Cosmology with the Baryon Oscillation Spectroscopic Survey (BOSS)

Florian Beutler

Collaborators: Shun Saito, Hee-Jong Seo + BOSS collaboration

June, 2014

Lawrence Berkeley National Lab

Outline of the talk

- Part I:
  - The BOSS-CMASS sample.
  - What are Baryon Acoustic Oscillations?
  - What is the Alcock-Paczynski effect?
  - What are redshift-space distortions?
  - The CMASS power spectrum multipoles.
  - Constraining σ_8.
- Part II:
  - Constraints on the neutrino mass.

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- CMASS: $0.43 < z < 0.7$
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- The effective volume is $6\,\mathrm{Gpc}^3$ for CMASS and $2.4\,\mathrm{Gpc}^3$ for LOWz.
- DR9: 3275 deg^2
-
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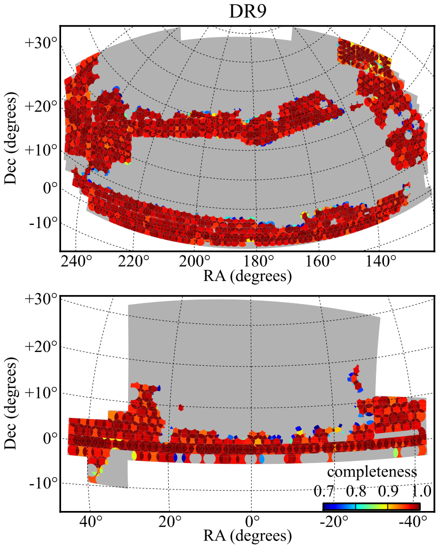

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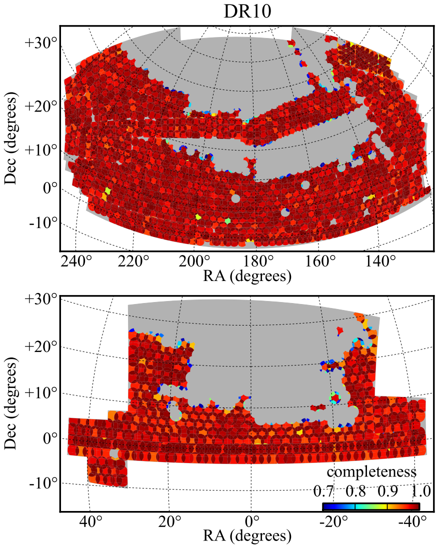

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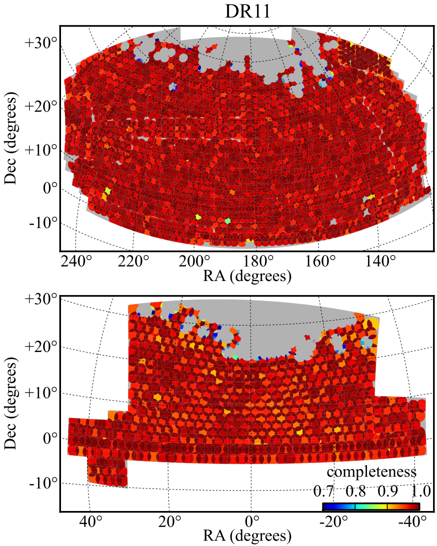
- DR11: 8509.6 deg^2



The correlation function is defined via the excess probability of finding a galaxy pair at separation r:

$$dP = \overline{n}^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

→ The correlation function measures the degree of clustering on different scales.

In practice we just count galaxy pairs:

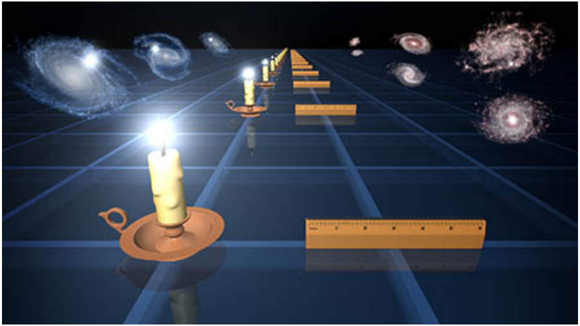
$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

The correlation function and the power spectrum are just Fourier transforms of each other

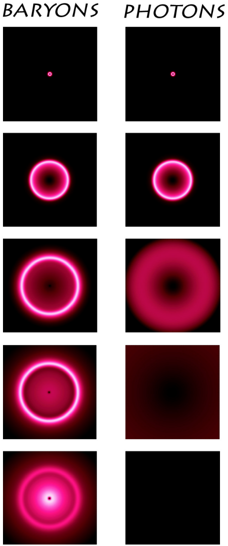
$$P(k) = \int \xi(r) \exp(ik \cdot r) d^3 r$$

$$\xi(r) = \frac{1}{(2\pi)^3} \int P(k) \exp(-ik \cdot r) d^3 k$$

Part I, What are Baryon Acoustic Oscillations?



credit: Nasa



- Preferred distance scale between galaxies as a relict of sound waves in the early Universe.
- Can be used as a standard ruler.
- The systematic errors are far below the current statistical errors.

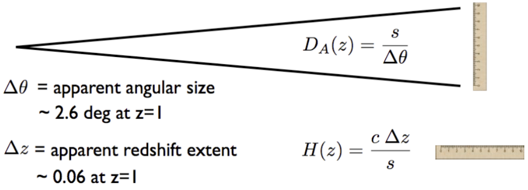
credit: Martin White

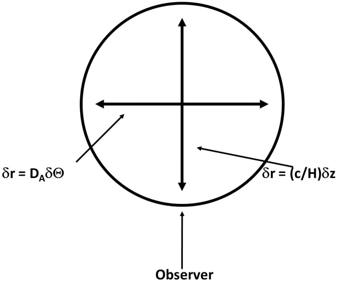
The BAO signal is expected to be isotropic. However, the fiducial cosmological model, which we used to transfer the observables into co-moving distances affects the radial distance differently than the angular distance.

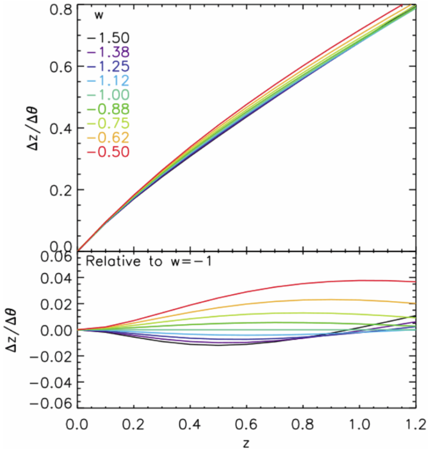
The radial BAO signal is given by $H(z) = c\Delta z/s$.

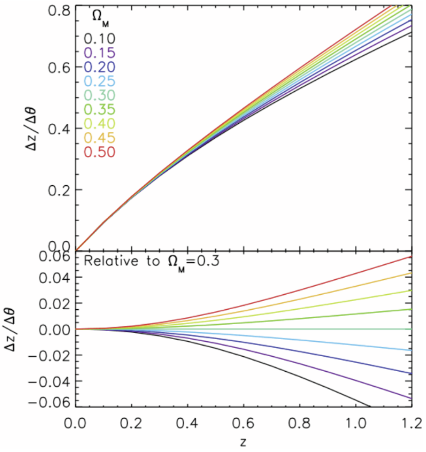
The tangential BAO signal is given by $D_A(z) = s/\Delta\theta$.

$\rightarrow \delta z/\delta\theta \sim D_A(z)H(z) \sim F_{\rm AP}$







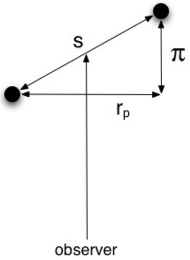


$$\Omega_\Lambda/(1+z)^{1+w}$$

$$H(z) = H_0\left[\Omega_m/(1+z)^{-3} + \Omega_{\rm DE}/(1+z)^{-3(1+w)}\right]^{1/2}.$$

The redshift of a galaxy has two velocity components which we can't distinguish

$$\vec{s} = \vec{r}\left(1 + \frac{u(\vec{r})}{r}\right).$$



The effect is proportional to the growth rate

$$\frac{f(z)}{b_1} = \frac{\Omega_m^{0.55}(z)}{b_1}$$

f = growth rate, b_1 = linear bias, $\Omega_m = \frac{\rho_m}{\rho_0}$

Part I, What are redshift space distortions?

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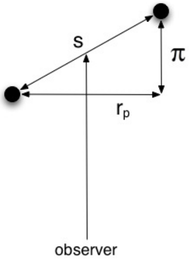

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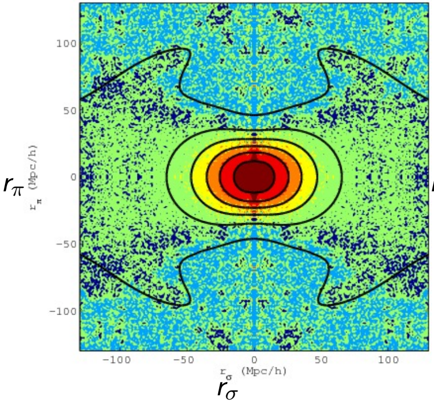
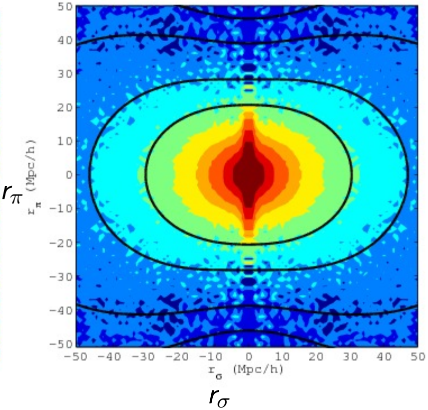
The matter clustering is normalized by the r.m.s. mass fluctuation amplitude in spheres of $8\,\mathrm{Mpc}/h$ (σ_8). Since we only measure the galaxy clustering we are sensitive to $b_1\sigma_8$ and therefore our observable is

$$b_1\sigma_8 \times \frac{f(z)}{b_1} = f(z)\sigma_8$$

Part I, What are redshift space distortions?



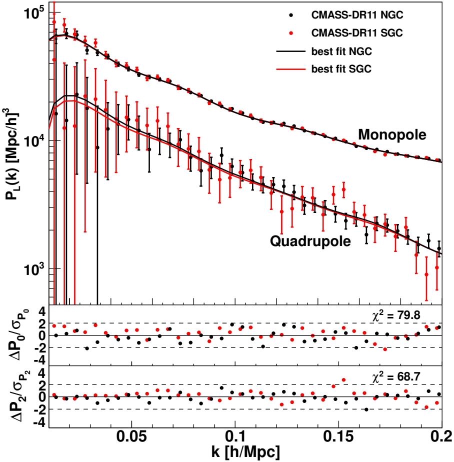


Reid et al. (2012)

Part I, Power spectrum measurement

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\; P(k,\mu)\mathcal{L}_\ell(\mu)$$

Power spectrum estimator by Yamamoto et al. (2005)

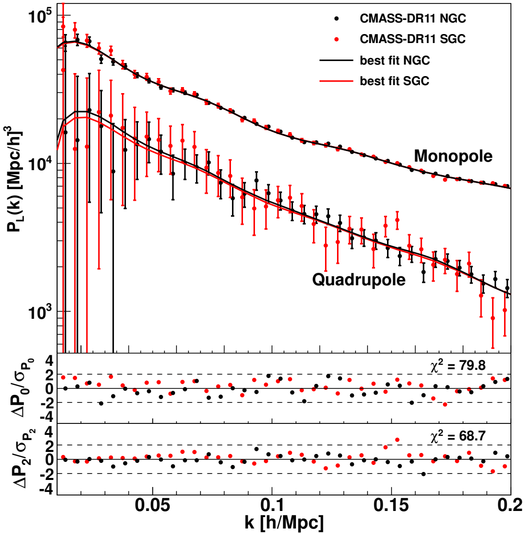


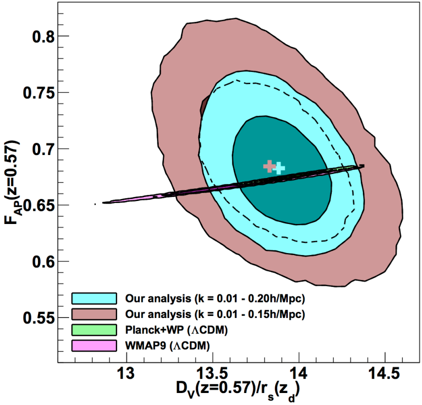
Our power spectrum model is based on renormalized perturbation theory (Taruya et al. 2011, McDonald & Roy 2009)

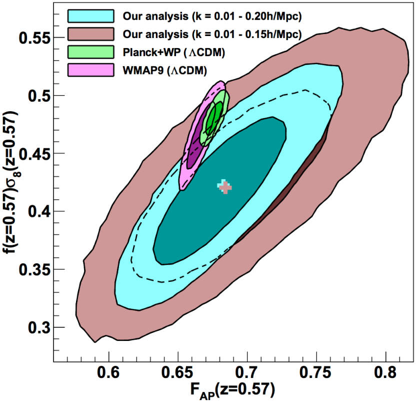
$$\begin{aligned} P_{\rm g}(k,\mu) = \exp\left\{-(fk\mu\sigma_v)^2\right\}\big[&P_{\rm g,\delta\delta}(k) \\ &+ 2f\mu^2 P_{\rm g,\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) \\ &+ b_1^3 A(k,\mu,\beta) + b_1^4 B(k,\mu,\beta)\big], \end{aligned}$$

with

$$\begin{aligned} P_{\rm g,\delta\delta}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) \\ &+ 2b_{\rm 3nl} b_1 \sigma_3^2(k) P_{\rm m}^{\rm L}(k) + b_2^2 P_{b22}(k) \\ &+ 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + N, \\ P_{\rm g,\delta\theta}(k) &= b_1 P_{\delta\theta}(k) + b_2 P_{b2,\theta}(k) + b_{s2} P_{bs2,\theta}(k) \\ &+ b_{\rm 3nl}\sigma_3^2(k) P_{\rm m}^{\rm lin}(k), \end{aligned}$$


CMASS-DR11 NGC
CMASS-DR11 SGC
best fit NGC
best fit SGC
Monopole
Quadrupole
$P_L(k)$ [Mpc/h]^3
10^5
10^4
10^3
$\Delta P_0/\sigma_{P_0}$
χ^2 = 79.8
$\Delta P_2/\sigma_{P_2}$
χ^2 = 68.7
0.05
0.1
0.15
0.2
k [h/Mpc]


0.8
0.75
0.7
0.65
0.6
0.55
$F_{AP}(z=0.57)$
13
13.5
14
14.5
$D_V(z=0.57)/r_s(z_d)$
Our analysis (k = 0.01 - 0.20h/Mpc)
Our analysis (k = 0.01 - 0.15h/Mpc)
Planck+WP (ΛCDM)
WMAP9 (ΛCDM)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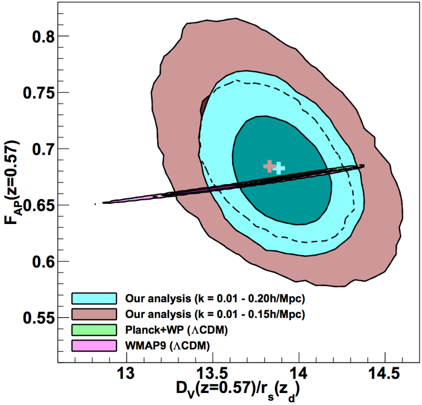
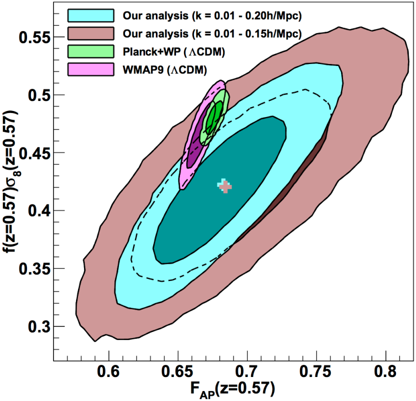
Planck+WP (ΛCDM)
WMAP9 (ΛCDM)
0.55
0.5
0.45
0.4
0.35
0.3
$f(z=0.57)\sigma_8(z=0.57)$
0.6
0.65
0.7
0.75
0.8
$F_{AP}(z=0.57)$





Let's remember that there is some tension here: Planck predicts $f(z = 0.57)\sigma_8(z = 0.57) = 0.481 \pm 0.010$

The BOSS-CMASS constraints are:

$$V^{\rm data} = \begin{pmatrix} D_V(z_{\rm eff})/r_s(z_d) \\ F_{\rm AP}(z_{\rm eff}) \\ f(z_{\rm eff})\sigma_8(z_{\rm eff}) \end{pmatrix} = \begin{pmatrix} 13.88 \\ 0.683 \\ 0.422 \end{pmatrix} \quad \begin{matrix} \pm 1.3\% \\ \pm 4.6\% \\ \pm 11\% \end{matrix}$$

where $F_{\rm AP}(z_{\rm eff}) = (1+z_{\rm eff})D_A(z_{\rm eff})H(z_{\rm eff})/c$ at the the effective redshift $z_{\rm eff} = 0.57$. The symmetric covariance matrix between these constraints is given by

$$10^3 C = \begin{pmatrix} 36.400 & -2.0636 & -1.8398 \\ & 1.0773 & 1.1755 \\ & & 1.8478 + 0.196 \end{pmatrix}$$

See Anderson et al. (2013) and Beutler et al. (2013)

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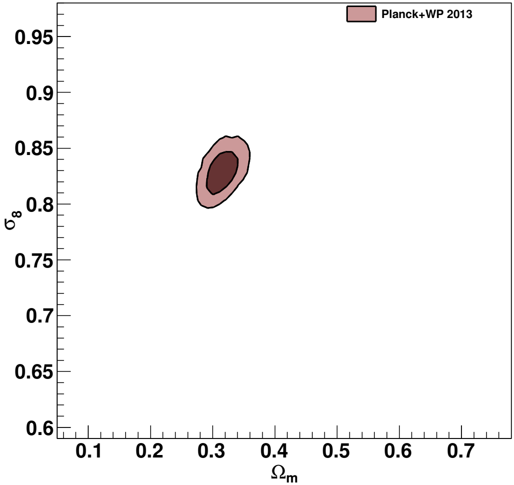
→ You can use these constraints to test your own favorite cosmological model.

Part I, σ_8-Ω_m likelihood



Planck: $\sigma_8 = 0.829 \pm 0.012$

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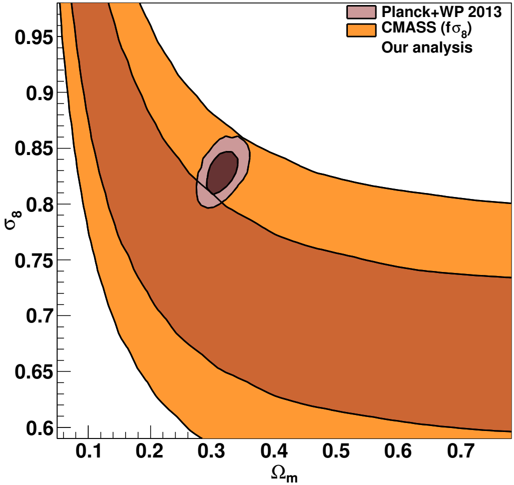

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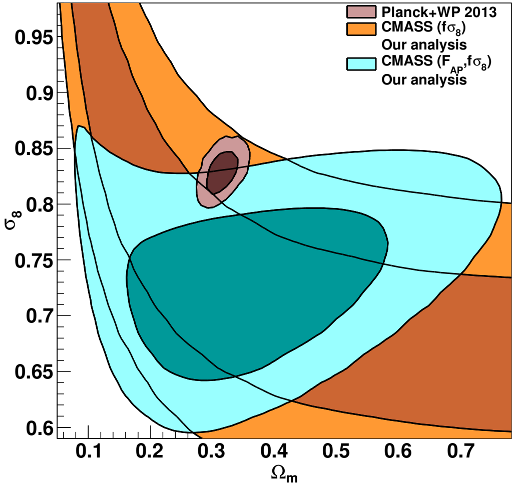

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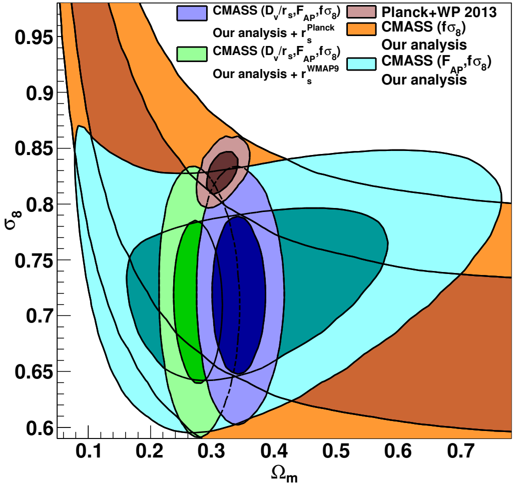

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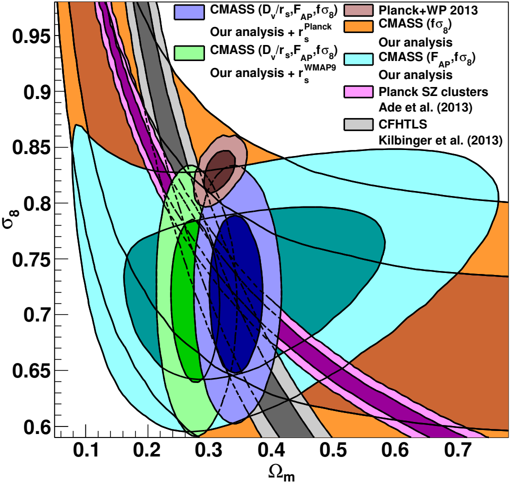

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The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Signs of neutrino mass in current cosmological datasets

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[2] *Kavli Institute for the Physics and Mathematics of the Universe (WPI),Todai Institues for Advanced Study, The University of Tokyo, Chiba 277-8582, Japan,*

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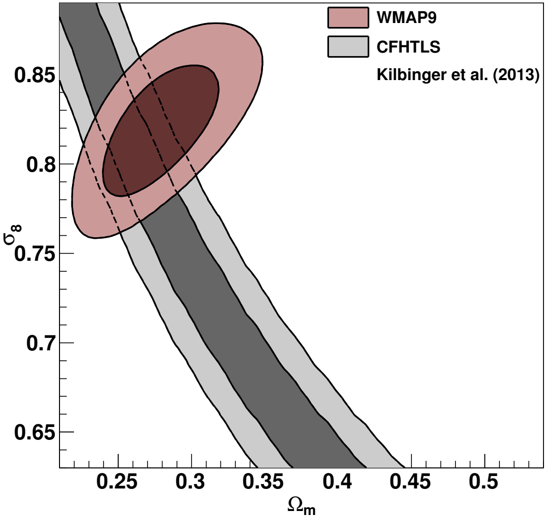
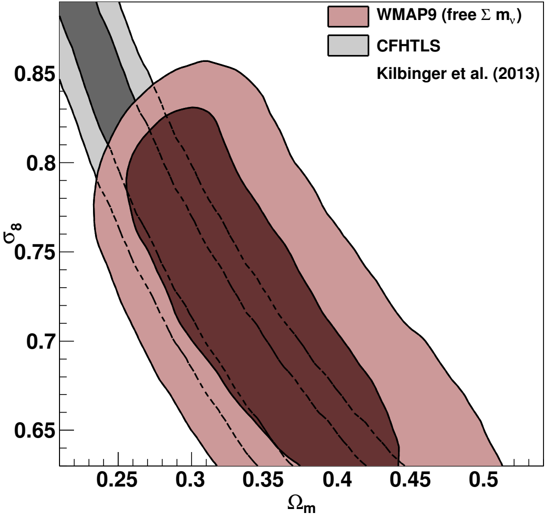
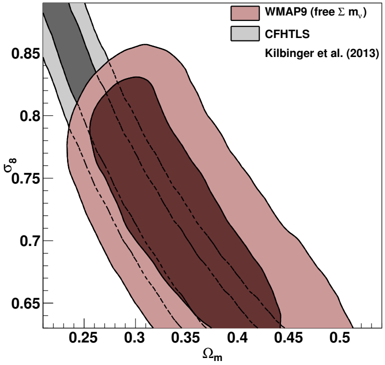
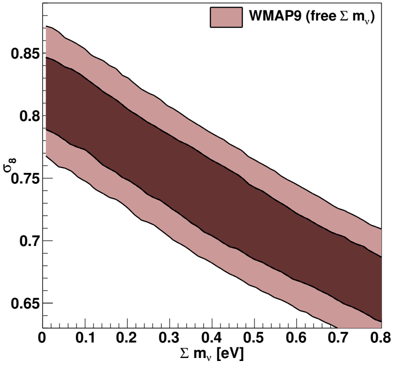
- Additional constraints come from gravitational lensing of the CMB.
- The remaining degeneracy can be broken by using low redshift σ_8 constraints.


WMAP9
CFHTLS
Kilbinger et al. (2013)
0.85
0.8
0.75
0.7
0.65
σ_8
0.25
0.3
0.35
0.4
0.45
0.5
Ω_m

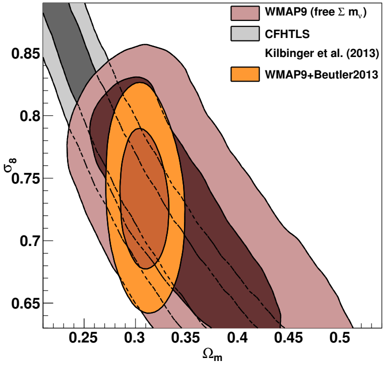
Part II, Neutrino mass constraints

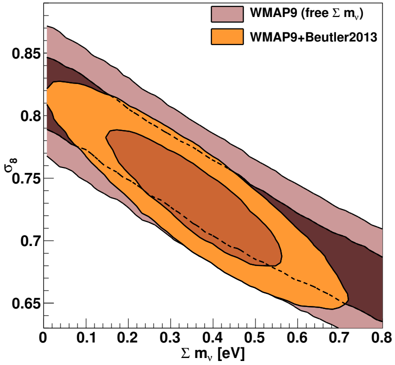




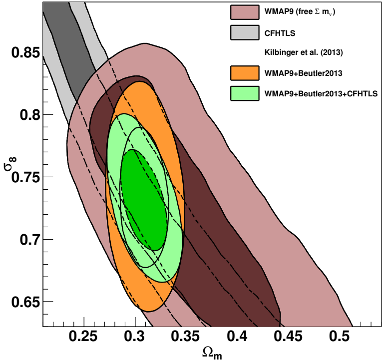


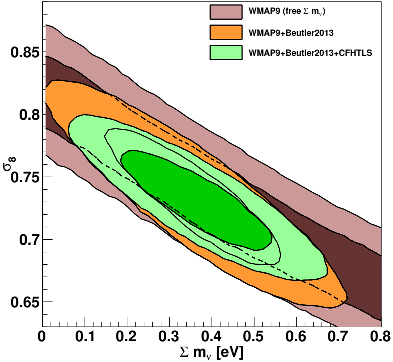
dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	95% c.l.
WMAP9	< 0.75	< 1.3



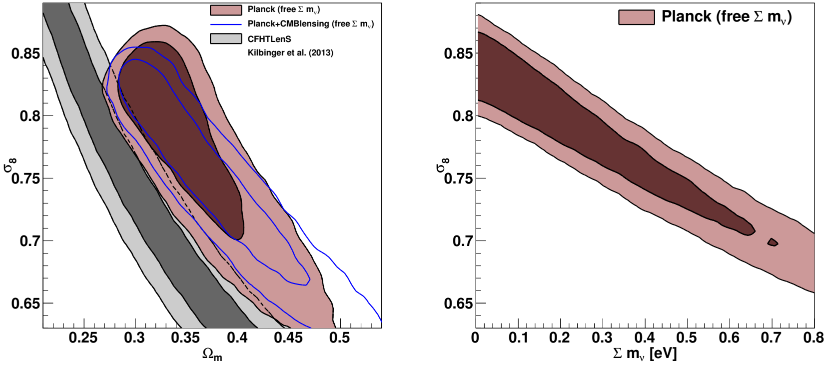


dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	95% c.l.
WMAP9	< 0.75	< 1.3
WMAP9+CMASS	0.36 ± 0.14	0.36 ± 0.28

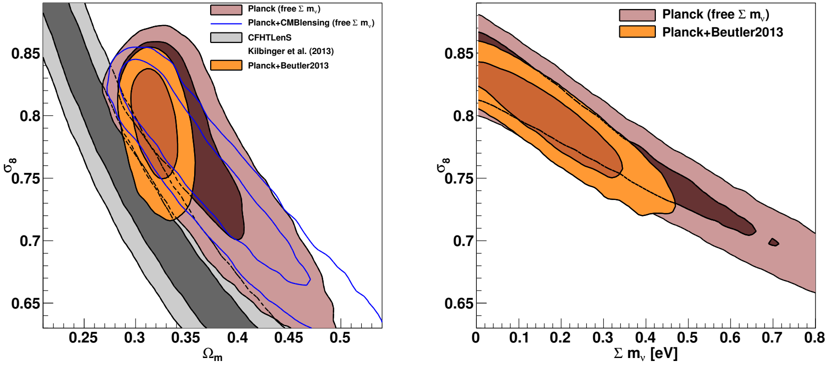




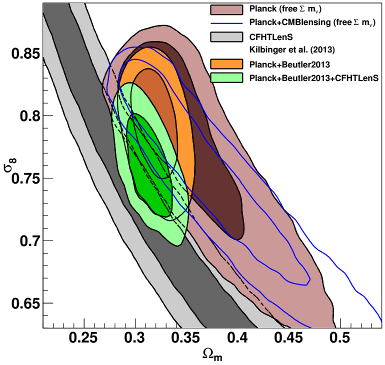
dataset(s)	$\sum m_\nu$ [eV]	
	68% c.l.	95% c.l.
WMAP9	< 0.75	< 1.3
WMAP9+CMASS	0.36 ± 0.14	0.36 ± 0.28
WMAP9+CMASS+CFHTLenS	0.37 ± 0.12	0.37 ± 0.24

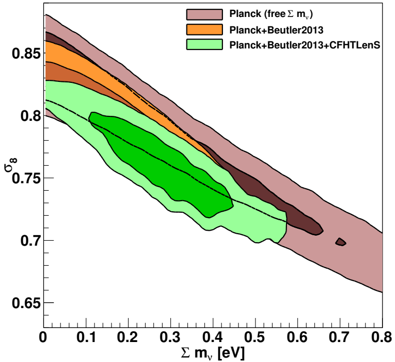


dataset(s)	$\sum m_\nu$ [eV]	
	68% c.l.	95% c.l.
Planck	< 0.41	< 0.95

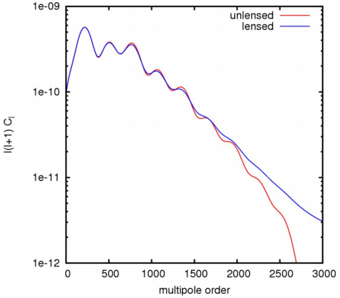


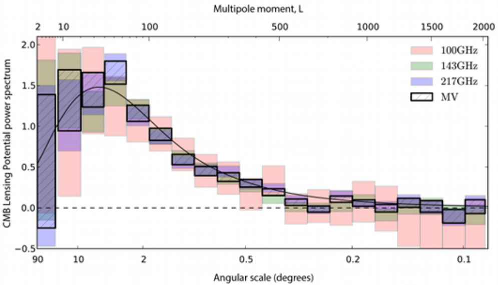
dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	95% c.l.
Planck	< 0.24	< 0.67
Planck+CMASS	0.20 ± 0.13	< 0.40



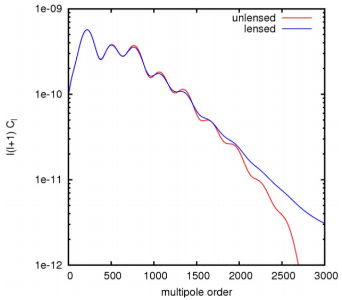


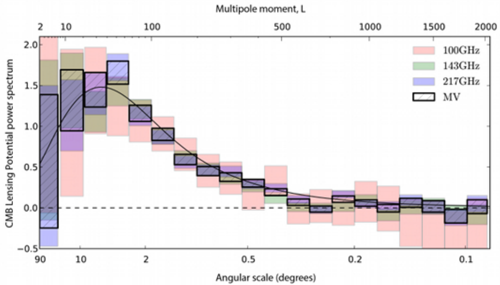
dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	95% c.l.
Planck	< 0.24	< 0.67
Planck+CMASS	0.20 ± 0.13	< 0.40
Planck+CMASS+CFHTLenS	0.29 ± 0.13	$0.29^{+0.29}_{-0.23}$





credit: Planck col.



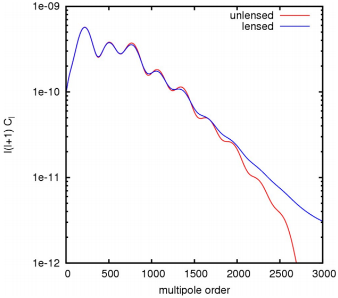


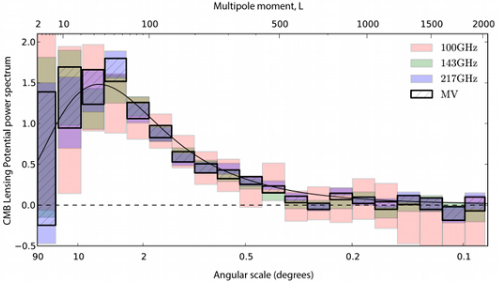
credit: Planck col.

$$T^{\text{lensed}}(\hat{n}) = T^{\text{unlensed}}(\hat{n} + \nabla\phi(\hat{n}))$$

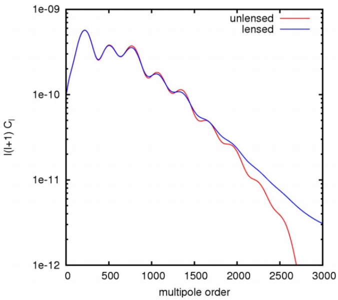
with the CMB lensing potential

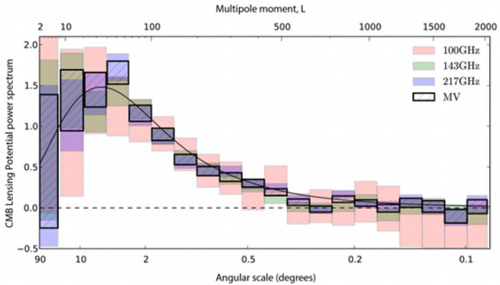
$$\phi(\hat{n}) = -2\int_0^{\chi(z_*)} d\chi \frac{\chi(z_*) - \chi}{\chi(z_*)\chi}\Psi(\chi\hat{n}, \eta_0 - \chi)$$





credit: Planck col.

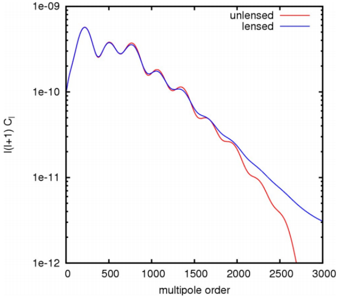


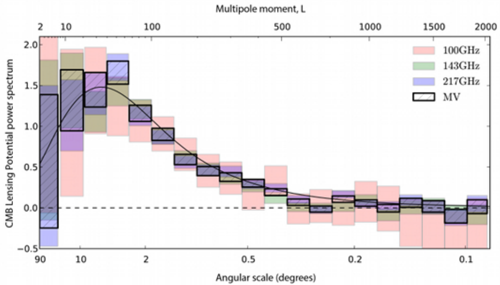


credit: Planck col.

- Lensing leads to a damping of the high ℓ peaks in the temperature power spectrum

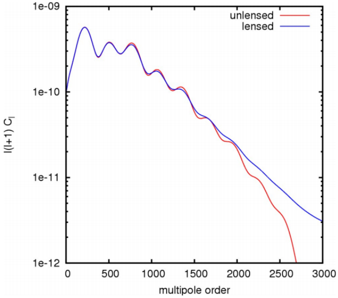
Part II, Lensing contribution to Planck

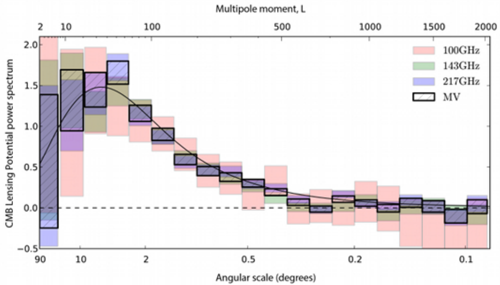




credit: Planck col.

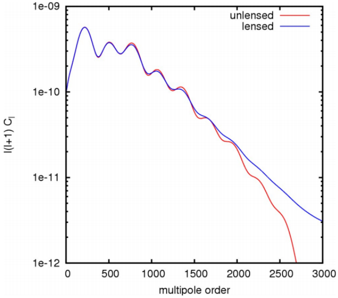
- Lensing leads to a damping of the high ℓ peaks in the temperature power spectrum $\rightarrow 10\sigma$ detection.

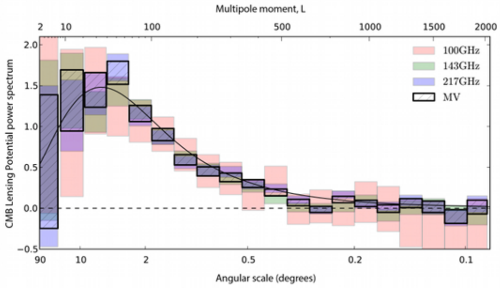




credit: Planck col.

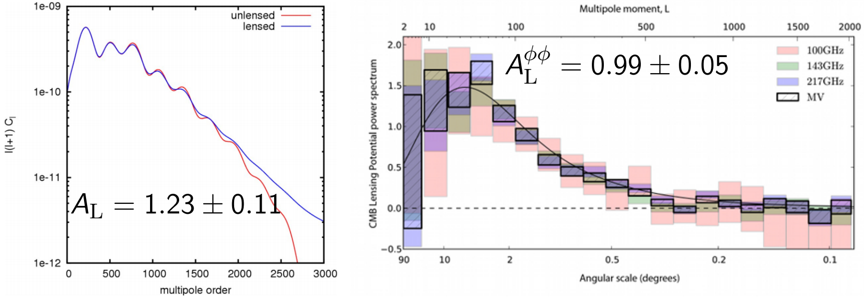
- Lensing leads to a damping of the high ℓ peaks in the temperature power spectrum $\rightarrow 10\sigma$ detection.
- Gravitational lensing introduces non-Gaussianity into the CMB fluctuations, which can be measured with the 4-point function or trispectrum





credit: Planck col.

- Lensing leads to a damping of the high ℓ peaks in the temperature power spectrum $\rightarrow 10\sigma$ detection.
- Gravitational lensing introduces non-Gaussianity into the CMB fluctuations, which can be measured with the 4-point function or trispectrum $\rightarrow 25\sigma$ detection.



credit: Planck col.

- Lensing leads to a damping of the high ℓ peaks in the temperature power spectrum $\rightarrow 10\sigma$ detection.
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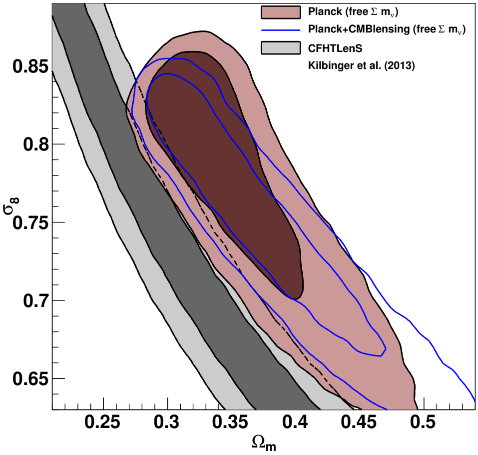
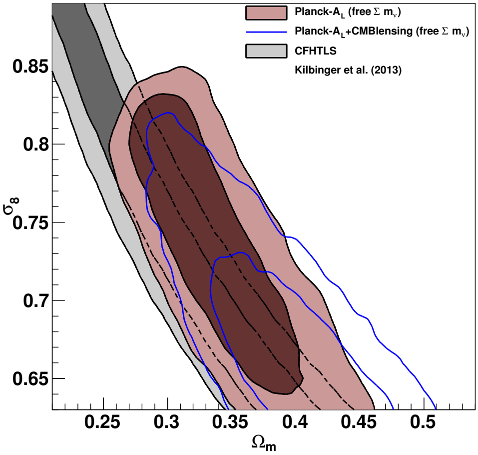


See Planck collaboration XVI section 5.1

Part II, Lensing contribution to Planck



See Planck collaboration XVI section 5.1

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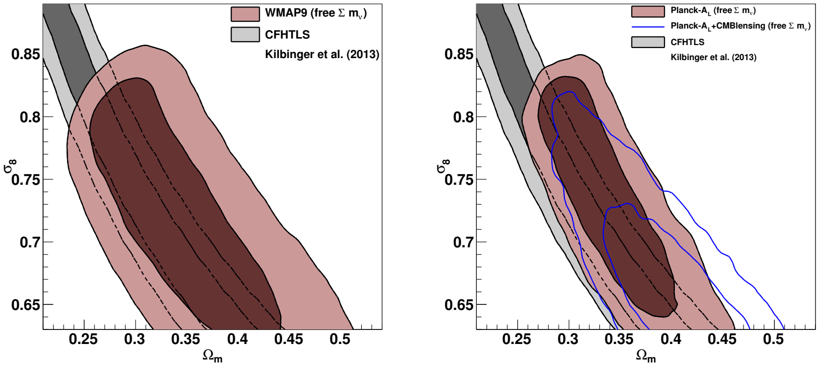
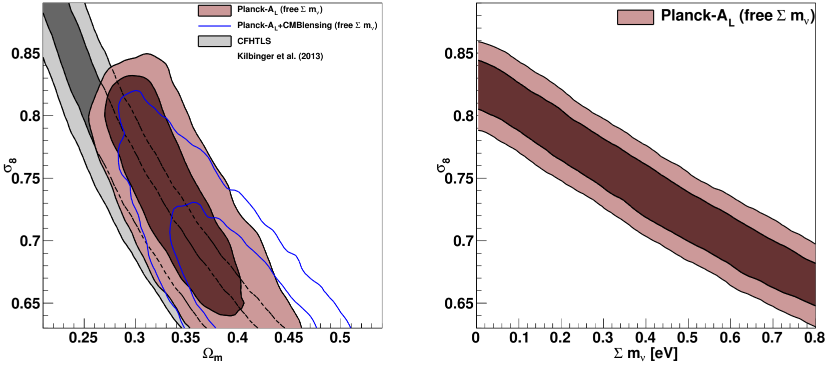
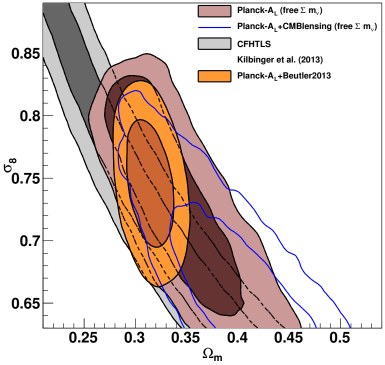
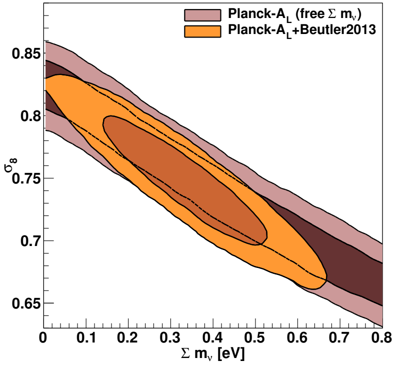


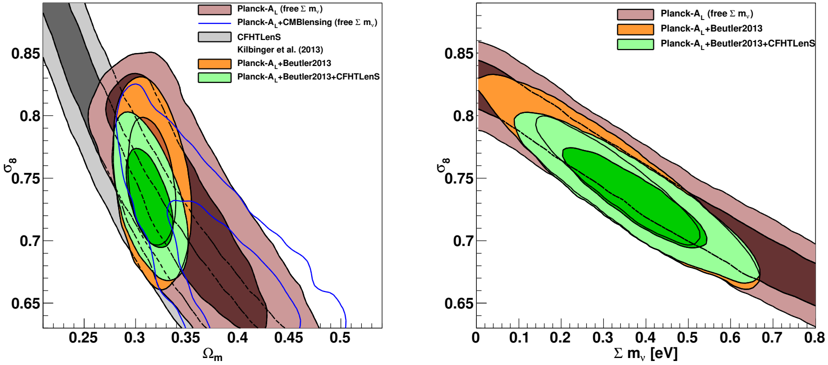


dataset(s)	$\sum m_\nu$ [eV]	
	68% c.l.	95% c.l.
Planck-$\mathrm{A_L}$	< 0.71	< 1.2





dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	95% c.l.
Planck-A_L	< 0.71	< 1.2
Planck-A_L+CMASS	0.34 ± 0.14	0.34 ± 0.26



dataset(s)	$\sum m_\nu$ [eV]	
	68% c.l.	95% c.l.
Planck-A$_\mathrm{L}$	< 0.71	< 1.2
Planck-A$_\mathrm{L}$+CMASS	0.34 ± 0.14	0.34 ± 0.26
Planck-A$_\mathrm{L}$+CMASS+CFHTLenS	0.38 ± 0.11	0.38 ± 0.24

Summary:

- There is tension between WMAP9 and Planck, which has a significant impact on the neutrino mass constraints.

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WMAP9+CMASS	0.36 ± 0.14	0.36 ± 0.28
Planck+CMASS	0.20 ± 0.13	< 0.37
Planck-A_L+CMASS	0.34 ± 0.14	0.34 ± 0.26

dataset(s)	$\sum m_\nu$ [eV] 68% c.l.	$\sum m_\nu$ [eV] 95% c.l.
WMAP9+CMASS+CFHTLenS	0.37 ± 0.12	0.37 ± 0.24
Planck+CMASS+CFHTLenS	0.29 ± 0.13	$0.29^{+0.29}_{-0.23}$
Planck-A_L+CMASS+CFHTLenS	0.38 ± 0.11	0.38 ± 0.24

Conclusion

- Introducing a neutrino mass lowers the tension between the σ_8 prediction of WMAP9 and low redshift datasets.
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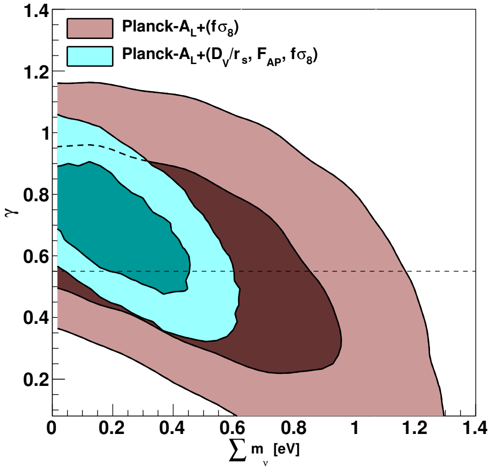
  $\rightarrow$ Without the lensing contribution Planck+CMASS also shows preference for a non-zero neutrino mass with $2.5 - 3.5\sigma$ significance.
- The preference for non-zero neutrino mass is dominated by the growth of structure constraints.

Thank you very much

Appendix: GR test with free neutrino mass



$$\gamma = 0.67 \pm 0.14$$

Appendix: Testing RSD and CFHTLenS