Neutrino mass from cosmological observations: galaxy-clustering

Carmelita Carbone
(INAF – Astronomical Observatory of Bologna)

Neutrino Oscillation Workshop
Conca Specchiulla (Otranto, Lecce, Italy) September 9-16, 2012

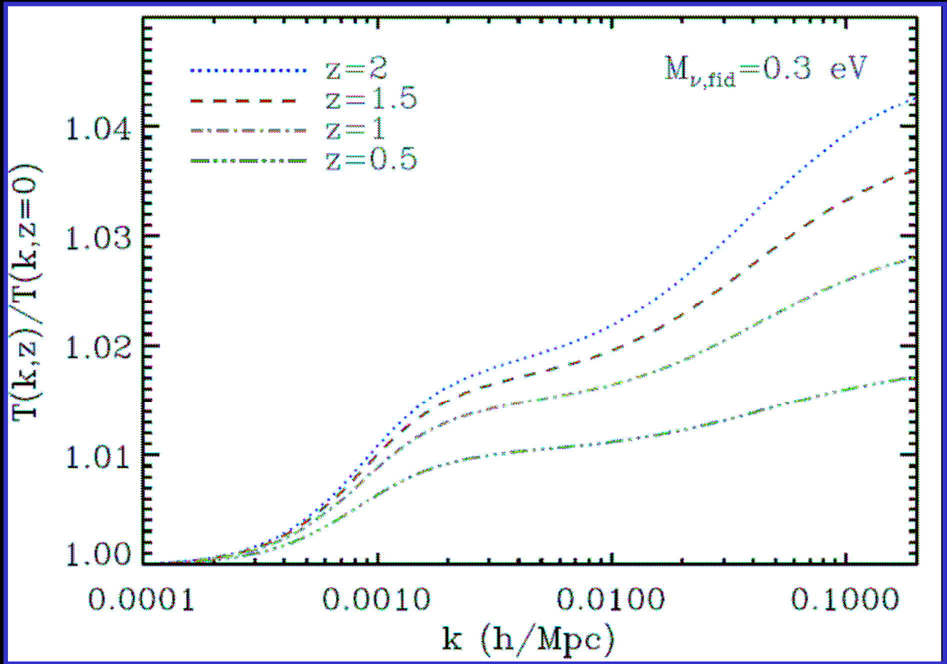
ΛCDM+ν: WMAP7+BAO+H_0 → M_ν<0.58 (1.3 if w≠-1) eV at 95% C.L.

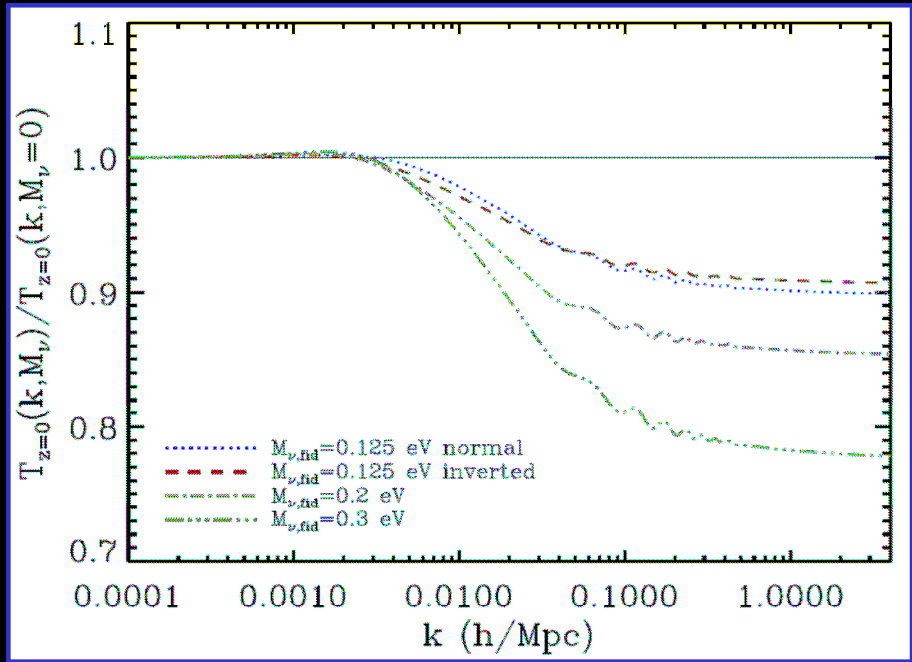
Probe	Current $\sum m_\nu$ (eV)	Forecast $\sum m_\nu$ (eV)	Key Systematics	Current Surveys	Future Surveys
CMB Primordial	1.3	0.6	Recombination	WMAP, Planck	None
CMB Primordial + Distance	0.58	0.35	Distance measurements	WMAP, Planck	None
Lensing of CMB	∞	0.2 – 0.05	NG of Secondary anisotropies	Planck, 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] Euclid
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	0.9	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 Euclid

Abazajian et al. 2011

Each of these probes faces technological, observational, and theoretical challenges

Massive neutrino effects on the matter transfer function (Only 3 active neutrinos)



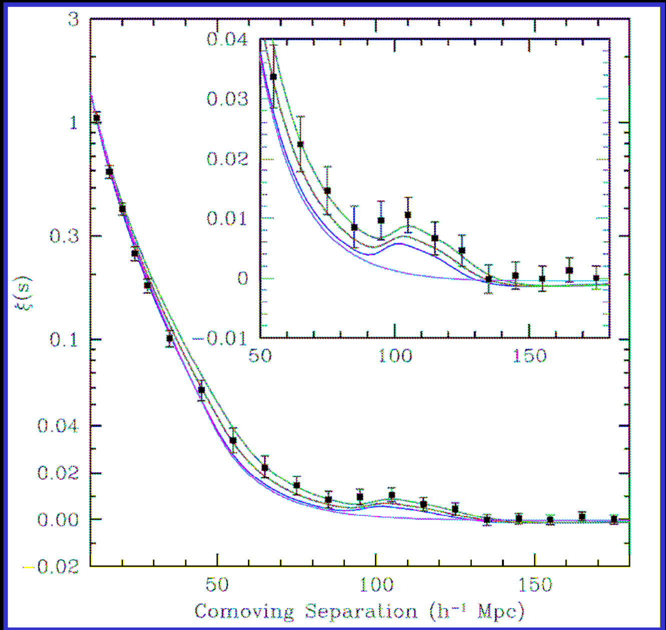


CC et al. 2011

$$\Phi(\vec{k},a) = \Phi_{\mathrm{p}}(\vec{k}) \times \left\{\text{Transfer Function}(k)\right\} \times \left\{\text{Growth Function}(a)\right\}$$

$$P_{\mathrm{matter}}(k,z) = \frac{8\pi^2 c^4 k_0 \Delta^2_{\mathcal{R}}(k_0)}{25 H_0^4 \Omega_m^2} T^2(k,z) \left[\frac{G(z)}{G(z=0)}\right]^2 \left(\frac{k}{k_0}\right)^{n_s} e^{-k^2\mu^2\sigma_r^2}$$

Baryon Acoustic Oscillations (BAO)

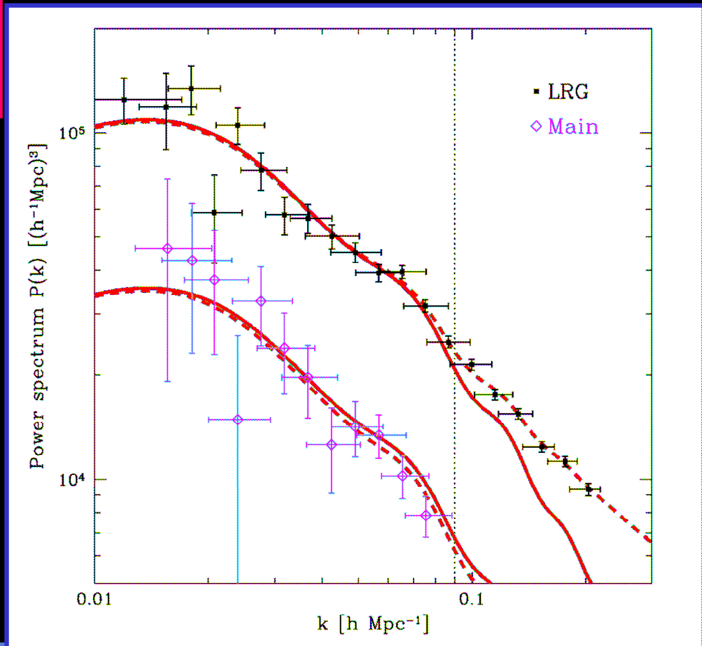


The large-scale redshift-space correlation function of the SDSS-LRG sample. The models are $\Omega_m h^2$=0.12 (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2$ = 0.024 and n_s=0.98. The magenta line shows a pure CDM model ($\Omega_m h^2$=0.105), which lacks the acoustic peak.

$$r_{\parallel} = \frac{c\Delta z}{H(z)}$$

$$r_{\perp} = (1+z)D_A(z)\Delta\theta$$

Measured power spectra for the full SDSS-LRG and SDSS main galaxy samples. The solid curves correspond to the linear theory ΛCDM fits to WMAP3 alone, normalized to galaxy bias b=1.9 (top) and b=1.1 (bottom) relative to the z=0 matter power. The dashed curves include nonlinear corrections with at k> 0.09



Forecast errors for Euclid: Fisher matrix for BAO+P(k)-shape

$$P_{\rm obs}(k_{\rm ref\perp}, k_{\rm ref\|}, z) = \frac{D_A(z)^2_{\rm ref} H(z)}{D_A(z)^2 H(z)_{\rm ref}} P_{\rm g}(k_{\rm ref\perp}, k_{\rm ref\|}, z) + P_{\rm shot}$$

$$P_{\rm g}(k_{\rm ref\perp}, k_{\rm ref\|}, z) = b(z)^2 \left[1 + \beta(z,k) \frac{k^2_{\rm ref\|}}{k^2_{\rm ref\perp} + k^2_{\rm ref\|}}\right]^2 \times P_{\rm matter}(k, z)$$

$$\begin{aligned} F_{ij}^{\rm LSS} &= \int_{\vec{k}_{\rm min}}^{\vec{k}_{\rm max}} \frac{\partial \ln P_{\rm obs}(\vec{k})}{\partial p_i} \frac{\partial \ln P_{\rm obs}(\vec{k})}{\partial p_j} V_{\rm eff}(\vec{k}) \frac{d\vec{k}}{2(2\pi)^3} \\ &= \int_{-1}^{1} \int_{k_{\rm min}}^{k_{\rm max}} \frac{\partial \ln P_{\rm obs}(k,\mu)}{\partial p_i} \frac{\partial \ln P_{\rm obs}(k,\mu)}{\partial p_j} V_{\rm eff}(k,\mu) \frac{2\pi k^2 dk d\mu}{2(2\pi)^3} \end{aligned}$$

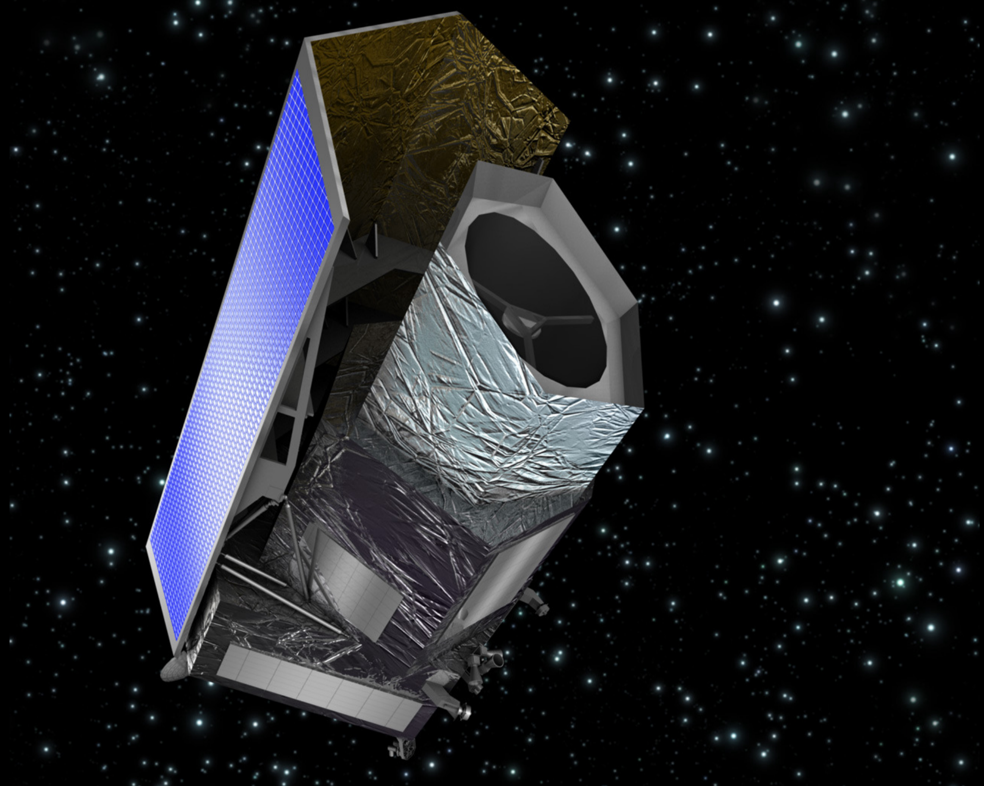
$$\left[\frac{\Delta P_{\rm g}}{P_{\rm g}}\right]^2 = \frac{2(2\pi)^2}{V_{\rm survey} k^2 \Delta k \Delta\mu} \left[1 + \frac{1}{n_{\rm g} P_{\rm g}}\right]^2$$

$$\boxed{V_{\rm eff}(k,\mu) = \left[\frac{n_{\rm g} P_{\rm g}(k,\mu)}{n_{\rm g} P_{\rm g}(k,\mu) + 1}\right]^2 V_{\rm survey}}$$

$$F_{ij} = \frac{1}{2} {\rm Tr}\left[\mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \theta_i} \mathbf{C}^{-1} \frac{\partial \mathbf{C}}{\partial \theta_j}\right] + \frac{\partial \boldsymbol{\mu}^t}{\partial \theta_i} \mathbf{C}^{-1} \frac{\partial \boldsymbol{\mu}}{\partial \theta_j}$$

$\mathbf{M}_\nu$+ $\{\Omega_m, \Omega_{de}, h, \Delta^2_{\mathcal{R}}(k_0), \Omega_b, w_0, w_a, n_s\}$

Euclid: Mapping the geometry of the dark Universe



Euclid is an ESA M-class mission selected for launch in 2019 in the Cosmic Vision 2015-2025 programme. The main goal of Euclid is to understand the origin of the accelerating expansion of the Universe. To achieve this goal, it is proposed to build a satellite equipped with a 1.2 m telescope and three imaging and spectroscopic instruments working in the visible and near-infrared wavelength domains. These instruments will explore the expansion history of the Universe and the evolution of cosmic structures by measuring shapes and red-shifts of galaxies as well as the distribution of galaxy-clusters as function of redshift $0.5<z<2$, over 15000 deg^2 of the sky. The satellite will be launched by a Soyuz ST-2.1B rocket and transferred to the L2 Lagrange point for a 6 years mission.

Neutrino constraints from the Euclid galaxy survey at 1-σ

Table 1: Parameter 1-σ errors for slitless spectroscopy

fiducial→	M_ν=0.3 eV[a]	M_ν=0.2 eV[a]	M_ν=0.125 eV[b]	M_ν=0.125 eV[c]	M_ν=0.05 eV[b]	$N_{\rm eff}$=3.04[d]
			slitless+BOSS			
Ω_m	0.0140	0.0137	0.0139	0.0138	0.0137	0.0124
Ω_{de}	0.0260	0.0265	0.0258	0.0257	0.0253	0.0256
Ω_b	0.0032	0.0031	0.0032	0.0032	0.0032	0.0034
h	0.0116	0.0112	0.0113	0.0114	0.0113	0.0137
M_ν	0.1459	0.1461	0.1795	0.1435	0.1428	−−
$N_{\rm eff}$	−−	−−	−−	−−	−−	0.5435
ns	0.0233	0.0225	0.0314	0.0228	0.0220	0.0326
w_0	0.0815	0.0837	0.0812	0.0808	0.0801	0.0807
w_a	0.3461	0.3573	0.3450	0.3440	0.3386	0.3324
FoM	51.75	48.44	52.44	52.68	54.25	55.23
			slitless+BOSS+Planck			
Ω_m	0.0034	0.0035	0.0033	0.0035	0.0035	0.0031
Ω_{de}	0.0064	0.0064	0.0062	0.0064	0.0065	0.0064
Ω_b	0.0006	0.0056	0.0006	0.0005	0.0005	0.0005
h	0.0043	0.0043	0.0043	0.0043	0.0042	0.0046
M_ν	0.0347	0.0433	0.0311	0.0441	0.0526	−−
$N_{\rm eff}$	−−	−−	−−	−−	−−	0.0865
ns	0.0022	0.0022	0.0022	0.0022	0.0022	0.0041
w_0	0.0732	0.0721	0.0716	0.0715	0.0709	0.0705
w_a	0.1760	0.1742	0.1713	0.1725	0.1722	0.1664
$\Delta^2_{\mathcal{R}}(k_0)$	0.0250	0.0226	0.0226	0.0227	0.0244	0.0227
FoM	245.07	242.80	259.32	247.96	240.31	294.15

[a] for degenerate spectrum: $m_1 \approx m_2 \approx m_3$; [b] for normal hierarchy: $m_3 \neq 0$, $m_1 \approx m_2 \approx 0$
[c] for inverted hierarchy: $m_1 \approx m_2$, $m_3 \approx 0$; [d] fiducial cosmology with massless neutrinos

Only 3 active neutrinos for M_ν errors

CC et al. 2011

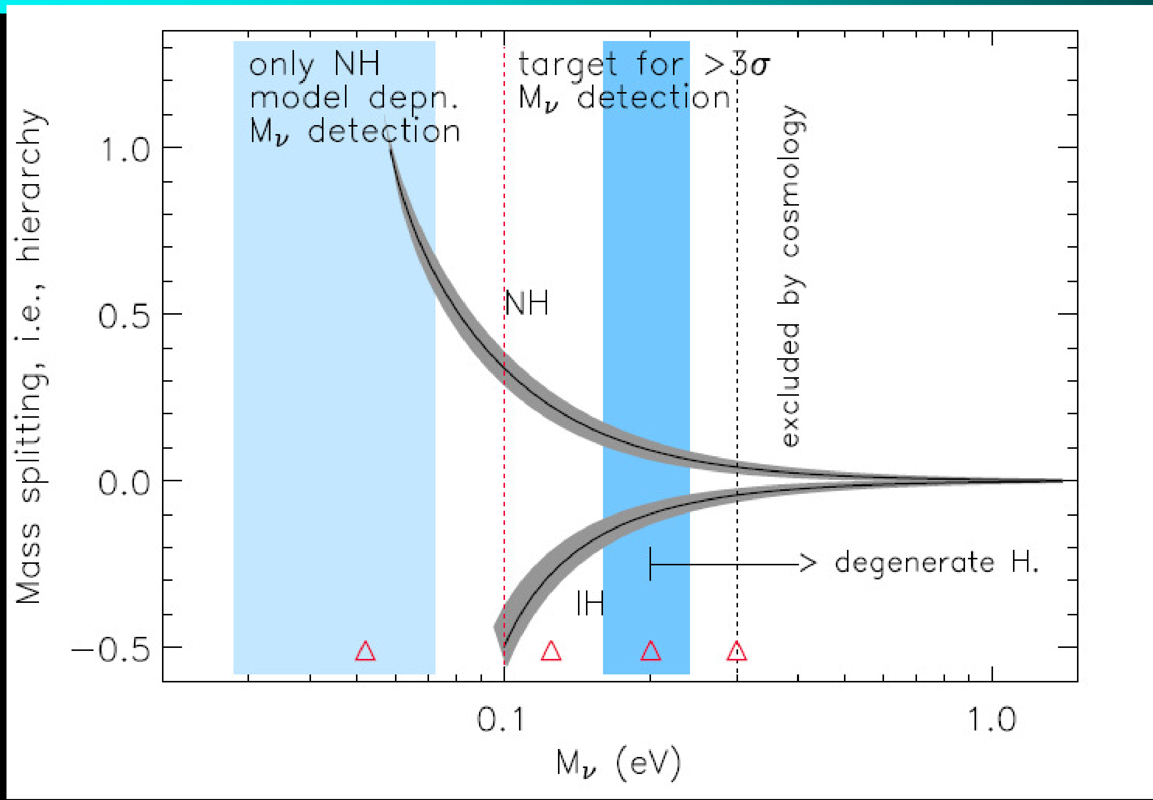


Table 5: $\sigma(M_\nu)$ and $\sigma(N_{\rm eff})$ marginalised errors from LSS+CMB

General cosmology						
fiducial→	M_ν=0.3 eV[a]	M_ν=0.2 eV[a]	M_ν=0.125 eV[b]	M_ν=0.125 eV[c]	M_ν=0.05 eV[b]	$N_{\rm eff}$=3.04[d]
slitless+BOSS+Planck	0.035	0.043	0.031	0.044	0.053	0.086
ΛCDM cosmology						
slitless+BOSS+Planck	0.017	0.019	0.017	0.021	0.021	0.023

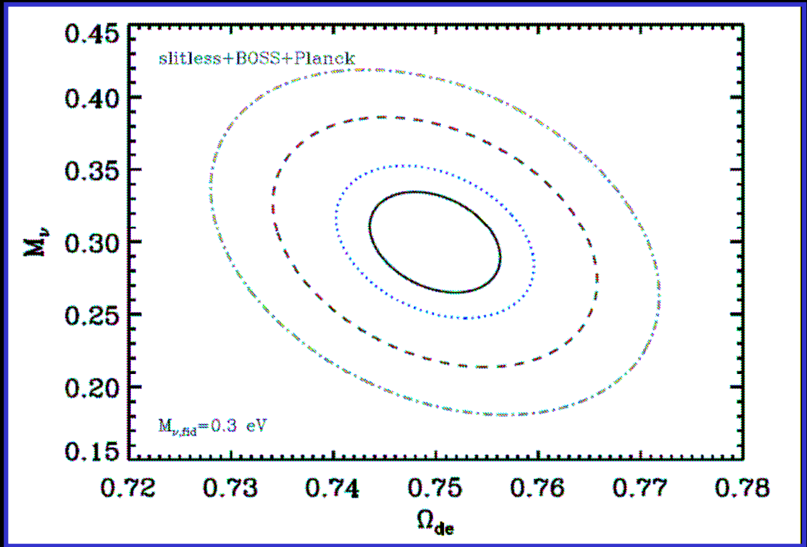
20%

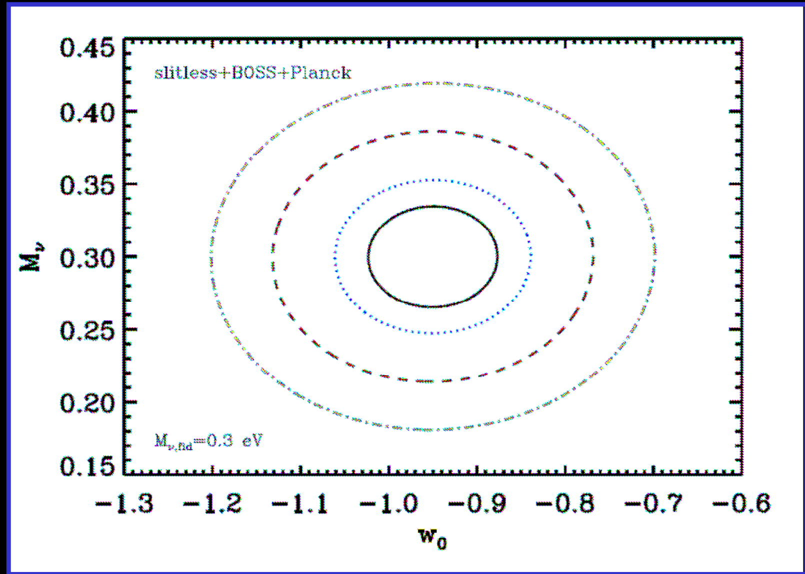
[a]for degenerate spectrum: $m_1 \approx m_2 \approx m_3$; [b]for normal hierarchy: $m_3 \neq 0$, $m_1 \approx m_2 \approx 0$
[c]for inverted hierarchy: $m_1 \approx m_2$, $m_3 \approx 0$; [d]fiducial cosmology with massless neutrinos

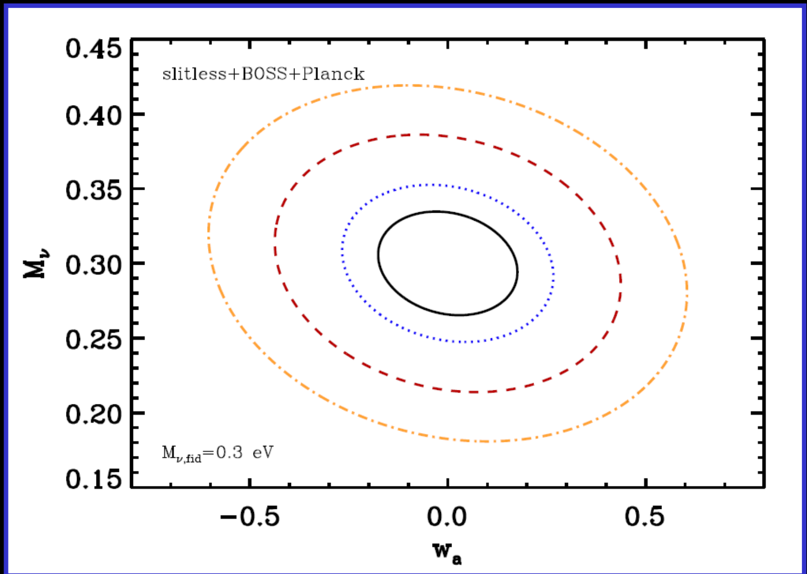
Only 3 active neutrinos for M_ν errors

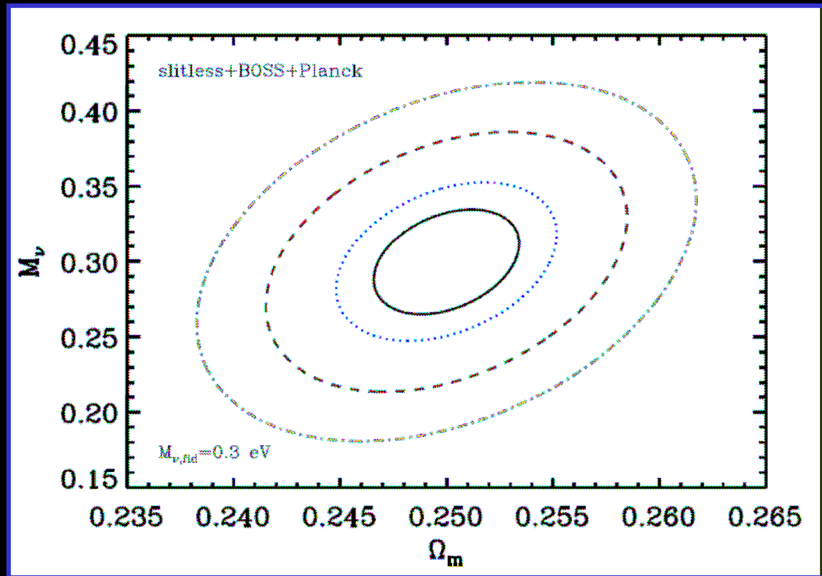
CC et al. 2011

Marginalised 1-σ errors for M_ν from Euclid+Planck (CC et al. 2011)



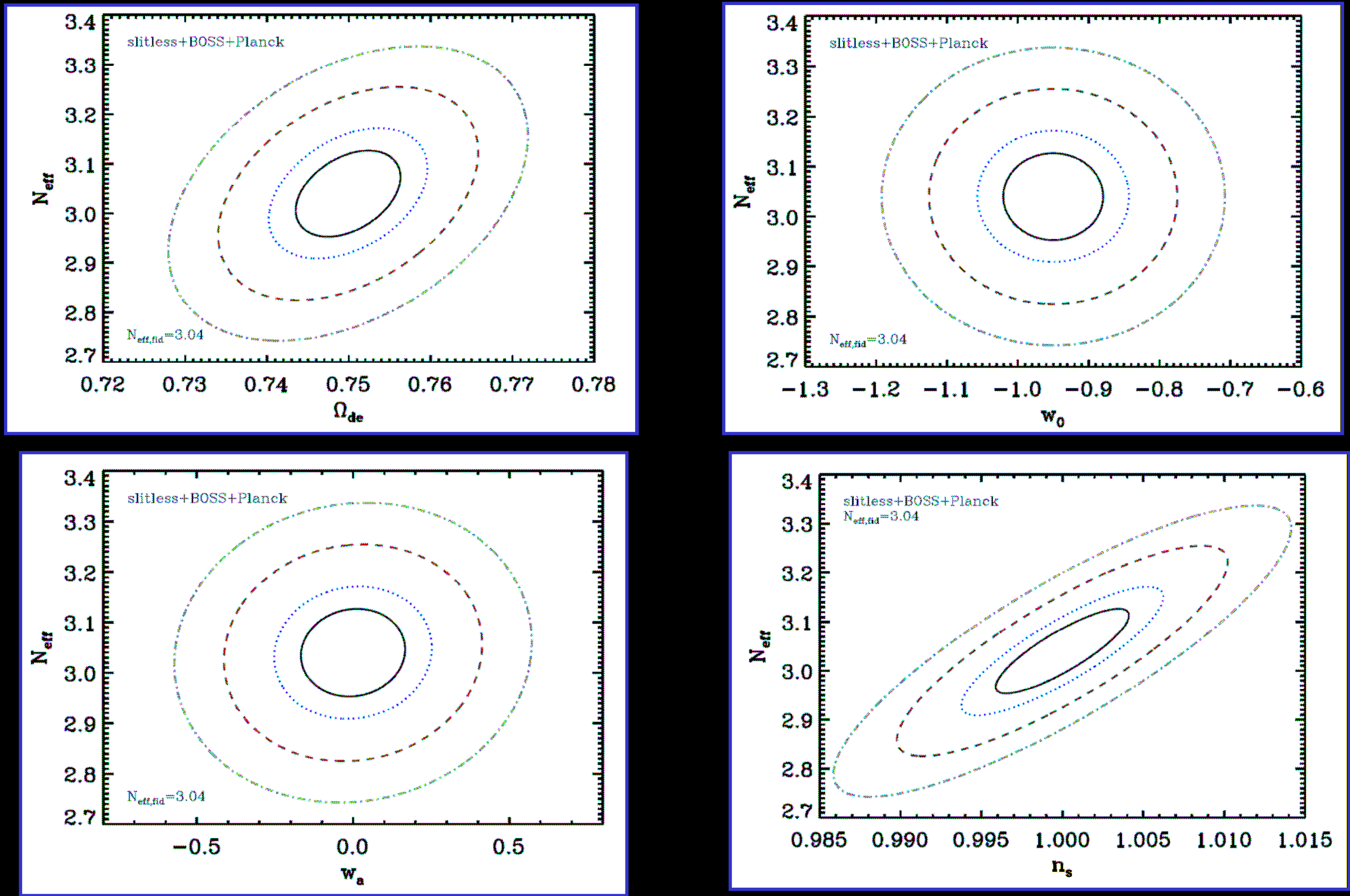






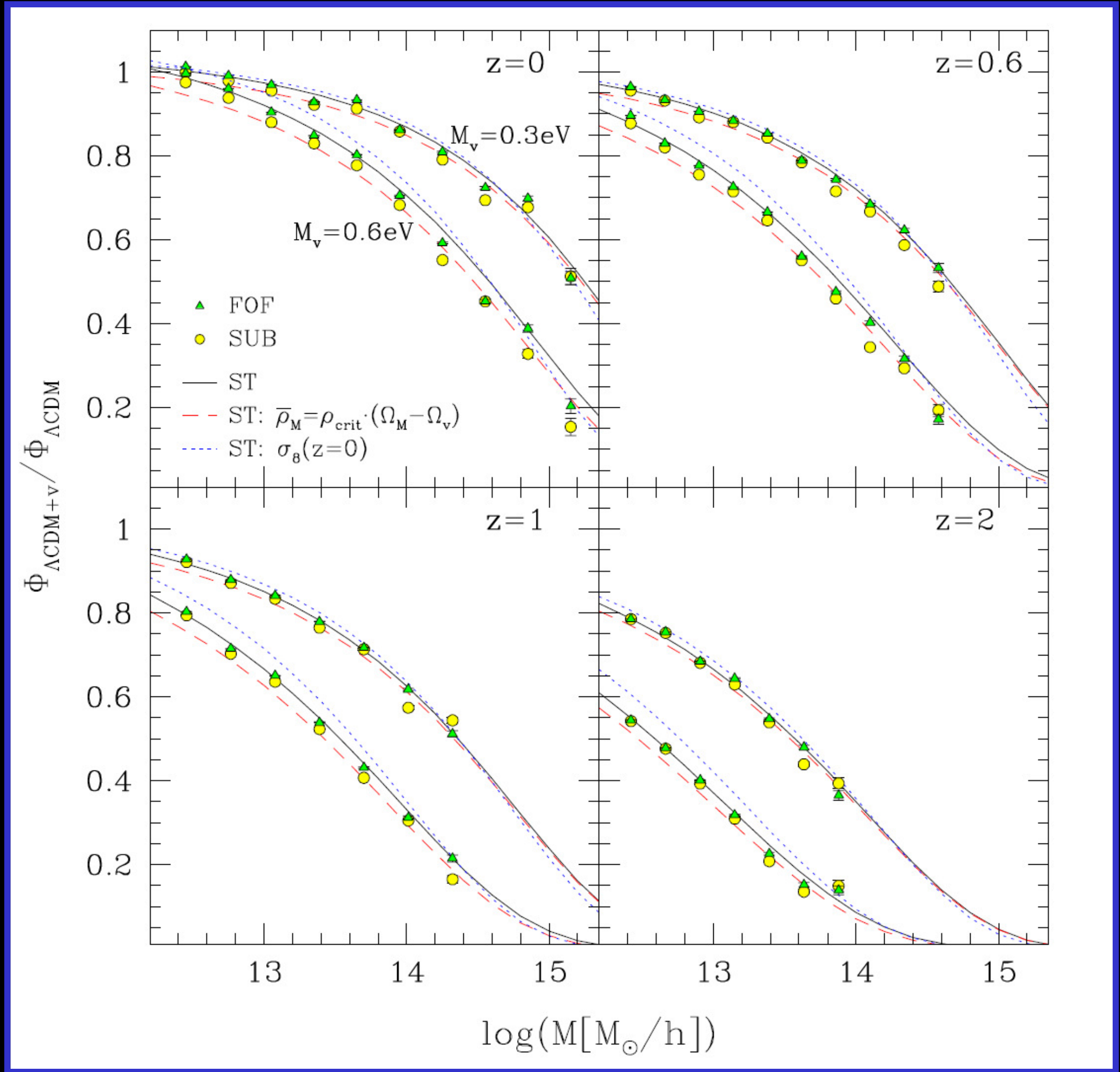
CC et al. 2011

Marginalised 1-σ errors for N_{eff} from Euclid+Planck (CC et al. 2011)



CC et al. 2011

Effects of massive neutrinos on the the halo mass function



Only 3 active neutrinos

Marulli, CC et al. 2011

General cosmology

	BAO+COUNTS[a]+CMB		BAO+COUNTS[b]+CMB	
	σ	r	σ	r
Ω_m	0.0106	0.4046	0.0057	0.6860
Ω_K	0.0039	0.3854	0.0031	0.6551
Ω_b	0.0016	0.0125	0.0008	0.3456
h	0.0125	-0.0380	0.0061	-0.3841
M_ν	0.1853	1.0000	0.1064	1.0000
n_s	0.0024	-0.0297	0.0023	0.0722
w_0	0.2133	0.0020	0.1477	0.7178
w_a	0.7218	-0.2123	0.5119	-0.7616
$\log(10^{10} A_s)$	0.0222	0.8878	0.0175	0.8599

ΛCDM

	BAO+COUNTS[a]+CMB		BAO+COUNTS[b]+CMB	
	σ	r	σ	r
Ω_m	0.0036	-0.8361	0.0008	0.1401
Ω_b	0.0009	-0.7042	0.0003	0.5604
h	0.0068	0.7796	0.0021	-0.3582
M_ν	0.0758	1.0000	0.0339	1.0000
n_s	0.0023	0.2220	0.0023	0.5414
$\log(10^{10} A_s)$	0.0138	0.7522	0.0103	0.9441

Nuisance parameters kept fixed to the fiducial values

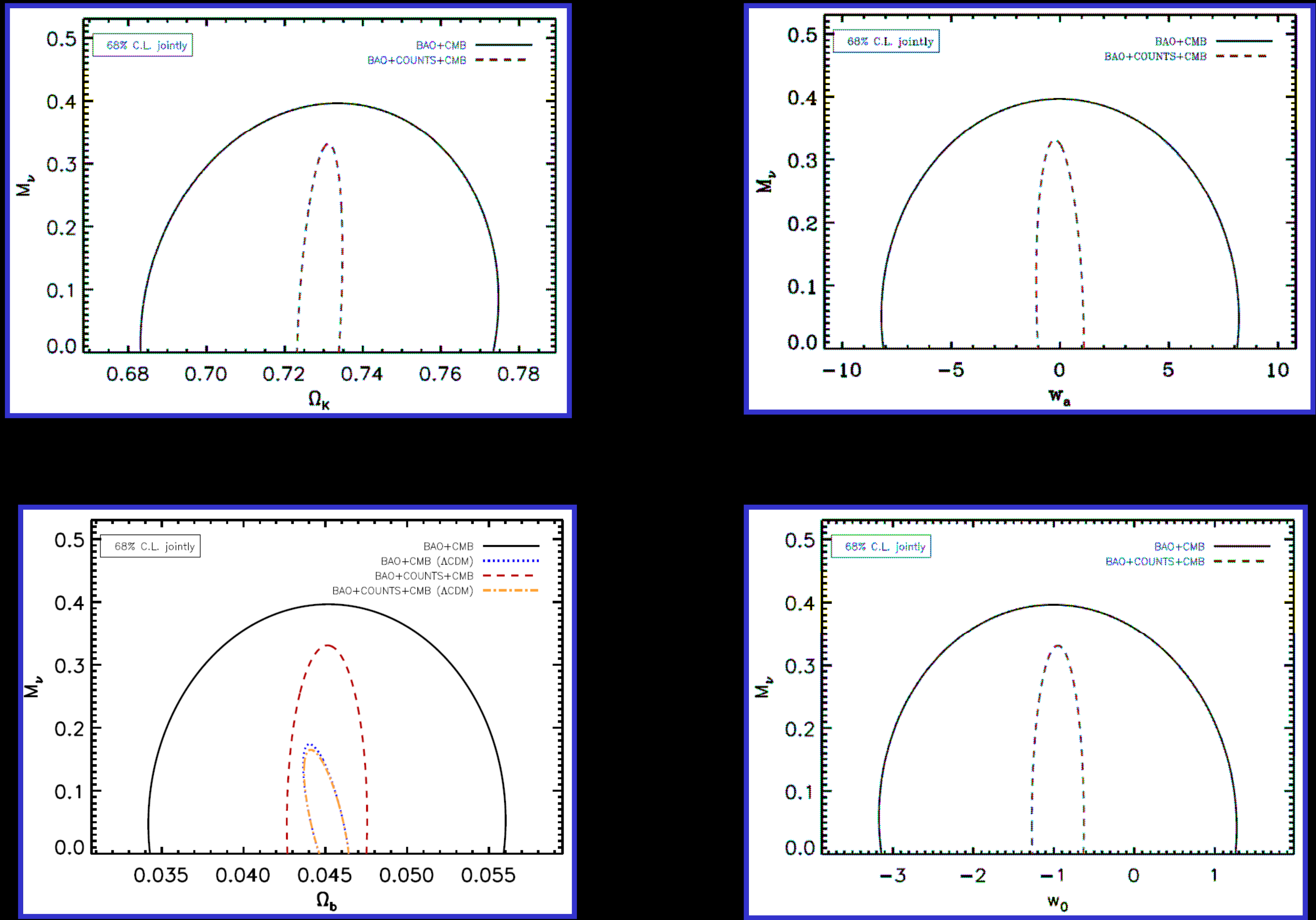
Only 3 active neutrinos for M_ν errors

$$r \equiv \frac{(F^{-1})_{\alpha\beta}}{\sqrt{(F^{-1})_{\alpha\alpha}(F^{-1})_{\beta\beta}}}$$

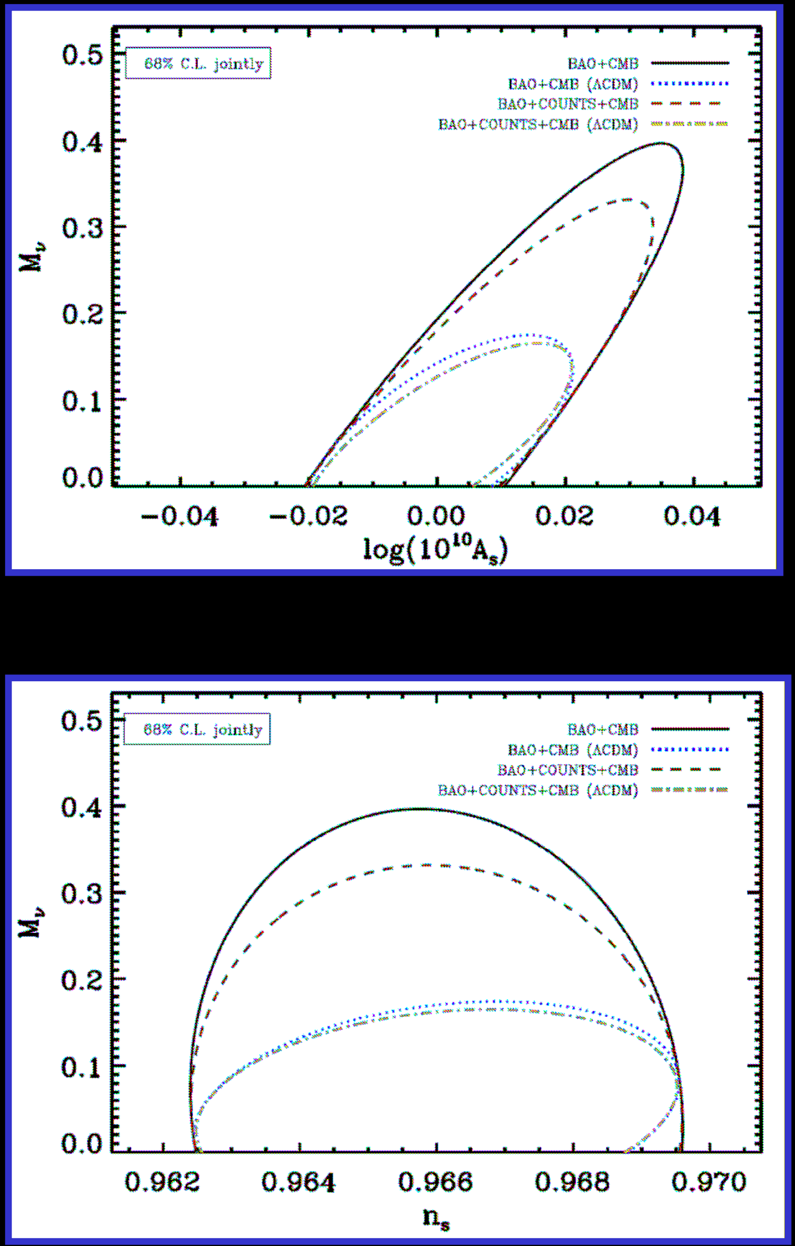
Correlation coefficients

CC et al. 2012

Confidence contours at 68% C.L. for galaxy-clusters (CC et al. 2012)

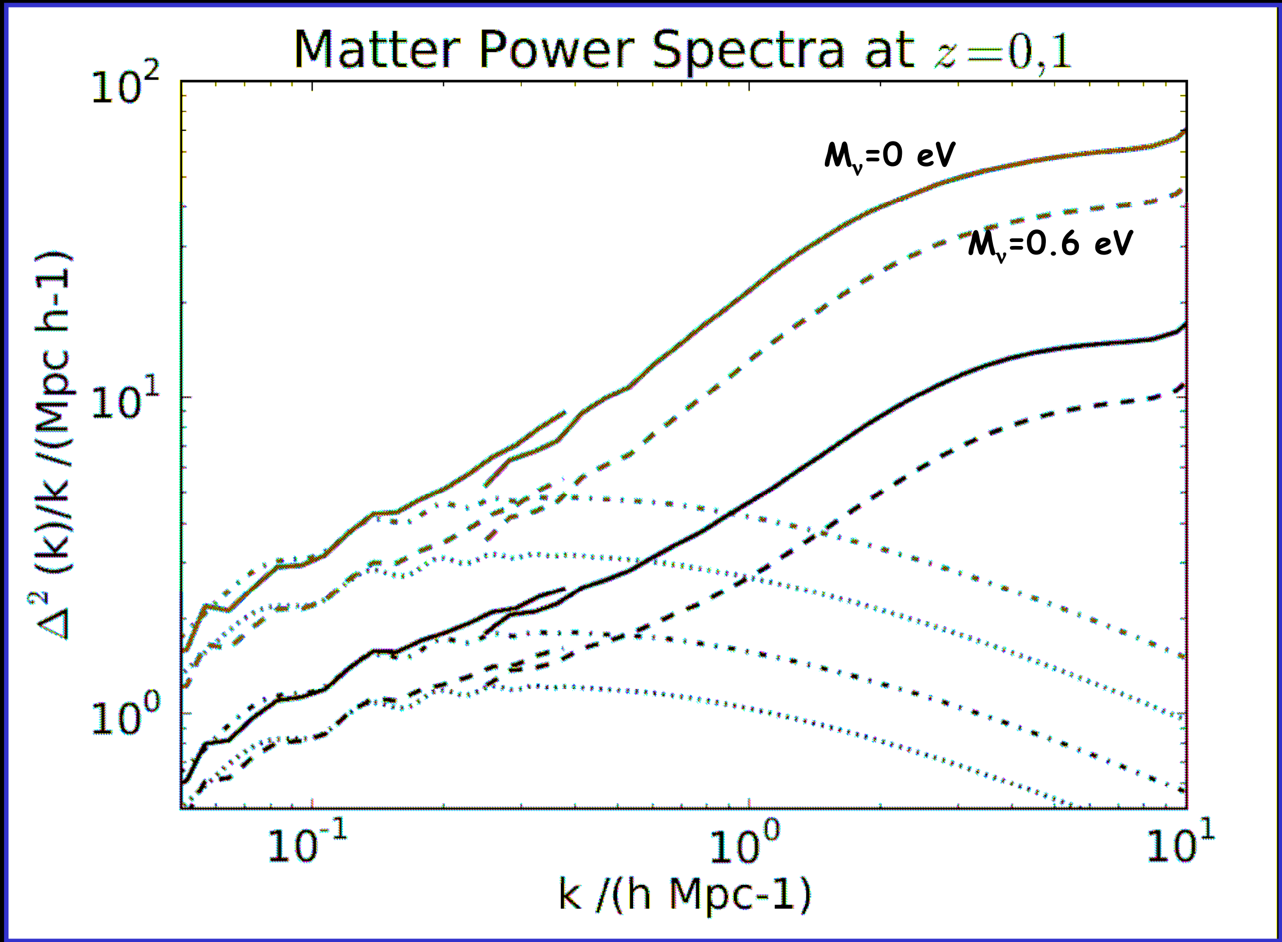


Confidence contours at 68% C.L. for galaxy-clusters (CC et al. 2012)



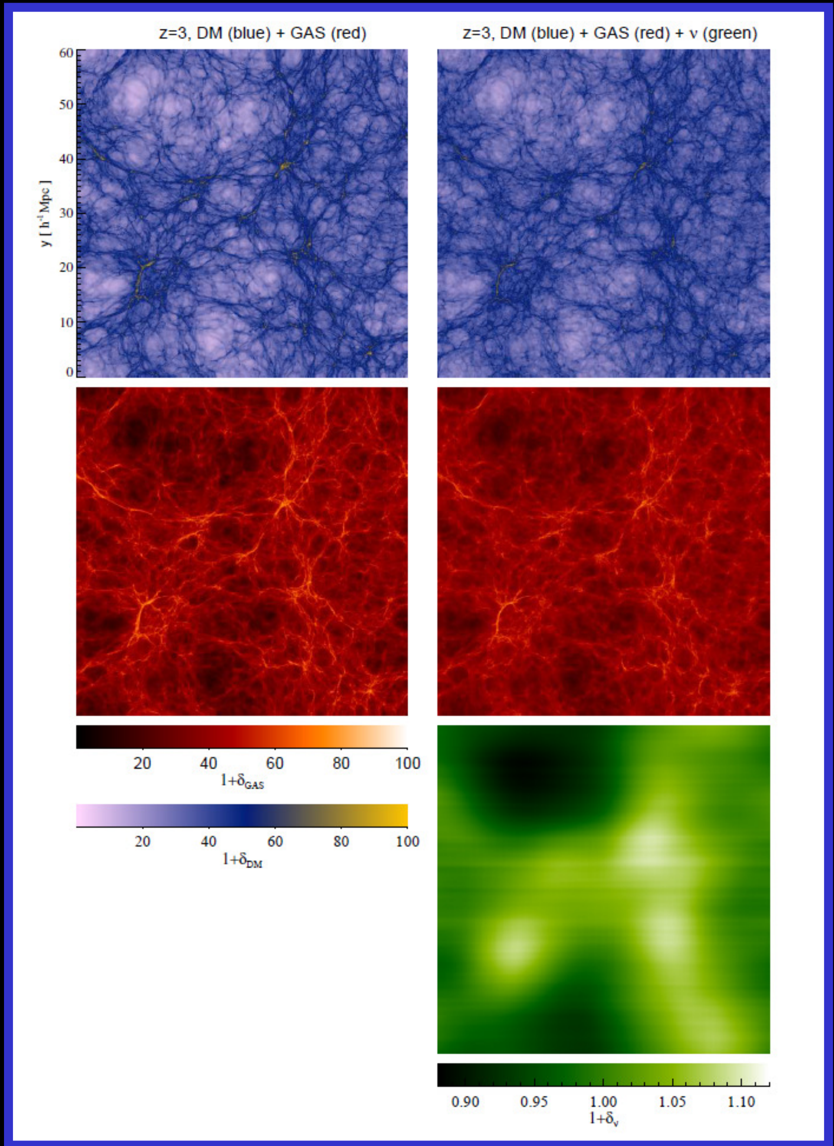
Non-linear effects on the matter power spectrum due to neutrinos

Only 3 active neutrinos



Bird et al. 2011

Gadget-III modified to include massive nutrinos with a particle-based implementation.



Viel et al. 2010

Density slices of thickness 6 h^{-1} comoving Mpc at z=3 extracted from two 60 h^{-1} Mpc hydrodynamical simulations with gas and dark matter and no neutrinos. The right column shows a simulation that includes neutrinos with $\mathbf{M}_{\nu}$ =1.2 eV. The presence of neutrinos (bottom panel, green) clearly affects both the gas (red) and the dark matter (blue) distribution.

DEMNUni simulations (PI: C. Carbone)

- **5×10^6 cpu-hours on BGQ/FERMI at CINECA to build up 10 mixed dark matter cosmological simulations**
- **Ω_m=0.271, Ω_Λ=0.729, Ω_b=0.045, h=0.703, σ_8=0.809, n_s=0.966, $0<M_\nu<0.3$ eV, $-1<w<-0.9$**
- **box-side size: 2 Gpc/h (64 times larger than Millennium)**
- **particle number: 2×2048^3 (CDM+ν)**
- **CDM mass: $6.5 \times 10^{10}\ M_\odot/h$**
- **softening length: 20 kpc/h**
- **starting redshift: z_{in}=99 (depends on M_ν for particle-based ν)**
- **# snapshots: 64**

GOALS

- mock galaxy catalogs via box-stacking and HOD
- mock shear maps via box-stacking and ray-tracing
- mock CMB weak-lensing and ISW/Rees-Sciama maps
- CMB/shear/galaxy-clustering statistics
- reference skies for future galaxy/shear/CMB-lensing probes, e.g. Euclid

The above includes a constant DE-background and M_ν effects at non-linear level