



UST Journal Club @ KASI

Dec. 02, 2015

# Theoretical Models of Dark Energy

by Jaewon Yoo



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Int. J. Mod. Phys. D 21, 1230002 (2012) (arxiv: 1212.4726)

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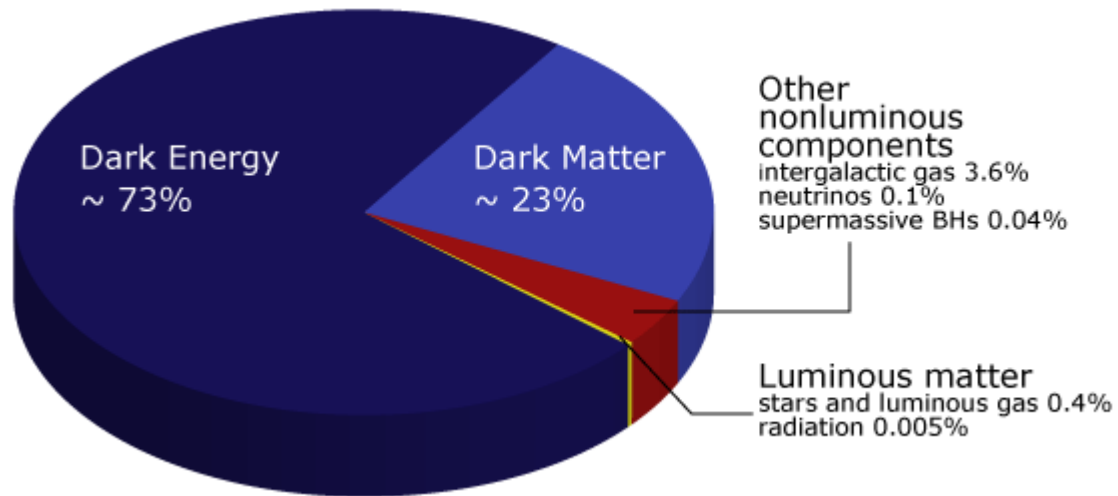
**04**

## Non Dark Energy model

- Inhomogeneous LTB model

# Motivation

- The composition of the universe



- Supernovae as a standard candle



Let's see the sky!



# Motivation

- Observational evidences on Dark Energy

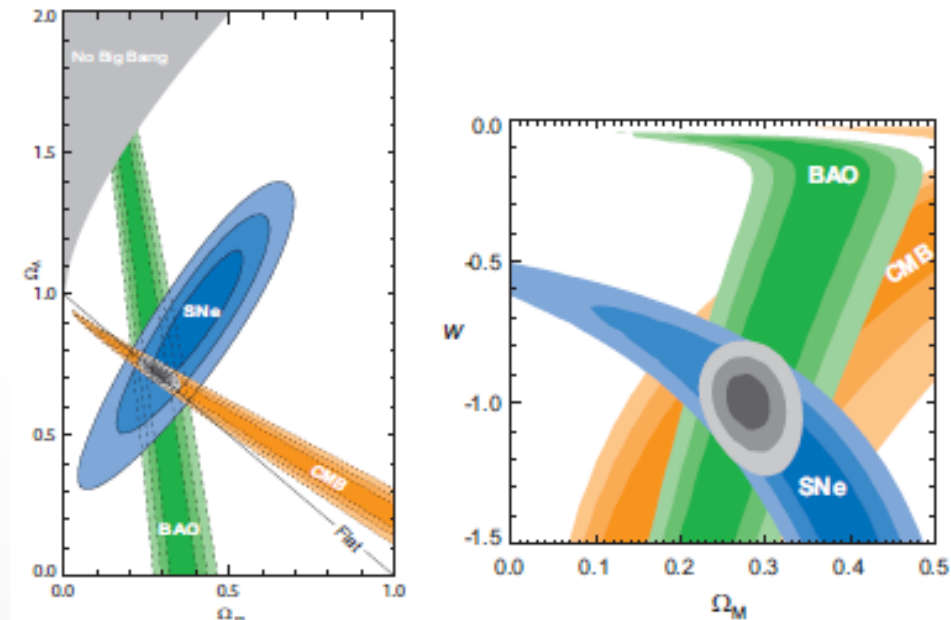


Figure 1: There is strong evidence for the existence of dark energy. Plotted are  $\Omega_m$  -  $\Omega_\Lambda$  (left panel) and  $\Omega_m$  -  $w$  (right panel) confidence regions constrained from the observations of SN Ia, CMB and BAO. From Ref. Astrophys.J. 686 (2008) 749{778, [arXiv:0804.4142]

❖  $w \equiv \frac{p}{\rho}$ , accelerated expansion of the Universe, when  $-1 \leq w < -\frac{1}{3}$



# Motivation

- Cosmological constant

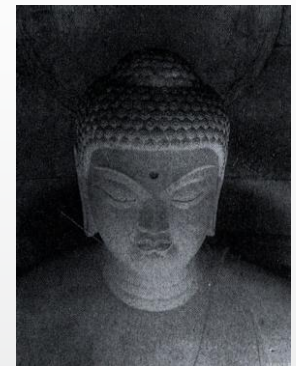
$\Lambda$

= Einstein's biggest blunder?!

= vacuum energy?

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}.$$

$$S = -\frac{1}{16\pi G} \int d^4x \sqrt{-g} (R + 2\Lambda) + S_M$$



색즉시공(色卽是空), 공즉시색(空卽是色) ??

# Motivation

- Cosmological constant problem

## Fine-tuning problem

Theoretical expectation:  $\rho_{\Lambda} \sim (10^{18} \text{GeV})^4 \sim 2 \times 10^{110} \text{erg/cm}^3$

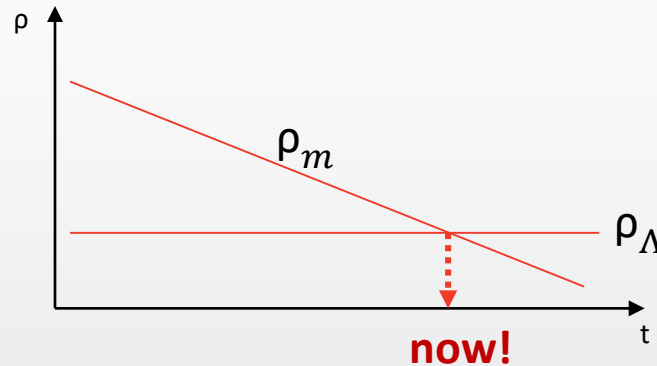
Observation:  $\rho_{\Lambda}^{\text{obs}} \leq (10^{-12} \text{GeV})^4 \sim 2 \times 10^{-10} \text{erg/cm}^3$

**10<sup>120</sup>**  
discrepancy

*“The worst theoretical prediction in the history of physics!”*

***Why small?***

## Coincidence problem



***Why now?***

# Modify Matter vs. Modify Gravity

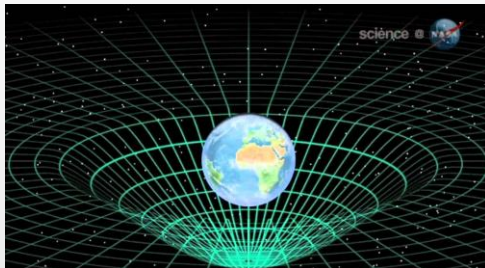
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



Gravity



Matter



❖  $G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R$  describes geometry of spacetime





# Modified Matter model

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

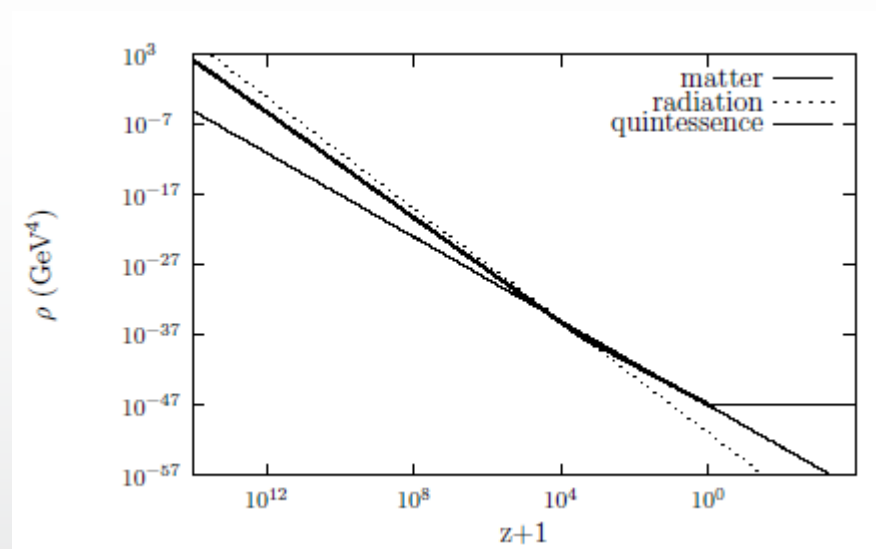
- Quintessence



$$S = \int d^4x \sqrt{-g} \left[ -\frac{1}{16\pi G} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + S_M.$$

$$w_Q = \frac{p_Q}{\rho_Q} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

 *Scalar field ( $\Phi$ )?*





# Modified Matter model

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

## ■ K-essence

$$S = \int d^4x \sqrt{-g} \left[ -\frac{1}{16\pi G} R + p(\phi, X) \right] + S_M$$

The full action including a k-essence term is given by

$$S = \int d^4x \sqrt{-g} \left[ -\frac{1}{16\pi G} R + p(\phi, X) \right] + S_M, \quad (24)$$

where  $X$  is the canonical kinetic energy of the field,

$$X \equiv \frac{1}{2}(\nabla\phi)^2, \quad (25) \quad (31)$$

and the Lagrangian  $p(\phi, X)$  plays a role of the pressure  $p_K$ . Here we consider a model with

$$p_K = p(\phi, X) = \tilde{p}(X)/\phi^2, \quad (26) \quad (32)$$

which has the desired property for dark energy.

For small  $X$ ,  $\tilde{p}(X)$  could be expanded as  $\tilde{p}(X) = \text{const.} + X + \mathcal{O}(X^2)$ . If we ignore the non-linear term  $\mathcal{O}(X^2)$  and take an additional potential, then we come back to the quintessence model. The scalar field for which these higher order kinetic energy terms play an essential role is k-essence.

The energy density of the k-field is

$$\rho_K = (2X\tilde{p}_X - \tilde{p})/\phi^2 \equiv \tilde{\rho}/\phi^2 \quad (27) \quad (34)$$

so that the equation of state parameter for the k-field is

$$w_K \equiv \frac{p_K}{\rho_K} = \frac{\tilde{p}}{\tilde{\rho}} = \frac{\tilde{p}}{2X\tilde{p}_X - \tilde{p}} \quad (28) \quad (35)$$

where  $_X$  means derivative with respect to  $X$ . If the Lagrangian  $p$  satisfies the condition  $Xp_{p_X} \ll p$  for some range of  $X$  and  $\phi$ , then the equation of state is  $p \approx -p$  so that we have an accelerated expansion solution. We shall find the form of  $\tilde{p}(X)$  to satisfy this requirement.

The effective speed of sound  $c_s$  of k-essence is defined by [107]

$$c_s^2 = \frac{p_X}{\rho_X} = \frac{\tilde{p}_X}{\tilde{\rho}_X} \quad (29) \quad (36)$$

From observations we know that our Universe is almost flat, so we ignore the curvature term in the Friedmann equation :

$$H^2 \equiv \dot{N}^2 = \frac{8\pi G}{3}(\rho_M + \rho_K), \quad N \equiv \ln a. \quad (30) \quad (37)$$

for the k-field,

$$\frac{dy}{dN} = \frac{3}{2} \frac{(w_K(y) - 1)}{r'(y)} \left[ r(y) - \sqrt{\frac{p_K}{\rho_K}} \right], \quad (40)$$



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## Viatcheslav Mukhanov

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**Viatcheslav Mukhanov** (Russian: Вя́чеслав Фёдорович Му́ханов; born October 2, 1956) is a **theoretical physicist** and **cosmologist**. He is best known for the theory of Quantum Origin of the Universe Structure. Working in 1980-1981 with Gennady Chibisov in the Lebedev Physical Institute in Moscow he predicted the spectrum of inhomogeneties in the Universe, which are originated from the initial quantum fluctuations. The numerous experiments in which there were measured the temperature fluctuations of the Cosmic Microwave Background Radiation are in excellent agreement with this theoretical prediction, thus confirming that the galaxies and their clusters originated from the initial quantum fluctuations. Later on V. Mukhanov proved that the results, he obtained with G. Chibisov in 1981, are of the generic origin and he has developed the general consistent quantum cosmological perturbation theory.

**Contents** [hide]

- Awards
- Publications
- See also
- References
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### Awards [ edit ]

- Oskar Klein Medal, Stockholm University, Sweden (2006).
- Tomalla prize, Switzerland (2009)
- Blaise Pascal Chair, ENS, Paris, France (2011)
- Arnaldi Medal (2012)
- Gruber Prize in Cosmology (2013)
- Friedrich Wilhelm Joseph von Schelling-Preis, Bavarian Academy of Sciences and Humanities.
- Max Planck Medal (2015)

### Publications [ edit ]

- Mukhanov, Viatcheslav and Chibisov Gennady: "Quantum fluctuations and a nonsingular Universe", JETP Lett. 33, No.10, 532 (1981), see also <http://arxiv.org/abs/astro-ph/0303077>
- Mukhanov, V. F., and Feldman, H. A., and Brandenberger, R. H.: "Theory of Cosmological Perturbations", Physics Reports (1992)

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#### Viatcheslav Mukhanov



**Born**2 October 1956 (age 59)  
Kanaash, Chuvash ASSR,  
Russian SFSR

**Residence**Germany

**Fields**Cosmology, Theoretical physics

**Institutions**Ludwig Maximilian University of Munich

**Alma mater**Moscow Institute of Physics and Technology

**Doctoral advisor**Vitaly Ginzburg

**Known for**Predicting Quantum Origin of the Universe Structure

**Notable awards**Oskar Klein Medal, Stockholm University, Sweden (2006), Tomalla prize, Switzerland (2009), Blaise Pascal Chair, ENS, Paris, France (2011), Arnaldi Medal (2012), Gruber Prize in Cosmology (2013)

# Modified Matter model

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

- Coupled dark energy and matter

modified energy conservation equations

$$\begin{aligned}\dot{\rho}_m + 3H(\rho_m) &= \delta, \\ \dot{\rho}_\phi + 3H(\rho_\phi + p_\phi) &= -\delta,\end{aligned}$$

finding an appropriate form of the coupling  $\delta$

$$\begin{aligned}\delta &= \kappa Q \rho_m \dot{\phi}, \\ \delta &= \alpha H(\rho_m + \rho_\phi),\end{aligned}$$

## Chameleon mechanism



$$S = \int d^4x \sqrt{-g} \left[ -\frac{1}{16\pi G} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + \int d^4x \mathcal{L}_m(\psi_m^{(t)}, g_{\mu\nu}^{(t)})$$

$$g_{\mu\nu}^{(t)} = e^{2\kappa\beta_1\phi} g_{\mu\nu}.$$

$$|\vec{F}| = \frac{GM_1M_2}{r^2} (1 + 2\beta_1\beta_2).$$

$$G_{eff} = G(1 + 2\beta_1\beta_2)$$

# Modified Matter model

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

- Unified dark energy and matter

## Chaplygin gas

$$p = -\frac{A}{\rho^\alpha}$$

$$\rho(t) = \left[ A + \frac{B}{a^{3(1+\alpha)}} \right]^{\frac{1}{1+\alpha}}$$

In the early epoch,  $a \ll 1$ , the Chaplygin gas energy density behaves as  $\rho \propto a^{-3}$  which corresponds to the matter dominated Universe. In the late epoch,  $a \gg 1$ , the energy density behaves as  $\rho \approx A^{1/(1+\alpha)} = \text{const.}$  which corresponds to the de Sitter Universe.

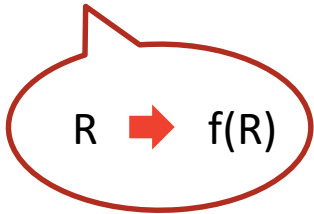
Thus the Chaplygin gas behaves as dark matter in the early epoch and dark energy in the later epoch.

➡ It explains **both dark sectors in terms of a single component.**

# Modified Gravity model

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

- $f(R)$  gravity



$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \boxed{f(R)} + \int d^4x \sqrt{-g} \mathcal{L}_M$$

$$w_{DE} \equiv \frac{p_{DE}}{\rho_{DE}} = -\frac{2A\dot{H} + 3AH^2}{3AH^2 - 8\pi G \rho_m}.$$

$$G_{eff} \equiv -\frac{G}{f_{,R}} \frac{1 - 4mk^2/(a^2 R)}{1 - 3mk^2/(a^2 R)}, \quad m \equiv \frac{Rf_{,RR}}{f_{,R}}.$$



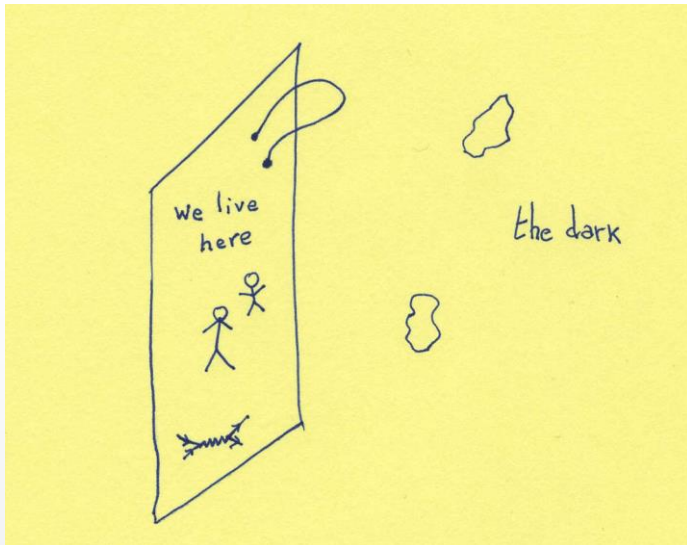
# Modified Gravity model

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

- DGP model



5<sup>th</sup> Dimension!



5D

4D

$$S = -\frac{M_{(5)}^3}{2} \int d^5 X \sqrt{-\tilde{g}} \tilde{R} - \frac{M_{pl}^2}{2} \int d^4 x \sqrt{-g} R + \int d^4 x \sqrt{-g} \mathcal{L}_m$$

$$\tilde{G}_{AB} \equiv \tilde{R}_{AB} - \frac{1}{2} \tilde{R} \tilde{g}_{AB} = 0 \quad 5D$$

$$G_{\mu\nu} - \frac{1}{r_c} (K_{\mu\nu} - K g_{\mu\nu}) = 8\pi G T_{\mu\nu} \quad 4D$$

$$H^2 + \frac{k}{a^2} = \left( \sqrt{\frac{\rho}{3M_{pl}^2} + \frac{1}{4r_c^2} + \frac{\epsilon}{2r_c}} \right)^2 \quad 4D$$



# Non Dark Energy model

- Inhomogeneous LTB model

We are living in large underdense void!  
Throw away the Friedmann-Lemaitre-Robertson-Walker (FLRW) metric !!  
(homogeneous and isotropic universe)

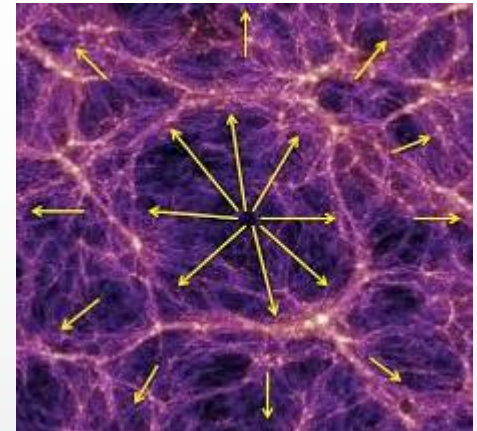
$$ds^2 \equiv g_{\mu\nu} dx^\mu dx^\nu = dt^2 - a^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 d\Omega^2 \right]$$

Metric for a spherically symmetric inhomogeneous Universe

$$ds^2 = dt^2 - X^2(r, t) dr^2 - R^2(r, t) d\Omega^2$$

Einstein equations for the dust dominated LTB Universe

$$\begin{aligned} H_\perp^2 + 2H_\parallel H_\perp - \frac{\beta}{R^2} - \frac{\beta'}{RR'} &= 8\pi G\rho, \\ 6\frac{\ddot{R}}{R} + 2H_\perp^2 - 2\frac{\beta}{R^2} - 2H_\parallel H_\perp + \frac{\beta'}{RR'} &= -8\pi G\rho, \end{aligned}$$





# What to do?

- Dark Energy projects

Probes	SN Ia	CMB	BAO	WL
Stage I	Higher-Z Team [10, 33], SNLS [34, 35, 36], ESSENCE [37, 38], NSF [39], CSP [40, 41], LOSS [42, 43, 44], SDSS [45, 46], SCP [21, 47, 48], CfA [49, 50], Palomar QUEST Survey [51]	COBE [52], TOCO [53], BOOMERang [54], Maxima [55], WMAP [14, 15, 16, 17]	2dFGRS [56], SDSS [57], 6dFGRS [58], WiggleZ [59]	CFHTLS [60, 61]
Stage II	Pan-STARRS1 [62], HST [63], KAIT [64]	Planck [65, 66], [67], SPT [68], [69], ACT [70]	SDSS II [71], SDSS III [72], BOSS [73, 74], LAMOST [75], WEAVE [76]	Pan- STARRS1, DLS [77, 78], KIDS [79]
Stage III	DES [80], Pan- STARRS4, ALPACA [81], ODI [82]	ALPACA, CCAT [83]	DES, HET- DEX [84], BigBOSS [85], AL- PACA, SuMIRe [86]	DES, Pan- STARRS4, ALPACA, ODI
Stage IV	LSST [87], WFIRST [88]	EPIC [89, 90], LiteBIRD [91], [92], B-Pol [93]	LSST, SKA [94], WFIRST, Euclid [95]	LSST, SKA, WFIRST, Euclid

Table 1: Dark energy projects. Classification is taken from ref. Report of the Dark Energy Task Force, astro-ph/0609591.

Stage I: completed projects that already released data

Stage II: on-going projects

Stage III: intermediate-scale, near-future projects

Stage IV: large-scale, longer-term future projects

# What to do?

- Effective Newton's constant  $G_{eff}$

satellite measurement



- Eötvös parameter  $\eta$



*From Einstein's biggest blunder to the Nobel Prize in Physics 2011*

*- Now we are ready to meet the most mysterious  
cosmological discoveries!*






# THANK YOU!



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