SKAによる再電離時の21CM線観測を用いた宇宙論パラメータの精密測定

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◇ 宇宙論における21cm線観測の利用

$\lambda_{21} = 21\ \mathrm{cm}$

物質分布（密度揺らぎ）の情報を持つ

宇宙論パラメータ（Ω_{CDM}等）を制限できる(CMB観測のように)

M.McQuinn, O.Zahn, M.Zaldarriaga, L.Hernquist, S.R. Furlanetto (2006) Astrophys.J.653:815-830,2006

◇ 宇宙論における21cm線観測の利用

今回は以下の内容について話します

◆ ニュートリノ質量

Y. Oyama, K. Kohri, M. Hazumi,
JCAP 1602, no. 02, 008 (2016).

◆ Dark energyのEOS

K. Kohri, Y. Oyama, T. Sekiguchi,
T. Takahashi, arXiv:1608.01601.

◆ 素粒子論モデルの制限

・軽いグラビティーノ
dark matterの質量

Y. Oyama, M. Kawasaki,
arXiv:1605.09191.

他にも

ゆらぎのスケール依存性, 非ガウス性などの
決定に有効である可能性が指摘されている

◆ Contents

1. 21cm線観測の概要

2. SKA等の将来の21cm線観測による宇宙論モデルの制限

   (1) ニュートリノ質量

   (2) Dark energy

   (3) 軽いグラビティーノdark matter

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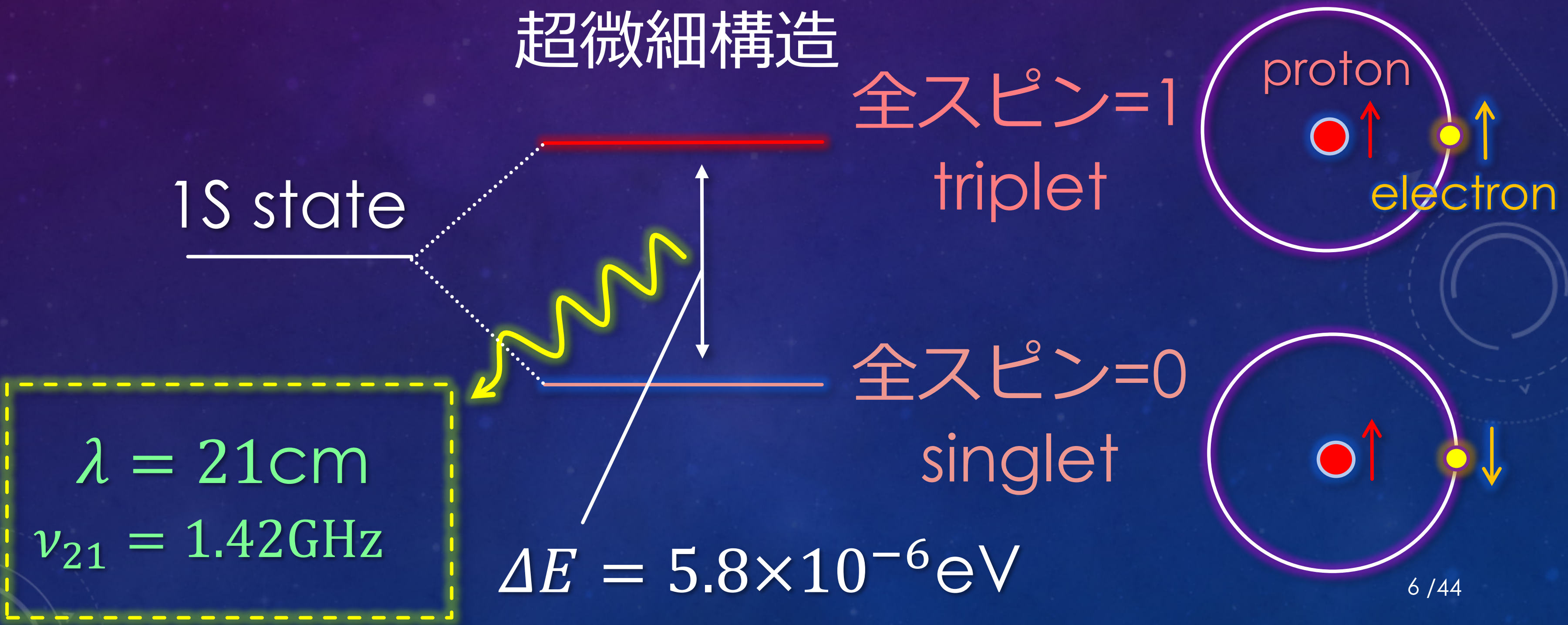
◇ 21cm線

中性水素原子の超微細構造が起源の電波

◆陽子・電子のスピン・スピン相互作用に起因



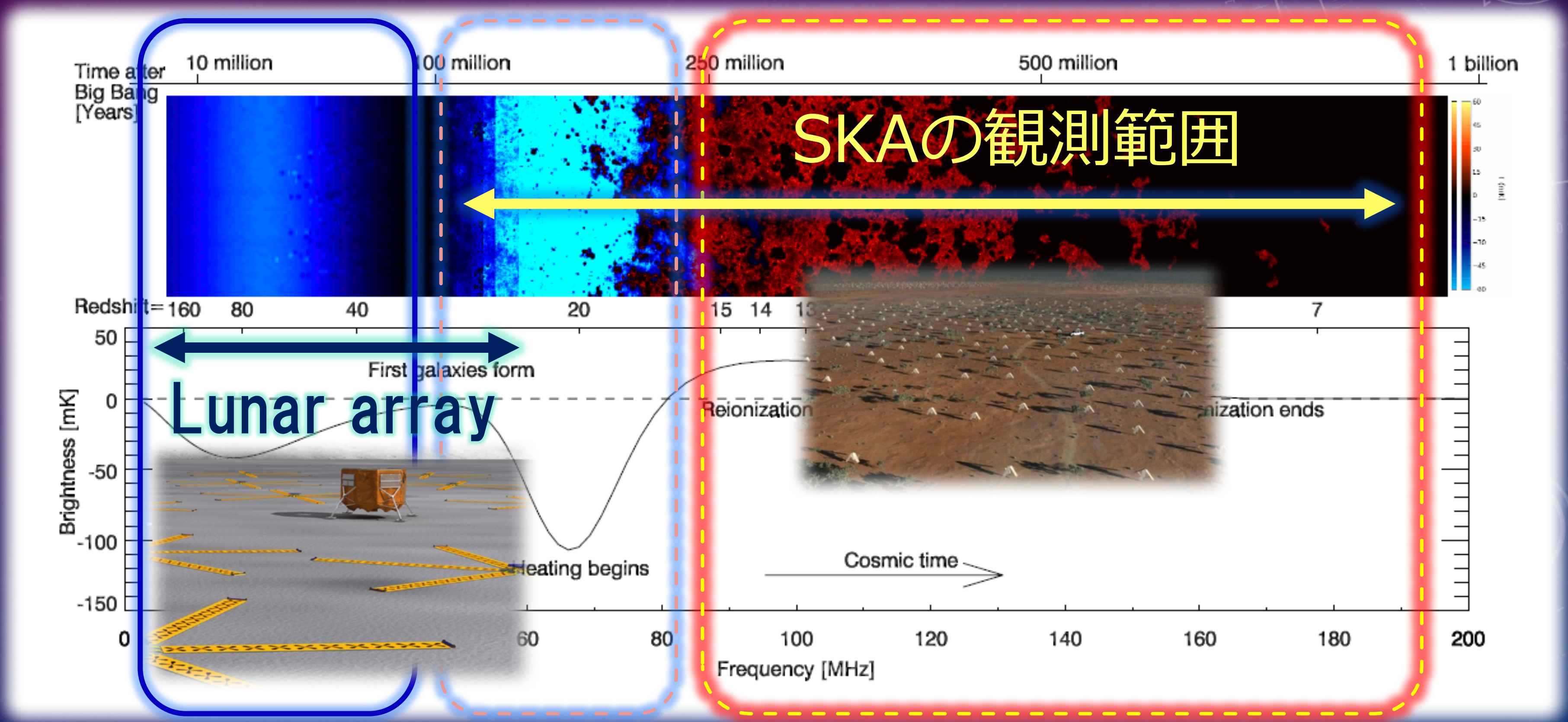
$\lambda = 21\mathrm{cm}$

$\nu_{21} = 1.42\mathrm{GHz}$

$\Delta E = 5.8\times10^{-6}\mathrm{eV}$

◇ 観測対象：Cosmic dawn–再電離

Dark age Cosmic dawn 再電離(reionization)



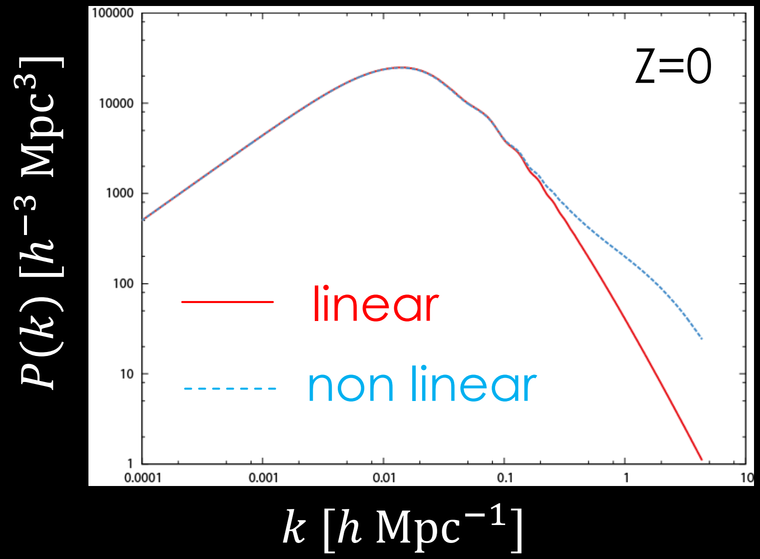
21cm線吸収線

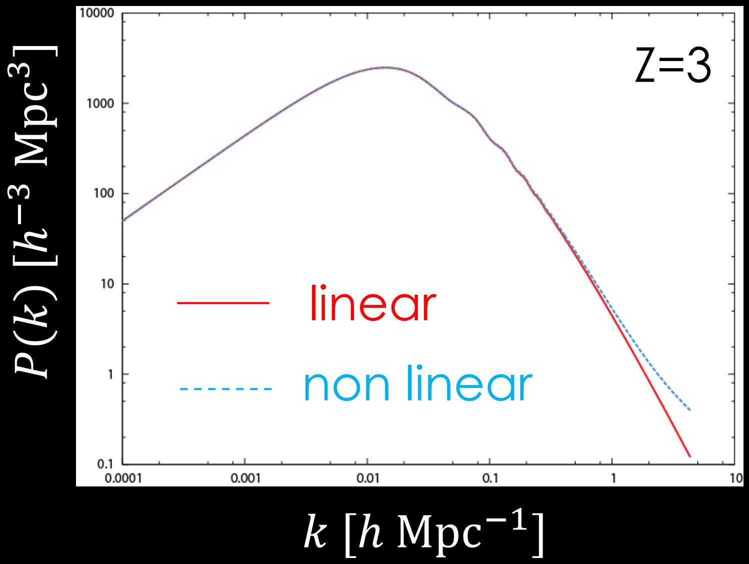
21cm線放射線

※ 下段のグラフは輝度温度 **J. R. Pritchard and A. Loeb**

◇ 21cm線観測の利点

1. high z ほど密度揺らぎの非線形性が小さい





2.広い赤方偏移の範囲の観測

独立な波数のmode + 密度揺らぎの時間発展

◇ 21cm線輝度温度：$\Delta T_b \equiv T_b - T_{\mathrm{CMB}}$

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

Fluctuation of baryon

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

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（$15 \lesssim z$)

Spin temperature : T_S

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

n_1, n_0: number density of spin 1, 0 state

T_S depends on the following,

(1) H-H, H-e, H-p collision

(2) CMB photon

(3) Lya photon

(4) Variation of neutral fraction x_{HI}

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

スピン温度の従う方程式

$$\frac{\partial}{\partial t}\left(\frac{T_{\nu_{21}}}{T_s}\right)=\frac{1}{n_0}\frac{\partial n_0}{\partial t}-\frac{1}{n_1}\frac{\partial n_1}{\partial t}$$

$$T_S, T_g, T_\alpha, T_{\mathrm{CMB}} \gtrsim T_{\mathrm{CMB0}} \approx 2.7K \gg T_{\nu_{21}} \equiv \frac{h\nu_{21}}{k_B} = 0.068\mathrm{K}$$

$$\frac{\partial}{\partial t}\left(\frac{1}{T_s}\right)=4\left[\boxed{C_{10}\left(\frac{1}{T_g}-\frac{1}{T_s}\right)}+\boxed{P_{10}\left(\frac{1}{T_\alpha}-\frac{1}{T_s}\right)}+\boxed{A_{10}\frac{T_{\mathrm{CMB}}}{T_{\nu_{21}}}\left(\frac{1}{T_\gamma}-\frac{1}{T_s}\right)}\right]$$

collision **Lya** **CMB Photon**

$$-\boxed{\frac{1}{x_{HI}}\frac{\partial x_{HI}}{\partial t}\frac{1}{T_s}}$$

x_{HI}の時間変化

平衡状態のスピン温度

$$\frac{\partial}{\partial t}\left(\frac{1}{T_s}\right) \approx 0, \qquad \frac{\partial x_{HI}}{\partial t} \approx 0$$

$$T_S = \frac{T_{\mathrm{CMB}} + y_c T_g + y_\alpha \, T_\alpha}{1 + y_c + y_\alpha}$$

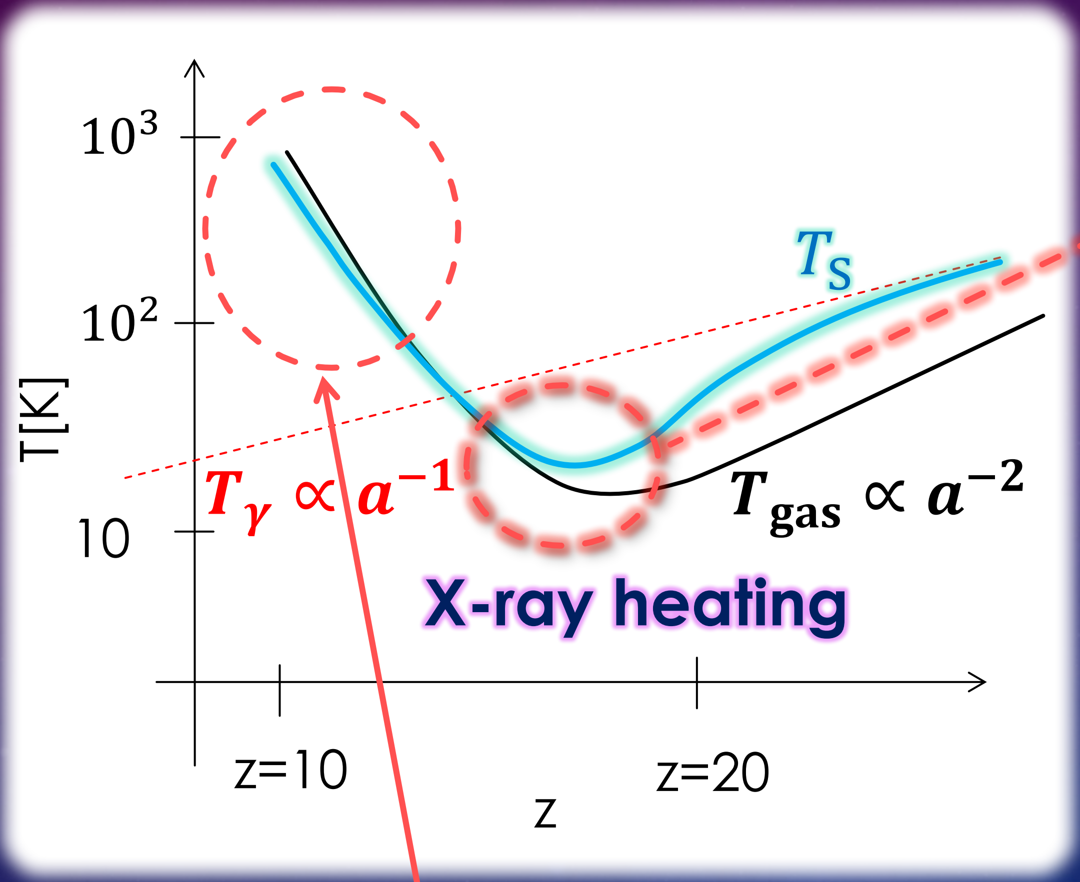
$$y_c \equiv \frac{C_{10}}{A_{10}} \frac{T_{21}}{T_g} \qquad y_\alpha \equiv \frac{P_{10}}{A_{10}} \frac{T_{21}}{T_\alpha} \qquad T_{\nu_{21}} \equiv \frac{h\nu_{21}}{k_B}$$

$$y_c \gg y_\alpha \, , 1$$
$$T_S \approx T_g$$

$$y_\alpha \gg y_c \, , 1$$
$$T_S \approx T_\alpha$$

$$1 \gg y_c \, , y_\alpha$$
$$T_S \approx T_{\mathrm{CMB}}$$

T_S at the reionization



$10 \lesssim z < 20$

X-ray heating

$$T_S \approx T_{gas} \gg T_\gamma$$

Lya(from stars)

Brightness temp
near z ~ 10

$$\Delta T_b \propto \left[1 - \cancel{\frac{T_\gamma}{T_S}}\right]$$

21cm line fluctuation δ_{21}

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

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

Baryon

Neutral fraction

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

$$\delta_{21} \approx \boxed{\delta_{\mathrm{b}}} + \boxed{\delta_{x_{\mathrm{HI}}}} - \boxed{\delta_{\partial v}}$$

Fourier component (linear)

$$\tilde{\delta}_{21} \approx \tilde{\delta}_{\mathrm{b}} + \tilde{\delta}_{\mathrm{HI}} + \boxed{\mu^2 \tilde{\delta}_{\mathrm{b}}} \qquad \mu \equiv \frac{k_{||}}{|k|}$$

Redshift space distortion

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

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

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

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

$P_{\delta\delta}$: Matter power spectrum

$P_{\mathrm{x}\delta} = \bar{x}_i P_{\delta_x\delta}$: Density-ionization power spectrum

$P_{\mathrm{xx}} = \bar{x}_i^2 P_{\delta_x\delta_x}$: Ionization power spectrum

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

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3. Summary

◆ Constraints on the neutrino mass

Y. Oyama, K. Kohri, M. Hazumi,
JCAP 1602, no. 02, 008 (2016).

◇ Growth of the density fluctuation δ_m

Large scale (> Free streaming scale)

$$\Omega_m = \boxed{\Omega_{CDM} + \Omega_b + \Omega_\nu}$$

All components contribute the growth of $\boldsymbol{\delta_m \propto a}$.

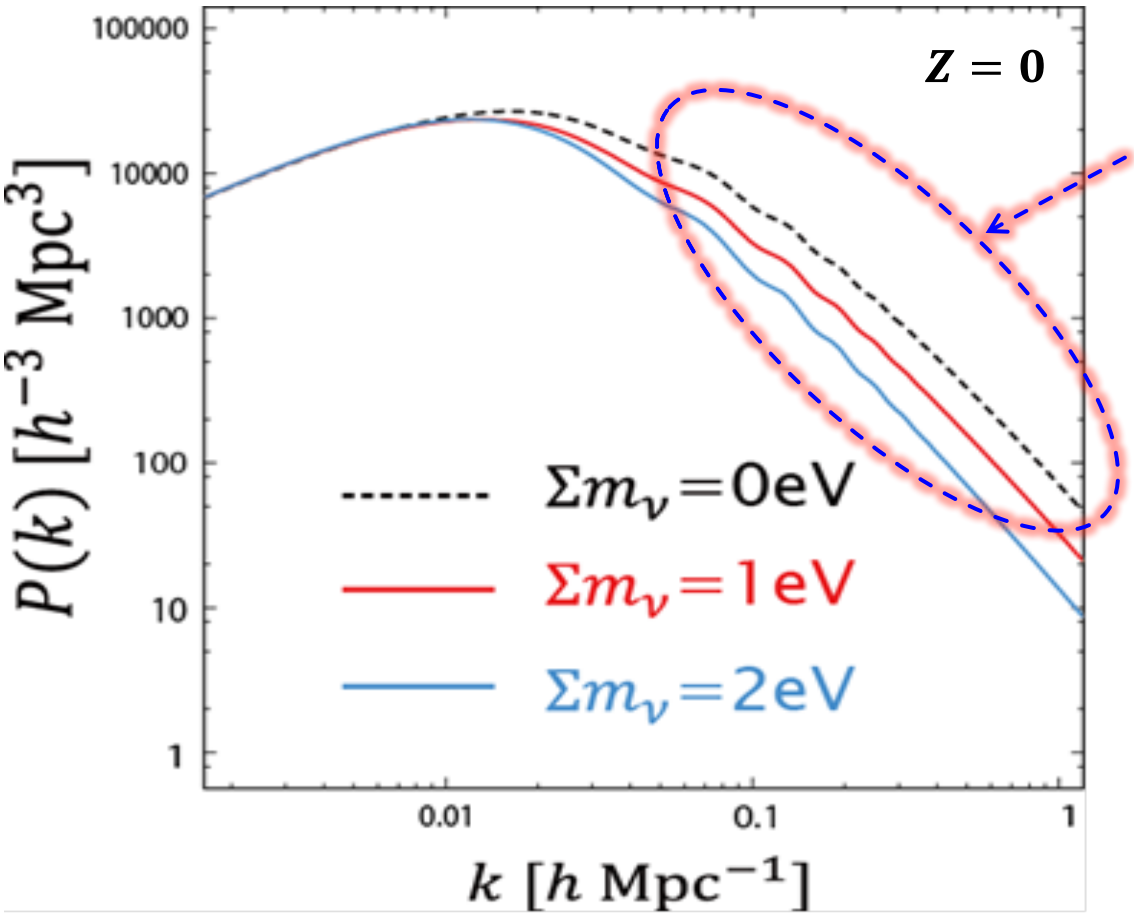
Small scale (< Free streaming scale)

$$\Omega_m = \boxed{\Omega_{CDM} + \Omega_b} + \Omega_\nu$$

Neutrino does not contributes the growth of $\boldsymbol{\delta_m}$.

$$\boldsymbol{\delta_m \propto a^{1-\frac{3}{5}f_\nu}, \quad f_\nu \equiv \frac{\rho_\nu}{\rho_m}}$$

Matter power spectrum $P(k) = \langle|\delta_k|^2\rangle$



Suppression due to the free streaming

Total mass $\Sigma m_\nu = m_1 + m_2 + m_3$.
(Here, $m_1 = m_2 = m_3$**)** . $\Omega_m h^2$ **is fixed.**

Analysis methods

Fisher Information matrix $\boldsymbol{F_{ij}}$

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

$L(\boldsymbol{\theta}|\boldsymbol{x})$: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 $\hat{\theta}$.

Fisher matrix of 21 cm line observations

M.McQuinn et. al, Astrophys.J.653:815-830,2006

$$F_{\alpha\beta} = \sum_i \frac{1}{\left[\delta P_{T_b}(\boldsymbol{u}_i)\right]^2} \frac{\partial P_{T_b}(\boldsymbol{u}_i)}{\partial \theta_\alpha} \frac{\partial P_{T_b}(\boldsymbol{u}_i)}{\partial \theta_\beta}$$

21cm line power spectra : $P_{T_b}(\boldsymbol{u}_i) \equiv (\delta \bar{T}_b)^2 P_{21}(\boldsymbol{u}_i)$

Detector Noise : $P_{Noise}(u_\perp) \equiv \left(\frac{\lambda^2 T_{sys}}{A_e}\right)^2 \frac{1}{n_b(u_\perp) t_0}$

$$\delta P_{T_b}(\boldsymbol{u}_i) \equiv (P_{T_b}(\boldsymbol{u}_i) + P_{Noise}(u_{\perp,i}))/(N_c^{1/2})$$

$$\left\{\begin{array}{l} \boldsymbol{u} = (\boldsymbol{u}_\perp, u_\parallel) = (d_A(z)\boldsymbol{k}_\perp, y(z)k_\parallel) \\ d_A(z) \text{ : commoving angular diameter distance} \\ y(z) = \lambda_{21}(1+z)/H(z) \end{array}\right.$$

◇ CMB polarization experiments

- **POLARBEAR-2**

95, 150 GHz

- **Simons Array**

POLARBEAR-2 × 3
95, 150, 220 GHz

KEK CMB group is developing these experiments.

We took account of combinations of above 2 experiments and Planck satellite.

◇ 21cm line experiment

◆ SKA (Square kilometer Array)

http://www.skatelescope.org/

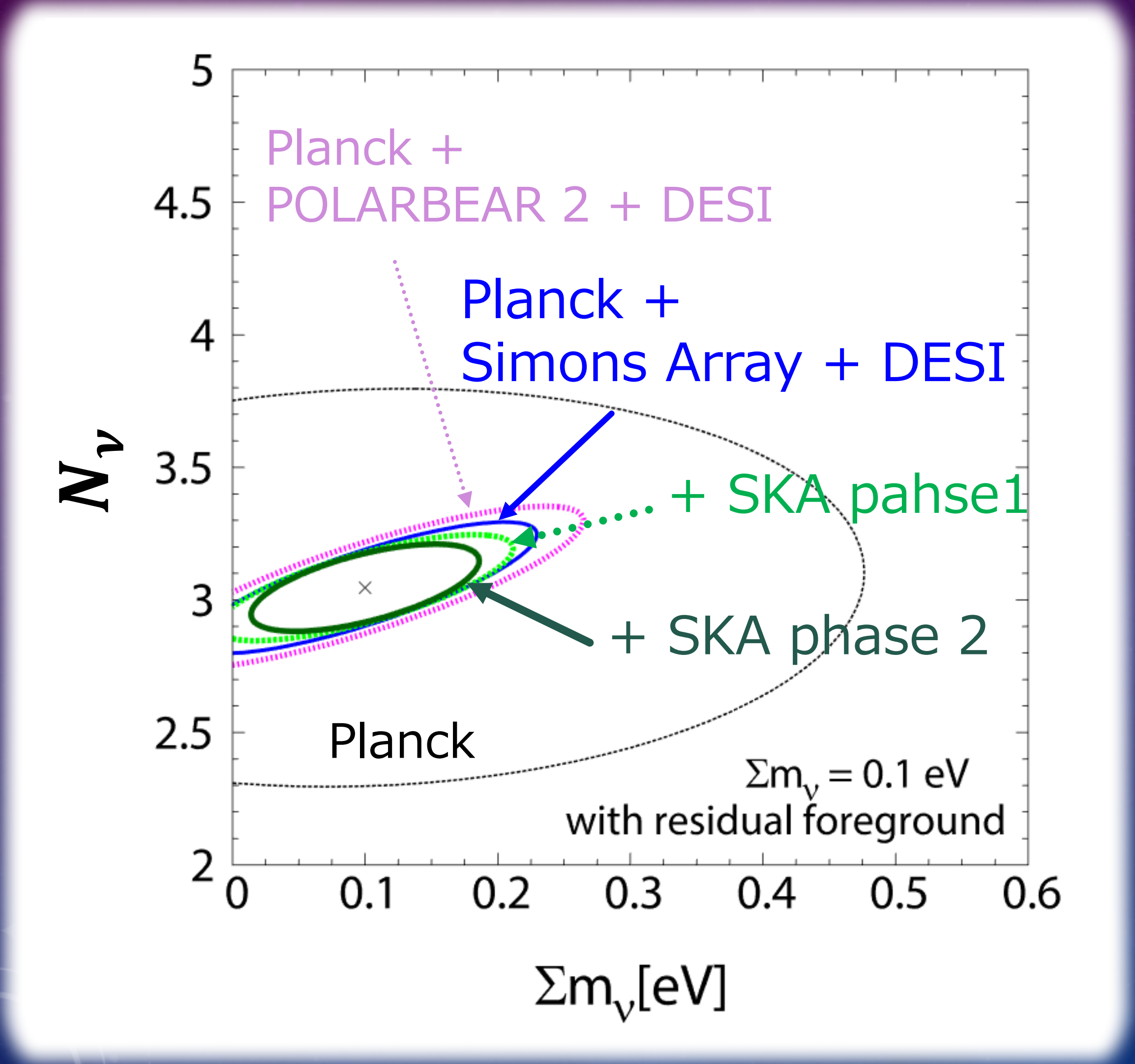
SKA low frequency (Australia)

Construction of Phase1 will start in 2018.

SKA 1 は re-baseline後の
スペックを想定

SKA 2 は re-baseline前のSKA1の
集光面積の4 倍（当初のスペック）

◆ Constraints on the neutrino total mass and effective number of neutrino species N_ν



95% C.L. expected contours

$\Sigma m_\nu = 0.1\mathrm{eV}$

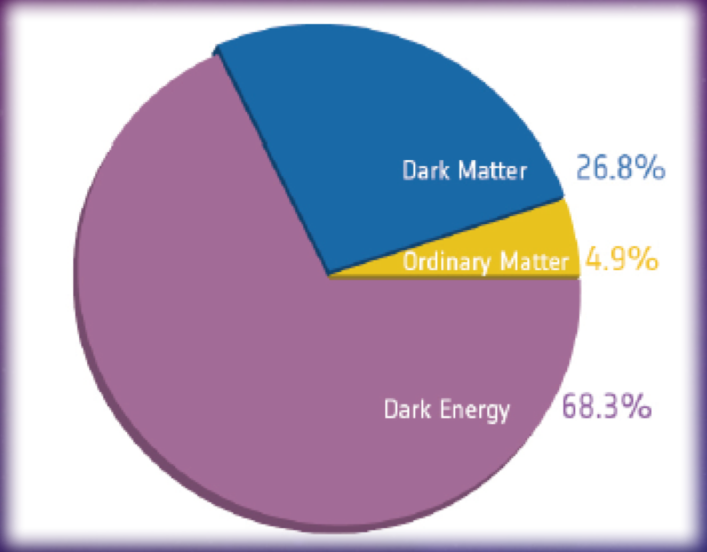
The neutrino total mass is detectable at 95%C.L.,

by Simons Array (CMB) + DESI (BAO) + SKA 2 (21cm line).

- Dark energy equation of state (EoS)

K. Kohri, Y. Oyama, T. Sekiguchi,
T. Takahashi, arXiv:1608.01601.

Dark energy



ESA, Planck, http://sci.esa.int/planck/

Friedmann 方程式

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3}(\rho + 3p) = -\frac{4\pi}{3}\rho(1+3w)$$

Equation of state (EoS) : $w = \frac{p}{\rho}$

$w < -\frac{1}{3}$ の時，$0 < \frac{\ddot{a}}{a}$ となり加速膨張が実現する (dark energy)

$w = -1$ の時は$\rho = \text{constant}$ となりcosmological constant

Dynamical dark energy

Expansion ratio of the Universe (Hubble parameter)

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

Contribution of the dark energy

一般には dark energyのEoSは
時間依存するように，
拡張した場合も考えられる．

Equation of state (EOS)

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

本研究では，そのような時間依存するdark energy ($w_X \neq \mathrm{constant}$)に対する，21cm線観測の将来的な感度について調べた．

◆ Energy density of the dark energy

$$\rho_X = \rho_{X0} \exp\left[3\int_a^1 \frac{da'}{a'}[1+w(a')]\right]$$

CPL parametrization

$$\rho_X(z) = \rho_{X0}(1+z)^{3(1+w_0+w_1)} \exp\left[-\frac{3w_1 z}{1+z}\right]$$

HM parametrization (Suddenly changing model)

$$\rho_X(z) = \rho_{X0}(1+z)^{3(1+w_0)} \left[\frac{w_0 + w_1(1+z_s)^p}{w_0(1+z)^p + w_1(1+z_s)^p}\right]^{3(w_0-w_1)/p}$$

Wetterich parametrization (Early dark energy model)

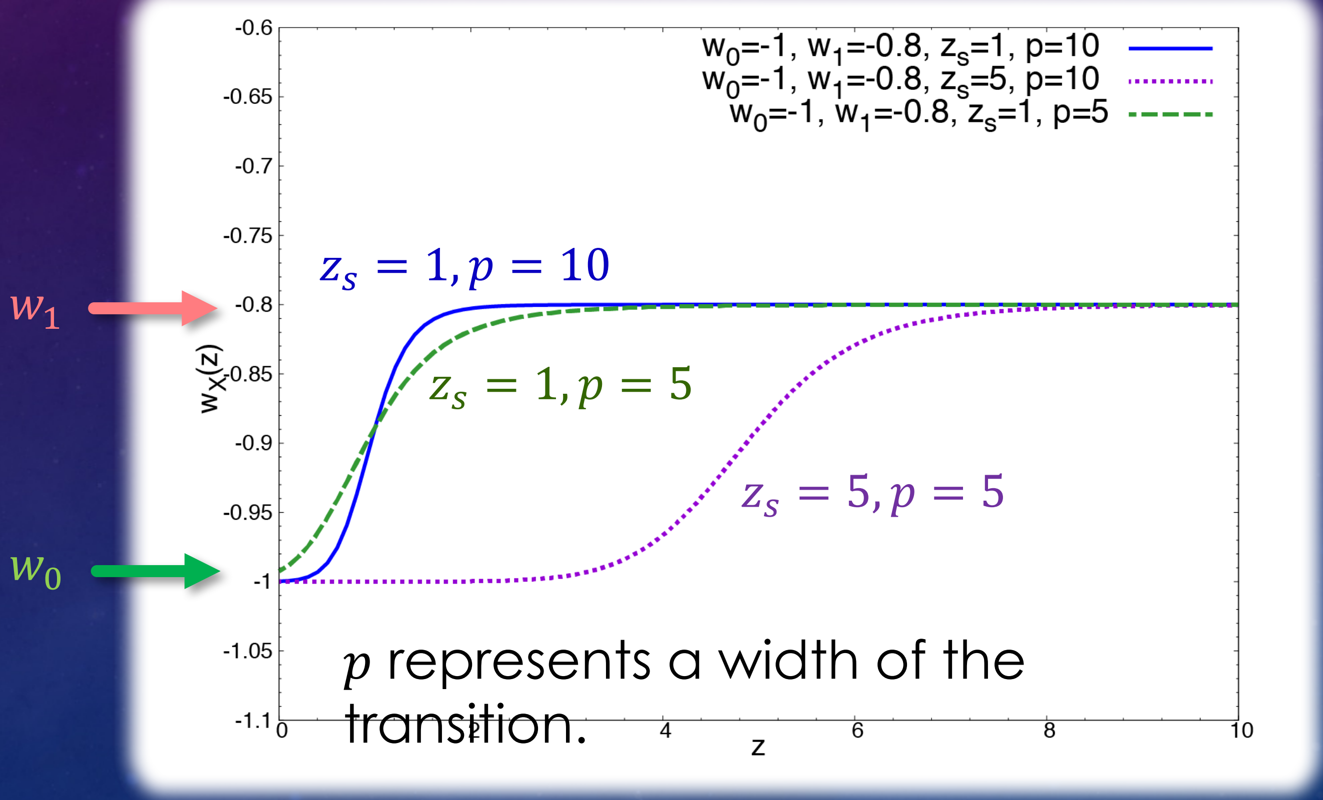
$$\rho_X(z) = \rho_{X0}(1+z)^{3(1+\alpha_X(z))}, \quad \alpha_X(z) = \frac{w_0}{1+b\log(1+z)}$$

今回はこれについてだけ（制限に21cm線が非常に有効な場合がある）

- **Parametrization of EoS [Hannestad, Mortsell 2004]**

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

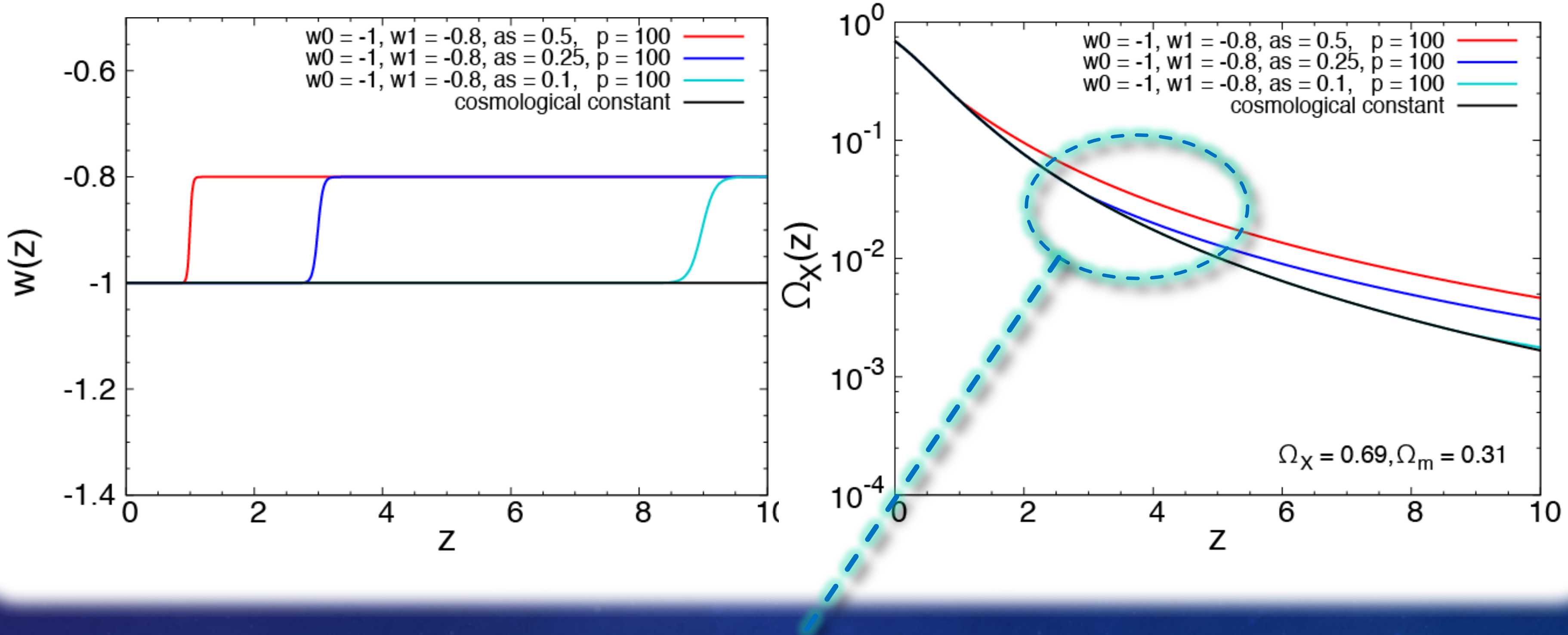
w_X suddenly changes at a transition redshift $z_s = \frac{1}{a_s} - 1$.



p represents a width of the transition.

◆ Energy density of the dark energy

$$\Omega_X(z) \equiv \frac{\rho_X(z)}{\rho_{crit}(z)} = \frac{8\pi G}{3c^2 H(z)^2}\rho_X(z)$$



High zの観測によって、近傍のSN等の観測より過去にtransitionするような場合を原理的には制限可能

Alcock-Paczynski test (銀河サーベイ, 21cm line)

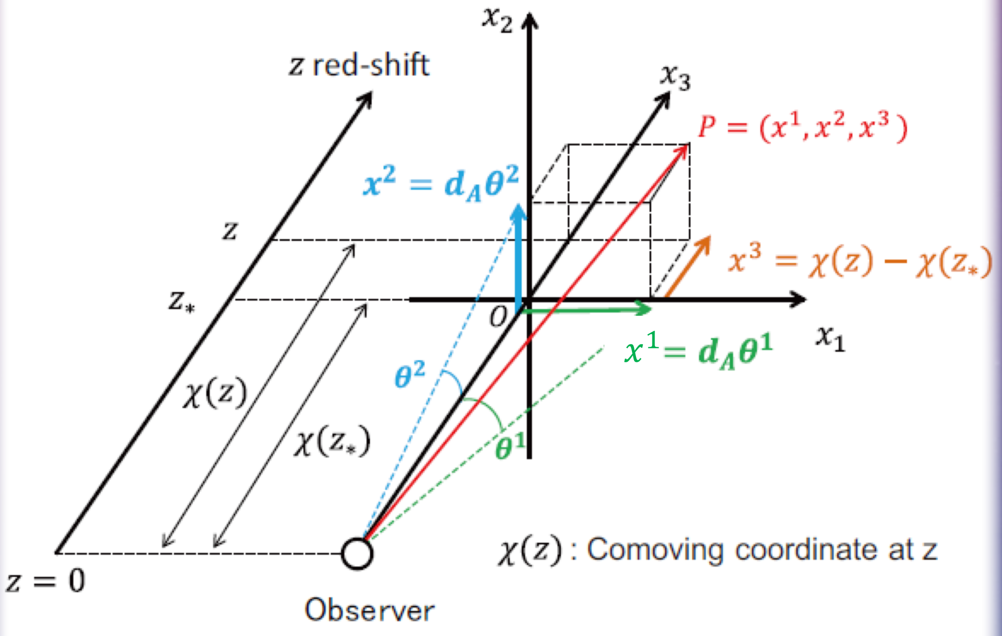


Figure 7.2: Comoving coordinate (x^1, x^2, x^3).

視線垂直方向

$$x^1, x^2 = d_A(z_*)\theta^1, d_A(z_*)\theta^2$$

角形距離$d_A(z_*)$で決まる

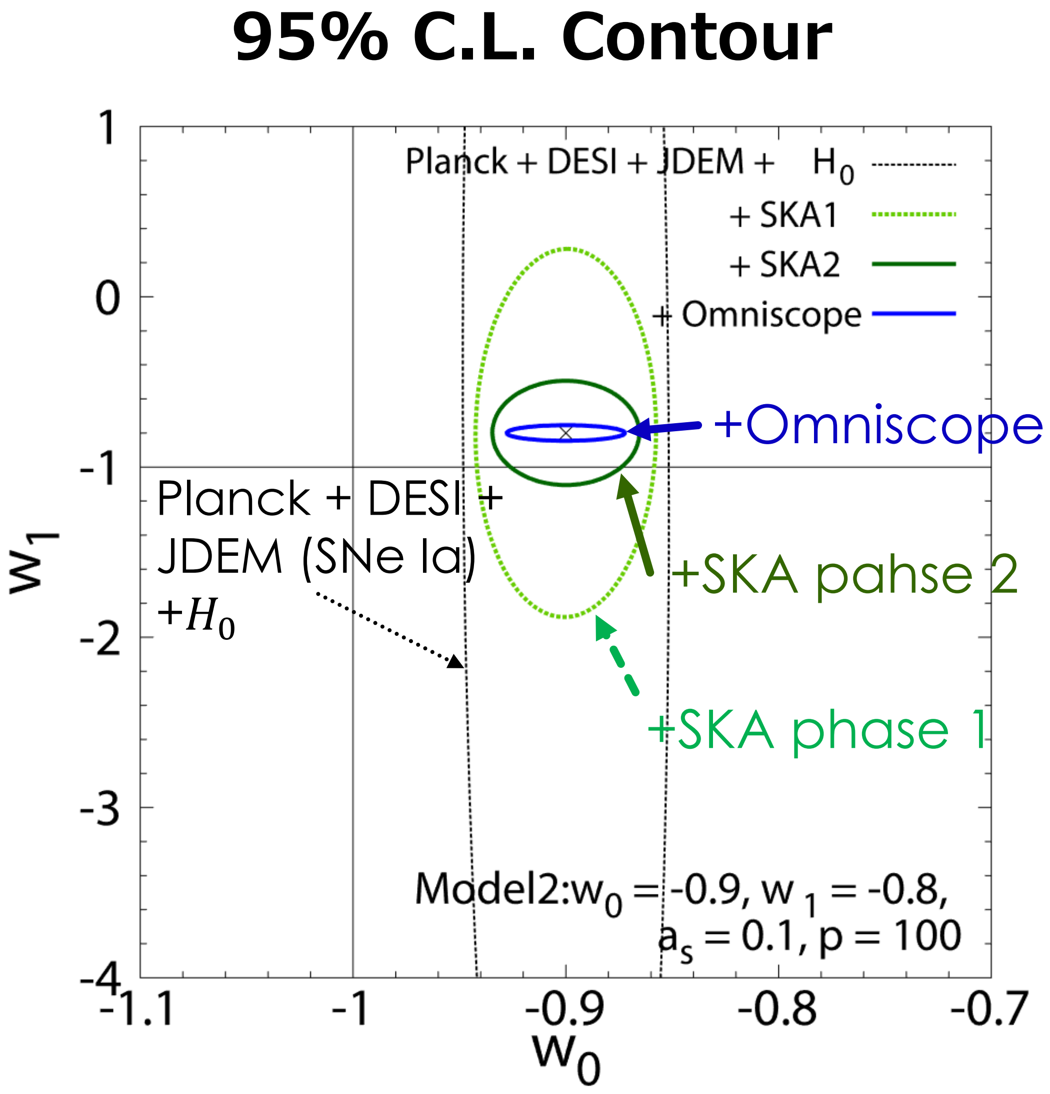
視線垂直方向

$$x^3 = \int_{z_*}^{z} \frac{dz'}{H(z')} \sim \frac{(z - z_*)}{H(z_*)}$$

共動距離で決まる

揺らぎの2点相関で見た場合，BAOのスケールが間違った宇宙論パラメータの元では非等方に歪む

◆ Expected constraint of HM parametrization



95% C.L. Contour

+Omniscope

+SKA pahse 2

+SKA phase 1

Planck + DESI + JDEM (SNe Ia) $+H_0$

Transition :

$a_s = 0.1 \ (z_s = 9)$

$p = 100$

(transitionの幅)

BAO, SNe Ia のサーベイ範囲外でTransitionが生じるため，それらによるw_1の制限は弱い

一方，よりhigh zの観測である21cm線は，w_1に感度がある．

◆ Constraining the light gravitino mass

Y. Oyama, M. Kawasaki,
arXiv:1605.09191.

◆Motivations

Light gravitino : $m_{3/2} \lesssim \mathcal{O}(1-10)$ eV

The scenarios can be consistent with many of baryogenesis/leptogenesis scenarios.

Since light gravitinos behave as warm dark matter in late epochs, we can obtain their signature from matter fluctuations.

CMB lensing : K.Ichikawa et.al., 2009.
Cosmic Shear: A.Kamada et.al., 2014.

Effects of light gravitino on the growth of density fluctuations

1. Increasing radiation

   Light gravitinos contribute
   the energy density of radiation
   at the early Universe.

2. **Free streaming effect**
   (Main signature)

   Fluctuations of matter are
   suppressed in small scales

Temperature of light gravitino: $T_{3/2}$

At the early Universe,
Light gravitinos are relativistic particles.

Effective number of neutrino species

$$N_{3/2} = \frac{\rho_{3/2}}{\rho_\nu} = \left(\frac{T_{3/2}}{T_\nu}\right)^4 = \left(\frac{g_{*\nu}}{g_{*3/2}}\right)^{4/3}$$

ρ_ν : Energy density of one generation of neutrino

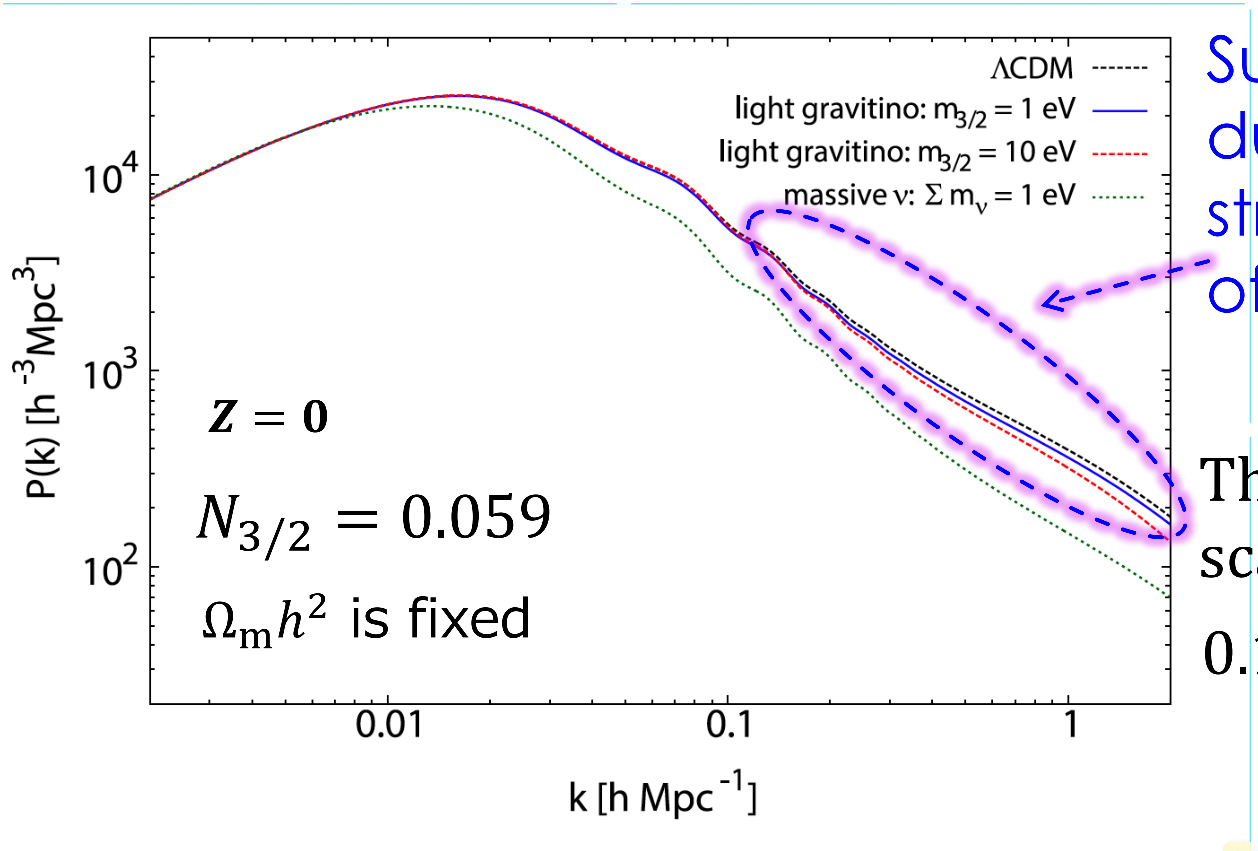
T_ν : Temperature of neutrino

$g_{*\nu}$: The effective degree of freedom at decoupling of neutrinos ($= 10.75$)

$g_{*3/2}$: The effective degree of freedom at decoupling of light gravitinos

Free streaming effect of light gravitino

Matter power spectrum $P(k) = \langle|\delta_k|^2\rangle$ (Linear, z=0)



$Z = 0$

$N_{3/2} = 0.059$

$\Omega_m h^2$ is fixed

Suppression due to the free streaming effect of light gravitino

The free streaming scale is about $0.1h\mathrm{Mpc}^{-1} \lesssim k.$

Cosmological parameter set

Fiducial parameters

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

$$= (0.1417, 0.0223\ 0.6911\ 0.9667\ 2.142\times 10^{-9}, 0.066, 0.25)$$

Parameters related to light gravitino

$$N_{3/2} = \frac{\rho_{3/2}}{\rho_\nu} = 0.059 \quad (g_{*3/2} = 90)$$

$$f_{3/2} \equiv \frac{\Omega_{3/2}}{\Omega_{\mathrm{DM}}} = 0.01071 \quad (m_{3/2} = 1\ \mathrm{eV})$$

Constraints on $f_{3/2}$ ($f_{3/2} = 0.01071$)

1σ error of $f_{3/2}$ ($N_{3/2} = 0.059$ is fixed.)

Planck + Simons Array + DESI (BAO) + H_0

$$\sigma(f_{3/2}) = 0.00346 \rightarrow \sigma(m_{3/2}) = 0.33 \text{ eV}$$

+ SKA 1 $\sigma(f_{3/2}) = 0.00263 \rightarrow \sigma(m_{3/2}) = 0.25$ eV

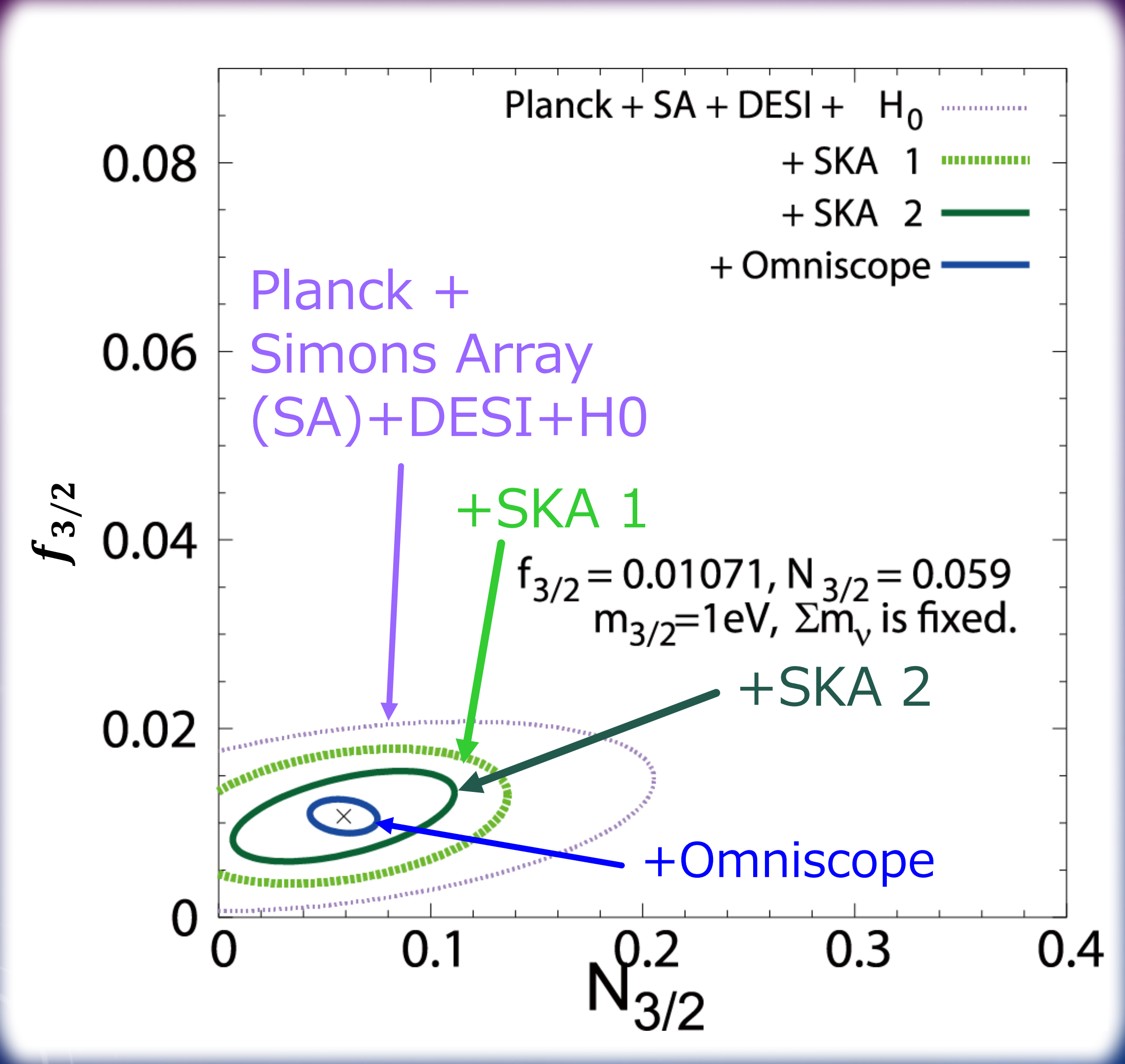
+ SKA 2 $\sigma(f_{3/2}) = 0.00165 \rightarrow \sigma(m_{3/2}) = 0.16$ eV

+ Omniscope

$$\sigma(f_{3/2}) = 0.00071 \rightarrow \sigma(m_{3/2}) = 0.067 \text{ eV}$$

Constraints on $f_{3/2}$ and $N_{3/2}$

95% C.L. Contours



Planck + Simons Array (SA)+DESI+H0

+SKA 1

+SKA 2

+Omniscope

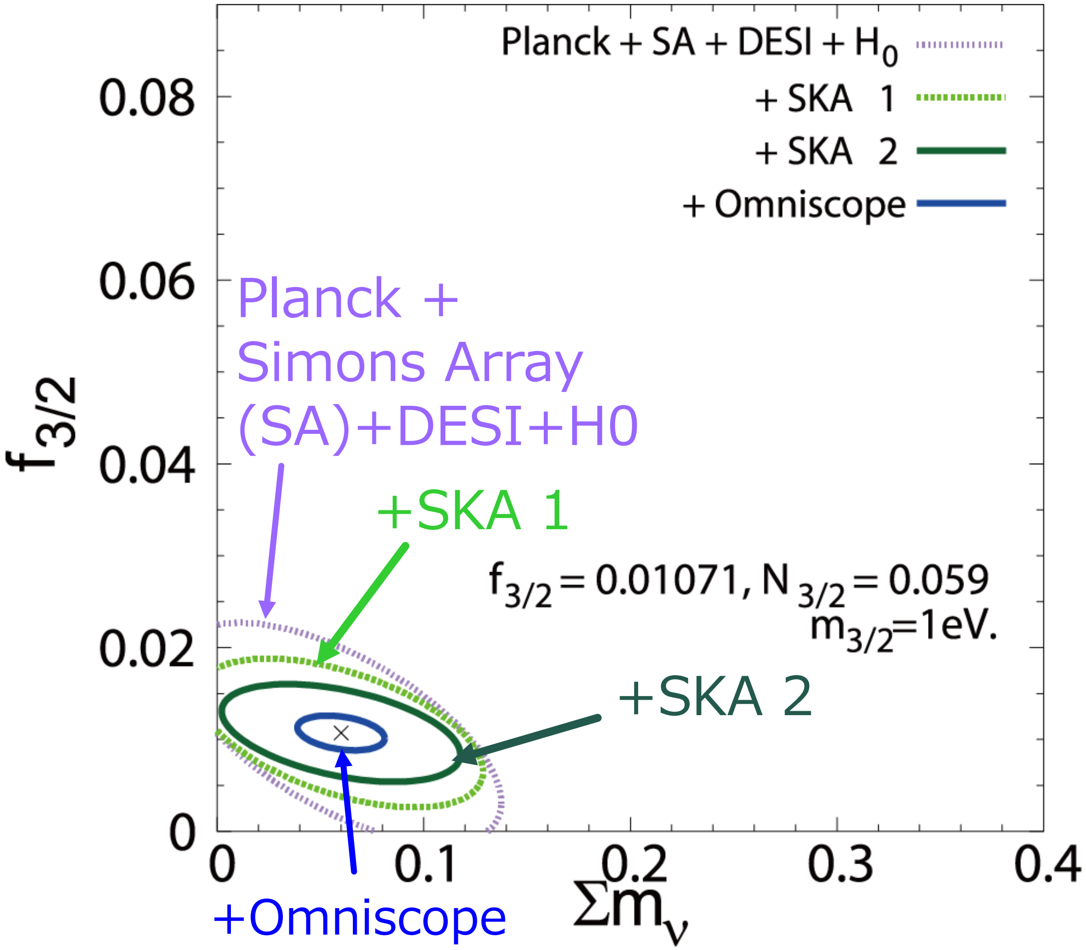
Planck +Simons Array + DESI + H0 + SKA2

The combination can detect nonzero $N_{3/2}$.

(DESI is a future observation of BAO.)

Constraints on $f_{3/2}$ and Σm_ν

95% C.L. Contours in $f_{3/2} - \Sigma m_\nu$ plane



Planck + Simons Array (SA)+DESI+H0

+SKA 1

+SKA 2

+Omniscope

Planck +Simons Array + DESI + H0 + SKA1

They can discriminate the signature of light gravitinos from that of neutrinos .

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3. Summary

Summary

- We studied sensitivities of **21cm line** + **CMB observations** to several cosmological parameters

- **Planck + Simons Array + SKA phase1** can detect **the neutrino total mass at 2σ (if $\Sigma m_\nu \sim 0.1$eV.)**

- **For the suddenly transition dark energy model,** **21 cm observations** can significantly improve the constraints on the EoS parameters.

- We found that **SKA 1 and 2** can strongly improve **constraints of the mass of light gravitino $m_{3/2}$.**