CONSTRAINING THE NEUTRINO MASSES WITH FUTURE COSMOLOGICAL 21CM LINE OBSERVATION

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◇ Introduction

Parameters of neutrino

- Known parameters

Δm^2_{21}, $|\Delta m^2_{31}|$, $\theta_{23}, \theta_{12}, \theta_{13}$

- Unknown parameters

Absolute mass

Dirac CP phase: δ, Majorana CP phase: α, β

Sign of Δm^2_{31}: mass hierarchy

◇ Current neutrino mass bound

Tritium beta decay

(Troitsk, Maintz)

$$m_{\nu_e} \equiv \left(\sum_i |U_{ei}|^2 m_i^2\right)^{\frac{1}{2}} < 2.05 - 2.3\text{eV (95\%CL)}$$

C. Kraus, et al., Eur. Phys. J. C 40 (2005) 447.

V.M. Lobashev, Nucl. Phys. A 719 (2003) 153.

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1. ニュートリノによる密度ゆらぎの成長及びCMBへの影響
2. CMB偏光, 21cm線観測による将来のニュートリノ質量への制限
3. 宇宙論的観測によるレプトン（ニュートリノ）数非対称性への制限
4. Summary

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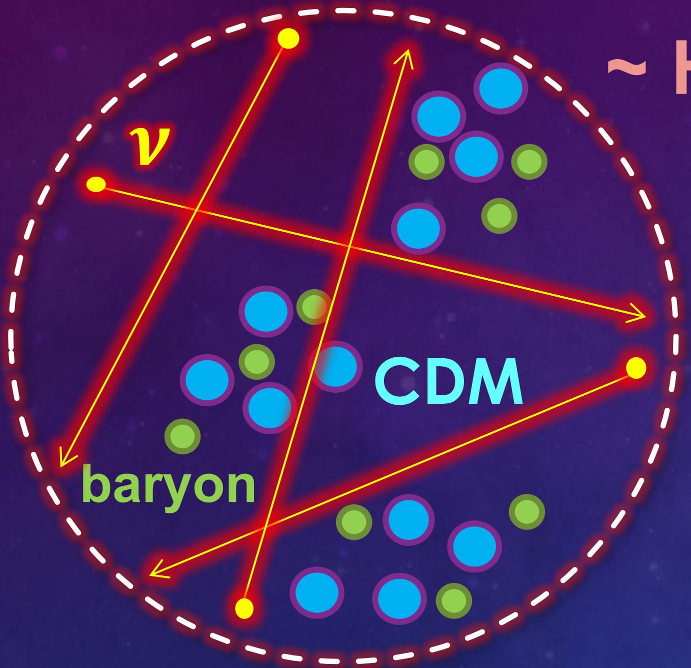
Massive neutrinoによる密度揺らぎの重力成長への影響

◇ Effects of neutrinos on the growth of the density fluctuations



~ Horizon scale

When neutrinos are relativistic $m_\nu c^2 \ll k_B T$,

neutrinos run up to the horizon scale (Free-streaming)

This effect erases their own fluctuations within such scales.

◇ Growth of the density fluctuation $\delta_m \equiv \frac{\rho_m - \bar{\rho}_m}{\bar{\rho}_m}$

Large scale (> Free streaming scale)

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

$$\Omega_m \equiv \frac{\rho_m}{\rho_{crit}} = \frac{3\pi G}{3c^2 H^2}\rho_m$$

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

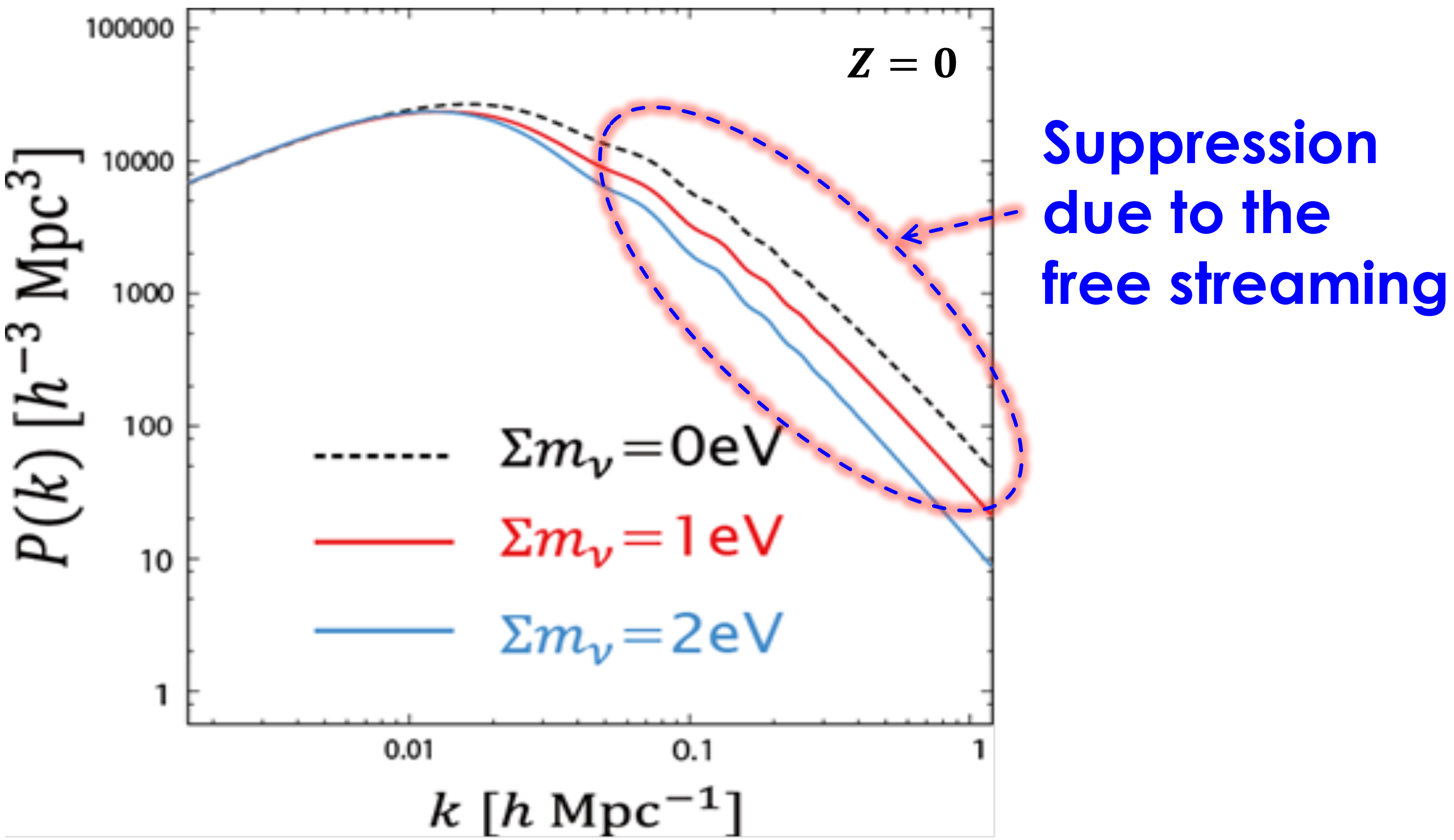
Small scale (< Free streaming scale)

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

Neutrino does not contributes the growth of δ_m.

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

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

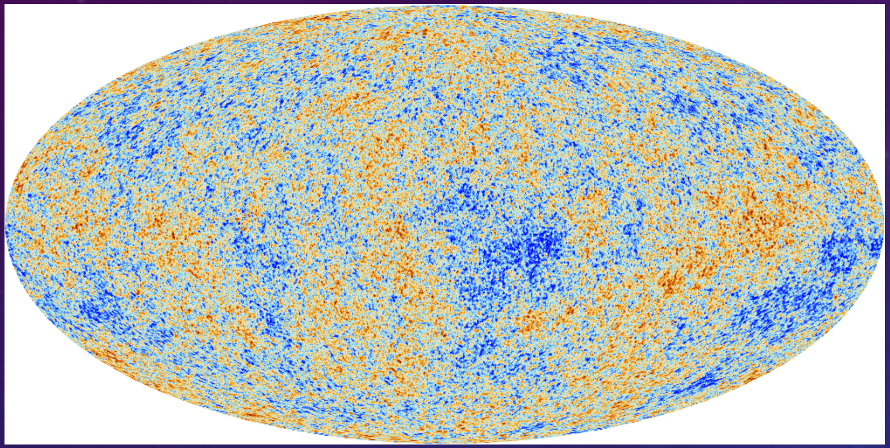


Total mass $\Sigma m_\nu = m_1 + m_2 + m_3$.
(Here, $m_1 = m_2 = m_3$). $\Omega_m h^2$ is fixed.

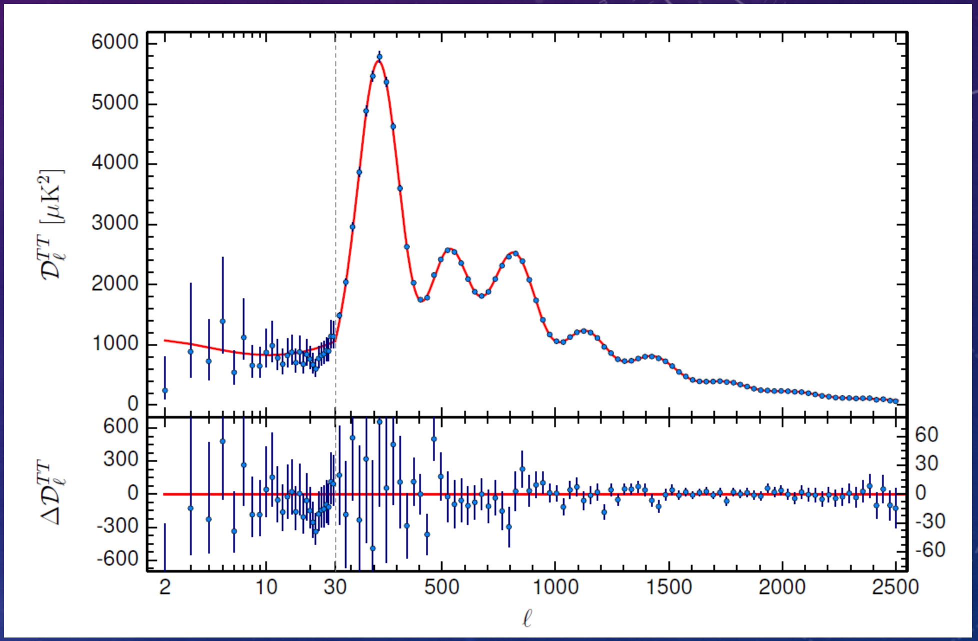
CMB偏光に対する Massive neutrinoの影響

Planck 衛星によりCMB温度揺らぎはほぼCosmic varianceの精度で観測

PlanckによるCMB温度揺らぎmap



Planckの観測による
CMB温度揺らぎの角度パワースペクトル



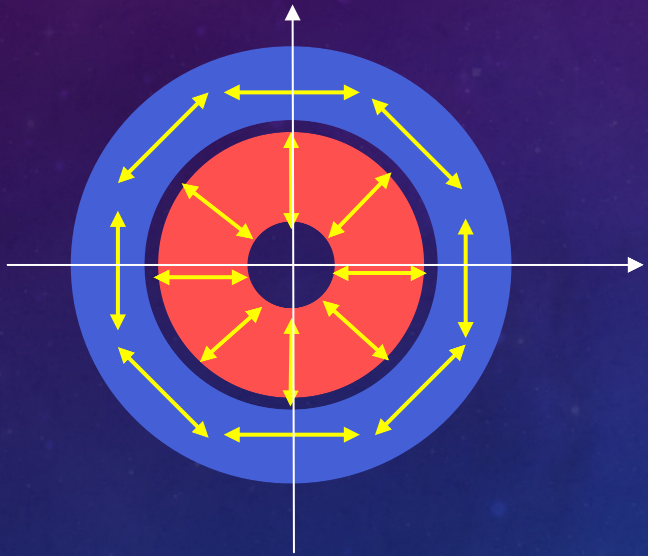
この先, CMB観測の最前線はCMB偏光

CMB偏光

CMBは最終散乱時に，電子との散乱により偏光が生じる
(四重極の温度揺らぎがあると生成)

E mode

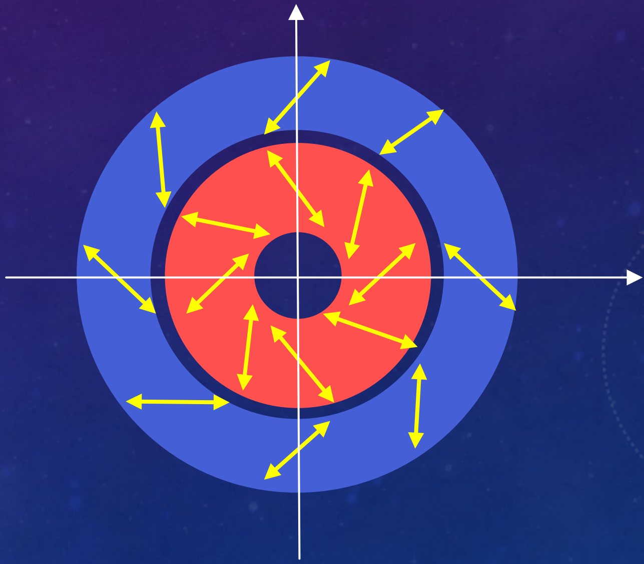
温度揺らぎに対して平行か垂直



Scalar, tensor(重力波)
両方で生じる

B mode

温度揺らぎに対して45°傾く



Tensor(重力波) 及び CMBの
重力レンズ効果で生じる

Gravitational lensing of CMB

Lensing B mode

$$C_l^{BB} = \int \frac{d^2 l'}{(2\pi)^2} [l' \cdot (l - l')]^2 C_{|l-l'|}^{\phi\phi} C_{l'}^{EE} \sin^2 2\varphi_{l'}$$

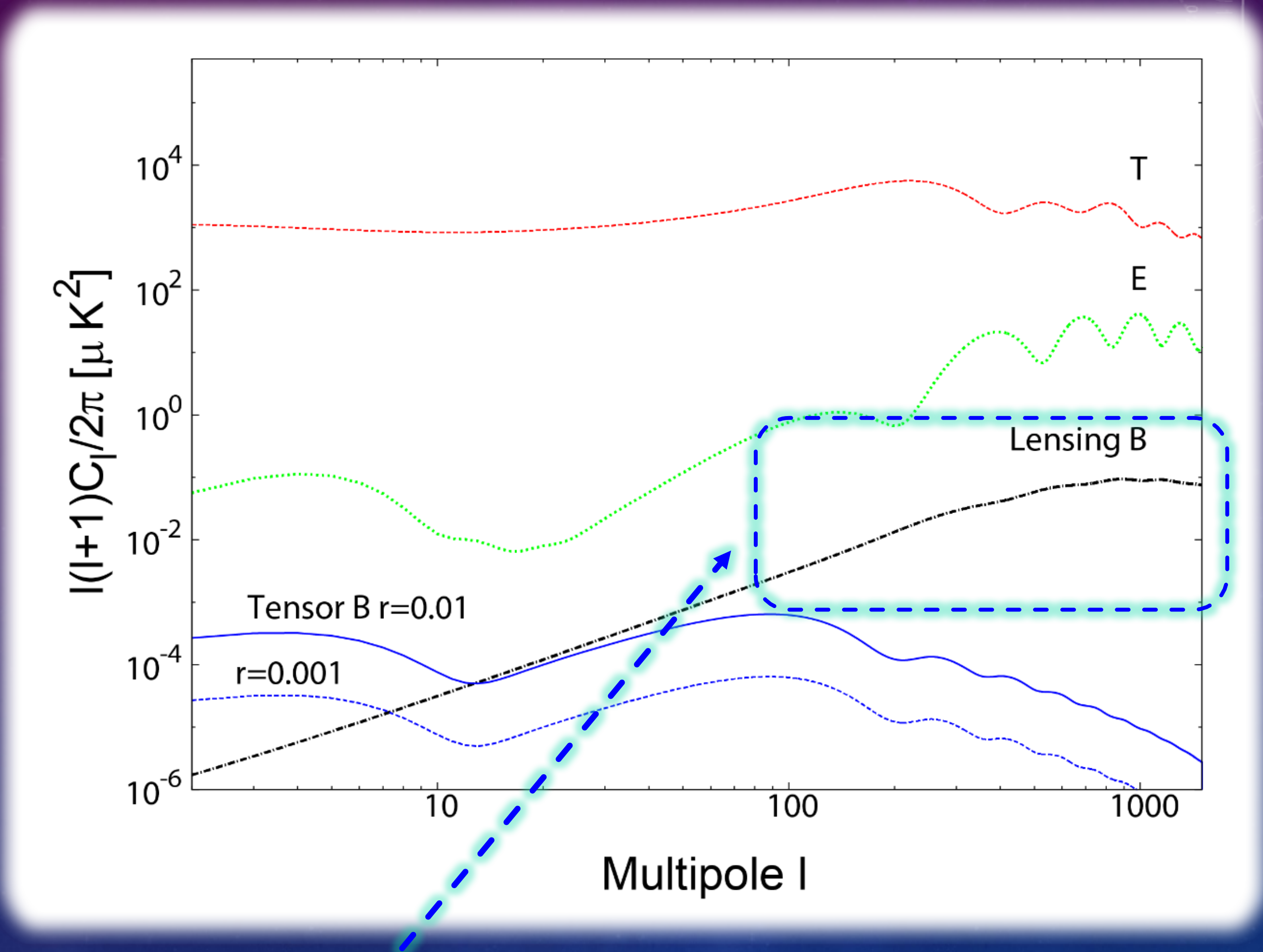
ϕ : Lensing potential

(Integral of a gravitational potential)

$$\phi(\vec{\theta}) = -2 \int_0^{\chi_S} d\chi \frac{\chi_S - \chi}{\chi_S \chi} \psi(\chi, \vec{\theta}, t(\chi))$$

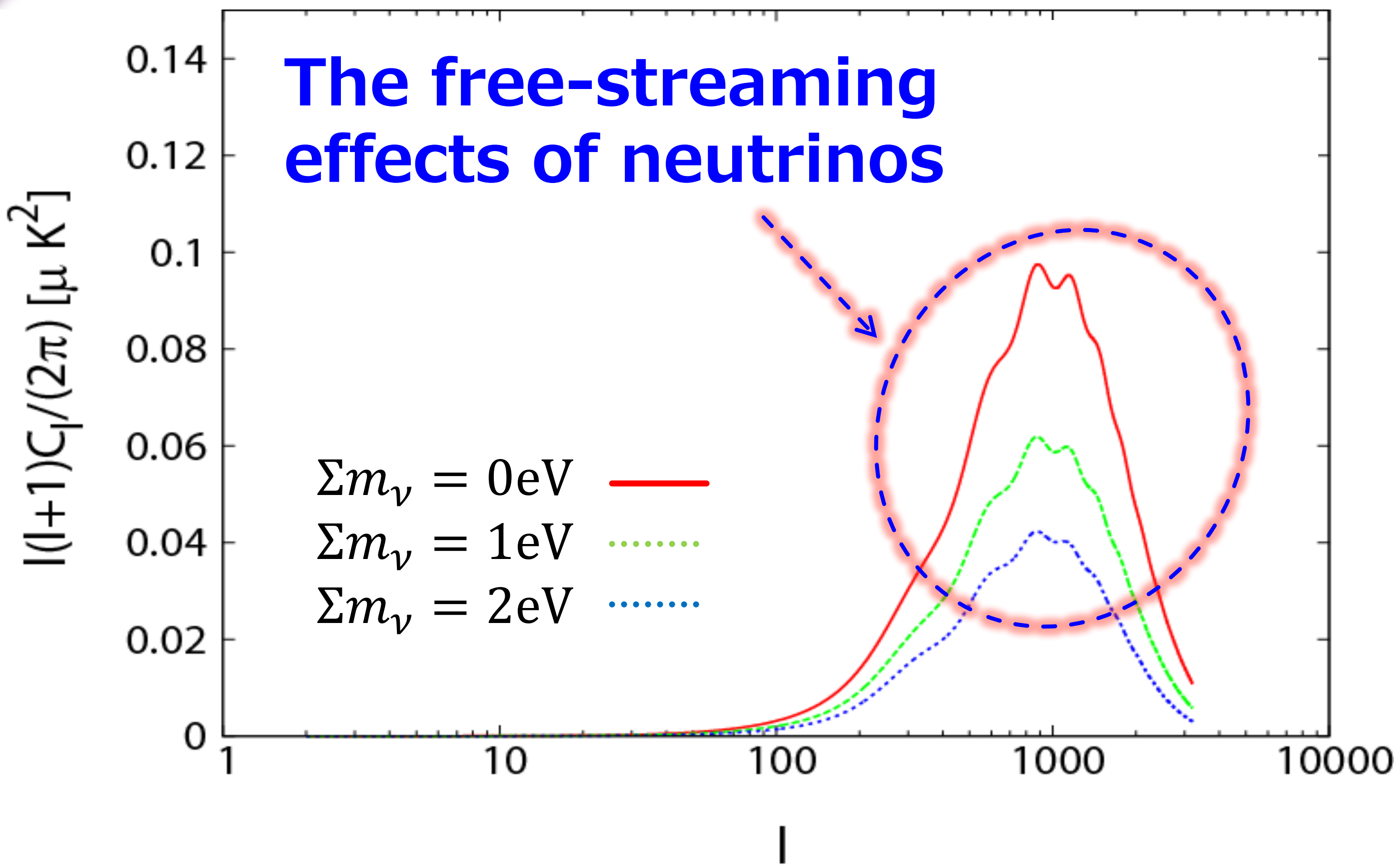
χ : comoving distance

CMB TT, EE, BBの角度パワースペクトル



Lensing B modeは
POLARBEAR望遠鏡によって既に観測されている

Power spectra of CMB polarization (lensing B-mode C_l^{BB})



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

◇ CMB 偏光観測実験

◆ POLARBEAR-2

95, 150 GHz

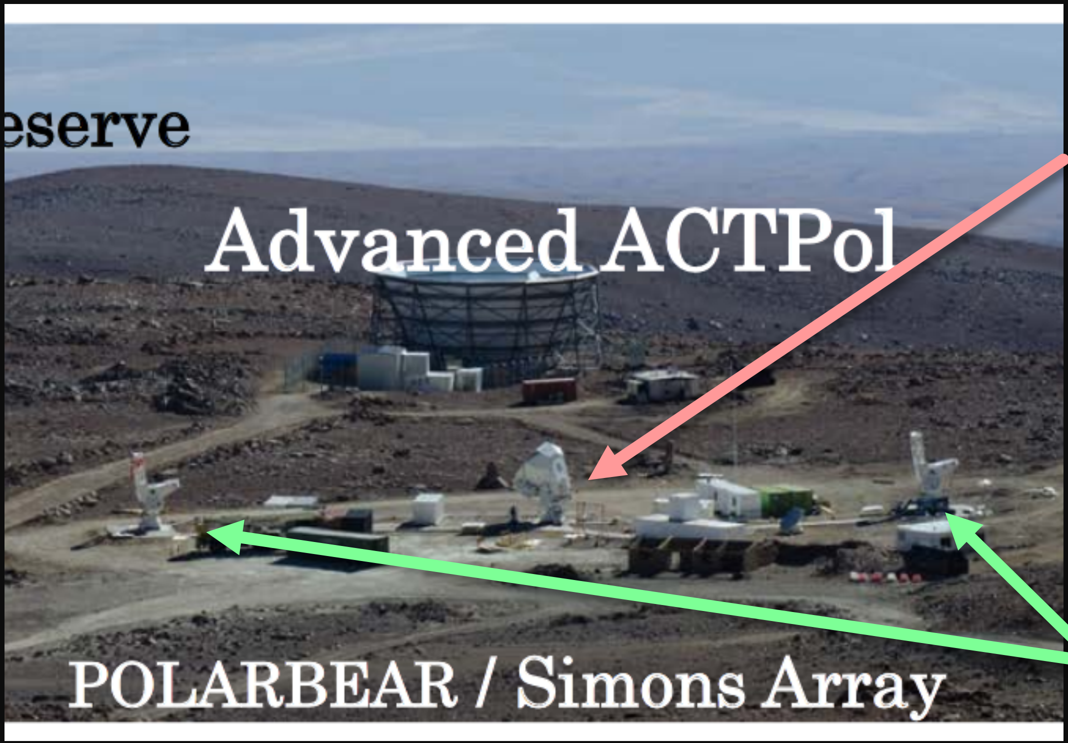
◆ Simons Array

POLARBEAR-2 × 3
95, 150, 220 GHz

KEK CMB group is developing these experiments.

2017~2020年くらいまでに観測開始予定

Simons Arrayの現在の状況 (チリ, アタカマ高地)



KEK素核研の活動報告書(2016)より

POLARBEAR-2
2017年初頭に観測開始

Simons Array
2018年以降

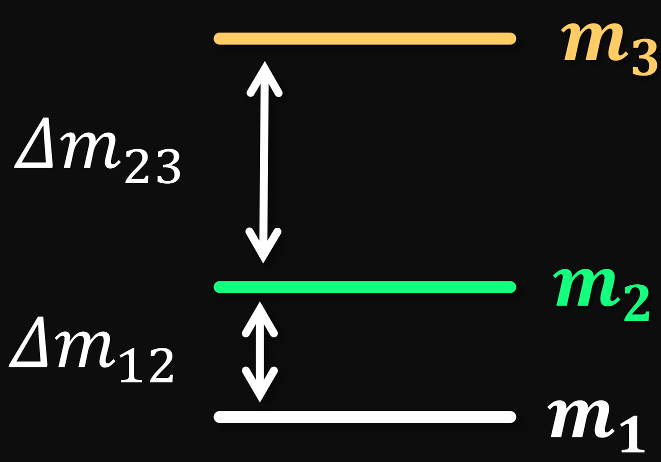
２台目&３台目
POLARBEAR-2は現在
建設中

ニュートリノ質量階層構造 (neutrino mass hierarchy)

◇ The neutrino mass hierarchy

Normal hierarchy

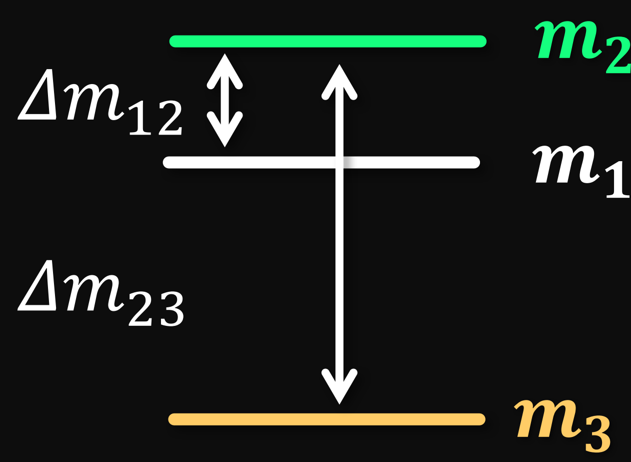
$m_3 \gg m_2 > m_1$



$\Sigma m_\nu \gtrsim 0.05$ eV

Inverted hierarchy

$m_2 > m_1 \gg m_3$

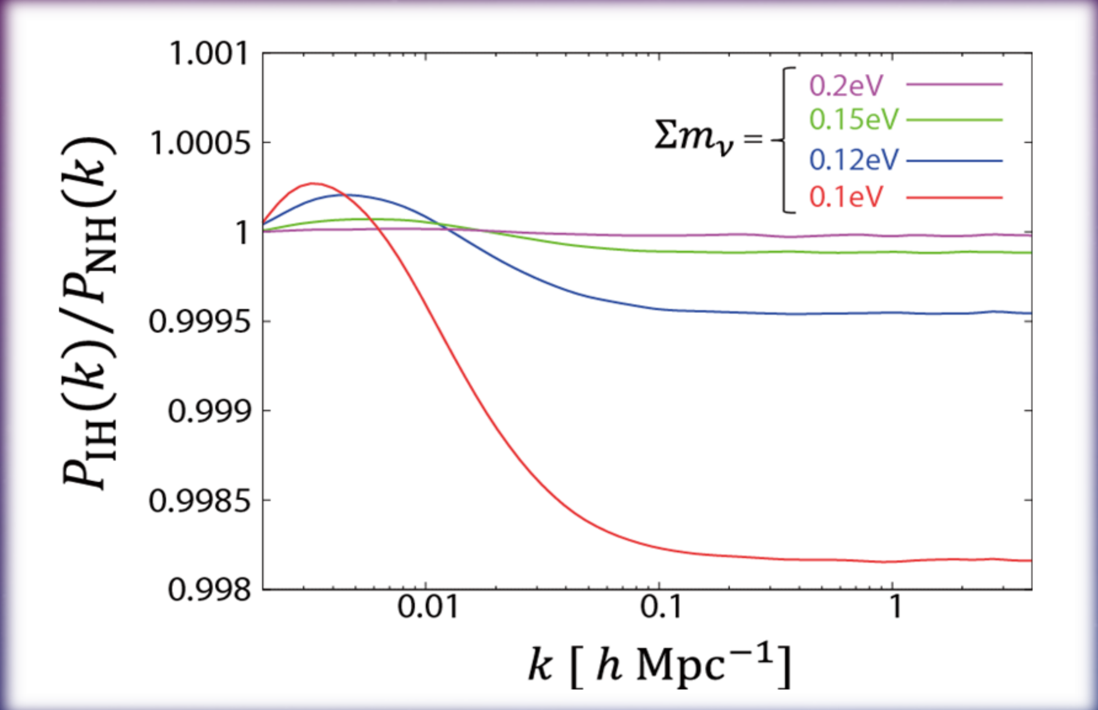


$\Sigma m_\nu \gtrsim 0.1$eV

Each neutrino becomes non-relativistic ($m_\nu c^2 \gg k_B T$) at different time.

◇ 質量階層構造の違いによる影響

z = 8 におけるパワースペクトルの比



P_{NH} 正常階層

P_{IH} 逆階層

※ $|m^2{}_3 - m^2{}_2|$は固定

$\Sigma m_\nu \to$ 小

質量階層構造による違い ⇨ 増大

ニュートリノ有効世代数 N_ν による影響

◆ ニュートリノの有効世代数N_ν

Energy density of neutrino

$$\rho_\nu + \rho_{\bar{\nu}} = N_\nu \frac{7}{8}\frac{\pi^2}{15} T_\nu^4$$

ニュートリノ１世代の
エネルギー密度

(3からのズレはFermi-Dirac分布のhigh energy tailを通したe+, e-とのcoupling効果)

T_ν : ニュートリノ温度

N_ν :有効世代数

Standard cosmologyでは $N_\nu \simeq 3.046$

他の放射成分(dark radiation, sterile neutrino)によってN_ν がより大きな値の可能性もある.

◇ ニュートリノの有効世代数による影響

N_ν増加 ⟶ Matter-radiation equalityが遅れる

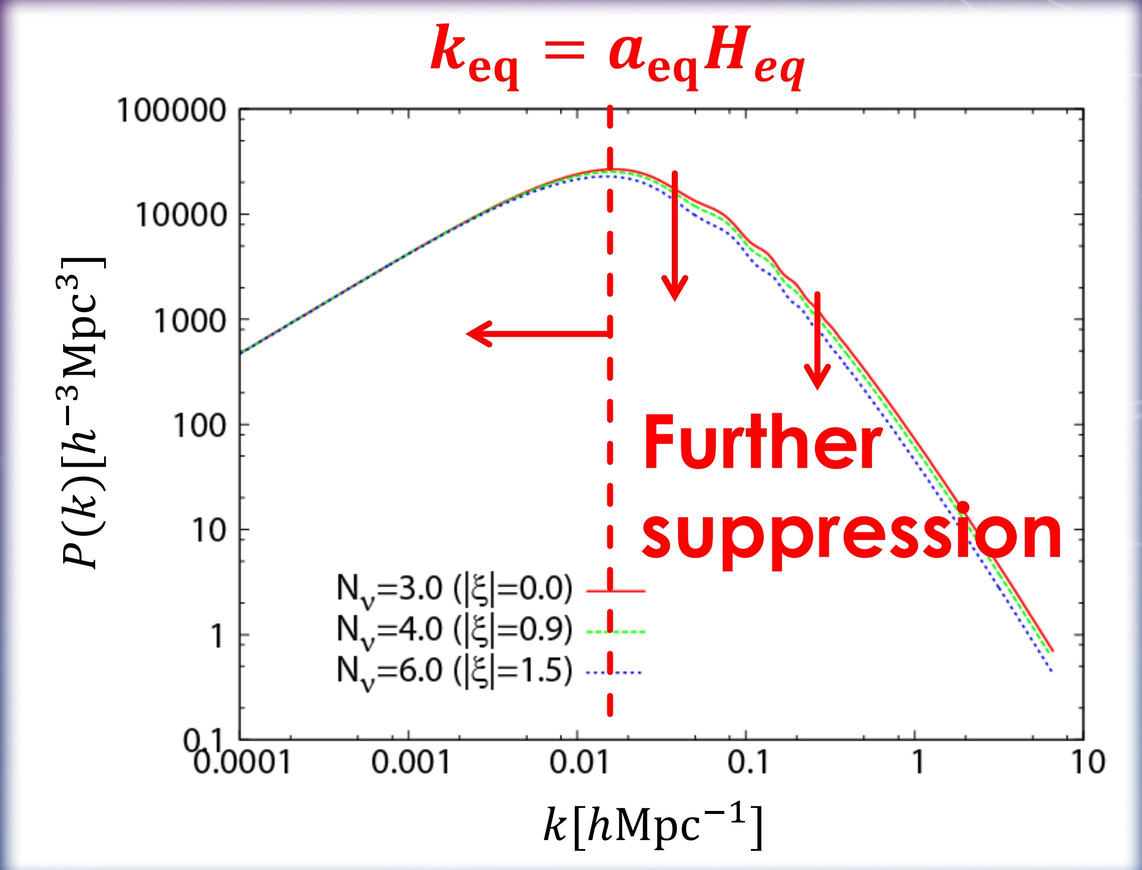
（ニュートリノは当初放射成分のため）

Stagspansion

$$\delta_m \propto 1 + \frac{3}{2}\frac{a}{a_{\rm eq}}$$

$a \ll a_{\rm eq}$

$\delta_m \sim \mathrm{const}$



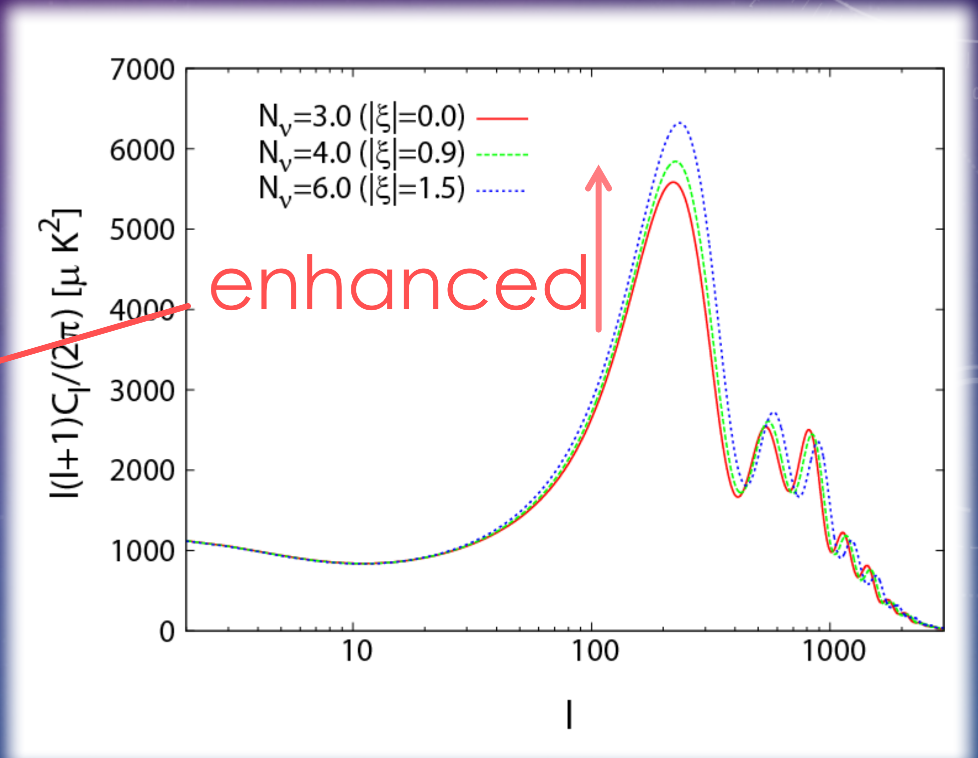
◇ Impact on CMB

More radiation induces stronger decay of gravitational potential Φ

Early integrated Sachs-Wolfe effect

$$\left.\frac{\delta T}{T}\right|_{\mathrm{ISW}} = \frac{2}{c^2}\int_{t_{\mathrm{dec}}}^{t_0} \dot{\Phi}\, dt$$

Gravitational blue shift



ニュートリノ質量の現在の制限

◇ Neutrino mass constraints by Cosmology

Planck (2015) TT, lowP + lensing
+ BAO+ SNe + H0

$\Sigma m_\nu < 0.23$ eV (95% C.L),

N_ν は固定

Planck TT, lowP + lensing + BAO

$\Sigma m_\nu < 0.32$ eV (95% C.L),

$N_\nu = 3.2 \pm 0.5$ (95% C.L)

Future constraints of the neutrino mass

Tritium beta decay (KATRIN) m_{ν_e} < 0.23eV

A. Osipowicz et al, hep-ex/0109033

Galaxy lensing (Euclid, WFIRST 等) Σm_ν < 0.07 eV

Galaxy survey (LSST 等) Σm_ν < 0.1 eV

K. N. Abazajian et al, arXiv: 1103.5083 (2011)

本日は, CMB lensing & 21 cm line によるneutrino massの将来の制限について話す

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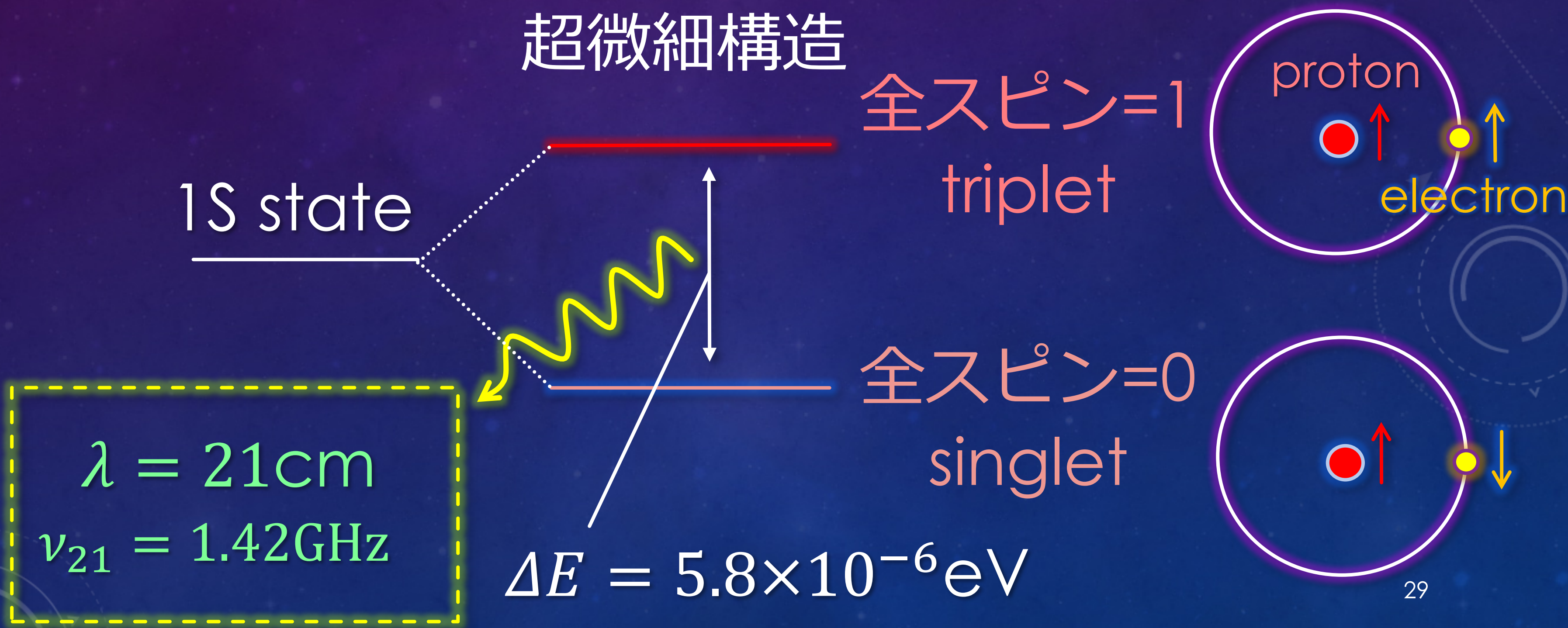
◇ 21cm線

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



◇ 宇宙論における21cm線観測の利用

中性水素
ガス(IGM)

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

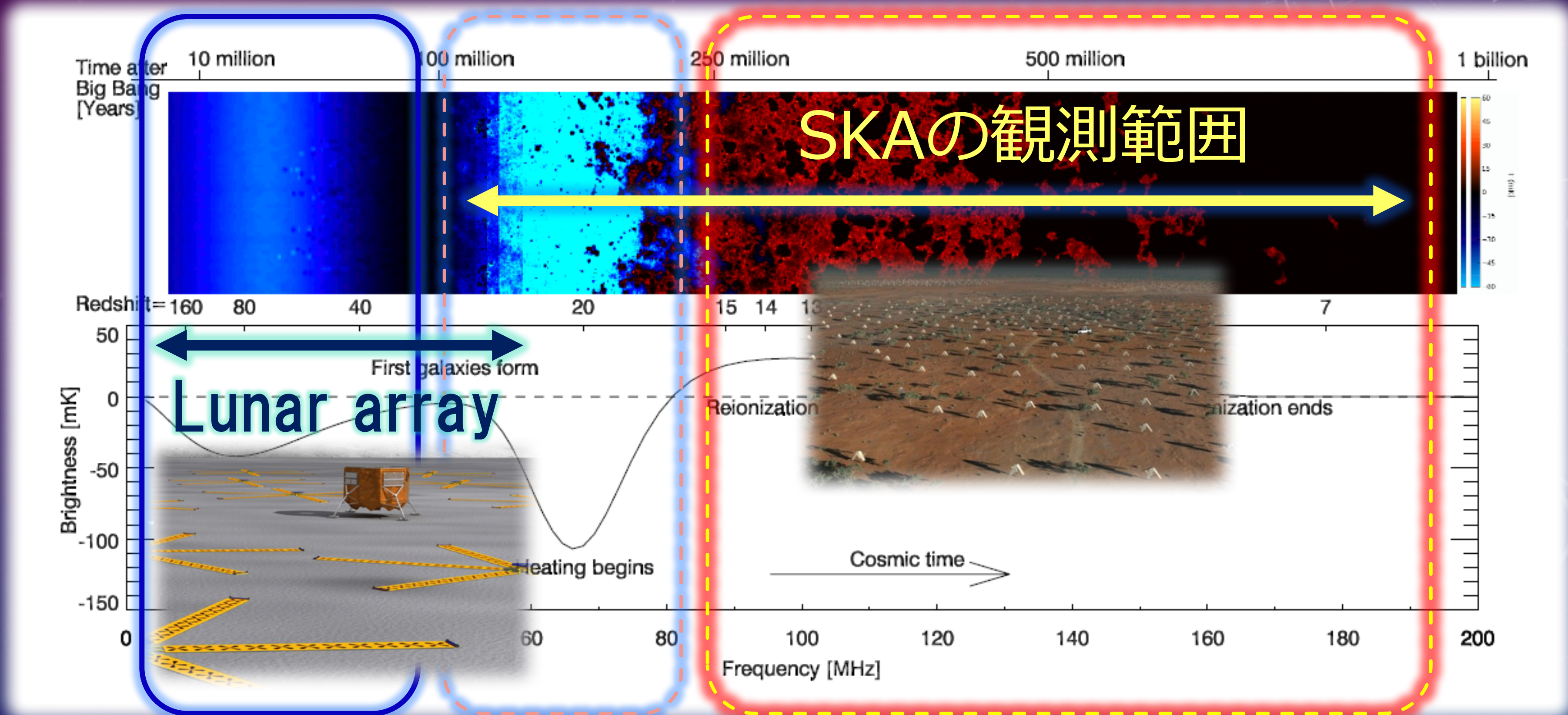
物質分布（密度揺らぎ）の情報を持つ

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

◇ 観測対象：Cosmic dawn–再電離

Dark age Cosmic dawn 再電離(reionization)

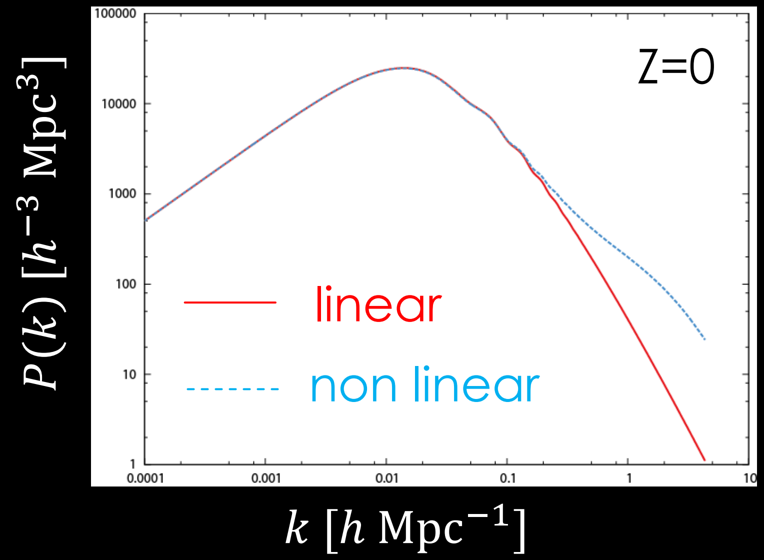


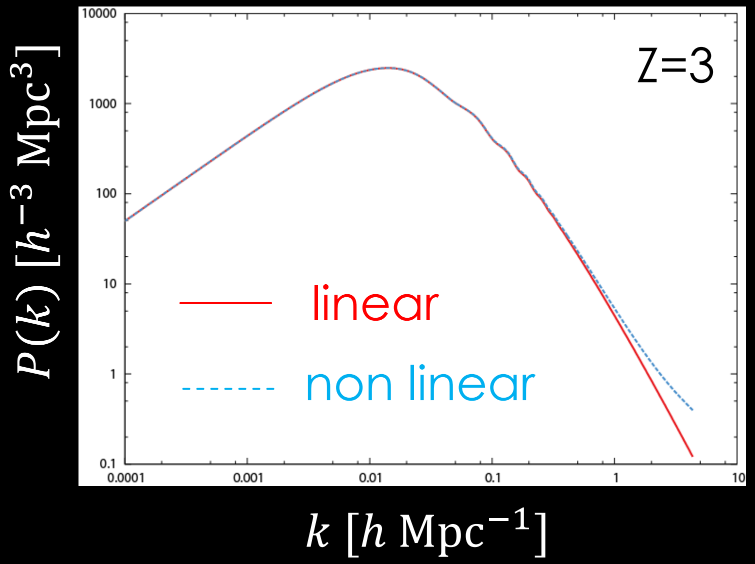
21cm線吸収線　　21cm線放射線

※ 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： $\Delta T_b \equiv T_b - T_{\mathrm{CMB}}$

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

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

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**（$15 \lesssim z$ ）

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}

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

21cm line fluctuation δ_{21}

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

$T_S \gg T_{\mathrm{CMB}}$: z~10

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

$$\boldsymbol{\delta_{21}} \approx \boldsymbol{\delta}_{\mathrm{b}} + \boldsymbol{\delta}_{x_{\mathrm{HI}}} - \boldsymbol{\delta}_{\partial v}$$

<u>Fourier component (linear)</u>

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

Redshift space distortion

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

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

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

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

- $P_{\delta\delta}$: 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 : $x_i = 1 - x_{\rm HI}$

21cm line observations

LOFAR

MWA

PAPER

21CMA

Next generation ～2020

◆ SKA(Square Kilometre Array)

in Australia

2018:
Construction starts.

http://www.skatelescope.org/

◆ Omniscope

Max Tegmark,
Matias Zaldarriaga

Phys. Rev. D 82, 103501 (2010)

From Max Tegmark's presentation

- **Analysis methods**

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

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

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

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

◆ Cosmological parameter set

Fiducial parameters

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

$$= (0.1417, 0.02216, 0.6914, 0.9611, 2.214\times10^{-9}, 0.0952, 0.25)$$

Parameters related to neutrino

(1) Total neutrino mass Σm_ν, number of species N_ν

$$\Sigma m_\nu = 0.1\ \mathrm{eV}, \qquad N_\nu = 3.046$$

(2) Total neutrino mass, mass hierarchy

$$\Sigma m_\nu = 0.1\ \mathrm{eV}\ (\mathrm{inverted})\ \mathrm{or}\ 0.05\ \mathrm{eV}\ (\mathrm{normal})$$

◇ 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)

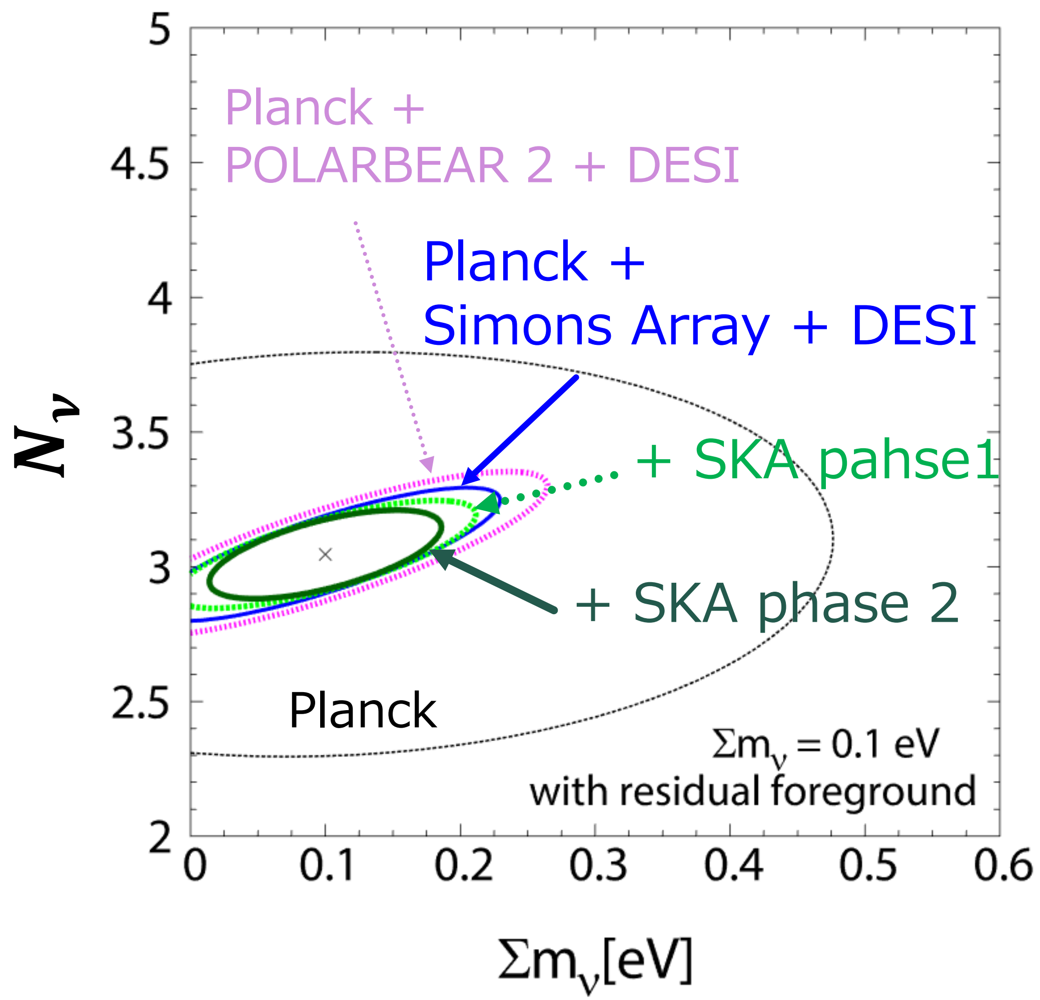
Construction of Phase1 will start in 2018.

We took account of Phase1 and Phase2 (Phase2 has 4 times larger collecting area.)

- **Constraints on the sum of the neutrino masses Σm_ν and neutrino number of species N_ν**

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

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



95% C.L. expected contours

$\boldsymbol{\Sigma m_\nu = 0.1}$**eV**

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

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

- **Constraints on the neutrino mass hierarchy**

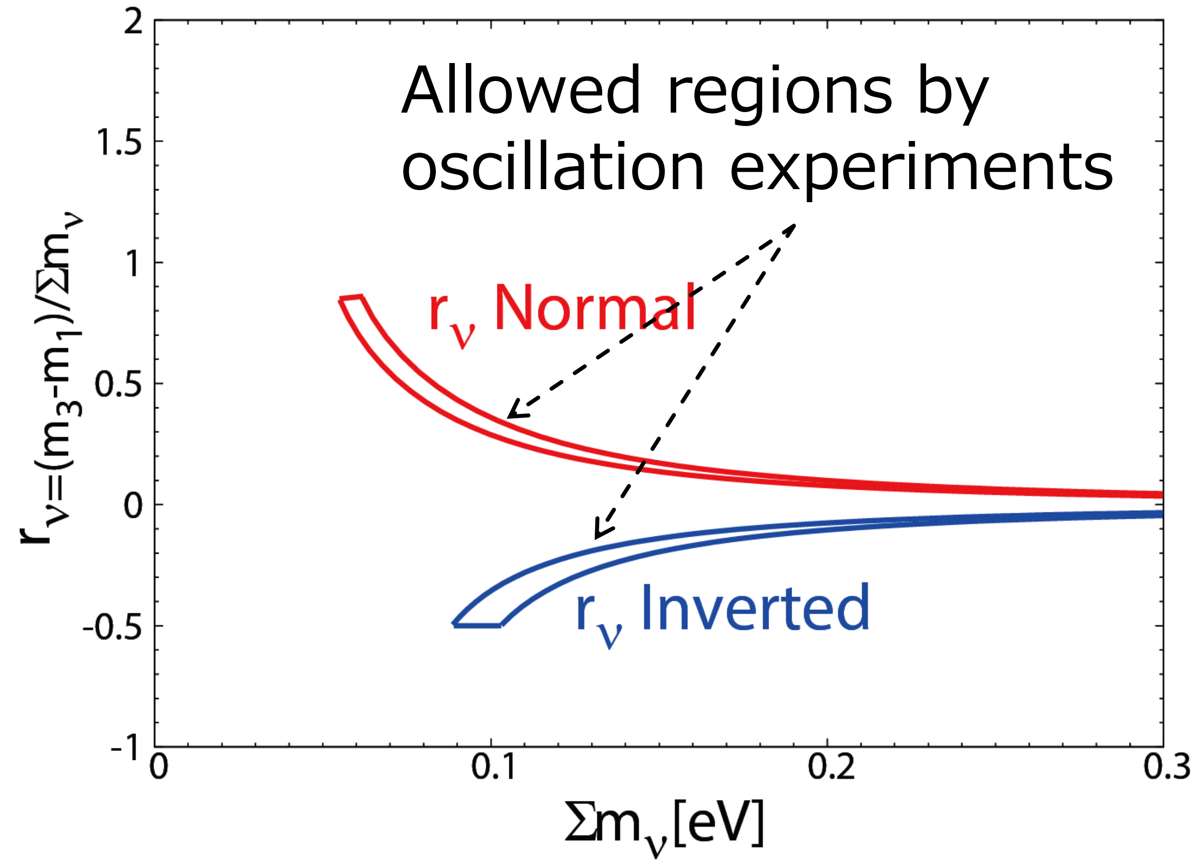
Y. Oyama, K. Kohri, M. Hazumi,
JCAP 1602, no. 02, 008 (2016).

◆ Parameterization of the mass hierarchy

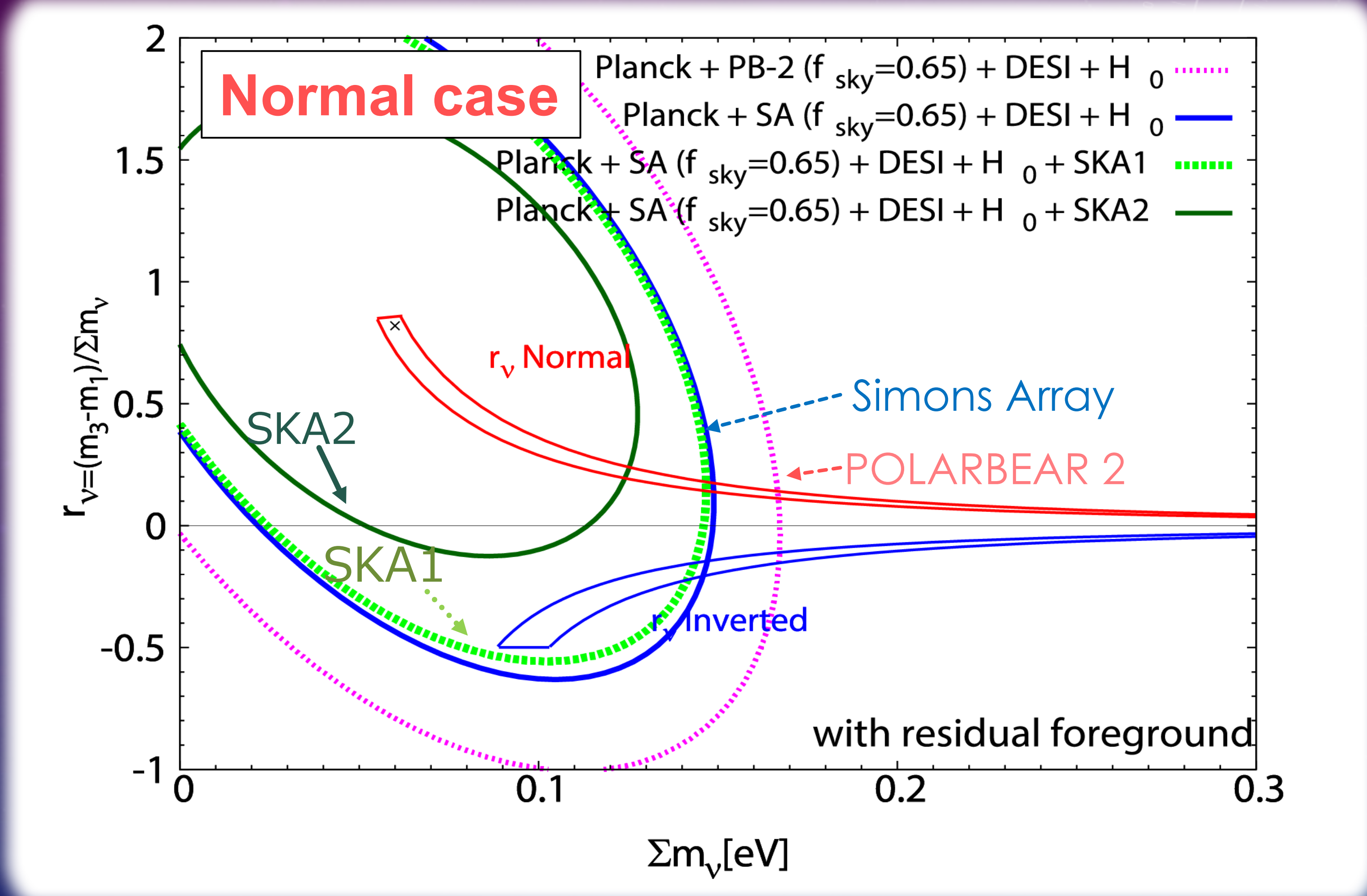
$$r_\nu \equiv \frac{m_3 - m_1}{\Sigma m_\nu}$$

T. Jimenez, et al., JCAP 1005:035,2010

- Normal $r_\nu > 0$
- Inverted $r_\nu < 0$



◆ Contours of 95% C.L. forecasts in r_ν-Σm_ν plane.



In this fiducial model, SKA phase2 + Simons Array has enough sensitivity to determine the mass hierarchy.

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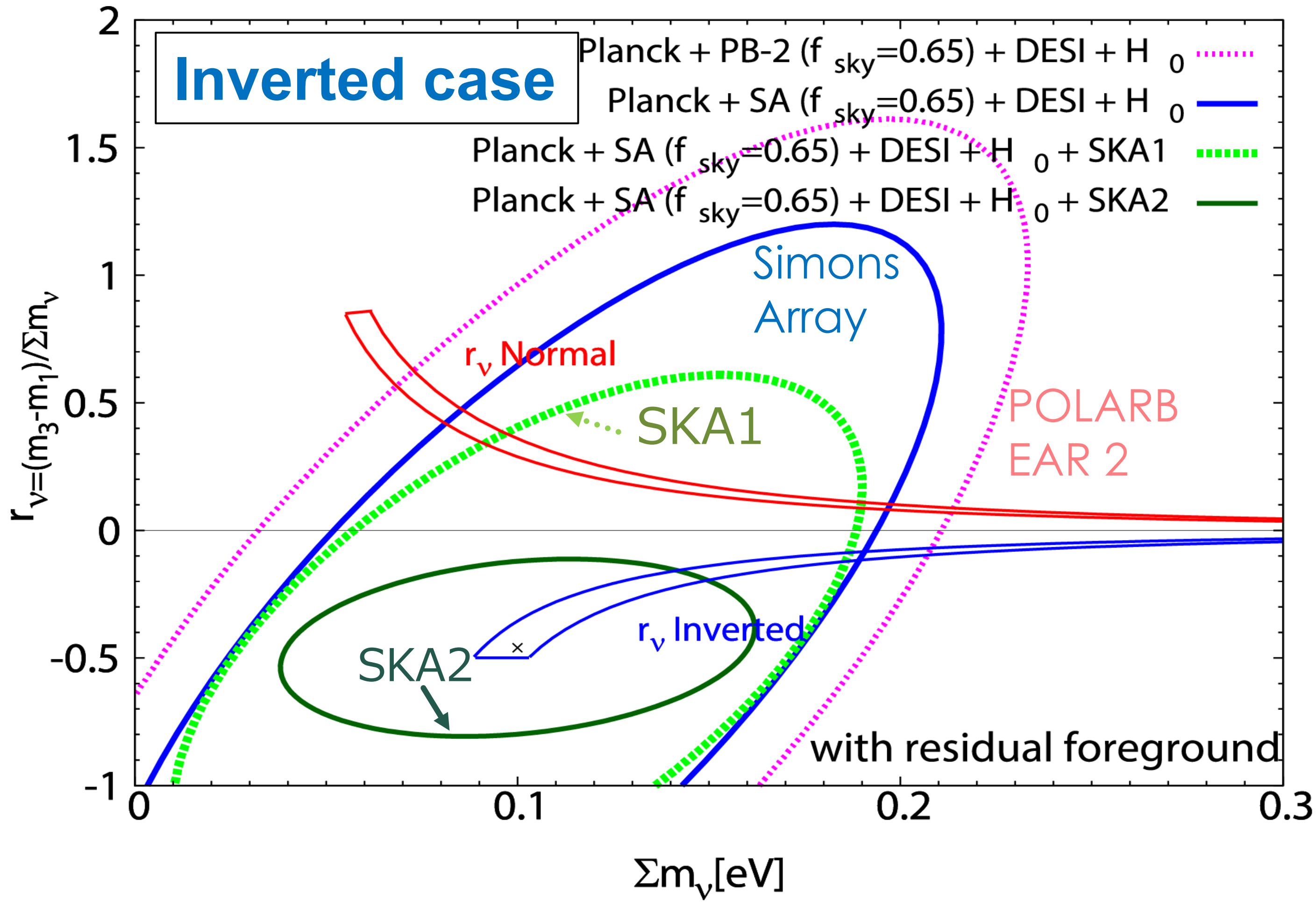

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◆ Motivations

● **Lepton number asymmetry : ξ_ν**

$$\xi_\nu \equiv \frac{\mu_\nu}{T_\nu} \sim \frac{n_\nu - n_{\bar{\nu}}}{s} = \text{const}$$

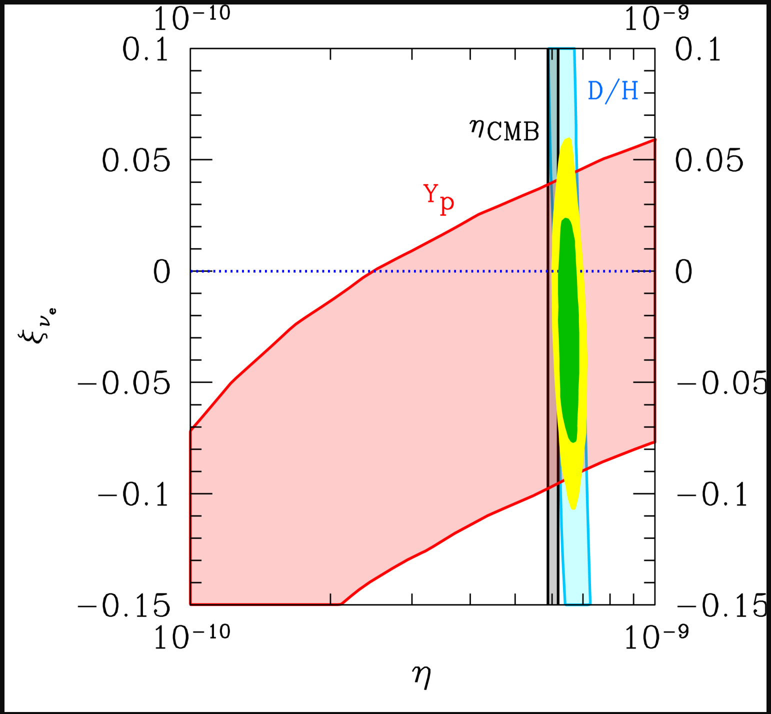
ξ_ν is **not so strongly constrained** by current observations ($|\xi_\nu| \lesssim \mathcal{O}(0.01-0.1)$).

In future

Cosmological observations (e.g. CMB, 21cm) will constrain ξ_ν **more strongly**.

Current constraint

The strongest constraints of ξ_ν come from light element measurement.



1 and 2 σ constraint in ξ_{ν_e} - $\eta \equiv n_b/n_\gamma$ plane

$-0.1 \lesssim \xi_{\nu_e} \lesssim 0.05$ (95% C.L.)

Kohri, Oyama, Sekiguchi, Takahasi (2014)

◆ Impacts of lepton asymmetry on growth of fluctuations

Main effects:

1. Background expansion rate

ξ_ν contributes an **extra radiation**.

2. Helium abundance

Big Bang Nucleosynthesis (BBN)

◆ Impacts of lepton asymmetry on growth of fluctuations

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Big Bang Nucleosynthesis (BBN)

1. Background expansion rate

Energy density of neutrino

(massless limit)

$$\rho_\nu + \rho_{\bar{\nu}} = N_\nu \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 \left[1 + \left\{\frac{30}{7}\left(\frac{\xi_\nu}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_\nu}{\pi}\right)^4\right\}\right]$$

ξ_ν contributes an extra radiation.

The time of matter radiation equality becomes **later time**.

◆ Impacts of lepton asymmetry on growth of fluctuations

Main effects:

1. Background expansion rate

ξ_ν contributes an **extra radiation.**

2. Helium abundance

Big Bang Nucleosynthesis (BBN)

2. Impacts on helium abundance

$\xi_\nu \rightarrow$ **increases**

1. Number of neutrons decreases

$p + e^- + \bar{\nu}_e \rightarrow n$
is suppressed

$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{m_n - m_p}{T} - \xi_{\nu_e}\right)$$

Abundance of $^4\mathrm{He}$ is sensitive to the neutron's one.

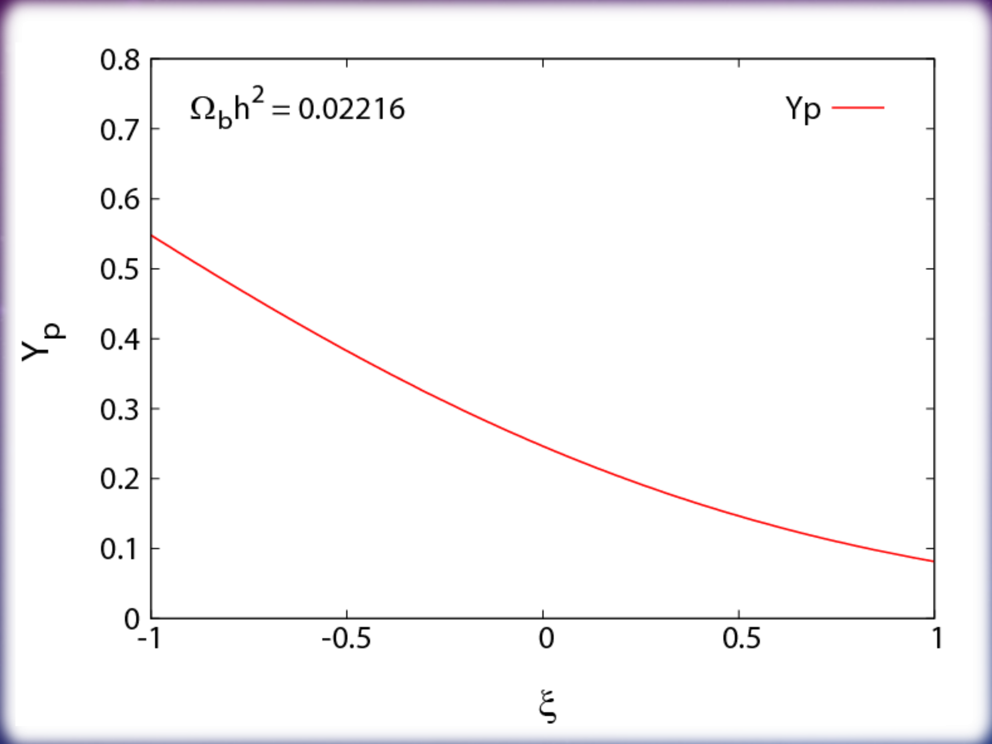
2. Expansion rate becomes larger

Earlier BBN era

The former effect is more influential.

2. Impacts on helium abundance

Helium fraction: $Y_p \equiv \dfrac{{}^4\text{He total mass}}{\text{baryon total mass}}$



$\xi_{\nu_e} \rightarrow$ **increases**

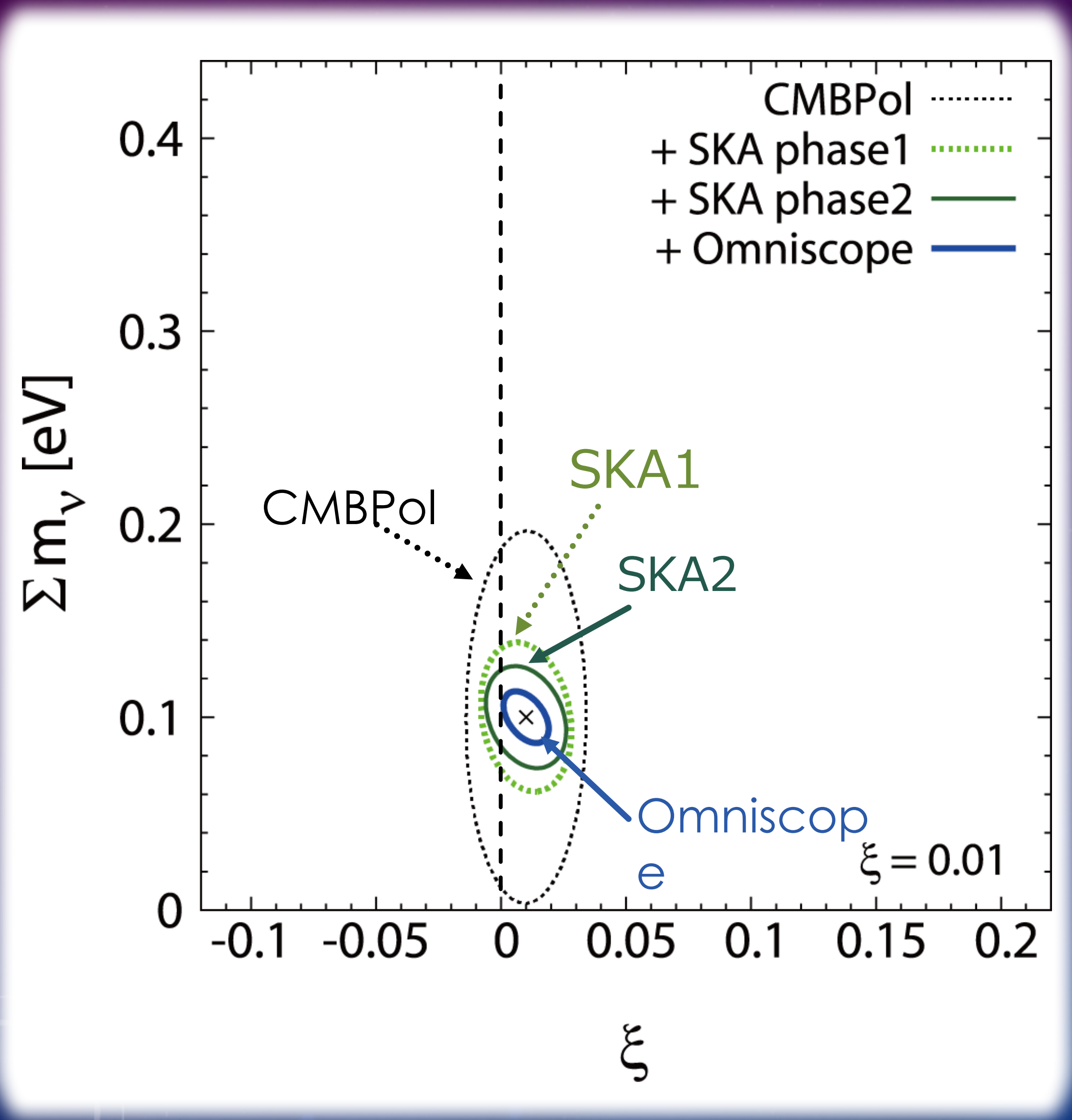
Helium fraction decreases

Y_p affects the **position of acoustic peak** and the **silk damping scale of CMB**.

◆ Constraints on ξ-Σm_ν plane

K. Kohri, Y. Oyama,
T. Sekiguchi, T. Takahashi,
JCAP09 (2014)014.

◆ Constraints on ξ-Σm_ν plane



Forecast (95% C.L.)

$\xi = 0.01$

If $\xi \lesssim 0.01$, Omniscope + CMBPol can detect ξ.

◆ Contents

1. ニュートリノによる密度ゆらぎの成長及びCMBへの影響
2. CMB偏光, 21cm線観測による将来のニュートリノ質量への制限
3. 宇宙論的観測によるレプトン（ニュートリノ）数非対称性への制限
4. Summary

Summary

- 初期宇宙で熱浴から生成されたneutrinoは**密度ゆらぎの重力成長やCMBの重力レンズ効果**等に影響を与え, その質量の存在による影響を**宇宙論的な観測を通して測定することができる**.

- 将来の**高精度なCMB偏光観測**や**宇宙再電離の時期の21cm線の観測**によって, **ニュートリノ質量を非常に強く制限 or 測定出来る可能性がある**.

- **Planck + Simons Array + SKA phase1** では**2σの制度でニュートリノ質量和をnonzeroから区別できる感度がある** (Σm_ν~0.1eV程度の場合).

- **レプトン（ニュートリノ）数非対称性**を将来の**CMB & 21cm線観測によってBBNによる制限以上の精度で制限できる可能性がある**.

- Back up slide

◇ 宇宙論における21cm線観測の利用

◆ 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

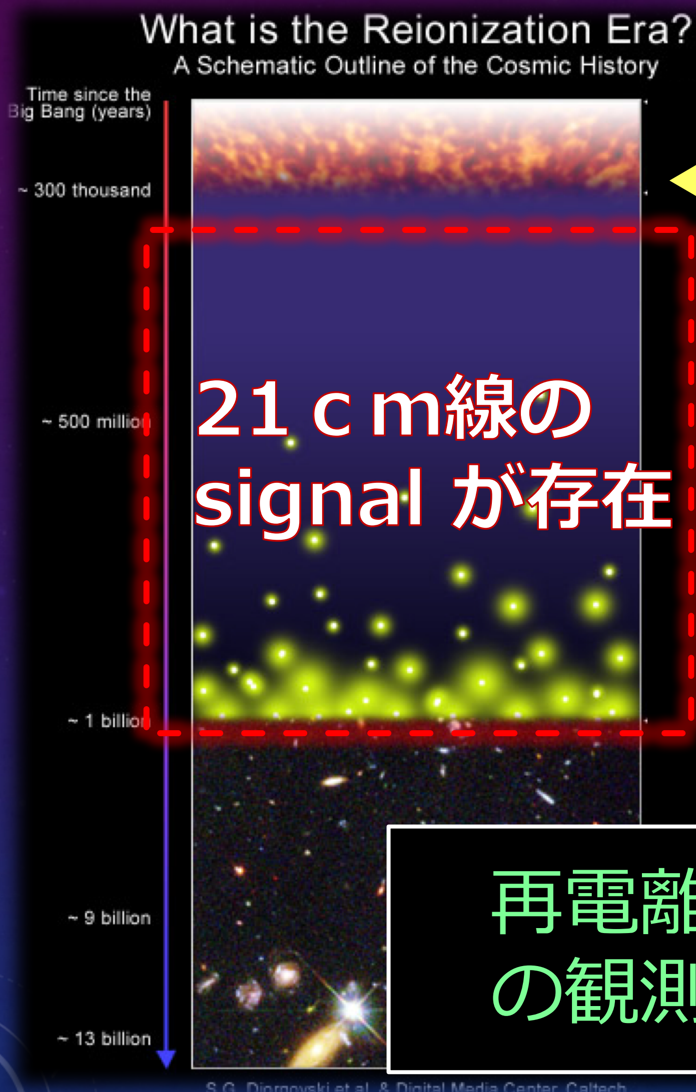
・軽いグラビティーノ dark matterの質量

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

◇ 観測対象：Cosmic dawn−再電離



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

CMB z~1000

Dark age

Cosmic dawn
(後期Dark age) $15 \lesssim z \lesssim 30$

再電離 $6 \lesssim z \lesssim 15$

再電離-Cosmic dawn
の観測が現在の目標

スピン温度の従う方程式

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

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

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

collision　　Lya　　CMB Photon

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

x_{HI}の時間変化

平衡状態のスピン温度

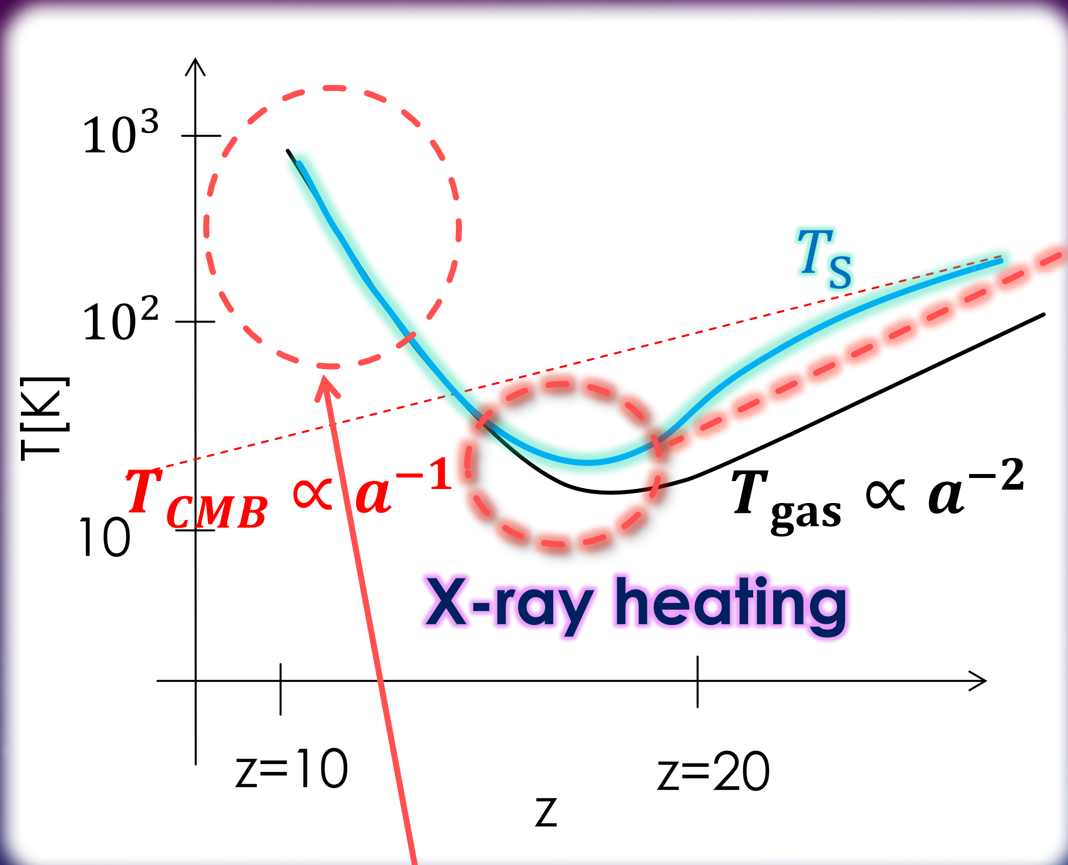
$$\frac{\partial}{\partial t}\left(\frac{1}{T_s}\right) \approx 0, \qquad \frac{\partial x_{HI}}{\partial t} \approx 0$$

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

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

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

T_S at the reionization



$10 \lesssim z < 20$

X-ray heating (from SNR)

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

Lya(from stars)

Brightness temp near z ~ 10

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

Ionization power spectra P_{xx} and $P_{\mathrm{x}\delta}$

$$\mathcal{P}_{xx}(k) = b_{\mathrm{xx}}^2[1 + \alpha_{\mathrm{xx}}(kR_{\mathrm{xx}}) - (kR_{\mathrm{xx}})^2]^{-\frac{\gamma_{\mathrm{xx}}}{2}}\mathcal{P}_{\delta\delta}(k)$$

$$\mathcal{P}_{x\delta}(k) = b_{\mathrm{x}\delta}^2 \exp[-\alpha_{\mathrm{x}\delta}(kR_{\mathrm{x}\delta}) - (kR_{\mathrm{x}\delta})^2]\ \mathcal{P}_{\delta\delta}(k)$$

Y. Mao, M. Tegmark, M. McQuinn, M. Zaldarriaga, O. Zahn,
Phys. Rev. D 78, 023529 (2008)

$$\begin{cases} \mathcal{P}_{\delta\delta}(k) \equiv \left(\Delta\bar{T}_b^{obs}\right)^2 P_{\delta\delta}(k) \\ \mathcal{P}_{x\delta}(k) \equiv \left(\Delta\bar{T}_b^{obs}/\bar{x}_{\mathrm{HI}}\right)^2 \bar{x}_{\mathrm{HI}} P_{\mathrm{x}\delta}(k) \\ \mathcal{P}_{xx}(k) \equiv \left(\Delta\bar{T}_b^{obs}/\bar{x}_{\mathrm{HI}}\right)^2 P_{\mathrm{xx}}(k) \end{cases}$$

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

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

$\boldsymbol{u} = (\boldsymbol{u}_\perp, u_\parallel) = (d_A(z)\boldsymbol{k}_\perp, y(z)k_\parallel)$

$d_A(z)$: commoving angular diameter distance

$y(z) = \lambda_{21}(1+z)/H(z)$

- Focused 21cm and CMB experiments

◇ 21cm line experiment

◆ SKA (Square kilometer Array)

http://www.skatelescope.org/

SKA low frequency (Australia)

Construction of Phase1 will start in 2018.

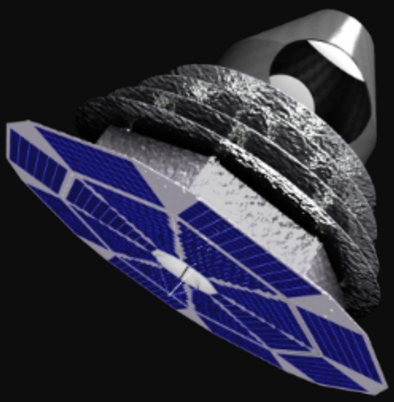
SKA phase 1 (2020年代に観測開始予定)
SKA phase 2 (phase 1の４倍の集光面積を目指す)

CMB polarization experiments

- **Simons Array**

POLARBEAR-2 × 3
95, 150, 220 GHz

- COrE+



CMB bands:
75, 105, 135, 165, 195, 225 GHz

Note: we took account of combinations of Simons Array with Planck satellite.