Hubble-induced phase transitions and Higgs Vacuum Stability

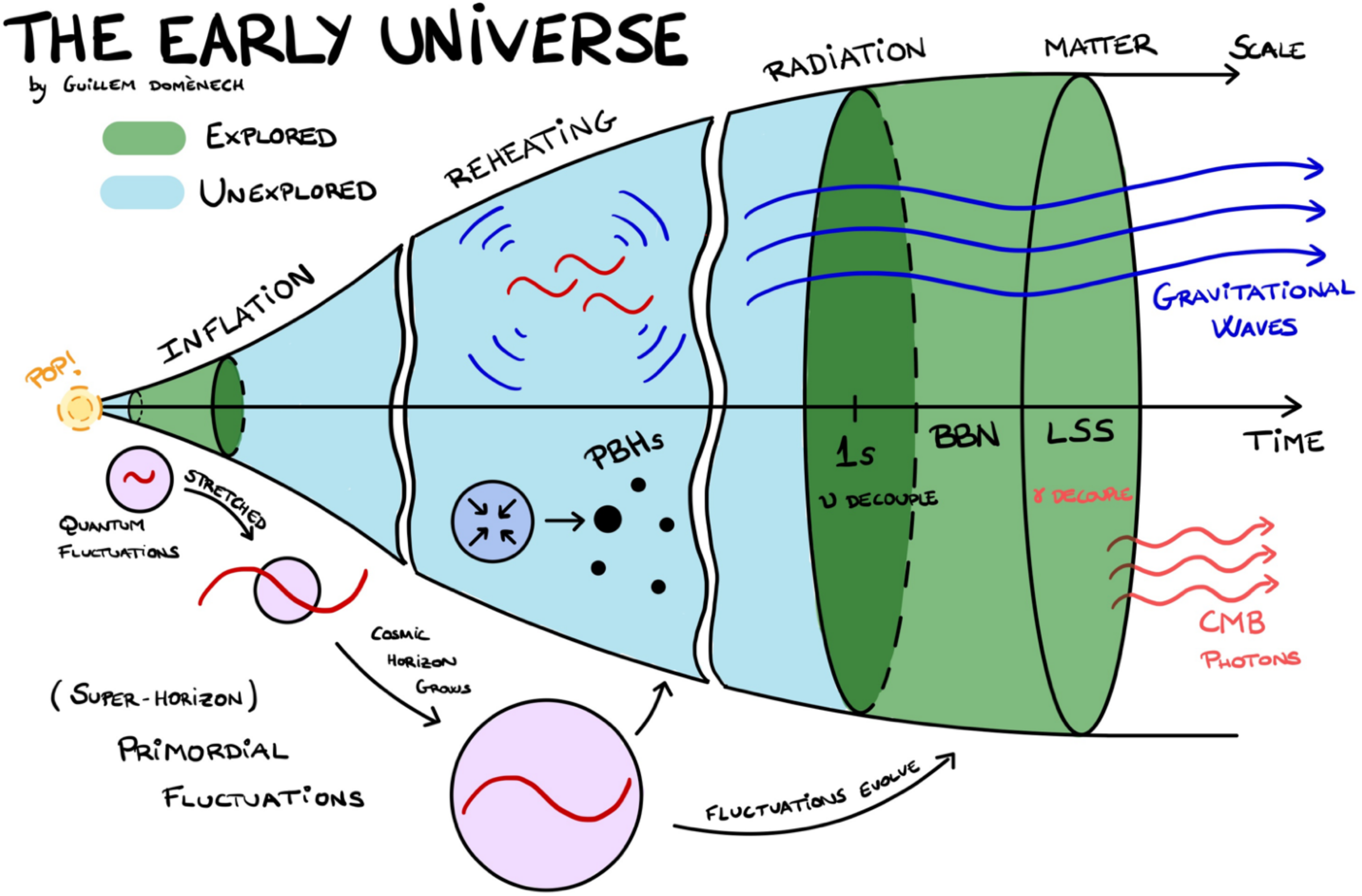
Based on G. Laverda, JR, JCAP 03 (2024) 033 & JHEP 05 (2024) 339

Giorgio Laverda

IPARCOS
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Cofinanciado por la Unión Europea
AGENCIA ESTATAL DE INVESTIGACIÓN
BUILDINGUNIVERSE

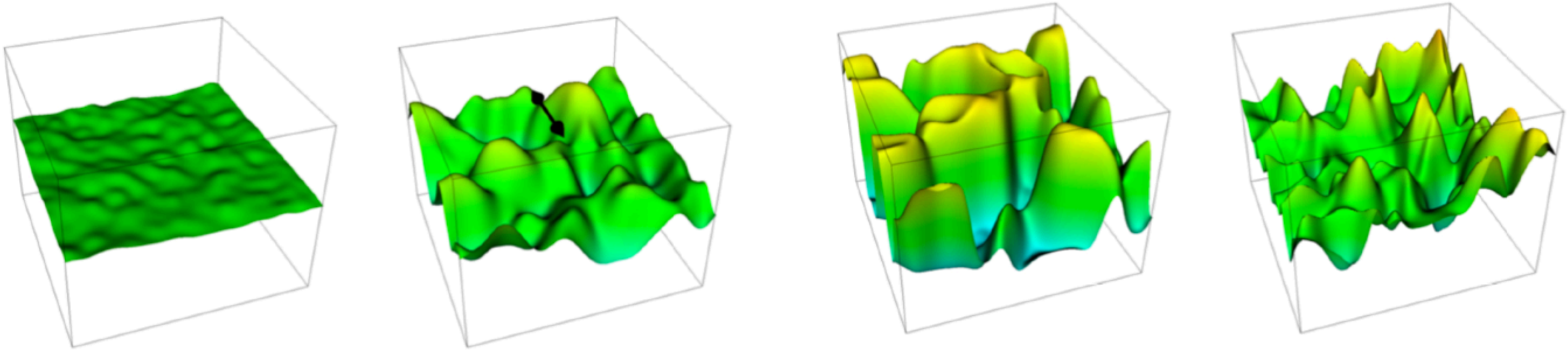
THE EARLY UNIVERSE

by Guillem Domènech



Hubble-induced phase transitions

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2}{2}R - \frac{1}{2}(\partial\chi)^2 - f(R, R_{\mu\nu})\chi^2 - V(\chi)$$



- Natural triggering mechanism for phase transitions
- Non-thermal & non-perturbative
- Short-lived topological defects

A dedicated program

1. Quintessential Affleck-Dine baryogenesis with non-minimal couplings,
   D. Bettoni, J. Rubio Phys.Lett.B 784 (2018) 122-129
2. Gravitational waves from global cosmic strings in quintessential inflation,
   D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034
3. Hubble-induced phase transitions: Walls are not forever.
   D. Bettoni, J. Rubio, JCAP 01 (2020) 002
4. Hubble-induced phase transitions on the lattice with applications to Ricci reheating.
   D. Bettoni, J.Rubio, JCAP 01 (2022) 01, 002
5. Ricci reheating reloaded,
   G. Laverda, JCAP 03 (2024) 033
6. From Hubble to Bubble,
   M. Kierkla, G.Laverda, M. Lewicki, A. Mantziris, M.Piani, JHEP 11 (2023) 077
7. The rise and fall of the Standard-Model Higgs: electroweak vacuum stability during kination.
   G. Laverda, J. Rubio, JHEP 05 (2024) 339

For a review see D. Bettoni, JR, Galaxies 10 (2022) 1, 22

A simple scenario

- A single field ϕ for both inflation and dark energy (quintessential inflation)
- An unavoidable non-minimal coupling of the Higgs field H to gravity
- No additional degrees of freedom beyond the electroweak scale

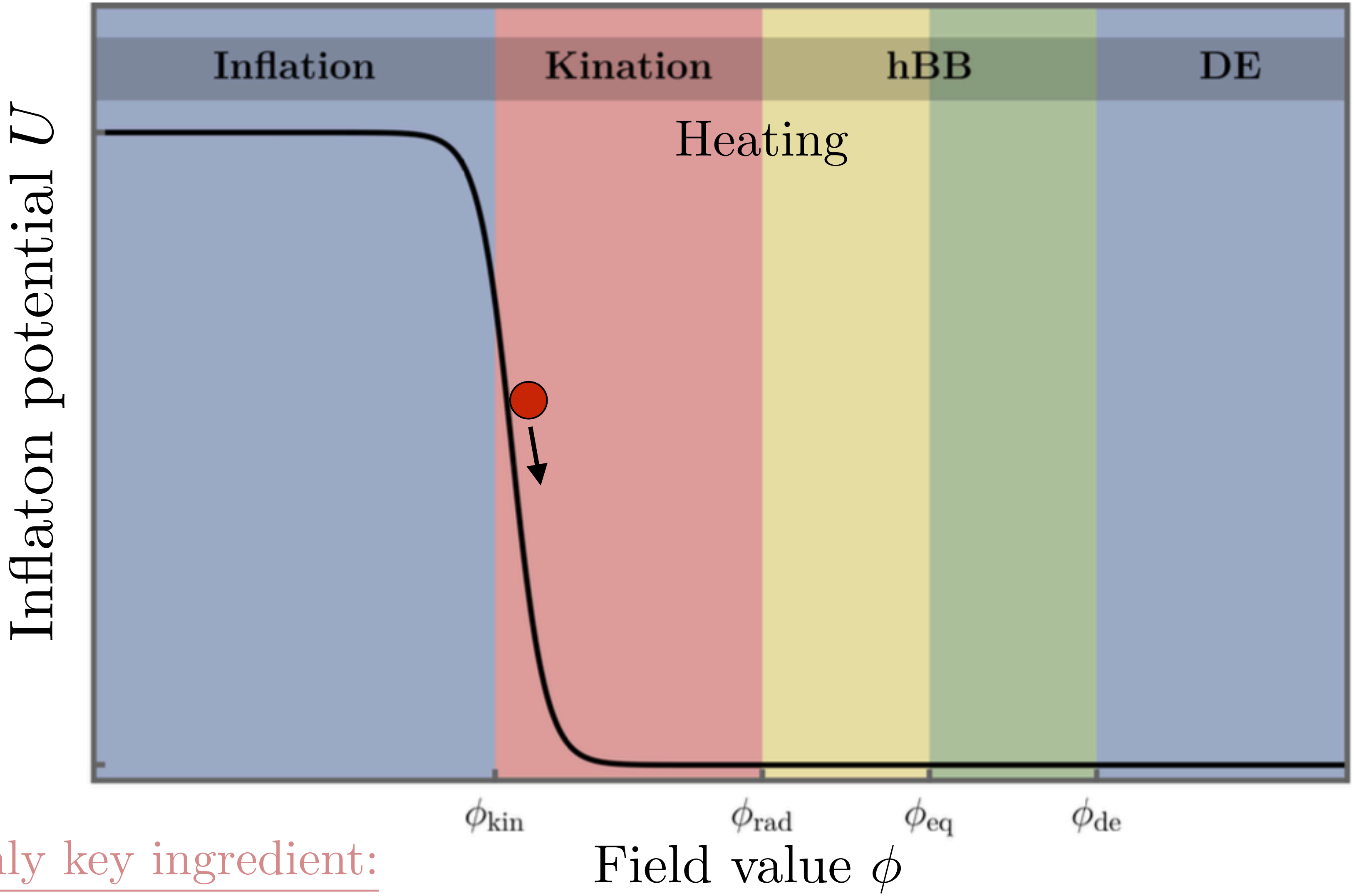
$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\mathrm{P}}^2}{2} R - g^{\mu\nu}(D_\mu H)^\dagger (D_\nu H) - \lambda \left(H^\dagger H - \frac{v_{\mathrm{EW}}^2}{2}\right)^2 - \xi H^\dagger H R + \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_\phi .$$

Interesting outputs

- The Higgs field is safely stabilized during inflation (no isocurvature pert.)
- Appealing connection between SM parameters and (post-)inflationary era
- The Higgs field itself can be responsible for heating the Universe

G. Laverda, JR, JCAP 03 (2024) 033 & JHEP 05 (2024) 339

Quintessential inflation

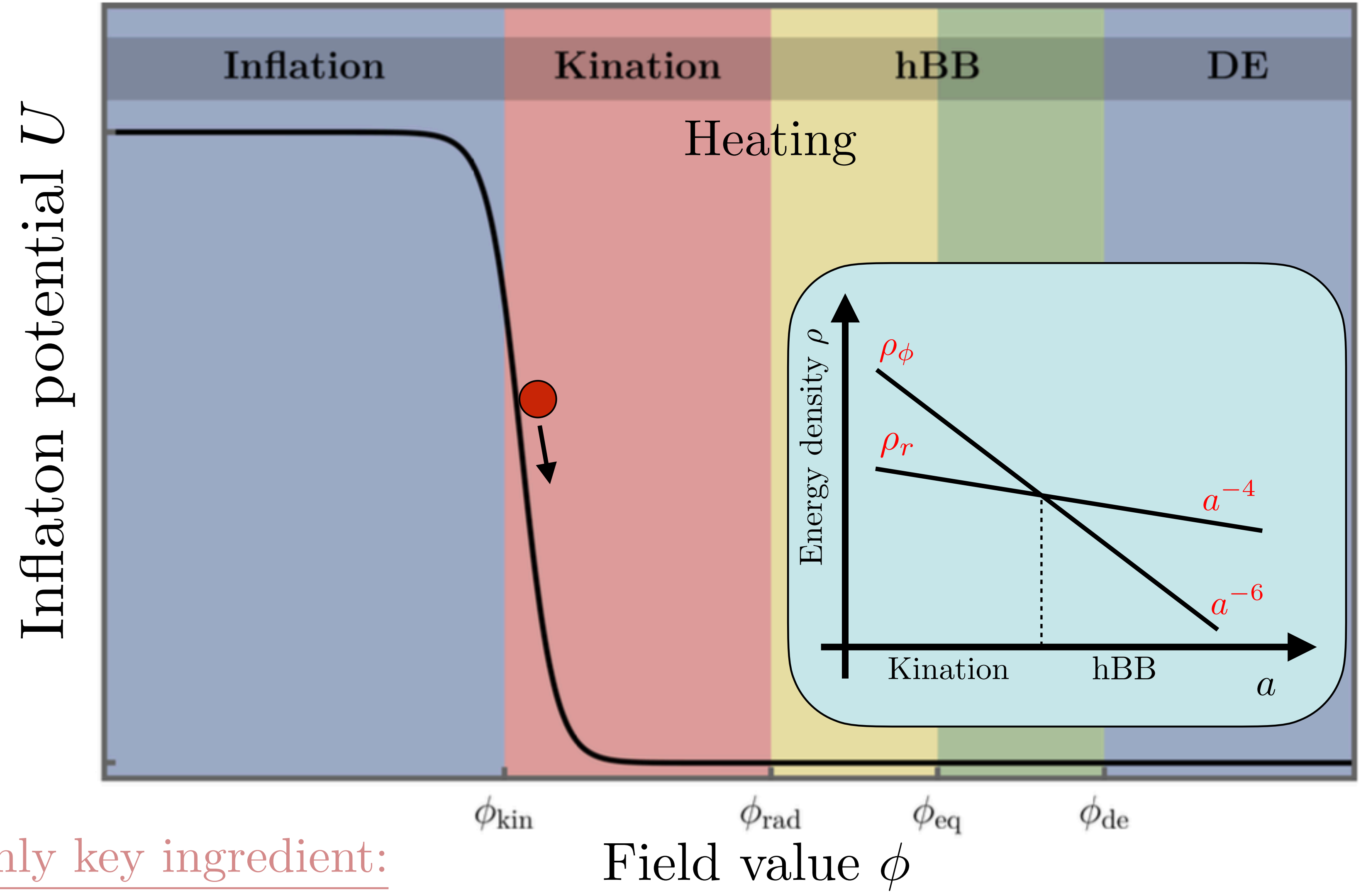


Only key ingredient:

Period of kination

For a review see e.g. D. Bettoni, JR, Galaxies 10 (2022) 1, 22

Quintessential inflation

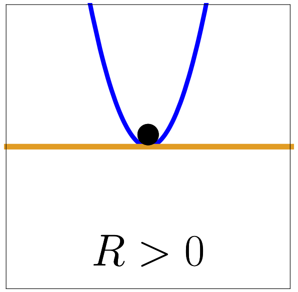


Only key ingredient:

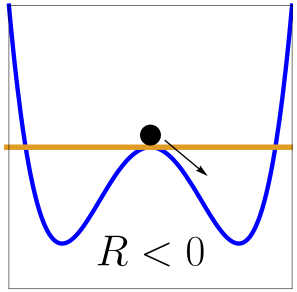
Period of kination

For a review see e.g. D. Bettoni, JR, Galaxies 10 (2022) 1, 22

Hubble-induced Higgs mass

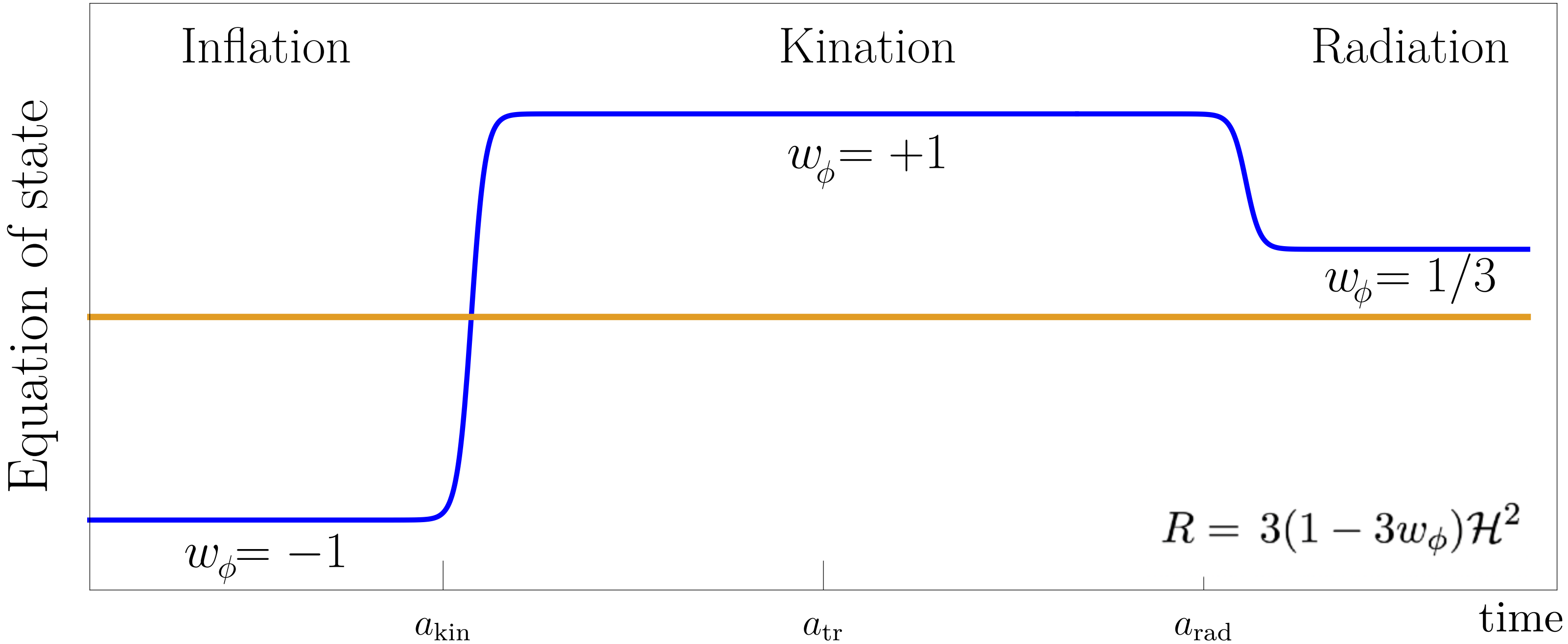


$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial h)^2 - \frac{1}{2}\xi R h^2 - \frac{\lambda}{4}h^4$$



Energetically subdominant / Spectator field

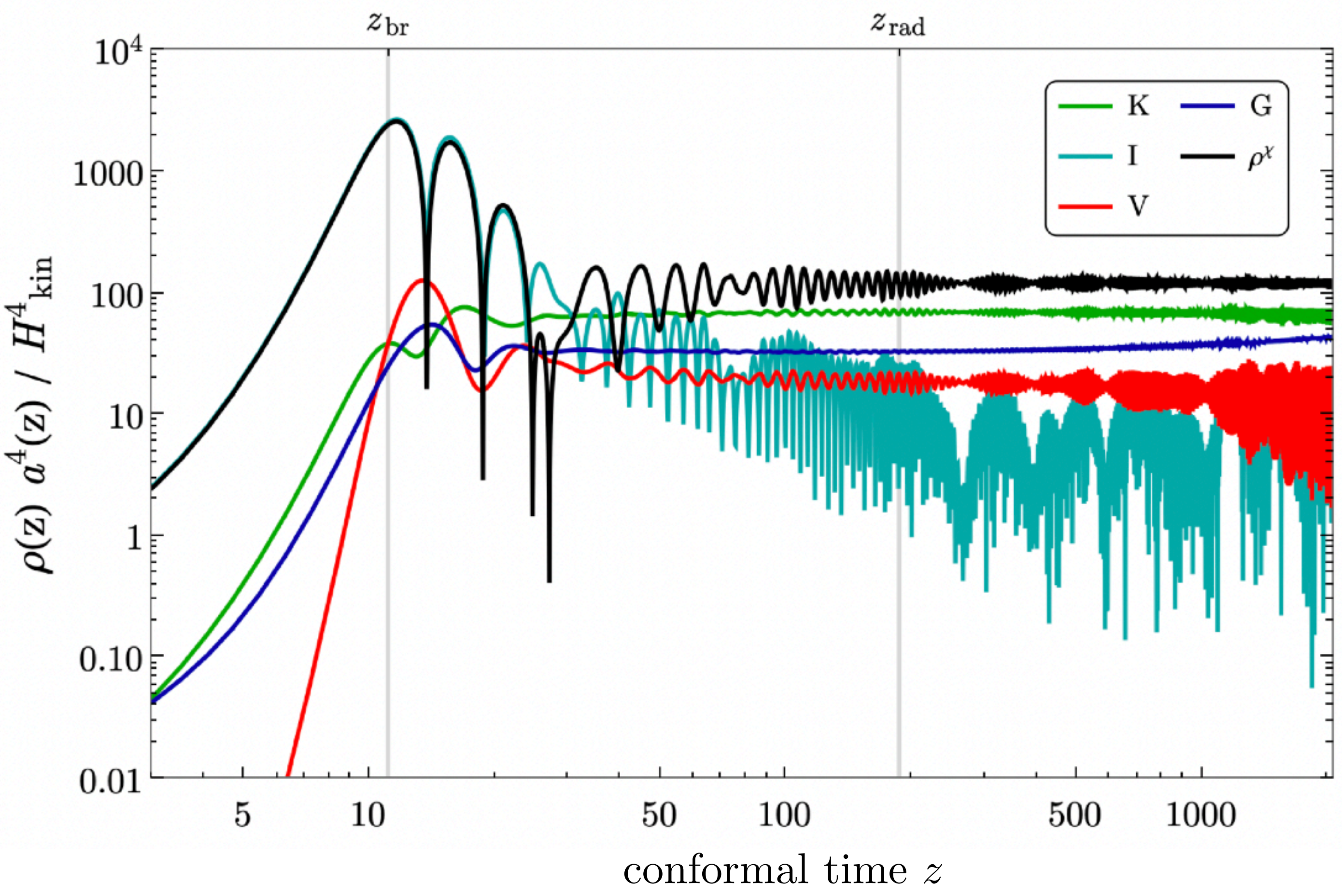
Negligible contribution to the effective Planck mass, $\xi h^2 \ll M_P^2$



D. Bettoni, JR, Phys.Lett.B 784 (2018) 122-129; D. Bettoni, G. Domènech, JR, JCAP 02 (2019) 034, D. Bettoni, JR, JCAP 01 (2020) 002, D. Bettoni, A. López-Eiguren, JR, JCAP 01 (2022) 01, 002

See also Figueroa & Byrnes 1604.03905, Dimopoulos, Markkanen 1803.07399, Opferkuch, Schwaller, Stefanek 1905.06823 (homogeneous approx. only)

Tachyonic particle production

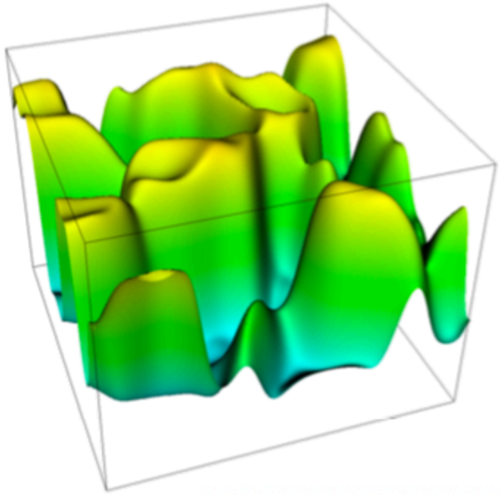


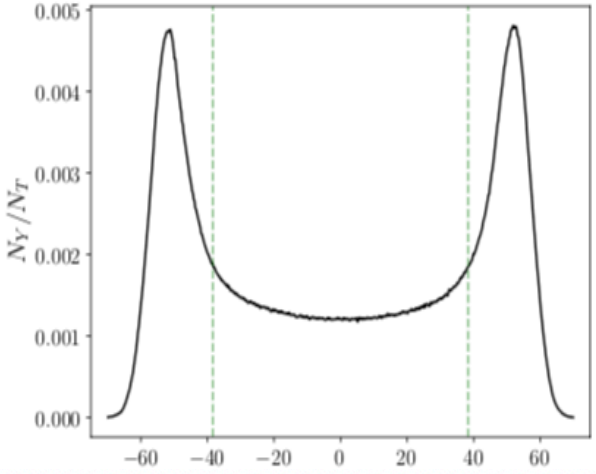
Lattice-based fitting formulas: O(100) 3+1 classical lattice simulations

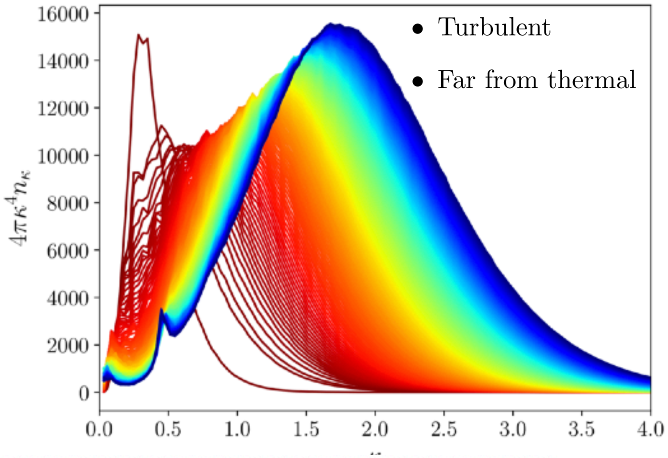
$$\rho_{\rm tac}(\lambda(\mu), \xi) = 16\, \mathcal{H}^4_{\rm kin}\ \exp\left(\beta_1(\lambda) + \beta_2(\lambda)\, \nu + \beta_3(\lambda) \ln \nu\right) \qquad \nu = \sqrt{\frac{3\xi}{2}}$$

G. Laverda, JR, JCAP 03 (2024) 033

Non-linear non-homogeneous dynamics

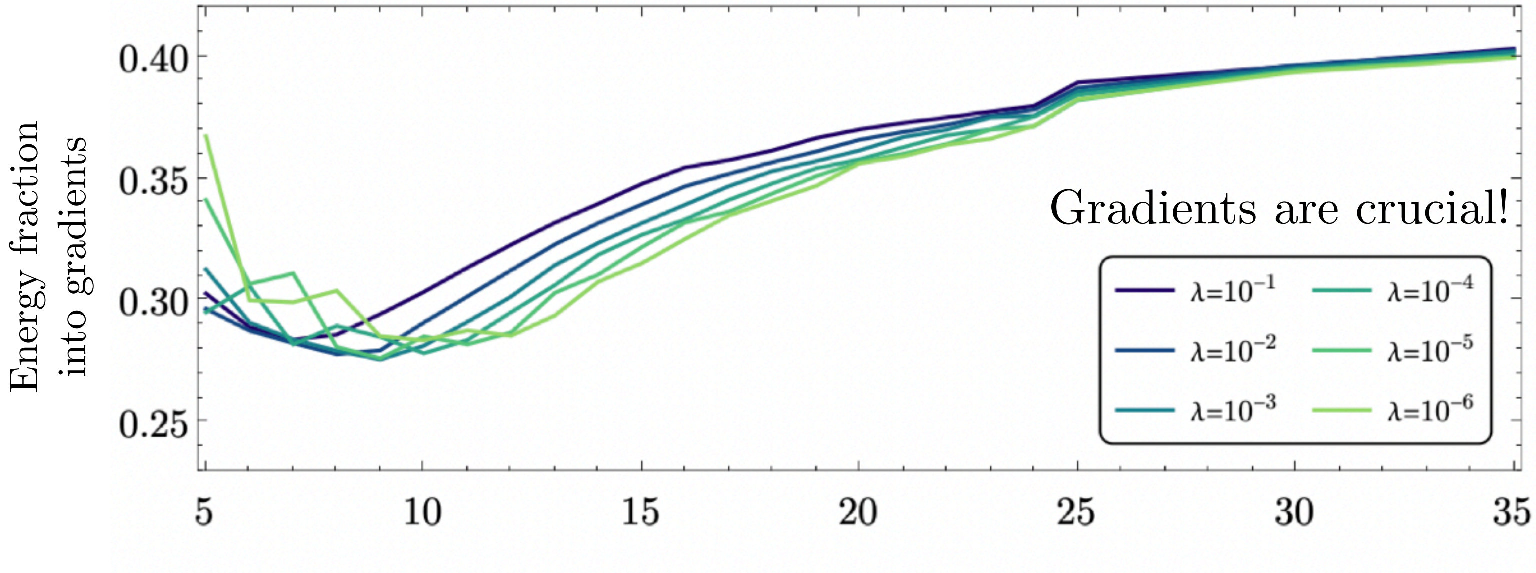






- Turbulent
- Far from thermal

D.Bettoni, A. Lopez-Eiguren, JR, JCAP 01 (2022) 01, 002

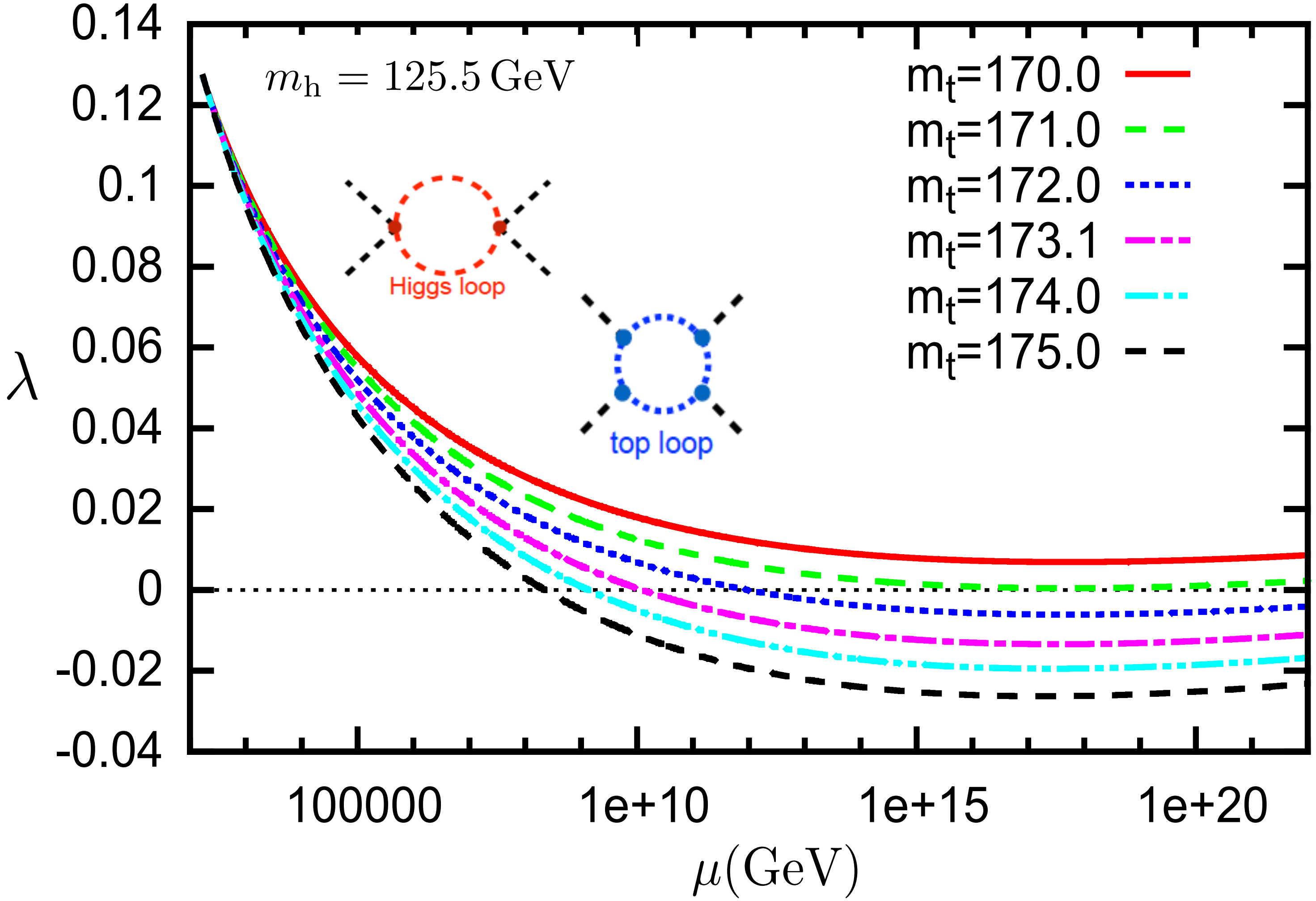


Gradients are crucial!

G. Laverda, JR, JCAP 03 (2024) 033

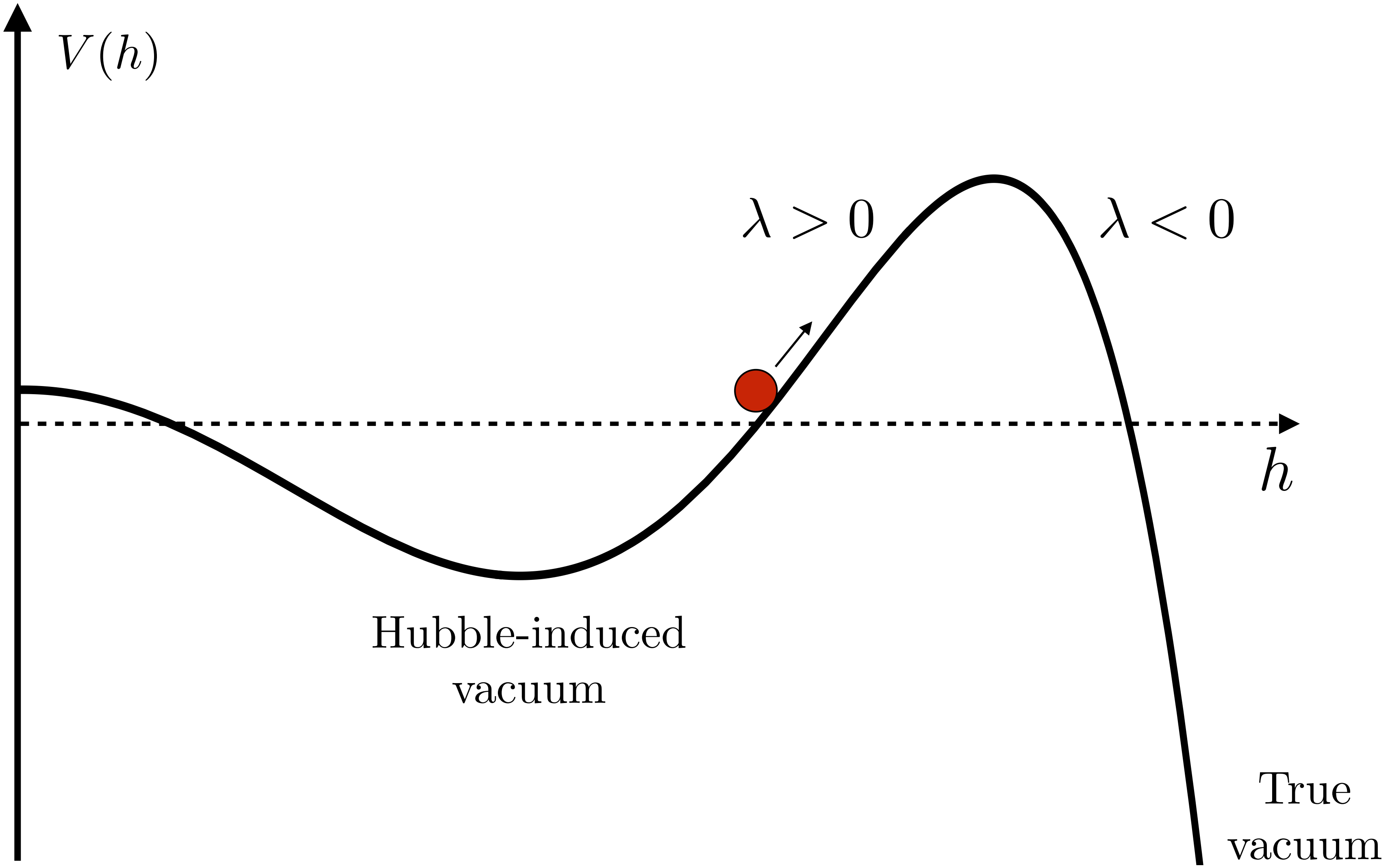
Beyond tree level

Quantum contributions of heavy SM particles to effective potential important

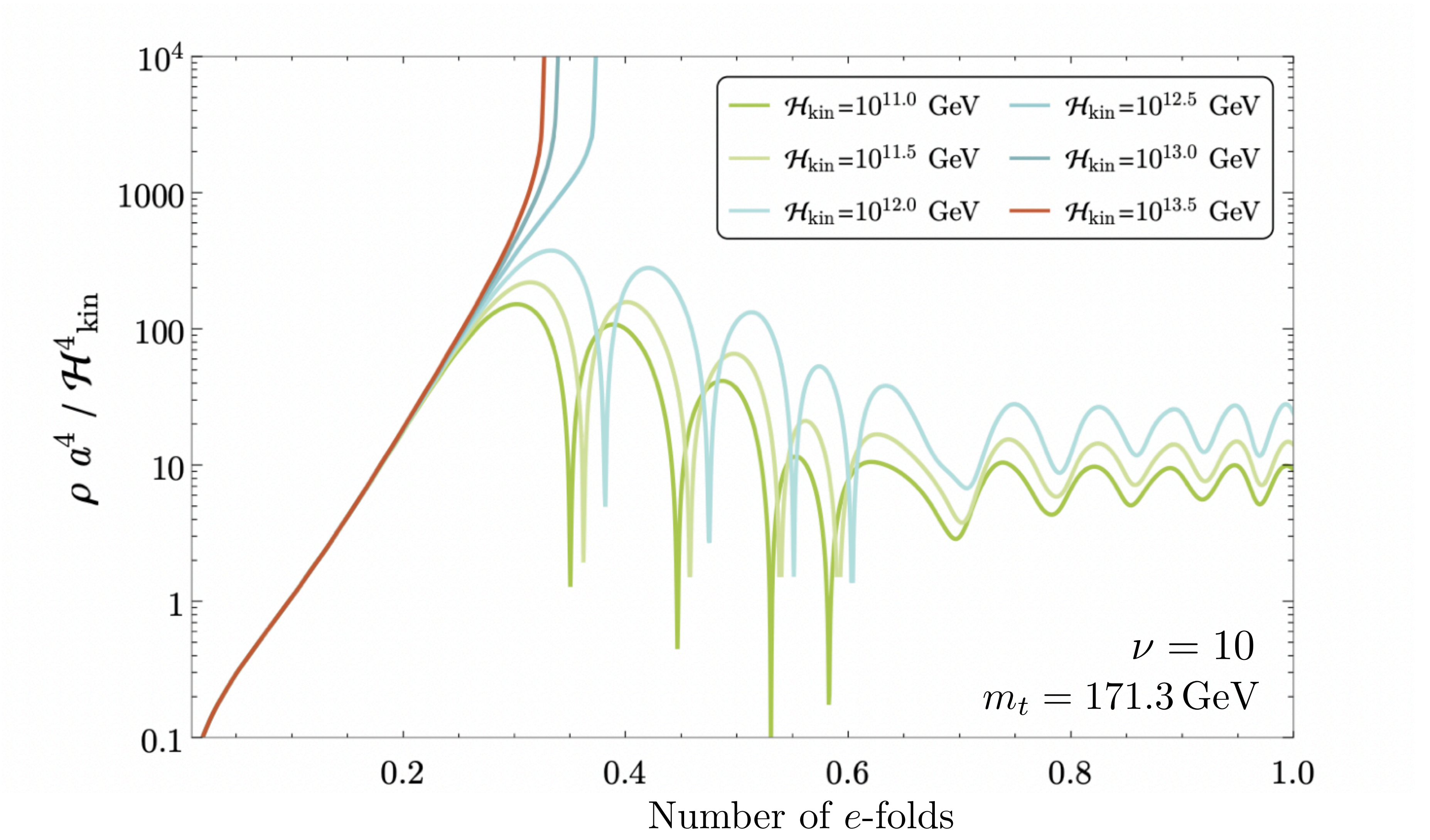


JR et al., Phys.Rev.D 90 (2014) 027307, Phys.Rev.D 92 (2015) 8, 083512, JCAP 02 (2018) 040

Higgs effective potential



Vacuum stability during kination



G. Laverda, JR, 2402.06000

Scanning of parameter space

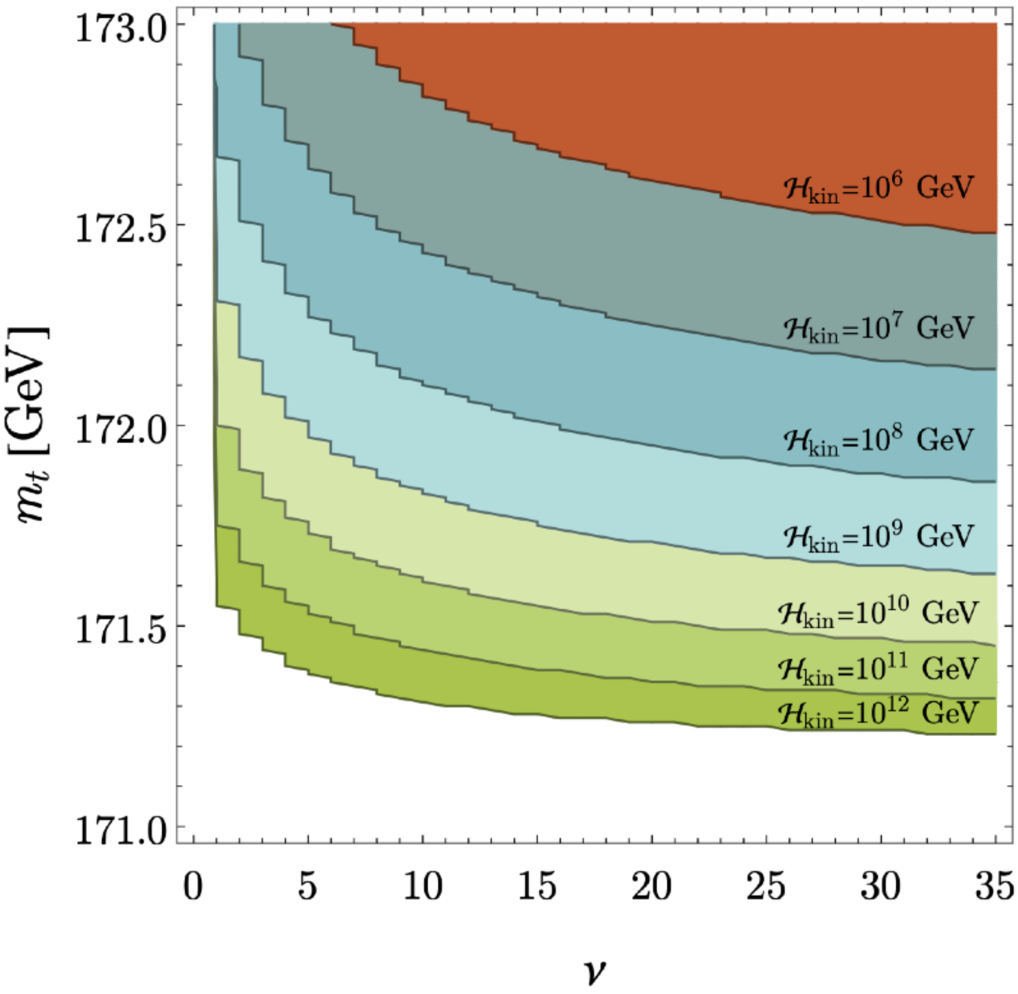
- Three-loop renormalisation-group running of the Higgs self-coupling
- Agnostic approach to top quark mass values, $m_t = 170 - 173$ GeV
- Wide range for non-minimal coupling parameter $\xi \sim 1 - 700$
- Wide range for the onset scale of kination $\mathcal{H}_{\text{kin}} \sim 10^6 - 10^{15}\ \text{GeV}$
- O(1000) 3+1-dimensional classical lattice simulations.
- Checking for existence and crossing of the barrier

$$\xi < \frac{y_\Lambda^4 \mu_\Lambda^2}{32\, e^{3/2} \pi^2\, \mathcal{H}^2}$$

$$\rho_{\text{tac}}(\lambda(\mu), \xi) < V(h_{\text{max}}(\xi, y_\Lambda, \mathcal{H}, \mu_\Lambda))$$

G. Laverda, JR, 2402.06000

Stability constraints on the top mass

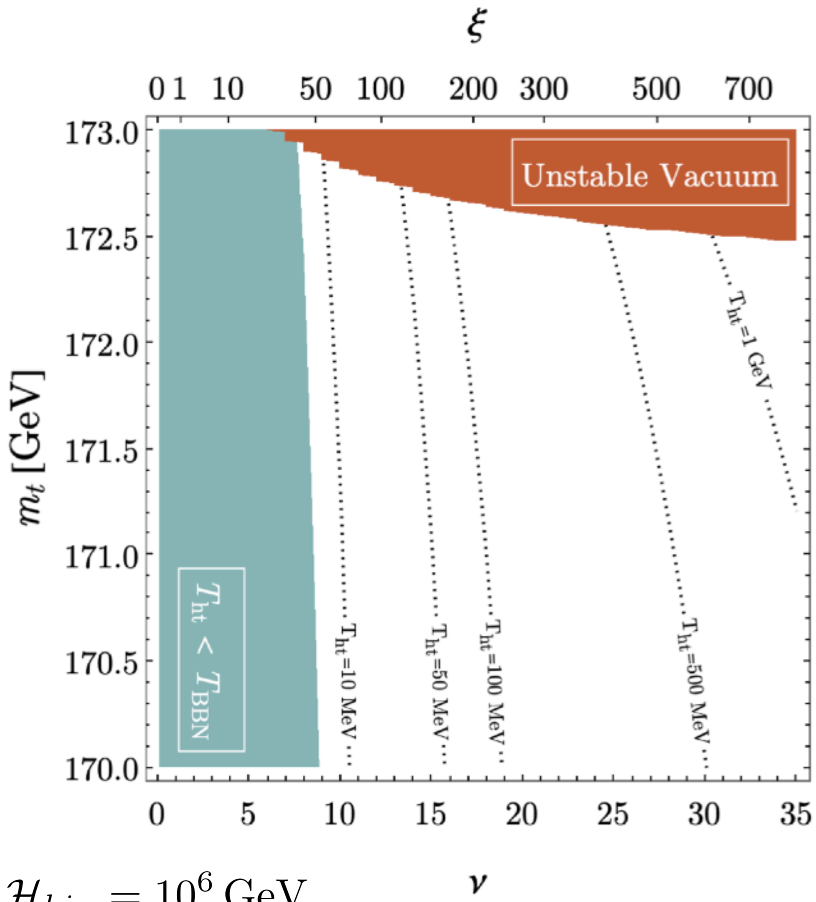


Favours lower masses for the top quark

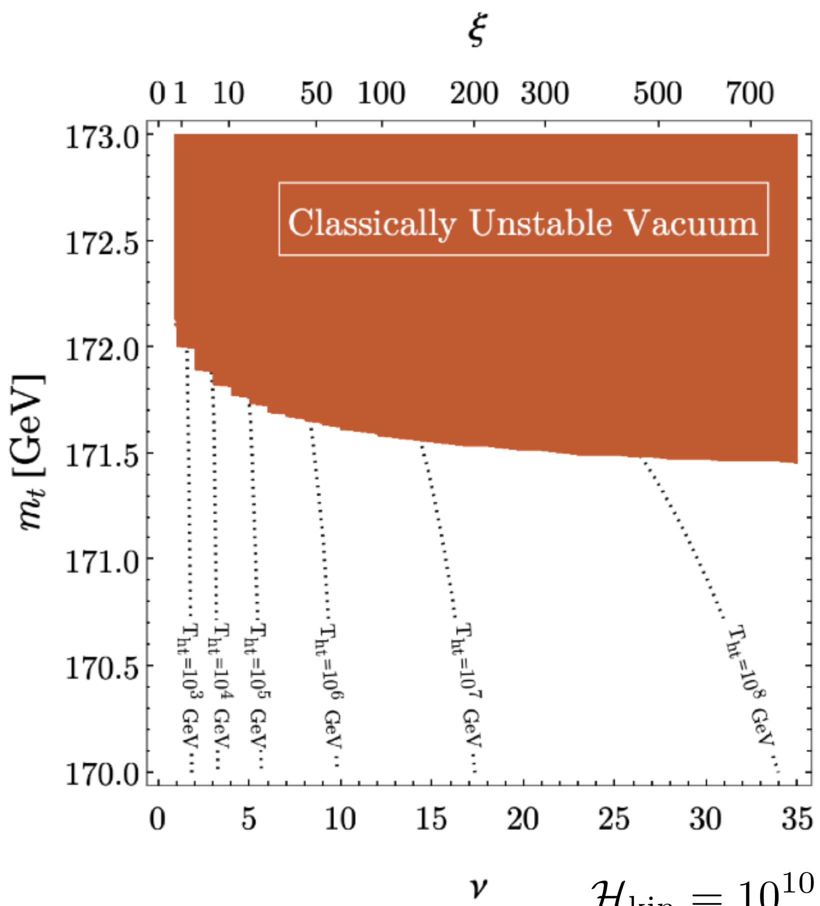
G. Laverda, JR, 2402.06000

Heating the Universe before BBN

Explosive tachyonic Higgs production allows to heat the Universe.
Additional restrictions on parameter space



$\mathcal{H}_{kin} = 10^6$ GeV



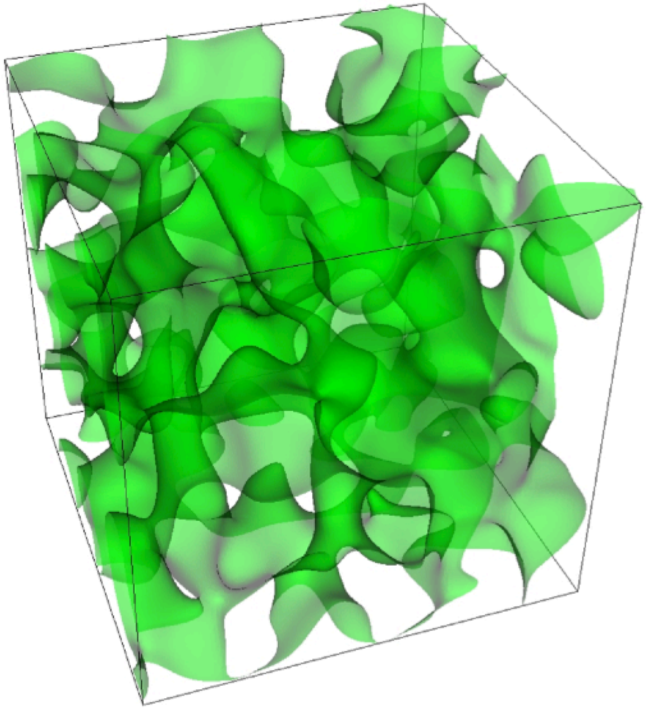
$\mathcal{H}_{\rm kin} = 10^{10}$ GeV

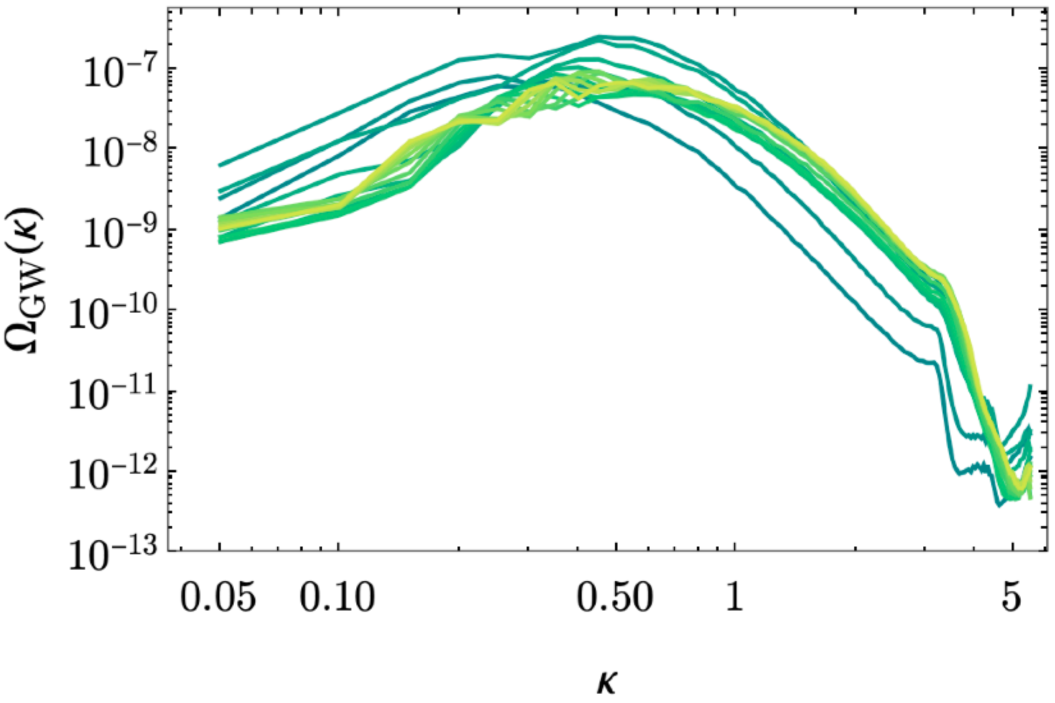
Lower bound on the inflationary scale

G. Laverda, JR, 2402.06000

Gravitational waves

$$(h_{ij}^{TT})'' + 2H(h_{ij}^{TT})' - \frac{\nabla^2 h_{ij}^{TT}}{a^2} \simeq \frac{2a^2}{M_P^2}\Pi_{ij}^{TT}$$



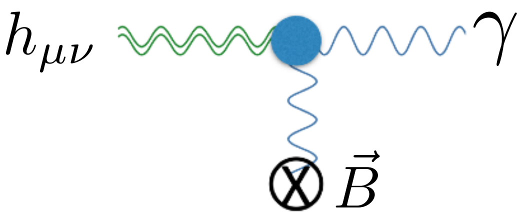


D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034

Ultra High-Frequency GW detectors

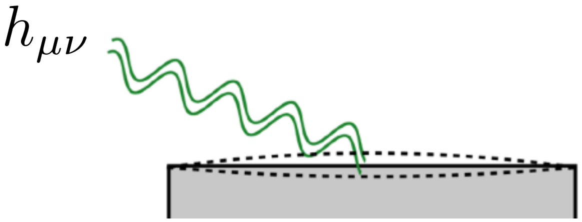
Inverse Gertsenshtein effect

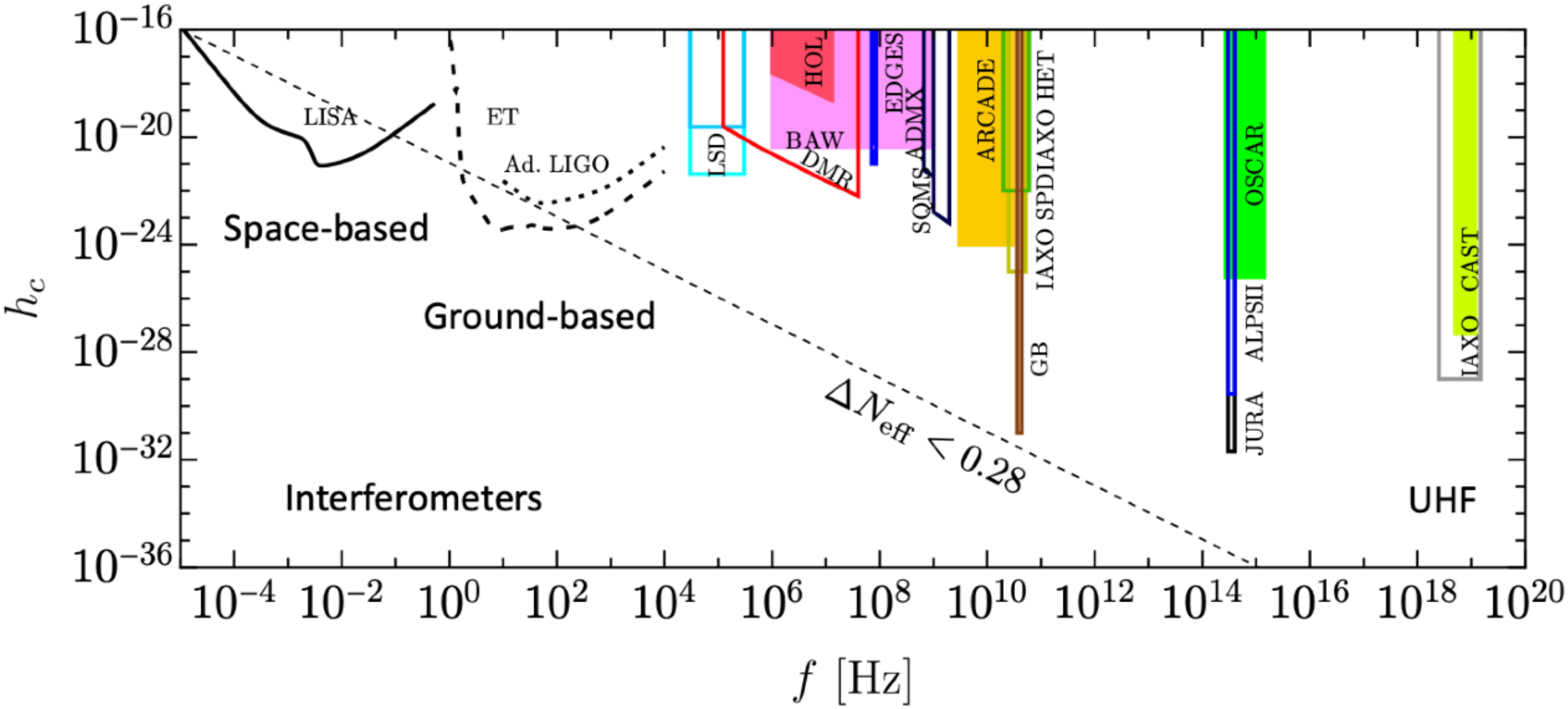
$$\mathcal{L} = -\frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma}$$



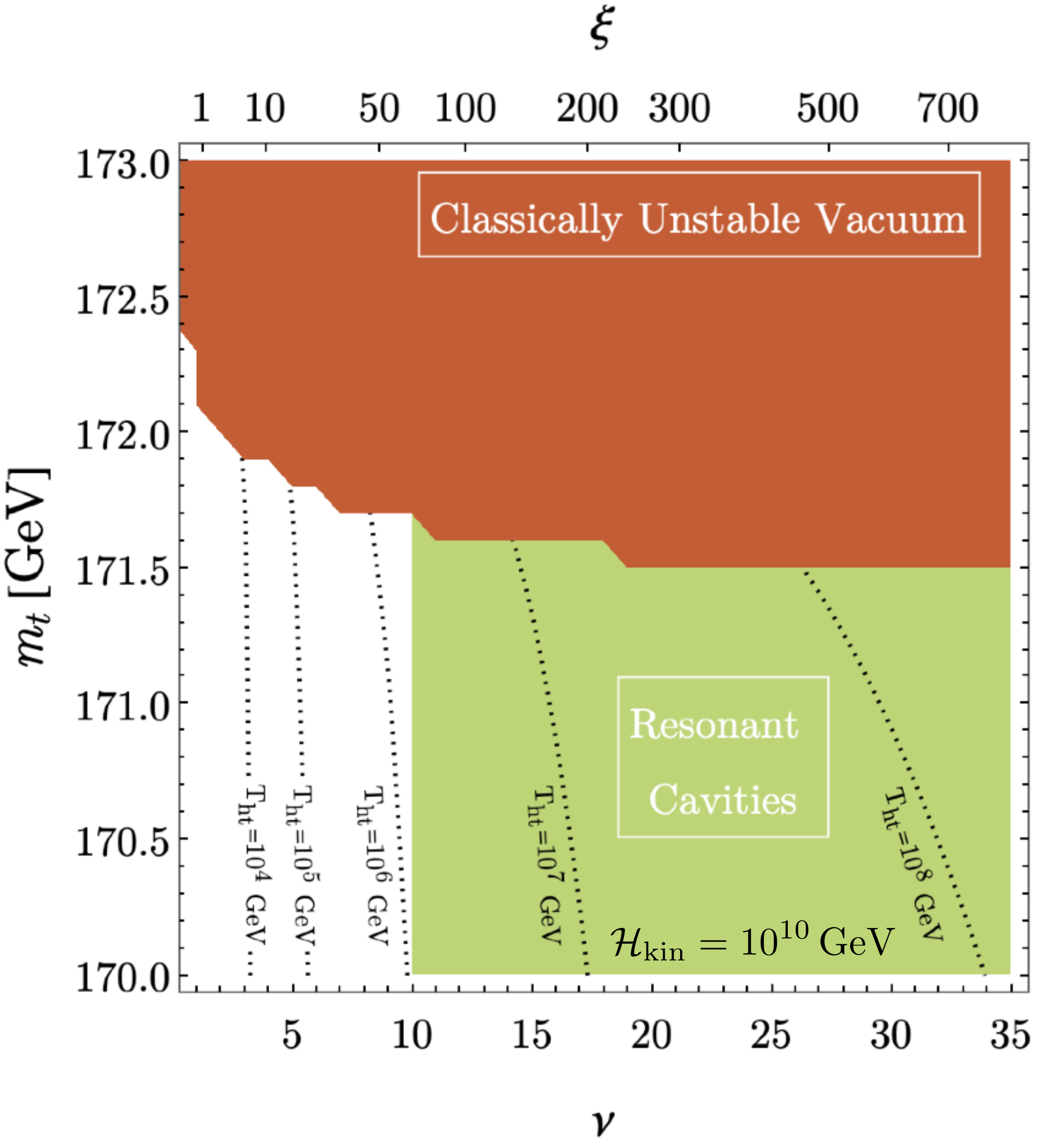
Mecanical resonators

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\nu\rho}(x) \frac{dx^\nu}{d\tau} \frac{dx^\rho}{d\tau} = 0$$





Potentially observable



Conclusions

- A non-minimally coupled Higgs is safely stabilized during inflation but undergoes a tachyonic instability during kination.
- The transition between the two phases acts as a natural cosmic clock. triggering a copious non-perturbative production of Higgs particles and bringing its amplitude close to the instability scale.
- Lower top quark masses are generically favored.
- The Higgs field itself can be responsible of heating the Universe after inflation.
- For $m_t = 171.3$ GeV, the heating temperature can be as large as 10^5 GeV.
- Potential gravitational waves signatures

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(Heidelberg U.)

Data Inference and Machine Learning
Emille Ishida
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Galaxy Clusters
Florian Pacaud
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Testing Fundamental Physics with GW
Marek Lewicki
(Warsaw U.)

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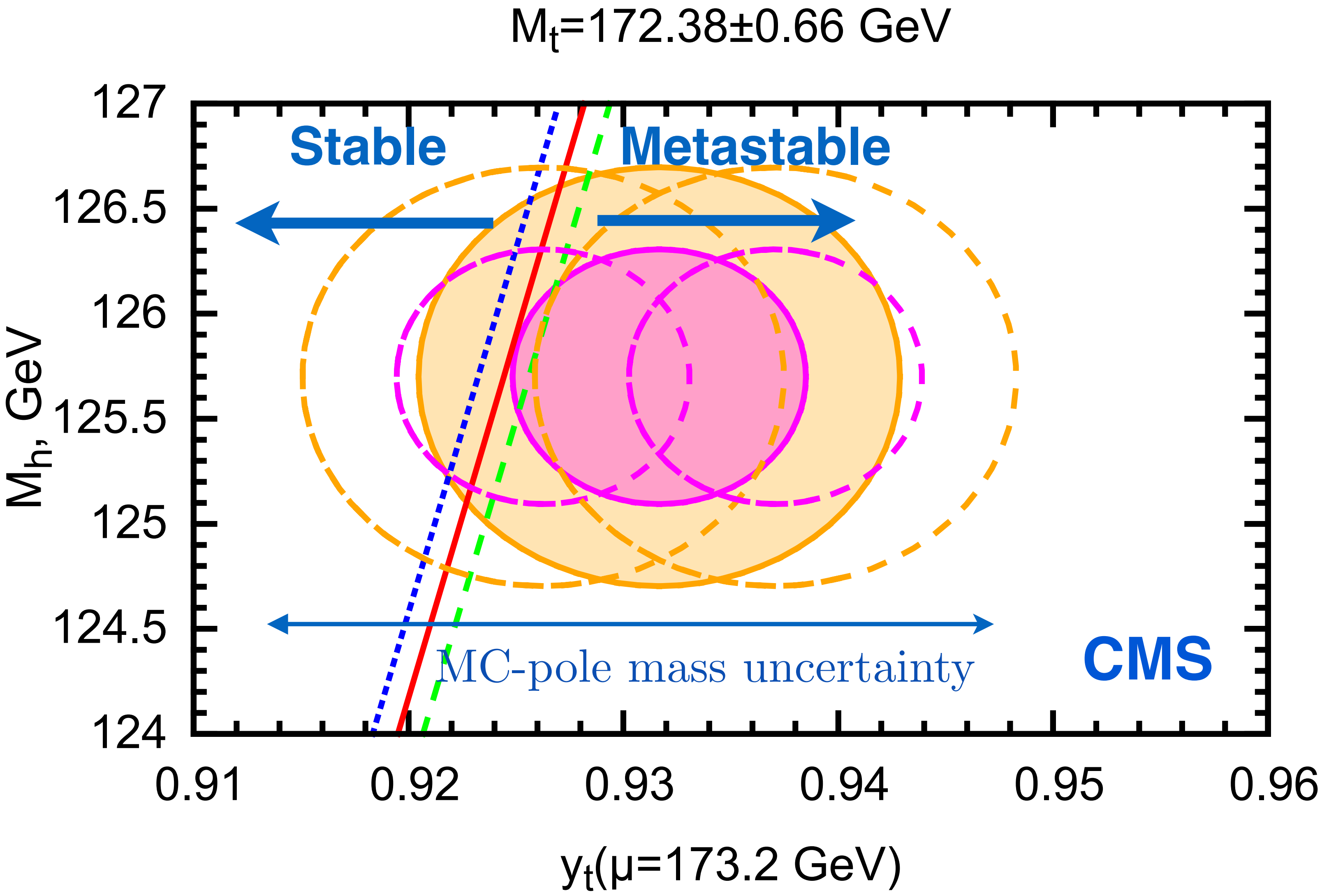
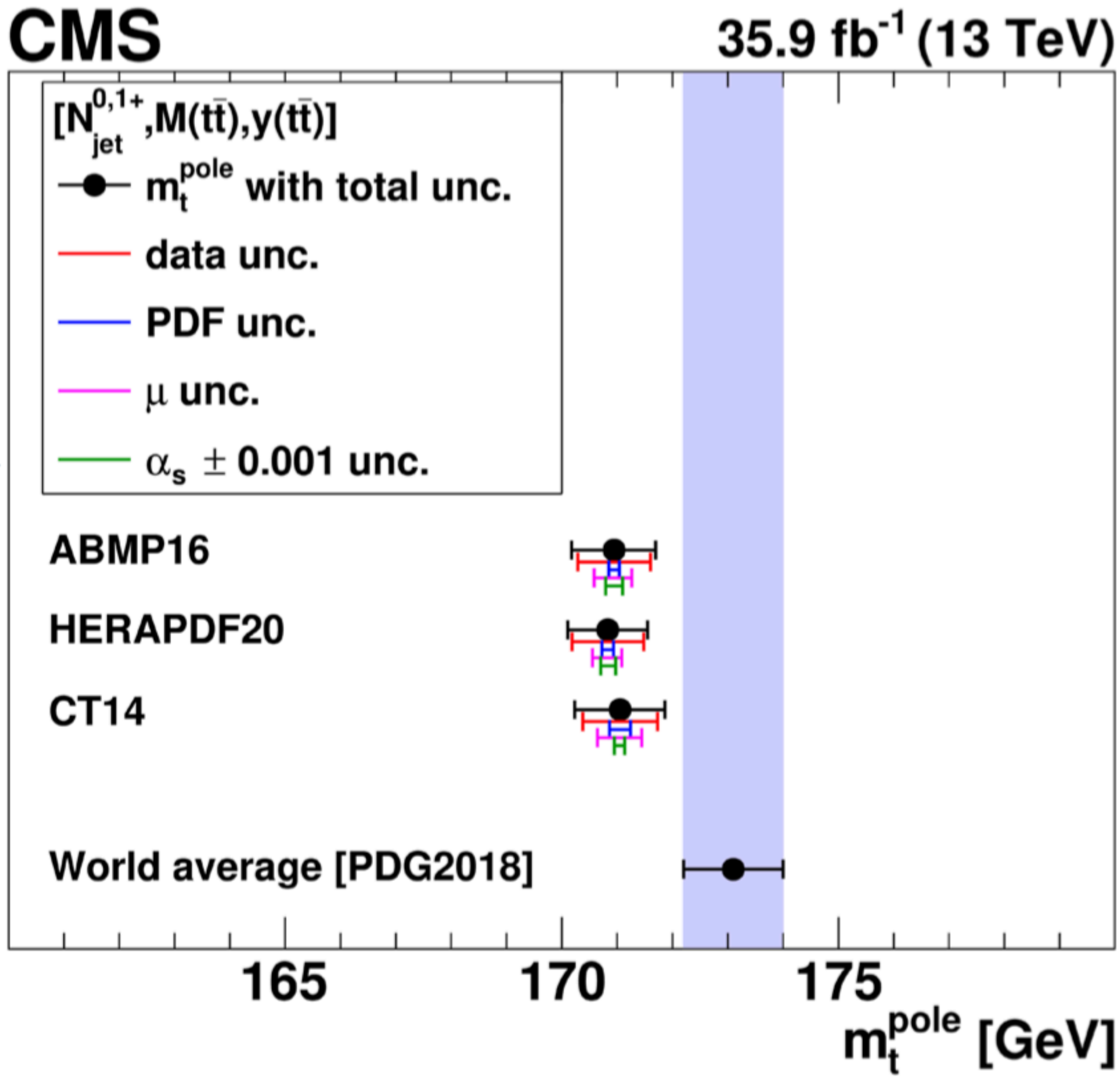
An open question



F. Bezrukov, M. Shaposhnikov, J.Exp.Theor.Phys. 120 (2015) 335-343,

Top mass measurements



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