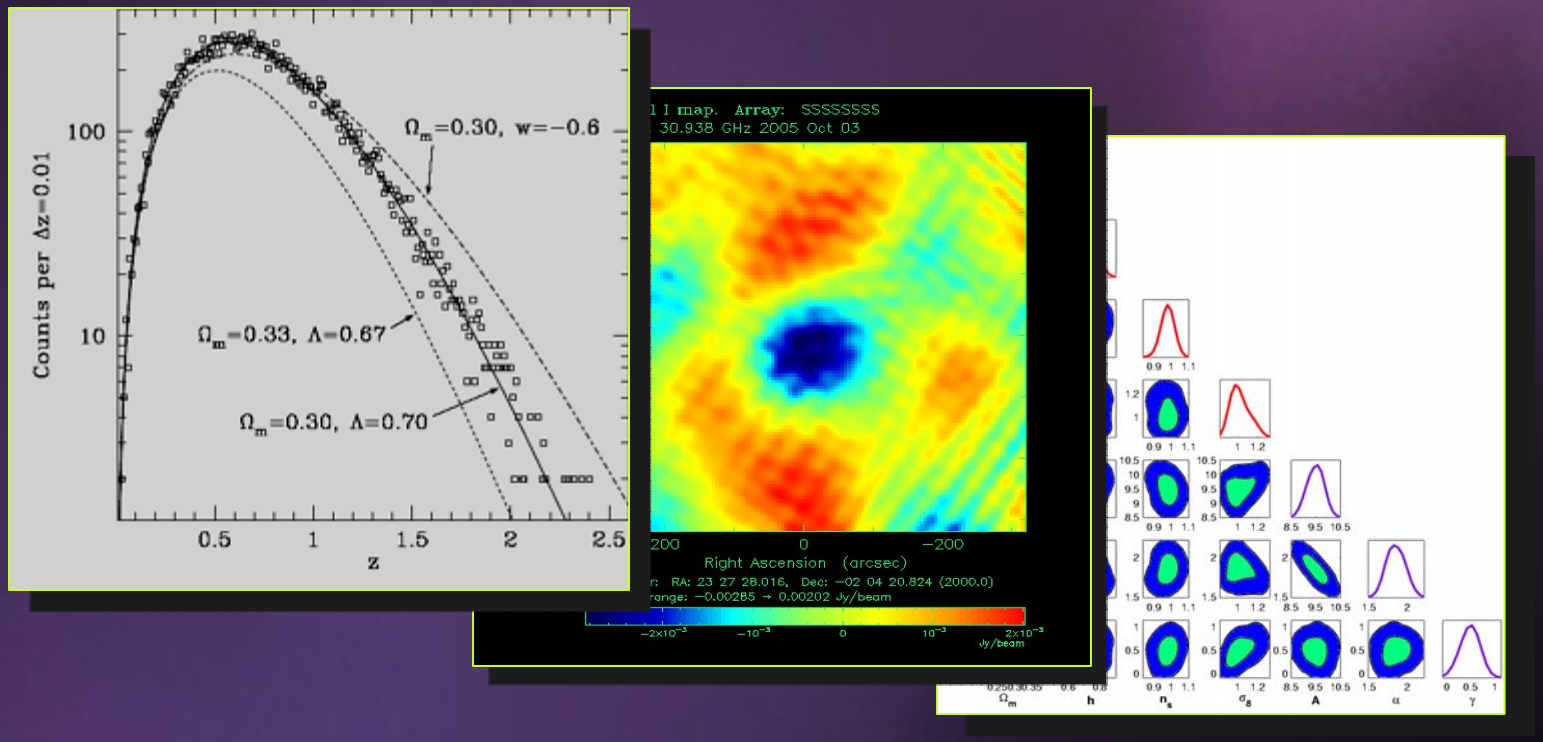
Clusters and cosmology



The KICP Inaugural Symposium,
Dec 12, 2005

Mike Gladders, Carnegie Observatories

Outline: Clusters and cosmology

- Codex Aggereris Caelestise
  (The Book of celestial Aggregates...a primer)
- Galaxy clusters as a fair sample of the universe...
- Strong lensing - all is not well ... should you care?
- Counting and weighing: the Evolution of N(M,z)

Clusters and cosmology

Using Clusters as standard rods For H_0 measures (c.f. w. Freedman's talk; j. Carlstrom)

Clusters as sites for Sne Searches (c.f. M. Kowalski's talk)

Things I hadn't remembered to put in by last night...

Galaxy Clusters: A Primer

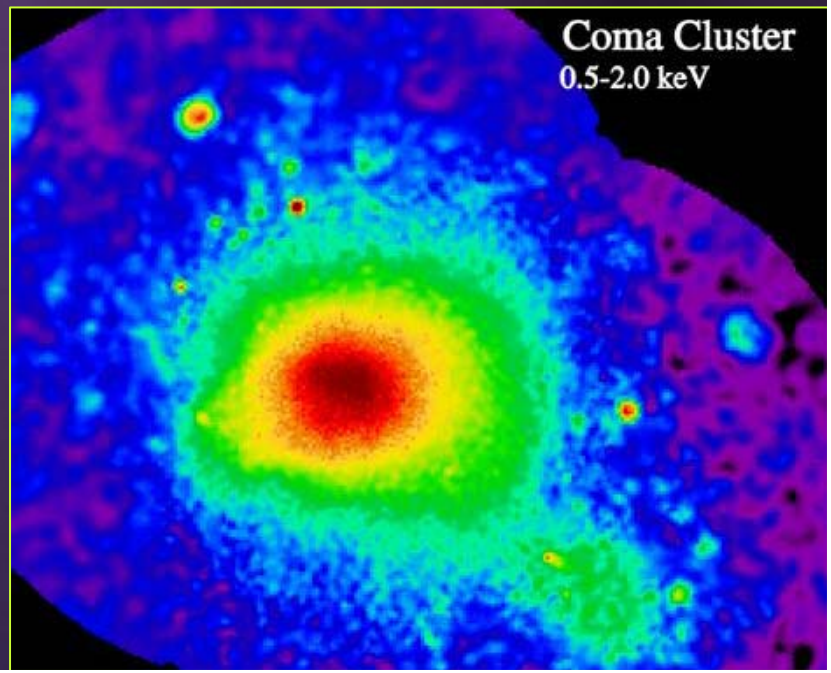
- The nearest good examples First Noted by Messier (1781: Virgo cluster) and Herschel (1785: the coma cluster). The Modern(ish) description as a "Cluster" ("of spiral Nebulae") originates with shapley & Ames (1926) and Hubble & Humason (1931).

- Attempts to infer the masses of clusters using the virial theorem (Eddington 1916) followed shortly thereafter (zwicky 1933,1937) and mark both the (unheralded) discovery of dark matter, and the realization of galaxy clusters as the "best" place to look for gravitational lensing.

Galaxy Clusters: A Primer

Lopez-Cruz(1997)

S. Snowden, ROSAT



Galaxy Clusters: A Primer

- Clusters are now known to be Aggregates of baryons (stars, principally in galaxies; gas, principally between galaxies) and dark matter, with total masses ranging up to ~ 10^{15} M_{sun}

- Galaxy clusters are the spiders in the cosmic web. They sit at the intersections of filaments, accumulating mass over time through the accretion of galaxies, groups, and other clusters

- Clusters are the most dark matter dominated regions of the universe. Most of the mass in clusters (~80-90%) is dark matter, and most of the remaining mass (Baryons) is in the form of hot gas(~80-90%).

Galaxy Clusters: A Primer

- Clusters evolve through gravitational collapse over cosmic time, and arise from the most extreme moderate-scale fluctuations in the early universe.

- Clusters are massive (and bright) objects with unique observational signatures. Distant clusters are not trivial to detect and characterize, but represent unique sites for studying both galaxy evolution and Cosmology.

- Various cluster surveys have recently pushed to redshifts beyond z= 1 (though confirmed clusters at such high-z are still modest in number). Near-future cluster surveys promise to greatly expand this work.

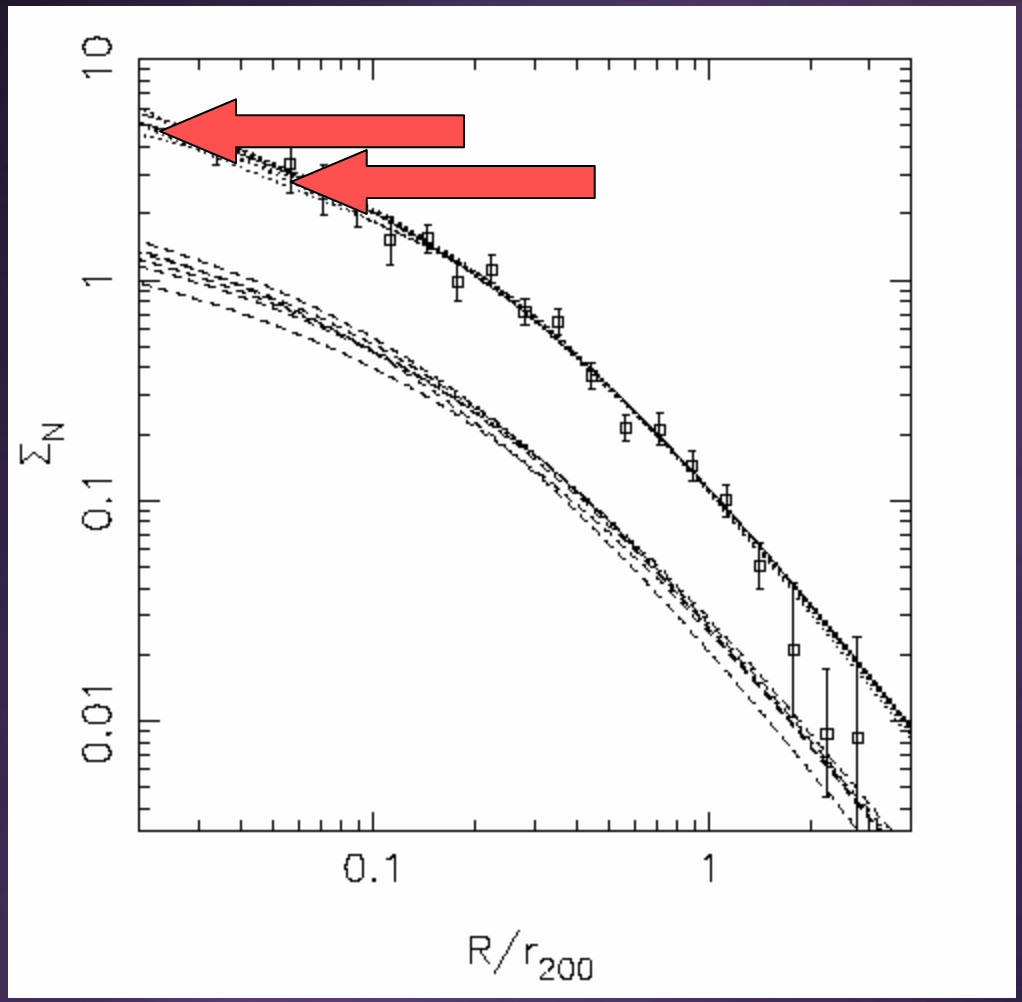
Clusters & Cosmology: Contents

In theory we believe that clusters :

- Relatively large and representative co-moving volumes in the early universe (e.g. White *et al.* 1993)
- Are sufficiently massive that there is an insignificant amount of spatial differentiation in the initial constituents (unlike galaxies!)

Are these statements observationally supported?

Cluster Cosmology Contents

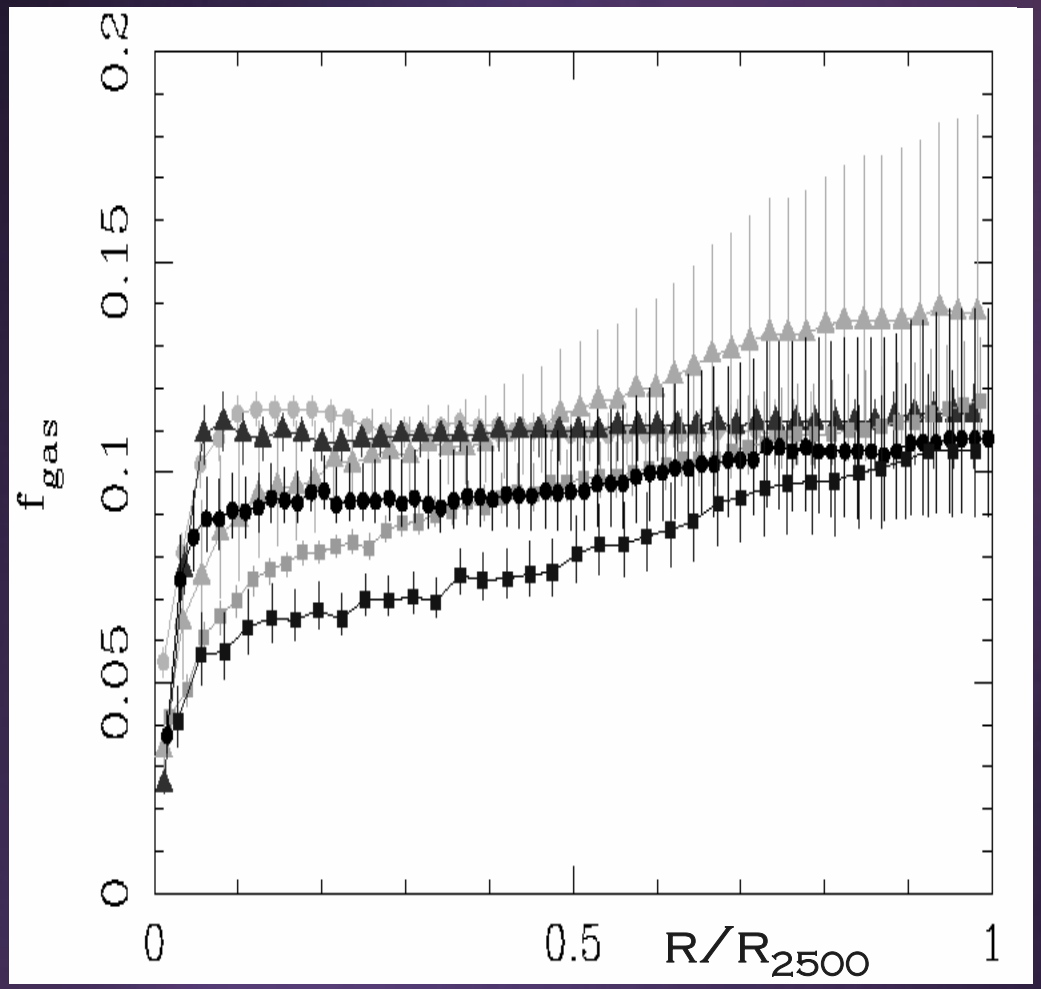


Carlberg et al.(1997)

14 x-ray selected, optically studied Clusters at z~0.33

observed combined light profile (points, and solid line) tracks the Combined mass profile (dotted lines) very well

Cluster Cosmology Constraints



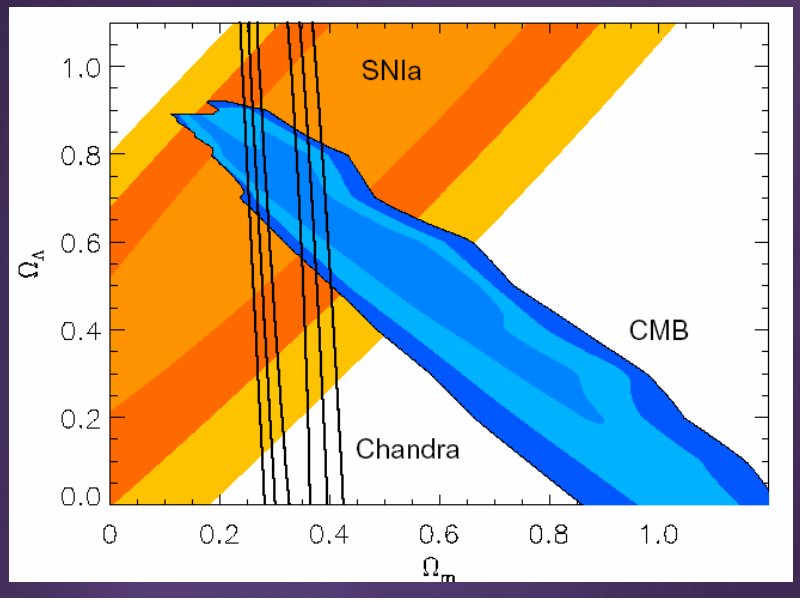
Pointecouteau et al. (2004)

Detailed study of a typical low-z relaxed cluster shows the F_{GAS} is essentially flat with radius

Similarly, Allen et al. (2002)

Cluster Cosmology Constraints

The apparent fact that hot gas dominates the cluster baryon content, and that clusters tend to a "universal" gas fraction allows for a simple cosmological test in combination with an independently measured value of Ω_b, as first highlighted by White & Frenk (1991)



Allen *et al.* 2002

using $\Omega_b h^2$=0.0205+-0.0018
yields Ω_M=0.30+0.04-0.03

(c.f. G. Steigman's Review, this meeting)

using $\Omega_b h^2$=0.020-0.025 (95%CL)
yields Ω_M=0.29-0.37 +- (<0.03)

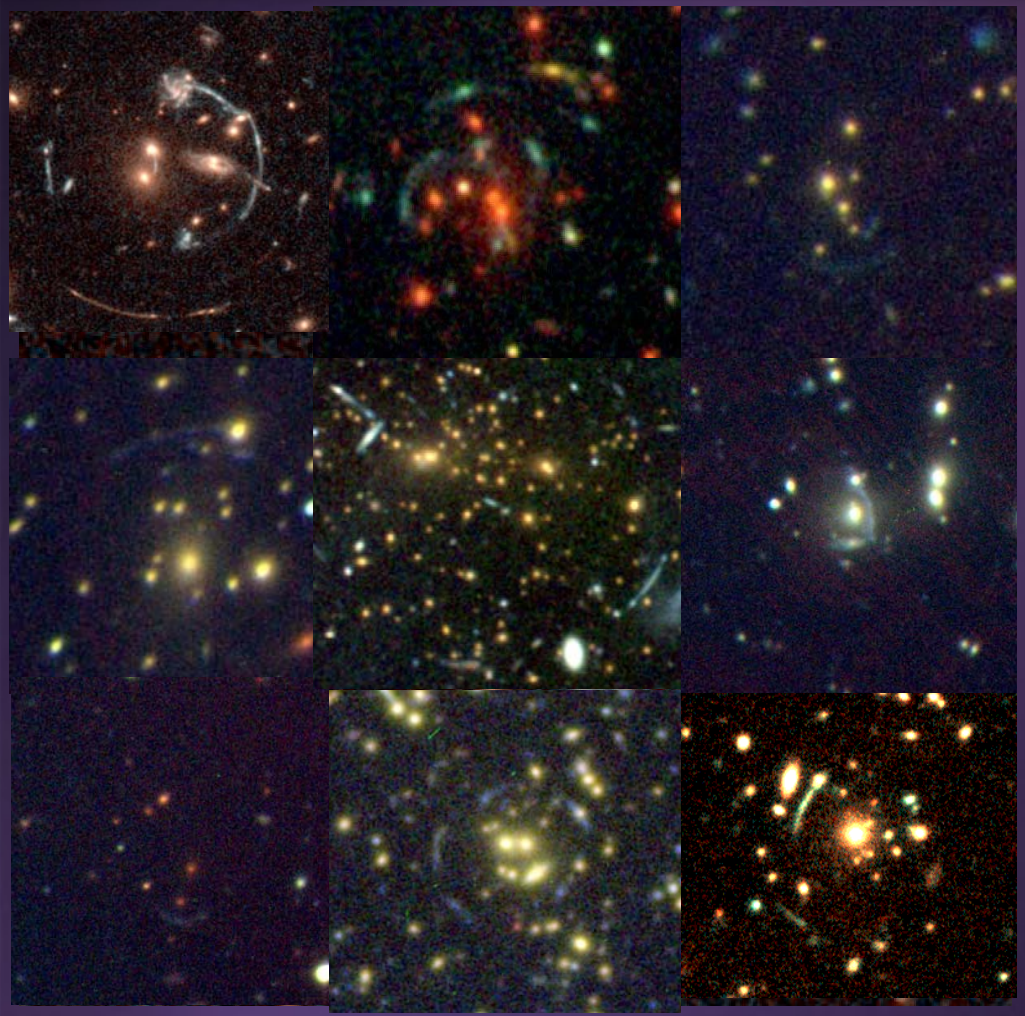
Cluster Cosmology Contents

"The mean density of the universe is equal to the mass of a large cluster divided by the co-moving volume in the field from which that mass originated." : Carlberg et al. (1996) studied 16 x-ray selected clusters at z~0.33 and argued for Ω_M=0.24+-0.04+-0.09

Arguments along the lines also have dissenting voices, notably Blanchard & douspis (2005) who argue that the "representative sample" presumption is not well supported...

Clusters and cosmology

Cluster cosmology I: strong lensing



RCS0224-0002 (Gladders *et al.* 2001) at z=0.77 as observed by HST

One example of rapidly growing samples of cluster strong lenses

There are many more (RCS-1,RCS-2,SDSS)

Clusters and cosmology

Cluster cosmology I: strong lensing

The number of cluster strong lenses to a given flux limit is a function of the source population details (observationally well constrained) the lens population, and the cosmology.

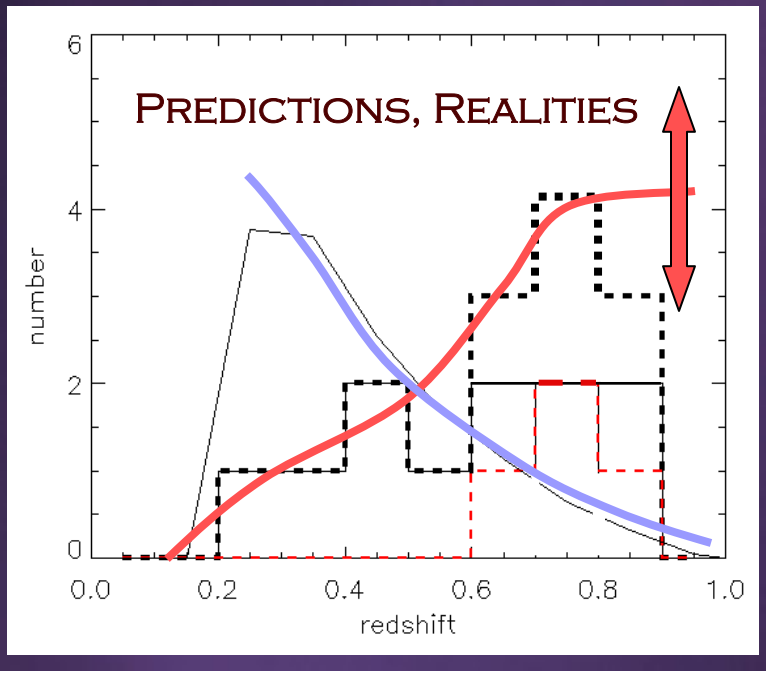
In a sequence of papers in the mid-90's, Bartelmann et al. developed a prediction for the total number of arcs expected in various broad cosmological models

SCDM	1 per 1100 Square degrees
ΛCDM	1 per 120 Square degrees
OCDM	1 per 20 Square degrees

Clusters and Cosmology

Cosmology II: Strong Lensing

But, more recent work, taking advantage of greater knowledge of the source population, and more extensive N-body simulations, claims to have resolved this order-of-magnitude discrepancy in arc counts in ΛCDM models (e.g. Dalal *et al.* 2004)



However...

The Redshift distributions do Not agree. Fitting the total number of arcs over-predicts the low-z arc population (even in the early EMSS sample, marginally, and significantly in the newer samples.)

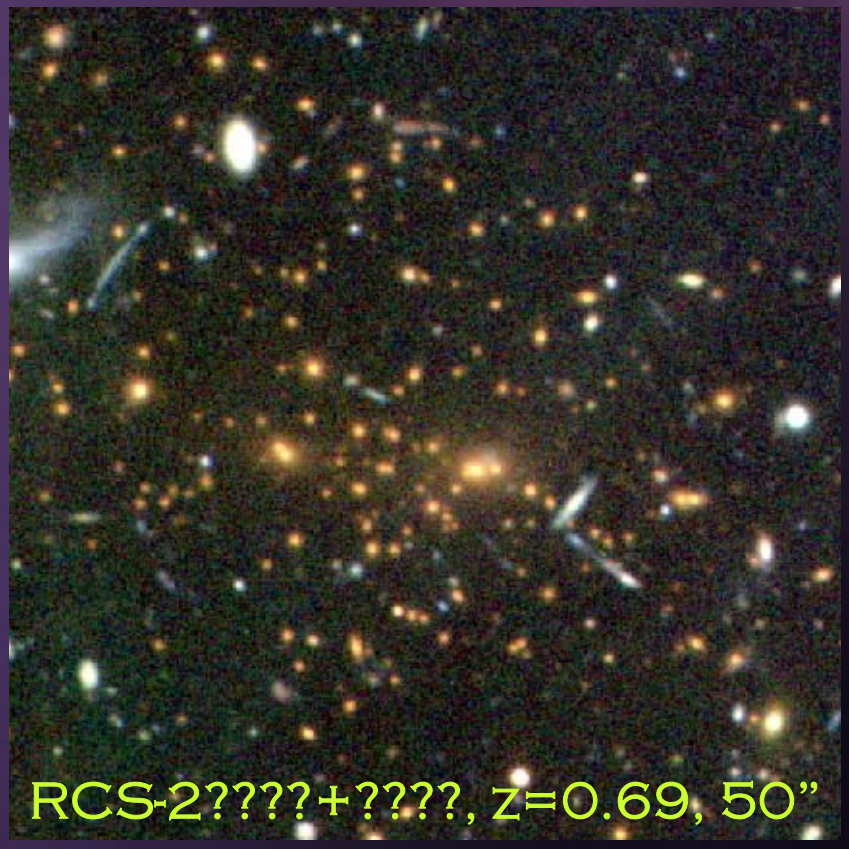
Clusters and cosmology

Cluster cosmology I: strong lensing

Roger Blandford:

"what is the largest Einstein radius so far observed?"

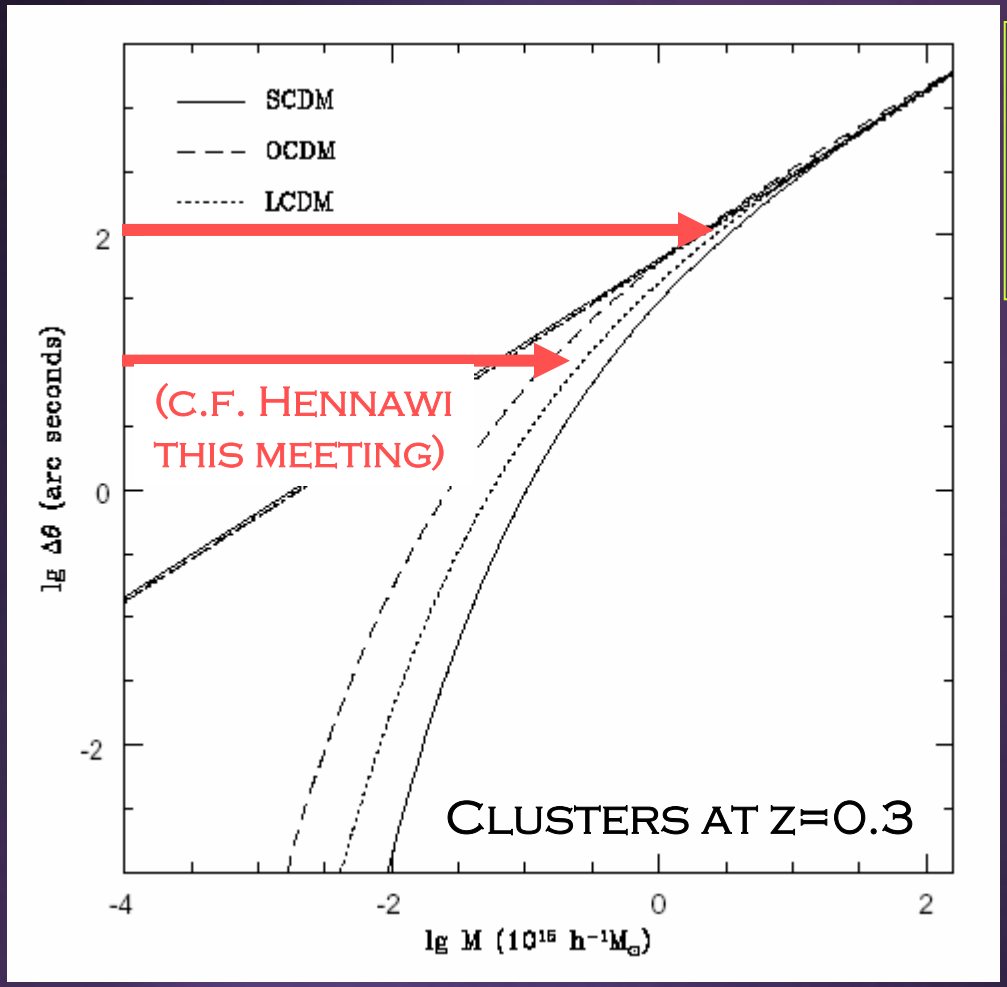
Abell 1689, z=0.18, 50"



RCS-2????+????, z=0.69, 50"

Clusters and cosmology

Cluster cosmology I: strong lensing



Very large separation lenses are less sensitive to the details of the lens mass distribution!

e.g., Li & Ostriker (2005)

Clusters and cosmology

Cluster cosmology I: strong lensing

Extreme lensing system such as these present a direct Test of the projected surface mass distribution in the universe which is rather insensitive to the subtleties of lens structural parameters which complicate (and empower) more detailed analyses.

They also tend to tag the most massive systems. This new rcs-2 cluster has a measured velocity dispersion of 1650 km/sec! (from 58 members).

Interestingly, An initial sz observation of this cluster by the sza does not indicate such a massive system. observations optically selected clusters observed in x-rays and SZ also suggest a lowered gas fraction in at least some systems (hicks et al. 2005) – do we currently have a x-ray biased worldview?

Clusters and Cosmology

Cluster Cosmology III: Cluster Mass Function

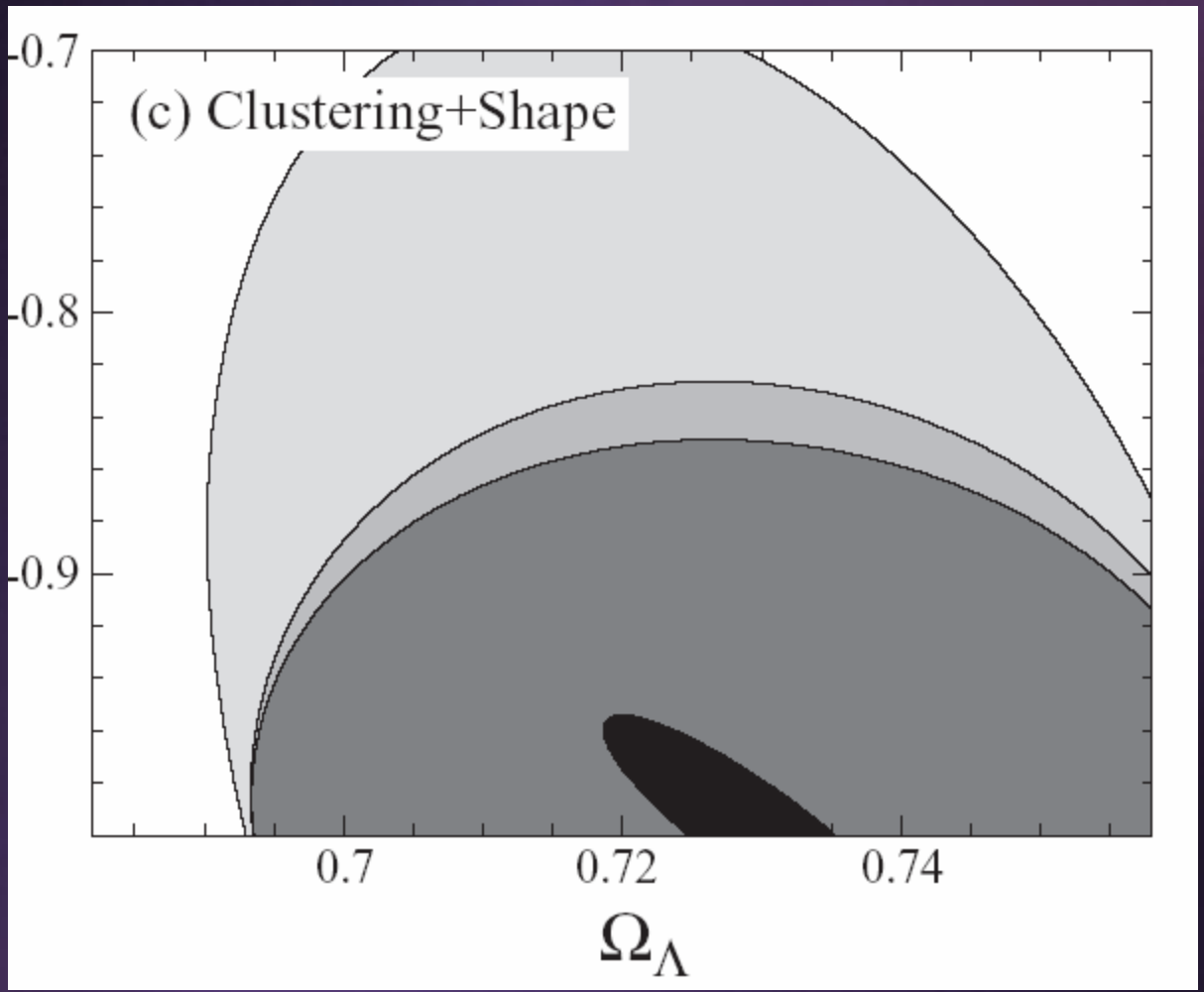
The evolution of the number of clusters at a given mass as a function of redshift is in principle an exquisitely sensitive test of cosmology.

This is because these systems arise from the exponential tail of the initial perturbations, and are hence sensitive to the overall scaling of the initial fluctuation spectrum (σ_8) and the overall mass density (Ω_M).

This "growth of structure" sensitivity is further complemented by a sensitivity to the evolution of the co-moving volume element. The latter dominates at lower redshift and the former at higher redshift in a ΛCDM universe and enables cluster counting as a probe of dark energy.

Clusters and Cosmology

Clusters & Cosmology III: Cluster Mass Function



Lima & Hu (2005)

Realistic Predictions for dark energy constraints from the South Pole Telescope (Carlstrom *et al.*)

$\sigma(\Omega_\Lambda, w)=(0.02, 0.11)$

Doesn't this look great! (?)

Clusters and Cosmology

Cluster Cosmology III: Cluster Mass Function

Reality Check:

"Cluster counting" cosmology tests have been suggested for nearly 20 years, starting with Evrard (1989).

A great swath of papers have been published in the intervening two decades, of both theoretical and observational flavours, and robust and significant cosmological constraints have been less than obvious.

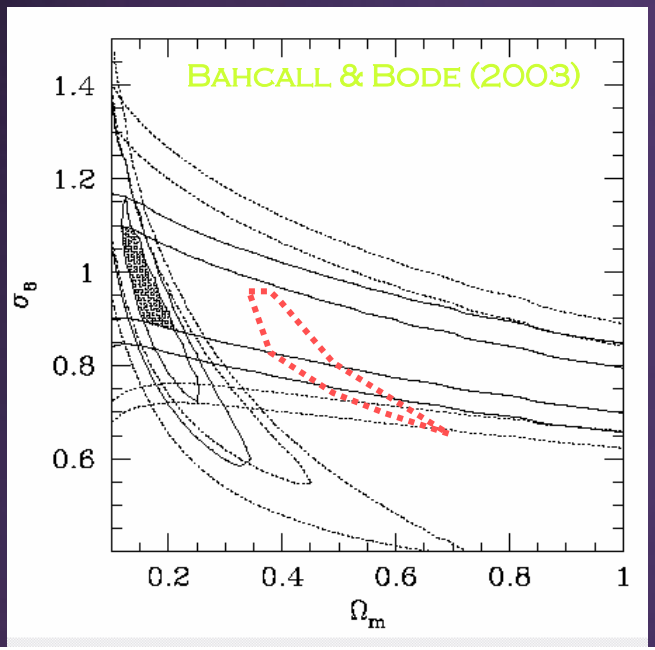
In the last 10 years computed values of σ_8 and Ω_M , based principally on small ROSAT X-ray selected cluster samples, have ranged from ~0.5--1.0, and 0.2--0.9 (sometimes even with the same data!)

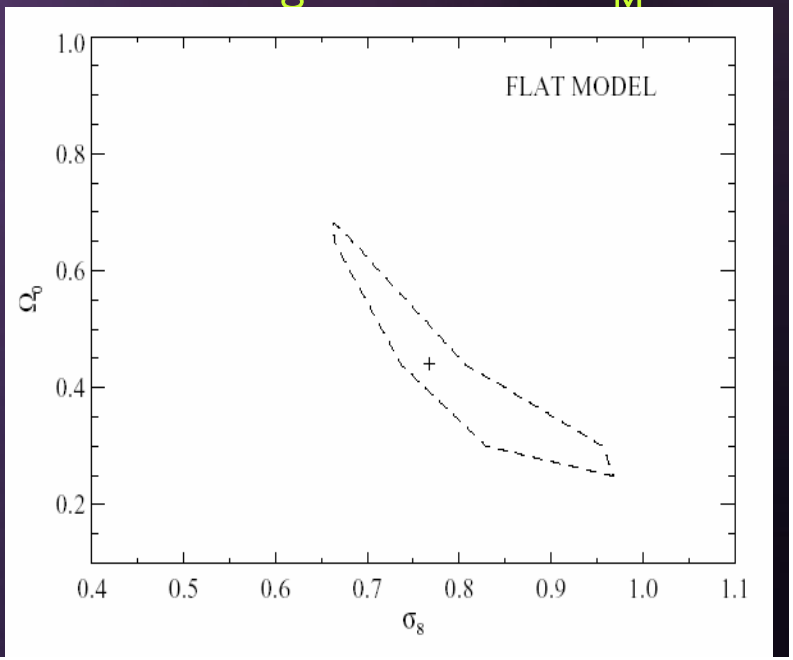
Clusters and Cosmology

Clusters & Cosmology III: Cluster Mass Function

Is something wrong?

Not really no...the required data (clusters, preferably large samples, with good mass and redshift measurements) have been difficult to gather. In recent years, measurements have tended to high σ_8 and low Ω_M





Clusters and Cosmology

Cluster Cosmology III: Cluster Mass Function

New sample, "modern" analysis:

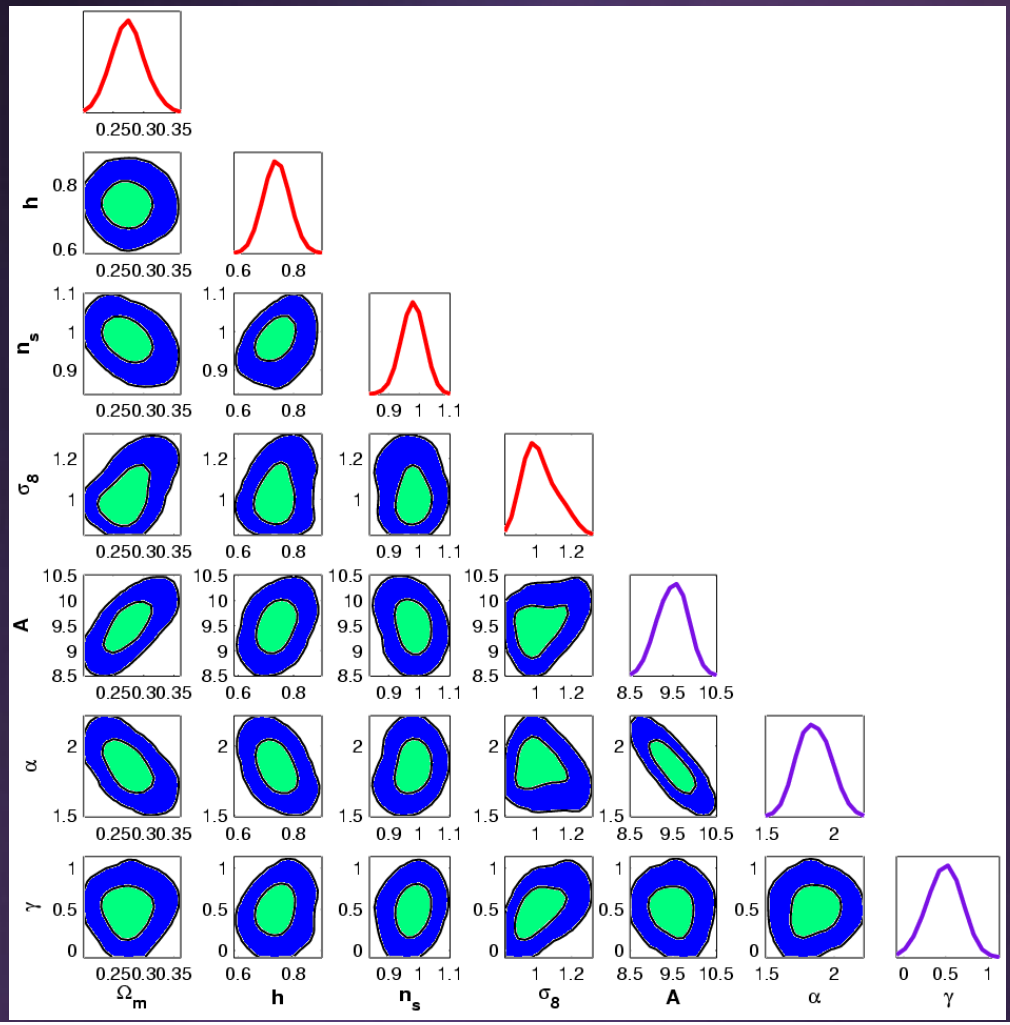
The RCS-1 cluster sample contains ~1200 clusters with well measured richnesses above a conservatively chosen richness and significance threshold. We have nearly completed an initial analysis of this (order of magnitude) larger cluster sample in the context of a flat w=-1 cosmology.

We fit for 5 parameters: σ_8 and Ω_M, and three parameters describing the slope, intercept and evolution of the mass-richness relation, using a "self-calibration" approach (e.g. Majumdar & Mohr 2004), with gausian priors on ***n*** and ***h***.

The initial results are extremely encouraging!

CLUSTERS AND COSMOLOGY

CLUSTER COSMOLOGY III: CLUSTER MASS FUNCTION



GLADDERS *ET AL.* (2005)

	MEAN	STD.DEV
Ω_M	0.275	0.025
σ_8	1.02	0.089

$M = 10^A R^\alpha (1+z)^\gamma$

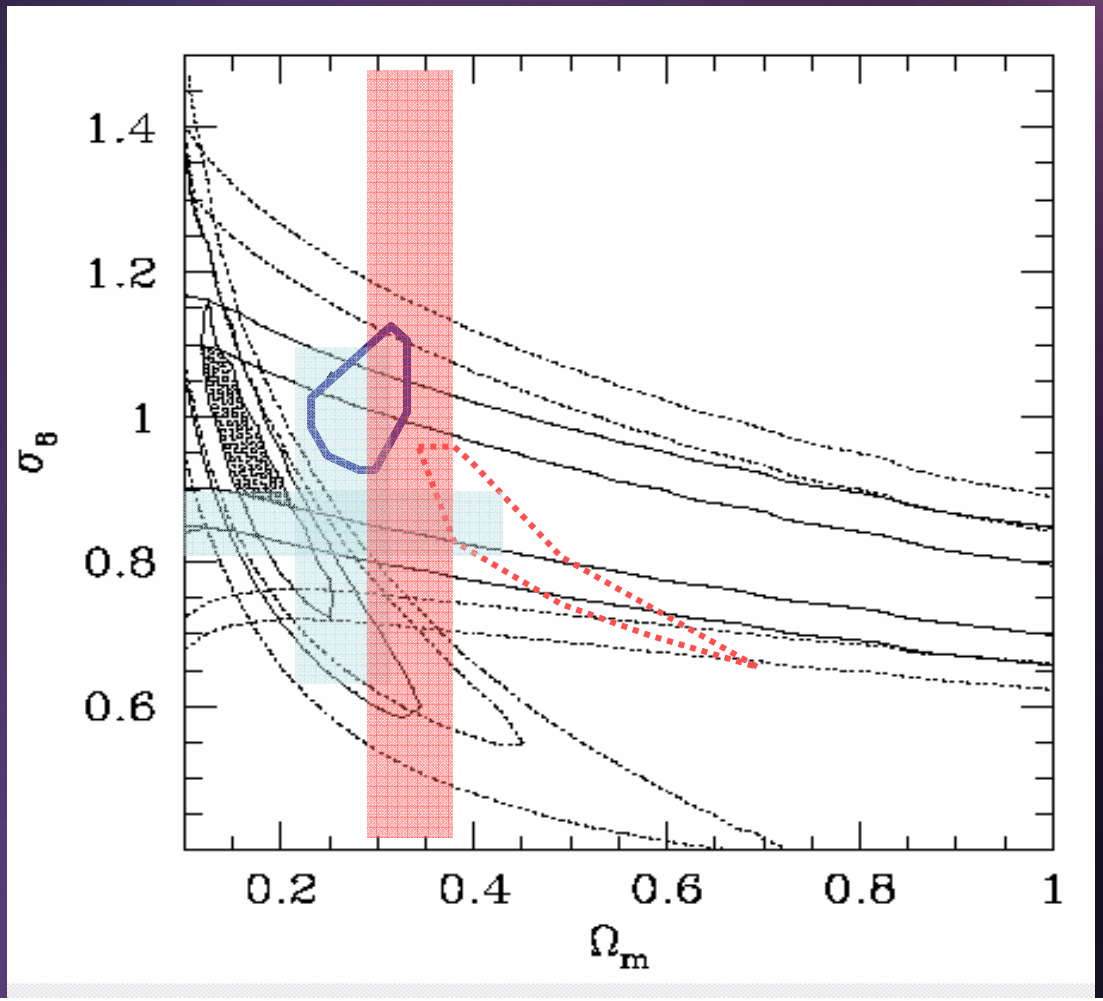
A	9.49	0.32
α	1.85	0.11
γ	0.48	0.19

A	9.95	0.89
α	1.64	0.28

(YEE & ELLINGSON 2003)

CLUSTERS AND COSMOLOGY

CLUSTER COSMOLOGY III: CLUSTER MASS FUNCTION



Conclusions: cosmology

The "baryon fraction" test appears to work, with some Dissent. Can this be pushed further? Do we have to be concerned about the universality of the gas fraction?

Cluster strong lensing makes little sense in detail... Are we being pushed to invoke non-gaussianity, or constraining dark matter?

There is hope that N(M,z) will live up to its (mostly) theoretical promise. Stay tuned...