将来の21cm線放射の観測による暗黒エネルギーの性質の解明

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観測的宇宙論ワークショップ　2015/11/19

◇ Dynamical dark energy

Expansion ratio of the Universe (Hubble parameter)

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

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 ($w_X \neq \text{constant}$).

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Dynamical dark energy model

一般にdark energyのEOS $w_X(a')$は時間依存

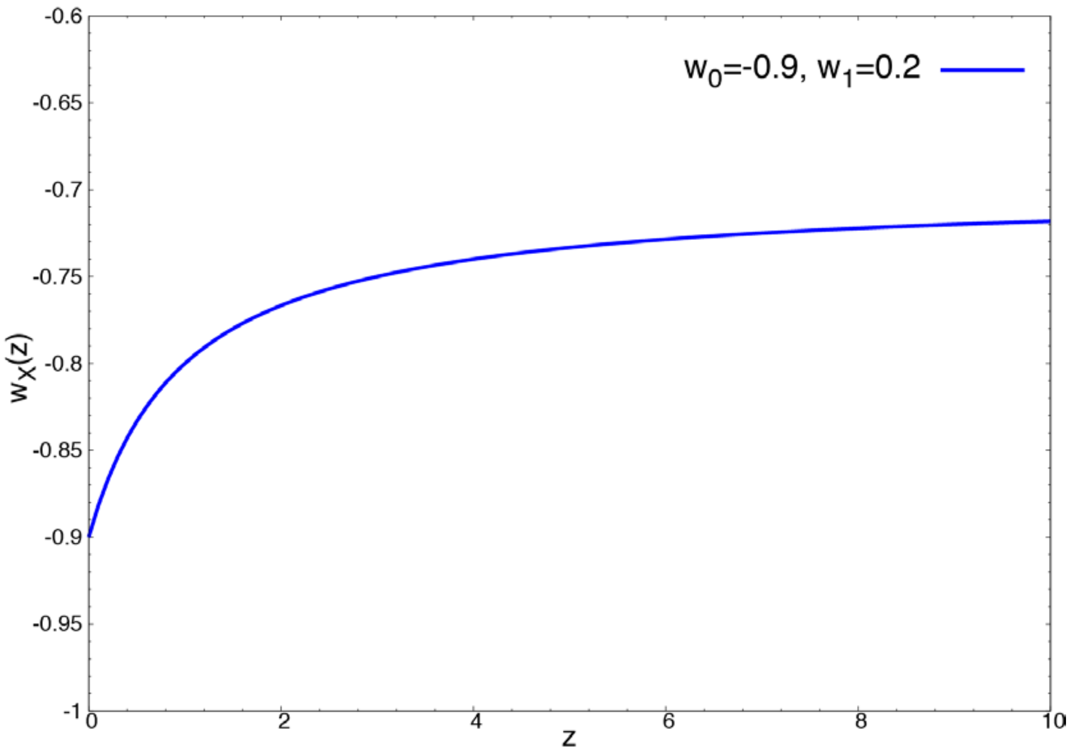
$w_X(a')$の時間依存性はモデルによって異なる

ここでは特定のmodelを用いず,
現象論的に数個のパラメータを導入することでEOSの時間依存性を表しそれらのパラメータを制限するという方法を考慮する

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

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

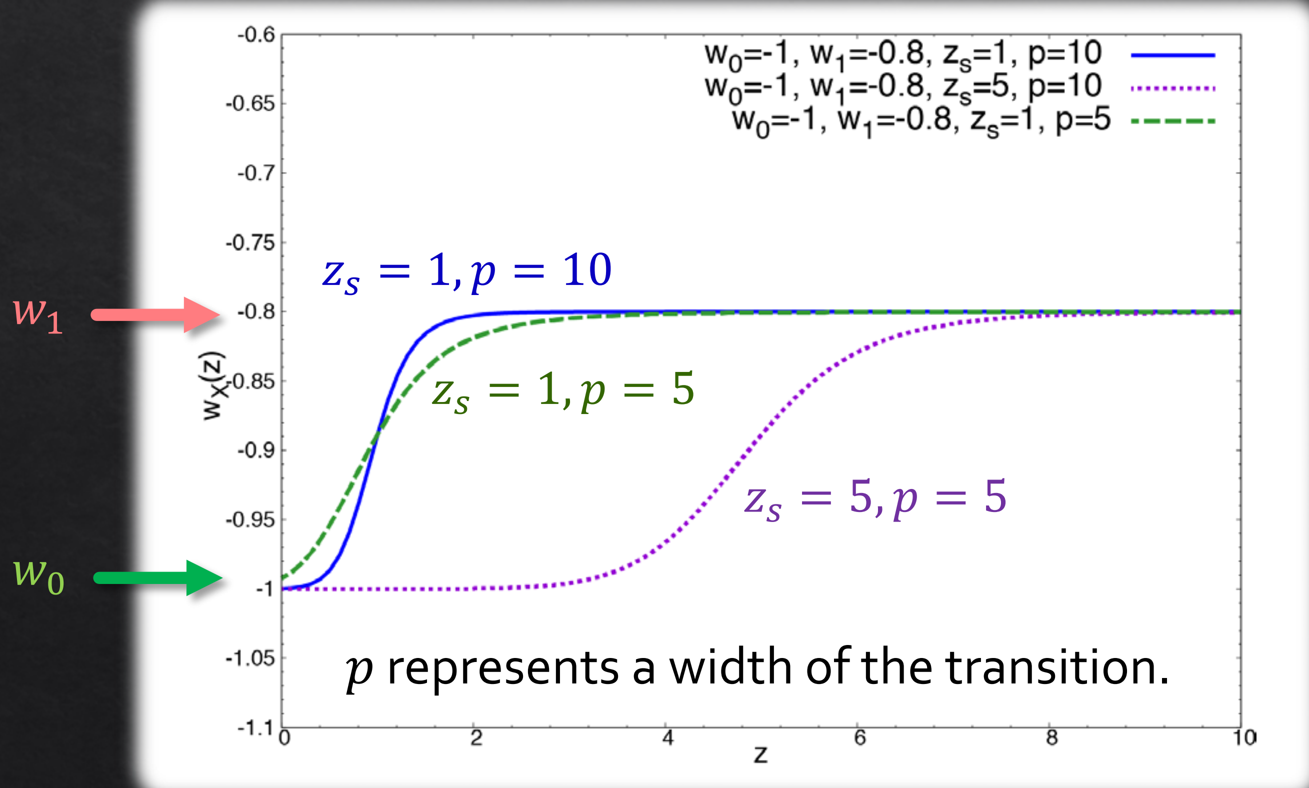
A very simple model : w_X is proportional to the scale factor a.



◆ 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 $z_s = \frac{1}{a_s} - 1$.

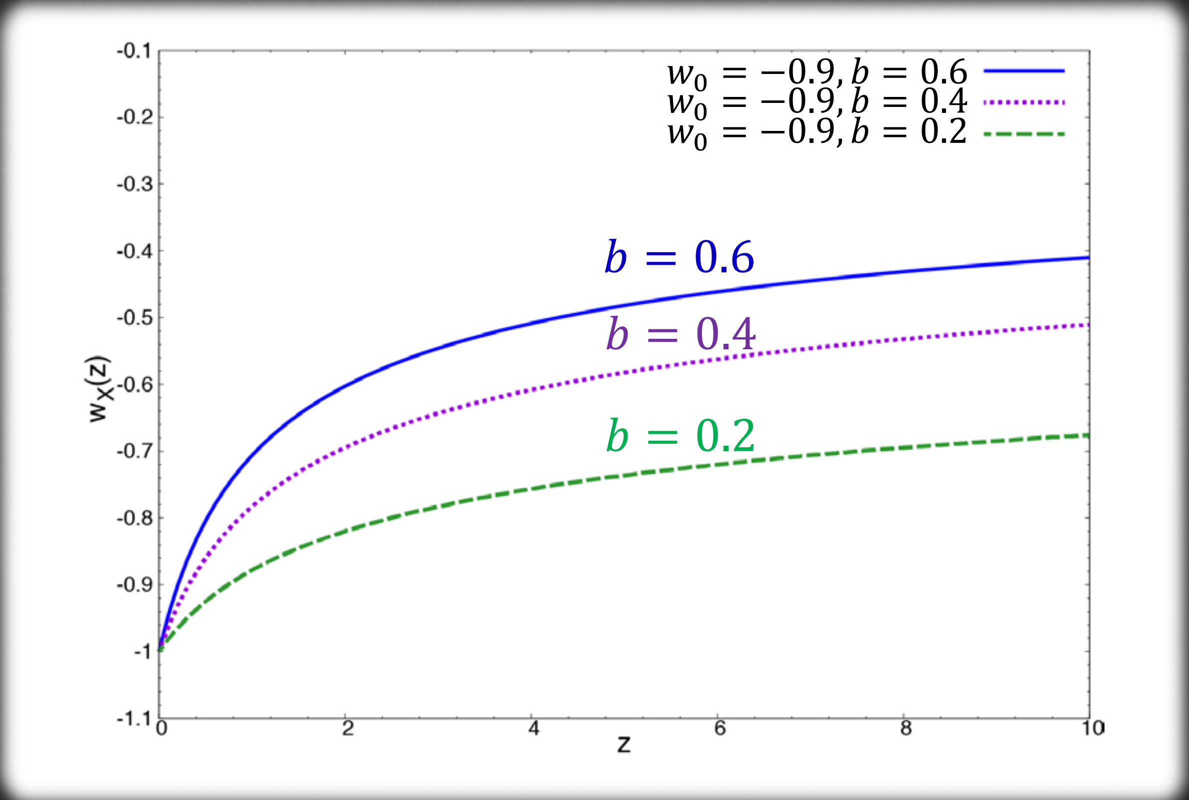


p represents a width of the transition.

Parametrization 3 [Wetterich 2004]

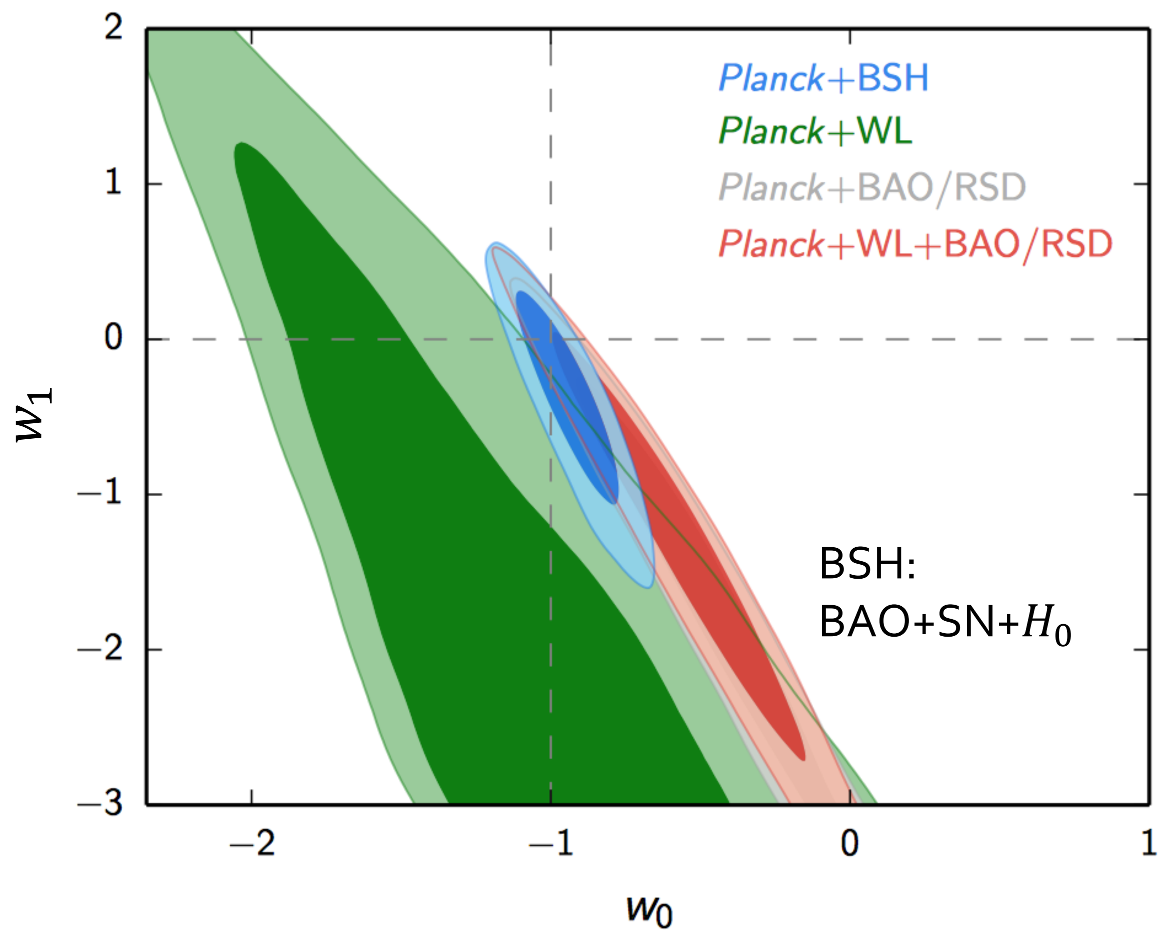
$$w_X(z) = \frac{w_0}{[1 + b\log(1+z)\,]^2}$$

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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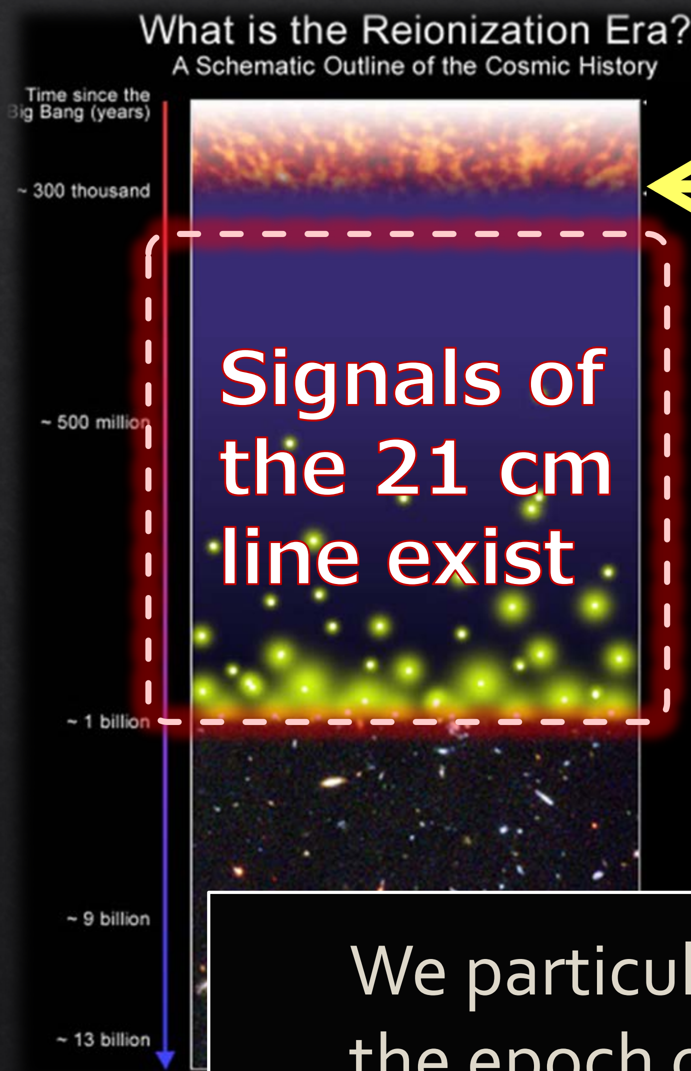
◇ Cosmological 21 cm radiation



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

CMB z~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.

◇ 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

T_b : Brightness temp of 21 cm line

T_S : Spin temp

T_{CMB} : CMB temp

x_{HI}: Neutral fraction

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

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

◇ スピン温度 T_S

T_Sの定義： $\frac{n_1}{n_0} \equiv \frac{g_1}{g_0} \exp\left(-\frac{h\nu_{21}}{k_B T_S}\right)$

n_1, n_0: スピン1, 0 状態の数密度

T_Sに影響する効果

(1) 水素原子，電子，陽子との衝突

(2) CMB光子の吸収，放射

(3) Lyα光子の吸収，放射

(4) 中性水素比x_{HI}の変化

$x_{HI} \equiv n_{HI}/n_H$

◇ 21cm line fluctuation δ_{21}

$$\delta_{21} \equiv \frac{\Delta T_b - \Delta \bar{T}_b}{\Delta \bar{T}_b}$$

$T_S \gg T_\gamma$: z~10

Baryon | Neutral fraction | Peculiar velocity $\equiv \frac{1+z}{H(z)} \frac{dv_{p||}}{dr}$

$$\delta_{21} \approx \delta_b + \delta_{x_{HI}} - \delta_{\partial v}$$

Fourier component (in matter dominated era)

$$\tilde{\delta}_{21} \approx \tilde{\delta}_b + \tilde{\delta}_{HI} + \mu^2 \tilde{\delta}_b, \quad \mu \equiv \frac{k_{||}}{|k|}$$

◇ Power spectrum of 21cm $P_{21}(k,\mu)$

$$\langle \tilde{\delta}_{21}(\boldsymbol{k})\tilde{\delta}^*_{21}(\boldsymbol{k}')\rangle \equiv (2\pi)^3\delta^D(\boldsymbol{k}-\boldsymbol{k}')\, P_{21}(k,\mu)$$

$$P_{T_b} \equiv \left(\bar{T}_b\right)^2 P_{21}$$

$$= \left(\bar{T}_b/\bar{x}_{\rm HI}\right)^2 \left\{ \left[\bar{x}_{\rm HI}^2 P_{\delta\delta} - 2\bar{x}_{\rm HI}P_{\rm x\delta} + P_{\rm xx}\right] + 2\mu^2\left[\bar{x}_{\rm HI}^2 P_{\delta\delta} - \bar{x}_{\rm HI}P_{\rm x\delta}\right] + \mu^4 \bar{x}_{\rm HI}^2 P_{\delta\delta} \right\}$$

- $P_{\delta\delta}$: Matter power spectrum
- $P_{\rm x\delta} = \bar{x}_i\ P_{\delta_x\delta}$: Density-ionization power spectrum
- $P_{\rm xx} = \bar{x}_i^2 P_{\delta_x\delta_x}$: Ionization power spectrum

Ionization fraction : $x_i = 1 - x_{\rm HI}$

◆ u-space vector : $\boldsymbol{u}$

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

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

$\boldsymbol{u}$: u-space vector

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)**

http://www.skatelescope.org/

in Australia

2018:
Construction starts.

◆ **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

$$\left(\Omega_m h^2, \Omega_b h^2, \Omega_\Lambda, n_s, A_s, \tau, Y_p\right)$$
$$= (0.1417, 0.02216, 0.6914, 0.9611, 2.214 \times 10^{-9}, 0.0952, 0.25)$$

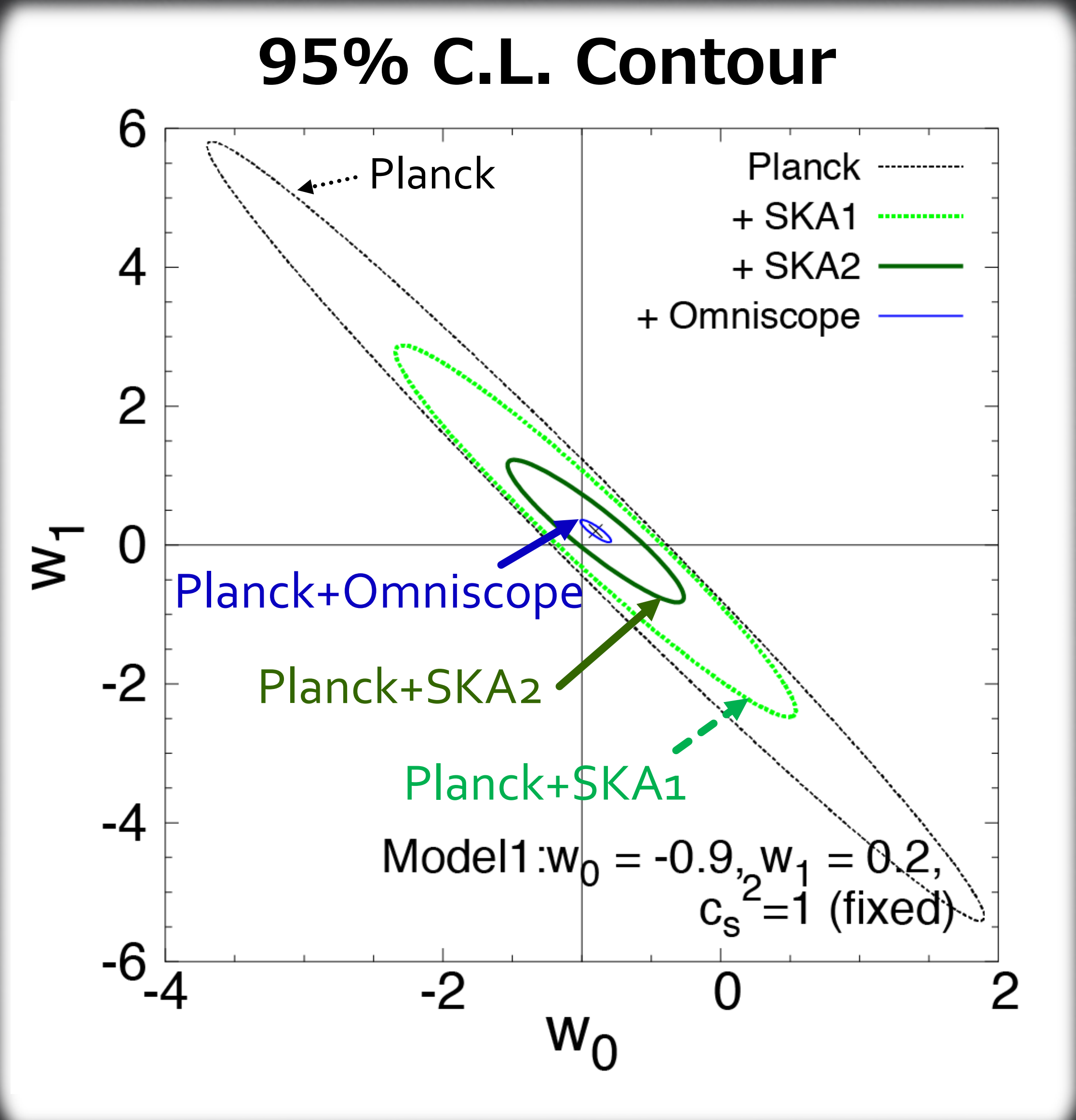
Parametrization of dark energy models

（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 $w_0 = -0.9, b = 1$

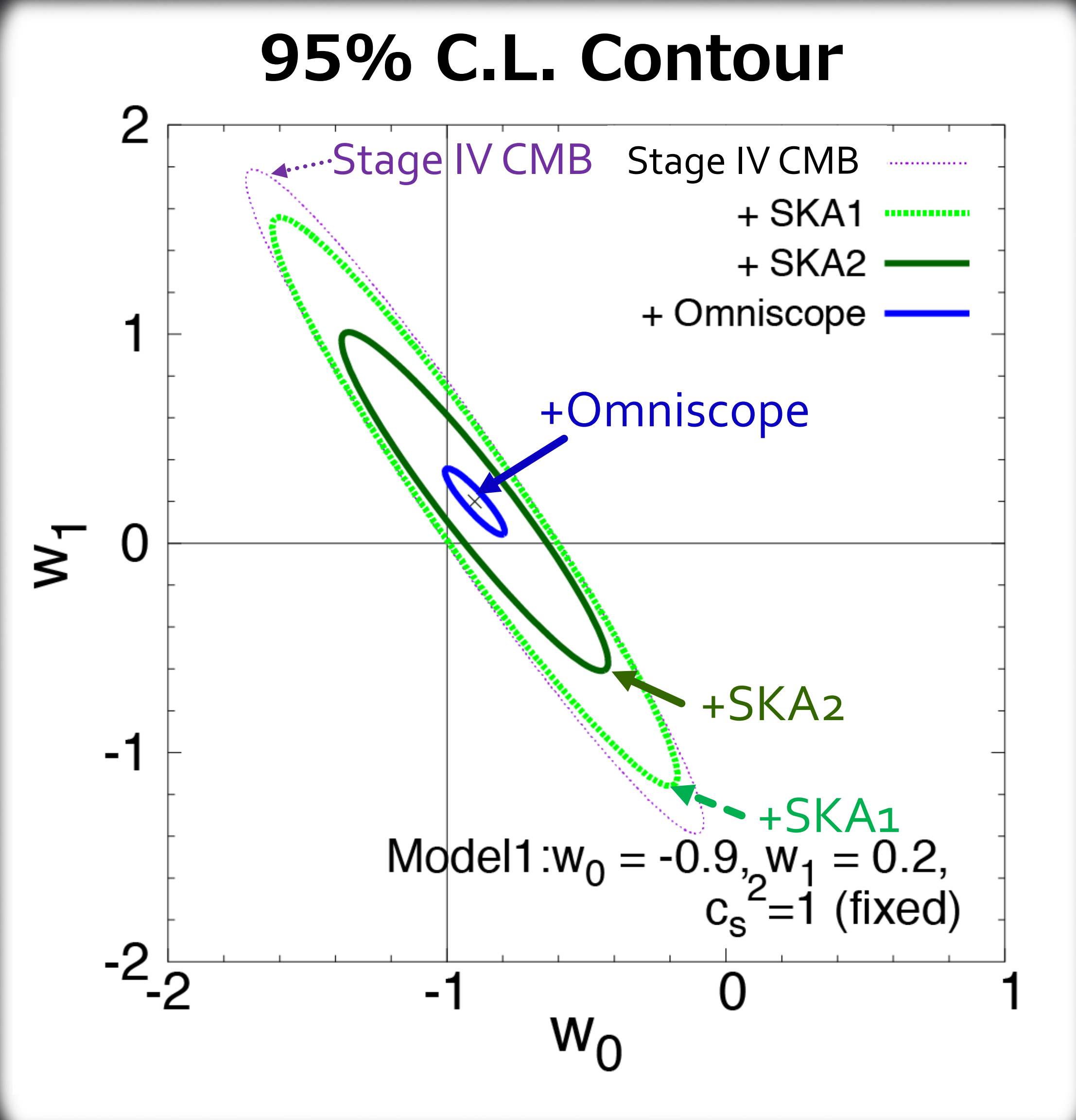
◇ Expected constraint of Parametrization 1



(Preliminary result)

A constraint of SKA 1 + Planck is twice as good as that of Planck only.

◆ Expected constraint of Parametrization 1

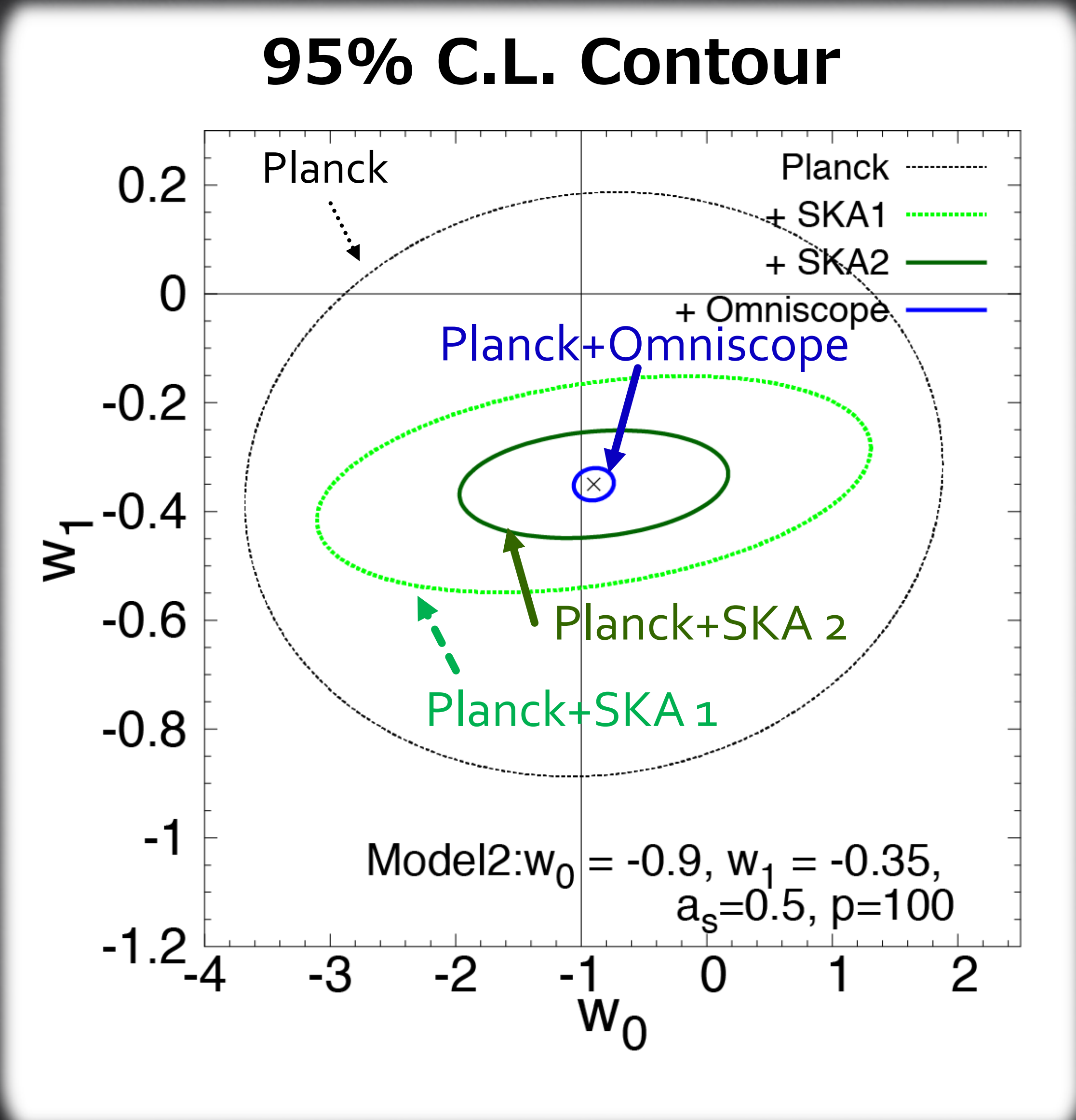


(Preliminary result)

Stage IV CMB:
(we assume a CMBPol like experiment)

A constraint of SKA 2 + stage IV CMB is twice as good as that of Stage IV CMB only.

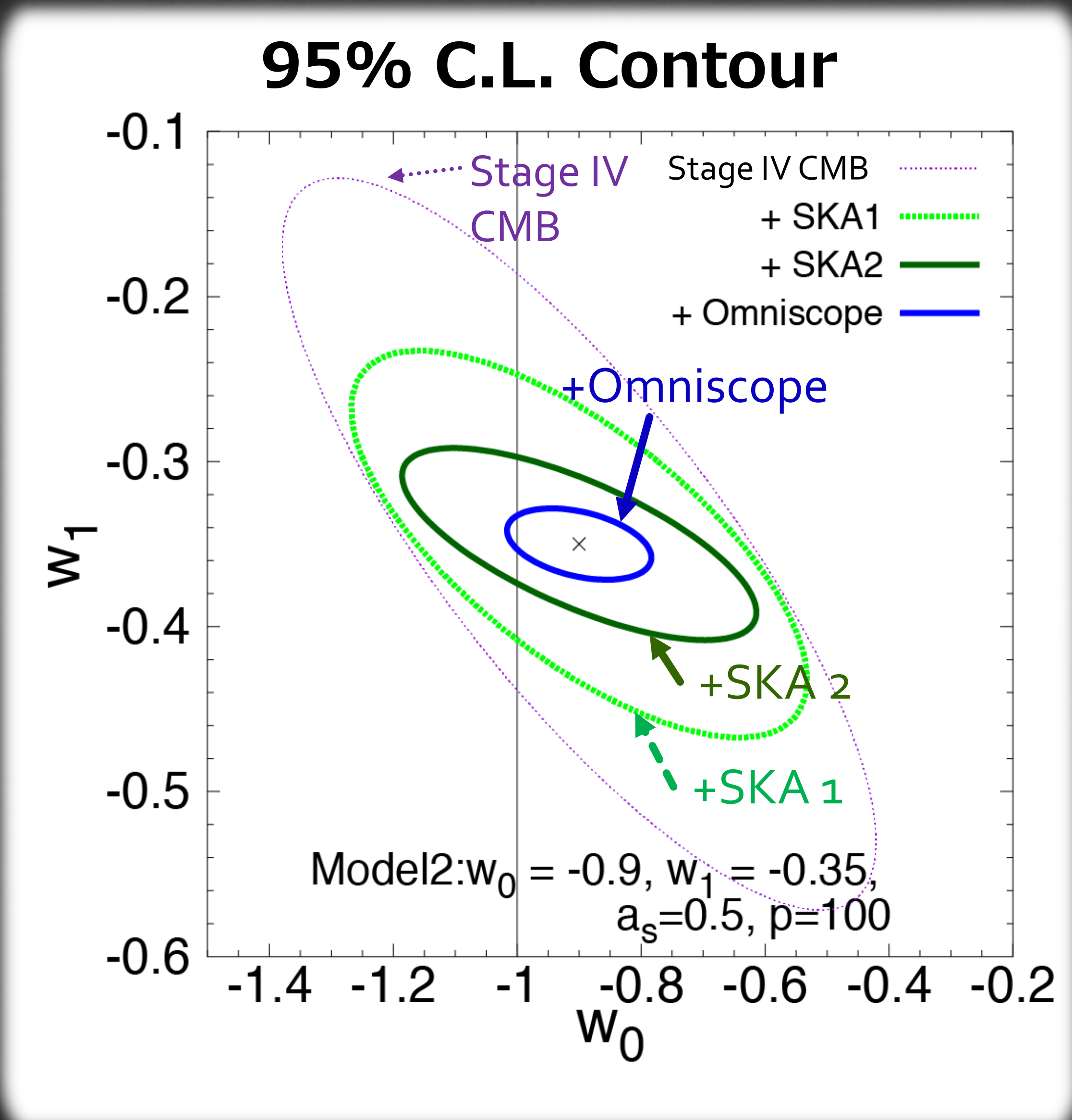
◇ Expected constraint of Parametrization 2



(Preliminary result)

For $a_s \sim 0.5$, constraints of 21 cm + Planck are several times as good as that of Planck only.

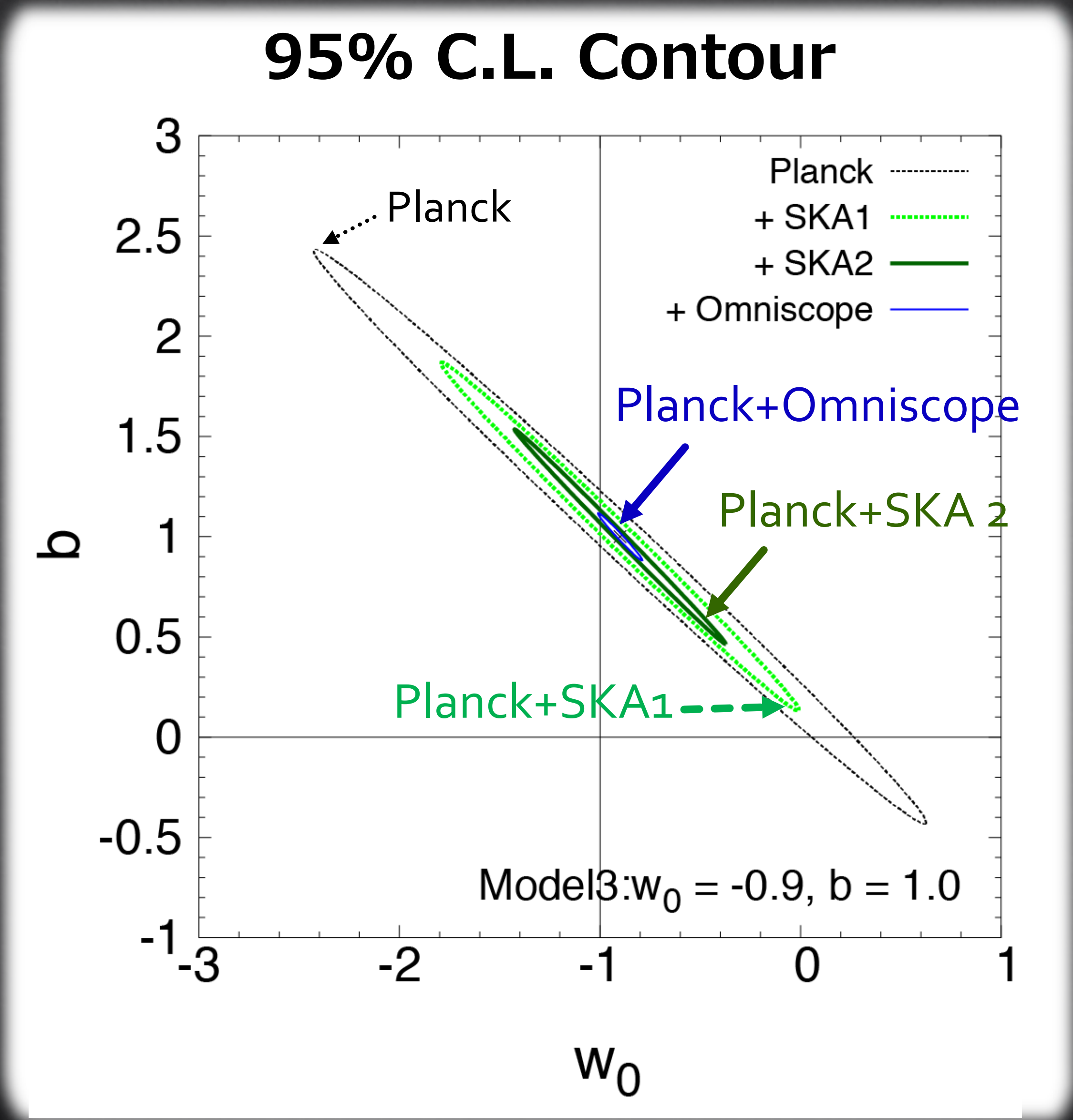
Expected constraint of Parametrization 2



(Preliminary result)

For $a_s \sim 0.5$, constraints of 21 cm + stage IV CMB are several times as good as that of stage IV CMB only.

◇ Expected constraint of Parametrization 3

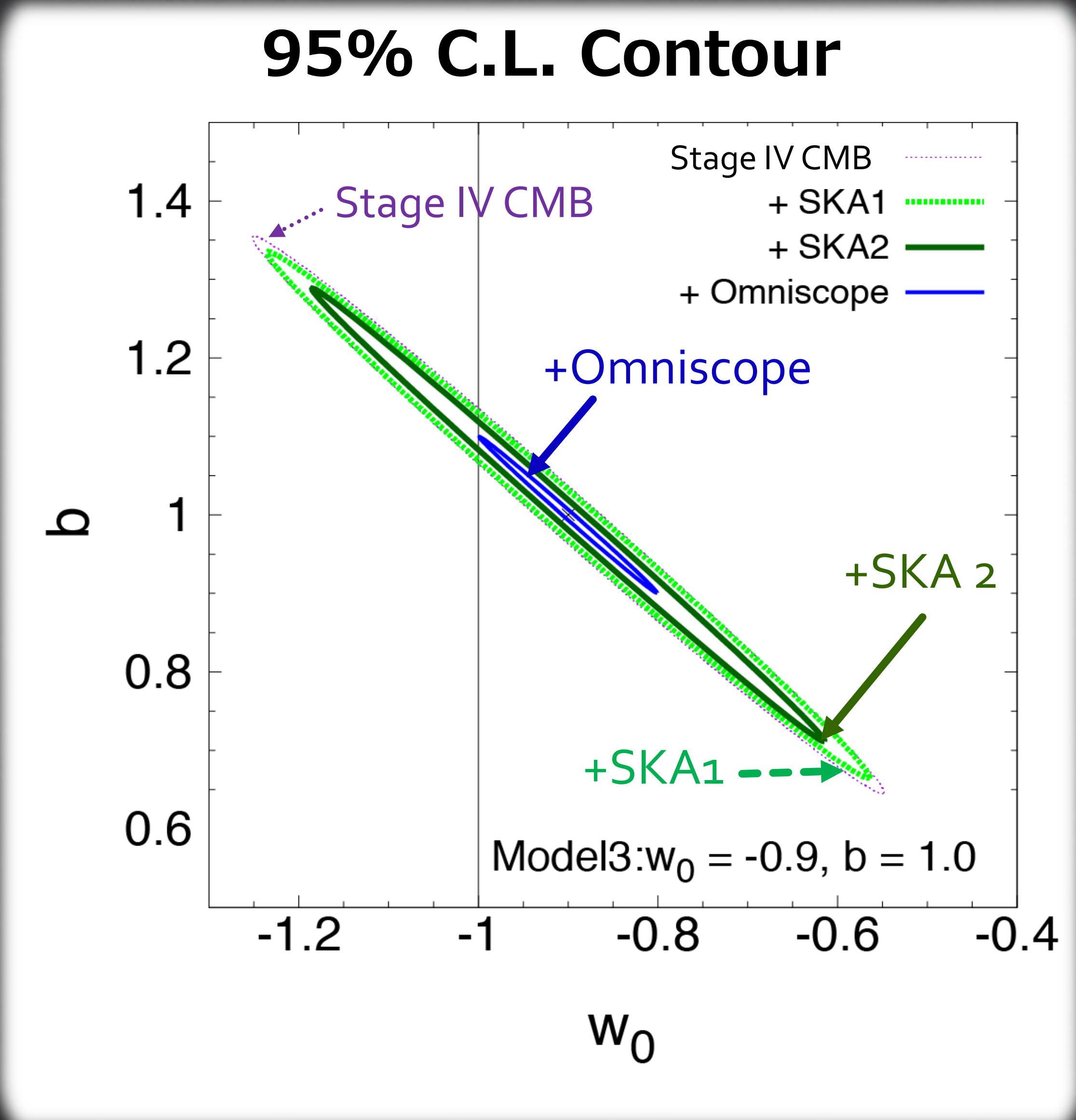


(Preliminary result)

For the early dark energy model, constraints of 21 cm + Planck are several times as good as that of Planck only.

◆ Expected constraint of Parametrization 3

(Preliminary result)



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4. Summary

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

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

- **For suddenly transition model,** constraints of 21 cm + Planck are **several times** as good as that of Planck only.

- **For early dark energy model,** constraints of the combination are **several times** as good as that of Planck only.

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