粒子宇宙学研究进展

中科院高能所
张新民

“2012年两岸粒子物理与宇宙学研讨会”，
2012年5月9日， 重庆

粒子宇宙学

(微观） 粒子物理标准模型

LEP,
Tevatron …… LHC

三代夸克和轻子

SU(3) C × SU(2)L × U(1)Y

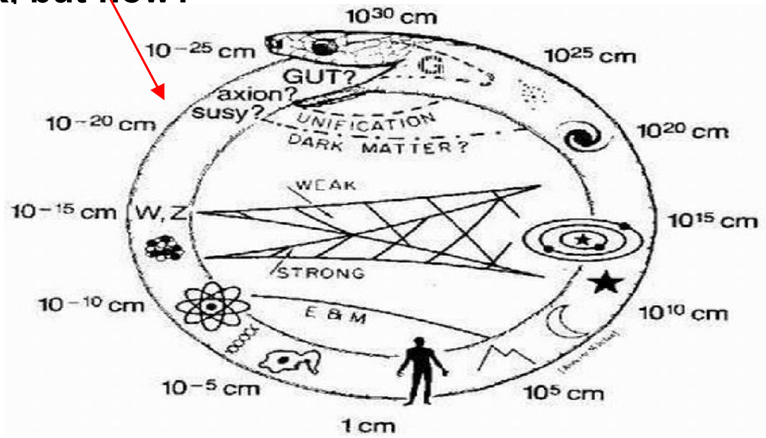
问题: **Higgs not discovered;**
symmetry breaking OK, but how?

Higgs? 125 GeV?
SUSY?
Extra dimension?

（宇观） 大爆炸宇宙模型

1998年，SN发现暗能量; （邵逸夫奖，Nobel prize!）
2000年，Maxima, BoomeranG

2003年，WMAP，SDSS，2dfGRS
2004年， “Golden Sample”, SNLS
2006年， WMAP3 COBE Nobel Prize!
2008年， WMAP5 （2010年邵逸夫奖）
2008年， Pamela, ATIC
2009年， Fermi LAT
2010年，WMAP7
Inflation + dark matter + dark energy + baryon matter

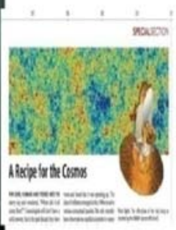


新世纪 新特征:
极小与极大，
粒子物理与宇宙学
的交叉研究

过去十年“宇宙学”研究进展

PRECISION COSMOLOGY

In the past decade, cosmologists have deduced a very precise recipe for the content of the universe, as well as instructions for putting it together, transforming cosmology from a largely qualitative endeavor to a precision science with a standard theory.



1） 本世纪前十年十大科学成就：精确宇宙学

本世纪首个十年即将结束之际，《科学》杂志审视了进入新千 年以来的那些改变科学面貌的进步，

评选出了十项科学成就作为“本十年卓见”（Insights of the Decade）。

精确宇宙学：在过去十年中，研究人员非常精确地推测出宇宙物质的成分是普通物质、暗物质和暗能量。同时，他们阐述了将这些成分组成宇宙的方法。这些进展 将宇宙学转变成为一种有着标准理论的精确科学，而留给其他理论的活动空间已十分狭小。

(注：WMAP 贡献巨大！中国科学家贡献不可忽略！)

2） 2011年度诺贝尔物理奖

3) 2006 年度诺贝尔物理奖

十年的“精确宇宙学”成就了2011， 2006年度的诺奖！

1) **Inflation dynamics?**
2) **Nature of dark energy?**
3) **Nature of dark matter?**
4) **Why no anti-matter (Baryo/Leptogenesis)**
5) **Singularity of Big-Bang cosmology model??**
(大爆炸前是什么？？）
6) **Testing new physics or fundamental symmetry, CPT with CMB…observations?**

报告提纲

1）暗能量

SDSS-III新数据，宇宙学参数新结果

。。。Gongbo Zhao, arXiv:1203.6616

Quintom-Galileon 理论: **On dark energy models of single scalar field**

Mingzhe Li et al, arXiv:1112.4255 [hep-th]

Bouncing Galileon Cosmologies , T, Qiu et al, JCAP 1110:036,2011

2）中微子宇宙学

宇宙学中微子质量限; 中微子暗能量

Baryo/Leptogenesis, Quintessential Leptogenesis & CMB pol

3）暗物质: Cold or Warm WIMPs

CosRayMC: a global fitting method in studying the properties of the new sources of cosmic e$^{\pm}$ excesses

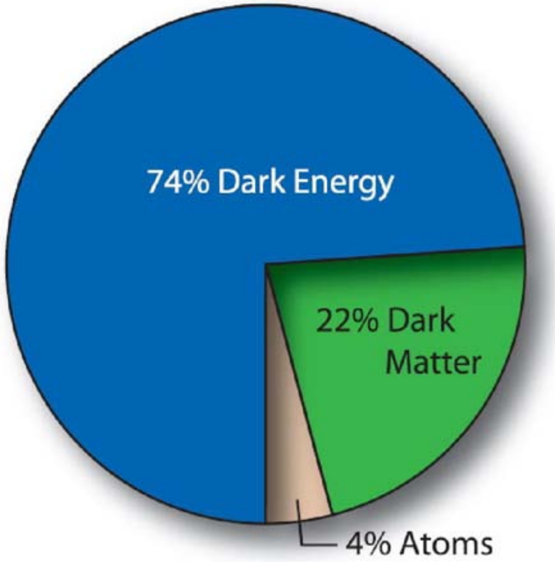
Jie Liu et al, Phys.Rev.D85:043507,2012

Gamma-rays From Warm WIMP Dark Matter Annihilation

Qiang Yuan, Yixian Cao, Jie Liu, Pengfei Yin, Liang Gao, Xiao-Jun Bi, Xinmin Zhang

e-Print: **arXiv:1203.5636** [astro-ph.HE]

暗能量简介



观测证据： 1998年，SN发现加速膨胀；

1998年世界十大科技进展，2006年 邵逸夫奖，2011年Nobel Prize.

2003年，WMAP，SDSS， 精确宇宙学；

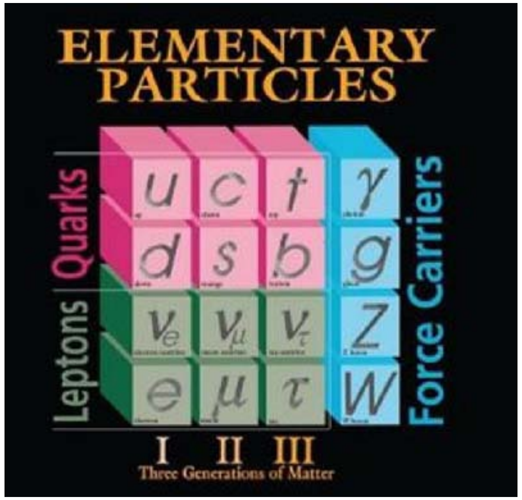
2003年世界十大科技进展

2010年， WMAP 邵逸夫奖（Nobel Prize？）

基本特征：

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

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



1. 负压　　2. 完全或者几乎不结团

注意：宇宙学框架下物质描述：密度 \rho，状态方程 w

例如：　辐射 w=1/3；　物质 w=0；

冷暗物质w=0

暗能量：w=? 只知 w < -1/3

太粗略了!!!

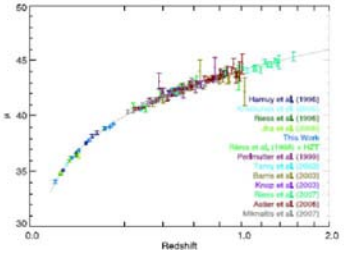
同时，不同的 w 代表不同的理论模型。。。。。

怎样测定 w(z) ??

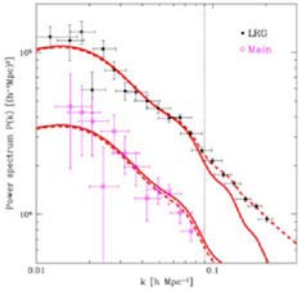
1) w(z) 不能直接观测， 是个被推导出来的量 (标准宇宙学理论模型）

2）天文观测量：

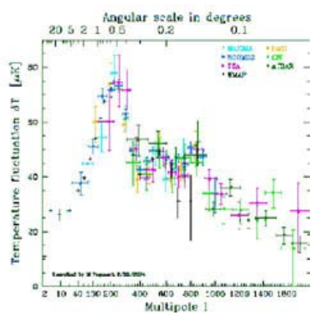
SN： 光度距离



LSS： 功率谱



CMB： 温度角功率谱， 极化

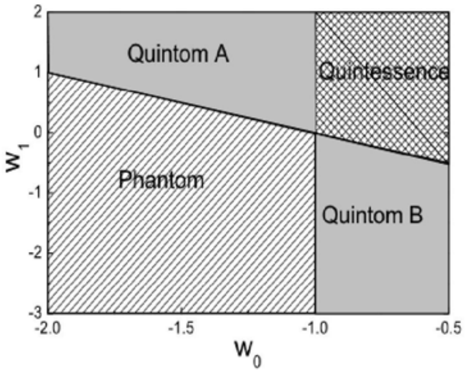


。。。。。。。**GRB, WL ……**

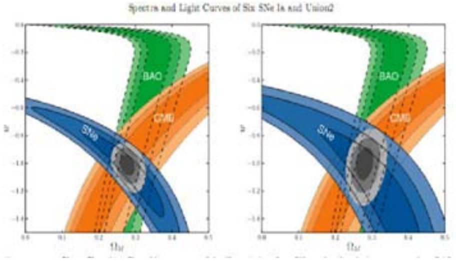
3）**w(z)** 参数化 （目的： 可行性；
减少参数。。。）

i） **w=w_0+w_1 z (for small z)**
ii）**w(z) = w_0 + (1-a) w_a**
= w_0 + w_a z/(1+z)

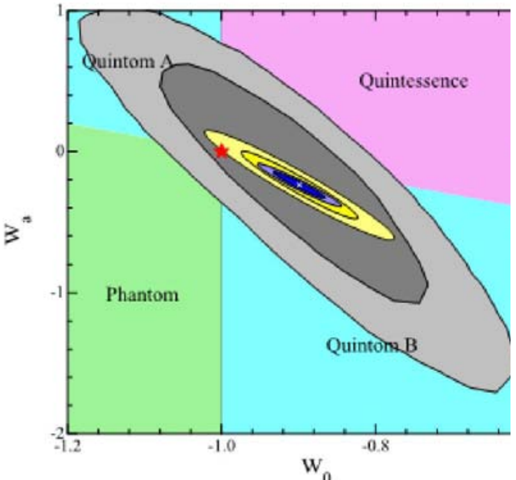
=========〉



4) 数值计算，整体拟合分析

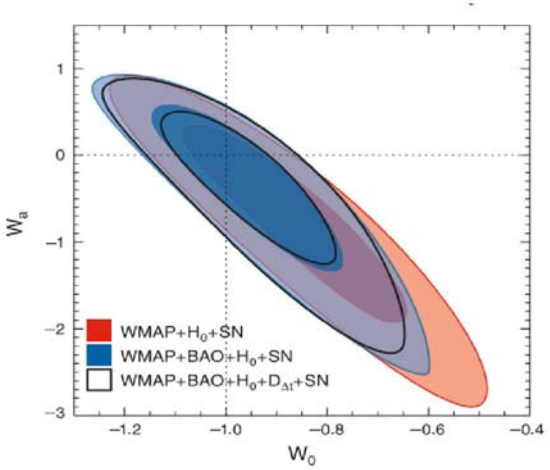


Current status in determining the EoS of dark energy

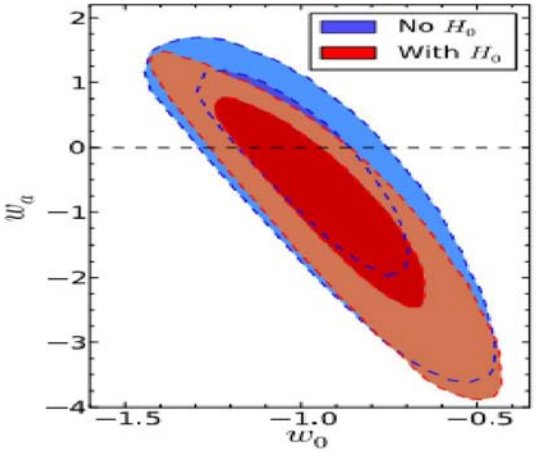


G. Zhao and X. Zhang

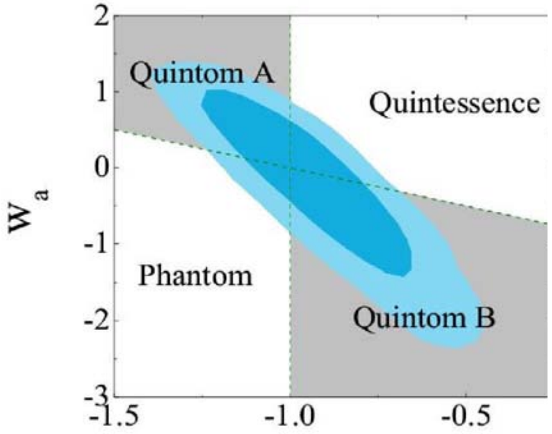
Phys.Rev.D81:043518,2010



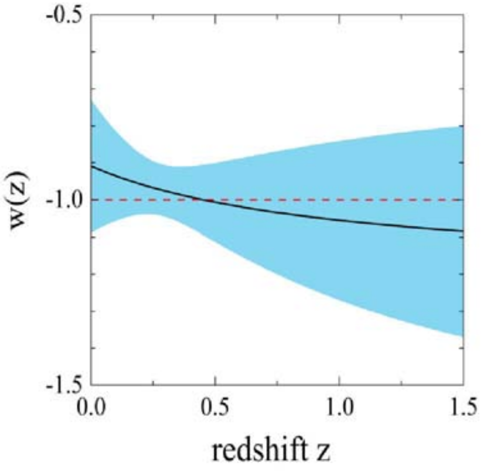
WMAP7 E. Komatsu *et al.*
e-Print: **arXiv:1001.4538**



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;

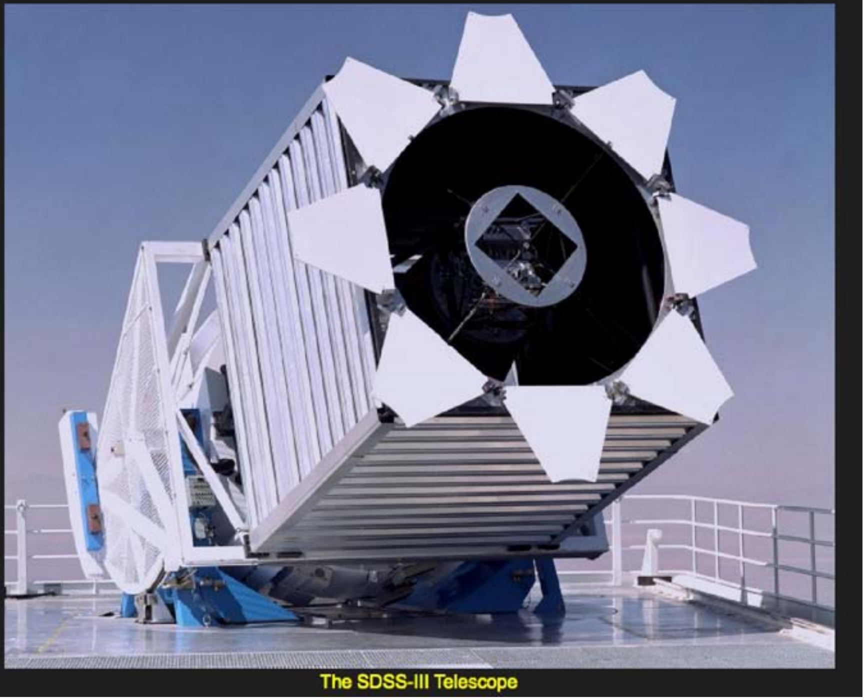
The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological implications of the large-scale two-point correlation function

Ariel G. Sánchez[1*], C. G. Scóccola[2,3], A. J. Ross[4], W. Percival[4], M. Manera[4], F. Montesano[1], X. Mazzalay[1], A. J. Cuesta[5], D. J. Eisenstein[6], E. Kazin[7], C. K. McBride[6], K. Mehta[8], A. D. Montero-Dorta[9], N. Padmanabhan[5], F. Prada[9,10,11], J. A. Rubiño-Martín[2,3], R. Tojeiro[4], X. Xu[8], M. Vargas Magaña[12], E. Aubourg[12], N. A. Bahcall[13], S. Bailey[14], D. Bizyaev[15], A. S. Bolton[16], H. Brewington[15], J. Brinkmann[15], J. R. Brownstein[16], J. Richard Gott, III[13], J. C. Hamilton[12], S. Ho[14,17], K. Honscheid[18], A. Labatie[12], E. Malanushenko[15], V. Malanushenko[15], C. Maraston[4], D. Muna[19], R. C. Nichol[4], D. Oravetz[15], K. Pan[15], N. P. Ross[14], N. A. Roe[14], B. A. Reid[14,20], D. J. Schlegel[14], A. Shelden[16], D. P. Schneider[21,22], A. Simmons[15], R. Skibba[8], S. Snedden[15], D. Thomas[4], J. Tinker[19], D. A. Wake[23], B. A. Weaver[19], David H. Weinberg[24], Martin White[14,25], I. Zehavi[26], and G. Zhao[4,27]

[1] *Max-Planck-Institut für extraterrestrische Physik, Postfach 1312, Giessenbachstr., 85741 Garching, Germany.*
[2] *Instituto de Astrofísica de Canarias (IAC), C/Vía Láctea, s/n, La Laguna, Tenerife, Spain.*
[3] *Dpto. Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain.*
[4] *Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth PO1 3FX, UK.*
[5] *Department of Physics, Yale University, 260 Whitney Ave, New Haven, CT 06520, USA.*
[6] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138.*
[7] *Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, Victoria 3122, Australia.*
[8] *Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ 85721, USA.*
[9] *Instituto de Astrofisica de Andalucia (CSIC), Glorieta de la Astronomia, E-18080 Granada, Spain.*
[10] *Campus of International Excellence UAM+CSIC, Cantoblanco, E-28049 Madrid, Spain.*
[11] *Instituto de Fisica Teorica (UAM/CSIC), Universidad Autonoma de Madrid, Cantoblanco, E-28049 Madrid, Spain.*
[12] *APC, University of Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, France.*
[13] *Department of Astrophysical Sciences, Princeton University, Peyton Hall, Princeton, NJ 08540, USA.*
[14] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, USA.*
[15] *Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349-0059, USA.*
[16] *Department of Physics and Astronomy, The University of Utah, 115 S 1400 E, Salt Lake City, UT 84112, USA*
[17] *Department of Physics, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, PA 15213, USA.*
[18] *Department of Physics and CCAPP, Ohio State University, Columbus, OH, USA.*
[19] *Center for Cosmology and Particle Physics, New York University, NY 10003, USA.*

SDSS-III Survey Instruments

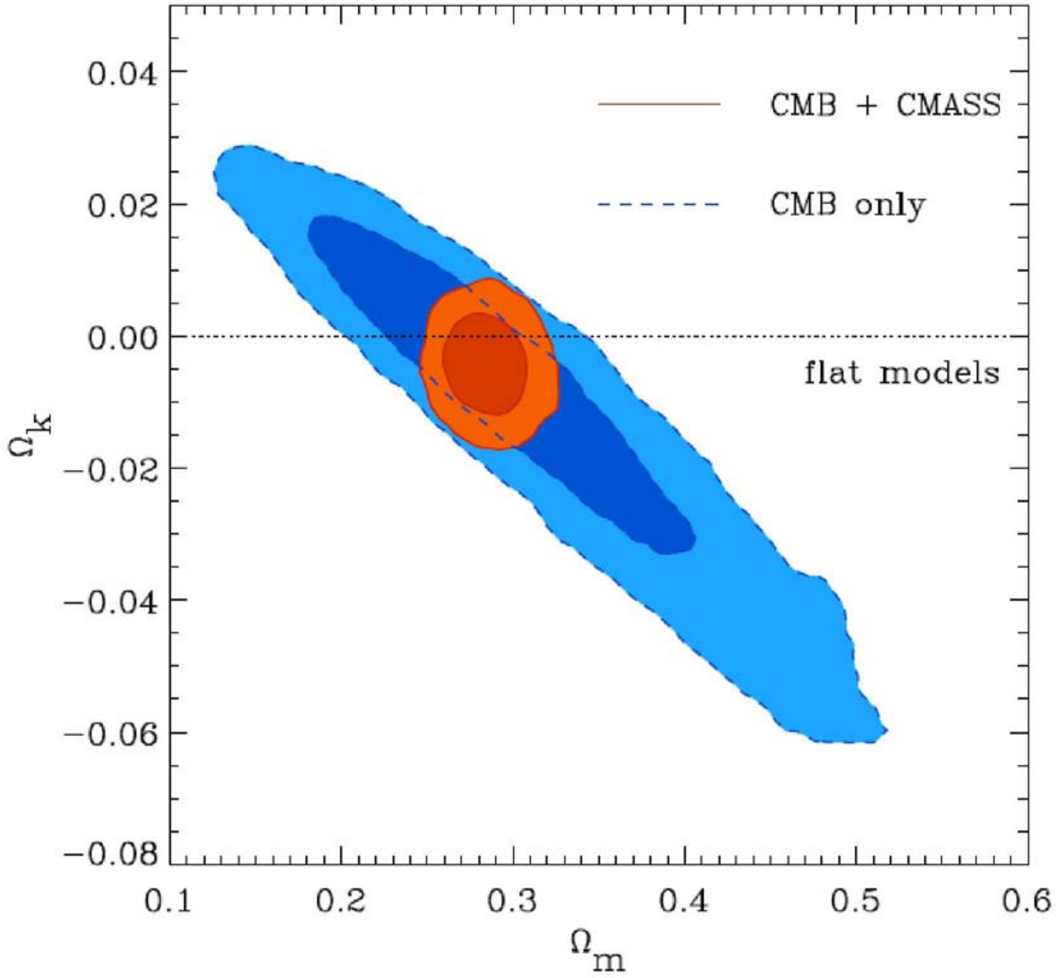
Apache Point Observatory
(SDSS 2.5m telescope at left)



The SDSS-III Telescope

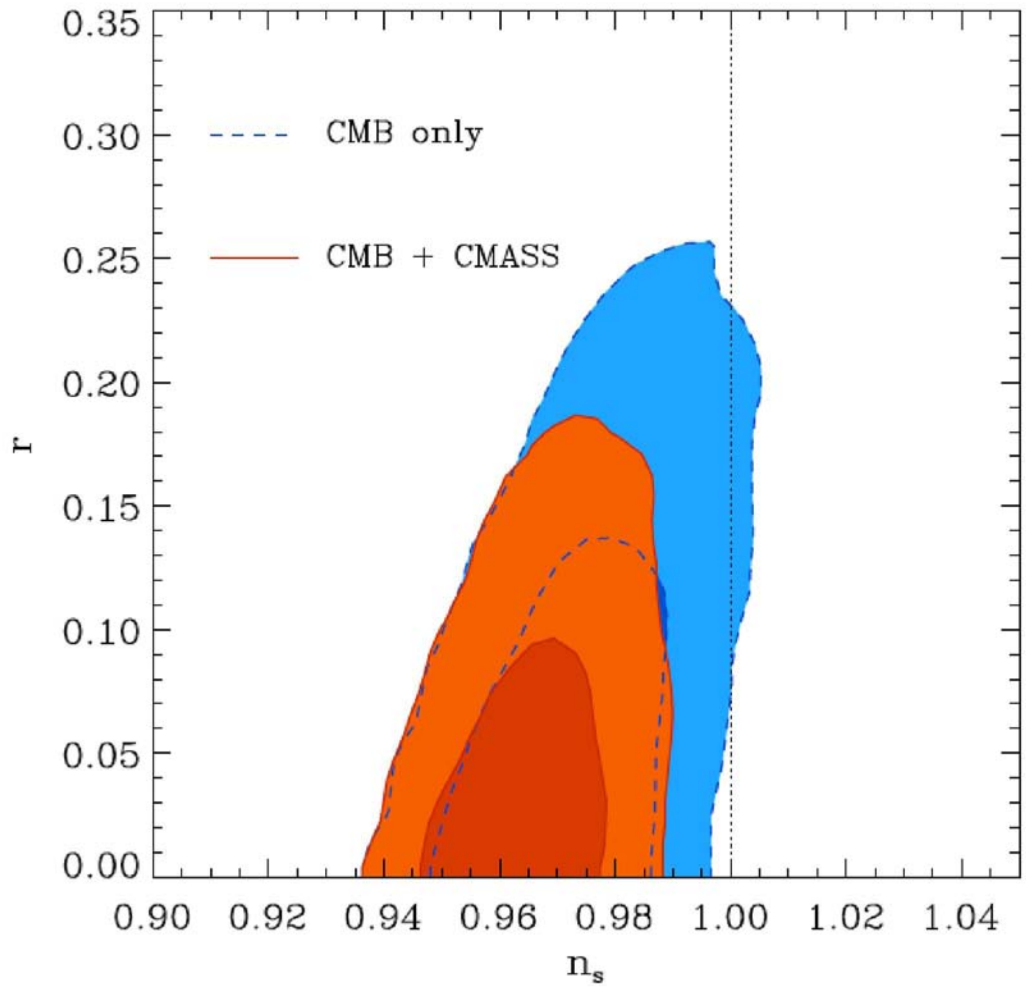
Curvature

GBZ with BOSS team
arXiv:1203.6616



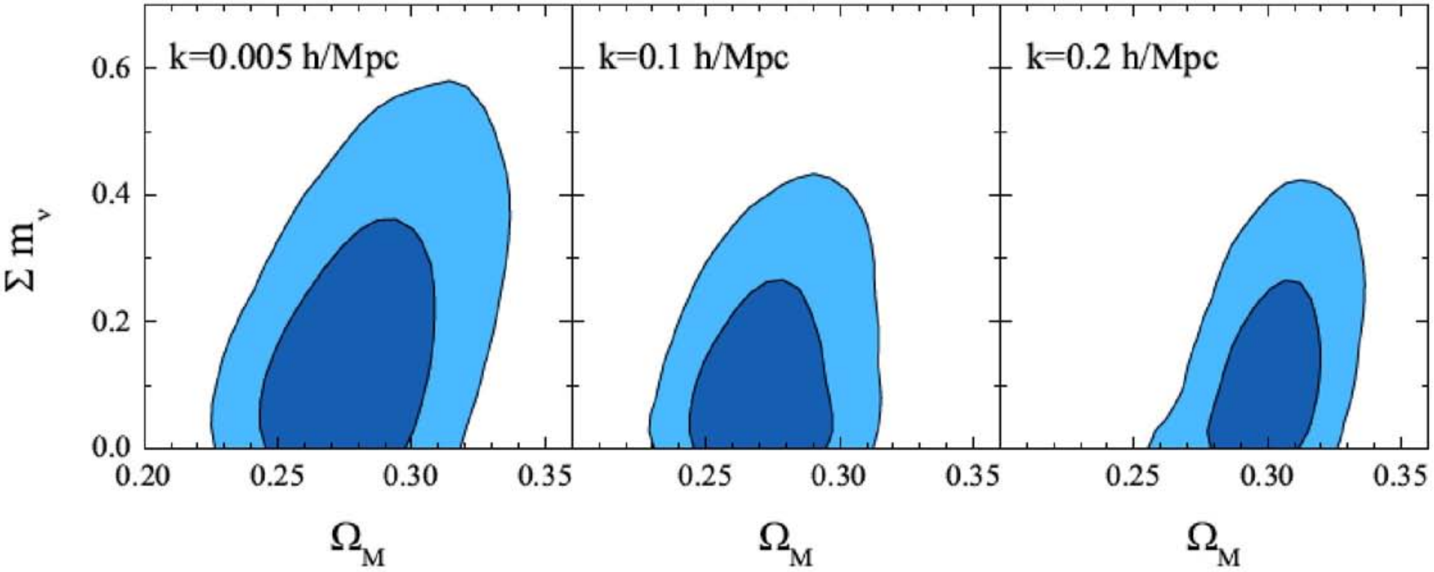
Inflationary models

GBZ with BOSS team
arXiv:1203.6616



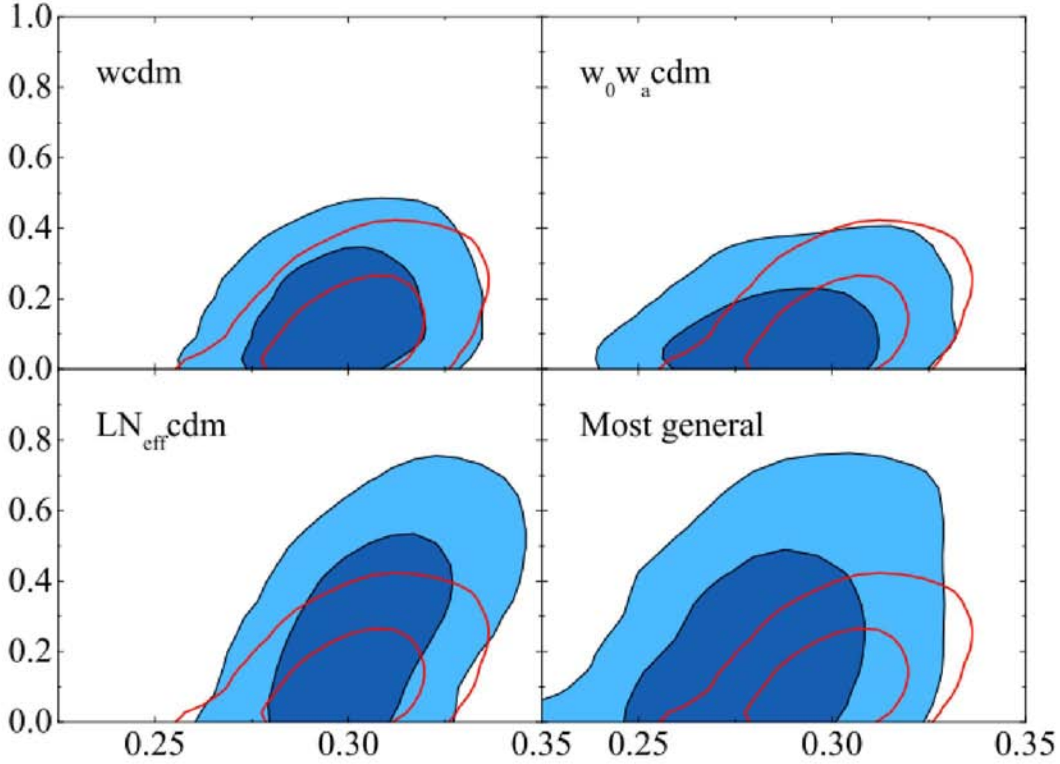
Neutrino mass

GBZ et al
In preparation



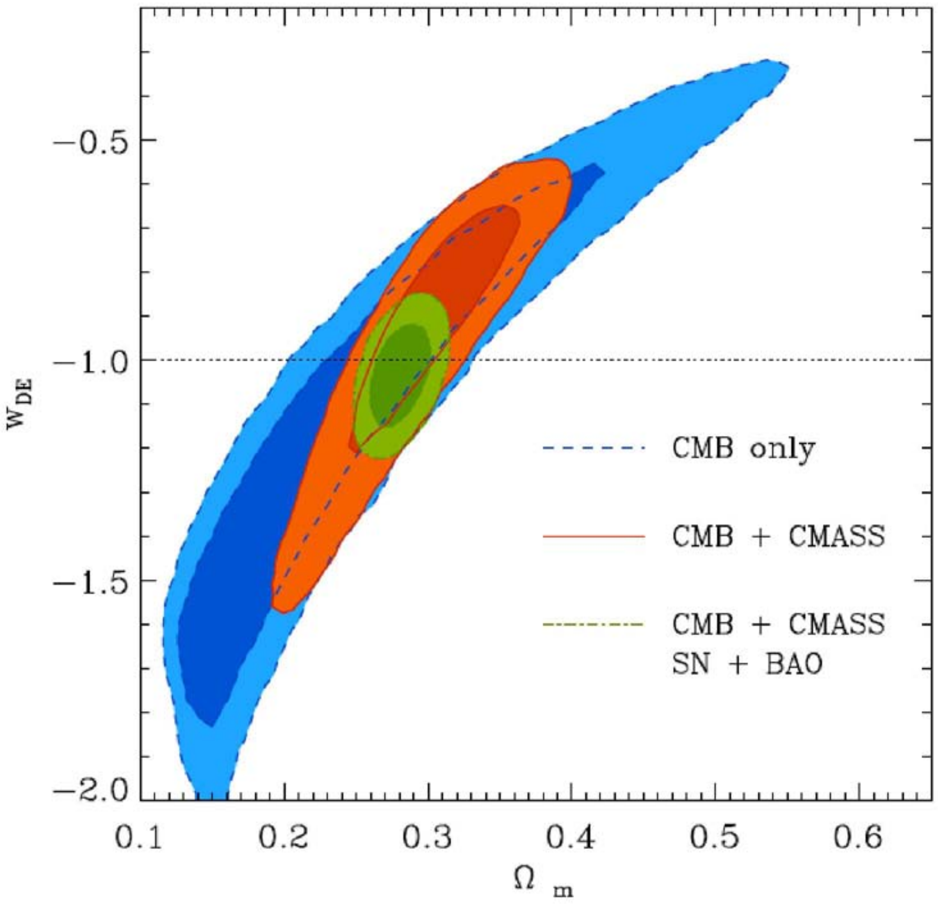
Neutrino mass

GBZ et al
In preparation



Dark Energy

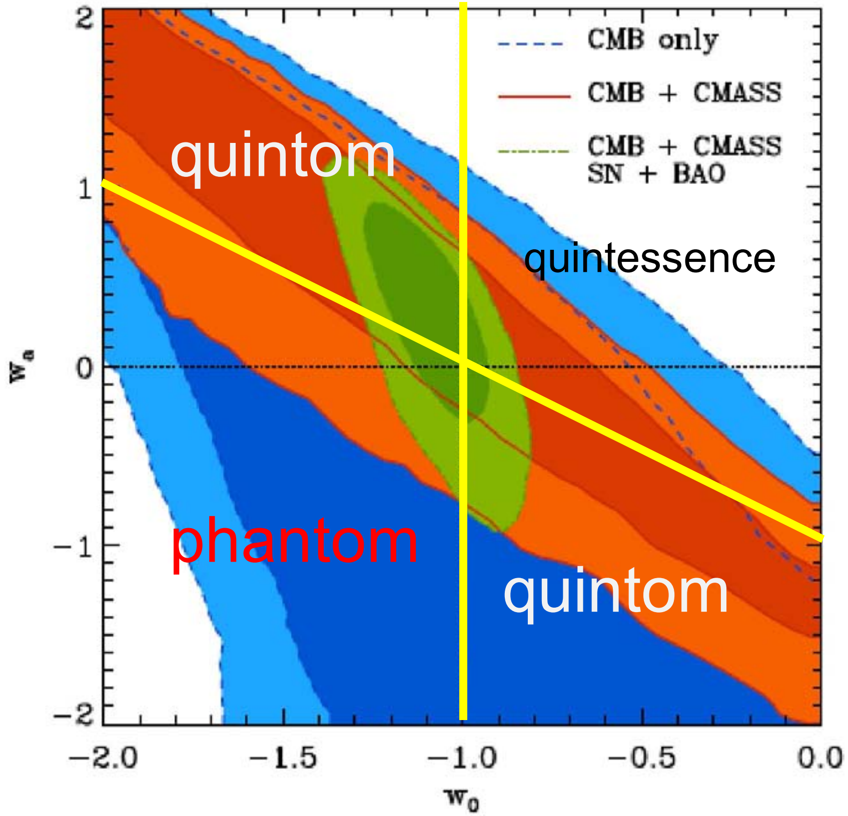
GBZ with BOSS team
arXiv:1203.6616



Dynamics of Dark Energy??

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

GBZ with BOSS team
arXiv:1203.6616



Dark energy perturbation fully included

Table A6. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model extended by allowing for variations on $w_{\rm DE}(a)$ (parametrized according to equation [12]), obtained using different combinations of the datasets described in Section [2.1] and [3].

	CMB	CMB + CMASS	CMB + CMASS +SN	CMB + CMASS +BAO	CMB + CMASS + BAO + SN
w_0	$-1.12^{+0.52}_{-0.51}$	$-1.12^{+0.61}_{-0.58}$	$-1.09^{+0.11}_{-0.11}$	$-0.95^{+0.27}_{-0.27}$	$-1.08^{+0.11}_{-0.11}$
w_a	$-0.3^{+1.2}_{-1.7}$	$0.32^{+0.98}_{-0.99}$	$0.12^{+0.48}_{-0.47}$	$0.05^{+0.62}_{-0.61}$	$0.23^{+0.42}_{-0.42}$
100Θ	$1.0409^{+0.0016}_{-0.0016}$	$1.0409^{+0.0016}_{-0.0016}$	$1.0408^{+0.0015}_{-0.0016}$	$1.0409^{+0.0016}_{-0.0016}$	$1.0408^{+0.0016}_{-0.0016}$
$100\omega_b$	$2.219^{+0.042}_{-0.042}$	$2.218^{+0.042}_{-0.041}$	$2.215^{+0.040}_{-0.040}$	$2.218^{+0.00042}_{-0.042}$	$0.0221^{+0.041}_{-0.041}$
$100\omega_{dm}$	$11.22^{+0.47}_{0.47}$	$11.31^{+0.46}_{-0.46}$	$11.40^{+0.45}_{-0.45}$	$11.28^{+0.48}_{-0.47}$	$11.38^{+0.47}_{-0.47}$
τ	$0.0852^{+0.0061}_{-0.0069}$	$0.0833^{+0.0062}_{0.0067}$	$0.0823^{+0.0058}_{-0.0067}$	$0.0833^{+0.0061}_{-0.0068}$	$0.0825^{+0.0060}_{-0.0068}$
n_s	$0.965^{+0.011}_{-0.011}$	$0.965^{+0.011}_{-0.011}$	$0.963^{+0.011}_{-0.011}$	$0.965^{+0.011}_{-0.012}$	$0.963^{+0.011}_{-0.011}$
$\ln(10^{10}A_s)$	$3.083^{+0.030}_{-0.029}$	$3.082^{+0.030}_{-0.030}$	$3.083^{+0.029}_{-0.029}$	$3.080^{+0.029}_{-0.029}$	$3.083^{+0.030}_{-0.029}$
$\Omega_{\rm DE}$	$0.760^{+0.081}_{-0.087}$	$0.722^{+0.081}_{-0.091}$	$0.730^{+0.016}_{-0.016}$	$0.706^{+0.032}_{-0.032}$	$0.724^{+0.014}_{-0.014}$
$\Omega_{\rm m}$	$0.239^{+0.087}_{-0.081}$	$0.278^{+0.091}_{-0.081}$	$0.269^{+0.016}_{-0.016}$	$0.294^{+0.032}_{-0.032}$	$0.276^{+0.014}_{-0.014}$
σ_8	$0.87^{+0.12}_{-0.12}$	$0.82^{+0.11}_{-0.11}$	$0.832^{+0.049}_{-0.049}$	$0.792^{+0.057}_{-0.057}$	$0.821^{+0.048}_{-0.048}$
$t_0/$Gyr	$13.64^{+0.22}_{-0.22}$	$13.79^{+0.16}_{-0.16}$	$13.763^{+0.089}_{-0.091}$	$13.827^{+0.085}_{-0.086}$	$13.80^{+0.083}_{-0.083}$
$z_{\rm re}$	$10.4^{+1.2}_{-1.2}$	$10.3^{+1.2}_{-1.2}$	$10.2^{+1.2}_{-1.2}$	$10.3^{+1.2}_{-1.2}$	$10.3^{+1.2}_{-1.2}$
h	$0.78^{+0.14}_{-0.14}$	$0.72^{+0.11}_{-0.11}$	$0.712^{+0.020}_{-0.020}$	$0.680^{+0.038}_{-0.038}$	$0.070^{+0.016}_{-0.016}$
$D_{\rm V}(z_m)/$Mpc	1974^{+86}_{-83}	2040^{+47}_{-45}	2027^{+25}_{-25}	2046^{+20}_{-20}	2038^{+19}_{-19}
$f(z_{\rm m})$	$0.733^{+0.077}_{-0.078}$	$0.770^{+0.084}_{-0.089}$	$0.766^{+0.022}_{-0.022}$	$0.753^{+0.040}_{-0.040}$	$0.771^{+0.019}_{-0.019}$

宇宙学标准理论： **Einstein** 引力 **+** 宇宙学原理
线性扰动理论
巨大成功 《**====== CMB (WMAP …**）
WMAP得不了诺奖，宇宙学理论应该得诺奖！

但是： Difficulty with dark energy perturbation
when w crosses -1 --→发散问题

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

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

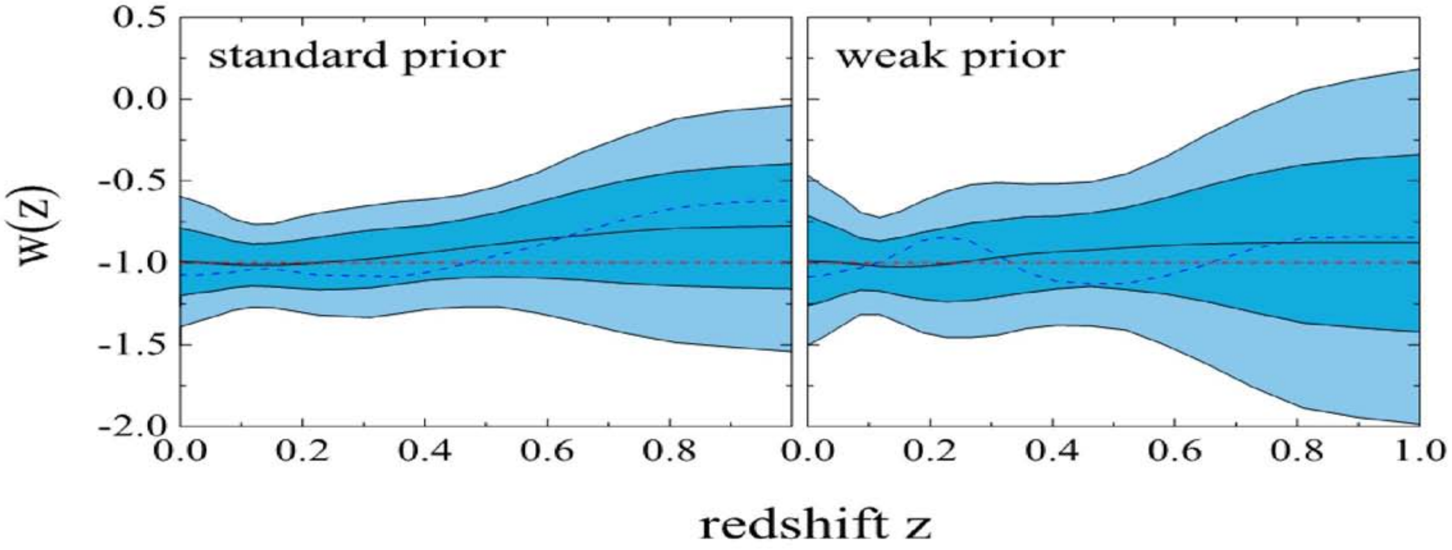
$$\boxed{1+w \to 0, \dot{w} \neq 0 \;\Rightarrow\; \dot{\delta}, \dot{\theta}, \delta, \theta \to \infty}$$

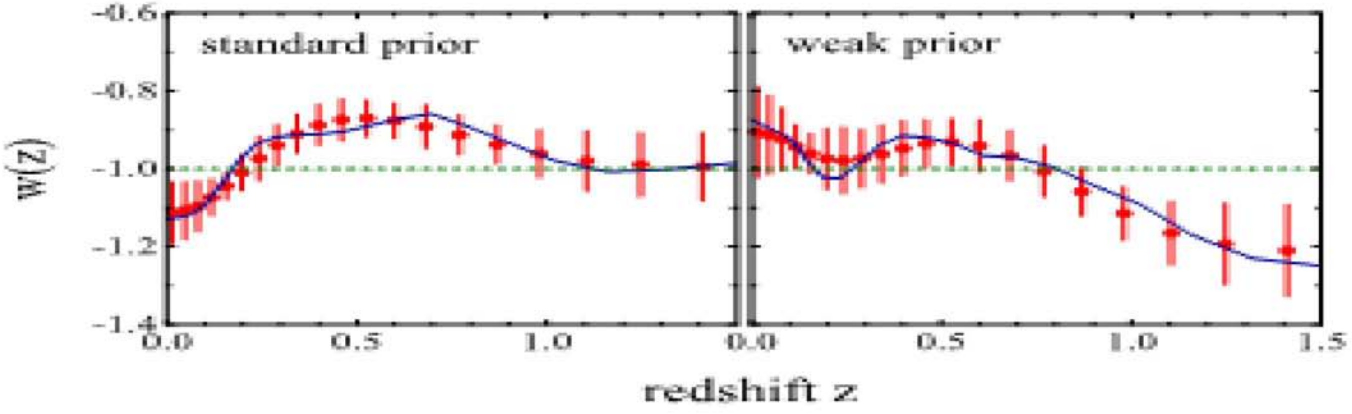
Similar to the non-renormalization without Higgs in the electroweak theory
Here, also need extra degree of freedom --------Quintom field

5.5 The dark energy equation of state

Until now we have assumed that the dark energy component corresponds to a cosmological constant, with a fixed equation of state specified by $w_{\rm DE} = -1$. In this Section, we allow for more general dark energy models. In Section 5.5.1 we explore the constraints on the value of $w_{\rm DE}$ (assumed redshift-independent). In Section 5.5.2 we obtain constraints on the time evolution of this parameter, parametrized according to equation (12). Section 5.5.3 deals with the effect of the assumption of a flat universe on the constraints on $w_{\rm DE}$.

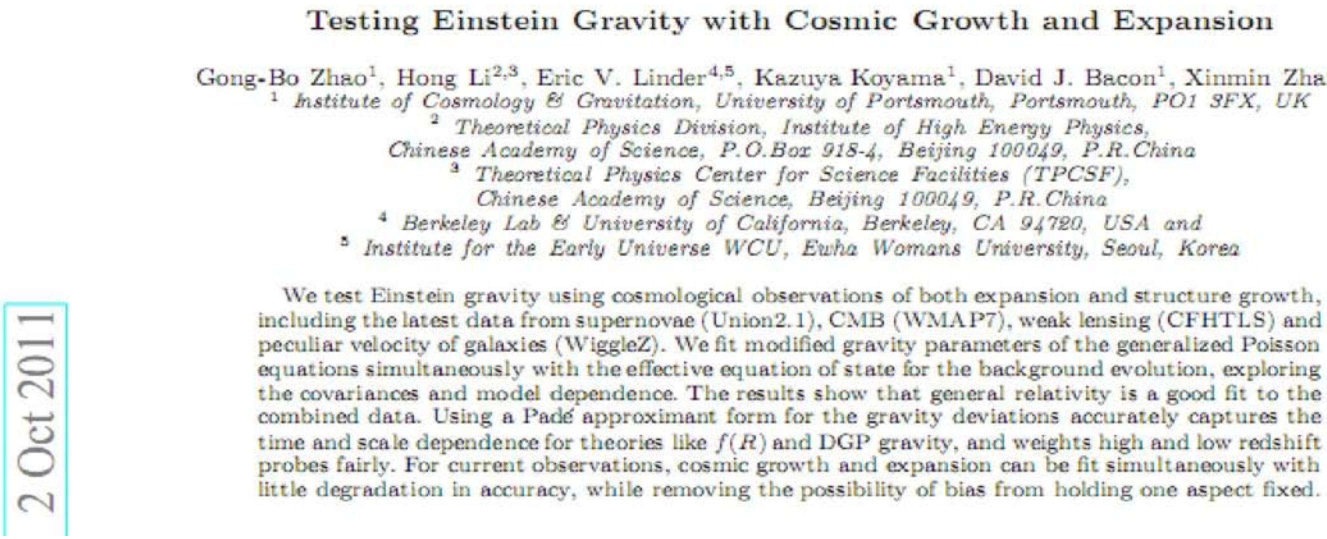
In these tests we consider models with $w_{\rm DE} < -1$, corresponding to phantom energy (see Copeland et al. 2006, and references therein). When exploring constraints on dynamical dark energy models, these are allowed to cross the so-called phantom divide, $w_{\rm DE} = -1$. In the framework of general relativity, a single fluid, or a single scalar field without higher derivatives, cannot cross this threshold since it would become gravitationally unstable (Feng et al. 2005; Vikman 2005; Hu 2005; Xia et al. 2008), requiring at least one extra degree of freedom. However, models with more degrees of freedom are difficult to implement in general dark energy studies. Here we follow the parametrized post-Friedmann (PPF) approach of Fang et al. (2008), as implemented in CAMB, which provides a simple solution to these problems for models in which the dark energy component is smooth compared to the dark matter. Alternatively, as proposed by Zhao et al. (2005), it is possible to consider the dark energy perturbations using a two-field model, with one of the fields being quintessence-like and the other one phantom-like (e.g. the quintom model proposed in Feng et al. 2005) without introducing new internal degrees of freedom. Both approaches give consistent results.





Fitting w1--w20 with WMAP7 + H(z),+Union2.1 + BAO (SDSS DR7)

Gongbo Zhao et al (in preparation)



2 Oct 2011

Testing Einstein Gravity with Cosmic Growth and Expansion

Gong-Bo Zhao[1], Hong Li[2,3], Eric V. Linder[4,5], Kazuya Koyama[1], David J. Bacon[1], Xinmin Zhang[2,3]
[1] *Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK*
[2] *Theoretical Physics Division, Institute of High Energy Physics,*
Chinese Academy of Science, P.O.Box 918-4, Beijing 100049, P.R.China
[3] *Theoretical Physics Center for Science Facilities (TPCSF),*
Chinese Academy of Science, Beijing 100049, P.R.China
[4] *Berkeley Lab & University of California, Berkeley, CA 94720, USA and*
[5] *Institute for the Early Universe WCU, Ewha Womans University, Seoul, Korea*

We test Einstein gravity using cosmological observations of both expansion and structure growth, including the latest data from supernovae (Union2.1), CMB (WMAP7), weak lensing (CFHTLS) and peculiar velocity of galaxies (WiggleZ). We fit modified gravity parameters of the generalized Poisson equations simultaneously with the effective equation of state for the background evolution, exploring the covariances and model dependence. The results show that general relativity is a good fit to the combined data. Using a Padé approximant form for the gravity deviations accurately captures the time and scale dependence for theories like $f(R)$ and DGP gravity, and weights high and low redshift probes fairly. For current observations, cosmic growth and expansion can be fit simultaneously with little degradation in accuracy, while removing the possibility of bias from holding one aspect fixed.

on modified gravity
- a) GR works well;
- b) Background evolution:

----〉Quintom behaviour

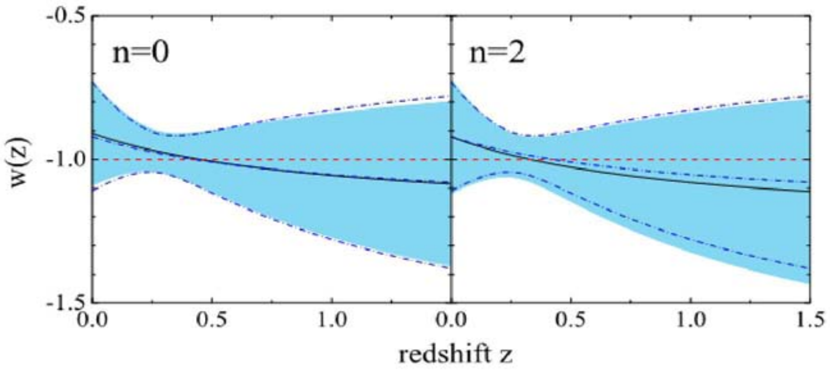


FIG. 4: The reconstructed $w(z)$ with 68% CL error are shown allowing for modified gravity (marginalized over c, s) in the scale independent (left panel) and scale-dependent k^2 (right panel) cases by the filled bands. The reconstruction for true dark energy, with gravity fixed to GR, is shown by the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

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Quintom cosmology: Theoretical implications and observations

Yi-Fu Cai [a], Emmanuel N. Saridakis [b,*], Mohammad R. Setare [c,d], Jun-Qing Xia [e]

[a] Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918-4, Beijing 100049, PR China
[b] Department of Physics, University of Athens, GR-15771 Athens, Greece
[c] Department of Science, Payame Noor University, Bijar, Iran
[d] Research Institute for Astronomy and Astrophysics of Maragha, P. O. Box 55134-441, Maragha, Iran
[e] Scuola Internazionale Superiore di Studi Avanzati, Via Bonomea 265, 34136 Trieste, Italy

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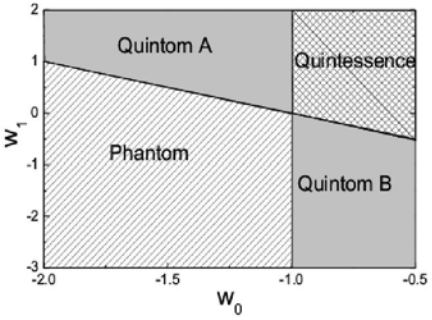
- **自2004年，w 越过 -1 研究形成热潮 ！？**

（**Quintom，Phantom divide, Crossing w=-1 ….**）

i）理论上的兴趣

（**no-go** 定理）

ii）拟合采用的参数化 **----------------**〉



(解决发散难题， 使得能够计算！

WMAP, BOSS ……）

iii) 拟合结果：

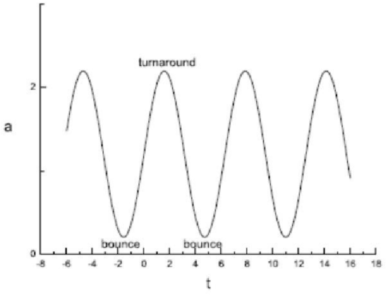
W 或 **MG** 中有效 **W ====➔ best fit:** 越过**-1**

iv）*宇宙演化作为整体考虑：*

现在的大爆炸宇宙模型---》奇点

Quintom bounce➔ nonsingular cosmology

-------〉循环宇宙



NO-GO Theorem

- For theory of dark energy in the 4D Friedmann-Roberston-Walker universe described by a single perfect fluid(1) or a single scalar field with a lagrangian $\mathcal{L} = \mathcal{L}(\phi, \partial_\mu \phi \partial^\mu \phi)$ (2), which minimally (3) couples to Einstein Gravity (4), its equation of state cannot cross over the cosmological constant boundary.

Feng, Wang & Zhang, Phys. Lett. B 607:35, 2005, **astro-ph/0404224** ; (引用607次）
Vikman, Phys. Rev. D 71:023515, 2005, **astro-ph/0407107** ; (引用305次）
Waye Hu， Phys. Rev. D 71:047301, 2005; (引用168次）
Caldwell & Doran, Phys. Rev. D 72:043527, 2005;
Zhao, Xia, Li, Feng & Zhang, Phys. Rev. D 72:123515, 2005;
Kunz & Sapone, Phys. Rev. D 74:123503, 2006;

……

Xia, Cai, Qiu, Zhao, & Zhang, Int.J.Mod.Phys.D17:1229,2008

To realize Quintom, one of the conditions should be violated

Galileon Theories

Galileon Models: Lagrangian with higher derivative operator, but the equation of motion remains second order, so the model can have w cross -1 without ghost mode.

Basically 5 kinds of Galileon model:

C. Deffayet et al., Phys.Rev.D79:084003,2009.
A. Nicolis et al., Phys.Rev.D79:064036,2009;

$$\mathcal{L}_1 = \Pi \,, \quad \mathcal{L}_2 = \nabla_\mu \Pi \nabla^\mu \Pi \,, \quad \mathcal{L}_3 = \Box \Pi \nabla_\mu \Pi \nabla^\mu \Pi \,,$$

$$\mathcal{L}_4 = \nabla_\lambda \Pi \nabla^\lambda \Pi [2(\Box \Pi)^2 - 2(\nabla_\mu \nabla_\nu \Pi)(\nabla^\mu \nabla^\nu \Pi) - \frac{1}{2} R \nabla_\mu \Pi \nabla^\mu \Pi] \,,$$

$$\mathcal{L}_5 = \frac{5}{2} \nabla_\lambda \Pi \nabla^\lambda \Pi [(\Box \Pi)^3 - 3(\Box \Pi)(\nabla_\mu \nabla_\nu \Pi)(\nabla^\mu \nabla^\nu \Pi) + 2(\nabla_\mu \nabla^\nu \Pi)(\nabla_\nu \nabla^\rho \Pi)(\nabla_\rho \nabla^\mu \Pi) - 6 G_{\nu\rho} \nabla_\mu \Pi \nabla^\rho \Pi (\nabla^\mu \nabla^\nu \Pi)] \,.$$

But can be generalized

C. Deffayet et al., arXiv:1103.3260 [hep-th]

$$\mathcal{L}_1 = P(X, \Pi) \,, \quad \mathcal{L}_2 = G_1(X, \Pi) \Box \Pi \,, \quad \mathcal{L}_3 = G_{2,X}(X, \Pi)[2(\Box \Pi)^2 - 2(\nabla_\mu \nabla_\nu \Pi)(\nabla^\mu \nabla^\nu \Pi)] + R G_2(X, \Pi) \,,$$

$$\mathcal{L}_5 = G_{3,X}(X, \Pi)[(\Box \Pi)^3 - 3(\Box \Pi)(\nabla_\mu \nabla_\nu \Pi)(\nabla^\mu \nabla^\nu \Pi) + 2(\nabla_\mu \nabla^\nu \Pi)(\nabla_\nu \nabla^\rho \Pi)(\nabla_\rho \nabla^\mu \Pi)] - 6 G_{\mu\nu} (\nabla^\mu \nabla^\nu \Pi) G_3(X, \Pi) \,.$$

An example of Galileon Theory

The action:

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + F^2 e^{2\Pi}(\partial\Pi)^2 + \frac{F^3}{M^3}(\partial\Pi)^2\Box\Pi + \frac{F^3}{2M^3}(\partial\Pi)^4\right]$$

which was also used in arXiv: 1007.0027 for "Galileon Genesis".

Stress energy tensor:

$$\begin{aligned} T_{\mu\nu} &= -F^2 e^{2\Pi}[2\partial_\mu\Pi\partial_\nu\Pi - g_{\mu\nu}(\partial\Pi)^2] - \frac{F^3}{2M^3}(\partial\Pi)^2[4\partial_\mu\Pi\partial_\nu\Pi - g_{\mu\nu}(\partial\Pi)^2] \\ &\quad -\frac{F^3}{M^3}[2\partial_\mu\Pi\partial_\nu\Pi\Box\Pi - \partial_\mu\Pi\partial_\nu(\partial\Pi)^2 - \partial_\nu\Pi\partial_\mu(\partial\Pi)^2 + g_{\mu\nu}\partial_\sigma\Pi\partial^\sigma(\partial\Pi)^2]\,. \end{aligned}$$

From which we get energy density and pressure:

$$\begin{aligned} \rho &= F^2[-e^{2\Pi}\dot{\Pi}^2 + \frac{1}{\bar{H}^2}(\dot{\Pi}^4 + 4H\dot{\Pi}^3)] \\ P &= F^2[-e^{2\Pi}\dot{\Pi}^2 + \frac{1}{3\bar{H}^2}(\dot{\Pi}^4 - 4\dot{\Pi}^2\ddot{\Pi})] \end{aligned}$$

where $\bar{H} \equiv \sqrt{\frac{2M^3}{3F}}$

The Paths of Gravity in Galileon Cosmology

Stephen Appleby[1] and Eric V. Linder[1,2]
[1] *Institute for the Early Universe WCU, Ewha Womans University, Seoul, Korea and*
[2] *Berkeley Lab & University of California, Berkeley, CA 94720, USA*
(Dated: December 12, 2011)

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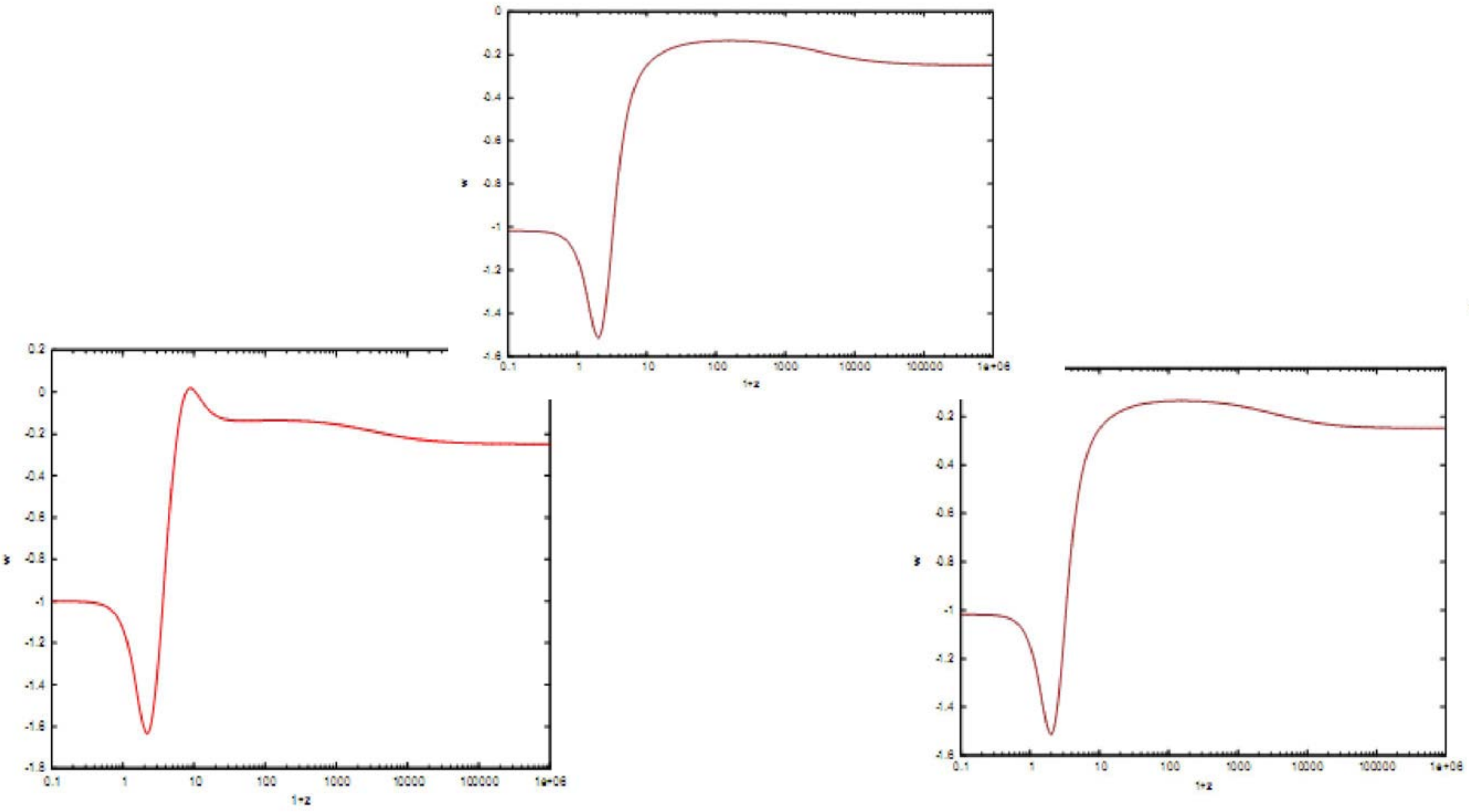


Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Bouncing Galileon cosmologies

Taotao Qiu,[a] Jarah Evslin,[b] Yi-Fu Cai,[b,c] Mingzhe Li[d]
and Xinmin Zhang[b]

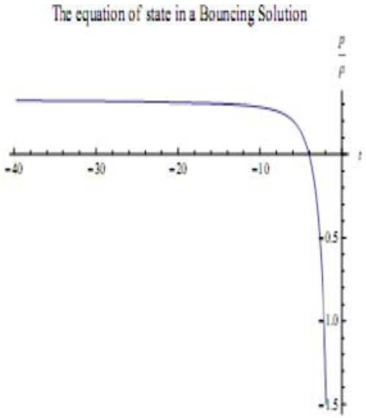


Figure 4. The ratio of the pressure to the density of the Galileon field begins at 1/3, which is the same as that of normal radiation. It steadily decreases and crosses $w = -1$ just before the bounce. In the numerical calculation, the values of parameters are listed in (3.18).

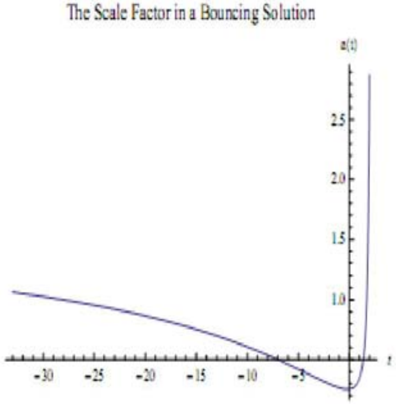
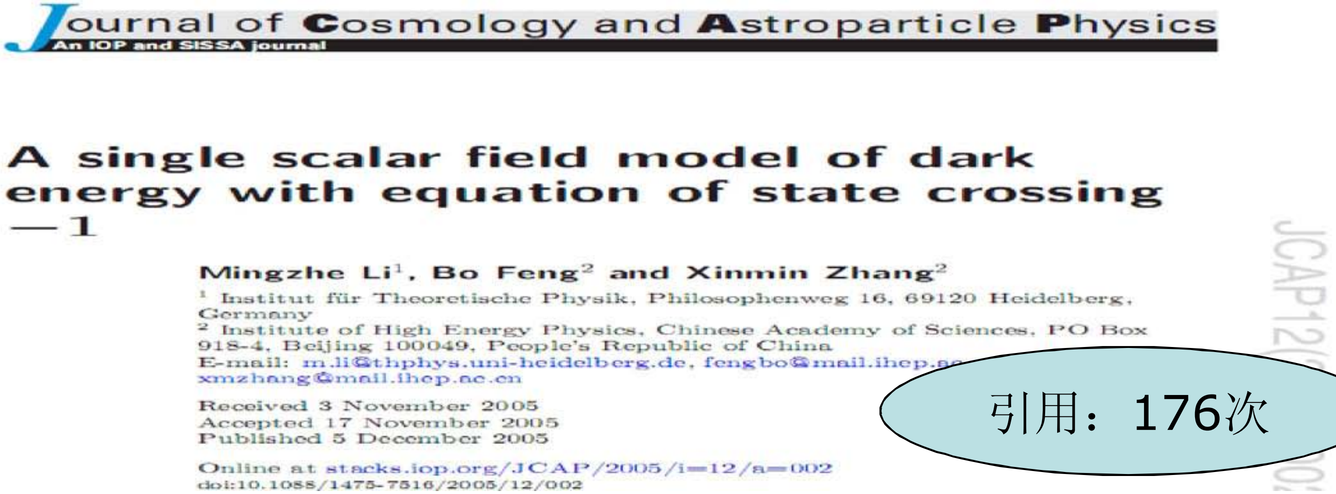


Figure 2. The scale factor $a(t)$ in a bouncing solution first shrinks as in a radiation dominated phase, then arrives at a nonzero minimal value at the bouncing point and after that enters an expanding phase. In the numerical calculation, the values of parameters are listed in (3.18).



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A single scalar field model of dark energy with equation of state crossing −1

Mingzhe Li[1], **Bo Feng**[2] **and Xinmin Zhang**[2]
[1] Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany
[2] Institute of High Energy Physics, Chinese Academy of Sciences, PO Box 918-4, Beijing 100049, People's Republic of China
E-mail: m.li@thphys.uni-heidelberg.de, fengbo@mail.ihep.a
xmzhang@mail.ihep.ac.cn

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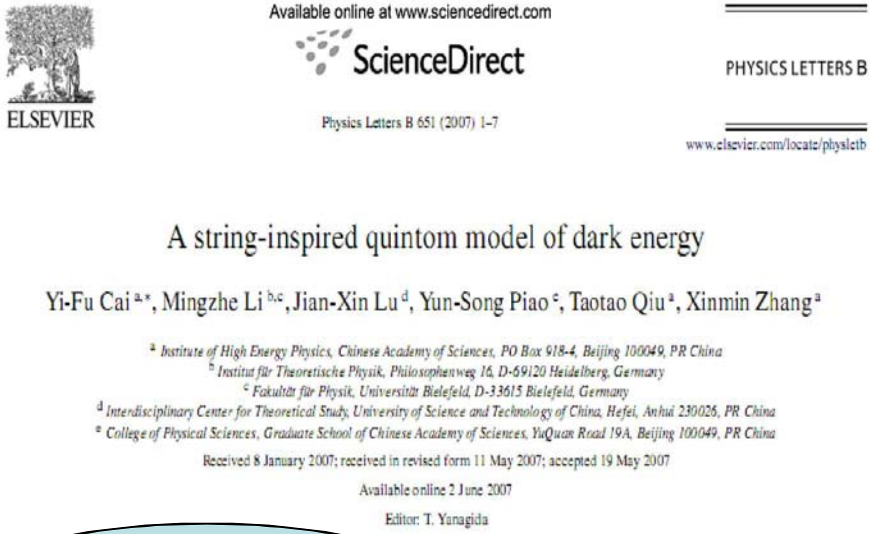

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A string-inspired quintom model of dark energy

Yi-Fu Cai[a,*], Mingzhe Li[b,c], Jian-Xin Lu[d], Yun-Song Piao[e], Taotao Qiu[a], Xinmin Zhang[a]

[a] *Institute of High Energy Physics, Chinese Academy of Sciences, PO Box 918-4, Beijing 100049, PR China*
[b] *Institut für Theoretische Physik, Philosophenweg 16, D-69120 Heidelberg, Germany*
[c] *Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*
[d] *Interdisciplinary Center for Theoretical Study, University of Science and Technology of China, Hefei, Anhui 230026, PR China*
[e] *College of Physical Sciences, Graduate School of Chinese Academy of Sciences, YuQuan Road 19A, Beijing 100049, PR China*

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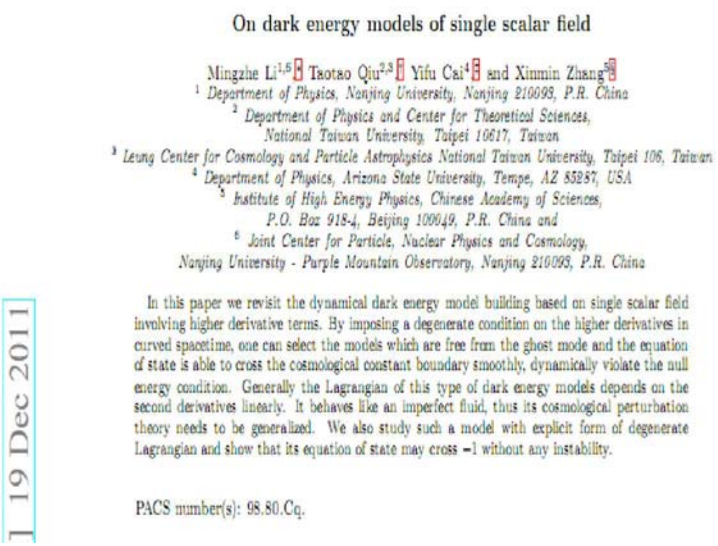


1 19 Dec 2011

On dark energy models of single scalar field

Mingzhe Li[1,5] Taotao Qiu[2,3] Yifu Cai[4] and Xinmin Zhang[5]
[1] *Department of Physics, Nanjing University, Nanjing 210093, P.R. China*
[2] *Department of Physics and Center for Theoretical Sciences, National Taiwan University, Taipei 10617, Taiwan*
[3] *Leung Center for Cosmology and Particle Astrophysics National Taiwan University, Taipei 106, Taiwan*
[4] *Department of Physics, Arizona State University, Tempe, AZ 85287, USA*
[5] *Institute of High Energy Physics, Chinese Academy of Sciences, P.O. Box 918-4, Beijing 100049, P.R. China and*
[6] *Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing University - Purple Mountain Observatory, Nanjing 210093, P.R. China*

In this paper we revisit the dynamical dark energy model building based on single scalar field involving higher derivative terms. By imposing a degenerate condition on the higher derivatives in curved spacetime, one can select the models which are free from the ghost mode and the equation of state is able to cross the cosmological constant boundary smoothly, dynamically violate the null energy condition. Generally the Lagrangian of this type of dark energy models depends on the second derivatives linearly. It behaves like an imperfect fluid, thus its cosmological perturbation theory needs to be generalized. We also study such a model with explicit form of degenerate Lagrangian and show that its equation of state may cross −1 without any instability.

PACS number(s): 98.80.Cq.

On dark energy models of single scalar field

Mingzhe Li[1,6],[*] Taotao Qiu[2,3],[†] Yifu Cai[4],[‡] and Xinmin Zhang[5][§]
[1] *Department of Physics, Nanjing University, Nanjing 210093, P.R. China*
[2] *Department of Physics and Center for Theoretical Sciences,*
National Taiwan University, Taipei 10617, Taiwan
[3] *Leung Center for Cosmology and Particle Astrophysics National Taiwan University, Taipei 106, Taiwan*
[4] *Department of Physics, Arizona State University, Tempe, AZ 85287, USA*
[5] *Institute of High Energy Physics, Chinese Academy of Sciences,*
P.O. Box 918-4, Beijing 100049, P.R. China and
[6] *Joint Center for Particle, Nuclear Physics and Cosmology,*
Nanjing University - Purple Mountain Observatory, Nanjing 210093, P.R. China

In this paper we revisit the dynamical dark energy model building based on single scalar field involving higher derivative terms. By imposing a degenerate condition on the higher derivatives in curved spacetime, one can select the models which are free from the ghost mode and the equation of state is able to cross the cosmological constant boundary smoothly, dynamically violate the null energy condition. Generally the Lagrangian of this type of dark energy models depends on the second derivatives linearly. It behaves like an imperfect fluid, thus its cosmological perturbation theory needs to be generalized. We also study such a model with explicit form of degenerate Lagrangian and show that its equation of state may cross -1 without any instability.

PACS number(s): 98.80.Cq.

For a scalar field with higher (but finite) derivatives, its Lagrangian generally has the form,

$$\mathcal{L} = \mathcal{L}(\phi, \phi_{\mu_1}, \phi_{\mu_1\mu_2}, ..., \phi_{\mu_1...\mu_N}) \ , \tag{6}$$

where $\phi_{\mu_1} \equiv \nabla_{\mu_1}\phi$, $\phi_{\mu_1\mu_2} \equiv \nabla_{\mu_2}\nabla_{\mu_1}\phi$ and so on are the covariant derivatives of ϕ and $N \geq 2$. The equation of motion from this Lagrangian is

$$\frac{\partial\mathcal{L}}{\partial\phi} + \sum_{n=1}^{N}(-1)^n\nabla_{\mu_1}...\nabla_{\mu_n}(\frac{\partial\mathcal{L}}{\partial\phi_{\mu_1...\mu_n}}) = 0 \ . \tag{7}$$

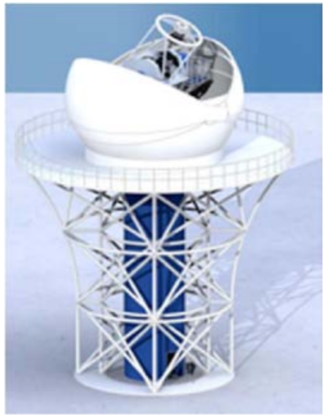
Generally this is a $2N$th order derivative equation, the whole system contains N degrees of freedom and some of them are ghosts. In order to keep the discussions simple and without loss of general properties of higher derivative field theories, we only consider the case $N = 2$ in curved spacetime, the Lagrangian is a scalar function of ϕ, ϕ_μ and $\phi_{\mu\nu}$. The equation of motion is

$$\frac{\partial\mathcal{L}}{\partial\phi} - \nabla_\mu(\frac{\partial\mathcal{L}}{\partial\phi_\mu}) + \nabla_\mu\nabla_\nu(\frac{\partial\mathcal{L}}{\partial\phi_{\mu\nu}}) = 0 \ . \tag{8}$$

Expanding this equation and consider the symmetry $\phi_{\mu\nu} = \phi_{\nu\mu}$, we have the following equation,

$$\begin{aligned}
&\frac{\partial\mathcal{L}}{\partial\phi} - \frac{\partial^2\mathcal{L}}{\partial\phi\partial\phi_\mu}\phi_\mu + (\frac{\partial^2\mathcal{L}}{\partial\phi\partial\phi_{\mu\nu}} - \frac{\partial^2\mathcal{L}}{\partial\phi_\nu\partial\phi_\mu})\phi_{\nu\mu} + \frac{\partial^3\mathcal{L}}{\partial\phi\partial\phi\partial\phi_{\mu\nu}}\phi_\mu\phi_\nu + 2\frac{\partial^3\mathcal{L}}{\partial\phi\partial\phi_\rho\partial\phi_{\mu\nu}}\phi_{\rho\mu}\phi_\nu + \frac{\partial^3\mathcal{L}}{\partial\phi_\rho\partial\phi_\sigma\partial\phi_{\mu\nu}}\phi_{\sigma\mu}\phi_{\rho\nu} + \\
&\frac{\partial^2\mathcal{L}}{\partial\phi_\rho\partial\phi_{\mu\nu}}(\phi_{\nu\rho\mu} - \phi_{\nu\mu\rho}) + 2\frac{\partial^3\mathcal{L}}{\partial\phi\partial\phi_{\rho\sigma}\partial\phi_{\mu\nu}}\phi_{\rho\sigma\mu}\phi_\nu + 2\frac{\partial^3\mathcal{L}}{\partial\phi_\alpha\partial\phi_{\rho\sigma}\partial\phi_{\mu\nu}}\phi_{\rho\sigma\mu}\phi_{\alpha\nu} + \frac{\partial^3\mathcal{L}}{\partial\phi_{\alpha\beta}\partial\phi_{\rho\sigma}\partial\phi_{\mu\nu}}\phi_{\alpha\beta\mu}\phi_{\rho\sigma\nu} + \\
&\frac{\partial^2\mathcal{L}}{\partial\phi_{\rho\sigma}\partial\phi_{\mu\nu}}\phi_{\rho\sigma\nu\mu} = 0 \ .
\end{aligned} \tag{9}$$

暗能量探测计划



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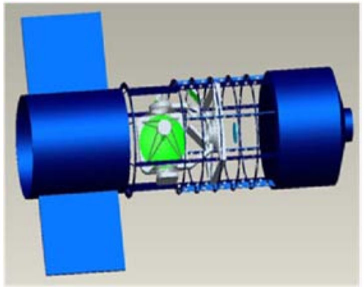

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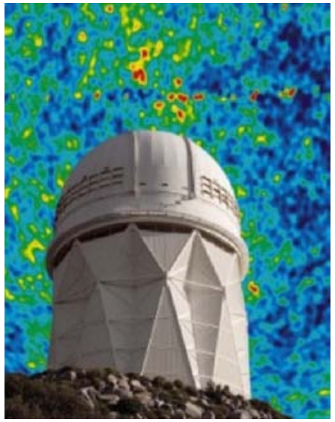
平台

**Large Synoptic Survey
Telescope**



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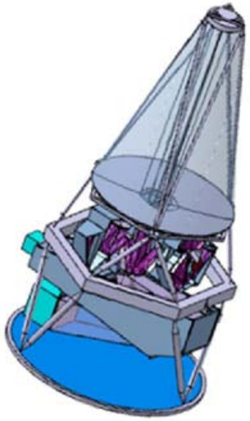
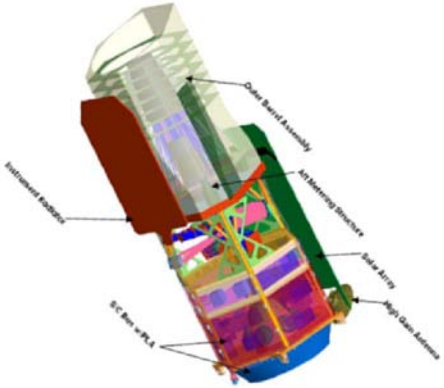


Euclid

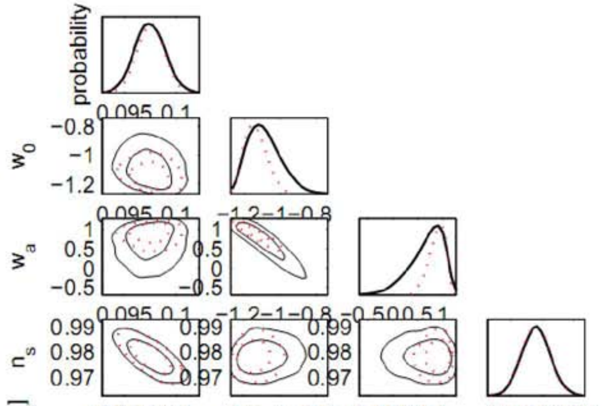
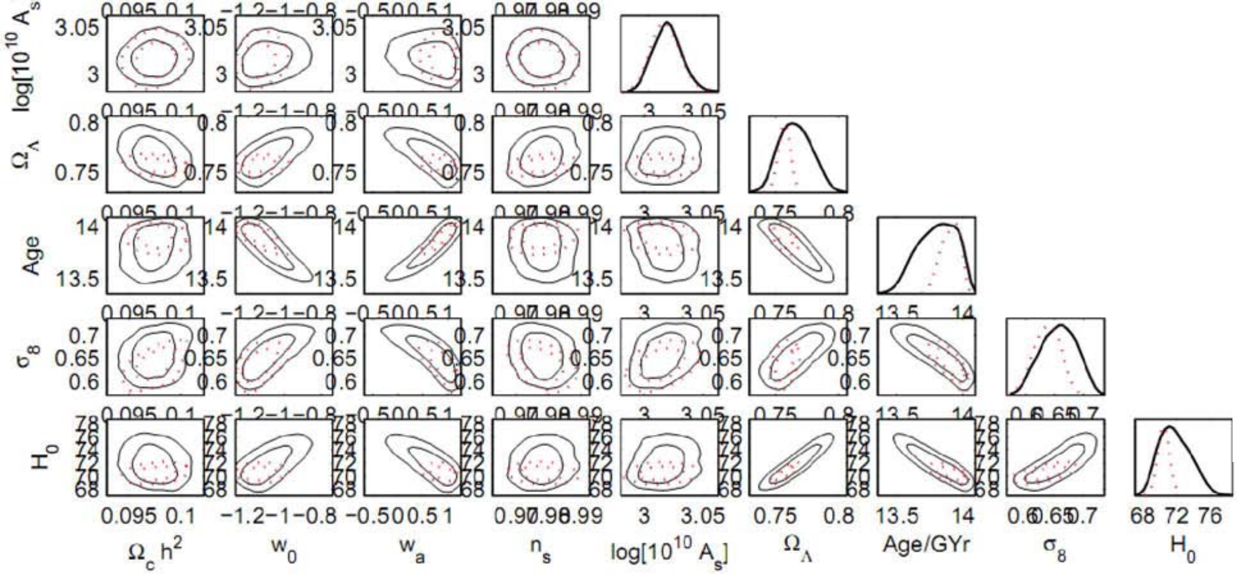


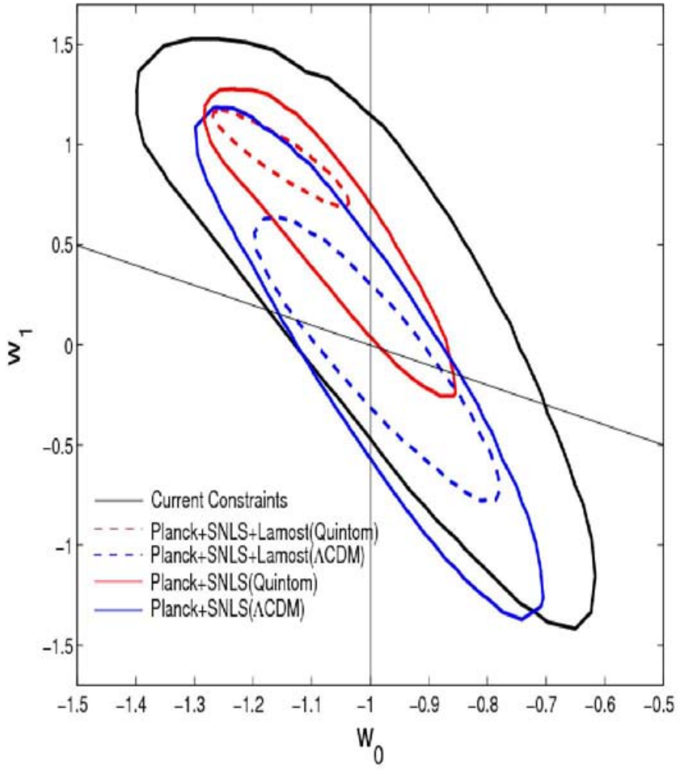
**Wide Field Infrared
Survey Telescope**

~2020

我国暗能量探测
可行性研究—LAMOST

李虹等



$$w(z) = w_0 + w_a z/(1+z)$$

PROBING DARK ENERGY WITH THE KUNLUN DARK UNIVERSE SURVEY TELESCOPE

GONG-BO ZHAO[1,2], HU ZHAN[3], LIFAN WANG[4], ZUHUI FAN[5], AND XINMIN ZHANG[1,6]

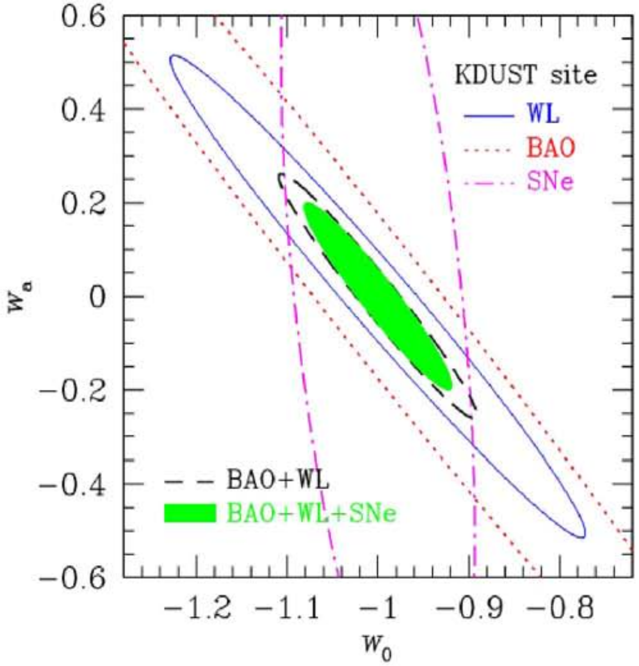


FIG. 3.— Forecasts of 1σ errors on the dark energy EOS parameters w_0 and w_a for KDUST WL (solid line), BAOs (dotted line), SNe (dashed line), and the three combined (shaded area). We have included *Planck* priors in all the results. Although the CMB priors have a significant impact on the SN results and to a lesser degree on WL and BAO results, they have much smaller effect on the WL+BAO+SN joint constraints.

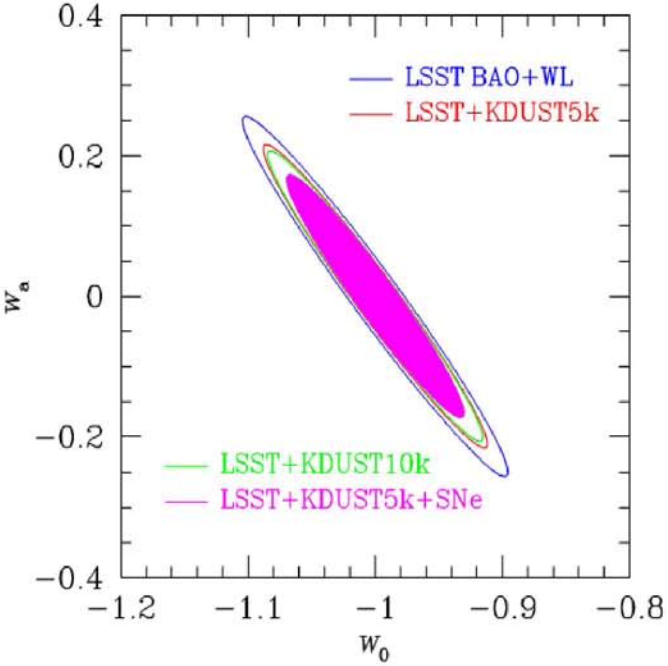
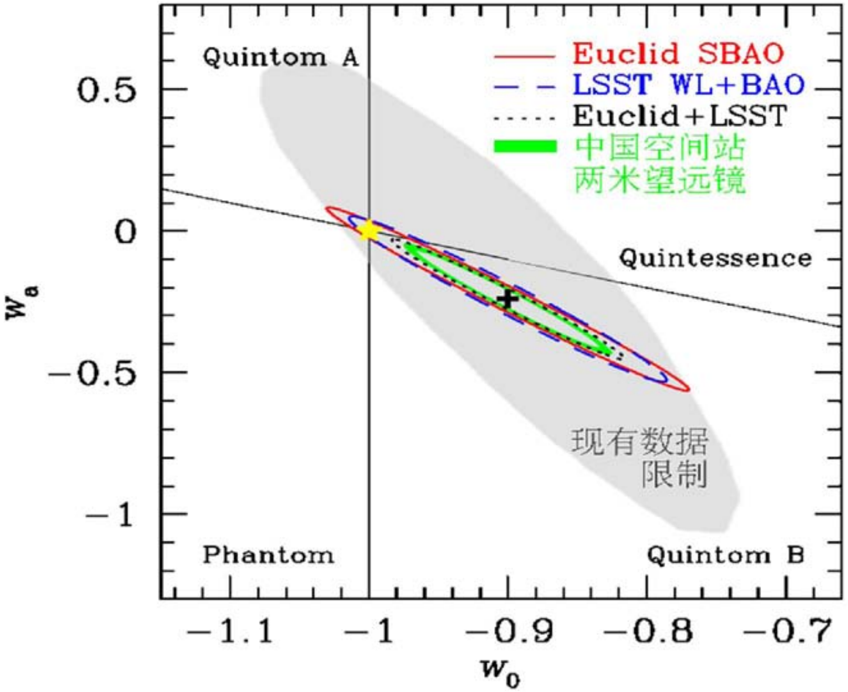


FIG. 4.— Forecasts of 1σ errors on the dark energy EOS parameters w_0 and w_a for LSST BAO+WL (blue contour), a combination of LSST and KDUST 10,000 deg^2 *JH* survey (labeled as KDUST10k) as listed in Table 1 using BAO+WL (green contour), a combination of LSST and half of KDUST10k (labeled as KDUST5k) using BAO+WL (red contour), and a combination of LSST and KDUST5k using BAO+WL+SNe (magenta area).

中国空间站暗能量研究预期



对暗能量状态方程参数w_0与w_a的限制

加强国际合作

1）BOSS, DES (赵公博。。。）
2）Planck （夏俊卿。。。）
3）BigBoss （上海台，科大。。。）
4）LSST (詹虎。。。）
5）Euclid (赵公博，夏俊卿，Charling Tao….)
6）TMT

……

暗能量研究时间表？？

- **LSST……能解决暗能量问题吗？**

什么算解决了？

* 整个问题解决需要很长时间，但阶段性成果也很重要

（注意：**1998**年前，宇宙学常数问题已多年）

类似：旧量子论---〉量子力学----〉量子场论 ----〉

漫长但每一步都很重要，可能突破！！！

要充分肯定！

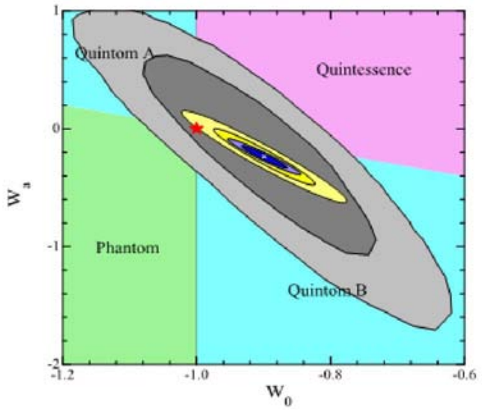
近十年目标：发现动力学或确定宇宙学常数==〉

即**Einstein** 还是 非**Einstein ?!**

（当然确定哪一个动力学模型需更长时间）

目前：**(w_0, w_a) O(10%) ===〉**重要成果

不久将来： **at level of O(1%)===〉**重大成果



减小误差：系统误差; 统计误差

计算方法带来的误差

参数间简并性：曲率，中微子质量，张标比，

暗能量扰动， W 参数化，

Shift parameter or full data ======〉MCMC global fit (计算量大）

Some Topics
on Neutrino Cosmology

简介中微子与暗物质，暗能量及
宇宙正反物质不对称产生机制的联系

中科院高能所 **张新民**

CCAST workshop on
“Neutrino Physics in the Daya Bay Era”
2010年**11**月**4-5**日

中微子与宇宙学

中微子在宇宙学中至关重要

I. 中微子与 正反物质不对称 （Leptogenesis）

II. 中微子和 暗能量 $\rho \sim (2*10^{-3} eV)^4$

III. 中微子和 暗物质

1）热暗物质 m_\nu < 0.51 eV （Li Hong et al)

2) ATIC and PAMELA Results on Cosmic e+- Excesses and Neutrino Masses

Bi, Gu, Li and Zhang

3) Steril neutrino as warm dark matter

4) Lepton asymmetry (Leptogenesis) and WIMP asymmetry

Andrei Sakharov （1967年） 三个条件:

i) B violation ←----GUT theory

ii) C and CP violation ←-----K, B system …

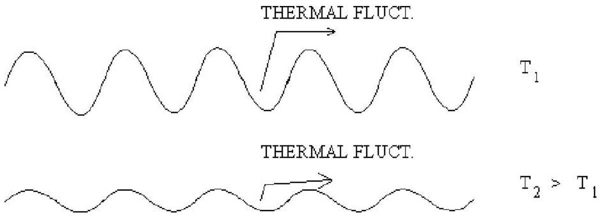
iii)Out of thermo-equilibrium (CPT conserved)

Freezing out of the heavy particles

$$\begin{aligned}\langle B\rangle &= \mathrm{Tr}(\rho B) = \mathrm{Tr}\left((CPT)(CPT)^{-1}\exp(-\beta H)B\right)\\ &= \mathrm{Tr}\left(\exp(-\beta H)(CPT)^{-1}B(CPT)\right) = -\mathrm{Tr}(\rho B) = 0\end{aligned}$$

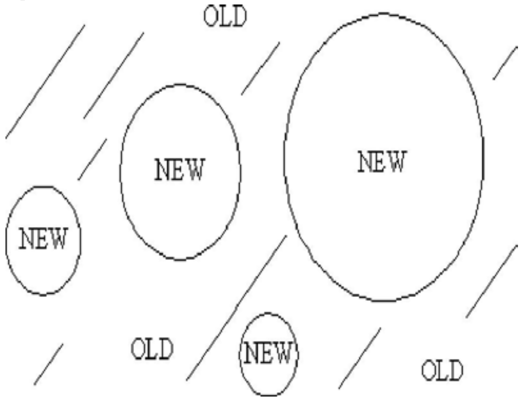
If CPT is broken, can be generated in thermo-equilibrium

i) B violation ←----anomaly, non-trivial vacuum, sphaleron



ii) C and CP violation ←-----CKM mechanism
(however, too small-→new physics)

iii) First order phase transition



Need Higgs mass
< 40 GeV!
→Need
New physics

Electroweak Baryogenesis
and New Physics

i) Need new physics

80年代末，2- Higgs，L-R symmetry, SUSY

ii) Effective lagrangian method ---→ anomalous couplings

$$\mathcal{L}^{\text{new}} = \sum_i \frac{c_i}{\Lambda^{d_i - 4}} O^i \ ,$$

Effective lagrangian approaches to EW baryogenesis

1) Higher dimensional operator relevant to Higgs mass limit

$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} ,$$

Effective potential:

$$V_T^{\text{eff}} = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \tfrac{1}{4}\lambda_T \phi^4 ,$$

vhere

$$D = \frac{1}{8v^2}(2M_W^2 + 2m_t^2 + M_Z^2) ,$$

$$T_0^2 = \frac{1}{D}\left[\frac{m_H^2}{4} - 2Bv^2\right] ,$$

$$B = \frac{3}{64\pi^2 v^4}(2M_W^4 + M_Z^4 - 4m_t^4) ,$$

$$E = \frac{1}{6\pi v^3}(2M_W^3 + M_Z^3) ,$$

$$\lambda_T = \lambda - \frac{3}{16\pi^2 v^4}\left[2M_W^4 \ln\frac{M_W^2}{\alpha_B T^2} + M_z^4 \ln\frac{M_Z^2}{\alpha_B T^2} - 4m_t^4 \ln\frac{m_t^2}{\alpha_F T^2}\right] ,$$

where $\ln\alpha_B = 2\ln 4\pi - 2\gamma \simeq 3.91$ and $\ln\alpha_F = 2\ln\pi - 2\gamma \simeq 1.14$.

$$V_3^{(r)} = \alpha \frac{v^2}{\Lambda^2}\phi^2\left[-\phi^2 + v^2 + \frac{1}{3}\frac{\phi^4}{v^2}\right] .$$

$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} \quad \Longrightarrow \quad m_H^2 < (35\ GeV)^2 + 8\alpha \frac{v^4}{\Lambda^2}$$

Xinmin Zhang PRD47, 3065 (1993)
Cedric Delaunay, Christophe Grojean,
James D. Wells
JHEP 0804:029,2008

Electroweak vacuum stability
A. Datta, B.-L. Young and X. Zhang
PLB385, 225 (1996)

Prediction for a light Higgs !

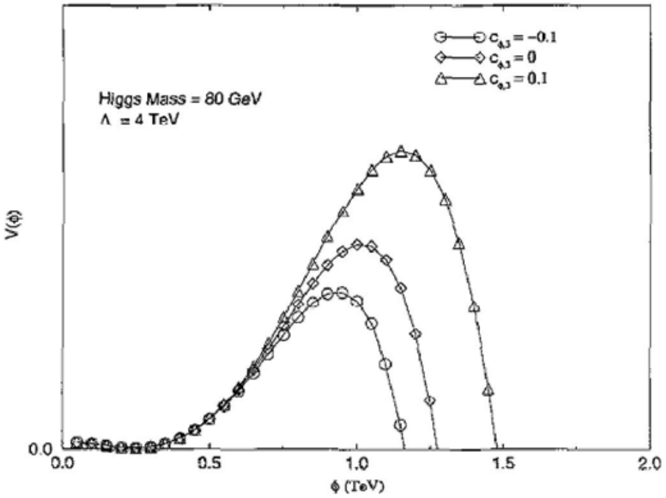


Fig. 1. The effective potential for various values of $c_{\phi,3}$. The Higgs mass is taken as 80 GeV and the scale of new physics $\Lambda = 4$ TeV. The curve with $c_{\phi,3} = 0$ corresponds to the standard model.

125 GeV Higgs and
its implication in cosmology

i)Within the SM, it is all consistent:
precision measurement;
Vacuum stability;

Ii)Interesting implications for SUSY

iii) Implications for cosmology:

a) Supporting for the idea of building dark energy models with fundamental scalar fields;

b)Electroweak baryogenesis =➔low cutoff

2) Operator relevant to baryon number generation

(Why top? Interacting strongly with the bubble wall)

$$\mathcal{O}^t = c_t e^{i\xi}\frac{\phi^2 - v^2/2}{\Lambda^2}\Gamma_t\bar{\Psi}_L\tilde{\Phi}t_R, \quad ===\rightarrow \quad \Gamma_t^{\rm eff} = \Gamma_t\left\{1 + c_t e^{i\xi}\frac{\phi^2 - v^2/2}{\Lambda^2}\right\}.$$

$$\frac{n_B}{s} \sim \kappa c_t \sin\xi \times 10^{-9}. \quad =====\rightarrow \quad \kappa c_t \sin\xi \geq 4.$$

Anomalous top-Higgs couplings:

$$\mathcal{L}^{\rm eff} \sim \frac{m_t}{t}\bar{t}\left\{\left[1 + \left(\frac{c_t}{16}\right)\cos\xi\right] + i\left(\frac{c_t}{16}\right)\sin\xi\gamma_5\right\}tH,$$

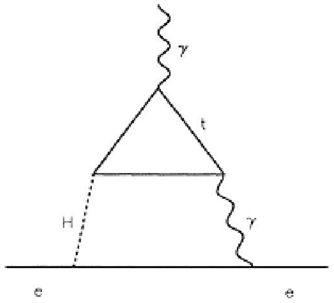
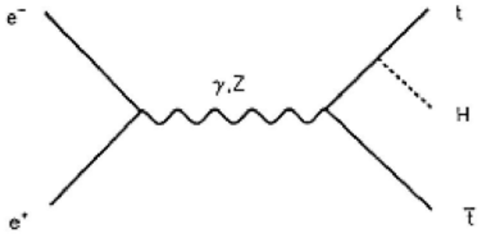


FIG. 1. Dominant contribution to d_e, the electric dipole moment of the electron.



X. Zhang et al,
PRD 50, 7042 (1994)
Lars Fromme,
Stephan J. Huber,
JHEP 0703:049,2007

Electroweak baryogenesis

and anomalous Top, Higgs coups

$$O_3 = \alpha \frac{\phi^6}{\Lambda^2} \quad \Longrightarrow \quad m_H^2 < (35\ GeV)^2 + 8\alpha \frac{v^4}{\Lambda^2}$$

$$\mathcal{O}^t = c_t\, e^{i\xi} \frac{(\phi^2 - \frac{v^2}{2})}{\Lambda^2} \Gamma_t\, \overline{\Psi_L} \tilde{\Phi} t_R \quad \Rightarrow \quad \frac{n_B}{s} \sim \kappa\, c_t \sin\xi\ 10^{-9}$$

Probing for anomalous Top, Higgs
couplings at Tevatron, LHC, ILC…

Leptogenesis and Neutrino

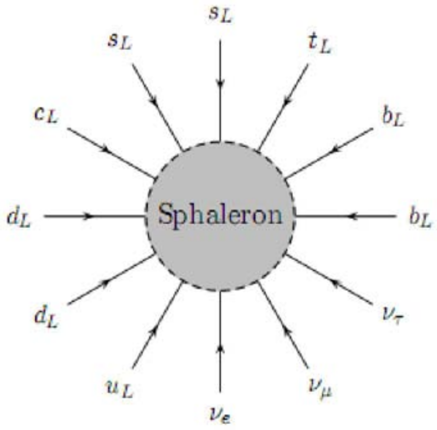
Leptogenesis 是指正反轻子不对称的产生机制

为什么轻子不对称与重子不对称有关?

Sphaleron 过程将部分轻子数转化为重子数

$$100\text{GeV} < T < 10^{12}\text{GeV}$$

$$B = \frac{28}{79}(B - L)$$



要考虑gauge interaction, Yukawa interaction and also QCD sphaleron

V.A. Kuzmin, V.A. Rubakov and

M.E. Shaposhnikov, Phys. Lett. B 155, 36 (1985);

R. Mohapatra and X. Zhang, Phys.Rev.D45,

2699- 2705, (1992)

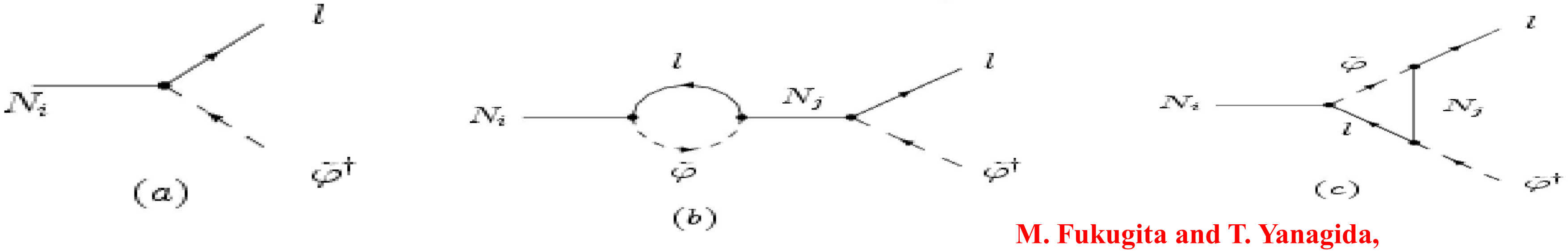
Type-I Seesaw 模型下的 Leptogenesis 机制

1. 右手中微子的 Majorana 质量项破坏轻子数
2. 右手中微子的 Yukawa 耦合项破坏 C 和 CP
3. 右手中微子脱离热平衡

$$\begin{aligned}\delta\mathcal{L} &= i\bar{\nu}_{Ri}\gamma^{\mu}\partial_{\mu}\nu_{Ri} - \frac{1}{2}M_{ij}\bar{\nu}^{C}_{Ri}\nu_{Rj} - y^{\nu}_{\alpha i}\bar{l}_{L\alpha}\tilde{\varphi}\nu_{Ri} + h.c.\\ &= \frac{i}{2}\bar{N}_{i}\gamma^{\mu}\partial_{\mu}N_{i} - \frac{1}{2}M_{i}\bar{N}_{i}N_{i} - y^{\nu}_{\alpha i}\bar{l}_{L\alpha}\tilde{\varphi}N_{i} + h.c.\end{aligned}$$

$$N_i = \nu_{Ri} + (\nu_{Ri})^C$$

$$m_\nu \simeq -(m_D)^* M^{-1} (m_D)^\dagger \qquad m_D = y^\nu v \qquad v \equiv \langle\tilde{\varphi}\rangle \simeq 174\text{GeV}$$



$$\varepsilon_i = \frac{\sum_\alpha \left[\Gamma\left(N_i \to l_\alpha + \tilde{\varphi}^\dagger\right) - \Gamma\left(N_i \to \bar{l}_\alpha + \tilde{\varphi}\right)\right]}{\sum_\alpha \left[\Gamma\left(N_i \to l_\alpha + \tilde{\varphi}^\dagger\right) + \Gamma\left(N_i \to \bar{l}_\alpha + \tilde{\varphi}\right)\right]}$$

M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986); P. Langacker, R.D. Peccei, and T. Yanagida, Mod. Phys. Lett. A 1, 541 (1986); M.A. Luty, Phys. Rev. D 45, 455 (1992); R.N. Mohapatra and X. Zhang, Phys. Rev. D 45, 2688 (1992).

90年代初，大家并不感兴趣！！？？

Motivation for long-baseline neutrino oscillation experiments

- Neutrino CP violation
- Actually not direct, still interesting?
- LBL neutrino oscillating experiment

  in China!

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

Cohen & Kaplan

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

$$= \frac{g_b T^3}{6}\left[\frac{\mu_b}{T} + O\left(\frac{\mu_b}{T}\right)^3\right] \approx c\frac{g_b \dot{Q} T^2}{6M} \qquad \eta = n_B/s \approx \frac{15c}{4\pi^2}\frac{g_b\dot{Q}}{g_* MT}$$

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

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

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)

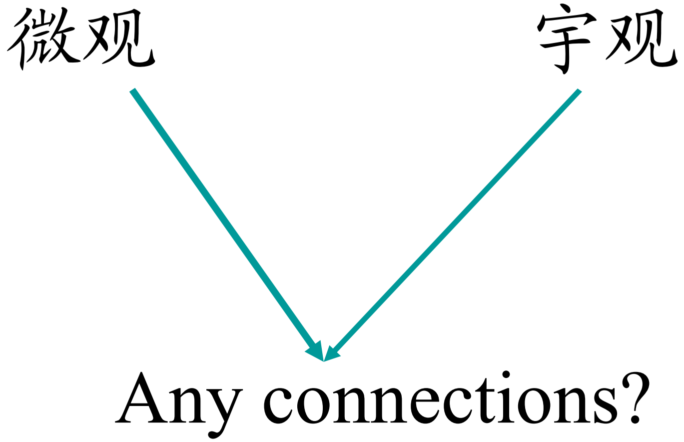
一个统一描述 Ω_{DE} 和 Ω_B 的模型

问题的提出：

Dirac 理论

反粒子 ←- - - - -→Baryogenesis

“真空不空” ←- - - - -→ Dark Energy



微观

宇观

Any connections?

Available online at www.sciencedirect.com

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PHYSICS LETTERS B

Physics Letters B 651 (2007) 357–362

www.elsevier.com/locate/physletb

Cosmological *CPT*-violation, baryo/leptogenesis and CMB polarization

Mingzhe Li[a], Jun-Qing Xia[b,*], Hong Li[c], Xinmin Zhang[b]

[a] *Institut für Theoretische Physik, Philosophenweg 16, 69120 Heidelberg, Germany*
[b] *Institute of High Energy Physics, Chinese Academy of Science, PO Box 918-4, Beijing 100049, PR China*
[c] *Department of Astronomy, School of Physics, Peking University, Beijing 100871, PR China*

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Editor: T. Yanagida

Abstract

In this Letter 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.

PACS: 98.80.Es; 98.80.Cq

CMB检验CPT对称性的基本思想

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

CPT破坏 $\longrightarrow$ **旋转角** $\Delta\alpha \neq 0$

$$\tan\alpha \equiv \frac{B_z}{B_y} = \tan\left(\frac{1}{2} C\phi + I\right) \quad \alpha = \frac{1}{2} C\phi + I \quad \Delta\alpha = \frac{1}{2} C \Delta\phi$$

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

$$C_l'^{TT} = C_l^{TT}$$

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

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

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

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

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

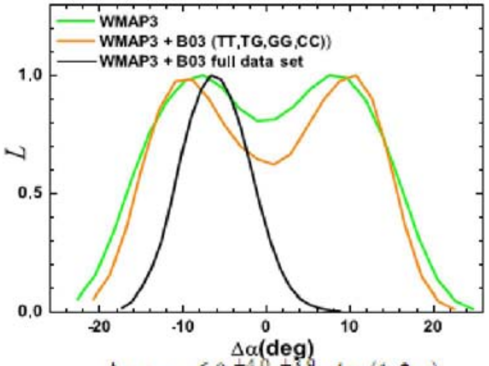
(Note here the notation: G ~ E, C~ B)

1）**Gravitational leptogenesis and its signatures in CMB.**
Bo Feng, Hong Li, Ming-zhe Li, Xin-min Zhang,
Phys.Lett.B620:27-32,2005.

当时没有数据，用模拟的数据做了研究

2）**Bo Feng, Mingzhe Li ,**
Jun-Qing Xia,
Xuelei Chen and Xinmin Zhang
Phys. Rev. Lett. 96,
221302 (2006)

使用的数据是**WMAP**和**BOOMERanG**的极化数据；
MCMC方法，修改的**CosmoMC**



$$\Delta\alpha = -6.0^{+4.0\ +3.9}_{-4.0\ -3.7}\ \mathrm{deg}(1, 2\sigma)$$

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).

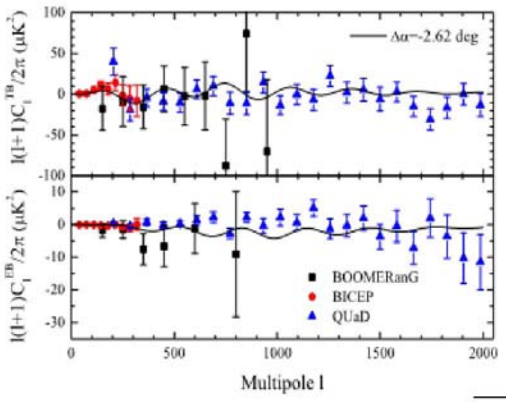
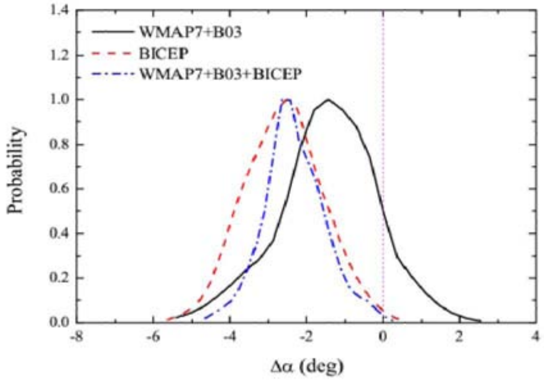


Fig. 1. The binned TB and EB spectra measured by the small-scale
of BOOMERanG (black squares), BICEP (red circles) and QUaD (b
black solid curves show the theoretical prediction of a model with
(For interpretation of colors in this figure, the reader is referred
of this Letter.)

Current status on the measurements of the rotation angle



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

3σ detection ===➔

$PLANCK:\ \sigma = 0.057$ deg （夏俊卿， Planck 组）

Test CPT with CMB

1) 特点：积累效应，最灵敏

2）现状：evidence, but rotation angle measured still consistent with zero

3) 方法 accepted （WMAP组。。。。）

成为CMB测量的一个例行工作:

i) B-mode: tensor perturbation r

rotation: E-→ B

ii)实验上校准，意义重大

不管Planck测出的Rotation Angle 是否是零，科学上都非常重要。

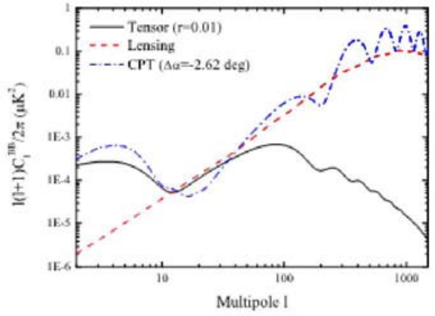
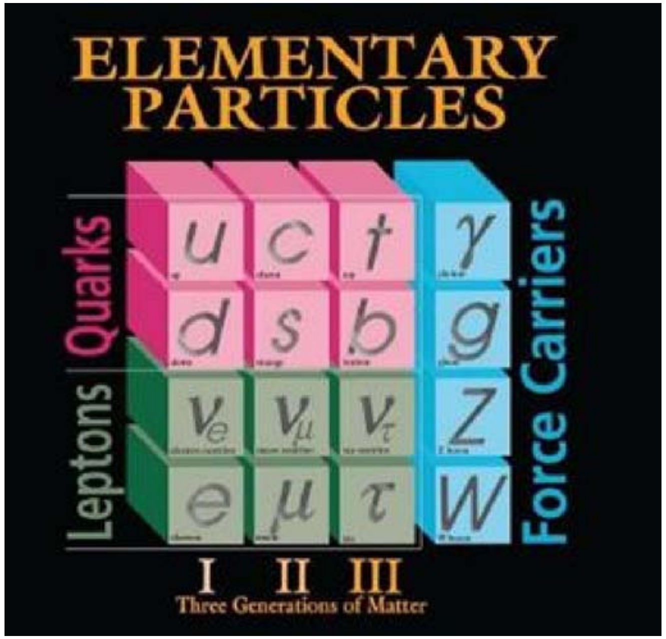


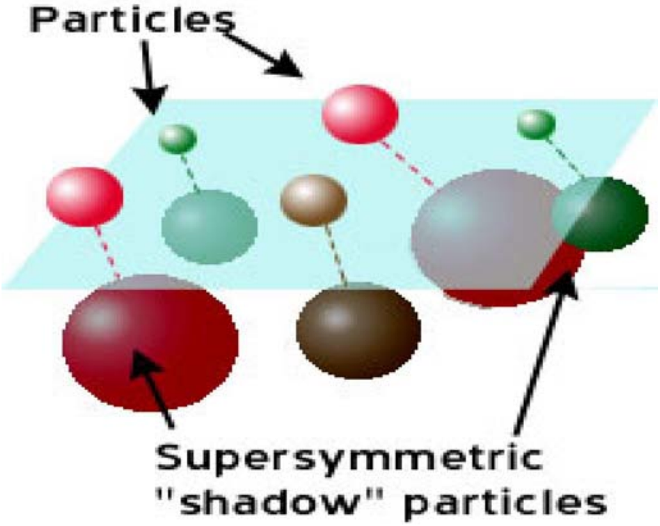
FIG. 4: The theoretical predictions of the BB power spectra from three different sources: primordial tensor B-mode with $r = 0.01$ (black solid line); lensing-induced (red dashed line) and rotation-induced (blue dash-dot line). The cosmological parameters used here are $\Omega_b h^2 = 0.022$, $\Omega_c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

暗物质：需要新物理



（有质量中微子：Hot DM）

候选者：



WIMP(弱作用重粒子)
代表一类模型

例如，超对称模型中的中性伴（neutralino）；
KK State in extra dimension theory

WIMPs 暗物质

李明哲　毕效军　张新民

摘要：

暗物质是21世纪宇宙学和粒子物理研究的热点问题。WIMPs是一种流行的暗物质粒子候选者，即weakly interacting massive particles的缩写，译为“弱作用重粒子”。目前我国计划中的暗物质粒子探测实验项目都是围绕着WIMPs暗物质开展的。本文将详细地阐述与WIMPs暗物质相关的基本问题，并力图澄清一些易于误解的概念。

《现代物理知识》2011年 第4期

介绍内容

- Cold WIMPs
- Warm WIMPs

  Boost factor?
- SuperWIMPs

  Quintessino; heavy charged massive particles
- Asymmetric WIMPs

  Connecting to Baryo/Leptogenesis

WIMP Miracle

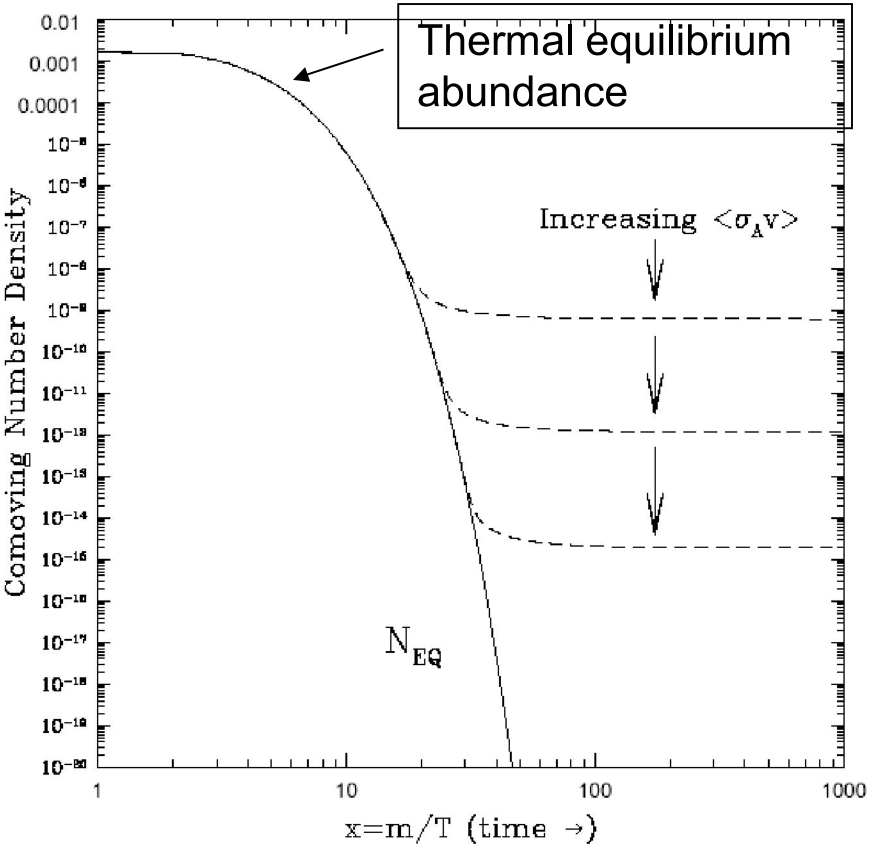
WIMP thermal production

At T >> m, $f+\bar{f} \leftrightarrow \chi+\chi$

At T < m, $\chi+\chi \rightarrow f+\bar{f}$

At T ~ m/22, $\Gamma = n\langle\sigma v\rangle \sim H$, decoupled, relic density is inversely proportional to the interaction strength $\Omega_\chi h^2 \approx \frac{3\cdot 10^{-27} cm^3 s^{-1}}{\langle\sigma v\rangle_{T_f}}$

For the weak scale interaction and mass scale (non-relativistic dark matter particles) $\langle\sigma v\rangle \sim 3\cdot 10^{-26} cm^3 s^{-1}$,
if $\alpha \sim 10^{-2}$ $M_{\text{weak}} \sim 100GeV$ and $v^2 \approx c^2/22$



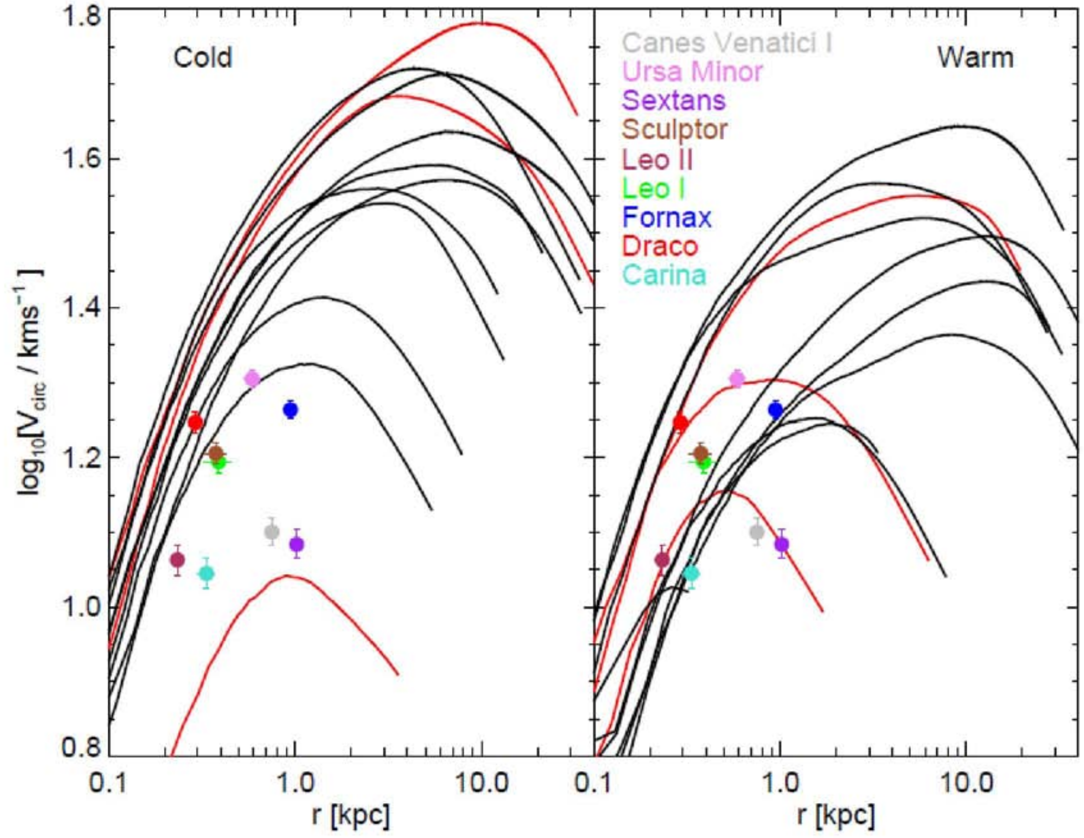
Thermal equilibrium abundance

WIMP is a natural dark matter candidate giving right relic density

简要评述(景益鹏报告）

- 冷暗物质的Concordance宇宙学模型：理论上由于大量数值模拟的工作对各种宇宙尺度的结构深刻的理解；在星系及更大的尺度上得到了大量观测数据的支持；
- 近期危机：在亚星系（sub－galactic）尺度上，温暗物质模型可能能够更好解释观测数据（在星系及更大的尺度上，与冷暗物质模型没有差异）
- 冷还是温：对粒子物理和暗物质探测具有重要的意义

Circular Velocity of MW satellites compared with CDM and WDM predictions



Lovell et al. 2012

How to define “cold”

- Definition of cold, warm or hot depends on the effect of their “free-stream” motion on the formation of objects
  - Hot dark matter (eV neutrinos) that washes out fluctuations on cluster scale (10 Mpc/h);
  - Warm dark matter (sterile neutrinos) that washes out fluctuations on galaxy scale (1 Mpc/h);
  - Cold dark matter that has effectively zero thermal velocity

两种产生机制:

1. 热产生机制（**Thermal**）

（像光子退耦一样）

=➔Cold WIMPs

2. 非热产生机制 **(Non-Thermal)**

(BBN 中自由中子**decay)**

==➔cold or warm WIMPs

张新民等

JHEP 9912:003,1999.

arXiv: hep-ph/9901357

Phys.Rev.Lett.86:954,2001.

arXiv: astro-ph/0009003

张新民大会报告：**Cosmo99;　SUSY04**

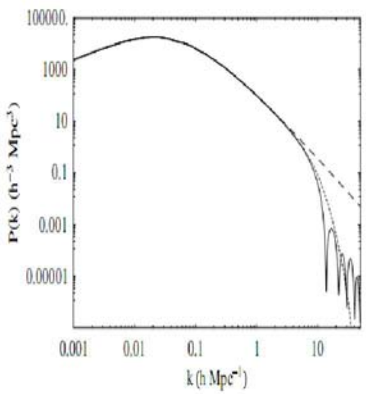


FIG. 1. Comparison of the power spectra of the CDM model (long-dashed curve), the WDM model with $m_W = 1$ keV (short-dashed curve), and the NTDM model with $r_c = 1.5 \times 10^{-7}$ (solid curve).

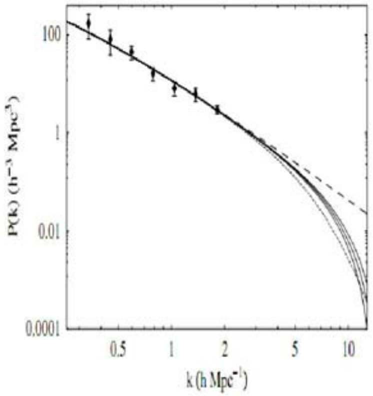


FIG. 2. The power spectra of the CDM model (long-dashed curve), the WDM model with $m_W = 750$ eV (short-dashed curve), and the NTDM models with $r_c = (1.3, 1.4, 1.5) \times 10^{-7}$ (solid curves, from top down), compared to the observed Lyman-α $P(k)$ at $z = 2.5$ (filled diamonds with error bars).

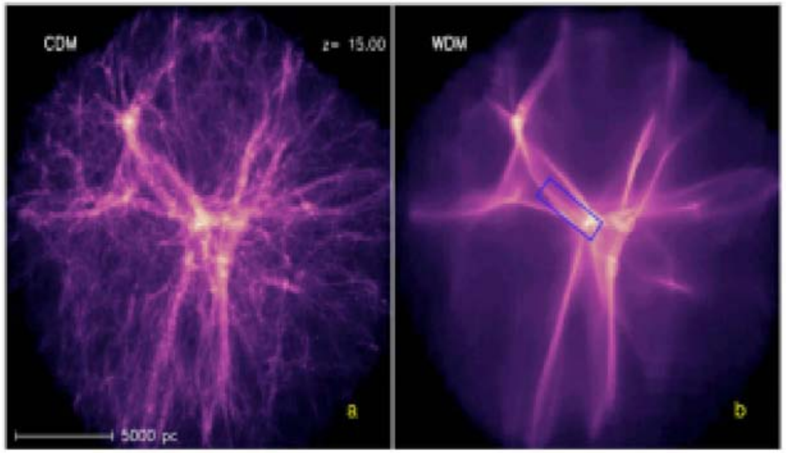


Figure 2. A comparison of small-scale structure from standard Cold Dark Matter (left) vs Warm Dark Matter with a 3 keV dark matter particle (Gao & Theuns 2007).

Comment on Thermal WIMPs Miracle and non-thermal WIMPs Miracle

i) Thermal WIMPs miracle:

Thermal production   CMB, Hot Big-Bang

ii) Non-thermal processes:

Free neutron decay in BBN
reheating processes
Cosmic string decay
-----→ non-thermal WIMPs Miracle?!

If DM is warm, impacts on the current experiments
especially in China are very important
==========→Non-thermal WIMPs

Gamma-rays From Warm WIMP Dark Matter Annihilation

Qiang Yuan[1], Yixian Cao[2], Jie Liu[3], Peng-Fei Yin[1], Liang Gao[2], Xiao-Jun Bi[1] and Xinmin Zhang[3]
[1] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics,*
Chinese Academy of Sciences, Beijing 100049, P.R.China
[2] *Partner Group of the Max Planck Institute for Astrophysics,*
National Astronomical Observatories, Chinese Academy of Sciences, Beijing, 100012, P.R. China
[3] *Division of Theoretical Physics, Institute of High Energy Physics,*
Chinese Academy of Science, Beijing 100049, P.R.China

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The weakly interacting massive particle (WIMP) often serves as a candidate for the cold dark matter, however when produced non-thermally it could behave like warm dark matter. In this paper we study the properties of the γ-ray emission from annihilation of WIMP dark matter in the halo of our own Milky-Way Galaxy with high resolution N-body simulations of a Milky-Way like dark matter halo, assuming different nature of WIMPs. Due to the large free-streaming length in the scenario of warm WIMPs, the substructure contend of the dark matter halo is significantly different from that of the cold WIMP counterpart, resulting in distinct predictions of the γ-ray signals from the dark matter annihilation. We illustrate these by comparing the the predicted γ-ray signals from the warm WIMP annihilation to that of cold WIMPs. Pronounced differences from the subhalo skymap and statistical properties between two WIMP models are demonstrated. Due to the potentially enhanced cross section of the non-thermal production mechanism in warm WIMP scenario, the Galactic center might be prior for the indirect detection of warm WIMPs to dwarf galaxies, which might be different from the cold dark matter scenario. As a specific example we consider the non-thermally produced neutralino of supersymmetric model and discuss the detectability of warm WIMPs with Fermi γ-ray telescope.

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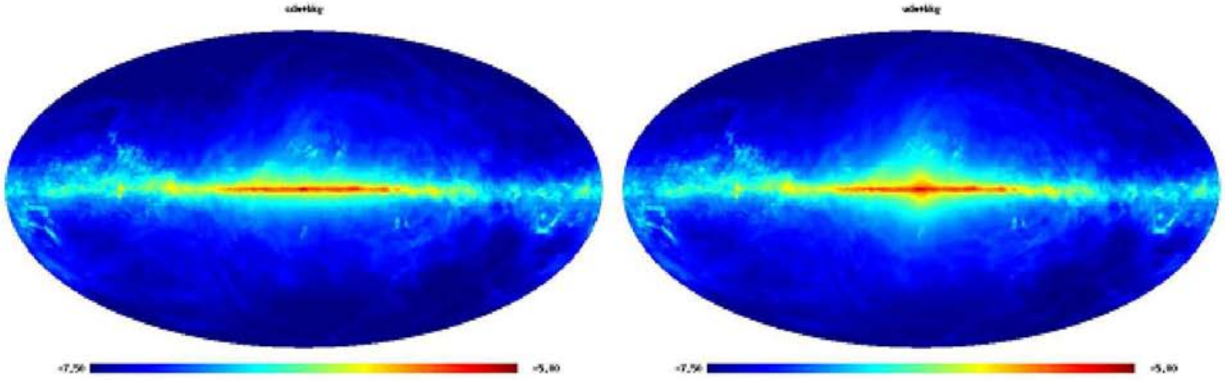

FIG. 5: Skymaps of the total γ-ray emission with background predicted by GALPROP included, for energies $E > 10$ GeV. The left panel is for the cold WIMP case, and the right panel is for the warm WIMP case.

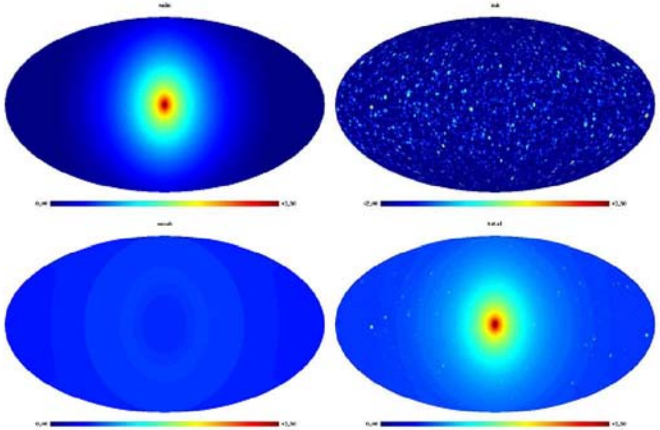

FIG. 8: Skymaps of the J-factors of the smooth halo (top-left), resolved subhalos (top-right), unresolved subhalos (bottom-left) and the total contribution (bottom-right) for CDM.

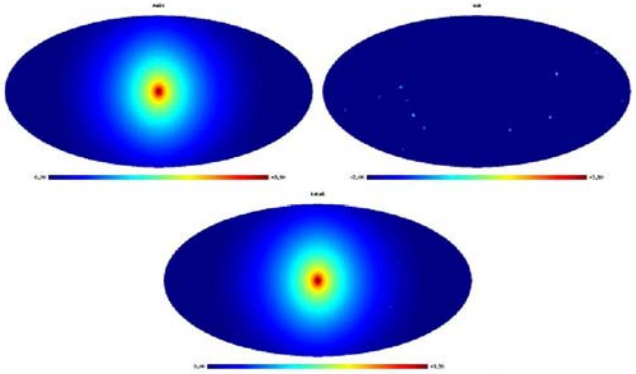

FIG. 2: Skymaps of the J-factors of the main halo (top-left), resolved subhalos (top-right) and total contribution (bottom) for WDM.

太阳系附近未能搜寻到暗物质

- 据英国《自然》杂志网站4月19日报道，在迄今最大型的同类调查中，在太阳系周围彻底搜寻暗物质踪迹的宇宙学家们空手而归。科学家们认为，最新研究将颠覆传统的暗物质理论，但也有研究人员对该研究方法和结论提出了质疑。
- 好问题：如果“地球附近”没有暗物质,
  真的很不幸 if in the “ DM desert ” !?

结论：要慎重

理论、模拟多研究

LAMOST 暗物质研究计划

总结

1）过去的十余年粒子宇宙 学
取得了很多重要的进展；

“天文+物理” 交叉研究的良好氛围
=======〉创新文化重大成就

精确宇宙学 ===➔国际性重大成果

2）提出的问题更多；

Thanks!