Celebration of 60 years' old birthdays of Prof. Maeda and Prof. Nakamura

Inflation and dark energy: theoretical progress over 20 years

Shinji Tsujikawa
Tokyo University of Science

Cosmic acceleration

Observations suggest that there are two eras of cosmic acceleration:

- Inflation: energy scale $H \sim 10^{13}$ GeV
- Dark energy: energy scale $H \sim 10^{-42}$ GeV

In General Relativity, the scale factor satisfies

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(1+3w)\rho \qquad \text{where} \quad w = P/\rho \qquad \begin{array}{l} P: \ \text{pressure} \\ \rho: \ \text{density} \end{array}$$

The cosmic acceleration ($\ddot{a} > 0$) occurs for the equation of state

$$w = P/\rho < -1/3 \qquad \text{(Negative pressure)}$$

Original papers of inflation

The idea of inflation was proposed by several people independently.

- **Curvature inflation**

  Starobinsky, Phys. Lett. B 91, 99 (1980)

  The higher-order curvature term leads to inflation.

$$f(R) = R + R^2/(6M^2)$$

- **“Old” inflation**

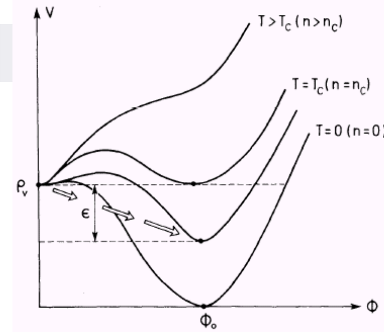
  Sato, Mon. Not. R. Astron. Soc. 195, 467 (1981)

  Kazanas, Astrophys. J. Lett. 241, L59 (1980)

  Guth, Phys. Rev. D 23, 347 (1981)

  Inflation occurs due to the first-order phase transition of a vacuum.

Inflation based on Grand unified theories



First-order phase transition of a vacuum and the expansion of the Universe

Katsuhiko Sato *Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark* and Department of Physics, Kyoto University, Kyoto, Japan†*

472 citations

Received 1980 September 9; in original form 1980 February 21

Inflationary universe: A possible solution to the horizon and flatness problems

Alan H. Guth*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

Received 11 August 1980

3641 citations

DYNAMICS OF THE UNIVERSE AND SPONTANEOUS SYMMETRY BREAKING

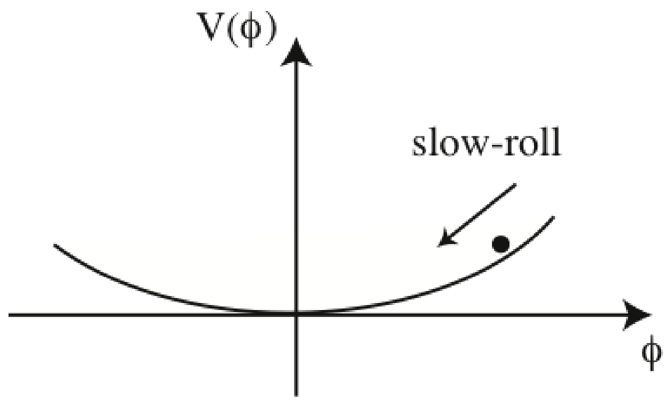
DEMOSTHENES KAZANAS[1]
NASA Goddard Space Flight Center, Laboratory for High Energy Astrophysics
Received 1980 May 5; accepted 1980 July 3

135 citations

ABSTRACT

It is shown that the presence of a phase transition early in the history of the universe, associated with spontaneous symmetry breaking (believed to take place at very high temperatures at which the various fundamental interactions unify), significantly modifies its dynamics and evolution. This is due to the energy "pumping" during the phase transition from the vacuum to the substance, rather than the gravitating effects of the vacuum. The expansion law of the universe then differs substantially from the $R \propto t^{1/2}$ relation considered so far for the very early time expansion. In particular it is shown that under certain conditions this expansion law is exponential. It is further argued that under reasonable assumptions for the mass of the associated Higgs boson this expansion stage could last long enough to potentially account for the observed isotropy of the universe.
Subject heading: cosmology

So far many inflation models have been proposed.
Most of them are based on a scalar field with a potential.



$$H^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) \approx \frac{8\pi G}{3} V(\phi)$$

$$H \approx \text{const}, \quad a \approx e^{Ht}$$

f(R), old, new, chaotic, extended, power-law, hybrid, natural, supernatural, extra-natural, eternal, D-term, F-term, brane, oscillating, tachyon, dilaton, Quintessenatial, K-inflation, ghost condensate, KKLMMT, DBI, hill-top, Higgs, Galileon, ….

Over 3300 papers in which the titles include the word “inflation”.

CMB observations can allow the discrimination of models.

Consider the general scalar-field action

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_{\rm pl}^2 R + P(\phi, X) \right] \quad \text{where} \quad X = -(1/2) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

This covers most of scalar-field inflation models.

- **Spectra of scalar and tensor perturbations**

Garriga and Mukhanov (1999), Hwang and Noh (2002), Seery and Lidsey (2005), …

Spectral index of scalar perturbations: $n_s = 1 - 2\epsilon - \eta - s$

Tensor to scalar ratio: $r = 16 c_s \epsilon$

Non-gaussianity parameter:

$$f_{nl}{}^{\rm eq} = -0.28(1 - 1/c_s^2) - 1.53\epsilon - 0.42\eta + 0.02(\epsilon/\epsilon_X)s$$

where $\epsilon = -\frac{\dot{H}}{H^2}, \quad \eta = \frac{\dot{\epsilon}}{H\epsilon}, \quad s = \frac{\dot{c}_s}{H c_s}, \quad \epsilon_X = -\frac{\dot{X}}{H^2}\frac{\partial H}{\partial X}, \quad c_s^2 = \frac{P_{,X}}{P_{,X} + 2XP_{,XX}}$

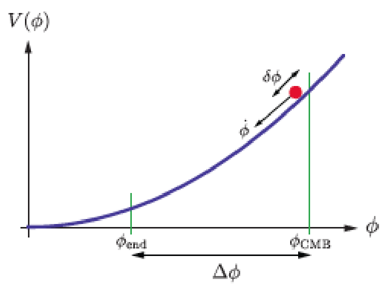
Standard inflation

$$P(\phi, X) = X - V(\phi) \quad \Rightarrow \quad c_s^2 = 1 \quad \text{and} \quad f_{nl} \sim \{\epsilon, \eta\} \ll 1$$

$$n_s = 1 - 2\epsilon - \eta \quad \text{and} \quad r = 16\epsilon$$

A. Linde

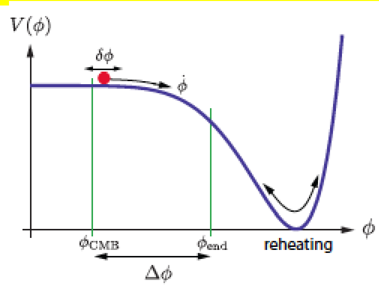
(i) Large-field inflation [e.g., chaotic inflation (1983)]



During inflation the field evolves over the large-distance: $\Delta\phi > m_{\rm pl}$

$$n_s < 1, \quad r = \mathcal{O}(0.1)$$

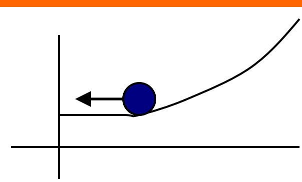
(ii) Small-field inflation [e.g., natural inflation (1990)]



During inflation the field evolves over the small-distance: $\Delta\phi < m_{\rm pl}$

$$n_s < 1, \quad r < \mathcal{O}(0.1)$$

(iii) Hybrid inflation (1994)



Inflation ends due to the waterfall transition to the global minimum.

$$n_s > 1, \quad r \ll 1$$

Observational bounds (WMAP 5-yr)

Taken from Baumann (2009)

Lyth bound

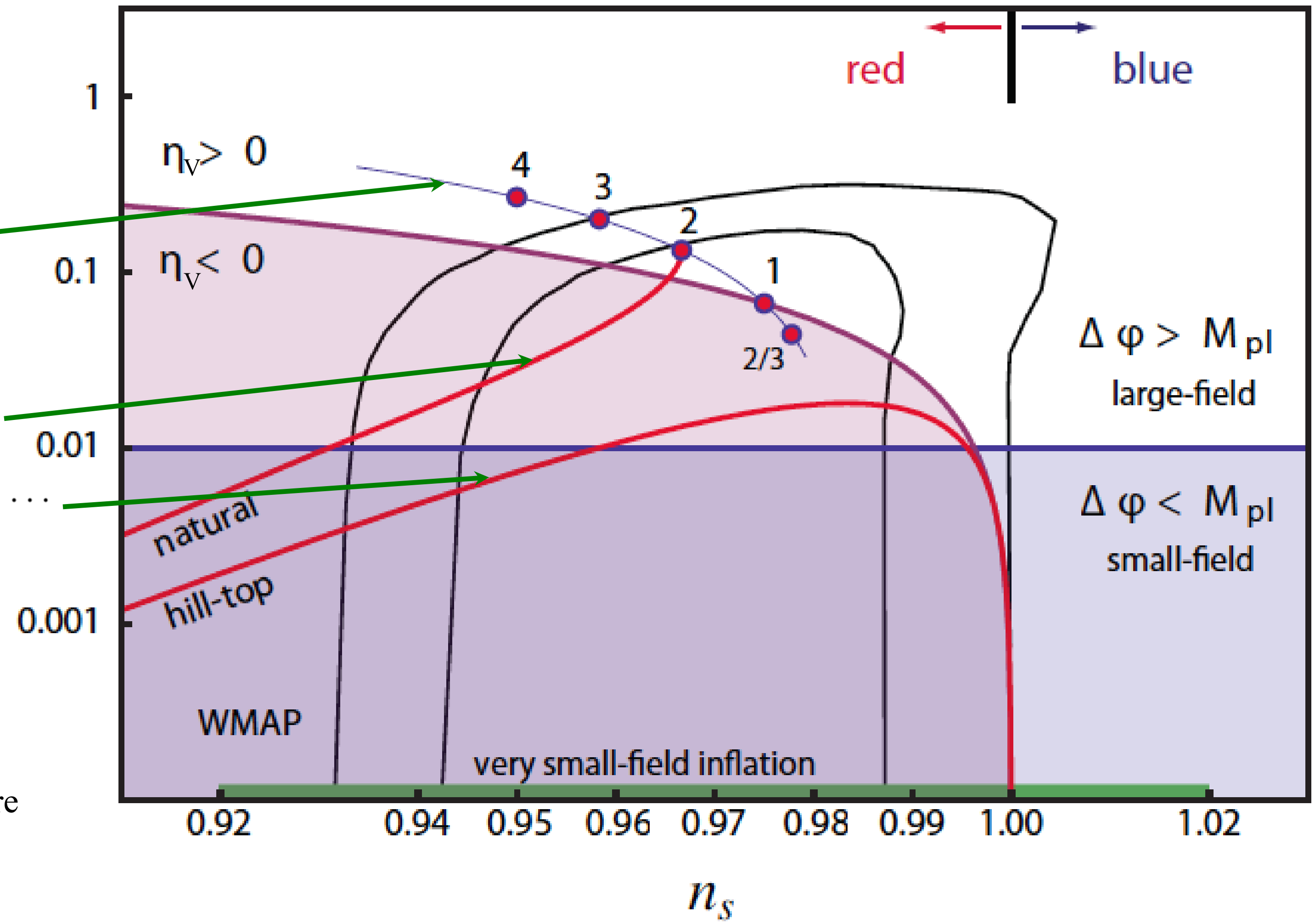
$$\frac{\Delta\phi}{M_{\rm pl}} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}$$

Chaotic inflation

$$V(\phi) = c\phi^p$$

$$V(\phi) = V_0[1-\cos(\phi/f)]$$

$$V(\phi) = V_0[1-(\phi/M)^2] + \cdots$$



$$\eta_V = -M_{\rm pl}^2 V_{,\phi\phi}/V$$

characterizes the curvature of the potential.

Kinetic inflation

$c_s^2 \neq 1$ in these theories → $f_{nl} \sim 1/c_s^2$ can be large

Kinetic-type inflation appears in many contexts:

(i) Low energy effective string theory **(Armendariz-Picon, Damour, Mukhanov, 1999)**

$$\mathcal{L} = \frac{1}{2}F(\phi)R - \frac{1}{2}\omega(\phi)(\nabla\phi)^2 - \frac{1}{2}\alpha'\xi(\phi)(\nabla\phi)^4 + \cdots$$

(ii) DBI theories **(Silverstein and Tong, 2004)**

$$\mathcal{L} = -f(\phi)^{-1}\sqrt{1-2f(\phi)X} + f(\phi)^{-1} - V(\phi)$$

(iii) Ghost condensate **(Arkani-Hamed et al, 2004)**

$$\mathcal{L} = -X + cX^2$$

(iv) Galileon gravity: **(Nicolis et al, 2008)**

The Lagrangian is constructed to satisfy the Galilean symmetry $\partial_\mu\phi \to \partial_\mu\phi + b_\mu$ in flat space-time, e.g., $\Box\phi(\nabla\phi)^2$

Or its generalization: $\mathcal{L} = P(\phi, X) + F(\phi, X)\Box\phi$

Kobayashi, Yamaguchi, Yokoyama (2010), Mizuno and Koyama (2010)

In these models f_{nl} can be as large as $\gtrsim 10$

→ Testable in Planck sattelite

Starobinsky's inflation model (modified gravity model)

$$f(R) = R + R^2/(6M^2)$$

See K. Maeda, PRD37: 858 (1988)
for the analysis in Bianchi specetime.

The slow-roll parameter is

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{M^2}{6H^2} \quad \Rightarrow \quad a \simeq a_i \exp\left[H_i(t-t_i) - (M^2/12)(t-t_i)^2\right]$$

(quasi-exponential expansion)

Inflation ends around $H \sim M \sim 10^{-6} m_{\rm pl}$

For this model the scalar spectral index and the tensor-to-scalar ratio are

$$n_s - 1 \simeq -4\epsilon \simeq -\frac{2}{N_k} = -3.6 \times 10^{-2} \left(\frac{N_k}{55}\right)^{-1}$$

$$r \simeq \frac{12}{N_k^2} \simeq 4.0 \times 10^{-3} \left(\frac{N_k}{55}\right)^{-2}$$

N_k : The number of e-foldings from the end of inflation

Starobinksy (1983)
Kofman et al (1987)
Hwang and Noh (2001),…

These values satisfy the WMAP bounds:

$$n_s = 0.960 \pm 0.013 \quad \text{and} \quad r < 0.22$$

Einstein frame

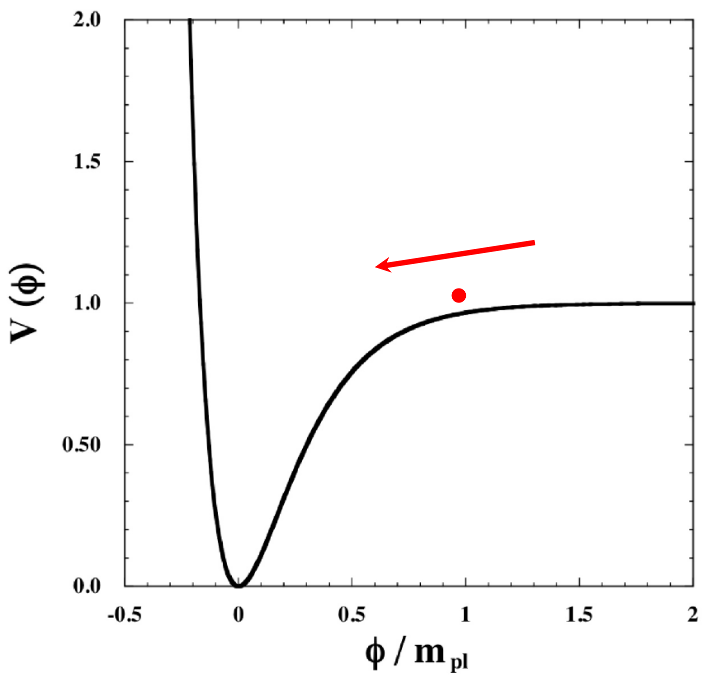
See K. Maeda, PRD39: 3159 (1989) for conformal transformations.

Under the conformal transformation $\tilde{g}_{\mu\nu} = F g_{\mu\nu}$, where $F = \partial f / \partial R$, the action of f(R) gravity in the Einstein frame is

$$S_E = \int d^4x \sqrt{-\tilde{g}} \left[\frac{1}{2\kappa^2} \tilde{R} - \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$$

where $\kappa\phi \equiv \sqrt{3/2}\ \ln F$ and $V(\phi) = (FR - f)/(2\kappa^2 F^2)$

$$f(R) = R + R^2/(6M^2) \quad \Rightarrow \quad V(\phi) = \frac{3M^2}{4\kappa^2}\left(1 - e^{-\sqrt{2/3}\kappa\phi}\right)^2$$



- Inflation is realized for $\phi > 0.2 m_{\rm pl}$
- The scalar spectral index and the tensor-to-scalar ratio are the same as those in the Jordan frame.
- Reheating proceeds gravitationally by the oscillation of the Ricci scalar.

(P)reheating in the Starobinsky's inflation model

Consider a massive field χ non-minimally coupled to gravity:

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{f(R)}{2\kappa^2} - \frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{2}\xi R\chi^2\right]$$

where

$$f(R) = R + R^2/(6M^2)$$

Each Fourier mode with a comoving wavenumber k obeys

$$\frac{\mathrm{d}^2u_k}{\mathrm{d}\eta^2} + \left[k^2 + m_\chi^2 a^2 + \left(\xi - \frac{1}{6}\right)a^2R\right]u_k = 0$$

where $u_k = a\chi_k$

(i) $\xi = 0$ → Reheating occurs perturbatively.

Reheating temperature: $T_r \lesssim 3\times10^{17}g_*^{1/4}\left(\frac{M}{m_{\rm pl}}\right)^{3/2}$ GeV

Vilenkin (1985), Mijic et al (1986)

(ii) $|\xi| \gtrsim 1$ → Explosive particle production (preheating) occurs.

$R \simeq -\frac{4M}{t}\sin(Mt)$ → The oscillation of R leads to the parametric resonance for the field fluctuation.

S.T., Maeda, Torii (1999)

Inflation with a non-minimally coupled scalar field

$$\mathcal{L} = \frac{1}{2\kappa^2}R - \frac{1}{2}\xi\phi^2 R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)$$

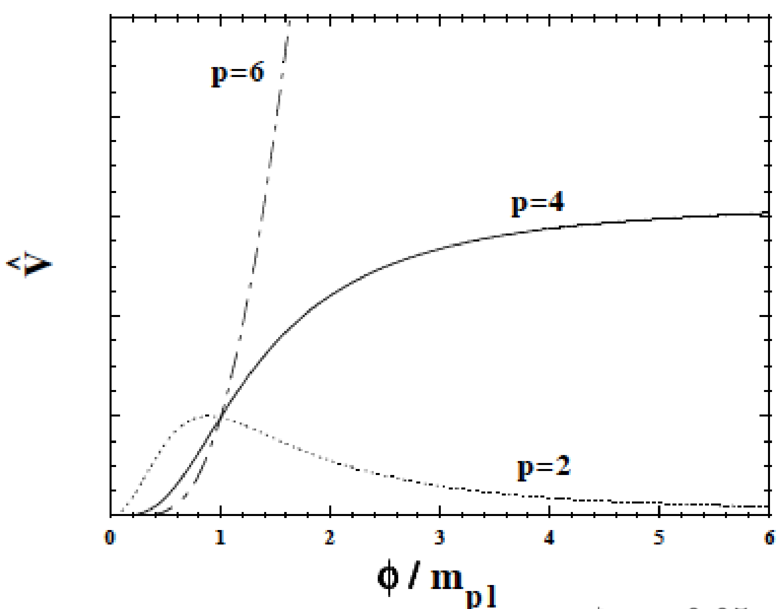
Futamase and Maeda (1989), Fakir and Unruh (1990)

The potential in the Einstein frame is $\hat{V}(\phi) = \dfrac{V(\phi)}{(1-\xi\kappa^2\phi^2)^2}$

Consider a negative non-minimal coupling with a power-law potential:

$V(\phi) = c\phi^p$ → When $p = 4$ the potential is nearly flat for $|\xi| \gg 1$

Potential in the Einstein frame



$\xi = -0.05$

The non-minimally coupled inflation was recently revived as 'Higgs Inflation' with the Higgs potential

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 \quad \text{with} \quad v \sim 100 \text{ GeV}$$

Bezrukov and Shaposhnikov (2008)

During inflation we have

$$V(\phi) \simeq \frac{1}{4}\lambda\phi^4 \quad \text{with} \quad |\xi| \gg 1$$

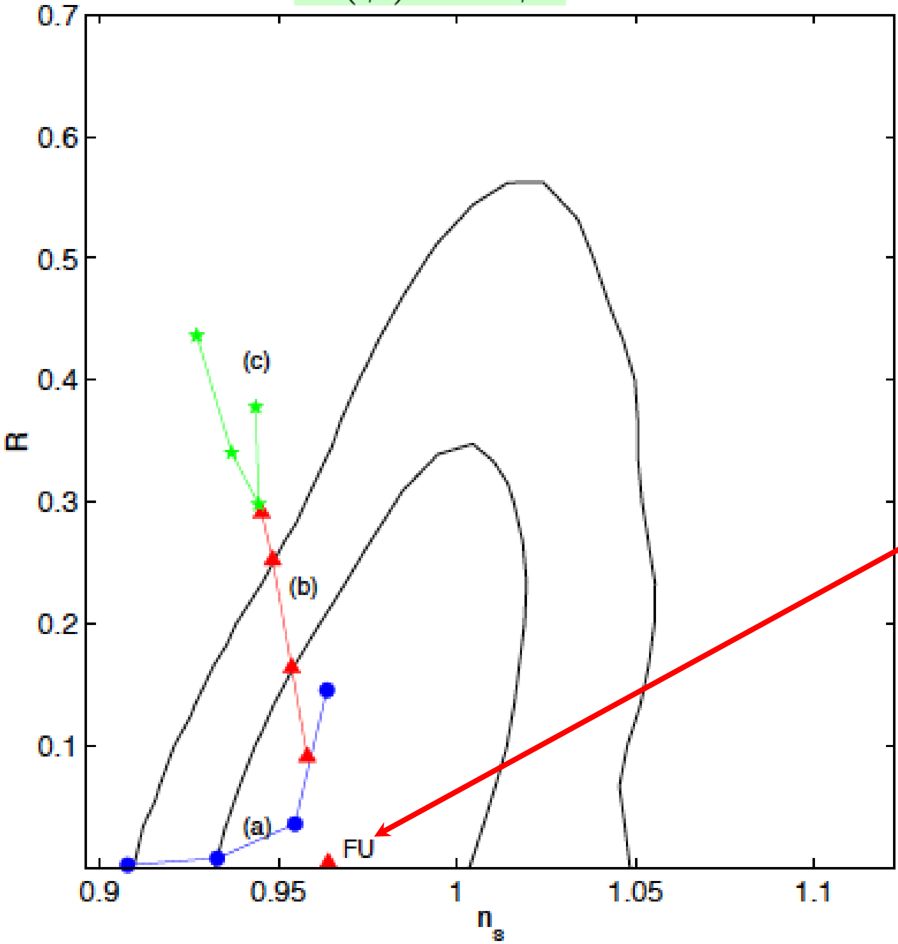
The WMAP normalization gives

$$|\xi| \simeq 5 \times 10^4 \sqrt{\lambda}$$

Observational constraints on inflation with non-minimal coupling

S.T. and Gumjudpai (2004)

$V(\phi) = c\phi^p$



(a) $p = 2$

$\xi = 0, -0.003, -0.007, -0.011$

(b) $p = 4$

$\xi = 0, -0.0003, -0.0017, -0.005$

(c) $p = 6$

$\xi = 0, -0.001, -0.0035, -0.01$

Fakir/Unruh and Futamase/Maeda scenario ($|\xi| \gg 1$)

$$n_s - 1 \simeq -2/N_k$$

$$r \simeq 12/N_k^2$$

(same as the Starobinsky's f(R) model)

Favored observationally.

See also Salopek, Bond, Bardeen (1989), Makino and Sasaki (1991), Komatsu and Futamase (1998),…

Prof. Maeda’s group started in 1989.

Taken in 1989 in the Maeda’s lab
(I was a high school student at this time!)

I belonged to the Maeda’s lab from 1996 to 2001.

Dark Energy (1998~)

Perlmutter et al, Riess et al (1998)

$$m_B - M = 5\log_{10}(d_L/10pc)$$

m_B : apparent magnitude

M : absolute magnitude ($M \simeq -19$)

$d_L(z) = (1+z)\int_0^z \frac{dz}{H(z)}$: luminosity distance

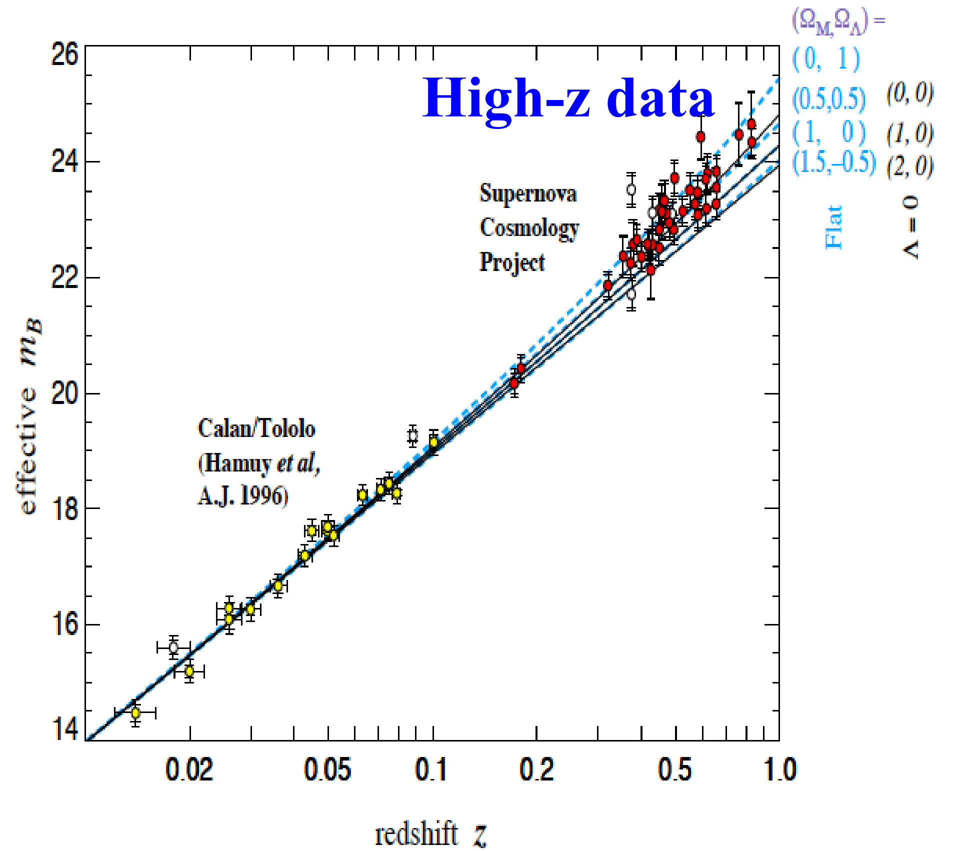
From Supernovae observations they showed that the cosmological constant ($w_{\rm DE} = -1$) exists at the 99 % confidence level.

Matter ratio today :

$$\Omega_m^{(0)} = 0.28^{+0.09}_{-0.08}$$

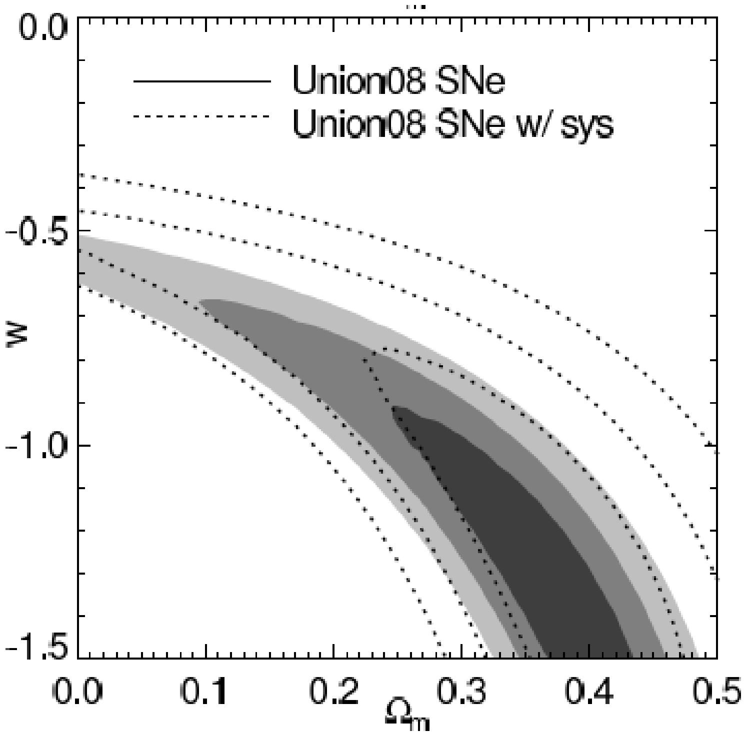
(Perlmutter et al, 1998)

About 70 % is dark energy responsible for the cosmic acceleration today.

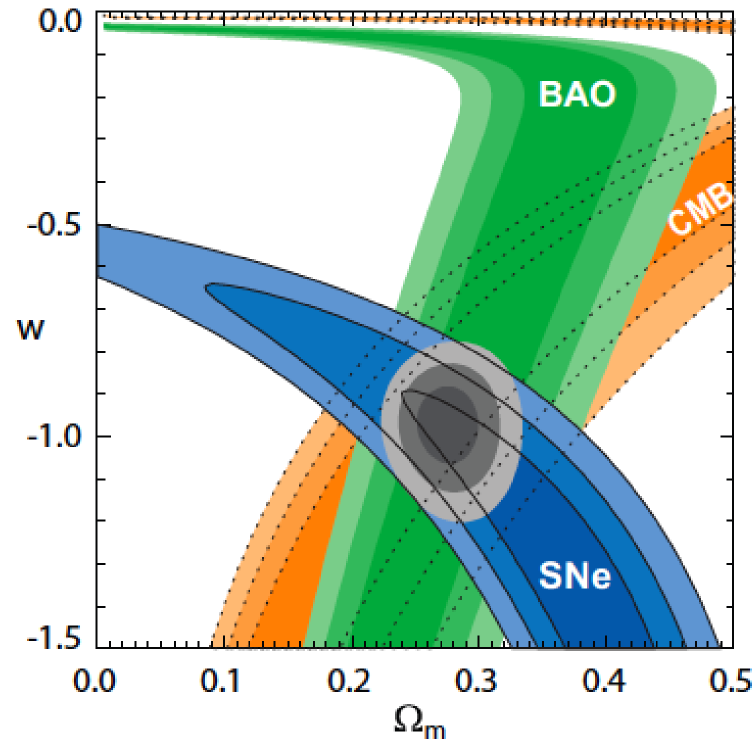


Recent observational constraints (for constant w)

SN Ia data only



SN Ia + CMB + BAO



For the time-dependent w with the parametrization $w(a) = w_0 + w_a(1-a)$, the constraint is

$$w_0 = 0.93 \pm 0.13, \quad w_a = -0.41^{+0.72}_{-0.71} \quad (68\%\ \mathrm{CL})$$ (Komatsu et al., 2010)

The data still allow the large variation of w.

Cosmological constant

There are two approaches to the cosmological constant problem.

(i) Cosmological constant is small enough to explain dark energy today. → economical

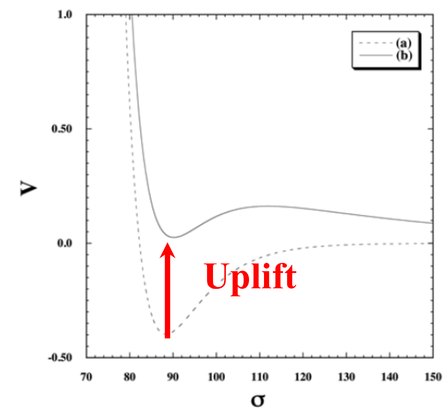
(ii) Cosmological constant vanishes completely. → We have to find another source for dark energy.

- **Example of (i): de Sitter vacua in string theory: KKLT scenario (2003)**

Flux compactification in Type II string theory

$$V = \underbrace{e^{\kappa^2 K}\left[D_i W (K^{ij*})(D_j W)^* - 3\kappa^2 |W|^2\right]}_{\text{Having anti de Sitter minimum}} + \underbrace{D/\sigma^3}_{\text{D3-brane gives rise to a positive energy}}$$

K: Kahler potential
W: Superpotential



The small vacuum energy is possible depending on the number of fluxes.

- **Example of (ii): Gluino condensation model (Dine et al, 1985)**

The vanishing vacuum energy is possible even in the world of broken supersymmetry.

$$V = e^{\kappa^2 K}\left[\underline{D_i W (K^{ij*})(D_j W)^*} - \underline{3\kappa^2 |W|^2}\right]$$

Cancellation

In general, however, non-perturbative corrections can lead to a non-vanishing vacuum energy.

Dynamical dark energy models $(w \neq -1)$

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

(A) Modified gravity models

(i) f(R) gravity

$L = f(R)$ R: Ricci scalar

(ii) Scalar-tensor theory

$L = F(\phi)R - \omega(\phi)X - V(\phi)$

where $X = -(1/2)(\nabla\phi)^2$

(iii) DGP braneworld

(iv) Gauss-Bonnet models

(v) Galileon gravity

….

(B) Modified matter models

(i) Quintessence

$L = R/16\pi G + X - V(\phi)$

(ii) K-essence

$L = R/16\pi G + P(\phi, X)$

(iii) Chaplygin gas

$P = -A/\rho$

….

Void model,
Backreaction model

Modified matter models of dark energy

- **Canonical scalar field:** $\mathcal{L} = -(\nabla\phi)^2/2 - V(\phi)$

Acceleration induced by the potential energy of a scalar field

Chiba, Sugiyama, Nakamura (1997) **'X matter'**

Caldwell, Dave, Steinhardt (1998) **'Quintessence'**

There are also pioneering works of scalar-field dynamics in cosmology:

Fujii (1982), Wetterich (1988), Ratra and Peebles (1988), …

- **Kinetic field:** $\mathcal{L} = P(\phi, X)$ **where** $X = -(\nabla\phi)^2/2$

Acceleration induced by the kinetic energy of a scalar field.

Chiba, Okabe, Yamaguchi (1999) **'Kinetically driven quintessence'**

Armendariz-Picon, Mukhanov, Steinhardt (2000) **'k-essence'**

The Lagrangian such as $P = f(\phi)(-X + X^2)$ **leads to the late-time acceleration.**

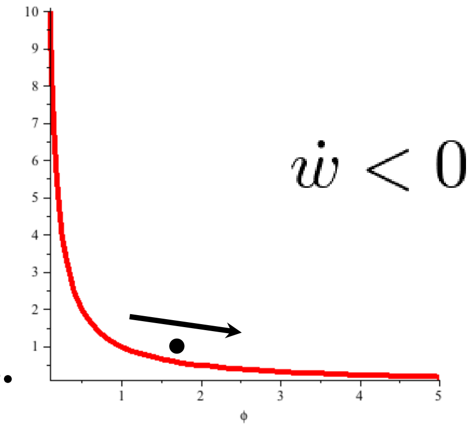
Classification of Quintessence potentials   Caldwell and Linder (2003)

(A) Freezing models

As the potential becomes flatter, the evolution of the field slows down.

w decreases toward -1.

Example: $V(\phi) = M^{4+n}\phi^{-n}$ → This appears in super-symmetric QCD theories. (Binetry, 1999)

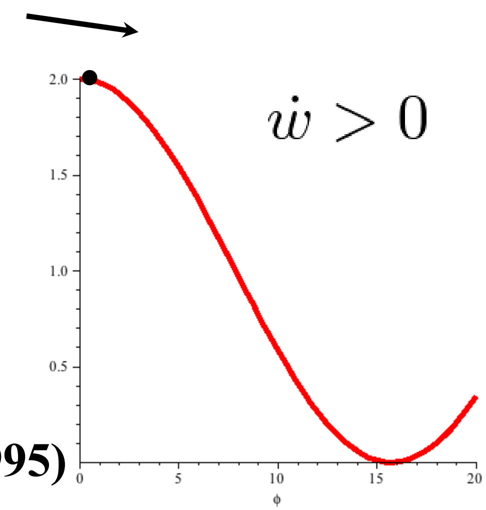


(B) Thawing models

In the past the field is nearly frozen, but it starts to evolve only recently.

w increases from -1.

Example: $V(\phi) = \mu^4[1 + \cos(\phi/f)]$ → This appears as a PNGB boson (Friemann et al, 1995)



Particle physics models of quintessence

To explain the cosmic acceleration today, the mass of the field $m_\phi = V_{,\phi\phi}$ is required to be very light.

$$m_\phi \approx H_0 \approx 10^{-33}\ \mathrm{eV}$$

- In particle physics models, the flatness of the potential may be spoiled by radiative corrections to the potential (Kolda and Lyth, 1999).
- Such a light scalar field may interact with standard model particles (Carroll, 1999).

Good model based on particle physics

Pseudo-Nambu-Goldston model (axion field)

$$V(\phi) = \mu^4[1+\cos(\phi/f)] \quad \Rightarrow \quad m_\phi^2 = -\mu^4/f^2$$

The small mass can be protected against radiative corrections.

See e.g.,

Kim ane Nilles (2003)

Hall, Nomura, Oliver (2005)

Modified gravity models of dark energy

- **At large distances the gravitational law may be modified from General Relativity (GR) to give rise to cosmic acceleration.**

- **Meanwhile, on small scales (local regime), gravitational theory needs to be close to GR to satisfy local gravity constraints.**

Let us consider f(R) gravity as a simplest example.
The following conditions need to be satisfied.

Please see the review:
De Felice and S.T. (2010)

1. $f_{,R} > 0$ ➡ **To avoid ghosts**

2. $f_{,RR} > 0$ ➡ **The mass of the scalar-field degree of freedom needs to be positive for consistency with LGC:** $M^2 \approx 1/(3f_{,RR}) > 0$

3. $f(R) \to R - 2\Lambda \quad \text{for} \quad R \gg H_0^2$

   ➡ **For the presence of the matter era and for consistency with LGC.**

4. $0 < \frac{Rf_{,RR}}{f_{,R}}(r = -2) < 1 \quad \text{at} \quad r = -\frac{Rf_{,R}}{f} = -2$ ➡ **The stability of the dS solution**

Viable f(R) dark energy models

1. $f(R) = R - \mu R_c \dfrac{(R/R_c)^{2n}}{(R/R_c)^{2n}+1}$ (n>0) Hu and Sawicki, 2007

2. $f(R) = R - \mu R_c \left[1 - (1 + R^2/R_c^2)^{-n}\right]$ (n>0) Starobinsky, 2007

3. $f(R) = R - \mu R_c \tanh(R/R_c)$ S.T., 2007

These satisfy f(R=0)=0. $\longrightarrow$ Cosmological constant disappears in flat space-time.

R_c is roughly of the order of the present cosmological Ricci scalar.

The models approach the LCDM for $R \gg R_c$

$$f(R) \simeq R - \mu R_c[1 - (R/R_c)^{-2n}] \quad (n > 0)$$

(for the models 1 and 2)

$\Rightarrow$ The local gravity constraints can be satisfied for

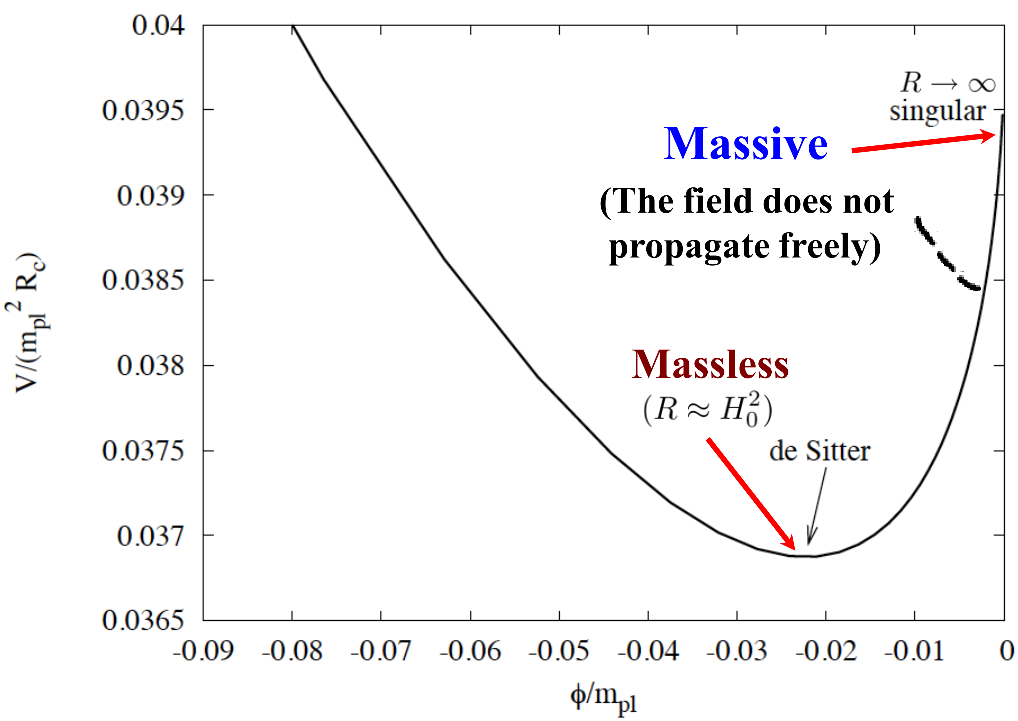
$$n > 0.9$$

(Capozziello and S.T., 2008)

Chameleon mechanism in f(R) dark energy models

Viable f(R) models have been constructed to satisfy local gravity constraints in the regions of high density.

Potential in Einstein frame for the Starobinsky's model



The effective potential is

$$V_{\rm eff}(\phi) = V(\phi) + \underline{\rho_m e^{-\phi/\sqrt{6}}}$$

Matter coupling

- **Frolov (2008), Kobayashi and Maeda (2008)**

  Relativistic stars may be difficult to exist because of the singularity.

- **S.T., Tamaki, Tavakol (2009)**
  Upadhye and Hu (2009)
  Babichev and Langlois (2009)

  Relativistic stars exist, while the boundary conditions need to be chosen carefully.

- **For general varying density stars**

  De Felice and Maeda, in preparation

Vainshtein mechanism

The scalar-field self interaction such as $\Box\phi(\partial_\mu\phi\partial^\mu\phi)$ allows the possibility to recover the GR behavior at high energy (without a field potential).

(i) DGP braneworld (Dvali et al, 2000)

The GR behavior can be recovered in a solar system, but the DGP model suffers from the ghost problem as well as incompatibility with observational constraints.

(ii) Galileon gravity (Nicolis et al, 2008, Deffayet et al, 2009)

The Lagrangian is restricted to satisfy the Galilean symmetry $\partial_\mu\phi \to \partial_\mu\phi + b_\mu$ in the flat space-time:

$$\mathcal{L}_1 = M^3\phi\,, \quad \mathcal{L}_2 = (\nabla\phi)^2\,, \quad \mathcal{L}_3 = (\Box\phi)(\nabla\phi)^2/M^3\,,$$
$$\mathcal{L}_4 = (\nabla\phi)^2\left[2(\Box\phi)^2 - 2\phi_{;\mu\nu}\phi^{;\mu\nu} - R(\nabla\phi)^2/2\right]/M^6,$$
$$\mathcal{L}_5 = (\nabla\phi)^2[(\Box\phi)^3 - 3(\Box\phi)\,\phi_{;\mu\nu}\phi^{;\mu\nu} + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\rho}\phi_{;\rho}{}^{\mu} - 6\phi_{;\mu}\phi^{;\mu\nu}\phi^{;\rho}G_{\nu\rho}]/M^9$$

M: some mass scale

The equations remain at second-order.

A tracker solution in Galileon cosmology

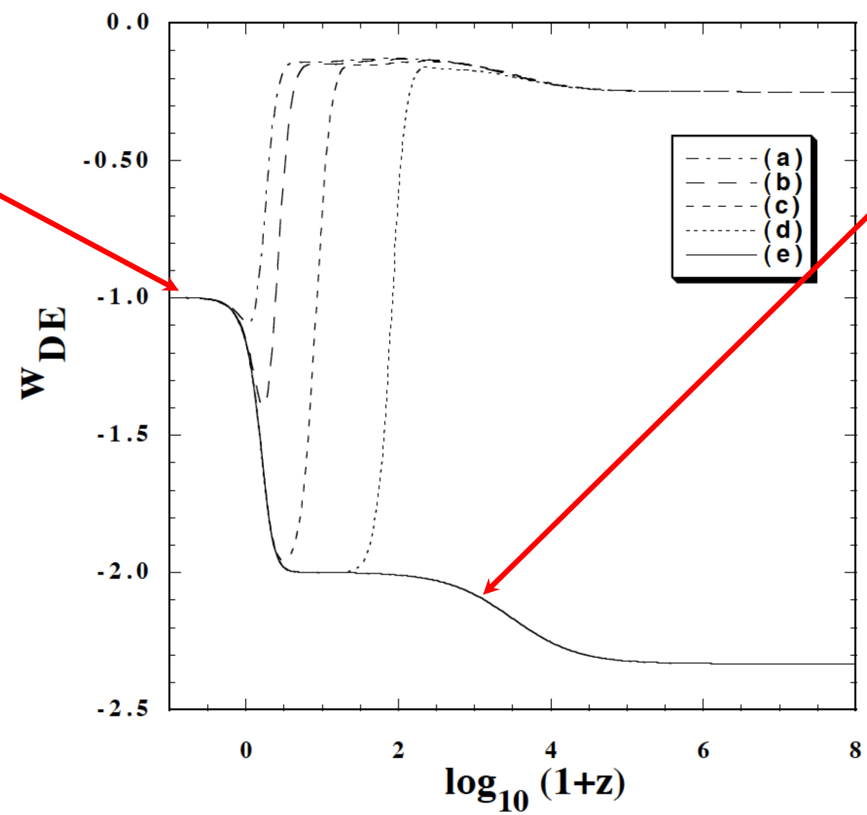
De Felice and S.T., PRL (2010)

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R + \frac{1}{2}\sum_{i=1}^{5} c_i\mathcal{L}_i\right] + S_m$$

$\mathcal{L}_i \quad (i = 1, \cdots, 5)$ are covariant field Lagrangians

There is a tracker solution that finally approaches the de Sitter (dS) attractor.

dS attractor



Tracker

The dark energy equation of state evolves as

$-7/3$ (radiation era)

-2 (matter era)

-1 (dS era)

Summary of dark energy models

(1) Cosmological constant (w= -1)

Observationally, good. Theoretically, further progress is required.

(2) Modified matter models

Quintessence, k-essence: So far these are not distinguished from LCDM observationally.

Chaplygin gas: × Ruled out from observations of large-scale structure.

(3) Modified gravity models

f(R) gravity, scalar-tensor theory: Possible to design viable models.

DGP braneworld： × Ruled out from observations and ghost problem.

Gauss-Bonnet gravity: × Ruled out from the instability of perturbations.

($f = \frac{1}{2}R + F(G)$ and $f = \frac{1}{2}R + F(\phi)G - \frac{1}{2}(\nabla\phi)^2 - V(\phi)$)

Galieon gravity: The analysis of density perturbations is required to test this model.

Hope to find the origin of inflation and dark energy
in future.

and

I hope that Prof. Maeda and Prof. Nakamura will continue to provide immense impact to cosmology and gravitation!