Implications for Dark Energy from Cluster Surveys

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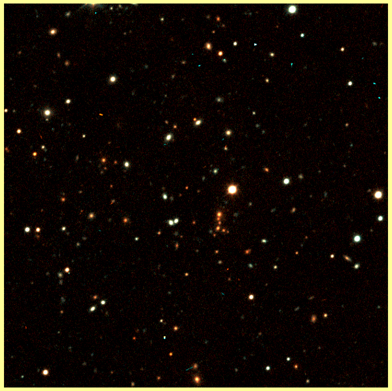
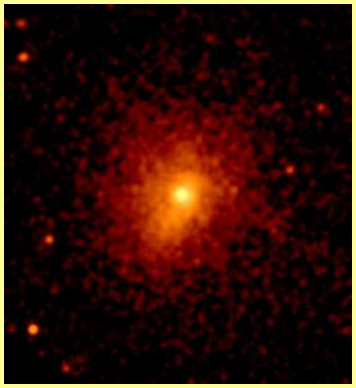
What Are Galaxy Clusters?

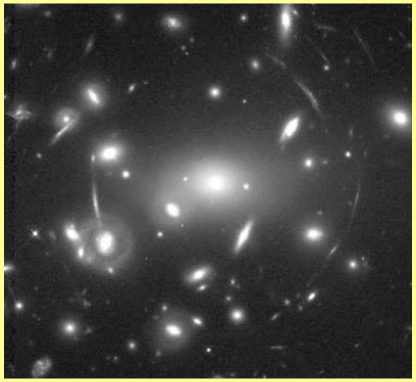
Galaxy clusters are the most massive, collapsed structures in the universe. They contain galaxies, hot, ionized gas ($10^{7\text{-}8}$K) and dark matter. They are good probes, because they are massive and "easy" to detect. (But, we don't understand them all too much!)



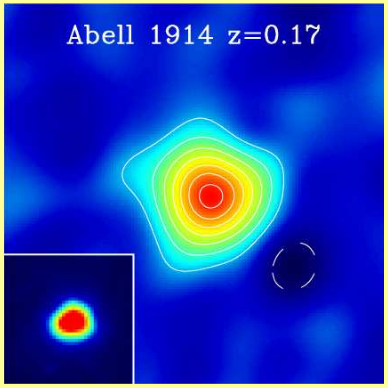
Light from galaxies



X-ray emission



Gravitational lensing



Sunyaev-Zel'dovich Effect

Past Cluster Surveys

Example from XRay:

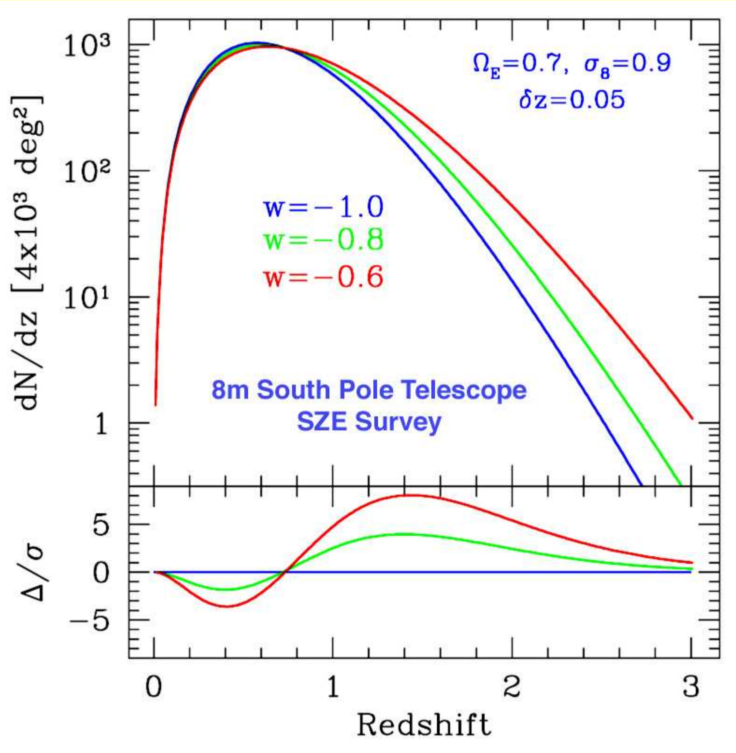
SURVEY	Fluxlim (erg/s/cm^2)	Area (deg^2)	No of clusters
XBACS (96)	5.0E-12	All Sky	276
BCS (98)	4.5e-12	13,578	199
RASS1BS (99)	3-4E-12	8,235	130
Ledlow (99)	~	14,155	294
Ebcs (00)	3.0E-12	13,578	299
HiFLUGS (02)	20.0E-12	13,578	63
NORAS (00)	3.0E-12	13,578	378
NEP (01)	0.03E-12	80.7	64
CIZA (02)	5.0E-12	14,058	73
SGP (02)	3.0E-12	3,322	112
MACS (01)	1.0E-12 (z>0.3)	22,735	120
REFLEX (01)	3.0E-12	13,905	452 (2460)

Upcoming/Planned Surveys

Survey	Sensitivity	Area (deg^2)	No of clusters
Planck	~5mK (HFI)	All sky	5,000-20,000
SPT	>1mK	4000	>15,000
ACT	~1mK	100	1000-2000
APEX-SZ	~1mK	150-200	1000-2000
SZA	<1mK	12	> 100 (detail)
RCS-2	2.10^{14} M_{sun}	1000	5000-10,000
XMM-LSS	1.25e-14	64	~1000
XMM-Serendpt	3.75e-14	800	~ 5000
DUO (declined)	2.1E-13; 2.85e-14	6000; 200	8000; 1600

Cluster Redshift Distribution: effect of *w*

$$\frac{dN(z)}{dz d\Omega} = \frac{dV}{dz\, d\Omega} n(z) = \frac{c}{H(z)} d_A^2 (1+z)^2 \int_0^\infty dM\, f(M) \frac{dn(M,z)}{dM}$$

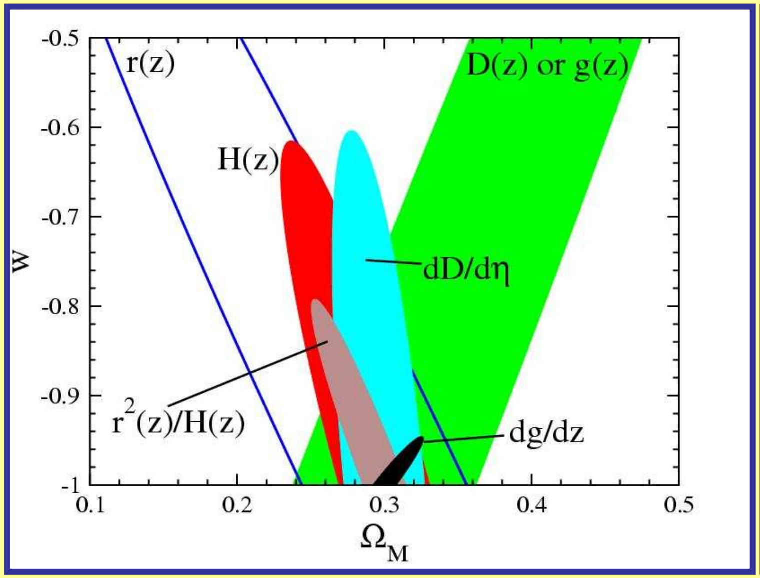


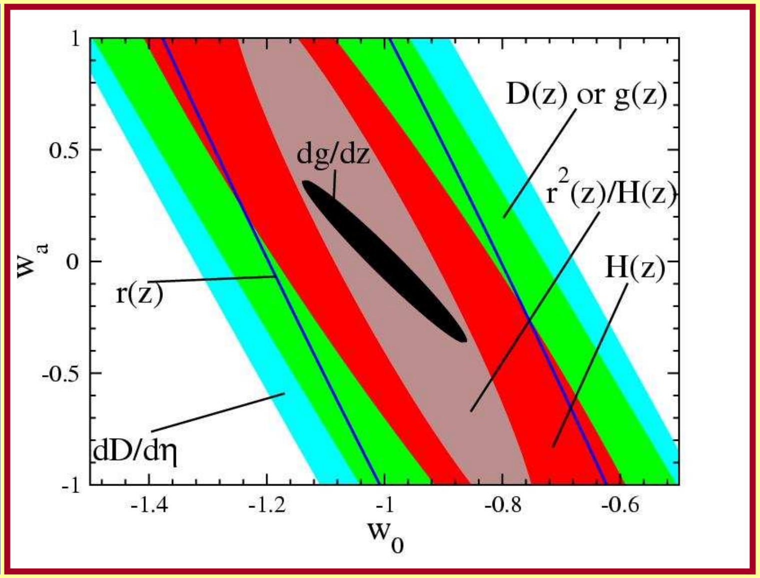
Cluster redshift distribution probes:

1) **volume-redshift relation : $\phi(H(z))$**
2) **abundance evolution ---**
   - **growth function : $\phi(H(z))$**
   - **density fluctuation: σ_8, n_s**
3) **cluster structure and evolution.**

f(M) contains the connections between the better understood theory of the formation of massive halos and the real world observations.

‘Underlying’ probes of *w* : *where do clusters fall?*



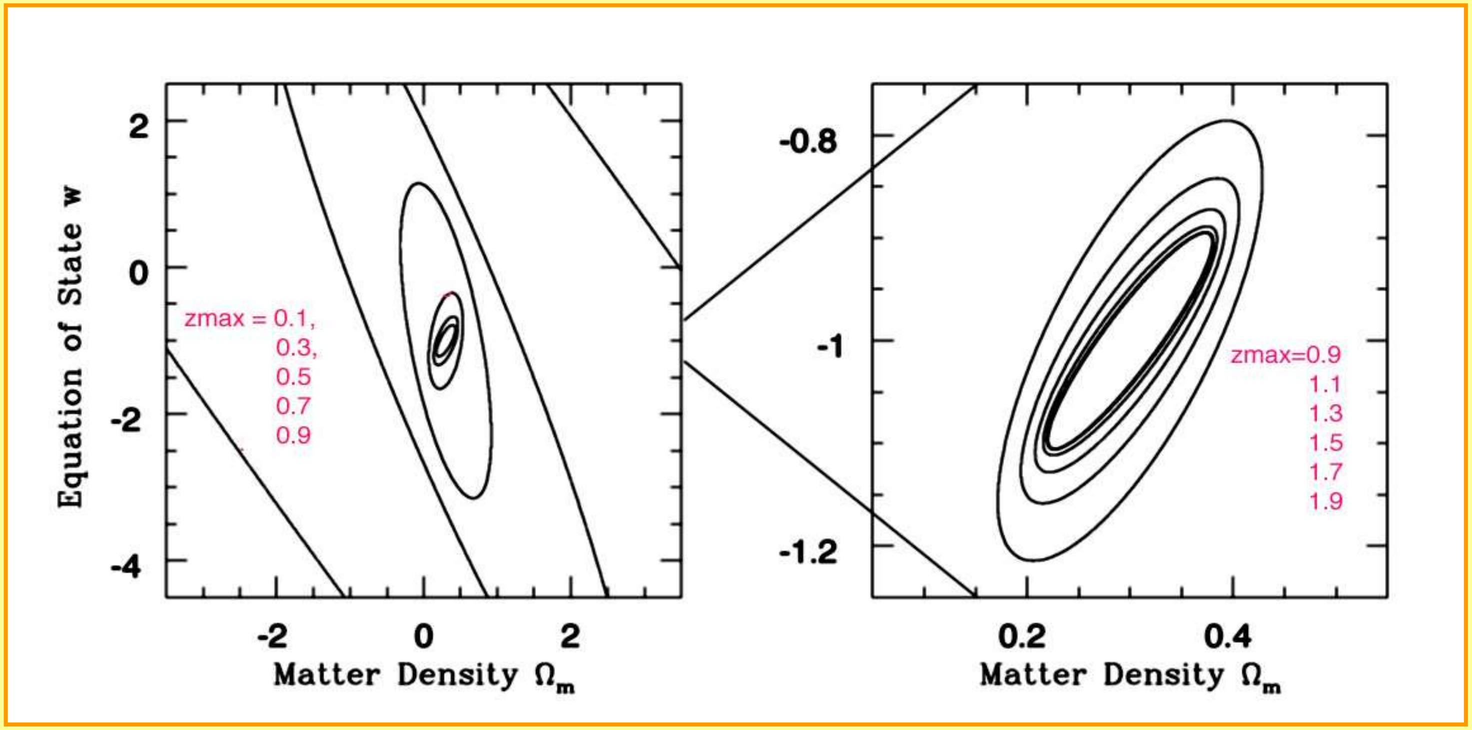


Cooray etal 2004

10% error on expansion history, distance, volume, growth and rates of change of growth

Cluster surveys: volume –vs- growth function

Rotating ellipses...



Levine, Shultz & White, 2002

selection function f(M) :

We would like ***survey to be mass-limited above M_{lim}***

(A 4000 deg survey to $M_{lim} = 10^{14} h^{-1}$ can constrain w to few percents!!)

However, we have ***surveys to be flux limited above S_{lim}***

Mass selection function (*some* flux-mass relation)

$$S_\nu = f(\nu) A_{SZ} M^\alpha E(z)^{2/3} (1+z)^\gamma \qquad ; H(z) = H_0 E(z)$$

$$S_\nu = f(\nu) \exp[A(z)] M^{\alpha(z)}$$

We are left with unknown cluster parameters.
Remember: Existing cluster catalogs give us an idea of these scalings.
However, much difference between observational and simulation results.

Cluster uncertainties lead to diluting dark energy constraints
(to un-interesting levels ~ 10's of % constraint on w)

Comments on Cluster Structure & Evolution

Tight scaling relations in cluster properties exist both in observations and in hydro simulations of structure (Evrard 99, Bryan & Norman 98, Mathiesen & Evrard 01)

These virial scaling relations appear to persist at intermediate redshift in observations (Mohr etal 99, 00; Sanderson etal 03, etc) **and high redshifts** (Ettori etal 04)

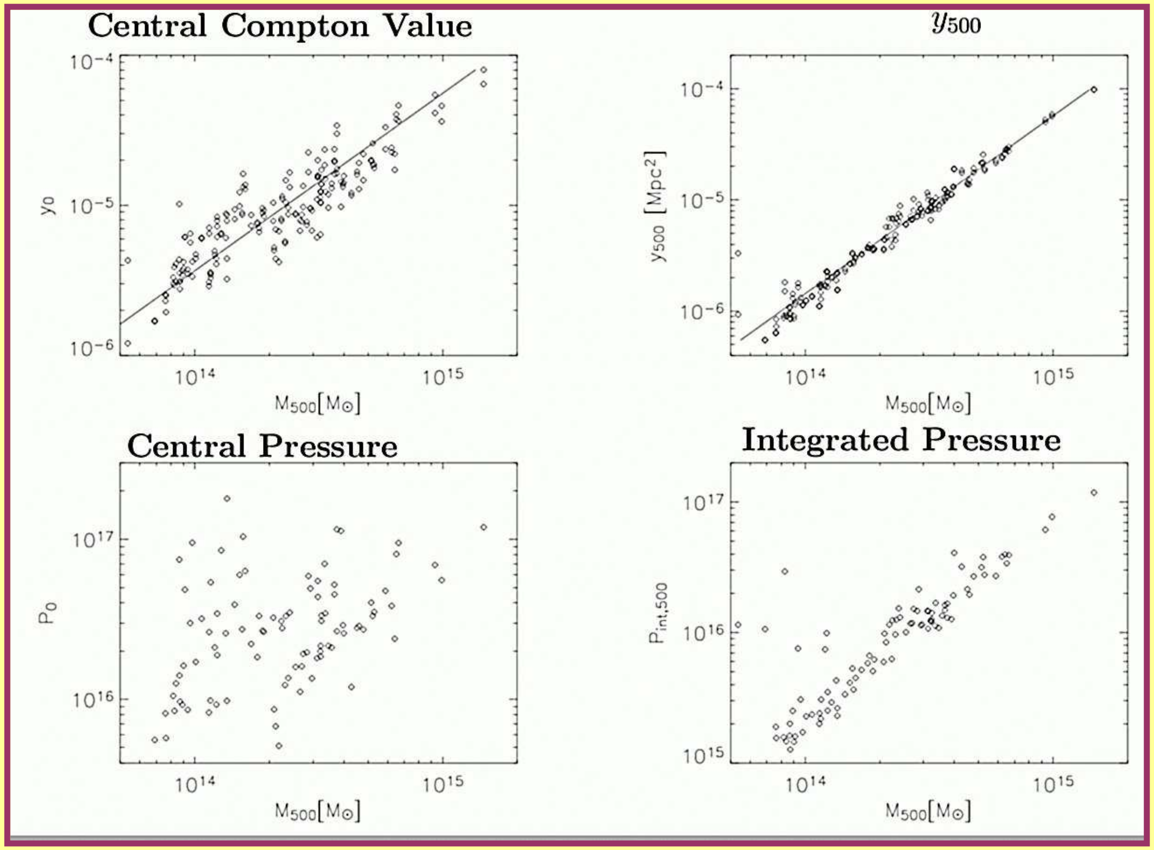
However, we know clusters are 'messy', with detailed substructures seen in Chandra observations. At high redshifts, they are young and have frequent mergers.
From simulations, mergers show departure from hydrostatic equilibrium (Ricker & Sarazin 02)

So, Is this the end of the story?

No, mergers are common but major mergers are rare (Lacey & Cole 94, Sheth & Tormen 99)
So, 'statistically' departure from equilibrium is in general 'small'

Dynamical relaxation occurs quickly . Example: 75 major mergers for 24 clusters, approx merger timescale 2.7 Gy, relaxation timescale 2.5 Gyr. Sample almost always at quasi-hydrostatic equlibrium (from Mathiesen & Evrard 01)

Observables as mass proxy: the SZ flux



Motl etal 2005

Simulations suggest that the integrated SZ flux (here y500) has less scatter than other observables (like Xray temp/flux) and is a better mass proxy

‘Self-Calibration’ or Techniques to overcome cluster-physics uncertainties...

Self Calibration is vital for cluster surveys to work in presence of uncertain cluster physics

Options:

1.Using shape of mass-function in redshift slices

(Hu 2003, Majumdar 2005)

2.Using the cluster power spectrum and P(k) oscillations

(Majumdar & Mohr 2004, Hu & Haiman 2004, Huetsi 2005)

3.Adding information from counts-in-cell

(Lima & Hu 2004, 2005)

4.Limited mass follow-up (using XRay temp/weak lensing)

(Majumdar & Mohr 2003,2004, Majumdar 2005)

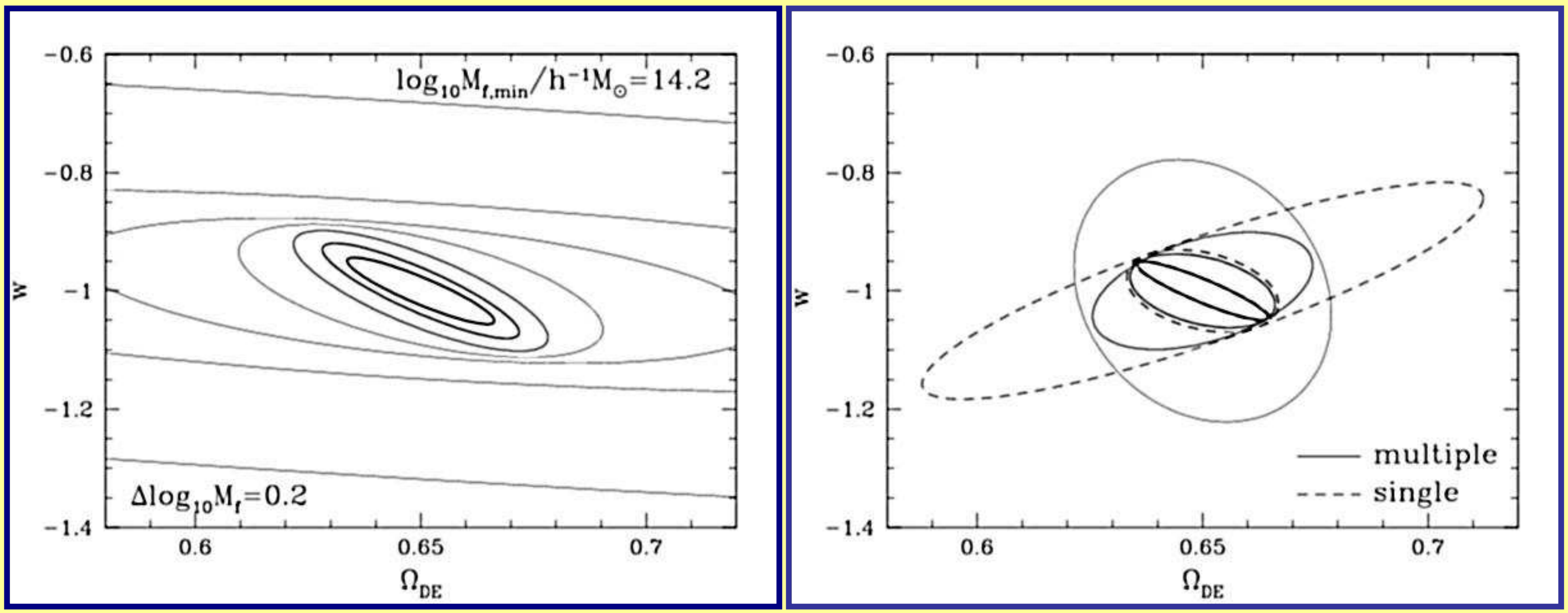
5.Time or flux slicing of survey: using shape of dndz

(Majumdar 2005)

1) Using self-consistency with mass-function

Demand consistency with the well determined shape of mass function from cosmological simulations to calibrate any uncertainty in dndz due to uncertain mass-observable reln.

(Hu 2003)

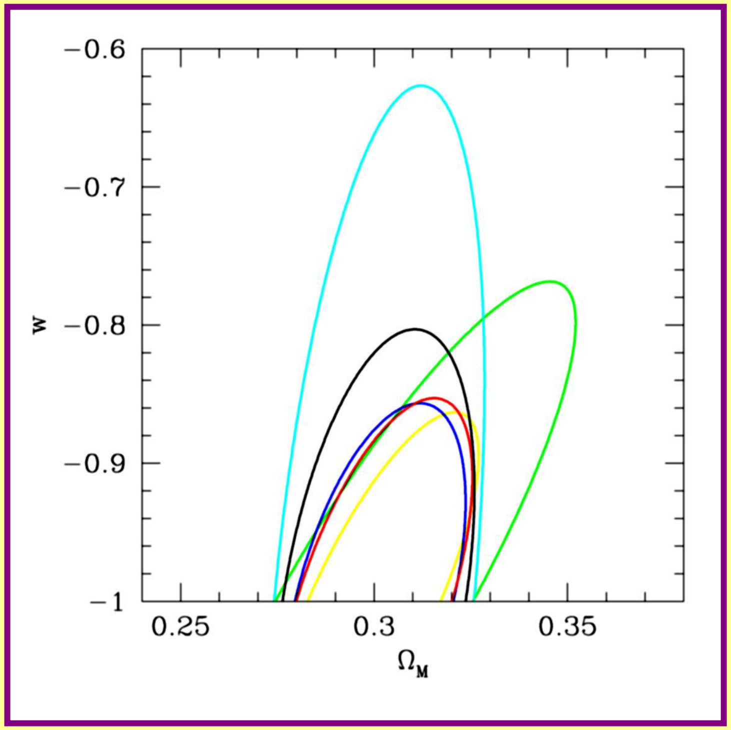


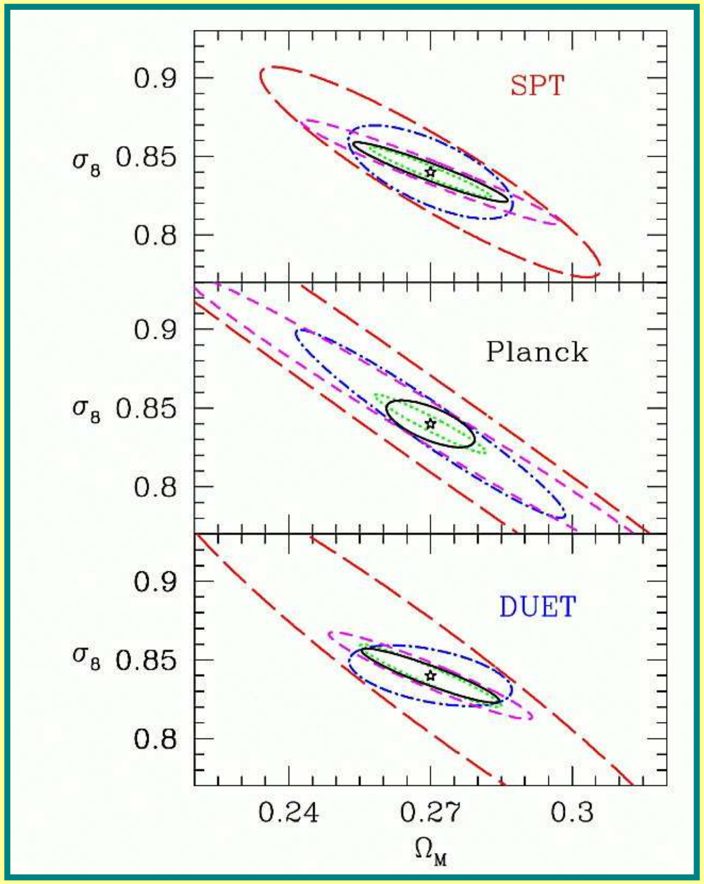
Result of division of number counts into different mass-bins
(but, strong CMB priors!)

2a) Adding cluster P(k) to dndz

Knowing the cluster positions and redshifts, P(k) is easily obtainable. Isotropized P(k) is weak by itself but gives orthogonal constraints to that from dndz.

Majumdar & Mohr 2004

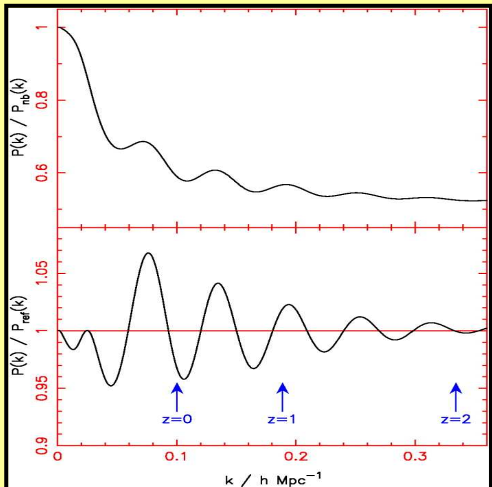


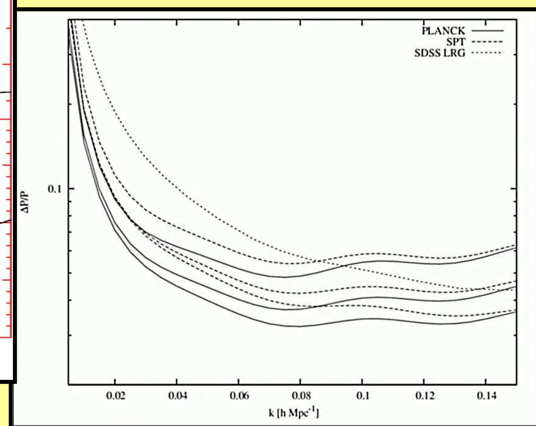


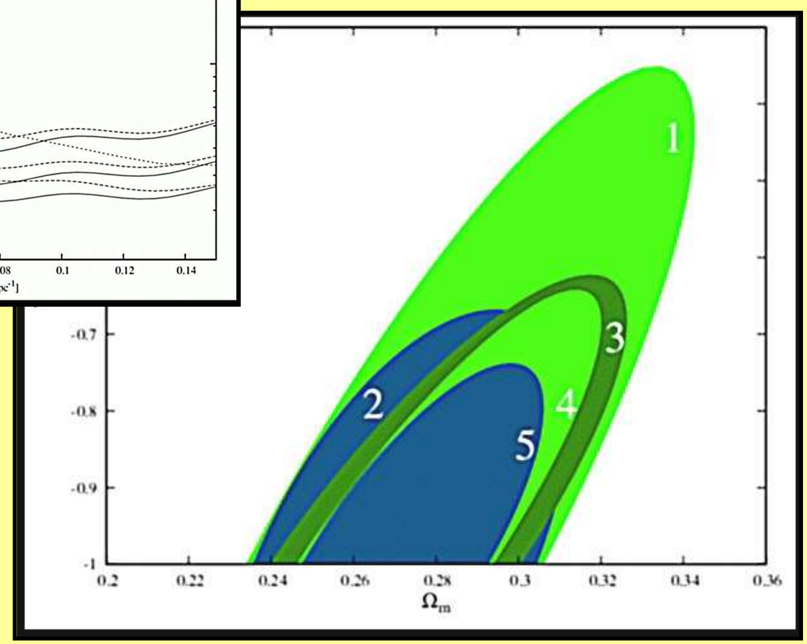
COSMO in Bonn

2b) Using acoustic oscillations of cluster P(k)

P(k) has baryonic wiggles that can be detected. Competetive to detected wiggles based on the SDSS Luminous Red Galaxy sample (Huetsi 2005, Hu & Haiman 2004)







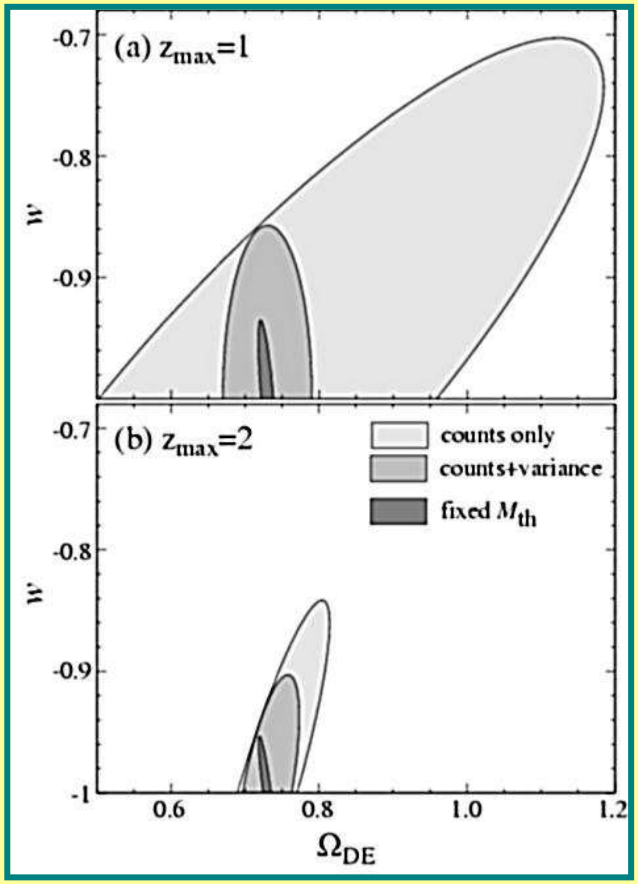
1) **P(k) without oscillations + CMB**
2) **(1) + prior on bias (4 z-bins)**
3) **P(k) with oscillations**
4) **(3) + CMB**
5) **(4) + prior on bias**

COSMO in Bonn

3) Information from excess variance in counts in cells..

In reality, clusters are not Poisson distributed. There are fluctuations in their spatial number density given by a sample covariance. Both the mass function and bias (which gives the cell to cell variance can be computed from simulations).

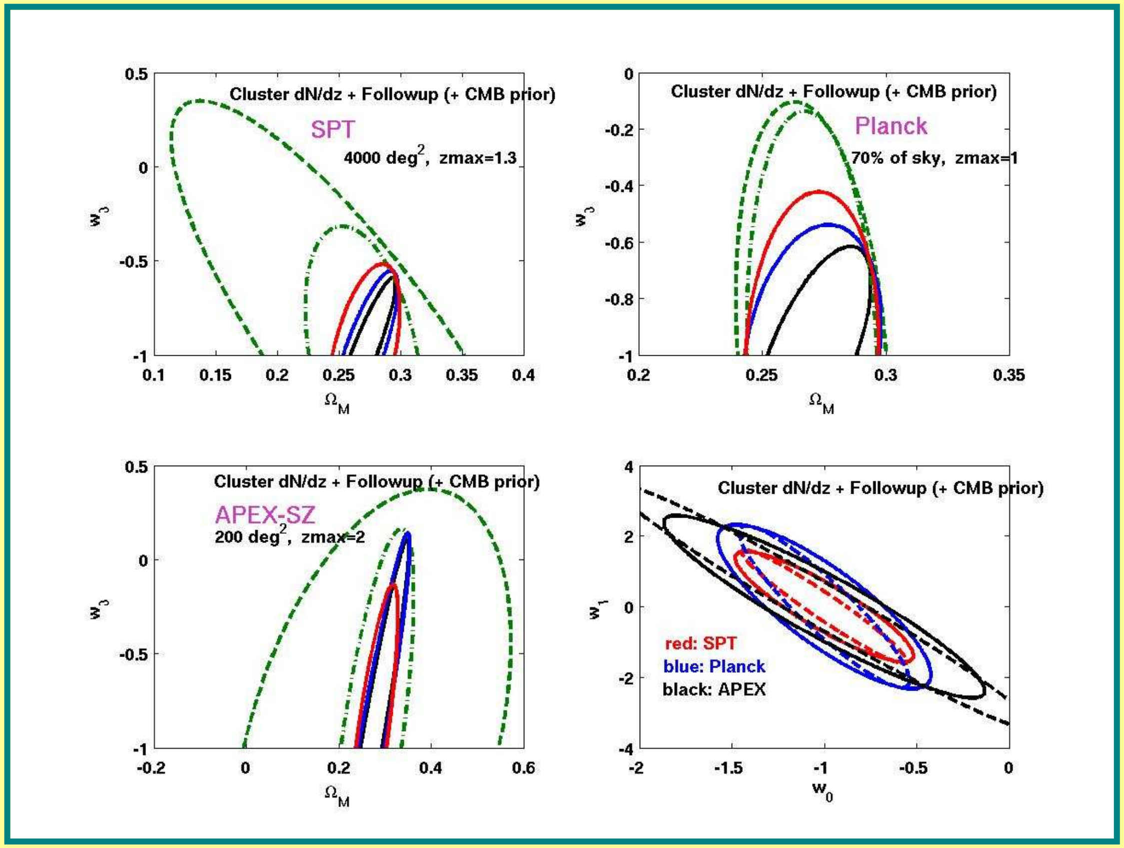
Lima & Hu 2004



Variation of P(k) method. However, measuring P(k) generally requires precise redshift knowledge (greater than that for dndz)

4) Limited direct follow-up of clusters

Followup of suitable selected limited (~100 clusters) to have independent mass measurements can restore self-calibration. This approach need extra effort but has the maximum impact (Majumdar & Mohr 2003,2004, Majumdar 2005)

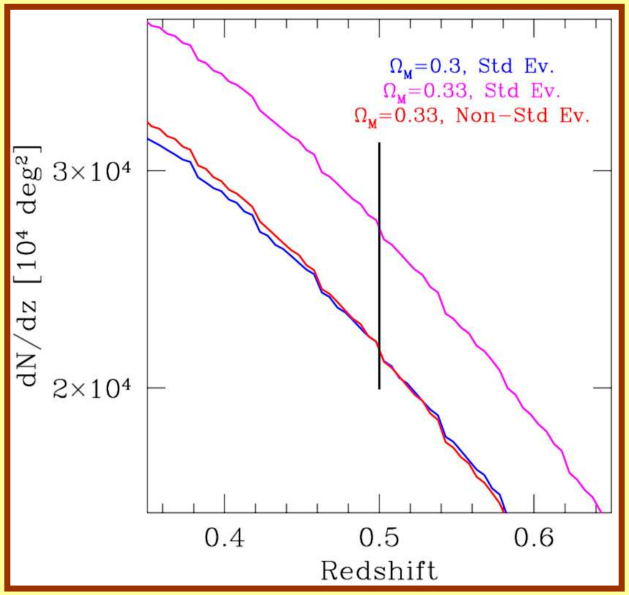


Weak cluster + CMB priors are as good as strong cluster priors.

Why does follow-up help?

Introducing a non-standard evolution model to offset a change of $\delta\Omega_m$=0.03 leads to a 20% offset in the X-ray flux- temperature (fx-Tx) relationship for the clusters in this z=0.5 redshift bin.

Assuming scatter in Lx-T of 50%, the 100 clusters with measured Tx in this redshift bin would provide enough information to discern this shift with great confidence (~6σ significance).



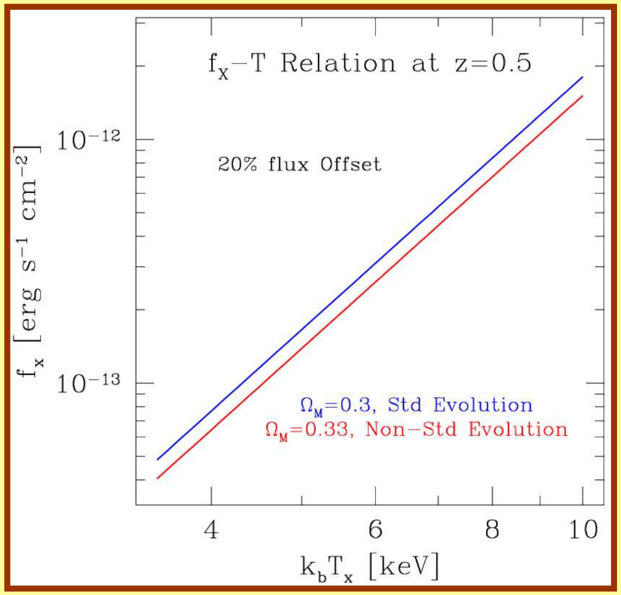
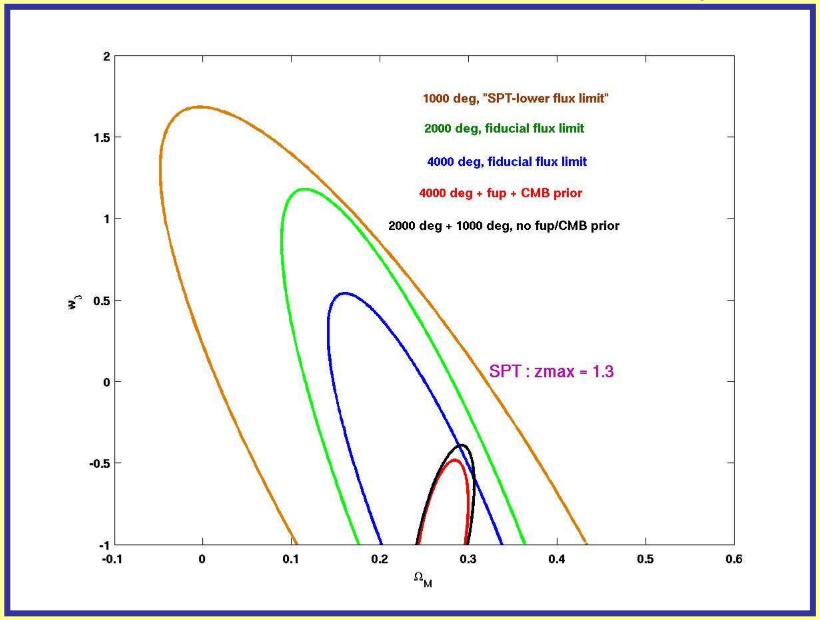


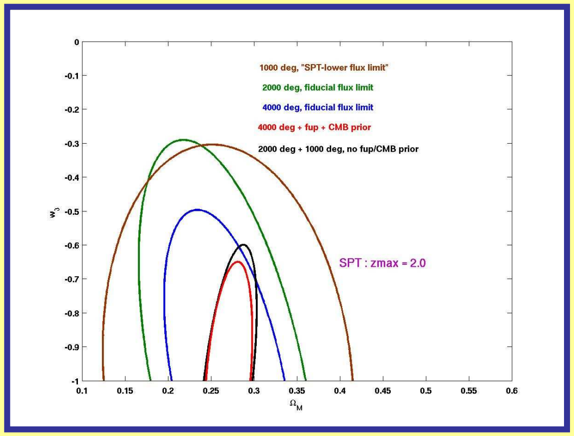
Figure courtesy: Joe Mohr

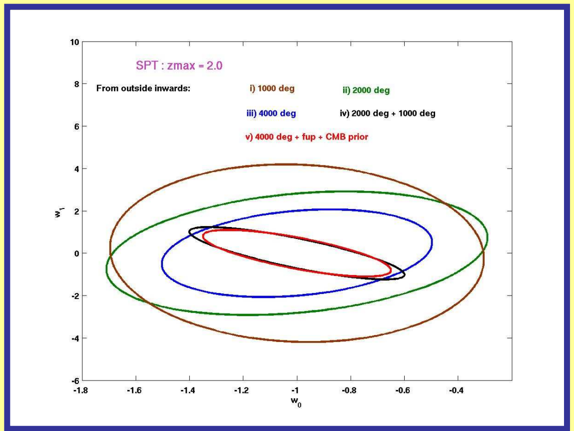
5) Using the shape of dN/dz: slicing survey time

Slicing survey time to components such that one component looks at and effectively smaller area with a corresponding lower limiting flux. The same survey then gives two slightly different dN/dz → strong degeneracy between cluster physics and cosmology are slightly rotated.
Adding the samples lead to stronger constraints.
No extra information added!

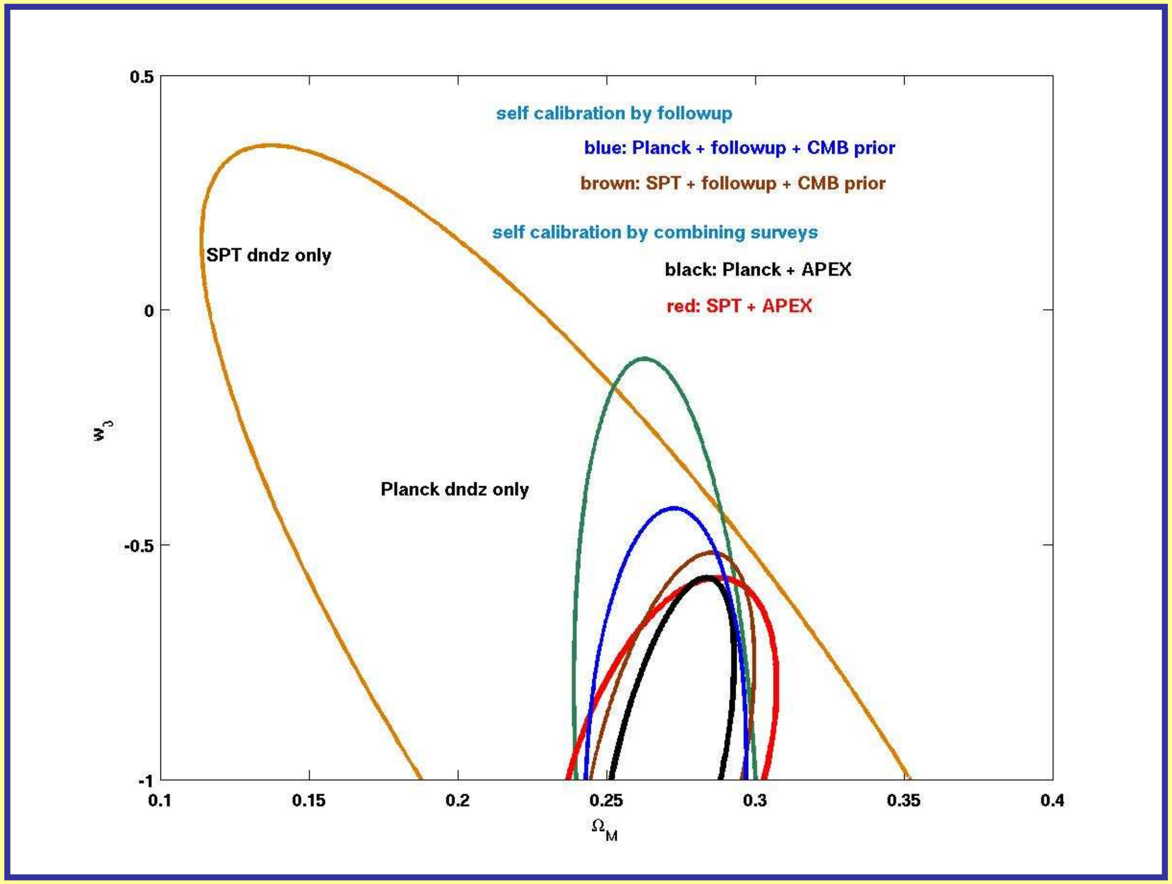
Majumdar 2005







Adding diff cluster surveys: You help me, I help you...we help each other...



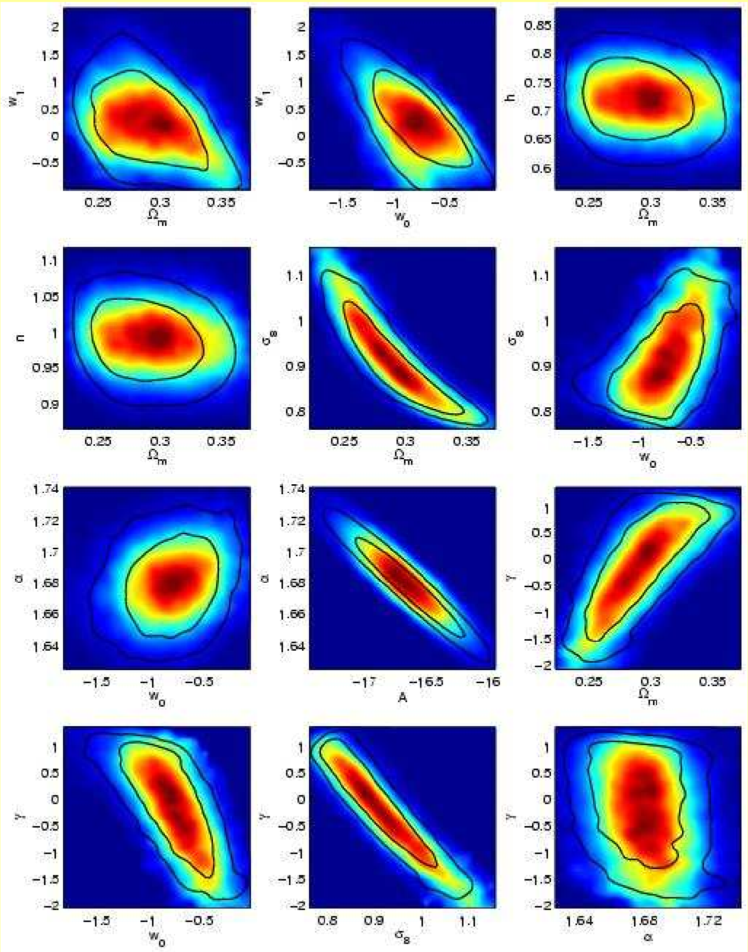
Example:
Planck ~ 10000 clusters
APEX ~ 1500 clusters

Adding them together:
(in presence of w1)

i)reduces Planck error on w0 by factor of 2.5
ii)reduces APEX error on w0 by factor > 4

Majumdar 2005

MCMC constraints from dndz only…

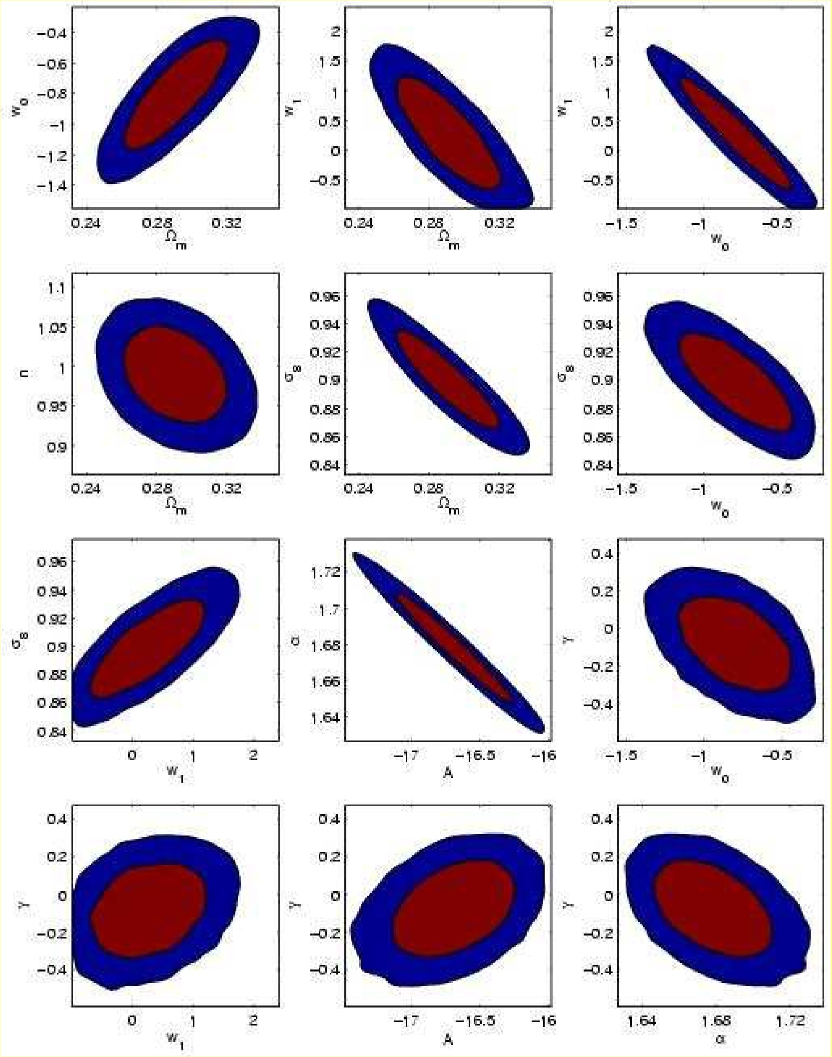


Constraints for SPT survey:
4000 deg, fluxlim = 12 mJy
fiducial cosmology from WMAP
fiducial γ = -0.1
$w(a) = w_0 + w_a(1-a)$

Ω_M = 0.03
σ_8 = 0.075
ω_0 = 0.3
ω_a = **0.8**
γ = 0.7

Cox & SM 04

And with mass followup to dndz …

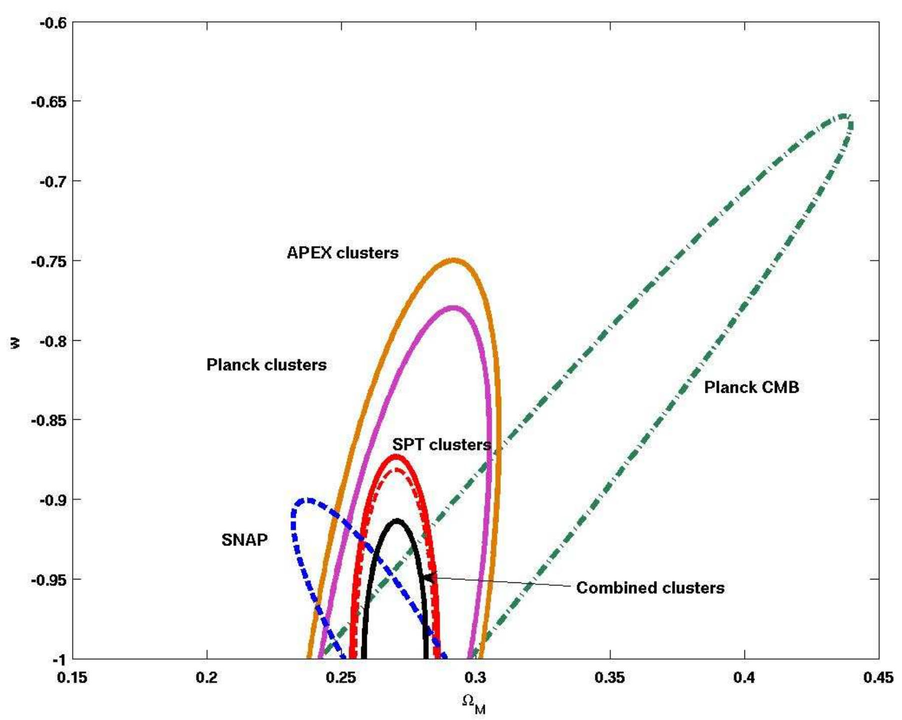


Cox & SM 04

Improved constraints for SPT:
100 clusters followed up with mass uncertainty of 30-50%

$\Omega_M = 0.015$
$\sigma_8 = 0.03$
$w_0 = 0.16$
$w_a = 0.45$
$\gamma = 0.2$

Back to Fisher: Where does cluster surveys stand?



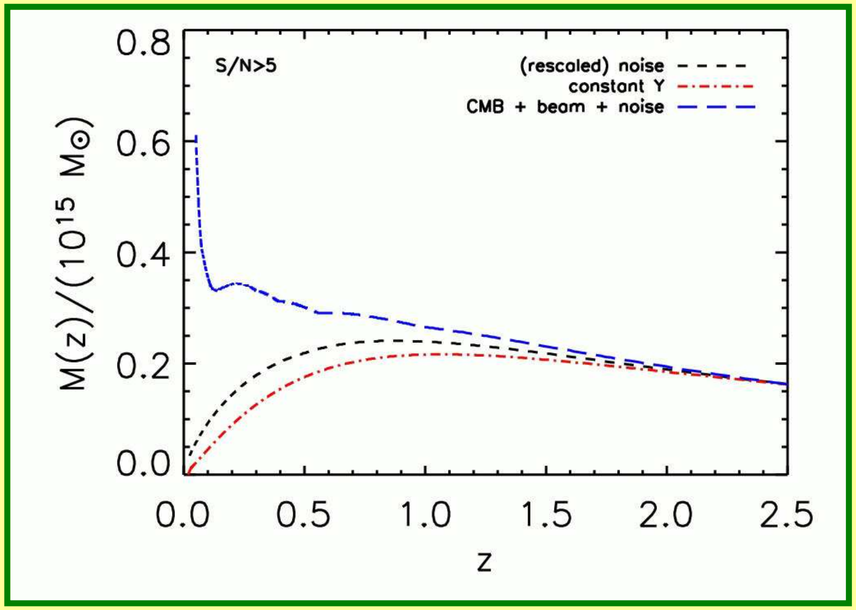
Only dN/dz, no extra information.
Majumdar 2005

Competetive!
Complimentary!

Tackling Real Issues (like) Selection function

Observational:

1. Can we detect all the clusters?
3. How many clusters will get resolved/beam dilution?
4. Point sources at these low fluxes
5. Correlated contamination?
5. Non-gaussian scatter in mass-observable reln
6. How higher in z should we have to followup?



Melin etal 2005

So, what are the implications?

- Cluster surveys as probes of dark energy are complimentary and competetive with other probes. Upcoming surveys, by themselves, can constrain w_{eff} to ~5-10% or w_0 to ~20% and w_1 to ~50% (with reasonable priors). Maximum benefit will, ofcourse, come from combining different probes (like clusters+SNe+CMB+Lensing+Lyman-alpha etc)

- Uncertainty in cluster structure and evolution can dilute the predictive power of these surveys to constrain dark energy.

- However, numerous techniques now exist that can overcome this bottleneck and make these surveys self-calibrating, thus reducing mass-observable uncertainties.

- We need to understand the selection function better in order to reap benefits from these surveys. As in any survey, the better we understand the systematics, the better we can trust our results. Much progress has been made in this area in the lat few years.

The future looks promising at present.