Baryogenesis from Phase Transitions below a GeV

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Based on ongoing work in collaboration with Jacopo Nava, Silvia Pascoli and Filippo Sala

Motivation

- Open Problem of the Standard Model: Matter-Antimatter Asymmetry

- The idea of connecting baryogenesis models with First Order Phase Transitions (FOPTs), which lead to Gravitational Waves Signal has been extensively studied in literature

- Hint of a Stochastic Gravitational Wave Background from a First Order Phase Transition (FOPT) from Pulsar Timing Arrays?
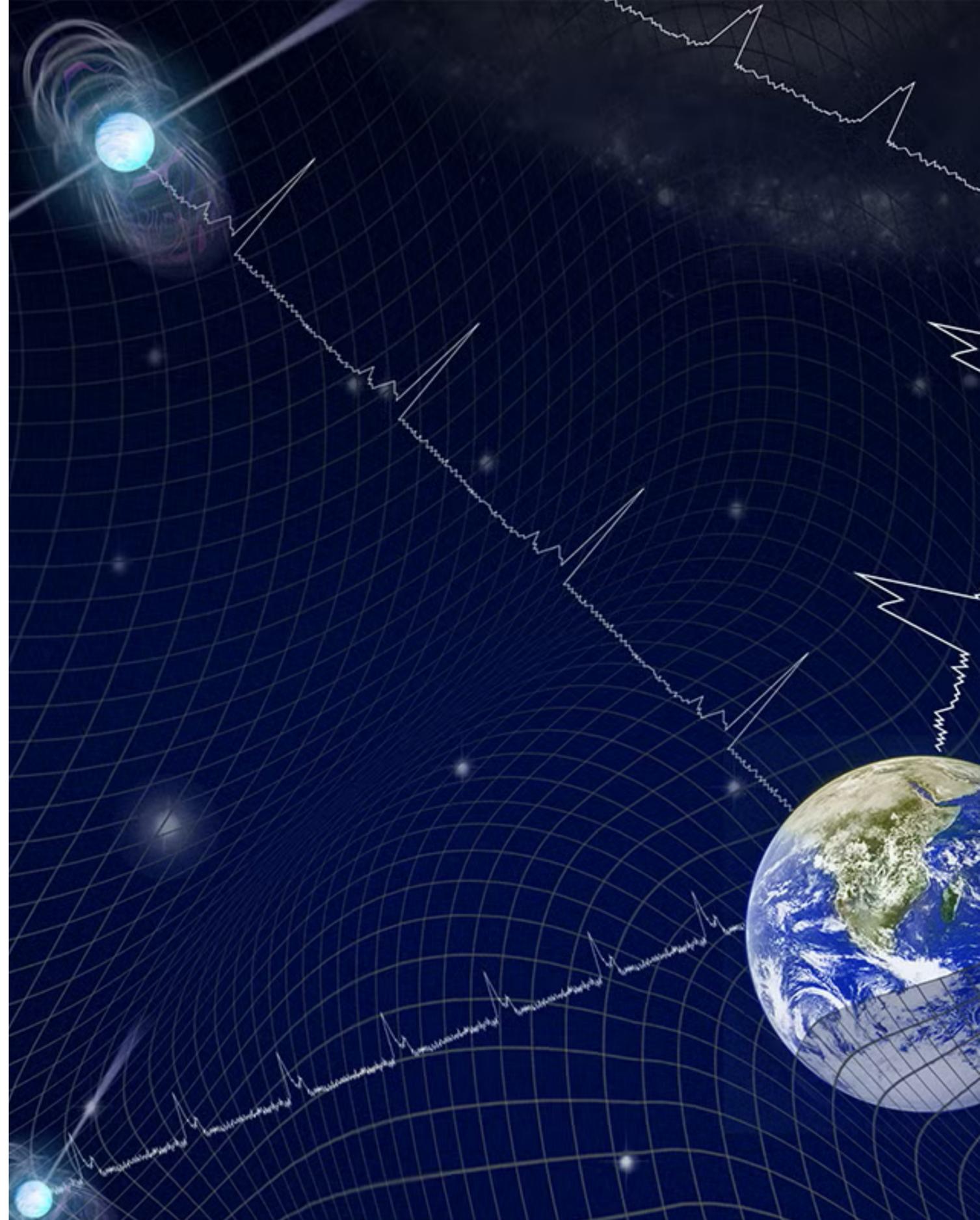
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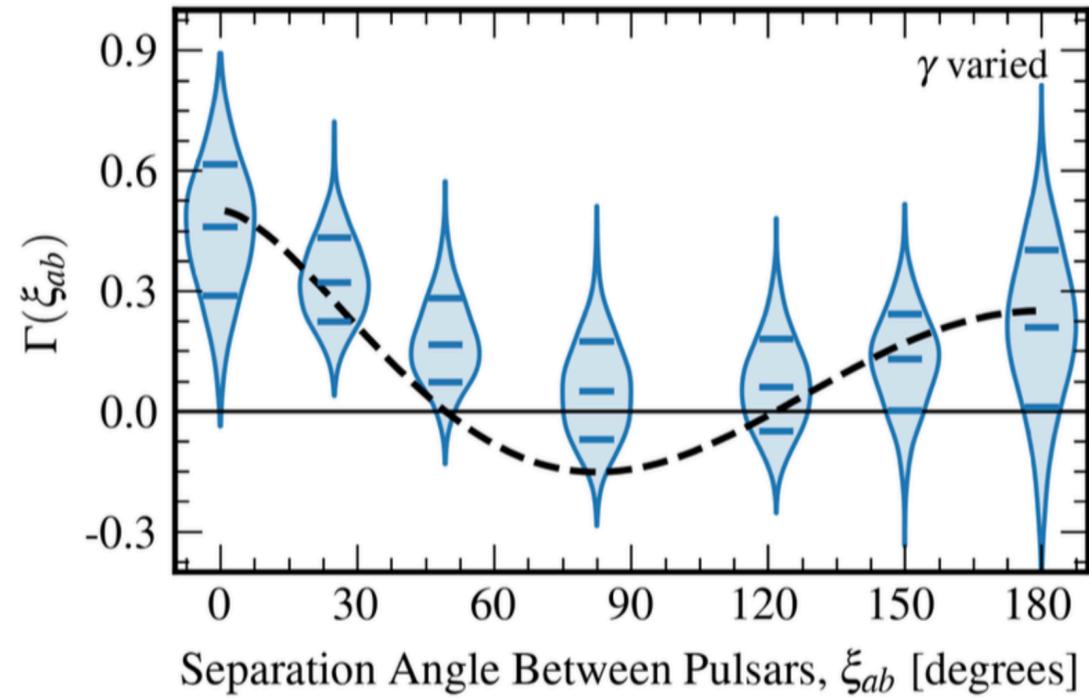
QUESTION…Can we link the Pulsar Timing Arrays signal with the generation of the baryon asymmetry?
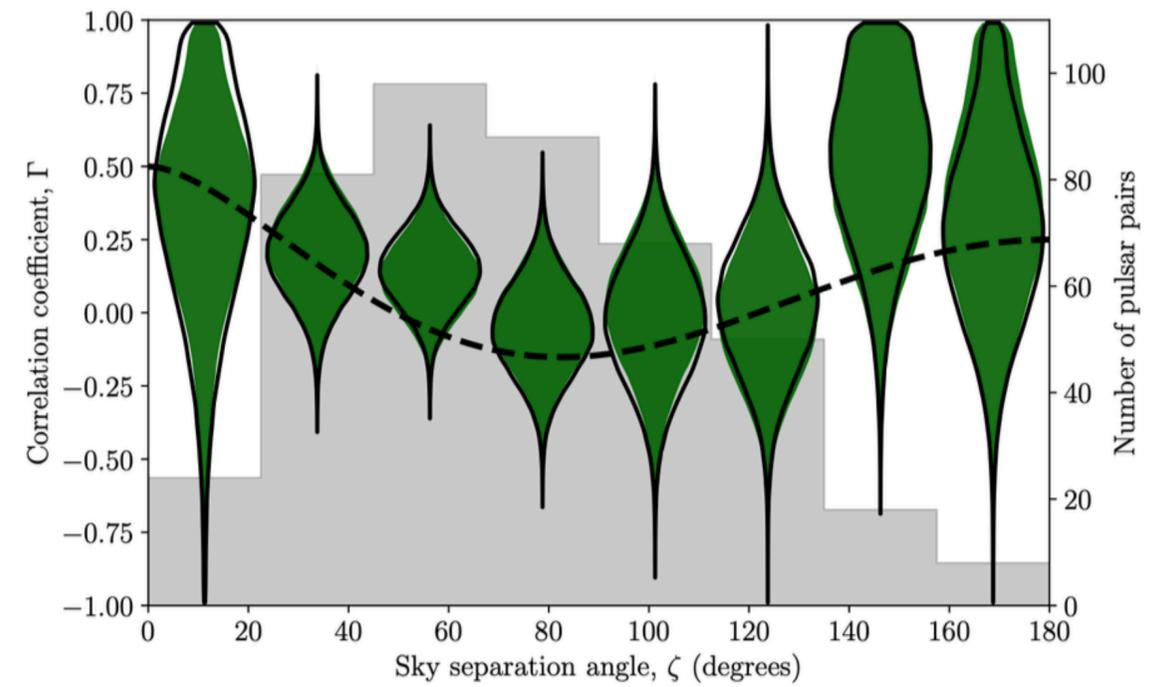
Pulsar Timing Arrays

- **Pulsar:** rapidly rotating magnetised neutron star which emits electromagnetic radiation along the rotation axis

- **Pulsar Timing Residuals**: difference between the expected time of arrival and the observed time of arrival of the light from pulsars

- **Pulsar Timing Arrays**: concept of timing very stable millisecond pulsars to detect GWs
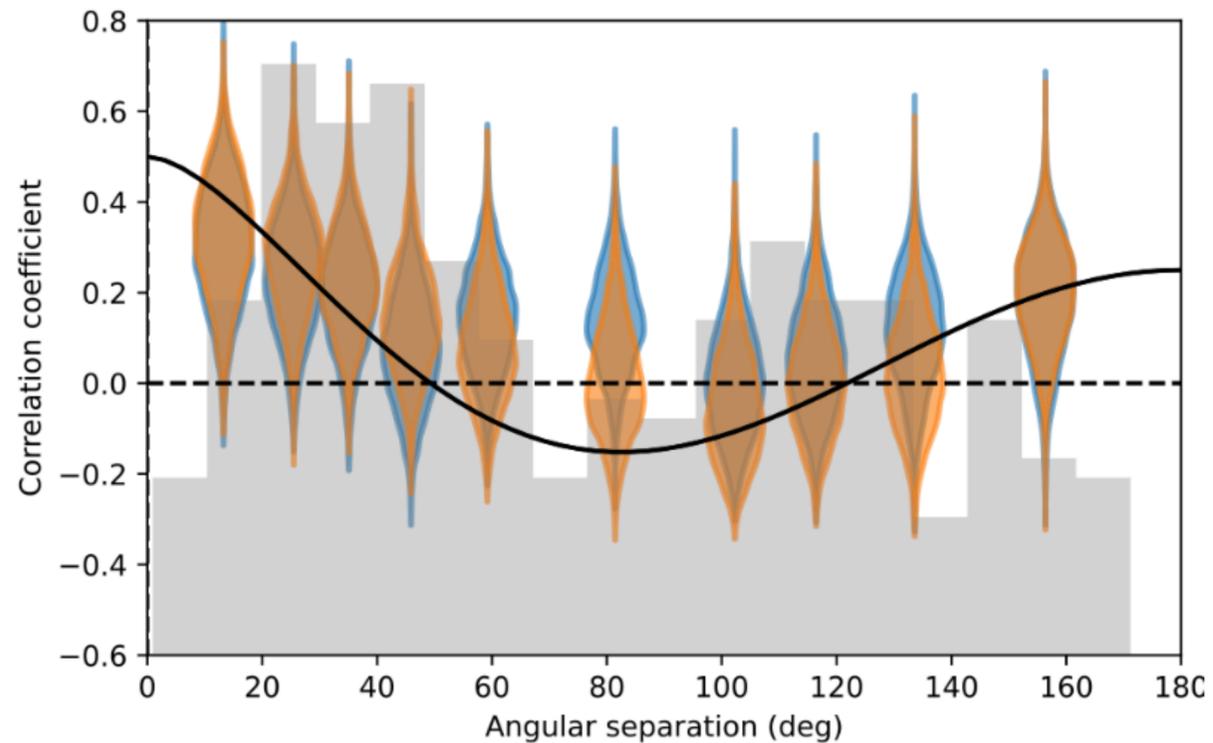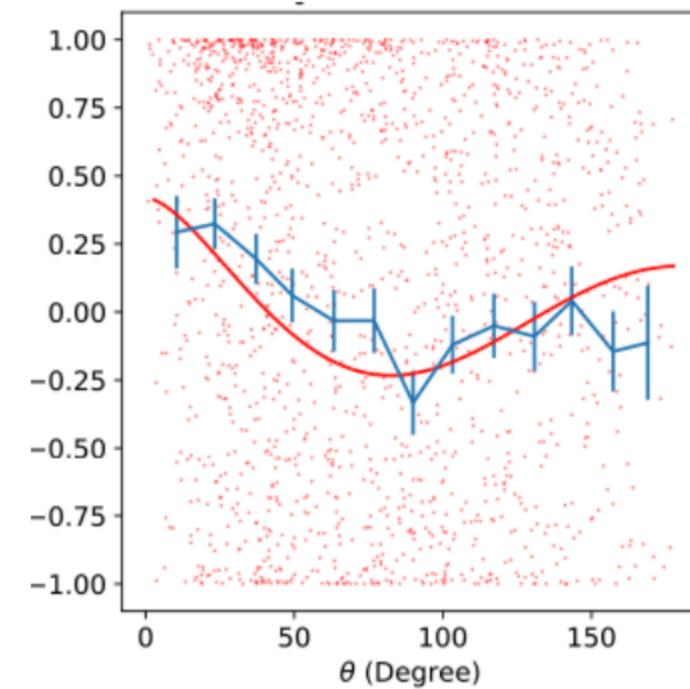
Pulsar Timing Arrays

[NANOGrav, 2306.16213]

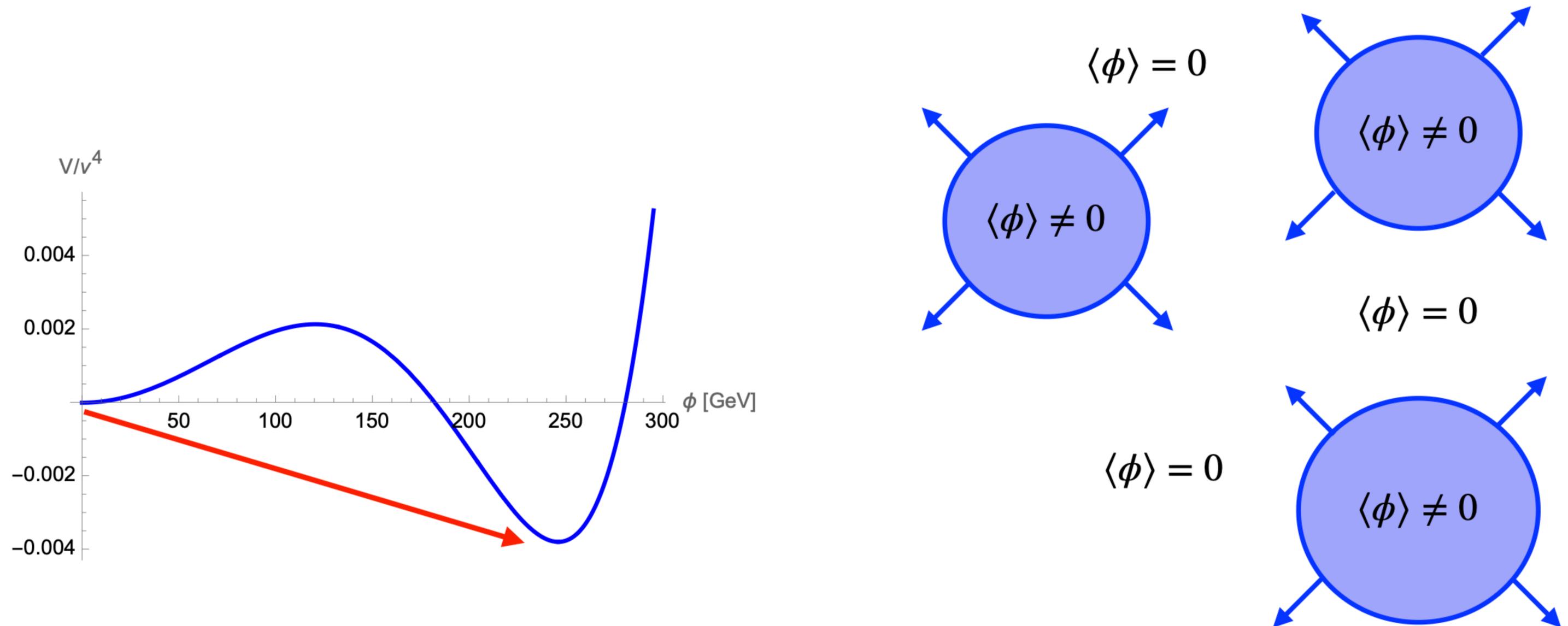[PPTA, 2306.16215]

[EPTA, 2306.16214]

[CPTA, 2306.16216]

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Cosmological First Order Phase Transitions

- A Phase Transition (PT) from a false minimum to a true minimum is said to be of the First Order when it happens via bubble nucleation

Cosmological First Order Phase Transitions

- PT parameters for the GW prediction

  - **Nucleation Temperature** T_n

    $$\Gamma(T_n) \simeq H(T_n)^4$$

  - **Bubble Wall Velocity** v_w

- GW spectrum

  $$\Omega_{GW} \propto \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

- **Phase Transition Stength**

  $$\alpha = \left.\frac{\Delta V}{\rho_{rad}}\right|_{T_{nuc}}$$
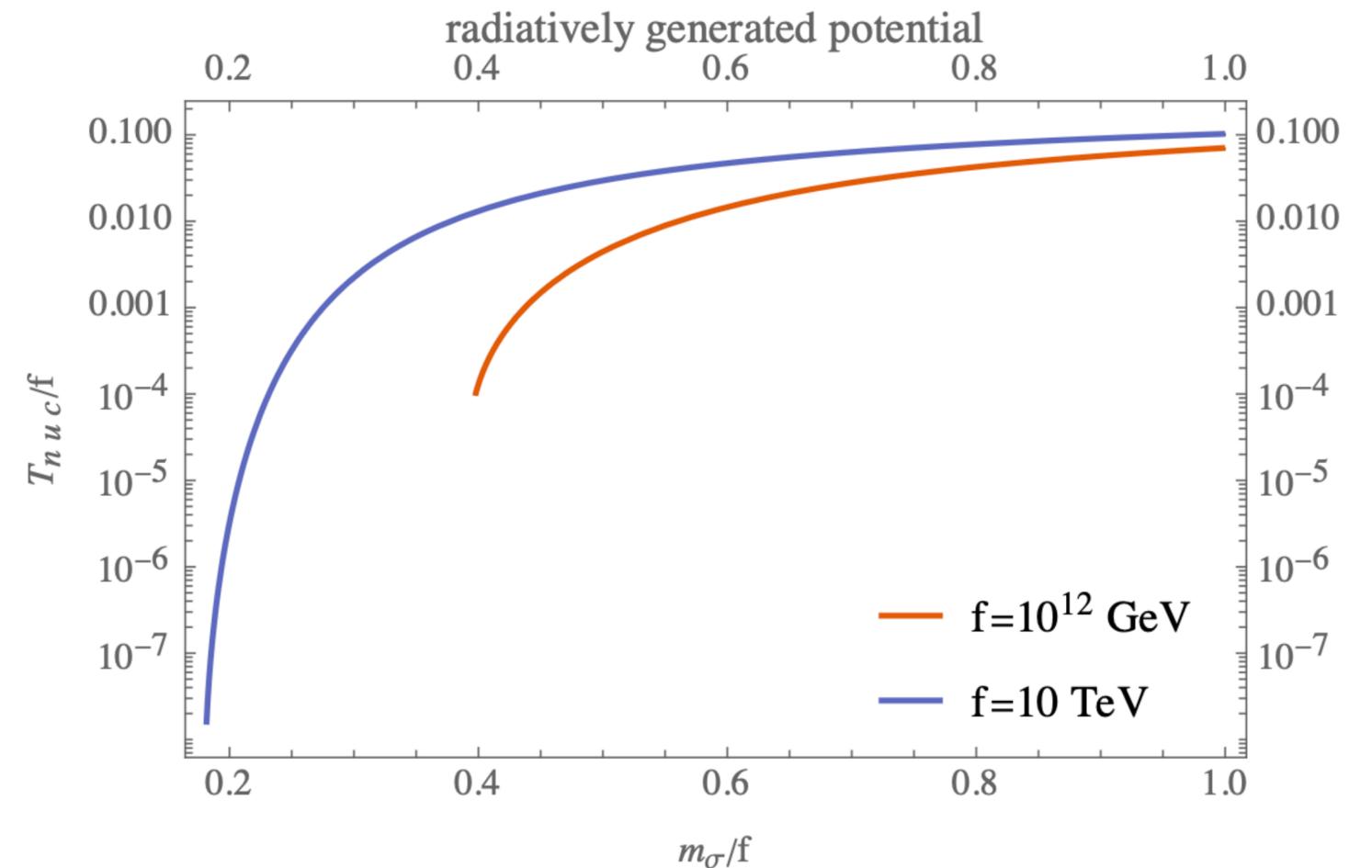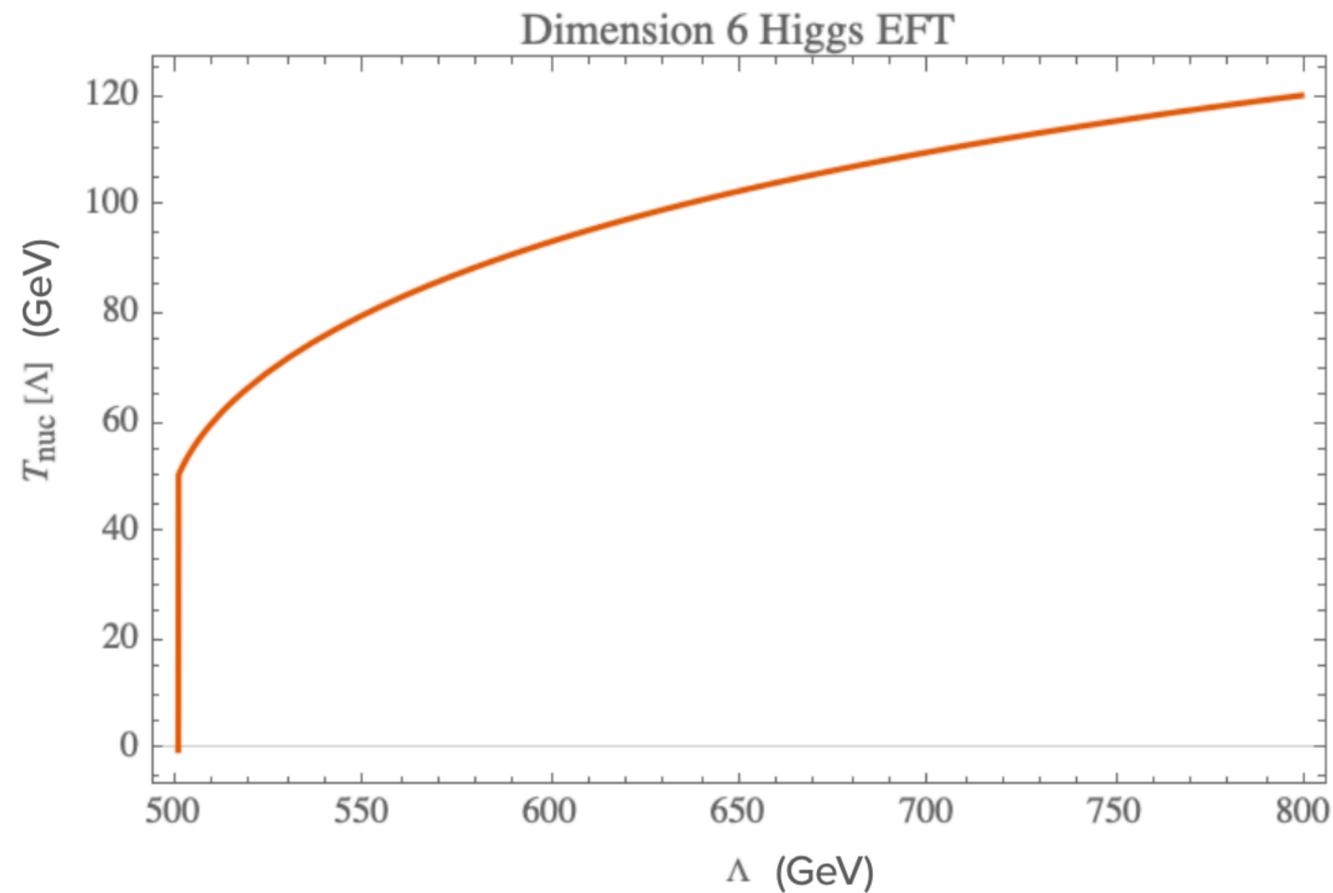
- **Phase Transition Rate**

  $$\beta_H \equiv \frac{\beta}{H} = \left. T\frac{dS}{dT}\right|_{T_{nuc}}$$

$$\nu_{\text{peak}} \sim \text{nHz} \qquad \text{for v} \lesssim 100 \text{ MeV}$$

for Pulsar Timing Arrays

Nucleation Temperature

- In the Standard Model all PTs are cross-overs. Examples of extensions of the SM that predict FOPTs:

  1. $|H|^6/\Lambda^2$ Effective Field Theory [e.g. Delaunay+ 0711.2511]

  2. Nearly-conformal potential $\longrightarrow$ Supercool PT ($\alpha \gg 1$) [e.g. Baldes+ 2110.13926]

Baryogenesis from Dark Matter-Neutron Oscillations

[Bringmann,Cline,Cornell 1810.08215]

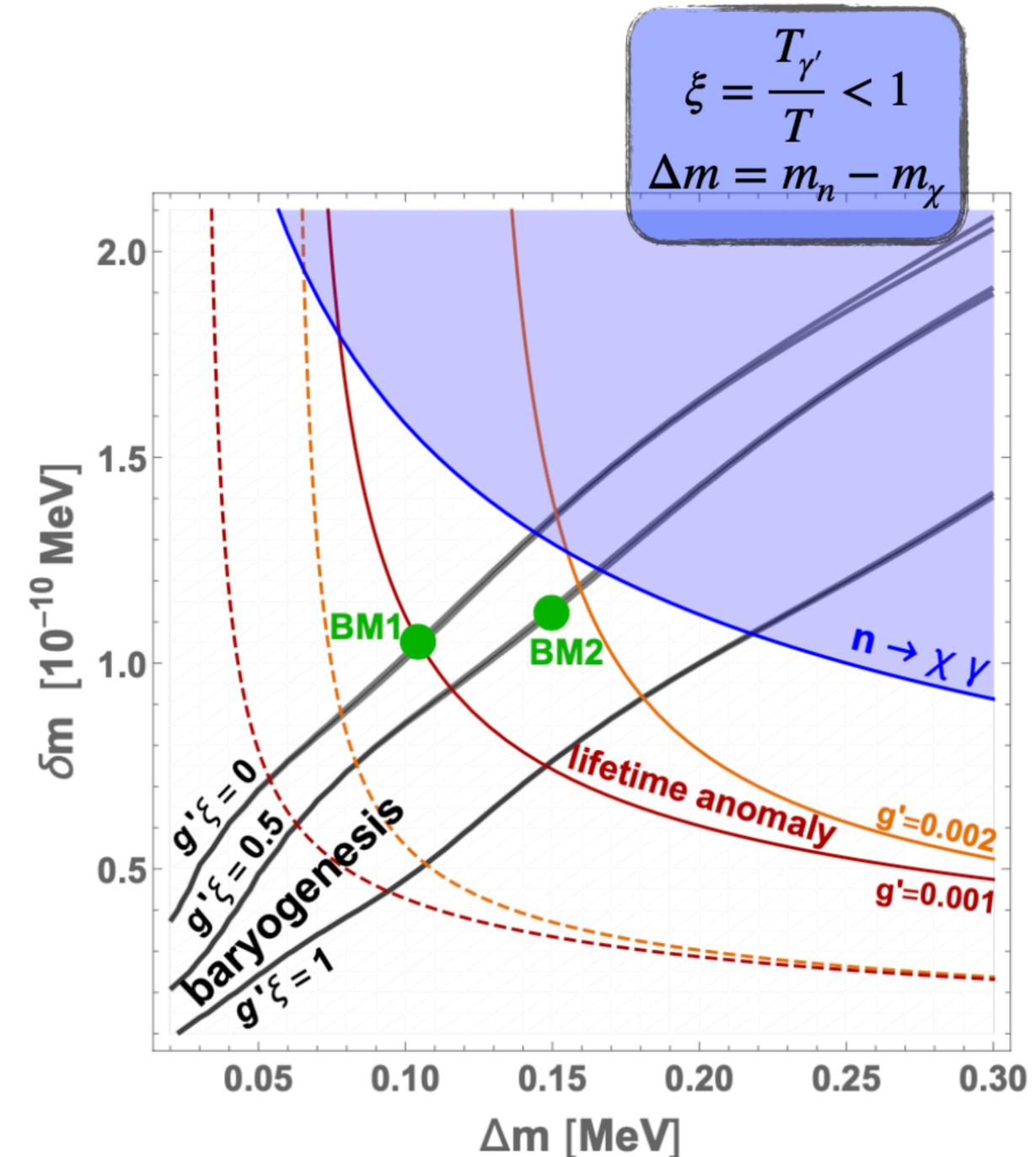- Motivations: Asymmetric Dark Matter & Darkogenesis + Neutron Lifetime Anomaly

$$\mathscr{L}_{\mathrm{mix}} = -\delta m \bar{n}\chi + \mathrm{h.c.}$$

- Baryon Asymmetry generated via resonant oscillations between Dark Matter χ and the neutron n

$$\eta_B \sim \frac{\delta m^2}{\Gamma_n}$$

- $U(1)'$ dark gauge interaction $\longrightarrow$ Dark Photon with gauge coupling g' that gets its mass via the Higgs Mechanism

$$\delta m \propto \langle \phi \rangle = \frac{v}{\sqrt{2}} \lesssim 45 - 60\,\mathrm{MeV}$$

$$\xi = \frac{T_{\gamma'}}{T} < 1$$
$$\Delta m = m_n - m_\chi$$

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Can we obtain the VEV (necessary for the generation of the baryon asymmetry) via radiative symmetry breaking?

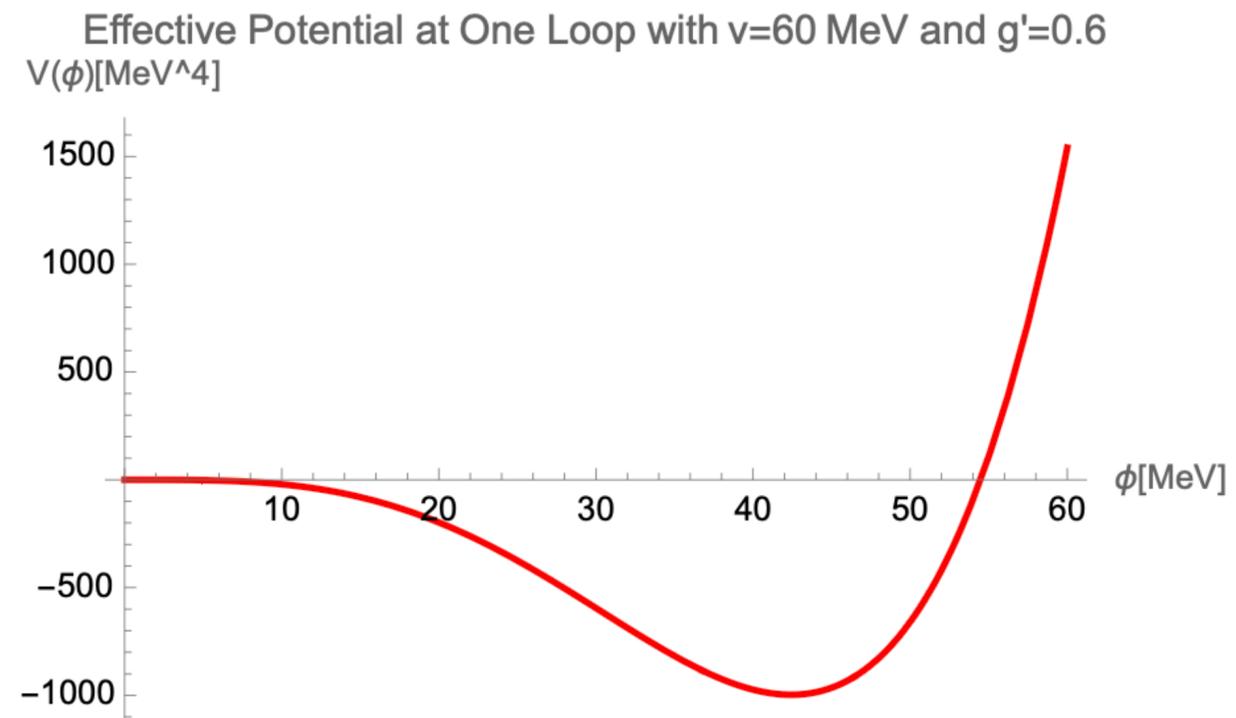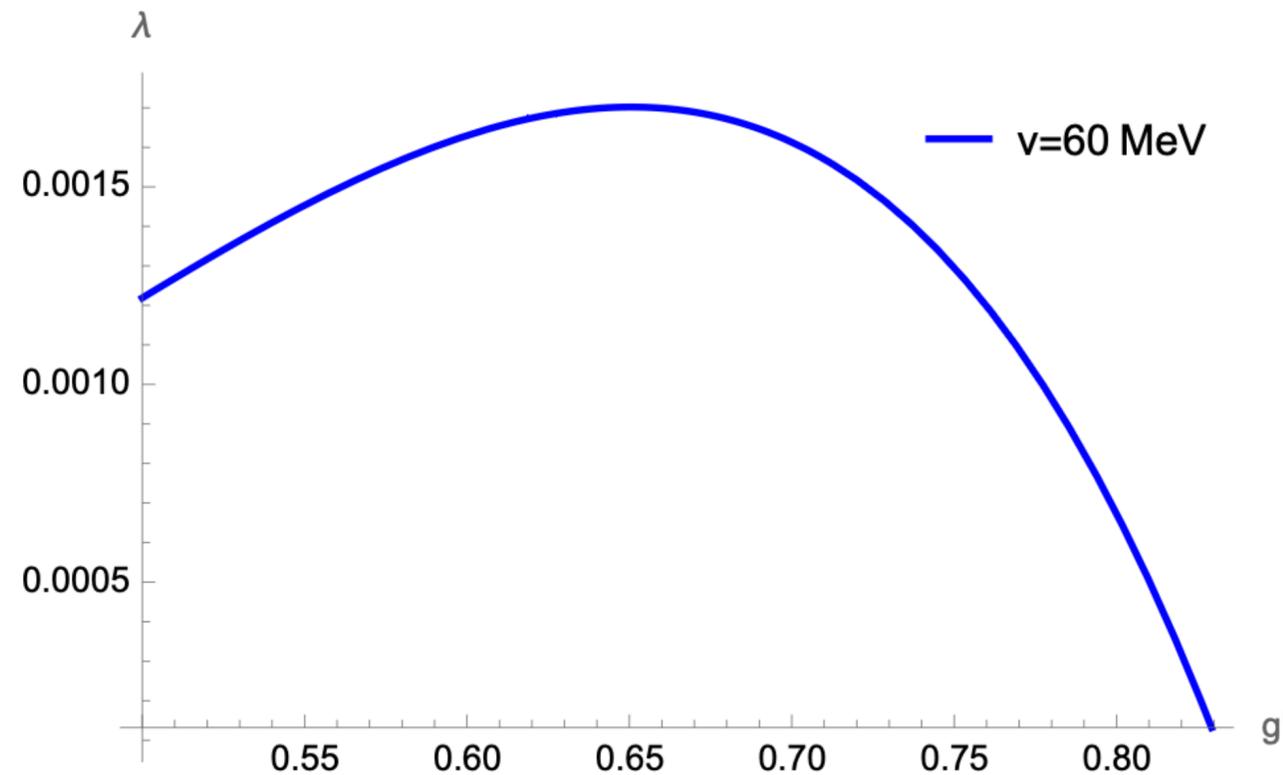# Yes! VEV can be obtained via Radiative Symmetry Breaking

- **Coleman-Weinberg model ⟶ Weakly-coupled supercool FOPT** [Coleman,Weinberg, Phys.Rev. D-1888]

Tree level potential is classically scale invariant

$$V_0 = \lambda \phi^4$$

We add radiative corrections at 1-loop

$$V_{1-\text{loop}}^{T=0}(\phi) = \lambda \phi^4 + \frac{1}{64\pi^2}\left[3m_A^4(\phi)\left(\log\frac{m_A^2(\phi)}{M^2} - \frac{5}{6}\right) + m_r^4(\phi)\left(\log\frac{m_r^2(\phi)}{M^2} - \frac{3}{2}\right) + m_i^4(\phi)\left(\log\frac{m_i^2(\phi)}{M^2} - \frac{3}{2}\right)\right]$$

$$g'\xi = 0.5$$

Effective Potential at One Loop with v=60 MeV and g'=0.6

GW Parameters

Computation

- We add thermal corrections from the High Temperature Expansion

$$V(\phi, T) = \frac{m^2(T)}{2}\phi^2 - \frac{\delta(T)}{3}\phi^3 + \frac{\lambda(T)}{4}\phi^4$$

with

$$m^2(T) = \frac{1}{4}g'^2 T^2 \qquad\qquad \delta(T) = \frac{3}{4\pi}g'^3 T \qquad\qquad \lambda(T) = \frac{3}{8\pi^2}g'4\log\left(\frac{T}{B}\right)$$

- Nucleation Condition during vacuum domination   [Levi,Opferkuch,Redigolo 2212.08085]

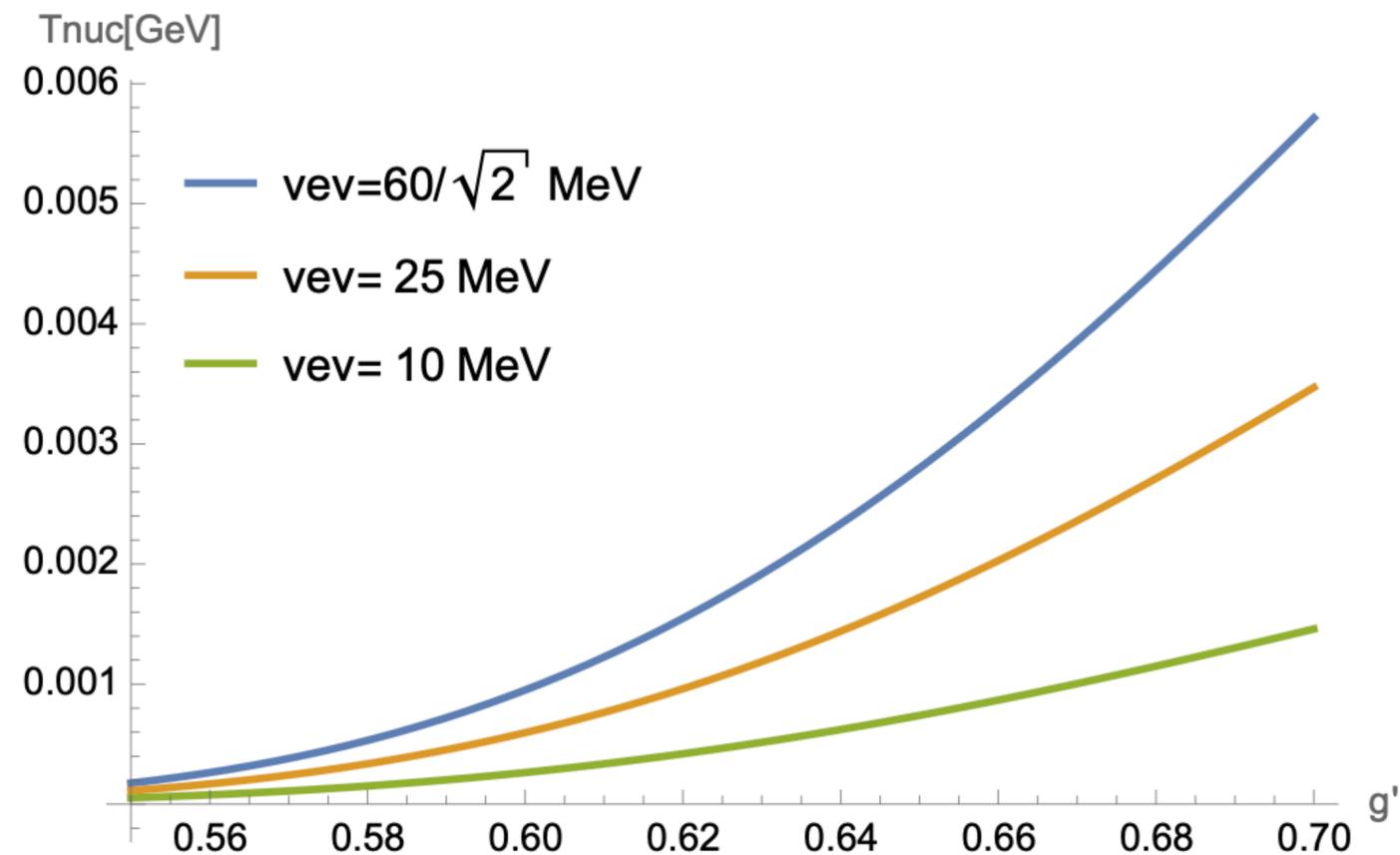$$\frac{3\pi^3(1 + e^{-1/\sqrt{|k_n|}})}{g'^3\left(1 + \frac{9|k_n|}{2}\right)} = 4\log\left(\frac{B}{H_V}\right) - 24|k_n|, \qquad\qquad k_n \equiv k(T_{nuc}) = \frac{1}{6}\log\left(\frac{T_{nuc}}{B}\right)$$

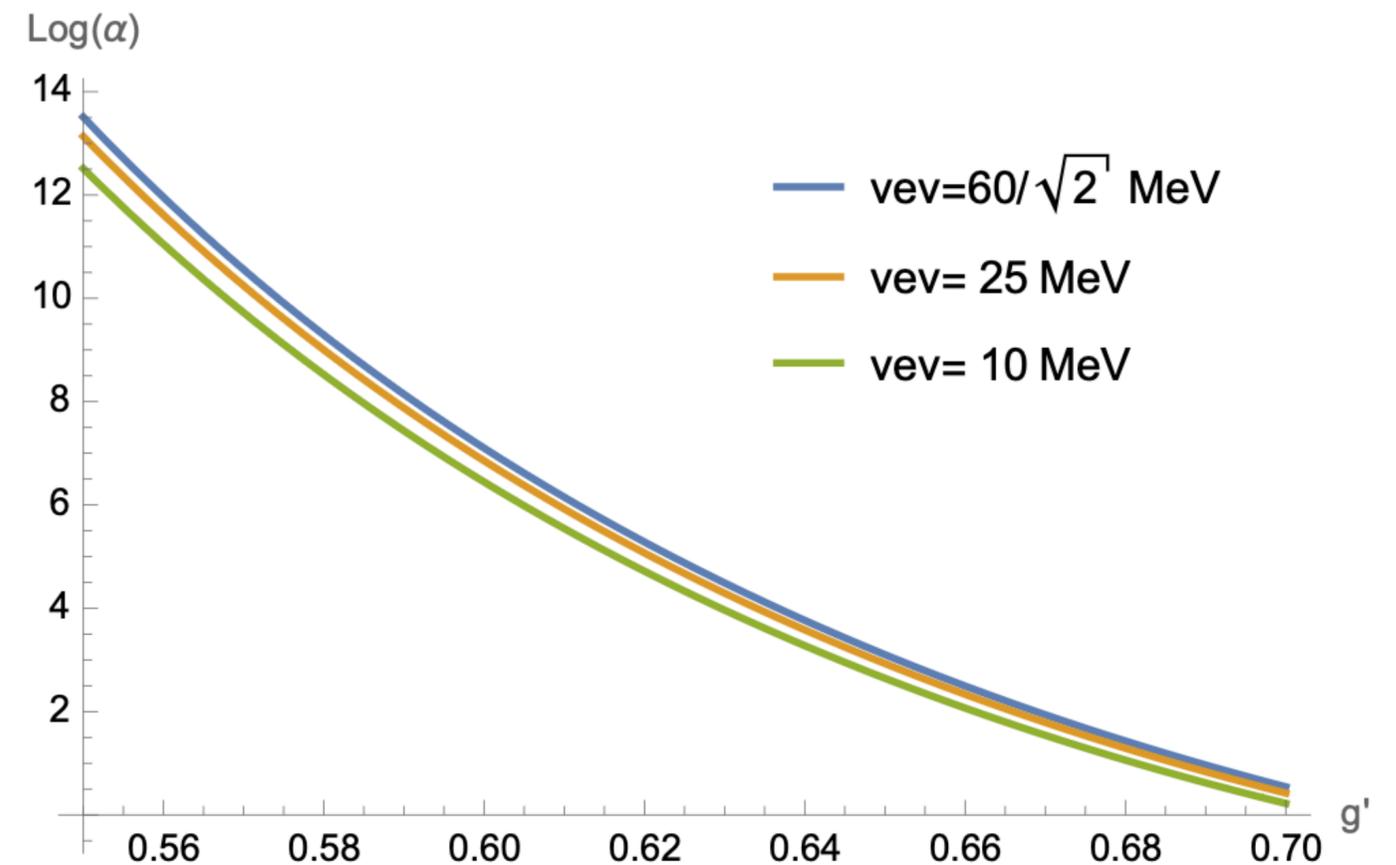For the Coleman-Weinberg model

GW Parameters

Results

- The tunnelling rate is dominated by thermal effects

Nucleation Temperature T_{nuc}

Phase Transition Strength α

GW Parameters

Results

Phase Transition Rate β/H

GW Parameters

Results

βH

vev=$60/\sqrt{2}$ MeV

vev= 25 MeV

vev= 10 MeV

Phase Transition Rate β/H

PTAs data fit [Freese,Winkler 2401.13729]

Strong FOPT

β/H_*

thin-wall (68%/95%)

thick-wall (68%/95%)

Dark FOPT

α

thin-wall (68%/95%)

thick-wall (68%/95%)

T [GeV]

$\beta/H \lesssim 100$ ✔

Conclusions and Outlook

- **We have proposed a baryogengesis model that relies on a $U(1)'$ supercooled phase transition that could explain the GW signal at PTAs**

- Further exploration of the parameter space

- Find other baryogenesis models that predict GWs at PTAs

Thank you for your attention!

BACK UP SLIDES

The Baryon Asymmetry of the Universe

- We live in a Universe with more matter than antimatter

$$\eta_B = \frac{n_B - \bar{n}_B}{n_\gamma} \approx \frac{n_B}{n\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

[PLANCK 2018]

- The Standard Model and the Standard Cosmological Model can't explain this value

- Baryogenesis Models

  - They satisfy Sakharov's conditions (B violation, C and CP violation, departure from equilibrium)

  - Many models are difficult to test, however new ideas predict new physics that could shop up in experiments in the next decade

How to compute the Nucleation Temperature

- Nucleation Condition

$$\Gamma(T_{nuc}) \simeq H(T_{nuc})$$

$$\Gamma(T) \simeq \max\left[T^4\left(\frac{S_3/T}{2\pi}\right)^{3/2}\exp(-S_3/T), R_0^{-4}\left(\frac{S_4}{2\pi}\right)^2\exp(-S_4)\right]$$

$$H(T)^2 = \frac{1}{3M_{pl}^2}(\rho_{rad} + \rho_{vac} + \rho_{wall})$$

$$\rho_{wall} \approx 0 \qquad \rho_{rad} = \frac{\pi^2 g_*}{30}T^4 \qquad \rho_{vac} = \Delta V$$
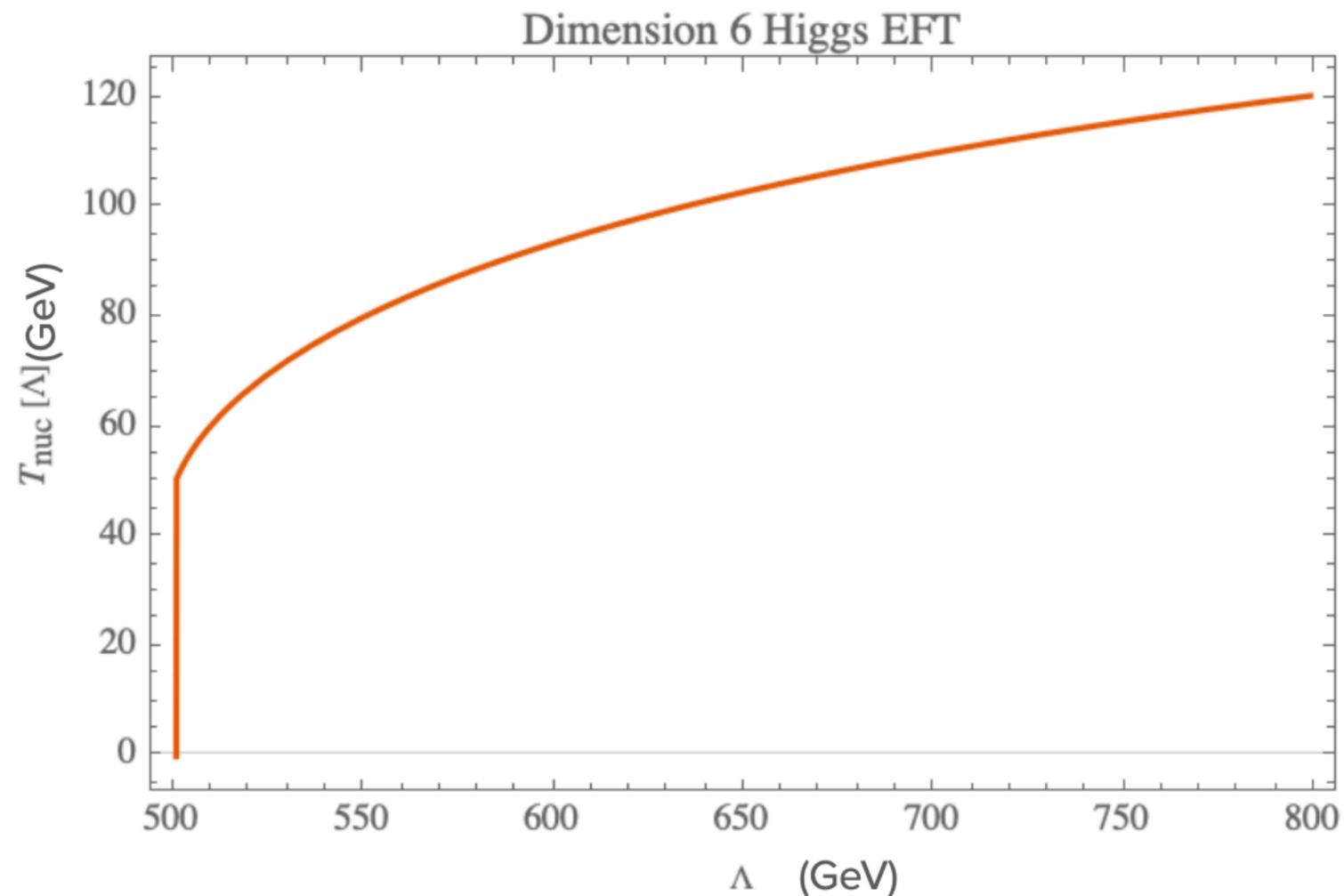
- Equation of Motion

$$\phi''(r) + \frac{d-1}{r}\phi'(r) = \frac{dV}{d\phi} \qquad (d = 3,4)$$

with boundary conditions $\qquad \phi'(0) = 0 \qquad \lim_{r\to\infty}\phi(r) = 0$

- Solutions $\longrightarrow$ Overshoot-Undershoot Algorithm

  $\longrightarrow$ (Semi-) Analytical Approximations

Nucleation Temperature
$|H|^6$ Effective Field Theory

Dimension 6 Higgs EFT

- Potential at tree level

$$V(H) = m^2 |H|^2 + \lambda |H|^4 + \frac{|H|^6}{\Lambda^2}$$

- High Temperature Expansion

$$V_{eff}(\phi, T) \simeq D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda(T)}{4}\phi^4 + \frac{1}{8}\frac{\phi^6}{\Lambda^2}$$

Nucleation Temperature
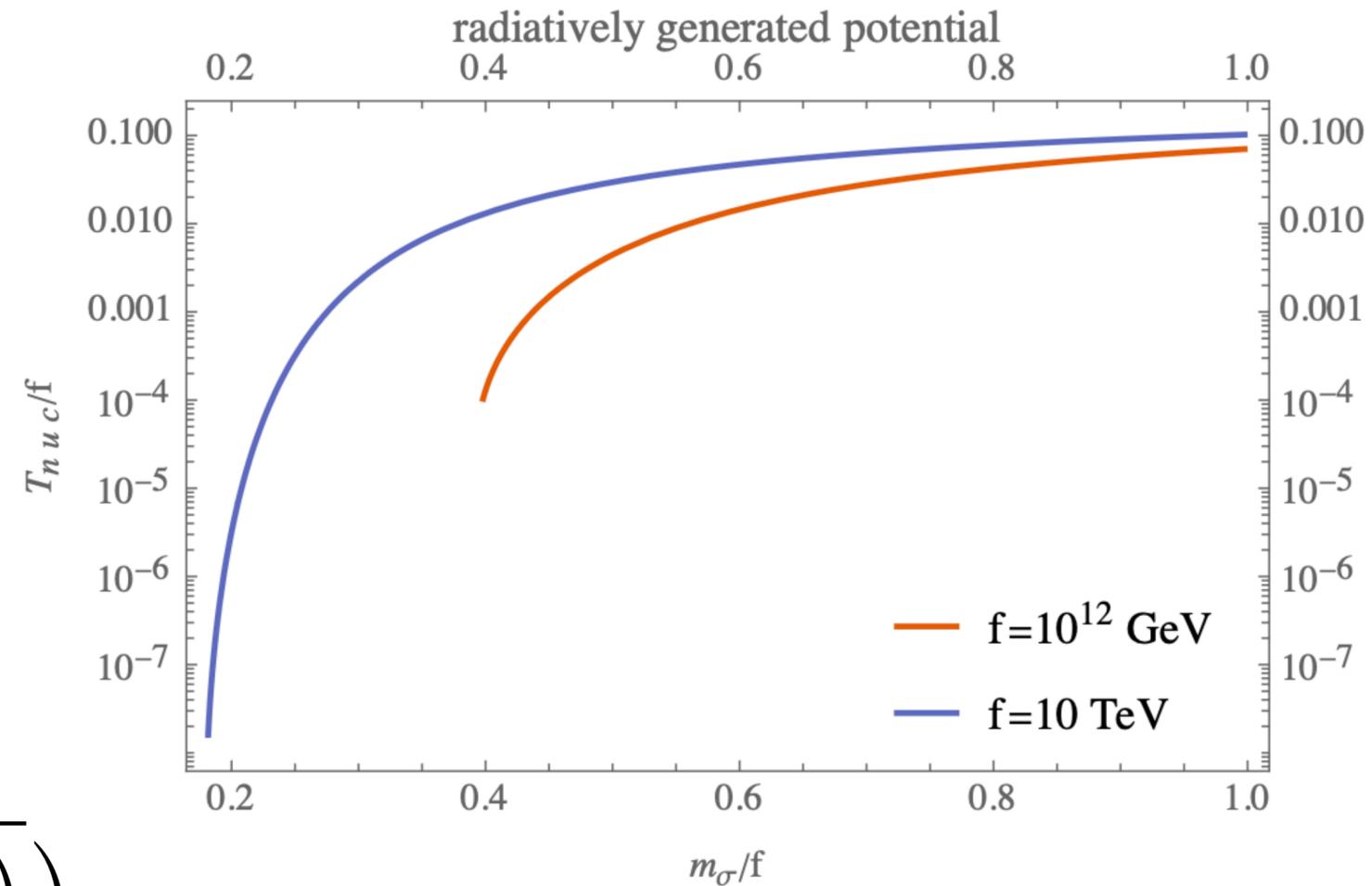
Light dilaton potential

- Potential $\quad V(\chi, T) = V_\chi^{T=0}(\chi) + \Delta V_T^{1-loop}(\chi, T)$

Tree level $\quad V_\chi^{T=0}(\chi) = c_\chi g_\chi^2 \chi^4 \left(1 - \dfrac{1}{1 + \gamma_\epsilon/4} \left(\dfrac{\chi}{f} \right)^{\gamma_\epsilon} \right)$

1-loop thermal corrections
$$\Delta V_T^{1-\text{loop}}(\chi, T) = \sum_{\text{CFT bosons}} \frac{nT^4}{2\pi^2} J_b \left(\frac{m_{CFT}^2}{T^2} \right)$$

radiatively generated potential

- Analytical Formula for T_{nuc}

$$T_{nuc} = \sqrt{H_\Lambda T_c} \left(\frac{2\pi}{S_4} \right)^{1/16} \exp\left(\frac{1}{2} \sqrt{-A + \left(\ln \frac{T_c}{H_\Lambda} + \frac{1}{8} \ln \frac{S_4}{2\pi} \right)} \right)$$

Baryogenesis from Dark Matter-Neutron Oscillations

- Low energy Lagrangian

$$\mathscr{L}_{eff} = \bar{\chi}(i\not{D} - m_\chi)\chi + \bar{n}(i\not{\partial} - m_n + \mu_n\sigma^{\mu\nu}F_{\mu\nu})n - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'^\mu A'_\mu - \delta m\,\bar{n}\chi - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \mathrm{h.c}$$

- UV model: relevant interactions

$$\mathscr{L}_{UV} = \mu\Phi_{1,a}\Phi_2^{*a}\phi + \lambda_1\bar{d}^a P_L\chi\Phi_{1,a} + \lambda_2\epsilon^{abc}\bar{u}_a^C P_R d_b\Phi_{2,c} + \mathrm{h.c.}$$

$$\downarrow \quad \text{INTEGRATE OUT THE HEAVY TRIPLET SCALARS}$$

$$\frac{\lambda_1\lambda_2\mu}{m_{\Phi_1}^2 m_{\Phi_2}^2}\phi\,\epsilon^{abc}(\bar{u}_a^C P_R d_b)(\bar{\chi}P_R d_c)$$

$$\downarrow \quad \text{THE SCALAR } \phi \text{ GETS A VEV}$$

$$\delta m = \frac{\lambda_1\lambda_2\beta\langle\phi\rangle\mu}{m_{\Phi_1}^2 m_{\Phi_2}^2} \sim 10^{-10}\,\mathrm{MeV}$$