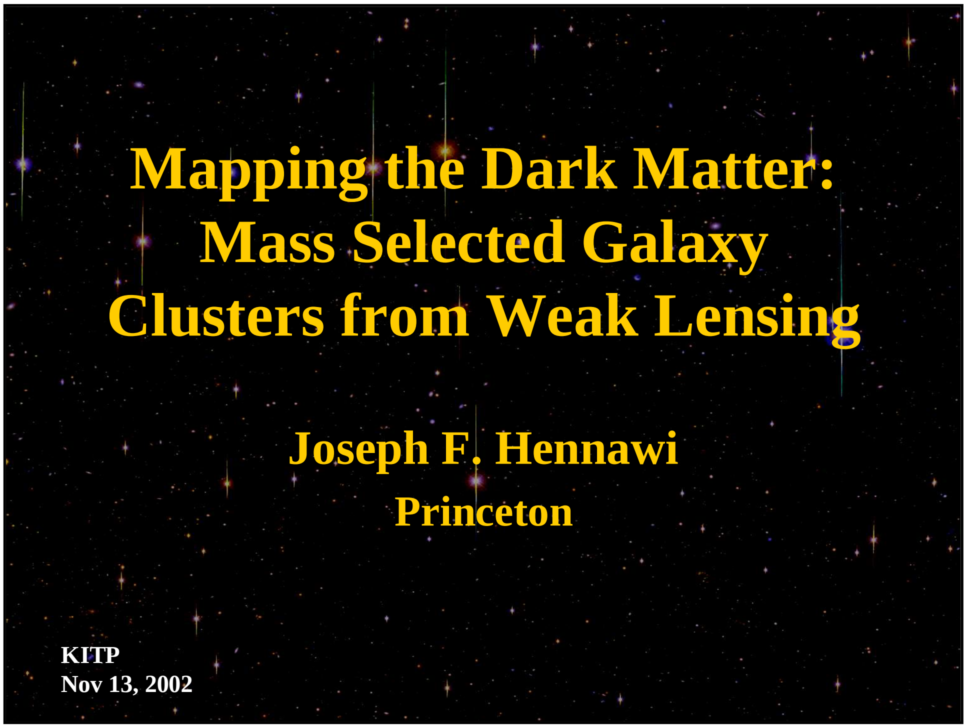

Mapping the Dark Matter: Mass Selected Galaxy Clusters from Weak Lensing

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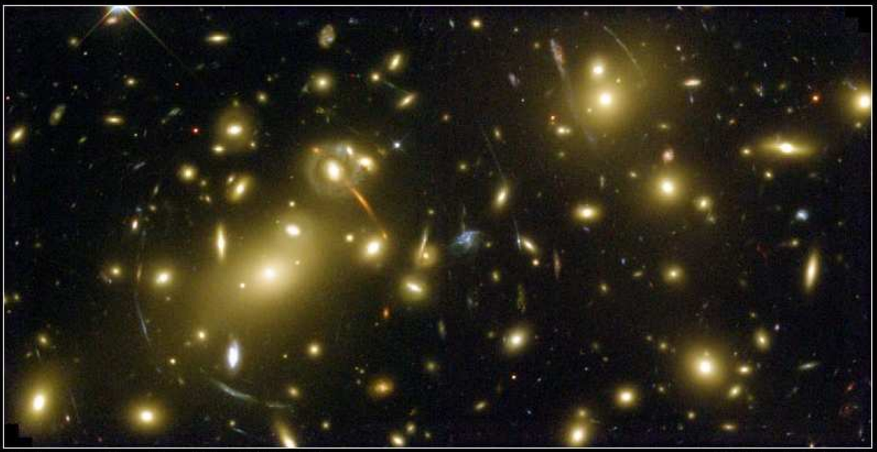
Outline

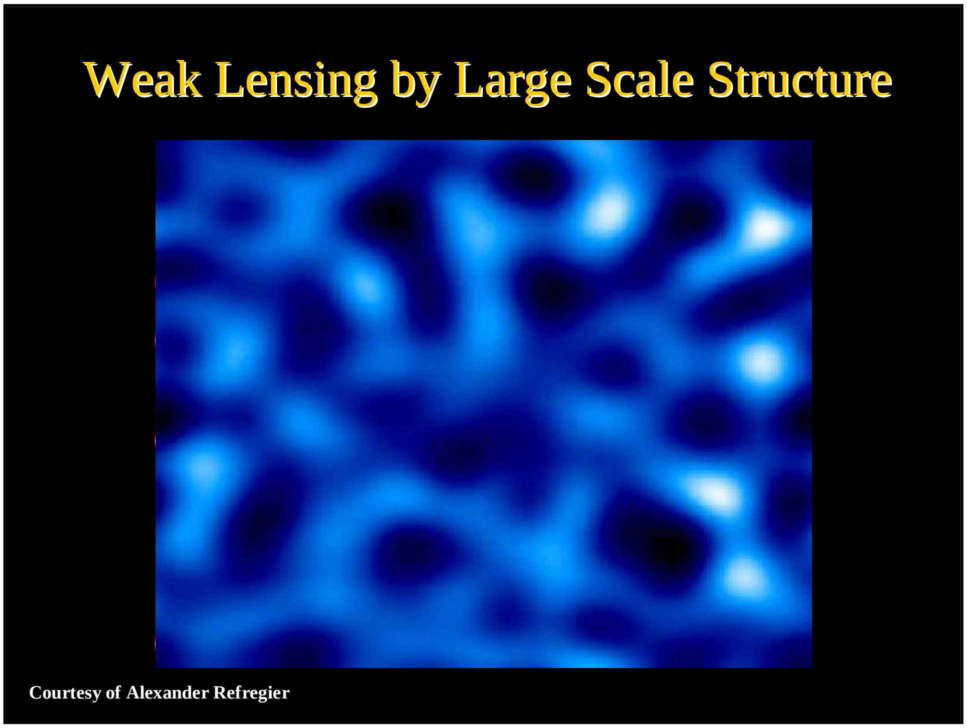
- Galaxy clusters from weak lensing
- Dark clusters?
- Cluster Tomography
- N-body simulations
- Optimal filtering
- Constraining dark energy

Gravitational Lensing



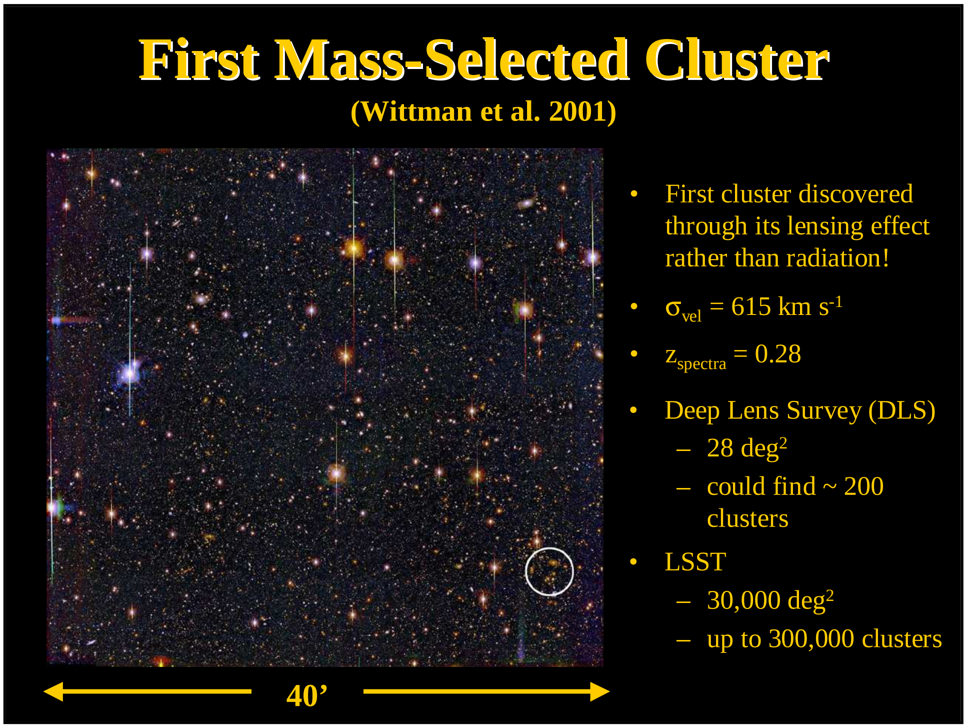
Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08



Weak Lensing by Large Scale Structure

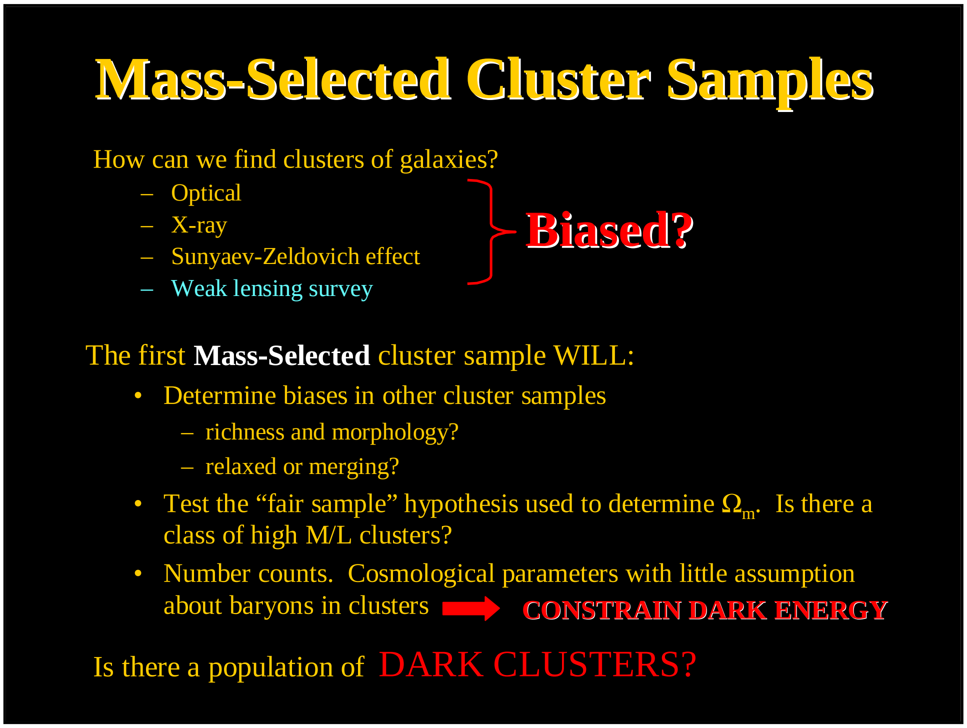
Courtesy of Alexander Refregier



First Mass-Selected Cluster

(Wittman et al. 2001)

- First cluster discovered through its lensing effect rather than radiation!
- σ_{vel} = 615 km s^{-1}
- $z_{spectra}$ = 0.28
- Deep Lens Survey (DLS)
  - 28 deg^2
  - could find ~ 200 clusters
- LSST
  - 30,000 deg^2
  - up to 300,000 clusters



Mass-Selected Cluster Samples

How can we find clusters of galaxies?

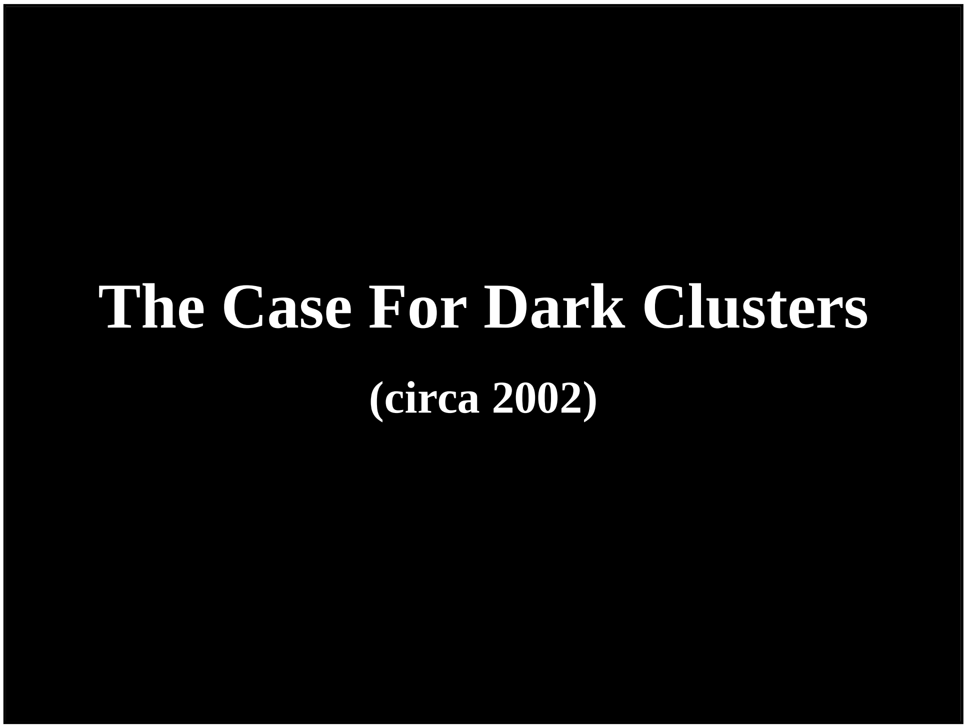
- Optical
- X-ray
- Sunyaev-Zeldovich effect
- Weak lensing survey

Biased?

The first **Mass-Selected** cluster sample WILL:

- Determine biases in other cluster samples
  - richness and morphology?
  - relaxed or merging?
- Test the “fair sample” hypothesis used to determine Ω_m. Is there a class of high M/L clusters?
- Number counts. Cosmological parameters with little assumption about baryons in clusters ➡ CONSTRAIN DARK ENERGY

Is there a population of DARK CLUSTERS?



The Case For Dark Clusters

(circa 2002)

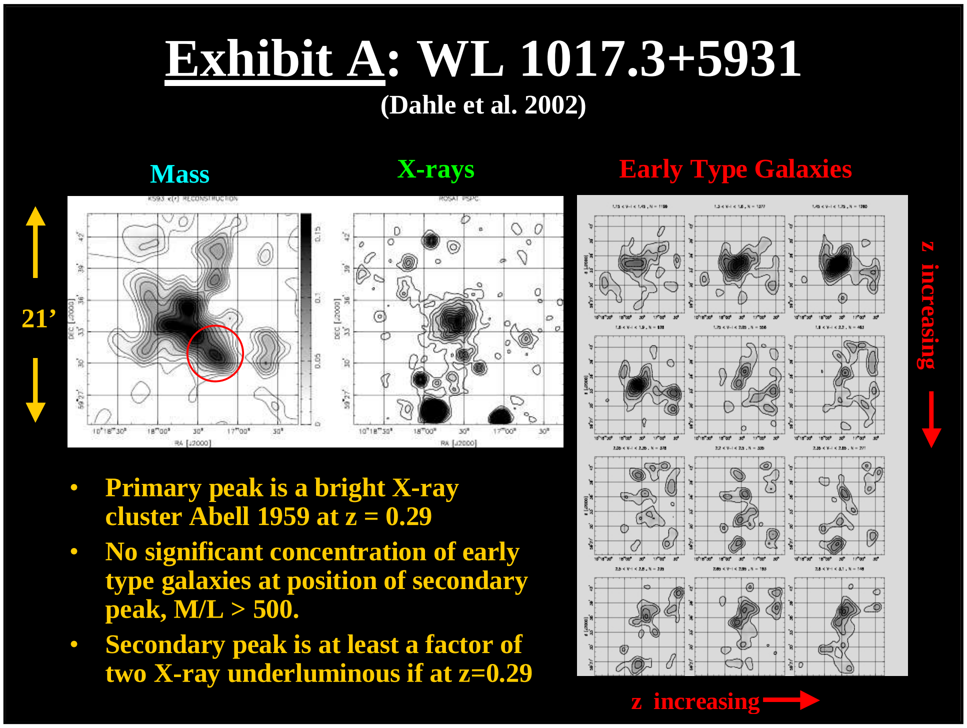


Exhibit A: WL 1017.3+5931

(Dahle et al. 2002)

- Primary peak is a bright X-ray cluster Abell 1959 at z = 0.29
- No significant concentration of early type galaxies at position of secondary peak, M/L > 500.
- Secondary peak is at least a factor of two X-ray underluminous if at z=0.29

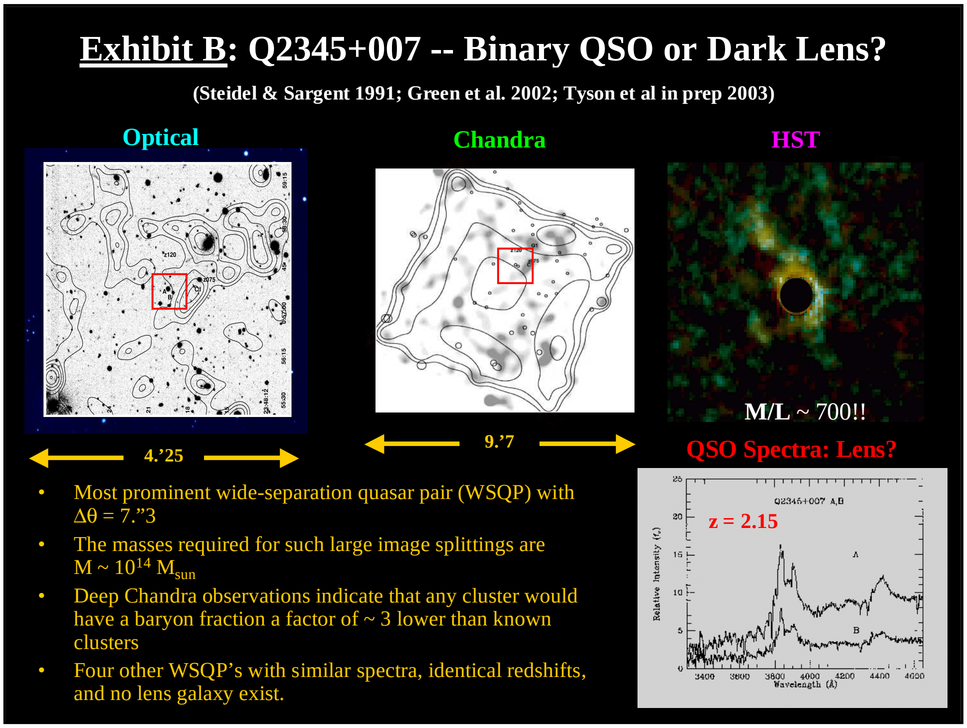


Exhibit B: Q2345+007 -- Binary QSO or Dark Lens?

(Steidel & Sargent 1991; Green et al. 2002; Tyson et al in prep 2003)

- Most prominent wide-separation quasar pair (WSQP) with $\Delta\theta = 7.''3$
- The masses required for such large image splittings are $M \sim 10^{14}\, M_{sun}$
- Deep Chandra observations indicate that any cluster would have a baryon fraction a factor of ~ 3 lower than known clusters
- Four other WSQP’s with similar spectra, identical redshifts, and no lens galaxy exist.

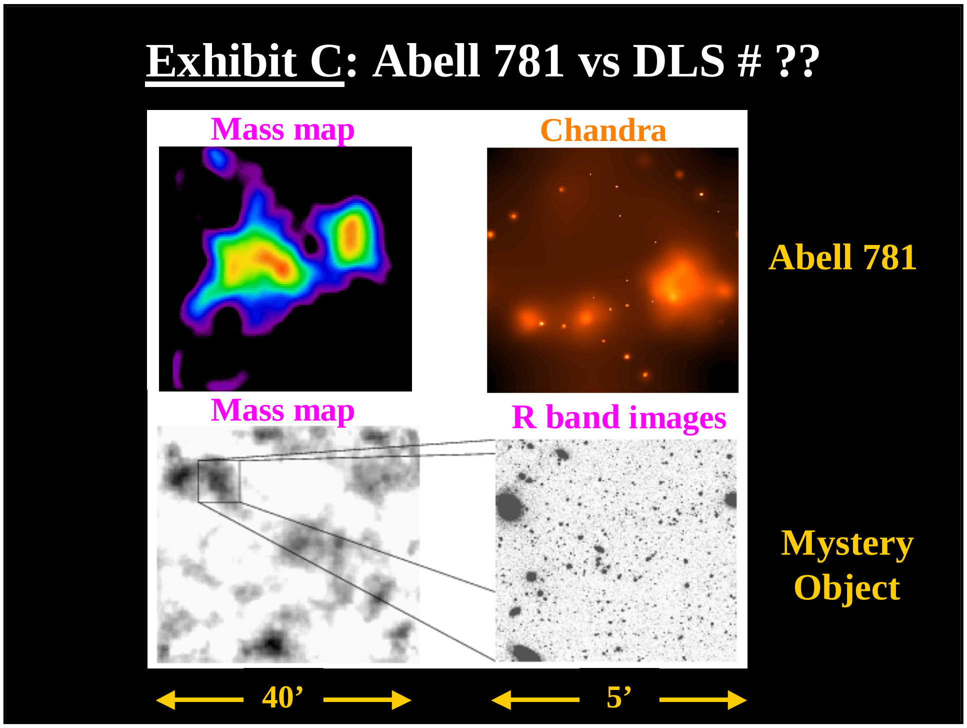
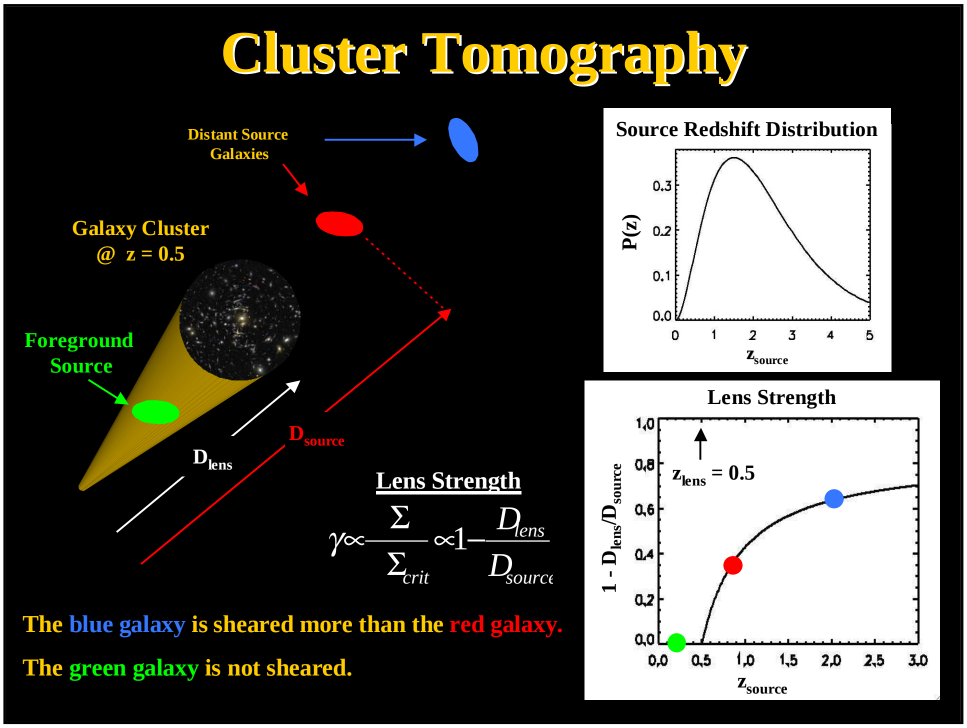


Exhibit C: Abell 781 vs DLS # ??



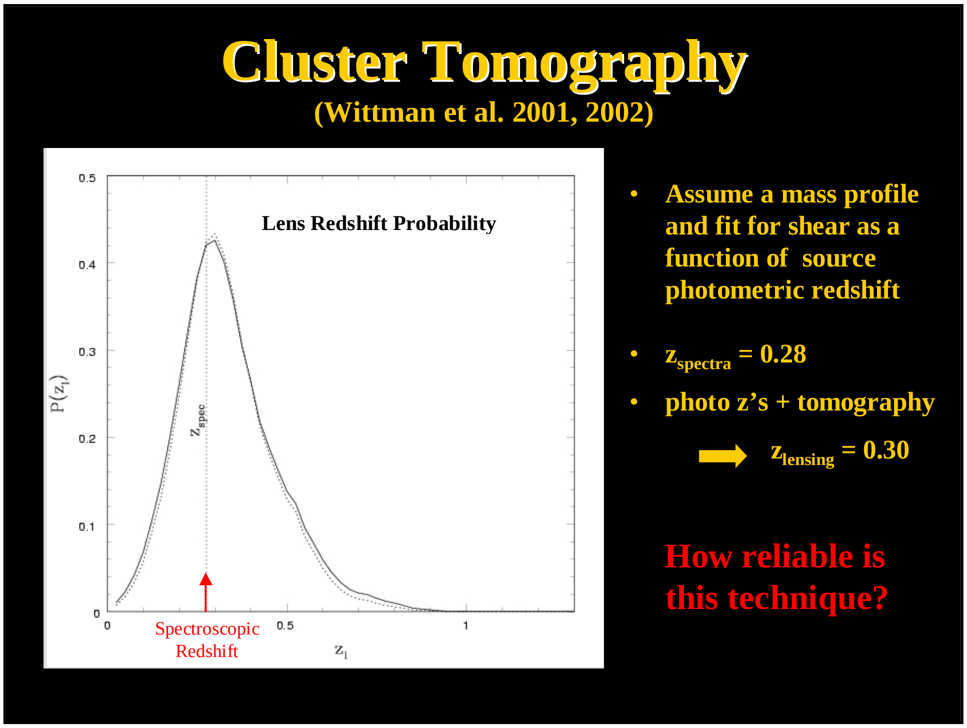
Cluster Tomography

Lens Strength

$$\gamma \propto \frac{\Sigma}{\Sigma_{crit}} \propto 1 - \frac{D_{lens}}{D_{source}}$$

The blue galaxy is sheared more than the red galaxy.

The green galaxy is not sheared.



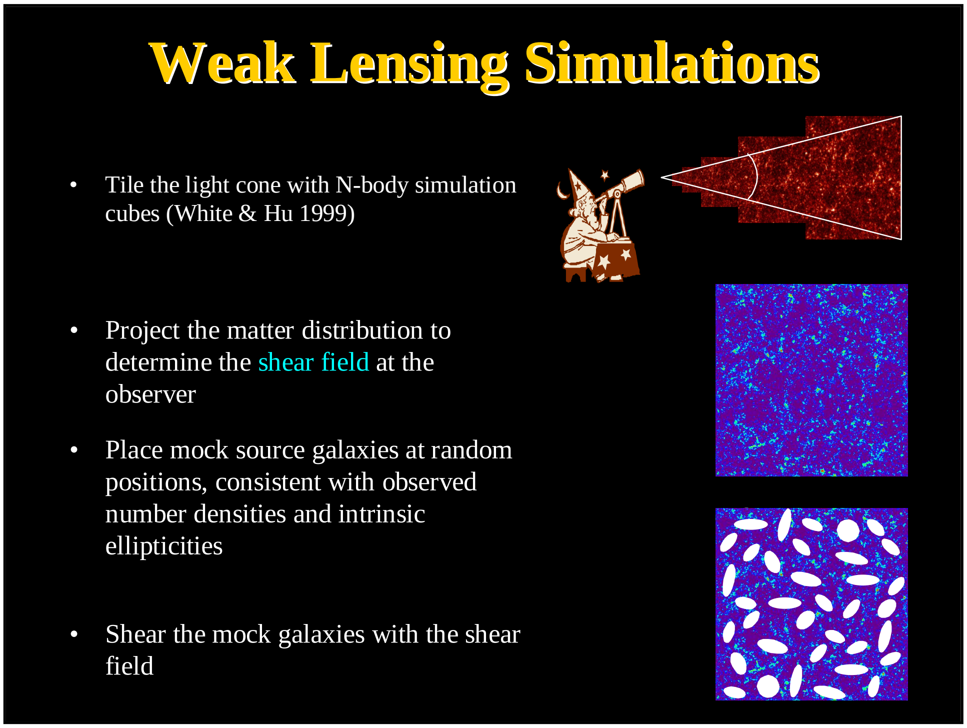
Cluster Tomography

(Wittman et al. 2001, 2002)

- Assume a mass profile and fit for shear as a function of source photometric redshift
- $z_{spectra} = 0.28$
- photo z's + tomography

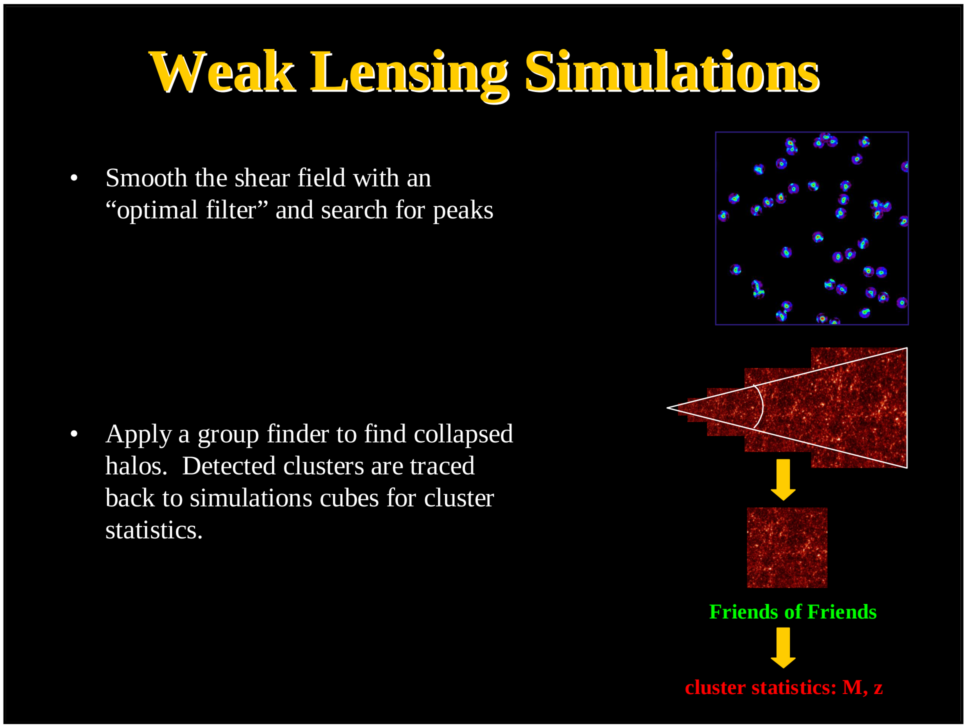
$\Rightarrow$ $z_{lensing} = 0.30$

How reliable is this technique?



Weak Lensing Simulations

- Tile the light cone with N-body simulation cubes (White & Hu 1999)
- Project the matter distribution to determine the shear field at the observer
- Place mock source galaxies at random positions, consistent with observed number densities and intrinsic ellipticities
- Shear the mock galaxies with the shear field

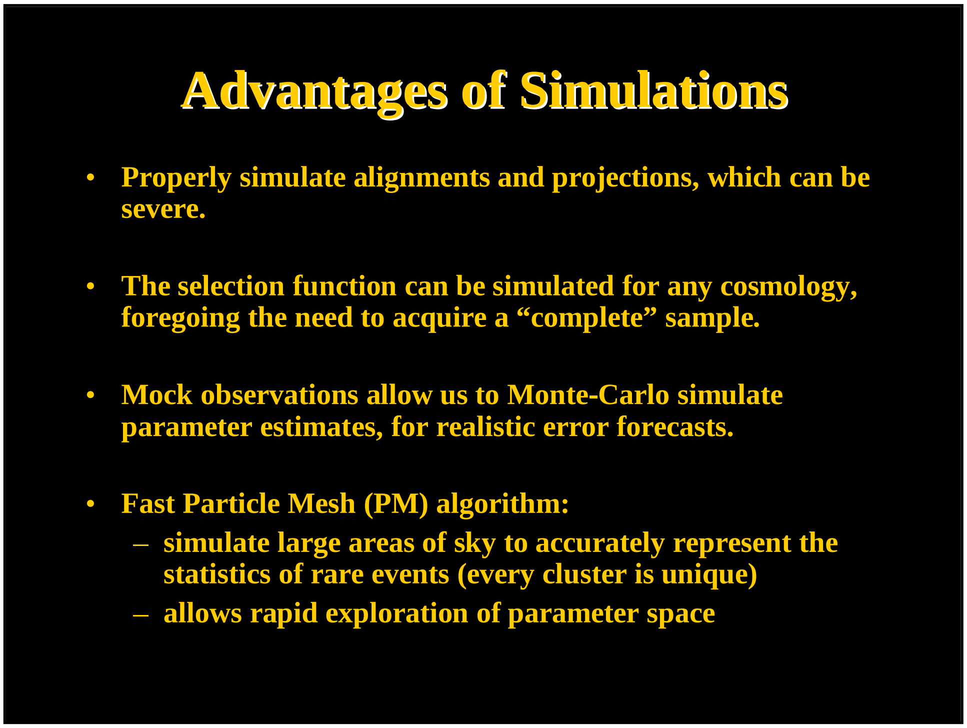


Weak Lensing Simulations

- Smooth the shear field with an “optimal filter” and search for peaks
- Apply a group finder to find collapsed halos. Detected clusters are traced back to simulations cubes for cluster statistics.

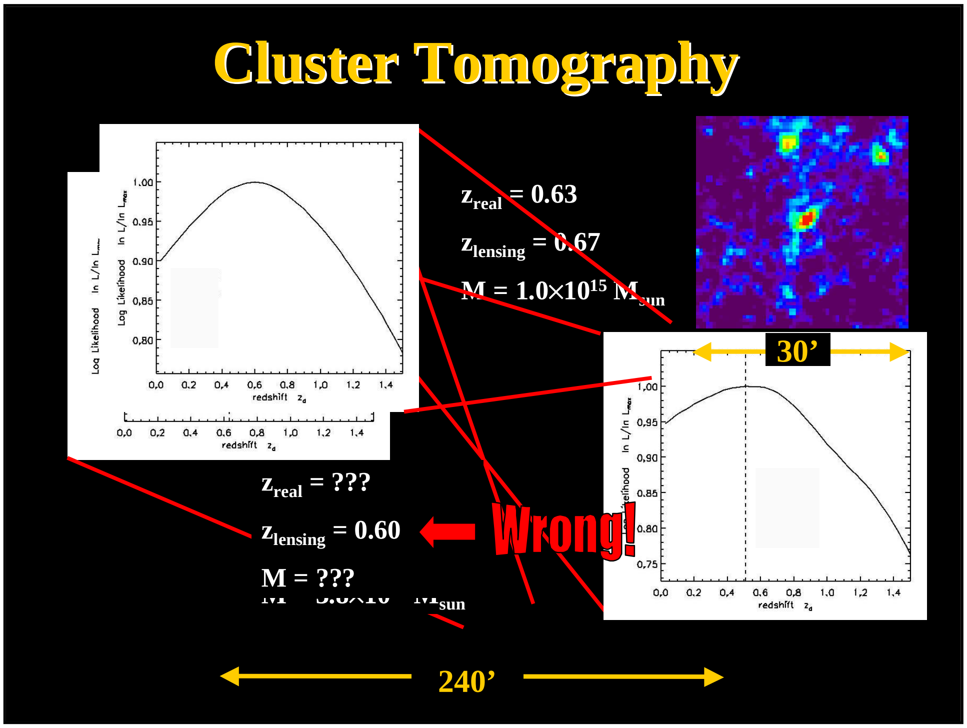
Friends of Friends

cluster statistics: M, z



Advantages of Simulations

- **Properly simulate alignments and projections, which can be severe.**
- **The selection function can be simulated for any cosmology, foregoing the need to acquire a “complete” sample.**
- **Mock observations allow us to Monte-Carlo simulate parameter estimates, for realistic error forecasts.**
- **Fast Particle Mesh (PM) algorithm:**
  - **simulate large areas of sky to accurately represent the statistics of rare events (every cluster is unique)**
  - **allows rapid exploration of parameter space**



Cluster Tomography

z_{real} = 0.63

$z_{lensing}$ = 0.67

M = 1.0×10^{15} M_{sun}

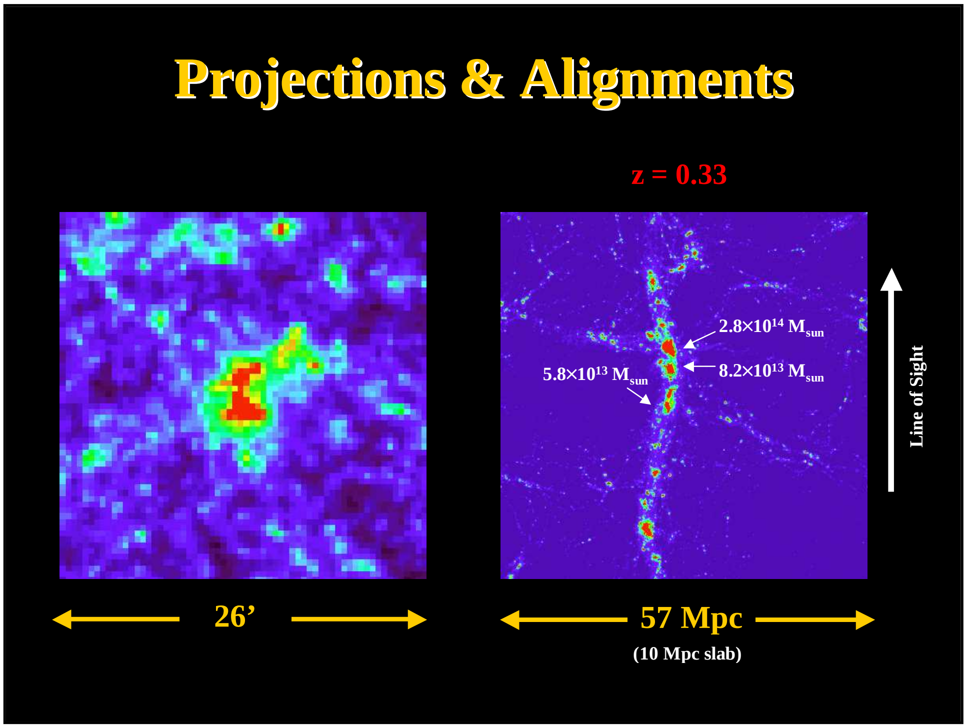
30’

z_{real} = ???

$z_{lensing}$ = 0.60 ⬅ **Wrong!**

M = ???

240’



Projections & Alignments

z = 0.33

2.8×10^{14} M_{sun}

8.2×10^{13} M_{sun}

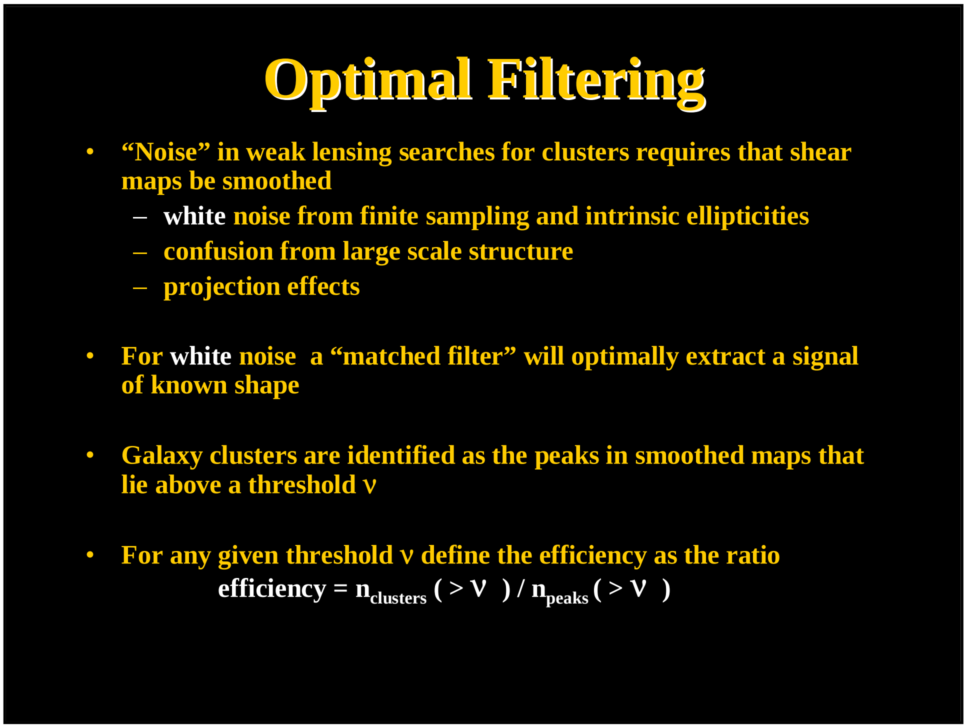
5.8×10^{13} M_{sun}

Line of Sight

26’

57 Mpc

(10 Mpc slab)



Optimal Filtering

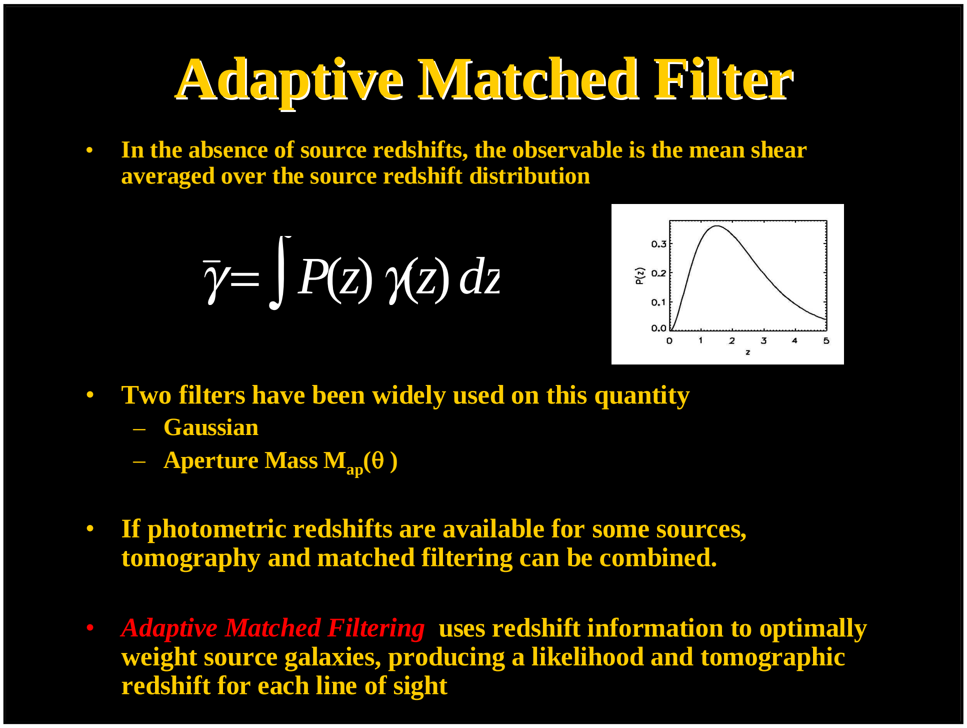
- “Noise” in weak lensing searches for clusters requires that shear maps be smoothed
  - white noise from finite sampling and intrinsic ellipticities
  - confusion from large scale structure
  - projection effects

- For white noise a “matched filter” will optimally extract a signal of known shape

- Galaxy clusters are identified as the peaks in smoothed maps that lie above a threshold ν

- For any given threshold ν define the efficiency as the ratio

$$\text{efficiency} = n_{\text{clusters}}(>\nu)\,/\,n_{\text{peaks}}(>\nu)$$



Adaptive Matched Filter

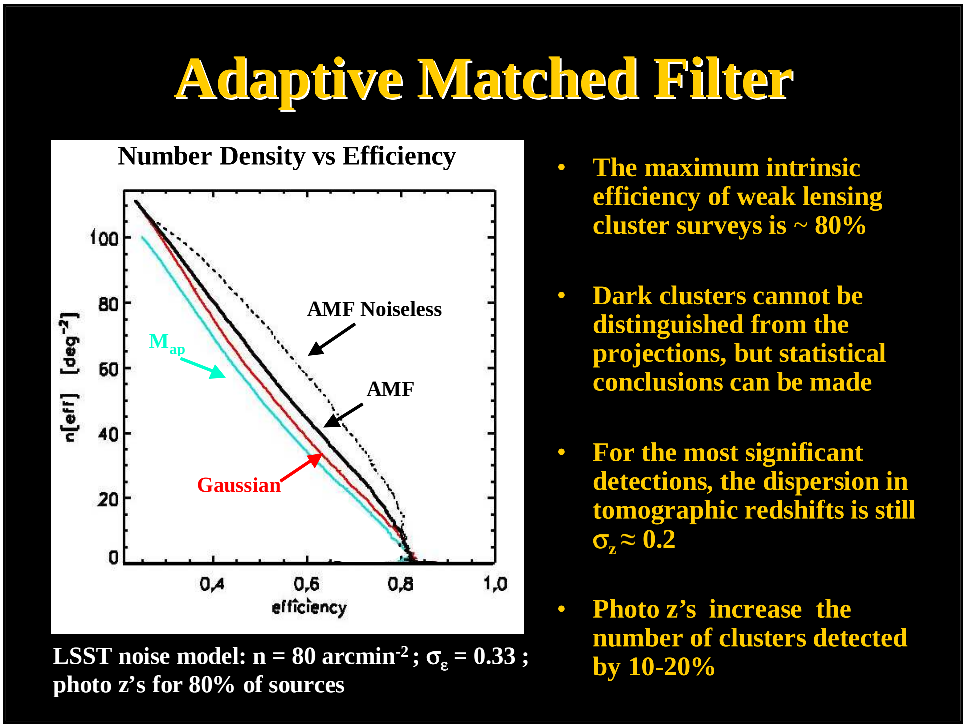
- In the absence of source redshifts, the observable is the mean shear averaged over the source redshift distribution

$$\bar{\gamma} = \int P(z)\,\gamma(z)\,dz$$

- Two filters have been widely used on this quantity
  - Gaussian
  - Aperture Mass $M_{ap}(\theta)$

- If photometric redshifts are available for some sources, tomography and matched filtering can be combined.

- *Adaptive Matched Filtering* uses redshift information to optimally weight source galaxies, producing a likelihood and tomographic redshift for each line of sight

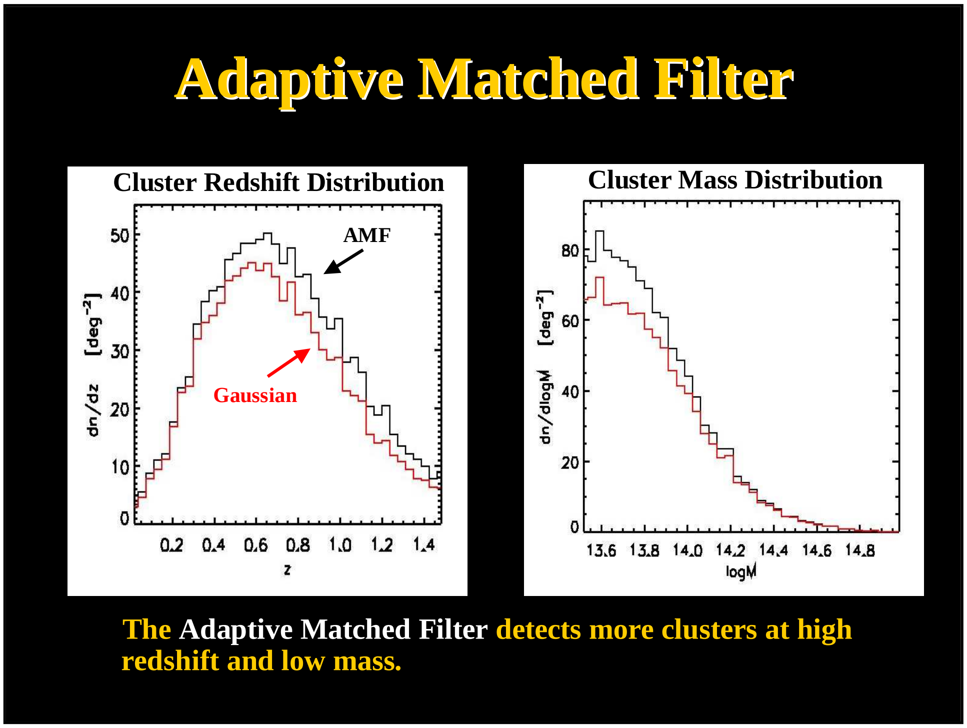


Adaptive Matched Filter

Number Density vs Efficiency

LSST noise model: n = 80 arcmin^{-2} ; σ_ε = 0.33 ; photo z's for 80% of sources

- The maximum intrinsic efficiency of weak lensing cluster surveys is ~ 80%
- Dark clusters cannot be distinguished from the projections, but statistical conclusions can be made
- For the most significant detections, the dispersion in tomographic redshifts is still $\sigma_z \approx 0.2$
- Photo z's increase the number of clusters detected by 10-20%

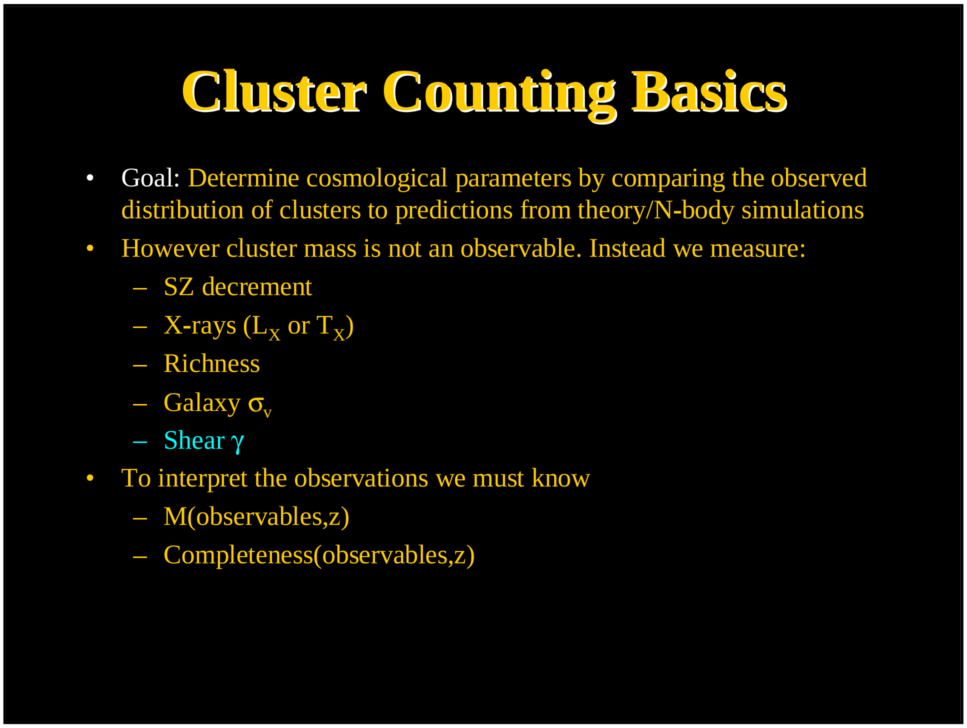


Adaptive Matched Filter

Cluster Redshift Distribution

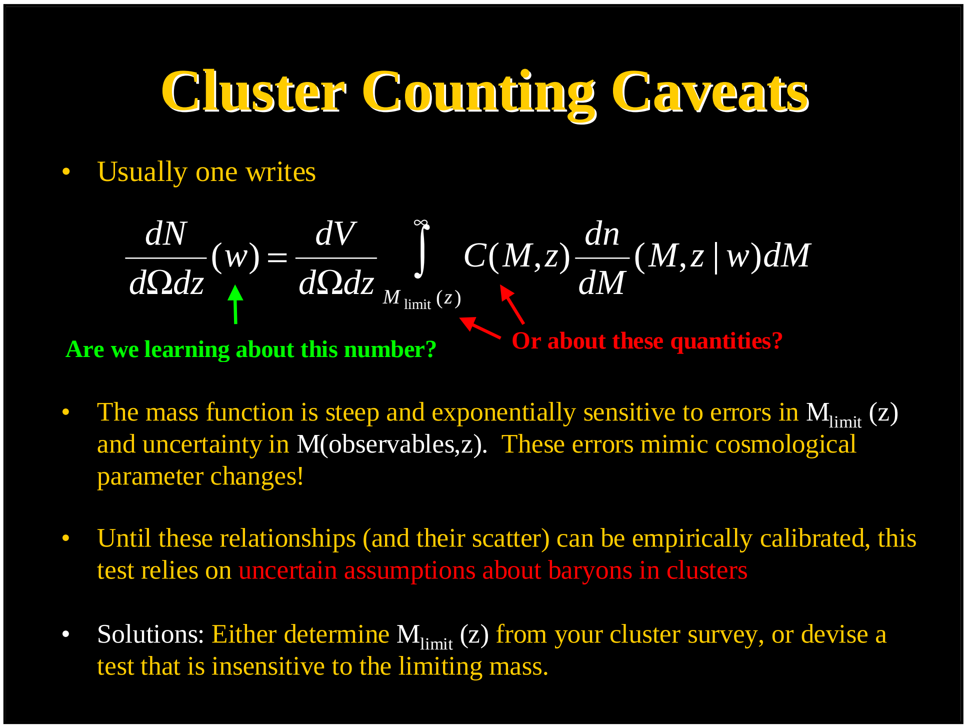
Cluster Mass Distribution

The Adaptive Matched Filter detects more clusters at high redshift and low mass.



Cluster Counting Basics

- Goal: Determine cosmological parameters by comparing the observed distribution of clusters to predictions from theory/N-body simulations
- However cluster mass is not an observable. Instead we measure:
  - SZ decrement
  - X-rays (L_X or T_X)
  - Richness
  - Galaxy σ_v
  - Shear γ
- To interpret the observations we must know
  - M(observables,z)
  - Completeness(observables,z)



Cluster Counting Caveats

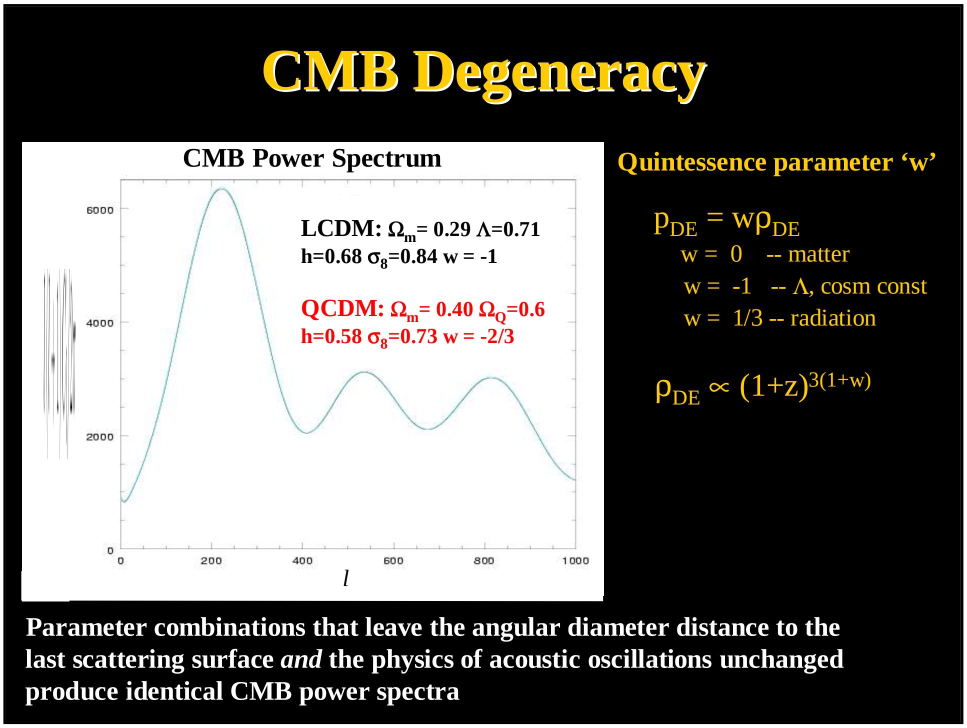
- Usually one writes

$$\frac{dN}{d\Omega dz}(w) = \frac{dV}{d\Omega dz}\int_{M_{\rm limit}(z)}^{\infty} C(M,z)\frac{dn}{dM}(M,z\,|\,w)\,dM$$

Are we learning about this number?

Or about these quantities?

- The mass function is steep and exponentially sensitive to errors in $M_{\rm limit}$ (z) and uncertainty in M(observables,z). These errors mimic cosmological parameter changes!
- Until these relationships (and their scatter) can be empirically calibrated, this test relies on uncertain assumptions about baryons in clusters
- Solutions: Either determine $M_{\rm limit}$ (z) from your cluster survey, or devise a test that is insensitive to the limiting mass.



CMB Degeneracy

Quintessence parameter 'w'

$\rho_{DE} = w\rho_{DE}$

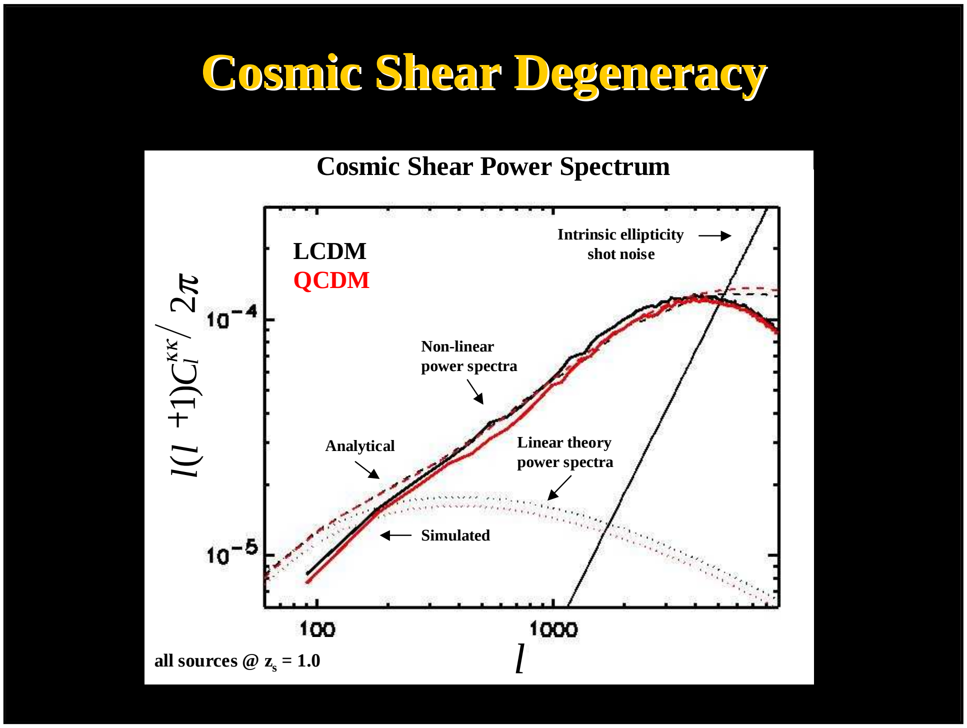
w = 0 -- matter

w = -1 -- Λ, cosm const

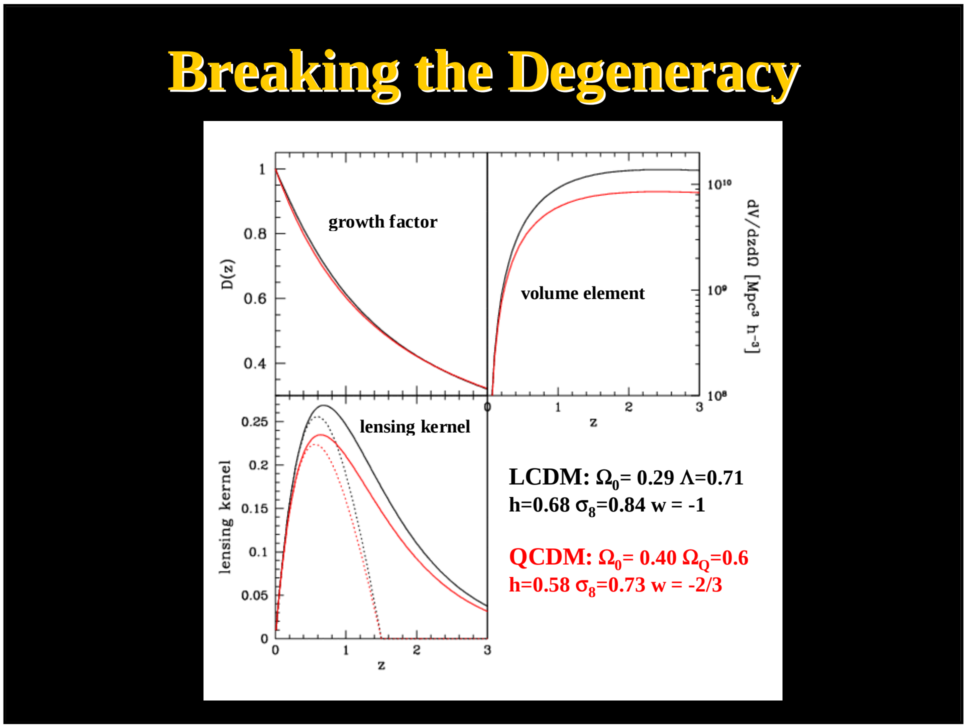
w = 1/3 -- radiation

$\rho_{DE} \propto (1+z)^{3(1+w)}$

Parameter combinations that leave the angular diameter distance to the last scattering surface *and* the physics of acoustic oscillations unchanged produce identical CMB power spectra



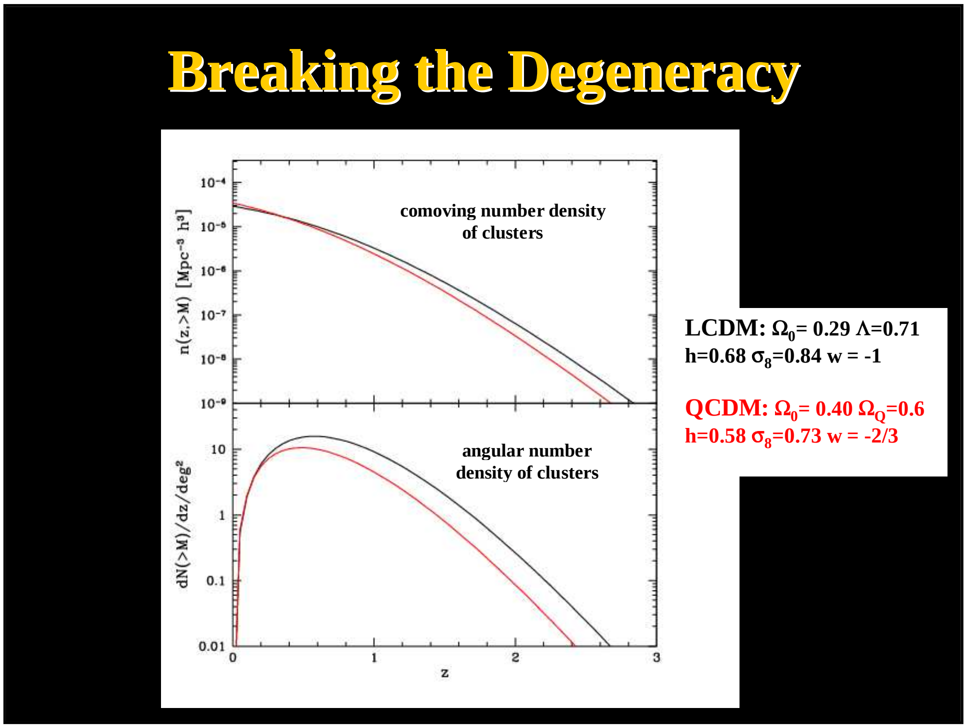
Cosmic Shear Degeneracy



Breaking the Degeneracy

LCDM: Ω_0= 0.29 Λ=0.71
h=0.68 σ_8=0.84 w = -1

QCDM: Ω_0= 0.40 Ω_Q=0.6
h=0.58 σ_8=0.73 w = -2/3



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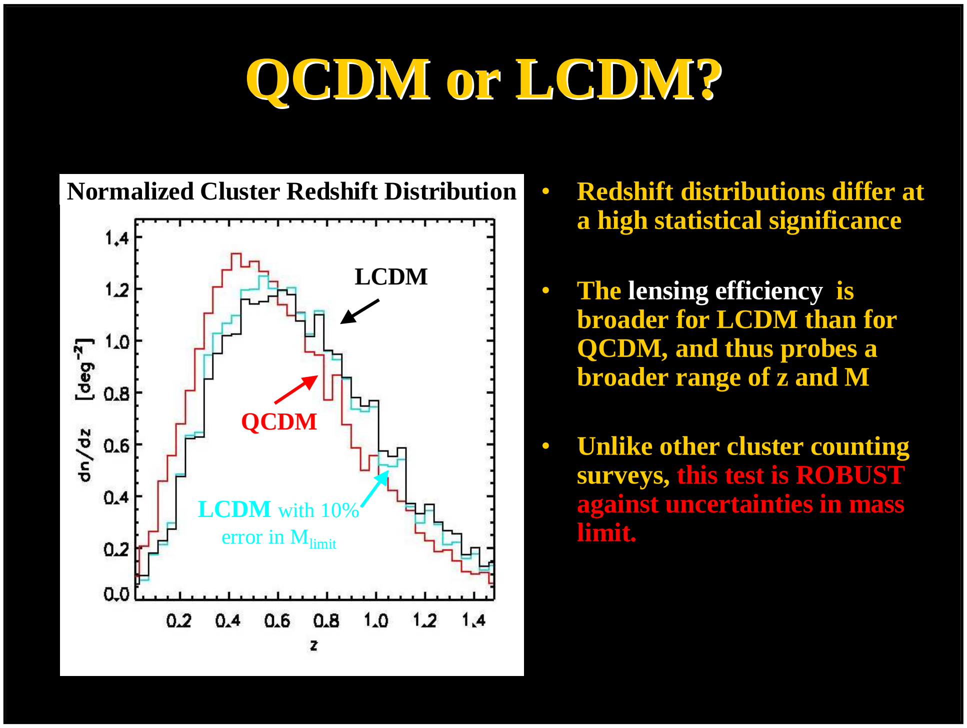
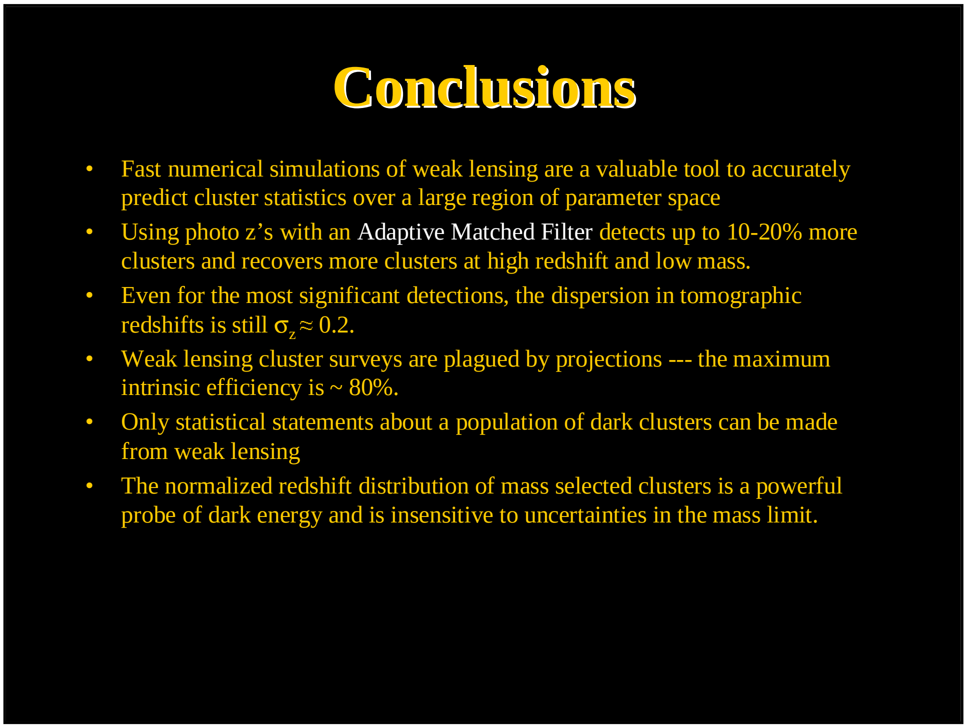


QCDM or LCDM?

- **Redshift distributions differ at a high statistical significance**
- **The lensing efficiency is broader for LCDM than for QCDM, and thus probes a broader range of z and M**
- **Unlike other cluster counting surveys, this test is ROBUST against uncertainties in mass limit.**



Conclusions

- Fast numerical simulations of weak lensing are a valuable tool to accurately predict cluster statistics over a large region of parameter space
- Using photo z's with an Adaptive Matched Filter detects up to 10-20% more clusters and recovers more clusters at high redshift and low mass.
- Even for the most significant detections, the dispersion in tomographic redshifts is still $\sigma_z \approx 0.2$.
- Weak lensing cluster surveys are plagued by projections --- the maximum intrinsic efficiency is ~ 80%.
- Only statistical statements about a population of dark clusters can be made from weak lensing
- The normalized redshift distribution of mass selected clusters is a powerful probe of dark energy and is insensitive to uncertainties in the mass limit.