# Dark Energy
# and
# CPT Test with CMB Polarization

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**Institute of high energy physics**

## Outline

1) Brief review on the models of dark energy, especially on Quintom model;
2) Current constraints on the equation of state of dark energy;
3) Interacting dark energy:
   Testing CPT symmetry with CMB polarization;
4)Summary

Workshop on Frontiers of Cosmology at Dome A, Antarctica
July 18-23, Beijing/Suzhou

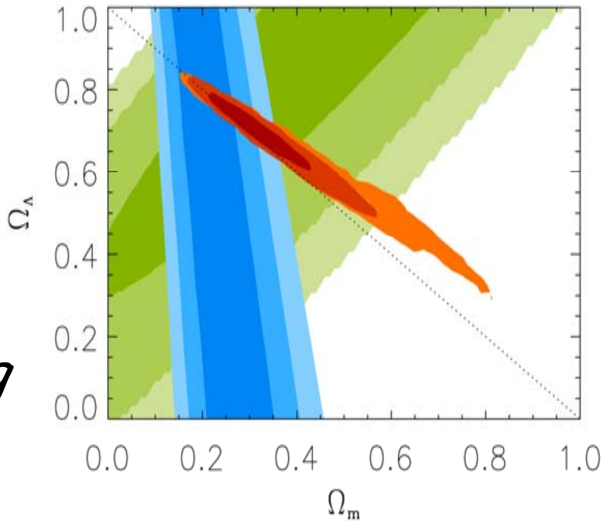
# Dark Energy:

egative pressure:

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

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

∗ *Smoothly distributed, (almost ) not clustering*



## dates:

## mological constant (or vacuum Energy)

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

$$\downarrow$$

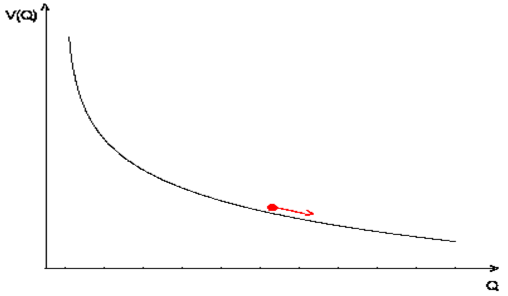
$$w = p/\rho = -1 \qquad \mathrm{m}_\nu \sim 10^{-3}\,\mathrm{eV}$$

$$\rho^{th}/\rho^{ob} \sim 10^{120}$$

**cosmological constant problem!**

## ynamical Field: Quintessence

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

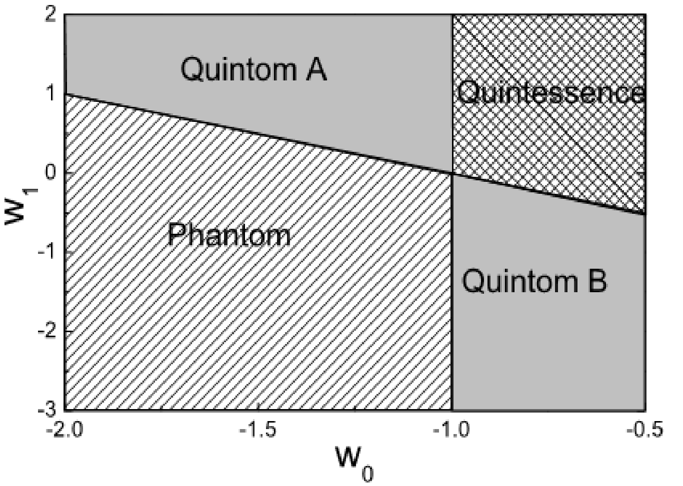


$$W(Q) = \frac{\frac{1}{2}\dot{Q}^2 - V}{\frac{1}{2}\dot{Q}^2 + V} \qquad -1 \le w_Q \le 1$$

# Equation of state w=p/ ρ : characterize the properties of the dark energy models

* Vacuum : w=-1
* Quintessence: $w \geq -1$

## Important determining the equation of state of dark energy with cosmological observations



## Parameterization of equation of state:

A) w=w_0+w_1 z  (for small z)
B) w=w_0+w_1 z / (1+z)  (used mostly in the literature)
C) w=w_0+w_1 sin(w_2 ln(a)+w_3)

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

* Quintom: w crosses -1

For example: $\mathcal{L}_{int} = \frac{1}{2}F(T)\partial_\mu Q \partial^\mu Q - V(Q)$

single scalar: $W(Q) = \frac{\frac{1}{2}F(T)\dot{Q}^2 - V}{\frac{1}{2}F(T)\dot{Q}^2 + V}$

No-Go Theorem!!

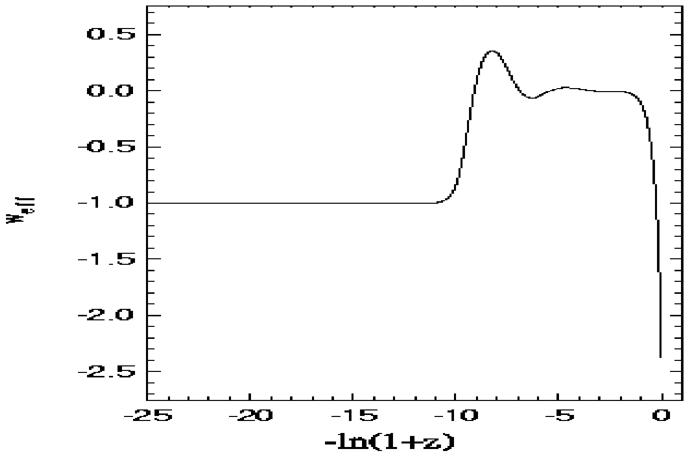
# No-Go Theorem:

For theory of dark energy (DE) in the 4D Friedmann-Robertson-Walker (FRW) universe described by a single perfect fluid or a single scalar field with a lagrangian of $\mathcal{L} = \mathcal{L}(\phi, \partial_\mu\phi\partial^\mu\phi)$ , which minimally couples to Einstein Gravity, its equation of state w cannot cross over the cosmological constant boundary.

Examples of Quintom models:

1) Two scalar fields:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}\partial_\mu\phi_2\partial^\mu\phi_2 - V_0[\exp(-\frac{\lambda}{m_p}\phi_1) + \exp(-\frac{\lambda}{m_p}\phi_2)]$$



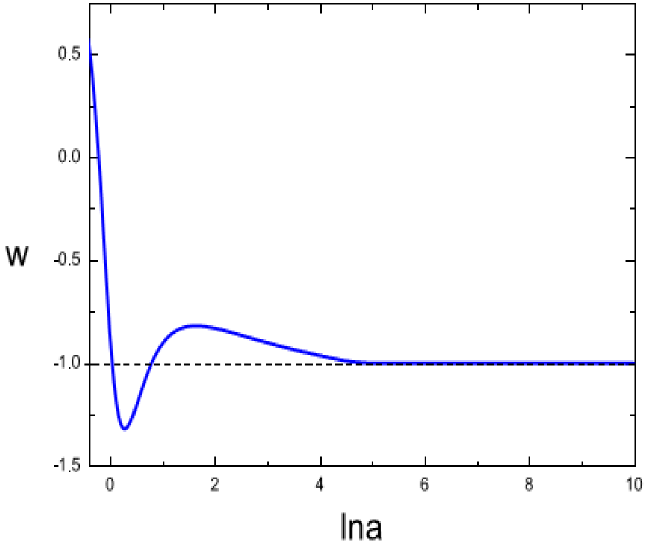
2) Single scalar with high derivatives:

$$\mathcal{L} = \frac{1}{2}A(\phi)\nabla_\mu\phi\nabla^\mu\phi + \frac{C(\phi)}{2M_{pl}^2}(\Box\phi)^2 - V(\phi)$$

3) Modified Born-Infeld action:

$$\mathcal{L} = -V(\phi)\sqrt{1 - \alpha'\nabla_\mu\phi\nabla^\mu\phi + \beta'\phi\Box\phi}$$

$$V(\phi) = \frac{V_0}{e^{-\lambda\phi} + e^{\lambda\phi}}$$



# Comments on Quintom model:

## 1) Quintom Bounce

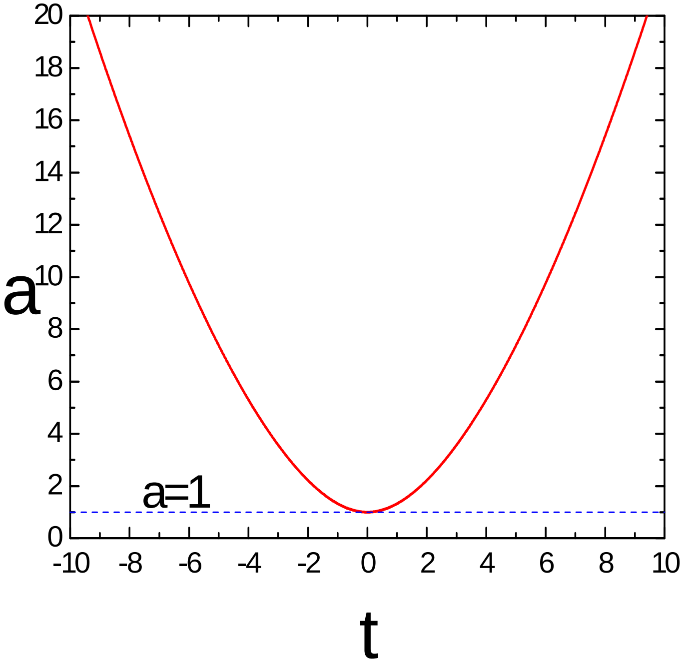
The expanding of the universe is transited from a contracting phase; during the transition the scale factor of the universe a is at its minimum but non-vanishing, thus the singularity problem can be avoided.

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).**

# Examples:

1) Two Field Quintom

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - \frac{1}{2}\partial_\mu\phi_2\partial_\mu\phi_2 - V(\phi_1,\phi_2)\right]$$

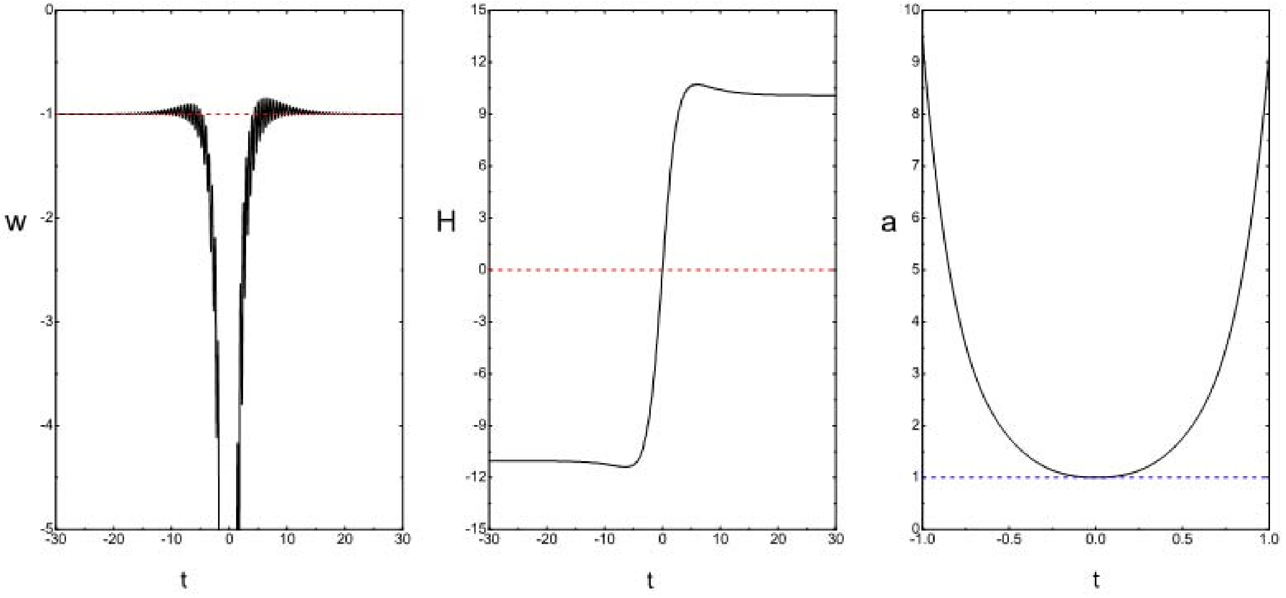


FIG. 2: The plots of the evolutions of the EoS $w$, hubble parameter $H$ and the scale factor $a$. In the numerical calculation we choose $V(\phi_1,\phi_2) = V_1 e^{-\lambda_1 \frac{\phi_1^2}{M^2}} + V_2 e^{-\lambda_2 \frac{\phi_2^2}{M^2}}$ with parameters: $V_1 = 15$, $V_2 = 1$, $\lambda_1 = -1.0$, $\lambda_2 = 1.0$, and for the initial conditions $\phi_1 = 0.5$, $\dot{\phi}_1 = 0.1$, $\phi_2 = 0.3$, $\dot{\phi}_2 = 4$.

# Examples:

) A single scalar with high-derivative term

$$S = \int d^4x\sqrt{-g}\left[-V(\phi)\sqrt{1-\alpha'\nabla_\mu\phi\nabla^\mu\phi+\beta'\phi\Box\phi}\right]$$

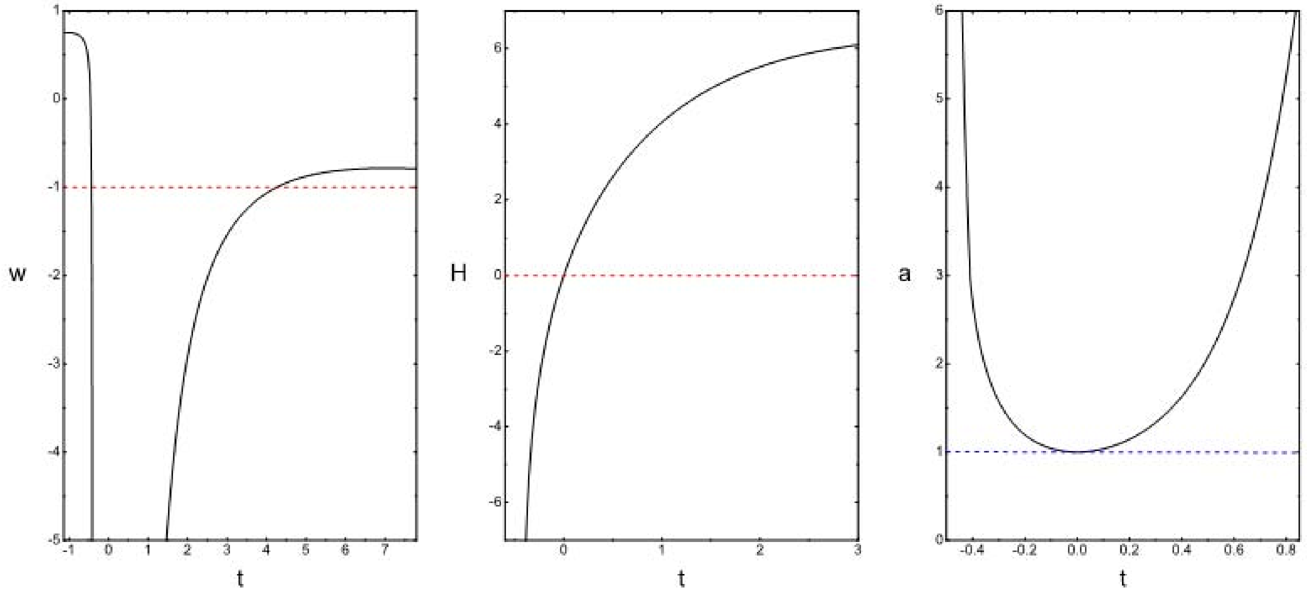


FIG. 4: The plots of the evolution of the EoS $w$, the hubble parameter $H$ and the scale factor $a$. Here in the numerical calculation we take the potential $V(\phi) = V_0 e^{-\lambda\phi^2}$, $\alpha = -0.2$, $\beta = 2$, $\lambda = 2$, $V_0 = 5$, and the initial values are $\phi = 1$, $\dot{\phi} = 3$, $H = -1$, and $\psi = -80$.

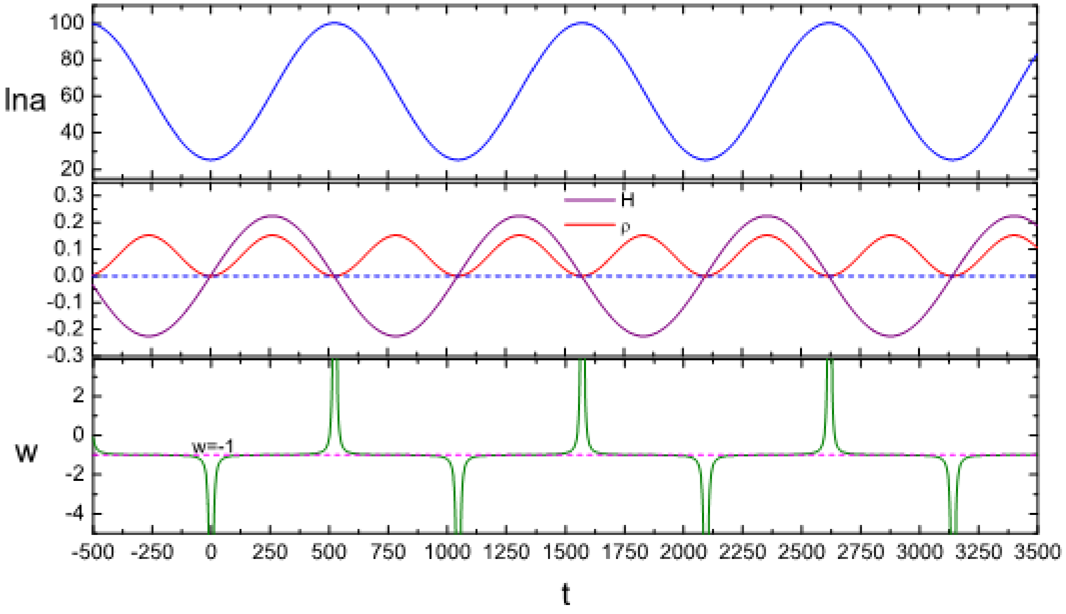
# 2) Oscillating universe with Quintom matter

**Xiong et al., arXiv:0805.0413**

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

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

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



# Bounce + inflation

Large field model: [R.Brandenberger, and X.M. Zhang, arXiv:0903.2065]

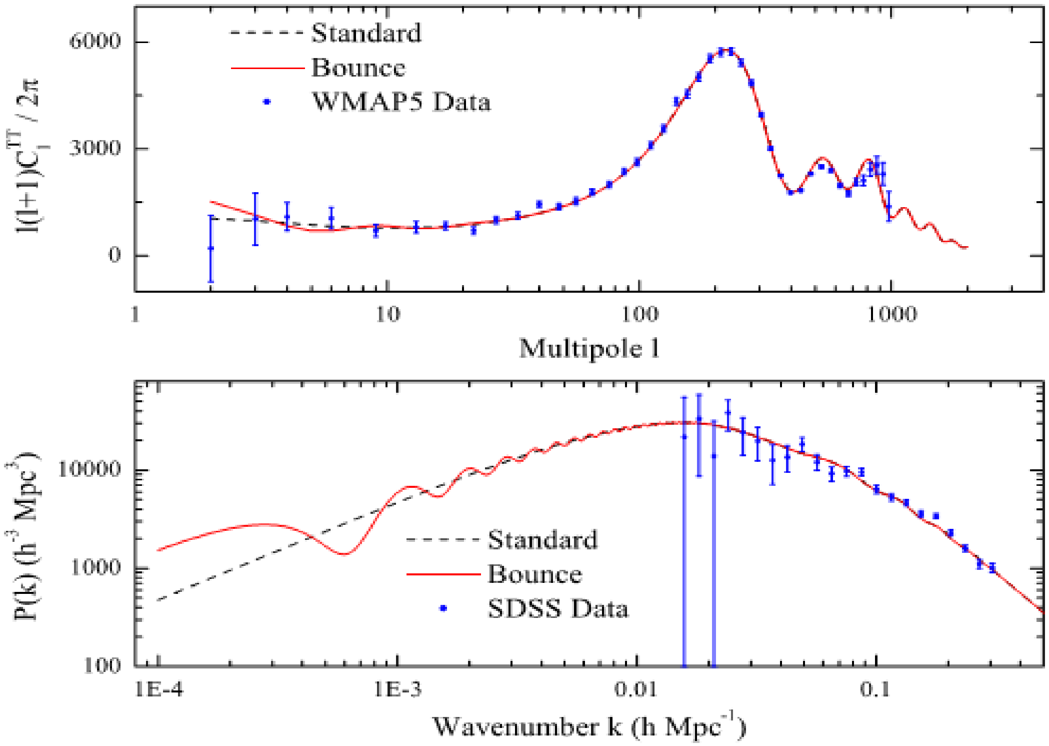
the resulted power spectrum is far from scale-invariant

Small field model:

For example,

$$V = \frac{1}{4}\lambda\phi^4\left(\ln\frac{|\phi|}{v} - \frac{1}{4}\right) + \frac{1}{16}\lambda v^4$$

Phys.Rev.D79:021303,2009



# Testing Oscillating Primordial Spectrum and Oscillating Dark Energy with Astronomical Observations

J.Liu, H.Li, J.-Q. Xia & X.Zhang, e-Print: **arXiv:0901.2033**

**JCAP07(2009)017**

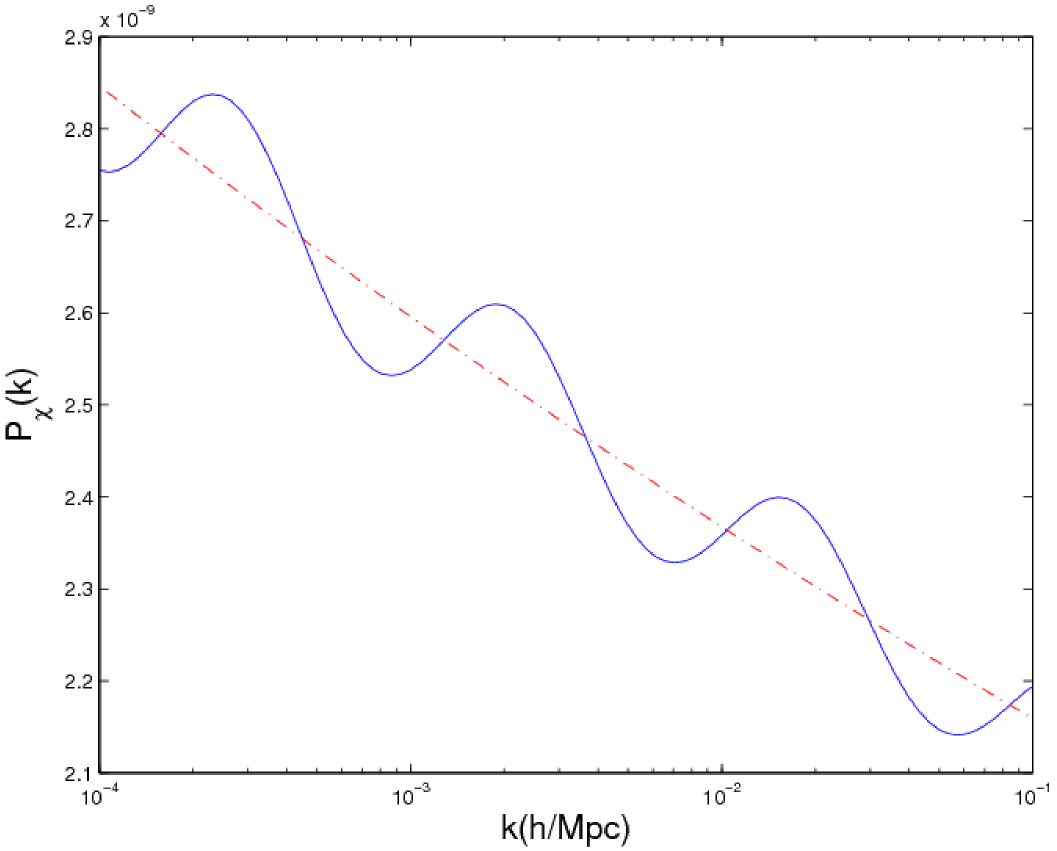
$$\ln \mathcal{P}_\chi(k) = \ln A_s(k) + [n_{s0}(k_0) - 1] \ln\left(\frac{k}{k_0}\right) - \frac{n_{\rm amp}}{n_{\rm fre}} \cos\left[n_{\rm fre} \ln\left(\frac{k}{k_0}\right)\right]$$

$$n_s = \frac{d \ln \mathcal{P}_\chi(k)}{d \ln k} = n_{s0} + n_{\rm amp} \sin\left[n_{\rm fre} \ln\left(\frac{k}{k_0}\right)\right]$$

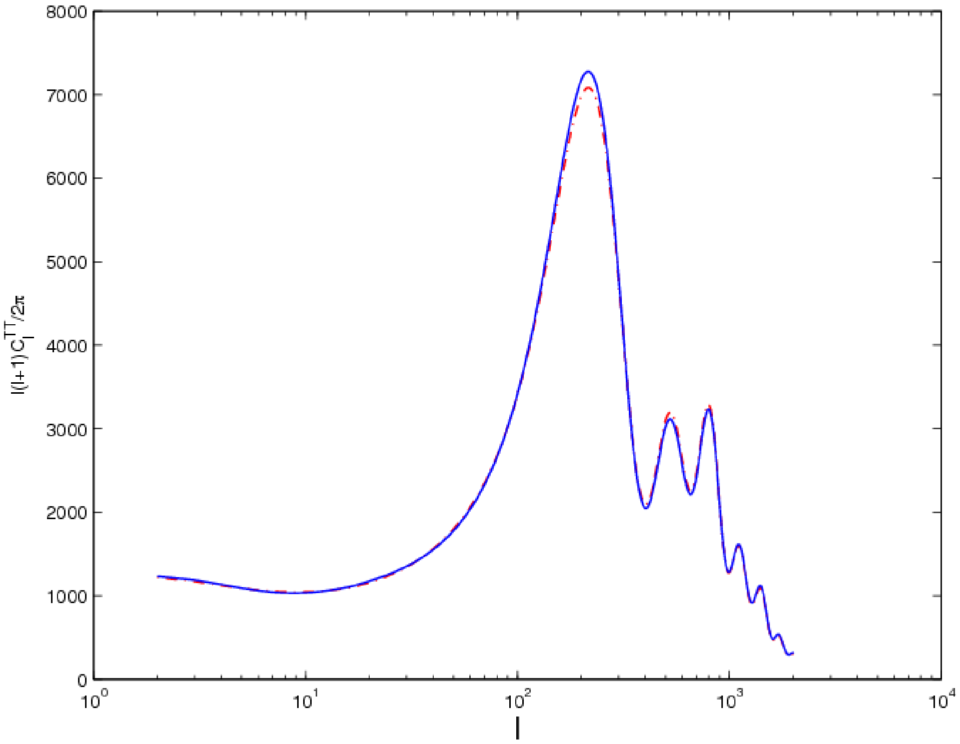
This can be motivated by:

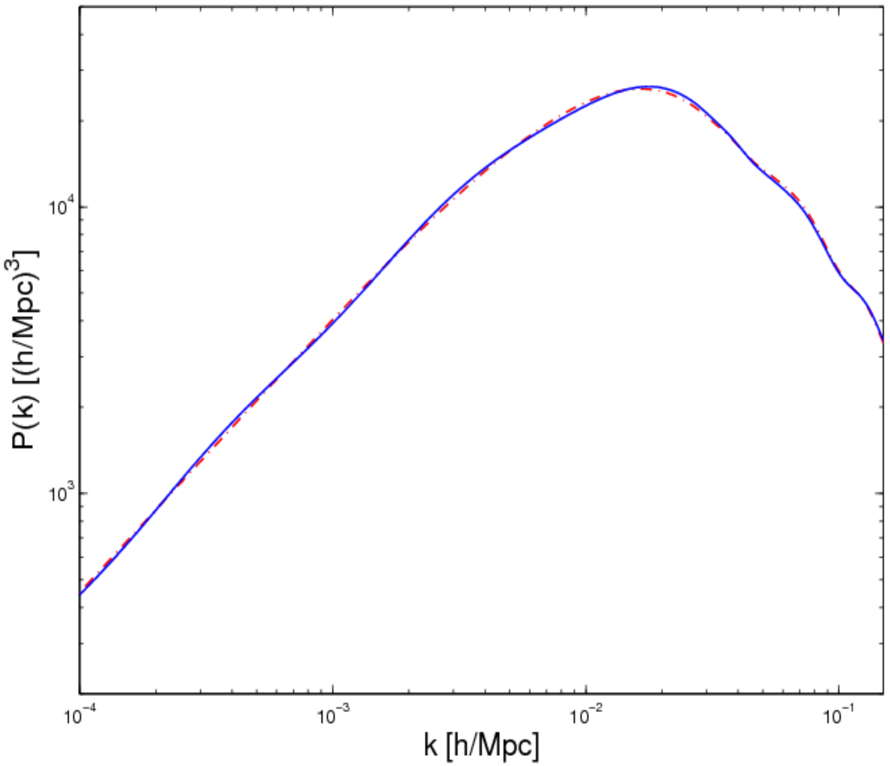
$$V(\phi) = \Lambda^4[1 + \cos(\phi/f) + \delta \cos(N\phi/f + \theta)].$$

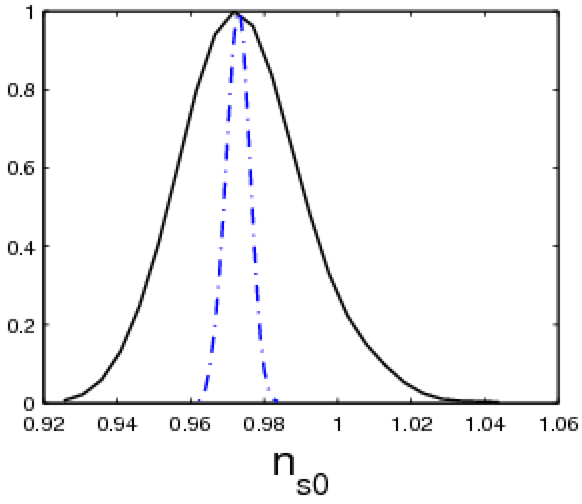
**Natural inflation,**
**Planck scale physics and**
**oscillating primordial spectrum**
X.L. Wang, et al.
**Int.J.Mod.Phys.D14:1347,2005**

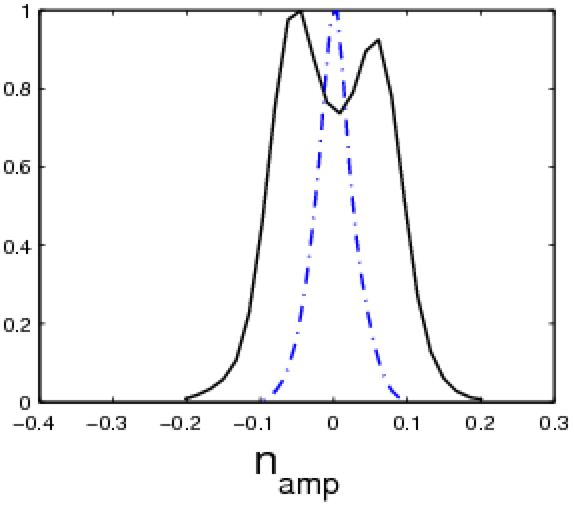


# The effects on the TT power spectrum and matter power spectrum






1
0.8
0.6
0.4
0.2
0
0.92
0.94
0.96
0.98
1
1.02
1.04
1.06
$n_{s0}$


1
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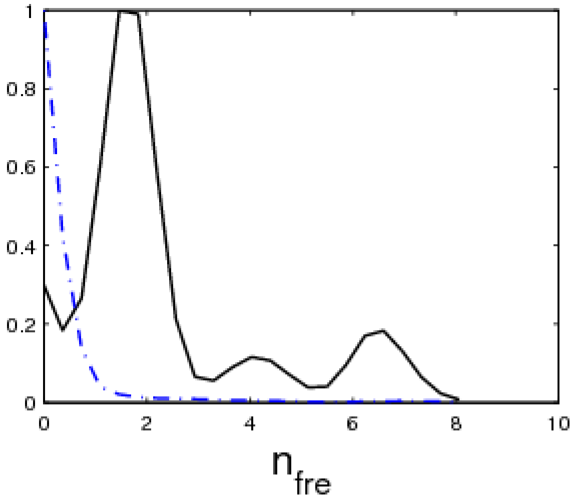
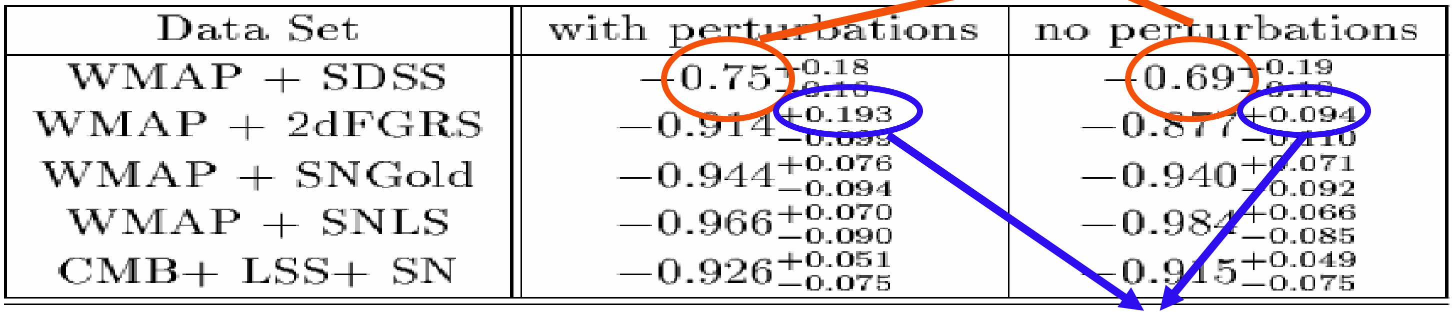
0.3
$n_{amp}$

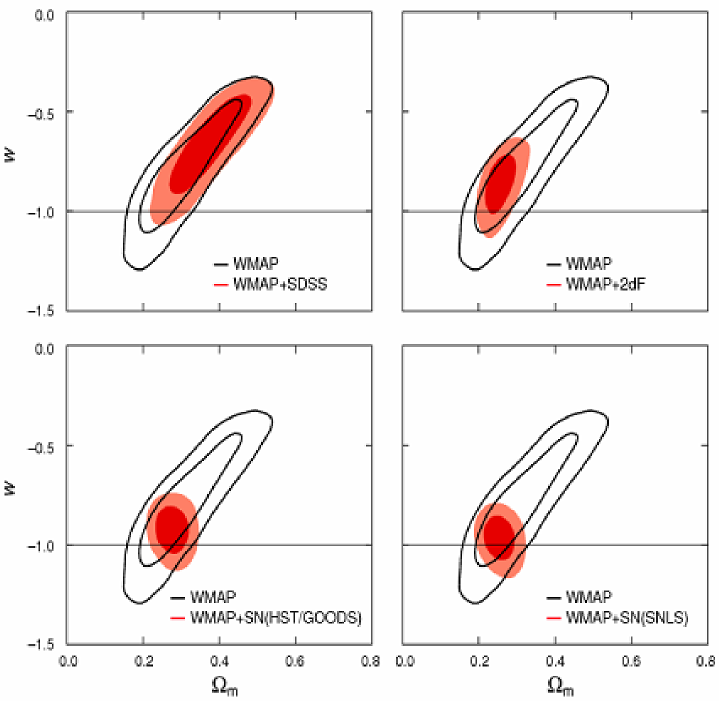

1
0.8
0.6
0.4
0.2
0
0
2
4
6
8
10
$n_{fre}$

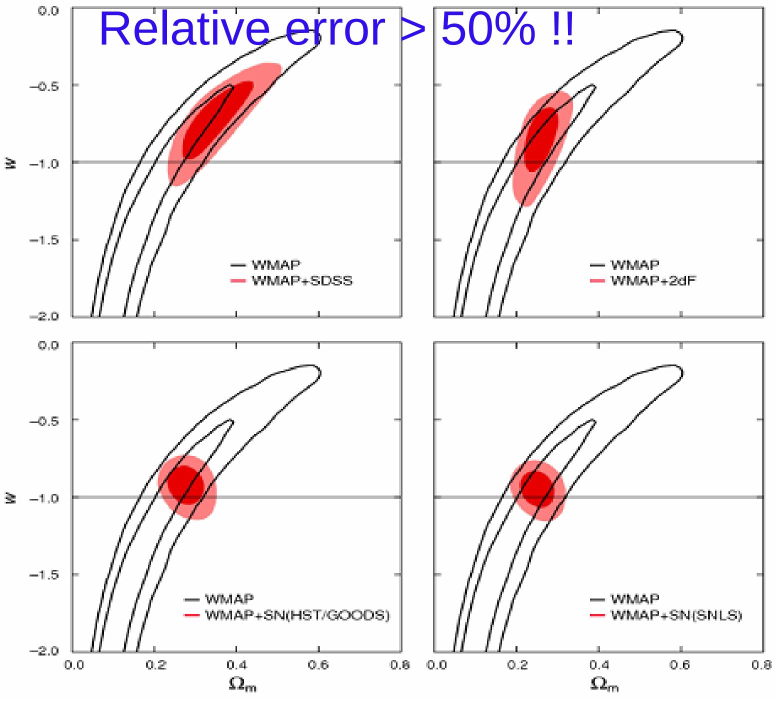
# 3) on dark energy perturbation

Relative error: ~9%



| Data Set | with perturbations | no perturbations |
|---|---|---|
| WMAP + SDSS | $-0.751^{+0.18}_{-0.16}$ | $-0.697^{+0.19}_{-0.16}$ |
| WMAP + 2dFGRS | $-0.914^{+0.193}_{-0.099}$ | $-0.877^{+0.094}_{-0.110}$ |
| WMAP + SNGold | $-0.944^{+0.076}_{-0.094}$ | $-0.940^{+0.071}_{-0.092}$ |
| WMAP + SNLS | $-0.966^{+0.070}_{-0.090}$ | $-0.984^{+0.066}_{-0.085}$ |
| CMB+ LSS+ SN | $-0.926^{+0.051}_{-0.075}$ | $-0.915^{+0.049}_{-0.075}$ |





Relative error > 50% !!

Spergel et al. Astro-ph/0603449

# Difficulty with dark energy perturbation when w crosses -1

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

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

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

# Perturbation with Quintom dark energy

$$\dot{\delta}_i = -(1+w_i)(\theta_i - 3\dot{\Phi}) - 3\mathcal{H}(1-w_i)\delta_i - 3\mathcal{H}\frac{\dot{w}_i + 3\mathcal{H}(1-w_i^2)}{k^2}\theta_i$$

$$\dot{\theta}_i = 2\mathcal{H}\theta_i + \frac{k^2}{1+w_i}\delta_i + k^2\Psi \; .$$

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

Here $\delta$ and $\theta$ are the density perturbation and the divergence of the fluid velocity respectively

**Perturbation of DE is continuous during crossing!**

**Zhao et.al Phys.Rev.D 72,123515,2005**

# Our strategy to handle perturbations when w crosses -1

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

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

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

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

# Global fitting procedure

- **Cosmological parameters:**

$$P \equiv \omega_b, \omega_c, \Omega_K, \theta, \tau, \Sigma M_\nu, n_s, A_s, \alpha_s, r, w_0, w_1$$

$$\ln \mathcal{P}_\chi(k) = \ln A_s(k_{s0}) + (n_s(k_{s0}) - 1)\ln\left(\frac{k}{k_{s0}}\right) + \frac{\alpha_s}{2}\left(\ln\left(\frac{k}{k_{s0}}\right)\right)^2$$

$$w(a) = w_0 + w_1(1-a)$$

Perturbation divergent when w across -1 , new method

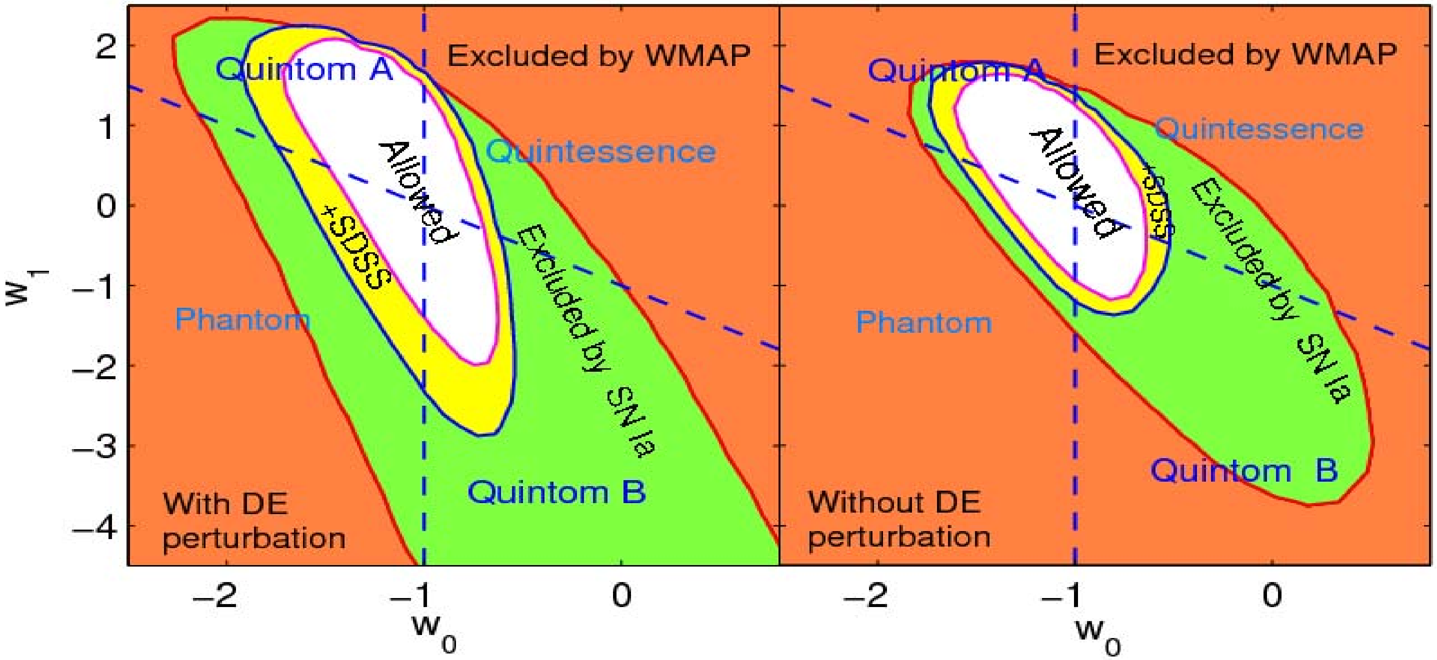
$$w(a) = w_0 + w_1 \sin(w_2 \ln a)$$

- **Method : modified CosmoMC,** Perturbation included

  G.-B. Zhao, et al., PRD 72 123515 (2005)

- **Calculated at ShangHai Supercomputer Center (SSC)**
- **Data: CMB, LSS, SNe**

# Constrains on dark energy with SN Ia + SDSS + WMAP-1

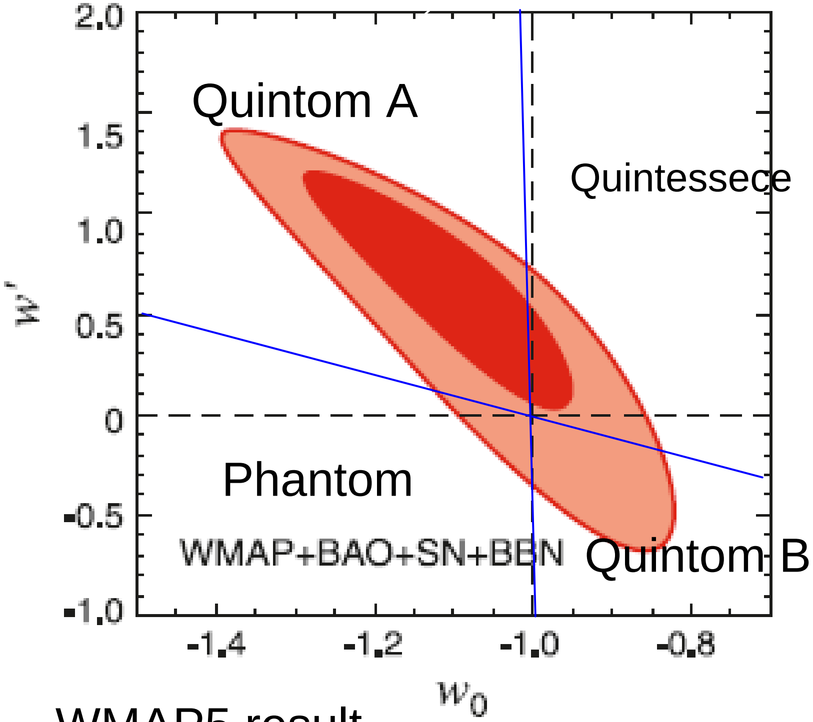


**Observing dark energy dynamics with supernova, microwave background and galaxy clustering**

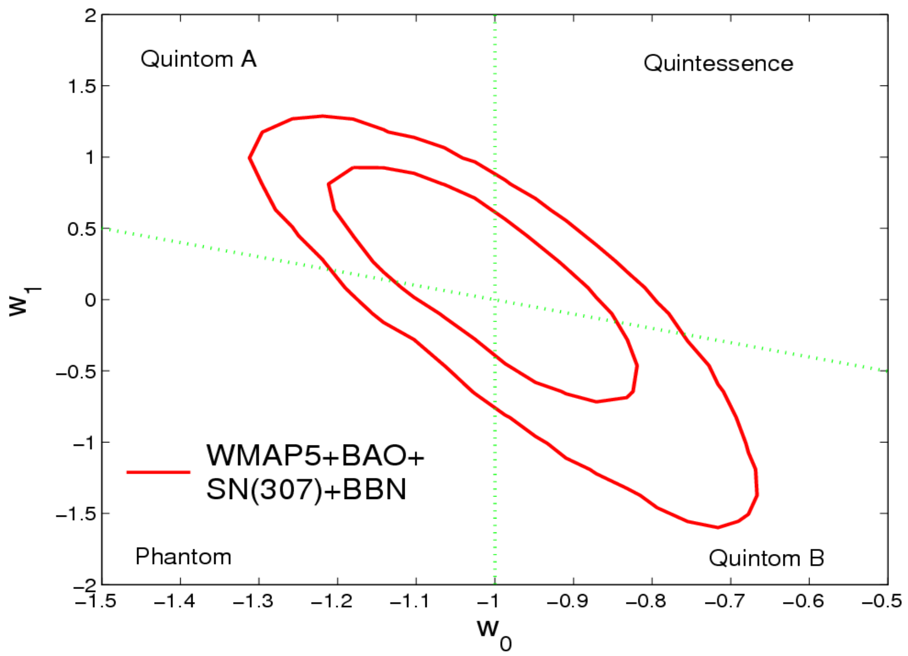
Jun-Qing Xia, Gong-Bo Zhao, Bo Feng, Hong Li and Xinmin Zhang

**Phys.Rev.D73, 063521, 2006**

# Current constraint on the equation of state of dark energy



WMAP5 result
E. Komatsu et al., arXiv:0803.0547



Xia, Li, Zhao, Zhang,
Phys. Rev. D78, 083524 (2008)

Difference:

Data: SN (SNLS+ESSENCE+Riess et al.)
vs SN (307,Kowalski et al., arXiv:0804.4142)

Method: WMAP distance prior vs Full CMB data.
However, results similar (Li et al., arXiv: 0805.1118)

Status:
1) Cosmological constant fits data well;
2) Dynamical model not ruled out;
3) Best fit value of equation of state:
slightly w across -1 → Quintom model

# On using the WMAP distance priors in constraining the time evolving equation of state of dark energy

Hong Li[1], Jun-Qing Xia[2], Gong-Bo Zhao[3], Zu-Hui Fan[1] & Xinmin Zhang[2]

Table II.

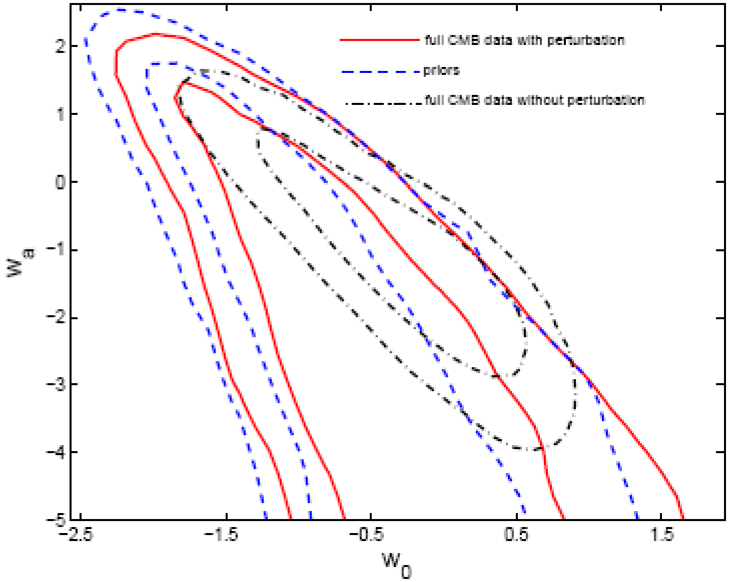
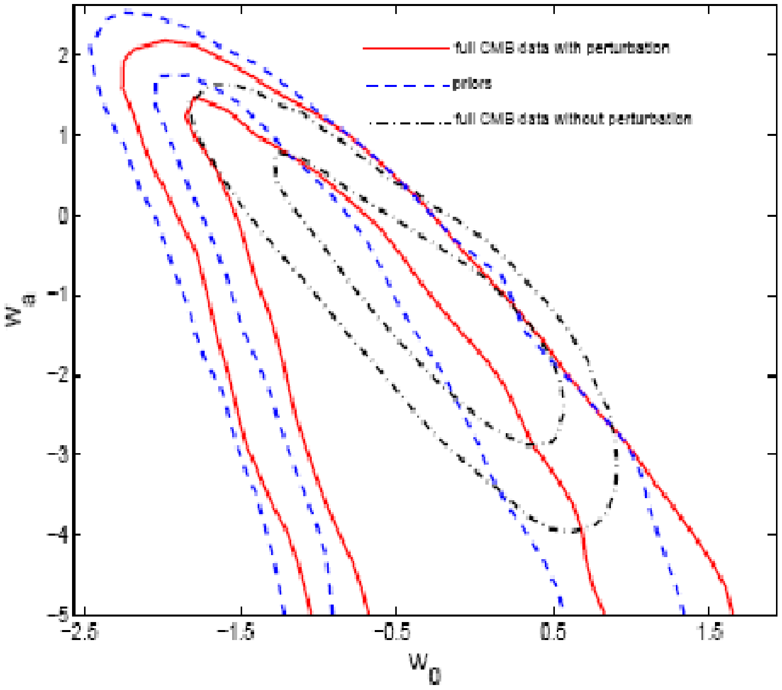
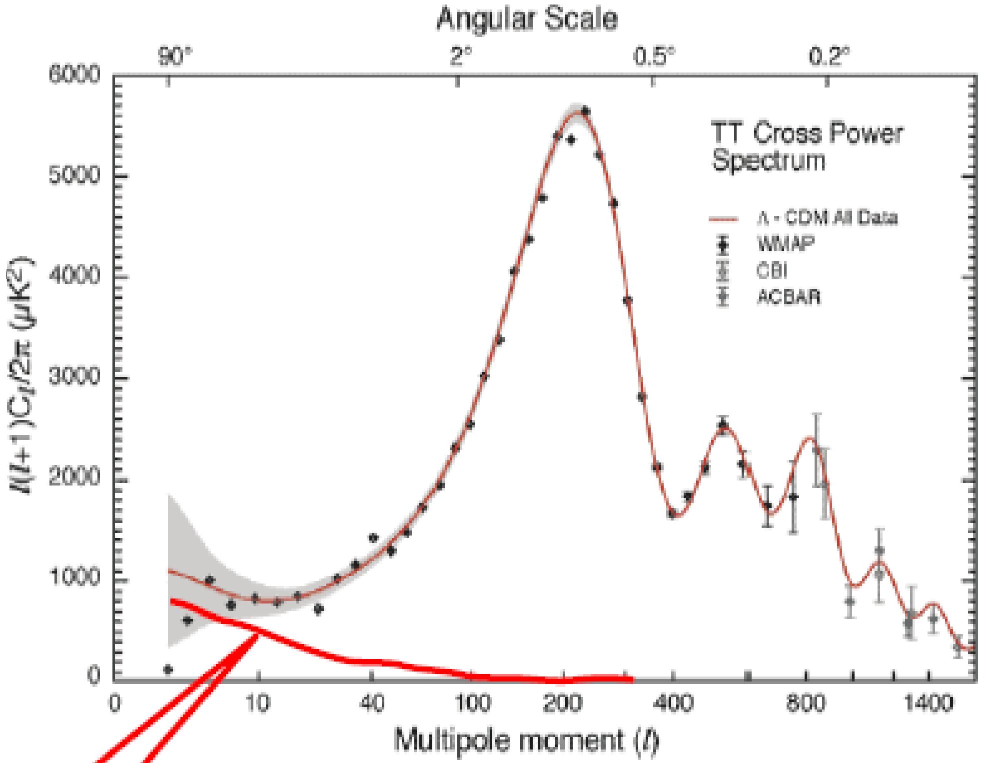
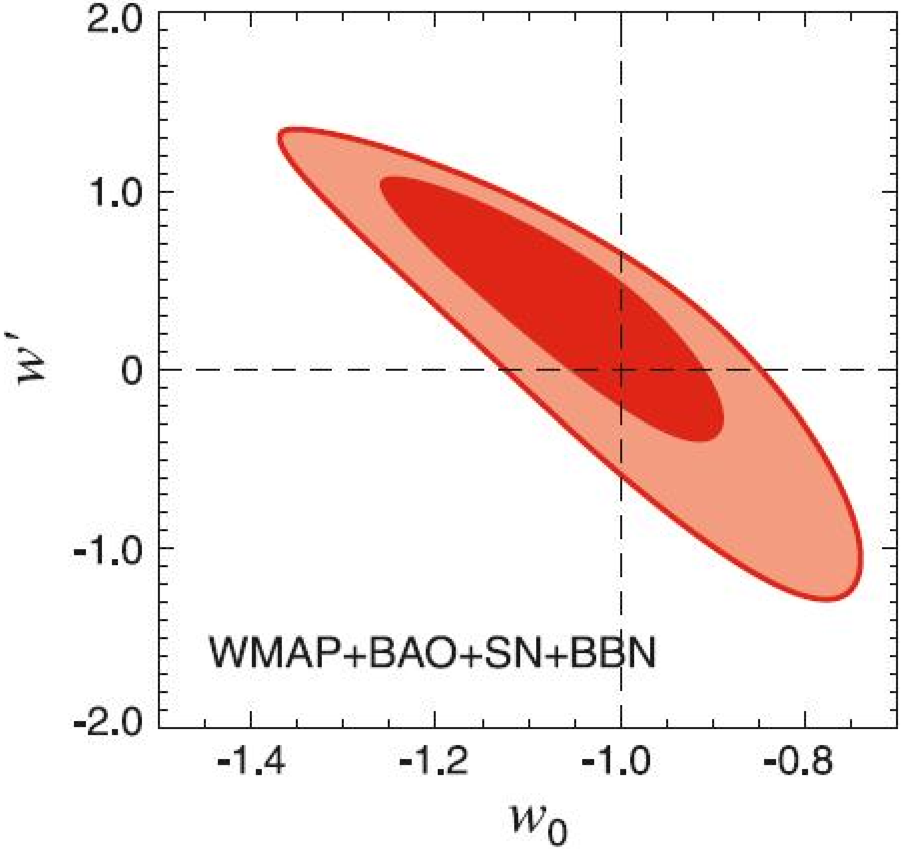


Fig. 2.— 68% and 95% confidence levels constraints on $(w_0,w_a)$ from full WMAP5 data and WMAP distance priors respectively. Red solid lines are obtained from the full WMAP5 data including dark energy perturbations; black dash-dotted lines are from the full WMAP5 data incorrectly neglecting dark energy perturbations; and blue dashed lines are from WMAP distance priors.


full CMB data with perturbation
priors
full CMB data without perturbation
$w_a$
$w_0$
2
1
0
−1
−2
−3
−4
−5
−2.5
−1.5
−0.5
0.5
1.5


Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
$l(l+1)C_l/2\pi\ (\mu K^2)$
6000
5000
4000
3000
2000
1000
0
0
10
40
100
200
400
800
1400
Multipole moment ($l$)

ISW Effect



**or the published version :**

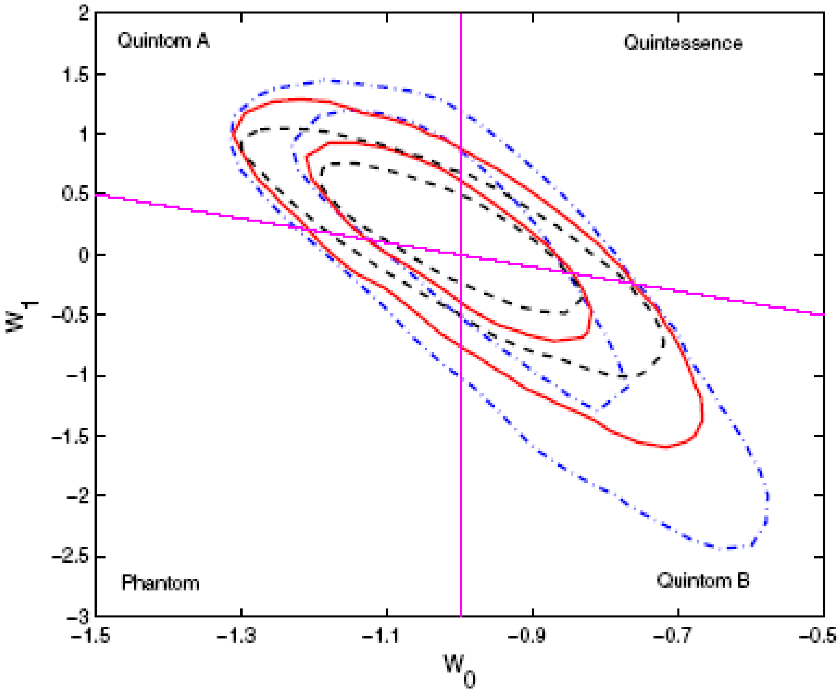


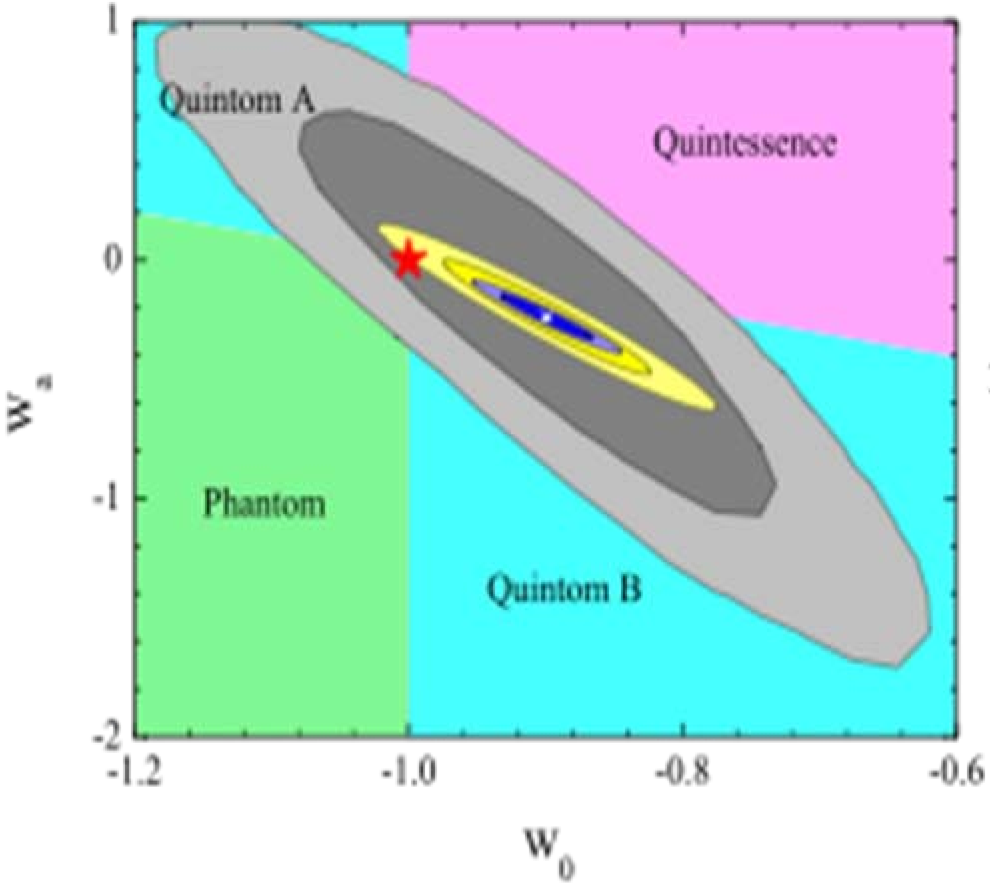
FIG. 2 (color online). Constraints on the dark energy EoS parameters $w_0$ and $w_1$ from the current observations, CMB + BAO + SN. The red solid lines and the blue dash-dot lines are obtained for the flat and nonflat universe, respectively. Also, the black dashed lines are obtained when (incorrectly) neglecting dark energy perturbations. The magenta solid lines stand for $w_0 = -1$ and $w_0 + w_1 = -1$. In this numerical calculation the systematic uncertainties of the union compilation is not considered.

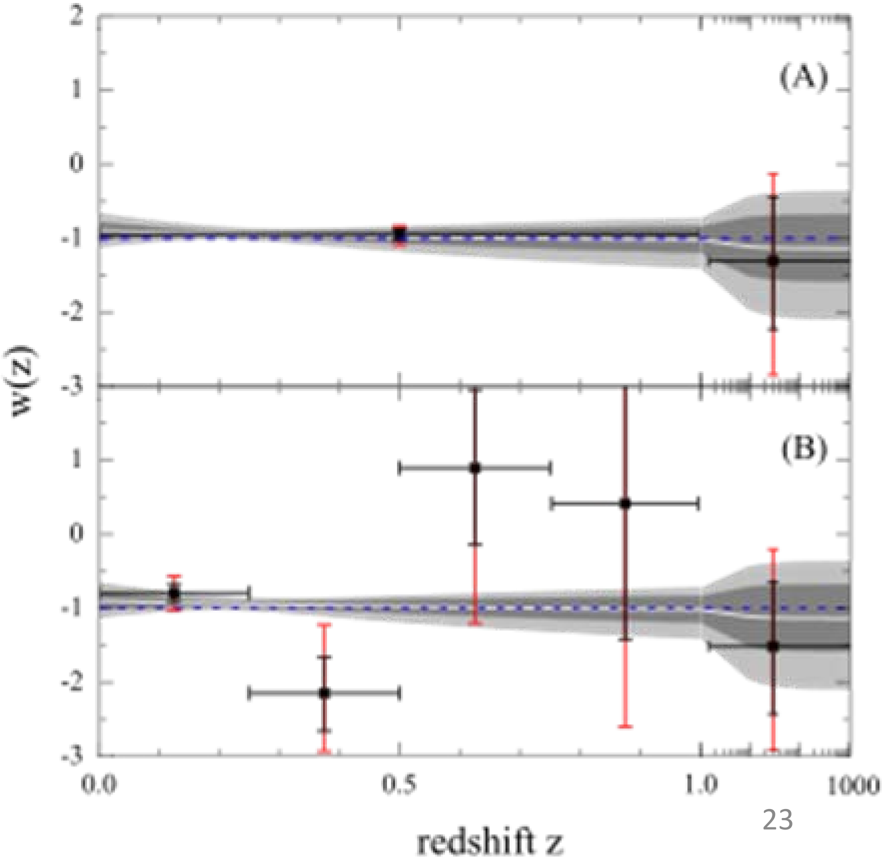
# New results with

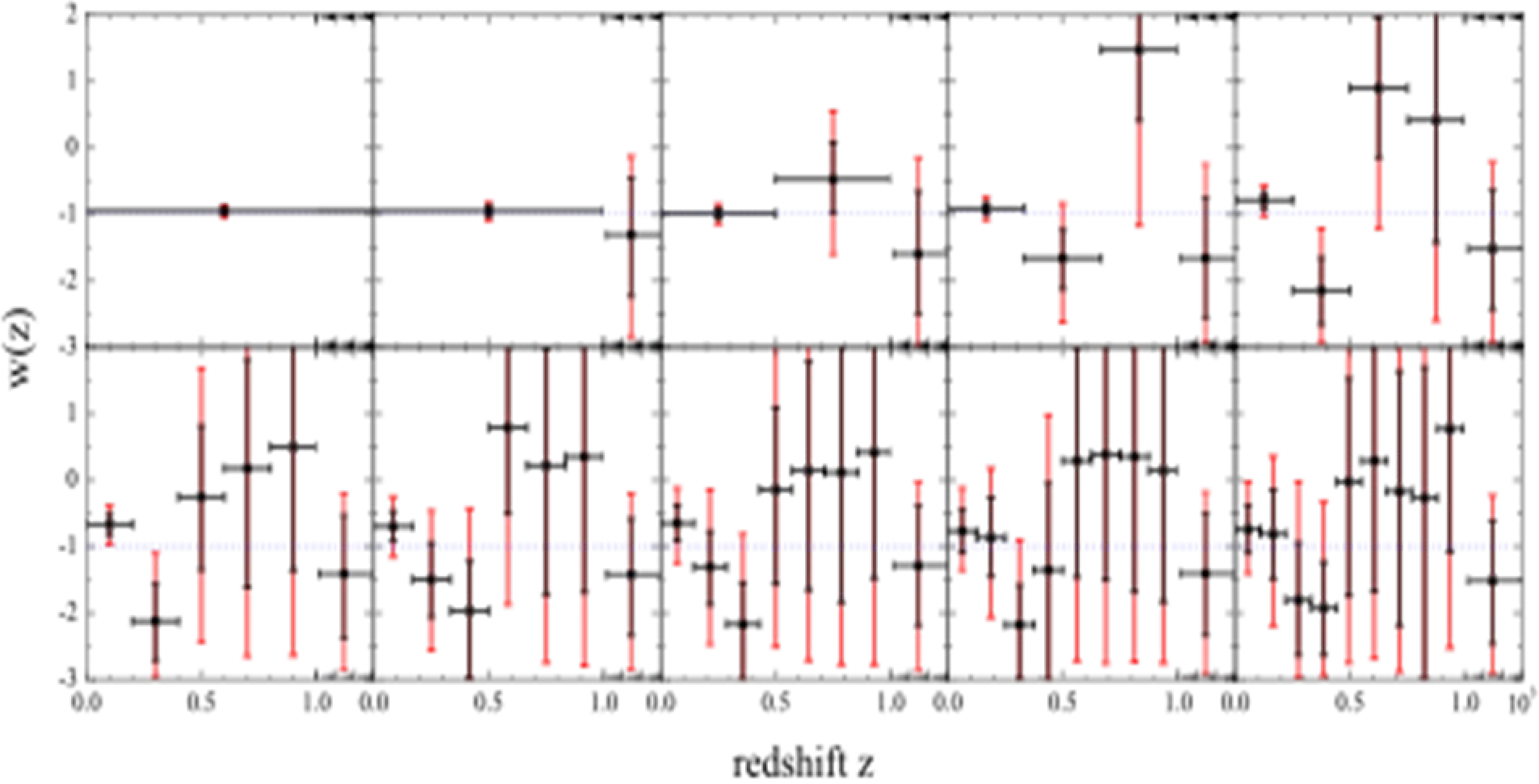
Data: WMAP5 + small-scale CMB + SDSS LRG + ”constitution” sample (SN: CFA+UNION)

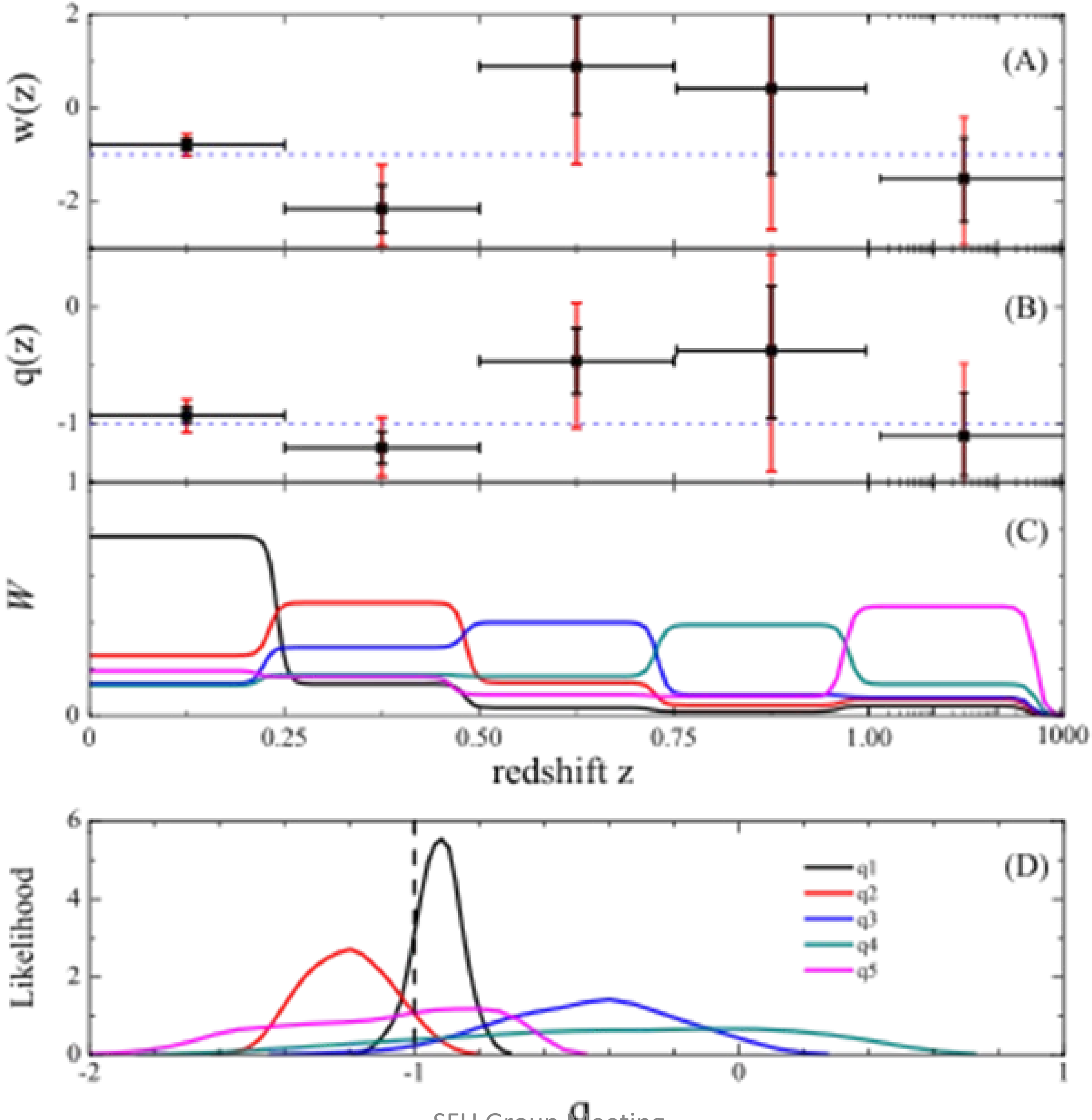
$$w(z) = \begin{cases} \text{Sum of the tanh bins}, & \mathcal{X}_{\rm I} = \{w_i\}; \\ w_0 + w_a \cdot z/(1+z), & \mathcal{X}_{\rm II} = \{w_0, w_a\}; \end{cases}$$

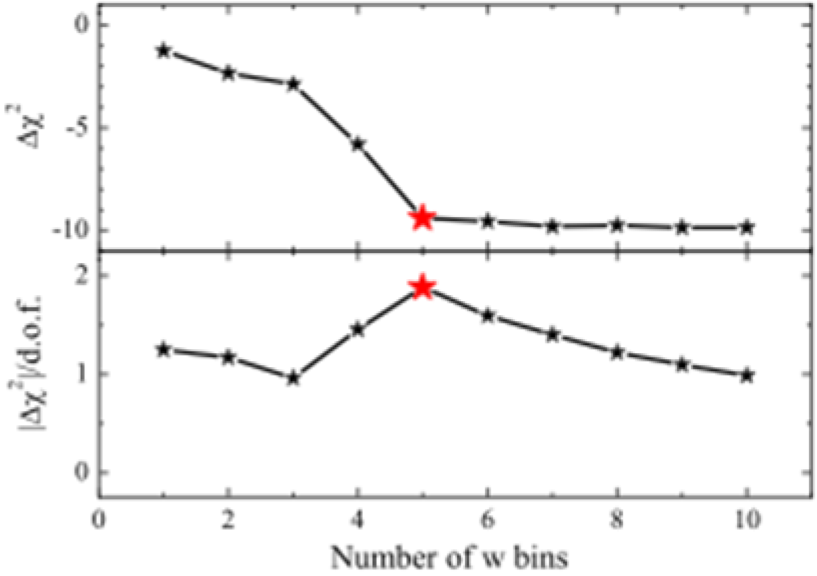
$$w(z) = \sum_{i=1}^{N-1} \frac{(w_{i+1} - w_i)}{2}\left[1 + \tanh\left(\frac{z - z_{i+1}}{\xi}\right)\right] + w_1$$



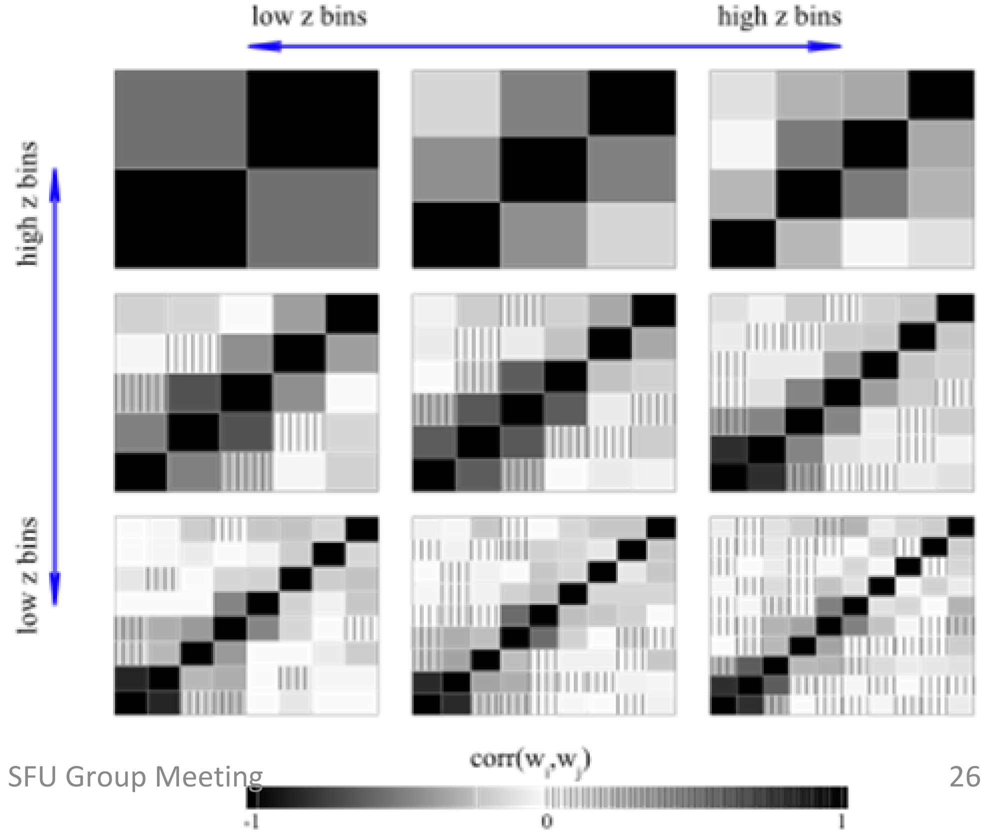



w(z)
2
1
0
-1
-2
-3
0.0
0.5
1.0
10^1
redshift z


w(z)
2
0
-2
(A)
q(z)
0
-1
1
(B)
(C)
W
0
0
0.25
0.50
0.75
1.00
1000
redshift z
Likelihood
6
4
2
0
-2
-1
0
1
q
(D)
q1
q2
q3
q4
q5



$\Delta\chi^2$
0
-5
-10
$|\Delta\chi^2|$/d.o.f.
2
1
0
0
2
4
6
8
10
Number of w bins



low z bins
high z bins
high z bins
low z bins
corr($w_i$,$w_j$)
-1
0
1

# Interacting Quintessence

* If Quintessence –like scalar field responsible for the current acceleration of the Universe ,expected also to interact with the matter directly. **Open new possibilities for the detection.**

* Direct coupling with ordinary matter

Constraint from the limits on the long-range force

* Interaction with derivative

Goldstone theorem: Spin-dependent force

a unified model of DE and Baryo(Lepto)genesis

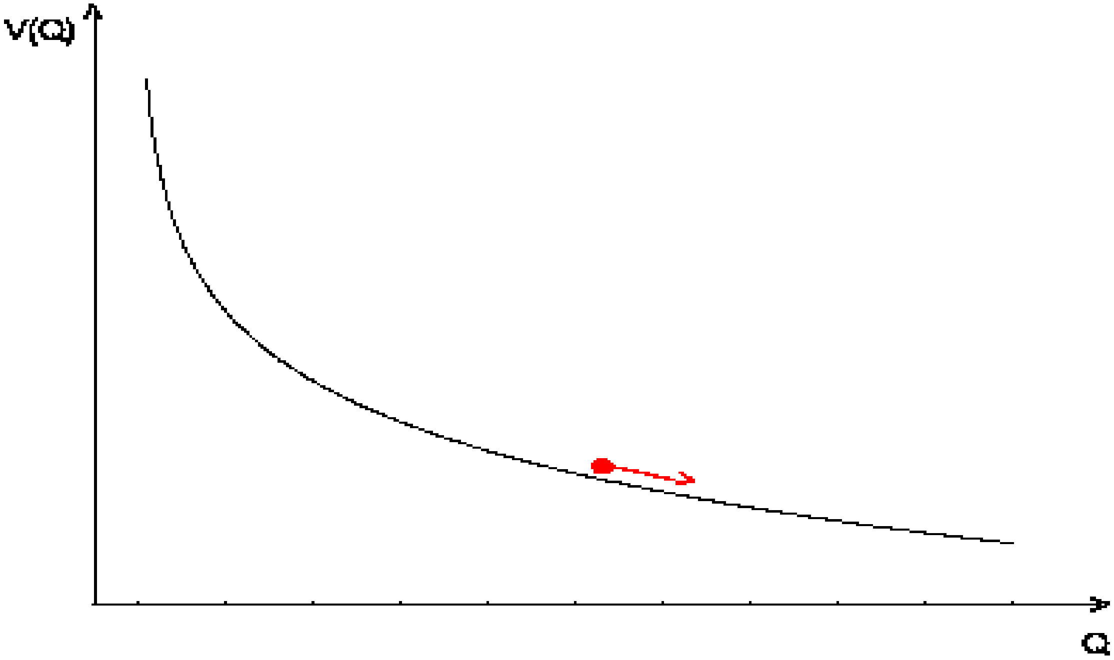
Quintessino as DM

* Interacting with DM (Peebles et al )

* Interacting with neutrinos: mass varying neutrino

# Example of Interacting Dark Energy

$QF_{\mu\nu}F^{\mu\nu}$ Variation of the Fine Structure Constant



# Neutrino Dark Energy

$$\begin{tikzcd}
\frac{Q}{\Lambda}\frac{ll\,\phi\phi}{M} \arrow[dr] & \\
& m_\nu \text{ mass varying} \\
Q\overline{N}_R^c N_R \arrow[ur] &
\end{tikzcd}$$

Connection with Neutrino:

1. $\Lambda$ CDM: $\rho_\lambda \propto (10^{-3}ev)^4 \propto (m_\nu)^4$
2. QCDM: $m_Q \propto 10^{-33}eV \propto \frac{m_\nu^2}{M_{pl}}$

***Gu, Wang, Zhang， PRD68, 087301 (2003)***
***Fardon, Nelson, Weiner, JCAP 0410:005(2004)***

Neutrino can decay
Xiao-Jun Bi, Bo Feng, Hong Li, Xinmin Zhang, PRD72:123523,2005

Neutrino oscillations as a probe of dark energy
D. Kaplan, A. Nelson, N. Weiner, Phys.Rev.Lett.93:091801,2004

GRB: Delay of flight time？
Li, Dai, Zhang, PRD71:113003,2005

Relaxing the cosmological limit on the Neutrino mass
Gong-Bo Zhao, Jun-Qing Xia, Xin-Min Zhang, JCAP 0707:010,2007

# Interacting Dark Energy
# CPT Violation, Baryo-/Leptogenesis
# and CMB Polarization

couplings:

nified model of dark energy, dark matter
and baryon matter

model of baryogenesis and dark energy
----Quintessential baryo/leptogenesis

SYing, Quintessino is dark matter particle
ed model of dark matter and dark energy

PT violation with WMAP and Boomerang

# Quintessential Baryo(Lepto)genesis

***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)***

$$L_{\text{int}} = c\,\frac{\partial_\mu Q}{M} J_B^\mu \Rightarrow \qquad \mu_b = c\,\frac{\dot{Q}}{M} = -\mu_{\bar{b}}$$

In thermo equilibrium⇒

*Cohen & Kaplan*

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

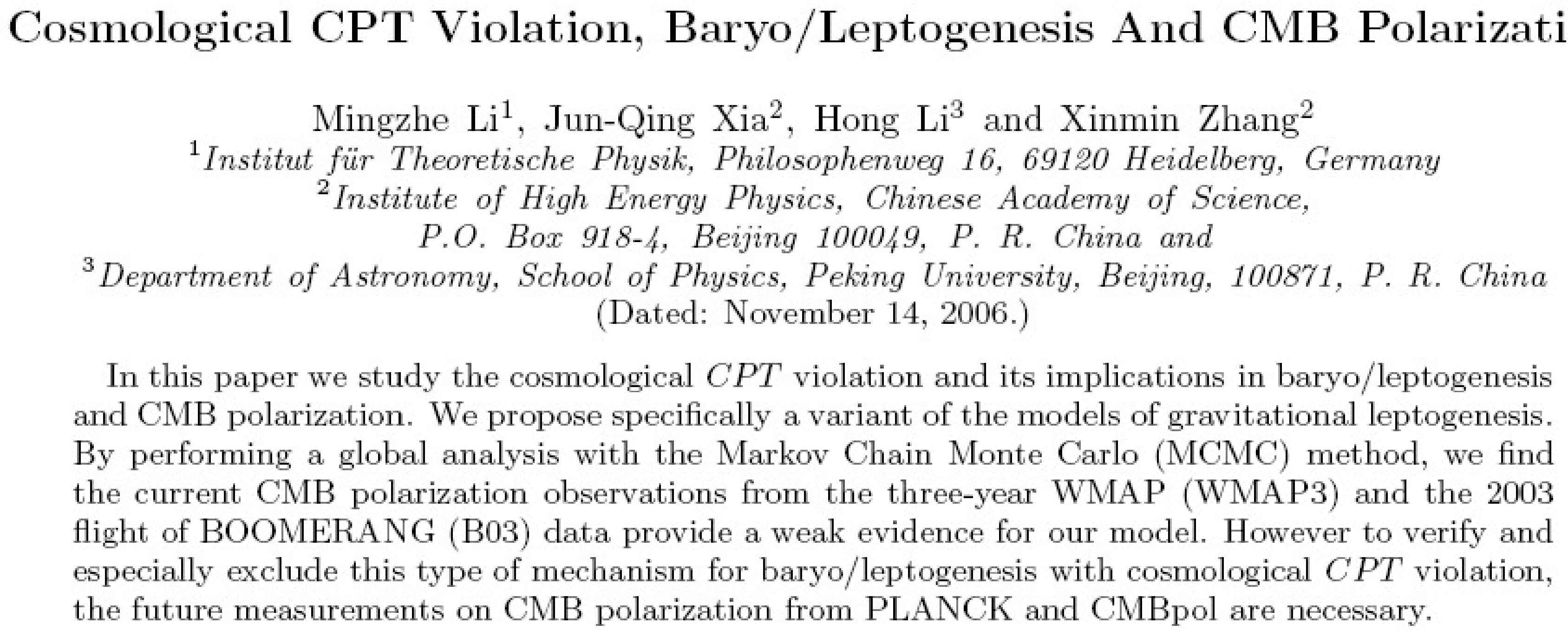
$$= \frac{g_b T^3}{6}\left[\frac{\mu_b}{T} + O\left(\frac{\mu_b}{T}\right)^3\right] \approx c\,\frac{g_b \dot{Q} T^2}{6M}$$

$$s \approx \frac{2\pi^2}{45} g_* T^3 \qquad \eta = n_B / s \approx \frac{15c}{4\pi^2}\frac{g_b \dot{Q}}{g_* M T}$$

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

Cosmological CPT violation!

Physics Letters B 651 (2007) 357–362



# Cosmological CPT Violation, Baryo/Leptogenesis And CMB Polarization

Mingzhe Li[1], Jun-Qing Xia[2], Hong Li[3] and Xinmin Zhang[2]
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[2]*Institute of High Energy Physics, Chinese Academy of Science,*
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(Dated: November 14, 2006.)

In this paper we study the cosmological $CPT$ violation and its implications in baryo/leptogenesis and CMB polarization. We propose specifically a variant of the models of gravitational leptogenesis. By performing a global analysis with the Markov Chain Monte Carlo (MCMC) method, we find the current CMB polarization observations from the three-year WMAP (WMAP3) and the 2003 flight of BOOMERANG (B03) data provide a weak evidence for our model. However to verify and especially exclude this type of mechanism for baryo/leptogenesis with cosmological $CPT$ violation, the future measurements on CMB polarization from PLANCK and CMBpol are necessary.

$$\partial_\mu J^\mu_{(B-L)_\mathrm{L}} \sim -\frac{e^2}{12\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{\alpha_\mathrm{em}}{3\pi} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$J^\mu_{(B-L)_\mathrm{L}} = (1/2)\,\underbrace{J^\mu_{(B-L)}}_{\Downarrow} - (1/2)\,\underbrace{J^{5\mu}_{(B-L)}}_{\Downarrow}$$

Leptogenesis

Anomaly for CMB

# Cosmological CPT violation: predicting <TB> and <EB>

$$\mathcal{L} \sim -\frac{1}{2} C \partial_\mu Q K^\mu \qquad K^\mu = A_\nu \tilde{F}^{\mu\nu} = \frac{1}{2} A_\nu \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

$$\boxed{\partial_\mu Q \to \partial_\mu f(R)}$$

Hong Li et al

$$\tan\alpha \equiv \frac{B_z}{B_y} = \ldots = \tan(\frac{1}{2} C Q + I) \qquad \alpha = \frac{1}{2} C Q + I \quad \Delta\alpha = \frac{1}{2} C \Delta Q$$

$$\begin{cases} Q' = Q\cos 2\Delta\alpha + U \sin 2\Delta\alpha \\ U' = -Q \sin 2\Delta\alpha + U \cos 2\Delta\alpha \end{cases}$$

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

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

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

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

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

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

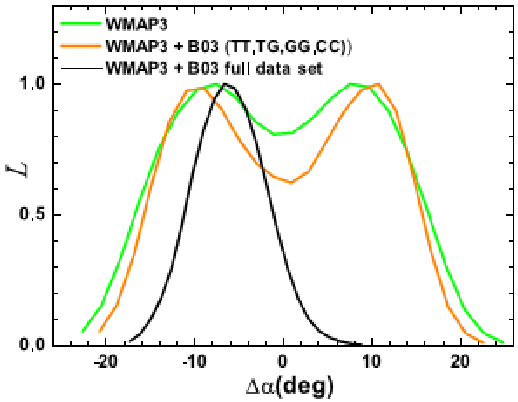

FIG. 1 (color online). One-dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP data alone (green or light gray line), WMAP and the 2003 flight of BOOMERANG B03 TT, TG, GG and CC (orange or gray line), and from WMAP and the full B03 observations (TT, TG, GG, CC, TC, GC) (black line).

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)

PRL **96,** 221302 (2006) PHYSICAL REVIEW LETTERS week ending 9 JUNE 2006

# Searching for *CPT* Violation with Cosmic Microwave Background Data from WMAP and BOOMERANG

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(Received 23 January 2006; revised manuscript received 16 May 2006; published 7 June 2006)

We search for signatures of Lorentz and *CPT* violations in the cosmic microwave background (CMB) temperature and polarization anisotropies by using the Wilkinson Microwave Anisotropy Probe (WMAP) and the 2003 flight of BOOMERANG (B03) data. We note that if the Lorentz and *CPT* symmetries are broken by a Chern-Simons term in the effective Lagrangian, which couples the dual electromagnetic field strength tensor to an external four-vector, the polarization vectors of propagating CMB photons will get rotated. Using the WMAP data alone, one could put an interesting constraint on the size of such a term. Combined with the B03 data, we found that a nonzero rotation angle of the photons is mildly favored: $\Delta\alpha = -6.0^{+4.0}_{-4.0}{}^{+3.9}_{-3.7}$ deg$(1, 2\sigma)$.

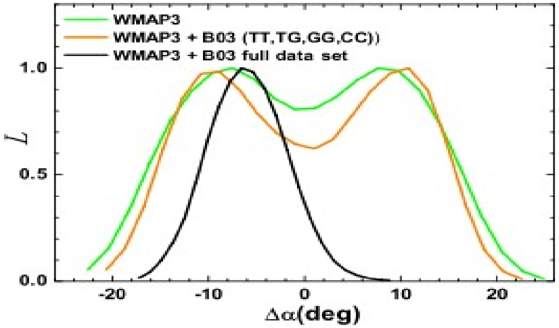

FIG. 1 (color online). One-dimensional constraints on the rotation angle $\Delta\alpha$ from WMAP data alone (green or light gray line), WMAP and the 2003 flight of BOOMERANG B03 TT, TG, GG and CC (orange or gray line), and from WMAP and the full B03 observations (TT, TG, GG, CC, TC, GC) (black line).

PHYSICAL REVIEW D **76,** 123014 (2007)

# Constraints on *CPT* violation from Wilkinson Microwave Anisotropy Probe three year polarization data: A wavelet analysis

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(Received 7 May 2007; published 28 December 2007)

We perform a wavelet analysis of the temperature and polarization maps of the cosmic microwave background (CMB) delivered by the Wilkinson Microwave Anisotropy Probe experiment in search for a parity-violating signal. Such a signal could be seeded by new physics beyond the standard model, for which the Lorentz and *CPT* symmetries may not hold. Under these circumstances, the linear polarization direction of a CMB photon may get rotated during its cosmological journey, a phenomenon also called cosmological birefringence. Recently, Feng *et al.* have analyzed a subset of the Wilkinson Microwave Anisotropy Probe and BOOMERanG 2003 angular power spectra of the CMB, deriving a constraint that mildly favors a nonzero rotation. By using wavelet transforms we set a tighter limit on the CMB photon rotation angle $\Delta\alpha = -2.5 \pm 3.0$ ($\Delta\alpha = -2.5 \pm 6.0$) at the one (two) $\sigma$ level, consistent with a null detection.

$$\Delta\mathcal{L} = -\tfrac{1}{4}p_\mu \epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}A_\nu,$$

where $F^{\mu\nu}$ is the Maxwell tensor and $A^\mu$ the 4-potential. The 4-vector $p_\mu$ may be interpreted as the derivative of the quintessence field or the gradient of a function of the Ricci scalar [18]. In either case a $P$ violation always arises provided that $p_0$ is nonzero, while $C$ and $T$ remain intact. Hence, $CP$ and $CPT$ symmetries are also violated, as well as Lorentz invariance, since $p^\mu$ picks up a preferred direction in space-time. The net effect on a propagating photon is to rotate its polarization direction by an angle $\Delta\alpha$, hence

The Astrophysical Journal Supplement Series, 180:330–376, 2009 February doi:10.1088/0067-0049/180/2/330

# FIVE-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE** OBSERVATIONS: COSMOLOGICAL INTERPRETATION

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[10] Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
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[14] UCLA Physics and Astronomy, P.O. Box 951547, Los Angeles, CA 90095-1547, USA

When the polarization plane is rotated by $\Delta\alpha$, the intrinsic (primordial) TE, EE, and BB spectra are converted into TE, TB, EE, BB, and EB spectra as (Lue et al. 1999; Feng et al. 2005)

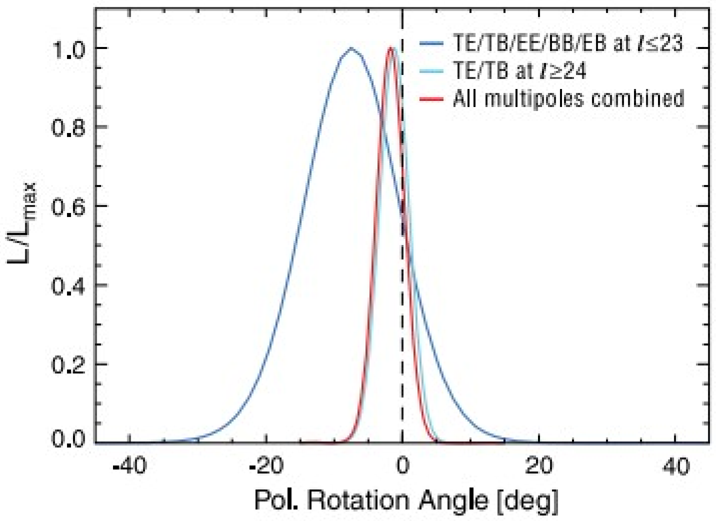
$$C_l^{\mathrm{TE,obs}} = C_l^{\mathrm{TE}} \cos(2\Delta\alpha), \tag{55}$$

$$C_l^{\mathrm{TB,obs}} = C_l^{\mathrm{TE}} \sin(2\Delta\alpha), \tag{56}$$

$$C_l^{\mathrm{EE,obs}} = C_l^{\mathrm{EE}} \cos^2(2\Delta\alpha) + C_l^{\mathrm{BB}} \sin^2(2\Delta\alpha), \tag{57}$$

$$C_l^{\mathrm{BB,obs}} = C_l^{\mathrm{EE}} \sin^2(2\Delta\alpha) + C_l^{\mathrm{BB}} \cos^2(2\Delta\alpha), \tag{58}$$

$$C_l^{\mathrm{EB,obs}} = \tfrac{1}{2}\left(C_l^{\mathrm{EE}} - C_l^{\mathrm{BB}}\right) \sin(4\Delta\alpha), \tag{59}$$



THE ASTROPHYSICAL JOURNAL, 679: L61–L63, 2008 June 1

# TESTING CPT SYMMETRY WITH CMB MEASUREMENTS: UPDATE AFTER WMAP5

JUN-QING XIA,[1] HONG LI,[2] GONG-BO ZHAO,[3] AND XINMIN ZHANG[1]

*Received 2008 March 16; accepted 2008 April 16; published 2008 April 25*

## ABSTRACT

In this Letter we update our previous results on the test of CPT symmetry with cosmic microwave background (CMB) measurements. A CPT-violating interaction in the photon sector $\mathcal{L}_{CS} \sim p_\mu A_\nu \tilde{F}^{\mu\nu}$ gives rise to a rotation of the polarization vectors of the propagating CMB photons. Recently the *WMAP* group used the newly released polarization data of WMAP5 to measure this rotation angle $\Delta\alpha$ and obtained $\Delta\alpha = -1.7° \pm 2.1°$ (1 $\sigma$). However, in their analysis the BOOMERANG 2003 data are not included. Here we revisit this issue by combining the full data of WMAP5 and BOOMERANG 2003 angular power spectra for the measurement of this rotation angle $\Delta\alpha$ and find that $\Delta\alpha = -2.6° \pm 1.9°$ at a 68% confidence level.

*Subject headings:* cosmic microwave background — cosmological parameters — cosmology: theory

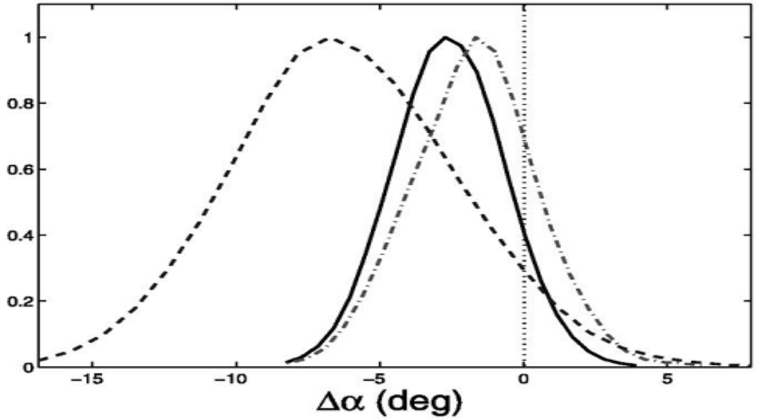


FIG. 1.—One-dimensional distributions on the rotation angle $\Delta\alpha$ from CMB data. The dashed line shows our previous limit on $\Delta\alpha$ from WMAP3 and B03. The dash-dotted line shows the limit from the full data of WMAP5. The solid line is from the full data of WMAP5 and B03. The horizontal dotted line shows $\Delta\alpha = 0$. [*See the electronic edition of the Journal for a color version of this figure.*]

PRL **102,** 161302 (2009) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2009

# Parity Violation Constraints Using Cosmic Microwave Background Polarization Spectra from 2006 and 2007 Observations by the QUaD Polarimeter

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(QUaD Collaboration)

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We constrain parity-violating interactions to the surface of last scattering using spectra from the QUaD experiment's second and third seasons of observations by searching for a possible systematic rotation of the polarization directions of cosmic microwave background photons. We measure the rotation angle due to such a possible "cosmological birefringence" to be $0.55^\circ \pm 0.82^\circ$ (random) $\pm 0.5^\circ$ (systematic) using QUaD's 100 and 150 GHz temperature-curl and gradient-curl spectra over the spectra over the multipole range $200 < \ell < 2000$, consistent with null, and constrain Lorentz-violating interactions to $< 2 \times 10^{-43}$ GeV (68% confidence limit). This is the best constraint to date on electrodynamic parity violation on cosmological scales.

1) $\Delta\alpha = -6.0 \pm 4.0$ deg

Bo Feng et al., PRL 96, 221302 (2006)

2) Wavelet Analysis:

WMAP3(TT,TG,GG,CC,TC,GC)

$$\Delta\alpha = -2.5 \pm 3.0$$

P.Cabella, Natoli & Silk,
PRD76, 123014 (2007)

3) $\Delta\alpha = -6.2 \pm 3.8$ deg

J.Q.Xia et al., arXiv:0710.3325

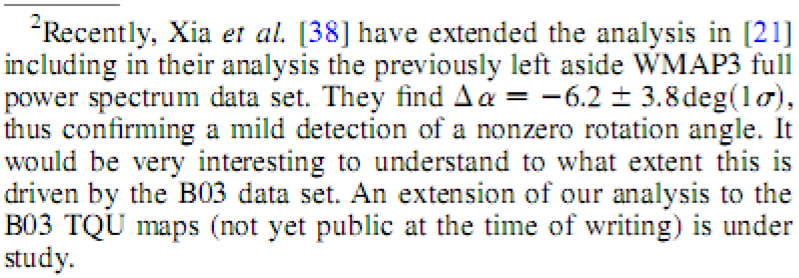
4) $\Delta\alpha = -1.7 \pm 2.1$ deg

Komatsu et al., arXiv:0803.0547

5) $\Delta\alpha = -2.6 \pm 1.9$ deg

J.Q.Xia et al., arXiv:0803.2350

6) $PLANCK: \ \sigma = 0.057$ deg



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[2] Recently, Xia *et al.* [38] have extended the analysis in [21] including in their analysis the previously left aside WMAP3 full power spectrum data set. They find $\Delta\alpha = -6.2 \pm 3.8\,\mathrm{deg}(1\sigma)$, thus confirming a mild detection of a nonzero rotation angle. It would be very interesting to understand to what extent this is driven by the B03 data set. An extension of our analysis to the B03 TQU maps (not yet public at the time of writing) is under study.

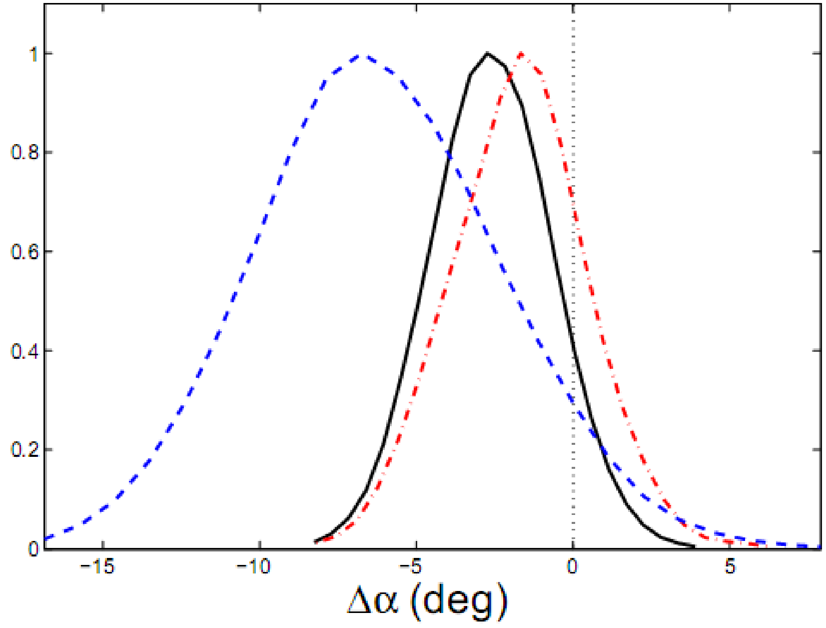

FIG. 1.— One dimensional distributions on the rotation angle $\Delta\alpha$ from CMB data. The blue dashed line shows our previous limit on $\Delta\alpha$ from WMAP3 and B03. The red dash-dot line shows the limit from the full data of WMAP5. The black solid line is from the full data of WMAP5 and B03. The horizontal dotted line shows $\Delta\alpha = 0$.

# Spatial dependent $\Delta\ \alpha$

- **Cosmological CPT violating effect on CMB polarization.**
  Mingzhe Li , Xinmin Zhang.
  Published in **Phys.Rev.D78:103516,2008**.
  e-Print: **arXiv:0810.0403**

- **De-Rotation of the Cosmic Microwave Background Polarization: Full-Sky Formalism.**
  Vera Gluscevic, Marc Kamionkowski, Asantha Cooray . May 2009. 11pp.
- e-Print: **arXiv:0905.1687** [astro-ph.CO]
- **A Constraint on Planck-scale Modifications to Electrodynamics with CMB polarization data.**
  Giulia Gubitosi, Luca Pagano, Giovanni Amelino-Camelia, Alessandro Melchiorri, Asantha

  Cooray. Apr 2009.e-Print: **arXiv:0904.3201** [astro-ph.CO]
- **Constraining a spatially dependent rotation of the Cosmic Microwave Background Polarization.**
  Amit P.S. Yadav, Rahul Biswas , Meng Su, Matias Zaldarriaga . Feb 2009.
  e-Print: **arXiv:0902.4466** [astro-ph.CO]
- **How to De-Rotate the Cosmic Microwave Background Polarization.**
  Marc Kamionkowski (Caltech) . Oct 2008.
  Published in **Phys.Rev.Lett.102:111302,2009**.
  e-Print: **arXiv:0810.1286** [astro-ph]

# Summary

1) Current status on constraints on dark energy:

  - a) Cosmological constant fits data well;
  - b) Dynamical model not ruled out;

2) B-Mode: Tensor Perturbation; CPT violation effects