UST Journal Club @ KASI

Dec. 02, 2015

Theoretical Models of Dark Energy

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

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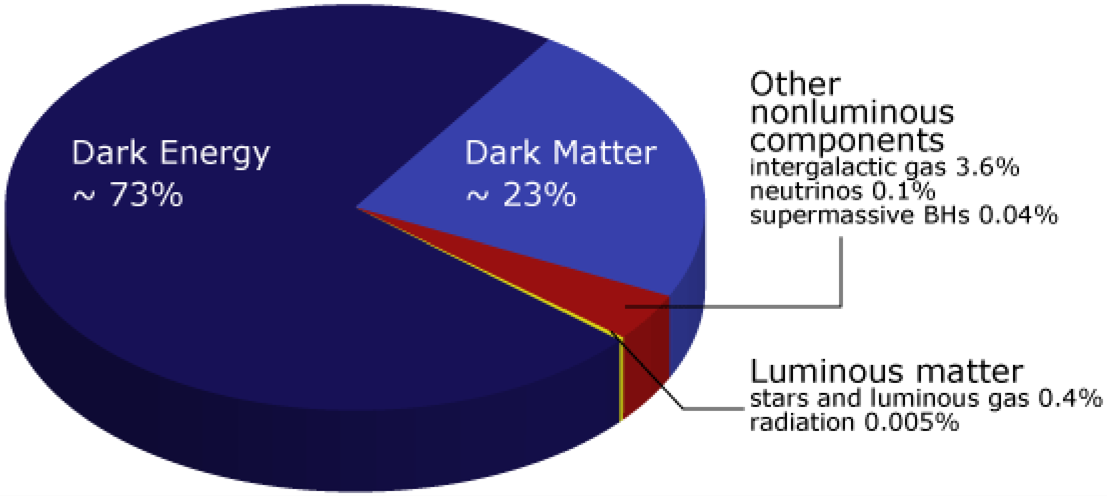
Motivation

- The composition of the universe



- Supernovae as a standard candle

Motivation

- Observational evidences on Dark Energy

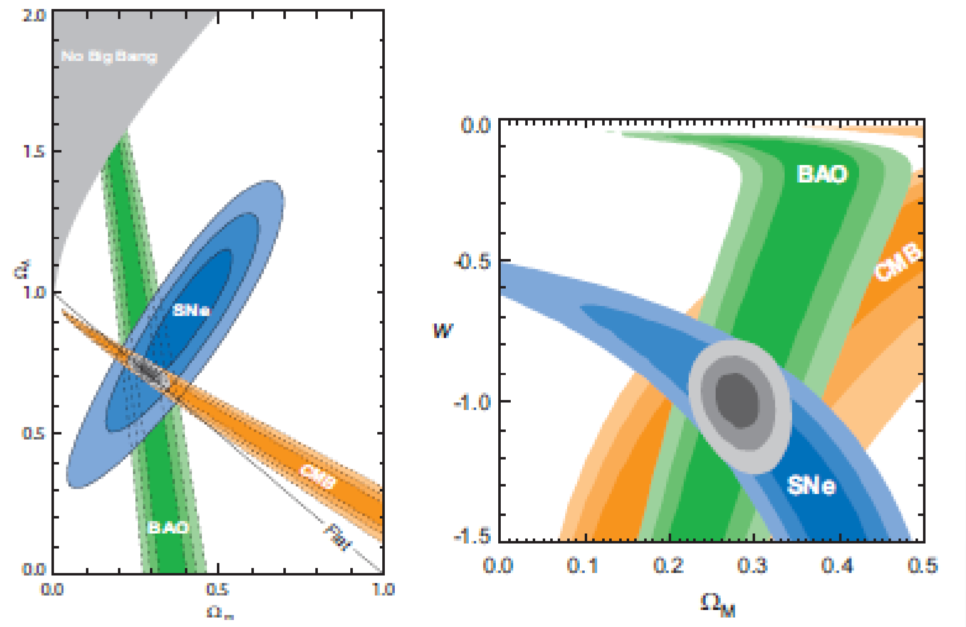


Figure 1: There is strong evidence for the existence of dark energy. Plotted are Ω_m -Ω_Λ (left panel) and Ω_m - ω (right panel) confidence regions constrained from the observations of SN Ia, CMB and BAO. From Ref. Astrophys.J. 686 (2008) 749{778, [arXiv:0804.4142]

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

Motivation

- Cosmological constant

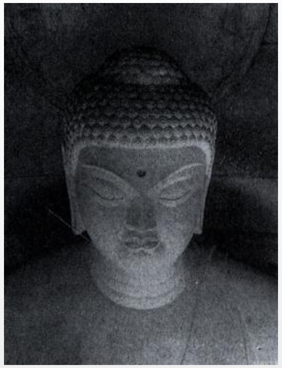
$$\Lambda$$

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

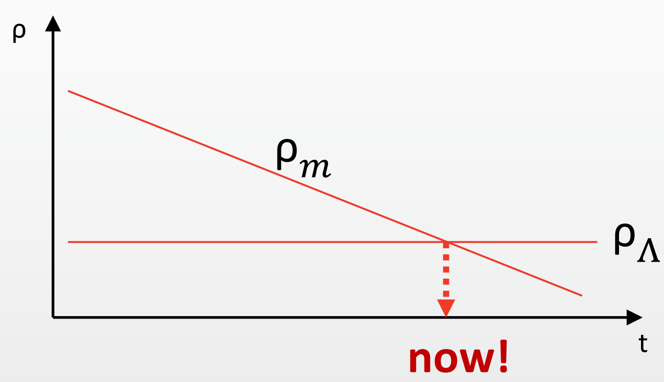
Observation: $\rho_\Lambda^{obs} \leq (10^{-12} GeV)^4 \sim 2 \times 10^{-10} erg/cm^3$

$\mathbf{10^{120}}$ discrepancy

"The worst theoretical prediction in the history of physics!"

Why small?

Coincidence problem



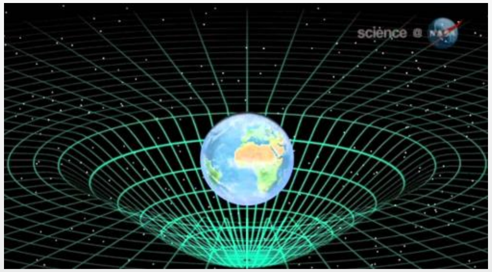
Why now?

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

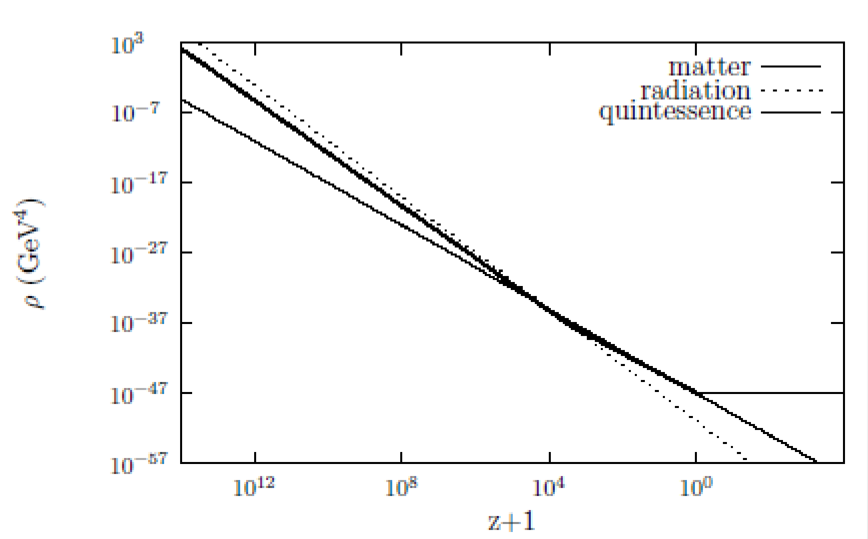
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- Quintessence

Scalar field (Φ)?

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

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



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,

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

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

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

which has the desired property for dark energy.

For small X, $\tilde{p}(X)$ could be expanded as $\tilde{p}(X) = const. + X + \mathcal{O}(X^2)$. 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

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

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

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

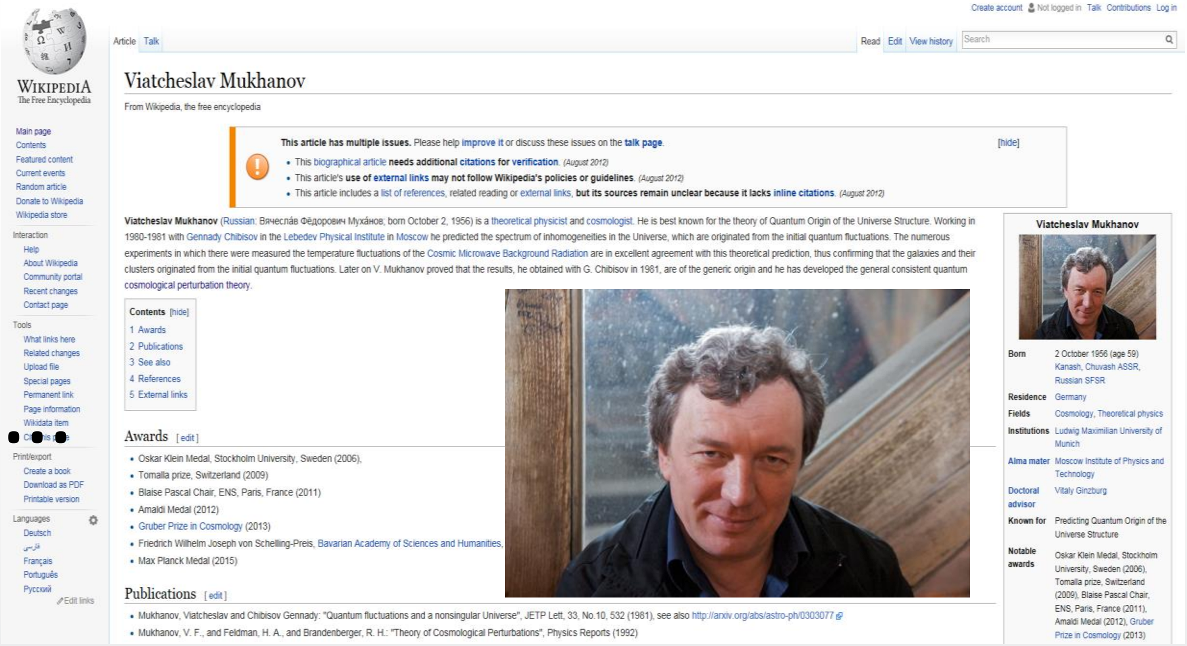
where $_{,X}$ means derivative with respect to X. If the Lagrangian p satisfies the condition $Xp_{,X} \ll p$ for some range of X and ϕ, then the equation of state is $p \approx -\rho$ so that we have an accelerated expansion solution. We shell find the form of $\tilde{p}(X)$ to satisfy this requirment.

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

$$c_s^2 = \frac{p_{,X}}{\rho_{,X}} = \frac{\tilde{p}_{,X}}{\tilde{\rho}_{,X}}. \quad (29)$$

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

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



Modified Matter model

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

- Coupled dark energy and matter

modified energy conservation equations

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

finding an appropriate form of the coupling δ

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

<u>Chameleon mechanism</u>

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

$$g_{\mu\nu}^{(i)} = e^{2\kappa\beta_i\phi} g_{\mu\nu}$$

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

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

Modified Matter model

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

- Unified dark energy and matter

<u>Chaplygin gas</u>

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

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

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 $\rho \approx A^{1/(a+\alpha)} = const.$ 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 **<u>both dark sectors in terms of a single component</u>**.

Modified Gravity model

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

- f(R) gravity

R ➡ f(R)

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

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

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

Modified Gravity model

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

- DGP model

5th Dimension!

5D 4D

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

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

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

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

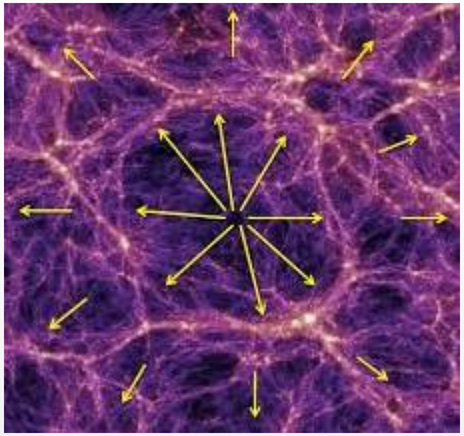
Non Dark Energy model

- 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

$$H_\perp^2 + 2H_\parallel H_\perp - \frac{\beta}{R^2} - \frac{\beta'}{RR'} = 8\pi G\rho,$$

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

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?

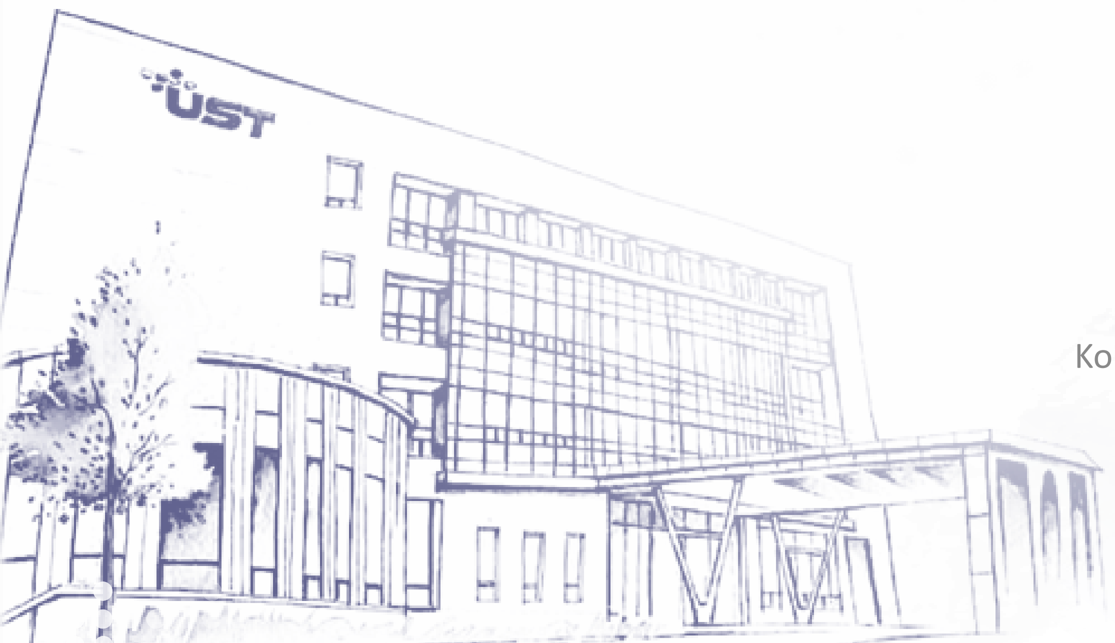
- Effective Newton's constant G_{eff}
- Eötvös parameter η

satellite measurement

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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