Quintessential Inflation with α-attractors

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Work done with

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JCAP 06 (2017) 027

arXiv: 1712.01760 [astro-ph.CO]

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Accelerated Expansion

- Observations suggest that expansion is accelerated at early and late times
- **Primordial: Horizon & Flatness, Scale invariant perturbations**
- **Current: SN-Ia, Age problem, Planck 2015:** $w = -1.006 \pm 0.045$
- Accelerated expansion → Universe dominated by **Dark Energy** $w < -\frac{1}{3}$
- Accelerated expansion = **quasi-de Sitter** $w \approx -1$
- **Inflationary Paradigm: Early Universe dominated by potential density $V(\varphi)$ of scalar field (inflaton field)**
  Guth; Starobinsky 1980
- **Current Dark Energy: Non-zero vacuum density** $\Lambda \neq 0$
  - But Λ = fine-tuned as vacuum density $\sim 10^{-120}$ of Planck density
    "worse fine-tuning in Physics" Laurence Krauss
- **Quintessence: Universe dominated by $V(\varphi)$ of another scalar field; the 5th element after baryons, CDM, γ's & ν's**
  Ratra & Peebles 1989
  - Does not resolve Λ - problem: vacuum density assumed zero

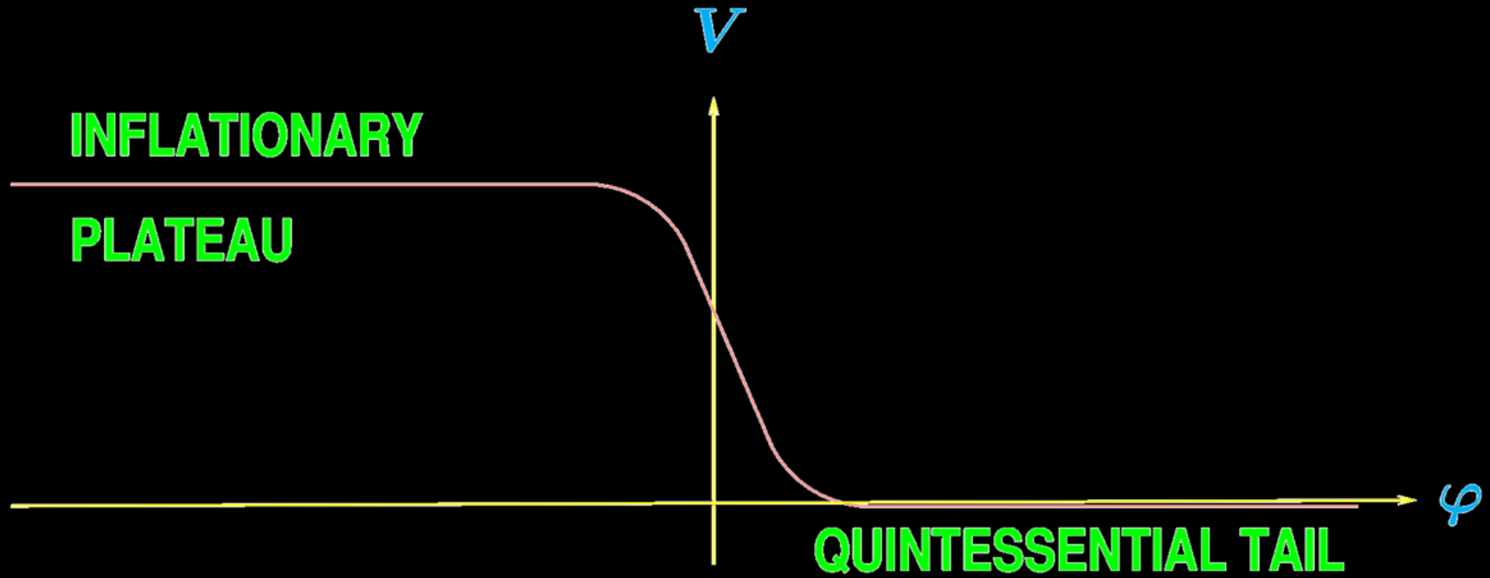
Quintessential Inflation

- Quintessence problems:
  - Initial conditions
  - Coincidence

  } ameliorated by **tracker quintessence**
  - Potential flatness against radiative corrections
  - 5th force problem: violation of the Principle of Equivalence
- **Quintessential Inflation: Both inflation and current acceleration due to the same field (cosmon)**

  Peebles & Vilenkin 1999
  - Natural: inflation & quintessence based on the same idea
  - Economic: fewer parameters / mass scales & couplings
  - Common theoretical framework
  - Initial conditions for quintessence determined by inflationary attractor
  - Coincidence resolved by mass scales & couplings only

Quintessential Inflation



- **Potential for Quintessential Inflation features two flat regions: Inflationary Plateau & Quintessential Tail.** **Differ by $\sim 10^{108}$**
  - Form of Potential = artificial + Physics at extreme scales
- **Inflaton does not decay; must survive until the present**
  - Non-oscillatory inflation
  - Reheating achieved by means other than inflaton decay
- **Radiative corrections and 5th force problems unresolved**

α- attractors to the rescue

- **Scalar kinetic term features poles due to non-trivial Kähler manifold**

$$\boxed{\mathcal{L}_{\text{kin}} = K_{n\bar{m}} \partial_\mu \Phi_n \partial^\mu \bar{\Phi}_m} \qquad K_{n\bar{m}} \equiv \frac{\partial^2 K}{\partial \Phi_n \partial \bar{\Phi}_m}$$

example: $K = -\frac{3\alpha}{2} m_P^2 \ln \frac{(1 - Z\bar{Z})}{(1 - Z^2)(1 - \bar{Z}^2)}$

$$Z \equiv \frac{\Phi}{\sqrt{3\alpha}} \quad \bar{Z} \equiv \frac{\bar{\Phi}}{\sqrt{3\alpha}} \quad \Phi = \bar{\Phi} = \phi/\sqrt{2}$$

Kallosh, Linde, Roest (2013)

$$\boxed{\mathcal{L}_{\text{kin}} = \frac{\frac{1}{2}\partial_\mu \phi \, \partial^\mu \phi}{(1 - \frac{\phi^2}{6\alpha})^2} m_P^2} \qquad \boxed{\phi = \sqrt{6\alpha} \tanh \frac{\varphi}{\sqrt{6\alpha} m_P}}$$

$$|\phi| < \sqrt{6\alpha}$$

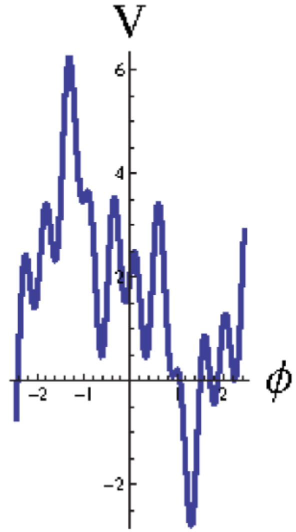
canonically normalised $\frac{\mathrm{d}\phi}{1 - \frac{\phi^2}{6\alpha}} = \frac{\mathrm{d}\varphi}{m_P}$

Stretching and flattening of the potential is similar to stretching of inhomogeneities during inflation

Kallosh, AL 2013

Potential in the **original variables** with kinetic term

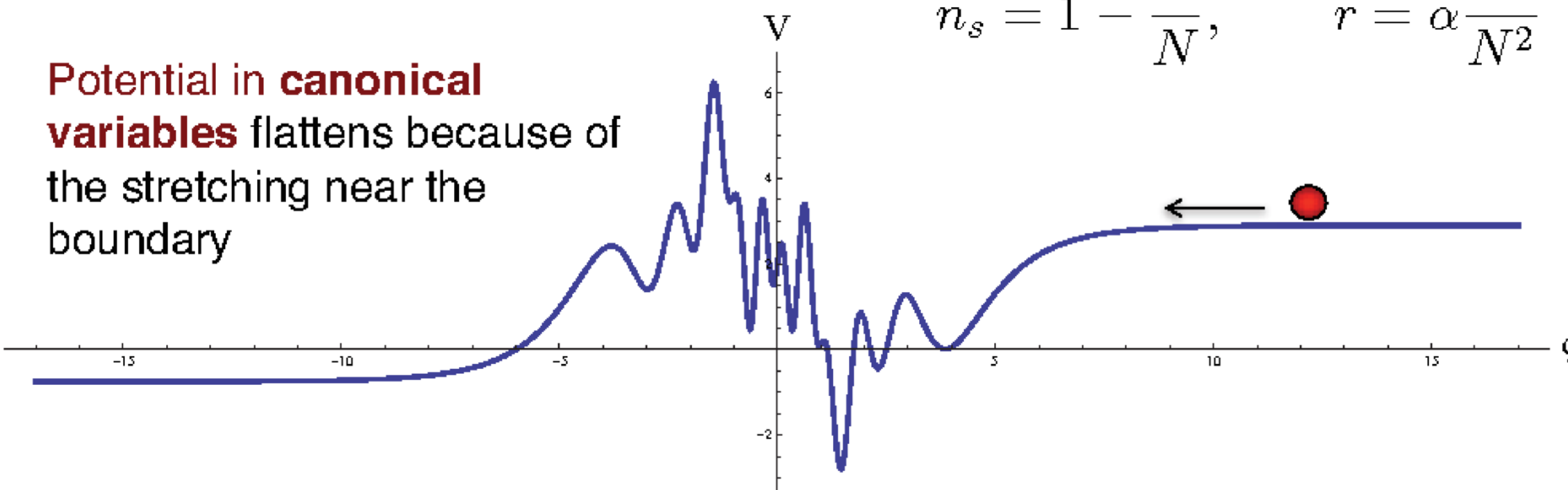
$$\frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



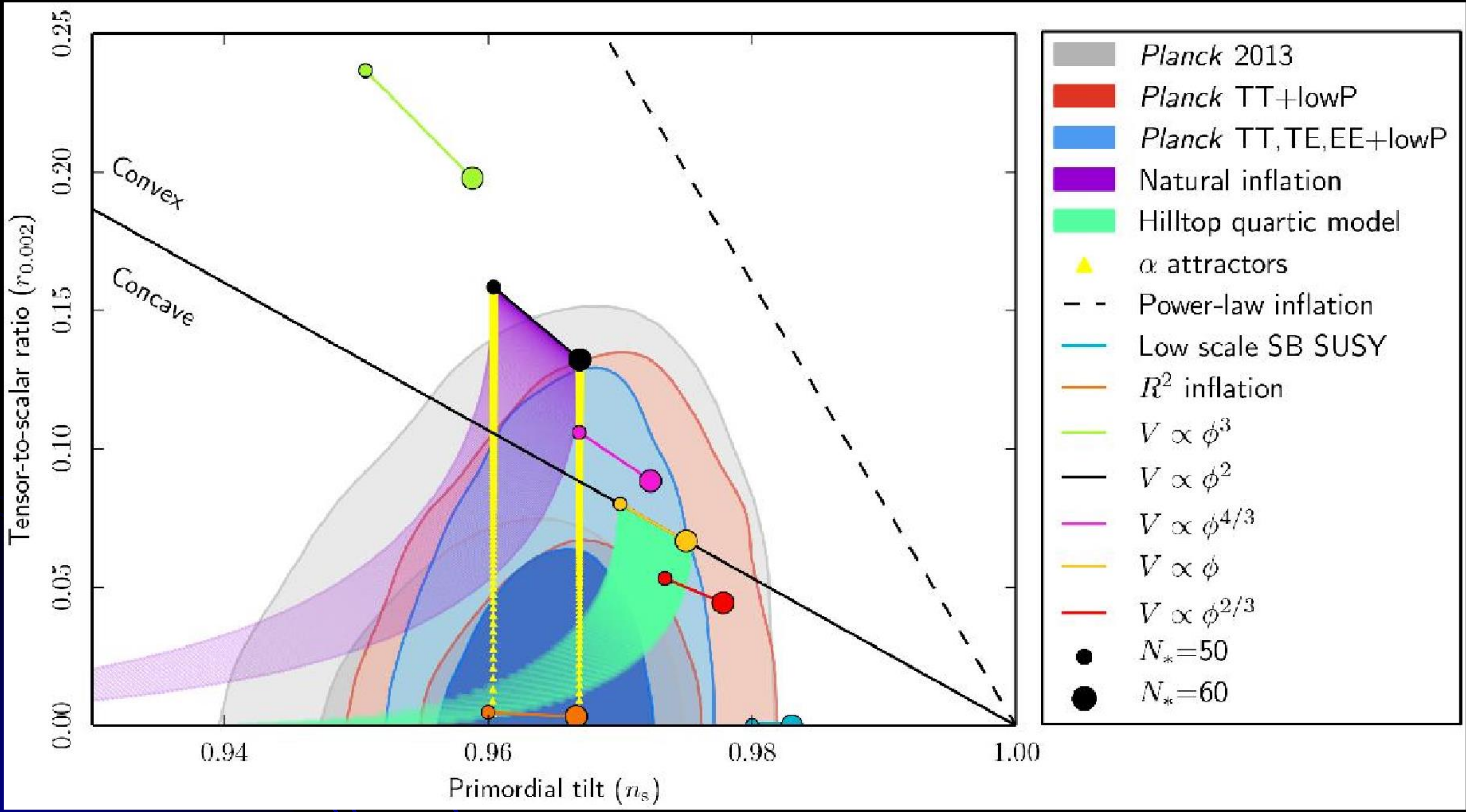
All of these models predict

$$n_s = 1 - \frac{2}{N}, \qquad r = \alpha\frac{12}{N^2}$$

Potential in **canonical variables** flattens because of the stretching near the boundary



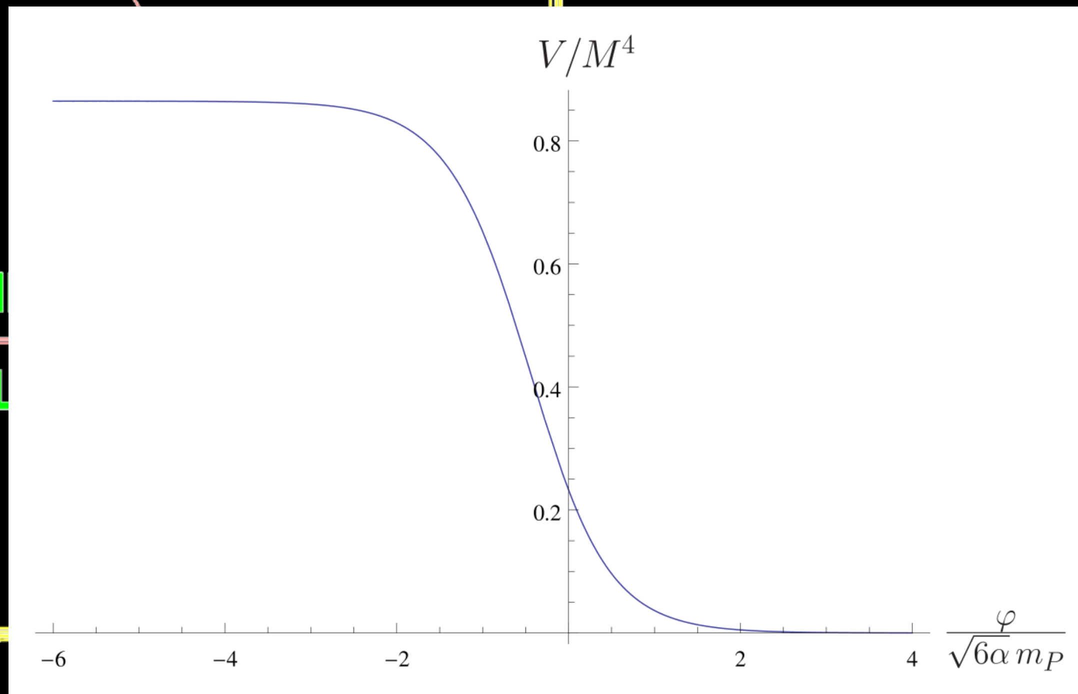
α- attractors to the rescue



- **In excellent agreement with Planck observations**

$3 \lesssim \sqrt{6\alpha} \lesssim 5$ or $1.5 \lesssim \alpha \lesssim 4.2$

The model



- Exponential potential
- Poles from α-attractors
- No vacuum density
- **Switch to canonical field**

$$\frac{\frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi}{\left(1-\frac{\phi^2}{6\alpha}\right)^2}$$

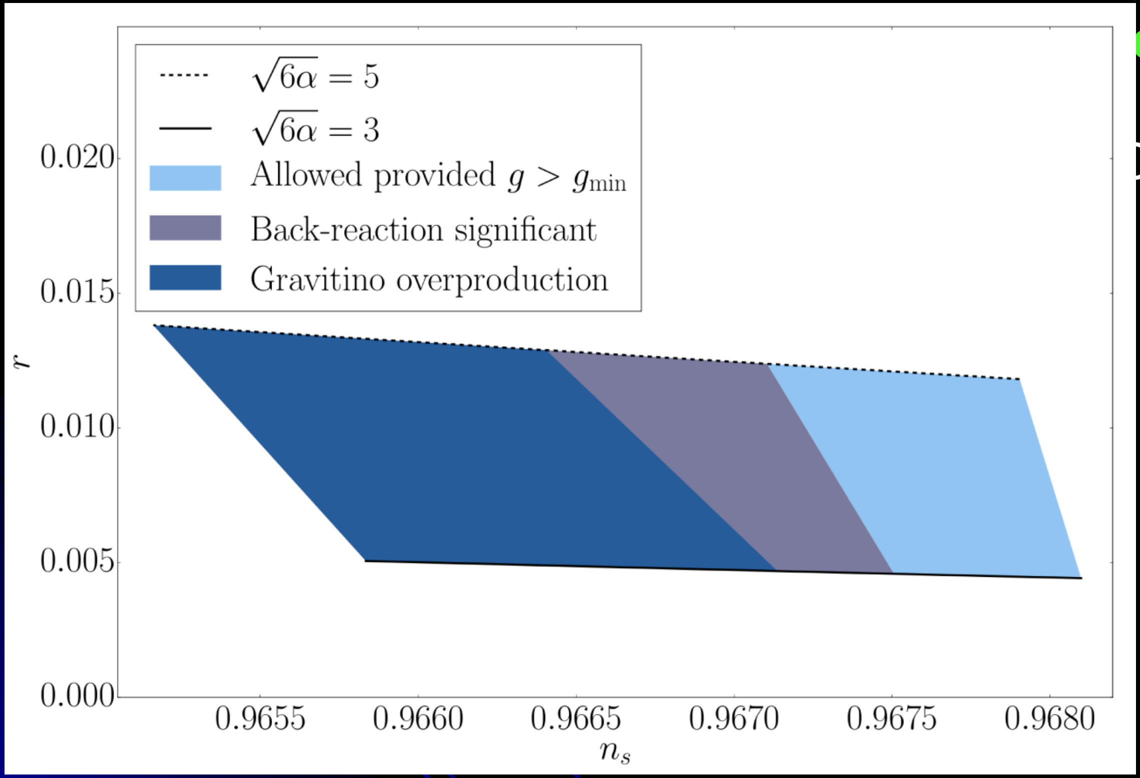
$$V(\phi)=V_0\,e^{-\kappa\phi}$$

$$V(\varphi)=e^{-2n}M^4\left\{\exp\left[n\left(\tanh\frac{\varphi}{\sqrt{6\alpha}\,m_P}+1\right)\right]-1\right\}$$

$$M^4\equiv e^{n}V_0 \qquad \Lambda=e^{-2n}M \qquad n\equiv\kappa\sqrt{6\alpha}$$

Inflation

- In the limit: $\varphi \to -\infty$ $\quad V(\varphi) \simeq M^4 \exp\left(-2ne^{\frac{2\varphi}{\sqrt{6\alpha} m_P}}\right)$
  ($\phi \to -\sqrt{6\alpha}$)



ent with CMB observations

OBE: $\mathbf{M} \simeq 10^{16}\,\mathbf{GeV}$

$N_* = 62 \quad \sqrt{6\alpha} = 4$

$n_s = 0.968$ √

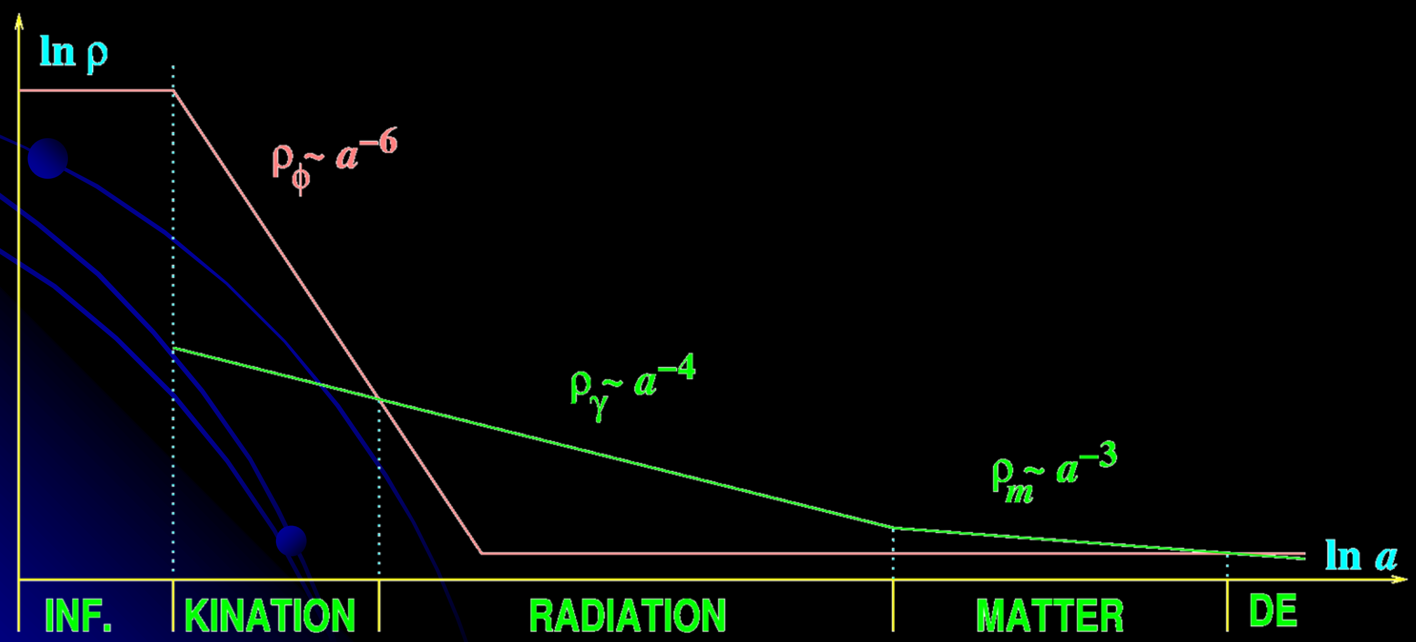
$0.004 \lesssim r \lesssim 0.012$

$n'_s = -5 \times 10^{-4}$

Planck: $n_s = 0.968 \pm 0.006 \quad n'_s = -0.003 \pm 0.007 \quad r \lesssim 0.07$

Kination

- **Kination: After inflation kinetic density dominates**
  - Inflaton oblivious of potential $\ddot{\varphi} + 3H\dot{\varphi} \simeq 0$
  - Field rolls to quintessential tail
- **Reheating: Radiation eventually dominates** $\rho_{\rm kin} \equiv \frac{1}{2}\dot{\varphi}^2 \propto a^{-6}$
  - Field rolls for a while but eventually freezes $\rho_\gamma \propto a^{-4}$
  - Residual density = Dark Energy today √



Kination

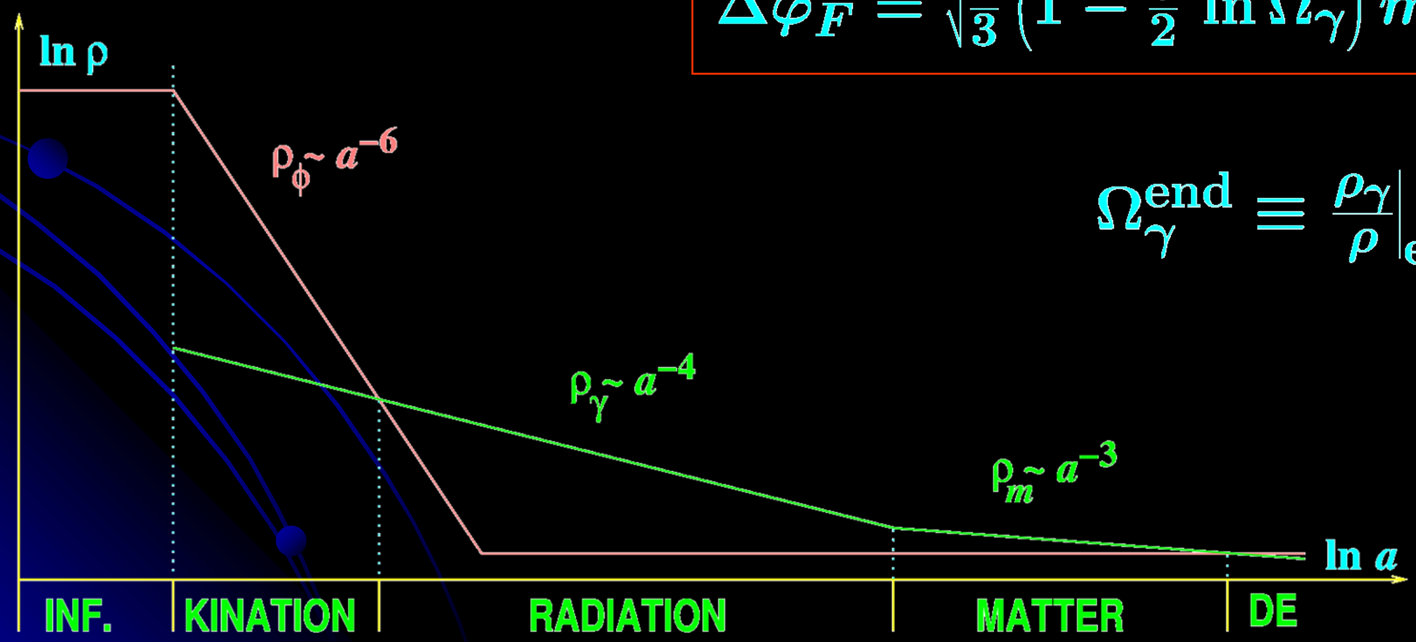
- Maximum roll for minimum reheating efficiency (minimum residual density)

Kination: $$\varphi = \varphi_{\rm end} + \sqrt{\tfrac{2}{3}}\, m_P \ln(t/t_{\rm end})$$

Radiation: $$\varphi = \varphi_{\rm reh} + \sqrt{\tfrac{2}{3}}\, m_P \left(1 - \sqrt{t_{\rm reh}/\,t}\,\right)$$

$$\boxed{\Delta\varphi_F = \sqrt{\tfrac{2}{3}}\left(1 - \tfrac{3}{2}\ln\Omega_\gamma\right) m_P}$$

$$\Omega_\gamma^{\rm end} \equiv \left.\frac{\rho_\gamma}{\rho}\right|_{\rm end}$$



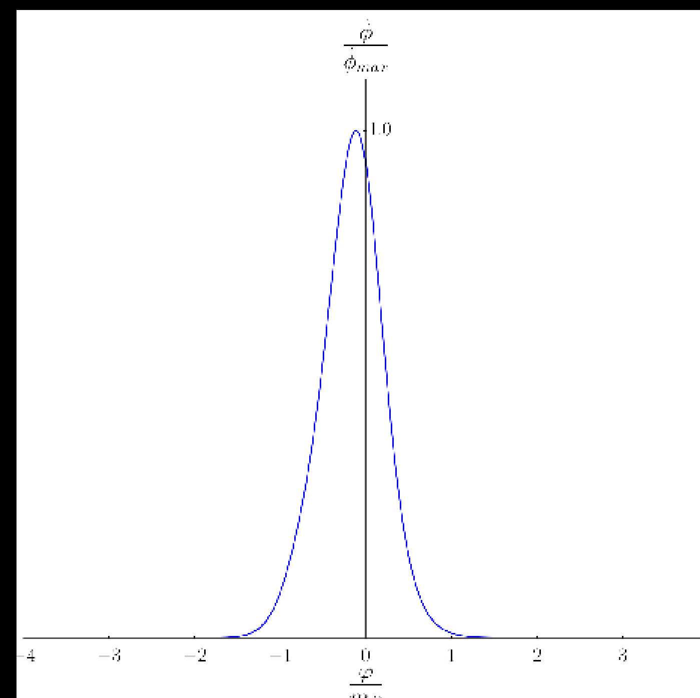
Instant Preheating

- **Instant Preheating: Due to ESP at ϕ_0, which causes particle production by breaking adiabaticity**

  Felder, Kofman, Linde (1999)

$$\mathcal{L} = \mathcal{L}(\phi_0) + \mathcal{L}_{\rm int} \qquad \boxed{\mathcal{L}_{\rm int} = -\frac{1}{2} g^2 (\phi - \phi_0)^2 \chi^2 - h\chi\psi\bar{\psi}}$$

- Breaking adiabaticity: $|\dot{m}_\chi| \gg m_\chi^2$



- Production window: $\phi_0 - \sqrt{\frac{|\dot{\phi}|}{g}} \leq \phi \leq \phi_0 + \sqrt{\frac{|\dot{\phi}|}{g}}$

$$\Rightarrow \quad \phi_{\rm IP} = \sqrt{\frac{\dot{\phi}_{\rm IP}}{g}}$$

- Near poles ϕ hardly varies

$$\Rightarrow \phi_0 \simeq 0 \Rightarrow \phi \simeq \varphi$$ **canonical**

Instant Preheating

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  Felder, Kofman, Linde (1999)

$$\rho_\gamma^{\rm IP} = \frac{g^2 \dot{\phi}_{\rm IP}^2}{8\pi^3} \quad \& \quad \Omega_r^{\rm IP} = \frac{g^2}{4\pi^3} \quad \Rightarrow \quad T_{\rm reh} = \left[\frac{30}{\pi^2 g_*} \rho_r^{\rm IP} (\Omega_r^{\rm IP})^2\right]^{1/4}$$

- Gravitino overproduction: $T_{\rm reh} < 10^9\,{\rm GeV} \;\Rightarrow\; \boxed{g \lesssim 10^{-2}}$
- Backreaction: $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = -\frac{g^{5/2}\dot{\phi}^{3/2}}{8\pi^3} \;\Rightarrow\; \boxed{g \lesssim 10^{-3}}$
  - However there is no backreaction if $h = \mathcal{O}(1)$
- Spike of GWs: $\boxed{g \gtrsim 10^{-4}}$

Instant Preheating

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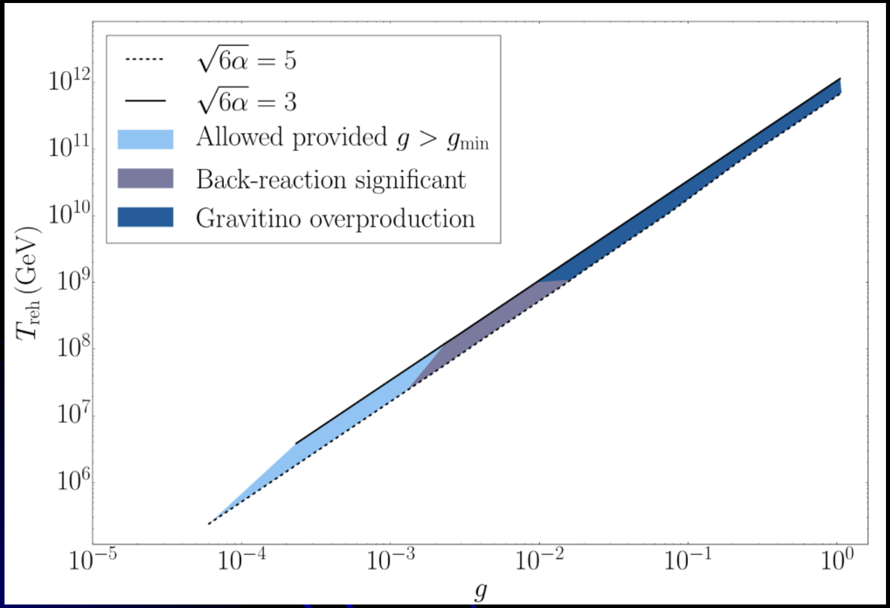
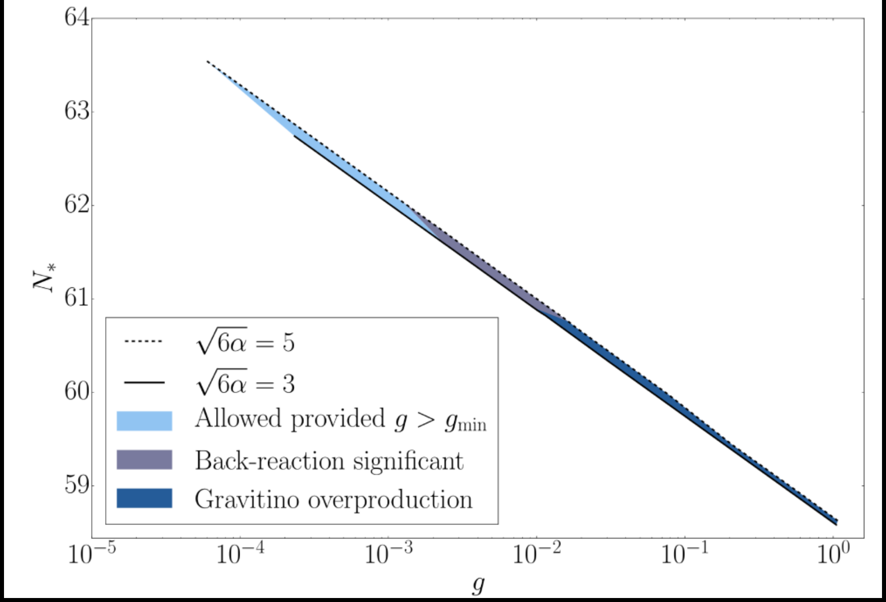




- **Results:** $T_{\rm reh} \sim 10^5 - 10^8\,\mathrm{GeV}$ $\surd$ & $N_* = 62 - 63$
  - Without gravitino or backreaction: $T_{\rm reh} \sim 10^{11}\,\mathrm{GeV}$ $N_* \simeq 59$

Quintessence

- In the limit: $\varphi \to +\infty$ $\quad (\phi \to \sqrt{6\alpha})$ $\quad V \simeq 2ne^{-2n} M^4 e^{-\frac{2\varphi}{\sqrt{6\alpha} m_P}}$
- **Quintessential tail: exponential** $\boxed{V = V_{\mathrm{Q}} \exp\left(-\lambda\varphi/m_P\right)}$

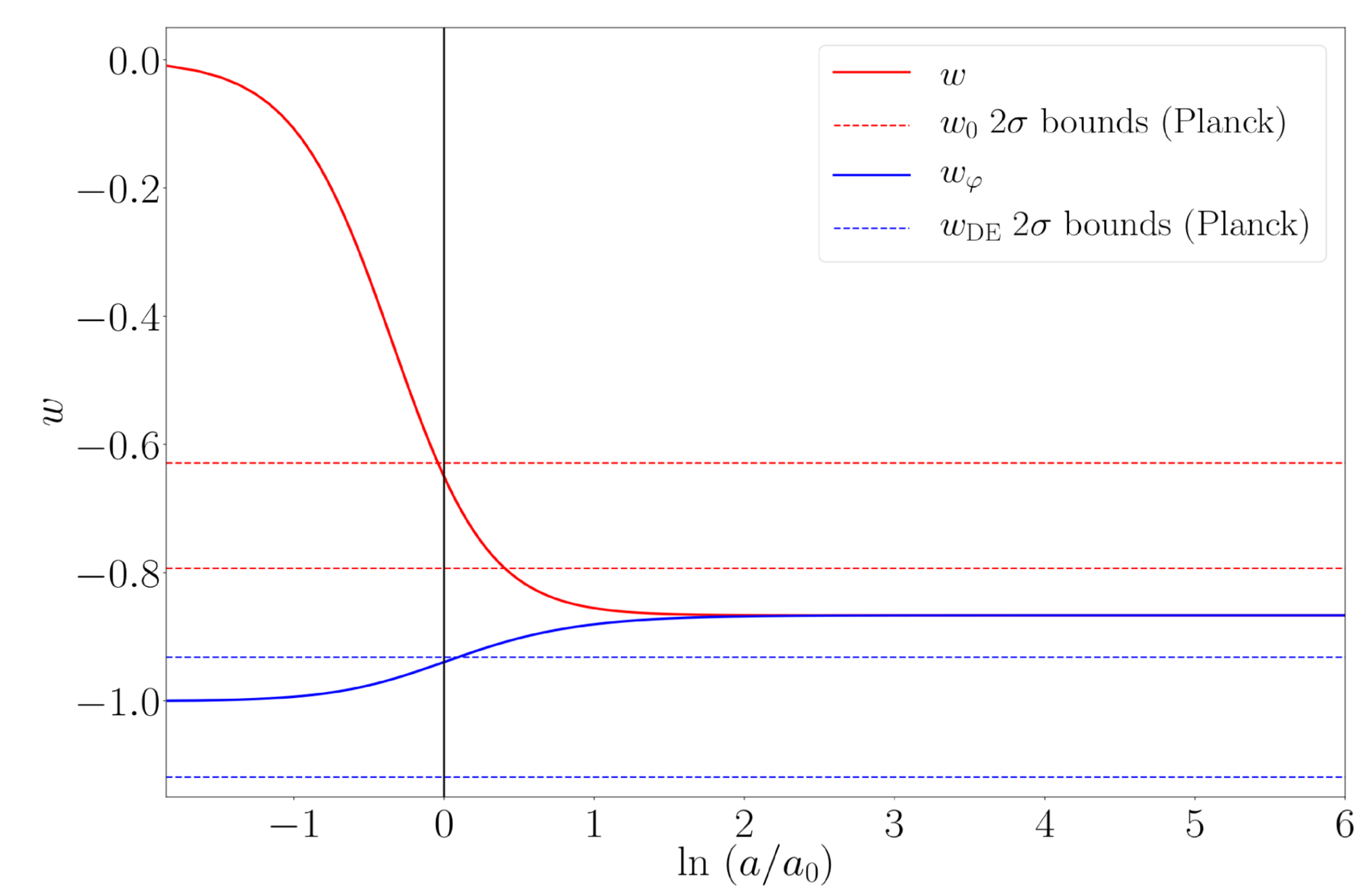
$$V_Q = 2ne^{-2n} M^4 \qquad \lambda = 2/\sqrt{6\alpha} = (2/n)\kappa$$

  - Small α → large λ : subdominant quintessence
    ∃ attractor which mimics background → no acceleration
  - Small λ → large α : super-Planckian non-canonical field

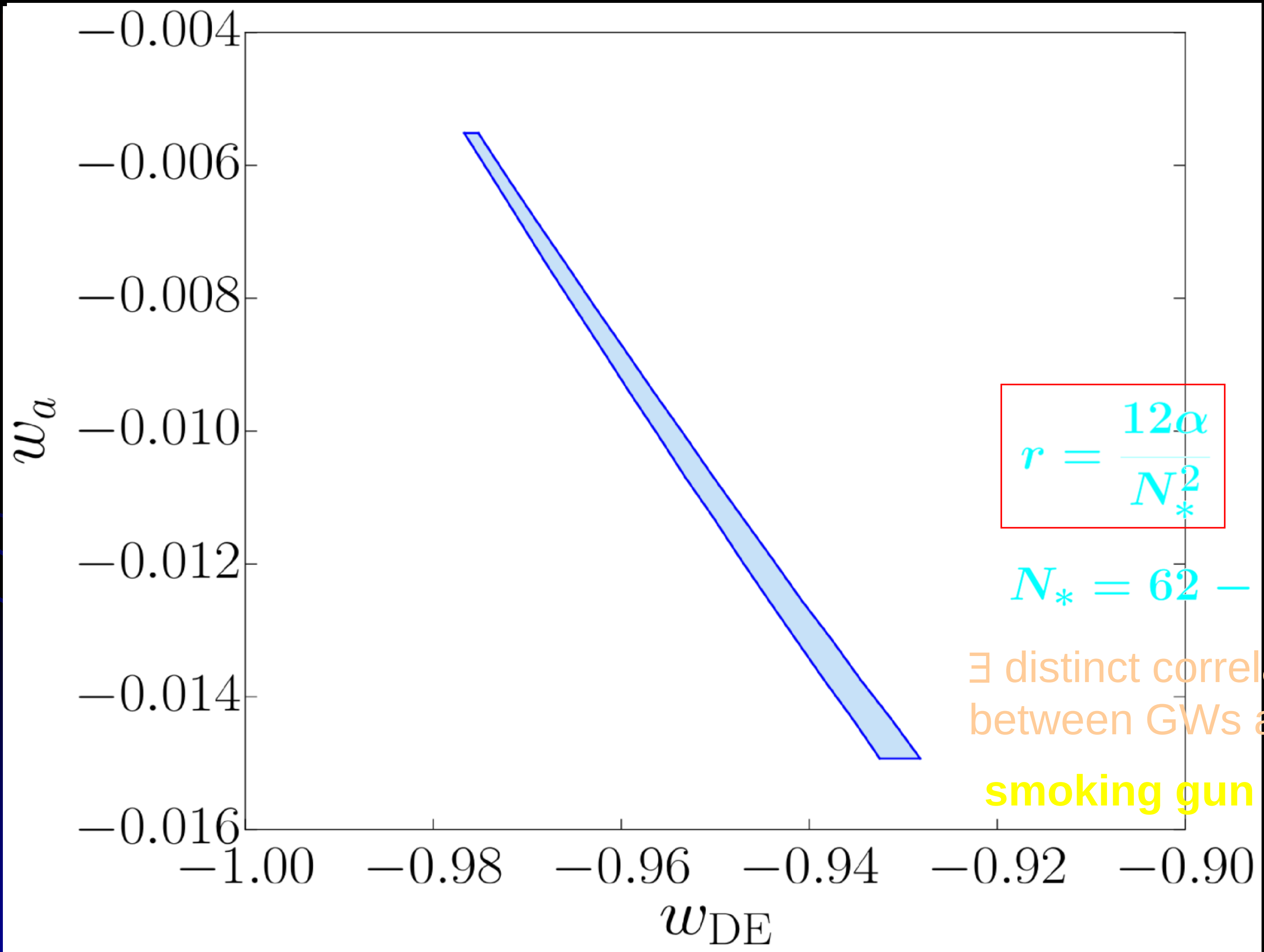
- **Range with Planckian** ϕ **and successful acceleration:**

$$3 \lesssim \sqrt{6\alpha} \lesssim 5 \quad \text{or} \quad \boxed{1.5 \lesssim \alpha \lesssim 4.2}$$

Quintessence



Quintessence



$$\boxed{r = \frac{12\alpha}{N_*^2}}$$

$$N_* = 62 - 63$$

∃ distinct correlation between GWs and w_a

smoking gun

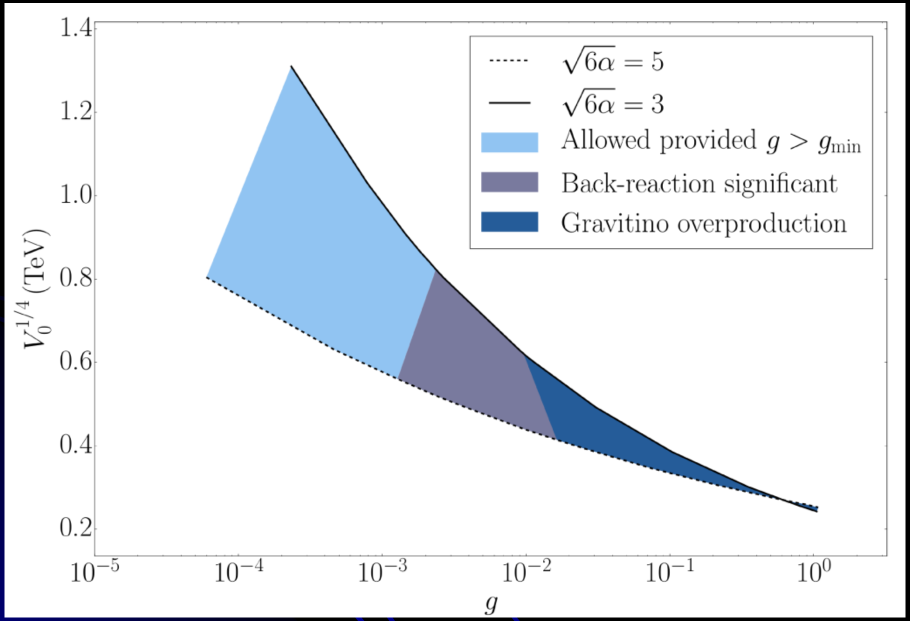
Quintessence

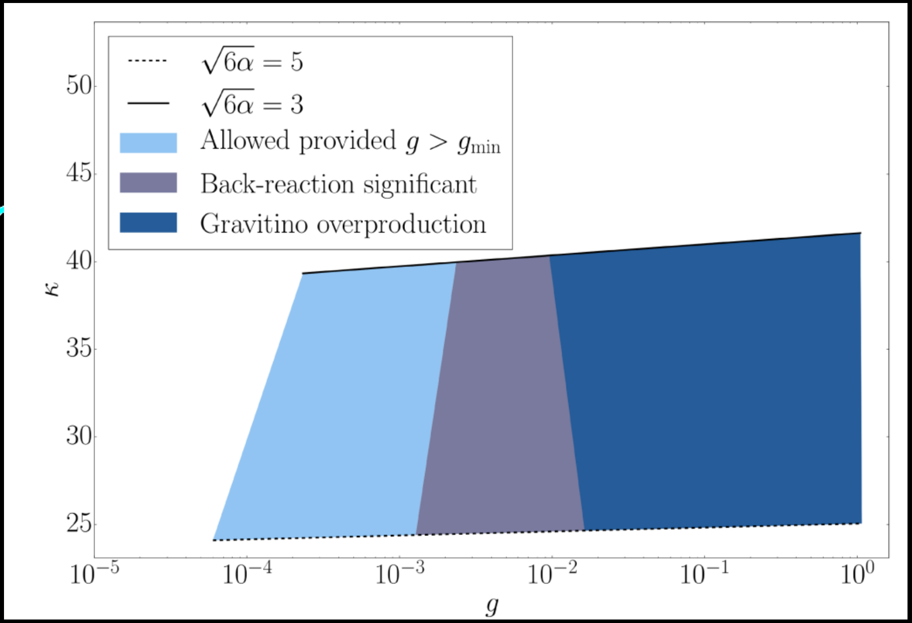
- Residual potential density comparable to present density

$$\boxed{V = V_Q \exp\left(-\lambda\varphi/m_P\right)}$$

$$V_Q = 2ne^{-2n}M^4$$

$$\lambda = 2/\sqrt{6\alpha} = (2/n)\kappa$$



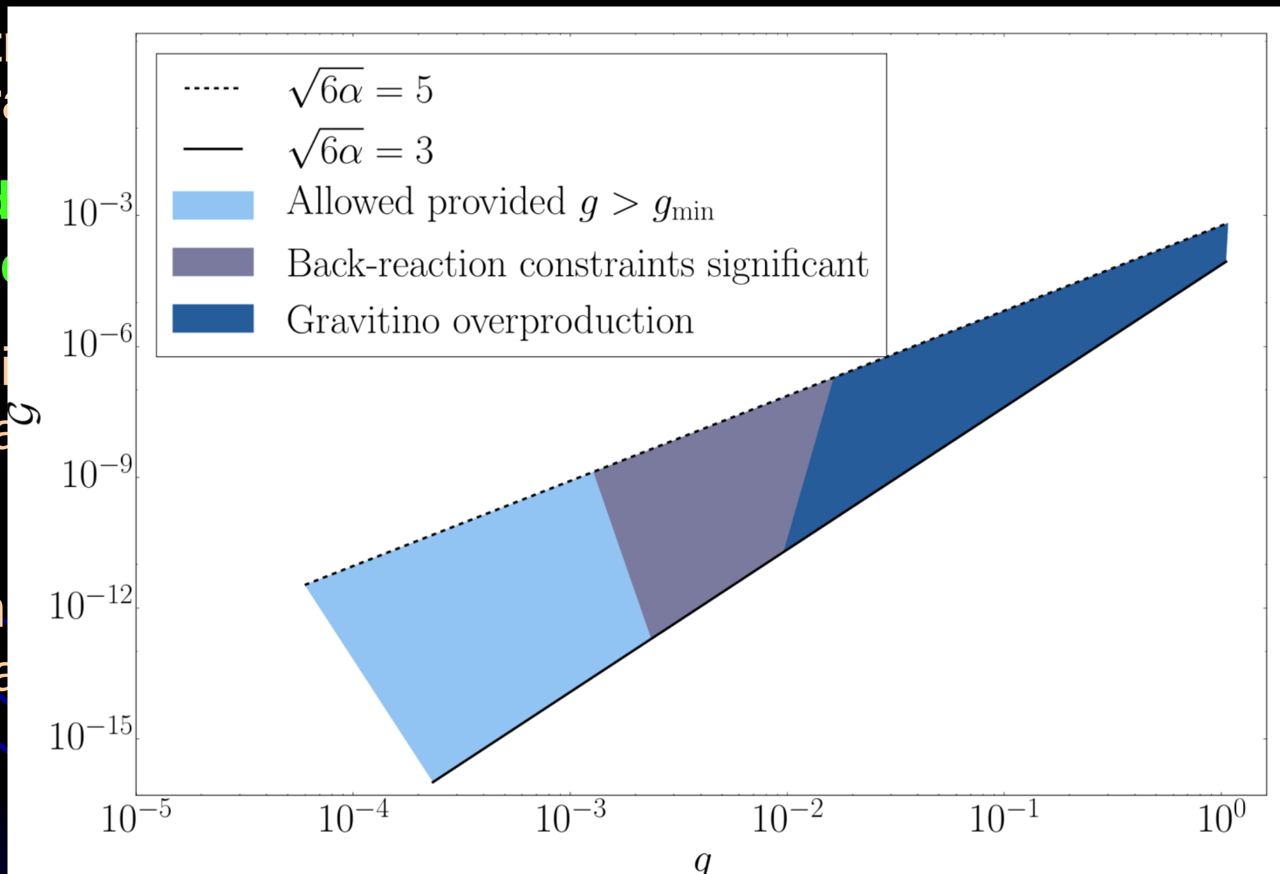


- **Results:**

$\kappa = 24 - 40$ & $V_0^{1/4} \sim \text{TeV}$

"Asymptotic Freedom"

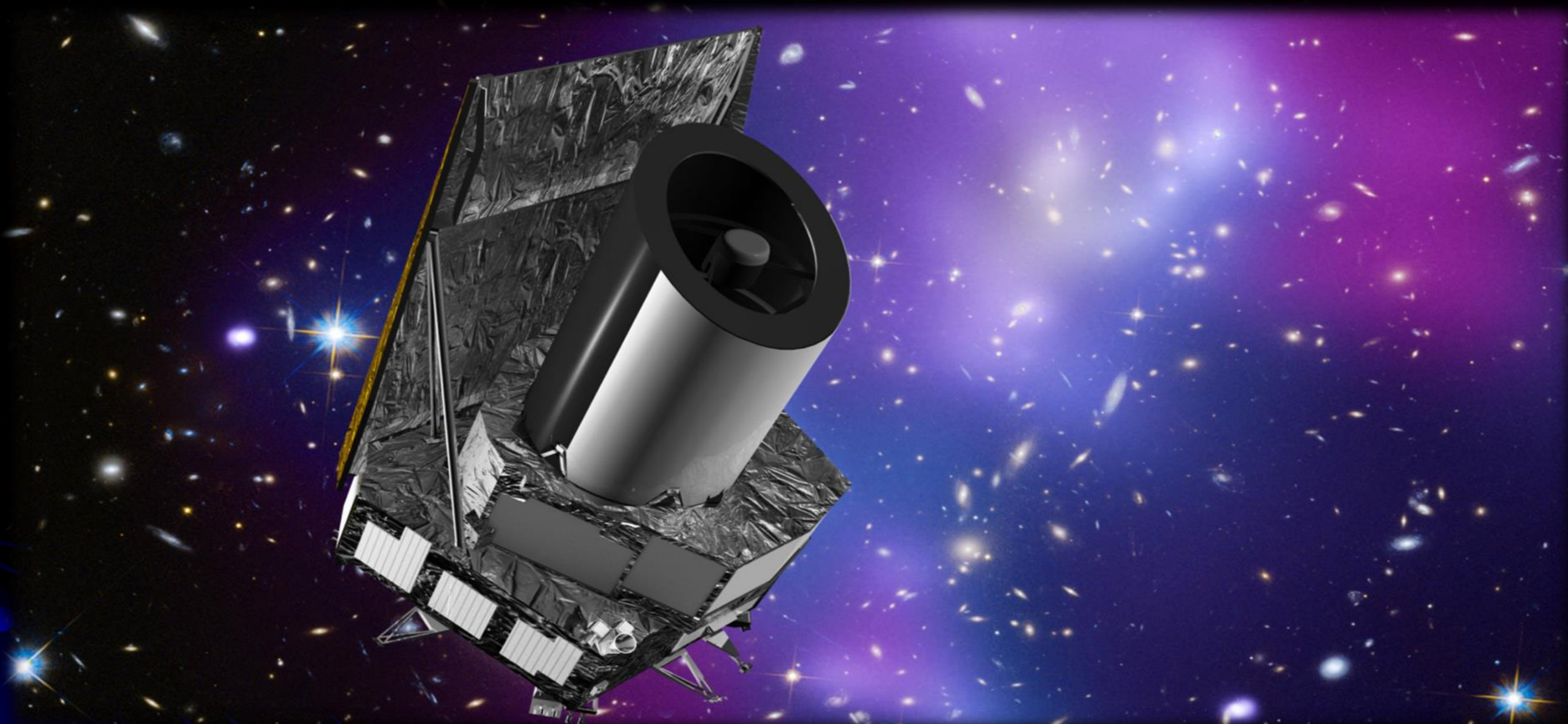
- **α-attr** **ns and** **intera**
- **Field** **flatn**
- consi intera
- stren intera $\frac{4\varphi_F}{\sqrt{6\alpha}\, m_P}\Big)$



φ_F essed √

$$\Omega_r^{\mathrm{IP}} = \frac{g^2}{4\pi^3} \quad \Rightarrow \quad \mathcal{G} \sim e^{-4/3\sqrt{\alpha}} \left(\frac{g}{2\pi^{3/2}}\right)^{4/\sqrt{\alpha}}$$

Conclusions



- Correlated predictions for tensors and w_a **Smoking gun** Kallosh, Linde, Yamada (2017)
- **α-attractors naturally avoid radiative corrections and 5th force problems, while generate a potential with multiple plateaus, which can accommodate Quintessential Inflation**

Gravitational Reheating

- **Gravitational Reheating: Due to inflationary particle production of all light, non-conformally invariant fields**
  Ford (1987)

$$\rho_\gamma^{\rm end} = q\,\frac{\pi^2}{30} g_*^{\rm end} T_H^4 = \frac{q\, g_*^{\rm end}}{480\pi^2} H_{\rm end}^4 \qquad T_H \equiv \frac{H_{\rm end}}{2\pi}$$

- Reheating temperature:

$$T_{\rm reh} = \frac{q^{3/4}}{24\pi^2}\left(\frac{g_*^{\rm end}}{g_*^{\rm reh}}\right)^{1/4}\sqrt{\frac{g_*^{\rm end}}{10}}\,\frac{H_{\rm end}^2}{m_P} \propto \frac{V_{\rm end}}{m_P^3}$$

$$\boxed{T_{\rm reh} \sim 10^5\,{\rm GeV}}$$

Gravitino constraint $\surd$

- Inflationary e-folds:

$$N_* \simeq 62 + \ln\left(\frac{{\rm V}_{\rm end}^{1/4}}{{\rm m_P}}\right) + \frac{1}{3}\ln\left(\frac{{\rm V}_{\rm end}^{1/4}}{{\rm T_{reh}}}\right) \simeq 63.5$$

- Frozen field:

$$\Omega_\gamma = \frac{\rho_\gamma}{\rho} \sim \frac{H^4}{(H m_P)^2} \sim 10^{-10} \Rightarrow \boxed{\Delta\varphi_F \simeq 43\, m_P}$$

- **However, spike in GWs challenges BBN**
  - More efficient reheating is needed