Gauss-Bonnet Coupled Quintessential Inflation

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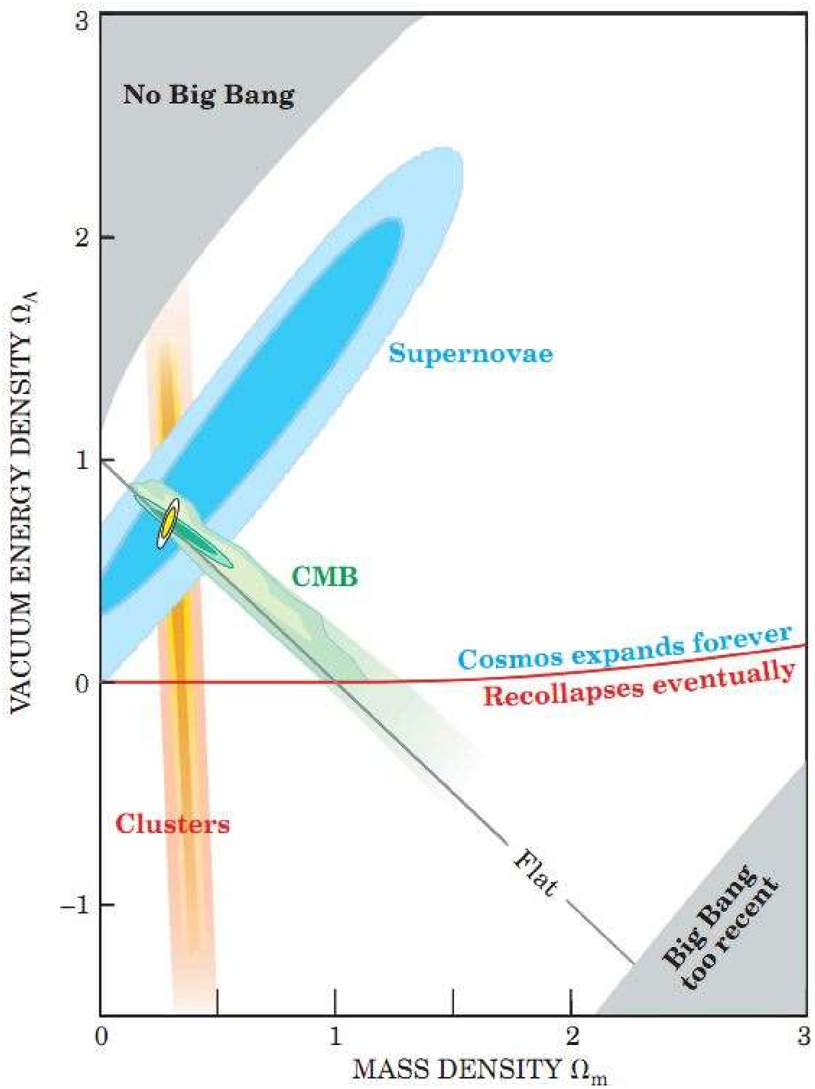
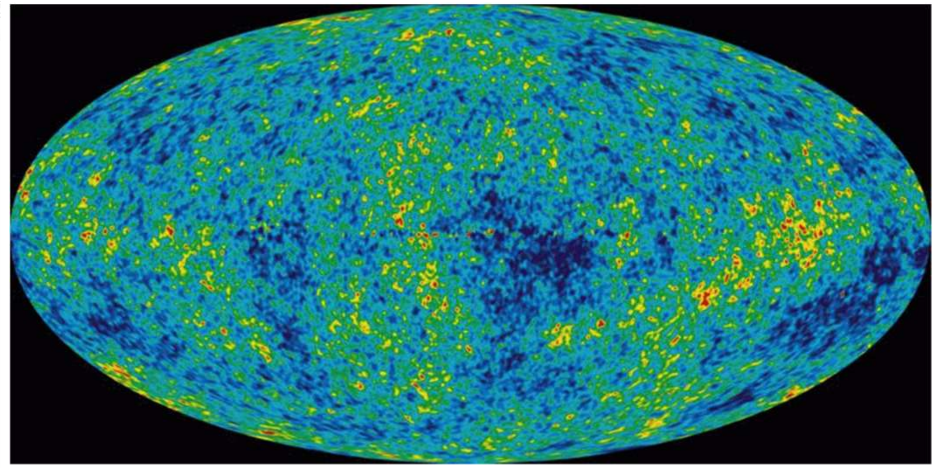
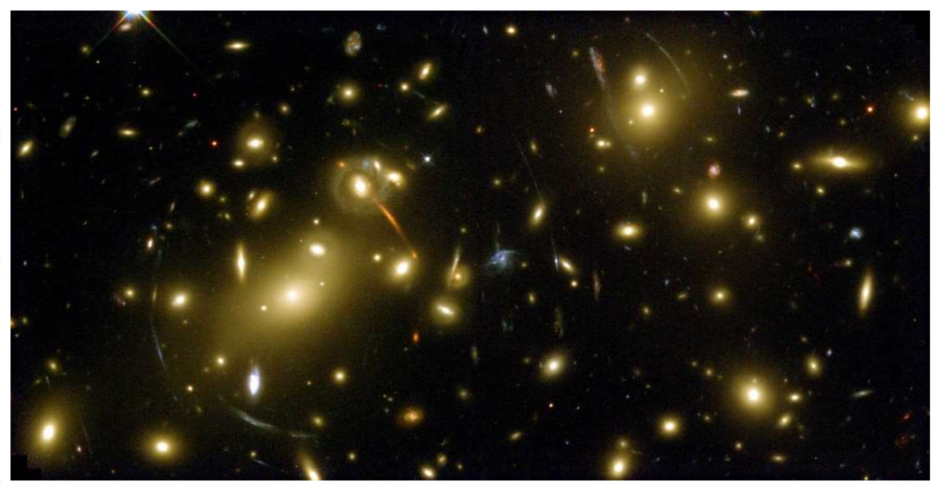
Work done under the supervision of Dr. Konstantinos Dimopoulos, in collaboration with Prof. Carsten van de Bruck and Chris Longden from Sheffield University.

Accelerating Expansion

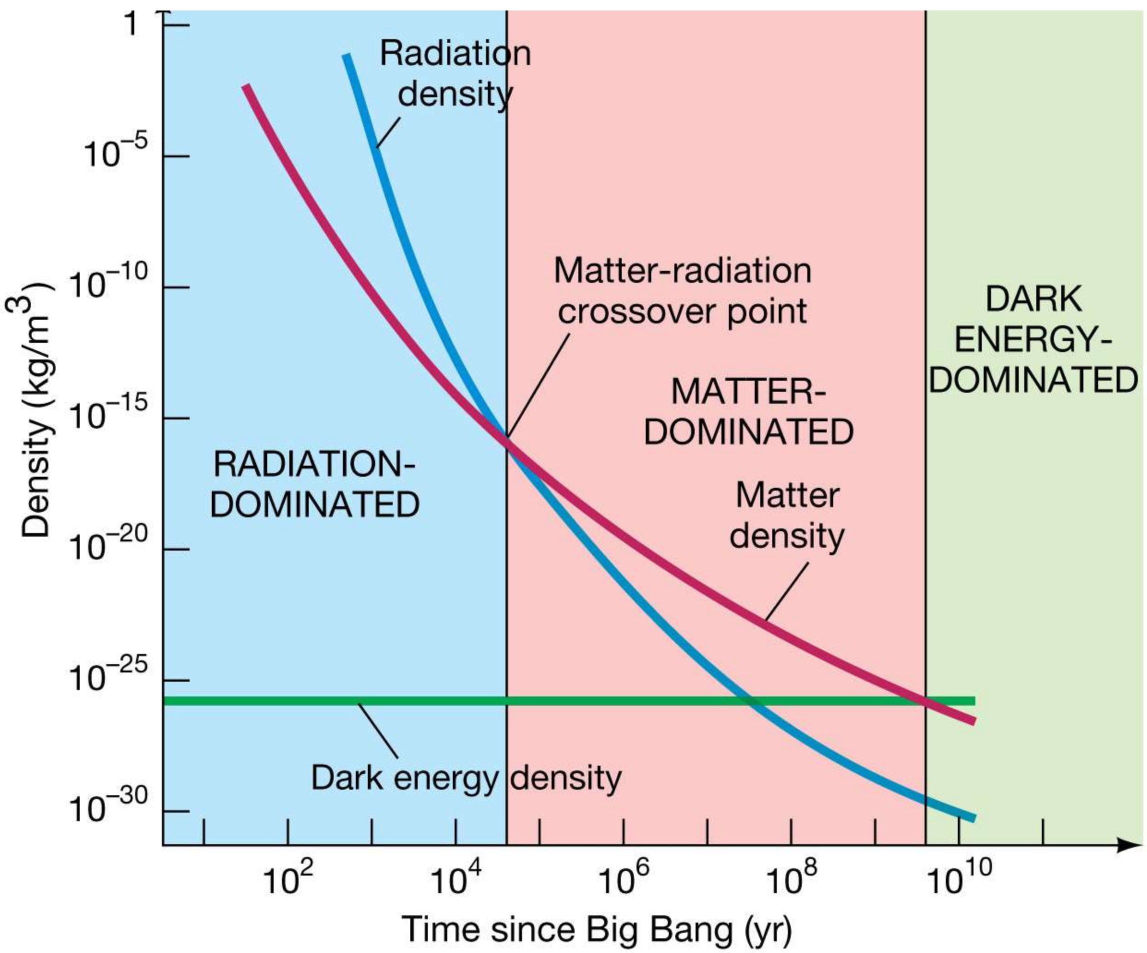






Cosmological Constant Model

- Cosmological Constant – energy density of empty vacuum with negative pressure
- $\rho_\Lambda \approx (10^{-3}\text{eV})^4$
- Equation of state parameter: ω=-1
- Problems with CC:
  - Cosmological Constant Problem
  - Fine-tuning
  - Future Horizons



Quintessence

- Dynamical scalar field, varying in space and/or time
- Dominates the energy density of the Universe at the present time

$$\omega \leq -\frac{1}{3}$$

- Ratra & Peebles, 1988 (before discovery of Dark Energy!)

- Problems with Quintessence:
  - Fine tuning problem persists (initial conditions)
  - Fifth force problem

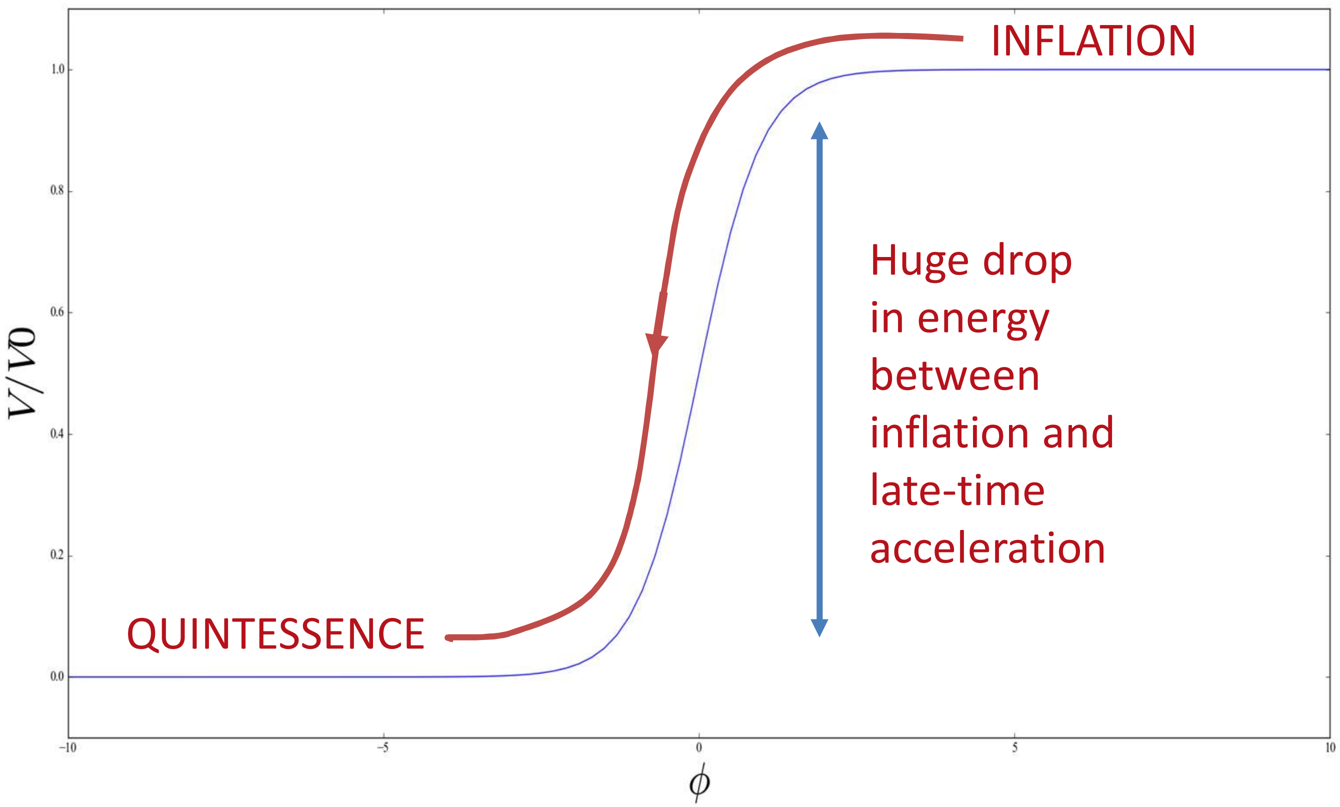
Quintessential *Inflation*

- Links the two observed phases of accelerated expansion – inflation and dark energy, with the same mechanism.

- Considerations:
  - Persisting fine-tuning problem but initial conditions fixed.
  - Persisting fifth force problem.
  - Very large difference between plateaus – must work at two very different energy scales whilst maintaining flat plateaus.
  - Avoid super-planckian field values.
  - Should not feature Λ scale: $\rho_\Lambda \approx (10^{-3}\mathrm{eV})^4$

Tanh as a Prototype Potential

$$V(\phi) = \frac{V_0}{2}\left(1 + \tanh\left[p\frac{(\phi - \phi_c)}{m_P}\right]\right)$$



- Two plateaus
- Rolls super-Planckian when the exponential is very steep
- Radiative corrections threaten flatness of late-time plateau
- How can we fix this?

Introducing a Gauss-Bonnet Term

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{m_P^2}{2}R - \frac{1}{2}(\partial\phi)^2 - \frac{m_P^2}{2}G(\phi)E - V(\phi)\right]$$

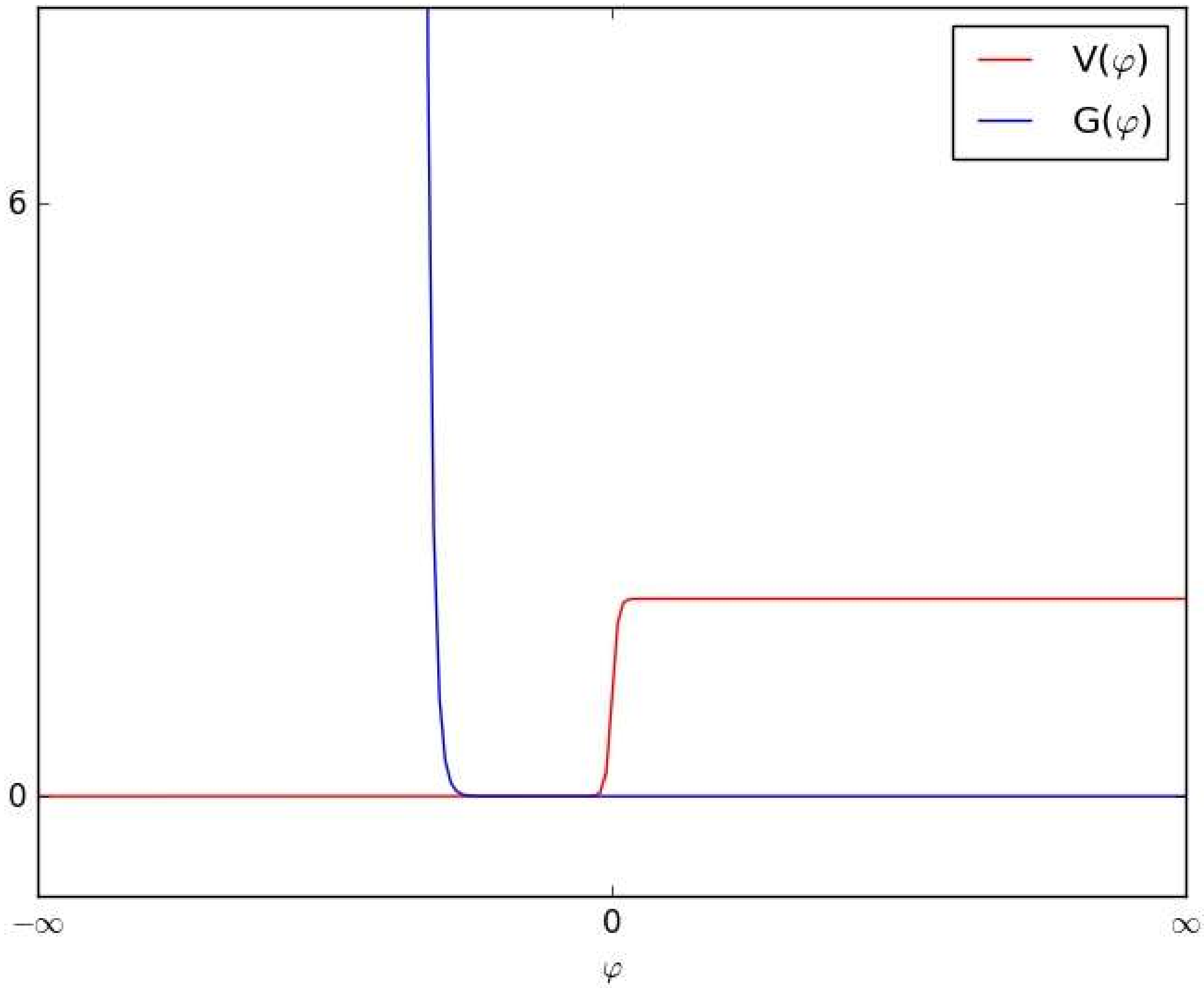
Gauss-Bonnet: $E = R^2 - 4R^{\mu\nu}R_{\mu\nu} + R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma}$

- Total derivative
- No ghosts
- No effect on equations of motion

Coupling to the Gauss-Bonnet: $G(\phi) = G_0 e^{\frac{-q\phi}{m_P}}$

- Varies with ϕ
- Affects equations of motion
- Suppressed until late times
- Freezes the inflaton's motion

GB Introduces Minimum to Effective Potential



- Minimum in effective potential
- Arises from non-constant coupling to GB term
- We can control its location

Inflationary Observables

$$n_s \approx 1 - \frac{2}{N}$$

$$r \approx \frac{2}{p^2 N^2}$$

For N = 50 (60):

$$n_s \approx 0.960\ (0.967)$$

$$r_{\max} \approx 0.0008\ (0.0006)$$

Planck 1σ (2σ) : $n_s = 0.968 \pm 0.006\ (0.01)$

Model Constraints

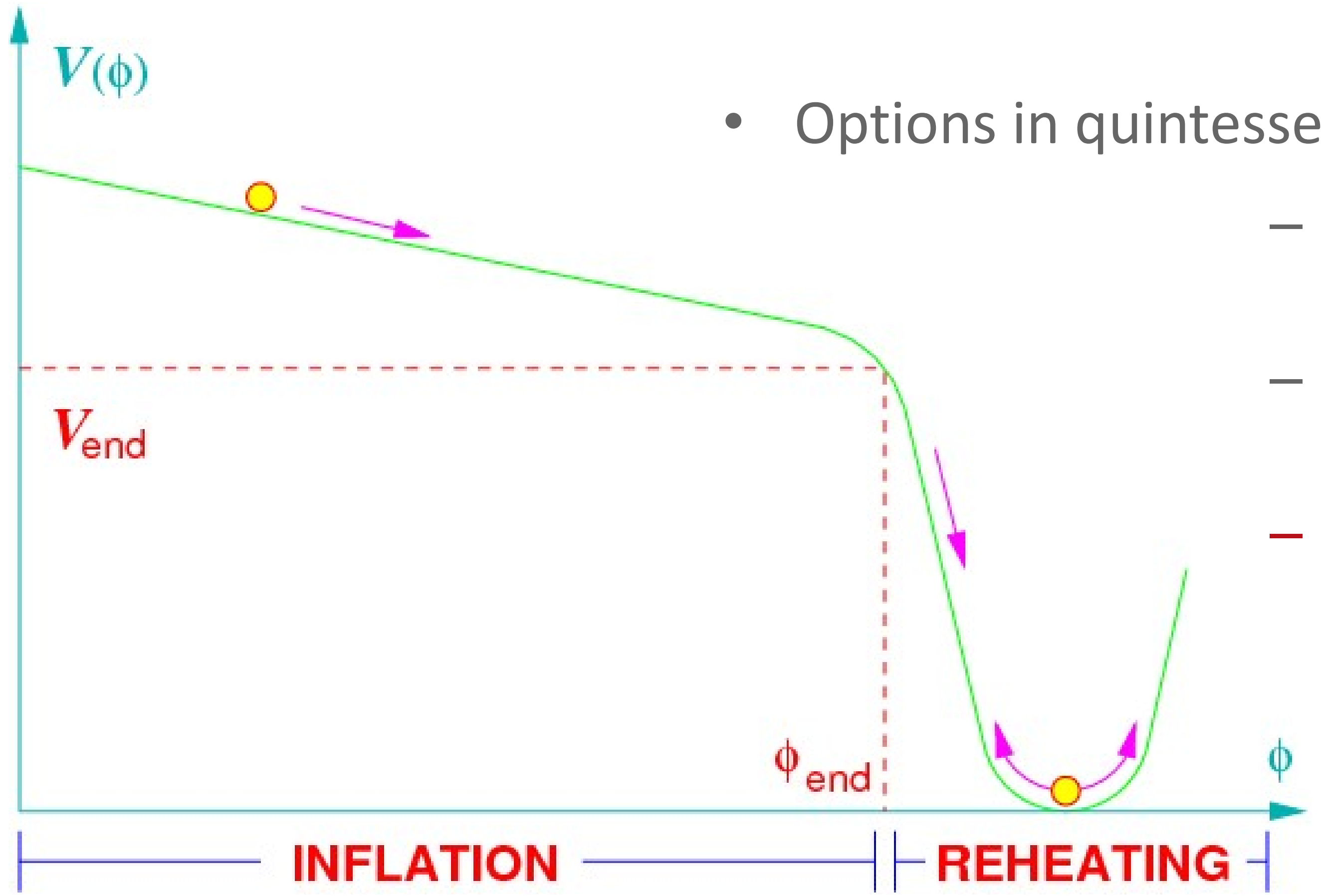
Remain sub-Planckian: $\phi < m_P$

Satisfy dark energy observations:

$$\rho(\phi_0) = \rho_{DE} = 10^{-120} m_P^4$$

Reheating in Quintessential Inflation

Models of quintessential inflation have non-oscillatory behaviour. Cannot reheat the Universe in the traditional perturbative way.



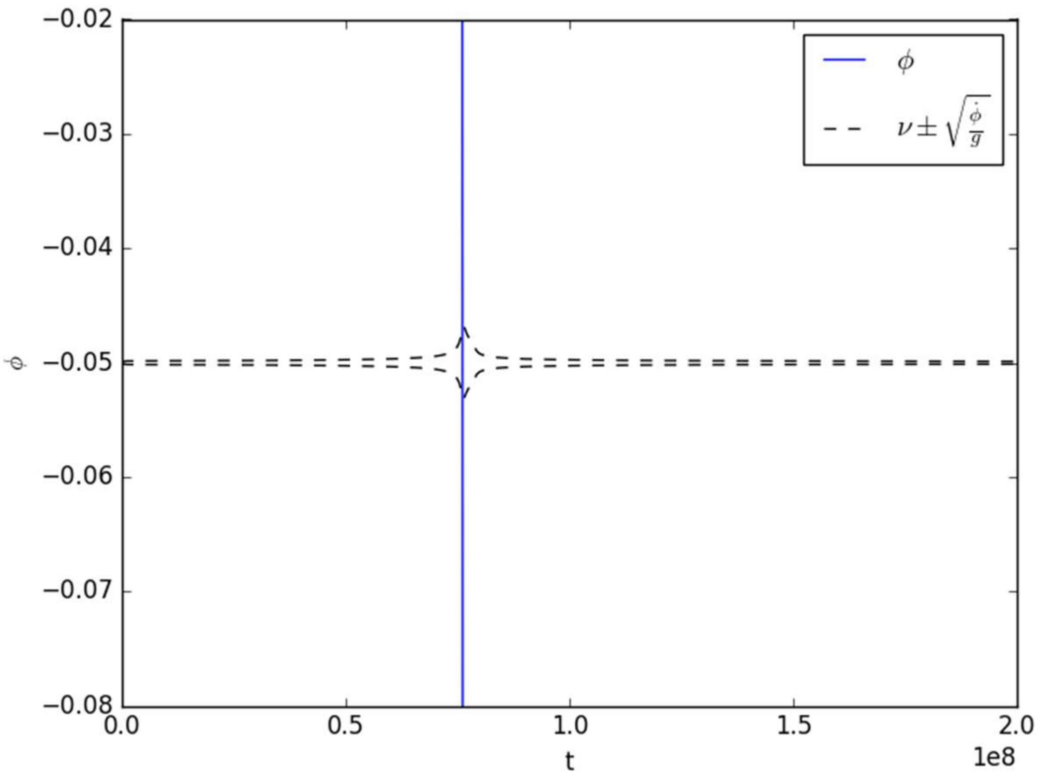
- Options in quintessential inflation:
  - Gravitational reheating
  - Curvaton reheating
  - Instant preheating

Instant Preheating

Felder, Kofman & Linde, Phys. Rev. D 59 (1999)

$$\mathcal{L} = -\frac{1}{2} g^2 \chi^2 |\phi - \upsilon|^2 - h\bar{\varphi}\varphi\chi$$

Adiabaticity constraint violated, particle production: $|\dot{m}_\chi| \gg {m_\chi}^2$



- Region of particle production:

$$\phi = \nu \pm \sqrt{\frac{|\dot{\phi}|}{g}}$$

- Shift symmetry allows us to incorporate instant preheating in to a range of model parameters

Correct History of Universe Evolution

For radiation domination: $\rho(\chi *) > \rho(\phi_a{}^{\dagger})$

Kinetic > potential energy : $\frac{1}{2}\dot{\phi}_a^2 > \mathrm{V}(\phi_a)$

Kinetically dominated field evolves as a^{-6}

Radiation evolves as a^{-4}.

Ensures sufficient R.D.

* ϕ_a refers to *after* instant preheating.
† We assume all the energy is instantaneously converted into radiation and thermalised

Model Constraints

Sub-Planckian: $\phi < m_P$

DE observations: $\rho(\phi_0) = \rho_{DE}$

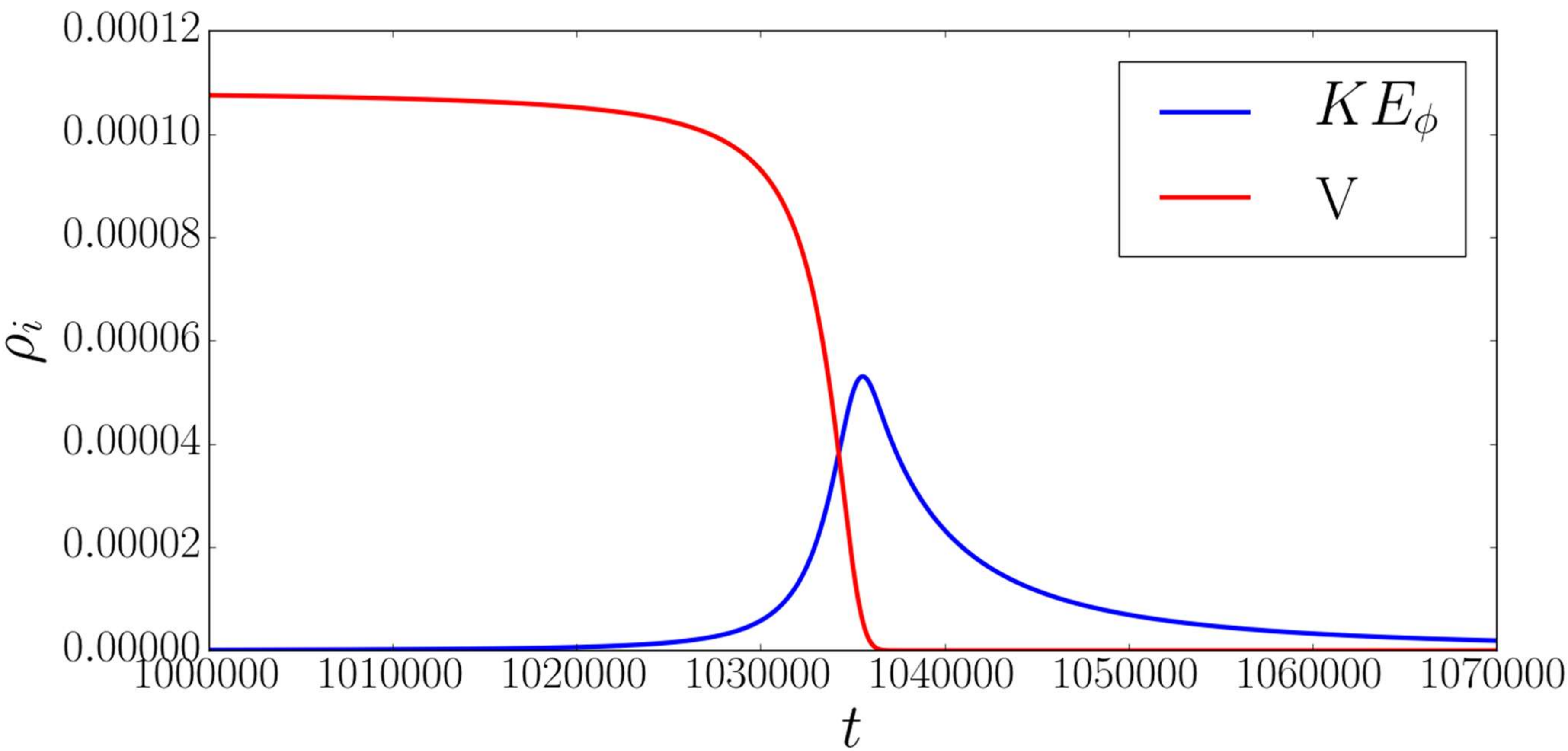
Radiation Domination:

$$\frac{1}{2}\rho(\phi_b{}^*) < \rho_\chi < \rho(\phi_b) - 2V(\phi_{IP})$$

$$\mathrm{K.E.}(\phi) > 3V(\phi)$$

* ϕ_b refers to *before* instant preheating.

Model Constraints



Dark Energy Constraint
$\rho(\phi_0) = \rho_{DE}$

- GB Coupling freezes time evolution of field:
- At very late times:

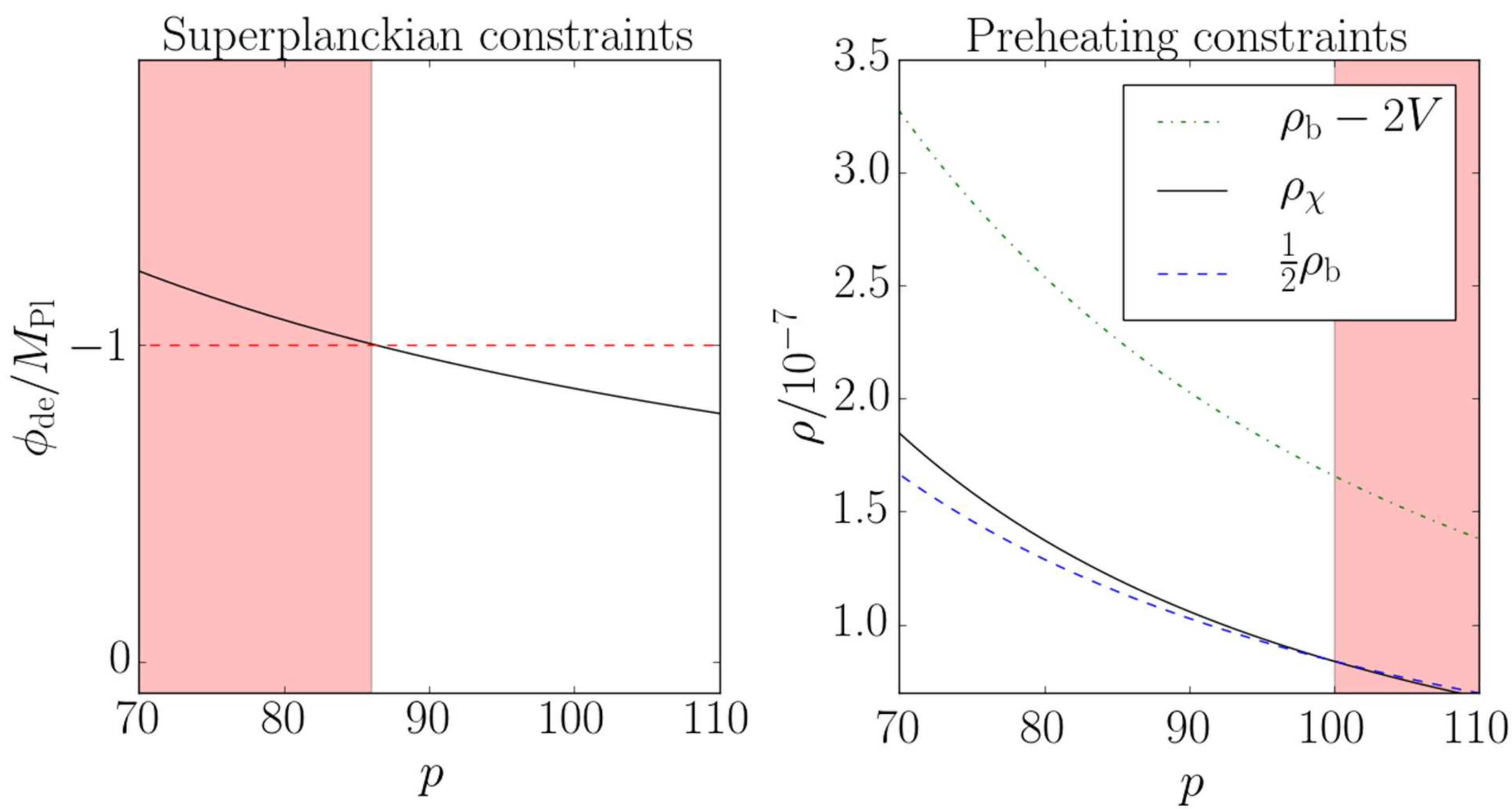
$$\frac{\phi_S}{m_P} = \frac{1}{q-2p} \ln \frac{2qV_0G_0}{3pm_P^2} \quad (1)$$

- In terms of the density parameters:

$$V + \frac{V_{,\phi}^2}{18H^2} + \left[3\Omega_\Lambda + \frac{2}{3}(7+3w)V_{,\phi}\, G_{,\phi}\right] m_P^2 H^2 + 2(1+3w)(13+3w)\left(m_P^2 G_{,\phi}\right)^2 H^6 = 0 \quad (2)$$

- Inserting $\Omega_\Lambda = 1$ into Eq.(2) → we recover Eq.(1)
- Inserting $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $\mathrm{H} = H_0$ → we find ϕ_0
- We can use dark energy constraint to constrain parameters

Results



$$q = 4p, G_0 m_P^2 = 1, g = 0.8$$

Results

- Natural choice of parameter values:

$$g < 1\,, G_0 > m_P^{-2}, q > 2n$$

- Final constraints for *prototype* model:

$$50 \lesssim p \lesssim 350$$

- Large viable parameter space
- Working model realisation applicable to any potential with two plateau regions

Theoretical Consideration - Fifth Force Problem

- Mass dependent couplings to the standard model:

$$m_{eff}{}^2 = V'' \approx H$$

- Compton Wavelength ~ H^{-1} – we must include the interaction terms in the Lagrangian:

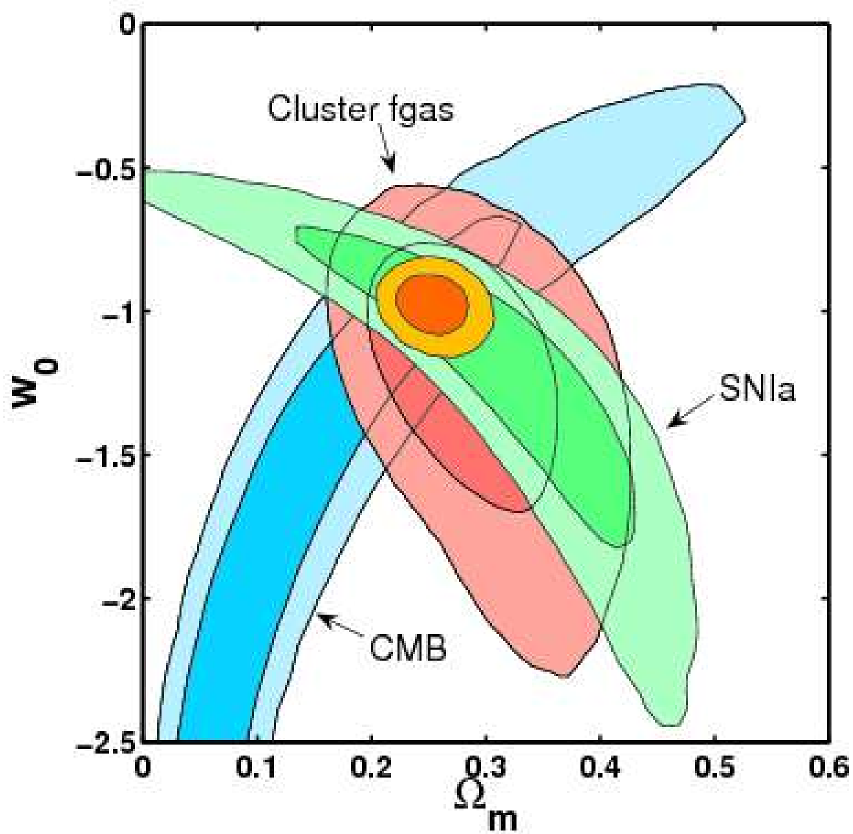
$$\sim \frac{\beta_i \phi}{m_p} \mathcal{L}_i$$

- To ensure suppression of these terms:

$$\beta_i \phi < m_p$$

- Motivation for our paper, $\phi < m_P$, avoids fine-tuning of β_i.

Distinguishing Between Cosmological Constant and Quintessence



Experimental Observations of the Equation of State

- Cosmological constant, ω = -1
- Quintessential inflation, not always ω = -1, time dependent.

Gauss-Bonnet Coupled Quintessential Inflation - Summary

- Coupling between Gauss-Bonnet term and scalar field maintains a sub-Planckian field.
- Ensures the stability of the second plateau and late-time acceleration.
- Inflationary observables in agreement with Planck results.
- Parameter space matching dark energy observations today.
- Quintessential Inflation is a natural (minimal and economical) alternative to ΛCDM

Thank you for listening, any questions?

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