Pseudo-Nambu-Goldstone Dark Matter, First-order Phase Transitions, and Gravitational Waves

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Based on Zhao Zhang, Chengfeng Cai, Xue-Min Jiang, Yi-Lei Tang, Zhao-Huan Yu, Hong-Hao Zhang, arXiv:2102.01588, JHEP

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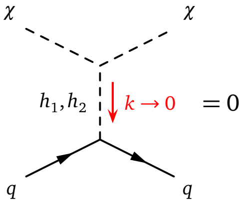
Pseudo-Nambu-Goldstone Dark Matter

- **Dark matter (DM) direct detection** has put **stringent constraints** on DM-nucleon scattering, greatly challenging the **thermal DM paradigm**
- The direct detection constraints can be circumvented if the DM particle is a **pseudo-Nambu-Goldstone boson (pNGB)** protected by an **approximate global symmetry** [Gross, Lebedev, Toma, 1708.02253, PRL]
- Introduce a complex scalar $S=(v_s+s+i\chi)/\sqrt{2}$ and a global U(1) symmetry $S\to e^{i\alpha}S$ softly broken by a quadratic potential term $-m_\chi^2(S^2+S^{\dagger 2})/4$
- After spontaneous symmetry breaking, χ becomes a **stable pNGB**, acting as a **DM candidate**
- The DM-quark scattering amplitude

$$\mathcal{M}(\chi q\to\chi q)\propto\frac{m_q s_\theta c_\theta}{v v_s}\,\frac{t(m_{h_1}^2-m_{h_2}^2)}{(t-m_{h_1}^2)(t-m_{h_2}^2)}\xrightarrow{t\to 0}0$$



- In the **zero momentum transfer limit** $t=k^2\to 0$, the DM-nucleon scattering cross section $\sigma_{\chi N}^{\mathrm{SI}}$ **vanishes** at tree level

Experimental Approaches to pNGB DM

One-loop corrections typically lead to $\sigma_{\chi N}^{\mathrm{SI}} \lesssim \mathcal{O}(10^{-50})\ \mathrm{cm}^2$

[Azevedo *et al.*, 1810.06105, JHEP; Ishiwata & Toma, 1810.08139, JHEP]

Beyond capability of current and near future direct detection experiments

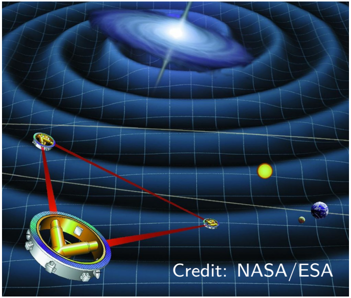
Other experimental approaches are crucial for exploring pNGB DM

The discovery of **gravitational waves (GWs)** by LIGO in 2015 opens a new window to new physics models

Introducing new scalar fields may change the **electroweak phase transition** to be a **first-order phase transition (FOPT)**

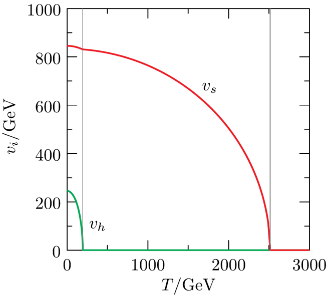
A cosmological FOPT could induce a **stochastic GW background** with $f \sim \mathrm{mHz}$

Potential signals in **future space-based GW interferometers** like **LISA**, **TianQin**, **Taiji**, **DECIGO**, and **BBO**



First-order Phase Transition from pNGB DM

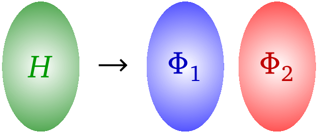
😟 However, the **original pNGB DM model** can only results in **second-order** phase transitions [Kannike & Raidal, 1901.03333, PRD] 👈



😔 Introducing more terms to break the global U(1) symmetry can result in FOPTs, **at the cost of** the vanishing DM-nucleon scattering [Kannike, Loos, Raidal, 1907.13136, PRD; Alanne *et al.*, 2008.09605, JHEP]

😊 GW signals from strong FOPTs can be achieved in the **two-Higgs-doublet models (2HDMs)** [Dorsch *et al.*, 1611.05874, JCAP; X Wang, FP Huang, XM Zhang, 1909.02978, PRD; RY Zhou & LG Bian, 2001.01237]

🤔 We may expect a similar situation in the **2HDM extension of pNGB DM** [XM Jiang, CF Cai, **ZHY**, YP Zeng, HH Zhang, 1907.09684, PRD]



2HDM extension of pNGB DM

- **Two Higgs doublets** Φ_1 and Φ_2 with $Y = 1/2$, **complex scalar singlet** S
- Scalar potential respects a softly broken global U(1) symmetry $S \to e^{i\alpha} S$
- Two **common assumptions** for 2HDMs
  - CP is conserved in the scalar sector
  - There is a Z_2 symmetry $\Phi_1 \to -\Phi_1$ or $\Phi_2 \to -\Phi_2$ forbidding quartic terms that are odd in Φ_1 or Φ_2, but it can be softly broken by quadratic terms
- Scalar potential constructed with Φ_1 and Φ_2

$$V_1 = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

- U(1) **symmetric** potential terms involving S

$$V_2 = -m_S^2|S|^2 + \frac{\lambda_S}{2}|S|^4 + \kappa_1|\Phi_1|^2|S|^2 + \kappa_2|\Phi_2|^2|S|^2$$

- Quadratic term **softly breaking** the global U(1): $V_{\text{soft}} = -\dfrac{m_S'^2}{4}S^2 + \text{H.c.}$

Scalars

- Φ_1, Φ_2, and S develop VEVs v_1, v_2 and v_s

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}, \quad S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

- χ is a **stable pNGB** with $m_\chi = m'_S$, acting as a **DM candidate**
- Mass terms for **charged scalars** and CP**-odd scalars**

$$-\mathcal{L}_{\text{mass}} \supset \left[m_{12}^2 - \frac{1}{2}(\lambda_4 + \lambda_5)v_1 v_2\right](\phi_1^-, \quad \phi_2^-)\begin{pmatrix} v_2/v_1 & -1 \\ -1 & v_1/v_2 \end{pmatrix}\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$$
$$+ \frac{1}{2}(m_{12}^2 - \lambda_5 v_1 v_2)(\eta_1, \quad \eta_2)\begin{pmatrix} v_2/v_1 & -1 \\ -1 & v_1/v_2 \end{pmatrix}\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix} = R(\beta)\begin{pmatrix} G^+ \\ H^+ \end{pmatrix}, \quad \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = R(\beta)\begin{pmatrix} G^0 \\ a \end{pmatrix}, \quad R(\beta) = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$$

- $G^\pm$ and G^0 are **massless Nambu-Goldstone bosons** eaten by $W^\pm$ and Z
- $H^\pm$ and a are **physical states**

$$m_{H^+}^2 = \frac{v_1^2 + v_2^2}{v_1 v_2}\left[m_{12}^2 - \tfrac{1}{2}(\lambda_4 + \lambda_5)v_1 v_2\right], \quad m_a^2 = \frac{v_1^2 + v_2^2}{v_1 v_2}(m_{12}^2 - \lambda_5 v_1 v_2)$$

CP-even Scalars and Weak Gauge Bosons

Mass terms for **CP-even scalars** $\quad -\mathcal{L}_{\text{mass}} \supset \frac{1}{2}(\rho_1, \quad \rho_2, \quad s)\mathcal{M}^2_{\rho s}\begin{pmatrix}\rho_1\\ \rho_2\\ s\end{pmatrix}$

$$\mathcal{M}^2_{\rho s} = \begin{pmatrix} \lambda_1 v_1^2 + m_{12}^2 \tan\beta & \lambda_{345} v_1 v_2 - m_{12}^2 & \kappa_1 v_1 v_s \\ \lambda_{345} v_1 v_2 - m_{12}^2 & \lambda_2 v_2^2 + m_{12}^2 \cot\beta & \kappa_2 v_2 v_s \\ \kappa_1 v_1 v_s & \kappa_2 v_2 v_s & \lambda_S v_s^2 \end{pmatrix}, \quad \lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

$$\begin{pmatrix}\rho_1\\ \rho_2\\ s\end{pmatrix} = O\begin{pmatrix}h_1\\ h_2\\ h_3\end{pmatrix}, \quad O^{\mathrm{T}}\mathcal{M}^2_{\rho s}O = \mathrm{diag}(m^2_{h_1}, m^2_{h_2}, m^2_{h_3}), \quad m_{h_1} \le m_{h_2} \le m_{h_3}$$

One of h_i should behave like the **125 GeV SM Higgs boson**

Mass terms for **weak gauge bosons**

$$-\mathcal{L}_{\text{mass}} \supset \frac{g^2}{4}(v_1^2 + v_2^2) W^{-,\mu} W^+_\mu + \frac{1}{2}\frac{g^2}{4c_{\mathrm{W}}^2}(v_1^2 + v_2^2) Z^\mu Z_\mu, \quad c_{\mathrm{W}} \equiv \cos\theta_{\mathrm{W}}$$

$$m_W = \frac{gv}{2}, \quad m_Z = \frac{gv}{2c_{\mathrm{W}}}, \quad v \equiv \sqrt{v_1^2 + v_2^2} = (\sqrt{2}G_{\mathrm{F}})^{-1/2} = 246.22 \text{ GeV}$$

Four Types of Yukawa Couplings

Yukawa interactions for the **mass eigenstates**

$$\mathcal{L}_{\mathrm{Y}} = \sum_{f=\ell_j,d_j,u_j} \left[-m_f \bar{f} f - \frac{m_f}{v} \left(\sum_i \xi^f_{h_i} h_i \bar{f} f + \xi^f_a a \bar{f} i\gamma_5 f \right) \right]$$

$$- \frac{\sqrt{2}}{v} [H^+ (\xi^{\ell_i}_a m_{\ell_i} \bar{\nu}_i P_{\mathrm{R}} \ell_i + \xi^{d_j}_a m_{d_j} V_{ij} \bar{u}_i P_{\mathrm{R}} d_j + \xi^{u_i}_a m_{u_i} V_{ij} \bar{u}_i P_{\mathrm{L}} d_j) + \mathrm{H.c.}]$$

	Type I	Type II	Lepton specific	Flipped
$\xi^{\ell_j}_{h_i}$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$	$O_{1i}/\cos\beta$	$O_{2i}/\sin\beta$
$\xi^{d_j}_{h_i}$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$	$O_{2i}/\sin\beta$	$O_{1i}/\cos\beta$
$\xi^{u_j}_{h_i}$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$	$O_{2i}/\sin\beta$
$\xi^{\ell_j}_a$	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
$\xi^{d_j}_a$	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
$\xi^{u_j}_a$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$

For **every type** of Yukawa couplings, we can prove that the DM-nucleon scattering amplitude at tree level **vanishes** in the zero momentum transfer limit

[XM Jiang, CF Cai, **ZHY**, YP Zeng, HH Zhang, 1907.09684, PRD]

Phenomenological Constraints

- 12 free parameters in the model

$$v_s,\ m_\chi,\ m_{12}^2,\ \tan\beta,\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ \lambda_S,\ \kappa_1,\ \kappa_2$$

- Require **positive** $m_{h_i}^2$, m_a^2, and $m_{H^+}^2$, and a **bounded-from-below** potential
- One of the CP-even Higgs bosons, $h_{\rm SM}$, has a mass within the 3σ range of the measured SM-like Higgs boson mass $m_h = 125.18 \pm 0.16$ GeV [PDG 2018]
- The SM-like Higgs boson $h_{\rm SM}$ is further tested 95% C.L. by `Lilith` based on **current LHC Higgs measurements** [Kraml *et al.*, 1908.03952, SciPost Phys.]
- Constraints from **B-meson decays** $B_d \to \mu^+\mu^-$, $B_s \to \mu^+\mu^-$, and $B \to X_s\gamma$ with **flavor-changing neutral currents** (FCNCs) [Haller *et al.*, 1803.01853, EPJC]
- Require the predicted **DM relic density** $\Omega_{\rm DM}h^2$ lying within the 3σ range of the Planck measured value 0.1200 ± 0.0012 [Planck coll., 1807.06209, A&A]
- Constraints on **DM annihilation** from combined **γ-ray observations** of dwarf galaxies by Fermi-LAT and MAGIC [MAGIC & Fermi-LAT, 1601.06590, JCAP]

Effective Potential

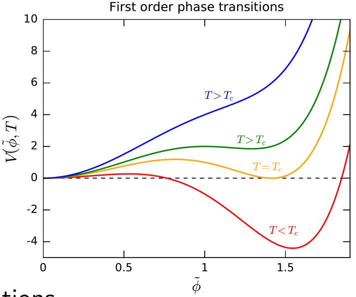
🌶️ Different **local minima** in the **effective potential** V_{eff} of the scalar fields

👉 Different **phases** 👉 **Phase transitions**

🌸 We assume that only the CP-even neutral scalar fields (ρ_1, ρ_2, s) develop VEVs in the cosmological history

🐉 As a function of the **classical background fields** $(\tilde{\rho}_1, \tilde{\rho}_2, \tilde{s})$ and the **temperature** T,

$$V_{\text{eff}}(\tilde{\rho}_1, \tilde{\rho}_2, \tilde{s}, T) = V_0 + V_1 + V_{\text{CT}} + V_{1\text{T}} + V_{\text{D}}$$



🍅 Tree-level potential V_0

🍒 1-loop zero-temperature corrections V_1

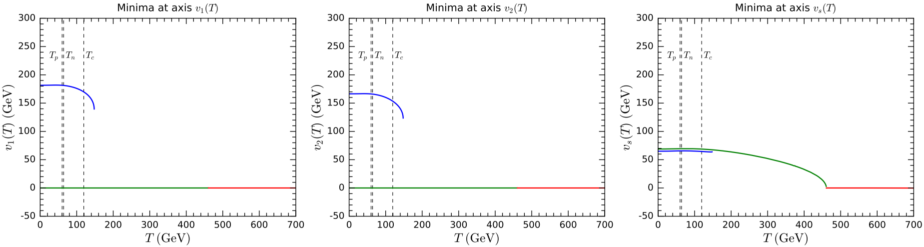
🍑 Counter terms V_{CT} for keeping the VEV positions and the renormalized mass-squared matrix of the CP-even neutral scalars

🍓 1-loop finite-temperature corrections $V_{1\text{T}}(T)$

🍉 Daisy diagram contributions $V_{\text{D}}(T)$ beyond 1-loop at finite temperature

Temperature Evolution of Local Minima

- We utilize CosmoTransitions to analyze the phase transitions
- At sufficiently high temperatures, the only minimum in the effective potential is the **gauge symmetric minimum** $(\tilde{\rho}_1, \tilde{\rho}_2, \tilde{s}) = (0, 0, 0)$
- As the Universe cools down, **extra minima** may appear
- **Multi-step** cosmological phase transitions typically occur in this model
- If there are two coexisted minima separated by a **high barrier**, a **strong FOPT** could take place, resulting in **stochastic gravitational waves**
- At last, the system is trapped at the **true vacuum** $(\tilde{\rho}_1, \tilde{\rho}_2, \tilde{s}) = (v_1, v_2, v_s)$



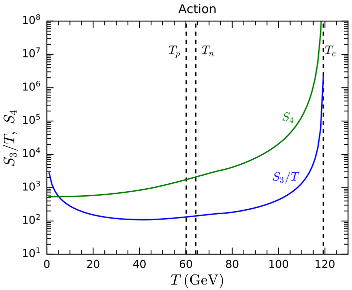
Bubble Nucleation in a FOPT

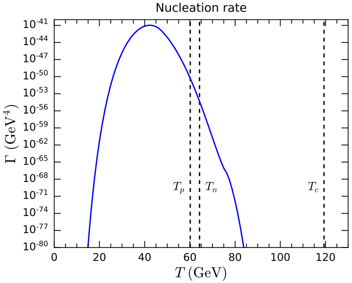
- A FOPT from a **false vacuum** to the **true vacuum** nucleates **bubbles**, inside which the system is trapped at the true vacuum
- **Bubble nucleation rate** $\Gamma \sim T^4 e^{-S}$
- The action $S = \min(S_4, S_3/T)$
- O(4)-symmetric quantum tunneling action S_4
- O(3)-symmetric thermal fluctuation action

$$S_3 = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2}\frac{d\phi_i}{dr}\frac{d\phi_i}{dr} + V_{\text{eff}}(\phi_i, T)\right]$$

- Bounce solution $\phi_i(r) = \left(\tilde{\rho}_1(r), \tilde{\rho}_2(r), \tilde{s}(r)\right)$ with the bubble radius r satisfying

$$\begin{cases} \dfrac{d^2\phi_i}{dr^2} + \dfrac{2}{r}\dfrac{d\phi_i}{dr} = \dfrac{\partial V_{\text{eff}}}{\partial \phi_i} \\ \left.\dfrac{d\phi_i}{dr}\right|_{r=0} = 0, \quad \phi_i(\infty) = \phi_i^{\text{false}} \end{cases}$$





Key Quantities of a FOPT

☀️ The **released vacuum energy density** in the FOPT

$$\rho_{\text{vac}} = V_{\text{eff}}(\phi_i^{\text{false}}, T) - V_{\text{eff}}(\phi_i^{\text{true}}, T) - T\frac{\partial}{\partial T}[V_{\text{eff}}(\phi_i^{\text{false}}, T) - V_{\text{eff}}(\phi_i^{\text{true}}, T)]$$

👉 **Gradient energy** of the scalar field $\Rightarrow$ **Bubble expansion** 🎈

👉 **Thermal energy** 🔥 and **bulk kinetic energy** 🚿 of the plasma

💪 **Phase transition strength** $\alpha \equiv \dfrac{\rho_{\text{vac}}}{\rho_{\text{rad}}}$, where $\rho_{\text{rad}} = \dfrac{\pi^2}{30} g_* T^4$ is the radiation energy density in the plasma with g_* the effective relativistic degrees of freedom

⌛ $\beta(T') \equiv -\left.\dfrac{dS}{dt}\right|_{t=t'} = \left.\left(HT\dfrac{dS}{dT}\right)\right|_{T=T'}$ roughly describes the **inverse time duration** of the FOPT at a characteristic temperature T'

👉 A larger α implies a **stronger** FOPT, and a smaller β means a **longer** FOPT

🌿 The dimensionless quantity $\tilde{\beta}(T') \equiv \dfrac{\beta(T')}{H(T')}$ compares the cosmological expansion time scale H^{-1} with the phase transition time scale β^{-1} at $T = T'$

Key Temperatures of a FOPT

Critical temperature T_c : the potential values at the two minima are equal

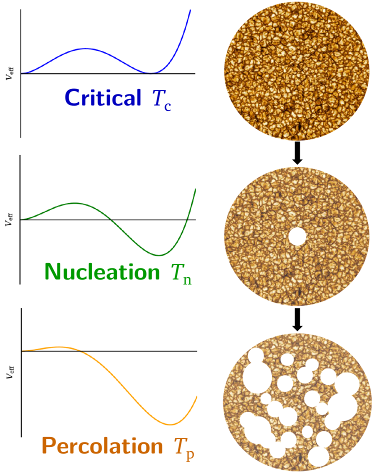
Nucleation temperature T_n : one single bubble is nucleated within a Hubble volume

$$\frac{S_3(T_\mathrm{n})}{T_\mathrm{n}} \simeq 141.5 - 2\ln\frac{g_*}{100} - 4\ln\frac{T_\mathrm{n}}{100\ \mathrm{GeV}} - \ln\frac{\tilde{\beta}(T_\mathrm{n})}{100}$$

Percolation temperature T_p : percolation occurs when the fraction of space converted to the true vacuum reaches $\sim 29\%$, corresponding to the **maximum of bubble collisions**

$$\frac{S_3(T_\mathrm{p})}{T_\mathrm{p}} \simeq 132.0 - 2\ln\frac{g_*}{100} - 4\ln\frac{T_\mathrm{p}}{100\ \mathrm{GeV}} - 4\ln\frac{\tilde{\beta}(T_\mathrm{p})}{100} + 3\ln v_\mathrm{w}$$

v_w is the **velocity of the bubble wall**



[X Wang, FP Huang, XM Zhang, 2003.08892, JCAP]

Bubble Expansion in the Plasma

🎈 The bubble expansion depends on the interactions between the bubble wall and the plasma, analogous to **chemical combustion in a relativistic fluid**

🐚 **Hydrodynamic** analyses show that bubble expansion have various **modes**

🐻 Subsonic deflagrations 🐮 Supersonic deflagrations (hybrid)

🦁 Jouguet detonations 🐷 Weak detonations 🐰 Runway bubble walls

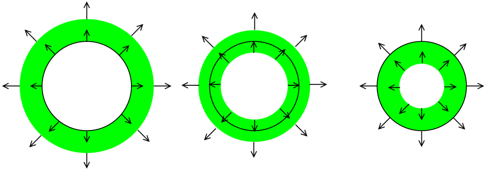
🐒 It is difficult to completely work out the bubble wall velocity v_w

🦁 For **Jouguet detonations**, the Chapman-Jouguet condition leads to a bubble wall velocity of

$$v_{CJ} = \frac{1+\sqrt{3\alpha^2+2\alpha}}{\sqrt{3}(1+\alpha)},$$

which is larger than the **sound speed** in the plasma $c_s \simeq 1/\sqrt{3}$

👉 This is a **typical** assumption when evaluating GW signals



Subsonic deflagration $v_w < c_s$ Supersonic deflagration $v_w > c_s$ Detonation $v_w > c_s$

[Espinosa et al., 1004.4187, JCAP]

Energy Budget of a FOPT

Define **efficiency factors** by the fractions of the available vacuum energy

κ_ϕ : the fraction converted into the **gradient energy** of the scalar fields

- It is typically **negligible**, except for runaway bubble walls ($v_\mathrm{w} \to 1$)

κ_v : the fraction converted into the kinetic energy of the **fluid bulk motion**

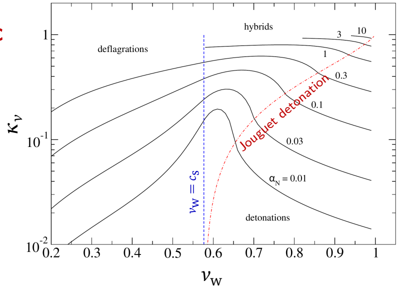
- It depends on the **FOPT strength** α and the **bubble wall velocity** v_w

κ_turb : the fraction converted into the kinetic energy of **magnetohydrodynamic (MHD) turbulence**

- Recent simulations suggest that $\kappa_\mathrm{turb} \simeq$ 5–10% κ_v at most

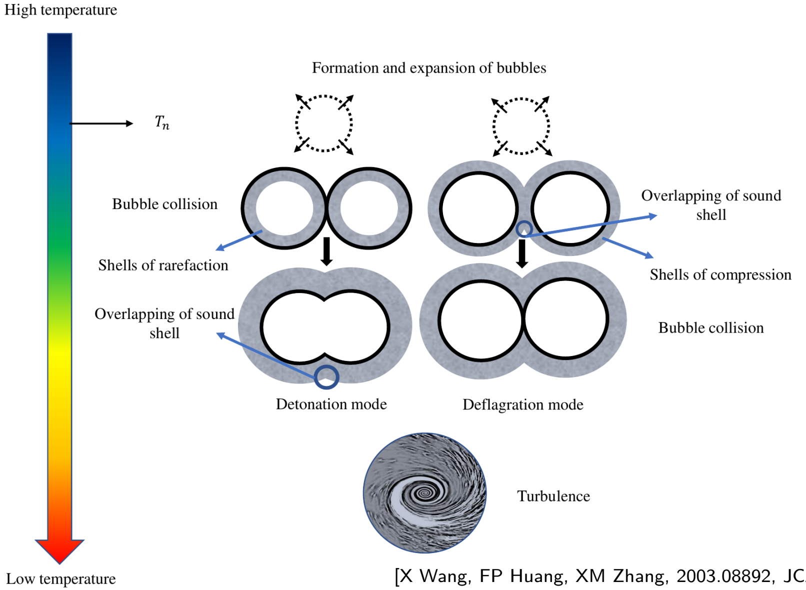
For **Jouguet detonations**, $v_\mathrm{w} = v_\mathrm{CJ}$,

and $\kappa_v^\mathrm{CJ} = \dfrac{\sqrt{\alpha}}{0.135 + \sqrt{0.98 + \alpha}}$



[Espinosa et al., 1004.4187, JCAP]

Physical Processes in a FOPT



[X Wang, FP Huang, XM Zhang, 2003.08892, JCAP]

GW Sources in a FOPT

- An electroweak FOPT could induce significant **perturbations** of the metric and produce **stochastic GWs around $f \sim$ mHz**, whose spectrum depend on α and $\tilde{\beta}$ at $t = t_*$ (corresponding to $T \sim T_\mathrm{p}$) when the GWs are produced
- The resulting **GW spectrum** is commonly expressed as $\Omega_\mathrm{GW} = \frac{f}{\rho_\mathrm{c}} \frac{d\rho_\mathrm{GW}}{df}$
- ρ_GW is the present GW energy density, ρ_c is the critical density
- Three **GW sources**: $\Omega_\mathrm{GW} = \Omega_\mathrm{col} + \Omega_\mathrm{sw} + \Omega_\mathrm{turb}$
- **Bubble collisions**: $\Omega_\mathrm{col} \propto \kappa_\phi^2$ is **negligible** except for runaway bubble walls
- **Sound waves**: sound shells propagate into the fluid as sound waves

$$\Omega_\mathrm{sw} h^2 = 1.17 \times 10^{-6} \, \frac{\Upsilon v_\mathrm{w}}{\tilde{\beta}} \left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{f}{f_\mathrm{sw}}\right)^3 \left(\frac{7}{4 + 3f^2/f_\mathrm{sw}^2}\right)^{7/2}$$

- This is the **dominant** source; Υ accounts for the duration of sound waves
- **MHD turbulence**: bubble collisions stir up turbulence in the fluid

$$\Omega_\mathrm{turb} h^2 = 3.35 \times 10^{-4} \, \frac{v_\mathrm{w}}{\tilde{\beta}} \left(\frac{\kappa_\mathrm{turb} \alpha}{1+\alpha}\right)^{3/2} \left(\frac{100}{g_*}\right)^{1/3} \frac{(f/f_\mathrm{turb})^3}{(1 + f/f_\mathrm{turb})^{11/3} (1 + 8\pi f/h_*)}$$

GW Signals from pNGB DM and 2 Higgs Doublets

Random scans for **Type-I** and **Type-II** Yukawa couplings

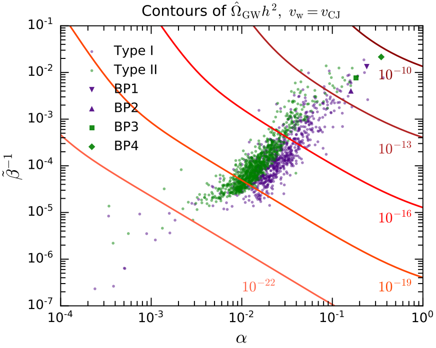
$$10\ \text{GeV} < v_s < 1\ \text{TeV}, \quad 58\ \text{GeV} < m_\chi < 800\ \text{GeV},$$
$$\text{GeV}^2 < |m_{12}^2| < (500\ \text{GeV})^2, \quad 0.5 < \tan\beta < 20,$$
$$0.8 < \lambda_1, \lambda_2, \lambda_S, |\lambda_3|, |\lambda_4|, |\lambda_5| < 8, \quad 0.01 < |\kappa_1|, |\kappa_2| < 8$$

The parameter points are required to give an observed DM relic abundance, and to pass all the existed experimental constraints, and to cause a **FOPT**

The resulting **relic GW spectra** are further estimated, assuming **Jouguet detonations** with $v_\mathrm{w} = v_\mathrm{CJ}$

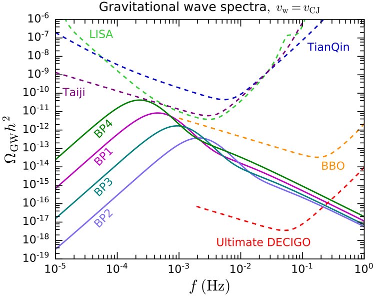
Contours correspond to the **peak amplitude** of the GW spectrum $\hat{\Omega}_\mathrm{GW}h^2$

A **larger** α and a **larger** $\tilde{\beta}^{-1}$ imply a stronger and longer FOPT, leading to a **more significant** GW signal



Benchmark Points (BPs)

	BP1	BP2	BP3	BP4
Type	I	I	II	II
v_s (GeV)	542.40	384.26	64.987	138.82
m_χ (GeV)	117.88	78.191	134.03	76.678
m_{12}^2 (10^4 GeV^2)	2.0210	0.015876	17.696	15.042
$\tan\beta$	2.8616	3.2654	0.91655	1.1732
λ_1	2.1496	2.1882	1.5297	0.87839
λ_2	0.80887	0.85479	1.2074	0.80222
λ_3	2.3925	2.2628	1.5741	2.8002
λ_4	3.0027	1.4715	5.3967	4.4643
λ_5	−6.2187	−4.0567	−7.8556	−7.5755
λ_S	3.4048	2.5502	6.0689	4.8644
κ_1	−1.4852	1.0295	0.80378	−0.38075
κ_2	1.1727	−1.2142	−0.83745	−0.14591
m_{h_1} (GeV)	125.11	91.459	125.38	124.87
m_{h_2} (GeV)	282.02	124.77	158.83	307.56
m_{h_3} (GeV)	1014.5	641.83	650.98	582.08
m_a (GeV)	664.75	496.49	911.87	874.04
$m_{H^\pm}$ (GeV)	402.96	280.94	655.60	631.66
$\langle\sigma_{\text{ann}} v\rangle_{\text{dwarf}}$ (10^{-26} cm^3/s)	1.30	0.368	1.72	0.682
α	**0.240**	**0.160**	**0.181**	**0.346**
$\tilde\beta^{-1}$ (10^{-2})	**1.33**	**0.402**	**0.771**	**2.15**
T_p (GeV)	55.3	74.9	60.2	47.2
SNR_{LISA}	96.6	37.7	60.1	120
$\text{SNR}_{\text{Taiji}}$	83.3	23.9	42.3	155
$\text{SNR}_{\text{TianQin}}$	5.50	2.39	3.07	9.20



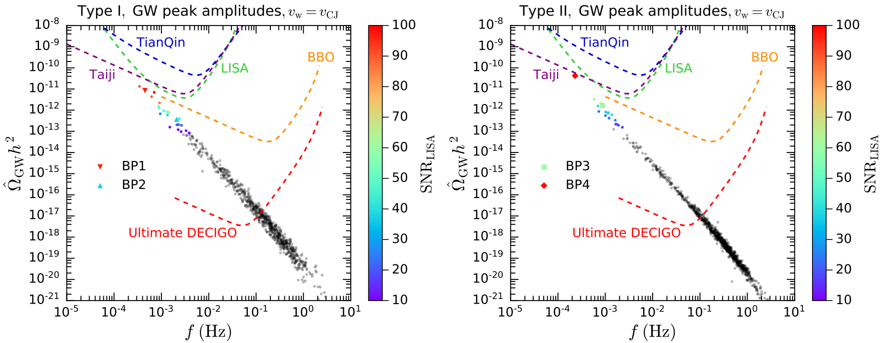
For a practical observation time $\mathcal{T}$, the **signal-to-noise ratio** is

$$\text{SNR} \equiv \sqrt{\mathcal{T}\int_{f_{\min}}^{f_{\max}} \frac{\Omega_{\text{GW}}^2(f)}{\Omega_{\text{sens}}^2(f)}\,df}$$

Take $\mathcal{T} = 3$ yr for LISA, Taiji, TianQin

For the six (four) link configuration, the detection threshold is $\text{SNR}_{\text{thr}} = 10\ (50)$

Peak Amplitudes and Signal-to-noise Ratios



🎨 The **colored points** leads to $\mathrm{SNR}_\mathrm{LISA} > 10$, promising to be probed by **LISA**

🦄 Based on current information, the sensitivity of **Taiji** could be similar to LISA, while **TianQin** may be somehow less sensitive

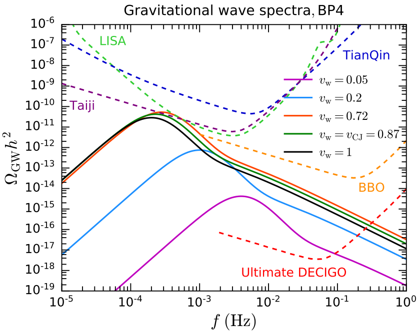
🎯 Far future plans aiming at $f \sim \mathcal{O}(0.1)$ Hz, like **BBO** and **DECIGO**, may explore much more parameter points

Dependence on Bubble Expansion Modes and v_w

⚓ The previous results for GW signals are estimated by assuming **Jouguet detonations** with $v_w = v_{CJ}$

⚒ For different **bubble expansion modes**, the dependence of κ_v on v_w and α is different

⚖ In order to show such a dependence, we additionally estimate the GW spectra for **BP4** under the following assumptions



- **Subsonic deflagrations** with $v_w = 0.05$ 👉 very weak GW signal
- **Subsonic deflagrations** with $v_w = 0.2$ 👉 weak GW signal
- **Detonations** with $v_w = 1$ 👉 strong GW signal
- **Jouguet detonations** with $v_w = v_{CJ} = 0.87$ 👉 $\mathrm{SNR}_{\mathrm{TianQin}} = 9.2$
- **Supersonic deflagrations** with $v_w = 0.72$ 👉 strongest GW signal
  👉 $\mathrm{SNR}_{\mathrm{TianQin}} = 15.8$ 👉 could be properly tested by TianQin

Summary

- In the **pNGB DM framework** with **two Higgs doublets**, the DM candidate can evade direct detection bounds and achieve the observed relic abundance
- We investigate the **existed experimental constraints** and the potential **stochastic GWs** from **electroweak FOPTs**
- Some parameter points could induce strong GW signals, which have the opportunity to be probed in future **LISA**, **Taiji**, and **TianQin** experiments.

Summary

- In the **pNGB DM framework** with **two Higgs doublets**, the DM candidate can evade direct detection bounds and achieve the observed relic abundance
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Thanks for your attention!

Yukawa Couplings

😨 In 2HDMs, diagonalizing the **fermion mass matrix** **cannot** make sure that the **Yukawa interactions** are simultaneously diagonalized

👉 **Tree-level FCNCs** 👉 violate flavor physics observations

😊 If all fermions with the same quantum numbers just couple to the one **same** Higgs doublet, the FCNCs will be **absent** at tree level

[Glashow & Weinberg, PRD 15, 1958 (1977); Paschos, PRD 15, 1966 (1977)]

🐍 This can be achieved by assuming particular Z_2 **symmetries** for the Higgs doublets and fermions

🐫 **Four independent types** of Yukawa couplings without tree-level FCNCs

Type I: $\mathcal{L}_{\mathrm{Y,I}} = -y_{\ell_i} \bar{L}_{i\mathrm{L}} \ell_{i\mathrm{R}} \Phi_2 - \tilde{y}_d^{ij} \bar{Q}_{i\mathrm{L}} d'_{j\mathrm{R}} \Phi_2 - \tilde{y}_u^{ij} \bar{Q}_{i\mathrm{L}} u'_{j\mathrm{R}} \tilde{\Phi}_2 + \mathrm{H.c.}$

Type II: $\mathcal{L}_{\mathrm{Y,II}} = -y_{\ell_i} \bar{L}_{i\mathrm{L}} \ell_{i\mathrm{R}} \Phi_1 - \tilde{y}_d^{ij} \bar{Q}_{i\mathrm{L}} d'_{j\mathrm{R}} \Phi_1 - \tilde{y}_u^{ij} \bar{Q}_{i\mathrm{L}} u'_{j\mathrm{R}} \tilde{\Phi}_2 + \mathrm{H.c.}$

Lepton specific: $\mathcal{L}_{\mathrm{Y,L}} = -y_{\ell_i} \bar{L}_{i\mathrm{L}} \ell_{i\mathrm{R}} \Phi_1 - \tilde{y}_d^{ij} \bar{Q}_{i\mathrm{L}} d'_{j\mathrm{R}} \Phi_2 - \tilde{y}_u^{ij} \bar{Q}_{i\mathrm{L}} u'_{j\mathrm{R}} \tilde{\Phi}_2 + \mathrm{H.c.}$

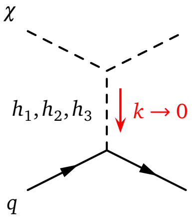
Flipped: $\mathcal{L}_{\mathrm{Y,F}} = -y_{\ell_i} \bar{L}_{i\mathrm{L}} \ell_{i\mathrm{R}} \Phi_2 - \tilde{y}_d^{ij} \bar{Q}_{i\mathrm{L}} d'_{j\mathrm{R}} \Phi_1 - \tilde{y}_u^{ij} \bar{Q}_{i\mathrm{L}} u'_{j\mathrm{R}} \tilde{\Phi}_2 + \mathrm{H.c.}$

[Branco *et al.*, 1106.0034, Phys. Rept.]

Vanishing of DM-nucleon Scattering

- Take the **type-I** Yukawa couplings as an example
- **Higgs portal** interactions $\mathcal{L}_{h_i\chi^2} = \frac{1}{2}\sum_{i=1}^{3} g_{h_i\chi^2} h_i \chi^2$

$$g_{h_i\chi^2} = -\kappa_1 v_1 O_{1i} - \kappa_2 v_2 O_{2i} - \lambda_S v_s O_{3i}$$



$= 0$

- **DM-quark scattering** amplitude

$$\mathcal{M}(\chi q \to \chi q) \propto \frac{m_q}{v s_\beta}\left(\frac{g_{h_1\chi^2}O_{21}}{t-m_{h_1}^2} + \frac{g_{h_2\chi^2}O_{22}}{t-m_{h_2}^2} + \frac{g_{h_3\chi^2}O_{23}}{t-m_{h_3}^2}\right)$$

$$\xrightarrow{t\to 0} \frac{m_q}{v s_\beta}(\kappa_1 v_1,\ \ \kappa_2 v_2,\ \ \lambda_S v_s)\, O(\mathcal{M}_h^2)^{-1} O^{\mathrm{T}} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \frac{m_q}{v s_\beta}(\kappa_1 v_1,\ \ \kappa_2 v_2,\ \ \lambda_S v_s)\,(\mathcal{M}_{\rho s}^2)^{-1} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

Interaction basis expression

$$= \frac{m_q}{v s_\beta \det(\mathcal{M}_{\rho s}^2)}(\kappa_1 v_1 \mathcal{A}_{12} + \kappa_2 v_2 \mathcal{A}_{22} + \lambda_S v_s \mathcal{A}_{32}) = 0$$

$$\mathcal{M}_h^2 \equiv \mathrm{diag}(m_{h_1}^2, m_{h_2}^2, m_{h_3}^2)$$

$$O(\mathcal{M}_h^2)^{-1} O^{\mathrm{T}} = (\mathcal{M}_{\rho s}^2)^{-1} = \frac{\mathcal{A}}{\det(\mathcal{M}_{\rho s}^2)}, \quad \mathcal{A}_{12} = -(\lambda_{345} v_1 v_2 - m_{12}^2)\lambda_S v_s^2 + \kappa_1 \kappa_2 v_1 v_2 v_s^2$$

$$\mathcal{A}_{22} = (\lambda_1 v_1^2 + m_{12}^2 \tan\beta)\lambda_S v_s^2 - \kappa_1^2 v_1^2 v_s^2, \quad \mathcal{A}_{32} = -(\lambda_1 v_1^2 + m_{12}^2 \tan\beta)\kappa_2 v_2 v_s + (\lambda_{345} v_1 v_2 - m_{12}^2)\kappa_1 v_1 v_s$$

Constraints from Flavor Physics and DM Indirect Detection