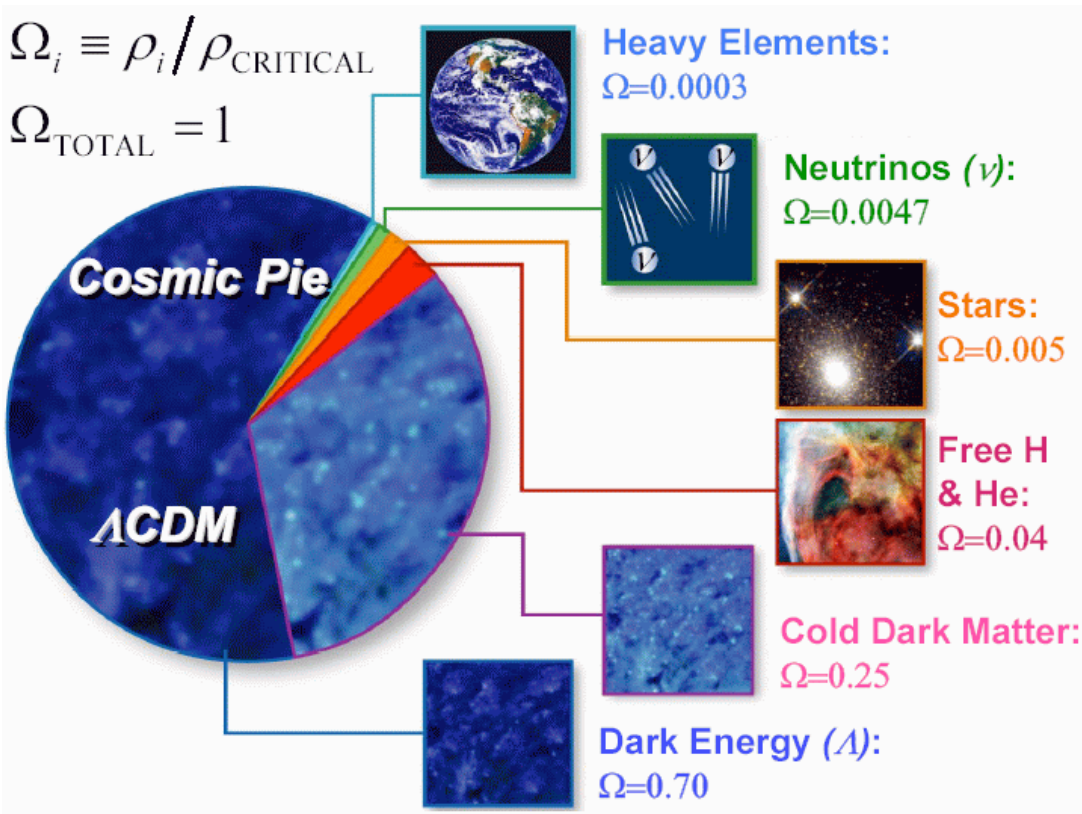
DARK ENERGY SURVEY

The Dark Energy Survey

Juan Estrada AAS2007

A survey of the southern galactic cap (z~1) to constrain the Dark Energy parameter (w) with 4 complementary techniques.

Dark Energy



We do not know what is the nature of 95% of the energy in the universe.

To make things work in our calculations we had to add Λ (70% of the pie), for which we can not even agree on a model.

1998 and 2003 Science breakthroughs of the year

Cosmology

(for experimental particles physicists)

DARK ENERGY SURVEY

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3}$$

Expansion of the universe with a perfect fluid with density ρ and pressure p

$$\frac{\ddot{R}}{R} = -\frac{4\pi G_N}{3}(\rho + 3p)$$

$$p = w\rho$$

$$\dot{\rho} = -3H(\rho + p)$$

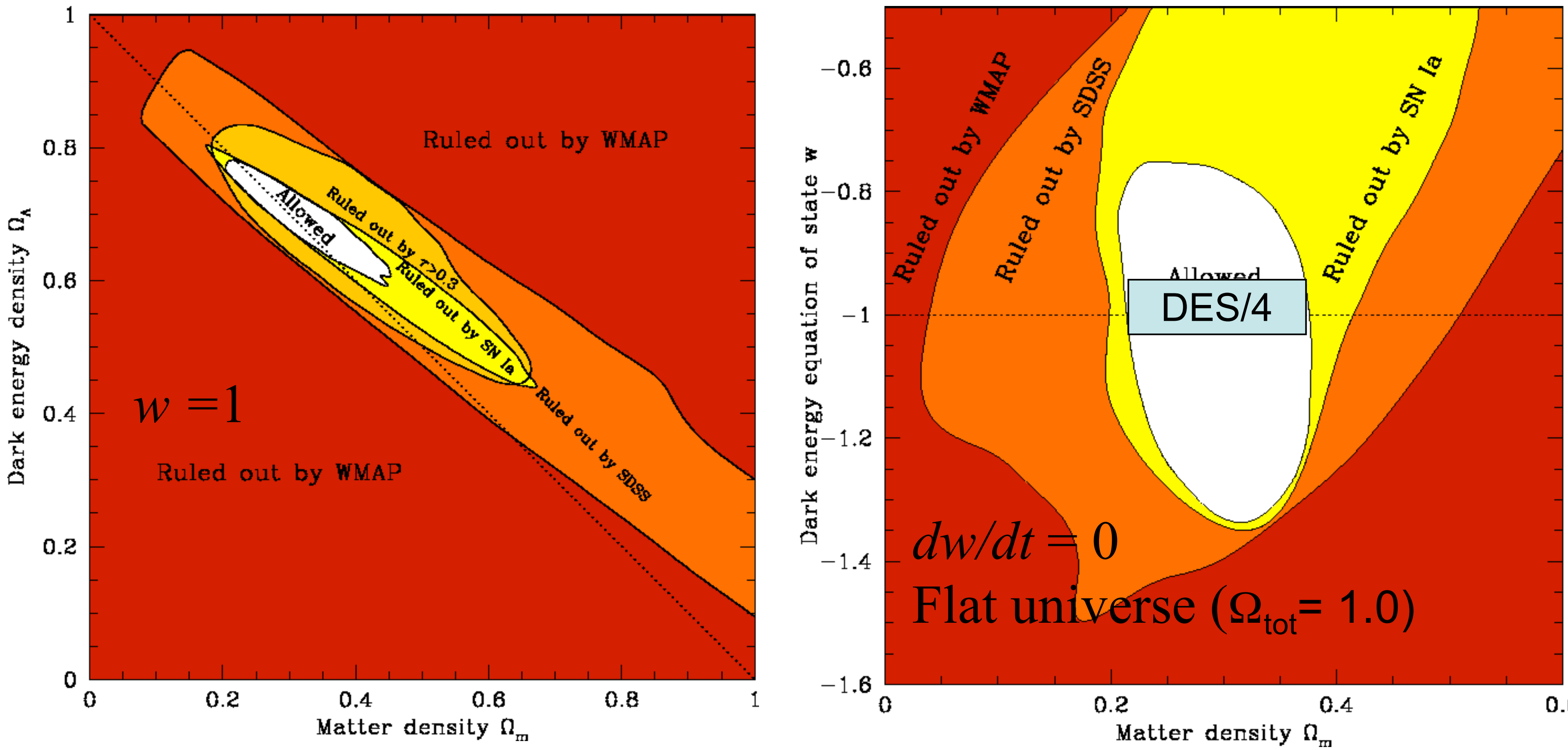
$$\rho(t) \propto R^{-3(1+w)}$$

$$R(t) \propto t^{2/[3(1+w)]}$$

- In the case of two components [one being matter with w=0, the other component will be called DE].

$$H^2 = H_0^2\left[\Omega_m (1+z)^3 + \Omega_{DE}(1+z)^{3(1+w)}\right]$$

Current Limits on Ω_Λ and *w*



Currently most measurements point to Λ=0.7 assuming w=-1, but not yet good measurements in w.

DES Collaboration

- **Fermilab**
- **University of Illinois at Urbana-Champaign**
- **University of Chicago**
- **Lawrence Berkeley National Laboratory**
- **University of Michigan**
- **NOAO/CTIO**
- **Spain-DES Collaboration:**
  Institut d'Estudis Espacials de Catalunya (IEEC/ICE), Institut de Fisica d'Altes Energies (IFAE), CIEMAT-Madrid:
- **United Kingdom-DES Collaboration:**
  University College London, University of Cambridge, University of Edinburgh, University of Portsmouth, University of Sussex
- **The University of Pennsylvania**
- **Brazil-DES Consortium**
- **The Ohio State University**
- **Argonne National Laboratory**

17 institutions and 110 participants

DES Science Goals : 4 techniques

DARK ENERGY SURVEY

Galaxy Cluster counting

(collaboration with SPT, see next slides)

20,000 clusters to z=1 with $M>2x10^{14}M_{sun}$

Spatial clustering of galaxies (BAO)

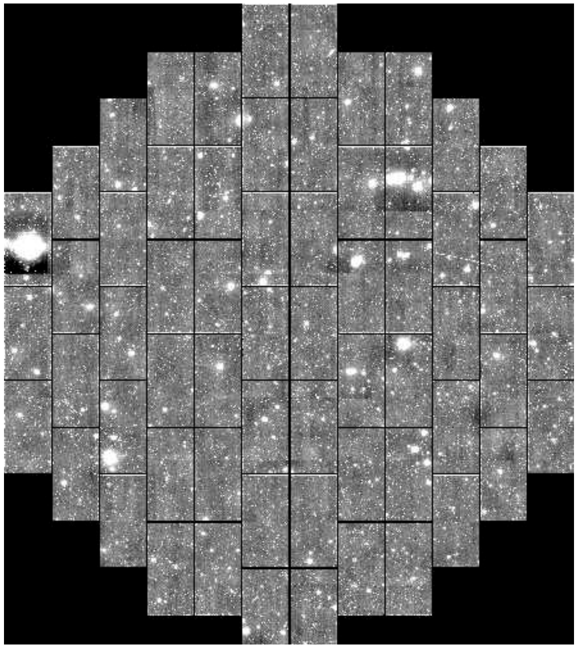
300 million galaxies to z ~ 1

Weak lensing

300 million galaxies with shape measurements over 5000 sq deg

Supernovae type Ia (secondary survey)

~1100 SNe Ia, to z = 1

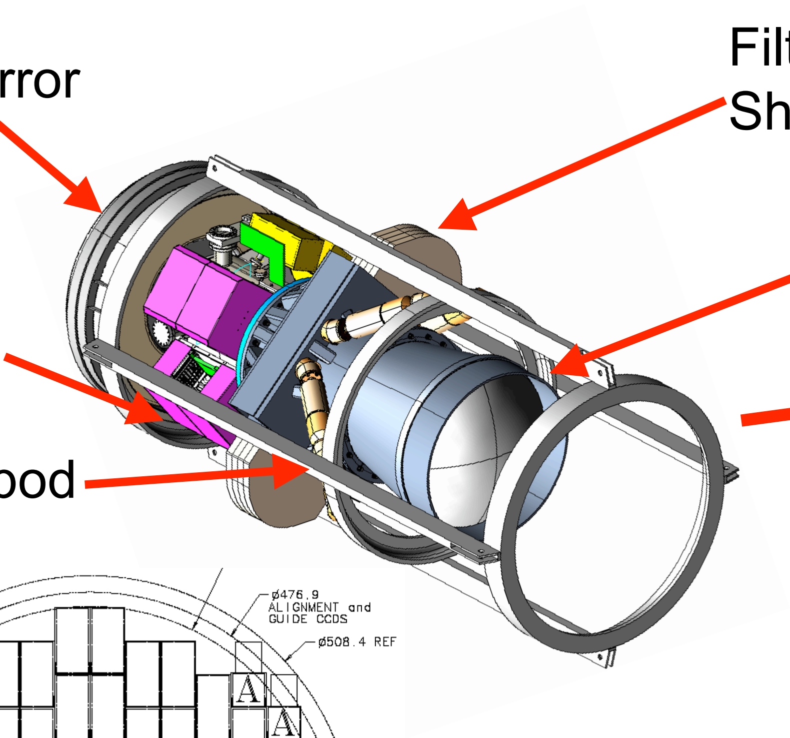


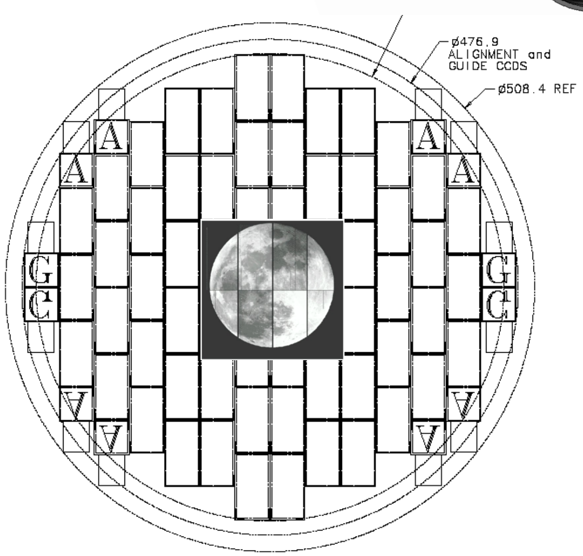
DES Image simulation FNAL/NOAO

One experiment covering the main probes for dark energy. This will facilitate study of systematic effects and correlations between techniques.

DECam : new instrument for DES

Replace the PF cage on the CTIO Blanco 4m telescope with a new 3 deg^2 optical CCD camera.

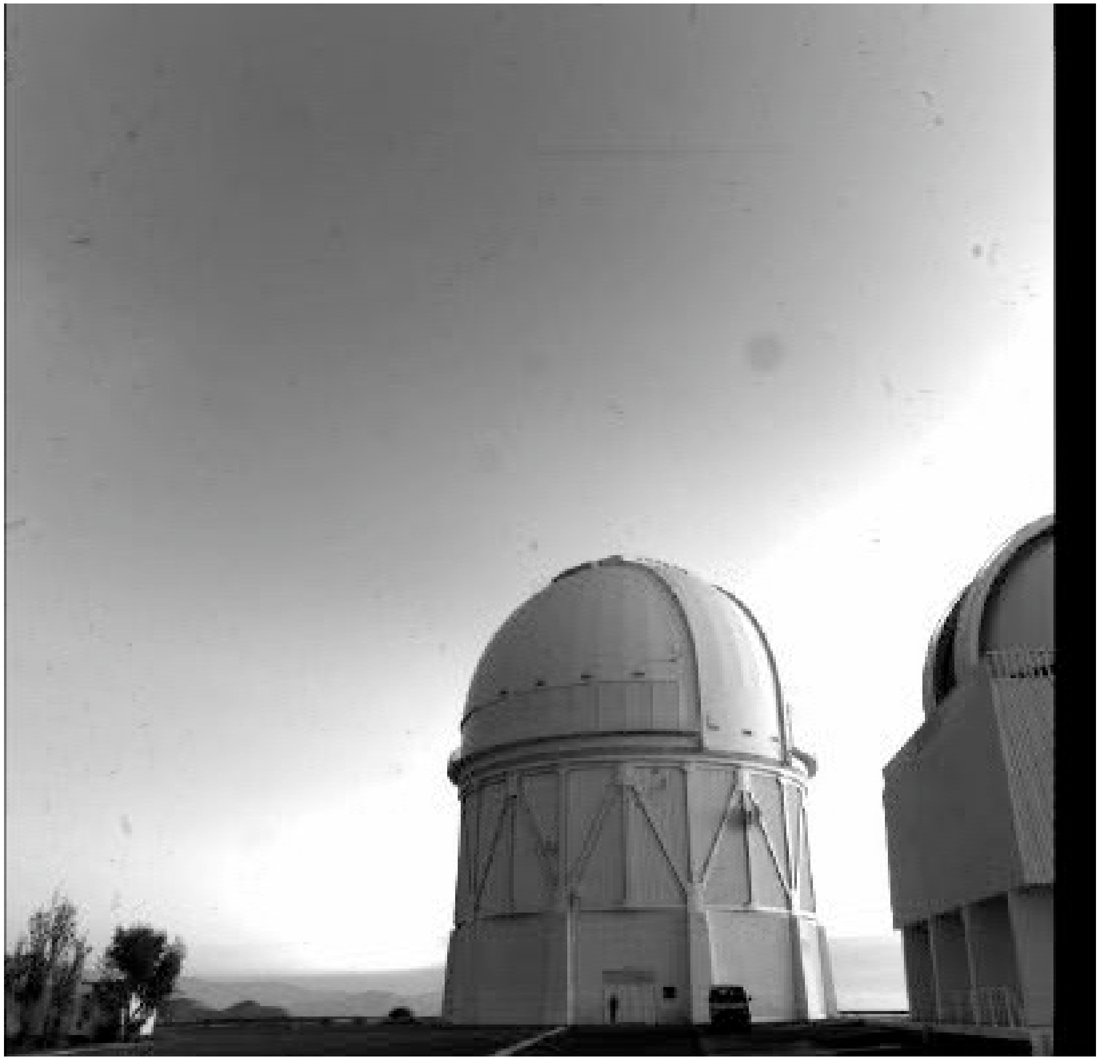




Focal Plane:

62 2kx4k Image CCDs: 520 MPix
8 2kx2k focus, alignment CCDs
4 2kx2k guide CCDs
0.27''/pixel (15x15 μm)

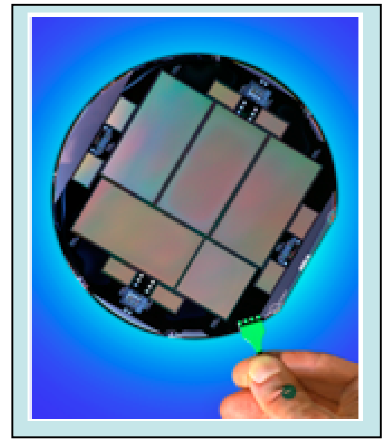
One night for Blanco 4m at CTIO

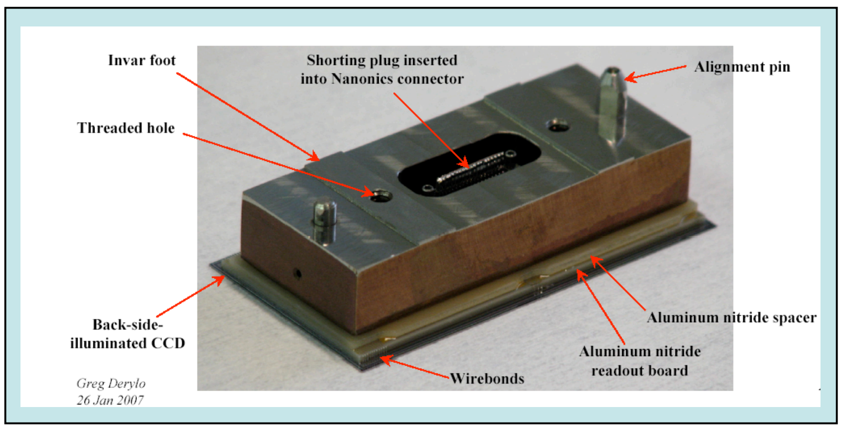


Status of Hardware

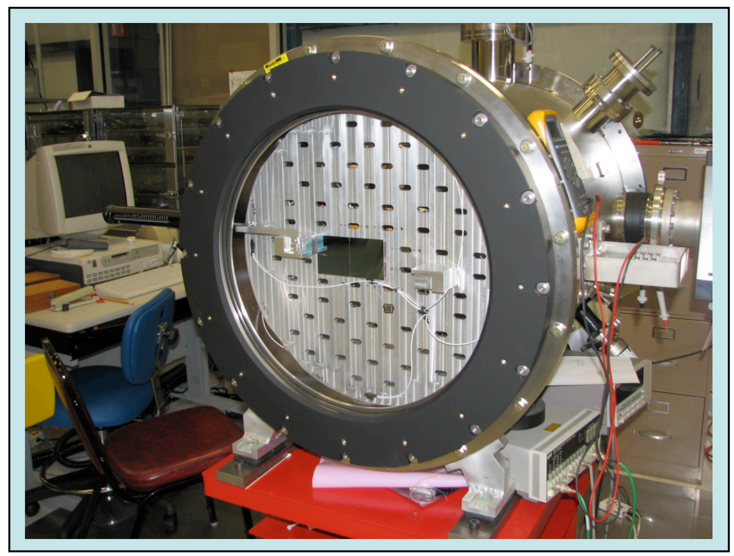
- DECam CCD mask done.
- ~100 engineering DECam CCDs delivered and tested.
- Prototype packaging successful.
- Full size prototype vessel built (4 CCD mosaic in operation).
- Readout electronics designed, prototypes meet specs.
- Optical design completed.

DECam wafer





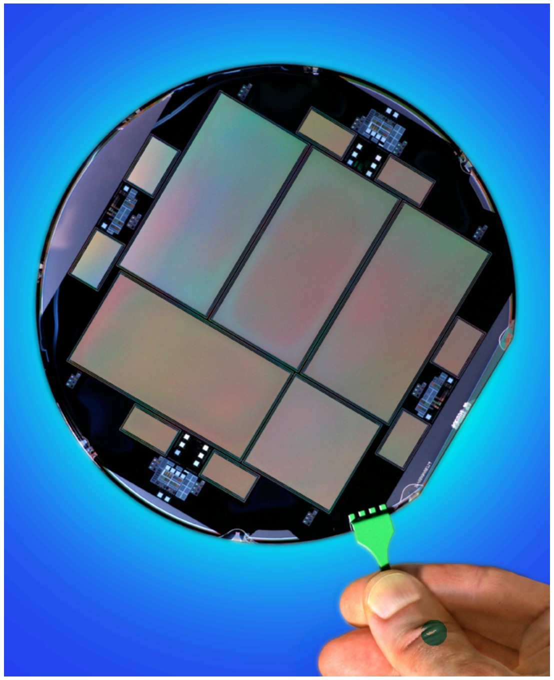
DECam CCD package



DECam prototype cryostat

Focal Plane Detectors

new fabrication process for CCDs with higher QE in the red, these are devices **about 10 times thicker than a usual scientific CCDs**. Only used in astronomical experiment for short time and in small numbers.



New technology:

⇒Need to understand how these devices perform, what are there limitations and their general specs.

For our focal plane:

⇒Find 70 devices that will satisfy the scientific requirements for our instrument. (grading)

⇒Develop a scheme to mount these devices in the focal plane (packaging) and read them out (camera electronics).

8 Mpix and 2 outputs. Charge has to move 7.5 cm to get out

Focal Plane Detectors

Science goal for DES: z~1

~50% of time in z-filter

825-1100nm

Astronomical CCDs are usually thinned to 30-40 microns (depletion):

Good 400nm response

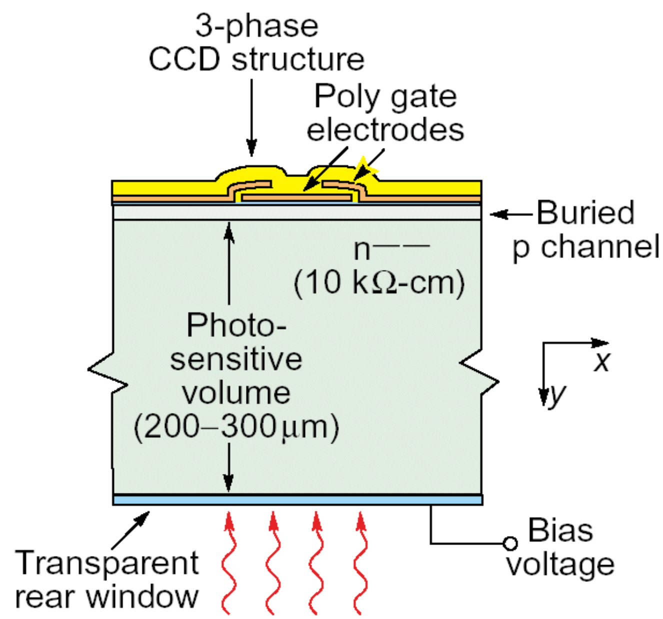
Poor 900nm response

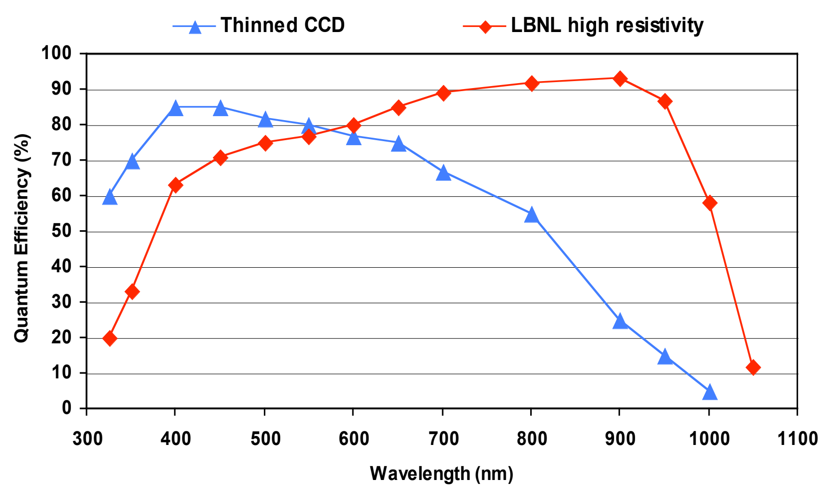
LBNL full depletion CCD

–250 microns thick

–high resistivity silicon

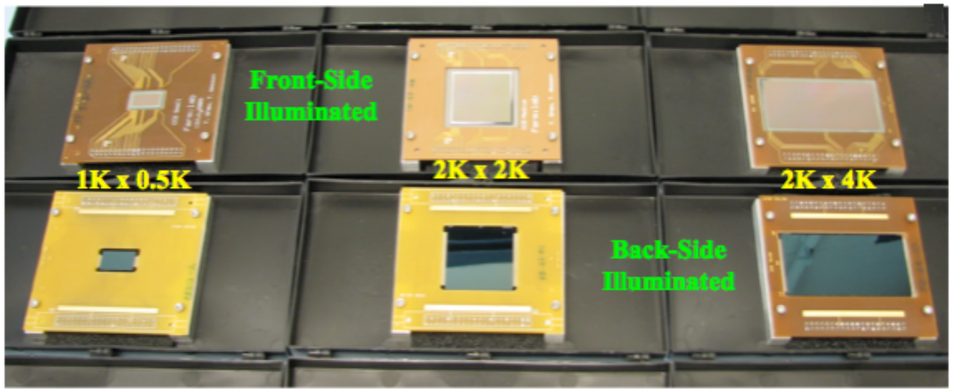
–QE> 50% at 1000 nm

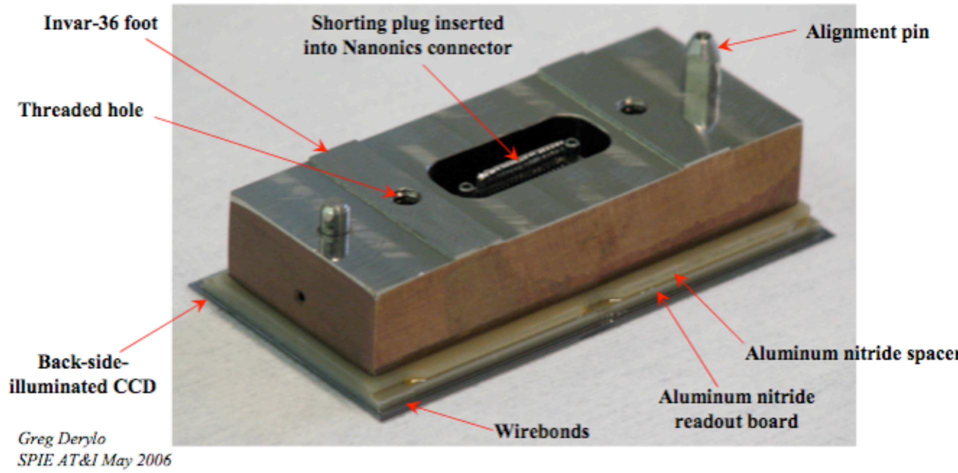


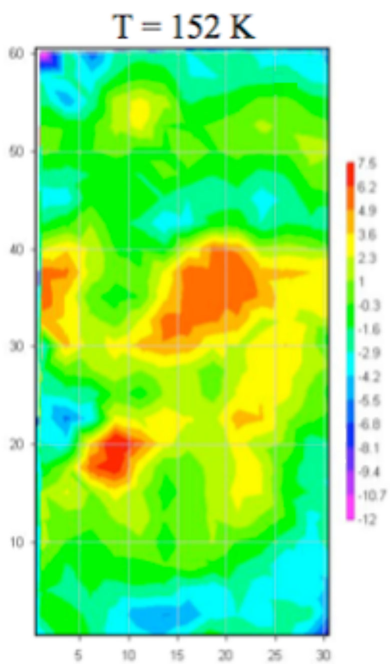


DARK ENERGY SURVEY

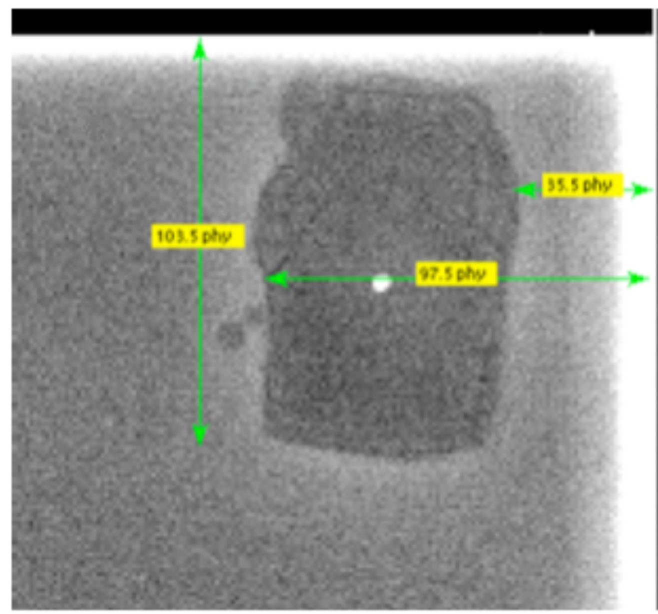
CCD packaging at SiDet







The packaging is done at SiDet. It is not trivial to build a package to mount these devices in the focal plane (no dead space between them, -100K, flatness of 10 um) .



DARK ENERGY SURVEY

DES technical requirements

	measurement	specification
T-10	nonlinearity ✓	< 1 %
T-11	full well ✓	> 130000 e-
T-12	residual image ✓	< 10 e- from 3×10^6 e- spread over 5 pixels
T-13	readout rate ✓	250 kpix/s
T-14	CTI ✓	$< 10^{-5}$
T-20	QE [g, r, i, z] ✓	[60%, 75%, 70%, 65%]
T-21	QE instability ✓	≤ 0.3% in 12-18 hours
T-23	QE uniformity in focal plane	≤ 5% in 12-18 hours
T-25	readout noise ✓	≤ 15 e-/pix
T-27	charge diffusion ✓	1-D $\sigma < 7.5\ \mu m$
T-28	flatness 1 cm^2 region ✓	< 3 μm r.m.s. in deviation from flat
T-29	flatness between T-28 regions ✓	< 10 μm deviation
T-30	cosmetic defects ✓	< 5 % loss from non-usable pixels
TP-1	dark current ✓	< dark current 25 e/pix/hour
TP-2	crosstalk ✓	$< 10^{-3}$

The specifications for the detectors are discussed in DocDB-20.

High QE in the red

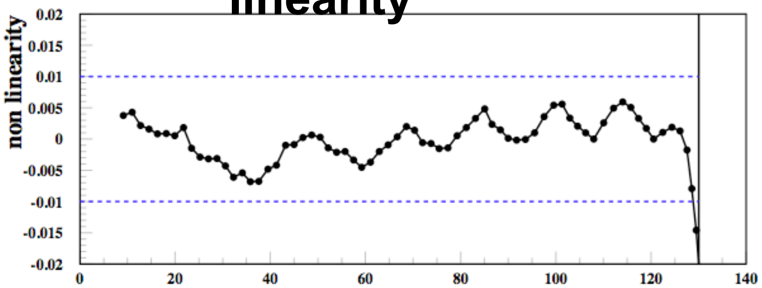
(a special feature 250 μm).

(preliminary) Impact on science not fully evaluated yet.

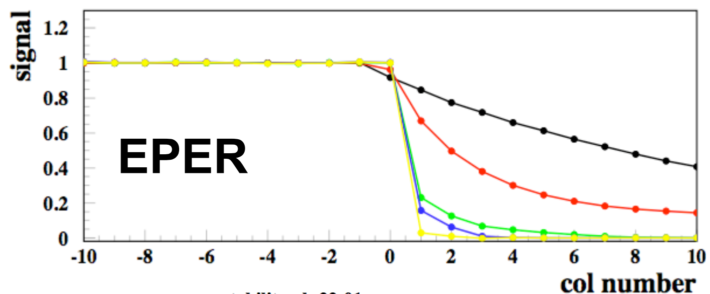
✓ : achieved in engineering CCDs

Performance of Engineering CCDs

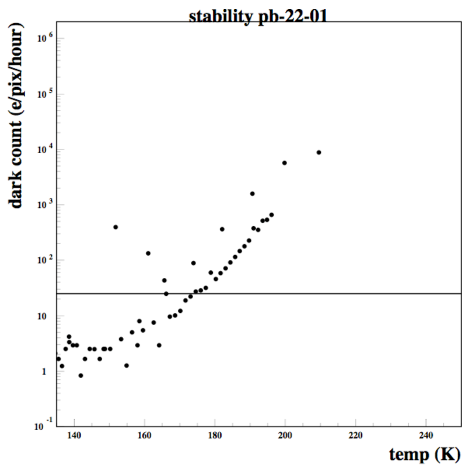
linearity



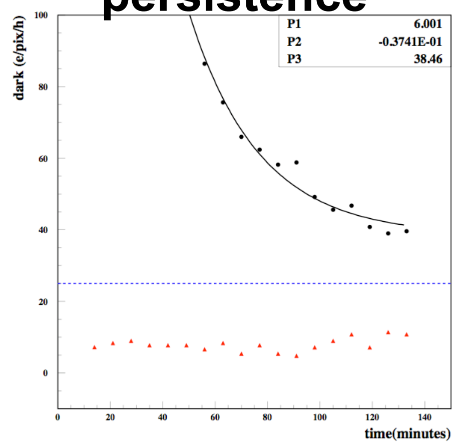
EPER



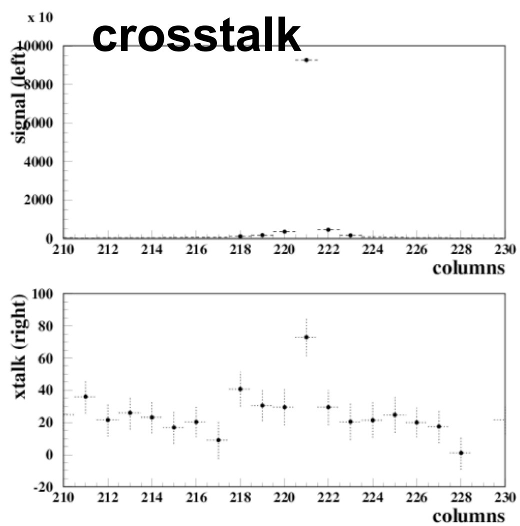
Dark current



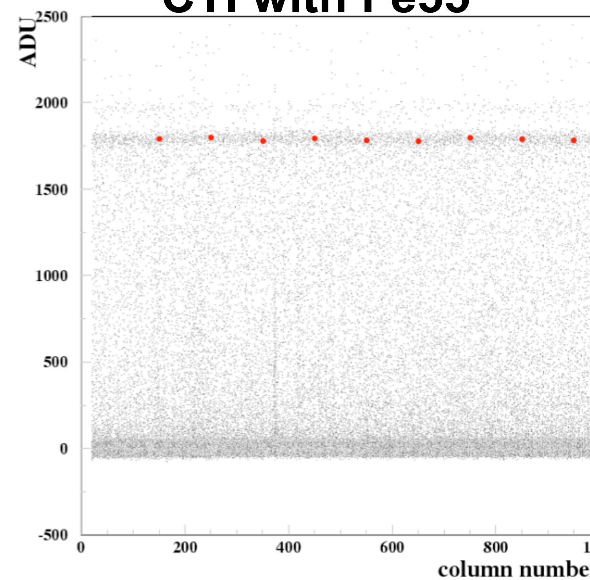
persistence



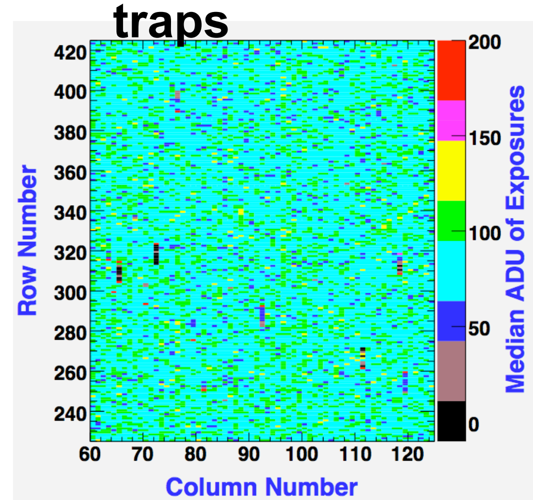
crosstalk



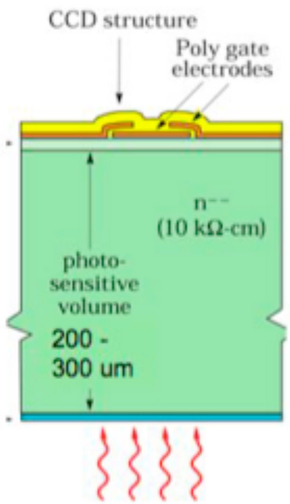
CTI with Fe55



traps



Ex.1: Charge diffusion

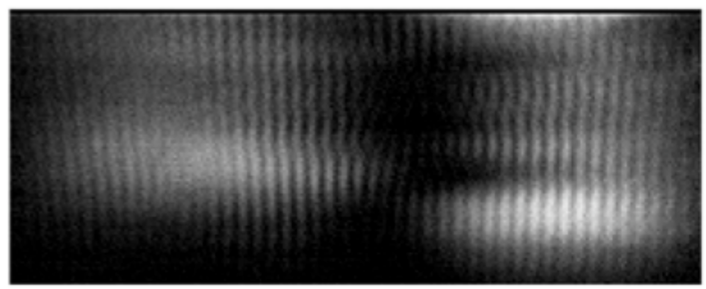


Holes produced in the back surface have to travel to the collection area. This gives the opportunity for diffusion. (fully depleted)

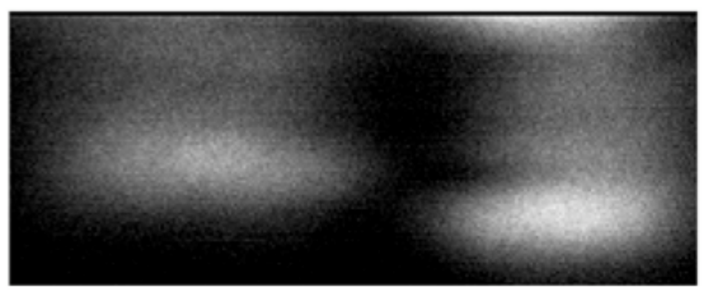
The 40V applied to the substrate (Vsub) to control diffusion

Imaging a diffraction pattern

high Vsub

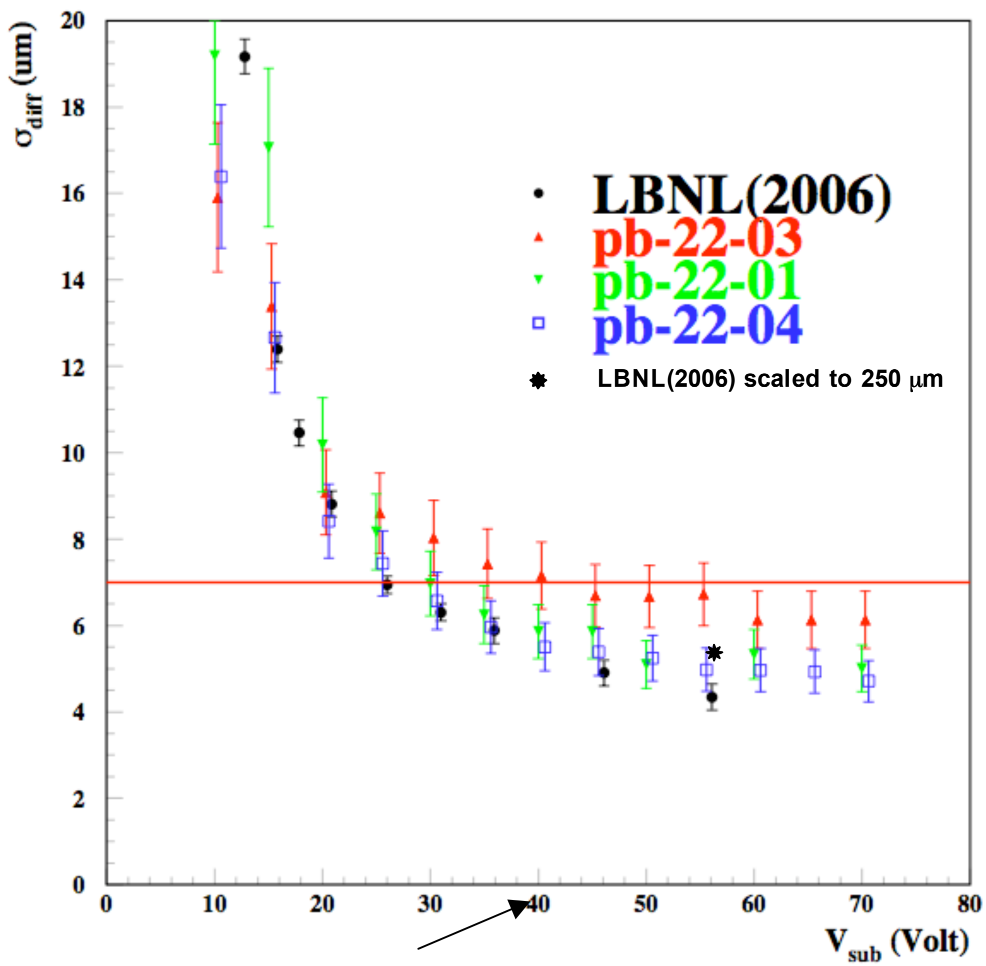


low Vsub



Diffusion is measured from the analysis of these images

Ex.1: Diffusion results

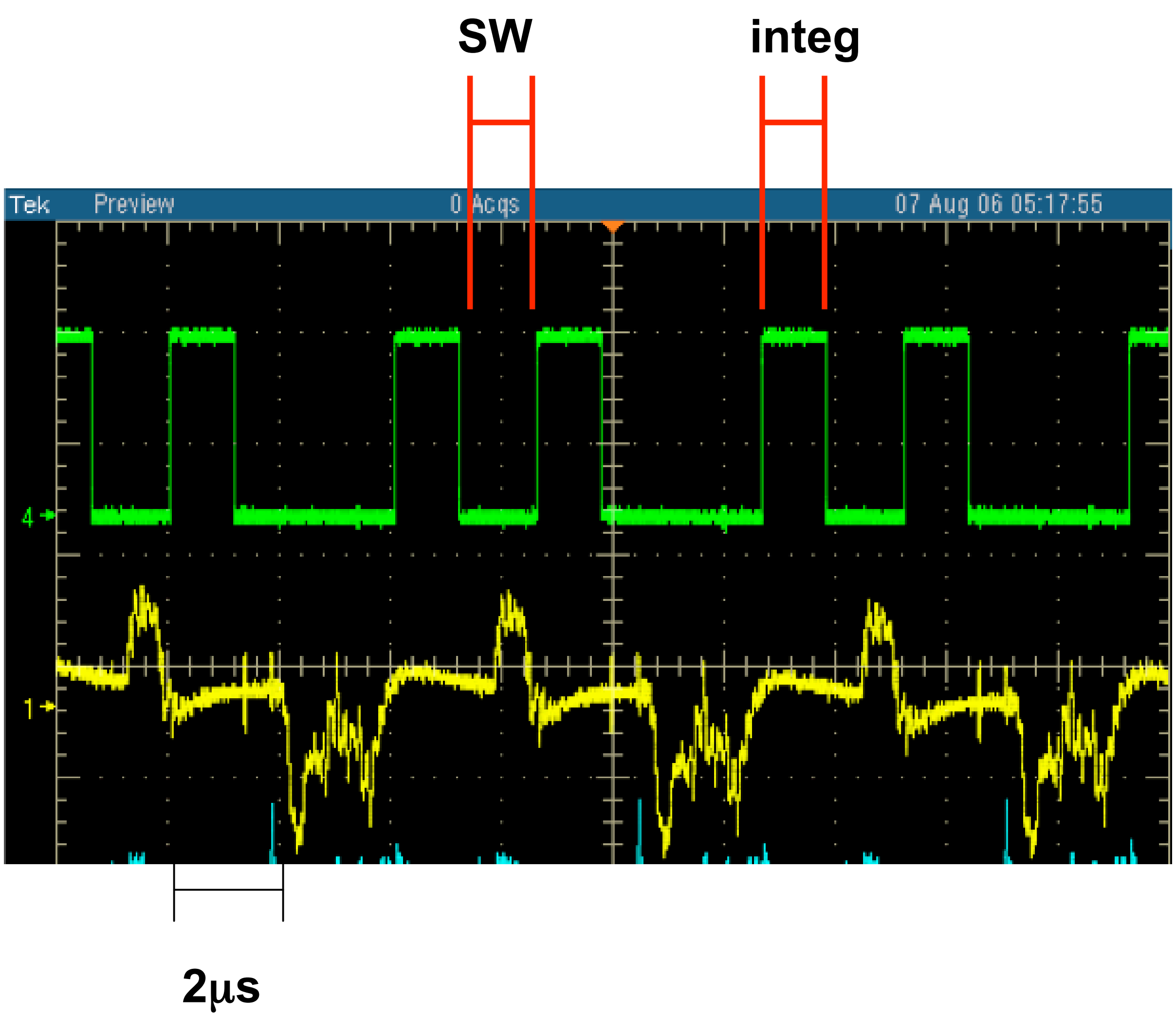


voltage for DES CCDs

Results of the DES devices (blue,red and green) are compared with measurements done at LBNL for a 200 μm SNAP CCD (black).

These results also show that the devices are fully depleted before 40 V.

Ex.2: Noise in Correlated Double Sampling



Our technical requirement:

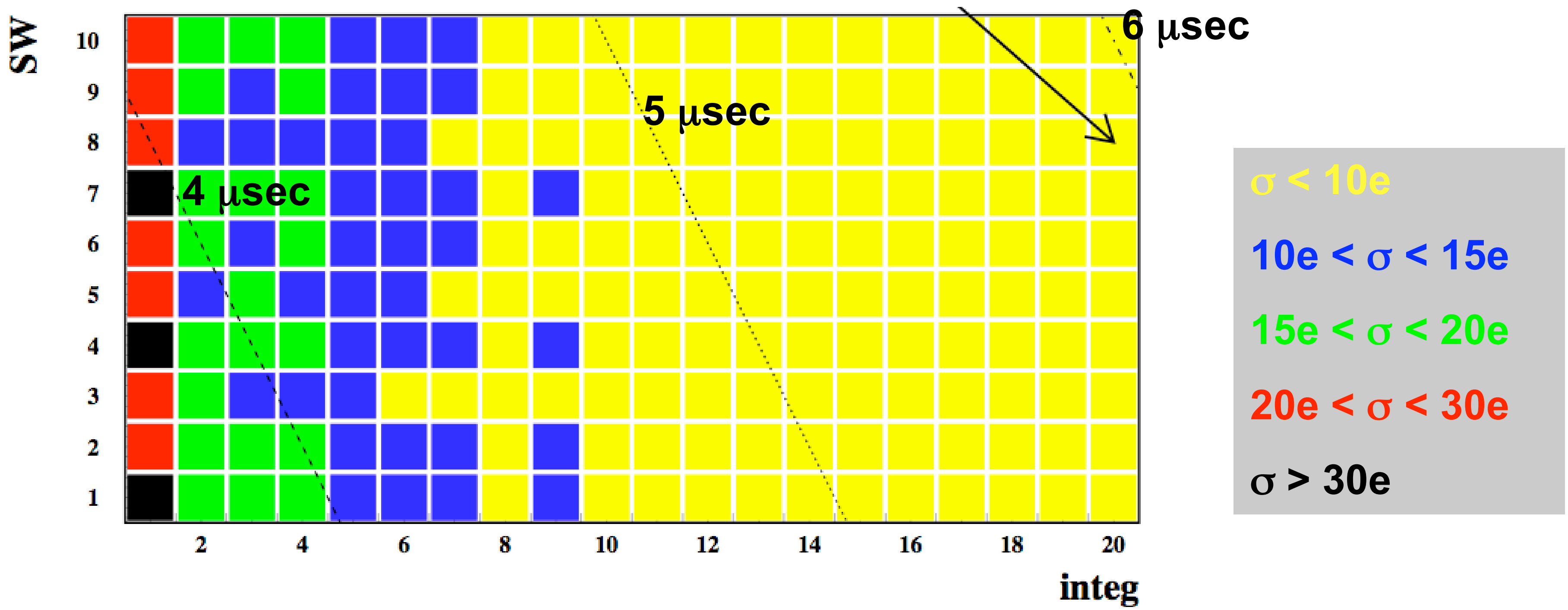
- **< 4 usec/pix pixel**
- **< 15 e noise.**

Integration window

Video output

Noise is sensitive to CDS timing.

Ex.2: Noise vs readout speed

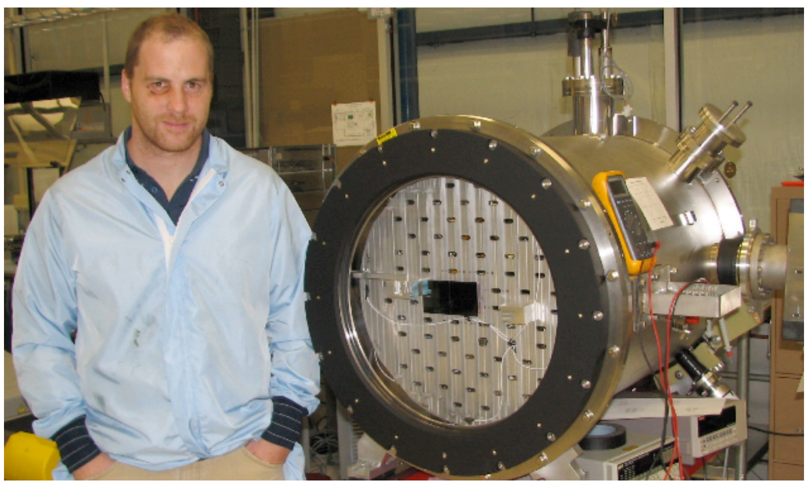


Two points satisfy the spec. To avoid susprises more ambitious goal of 10e noise is achieved at 4.8 μsec/pix (83% readout speed goal). Will study this problem in new 12 channel board and new V2 packages (JFET on package).

MultiCCD

We have checked the technical requirements on individual CCDs. Some specs need testing on full size focal plane.

Crosstalk and noise will to be checked on multiCCD.

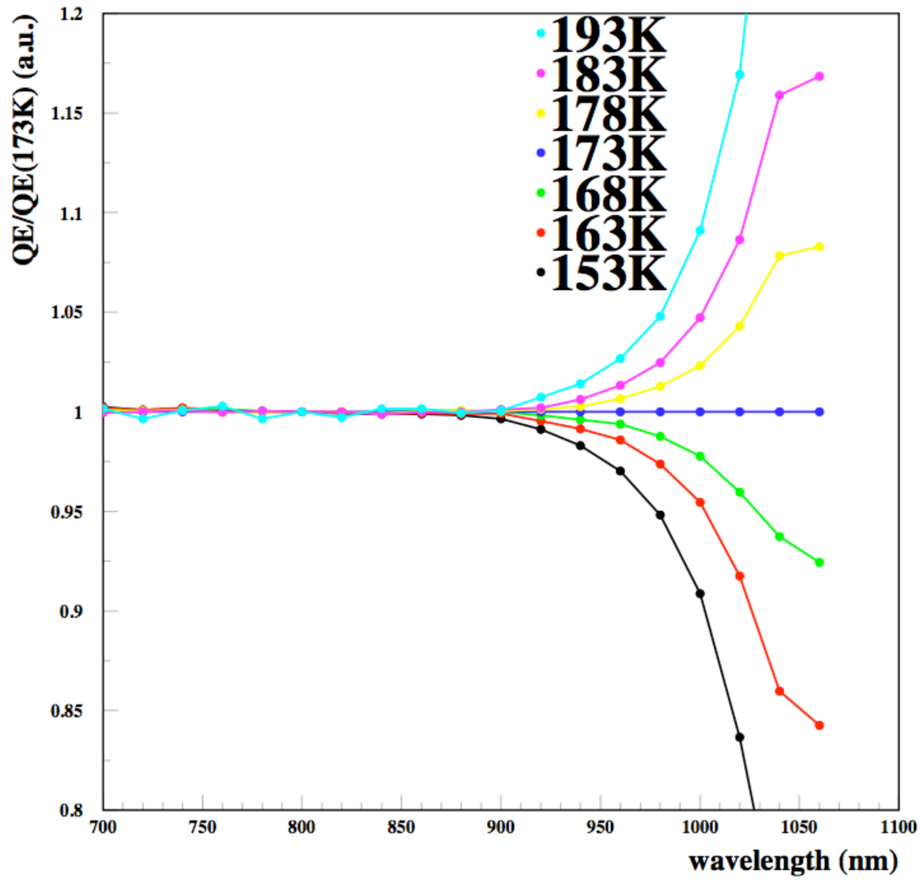


4 CCDs installed and working!

QE uniformity and stability

To keep QE uniformity at 5%, we need ΔT < 10K.

QE stability 0.3% means ΔT <1K (not yet verified).



Survey

DARK ENERGY SURVEY

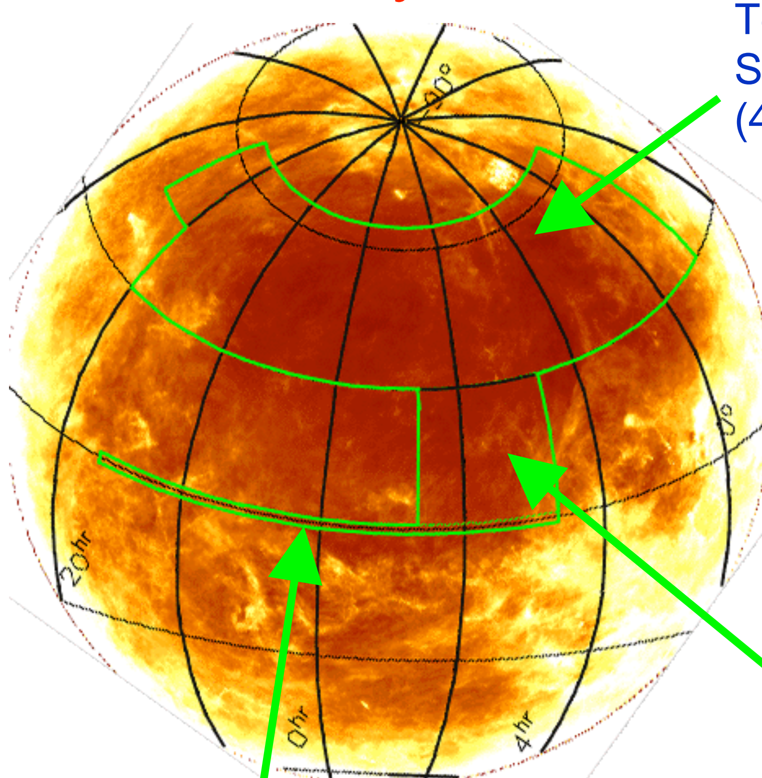
Primary Survey:

- •Survey Area 5000 sq. deg. in Southern Galactic Cap
- •SDSS g,r,i,z filters 10 σ Limiting mag: 24.6, 24.1, 24.0, 23.9
- •Connection to SDSS stripe 82 for photo-z calibration
- •Multiple tilings (4+) in nominally 100sec units

Secondary Survey (10% of time):

- •9 deg^2
- •For Supernovae sample

Survey Area



Overlap with South Pole Telescope Survey (4000 sq deg)

Connector region (800 sq deg)

Overlap with SDSS Stripe 82 for calibration (200 sq deg)

Installed in 2010

Survey : 30% of the telescope time from 20010-2014

SDSS vs other surveys

- PanSTARRS 1 (2007-2010):
  - 1.8m telescope
  - 7 degrees^2 fov (1.4 Gpix)
  - 30000 degrees^2
  - mag < 24
- DES (2010-2015)
  - 4m telescope
  - 3 degrees^2 fov (0.5 Gpix)
  - 5000 degrees^2
  - mag < 24
- PanSTARRS 4 (?):
  - PS1x4
  - Mag < 27
- LSST (starting 2014?):
  - 8.4m telescope
  - 10 degrees^2 fov(3 Gpix)
  - 20,000 degrees^2
  - mag 29 AB

•DES is the only one that matches SPT until LSST. Unique opportunity.

•Done with the sky soon:

> **•The sky has only 40000**
>
> •Above mag 27 you start to be limited by the object overlap due to the sky dispersion.

Key for DES success: Photo-z

DARK ENERGY SURVEY

Estimate individual galaxy redshifts by measuring relative flux in multiple filters (track the 4000 A break)

$\sigma(z) < 0.1$ (~0.02 for clusters)

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

- **Good detector response in *z* band filter needed to reach z>1**

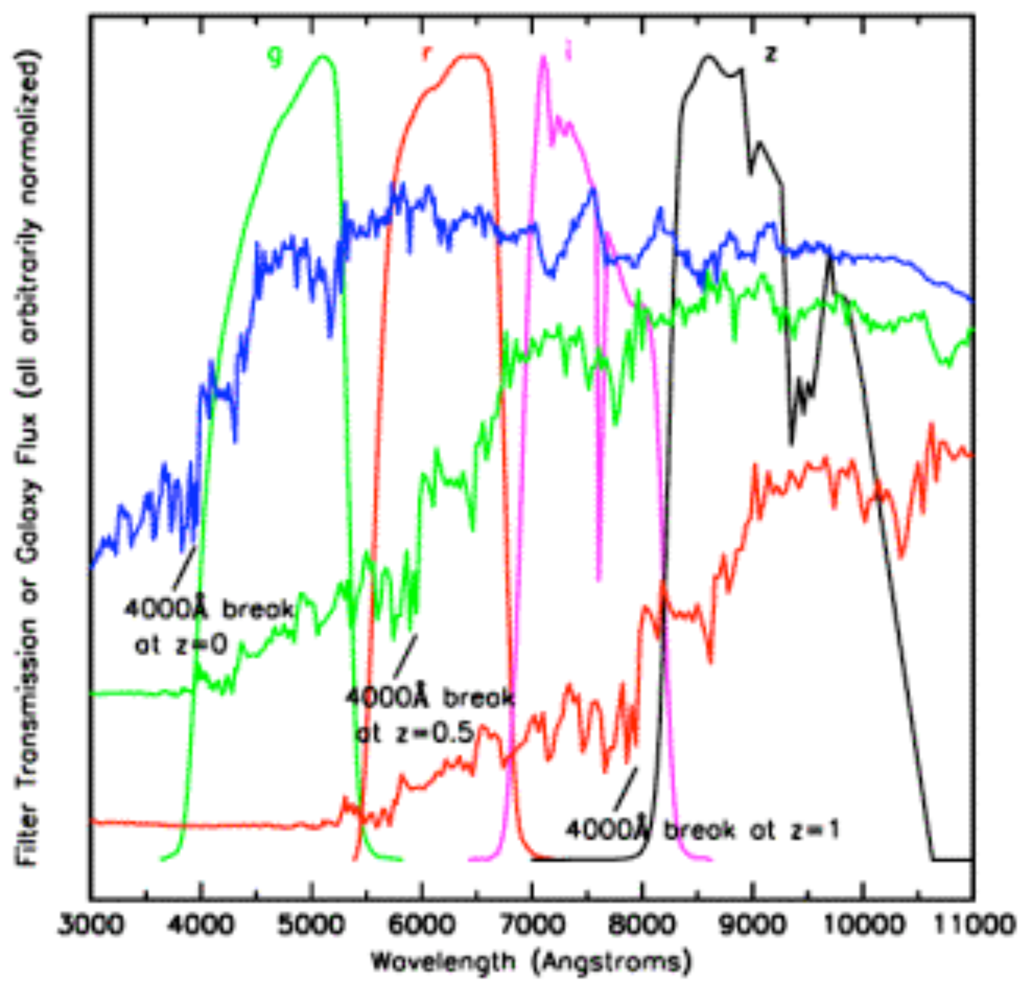


Photo-z : DES + VHS

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

Key: Photo-z systematic errors under control using *existing* spectroscopic training sets to DES photometric depth: low-risk

A small change for DES baseline, with a big payback.

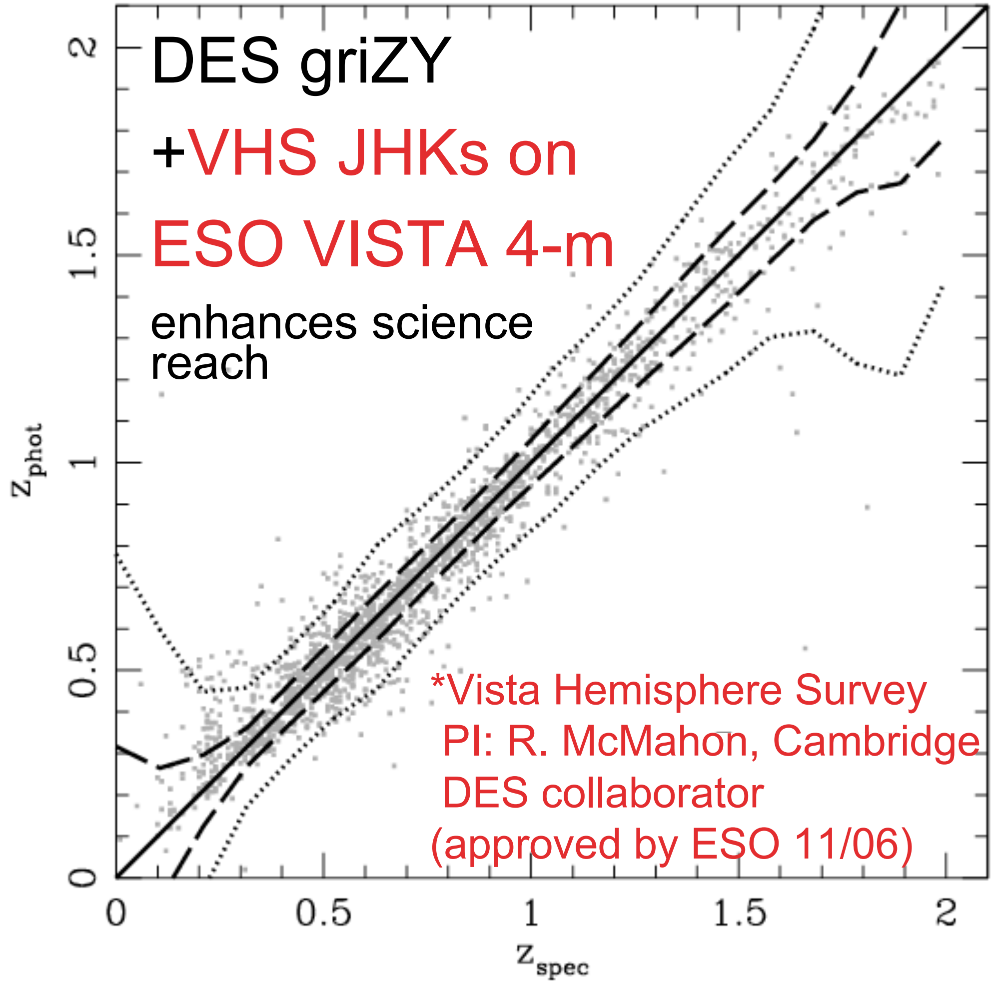


Photo-z's in DES clusters

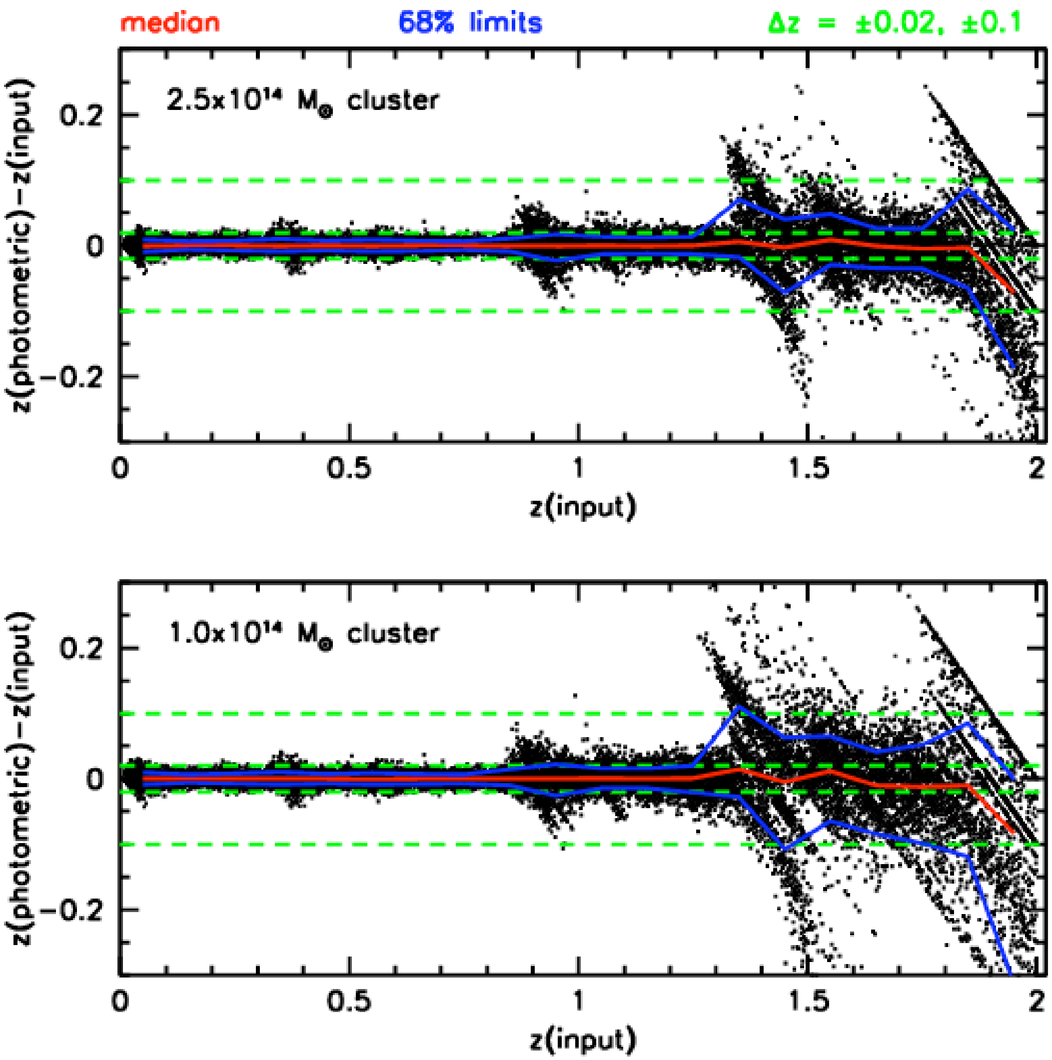


Photo-z estimation of redshift works very well for clusters of galaxies

$\Delta z < 0.02$ for $z<1.3$

(Recall cluster galaxies are very uniform)

Cluster Counts

The distribution of the number of clusters as a function of redshift is sensitive to Ω_Λ and w.

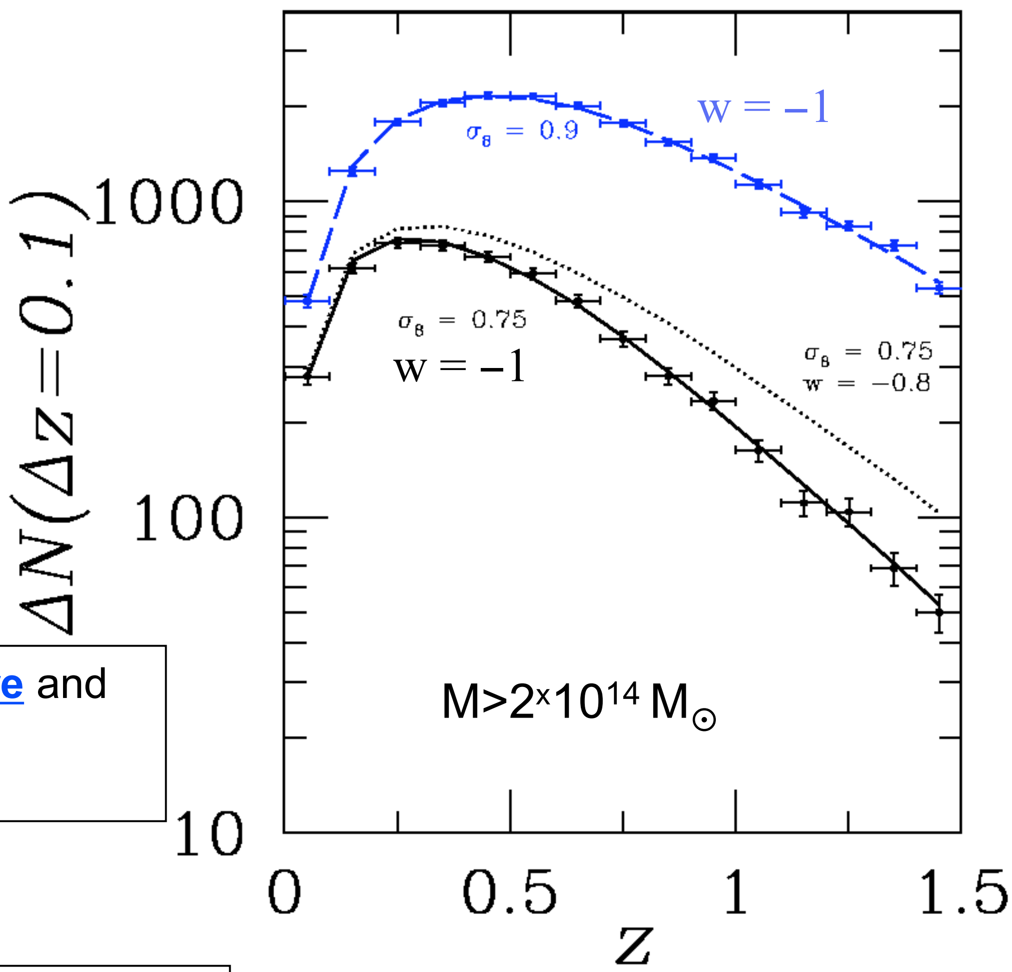
$$\frac{dN(M)}{dz d\Omega} = \frac{dV}{dz d\Omega}(z) n_{co}(M,z)$$

Volume: distance meas. Expansion history of Universe. Geometry

Abundance evolution: growth of structure and initial mass power spectrum.

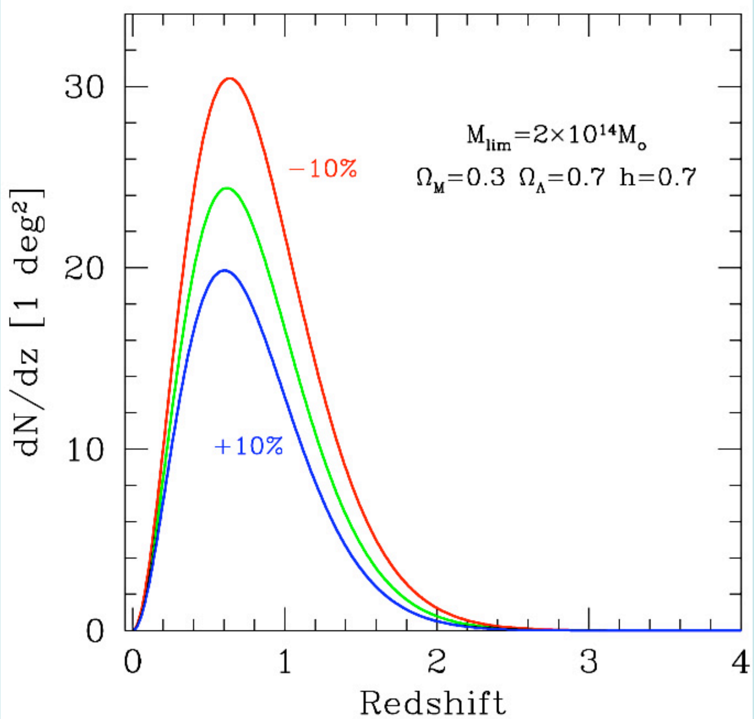
Mass selection also has cosmology, for example luminosity distance.

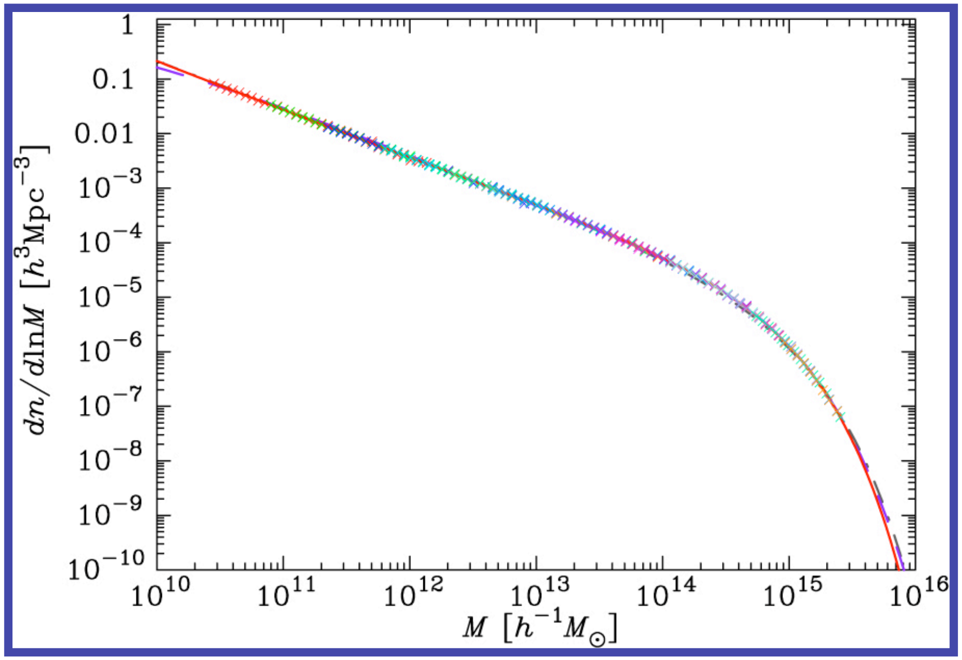
Number of Clusters vs. Redshift



Mass dependence

Sensitivity to Mass





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

Cluster Counts Systematics

DARK ENERGY SURVEY

Main systematics:

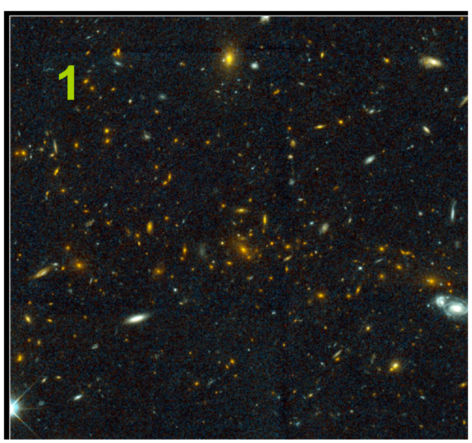
– **Cluster selection function**

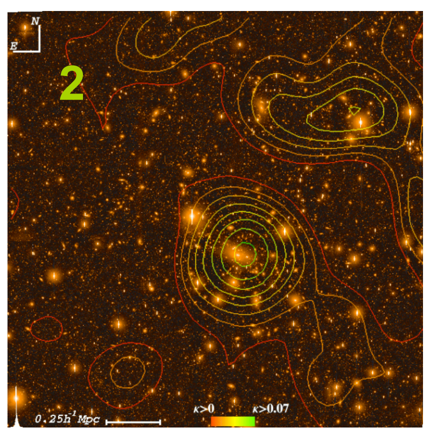
– **Cluster mass estimate**

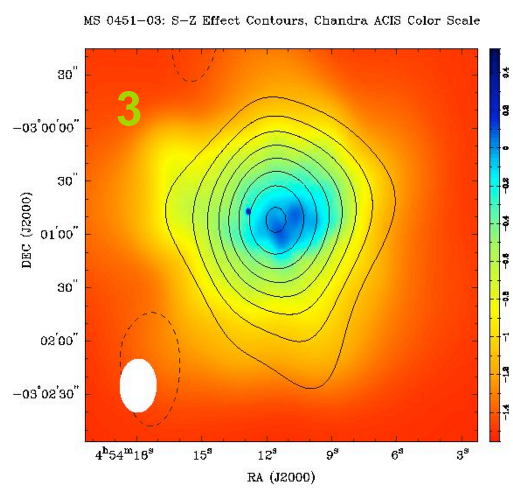
To work on these for DES we have three different ways of selecting clusters and estimating their mass:

1. **Optical richness**
2. **Weak lensing**
3. **Sunyaev-Zel'dovich effect (SPT)**

we will be able to compared the results on these three different techniques of looking at clusters.



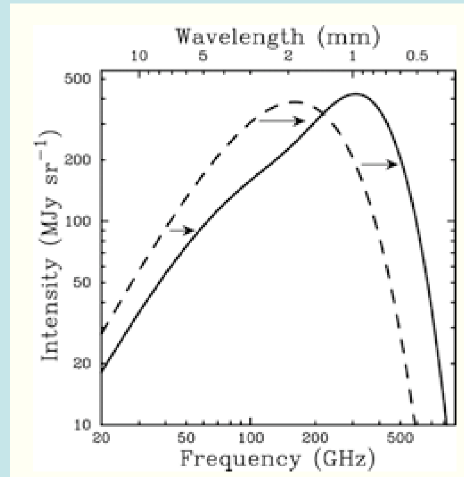


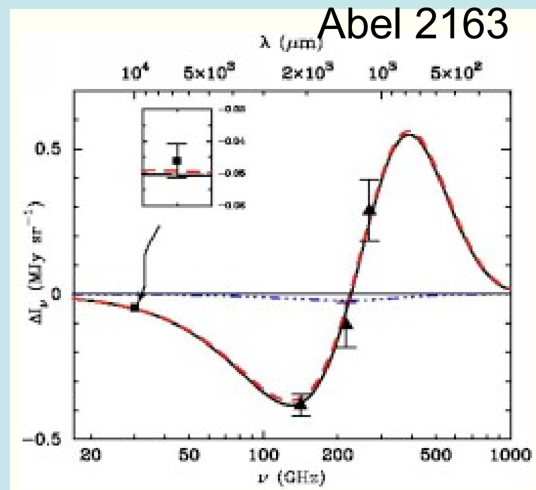


South Pole Telescope (SPT)

4000 deg^2 are shared with SPT.
Started operations in 2007.

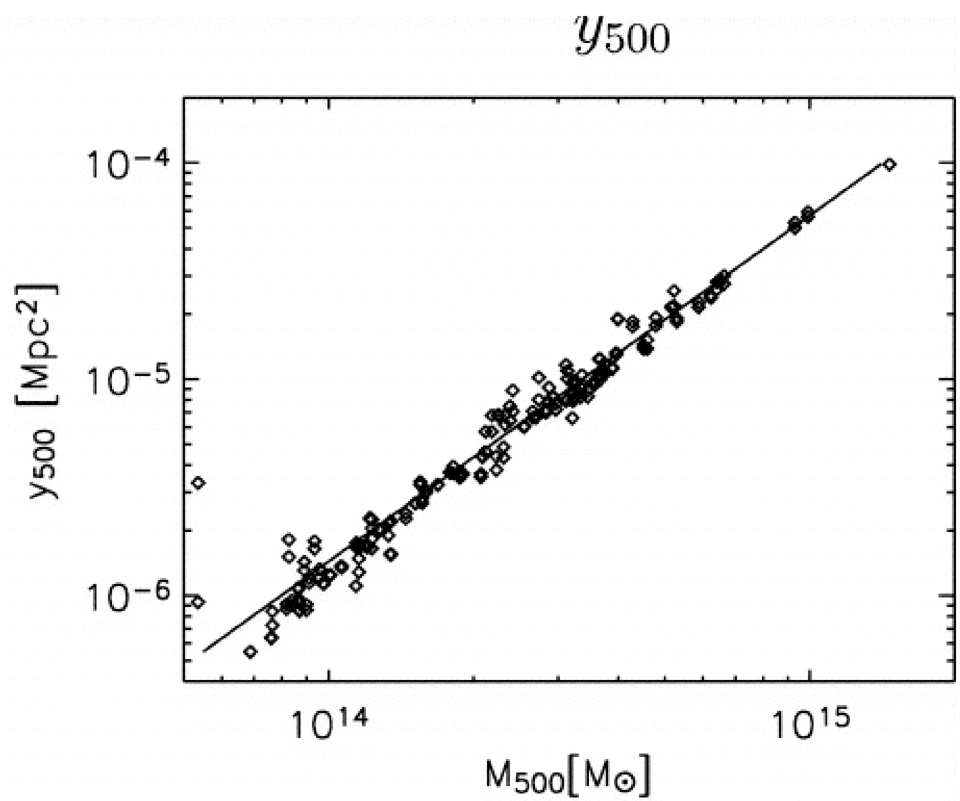
Cluster mass measurements and detections with SPT combined with photo-z from DES produce a powerful sample for cosmology.





http://astro.uchicago.edu/sza/primer.html

Mass obervable from S-Z (model independent)



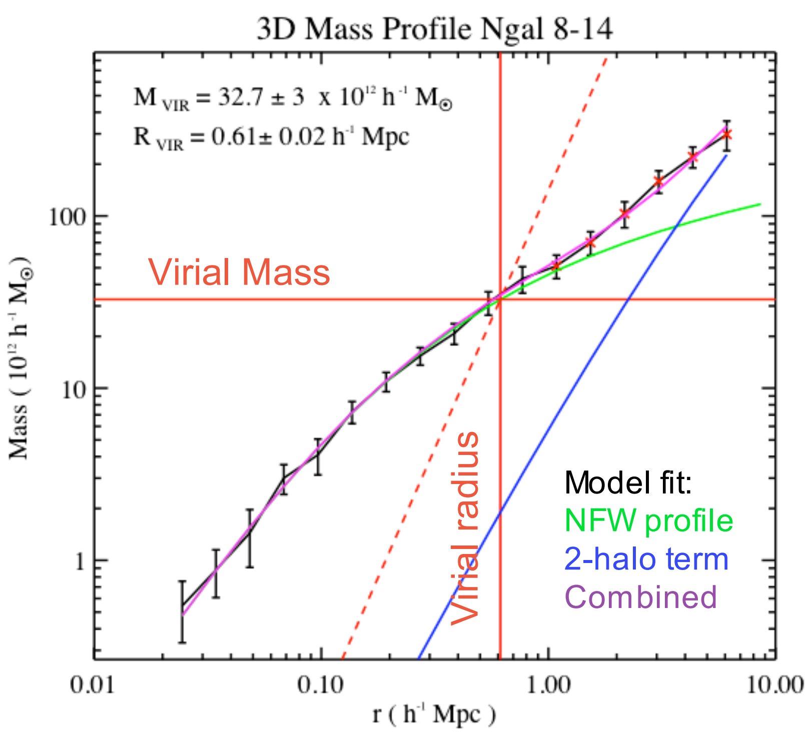
Here a simulation, but can can calibrate with X-rays to understand this.

Scaling relations: SZ- Current simulations suggest a small scatter of order 10% in the SZE flux vs. mass relation within r_{200} and M_{200} (de Silva et al 2004, Motl et al 2005). Observational samples are still small, but investigations have begun, for example Benson et al (2005), LaRoque et al (2005). The SZA cluster survey, coupled with high-resolution simulations, will enable us to measure the shape, evolution, and scatter in this relation with higher precision.

DARK ENERGY SURVEY

How to measure the mass-observable relation?

- Weak lensing measurements of the cluster-mass correlation function calibrate the mass-observable relation

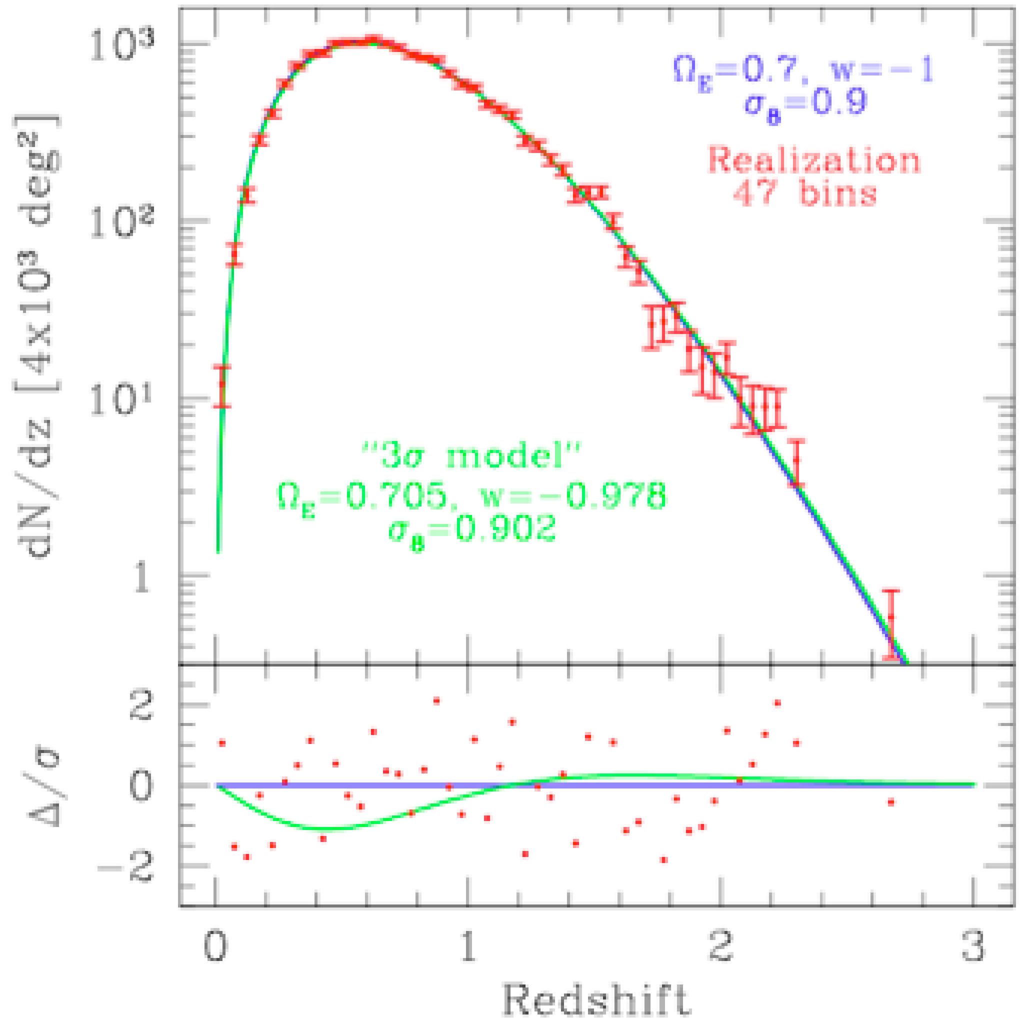


- The cluster-mass correlation function can be non-parametrically inverted to obtain the mass profile (Johnston et al. 2006)
- Key feature: the same data used to detect the clusters is used for the lensing measurements
- Profiles provide tests of halo structure and halo clustering

Clusters redshift distribution

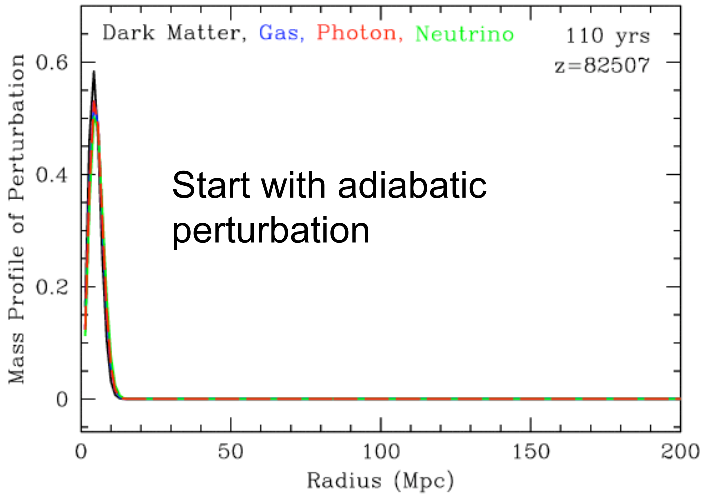
$\Omega_E = 0.7$ $w = -1.0$ $\sigma_8 = 0.9$	$\Omega_E = 0.705$ $w = -0.978$ $\sigma_8 = 0.902$

DES+SPT we can separate these two models with a 3 sigma significance (30% mass resolution).

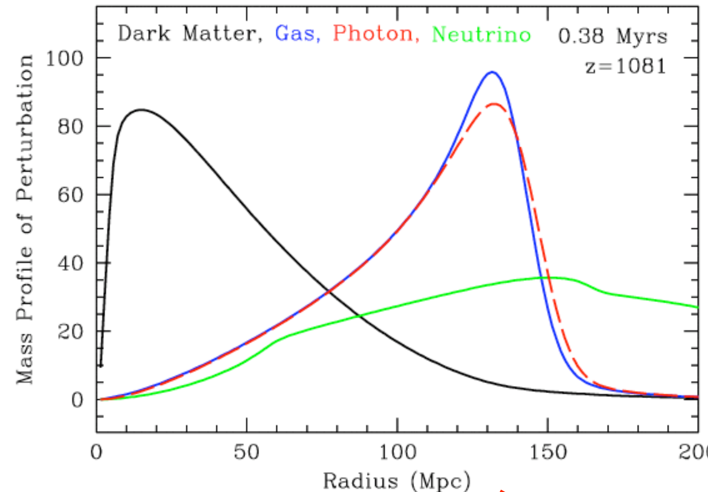


Dark matter clustering (BAO)

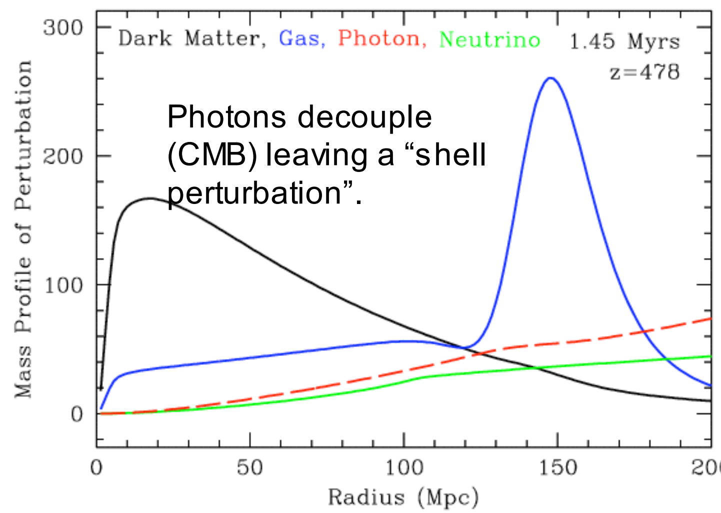
DARK ENERGY SURVEY

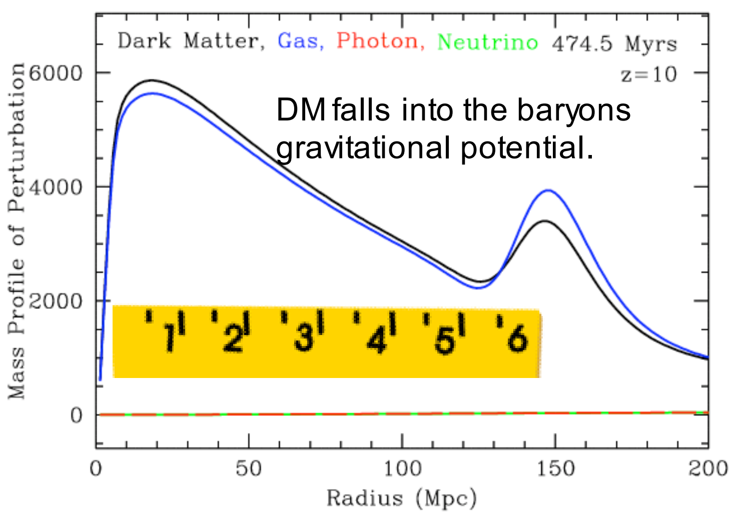


Pressure in photons produces a sound wave, gas follows.



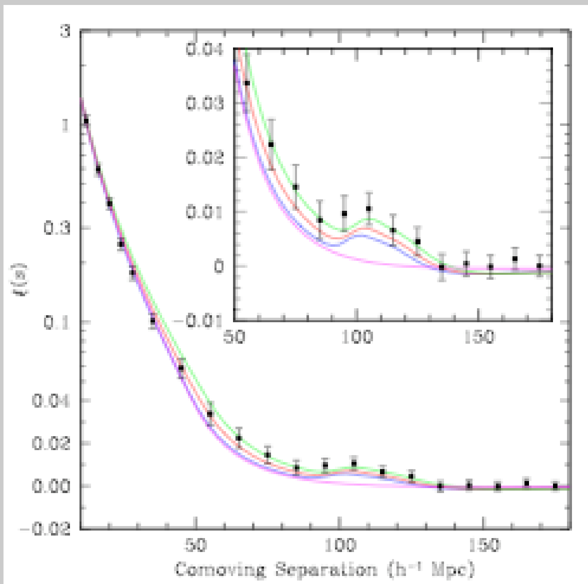
Baryon Acoustic Oscillations imprint the sound horizon scale into the DM distribution. Standard rod.





BAO detected in SDSS galaxies

47k LRGs (SDSS)



Eisenstein et al 2005

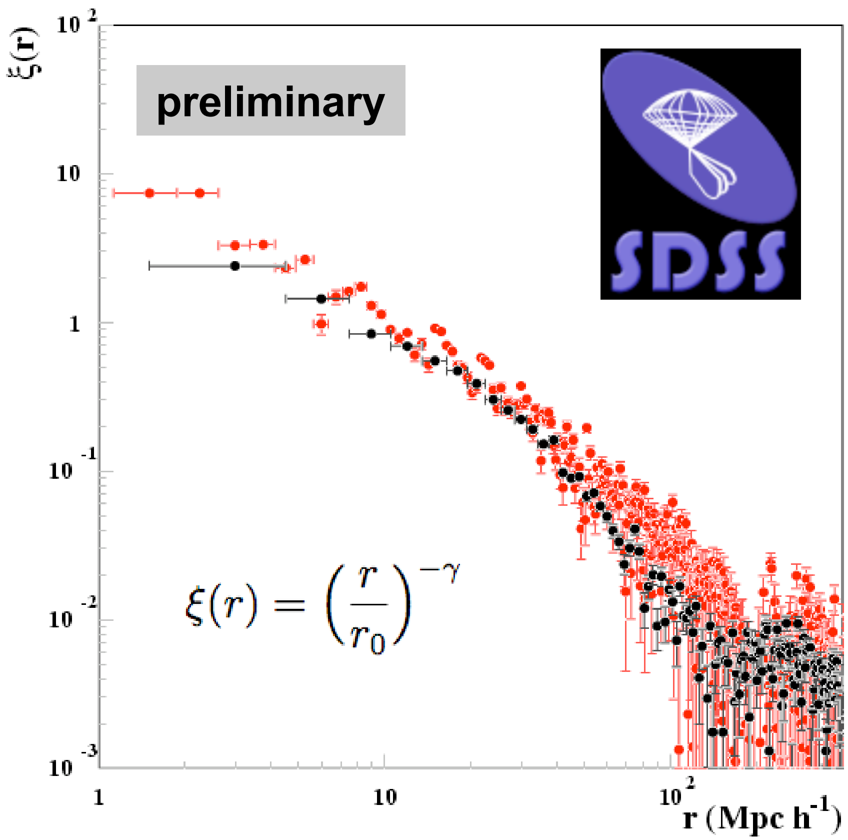
The BAO feature was detected using the sample of SDSS galaxies that have spectra.

We are now trying to see the signal using galaxy clusters without spectra.

Cluster Correlation Function

Measures essentially what is the excess probability of finding a pair of clusters at a distance R compared with a uniform distribution $$\xi(r)+1 = NN(r)/RR(r)$$

(the estimator used is a bit more sophisticated to reduce variance)

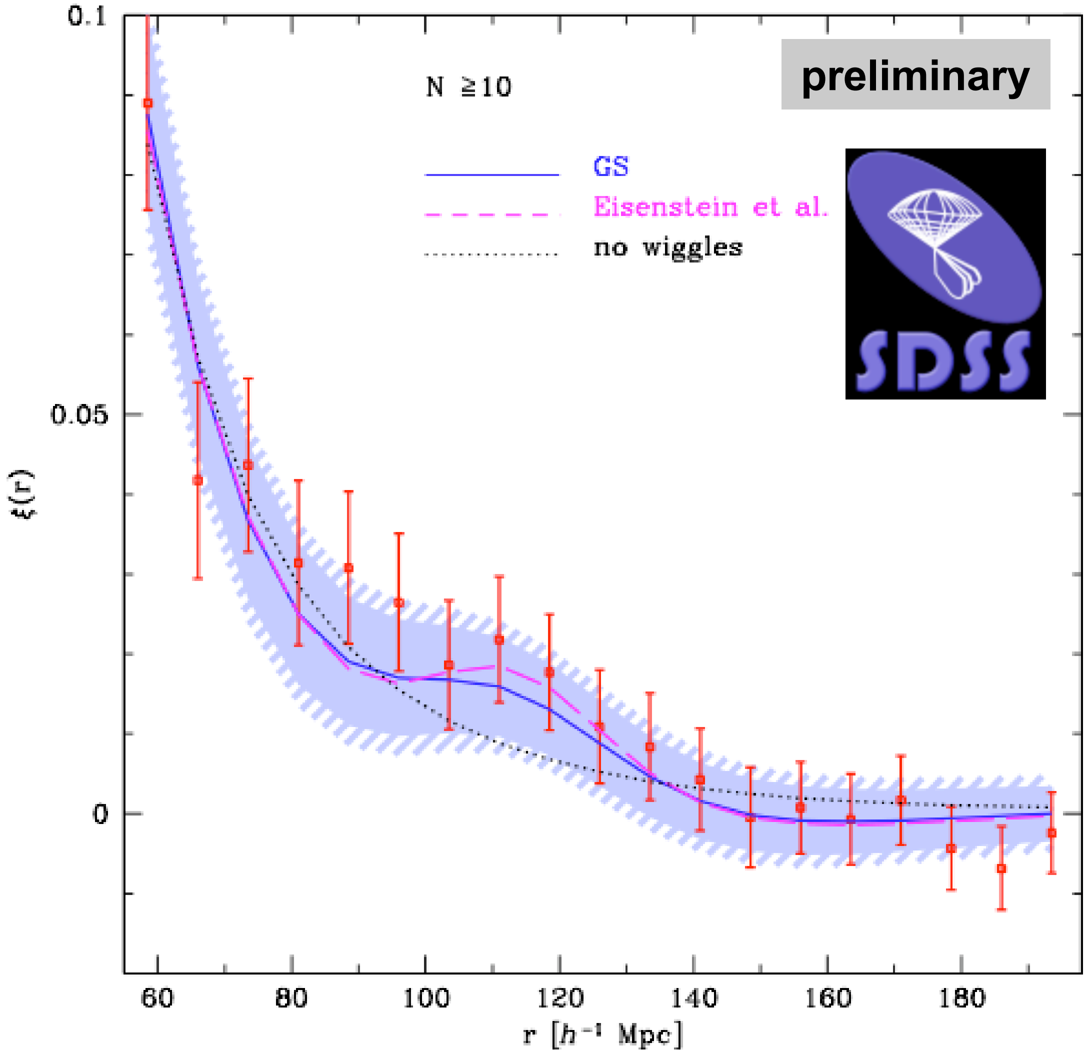


SDSS clusters $N_{gals} \geq 10$

Hubble Volume Simulation
dark matter halo catalog with **$M>10^{14}M_\odot$** approximately correct for $N_{gals} \geq 10$.

r_0= 11.8 Mpc/h γ= 1.52

BAO in Clusters Correlation Function



N_{gals} cut	N	r_o	γ	n	s	b	χ^2_{BAO}	χ^2_{nw}
10	13823	10.2	1.4	2.77	0.95	3.7	8.6	11.6
13	12519	10.8	1.4	2.51	0.95	3.8	7.4	11.6
15	7597	12.5	1.5	1.52	0.92	3.8	6.7	9.7
21	2766	17.3	1.7	0.59	0.92	3.9	4.9	5.9

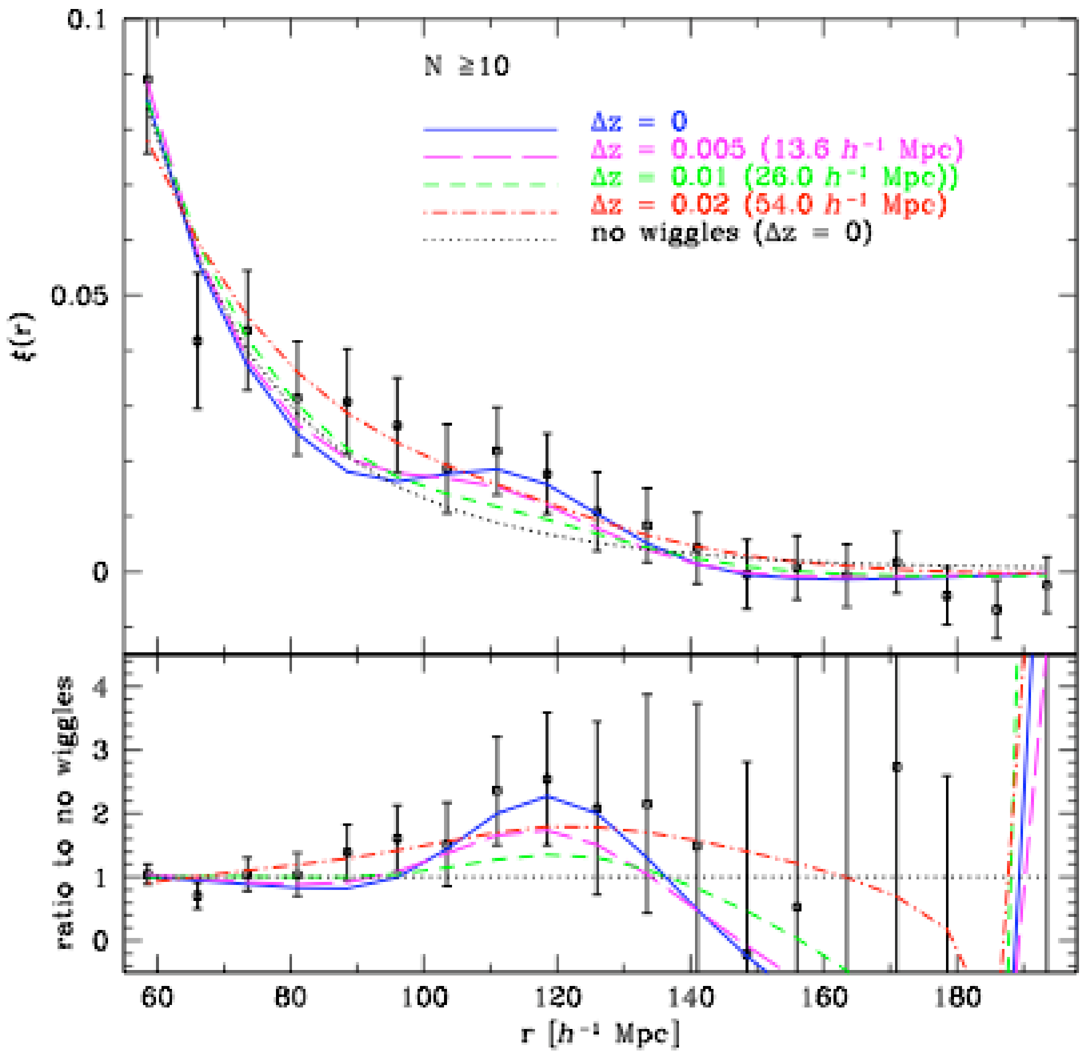
The position of the peak is a cosmological probe. Not used here yet. Currently working in modeling the photo-z error.

2 important aspects:

•First detection of BAO in clusters.
•Shows that we can do this with photo-z.

J. E., E. Sefusatti et al, in preparation

BAO and photo-z error



J. E., E. Sefusatti et al, in preparation

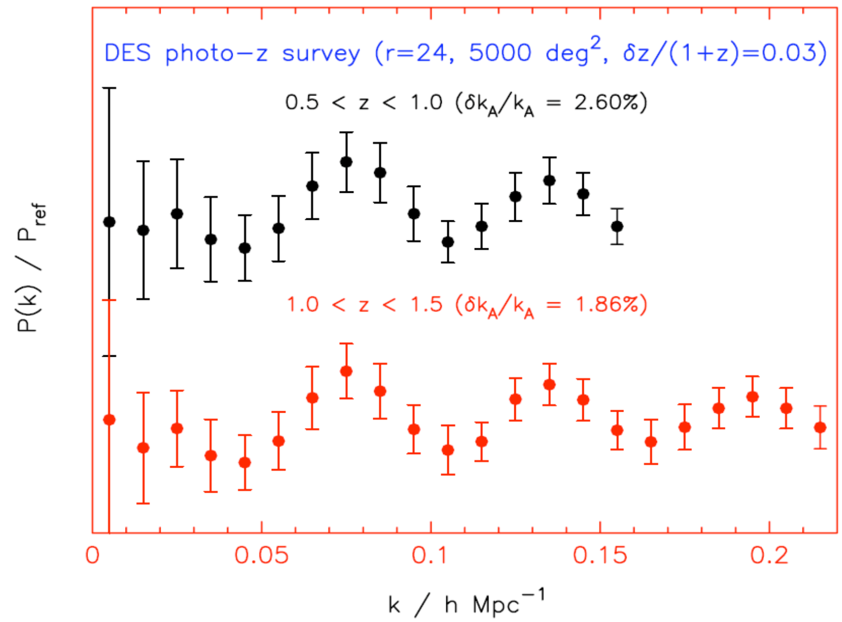
Correlation of galaxies and BAO

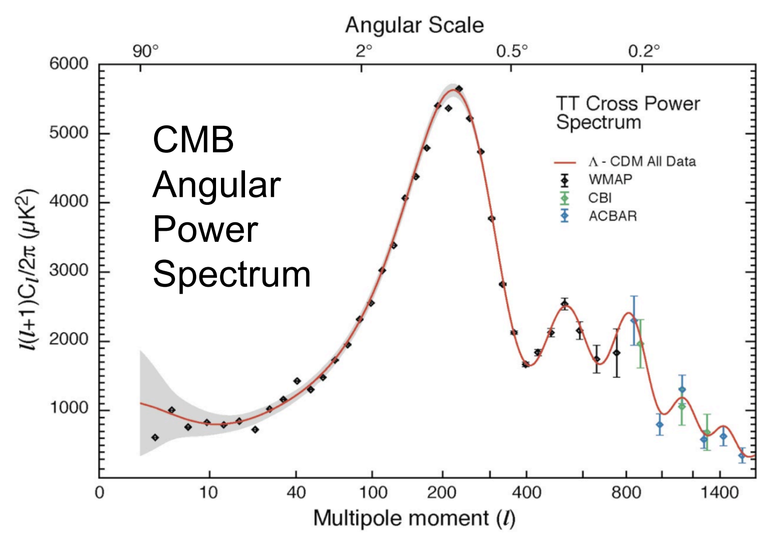
300 million galaxies extending beyond a redshift z~1.

Evolution of structure:
Start with primordial P(k) ∝ k^n (inflation) transfer function maps the primordial spectrum to what we get now. Modes with a scale that enters the horizon before a_{eq} decay. BAO will also leave an imprint at the horizon scale.

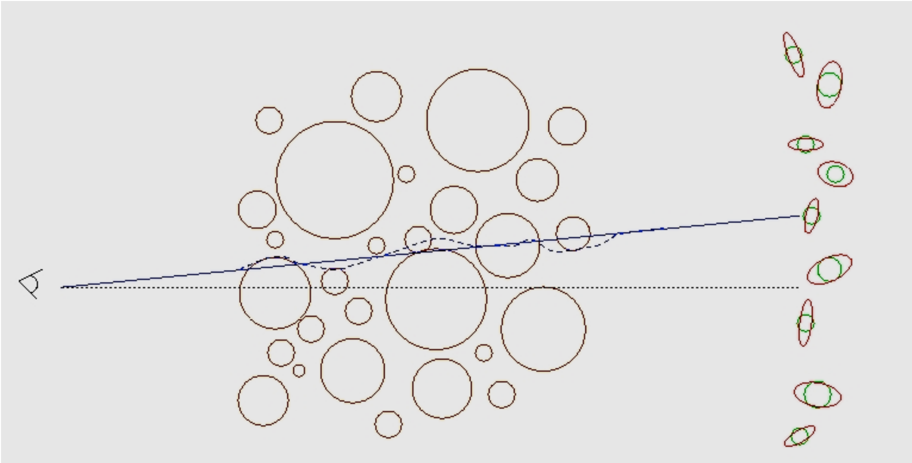
Power spectrum: measure the BAO scale as a function of redshift as a standard rod (geometrical probe).

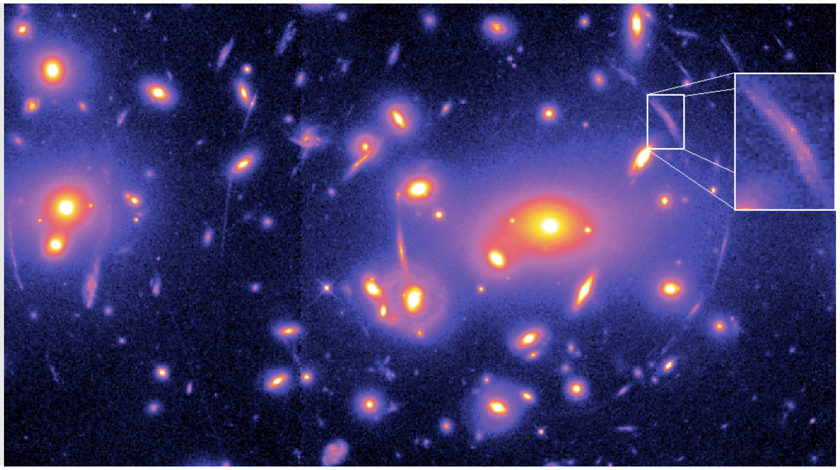
Simulations show that we can do this with a photo-z survey.





Weak Lensing





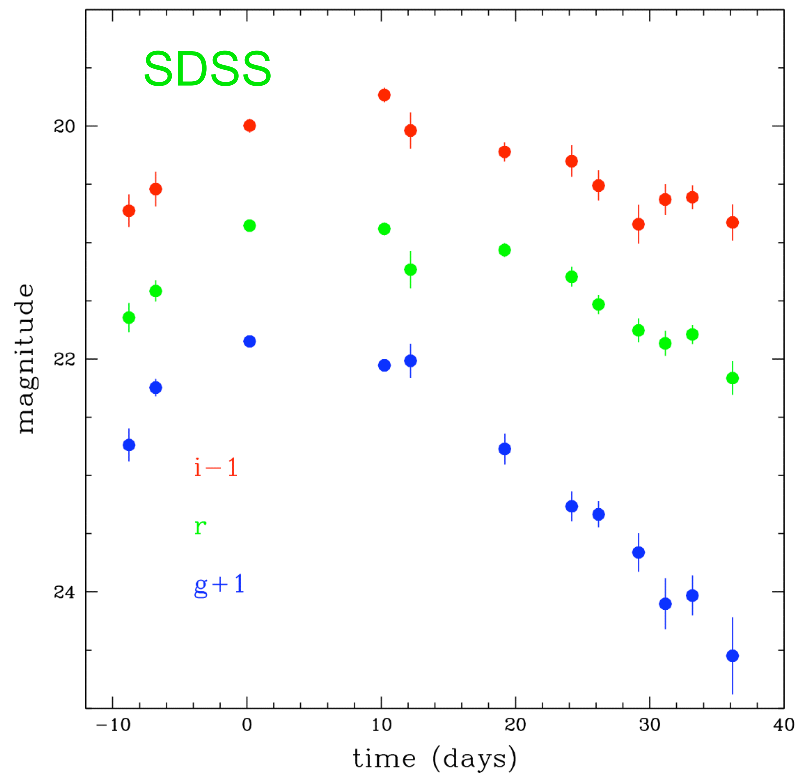
Measure shapes for ~300 million source galaxies with ⟨z⟩ = 0.7 Direct measure of the distribution of mass in the universe, as opposed to the distribution of light as in other methods (eg. Galaxy surveys). Independently calibrates SZ cluster masses.

- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on **geometry** of Universe
- Foreground mass distribution depends on **growth of structure**

SN Ia

Baseline: repeat observations of 9 deg^2 using 10% of survey time: 5 visits per lunation in *riz*

- **~1100-1400 well-measured SN Ia light curves to z~1. (standard candles for geometrical probe)**
- Benefits from improved *z*-band response (fully depleted CCDs)
- Spectroscopic follow-up of large SN subsample+host galaxies (LBT, Magellan, Gemini, Keck, VLT,…)



No spectra for most of the sample.

Rely on Light curves measured with SDSS filters.

Forecast

<u>Assumptions:</u>

Clusters:

σ_8=0.75, z_{max}=1.5,
WL mass calibration

BAO: ℓ_{max}=300

WL: ℓ_{max}=1000

(no bispectrum)

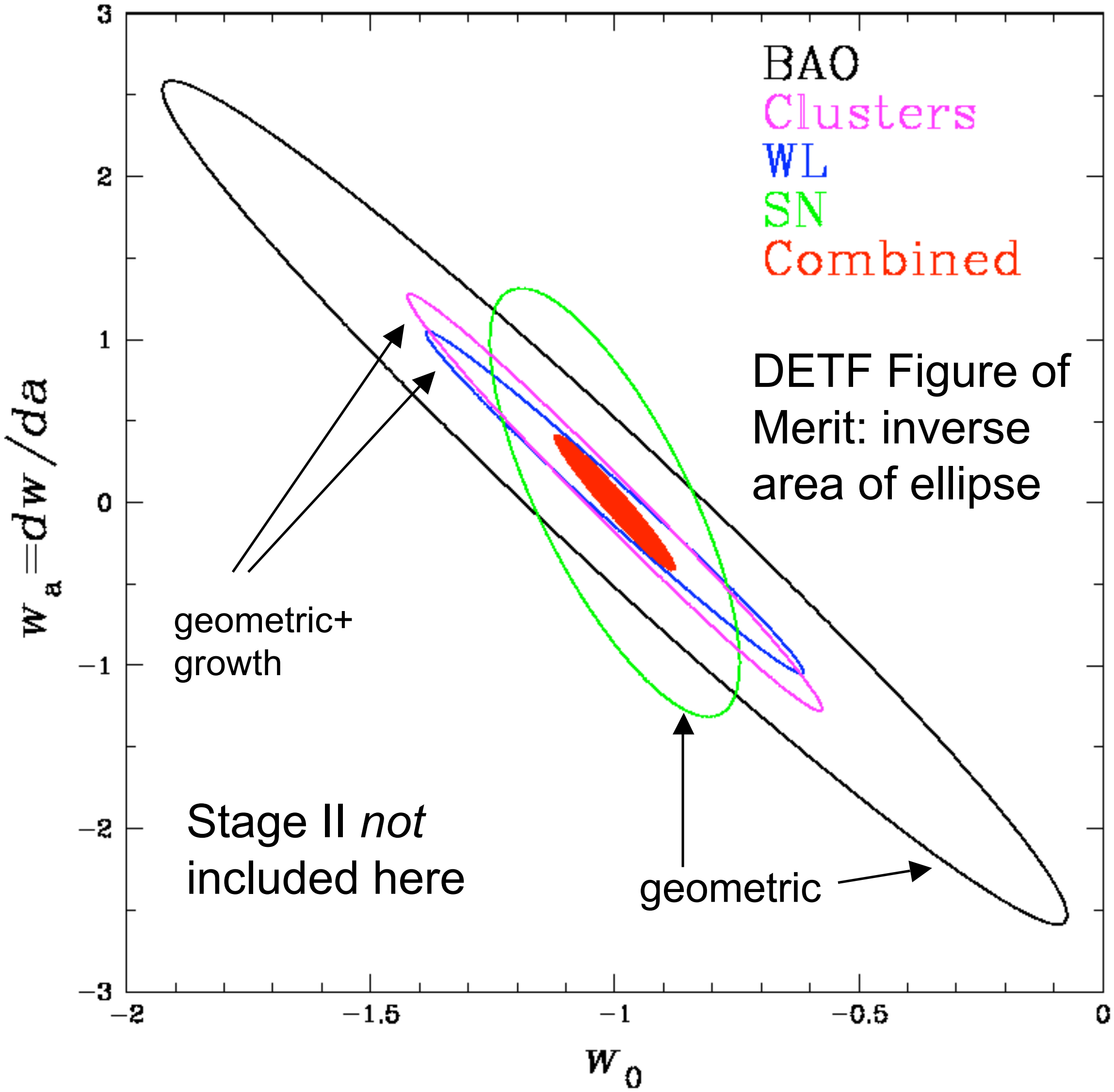
Statistical+photo-z systematic errors only

Spatial curvature, galaxy bias marginalized, Planck CMB prior

In terms of the DETF:

Factor 4.6 improvement over Stage II

$w(z) = w_0 + w_a(1-a)$ 68% CL



Conclusion

- DES has recently been recommended for CD1 approval (DOE step to become a real project as opposed to general R&D).
- Combination with SPT gives a great advantage in reducing the systematics for cluster physics (also VISTA).
- Expect very interesting results from this experiment starting on 2012.

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	$[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.