HIGGS INFLATION

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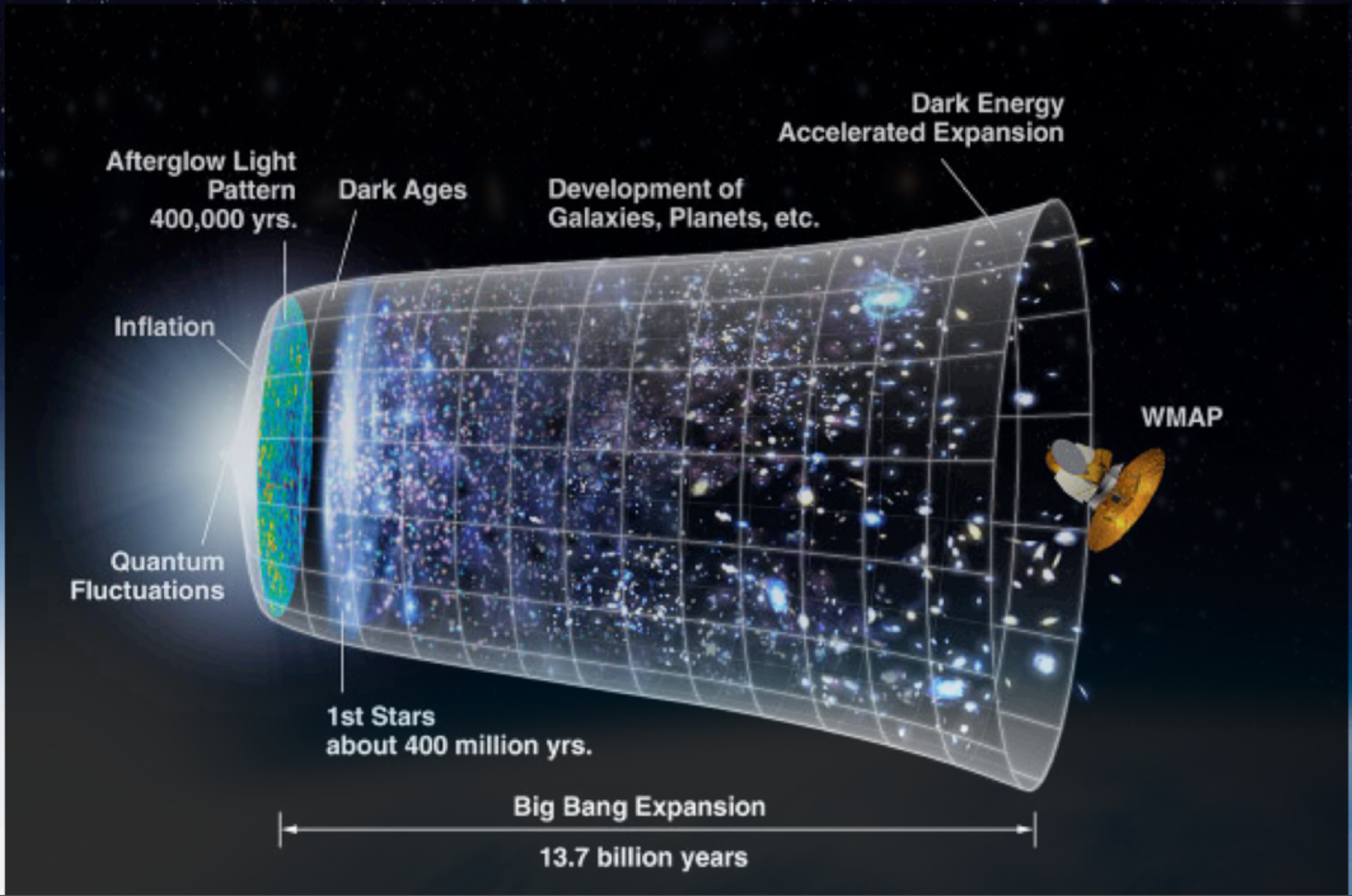
Hot Big Bang theory has loopholes:

- Horizon problem $E(T_0) = 10^{17}\ \text{GeV} \Longrightarrow \begin{cases} 10^{83} & \text{acausal regions} \\ 10^{55} & \text{fine tuning} \end{cases}$
- Flatness problem $E(T_0) = 1\ \text{MeV} \Longrightarrow \begin{cases} 10^{22} & \text{acausal regions} \\ 10^{15} & \text{fine tuning} \end{cases}$



Inflation in a nutshell

Ordinary matter decelerates the Universe

$$\left(\frac{\dot a}{a}\right)^2 = \frac{\kappa}{3}\rho$$

$$\frac{\ddot a}{a} = -\frac{\kappa}{6}\underbrace{(\rho + 3P)}_{\geq 0 \text{ SEC}}$$

Friedmann equations in GR

How to violate SEC?

- Cosmological constant: $P = -\rho$ ... but inflation never ends!

- Scalar field: $S = \int d^4x\sqrt{-g}\left[\frac{R}{2\kappa} + \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$

$$\rho = \frac{\dot\phi}{2} + V(\phi), \quad P = \frac{\dot\phi}{2} - V(\phi)$$

$$H^2 = \frac{\kappa}{3}\left(\frac{\dot\phi}{2} + V(\phi)\right) \simeq \text{ const when } \begin{cases} \dot\phi^2 \ll V(\phi) \\ V(\phi) \simeq \text{ const} \end{cases}$$

$$a(t) \sim e^{Ht}$$

Inflation and Modification of GR

Minimally coupled $$L = \sqrt{-g}\frac{R}{2\kappa} + L(\phi) + L_{\rm m}(g_{\mu\nu}, \Psi)$$

Non-M coupled, J-frame $$L_J = \sqrt{-g}f(\phi)\frac{R}{2\kappa} + L_J(\phi) + L_{\rm m}(g_{\mu\nu}, \Psi)$$

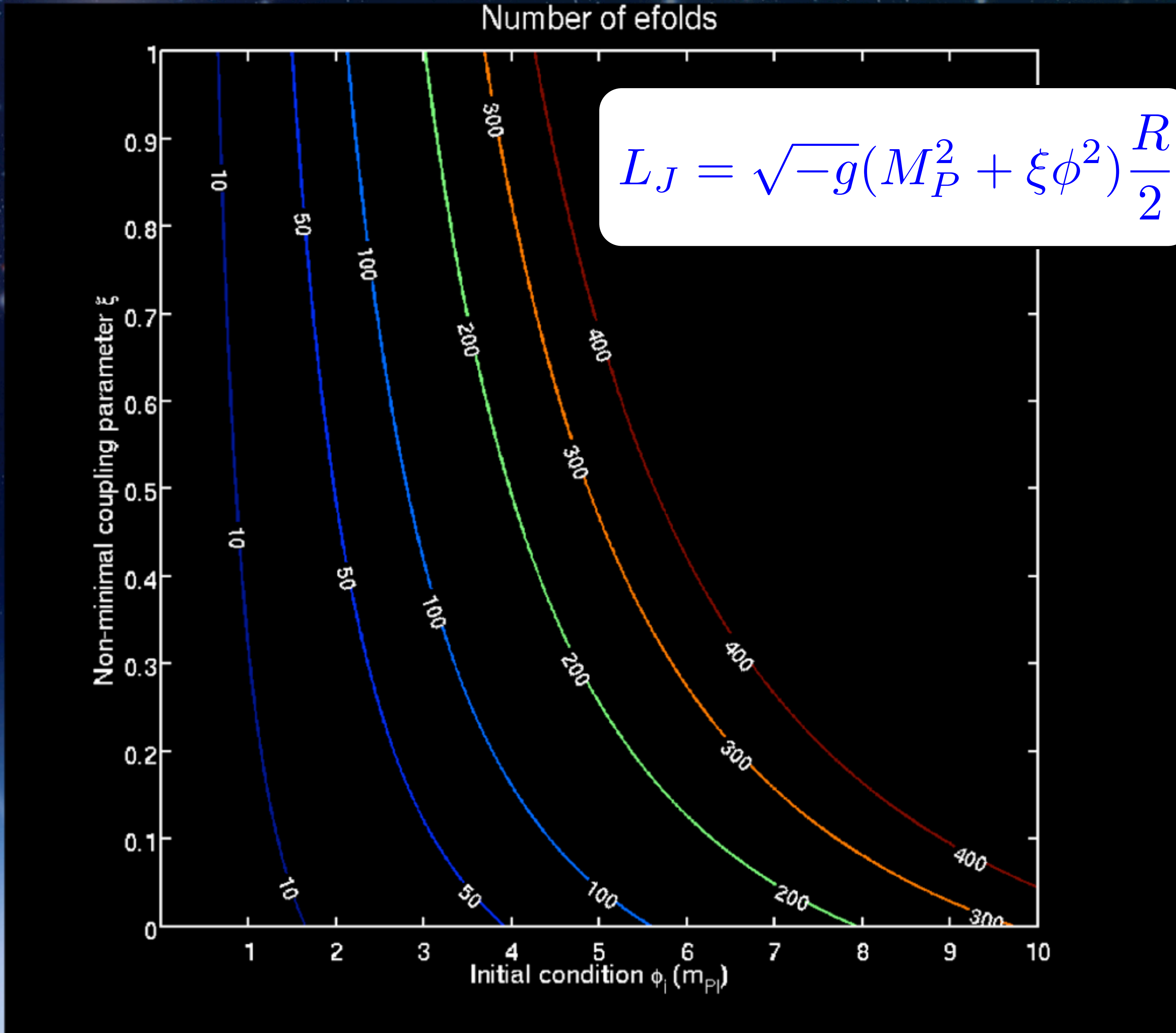
Non-M coupled, E-frame $$L_E = \sqrt{-\hat{g}}\frac{\hat{R}}{2\kappa} + L_E(\phi) + L_{\rm mJ}(\hat{g}_{\mu\nu}, A(\phi)\Psi)$$

Might give:
- Inflation
- Late-time acceleration

But also:
- Local effect (galactic rotation curves, Solar System anomalies)
- Wrong structure formation and dynamics
- Connections with the Standard Model (Higgs Inflation)

Non-minimal coupling
(Prelude to BEH-inflation)

$$L_J = \sqrt{-g}(M_P^2 + \xi\phi^2)\frac{R}{2}$$



Higgs Inflation: basic idea

$$L = L_{\rm sm} - \frac{M^2}{2}R - \xi H^\dagger H R$$

Non-minimal coupling to gravity

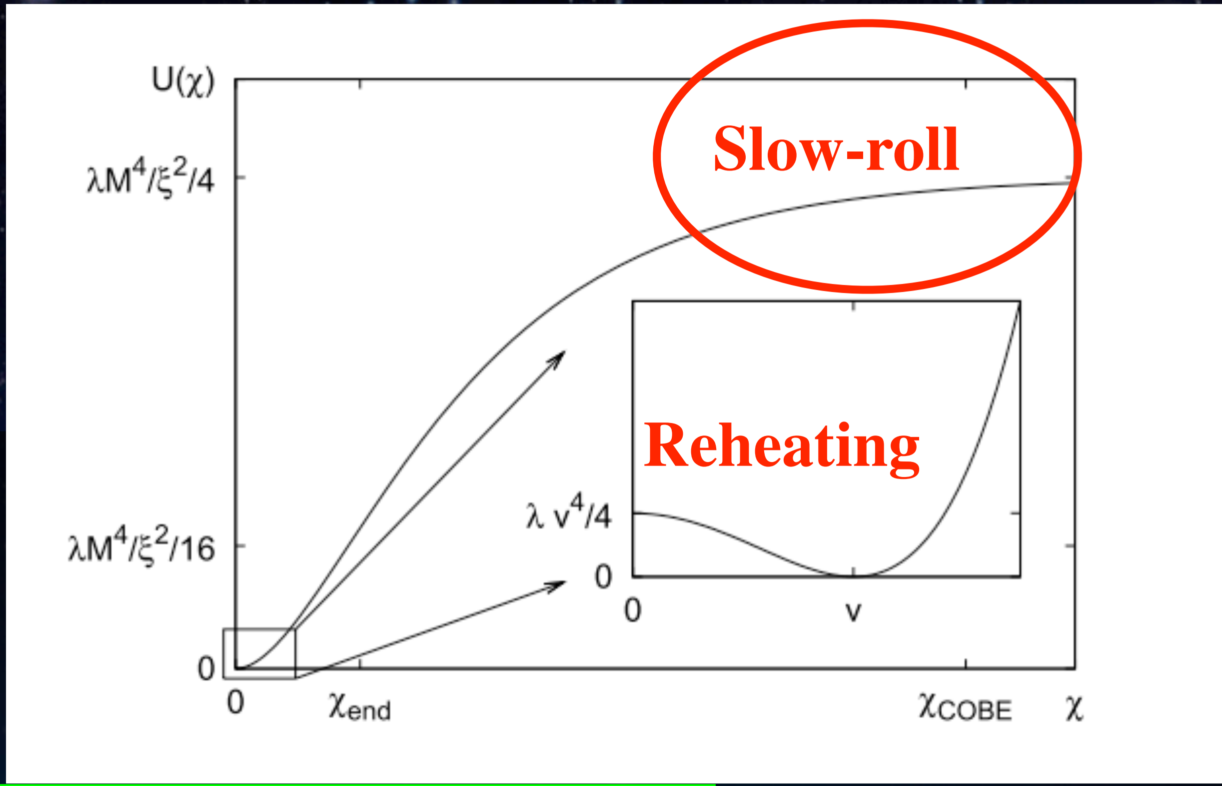
$$L_{sm} = -(D_\mu H)^\dagger (D^\mu H) - \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2 \qquad \sqrt{2} H = \begin{pmatrix} 0 \\ h \end{pmatrix}$$

Conformal transformation to Einstein frame

$$g_{\mu\nu} \to \Omega^2 g_{\mu\nu} = \left(1 + \frac{\xi h^2}{M_P^2} \right) g_{\mu\nu}$$

Field redefinition

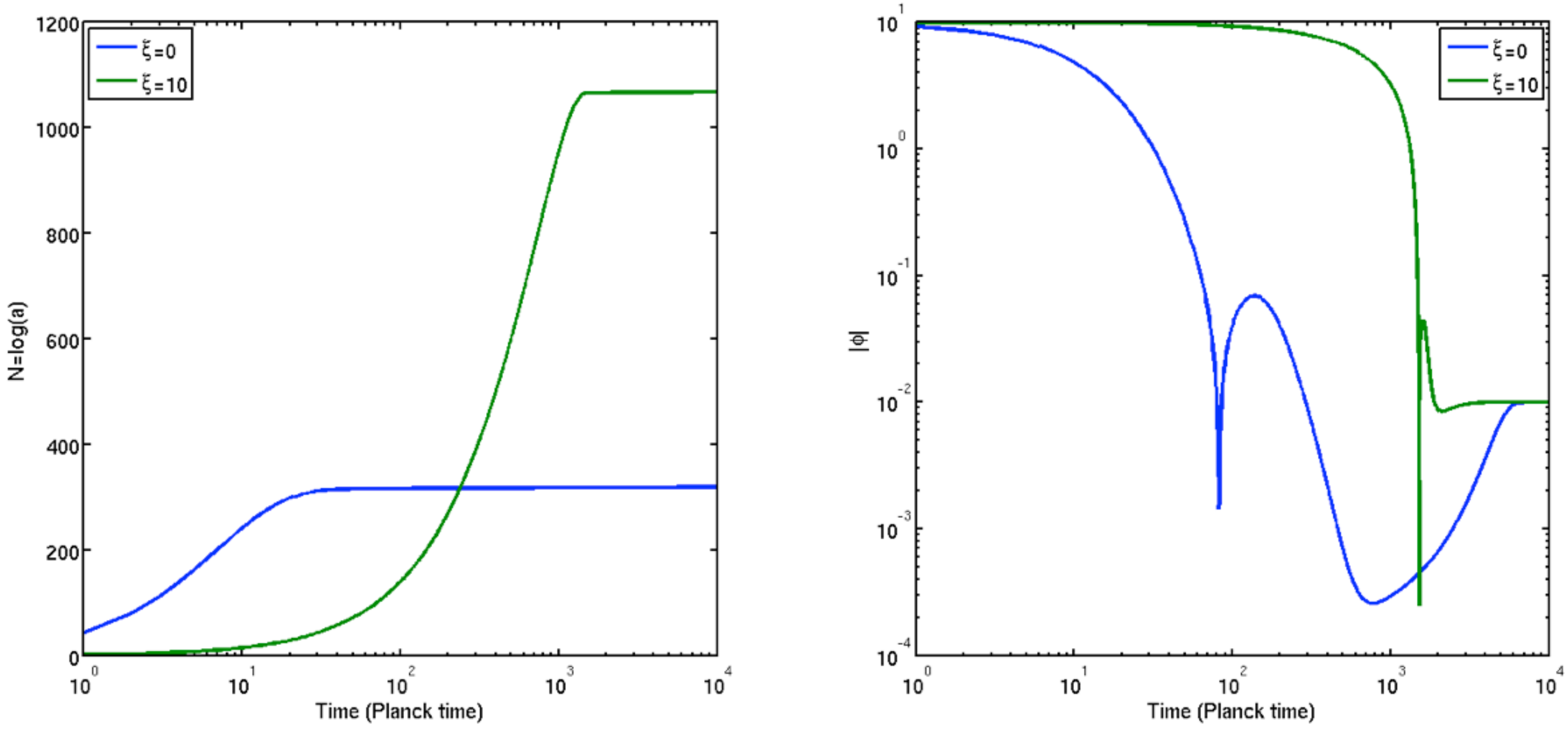
$$\frac{d\xi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2 / M_P^2}{\Omega^4}}$$

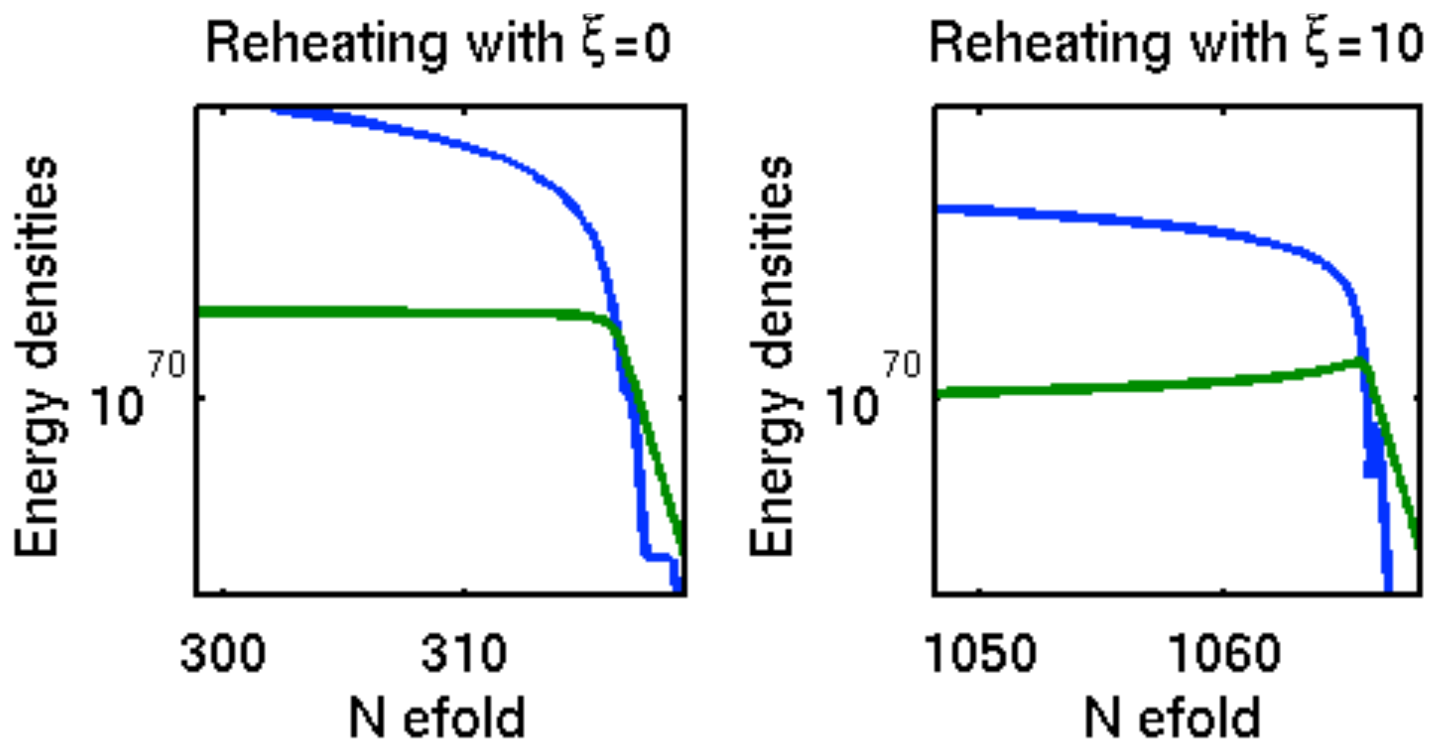


$$U(\chi) = \frac{\lambda}{4\Omega(\chi)^4} \left[h(\chi)^2 - v^2 \right]^2$$

$$S_E = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 R + \frac{1}{2} (\partial \chi)^2 - U(\chi) \right]$$

Bezrukov Shaposhnikov (2008)



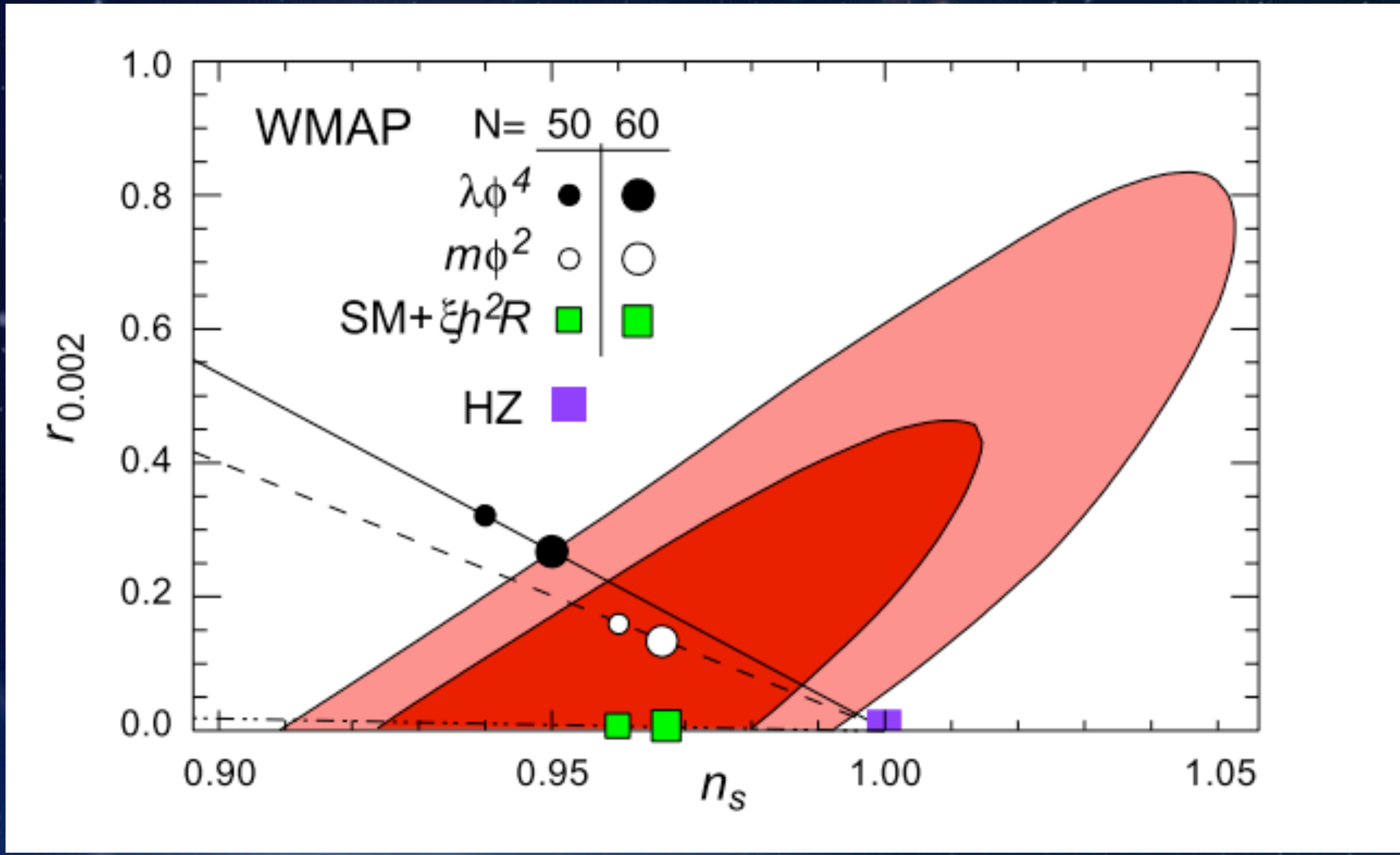


Freshly baked by A Fuzfa

Connecting SM with cosmological perturbations

Slow-roll parameters

$$\epsilon \simeq \frac{4M_P^4}{3\xi^2 h^4} \qquad \eta \simeq -\frac{4M_P^2}{3\xi h^2} \qquad \zeta^2 \simeq \frac{16M_P^4}{9\xi^2 h^4}$$



$$\xi \simeq 44700\sqrt{\lambda}$$

$(62 \ \text{e} - \text{folds})$

$$n_s \simeq 0.97$$

$$r \simeq 0.0033$$

Results are independent of the Higgs expectation value < h >

Radiative corrections do not alter the potential flatness

Bezrukov Shaposhnikov (2008)

Radiative Corrections

Weak-field regime expansion: $g_{\mu\nu} = \eta_{\mu\nu} + M_P^{-1} h_{\mu\nu}$

$$L \sim \frac{\xi}{M_P}\phi^2\eta^{\mu\nu}\partial^2 h_{\mu\nu}$$

The theory becomes strongly coupled at an energy (in both frames) $E \sim \frac{M_P}{\xi}$

Inflationary scale is where the potential is flat: $\Lambda_{\text{inf}} \sim \frac{M_P}{\sqrt{\xi}} \gg E$

IS THE THEORY INCONSISTENT?

The answer is NO: asymptotic shift symmetry of the action protects the flatness of the potential from quantum corrections (Bezrukov et. al. 2010)

Extra Bonus: reheating provides for neutrino masses, baryon asymmetry, proton decay, and sterile neutrino dark matter!

All looks good from the particle side...but do galaxies still form?

Modifying gravity is a dangerous business!

$$L_J = \sqrt{-g}\,\frac{f(\phi)}{2\kappa}R$$

Effective Newton constant $\kappa = 4\pi G_{\text{eff}}(\phi)$

Upper bound on time variation: $\frac{\dot{G}_{\text{eff}}}{G_{\text{eff}}} < 10^{-12}\,\text{yr}^{-1}$

Higgs-Gravity needs to be tested in terms of deviations from GR

- Local constraints from PPN analysis (Cassini Doppler Signal Lunar ranging, etc)
- Structure formation in the matter era
- Late time acceleration (dark energy)

Other effects to be considered:

- Variation of the Higgs VEV at the end of reheating
- SM extension: right-handed, sterile neutrino, dark matter and dark energy (AWE)
- ...

... a lot of work still to be done!