LATE TIME ACCELERATION IN A SLOW MOVING GALILEON FIELD

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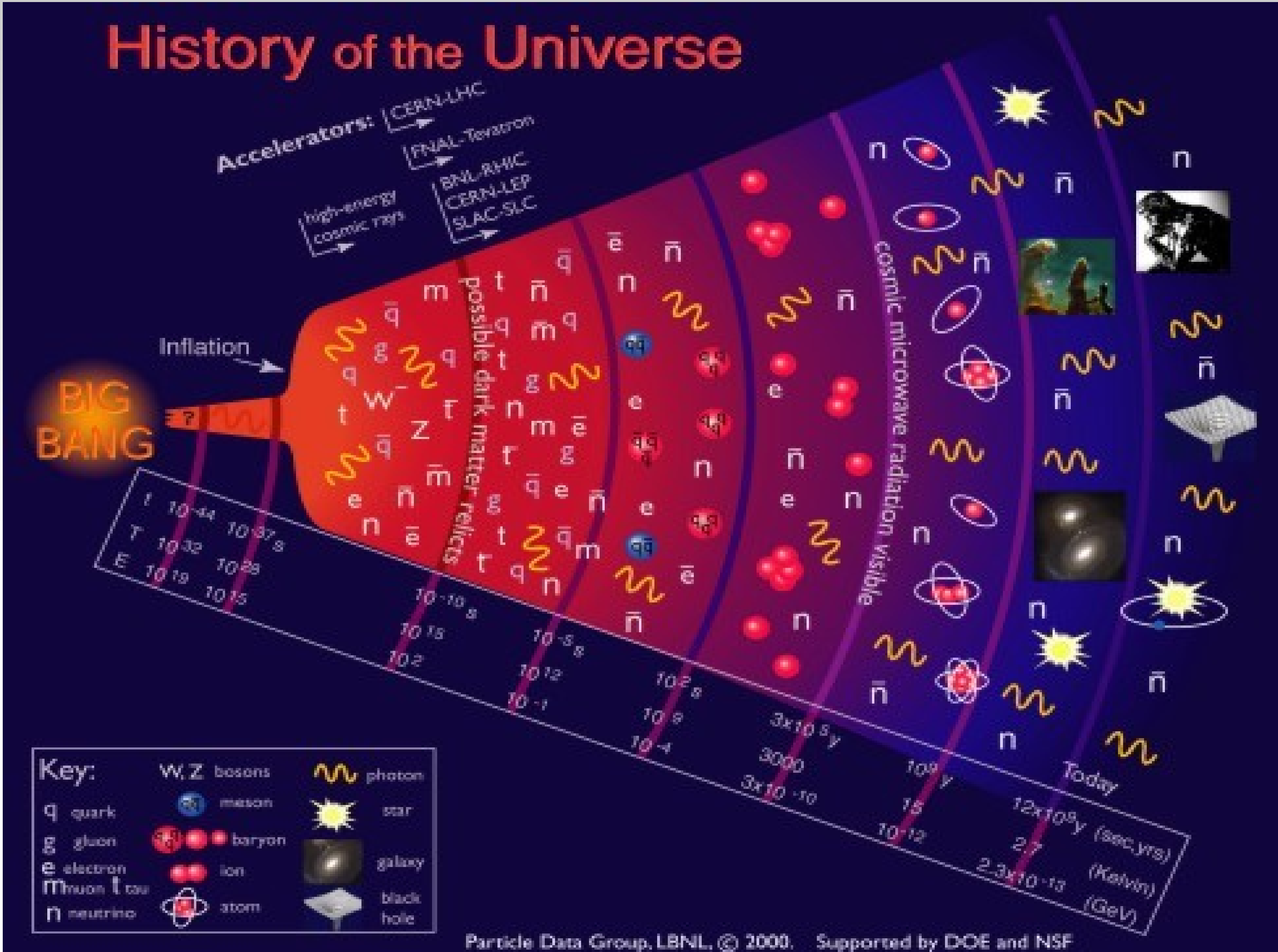
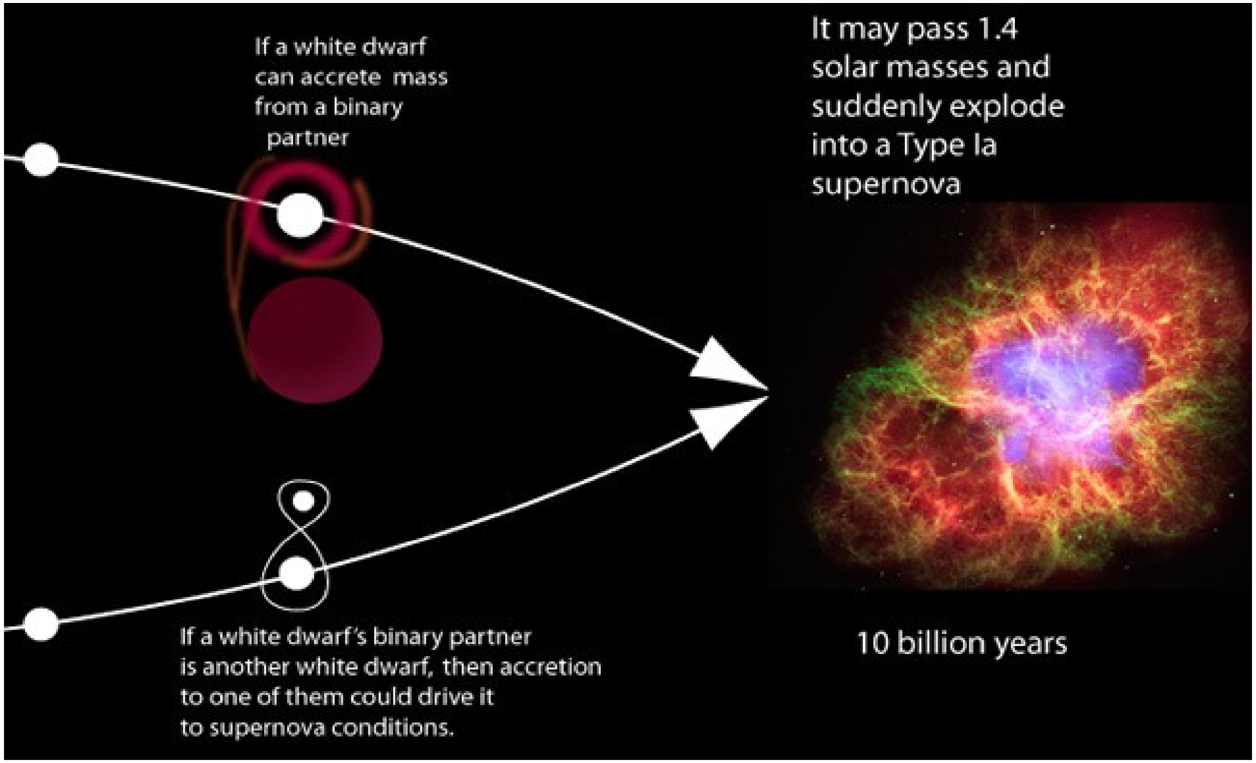

History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Evidence of Accelerating Universe

- Distance measurements of different Type Ia Supernovae
- The luminosity distance is actually measured.

$$d_L^2 \equiv \frac{L_s}{4\pi\mathcal{F}}$$

- Where F is the energy flux at a distance d.



Evidence of Accelerating Universe

$$H(z) \equiv \frac{\dot{a}}{a} = c\left[\frac{d}{dz}\left(\frac{d_L(z)}{1+z}\right)\right]^{-1}$$

$$H^2(z) = \frac{8\pi G}{3}\rho(z)$$

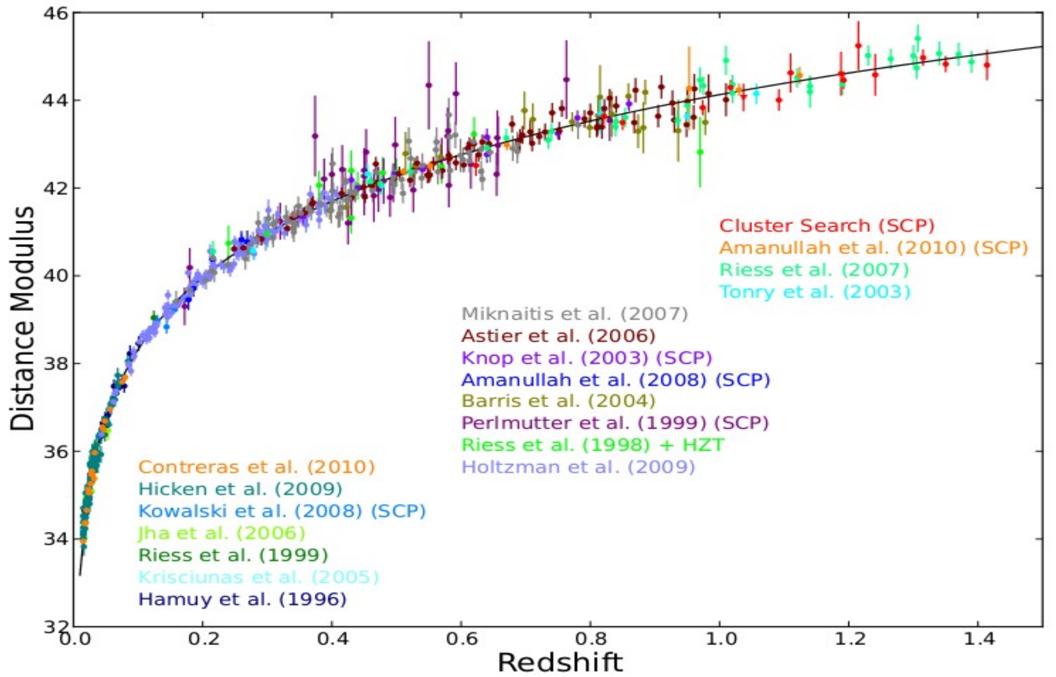
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

For accelerated expansion of the universe,

$$p > -\frac{1}{3}\rho$$

Nobel Prize in Physics 2011

Luminosity Distance of different supernovae 1a at different redshift z



Dark Energy is believed to cause this accelerated expansion of the universe

Just after Big Bang, the Universe went through a rapid phase of expansion known as "Inflation".

During the inflationary phase, the Universe has expands to 50 − 60 e-foldings.

This era is known as the Inflationary era (10^{-36} to 10^{-33} or 10^{-32} s after Big Bang).

This era is followed by radiation and matter dominated era (structure is formed; stars, galaxies etc.).

Recent cosmological observations suggest that the Universe is currently undergoing another phase of accelerated expansion. But the rate of expansion is not as high as the rate of inflation.

It is conjectured that the late time acceleration can be attributed to an exotic fluid with negative pressure namely Dark Energy

Dark Energy constitutes about ~ 70% of the total energy content of the Universe

The simplest candidate for Dark Energy consistent with the observation is a cosmological constant.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\Lambda g_{\mu\nu}$$

$$T^{\mu}_{\nu} = \mathrm{diag}(-\rho, p, p, p)$$

$$T_{\mu\nu} = -\Lambda g_{\mu\nu}/(8\pi G)$$

$$a(t) = \exp\left(\frac{\Lambda}{3} t\right)$$

$$\rho = \frac{\Lambda}{8\pi G}$$

$$p = -\frac{\Lambda}{8\pi G} \,.$$

$$H^2 = \Lambda/3$$

$$\Lambda \approx (2.133h \times 10^{-42}\ \mathrm{GeV})^2 \qquad \rho_\Lambda = \frac{\Lambda}{8\pi G} \approx 10^{-123} M_{\mathrm{Pl}}^4 = 10^{-47}\ \mathrm{GeV}^4$$

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Can zero point energy be a solution?

$$\rho_{\rm vac} = \int_0^{k_{\max}} \frac{d^3k}{(2\pi)^3} E = \int_0^{k_{\max}} \frac{d^3k}{(2\pi)^3} \frac{\sqrt{k^2+m^2}}{2}$$

In the large momentum limit (k >> m)

$$\rho_{\rm vac} \approx \int_0^{k_{\max}} \frac{k^3 dk}{(2\pi)^2} = \frac{k_{\max}^4}{16\pi^2}$$

$$k_{\max} = M_{\rm Pl} \qquad \rho_{\rm vac} \approx 10^{74}\ {\rm GeV}^4$$

10^{121} order of magnitude larger than the observed value of cosmological constant

Problem of *Fine Tuning!*

Alternate to Cosmological Constant

Assumes the presence of a scalar field (*Quintessence*)

$$\begin{aligned} S &= S_{\rm Ein} + S_\phi + S_{\rm Matter} \ , \\ S &= \int d^4x\sqrt{-g}\frac{R}{16\pi G} + \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + \int d^4x\sqrt{-g}\mathcal{L}_m \end{aligned}$$

$$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi + V(\phi)\right)$$

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\begin{aligned} \rho_\phi &= -T^0_0 = \frac{1}{2}\dot{\phi}^2 + V(\phi) \ , \\ p_\phi\delta^i_j &= T^i_j \ , \\ p_\phi &= \frac{1}{2}\dot{\phi}^2 - V(\phi) \ . \end{aligned}$$

$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

$$w_\phi = \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

Late time cosmic acceleration is realised if

$$V(\phi) >> \dot{\phi}^2/2 \qquad w_\phi \approx -1$$

The scalar field has to roll down the potential very slowly

$$\rho_\phi \propto \exp\left(-3\int(1+w_\phi)\frac{da}{a}\right)$$

Energy density tends to a constant value.

Slower variation of the energy density of the scalar field than that of matter

The scalar field models can alleviate the fine tuning problem

But a large number of scalar models is permitted

Another alternate approach:
Modified Gravity

Gravity gets quantum mechanically corrected at small scales
(beyond the observational reach)

might be possible that Gravity may suffer modifications at large scales
(never tested directly)

Any modification should not conflict with the local physics

We consider here Galileon Gravity
(Nicolis, Rattazzi et al., PRD 79 064306 (2009),
Deffayet et al., PRD 79 084003 (2009))

Motivated by Dvali-Gabadadze-Porrati model (PLB 485, 208 (2000))

The Galileon field π respects the Galileon symmetry
(shift symmetry $\pi \to \pi + a + b_\mu x^\mu$) in flat space-time

In curved space-time $\mathcal{L} = -\frac{1}{2} g^{\mu\nu} \pi_{;\mu} \pi_{;\nu} + \frac{G^{\mu\nu}}{2M^2} \pi_{;\mu} \pi_{;\nu}$

respects the Galileon symmetry.

The action

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

The equations of motion

$$M_{\rm pl}^2 G_{\mu\nu} = T_{\mu\nu}^{(m)} + T_{\mu\nu}^{(r)} + T_{\mu\nu}^{(\pi)} ,$$

$$\Box\pi + \frac{1}{M^2}\Big[\frac{R}{2}\Box\pi - R^{\mu\nu}\pi_{;\mu\nu}\Big] - V'(\pi) = -\frac{\beta}{M_{\rm Pl}} T^{(m)}$$

$$\Box = \tfrac{1}{\sqrt{-g}}\partial_\mu(\sqrt{-g}\partial^\mu)$$

Time derivative of Galileon field π is smaller than that of a canonical scalar field (slow moving)

Friedmann Equations

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

$$\dot{\rho}_r + 4H\rho_r = 0.$$

$$x = \frac{\dot{\pi}}{\sqrt{6}HM_{\rm Pl}}, \quad y = \frac{\sqrt{V(\pi)}}{\sqrt{3}HM_{\rm Pl}},$$

$$\epsilon = \frac{H^2}{2M^2}, \quad \lambda = -M_{\rm Pl}\frac{V'(\pi)}{V(\pi)}.$$

$$\frac{\mathrm{d}x}{\mathrm{d}N} = x\left(\frac{\ddot{\pi}}{H\dot{\pi}} - \frac{\dot{H}}{H^2}\right),$$

$$\frac{\mathrm{d}y}{\mathrm{d}N} = -y\left(\sqrt{\frac{3}{2}}\lambda x + \frac{\dot{H}}{H^2}\right),$$

$$\frac{\mathrm{d}\epsilon}{\mathrm{d}N} = 2\epsilon\frac{\dot{H}}{H^2},$$

$$\frac{\mathrm{d}\Omega_r}{\mathrm{d}N} = -2\Omega_r\left(2 + \frac{\dot{H}}{H^2}\right),$$

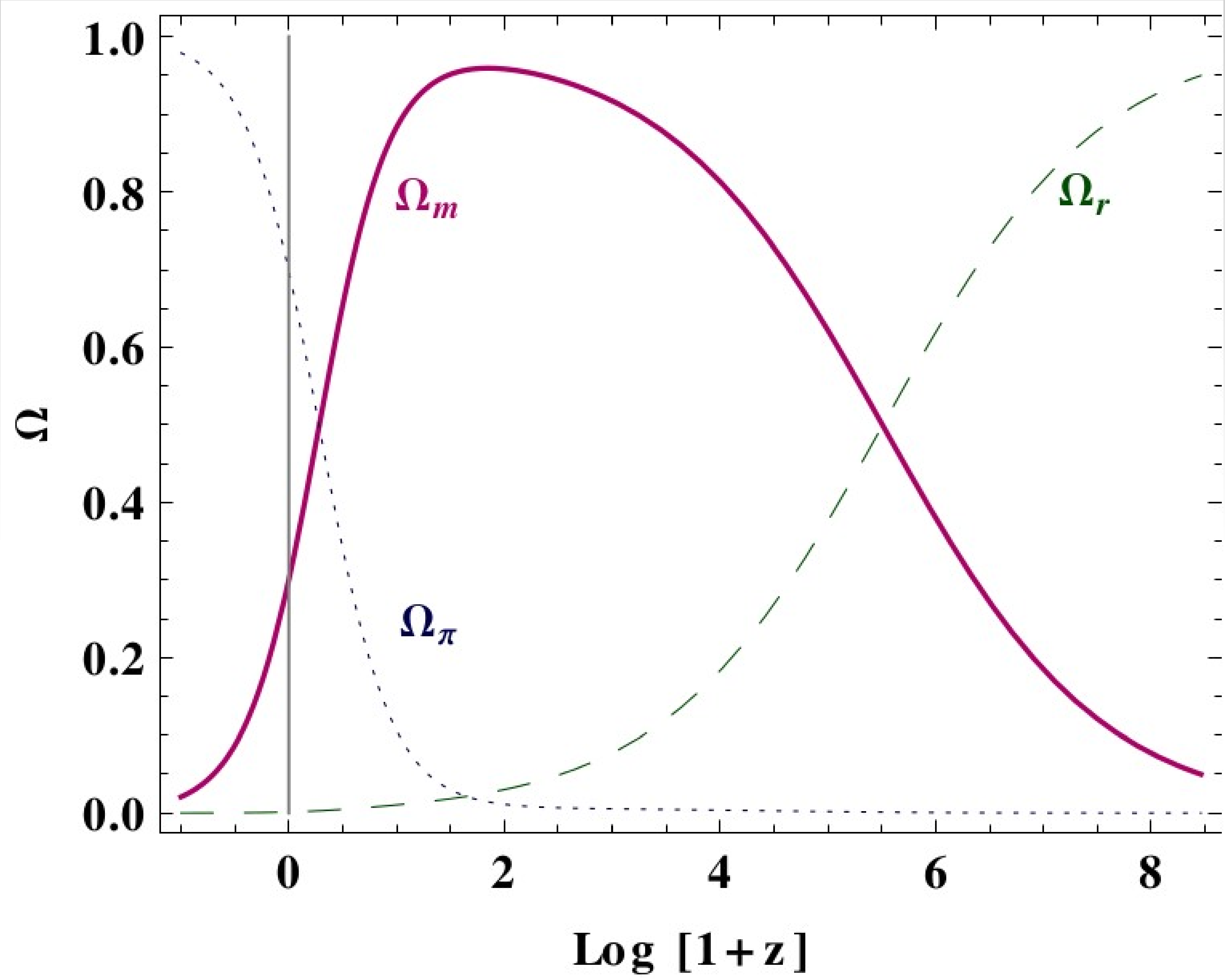
$$\frac{\mathrm{d}\lambda}{\mathrm{d}N} = \sqrt{6}x\lambda^2(1-\Gamma),$$

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

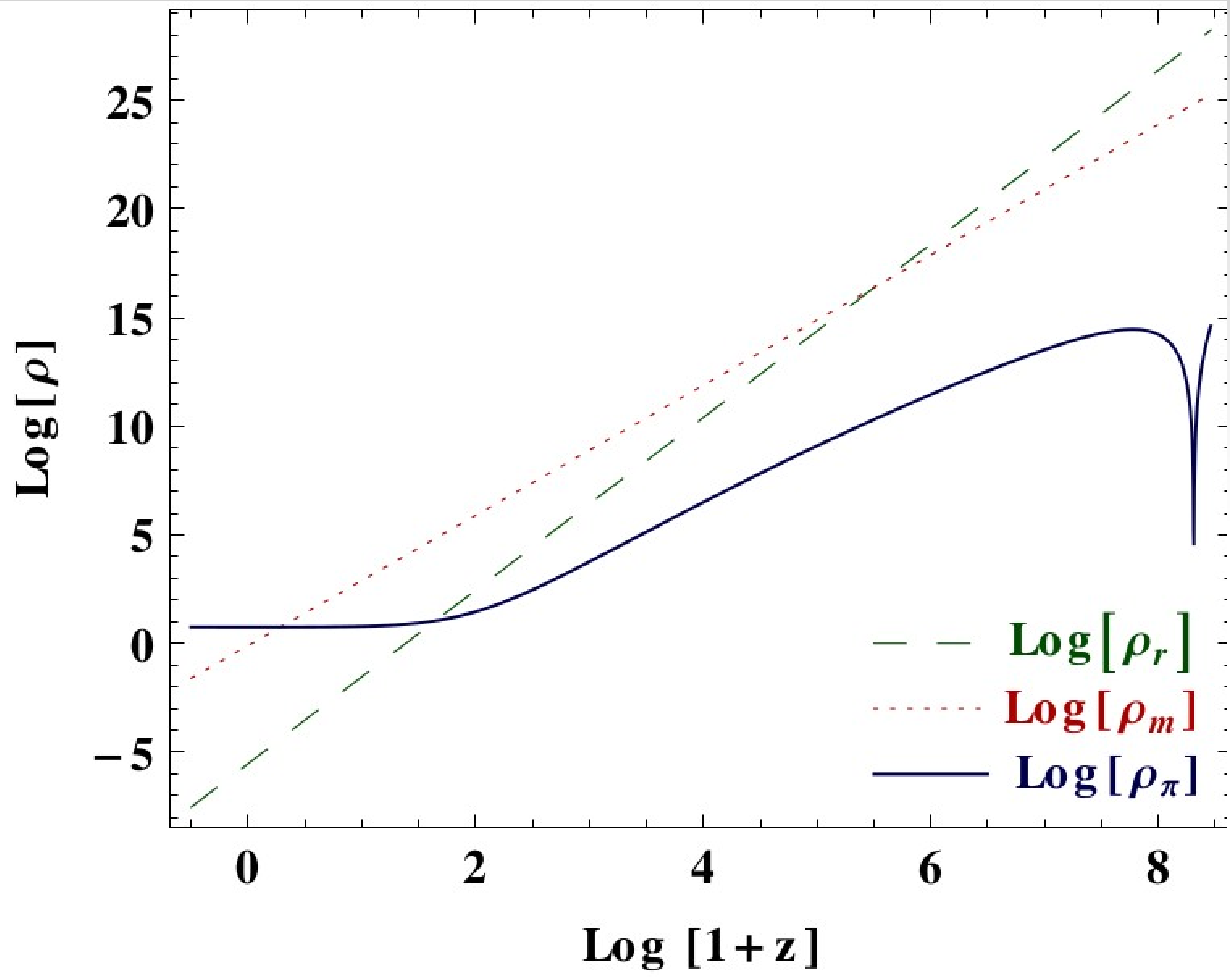
$$V(\pi) = V_0 e^{\frac{-\lambda\pi}{M_{\rm Pl}}}$$

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

Evolution Equations

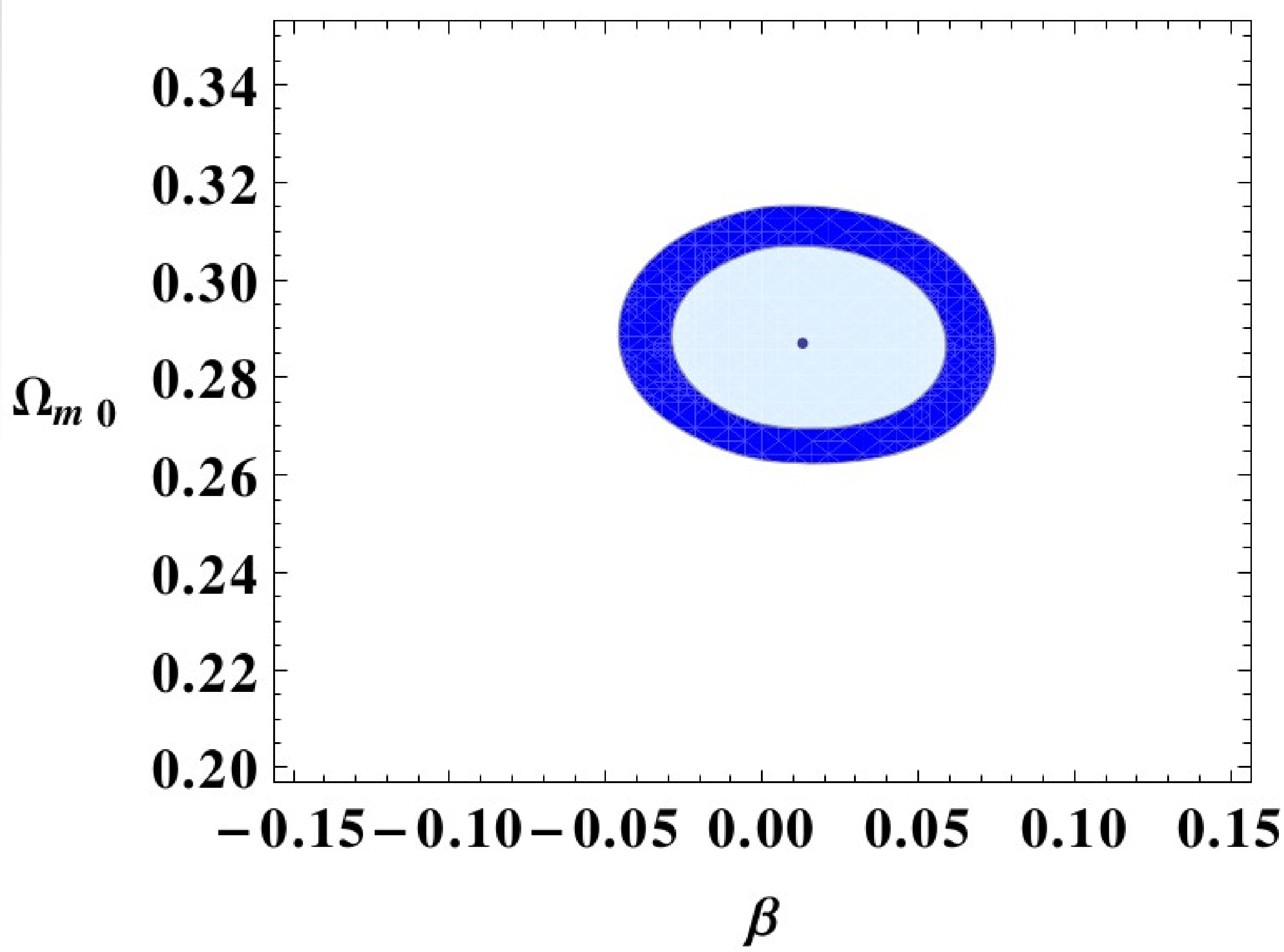


1.0
0.8
0.6
0.4
0.2
0.0
Ω
0
2
4
6
8
Log [1+z]
Ω_m
Ω_r
Ω_π



Log[ρ]
25
20
15
10
5
0
−5
0
2
4
6
8
Log [1+z]
Log[ρ_r]
Log[ρ_m]
Log[ρ_π]

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



Conclusions

We consider a modified gravity model (Galileon model) to explain late time cosmic acceleration

Here the Galileon field π obeys a shift symmetry

We have studied the model by taking an exponential form of the potential

Though the potential breaks the symmetry, it serves an important role in obtaining a viable cosmology

We have demonstrated that this model gives an accelerating Universe at late times