# Current Cosmic Acceleration with Slotheon

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# Observational evidences of current Cosmic Acceleration

- **Supernovae type Ia** → **Universe is Accelerating**

  standard candles
  Their intrinsic luminosity is know

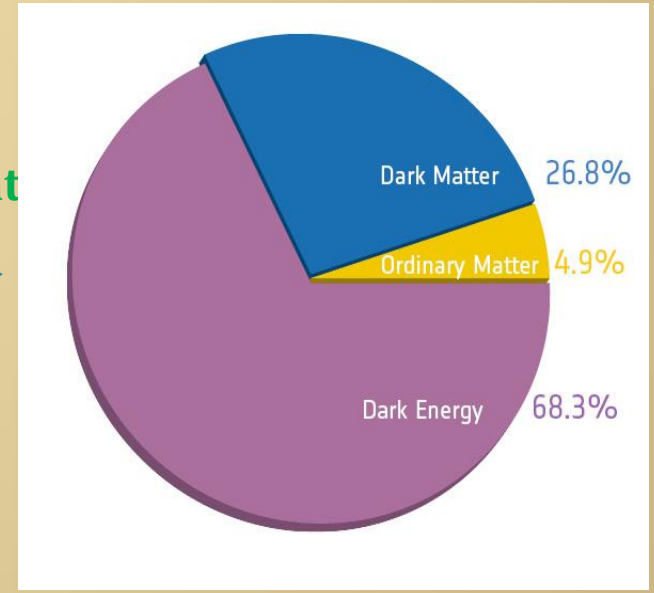
- **Large Scale Structure**

  Clustering of matter gives information on

  cosmological parameters, especially matter content

- **Cosmic Microwave Background**

  CMB is a strong pillar of the Big Bang cosmology




It is a powerful tool to use in order to constrain several cosmological parameters

# Dynamical dark energy models

$w \neq -1$

There are two approaches.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ (Einstein equation)

## (i) Modified gravity

f(R) gravity,
Scalar-tensor theory,
Braneworlds,
Gauss-Bonnet gravity,
.....

## (ii) Modified matter

Quintessence,
K-essence,
Tachyon,
Chaplygin gas,
.....

- Should be free from negative energy instability
- Should not conflict with local physics

# Slotheon Gravity

$$S_{\rm sloth} = \frac{1}{2}\int {\rm d}^4x\sqrt{-g}\left[M_{\rm P}^2 R - \left(g^{\alpha\beta} - \frac{G^{\alpha\beta}}{M^2}\right)\partial_\alpha\pi\partial_\beta\pi\right]$$

C. Germani *et al*,
PRD 85,103501,2012

Galileon symmetry : $\pi \to \pi + c + c_\mu x^\mu$

The name comes from the fact that on a given metric

$$H_k \sim \dot{\pi}^2\left(1 + \frac{G^{tt}}{M^2}\right) \geqslant \dot{\pi}^2$$

Given a energy density the field is slower than its canonical cousin!!

Gravitationally enhanced friction

# Slotheon in a Potential

D.Adak, A. Ali, D. Majumdar
PRD 88, 024007, 2013

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}\left(M_{\rm pl}^2 R - \left(g^{\mu\nu} - \frac{G^{\mu\nu}}{M^2}\right)\pi_{;\mu}\pi_{;\nu}\right) - V(\pi)\right] + \mathcal{S}_m\left[\psi_m; e^{2\beta\pi/M_{\rm pl}} g_{\mu\nu}\right]$$

Crucial coupling between matter and the scalar field

- The action is not galileon invariant
- It is free from Ostrograsky ghost problem
- The slowing of field is solely due to gravitational interaction

## Equation of motion in flat FRW background

$$3M_{\rm pl}^2 H^2 = \rho_m + \rho_r + \frac{\dot\pi^2}{2} + \frac{9H^2\dot\pi^2}{2M^2} + V(\pi)\,,$$

$$M_{\rm pl}^2(2\dot H + 3H^2) = -\frac{\rho_r}{3} - \frac{\dot\pi^2}{2} + V(\pi) + \frac{\dot\pi^2}{2M^2}\left(2\dot H + 3H^2\right) + \frac{2H\dot\pi\ddot\pi}{M^2}\,,$$

$$-\frac{\beta}{M_{\rm pl}}\rho_m = \ddot\pi + 3H\dot\pi + \frac{3H^2}{M^2}\left(\ddot\pi + 3H\dot\pi + \frac{2\dot H\dot\pi}{H}\right) + V'(\pi).$$

$$\dot\rho_m + 3H\rho_m = \frac{\beta}{M_{\rm pl}}\dot\pi\rho_m,$$

$$\dot\rho_r + 4H\rho_r = 0.$$

# Autonomous System

## Equations

$$\frac{\mathrm{d}x}{\mathrm{d}N} = x\left(\frac{\ddot{\pi}}{H\dot{\pi}} - \frac{\dot{H}}{H^2}\right),$$
$$\frac{\mathrm{d}y}{\mathrm{d}N} = -y\left(\sqrt{\frac{3}{2}}\lambda x + \frac{\dot{H}}{H^2}\right),$$
$$\frac{\mathrm{d}\epsilon}{\mathrm{d}N} = 2\epsilon\frac{\dot{H}}{H^2},$$
$$\frac{\mathrm{d}\Omega_r}{\mathrm{d}N} = -2\Omega_r\left(2 + \frac{\dot{H}}{H^2}\right),$$
$$\frac{\mathrm{d}\lambda}{\mathrm{d}N} = \sqrt{6}x\lambda^2(1-\Gamma),$$

## Variables

$$x = \frac{\dot{\pi}}{\sqrt{6}HM_{\mathrm{pl}}}, \quad y = \frac{\sqrt{V(\pi)}}{\sqrt{3}HM_{\mathrm{pl}}},$$
$$\epsilon = \frac{H^2}{2M^2}, \quad \lambda = -M_{\mathrm{pl}}\frac{V'(\pi)}{V(\pi)},$$

$$N \equiv \ln a,\ \Gamma = \frac{VV_{,\pi\pi}}{V_{,\pi}^2}$$

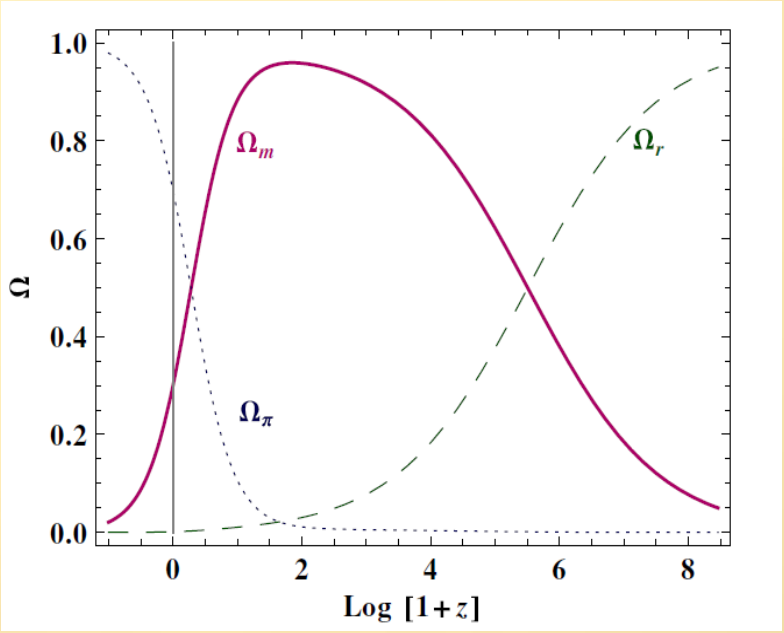
$$\Omega_m = 1 - (x^2(1+18\epsilon) + y^2 + \Omega_r)$$

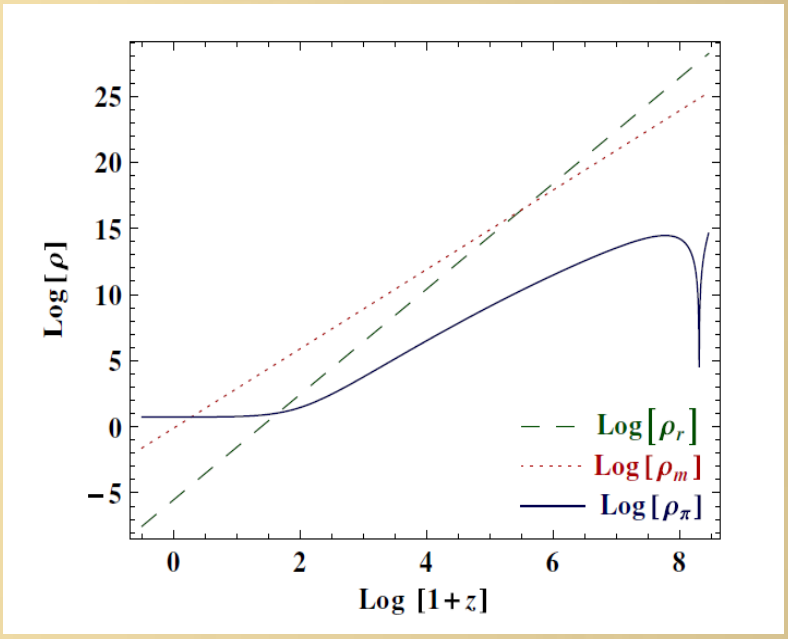
## Form of potential

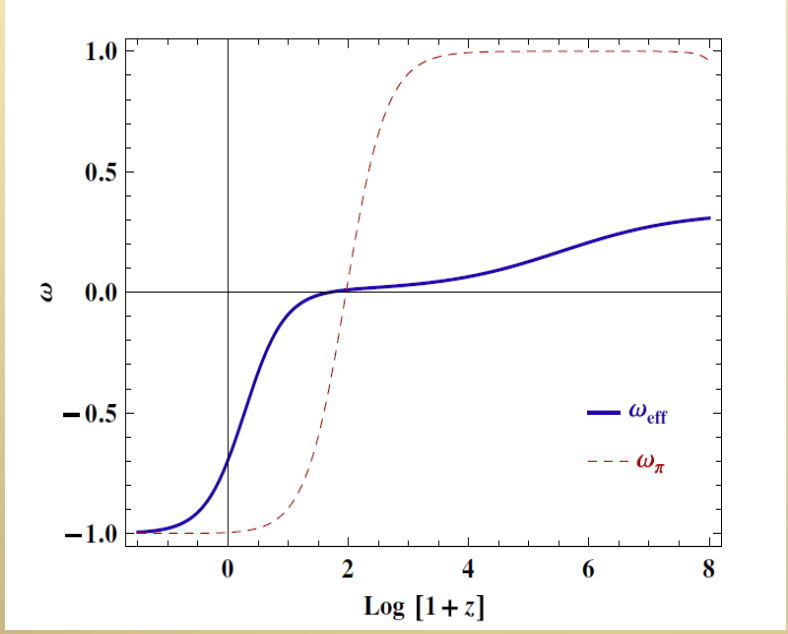
$$V(\pi) = V_0 e^{\frac{-\lambda\pi}{M_{\mathrm{pl}}}}$$

- Γ =1 and therefore λ is a constant
- When ε =0 the model is similar to the standard coupled dark energy model

# Numerical Analysis

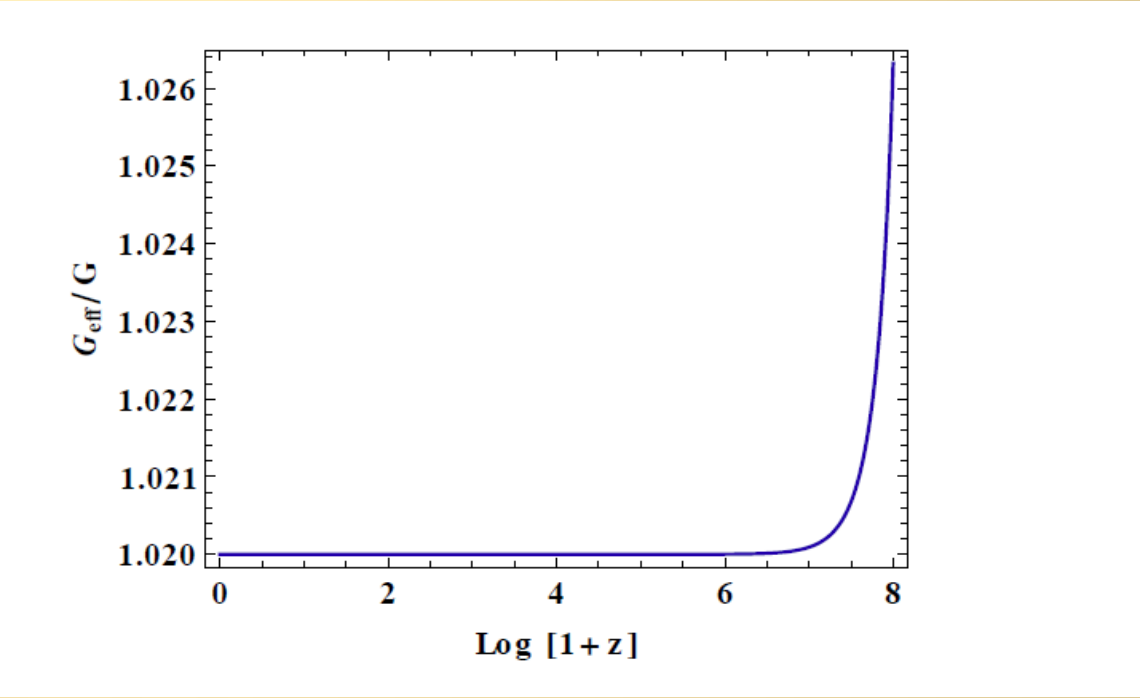



- Tracker behavior of the field is depicted
- Successive sequence of radiation, matter and dark energy epochs are obtained

# Cosmological Perturbation



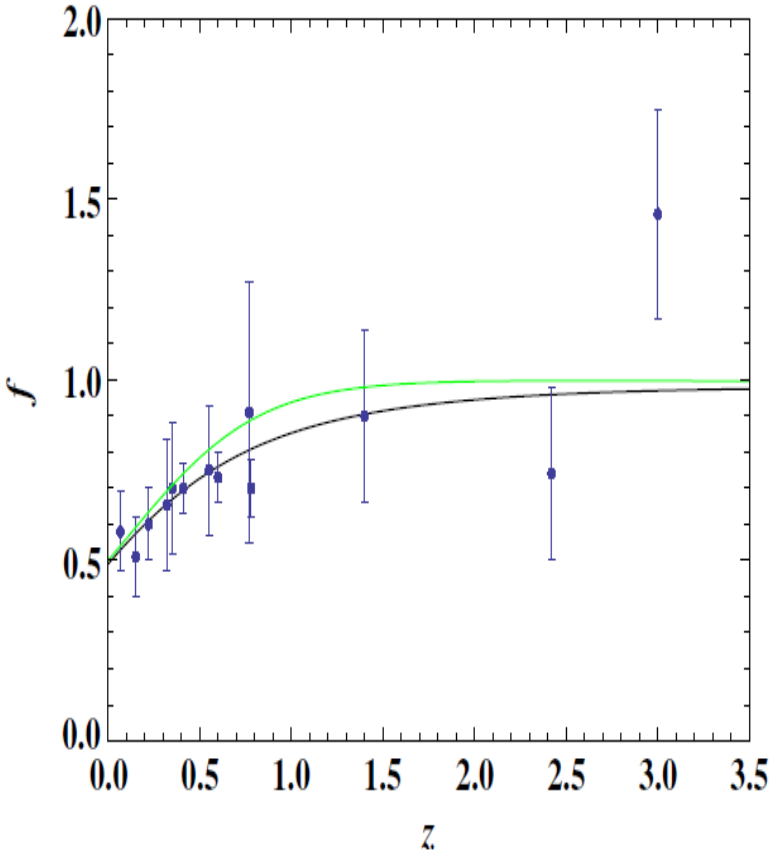

In the de Sitter phase: $G_{\rm eff} = G(1+2\beta^2) > G$

- The model reduces to coupled quintessence scenario at large scale thereby giving strong constraints on β
- Geff is large in the higher redshift which gives different BBN Constraints than in General relativity

# Observational Evidences

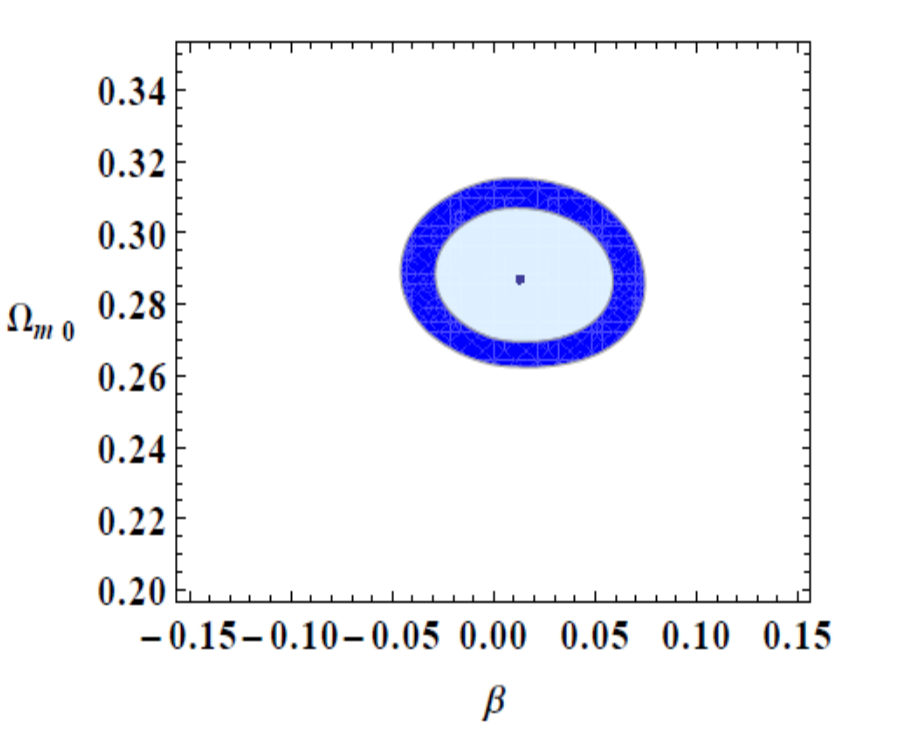
Growth factor:

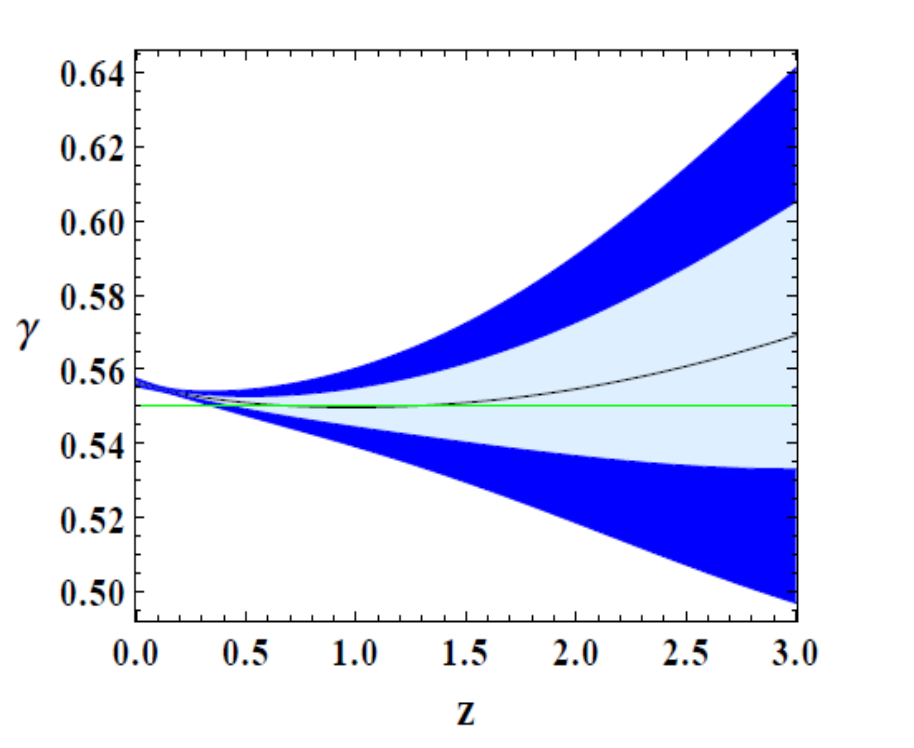
$$f = \frac{\mathrm{d}\ln\delta_m}{\mathrm{d}\ln a}\,.$$




- deviation from ΛCDM model is not significant
- f < 1 for all redshift which means growth is in accordance with Einstein- de-Sitter model

$$\chi^2 = \chi^2_{Growth} + \chi^2_{SN} + \chi^2_{BAO} + \chi^2_{CMB}$$




- β is highly constrained
- At present the evolution of γ is consistent with dark energy models
- But the value of γ at all redshift is large compared to that of ΛCDM

# Conclusion

- Adding a potential to Slotheon gravity breaks the symmetry but gives a viable cosmology
- With exponential potential the model gives an accelerating universe at late times
- The model is similar to coupled quintessence at late times
- The deviation of growth factor compared to ΛCDM is negligible
- From observational data β is constrained to small range of values and present density of matter is constrained around the concordance values.
- The growth index is large for all redshift compared to ΛCDM

# THANK YOU