Higgs vacuum stability during kination

PLANCK 2024, 4th of June, Lisbon

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In collaboration with: **Javier Rubio**

Based on:
The rise and fall of the SM Higgs: electroweak vacuum stability during kination,
JHEP 2024, 339 (2024) [arXiv:2402.06000]

The setup:

- **Kination** (w=+1) following inflation (e.g. in *Quintessential Inflation*, one extra degree of freedom ϕ for both inflation and dark energy)
- The Higgs is **non-minimally coupled to curvature**
- No additional BSM degrees of freedom

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

The outcome:

- **SM parameters** linked to post-inflationary physics
- **Stable** Higgs field during inflation
- The Higgs is responsible for reheating the Universe after inflation via **a tachyonic instability during kination**

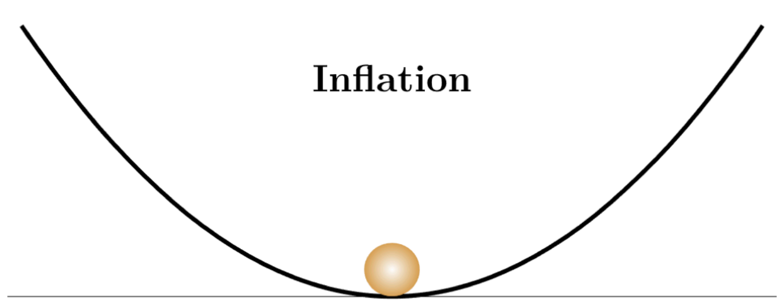
Non-minimally coupled spectator Higgs

	Inflation	Kination
Inflaton Energetically dominating, dictates the background expansion $R = 3(1-3w)H^2$	$w = -1$ $R = 12H^2$	$w = +1$ $R = -6H^2$

Higgs

Energetically subdominant (spectator field)

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



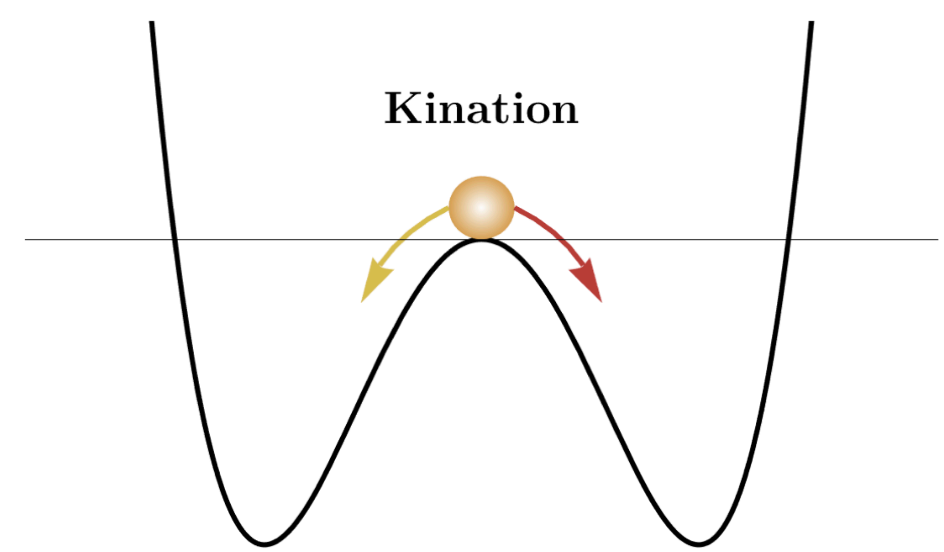


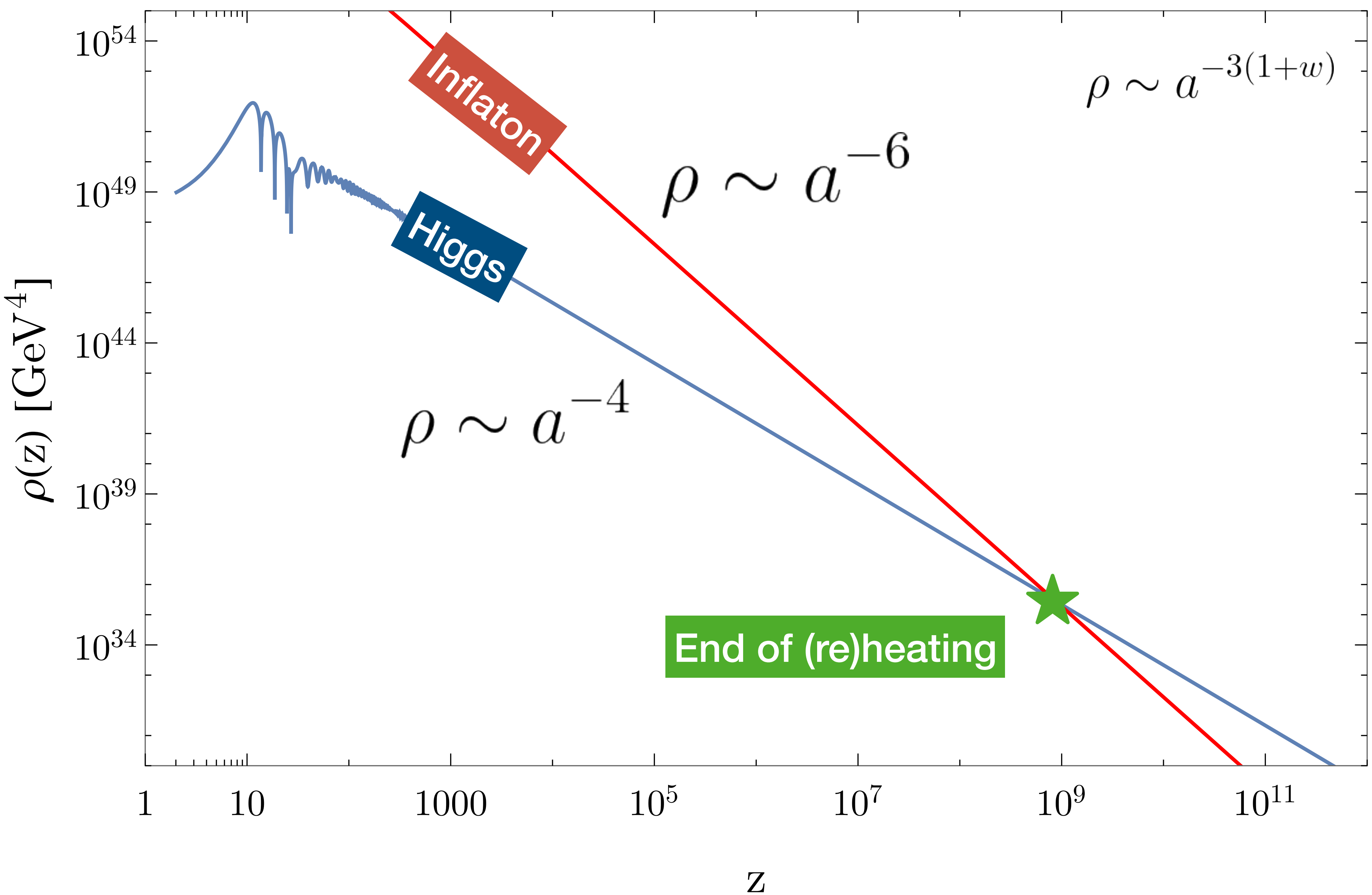
Image credit: *Quintessential Inflation: A Tale of Emergent and Broken Symmetries*, Bettoni, Rubio (2022)

(Re)heating

$$V\big|_{\rm kin} = -3\xi H^2 h^2 + \frac{1}{4}\lambda h^4$$

→ **Tachyonic** amplification of quantum fluctuations (particle production)

→ The radiation-like Higgs energy-density eventually **dominates** over the inflaton background



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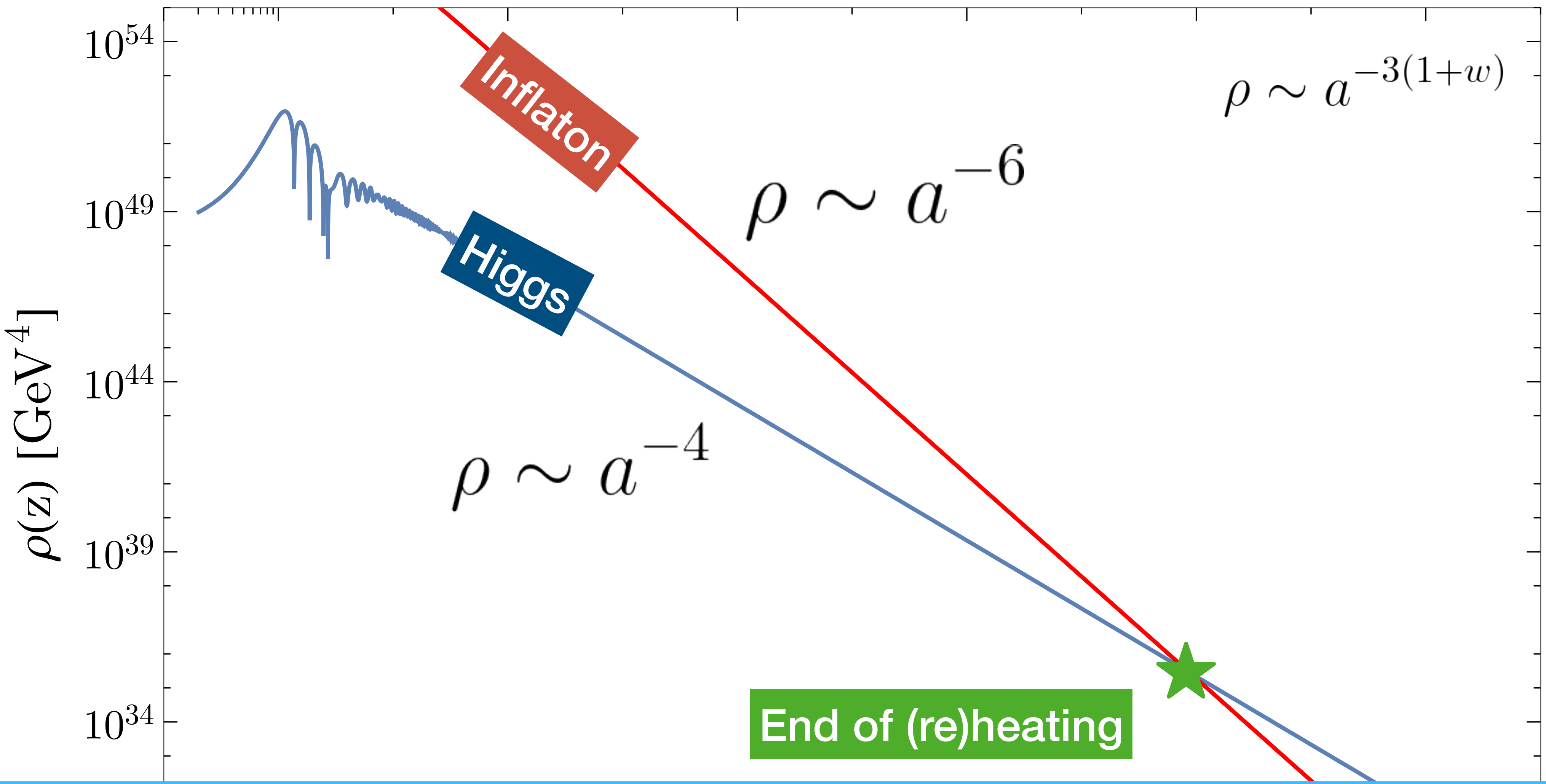
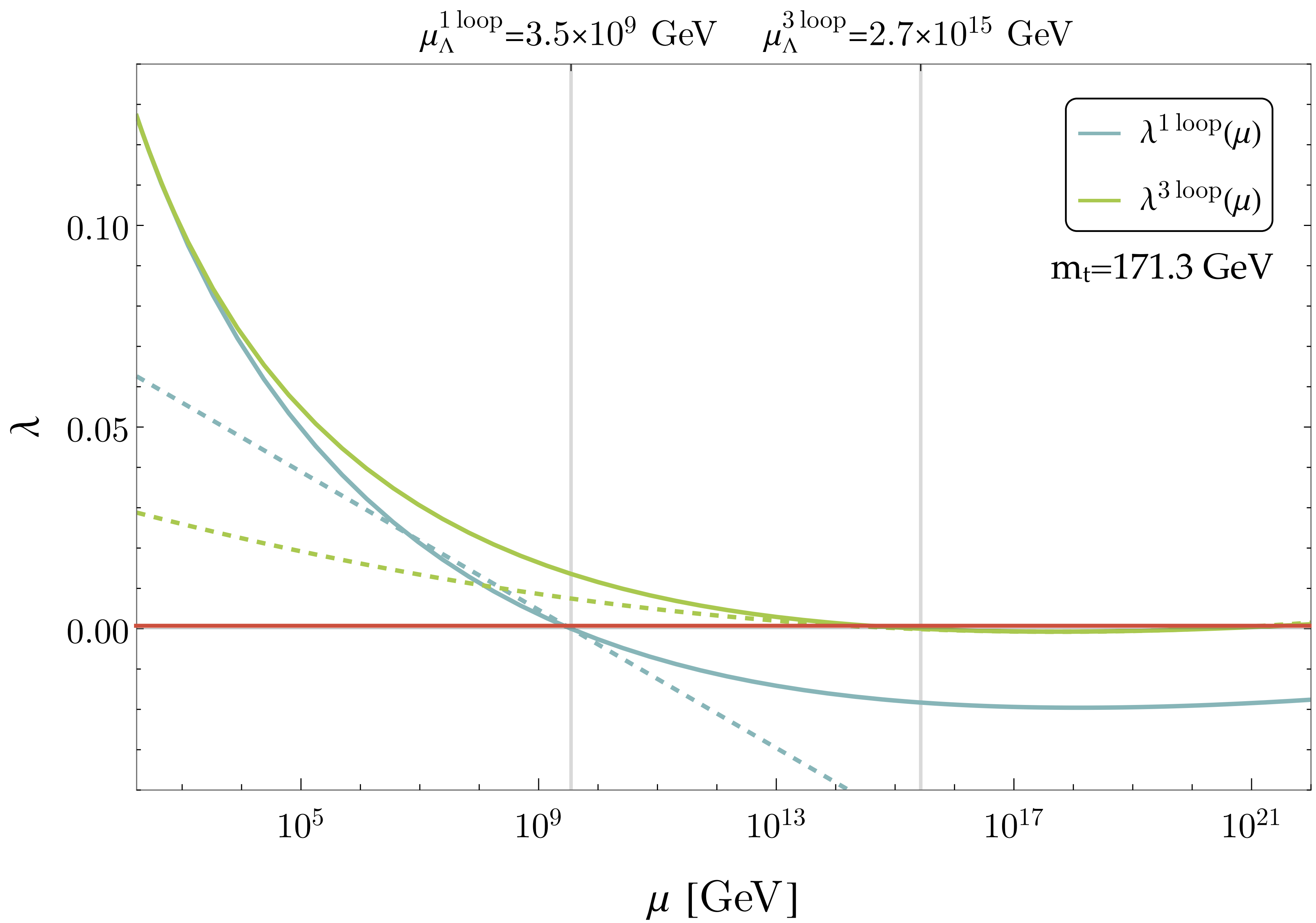


For more details, see talk by J. Rubio:
"Hubble-induced phase transitions as a natural quintessential inflation reheating mechanism"
- Thu 6/06 at 16.40 -

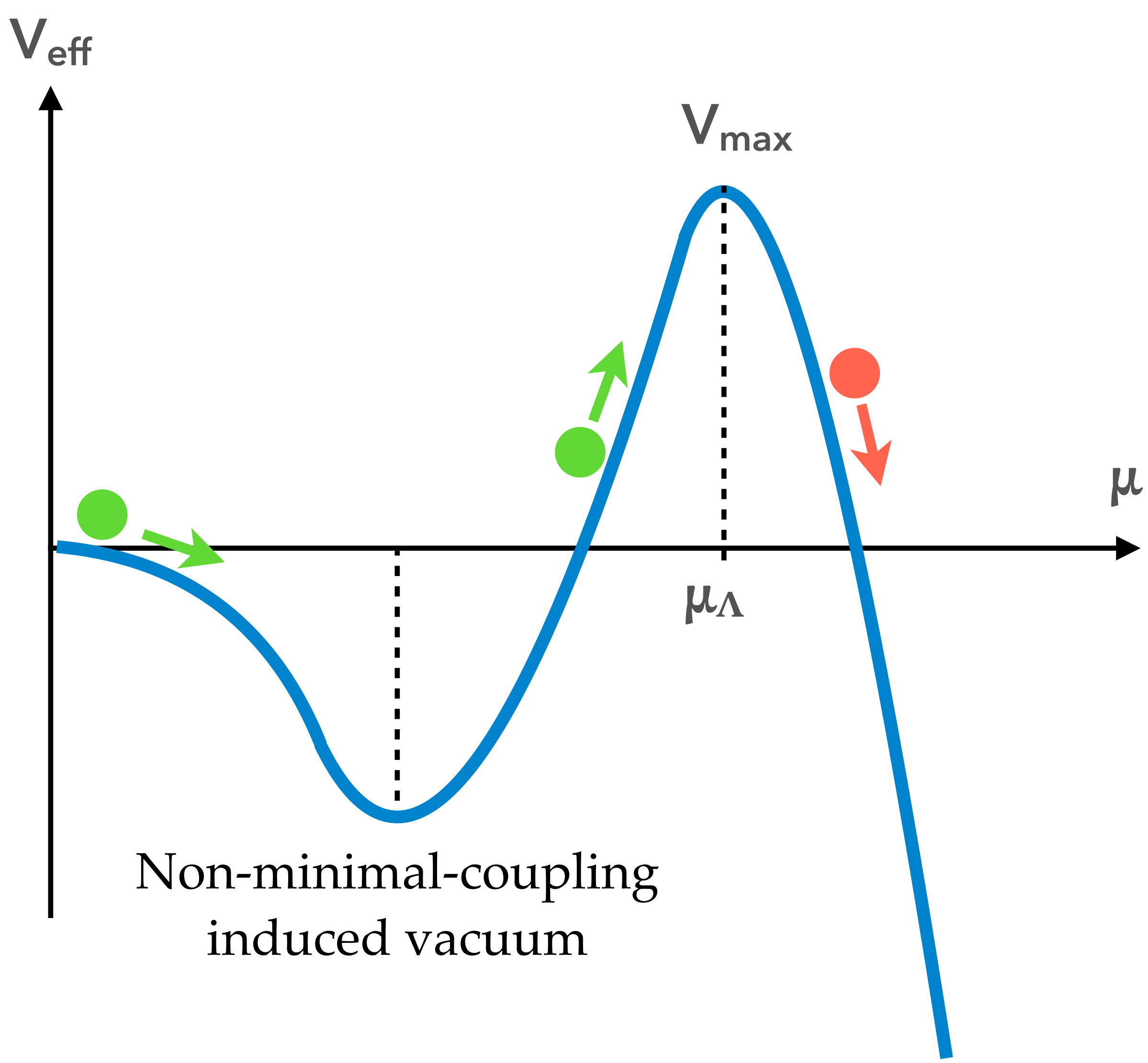
Beyond tree level



- $\lambda(\mu)$ runs with the energy scale and can become **negative (vacuum stability problem)**
- Important actors in the running: **loop expansion** and **top quark mass**
- Theoretical and experimental uncertainties on the top mass, with pole mass being typically smaller than reconstructed mass.

[ATLAS+CMS, 2401.04824] [CMS, 2302.01967][CMS, 1904.05237]

Effective potential in kination



- **Classical fluctuations** can push the Higgs beyond the barrier (with catastrophic consequences)
- Non-minimal coupling amplifies fluctuations driving them close to the **instability scale**
- Parameter space (m_t, υ, H_{kin})

$$\nu = \sqrt{\frac{3\xi}{2}}$$

1) Stability criterion

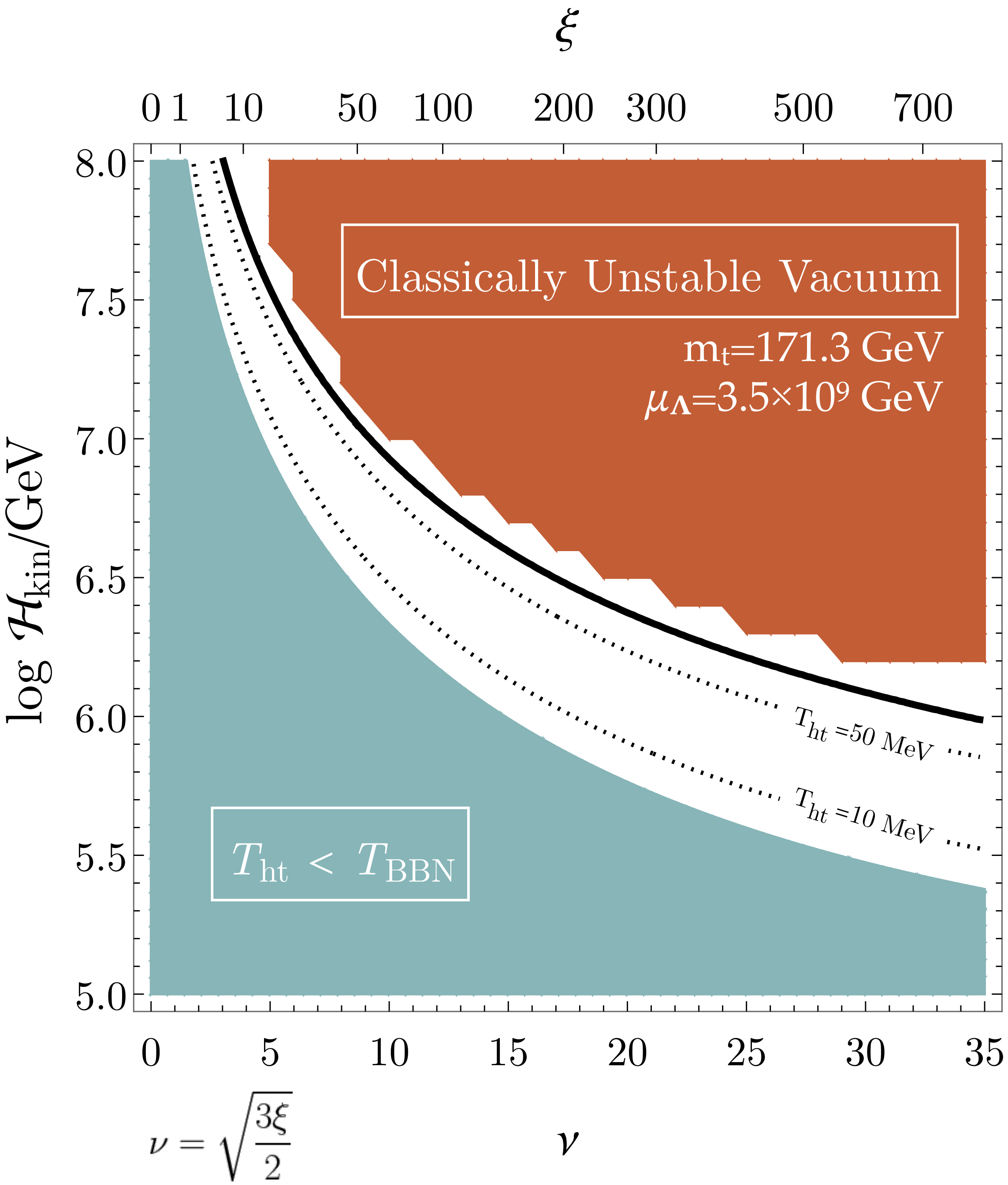
$$\rho_{\rm tac} < V_{\rm max}$$

2) Parametric formulas:

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

[*Ricci Reheating Reloaded*, GL, J.Rubio, 2307.03774]

One-loop running



- Approximate logarithmic RGI running around the instability scale

$$V_{\rm eff}^{\rm 1loop} \simeq \frac{1}{2}\xi R h^2 - \frac{3}{64\pi^2} y_\Lambda^4 h^4 \ln\left(\frac{h^2}{\mu_\Lambda^2}\right)$$

- Compare to the Higgs energy density to get the stability constraint

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

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

- **Heating temperature constraint** from BBN

$$T_{\rm ht} > 5\ {\rm MeV} \qquad T_{\rm ht} = \left(\frac{30\,\rho_h^{\rm ht}}{\pi^2 g_*^{\rm ht}}\right)^{1/4}$$

- Test instability region with **more than 1000 classical lattice simulations** using *CosmoLattice*

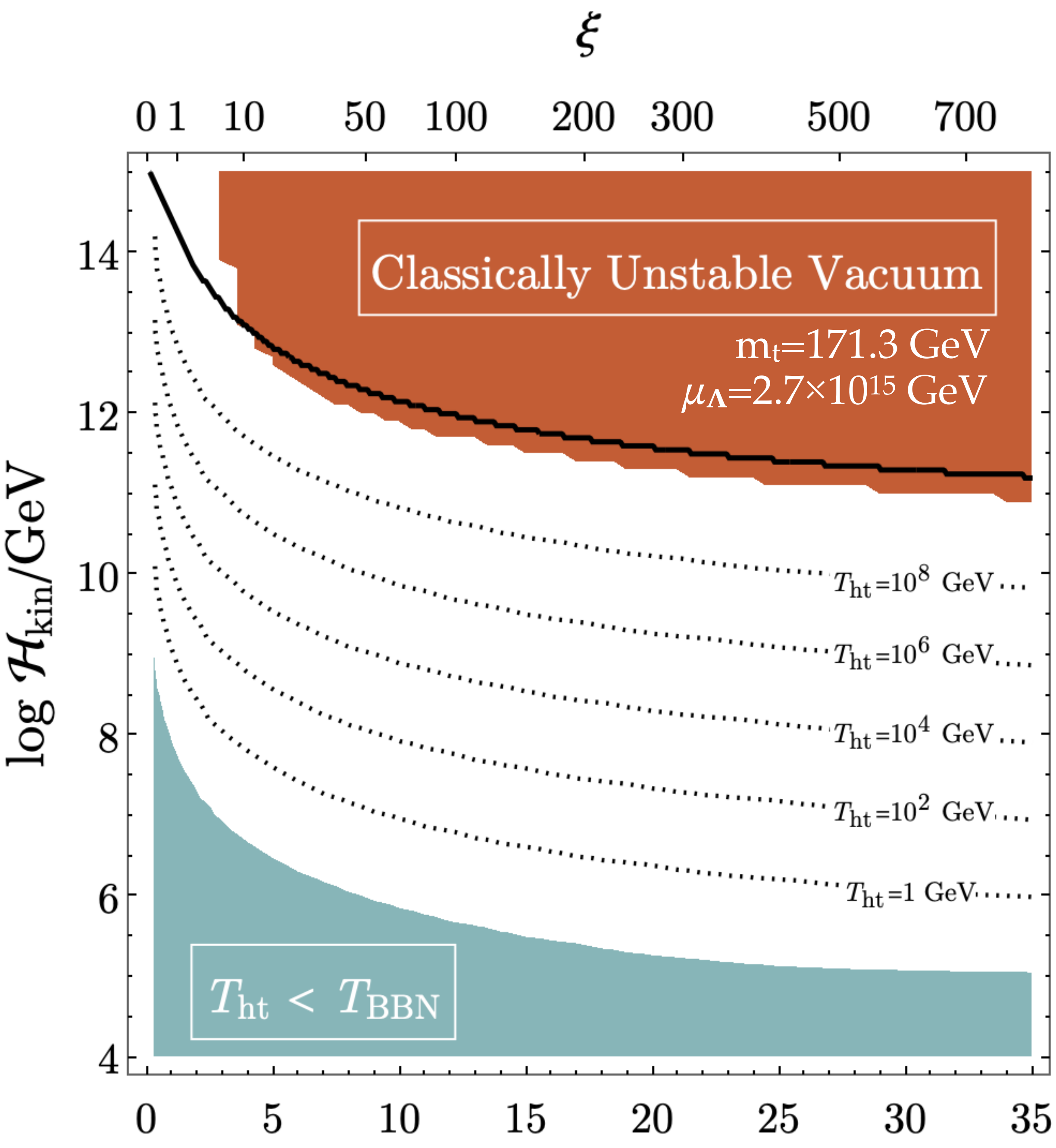
[CosmoLattice, 2102.01031]

BBN constraints complementary in closing the parameter space

Smaller top masses imply higher instability scales

Larger separation of scales between H_{kin} and μ_Λ favours stability

Three-loop running



$\nu = \sqrt{\frac{3\xi}{2}}$

- Proceeding as before (but numerically) and testing the parameter space with **thousands of lattice simulations**
- **Approximation** for the 3-loop running

$$\lambda^{3\text{loop}}(\mu) = \lambda_0 + b \ln^2\left[\frac{\mu}{q\,\mathrm{M_P}}\right]$$

$$\lambda_0 = 0.003297((m_h - 126.13) - 2(m_t - 171.5))$$

$$q = 0.3\exp\left[(0.5(m_h - 126.13) - 0.03(m_t - 171.5))\right]$$

$$b = 0.00002292 - 1.12524 \times 10^{-6}((m_h - 126.13) - 1.75912(m_t - 171.5))$$

[Bezrukov, 1403.6078]

- **Heating temperature constraint** from BBN

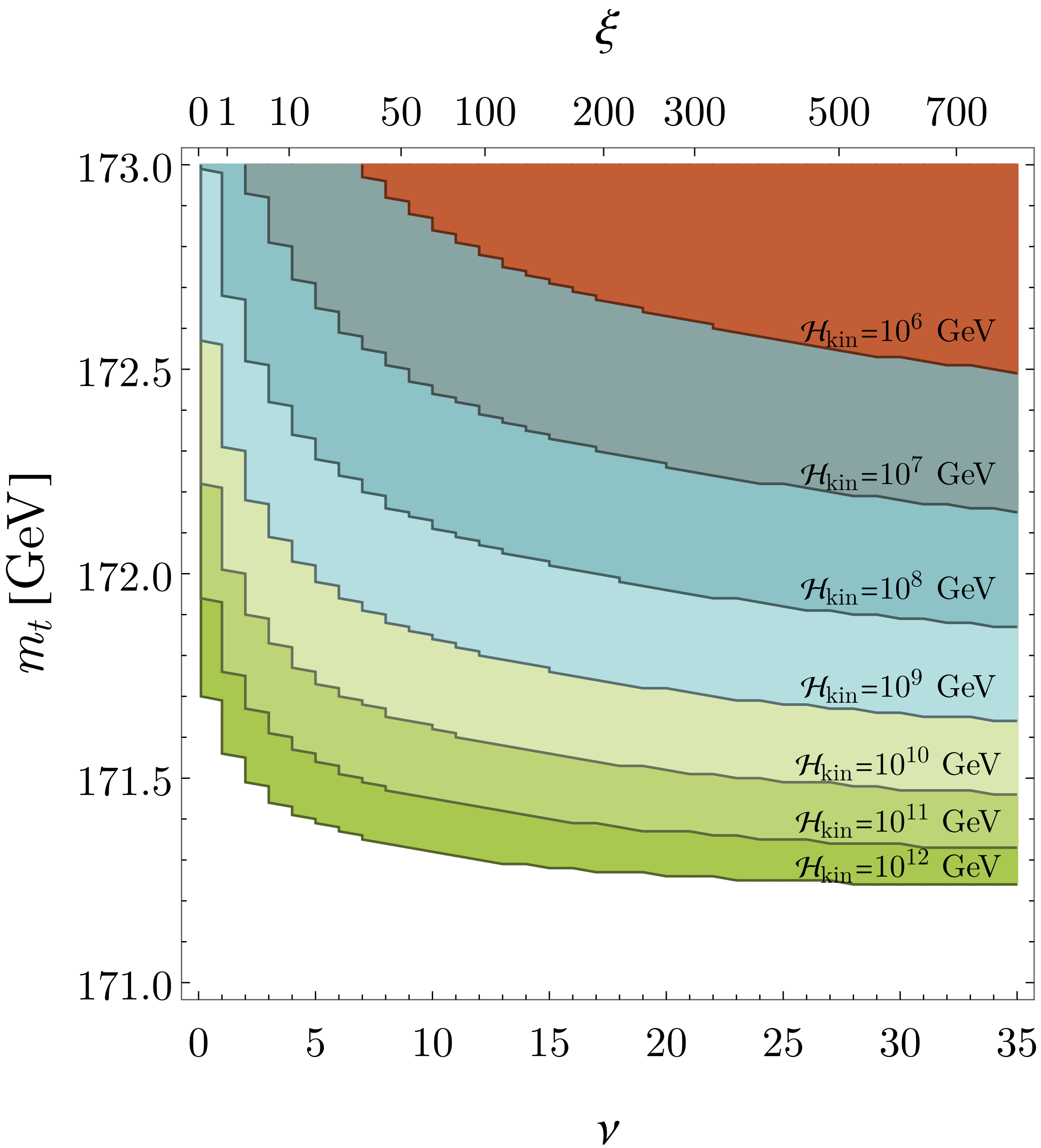
$$T_{\rm ht} > 5\ \mathrm{MeV} \qquad T_{\rm ht} = \left(\frac{30\,\rho_h^{\rm ht}}{\pi^2 g_*^{\rm ht}}\right)^{1/4}$$

Separation of scales allows for a larger viable parameter space

Heating temperatures up to **10^9 GeV** can be achieved

Good **agreement** between simulations and semi-analytic results

Three-loop running (stability only)



$$\nu = \sqrt{\frac{3\xi}{2}}$$

- The semi-analytical parametric formulas can correctly identify the instability region (previous slide)
- We can use the approximated running to explore the (m_t, ν) parameter space.

$$\lambda^{3\rm loop}(\mu) = \lambda_0 + b\ln^2\left[\frac{\mu}{q\,\mathrm{M_P}}\right]$$

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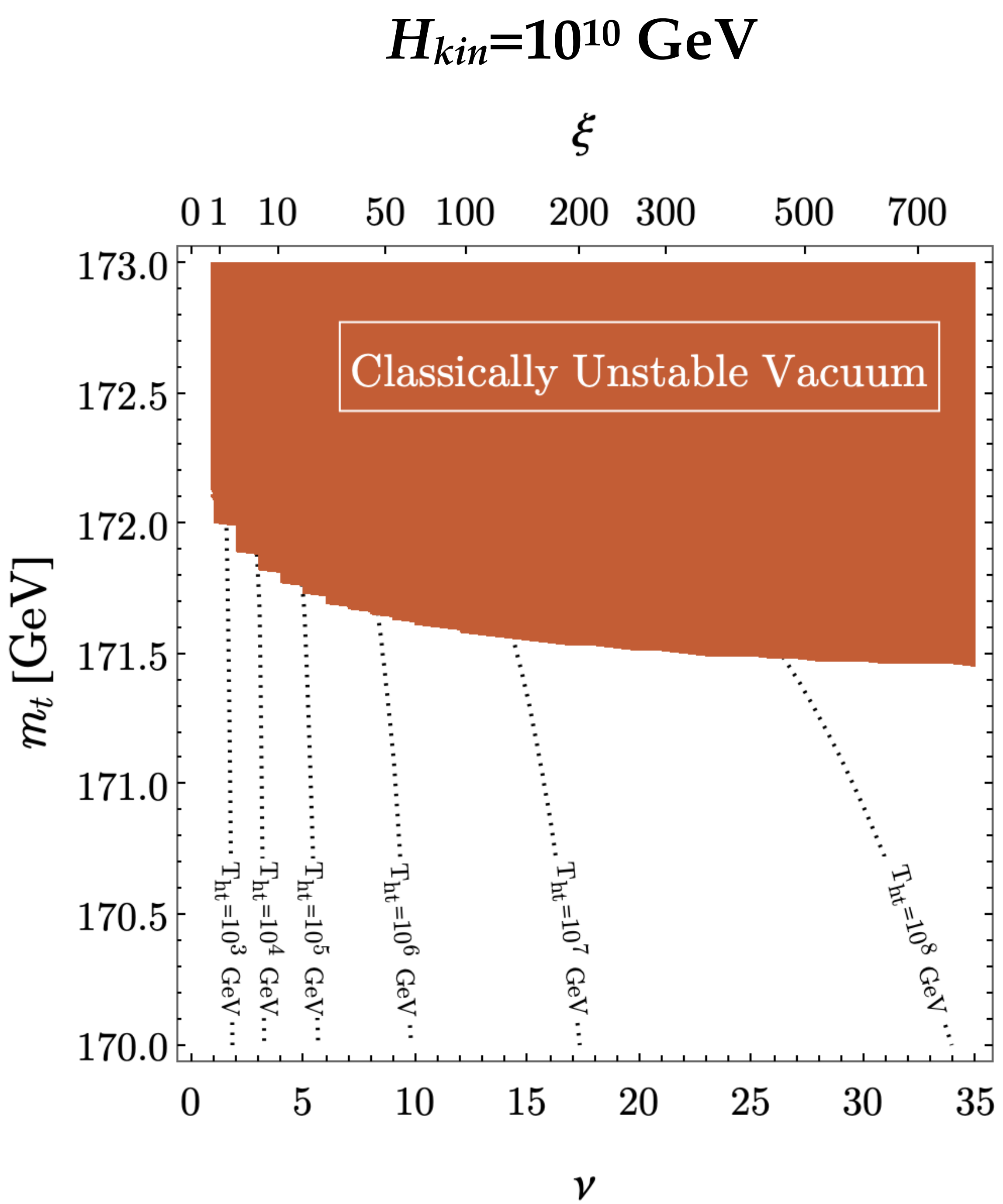
[Bezrukov, 1403.6078]

- We fix H_{kin} and compute the stability constraint keeping an **agnostic approach** about the specific value of the **top mass (ranging from 170-173 GeV)**

Combined constraints on top masses



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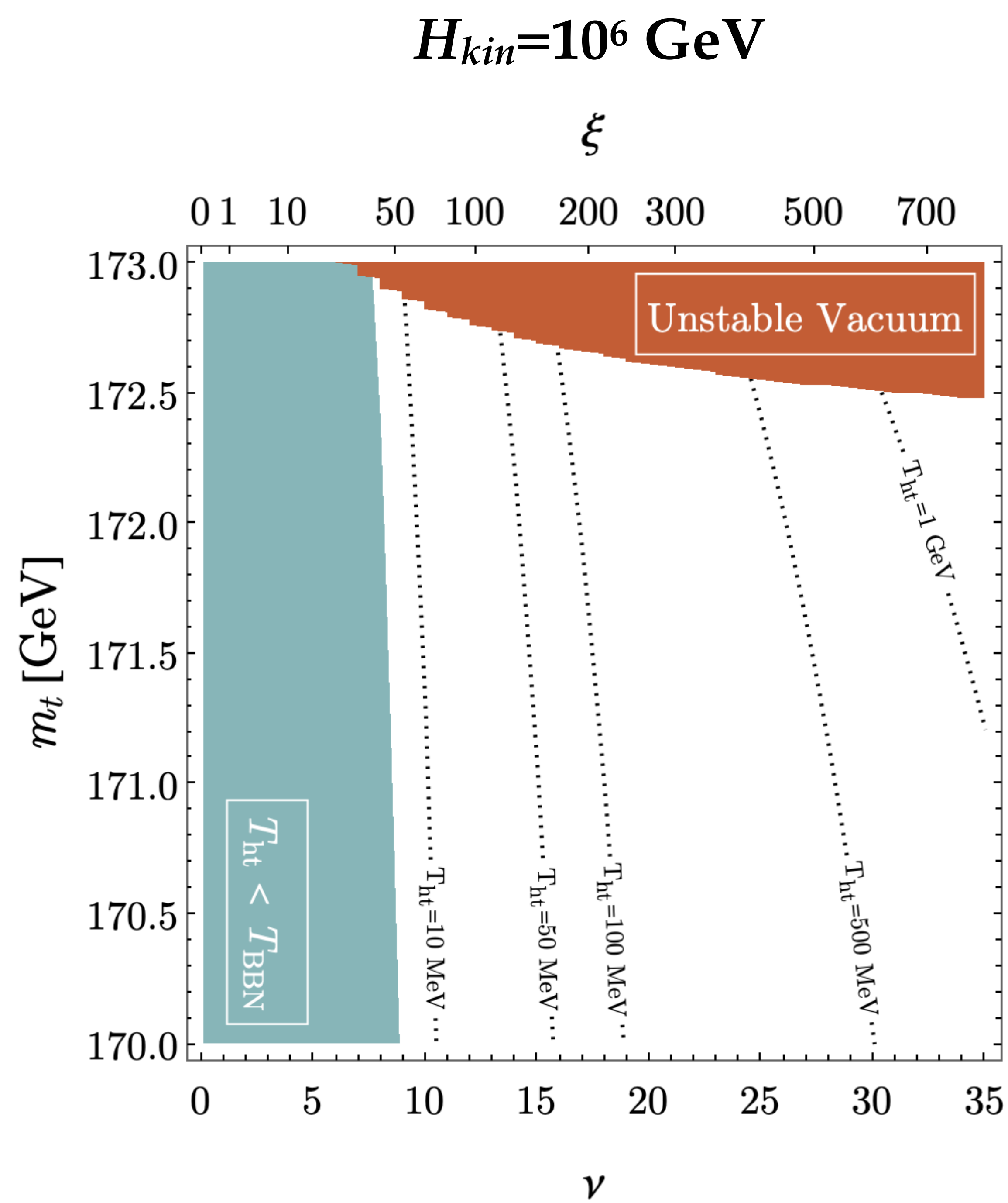


Take-home message

- Hubble-induced phase transitions are a natural occurrence for non-minimally-coupled fields in the early Universe

- Non-minimal coupling stabilises the Higgs during inflation and leads to tachyonic particle production during kination

- The Higgs can be responsible for heating, its stability can be checked against the height of the barrier in the effective potential. A connection is formed between SM parameters and physics of the early Universe

References

- ***The Rise and Fall of the SM Higgs: Electroweak Vacuum Stability during Kination***, JHEP 2024, 339 (2024) [arXiv:2402.06000]

- ***Ricci Reheating Reloaded***, JCAP 03 (2024) 033 [arXiv: 2307.03774]

- *Quintessential Inflation: A Tale of Emergent and Broken Symmetries*, D. Bettoni, J. Rubio, [arXiv:2112.11948]

- *Hubble-induced phase transitions: Walls are not forever*, D. Bettoni, J. Rubio, [arXiv:1911.03484]

Additional Slides

Quintessential inflation

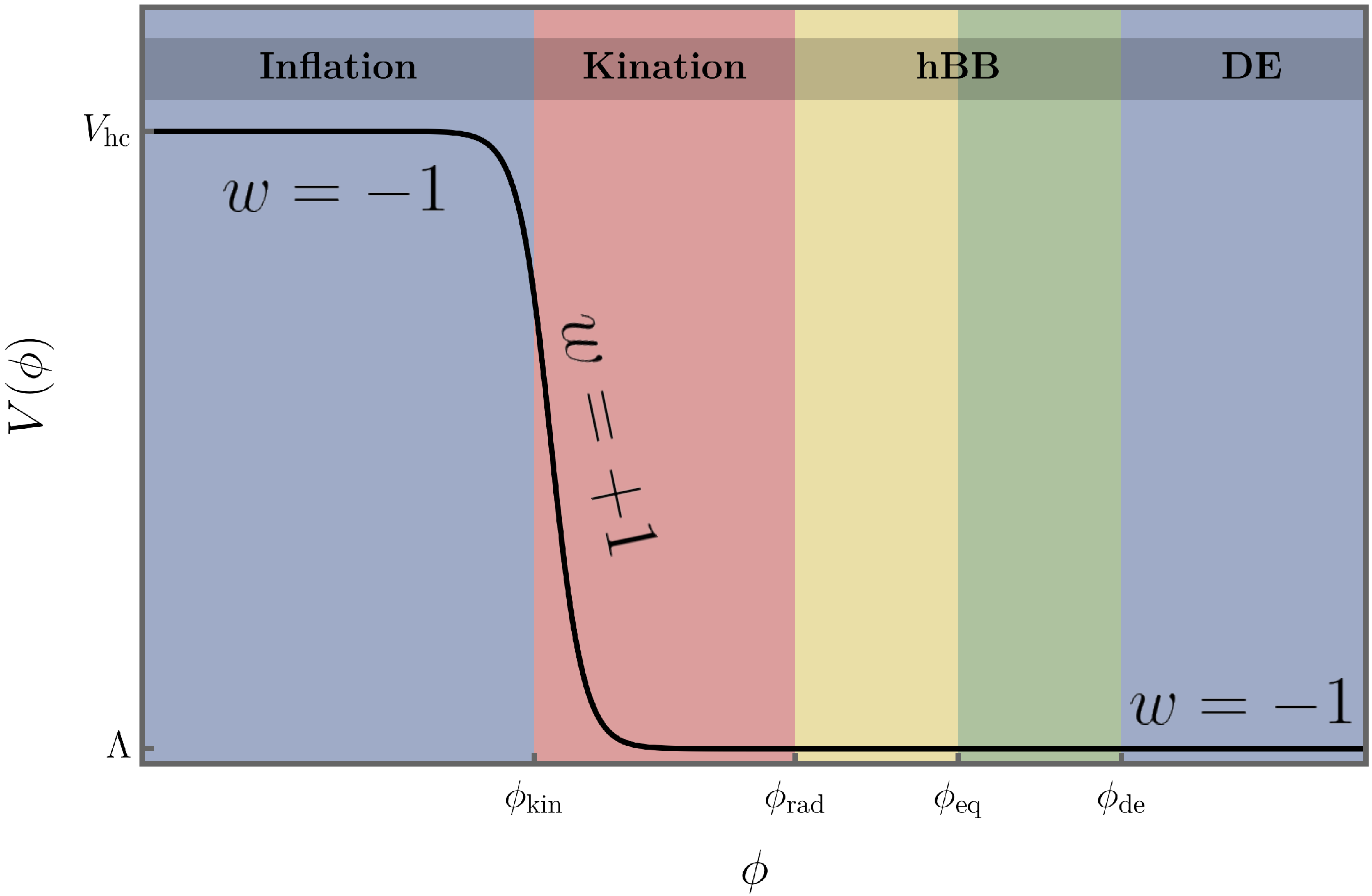
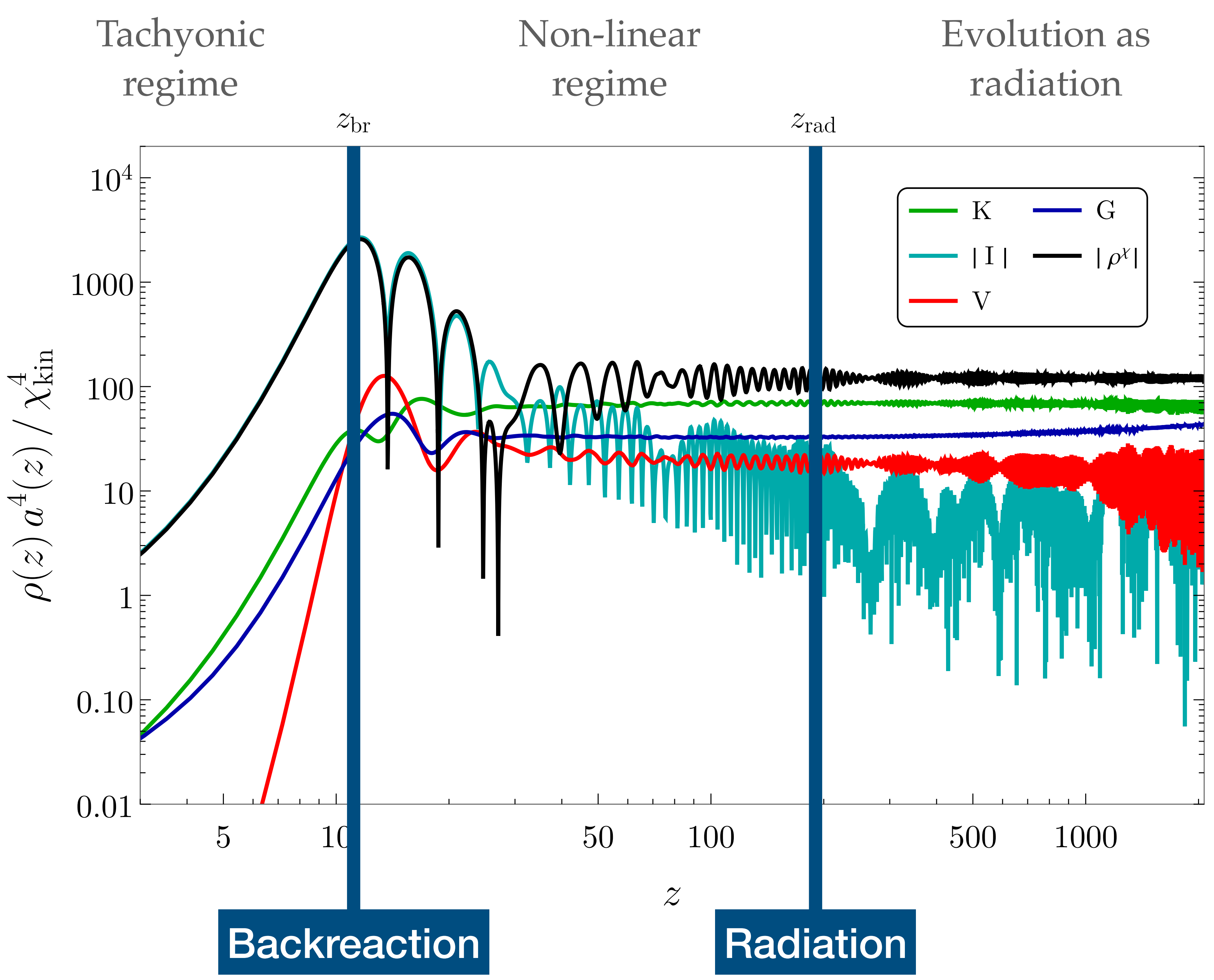


Image credit: *Quintessential Inflation: A Tale of Emergent and Broken Symmetries*, Bettoni, Rubio (2022)

Hubble-induced phase transition on the lattice



Objective:

To characterise the non-linear heating stage with a large number of simulations

- Classical simulations in 3+1 dimensions (with *CosmoLattice*)
- Scanning of parameter space (υ, λ) with **hundreds of simulations**

$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \xi R\chi + \lambda\chi^3 = 0$$

$$R = -6H^2 \qquad \nu = \sqrt{\frac{3\xi}{2}}$$

Top mass measurements

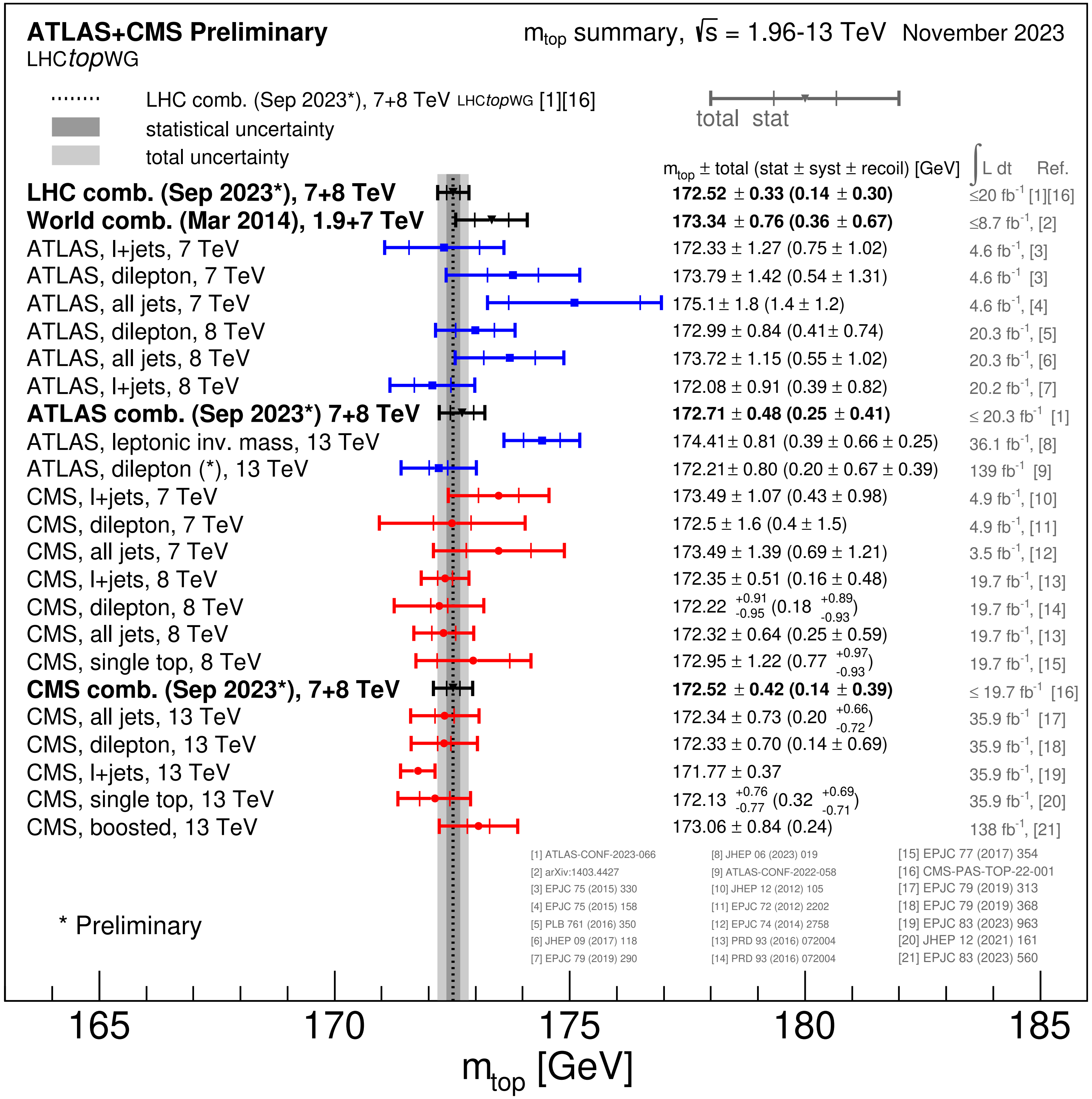


Image credit: LHC Top Working Group (2023)