Can We See Large-scale Structure by Gravitational Waves?

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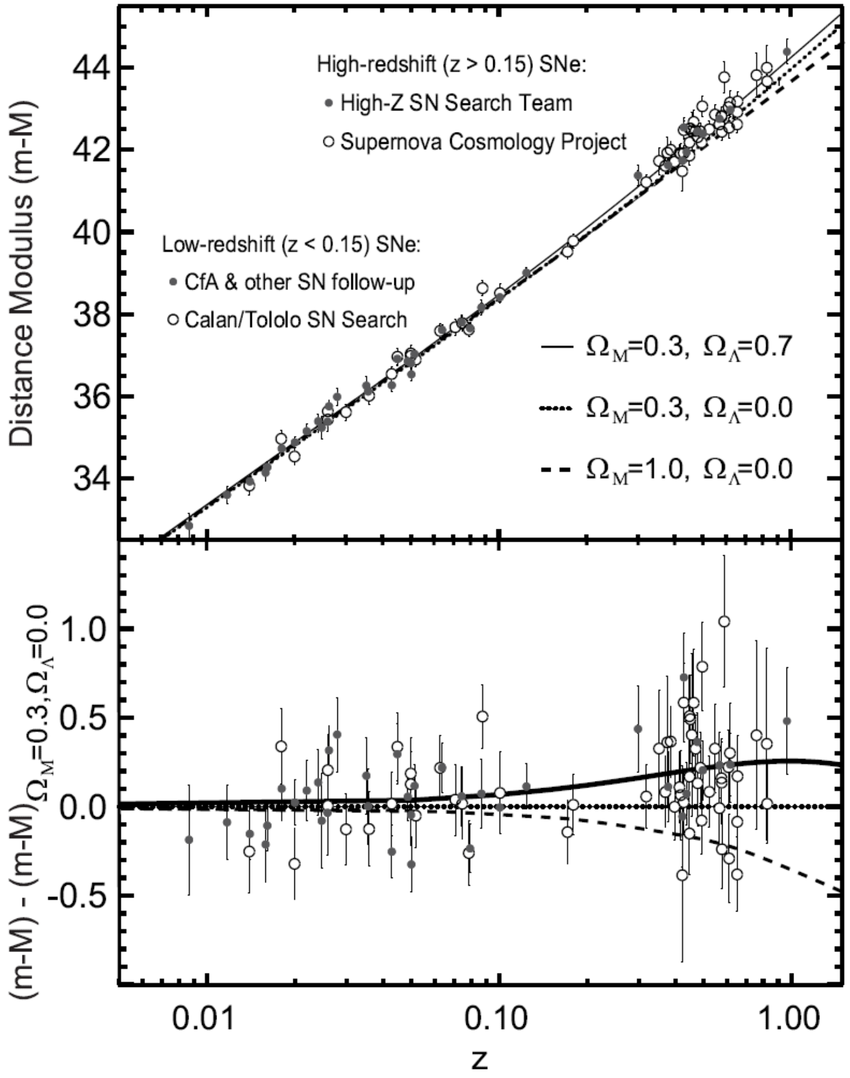
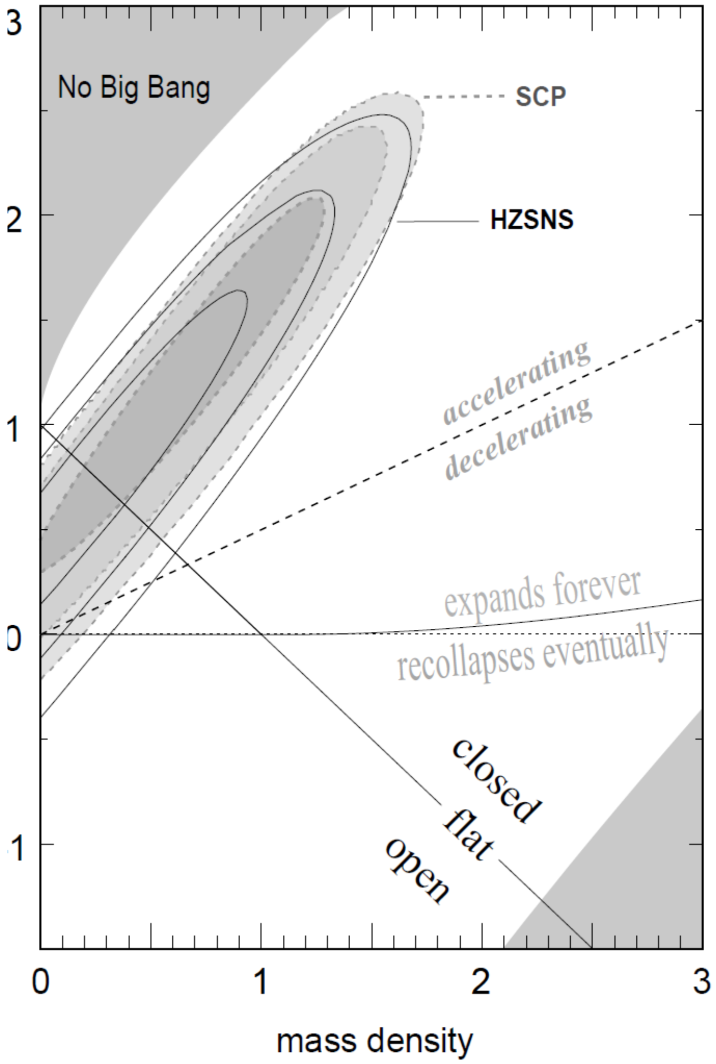
13 th July 2027
Summer Mini-Workshop of GW @台湾師範大学

My talk

- Lensing effect in m-z relation of SN
- Neutrino and structure formation
- How to calculate the lensing effect
- Constraint on neutrino mass
- How about GW?

Introduction





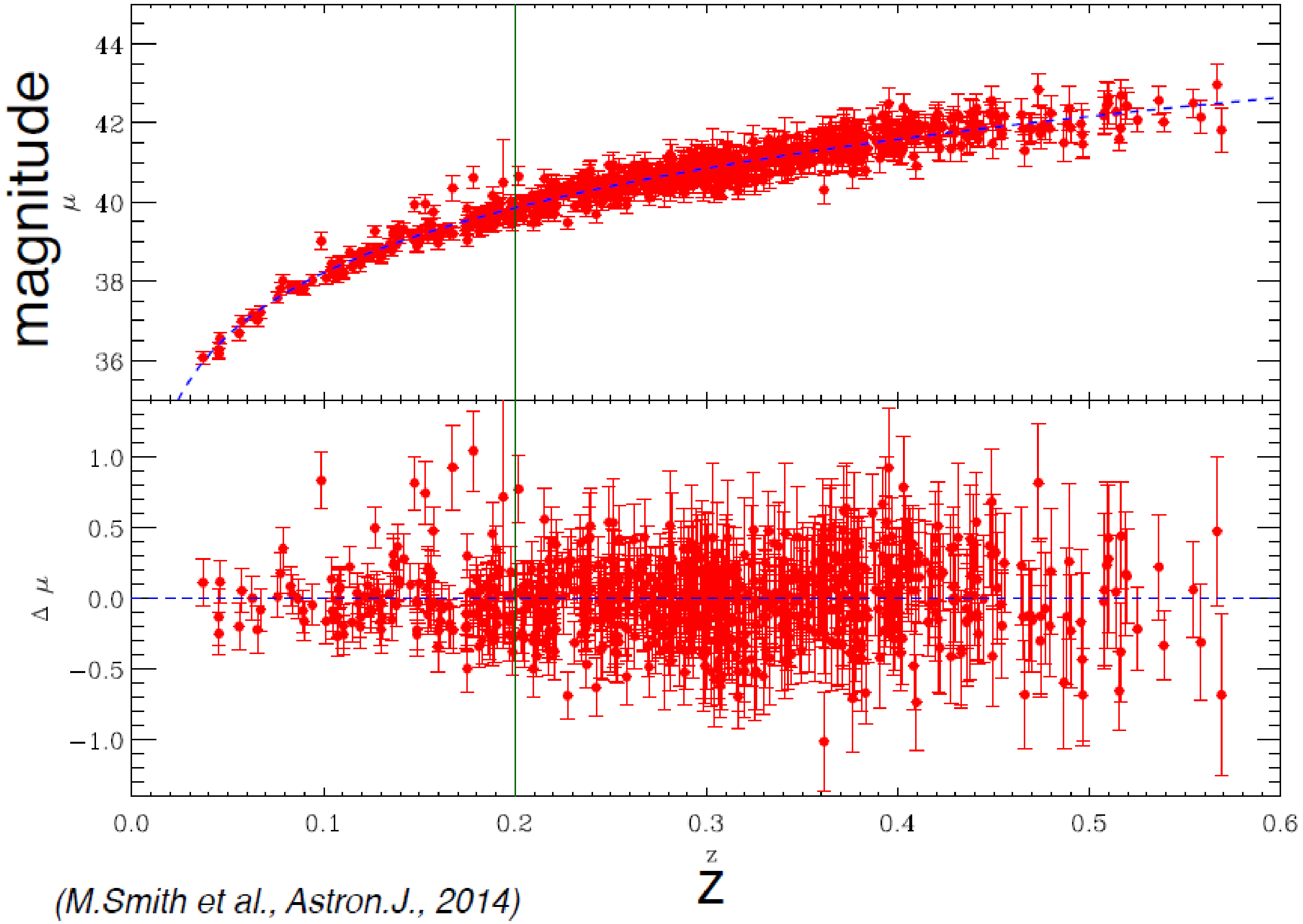
Accelerating Universe

Dark Energy

Modified Gravity

S. Perlmutter &B.P.Schmidt

Observed dispersion



(M.Smith et al., Astron.J., 2014)

Various origin of the dispersion

- Observation

  Fitting of Light curve

- Intrinsic dispersion

  $$\sigma_{\mathrm{int}} \approx 0.12\,\mathrm{mag}$$

- Weak lensing by LSS

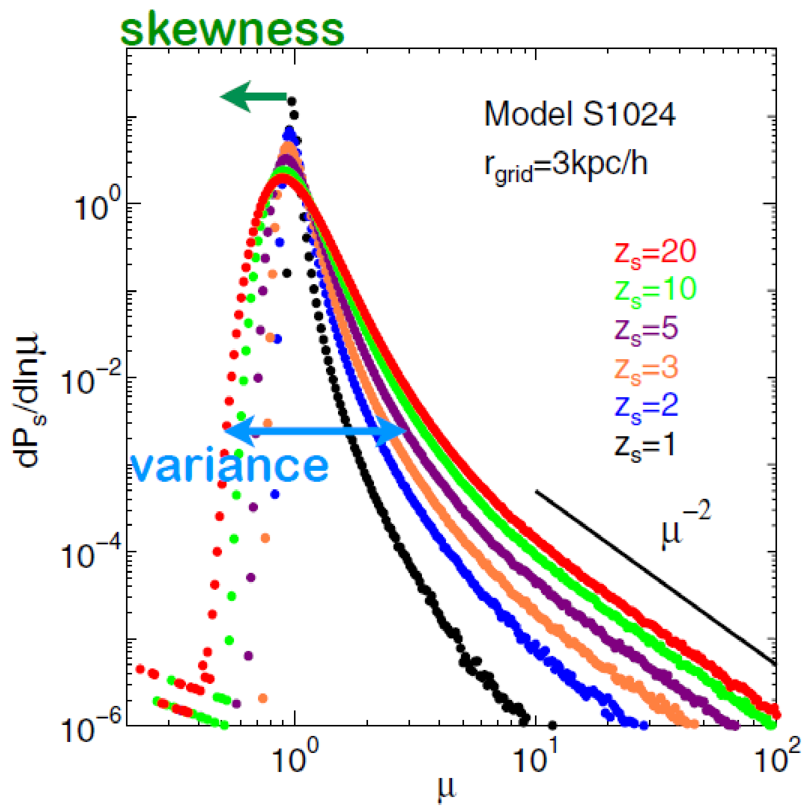
  Small but

  z-dependence

  Non-Gaussian

The lensing effect

The lensing effect by local scale inhomogeneity is now regarded as a noise but maybe useful information if we have a definite theoretical relation between the lensing effect and local inhomogeneity

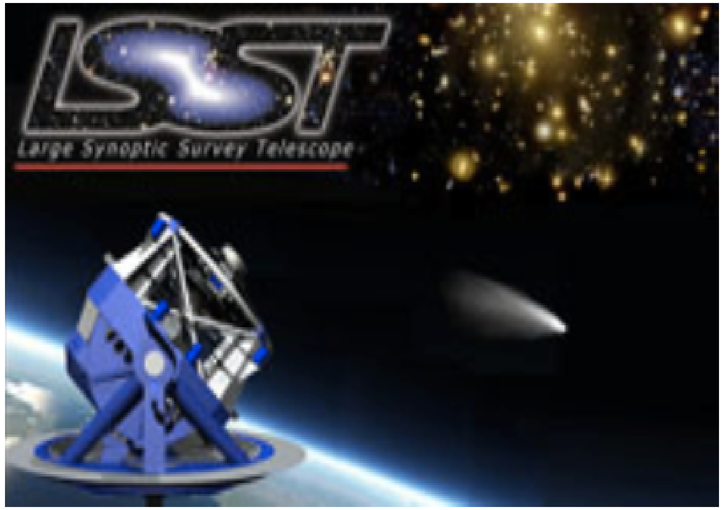


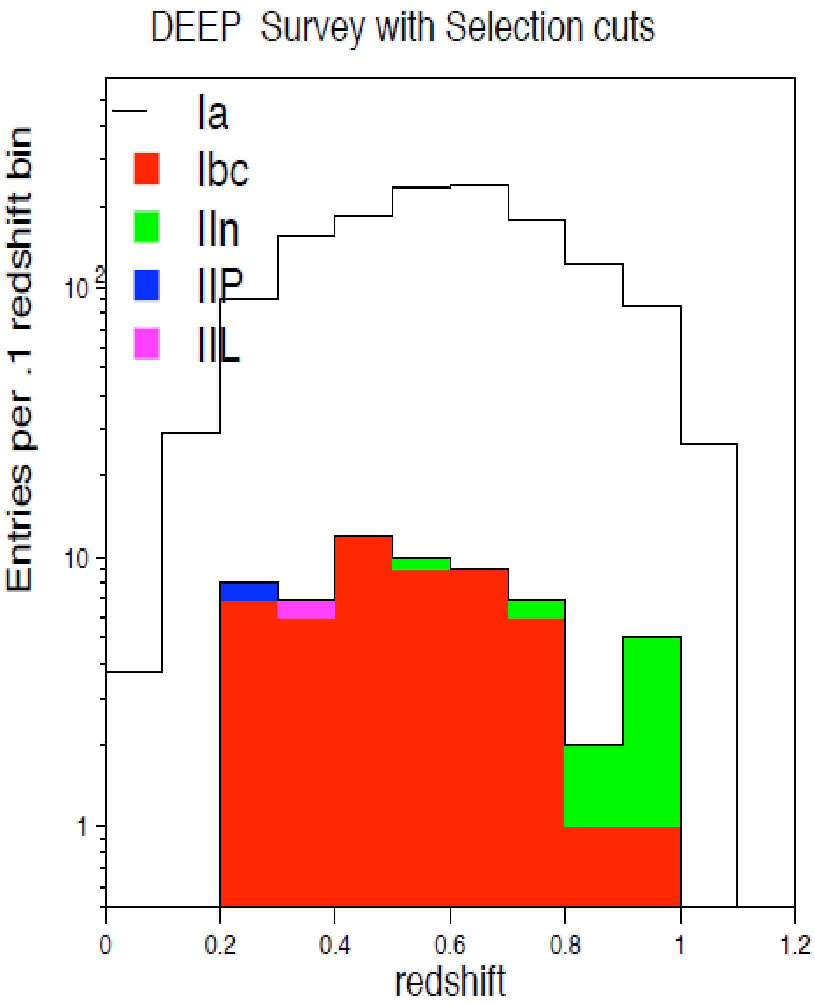
magnification PDF
by ray-tracing simulation

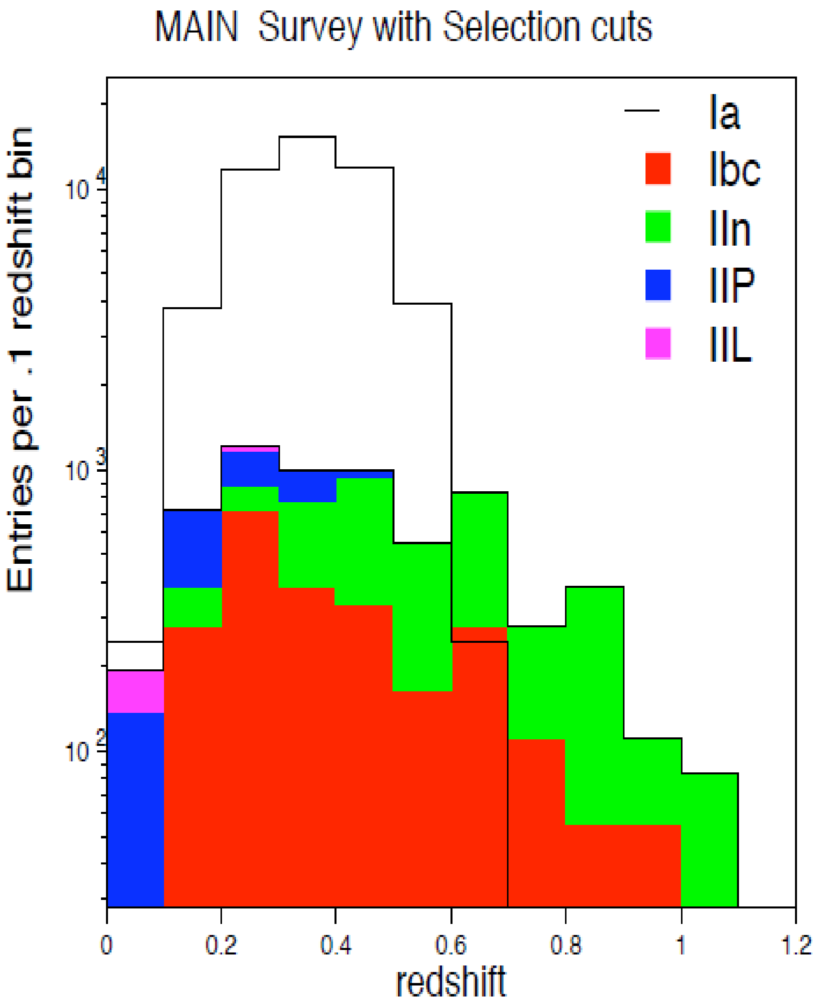
(R.Takahashi et al., Astron.J., 2011)

Can we say anything about cosmology using the lensing effect in m-z relation?

LSST


LSST
Large Synoptic Survey Telescope

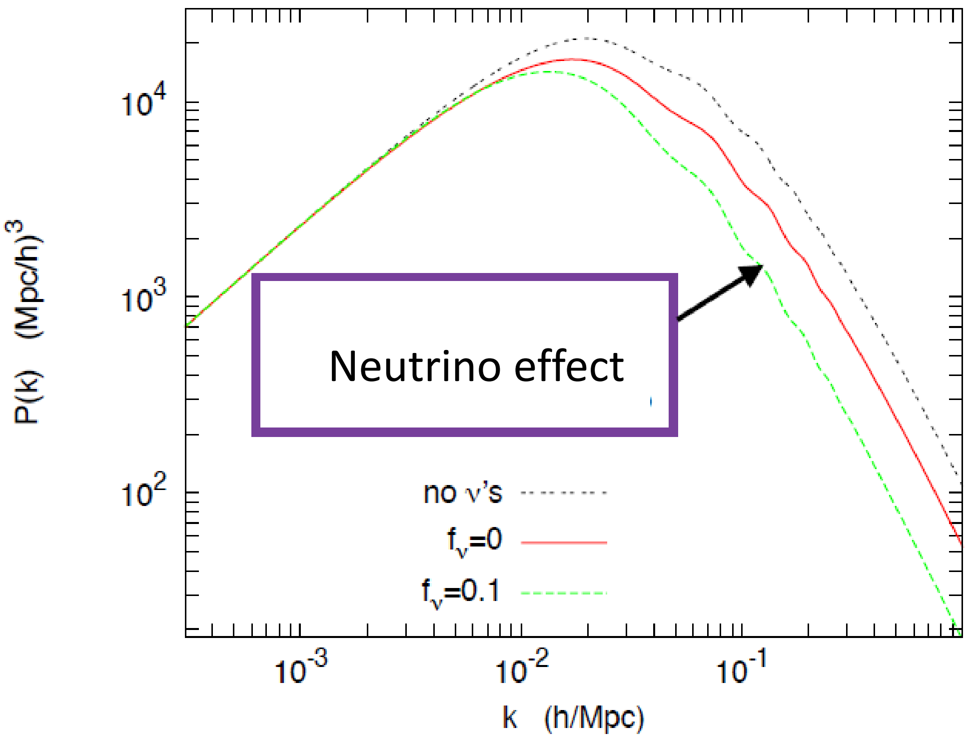

DEEP Survey with Selection cuts
Ia
Ibc
IIn
IIP
IIL
Entries per .1 redshift bin
redshift
1
10
10^2
0
0.2
0.4
0.6
0.8
1
1.2


MAIN Survey with Selection cuts
Ia
Ibc
IIn
IIP
IIL
Entries per .1 redshift bin
redshift
10^2
10^3
10^4
0
0.2
0.4
0.6
0.8
1
1.2

Large scale structure with massive neutrino

free-streaming length:

$$k_{\rm fs}(z) \simeq \frac{0.677}{(1+z)^{1/2}} \left(\frac{m_\nu}{1\ \rm eV}\right) (\Omega_{m0} h^2)^{1/2}\ \rm Mpc^{-1}$$



Power spectrum (linear)

$$f_\nu \equiv \frac{\Omega_\nu}{\Omega_{\rm m}} = 0.05 \left(\frac{N_\nu^{\rm nr} m_\nu}{0.658\ \rm eV}\right) \left(\frac{0.14}{\Omega_{\rm m} h^2}\right).$$

For $k \gg k_{\rm fs}(z)$

$$\left|\frac{\Delta P}{P}\right| \approx 2 f_\nu \left[1 + \frac{3\ln(D_{z=4})}{5}\right] \approx 8 f_\nu.$$

Neutrino oscillation

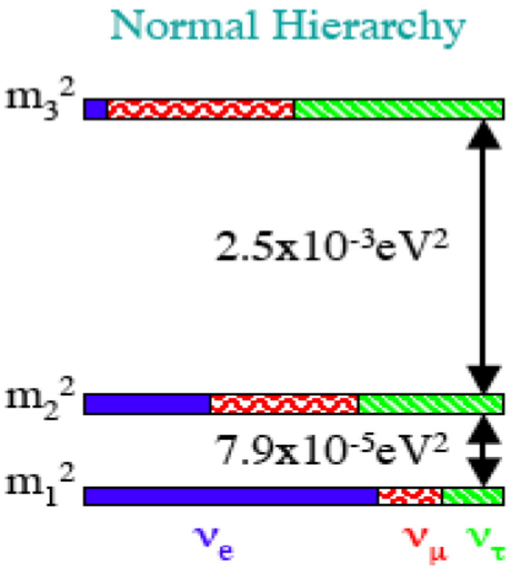
Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\|\Delta m^2\|$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$

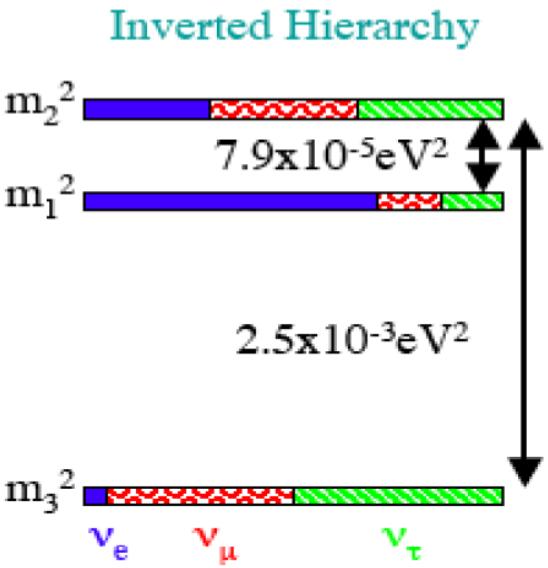
(K.Olive et al., Chin.Phys.C, 2014)

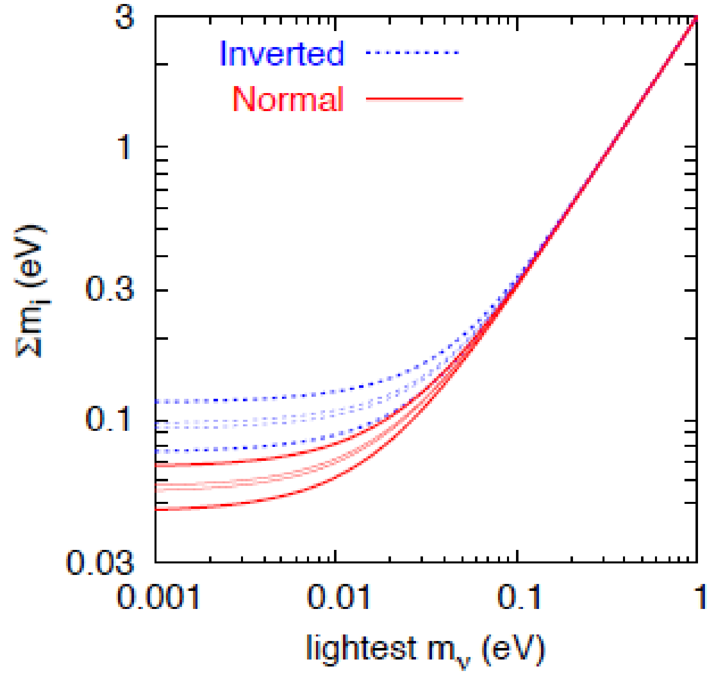
$$\Delta m^2_{21} \equiv m_2^2 - m_1^2$$
$$\Delta m^2 \equiv m_2^2 - \left(m_2^2 + m_1^2\right)/2$$

lower limit

$$0.056(0.095)\ \text{eV} < \sum m_i$$







Present limit

tritium beta-decay experiments...

(V.N.Aseev et al., Phys.Rev.D, 2011)

$$m_{\bar{\nu}_e} < 2.05 \text{ eV}$$

CMB + BAO（バリオン音響振動）

$$\sum m_\nu < 0.23 \text{ eV} \quad \text{(95\% CL)}$$

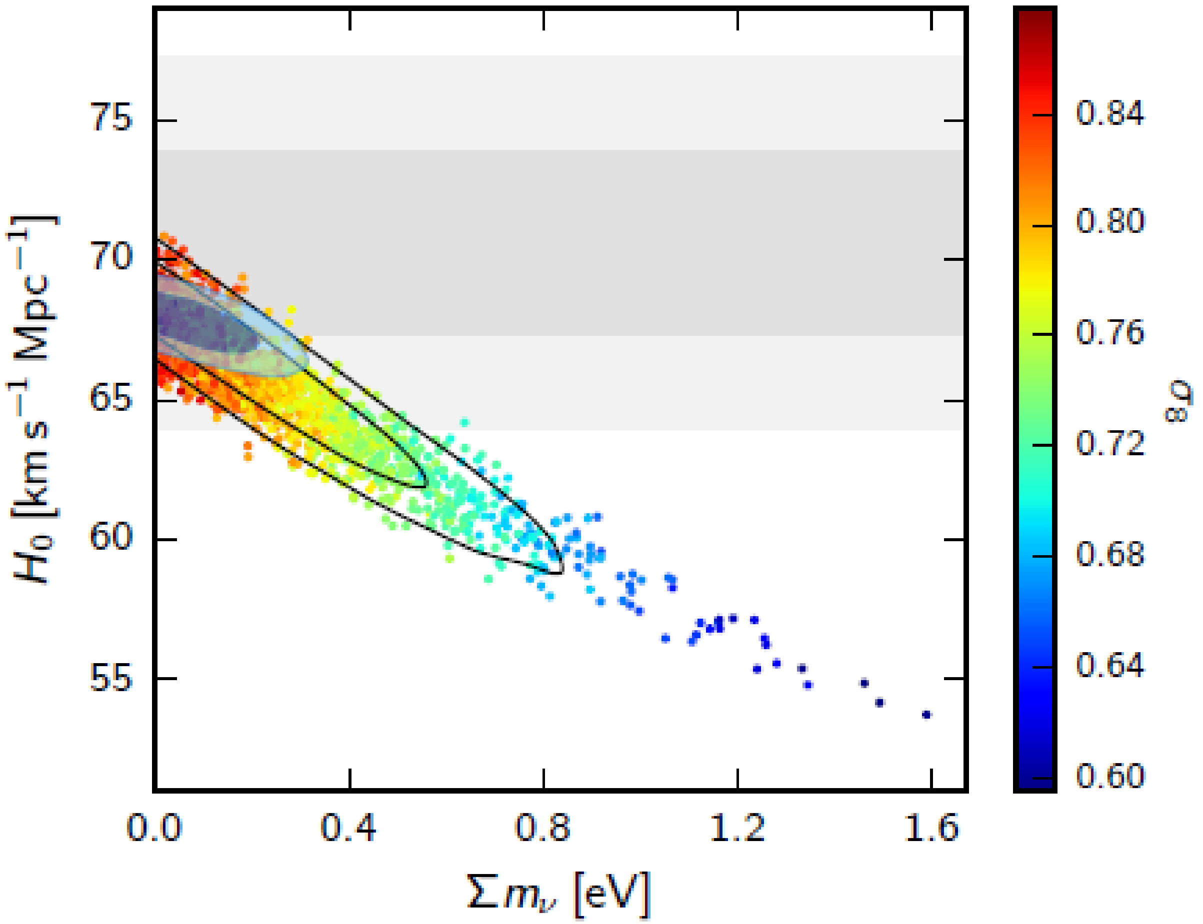
(Planck Collaboration, A&A, 2014)

Ly-α forest + galaxy clustering(e.g. BAO) + CMB +SNe

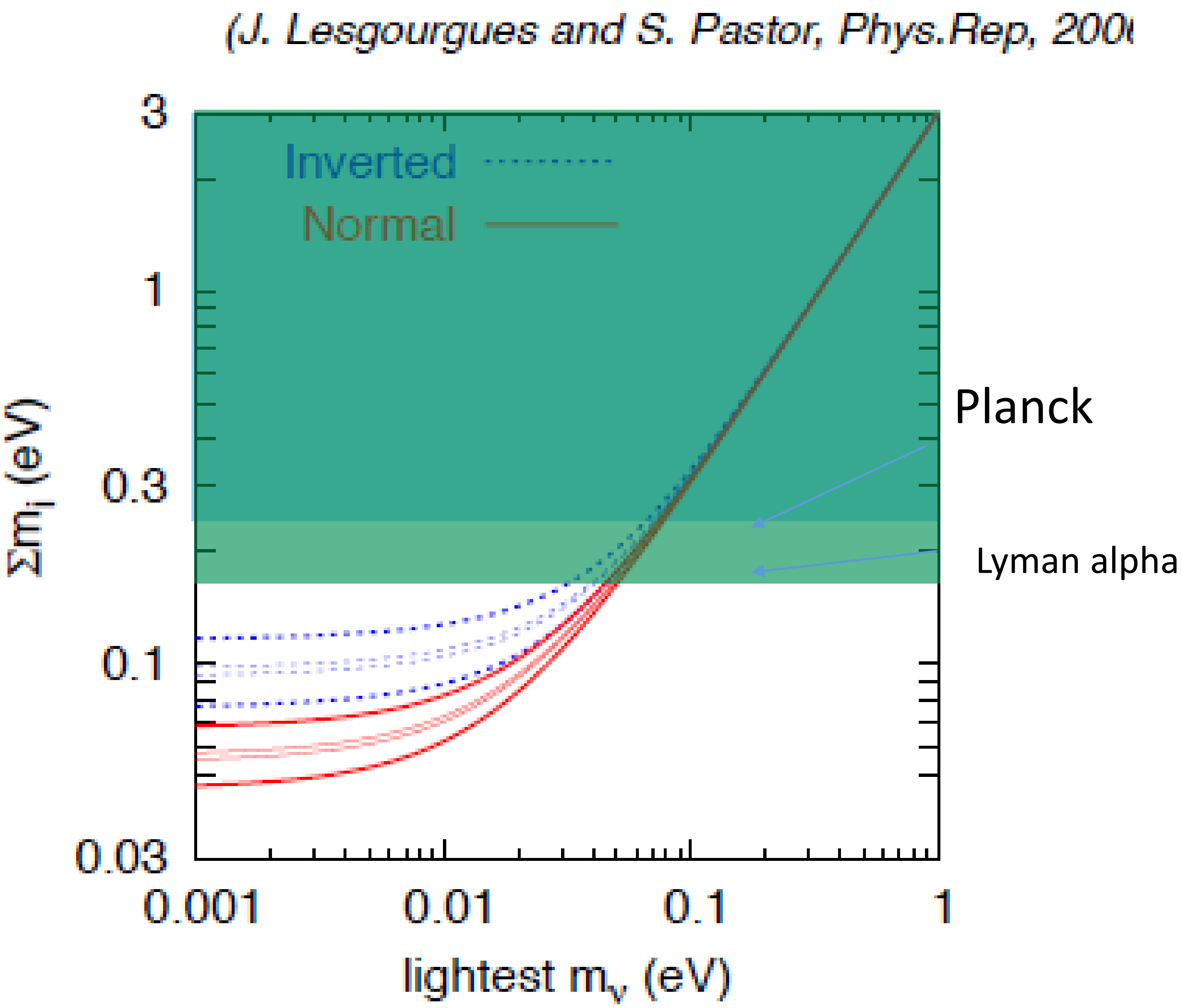
$$\sum m_\nu < 0.17 \text{ eV} \quad \text{(95\% CL)}$$

(U. Seljak, A. Slosar, and P. McDonald, JCAP, 2006)

(Planck 2015)

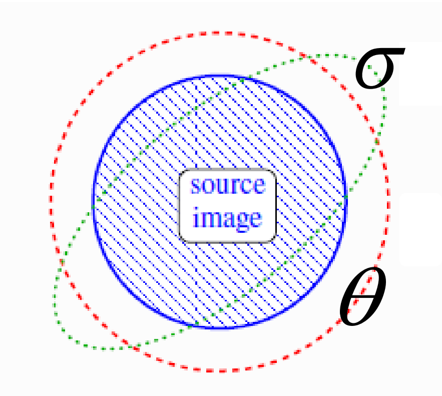


Normal or Inverted hierarchy?



Light(GW) Propagation in an inhomogeneous Universe

Evolution of expansion and shear along the null geodesic obey the following equations as far as geometric approximation is valid



$$\frac{d}{d\lambda}\theta = -R_{\alpha\beta}k^{\alpha}k^{\beta} - \frac{1}{2}\theta^2 - 2\sigma^2,$$
$$\frac{d}{d\lambda}\sigma_{ab} = -C_{\alpha\mu\beta\nu}e^{\alpha}{}_{a}k^{\mu}e^{\beta}{}_{b}k^{\nu} - \theta\sigma_{ab},$$

on a realistic inhomogeneous universe

$$ds^2 = a^2(\eta)\left[\,-(1+2\Phi)\,d\eta^2 + (1-2\Phi)\,\left(dr^2 + r^2 d\Omega^2\right)\right]$$

$$\Delta\Phi = 4\pi G a^2 \bar{\rho}_m \delta_m = \frac{3}{2}\Omega_m \mathcal{H}^2 \delta_m,$$

Realistic means $\delta_m \gg 1$, but $\Phi \ll 1$

$$\Rightarrow \quad \tilde{d}_L(z) \to d_L(z)\left\{1 - \frac{1}{2}\int_0^{r_s} dr\, \frac{r(r-r_s)}{r_s}\left[\,\delta R_{\alpha\beta}k^{\alpha}k^{\beta} + \tilde{\sigma}^2\right]\right\} + \text{doppular terms},$$

Einstein Equation

Assuming k=0 totally flat universe

$$\delta_d(z_s,\mathbf{n}) \equiv \frac{\delta d_L^{FRW}(z_s,\mathbf{n})}{d_L^{FRW}(z_s)} = -\int_0^{\chi_s} d\chi \frac{(\chi_s-\chi)\chi}{\chi_s}\left(4\pi G a^2 \delta\rho_m + \sigma^2\right) + \text{ Doppler term}$$

Shear $O(\Phi^2)$

We neglect shear term and Doppler term by sample selection.
Namely, we select SNs satisfying z>0.1 and not very close to any galaxies in order
To avoid strong lensing events

$$\delta_d(z_s,\mathbf{n}) = -\frac{3H_0^2\Omega_{m,0}}{2}\int_0^{\chi_s} d\chi \frac{(\chi_s-\chi)\chi}{\chi_s}(1+z(\chi))\delta_m(z(\chi),\mathbf{n})$$

For the application to the m–z relation

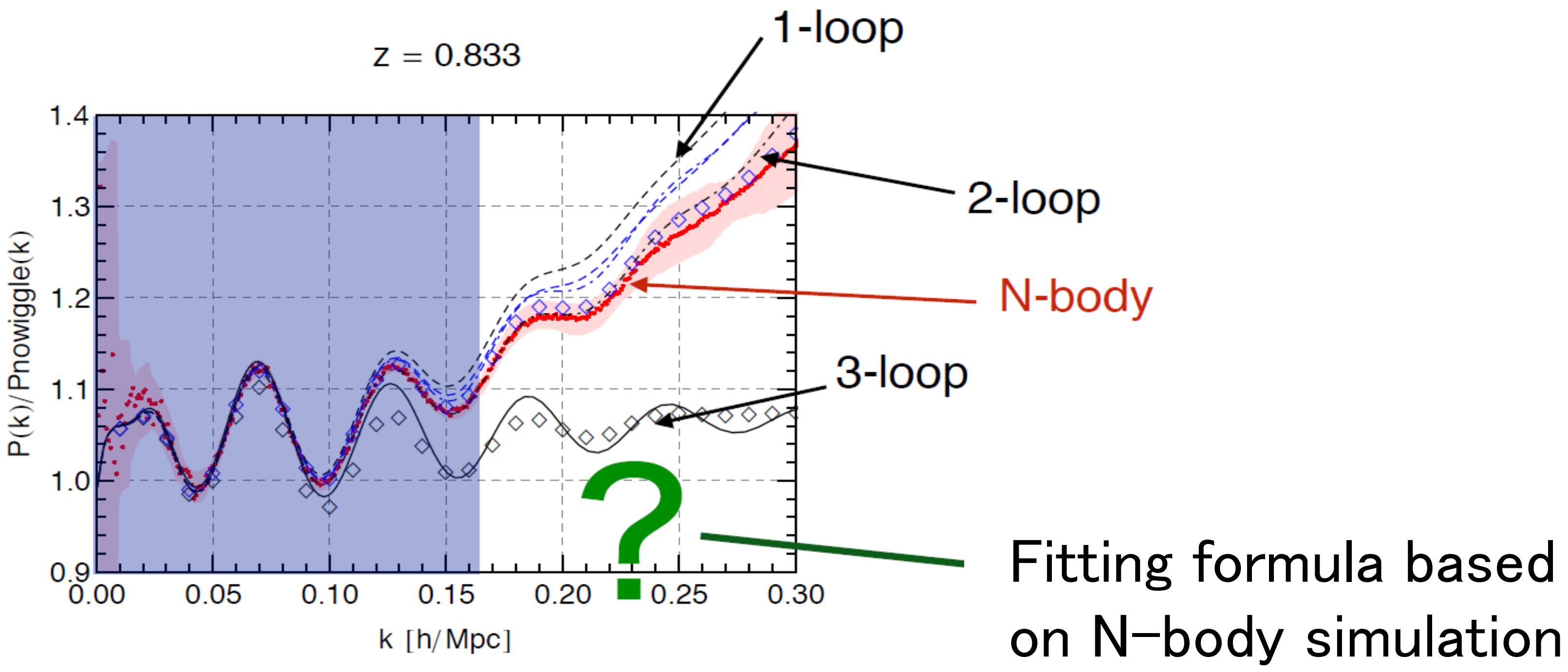
$$\delta m(z_s,\mathbf{n}) = \frac{5}{\ln 10}\ln\left(1+\delta_d(z_s,\mathbf{n})\right) \approx \frac{5}{\ln 10}\delta_d(z_s,\mathbf{n})$$

Dispersion on m-z relation

$$\sigma^2_{\rm lens}(z_s) \equiv \left\langle \delta m(z_s,\mathbf{n})^2 \right\rangle \cong \left(\frac{15H_0^2\Omega_{m,0}}{2\ln 10}\right)^2 \int_0^{\chi_s} d\chi \left[\frac{(\chi_s-\chi)\chi}{\chi_s}\right]^2 \int_0^{k_{\max}} \frac{kdk}{2\pi} P_m(z,k)$$

k_{max}~10 for Galaxy scale

We need highly non-linear Pawer Spectrum

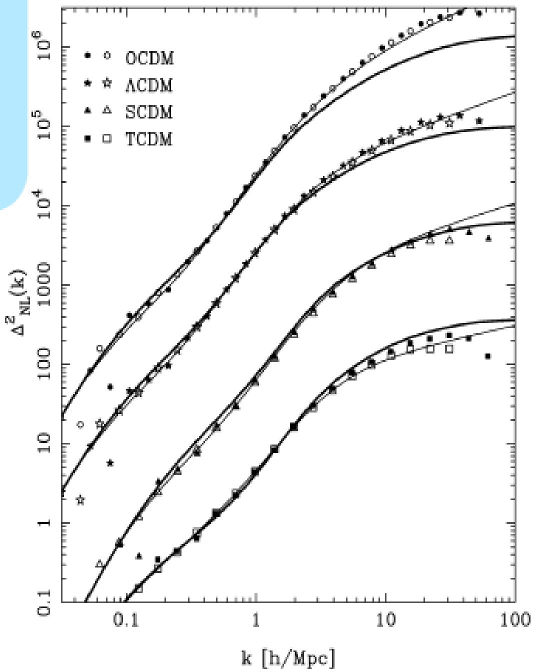


(Blas, D., Garny, M., & Konstandin, T., JCAP, 2014)

We use an improved fitting formula for nonlinear Power Spectrum

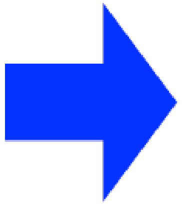
Power spectrum based on halo model with parameters fitted by N-body simulation

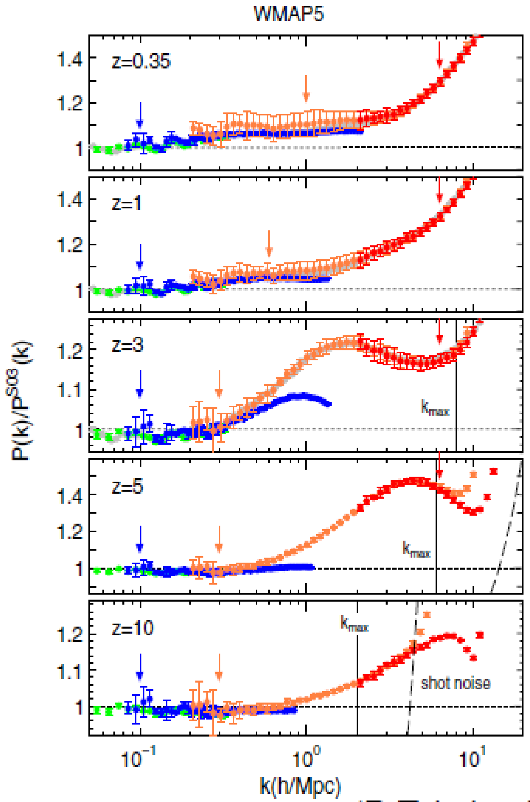
N=256^3



(R.E.Smith et al., Mon.Not.Roy.Astron.Soc., 2003)

improved



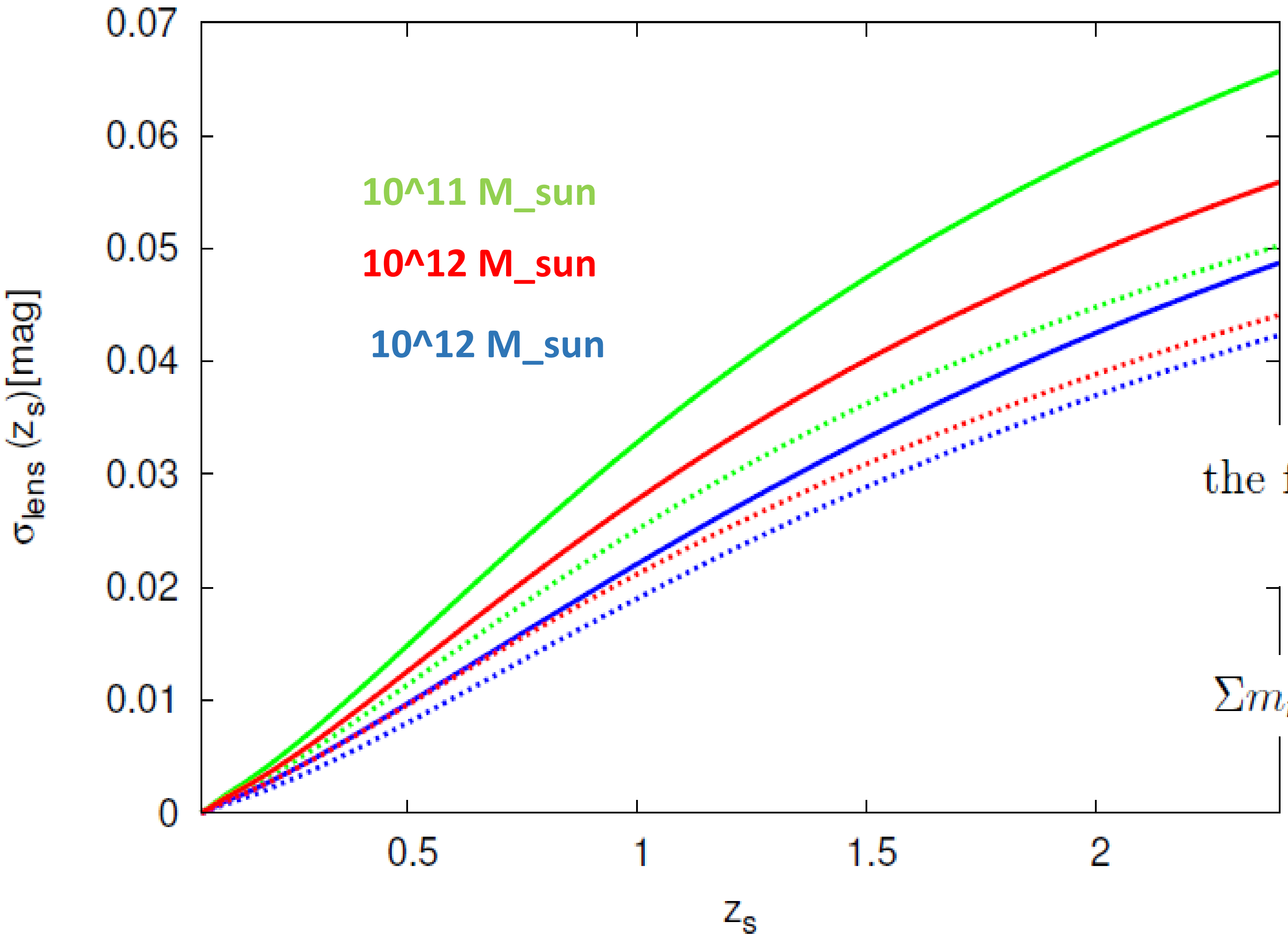


N=1024^3

(R.Takahashi et al., Astrophys.J., 2012)

we use an improved fitting formula, proposed by Bird et al. (2012) for taking account of the effects of massive neutrino for $k < 7[h\mathrm{Mpc}^{-1}]$ at $z \leq 3$.

Lensing dispersion



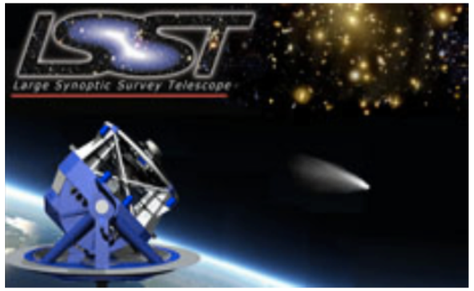
the fiducial ΛCDM model (solid lines)

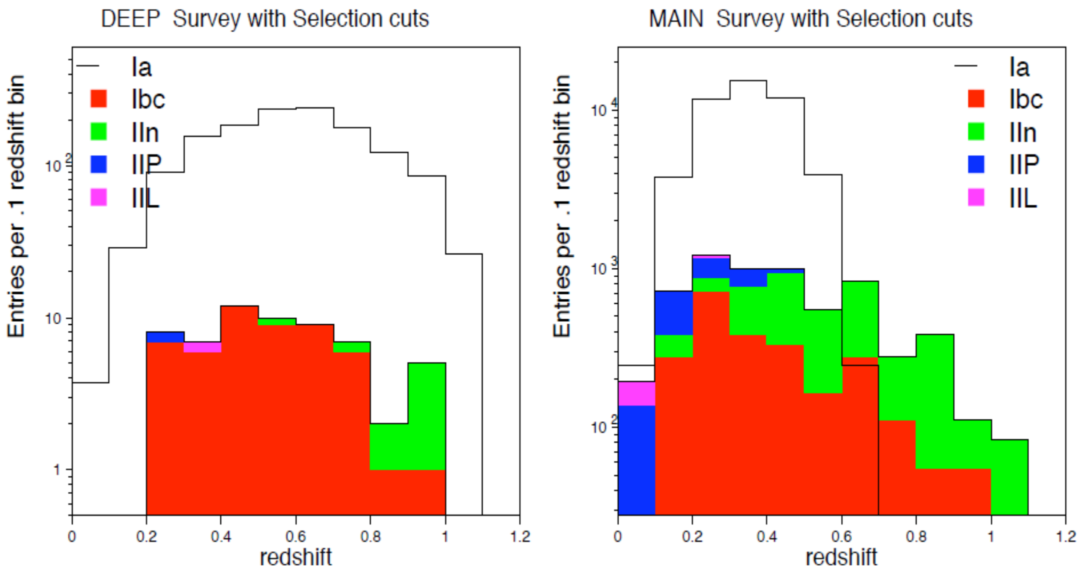
$(\Sigma m_\nu)_{,f} = 0.06$[eV],

$\Sigma m_\nu = 0.6$ [eV], (dotted lines).

Future Projects

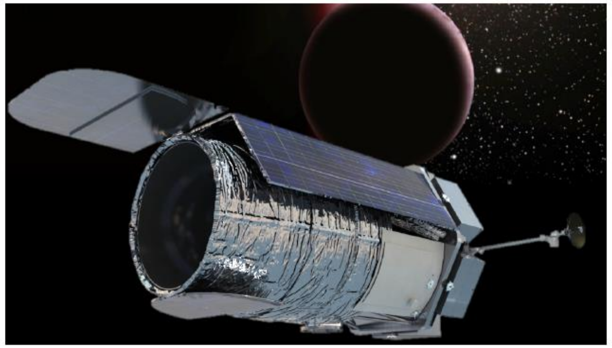
LSST

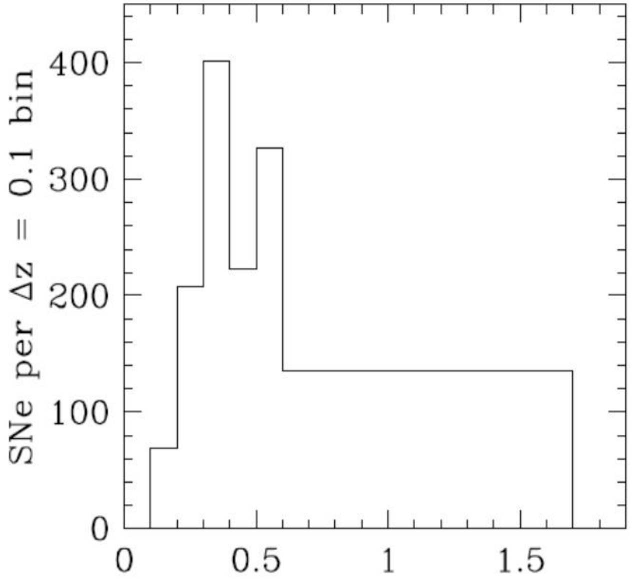




(LSST Science Book, Version 2.0, 2009)

WFIRST





(WFIRST-AFTA 2015 Report)

Expected number of SNIa in each redshift bin

Survey	WFIRST	LSST(main)
z=0.2	0.6×10^2	4×10^3
0.3	2.0×10^2	1×10^4
0.4	4.0×10^2	2×10^4
0.5	2.2×10^2	1×10^4
0.6	3.2×10^2	4×10^3
0.7	1.4×10^2	2×10^2
0.8-1.7	1.4×10^2 (for each bin)	

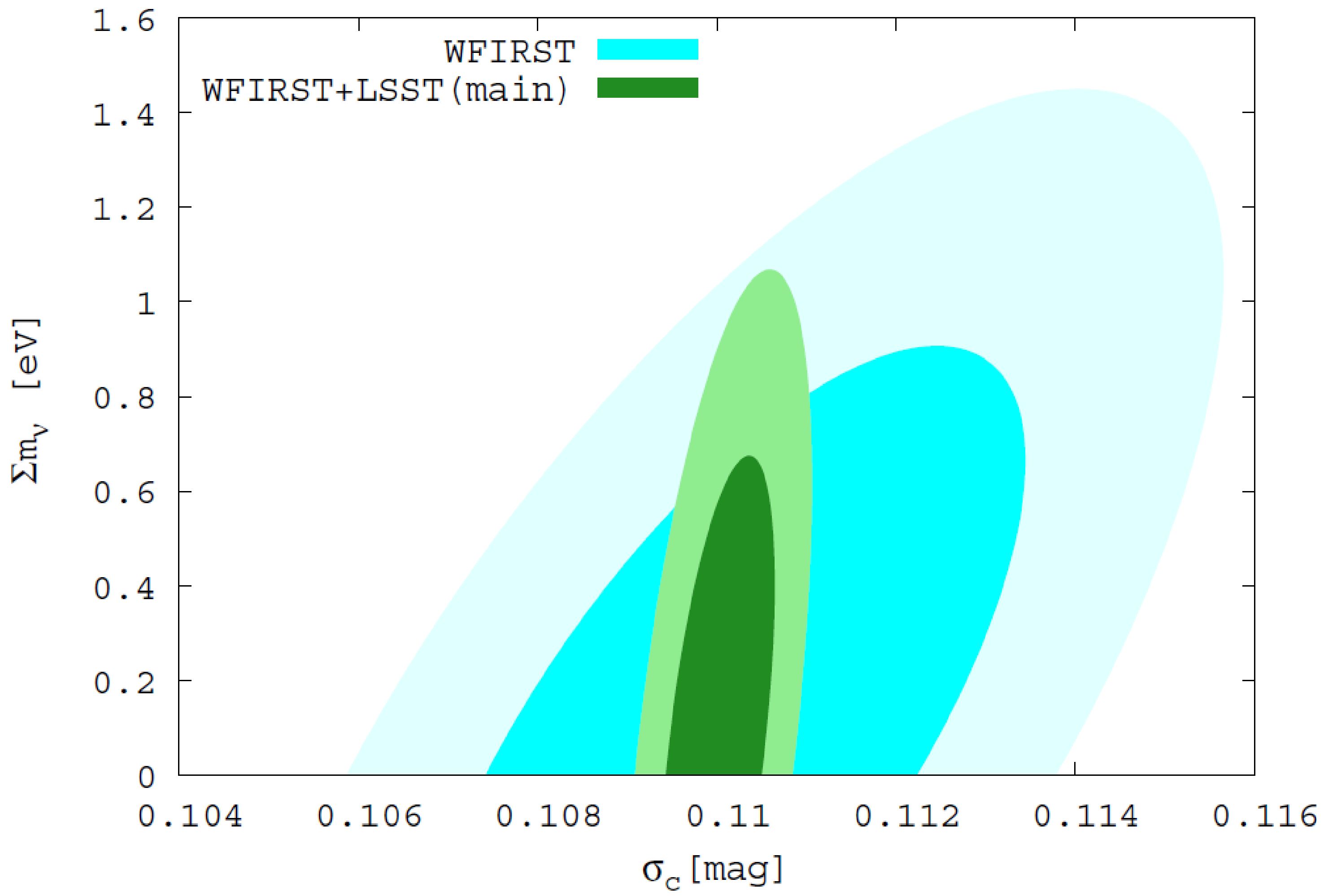
Doppler effect is dominant for z < 0.1

(L. Hui, & P. B. Greene, Phys. Rev. D, 2006)

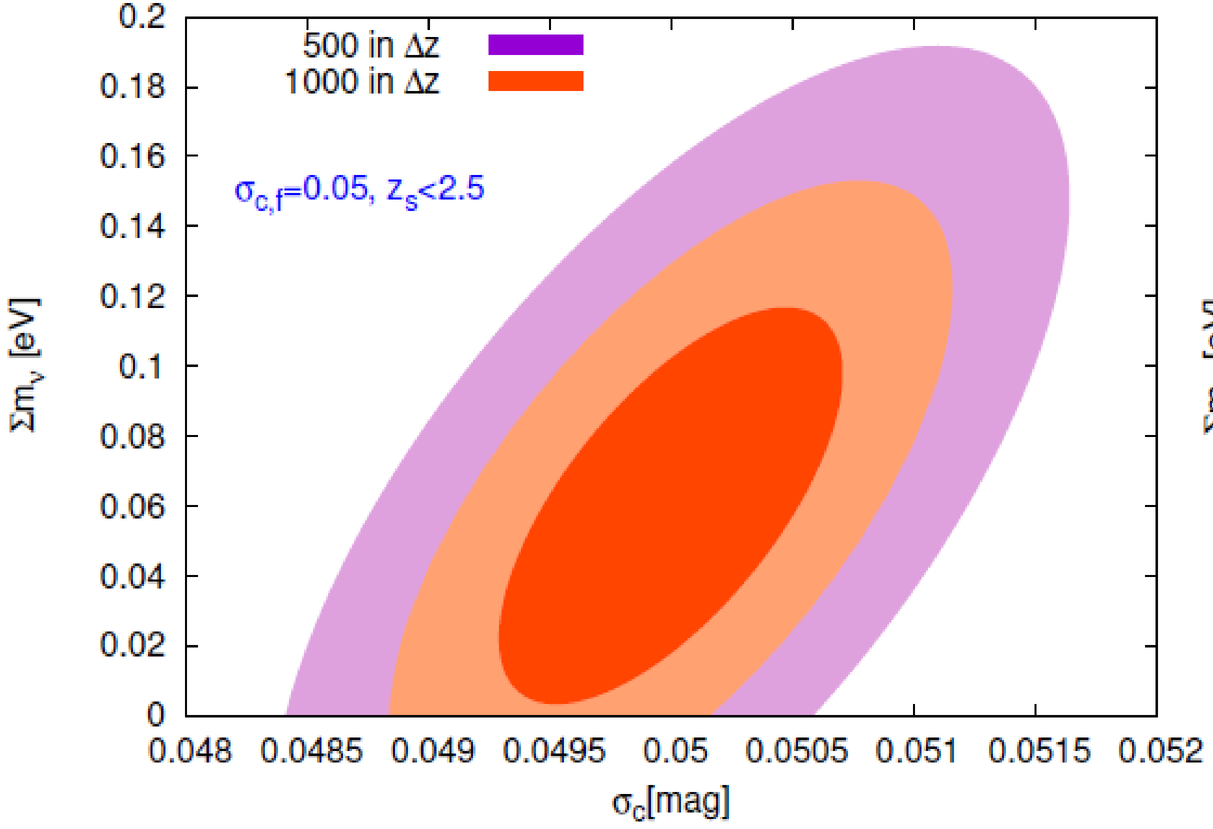
Result

2 free parameters $\sum m_\nu,\ \sigma_c$ $\sigma^2 = \sigma^2_{\rm lens}(z) + \sigma^2_c$

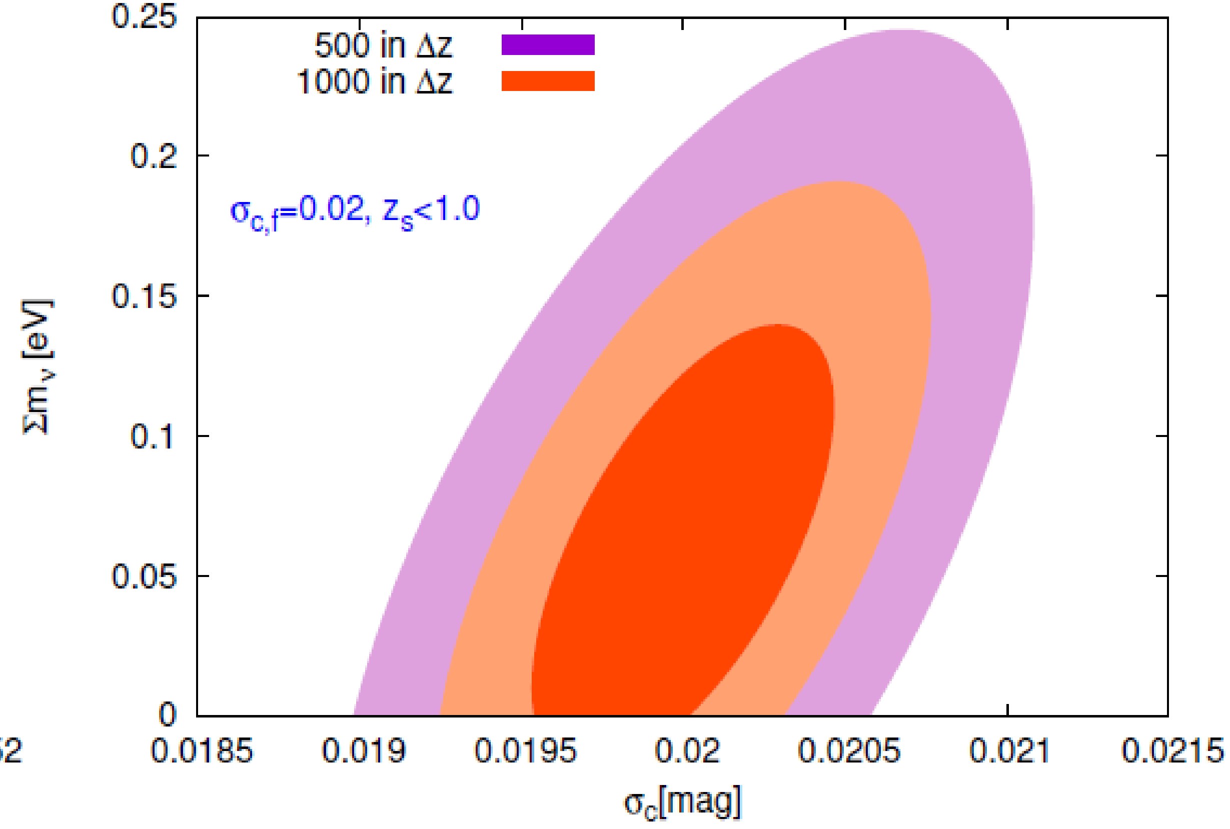
Other parameters such as $\Omega_m,\ n_s, \tau....$ are all fixed (WMAP 5years)



High-z data with half sigma_c



With very small sigma_c
GW from NSNS/NSBH binaries



More information in the data

The above result is obtained by only using minimum information in the expected observation

- PDF of m-z/d-z relation

  Non−Gaussianity in d−z relation comes from the non−Gaussianity of the density distribution which contains more cosmological information

- Shear contribution

$$\sigma_{11} \propto \left(\partial_1^2 - \partial_2^2\right)\phi, \quad \sigma_{12} \propto \partial_1 \partial_2 \phi \quad \Rightarrow \quad \sigma^2 \approx \frac{\phi^2}{\ell^4}$$

Important in small scales

$$\delta_d(z_S) = -\int_0^{z_S} dz\, W(z_S, z)\left(4\pi G a^2 \bar{\rho}_m \delta_m + \sigma^2\right)$$

$$\Rightarrow \quad \left\langle \delta_d(z) \right\rangle \propto -\int dz'\, W\left(z, z'\right) \left\langle \sigma^2 \right\rangle \neq 0$$

Systematic deviation from the standard distance

Can we see a giant void?

Giant voids (δ_g~— 0.2) with size ~400 Mpc/h at z~0.2 are found in galaxy survey

N-body+baryon simulation indicates galaxy bias ~2, thus $\delta_m \sim -0.1$

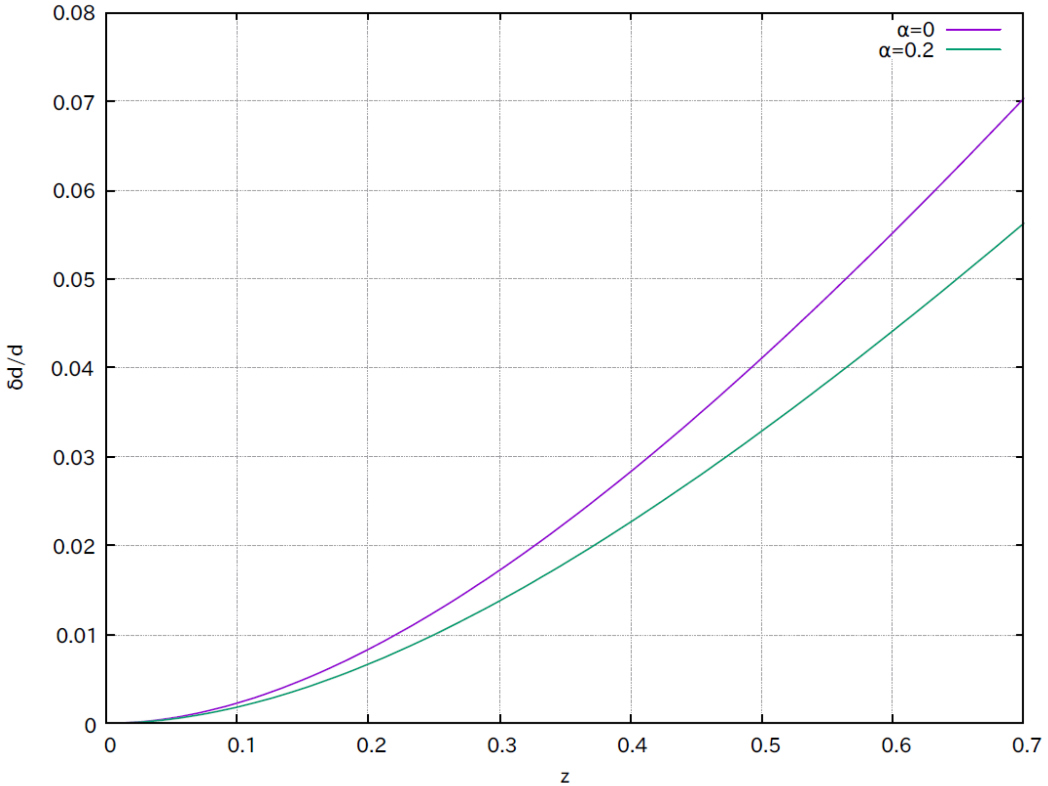
If the density of void is α times the background density

$$\rho_{\text{void}} = \alpha \ \bar{\rho}_m \Rightarrow \delta_m = \frac{\delta \rho_m}{\bar{\rho}_m} = -(1-\alpha)$$

Then our formula gives

$$\delta_d(z_s, \mathbf{n}) = \frac{3H_0^2 \Omega_{m,0}}{2}(1-\alpha)\int_0^{\chi_s} d\chi \frac{(\chi_s - \chi)\chi}{\chi_s}(1+z(\chi))$$

$$= 3(1-\alpha)\left[\frac{\sqrt{1+z_s}+1}{\sqrt{1+z_s}-1}\ln(1+z_s) - 4\right]$$



Summery and future study

- The lensing dispersion in m–z relation by LSS can be calculated semi-analytically and gives a constraint on neutrino mass using the expected data by LSST and WFIRST.
- High z observation of the order of 500 for each redshift bin up to z~2 will improve the constraint of the order of 0.1 eV if the intrinsic ambiguity of the absolute magnitude is reduced in half
- D–z relation derived from GW observation from is in principle ideal method for this purpose since the intrinsic ambiguity of the distance is very small
- Using Non-Gaussianity property and tomographic analysis may improve the constraint and give us more information on cosmology