Collider Tests of Nanohertz Gravitational Waves from Minimal Dark Phase Transition

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LiSP & Ke-Pan Xie, arXiv: 2307.01086

PTA observations & explanations

- Recent pulsar timing array (PTA) collaborations show compelling evidence of stochastic gravitational waves (GW) at nHz frequency
- Data set: NANOGrav (15yr, 67 pulsars), CPTA (3.4yr, 57 pulsars), EPTA (10.3yr, 25 pulsars) and PPTA (30yr, 18 pulsars) (2306.16213-16216)
- The significance of Hellings-Downs (quadrupolar) correlation from NANOGrav, CPTA and EPTA is at 3-4 sigma, while from PPTA is 2 sigma
- Conclusive nHz GW signals? Remains to be seen. More data collection & analyses needed

PTA observations & explanations

- Astrophysical explanation

Inspiraling of supermassive black hole binaries (SMBHB)

- Cosmological explanations

Cosmic inflation, scalar-induced GW, first-order phase transition (FOPT), cosmic strings, domain walls, etc.

- Bayesian analysis from NANOGrav: *strong evidence* of cosmological source against standard SMBHB explanation (2306.16213) (not universal, data/model-dependent)

A true stochastic GW era for cosmologists? Not decisive yet, but exciting!

Model-independent fits of FOPT

NANOGrav, 2306.16213

Bayesian Estimators, Maximum Posterior Values, and 68% Credible Intervals for the Parameters of the New-physics Models

Parameter	Bayes Estimator		Maximum Posterior		68% Credible Interval	
	NP	NP+SMBHB	NP	NP+SMBHB	NP	NP+SMBHB
Cosmological Phase Transition (PT-BUBBLE)						
$\log_{10} T_*/\mathrm{GeV}$	-0.76 ± 0.49	-0.71 ± 0.70	-0.90	-0.89	$[-1.33, -0.39]$	$[-1.34, -0.34]$
$\log_{10} \alpha_*$	-0.26 ± 0.47	-0.23 ± 0.52	1^*	0.74	$[0.03, 1^*]$	$[0.01, 1^*]$
$\log_{10} H_* R_*$	-0.42 ± 0.26	-0.47 ± 0.39	0^*	-0.06	$[-0.56, 0^*]$	$[-0.58, 0^*]$
a	2.04 ± 0.48	2.07 ± 0.49	1.97	2.01	$[1.49, 2.54]$	$[1.54, 2.63]$
b	1.97 ± 0.58	1.98 ± 0.58	1^*	1^*	$[1^*, 2.32]$	$[1^*, 2.33]$
c	2.03 ± 0.57	2.03 ± 0.57	3^*	2.93	$[1.69, 3^*]$	$[1.69, 3^*]$
$\log_{10} A_{\mathrm{BHB}}$	…	-15.68 ± 0.51	…	-15.65	…	$[-16.17, -15.21]$
γ_{BHB}	…	4.64 ± 0.35	…	4.65	…	$[4.30, 5.00]$
Cosmological Phase Transition (PT-SOUND)						
$\log_{10} T_*/\mathrm{GeV}$	-1.84 ± 0.41	-1.56 ± 1.06	-2.00	-1.95	$[-2.33, -1.48]$	$[-2.31, -1.30]$
$\log_{10} \alpha_*$	-0.22 ± 0.44	0.14 ± 0.56	-0.21	-0.15	$[-0.37, 1^*]$	$[-0.34, 0.73]$
$\log_{10} H_* R_*$	-0.81 ± 0.36	-0.87 ± 0.51	-1.05	-1.01	$[-1.28, -0.57]$	$[-1.26, -0.45]$
a	3.58 ± 0.47	3.74 ± 0.54	3^*	3^*	$[3^*, 3.72]$	$[3^*, 3.98]$
b	2.87 ± 0.57	2.92 ± 0.57	2^*	2^*	$[2^*, 3.17]$	$[2^*, 3.25]$
c	4.16 ± 0.56	4.09 ± 0.57	5^*	5^*	$[3.87, 5^*]$	$[3.77, 5^*]$
$\log_{10} A_{\mathrm{BHB}}$	…	-15.45 ± 0.55	…	-15.39	…	$[-16.04, -14.94]$
γ_{BHB}	…	4.63 ± 0.38	…	4.67	…	$[4.27, 5.03]$

J. Ellis, *et al*, 2308.08546

Scenario	Best-fit parameters
GW-driven SMBH binaries	$p_{\mathrm{BH}} = 0.25$
GW + environment-driven SMBH binaries	$p_{\mathrm{BH}} = 1$ $\alpha = 3.8$ $f_{\mathrm{ref}} = 12$ nHz
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$
Phase transition (PT)	$T_* = 0.24$ GeV $\beta/H = 6.0$
Domain walls (DWs)	$T_{\mathrm{ann}} = 0.79$ GeV $\alpha_* = 0.026$
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.6}/\mathrm{Mpc}$ $A = 10^{-1.1}$ $\Delta = 0.28$
First-order GWs (FOGWs)	$\log_{10} r = -16.25$ $n_t = 2.87$ $\log_{10} T_{\mathrm{rh}} = -0.45$
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\mathrm{P}}$

FOPT at 1-100 MeV temperature is favored to explain the PTA observations.

MeV-scale Dark FOPT

MeV-scale FOPT can be realized in an Abelian or non-Abelian dark sector

Why is a dark world interesting?

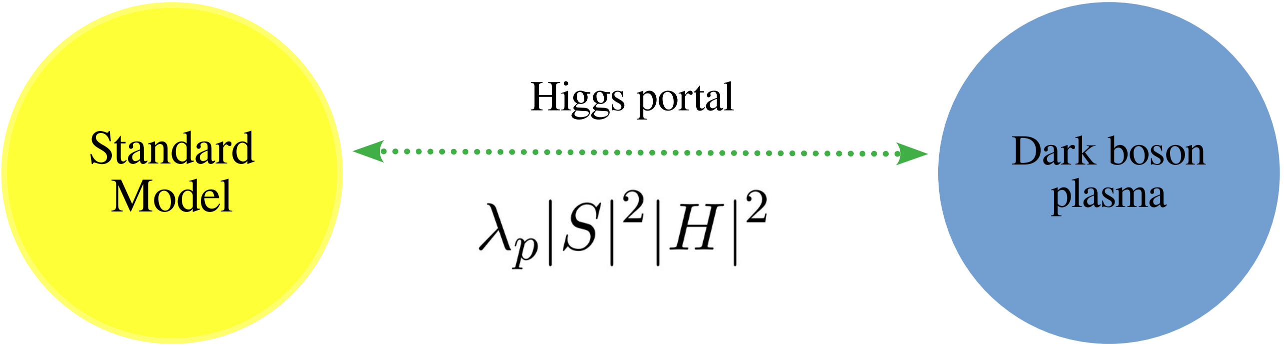
Pros

- DM candidate
- Scale origin of neutrino mass
- Scale origin of electroweak vacuum
- Phase transition
- …

Cons

- Free parameters >> Obs.
- Pheno. is described but not predicted
- Ambiguous ways to probe
- See and Hear?

A minimal Higgs-portal dark plasma



$U(1)_X \otimes Z_2$ dark species: a dark scalar & a dark gauge boson

Unique connection: the Higgs portal; kinetic mixing forbidden $A'_\mu \to -A'_\mu \,, \quad S \to S^*$

Free parameters: $m_S, m_{A'}, g_X, \lambda_p$

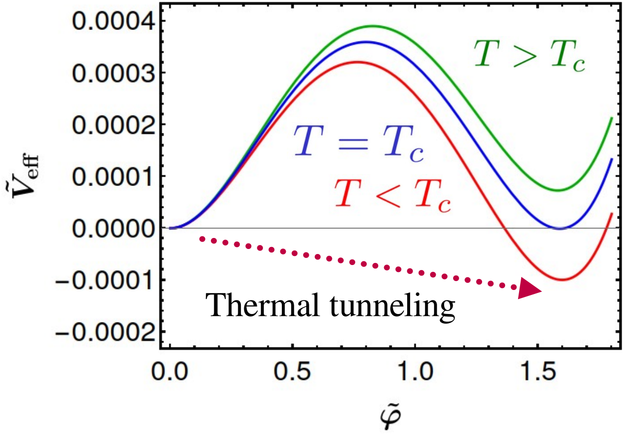
Dark FOPT

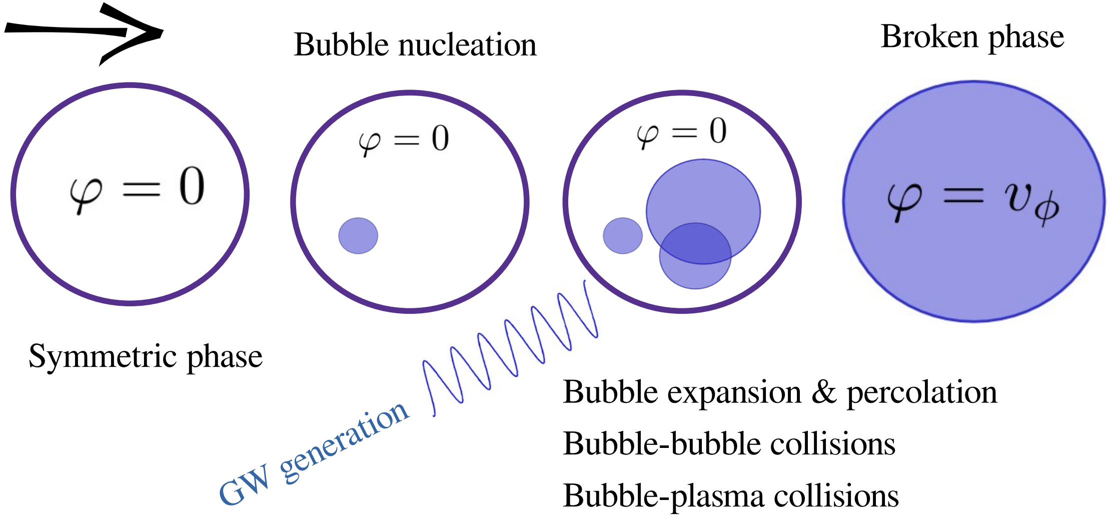
Vacuum tree-level dark scalar potential $V_0(S) = -\mu_S^2|S|^2 + \lambda|S|^4$

$\varphi = v_\phi$

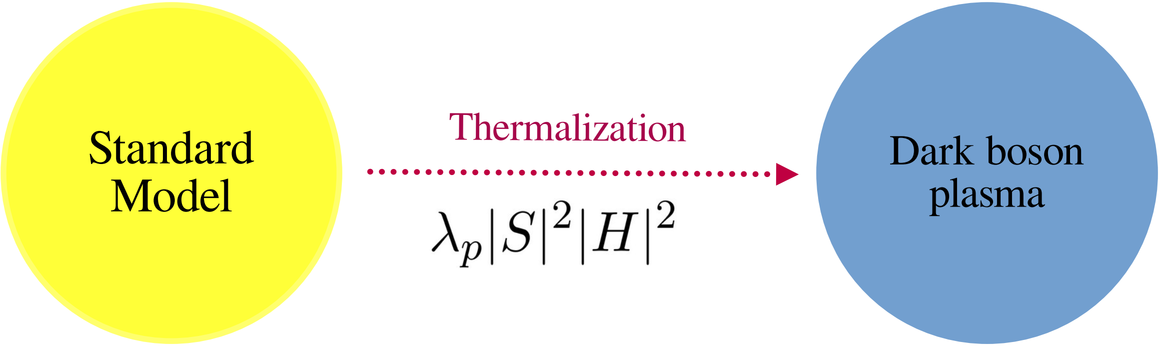
$S = (\varphi + \phi + i\chi)/\sqrt{2}$

Finite-T dark scalar potential $V_{\rm eff}(\varphi, T) = V_0 + V_{\rm CW} + V_{\rm CT} + V_T + V_{\rm daisy}$





How is collider test correlated to GW origin?



If $\boxed{\lambda_p = 0}$

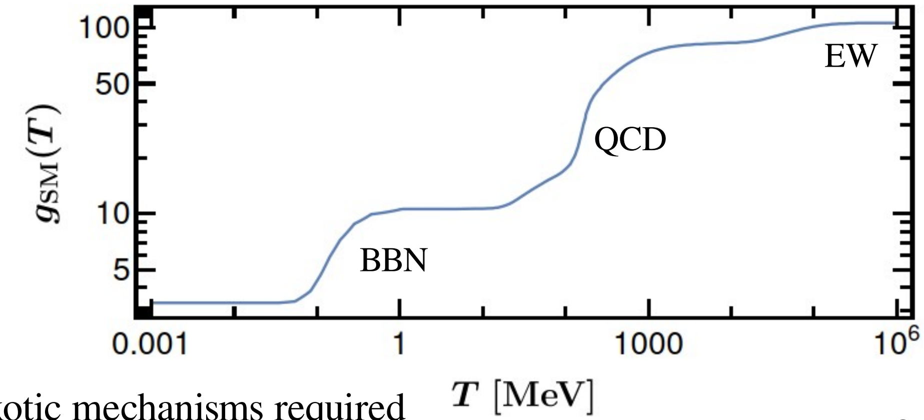
entropy conserves separately

$$\frac{T_{\rm D,n}}{T_{\rm SM,n}} = \left(\frac{g_{\rm SM,n}}{g_{\rm SM,i}}\right)^{1/3} \frac{T_{\rm D,i}}{T_{\rm SM,i}}$$

Symmetric reheating (minimal)

$$T_{\rm D,i} = T_{\rm SM,i} \quad \& \quad T_{\rm D,n} < T_{\rm SM,n}$$

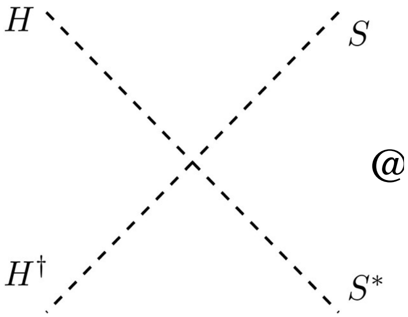
Colder dark plasma @ MeV FOPT



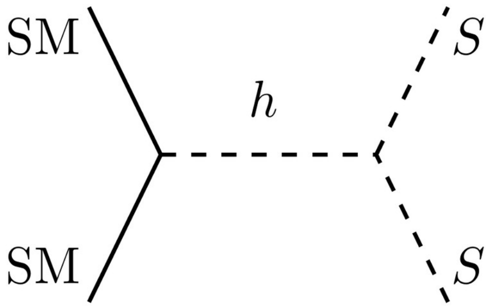
Asymmetric reheating $T_{\rm D,i} \lessgtr T_{\rm SM,i}$ Exotic mechanisms required

How is collider test correlated to GW origin?

If $\boxed{\lambda_p \neq 0}$ Thermalization between the SM and the dark plasma via Higgs portal



$@\ \langle H \rangle = 0, \langle S \rangle = 0$



$@\ \langle H \rangle = v_{\rm EW}, \langle S \rangle = 0$

Entropy conserves separately after decoupling

$$\frac{T_{\rm D,n}}{T_{\rm SM,n}} = \left(\frac{g_{\rm SM,n}}{g_{\rm SM,dec}}\right)^{1/3} \frac{T_{\rm D,dec}}{T_{\rm SM,dec}}$$

A lower decoupling temperature, a hotter dark plasma at nucleation temperature

How is collider test correlated to GW origin?

Dark FOPT strength suppressed by quartic temperature ratio

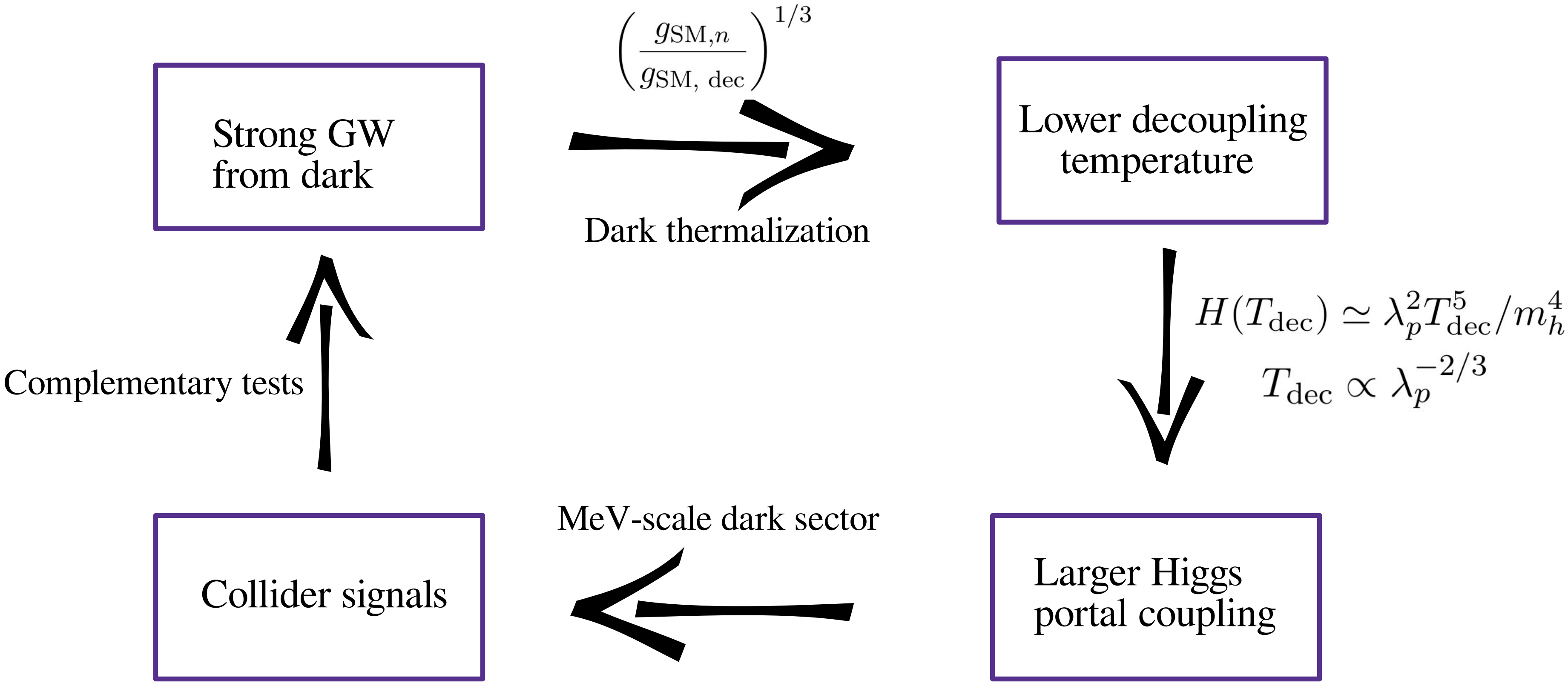
$$\alpha \lesssim 1 \approx \frac{\Delta V_{\rm eff}}{\rho_R} \propto \left(\frac{T_{\rm D,n}}{T_{\rm SM,n}}\right)^4 = \left(\frac{g_{\rm SM,n}}{g_{\rm SM,dec}}\right)^{4/3}$$

Sound-wave dominated GW peak amplitude (M. Hindmarsh, *et al*, 1504.03291; C. Caprini,*et al*, 1512.06239)

$$\Omega_{\rm sw}^{\rm peak} h^2 = 2.65 \times 10^{-6} (\mathcal{H}\tau_{\rm sw}) \left(\frac{v_w}{\beta/\mathcal{H}}\right) \left(\frac{100}{g_\rho(T_n)}\right)^{1/3} \left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 \quad \kappa_{\rm sw} \approx \frac{\alpha}{0.73 + 0.083\sqrt{\alpha} + \alpha}$$

strongly suppressed by $\left(\frac{T_{\rm D,n}}{T_{\rm SM,n}}\right)^8 \sim \left(\frac{T_{\rm D,n}}{T_{\rm SM,n}}\right)^{16}$ A factor of 1/2 leads to a suppression by several orders of magnitude!

How is collider test correlated to GW origin?

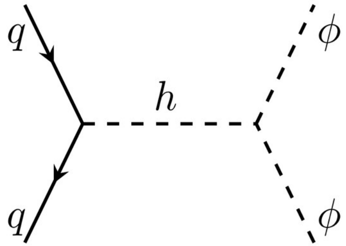


Most sensitive collider searches

Direct—Higgs invisible decay

$$\Gamma(h \to 2\phi) = \frac{\theta^2 m_h}{32\pi}\frac{m_h^2}{v_s^2}\left(1+\frac{2m_\phi^2}{m_h^2}\right)^2\sqrt{1-\frac{4m_\phi^2}{m_h^2}}$$

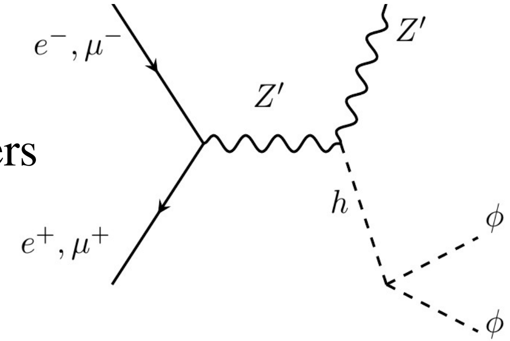
(HL) LHC



Current LHC bound (CMS, 1809.05937) $|\theta| \sim 10^{-5}$

Future HL-LHC sensitivity (J. de Blas, *et al*, 1905.03764) $|\theta| \sim 10^{-6}$

Lepton colliders



Future sensitivities from CEPC, ILC, FCC-ee, muon collider (O.Cerri, et al, 1605.00100; Y. Tan, *et al*, 2001.05912; C. Potter, *et al.* 2203.08330; M. Ruhdorfer, *et al*, 2303.14202)

$$|\theta| \sim 10^{-7}$$

Most sensitive collider searches

Indirect—strength/coupling modifiers

$$\sigma(i \to h)\mathrm{BR}(h \to f) \equiv \mu_i^f \times (\sigma_{i,\mathrm{SM}}\mathrm{BR}_{h\to f,\mathrm{SM}}) \equiv \frac{(\sigma_{i,\mathrm{SM}} \times \kappa_i^2)(\Gamma_{h\to f,\mathrm{SM}} \times \kappa_f^2)}{\Gamma_{h,\mathrm{SM}} \times \kappa_h^2}$$

Higgs-dark scalar mixing—universal modifiers $\mu_i^f = \cos\theta^2 \quad \kappa_i^2 = \cos\theta^2 = \kappa_h^2$

Current LHC bound $|\theta| \sim 0.1$
(ATLAS, 2207.00092;
CMS, 2207.00043)

CEPC, ILC, FCC-ee sensitivities $|\theta| \sim 0.06$
(J. de Blas, *et al*, 1905.03764)

Direct probe via Higgs invisible decay
will be the most sensitive channel

$$\theta \approx \frac{v_{\mathrm{EW}} v_\phi \lambda_p}{m_h^2 - m_\phi^2}$$

Direct Higgs-scalar coupling (λ_p)

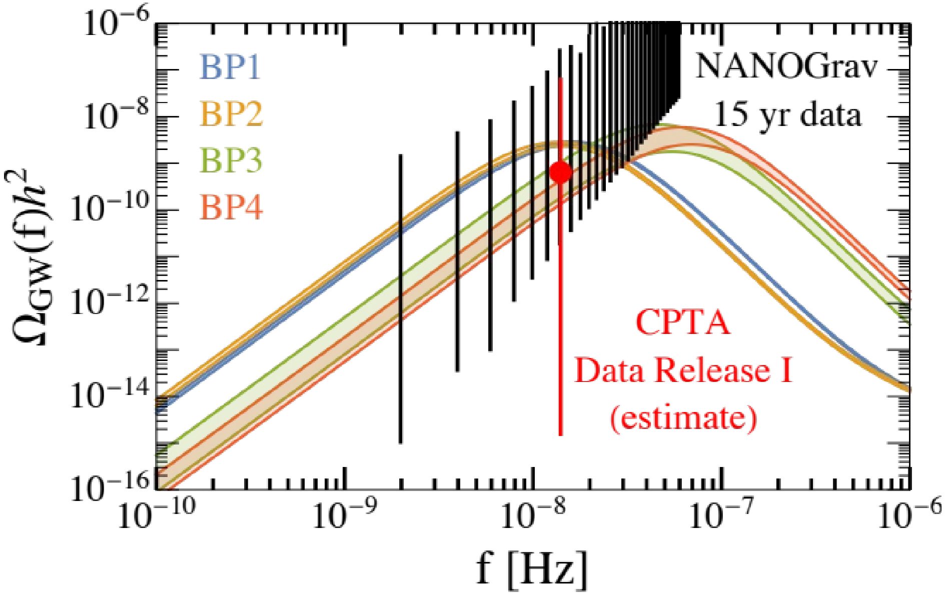
Indirect SM-scalar coupling (θ)

Benchmark points for GW

MeV-scale dark FOPT

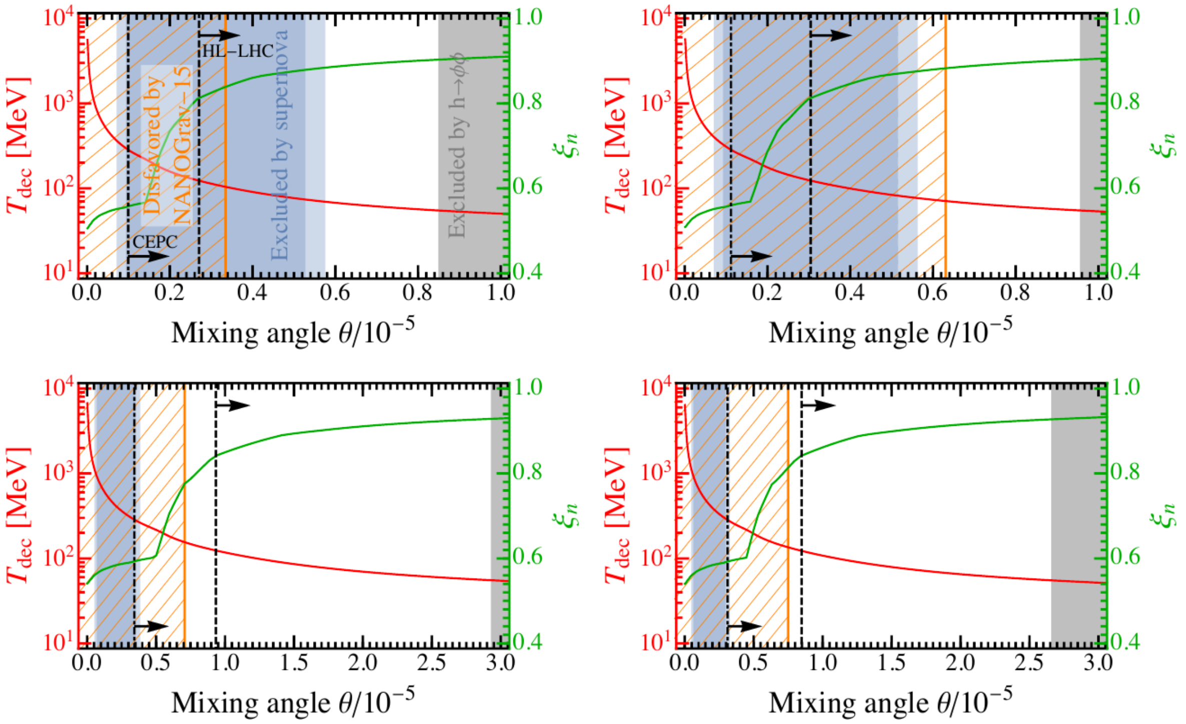
	m_ϕ [MeV]	v_s [MeV]	g_X	$\theta_{\max}/10^{-5}$	α	β/H_n	T_n [MeV]
BP1	8.46	42.5	1.01	0.849	0.309	11.2	9.56
BP2	9.16	47.9	0.981	0.955	0.269	8.17	11.2
BP3	23.0	147	0.892	2.93	0.523	12.3	24.3
BP4	31.6	133	1.13	2.66	0.684	16.8	23.9

TABLE I. The chosen BPs with the (m_ϕ, v_s, g_X) values. $\theta_{\max}$ is the maximal θ allowed by the LHC data, and the subsequent $(\alpha, \beta/H_n, T_n)$ is evaluated at $\theta_{\max}$.



Phenomenological treatment: make the predicted GW curves cross at least the first 14 frequency bins (most evident for GW) from NANOGrav data

Constraints & tests



White regions: phenomenologically viable for nHz GW @NANOGrav

CEPC, ILC, FCC-ee & muon colliders can fully test the white regions.

- Astrophysical bound—energy loss against supernova 1987A luminosity (P. S. B. Dev, *et al*, 2005.00490)

  Nucleon bremsstrahlung

  $$NN \to NN\phi$$

- Cosmic bound

  Dark scalar decay @BBN epoch (M. Hufnagel, *et al*, 1808.09324)

  $$\phi \to e^+e^-$$

- Relic dark gauge boson dark matter (S. Kanemura & LiSP, 2308.16390)

$$\left(\frac{\Omega_{\rm DM}h^2}{0.12}\right) \approx 0.33 \left(\frac{0.1}{g_X}\right)^4 \left(\frac{m_{A'}}{100\ {\rm GeV}}\right)^2$$

Summary

- Why consider model-specific FOPT?

↳

✔ To shed more light on the cosmological explanations of PTA data, fundamental parameters are required to find out the deterministic signals beyond GW

- Can we see and hear the minimal dark?

↳

✔ Hear the dark from GW by MeV-scale FOPT

✔ See the dark from colliders via Higgs invisible decay