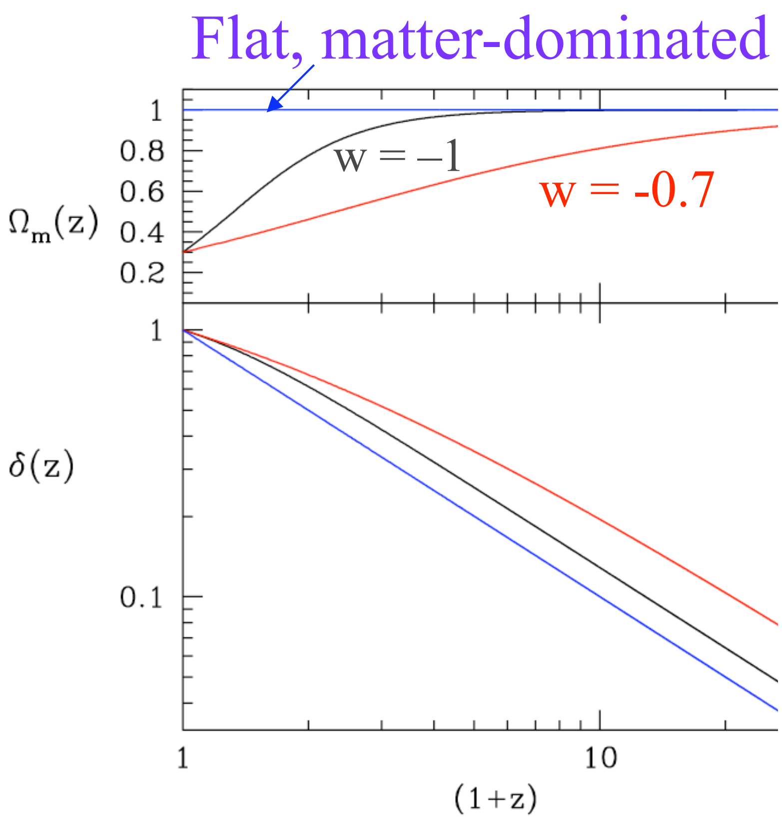
The Structure Formation Cookbook

1. Initial Conditions: A Theory for the Origin of Density Perturbations in the Early Universe $P_m(k) \sim k^n,\ n \sim 1$
   Primordial Inflation: initial spectrum of density perturbations

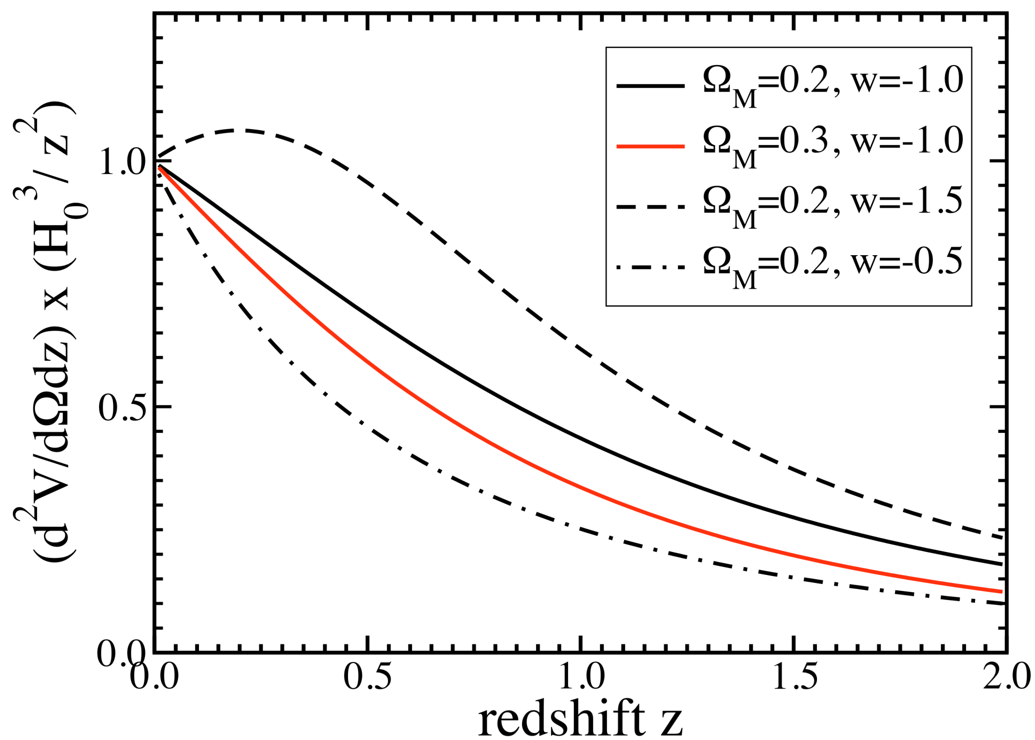
2. Cooking with Gravity: Growing Perturbations to Form Structure
   Set the Oven to Cold (or Hot or Warm) Dark Matter
   Season with a few Baryons and add Dark Energy $P_m(k) \sim T(k) k^n$

3. Let Cool for 13 Billion years $P_g(k) \sim b^2(k) T(k) k^n$
   Turn Gas into Stars

Growth of Density Perturbations



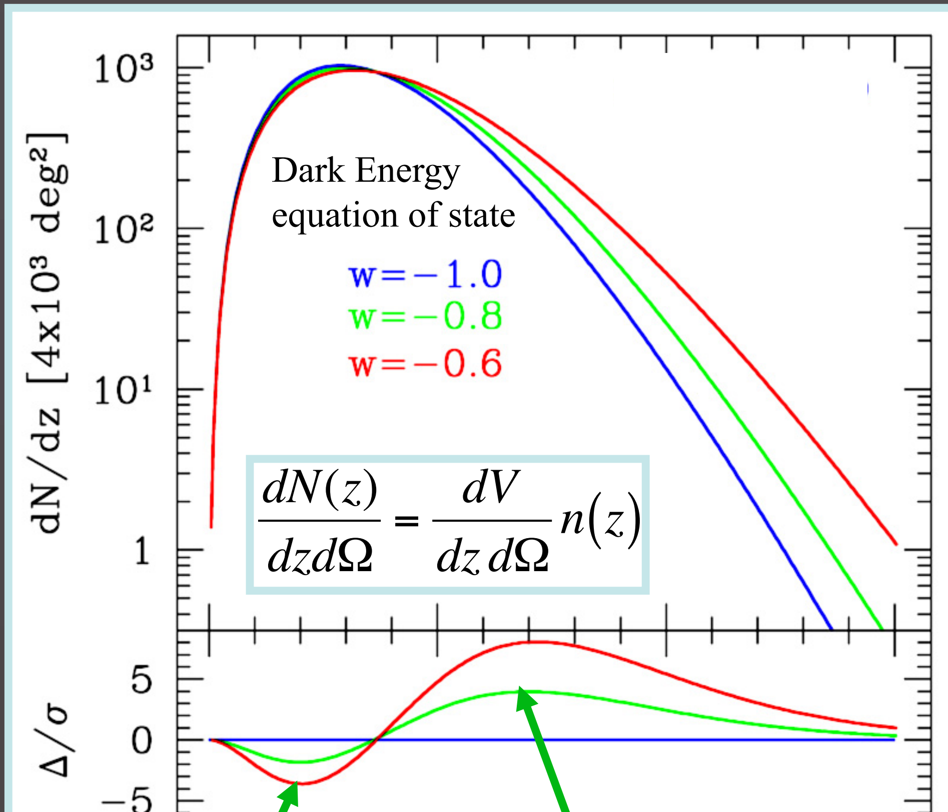
Volume Element



Raising *w* at fixed Ω_{DE}: decreases growth rate of density perturbations and decreases volume surveyed

Clusters and Dark Energy

Number of clusters above observable mass threshold



- Requirements
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy that can be used as cluster mass estimate:

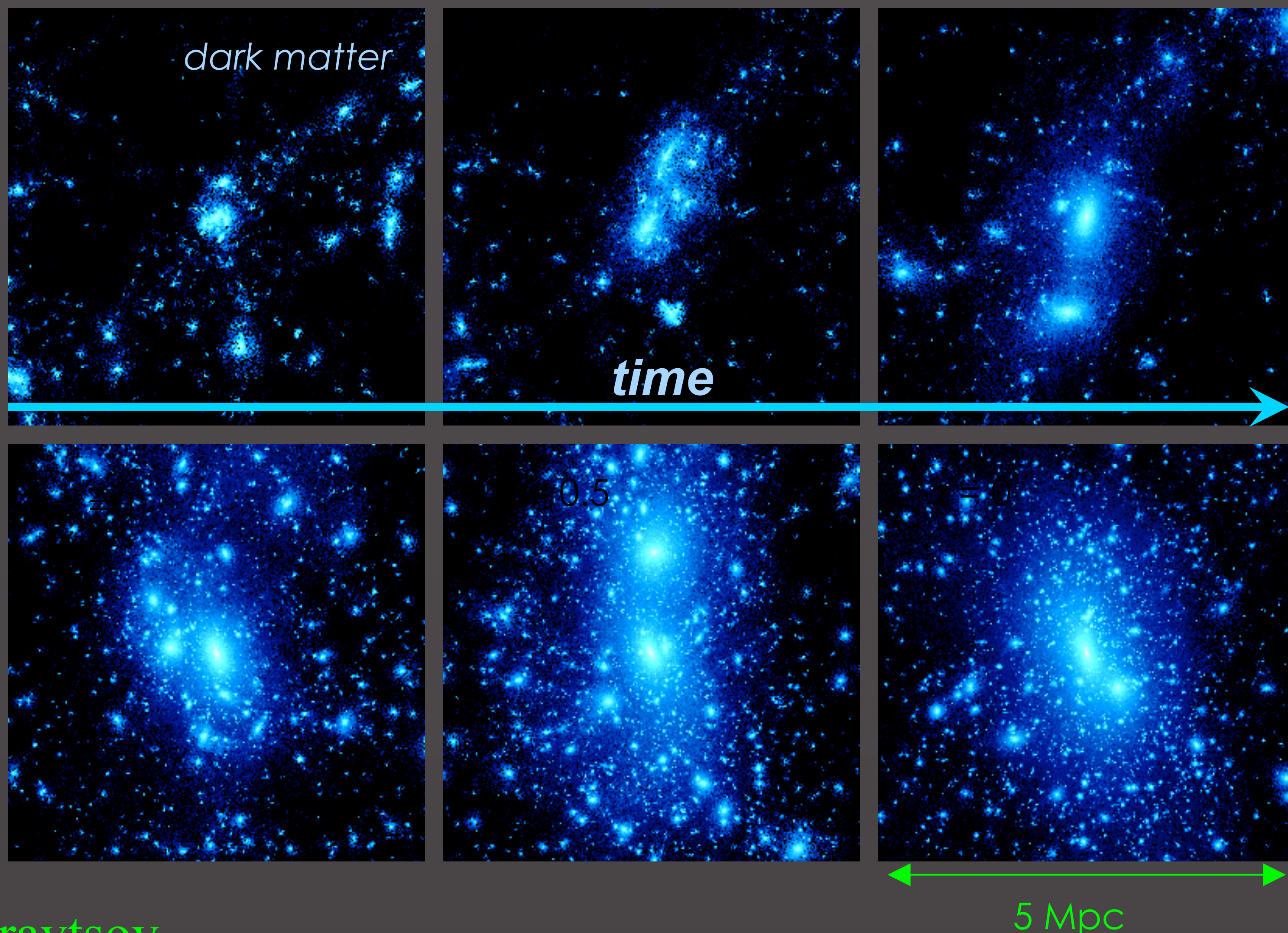
     g(O|M,z)

Primary systematic:

$$\frac{d^2N(z)}{dz\,d\Omega} = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_{O_{min}}^{\infty} f(O,z)\,dO \int_0^{\infty} g(O|M,z) \frac{dn(z)}{dM} dM$$

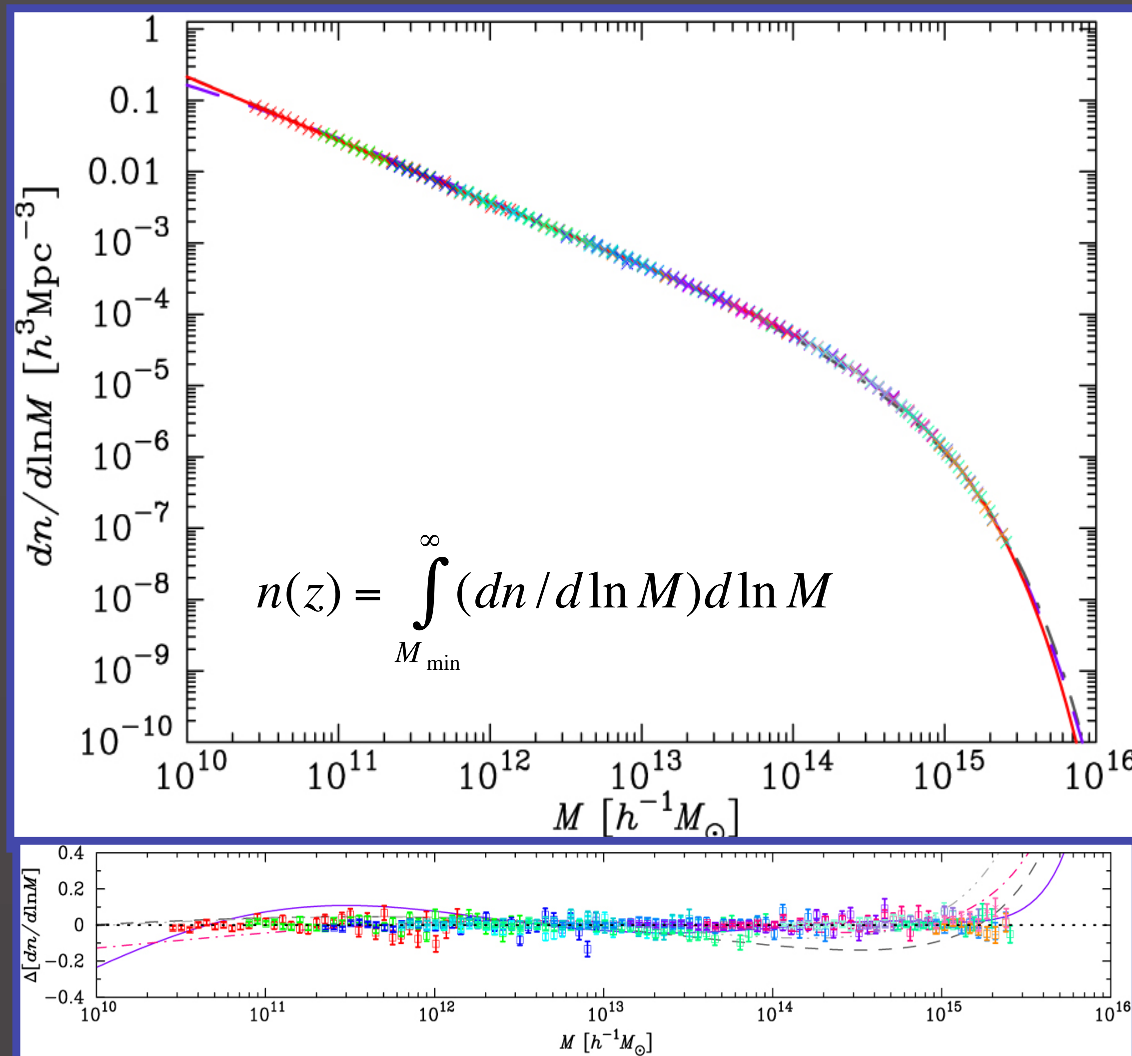
(geometry)

Halos form hierarchically



Kravtsov

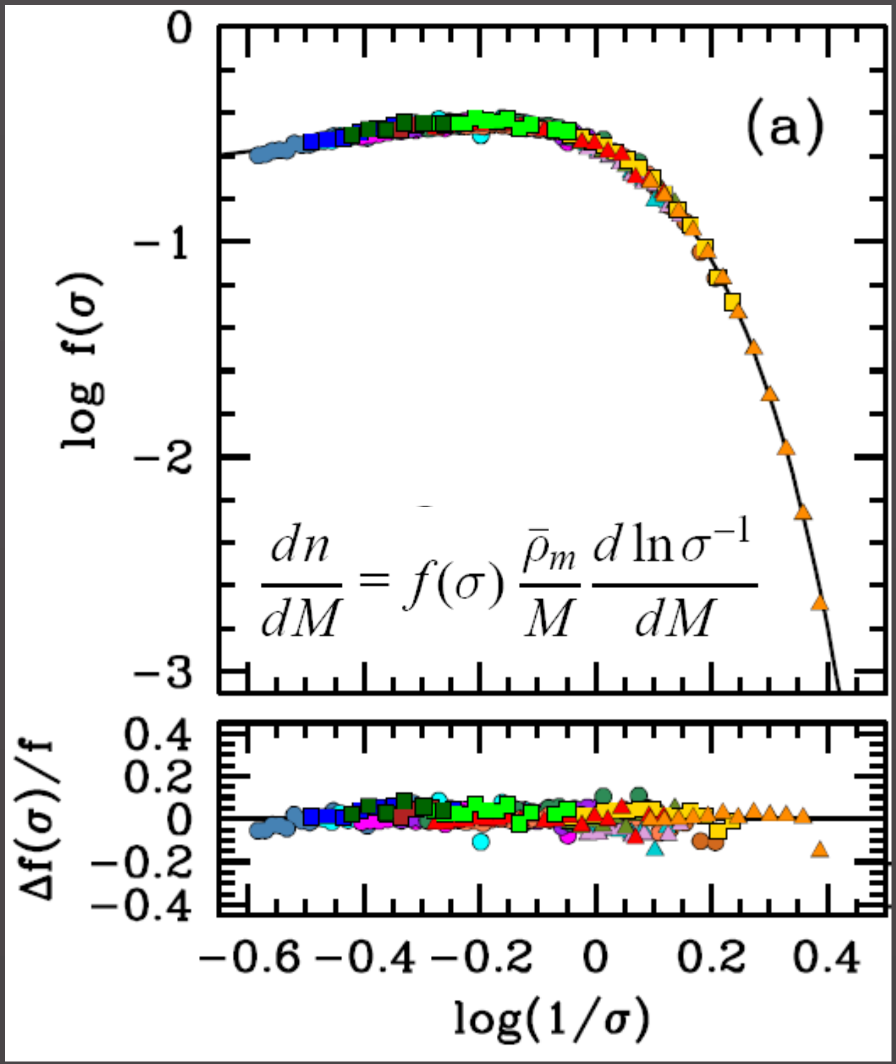
Theoretical Abundance of Dark Matter Halos



Warren etal

Halo Mass Function

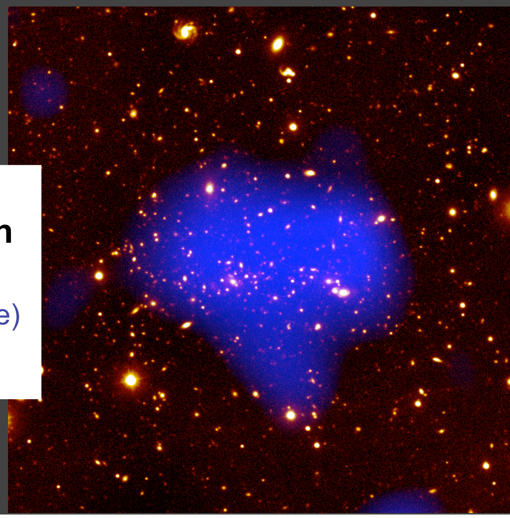
$$\sigma(M, z) = \sigma(M, z = 0)D(z)$$

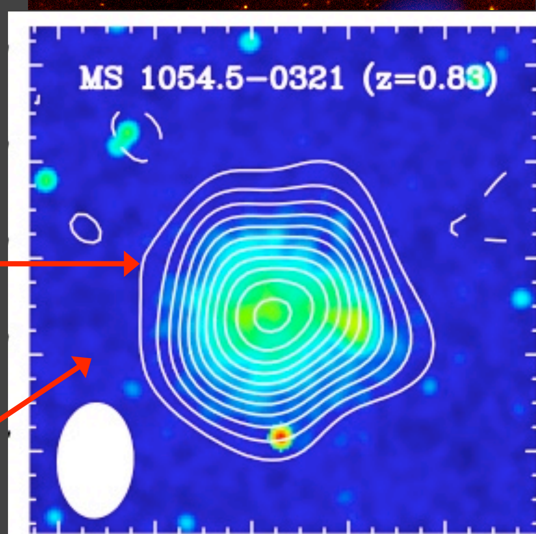


Tinker, Kravtsov et al. 2008, ApJ 688, 709

Clusters of Galaxies

MS1054, z =0.83 optical image with X-ray overlaid in blue (credit: Donahue)





SZ Effect (contours) (OVRO/BIMA)

X-ray (color)

- Clusters of galaxies are the largest gravitationally virialized objects in the Universe: $M \sim 10^{13}$-10^{15} M_{sun}
- ~50-90% of their baryonic mass is in the form of intracluster gas
- The gas is heated as it collapses into the cluster's gravitational potential well to temperatures of $T_{gas} \sim 10^7$-10^8 K
- The hot intracluster gas emits X-rays and causes the Sunyaev-Zel'dovich (SZ) effect
- Clusters serve as approximate proxies for massive dark matter halos

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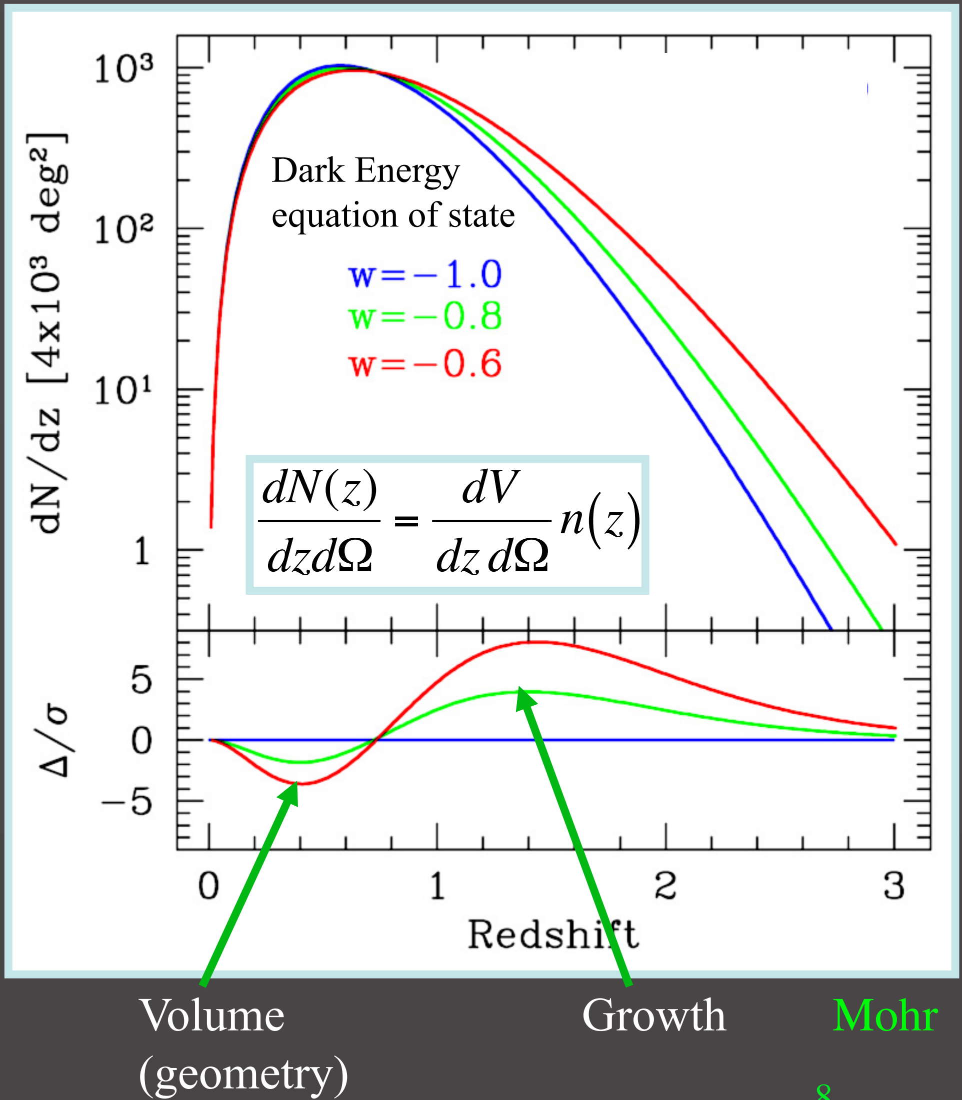
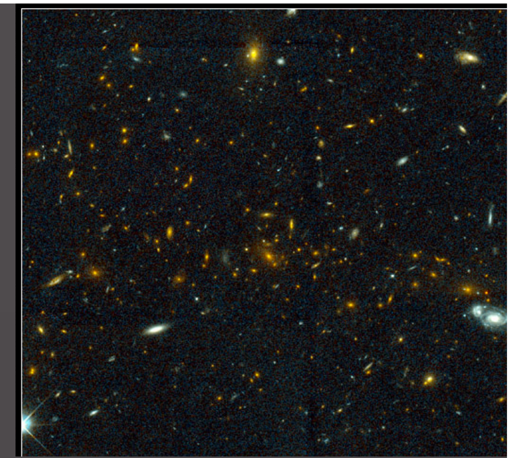


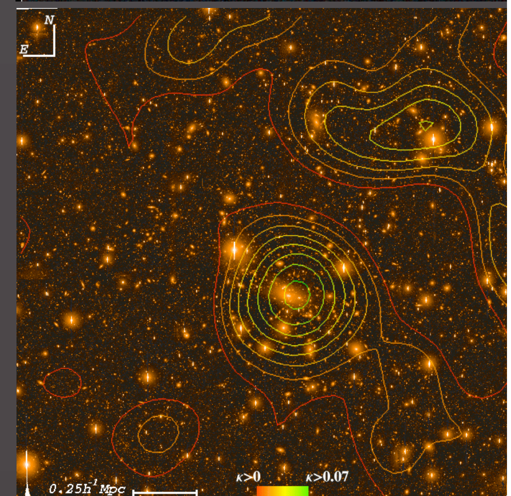
Mohr

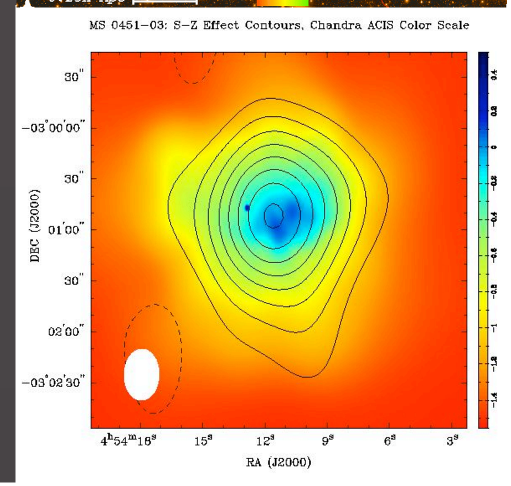
Cluster Selection

- 4 Techniques for Cluster Selection:
  - Optical galaxy concentration
  - Weak Lensing
  - Sunyaev-Zel'dovich effect (SZE)
  - X-ray

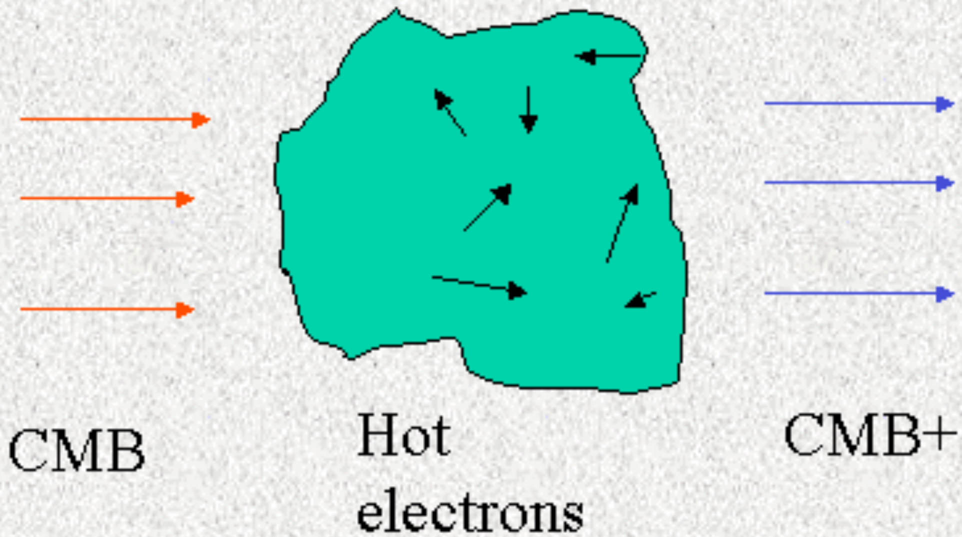
  - Cross-compare selection to control systematic errors

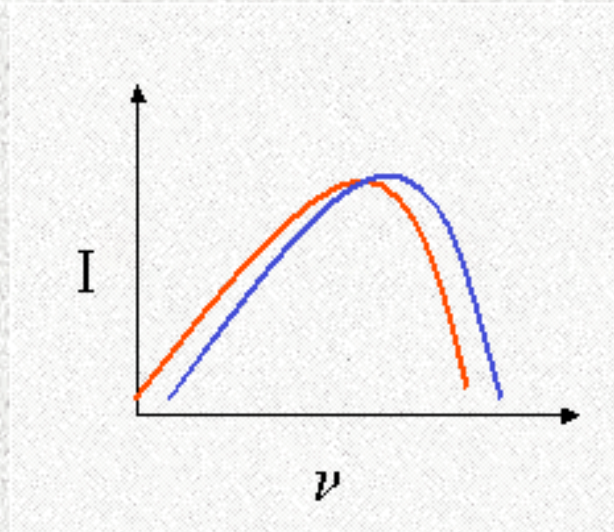






Sunyaev-Zel'dovich Effect





Optical depth: $\tau \sim 0.01$

Fractional energy gain per scatter: $\frac{kT}{m_e c^2} \sim 0.01$

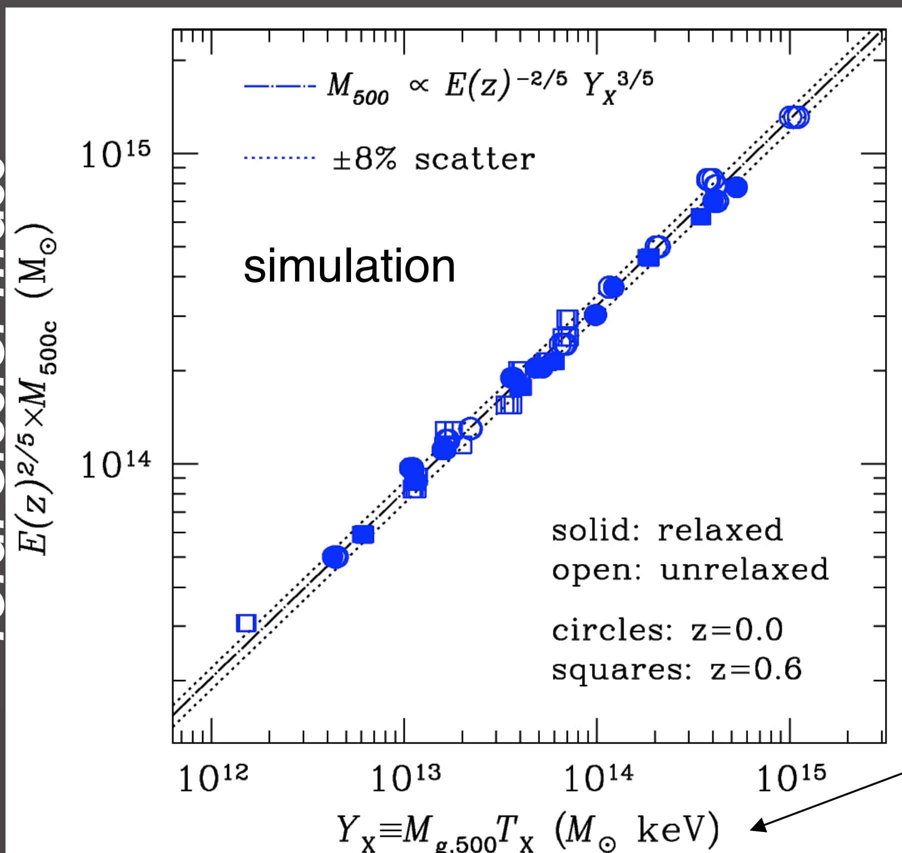
Holder

Cluster Scaling Relations

Kavli Institute for Cosmological Physics at the University of Chicago

Relations between observable integrated properties of intracluster gas and cluster mass are expected and observed to be tight, but the amplitude and slope are affected by galaxy formation physics

Total cluster mass



"pressure" = Y = gas mass x temperature

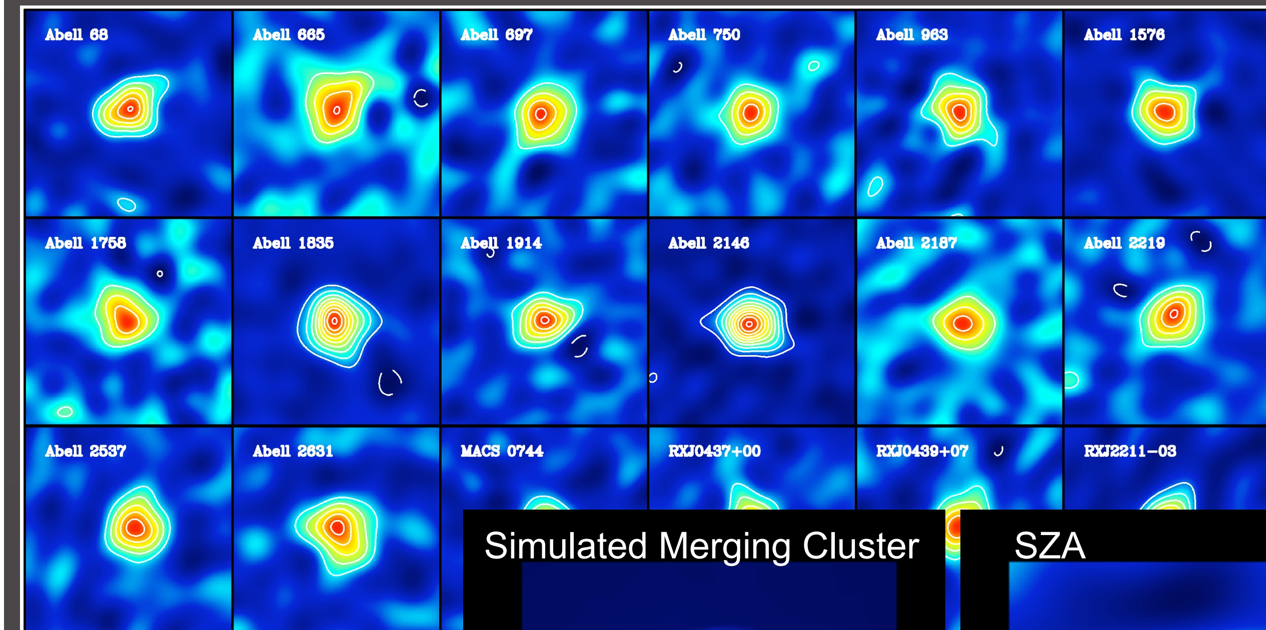
SZ signal:

$$Y \propto \int n_e T_e dV \propto T_{gas} M_{gas}$$

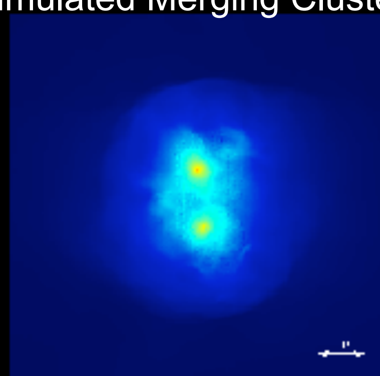
Nagai 2005;
Kravtsov, Vikhlinin, Nagai 2006, ApJ 650, 128

Cluster SZ Studies

- Examine clusters at high angular resolution
- Compare many probes to calibrate SZ signal

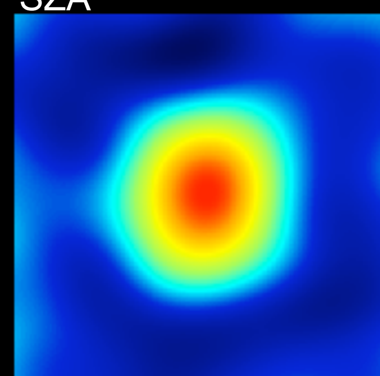


Simulated Merging Cluster

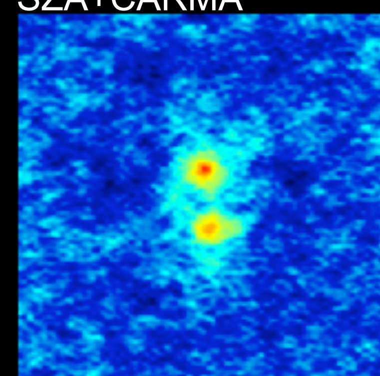


Nagai, Kravtsov, Vikhlinin (2007)

SZA



SZA+CARMA



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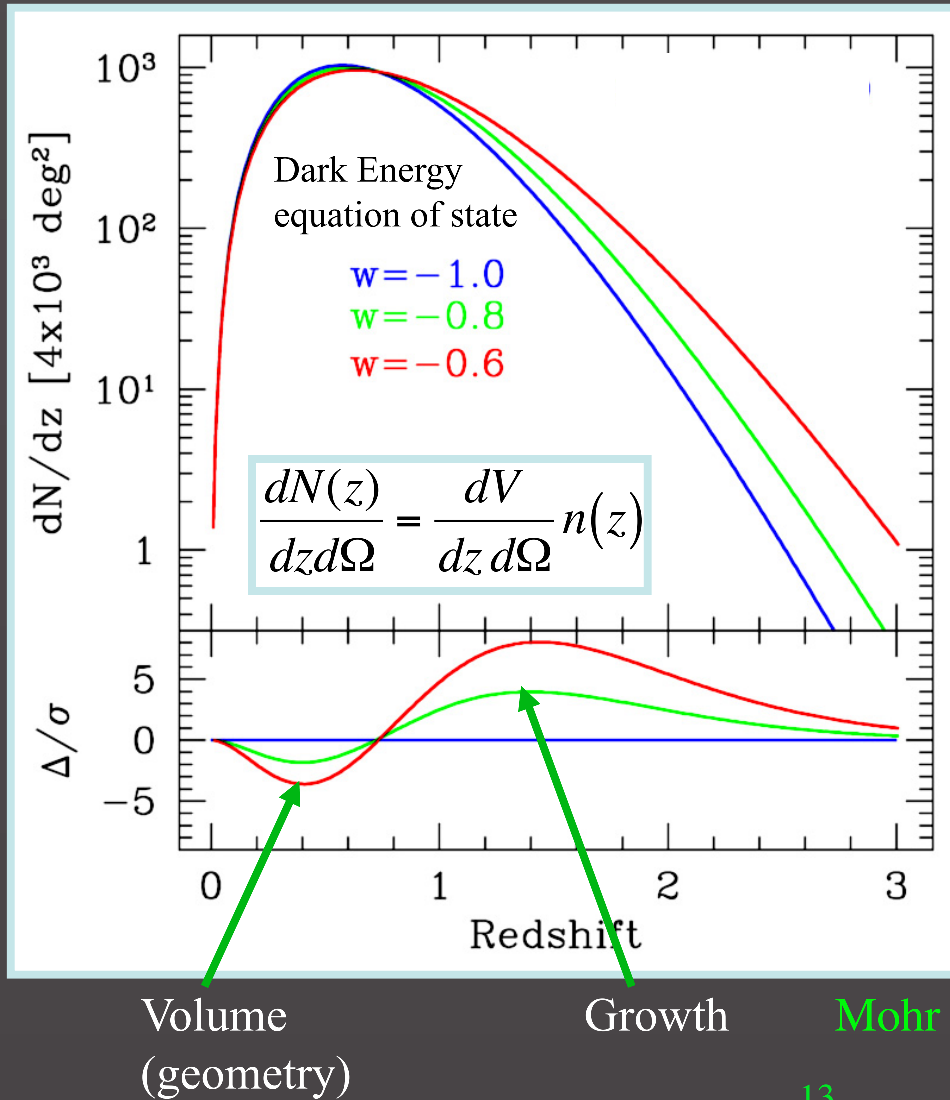
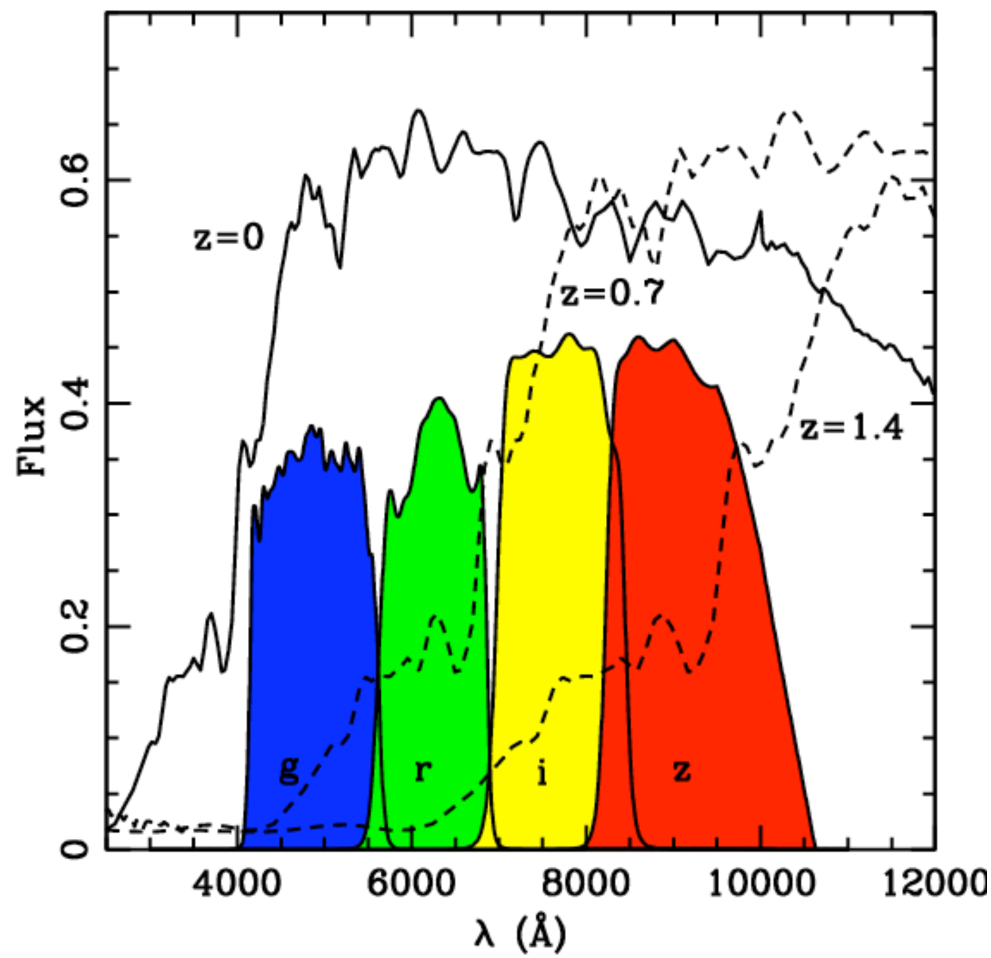


Mohr

Photometric Redshifts

DARK ENERGY SURVEY

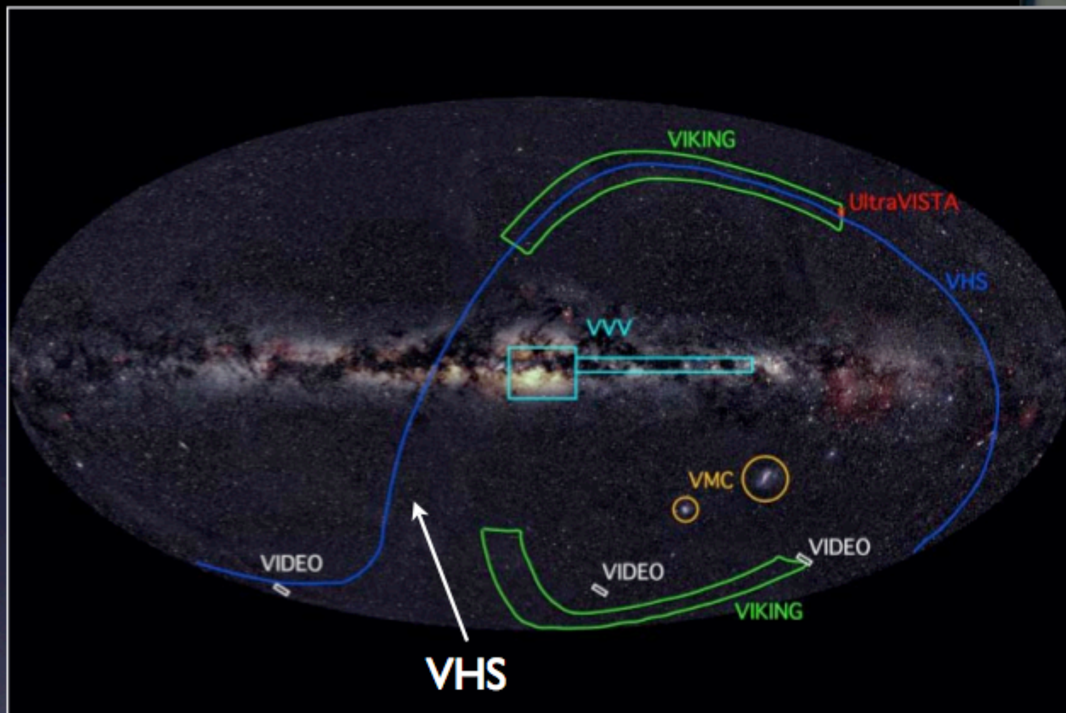
Redshifted Elliptical galaxy spectrum



- Measure relative flux in multiple filters: track the 4000 A break

- Precision is sufficient for Dark Energy probes, provided error distributions well measured.

VISTA Hemisphere Survey



120 sec JHK exposures

VISTA

4.1m primary mirror
1.5deg field of view
16 2kx2k HgCdTe

VHS

380 nights over 5 yrs
120 sec JHK exposures
Richard McMahon, PI

VHS limiting magnitudes [AB system; 5σ]	deg²	Y	J	H	K
VHS-DES	5000	**21.9**	21.2	20.8	20.2

DES collaborates with VHS: DES acquires Y imaging, VHS shares JHK data

Galaxy Photo-z Simulations

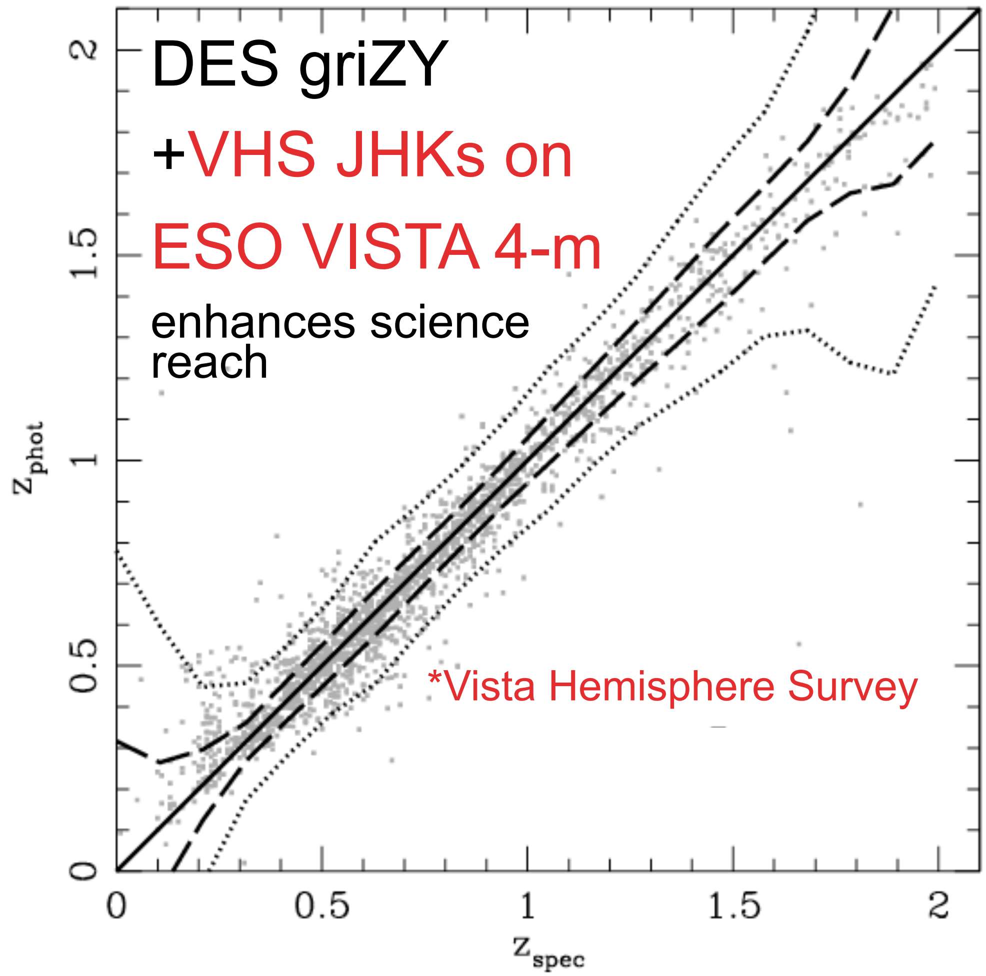
DARK ENERGY SURVEY

DES +VHS*

10σ Limiting Magnitudes

g	24.6		
r	24.1	J	20.3
i	24.0	H	19.4
Z	23.8	Ks	18.3
Y	21.6		

+2% photometric calibration error added in quadrature



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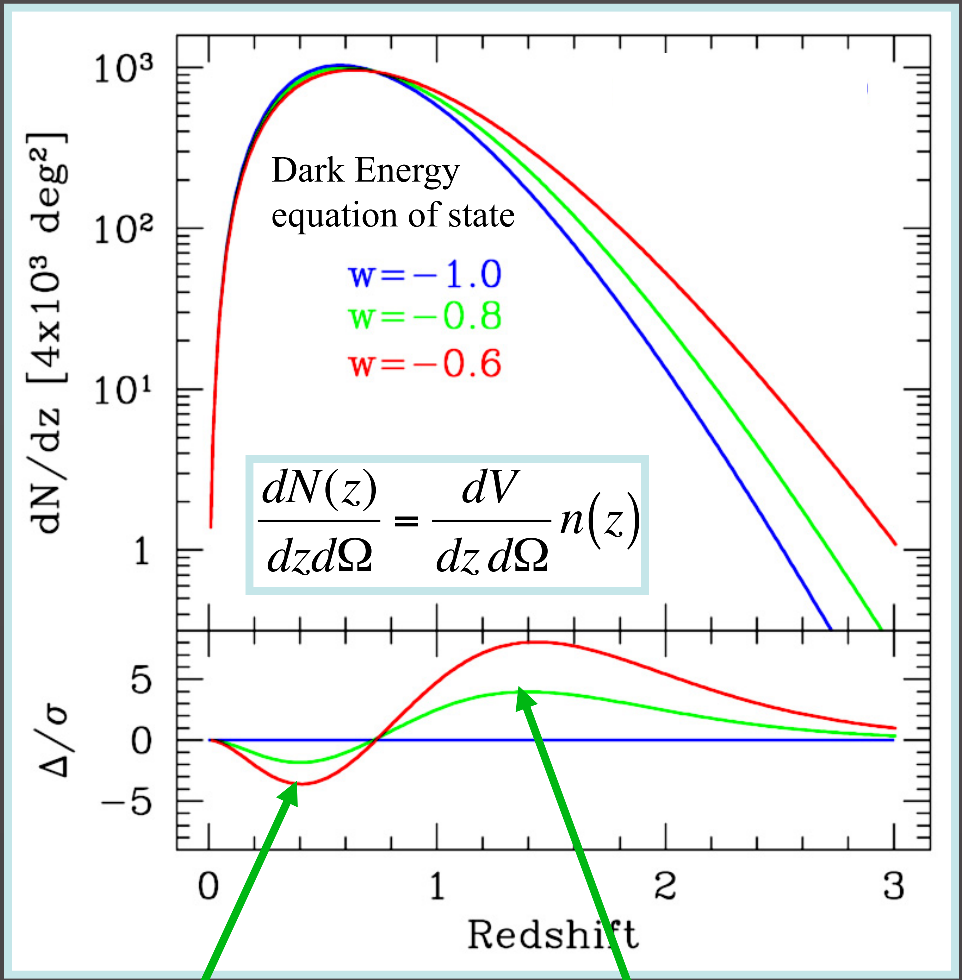


Volume (geometry)

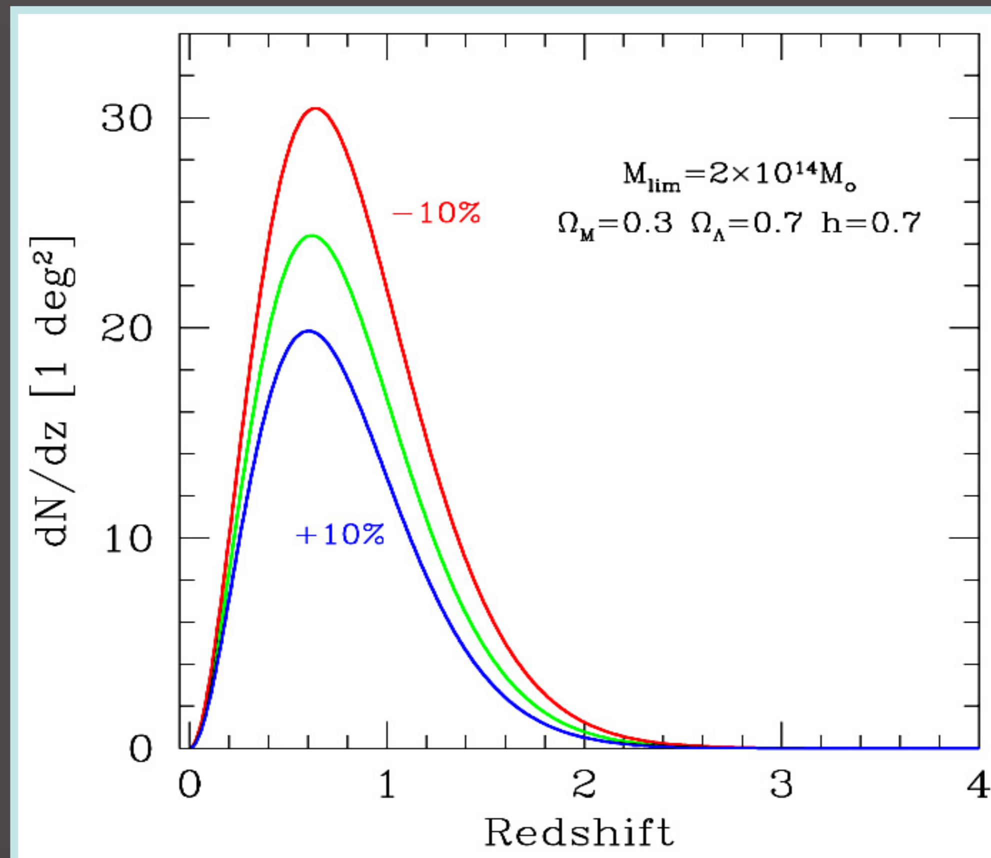
Growth

Mohr

Precision Cosmology with Clusters?

Effect of Uncertainty in mass-observable relation

Sensitivity to Mass Threshold



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

Mass threshold

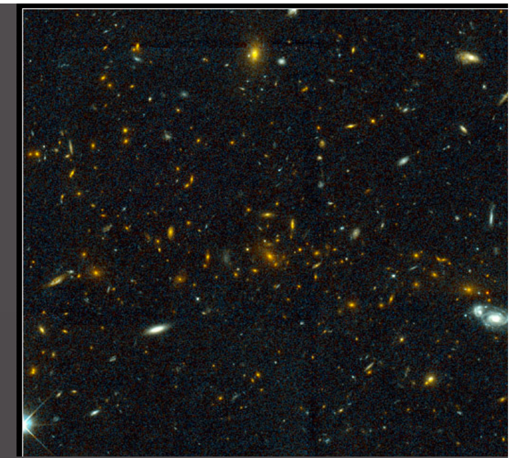
Cluster Mass Estimates

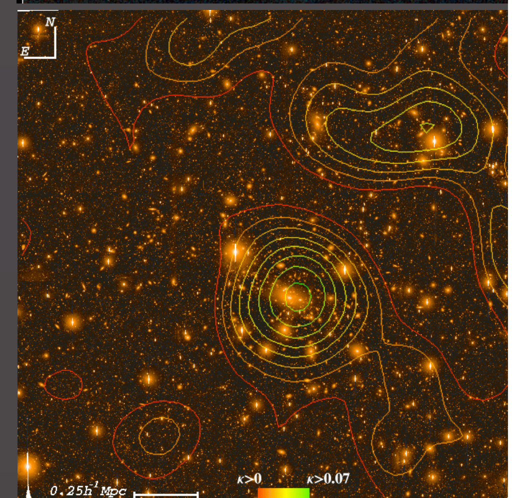
4 Techniques for Cluster Mass Estimation:

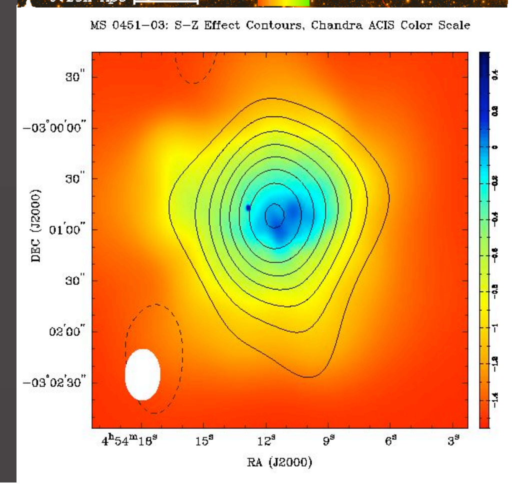
- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel'dovich effect (SZE)
- X-ray

- Cross-compare these techniques to reduce systematic errors
- Additional cross-checks:

  shape of mass function; cluster correlations (Lima & Hu)

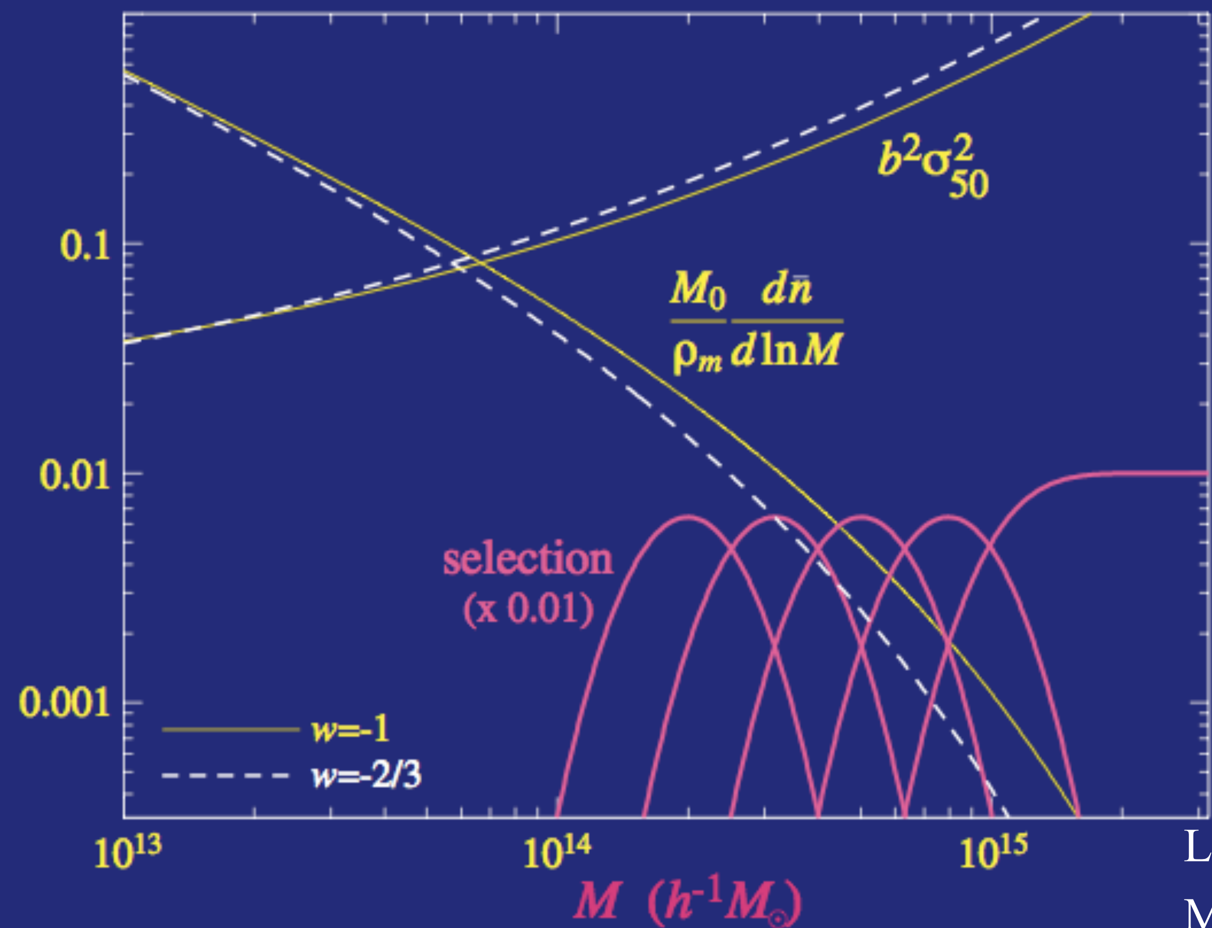






Joint Self-Calibration

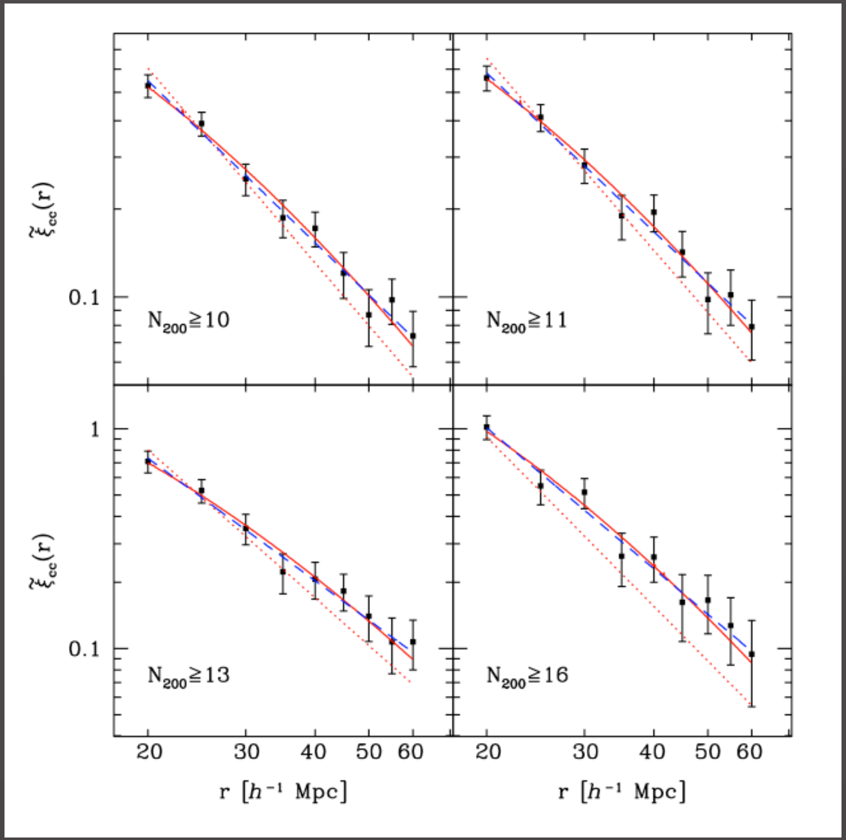
- Both counts and their variance as a function of binned observable
- Many observables allows for a joint solution of a mass independent bias and scatter with cosmology

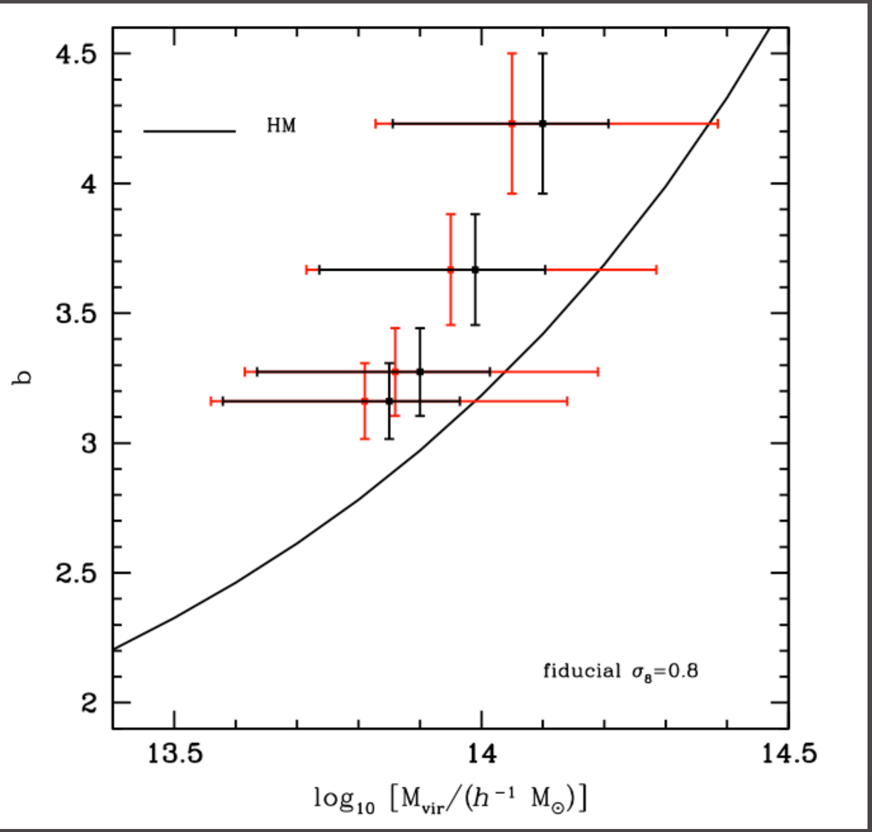


Lima & Hu

Majumdar & Mohr

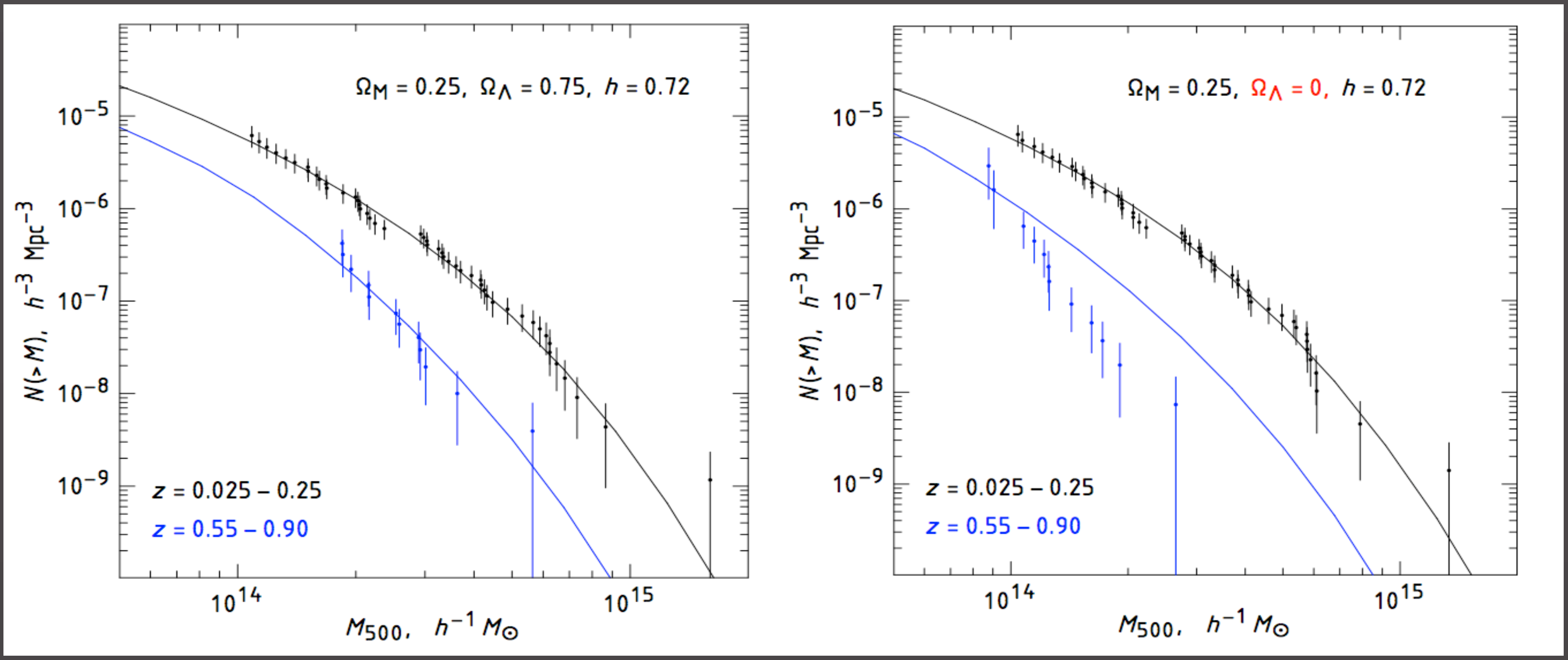
Cluster Clustering





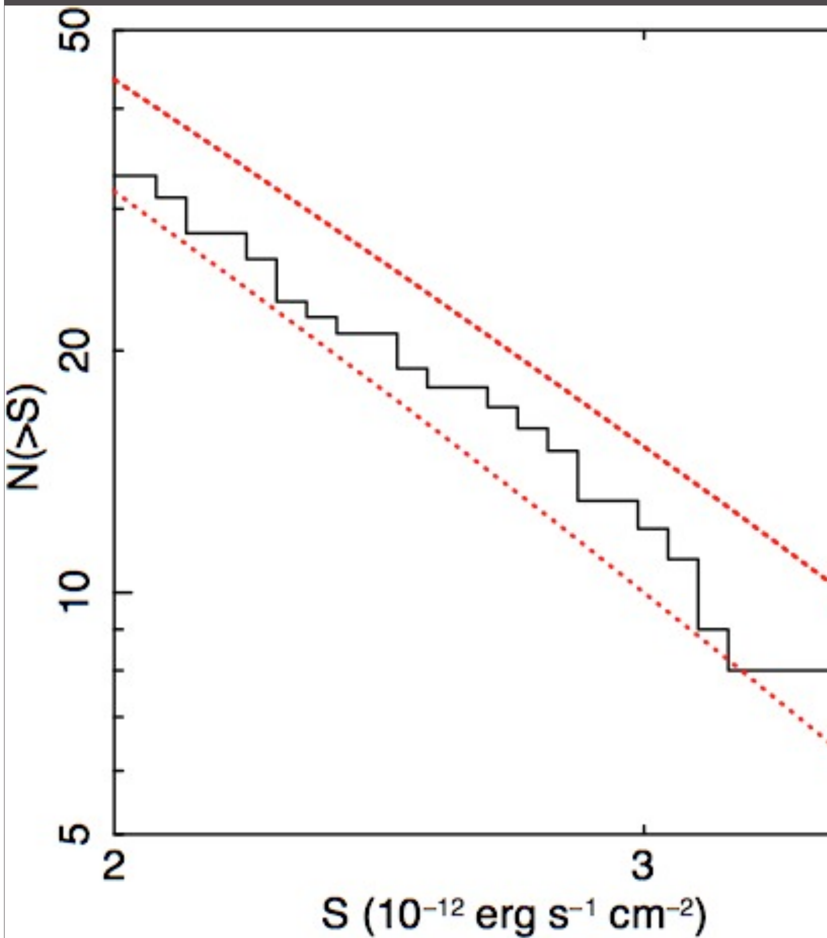
Clustering amplitude constrains cluster mass

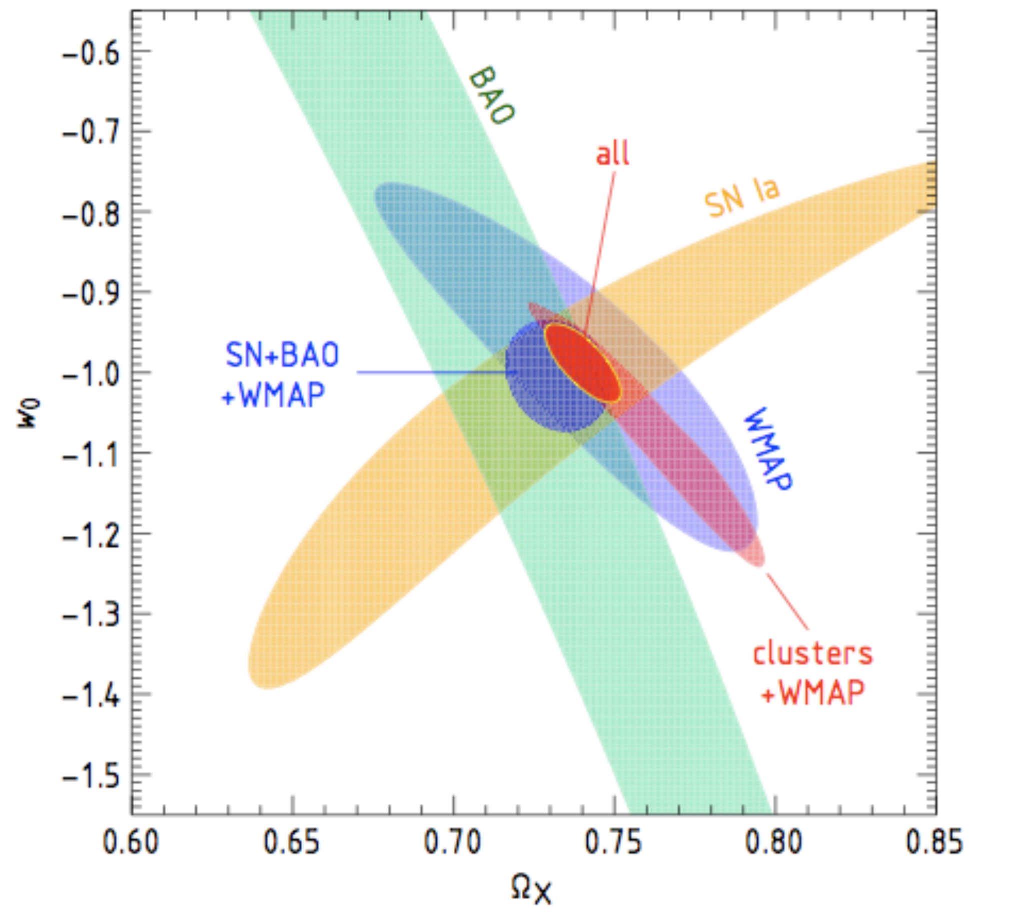
Current Constraints from X-ray Clusters



Vikhlinin etal

Current Constraints: X-ray clusters



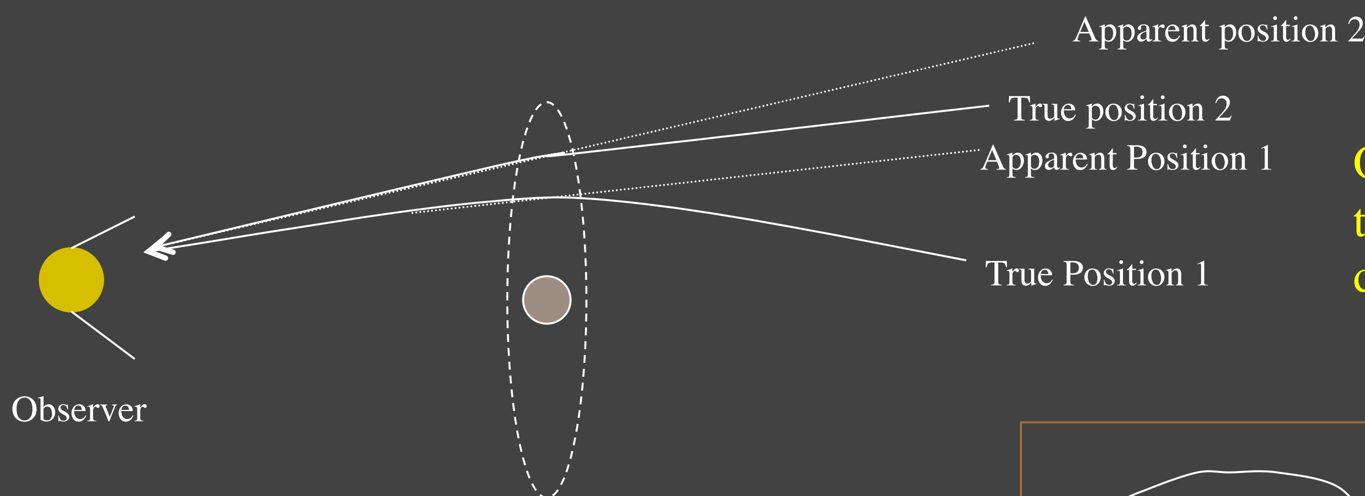


Mantz, et al 2007

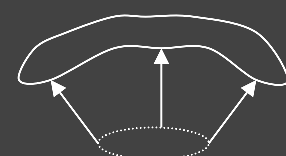
Vikhlinin, et al 2008

Gravitational Lensing

See the same effects that occur in more familiar optical circumstances: magnification and distortion (shear)



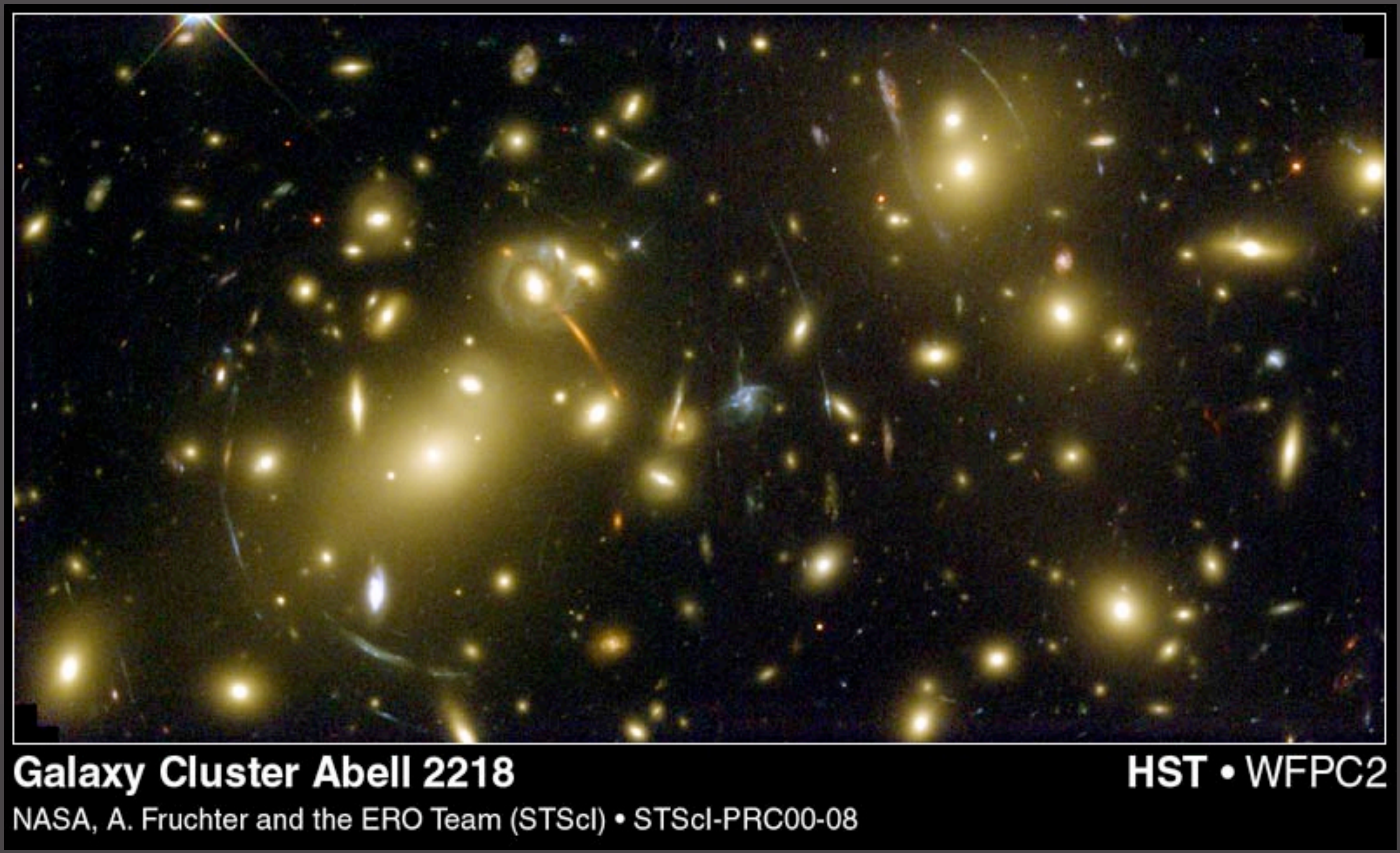
Objects farther from the line of sight are distorted less.



"Looking into" the lens: extended objects are tangentially distorted...

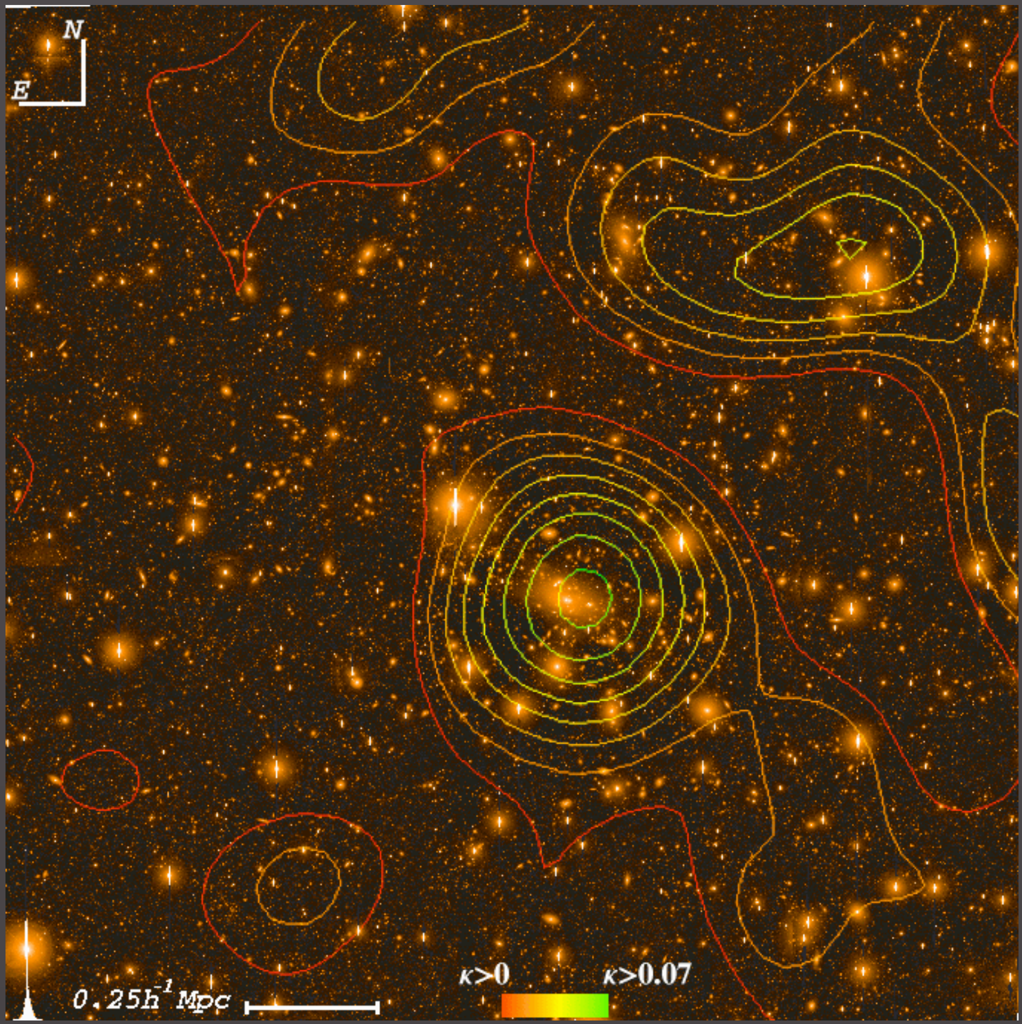
Lensing conserves surface brightness: bigger image ←→ magnified

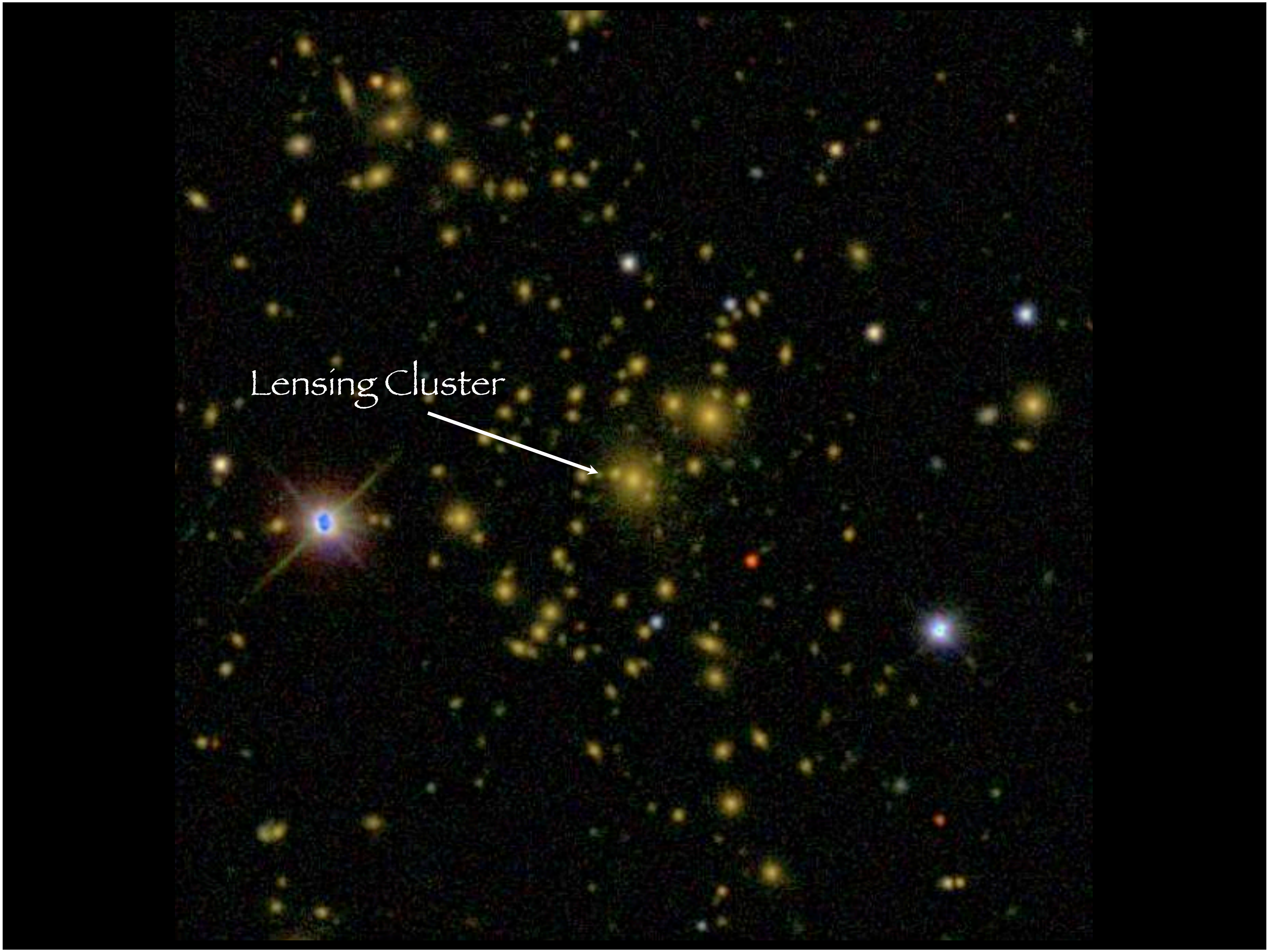
Gravitational Lensing by Clusters

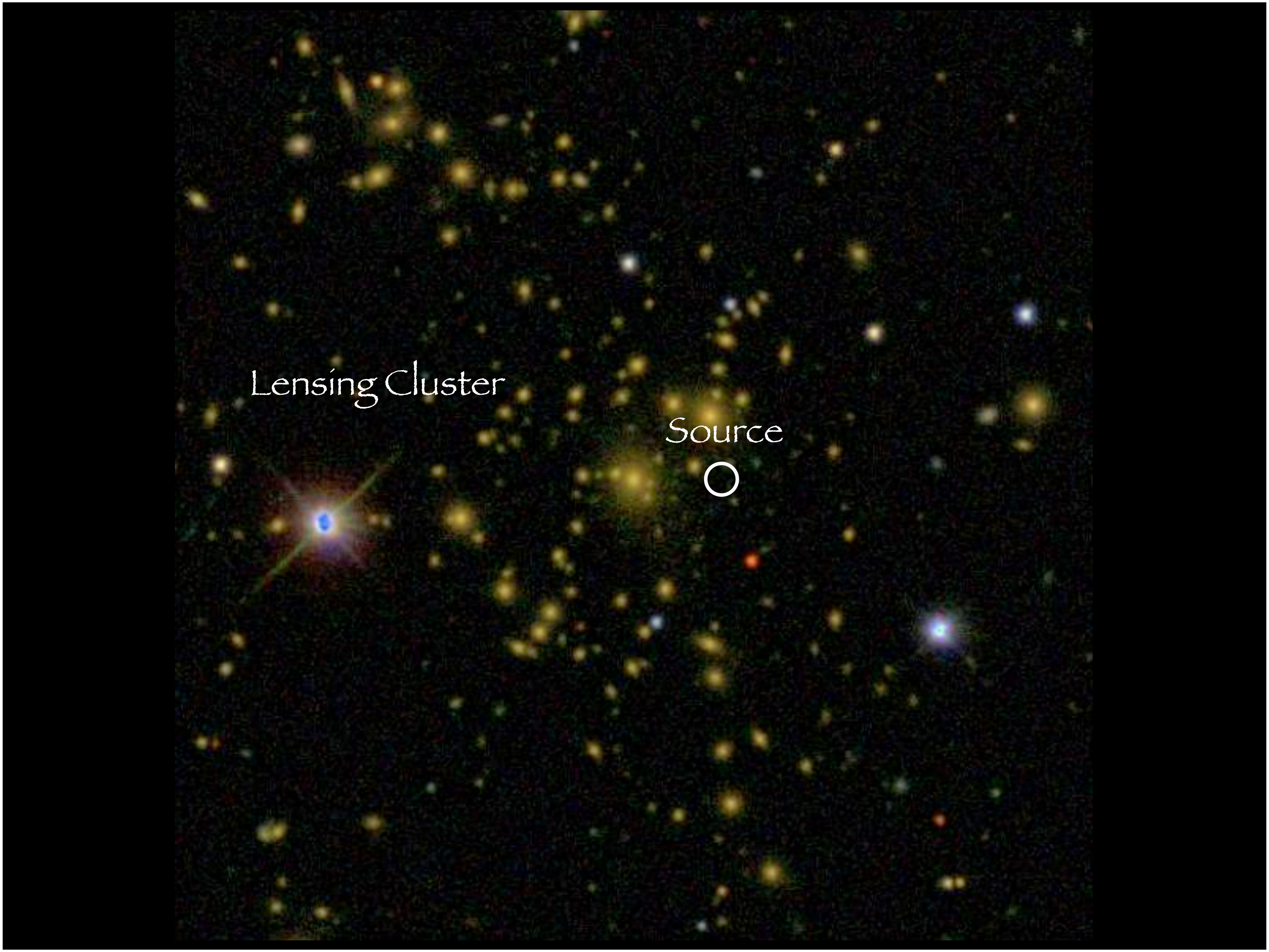


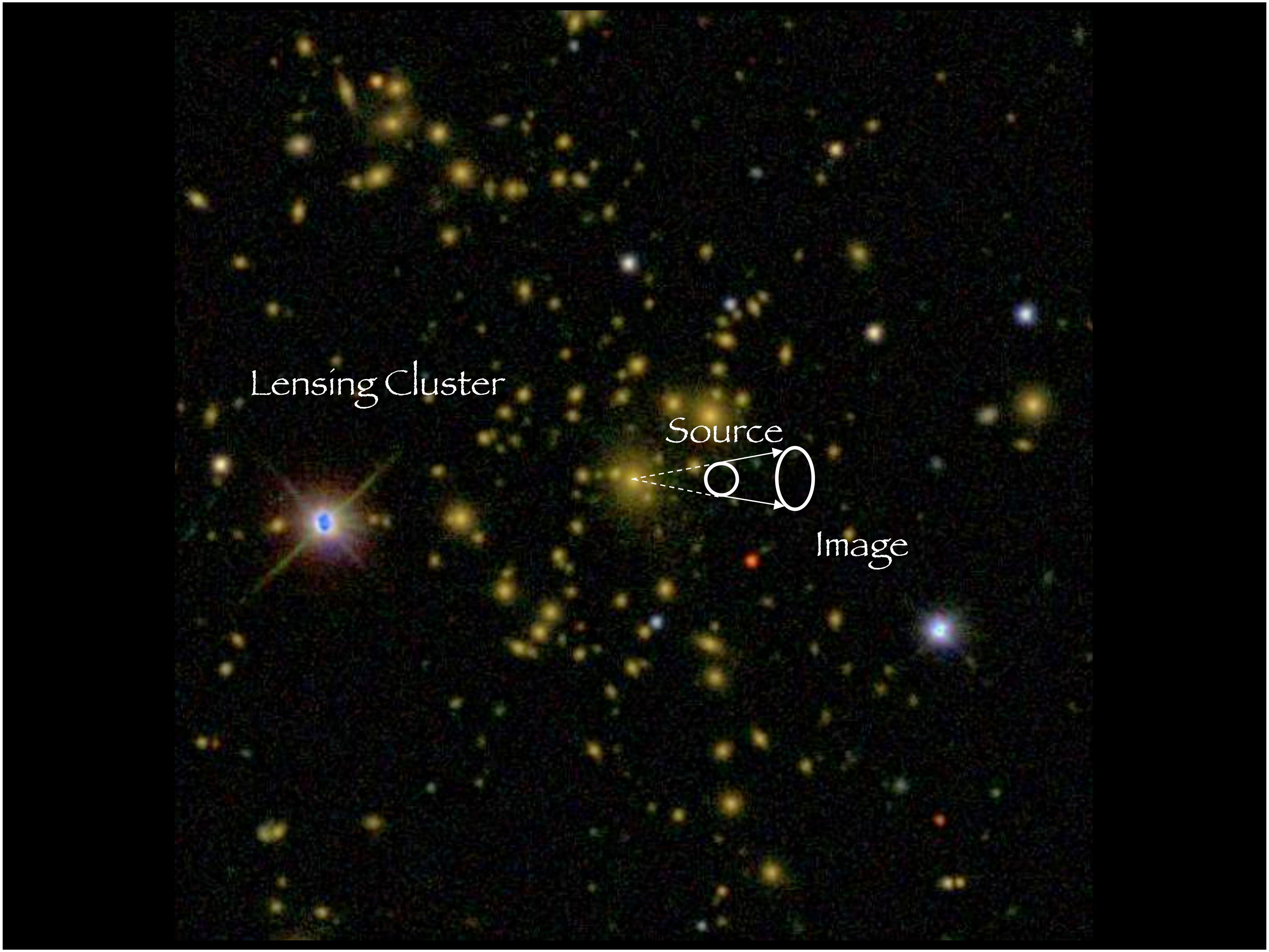
Strong Lensing

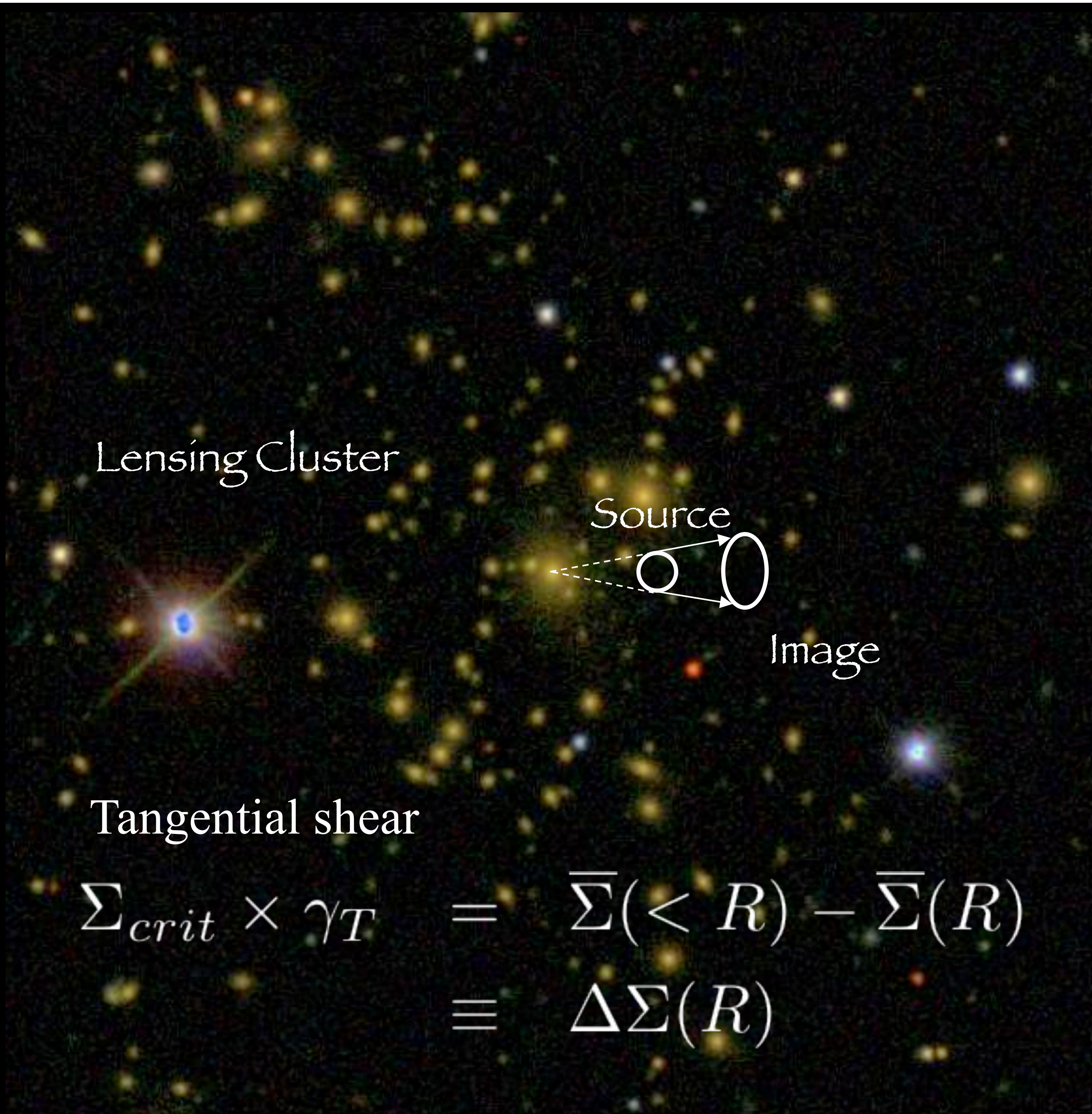
Deep images: WL reconstrution of Cluster Mass Profile




Lensing Cluster


Lensing Cluster
Source

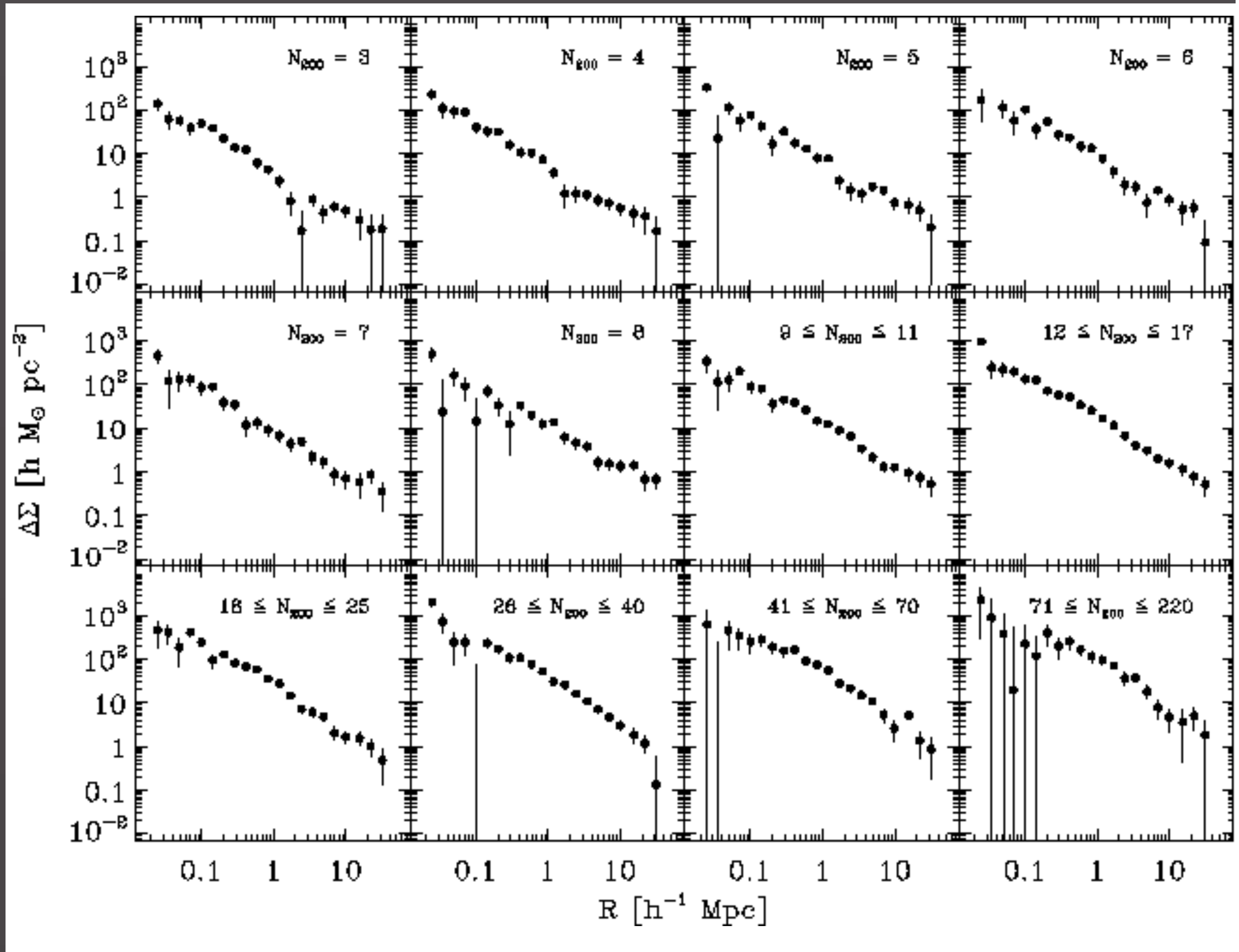

Lensing Cluster
Source
Image



$$\Sigma_{crit} \times \gamma_T = \bar{\Sigma}(< R) - \bar{\Sigma}(R) \equiv \Delta\Sigma(R)$$

Statistical Weak Lensing by Galaxy Clusters

Mean Tangential Shear Profile in Optical Richness (N_{gal}) Bins to 30 h^{-1}Mpc



Sheldon, Johnston, etal SDSS

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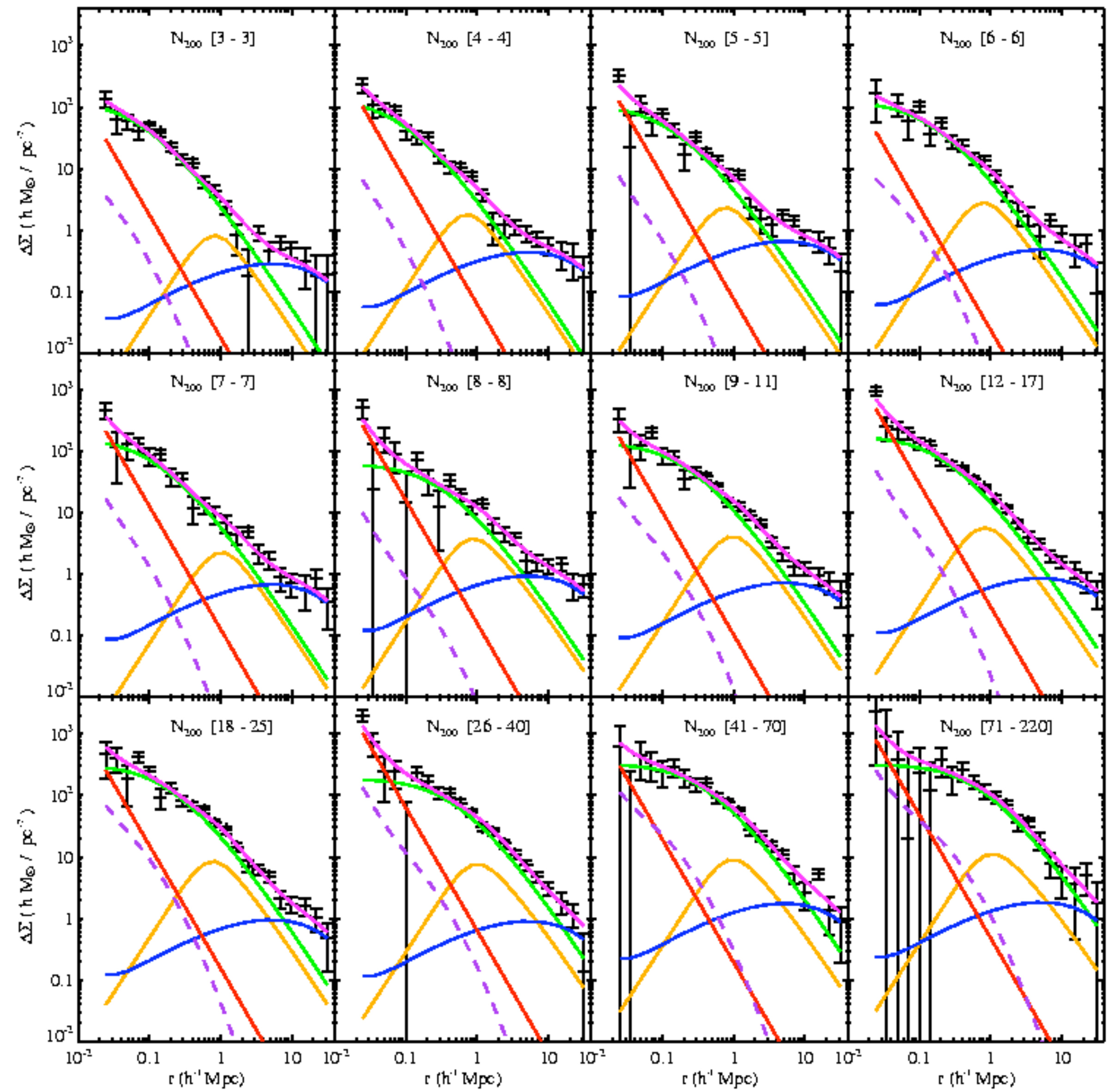
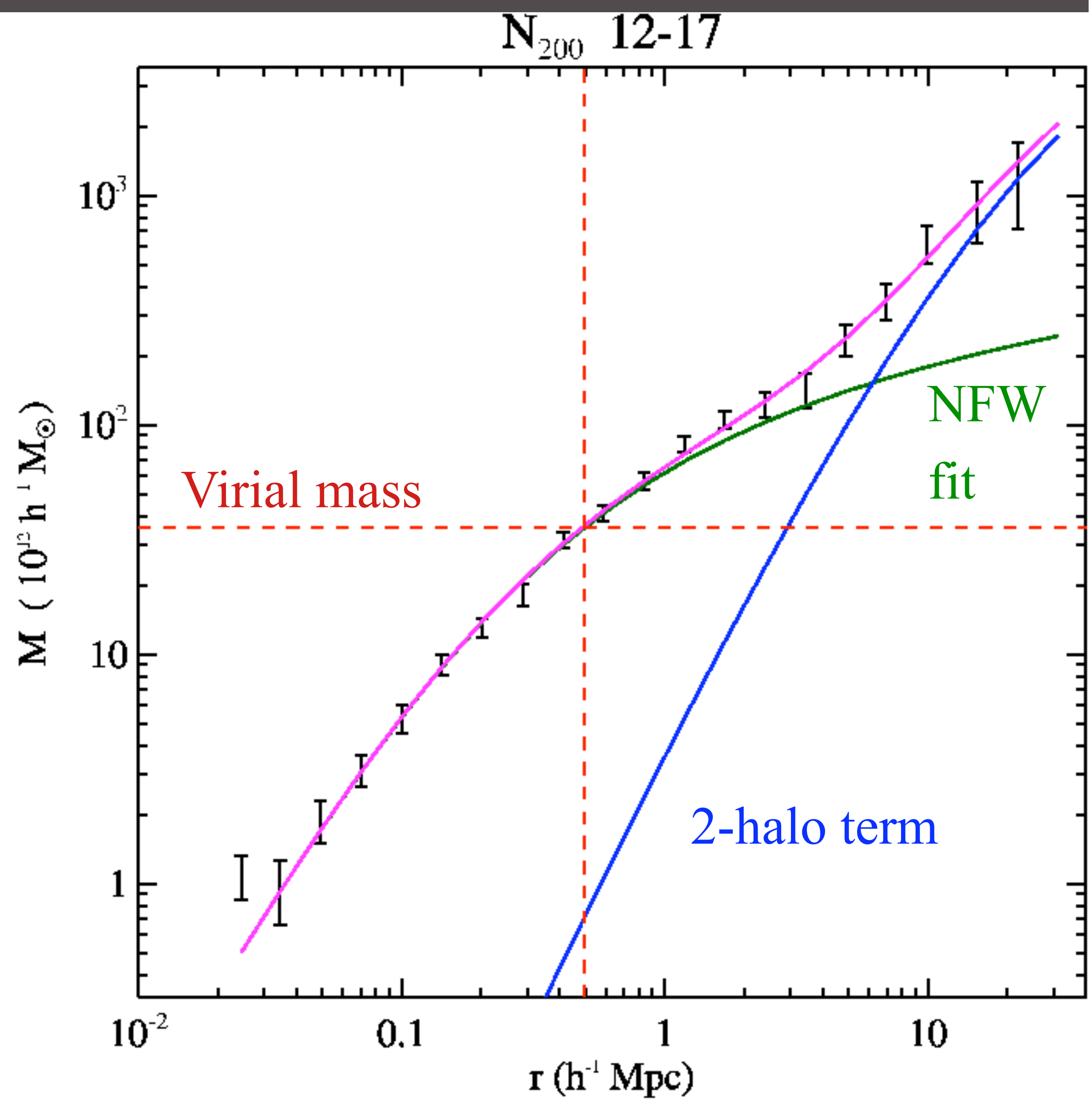


Johnston, Sheldon, etal SDSS

Mean 3D Cluster Mass Profile

from Statistical Lensing

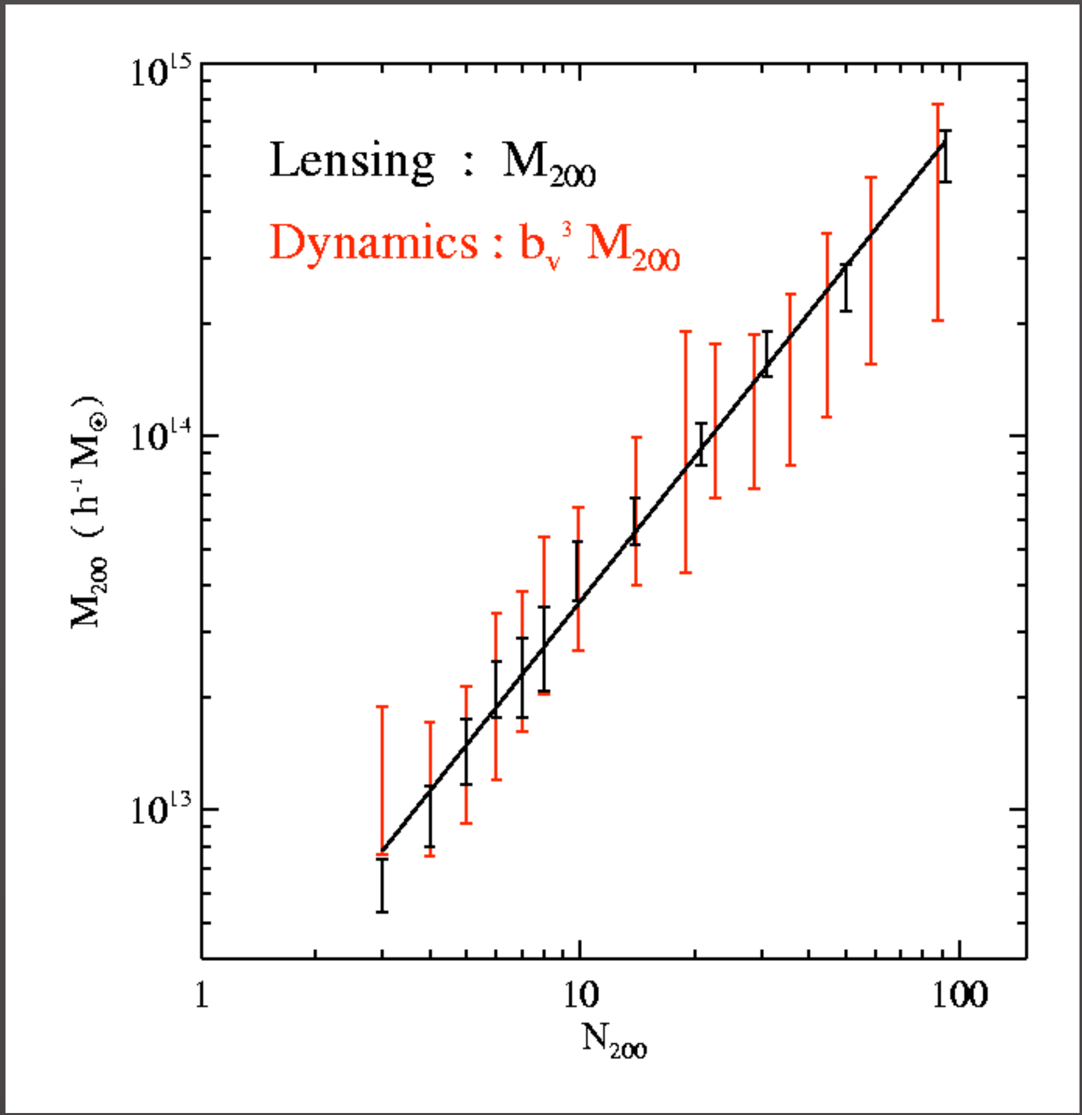
Johnston, etal



Statistical Weak Lensing Calibrates Cluster Mass vs. Observable Relation

Cluster Mass vs. Number of galaxies they contain

Future:
use this to independently calibrate, e.g., SZE vs. Mass



Statistical Lensing eliminates projection effects of individual cluster mass Estimates

~50% scatter in mass vs optical richness

Johnston, Sheldon, etal