# Collider physics as a window to the EW epoch

## On the complementarity between collider physics and gravitational waves in the 2HDM

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in collaboration with T. Biekötter, S. Heinemeyer, J. M. No and G. Weiglein

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HELMHOLTZ

DESY.

# Introduction

**EWPT**

- FOEWPT
- Non-standard vacuum thermal evolutions.

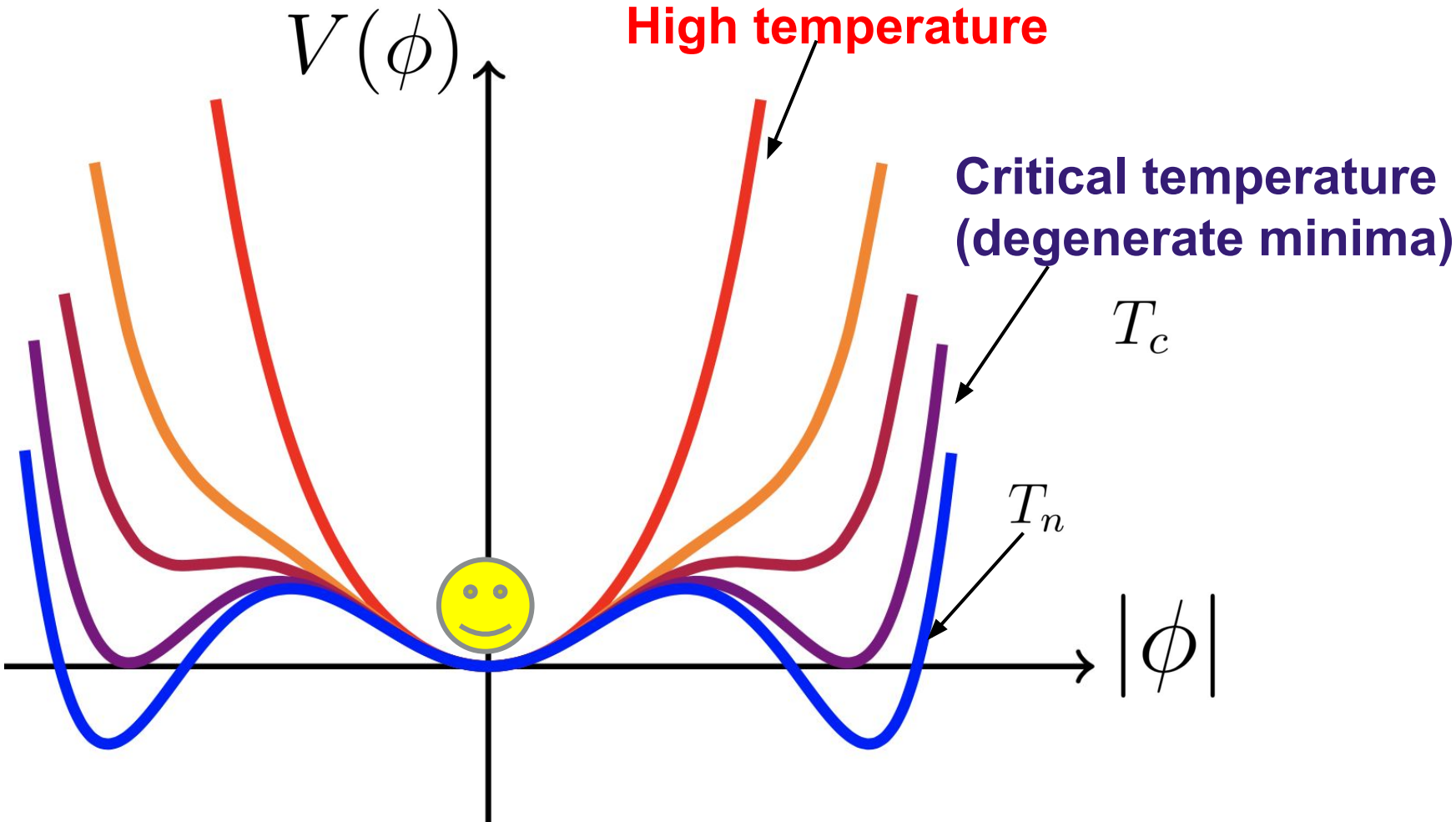
**FOEWPT**

- EW baryogenesis
- GW production
- New physics at the EW scale

**2HDM**

- Can realise a FOEWPT
- Main message: Should be probed at colliders before LISA flies

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$



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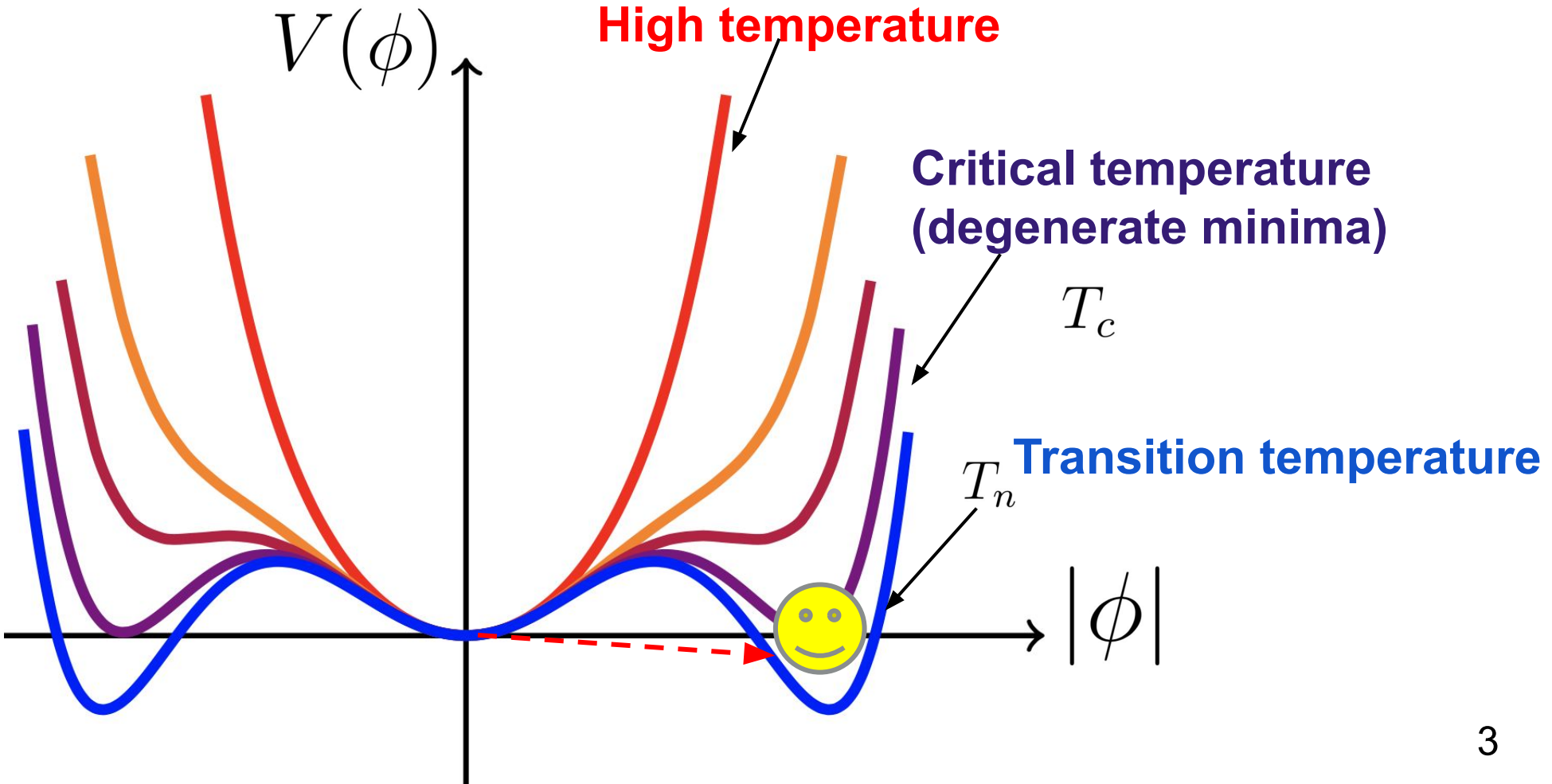


# Gravitational waves production

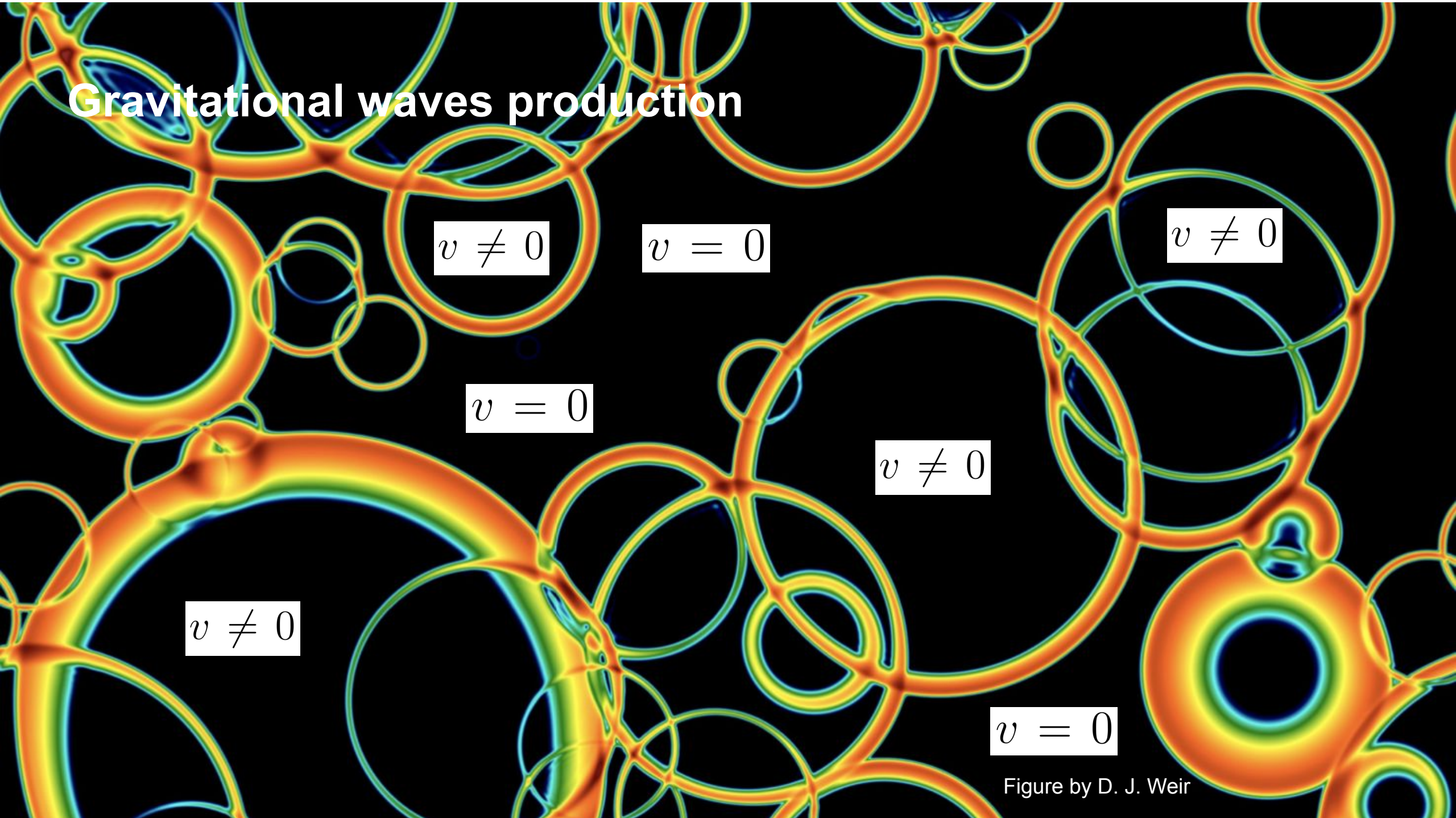



Figure by D. J. Weir

# The 2HDM

$$V_{\text{tree}} = m_{11}^2 \left|\Phi_1\right|^2 + m_{22}^2 \left|\Phi_2\right|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right],$$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \end{pmatrix}$$

2 CP-even scalars $H$ $h$

1 CP-odd scalar $A$

2 charged scalars $H^\pm$

$$V_{\text{eff}}^{T>0}\left(\rho_i, T\right) = V_{\text{tree}}\left(\rho_i\right) + V_{\text{CW}}\left(\rho_i\right)$$
$$+ V_{\text{CT}}\left(\rho_i\right) + V_{\text{T}}\left(\rho_i, T\right) + V_{\text{daisy}}\left(\rho_i, T\right)$$

# Recipe of a FOEWPT in the 2HDM

**We need relatively large quartic couplings → large mass splittings**

$$m_{A^0} - m_{H^0} \gtrsim v \text{ and } M \sim m_{H^0} \sim v$$

- Electroweak precision observables:

$$m_{A^0} \sim m_{H^\pm}$$

- Flavor observables:

$$m_{H^\pm} > 600 \text{ GeV in Type II 2HDM}$$

- Smoking gun collider signature
  G. C. Dorsch , S. J. Huber , T. Konstandin and J. M. No $A^0 \to ZH^0$

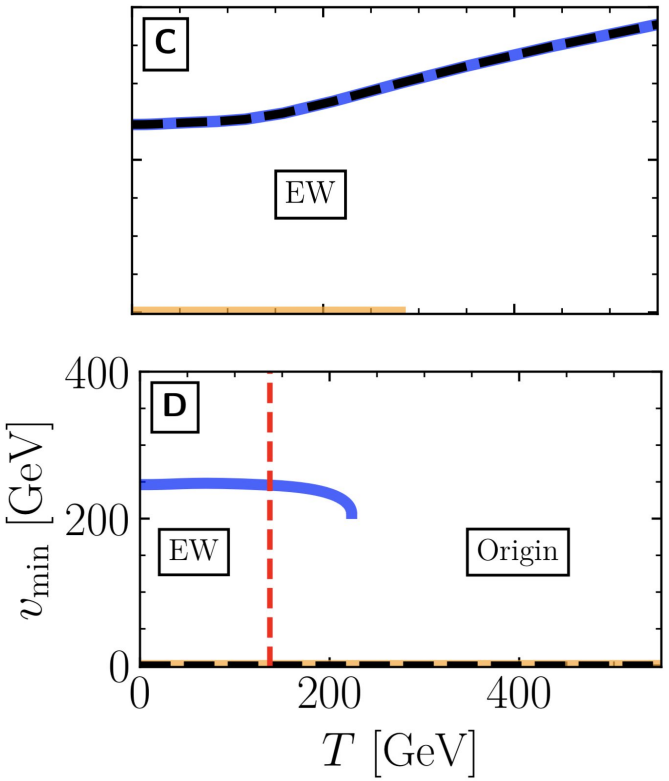
- Vacuum stability
- Perturbative unitarity
- EWPO
- Flavour
- SM Higgs measurements
- BSM scalars searches

$$\tan\beta = 3\ , \quad m_{h_1} = 125.09\,\text{GeV}\ , \quad 200\,\text{GeV} \leq m_H \leq 1\,\text{TeV}$$

$$500\,\text{GeV} \leq m_A = m_{H^\pm} \leq 1.2\,\text{TeV}\ , \quad \cos(\beta-\alpha) = 0, \quad M^2 = \frac{m_{12}^2}{s_\beta c_\beta} = m_H^2$$

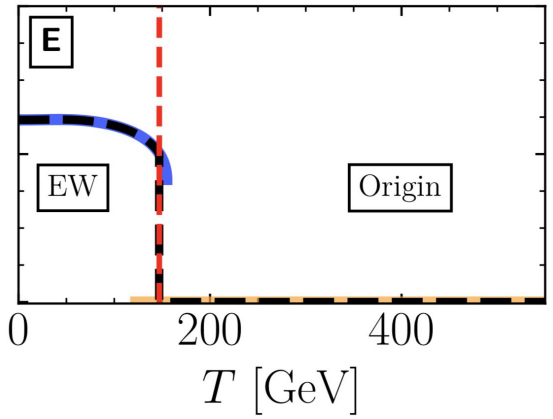
# Triple Higgs coupling as a probe of the vev thermal evolution

Electroweak symmetry non-restoration



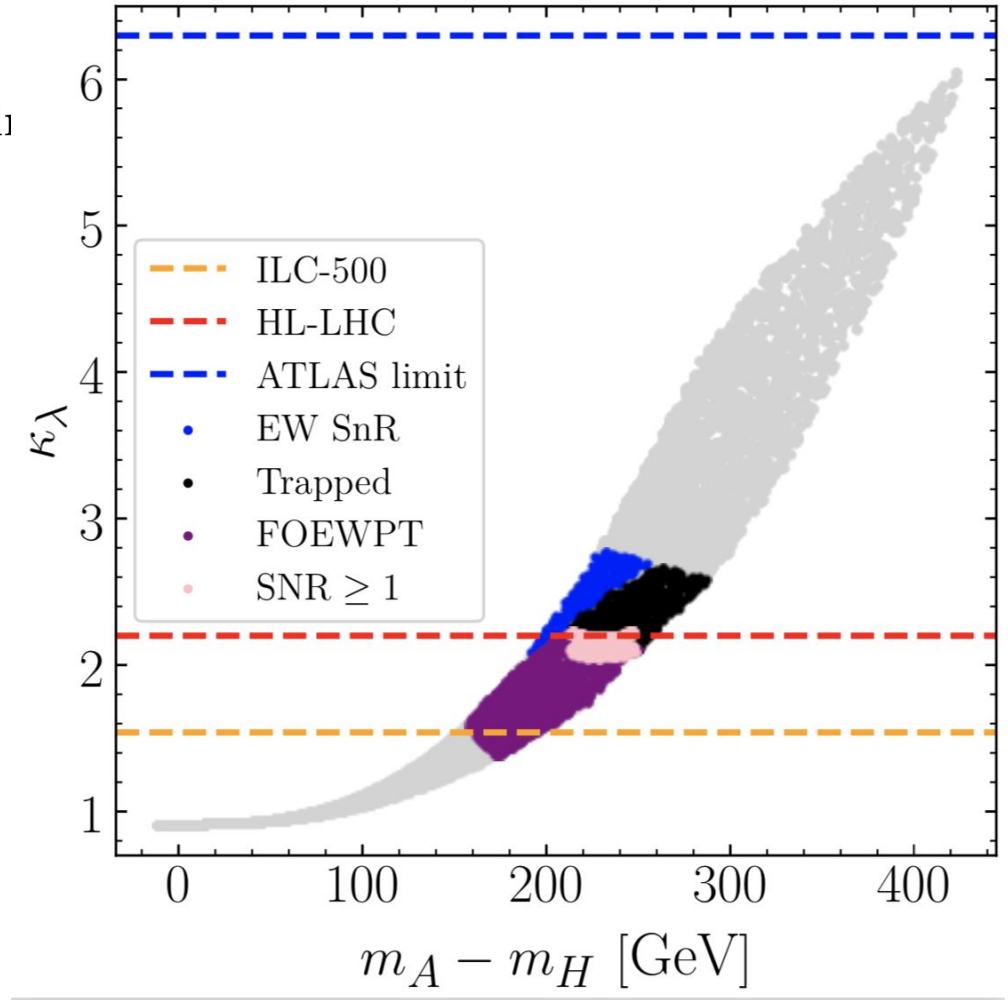

Vacuum trapping

$$v_{\rm min} \equiv \sqrt{v_1^2 + v_2^2}|_{\rm min}$$



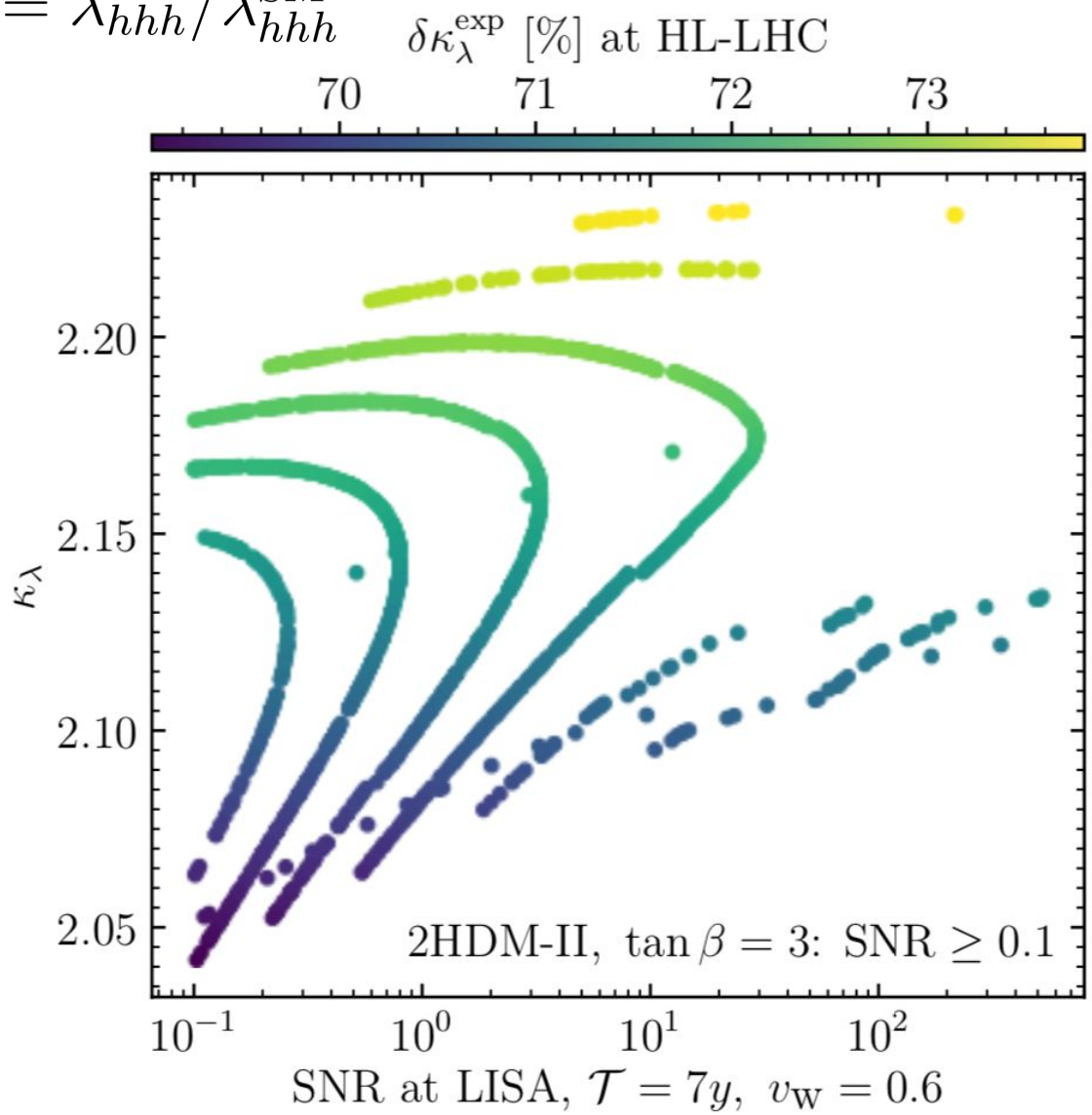

strong FOEWPT

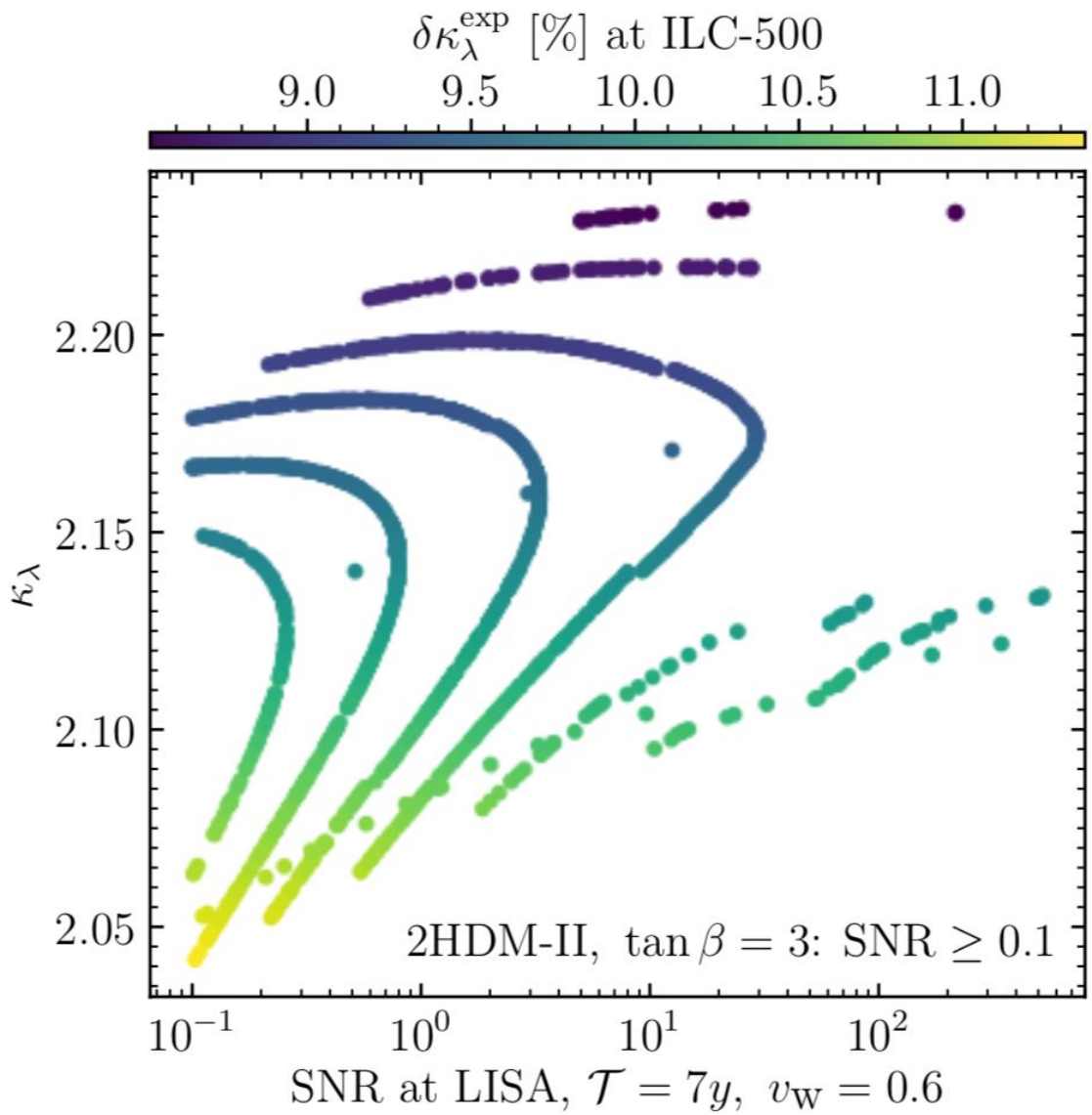
$$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$$



# GW and triple Higgs coupling: precision at future colliders

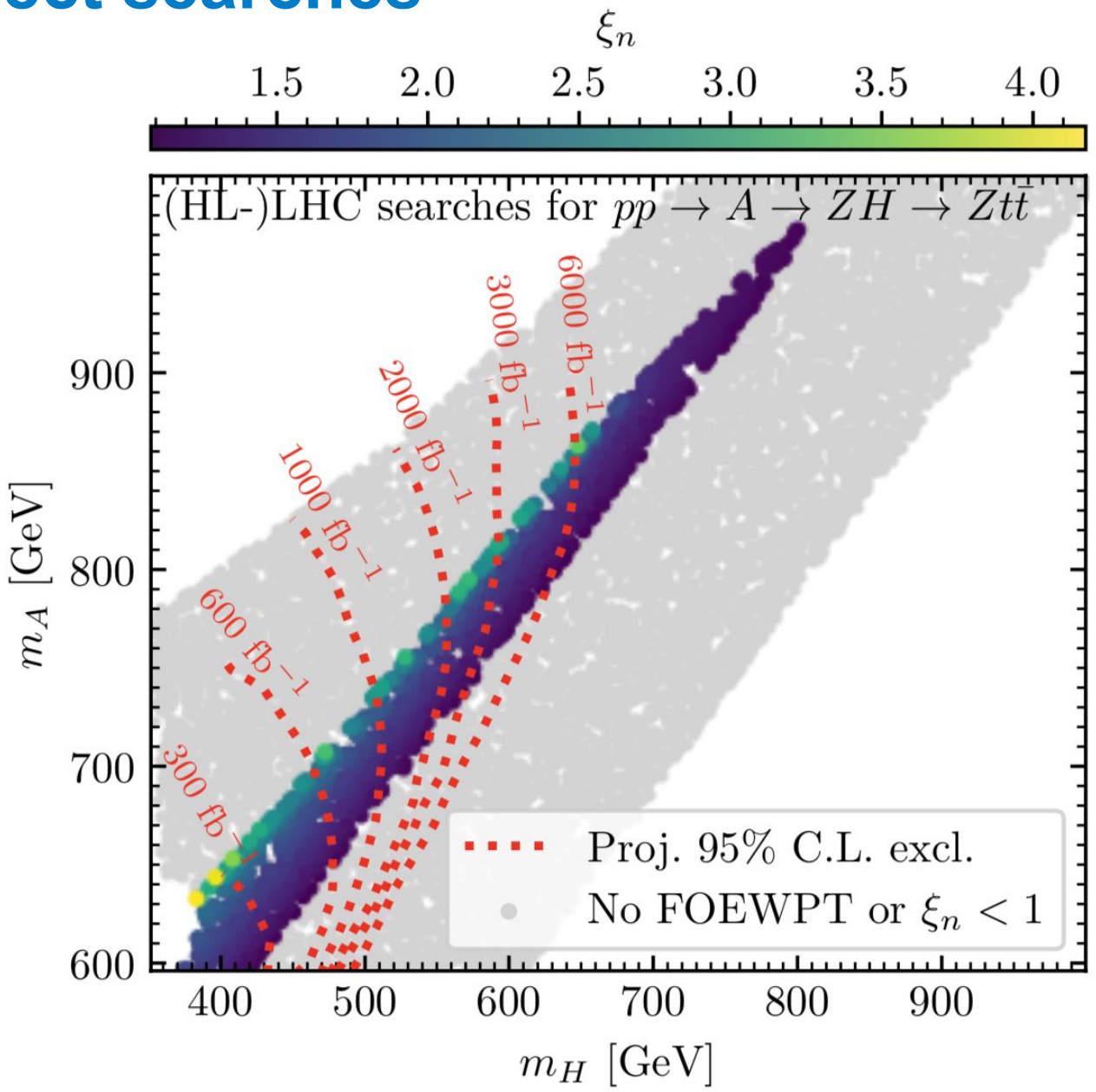
$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$



# FOEWPT and direct searches

$$\xi_n = \frac{v_n}{T_n} > 1,$$



# Conclusions

**2HDM type II**

Primordial GW background in reach of LISA **confined to contrived regions** of the parameter space.

These regions of the parameter space imply the observation of new physics at energy scales **accessible at the LHC:**

- Direct searches
- Triple Higgs coupling

Absence of any indications for new-physics at the LHC, in particular HL-LHC
puts **severe limitations** on the prospects of a detection of a GW background at LISA

# Thank you!

## Any questions?

**Contact**

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Synchrotron DESY

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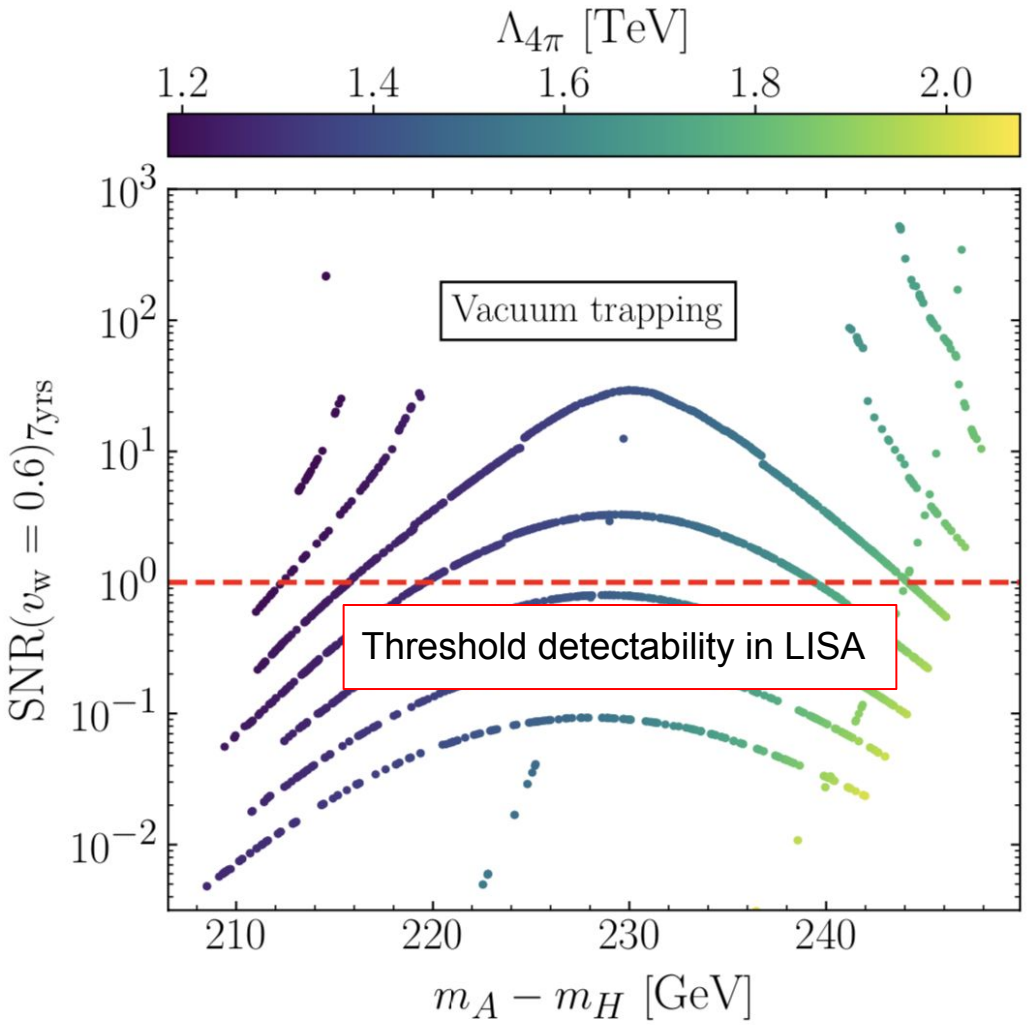
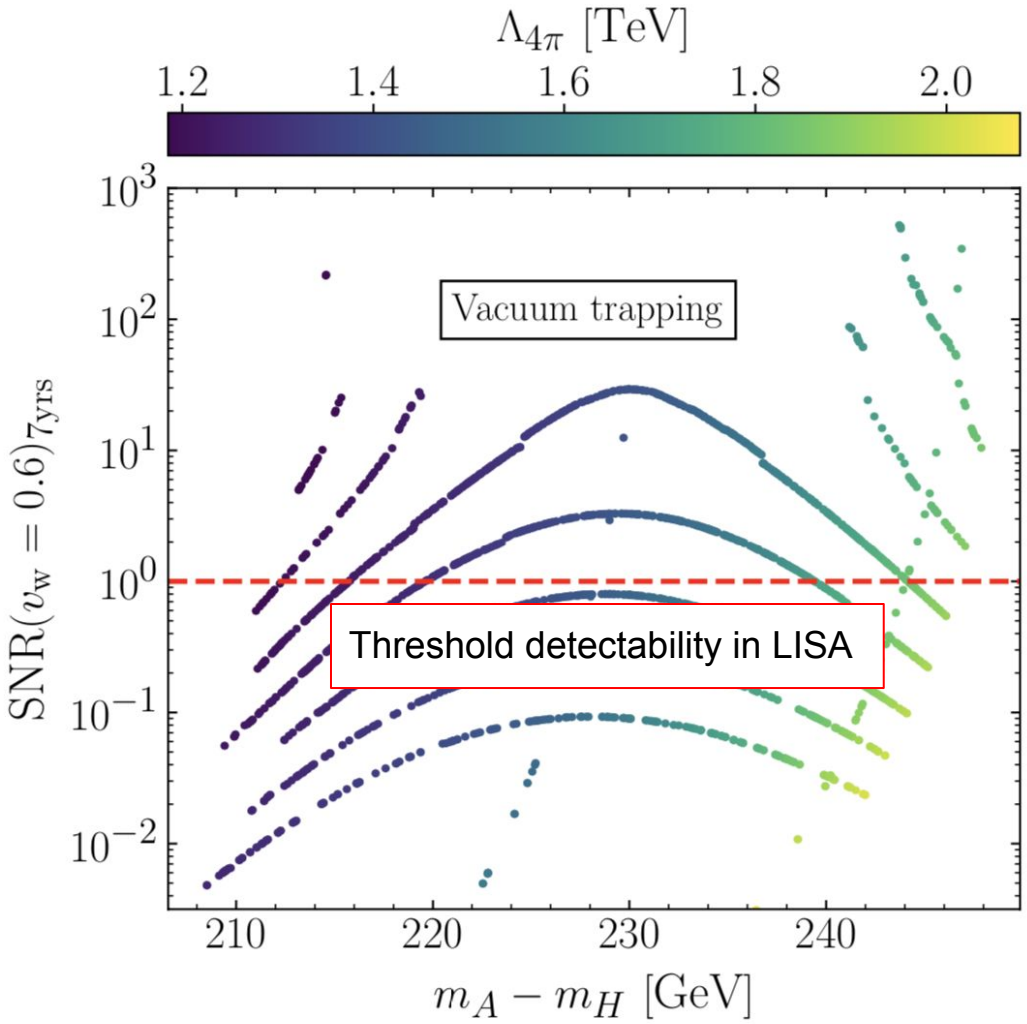
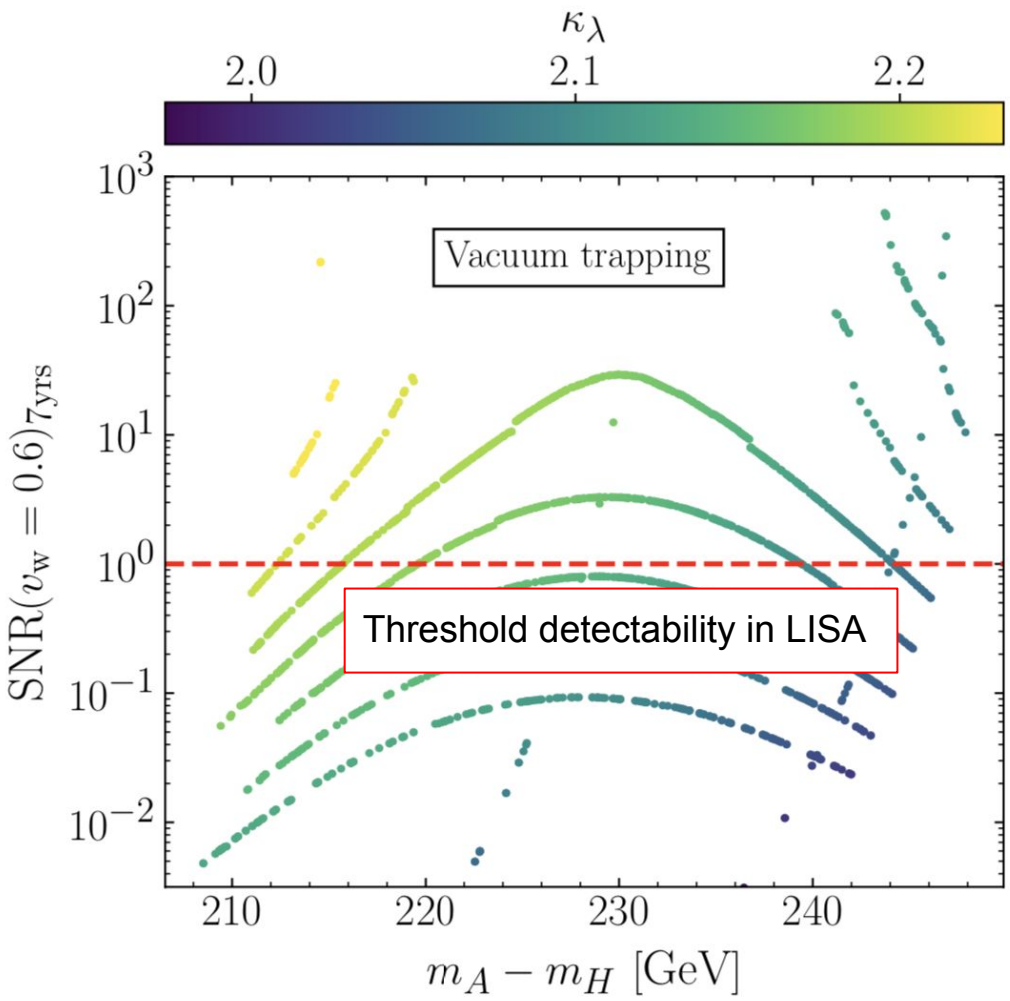
# Maximum energy scale of a perturbative 2HDM



# Gravitational waves in the 2HDM

$$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$$



# Introduction

**Mysteries of EWSB**

- How did the EW symmetry break in the early universe?
- Could we rescue the FOEWPT?

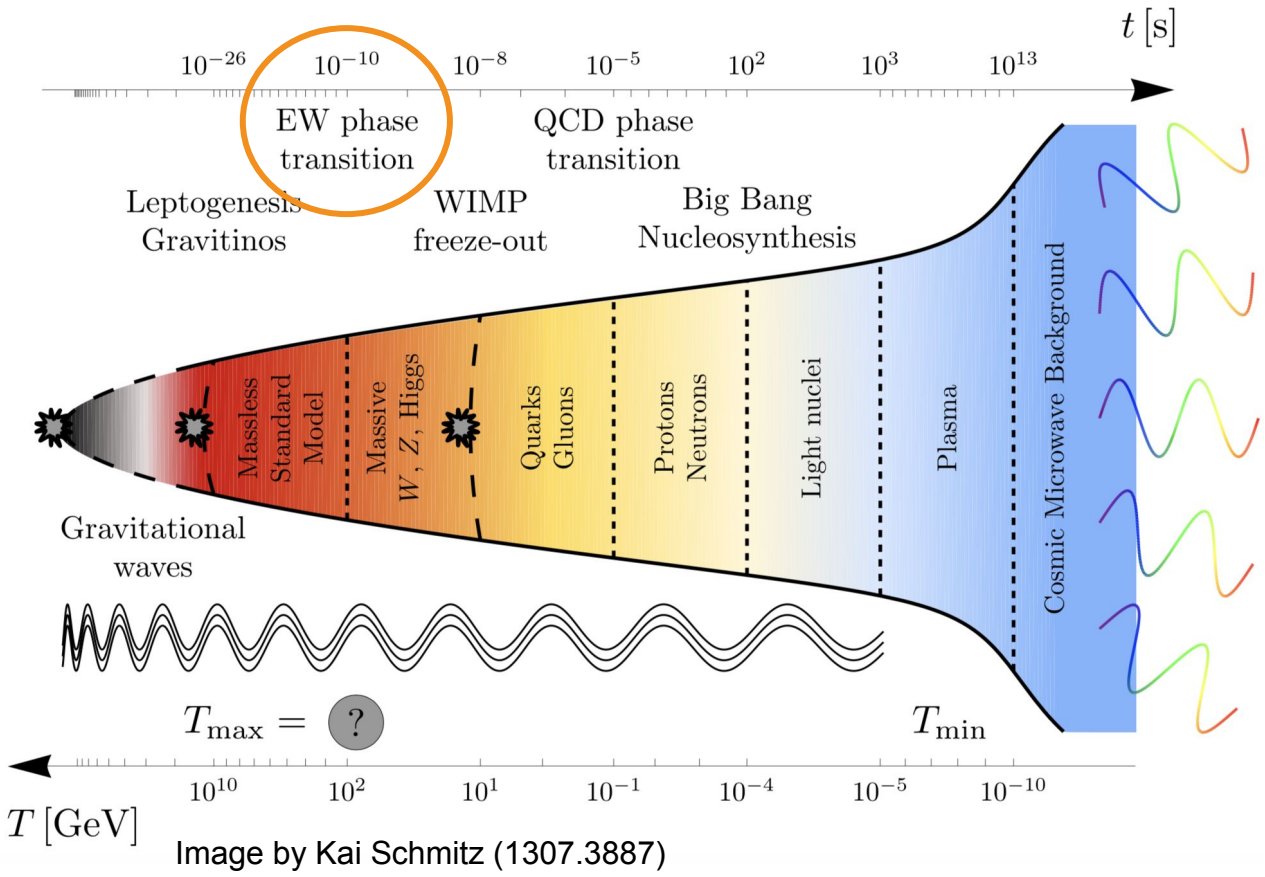



Image by Kai Schmitz (1307.3887)

**FOEWPT**

- EW baryogenesis
- GW production
- New physics at the EW scale

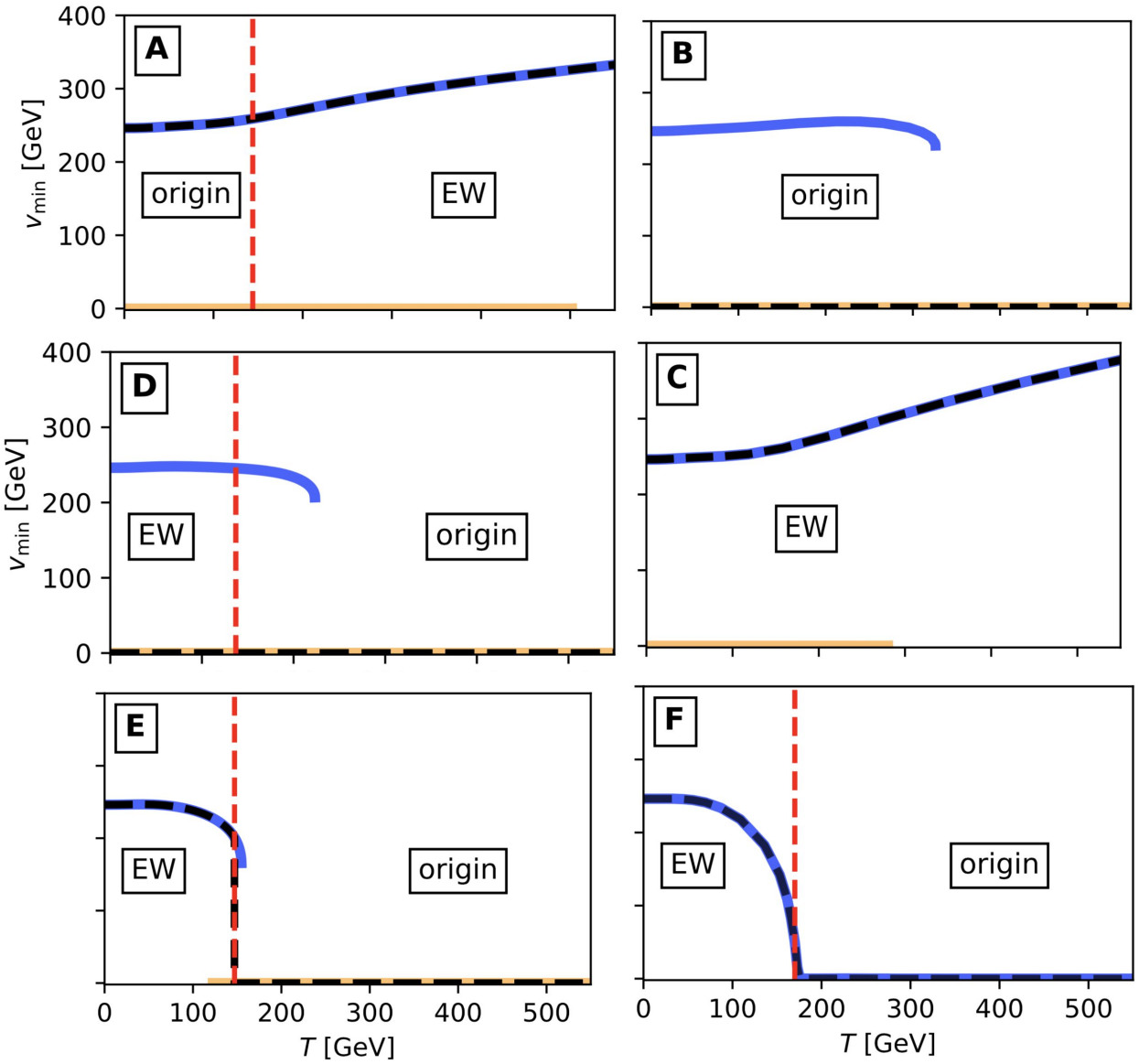
**2HDM**

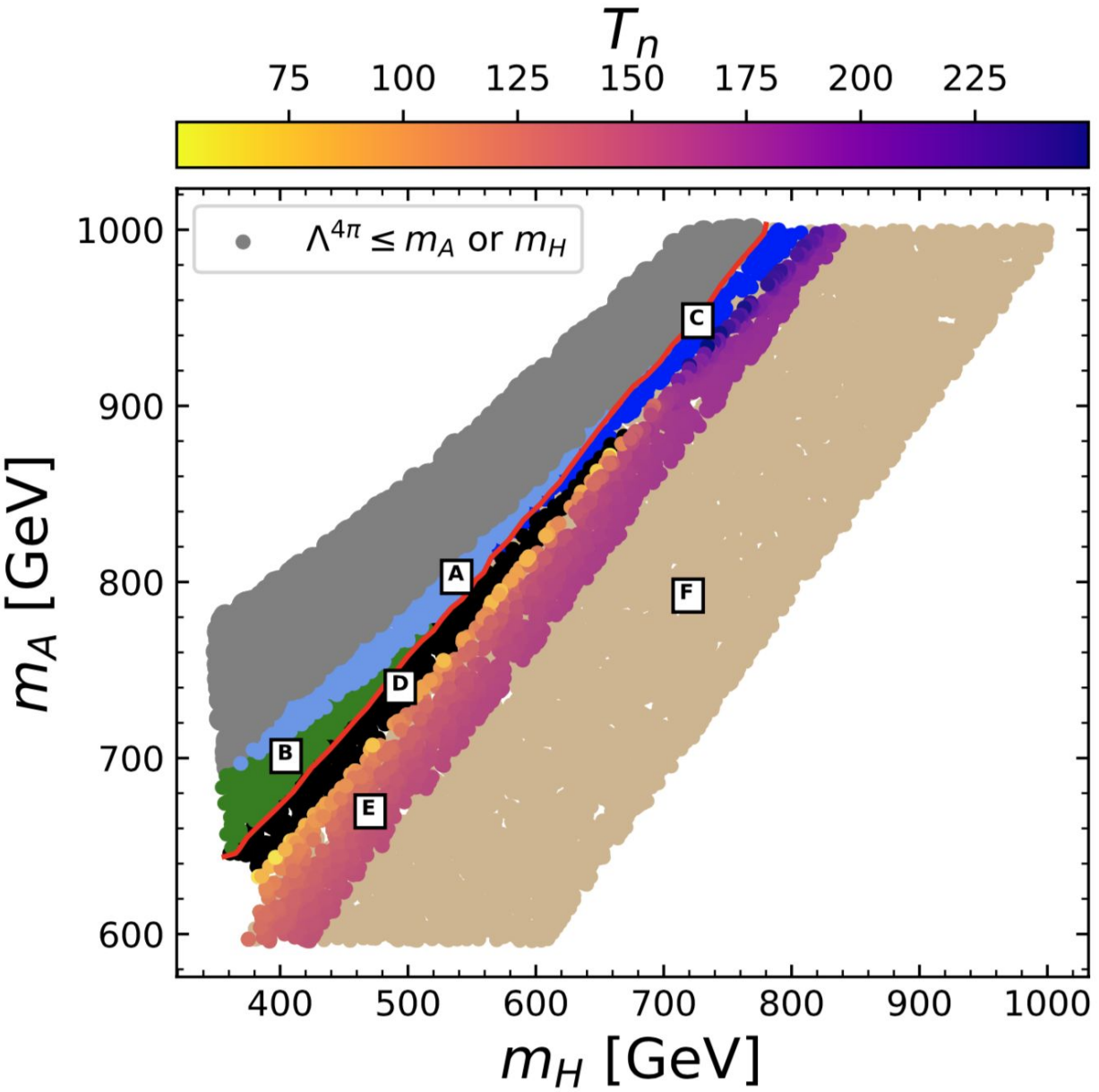
- Can realise a FOEWPT
  (Dorsch et al. 17', Gonçalves et al. 21', Aoki et al. 21')

**Our study**

- Tripple Higgs coupling as a probe of:
  - FOEWPT: critical view on the complementarity between colliders and GW experiments.
  - Non-standard vacuum thermal evolutions.

# The cosmic evolution of the vacuum in the 2HDM



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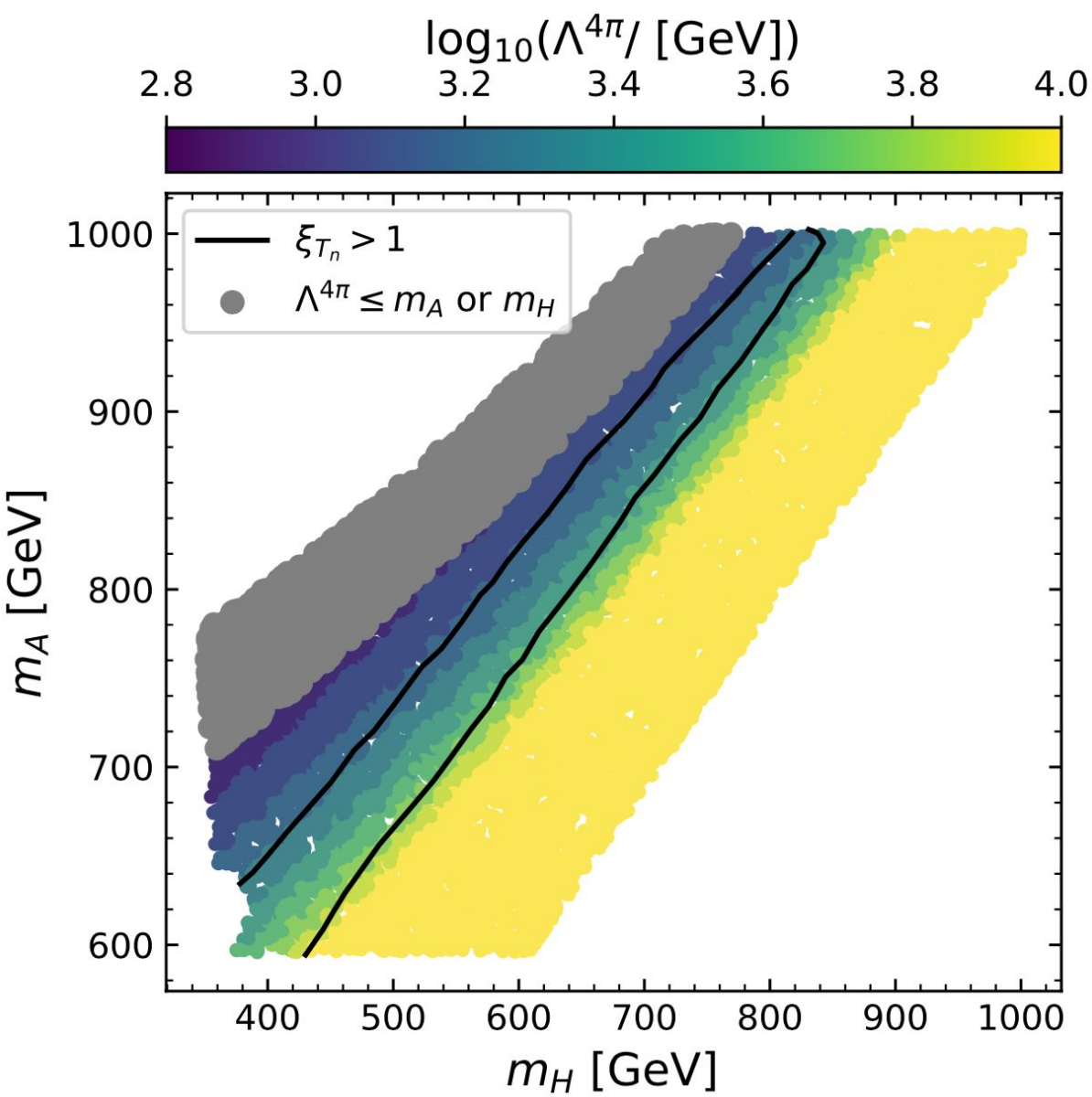
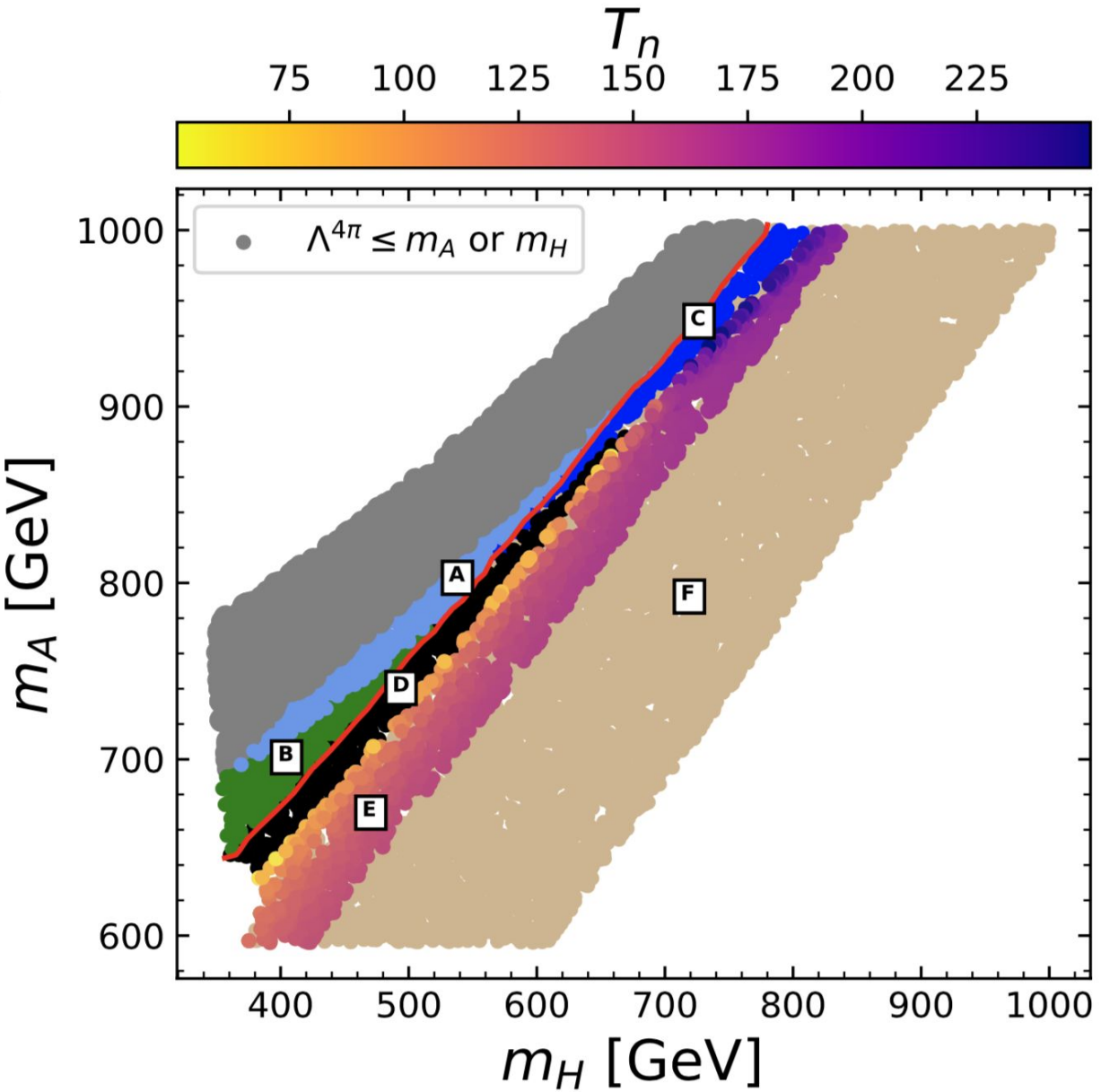
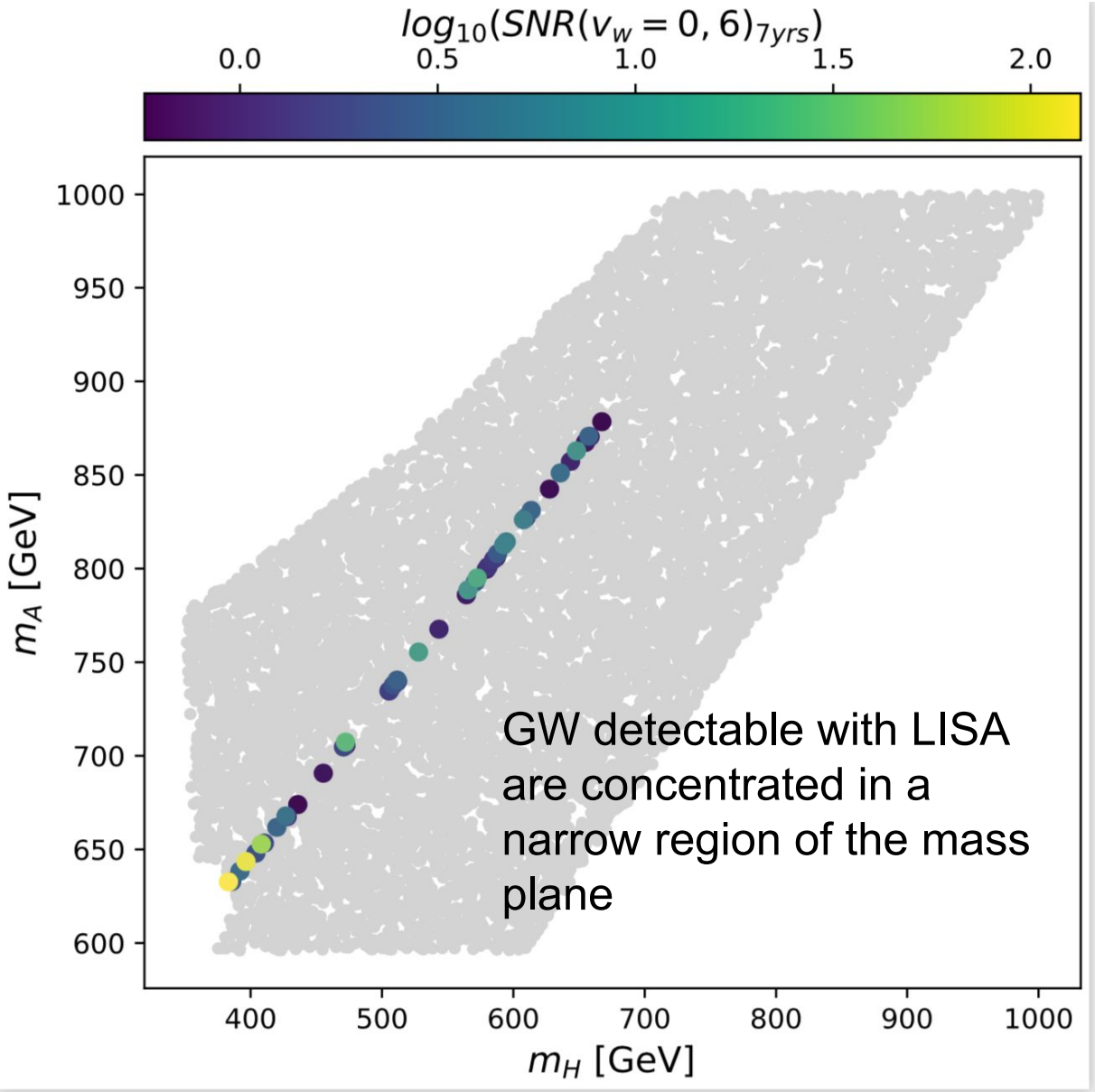
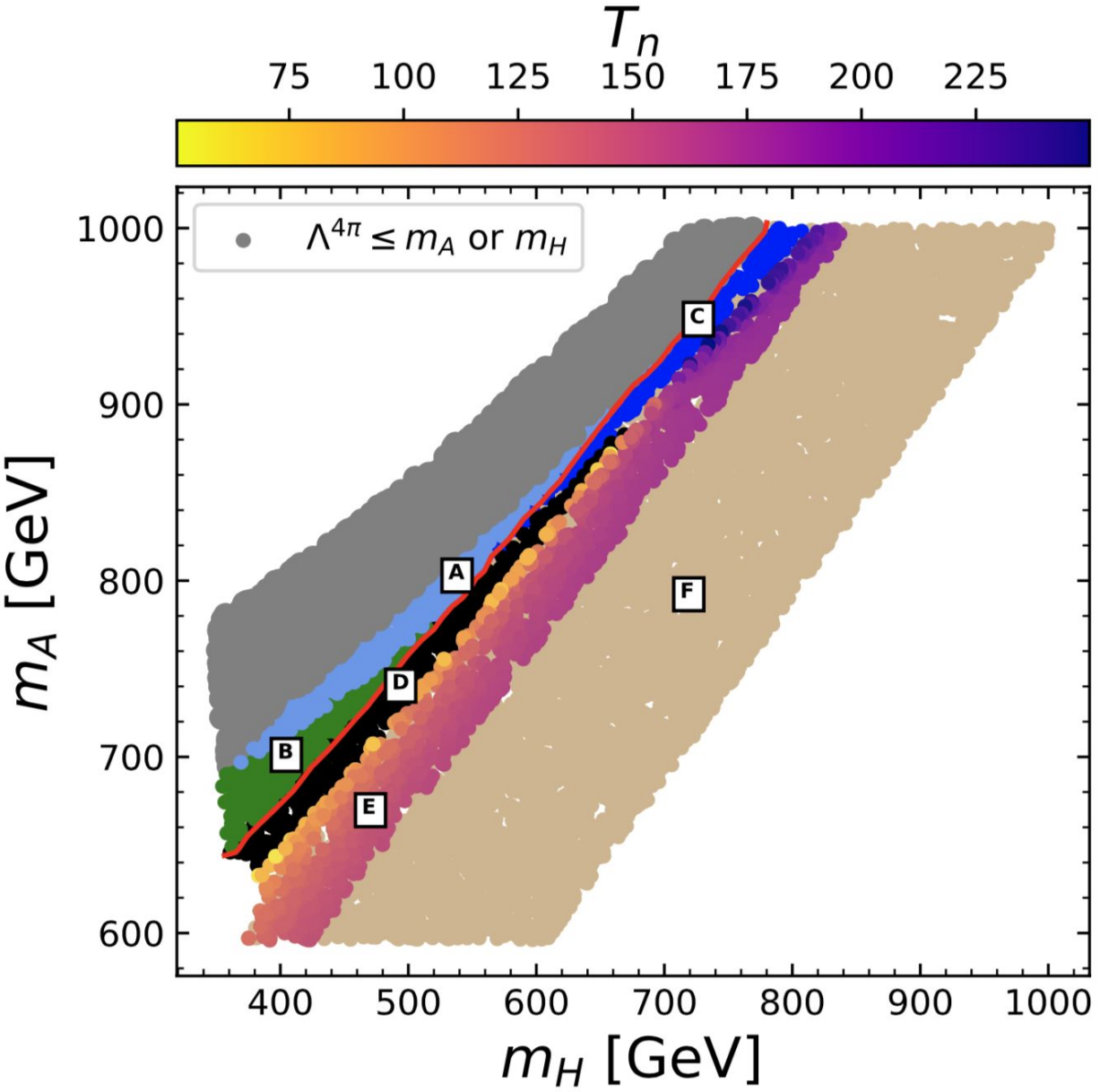


# Gravitational waves in the 2HDM



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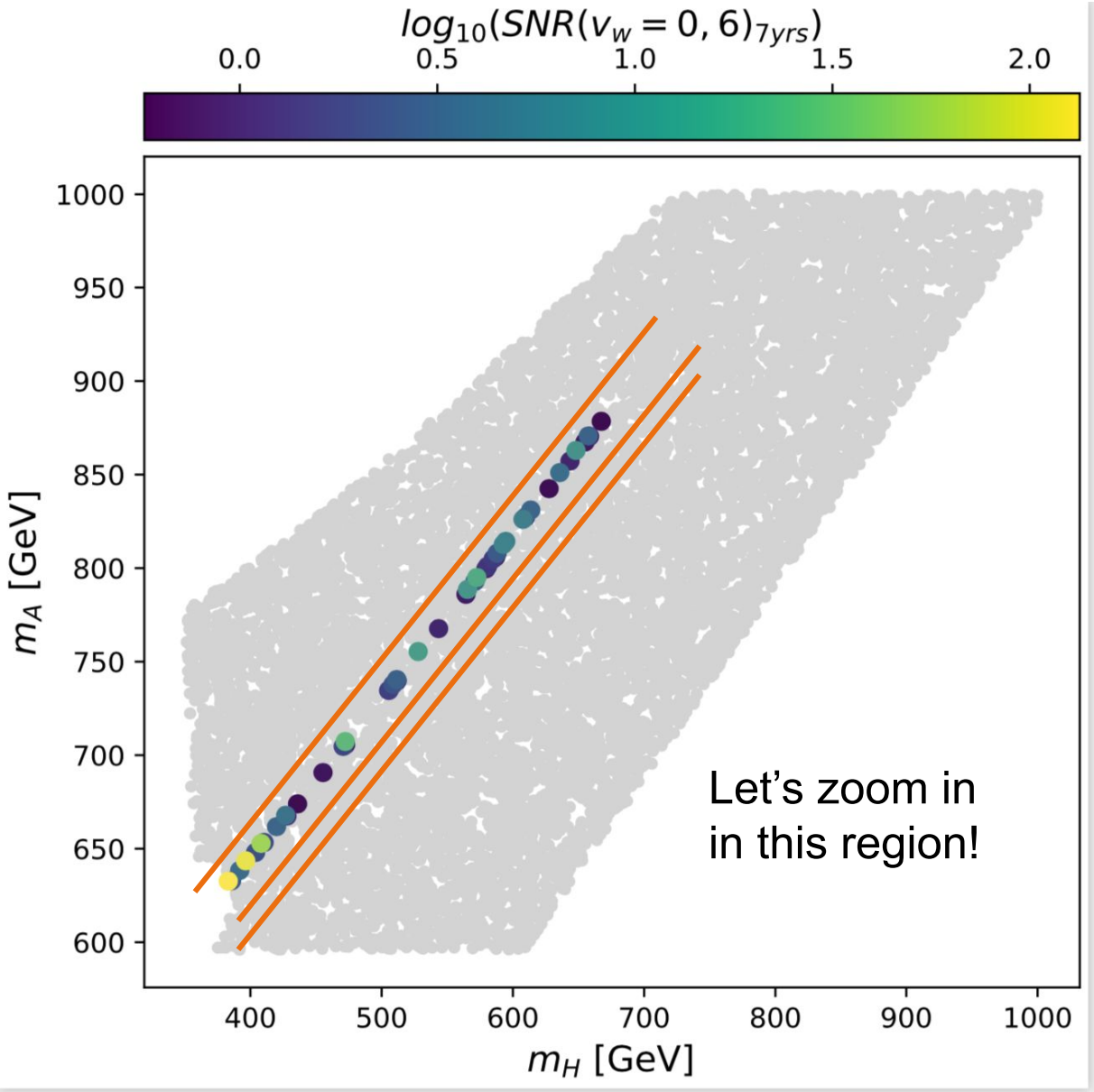


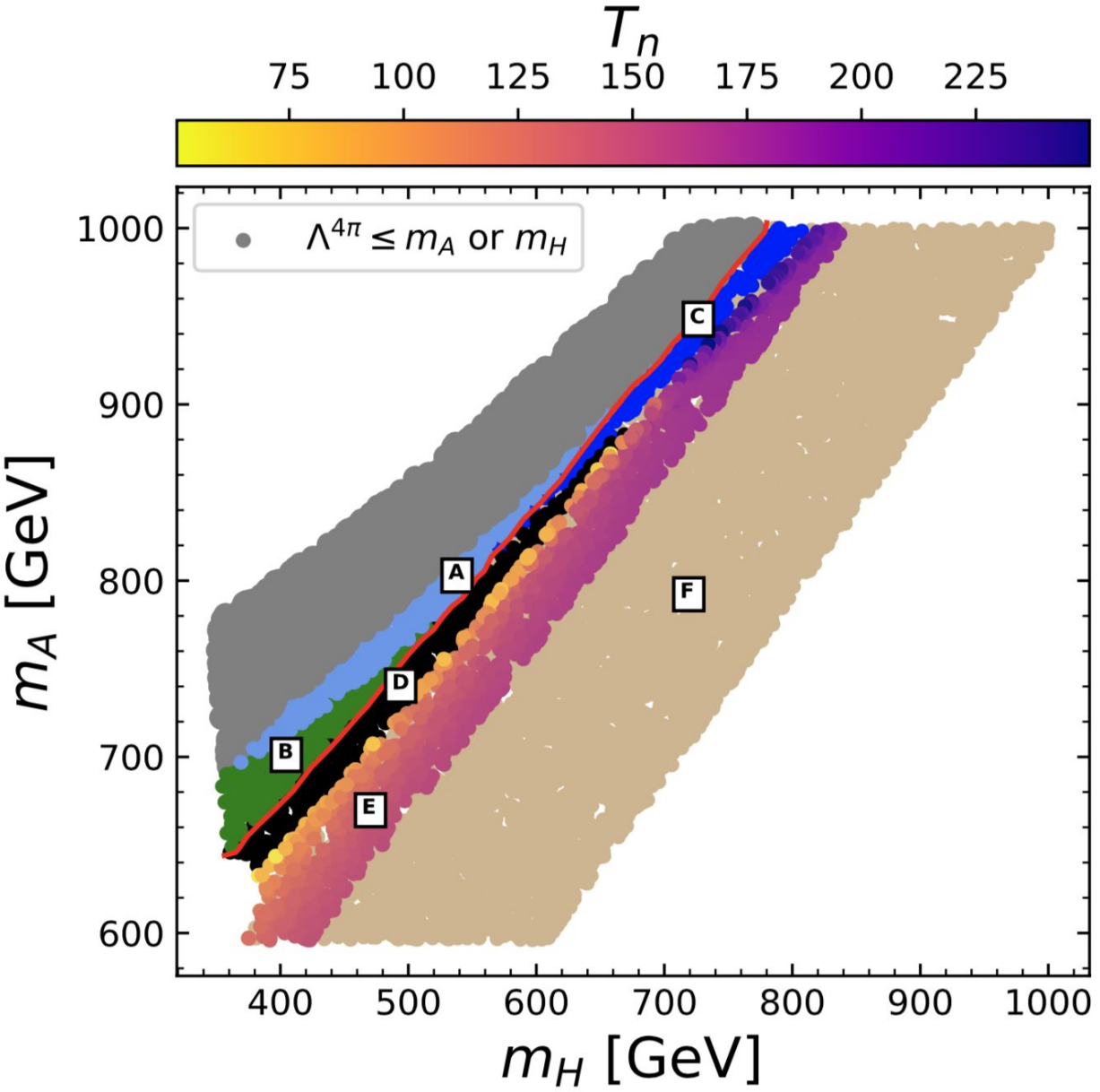

# Recipe for a FOEWPT in the 2HDM

1. **Add an energy barrier**

   a. Tree-level barrier → Not possible due to gauge invariance

   b. Barrier from radiative and thermal corrections:

**Example:**

Boson with tree-level mass: $m_i^2 = \mu_S^2 + \lambda_{HS} h^2$

Generates a term in the effective potential of the form: $-\frac{T}{12\pi}\left[\mu_S^2 + \lambda_{HS} h^2 + \Pi_S\right]^{3/2}$

Large quartics enhance the effective cubic term needed for the barrier

**Large quartics → Large splittings between the scalar masses**