Cosmological constraint on neutrino properties I: Cosmic Microwave Background

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第27回宇宙ニュートリノ研究会@ICRR

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KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Today's Goal

My today's tasks: in order to convince people here that
cosmological constraints on neutrino properties are important,

1) explain **How? From what? Why?**

2) review **how strongly and robustly** we can constrain them in current cosmological observations

1st half: ***Cosmic Microwave Background (CMB)***
well understood theoretically and experimentally
precise measurements by WMAP, PLANCK etc are available

2nd half: ***Large-Scale Structure (LSS)***
has started to enter the precision cosmology era like CMB
necessary to combine LSS with CMB to reach detection of O(0.1eV)

Contents

- 1. Simple Theoretical Background
- 2. Observational Results
  - WMAP9
  - WMAP9 + SPT/ACT
  - Planck
  - (Planck reanalysis)
- 3. Summary & Future

References:

Textbook: 松原 隆彦, “現代宇宙論”, S. Dodelson, “Modern Cosmology”

Review: W. Hu & S. Dodelson (2002)

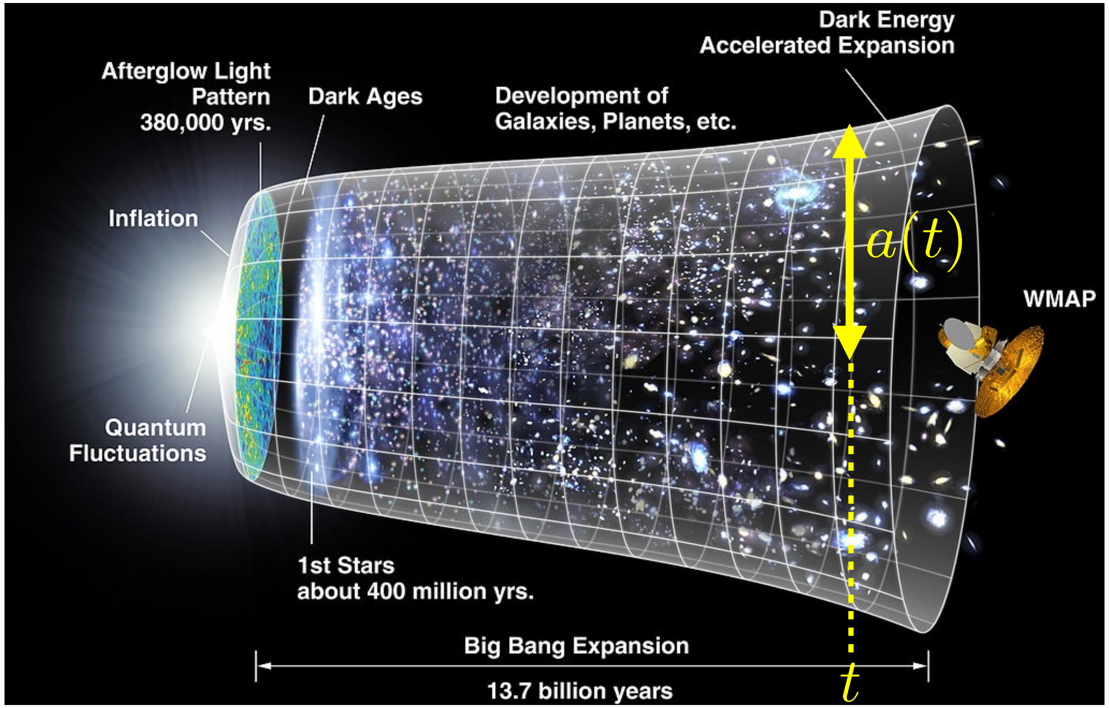
WMAP: Komatsu et al. (2010, 2012), Hinshaw et al. (2013)

SPT: Hou et al. (2013)

Planck Collaboration (2013 I, XVI)

Cosmic History

http://lambda.gsfc.nasa.gov



Past

- z ~ 3000 Rad-Matter equality
- z ~ 1300 Recombination
- z ~ 1100 Photon decoupling
- z ~ 10 Reionization
- z ~ 1 Dark energy dominant
- z = 0 Present

$$\Omega_{\mathrm{X}} = \rho_X / \rho_{\mathrm{crit}}$$

Scale factor $a(t)$

Redshift $$1 + z = \frac{a(t_0)}{a(t)}$$

Hubble parameter $$H = \frac{\dot{a}}{a}$$

flat ΛCDM model: 7 parameters

dark energy	Ω_Λ
baryon	Ω_{b}
cold dark matter (CDM)	Ω_{c}
Hubble constant	$H_0 = 100h\,[\mathrm{km/s/Mpc}]$
initial perturbation	$\Delta^2_{\mathcal{R}}(k_0), n_{\mathrm{s}}(k_0)$
reionization optical depth	τ_{re}

Cosmology constrains neutrinos via ‘GRAVITY’

- Einstein Eq.

$$H^2 = H_0^2 \left\{ \Omega_\Lambda + \Omega_\mathrm{m}(1+z)^3 + \Omega_r (1+z)^4 \right\}$$

Angular diameter distance $D_\mathrm{A}(z) = \frac{1}{1+z} \int_0^z \frac{c dz}{H}$

- Massless → Massive neutrinos

  - become non-relativistic at late times.

$$\Omega_\nu = 0.0217 \left(\frac{\sum m_\nu}{1\,\mathrm{eV}} \right) \left(\frac{0.7}{h} \right)^2$$

  - $m_{\nu,i} = \langle E_{\nu,i} \rangle$ yields to

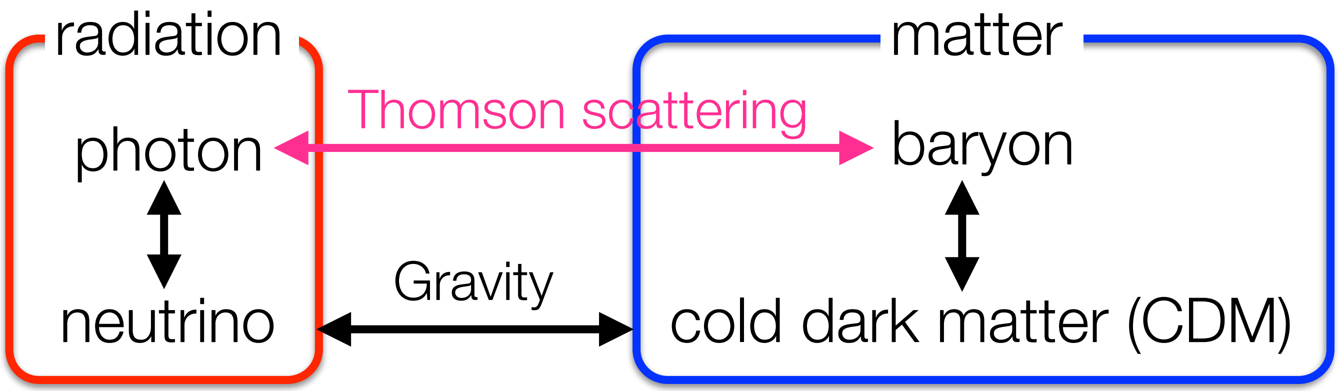
$$1 + z_{\mathrm{nr,i}} = 1890 \left(\frac{m_{\nu,i}}{1\,\mathrm{eV}} \right)$$

  - effective number of neutrinos (c.f. standard $N_\mathrm{eff} \sim 3.046$)

$$\rho_r = \left[1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_\mathrm{eff} \right] \rho_\gamma$$

Cosmic Microwave Background

- At early times, photon interacts with baryon via Thomson scattering



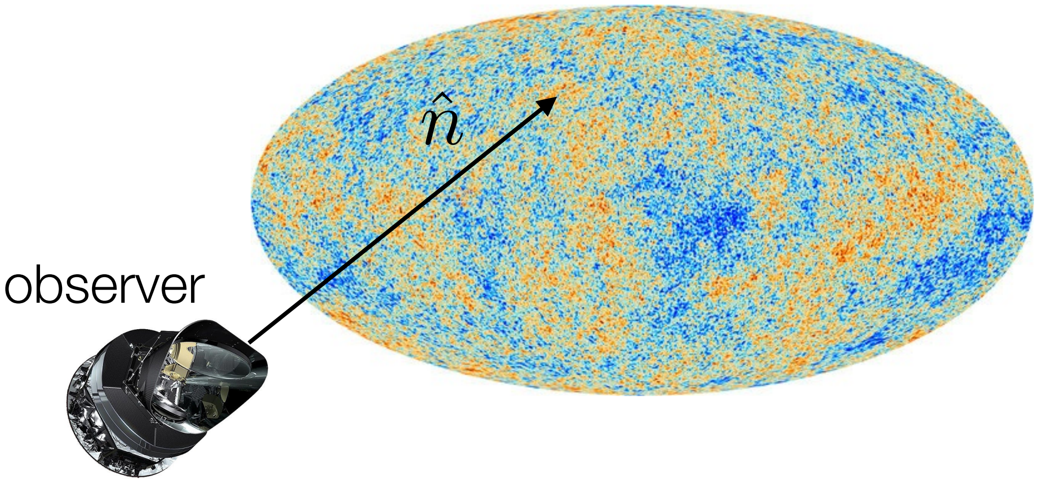
- Sound waves traveling in the baryon-photon fluid

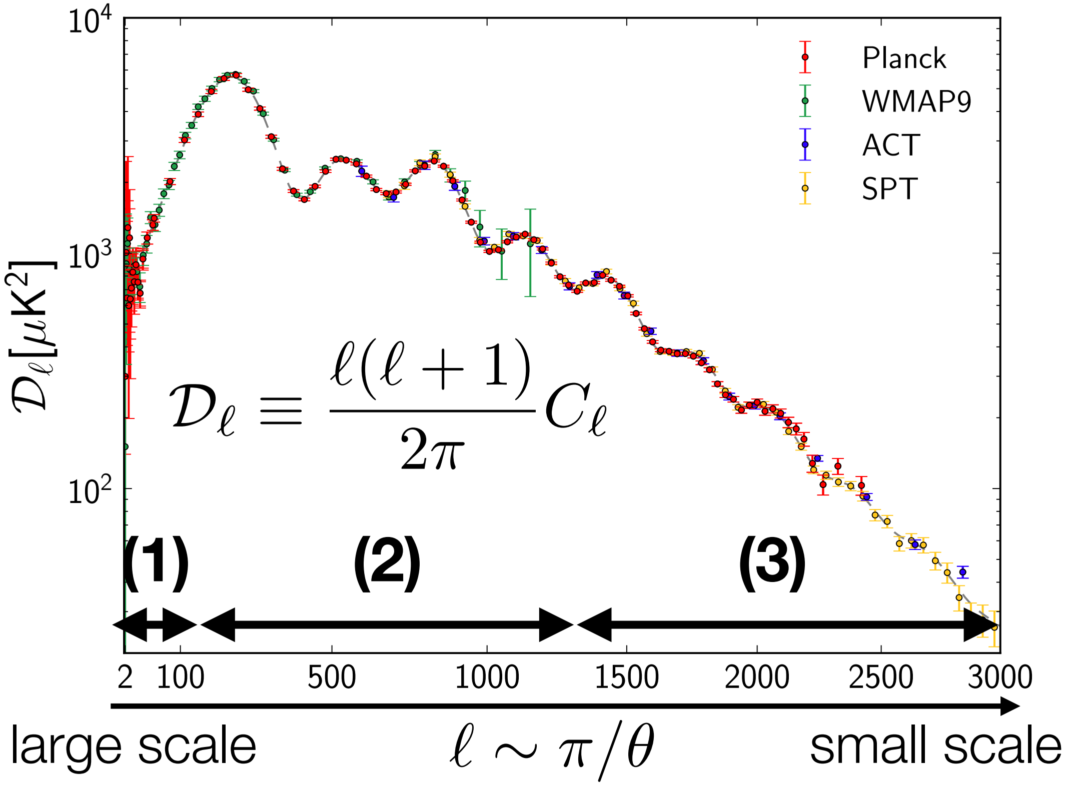
$$r_s = \int_0^{t_{LS}} dt \frac{c(1+z)}{\sqrt{3/(1+3\rho_{\rm b}/(4\rho_\gamma))}}$$

used as a 'standard ruler' in the BAO analysis (2nd talk)

- Right after recombination (z~1300), photon becomes decoupled.
→ observed as CMB photon of 2.726K

Statistical Tool to analyze CMB fluctuation





Observation

spherical harmonics expansion

$$\frac{\Delta T}{T}(\hat{n}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{n})$$

the angular power spectrum

$$C_\ell = \frac{1}{2\ell+1} \sum_m \langle |a_{\ell m}|^2 \rangle$$

Theory

$$C_\ell = \frac{2}{\pi} \int k^2 dk\, \underbrace{P_{\mathcal{R}}(k)}_{\propto k^{n_s - 4}} [\Delta_\ell(k,t)]^2$$

Photon transfer function describes the evolution depending on time and scale.

(1) Sachs-Wolfe Effect

- For the modes beyond the horizon at decoupling (l<100),

$$\left.\frac{\Delta T}{T}\right|_{\rm SW} = \underbrace{\frac{1}{3}\Phi}_{\text{SW}} + \underbrace{2\int dt\,\dot{\Phi}}_{\text{Integrated SW}}$$

- Sachs-Wolfe effect: since $\Delta_\ell(k, t_*) = j_\ell(k\chi_*)$, $\ell(\ell+1)C_\ell \propto \mathrm{Const}$

- Integrated Sachs-Wolfe effect: $\Phi = \mathrm{Const}$ if matter-dominant

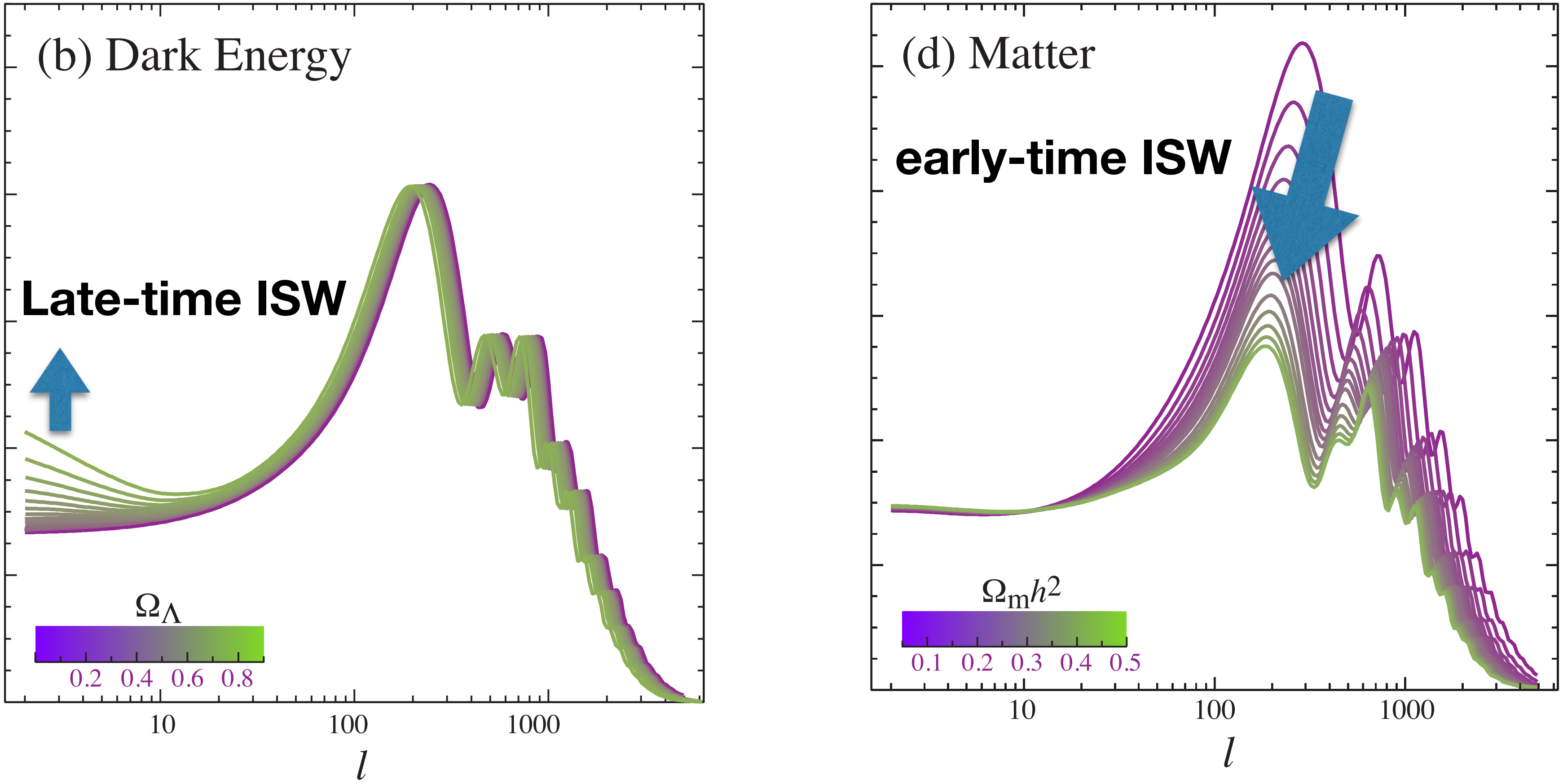
  1) early time ISW: not fully matter dominant at recombination

  important to understand *neutrino mass effect!*

  2) late time ISW: dark-energy dominant era

(1) Sachs-Wolfe Effect

Hu & Dodelson (2002)



(2) Acoustic Oscillation

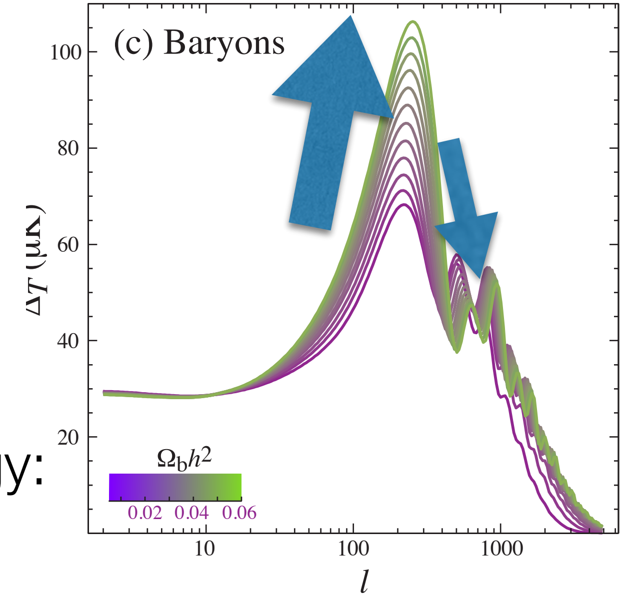
- For the modes within the horizon at decoupling (l>100),

$$\ddot{\delta_\gamma} + \frac{c_s^2}{a^2} k^2 \delta_\gamma = -\frac{4k^2}{3a^2}\Phi$$

This is just a harmonic oscillator and its solution is

$$\frac{1}{4}\delta_\gamma + \Phi = \left[\frac{1}{4}\delta_{\gamma 0} + (1 + \frac{3\rho_\mathrm{b}}{4\rho_\gamma})\right]\cos(kr_s) - \frac{3\rho_\mathrm{b}}{4\rho_\gamma}\Phi$$

odd-peak only depends on baryon density!



- Sound waves traveling in the baryon-photon fluid

$$r_s = \int_0^{t_{LS}} dt \frac{c(1+z)}{\sqrt{3/(1+3\rho_\mathrm{b}/(4\rho_\gamma))}}$$

One of the best measured quantities in cosmology:

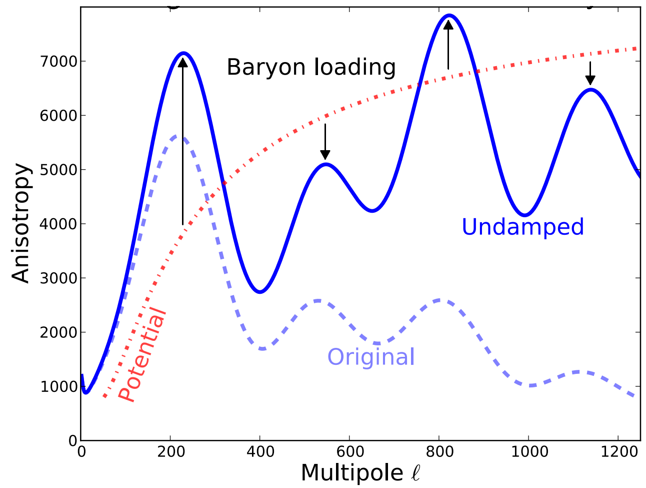
$$\frac{r_s(z_*)}{D_A(z_*)} = 1.19355 \pm 0.00078\,\mathrm{deg}$$

Planck Collaboration 2013

(3) Silk damping

- Recombination is not instantaneous, and hence diffused photon can be affected by friction due to the velocity difference with photon

- At smaller scales than photon's diffusion scale, the temperature fluctuation is washed out



- This scale as $1/\sqrt{Hn_{\rm e}}$, while the sound horizon scales as $1/H$ because $r_d \sim \sqrt{3ct/\lambda_C}\lambda_C$ where photon's mean free path

$$\lambda_C = 1/(\sigma_{\rm T} n_{\rm e})$$

Note $n_{\rm e} = (1 - Y_{\rm He}) n_{\rm b}$

Reionization & CMB polarization

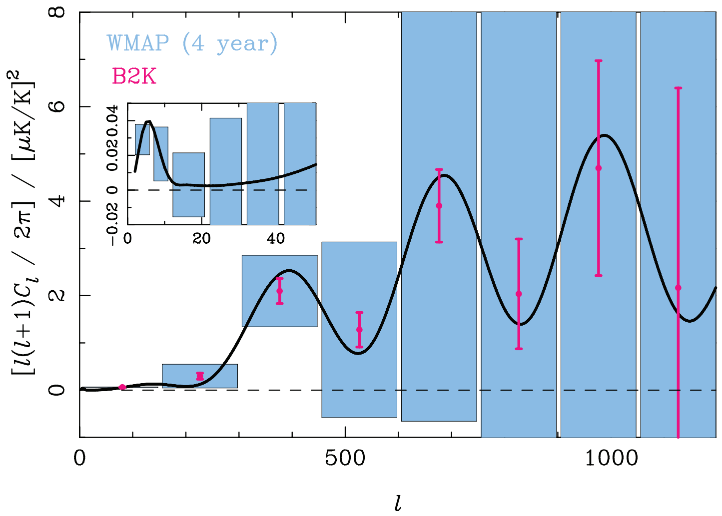
- The universe is known to be reionized at z ~ 10, and the CMB photon become scattered and obscured.

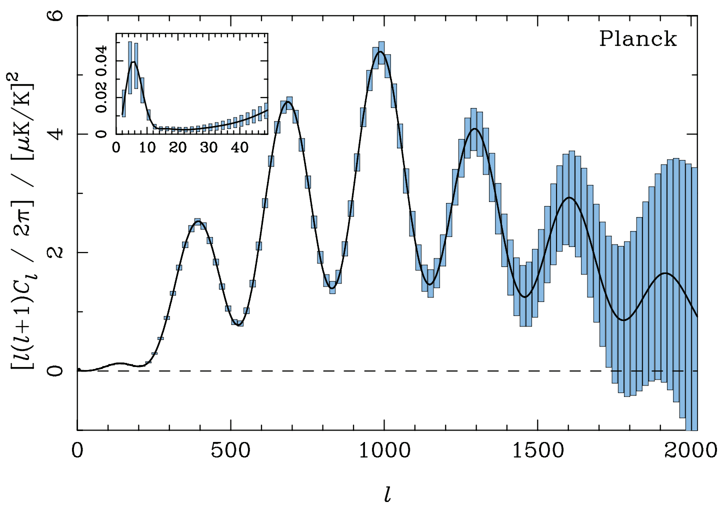
- The temperature power spectrum is reduced by a factor of $\exp[-2\tau_{\rm re}]$

$$\tau_{\rm re} = \int n_{\rm e} \sigma_T dt$$

degenerate with fluctuation parameters, $\Delta^2_{\mathcal{R}}(k_0), n_{\rm s}(k_0)$

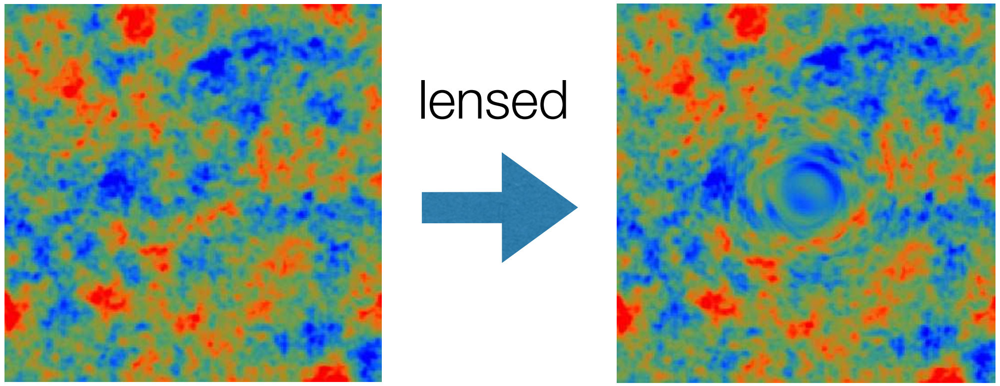
- Polarization can help!





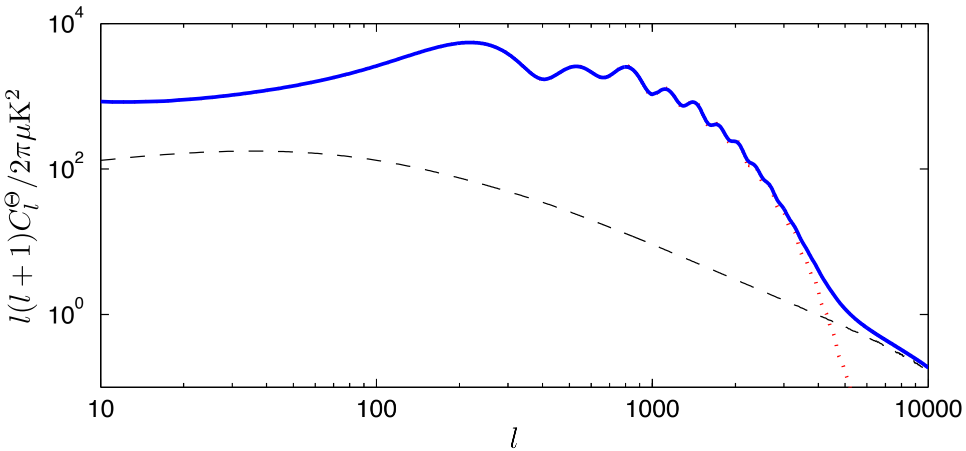
CMB lensing

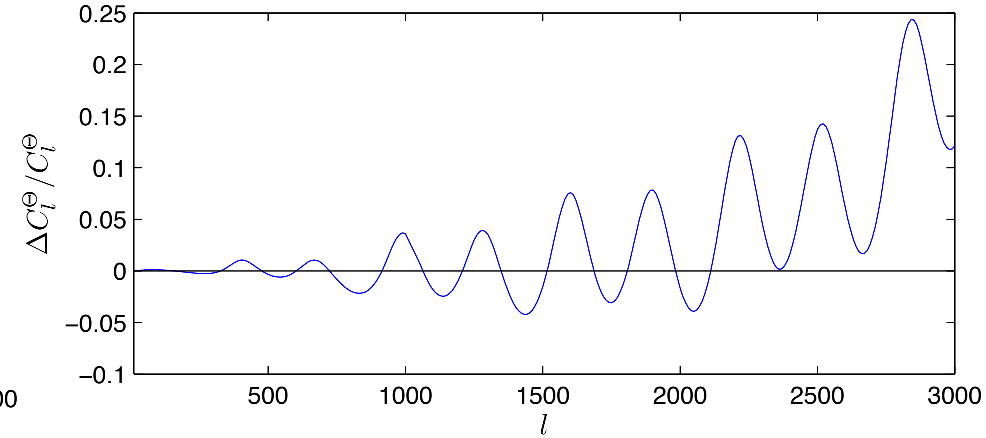
- Primary CMB is lensed by the foreground large-scale structure (LSS)



Hu & Okamoto (2002)

- Smooth out the acoustic peak (~deg scale) Lewis & Challinor (2006)





- Massive neutrinos can suppress LSS (2nd talk) → less lens effect
- Note the 4pt estimator is complementary Schmittfull et al. (2013)

CMB Constraint on $\sum m_\nu$

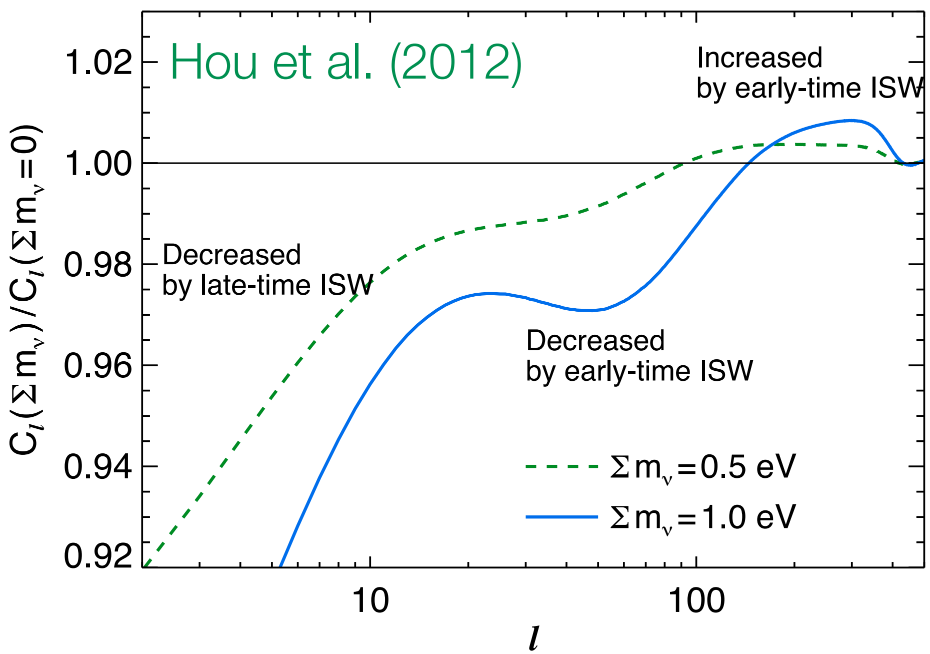
- increasing m means increasing matter at decoupling
- Relativistic neutrino's energy at recombination $E_i \sim 0.58\,\mathrm{eV}$

  In order to be non-relativistic at that time,

$$\sum m_\nu > 0.58 \times 3 = 1.74\,\mathrm{eV}$$

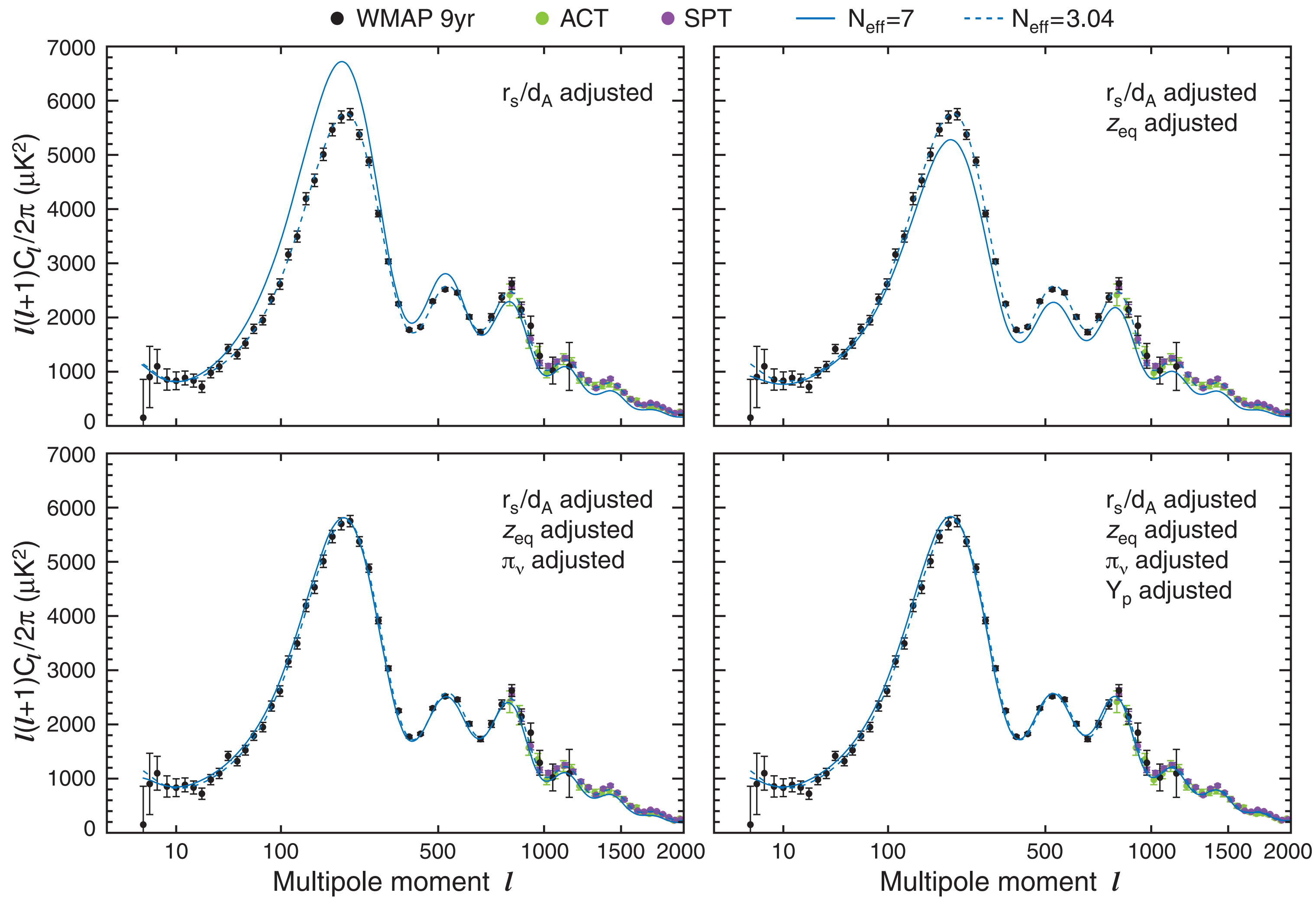
- One could reach beyond the limit by a little bit. e.g. ~1.5eV

Ichikawa, Fukugida, Kawasaki (2005)



CMB Constraint on $N_{\rm eff}$

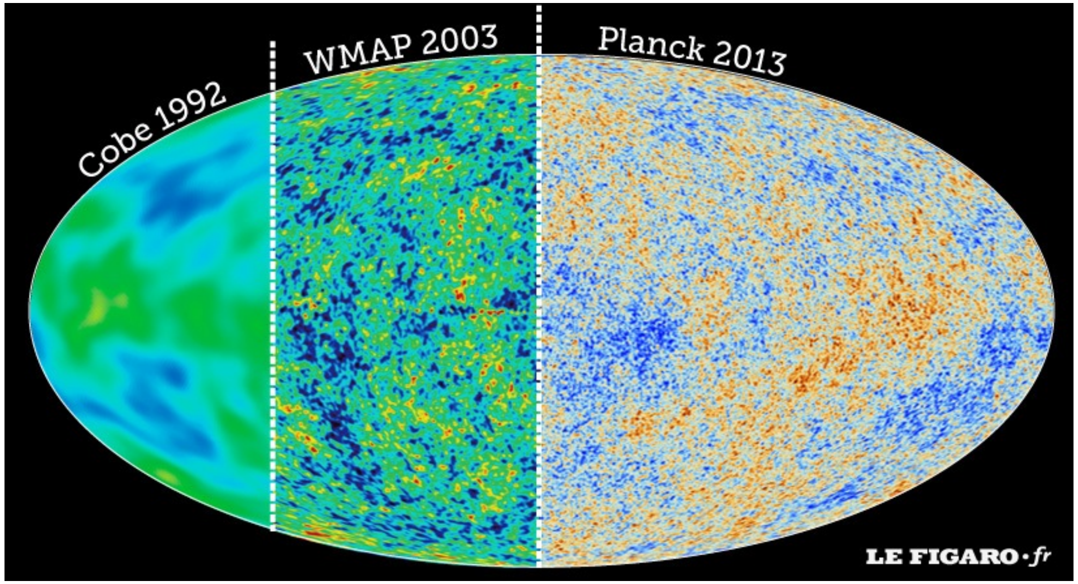
- increasing $N_{\rm eff}$ means increasing radiation at decoupling
- nicely illustrated by WMAP9 paper

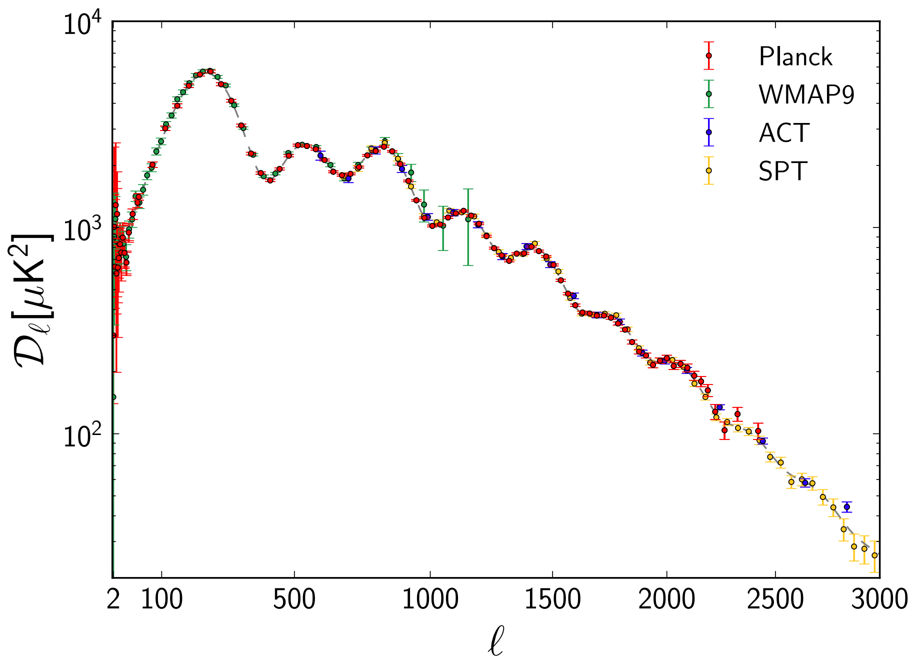


Successful observations of CMB

- **COBE** nicely measured the Planck distribution $2.725 \pm 0.001\,K$
- full-sky satellite: **WMAP, PLANCK**
- terrestrial small-sky but high-resolution: **SPT, ACT, POLARBEAR**

c.f. 西野さんのトーク





WMAP9 + SPT

- LCDM + $\sum m_\nu$

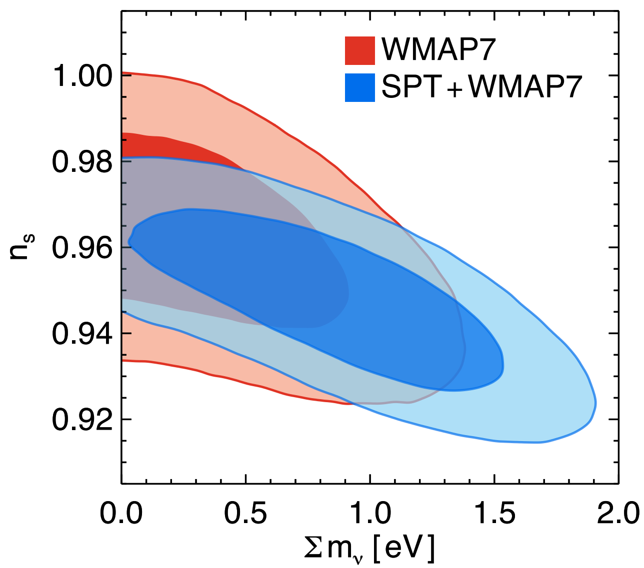
WMAP9 only $\sum m_\nu < 1.3\,\mathrm{eV}\,(95\%\,\mathrm{C.L.})$

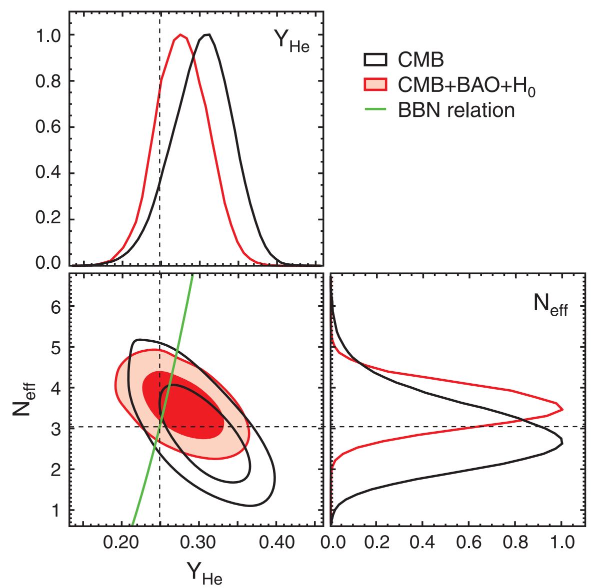
WMAP9 + ACT/SPT $\sum m_\nu < 1.5\,\mathrm{eV}\,(95\%\,\mathrm{C.L.})$

- LCDM + N_{eff} + Y_{He}

WMAP9 only $N_{\mathrm{eff}} > 1.7\,(95\%\,\mathrm{C.L.})$

WMAP9 + ACT/SPT $N_{\mathrm{eff}} = 2.92 \pm 0.79$





PLANCK

- LCDM + $\sum m_\nu$

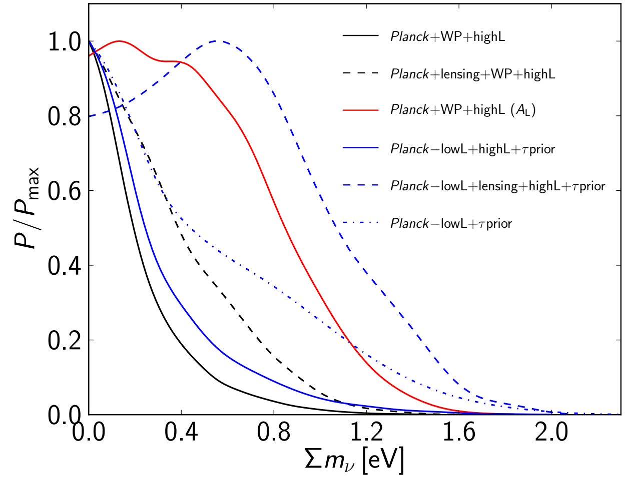
  Planck + WP + ACT/SPT

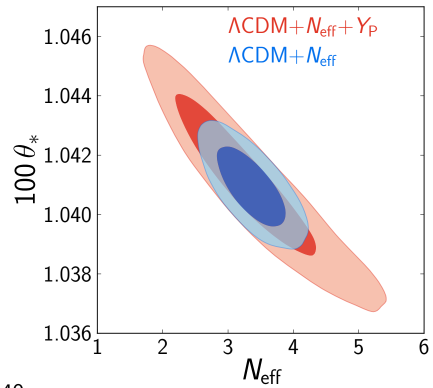
  $$\sum m_\nu < 0.66\,\mathrm{eV}\ (95\%\ \mathrm{C.L.})$$

  + CMB lensing marginalized

  $$\sum m_\nu < 1.08\,\mathrm{eV}\ (95\%\ \mathrm{C.L.})$$

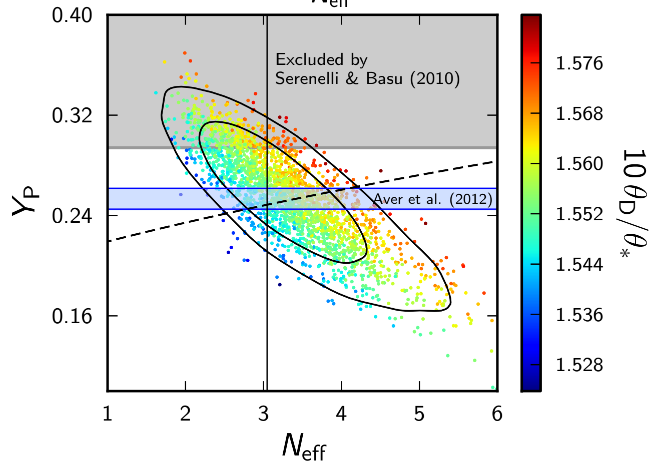
  We do see a discrepancy with CMB lensing (4pt)





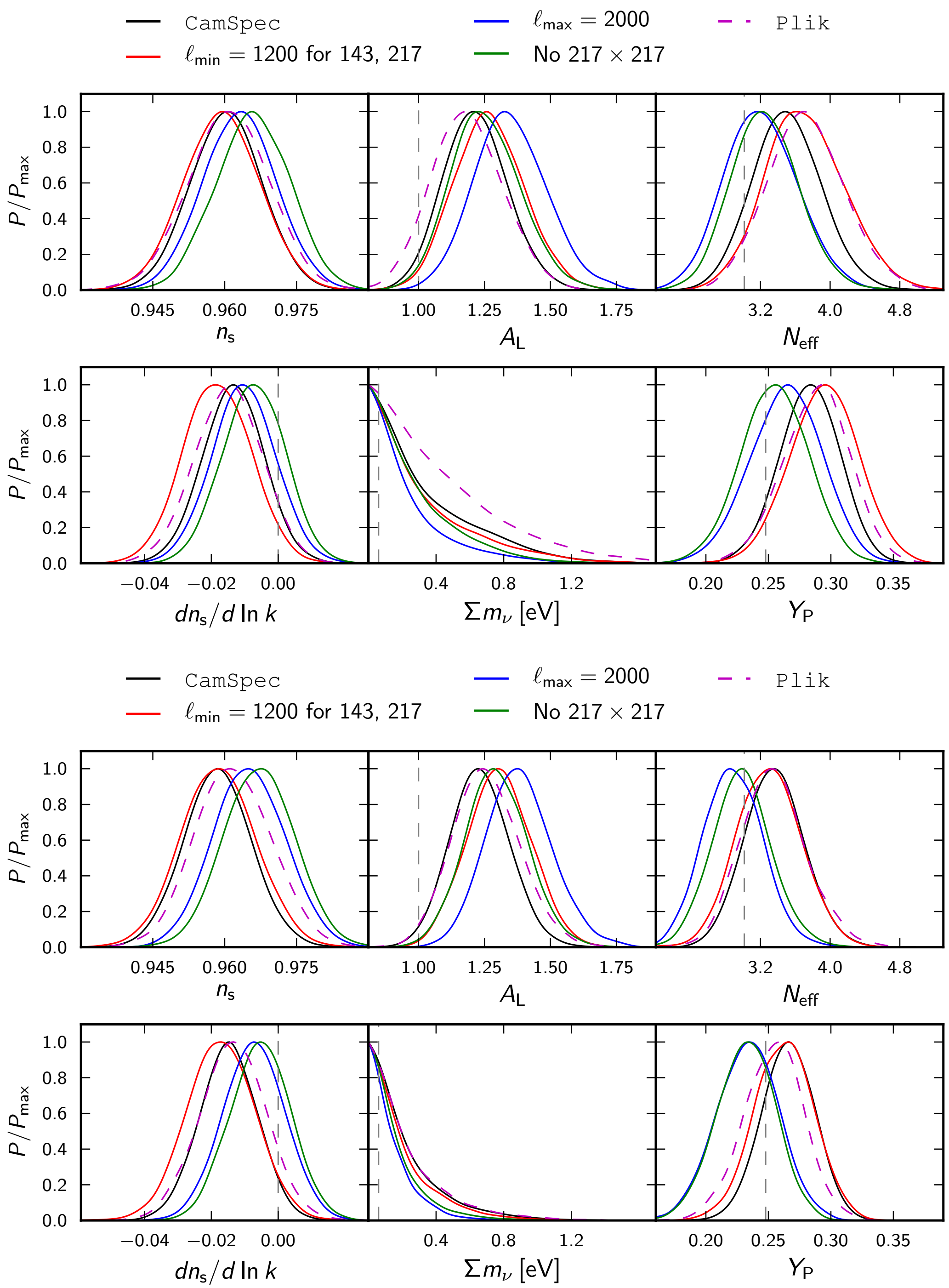
- LCDM + N_{eff} + Y_{He}

$$N_{\rm eff} = 3.33^{+0.59}_{-0.83} \quad (68\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}),$$
$$Y_{\rm P} = 0.254^{+0.041}_{-0.033} \quad (68\%;\ \textit{Planck}+\mathrm{WP}+\mathrm{highL}).$$



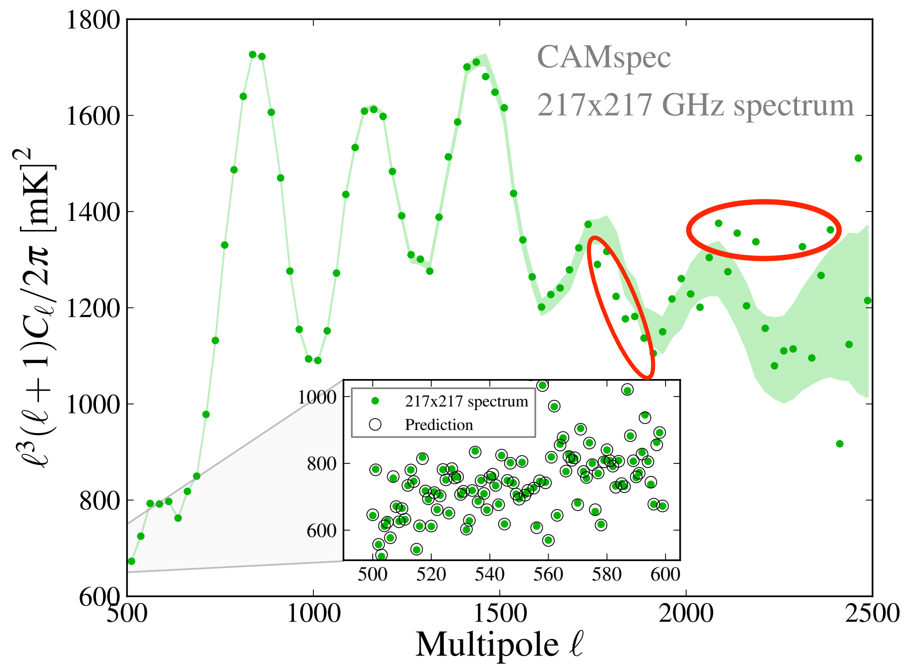
- Even in ΛCDM model, there is a discrepancy b/w WMAP & PLANCK

Systematics in PLANCK?



Appendix. B of Planck (2013XVI)

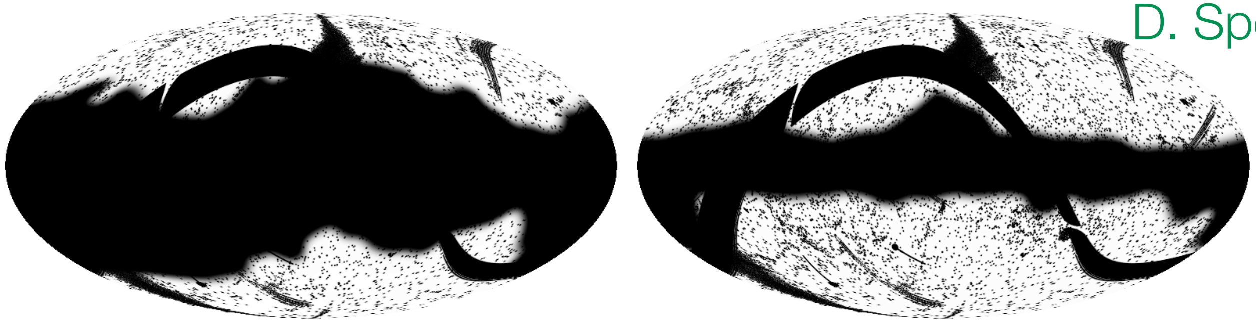
Compare **fiducial** with **No 217x217**



D. Spergel et al. (2013)

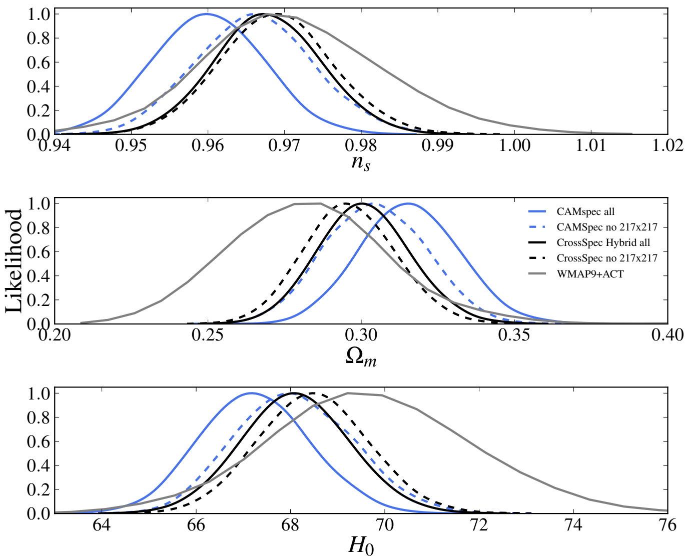
Reanalyzed by D. Spergel

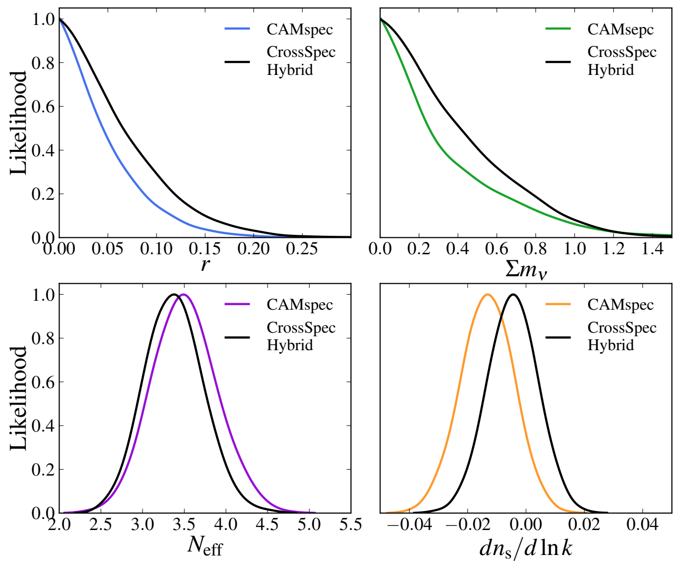
D. Spergel et al. (2013)

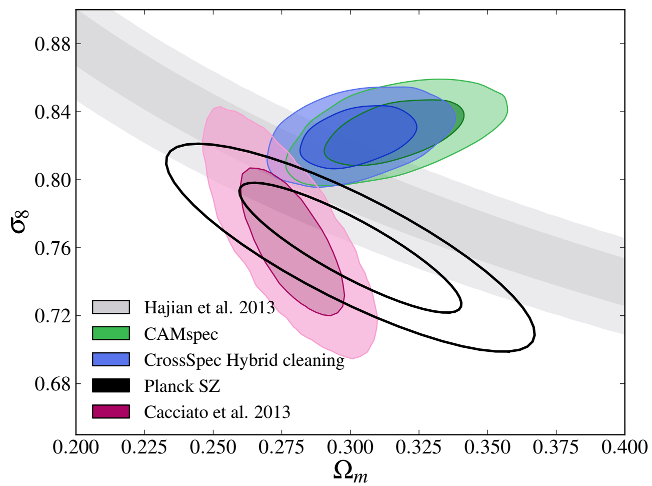


PLANCK
- conservative 24% sky
- marginalized over FG template

Their work
- less conservative 47% sky
- subtracted FG using 545GHz







$$N_{\rm eff} = 3.34 \pm 0.35$$

CMB: Summary & Future

- CMB plays a very important role in cosmology
  - precisely measure the basic parameters in ΛCDM universe

- Neutrino Mass & N_{eff} can be determined separately
  - $\sum m_\nu$ > 2.0eV is ruled out by CMB only
  - CMB lensing is potentially powerful but has a discrepancy
  - N_{eff} is close to the standard value 3.046
  - need other probes! → 2nd talk!

- Future
  - Planck's next data release (w/ polarization) will be summer in 2014
  - Many terrestrial experiments coming!   c.f. 西野さんのトーク

Cosmological constraint on neutrino properties II: Large-Scale Structure

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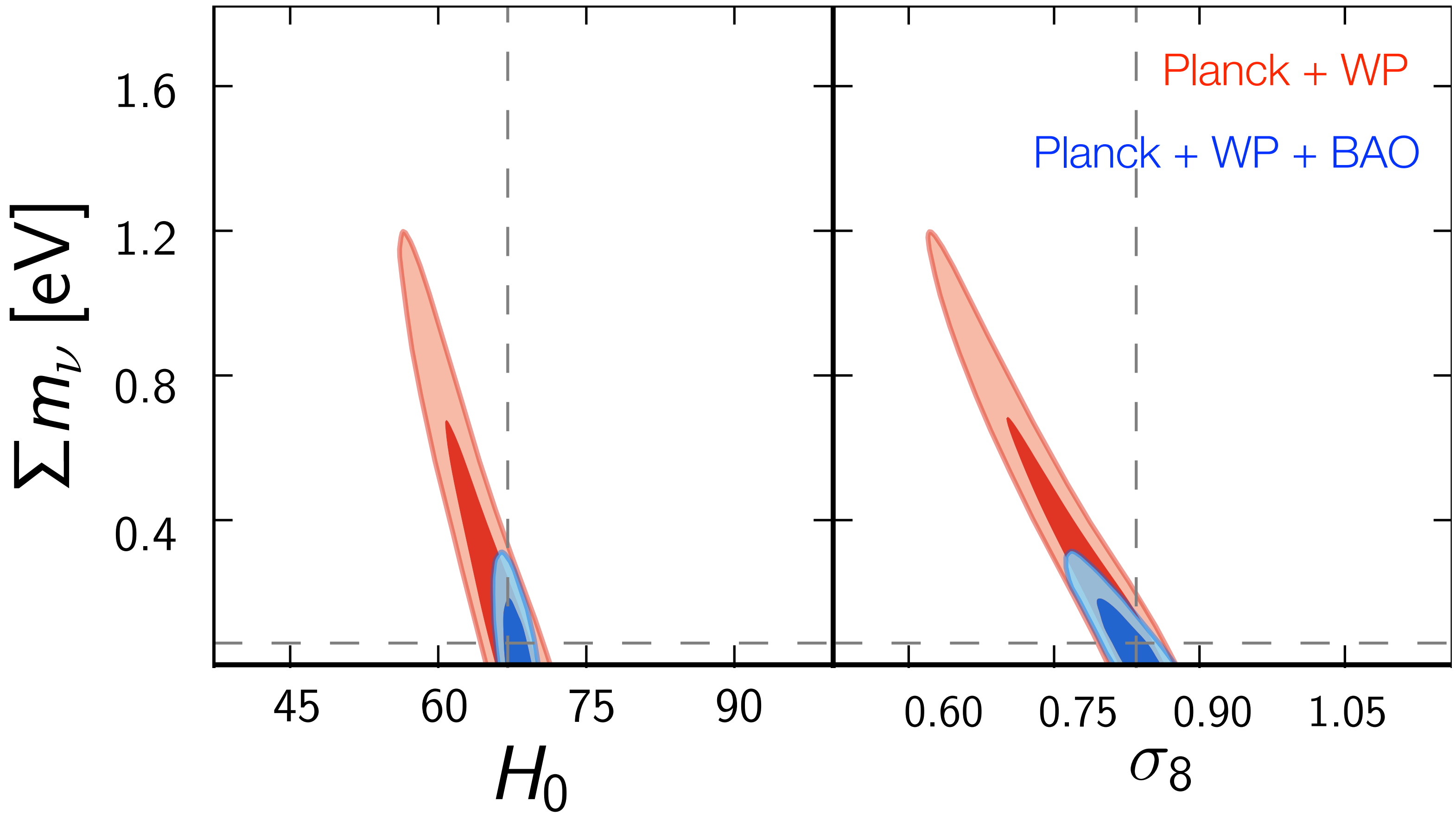
Contents

- 1. How to surpass the CMB constraints?
  - add low-redshift distance information
  - add large-scale structure information
- 2. Brief review of LSS observables
  - Pros & Cons
- 3. Neutrino mass from **Galaxy Clustering**
  - Baryon Acoustic Oscillations
  - Shape of galaxy power spectrum
  - Redshift-Space Distortion
- 4. Summary & Conclusion

How to go beyond CMB?

- degenerated with parameters which CANNOT be constrained by CMB

Planck paper XVI

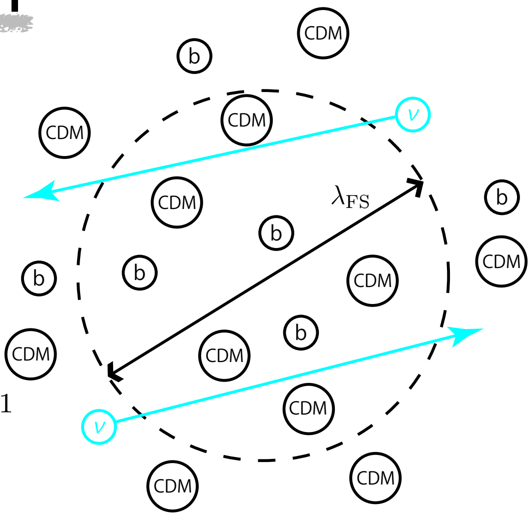


- low redshift distance → break with H_0

  low redshift fluctuation (or its growth)→ break even with σ_8

Neutrino Suppression

- Neutrino free-streaming scale

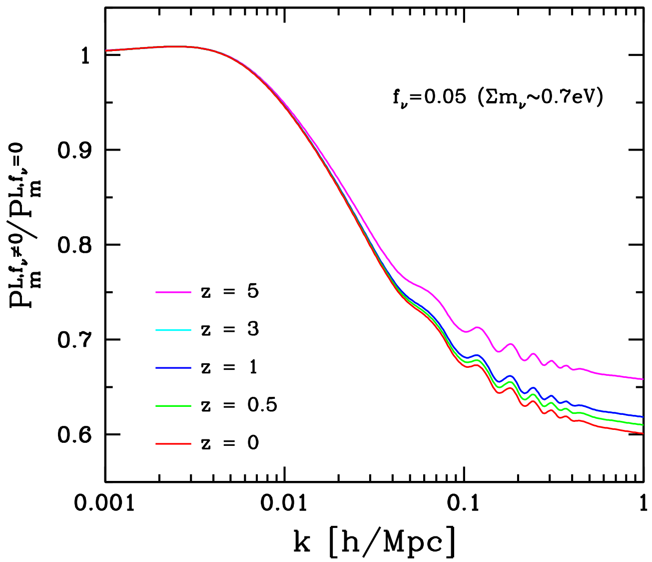


$$k_{\mathrm{FS},i} \equiv \sqrt{\frac{3}{2}}\frac{H(z)}{(1+z)\sigma_{v,\nu i}}$$

$$\simeq 0.0676\left(\frac{m_{\nu,i}}{0.1\ \mathrm{eV}}\right)\frac{\sqrt{\Omega_{w0}(1+z)^{-3(1+w_0)}+\Omega_{\mathrm{m}0}(1+z)^3}}{(1+z)^2}\ h\mathrm{Mpc}^{-1}$$

- Linear matter power spectrum $P_{\mathrm{m}}(k,z) = \langle|\delta_{\mathrm{m}}(k,z)|^2\rangle$

shape

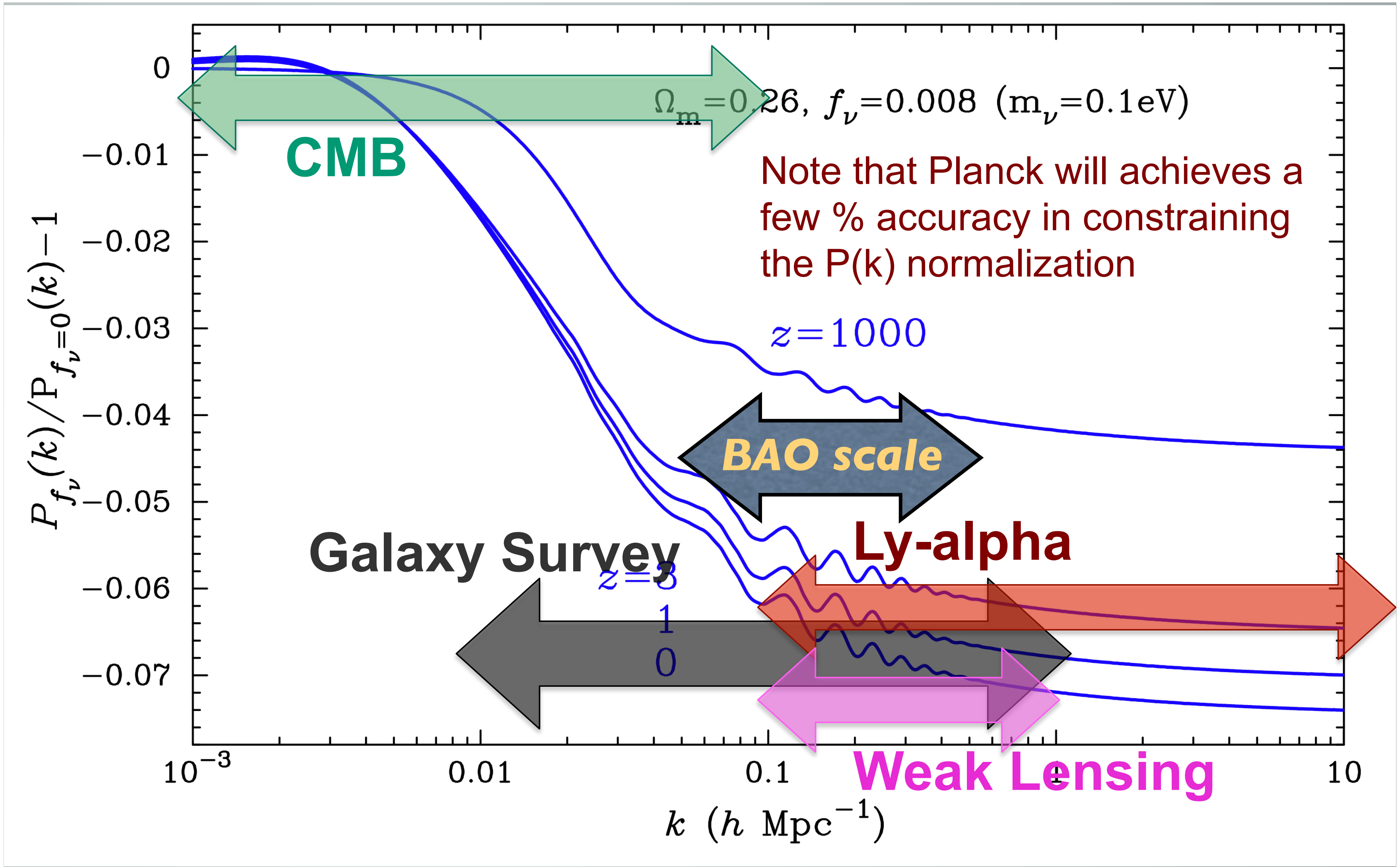


$$\approx 1 - 8\frac{\Omega_\nu}{\Omega_{\mathrm{m}}}$$

integrated suppression

$$\sigma_8^2 = \int \frac{dq}{q}\, P_{\mathrm{m}}^{\mathrm{L}}(q; z=0)\left[\frac{3\sin(kR)}{(kR)^3} - \frac{3\cos(kR)}{(kR)^2}\right]\Bigg|_{R=8\mathrm{Mpc}/h}$$

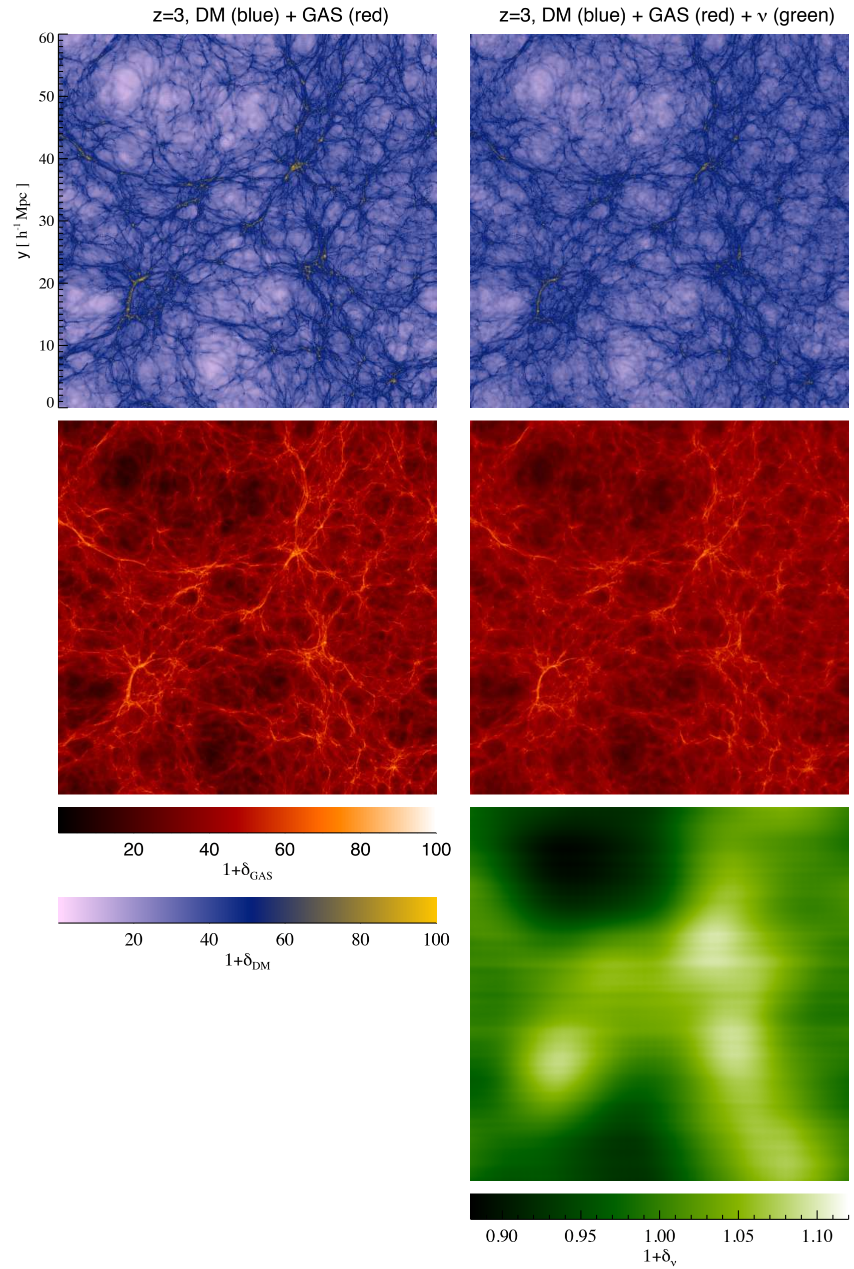
Quick Look



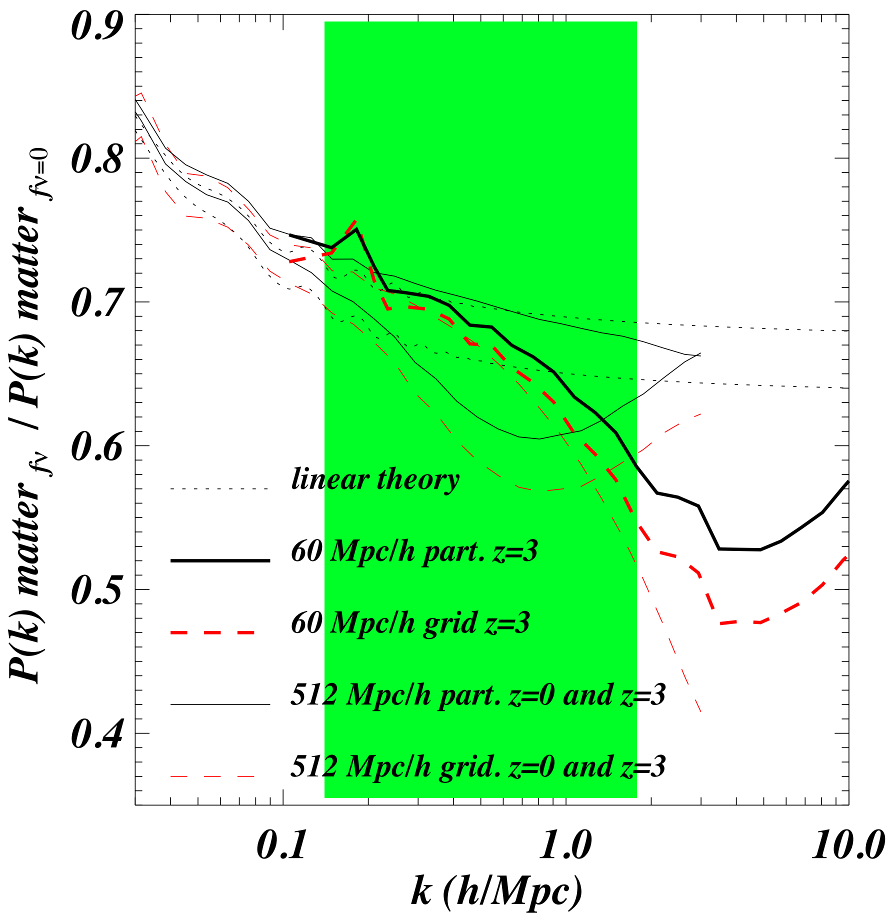
0
−0.01
−0.02
−0.03
−0.04
−0.05
−0.06
−0.07
$P_{f_\nu}(k)/P_{f_\nu=0}(k)-1$
10^{-3}
0.01
0.1
10
k (h Mpc^{-1})
Ω_m=0.26, f_ν=0.008 (m_ν=0.1eV)
CMB
Note that Planck will achieves a few % accuracy in constraining the P(k) normalization
z=1000
BAO scale
Galaxy Survey
z=3
1
0
Ly-alpha
Weak Lensing

Neutrino Suppression in Nonlinear theory

- N-body simulation



- Nonlinear Power Spectrum



Just has started!

LSS Observables

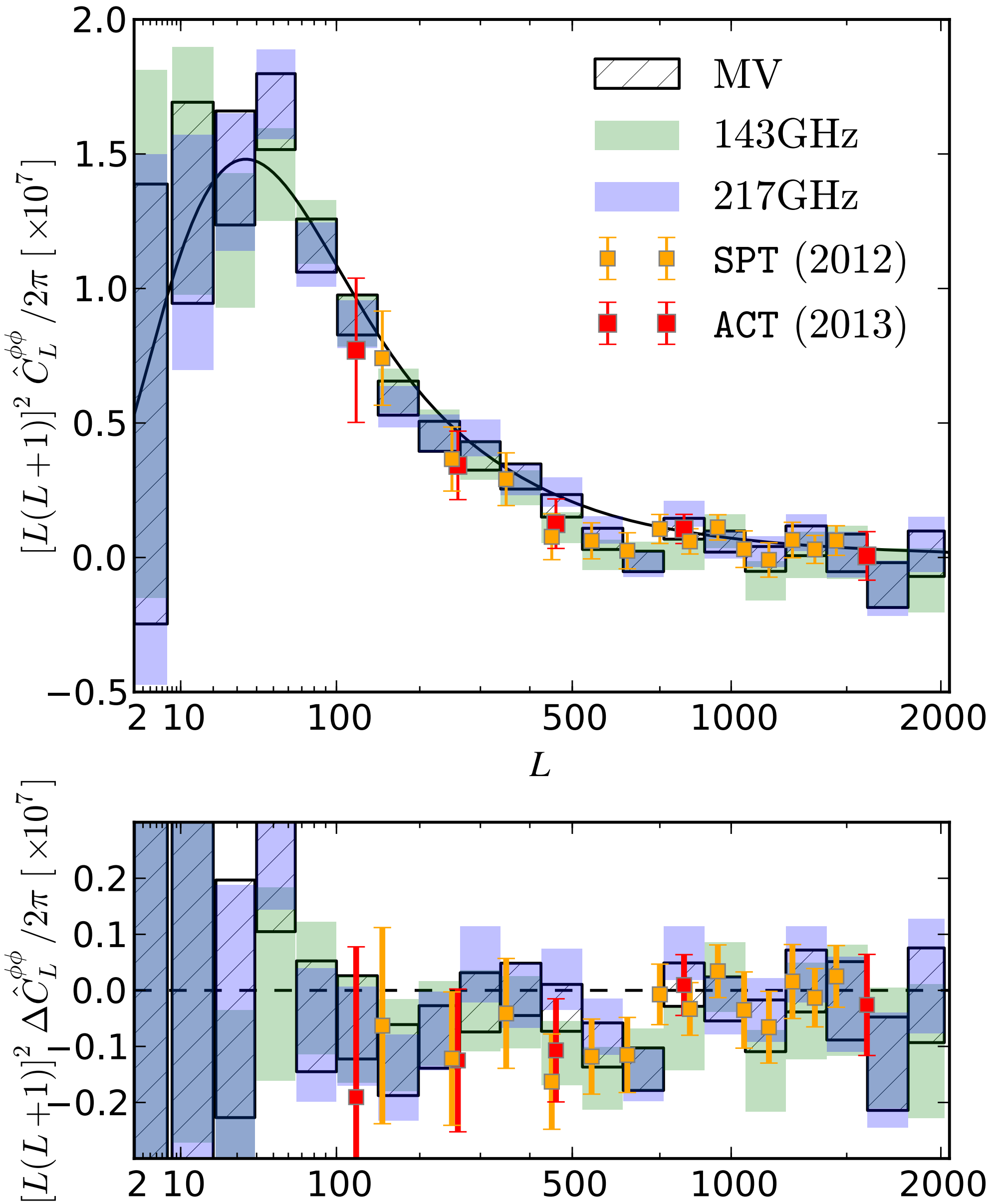
Abazajian et al. (2011, 2013)

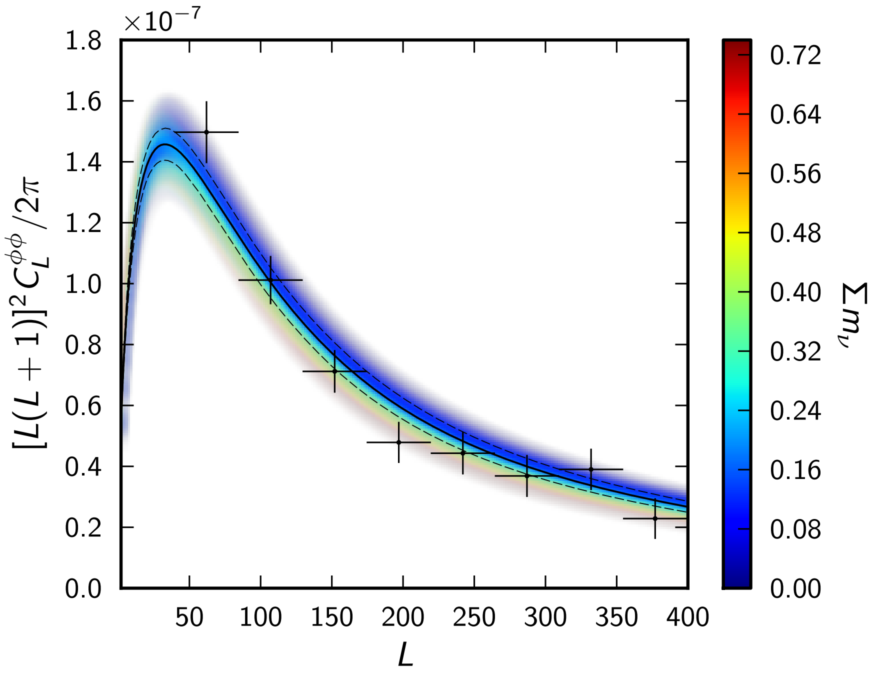
Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	0.2 – 0.05	NG of Secondary anisotropies	Planck, ACT [39], SPT [96]	EBEX [57], ACTPol, SPTPol, POLARBEAR [5], CMBPol [6]
Galaxy Distribution	0.6	0.1	Nonlinearities, Bias	SDSS [58, 59], BOSS [82]	DES [84], BigBOSS [81], DESpec [85], LSST [92], Subaru PFS [97], HETDEX [35]
Lensing of Galaxies	0.6	0.07	Baryons, NL, Photometric redshifts	CFHT-LS [23], COSMOS [50]	DES [84], Hyper SuprimeCam, LSST [92], Euclid [88], WFIRST[100]
Lyman α	0.2	0.1	Bias, Metals, QSO continuum	SDSS, BOSS, Keck	BigBOSS[81], TMT[99], GMT[89]
21 cm	∞	0.1 – 0.006	Foregrounds, Astrophysical modeling	GBT [11], LOFAR [91], PAPER [53], GMRT [86]	MWA [93], SKA [95], FFTT [49]
Galaxy Clusters	0.3	0.1	Mass Function, Mass Calibration	SDSS, SPT, ACT, XMM [101] Chandra [83]	DES, eRosita [87], LSST

- Important to trace characteristic time and scale dependence
- Key issue in each observable is how to control systematics

PLANCK CMB Lensing

Planck XVII (2013)

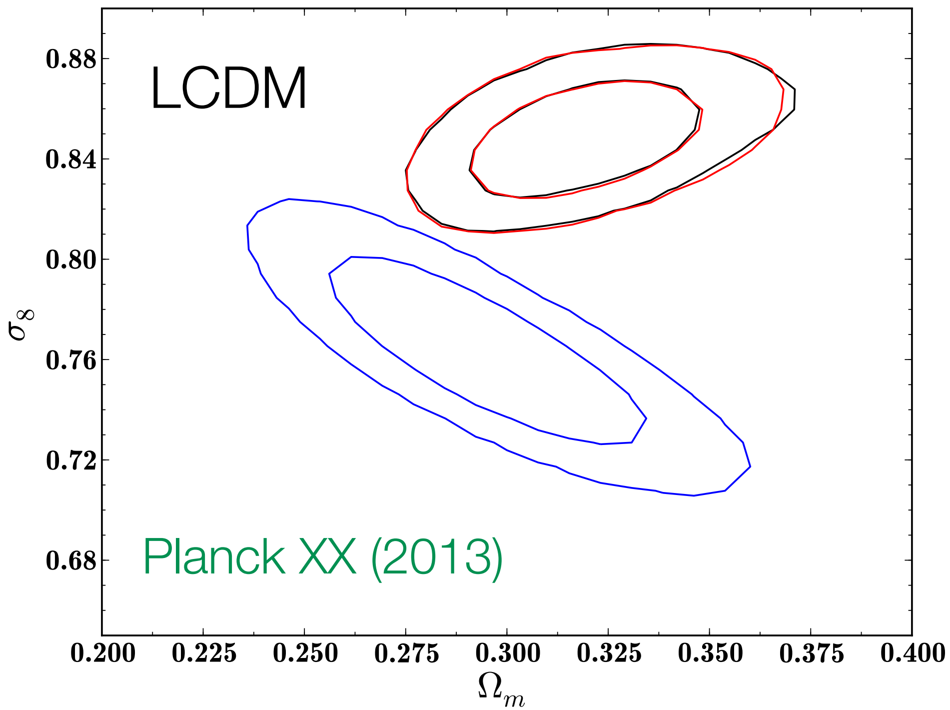




~0.2-0.3eV is favored

incompatible with 2pt

PLANCK SZ

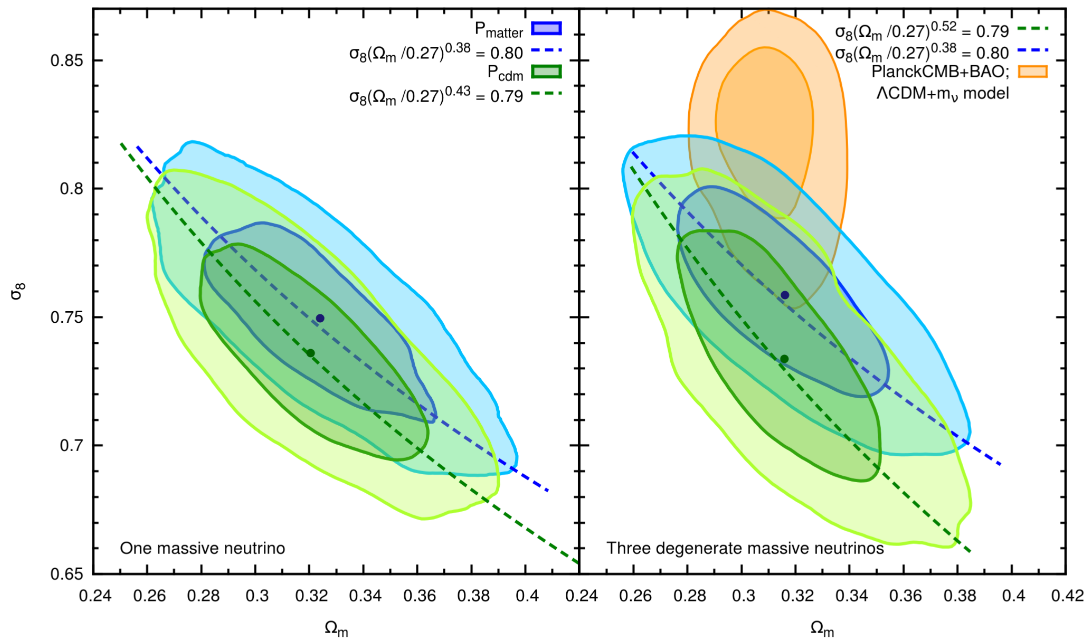


conuting # of SZ clusters

But halo is composed only of CDM plus baryon (not neutrino)!

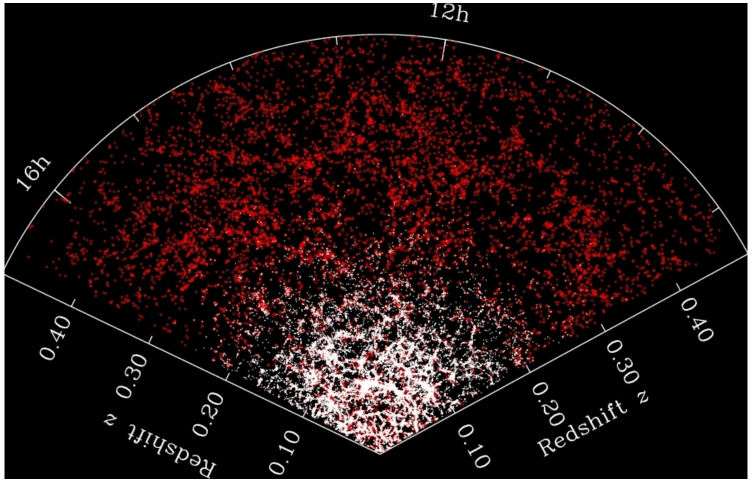
Ichiki & Takada (2010)
Navarro, S.S. et al. (2013)

Costanzi et al. (2013)



Why galaxy clustering?

- Galaxy clustering $\delta_g(\mathbf{x}) = \dfrac{n_g(\mathbf{x}) - \bar{n}_g}{\bar{n}_g}$



2pt statistics

Power Spectrum in Fourier Space

$$\langle \delta_g(\mathbf{k}) \delta_g(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k}') P_g(\mathbf{k})$$

Correlation Function in Configuration Space

$$\langle (1 + \delta_g(\mathbf{x}))(1 + \delta_g(\mathbf{x} + \mathbf{r})) \rangle = 1 + \xi(\mathbf{r})$$

- Reasons why 3D large-scale galaxy clustering is interesting:

1. By eye, looks like $\delta_g \sim \mathcal{O}(1)$ (c.f. CMB: $\delta T/T \sim \mathcal{O}(10^{-5})$)

2. Traces underlying matter distribution $P_g(k) \approx b_1^2 P_m(k)$

   - Baryon Acoustic Oscillations ~150Mpc → ***dark energy***

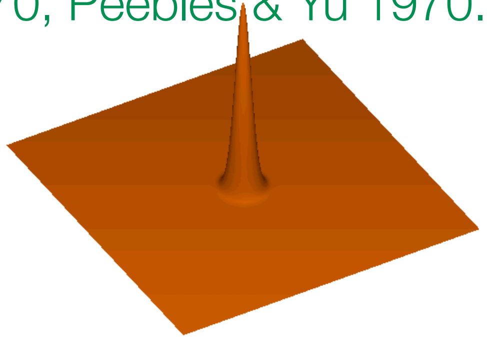
   - mildly nonlinear regime → ***initial condition, neutrino mass***

   - Redshift Space Distortions → ***modified gravity***

3. Observation is not technically challenging

Baryon Acoustic Oscillations (BAOs)

Sunyaev & Zel'dovich 1970, Peebles & Yu 1970...



©Eisenstein

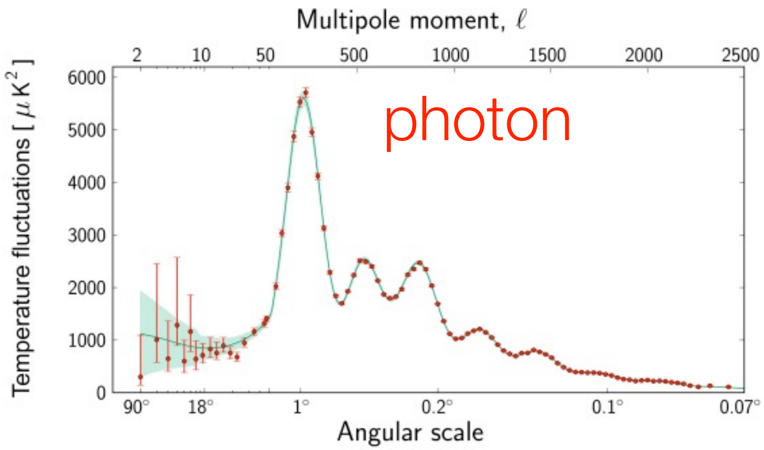
- Sound waves traveling in the baryon-photon fluid

$$r_s = \int_0^{t_{LS}} dt \frac{c(1+z)}{\sqrt{3/(1+3\rho_{\rm b}/(4\rho_\gamma))}}$$

- The sound horizon at recombination can be seen as acoustic peaks in CMB

$$\frac{r_s(z_*)}{D_A(z_*)} = 1.19355 \pm 0.00078\,\mathrm{deg}$$

Planck Collaboration 2013

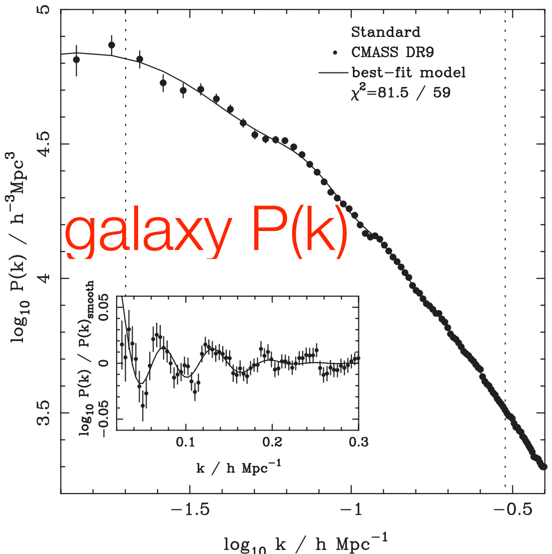


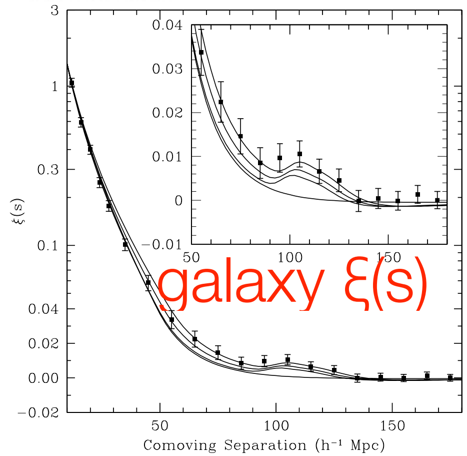
- After baryon-dragging epoch, BAOs are imprinted into matter

$$r_d = 147.49 \pm 0.59\,\mathrm{Mpc}$$

Hu & Sugiyama 1996

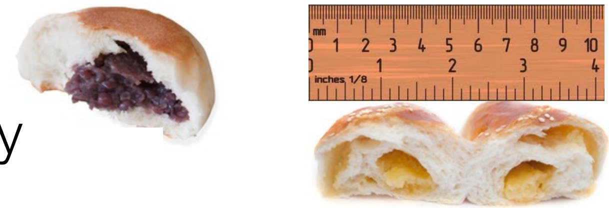
But suppressed by $\dfrac{\Omega_{\rm b}}{\Omega_{\rm m}} \sim \mathcal{O}(0.1)$





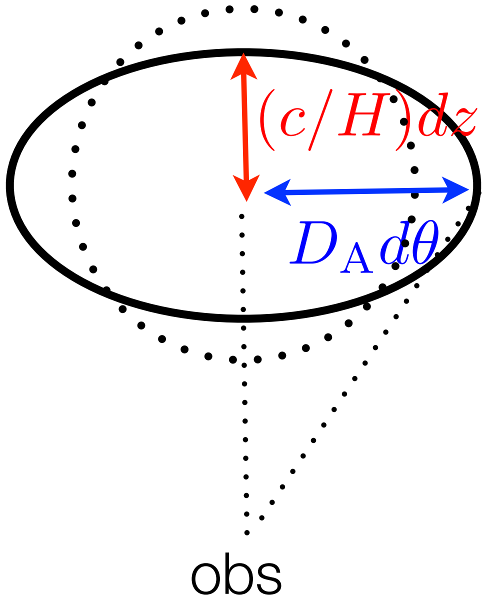
BAO as a ‘standard ruler’

THE TIME IS BAO



- When making a 3D map, d-z relation is necessary

Alcock & Paczynski (1979)



true cosmology: ***isotropic***

fiducial (wrong) cosmology: ***anisotopic***

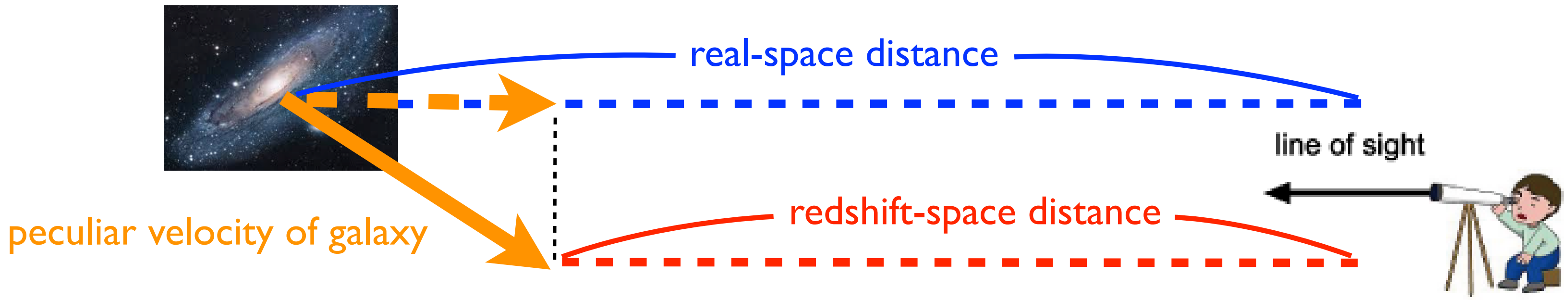
- In the BAO business: very robust against systematics

1D BAO: spherically-averaged $D_\mathrm{V} = \left[cz(1+z)^2 \frac{D_\mathrm{A}^2}{H}\right]^{1/3}$ $\boxed{\dfrac{D_\mathrm{V}}{r_\mathrm{d}}}$

2D BAO (AP test): $\boxed{D_\mathrm{A} \times H}$ Padmanabhan & White 2006

＊ shape of P(k) can be also useful for the AP signal

Redshift Space Distortion (RSD)

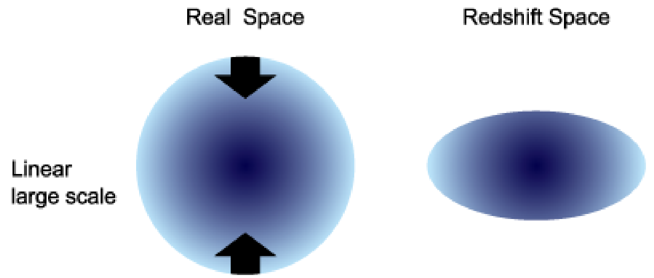


- A distance to a galaxy is measured by “redshift” which cannot be distinguished from its peculiar velocity

redshift space $\quad \vec{s} = \vec{r} + \dfrac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z} \quad$ line of sight direction

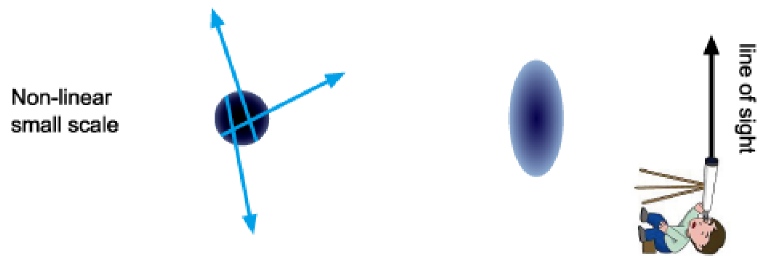
real space

- Another ***anisotropic*** distortion!



Large scale: Squashing effect
- amplitude become **larger**

Kaiser (1987)



Small scale: Finger-of-God
- amplitude become **smaller**

Jackson (1972)

RSD in linear theory

- In linear theory, the anisotropic P(k) in redshift space is

$$P_g(k,\mu) = b^2\left(1+\frac{f}{b}\mu^2\right)^2 P^L(k)$$

Kaiser (1987)

Legendre multipole expansion is useful to characterize P(k,μ)

$$P(k,\mu) = \sum_\ell P_\ell(k)\mathcal{L}_\ell(\mu)$$

Notice that, in linear theory, we only have
monopole (l=0), quadrupole (l=2), hexadecapole (l=4)

- The definition of 'f=dlnD/dlna' comes from the velocity field $f\sigma_8$

linear Euler equation $$\frac{\partial \mathbf{u}(\mathbf{x},\tau)}{\partial\tau} + \mathcal{H}(\tau)\,\mathbf{u}(\mathbf{x},\tau) = -\nabla\Phi(\mathbf{x},\tau)$$

gravity test

$$\boxed{f = \Omega_m(z)^\gamma \quad \gamma = 0.545 \text{ (GR)} \quad \gamma = 0.68 \text{ (DGP)}}$$

Note that RSDs are complementary to weak lensing (Φ+Ψ)

Jain & Khoury (2010)

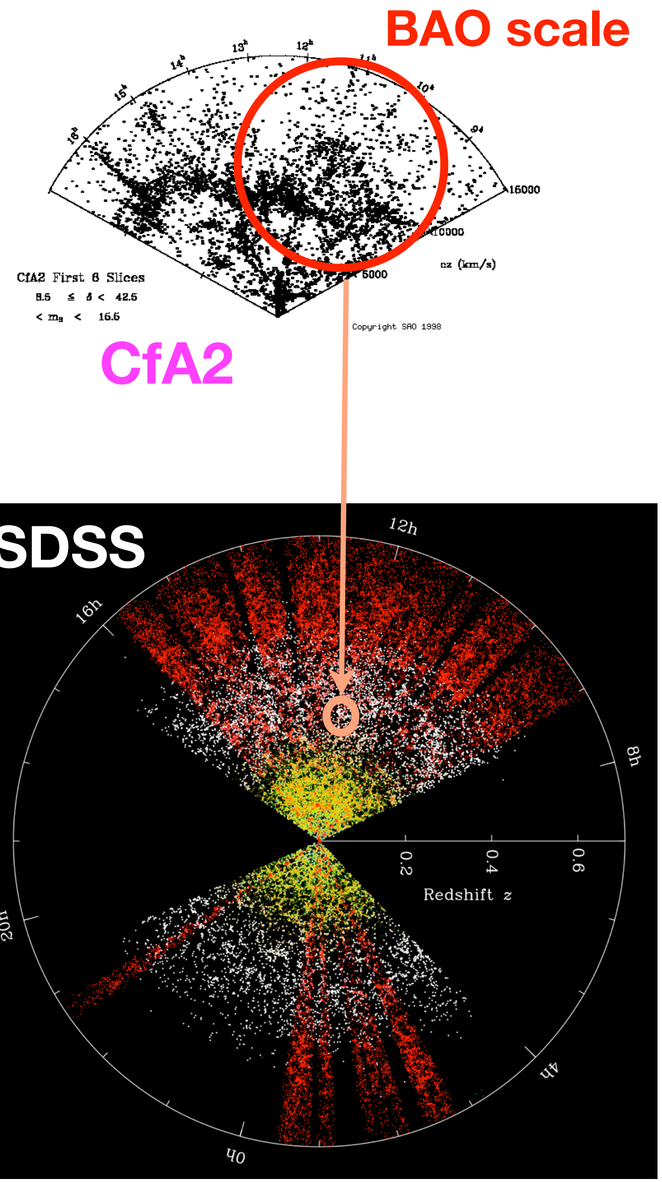
Galaxy Redshift Surveys

- Many gigantic galaxy redshift surveys for **BAO** and **RSD**

  Completed: CfA2, 2dF, SDSS-II, WiggleZ

  Ongoing: **BOSS**, VIPERS, FastSound

  Future: HETDEX, SuMiRe PFS, DESI, Euclid



- Complementary to imaging (photo-z) surveys

  surveys: DES, HSC, LSST etc...

  designed for weak lensing

  angular clustering is possible,
  but little information on RSD

Baryon Oscillation Spectroscopic Survey

- A part of Sloan Digital Sky Survey III (2009-2014) Eisenstein et al. 2011

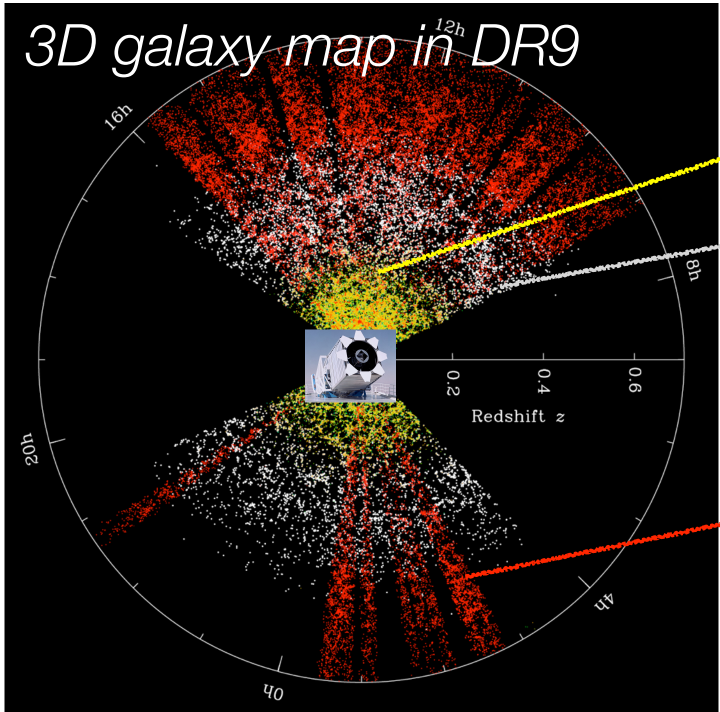
  - 2.5m telescope in Apache Point Observatory in NM, USA

  - image (u,g,r,i,z) bands with r~22.5 covering ~14,000deg^2 Fukugida et al. 1996

  - BOSS (DR9-DR12)

    1) 1.5 million luminous galaxies

    2) 150,000 quasars (Ly-α forest) e.g. Slosar et al. 2012



SDSS-II DR7

Main Galaxy z~0.1

Luminous Red Galaxy z~0.35

SDSS-III BOSS DR9

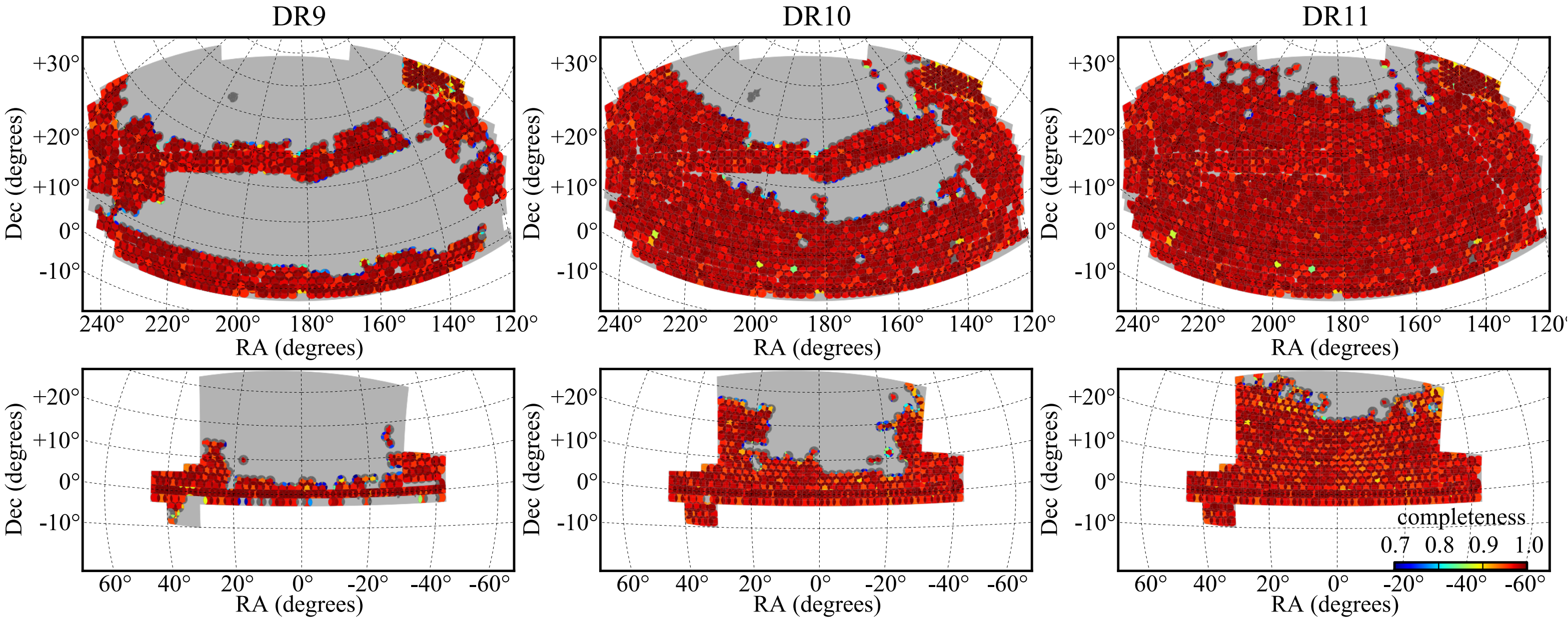
LOWZ z~0.32

CMASS z~0.57

Larger V_{survey} & Higher n_{gal}

Better Statistics!

Huge improvement of ‘CMASS’ from DR9 to DR11



	DR9	DR11
# of galaxies	264,283	690,827
Area [deg^2]	3,275	8,498
V_{eff} [$(\mathrm{Gpc}/h)^3$]	0.75 →	2.31

$$\boxed{\Delta P(k)_{\mathrm{DR9}}/\Delta P(k)_{\mathrm{DR11}} \sim 1.75}$$

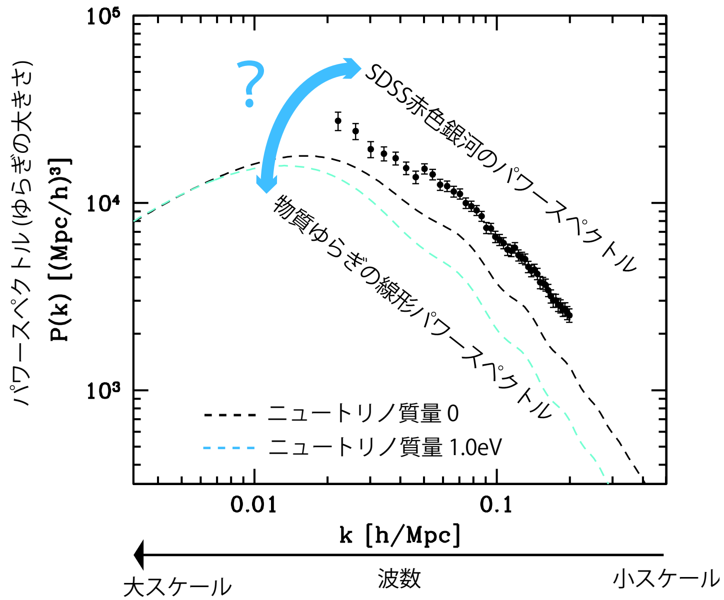
when	July, 2012	Dec, 2014

Nonlinear Issues in modeling P(k)

- Accurate prediction of the nonlinear galaxy P(k) is necessary:

gravitational evolution $\cancel{\delta_{\rm m} \ll 1}$

e.g., Taruya, Bernardeau, Nishimichi (2012)



redshift space distortions:

$$J \simeq \left(1 + \frac{\partial}{\partial z}\left[\frac{\vec{v}\cdot\hat{z}}{aH(a)}\right]\right)^{-1}$$

Taruya, Nishimichi, S.S. (2010), Nishimichi & Taruya (2012), Taruya et al. (2013)
Matsubara (2008a, 2008b, 2011, 2013)
Seljak & McDonald (2012), Okumura et al. (2012a, 2012b), Vlah et al. (2012,2013)
Reid & White (2010), Carlson et al. (2012), Wang et al. (2013)

galaxy bias $\delta_{\rm g}/\delta_{\rm h} \leftrightarrow \delta_{\rm m}$

$$\delta_{\rm g}(k) = b_0 \frac{1 + A_1 k^2}{1 + A_0 k}\delta_{\rm m}(k)$$

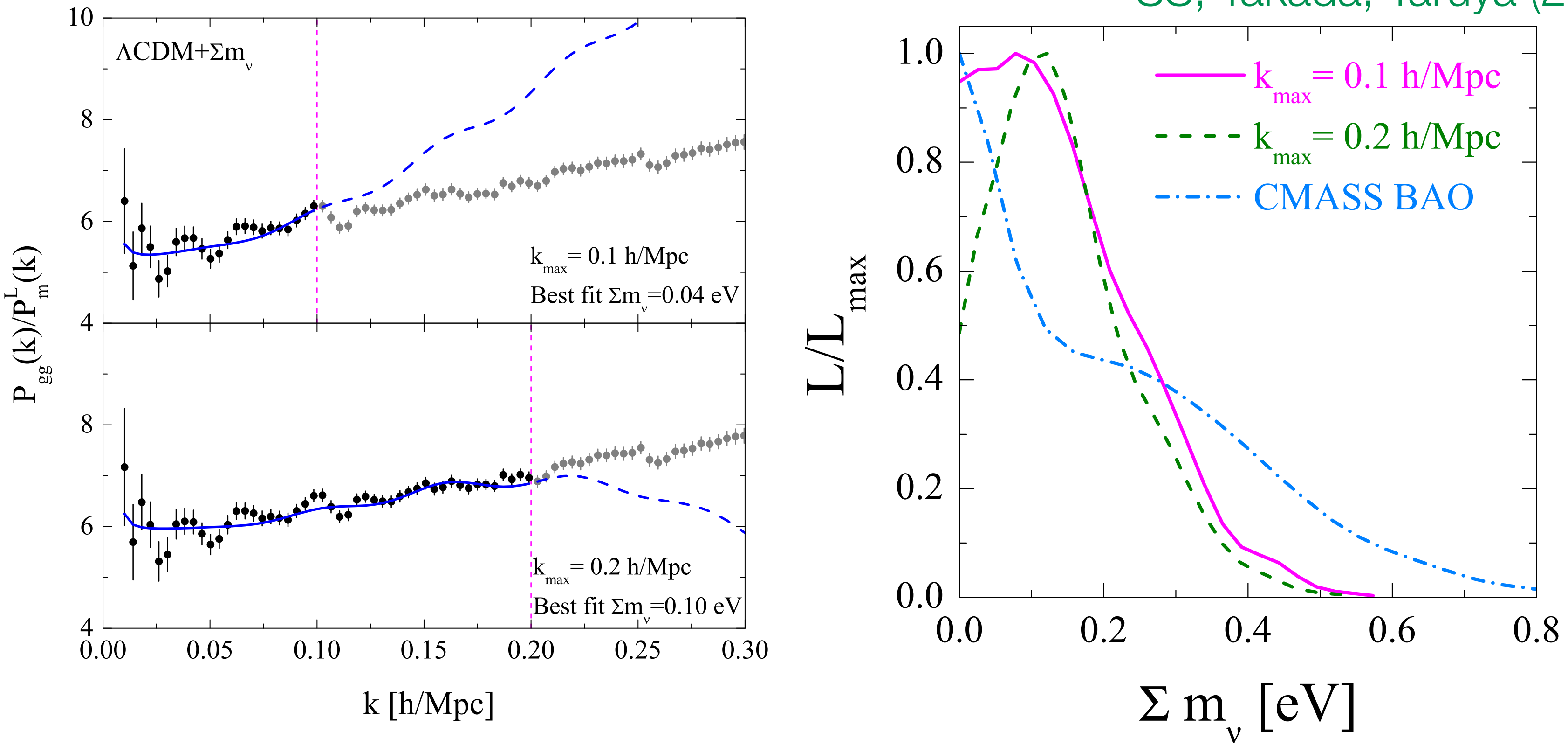
e.g. Nishimichi & Taruya (2011), Oka, S.S. et al. (2013)

DR9 analysis to use ‘shape’

G. Zhao, SS et al. (2013)

- Use just monopole. Model is based on Perturbation Theory.

SS, Takada, Taruya (2008,2010)



- combined with WMAP5

LCDM $\sum m_\nu < 0.34\,\mathrm{eV}\ (95\%\ \mathrm{C.L.})$

general $\sum m_\nu < 0.82\,\mathrm{eV}\ (95\%\ \mathrm{C.L.})$

Want to do for DR11 but…

SS et al., in prep

- BAO paper has not investigated LCDM + Σmν

- We could do but I personally don't want to redo the same thing…

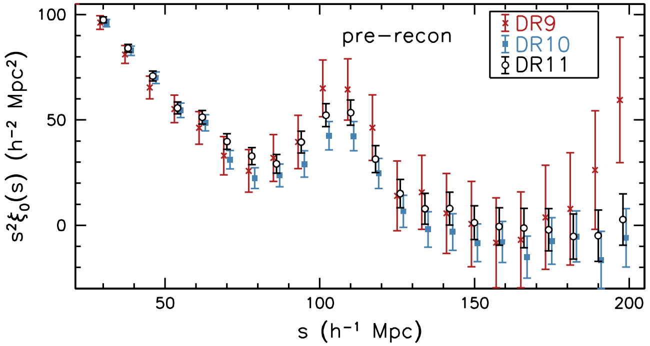
  - a lot of rooms to improve our modeling

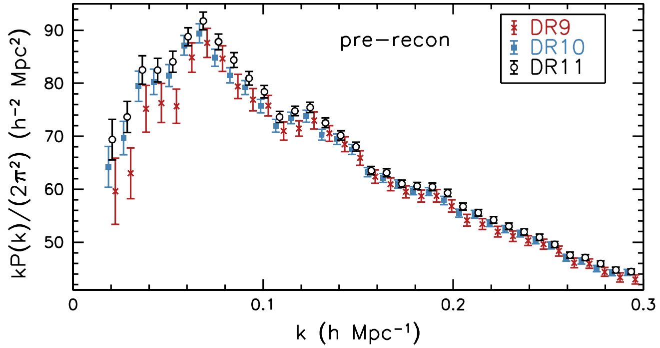
  - now can be compared in detail against simulations with neutrinos

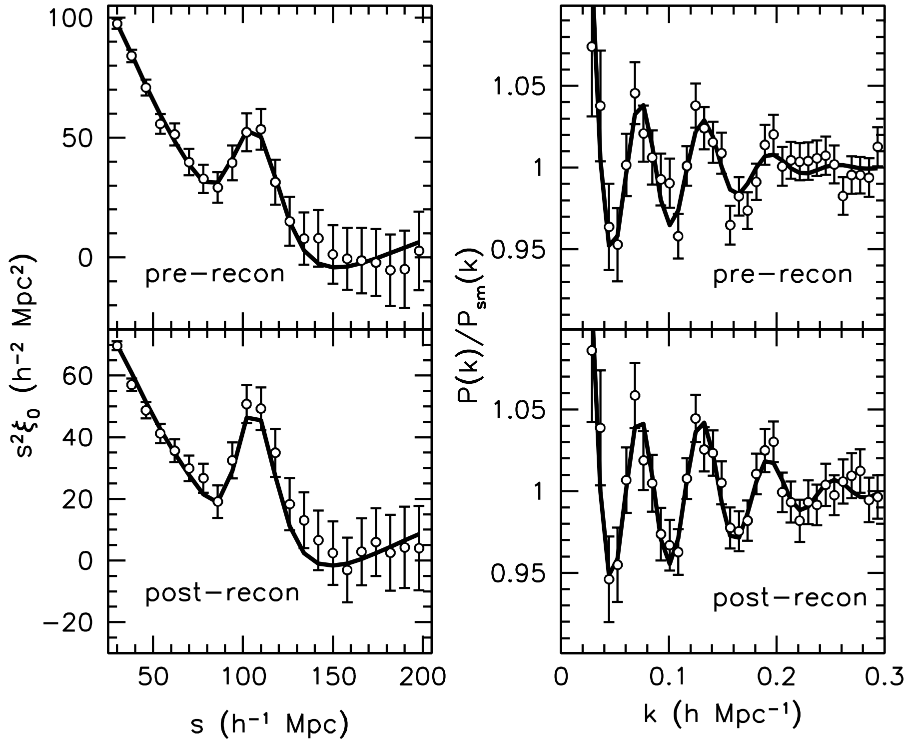
  - need to check if our model can return the input value of Σmν

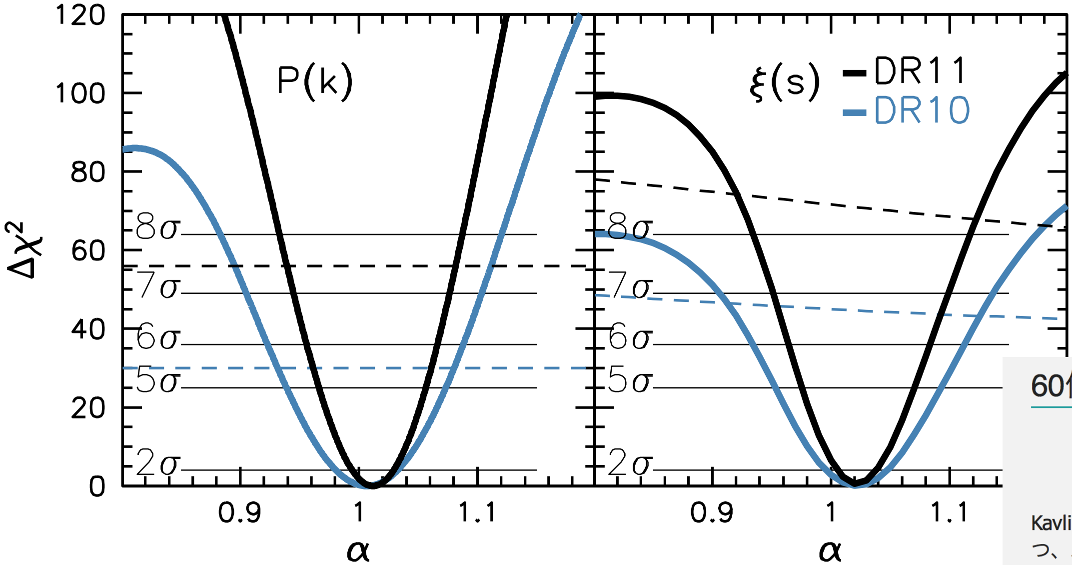
- Stay tuned!

1% measurement of cosmological distance!









DR11 detects BAO at **>7σ** level!

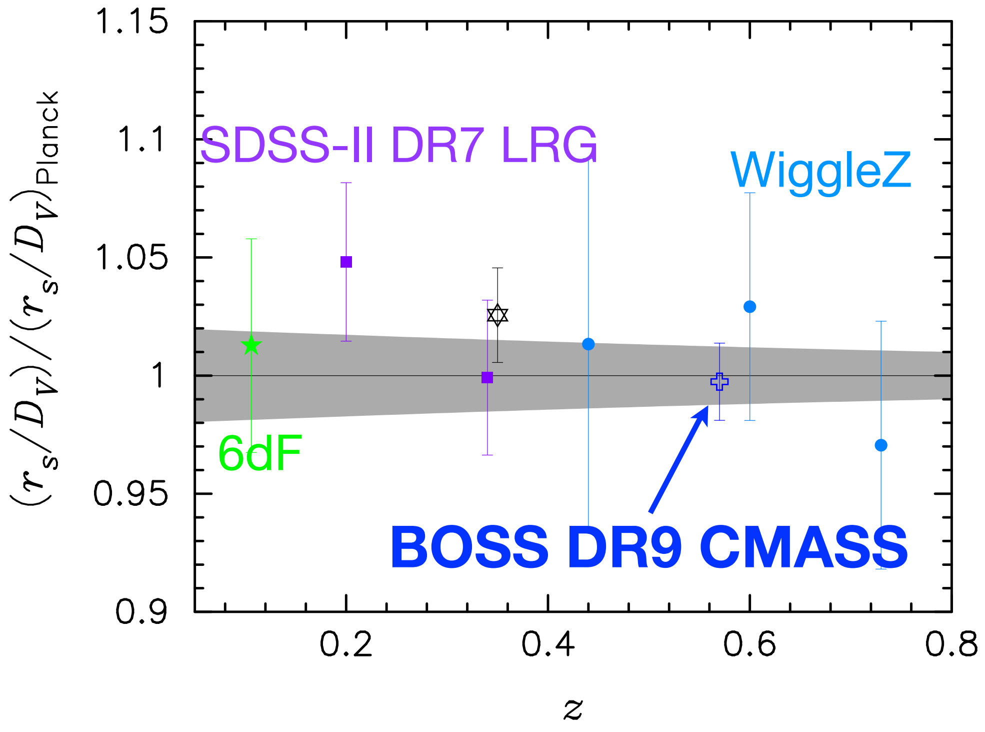
60億光年彼方まで、1%の精度で距離を測定

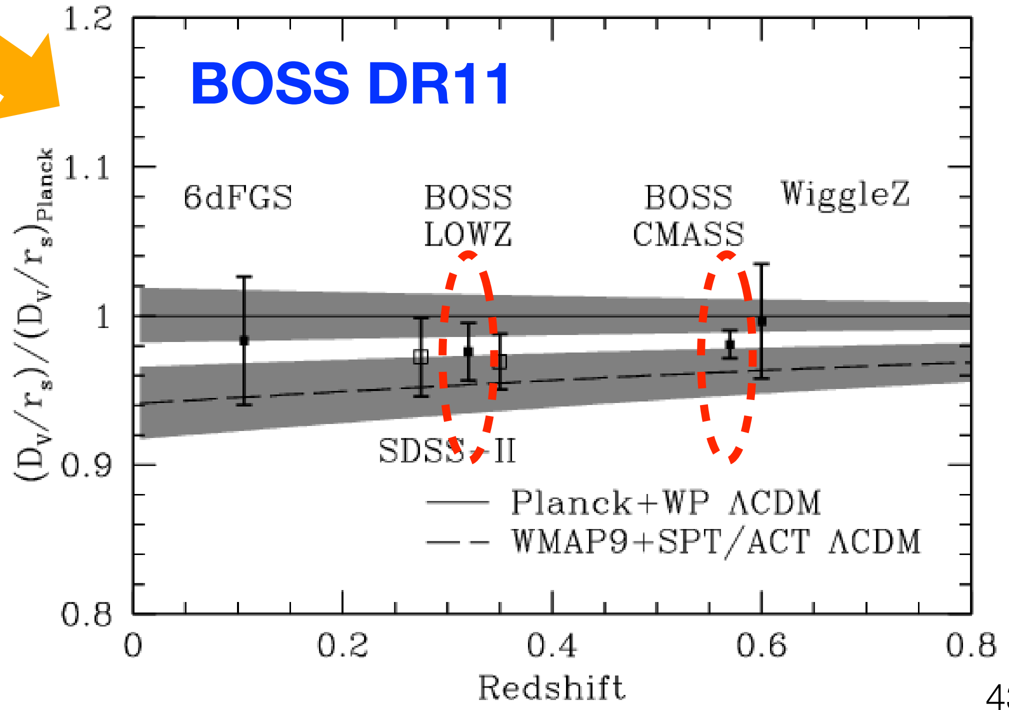
2014年1月9日
東京大学国際高等研究所 カブリ数物連携宇宙研究機構（Kavli IPMU）

Kavli IPMUが参加しているスローン・デジタル・スカイ・サーベイ III （SDSS-III）の4つのプログラムのひとつ、バリオン音響振動分光サーベイ (Baryon Oscillation Spectroscopic Survey; BOSS) のチームは、60億光年彼方にある銀河までの距離を誤差1%の精度で測定したことを2014年1月8日、米国ワシントンDCで開催中の米国天文学会において発表しました。この高精度の測定は、宇宙の真空を満たし、宇宙を加速膨張させている謎の「暗黒エネルギー」の正体の解明につながると期待されています。

In a flat ΛCDM universe

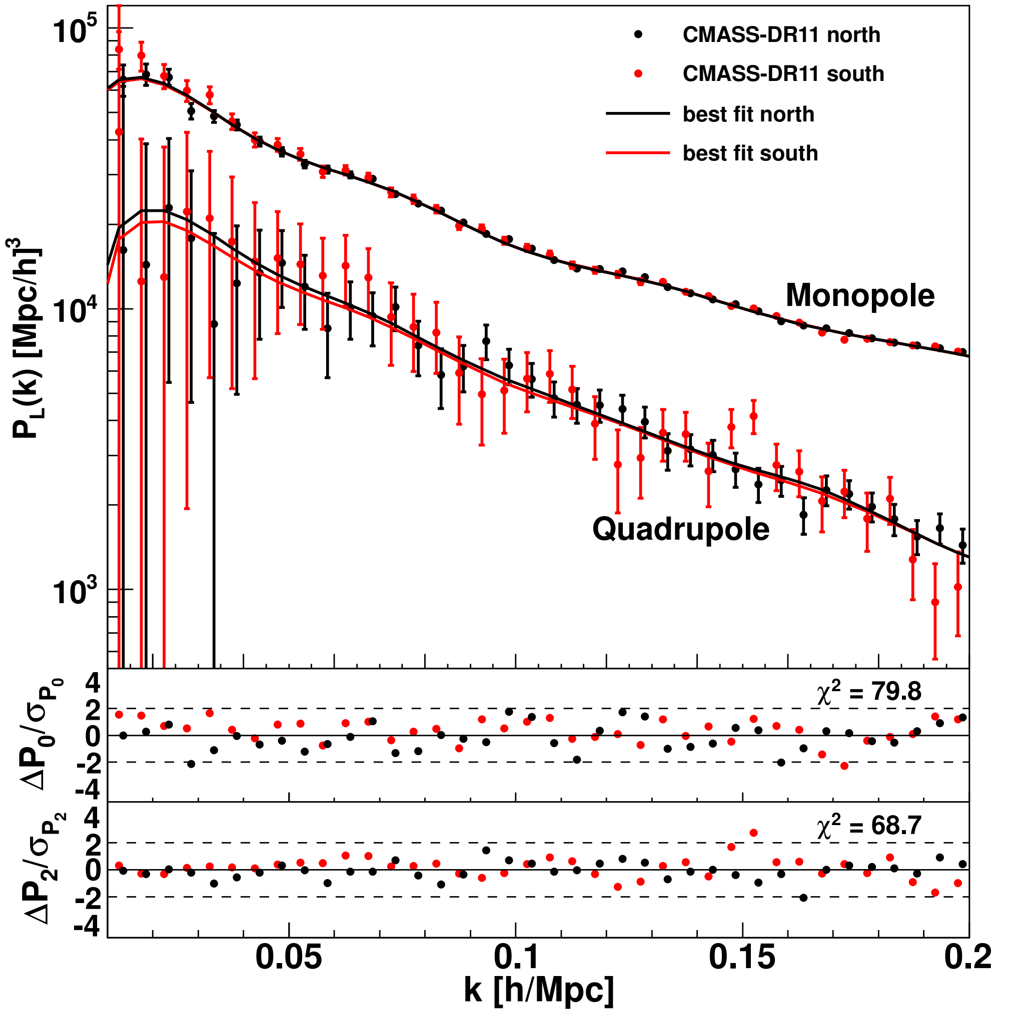
Planck collaboration XVI (2013)

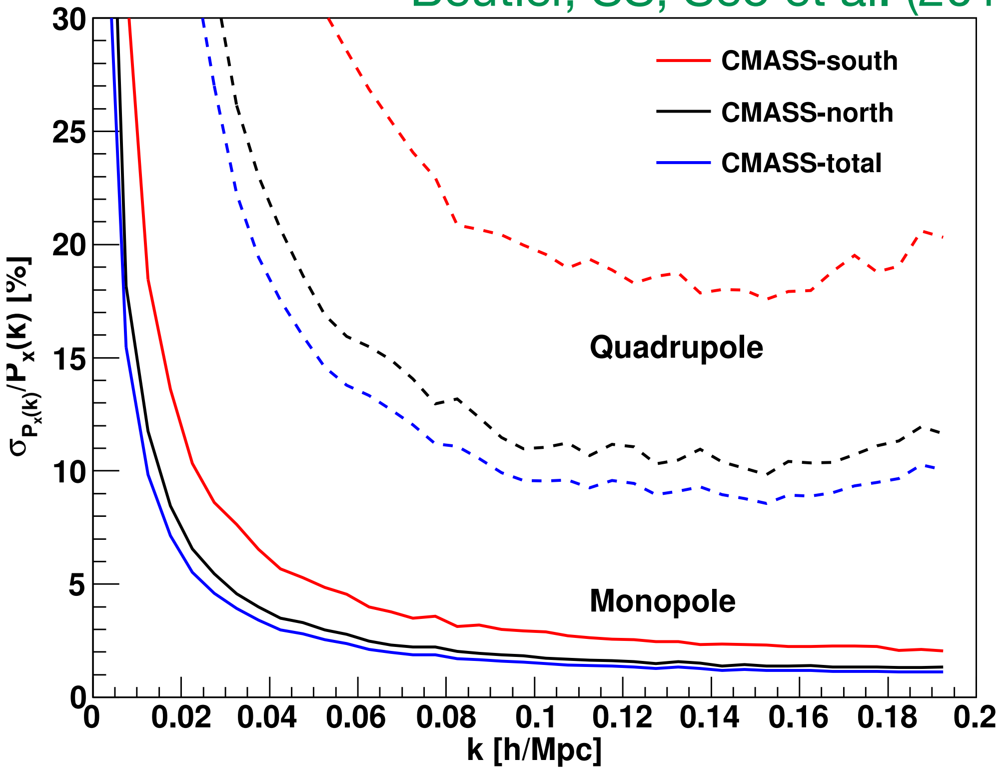




The first measurement of the BOSS $P_\ell(k)$

Beutler, SS, Seo et al. (2013)





- These are the anisotropic P(k) firstly measured in the BOSS sample.
- Impressive precision level! **~1%** for monopole & **~10%** for quadrupole.
- The difference b/w **north** and **south** is due to the survey window.

Performance of our model

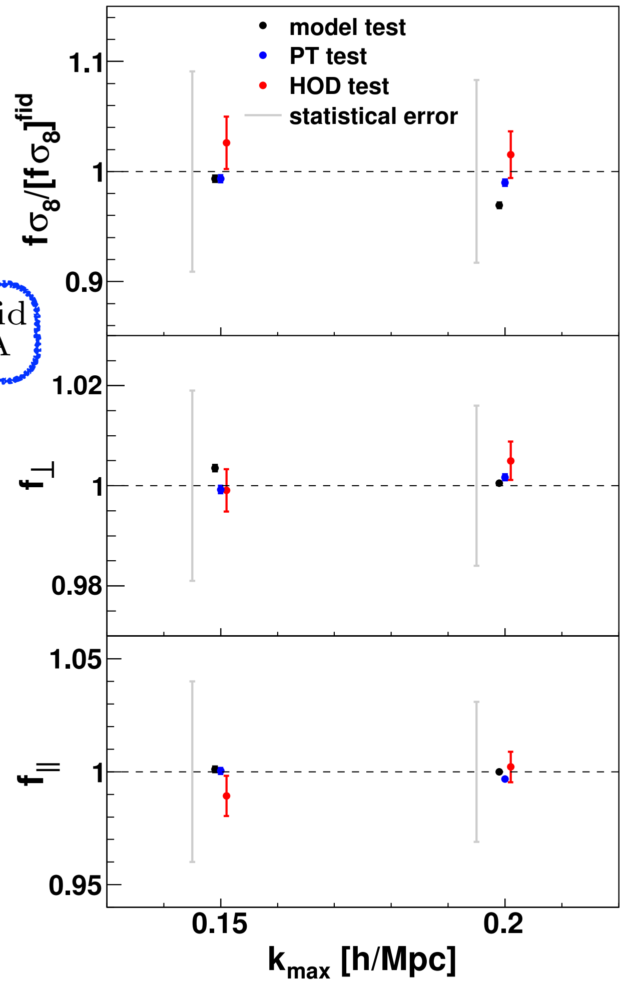
✔ Against mock catalog (LCDM simulation+HOD)

✔ 7 Free parameters $z_{\rm eff} = 0.57$

- parameters of interest: $\boxed{f\sigma_8, f_\perp = H^{\rm fid}/H, f_\parallel = D_{\rm A}/D_{\rm A}^{\rm fid}}$
- galaxy bias: b_1, b_2, N
- FoG suppression: $\sigma_{\rm v}$

✔ Passed 3 types of tests

- our fiducial model (also WMAP/Planck)
- PT uncertainties in theoretical modeling
- HOD uncertainties in mock catalog

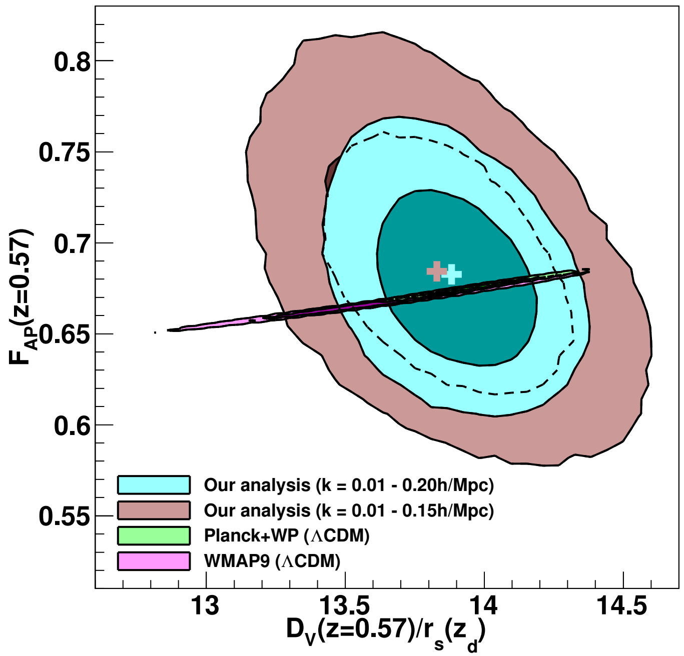


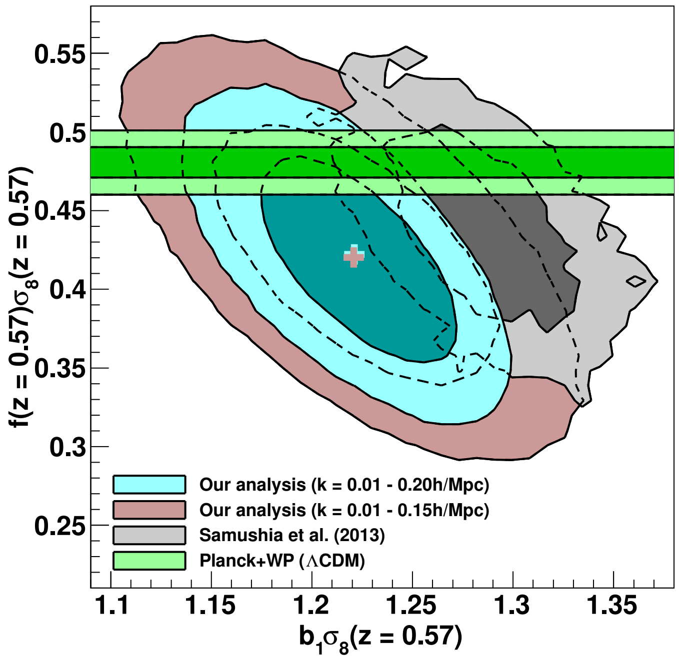
source	$f_\parallel$ $[H(z_{\rm eff})]$		$f_\perp$ $[D_A(z_{\rm eff})]$		$f(z_{\rm eff})\sigma_8(z_{\rm eff})$	
$k_{\rm max}$ $[h/{\rm Mpc}]$	0.15	0.20	0.15	0.20	0.15	0.20
model test	$0.11 \pm 0.13\%$	$0.00 \pm 0.10\%$	$0.352 \pm 0.061\%$	$0.052 \pm 0.049\%$	$-0.66 \pm 0.29\%$	$-3.08 \pm 0.26\%$
PT test	$0.04 \pm 0.14\%$	$-0.32 \pm 0.12\%$	$-0.075 \pm 0.074\%$	$0.168 \pm 0.060\%$	$-0.65 \pm 0.33\%$	$-1.01 \pm 0.30\%$
HOD test	$-1.07 \pm 0.89\%$	$0.21 \pm 0.67\%$	$-0.09 \pm 0.42\%$	$0.50 \pm 0.38\%$	$2.6 \pm 2.4\%$	$1.5 \pm 2.1\%$
statistical error	4.0%	3.1%	1.9%	1.6%	9.1%	8.3%

Results

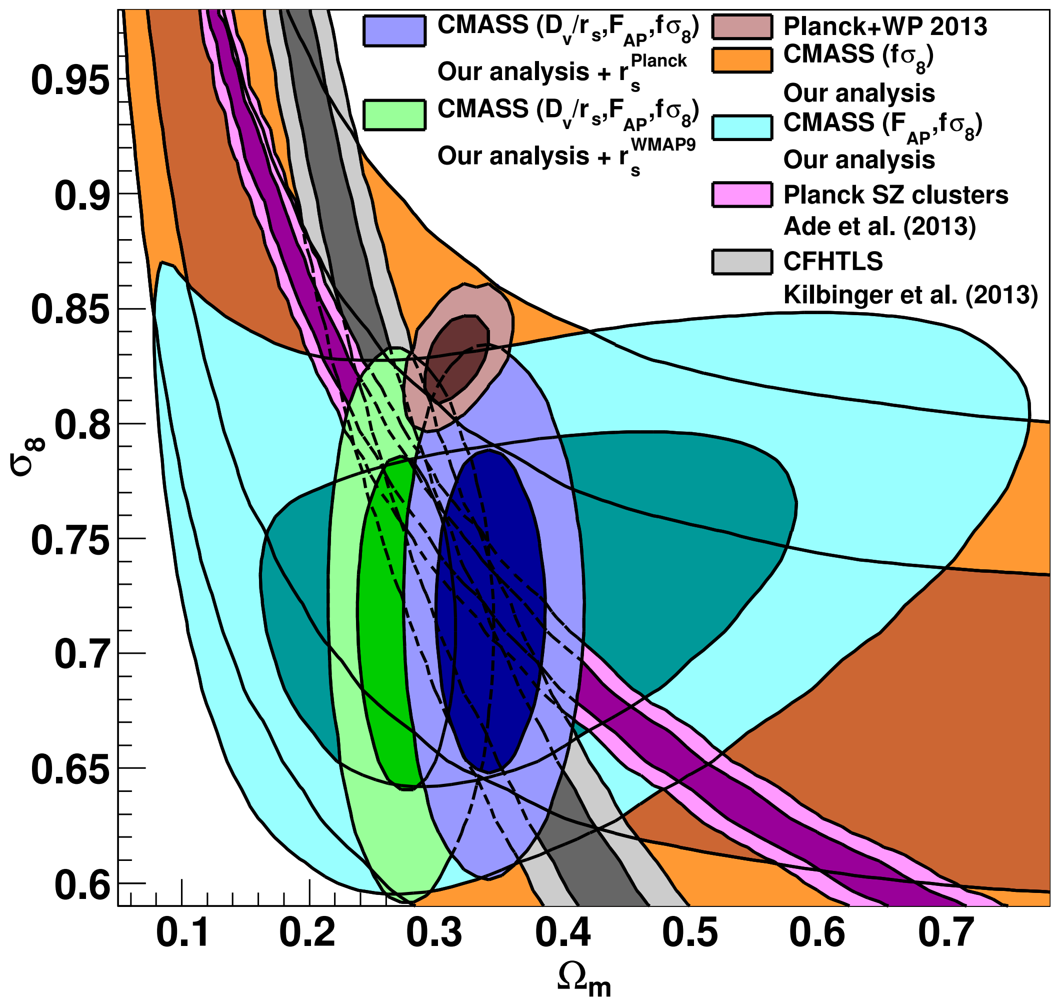
fitting range	0.01 - 0.15h/Mpc		0.01 - 0.20h/Mpc	
	best fit	mean $\pm 1\sigma$	best fit	mean $\pm 1\sigma$
$f_{\parallel}$	1.008	1.005 ± 0.057	1.014	1.018 ± 0.036
$f_{\perp}$	1.026	1.029 ± 0.023	1.029	1.029 ± 0.015
$f(z_{\rm eff})\sigma_8(z_{\rm eff})$	0.420	0.423 ± 0.052	0.422	$0.419 \pm (\overset{\rm stat}{0.042} + \overset{\rm sys}{0.014})$
$b_1\sigma_8(z_{\rm eff})$	1.221	1.222 ± 0.044	1.221	1.224 ± 0.031
$b_2\sigma_8(z_{\rm eff})$	1.7	0.7 ± 1.2	-0.21	-0.09 ± 0.62
σ_v	4.6 Mpc/h	4.3 ± 1.3 Mpc/h	4.63 Mpc/h	4.65 ± 0.81 Mpc/h
N	1030 [Mpc/h]^3	1080 ± 620 [Mpc/h]^3	1890 [Mpc/h]^3	1690 ± 600 [Mpc/h]^3
$D_V(z_{\rm eff})/r_s(z_d)$	13.83	13.85 ± 0.27	13.88	13.89 ± 0.18
$F_{\rm AP}(z_{\rm eff})$	0.684	0.686 ± 0.046	0.683	0.679 ± 0.031
$H(z_{\rm eff})r_s(z_d)/r_s^{\rm fid}(z_d)$	94.0 km/s/Mpc	94.1 ± 5.4 km/s/Mpc	93.5 km/s/Mpc	93.1 ± 3.3 km/s/Mpc
$D_A(z_{\rm eff})r_s^{\rm fid}(z_d)/r_s(z_d)$	1385 Mpc	1389 ± 31 Mpc	1389 Mpc	1388 ± 22 Mpc
β	0.344	0.346 ± 0.043	0.346	0.342 ± 0.037
$b_1 \times (0.8/\sigma_8)$	2.035	2.037 ± 0.073	2.035	2.040 ± 0.052
$b_2 \times (0.8/\sigma_8)$	2.8	1.2 ± 2.0	-0.4	-0.2 ± 1.0

low!!





Consistency check in ΛCDM+GR



Planck: large Ω_m & large σ_8

tension!!

Other low-z LSS measures

CMASS RSD only

RSD + AP (aniso)

RSD + AP (iso+aniso)

Weak lensing CFHTLS

Cluster Planck SZ

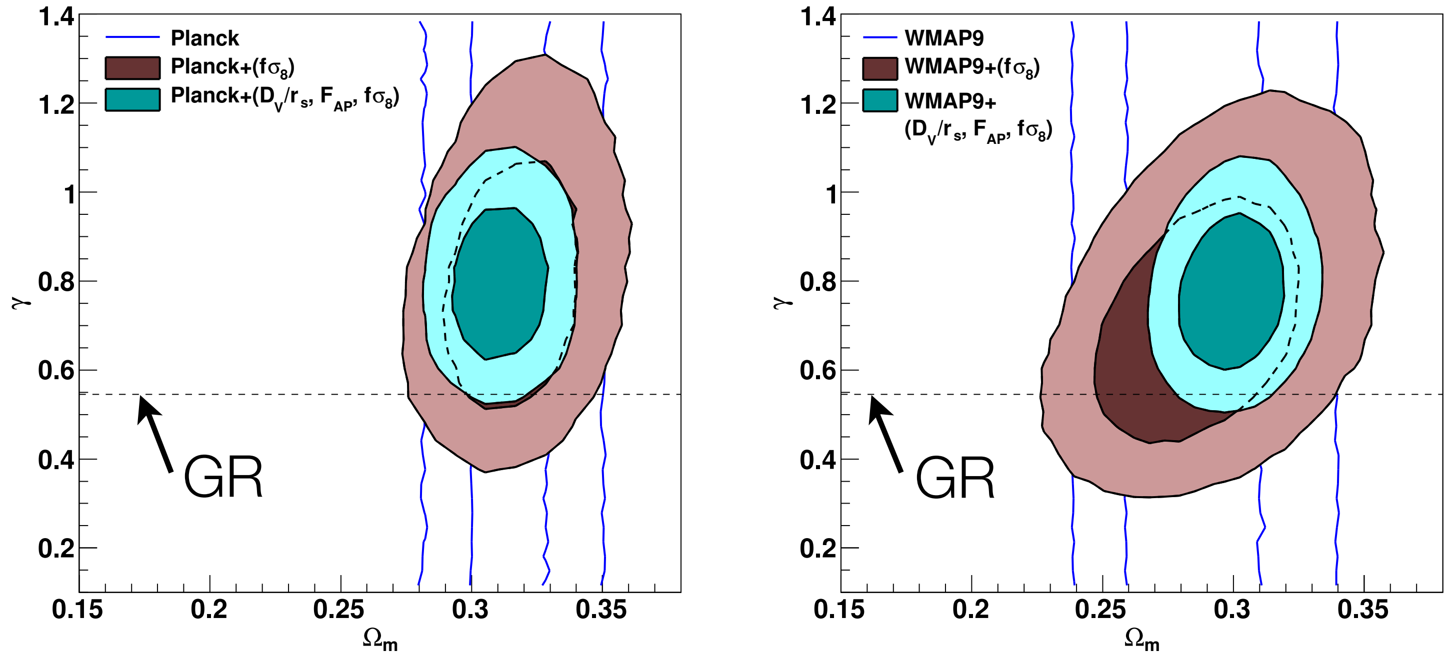
- This could suggest to extend cosmology to reduce σ_8 by 10%

$$\sum m_\nu \sim 0.2\,\mathrm{eV}$$ **~5% ↓**

$$N_{\rm eff} \sim 4$$ **~5% ↓**

Abandon GR?

$$f = \Omega_\mathrm{m}(z)^\gamma \qquad \gamma = 0.545 \text{ (GR)}$$



- Interestingly, RSD+AP leads to larger γ, i.e., **weaker gravity than GR at ~2σ level**, independently of the CMB prior choice

- Remark that this is just a LCDM+GR consistency check!
  In general, model-dependent analysis would be necessary

e.g., Taruya et al. 2013

Summary

- The low redshift measurements are necessary to break CMB limit to constrain the neutrino mass

- Galaxy survey provides us a unique opportunity to measure
  - distance from BAO
  - growth from P(k) shape & RSD

- Given the discrepancy b/w WMAP & Planck, it seems early to conclude anything.