Dark Energy vs. Modified Gravity

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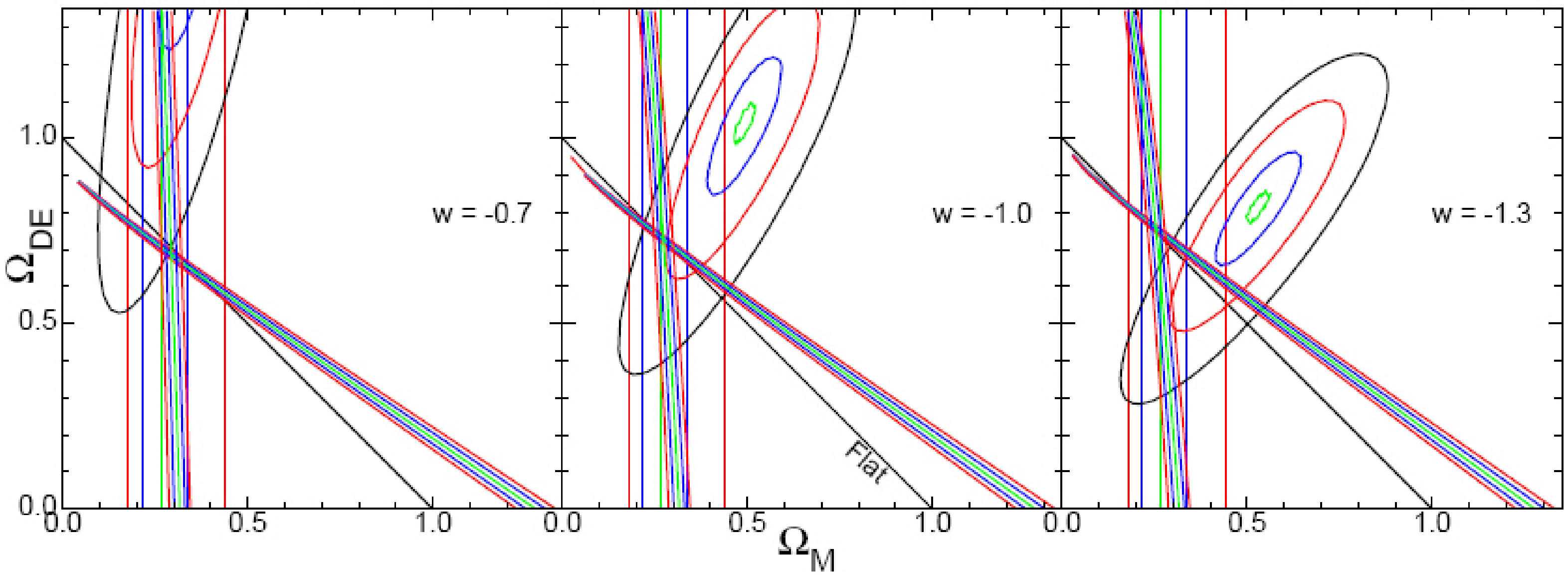
Outline

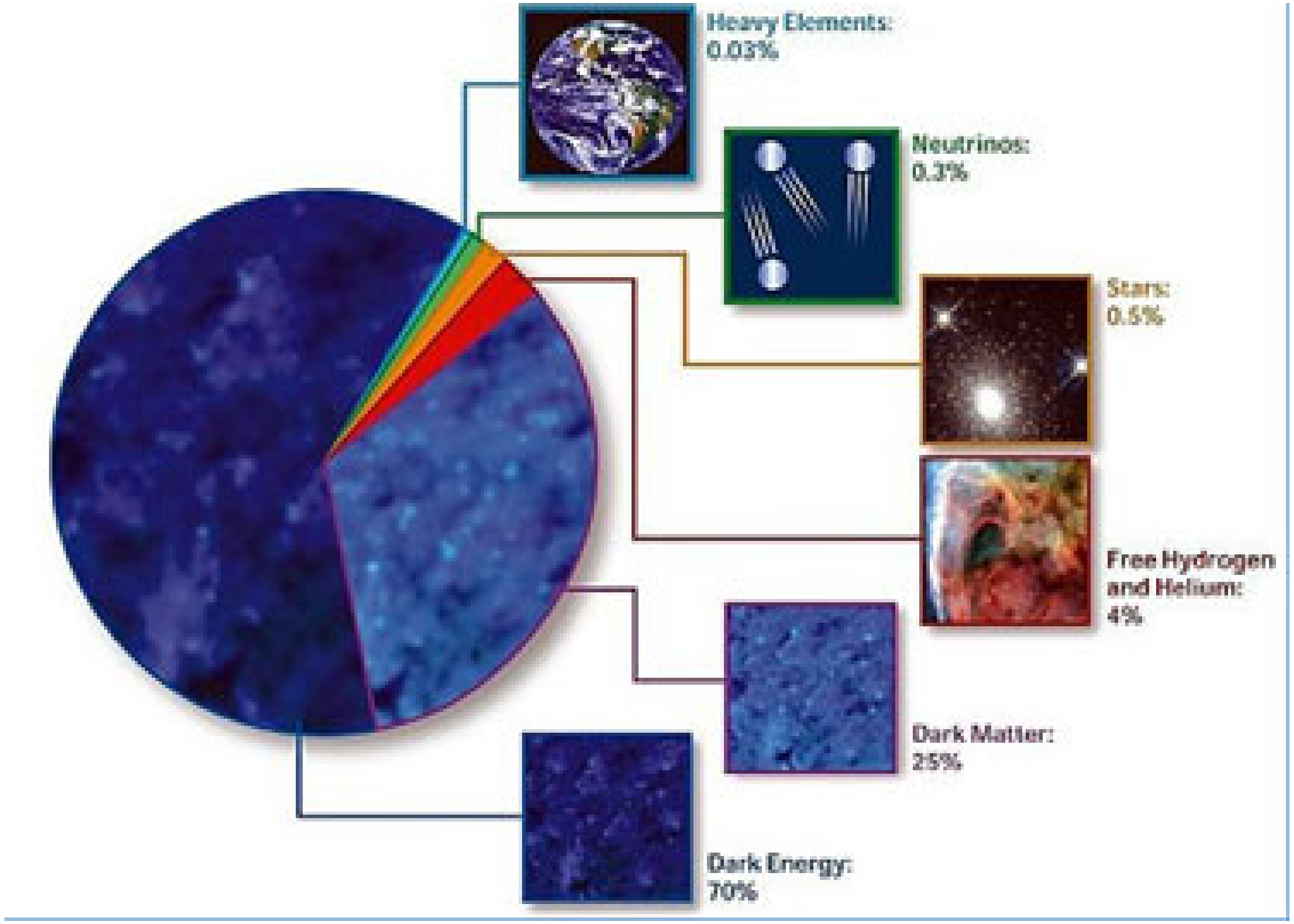
- Experimental Evidences
- Motivations
- Models
- Phenomena (Evolution of Background, Growth factors)
- Summary

Experimental Evidences
(Cosmological Concordance ?!)



- SNe Ia (Fig from E.L.Wright 06)
- CMB
- Values for H (Age of Universe)
- Baryonic Oscillations → SDSS

Experimental Evidence II



Motivations

$$\delta G_{\mu\nu}(\mathrm{MG}) + \mathrm{R}_{\mu\nu} - \frac{1}{2}\mathrm{g}_{\mu\nu}\mathrm{R} = 8\pi \mathrm{G T}_{\mu\nu} + 8\pi \mathrm{G T}_{\mu\nu}(\mathrm{DE})$$

$$S = \int d^n x \sqrt{-g}\left[\frac{1}{2}f(R,\phi) + \mathcal{L}_\phi(g_{\mu\nu},\phi,\partial\phi) + \mathcal{L}_m(g_{\mu\nu},\Psi)\right]$$

- Observations are inconsistent with the expected universe (GR[FLRW] + Matter). Based on homogeneous and isotropic space-time.
- Need to change either Gravity or Matter (if we still believe homogeneity and isotropy).

Generalized Gravity Theories I

- A broad class of alternative gravity theories
- Ψ : matter fields
- Φ : a scalar field

$$S = \int d^n x \sqrt{-g}\Big[\frac{1}{2} f(R,\phi) + \mathcal{L}_\phi(g_{\mu\nu}, \phi, \partial\phi) + \mathcal{L}_m(g_{\mu\nu}, \Psi)\Big]$$

$$\mathcal{L}_\phi = -\frac{M^2}{2}\omega(\phi)(\partial\phi)^2 - V(\phi)$$

$$(\partial\phi)^2 = \nabla_\mu\phi\nabla^\mu\phi. \;\; F(R,\phi) = \partial f(R,\phi)/\partial R.$$

Generalized Gravity Theories II

Generalized gravity	$\frac{1}{2}f(R,\phi)$	$\mathcal{L}_\phi(\phi,\partial\phi)$	$p(R,\phi)$	φ	$\tilde{V}(\varphi)$	Ref
Nonlinear gravity	$\frac{1}{2}f(R)$	$\omega=0,\ V=0$	$p=F(R)$	$\sqrt{\frac{3}{2}}\ln F$	$\frac{FR-f}{2F^2}$	[1]
R^2-gravity	$\frac{1}{2}(R+\alpha R^2)$	$\omega=0,\ V=0$	$p=1+2\alpha R$	$\sqrt{\frac{3}{2}}\ln F$	$\frac{FR-f}{2F^2}$	[2]
$1/R$-gravity	$\frac{1}{2}(R-\mu^4/R)$	$\omega=0,\ V=0$	$p=1+\mu^4/R^2$	$\sqrt{\frac{3}{2}}\ln F$	$\frac{FR-f}{2F^2}$	[3]
Scalar-tensor theory	$\frac{1}{2}F(\phi)R$	$\omega(\phi),\ V(\phi)$	$p=F(\phi)$	$\int\sqrt{\frac{\omega}{F}+\frac{3}{2}\frac{F'^2}{F^2}}d\phi$	$\frac{V}{F^2}$	[4]
Brans-Dicke theory	ϕR	$\omega(\phi)=2\frac{\omega}{\phi},\ V=0$	$p=\phi$	$\int\sqrt{\frac{\omega}{F}+\frac{3}{2}\frac{F'^2}{F^2}}d\phi$	0	[5]
Dilaton	$\frac{1}{2}e^{-\phi}R$	$\omega(\phi)=e^{-\phi},\ V=0$	$p=e^{-\phi}$	$\frac{5}{2}\phi$	0	[6]
NMC scalar	$\frac{1}{2}(1+\xi\phi^2)R$	$\omega=1,\ V(\phi)$	$p=1+\xi\phi^2$	$\int\frac{\sqrt{1+\xi(6\xi-1)\phi^2}}{1-\xi\phi^2}d\phi$	$\frac{V}{1-\xi\phi^2}$	[7]
CC ($\xi=\frac{1}{6}$)	$\frac{1}{2}(1+\frac{1}{6}\phi^2)R$	$\omega=1,\ V(\phi)$	$p=1+\frac{1}{6}\phi^2$	$\sqrt{6}\tanh^{-1}\frac{\phi}{\sqrt{6}}$	$\frac{V}{1-\frac{1}{6}\phi^2}$	[8]
Induced Gravity	$\frac{1}{2}\epsilon\phi^2R$	$\omega=1,\ V(\phi)$	$p=\epsilon\phi^2$	$\sqrt{6+\frac{1}{\epsilon}}\ln\phi$	$\frac{V}{\epsilon\phi^2}$	[9]
GR with a scalar	$\frac{1}{2}R$	$\omega=1,\ V(\phi)$	$p=1$	ϕ	V	

Generalized Gravity Theories III

[1] G. Magnano and L. M. Sokolowski, Phys. Rev. **D 50**, 5039. 1994 [gr-qc/9312008].

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Quartessence (Unification of DM & DE)

Model	ρ	Ref
Modified polytropic Cardassian	$[Aa^{3q(\nu-1)} + Ba^{-3q}]^{\frac{1}{q}}$	[10]
New generalized Chaplygin gas	Same	[11]
ΛCDM	$q = 1, \nu = 1$	[12]
Cardassian expansion	$q = 1$	[13]
Polytropic Cardassian	$\nu = 1$	[11]
generalized Chaplygin gas	$\nu = 2$	[14]
variable Chaplygin gas	$q = 2$	[15]
Chaplygin gas	$\nu = 2, q = 1$	[16]
Modified Chaplygin gas	$(A + Ba^{-3})^q$	[17]
Exponential Cardassian	$(Aa^{-3} + B)\exp[(\frac{qB}{Aa^{-3}+B})^{\nu}]$	[18]
Extra dimension inspired	$Aa^{-3}[1 + \exp(-Ba^{-3})]^q$	[19]
Phenomenological approach	$A(1 + Ba^{-1})^{q-\nu}[1 + Ca^{-\nu}]$	[20]
Leaking gravity (DGP)	$Aa^{-3} + B - \sqrt{B^2 + ABa^{-3}}$	[21]

Quartessence II

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[12] T. Koivisto, H. Kurki-Suonio, and F. Ravndal, Phys. Rev. **D 71**, 064027. 2005. [astro-ph/0409163]

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[14] M. C. Bento, O. Bertolami, and A. A. Sen, Phys. Rev. **D66**, 043507, 2002 [gr-qc/0202064].

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[16] A. Y. Kamenshchik, U. Moschella, and V. Pasquier, Phys. Lett. **B511**, 265 2001 [gr-qc/0103004].

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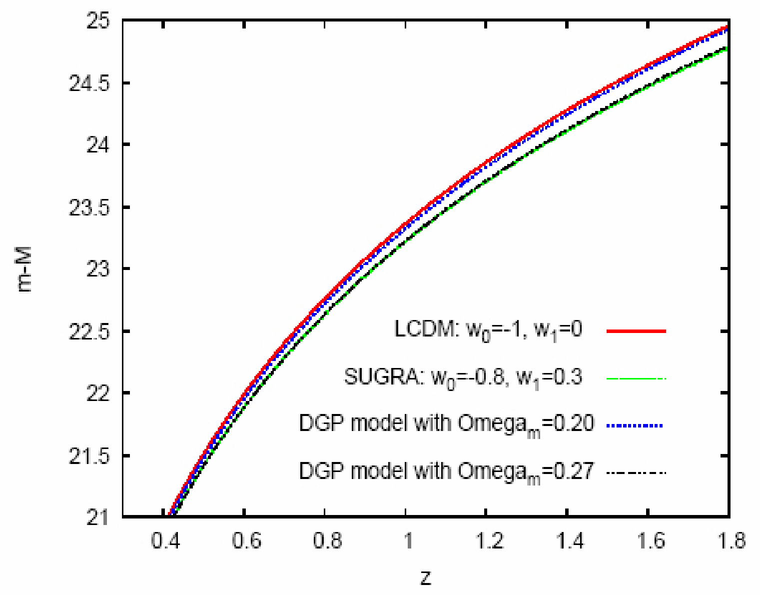
Background Evolution

$$H^2 - \delta H^2 = \sum_{i=\mathrm{rad,mat}} \frac{8\pi G}{3}\rho_i$$

$$\omega_{\mathrm{DE}} = -1 + \frac{1}{3}\frac{d\ln\delta H^2}{d\ln(1+z)}$$

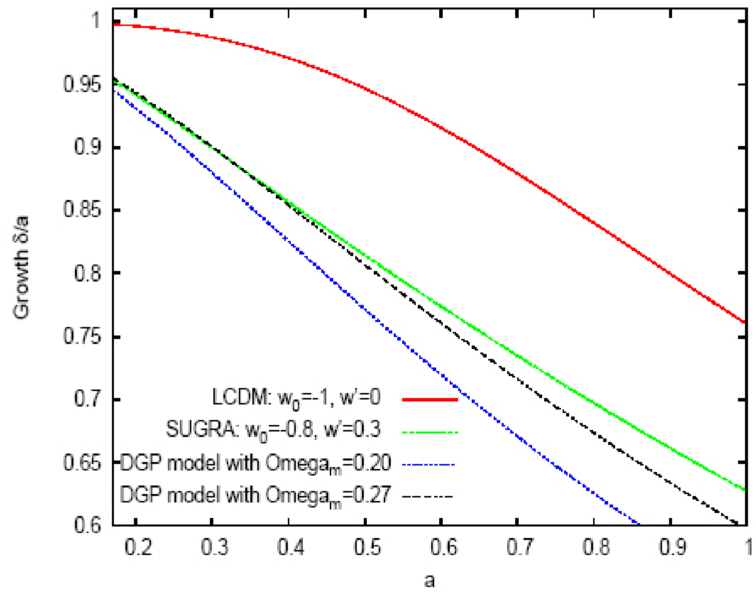


- SNe Hubble diagrams for DE and DGP models (Fig from M.Ishak et al, 06)

Growth Factors

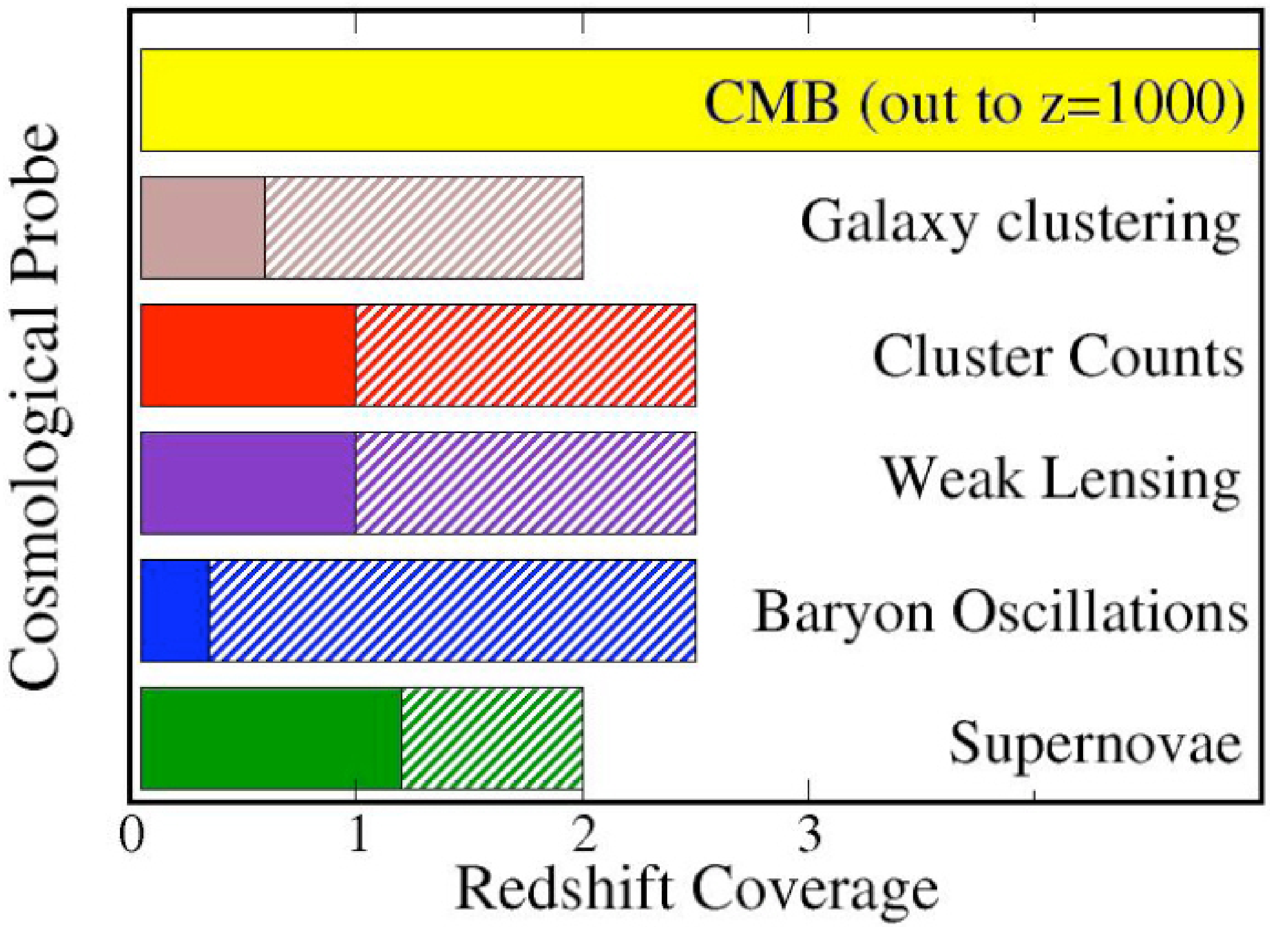
$$\ddot{\delta} + 2H_{DGP}\dot{\delta} - 4\pi G\rho(1 + \frac{1}{3\beta})\delta = 0$$

$$\beta = 1 - 2r_c H_{DGP}\left(1 + \frac{\dot{H}_{DGP}}{3H_{DGP}^2}\right)$$



- Growth factors of linear perturbations

DETF probes


CMB (out to z=1000)
Galaxy clustering
Cluster Counts
Weak Lensing
Baryon Oscillations
Supernovae
Cosmological Probe
0
1
2
3
Redshift Coverage

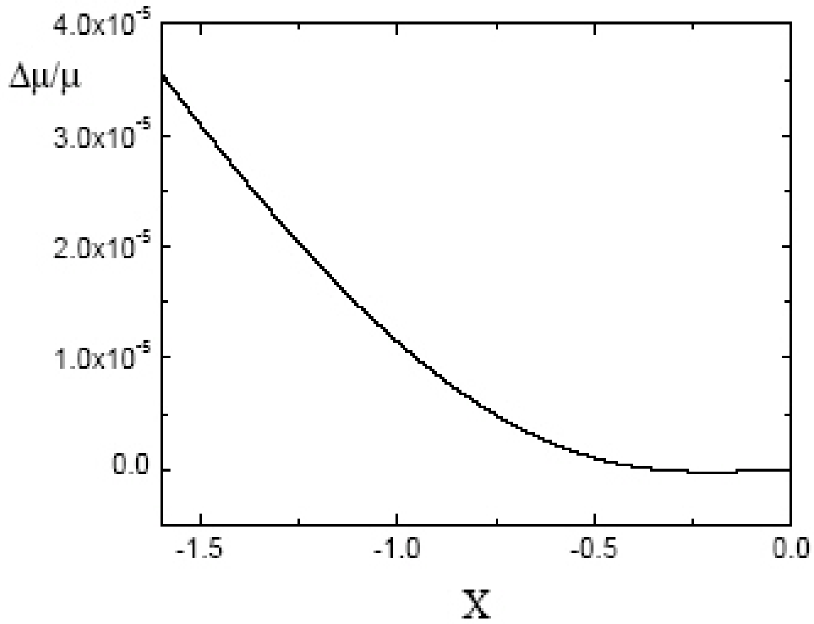
Time Varying Alpha (Late time)

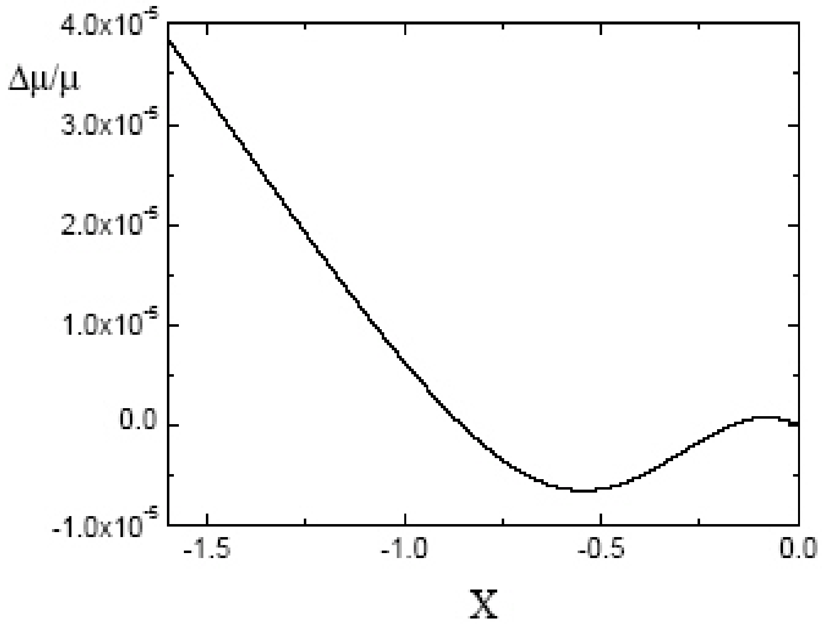
Table 4: Results for $\Delta\alpha/\alpha$ for comparisons with the Oklo, meteoritic, present-day, and equivalence principle bounds. Values of $\Delta\alpha/\alpha$, ξ, and ζ have been scaled by a factor of 10^6, values of $\dot{\alpha}/\alpha$ and $\Delta g/g$ have been scaled by a factor of 10^{17}.

$\frac{V(\phi)}{V_0}$	$(\frac{\Delta\alpha}{\alpha})_3$	$(\frac{\Delta\alpha}{\alpha})_{1.5}$	ξ	ζ	$(\frac{\Delta\alpha}{\alpha})_{0.14}$	$(\frac{\Delta\alpha}{\alpha})_{0.45}$	$\frac{\dot{\alpha}}{\alpha}$ (yr^{-1})	$\frac{\Delta g}{g}$
$\exp(\lambda\phi^2/2)$	-5.4	-3.4	0	-7.6	-0.24	-0.42	9.6	-2.5
	-5.4	-2.1	22	0	-0.011	-0.05	0.048	-0.074
	-0.93	-0.6	0	-1.3	-0.041	-0.073	1.7	-0.076
	-1.4	-0.6	5.8	0	-0.0028	-0.013	0.013	-0.0053
$\cosh(\lambda\phi)$	-5.4	-0.54	0	-29	-0.097	0.20	0.17	-36
	-5.4	-0.054	310	0	-0.0017	-0.029	0.0014	-1.5
	-4.5	-0.6	0	-24	-0.082	0.17	0.16	-26
	-34	-0.6	1900	0	-0.011	-0.18	0.012	-59

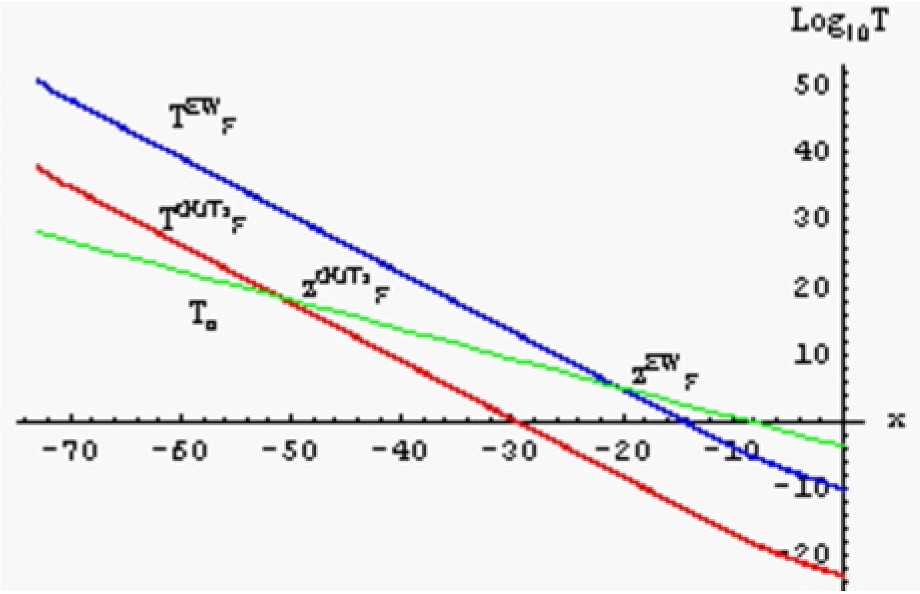
Time Varying Mass

- Time Varying proton to electron mass ratio. (SL, 07) : observation : E-5 Chand et.al, 04 (z ~ 2.8)





Spontaneous Baryogenesis

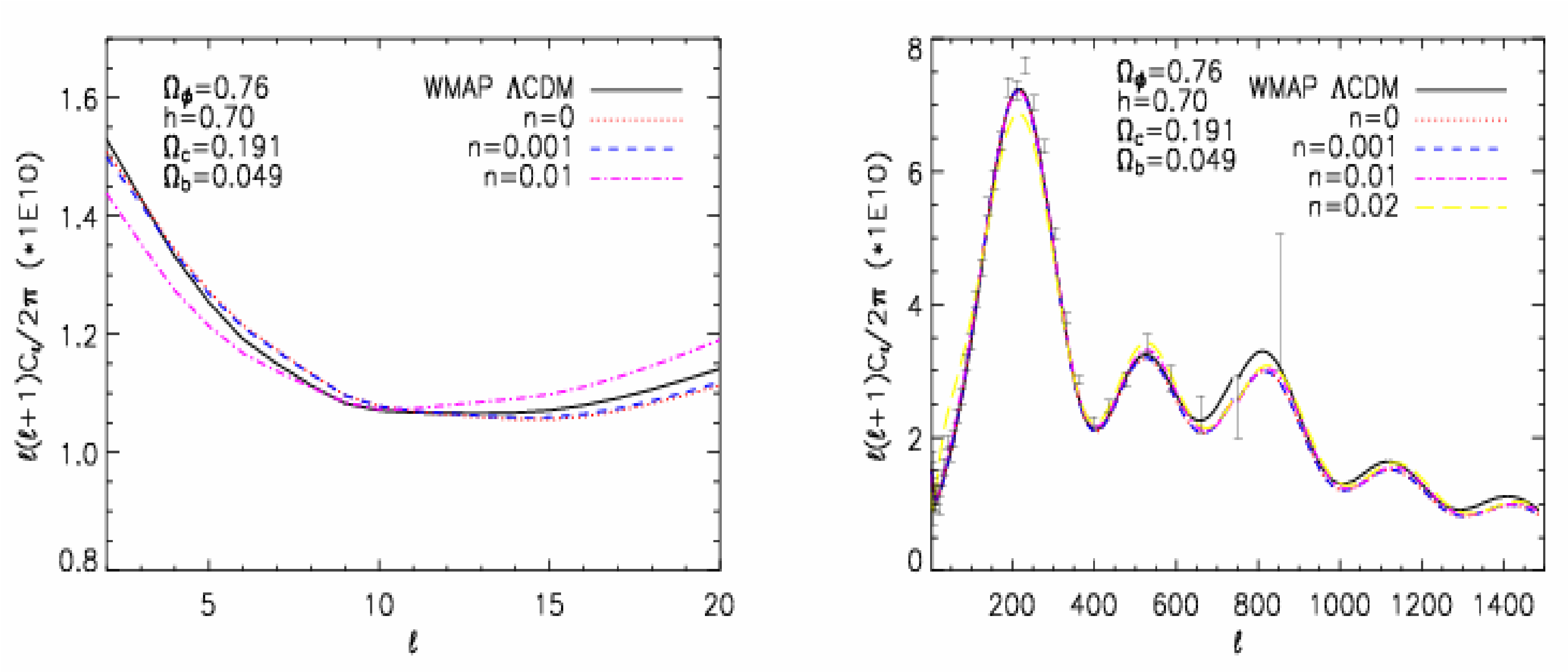


$$\frac{q}{M_*}\bar{M}\,\partial_\mu\phi\, j_B^\mu$$

To obtain the expected value of the baryon asymmetry (E-10), the freeze-out temperature are 10E10 GeV and 1Mev for GUTs and EW, respectively. (SL, personal note)

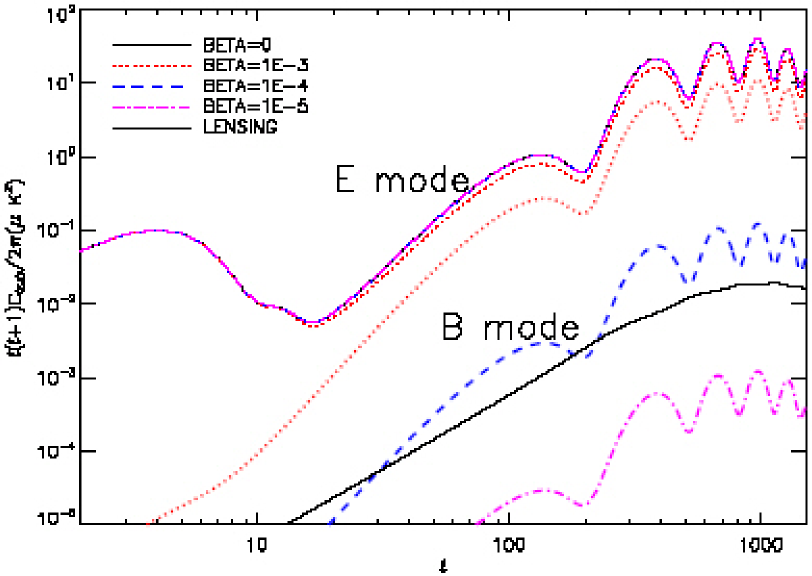
CMB T

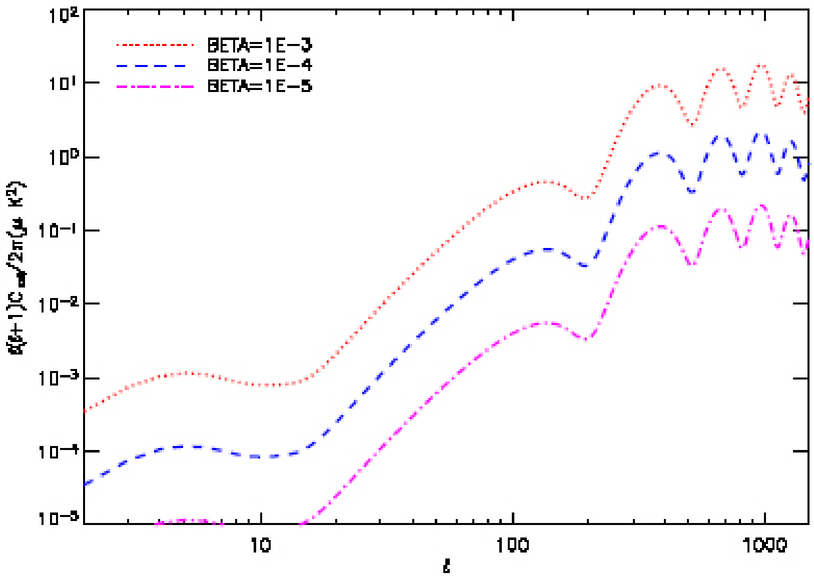
- S.L,G-C.Liu, K-W.Ng (06)



CMB E,B,EB

- Due to cosmological birefringence (double refraction), we have mixing between E and B modes (S.L, G-C.Liu, K-W.Ng, 06) : counter example of Schiff's conjecture





Summary

- Homogeneity and Isotropy should be checked.
- Alternative scenario on cosmology will give huge effects on particle physics.
- Both MG and DE models can satisfy current observations.
- Geometric tests are not enough to separate MG with DE.
- Need to distinguish possible models with upcoming observations.

Quintessence

- Quintessence = Fifth Element (精髓 정수)
- Air, Earth, Fire, Water (In Alchemy)
- b, DM, n, γ (In Cosmology)
- Tip : Milla Jovovich (In Film)

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Quintessence Potentials (SL 06)

Quintessence Potential	Reference	ω
$V_0 \exp(-\lambda\phi)$	Ratra & Peebles (1988), Wetterich (1988), Ferreira & Joyce (1998)	$\omega = \lambda^2/3 - 1$ $\lambda > 5.5 - 4.5, \Omega < 0.1 - 0.15$
$V_0/\phi^\alpha, \alpha > 0$	Ratra & Peebles (1988)	$\omega > -0.7$
$m^2\phi^2, \lambda\phi^4$	Frieman et al (1995)	PNGB $M^4[\cos(\phi/f) + 1]$
$V_0(\exp M_p/\phi - 1)$	Zlatev, Wang & Steinhardt (1999)	$\Omega_m \geq 0.2, \omega < -0.8$
$V_0 \exp(\lambda\phi^2)/\phi^\alpha$	Brax & Martin (1999,2000)	$\alpha \geq 11, \omega \simeq -0.82$
$V_0(\cosh\lambda\phi - 1)^p$	Sahni & Wang (2000)	$p < 1/2, \omega < -1/3$
$V_0 \sinh^{-\alpha}(\lambda\phi)$	Sahni & Starobinsky (2000), Ureña-López & Matos (2000)	early time : inverse power late time : exponential
$V_0(e^{\alpha\kappa\phi} + e^{\beta\kappa\phi})$	Barreiro, Copeland & Nunes (2000)	$\alpha > 5.5, \beta < 0.8, \omega < -0.8$
$V_0[(\phi - B)^\alpha + A]e^{-\lambda\phi}$	Albrecht & Skordis (2000)	$\omega \sim -1$
$V_0 \exp[\lambda(\phi/M_p)^2]$ $V_0 \cosh[\lambda\phi/M_p]$	Lee, Olive, & Pospelov (2004)	$\omega \sim -1$ $\omega \sim -1$

Matter Power Spectrum II

$$\bar{\delta}_c'' + \mathcal{H}\bar{\delta}_c' - \frac{3}{2}\mathcal{H}^2 \frac{(\delta\bar{\rho}_{\rm tot} + \bar{p}_{\rm tot})}{\bar{\rho}_{cr}} - \frac{(a \times {\rm coup})'}{a} = 0$$

$${\rm coup} = B_{(c),\bar{\phi}\bar{\phi}}\bar{\phi}'\delta\phi + B_{(c),\bar{\phi}}\delta\phi' = n\lambda(\bar{\phi}\delta\phi)'$$

$$\bar{\delta}_c^{(\pm)} = c_{(\pm)}\eta^{\nu(\pm)}$$

$$\nu_{(\pm)} = \frac{-(1+\xi) \pm \sqrt{24 + (1+\xi)^2}}{2(1-\xi)}$$

DE

- DARK ENERGY IS NOWHERE!