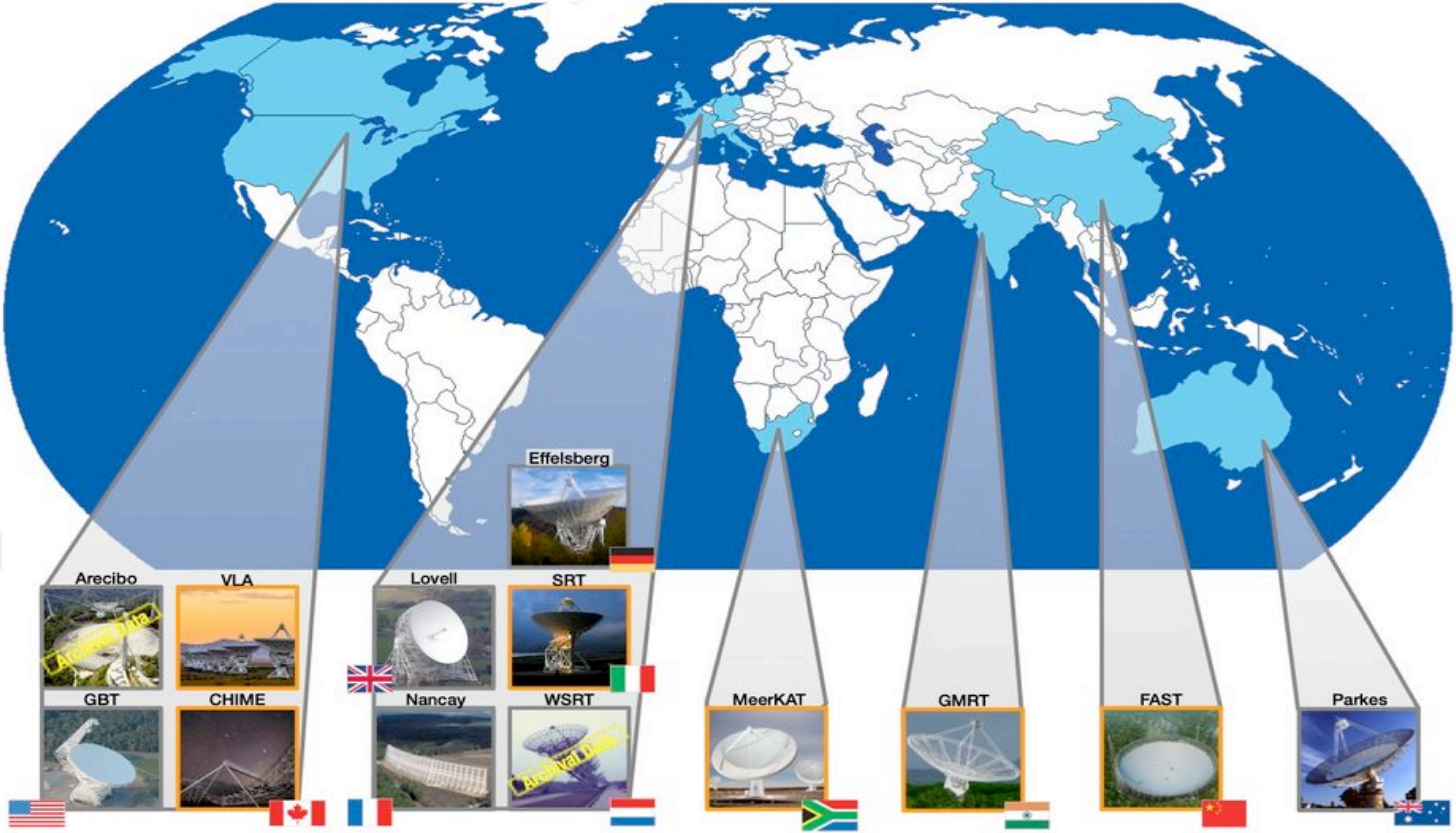
STRING THEORY
> 3 spatial dimensions
▪ Curled up? Size scale?
▪ Deviations from Newton's law
ELECTROWEAK BARYOGENSIS
▪ Baryon number violation (sphaleron)
▪ CP violation (e.g. EDM neutron)
▪ Thermal non-equilibrium
Big Bang
Inflation
BARYOGENESIS (E.G. GUT)
▪ Baryon number violation
▪ CP violation
▪ 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
esa
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

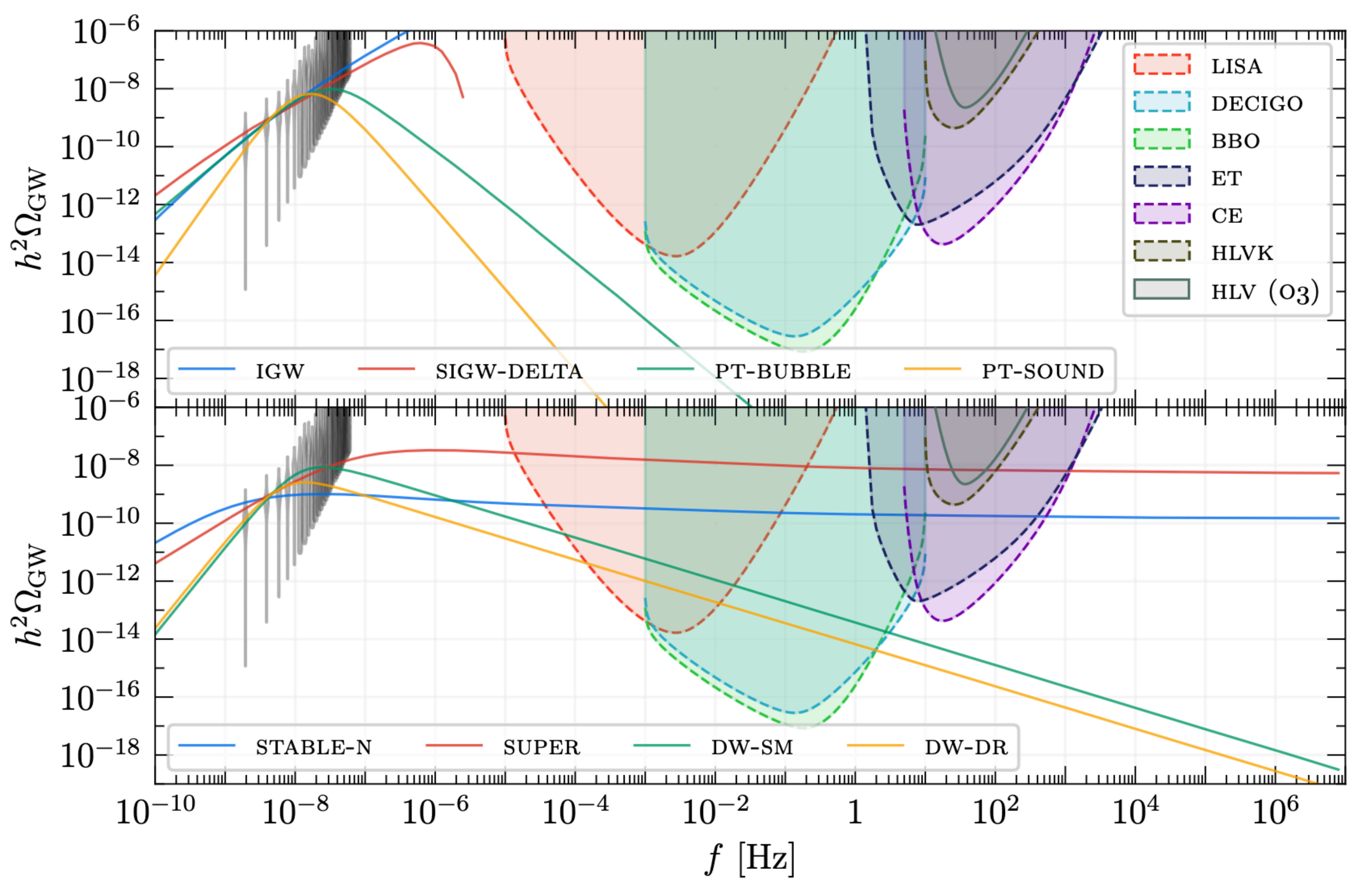
North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

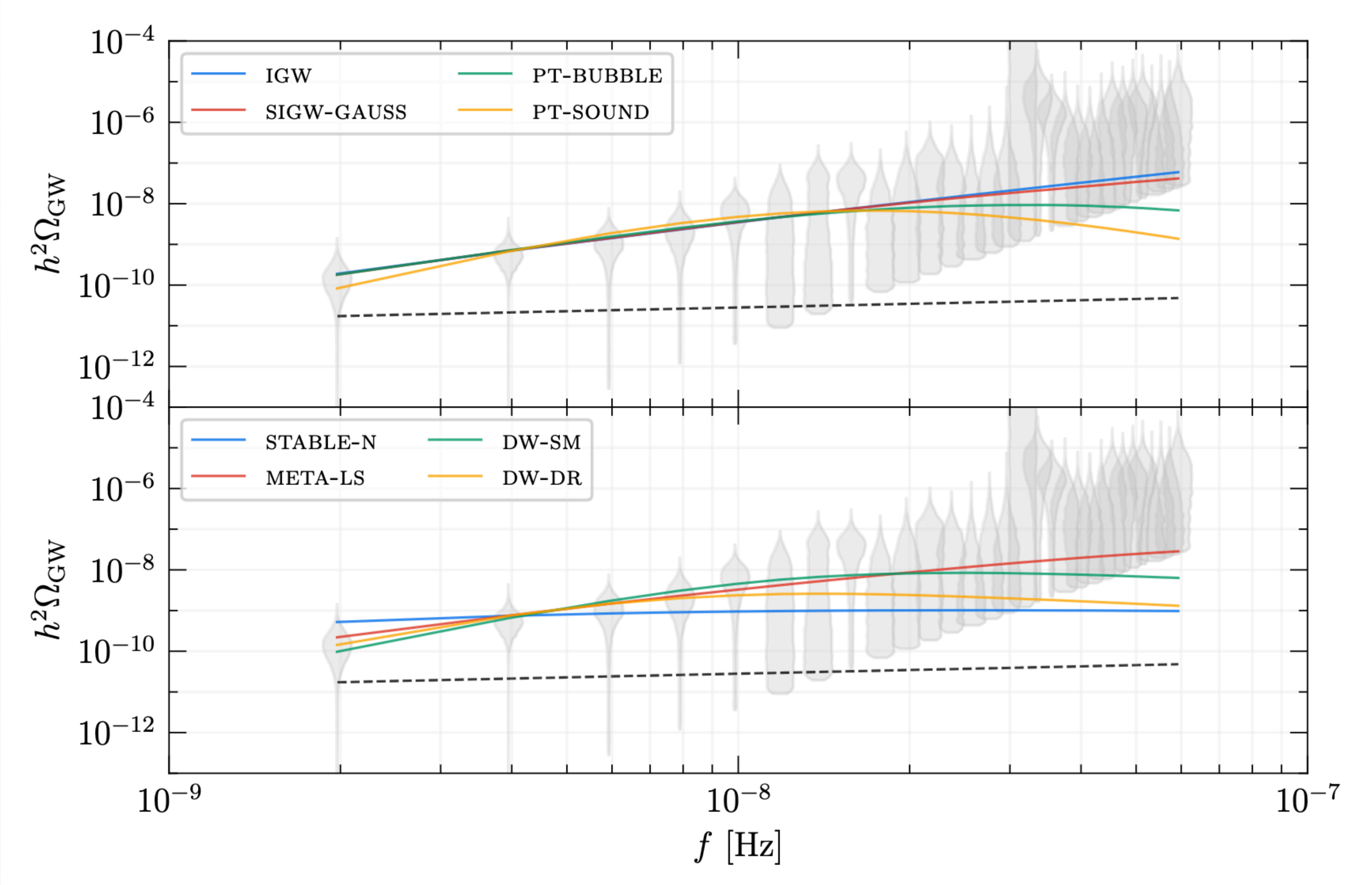
Detecting gravitational waves via regular observations of an ensemble of millisecond pulsars using the Green Bank Telescope, Arecibo Observatory, and the Very Large Array —>

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).


Effelsberg
Arecibo
VLA
Lovell
SRT
Archival Data
GBT
CHIME
Nancay
WSRT
Archival Data
MeerKAT
GMRT
FAST
Parkes

NANOGrav Observation - 15 Years

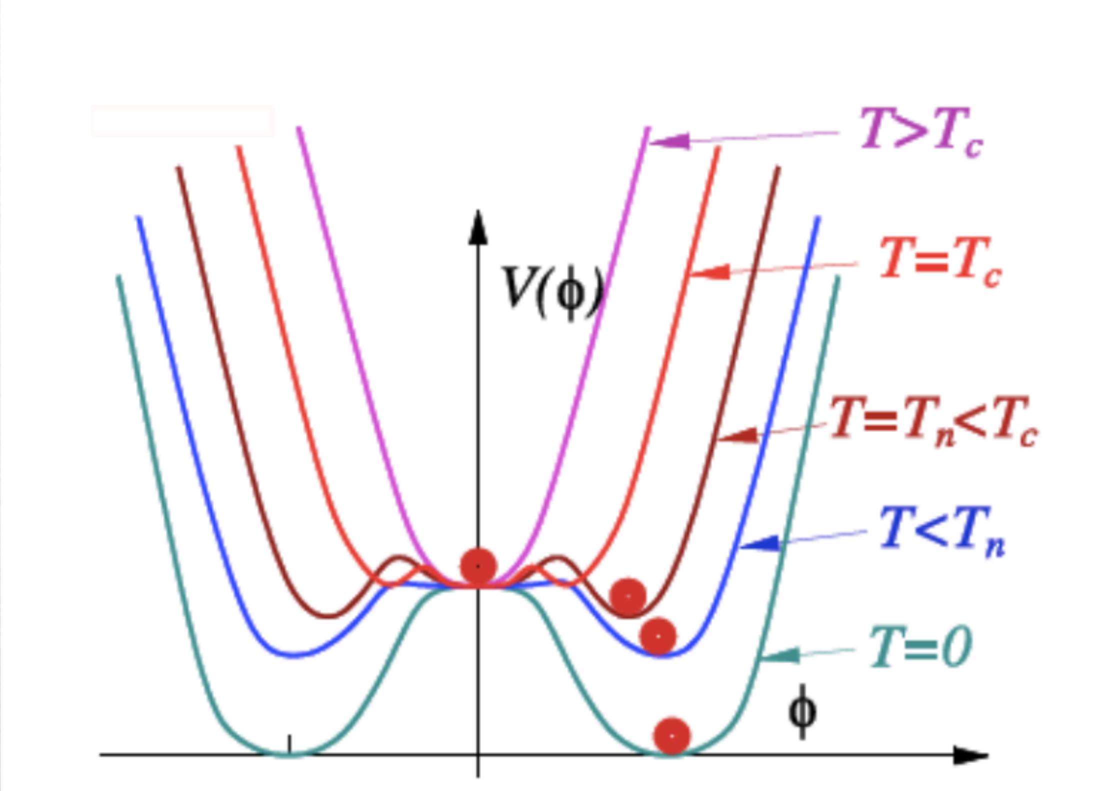




It can be explained with different possible scenarios: background from supermassive black holes binaries (SMBHB), induced GW, phase transitions, domain walls, etc.

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.

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

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

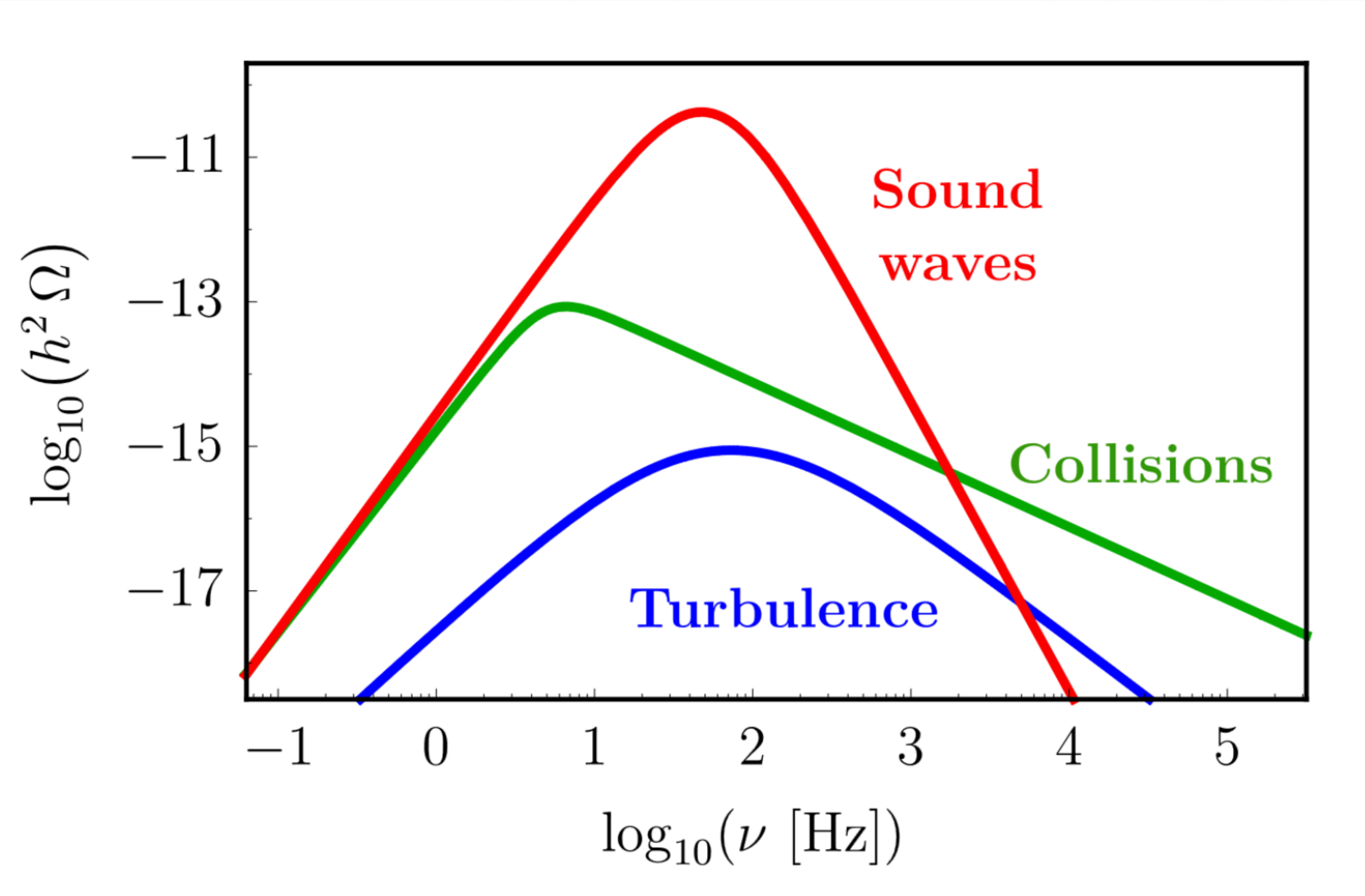
$$\alpha(T_n) = \frac{1}{\rho_{\text{rad}}} \left(\Delta V_{\text{eff}} - \frac{1}{4} \frac{d\Delta V_{\text{eff}}}{dT} \right) \Bigg|_{T_n} \qquad \beta = H_n T_n \frac{d(S_3/T)}{dT} \qquad H_n^2 = \frac{8\pi G}{3} \rho_{\text{rad}}(T_n)$$

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

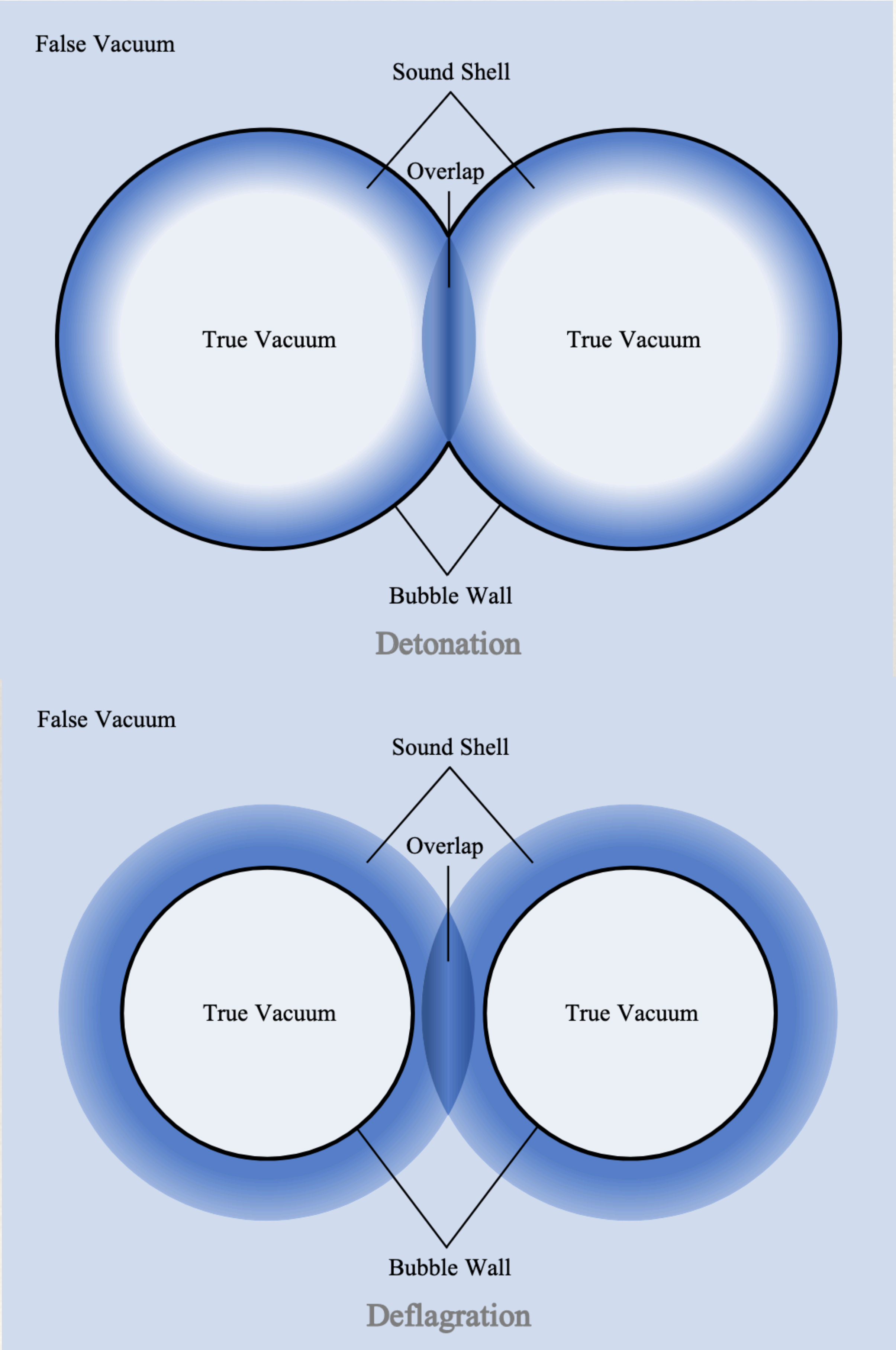
During the Universe's cooling process, a new energy minimum forms, separated from the original by a potential energy barrier. Bubble nucleation happens, with small regions transitioning to the new phase, forming bubbles of the new phase within the old phase. These bubbles grow due to the lower energy 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.

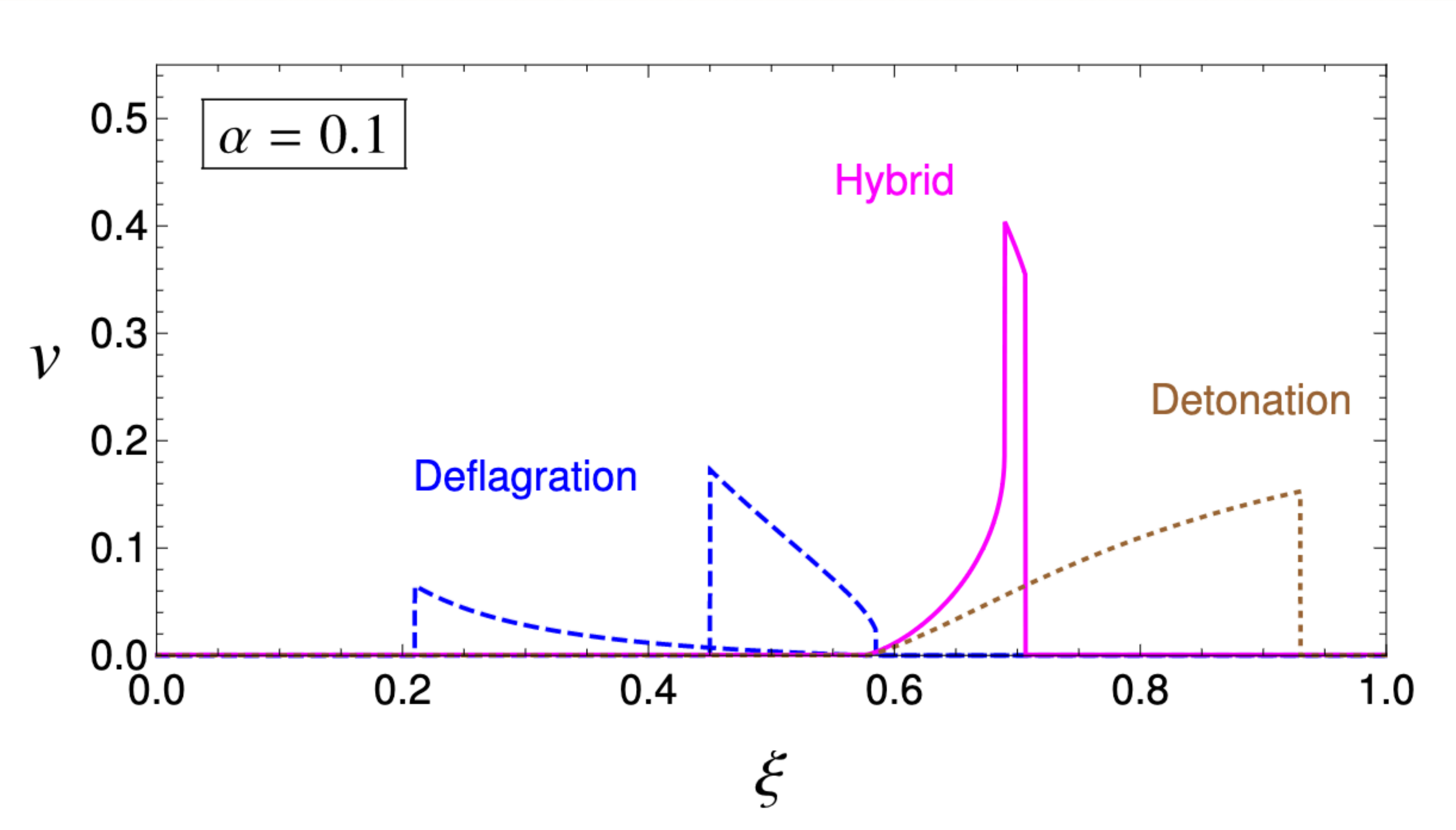
Constructing the velocity field involves superimposing self-similar velocity and enthalpy density profiles, originating from randomly nucleated, expanding bubbles. These profiles, based on $\xi = R/T$ - R (distance from the bubble's center) and T (time since nucleation), dynamically evolve. When these 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





arXiv:2112.14650

arXiv:2007.08537

Gravitational Waves from NANOGrav: Power Law

Power Law Approximation for GW signal of NANOGrav:

$$\Omega = \frac{8\pi^4 f^5 \Phi(f)}{H_0^2 \Delta f} \qquad \Phi = \frac{A^2}{12\pi^2 T_{\rm obs}} \left(\frac{f}{\rm yr^{-1}}\right)^{-\gamma} {\rm yr}^3$$

$$\Delta f = 1/T_{\rm obs} \text{ and } H_0 = h \times 100\,{\rm km\,s^{-1}Mpc^{-1}}$$

At first approximation NANOGrav and EPTA giving the best fit for a power law spectrum:

$$\gamma = \begin{cases} 3.2 \pm 0.6 & \text{NANOGrav} \\ 3.1^{+0.77}_{-0.68} & \text{EPTA} \end{cases}$$

$$A = \begin{cases} 6.4^{+4.2}_{-2.7} \times 10^{-15} & \text{NANOGrav} \\ 10^{-14.13 \pm 0.12} & \text{EPTA} \end{cases}$$

Gravitational Waves from FOPT: Full Sound Shell Model

Relic density of GW from FOPT:

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

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

Single broken power-law spectral form:

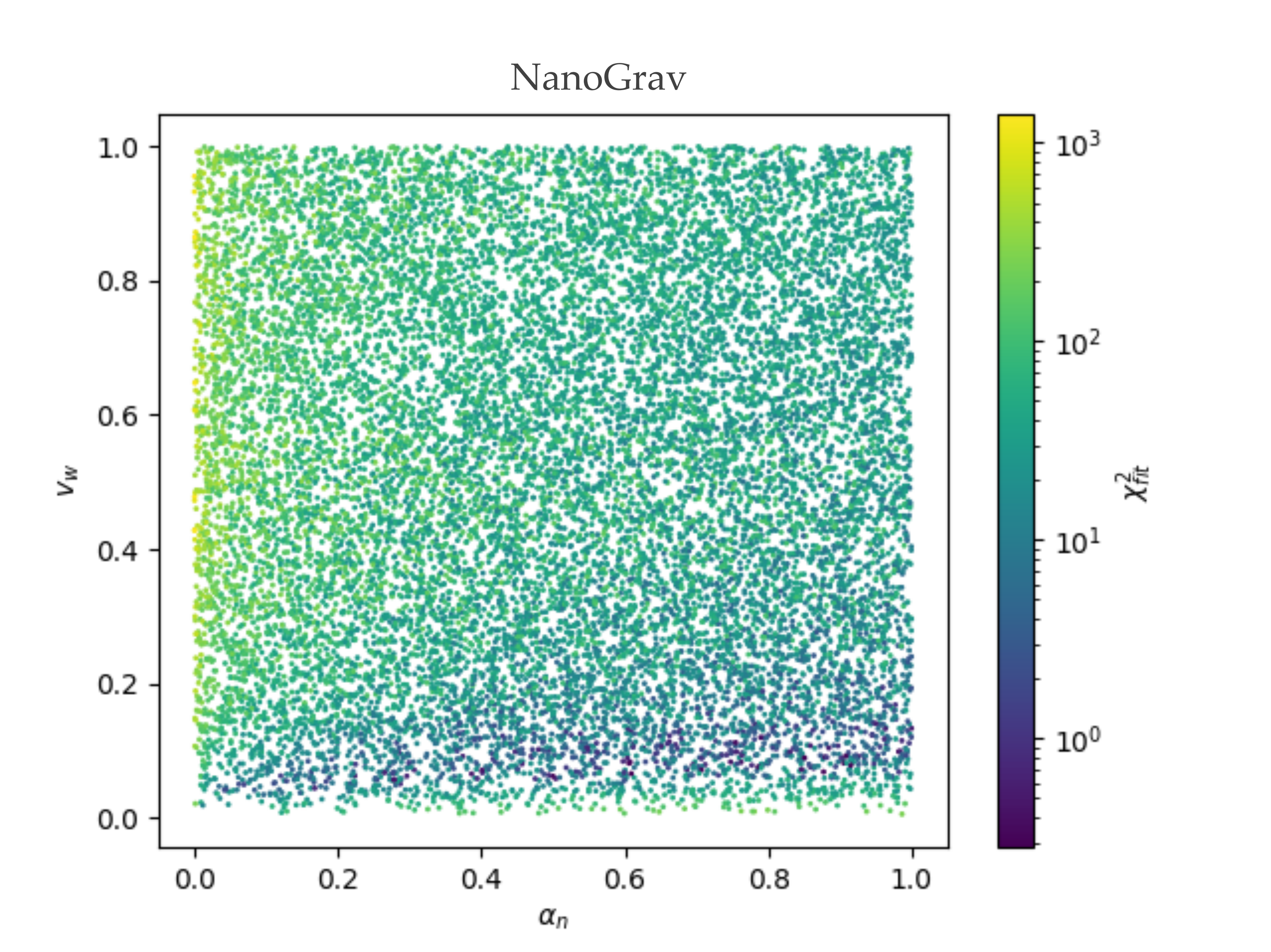
$$S(f)=\left(\frac{f}{f_p}\right)^3\left(\frac{7}{4+3(f/f_p)^2}\right)^{7/2}$$

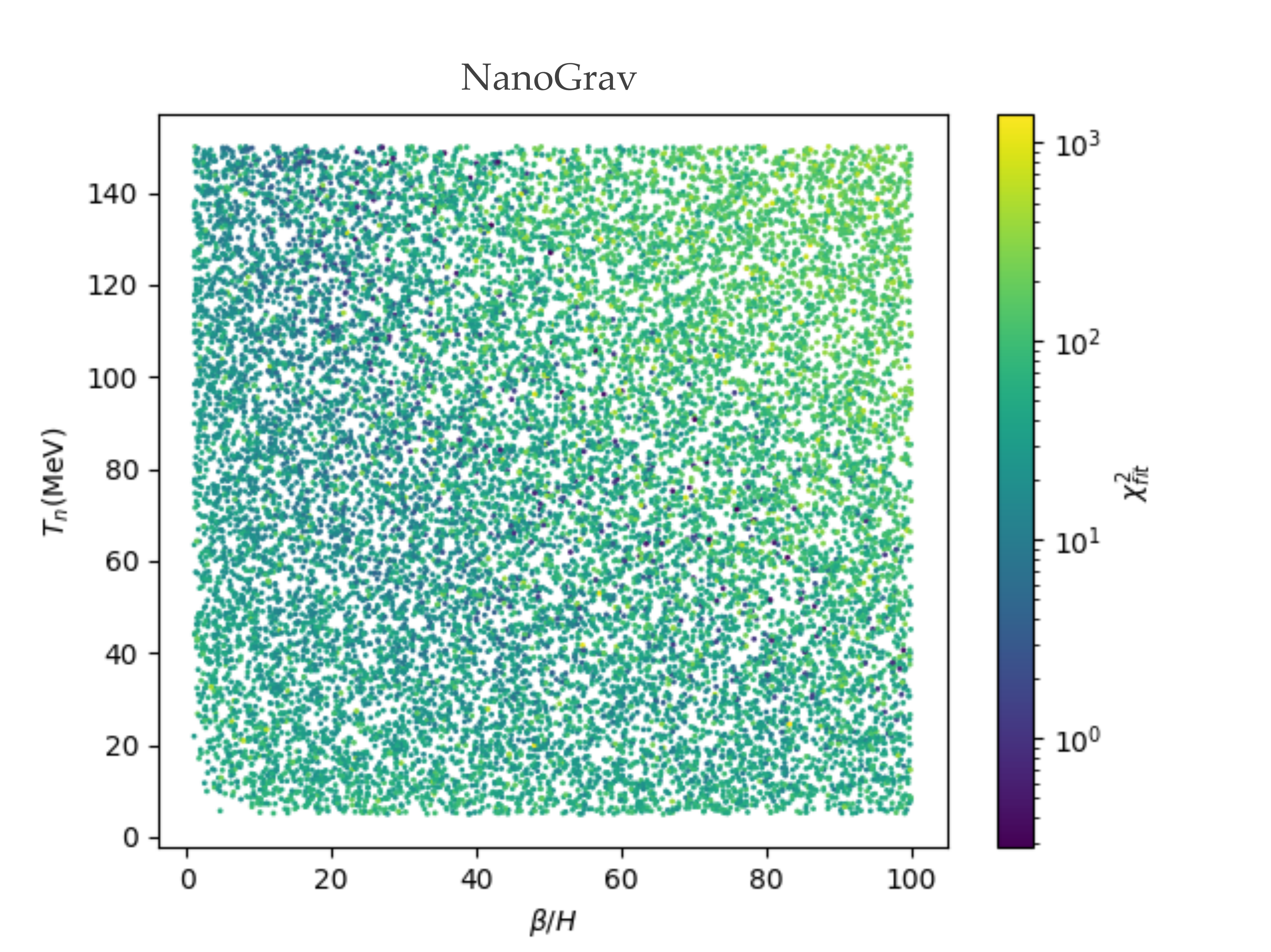
$$f_p = 8.9\times 10^{-6}\frac{1}{v_w}\left(\frac{\beta}{H_n}\right)\left(\frac{z_p}{10}\right)\left(\frac{T_n}{100\mathrm{GeV}}\right)\left(\frac{g_*(T_n)}{100}\right)^{1/6}\mathrm{Hz}$$

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 ($\tau_{\rm sh}$) 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:

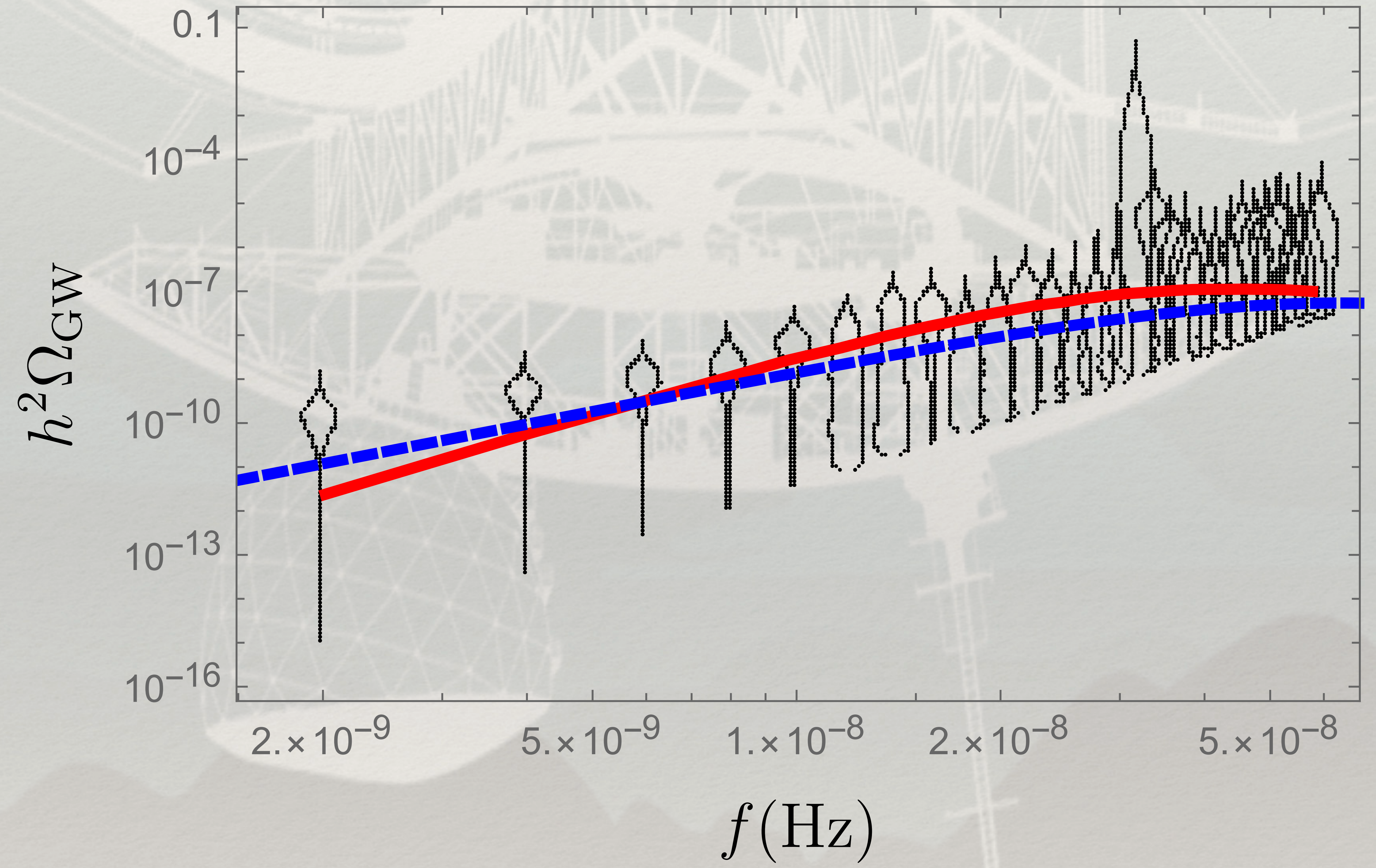




Frequentist approach:

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

Best Fit - NANOGrav



Numerical

Full Sound shell	
Parameter	Best fit value
α_n	0.85
β/H_*	42
T_n	133 MeV
v_w	0.09
$\chi_{\rm fit}$	1.4

Analytical

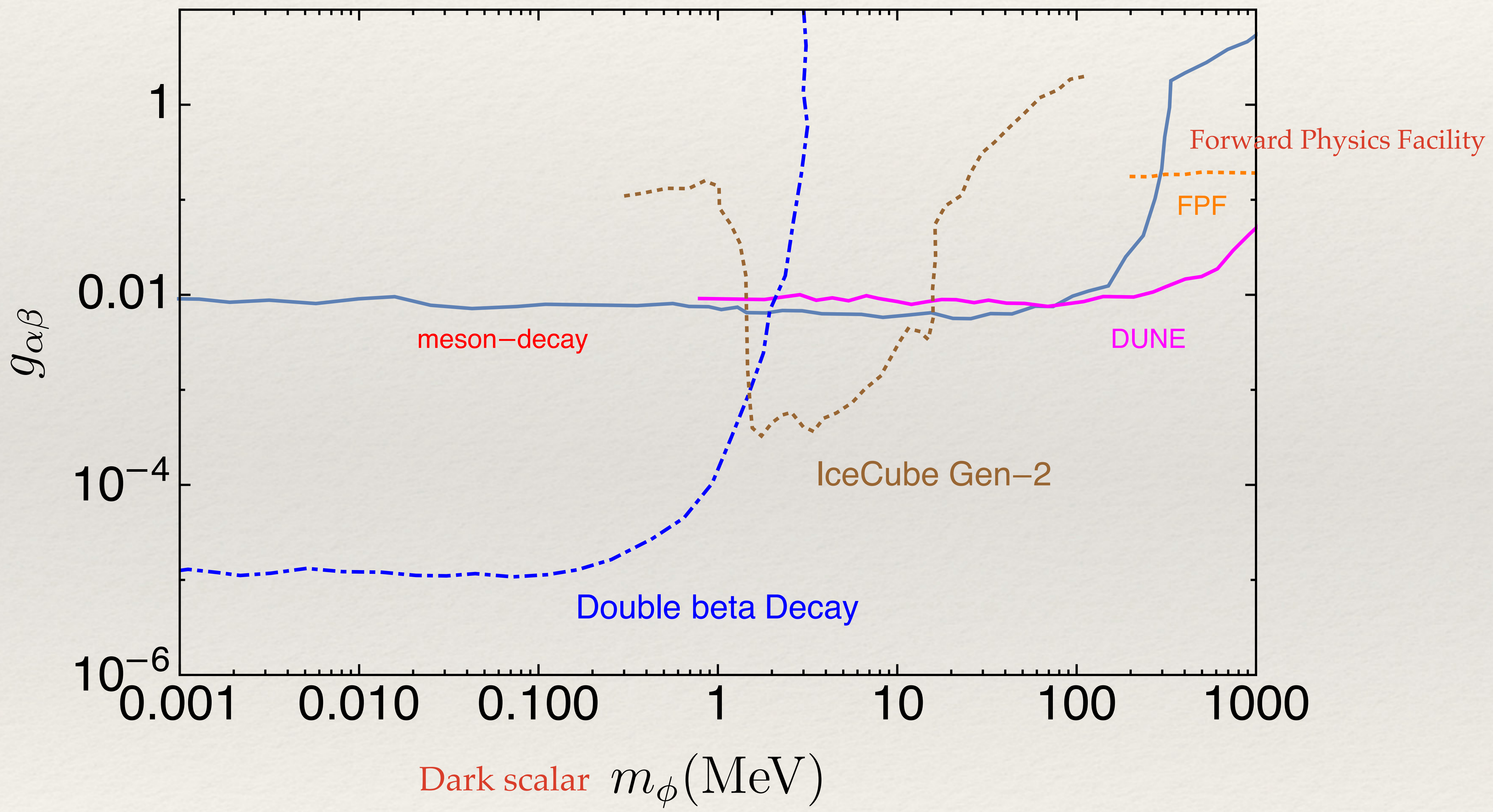
Broken power law fit	
Parameter	Best fit value
α_n	0.89
β/H_*	5.17
T_n	142 MeV
v_w	0.67
$\chi_{\rm fit}$	1.59

A possible (dark) phase transition at low temperatures!

We also did the Bayesian approach analysis to find the maximum likelihood!

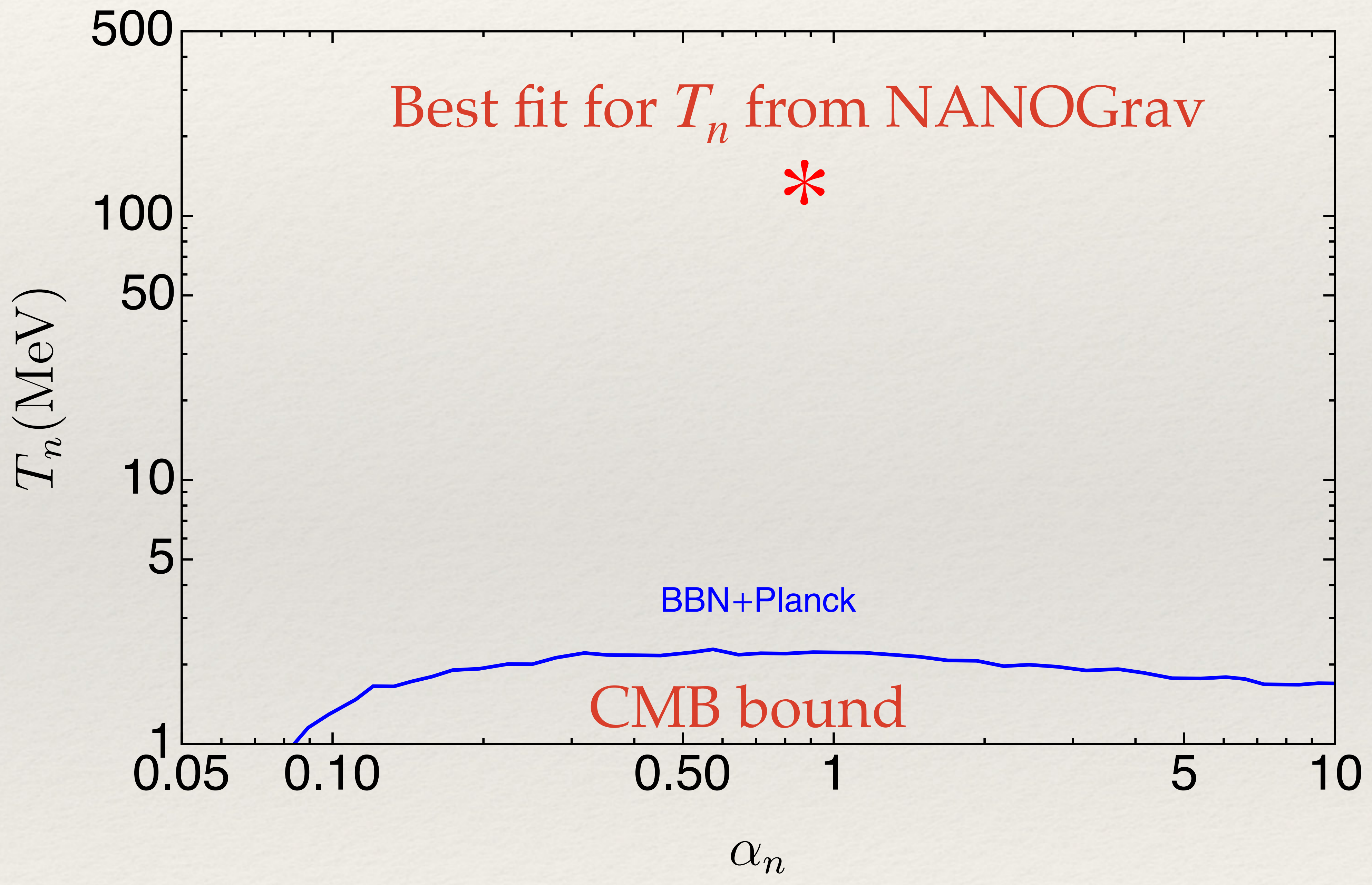
FOPT at low temperature and BSM Physics

Complementarity approach to probe phase transitions via GW and CMB detectors —>
To distinguish the SMBHB and phase transition explanations to the observed GW



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

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!