Prospects for Studying the Dark Energy with the VISTA Visible Camera

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Overview

- Overview of VISTA
- VISTA Optical Camera (VisCam) and Prospects for Studying the Dark Energy
- A Possible VisCam Collaboration

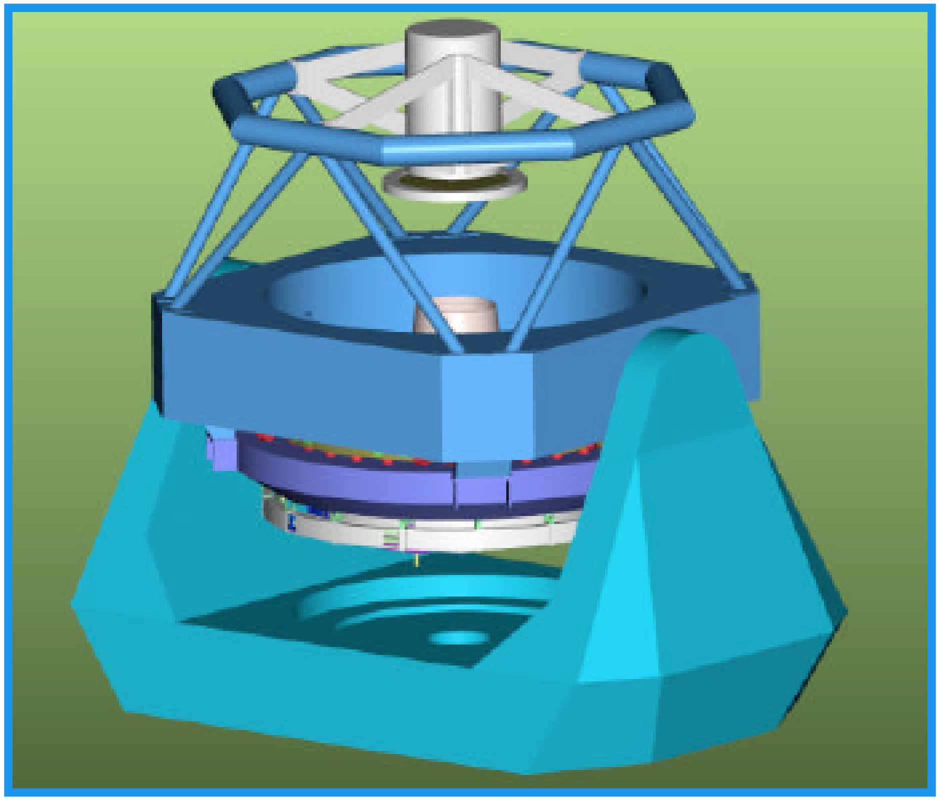
Visible and Infrared Survey Telescope for Astronomy (VISTA)

- VISTA is a 4m wide field survey telescope with IR camera
  - » Under construction by ESO and UK VISTA consortium
  - » Sited near Paranal at 2500m altitude in Chile (latitude ~28^o South)
  - » Observations with IR camera underway in early 2006
    - 1 square degree camera for zJHK observations
    - 0.34 arcsec pixels
  - » Provisions to add 2 square degree optical camera as funding becomes available (0.23 arcsec pixels with SDSS bands)

See http://www.vista.ac.uk

Surveys of the Southern Sky

- 75% of time will be dedicated to long term public surveys
  - » ESO survey committee will play the role of deciding which surveys to carry out
  - » It is envisioned that these large scale surveys will run for 12 years
- 25% of time available for PI led projects
- Telescope will be operated remotely by an operator in the VLT control building. Queue mode observing will produce ~400GB of data/night that will be transferred on physical media back to Europe



How VISTA IR camera Measures Up

- The combination of aperture and solid angle will make VISTA the premier IR survey instrument

Facility	Diameter	FOV	Grasp	Hemis
VISTA	4.0	1.0	16.0	S
VLT IRMOS	8.0	0.054	3.5	S
UKIRT	3.8	0.12	1.7	N
MMT IRCAM	6.5	0.013	0.5	N
AAT-IRIS II	3.9	0.016	0.2	S
DENIS	1.0	0.04	0.04	S
2MASS	1.3	0.02	0.034	N&S

How VISTA Optical camera Measures Up

- The combination of aperture and proposed solid angle for the VisCam would make VISTA the premier optical survey instrument in the southern hemisphere

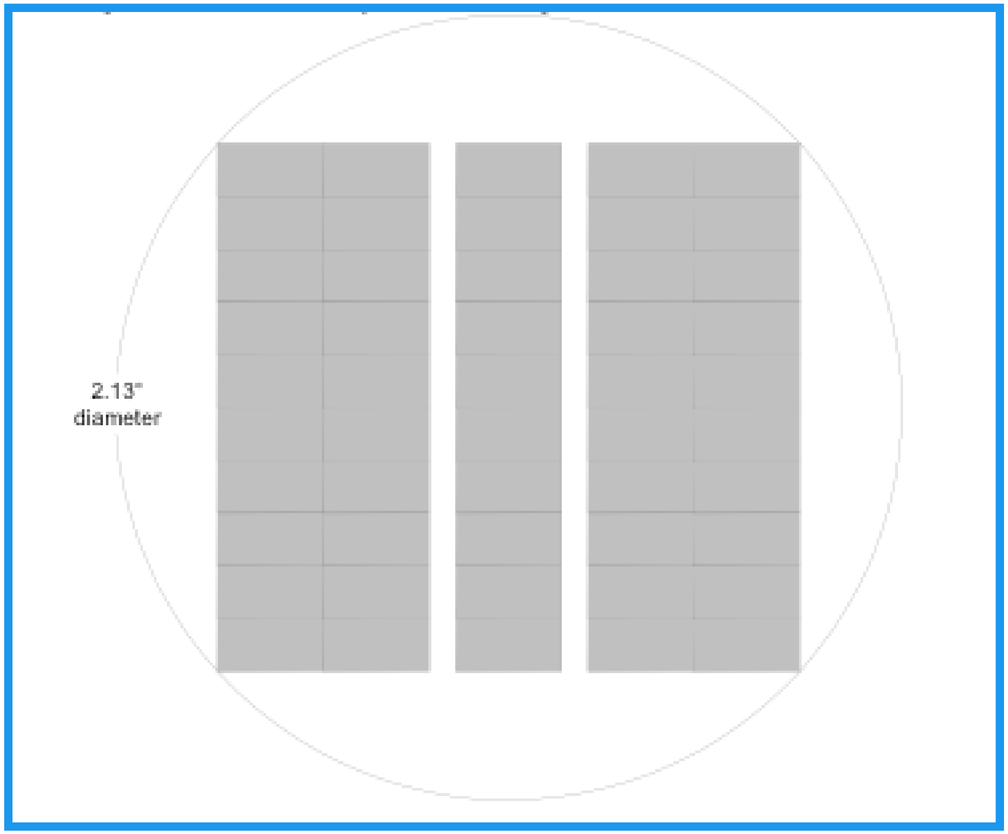
Facility	Diameter	FOV	Grasp	Hemis
VISTA	4.0	2.3	36.8	S
SDSS	2.5	4.5	28.1	N
Subaru-WFC	8.3	0.2	13.8	N
CFHT Megacam	3.6	1.0	13.0	N
MMT Megacam	6.5	0.17	7.2	N
ESO-VST	2.6	1.0	6.8	S
KPNO MOSAIC	4.0	0.3	4.8	N

A Word About the History

- VISTA was proposed successfully by a consortium of 18 British universities.
  - » Jim Emerson (Queen Mary University of London) is the director of the VISTA consortium
  - » VISTA was envisioned as a dual optical and IR survey instrument.
  - » Cameras are mounted at the cassegrain focus, and were designed to make the instrument swap as simple as possible.
  - » Design studies of both cameras and the telescope were carried out
- When the UK joined ESO, VISTA was transferred to ESO as part of the deal
  - » Due to a shortage of funds VisCam was shelved/delayed
  - » VISTA consortium has members on the ESO survey committee, but there is no "guaranteed" survey, although 75% of VISTA time will go to large dedicated surveys whose goals will be decided by the survey committee
  - » Interference from CFHT Megacam and the VST also played some role, although it is emphasized that VisCam is "red optimized" as compared to the "blue optimized" VST

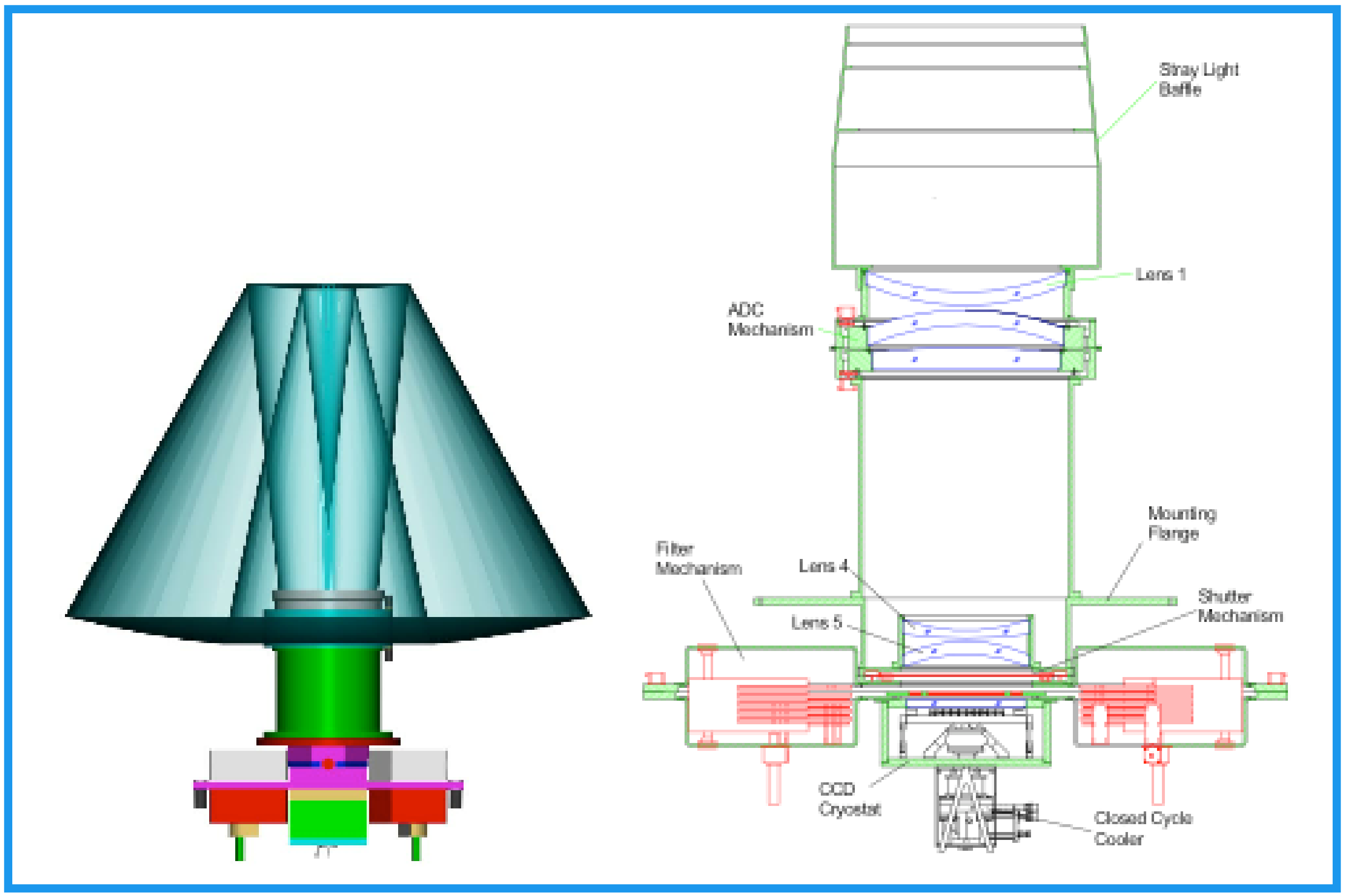
Some Details on VisCam

- The design study describes an $11million instrument consisting of a wide field corrector (including atmospheric dispersion corrector), the 50 (2kX4k) CCD camera, and what is called an autoguiding, autofocusing and wavefront sensing system
  - » 420 million 0.23 arcsec pixels



Telescope and Camera

- The VISTA telescope consists of an f/1.09 4m primary and an f/3 1.23m secondary



Telescope and Camera (cont)

- Optics are designed to deliver 0.3'' (50% EED) and 0.46'' (80% EED) in the optical and slightly worse in the IR throughout the field (remember 0.23'' and 0.34'' pixels, respectively)
- Image elongation is to be controlled at the 10% level throughout the field- presumably to allow 1% shear measurements on individual objects
- ADC is to work at zenith angles ranging from 76^o (u) to 67^o (r')
- Total FOV per exposure is 1.96 deg^2 . Two exposures offset by 33' will provide 95% coverage over 3 deg^2 FOV. Readout time to be <= 20s for entire focal plane.
- Plan is for IR surveys to begin in 2006 and for VisCam surveys to begin in 2008 (assuming VisCam construction begins in 2004- currently the shortage of funds guarantees that will not happen)

Primary and Secondary Active Control

- Closed loop low order wavefront sensing is used to control secondary focus and collimation. Periodic (on several hour timescale) high order wavefront sensing to monitor figure of primary mirror.

- Each camera contains hardware. System software common
  - » Autoguider
  - » Two fixed, low order curvature sensors operating continuously with update rates of 30s. Two sensors allow separation of secondary collimation from primary mirror astigmatism
  - » Single fixed high order Shack Hartmann sensor used once or twice per night to check/adjust the figure of the primary mirror

- Philosophy
  - » Guiding required
  - » Thin primary requires some means of measuring figure
  - » f/1 primary means image quality sensitive to focus and collimation
  - » Image quality maintenance needs to be carried out in parallel with science exposures

VISTA Science and Surveys

- VISTA delivers IR and Optical surveys that were originally meant to be organized into three different efforts
  1. Big Optical (10,000 deg^2 B=26+UVRI, 290n) and IR (5000deg^2 K=20.5+JH, 696n)
  2. Deep Optical (250 deg^2 B=28+VRI, 109n) and IR (250 deg^2 K=21.5+JH, 228n)
  3. Very Deep Optical (25 deg^2 B=29+VRI, 36n) and IR (25 deg^2 K=22.5+JH, 139n)

- These surveys were to take ~12 years (effectively 1500 nights were used for the surveys listed above after accounting for 25% PI led projects, 10% of time to Chile, and 400 nights to specialized monitoring programs)

Science Topics

- VISTA allows one to do much of what one could do with LSST but at a much lower cost and on a shorter timescale

- Some topics from VISTA web page
  - » Brown dwarf studies in clusters and the local disk
  - » IMF in star forming regions
  - » Detailed multi-color atlas of all galaxies at $z<0.1$
  - » Searches for low surface brightness and/or rare galaxies
  - » 3D map of the universe employing photo-z's to $z\sim1$ in big surveys
  - » Studies of power spectrum evolution (using galaxies) to $z\sim2$
  - » Galaxy cluster catalogs extending to $z\sim2$
  - » Cosmic shear constraints on the power spectrum

Science Topics (cont)

- Large scale monitoring with VISTA
  - » High redshift supernovae (several deg^2 per night in four bands- several SNe per night)
  - » Kuiper belt survey (deep wide field observations twice a night)
  - » Microlensing studies over more fields
  - » Kinematics over wide field through proper motions
  - » Quasar variability

- Studies of dark energy with galaxy cluster surveys
  - » Let me highlight what is possible with cluster surveys and then focus on possible results from a particular SZE survey that will begin from the South Pole in 2007.
  - » Optical and/or NIR followup of SZE (or X-ray) cluster surveys is critical, because it's the redshift distribution of detected clusters that is the most powerful cosmological constraint. Photometric redshifts are required.

Dark Energy and Its Equation of State

Density Parameter $$\Omega_i = \frac{8\pi G\rho_i}{3H^2}$$

Equation of State Parameter $$\mathrm{w} \equiv \frac{p}{\rho} \text{ where } \rho_E \propto \left(\frac{a}{a_0}\right)^{-3(1+\mathrm{w})}$$

Expansion history of the universe depends on the **amount** and **nature** of dark energy

Expansion History

$$H(z) = H_o E(z) \text{ where}$$

$$E^2(z) = \Omega_m (1+z)^3 + (1 - \Omega_m - \Omega_E)(1+z)^2 + \Omega_E (1+z)^{3(1+w)}$$

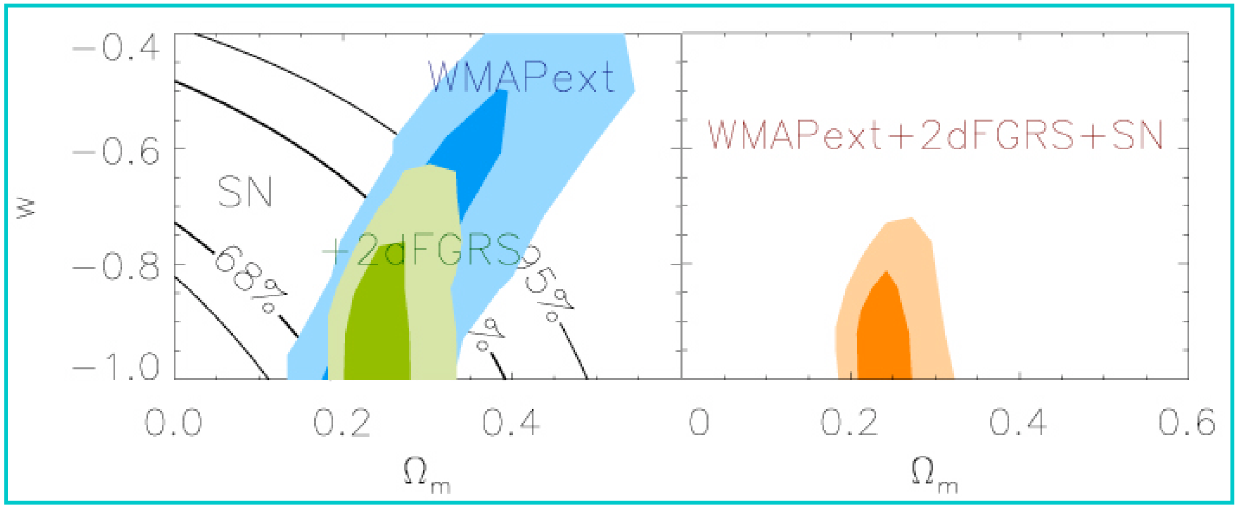
$$H = \frac{\dot{a}}{a} \text{ and } 1 + z = \frac{a_o}{a}$$

How Can One Study the Dark Energy?

1. Measuring (relative) distances or volumes out to z~2
2. Measuring the growth rate of cosmic structures
3. Detecting the very large scale, low contrast feature in the power spectrum of density fluctuations
4. Laboratory experiments?
5. Theoretical progress

Surveys of galaxy clusters provide the first three

Current Constraints



Spergel et al 2003

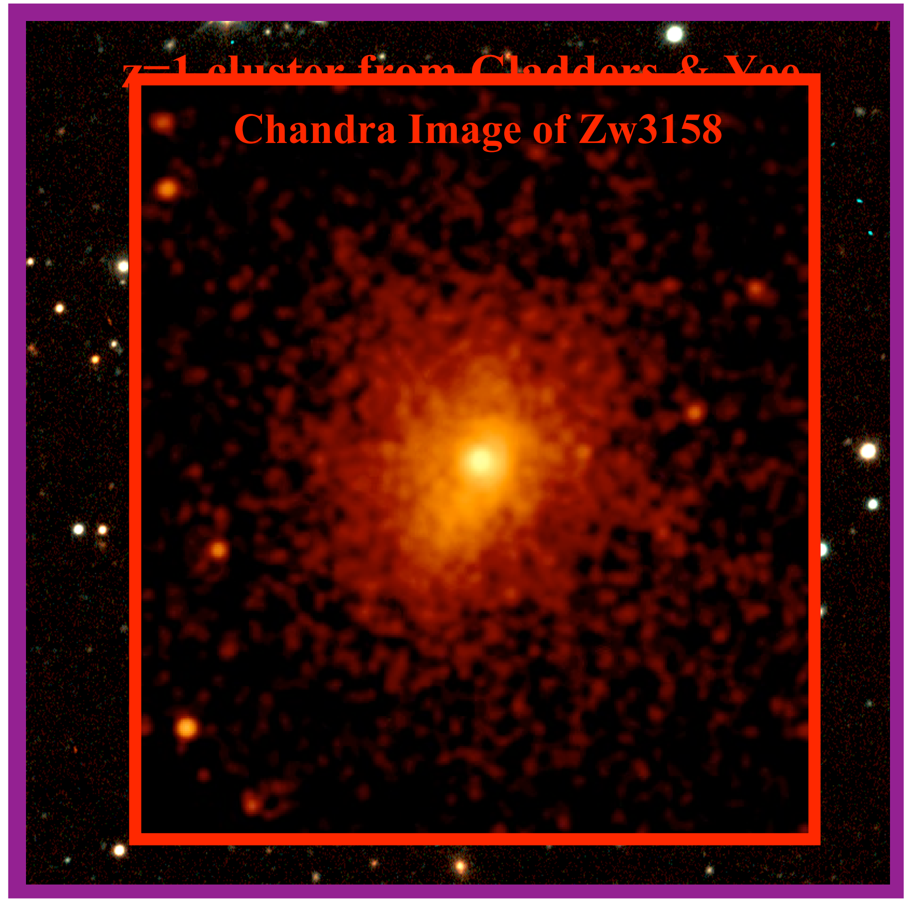
What Are Galaxy Clusters?

Galaxy clusters are the most massive (10^{14}-10^{15} solar masses), collapsed structures in the universe. They contain galaxies, hot ionized gas ($10^{7\text{-}8}$K) and dark matter.

In typical structure formation scenarios, low mass clusters emerge in significant numbers at z~2-3

Clusters are good probes, because they are massive and "easy" to detect through their:

- X-ray emission
- Sunyaev-Zel'dovich Effect
- Gravitational lensing
- Light from galaxies



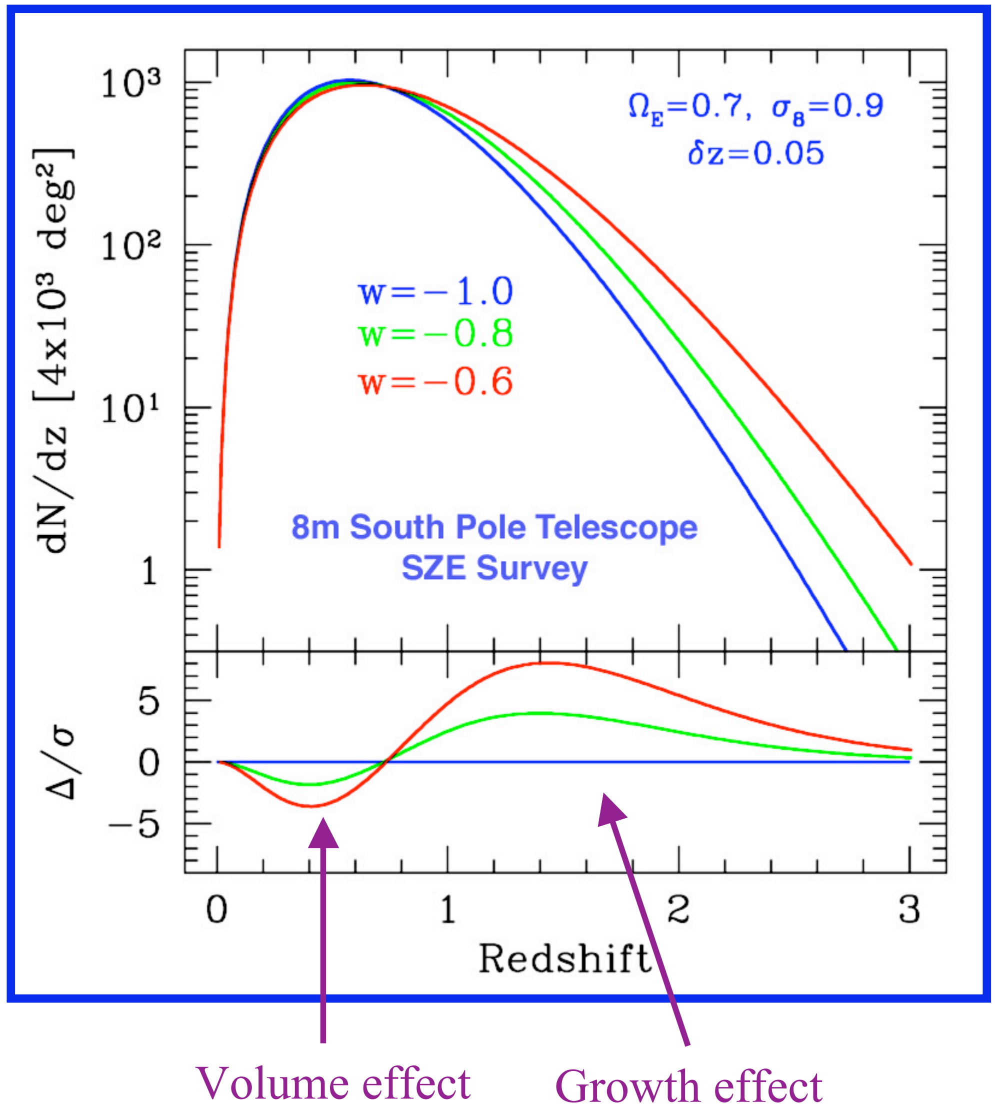
$$\frac{\Delta T(R)}{T_{cmb}} = -2\frac{\sigma_T}{m_e c^2}\int dl\, n_e(l,R)\, k_B T_e(l,R)$$

Cluster Redshift Distribution is Sensitive to the Dark Energy Equation of State

w constraints:

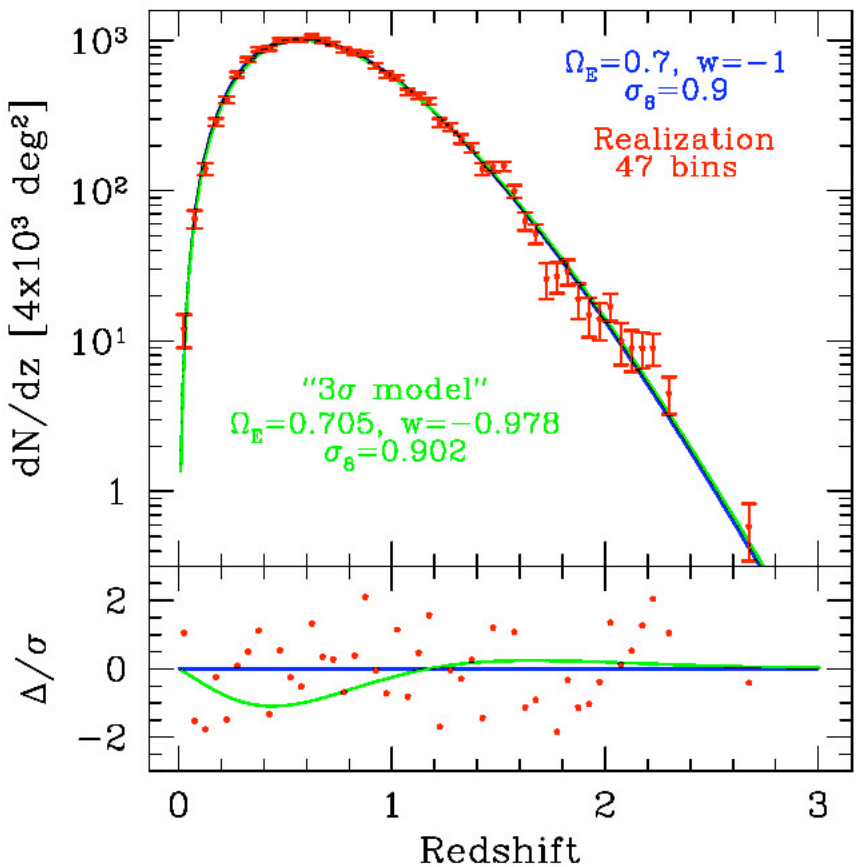
Raising **w** at fixed Ω_E:

- » decreases volume surveyed
- » decreases growth rate of density perturbations



Cosmological Constraints: Comparing Model and Observation

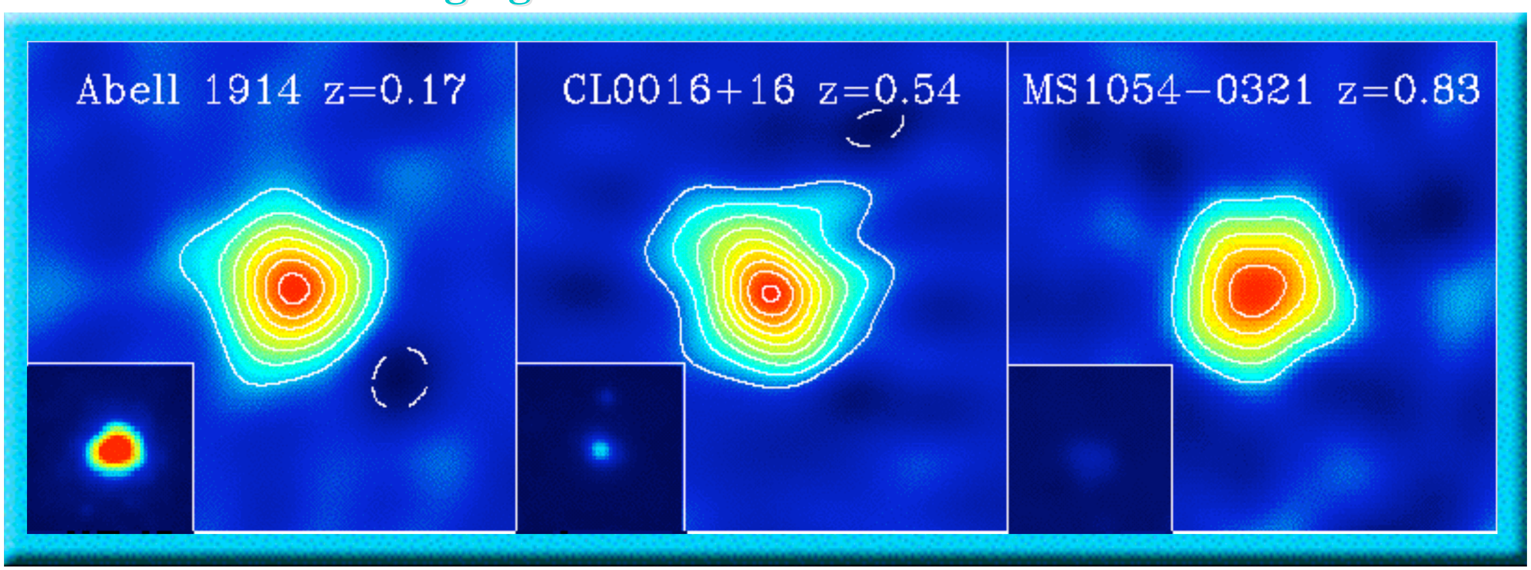
Constraints derived from likelihood comparison of observed and theoretical redshift distributions



Carlstrom-Joy Receivers at BIMA

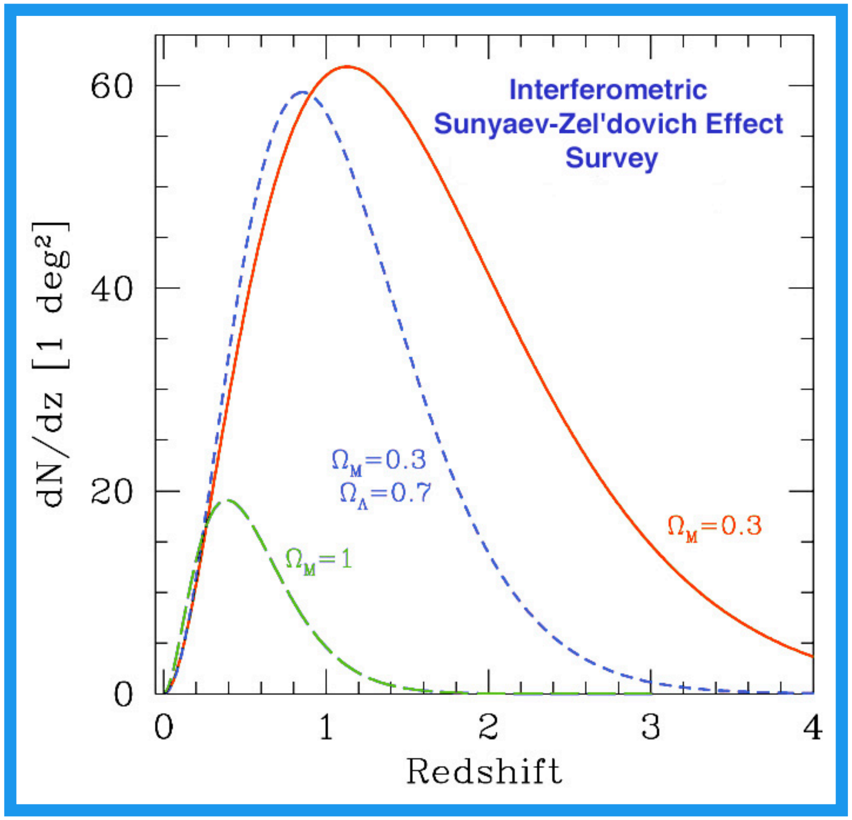
- SZE signatures of approximately 50 known galaxy clusters have been detected and imaged at BIMA over the past decade.
- Several new SZE facilities are under construction, including the SZA and the SPT, both Carlstrom projects

SZE Imaging Collaboration and ROSAT Archive



SZE contours every 75μK. Same range of X-ray surface brightness in all three insets.

Cosmology and the Galaxy Cluster Redshift Distribution



Cluster redshift distribution probes:

1) **volume-redshift relation**
2) **abundance evolution**
3) **cluster structure and evolution.**

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

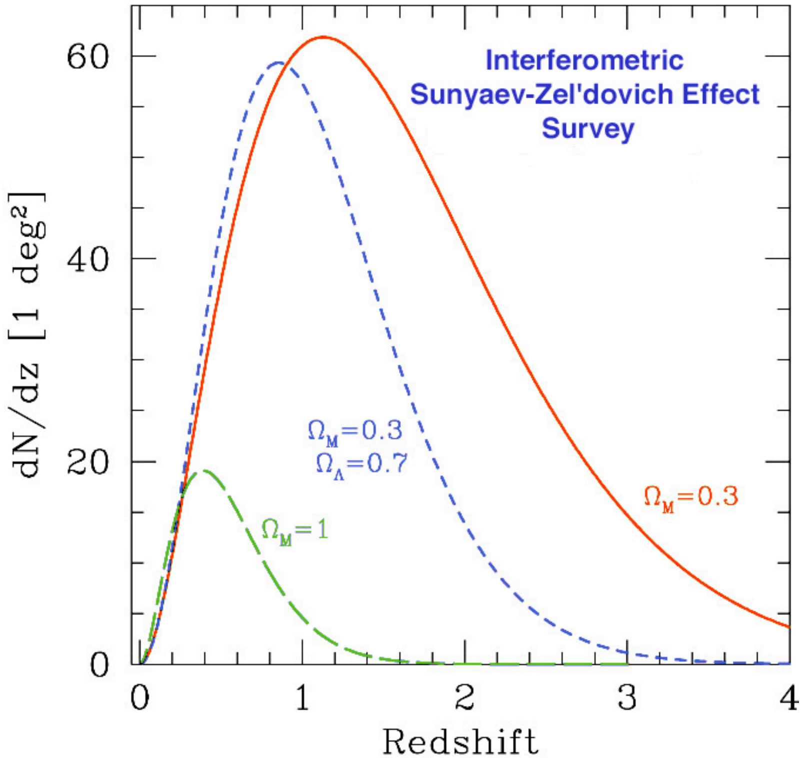
Mass Selection Function

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

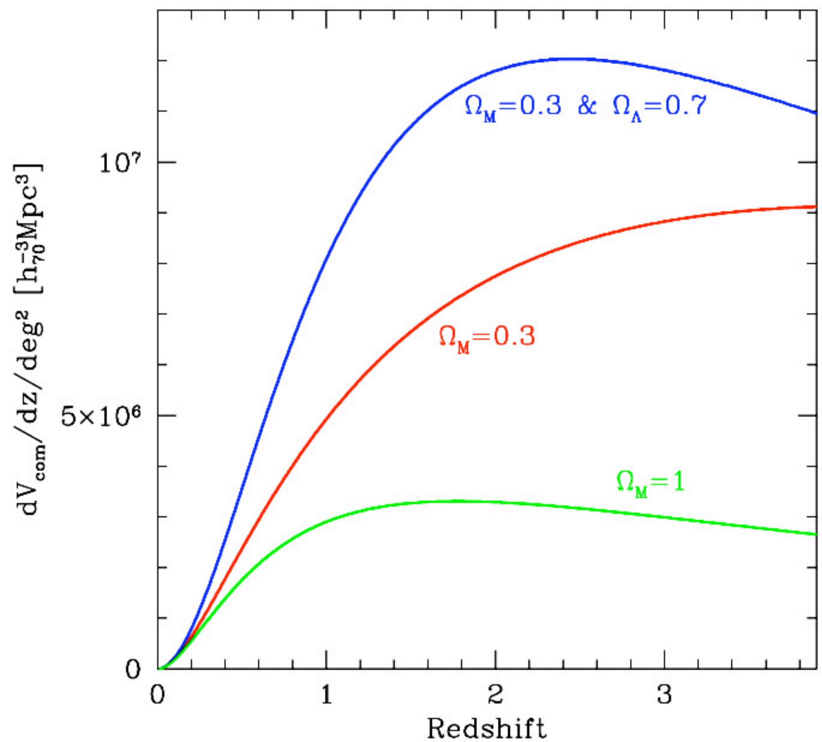
Volume Element | Abundance | Volume | Abundance

The Volume-redshift Relation

Redshift Distribution



Volume Element



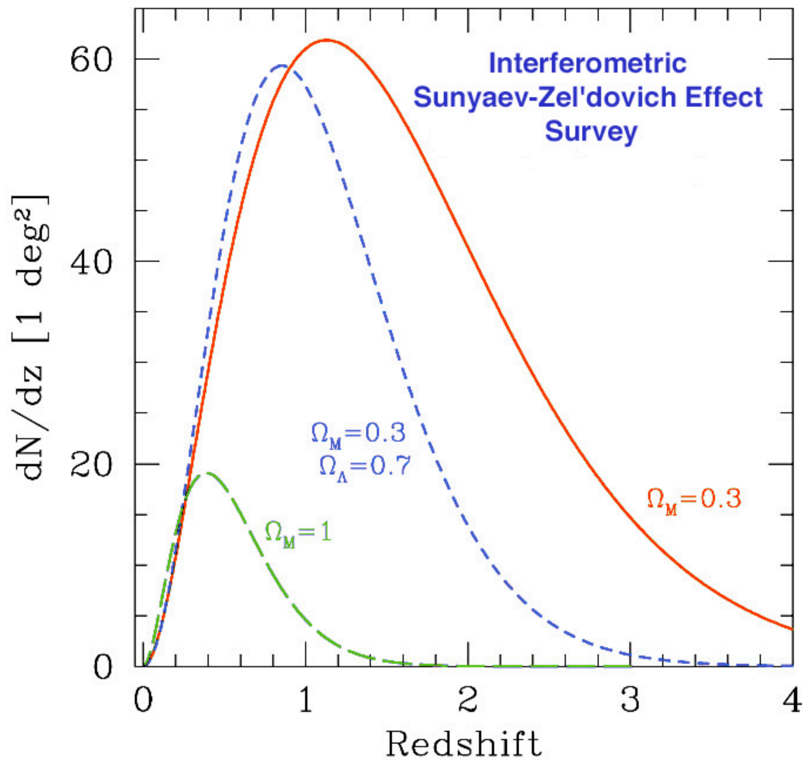
$$\frac{dV}{dz\,d\Omega} = \frac{c}{H(z)} d_A^2 (1+z)^2 \qquad d_A \propto \int_0^z \frac{dz'}{E(z')}$$

$d_A(1+z)$ is proper distance

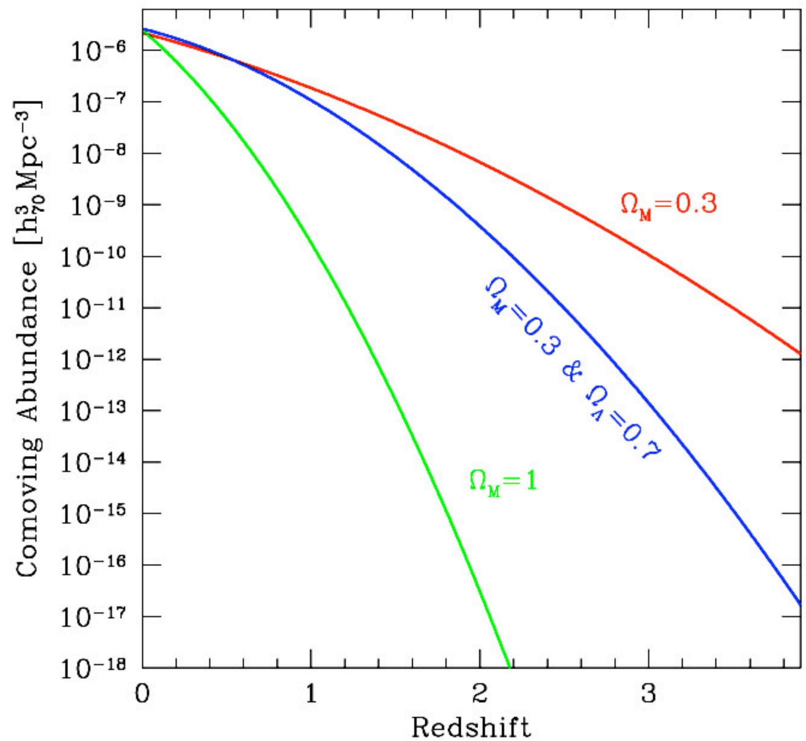
$H(z) = H_o E(z)$ is the Hubble parameter

Cluster Abundance Evolution

Redshift Distribution



Comoving Abundance



As we probe to higher redshift, clusters "disappear" much faster in a high density universe, because structures evolve faster.

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G \rho_o \delta$$

where $\delta \equiv \frac{\delta\rho}{\rho_o}$ and $H = \frac{\dot{a}}{a}$

$$\delta(z) = D_z \delta(z=0)$$

$$D_z = (1+z)^{-1} \text{ if } \Omega_m = 1$$

Note: Dual Nature of Galaxy Clusters

- It's critical- for almost any analysis- to keep in mind that clusters are young objects and yet as a population they exhibit striking regularity

- Evidence for cluster-subcluster merging abounds:
  - » 1980's: *Einstein* images of double clusters, Messy galaxy distributions
  - » 1990's: Statistical studies of (X-ray flux limited samples of) galaxy clusters reveal that more than half exhibit merger signatures
  - » Now: Chandra revealing merger signatures on even smaller physical scales

- Statistical studies of (X-ray flux limited samples of) galaxy clusters reveal regularity

- Implications:

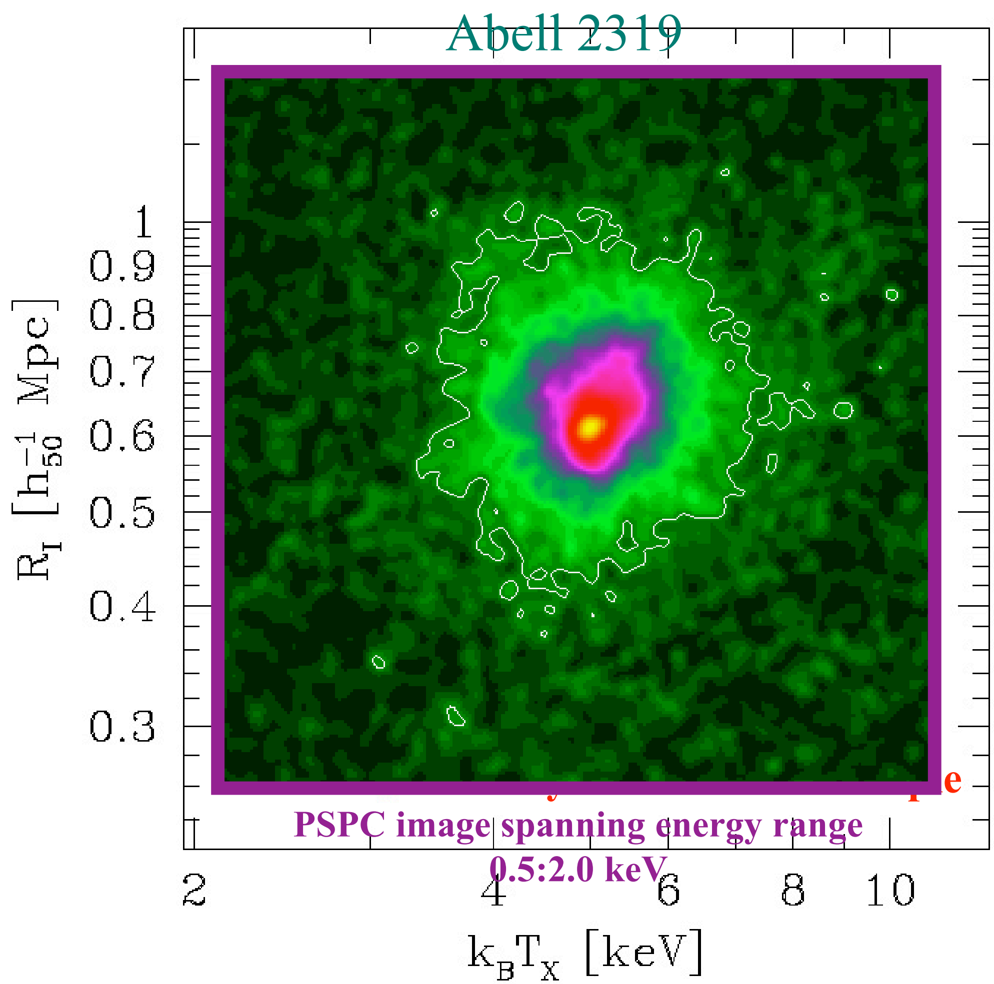
  Cluster population on the whole is relaxed

  While mergers are common, recent major mergers must be relatively rare

Evidence for Regularity: X-ray Size-Temperature Relation

- **For an X-ray flux limited sample of 45 galaxy clusters**:
  - » $\log(R_I) = 0.93 \log(T/6\text{ keV}) - 0.07$
  - » Raw Scatter in R_I: 15% (Intrinsic: 10%)

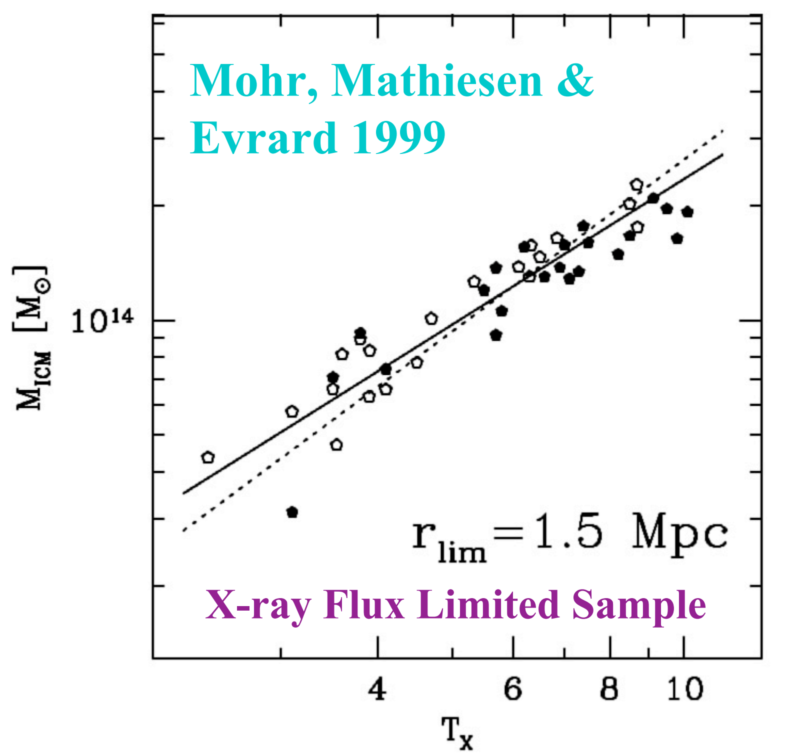
- **Galaxy Cluster Regularity**
  - » Cluster scatter around ST relation is similar to elliptical/S0 galaxy scatter around the Fundamental Plane
  - » Observed regularity in X-ray properties reflects underlying regularity in the dark matter

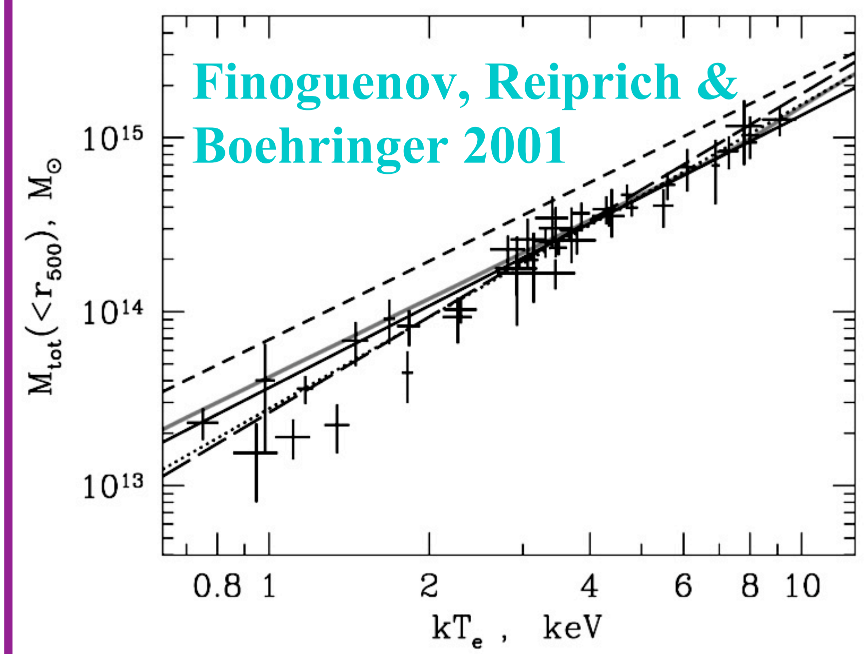


Mohr & Evrard, 1997, ApJ **491**, 38

Cluster Mass-Temperature Scaling Relations

- Emission weighted mean temperature is a good predictor of galaxy cluster mass (~20% scatter)

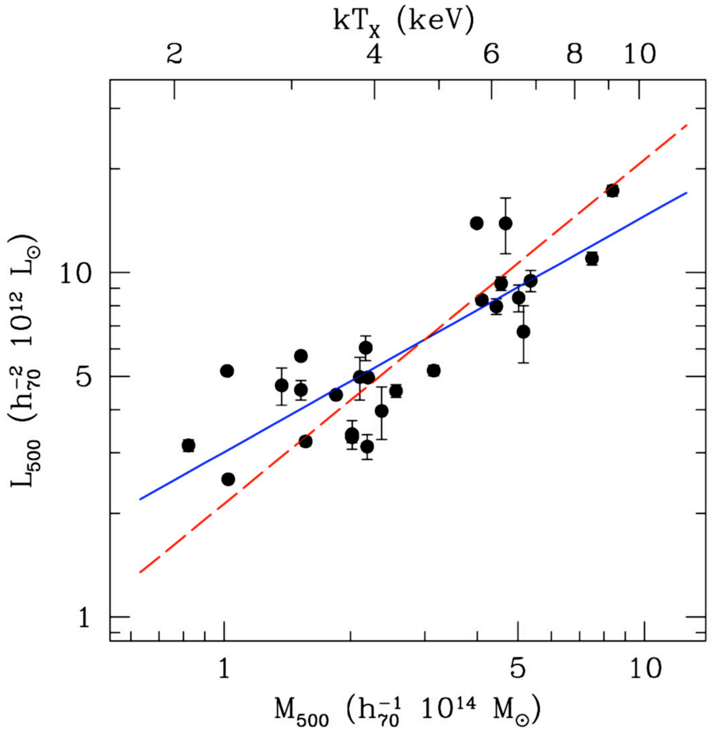




Similar scaling relations are also seen in hydrodynamical simulations of galaxy clusters.

Cluster NIR Light-Mass Scaling Relation

- With 2MASS photometry we have recently analyzed the Near-Infrared properties of clusters. One result is that the K-band galaxy light is correlated with the cluster mass.



Lin, Mohr & Stanford 2003

For the 27 clusters we examined, the scatter about the best fit power law relation is 28%

We will see that the existence of these scaling relations is sufficient to enable precision cosmological tests with very large cluster surveys!

Now let's take a closer look at large galaxy cluster surveys as a way of studying the dark energy…

Studying Dark Energy with High Yield Cluster Surveys

- High yield cluster surveys can in principle deliver percent level constraints on the equation of state of the dark energy and many other cosmological parameters of interest

  Haiman, Mohr & Holder 2000

  Holder, Haiman & Mohr 2001

  Weller et al 2001

  Levine et al 2002

  Hu & Kravtsov 2003

  Majumdar & Mohr 2003

  Hu 2003

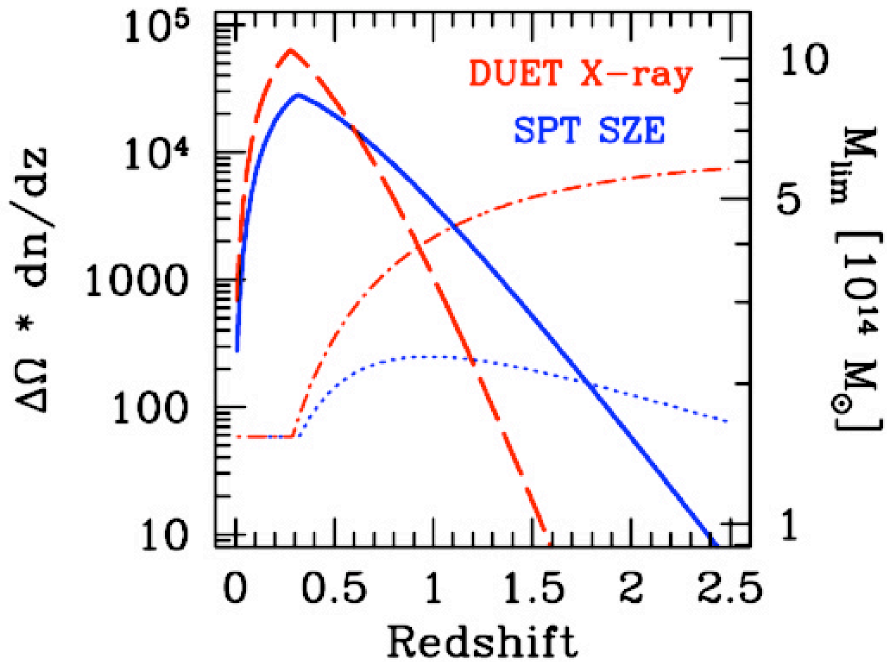
- Requirements:
  - » Large solid angle survey
  - » Control of systematics

Working Requirements:

1. Hierarchichal structure formation theory is correct
2. A mass-observable relation exists that can be used to estimate cluster halo masses from observables like X-ray luminosity, galaxy light, weak lensing shear, SZE luminosity
3. Crude redshift estimates are available for each cluster detected in the survey

Case Study:
Two High Yield Cluster Surveys

Majumdar & Mohr, ApJ 2003



Duet X-ray survey

- 10^4 deg^2 survey of SDSS region
- Employs XMM flight spare mirror and ACIS-like detectors

South Pole Telescope SZE survey

- 4000 deg^2 survey from South Pole
- Employs 8m telescope and bolometer array
- Now funded by NSF

Cluster Surveys are *Self-calibrating*

- These two surveys, each yielding ~15,000 clusters, contain enough information to constrain the interesting cosmological parameters and solve for the structure of galaxy clusters simultaneously!

We estimate parameter uncertainties using the Fisher matrix formalism.

Survey	Ω_m	Ω_{tot}	w	σ_8	h	n	Ω_b	Norm	Slope
Priors		0.010			0.032	0.050	0.004		
DUET	0.018	0.008	0.163	0.013	0.032	0.048	0.004	32%	0.006
SPT	0.015	0.009	0.166	0.013	0.032	0.048	0.004	21%	0.006

$$f_x(z) 4\pi d_L^2 = A M^{\beta} E^2(z)$$

Mass-observable relation

Self-calibrating character of cluster surveys was first shown by Jose Diego et al in an analysis of local cluster data. Levine et al. applied it to large cluster surveys.

But there is a big *caveat*:

This analysis assumes that the redshift evolution of cluster structure is known!

Importance of Cluster Structural Evolution

- If we allow for the fact that we do not know a priori how cluster structure evolves with redshift, then we cannot know how the mass-observable relations evolve

  Then mass estimate of a cluster with a particular flux at redshift **z** is less accurate

- Net result:

  Uncertainties on the equation of state grow by a factor of 1.5 to 3 for these surveys

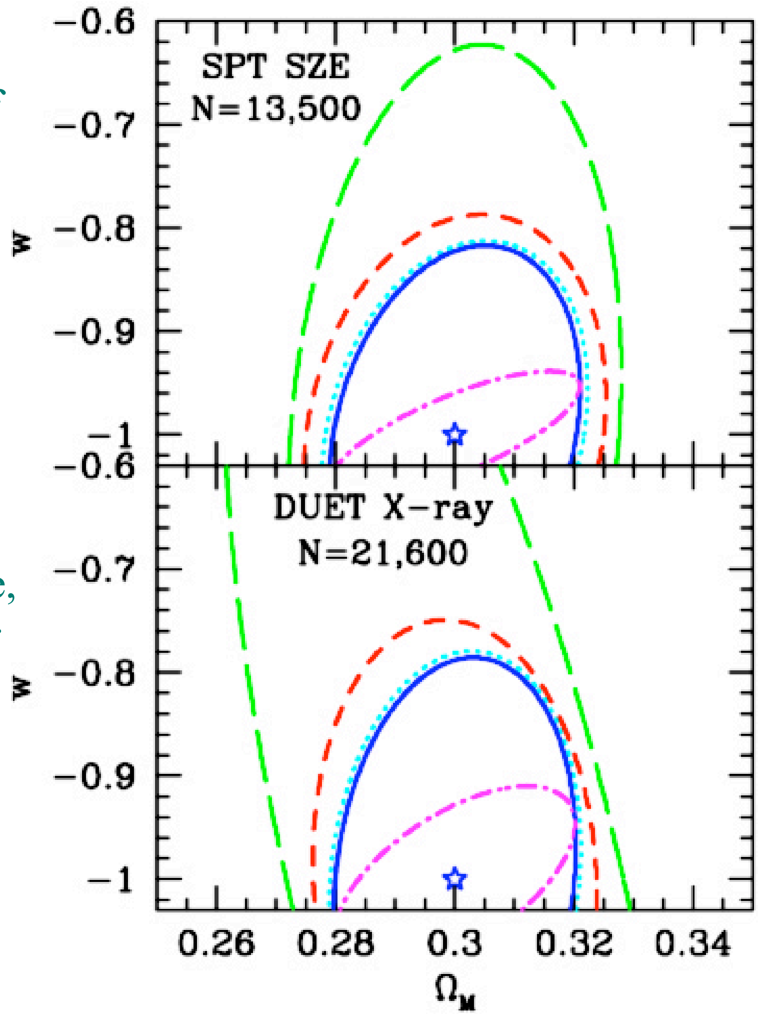
Survey	Ω_m	Ω_{tot}	w	σ_8	h	n	Ω_b	Norm	Slope	γ
Priors		0.010			0.032	0.050	0.004			
SPT	0.018	0.008	0.163	0.013	0.032	0.048	0.004	32%	0.006	
	0.018	**0.008**	**0.249**	**0.020**	**0.032**	**0.048**	**0.004**	**35%**	**0.006**	**0.460**
DUET	0.015	0.009	0.166	0.013	0.032	0.048	0.004	21%	0.006	
	0.026	**0.009**	**0.451**	**0.044**	**0.032**	**0.048**	**0.004**	**51%**	**0.010**	**1.300**

$$f_x(z)4\pi d_L^2 = AM^{\alpha}E^2(z)(1+z)^{\gamma}$$

Tight constraints on **w** require that we understand how the structure of galaxy clusters evolves with redshift.

Let's Examine the Effects of Survey Followup

- With followup measurements on a fraction of the cluster sample, one dramatically improves the constraints on the equation of state!
  - o No followup
  - o 1% followup
  - o 10% & 100% followup
  - o 100% followup + flat Universe



Majumdar & Mohr, 2003

- **Self-calibrating:**

  With followup of as little as 1% of the sample, the cluster survey allows one to solve for **w** and the structural evolution of galaxy clusters simultaneously

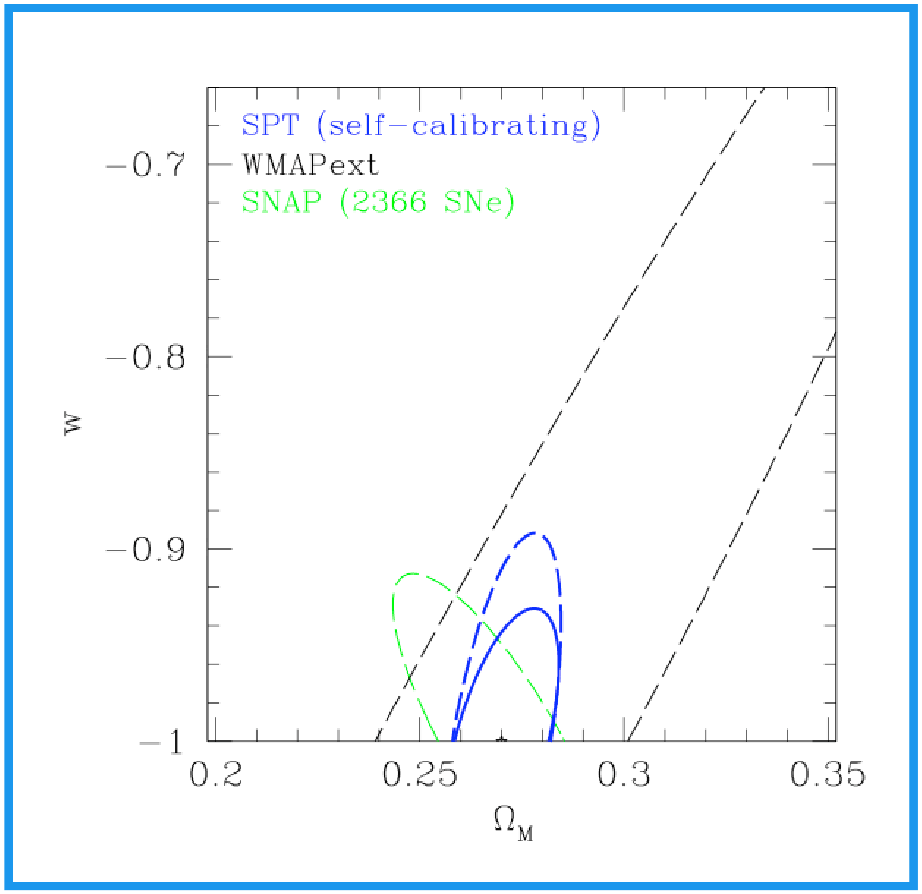
- **Complementary:**

  Parameter degeneracies differ from SNe

- **Competitive!**

SPT dN/dz + P(k) + Followup: Dark Energy Equation of State

- With fiducial model taken from WMAP (σ_8=0.84, Ω_m=0.27 Ω_k=0) there are 29000 clusters in the 4000 deg^2 SPT survey. We assume 30% accurate masses are available for 100 clusters between z of 0.3 and 1.2
- The joint constraints on the equation of state parameter and matter density are shown when letting curvature float (dashed) and fixing it at zero (solid)
  - » Marginalized w 68% uncertainty is 0.046 (flat) or 0.071 (varying)
- Parameter degeneracies are quite complementary to those from SNAP and even from WMAP

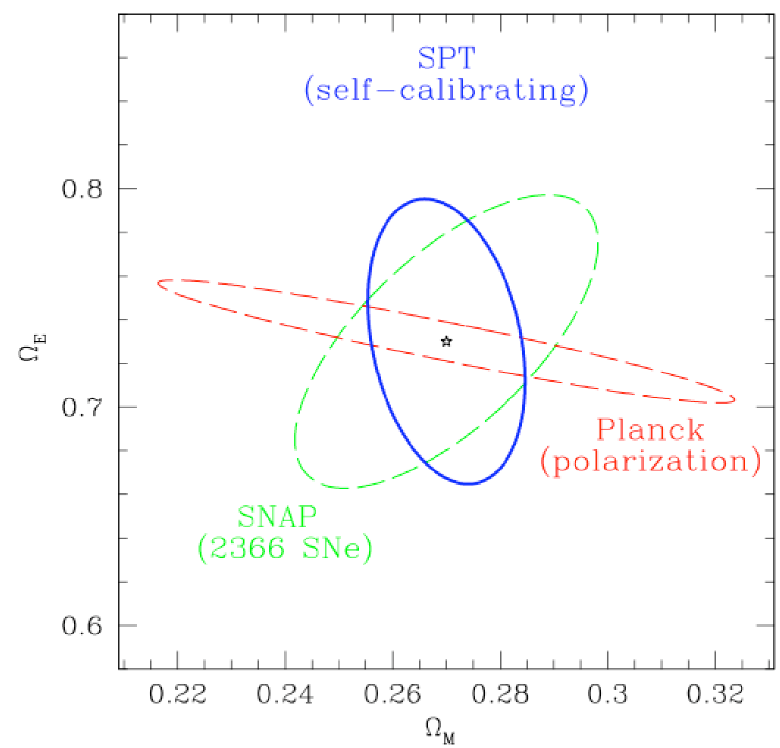


SPT dN/dz + P(k) + Followup: Curvature and Complementarity

- With fiducial model taken from WMAP (σ_8=0.84, Ω_m=0.27 Ω_k=0) there are 29000 clusters in the 4000 deg^2 SPT survey. We assume 30% accurate masses are available for 100 clusters between z of 0.3 and 1.2.

- The joint constraints on the dark energy and matter density are shown
  - Marginalized Ω_E 68% uncertainty is 0.043

- Parameter degeneracies are quite complementary to (and competitive with) those from SNAP and Planck



A Possible Collaboration to Build VisCam?

- The VISTA consortium and ESO are very interested in building VisCam
  - » Note that almost all the science listed requires optical multiband data (which the VISTA team hopes to get by coupling with ESO VST and perhaps even the CFHT Megacam)

- VISTA consortium continues to seek funds to build VisCam- two near term possibilities lie within the UK and EU. Probability of success if far from clear.

- US involvement could be the key
  - » If entire VisCam were built in the US, then the VisCam costs correspond to between 12% and 16% of the total VISTA costs (telescope + IR Camera ($45million) + VisCam ($11million) + ESO operations for 10-15 years at $1.5million/yr)
  - » Science collaborations with VISTA consortium could lead to enhanced access to at least the dedicated, public surveys

The Way Forward

- One way forward:
  - » continue conversation with VISTA consortium
  - » determine the distribution of effort
  - » go after US sources of funding
  - » submit a joint US-UK proposal to ESO to build VisCam

- Positive aspects:
  - » Established expertise here at Fermilab
  - » Strong science interest at Fermilab, U Illinois and U Chicago
  - » Timetable appears to be complementary with SDSS, SNAP and LSST
    - VISTA IR surveys begin 2006, VisCam surveys begin in 2008
    - 4 year construction timeline for VisCam
    - 10-12 year follow-on survey and science period with VISTA

Summary of Costs

- VISTA Consortium Phase A Design Study estimated costs: $11.1 million

Item		**Costs**
Focal Plane		$3.5m
50 CCD’s	$2.6m	
Controller	$0.75m	
Optics	5 elements	$1.3m
Sensors	Active control	$0.17m
Mechanisms	Filter wheel, shutter, ADC rotator	$0.10
Basic Hardware Total		$5.8m
Labor		$3.5m
20% Contingency		$1.9m