The Nature of Dark Energy and its Implications for Particle Physics and Cosmology

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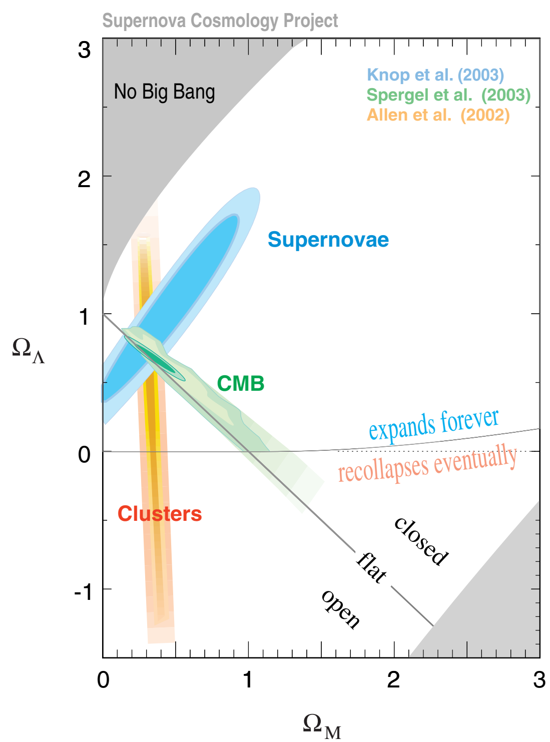
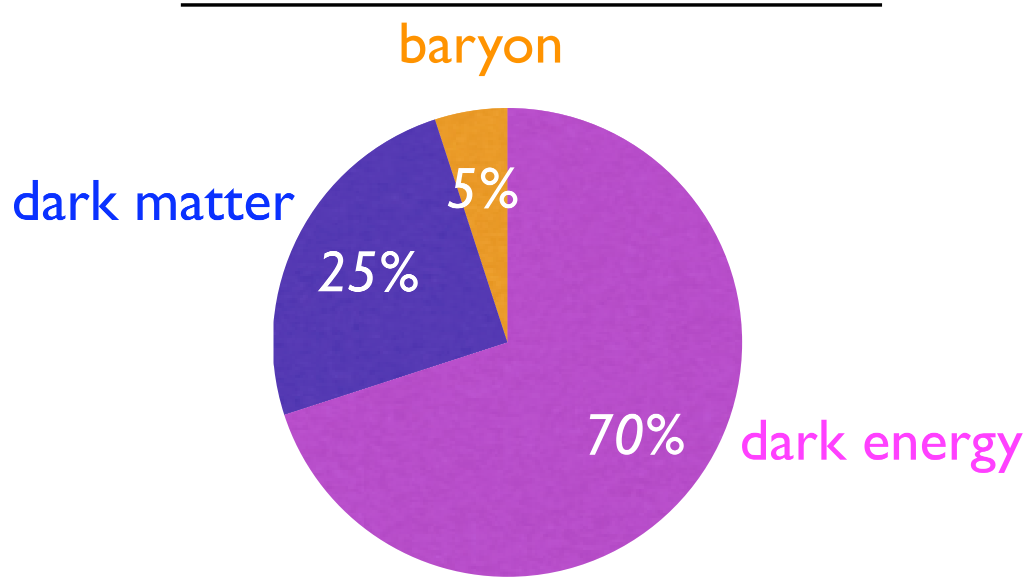
1. Introduction

- Current cosmological observations suggest that the universe is accelerating today.



[From the web page of SCP]

Contents of the universe



- The present universe is dominated by something "dark."

In particular, "dark energy" almost dominates the present universe.

However, we have not understood it yet.

Plan of this talk

1. Introduction

2. Current constraints and some implications

3. The nature of dark energy affects other aspects of cosmology?

4. Summary

2. Current constraints and some implications

- What is dark energy?

→ Some "energy" which accelerates the present universe

Cosmic acceleration: $$\frac{\ddot{a}}{a} = -\frac{1}{6M_{\rm pl}^2}(\rho + 3P)$$

a : scale factor
ρ : energy density
P : pressure

→ If the equation of state $w \equiv \frac{P}{\rho} < -\frac{1}{3}$, the universe can be accelerated.

(However, $w_m = 0$ for matter and $w_r = 1/3$ for radiation)

→ We need something weird with $w_X < -1/3$. → Dark Energy

Parameters characterizing dark energy

- Equation of state $w_X = \frac{p_X}{\rho_X}$
- Energy density $\Omega_X = \frac{\rho_X}{\rho_{\rm crit}}$

(for a constant equation of state)

$$\rho_X(a) = \rho_{\rm crit}\Omega_X a^{-3(1+w_X)}$$

★ Dark energy can also fluctuate, thus we need more to characterize DE.

➡ affects cosmic density fluctuation (CMB, LSS, ...)

- Speed of sound of DE $c_s^2 \equiv \left.\frac{\delta p}{\delta \rho}\right|_{\rm rest}$

(• Anisotropic stress of DE σ_X)

★ These quantities can be constrained by observations.

➡ Clues for dark energy

(First we discuss the effects of the background modification.)

★ Once Ω_X and w_X are specified, we can know how the universe is accelerated.

$$\frac{\ddot{a}}{a} = -\frac{\rho_{\rm crit}}{6M_{\rm pl}^2}\left(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_K a^{-2} + \Omega_X a^{-3(1+w_X)}\right)$$

(Or the background evolution)

$$H^2(a) = H_0^2\left(\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_K a^{-2} + \Omega_X a^{-3(1+w_X)}\right)$$

★ Ω_X and w_X can be constrained by various observations such as

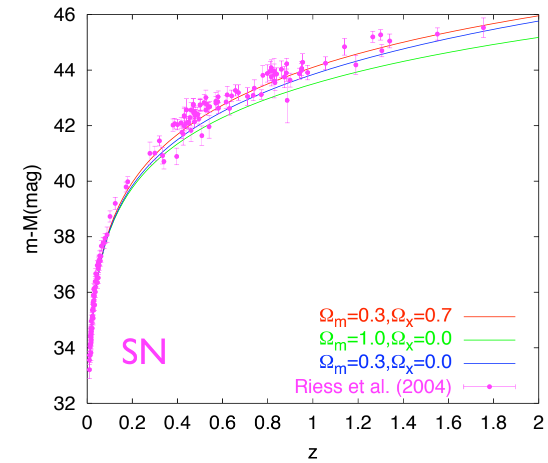
- Type Ia supernovae (SNeIa)
- Cosmic microwave background (CMB)
- Baryon acoustic oscillation (BAO)

⋮

- SNeIa

Luminosity distance $$d_L = \frac{1+z}{\sqrt{|\Omega_k|}} \mathcal{S}\left(\sqrt{|\Omega_k|}\int_0^z \frac{dz'}{H(z')/H_0}\right)$$

[Recent observations: A. G. Riess et al., arXiv:astro-ph/0611572; Davis et al., arXiv:astro-ph/0701510; Wood-Vasey et al, astro-ph/0701041]

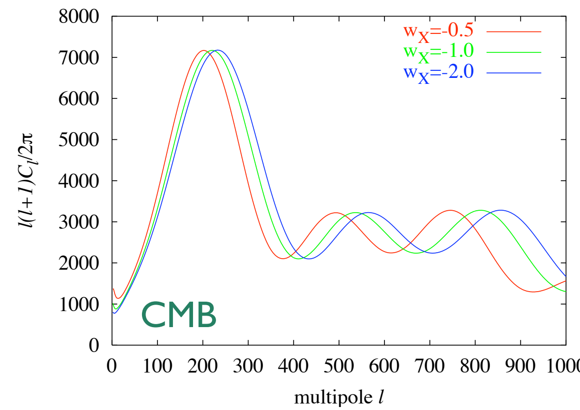


- CMB

Acoustic peak position gives the angular diameter distance to last scattering surface

Angular diameter distance $$d_A = \frac{1}{1+z}\int \frac{dz'}{H(z')}$$

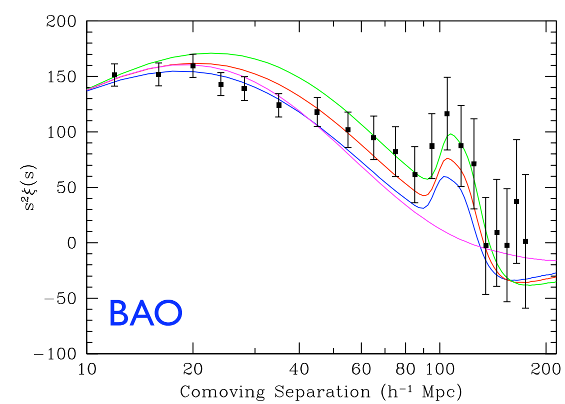
[Spergel et al., astro-ph/0603449; Wang&Mukherjee, astro-ph/0604051]



- BAO

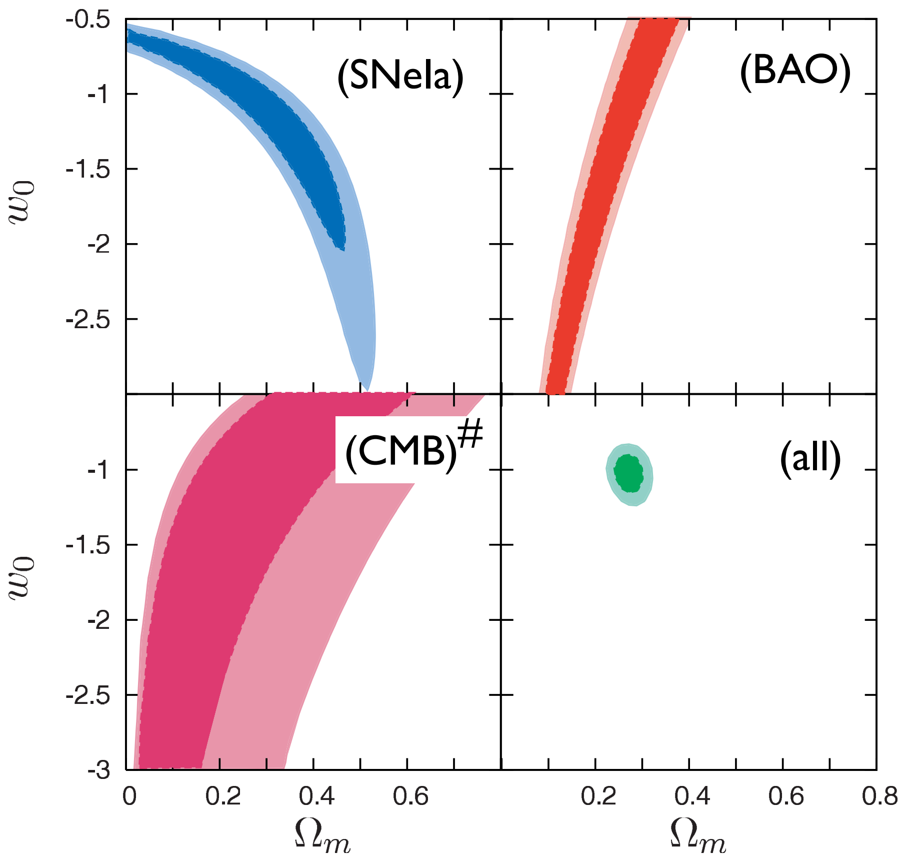
Baryon acoustic peak was detected by observing galaxy samples z ~ 0.35.

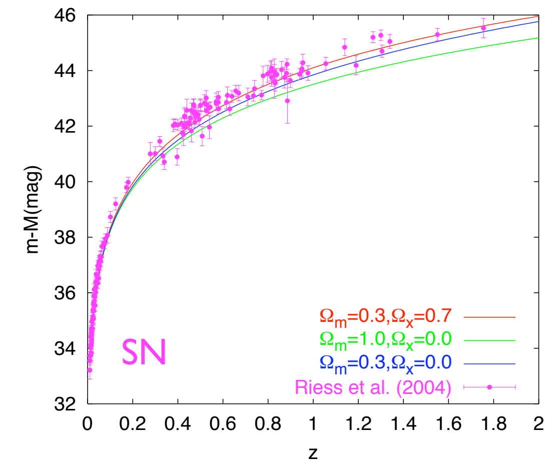
[Eisenstein et al,. ApJ 633, 560, 2005]

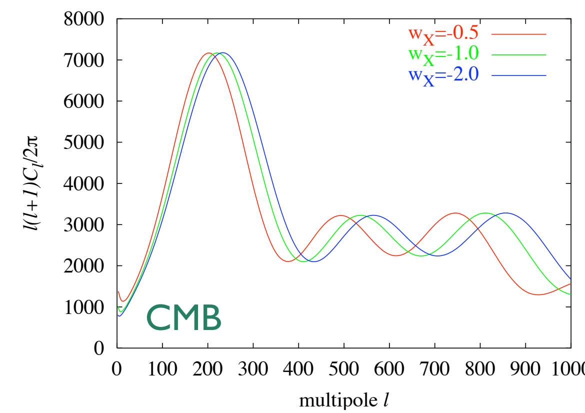


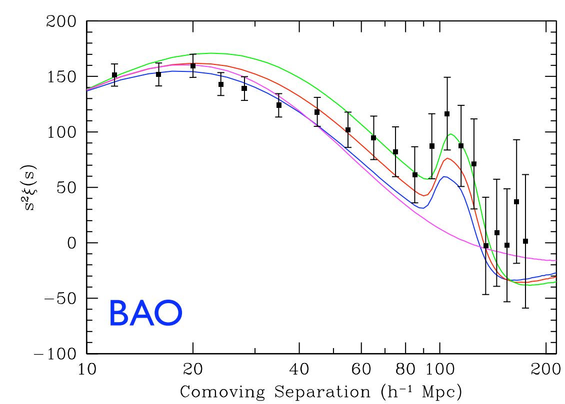
Observational Constraints on the eq. of state

- For a constant equation of state (and a flat univ.)









[Ichikawa & TT, PRD 73, 083526 (2006)]

#Constraint from the shift parameter (position of acoustic peak)

Recent constraints (for a flat universe and a constant equation of state.)

- Spergel et al (WMAP3), 2006

  [WMAP3+other CMB+2dF+SDSS+SN]

  $$w_X = 0.926^{+0.054}_{-0.053}$$ (with perturbation)

  [WMAP3+BAO]

  $$w_X = -0.86^{+0.25}_{-0.23}$$ (with perturbation)

  [WMAP3+SN(gold)]

  $$w_X = -0.919^{+0.081}_{-0.080}$$ (with perturbation)

  [WMAP3+SN(SNLS)]

  $$w_X = -0.967^{+0.073}_{-0.072}$$ (with perturbation)

- Tegmark et al, PRD74,123507,2006. (astro-ph/0608632)

  [WMAP3+SDSS]

  $$w_X = -1.00^{+0.17}_{-0.19}$$ (with perturbation)

- Percival et al, arXiv:0705.3323 [astro-ph]

  [CMB(theta)+SN(SNLS)+BAO(SDSS+2dF)]

  $$w_X = -1.004 \pm 0.089$$

- Wood-Vasey et al, astro-ph/0701041

  [SN(ESSENCE)+BAO(SDSS)]

  $$w_X = -1.05^{+0.13}_{-0.12}$$

Models for an accelerating universe proposed so far

(No criterion for the choice of models here.)

- Cosmological constant (Λ) ($w_X = -1$)
- Scaler field
  - Quintessence
  - K-essence (with a non-canonical kinetic term)
- DGP (Dvali-Gabadaze-Porrati) model
- f(R) gravity
- Cardassian model ($H^2 = \frac{1}{3M_{\rm pl}^2}(\rho + B\rho^n)$)
- Ghost condensate

⋮

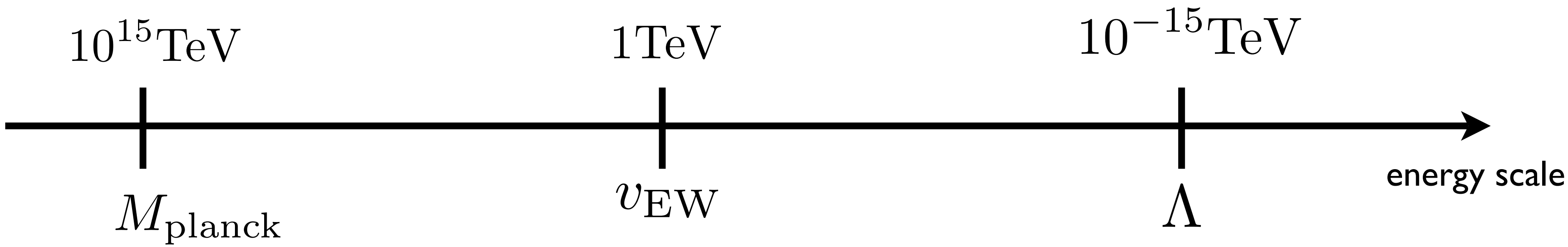
★ Too many!

★ Cosmological constant?

- A naive estimate of Λ in quantum field theory: $\rho_\Lambda \sim M_{\rm pl}^4 \sim (10^{18}{\rm GeV})^4$
- From cosmological observations: $\rho_\Lambda \sim \Lambda^4 \sim (10^{-3}{\rm eV})^4$

➡ $M_{\rm pl}^4/\Lambda^4 \sim 10^{120}$!

- **Numerical coincidence?**



➡ $v_{\rm EW}^2/M_{\rm pl} \sim \Lambda$ any reason?

- ....

★ Dark energy is dynamical?

An example: quintessence (a scalar field) Q

- "Tracker type" model

(the ratio $\rho_{\rm DE}/\rho_{\rm m}(\rho_{\rm rad})$ constant)

  - $V(Q) = \Lambda^{4+\alpha}/Q^{\alpha}$

    [Ratra,Peebles PRD 37,3406,1998]

  - $V(Q) = \Lambda^4 \exp(-\lambda Q)$

    [Ferreira,Joyce PRD 58,023503,1998]

  - $V(Q) = V_0\left[(Q-B)^2 + A\right]\exp(-\lambda Q)$

    [Skordis, Albrecht PRD 66,043523,2002]

  - $V(Q) = \left(\Lambda^4/Q^{\alpha}\right)\exp(\kappa Q^2)$

    [Brax,Martin PLB 468,40,1999]

  ⋮

- "Tracker oscillating" model

  - $V(Q) = \Lambda^4\left[1 + A\sin(\nu Q)\right]\exp\left(-\lambda Q\right)$

    [Dodelson,Kaplinghat,Stewart PRL 85,5276,2000]

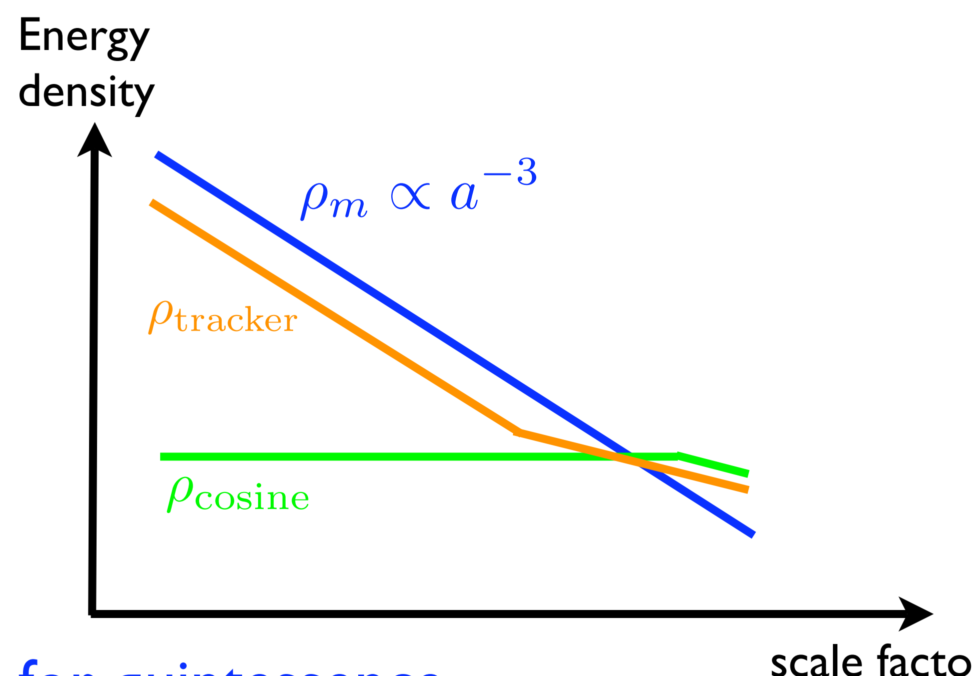
- "cosine type" model

(Psuedo-Nambu-Goldston boson)

$$V(Q) = \Lambda^4\left(1 - \cos(Q/f_Q)\right)$$

[Coble,Dodelson,Frieman PRD 55,1851,1997;
Viana,Liddle PRD 57,674,1998]

(mass scale: $m_Q \sim H_0 \sim 10^{-33}{\rm eV}$)



★ Various models even just for quintessence....

★ (Too) Many models proposed (but none of them are compelling).

→ Phenomenological approach using observations

★ Key questions:

- The equation of state is -1 (cosmological constant) or not?

- The equation of state is time-dependent ($dw_x/dz \neq 0$) or not ?

- Probe the time-dependence of the equation of state $w_x(z)$.

→ Although time dependence of w_x can be complicated, in most analysis, some simple parametrizations are adopted.

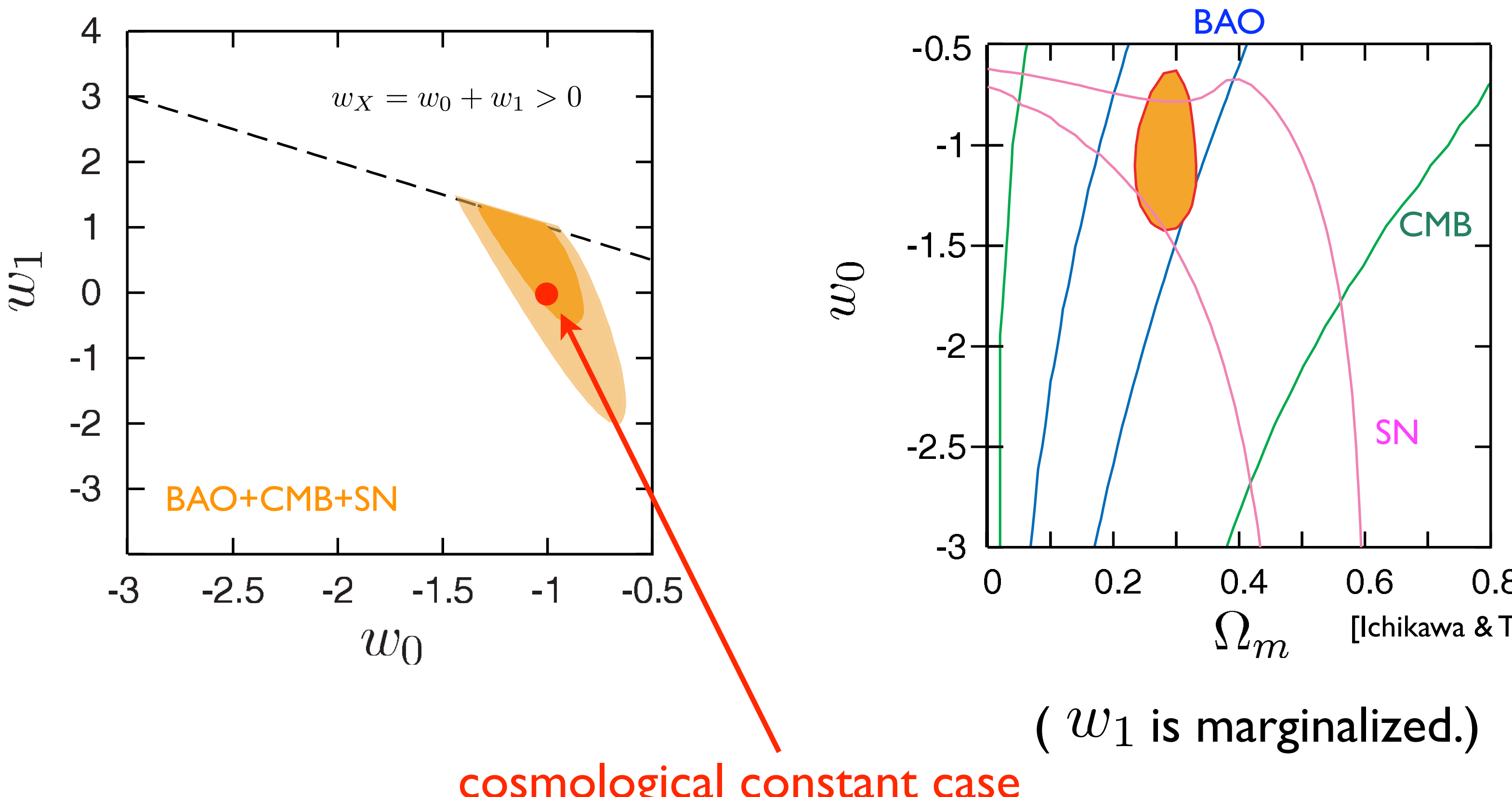
(and see dw_x/dz)

Observational Constraints on the eq. of state II

★ For the time-varying equation of state

- Assuming a simple model:

$$w_X = w_0 + w_1(1-a) = w_0 + w_1\frac{z}{1+z}$$ (A flat universe is assumed.)



[Ichikawa & TT, PRD 73, 083526 (2006)]

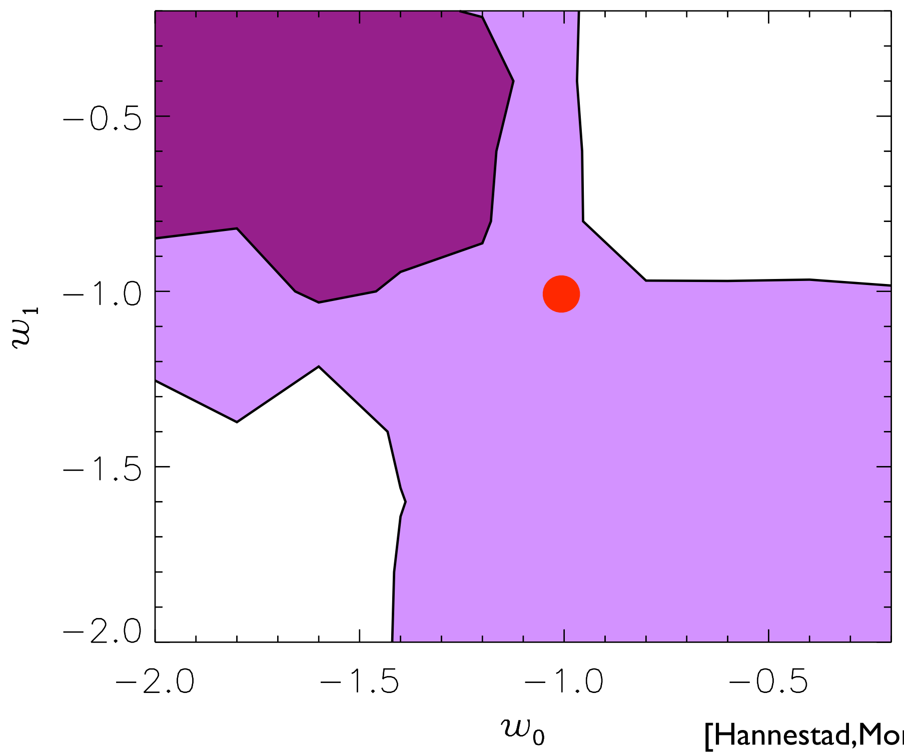
(w_1 is marginalized.)

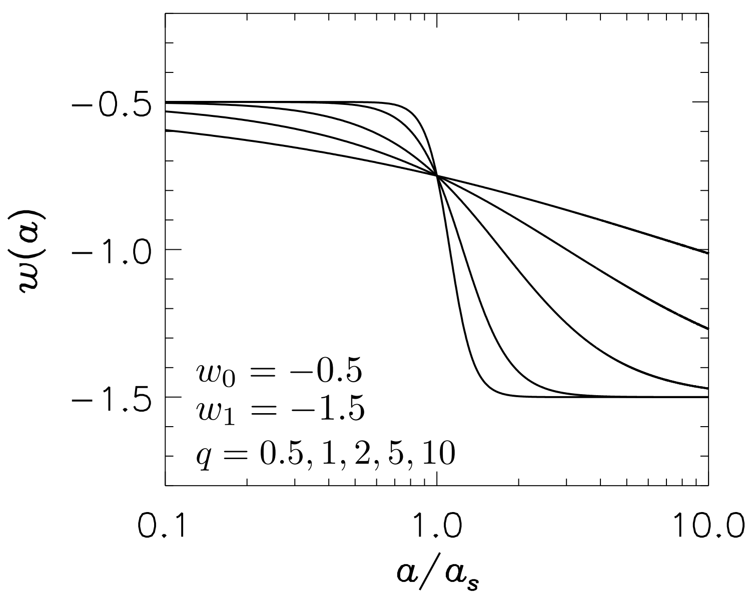
Observational Constraints on the eq. of state III

- Another parametrization [Hannestad,Mortsell JCAP0409,011,2004]

$$w(a) = w_0 w_1 \frac{a^q + a_s^q}{a^q w_1 + a_s^q w_0} \qquad \text{(LCDM: } w_0 = w_1 = -1 \text{)}$$

Some examples for the evolution of w



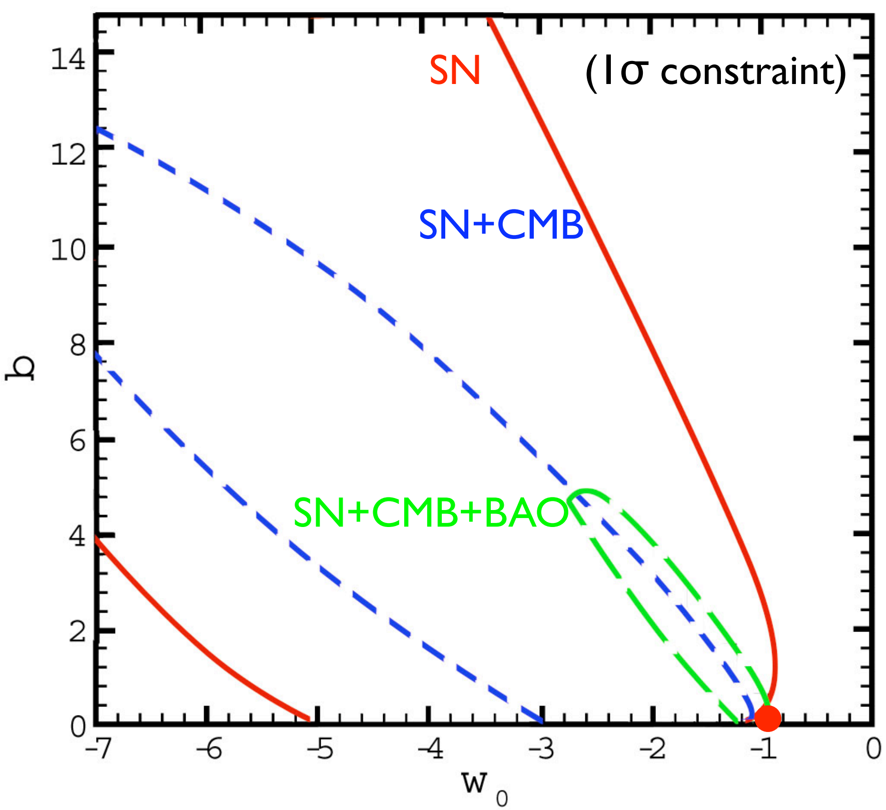


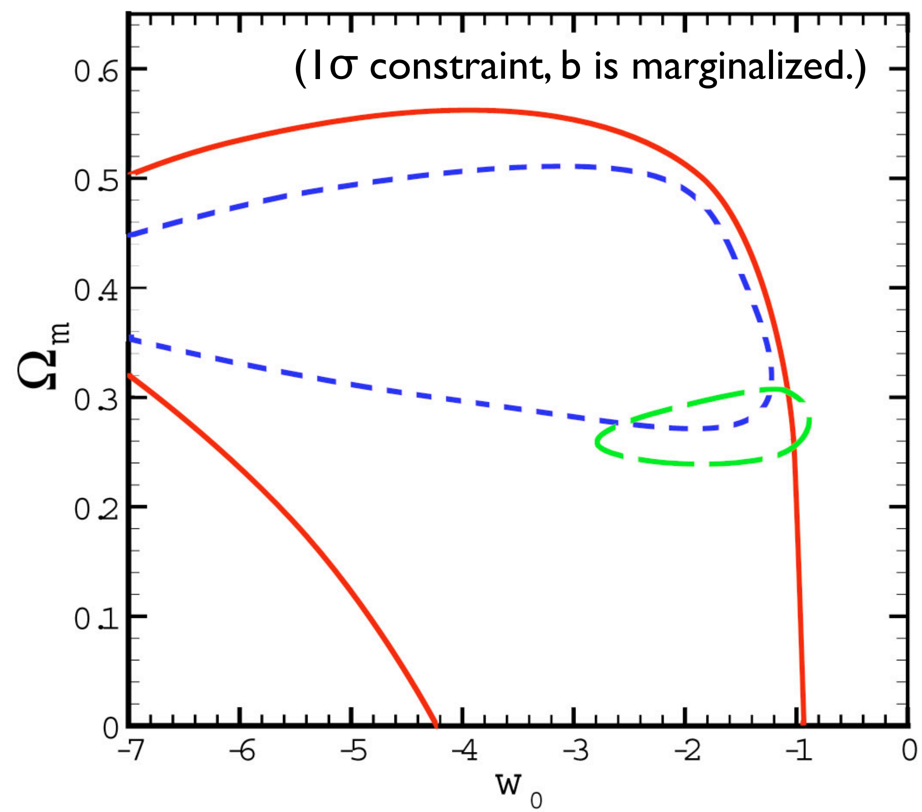
[Hannestad,Mortsell JCAP0409,011,2004]

Observational Constraints on the eq. of state IV

- Another parametrization [Wetterich PLB 594, 17, 2004]

$$w_X(z) = \frac{w_0}{[1 + b\log(1+z)]^2} \qquad (\text{LCDM: } w_0 = -1,\ b = 0)$$





[Movahed, Rahvar PRD 73, 083518, 2006]

(Short summary of this part)

- A cosmological constant is allowed (in almost all analysis).

  (looks pretty good in some analysis/data set.)

- Various dark energy models are still allowed.

- Many candidates for dark energy (accelerating universe) have been proposed, (fortunately/unfortunately) none of them are compelling.

(● For dark matter, plausible candidates in particle physics.)

★ In fact, more to be specified to characterize dark energy

- We also have to specify the perturbation nature of dark energy.

  - Speed of sound of DE $\boxed{c_s^2 \equiv \left.\frac{\delta p_X}{\delta \rho_X}\right|_{\rm rest}.}$

[Hu ApJ 506, 485, 1998;
Bean&Dore PRD 69,083503,2003]

  - Anisotropic stress of DE σ_X

[Hu ApJ 506, 485, 1998;
Koivisto&Mota PRD 73, 083502, 2006;
Ichiki&TT PRD, astro-ph/0703549]

$$\sigma'_X + 3\mathcal{H}\frac{c_a^2}{w_X}\sigma_X = \frac{8}{3}\alpha\left(\theta_X + \frac{h'}{2} + 3\eta'\right)$$: specified by "viscosity" parameter $\boxed{\alpha}$

- Perturbation equations for a general dark energy

For density pert., $\delta'_X = -(1+w_X)\left[k^2 + 9\mathcal{H}^2(c_s^2 - c_a^2)\right]\frac{\theta_X}{k^2} - 3\mathcal{H}(c_s^2 - w_X)\delta_X - (1+w_X)\frac{h'}{2}$

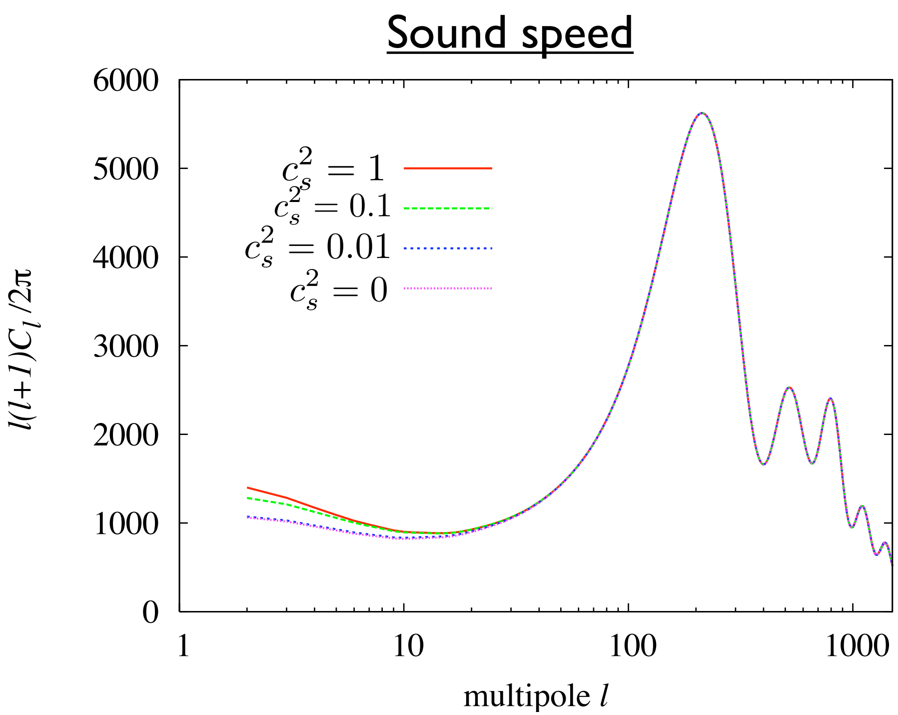
For velocity pert., $\theta'_X = -\mathcal{H}(1-3c_s^2)\theta_X + \frac{c_s^2 k^2}{1+w_X}\delta_X - k^2\sigma_X$

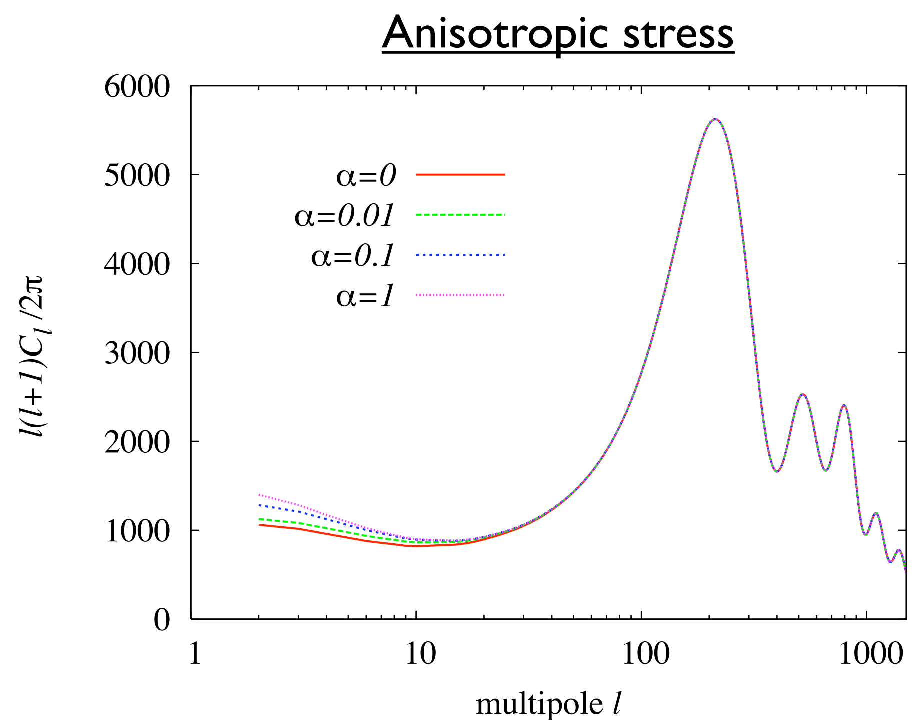
(the prime denotes a derivative w.r.t. the conformal time)

where $c_a^2 \equiv \frac{p'_X}{\rho'_X} = w_X - \frac{w'_X}{3\mathcal{H}(1+w_X)}.$ ⟵ Specified once EoS is given

➡ These can affect cosmic density density fluctuation

Effects of fluctuation of dark energy





- For quintessence (a scalar field with the canonical kinetic term), $c_s^2 = 1$
- For example, k-essence (a scalar field with a non-canonical kinetic term), $c_s^2 \neq 1$

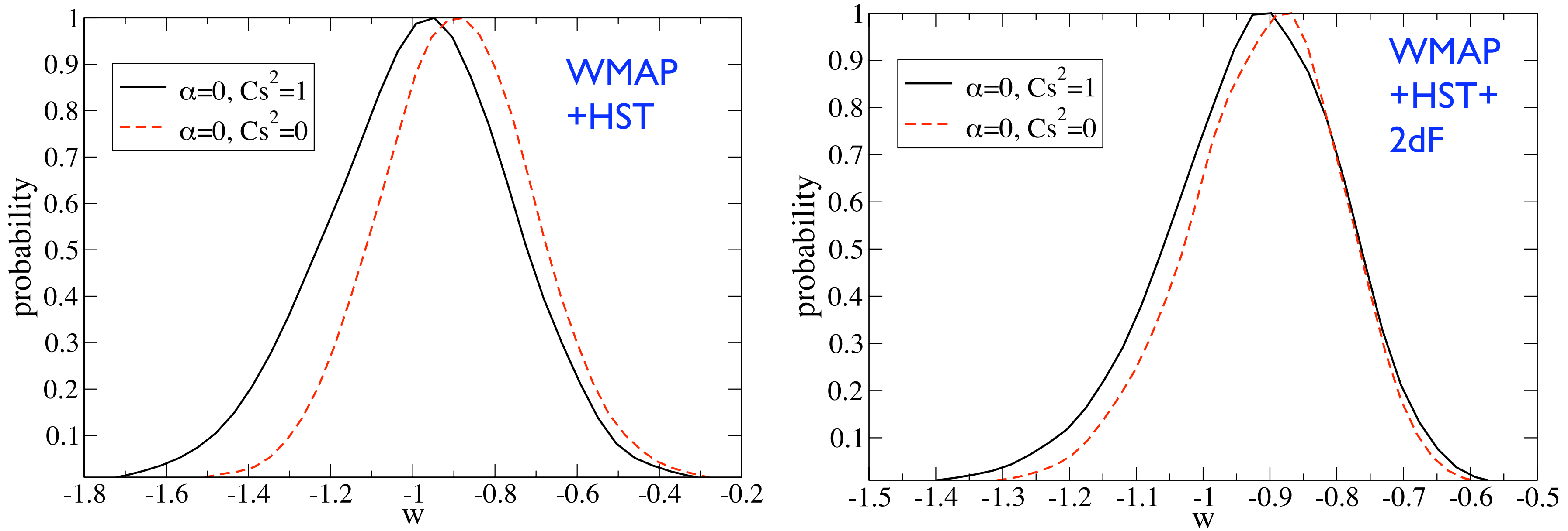
★ Low multipoles of CMB are mainly affected.

★ Even if the eq. of state is same, fluctuation make some difference.

★ Cross-correlation of ISW and LSS may be helpful.

★ Although the sound speed and anisotropic stress themselves cannot be severely constrained, constraints on other quantities can be affected.

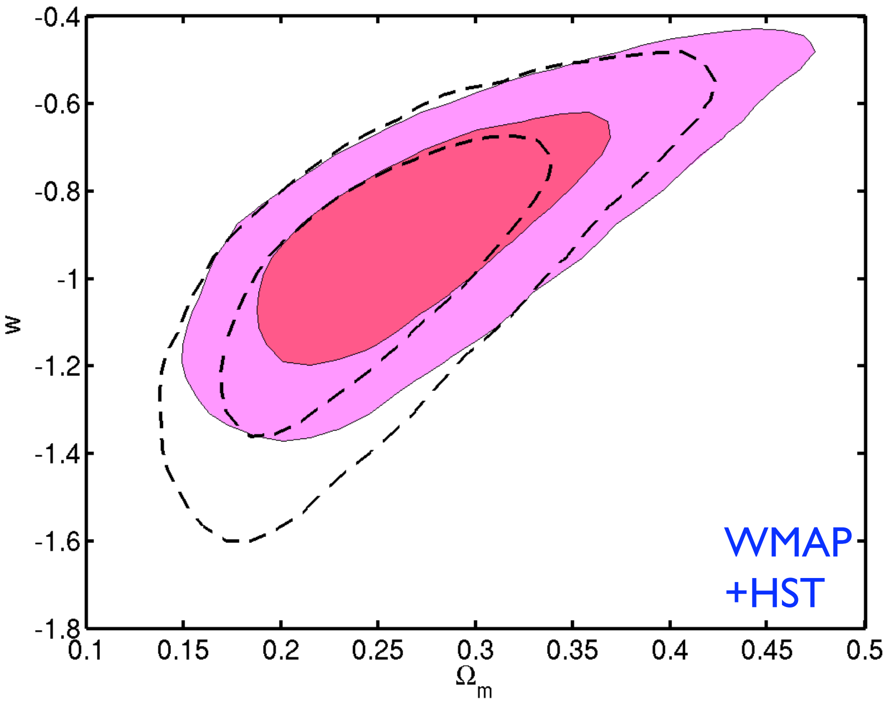
- Constraint on w with different assumptions for c_s^2 and α.

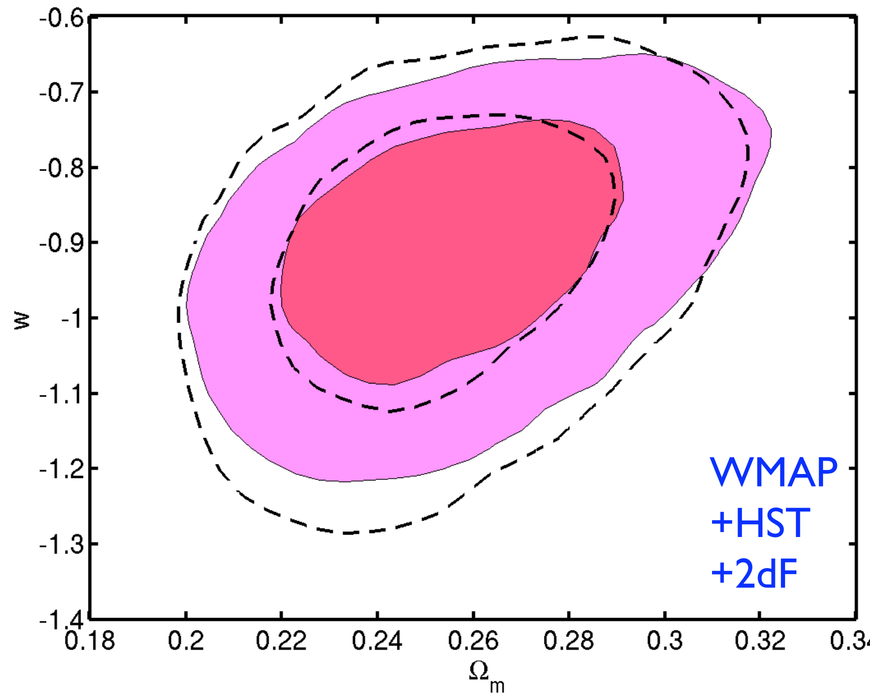


[Ichiki&TT PRD, astro-ph/0703549]

★ The assumption may cause ~10 % difference.

- Constraint on w with different assumptions for c_s^2 and α .





[Ichiki&TT PRD, astro-ph/0703549]

3. The nature of dark energy affects other aspects of cosmology?

★ Main concern of dark energy research is to figure out what the dark energy is.

→ the nature of dark energy can affect other aspects?

- Implications for other aspects?

  (Some examples)

  - Dark energy and mass varying neutrinos

    → Next Takahashi's talk

  - Relic abundance of DM can be affected by quintessence model?

  - The curvature of the universe

  - Primordial fluctuation (spectral index, gravity wave, scalar spectral running)

  ⋮

(Example 1)

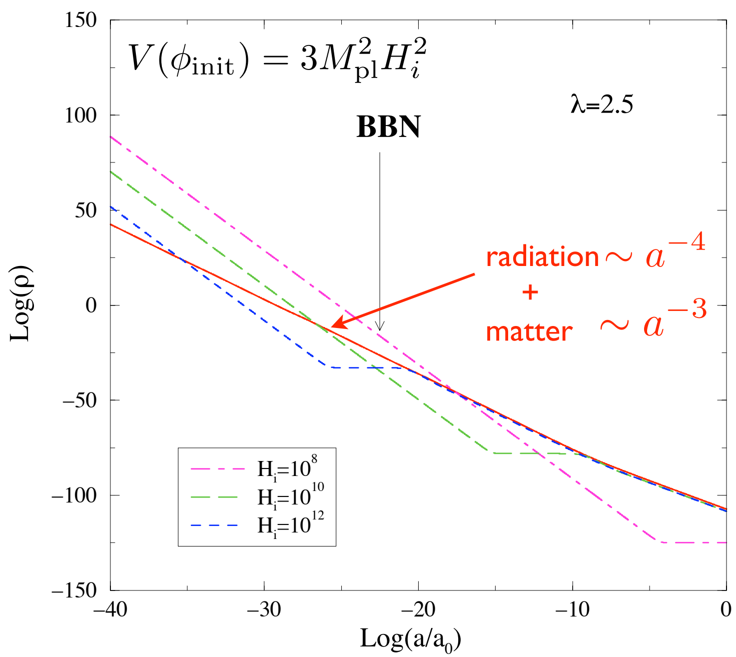
Relic abundance of DM in models with quintessence model

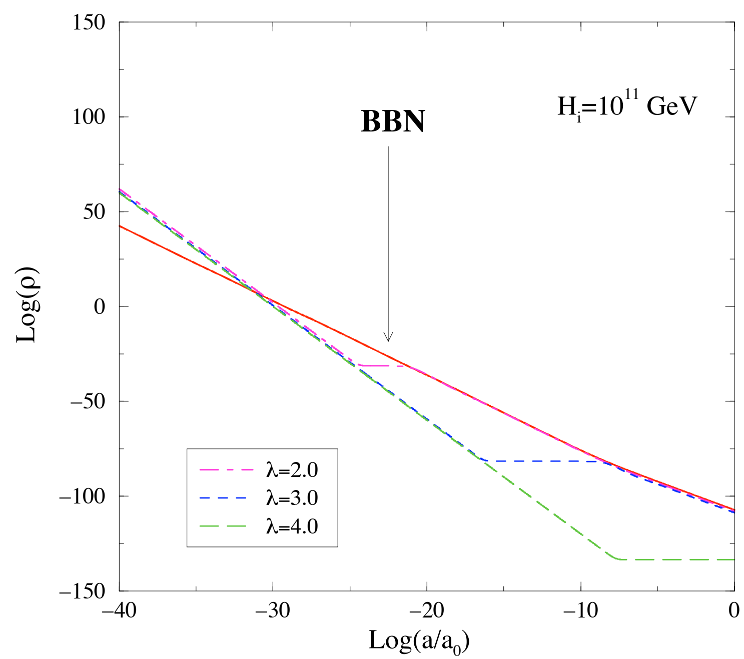
- In some models of quintessence, the kinetic energy of quintessence can dominate the universe.

[Salati PLB 571,121,2003;
Rosati PLB 570,5,2003;
Profumo & Ullio JCAP0311,006,2003;
Pallis JCAP 0510,015,2005]

- During kinetic energy-dominated phase, $\rho_\phi \propto a^{-6}$

Example: $V(\phi) = M_{\rm pl}^4 \exp\left(-\lambda\phi/M_{\rm pl}\right)$

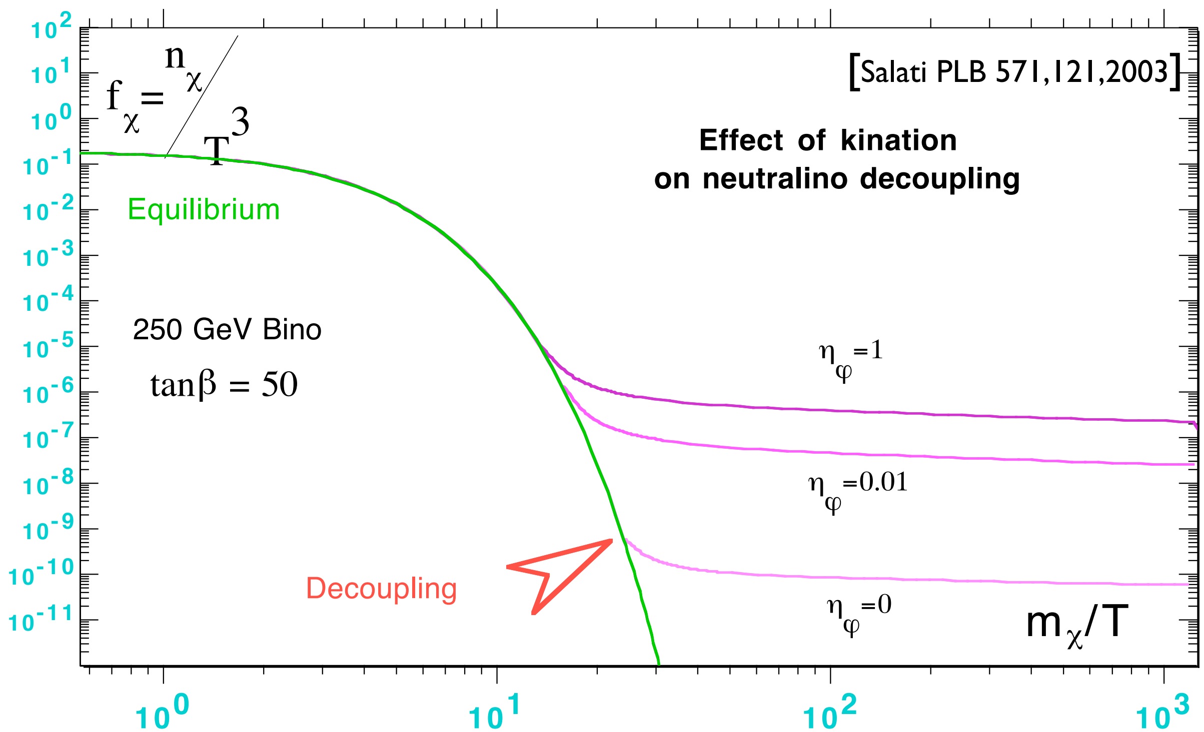




★ Relic abundance can be enhanced when DM decouple in kination domination period.

- Standard case ➡ DM decouples during radiation-dominated epoch $\left(H^2 = \frac{1}{3M_{\rm pl}^2}\rho \propto a^{-4}\right)$
- If DM decouples during Kination domination (kinetic energy dominated epoch)

$$\bullet\ H^2 = \frac{1}{3M_{\rm pl}^2}\rho \propto a^{-6} \qquad \bullet\ \frac{dn_\chi}{dt} + 3Hn_\chi = <\sigma v> \left\{(n_\chi^{(0)})^2 - n_\chi^2\right\}$$



Earlier decoupling

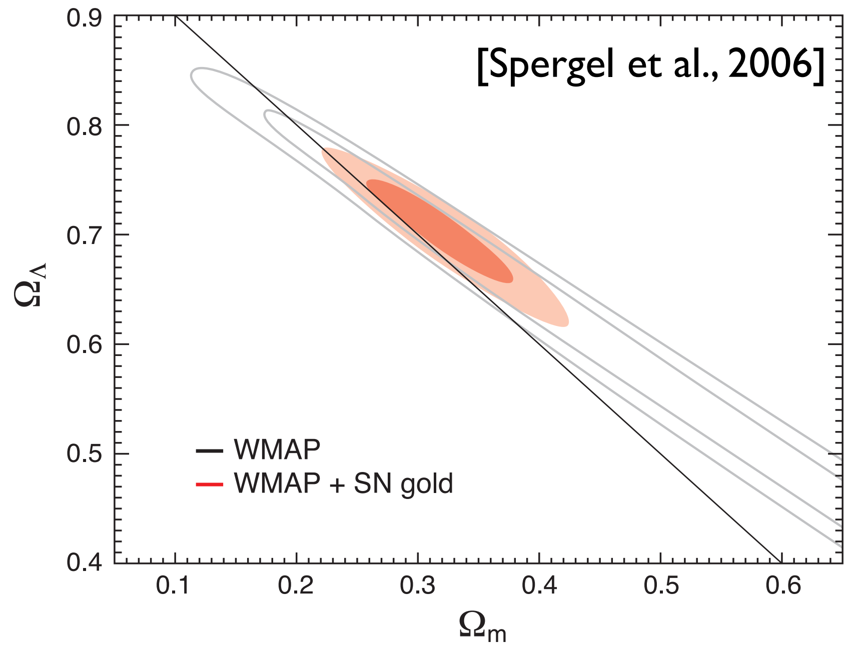
⬇

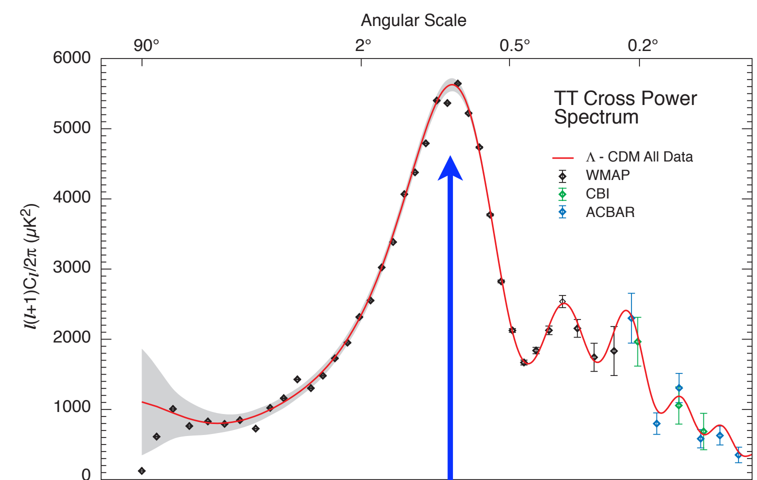
Enhanced relic abundance

(Example 2)

- **Effects on the constraint on the curvature of the universe**

  - It is usually said that current observations favor a flat universe.





The position of the peak

- The curvature of the universe shifts the peak position.

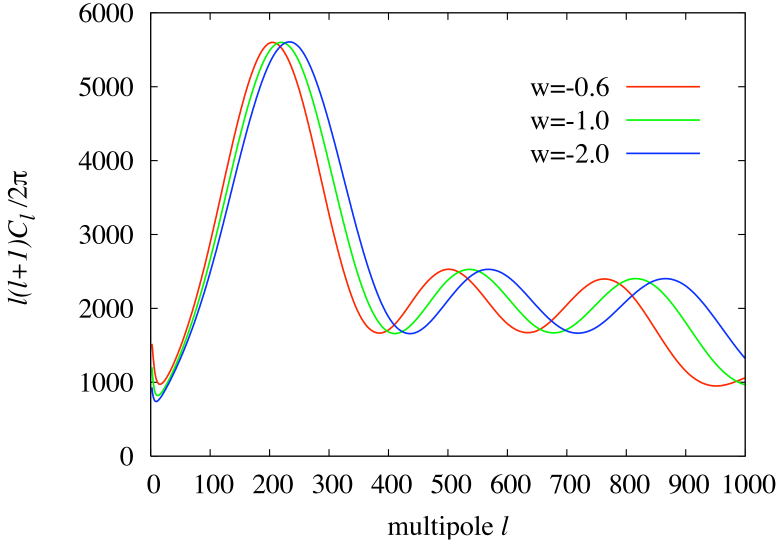
→ The universe is (almost) flat.

(Assuming a cosmological constant as dark energy.)

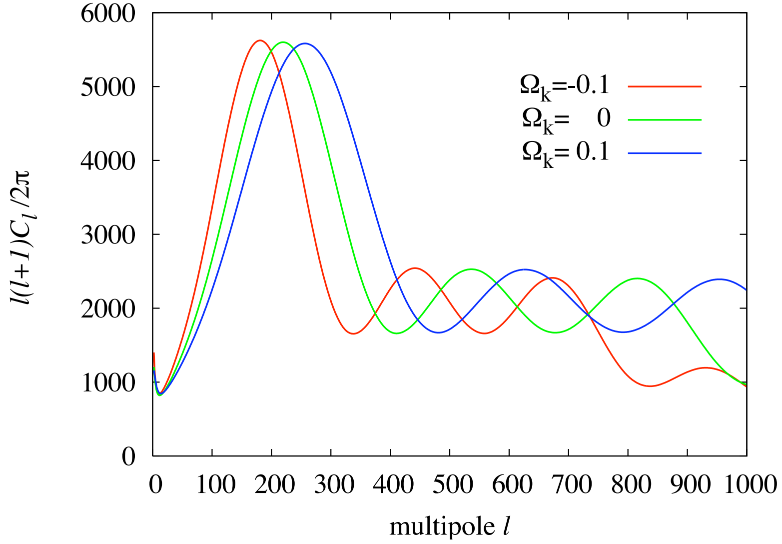
- The flatness is robust even if we assume different types of dark energy?

- The EoS of dark energy also affect the CMB power spectrum.

Varying w_X.



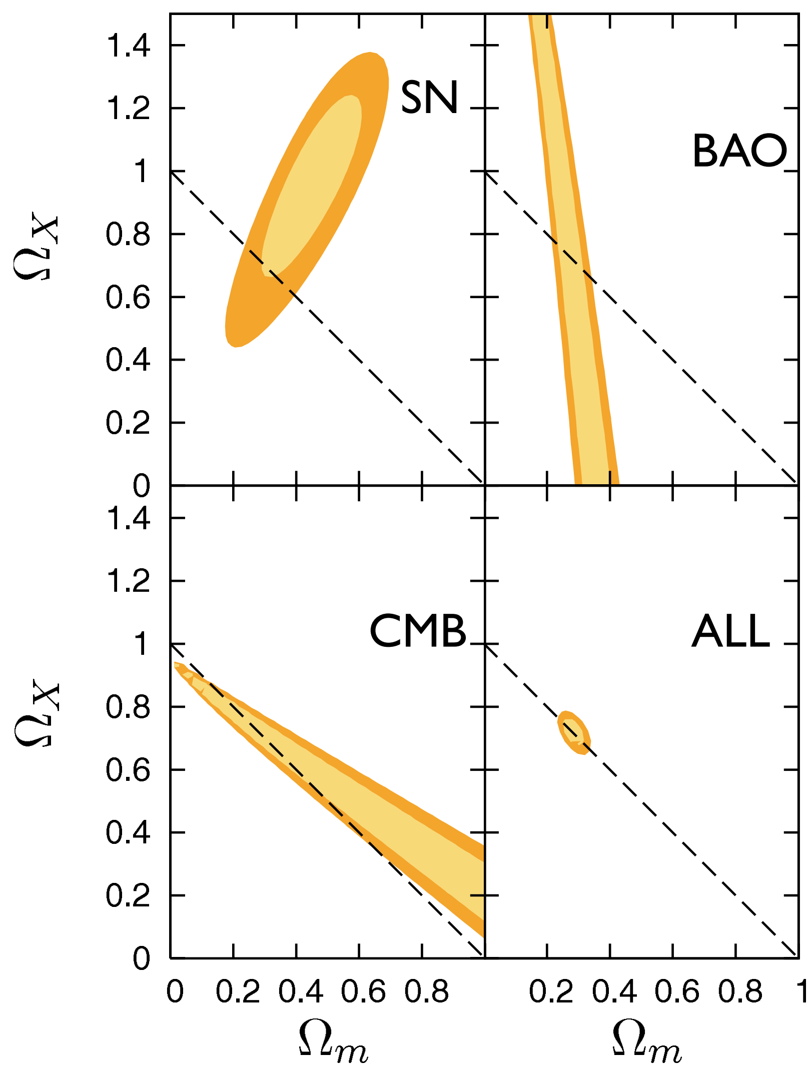
Varying Ω_k.



→ Degeneracy between EoS of DE and the curvature

Constraint on the curvature of the universe

- Assuming a cosmological constant as dark energy



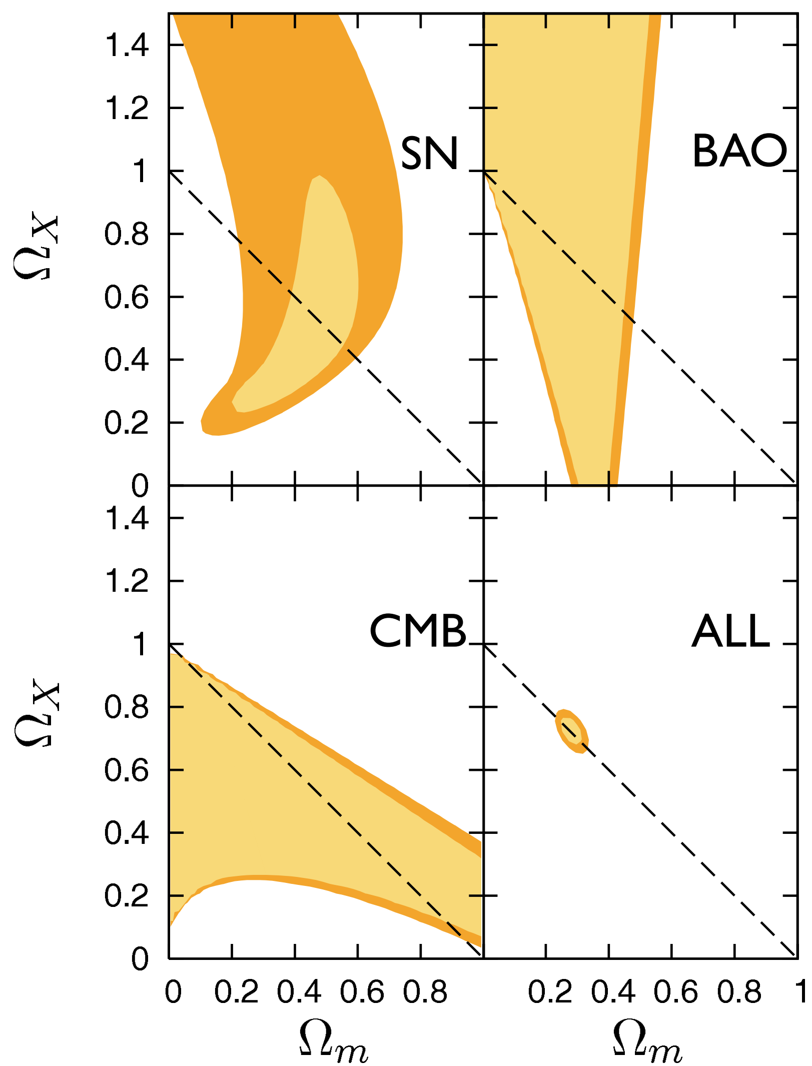
A flat universe is favored.

[Ichikawa & TT, PRD 73, 083526 (2006)]

<u>Constraint on the curvature of the universe</u>

- Assuming a constant equation of state w_X

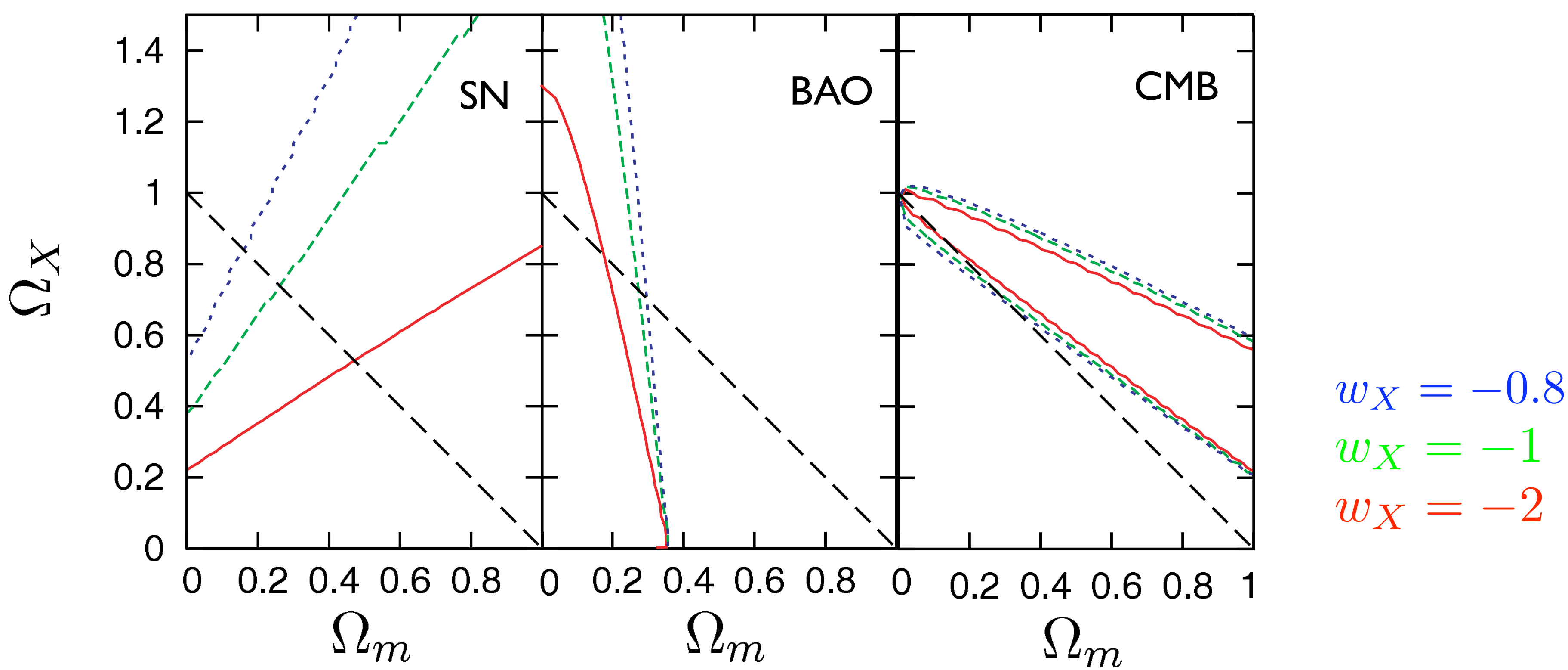
(w_X is marginalized over.)



A flat universe is favored even though we do not assume $w_X = -1$

[Ichikawa & TT, PRD 73, 083526 (2006)]

Contours of EoS giving the minimum chi2 for each (Ω_m, Ω_X).



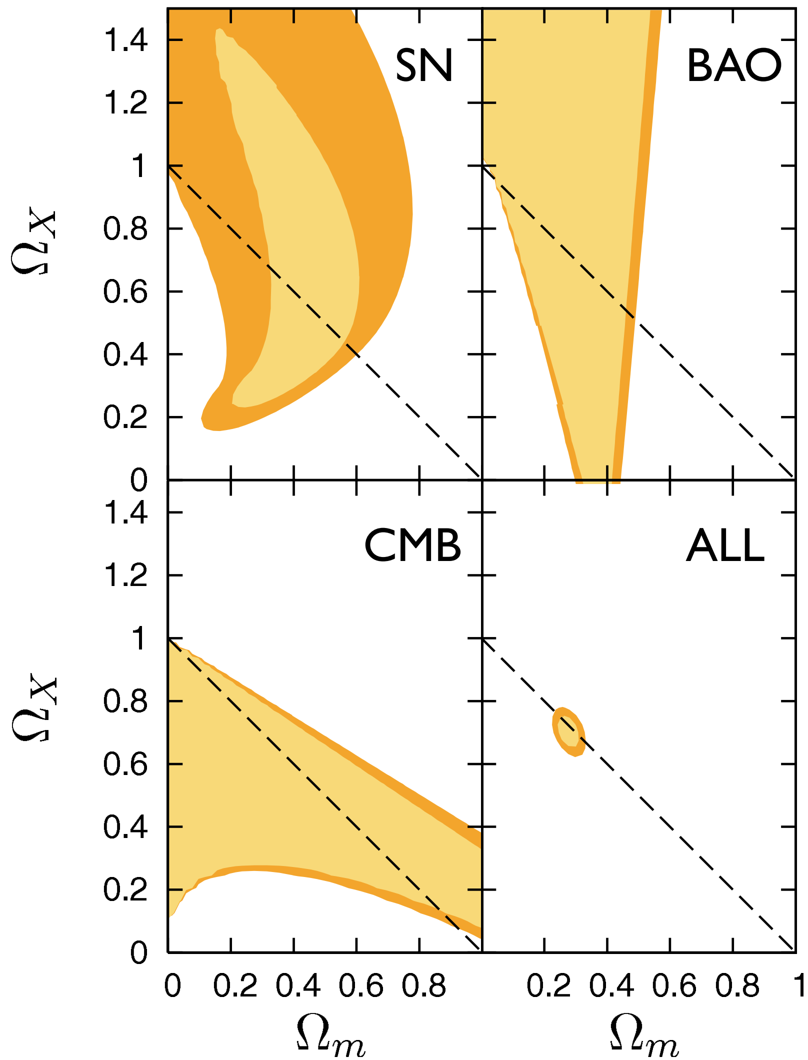
→ Each observation favors different values of EoS.

→ When all data combined, it gives a flat universe.

Constraint on the curvature of the universe

- Assuming a time-varying equation of state as

$$w_X = w_0 + (1-a)w_1$$
$$= w_0 + \frac{z}{1+z} w_1$$



(w_0 and w_1 are marginalized over.)

→ A flat universe is favored even though we assume a time-varying equation of state.

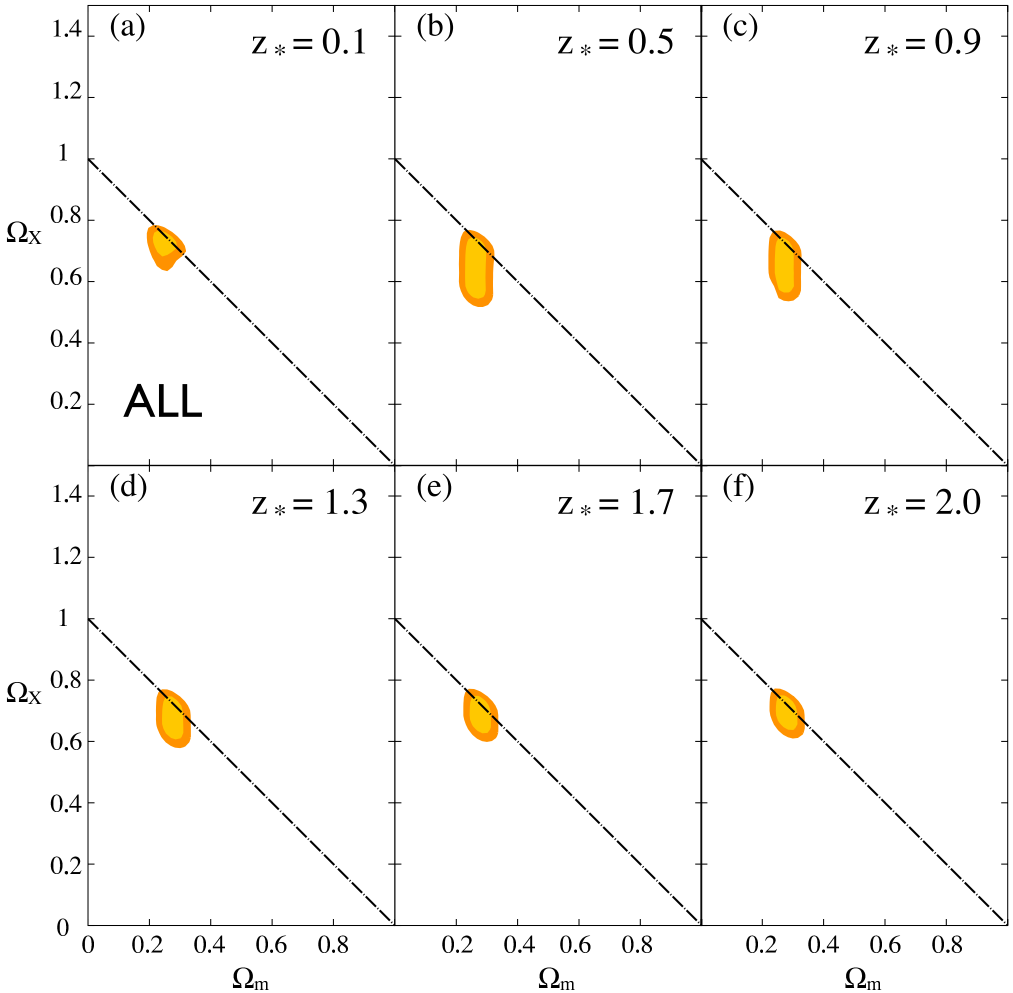
[Ichikawa & TT, PRD 73, 083526 (2006)]

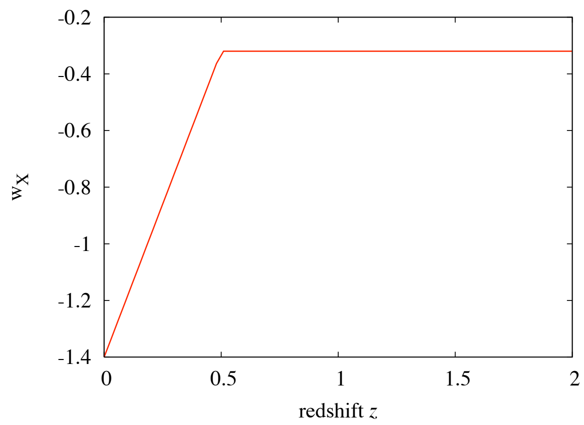
- The flatness is robust?

Constraint on the curvature of the universe

- Assuming a time-varying equation of state as

$$w_X(z) = \begin{cases} w_0 + \dfrac{w_1 - w_0}{z_*} z & (\text{for } z \le z_*) \\ w_1 & (\text{for } z \ge z_*) \end{cases}$$





An open universe can be allowed ($\Omega_k \sim 0.2$) for some case in this model.

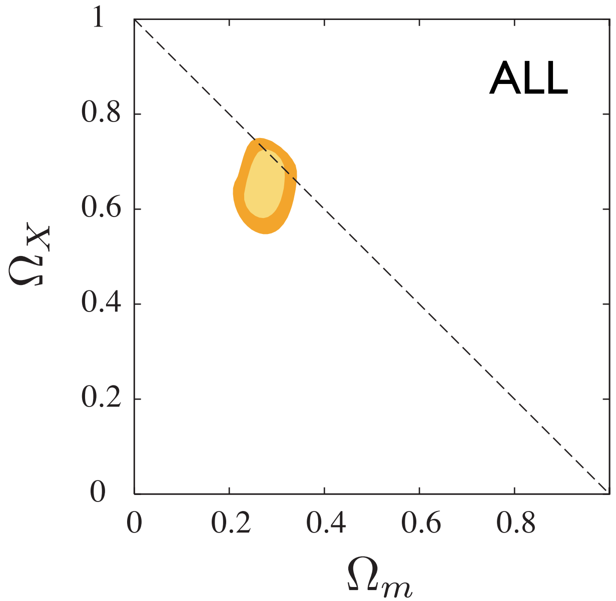
[Ichikawa, Kawasaki, Sekiguchi & TT, JCAP 12, 005(2006)]

Constraint on the curvature of the universe

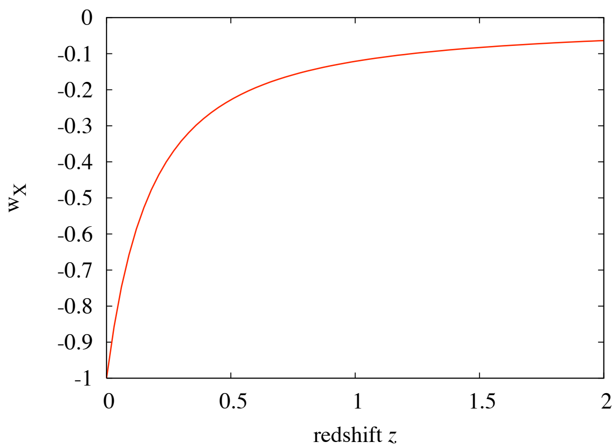
- Assuming a time-varying equation of state as

$$w_X(z) = \frac{w_0}{[1 + b\log(1+z)]^2}$$

[Wetterich PLB 594, 17, 2004]



[Ichikawa & TT, JCAP 02, 001(2007)]



→ An open universe can be allowed in this case too.

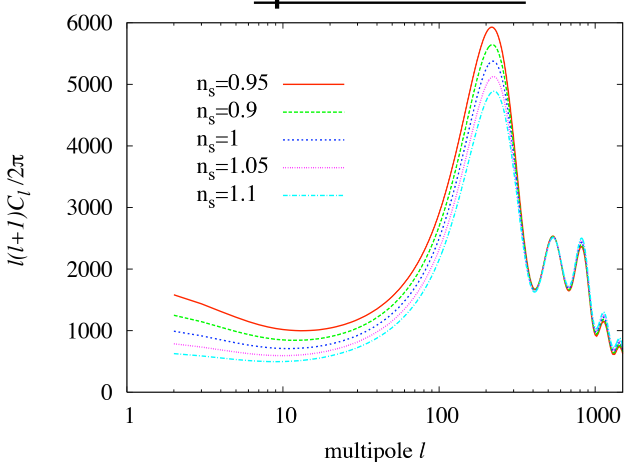
(Example 3)

- Effects on the constraints on primordial fluctuation

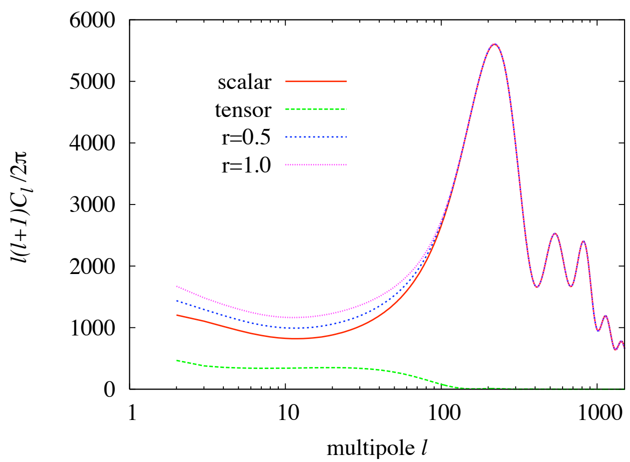
★ The nature of primordial fluctuation is now severely constrained by observations.

- Spectral index n_s : $P_{\mathcal{R}} \propto k^{n_s - 1}$
- Tensor-to-scalar ratio r : $r = \dfrac{P_T}{P_{\mathcal{R}}}$
- Running of the scalar spectral index αs : $\alpha_s = \dfrac{d\ln n_s}{d\ln k}$

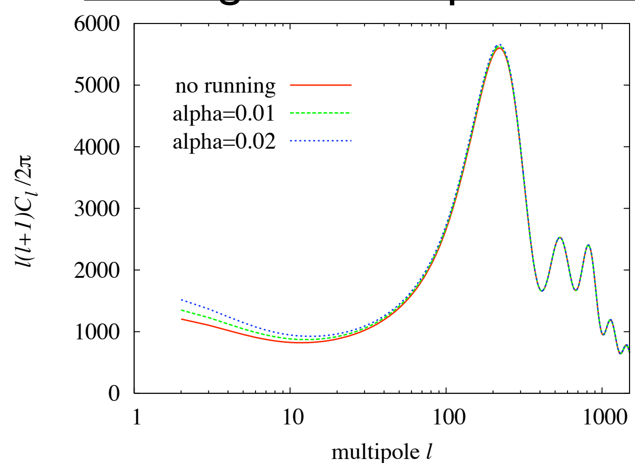
spectral index



tensor mode

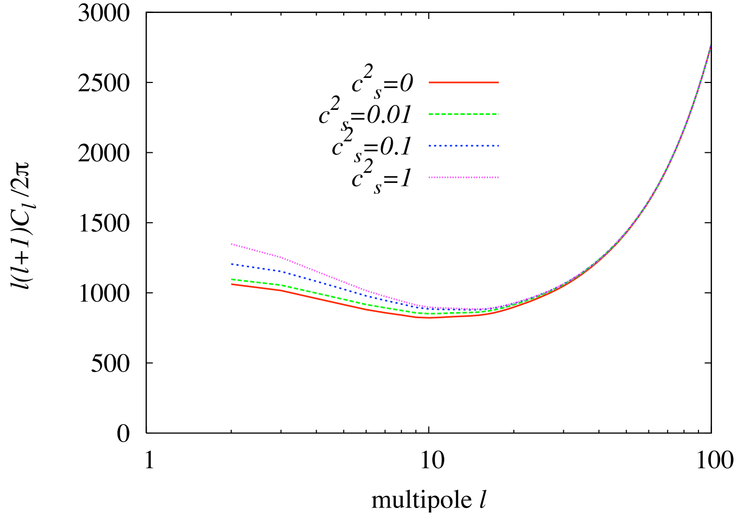


Running of scalar spectral index

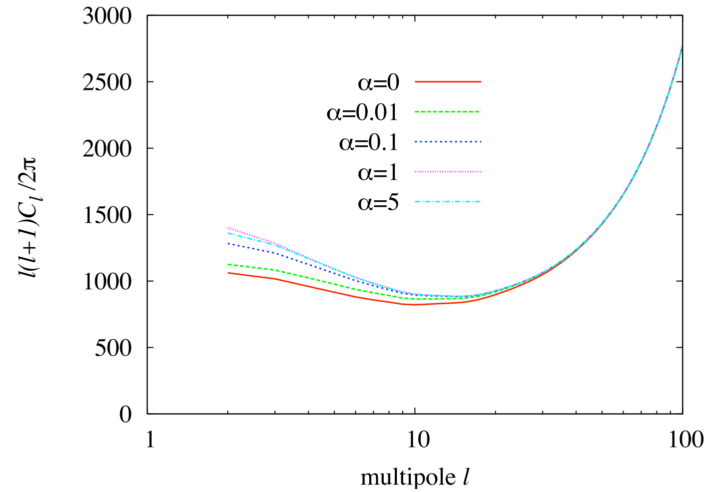


• Effects of dark energy and primordial fluctuation look similar?

Sound speed

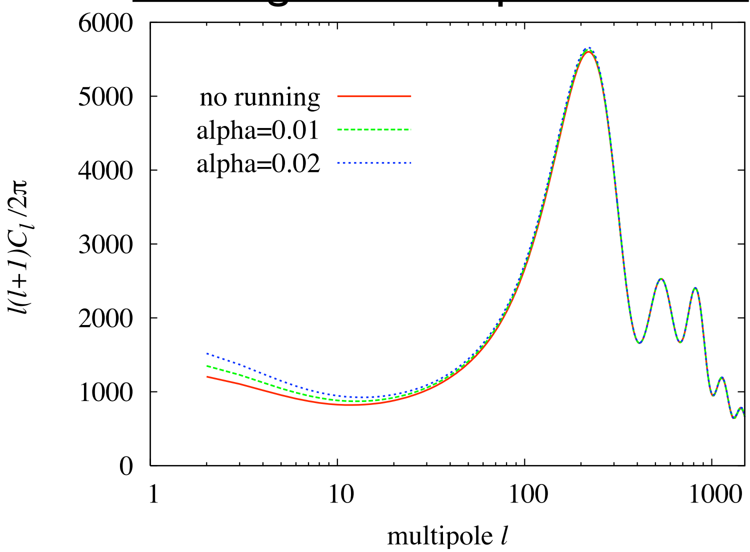


Anisotropic stress

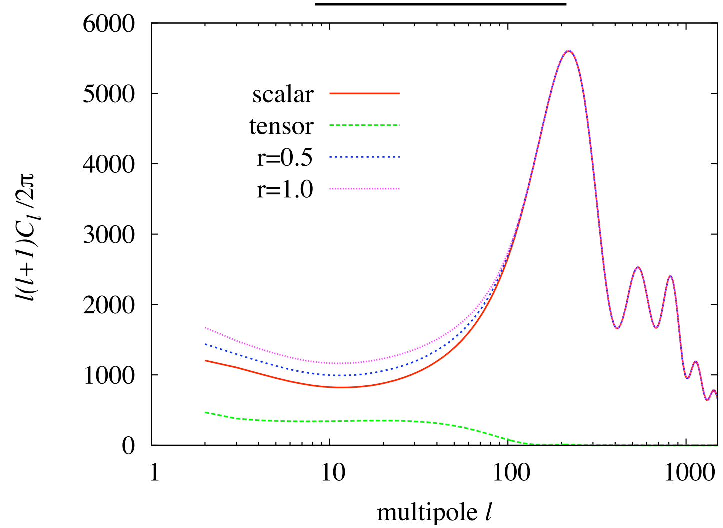


(w=-0.8)

Running of scalar spectral index

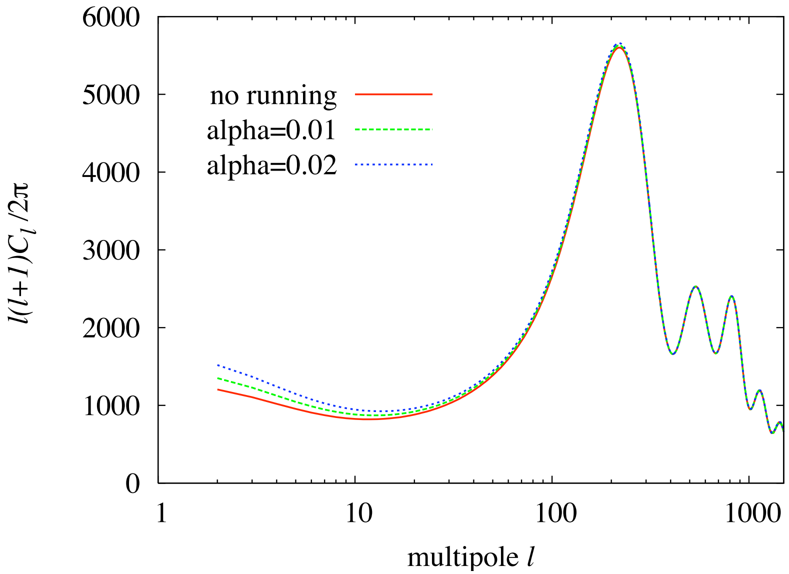


tensor mode

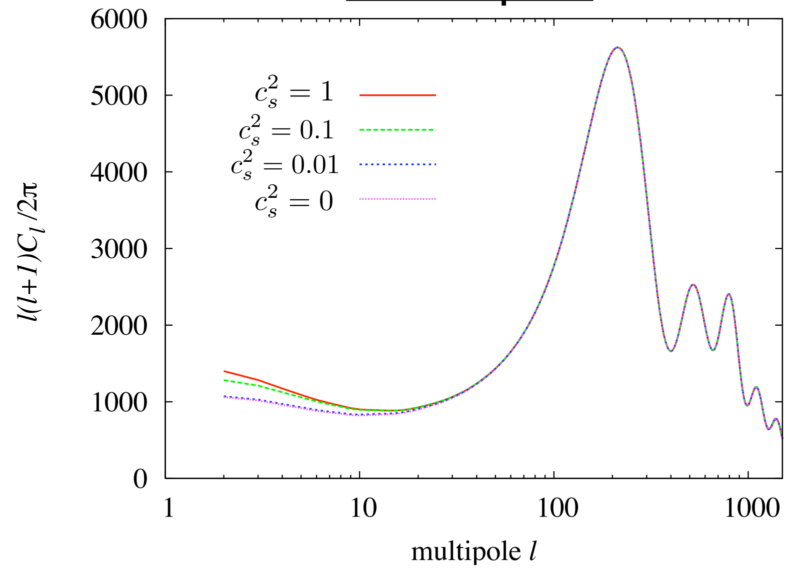


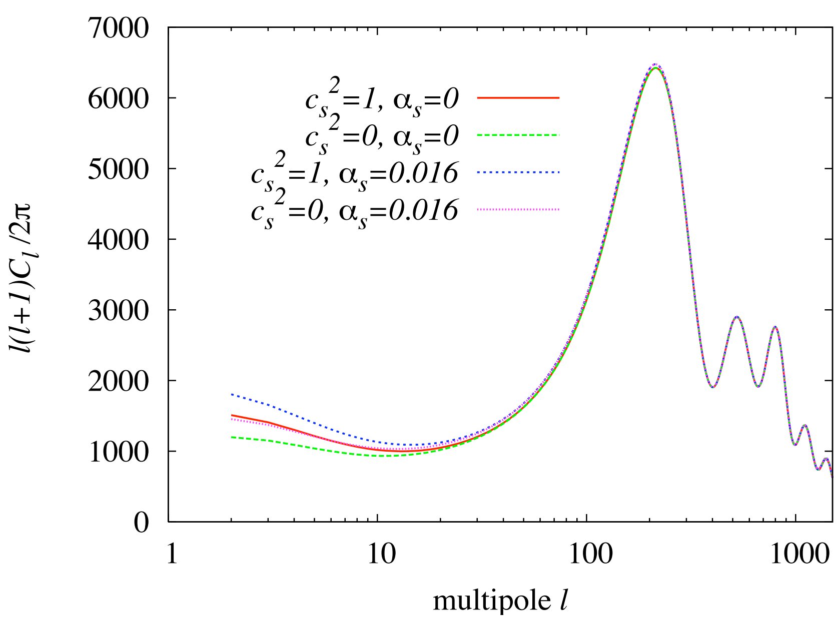
Dark energy fluctuation and the running of spectral index

Running of scalar spectral index



Sound speed





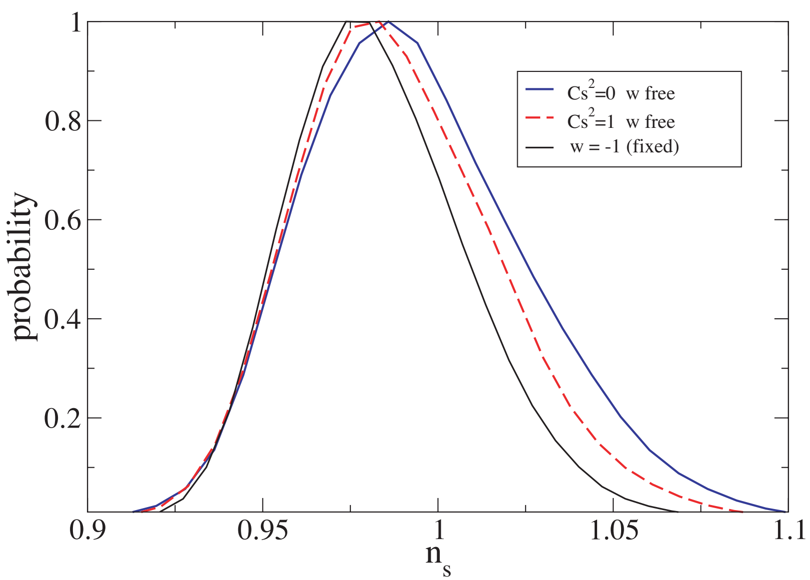
→ Degeneracy between the running and the sound speed

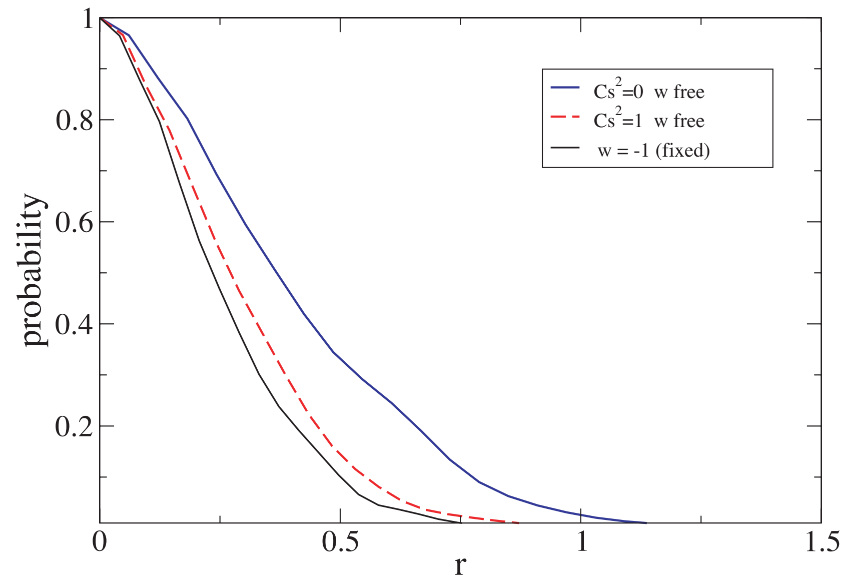
Constraint on the scalar spectral index and tensor-to-scalar ratio

- For some different values of c_s^2 and α

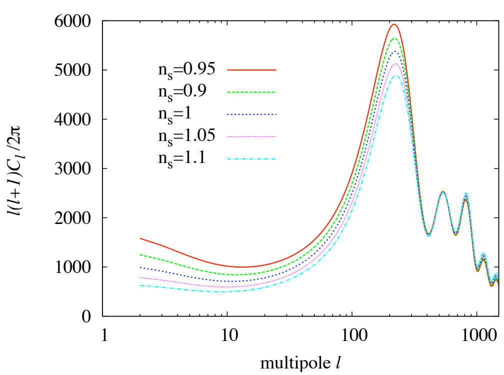
[Ichiki & TT in preparation]

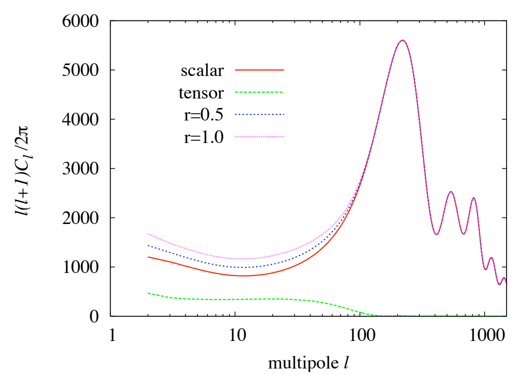
(Using MCMC approach)





[WMAP+HST]





- The nature of DE can also affect the constraints on the running spectral index.

4. Summary

- Current precise cosmological observations can constrain the equation of state for dark energy, severely in some cases.

- A cosmological constant is allowed (in almost all analysis), however, various kinds of dark energy can also still be allowed.

- The nature of dark energy also affects other aspects of cosmology (such as constraints on the curvature, primordial fluctuation, ...).

- Dark energy is one of the most important problems in today's science. We need to keep working on it.