VAST 2026 workshop
21st - 23rd October 2026

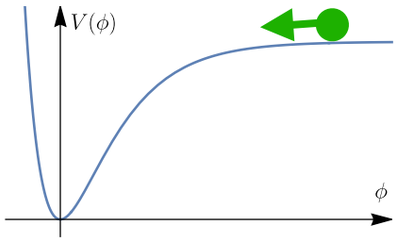
# Higgs vacuum stability, reheating and gravitational waves

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Johannes Gutenberg University, Mainz

In collaboration with: J. Rubio, D. Bettoni, A. Lopez-Eiguren

UNTERSTÜTZT VON / SUPPORTED BY
Alexander von HUMBOLDT STIFTUNG

$H \lesssim 10^{14}\ \mathrm{GeV}$

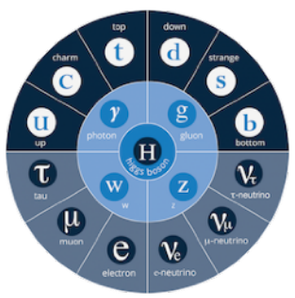





**THE PROBLEM OF REHEATING**

How do we link inflation to a thermalised SM bath?

$T \sim 5\,\mathrm{MeV}$




## THE INGREDIENTS

- Inflation followed by **kination** ($w = +1$)
- The Higgs is a spectator field **non-minimally coupled to curvature**

$$V(h) = \frac{1}{2}\xi R h^2 + \frac{1}{4}\lambda h^4$$

**The Higgs is sensitive to the cosmological history!**

## THE OUTCOMES

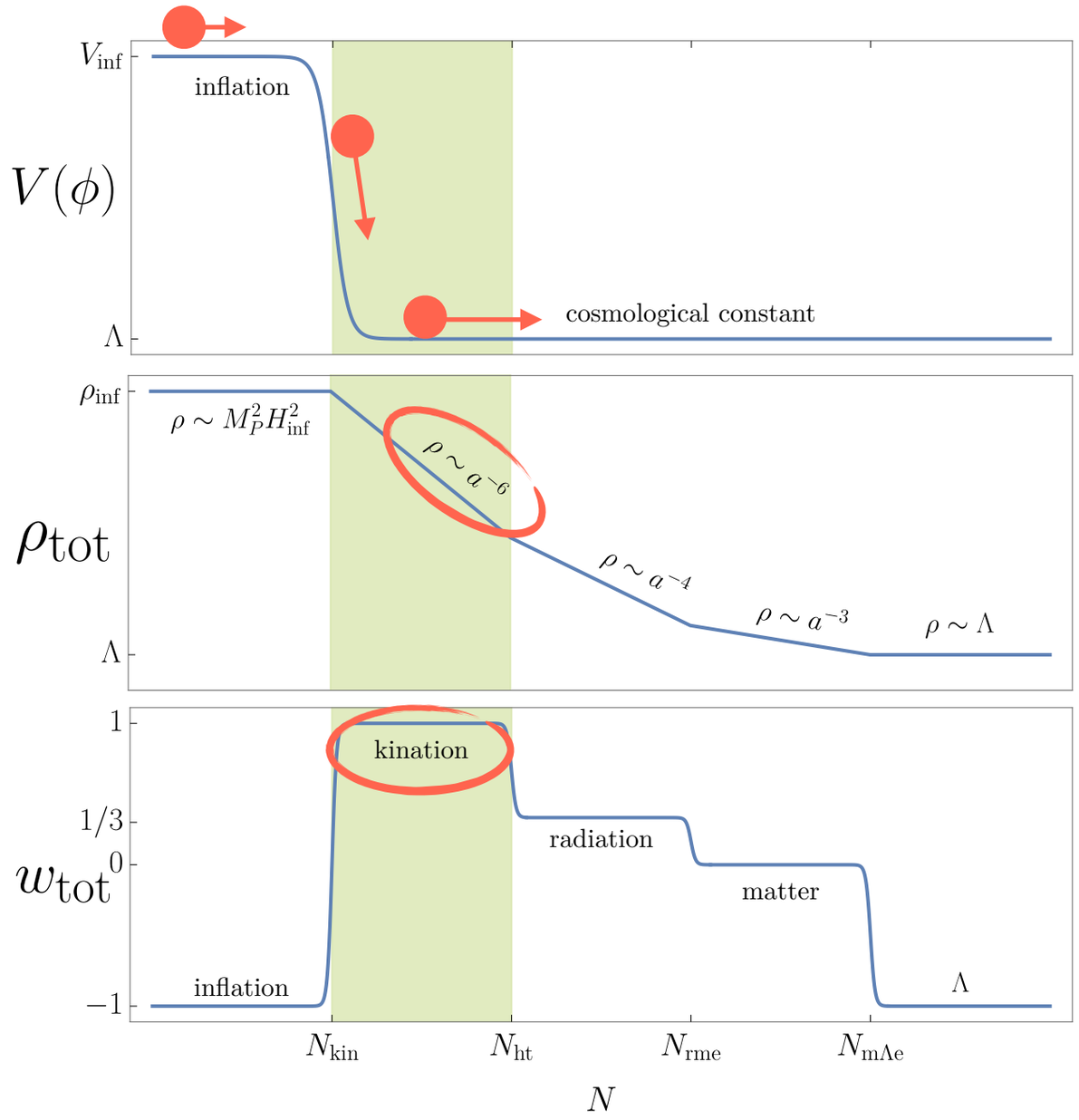
- The Higgs **reheats the early Universe**
- Background of **gravitational waves**
- Higgs **stability** during inflation
- Potential **instability** during kination
- Links between particle physics and cosmological observables

Image credits: CERN

# The Higgs' Hubble-induce phase transition

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm P}^2}{2}R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) - \lambda\left(H^\dagger H - \frac{v_{\rm EW}^2}{2}\right)^2 - \xi H^\dagger H R + \mathcal{L}_{\rm SM} + \mathcal{L}_\phi$$

- The inflaton field dynamics leads to **inflation** ($w = -1$) followed by **kination** ($w = +1$) (e.g. *quintessential inflation*)



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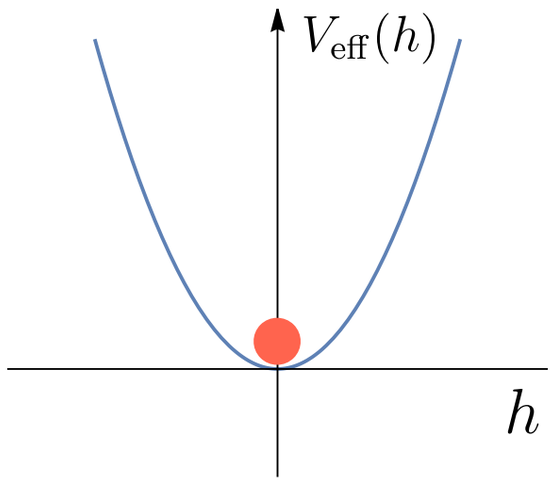
- The inflaton field dynamics leads to **inflation** ($w = -1$) followed by **kination** ($w = +1$) (e.g. *quintessential inflation*)
- The **Higgs** is a **spectator field** during inflation
- **Symmetry breaking** between inflation and kination *[Figueroa+ '16]*

$$V(h) = \frac{1}{2}\xi R h^2 + \frac{1}{4}\lambda h^4$$

$$R = 3(1-3w)H^2$$

- **Hubble-induced phase transition**: tachyonic instability and non-perturbative particle production *[Bettoni+ '19, '21]*

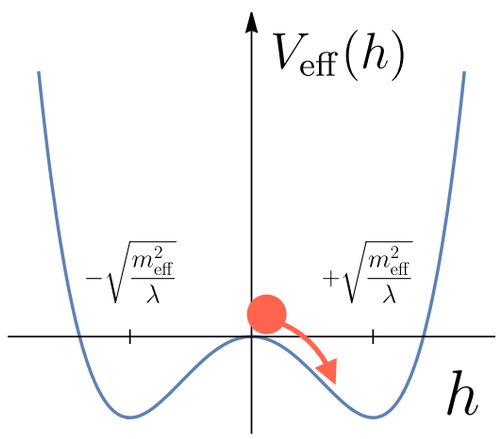
## INFLATION




$$w = -1$$
$$R = 12H^2$$
$$m_{\rm eff}^2 \gtrsim H_{\rm inf}^2$$

The Higgs is massive,
⟹ suppressed fluctuations,
⟹ suppressed isocurvature pert.

## KINATION




$$w = +1$$
$$R = -6H^2$$
$$m_{\rm eff}^2 \lesssim -H_{\rm inf}^2$$

The Higgs is tachyonic,
⟹ exponential growth fluctuations

# The Higgs' Hubble-induce phase transition

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm P}^2}{2}R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) - \lambda\left(H^\dagger H - \frac{v_{\rm EW}^2}{2}\right)^2 - \xi H^\dagger H R + \mathcal{L}_{\rm SM} + \mathcal{L}_\phi$$

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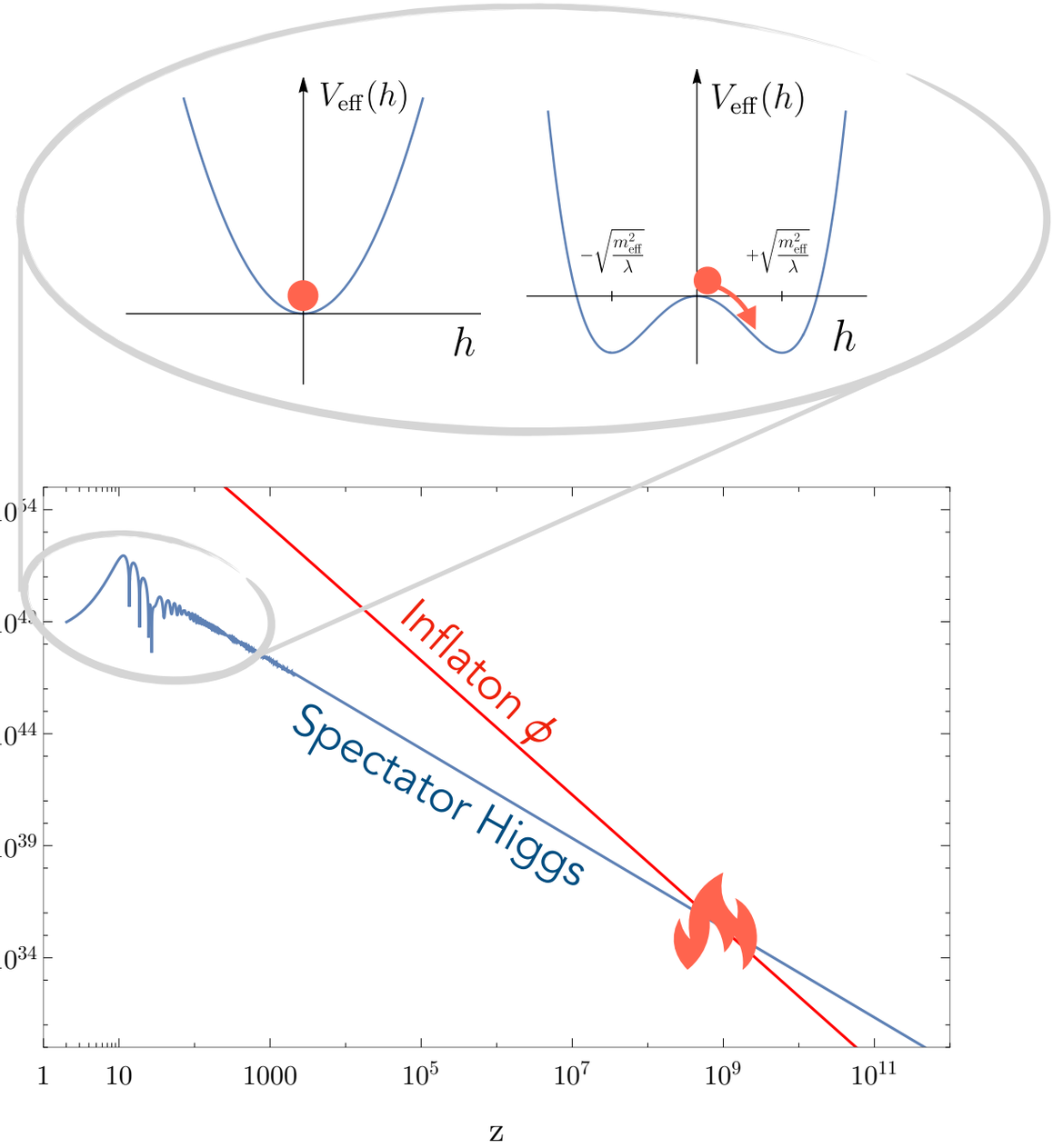
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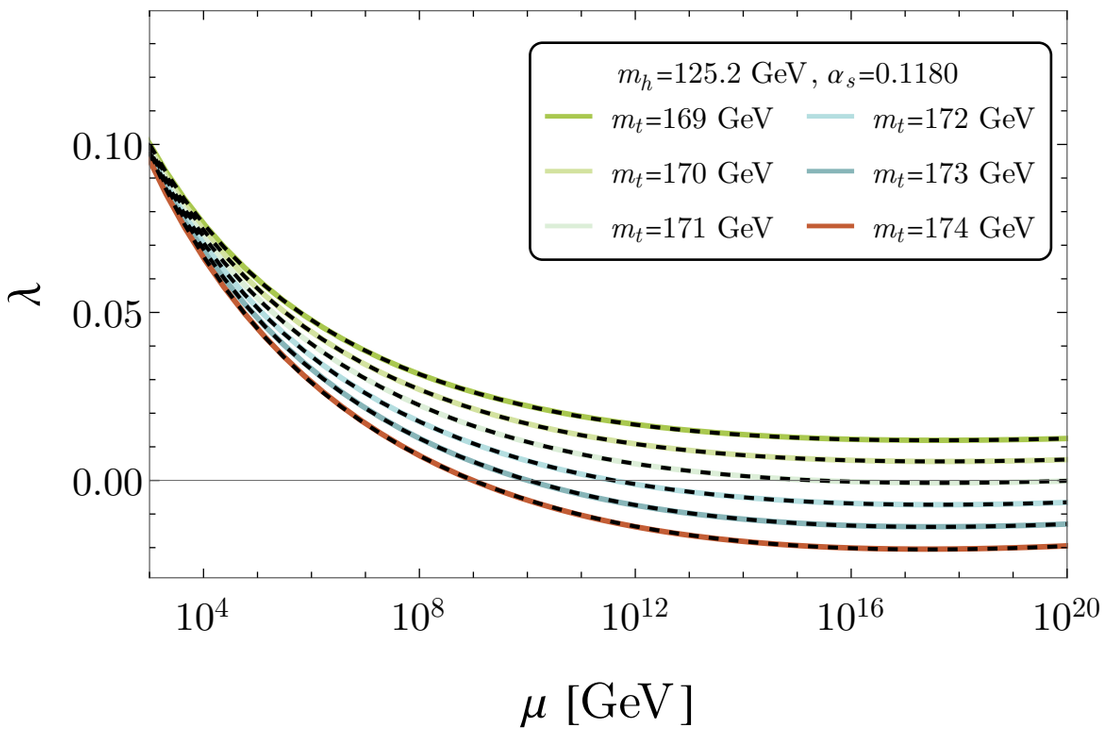
- **Reheating is automatic!** *(Ricci reheating) [Opferkuch+ '19]*

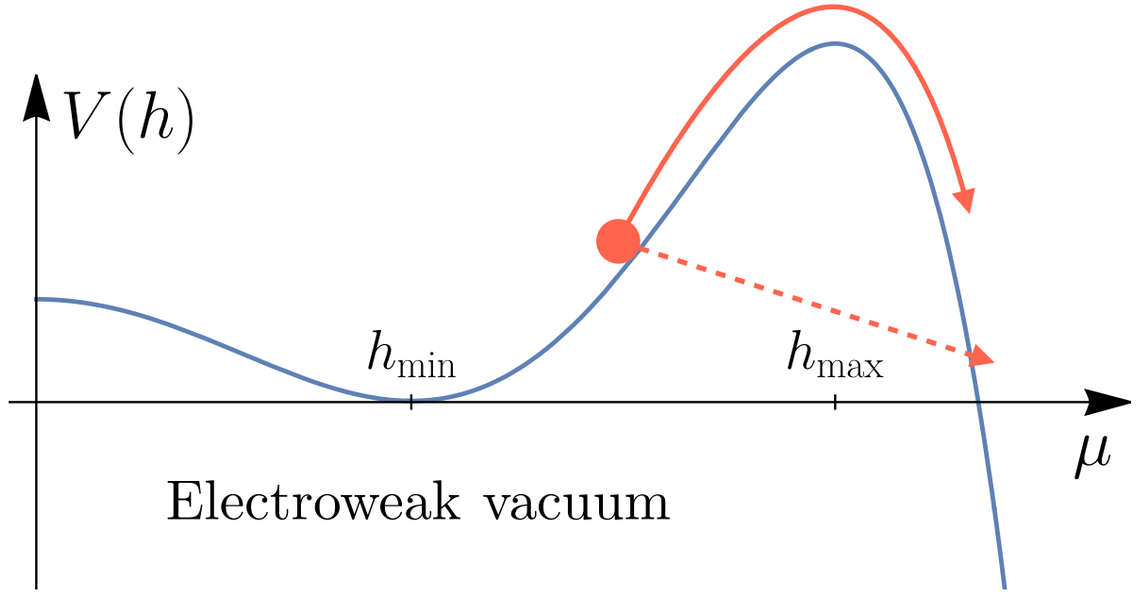
$$\rho_\phi \sim a^{-6} \qquad \rho_h \sim a^{-4}$$



# Beyond tree level: vacuum metastability

- Higgs quartic coupling $\lambda(\mu)$ runs to **negative values** at high scales
- Strong dependence on the exact value of **top quark pole mass**
- Effective potential can be **metastable** (two vacua separated by a barrier)



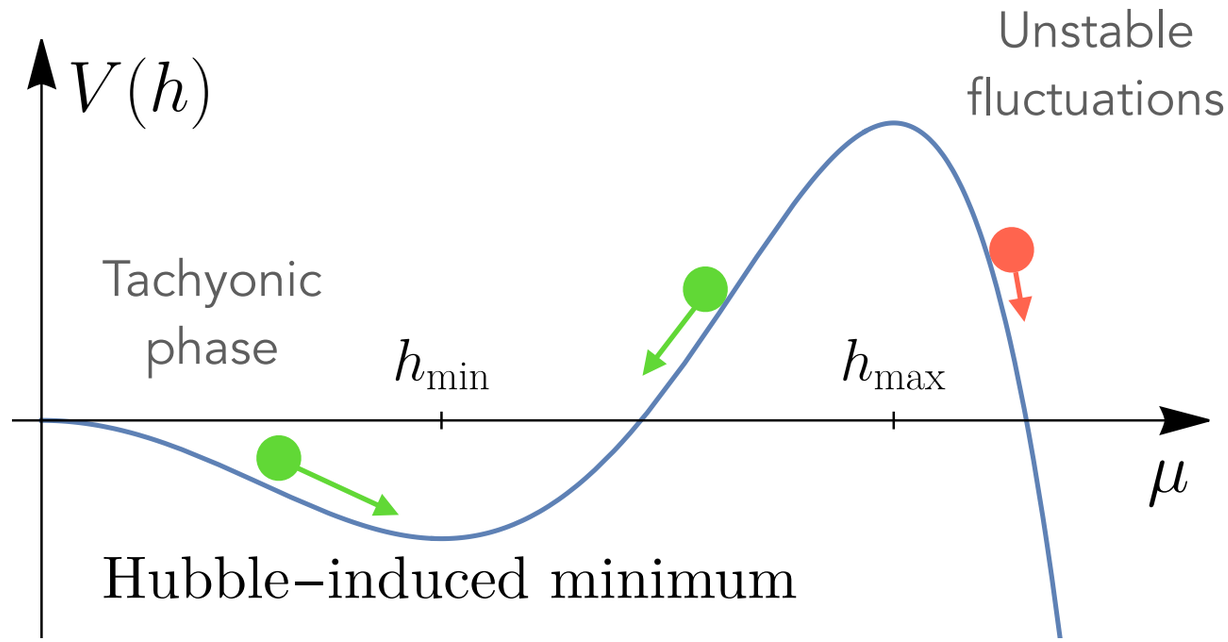
# Beyond tree level: vacuum metastability

- Non-minimal coupling during kination **worsens** the stability problem!

$$V(h) = \frac{1}{2}\xi(-6H^2)h^2 + \frac{1}{4}\lambda(\mu)h^4$$

- If we task the Higgs with reheating, we need a **stability criterion**

- Upper limit on maximum energy density (and also maximum amplitude) of **classical fluctuations**




**STABILITY CRITERION:**

$$\boxed{\rho_{\rm tac} < V_{\rm max}}$$

[Bezrukov+ '12]

Results from [GL, J. Rubio 2402.06000]

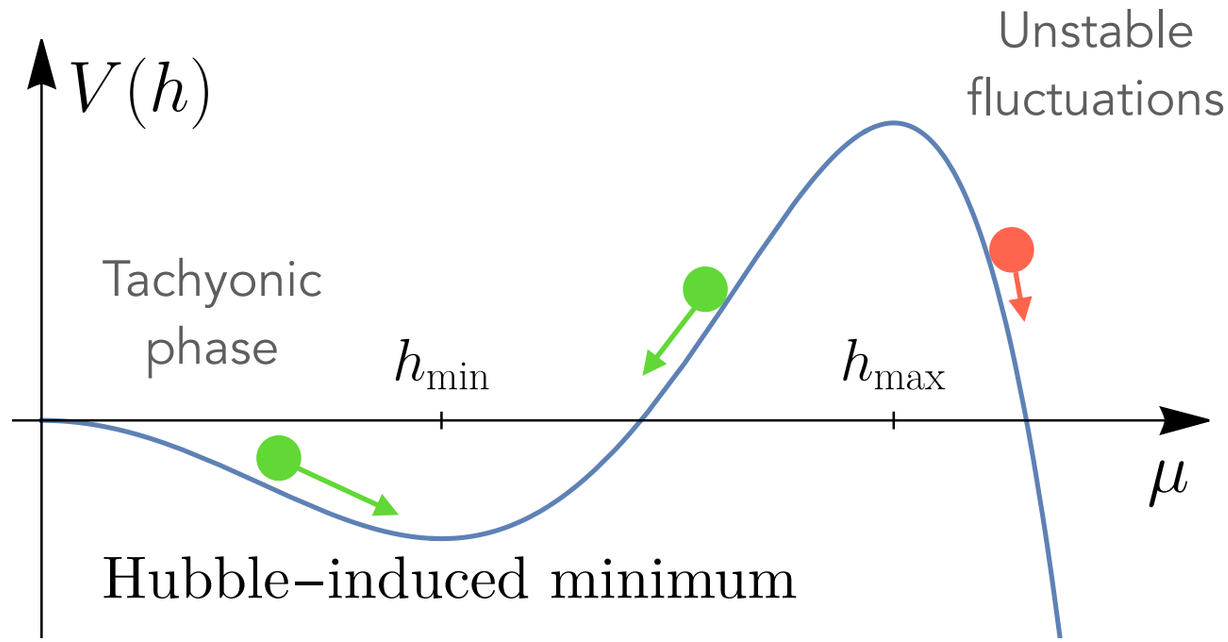
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**from numerical 3-loop running of $\lambda(\mu)$**

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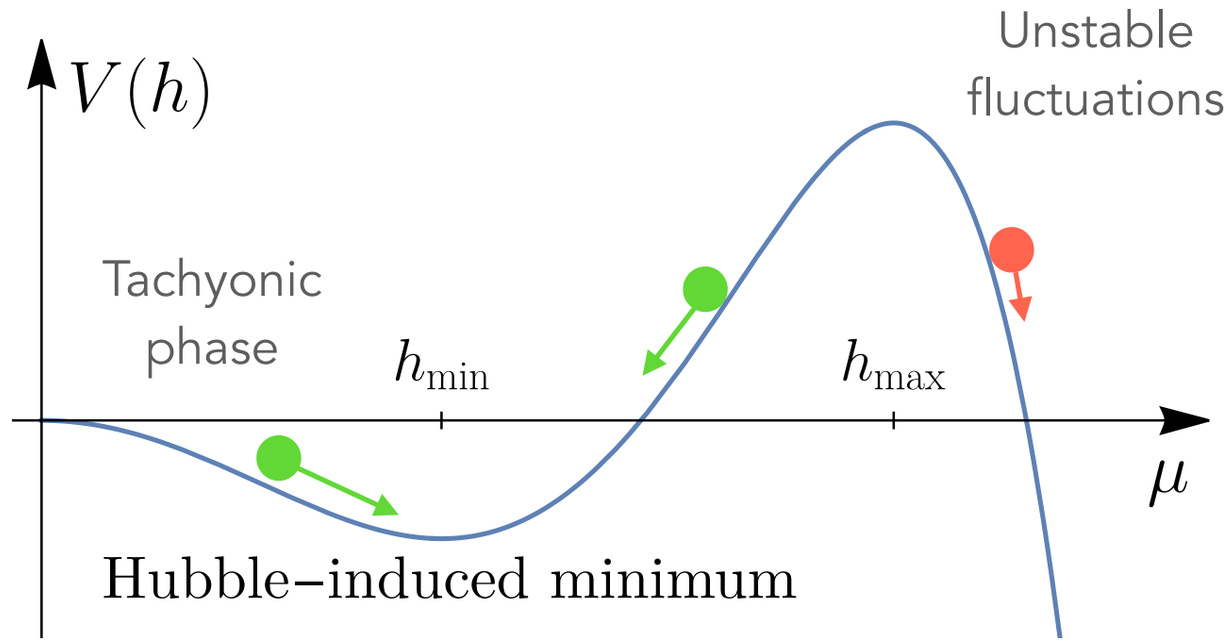
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**STABILITY CRITERION:**

$$\rho_{\rm tac} < V_{\rm max}$$

**from lattice simulations**

$$\rho_{\rm tac}(\lambda,\xi) = 16\,\mathcal{H}_{\rm kin}^4\,\exp\left(\beta_1 + \beta_2\,\nu + \beta_3\ln\nu\right)$$

[GL, J.Rubio, 2307.03774]

**from numerical 3-loop running of $\lambda(\mu)$**

[Bezrukov+ '12]

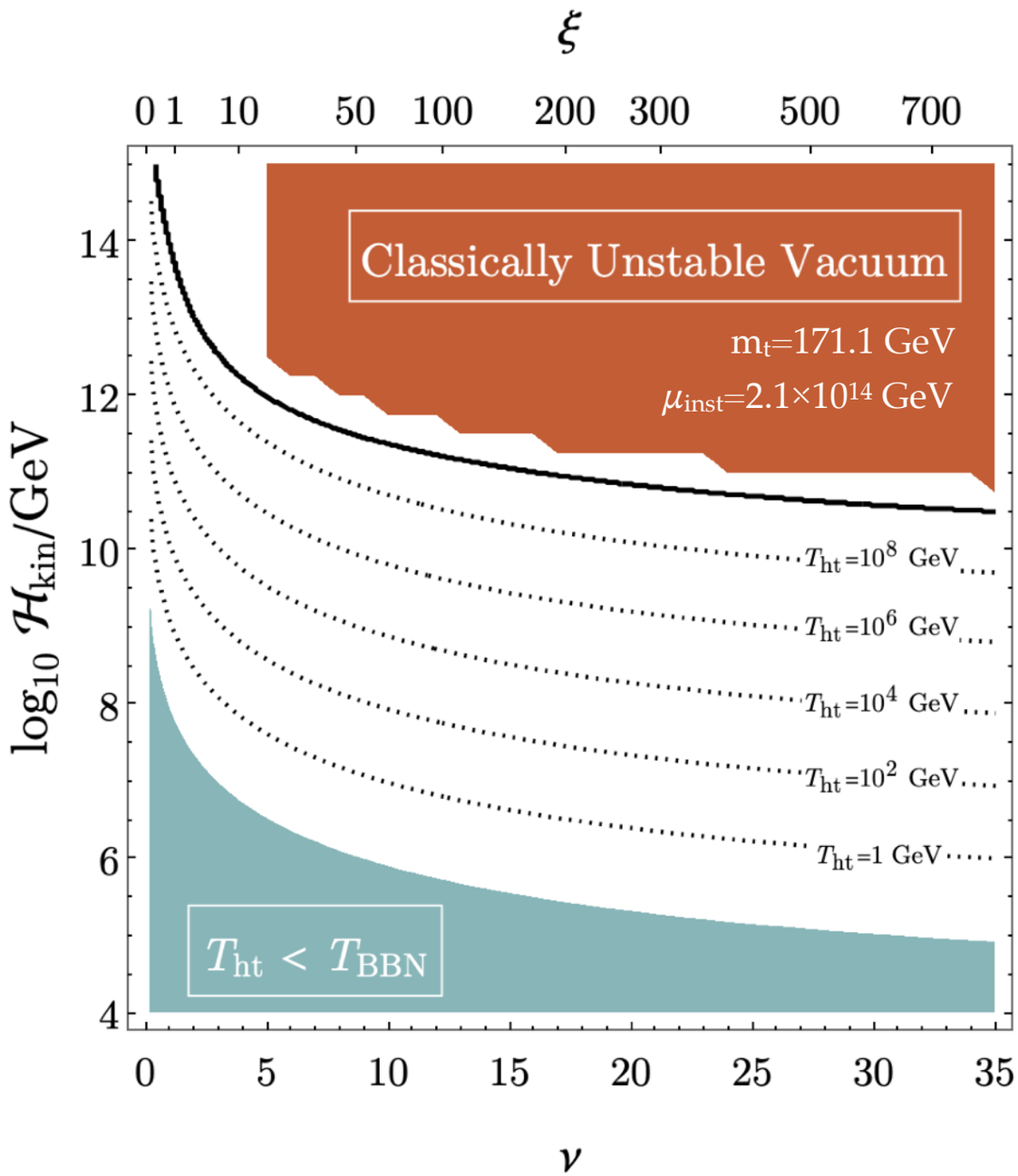


Results from [GL, J. Rubio 2402.06000]

# Stability constraints on reheating

- Fix the **top pole mass** and compute constraints from **stability** and **BBN temperature**
- Estimate stability region $\rho_{\rm tac} < V_{\rm max}$ with 3 loop running of $\lambda$
- Simulate stability of HIPT with **hundreds of lattice simulations via CosmoLattice** *[Figueroa+ '20, '21, '26]*

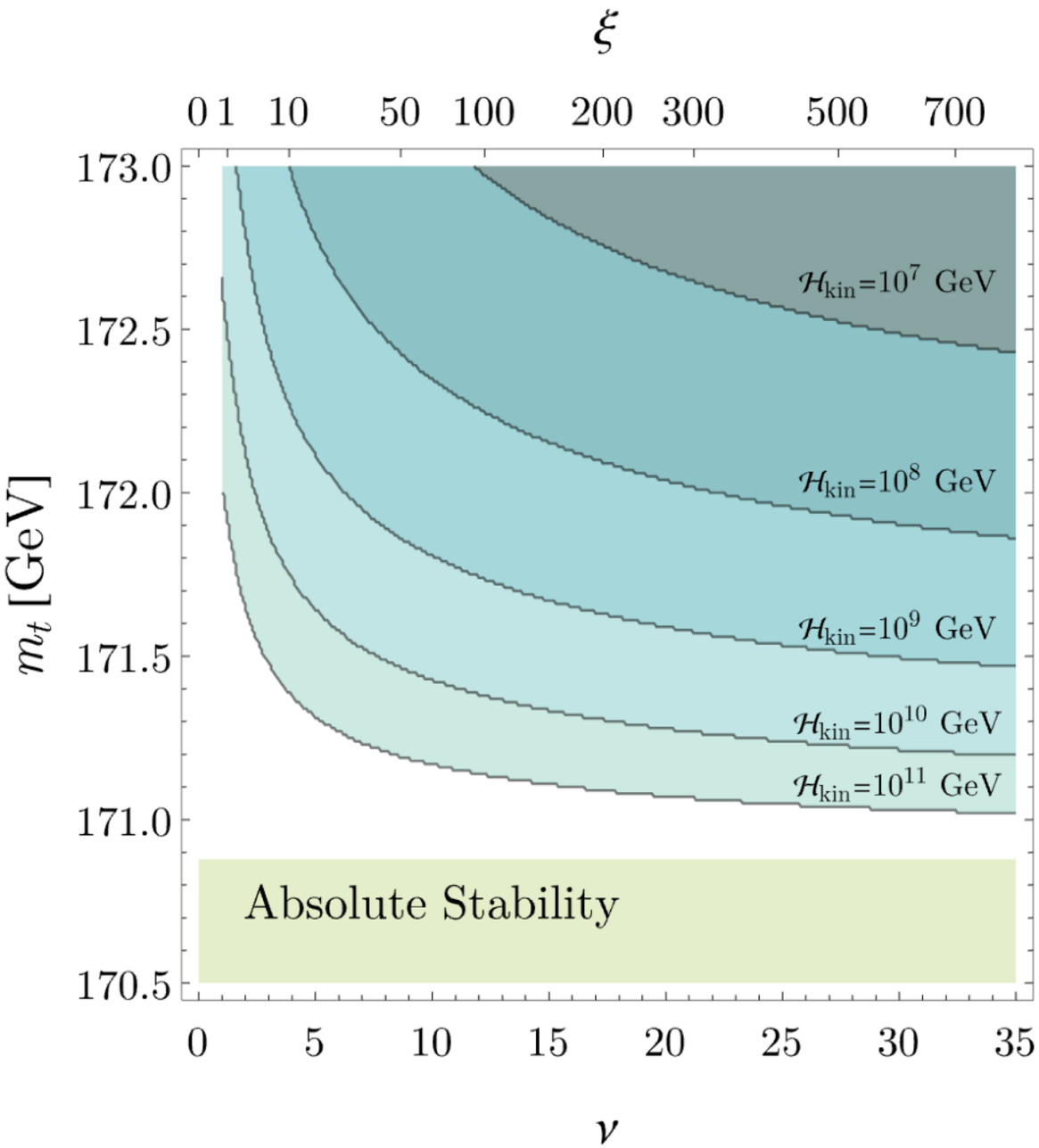
**The Higgs by itself can maintain vacuum stability while reheating the Universe at high temperatures!**




Results from [GL, J. Rubio 2402.06000]

# Effects of top quark pole mass

- Running $\lambda(\mu)$ depends **very sensitively** on the **top pole mass**
- **Agnostic** approach to incorporate uncertainties on the exact value
- Fix $H_{\rm kin}$ and compute the stability constraint with $m_t$ as free parameter
    1. high $m_t$ → lower instability scale
    2. low $m_t$ → higher instability scale
    3. Critical $m_t^c \simeq 170.9$ GeV




**Recent ATLAS result $m_t^{\rm pole} = 170.7 \pm 1.5$ GeV**

[ATLAS collab. 2507.02632]

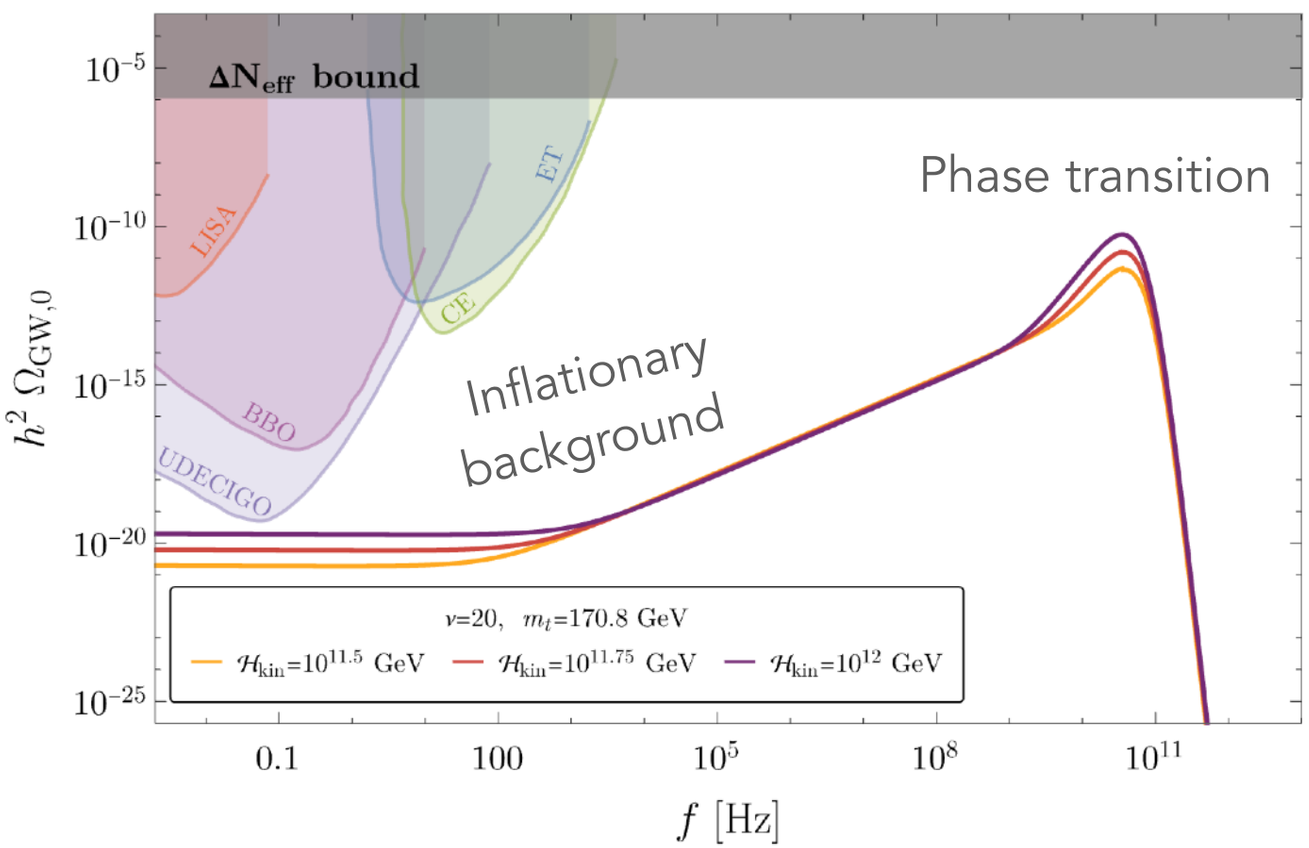
Results from [GL, J. Rubio 2402.06000]

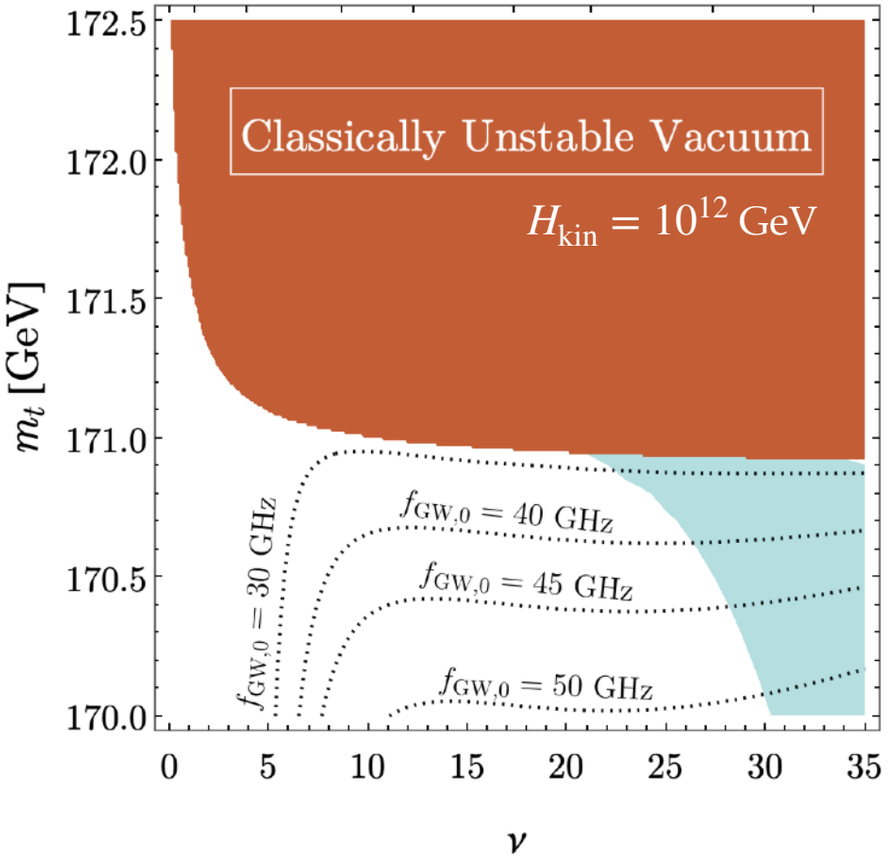
# Gravitational waves from the stable Higgs

- Non-linear dynamics lead to local **anisotropies** $\Longrightarrow$ source for **gravitational waves**

$$\ddot{h}_{ij} + 3H\dot{h}_{ij} - \frac{1}{a^2}\nabla^2 h_{ij} = \frac{2}{a^2 M_P^2}\,\Pi_{ij}^{\mathrm{TT}}$$

- Position of the peak depends on **rescattering** $\Longrightarrow$ dependence on $m_t$ via $\lambda$
- Connection between cosmological and particle physics measurements






Results from [GL, J. Rubio 2502.04445]

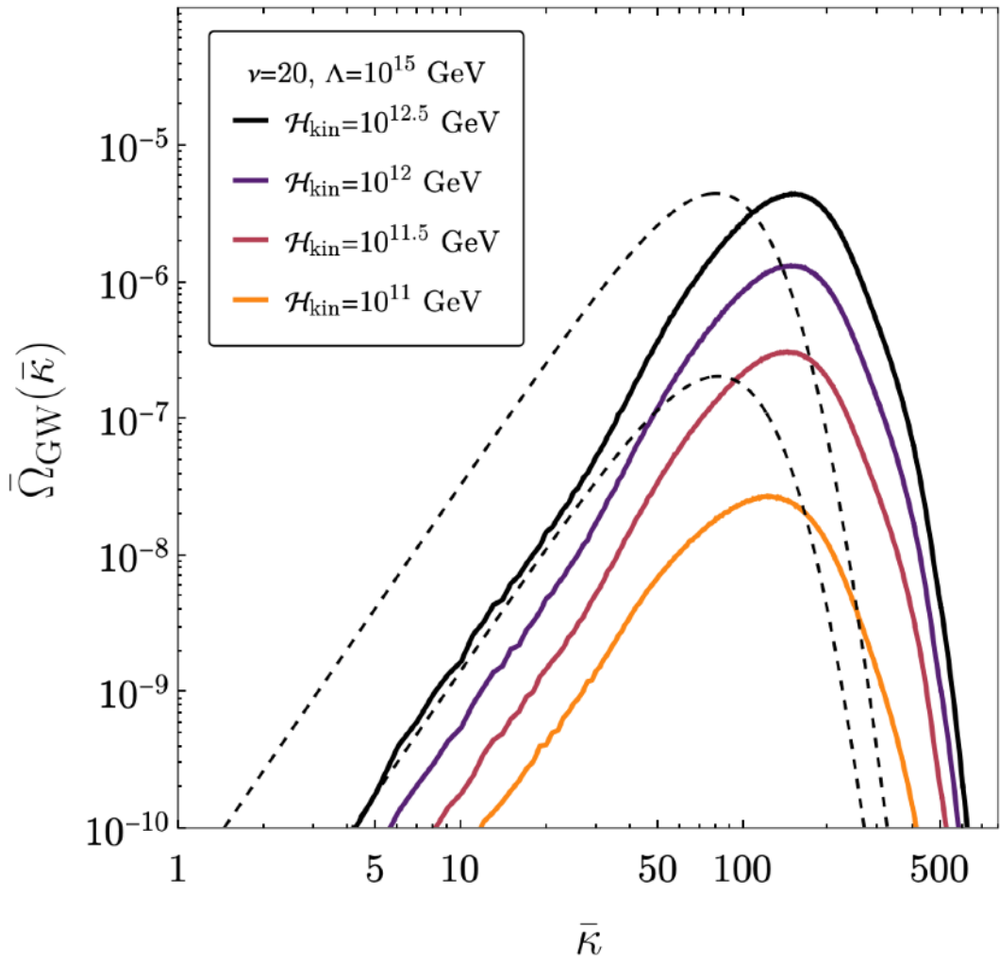
# What about new physics at high scales?

- **Higher-order operators** in effective potential solve the instability problem

$$V(H) = \xi R H^\dagger H + \lambda (H^\dagger H)^2 + \frac{1}{\Lambda^2}(H^\dagger H)^3$$

- New physics at high scales
  $\Longrightarrow$ **modified rescattering**
  $\Longrightarrow$ **change in frequency** and amplitude of the GW spectrum

- Distinct features w.r.t. standard scenario




Results from [GL, J. Rubio 2502.04445]

# Take-home message:

- Non-minimal coupling stabilises the Higgs during inflation, it leads to tachyonic particle production during kination and it produces a gravitational-wave signal

- The Higgs can be responsible for heating, its stability can be checked against the barrier in the effective potential

- Connection between SM parameters, cosmological parameters and gravitational waves

# Thanks!

For more details see:
GL, J. Rubio et al. 2307.03774, 2402.06000, 2409.15450, 2502.04445, 2505.00900

# Additional material

# Spectator field approximation

- Compute the Ricci scalar from Einstein equations

$$M_P^2\, R = \langle T^\phi \rangle \frac{1-\Delta_1}{1+\Delta_2} \quad \text{with} \quad \Delta_1 = (6\xi - 1)\frac{\langle T^\chi_{\xi=0}\rangle}{\langle T^\phi\rangle}\,, \quad \Delta_2 = (6\xi-1)\frac{\xi\langle\chi^2\rangle}{M_P^2}$$

- $\Delta_1$ controls the sign of the Ricci scalar $\Longrightarrow$ constraint $\langle\chi^2\rangle \ll M_P^2/\xi$
- $\Delta_2$ controls the magnitude of the Ricci scalar. It goes to zero for large amplitude fluctuations

$$\boxed{\langle\chi^2\rangle \ll M_P^2/\xi^2} \quad \text{in practice} \quad \langle\chi^2\rangle < 0.01 \times M_P^2/\xi^2$$

- Agreement with the cut-off derived from EFT

# EFT cut-off

- Weyl transformation to the Einstein frame

$$g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu} \ , \quad \Omega^2 = 1 - \frac{\xi \chi^2}{M_P^2} \qquad \text{assuming} \qquad \mathcal{L}_\phi = -\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$

- Expansion for small-field values of $\chi$

$$\mathcal{S} \simeq \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \mathcal{L}_\phi - \frac{1}{2}\left(1 + \frac{6\chi^2}{\Lambda_\xi^2} + \frac{\xi\chi^2}{M_P^2}\right)\partial^\mu\chi\partial_\mu\chi - \left(1 + \frac{2\xi\chi^2}{M_P^2}\right)\frac{\lambda}{4}\chi^4 + \frac{1}{2}\frac{\xi\chi^2}{M_P^2}T^\phi + \mathcal{O}(u^4\,\mathcal{L}_\chi,\ u^4\mathcal{L}_\phi)\right]$$

- Read out the lowest energy scale

$$\boxed{\Lambda_\xi = \frac{M_P}{\xi}}$$

- Constraint on the maximum amplitude of fluctuations:

$$\langle\chi^2\rangle < 0.01 \times M_P^2/\xi^2$$

# Transient amplification from inflation to kination

- The non-adiabatic transition from inflation to kination leads to the gravitational production of field fluctuations

- Simple computation of non-adiabatic amplification:

$$\omega_{\rm in}^2 = k^2 + m_{\rm in}^2 \quad \text{with} \quad m_{\rm in}^2 = 12 a^2 H^2 \quad \text{for} \quad w = -1 \qquad \text{(from inflation)}$$

$$\omega_{\rm out}^2 = k^2 + m_{\rm out}^2 \approx k^2 \quad \text{with} \quad m_{\rm out}^2 = 0 \quad \text{for} \quad w = 1/3 \qquad \text{(to radiation dom.)}$$

| | | |
|---|---|---|
| Sub horizon | $k^2 \gg m_{\rm in}^2$ | *no amplification* |
| Tachyonic band | $a^2 H^2 \lesssim k^2 \lesssim m_{\rm in}^2$ | $\langle \chi^2 \rangle = \frac{m_{\rm in}^2}{8\pi^2 a^2} \simeq 6\xi \left(\frac{H}{2\pi}\right)^2$ |
| Super horizon | $k^2 \ll a^2 H^2$ | $\langle \chi^2 \rangle \simeq \sqrt{3\xi} \left(\frac{H}{2\pi}\right)^2$ |

# High-frequency GW detectors

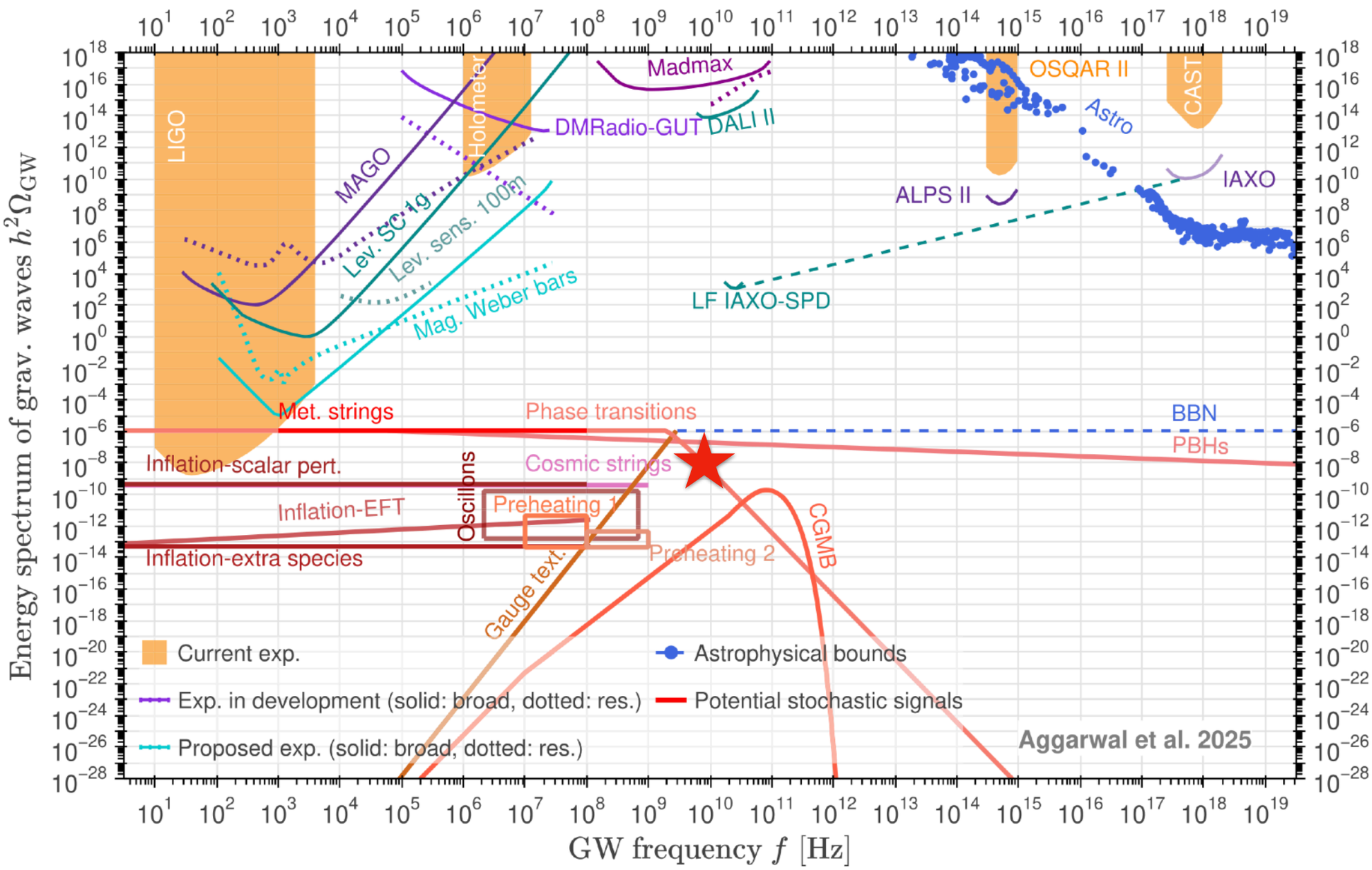





Image from: Challenges and Opportunities of Gravitational Wave Searches above 10kHz, Aggrawal et al. ‘25

# Rescaling of GW frequency and amplitude

- Rescaling due to non-standard expansion epoch during production *[Allahverdi et al. '21]*

$$\Omega_{\rm GW,0} = \left(\frac{a_*}{a_0}\right)^4 \left(\frac{H_*}{H_0}\right)^2 \Omega_{\rm GW,*} = 1.67\times 10^{-5} h^{-2} \left(\frac{100}{g_*(T_{\rm reh})}\right)^{\frac{1}{3}} \left(\frac{H_*}{H_{\rm reh}}\right)^{2\frac{3w-1}{3w+3}} \Omega_{\rm GW,*}$$

$$f_0 = \frac{a_*}{a_0} f_* = \frac{a_{\rm reh} H_{\rm reh}}{a_0} \frac{a_* H_*}{a_{\rm reh} H_{\rm reh}} \frac{f_*}{H_*} = 1.65\times 10^{-5}\,{\rm Hz} \left(\frac{T_{\rm reh}}{100\,{\rm GeV}}\right) \left(\frac{g_*(T_{\rm reh})}{100}\right)^{\frac{1}{6}} \left(\frac{f_*}{H_*}\right) \left(\frac{H_*}{H_{\rm reh}}\right)^{\frac{3w+1}{3w+3}}$$

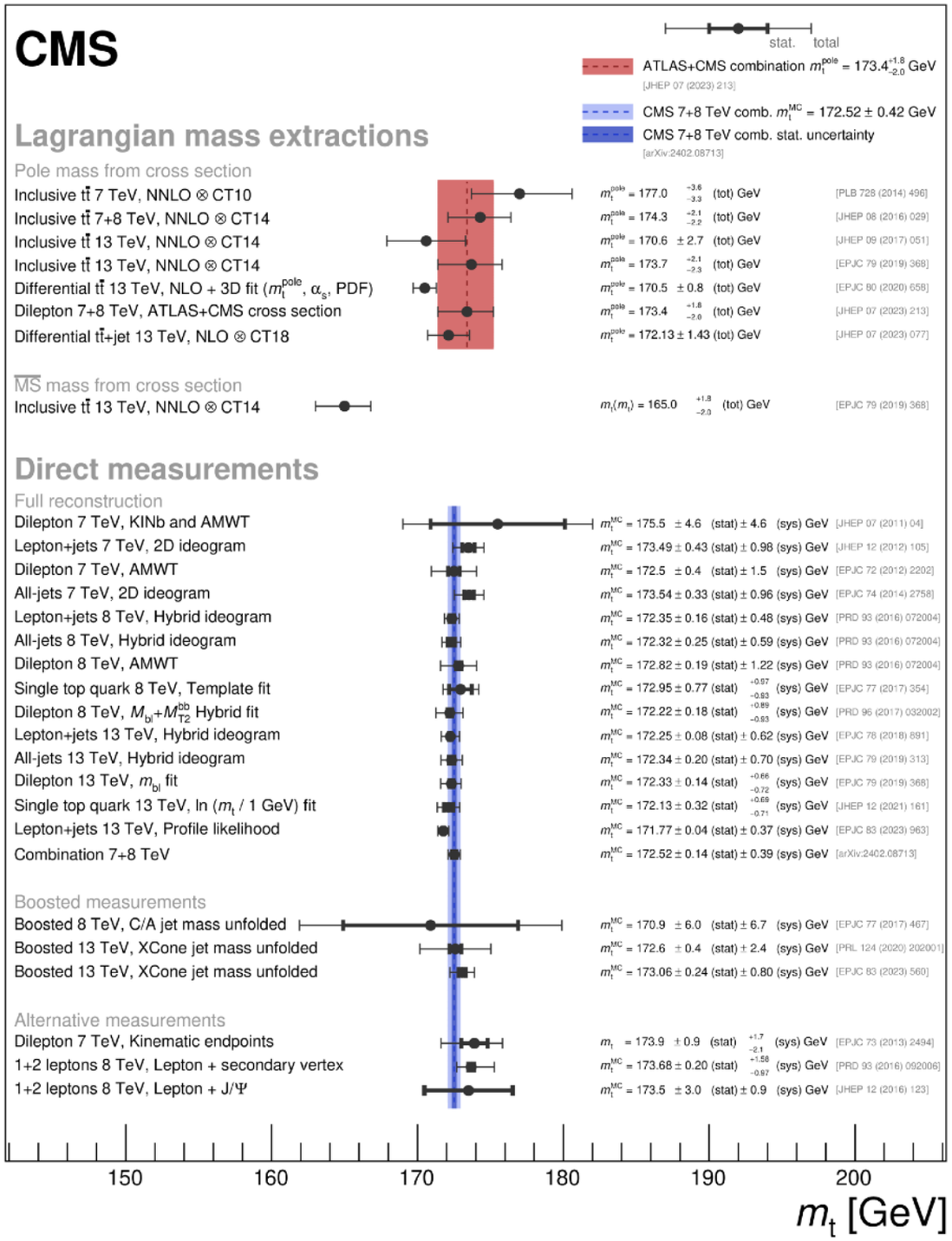
- In HIPT this translates into

$$\Omega_{\rm GW,0} = 1.67\times 10^{-5} h^{-2}\, \bar{\Omega}_{\rm GW}$$

$$f_0 \simeq 1.3\times 10^9\,{\rm Hz}\, \frac{\bar{\kappa}}{2\pi} \sqrt{a_{\rm rad}} \left(\frac{H_{\rm kin}}{10^{10}\,{\rm GeV}}\right)^{1/2} \left(\frac{\Theta_{\rm ht}}{10^{-8}}\right)^{-1/4}$$

$$\Theta_{\rm ht} \equiv \frac{\rho^\chi(a_{\rm rad})}{\rho^\phi(a_{\rm rad})} = \frac{16}{3} \left(\frac{H_{\rm kin}}{M_P}\right)^2 \left(1+\frac{\gamma_1+\gamma_2\,\nu}{\nu}\right)^3 \exp\left(\delta_1+\delta_2\,\nu+\delta_3\ln\nu\right)$$

# Top quark mass measurement




- Direct measurements lead to top quark reconstructed Monte Carlo mass

- Pole mass is measured indirectly (cross section measurements)

- Uncertainty in how to relate the reconstructed mass to theoretical definitions of top masses



Image from: Review of top quark mass measurements in CMS, CMS collaboration ‘24