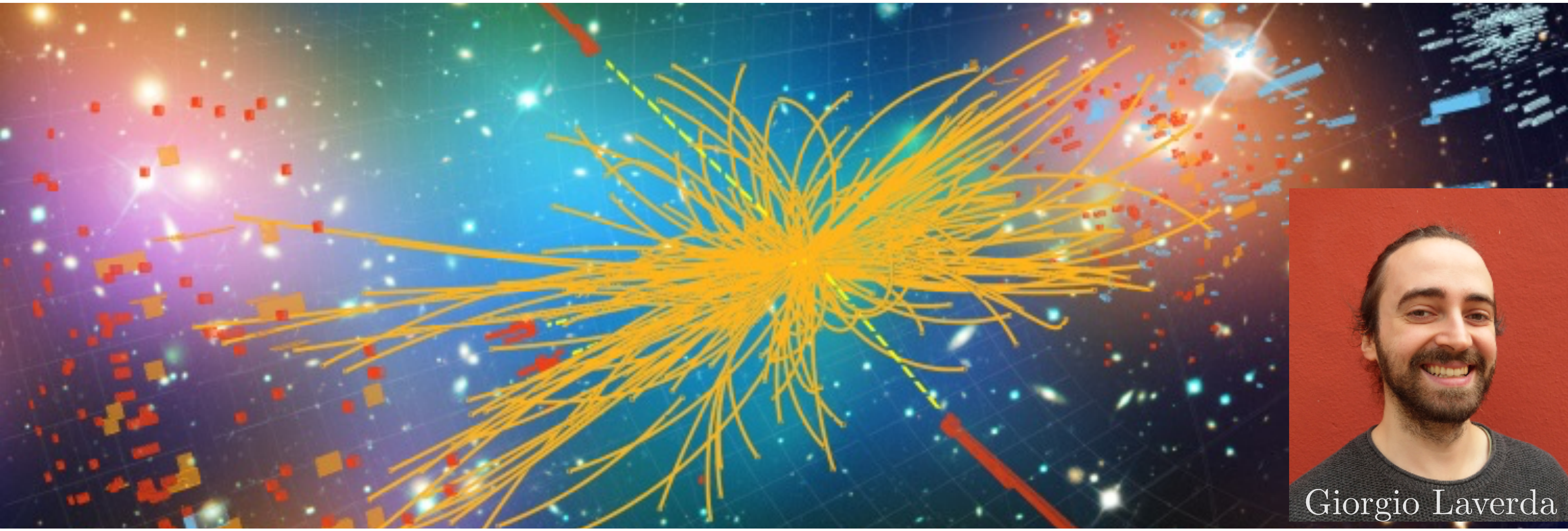
The Rise and Fall of the SM Higgs: EW Vacuum Stability during Kination

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



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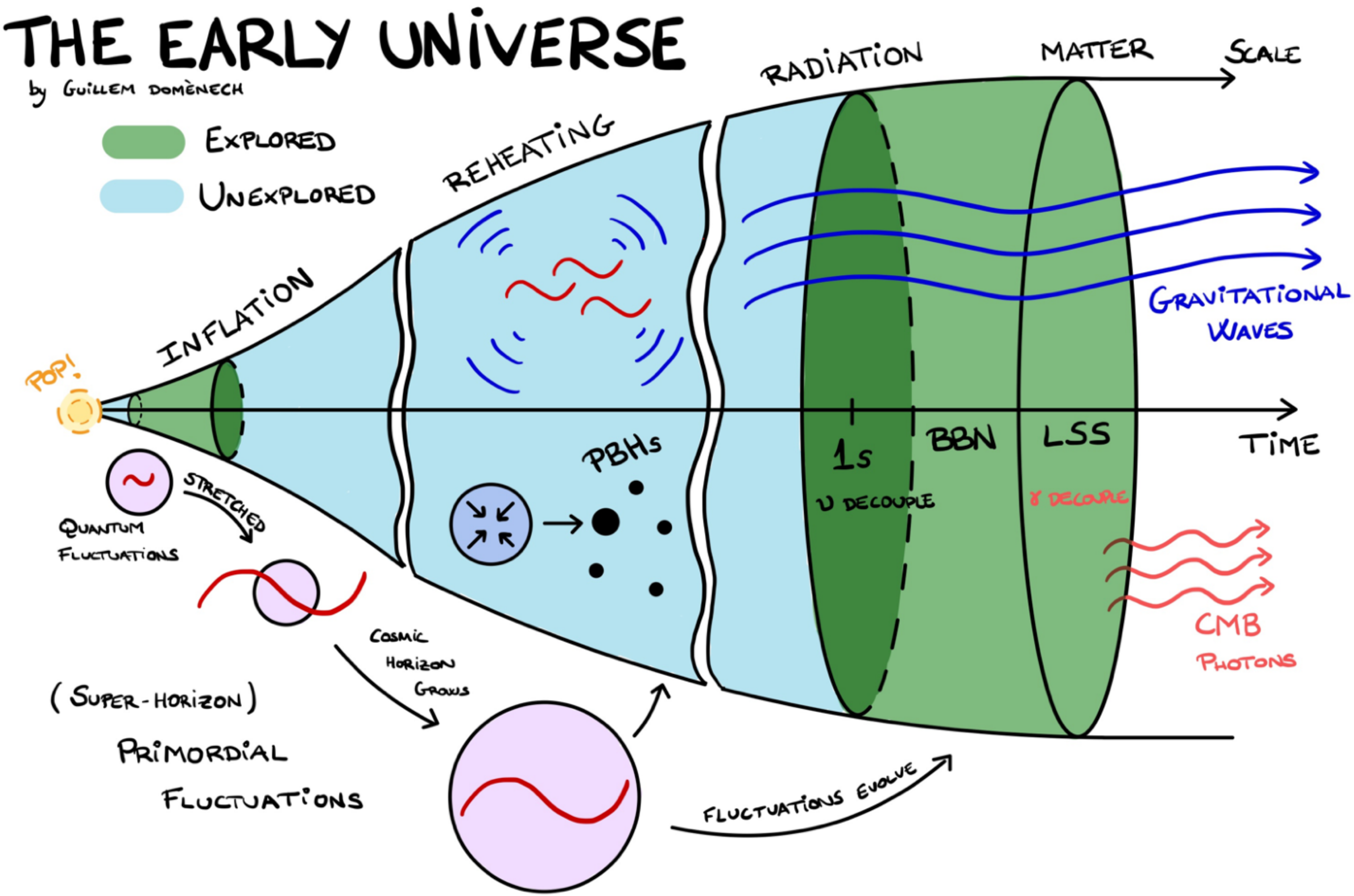
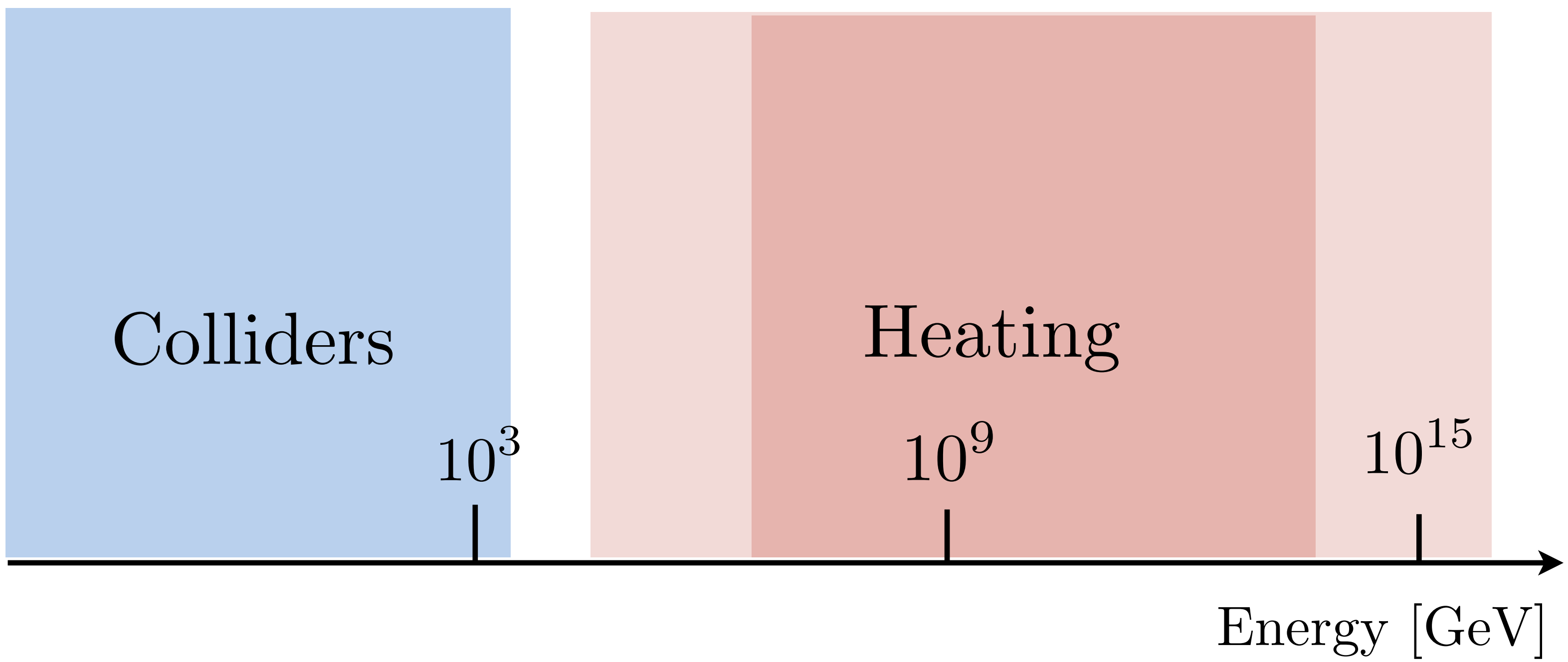
BUILDINGUNIVERSE


THE EARLY UNIVERSE
by GUILLEM DOMÈNECH
EXPLORED
UNEXPLORED
POP!
INFLATION
REHEATING
RADIATION
MATTER
SCALE
GRAVITATIONAL WAVES
TIME
PBHs
1s
ν DECOUPLE
BBN
LSS
γ DECOUPLE
CMB PHOTONS
QUANTUM FLUCTUATIONS
STRETCHED
COSMIC HORIZON GROWS
(SUPER-HORIZON)
PRIMORDIAL FLUCTUATIONS
FLUCTUATIONS EVOLVE

Reheating stage



- Unknown energy scale
- Unknown fields
- Unknown equation of state
- Unknown masses
- Unknown couplings
- Unknown distribution

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

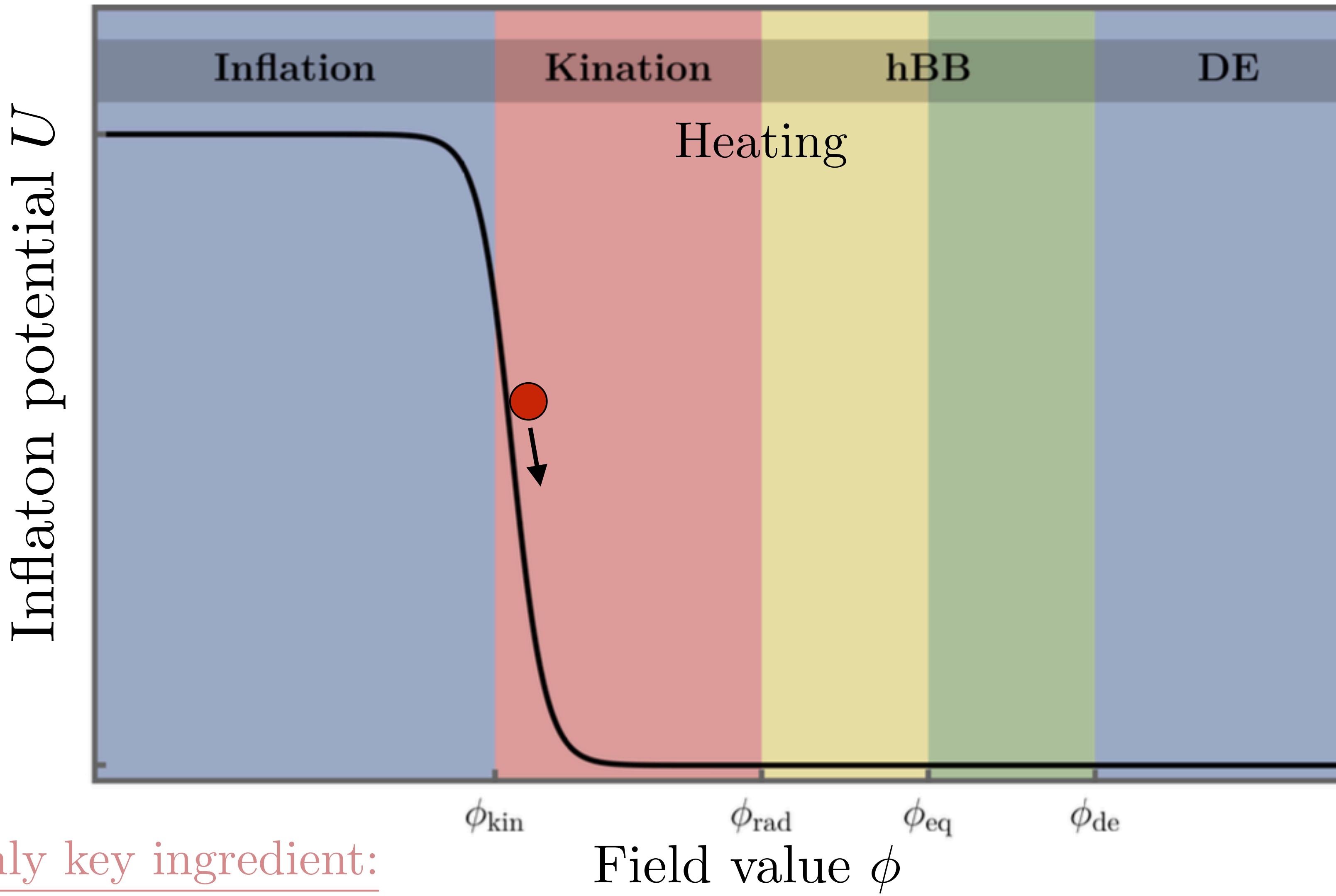
$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm P}^2}{2}R - g^{\mu\nu}(D_\mu H)^\dagger(D_\nu H) - \lambda\left(H^\dagger H - \frac{v_{\rm EW}^2}{2}\right)^2 - \xi H^\dagger H R + \mathcal{L}_{\rm SM} + \mathcal{L}_\phi$$

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

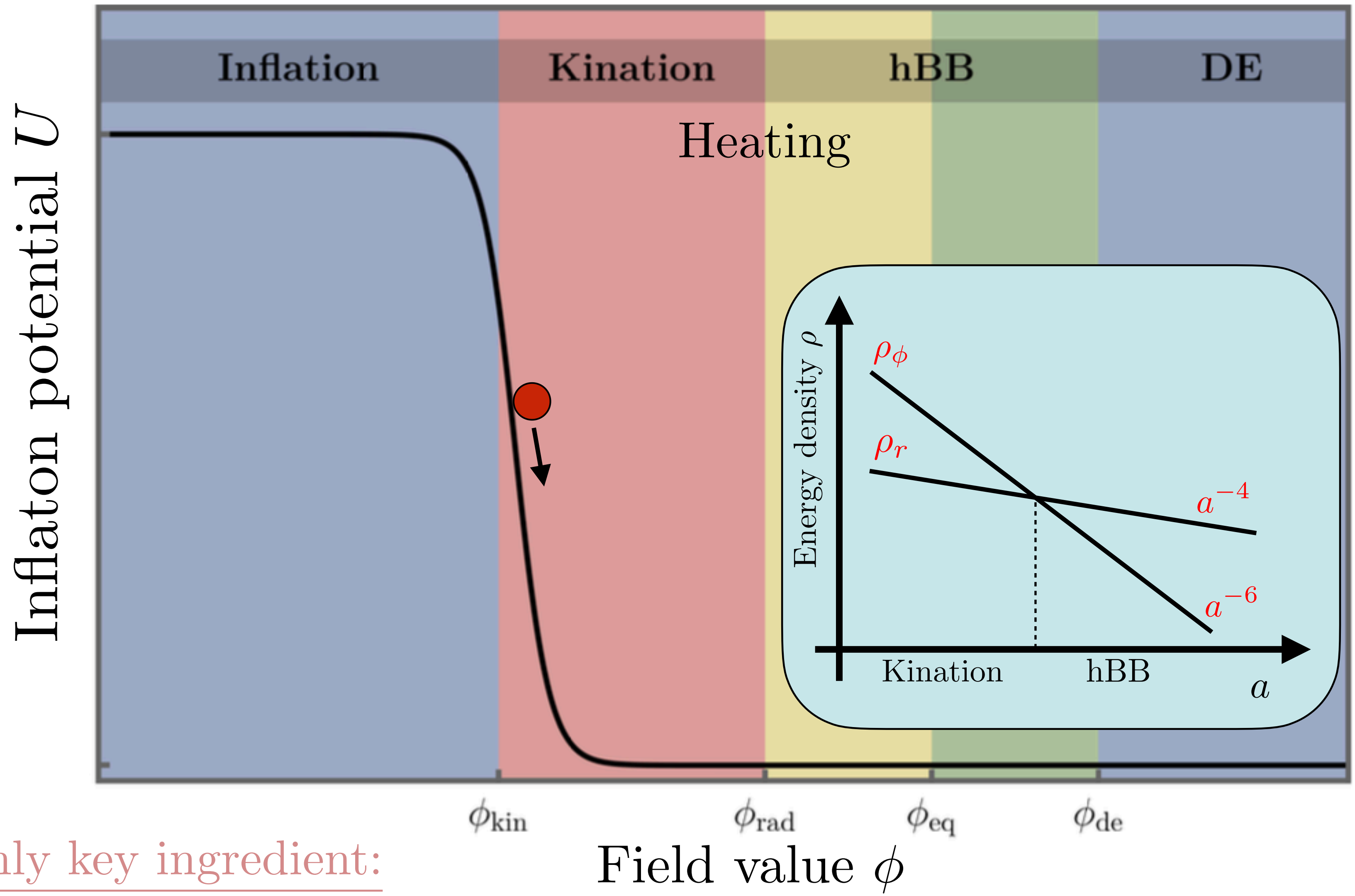
Quintessential inflation



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:

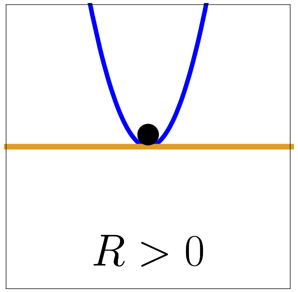
Period of kination

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

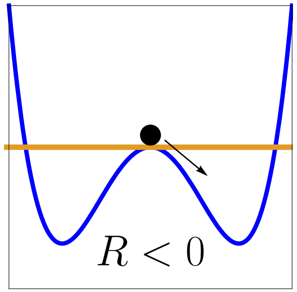
Hubble-induced Higgs mass

Not Higgs inflation

Higgs field is a spectator

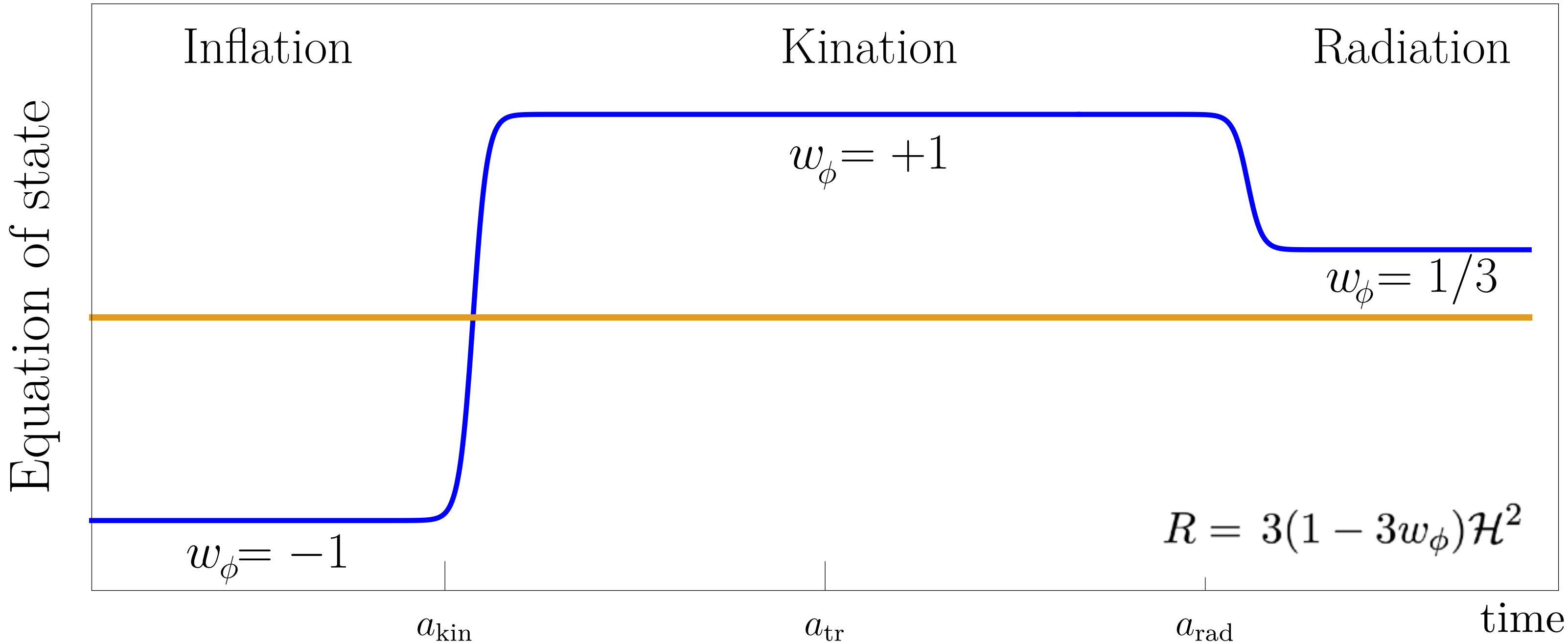


$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial h)^2 - \frac{1}{2}\xi R h^2 - \frac{\lambda}{4}h^4$$



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

$$Y \equiv \frac{a}{a_{\rm kin}} \frac{h}{h_*} \qquad \vec{y} \equiv a_{\rm kin} h_* \vec{x} \qquad h_* \equiv \sqrt{6\xi} H_{\rm kin}$$
$$z \equiv a_{\rm kin} h_* \tau$$

Spinodal/Tachyonic instability

$$S_\chi = \int d^3\vec{y}\, dz \left[\frac{1}{2}(Y')^2 - \frac{1}{2}|\nabla Y|^2 + \frac{1}{2}M^2(z)Y^2 - \cancel{V(Y)}\right]$$

$$M^2(z) \equiv (4\nu^2 - 1)\mathcal{H}^2 \qquad \nu \equiv \sqrt{\frac{3\xi}{2}}$$

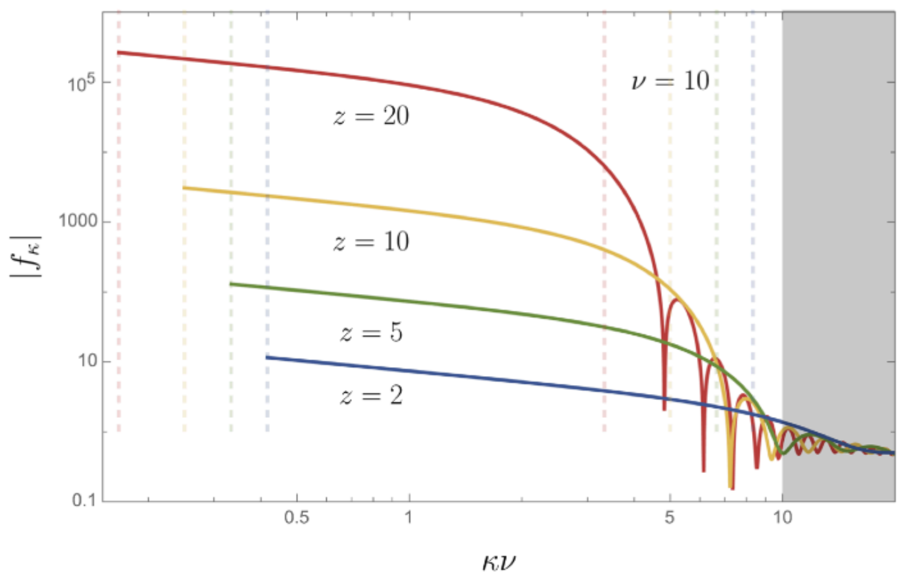
- The Z_2 symmetry of the action is preserved by the dynamics.
- The field is *not* classical but rather quantum.
- A homogeneous component description is *completely inaccurate.*

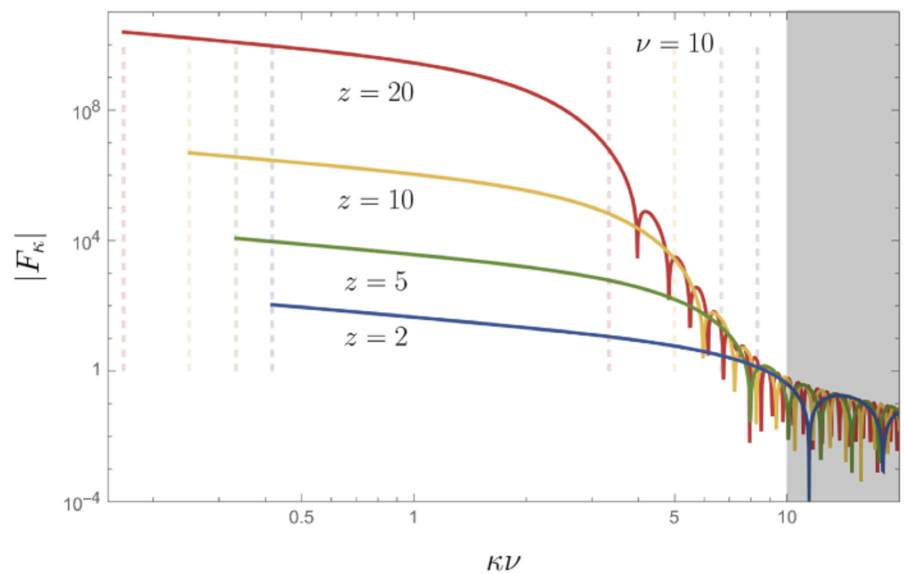
D. Bettoni, JR, JCAP 01 (2020) 002

Classicalization

$$f_\kappa'' + (\kappa^2 - M^2(z))f_\kappa = 0$$

$$F_\kappa(z) = \mathrm{Re}(f_\kappa^* f_\kappa')$$



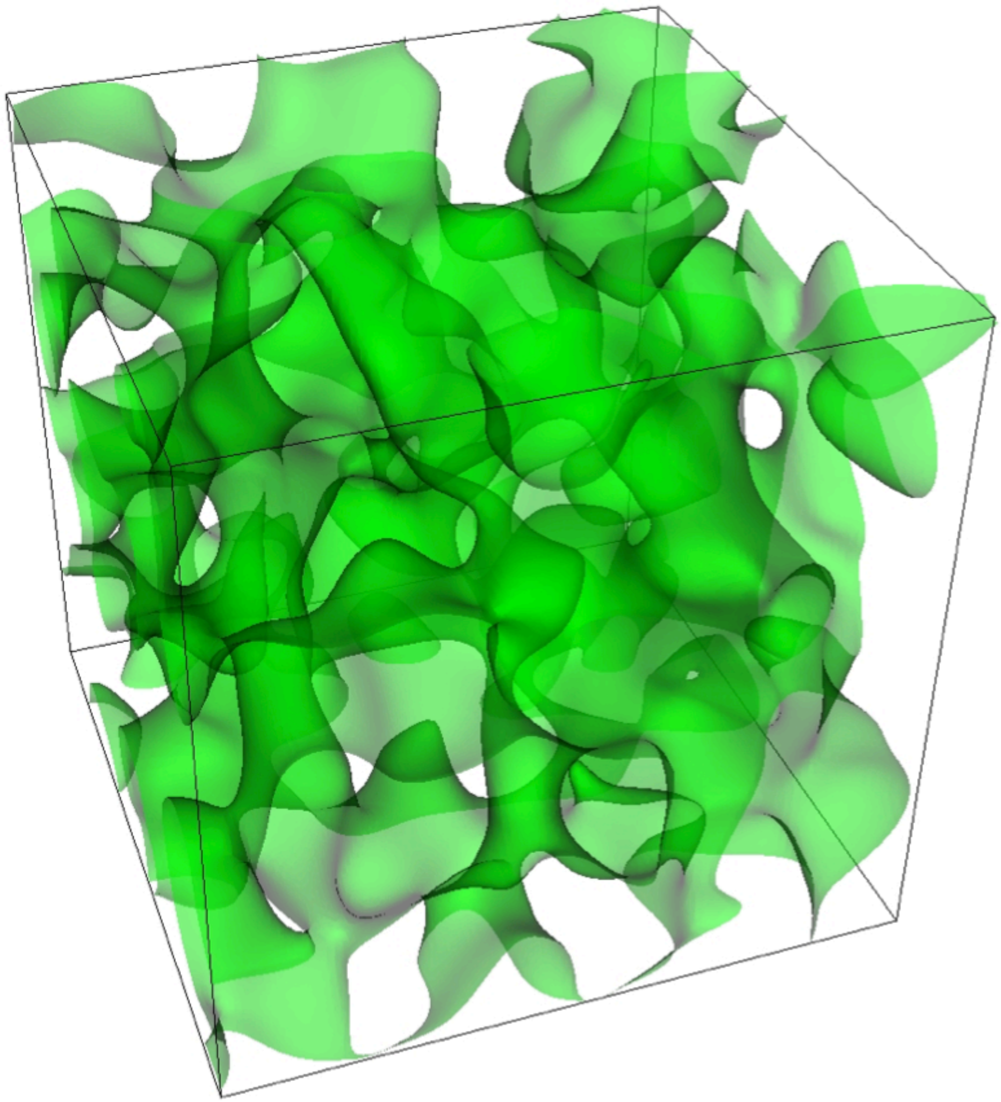


$$\Delta Y_\kappa^2\,\Delta\Pi_\kappa^2 = |F_\kappa(z)|^2 + \frac{1}{4} \geq \frac{1}{4}\left|\langle[Y_\kappa(z),\ \Pi_\kappa^\dagger(z)]\rangle\right|^2$$

- Following dynamics needs non-analytical techniques.
- High occupation numbers $\rightarrow$ Classical Lattice Simulations

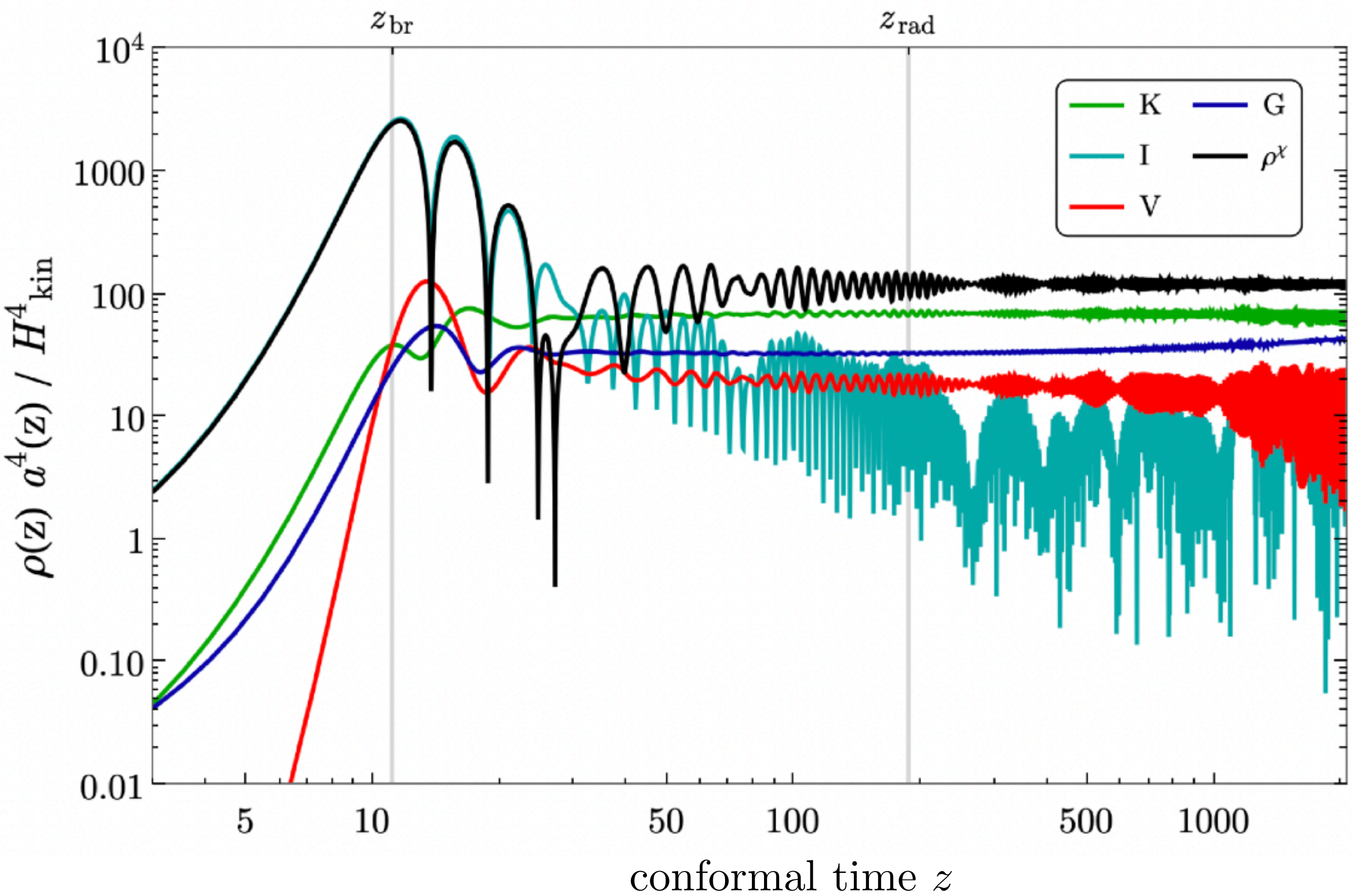
D. Bettoni, JR, JCAP 01 (2020) 002

Beating Domain Walls



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

Energy distribution



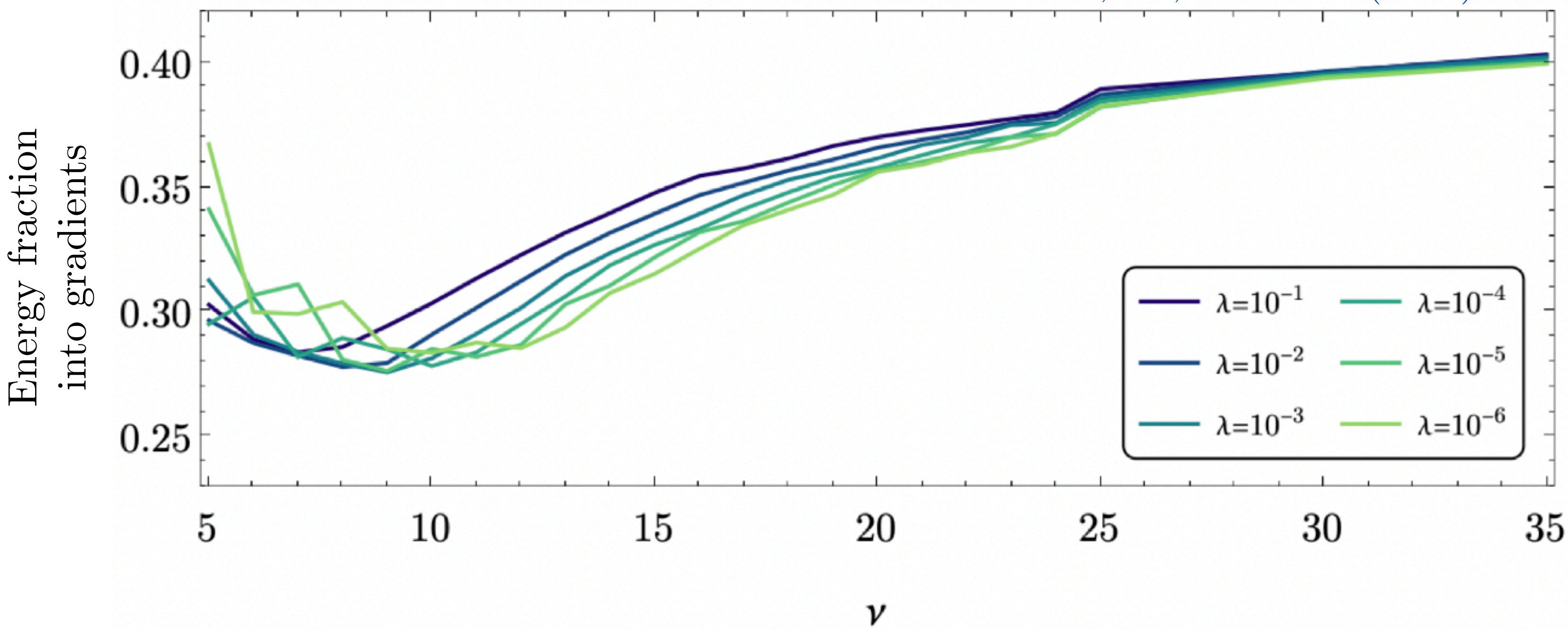
Lattice-based fitting formulas: O(100) 3+1 classical lattice simulations

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

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

Gradients are crucial

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



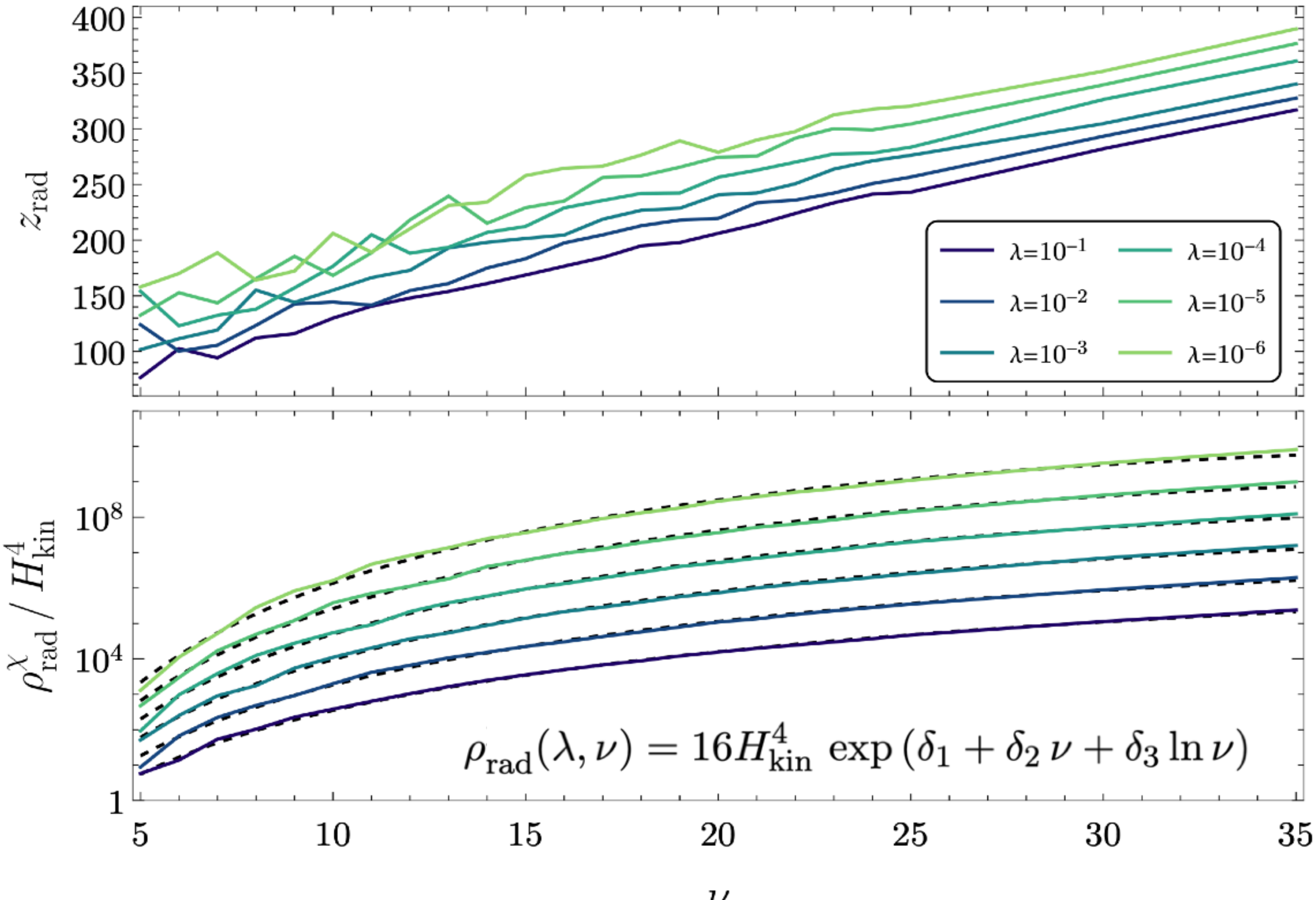
Radiation-like products for arbitrary potential

$$w_\chi = \frac{1}{3} + \frac{2}{3}\frac{(n-2)}{(n+1) + \langle(\nabla\chi/a)^2\rangle/\langle V\rangle} \qquad V \propto \chi^{2n}$$

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

Onset of radiation domination

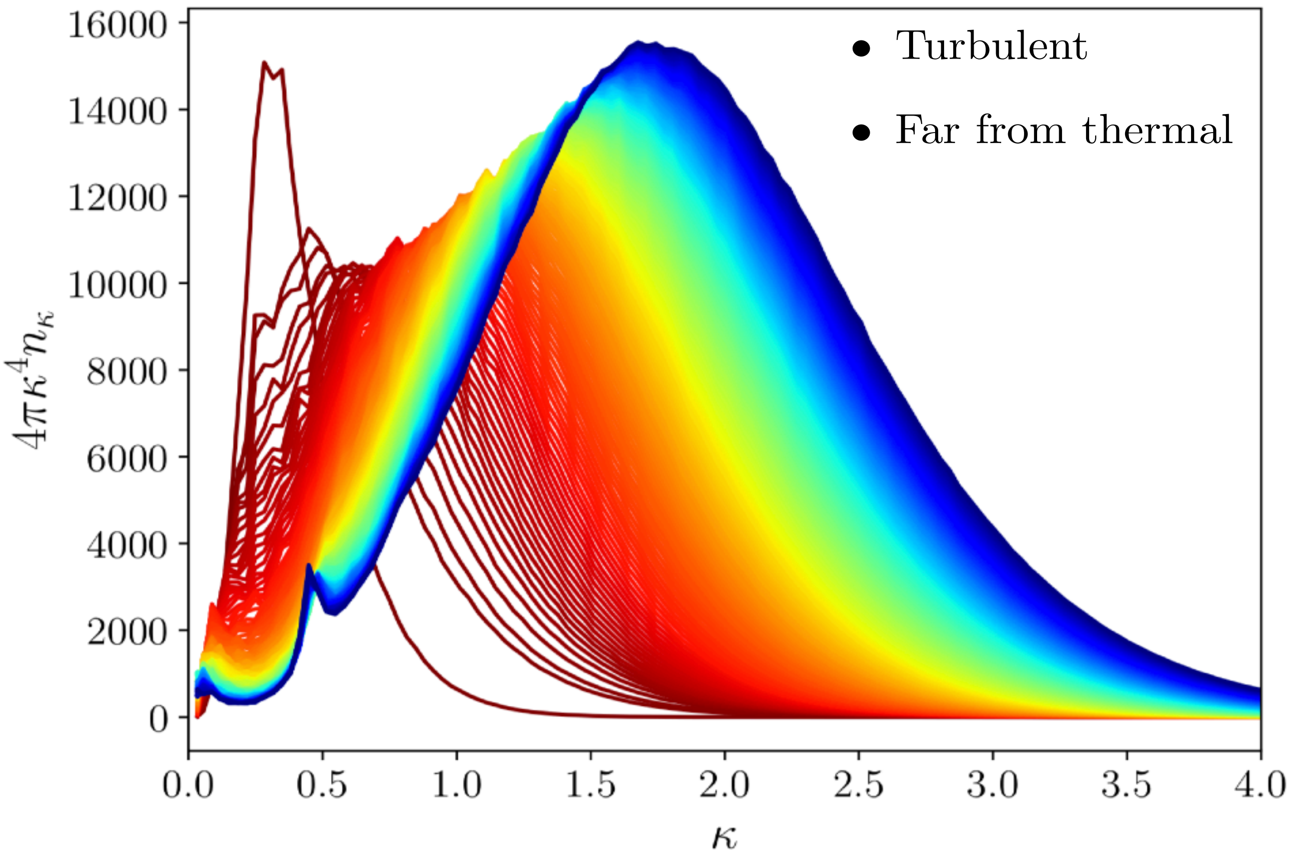
Lattice-based fitting formulas: O(100) 3+1 classical lattice simulations



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

Heating “temperature”

By-product
First lattice characterisation
of Ricci reheating

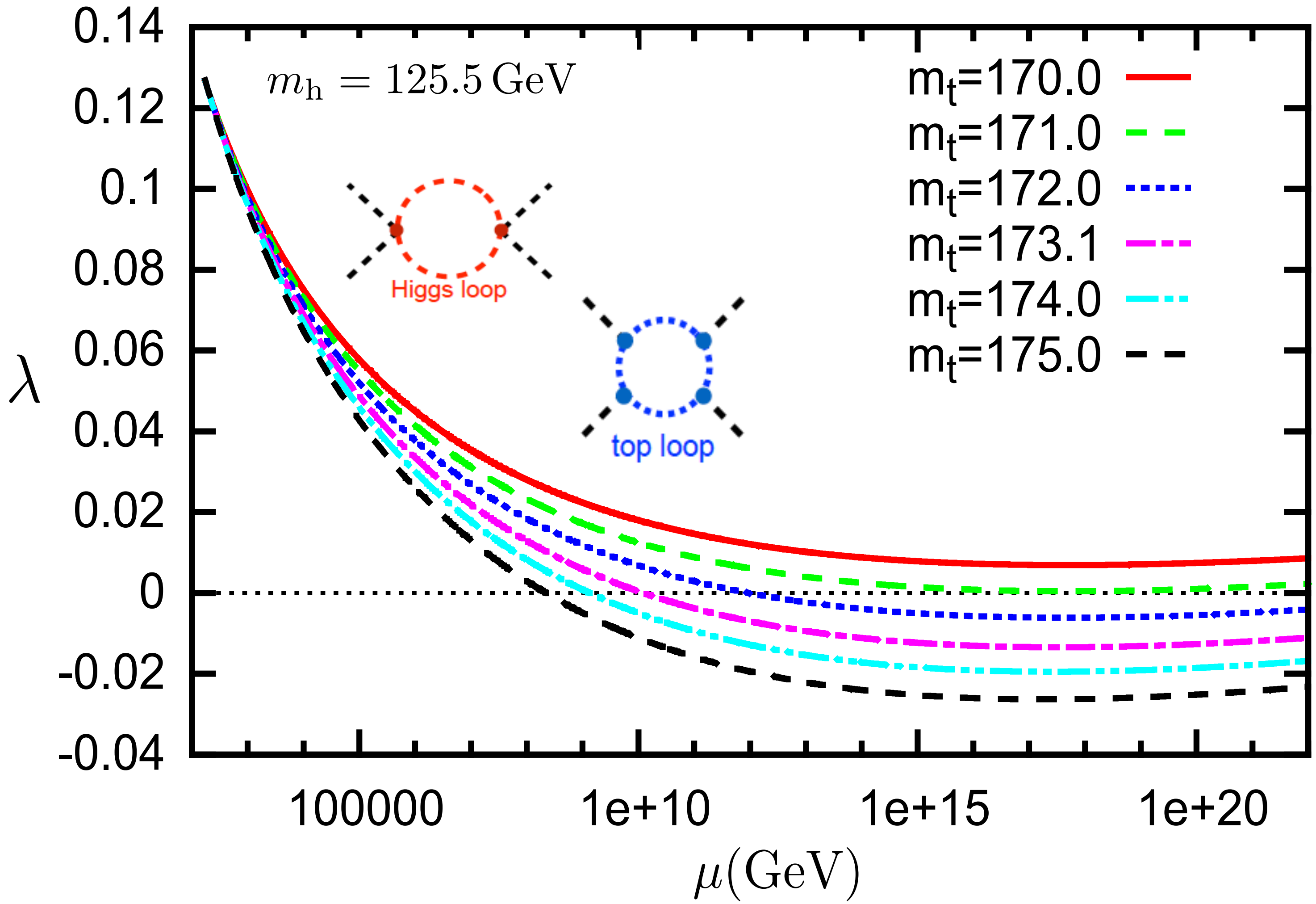


$$T_{\rm ht} \simeq 2.7\times 10^8\,{\rm GeV}\left(1+\frac{z_{\rm rad}}{\nu}\right)^{-3/4}\left(\frac{\rho_{\rm rad}/\rho^{\phi}_{\rm rad}}{10^{-8}}\right)^{3/4}\left(\frac{H_{\rm kin}}{10^{11}\,{\rm GeV}}\right)^{1/2}$$

D.Bettoni, A. Lopez-Eiguren, JR, JCAP 01 (2022) 01, 002
G. Laverda, JR, JCAP 03 (2024) 033

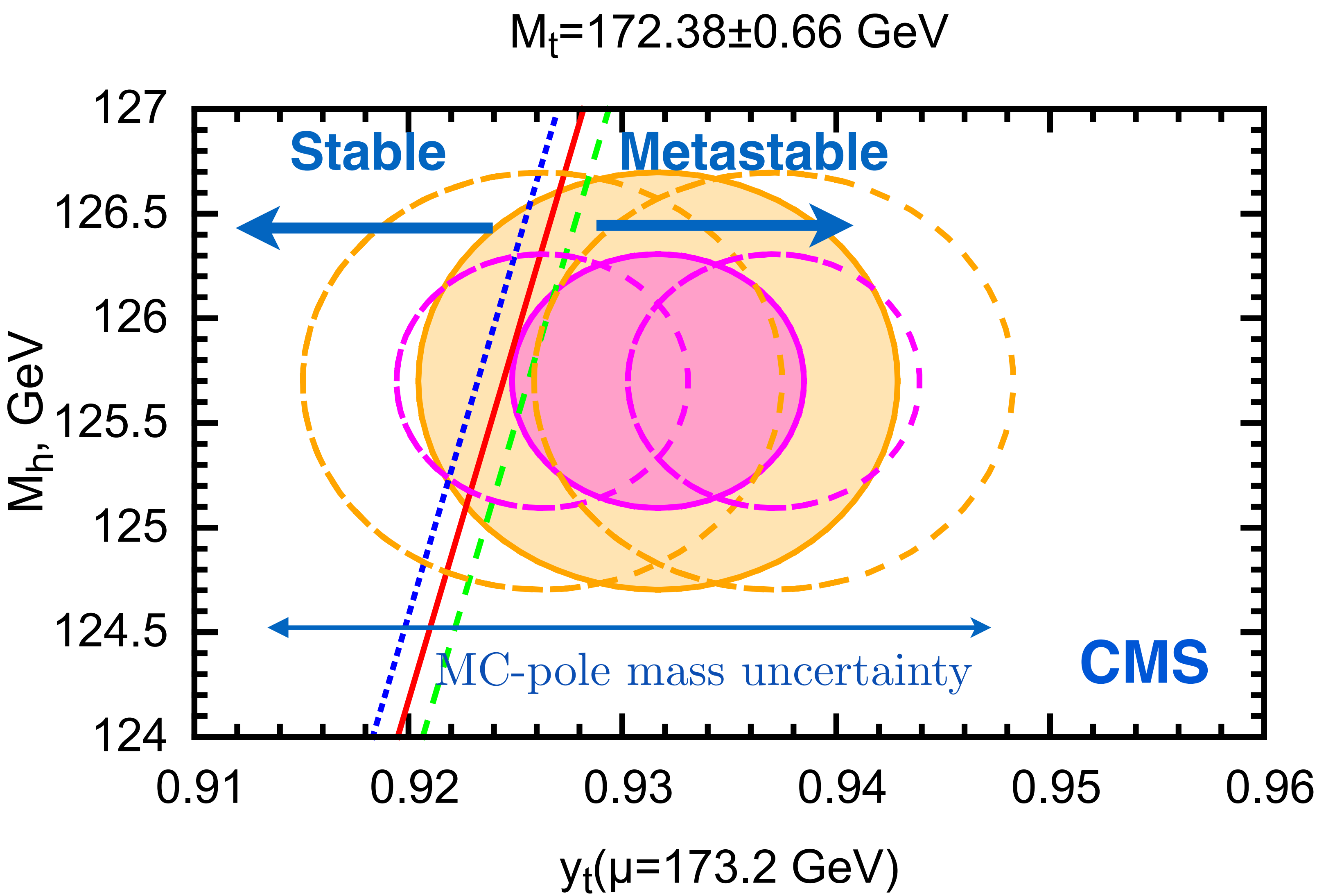
Beyond tree level

Quantum contributions of heavy SM particles to effective potential important



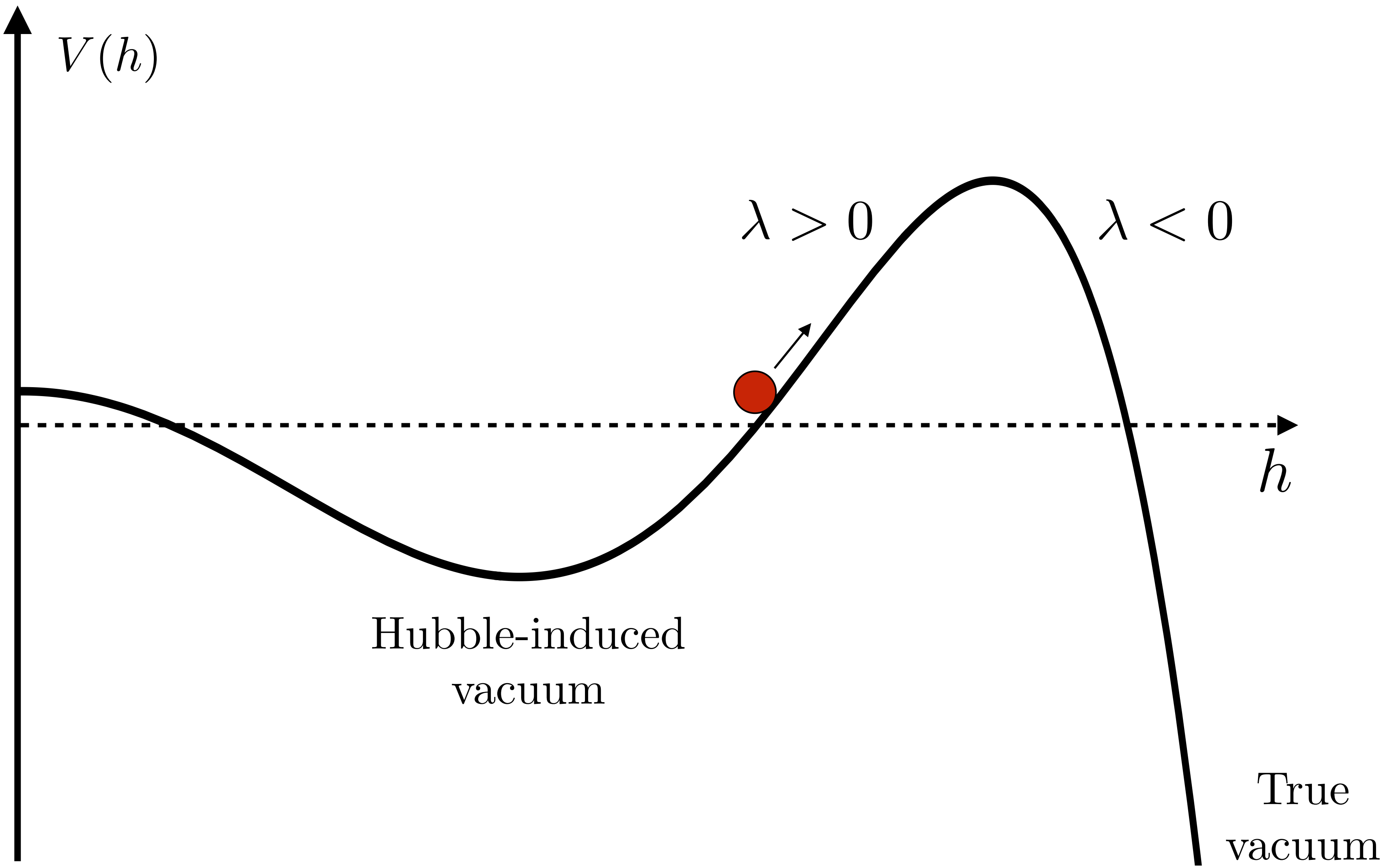
JR et al., Phys.Rev.D 90 (2014) 027307, Phys.Rev.D 92 (2015) 8, 083512, JCAP 02 (2018) 040

An open question

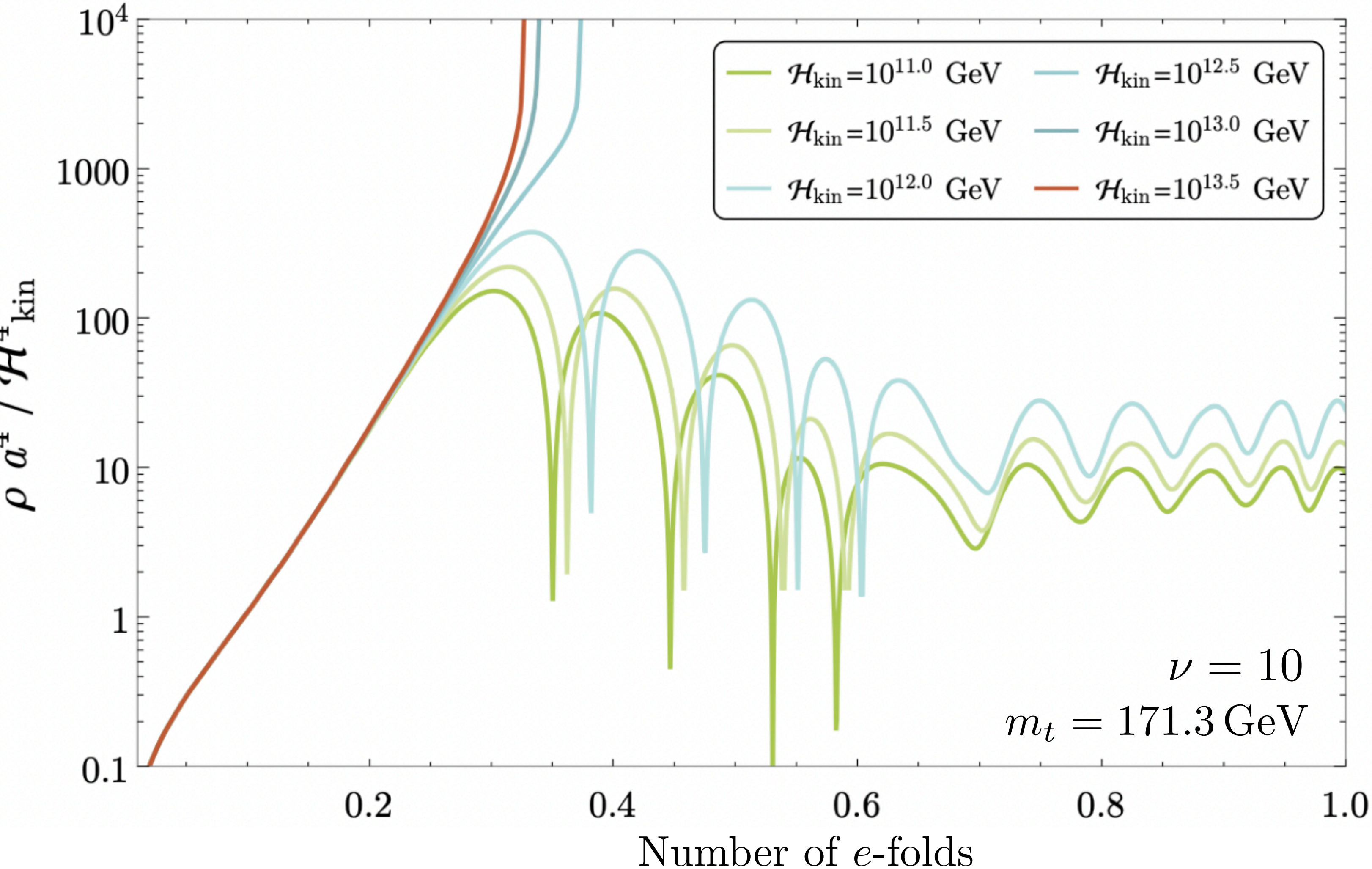


F. Bezrukov, M. Shaposhnikov, J.Exp.Theor.Phys. 120 (2015) 335-343,

Higgs effective potential



Vacuum stability during kination



G. Laverda, JR, 2402.06000

Scanning of parameter space

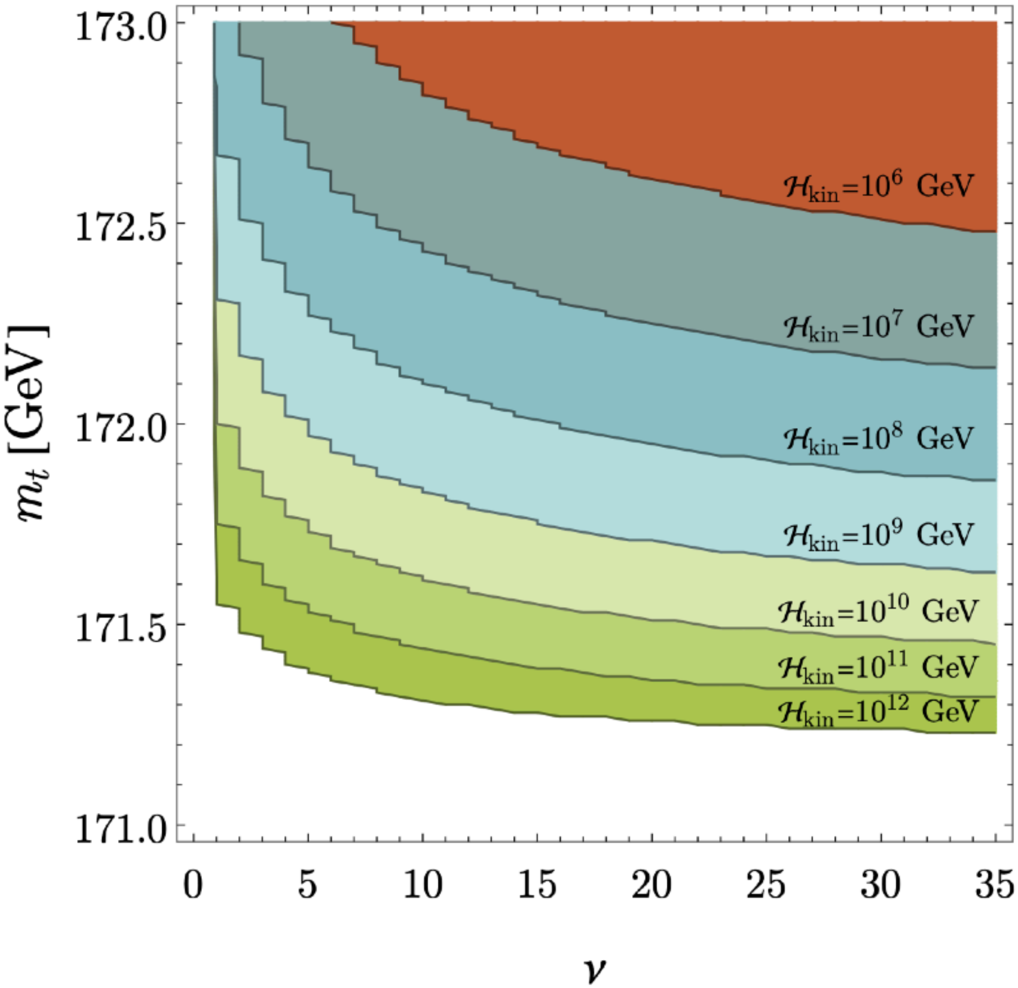
- Three-loop renormalisation-group running of the Higgs self-coupling
- Agnostic approach to top quark mass values, $m_t = 170 - 173$ GeV
- Wide range for non-minimal coupling parameter $\xi \sim 1 - 700$
- Wide range for the onset scale of kination $\mathcal{H}_{\rm kin} \sim 10^6 - 10^{15}$ GeV
- O(1000)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

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

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

G. Laverda, JR, 2402.06000

Stability constraints on the top mass

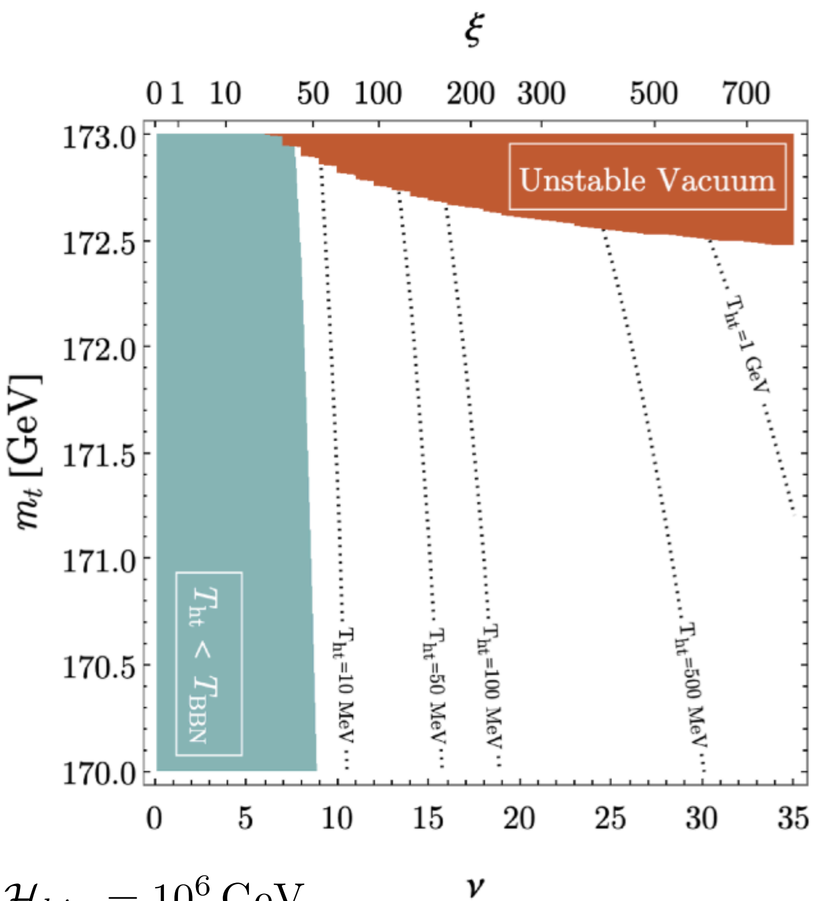


Favours lower masses for the top quark

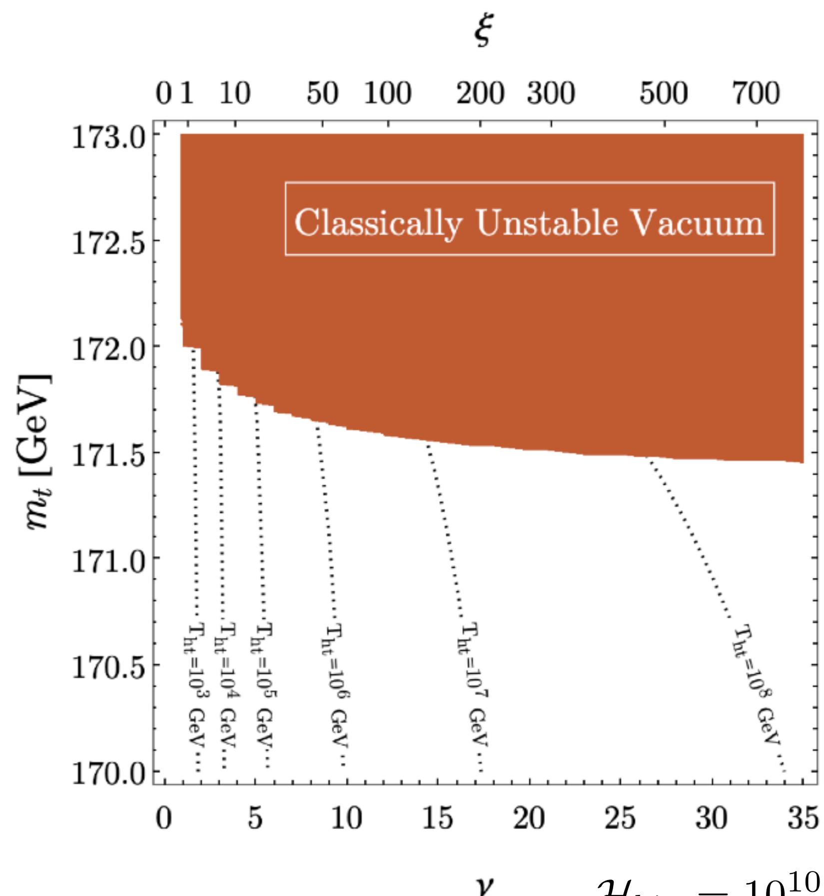
G. Laverda, JR, 2402.06000

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



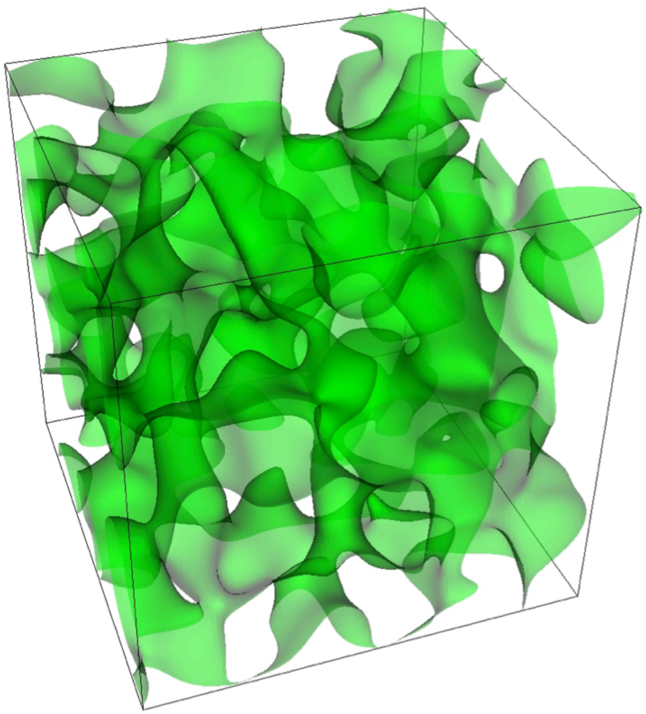
$\mathcal{H}_{\rm kin} = 10^{10}$ GeV

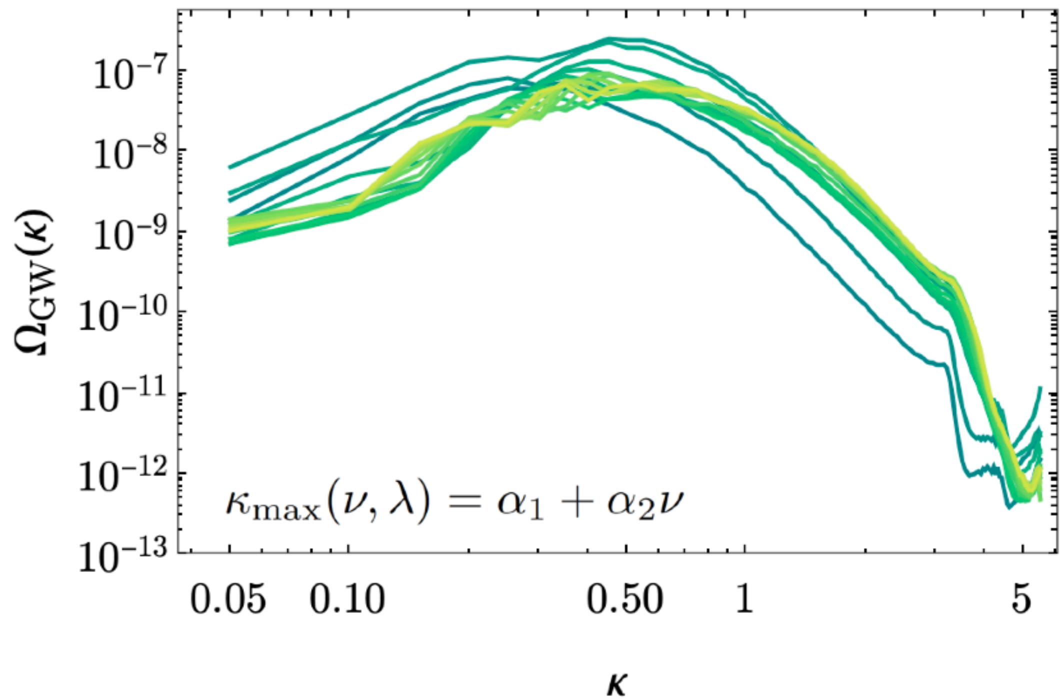
Lower bound on the inflationary scale

G. Laverda, JR, 2402.06000

Gravitational waves

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



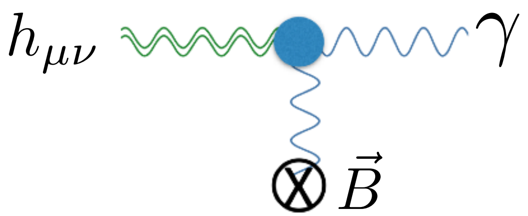


D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034

Ultra High-Frequency GW detectors

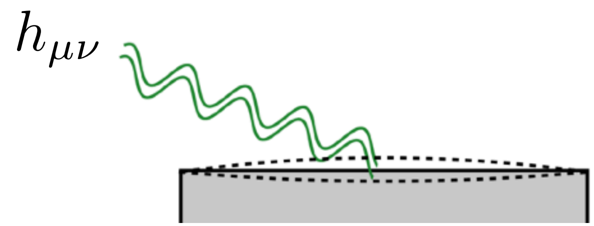
Inverse Gertsenshtein effect

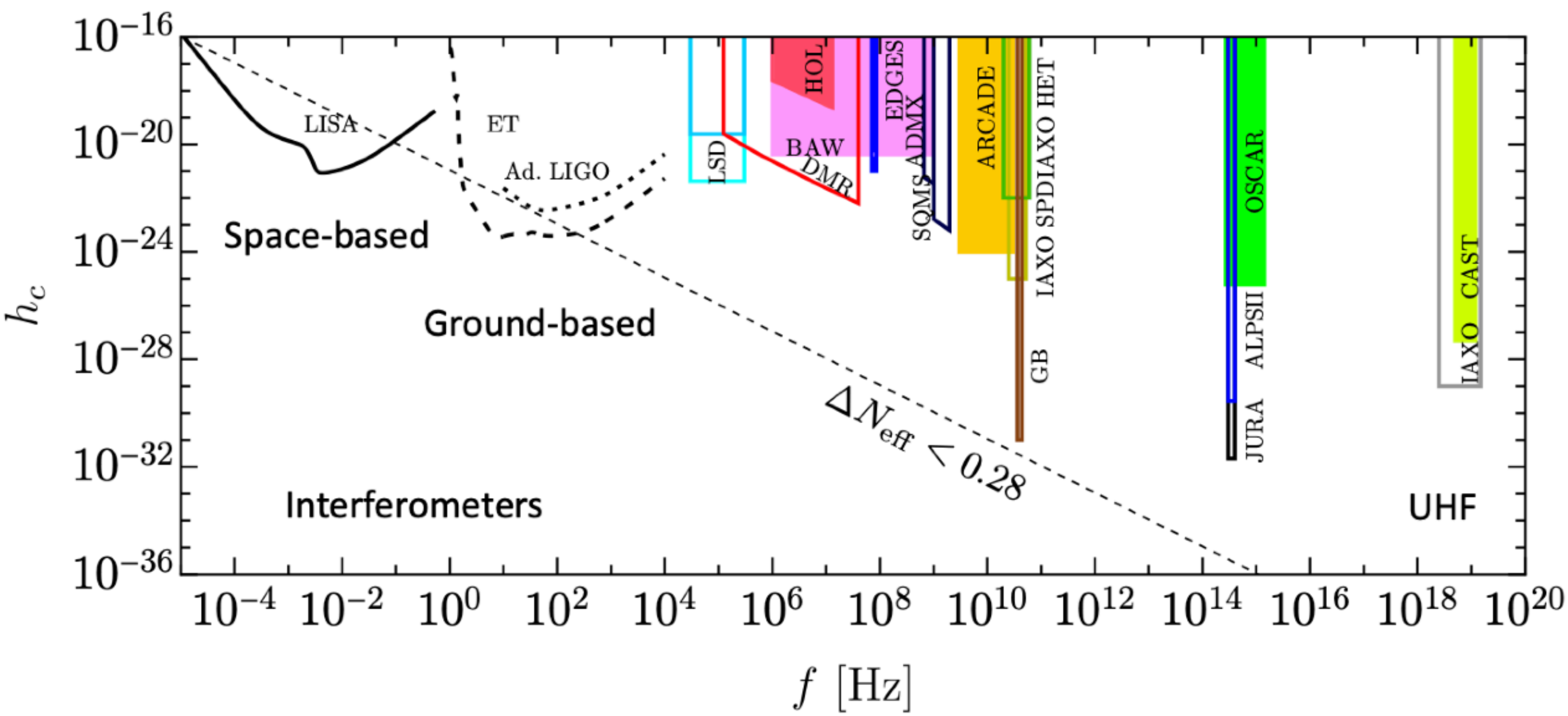
$$\mathcal{L} = -\frac{1}{4} g^{\mu\rho} g^{\nu\sigma} F_{\mu\nu} F_{\rho\sigma}$$



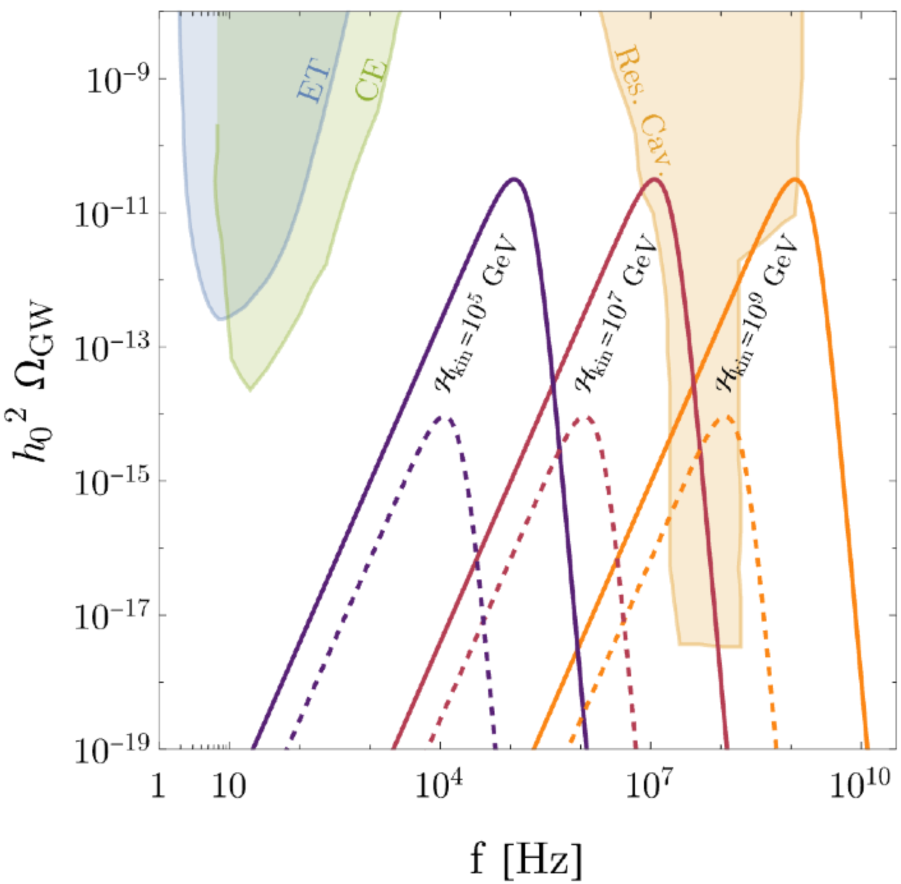
Mecanical resonators

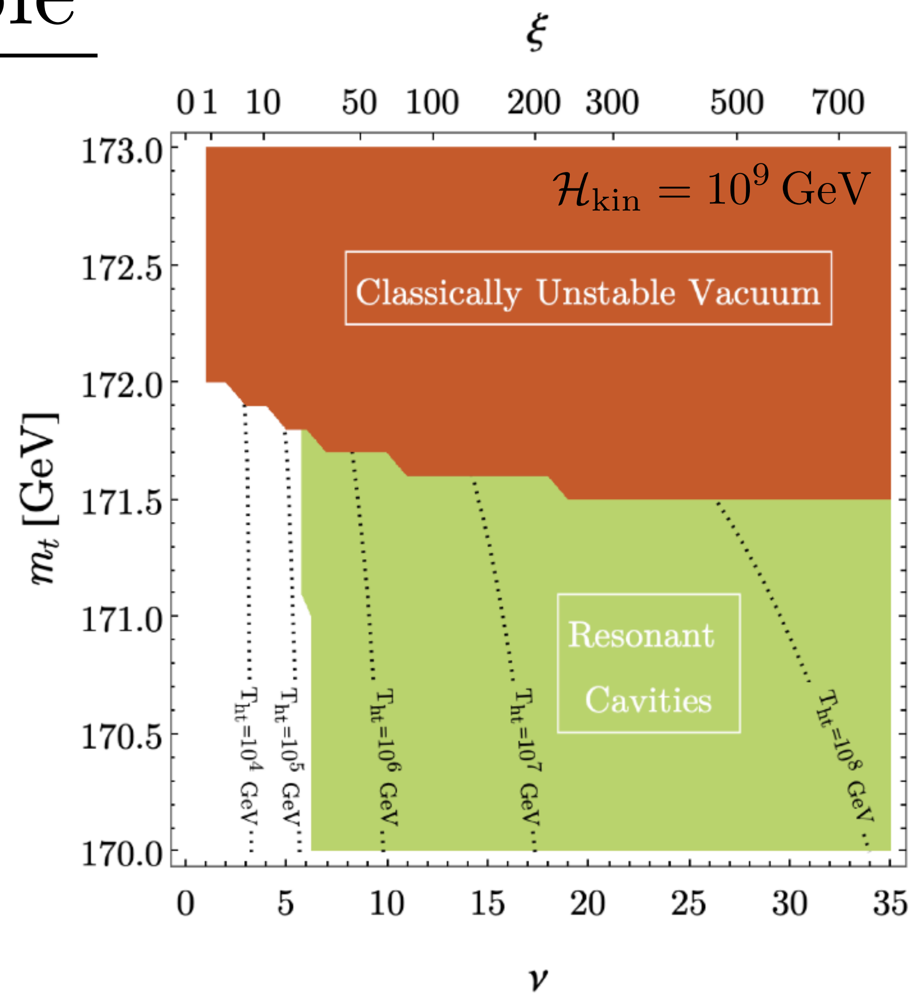
$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\nu\rho}(x) \frac{dx^\nu}{d\tau} \frac{dx^\rho}{d\tau} = 0$$





Potentially observable





5T external magnetic field, one-meter long cavity with a 5m radius

arXiv:2203.15668 [gr-qc] (Phys. Rev. D 108, 124009)

PRELIMINARY

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 10^9 GeV.
- Potential gravitational waves signatures

Ευχαριστώ!

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

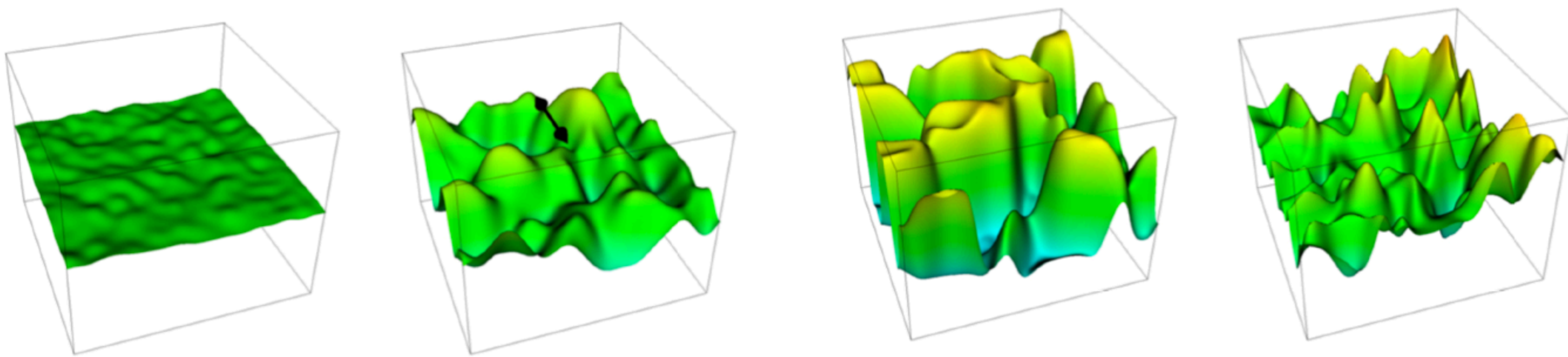
7. The rise and fall of the Standard-Model Higgs: electroweak vacuum stability during kination.
   G. Laverda, J. Rubio, JHEP 05 (2024) 339

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

BACKUP SLIDES

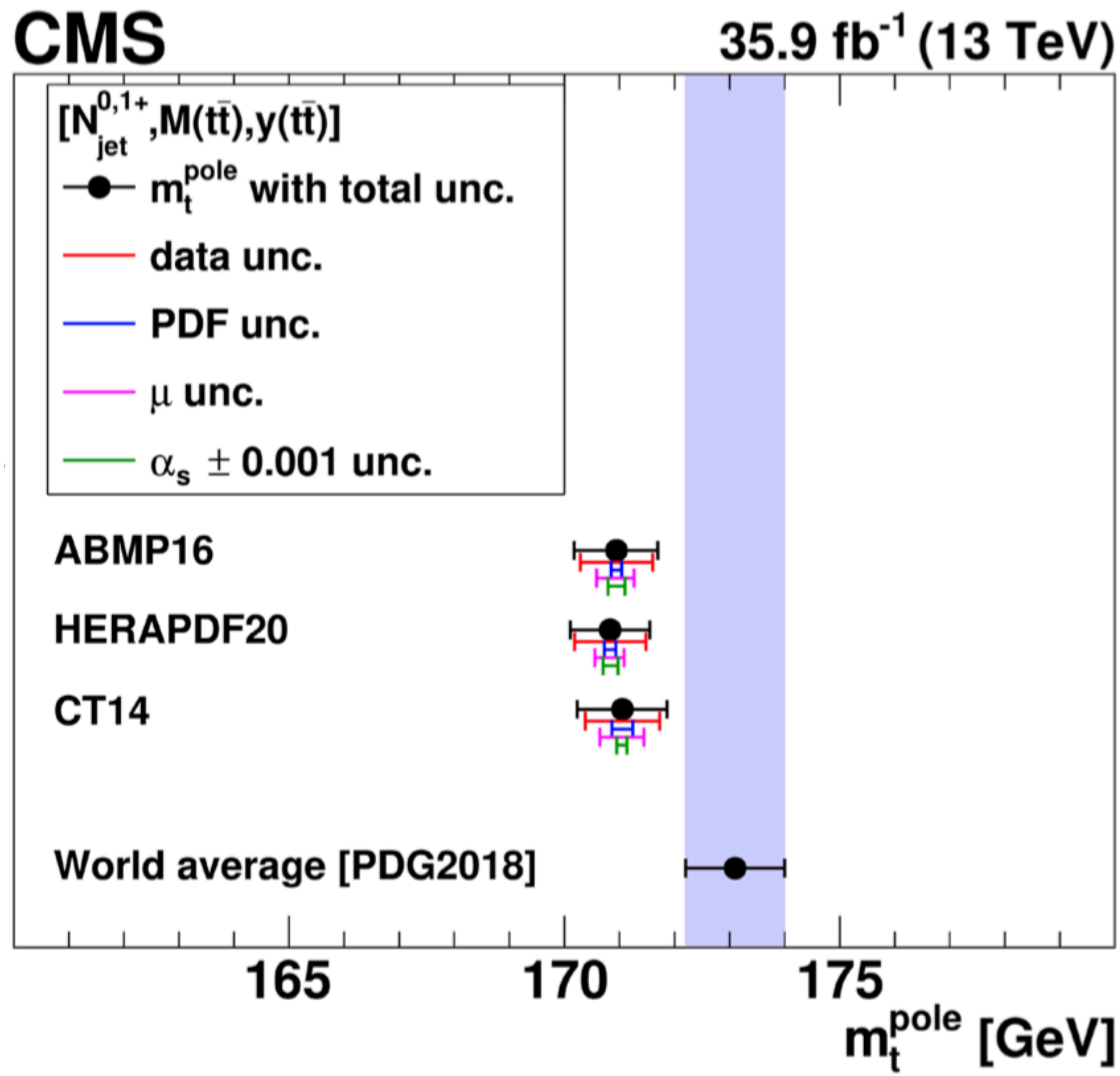
Hubble-induced phase transitions

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



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

Top mass measurements



BACK

Inverse Gertsenshtein effect, Sec. 4.2.2		
GW-OSQAR II (built) [306]	$(2.7 - 14) \cdot 10^{14}$ Hz	$h_{c,n,\mathrm{sto}} \simeq 8 \cdot 10^{-26}$
GW-CAST (built) [306]	$(5 - 12) \cdot 10^{18}$ Hz	$h_{c,n,\mathrm{sto}} \simeq 7 \cdot 10^{-28}$
GW-ALPs II (devised) [306]	$\sim 10^{15}$ Hz	$h_{c,n,\mathrm{sto}} \simeq 2.8 \cdot 10^{-30}$
Resonant polarization rotation, Sec. 4.2.4 [317]		
Cruise's detector (devised) [318]	$(0.1 - 10^5)$ GHz	$h_{0,n,\mathrm{mono}} \simeq 10^{-18}$
Cruise & Ingley's detector (prototype) [319, 320]	100 MHz	$8.9 \cdot 10^{-14}$
Enhanced magnetic conversion (theory), Sec. 4.2.5 [324]	~ 10 GHz	$h_{c,n,\mathrm{sto}} \simeq 10^{-30} - 10^{-26}$
Bulk acoustic wave resonators (built), Sec. 4.2.6 [330, 331]	(MHz – GHz)	$4.2 \cdot 10^{-21} - 2.4 \cdot 10^{-20}$
Superconducting rings, (theory), Sec. 4.2.7 [332, 333]	10 GHz	$h_{0,n,\mathrm{mono}} \simeq 10^{-31}$
Microwave cavities, Sec. 4.2.8		
Caves' detector (devised) [335]	500 Hz	$h \simeq 2 \cdot 10^{-21}$
Reece's 1st detector (built) [336]	1 MHz	$h \simeq 4 \cdot 10^{-17}$
Reece's 2nd detector (built) [337]	10 GHz	$h \simeq 6 \cdot 10^{-14}$
Pegoraro's detector (devised) [338]	$(1 - 10)$ GHz	$h \simeq 10^{-23}$
Graviton-magnon resonance (theory), Sec. 4.2.9 [339]	$(8 - 14)$ GHz	$1.1 \cdot 10^{-12} - 1.3 \cdot 10^{-13}$