Measuring Neutrino Masses and Dark Energy

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Motivation

Era of precision cosmology: CMB, LSS, SNIa, ...

- Neutrino masses ?
  (0.056 (0.095) $\mathrm{eV} < \sum m_\nu < 0.2 - 1.7\ \mathrm{eV}$, vs ~ 6 eV from lab)
- Dark energy ? ($w \sim -1,\ \Omega_X \sim 0.7,\ w(z)$?)

$\Rightarrow$ Breaking the $(\sum m_\nu, w)$ degeneracy

- Baryon acoustic oscillations detected by SDSS
- Weak lensing (tomography): CFHTLS, SNAP, LSST, ...
- Other observations

Neutrino Mass Effects

- Present matter density:

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93.2 \text{ eV}}$$

- Slow down fluctuation growth:

$$\Delta P_{\rm lin}(k)/P_{\rm lin}(k) \sim -8\,\Omega_\nu/\Omega_m \quad \text{at } k \gg k_{\rm nr}$$

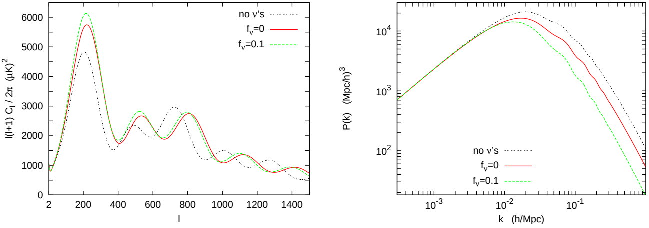
[Hu,Eisenstein,Tegmark '97]

- Late time infall into CDM halos:

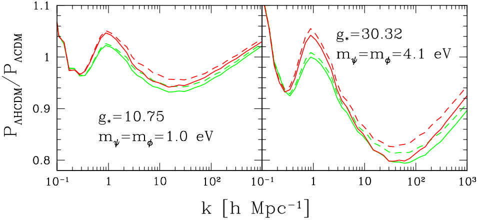
$$\rho_{halo}(r, M, z) \to \Delta P_{\rm nl}(k)/P_{\rm nl}(k) \sim 1\% \text{ at } k \gtrsim 1\, h \text{ Mpc}^{-1}$$

[Abazajian et al. '04; Hannestad,Ringwald, HT,Wong '05]

Neutrino Mass Effects (II)



[Lesgourgues,Pastor '06]



[Hannestad,HT,Wong '05]

Dark Energy Effects

- Redshift-distance relation:

$$H^2(z) = H_0^2 \left[\Omega_m(1+z)^3 + \Omega_X \exp\left[3\int_0^z dz' \frac{1+w(z')}{1+z'}\right]\right]$$

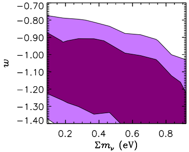
- Structure growth suppression:

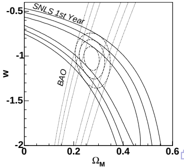
$$2\frac{d^2 g}{d\ln a^2} + [5 - 3\, w(a)\, \Omega_X(a)]\, \frac{dg}{d\ln a} + 3\,[1 - w(a)]\, \Omega_X(a)\, g(a) = 0$$

for the growth function $D(a) = ag(a)$

Degeneracy with $\sum m_\nu$: due to (w_X, Ω_X) and $(\sum m_\nu, \Omega_m = 1 - \Omega_X)$

- Baryon Acoustic Oscillations
- Weak gravitational lensing





Baryon Acoustic Oscillations (BAO)

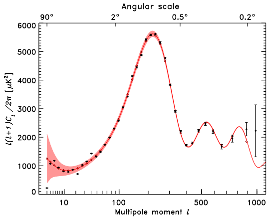
Oscillations in the photon-baryon fluid before recombination [Peeble,Yu '70; ...]

- Sound horizon at recombination

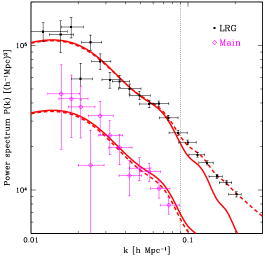
$$r_s(\eta_{\rm rec}) \approx 147\ {\rm Mpc}\,(\Omega_m h^2/0.13)^{-0.25}(\Omega_b h^2/0.024)^{-0.08}$$

- "Standard ruler":

$$r_{\parallel} = \Delta z/H(z),\ r_{\perp} = (1+z)\,D_A(z)\Delta\theta$$



[Spergel et al. '06]



[Tegmark et al. '06]

BAO (II): SDSS Detection in Galaxy Correlation Function

$\xi(\vec{r}) \equiv \langle \delta(\vec{x})\, \delta(\vec{x}+\vec{r}) \rangle \Rightarrow \xi(r) = \frac{1}{(2\pi)^3} \int dk\, P(k)\, \frac{\sin kr}{kr}\, 4\pi k^2$

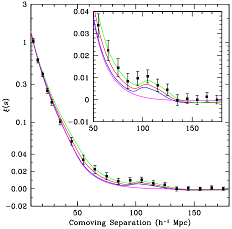
⇒ SDSS constraints on dark energy: [Eisenstein et al. '05]

parameter	WMAP+Main	WMAP+LRG
w (constant)	-0.92 ± 0.30	-0.80 ± 0.18

⇒ With massive neutrinos we found at $z = 0.35$

[Goobar,Hannestad,Mörtsell,HT '06]

$$A \equiv D_V(z)\, \frac{\sqrt{\Omega_m H_0^2}}{cz} = 0.469 \left(\frac{n}{0.98}\right)^{-0.35} (1 + 0.94\, \Omega_\nu/\Omega_m) \pm 0.017$$



[Eisenstein et al. '05]

Our Current Bounds on $\sum m_\nu$: 2 models

11 parameters: $(\Omega_m, h, \Omega_b h^2, N_\nu, w_X, n_s, \alpha_s, \tau, Q, b, \sum m_\nu)$

Data	$\sum m_\nu$ (95% C.L.)
1: CMB, LSS, SNIa	1.72 eV
2. CMB, LSS, SNIa, BAO	0.62 eV
3. CMB, LSS, SNIa, Ly-α	0.83 eV
4. CMB, LSS, SNIa, BAO, Ly-α	0.49 eV

8 parameters: $(..., w_X = -1, \alpha_s = 0, N_\nu = 3)$

Data	$\sum m_\nu$ (95% C.L.)
1: CMB, LSS, SNIa	0.70 eV
2. CMB, LSS, SNIa, BAO	0.48 eV
3. CMB, LSS, SNIa, Ly-α	0.35 eV
4. CMB, LSS, SNIa, BAO, Ly-α	0.27 eV

[Goobar,Hannestad,Mörtsell,HT '06]

Future BAO Surveys

Statistical errors $\frac{\sigma_P}{P}(k) \approx 2\pi \sqrt{\frac{1}{V_{\rm survey} k^2 \Delta k}} \left(1 + \frac{1}{n\,P(k)}\right)$

- Large volume ($\sim 1\ \mathrm{Gpc}^3$)
- Aim at high redshifts $\rightarrow$ still in linear regime
- Need spectroscopic redshifts (otherwise $\approx$ 20 larger area)
- With redshift slicing (5-7 slices, $1 < z < 3$) $\rightarrow w(z)$

WFMOS, HETDEX, JEDI, LSST, VADER (?)...

- Constraints on dark energy: $\sigma(w_0) \sim 10\%$ and $\sigma(w_1) \sim 20\%$

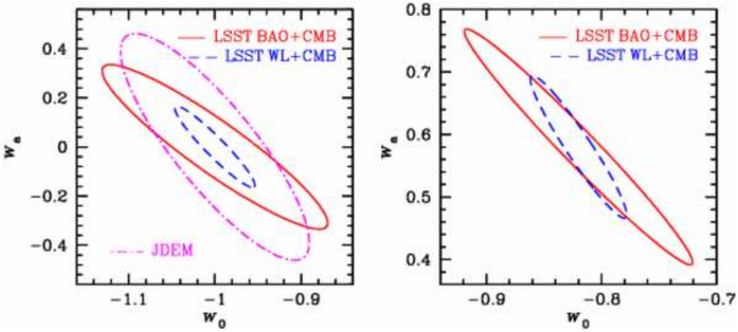
  [Glazebrook,Blake '05; Wang '06; ...]
- Constraints on neutrino masses: a full MCMC to be done

  [Hannestad,Lesgourgues,Perotto,HT,Wong, in preparation]
- Model/scenario comparison: with $H(z)$ and $D_A(z)$ data

  [Goobar,Hannestad,Mörtsell,HT]

Future BAO Surveys (II)

- Dependence on fiducial model
- Sensitivity comparison to weak lensing

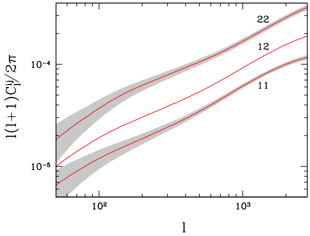


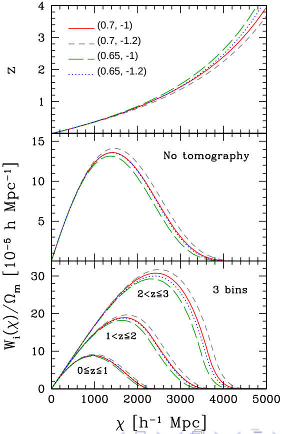
[LSST Collaboration, http://www.lsst.org]

Gravitational Weak Lensing (Tomography)

Convergence power spetrum

$$C_\ell^{ij} = \frac{9}{16}\, H_0^4\, \Omega_m^2 \int_0^{\chi_h} d\chi\, \frac{g_i(\chi)\, g_j(\chi)}{a^2\, \chi^2}\, P(\frac{\ell}{\chi}, z)$$





WL Systematics

- Photometric redshift uncertainties ~ 0.05
  $n_i(z) = \int_{z^i_{\rm ph}}^{z^{i+1}_{\rm ph}} dz_{\rm ph}\, n_{\rm gal}(z)\, p(z_{\rm ph}|z) \quad \Rightarrow \sigma_z, z_{bias}$ [Ma,Hu,Huterer '05]
- Shear calibration [STEP: Heymans et al. '05]
  - Multiplicative errors $\sim 1-2\%$
    $\hat{C}^{ij}_\ell = C^{ij}_\ell \times (1 + f_i + f_j)$ [Huterer,Takada,Bernstein,Jain '05]
  - Additive errors $\sim 10^{-4}$
    $\hat{C}^{ij}_\ell = C^{ij}_\ell + C^{\rm add}_\ell$
- Nonlinear corrections to matter power spectrum $\sim 5-10\%$
  "halo model" $\Rightarrow P_{\rm nl}(k)$ [Seljak '00; Ma,Fry '00; Smith et al. '03]

Our Analysis: Parameters and Surveys

- WL tomography with 1,3,5,8 bins, $0 < z < 3$
- Fiducial cosmological model (11 parameters):

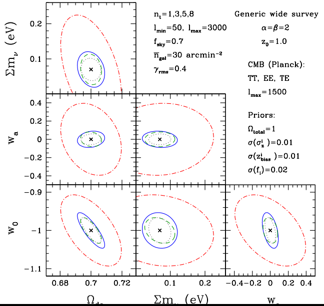
  $(w_0 = -1, w_a = 0, \sum m_\nu = 0.07\ \mathrm{eV}, N_{\mathrm{eff}} = 3,$
  $\Omega_c h^2 = 0.1225, \Omega_{\mathrm{DE}} = 0.7, \Omega_b h^2 = 0.0245, n_s = 1,$
  $\alpha_s = 0, \tau = 0.05, \sigma_8 = 0.9)$
- Systematics: priors on $\sigma_z = 0.05$ and $z_{bias} = 0$, $f_i = 0$
- Generic WL survey parameters:

	f_{sky}	z_0	γ_{rms}	$\bar{n}_{\mathrm{gal}}\ (\mathrm{arcmin}^{-2})$
Wide, LSST-like	0.7	1.0	0.4	30
Deep, SNAP-like	0.01	1.5	0.25	100

Error Forecast for $\sum m_\nu$ and w

Model	Cosmological probes	$\sigma(\sum m_\nu)$
11 parameters	Planck only	0.48 eV
11 parameters	Planck+Wide-1	0.15 eV
11 parameters	Planck+Wide-5	0.043 eV
7 parameters	Planck+Wide-1	0.082 eV
7 parameters	Planck+Wide-5	0.037 eV

WL tomography (wide) + Planck



	Planck	+ Wide-1	+ Wide-5
$\sigma(w_0)$	0.83	0.093	0.034
$\sigma(w_a)$	4.0	0.39	0.081

Summary

Breaking $(\sum m_\nu, w)$ degeneracy

- $\sum m_\nu \leq 0.48 - 0.62$ from WMAP3 + LSS + SNIa + BAO
- Future WL tomography constraints: $\sigma(\sum m_\nu) = 0.025 - 0.1$ eV
- CMB lensing $\sigma(\sum m_\nu) \sim 0.15$ eV (Planck)

$\Rightarrow$ Cosmological observations pin down $\sum m_\nu$ to < 0.1 eV, distinguish between normal hierarchy and inverted hierarchy

- $\sigma(w_0) \sim 10\%$, $\sigma(w_a) \sim 20\%$ from future BAO
- $\sigma(w_0) \sim 3.5\%$, $\sigma(w_a) \sim 8\%$ from future WL with 5 bins