Imperial College London

Electroweak Vacuum Stability in the Early Universe

Arttu Rajantie

HEP 2019, Athens, Greece

17 April 2019

In collaboration with:
Daniel Figueroa, Matti Herranen, Andreas Mantziris,
Tommi Markkanen, Sami Nurmi, Stephen Stopyra, Francisco Torrenti

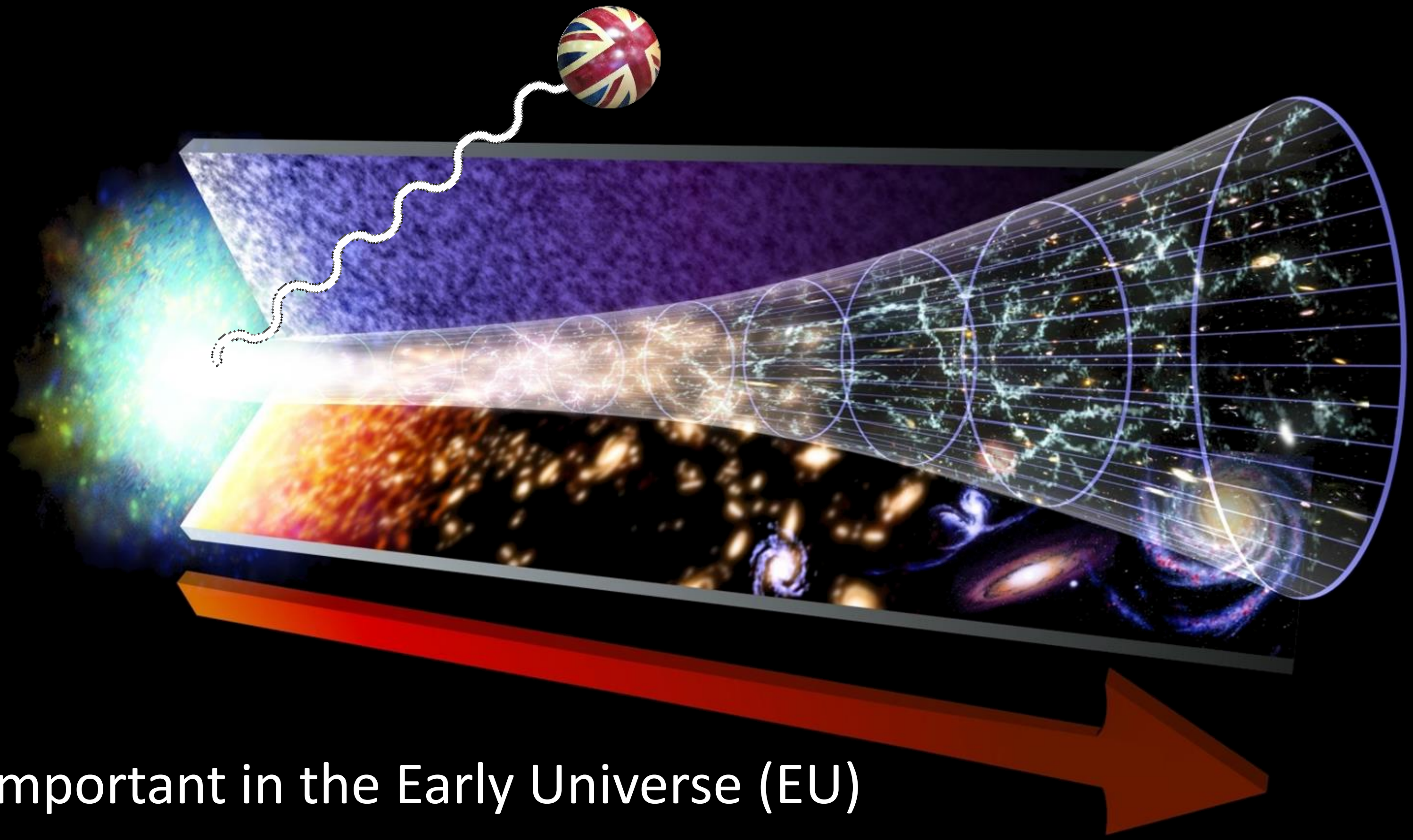
Imperial College London

Based on:

- Herranen, Markkanen, Nurmi & AR, PRL113 (2014) 211102
- Herranen, Markkanen, Nurmi & AR, PRL115 (2015) 241301
- AR & Stopyra, PRD95 (2017) 025008
- AR & Stopyra, PRD97 (2018) 025012
- Figueroa, AR & Torrenti, PRD98 (2018) 023532
- Markkanen, Nurmi, AR & Stopyra, JHEP 1806 (2018) 040
- Markkanen, AR & Stopyra, Front.Astron.Space Sci. 5 (2018) 40

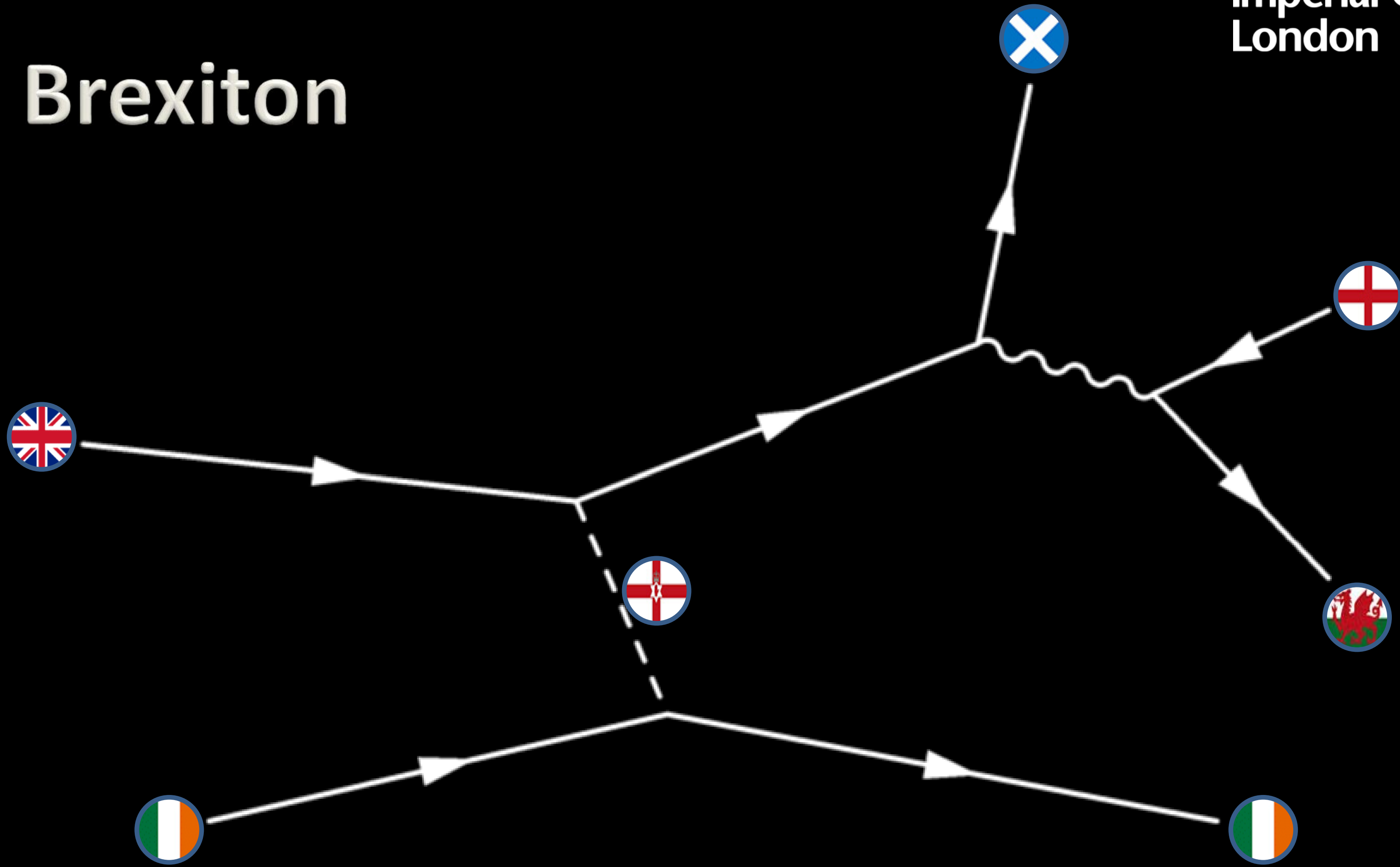
Imperial College London

Brexiton



- Important in the Early Universe (EU)
- Decouples from other fields and turns into a weakly interacting and slowly decaying spectator

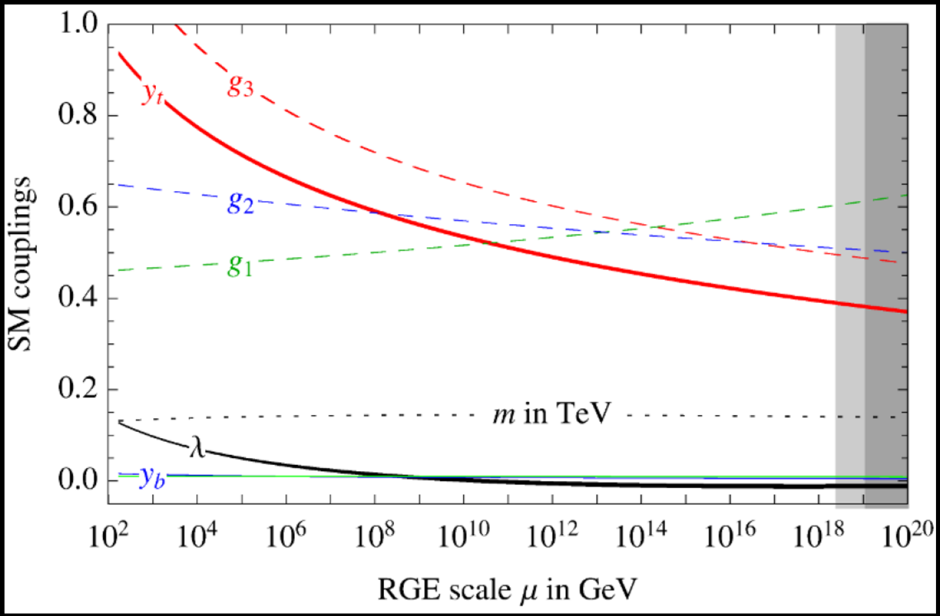
Brexiton



- Decays due to interactions

The Standard Model

- All renormalisable terms allowed by symmetries in Minkowski space
- 19 parameters –
  all have been measured
- Can be extrapolated all the way to Planck scale
- For central experimental values $M_{\mathrm{H}} = 125.18\ \mathrm{GeV}$, $M_{\mathrm{t}} = 173.1\ \mathrm{GeV}$
  - λ becomes negative at $\mu_\Lambda \approx 9.9 \times 10^9\ \mathrm{GeV}$
  - Minimum value $\lambda_{\min} \approx -0.015$ at $\mu_{\min} \approx 2.8 \times 10^{17}\ \mathrm{GeV}$



(Buttazzo et al 2013)

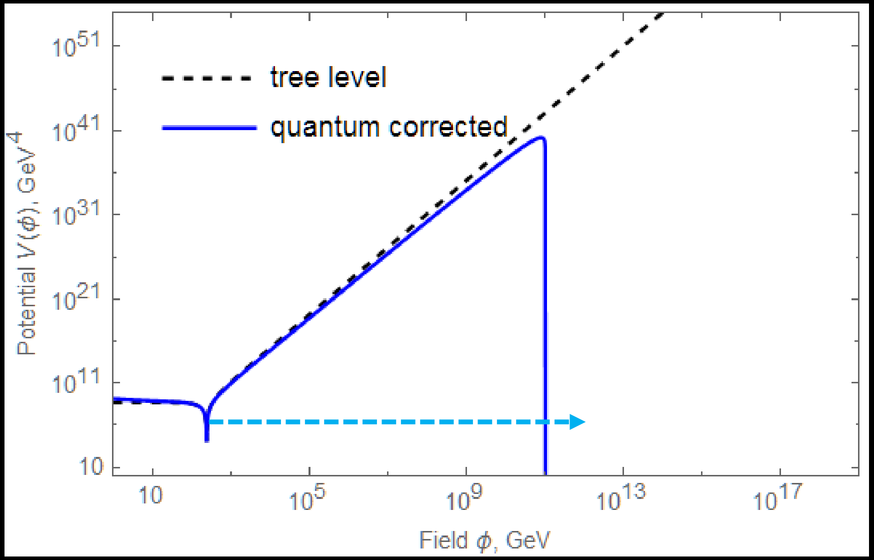
Vacuum Instability

- Higg effective potential

$$V(\phi) \approx \lambda(\phi)\phi^4$$

- Becomes negative at $\phi > \phi_c \approx 10^{10}\mathrm{GeV}$
- True vacuum at Planck scale?
- Current vacuum metastable against quantum tunnelling
- Barrier at

$\phi_{\mathrm{bar}} \approx 4.6 \times 10^{10}\ \mathrm{GeV}$, height $V(\phi_{\mathrm{bar}}) \approx (4.3 \times 10^{9}\ \mathrm{GeV})^4$

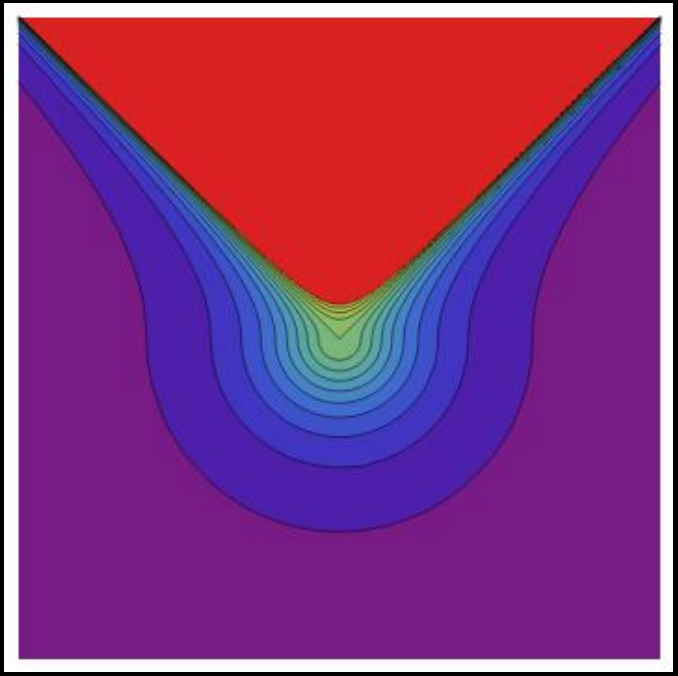


Tunneling Rate

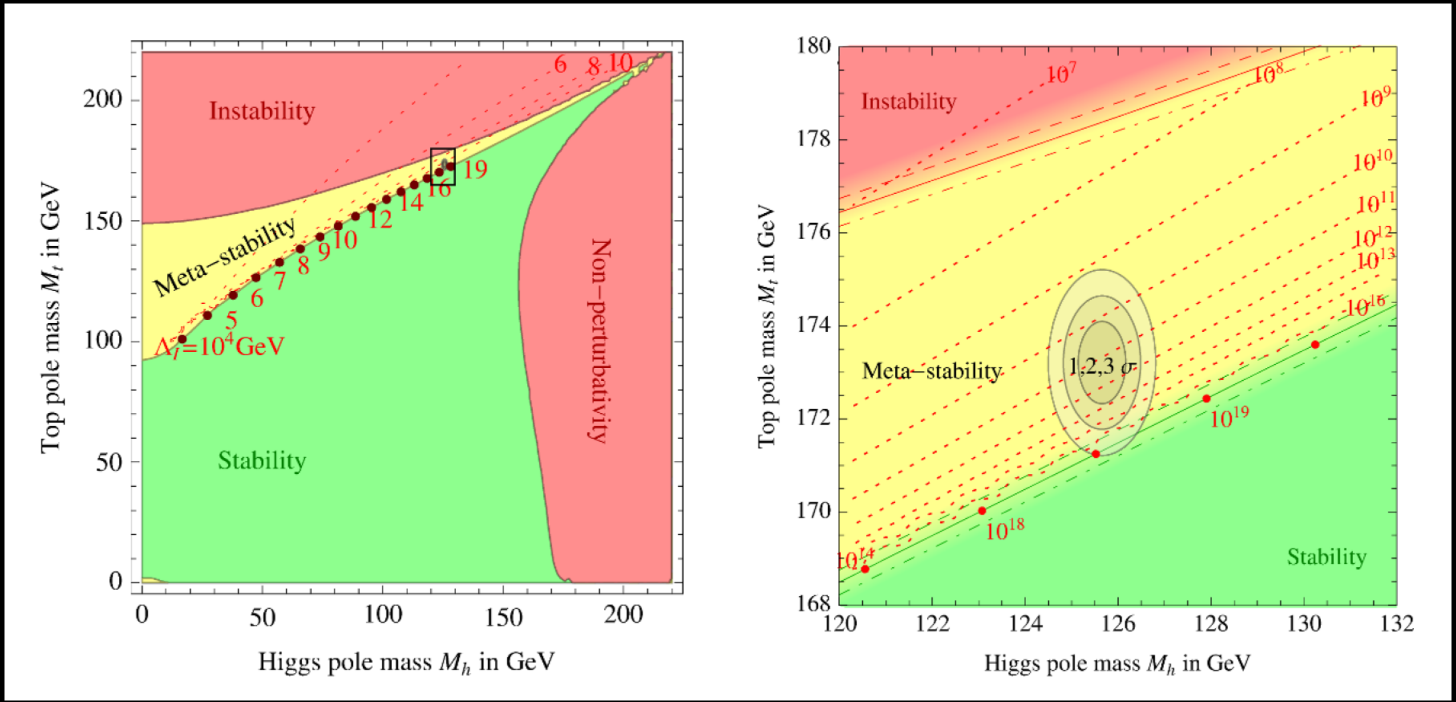
- Bubble nucleation rate:
  - $\Gamma \sim e^{-B}$, where
  - $B =$ "bounce" action (Coleman 1977)
  - Solution of Euclidean eoms
- Constant $\lambda < 0$:

$$\phi(r) = \sqrt{\frac{2}{|\lambda|}} \frac{2R}{r^2+R^2}$$

- Action $B = \dfrac{8\pi^2}{3|\lambda|}$
- When λ runs, $B \approx \dfrac{8\pi^2}{3|\lambda_{\mathrm{min}}|} \approx 1800$ and $\Gamma \sim \mu_{\mathrm{min}}^4 e^{-B}$
- Depends sensitively on Higgs and top masses



Instability Bounds



(Buttazzo et al. 2013)

- Number of bubbles in past lightcone: $\langle \mathcal{N} \rangle \approx 0.125\Gamma/H_0^4$
- If $\langle \mathcal{N} \rangle \ll 1$, no contradiction – Metastable

Imperial College London

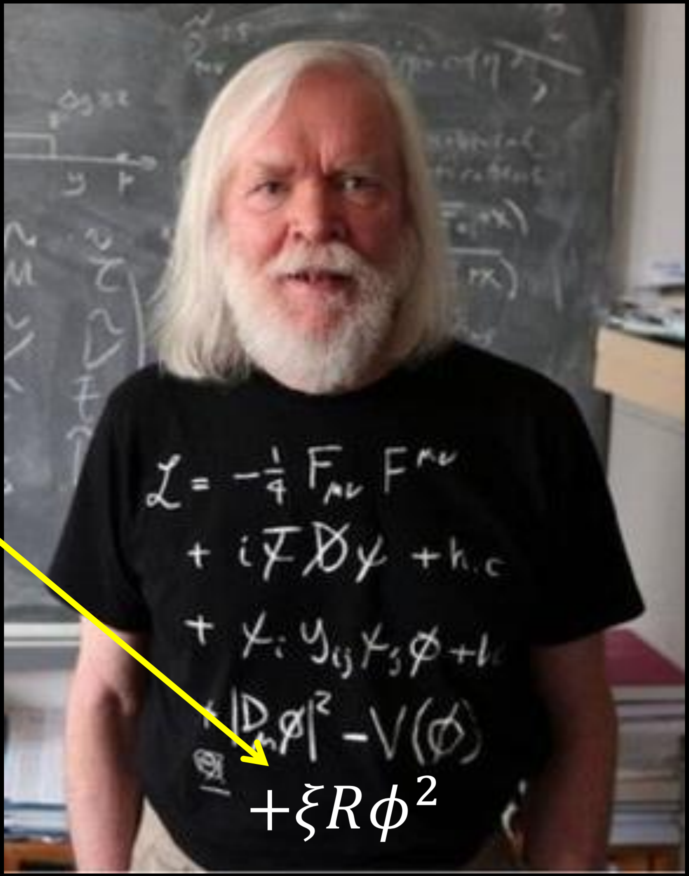
Higgs-Curvature Coupling

- Curved spacetime:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \xi R \phi^\dagger \phi$$

(Chernikov&Tagirov 1968)

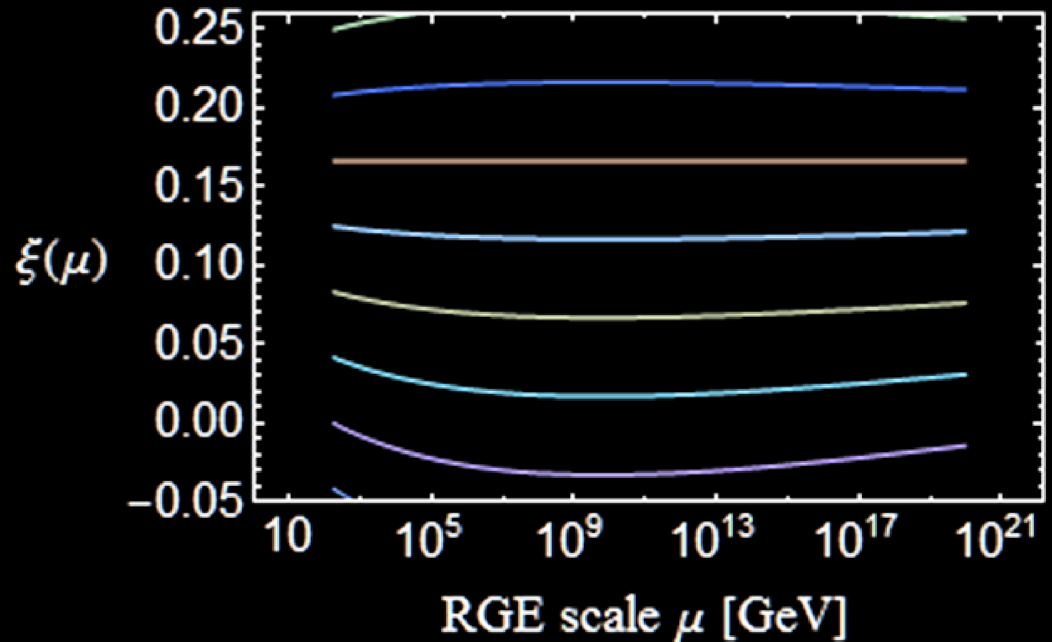
- Symmetries allow one more renormalisable term: Higgs-curvature coupling ξ
- Required for renormalisability, runs with energy – Cannot be set to zero!
- Last unknown parameter in the Standard Model



Running ξ

$$\mu\frac{d\xi}{d\mu}=\left(\xi-\frac{1}{6}\right)\frac{12\lambda+6y_t^2-\frac{3}{2}g'^2-\frac{9}{2}g^2}{16\pi^2}$$

- Becomes negative if $\xi_{\rm EW}=0$
- Conformal value $\xi=1/6$ RG invariant at 1 loop but not beyond



Measuring ξ

- Curved spacetime:

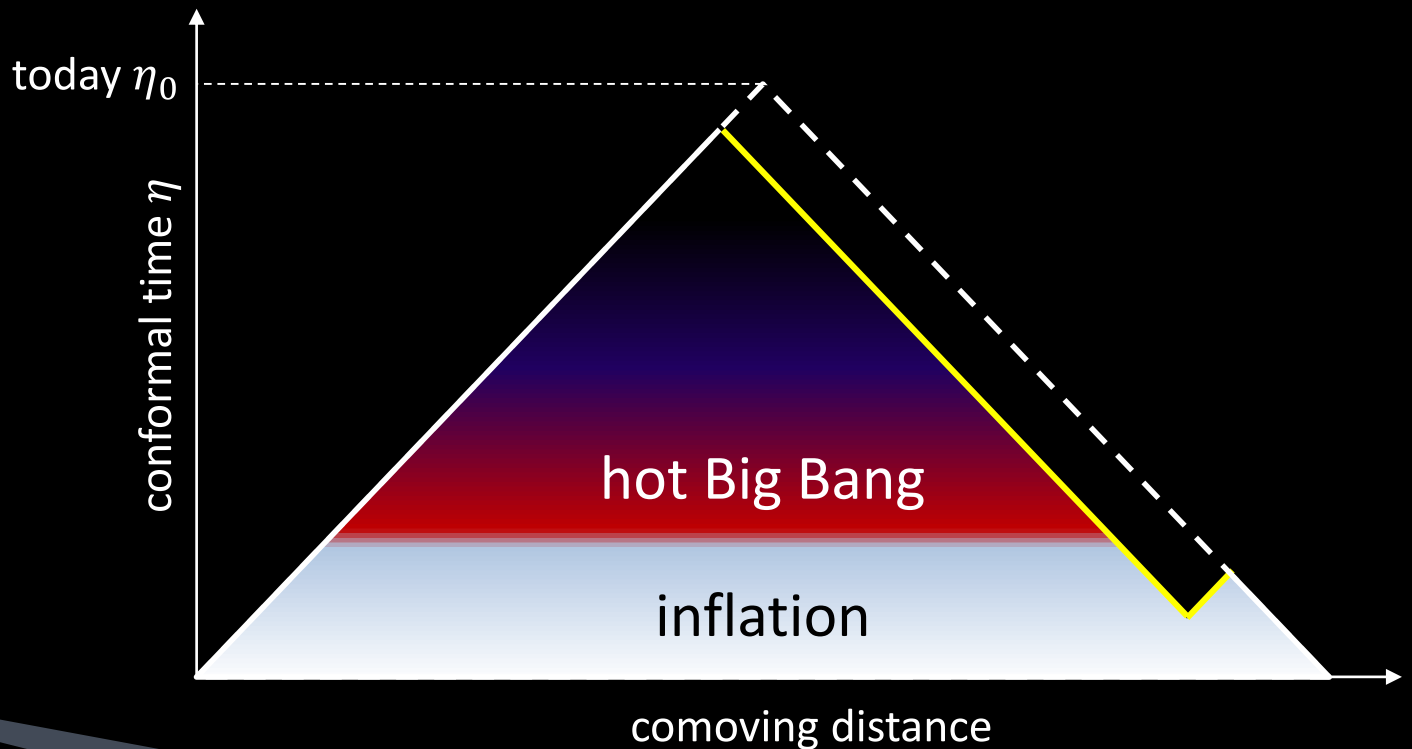
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \xi R \phi^\dagger \phi$$

- Ricci scalar R very small today
  $\Rightarrow$ Difficult to measure ξ
- Colliders: Suppresses Higgs couplings (Atkins&Calmet 2012)
  - LHC Bound $|\xi| \lesssim 2.6 \times 10^{15}$
  - Future (?) ILC: $|\xi| \lesssim 4 \times 10^{14}$
- In contrast, R was high in the early Universe

Past Light Cone

- Expected number of bubbles ($d\eta = dt/a$):

$$\langle \mathcal{N} \rangle = \frac{4\pi}{3} \int^{\eta_0} d\eta \, a(\eta)^4 (\eta_0 - \eta)^3 \Gamma(\eta)$$



Early Universe

- Assume:
  - Light, subdominant Higgs
  - Inflaton decoupled from the Higgs
- Effective Higgs mass term $m_{\mathrm{eff}}^2(t) = m_{\mathrm{H}}^2 + \xi R(t)$
- Ricci scalar in FRW spacetime:

$$R = 6\left(\frac{\dot{a}^2}{a^2} + \frac{\ddot{a}}{a}\right) = 3(1-3w)H^2$$

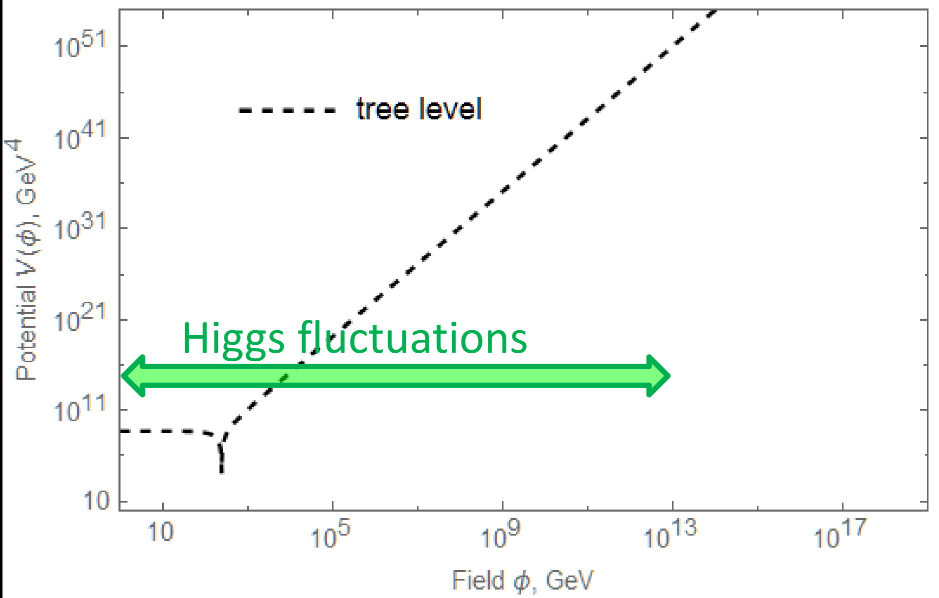
  - Radiation dominated $w = 1/3$ $R = 0$
  - Matter dominated $w = 0$ $R = 3H^2$
  - Inflation / de Sitter $w = -1$ $R = 12H^2$

Higgs Fluctuations from Inflation

- Inflation: $H \lesssim 9 \times 10^{13}$ GeV (Planck+BICEP2 2015)
- Equilibrium field distribution (Starobinsky&Yokoyama 1994)

$$P(\phi) \propto \exp\left[-\frac{8\pi^2}{3H^4}V(\phi)\right]$$

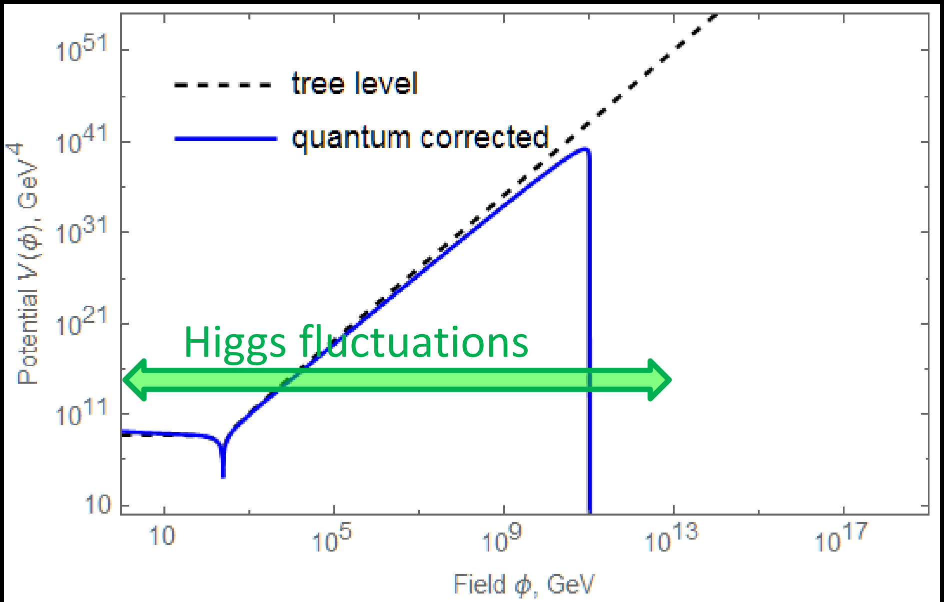
- Tree-level potential $V(\phi) = \lambda(\phi^2 - v^2)^2$
- Nearly scale-invariant fluctuations with amplitude $\phi \sim \lambda^{-1/4} H$



Imperial College London

Higgs Fluctuations from Inflation

- Equilibrium $P(\phi) \propto \exp\left[-\frac{8\pi^2}{3H^4}V(\phi)\right]$
- Running λ:
  Fluctuations take the Higgs over the barrier if $H \gtrsim \phi_{\text{bar}} \approx 10^{10}\text{GeV}$
  (Espinosa et al. 2008;
  Lebedev&Westphal 2013;
  Kobakhidze&Spencer-Smith 2013;
  Fairbairn&Hogan 2014;
  Hook et al. 2014)
- Does this imply $H \lesssim 10^{10}\text{GeV}$?



Higgs During Inflation

- Inflation: Constant $R = 12H^2$
- Effective mass term
$$m_{\mathrm{eff}}^2 = m_{\mathrm{H}}^2 + \xi R = m_{\mathrm{H}}^2 + 12\xi H^2$$
- Tree level: (Espinosa et al 2008)
  - $\xi > 0$: Increases barrier height
    Makes the low-energy vacuum more stable
  - $\xi < 0$: Decreases barrier height
    Makes the low energy vacuum less stable
- H contributes to loop corrections:
  For $H \gg \phi, V(\phi) \approx \lambda(H)\phi^4$ ⇨ No barrier! (HMNR 2014)

Effective Potential in Curved Spacetime

- One-loop computation in de Sitter:

$$V_{\rm SM}^{\rm eff}(\varphi(\mu)) = -\frac{1}{2}m^2(\mu)\varphi^2(\mu) + \frac{\xi(\mu)}{2}R\varphi^2(\mu) + \frac{\lambda(\mu)}{4}\varphi^4(\mu) + V_\Lambda(\mu) - 12\kappa(\mu)H^2 + \alpha(\mu)H^4$$
$$+\frac{1}{64\pi^2}\sum_{i=1}^{31}\left\{n_i\mathcal{M}_i^4(\mu)\left[\log\left(\frac{|\mathcal{M}_i^2|}{\mu^2}\right) - d_i\right] + n_i' H^4 \log\left(\frac{|\mathcal{M}_i^2(\mu)|}{\mu^2}\right)\right\}. \quad (5.3)$$

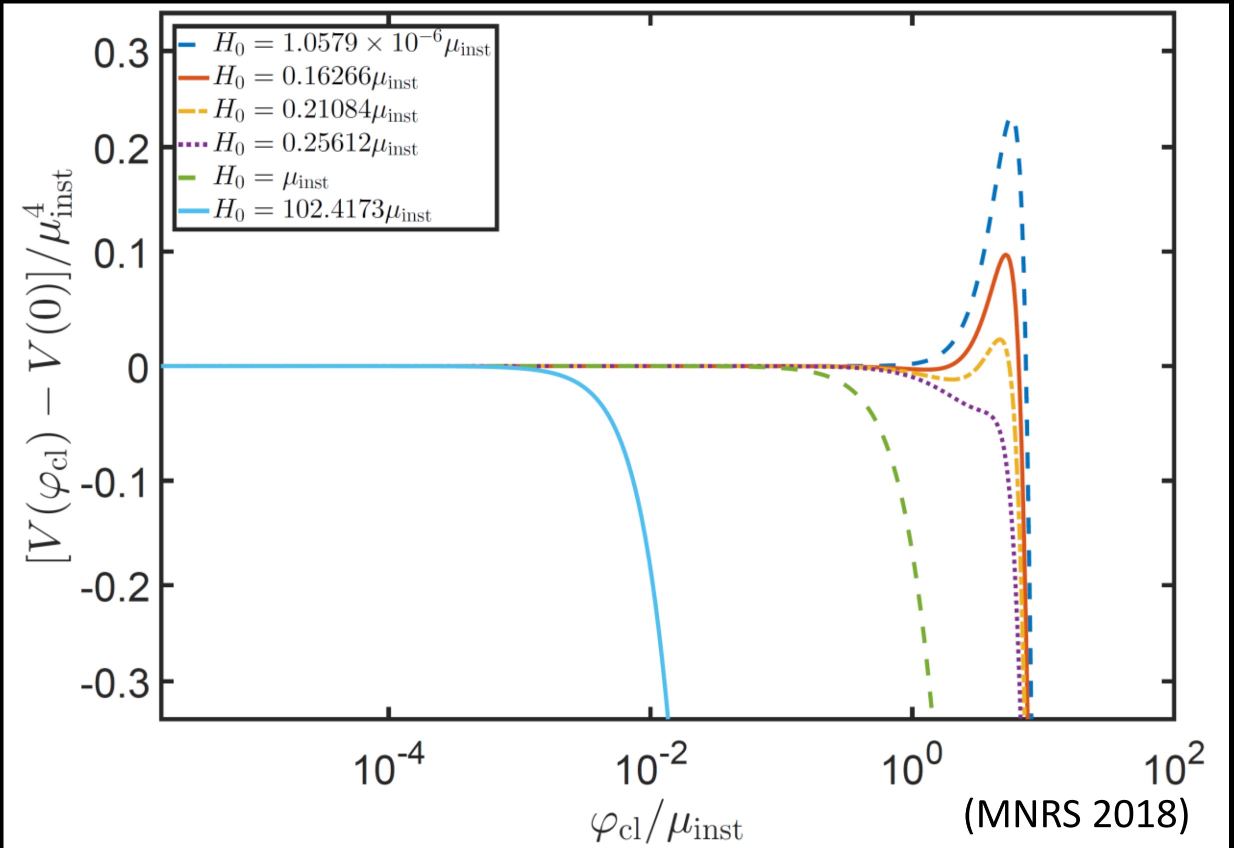
Ψ	i	n_i	d_i	n_i'	$\mathcal{M}_i^2$
$W^\pm$	1	2	3/2	−34/15	$m_W^2 + H^2$
	2	6	5/6	−34/5	$m_W^2 + H^2$
	3	−2	3/2	4/15	$m_W^2 - 2H^2$
Z^0	4	1	3/2	−17/15	$m_Z^2 + H^2$
	5	3	5/6	−17/5	$m_Z^2 + H^2$
	6	−1	3/2	2/15	$m_Z^2 - 2H^2$
q	7 − 12	−12	3/2	38/5	$m_q^2 + H^2$
l	13 − 15	−4	3/2	38/15	$m_l^2 + H^2$
h	16	1	3/2	−2/15	$m_h^2 + 12(\xi - 1/6)H^2$
χ_W	17	2	3/2	−4/15	$m_\chi^2 + \zeta_W m_W^2 + 12(\xi - 1/6)H^2$
χ_Z	18	1	3/2	−2/15	$m_\chi^2 + \zeta_Z m_Z^2 + 12(\xi - 1/6)H^2$
c_W	19	−2	3/2	4/15	$\zeta_W m_W^2 - 2H^2$
c_Z	20	−1	3/2	2/15	$\zeta_Z m_Z^2 - 2H^2$

Ψ	i	n_i	d_i	n_i'	$\mathcal{M}_i^2$
γ	21	1	3/2	−17/15	H^2
	22	3	5/6	−17/5	H^2
	23	−1	3/2	2/15	$-2H^2$
g	24	8	3/2	−136/15	H^2
	25	24	5/6	−136/5	H^2
	26	−8	3/2	16/15	$-2H^2$
ν	27 − 29	−2	3/2	19/15	H^2
c_γ	30	−1	3/2	2/15	$-2H^2$
c_g	31	−8	3/2	16/15	$-2H^2$

(MNRS 2018)

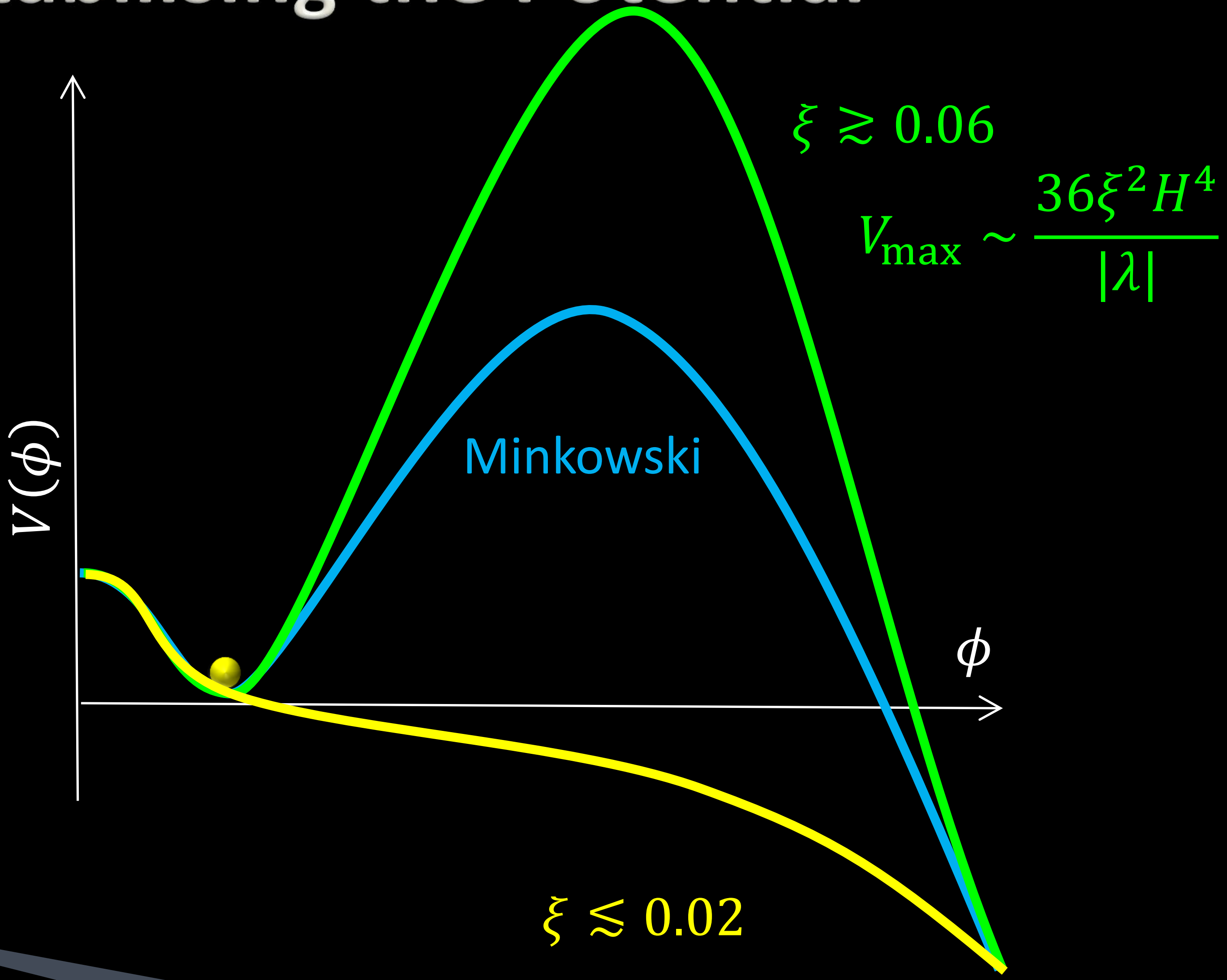
Potential in Curved Spacetime

- One-loop computation for $\xi = 0$ (in units of $\mu_{\text{inst}} \approx 6.6 \times 10^9$ GeV)

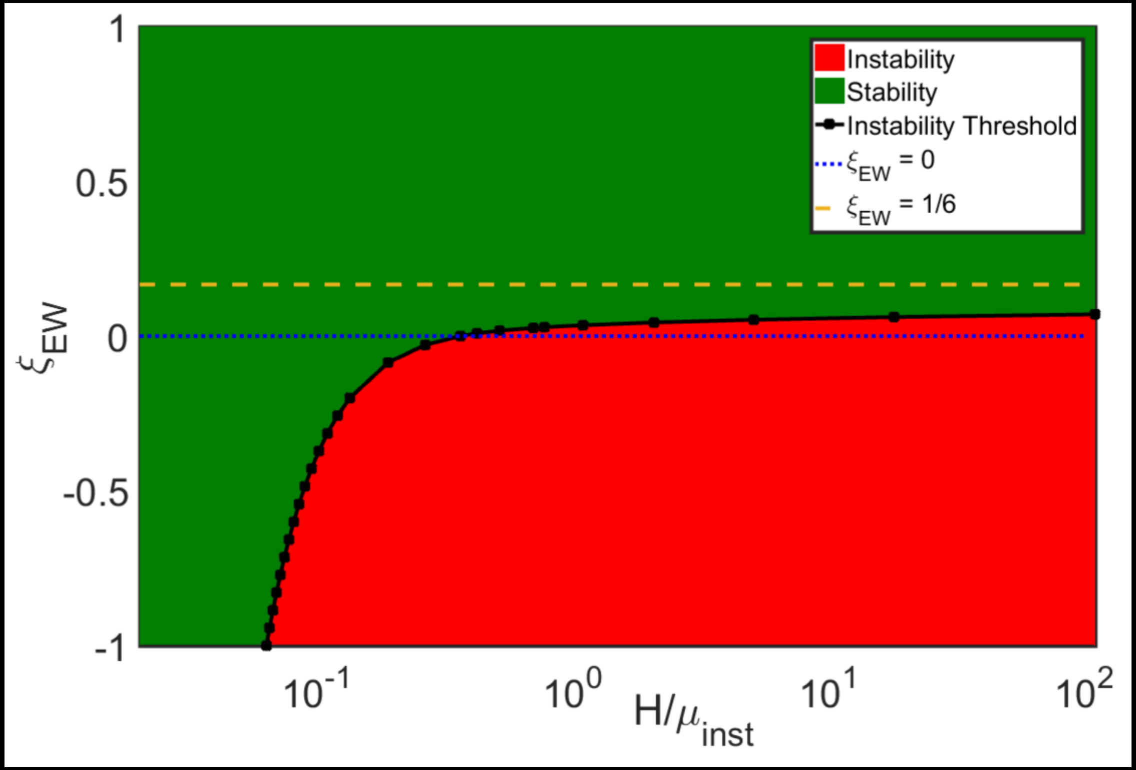


(MNRS 2018)

(De-)Stabilising the Potential



(De)Stabilising the Potential



(MNRS 2018)

- If $H \gtrsim \mu_{\text{inst}} = 6.6 \times 10^9 \text{GeV}$ and there is no new physics, vacuum stability during inflation requires $\xi \gtrsim 0$

Imperial College London

Time-Dependent Hubble Rate

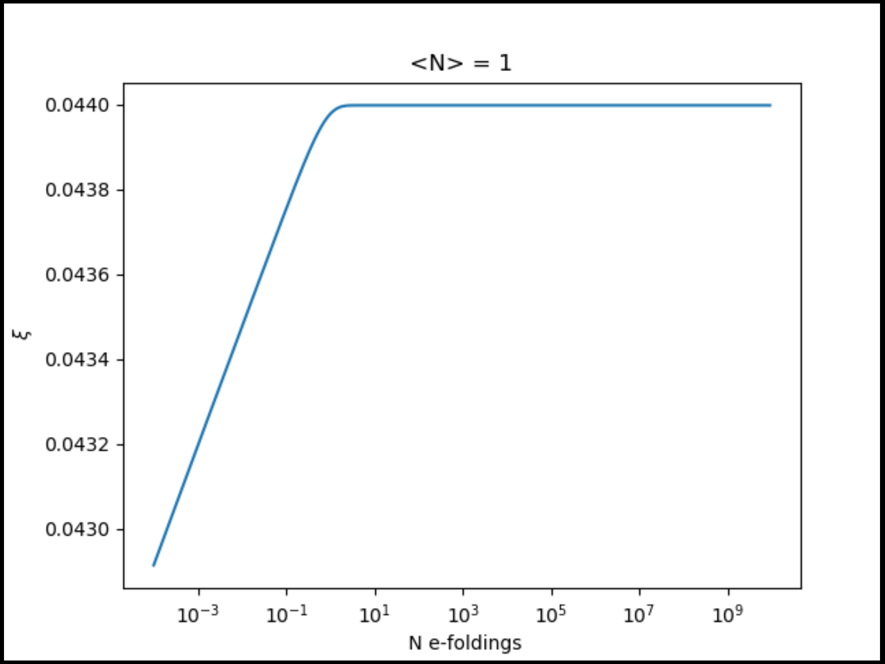
- In real inflationary models, H depends on time: Affects decay rate Γ and volume of past light cone
- Simplest case: Quadratic chaotic inflation

$$V(\chi) = \frac{1}{2} m^2 \chi^2$$

- Most bubbles produced near the end of inflation
- Stability requires

$$\xi \gtrsim 0.044$$

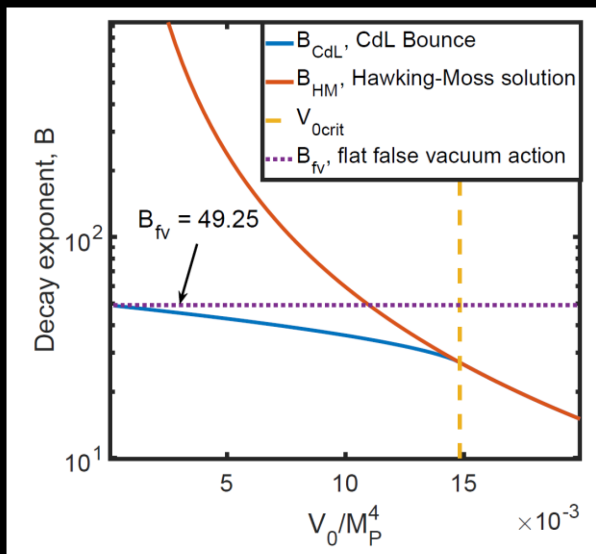
(Mantziris, Markkanen & AR, in progress)



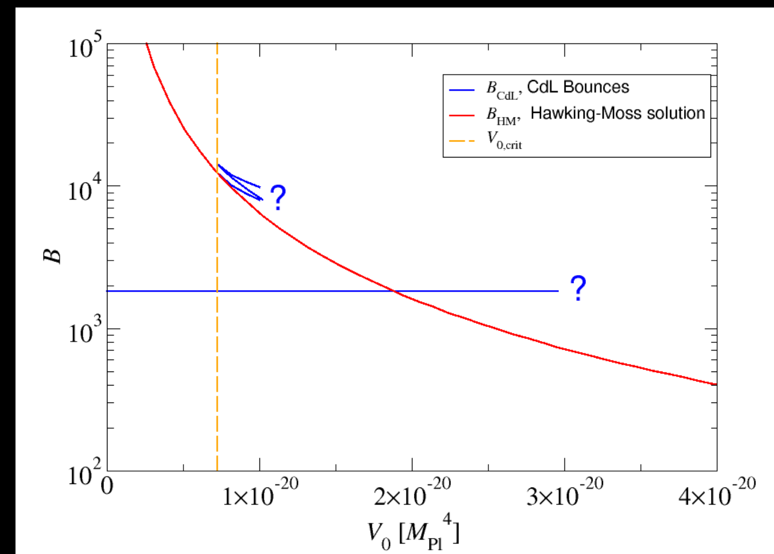
Imperial College London

Quantum Tunneling

Toy model potential

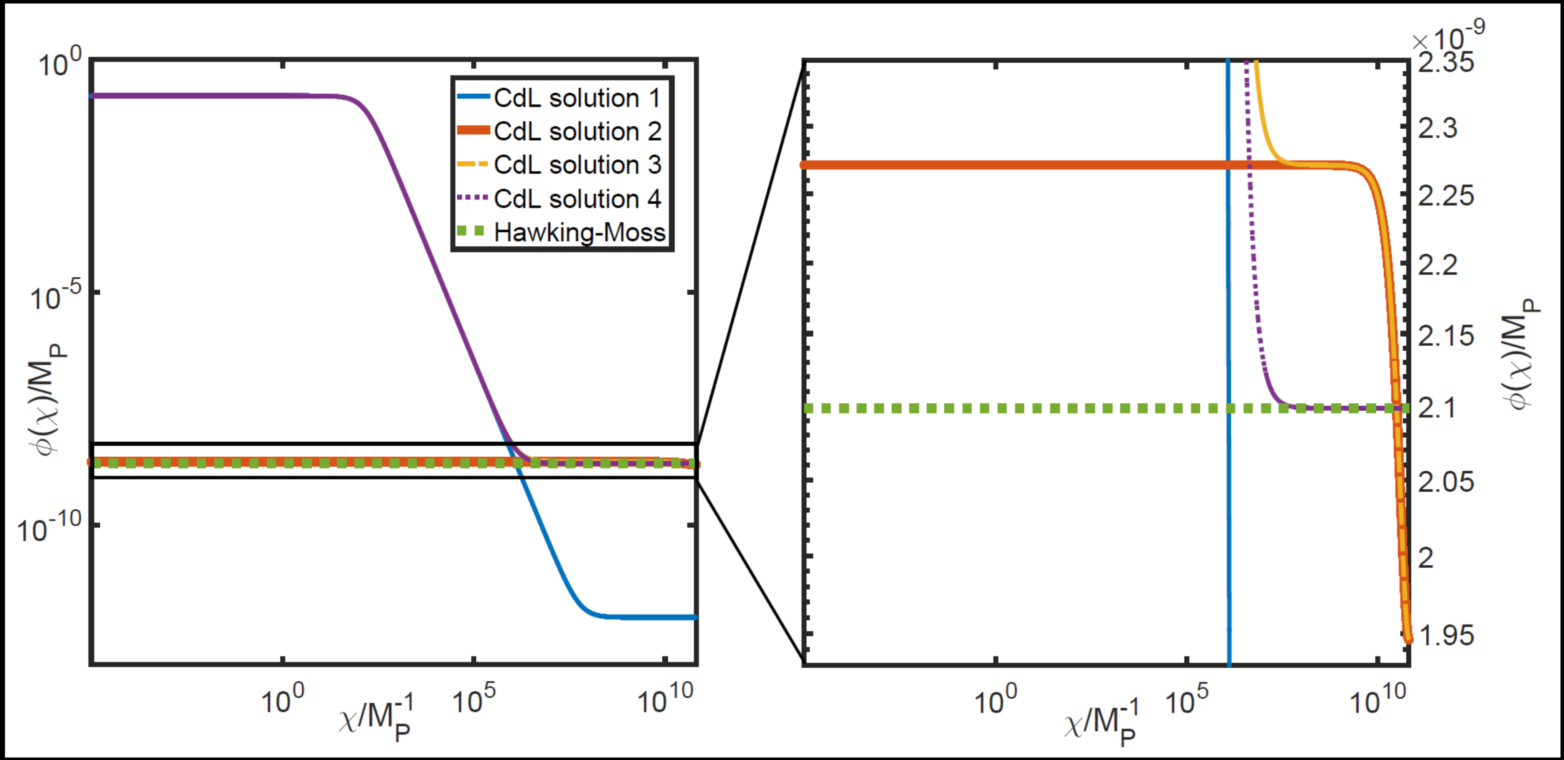


Standard Model potential



- Multiple coexisting solutions (AR&Stopyra, PRD 2018)
- Tunnelling rate $\Gamma \sim e^{-B}$ nearly constant until Hawking-Moss starts to dominate

Multiple Solutions



(AR&Stopyra, PRD 2018)

End of Inflation

- Reheating: Inflation ($R = 12H^2$) → radiation ($R = 0$)

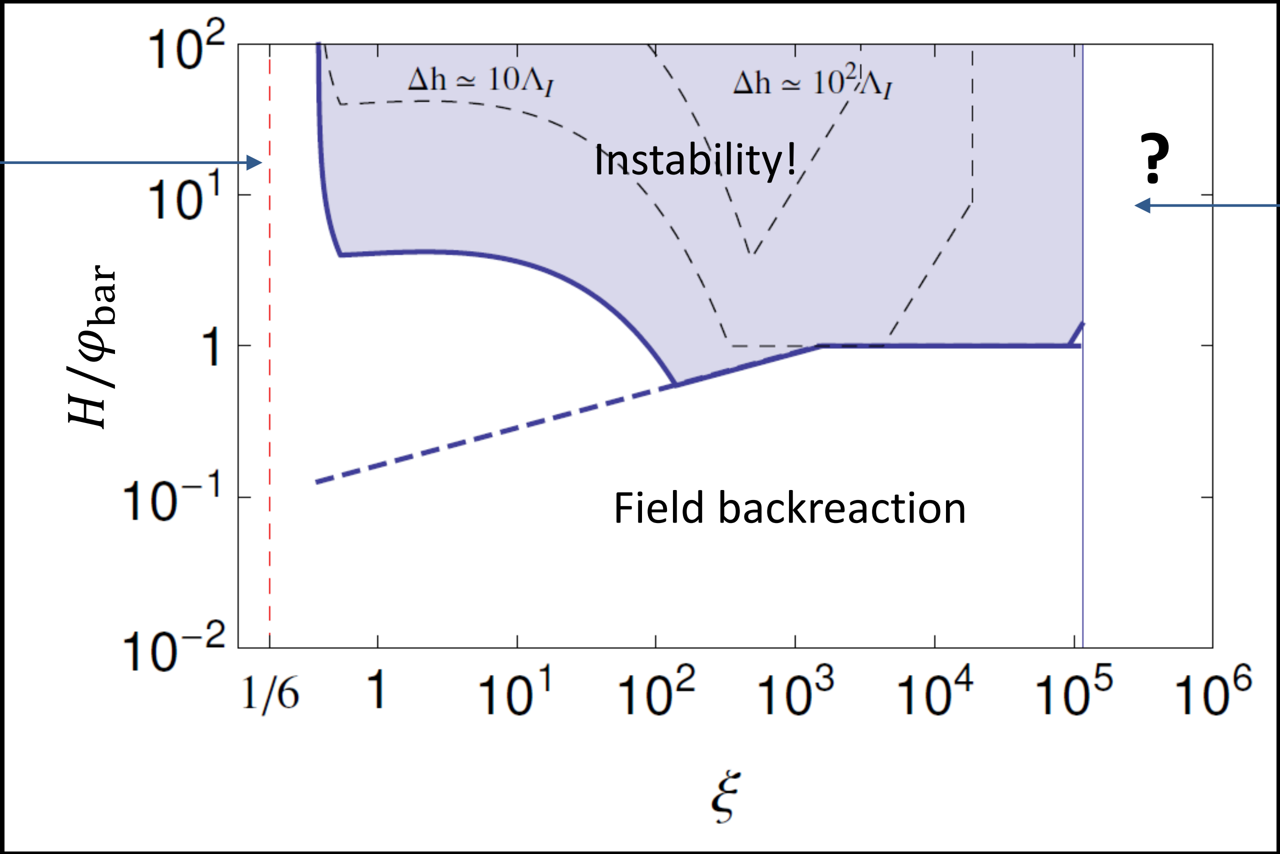
$$R(t) = \frac{2m^2\chi^2 - \dot{\chi}^2}{M_{\mathrm{Pl}}^2}$$

- Effective Higgs mass $m_{\mathrm{eff}}^2 = m_{\mathrm{H}}^2 + \xi R$ oscillates:
  - Parametric resonance ("Geometric preheating") (Bassett&Liberati 1998, Tsujikawa et al. 1999)
- R goes negative when $\chi \sim 0$
  - If $\xi > 0$, Higgs becomes tachyonic (HMNR 2015)
  - Exponential amplification

$$\langle\phi^2\rangle_H \sim \frac{2}{3\sqrt{3}\xi}\left(\frac{H}{2\pi}\right)^2 e^{\frac{2\sqrt{\xi}\chi_{\mathrm{ini}}}{M_{\mathrm{Pl}}}} \sim \frac{H^2}{\xi} e^{2\sqrt{\xi}}$$

Vacuum Decay at the End of Inflation

Not enough growth

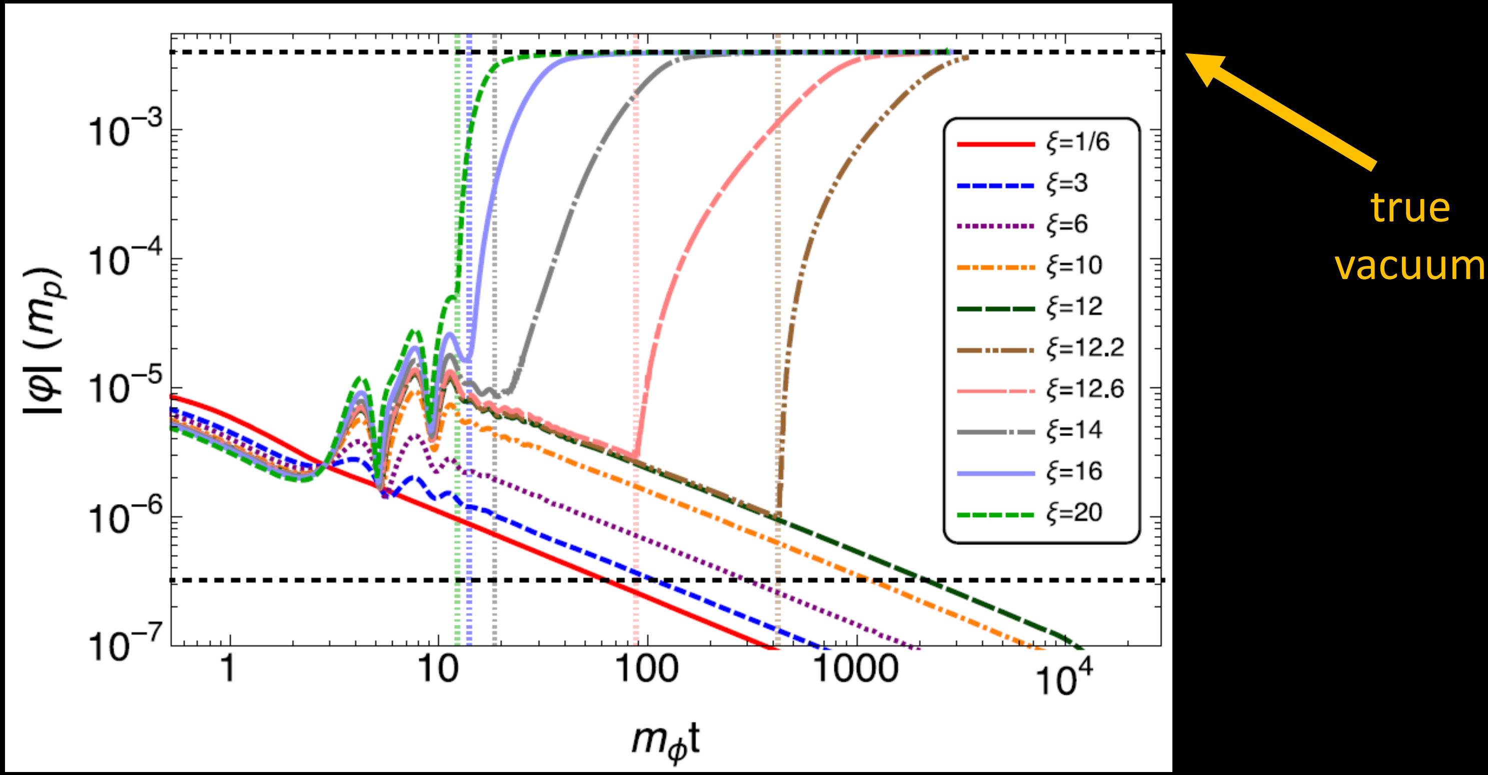


?

Becomes nonlinear

(HMNR 2015)

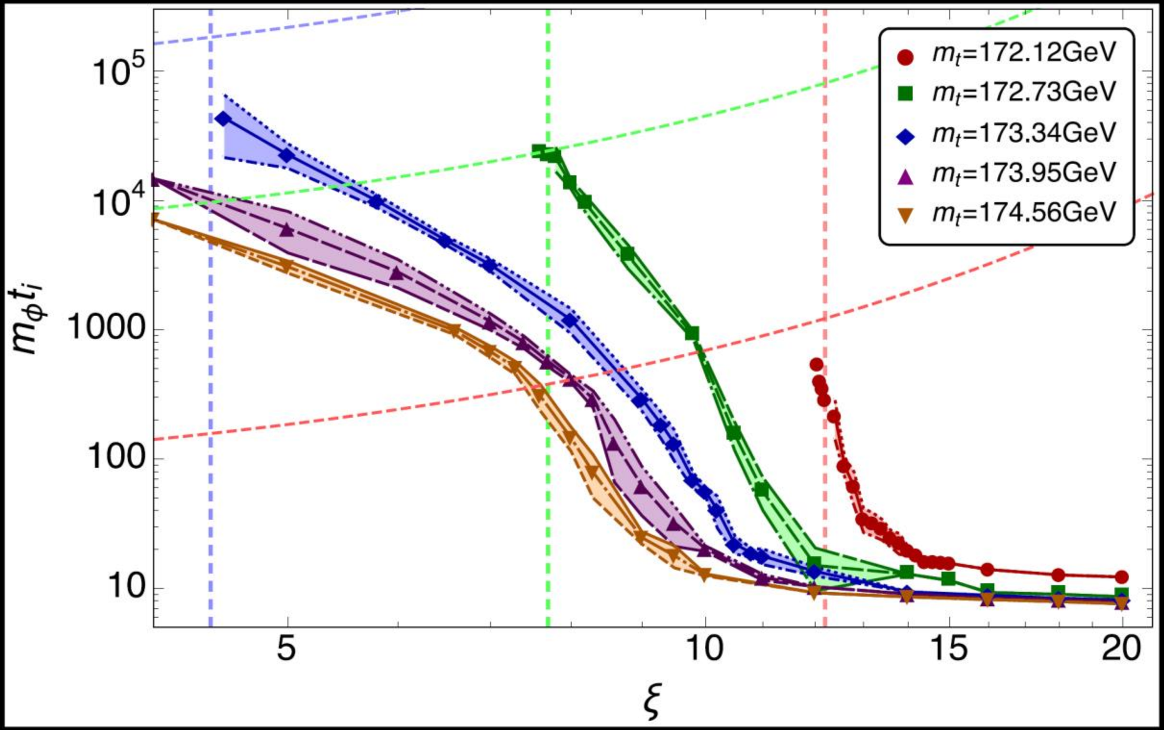
Lattice Simulations



Figueroa, AR & Torrenti, 2018

- $V(\chi) = \frac{1}{2}m^2\chi^2, M_{\text{top}} = 172.12\ \text{GeV}$

Instability Time



Figueroa, AR & Torrenti, 2018

- Stability depends on top mass and speed of reheating
- $M_{\mathrm{top}} = 173.34\ \mathrm{GeV}$: vacuum decay before $mt = 100$ if $\xi \gtrsim 9$

Constraints on ξ

- Minimal scenario:
  Standard Model + $m^2\chi^2$ chaotic inflation,
  no direct coupling to inflaton

$$0.044 \lesssim \xi \lesssim 9$$

- 15 orders of magnitude stronger than the LHC bound

$$|\xi| \lesssim 2.6 \times 10^{15}$$

- Caveats:
  - Assumes no direct coupling to inflaton
    – Would still need $|\xi| \lesssim O(1)$
  - Assumes no new physics
    – Could stabilise potential altogether
  - Assumes high scale inflation $H \gtrsim 10^9\ \mathrm{GeV}$