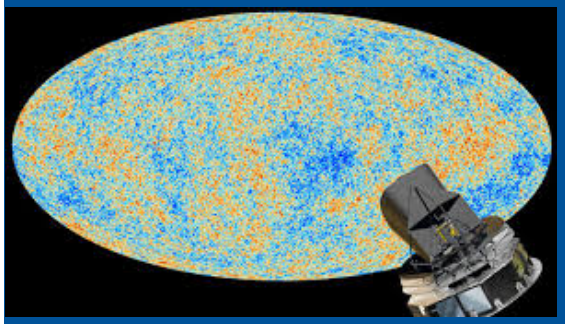
Determination of neutrino mass hierarchy from cosmology

Kazunori Kohri
(郡　　和範) in Japanese

IPNS, KEK and Sokendai
Tsukuba, Japan

国立大学法人
総合研究大学院大学
THE GRADUATE UNIVERSITY FOR ADVANCED STUDIES [SOKENDAI]

News from Planck satellite workshops 2014



In Ferrara, Italy, 1st December 2014
In Paris, France, 15th December 2014

- Total neutrino mass

$$\sum_{i=e,\mu,\tau} m_i < 0.21 \text{ eV at } 95\% \text{ C.L.}$$

(for TT,TE,EE lowP)

Preliminary

- Effective number of neutrino species

$$N_{\nu,\mathrm{eff}} = 2.98 \pm 0.40(0.18) \text{ at } 95\%(68\%) \text{ C.L.}$$

(for TT,TE,EE lowP+BAO)

Preliminary

No positive requirements for dark radiations

Future cosmological observations useful for neutrino masses determinations for m_ν~0.05eV

- Cosmological 21cm line
- CMB polarization (lensed B-mode)
- Baryon Acoustic Oscillation (BAO)

Hot and/or warm thermal-relic

- Neutrino becomes non-relativistic at

$$T_{\text{nonrela}} \sim m_{\nu} / 3$$

$$t_{\text{nonrela}} \sim \frac{M_{\text{pl}}}{T^2_{\text{nonrela}}}$$

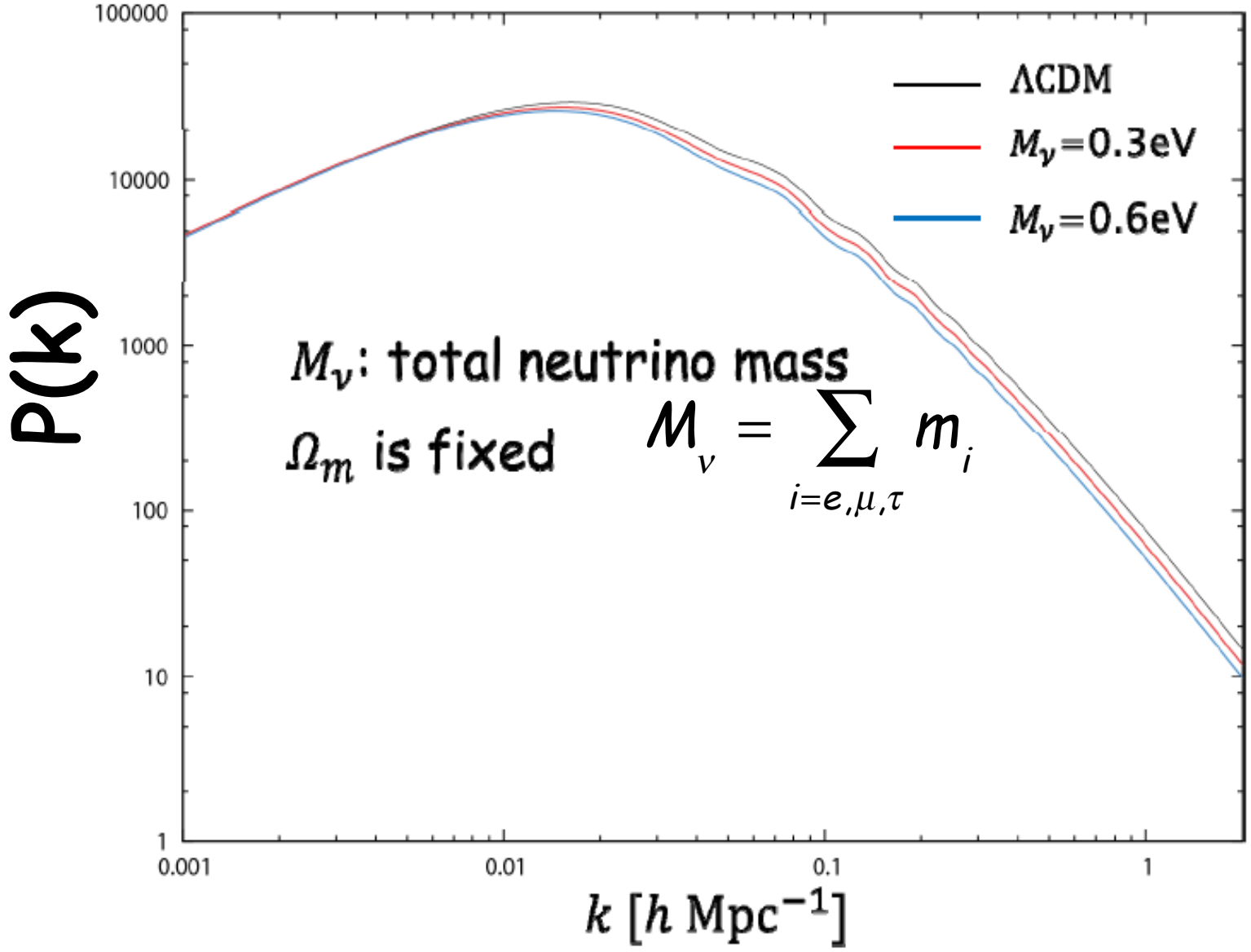
- Free-streaming length during its relativistic era

$$\lambda_{\text{FS}} \sim 2t_{\text{nonrela}} \frac{T_{\text{nonrela}}}{T_0} \sim 10^2 \text{Mpc} \left(\frac{m_{\text{DM}}}{1\text{eV}} \right)^{-1}$$

$$M_{\text{FS}} \sim \rho_{m,0} \lambda^3_{\text{FS}} \sim 10^{18} M_{\odot} \left(\frac{m_{\text{DM}}}{1\text{eV}} \right)^{-2}$$

note that $M_{\text{cluster}} < 10^{16} M_{\odot}$

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



Neutrinos with m_ν=O(0.01) eV become non-relativistic at $3T=m_\nu$=O(0.01) eV

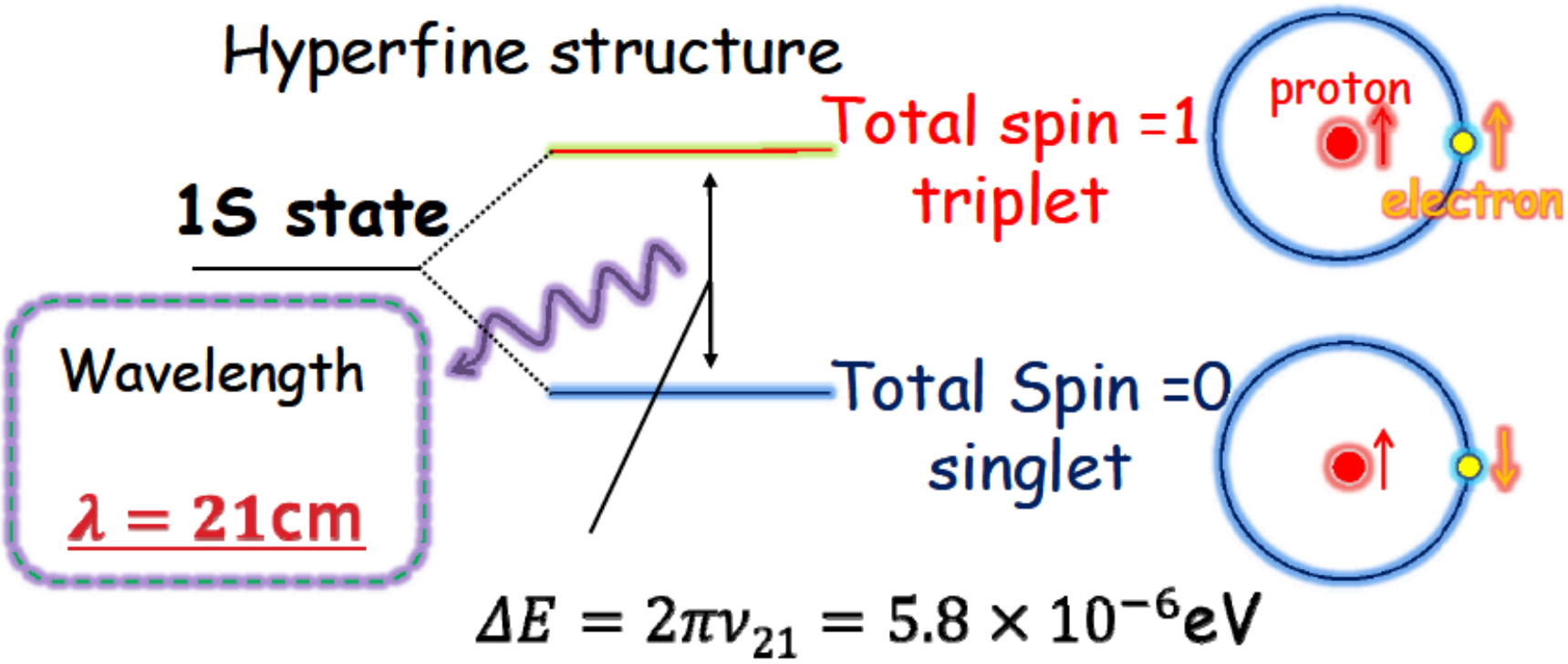
- Much after the recombination ($3T \ll 1$eV)
- Before galaxy formation ($3T \gg 0.001$eV)

21cm line and CMB lensed B-mode polarization observation should be the best tool to constrain mass hierarchy with $m_\nu \sim 0.05$ eV

◇ 21cm line

$$\frac{n_{upper}}{n_{lower}} \sim Exp\left[-\frac{\Delta E}{T_s}\right]$$

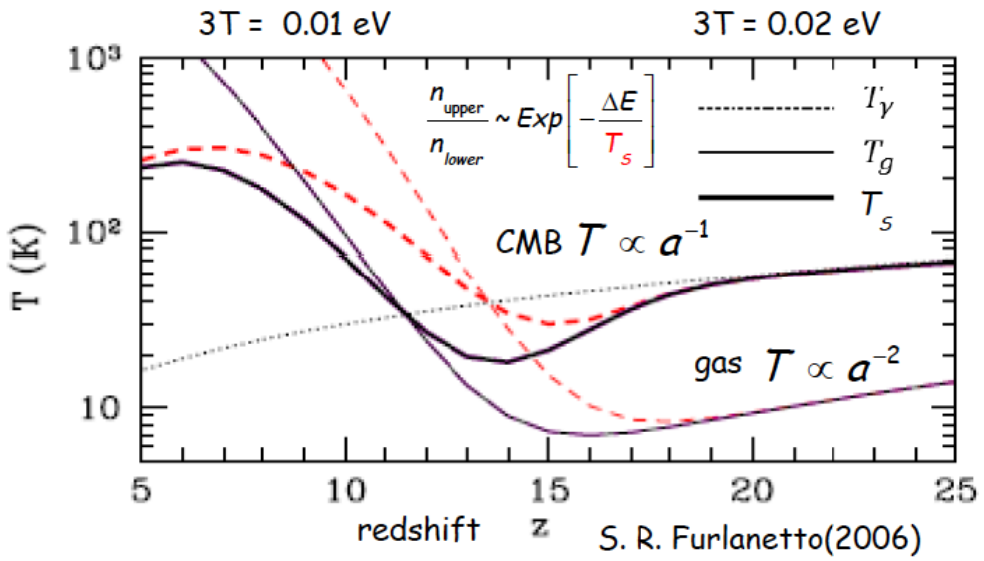
◆proton-electron's spin-spin interaction



Cosmological 21cm line was emitted at the reionization epoch,

Temperature T ~ 0.003eV – 0.01 eV

Evolution of spin temperature after star formation



Gas was heated by X-ray emission

$$T_g > T_\gamma$$

$z \approx 10$ by Ly-α heating $T_S \to T_g \gg T_\gamma$

21cm line power spectrum $P_{21}(k,\mu)$ traces the baryon power spectrum

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

$M_\nu \ < 0.1$ eV $\quad \delta_{x_{HI}} \ll 1$

$$P_{21}(k,\mu) = (1+\mu^2)^2 P_{\delta_H\delta_H}(k)$$

$P_{\delta_H\delta_H}(k)$: matter power spectrum

μ: cosine with respect to line of sight

Detail of ionization history gives us power spectrum

SKA (Square kilometer Array)

Location : Australia and South Africa

Antenna number
5000

Effective total
Antenna area
6×10^5 m^2

http://www.skatelescope.org/

Construction Phase (2016 –)

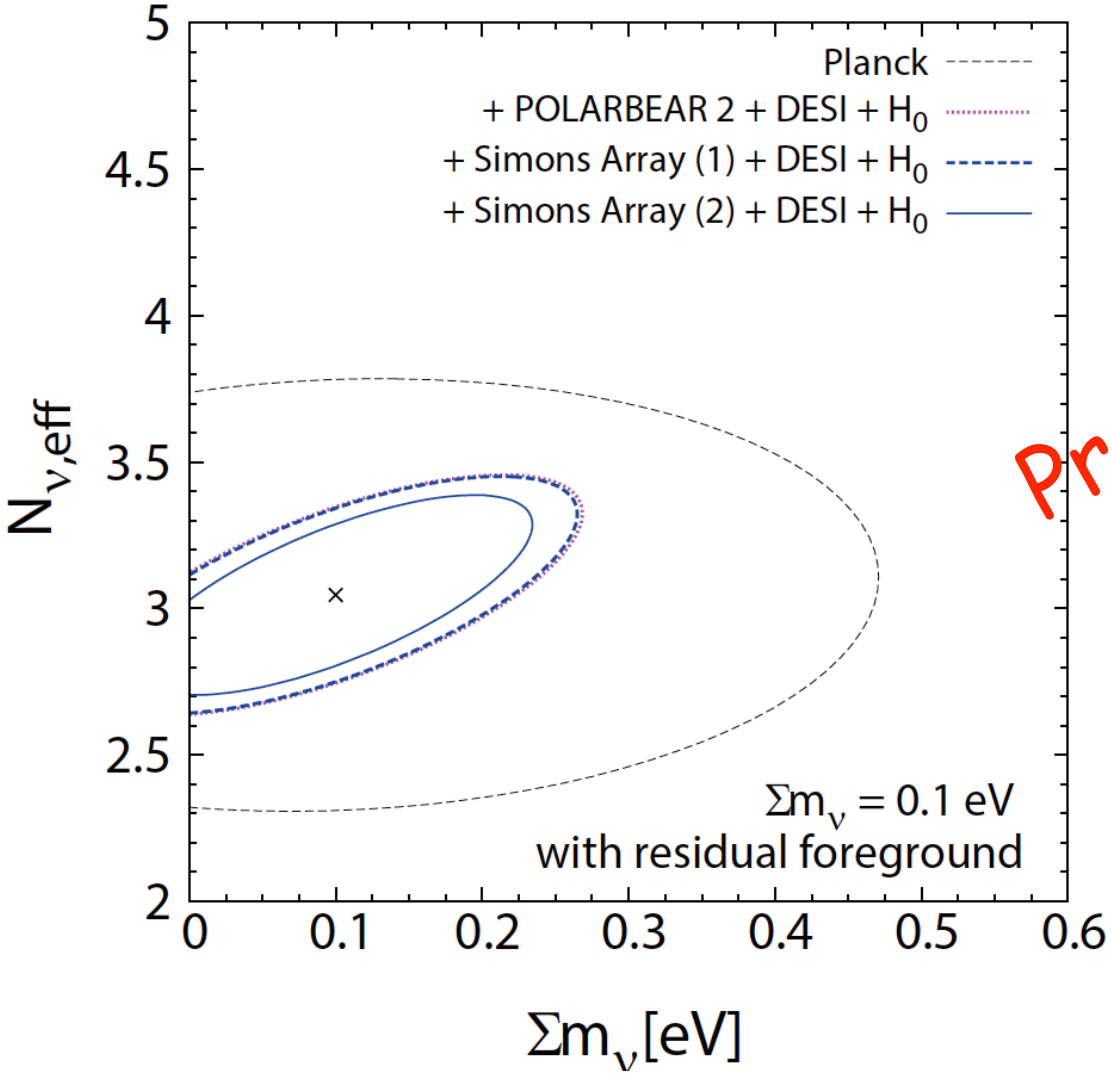
(KEK's) Future CMB polarization observations

- POLARBEAR 2
- Simons Array
- GroundBIRD
- LiteBIRD

See Osamu Tajima's talk

Future constraints without 21cm line, but only by CMB and BAO

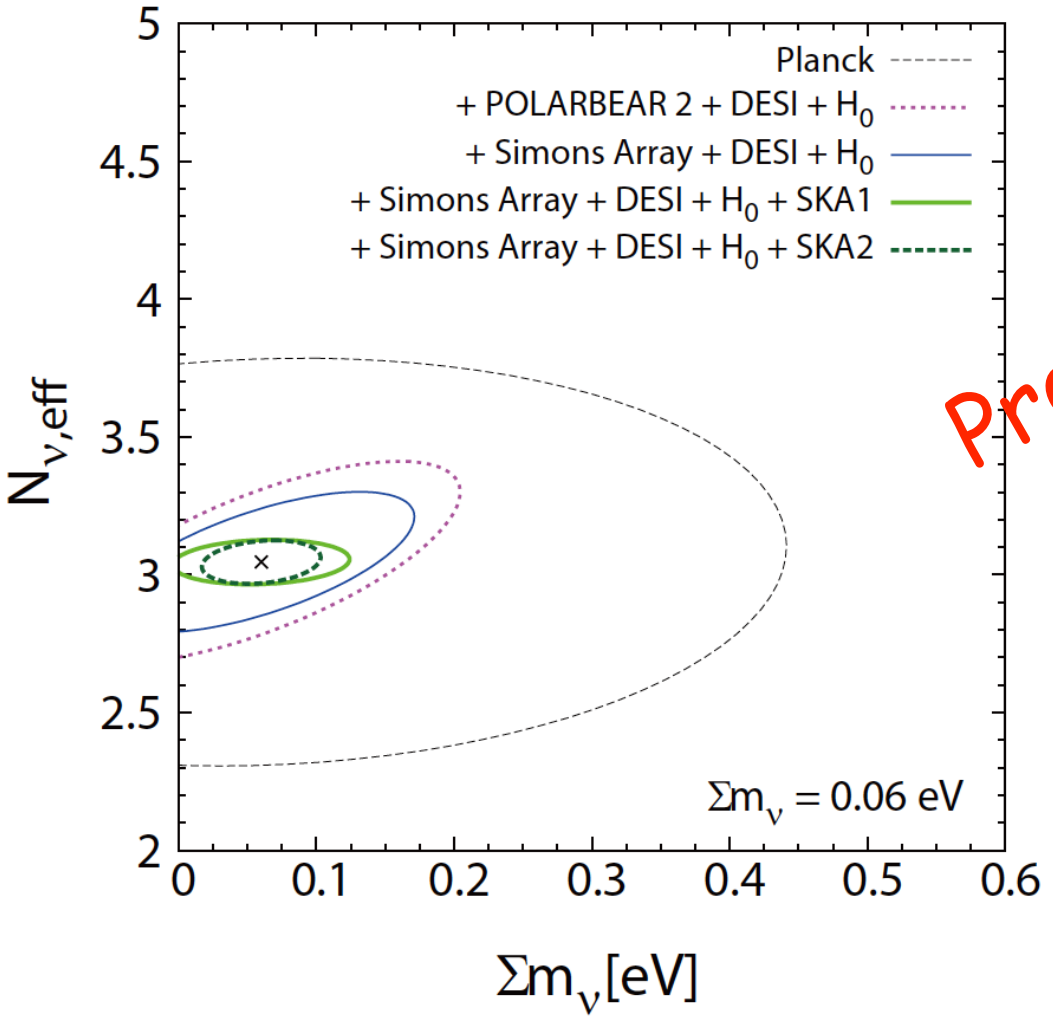
Baryon Acoustic oscillation (BAO) Observing galaxies/quasars by DESI



Preliminary

Oyama, Kohri, Hazumi (2015) in preparation

Future constraints on neutrino mass by 21cm, CMB, and BAO



Preliminary

Oyama, Kohri, Hazumi (2015) in preparation

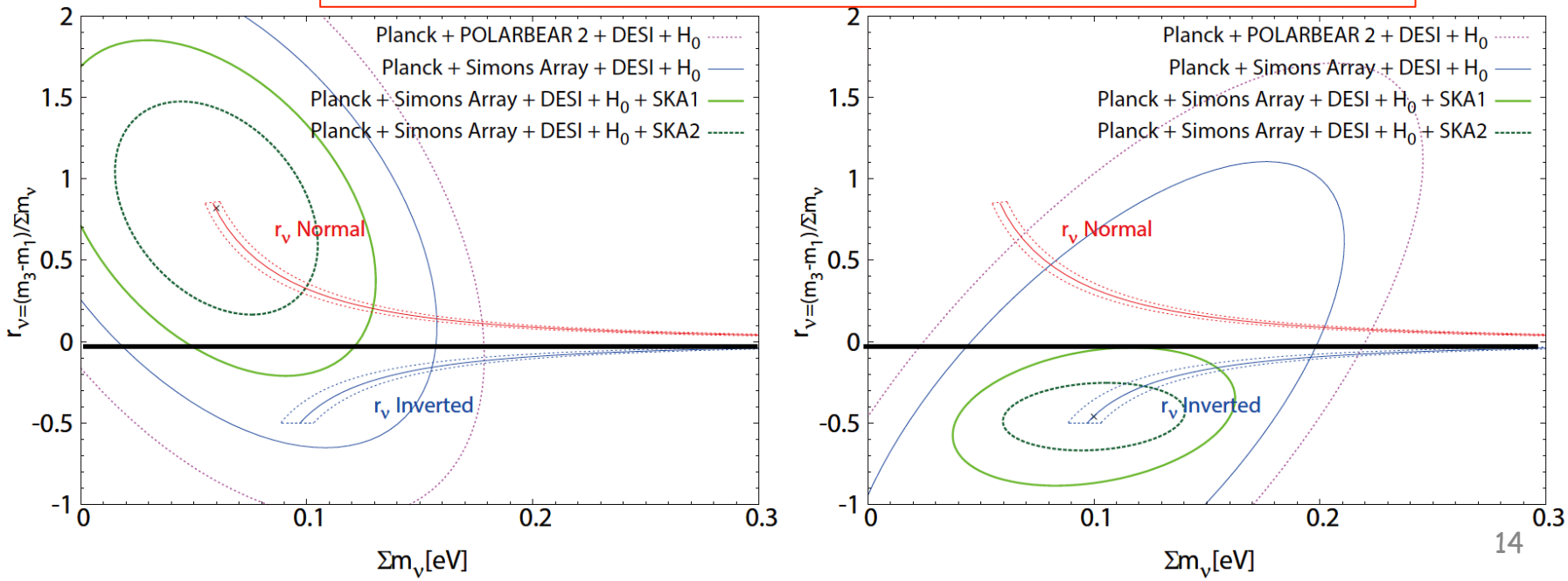
Future constraints on neutrino hierarchy by 21cm, CMB and BAO

Oyama, Kohri, Hazumi (2015) in preparation

Preliminary

- Hierarchy parameter

$$r_\nu \equiv \frac{m_3 - m_1}{\Sigma m_i} = \begin{cases} > 0 & \text{normal hierarchy} \\ < 0 & \text{inverted hierarchy} \end{cases}$$

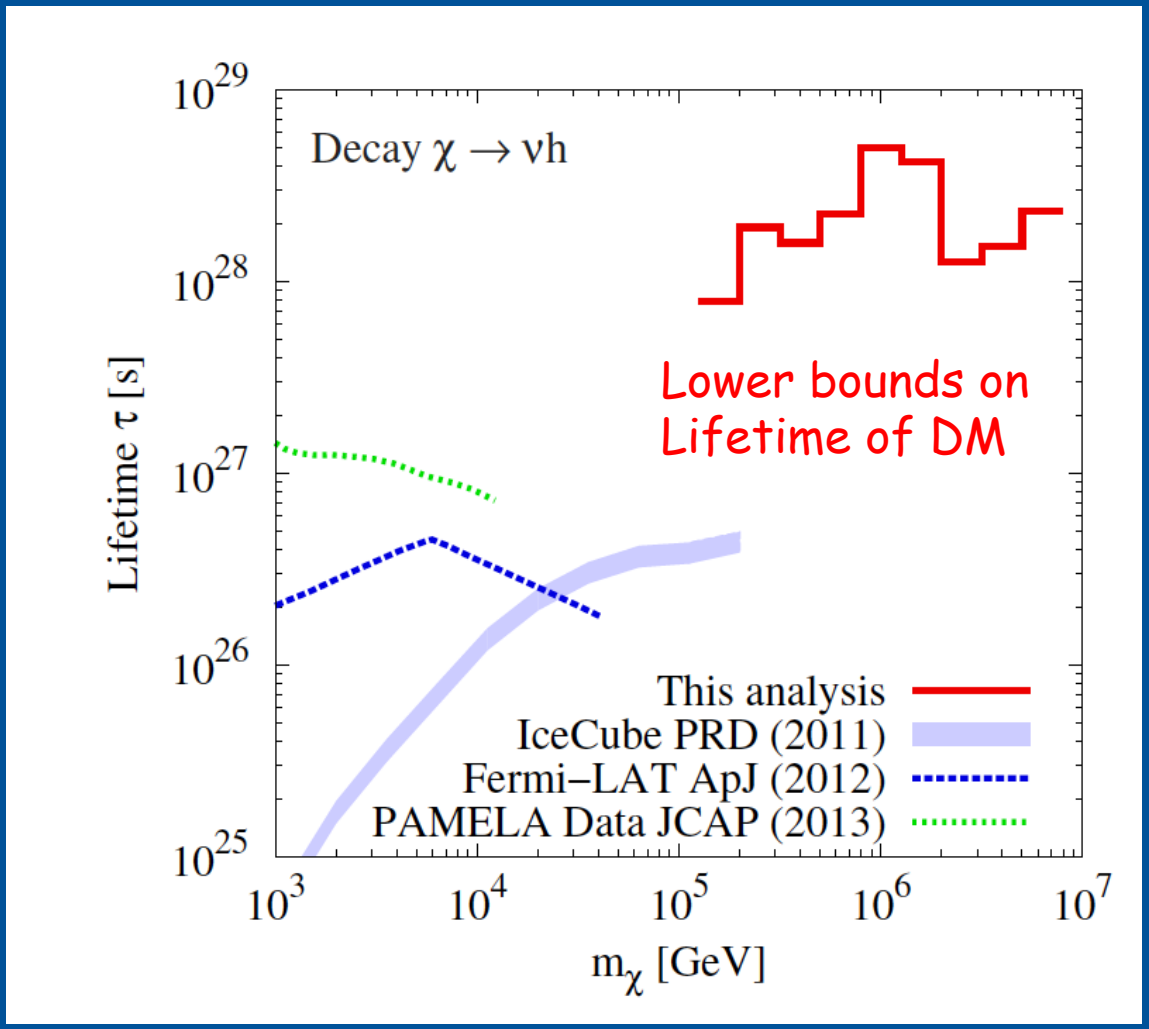


Summary

- Cosmology is very sensitive to neutrino masses of active (+sterile) neutrinos
- By using future observations such as cosmological 21cm line, CMB, and BAO (large scale structure), we will be able to determine absolute values of neutrino masses and their hierarchy
- One more comment …

Bounds on decaying Dark Matter to fit the IceCube PeV ν events

C.Rott, K.Kohri, S.-C.Park, arXiv:1408.4575



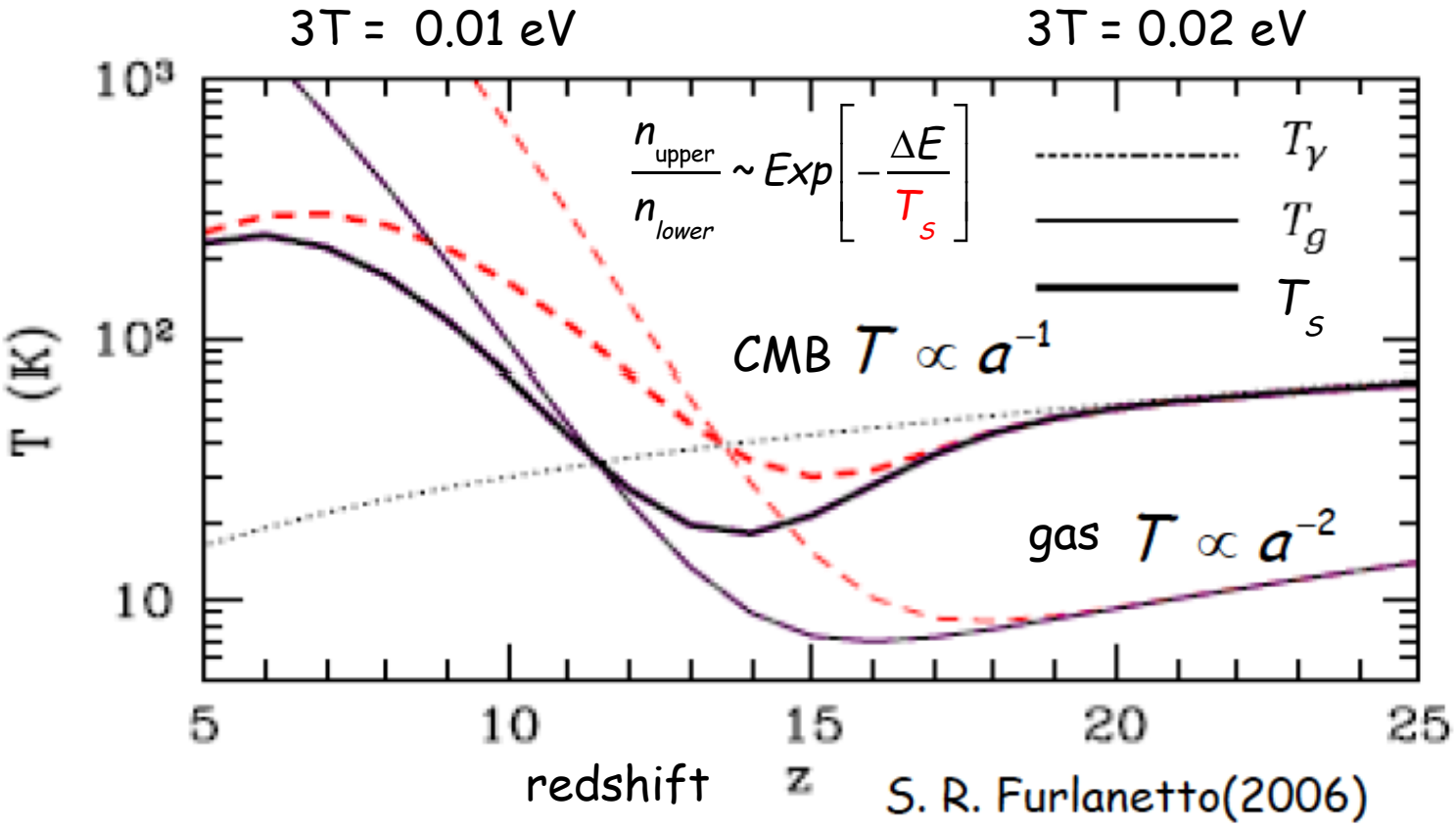
Spin temperature Ts

- Defined by the ratio of the occupation numbers in two states

$$\frac{n_{upper}}{n_{lower}} = \frac{g_{upper}}{g_{lower}} Exp\left[-\frac{\Delta E}{T_s}\right]$$

g_i = degree of reedom for a level "i"

Evolution of spin temperature after star formation



Gas was heated by X-ray emission

$$T_g > T_\gamma$$

$z \approx 10$ by Ly-α heating $T_S \to T_g \gg T_\gamma$

Omniscope

Max Tegmark, Matias Zaldarriaga arXiv:0805.4414v2 (2008)
Max Tegmark, Matias Zaldarriaga Phys. Rev. D 82, 103501 (2010)

Lower cost than usual interferometers

- J. R. Pritchard, E. Pierpaoli, Phys Rev D 78, 065009

Antenna number	Effective total anntena area
10^6	10^6 m^4