Gravitational waves and radiative neutrino mass from Peccei-Quinn symmetry breaking

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Work in progress

Peccei-Quinn symmetry breaking

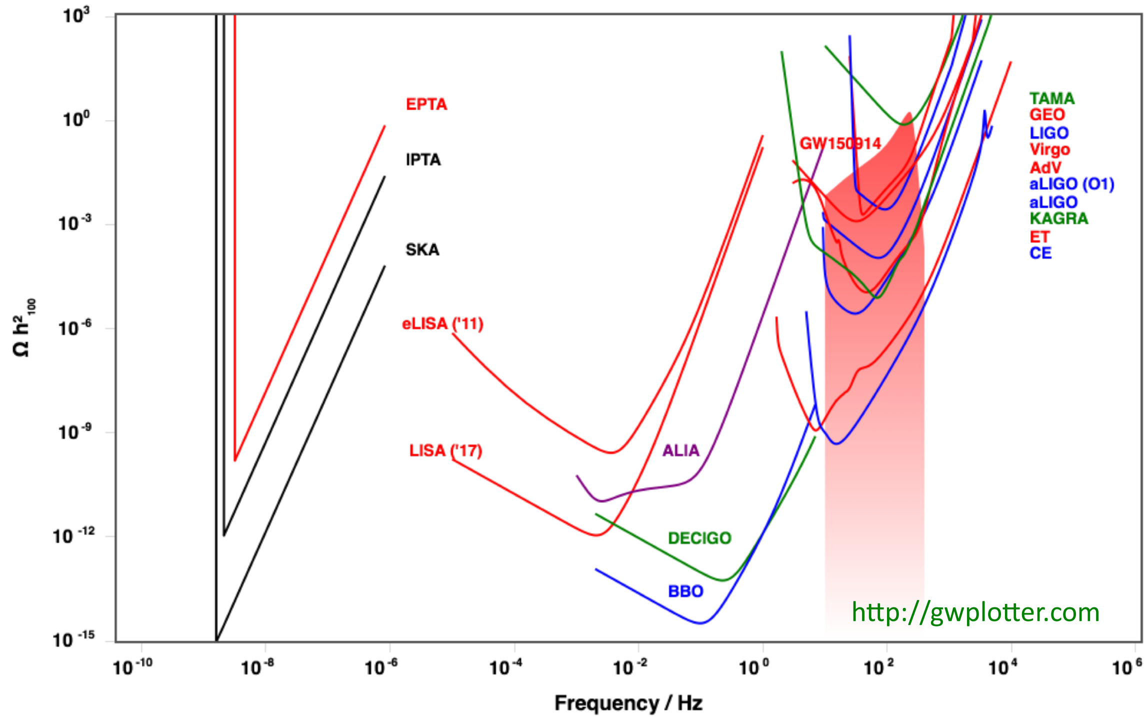
- Strong CP problem: Bell, Jackiw (1969); Adler (1969); Hooft (1976)
  - $\mathcal{L}_{\overline{\Theta}} = -\frac{\overline{\Theta} g^2}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma} \rightarrow \overline{\Theta} \lesssim \mathcal{O}(10^{-11})$
- Peccei-Quinn (PQ) mechanism:

  Peccei, Quinn, PRL38(1977)1440, PRD16(1977)1791
  - Global $U(1)_{PQ}$ symmetry
  - PQ-breaking scale: $f_a \equiv \sqrt{2} \left\langle |\vec{\phi}| \right\rangle$
  - CP-violating phase: $\overline{\Theta} \equiv \arg \left\langle \vec{\phi} \right\rangle \rightarrow a \equiv f_a \overline{\Theta}$
  - Pseudo Nambu-Goldstone boson is identified as axion *a*

  Weinberg, PRL40(1978)223; Wilczek, PRL40(1978)279
- Axion mass: $V(a) = \Lambda_a^4 \left(1 - \cos \frac{a}{f_a}\right) \simeq \frac{1}{2} m_a^2(T) a^2 + \cdots \quad \Lambda_a^4 \equiv m_a^2(T) f_a^2$
  - $m_{a,\mathrm{QCD}} \equiv m_a(T=0) \simeq 6.0 \times 10^{-6}\,\mathrm{eV} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a}\right)$ ($m_a \leftrightarrow f_a$)
- Constraint: $10^8\,\mathrm{GeV} \lesssim f_a \lesssim 10^{11}\,\mathrm{GeV}$ → Axion can be dark matter

  SN 1987A limit $\quad \Omega_a h^2 \sim 0.12$

Gravitational Wave detectors



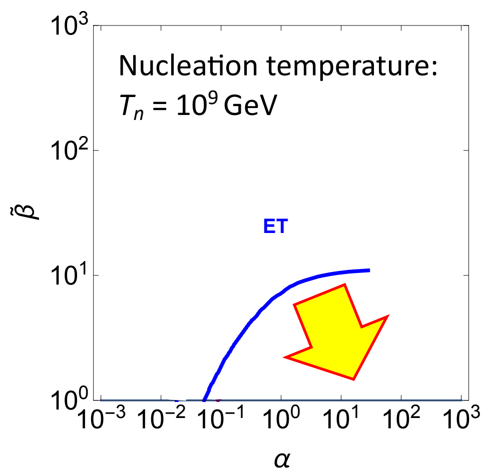
- LIGO/ET [10^2 Hz]
- LISA(DECIGO) [$10^{-3(1)}$ Hz]
- Pulsar timing [10^{-8} Hz]

Various signals of stochastic GW background are expected

・1st order Phase transition (FOPT)
・Topological defects (cosmic strings, …)
・Cosmic inflation
・…

Gravitational Waves from Phase Transition

- PT @ <u>EW scale</u> is motivated for **EW baryogenesis**
  - Covered by LISA(DECIGO) $f \simeq 10^{-3(1)}\,\mathrm{Hz}\,\frac{T_n}{10^2\,\mathrm{GeV}}\,\frac{\tilde{\beta}}{10^{-2(4)}}$
- PT @ <u>PQ scale</u> is motivated for **strong CP problem**
  - Covered by LIGO/Einstein telescope (ET) $f \simeq 10^2\,\mathrm{Hz}\,\frac{T_n}{10^9\,\mathrm{GeV}}\,\frac{\tilde{\beta}}{1}$
  - However, to achieve the sensitivities, large α & $\tilde{\beta}^{-1}$ is needed.



$$(\alpha, \tilde{\beta})_{\text{theory}} \leftrightarrow (f, \Omega_{\mathrm{GW}} h^2)_{\text{observation}}$$

α : potential difference between false & true vacuum
$\tilde{\beta}^{-1}$: duration time of phase transition

Supercooling: the Universe should be trapped in the false vacuum up to low temperature $T_n \ll f_a$.
The scale invariance can realize it.

FOPT from PQ sym. breaking

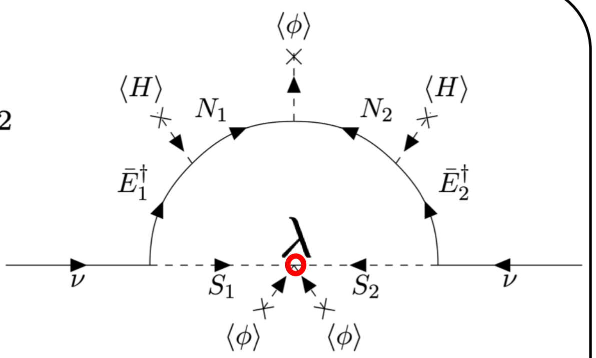
- H + ϕ (KSVZ type) (*) ϕ is the global $U(1)_{PQ}$-breaking scalar
  - Effective Higgs mass: $M_h^2 \simeq \left(\lambda_H - \frac{\lambda_{H\phi}^2}{\lambda_\phi}\right)\frac{v^2}{2} + \mathcal{O}\left(\frac{v}{f}\right) > 0 \rightarrow \boxed{\lambda_H \lambda_\phi > \lambda_{H\phi}^2}$
  - Thermal barrier created by large H corrections $\boxed{\frac{\lambda_{H\phi}^2}{16\pi^2} \gtrsim \lambda_\phi}$
  - → FOPT with perturbation theory is not realized. $\lambda_H \gg 16\pi^2$
- (H +) ϕ + S [Rose, Panico, Redi, Tesi, 1912.06139 (JHEP)]
  - FOPT with perturbation theory can be realized.
  - Scale invariance allows the supercooling
- (H +) ϕ + S_1 + S_2 [Matsui, Popov, Son, Ye]
  - Supercooled FOPT is explained by similar way.
  - Discuss the extension for the tiny neutrino masses

Tiny neutrino mass induced by EW & PQ-breaking

- In order to realize FOPT @PQ scale, at least 1 extra scalar S is needed in addition to ϕ.
- We propose the minimal extension with (ϕ, S_1, S_2)
  - New model based on "radiative inverse seesaw" [Ma (2009)]

Field	$SU(2)_L$	$U(1)_Y$	$U(1)_{PQ}$
ϕ	**1**	0	-2
S_1	**1**	0	1
S_2	**1**	0	3
N_1	**1**	0	0
N_2	**1**	0	-2
$\chi_1 = (E_1, \bar{E}_1^\dagger)$	**2**	$-\frac{1}{2}$	0
$\chi_2 = (E_2, \bar{E}_2^\dagger)$	**2**	$-\frac{1}{2}$	-2

← $\lambda \phi^2 S_1 S_2$



[Matsui, Popov, Son, Ye]

  - Z_2 symmetry remains after $U(1)_{PQ}$ breaking
  - λ term breaks individual $U(1)_{\phi, S1, S2}$ & fixes common $U(1)_{PQ}$ charges.
  - We consider approximate $U(1)_{\phi, S1, S2}$ with $\lambda \ll 1$.

Scale invariance

- Tree potential

$$V = \frac{\lambda_H}{4}|H|^4 + \frac{\lambda_{H\phi}}{2}|H|^2|\phi|^2 + \sum_{i=1,2}\left\{\frac{\lambda_{HS_i}}{2}|H|^2|S_i|^2\right\}$$

$$+ \frac{\lambda_\phi}{4}|\phi|^4 + \sum_{i=1,2}\left\{\frac{\lambda_{\phi S_i}}{2}|\phi|^2|S_i|^2 + \frac{\lambda_{S_i}}{4}|S_i|^4\right\} + \frac{\lambda_{S_1S_2}}{2}|S_1|^2|S_2|^2$$

$$+ \left(\lambda\phi^2 S_1 S_2 + \lambda' S_1^3 S_2^* + \text{h.c.}\right)$$

Small λ, λ′ is needed

~ 0: $v \ll f_a$

Flat direction along σ

$$\lambda_{\phi S} = -\sqrt{\lambda_\phi \lambda_S}$$

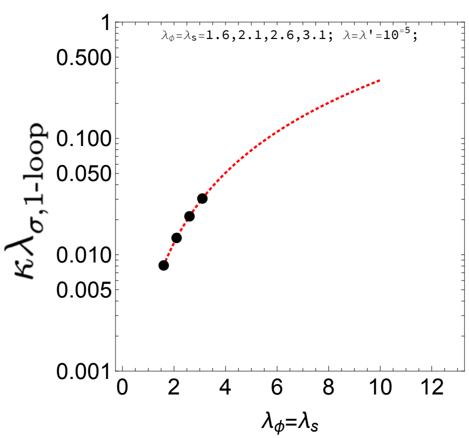
$\lambda_S \equiv \lambda_{S_i} = \lambda_{S_1S_2}, \quad \lambda_{\phi S} \equiv \lambda_{\phi S_i}, \quad \lambda_{HS} \equiv \lambda_{HS_i}$ (for simplicity)

  - Parametrize by $(S_1,\, S_2,\, \phi) = (s_\alpha c_\theta\, e^{i\alpha_1},\, s_\alpha s_\theta\, e^{i\alpha_2},\, c_\alpha\, e^{i\alpha_3})\frac{\sigma}{\sqrt{2}}$ & take $V = 0$ (flat direction)
  - Input parameters: λ_ϕ, λ_S (+ λ, λ′); f_a

- 1-loop Coleman-Weinberg potential

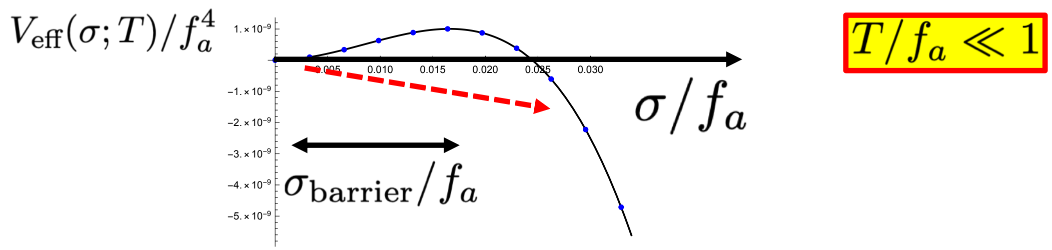
$$V_{\text{CW}}[M_i^2] \equiv \frac{\kappa}{4}\sum_i n_i M_i^4\left(\ln\left[\frac{M_i^2}{Q^2}\right] - c_i\right), \quad \kappa \equiv \frac{1}{16\pi^2}$$

$$\Rightarrow m_\sigma^2 \equiv \kappa\lambda_{\sigma,\text{1-loop}} f_a^2$$



Supercooled FOPT

- Dynamics at finite temperature
  - At lower temperature, the thermal barrier appears.



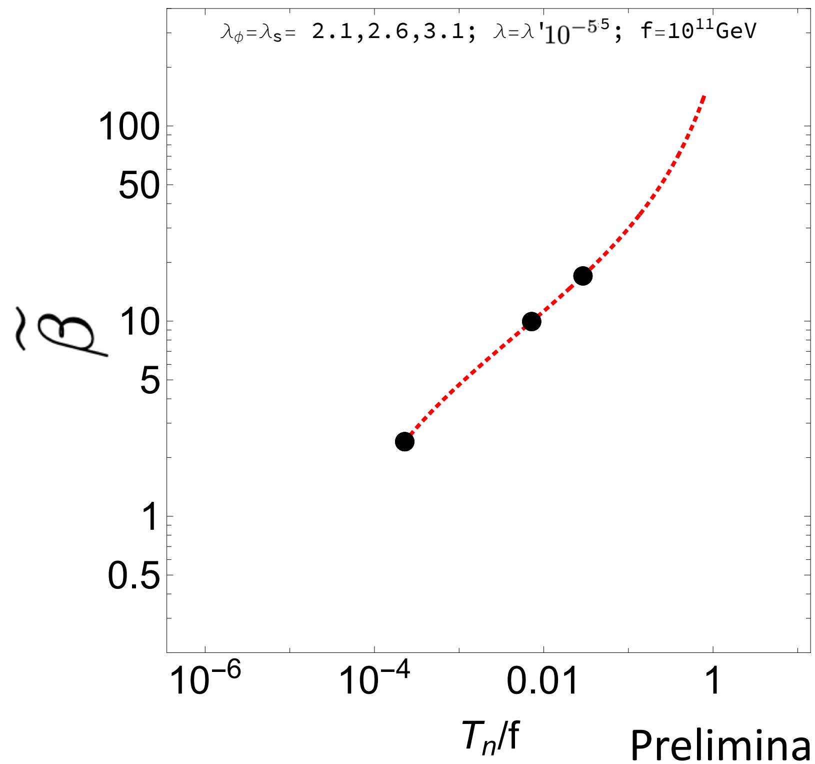
  - Supercooling occurs thanks to the logarism.

$$V_{\rm eff} \simeq DT^2\sigma^2 - ET\sigma^3 + \kappa\lambda_{\sigma,\text{1-loop}}\ln(T/f_a)\sigma^4$$

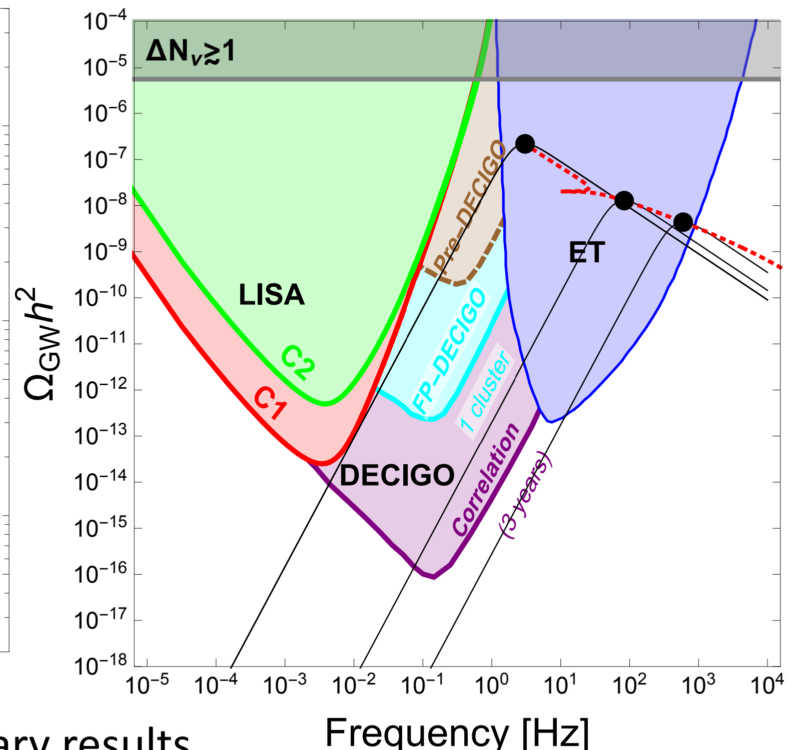
$$\Rightarrow \quad \frac{\sigma_{\rm barrier}}{f_a} \simeq \frac{T/f_a}{\sqrt{-\kappa\lambda_{\sigma,\text{1-loop}}\ln(T/f_a)}} \qquad \frac{S_3}{T} \propto \frac{1}{-\ln(T/f_a)}$$

  - We improved the bounce action estimation numerically using *Findbounce* without high-*T* approximation.
    Guada, Nemevsek, Pintar, 2002.00881

GWs from FOFT



Preliminary results



Supercooled PTs occur in a vacuum-dominated epoch. [Caprini et al., 1512.06239 (JCAP)]

$h^2\Omega_{\rm GW}[f] \simeq h^2\Omega_{\rm env}[f] \propto \widetilde{\beta}^{-2}$ (The α dependence drops out with α → ∞)

Consequence of our model

- PQ mechanism for strong CP problem
  - PQ breaking scale: f_a /GeV ~ [10^8 (SN 1987A), 10^{11} (axion DM)]
  - → Covered range for LIGO/ET
- GWs from FOPT at PQ breaking
  - Scale invariant model for Supercooling
  - → $\Omega_{\mathrm{GW}} h^2$ can be enhanced!
  - Estimation of the bounce action is improved numerically.
- Neutrino mass generation mechanism
  - Radiative inverse seesaw induced by EW & PQ breaking
  - We propose the minimal extension realizing FOPT @PQ.