# PATHS THROUGH THE DARK: COMPARING APPROACHES FOR FOPTS

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JG|U

**In collaboration** with Eric Madge, Maura E. Ramírez-Quezada and Pedro Schwaller

# GW detection opens a window to study physics BSM

**GWs down to the nHz regime**

→ **PTA**: EPTA, NANOGrav, IPTA

- SMBHB
- New Physics
  - FOPTs
  - DW
  - CS
  - Axion dynamics

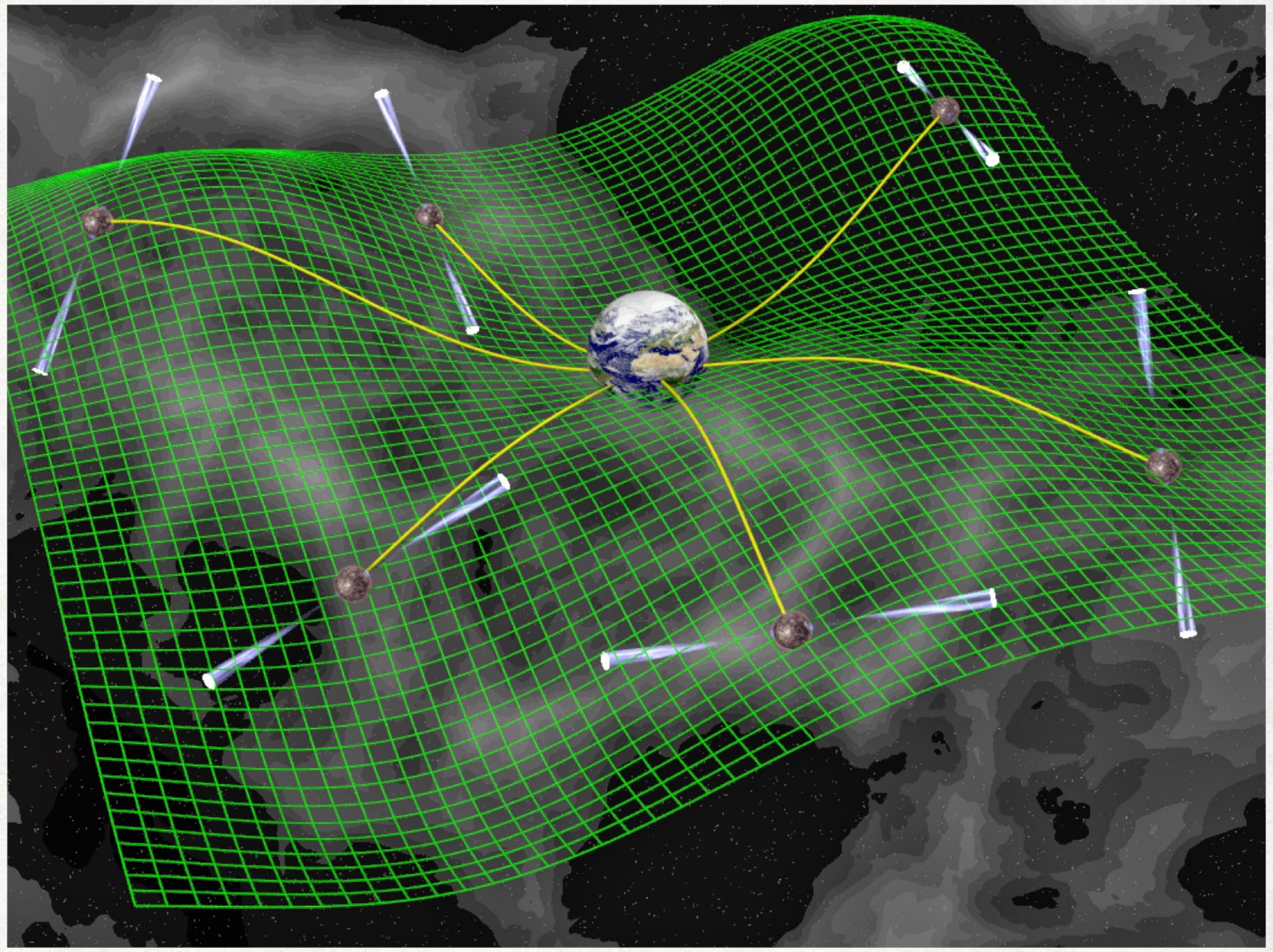


Image credit: David Champion

📖 https://arxiv.org/pdf/2306.14856

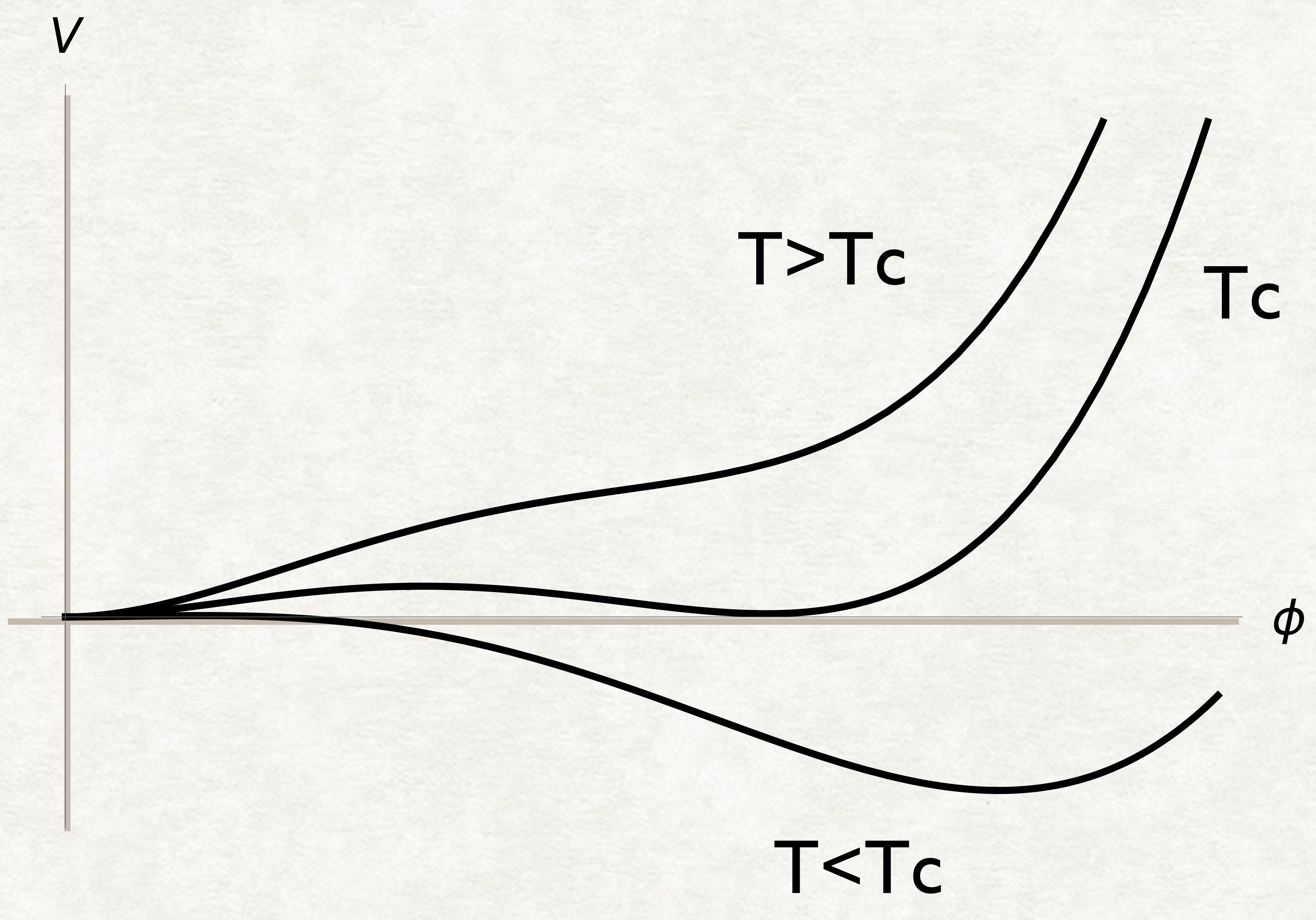
by E. Madge, E. Morgante, **CPI**, N. Ramberg, W. Ratzinger, S.Schenk, P. Schwaller

# GW detection opens a window to study physics BSM

**GWs down to the nHz regime**

→ **FOPT**

**Supercooling**: Delay of the FOPT below Tc



# GW detection opens a window to study physics BSM

**GWs down to the nHz regime**

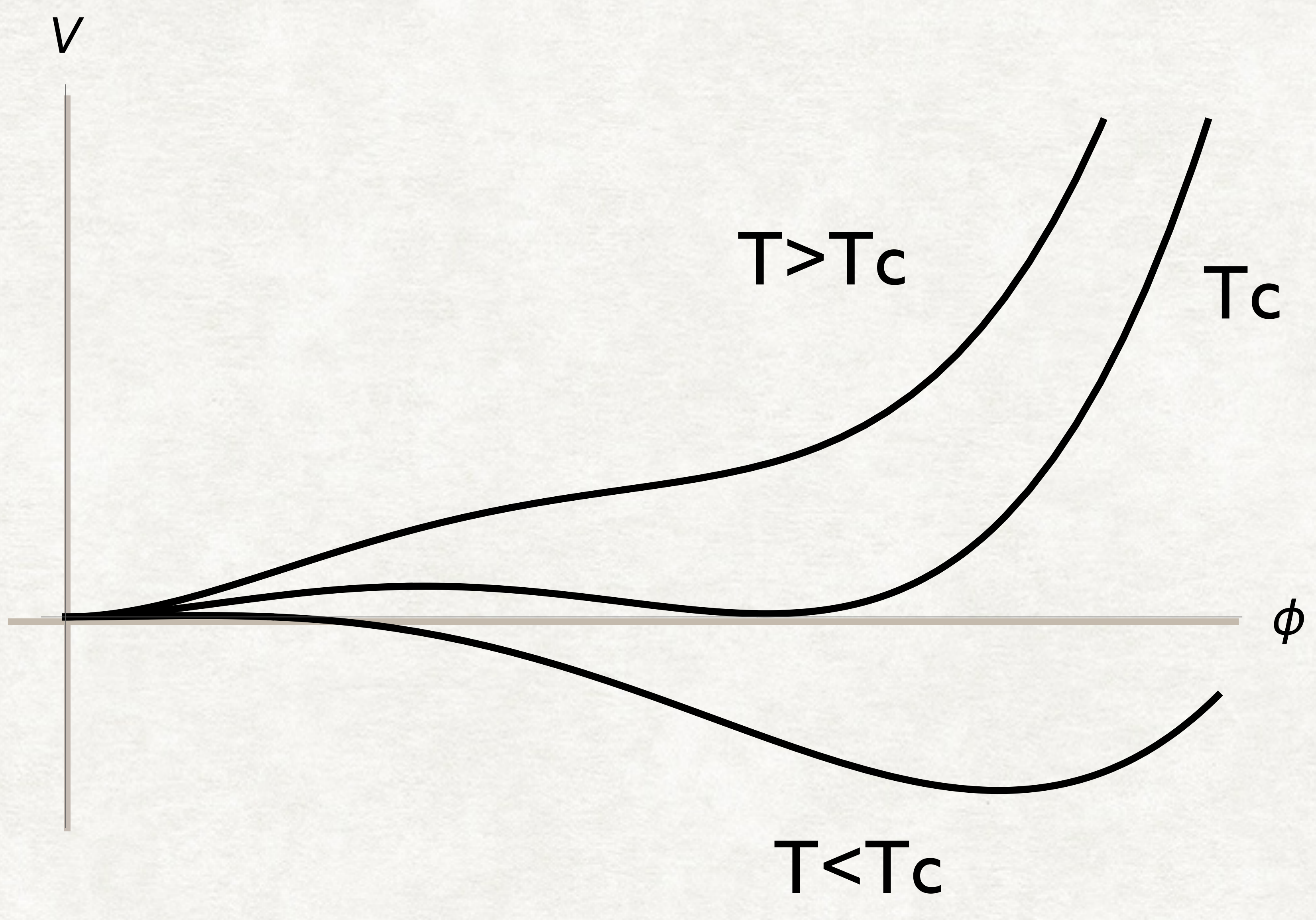
→ **FOPT**

**TFT**

$$\phi(\mathbf{x},\tau) = \sum_{n=-\infty}^{\infty} \phi_n(\mathbf{x}) e^{i\omega_n \tau}$$

$$\omega_n^{\text{bosons}} = 2\pi T n$$

**Supercooling**: Delay of the FOPT below Tc



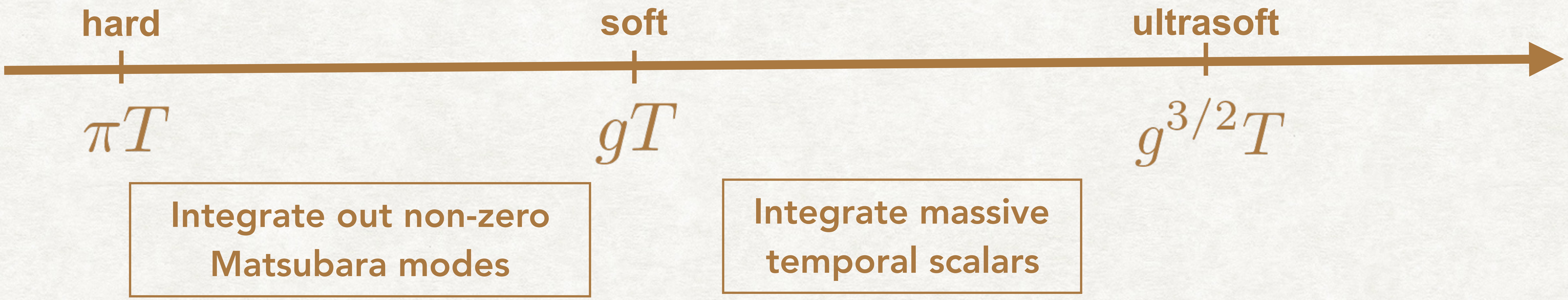

IR divergences: **Breakdown of perturbation theory**

# Resumation

## DAISY RESUMATION

$$V_{\text{ring}}(\phi, T) = -\frac{T}{12\pi} \sum_i n_i \left[ \left(m_i^2(\phi, T)\right)^{3/2} - \left(m_i^2(\phi)\right)^{3/2} \right]$$

## DIMENSIONAL REDUCTION (DR)



# MATCHING 3D AND 4D THEORY

**DRalgo**

## couplings

$$g_{3d}^2 = g^2 T - \frac{g^4 L_b T}{48\pi^2}$$

$$\lambda_{3d} = \lambda T + \frac{T}{16\pi^2}\left[g^4\left(2 - 3L_b\right) + 6g^2\lambda L_b - 10\lambda^2 L_b\right]$$

$$\lambda_A = 0 + \frac{g^4 T}{\pi^2}$$

$$\lambda_{A\Phi} = 2g^2 T + \frac{g^2 T}{24\pi^2}\left[24\lambda - g^2\left(L_b - 4\right)\right]$$

## masses

$$m_{3d}^2 = m^2 - \frac{T^2(3g^2 + 4\lambda)}{12} + \frac{L_b\left(3g^2 - 4\lambda\right)m^2}{16\pi^2} + \frac{g^4(8 + 216c_+ + 39L_b)T^2}{576\pi^2} + \frac{\lambda^2(12c_+ + 5L_b)T^2}{24\pi^2} - \frac{g^2\lambda(1 + 12c_+ + 3L_b)T^2}{24\pi^2} - \frac{8g_{3d}^4 - 16g_{3d}^2\lambda_{3d} + 16\lambda_{3d}^2 + \lambda_{A\phi}^2}{32\pi^2}\log\frac{\mu_3}{\mu_R}$$

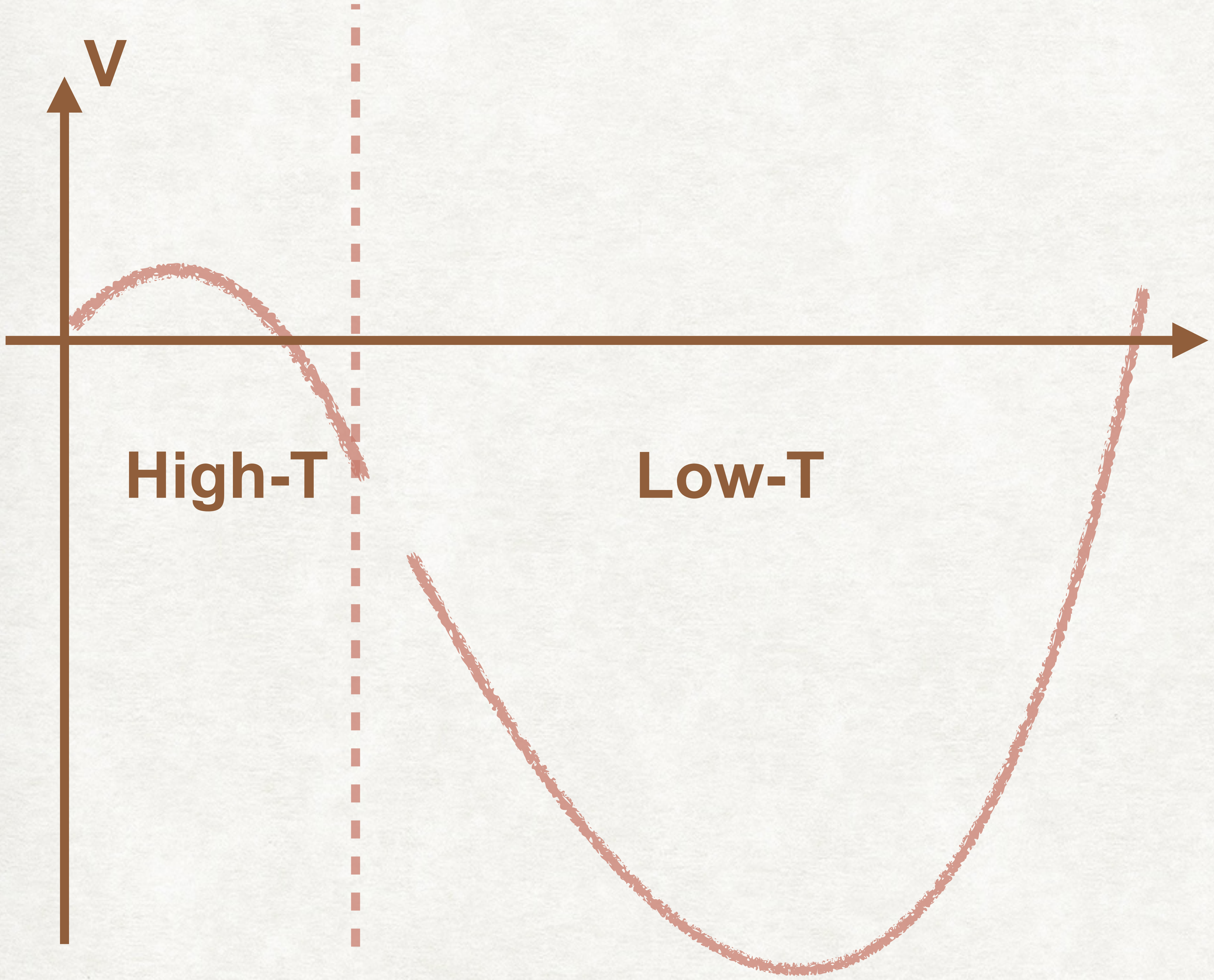
$$\mu_D^2 = \frac{g^2 T^2}{3} + \frac{g^2}{144\pi^2}\left[12\lambda T^2 + g^2(7 - L_b)T^2 - 36m^2\right]$$

## constants

$$c_+ = \frac{1}{2}\left(\gamma_E - L_b - 12\log A\right)$$

$$L_b = \log\frac{\mu_R^2 e^{2\gamma_E}}{16\pi^2 T^2}$$

# CW MODEL




📖 For more details look https://arxiv.org/pdf/2312.12413

M. Kierkla, B. Siezewska, T. V. I. Tenkanen
and J. van de Vis

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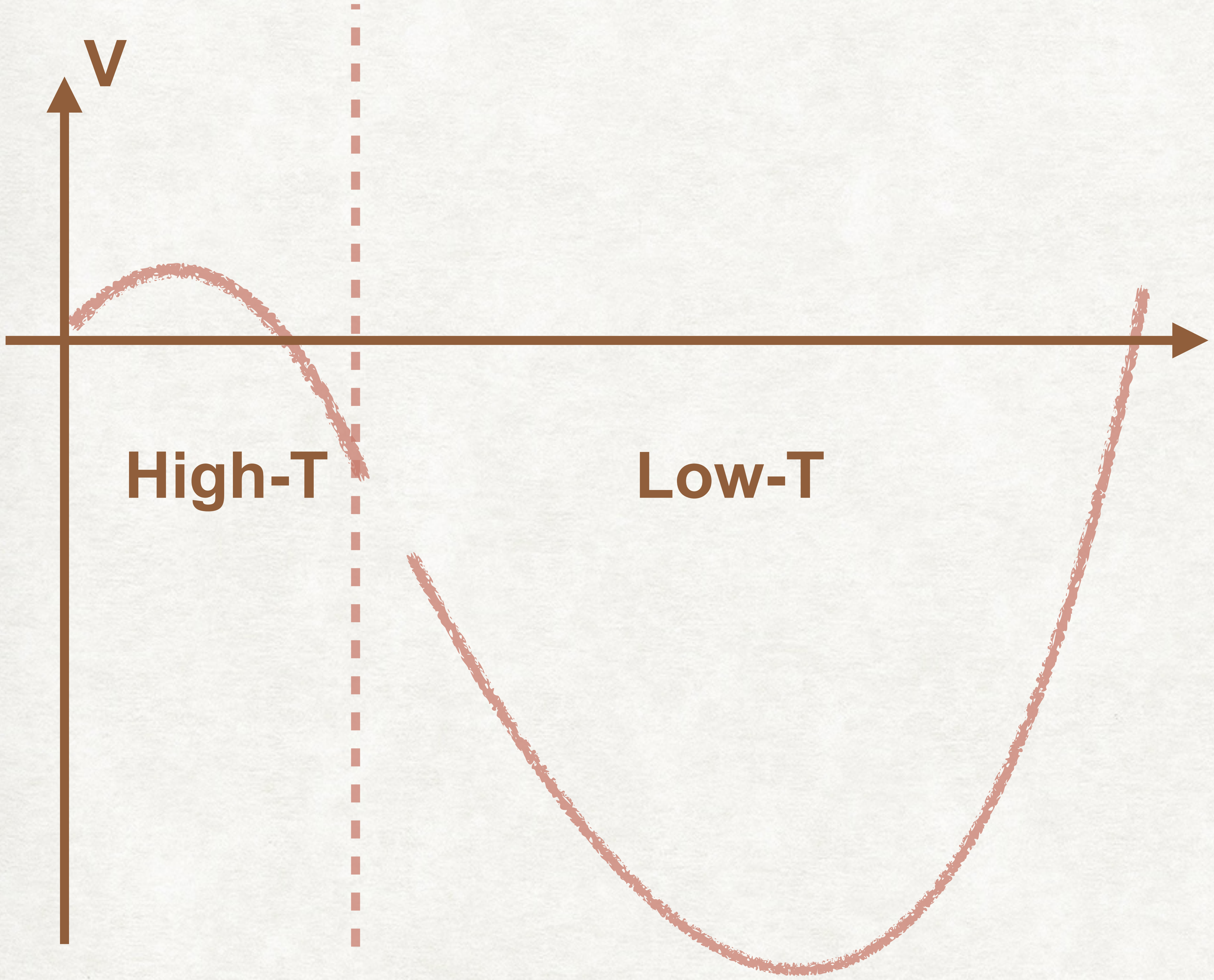
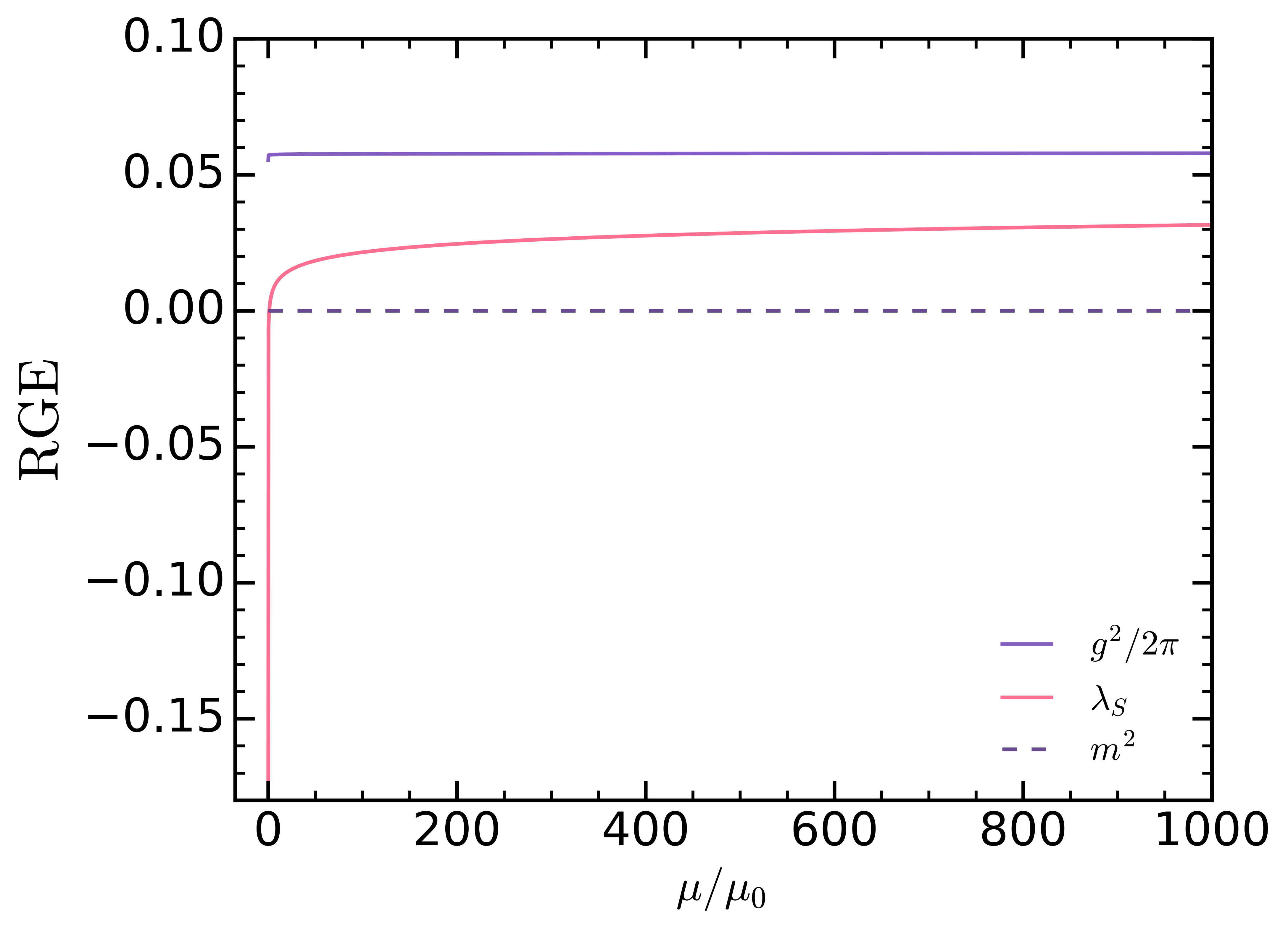



**Include running**

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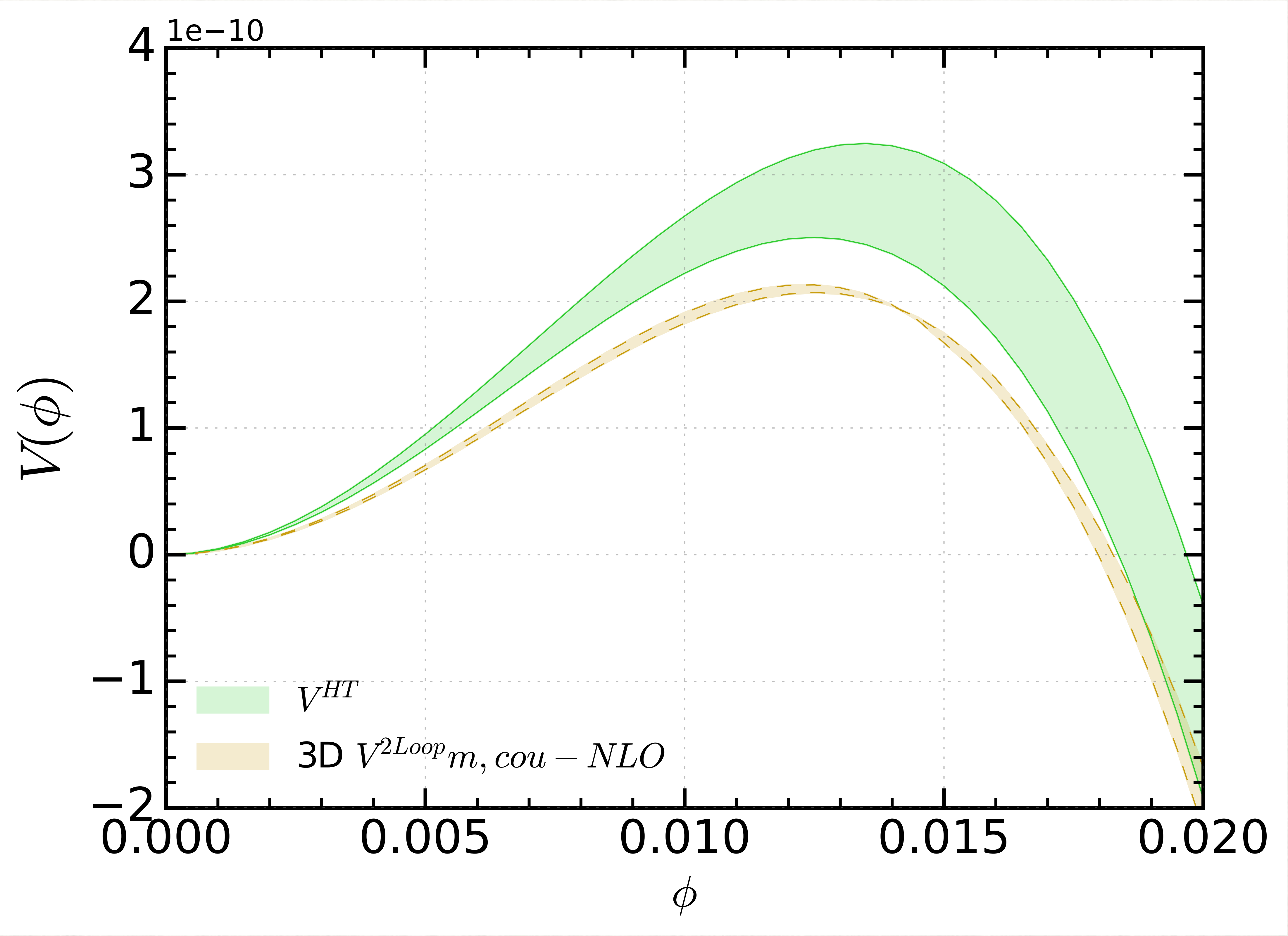
# CW MODEL PROBLEMS

**Dark photon: Extend SM with an additional U(1).**

Classical invariance + radiative breaking: **Coleman-Winberg potential**

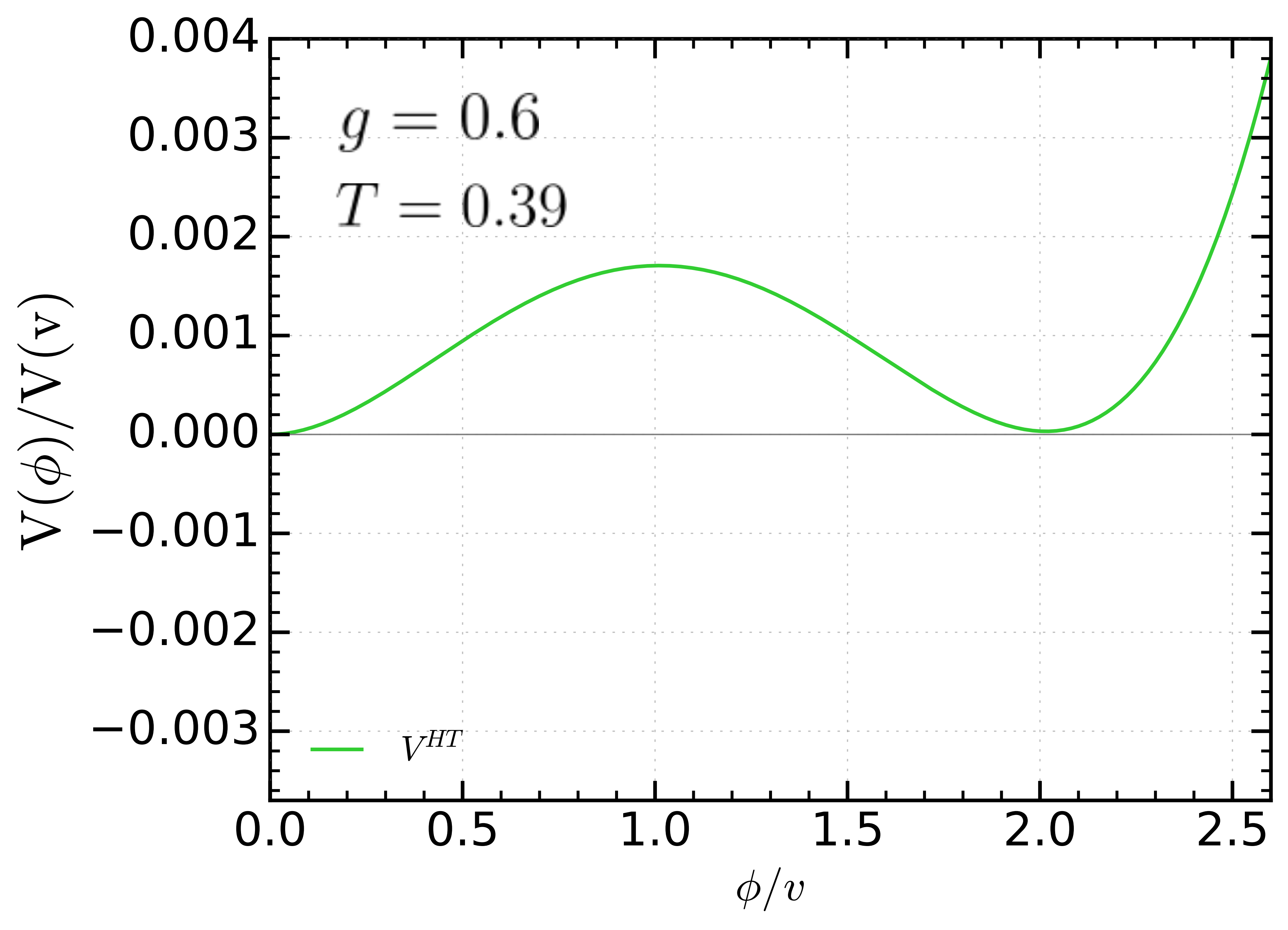
- $$V_{\rm CW} = \sum_i N_i \frac{m_i^4(\phi)}{64\pi^2}\left[\log\left(\frac{m_i^2(\phi)}{\mu_R^2}\right) - c_i\right]$$
- Scale dependence reduced at 2-loop
- $\mu_R = \pi T$ in the 4D approach.



# MODEL AND APPROACHES

$$\phi_{3d} \to \phi/\sqrt{T}$$

**4D:** $V_{eff}(\phi, T) = V_{tree}(\phi) + V_{CW}(\phi, \mu) + V_T(\phi, T) + V_{Daisy}(\phi, T)$



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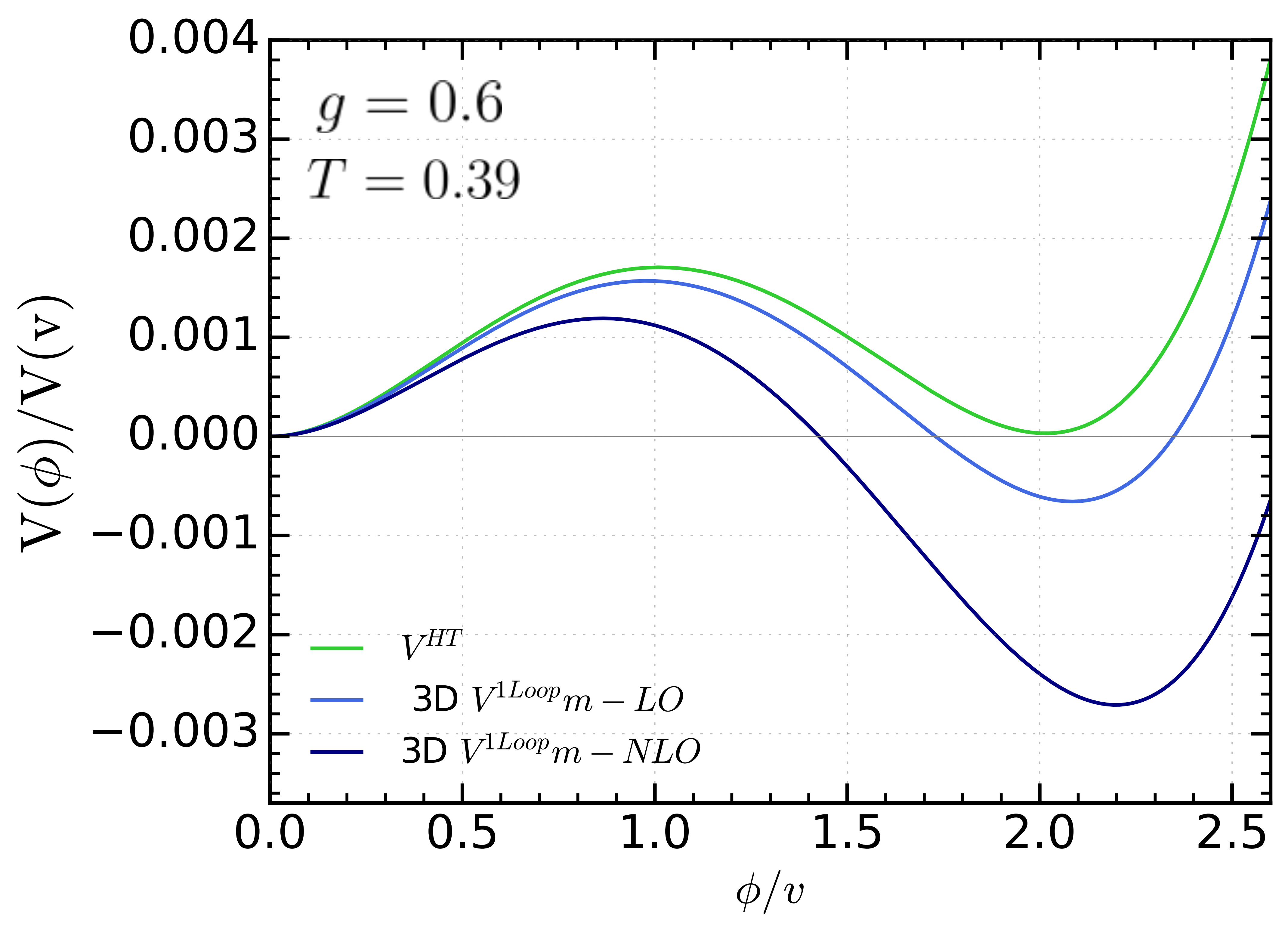
**3D soft:**

- masses at LO + couplings NLO

**NLO (1-Loop):**

- masses at NLO with 3d couplings NLO+couplings NLO



# MODEL AND APPROACHES

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**3D soft:**

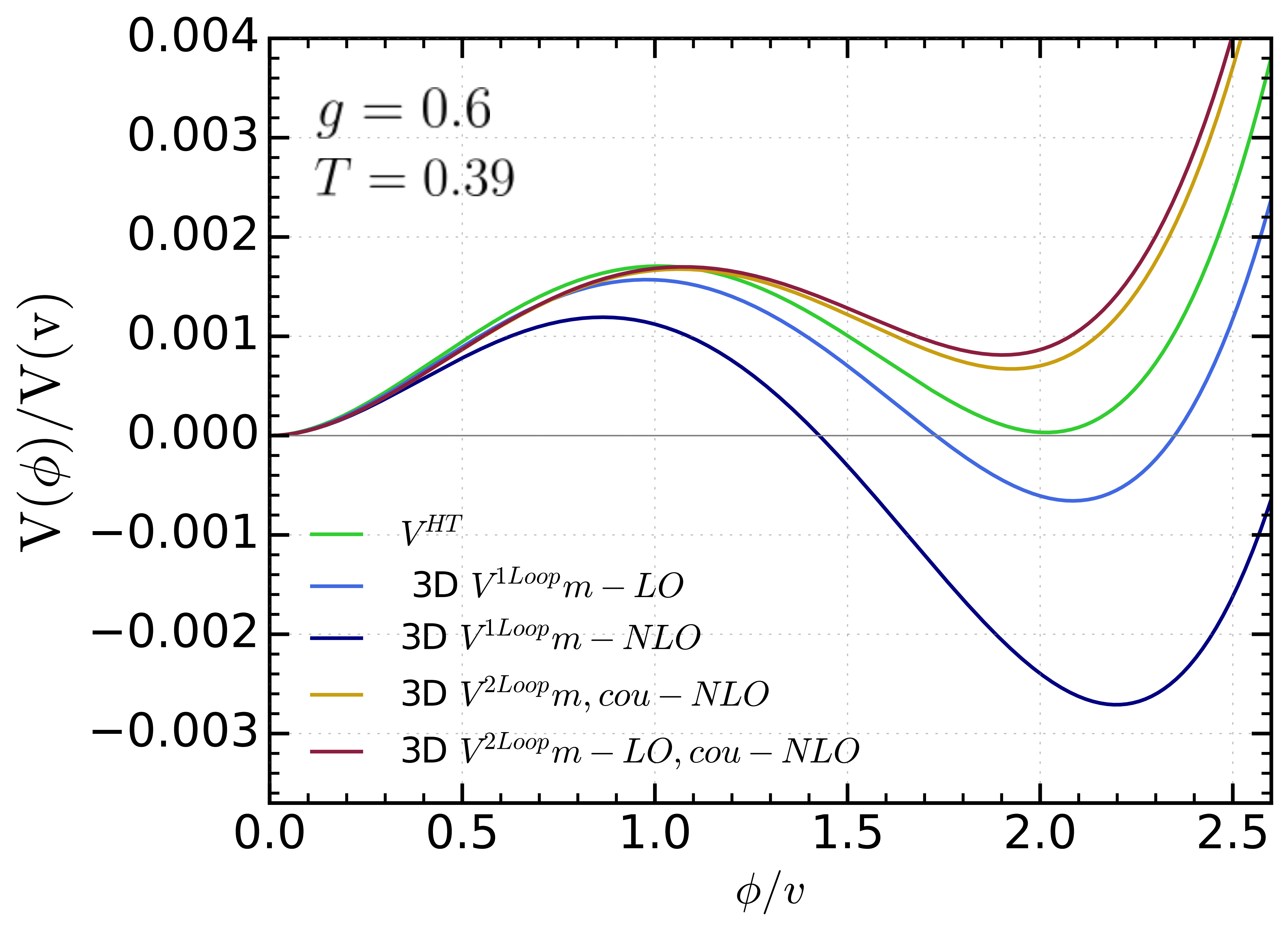
- masses at LO + couplings NLO

**NLO (1-Loop):**

- masses at NLO with 3d couplings NLO+couplings NLO

**NNLO (2-Loop):**

- masses at NLO with 3d couplings NLO+couplings NLO
- V-LO masses NLO with couplings at NLO + V-NLO+V-NNLO masses LO and couplings LO



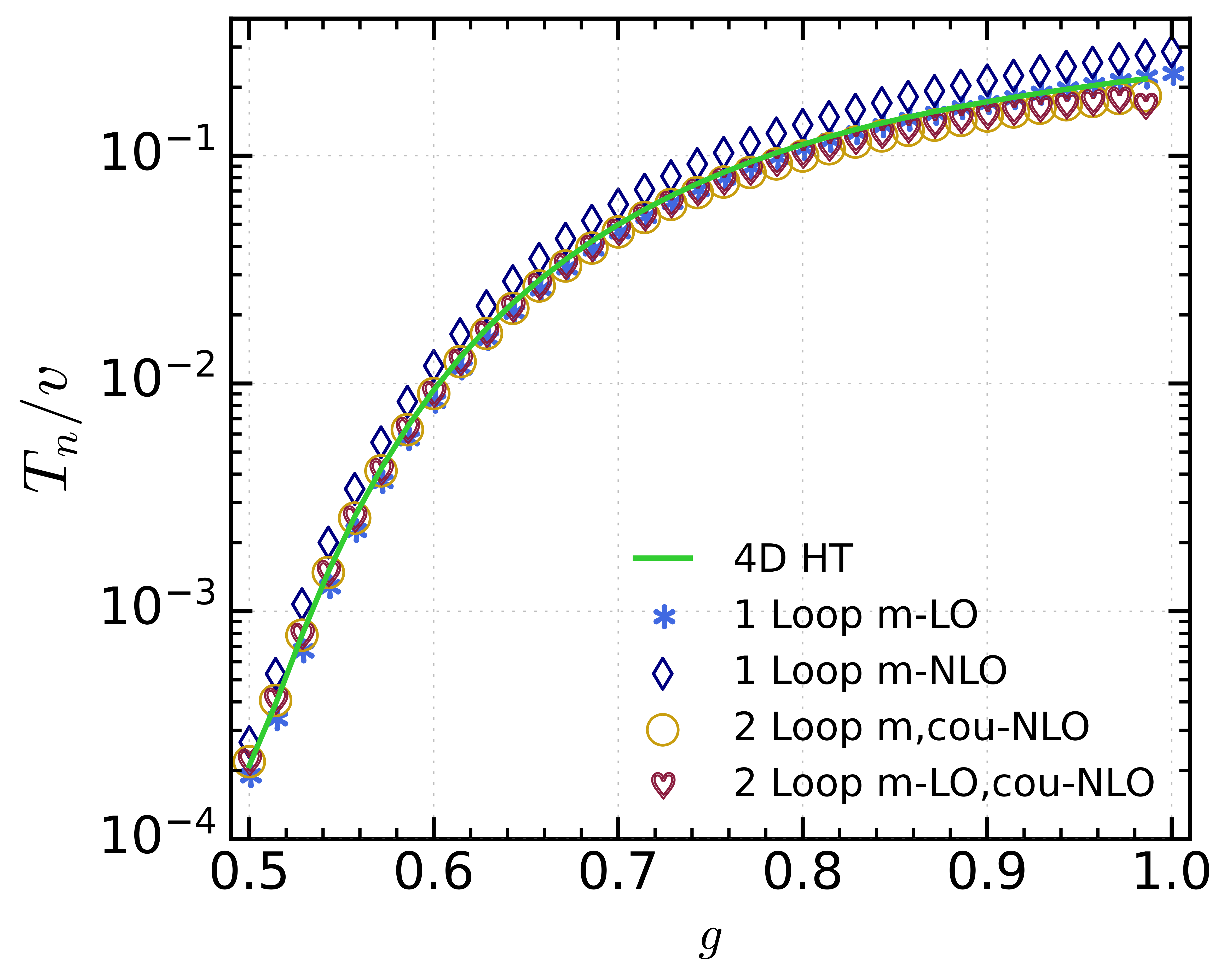
# FOPT PARAMETERS

Espinosa:

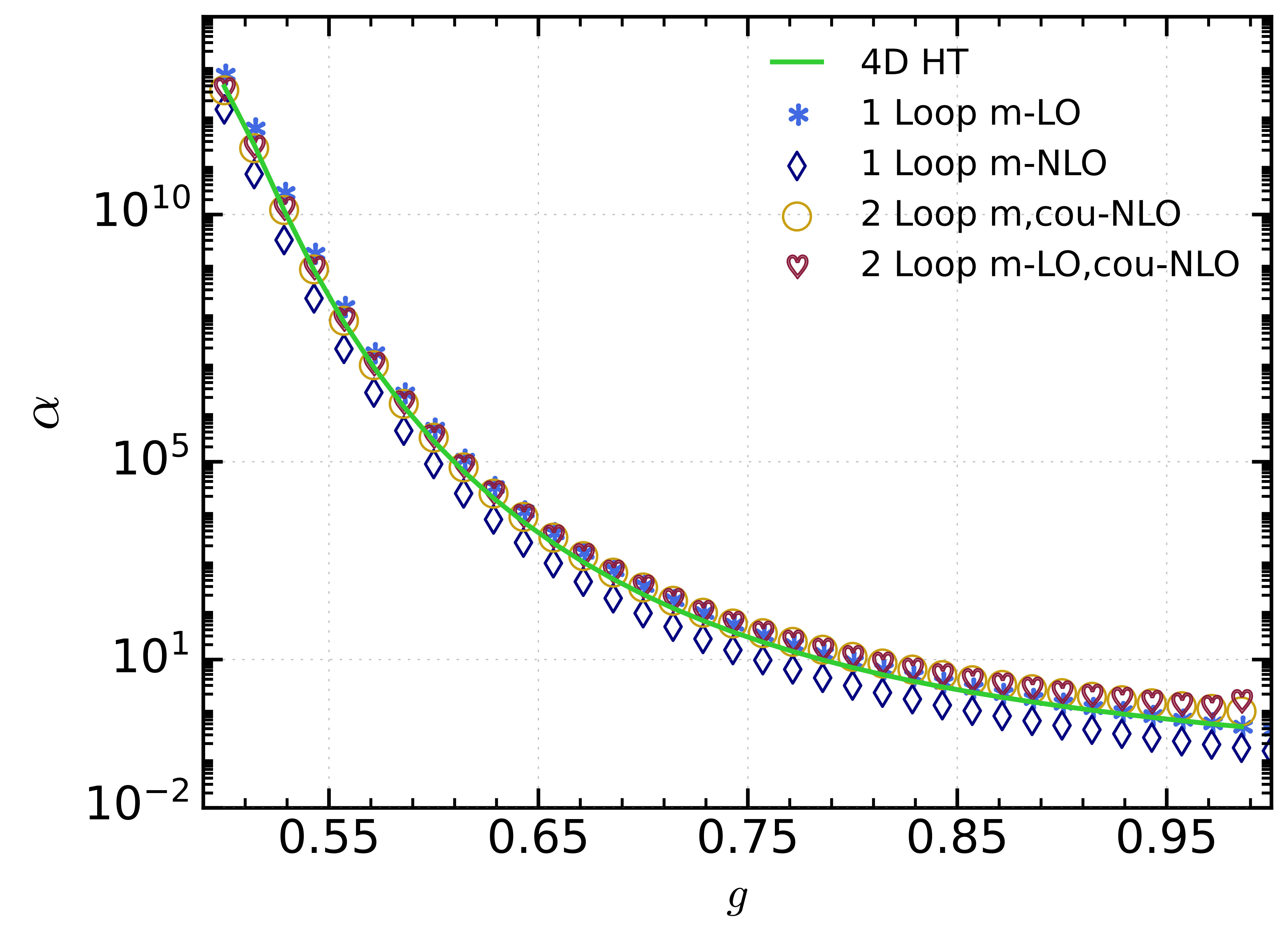
$$\frac{S_3}{T} = \frac{32\pi\sqrt{2}}{3}\int_0^{\phi_0} d\phi\, \frac{\left[V_{\rm eff}(\phi,T) - V_t(\phi)\right]^{3/2}}{\left(\frac{dV_t}{d\phi}\right)^2}$$

$$\alpha \simeq \frac{\Delta V_{CW}^{NLO}}{\rho_*} \qquad \rho_* = \frac{\pi^2}{30}\, g_*\, T_*^4$$

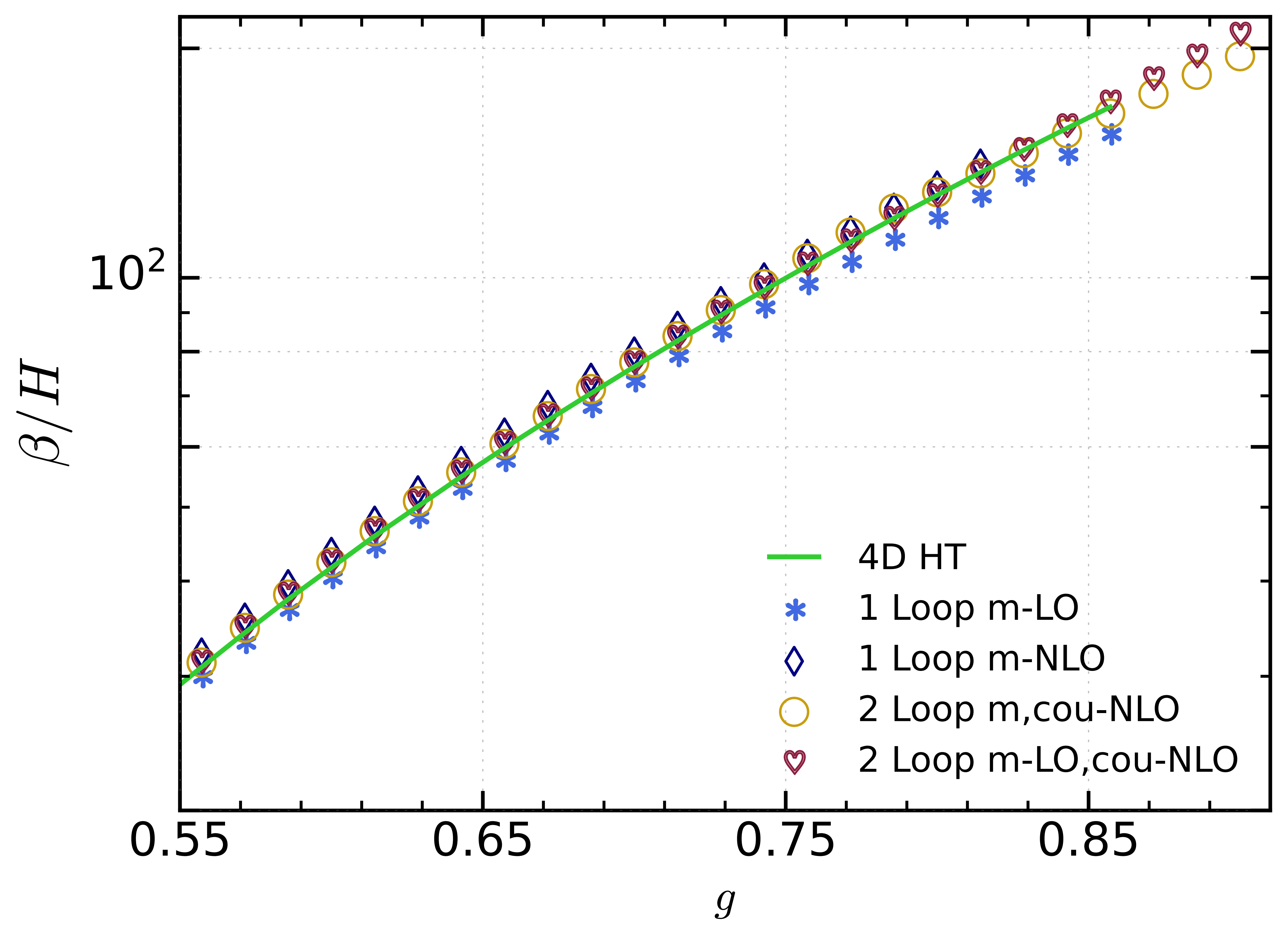
$$\frac{\Gamma(T_n)}{H(T_n)^4} = 1 \qquad \frac{\beta}{H_*} = T_*\,\frac{d}{dT}\left(\frac{S_3}{T}\right)\bigg|_{T=T_*}$$



# RESULTS

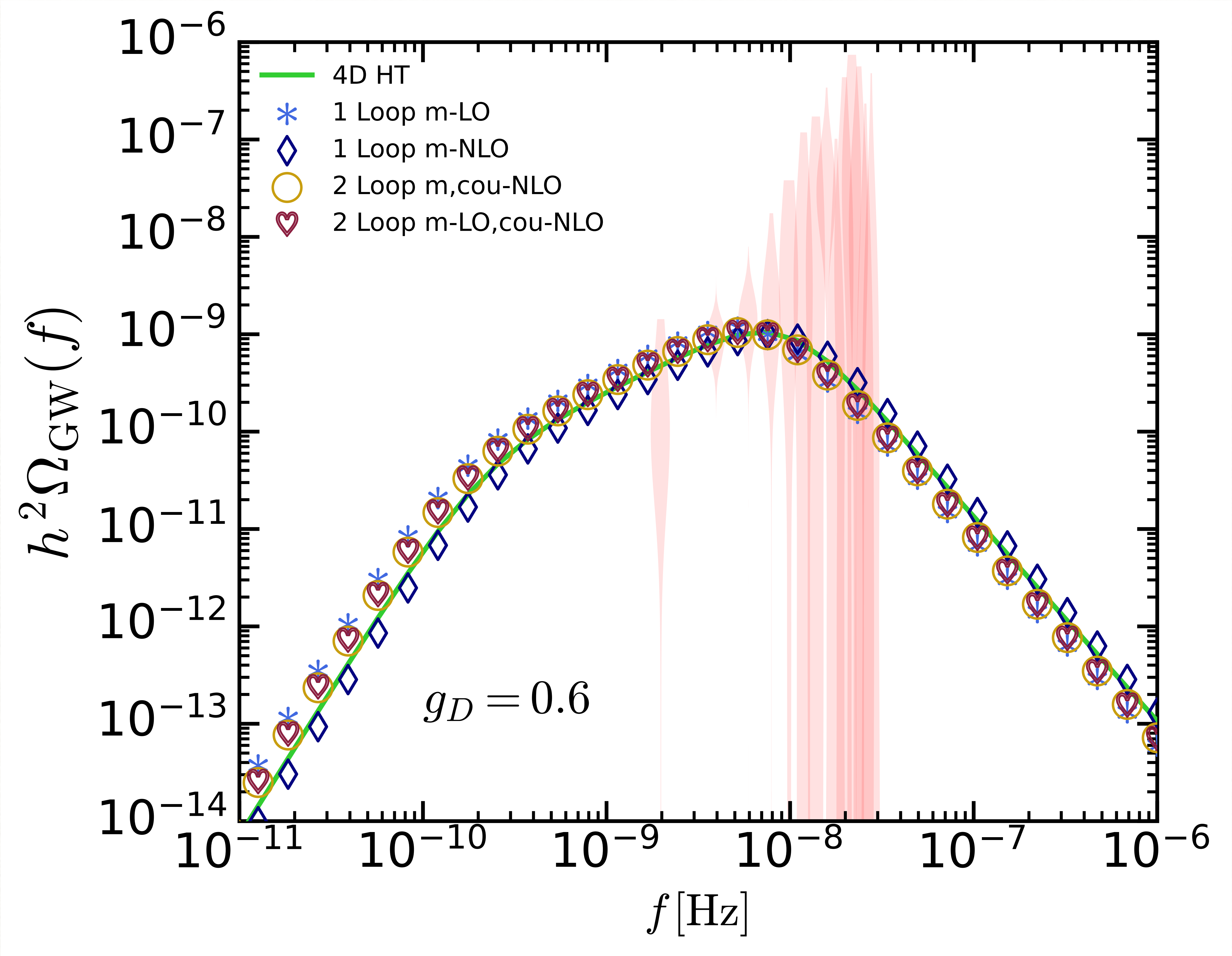


4D HT
1 Loop m-LO
1 Loop m-NLO
2 Loop m,cou-NLO
2 Loop m-LO,cou-NLO
$10^{10}$
$10^{5}$
$10^{1}$
$10^{-2}$
$\alpha$
0.55
0.65
0.75
0.85
0.95
$g$

$10^{2}$
$\beta/H$
4D HT
1 Loop m-LO
1 Loop m-NLO
2 Loop m,cou-NLO
2 Loop m-LO,cou-NLO
0.55
0.65
0.75
0.85
$g$

# CONCLUSIONS.




GW spectrum in the relativistic limit from
https://arxiv.org/pdf/2403.05615
by I. Baldes, M. Ditch, Y. Gouttenoire and F. Sala

- Include the running.
- Relaiable results using the HT with a proper choice of the scale.

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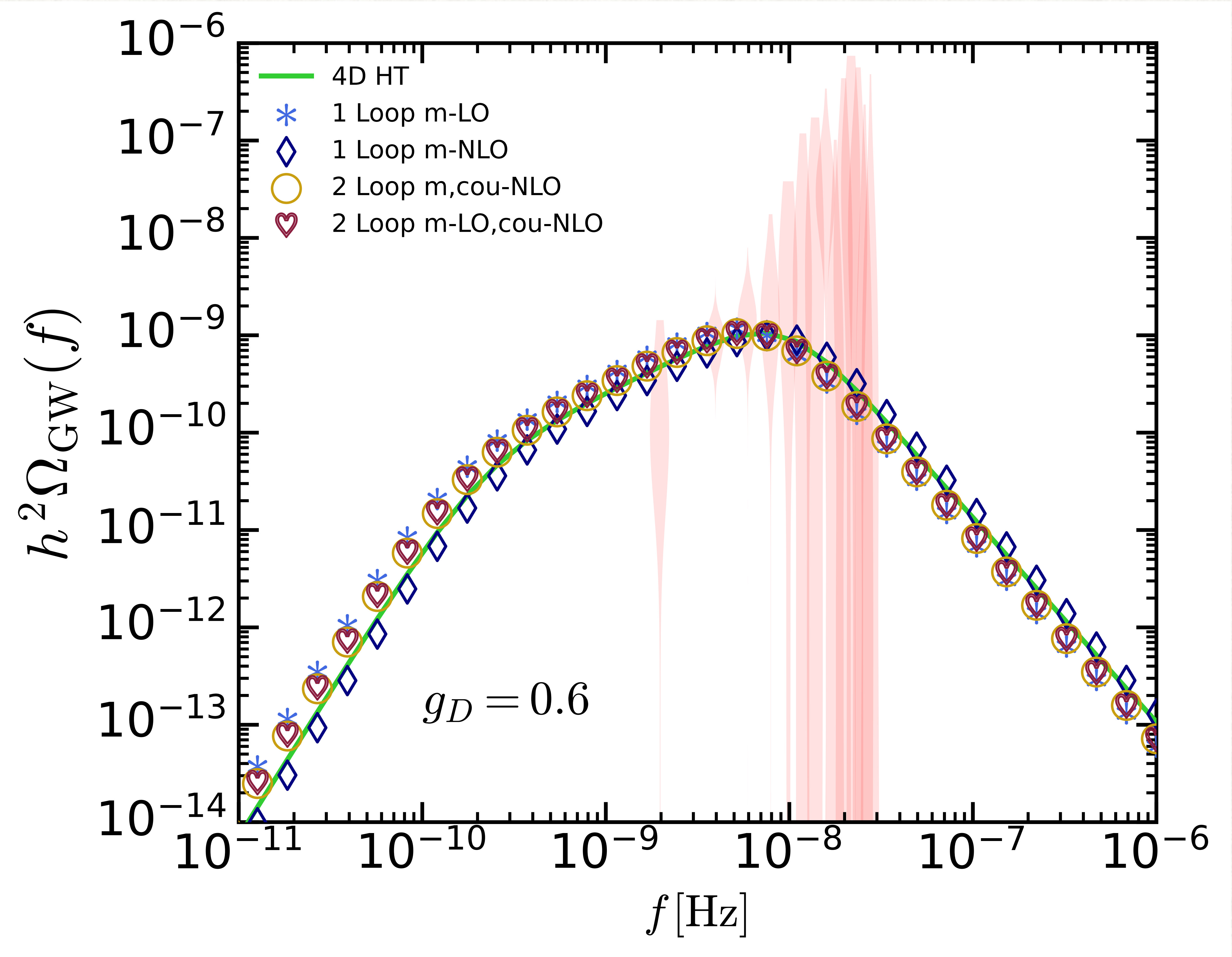


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**THANK YOU!**