Supercooled Dark Scalar Phase Transitions explanation of NANOGrav data

Jaime Hoefken Zink (NCBJ)
25/06/2025
[Phys. Lett. B 868 (2025) 139634]

Gravitational Wave Probes of Physics BSM

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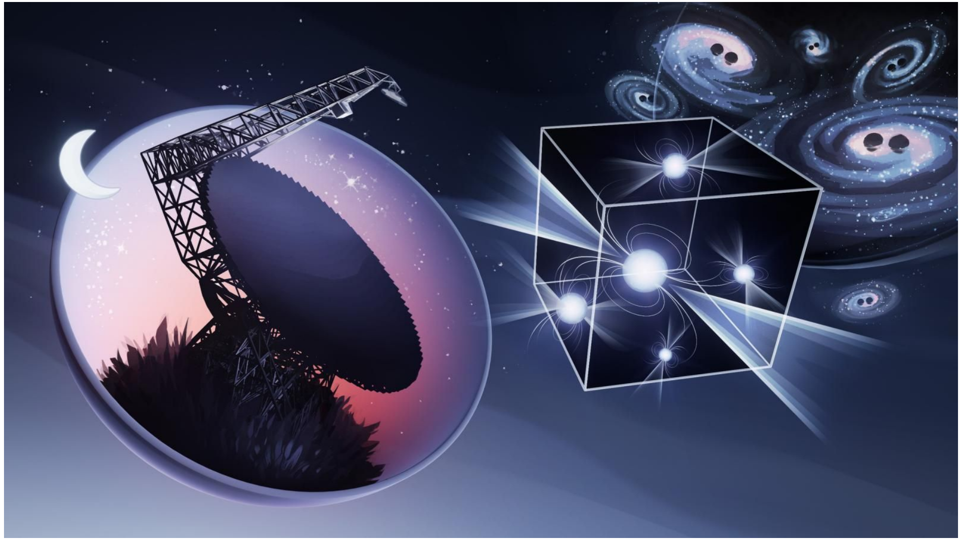
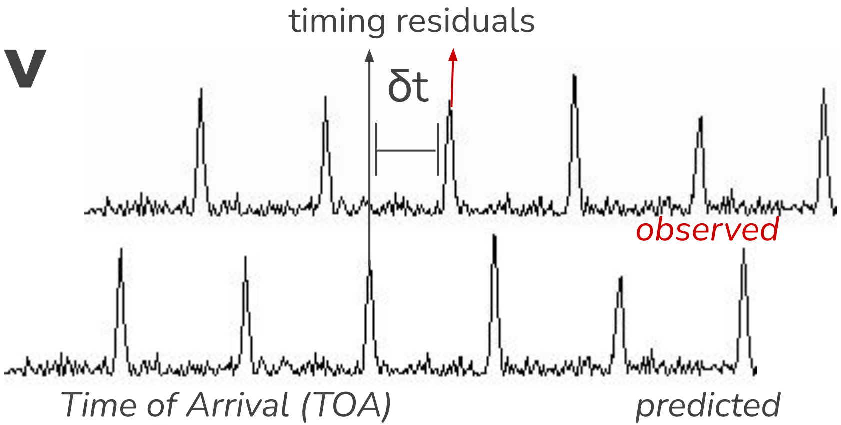
I. MOTIVATION

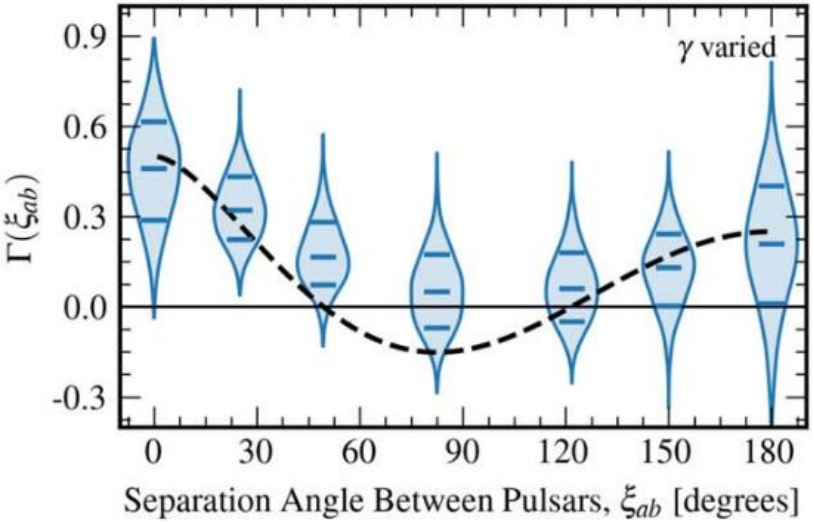
I. Motivation: NANOGrav



Credits: NANOGrav

$$\Phi_{\mathrm{HD},i} = \frac{A_{\mathrm{HD}}^2}{12\pi^2}\frac{1}{T}\left(\frac{f_i}{f_{\mathrm{ref}}}\right)^{-\gamma_{\mathrm{HD}}} f_{\mathrm{ref}}^{-3}$$

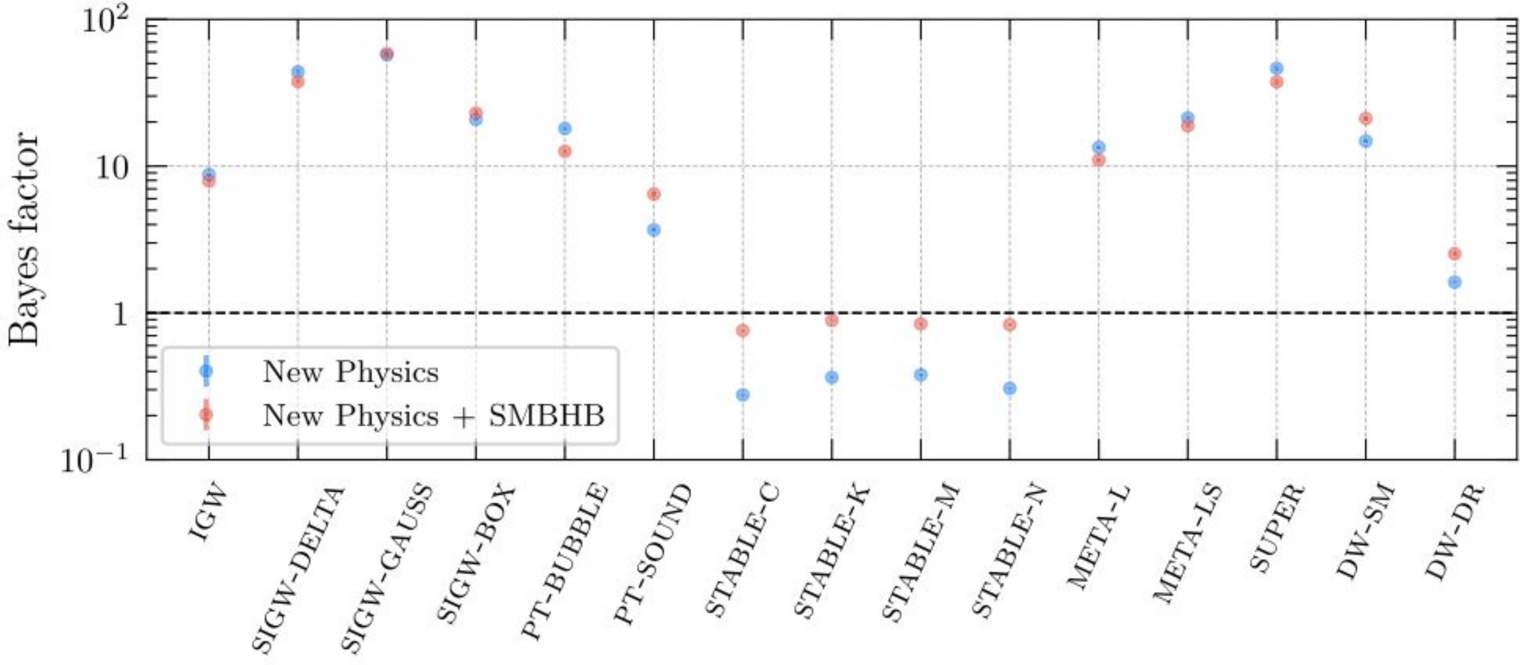




https://doi.org/10.3847/2041-8213/acdac6

I. Motivation: NANOGrav

One possible solution: Supercooled PT



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I. Motivation: Rich Dark Sectors

PHYSICAL REVIEW D **108,** 043014 (2023)

Exploring the dark sectors via the cooling of white dwarfs

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PHYSICAL REVIEW D **111,** 035028 (2025)

Panorama of new-physics explanations to the MiniBooNE excess

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Dark matter interactions in white dwarfs: A multi-energy approach to capture mechanisms

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PHYSICAL REVIEW D **111,** 115013 (2025)

Single pion resonant production in BSM scenarios: Cross sections and amplitudes

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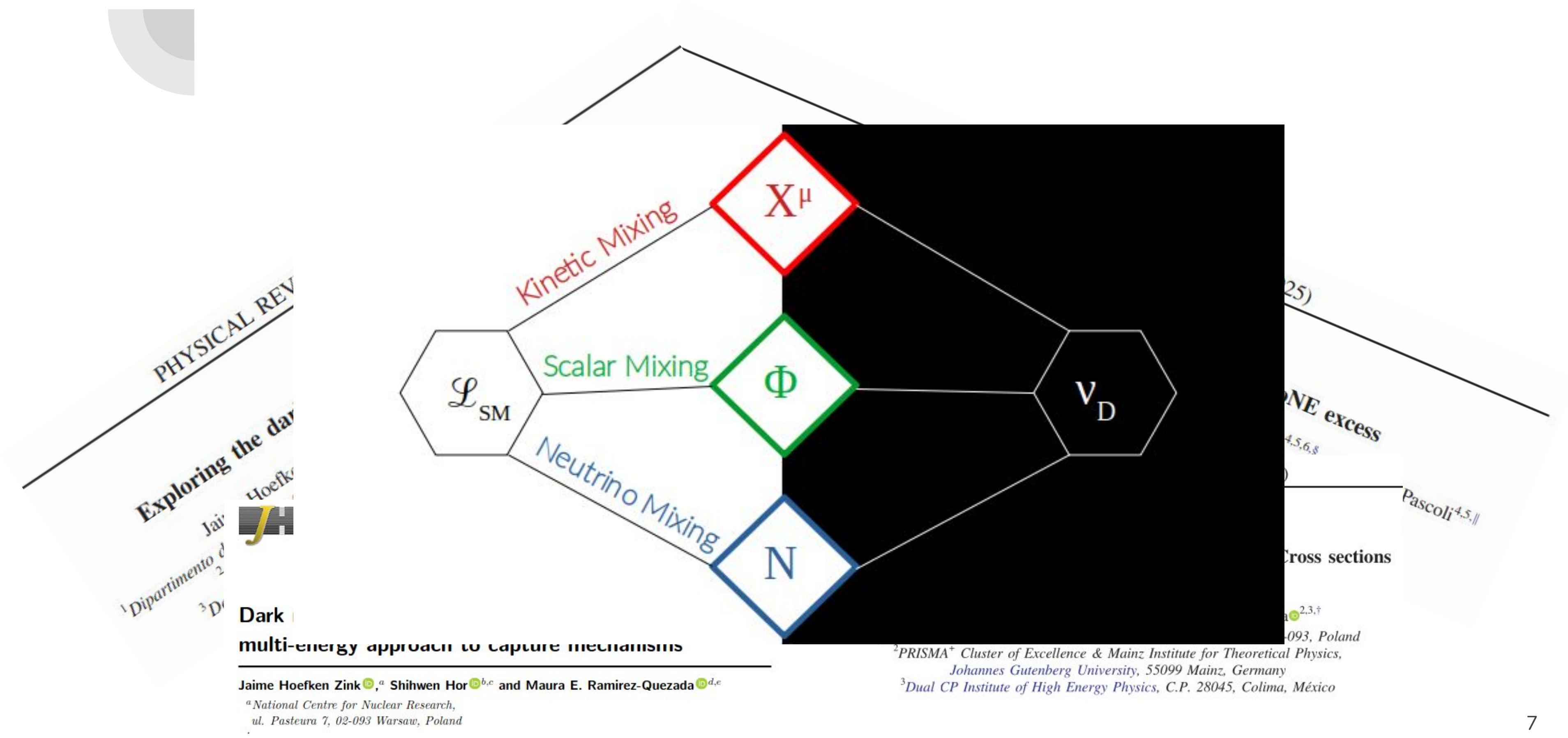
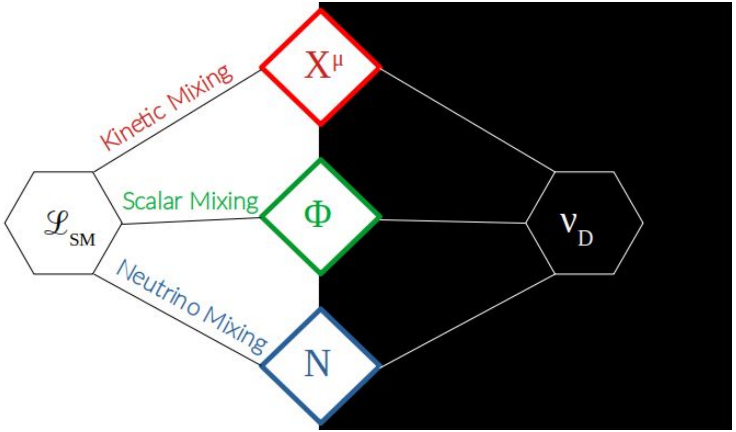
I. Motivation: Rich Dark Sectors



I. Motivation: Rich Dark Sectors



$$D_\mu \equiv \partial_\mu - i\sqrt{2} g_D Z'_\mu$$

$$V = -\mu_\phi^2 \phi^* \phi + \lambda_\phi \left(\phi^* \phi\right)^2$$

effectively

$$\lambda_{H\Phi}|H|^2|\Phi|^2$$

$$\begin{aligned}\mathscr{L} =& \mathscr{L}_{\mathrm{SM}} + \overline{\nu}_D i \not{D}^x \nu_D \\ & + (D_\mu^x \Phi)^\dagger (D^{x\mu} \Phi) - V(\Phi, H) \\ & - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin\chi}{2} B_{\mu\nu} X^{\mu\nu} \\ & + \overline{N} i \not{\partial} N - [y_\nu^\alpha (\overline{L}_\alpha \cdot \widetilde{H}) N^C + \frac{\mu'}{2} \overline{N} N^C + y_N \overline{N} \nu_D^C \Phi + \mathrm{h.c.}]\end{aligned}$$

ε

GOAL

BSM ingredients:
Φ (φ and χ)
Z'

Thermalization with SM:
$\lambda_{H\Phi} > 10^{-7}$
$\varepsilon > 10^{-9}$
[2104.03342, 0811.0326]

Explain NANOGrav data with the help of a minimal realization of the Dark Sector model.

Consider supercooled PTs subtleties

BSM - independence:
small $\lambda_{H\Phi}$, ε
$(\lambda_{H\Phi}\, v_\Phi / v_H)^2$ small

II. POTENTIAL

II. Potential

$$V_0 = -\frac{1}{2}\mu_\phi^2\phi^2 + \frac{\lambda_\phi}{4}\phi^4$$ → **Tree level**

$$V_{\rm CW} = \sum_i \frac{n_i}{64\pi^2}\left[m_i^4(\varphi)\left(\log\frac{m_i^2(\varphi)}{m_i^2(v_\phi)} - \frac{3}{2}\right) + 2m_i^2(\varphi)\, m_i^2(v_\phi)\right]$$ → **Coleman - Weinberg**

$$V_T = \sum_{i=\text{bosons}} \frac{n_i T^4}{2\pi^2} J_B\left(\frac{m_i^2(\varphi)}{T^2}\right) + \sum_{i=\text{fermions}} \frac{n_i T^4}{2\pi^2} J_F\left(\frac{m_i^2(\varphi)}{T^2}\right)$$ → **1-loop T - dependent**

$$V_{\rm daisy}(\varphi, T) = \sum_{i=\text{bosons}} \frac{T\tilde{n}_i}{12\pi}\left[m_i^3(\varphi) - \left(m_i^2(\varphi) + \Pi_i(T)\right)^{3/2}\right]$$ → **Daisy resummation**

II. Potential: On-shell renormalization scheme

$$V_{\rm CW} = \sum_i \frac{n_i}{64\pi^2}\left[m_i^4(\varphi)\left(\log\frac{m_i^2(\varphi)}{m_i^2(v_\phi)} - \frac{3}{2}\right) + 2m_i^2(\varphi)\,m_i^2(v_\phi)\right]$$

ON-SHELL

$$\left.\frac{d\left(V_1^{(0)} + V_{\rm ct}\right)}{d\varphi}\right|_{\varphi=v_\phi} = 0$$

$$\left.\frac{d^2\left(V_1^{(0)} + V_{\rm ct}\right)}{d\varphi^2}\right|_{\varphi=v_\phi} = m_\phi^2$$

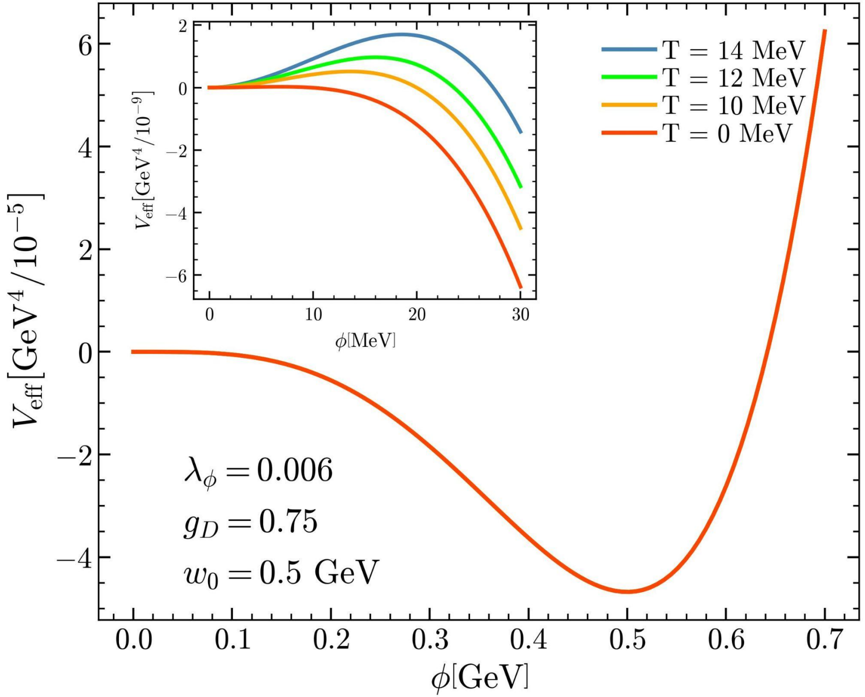
$$\left.\frac{d^2\left(V_1^{(0)} + V_{\rm ct}\right)}{d\varphi^2}\right|_{\varphi=v_\phi} = m_\phi^2 - \Sigma(p^2 = m_\phi^2) + \Sigma(0)$$

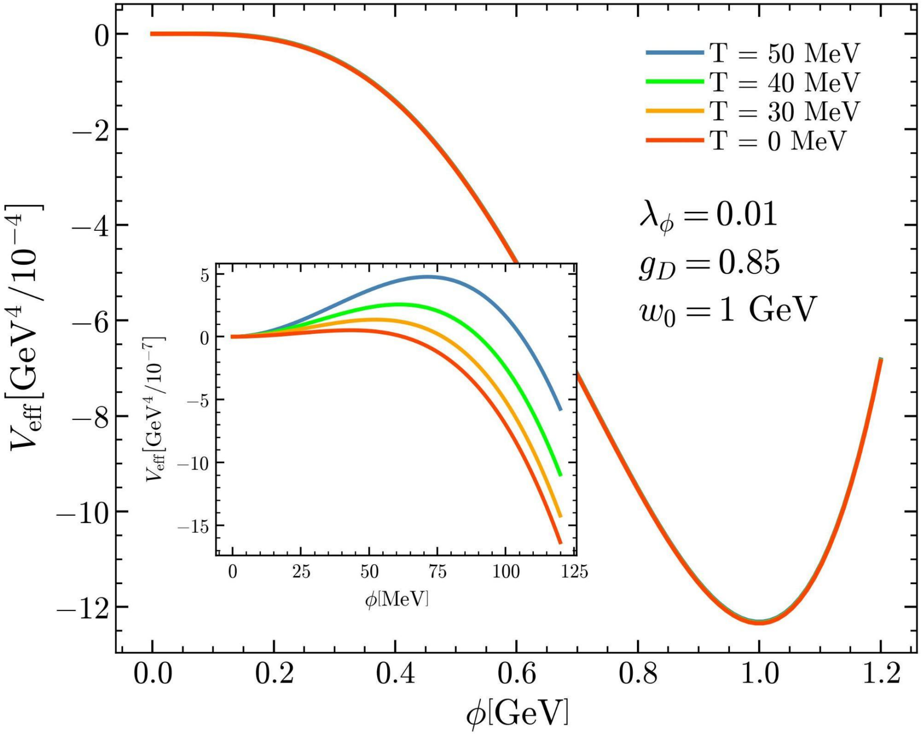
[JHEP 04 (2008), p. 029]

$$V_{\rm CW}^\chi = \frac{n_\chi m_\chi^4}{64\pi^2}(\varphi)\left(\log\frac{m_\chi^2(\varphi)}{m_\phi^2} - \frac{3}{2}\right)$$

Contribution of the Goldstone, χ

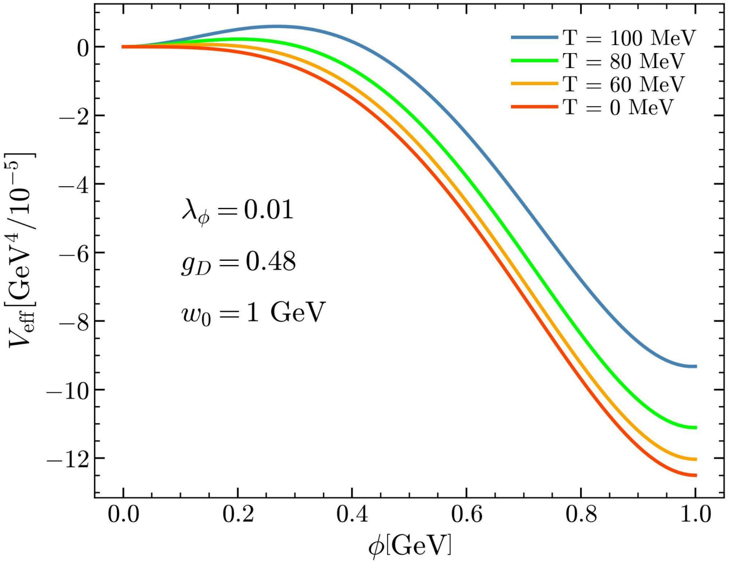
II. Potential (BP1 and BP4)





II. Potential: flat V(T=0)

$$g_D^{\rm roll} \to \frac{d^2 V_{\rm eff}(\varphi, T=0)}{d\varphi^2} = 0$$



$$g_D^{\rm roll} = \left\{ \frac{16\pi^2\lambda_\phi}{3} \left[1 - \frac{\lambda_\phi}{8\pi^2} (5 + 2\log 2) \right] \right\}^{1/4}$$

III. GW parameters: Supercooled PTs subtleties

III. GW parameters: Reference temperature, T_*

$$\int_{T_p}^{T_\mathrm{crit}} dT' \frac{\Gamma(T')\mathcal{V}(T_p, T')}{\mathcal{J}(T')H(T')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \simeq -\ln 0.71$$

When there is supercooling, the computation of the nucleation temperature is not enough:

$T_N \neq T_p$

III. GW parameters: Reference temperature, T_*

$$\int_{T_p}^{T_\text{crit}} dT' \frac{\Gamma(T')\mathcal{V}(T_p,T')}{\mathcal{J}(T')H(T')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \simeq -\ln 0.71$$

Volume at T_p of a bubble nucleated at T

$$\mathcal{V}(T_p,T) \equiv \frac{4\pi v_w^3}{3}\left(\int_{T_p}^{T} dT' \frac{e^{\int_{T_p}^{T'} dT''/\mathcal{J}(T'')}}{\mathcal{J}(T')H(T')}\right)^3$$

III. GW parameters: Reference temperature, T_*

$$\int_{T_p}^{T_{\rm crit}} dT' \frac{\Gamma(T')\mathcal{V}(T_p, T')}{\mathcal{J}(T')H(T')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \simeq -\ln 0.71$$

Full general **relation between t and T**: J(T) ≠ T

$$\frac{dT}{dt} = -H(T)\mathcal{J}(T) \equiv -3H \frac{\partial V_{\rm eff}/\partial T}{\partial^2 V_{\rm eff}/\partial T^2}\bigg|_{\varphi=0}$$

III. GW parameters: Reference temperature, T_*

$$\int_{T_p}^{T_{\rm crit}} dT' \frac{\Gamma(T')\mathcal{V}(T_p, T')}{\mathcal{J}(T')H(T')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \simeq -\ln 0.71$$

We include the **vacuum energy** released in the transition and (SM + BSM) dof

$$H(T) = \left[\frac{g_*(T)T^4}{90\pi^2 M_{\rm Pl}^2} + \frac{\Delta V_{\rm eff}(T)}{3M_{\rm Pl}^2}\right]^{1/2}$$

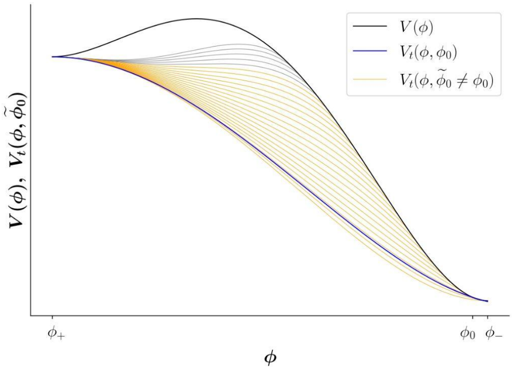
III. GW parameters: Reference temperature, T_*

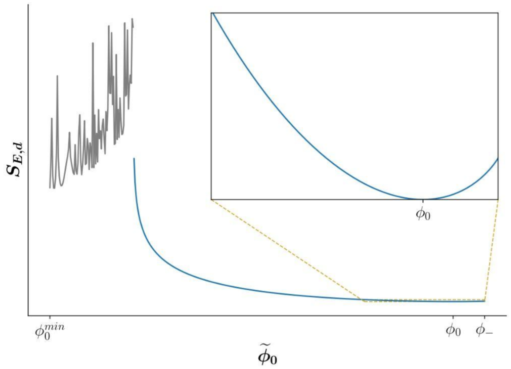
$$\int_{T_p}^{T_{\rm crit}} dT' \frac{\Gamma(T')\mathcal{V}(T_p, T')}{\mathcal{J}(T')H(T')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \simeq -\ln 0.71$$

$$\Gamma(T) \simeq T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}$$

The **decay rate** is computed from the Euclidean action, S_3, of the O(3)-symmetric tunneling solutions

We compute using the tunneling potential method (1805.03680, 1811.09185): much faster than the bounce action method





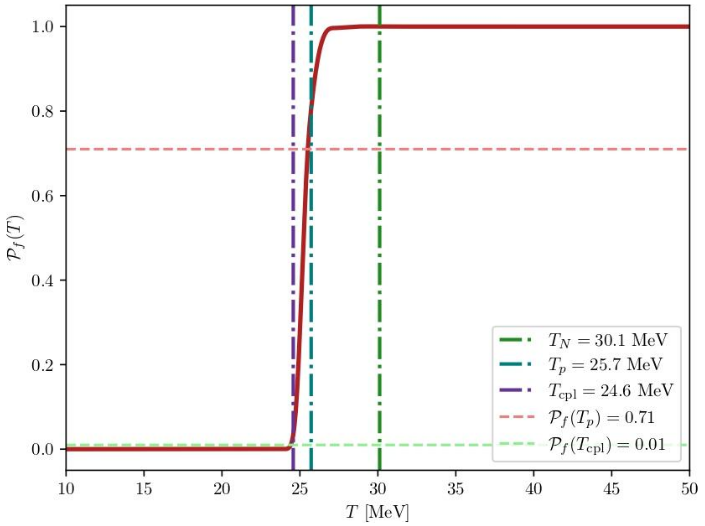
III. GW parameters: other conditions for PT

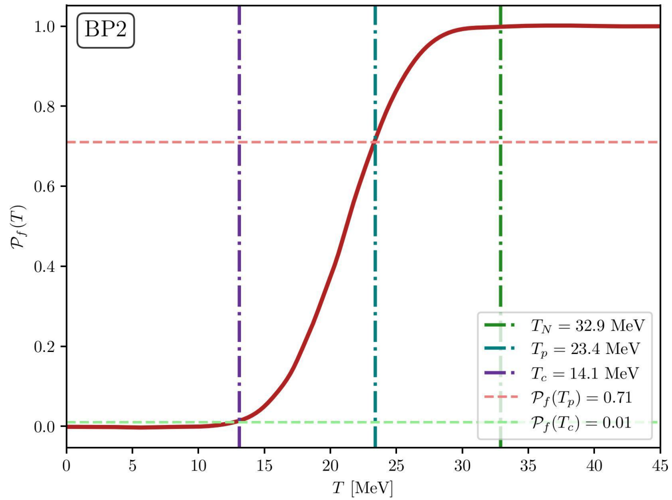
1. False vacuum volume must decrease [2212.07559]

$$\frac{d\mathcal{V}_f}{dt} < 0 \to 3 + T\frac{d\mathcal{V}_t^{\text{ext}}}{dT}$$

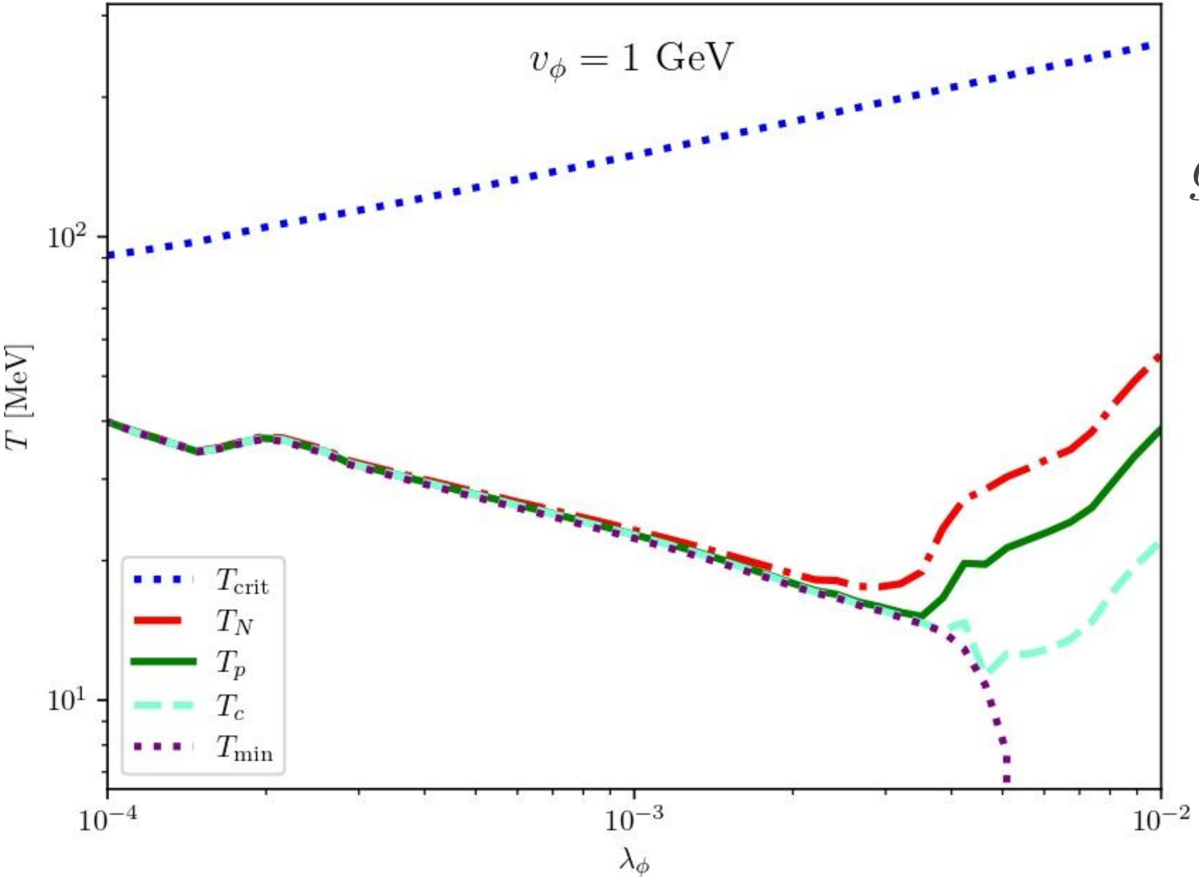
2. Transition must complete

$$\mathcal{P}_f(T_c) = 0.01$$





III. GW parameters: temperatures



$$g_D \simeq g_{\rm roll}$$

III. GW parameters: relevant quantities

1. Mean bubble separation

$$R_* = [n_B(T_p)]^{-1/3} = \left(\int_{T_p}^{T_{\rm crit}} dT' \frac{\Gamma(T')\mathcal{P}_f(T')}{H(T')\mathcal{J}(\mathcal{T}')} e^{-3\int_{T_p}^{T'} dT''/\mathcal{J}(T'')} \right)^{-1/3}$$

2. Strength of transition [2305.02357, 2004.06995]

$$\alpha = \frac{4}{3} \frac{\bar{\theta}_f(T_p) - \bar{\theta}_t(T_p)}{w_f(T_p)}$$

$$\bar{\theta} = (\rho - 3p/c^2_{s,t})/4$$ (pseudotrace)

$$w = -T(\partial V/\partial T)$$

$$c^2_s(T) = \partial_T V / \left(T\partial^2_T V\right)$$ (speed of sound)

3. Bubble wall velocity: relativistic [2112.07686]:

$\alpha > \alpha_\infty$ $\qquad v_w \to 1$

4. Reheating T (fast decay of φ) [1809.08242]

$$T_{\rm RH} \simeq T_p\,(1+\alpha)^{1/4}$$

IV. MODELING THE SPECTRUM

IV. Modeling the spectrum: SW

$$\Omega_{\mathrm{sw},*} = 0.38(H_* R_*)(H_* \tau_{\mathrm{sw}}) \left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^2 \left(\frac{f}{f_{\mathrm{sw}}}\right)^3 \times \left[1 + \frac{3}{4}\left(\frac{f}{f_{\mathrm{sw}}}\right)^2\right]^{-7/2}$$

$$p = \Delta V - \Delta P_{\mathrm{LO}} - \gamma \Delta P_{\mathrm{NLO}}$$

γ_{eq}: terminal Lorentz factor of wall
γ_*: Lorentz factor of wall without NLO pressure term

$\gamma_* > \gamma_{eq}$: leftover energy goes to plasma

IV. Modeling the spectrum: SW

$$\Omega_{\mathrm{sw},*} = 0.38(H_* R_*)(H_* \tau_{\mathrm{sw}}) \left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^2 \left(\frac{f}{f_{\mathrm{sw}}}\right)^3 \times \left[1 + \frac{3}{4}\left(\frac{f}{f_{\mathrm{sw}}}\right)^2\right]^{-7/2}$$

$$\tau_{\mathrm{sw}} \equiv \min\left[\frac{1}{H_*}, \frac{R_*}{U_f}\right]$$

length of the sound wave period

U_f : root - mean - square fluid velocity [1809.08242]

IV. Modeling the spectrum: SW

$$\Omega_{\rm sw,*} = 0.38(H_* R_*)(H_* \tau_{\rm sw}) \left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2 \left(\frac{f}{f_{\rm sw}}\right)^3 \times \left[1 + \frac{3}{4}\left(\frac{f}{f_{\rm sw}}\right)^2\right]^{-7/2}$$

$$\kappa_{\rm sw} = \frac{\alpha_{\rm eff}}{\alpha}\,\frac{\alpha_{\rm eff}}{0.73 + 0.083\sqrt{\alpha_{\rm eff}} + \alpha_{\rm eff}}$$

efficiency coefficient for sound waves

[1512.06239, 1004.4187], where:

$\alpha_{eff} \equiv \alpha(1 - \kappa_{col})$

IV. Modeling the spectrum: SW

$$\Omega_{\mathrm{sw},*} = 0.38(H_* R_*)(H_* \tau_{\mathrm{sw}}) \left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^2 \left(\frac{f}{f_{\mathrm{sw}}}\right)^3 \times \left[1 + \frac{3}{4}\left(\frac{f}{f_{\mathrm{sw}}}\right)^2\right]^{-7/2}$$

$$f_{\mathrm{sw}} = 3.4/\left[\left(v_w - c_s\right) R_*\right]$$

peak frequency

IV. Modeling the spectrum: SW

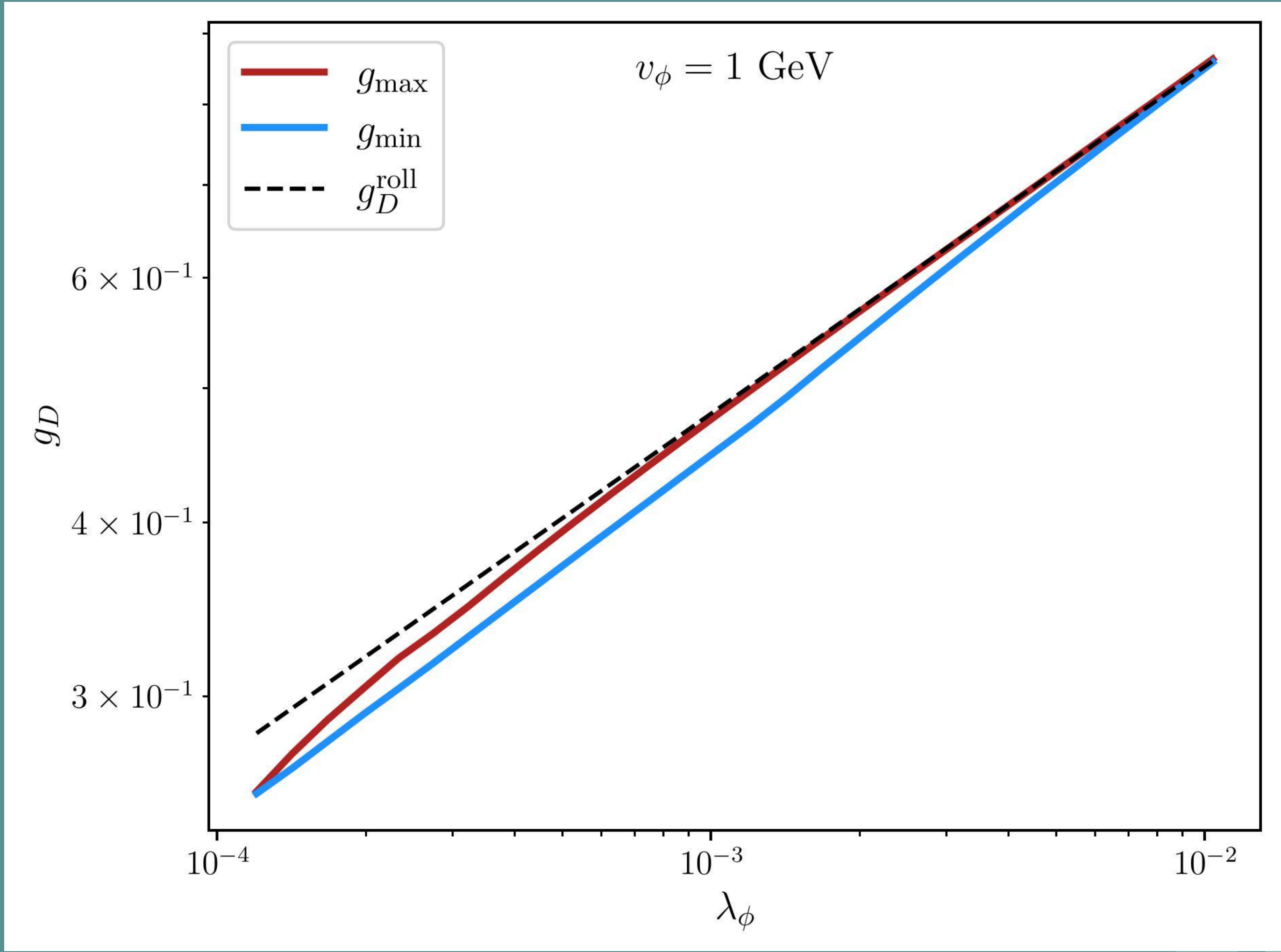
$$\Omega_{\mathrm{sw},*} = 0.38(H_*R_*)(H_*\tau_{\mathrm{sw}})\left(\frac{\kappa_{\mathrm{sw}}\alpha}{1+\alpha}\right)^2\left(\frac{f}{f_{\mathrm{sw}}}\right)^3 \times \left[1+\frac{3}{4}\left(\frac{f}{f_{\mathrm{sw}}}\right)^2\right]^{-7/2}$$

redshift: s(t) a³(t) conserved

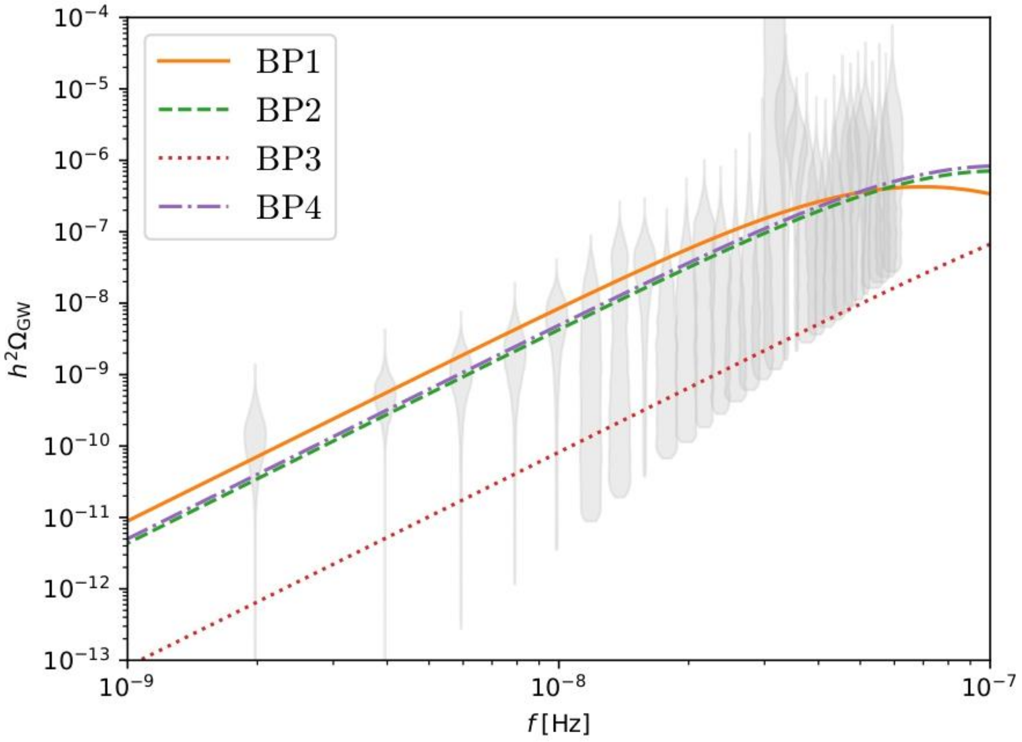
$$\Omega_0 h^2 = \mathcal{R}(T_{\mathrm{rs}}, T_0)\Omega_{\mathrm{rs}} h^2 = \frac{g_s(T_0)^{4/3}}{g_s(T_{\mathrm{rs}})^{1/3}}\frac{8\pi^3 G}{90}\frac{T_0^4}{H_0^2}\Omega_{\mathrm{rs}} h^2 = 1.67\times 10^{-5}\left(\frac{100}{g_{\mathrm{eff}}(T_{\mathrm{rs}})}\right)^{1/3}\Omega_{\mathrm{rs}}$$

$$T_{\mathrm{RH}} \simeq T_p\,(1+\alpha)^{1/4}$$

V. BENCHMARK POINTS AND RESULTS



$g_{\max}$
$g_{\min}$
g_D^{roll}
$v_\phi = 1$ GeV
6×10^{-1}
4×10^{-1}
3×10^{-1}
g_D
10^{-4}
10^{-3}
10^{-2}
λ_ϕ



hierarchy of masses

	v_ϕ [GeV]	λ_ϕ	g_D	T_p [MeV]	$H_* R_*$	α	m_φ [GeV]	$m_{Z'}$ [GeV]
BP1	0.5	0.006	0.75	12.37	0.489	361.5	0.055	0.375
BP2	1	0.006	0.75	23.37	0.651	451.8	0.110	0.750
BP3	3	0.006	0.75	70.29	0.644	367.6	0.329	2.25
BP4	1	0.010	0.85	38.39	0.723	94.92	0.141	0.854

The dark minimal model could in principle explain NANOGrav data

Summary

- NANOGrav data (NG15) points to a Gravitational Wave Background that might be explained by BSM scenarios, such as Supercooled First Order Phase Transitions of a dark scalar in the MeV - GeV energy range.
- Although fine-tuned, a minimal dark sector, consisting of a complex scalar singlet and a U(1) dark gauge may explain NG15.
- The supercooled nature of the FOPT requires a careful treatment, in order to avoid approximations that rely on assumptions that may not hold in a supercooled scenario (such a as the Bag model).
- The region that better explains NG15 data gets close to the conformal field scenario, with a hierarchy of mases: $m_{Z'} > m_{\varphi}$.
- NG15 constitutes another door opened to search for Rich Dark Sectors, that go beyond a minimal model, such as the one presented here.
- We need to move to MS-bar to explore the whole region and consider the running of the parameters of the model.

Extra slides

for questions

Where does the energy go?

$$p = \Delta V - \Delta P_{\mathrm{LO}} - \gamma \Delta P_{\mathrm{NLO}}$$

Pressure driving expansion of wall

$$\gamma_{\mathrm{eq}} \equiv \frac{\Delta V - \Delta P_{\mathrm{LO}}}{\Delta P_{\mathrm{NLO}}}$$

γ for which equilibrium is reached

$$\alpha_\infty \to \Delta V = \Delta P_{\mathrm{LO}}$$

α for which there is no pressure before γ grows

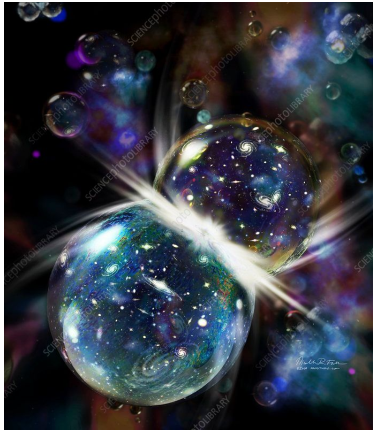
$$\gamma_*$$

γ reached by neglecting NLO

κ_{coll} energy to wall

$$\frac{E_w}{E_V} = \begin{cases} \frac{\gamma_{\mathrm{eq}}}{\gamma_*}\left[1 - \frac{\alpha_\infty}{\alpha}\left(\frac{\gamma_{\mathrm{eq}}}{\gamma_*}\right)^2\right], & \gamma_* > \gamma_{\mathrm{eq}} \\ 1 - \frac{\alpha_\infty}{\alpha}, & \gamma_* \leq \gamma_{\mathrm{eq}} \end{cases}$$

Other sources of GWs



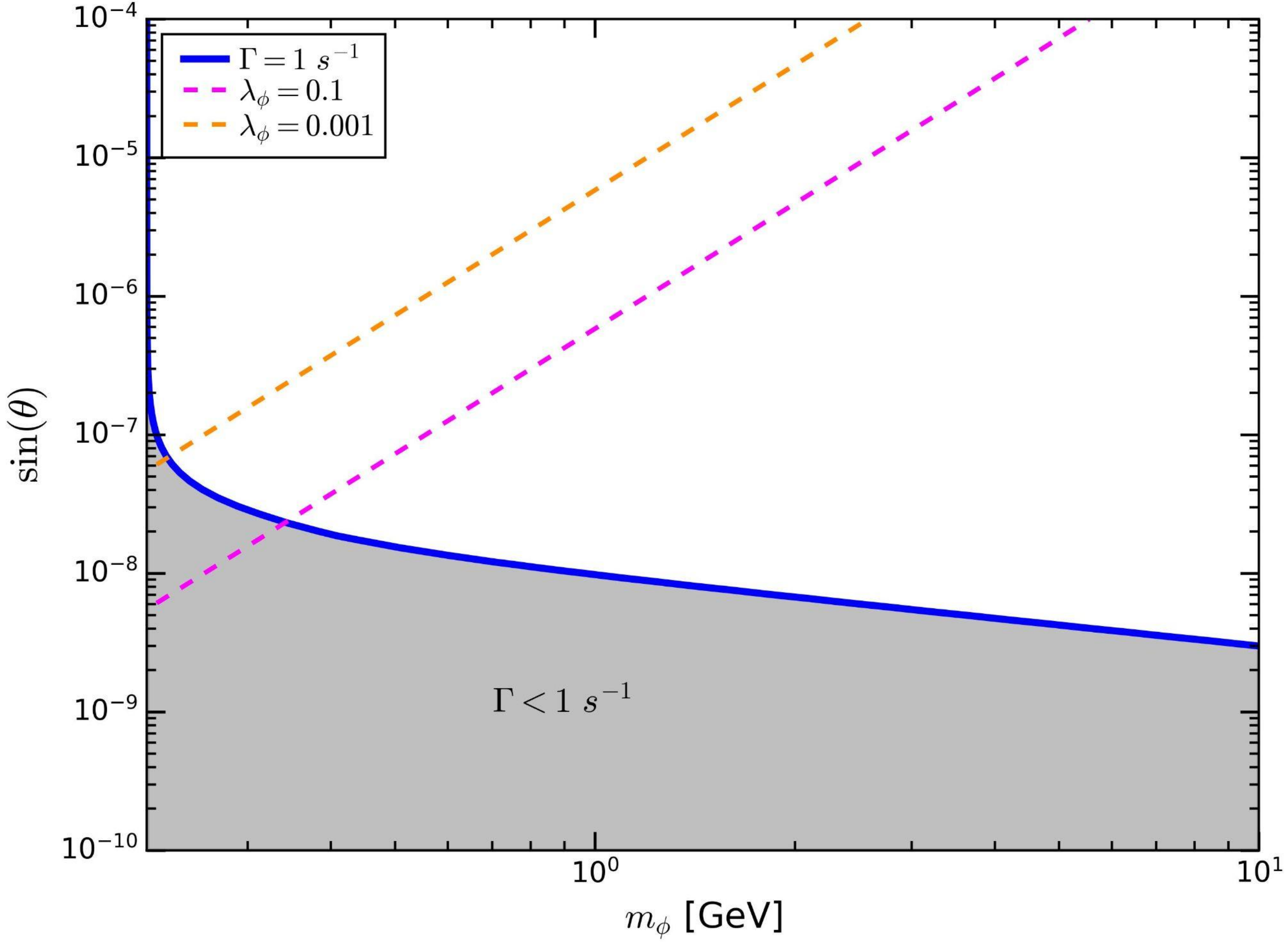
Credits: NICOLLE R. FULLER/SCIENCE PHOTO LIBRARY

$$\Omega_{\rm col,*} = 0.024(H_* R_*)^2 \left(\frac{\kappa_{\rm col}\alpha}{1+\alpha}\right)^2 \left(\frac{f}{f_{\rm col}}\right)^3 \left[1 + 2\left(\frac{f}{f_{\rm col}}\right)^{2.07}\right]^{-2.18}$$

$$f_{\rm col} = 0.51/R_*$$

$$\Omega_{\rm turb,*} = 6.8(H_* R_*)\frac{(1-H_*\tau_{\rm sw})}{1+8\pi f/H_*}\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^{3/2}\left(\frac{f}{f_{\rm turb}}\right)^3\left[1+\left(\frac{f}{f_{\rm turb}}\right)\right]^{-11/3}$$

$$f_{\rm turb} = 3.9/\left[(v_w - c_s)\,R_*\right]$$



Decay of φ to $\mu^+\mu^-$ ($m_\varphi > 2m_\mu$)

The decay to e^+e^- is not fast enough: we'd need dark fermions. To be discussed in the future.