Cold dark energy and cosmological parameter estimation

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Dark Cosmology Centre

What cold dark energy & why

- k-essence with negligible speed of sound

$$c_s^2 = \frac{\delta p_Q}{\delta \rho_Q} = \frac{\bar{\rho}_Q + \bar{p}_Q}{\bar{\rho}_Q + \bar{p}_Q + 4M^4}$$

$c_s^2 \to 0$

$\delta p_Q \ll \delta \rho_Q$

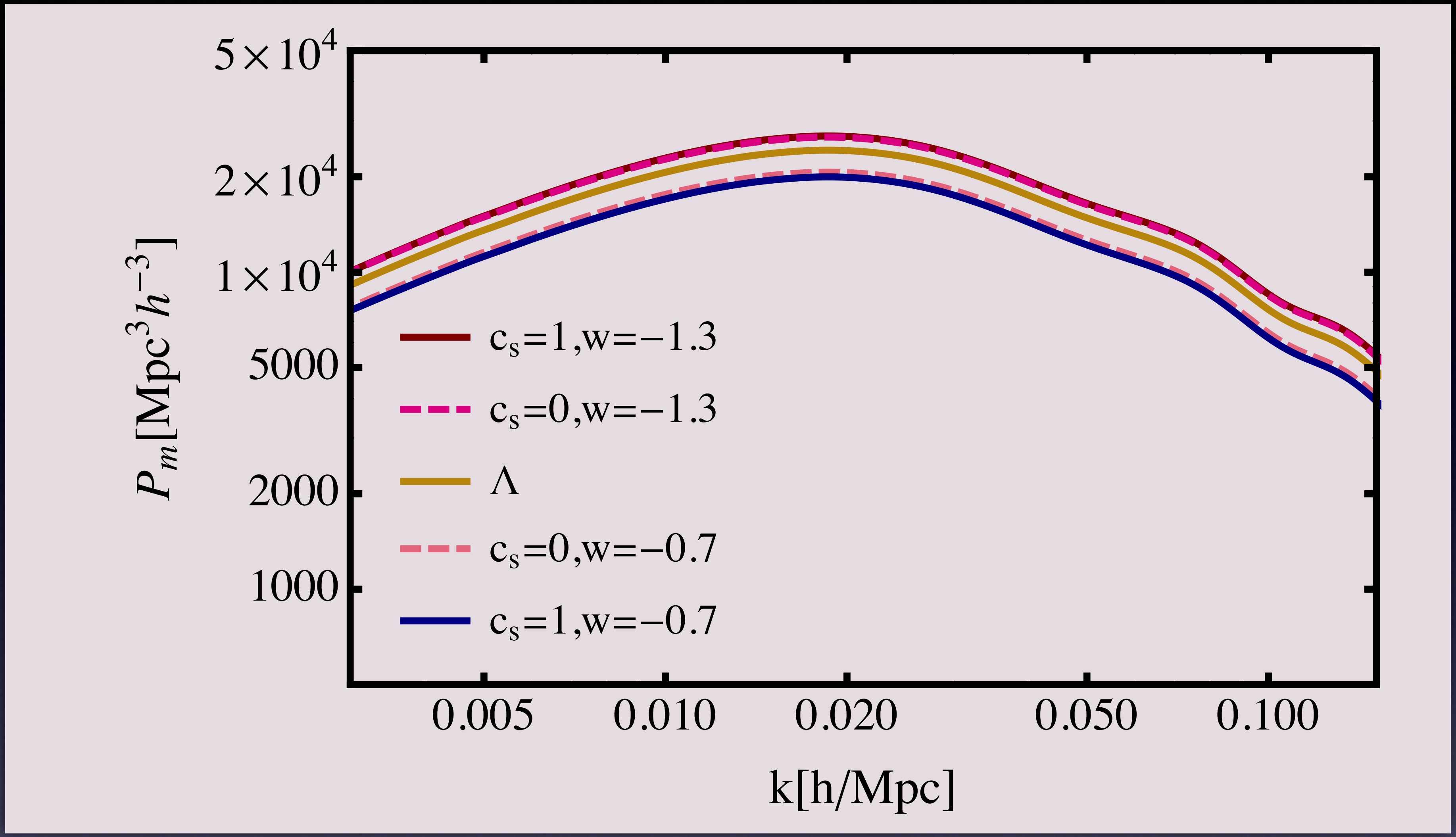
$M^4 = \bar{P}_{,XX} \bar{X}^2$

- comoving with CDM -> FLRW solution

- $c_s = 0$ vs. $c_s = 1$: ‘most extreme’ cases
  viable for $w < -1$

- DE pert. impact structure formation:
  linear & non-linear regime, sign for dynamical DE
  -> test scale dependence

Cold dark energy - CMB power spectrum

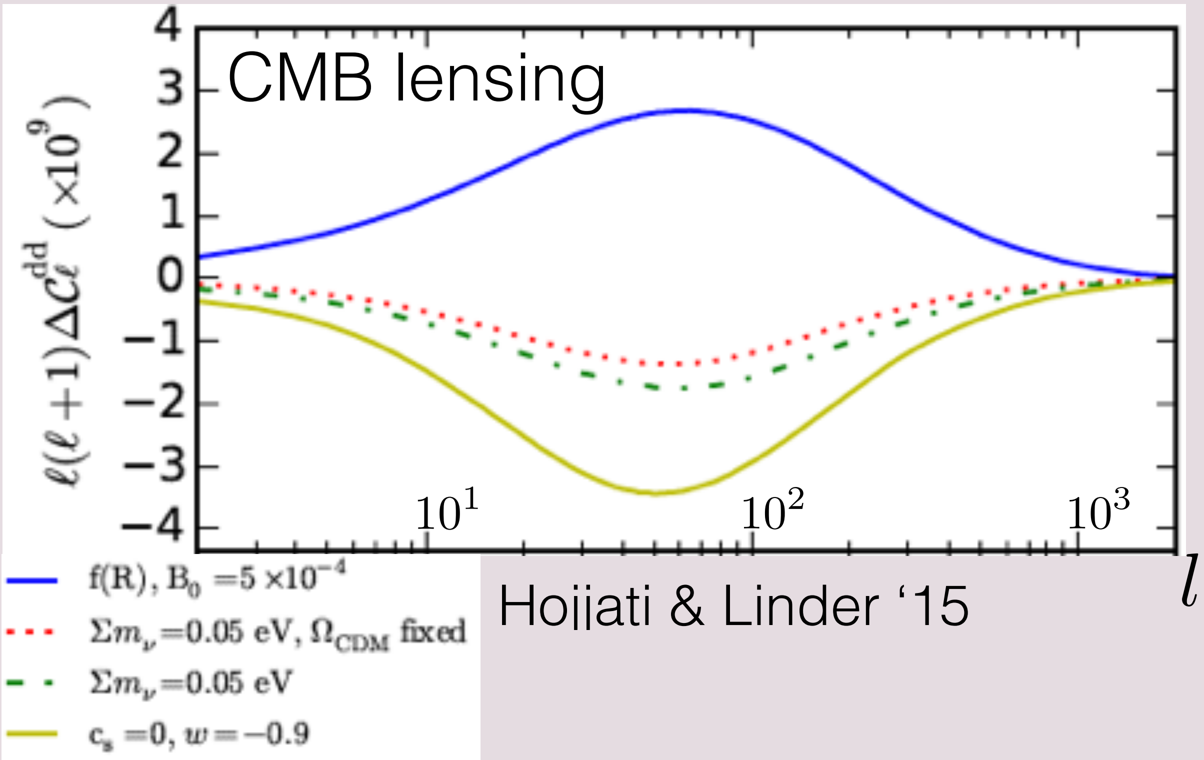


But e.g. Planck 2015 XIV results:

no change on w-limits when sound speed added as parameter

-> other probes, go non-linear

Cold dark energy - some observables



Hojjati & Linder '15

Majerotto, Sapone, Schäfer '15

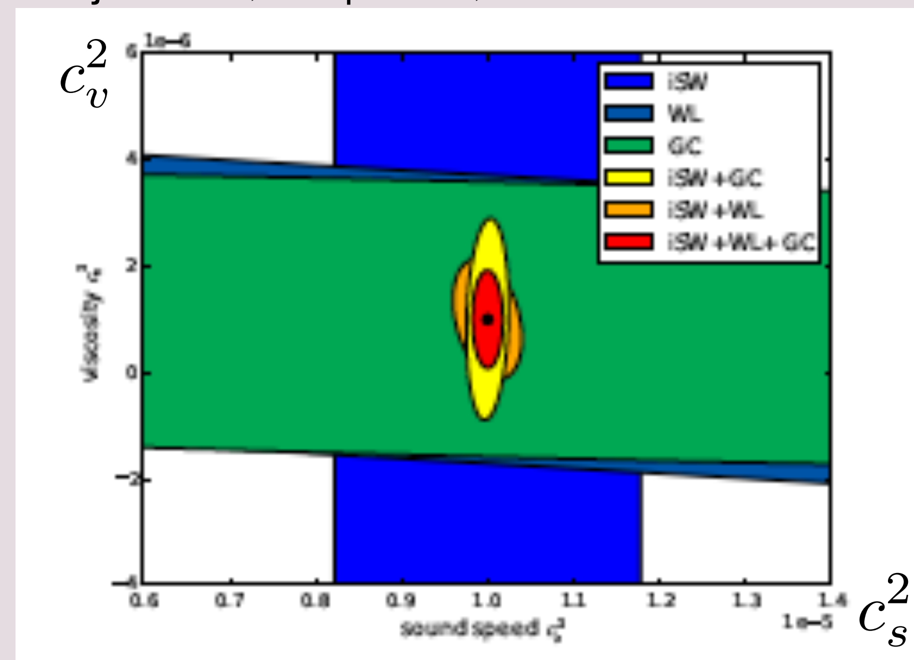
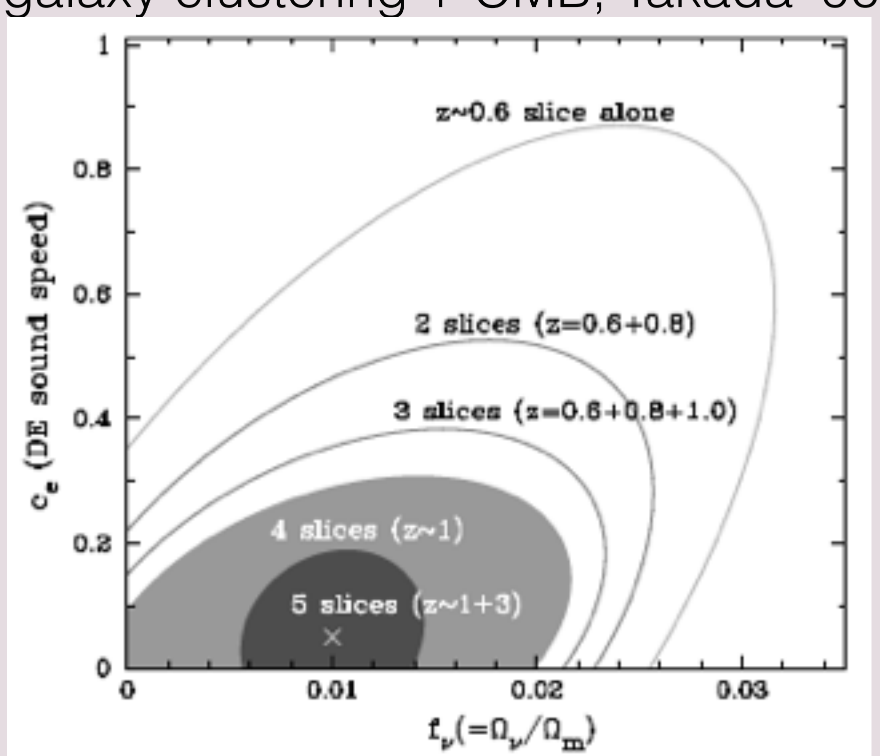


Figure 5. Forecasted 1σ-constraints on c_s^2 and c_v^2 for individual probes and all possible combinations, for the fiducial choice $c_s^2 = 10^{-5}$ and $c_v^2 = 10^{-6}$.

galaxy clustering + CMB, Takada '06



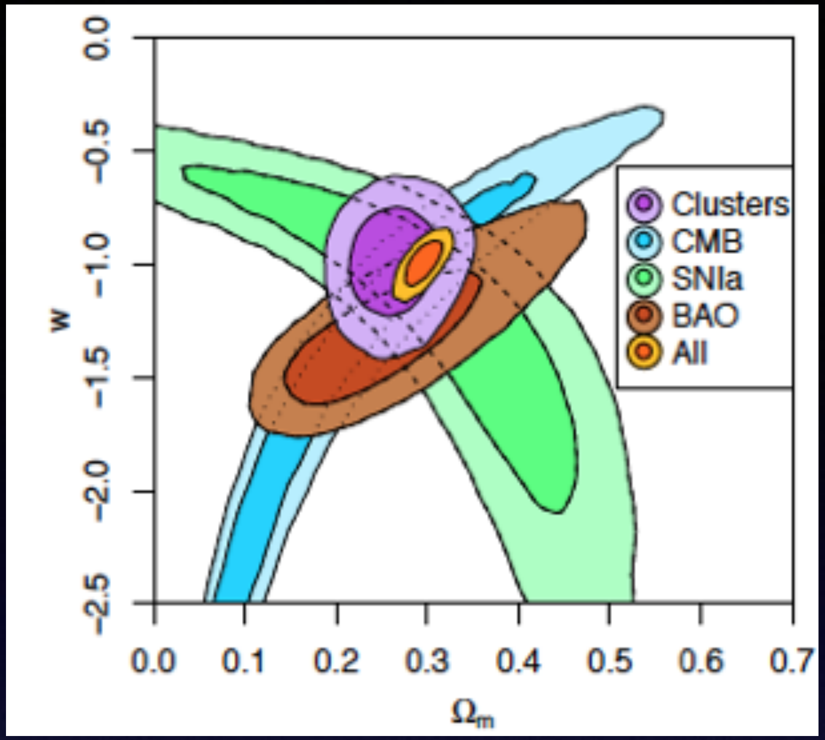
Planck +galaxy +cluster, Basse et al. '14

CMF	w_0	w_a (fixed)	$\hat{c}_s^2$	$\log \hat{c}_s^2$	$\log \hat{c}_s^2$ 68%(95%) C.I.
equation (3.1)	−0.83	0.00	10^{-6}	−6	$< -5.9(-3.5)$
equation (7.3)	−0.83	0.00	10^{-6}	−6	$< -1.4(1.4)$
$P_m^{lin}(k,z)$ only	−0.83	0.00	10^{-6}	−6	$< -2.5(0.12)$

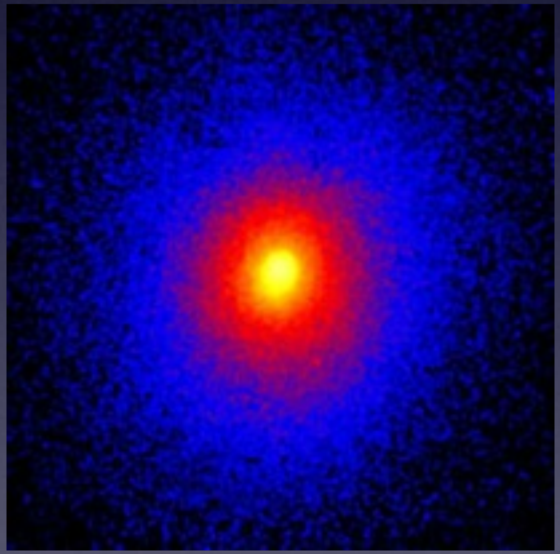
Parameter estimation - Cluster Cosmology

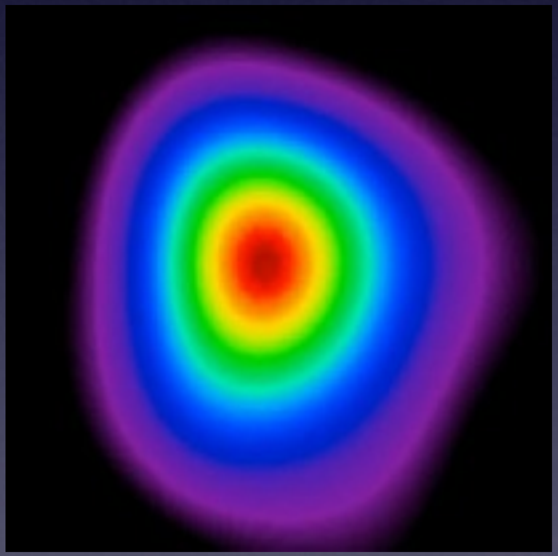
- Information on: expansion - background
  structure growth - linear / non-linear

- sensitive to scale dependence



Mantz et al ‘14b





Allen, Evrard, Mantz '11, credits: X-ray - Mantz, Optical - v. d. Linden, SZ - Marrone

- extended BCS (Ebeling et al ’98, 2000), REFLEX (Böhringer et al ’04), MACS (Ebeling et al ’01, ’07, ’10)
- X-ray follow-up 94 clusters (Mantz et al ‘14b)
- WtG: WL calibration 50 clusters (Subaru/CFHT, vd Linden et al ‘14)

Cluster number counts

Tinker-HMF:
(Tinker et al '08)

$$\frac{\mathrm{d}n_T}{\mathrm{d}M}(M,z) = f(\sigma)\,\frac{\bar{\rho}_m}{M}\,\frac{\mathrm{d}\log\sigma^{-1}}{\mathrm{d}M}$$

Sheth-Tormen:
(Sheth & Tormen '09)

$$\frac{\mathrm{d}n_{ST}}{\mathrm{d}M}(M,z) = \nu f(\nu)\,\frac{\bar{\rho}_m}{M^2}\,\frac{\mathrm{d}\log\nu}{\mathrm{d}\log M}$$

$$\nu f(\nu) = A\sqrt{\frac{a\nu}{2\pi}}\left[1+(a\nu)^{-p}\right]\exp\left[-a\nu\right]$$

with peak height $\nu = (\delta_c/\sigma_M)^2$

via Spherical Collapse: $\delta_c(z)$

$+\,f_{gas}$

Spherical Collapse formalism

- spherical homogeneous top-hat overdensity
  ≙ closed FLRW universe with scale factor R

- SC approximation valid for $c_s = 0$ and $c_s = 1$

Pseudo-Newtonian approach:

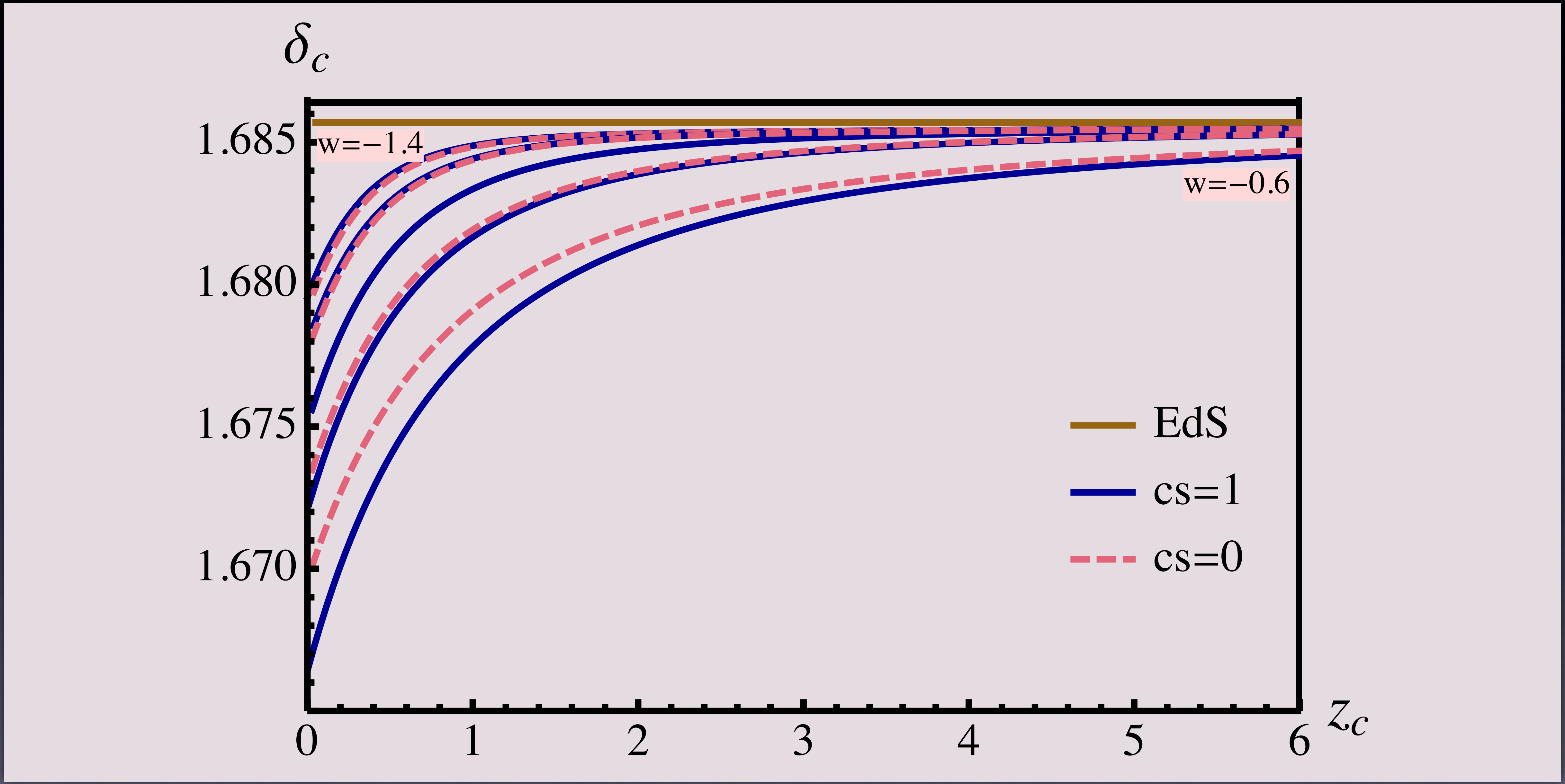
$$\dot{\delta}_i + 3H\left(c^2_{s,i} - w_i\right)\delta_i + \frac{\theta_i}{a}\left[(1+w_i) + \left(1 + c^2_{s,i}\right)\delta_i\right] = 0$$

$$\dot{\theta}_i + 2H\theta_i + \frac{\theta_i^2}{3a} = \nabla^2\phi$$

$$\nabla^2\phi = -4\pi G \sum_i \left(1 + 3c^2_{s,i}\right) a^2 \bar{\rho}_i \delta_i$$

see e.g. Pace et al.'14, Creminelli et al. '08

Linear density threshold of collapse $\delta_c(z)$

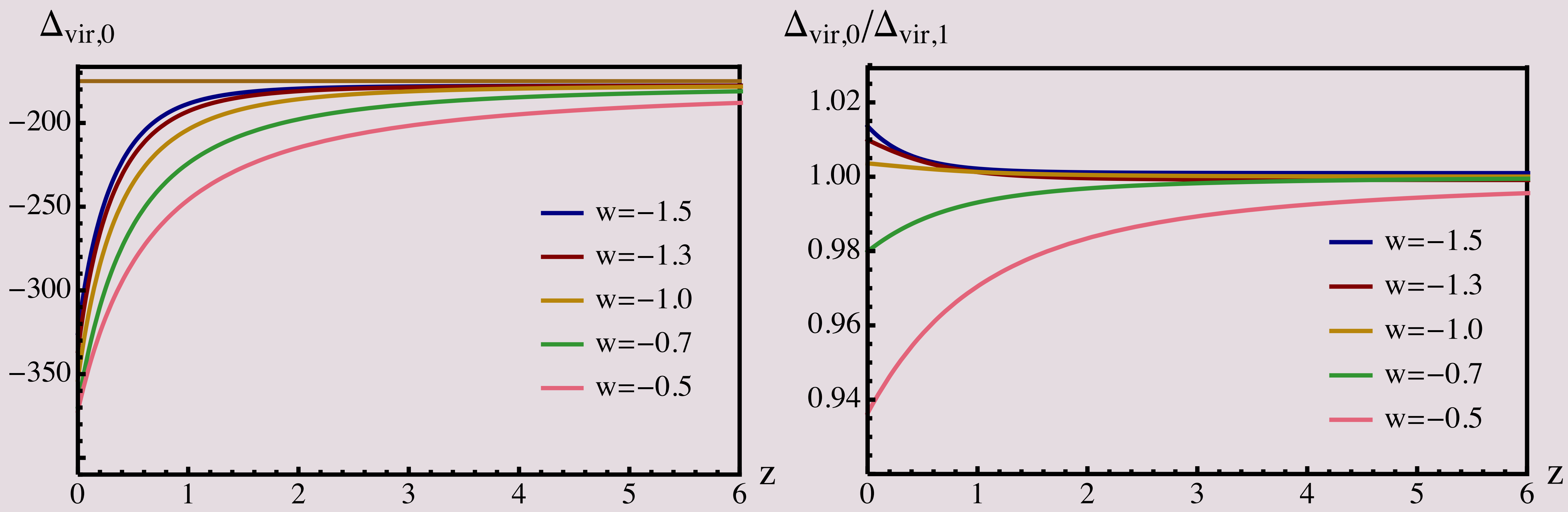


dependence on cosmological parameters

Virial threshold

$$\Delta_{vir} = (\delta_{NL,vir} + 1) = (\delta_i + 1)\left(\frac{a_{vir}}{a_i}\right)^3 \left(\frac{R_i}{R_{vir}}\right)^3$$

(with time of virialization depending on turn-around)



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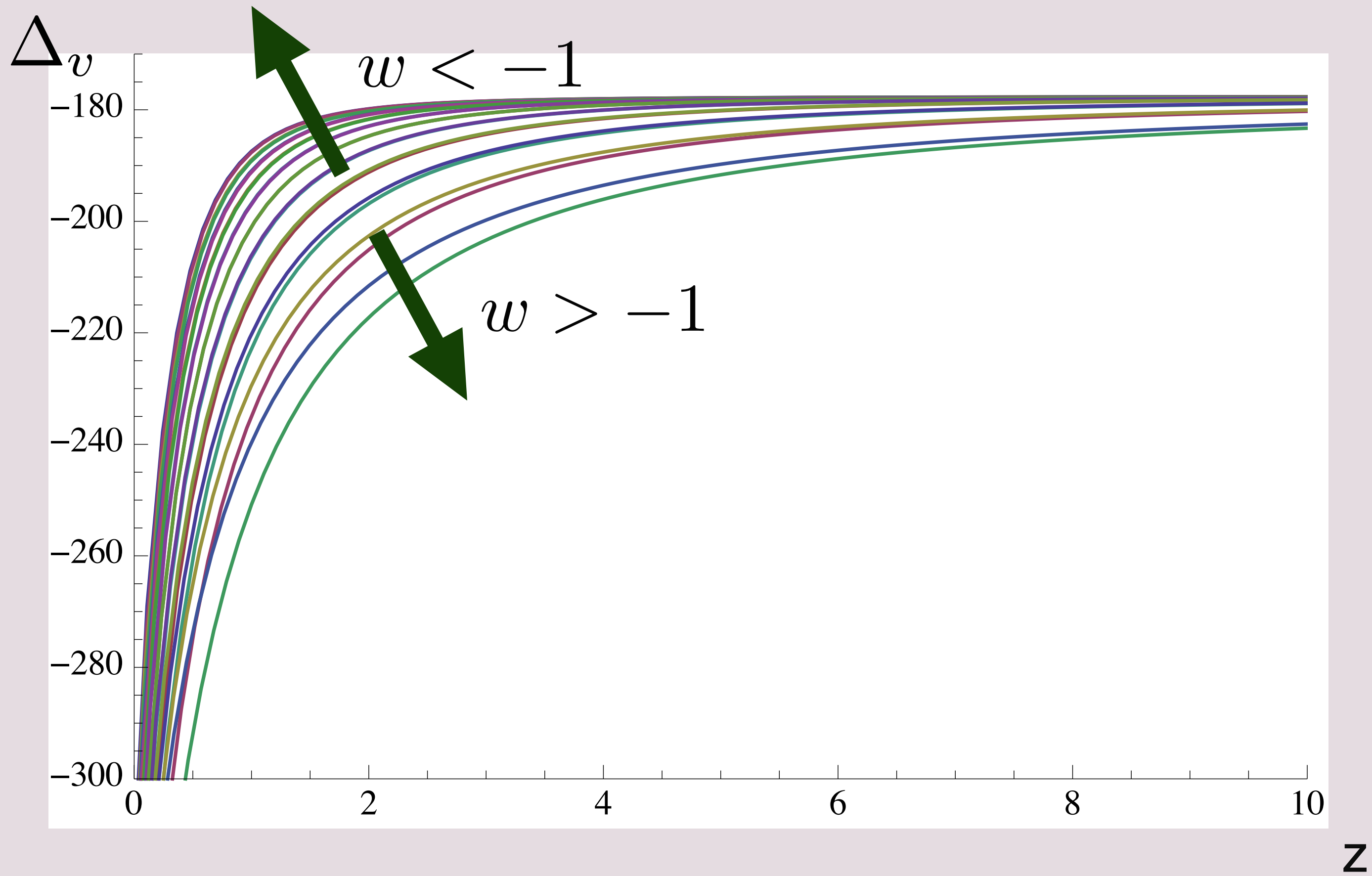


$$\Delta_{vir}(z) = -\left[18\pi^2 + a\,(1 - \Omega_m(z)) + b\,(1 - \Omega_m(z))^2\right] / \Omega_m(z)$$

include: DE mass

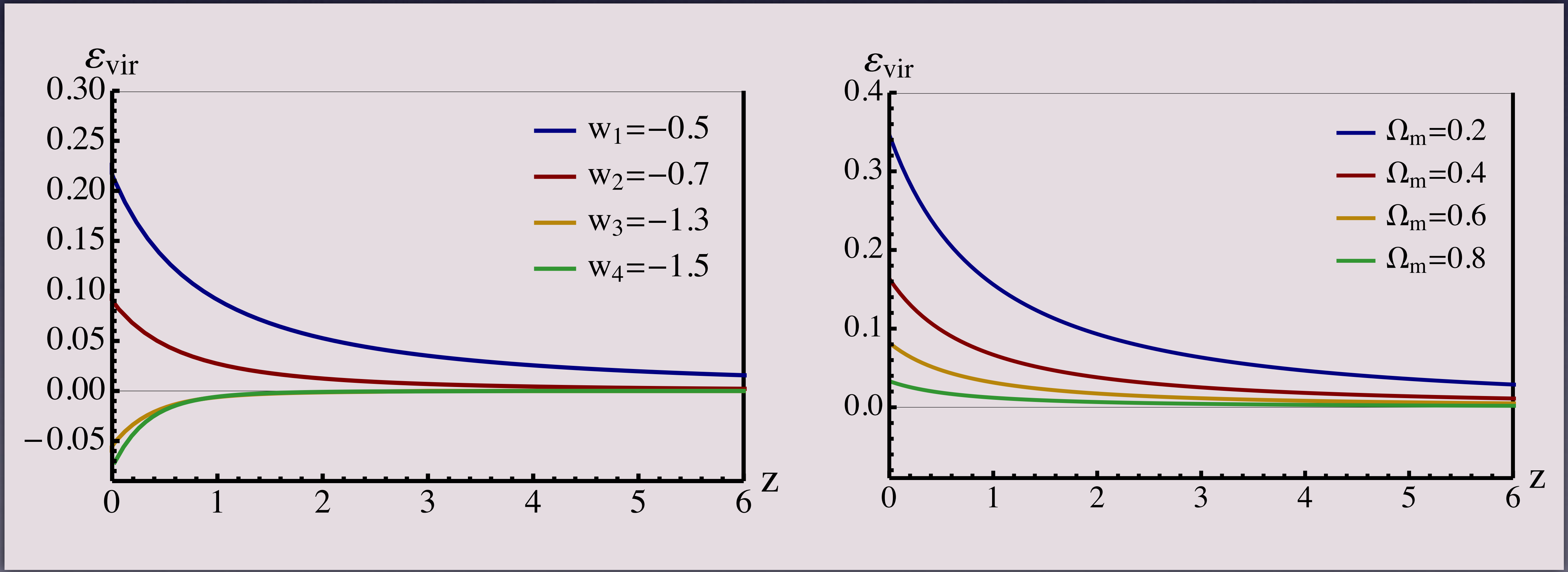
$$M_{e,v} = \frac{4\pi}{3} R_v^3 \bar{\rho}_{e,v} \delta_{e,v}$$

$$M_{m,v} = \frac{4\pi}{3} R_v^3 \bar{\rho}_{m,v} \left(\delta_{m,v} + 1\right)$$

$$\Bigg\} \quad \epsilon\left(z\right) = \frac{M_{e,v}}{M_{m,v}}$$

[Creminelli et al ’08]

$$M \rightarrow M\left(1+\epsilon\right) : \qquad \frac{\mathrm{d}n}{\mathrm{d}\log M}\left(M,z\right) \rightarrow \frac{\mathrm{d}n}{\mathrm{d}\log M}\left(M\left(1-\epsilon\right),z\right)$$



Calibrated HMF:

$\delta_c \;\; \Delta_{vir} \;\; \epsilon$

$$\frac{\mathrm{d}n_{cal}}{\mathrm{d}M}(M,z) = \frac{\mathrm{d}n_{ST}/\mathrm{d}M\,(M,z;c_s=0)}{\mathrm{d}n_{ST}/\mathrm{d}M\,(M,z;c_s=1)} * \frac{\mathrm{d}n_T}{\mathrm{d}M}(M,z)$$

- ★ Account for non-linear effects via ratio ST-HMFs
- ★ Shape of Tinker-HMF
  - solely based on linear order
  - accurate N-body fit
  - widely used in parameter estimation (cluster)

Calibrated HMF:

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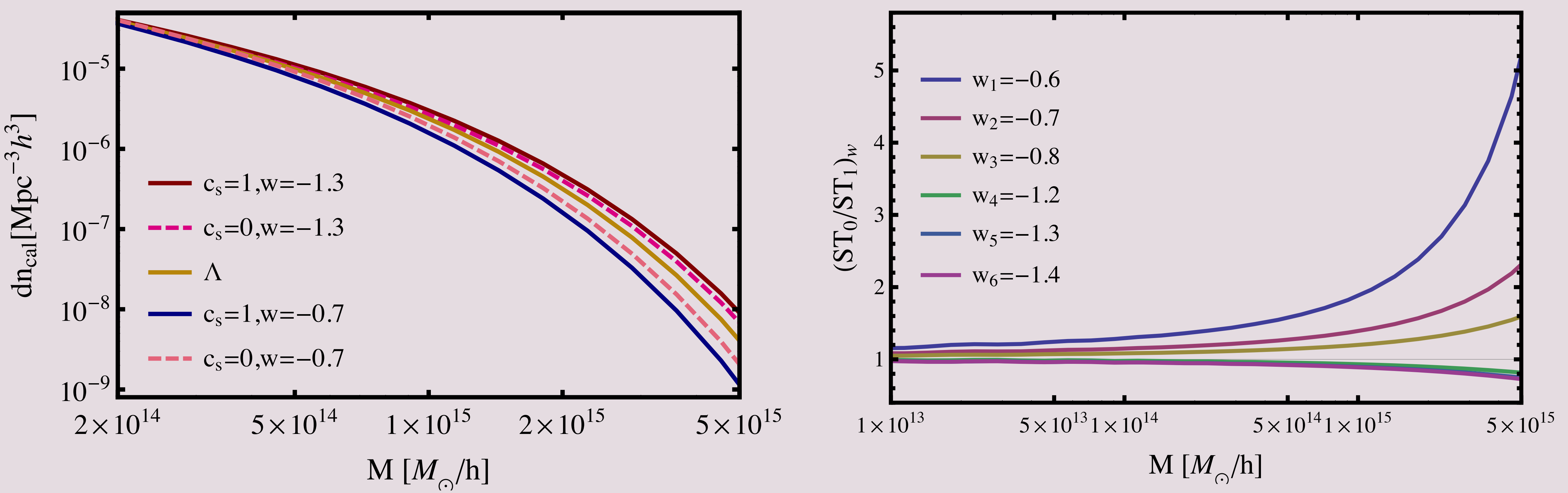

-> scale dependence, high-mass end

Calibrated HMF:

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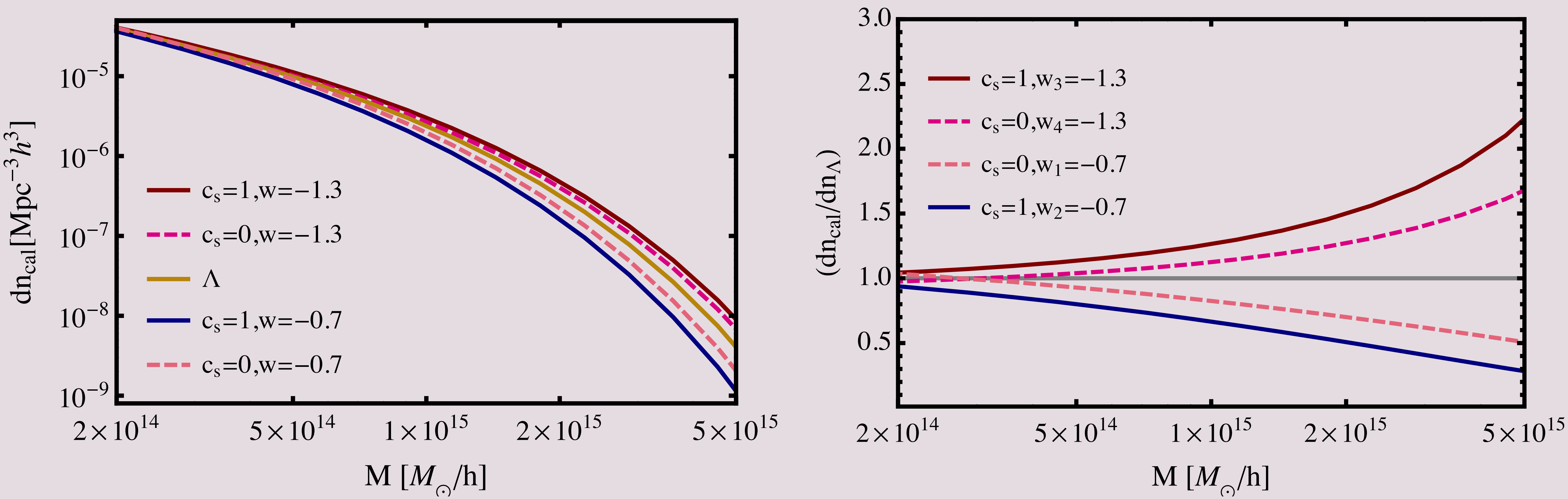


-> scale dependence, high-mass end

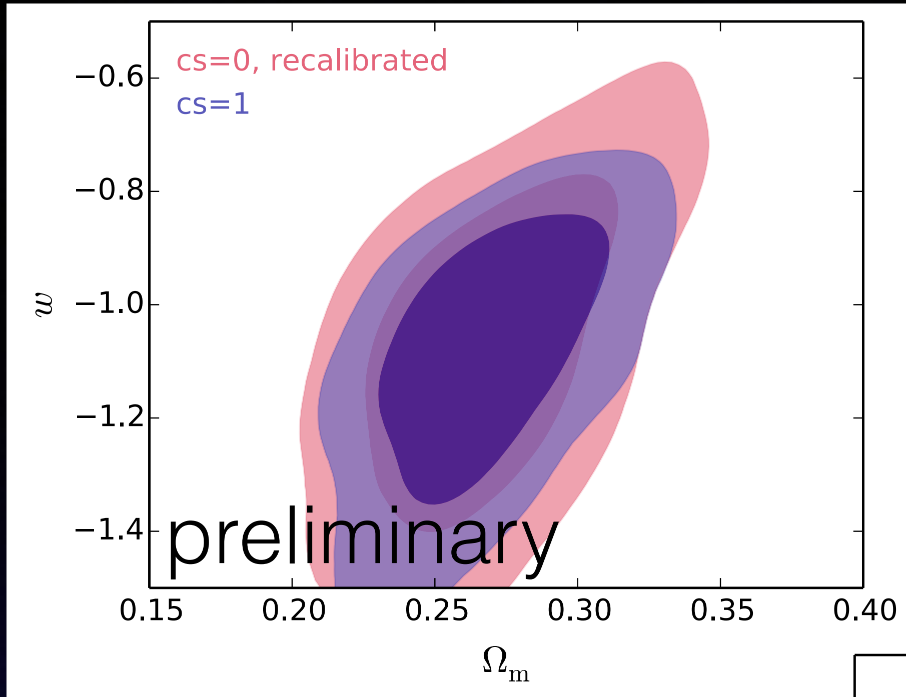
+ Cluster sample

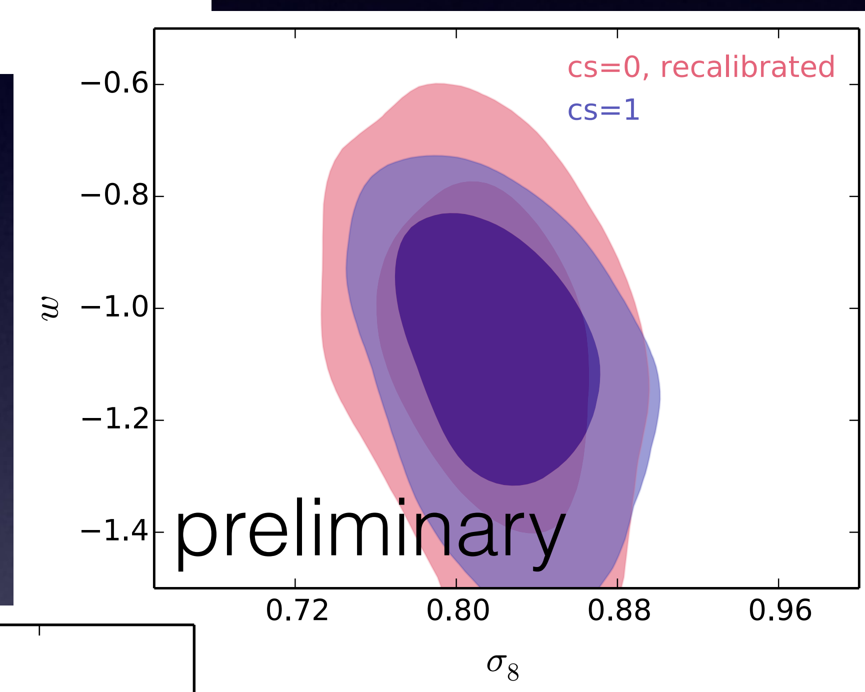
+ Account for errors & covariances in HMF

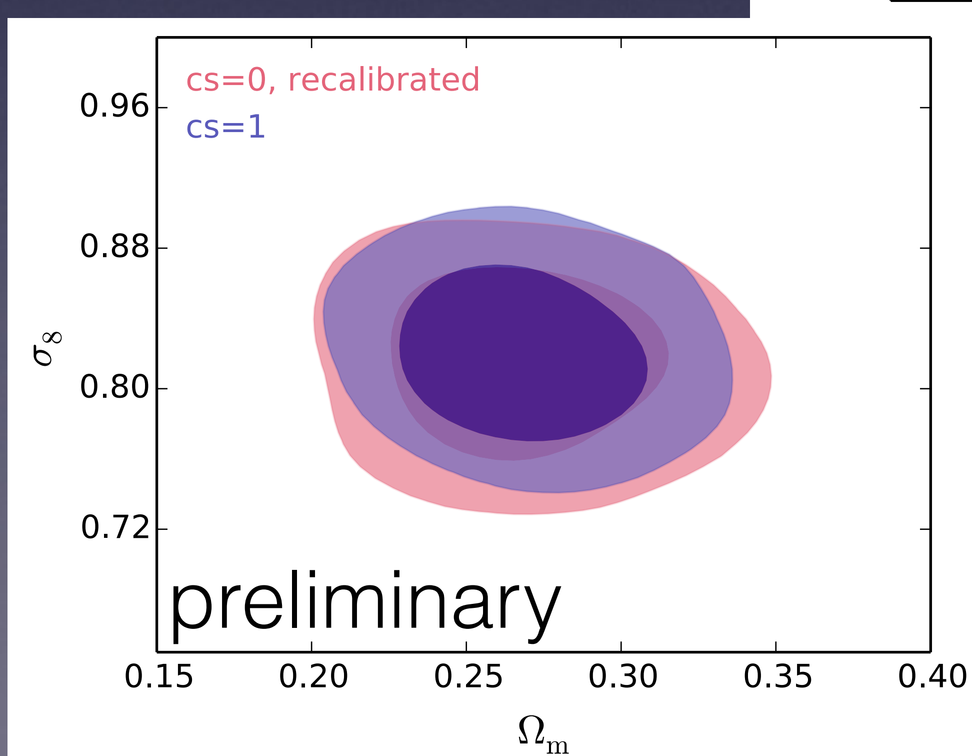
+ Spherical Collapse: $\delta_c\,, \Delta_{vir}, \epsilon$

+ Calibrated HMF: $\frac{\mathrm{d}n_{cal}}{\mathrm{d}M}\,(M,z) \propto \frac{(\mathrm{d}n_{ST}/\mathrm{d}M)_{c_s=0}}{(\mathrm{d}n_{ST}/\mathrm{d}M)_{c_s=1}}$

→ MCMC (CAMB & CosmoMC)







calibrated, preliminary*

$$\Omega_m = 0.263 \pm 0.015$$
$$w = -1.11 \pm 0.06$$
$$\sigma_8 = 0.813 \pm 0.032$$

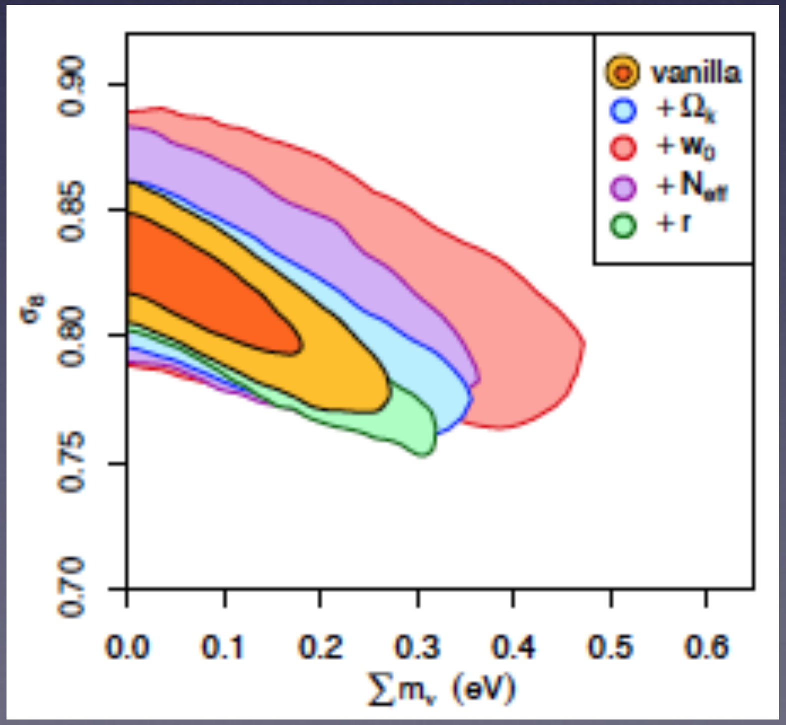
* CH (+Rapetti, Cataneo, Mantz, Allen, vd Linden, Applegate) to be submitted

- feasible to include non-linear model characteristics
- possible bias, needed for precision cosmology
- test for dynamical DE, scale dependence!
  different for modified gravity, neutrino mass

Improvements

- use lensing, other combinations
- bigger effect for early DE
- let the sound speed vary

cluster + CMB + SN + BAO

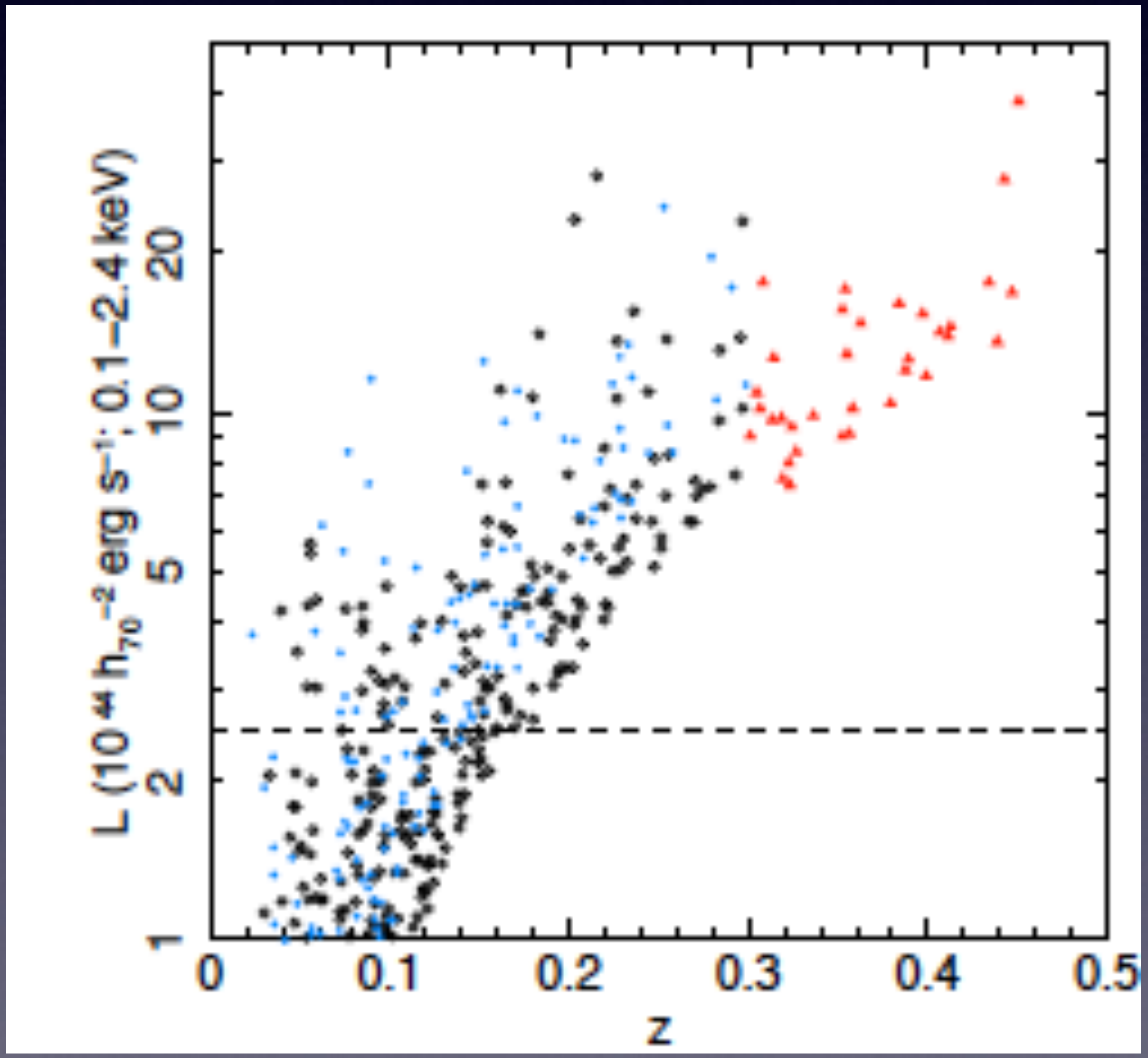


Mantz et al. ‘15a

backup

Cluster sample

Select bright, relaxed, redshift complete clusters: set of 224, $L > 2.55 * 10^{44} h_{70}^{-2} erg/s$



- extended BCS (Ebeling et al ’98, 2000)
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+

- X-ray follow-up of 94 clusters (Mantz et al ‘14b)
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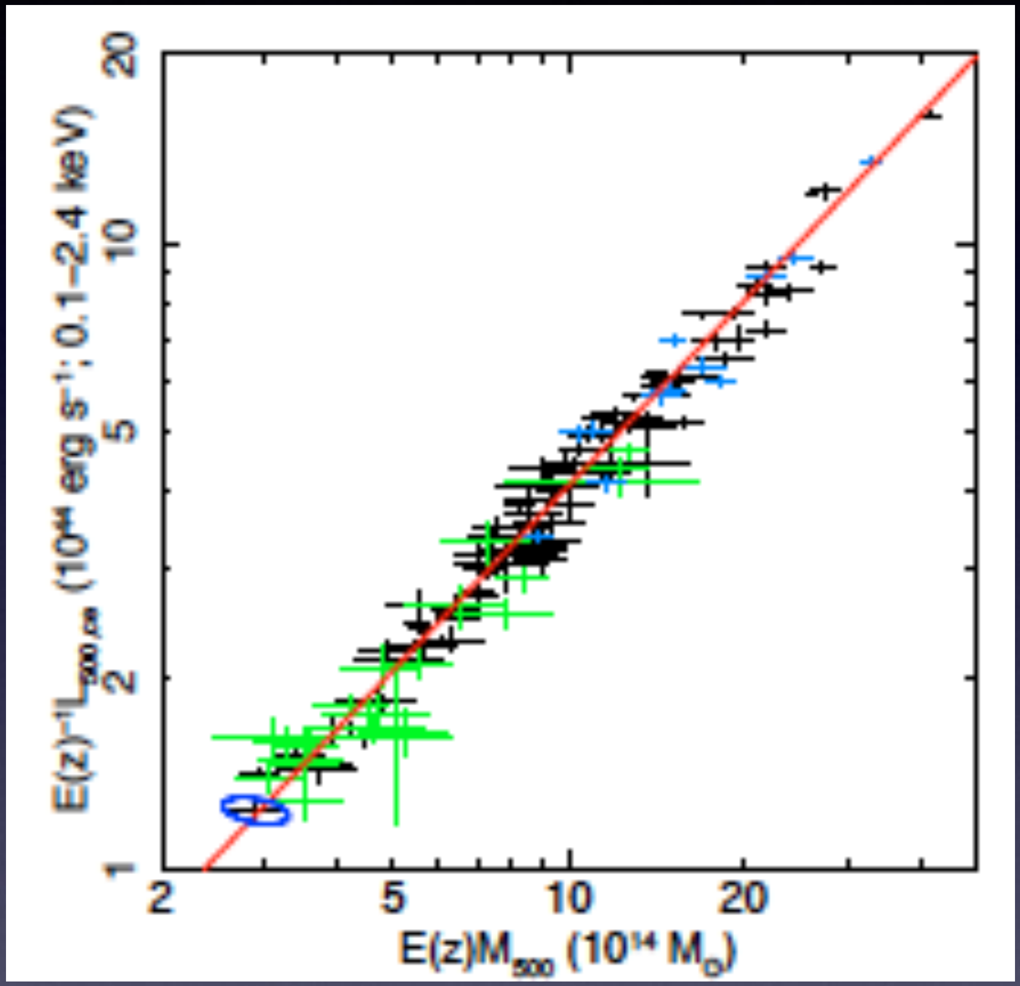
Scaling relations: observable-mass



Mantz et al ‘14b

X-ray follow-up of 94 clusters

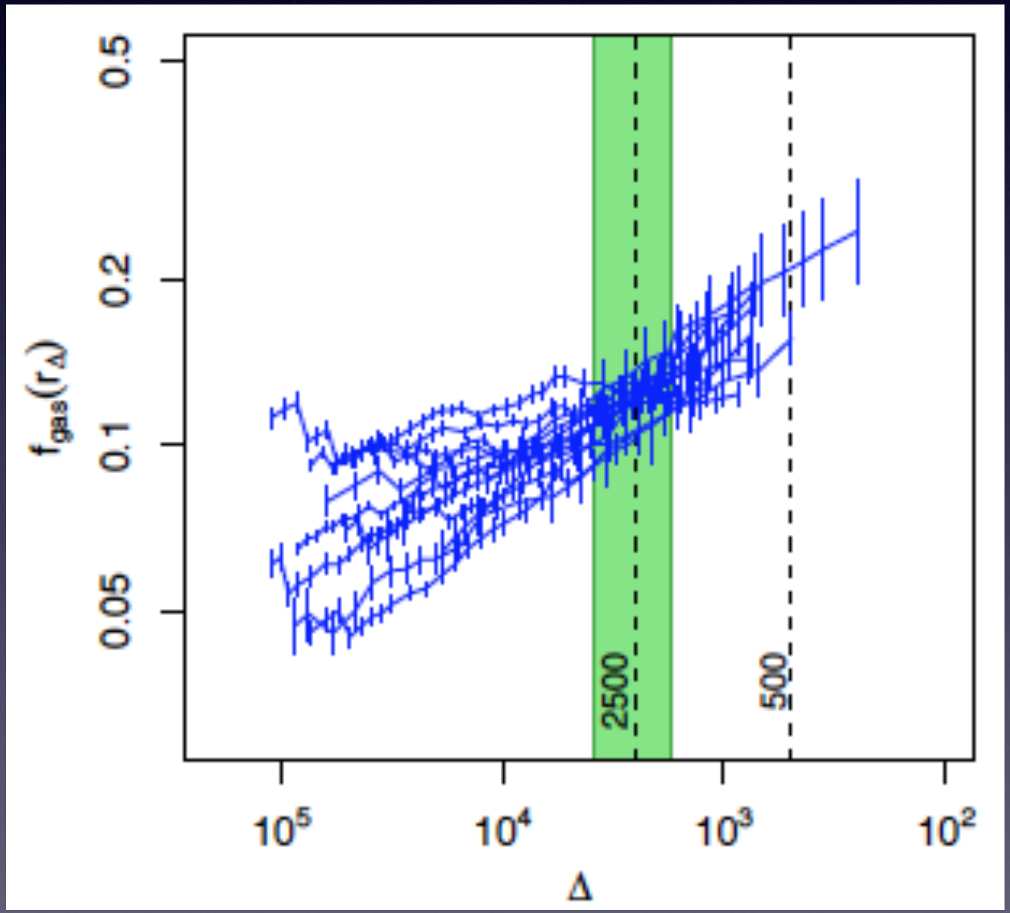
mean relation + intrinsic scatter, <10% scatter in L-M-relation

simultaneous analysis of (flux-lim.) survey and follow-up data

+ ‘Weighing the Giants’ (WtG): Weak lensing mass calibration of 50 clusters (Subaru/CFHT)

Gas mass fraction f_{gas}

$$f_{gas}^{\Lambda CDM}\left(z;\theta_{2500}^{\Lambda CDM}\right) = f_{gas}^{true}\left(z;\theta_{2500}^{\Lambda CDM}\right)\left(\frac{d_A^{\Lambda CDM}}{d_A^{true}}\right)^{3/2}$$



Mantz et al ‘14a

with

$$f_{gas}^{true}\left(z;\theta_{2500}^{\Lambda CDM}\right) \propto \left(\frac{\Omega_b}{\Omega_m}\right)$$

luminous & dyn. relaxed clusters

- 40 clusters within $0.07 < z < 1.1$

Tracking the radius evolution example