Gravitational Waves and Dark Sector - Connecting NANOGrav Pulsar Timing Data and Hubble Tension -

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Based on Y. Nakai (TDLI), F. Takahashi (Tohoku U.), M. Yamada (Tohoku U.), and MS
arXiv:2009.09754, PLB 2021.

NANOGrav

NANOGrav - **N**orth **A**merican **N**anohertz **O**bservatory for **Grav**itational Waves

http://nanograv.org/telescopes/

The 100-meter Green Bank Telescope, the world's largest fully steerable telescope. Image credit: NRAO

(West Virginia)

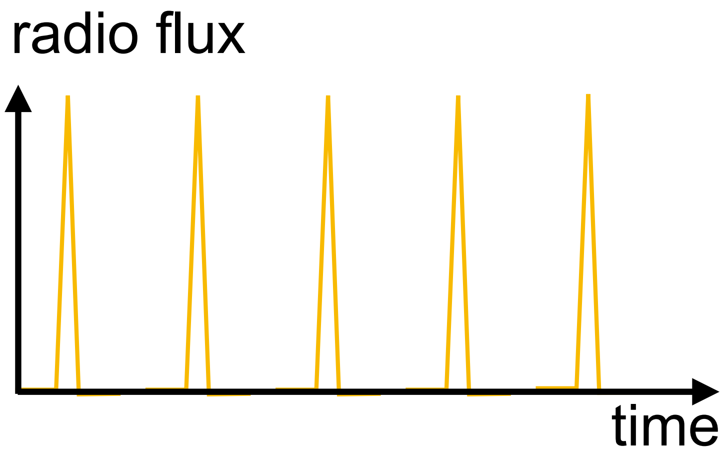
http://nanograv.org/telescopes/

The 305-meter dish of the William E. Gordon Telescope. Image credit: UCF / AO

(Puerto Rico)

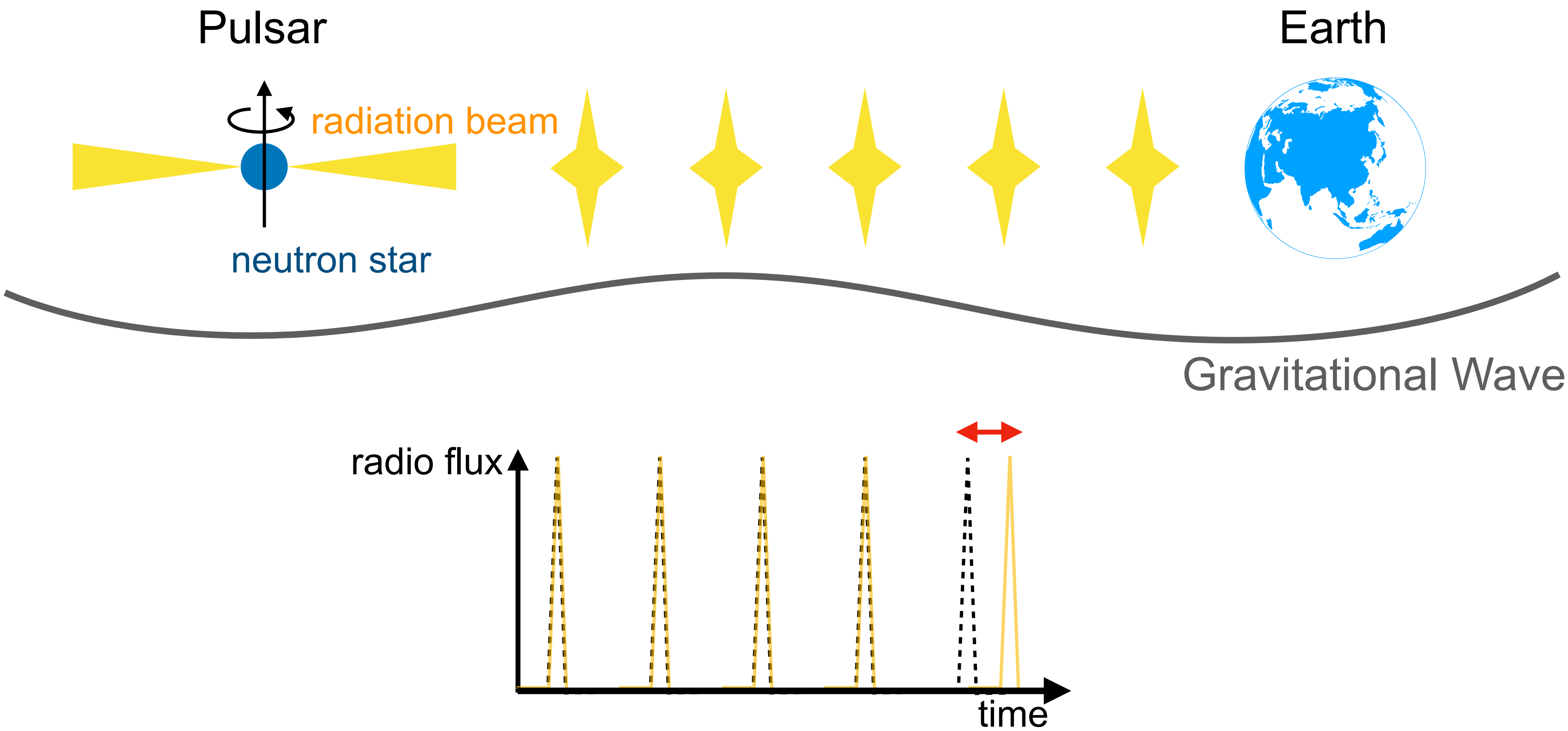
- 47 mili-second pulsars, data taking 2004-2017 (12.5 year data set)
- International Pulsar Timing Array (IPTA)
  — EPTA (Europe), InPTA (India), PPTA (Australia), NANOGrav
  — joint data, joint analysis

Pulsar Timing



- highly magnetized compact star
- rotation period: 1msec - 10 sec
- periodic pulse
- mili-second pulsars
  —very stable periodic pulse
  —pulsars in binary

Pulsar Timing



Residuals in pulse times of arrival (TOAs)

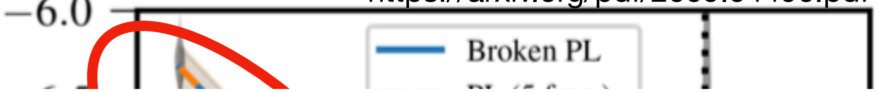
$$R_i = \mathrm{TOA}_i - \mathrm{TOA}_{i,\mathrm{MODEL}}$$

NANOGrav 12.5 year data

NANOGrav Collaboration (2020)

- New signal in the timing-residual cross power spectrum

https://arxiv.org/pdf/2009.04496.pdf



https://arxiv.org/pdf/2009.04496.pdf

— fitted by power-law spectrum $\Omega_{\rm GW}(f) \propto A_{CP}^2 \left(f/f_{\rm yr}\right)^{5-\gamma_{CP}}$

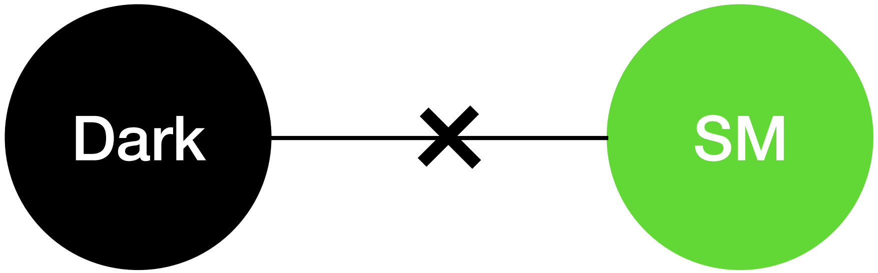
— e.g. a flat GW spectrum around nano Hz explains the signal

Possible Sources of GWs

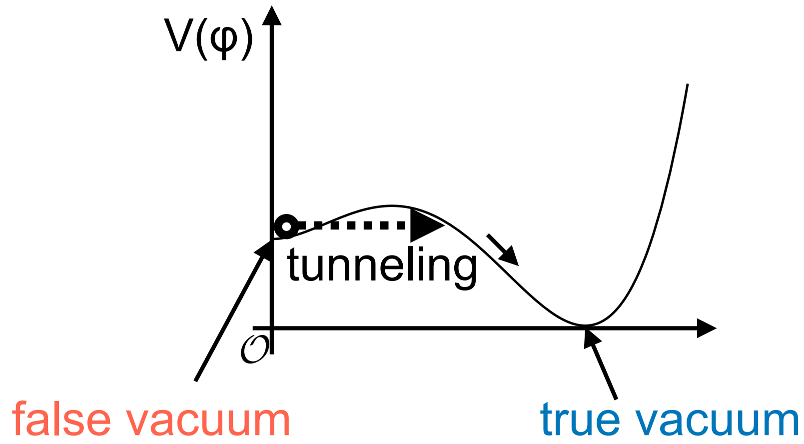
- Supermassive black holes
  The NANOGrav collaboration, 2009.04496
- Cosmic strings
  Ellis, Lewicki, 2009.06555, Blasi et al., 2009.06607,
  Buchmuller et al.,2009.10649, Samanta, Datta, 2009.13452
- Primordial black holes
  Vaskonen, Veermäe, 2009.07832, De Luca et al., 2009.08268,
  Kohri, Terada, 2009.11853, Sugiyama et al., 2010.02189, Zhou et al., 2010.03537, Domènech, Pi, 2010.03976
- Dark photon resonance by axion-like particle
  Ratzinger, Schwaller, 2009.11875, Namba, MS, 2009.13909
- Inflation, Domain wall, …(I am sure I do not list up all related papers..)
- **Phase transition**

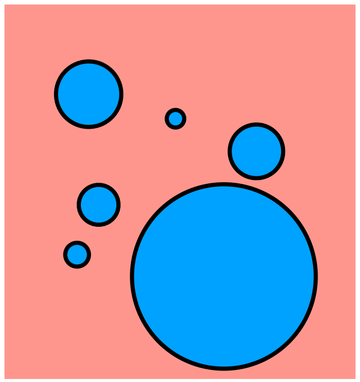
Dark Sector Phase Transition

- Dark sector that completely decouple from SM sector



- In dark sector, **first order phase transition** occurs at some temperature





GW production

- Three contributions to total power spectrum of GWs :
  - bubble collision - sound wave - turbulence

$$\Omega_{\rm GW} \approx \Omega_{\rm GW}^{\rm bc} + \Omega_{\rm GW}^{\rm sw} + \Omega_{\rm GW}^{\rm tu}$$

- Key quantities :
  - T_* , phase transition nucleation temperature
  - v_w, bubble wall speed
  - β , inverse of duration of phase transition
  - $\alpha' = \rho_{\rm vac}/\rho_{\rm rad,tot}(T_*)$
  - $\kappa_{\rm bubble} = \rho_{\rm bubble}/\rho_{\rm vac}, \kappa_{\rm SW} = \rho_{\rm SW}/\rho_{\rm vac}, \kappa_{\rm turb} = \rho_{\rm turb}/\rho_{\rm vac}$

GW production

See, e.g., C. Caprini et. al., 1512.06239, 1910.13125, Hindmash et. al., 2008.09136

$$\Omega_{\rm GW,0} = \sum_i \underbrace{\Omega_{\rm rad,0}\left(\frac{g_*(T_*)}{g_{*0}}\right)\left(\frac{g_{*s0}}{g_{*s}(T_*)}\right)^{4/3}}_{\text{scaling to today}} \underbrace{\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa_i\alpha'}{1+\alpha'}\right)^2}_{\text{common factor}} \tilde{\Omega}_{{\rm GW},i}$$

$$\alpha' = \rho_{\rm vac}/\rho_{\rm rad,tot}(T_*)$$

Bubble collision $\tilde{\Omega}_{\rm GW,bubble}(f) \simeq 1.0\left(\frac{0.11 v_w^3}{0.42+v_w^2}\right)\boxed{F_{\rm bubble}(f)}$

Sound wave $\tilde{\Omega}_{\rm GW,sw}(f) \simeq 0.16\, v_w\left(\frac{\beta}{H_*}\right)\left(1-\frac{1}{\sqrt{1+2t_{\rm sw}H_*}}\right)F_{\rm sw}(f)$

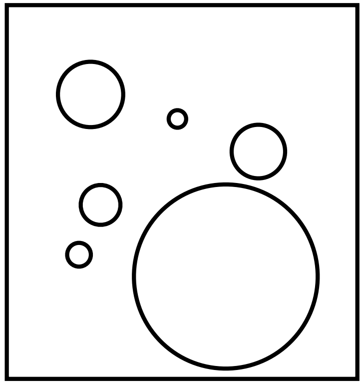
Turbulence $\tilde{\Omega}_{\rm GW,turb}(f) \simeq 20\, v_w\left(\frac{\beta}{H_*}\right)\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{-1/2}F_{\rm turb}(f)$

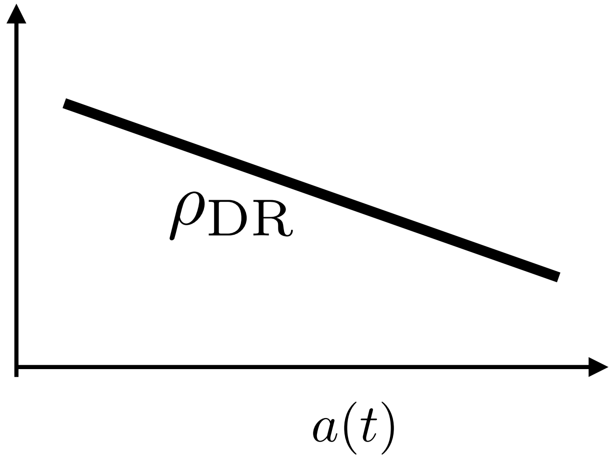
$$\boxed{\begin{array}{l} f_{\rm peak} \approx 10^{-8}\,{\rm Hz}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{0.1\,{\rm GeV}}\right) \\ T_* = {\rm MeV} \sim {\rm GeV}\end{array}}$$

Remnant in dark sector

Y. Nakai, M. Yamada, F. Takahashi, M.S. (2020)
See also M. Fairbairn, E. Hardy, A. Wickens (2019)

- After phase transition, energy goes into themal plasma, i.e. dark radiation





- Using entropy conservation and assuming strong first order PT ($\alpha \gg 1$),

$$\alpha' \simeq 0.07 \left(\frac{\Delta N_{\mathrm{eff}}}{0.5}\right)\left(\frac{g_{*0}}{g_*}\right)\left(\frac{g_{*s}}{g_{*s0}}\right)^{4/3}\left(\frac{g_*^{(\mathrm{D})}}{g_{*0}^{(\mathrm{D})}}\right)\left(\frac{g_{*s0}^{(\mathrm{D})}}{g_{*s}^{(\mathrm{D})}}\right)^{4/3}$$

$$\Omega_{\mathrm{GW}} h^2 \propto \alpha'^2 \propto \Delta N_{\mathrm{eff}}^2$$

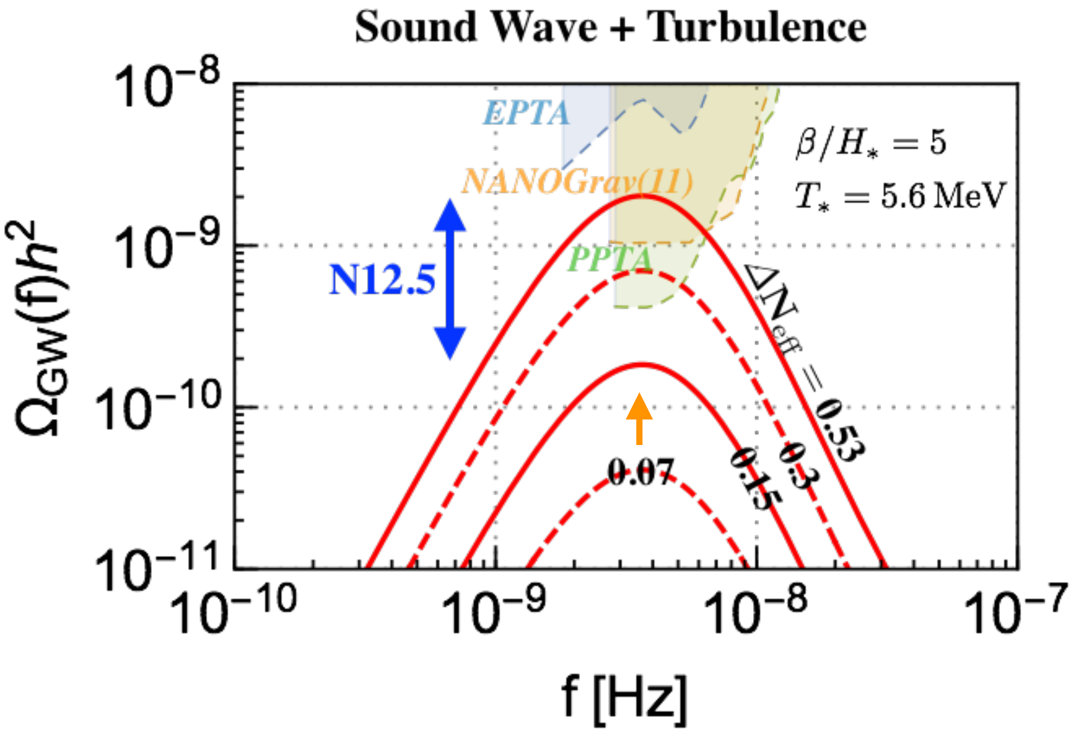
PLANK+BAO+H0 constraint

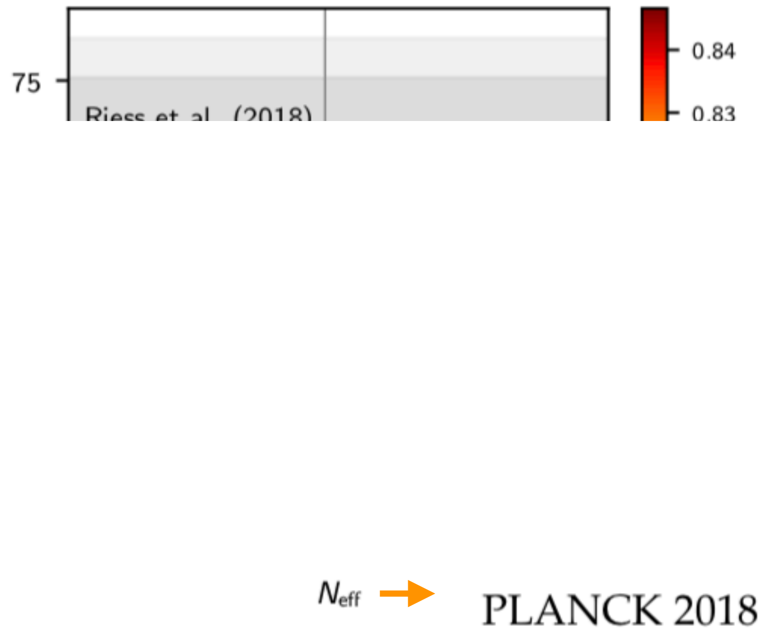
$$N_{\mathrm{eff}} = 3.27 \pm 0.15 \quad (68\%\ \mathrm{C.L.})$$

$$(N_{\mathrm{eff}}^{(\mathrm{SM})} = 3.046)$$

Result

Y. Nakai, M. Yamada, F. Takahashi, MS (2020)



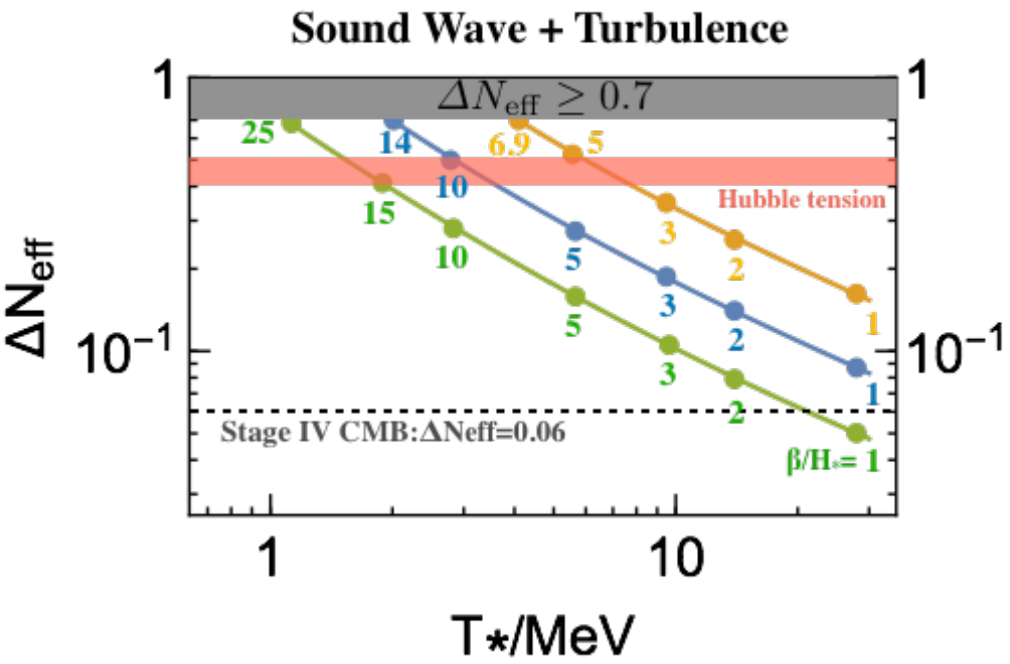


— **Peak around f~3×10^{-9} Hz ↔ flat spectrum**

— **Large amount of dark radiation ΔNeff >0.1**

— **Hubble tension might be reconciled**

Result



Peak frequency

$f \;=\; 3.7 \times 10^{-9}\,\mathrm{Hz}$

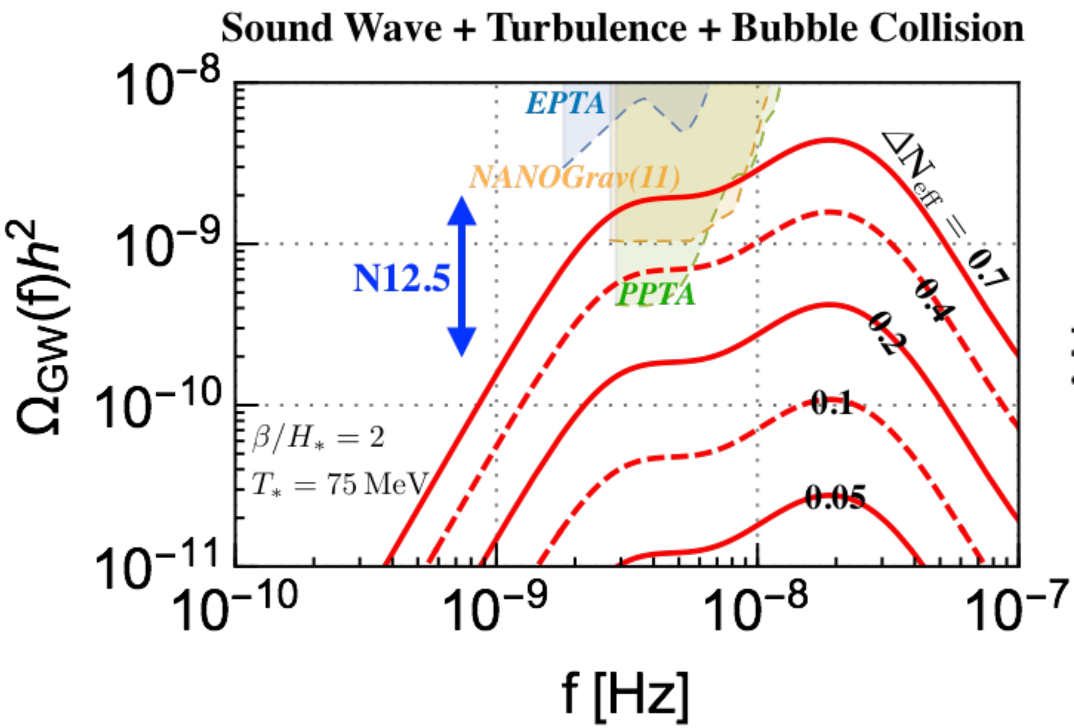
Peak amplitude

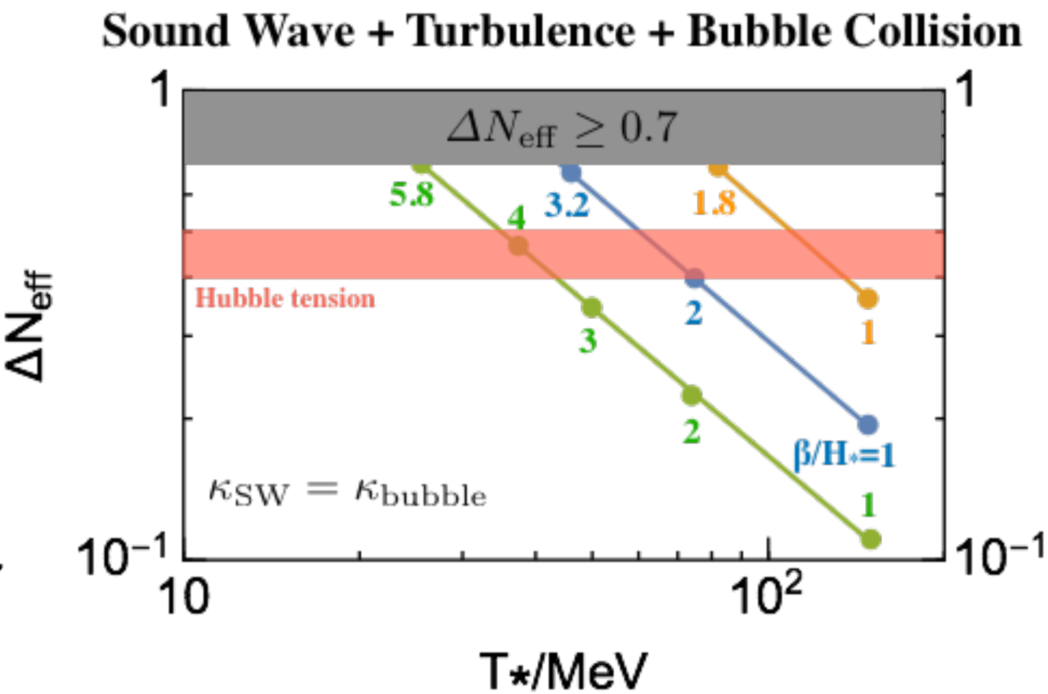
$\Omega_{\rm GW}(f)h^2 = 2\times10^{-9},\; 6\times10^{-10},\; 2\times10^{-10}$

— β/H∗~10, T∗~MeV

— ΔNeff > 0.1 can be measure near future

Result





— fitted by bubble peak
— ΔNeff > 0.1 is required to explain the signal

NANOGrav further analysis

https://arxiv.org/pdf/2104.13930.pdf

- Analyze GW signal via FOPT

$$\Omega_{\rm GW}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f)$$

- For bubble contribution, three cases are considered

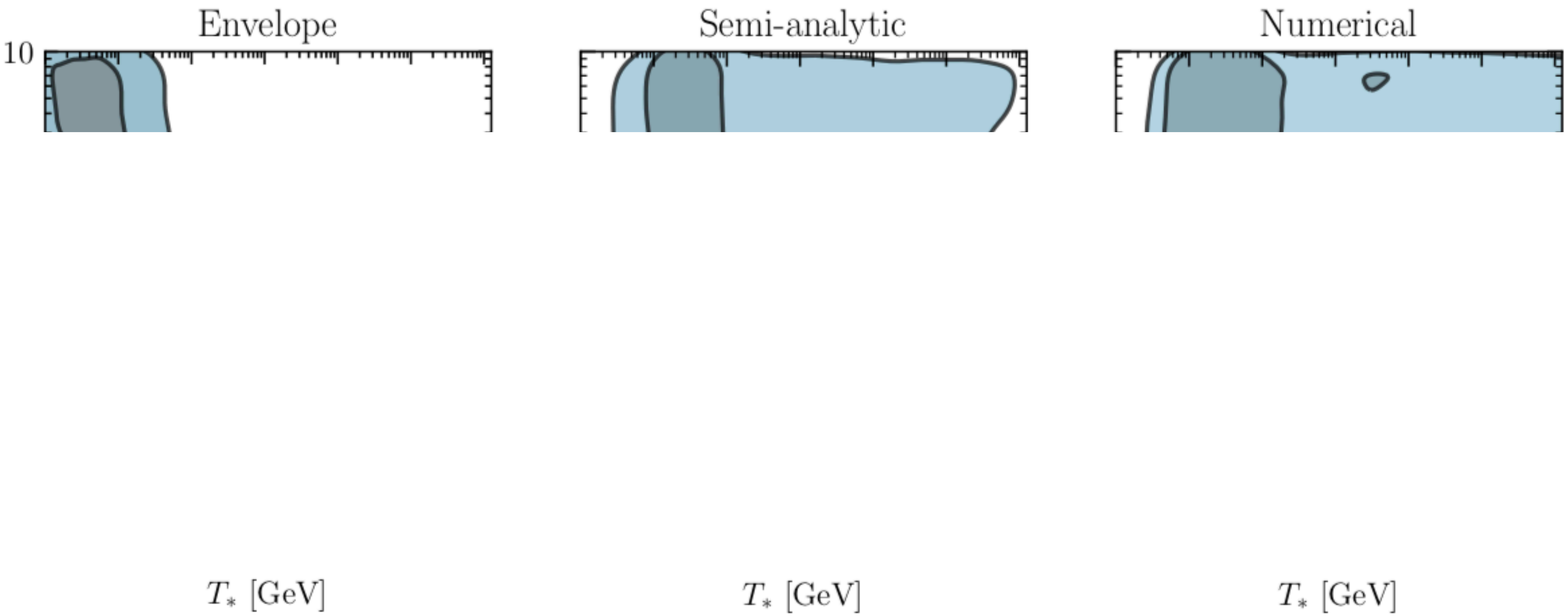
  — Envelope: surface disappears as soon as it collides & thin wall

  — Semi-analytic: multi-bubble simulation, evolution of two bubble collision is parametrized by two-bubble simulations

  — Numerical: lattice simulation

NANOGrav further analysis

https://arxiv.org/pdf/2104.13930.pdf



T∗ : phase transition temperature
α∗ : vacuum density/relativistic energy density at T∗

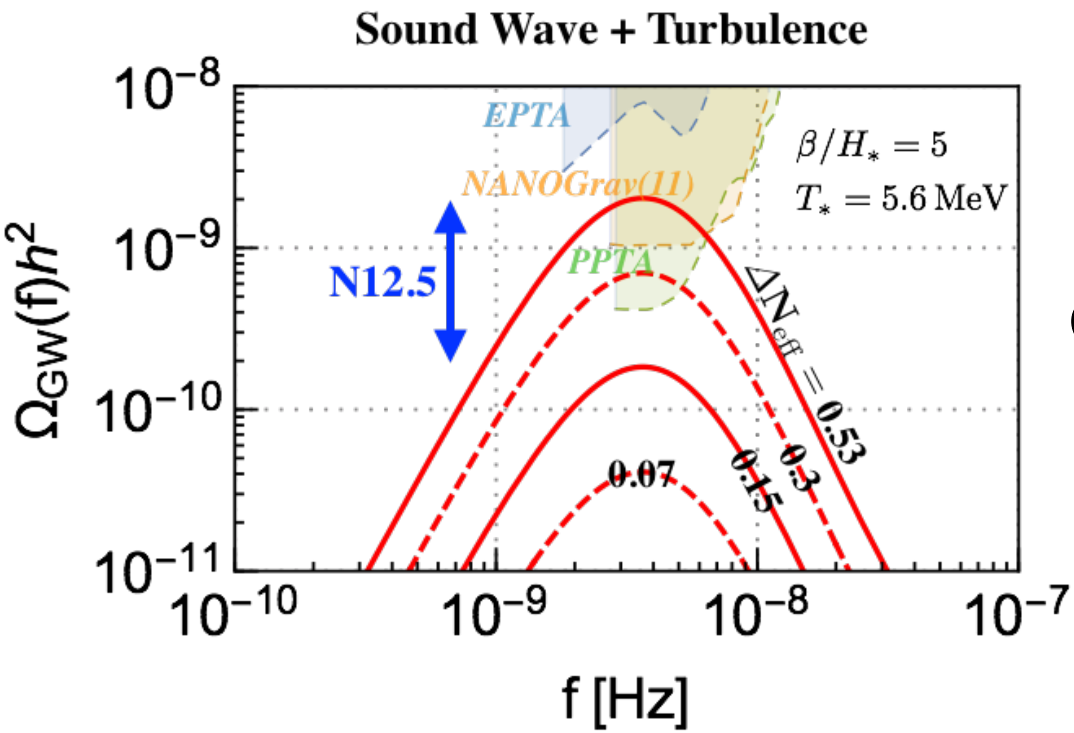
- 1-σ : GW spectrum peak below NANOGrav sensitivity window

$$\alpha_* \gtrsim 0.1 \ , \ T_* \lesssim 10\,\mathrm{MeV}$$

- 2-σ : GW spectrum peak above NANOGrav sensitivity window (w/o envelope)

Summary

- We consider a first order phase transition in a completely decoupled dark sector to explain NANOGrav data
- We predict $\Delta N_{\rm eff} \gtrsim 0.1$ which can be measured in the near future



Concrete model ?