Nanohertz Gravitational Waves from the Baryon-Dark Matter Coincidence

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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?

Motivation

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- Hint of a Stochastic Gravitational Wave Background from a First Order Phase Transition (FOPT) from Pulsar Timing Arrays?

QUESTION…Can we link the Pulsar Timing Arrays signal with the generation of the baryon asymmetry?

Cosmological First Order Phase Transitions and Gravitational Waves

- 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.

- PT parameters for the GW prediction:
  - **Nucleation Temperature** T_n $\quad \Gamma(T_n) \simeq H(T_n)^4$
  - **Phase Transition Strength** $\quad \alpha = \left.\frac{\Delta V}{\rho_{rad}}\right|_{T_{nuc}}$
  - **Phase Transition Rate** $\quad \beta_H \equiv \frac{\beta}{H} = T \left.\frac{dS}{dT}\right|_{T_{nuc}}$
  - **Bubble Wall Velocity** v_w

- PTAs signal ⟶ $\nu_{\text{peak}} \sim \text{nHz}$ for $\text{v} \lesssim 100\ \text{MeV}$

  ⟶ GW spectrum could be generated by a **supercooled** PT [Gouttenoire 2307.04239] [Freese,Winkler 2401.13729]

- The PT is said to be **supercooled** when the vacuum energy of the Universe dominates the energy density of the Universe.

Baryogenesis from Dark Matter-Neutron Oscillations

[Bringmann,Cline,Cornell 1810.08215]

- Motivations: Asymmetric Dark Matter + Neutron Lifetime Anomaly

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

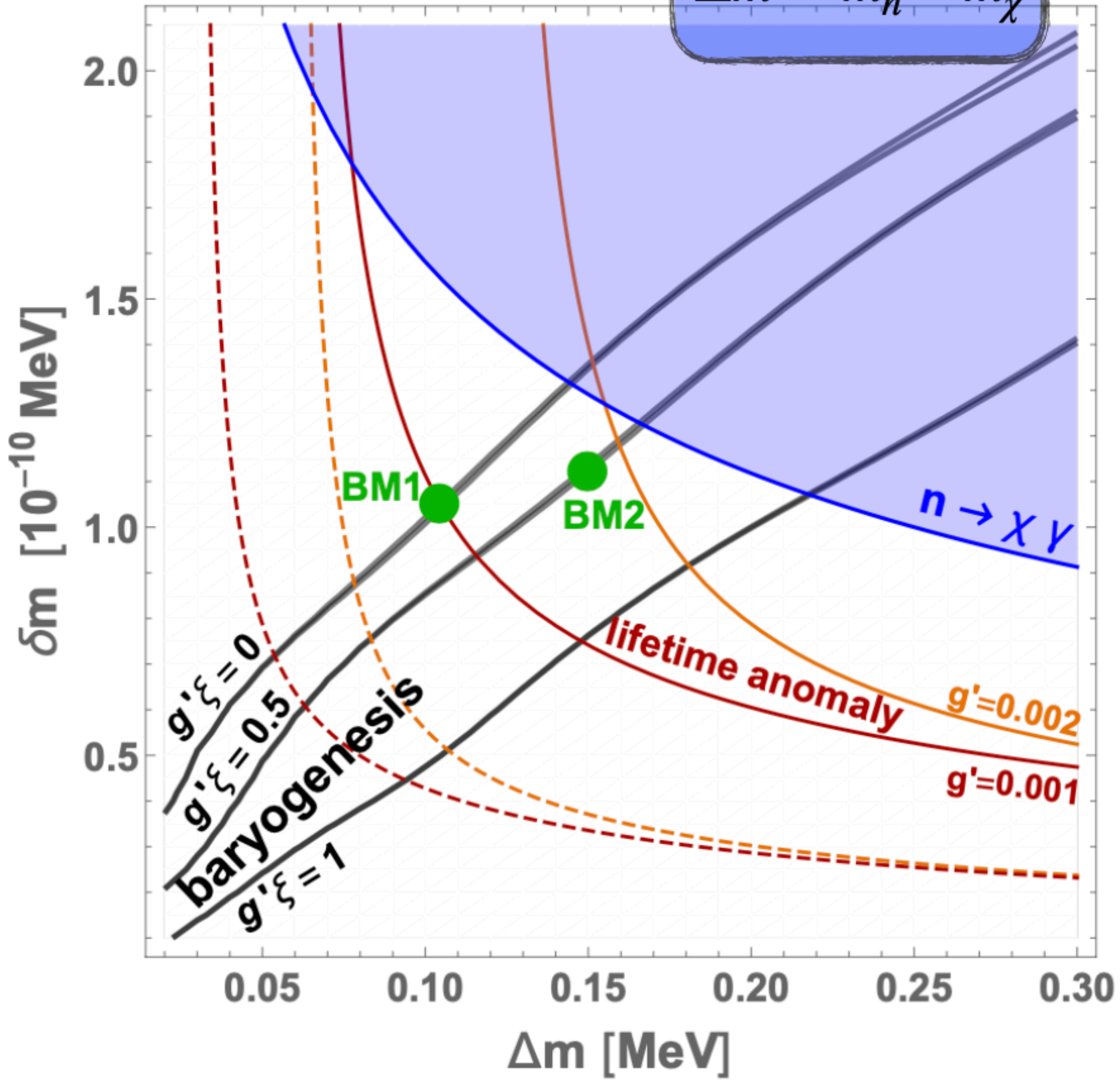
- Baryon Asymmetry generated via resonant oscillations between Dark Matter χ and the neutron n

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

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

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

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



VEV can be obtained via Radiative Symmetry Breaking

- **Coleman-Weinberg model** ⟶ **Weakly-coupled supercooled FOPT**

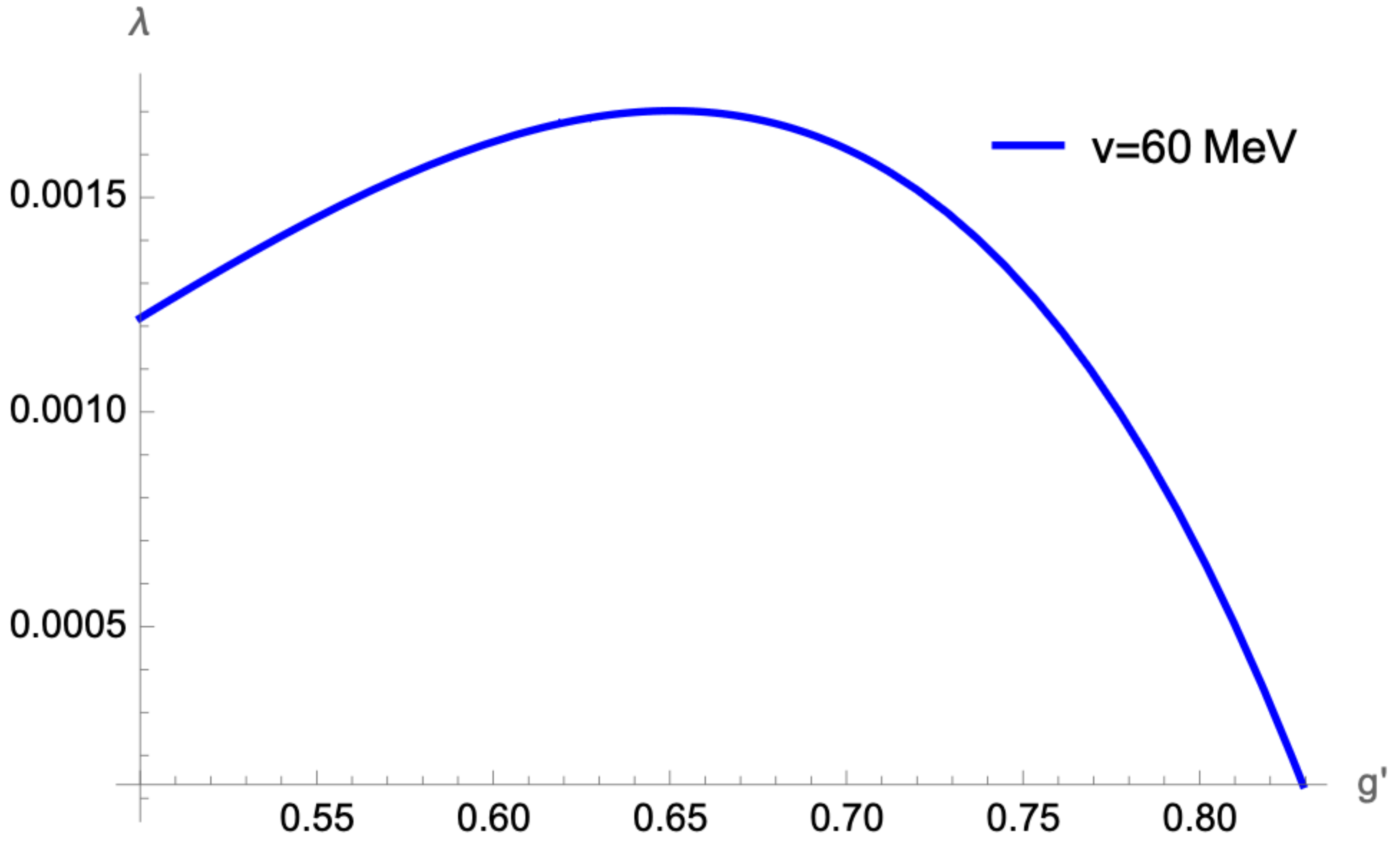
[Coleman,Weinberg, Phys.Rev. D-1888]

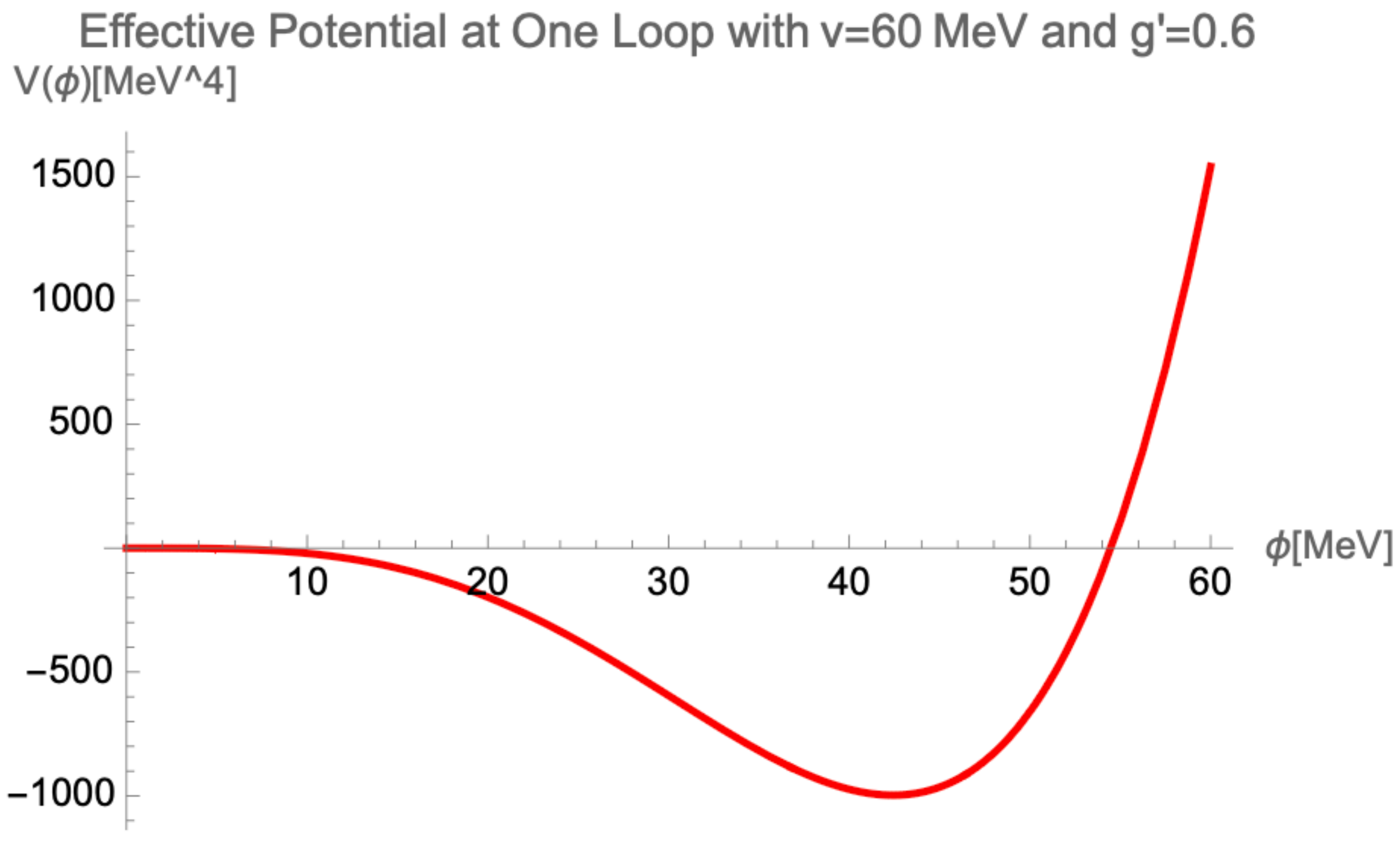
Tree level potential is classically scale invariant

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

We add radiative corrections at 1-loop

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



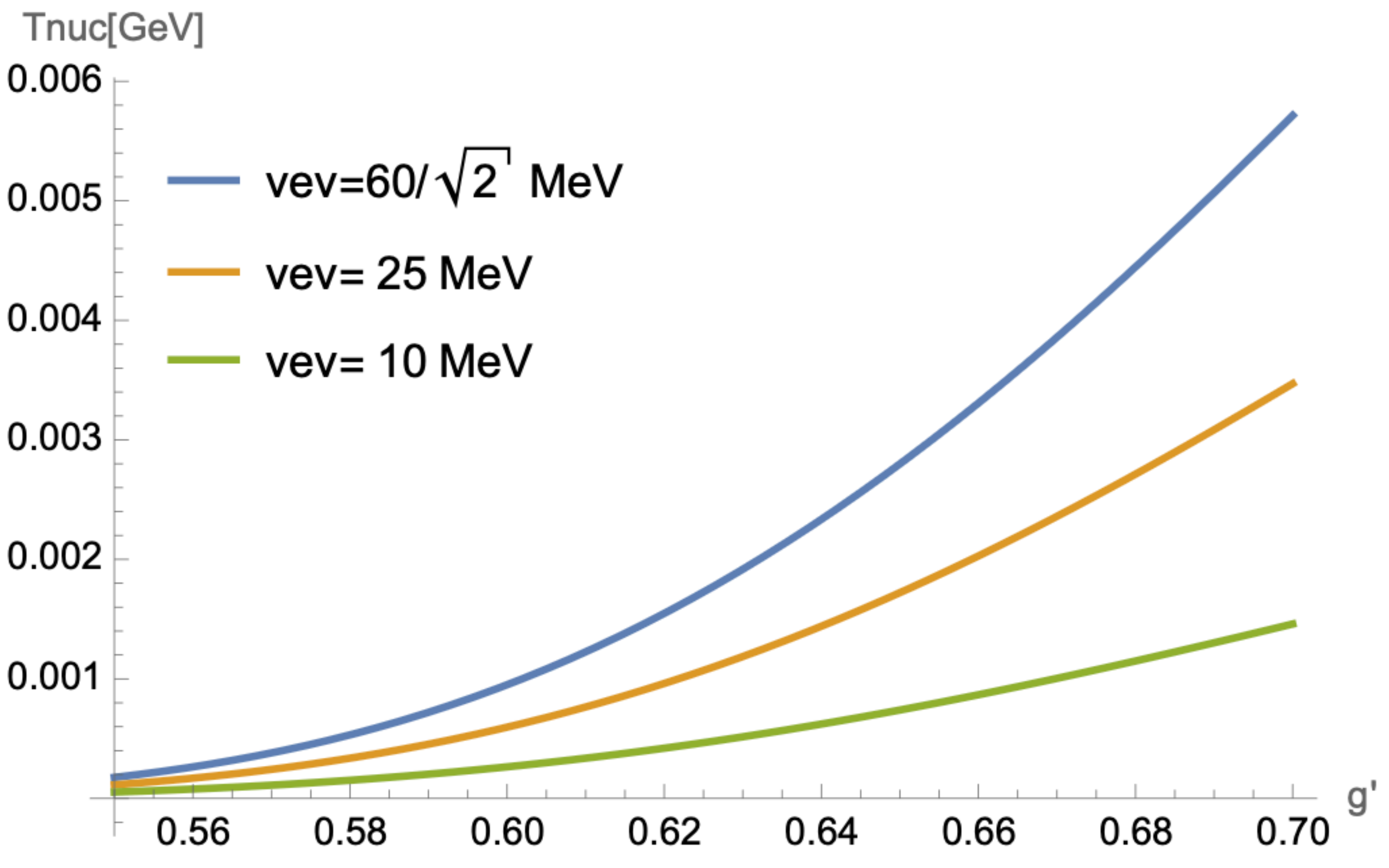


$g'\xi = 0.5$

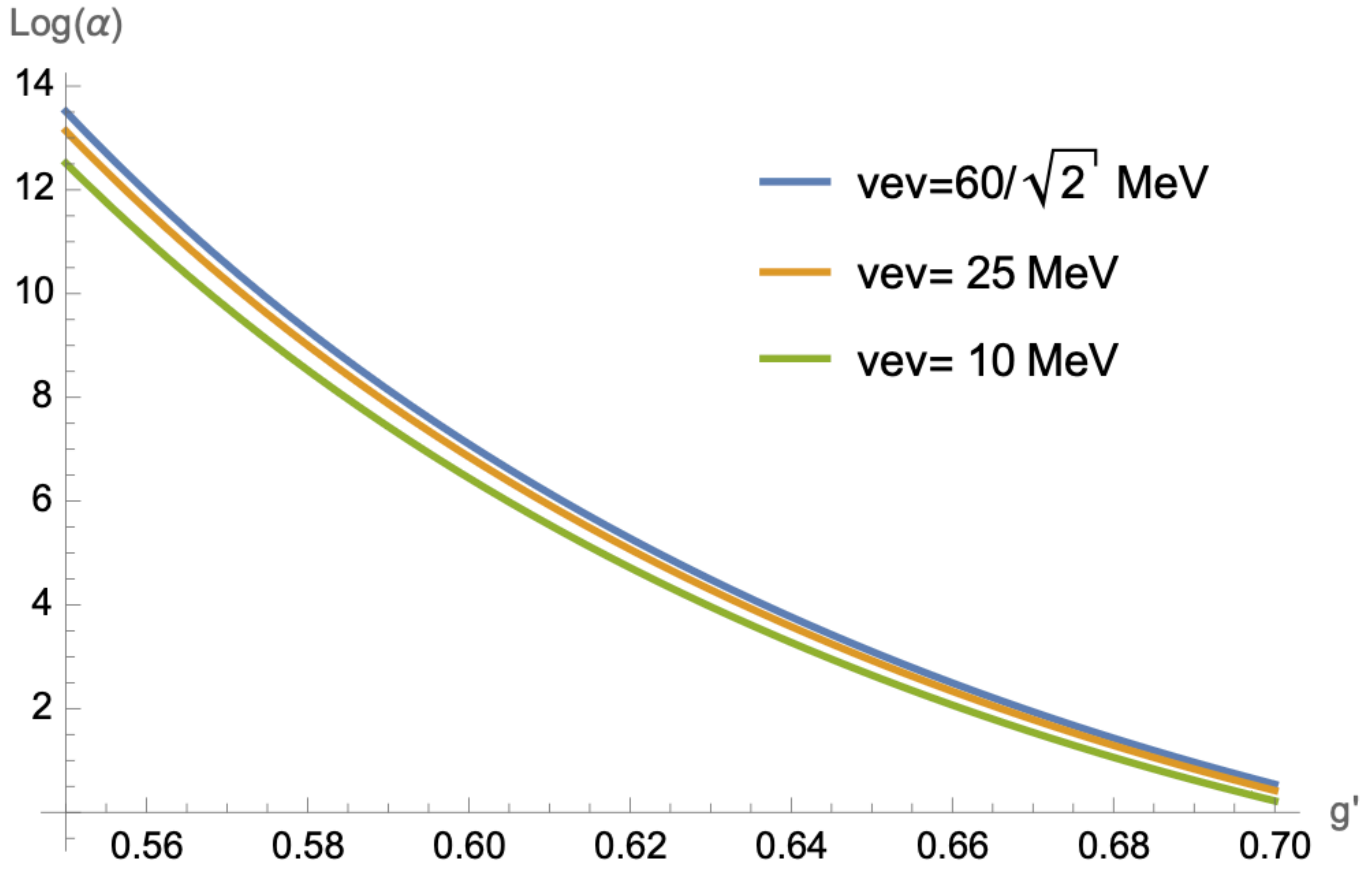
GW Parameters

Results

- The tunnelling rate is dominated by thermal effects



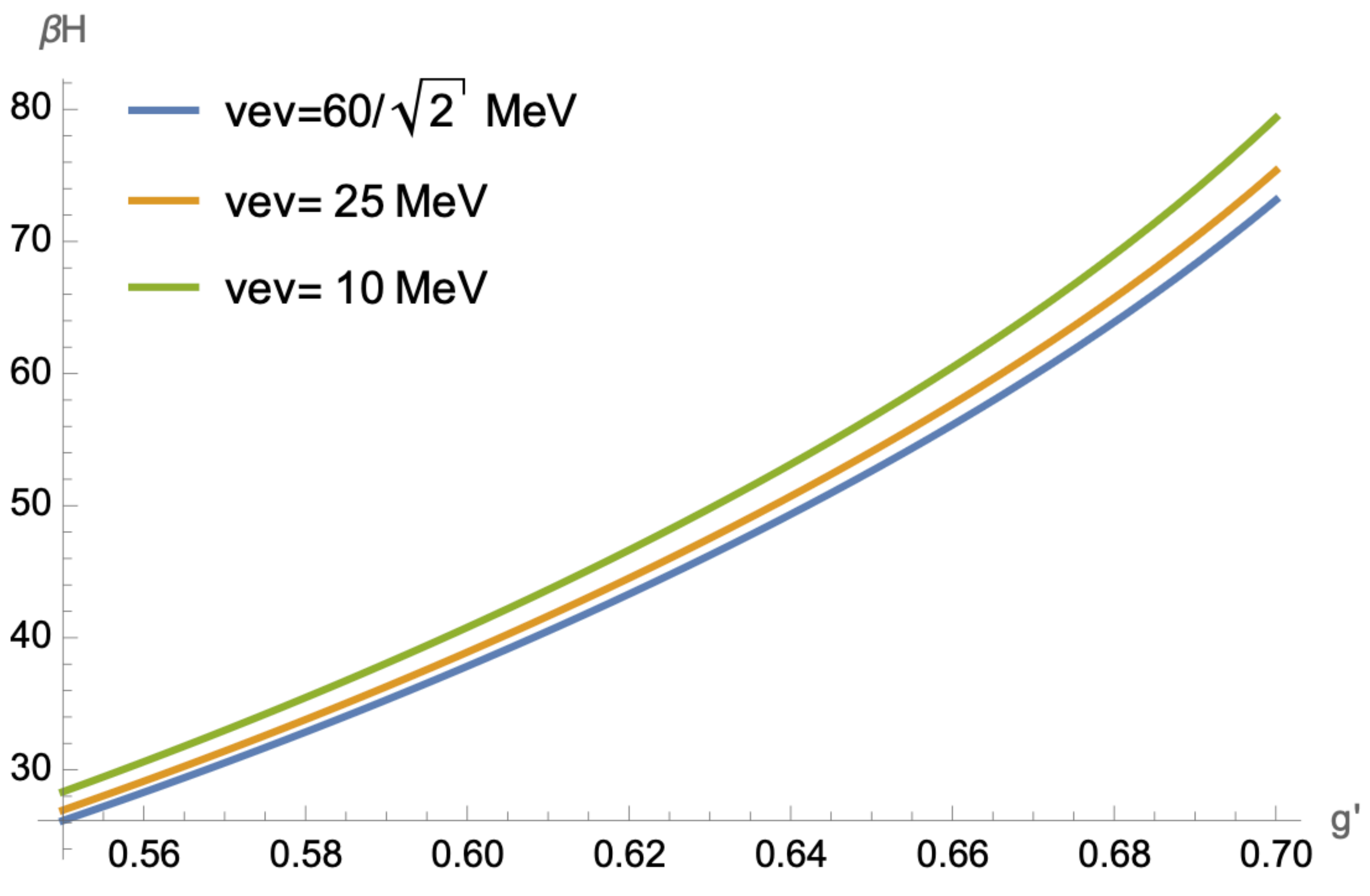
Nucleation Temperature T_{nuc}



Phase Transition Strength α

GW Parameters

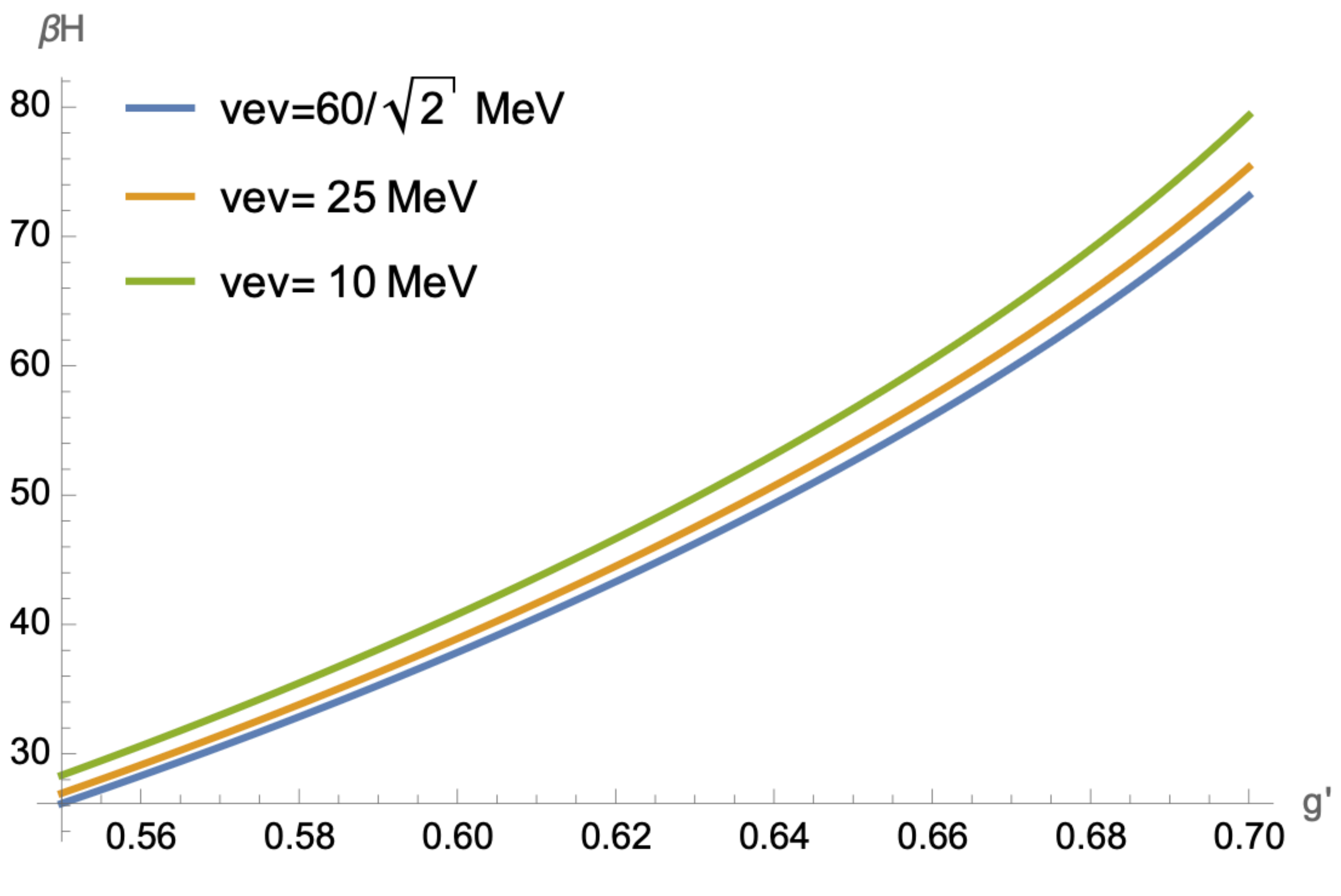
Results



Phase Transition Rate β/H

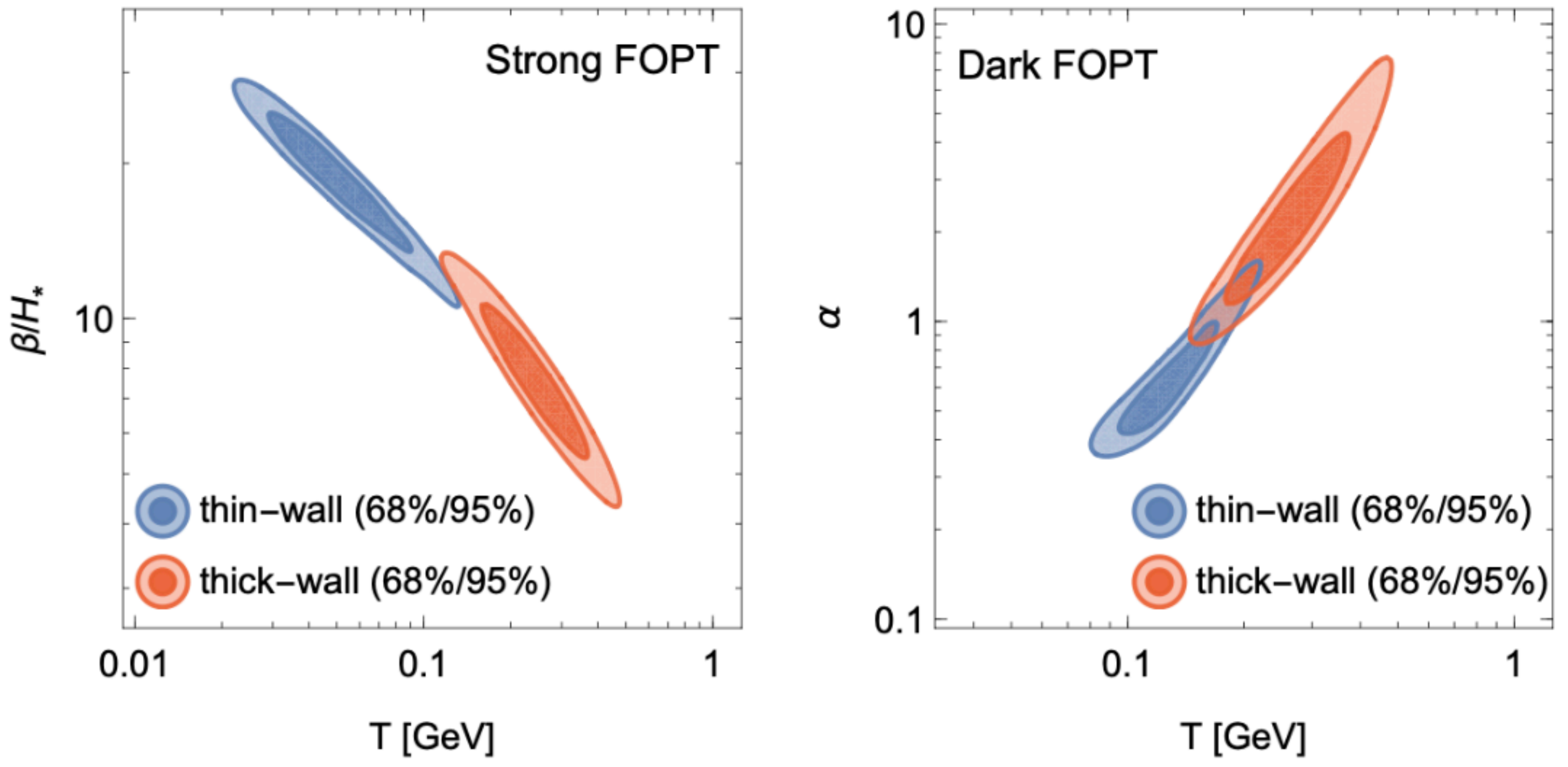
GW Parameters

Results



Phase Transition Rate β/H

PTAs data fit [Freese,Winkler 2401.13729]



$\beta/H \lesssim 100$ ✓

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!

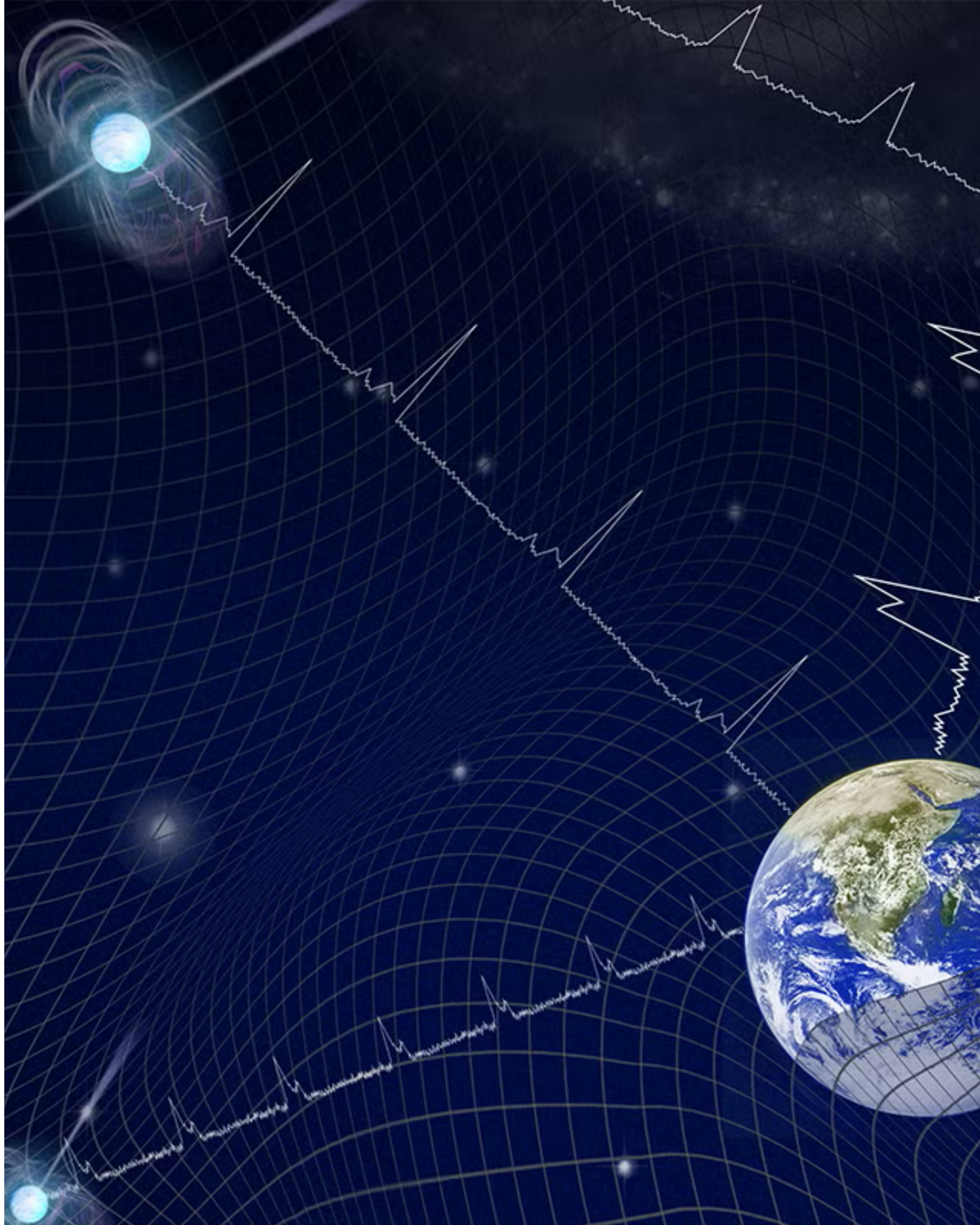
BACK UP SLIDES

Pulsar Timing Arrays

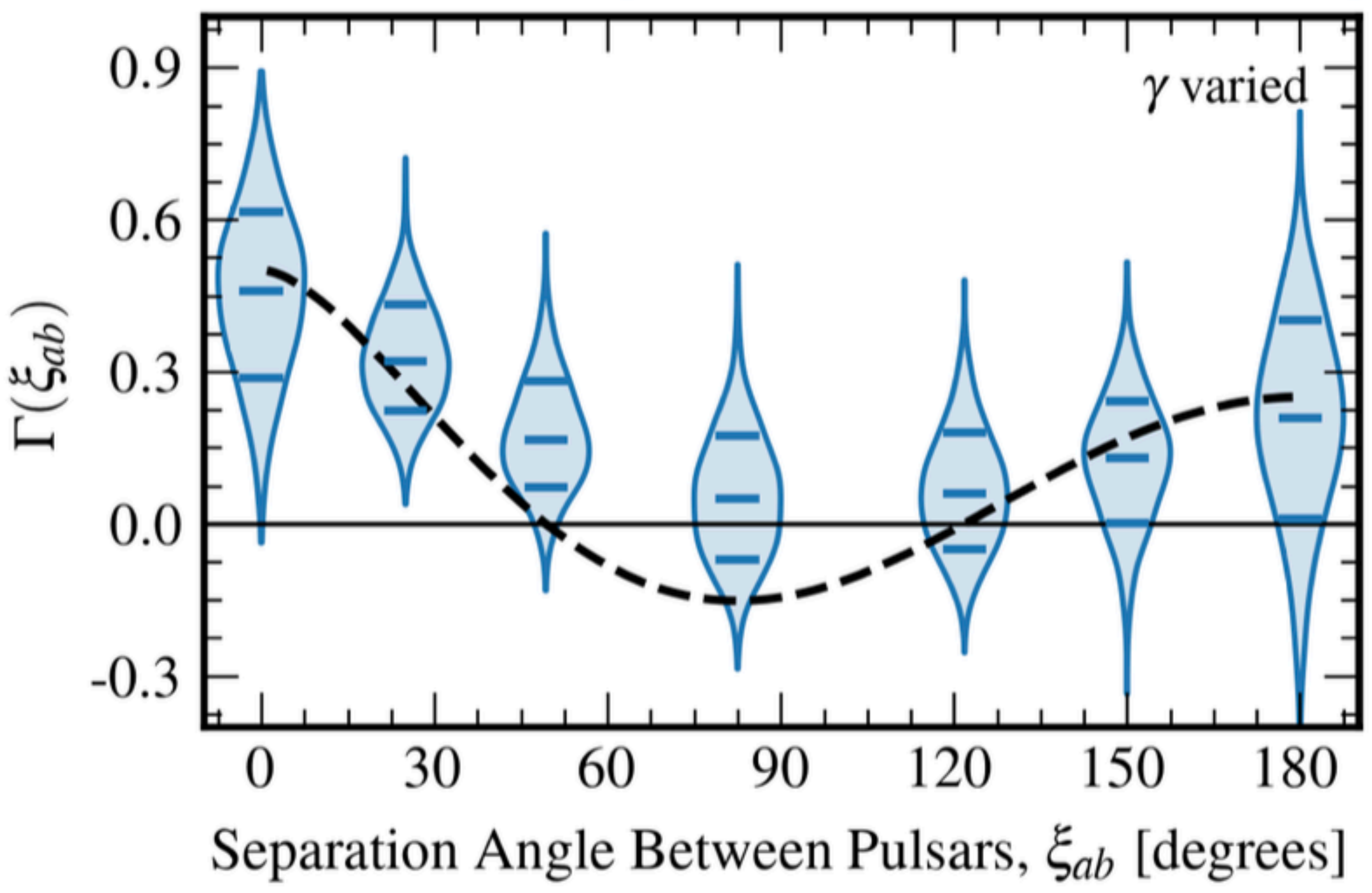
- **Pulsar:** rapidly rotating magnetised neutron star which emits electromagnetic radiation along the rotation axis

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

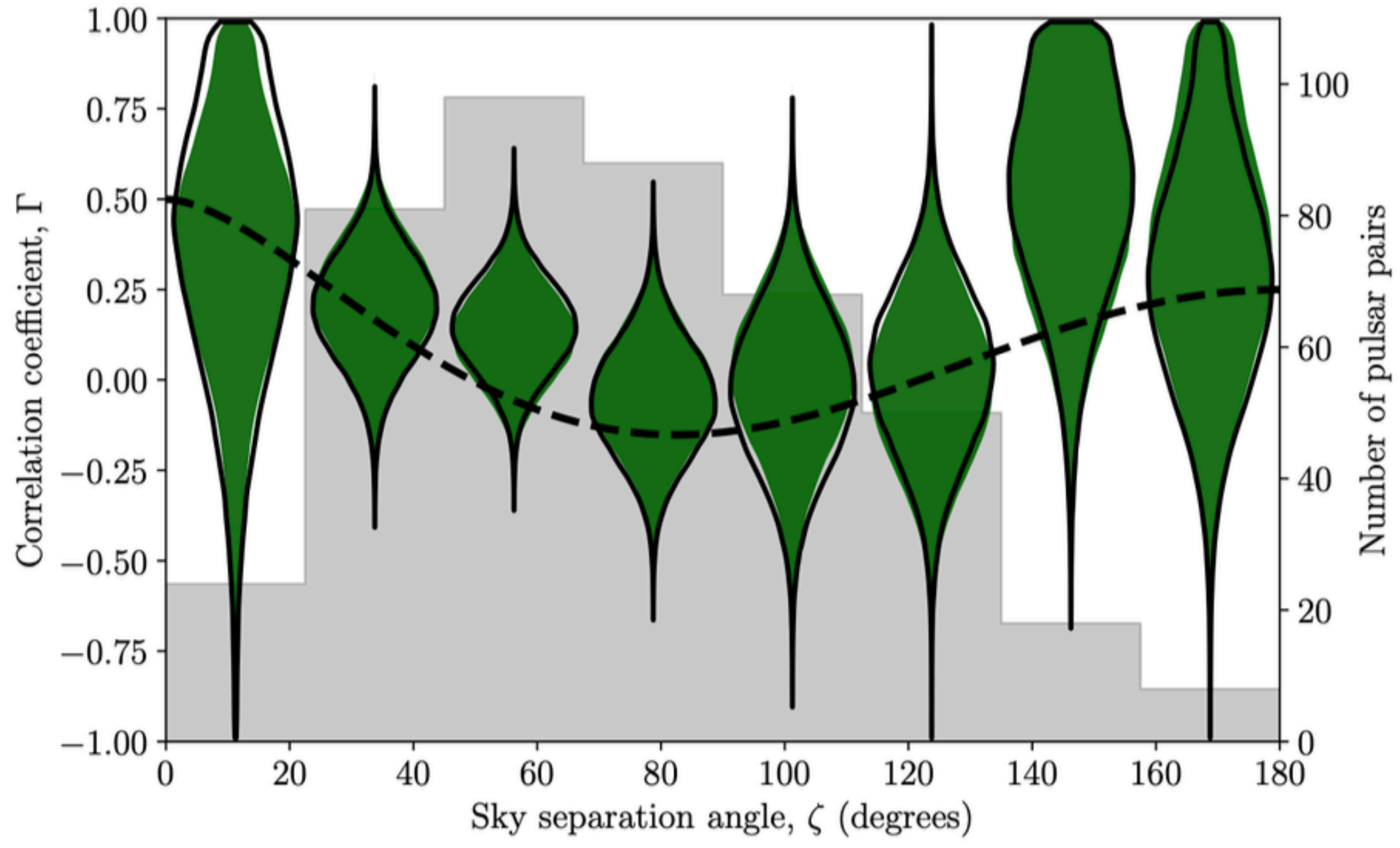
- **Pulsar Timing Arrays**: concept of timing very stable millisecond pulsars to detect GWs



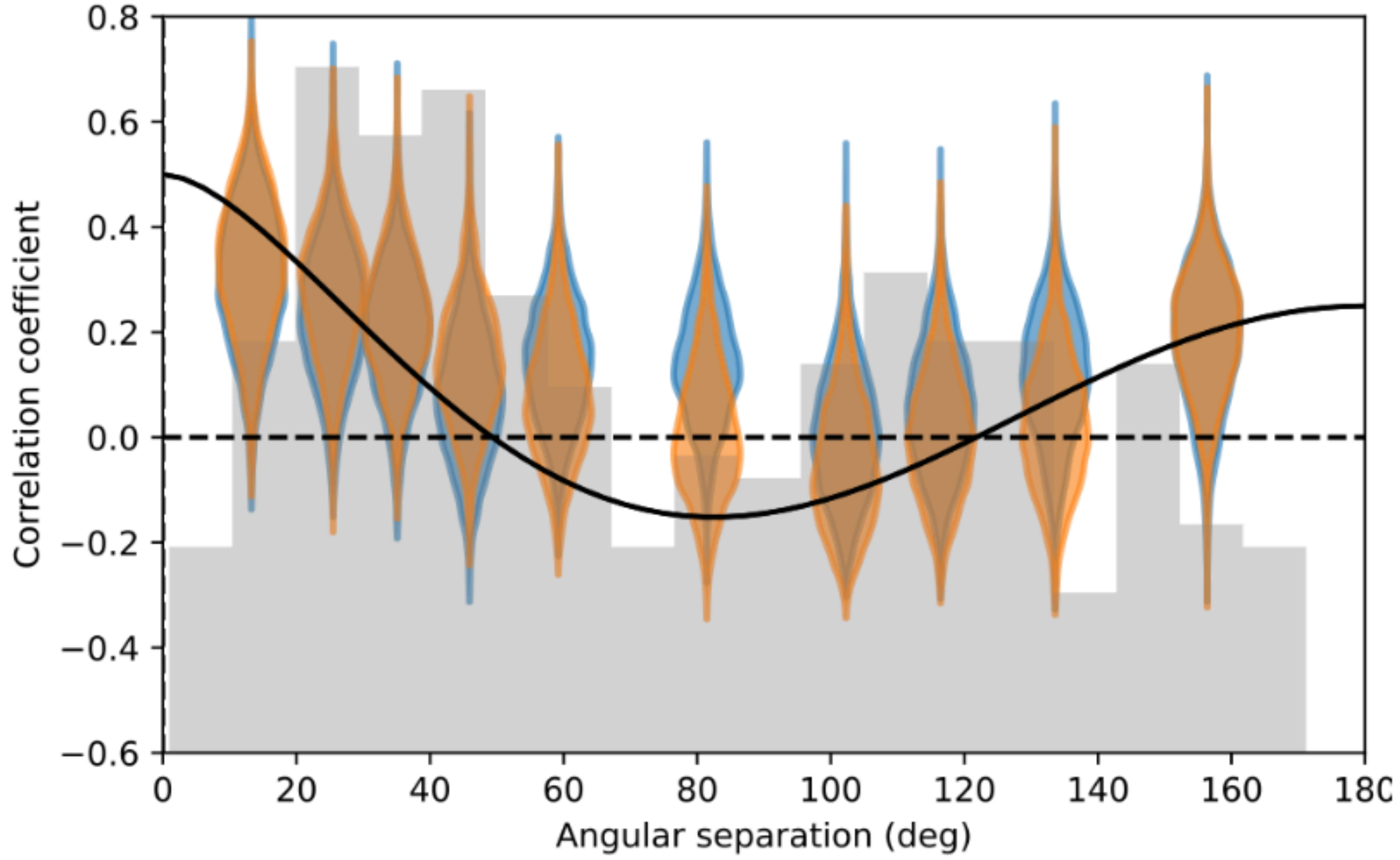
Pulsar Timing Arrays



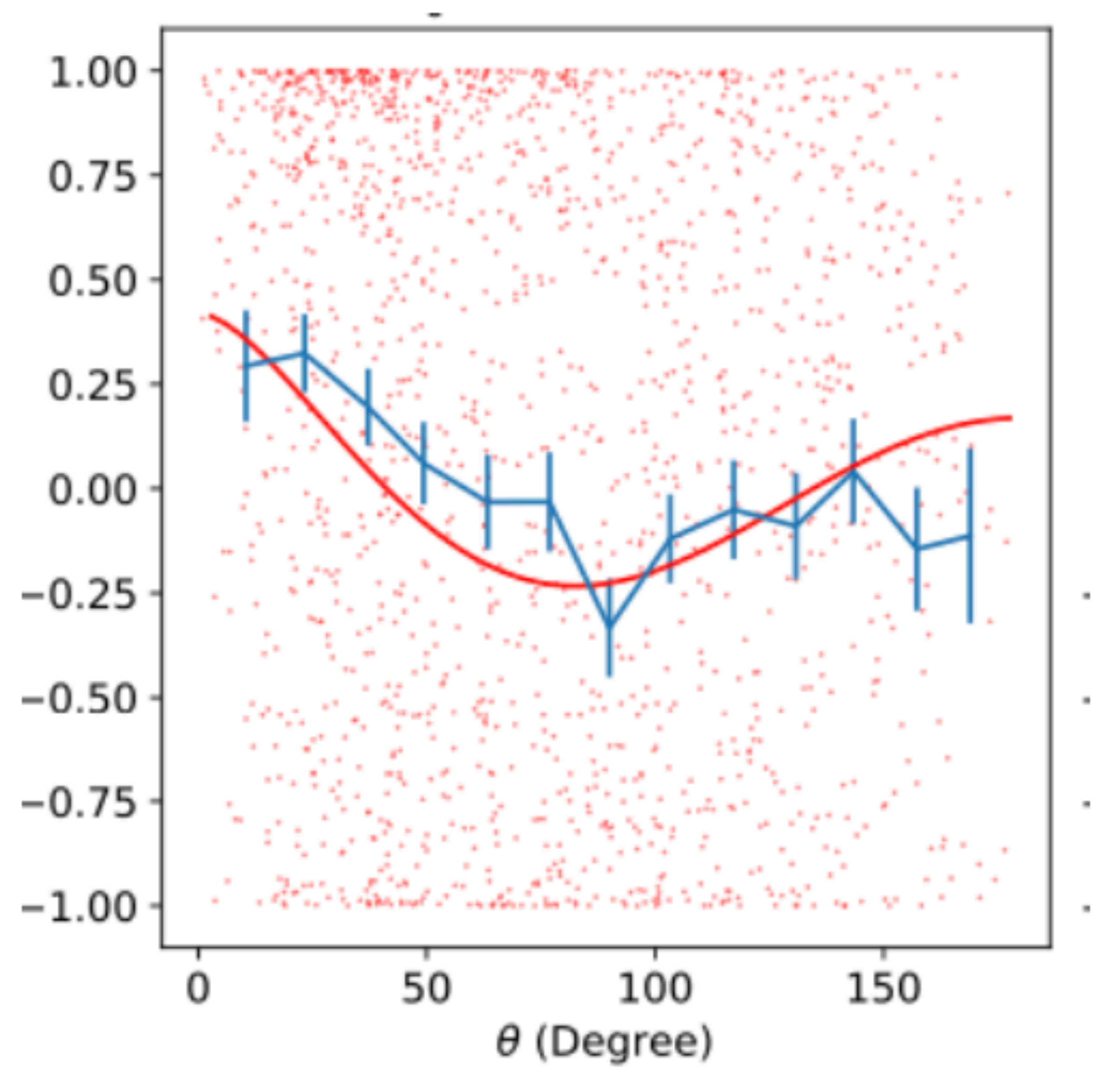
[NANOGrav, 2306.16213]



[PPTA, 2306.16215]



[EPTA, 2306.16214]



[CPTA, 2306.16216]

Cosmological First Order Phase Transitions

- PT parameters for the GW prediction

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  - **Bubble Wall Velocity** v_w

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- GW spectrum

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

$\nu_{\rm peak} \sim$ nHz for v $\lesssim 100$ MeV
for Pulsar Timing Arrays

The Baryon Asymmetry of the Universe

- We live in a Universe with more matter than antimatter

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

[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 $\phi'(0) = 0 \qquad \lim_{r\to\infty} \phi(r) = 0$

- Solutions → Overshoot-Undershoot Algorithm
  → (Semi-) Analytical Approximations

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Baryogenesis from Dark Matter-Neutron Oscillations

- Low energy Lagrangian

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

- UV model: relevant interactions

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

↓ Integrate out the heavy triplet scalars

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

↓ The scalar ϕ gets a vev

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

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

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

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

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

For the Coleman-Weinberg model