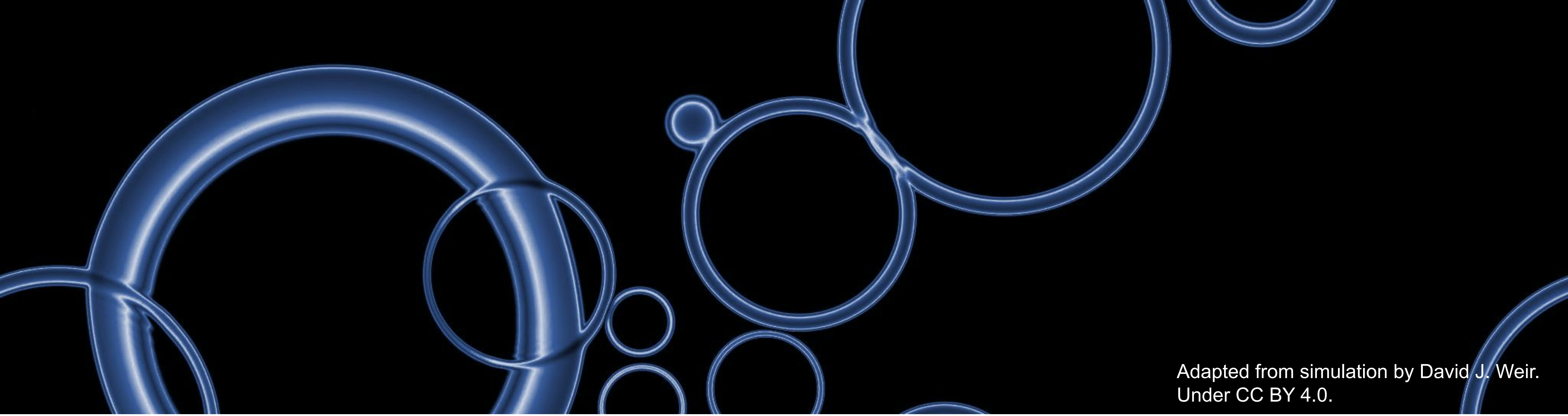


# Dimensionally reduced EFTs for cosmological phase transitions

**Higgs and Effective Field Theory (HEFT) 2024 · University of Bologna**

Luis Gil [he/him]

Based on [2406.02667], by:

M. Chala, J. C. Criado, LG and J. López Miras

FTAE High Energy Theory
UNIVERSIDAD DE GRANADA
Junta de Andalucía

# Bubbles and gravitational waves

## Thermally induced field phase transitions

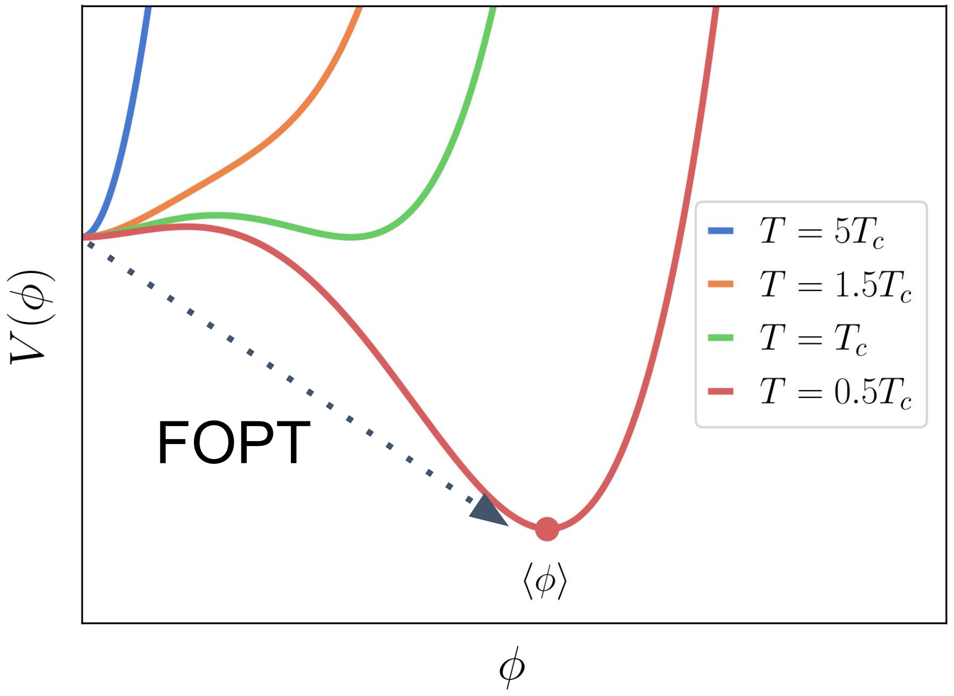


*Fig. 1: Temperature evolution of scalar potential*

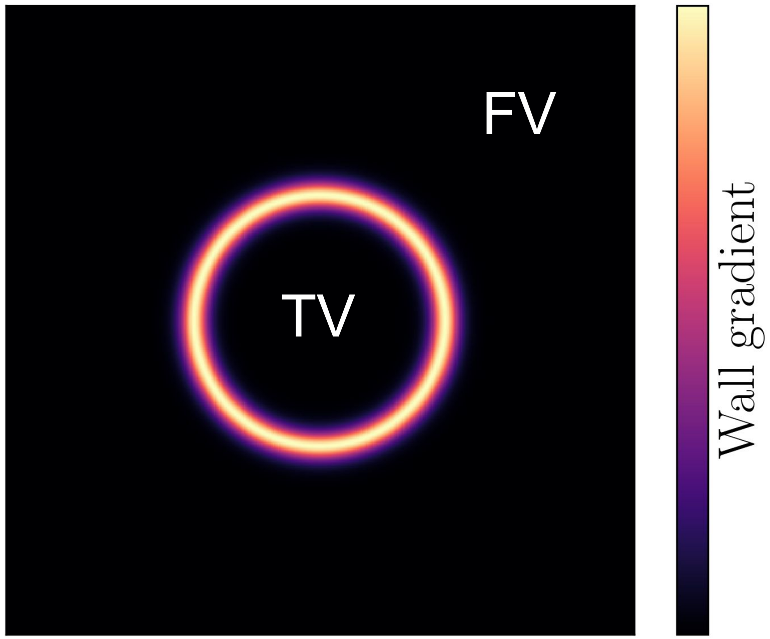


*Fig. 2: O(3) symmetric bounce solution*

# Bubbles and gravitational waves

[Caprini *et al.* - 1512.06239]

From PTs to GWs

As the transition rate grows, in a **first-order PT (FOPT)**:

1) Bubbles of true vacuum nucleate and expand in a hot plasma
2) Bubble fronts collide
3) Sound waves
4) Turbulence

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$$h\Omega_{\rm GW} \simeq h\Omega_{\phi} + h\Omega_{\rm sw} + h\Omega_{\rm turb}$$

**Out of equilibrium**

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Probe

**Out of equilibrium**

**Answers for electroweak baryogenesis**

# Bubbles and gravitational waves

From PTs to GWs

How do we connect a QFT model to these GW spectra?

# Bubbles and gravitational waves

## From PTs to GWs

How do we connect a QFT model to these GW spectra?

**Nucleation temperature**

$$S_3[\varphi_c] \sim 100 - 4\log\frac{T_*}{100\,\mathrm{GeV}}$$

**Strength parameter**

$$\alpha \approx -0.03\frac{V_3(\varphi_T)}{T_*^3}$$

**Inverse duration of PT**

$$\frac{\beta}{H_*} = T_*\frac{\mathrm{d}S_3[\varphi_c]}{\mathrm{d}T}\bigg|_{T_*}$$

**Terminal bubble wall velocity**

A whole different story…

[Laurent, Cline - 2204.13120]

# Bubbles and gravitational waves

## What is the state of the art?

**This list is NOT exhaustive!**

- Several studies of FOPTs in BSM extensions and in the SMEFT:
  - $N^4$LO Higgs potential at finite T **[Ekstedt *et al.* - 2405.18349]**
  - EWPT in dim-6 SMEFT **[Camargo-Molina *et al.* - 2103.14022]**
  - EWPT in dim-6 XSM **[Oikonomou *et al.* - 2403.01591]**
  - EWPT in ΣSM **[Niemi *et al.* - 1802.10500]**
- Tools for PT-related computations:
  - *CosmoTransitions* **[Wainwright - 1109.4189]**
  - *FindBounce* **[Guada *et al.* - 2002.00881]**
  - *DRalgo* **[Ekstedt *et al.* - 2205.08815]**
  - *BubbleDet* **[Ekstedt *et al.* - 2308.15652]**
- Theoretical uncertainties persist from the particle physics side:
  - LISA **[Caprini *et al.* - 1910.13125]**

Effective operators with derivatives **not included**

# 3D EFT approach

## Building our high-T EFT

**See earlier talk by M. Chala**

UV theory in 4D Minkowski:

$$\mathscr{L}_4 = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2}m^2\phi^2 - \kappa\phi^3 - \lambda\phi^4 + \overline{\Psi} i \partial\!\!\!/ \Psi - g\phi\overline{\Psi}\Psi$$

**[Gould, Xie - 2310.02308]**

At temperature T, in Euclidean space:

$$S_0 = (-i)\frac{1}{T}\int \mathrm{d}^3\mathbf{x} \sum_{n=-\infty}^{\infty} \left[ \frac{1}{2}(\partial_i \varphi_n)^2 + \frac{1}{2}\left(m^2 + (2\pi n T)^2\right)\varphi_n^2 + \overline{\psi}_n \partial\!\!\!/ \psi_n + \left(2\pi\left(n+\frac{1}{2}\right)T\right)^2 \overline{\psi}_n \psi_n \right]$$

Multiple thermal modes → ($T^2 \gg m^2$) → Hierarchy of scales → (Power counting) → EFT for scalar zero mode

# 3D EFT approach

## Building our high-T EFT

[Kajantie *et al.* - 9508379]
[Criado - 1901.03501]

We find an off-shell basis of operators up to (4D) dim-8 with the help of *BasisGen* and match at 1-loop (fermion only loops)[1]:

$$\mathscr{L}_3 = \frac{1}{2}K_3(\partial\varphi)^2 + \frac{1}{2}m_3^2\varphi^2 + \kappa_3\varphi^3 + \lambda_3\varphi^4 \\ + \alpha_{61}\varphi^6 + \beta_{61}\partial^2\varphi\partial^2\varphi + \beta_{62}\varphi^3\partial^2\varphi \\ + \alpha_{81}\varphi^8 + \alpha_{82}\varphi^2\partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi + \beta_{81}\varphi\partial^6\varphi + \beta_{82}\varphi^3\partial^4\varphi + \beta_{83}\varphi^2\partial^2\varphi\partial^2\varphi + \beta_{84}\varphi^5\partial^2\varphi$$

[1] Scalar loop contributions to effective operators are subleading (see Appendix A in [2406.02667]).

# 3D EFT approach

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$$+\alpha_{81}\varphi^8 + \alpha_{82}\varphi^2\partial_\mu\partial_\nu\varphi\partial^\mu\partial^\nu\varphi + \beta_{81}\varphi\partial^6\varphi + \beta_{82}\varphi^3\partial^4\varphi + \beta_{83}\varphi^2\partial^2\varphi\partial^2\varphi + \beta_{84}\varphi^5\partial^2\varphi$$

**dim-6**

Measure eff. ops. relevance

**dim-8**

Control EFT validity

[1] Scalar loop contributions to effective operators are subleading (see Appendix A in [2406.02667]).

# 3D EFT approach

## Computing relevant PT magnitudes

Eff. ops. depend solely on the Yukawa (g)

↓

Fix all other UV parameters in scan

**[Chala *et al.* - 1905.00911]**

**&**

Study all PT magnitudes as functions of the Yukawa

$m^2, \kappa, \lambda$

$T_*, \alpha, \beta/H_*$

**See earlier talk by M. Chala**

**Bounce solution must be computed perturbatively!**

# Results

## PT magnitudes and effective interactions

**[Chala, Criado, LG, López Miras - 2406.02667]**

$(m^2, \kappa, \lambda)_A = (20\,000 \text{ GeV}^2, -40 \text{ GeV}, 0.01)$   $(m^2, \kappa, \lambda)_B = (31\,643.5 \text{ GeV}^2, -71.1 \text{ GeV}, 0.045)$

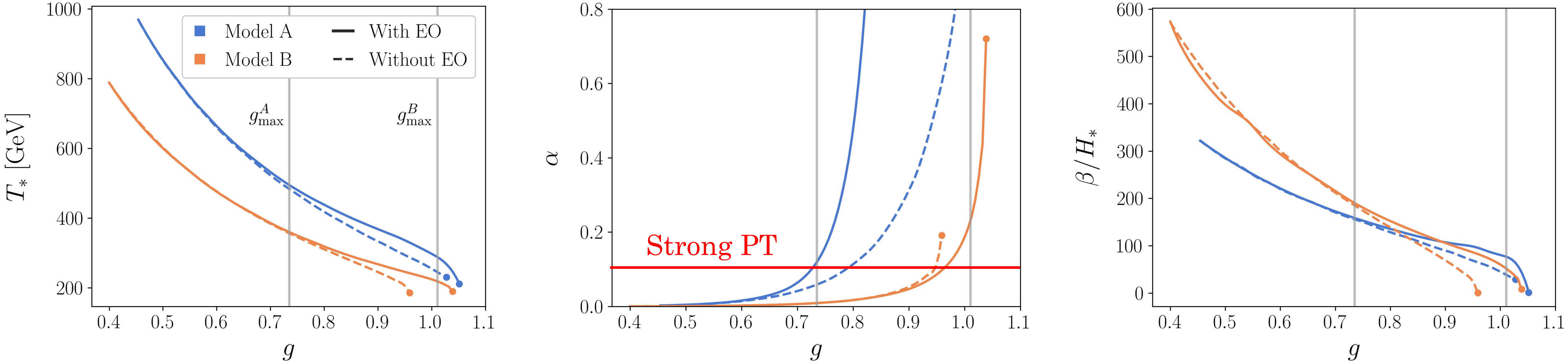


*Fig. 5: PT magnitudes in two models, with and w/o effective operators*

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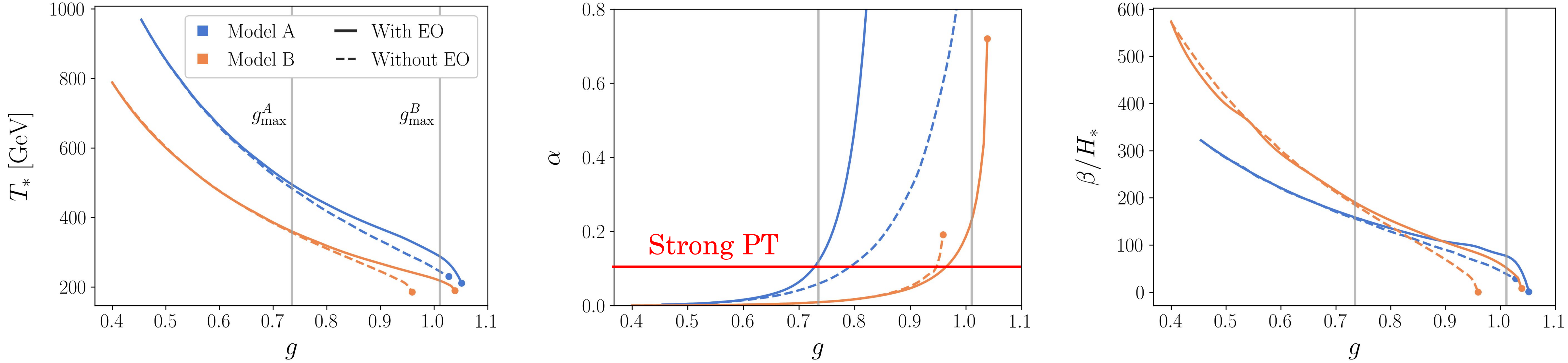


*Fig. 5: PT magnitudes in two models, with and w/o effective operators*

Two observations:

- Eff. ops. **allow for PTs in a wider range** of values of the Yukawa
- Including eff. ops. yields **very different estimations** at large Yukawas

# Results

## GW power spectra and effective interactions

**[Chala, Criado, LG, López Miras - 2406.02667]**

$$(m^2, \kappa, \lambda)_A = (20\,000 \text{ GeV}^2, -40 \text{ GeV}, 0.01) \qquad (m^2, \kappa, \lambda)_B = (31\,643.5 \text{ GeV}^2, -71.1 \text{ GeV}, 0.045)$$

$$g \lesssim g_{\max}$$

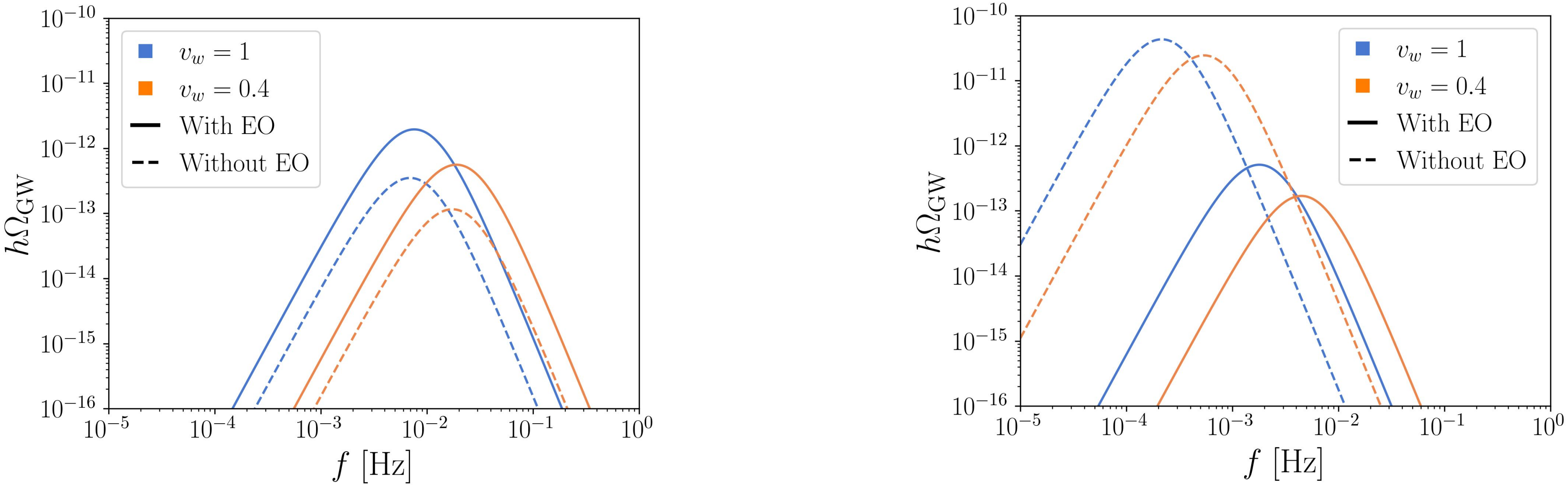


*Fig. 6: GW power spectra in two models, with and w/o effective operators*

(*) Generated with **PTPlot**

**[Caprini *et al.* - 1910.13125]**

# Results

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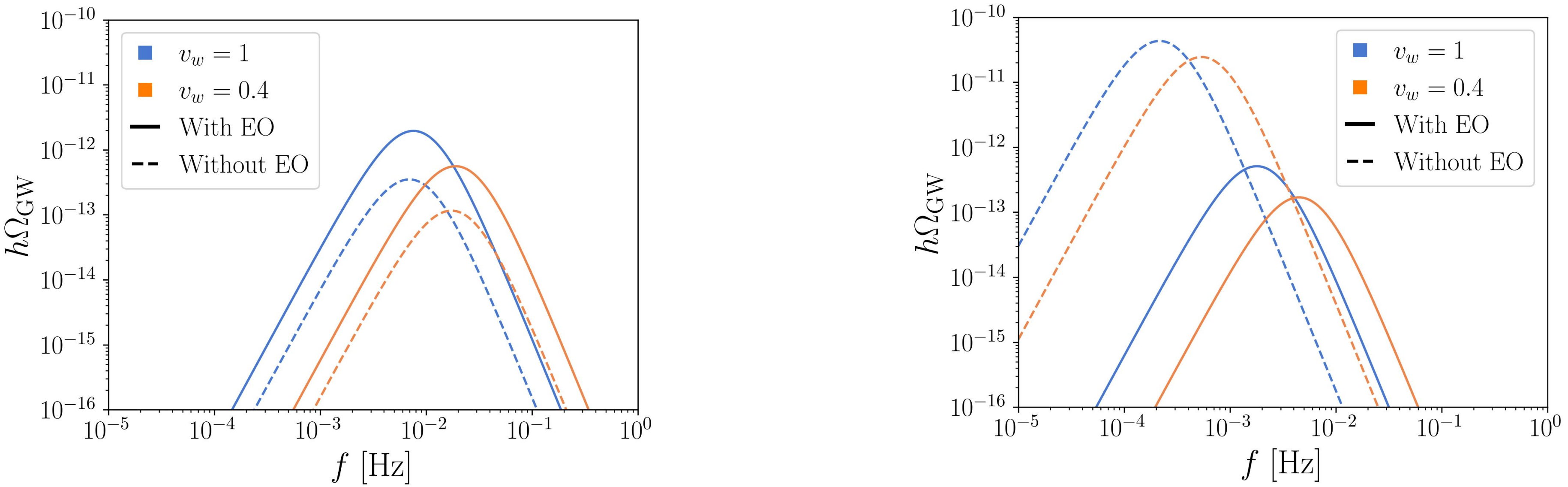


*Fig. 6: GW power spectra in two models, with and w/o effective operators*

Including eff. ops. can change the peak amplitude and frequency by **one order of magnitude**

# Take home messages

## We have learned

- Strong FOPTs occur in regions of parameter space **close the limit of validity** of the 3D EFT
- Higher dimensional effective operators **are thus relevant in the estimation of PT-related magnitudes** (order of magnitude differences in GW spectra)
- **Bounce solutions** can be obtained perturbatively in the presence of higher derivative terms

## Future work

- Application to well-motivated BSM models
- Adding loop corrections to scalar zero mode

# Thank you for your attention!

## ¡Gracias por vuestra atención!