Determination of neutrino mass hierarchy by 21 cm line and CMB B-mode polarization observations

Yoshihiko Oyama, Akie Shimizu and KK,
Physics Letters B718 (2013) 1186, arXiv:1205.5223

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Abstract

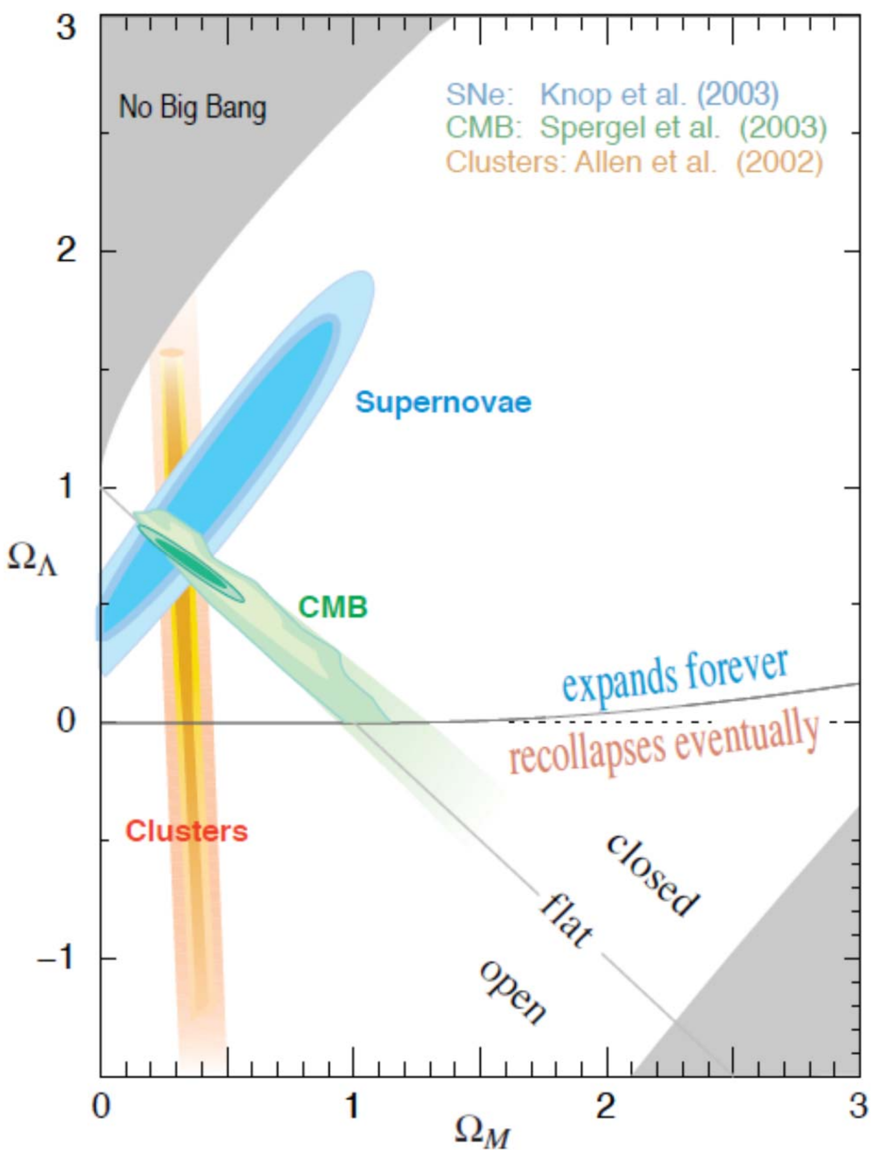
- Future 21 cm and CMB B-mode polarization data will constrain both neutrino masses and effective number of neutrino species (Forecast)

- Planck + POLARBEAR + Omniscope or CMBpol +Omniscope will distinguish inverted hierarchy from normal hierarchy

Brief Review of cosmology

Combined Figure

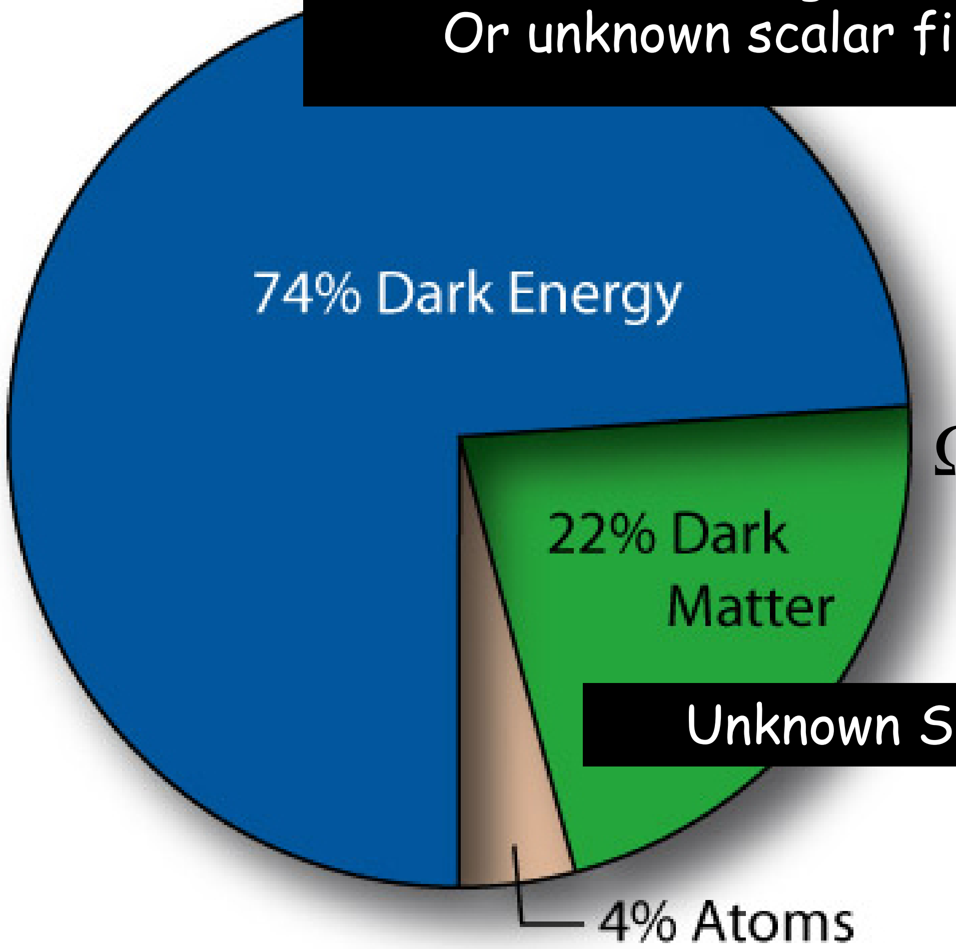
$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$



Riess et al (98), Lahav-Liddle PDG (09)

Contents in the current Universe

Einstein's Cosmological Constant
Or unknown scalar field?



$$\Omega_i \equiv \left.\frac{\rho_i}{\rho_c}\right|_0$$

$$\Omega_{\mathrm{CDM}} h^2 \sim 0.1$$

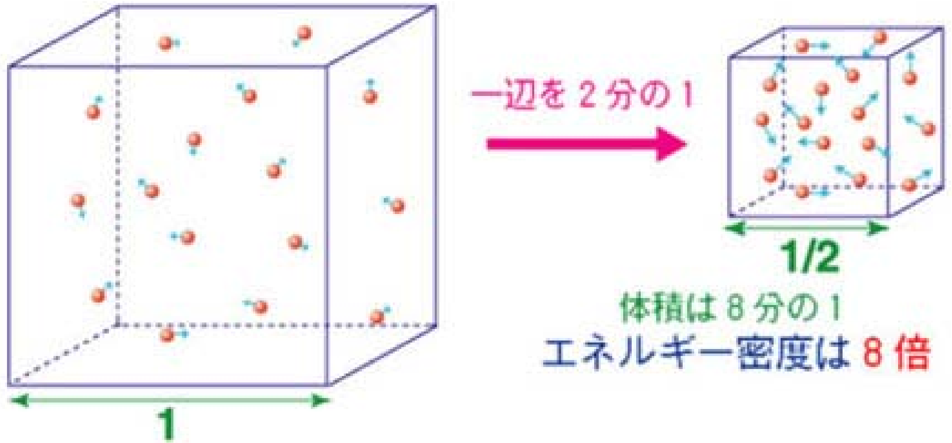
Unknown SUSY particles?

http://map.gsfc.nasa.gov/media/060916

Adiabatic expansion or compression

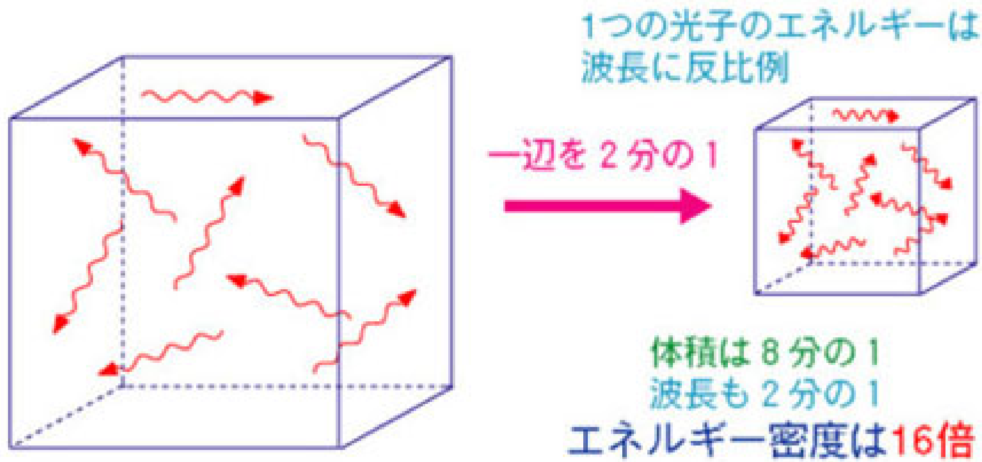
$T \propto 1/a$ (Adiabatic compression)

Matter



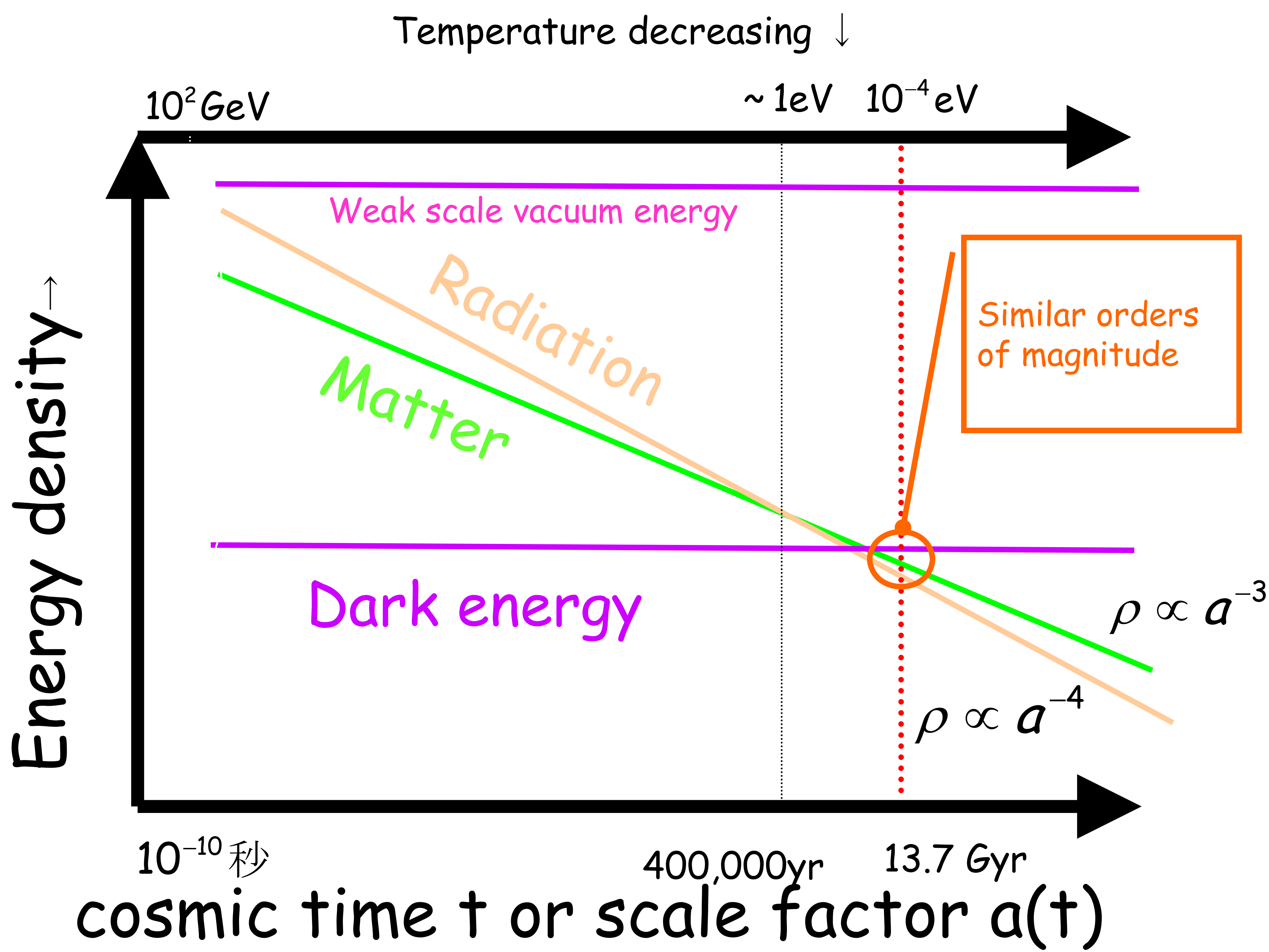
$$\rho \propto a^{-3}$$

Radiation



$$\rho \propto a^{-4}$$

From Prof. Funakubo's webpage in Saga University http://dirac.phys.saga-u.ac.jp/~funakubo/BAU/chapter2/chapter2-1.html



Temperature decreasing ↓
10^2GeV
~1eV
10^{-4}eV
Weak scale vacuum energy
Radiation
Matter
Similar orders of magnitude
Dark energy
$\rho \propto a^{-3}$
$\rho \propto a^{-4}$
Energy density→
10^{-10}秒
400,000yr
13.7 Gyr
cosmic time t or scale factor a(t)

Cosmit time and Cosmic temperature in radiation dominant (RD) Universe

- Metric

$$ds^2 = -dt^2 + a(t)^2 dx^2$$

- Friedmann equation （General Relativity）

$$\text{Hubble expansion :} \quad \left(\frac{1}{a}\frac{da}{dt}\right)^2 = H^2 = \frac{8\pi}{3M_p^2}\rho$$

$$\rho_{\text{radiation}} = \frac{\pi^2}{30} g T^4 \propto a(t)^{-4} \quad \rightarrow \quad a(t) \propto t^{1/2}$$

$$T \propto a^{-1} (\text{adiabatic expansion, } S\text{~}a^3T^3\text{=const.})$$

$$t \sim 1\text{sec}\left(T / \text{MeV}\right)^{-2} \quad \text{in RD}$$

redshift z

- Defined by a change of wavelength

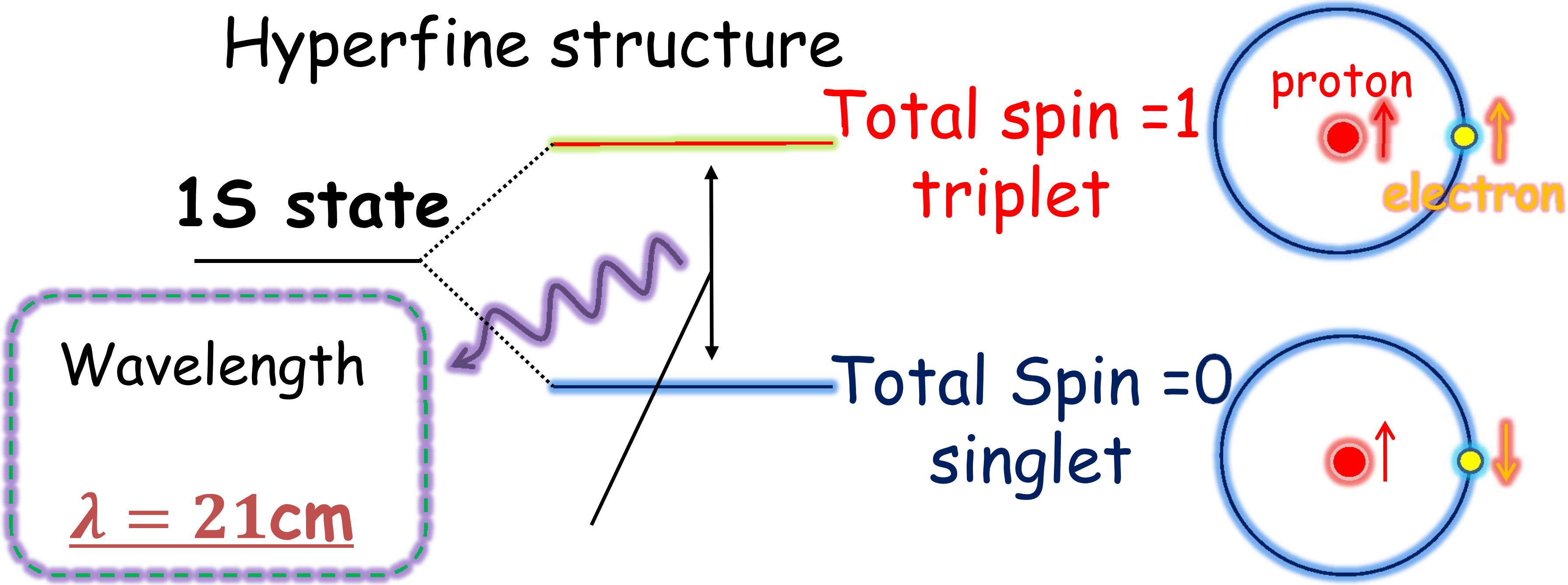
$$z = \frac{\Delta\lambda}{\lambda} \geq 0$$

- Cosmic temperature T and scale factor a(t)

$$1 + z = \frac{\lambda + \Delta\lambda}{\lambda} = \frac{a(t_0)}{a(t)} = \frac{T}{T_0} \geq 1$$

◇ 21cm line

◆proton-electron's spin-spin interaction



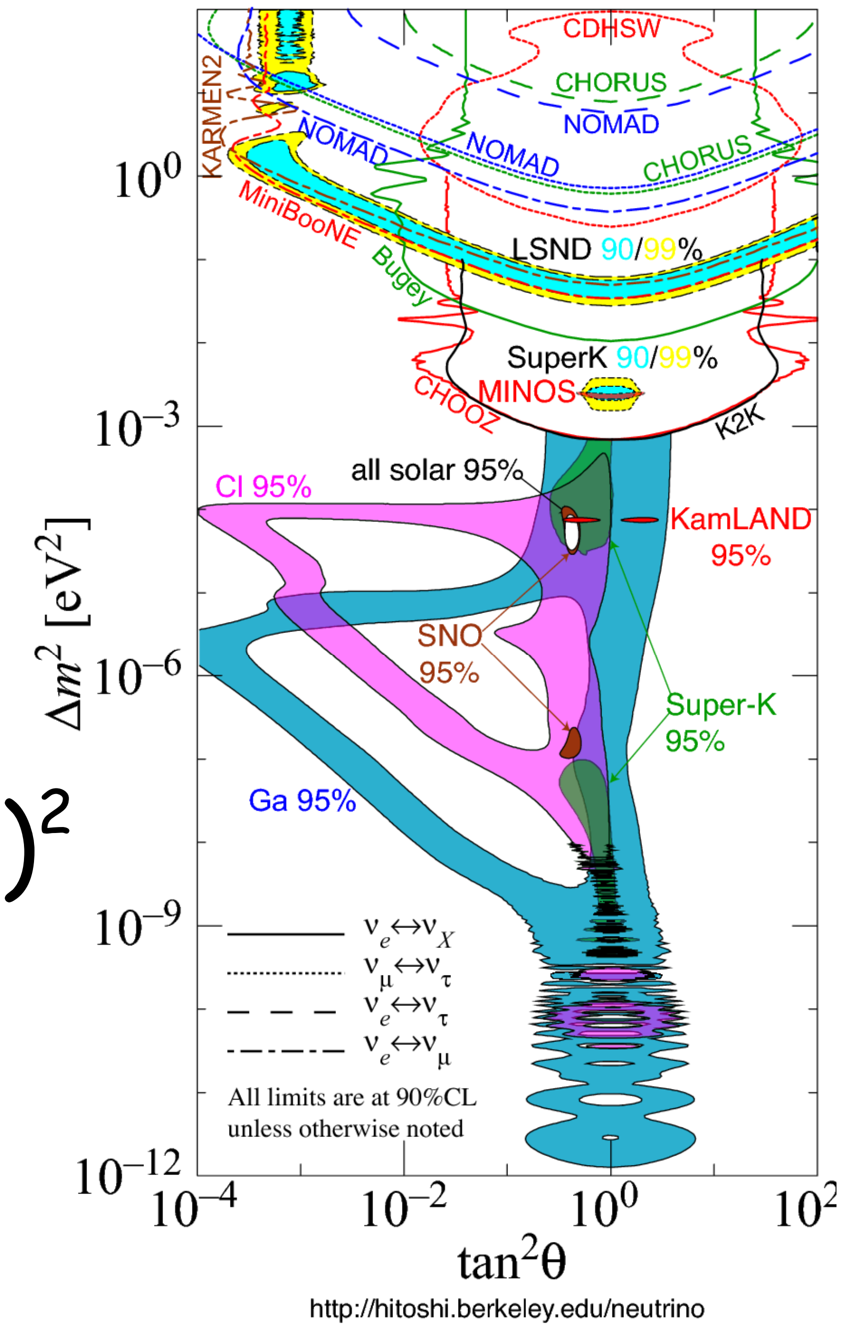
$$\Delta E = 2\pi\nu_{21} = 5.8\times10^{-6}\text{eV} \sim 2\pi\times1.4\text{GHz}$$

Neutrinos

Neutrino oscillation

$$\Delta m^2_{\nu,atm} \sim (0.05eV)^2$$

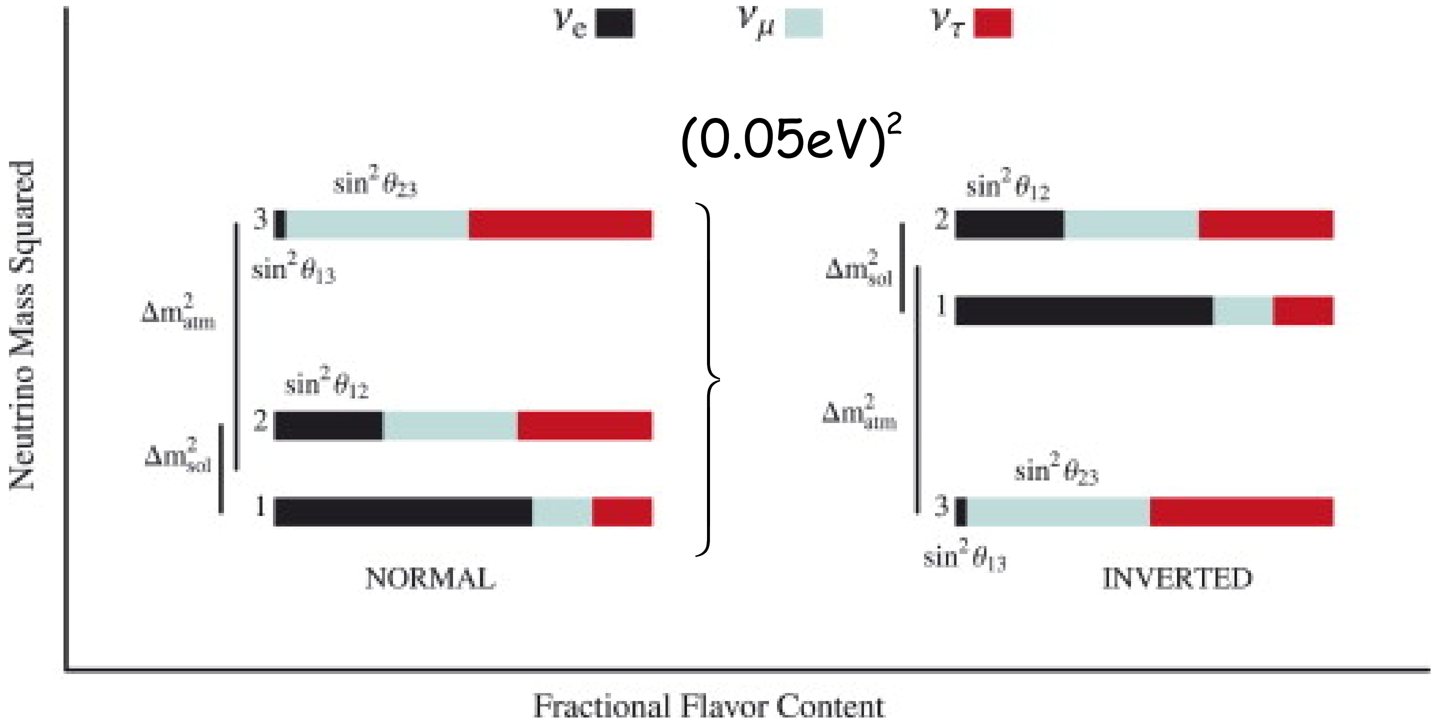
$$\Delta m^2_{\nu,solar} \sim (0.009eV)^2$$



Experimental lower bounds on total neutrino mass

- Neutrino oscillation

$$\Sigma m_{\nu i} >\sim 0.05\text{eV (normal hierarchy)}$$
$$\Sigma m_{\nu i} >\sim 0.10\text{eV (inverted hierarchy)}$$



Geer-Zisman (07)

Experimental upper bounds on m_ν

β-decay of tritium

Troitsk, Maintz $m_{\nu_e} < 2.05 - 2.30$ **eV (95%CL)**

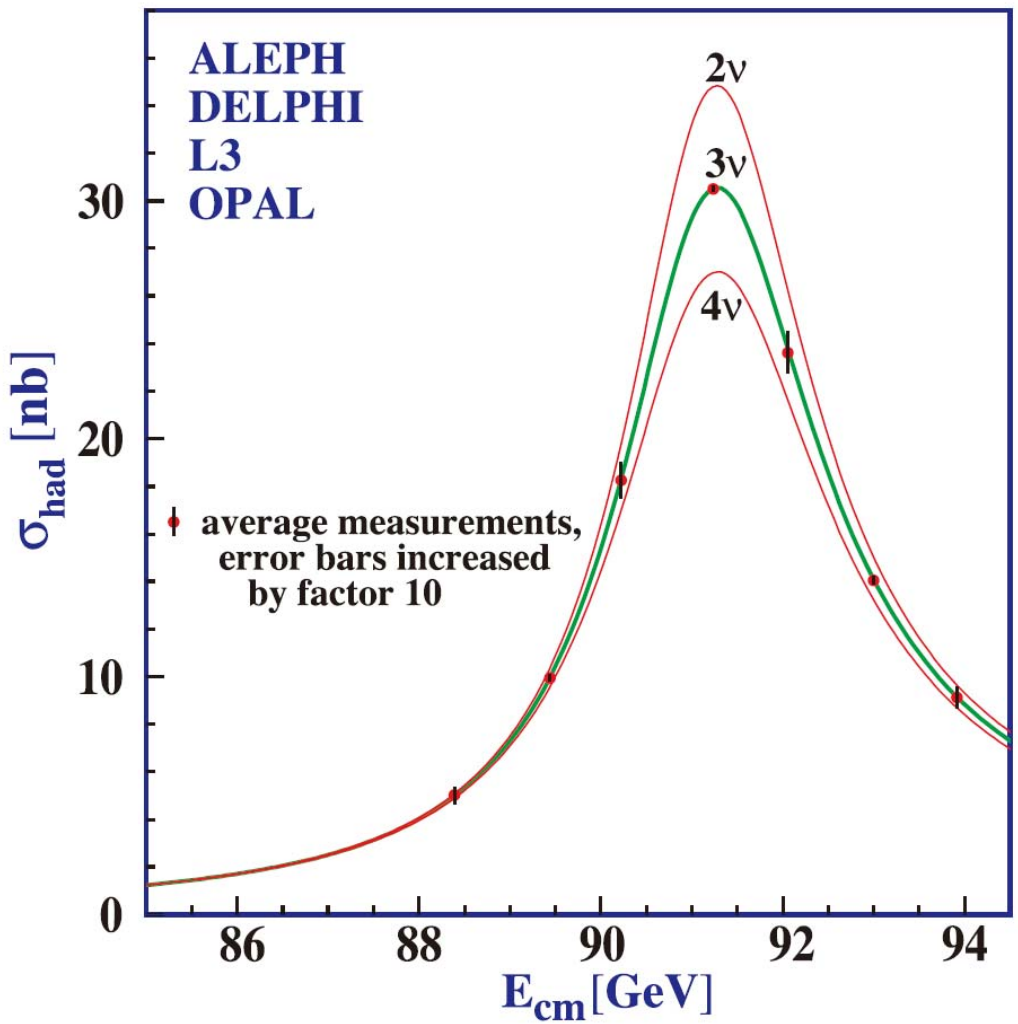
C. Kraus, et al., Eur. Phys. J. C 40 (2005) 447 [hep-ex/0412056]

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

Neutrino number of species in LEPII

- Coupled only

to Z boson



Cosmology and neutrinos

Hot and/or warm thermal-relic

- Becoming Non-relativistic at

  Temperature $$T_{nonrela} \sim m_{DM}/3$$

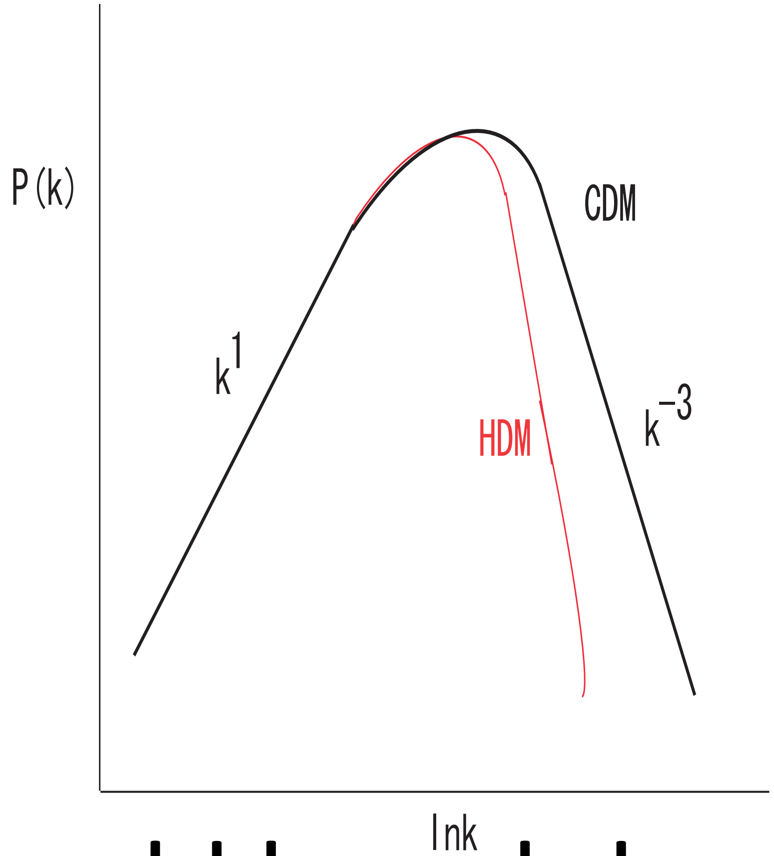
  Time $$t_{nonrela} \sim \frac{1}{g_*^{1/2}(T_{nonrela})} \frac{M_{pl}}{T^2_{nonrela}}$$

- Free-streaming length in relativistic era

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

$$M_{FS} \sim \rho_{m,0} \lambda_{FS}^3 \sim 10^{16} M_\odot \left(\frac{m_{DM}}{10\mathrm{eV}} \right)^{-2}$$

Power spectrum of CDM and HDM



Neurinos should be subdominant

Cosmological bounds?

Above free-streaming scale

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

Neutrino contributes to matter

$$\boldsymbol{\delta_m \propto a}$$

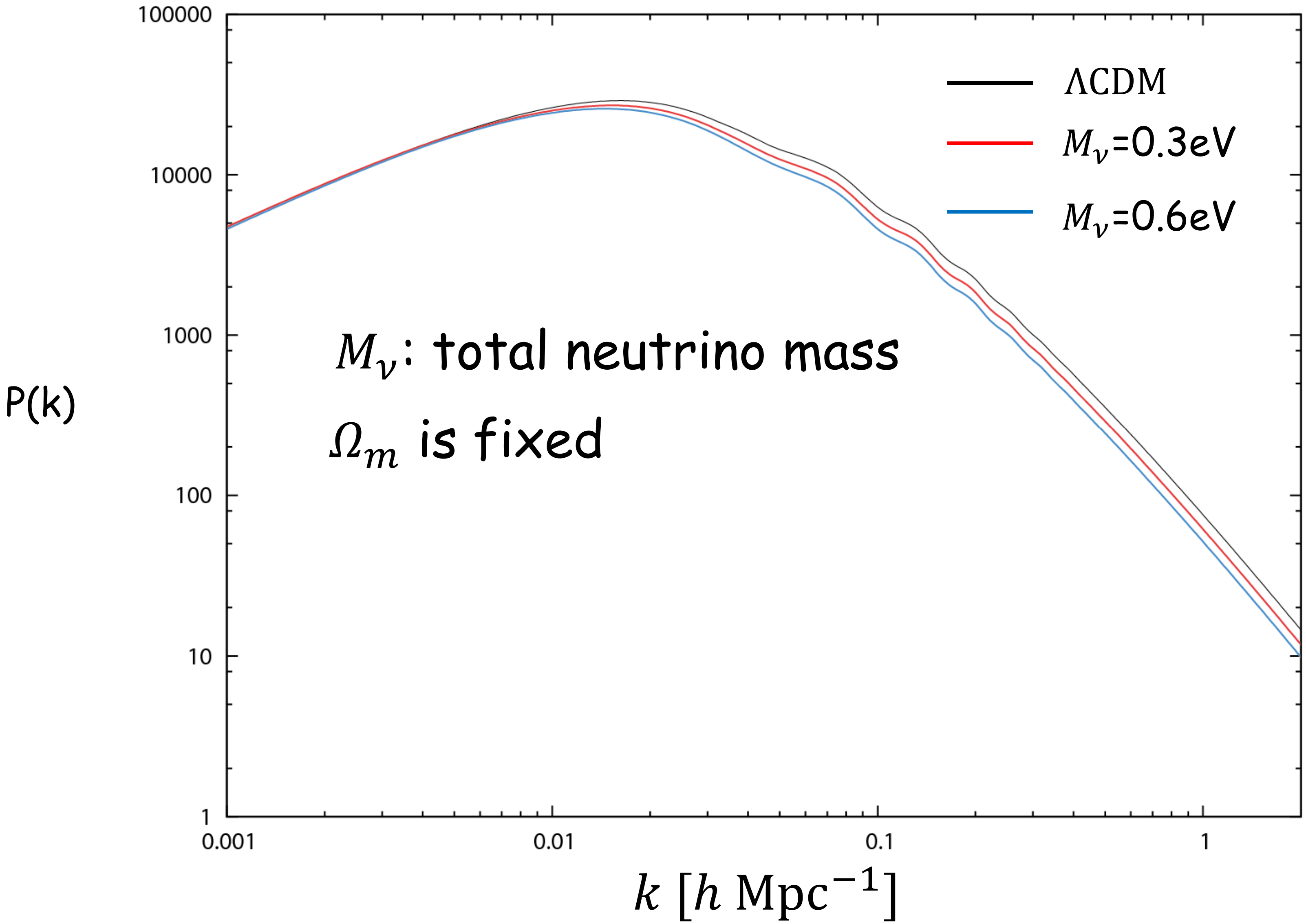
Below free-streaming scale

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

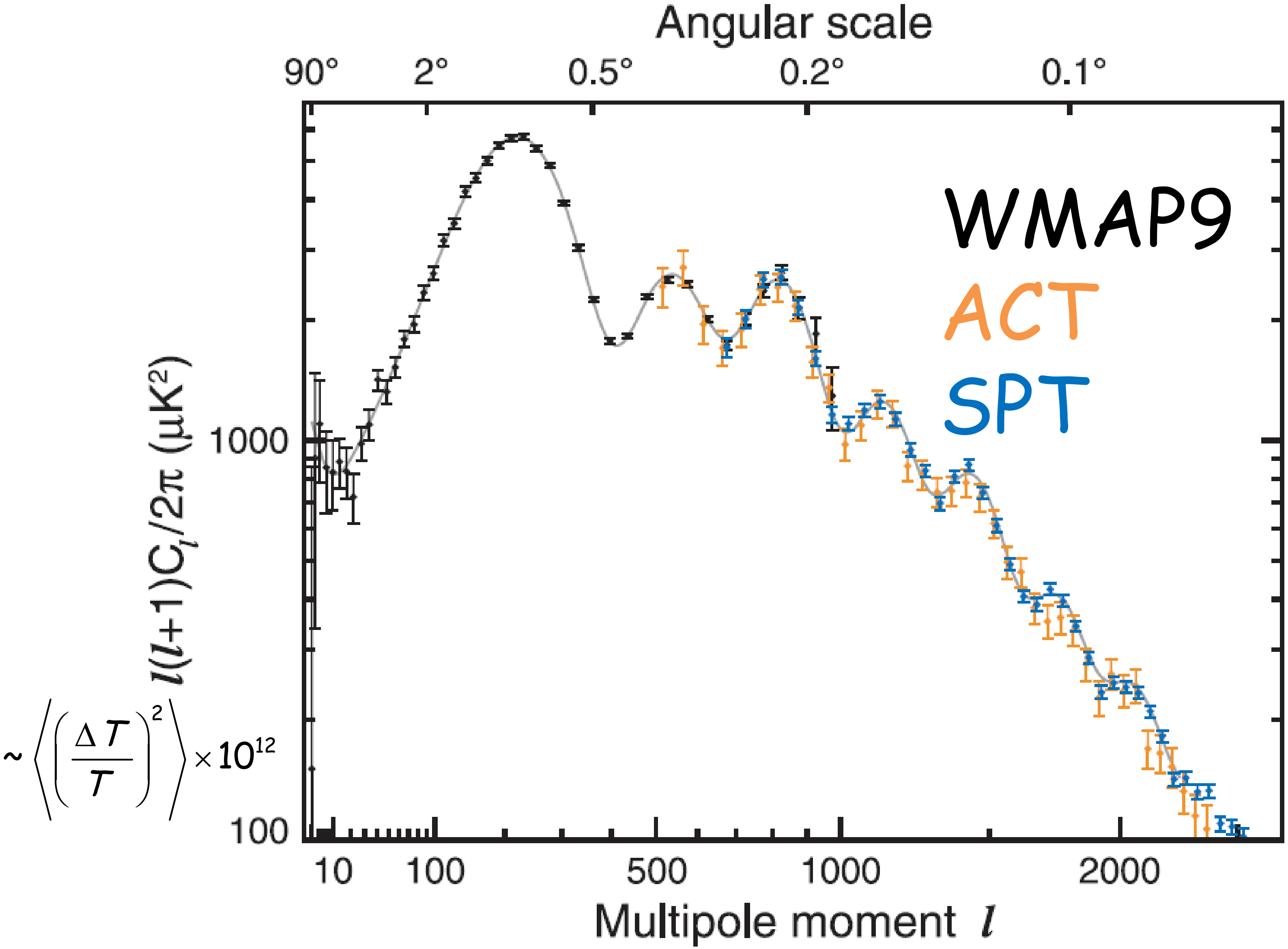
Neutrino is noninteracting radiation

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

Matter power spectrum $P(k) = \langle|\delta_{\boldsymbol{k}}|^2\rangle$

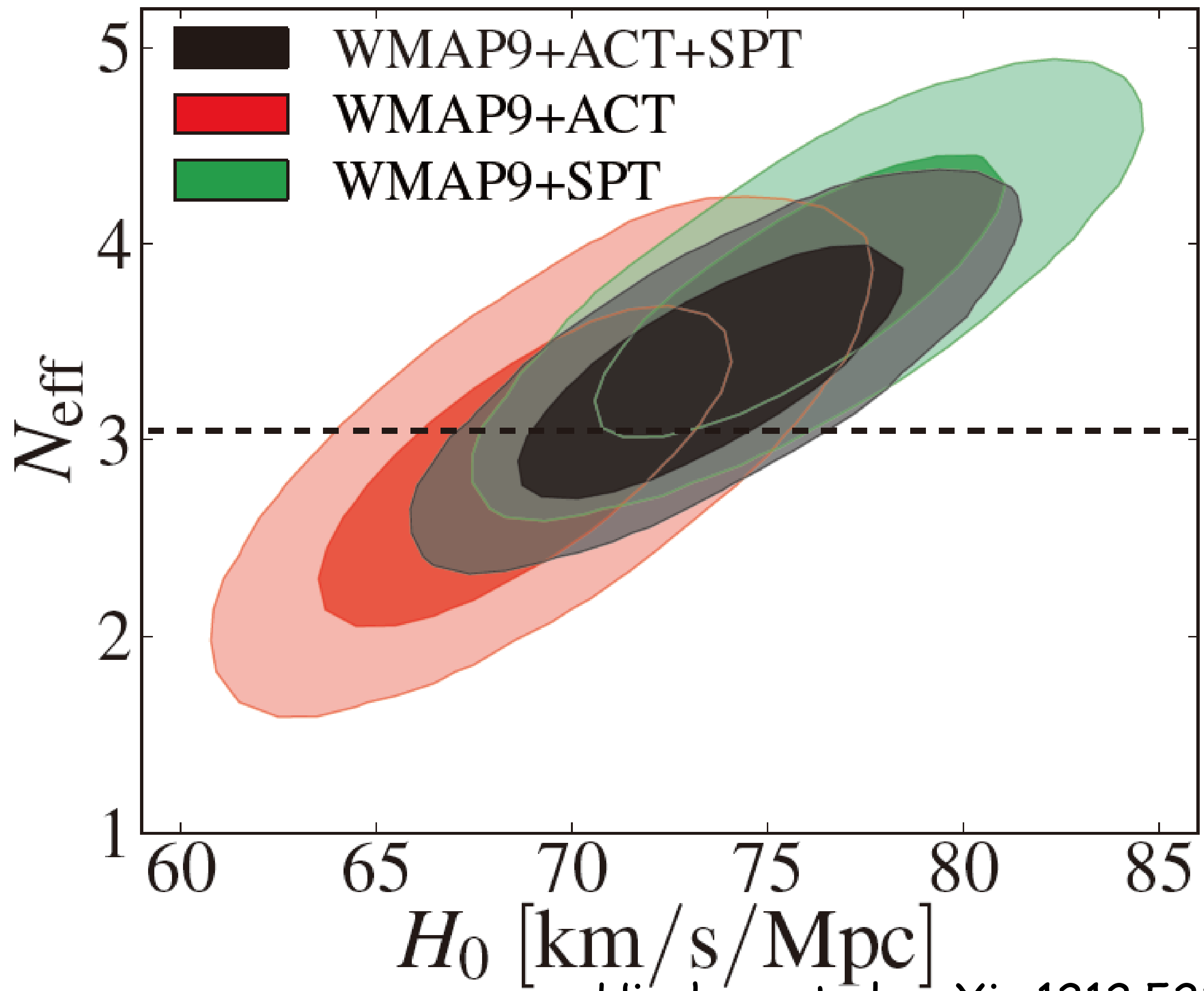


Angular power spectrum of TT



Hinshaw et al, arXiv:1212.5226

CMB TT + lensing



Hinshaw et al, arXiv:1212.5226

Current cosmological upper bounds on neutrino mass

CMB(WMAP 9-year)

Hinshaw et al, arXiv:1212.5226

- M_ν:total neutino mass

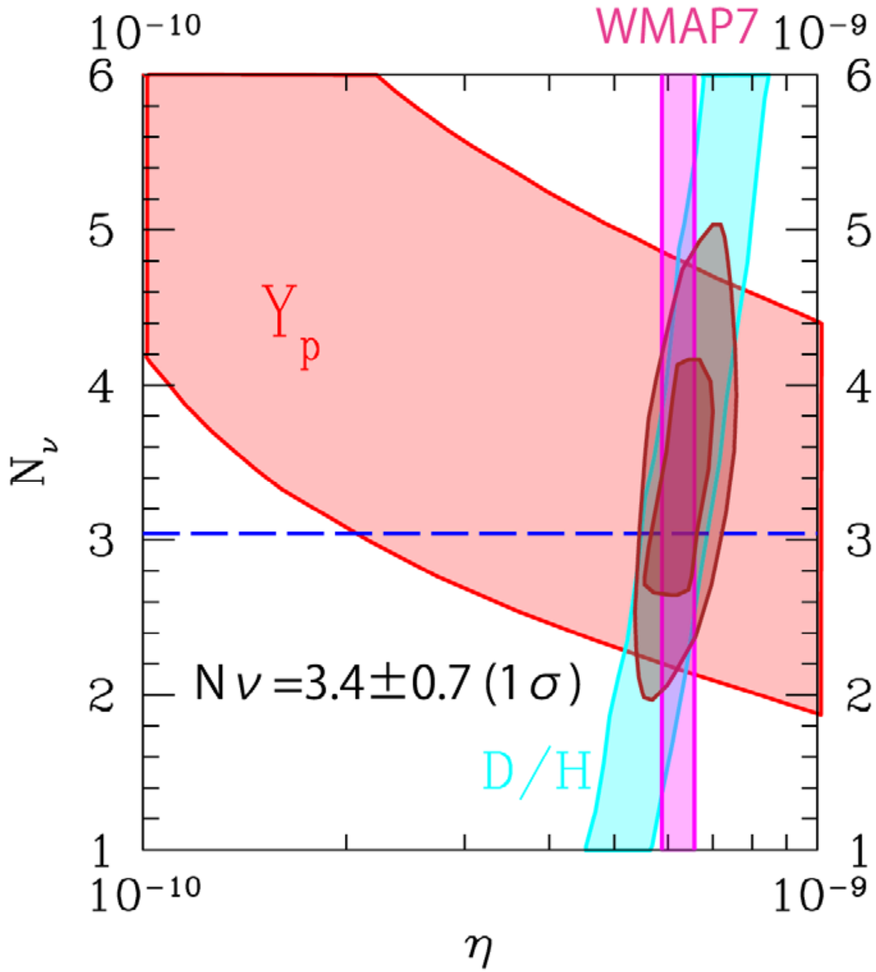
WMAP9 +BAO+H_0 $\Sigma m_\nu < 0.44$ eV (95%CL)

- N_ν:effective number of neutrino species

WMAP+SPT+ACT+BAO+H_0 $N_\nu = 3.84 \pm 0.40$ (68%CL)

Big bang nucleosynthesis

- No strong suggestion from BBN



He4(Aver et al,2008)+D/H(Pettini et al. 2008)

See also

$N_{\nu,eff} = 3.71^{+0.47}_{-0.45}$ at 1 σ

(Steigman, arXiv:1208.0032)

$N_{\nu,eff} = 3.0^{+0.5}_{-0.5}$ at 1 σ

(Pettini and Cooke, arXiv : 1205.3785)

Future constraints on total neutrino mass

Experiment:KATRIN m_{ν_e} < 0.23eV

A. Osipowicz et al, hep-ex/0109033

CMB : Planck M_ν < 0.6eV

CMB + weak lensing M_ν < 0.2 eV

Galaxy survey M_ν < 0.1 eV

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

21cm line ?

Neutrinos with $m_\nu \sim O(0.01)$ eV become non-relativistic at $z \sim O(10)$

- Much after the recombination ($z \ll 1100$)
- Before LSS formation ($z > 1$)

⇓

21cm line or CMB B-mode polarization observation should be the best tool to constrain mass hierarchy with 0.05 eV

21cm line

21 cm brightness temperature

$$\delta T_b^{obs}\left(\frac{\nu_{21}}{1+z}, \boldsymbol{r}, z\right) \approx A \frac{x_{HI} n_H}{(1+z)H(z)}\left[1-\frac{T_\gamma}{T_S}\right]\left[1-\frac{1+z}{H(z)}\frac{d\mathrm{v}_{p||}}{dr}\right]$$

Peculiar velocity

Optical depth
is small

$$1-e^{-\tau_{\nu_{21}}} \approx \tau_{\nu_{21}}$$

$$A \equiv \frac{3c^3 \hbar A_{21}}{16\nu_{21}^2 k_B}$$

χ_{HI}:neutral fraction

Spin temperature

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

◇ 21cm brightness temperature fluctuation δ_{21}

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

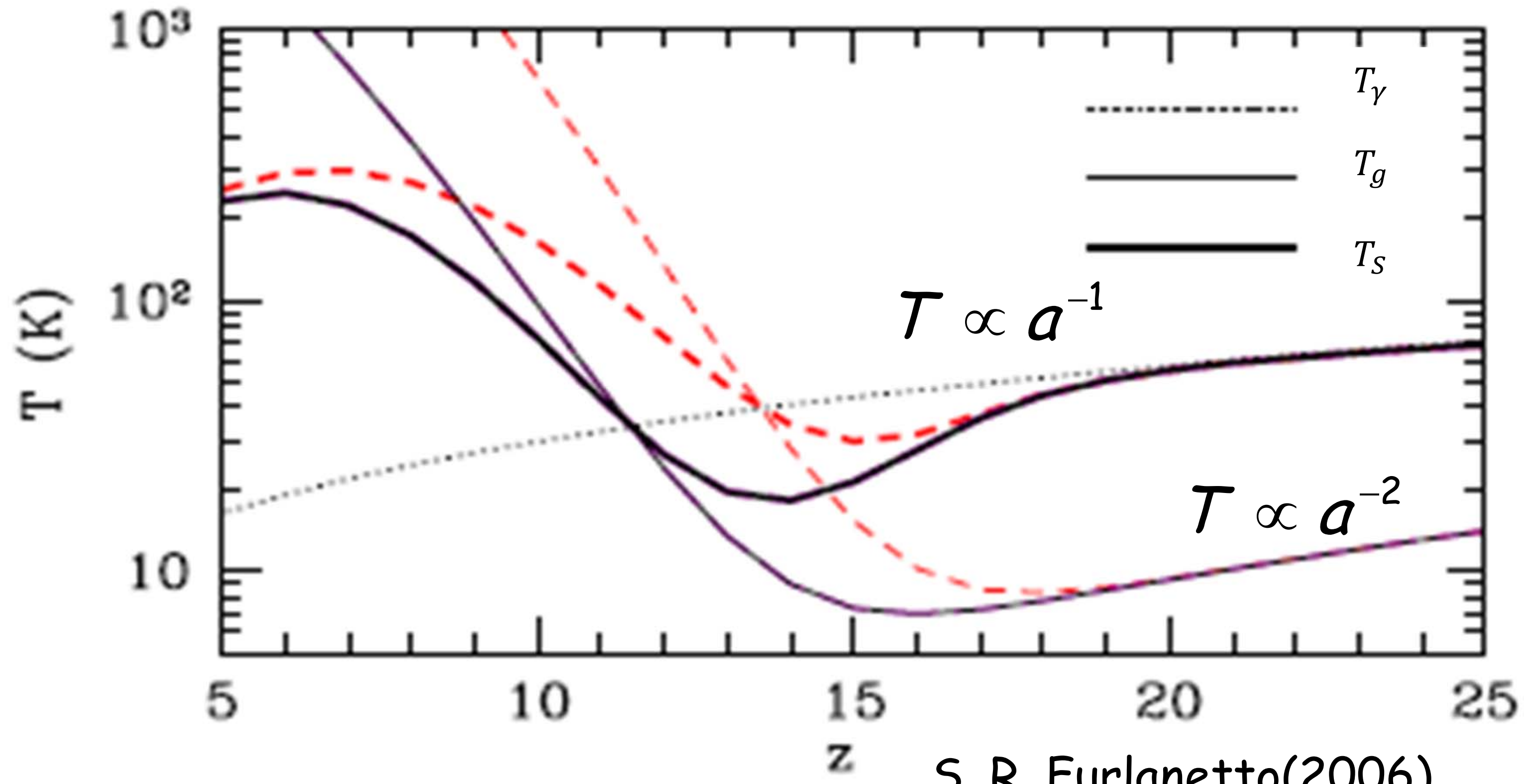
$$\delta_{\partial v} \equiv \frac{1+z}{H(z)} \frac{dv_{p||}}{dr}$$

$$\delta_{21} = \left(\frac{1}{1+\delta_{T_S}}\right) \left[1 + \delta_H + \delta_{x_{HI}} + \frac{\bar{T}_S}{\bar{T}_S - \bar{T}_\gamma} \delta_{T_S} - \frac{\bar{T}_\gamma}{\bar{T}_S - \bar{T}_\gamma} \delta_{T_\gamma} - \delta_{\partial v}\right]$$

$$+ \left[\delta_{x_{HI}} \delta_H + \frac{\bar{T}_S}{\bar{T}_S - \bar{T}_\gamma} \delta_{x_{HI}} \delta_{T_s} - \frac{\bar{T}_\gamma}{\bar{T}_S - \bar{T}_\gamma} \delta_{T_\gamma} \delta_{x_{HI}} \right.$$
$$\left. - \delta_{x_{HI}} \delta_{\partial v} + \frac{\bar{T}_S}{\bar{T}_S - \bar{T}_\gamma} \delta_{x_H} \delta_{T_s} - \frac{\bar{T}_S}{\bar{T}_S - \bar{T}_\gamma} \delta_{T_s} \delta_{\partial v}\right] - 1$$

$\delta_{x_{HI}}, \delta_{T_s}$ *can become* $\sim \mathcal{O}(1)$

Evolution of spin temperature after star formation



S. R. Furlanetto(2006)

Gas was heated by X-ray emission

$$T_g > T_\gamma$$

z ≈ 10 by Ly-a heating $T_S \rightarrow T_g \gg T_\gamma$

Fourier component of δ_{21}

$T_S \gg T_\gamma$: much after star formation

We can omit a factor $(1 - T_\gamma / T_S)$

$\delta_{x_{HI}} \ll 1$:When x_{HI} does not change so much

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

Fourier component of δ_{21}

$$\tilde{\delta}_{21} \approx \tilde{\delta}_H + \tilde{\delta}_{x_{HI}} + \mu^2 \tilde{\delta}_H$$

Peculiar velocity of gas

$$\mu \equiv \frac{k_{||}}{|k|}$$

Cosoine between line of sight and wave number vector

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

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

$T_S \gg T_\gamma$, $\delta_{x_{HI}} \ll 1$

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

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

Detail of ionization history gives us power spectrum

21cm Fisher matrix

M.McQuinn, O.Zahn, M.Zaldarriaga, L.Hernquist, S.R. Furlanetto

(2006) Astrophys.J.653:815-830,2006

$$F_{ij} = \frac{1}{2}\sum_{i}^{N} \frac{1}{P_{T_b}^{tot}(k,\mu)^2} \frac{\partial P_{T_b}^{tot}(k,\mu)}{\partial \theta_i} \frac{\partial P_{T_b}^{tot}(k,\mu)}{\partial \theta_j}$$

$$P_{T_b}^{tot} \equiv \left(\delta \bar{T}_b^{obs}\right)^2 P_{21} + P_{Noise}$$

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

Detector Noise

SKA (Square kilometer Array)

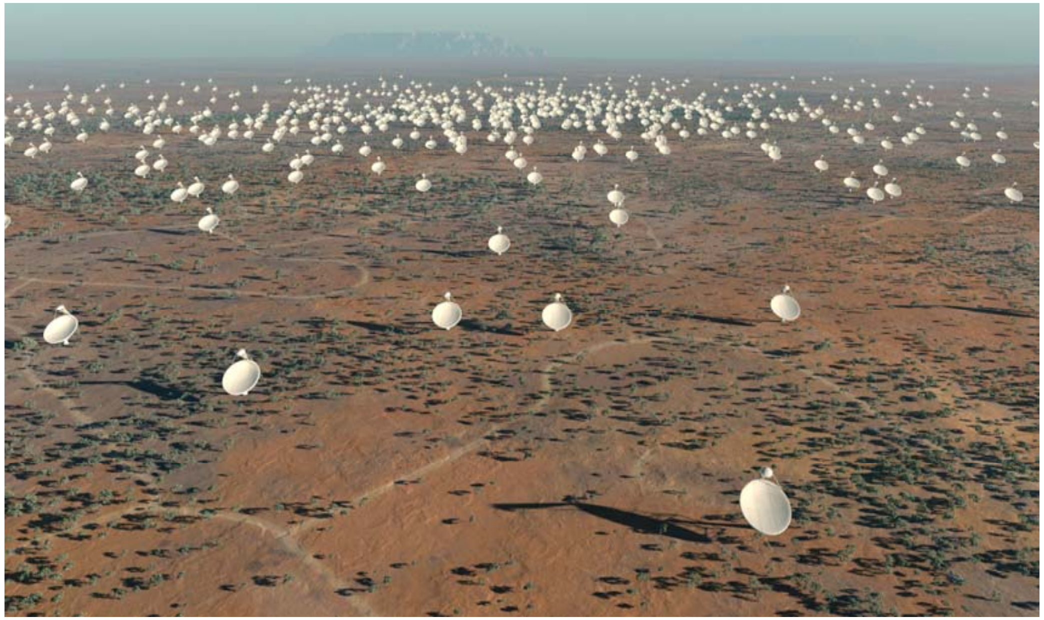
Location ：Australia and South Africa

Antenna number

5000

Effective total Antenna area

$6 \times 10^5\ \mathrm{m}^2$



http://www.skatelescope.org/

Construction Phase (2016 –)

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

Cosmic variance is comparable

Antenna number	Effective total anntena area
10^6	$10^6\ \mathrm{m}^2$

Cosmic Microwave Background (CMB)

POLARBEAR

- USA + JPN (KEK CMB group)

How Sub-Orbital Program Benefits a Satellite Mission

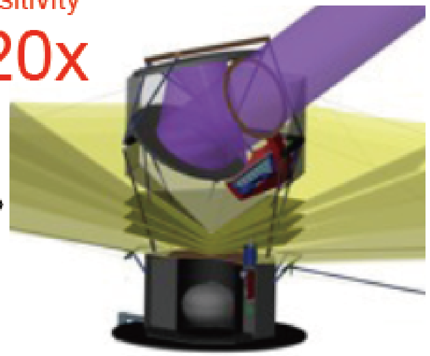
Cosmic variance is comparable

Satellite Mission

Sensitivity 60x

Sensitivity 20x

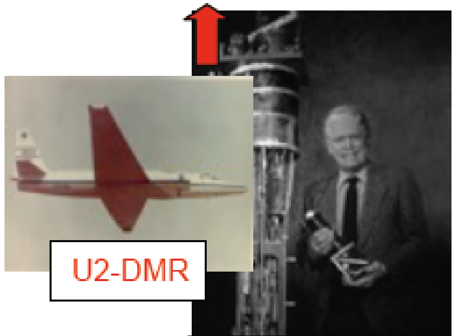
Sensitivity >20x



100 μK — 1 μK — 100 nK — few nK

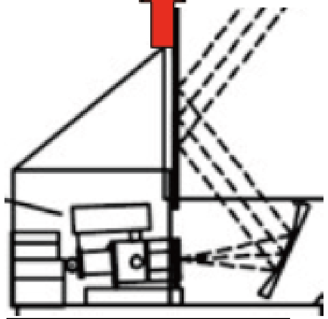
COBE	WMAP	Planck	CMBPOL
1989	2001	2009	2022

Sub-Orbital Precursor

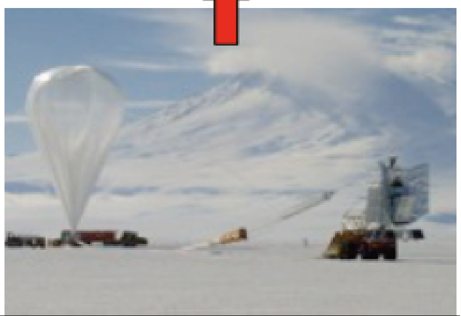


U2-DMR

Woody-Richards



QMAP, SK, TOCO



Archeops, Boomerang, Maxima

Multiple

Ground-based

&

Balloon-borne

Historical Interplay: Suborbital Experiments serve to

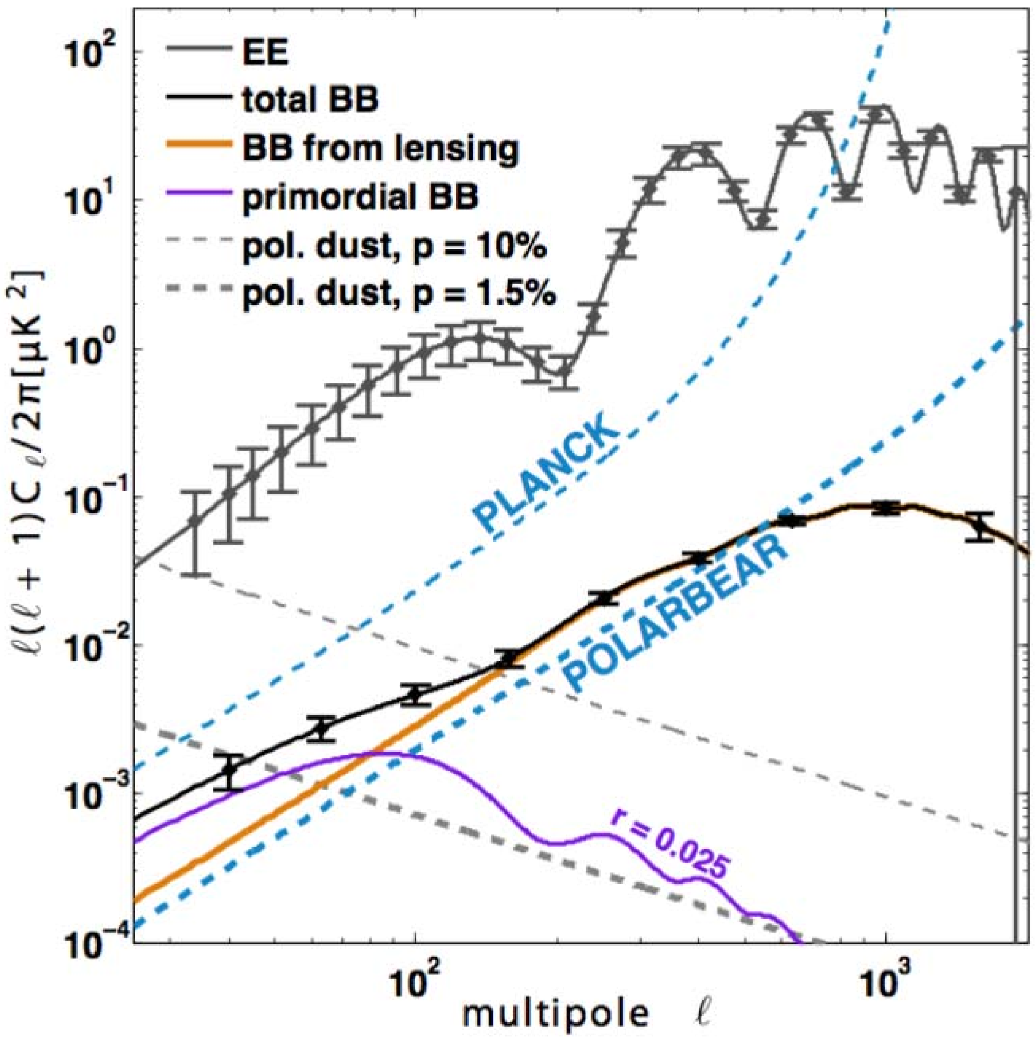
- **Shape scientific objective of a space mission**
- **Train leaders of future orbital missions**
- **Develop experimental methodologies**
- **Develop technologies at systems level**

Sensitivities of PLANCK and POLARBEAR

Kermish et al, arXiv:1210.7768 [astro-ph.IM]

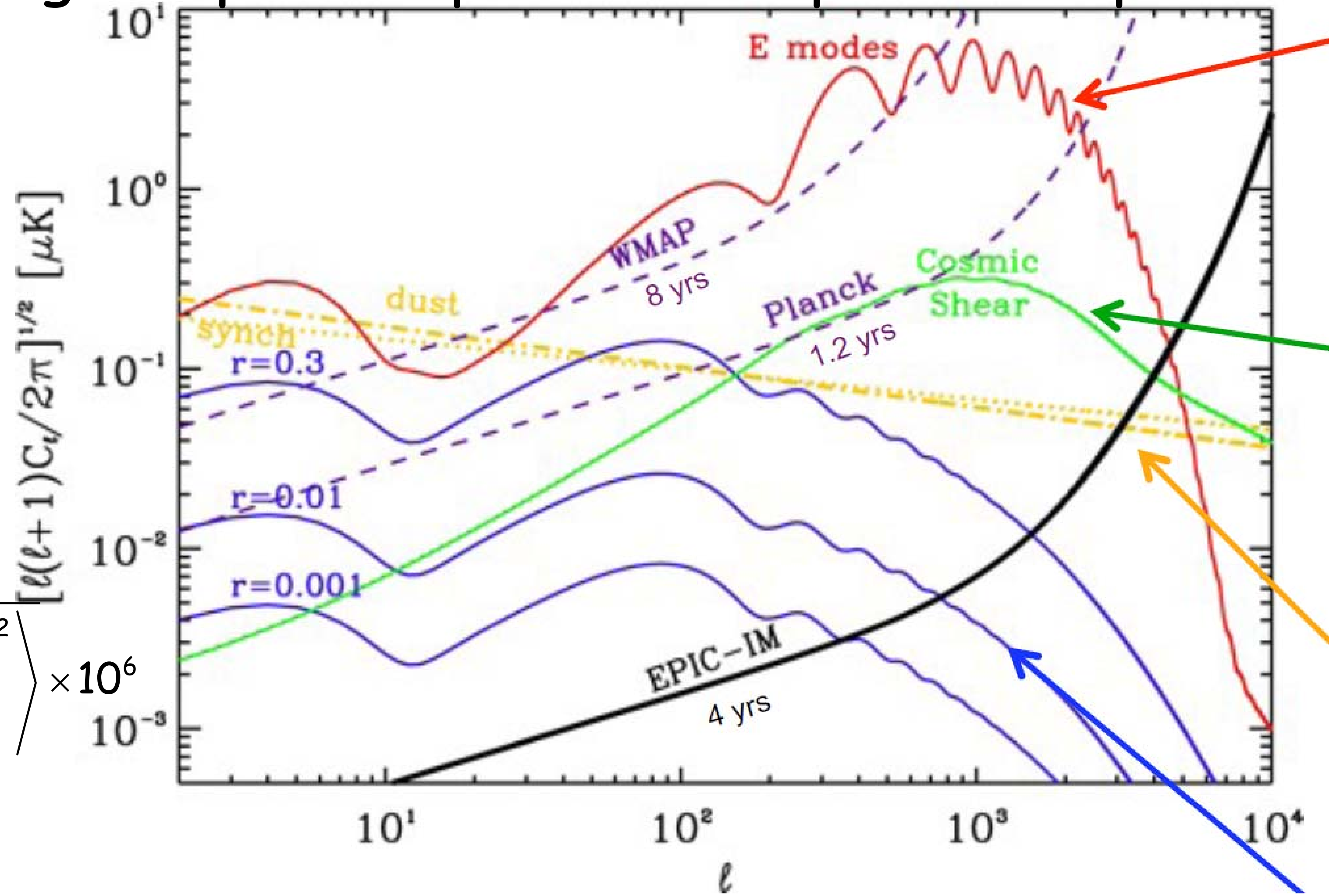
C_ℓ : angular power spectrum of polarized photon

$$\sim \left\langle \left(\frac{\Delta T}{T} \right)^2 \right\rangle \times 10^{12}$$



Sensitivities of CMBPol (EPIC)

C_ℓ : angular power spectrum of polarized photon



$$\sqrt{\left\langle \left(\frac{\Delta T}{T}\right)^2 \right\rangle} \times 10^6$$

http://cmbpol.uchicago.edu/depot/pdf/EOS_v7_CMBPOL.pdf

CMB B-mode polarization

By Planck (ESA), PolarBEAR (USA,Japan), CMPpol (USA)

- Fisher matrices C_ℓ : angular power spectrum

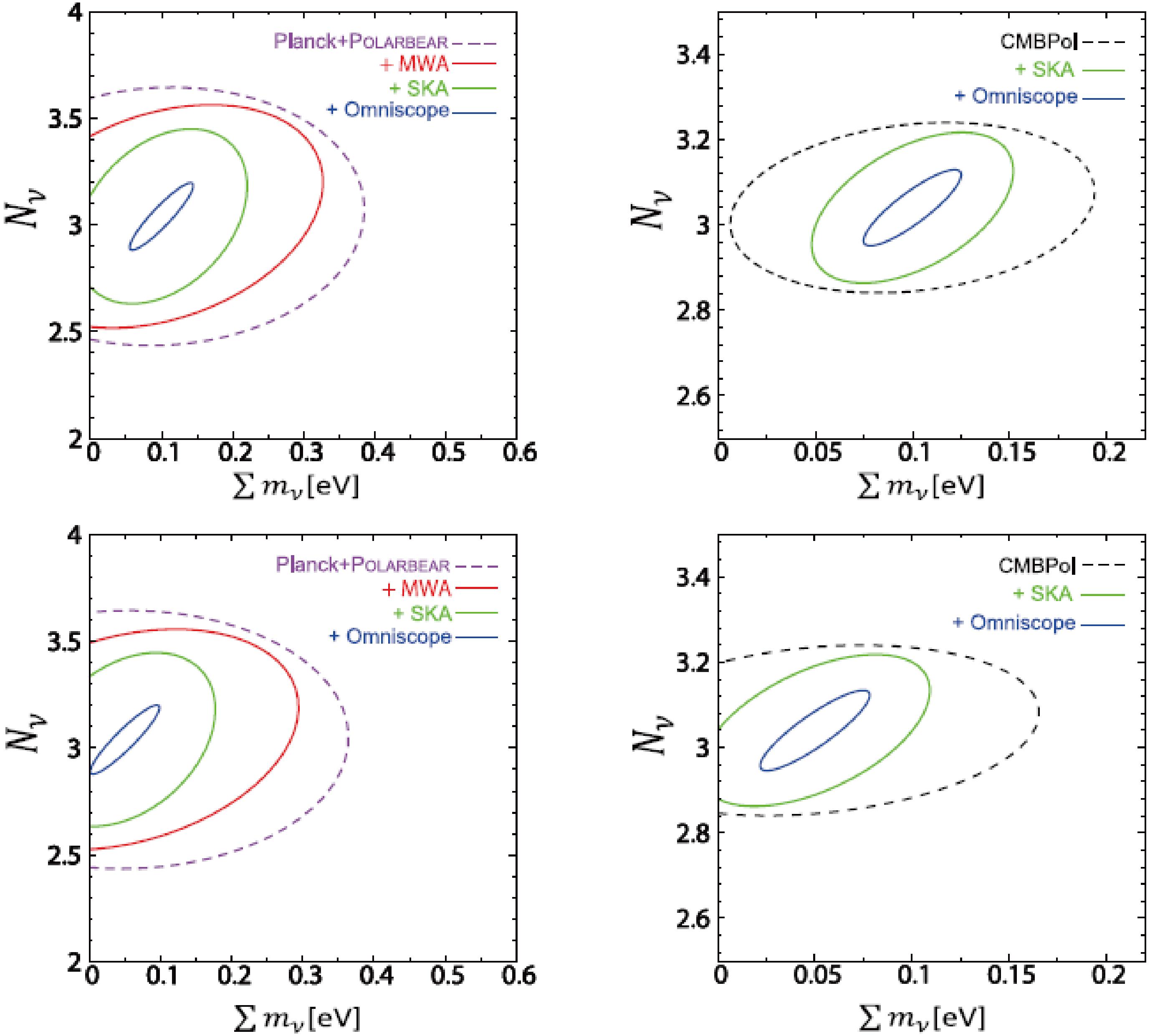
$$\mathbf{F}_{ij}^{\mathrm{CMB}} = \sum_{l} \frac{(2\ell+1)}{2} f_{\mathrm{sky}} \times \mathrm{Trace}\left[\mathbf{C}_\ell^{-1} \frac{\partial \mathbf{C}_\ell}{\partial p_i} \mathbf{C}_\ell^{-1} \frac{\partial \mathbf{C}_\ell}{\partial p_j}\right]$$

$$\mathbf{C}_\ell = \begin{pmatrix} C_\ell^{\mathrm{TT}} + N_\ell^{\mathrm{TT}} & C_\ell^{\mathrm{TE}} & C_\ell^{\mathrm{Td}} \\ C_\ell^{\mathrm{TE}} & C_\ell^{\mathrm{EE}} + N_\ell^{\mathrm{EE}} & 0 \\ C_\ell^{\mathrm{Td}} & 0 & C_\ell^{\mathrm{dd}} + N_\ell^{\mathrm{dd}} \end{pmatrix}$$

$$\mathbf{F}^{21\mathrm{cm+CMB}} \simeq \mathbf{F}^{\mathrm{CMB}} + \mathbf{F}^{21\mathrm{cm}}$$

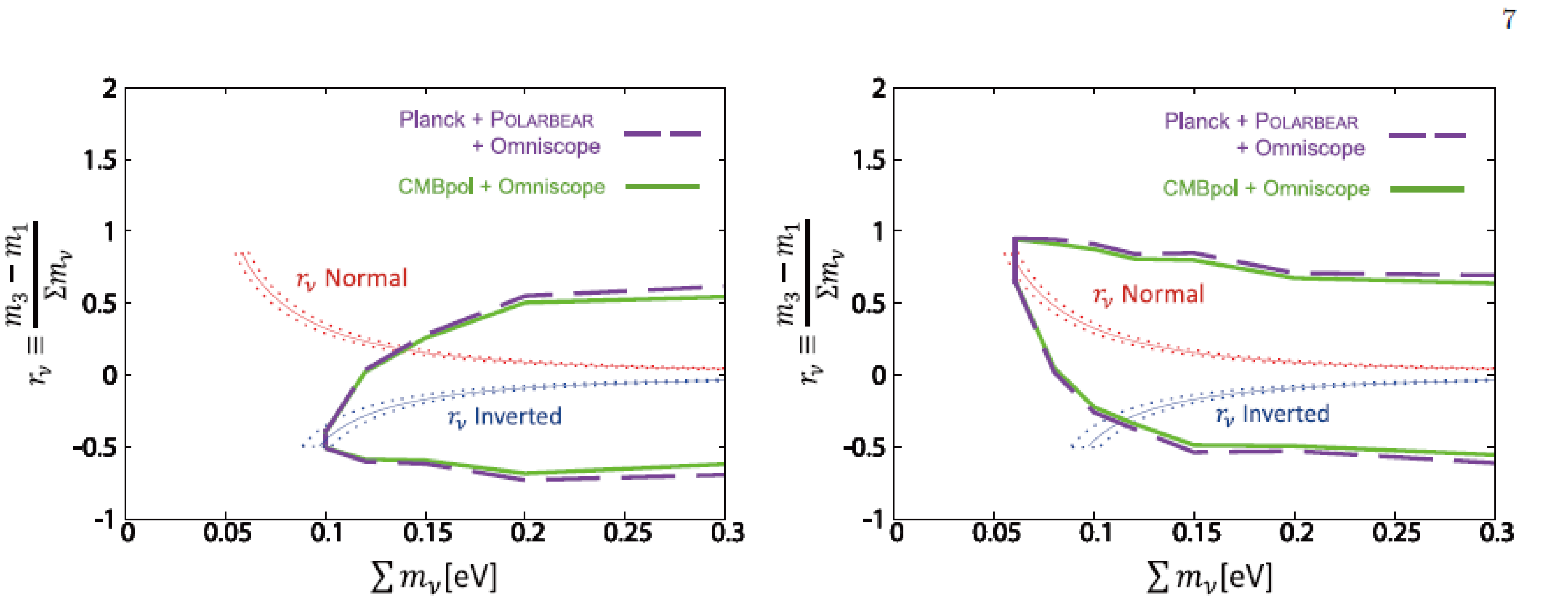
$$\mathbf{F}_{ij}^{21\mathrm{cm}} = \sum_{\mathrm{pixels}} \frac{1}{[\delta P_{21}(\mathbf{u})]^2} \left(\frac{\partial P_{21}(\mathbf{u})}{\partial p_i}\right) \left(\frac{\partial P_{21}(\mathbf{u})}{\partial p_j}\right)$$

Results



Yoshihiko Oyama, Akie Shimizu and KK, **arXiv:1205.5223**

Forecast for Hierarchy



Yoshihiko Oyama, Akie Shimizu and KK, **arXiv:1205.5223**

Conclusion

- Future 21 cm and CMB B-mode polarization data will constrain both neutrino masses and effective number of neutrino species
- Planck + POLARBEAR + Omniscope or CMBpol + Omniscope will distinguish inverted hierarchy from normal hierarchy

Future 21cm observation

Experiment	N_{ant}	$A_e(z=8)$ $[m^2]$	$L_{\min}$ [m]	$L_{\max}$ [km]	FOV [deg^2]	z
MWA	500	14	4	1.5	$\pi 16^2$	7.8-8.2
SKA	5000	120	10	5	$\pi 5.6^2$	7.8-10.2
Omniscope	10^6	1	1	1	2.1×10^4	7.8-10.2

Future CMB B-mode polarization

Experiment	ν [GHz]	$\Delta_{\rm TT}$ [μK$-'$]	$\Delta_{\rm PP}$ [μK$-'$]	$\theta_{\rm FWHM}$ [$'$]	$f_{\rm sky}$
Planck [32]	70	137	195	14	0.65
	100	64.6	104	9.5	0.65
	143	42.6	80.9	7.1	0.65
POLARBEAR [64]	150	-	8	3.5	0.017
CMBPol (EPIC-2m) [65]	70	2.96	4.19	11	0.65
	100	2.29	3.24	8	0.65
	150	2.21	3.13	5	0.65