Elucidating Dark Energy with 21 cm line observation

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◇ Dynamical dark energy

Expansion ratio of the Universe (Hubble parameter)

$$H^2 = H_0 \left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \boxed{\Omega_X \exp\left[3 \int_a^1 \frac{da'}{a'} (1 + w_X(a')) \right]} \right]$$

Contribution of the dark energy

Comoving distance：

$$d(z) = \int_0^z \frac{dz'}{H(z')}$$

Equation of state (EOS)

$$w_X(a') \equiv \frac{p_X(a')}{\rho_X(a')}$$

We investigate sensitivities of 21 cm line to the dynamical dark energy model ($w_X \neq$ constant).

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Dynamical dark energy model

Generally, EOS of dark energy $w_X(a')$ can depend on time.

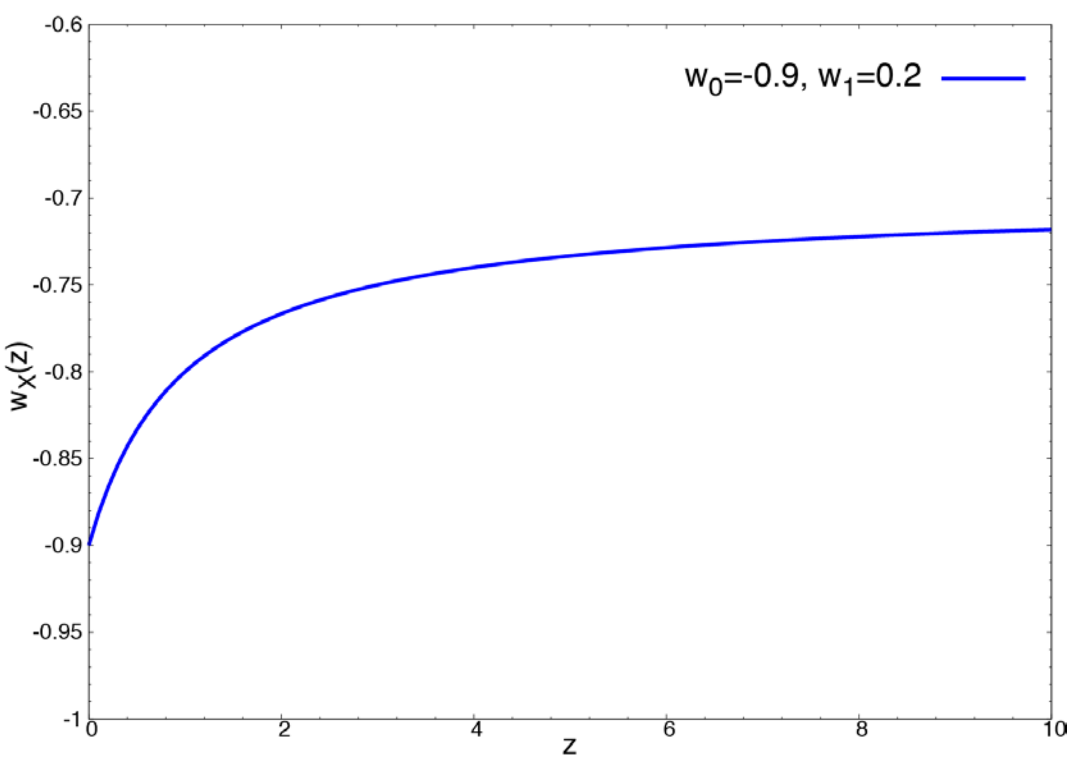
The evolution depends on dark energy models.

In this work, we assume phenomenological parameters of EOS to make our analysis model-independent.

◆ Parametrization 1 [Chevallier, Polarski 2001; Linder 2003]

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

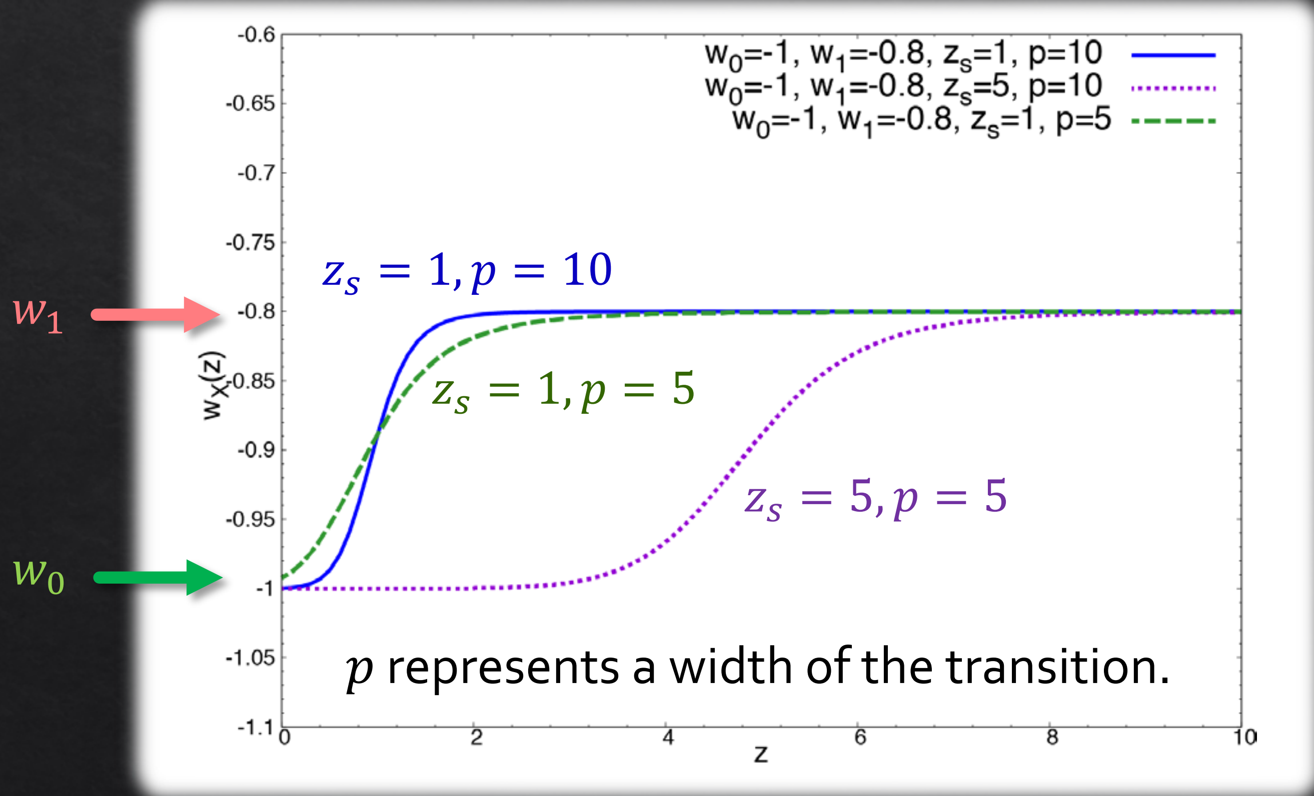
A very simple model : w_X is proportional to the scale factor a.



◆ Parametrization 2 [Hannestad, Mortsell 2004]

$$w_X(z) = w_0 w_1 \frac{a^p + a_s^p}{w_1 a^p + w_0 a_s^p} = w_0 w_1 \frac{1 + \left(\frac{1+z}{1+z_s}\right)^p}{w_1 + w_0 \left(\frac{1+z}{1+z_s}\right)^p}$$

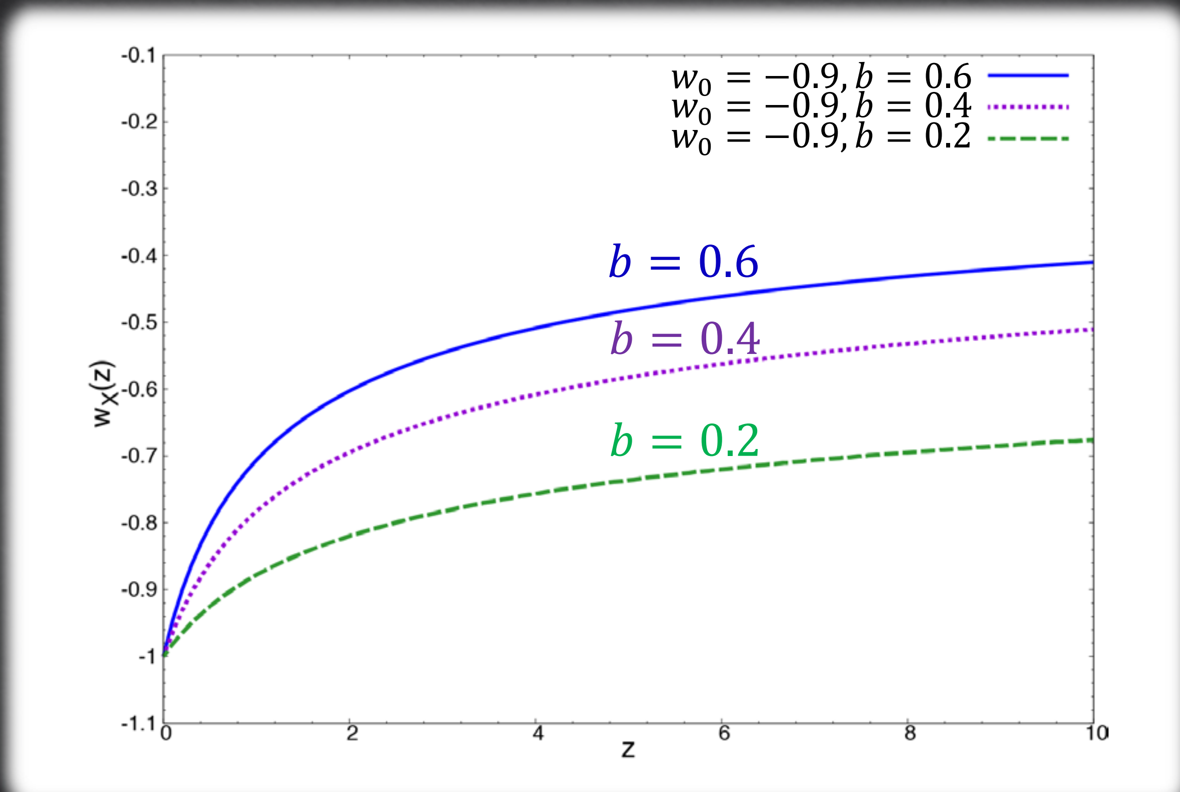
w_X suddenly changes at a transition redshift $z_s = \frac{1}{a_s} - 1.$



◆ Parametrization 3 [Wetterich 2004]

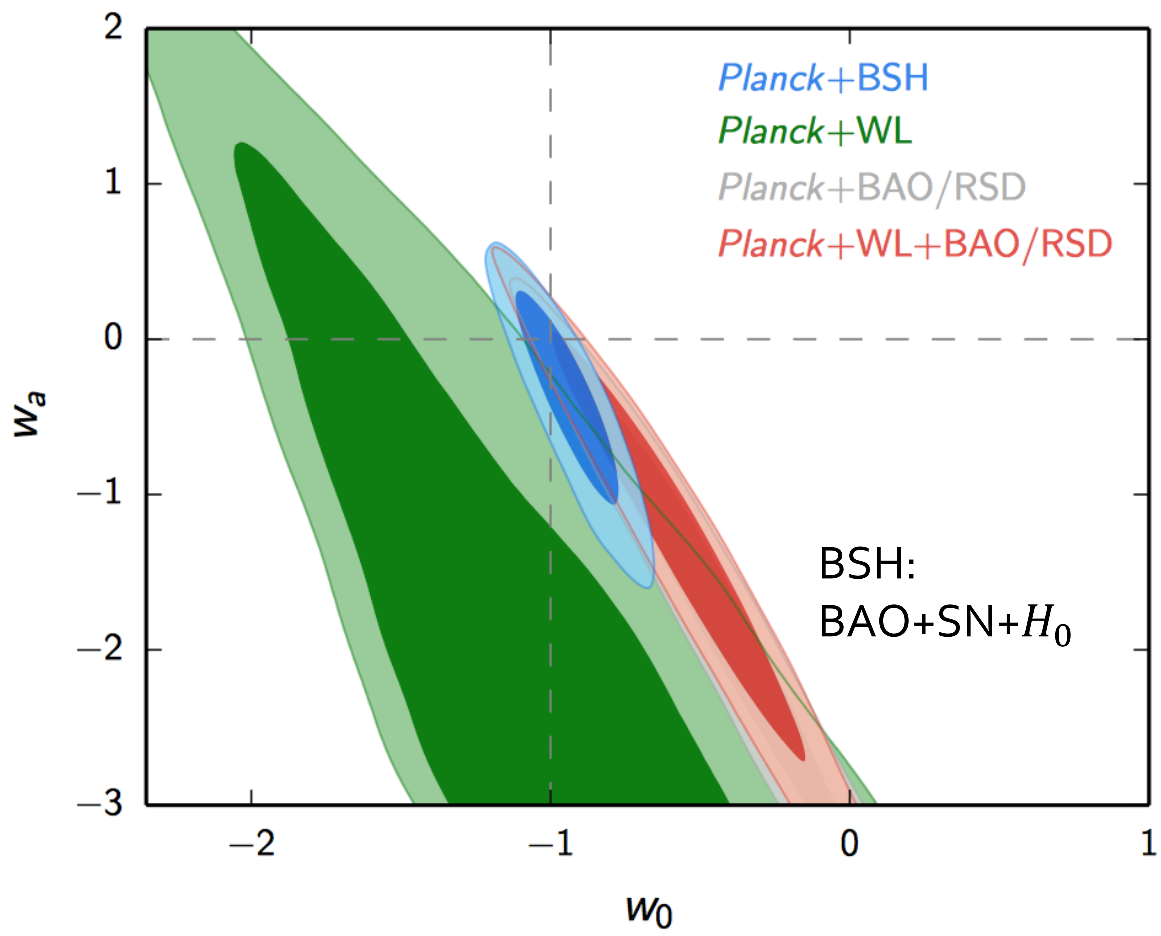
$$w_X(z) = \frac{w_0}{[1 + b\log(1+z)\,]^2}$$

Early dark energy : the contribution of dark energy has a relatively large impact in the early epoch.



◆ Current constraint of dynamical dark energy

Planck 2015 (Parametrization 1)



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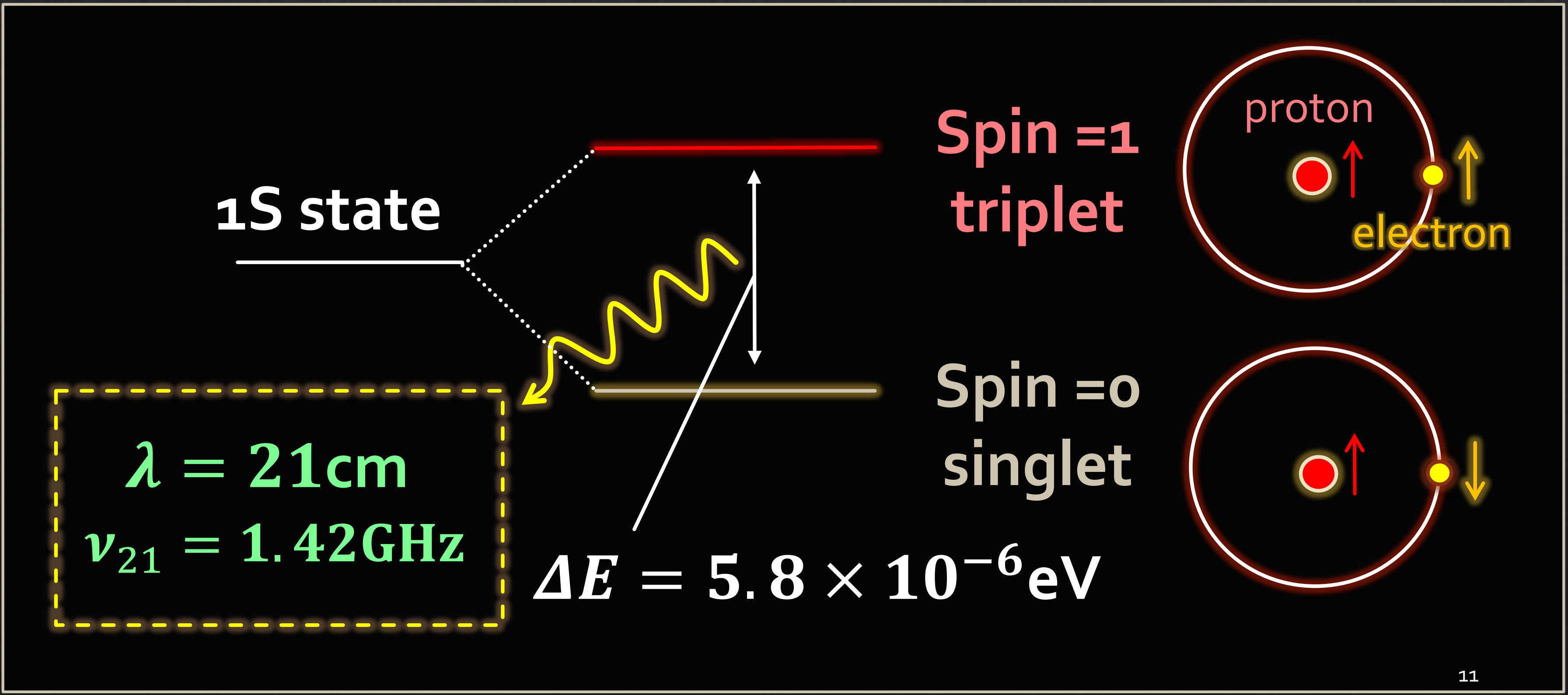
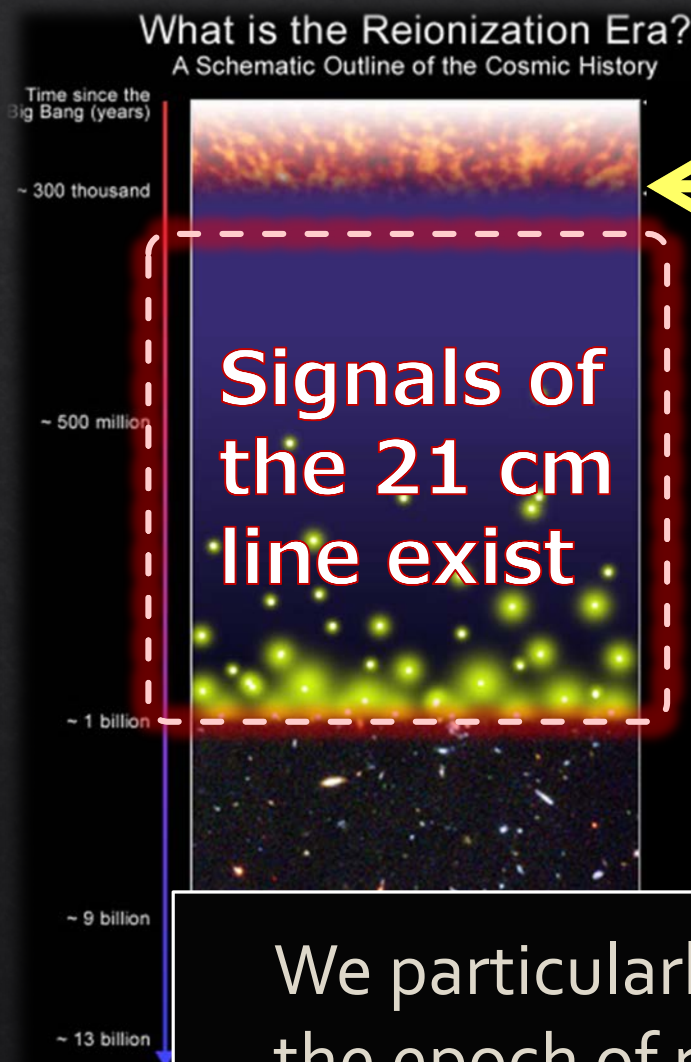
◇ 21cm line

21cm line results from **hyperfine splitting** of **neutral hydrogen**.



◇ Cosmological 21 cm radiation



S.G. Djorgovski et al. & Digital Media Center, Caltech.

CMB $z \sim 1000$

Dark age

Cosmic dawn $15 \lesssim z \lesssim 30$
(The late stage of the dark age)

The epoch of reionization

$6 \lesssim z \lesssim 15$

We particularly focused on
the epoch of reionization ($7 \lesssim z \lesssim 10$)

◇ Brightness temp T_b of 21 cm line

$$\Delta T_b \equiv T_b - T_{CMB}$$

$$\Delta T_b\left(\frac{\nu_{21}}{1+z}, \boldsymbol{r}, z\right) \approx 27 x_{\mathrm{HI}}(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{\frac{1}{2}}$$

$$\times\left[1-\frac{T_{\mathrm{CMB}}}{T_S}\right]\left[\frac{H(z)/(1+z)}{dv_{||}/dr_{||}}\right]\mathrm{mk}$$

Fluctuation of baryon

$\boldsymbol{T_b}$: Brightness temp of 21 cm line

$\boldsymbol{T_S}$: Spin temp

$\boldsymbol{T_{\mathrm{CMB}}}$: CMB temp

x_{HI}: Neutral fraction

$\boldsymbol{T_S > T_{\mathrm{CMB}}}$ **emission** （$6 \lesssim z \lesssim 15$）

$\boldsymbol{T_S < T_{CMB}}$ **absorption** （$15 \lesssim z$ ）

◆ Power spectrum of 21cm line : P_{21}

Fluctuation of 21 cm line $\delta_{21} \equiv \frac{\Delta T_b \ - \Delta \bar{T}_b}{\Delta \bar{T}_b}$

Its power spectrum is

$$P_{21}(\boldsymbol{u}) = \frac{1}{d_A(z)^2 y(z)} P_{21}(\boldsymbol{k})$$

$d_A(z)$: commoving angular diameter distance

$$y(z) = \frac{\lambda_{21}(1+z)^2}{H(z)}$$

<u>$\boldsymbol{u}$: u-space vector</u>

Fourier dual of angle θ_x, θ_y and frequency (line of sight direction) space: $\boldsymbol{\Theta} \equiv \theta_x \mathbf{e_x} + \theta_y \mathbf{e_y} + \Delta f \, \mathbf{e_z}$

$$\boldsymbol{u} = (u_1, u_2, u_3) = \left(k_1 \frac{d_A(z)}{2\pi}, , k_2 \frac{d_A(z)}{2\pi} k_3 \frac{y\ (z)}{2\pi} \right)$$

We can get information about $d_A(z)$ and $H(z)$ from this relation between k and u space.

◇ 21cm line observations

LOFAR

MWA

PAPER

21CMA

Next generation ～2020

◆ SKA (Square Kilometer Array)

in Australia

2018:
Construction starts.

http://www.skatelescope.org/

◆ Omniscope

From Max Tegmark's presentation

Max Tegmark,
Matias Zaldarriaga

Phys. Rev. D 82, 103501 (2010)

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◆ Fisher Information matrix F_{ij}

$$F_{\alpha\beta} \equiv \left\langle \frac{\partial^2 \ln L(\boldsymbol{\theta}|\boldsymbol{x})}{\partial\theta_\alpha \partial\theta_\beta} \right\rangle$$

$L(\boldsymbol{\theta}|\boldsymbol{x})$:Likelihood function

$\theta_{\alpha\beta}$:theoretical parameters

$\boldsymbol{x}$:data vector

Cramér-Rao bound

$$V_{\alpha\beta}(\widehat{\boldsymbol{\theta}}) \geq (F^{-1})_{\alpha\beta}$$

$V_{\alpha\beta}(\widehat{\boldsymbol{\theta}})$: variance of $\hat{\theta}$

We can estimate minimum variance of $\hat{\theta}$.

◆ Cosmological parameter set

Fiducial parameters

$$\left(\Omega_m h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau, Y_p\right)$$

$$= (0.1417, 0.02216, 0.6914, 0.9611, 2.214 \times 10^{-9}, 0.0952, 0.25)$$

Parametrization of dark energy models

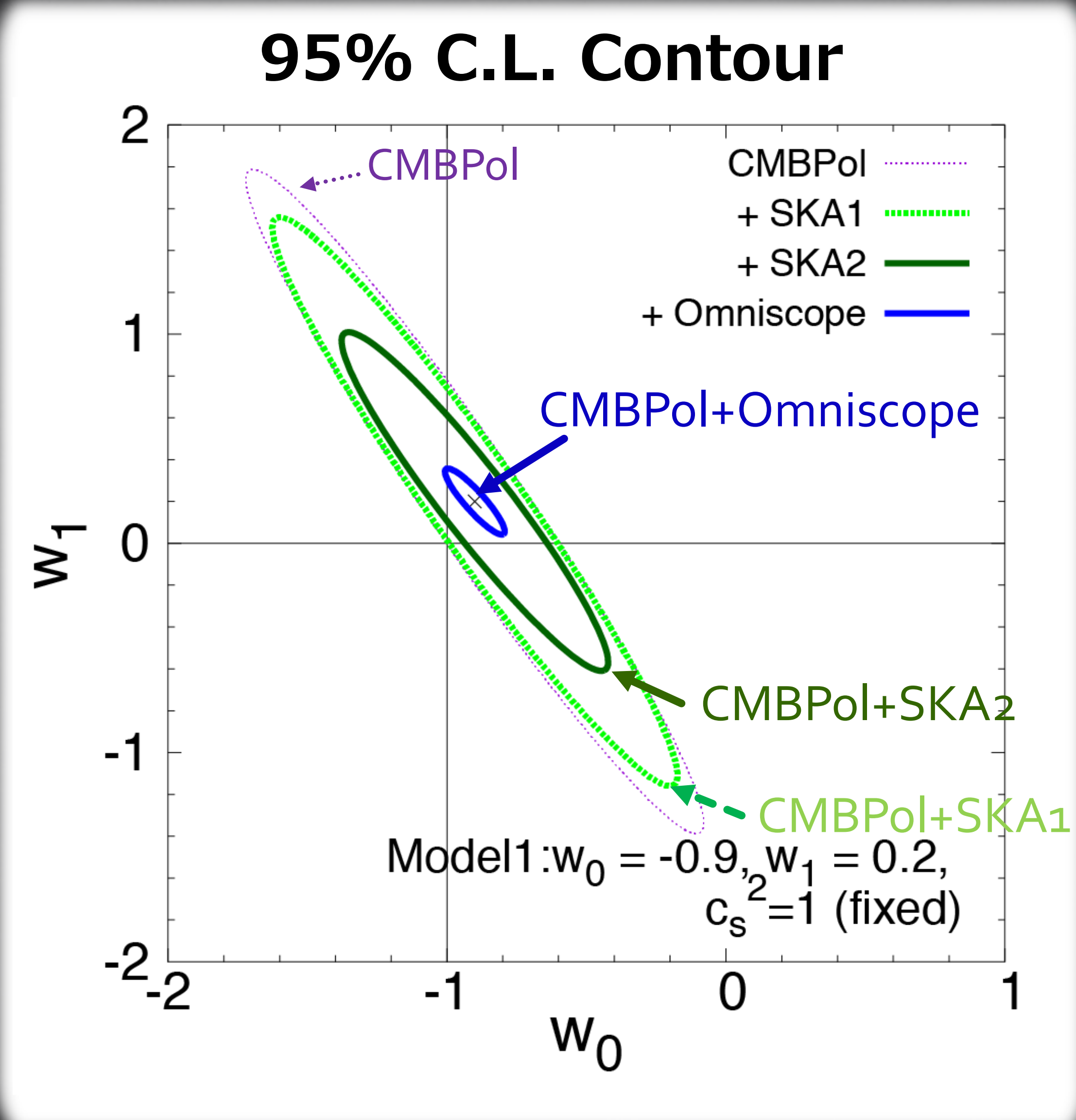
（1） Parametrization 1 $w_0 = -0.9, w_0 = 0.2$

（2） Parametrization 2 $w_0 = -0.9, w_0 = -0.35,$

$a_s = 0.5, p = 100$

（3） Parametrization 3 $w_0 = -0.9, b = 1$

◆ Expected constraint of Parametrization 1

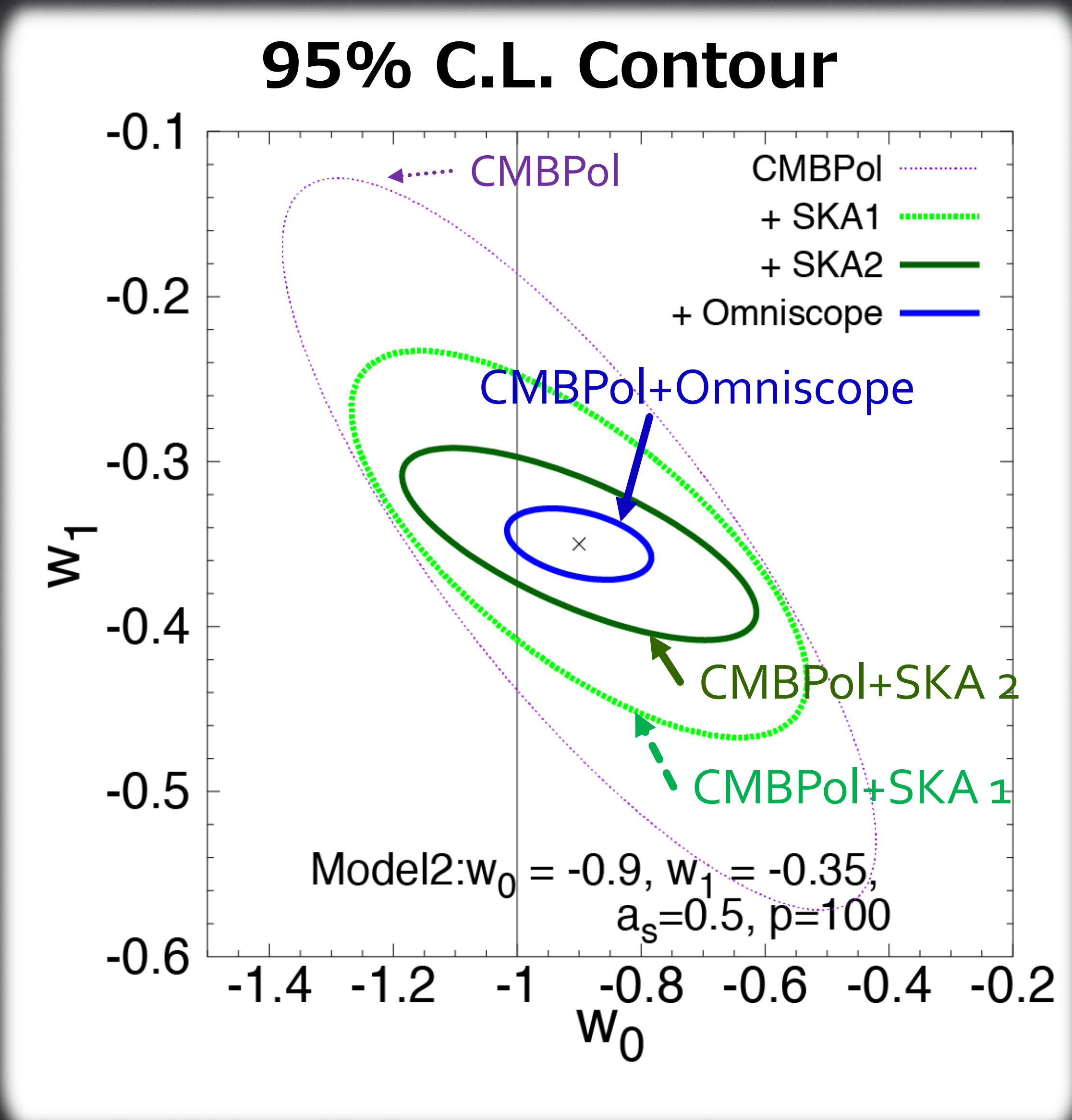


(Preliminary result)

CMBPol:
a future CMB satellite

Constraints of SKA 2 + CMB is twice as good as that of next generation CMB observation only.

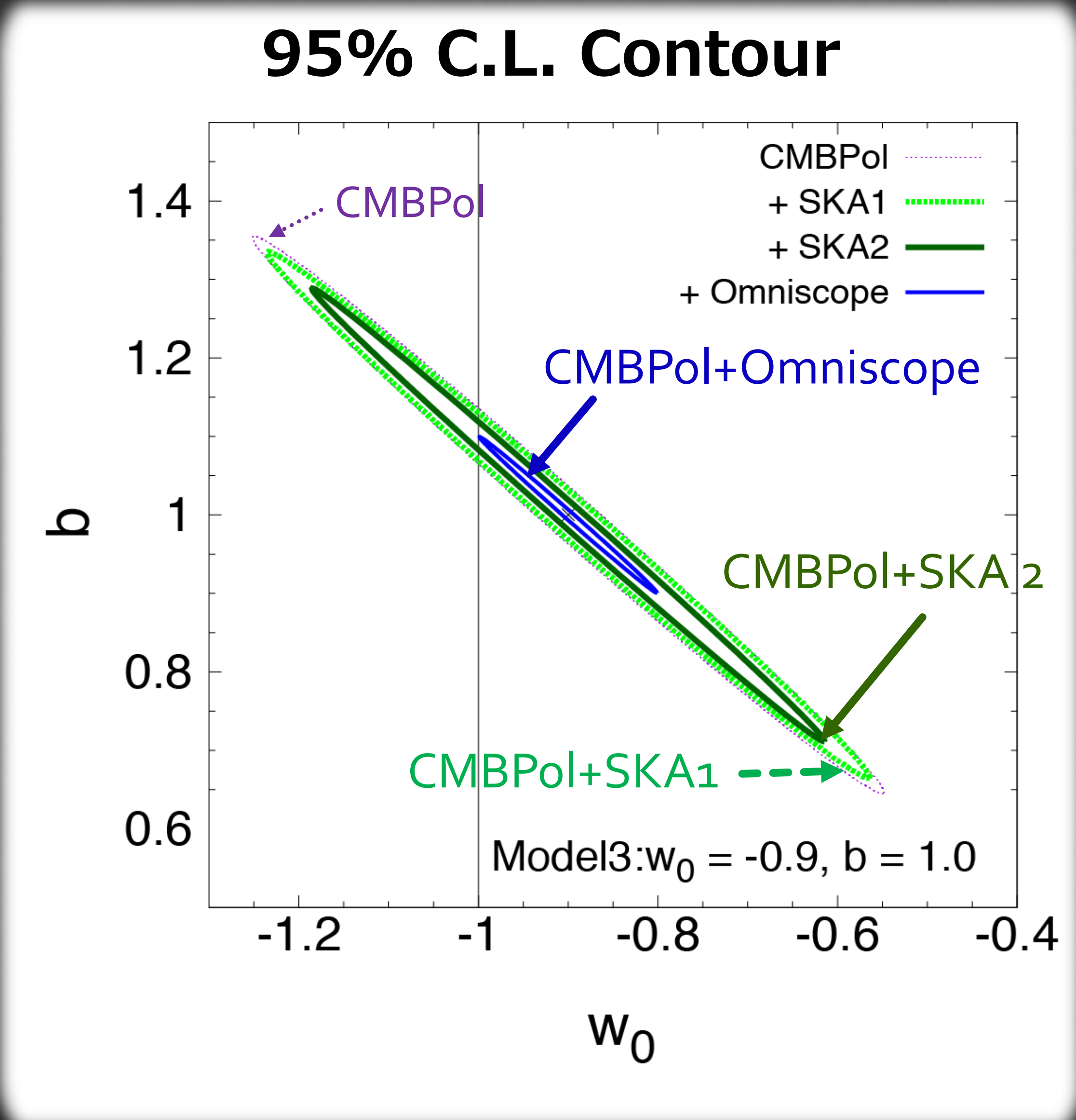
Expected constraint of Parametrization 2



(Preliminary result)

For $a_s \sim 0.5$, constraint of 21 cm + CMB is several times as good as that of CMB only.

◇ Expected constraint of Parametrization 3



(Preliminary result)

For the early dark energy model,
we need Omniscope level sensitivity.

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2. 21cm line observations

3. Future constraints of dynamical dark energy

4. Summary

4. Summary

- We studied sensitivities of **21cm line** to the **dynamical dark energy.**

- **CMBPol + SKA can strongly improve constraints of dynamical dark energy.**

- **For suddenly transition model,** constraint of 21 cm + CMB is **several times** as good as that of CMB only

- **For early dark energy model,**

  Ominiscope level sensitivity may be necessary.