Dark Energy and
CPT Test with CMB

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Outline

1) Brief review on the dark energy models;
2) Current constraints on equation of state of dark energy;
3) Interacting dark energy:
    - i) Neutrino dark energy (mass varying neutrino)
        - LV varying neutrino: "OPERA and Neutrino DE model"
        - Ciuffoli, Evslin, Liu and Zhang, arXiv: 1109.6641
    - ii) Quintessential Baryo/Leptogenesis
        (cosmological CPT violation)
4) Current status on CPT test with CMB polarization
5) Conclusion and discussions

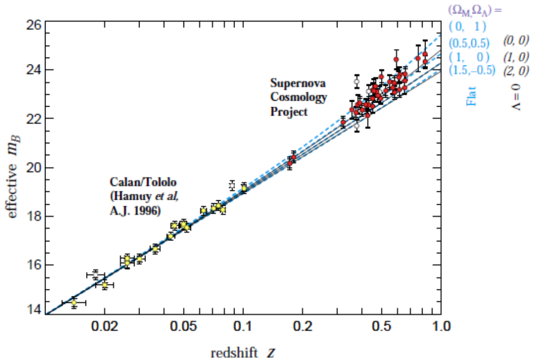
Brief Introduction to Dark Energy

Negative pressure:

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

$$\ddot{a} > 0 \quad \rightarrow \quad \rho + 3p < 0 \quad w = p/\rho < -1/3$$

* *Smoothly distributed, (almost) not clustering*



Candidates:

I Cosmological constant (or vacuum Energy)

$$T_{\mu\nu} = \frac{\Lambda}{8\pi G} g_{\mu\nu} \qquad \rho = -p = \frac{\Lambda}{8\pi G} \approx (2 \times 10^{-3}\, eV)^4$$

$$\downarrow$$

$$w = p/\rho = -1 \qquad \qquad m_\nu \sim 10^{-3}\,\mathrm{eV}$$

Neutrino
Dark Energy?!

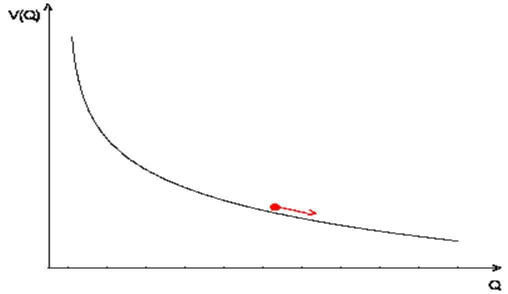
$$\rho^{th}/\rho^{ob} \sim 10^{120}$$ **cosmological constant problem!**

II Dynamical Field: Quintessence, Phantom, Quintom….

$$L = \frac{1}{2}\partial_\mu Q \partial^\mu Q - V(Q) \qquad \rho_Q = \frac{1}{2}\dot{Q}^2 + V, \; p_Q = \frac{1}{2}\dot{Q}^2 - V$$

$$W(Q) = \frac{\frac{1}{2}\dot{Q}^2 - V}{\frac{1}{2}\dot{Q}^2 + V} \qquad \dot{Q}^2 << V \quad \rightarrow \quad w \approx -1$$

Models? V=? $\dot{w} \neq 0$



Equation of state w=p/ρ:

characterize the properties of the dark energy models

- Vacuum : w=-1
- Quintessence: $w \geq -1$
- Phantom: w<-1
- Quintom: w across -1

Crucial Important: determining the equation of state of dark energy with cosmological observations

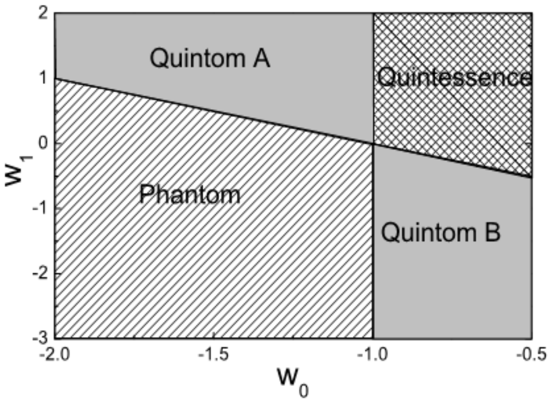
Parameterization of the equation of state:

(very much like S.T.U parameters introduced for the precision measurements **of the standard model**)

i) w=w_0+w_1 z (for small z)

ii) w=w_0+w_1 z / (1+z) =====➔
(used mostly in the literature)

iii) w=w_0+w_1 sin(w_2 ln(a)+w_3)



General parameters of cosmological models:

$$\mathbf{P} \equiv (\omega_b, \omega_c, \Omega_k, H_0, \tau, w_0, w_1, \Sigma m_\nu, n_s, A_s, \alpha_s, r)$$

Global analysis with
current astronomical
observational data:
SN (Union2.1, SNLS3)
LSS (SDSS),
CMB(WMAP7, …)
And code used
CAMB/CosmoMC

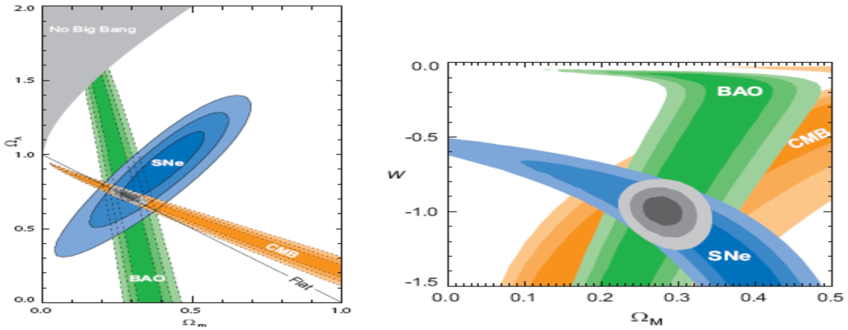


Figure 8: *Left panel*: Constraints upon Ω_M and Ω_Λ in the consensus model using BAO, CMB, and SNe measurements. *Right panel*: Constraints upon Ω_M and constant w in the fiducial dark energy model using the same data sets. From Kowalski et al. (2008).

However, difficulty with the dark energy perturbation
when w across -1 ===========➔ divergent

$$\dot{\delta}_i = -(1+w_i)(\theta_i - 3\dot{\Phi}) - 3\mathcal{H}(\frac{\delta P_i}{\delta \rho_i} - w_i)\delta_i \quad ,$$

$$\dot{\theta}_i = -\mathcal{H}(1-3w_i)\theta_i - \frac{\dot{w}_i}{1+w_i}\theta_i + k^2(\frac{\delta P_i/\delta\rho_i}{1+w_i}\delta_i - \sigma_i + \Psi)$$

δ , θ : density perturbation and the divergence of the fluid velocity respectively

$$\boxed{1 + w \to 0, \dot{w} \neq 0 \ \Rightarrow \ \dot{\delta}, \dot{\theta}, \delta, \theta \to \infty}$$

Perturbation with Quintom scenario of dark energy

(introducing extra degrees of freedom such as
2-scalar field, 1-scalar with higher derivatives……)

$$\begin{aligned}\dot{\delta}_i &= -(1+w_i)(\theta_i - 3\dot{\Phi}) - 3\mathcal{H}(1-w_i)\delta_i - 3\mathcal{H}\frac{\dot{w}_i + 3\mathcal{H}(1-w_i^2)}{k^2}\theta_i \\ \dot{\theta}_i &= 2\mathcal{H}\theta_i + \frac{k^2}{1+w_i}\delta_i + k^2\Psi\ .\end{aligned}$$

$$w_{quintom} = \frac{\sum_i P_i}{\sum_i \rho_i} \qquad \delta_{quintom} = \frac{\sum_i \rho_i \delta_i}{\sum_i \rho_i} \qquad \theta_{quintom} = \frac{\sum_i (\rho_i + p_i)\theta_i}{\sum_i (\rho_i + P_i)}$$

Perturbation of DE is continuous during crossing!

Feng, Wang, Zhang, Phys. Lett. B607, 35 (2005)
Zhao et.al., Phys.Rev.D 72,123515, (2005)
Y. Cai et. al., Phys Rept. **493:1-60, (2010)**

Our strategy to handle perturbations when w crosses -1

I. $w(z) \geq -1 + \varepsilon$ Quintessence – like perturbation

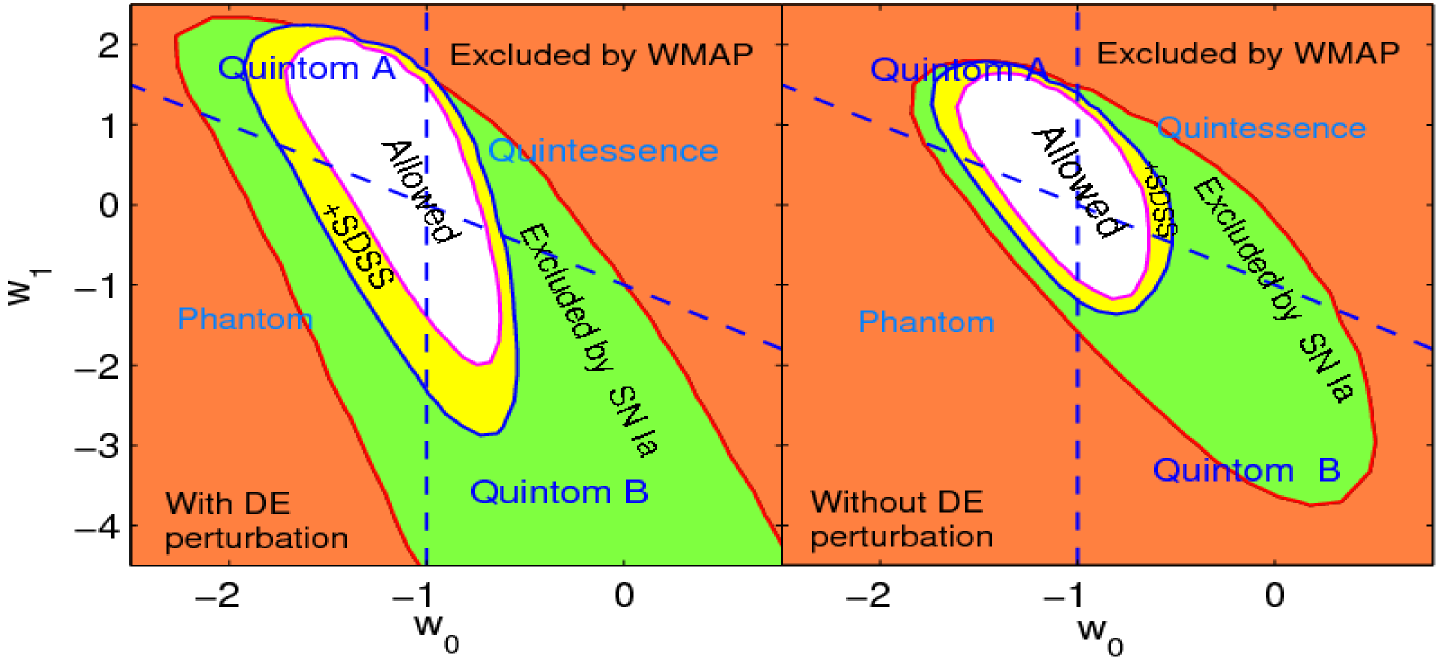
II. $w(z) \leq -1 - \varepsilon$ Phantom – like perturbation

III. $-1 - \varepsilon \leq w(z) \leq -1 + \varepsilon$ Quintom-based perturbation

$$\boxed{\dot{\delta} = 0, \quad \dot{\theta} = 0}$$

Zhao et.al Phys.Rev.D 72,123515, 2005
M. Li, Y. Cai, H. Li, R. Brandenberger, X. Zhang,
e-Print: arXiv:1008.1684
Similarly, W. Fang, Wayne Hu, Lewis **Phys.Rev.D78:087303, 2008**

Constraints on dark energy with SN Ia + SDSS + WMAP-1



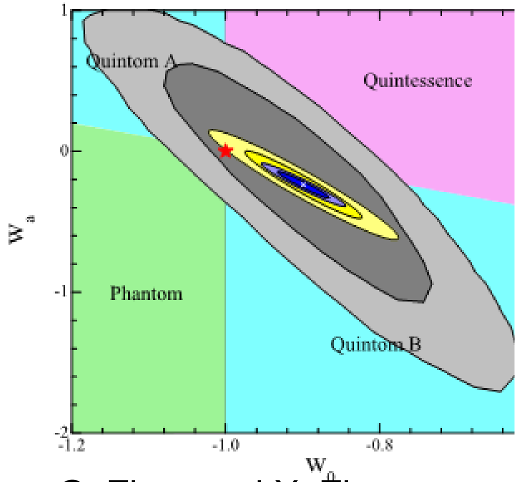
Observing dark energy dynamics with supernova, microwave background and galaxy clustering

Jun-Qing Xia, Gong-Bo Zhao, Bo Feng, Hong Li and Xinmin Zhang

Phys.Rev.D73, 063521, 2006

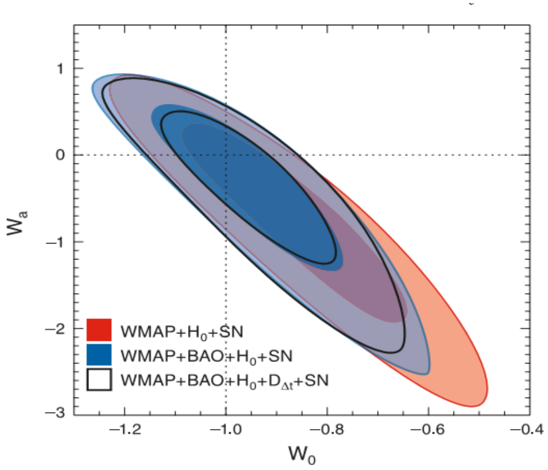
=➔ **Dark energy perturbation: theoretically consistence required; numerically important!**

Current status in determining the EoS of dark energy



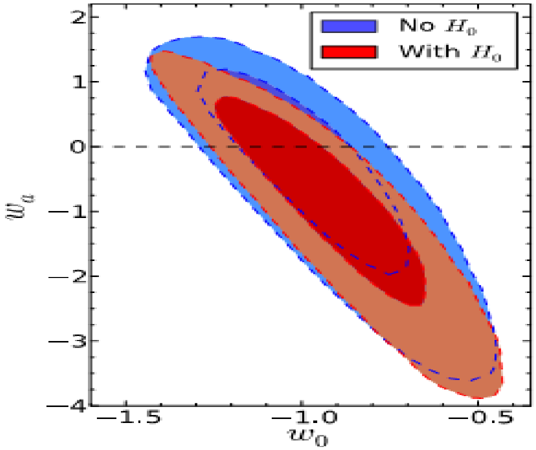
G. Zhao and X. Zhang

Phys.Rev.D81:043518,2010



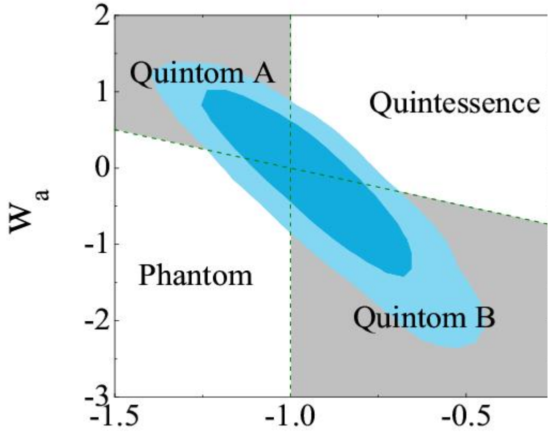
WMAP7 E. Komatsu *et al.*

e-Print: **arXiv:1001.4538**



SNLS3，

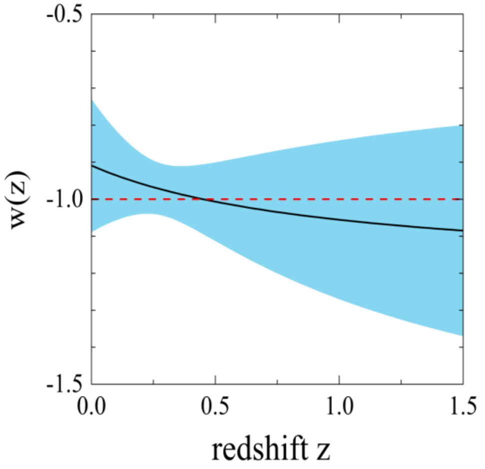
e-Print: arXiv:1104.1444



G. Zhao, H. Li, E. Linder,
K. Koyama, D. Bacon, XZhang

arXiV: 1109.1846 Sep 2011

with WMAP7+Union2.1+BAO+…



Results:

1) Current data has constrained a lot of the theoretical models;

2) Cosmological constant is consistent with the data;

3）dynamical models are not ruled out; quintom scenario mildly favored;

Interacting Dark Energy
----non-gravitational method

- Coupling constant vary： $QF_{\mu\nu}F^{\mu\nu}$
- Mass varying neutrino： P.Gu, X.Wang and X.Zhang ***PRD68, 087301 (2003)***

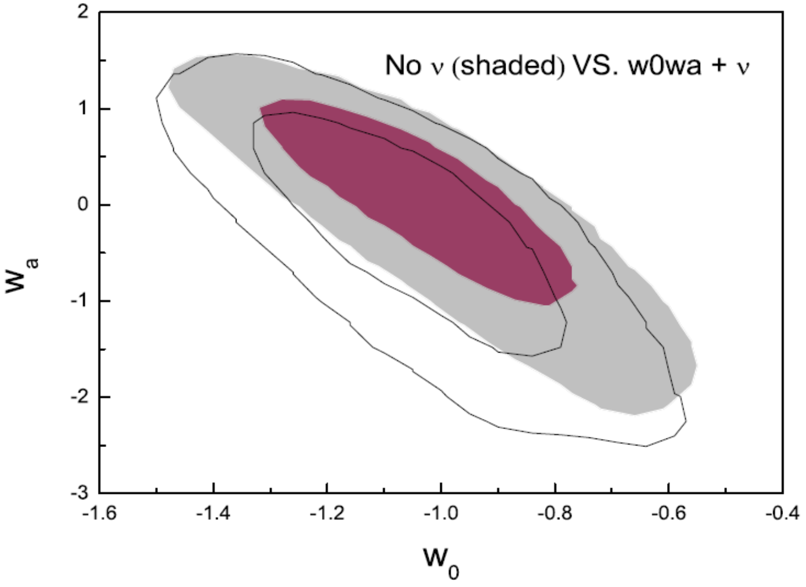
$$Q\bar{\nu}\nu$$

$$\rho = -p = \frac{\Lambda}{8\pi G} \approx (2\times 10^{-3}\,eV)^4$$
$$\downarrow$$
$$m_\nu \sim 10^{-3}\,\mathrm{eV}$$

Rob Fardon, Ann E. Nelson, Neal Weiner **JCAP 2004**.
G.Dvali, Nature 432:567-568,2004
R.D. Peccei, Phys.Rev. D71 (2005) 023527.
……

* Correlations
between EoS of DE
and neutrino mass

---------→
neutrino mass limit relaxed
by factor 2



H. Li
et al

Interacting Dark Energy

with derivatives couplings

* Direct coupling with ordinary matter

strongly constrained by the long-range force limits

large radiative corrections to the DE potential

* Interaction with derivative

Goldstone theorem: Spin-dependent force

$$\mathcal{L}_{\rm int} = \frac{c}{M}\partial_\mu \phi J^\mu$$

➡ **CPT violation when rolling down**

➡ **Baryo/Leptogenesis in thermo equilibrium**

Quintessential Baryo/Leptogenesis

⬇ **Anomaly Equation**

$$\mathcal{L} \sim -\frac{1}{2} C \partial_\mu \phi K^\mu$$

➡ **CMB polarization and CPT test**

$$K^\mu = A_\nu \tilde{F}^{\mu\nu} = \frac{1}{2} A_\nu \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

Cosmological CPT violation:

strength ~ O(H), unobservable in the laborary experiments

CMB: travelling around O(1/H),

so accumulated effect ~ O(1) observable !

Quintessential Baryo/Leptogenesis

M.Li, X.Wang, B.Feng, X. Zhang PRD65,103511 (2002)
De Felice, Nasri, Trodden, PRD67:043509(2003)
M.Li & X. Zhang, PLB573,20 (2003)

I) $L_{\text{int}} = c\frac{\partial_\mu Q}{M} J_B^\mu \Rightarrow \quad \mu_b = c\frac{\dot{Q}}{M} = -\mu_{\bar{b}}$ In thermo equilibrium⟹

Cohen & Kaplan

$$n_B = n_b - n_{\bar{b}} = \frac{g_b}{2\pi^2}\int_m^\infty E(E^2-m^2)^{1/2}\,dE \times \left[\frac{1}{1+\exp[(E-\mu_b)/T]} - \frac{1}{1+\exp[(E+\mu_b)/T]}\right]$$

$$= \frac{g_b T^3}{6}\left[\frac{\mu_b}{T} + O\left(\frac{\mu_b}{T}\right)^3\right] \approx c\,\frac{g_b \dot{Q} T^2}{6M}$$

$$\eta = n_B / s \approx \frac{15c}{4\pi^2}\,\frac{g_b \dot{Q}}{g_* M T}$$

$\dot{Q}$: depends on the model of Quintessence

II) $\partial_\mu J^\mu_{(B-L)_L} \sim -\frac{e^2}{12\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{\alpha_{\text{em}}}{3\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$ $\quad J^\mu_{(B-L)_L} = (1/2) J^\mu_{(B-L)} - (1/2) J^{5\mu}_{(B-L)}$

Leptogenesis

Anomaly for CMB

Cosmological CPT violation, baryo/leptogenesis and CMB polarization
M. Li, J. Xia, H. Li and X. Zhang
Phys. Lett. B651, 357 (2007)

Testing CPT symmetry with CMB polarizations

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + p_\mu A_\nu \widetilde{F}^{\mu\nu} \qquad p_\mu : \ (1)\ \text{Constant};\ (2)\ \frac{c}{M}\partial_\mu \phi\ ;\ (3)\ \partial_\mu f(R)$$

$$\Delta\alpha = \alpha_f - \alpha_i = \int_f^i p_\mu dx^\mu = \begin{cases} -p_0 \Delta\eta\ ,(1) & p_i = 0 \\ -\frac{c}{M}\Delta\phi\ ,(2) \\ -\Delta f(R)\ ,(3) \end{cases}$$

i: source

f: observer

$$C'^{TT}_l = C^{TT}_l$$

$$C'^{EE}_l = C^{EE}_l \cdot \cos^2 2\Delta\alpha + C^{BB}_l \sin^2 2\Delta\alpha$$

$$C'^{BB}_l = C^{EE}_l \cdot \sin^2 2\Delta\alpha + C^{BB}_l \cos^2 2\Delta\alpha$$

$$C'^{TE}_l = C^{TE}_l \cdot \cos 2\Delta\alpha$$

$$C'^{TB}_l = C^{TE}_l \cdot \sin 2\Delta\alpha$$

$$C'^{EB}_l = \frac{1}{2}(C^{EE}_l - C^{BB}_l) \sin 4\Delta\alpha$$

CPT violation
predicting <TB> and <EB>

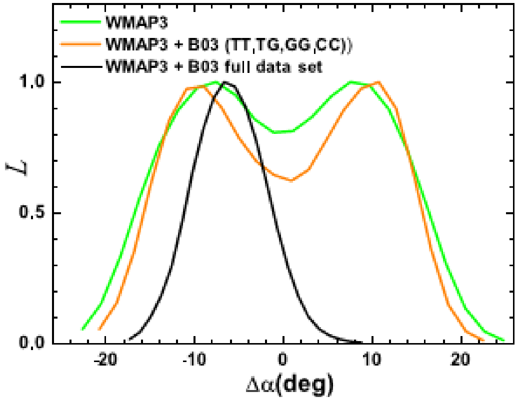


FIG. 1 (color online). One-dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP data alone (green or light gray line), WMAP and the 2003 flight of BOOMERANG B03 TT, TG, GG and CC (orange or gray line), and from WMAP and the full B03 observations (TT, TG, GG, CC, TC, GC) (black line).

Bo Feng, Hong Li, Mingzhe Li and Xinmin Zhang
Phys. Lett. B 620, 27 (2005);
Bo Feng, Mingzhe Li , Jun-Qing Xia, Xuelei Chen and Xinmin Zhang
Phys. Rev. Lett. 96, 221302 (2006)

Current status on the measurements of the rotation angle

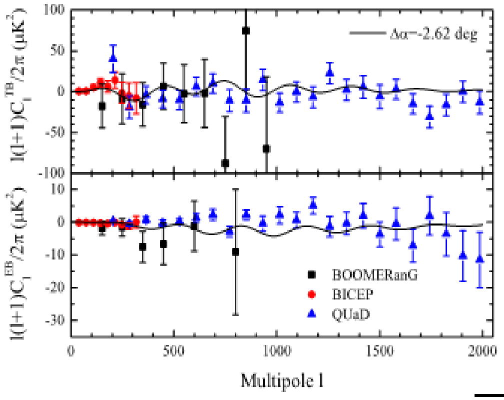
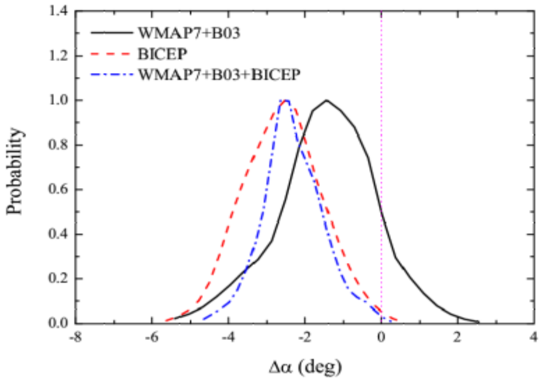


Fig. 1. The binned TB and EB spectra measured by the small-scale
of BOOMERanG (black squares), BICEP (red circles) and QUaD (b
black solid curves show the theoretical prediction of a model with
(For interpretation of colors in this figure, the reader is referred t
of this Letter.)



Group	$\Delta\alpha$ (degree)	Datasets
Feng et al	-6.0 ± 4.0	WMAP3+B03
Cabella et al	-2.5 ± 3.0	WMAP3
WMAP Collaboration	-1.7 ± 2.1	WMAP5
Xia et al	-2.6 ± 1.9	WMAP5+B03
WMAP Collaboration	-1.1 ± 1.4	WMAP7
QUaD Collaboration	0.64 ± 0.50	QUaD
Xia et al	-2.60 ± 1.02	BICEP
Xia et al	-2.33 ± 0.72	WMAP7+B03+BICEP
Xia et al	-0.04 ± 0.35	WMAP7+B03+BICEP+QUaD
Gruppuso et al	-1.6 ± 1.7	WMAP7

$3\,\sigma$ detection ===➔

$$PLANCK:\ \sigma = 0.057\ \text{deg}$$

Conclusion and Discussions (I)

Understanding the nature of accelerating universe
is a big challenge to particle physics

Current status

on constraints on EoS of dark energy

a) Cosmological constant fits data well;
b) Dynamical model not ruled out completely
future projects: w at level of O(1%), (w_0, w_a) O(10%) (comment 1);
c) Quintom model mildly favored (comment 2)

on modified gravity

a) GR works well;
b) Background evolution:
Quintom behaviour

"Testing Einstein Gravity with Cosmic Growth and Expansion"

Gongbo Zhao, Hong Li, Eric Linder, Kazuya Koyama, David Bacon, Xinmin Zhang,

arXiv: 1109.1846, Sept, (2011)

with **SN(Union2.1)+CMB(WMAP7) +WL(CFHTLS) + BAO + PV**

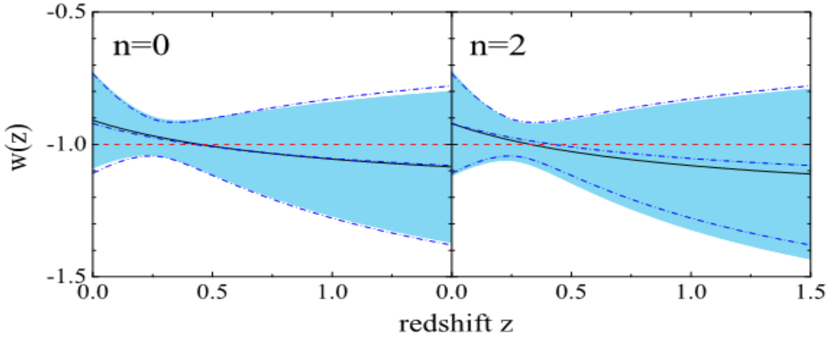
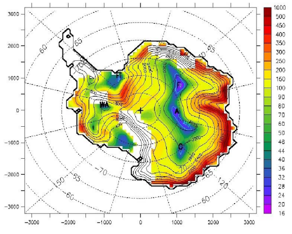
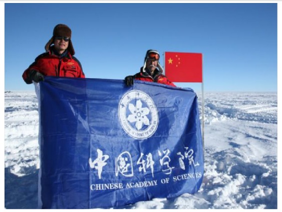


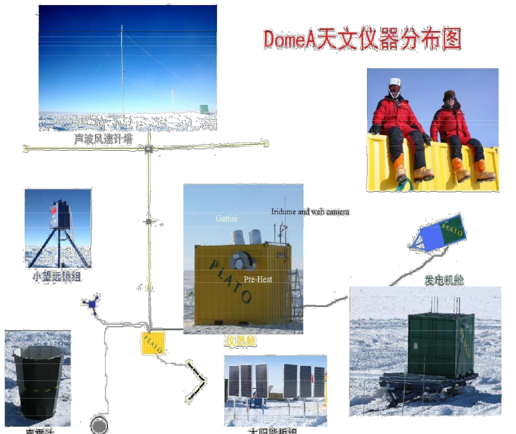
FIG. 4: The reconstructed $w(z)$ with 68% CL error are shown allowing for modified gravity (marginalized over c, s) in the scale independent (left panel) and scale-dependent k^2 (right panel) cases by the filled bands. The reconstruction for true dark energy, with gravity fixed to GR, is shown by the dash-dotted curves, the same in each panel.

Comment 1: Future Projects on Dark Energy Study

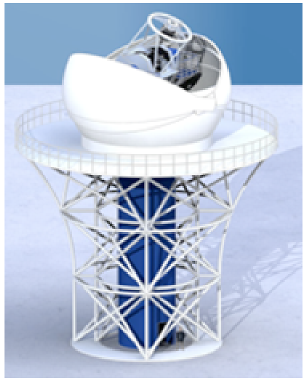


Height where Seeing is 0.1" or better 50% of the time (JJA 2004)

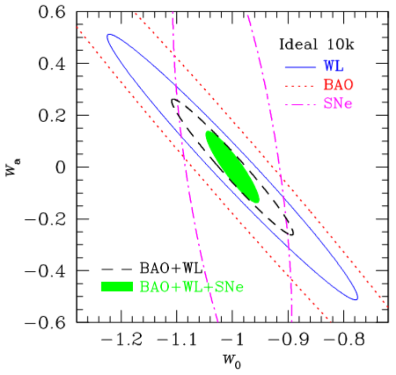




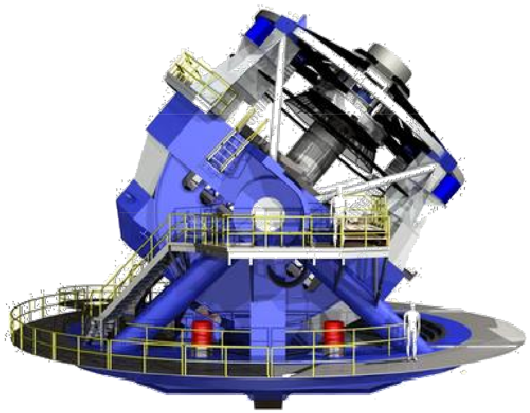
根据中科院遥感所程晓和黑龙江测绘局吴学峰提供的测量位置



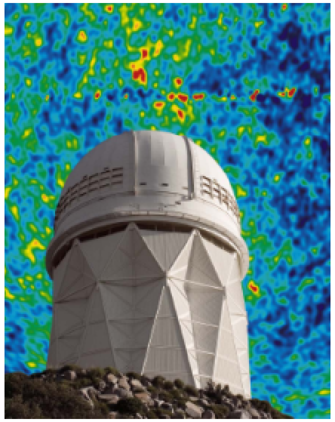
KDUST: Kunlun Dark Universe Telescope



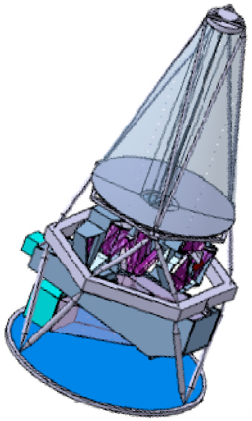
G. Zhao, H. Zhan, Lifan Wang, Z. Fan, X. Zhang, arXiV: 1005.3810



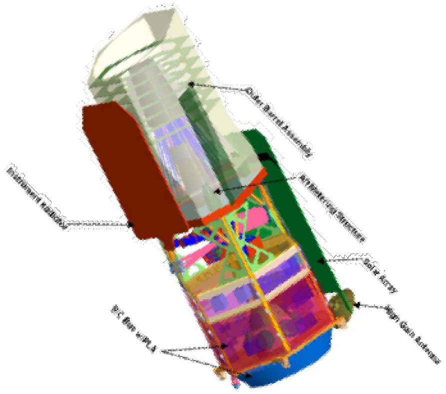
Large Synoptic Survey Telescope



BigBOSS



Euclid



Wide Field Infrared Survey Telescope

Comment 2: theoretical study

* cosmological constant problem

** Consistent DE and modified gravity models

*** quintom cosmology (**For a review, see, Yifu Cai et al, Phys.Rept. 493:1-60, (2010)**).

Current data show:

EoS of dark energy
and effective EoS of modified gravity
mildly favored==➔quintom with
w crosses over w=-1 during the evolution

Why interested these years theoretically?

1) Challenges to the model buildings
theoretically interesting! (no-go theorem)
==➔ Galileon theory
(a single scalar with higher derivatives and ghost free)

2) Quintom bouncing cosmology
standard cosmology-→singular
quintom cosmology-→non-singular

Quintom Bounce

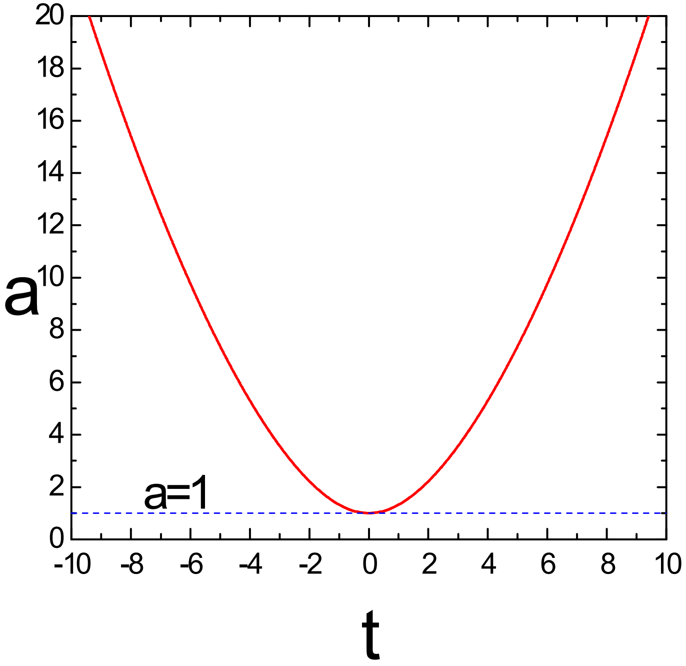
The expanding of the universe is transited from a contracting phase; during the transition the scale factor of the universe a is at its minimum but non-vanishing, thus the singularity problem can be avoided.

Contracting phase: $H < 0$; Expanding Phase: $H > 0$.

At the bouncing point: $H = 0$ Around it: $\dot{H} > 0$.

$$\dot{H} = -4\pi G(\rho + p) \Rightarrow w < -1$$

Transition to the observable universe $w > -1$.
(radiation dominant, matter dominant,…)
So w needs to cross -1, and
Quintom matter is required!



Yifu Cai et al., JCAP 0803:013(2008).
Yifu Cai et al., JHEP 0710:071(2007).

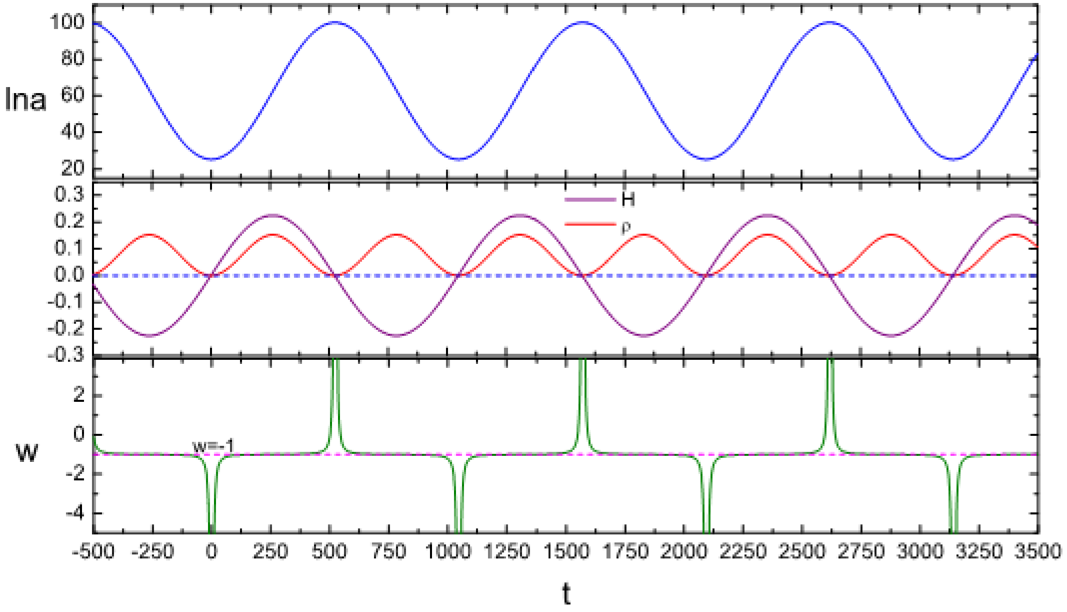
Oscillating universe with Quintom matter

Xiong et al., arXiv:0805.0413

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\partial_\mu\psi\partial^\mu\psi - V(\phi,\psi)\right]$$

$$V(\phi,\psi) = (\Lambda_0 + \lambda\phi\psi)^2 + \frac{1}{2}m^2\phi^2 - \frac{1}{2}m^2\psi^2$$

Solution: $\phi = \sqrt{A_0}\cos mt$, $\psi = \sqrt{A_0}\sin mt$ $H = \frac{\sqrt{3}}{3M_p}(\Lambda_0 + \Lambda_1 \sin 2mt)$



Conclusion and Discussions (II)

Interacting Dark Energy=➔Non-gravitational method to
detect the dark energy

a) Neutrino dark energy (mass varying neutrino)
(low cutoff required)

b) Derivative couplings:

No long range force limit;
No large radiative correction

===➔ Cosmological CPT violation:

Many speculation theoretically on Lorentz and CPT violation

Evidence: expanding universe, matter-antimatter asymmetry

==➔ Quintessential Baryo/Leptogenesis,
CMB polarization

* Derivative couplings to neutrino➔
Lorentz and CPT violation in neutrino sector

i) **"Dark energy and neutrino CPT violation",**
P, Gu, X. Bi and X. Zhang, e-Print: hep-ph/0511027

ii) **"Neutrino Oscillations, Lorentz/CPT Violation, and Dark Energy "**
Shin'ichiro Ando, Marc Kamionkowski, Irina Mocioiu,
e-Print: arXiv:0910.4391

Conclusion and Discussions (III)

On CPT test with CMB

* Feature: *CMB photon travelling over the distance around the observed universe, provides the most sensitive test to CPT*

** Rotation angle:
a cosmological parameter needed be measured by CMB

*** Sources of the CMB polarization for the B-mode:
i)Tensor perturbation;
i i)CPT violating effect;
iii)Lensing

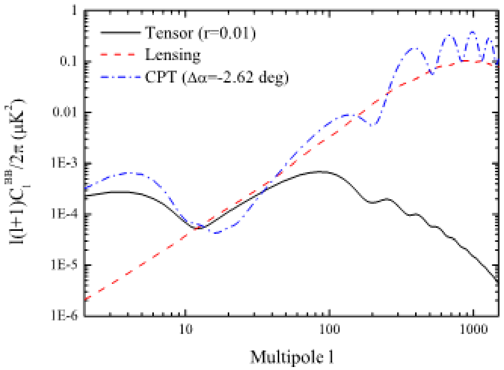


Fig. 4. The theoretical predictions of the BB power spectra from three different sources: primordial tensor B-mode with $r = 0.01$ (black solid line); lensing-induced (red dashed line) and rotation-induced (blue dash-dot line). The cosmological parameters used here are $\Omega_b h^2 = 0.022$, $\Omega_c h^2 = 0.12$, $\tau = 0.084$, $n_s = 1$, $A_s = 2.3 \times 10^{-9}$, and $h = 0.70$. (For interpretation of colors in this figure, the reader is referred to the web version of this Letter.)

**** Spatial dependent rotation angle:
DE scalar fluctuation
Anomalous axion string effect (?)

Thank you !