Inflation and Dark Energy from the Electroweak Phase Transition

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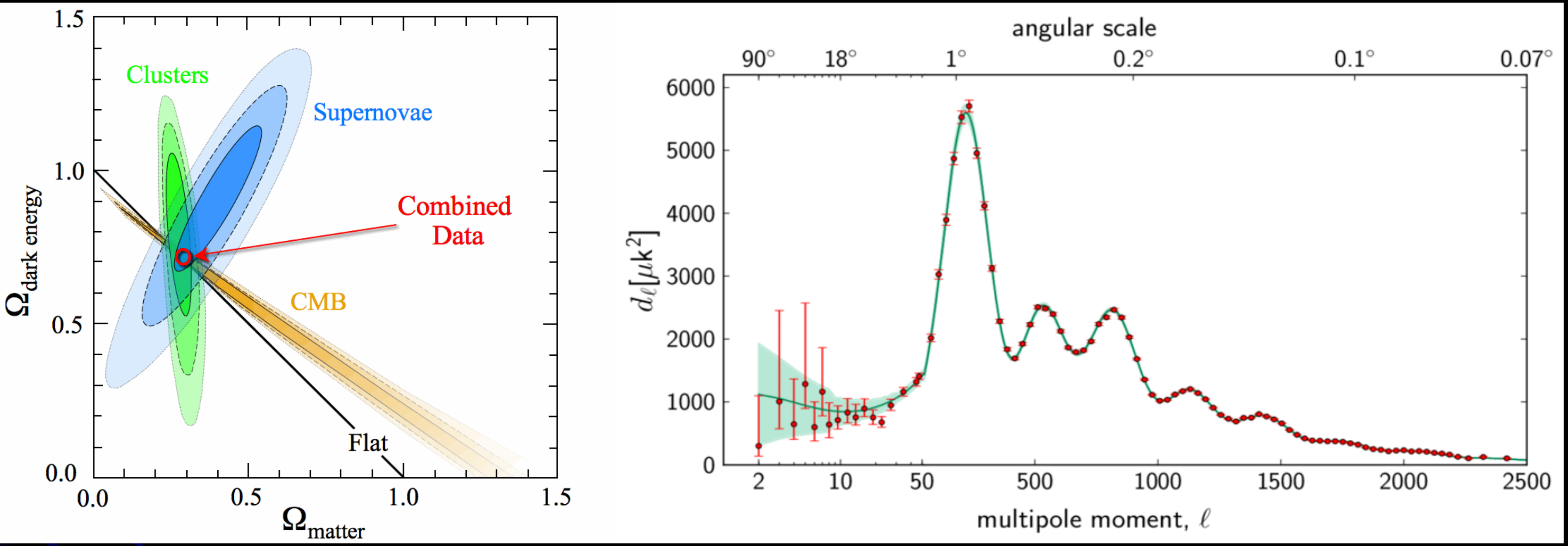
Inflation and Quintessence



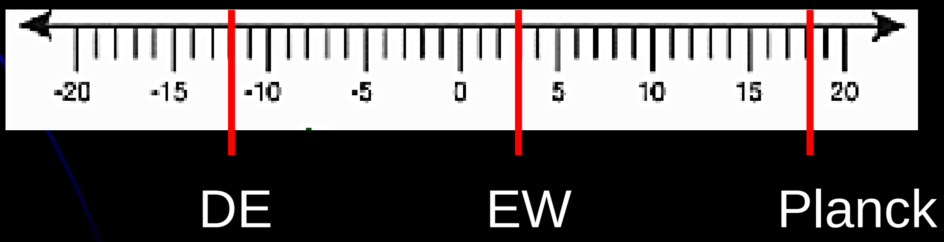
- **Universe engages in late Inflation at present**
  - Attributed to vacuum density, due to $\Lambda \neq 0$
  - But Λ = fine-tuned as vacuum density $\sim 10^{-120}$ of Planck density
- **Way out:** keep $\Lambda = 0$ and explain late inflation through **Dark Energy**
- **Quintessence: Universe dominated by potential density of another scalar; the 5th element after baryons, CDM, photons and neutrinos**

Quintessential Inflation

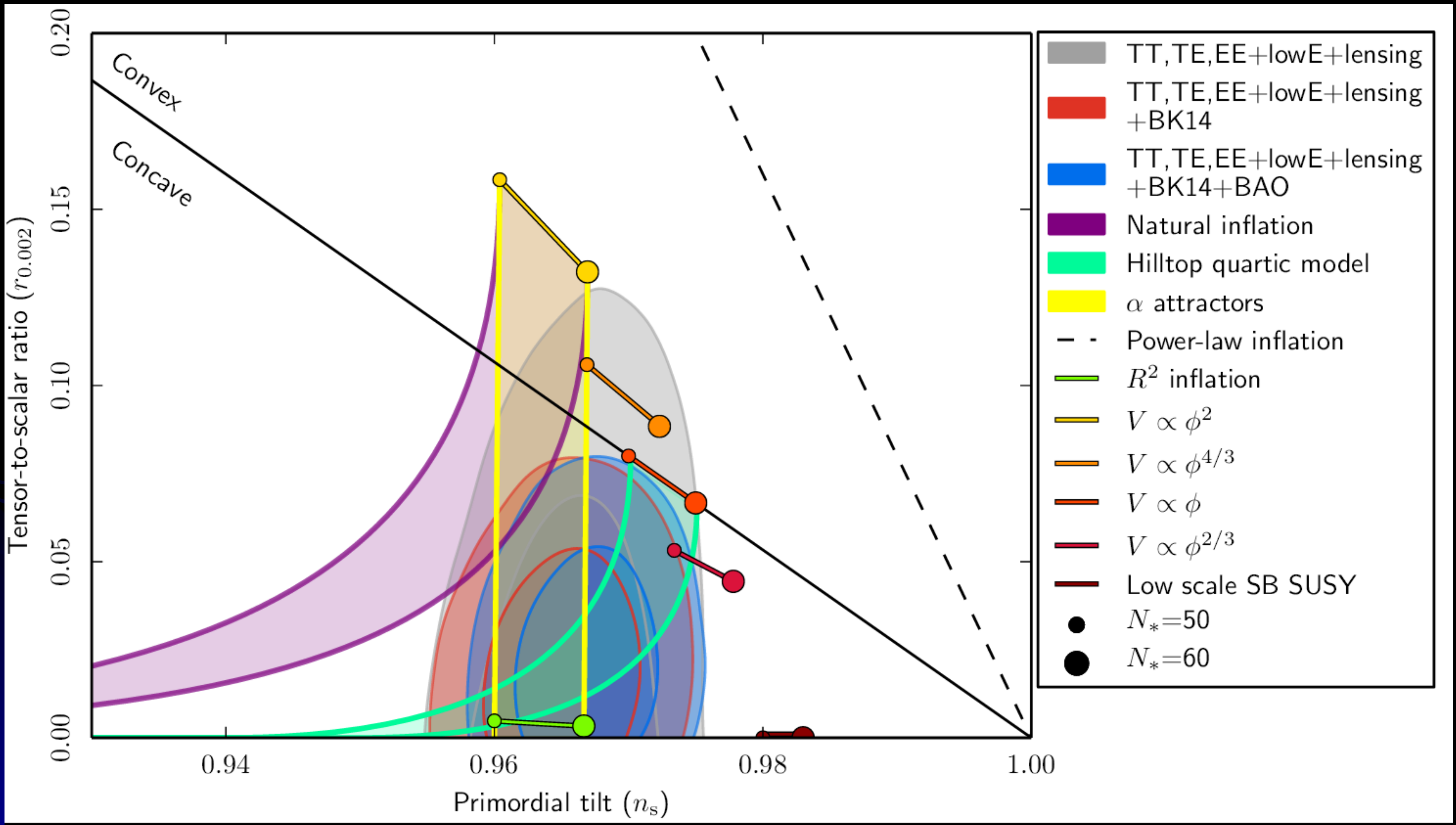
- **Quintessential Inflation: Both inflation and current acceleration due to the same field (cosmon)**
- **Successes:**
  - Natural: inflation & quintessence = the same idea
  - Economic: fewer parameters
  - Common theoretical framework
  - Initial conditions for quintessence determined by inflationary attractor
- **Problems:**
  - Form of Potential = artificial + Physics at extreme scales
  - Radiative corrections and 5th force problems (violation of equivalence)
- **Scales mystery: Electroweak Energy ~ Geometric mean of Planck and Dark Energy**

$$\mathrm{TeV} \sim \sqrt{\Lambda m_P}$$

$\log(E/\mathrm{GeV})$:



Starobinsky Inflation (first is best)



- **CMB:** $\alpha = 9.97 \times 10^{-6}$ **Planck sweet spot**

Our model

- EW Higgs with SSB potential: $U(h) = \frac{1}{4}\lambda_h (h^2 - v^2)^2$

$$\mathcal{L} = \frac{1}{2} m_P^2 R + \frac{1}{16\alpha^2} R^2 - \frac{1}{2}(\partial h)^2 - U(h)$$

$$V(\phi, h) = \alpha^2 m_P^4 \left(1 - e^{-\sqrt{\frac{2}{3}}\phi/m_P}\right)^2 + e^{-\sqrt{\frac{8}{3}}\phi/m_P} U(h)$$

- During inflation:

$$U(h) \lesssim H^4 \qquad \alpha \sim 10^{-5} \quad \Rightarrow \quad \frac{U(h)}{V_{\rm inf}} \lesssim \frac{H^4}{\alpha^2 m_P^4} \sim 10^{-10} \ll 1$$

- No effect on inflationary predictions √

Our model

$$V(\phi,h) = \alpha^2 m_P^4 \left(1 - e^{-\sqrt{\frac{2}{3}}\phi/m_P}\right)^2 + e^{-\sqrt{\frac{8}{3}}\phi/m_P} U(h)$$

- **After inflation:**
- Reheating produces the thermal bath, which restores EW symmetry

$$h \to 0 \quad \Rightarrow \quad U(0) = \frac{1}{4}\lambda_h v^4 \sim (100\,\mathrm{GeV})^4$$

$$\phi \to \phi_0 \; : \quad V'(\phi_0, 0) = 0 \quad \text{where} \quad e^{\sqrt{\frac{2}{3}}\phi_0/m_P} = 1 + \frac{U(0)}{\alpha^2 m_P^4}$$

- **At the EW tr**

$h \to v =$

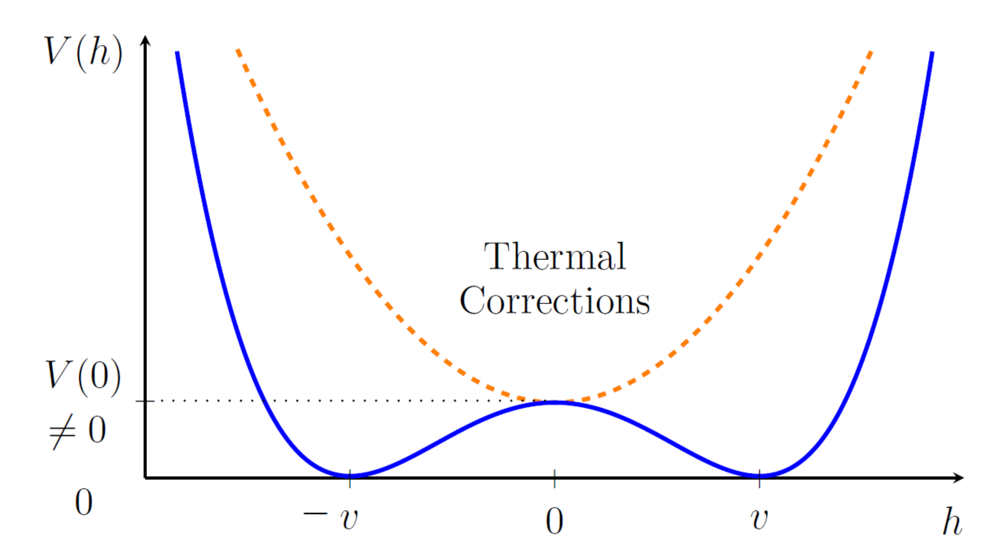
$= 0.129$

$V(\phi_0, v)$

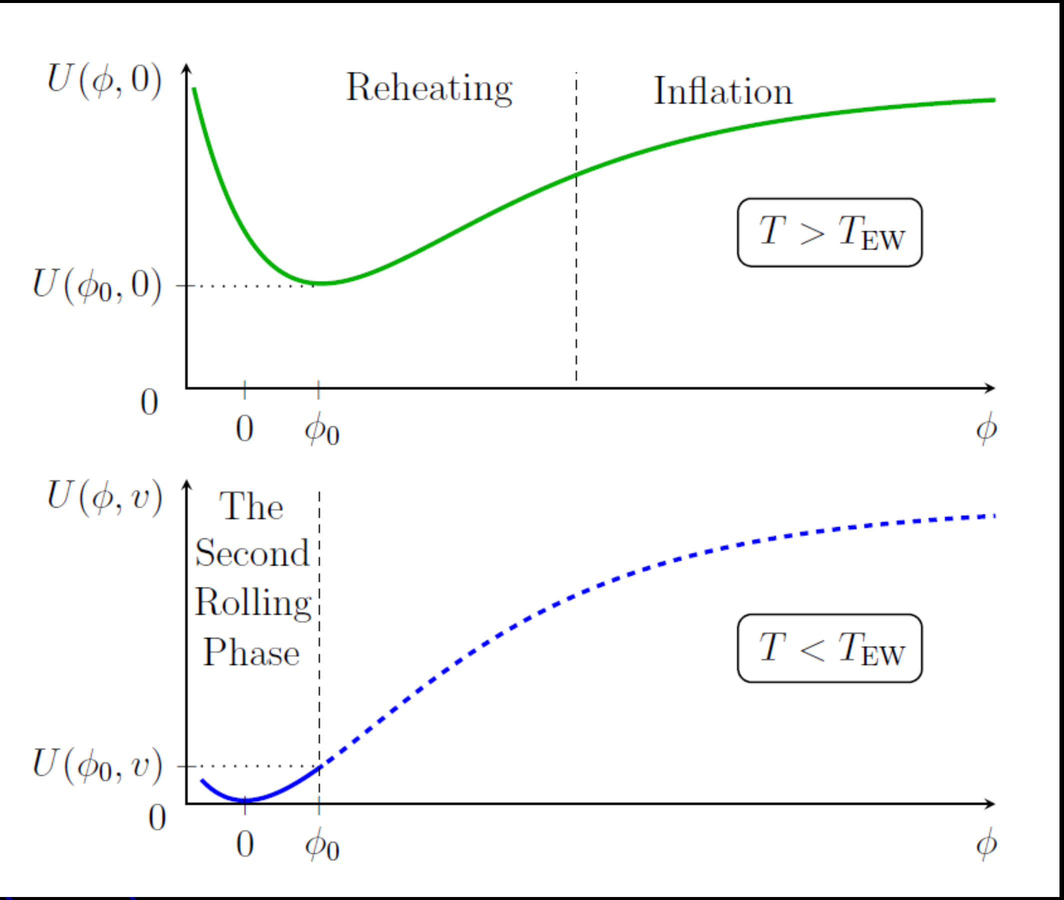
$= 246\,\mathrm{GeV}$

$V^{1/4} = \sqrt{\ldots}$

Energy √



Our model



But:

$$V''(\phi_0, v) \equiv m_{\rm eff}^2 \sim (\alpha m_P)^2 \sim (10^{13}\,{\rm GeV})^2 \gg H_{\rm ew}^2$$

Bait & Switch

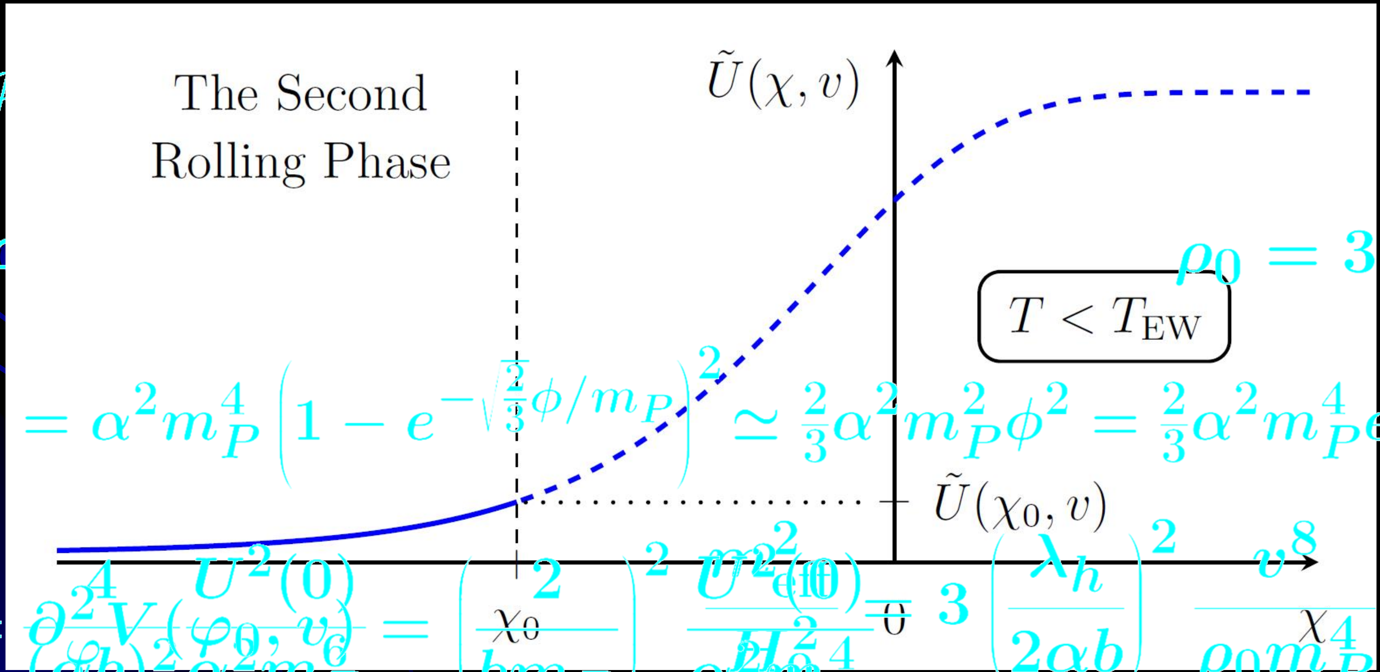
- Requirement: Field frozen until today: $m_{\rm eff} \lesssim H_0 \sim 10^{-42}\,{\rm GeV}$
- EW phase transition makes kinetic term non-canonical $\quad b \sim 1$

$$(\partial\phi)^2 \to \left(b\,\frac{m_P}{\phi}\right)^2 (\partial\phi)^2 \equiv (\partial\varphi)^2 \qquad \boxed{\phi = m_P\, e^{\varphi/bm_P}}$$

- Kinetic pole transposes minimum to infinity: $\varphi(\phi = 0) \to -\infty$

$V(\varphi$

φ_0



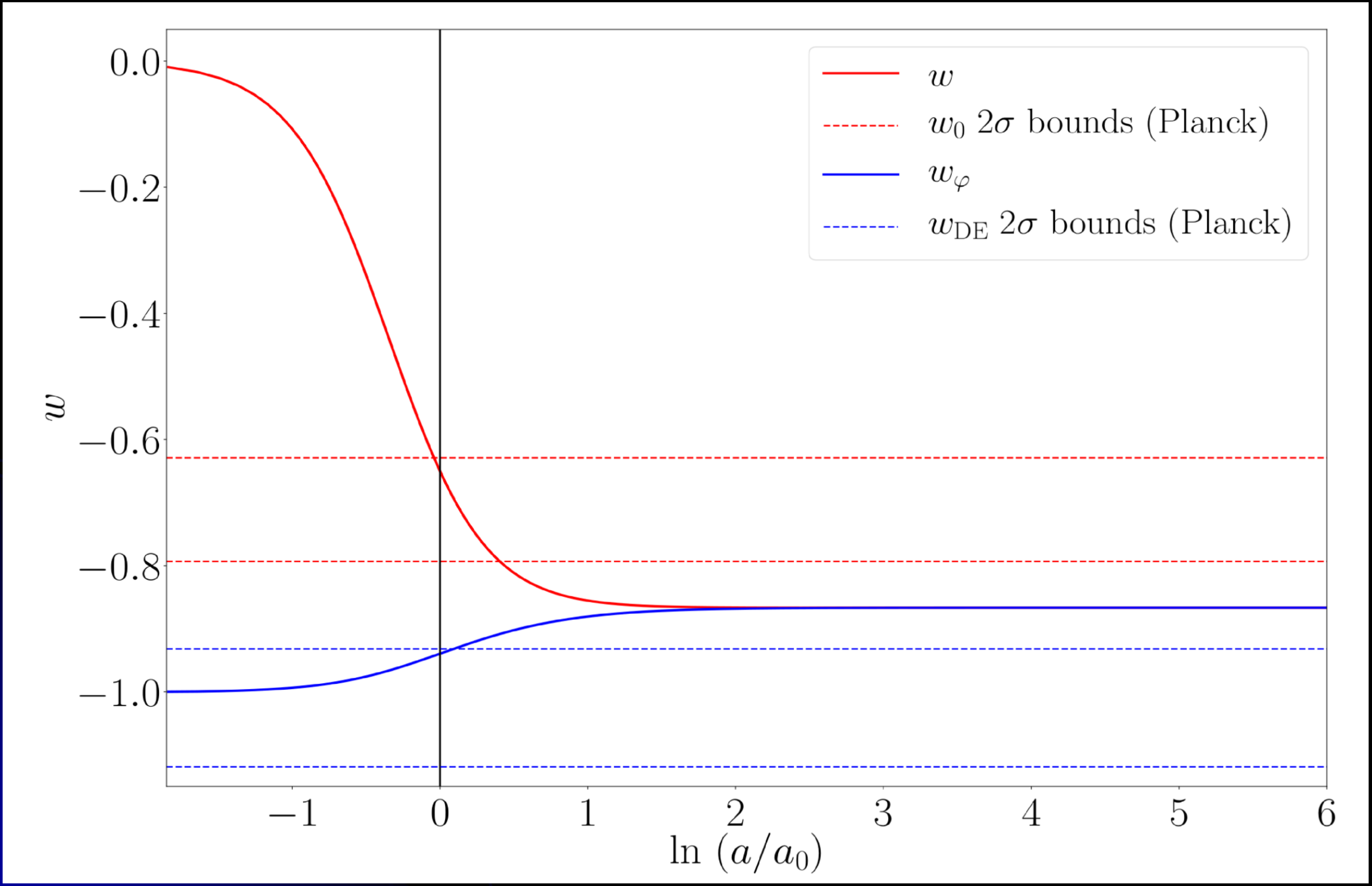
$$\rho_0 = 3H_0^2 m_P^2$$

$$V(\phi, v) = \alpha^2 m_P^4 \left(1 - e^{-\sqrt{\frac{2}{3}}\phi/m_P}\right)^2 \simeq \frac{2}{3}\alpha^2 m_P^2 \phi^2 = \frac{2}{3}\alpha^2 m_P^4 e^{2\varphi/bm_P}$$

$$m_{\rm eff}^2 = \partial^2_\varphi V(\varphi_0, v) = \frac{4\,U^2(0)}{(\alpha b)^2 \alpha^2 m_P^6} = \left(\frac{2}{bm_P}\right)^2 \frac{U^2(0)}{\alpha^2 m_P^4}$$

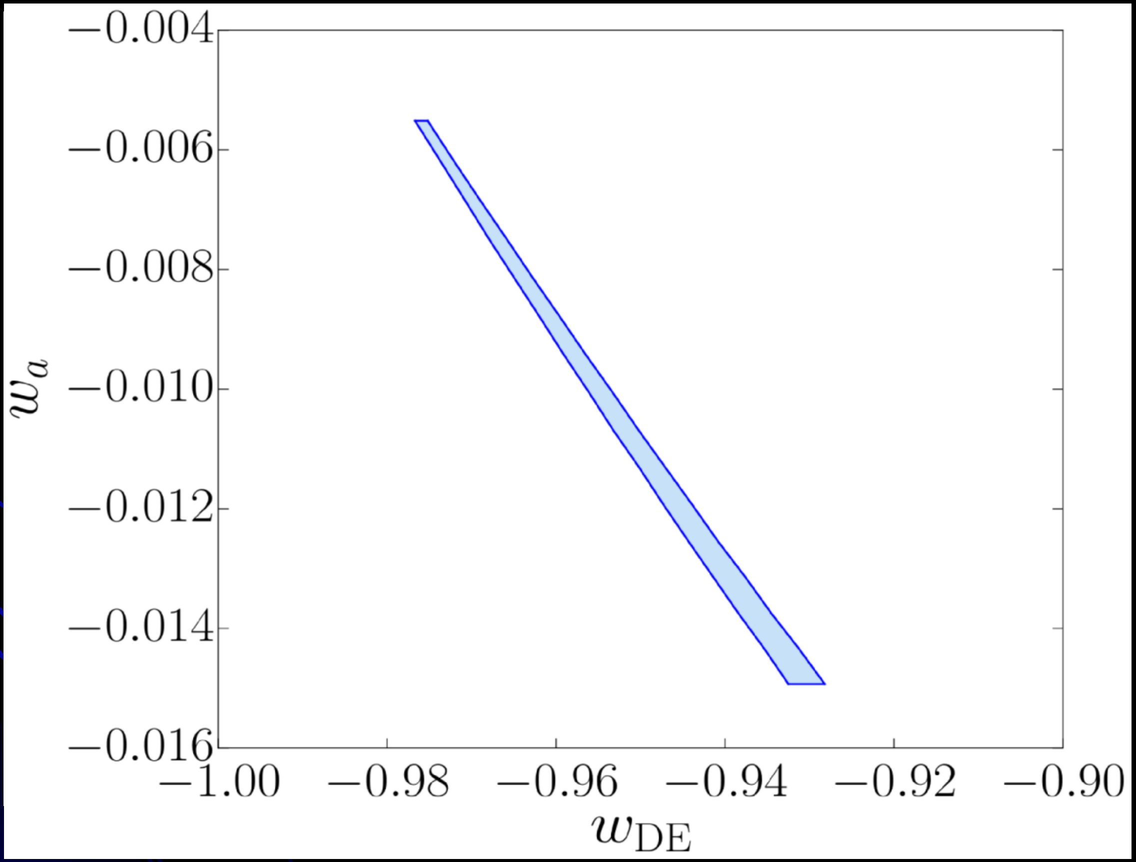
$$\frac{m_{\rm eff}^2}{H_0^2} = 3\left(\frac{\lambda_h}{2\alpha b}\right)^2 \frac{v^8}{\rho_0 m_P^4} \simeq \frac{1.03}{b} \quad \checkmark$$

Quintessence



Quintessence

$$w_\varphi = w_{\rm DE} + \left(1 - \frac{a}{a_0}\right) w_a \qquad w_a \equiv -({\rm d}w_\varphi/{\rm d}a)_0$$



Realisation of Bait & Switch

- Envisage some $f(R)$ coupling of scalaron with Higgs
- **Example:**

$$\mathcal{L} = \frac{1}{2} m_P^2 \tilde{R} - \frac{1}{2} \left[1 + \left(\frac{h}{v} \right)^2 \left(b \frac{m_P}{\phi} \right)^2 \right] (\partial\phi)^2 - V(\phi, h)$$

during inflation: $\left(\frac{h}{v} \right)^2 \left(b \frac{m_P}{\phi} \right)^2 (\partial\phi)^2 \sim \frac{h^2}{v^2} \epsilon H^2 m_P^2 \gg m_P^2 h^2$

$$(\partial\phi)^2 = \dot{\phi}^2 \quad \& \quad \epsilon \equiv -\dot{H}/H^2 \Rightarrow h \to 0 \quad \surd$$

- **Another example:**

$$\frac{1}{2} \left[1 + b^2 \left(\frac{R^2}{v^4} + \frac{\phi}{m_P} \right)^{-2} \right] (\partial\phi)^2$$

Conclusions

- Quintessential Inflation may naturally be achieved through a suitable coupling of the scalaron field of Starobinksy inflation to the electroweak Higgs field.
- Single dof with natural mass scales & couplings $3 \lesssim b \lesssim 5$
- Inflationary observables in excellent agreement with CMB
- Quintessence avoids any fine-tunings because the idea exploits **scales mystery:** $(EW)^2 \sim$ DE x Planck
- After inflation and before the EW transition the scalaron EV rests on minute residual potential density = Dark Energy
- **Bait & Switch:** At EW transition, pole at origin transposes min to infinity and results in successful exponential quintessence.
- Quintessence avoids excessive radiative corrections and 5th force problem because loops & interactions are exponentially suppressed
- Model produces running of DE barotropic parameter soon to be probed by observations, e.g. EUCLID


Thank you

"Asymptotic Freedom"

- Field can even be super-Planckian without endangering flatness of potential and without 5th force problem Kallosh, Linde (2016)
- consider interaction: $\delta V = \frac{1}{2} g^2 \phi^2 \sigma^2$ $g \sim 1$
- strength of interaction: $\mathcal{G} = \partial_\varphi^2 \partial_\sigma^2 \delta V$ $\Rightarrow$ $\mathcal{G} \simeq \frac{4g^2}{b^2} e^{2\varphi / b m_P}$

$b = 4$ & $\varphi = -126\, b m_P \Rightarrow \mathcal{G} \sim 10^{-28}$

exponentially suppressed √

- **Similarly, for loop contributions (radiative corrections)** √