A collider test of nano-Hertz gravitational waves from pulsar timing arrays

Ke-Pan Xie (谢柯盼)
Beihang University

2023.7.28 第十二届新物理研讨会@青岛

Based on arXiv: 2307.01086 with Shao-Ping Li

Recent big news (Jun 29, 2023)

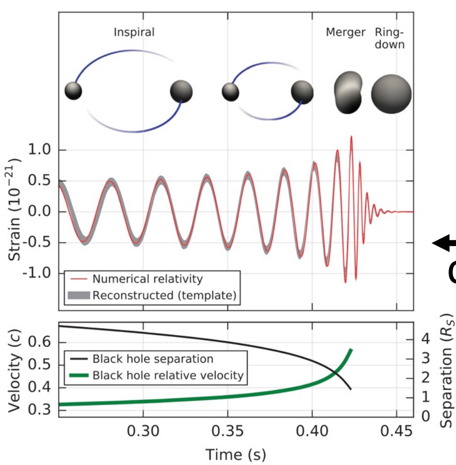
Evidence of nano-Hertz gravitational waves

Recent big news (Jun 29, 2023)

Evidence of nano-Hertz gravitational waves

Previous: binary mergers

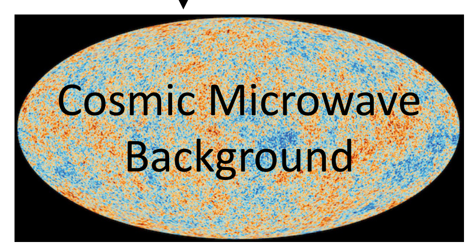
Now: stochastic GW background



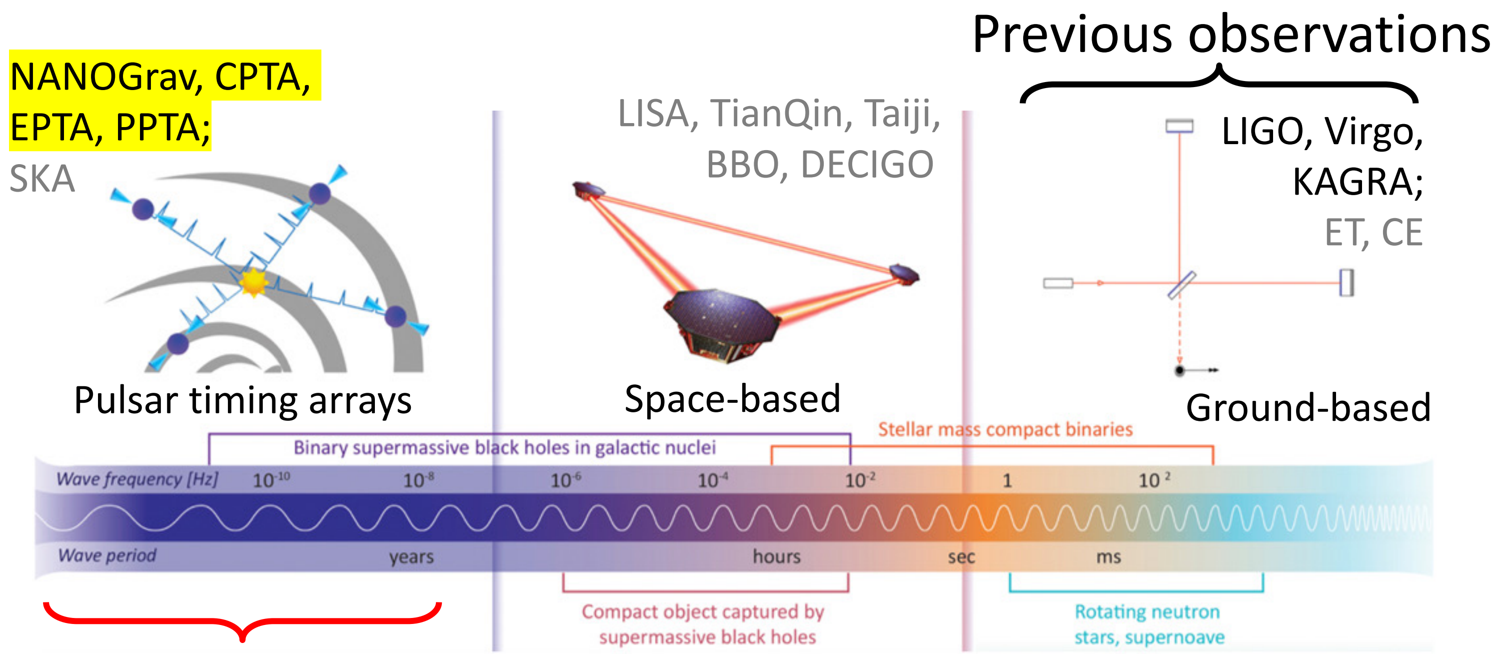
LIGO&Virgo
PRL 116, 061102 (2016)]

Rough comparison

Rough comparison



Nano-Hertz stochastic GW background

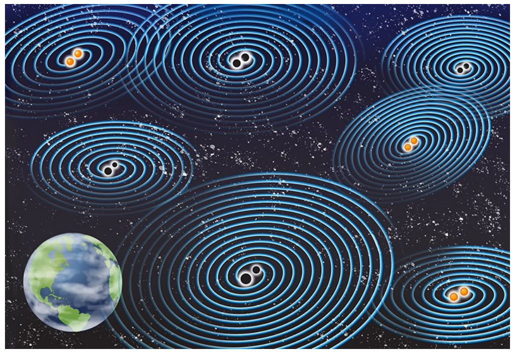


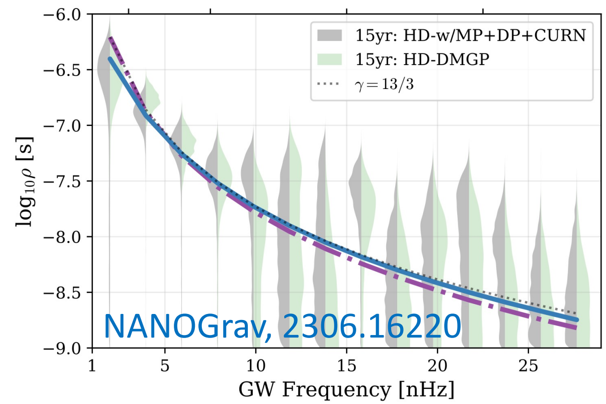
Recent: nano-Hertz GWs

	NANOGrav [2306.16213]	CPTA [2306.16216]	EPTA [2306.16214]	PPTA [2306.16215]
Radio telescope	Arecibo, GBT, VLA	FAST	LEAP	Parkes 64-m
Duration	15 yr	3.4 yr	10.3 yr	30 yr
Number of Pulsars	67	57	25	18
HD correlation	3.5-4σ	4.6σ	3σ	2σ

Explanations of the GW background

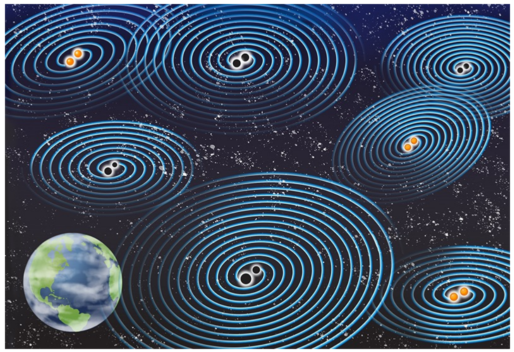
Astrophysical interpretation: supermassive black hole binaries

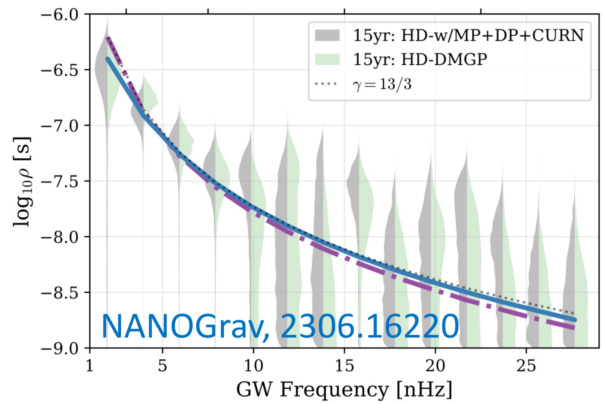




Explanations of the GW background

Astrophysical interpretation: supermassive black hole binaries





New physics interpretation: echoes from the early Universe

Less than 1 s after the Big Bang

- Scalar induced
- Phase transitions [This talk]
- Domain walls
- Cosmic strings, etc

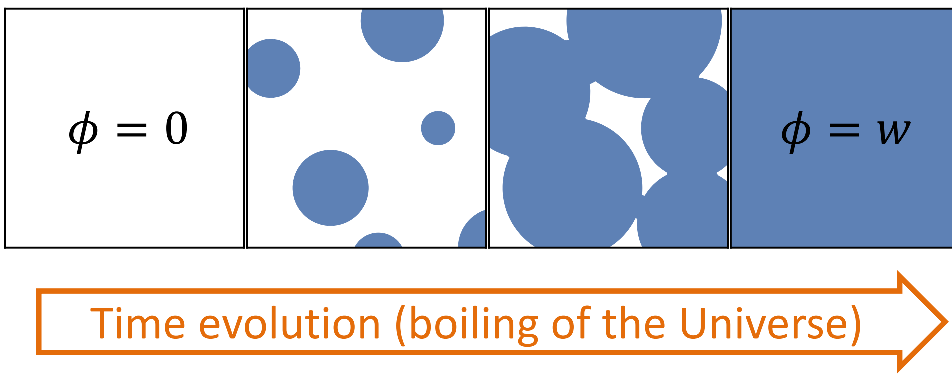
Bayesian analysis favors new physics interpretation[NANOGrav, 2306.16219]

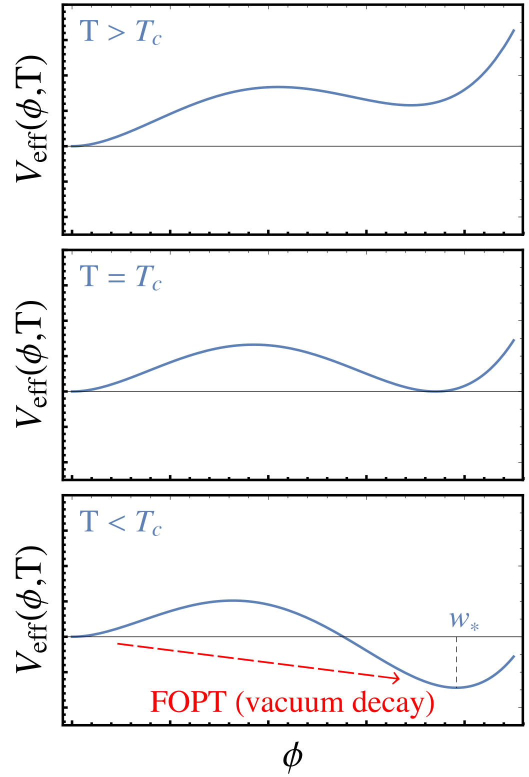
First-order phase transitions

Decay of the vacuum

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

Early Universe $\Rightarrow V_{\text{eff}}(\phi, T)$



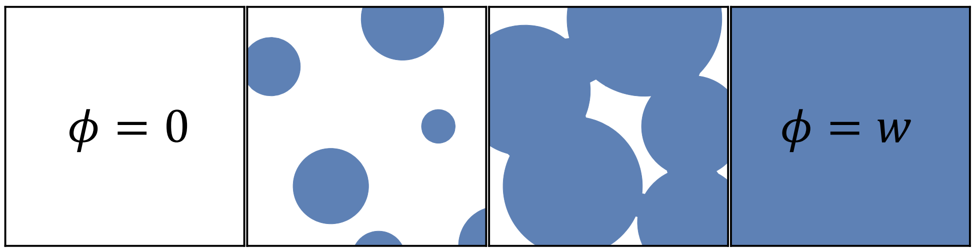


First-order phase transitions

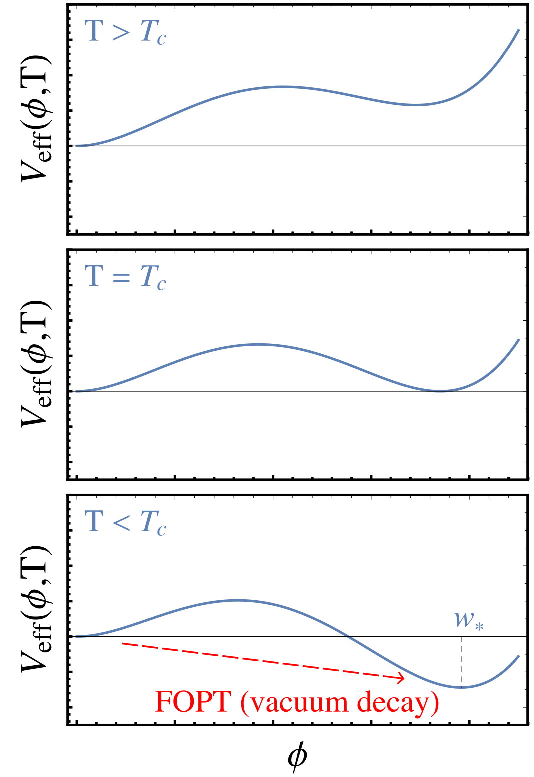
Decay of the vacuum

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$$

Early Universe $\Rightarrow V_{\rm eff}(\phi, T)$



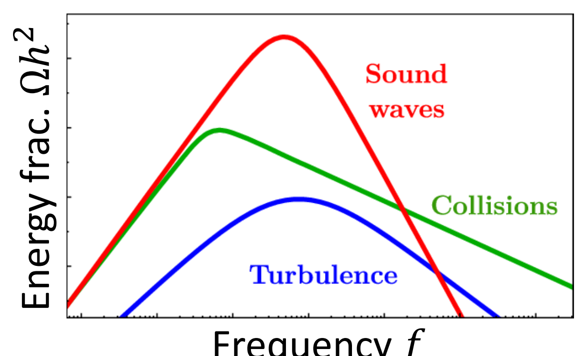
Time evolution (boiling of the Universe)



GW sources:[Caprini *et al*, JCAP 1604 (2016) 001]

1. Bubble collision; See Huai-Ke's talk
2. Sound waves in plasma;
3. Turbulence in plasma.

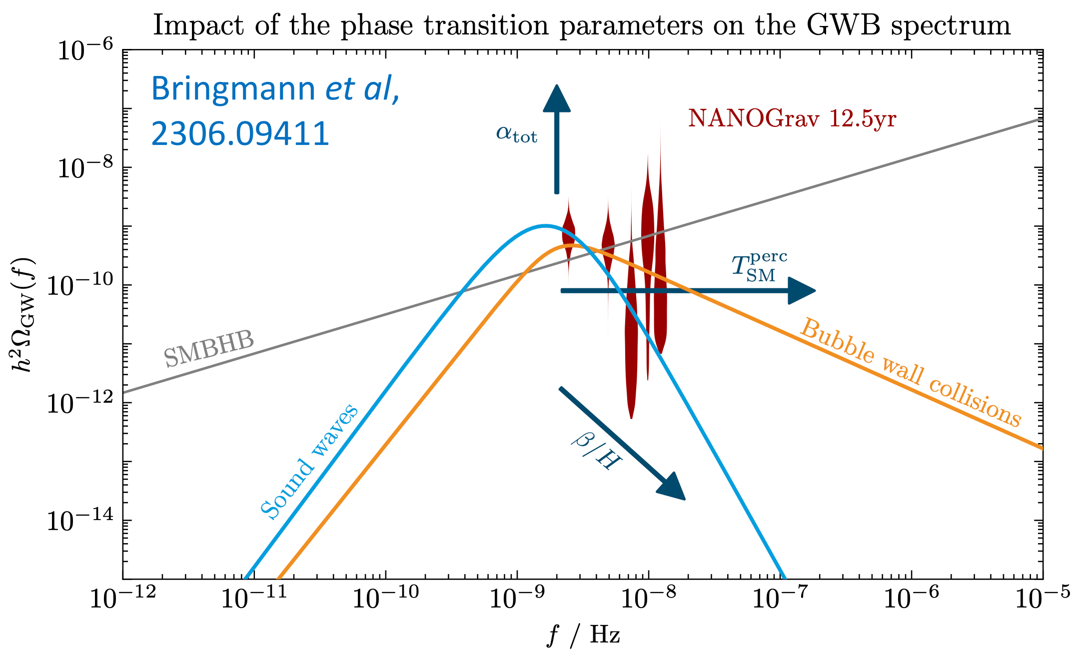
$$f_{\rm peak} \sim 10^{-9}\,{\rm Hz} \times \left(\frac{1}{v_w}\right)\left(\frac{\beta/H_n}{10}\right)\left(\frac{T_n}{\rm MeV}\right)$$

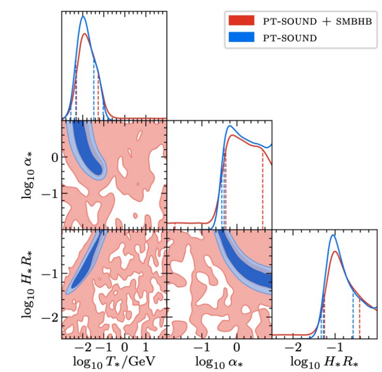


Explaining the nano-Hertz GWs

Relevant parameters[JCAP 1604 (2016) 001]

- Phase transition temperature T_n
- $\alpha \approx \Delta V_{\rm eff}/\left(\frac{\pi^2}{30}g_* T_n^4\right)$: FOPT latent heat over radiation energy
- β/H_n: Hubble time over FOPT duration
- Bubble expansion velocity v_w



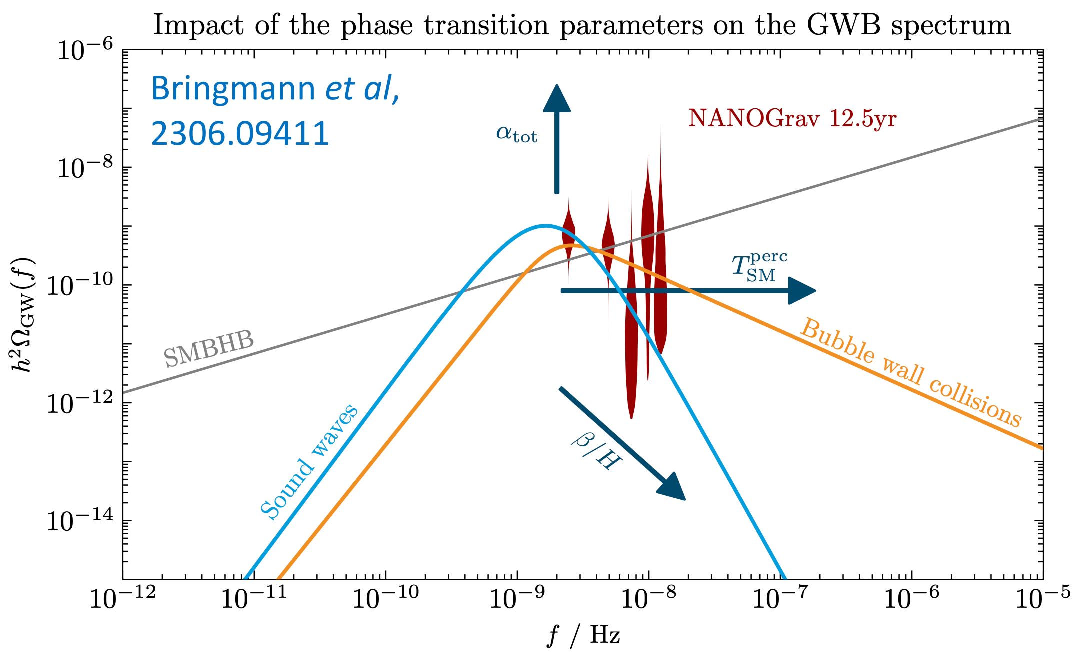


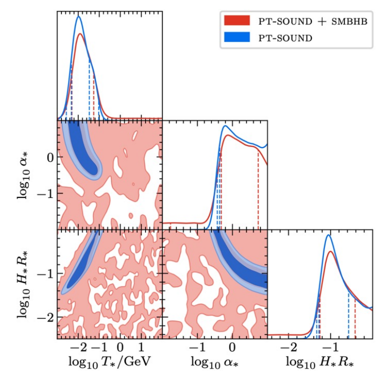
NANOGrav fit at 95% C.L.[2306.16219]
$T_n \in [2.7, 93]$ MeV;
$\alpha > 0.37$;
$\beta/H_n \in [3.29, 63.7]$;

Explaining the nano-Hertz GWs

Relevant parameters[JCAP 1604 (2016) 001]

- Phase transition temperature T_n
- $\alpha \approx \Delta V_{\rm eff}/\left(\frac{\pi^2}{30}g_* T_n^4\right)$: FOPT latent heat over radiation energy
- β/H_n: Hubble time over FOPT duration
- Bubble expansion velocity v_w

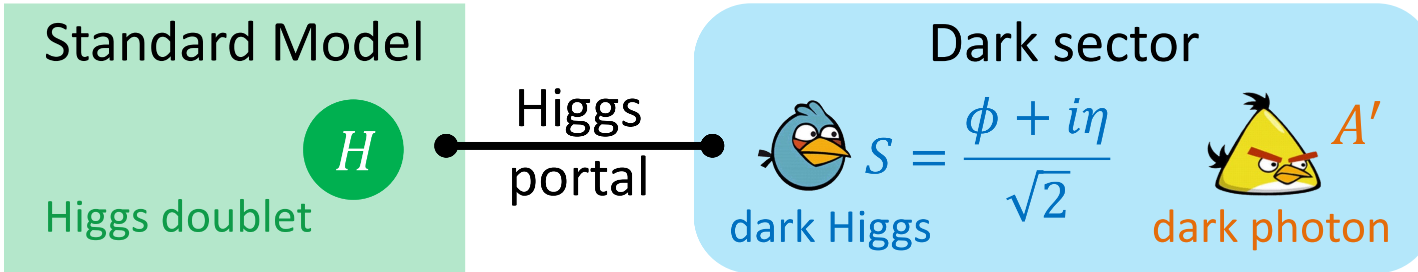




NANOGrav fit at 95% C.L.[2306.16219]
$T_n \in [2.7, 93]$ MeV;
$\alpha > 0.37$;
$\beta/H_n \in [3.29, 63.7]$;

Question: can we test this explanation with other experiments?

The Higgs portal dark $U(1)'$ model



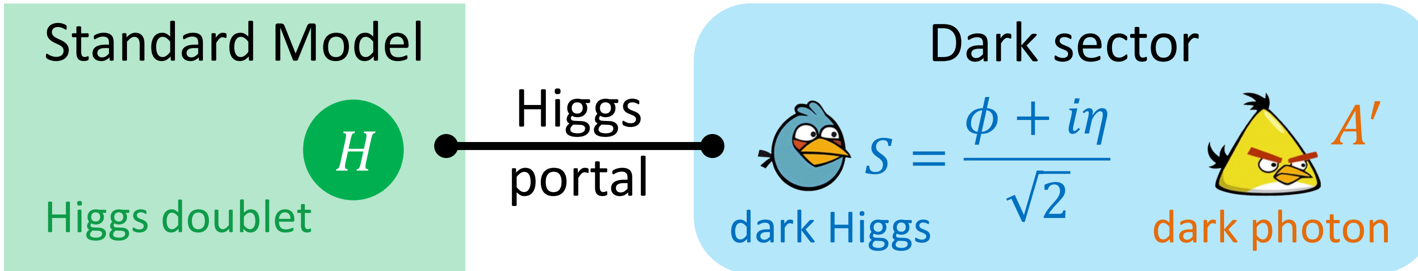
$$V(S,H) = \mu_h^2|H|^2 + \mu_s^2|S|^2 + \lambda_h|H|^4 + \lambda_s|S|^4 + \boxed{\lambda_{hs}|H|^2|S|^2}$$

Portal

$\langle h \rangle = v_{\rm ew} = 246$ GeV and $\langle \phi \rangle = v_s$:

EW & dark $U(1)'$ breaking; **dark sector** $m_{A'} = g_X v_s$

The Higgs portal dark $U(1)'$ model



$$V(S,H) = \mu_h^2|H|^2 + \mu_s^2|S|^2 + \lambda_h|H|^4 + \lambda_s|S|^4 + \lambda_{hs}|H|^2|S|^2$$

Portal

$\langle h \rangle = v_{\rm ew} = 246$ GeV and $\langle \phi \rangle = v_s$:

EW & dark $U(1)'$ breaking; **dark sector** $m_{A'} = g_X v_s$

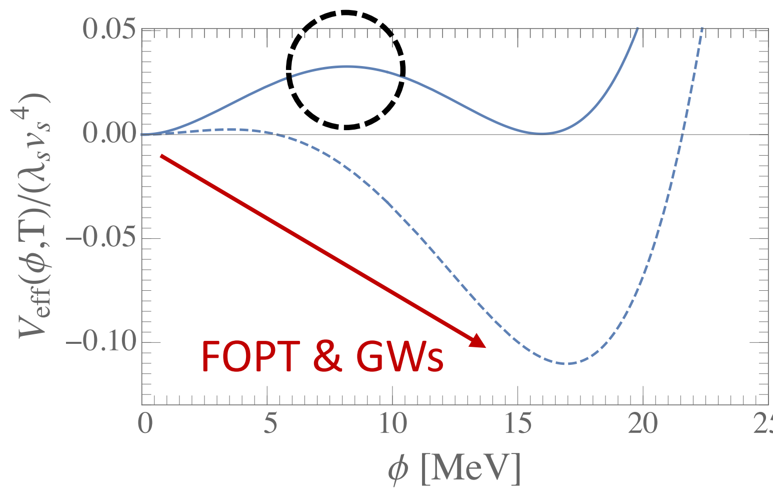
At MeV-scale:

$$V(\phi) \approx \frac{m_\phi^2}{8v_s^2}(\phi^2 - v_s^2)^2$$

In the early Universe

$$V_{\rm eff}(\phi,T) = V(\phi) + \Delta V_T(\phi,T)$$

A' in the loop $\approx \frac{g_X^2 T^2}{8}\phi^2 - \frac{g_X^3 T}{4\pi}\phi^3$



The Higgs portal dark $U(1)'$ model

Standard Model

H

Higgs doublet

Higgs portal

Dark sector

$S = \frac{\phi + i\eta}{\sqrt{2}}$

dark Higgs

A'

dark photon

$$\lambda_{hs} = \frac{m_\phi^2 - m_h^2}{2 v_{\rm ew} v_s} \sin 2\theta$$

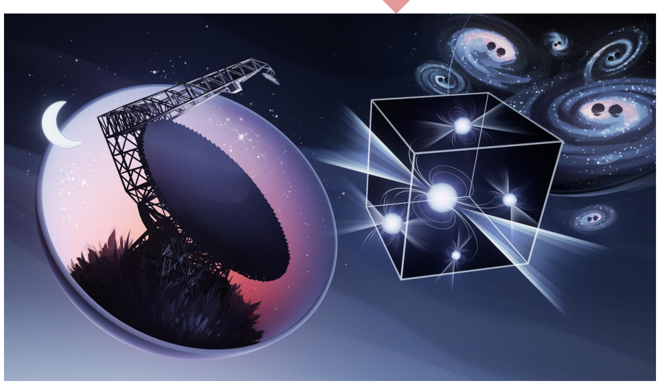
h-ϕ mixing angle

Current $|\theta| \lesssim 10^{-5}$

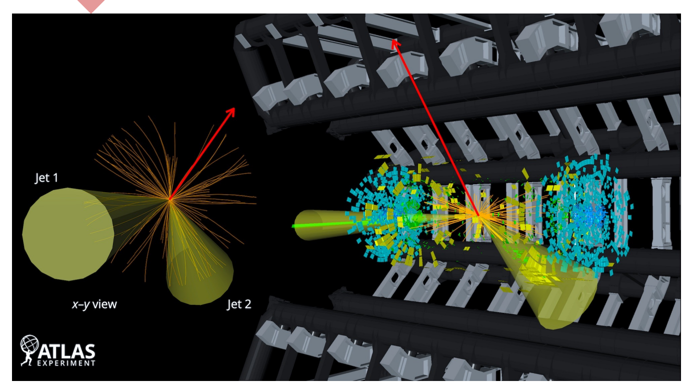
Positively correlated to GW signal strength

Higgs invisible decay

$\Gamma(h \to \phi\phi \to \text{inv.}) \propto \lambda_{hs}^2$

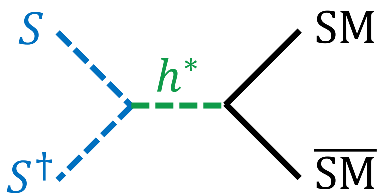


Test!



Dark sector has different temperature!

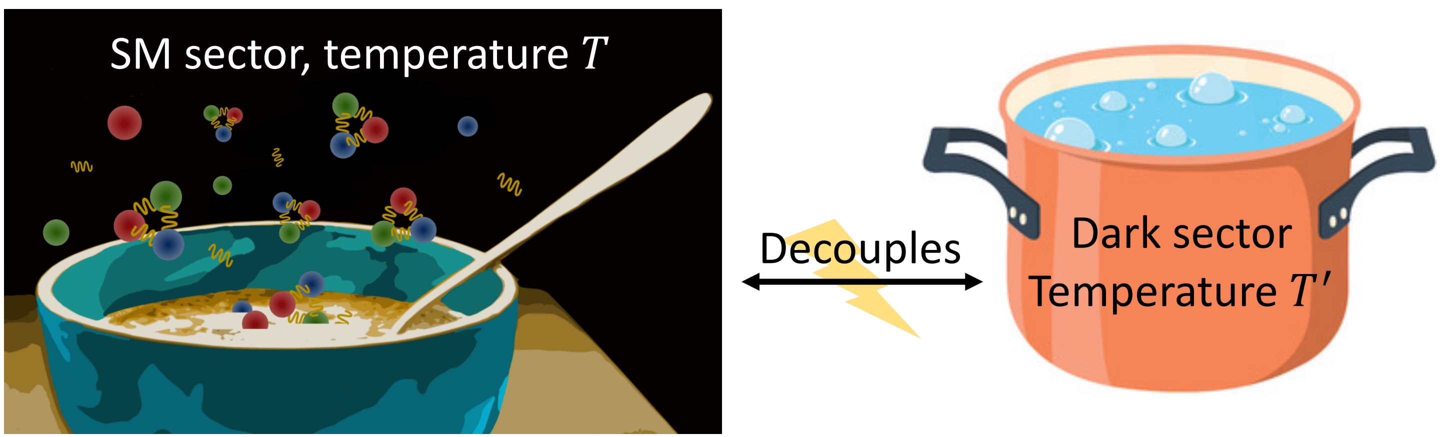
After EW phase transition (~ 100 GeV) thermal contact



$$\Gamma_{SS^\dagger}(T) = n_s\langle\sigma v\rangle \sim \frac{\lambda_{hs}^2 T^5}{m_h^4} \qquad H(T) \sim \frac{T^2}{M_{\rm Pl}}$$

- $\Gamma_{SS^\dagger}(T)/H(T) \sim T^3$

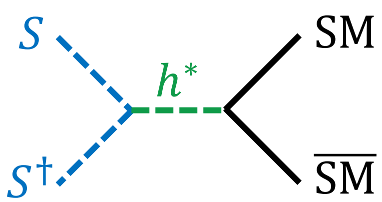
Two sectors decouple below $T_{\rm dec}$ ← Defined by $\Gamma_{SS^\dagger}(T_{\rm dec}) = H(T_{\rm dec})$



$T \neq T'$ at FOPT!

Dark sector has different temperature!

After EW phase transition ($\sim$ 100 GeV) thermal contact



$$\Gamma_{SS^\dagger}(T) = n_s\langle\sigma v\rangle \sim \frac{\lambda_{hs}^2 T^5}{m_h^4} \qquad H(T) \sim \frac{T^2}{M_{\rm Pl}}$$

- $\Gamma_{SS^\dagger}(T)/H(T) \sim T^3$

Defined by $\Gamma_{SS^\dagger}(T_{\rm dec}) = H(T_{\rm dec})$

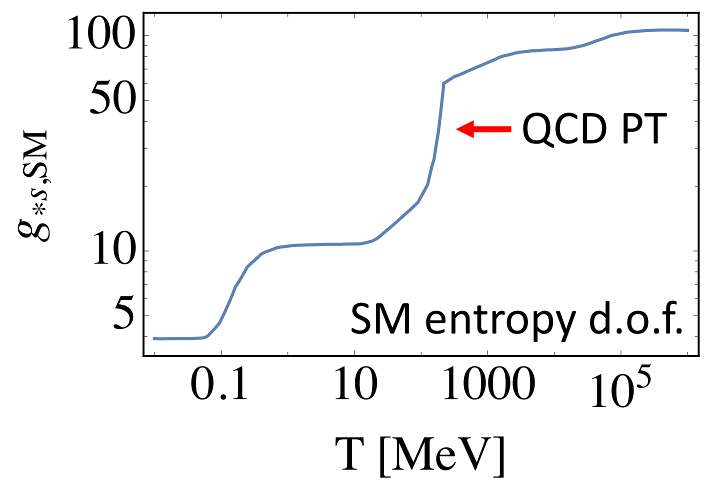
Two sectors decouple below $T_{\rm dec}$

Entropy conservation:

SM sector: $a^3 g_{*s,{\rm SM}}(T)T^3 = {\rm const.}$

Dark sector: $a^3 g'_{*s}(T')T'^3 = {\rm const.}$

$2+2=4$



$$\xi \equiv \frac{T'}{T} = \left(\frac{g_{*s,{\rm SM}}(T)}{g_{*s,{\rm SM}}(T_{\rm dec})}\right)^{1/3} < 1$$

Dark sector is “colder” than SM!

Dark, cold, and weak GWs…

Recall α parameter: FOPT latent heat over radiation energy

$$\alpha \approx \Delta V_{\rm eff} \Big/ \left(\frac{\pi^2}{30} \left(g_{*,\rm SM} T_n^4 + g'_* T_n'^4 \right) \right)$$

SM sector

Dark sector

$\sim T_n'^4$

Dark, cold, and weak GWs…

Recall α parameter: FOPT latent heat over radiation energy

$$\alpha \approx \Delta V_{\rm eff} \Big/ \left(\frac{\pi^2}{30} \left(g_{*,\rm SM} T_n^4 + g'_* T_n'^4 \right) \right)$$

SM sector

Dark sector

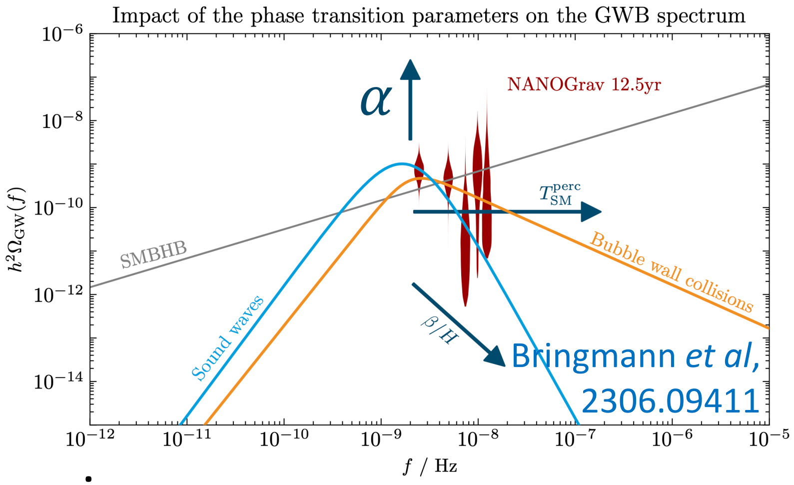
$\sim T_n'^4$

$$\xi_n \equiv \frac{T_n'}{T_n} < 1 \Rightarrow \alpha \propto \xi_n^4;$$

GW spectrum at production

$$\Omega_{\rm gw}^* \equiv \frac{1}{\rho_c} \frac{{\rm d}\rho_{\rm gw}^*}{{\rm d}\log f} \propto \alpha^2 \propto \xi_n^8$$

Sound wave scaling



- $\xi_n \sim 1/2$ yields a 10^{-3} suppression

Dark, cold, and weak GWs…

Recall α parameter: FOPT latent heat over radiation energy

$$\alpha \approx \Delta V_{\rm eff} \Big/ \left(\frac{\pi^2}{30} \left(g_{*,\rm SM} T_n^4 + g'_* T_n'^4 \right) \right)$$

SM sector

Dark sector

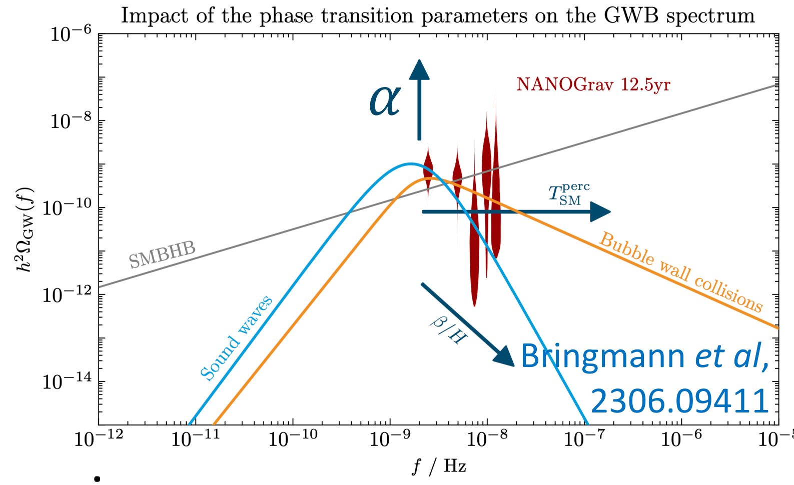
$\sim T_n'^4$

$$\xi_n \equiv \frac{T_n'}{T_n} < 1 \Rightarrow \alpha \propto \xi_n^4;$$

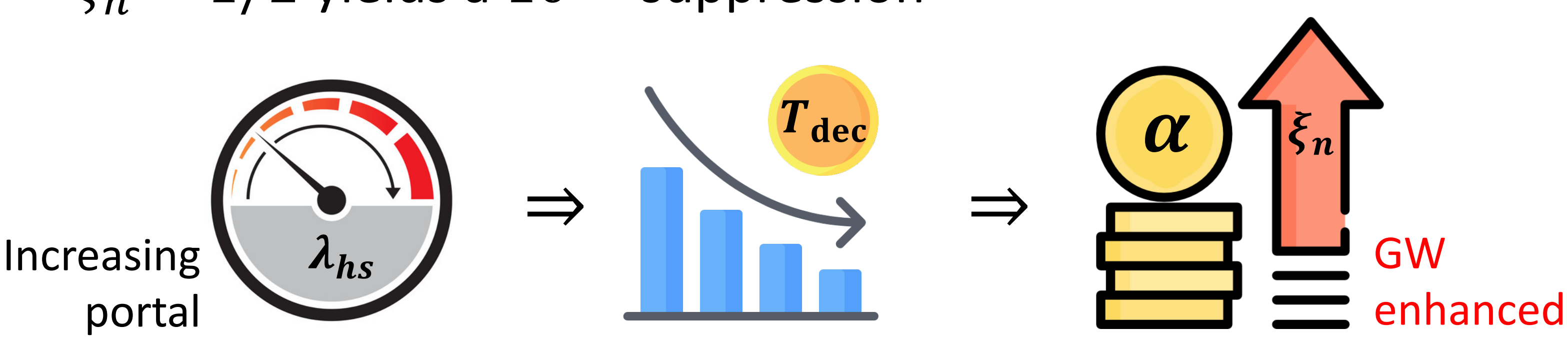
GW spectrum at production

$$\Omega_{\rm gw}^* \equiv \frac{1}{\rho_c} \frac{d\rho_{\rm gw}^*}{d\log f} \propto \alpha^2 \propto \xi_n^8$$

Sound wave scaling



- $\xi_n \sim 1/2$ yields a 10^{-3} suppression

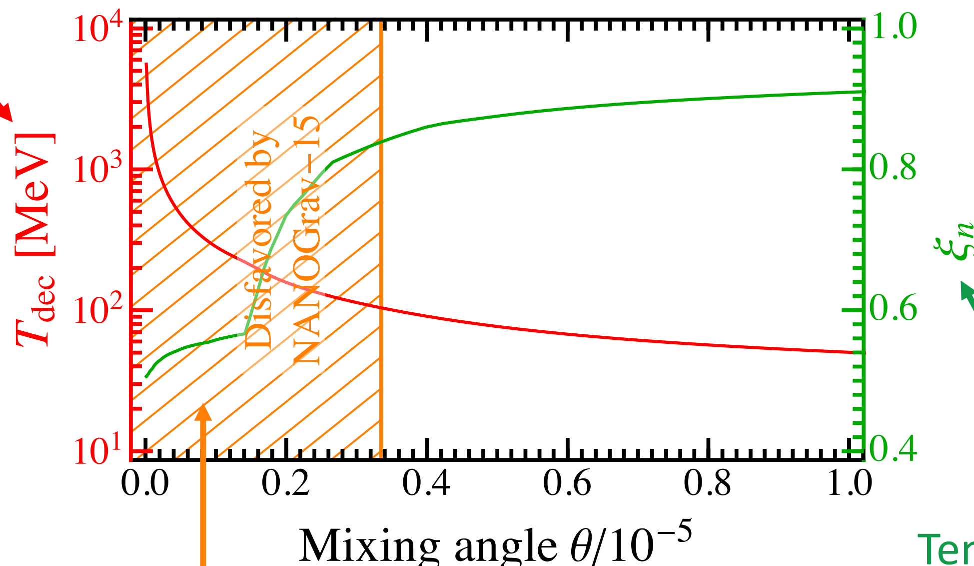


Our main result

1. Select the parameters of the dark sector: $\{m_\phi, v_s, g_X\}$.
2. Vary the mixing angle θ and consequently $\lambda_{hs} \approx \frac{m_\phi^2 - m_h^2}{v_{\rm ew} v_s}\theta$.

- Benchmark: $m_\phi = 8.46$ MeV; $v_s = 42.5$ MeV; $g_X = 1.01$

Decoupling temperature of SM & dark sectors



ξ_n too small and hence $\Omega_{\rm gw} \propto \xi_n^8$ weak

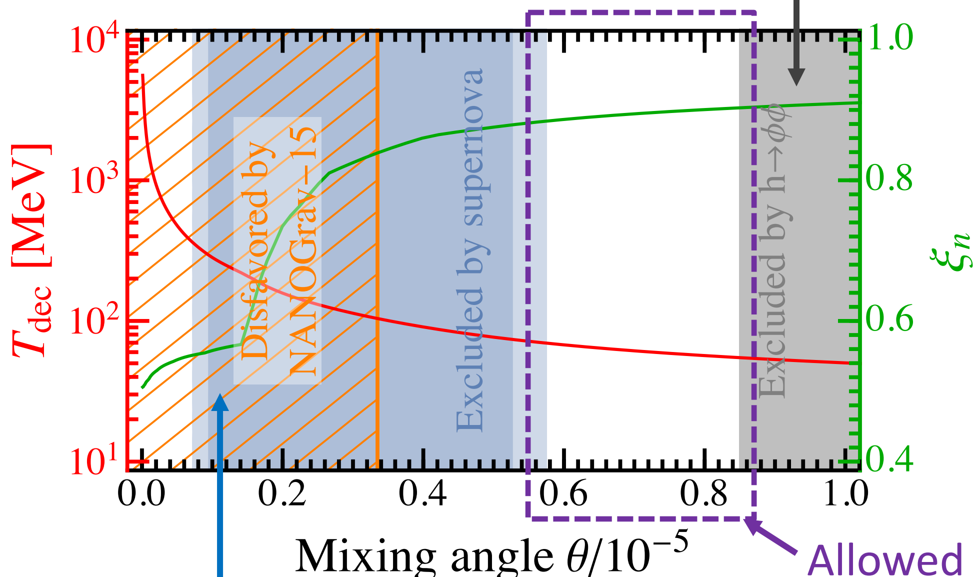
Temperature ratio $\xi = \frac{T'}{T}$ at FOPT

Our main result

1. Select the parameters of the dark sector: $\{m_\phi, v_s, g_X\}$.
2. Vary the mixing angle θ and consequently $\lambda_{hs} \approx \frac{m_\phi^2 - m_h^2}{v_{\rm ew} v_s}\theta$.

- Benchmark: $m_\phi = 8.46$ MeV; $v_s = 42.5$ MeV; $g_X = 1.01$

$\mathrm{Br}(h \to \mathrm{inv.}) < 16\%$; at 13 TeV & 139 fb^{-1} LHC
ATLAS-CONF-2021-053



Luminosity limit of SN1987A ($NN \to NN\phi$)
Dev, Mohapatra and Zhang, JCAP 08, 003 (2020)

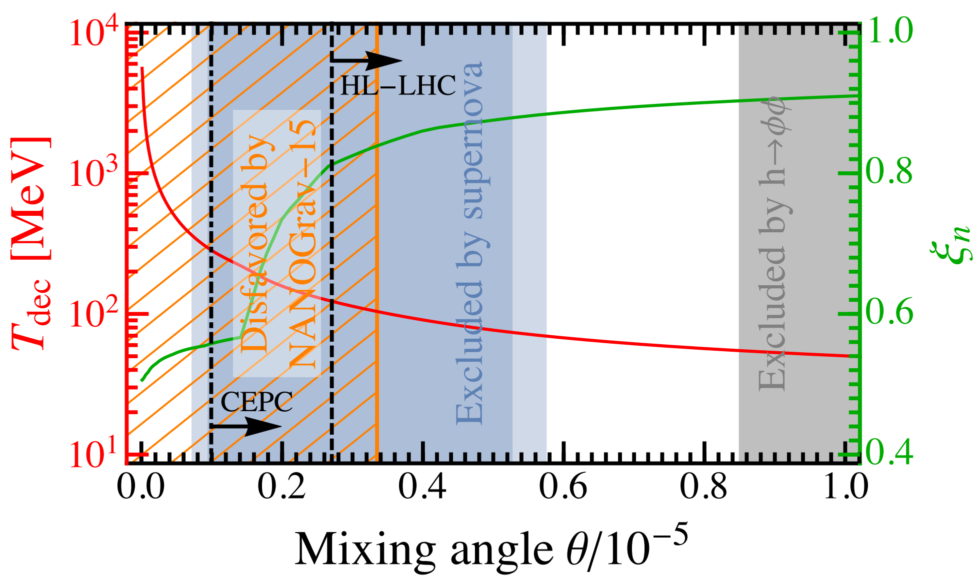
Allowed by all constraints (including BBN) and explains the nano-Hertz GWs

Our main result

1. Select the parameters of the dark sector: $\{m_\phi, v_s, g_X\}$.
2. Vary the mixing angle θ and consequently $\lambda_{hs} \approx \frac{m_\phi^2 - m_h^2}{v_{\rm ew} v_s}\theta$.

- Benchmark: $m_\phi = 8.46$ MeV; $v_s = 42.5$ MeV; $g_X = 1.01$

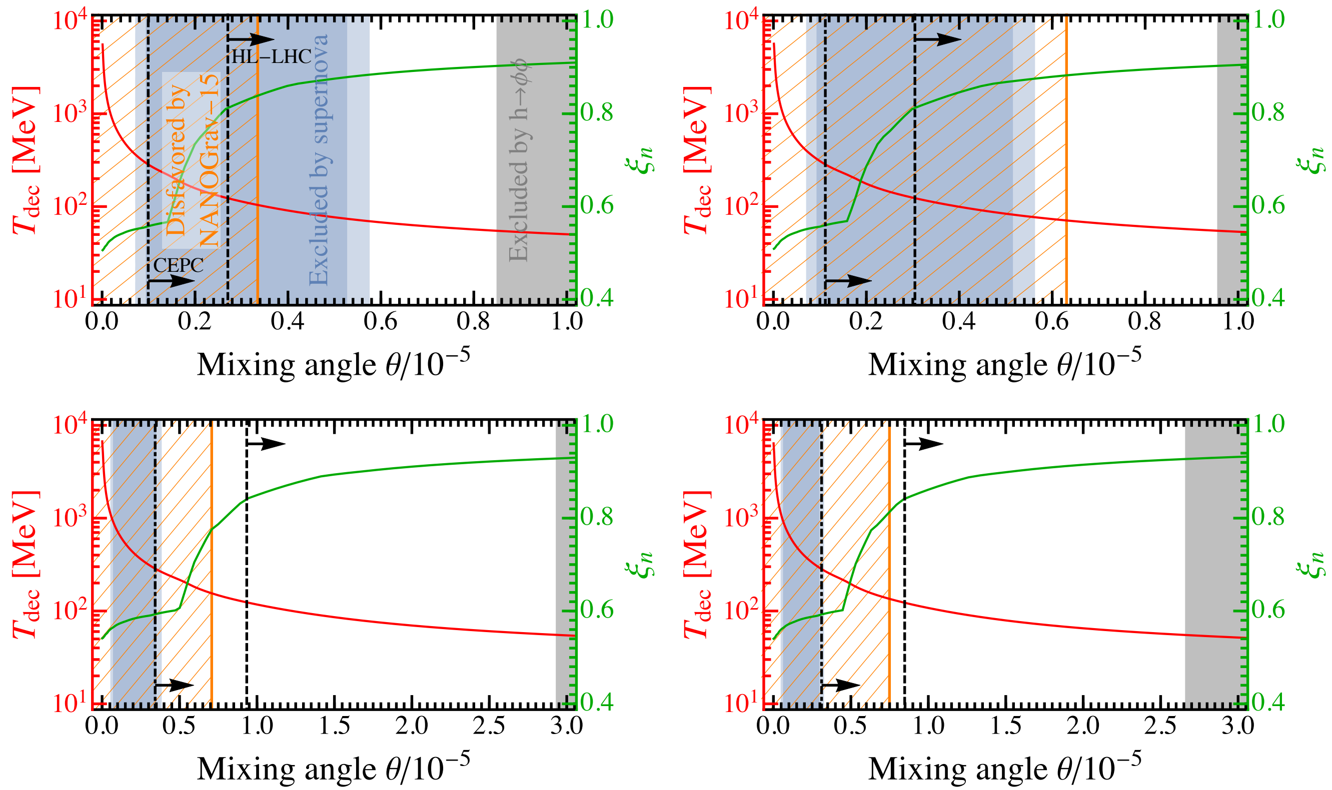
  Projection: HL-LHC: $\text{Br}(h \to \text{inv.}) < 1.9\%$ [de Blas *et al*, JHEP 01, 139 (2020)]
  CEPC: $\text{Br}(h \to \text{inv.}) < 0.26\%$ [Tan *et al*, CPC 44, 123001 (2020)]



Could be reached by future particle experiments!

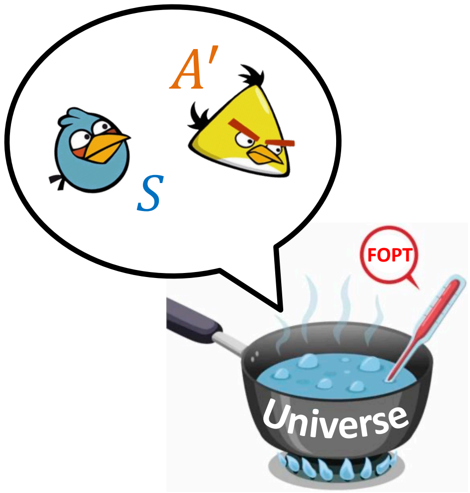
Summary of benchmarks

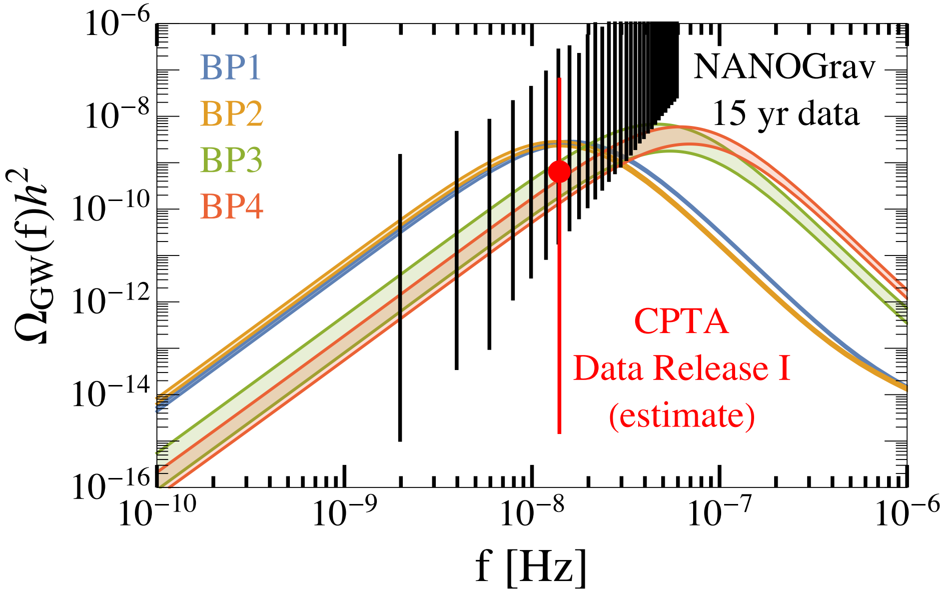
	m_ϕ [MeV]	v_s [MeV]	g_X	$\theta_{\max}/10^{-5}$	α	β/H_n	T_n [MeV]
BP1	8.46	42.5	1.01	0.849	0.309	11.2	9.56
BP2	9.16	47.9	0.981	0.955	0.269	9.17	11.2
BP3	23.0	147	0.892	2.93	0.523	12.3	24.3
BP4	31.6	133	1.13	2.66	0.684	16.8	23.9



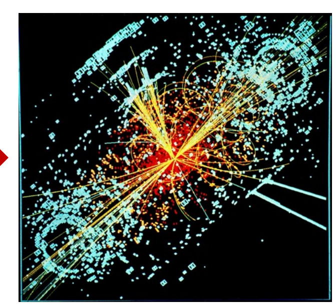
Closing remarks

A boiling Universe explains the recent reported nano-Hertz GWs



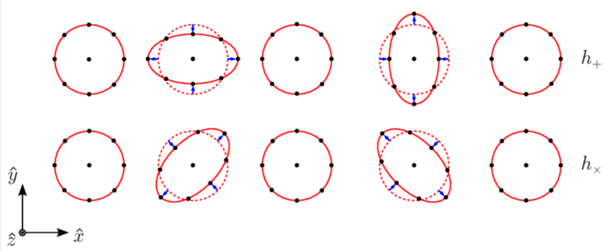
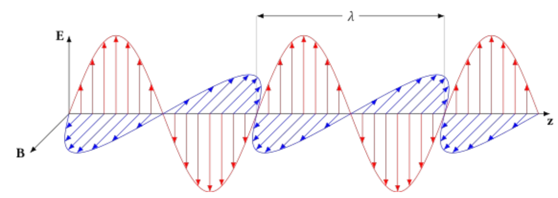


If the dark sector couples to SM via **Higgs portal**,
Then the FOPT explanation can be tested by $h \to \phi\phi \to \text{inv.}$ at the LHC and future CEPC, ILC and FCC-ee!



Thank you!

Backup: gravitational waves

	Gravitational waves	Electromagnetic waves
Physics	General relativity $R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi}{M_{\rm Pl}^2} T_{\mu\nu}$	Maxwell equations $\partial_\nu F^{\mu\nu} = -J^\mu$; $\partial_\nu \tilde{F}^{\mu\nu} = 0$
Source	Mass & energy	Electric charge
Property	Tensor $h_{\mu\nu} \approx g_{\mu\nu} - \eta_{\mu\nu}$	Vector A_μ
Polarization	Transverse wave, propagation in c	
		
Multipole	Quadrupole	Dipole
Astronomy	???	

Backup: potential

Joint potential

$$V(S,H) = \mu_h^2|H|^2 + \mu_s^2|S|^2 + \lambda_h|H|^4 + \lambda_s|S|^4 + \lambda_{hs}|H|^2|S|^2$$

The mass coefficients

$$\mu_{h,s}^2 = -\frac{1}{4}\left[m_h^2 + m_\phi^2 \mp \left(m_\phi^2 - m_h^2\right)\left(\cos 2\theta \mp \left(\frac{v_s}{v_{\rm ew}}\right)\sin 2\theta\right)\right]$$

The quartic coefficients

$$\lambda_h = \frac{1}{4v_{\rm ew}^2}\left[m_h^2 + m_\phi^2 - \left(m_\phi^2 - m_h^2\right)\cos 2\theta\right]$$

$$\lambda_s = \frac{1}{4v_s^2}\left[m_h^2 + m_\phi^2 + \left(m_\phi^2 - m_h^2\right)\cos 2\theta\right]$$

$$\lambda_{hs} = \frac{1}{2v_{\rm ew}v_s}\left(m_\phi^2 - m_h^2\right)\sin 2\theta$$

Input parameters:

- Higgs mass $m_h = 125$ GeV and VEV $v_{\rm ew} = 246$ GeV
- light scalar mass m_ϕ and VEV v_s, and h-s mixing angle θ

Backup: thermal potential

One-loop thermal potential

$$V_{\rm eff}(\phi,T')=V_0(\phi)+V_{\rm CW}(\phi)+V_T(\phi,T')$$

Coleman-Weinberg

$$V_{\rm CW}(\phi)=\sum_{i=\phi,A'}\frac{n_iM_i^4(\phi)}{64\pi^2}\left(\log\frac{M_i^2(\phi)}{\mu_R^2}-C_i\right)+V_{\rm CT}$$

One-loop thermal correction

$$V_T(\phi,T')=\sum_{i=\phi,\eta,A'}\frac{n_iT'^4}{2\pi^2}J_B\left(\frac{M_i^2(\phi)}{T'^2}\right)$$

Thermal integral $J_B(y)\equiv\int_0^\infty x^2{\rm d}x\log\left(1-e^{-\sqrt{x^2+y}}\right)$

Field-dependent masses $M_\phi^2(\phi)=-\frac{m_\phi^2}{2}\left(1-\frac{3\phi^2}{v_S^2}\right)$, $M_\eta^2(\phi)=-\frac{m_\phi^2}{2}\left(1-\frac{\phi^2}{v_S^2}\right)$ and $M_{A'}(\phi)=g_X\phi$

Coefficients $n_{\phi,\eta,A'}=1,1,3$ and $C_{\phi,A'}=3/2,5/6$.

Backup: calculation of FOPT & GWs

Vacuum decay rate [Linde, NPB 216 (1983) 421] $\Gamma(T) \sim \left(\frac{S_3}{2\pi T}\right)^{3/2} T^4 e^{-S_3/T}$

FOPT criterion $\Gamma(T) \sim H^4(T)$ [Bubble nucleation]

$$\frac{S_3}{T_n'} \approx 4\log\left(\frac{1}{4\pi}\sqrt{\frac{45}{\pi g_*(T_n)}}\frac{M_{\rm Pl}}{T_n'}\right) \approx 190$$

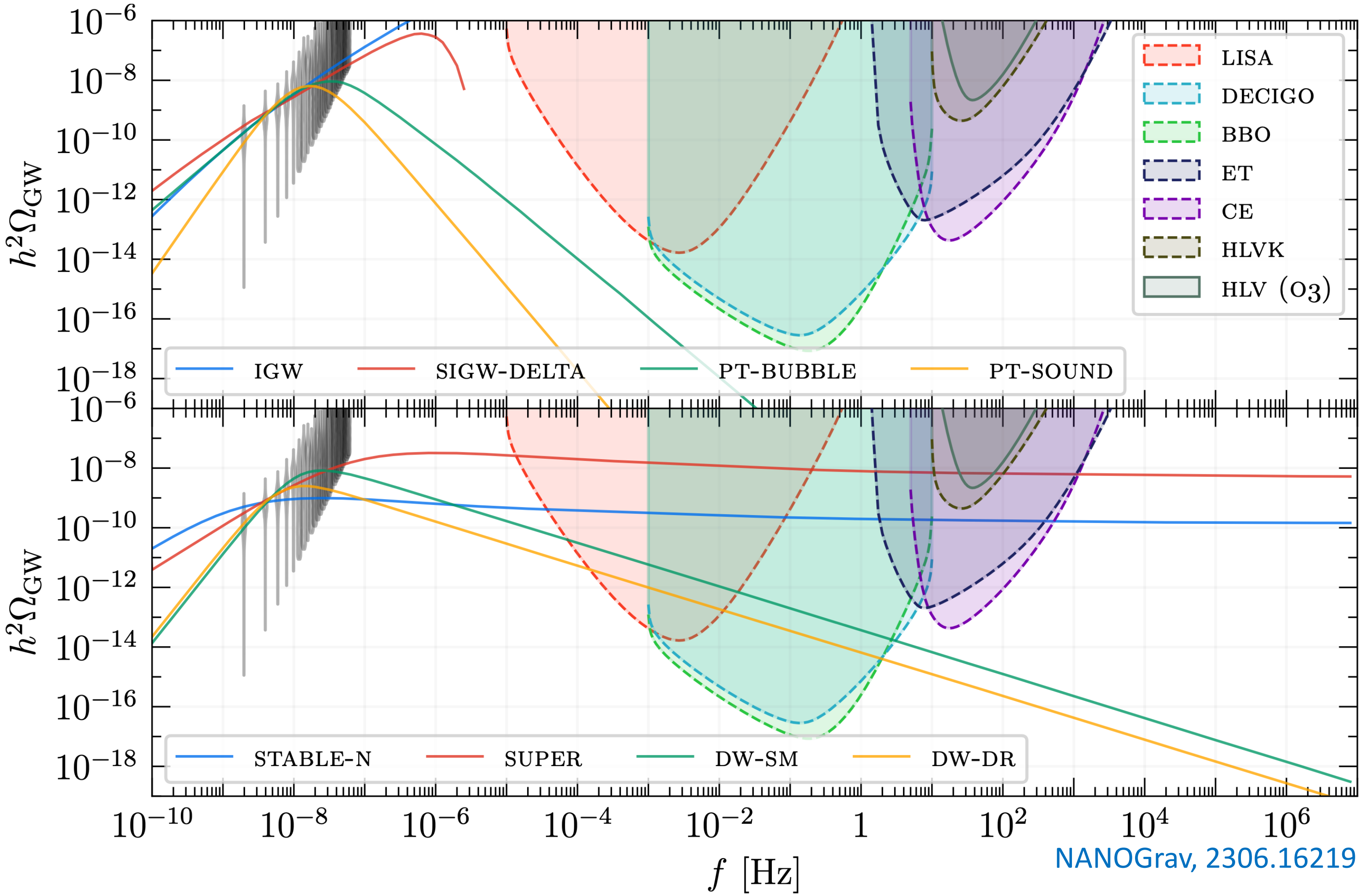
GW spectrum at production

$$\Omega_{{\rm gw},n}(f) \approx 1.59\times10^{-1}\times v_w \left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 \left(\frac{\beta}{H_n}\right)^{-1} \times \left(\frac{f}{f_{\rm sw}}\right)^3 \left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

GW spectrum today

$$\Omega_{\rm gw}(f)h^2 = \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm gw}}{{\rm d}\log f} \approx 1.238\times10^{-5}\left(g_{*,{\rm SM}}(T_n) + g_*'(T_n')\xi_n^4\right) \times \left(\frac{g_{*s,{\rm SM}}(T_0)}{g_{*s,{\rm SM}}(T_n) + g_{*,s}'(T_n')\xi_n^3}\right)^{4/3} \Omega_{{\rm gw},n}\left(\frac{a_0}{a}f\right)$$

Backup: NANOGrav fit for new physics



NANOGrav, 2306.16219