LCWS2024 International Workshop on Future Linear Colliders

Collider Tests of Nanohertz Gravity Waves

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Lisp & K.-P Xie: 2307.01086
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JSPS

PTA observations & explanations

- Recent pulsar timing array (PTA) collaborations show compelling evidence of stochastic gravitational waves (GW) at nHz (1e-9Hz) frequency
- Cosmological origins? Cosmic inflation, scalar-induced GW, first-order phase transition (FOPT), cosmic strings, domain walls, etc. could explain the PTA data.
- For cosmic origins, one needs to tell apart which source generates the nHz GW
- While not conclusive yet, it is exciting and interesting to combine the cosmic explanation of PTA observations with particle physics, particularly collider detection.

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?

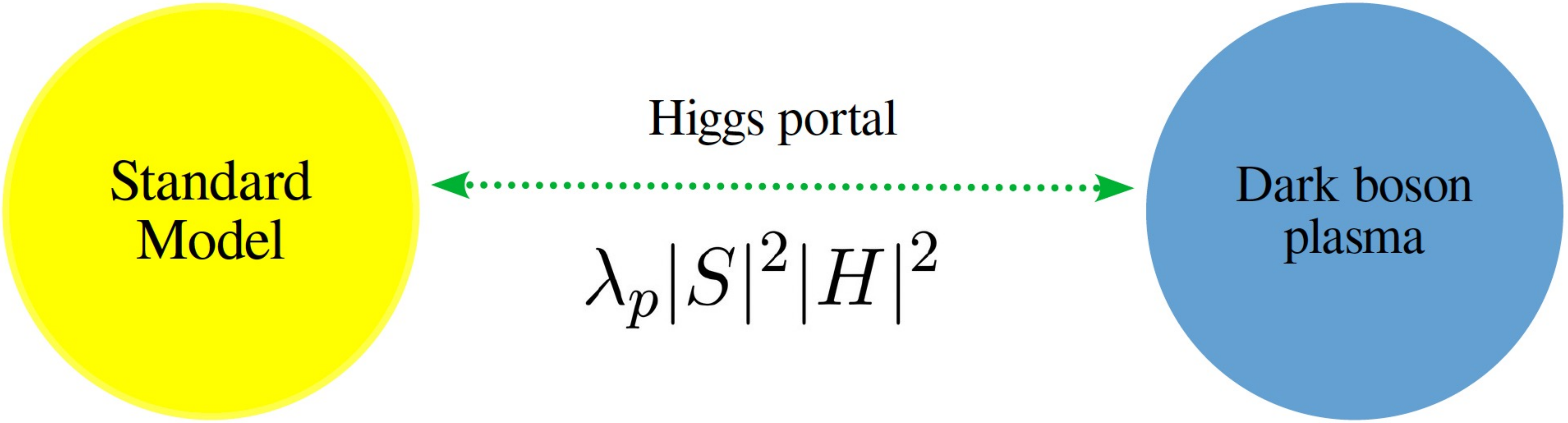
Pros

- 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

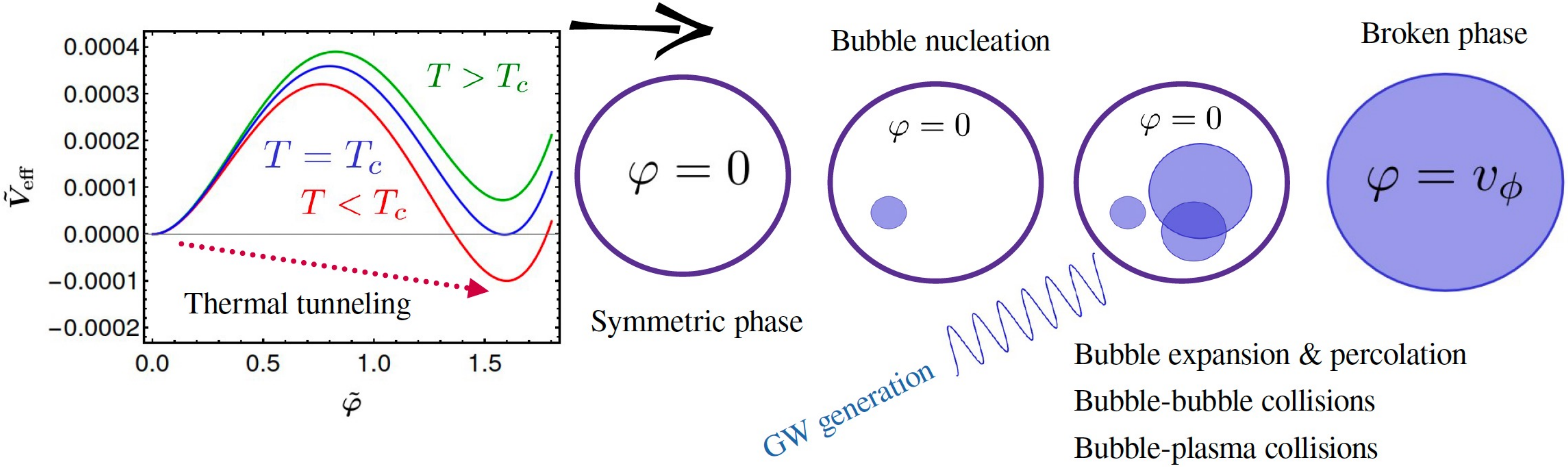
Unique connection: the Higgs portal; kinetic mixing forbidden $A'_\mu \to -A'_\mu\,, \quad S \to S^*$

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

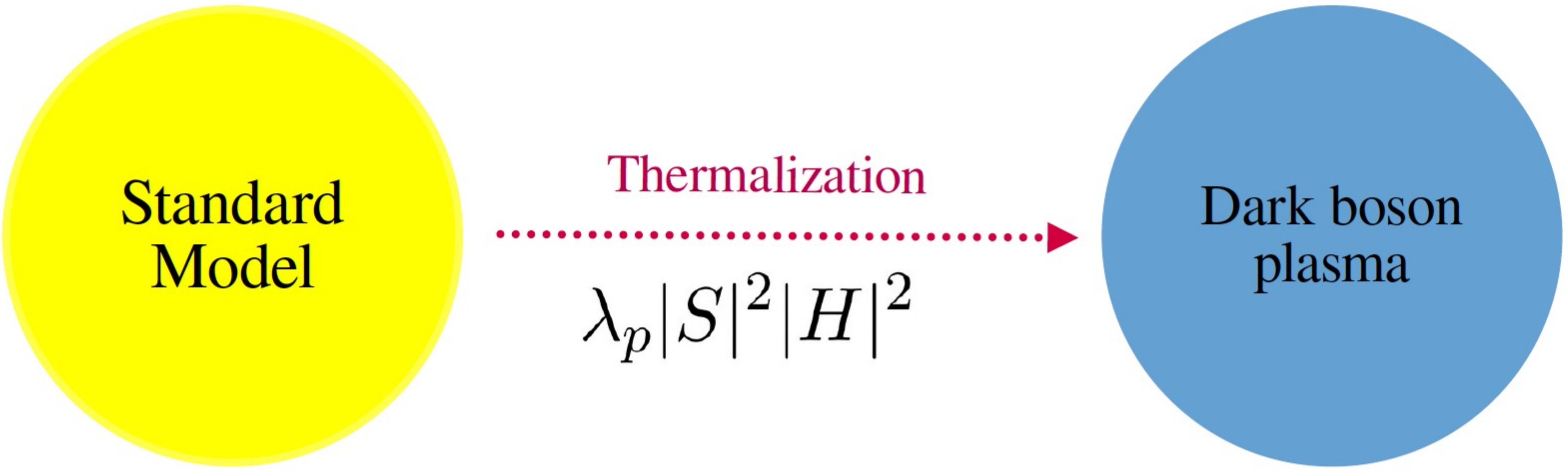
Dark FOPT

Vacuum tree-level dark scalar potential $V_0(S) = -\mu_S^2|S|^2 + \lambda|S|^4$ $\quad \varphi = v_\phi \quad S = (\varphi + \phi + i\chi)/\sqrt{2}$

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 correlated to GW origin?



If $\boxed{\lambda_p = 0}$

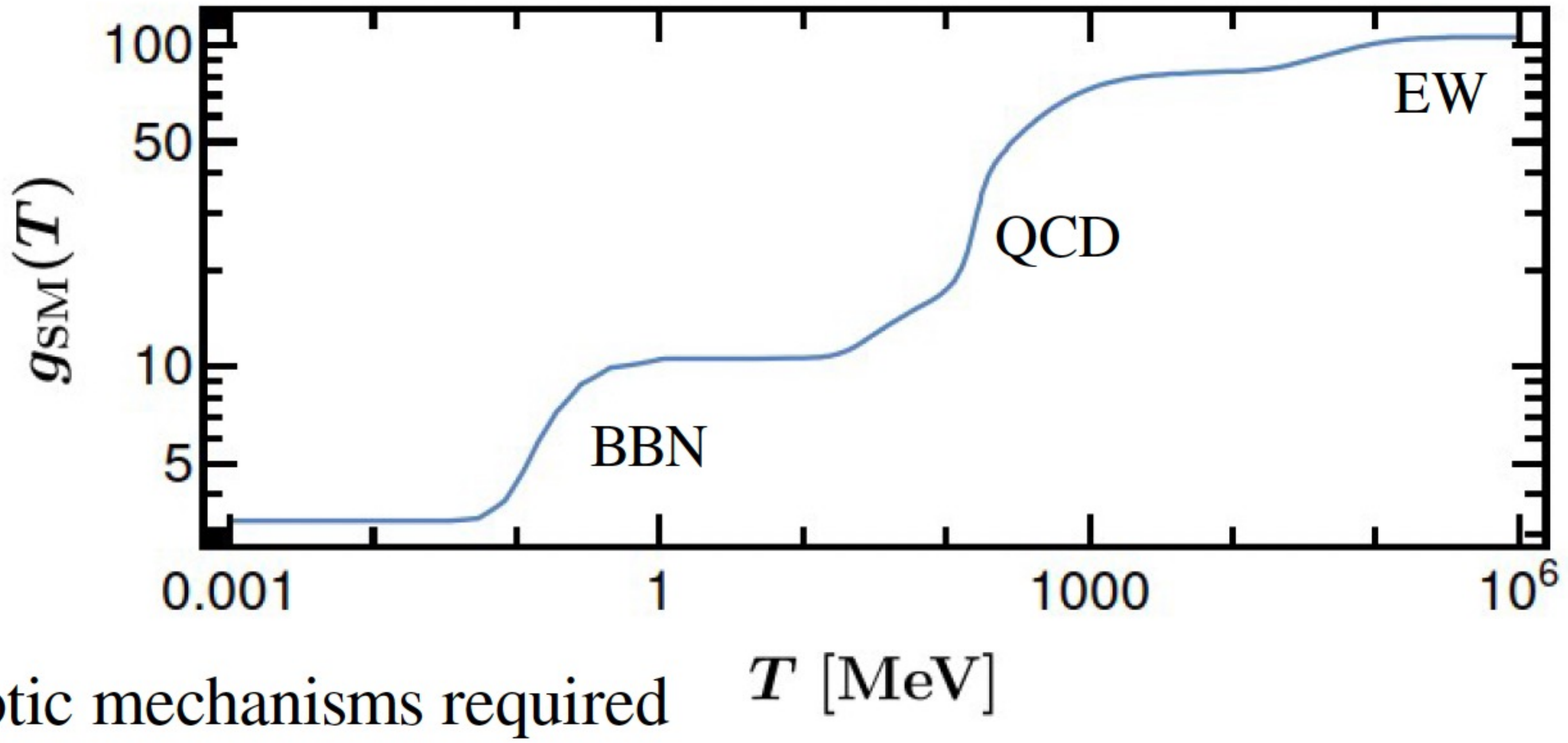
entropy conserves separately

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

Symmetric reheating (minimal)

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

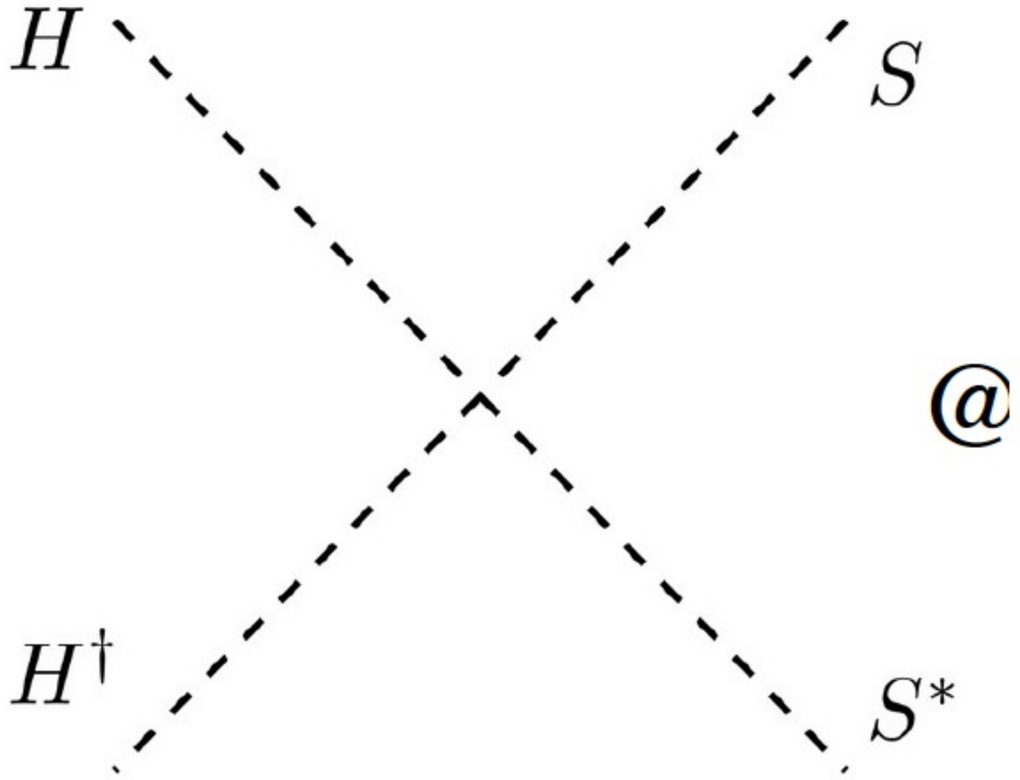
Colder dark plasma @ MeV FOPT



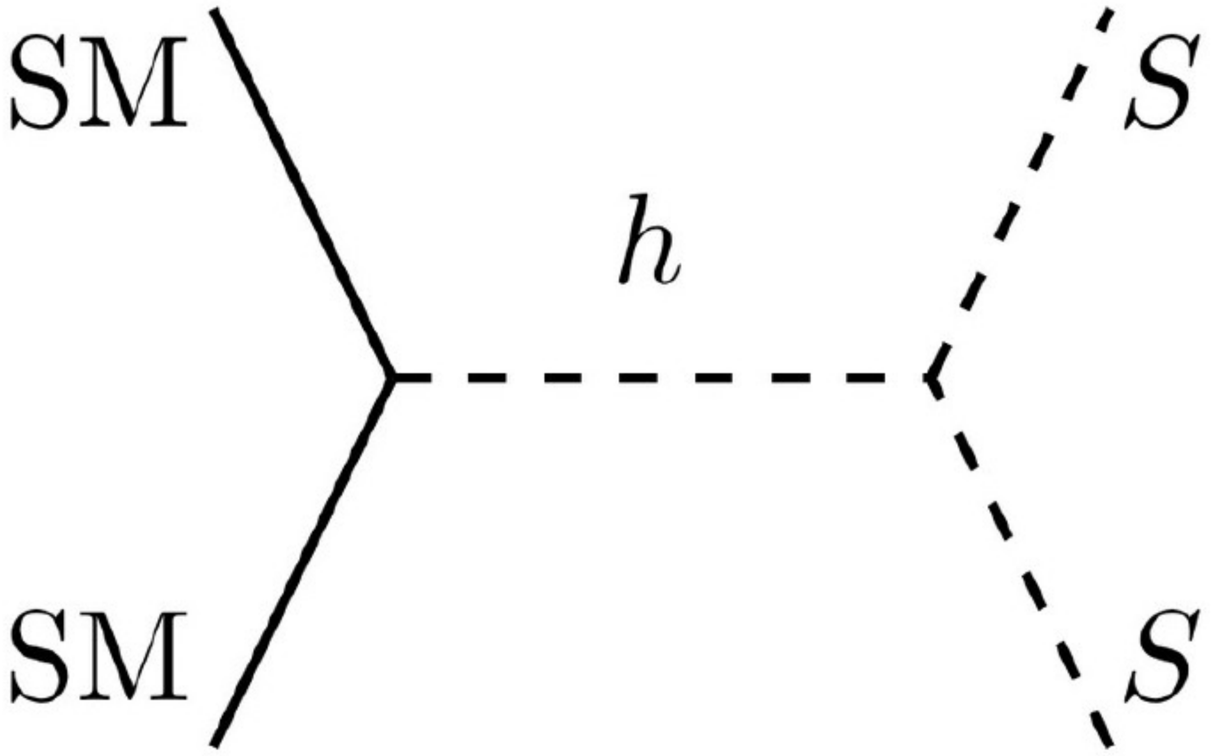
Asymmetric reheating $T_{\mathrm{D,i}} \lessgtr T_{\mathrm{SM,i}}$ Exotic mechanisms required

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

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

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

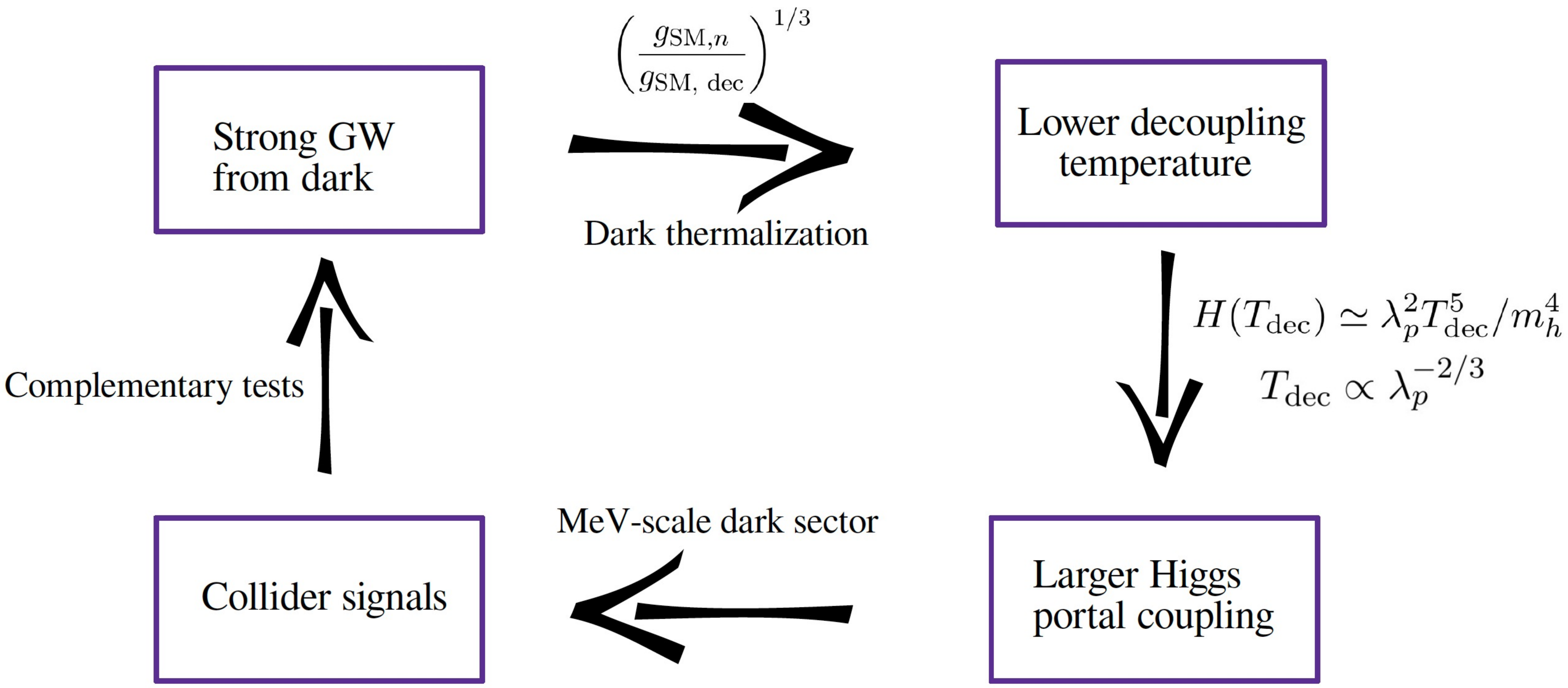
$$\alpha \lesssim 1 \approx \frac{\Delta V_{\rm eff}}{\rho_R} \propto \left(\frac{T_{\rm D,n}}{T_{\rm SM,n}}\right)^4 = \left(\frac{g_{\rm SM,n}}{g_{\rm SM,dec}}\right)^{4/3}$$

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?

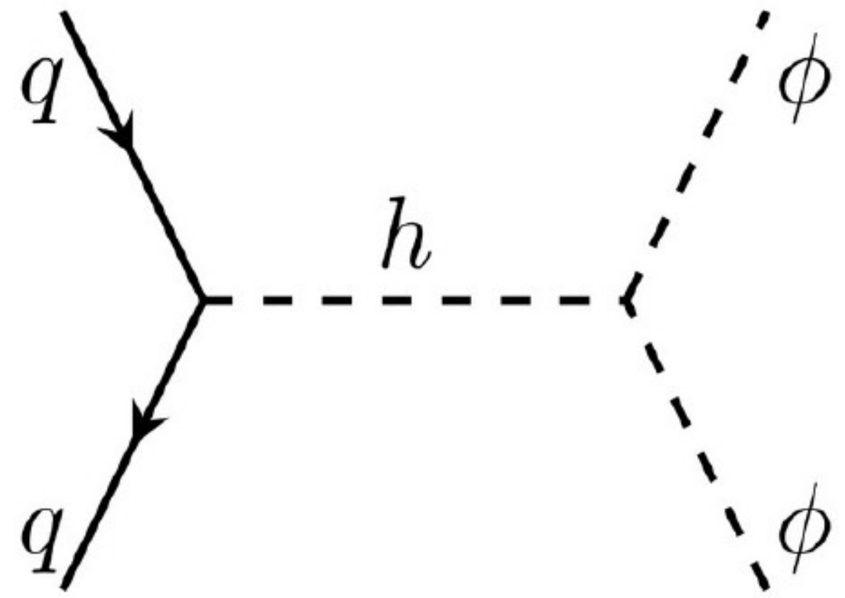


Sensitive collider searches

Direct—Higgs invisible decay

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

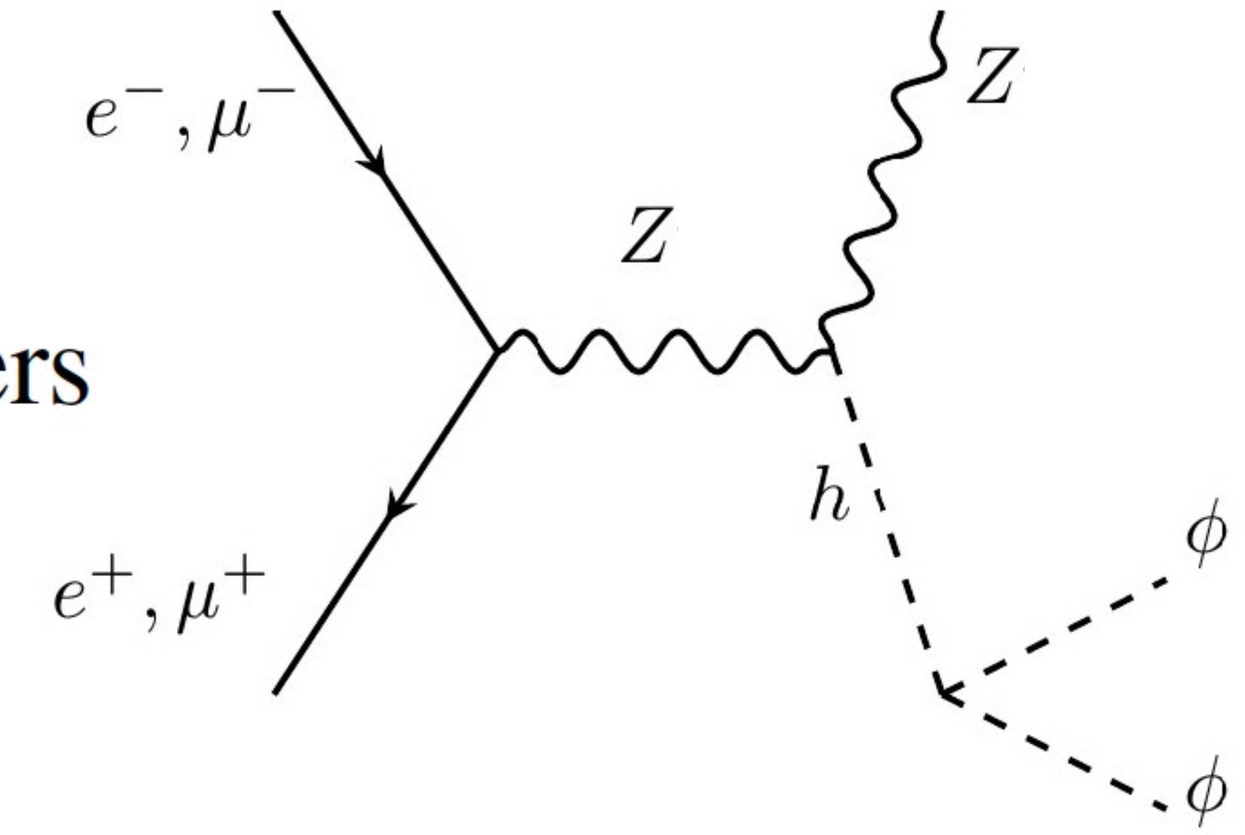
(HL) LHC



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)

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

Insensitive 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)

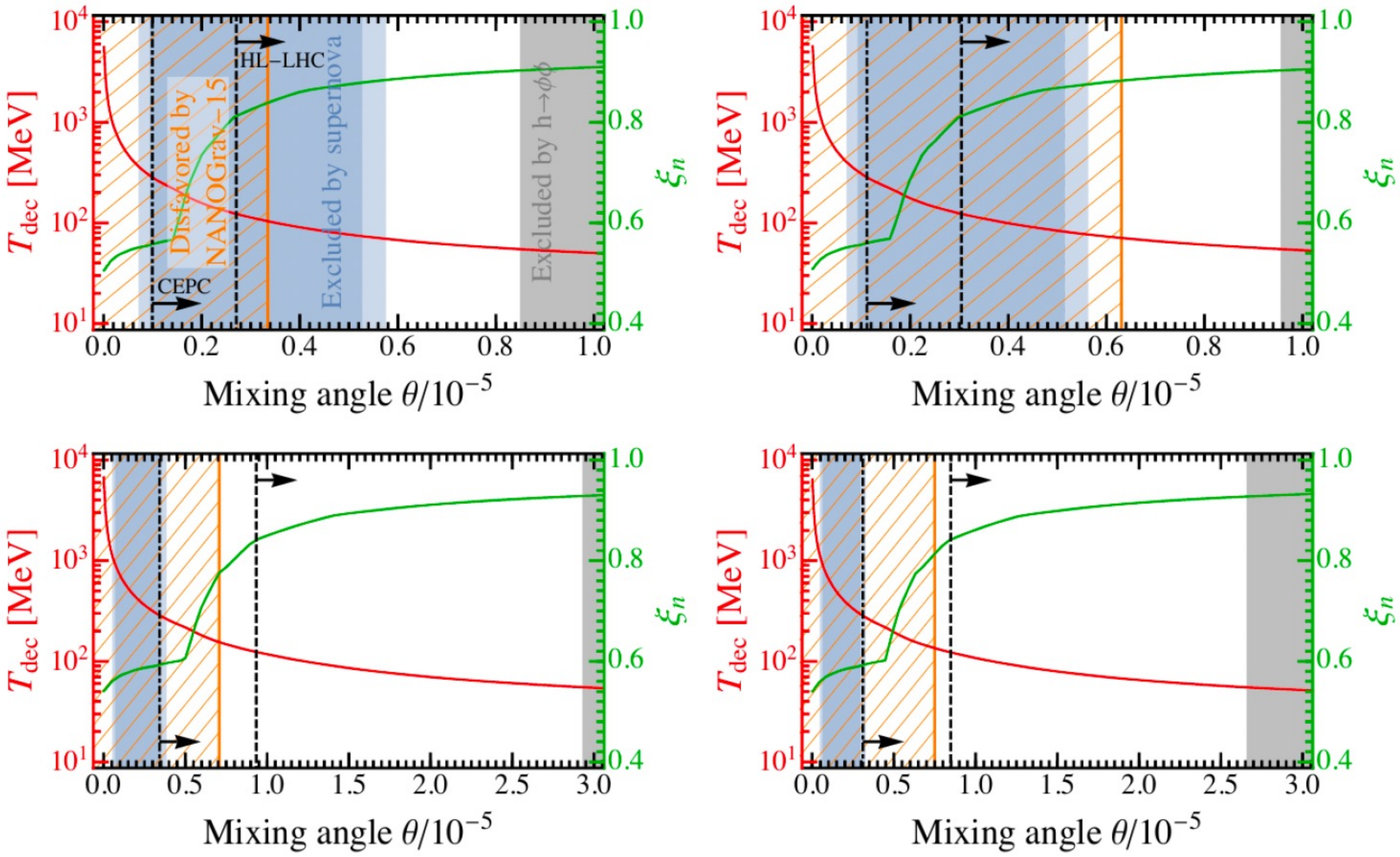
Direct probe via Higgs invisible decay will be the most sensitive channel

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

λ_p → Direct Higgs-scalar coupling

θ → Indirect SM-scalar coupling

Collider tests of nanohertz GW



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)

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

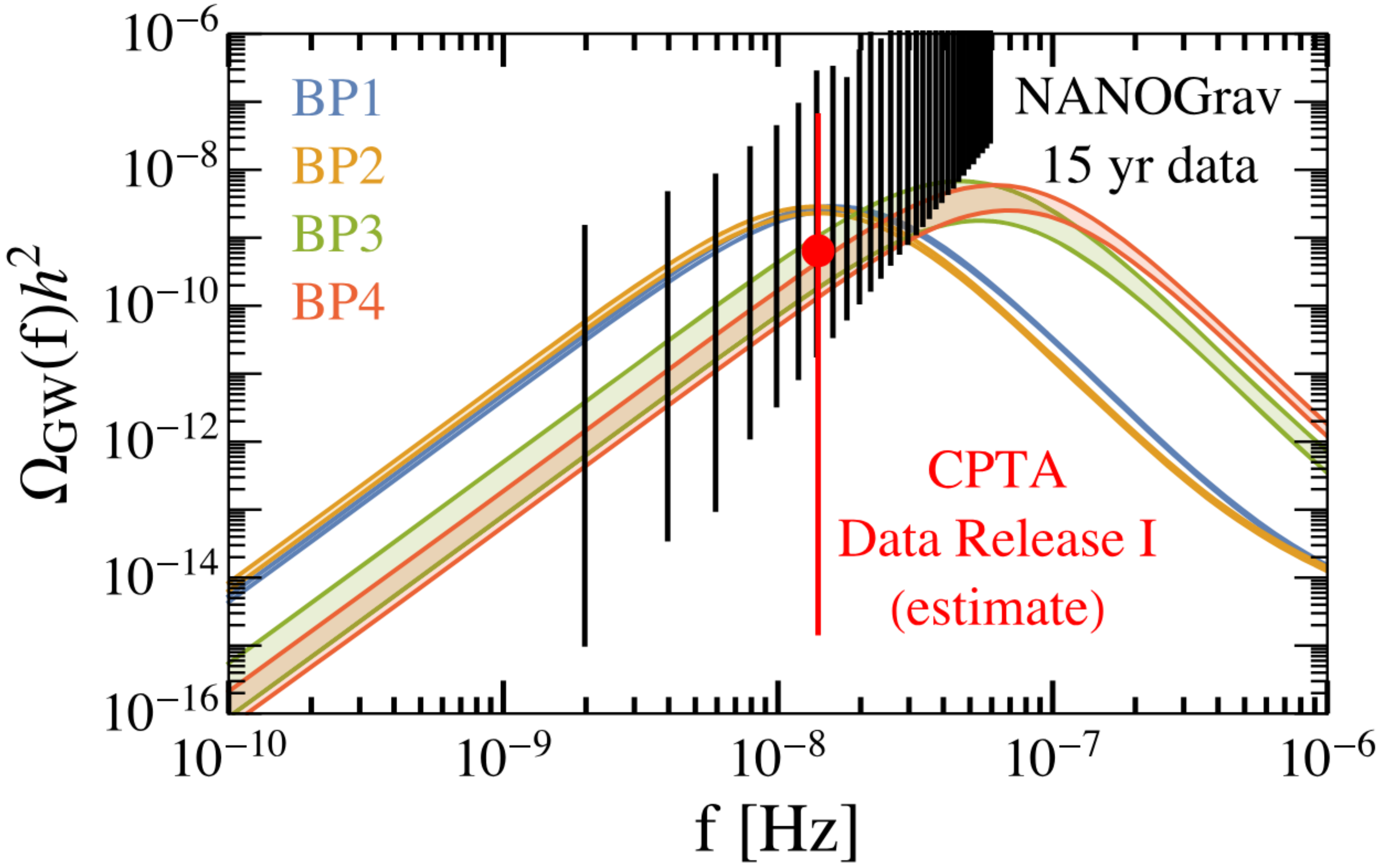
- Relic dark gauge boson dark matter (S. Kanemura & LiSP, 2308.16390)

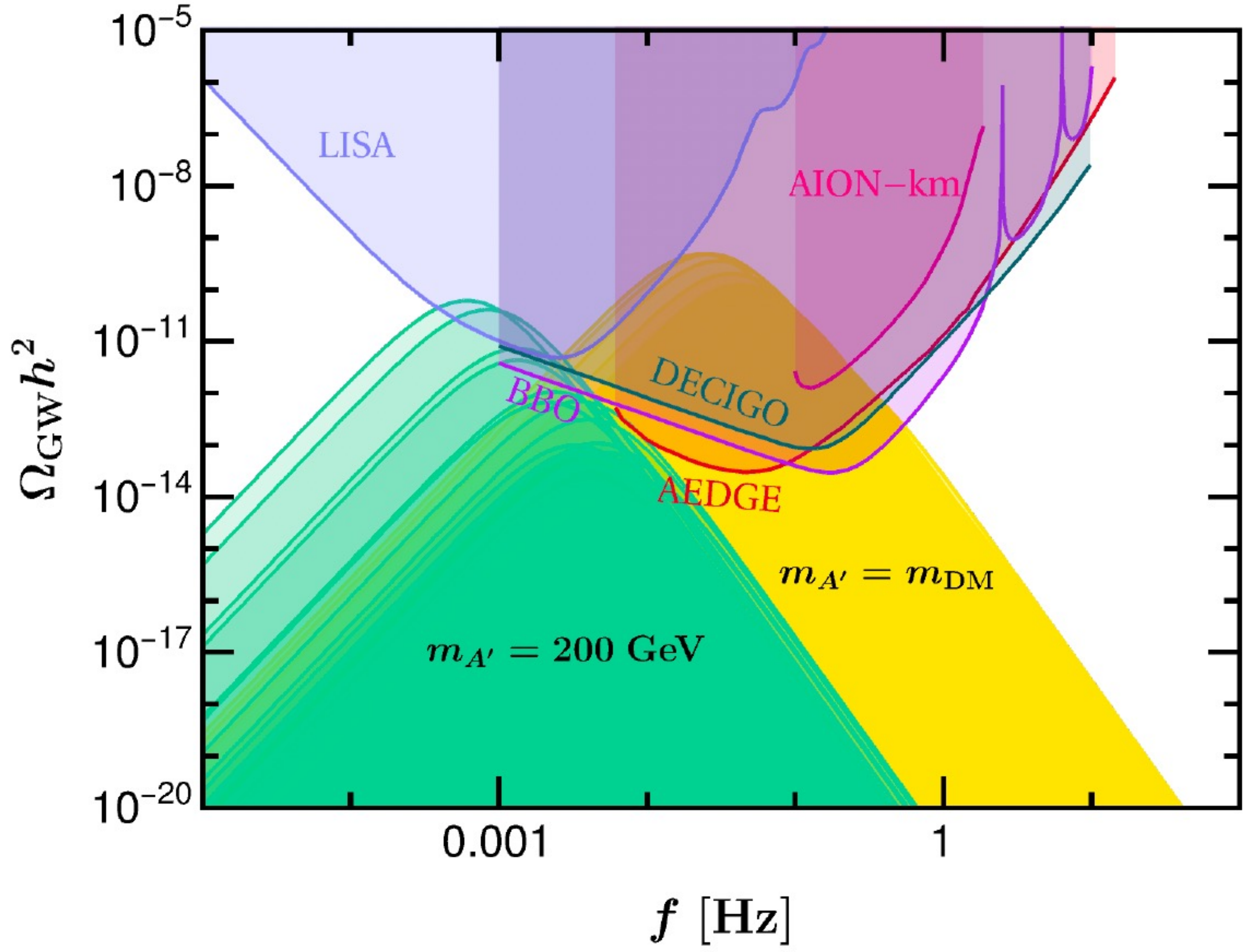
$$\left(\frac{\Omega_{\rm DM}h^2}{0.12}\right) \approx 0.33 \left(\frac{0.1}{g_X}\right)^4 \left(\frac{m_{A'}}{100\ \mathrm{GeV}}\right)^2$$

Summary

- An MeV-scale dark FOPT can generate observable nHz GW already within a minimal setup
- Higgs portal not only enhances the GW signals, but brings connections to collider tests—The key coupling connecting colliders and cosmology
- It is exciting to see the minimal dark via collider searches (Higgs invisible decay), hear the minimal dark (GW), and constrain the minimal dark via interdisciplinary considerations (BBN, CMB, colliders, astrophysics)

Nanohertz vs millihertz





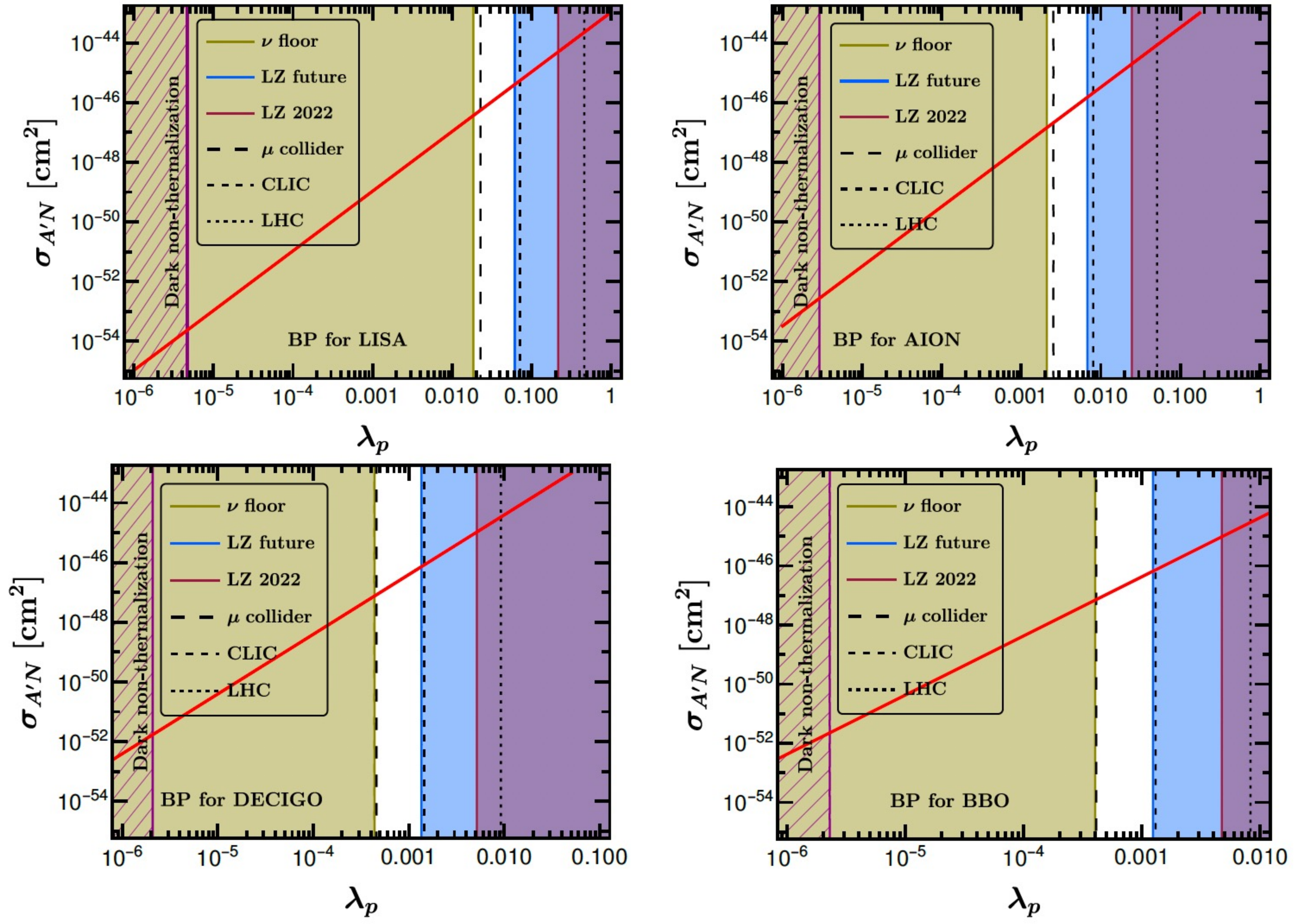
MeV-scale dark FOPT

	m_ϕ [MeV]	v_s [MeV]	g_X	$\theta_{\rm max}/10^{-5}$	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

Electroweak-scale dark FOPT

BP	λ	g_X	T_n	α	$\beta/\mathcal{H}$
LISA	1.7×10^{-2}	0.97	2.4 TeV	0.74	45
AION	3.0×10^{-3}	0.61	0.93 TeV	0.80	417
DECIGO	8.7×10^{-4}	0.44	0.48 TeV	0.89	1304
BBO	8.3×10^{-4}	0.43	0.58 TeV	0.30	1561

Collider tests of millihertz GW



- Vector boson can be DM for complementary millihertz GW detection
- The collider channel is instead

$$\mathrm{SM} \to \phi \to \mathrm{SM}$$

- DM indirect detection as the dominant complementary test to colliders and GW