THE DARK ENERGY CAMERA INTEGRATION TESTS ON TELESCOPE SIMULATOR

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on behalf of the Dark Energy Survey collaboration

TIPP 2011 ◆ Chicago, June 13 2011

OUTLINE

Dark Energy is a crisis in fundamental physics

The Dark Energy Survey 'counter-crisis' approach

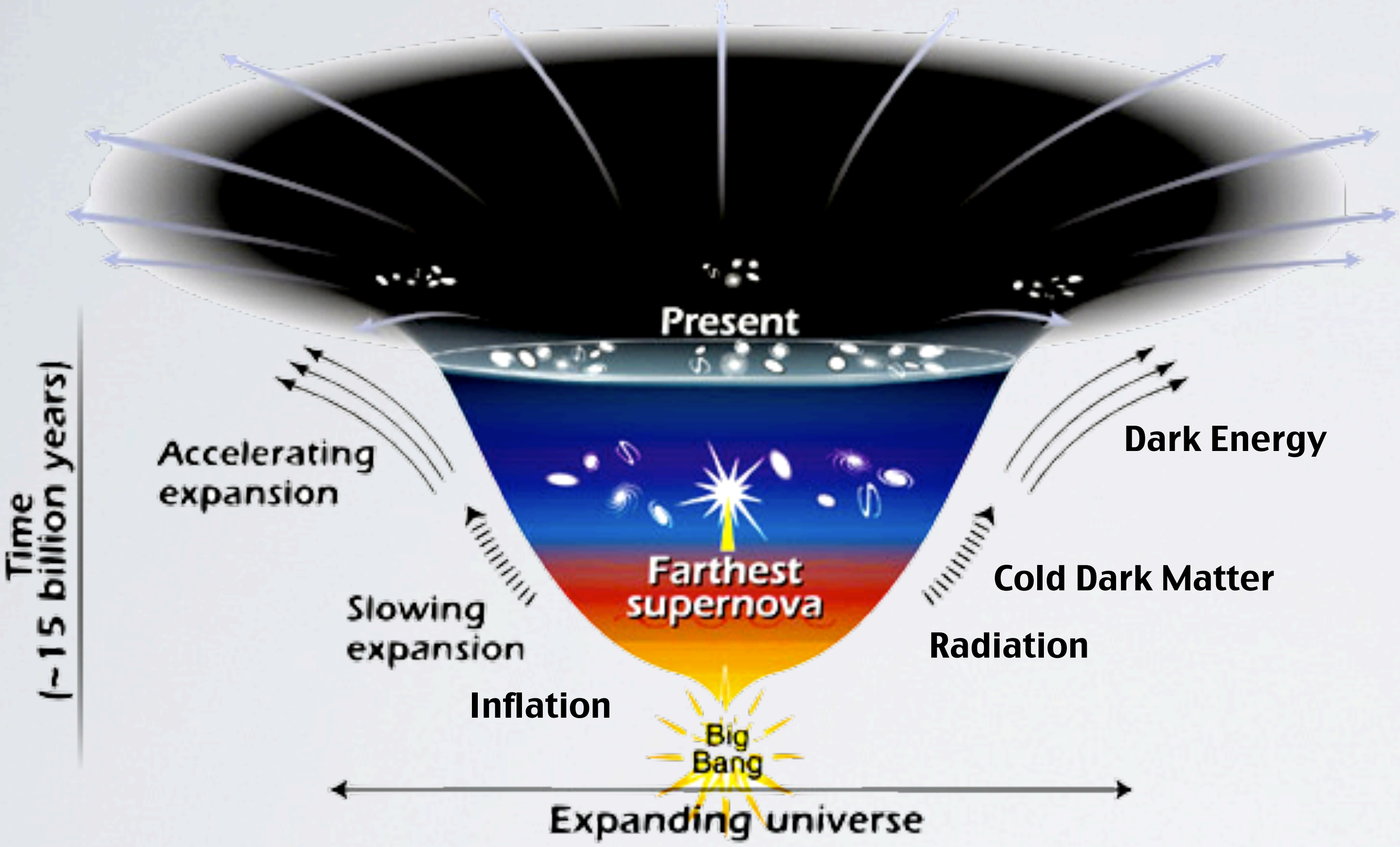
DES new instrument: the Dark Energy Camera

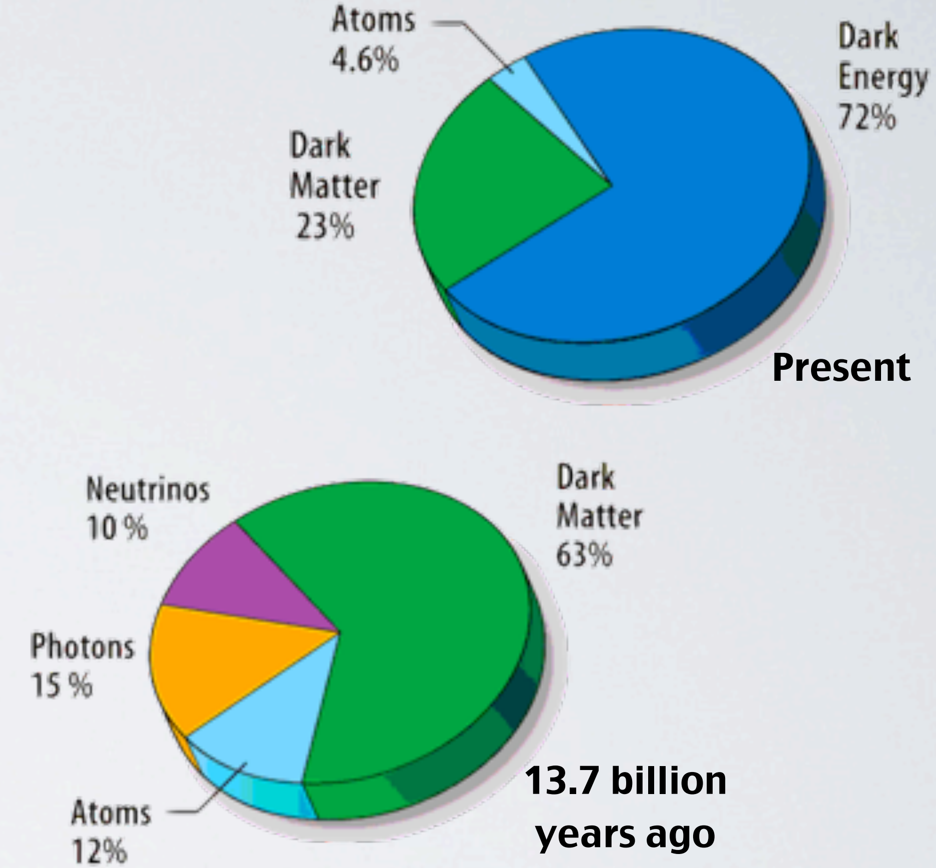
Telescope simulator tests for DECam

Telescope simulator integration tests: results & impact

DARK ENERGY IS A CRISIS IN FUNDAMENTAL PHYSICS

DARK ENERGY & ACCELERATED EXPANSION





$$\ddot{a}/a = -(3p + \rho)$$

spacetime geometry (scale factor) — energy content (equation of state)

$$p = w(a)\rho$$

This is how well we know Dark Energy today. (Komatsu et al. 2010) ➤➤

$$w_0 = -0.93 \pm 0.12$$
$$w_1 = +0.38 \pm 0.65$$
$$\Omega_\Lambda = 0.72 \pm 0.02$$

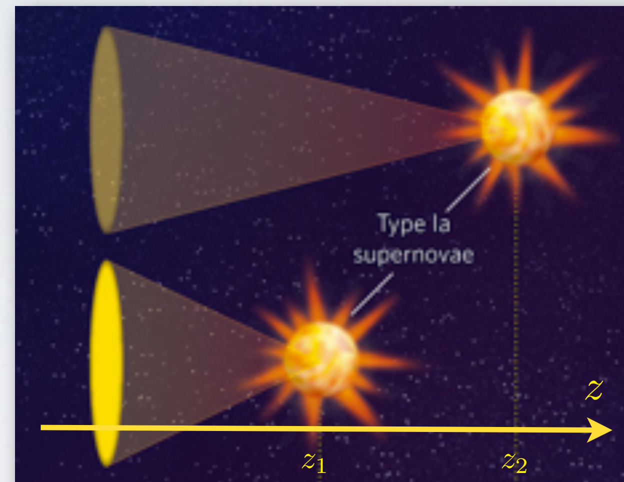
THE DARK ENERGY SURVEY 'COUNTER-CRISIS' APPROACH

ASTROPHYSICAL OBSERVABLES

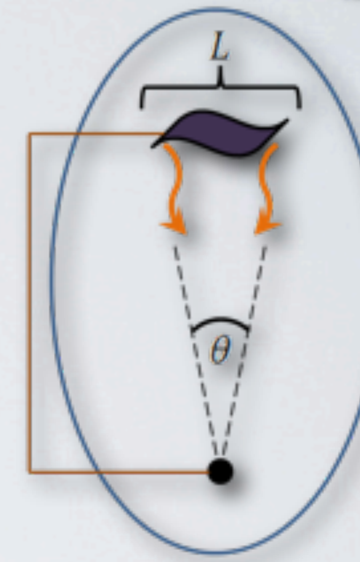
redshift

$$z = \Delta\lambda/\lambda$$

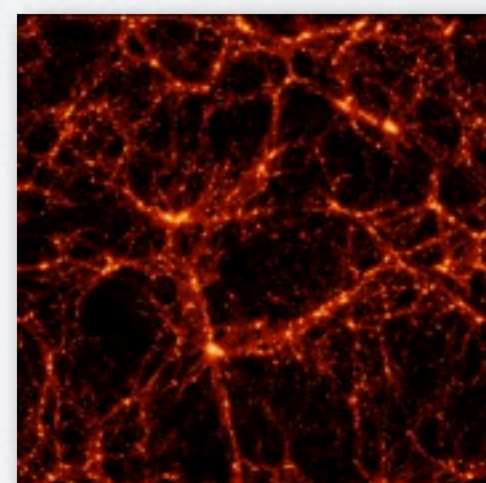
$D_L(z)$ Luminosity distance:
standard candle
1. supernovae (SNe)



$D_A(z)$ Angular diameter distance: **standard ruler**



2. baryon acoustic oscillations (BAO)
3. weak gravitational lensing (WL)
(and also Clusters)



redshift & scale factor

$$a = \frac{1}{1+z}$$

$G(\rho, z)$ Growth of structure:
galaxy clustering
4. galaxy cluster abundance (Clusters)
(but also BAO and WL)

DARK ENERGY SURVEY

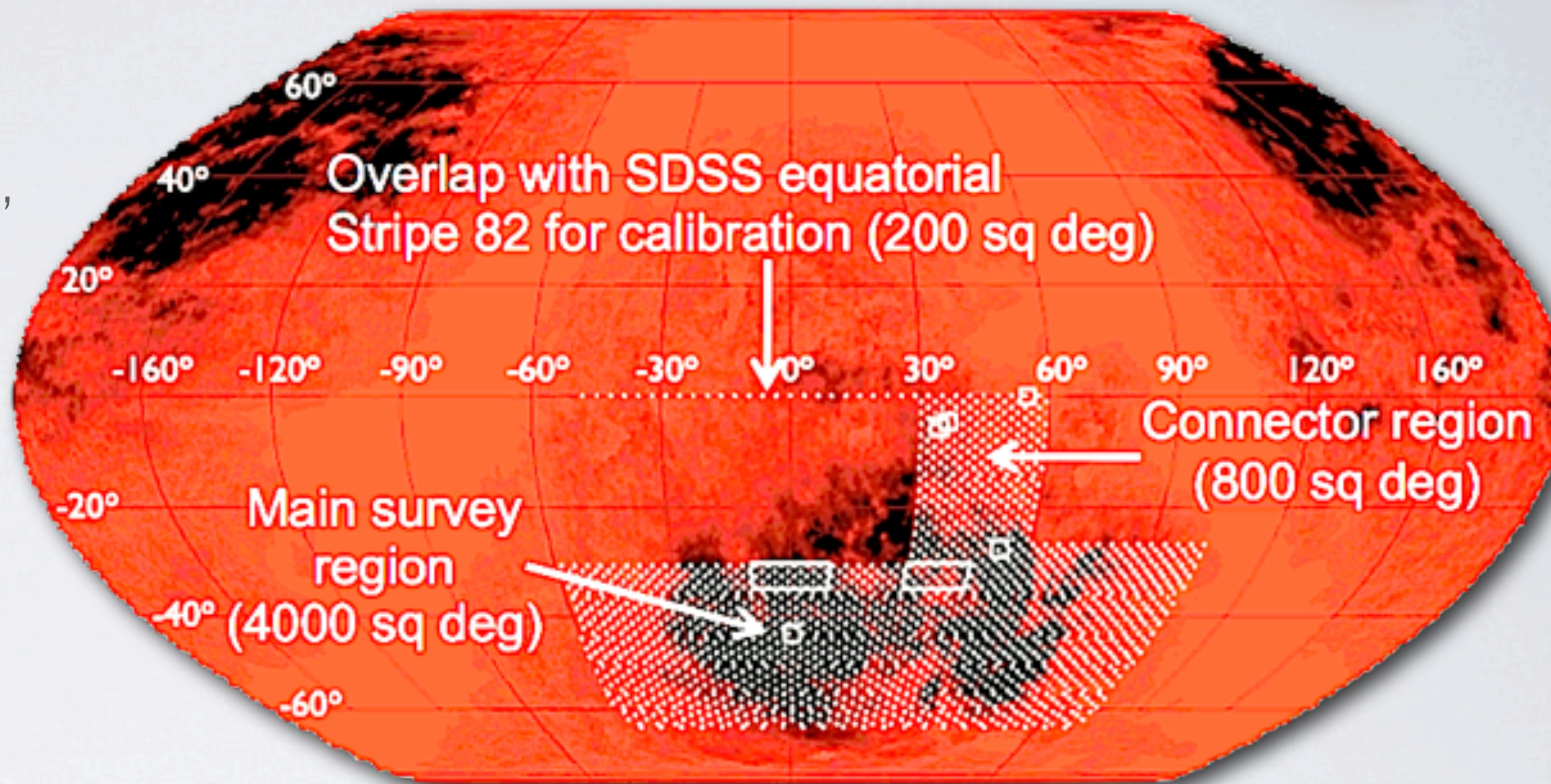
Survey

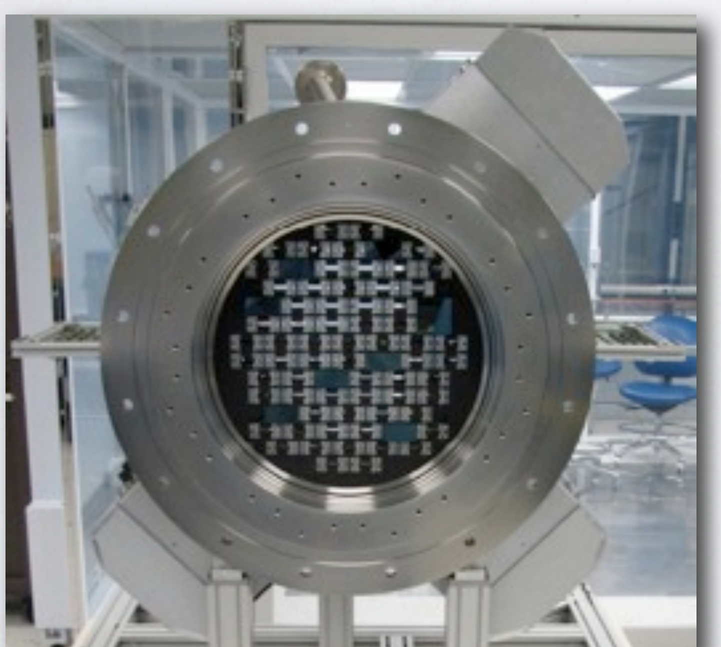
5000 sq deg grizY to 24th magnitude, seeing ~ 0.9 arcsec

30 sq deg repeat (SNe)

525 nights: 2012-2017

Overlap with SPT and VISTA surveys





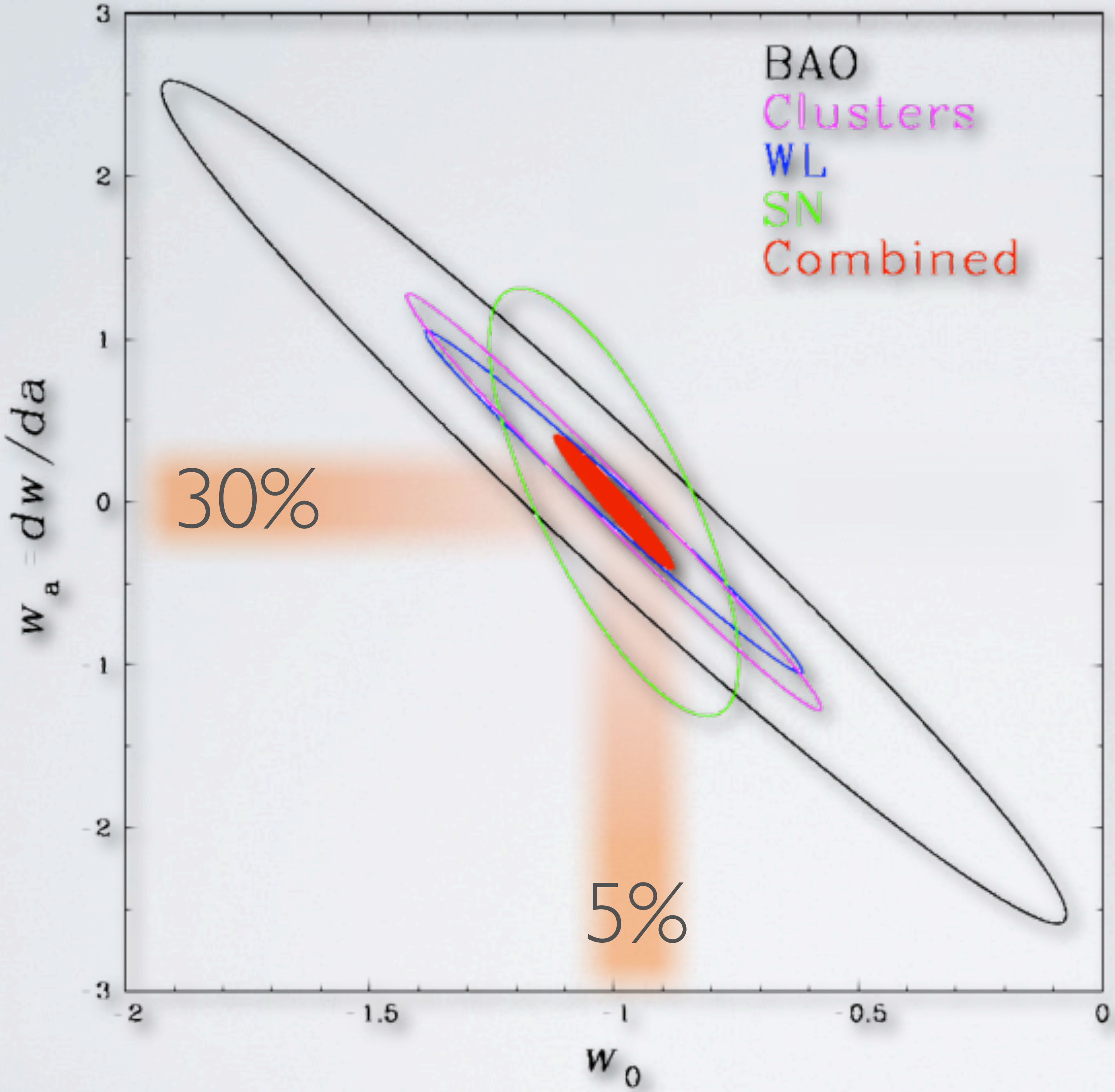
DEcam

3 sq deg FOV, **570 Mpix** optical CCD camera

Facility instrument for **CTIO Blanco 4-m telescope in Chile**

First light: Jan 2012

DES PROJECTED LIMITS



5000 deg^2, 0.9'' seeing, 24th mag (redshift~1.4)

300M galaxies, shapes, 100K clusters, 4K SNe

4 combined probes

3-5x improved Dark Energy measurement

DES TIMELINE

DECam

Oct 2010 - Feb 2011: tests on telescope simulator ➤➤

Mar-Dec 2011: integration, shipping, installation

Jan-Apr 2012: commissioning

mid-2012 onward: available for DES and community

DESpec

Concept for a wide-field spectrograph to follow up DES

Survey

Fall 2010: PRECam survey collected calibration data

2011-2012: Calibration pipeline, survey strategy development

Science

Spring - Summer 2011: Continued development of analysis framework and simulations

Fall 2011: Blind Cosmology Challenge

DES NEW INSTRUMENT: THE DARK ENERGY CAMERA

BLANCO TELESCOPE

DECam will replace the current Mosaic camera on the CTIO 4m telescope in Chile.

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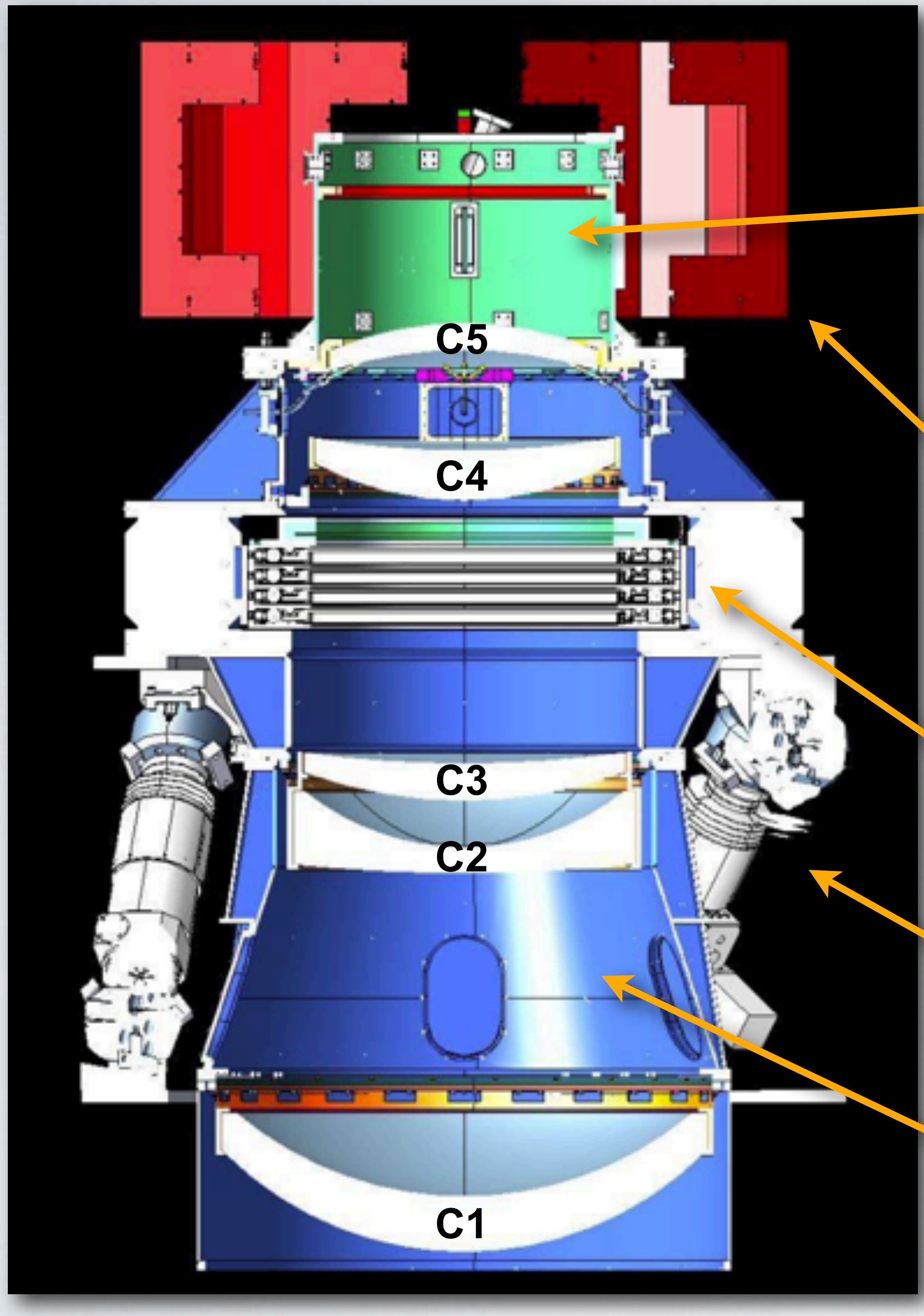
DECAM OVERVIEW



CCD focal plane is housed in a vacuum vessel (**the imager**)

LN2 is pumped from the telescope floor to a heat exchanger in the imager: cools the CCDs to -100 C

CCD readout electronic crates are mounted to the outside of the Imager and are actively cooled to eliminate thermal plumes

Filter changer with 8 filter capacity and **shutter** fit between lenses **C3** and **C4**.

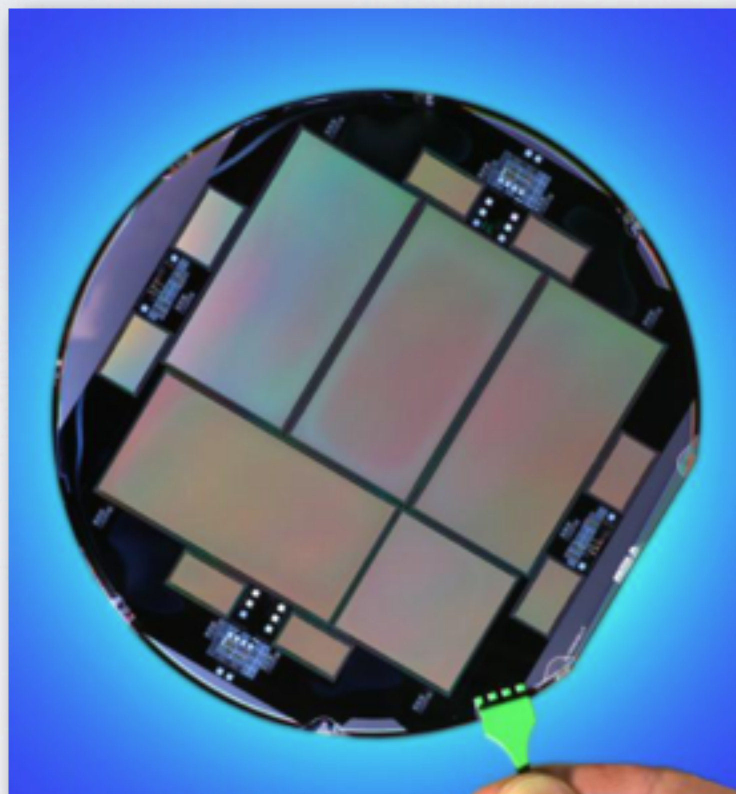
Hexapod provides focus and lateral alignment capability for the corrector-imager system

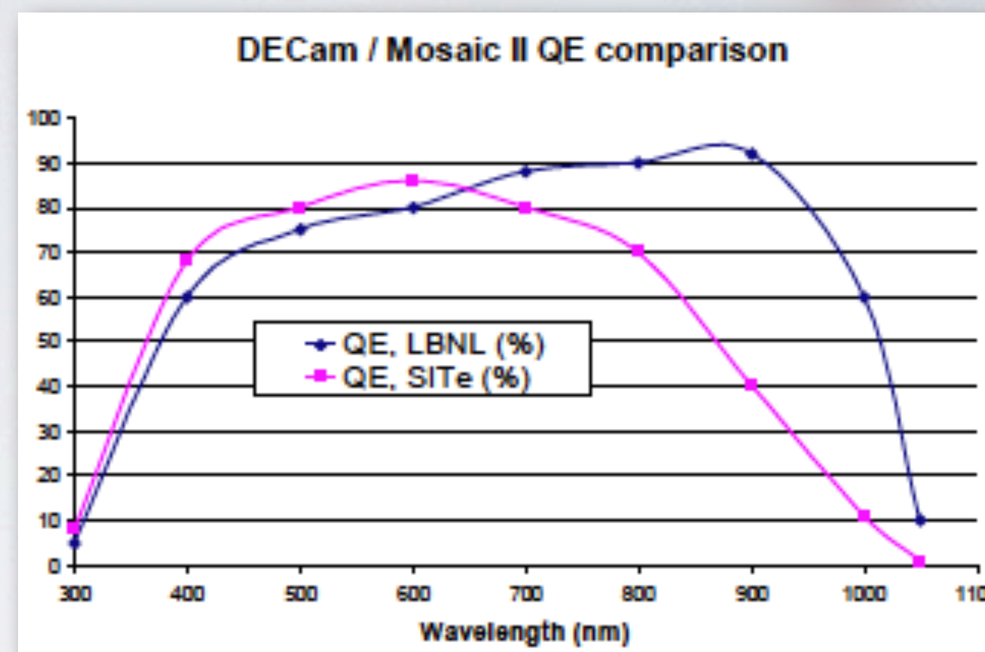
Barrel supports the **5 lenses** and imager

DECAM CCDS

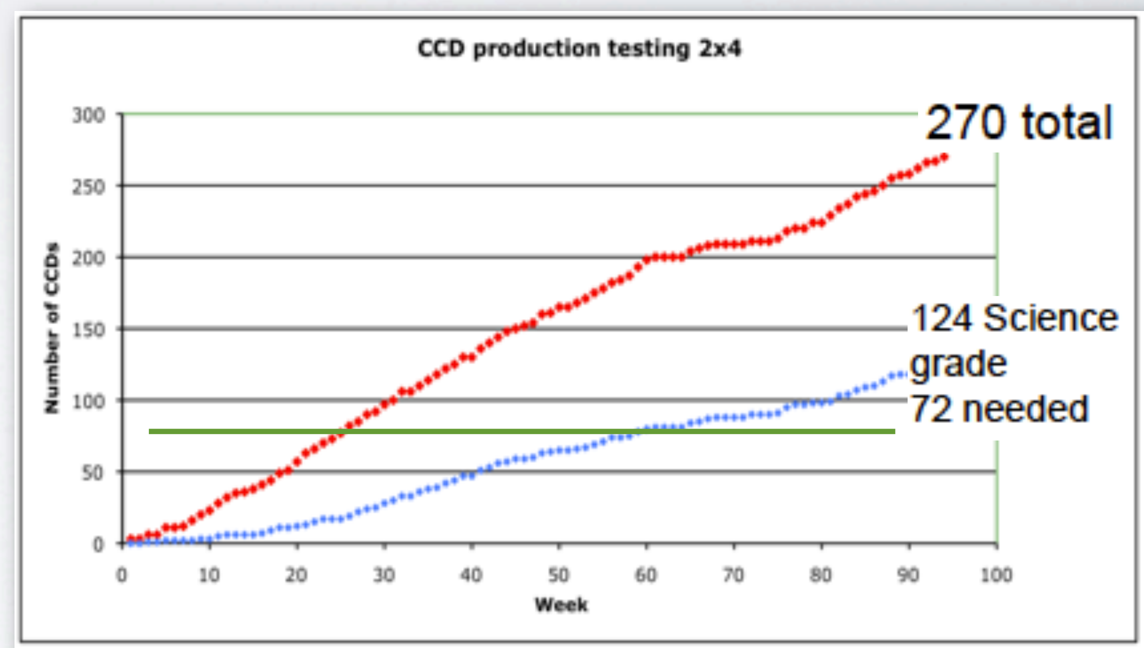
Red Sensitive CCD wafers, designed by LBNL, processed at DALSA and LBNL:

- – QE> 50% at 1000 nm
- – 250 microns thick
- – readout 250 kpix/sec
- – 2 RO channels/device
- – readout time ~17sec





CCDs are packaged and tested at Fermilab.



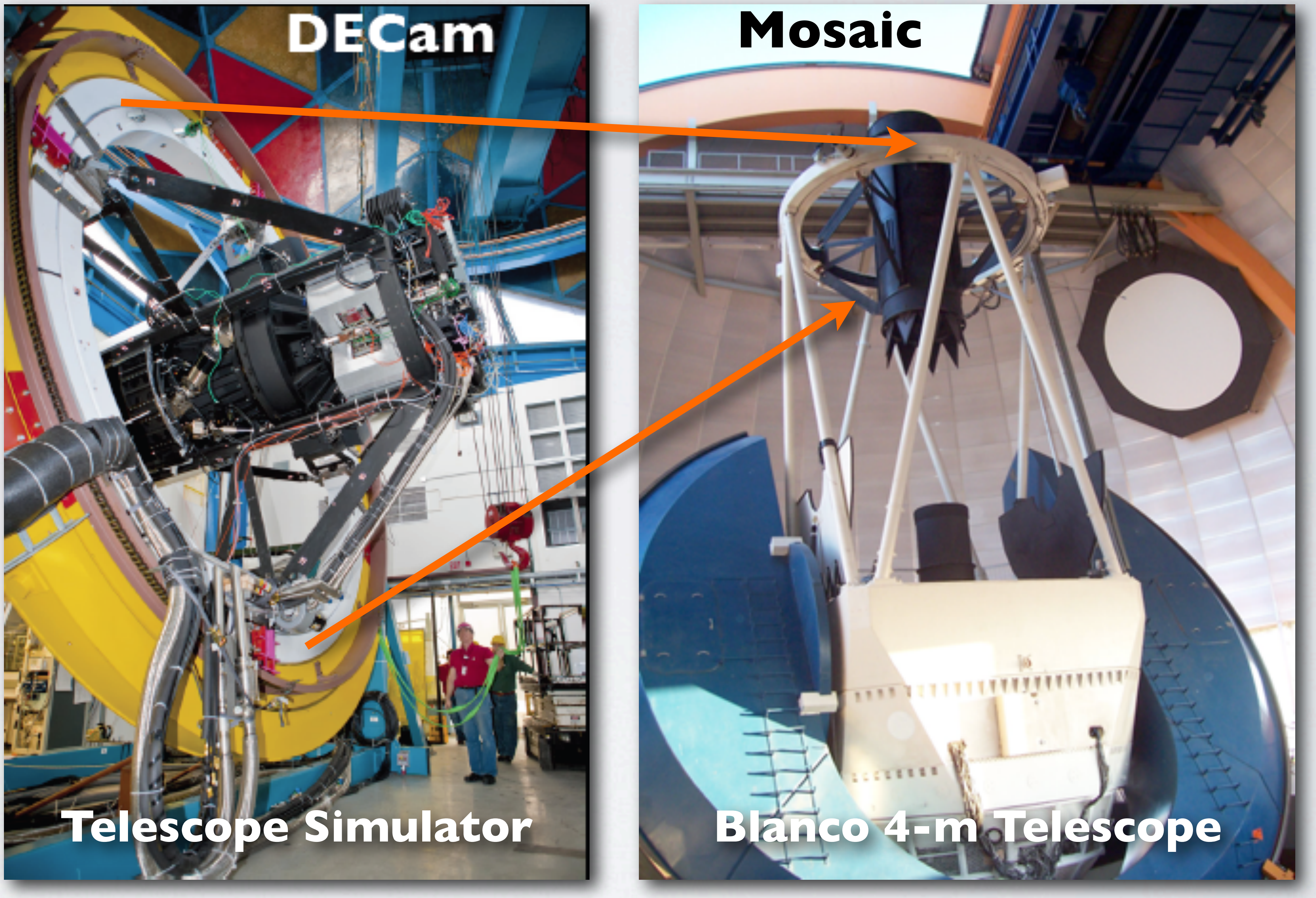
TELESCOPE SIMULATOR TESTS FOR DECAM

DECAM TELESCOPE SIMULATOR AT FERMILAB

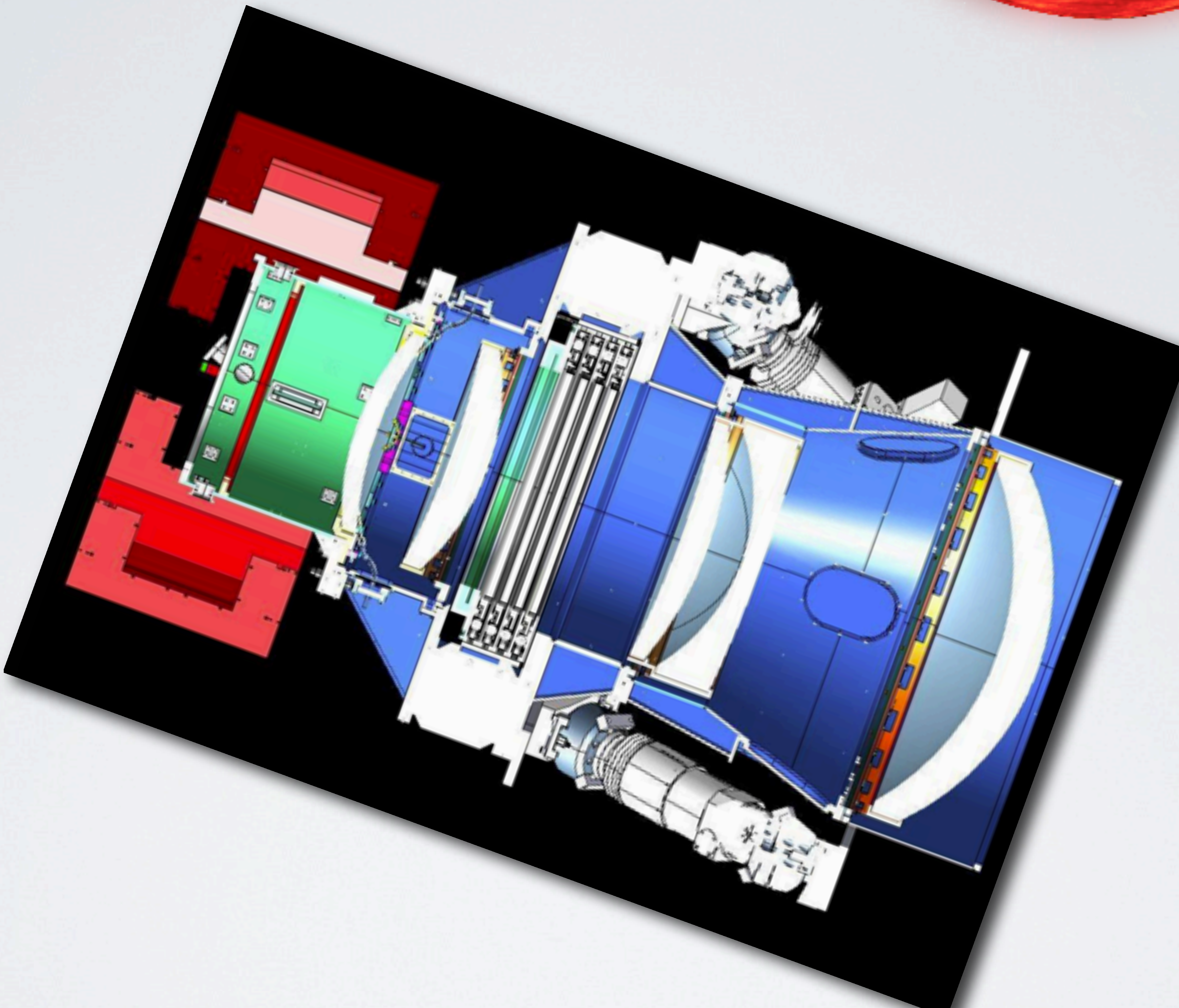
Platform for testing **DECam** operations and installation procedures prior to shipping to Chile.

Full system tests, including a **mock observing run**.

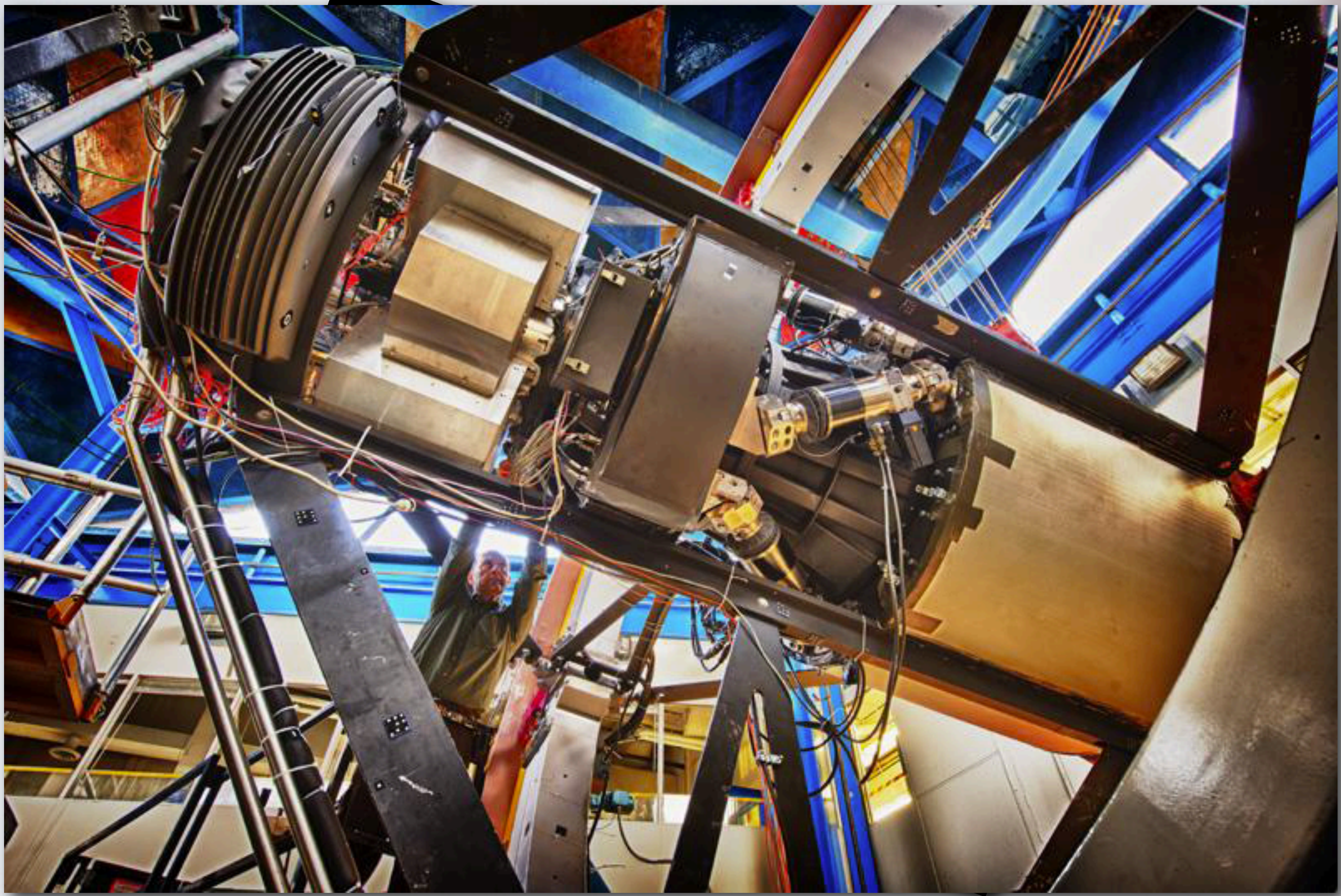
Imager with 24 CCDs, filter changer, shutter, hexapod, LN2 cooling, CCD readout crates.



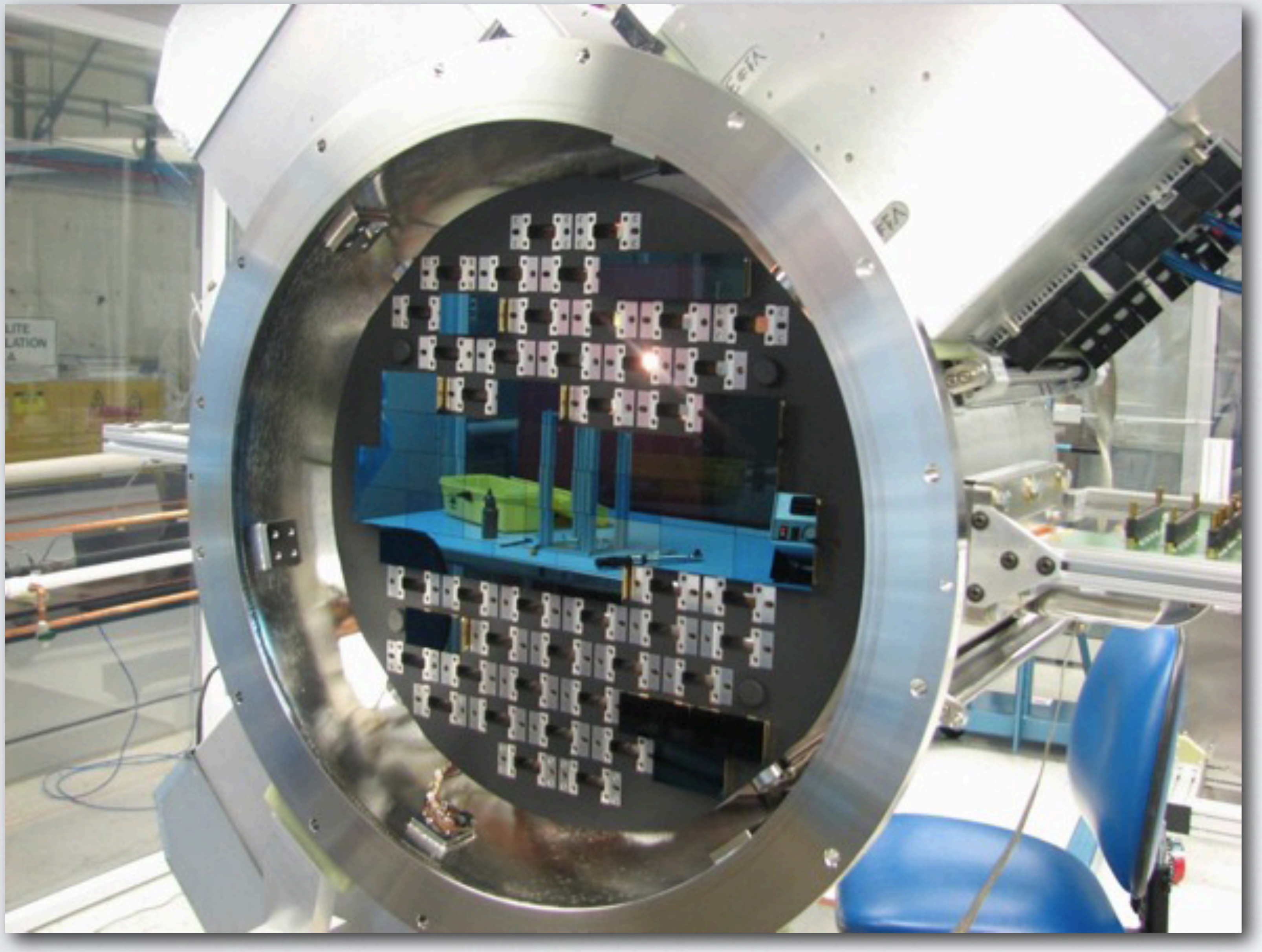
DECAM OVERVIEW



DECAM OVERVIEW



FOCAL PLANE VIEW



CCDs installed:

21 2k x 4k

3 2k x 2k (guider, focus)

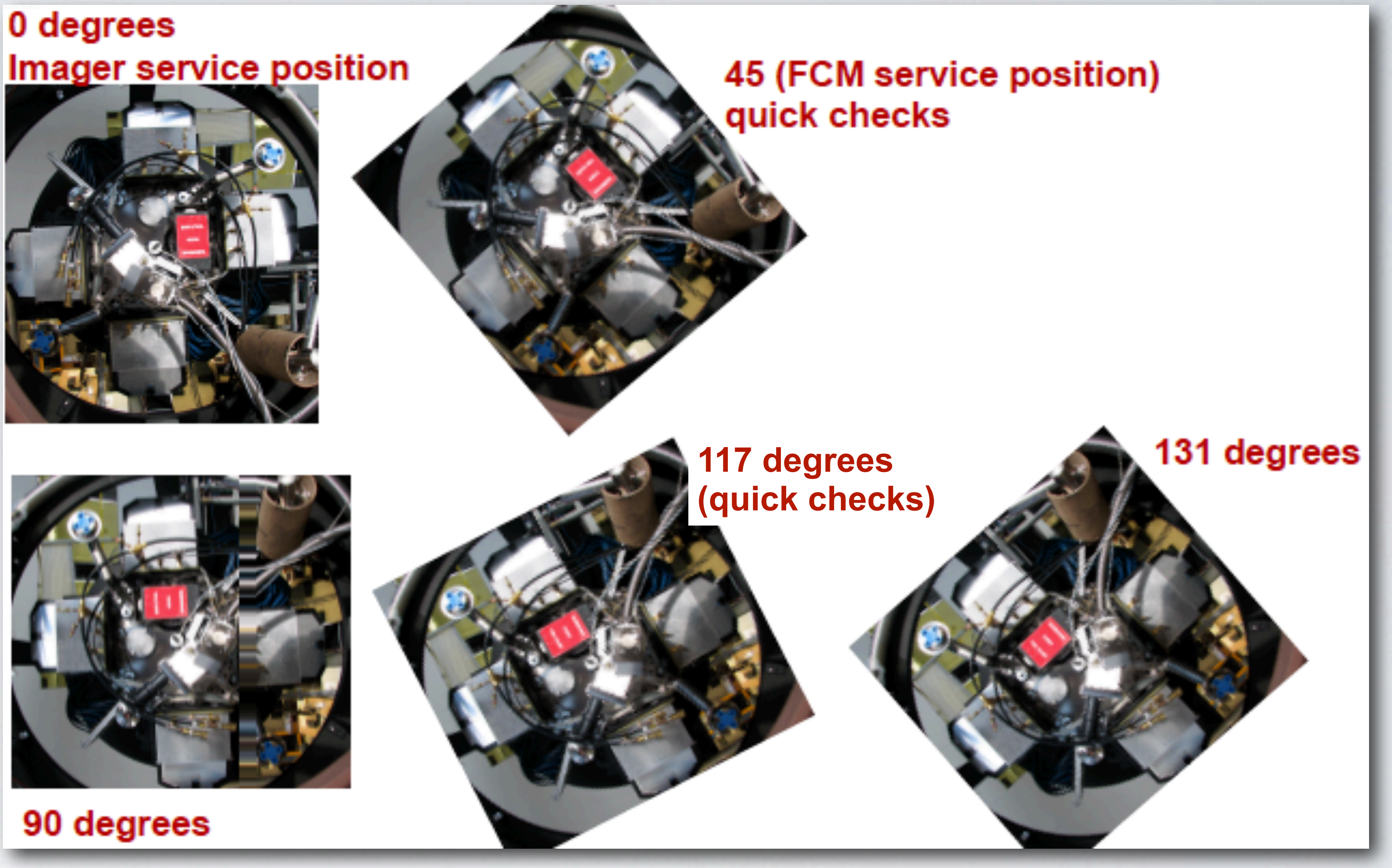
POSITIONS VISITED

full measurements at 0,90 and 131 degrees:

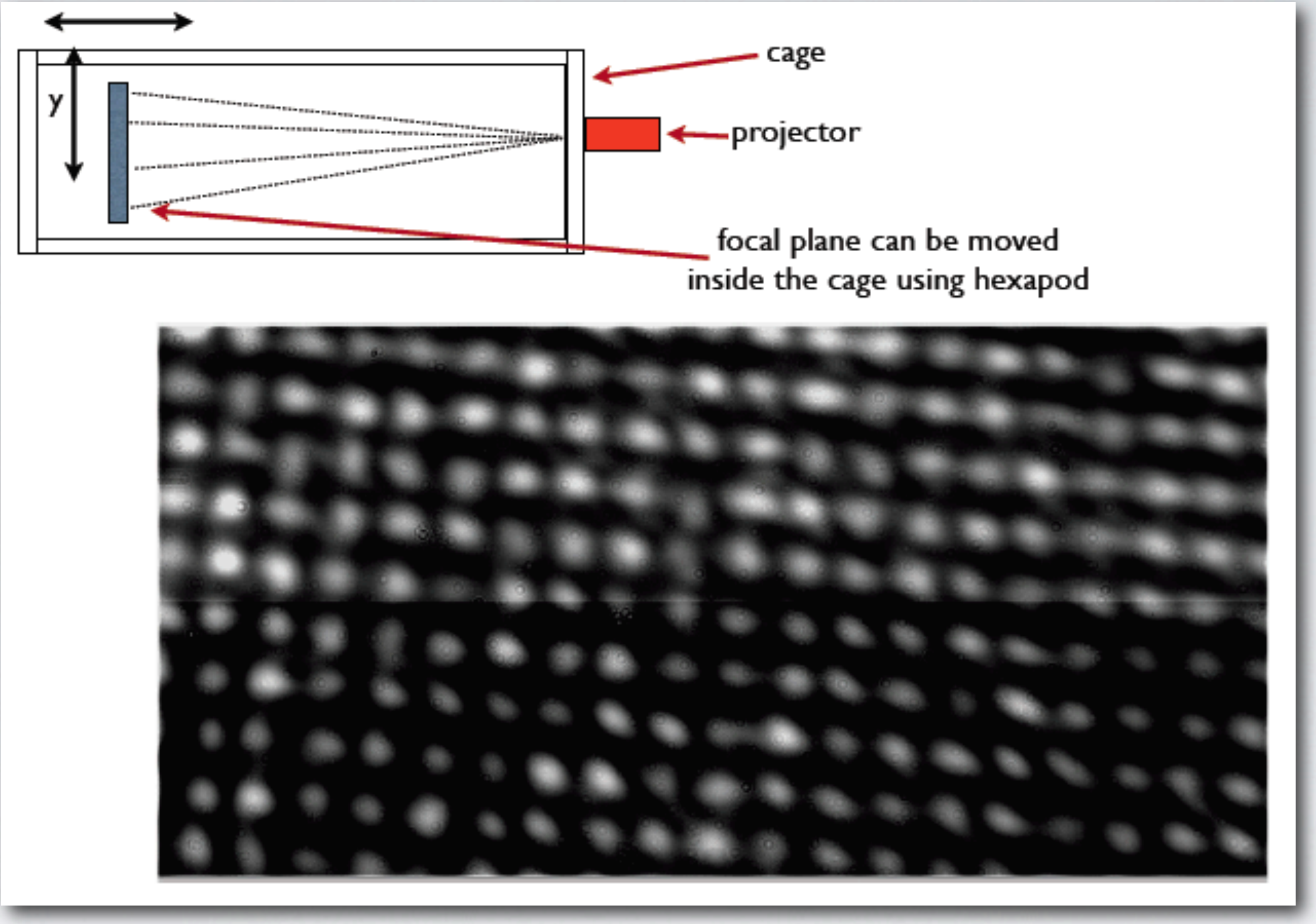
– filter reposition test
– photon transfer curve for shutter linearity test and noise
– hexapod x,y,z movement
– hexapod tilt movement
– about 2 days at each angle

quick checks at 45 and 117 degrees:

– quick check of projection system through the filter
– about 30 minutes in each angle

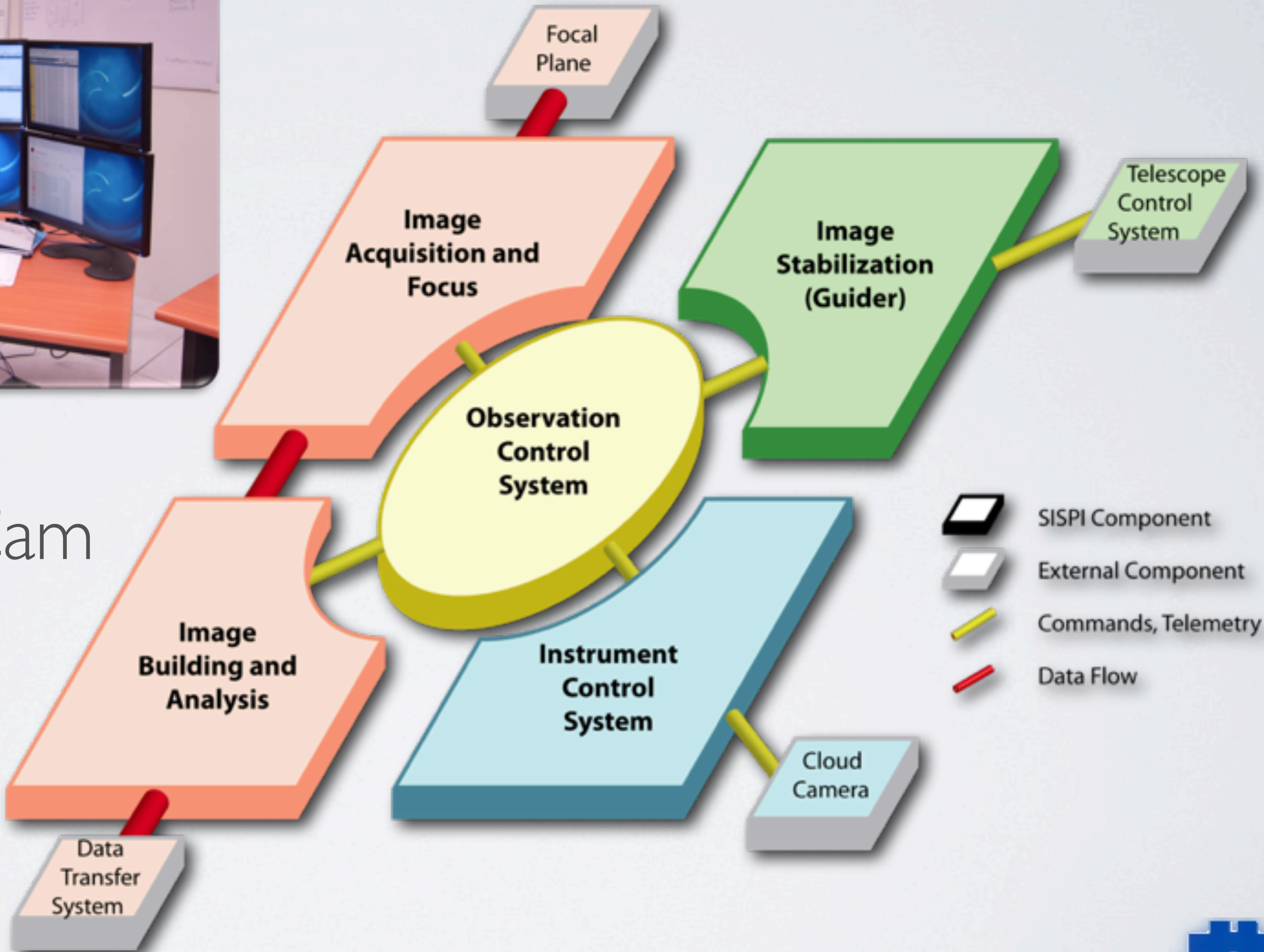


STAR PROJECTOR

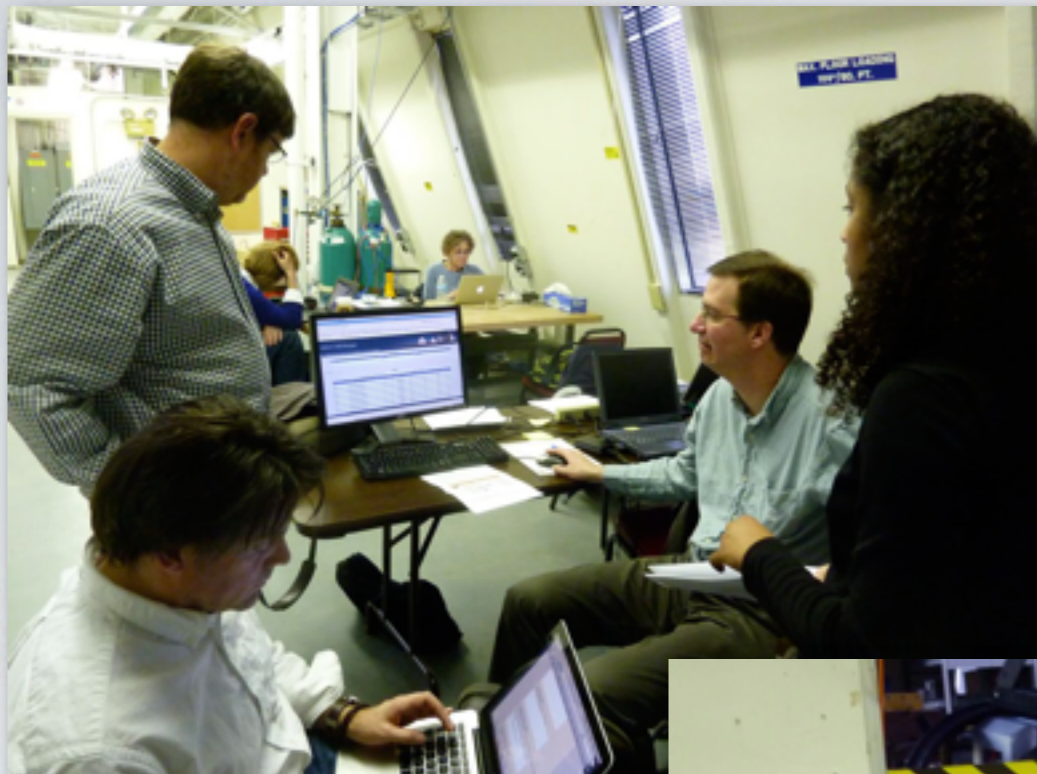


SOFTWARE: SISPI

SISPI is the DECam data acquisition and control system.



MOCK OBSERVING



4 **mock nights** on Feb. 14-18
8 **observers** (2 per night)
10 **experts** providing support
400 **images** taken

valuable **feedback** from observers

improvements implemented **in real time**

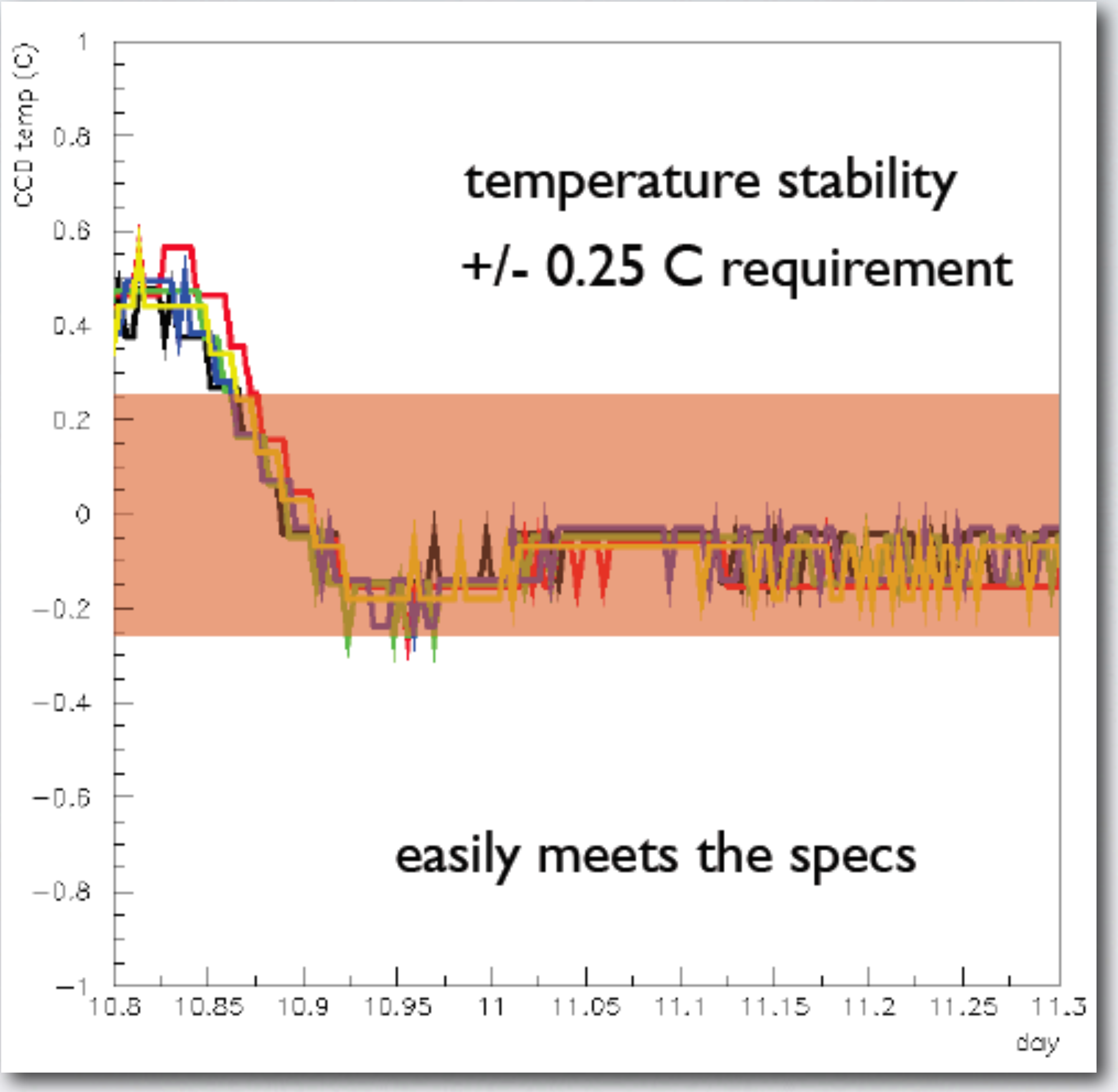
main survey and **supernova** modes exercised

auto-pilot software tested

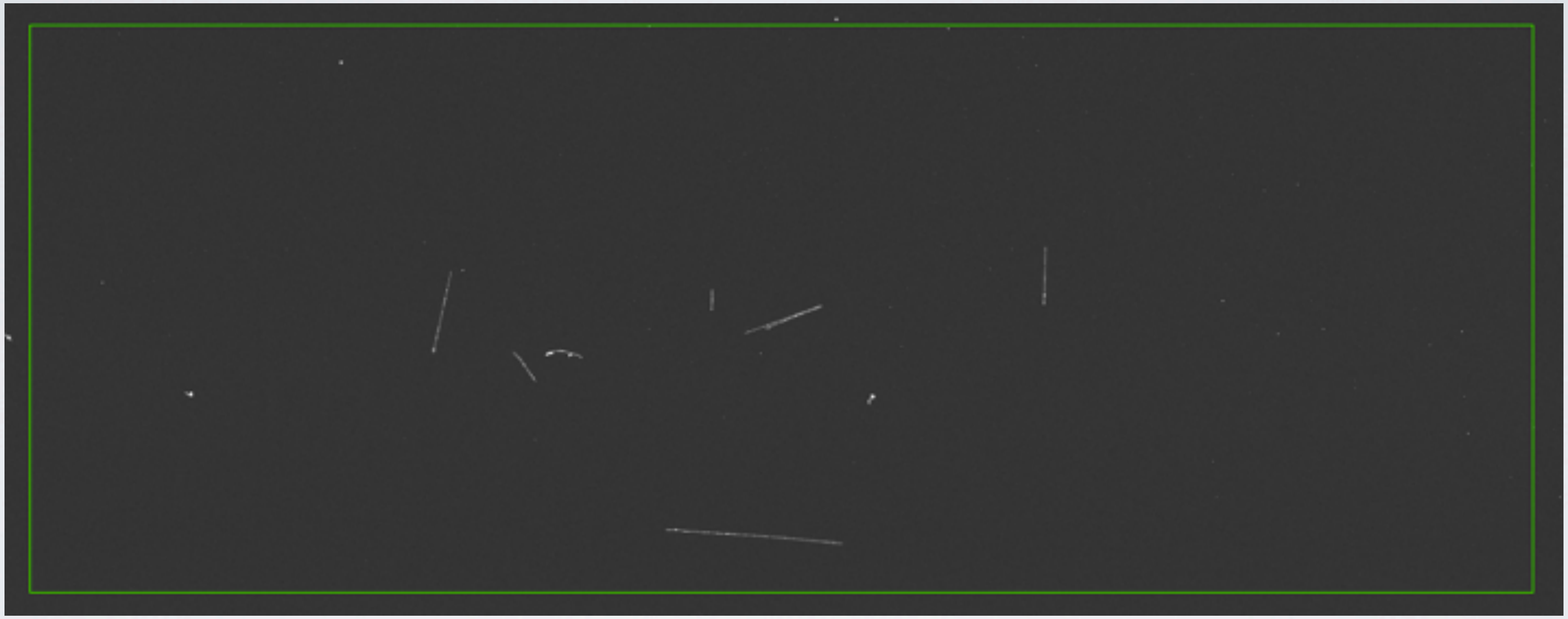
TELESCOPE SIMULATOR INTEGRATION TESTS: RESULTS & IMPACT

RESULTS: TEMPERATURE STABILITY

Temperature is stable and uniform across the focal plane.



RESULTS: CHARGED PARTICLE RATE

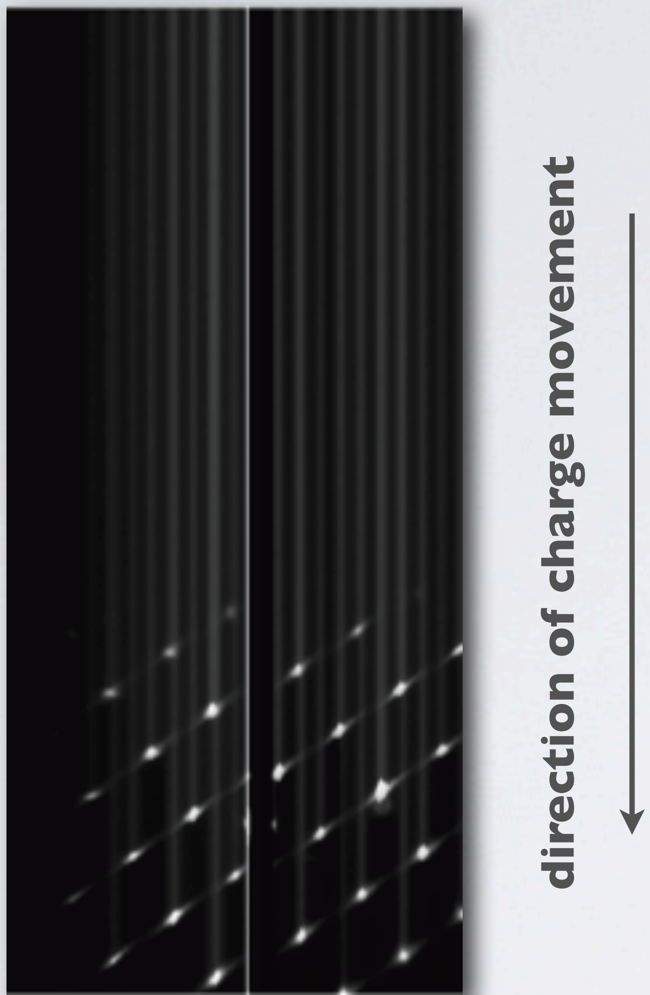


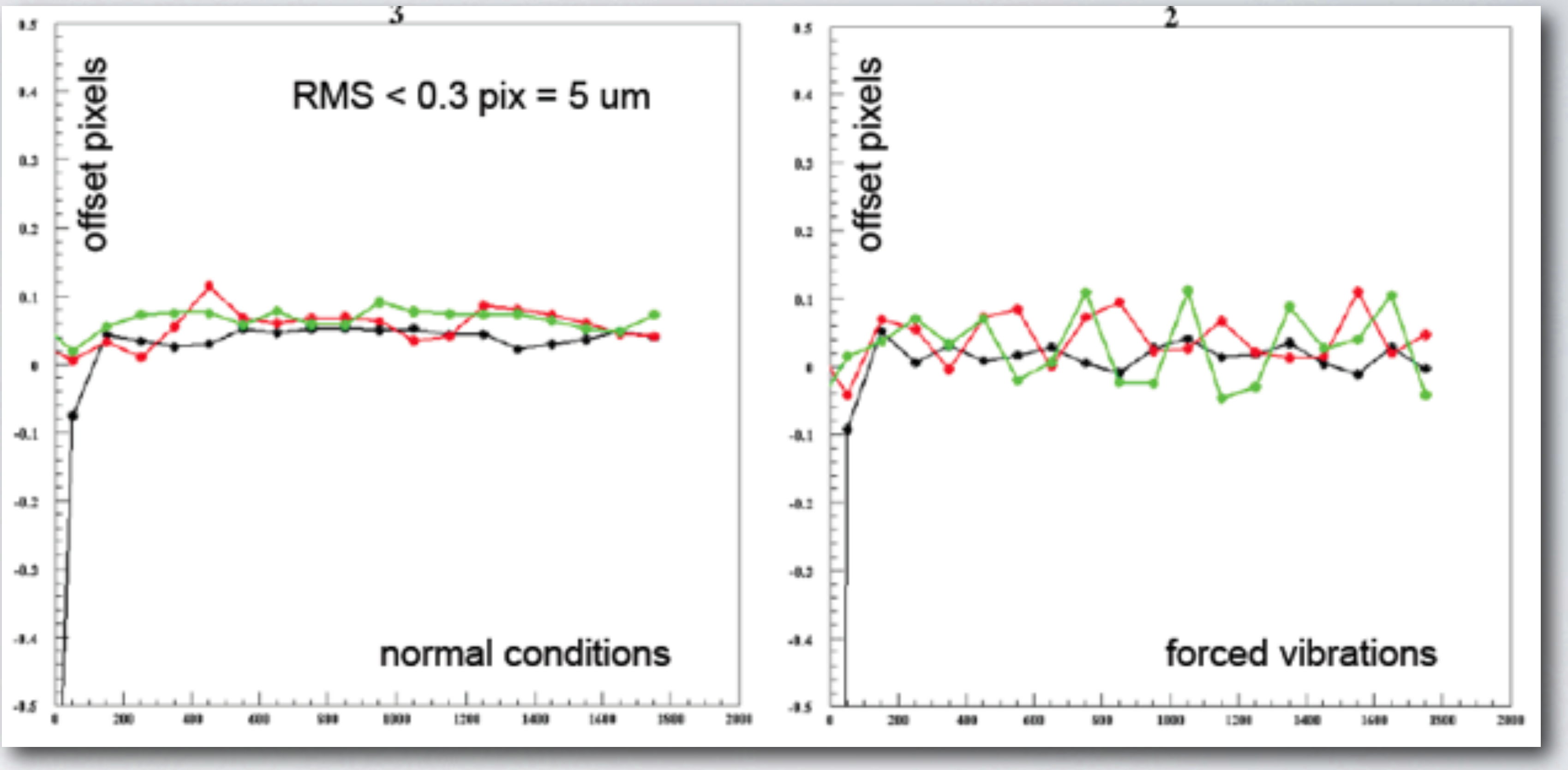
Detail of the observed hits in a 390 sec (6.5 min) dark exposure of the imager. Green rectangle corresponds to an areas of 183,592pix (0.41cm2).

Specs: Internal charged particle rate < 5 events/cm^2/min

Measured: 2.7 events/cm^2/min

RESULTS: VIBRATION



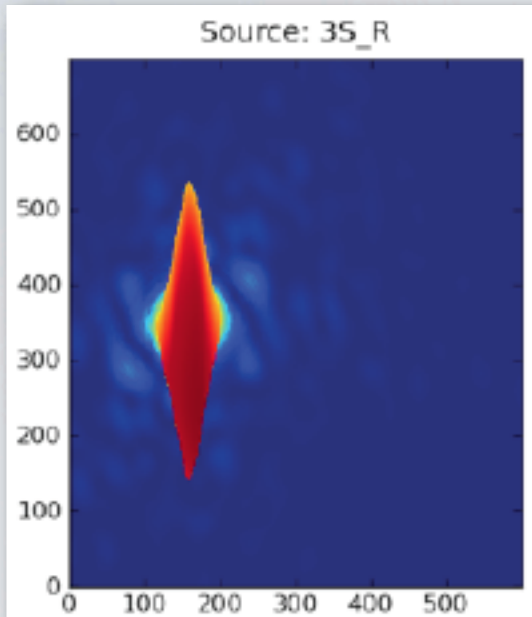


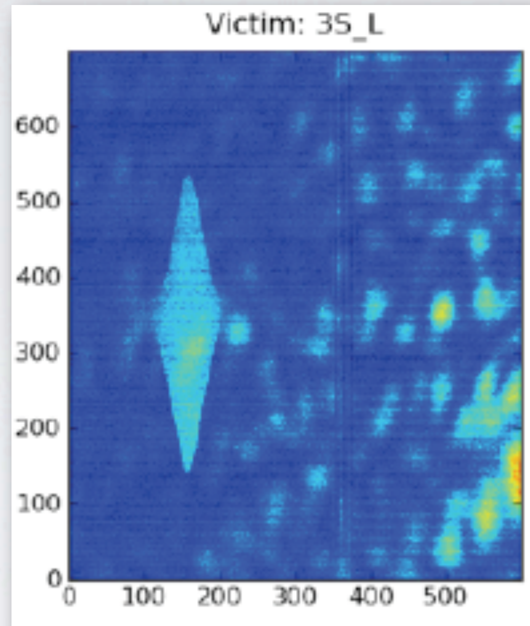
We read out the CCDs while illuminating with a pattern of dots.

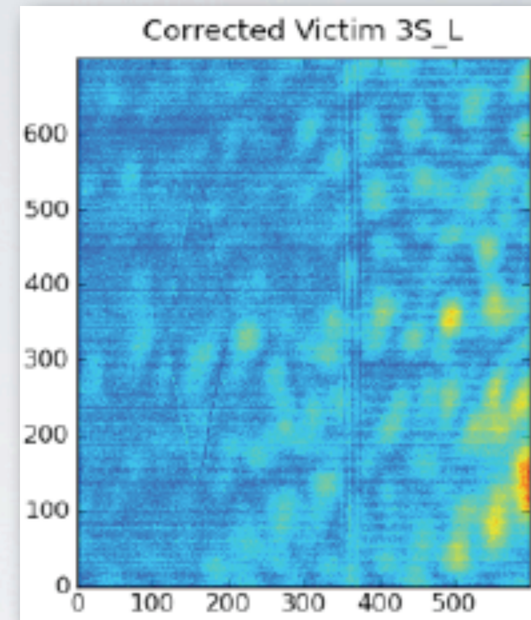
Each dot leaves a trail aligned with the direction of readout. When vibrations occur, the lines wiggle.

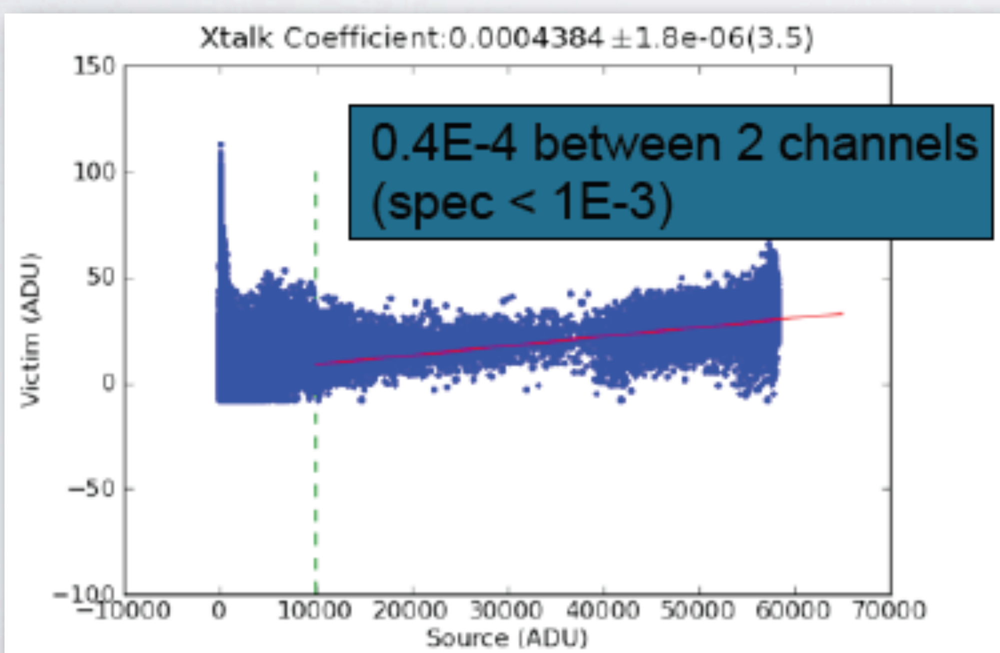
Results are consistent with measurements from accelerometers and easily meet specs.

RESULTS: CROSSTALK







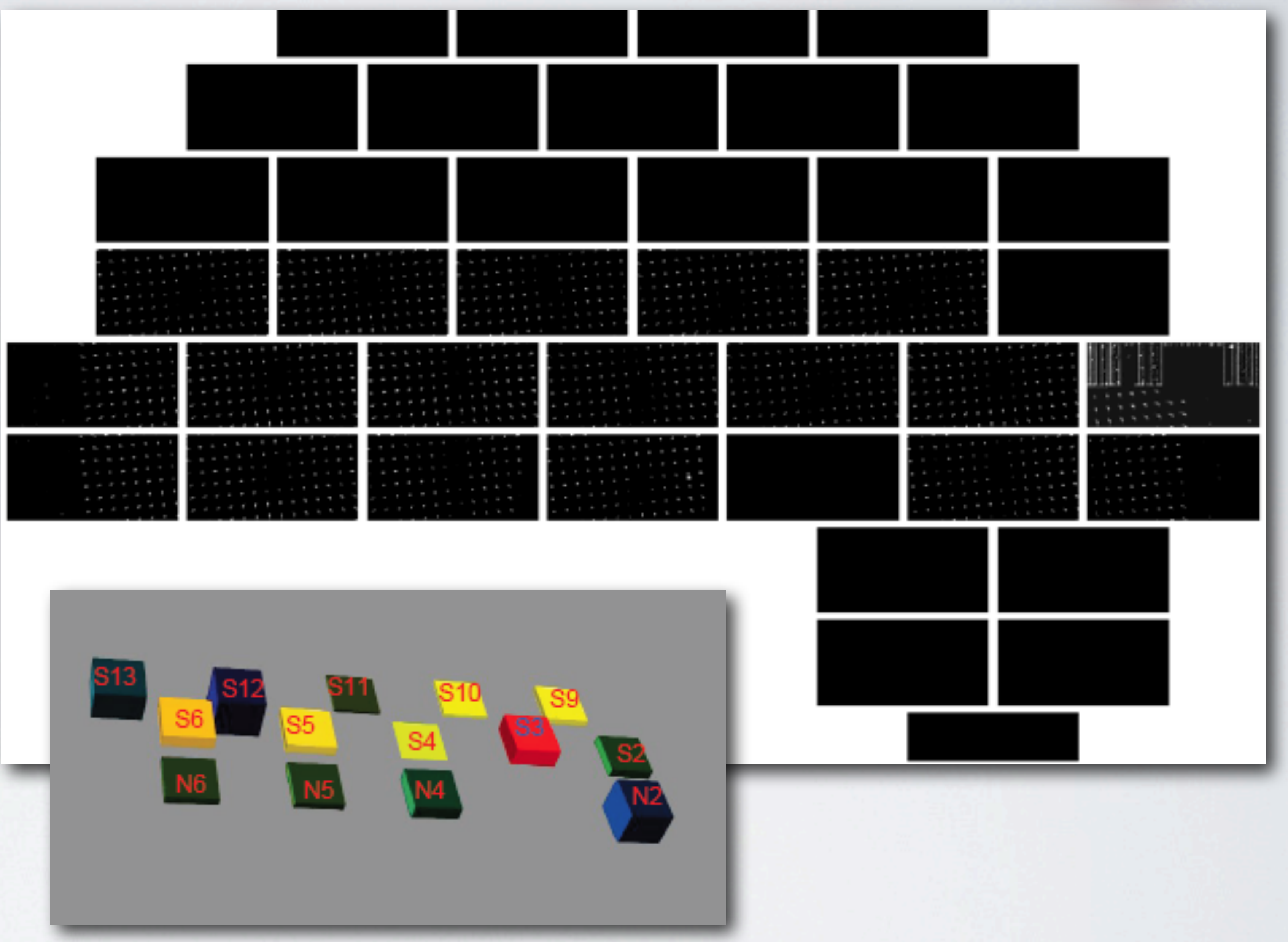


No measurable crosstalk between boards.

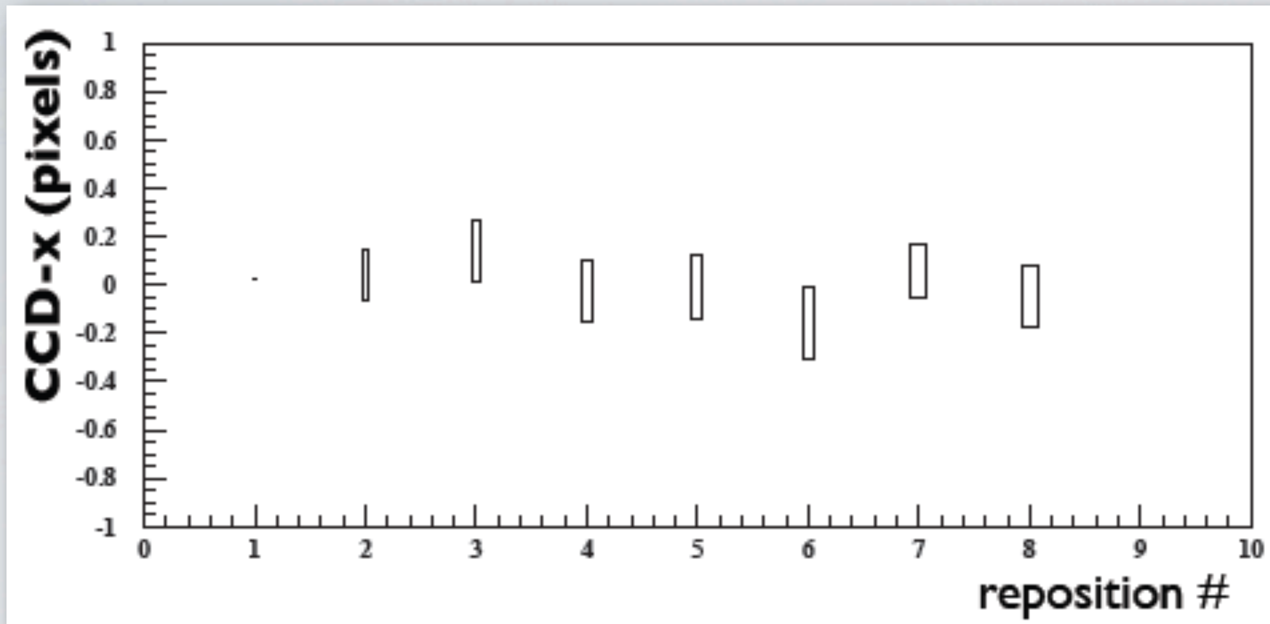
RESULTS: FLATNESS

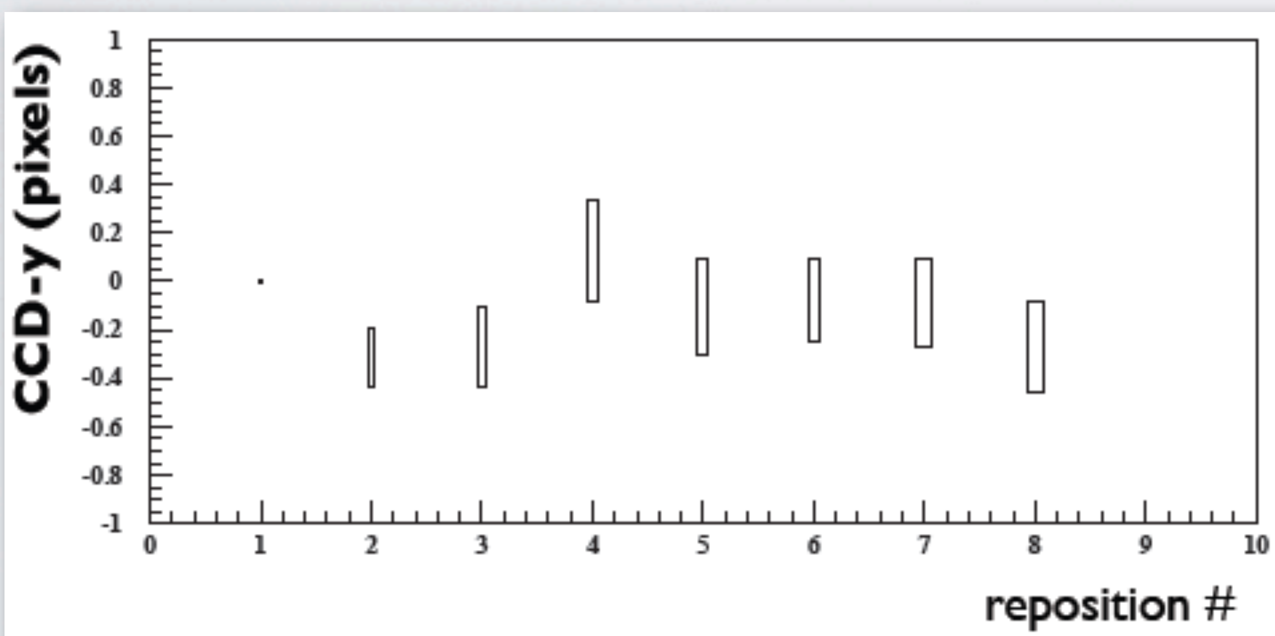
Small (~60 microns) imperfections mapped in the focal plane.

Meet specs, but improvement in flatness will be made for the next stage.



RESULTS: HEXAPOD

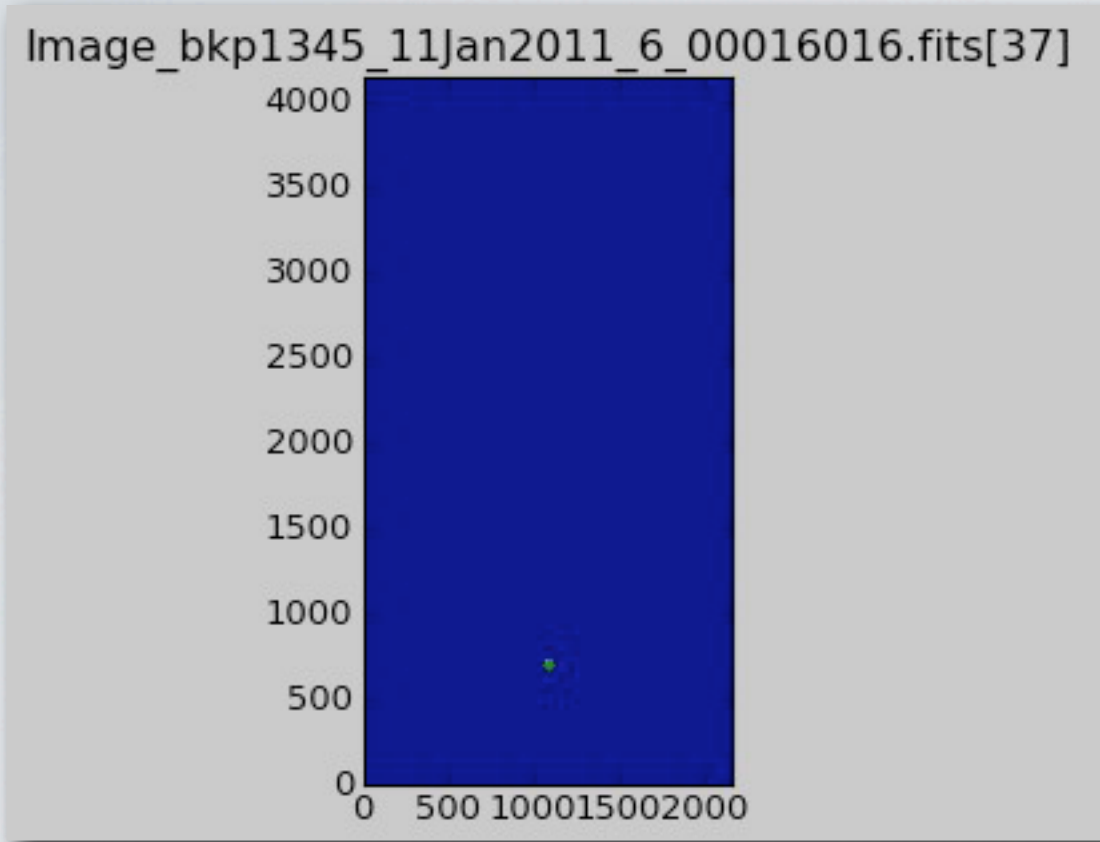


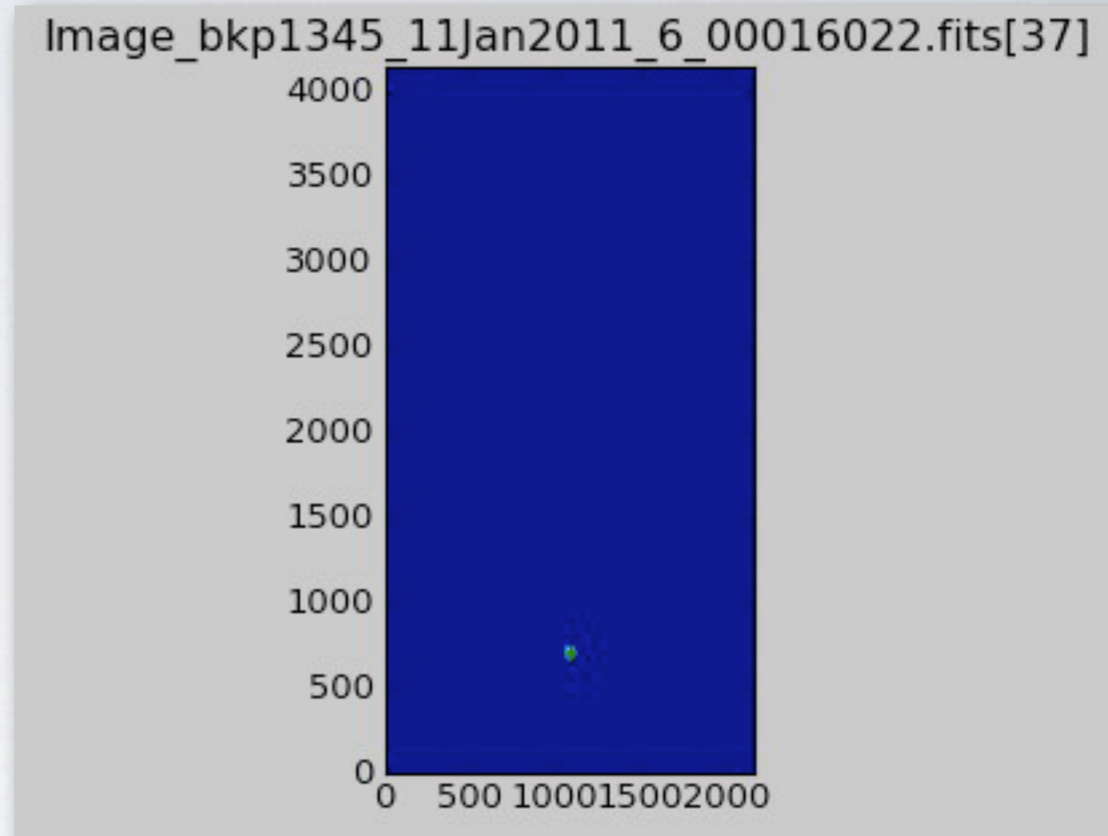


Hexapod repeatability: 0.2 pixels (3 microns).

Measured at all positions.

RESULTS: FILTER CHANGER





Images of dots projected through a pinhole move less than one pixel after filter repositions.

CONCLUSIONS

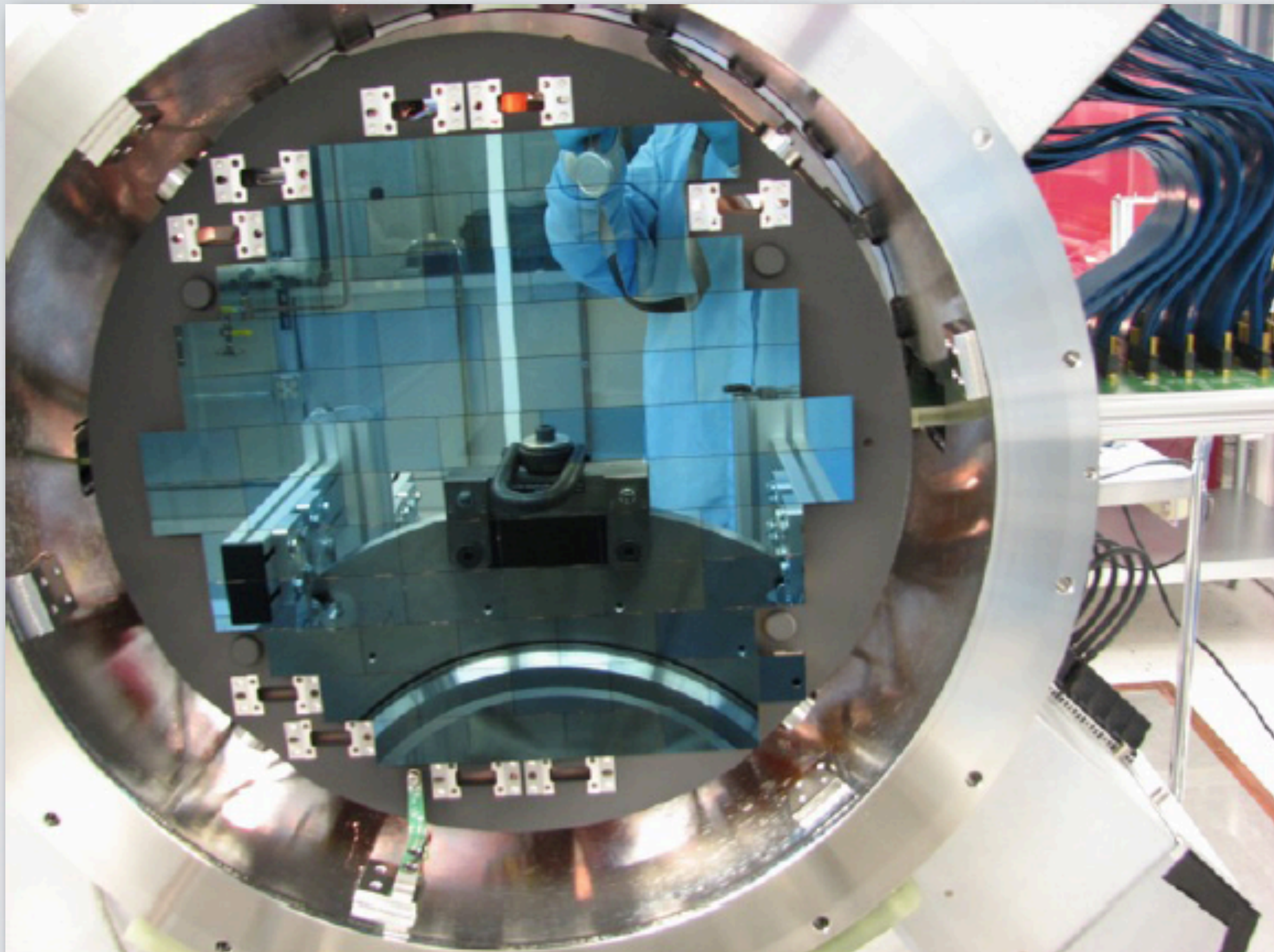
Installation platforms and procedures for handling the imager safely in Chile were developed.

Imager integrated with shutter, filter, hexapod and cooling system shown to work reliably and meet specs in all orientations.

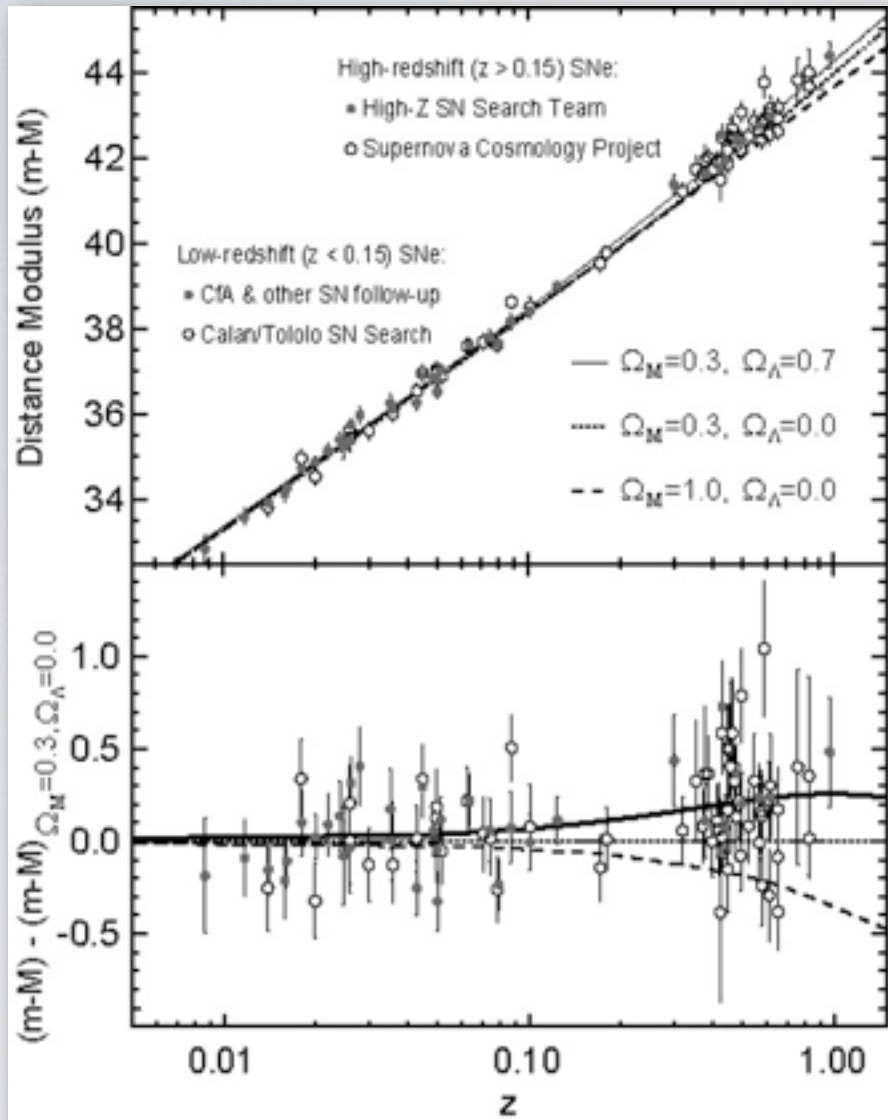
Major effort in software integration. We now essentially have the software we need to operate DECam in Chile.

BACKUP SLIDES

DECAM

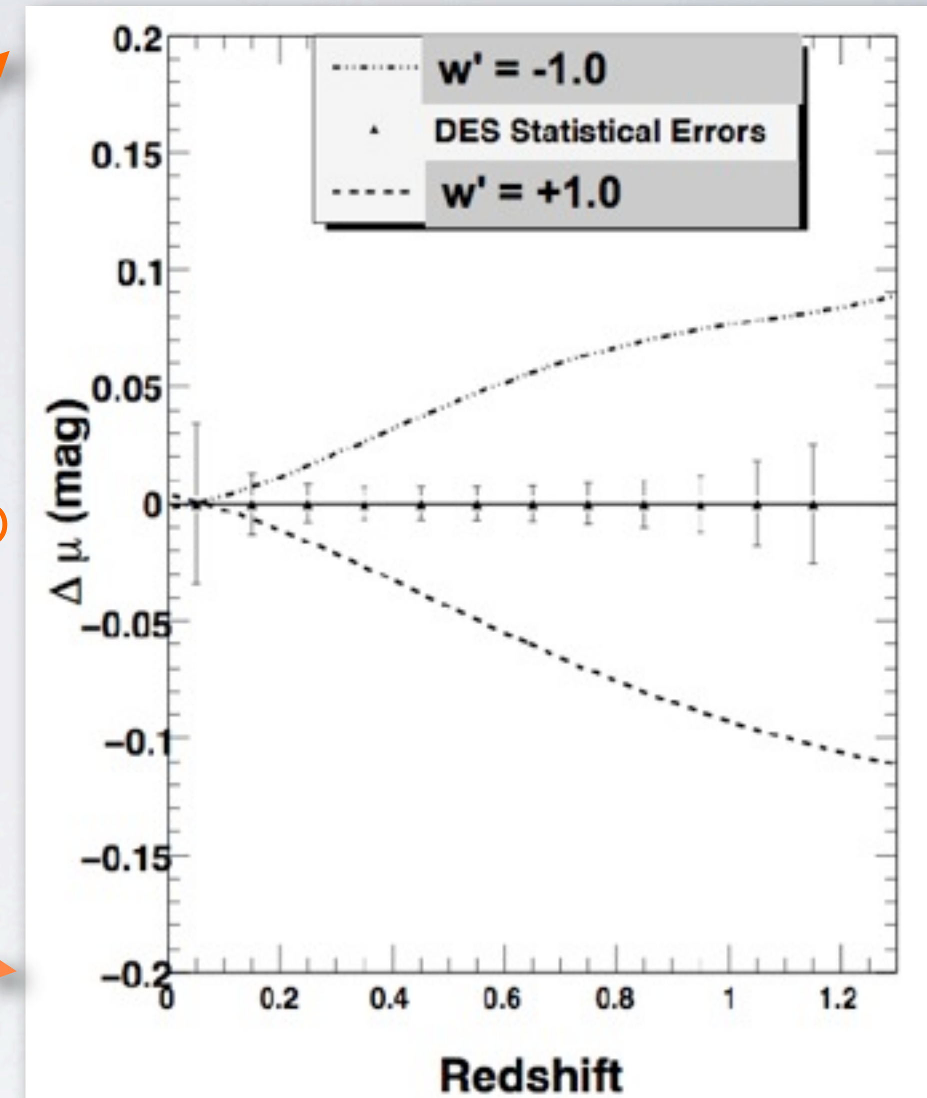


DES SCIENCE: SN



4000 SNe up to z ~ 1.2

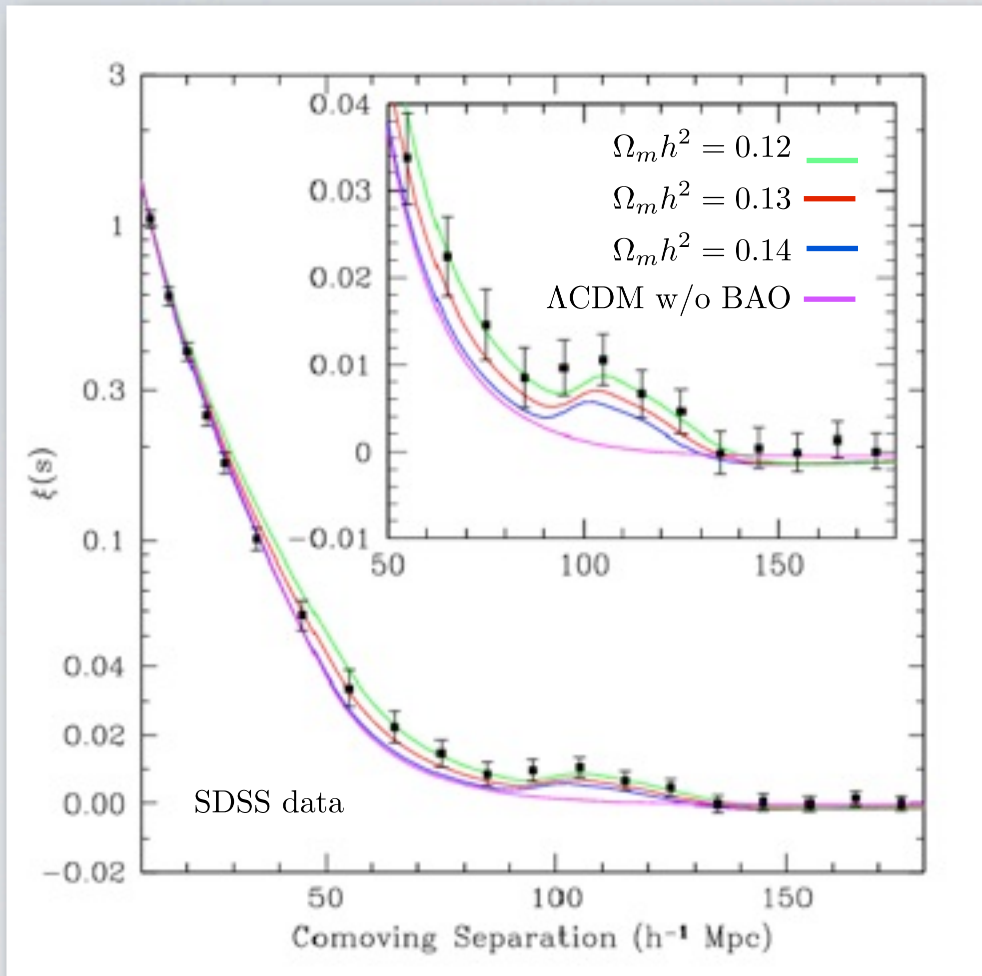
30 sq deg



First results: ~ 100 SNe. Measured w. (Riess et al. 1998, Perlmutter et al. 1999).

DES expected sensitivity. Large and deep sample for measurement of w(a).

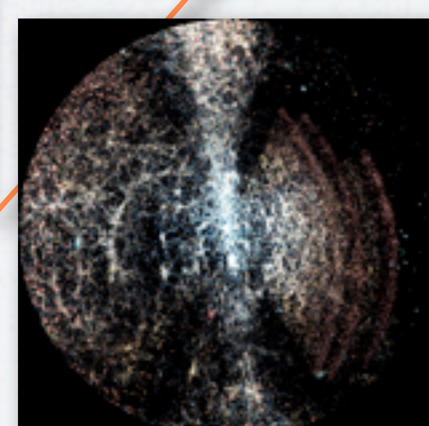
DES SCIENCE: BAO

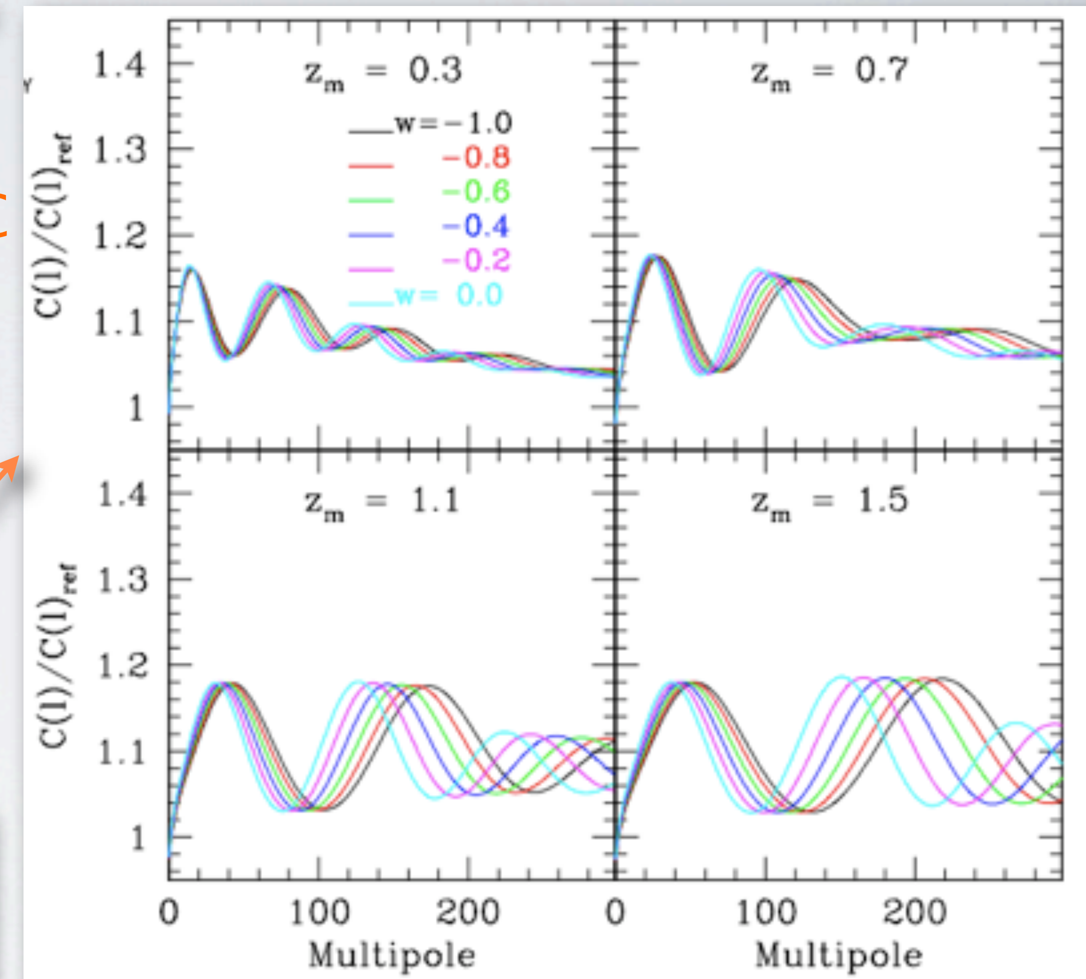


First results: mean spectroscopic redshift ~ 0.35. Measured Ω_m (Eisenstein et al. 2005)

mean photometric redshift~0.7

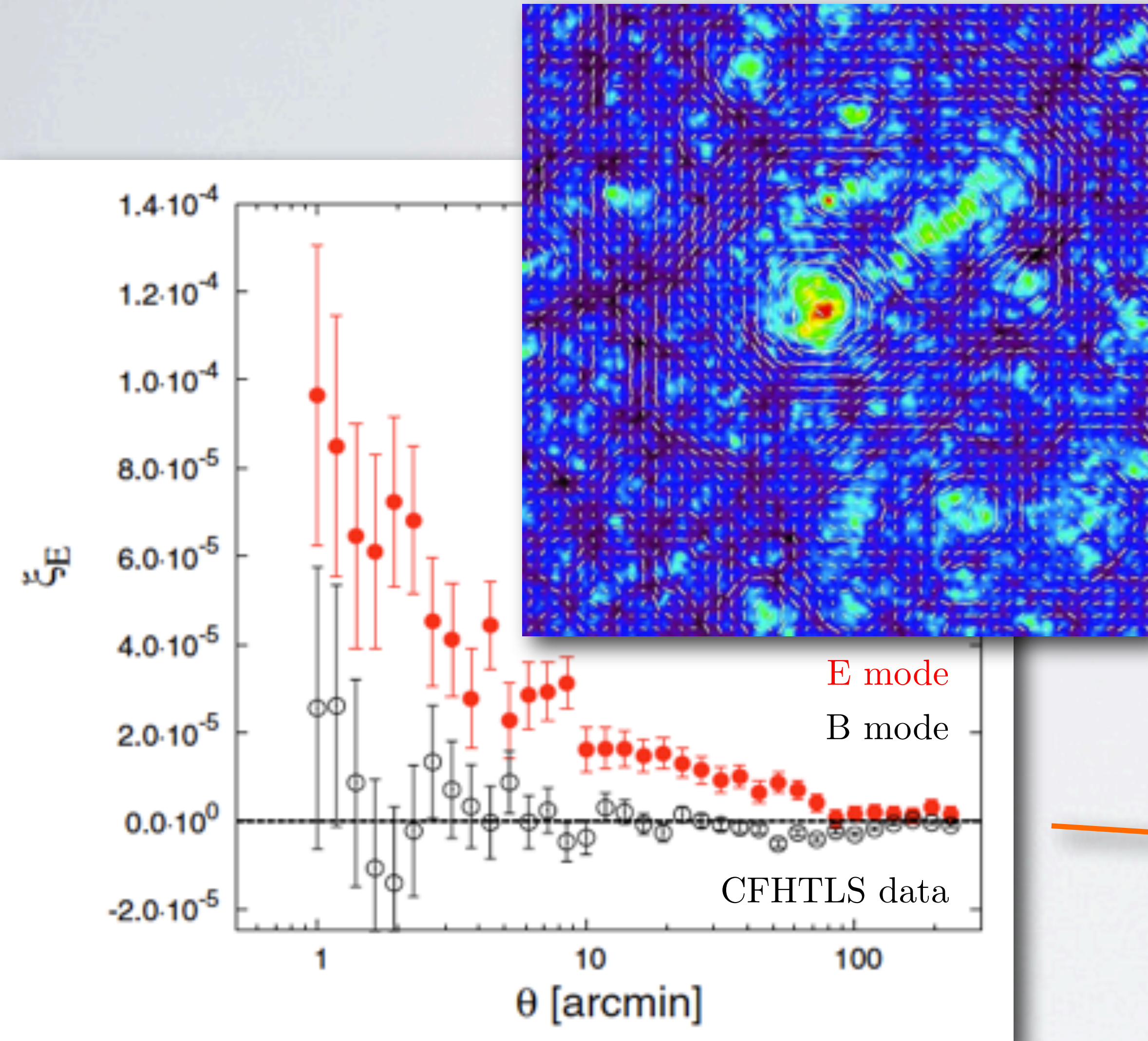
300M glxs





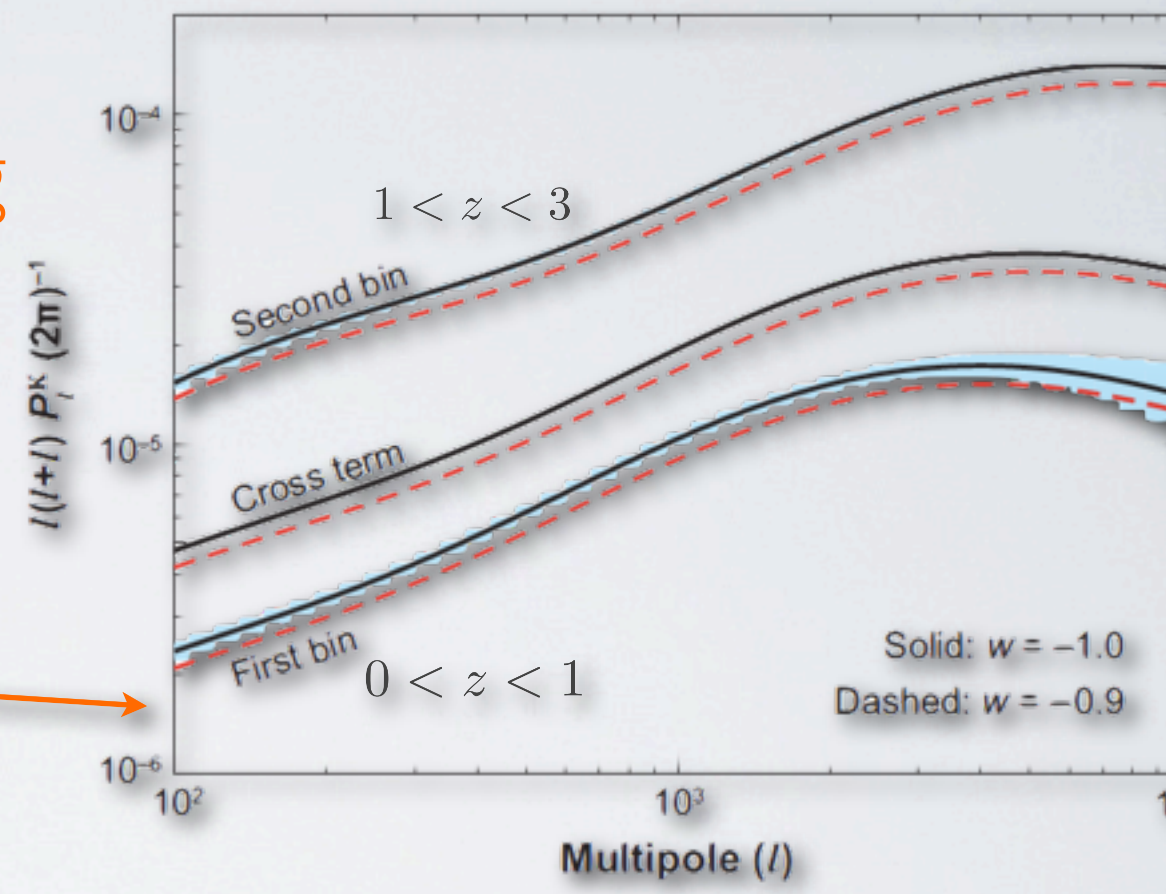
DES expected sensitivity. Can measure w by probing deeper.

DES SCIENCE: WL



5000 sq deg

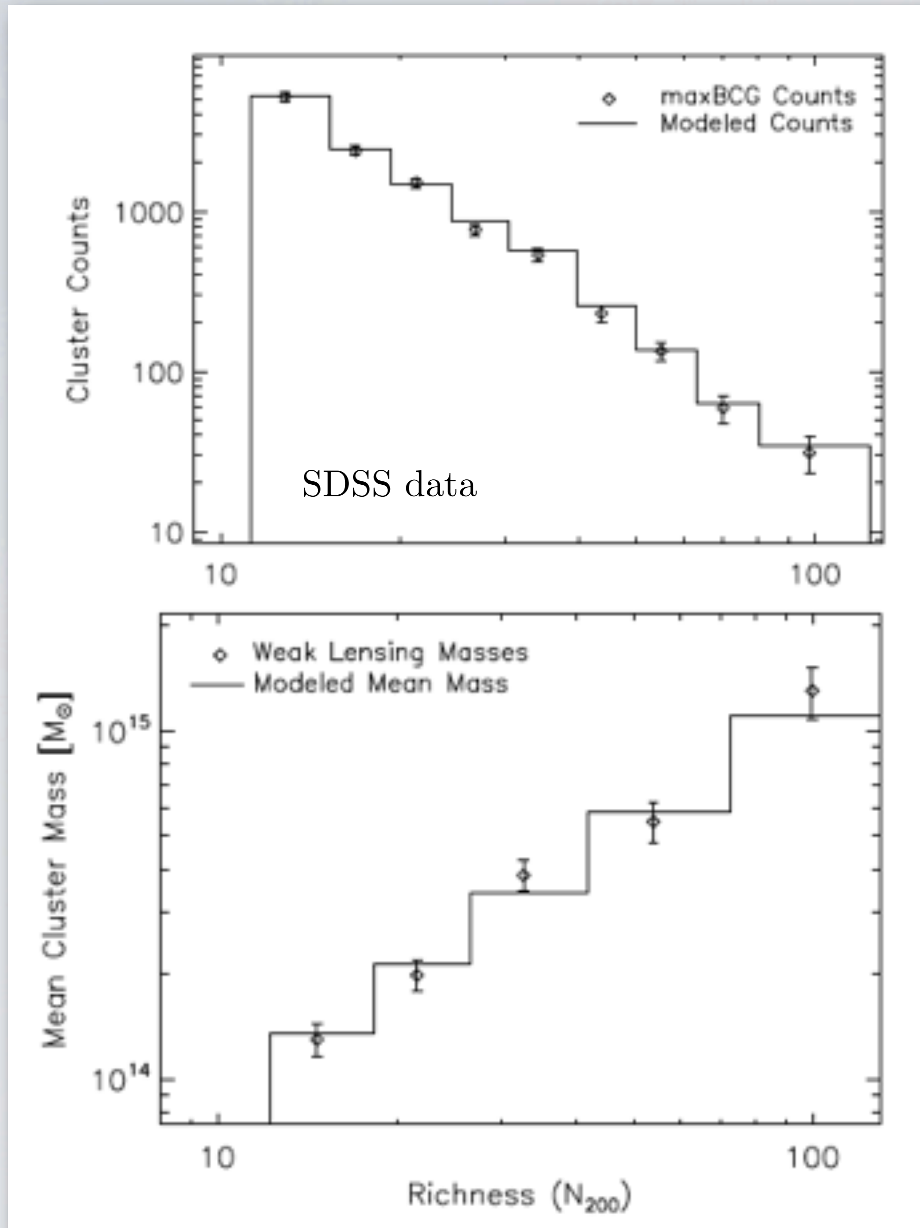
300M glxs



Current results: 54 sq deg, 24th magnitude. Measured Ω_m (Fu et al. 2008).

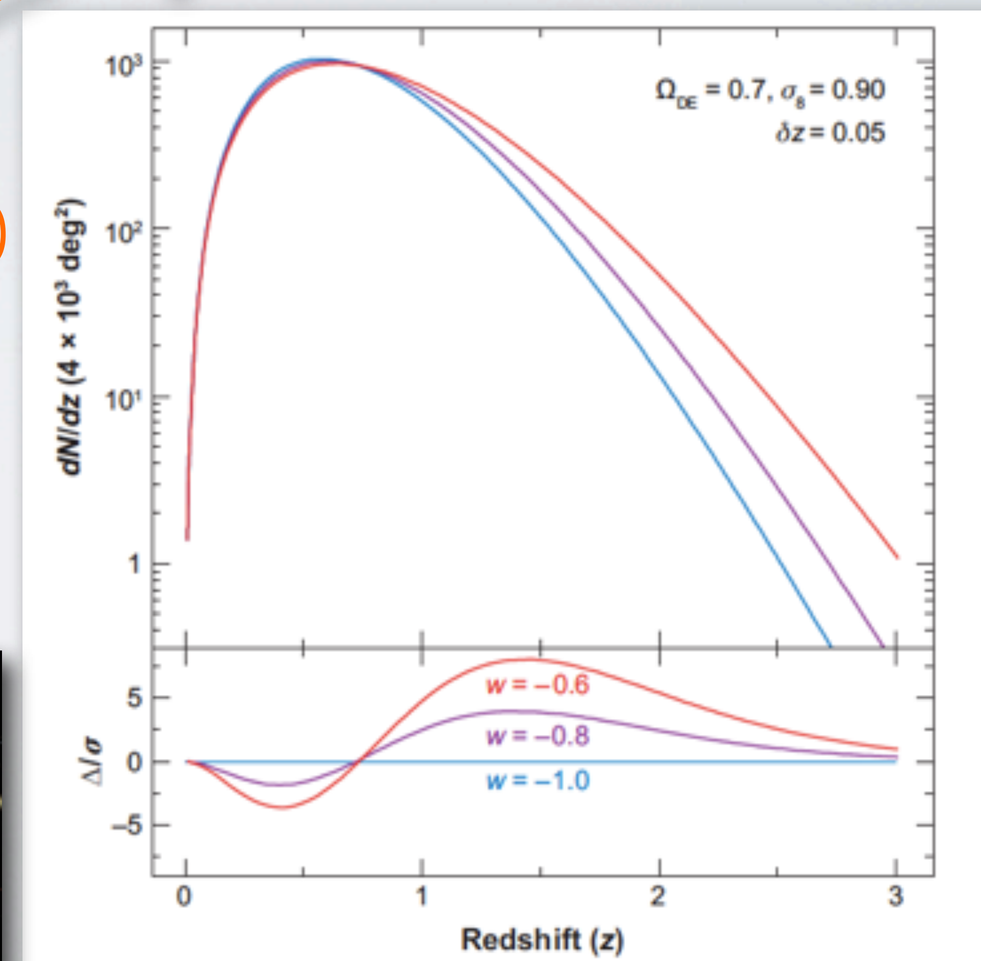
DES expected sensitivity. Source galaxies in first bin only. Can measure w by going wider.

DES SCIENCE: CLUSTERS



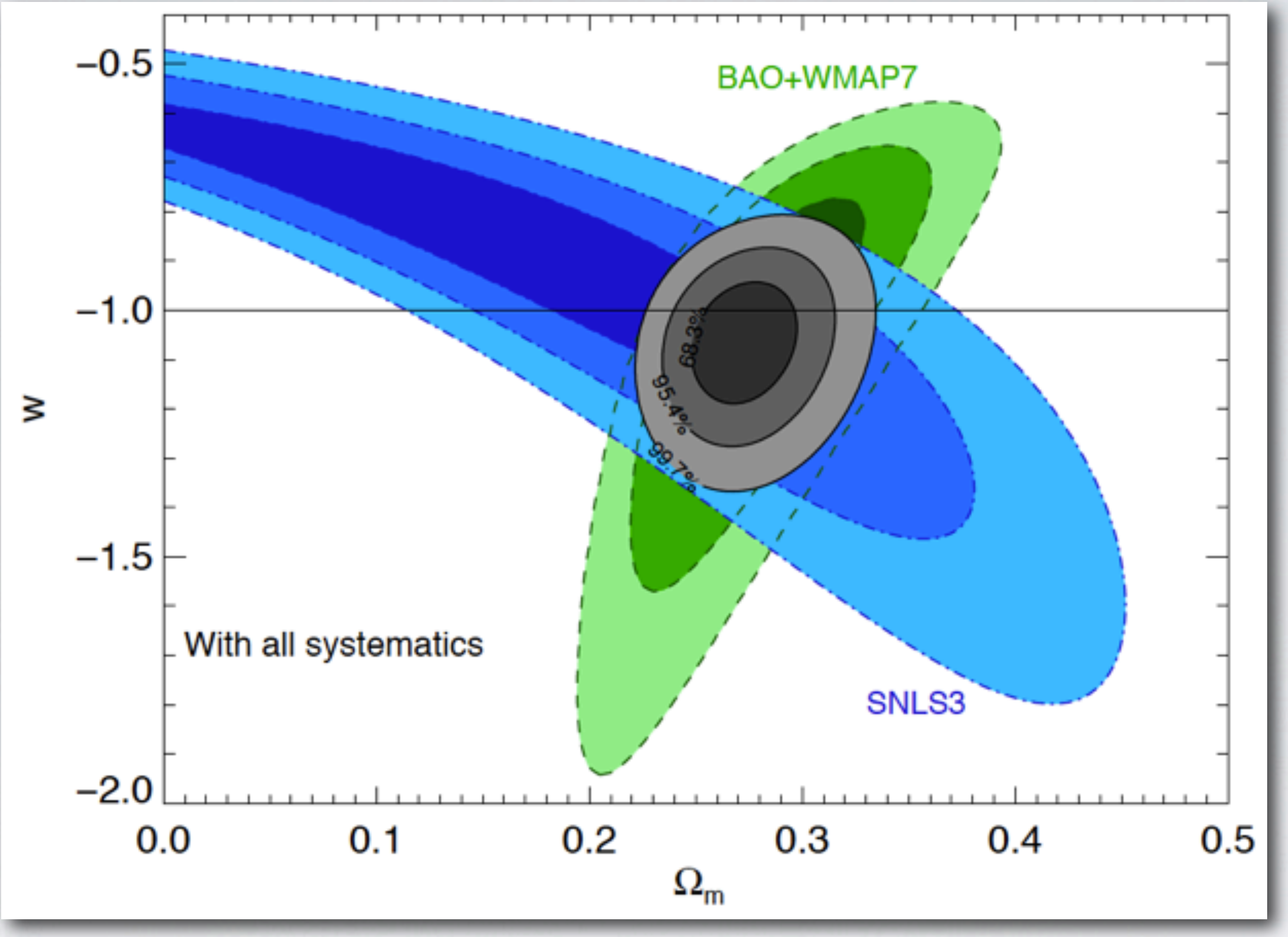
Current results: 6000 clusters, z ~0.35
Measured Ω_m (Rozo et al. 2010)

100,000 clusters
z ~ 1



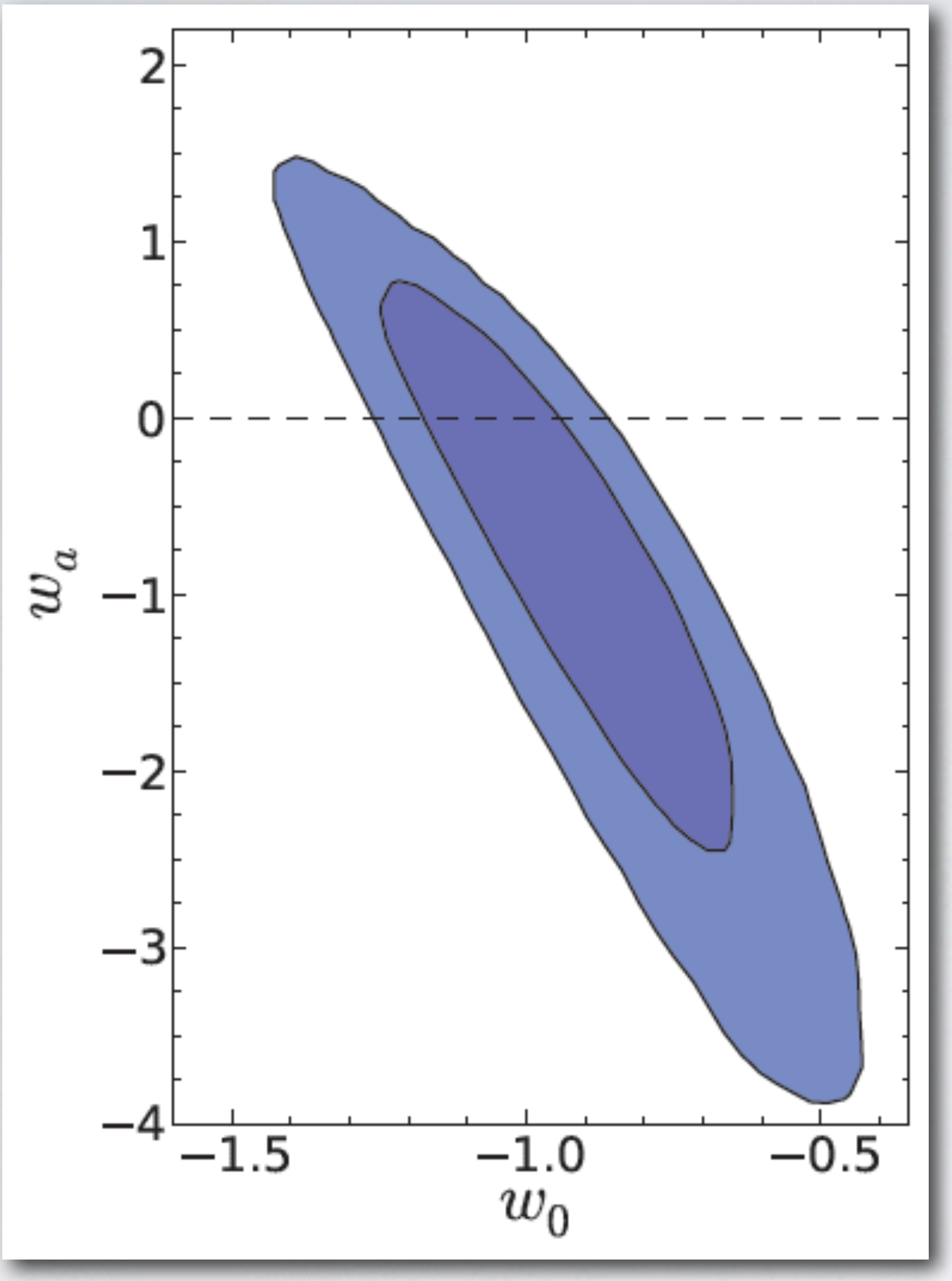
DES expected sensitivity. Measure w with deep & wide survey.

CURRENT LIMITS



Limits on ΛCDM model (Sullivan et al. 2011). **Not using: Clusters, WL**

CURRENT LIMITS



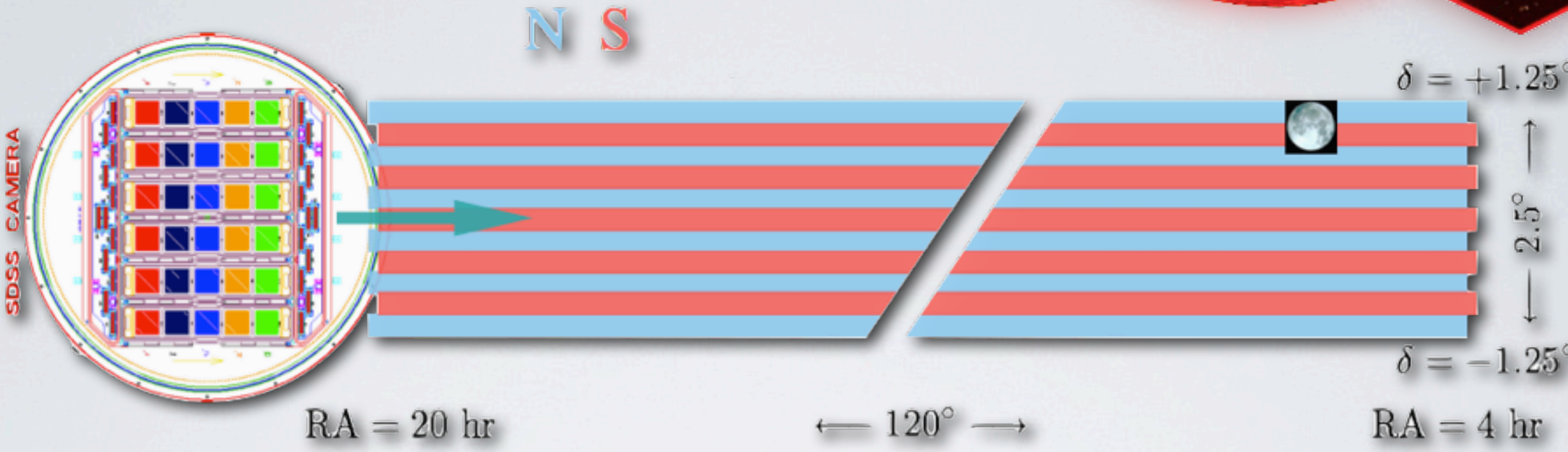
Constraints on **the two parameters** of the dark energy equation of state, in a flat universe. (Sullivan et al. 2011).

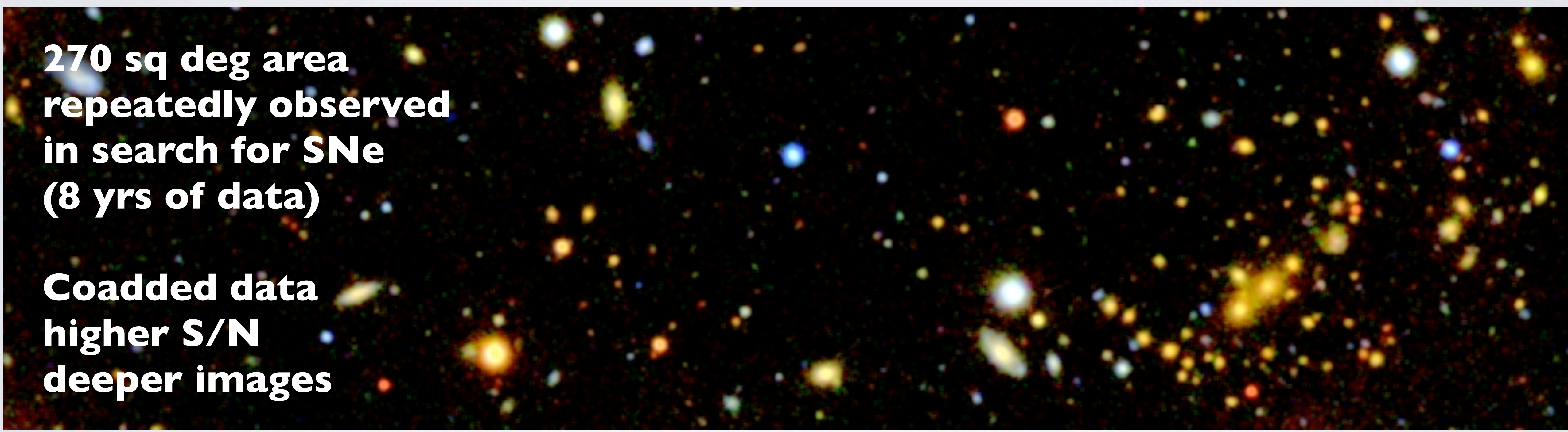
Not using: Clusters, WL.

CAN'T WAIT?

STUDYING COSMOLOGY IN THE SDSS COADD (AND PREPARING FOR DES)

THE SDSS COADD





270 sq deg area repeatedly observed in search for SNe (8 yrs of data)

Coadded data higher S/N deeper images

COADD: DATA

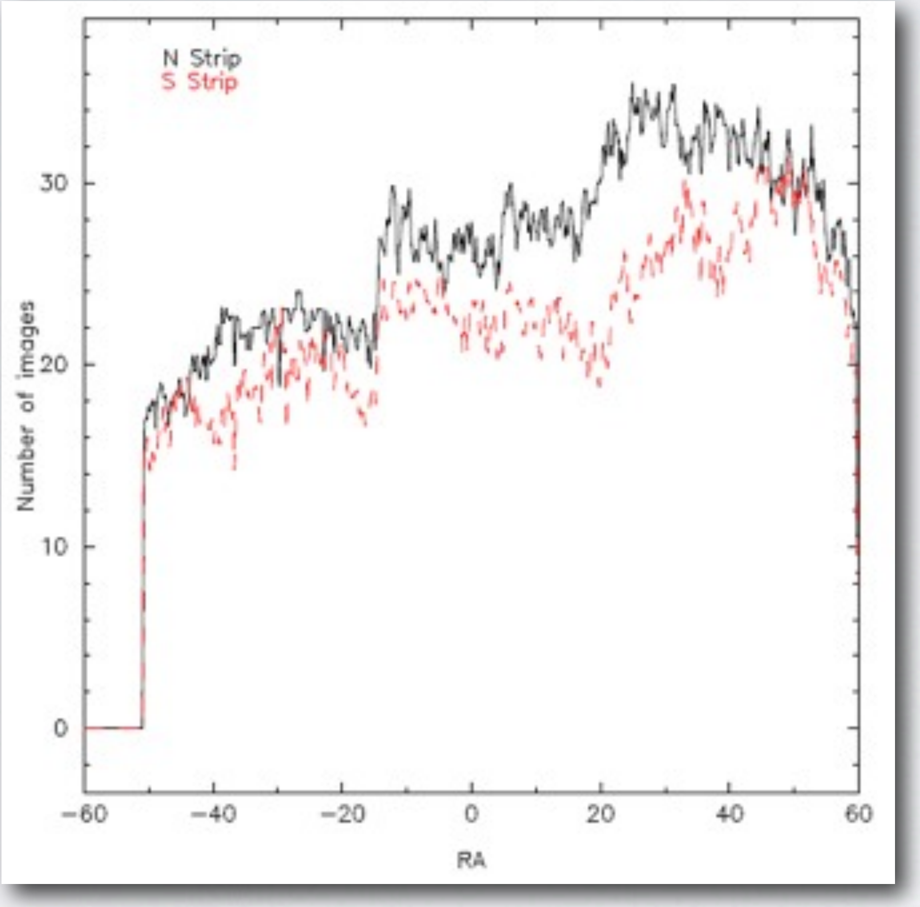
275 sq deg
13M glxs

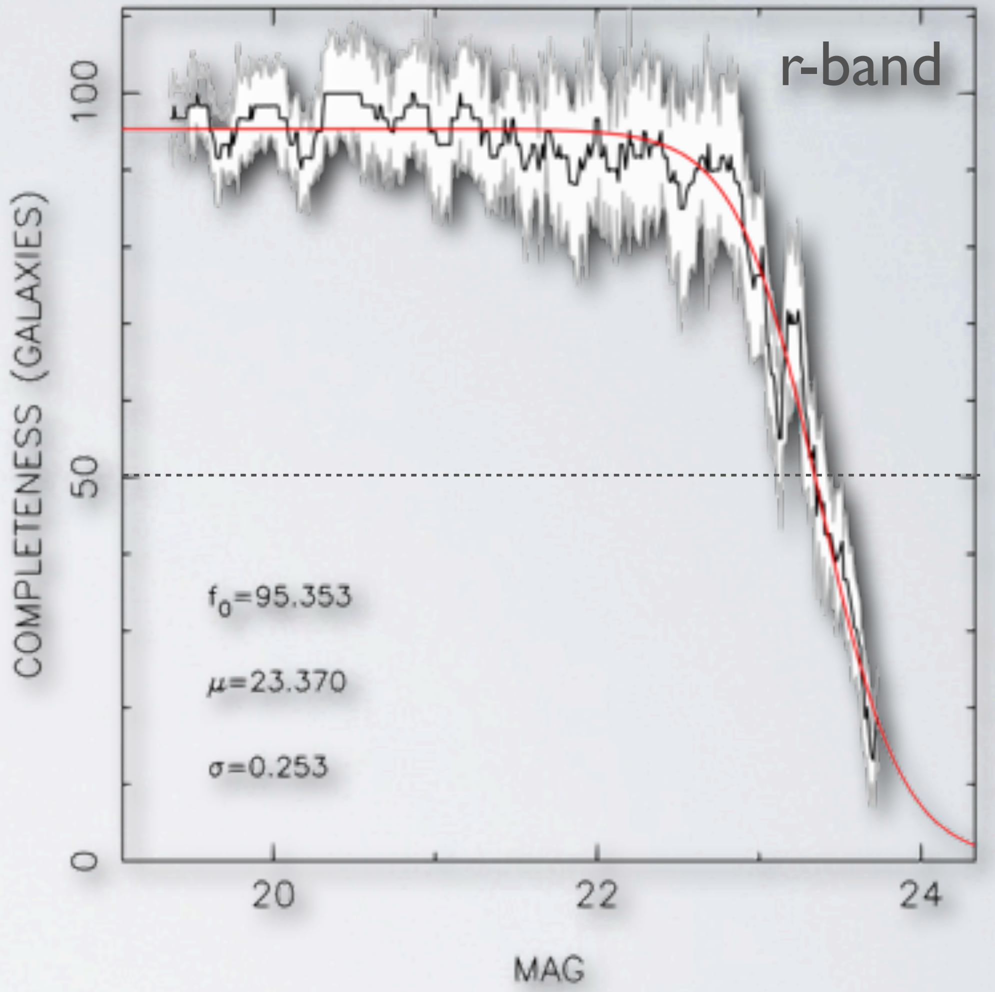
ugriz-bands
24th mag
(z ~ 0.8)

2% photometry

seeing ~1.3
6 glxs per sq arcmin

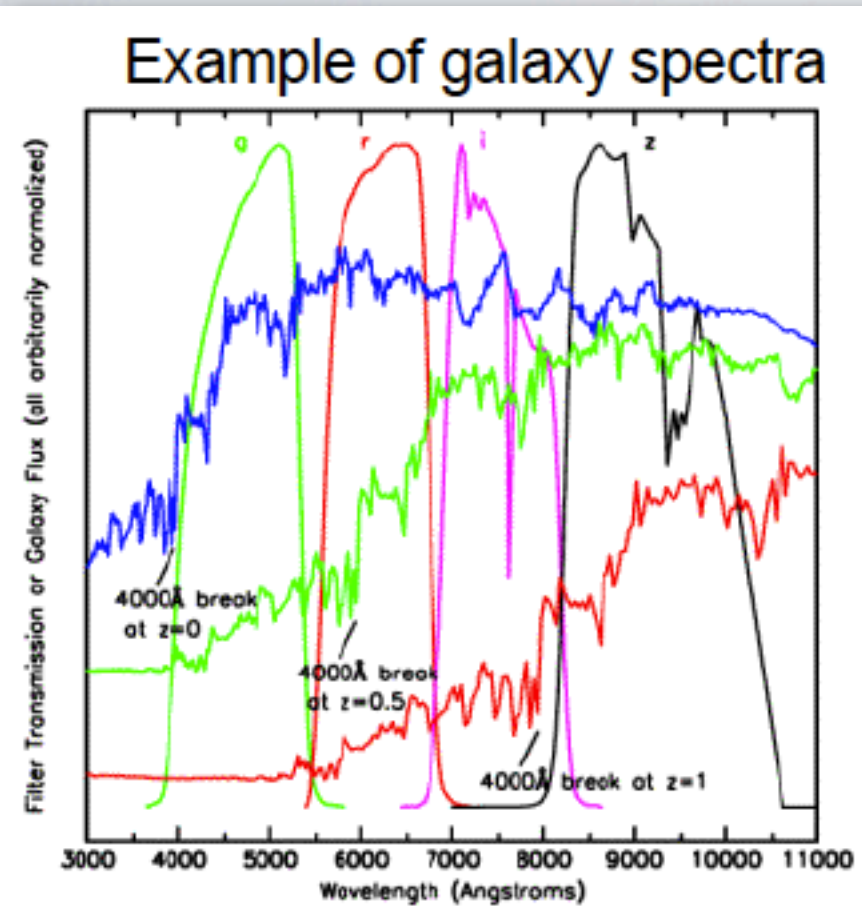
Spatial variations in # of images coadded (depth)





Completeness function example
Limiting mag at 50% completeness

COADD: PHOTO-Z



Challenge: Tell the redshifts by looking only at the area under the filter curves, not the spectra.

Collecting spectra from **all** surveys for our **training set**.

1 → 2 → **Neural Network** → 3

spectra	Survey
72,239	SDSS DR7
17,677	CNOC2
8,656	WiggleZ
7,766	SDSS-III/BOSS
6,975	DEEP2
5,537	VVDS
2,614	2SLAQ

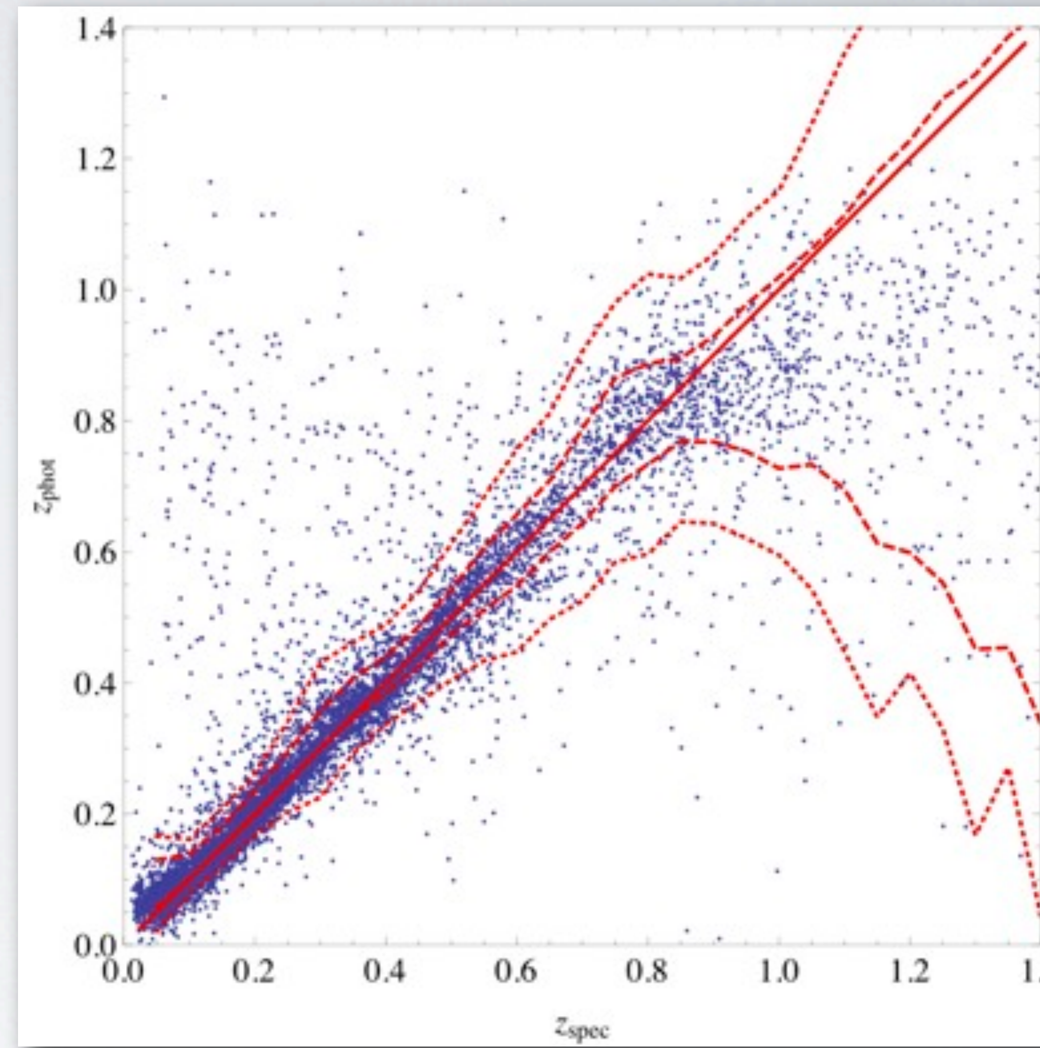
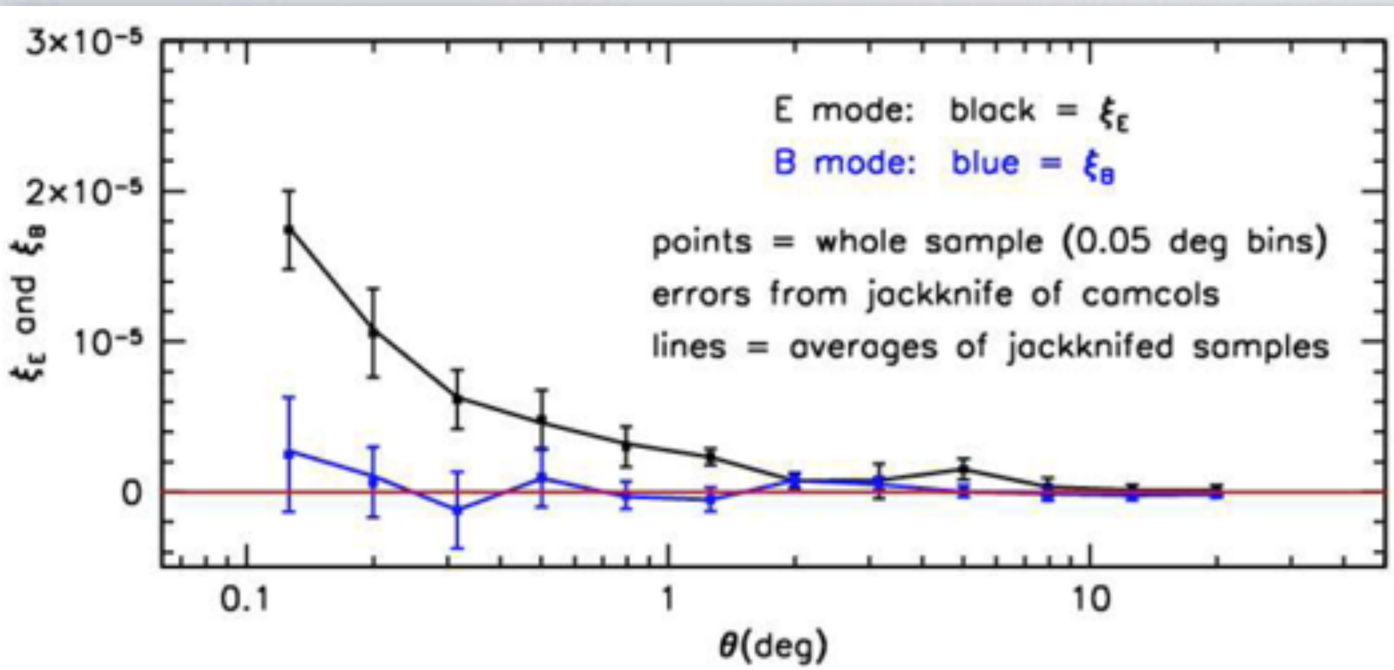
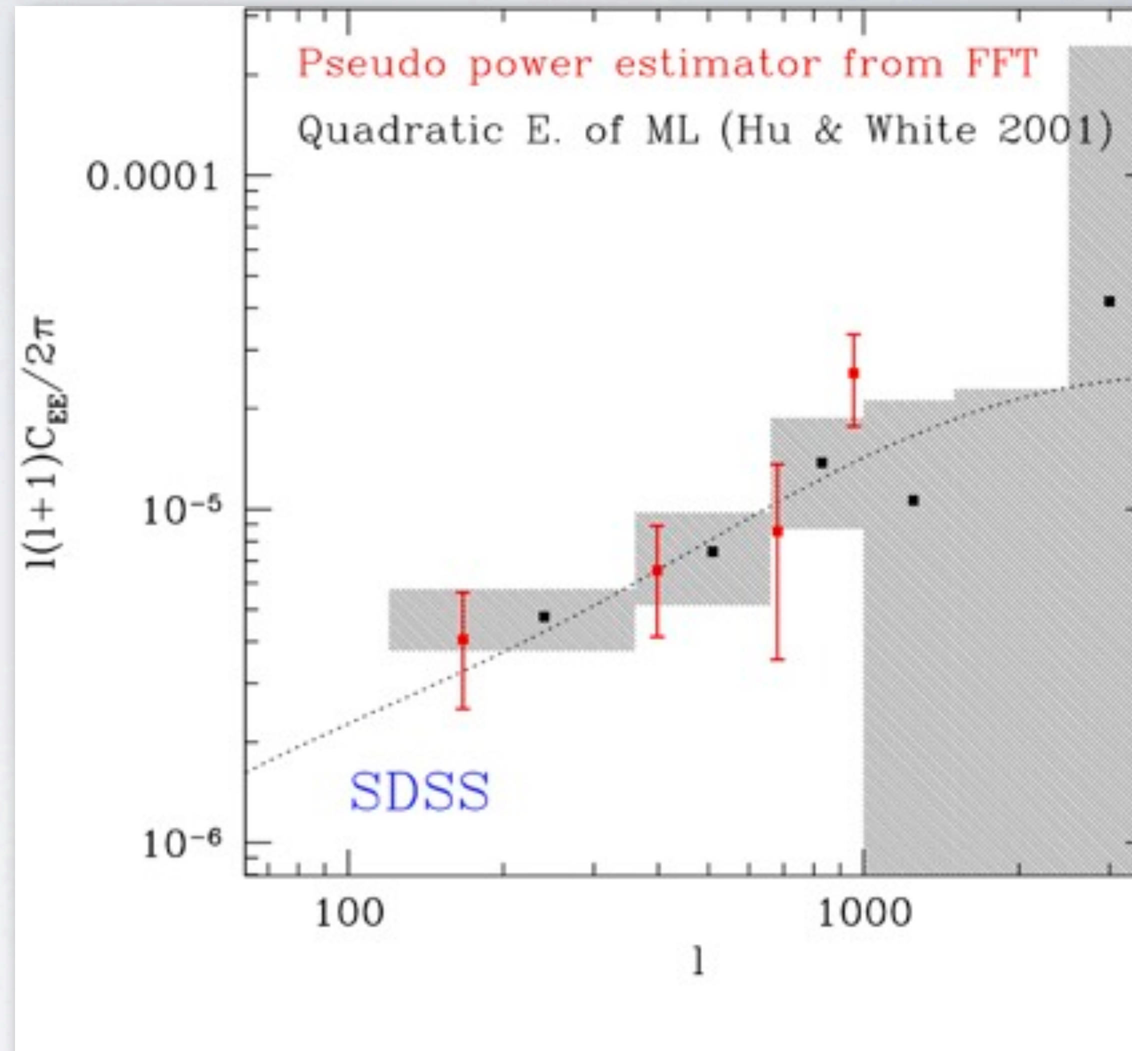


Photo-z estimates validation:
error < 0.04 for z<0.8

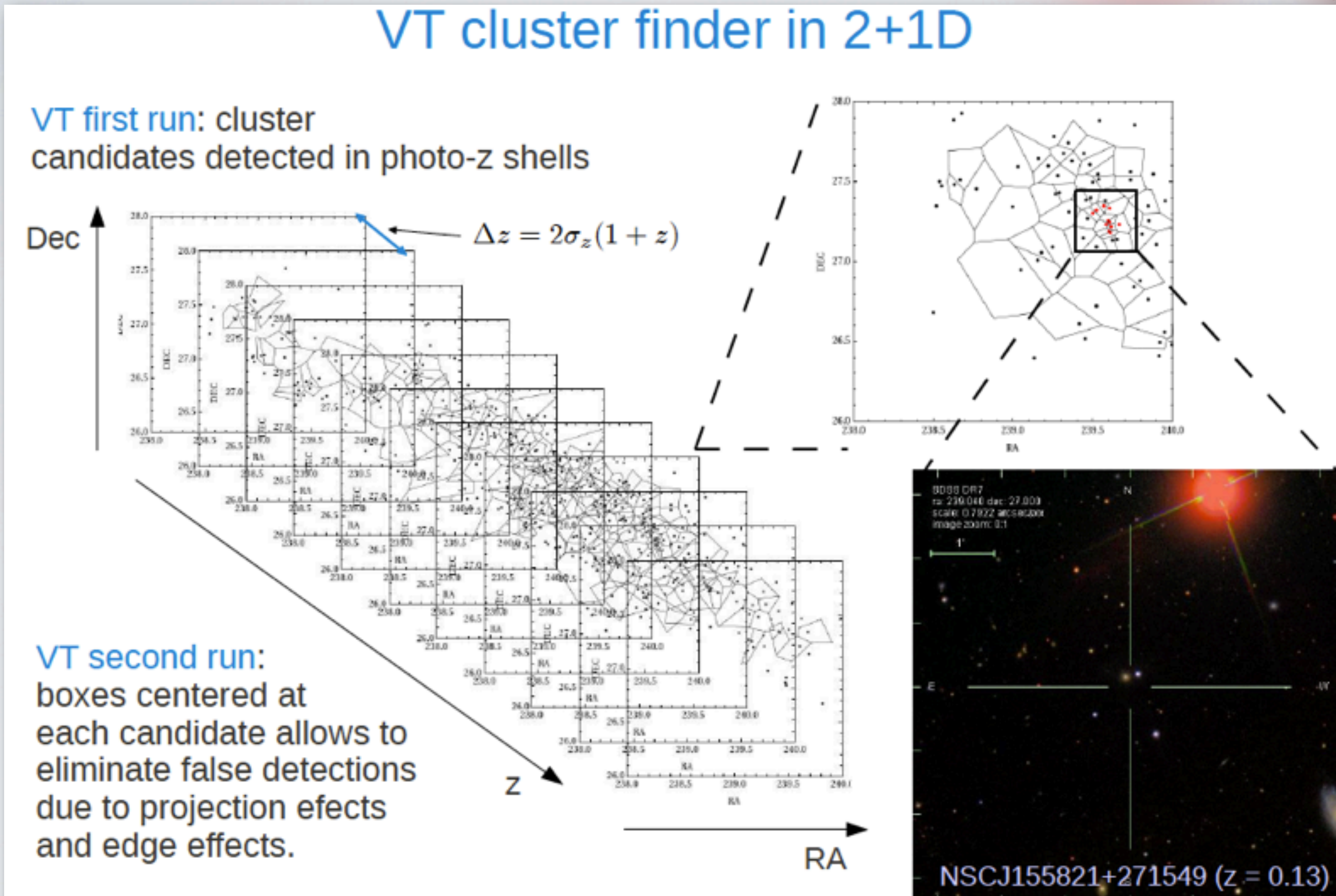
COADD:WL



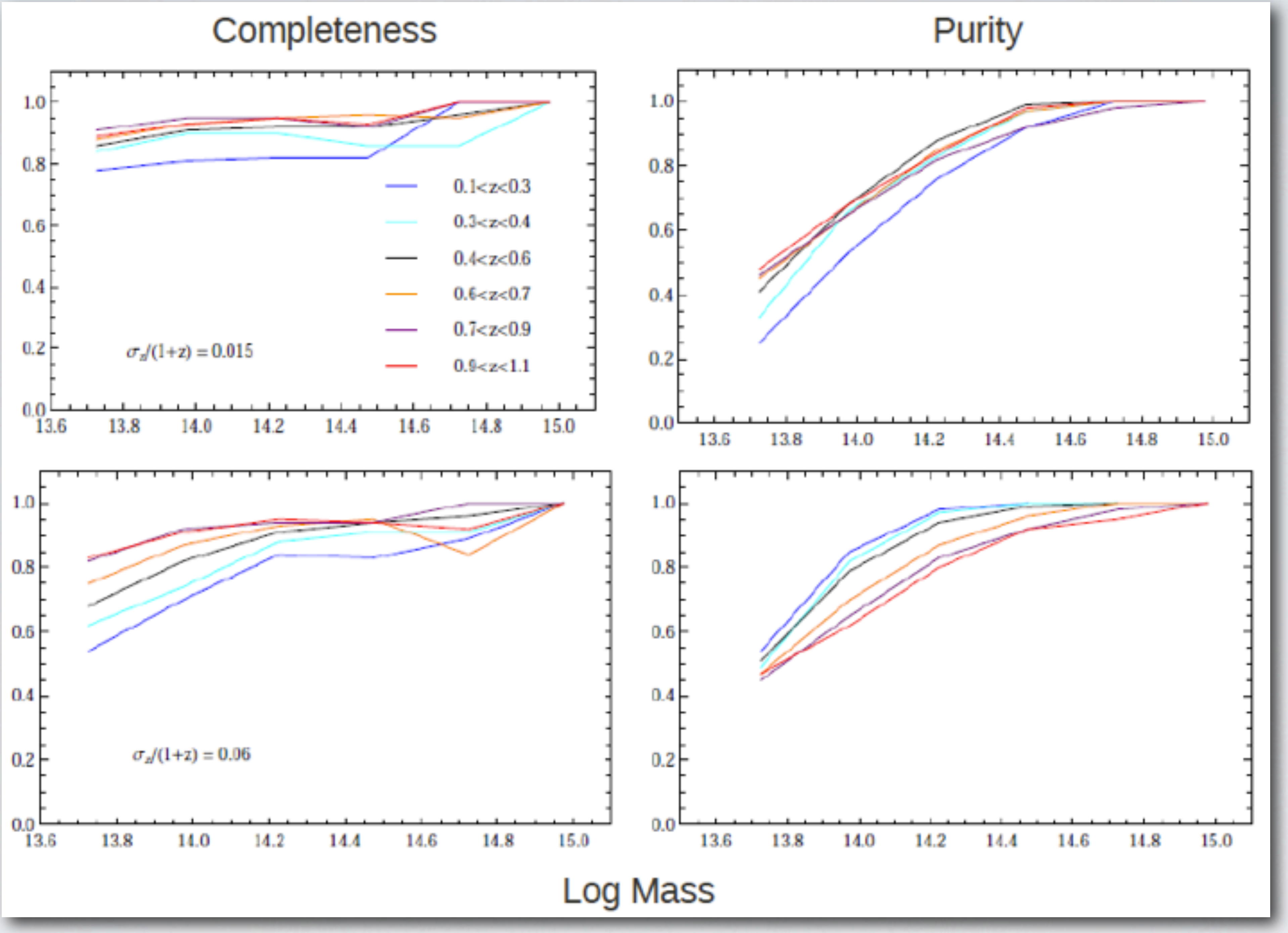


Shear-shear correlation function and power spectrum preliminary results.

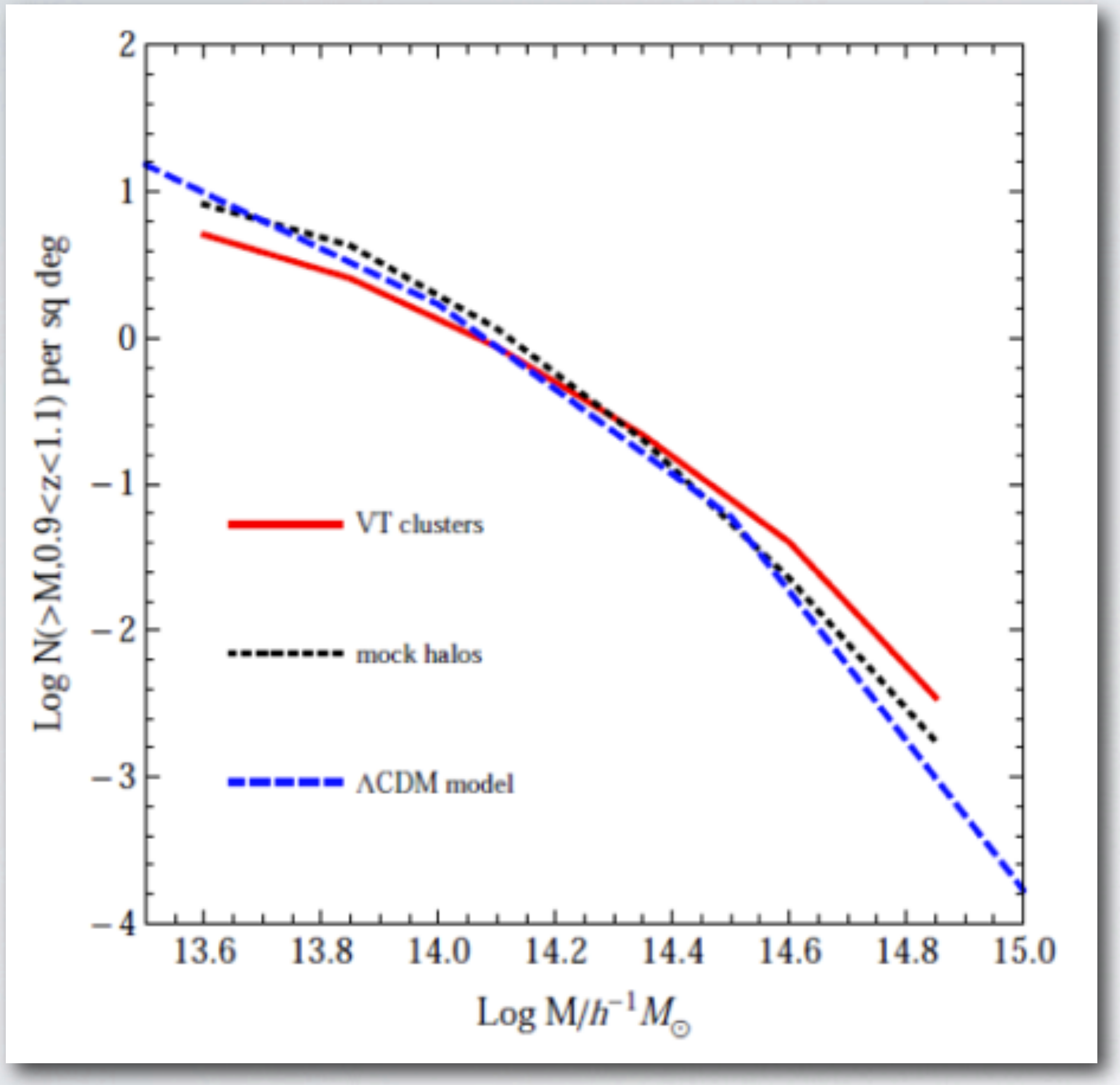
COADD: CLUSTERS



CLUSTER SELECTION FUNCTION



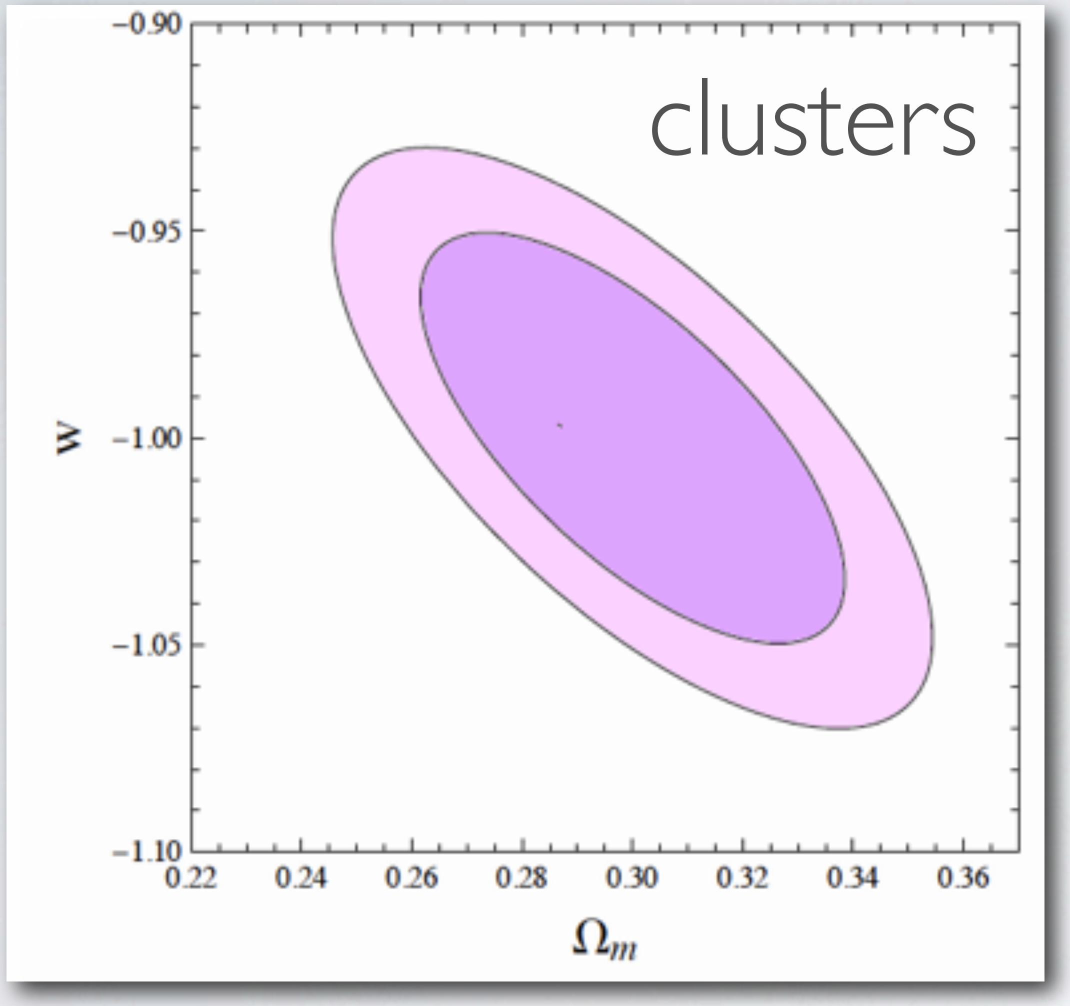
CLUSTER MASS FUNCTION



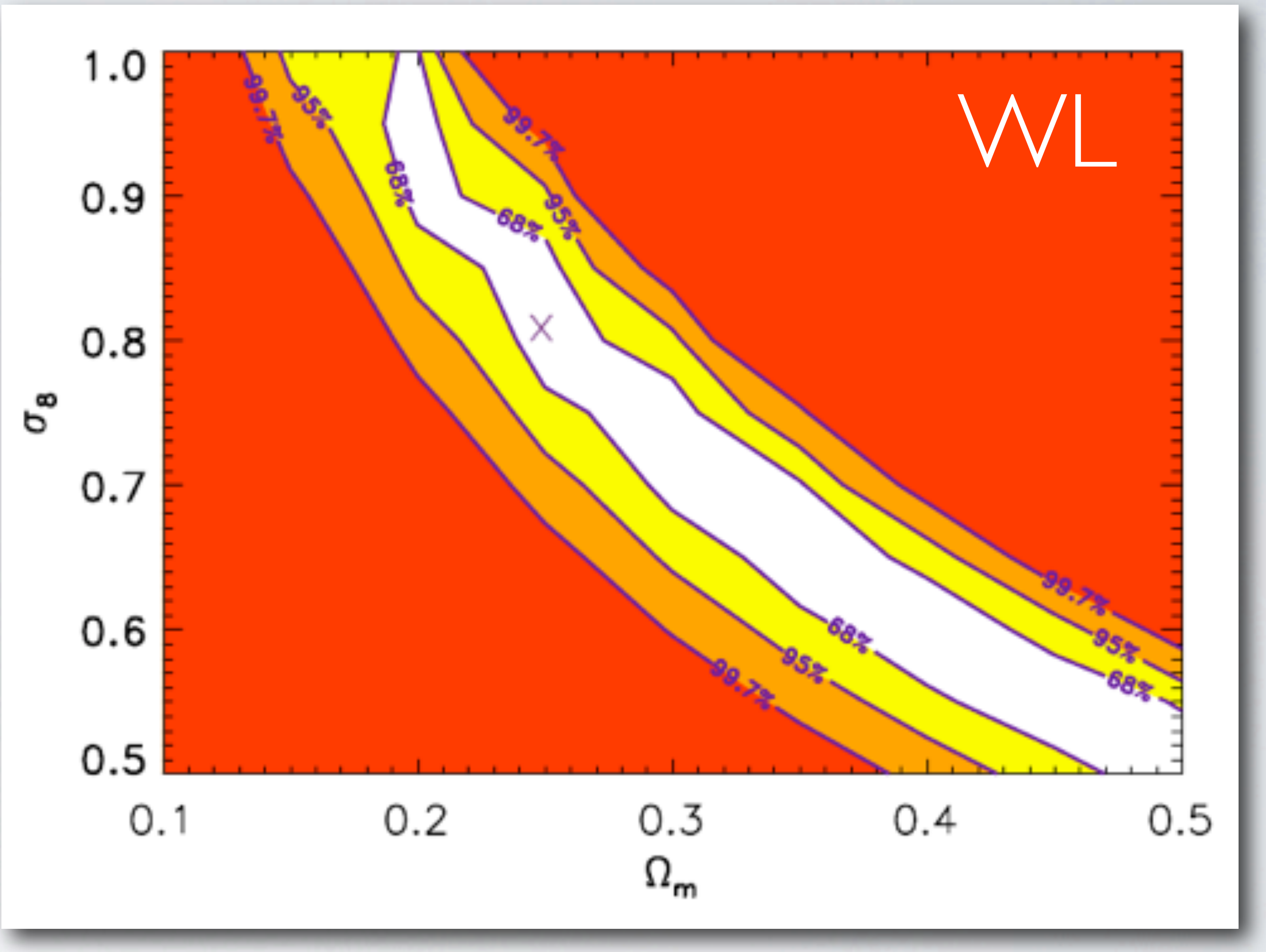
By applying the VT cluster finder on mock catalogs, we can measure the selection function for the Coadd catalog.

We apply that selection function back to the cluster number counts to obtain the mass function.

COADD PROJECTED LIMITS

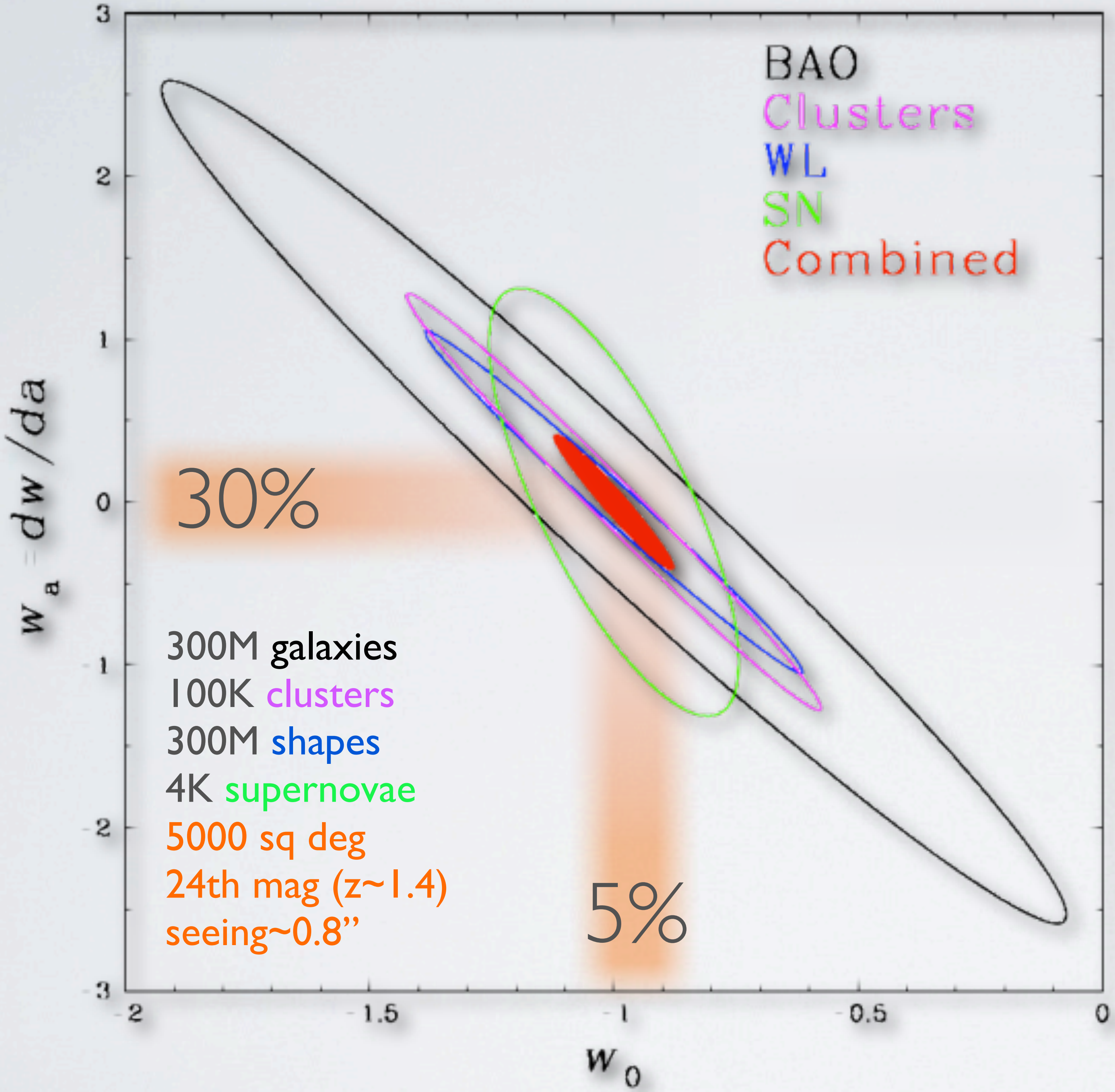


First measurement of w from optically selected cluster abundances alone.



Confirming measurement by CFHTLS group. Applying a new method.

SUMMARY



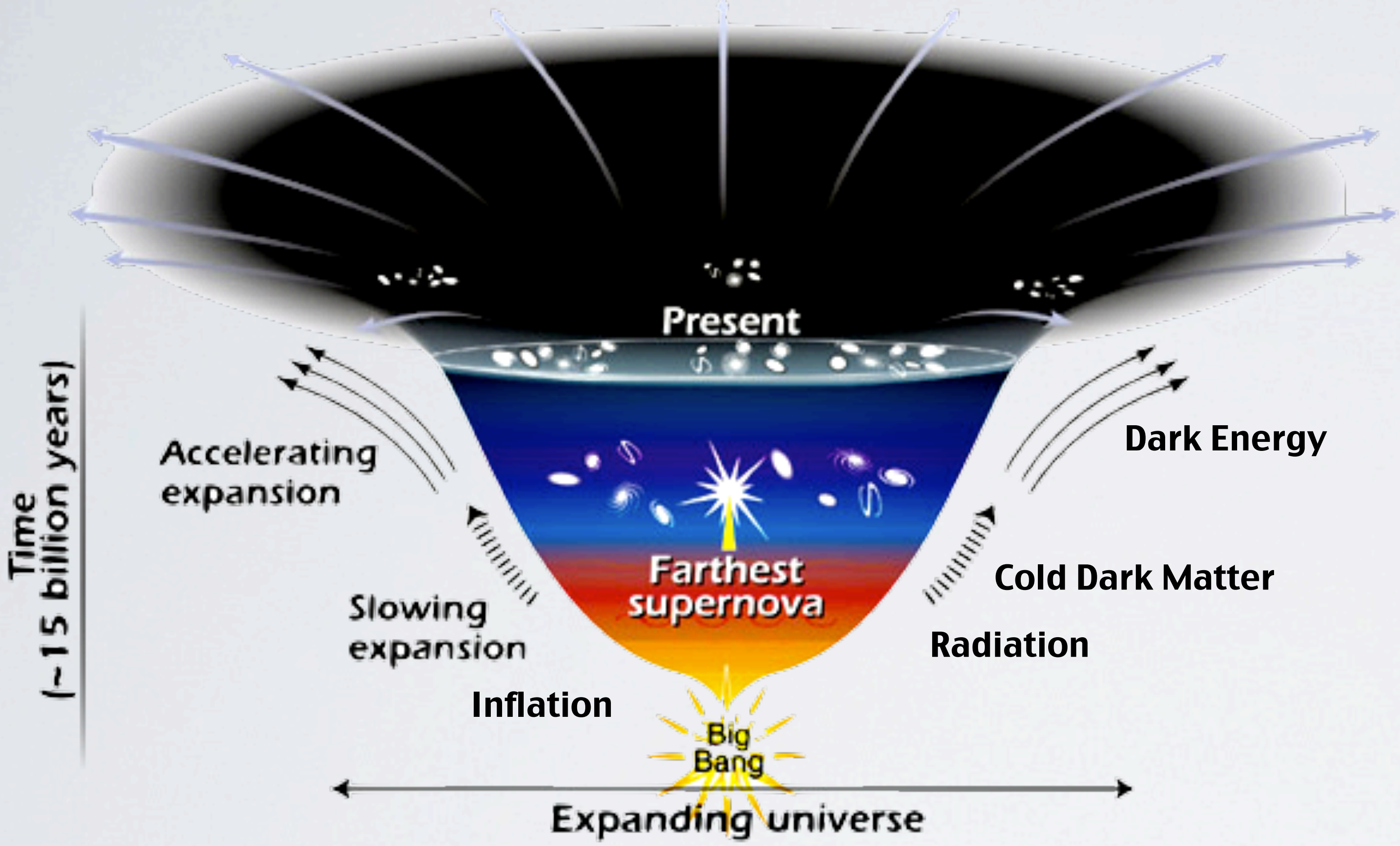
In this talk we have...

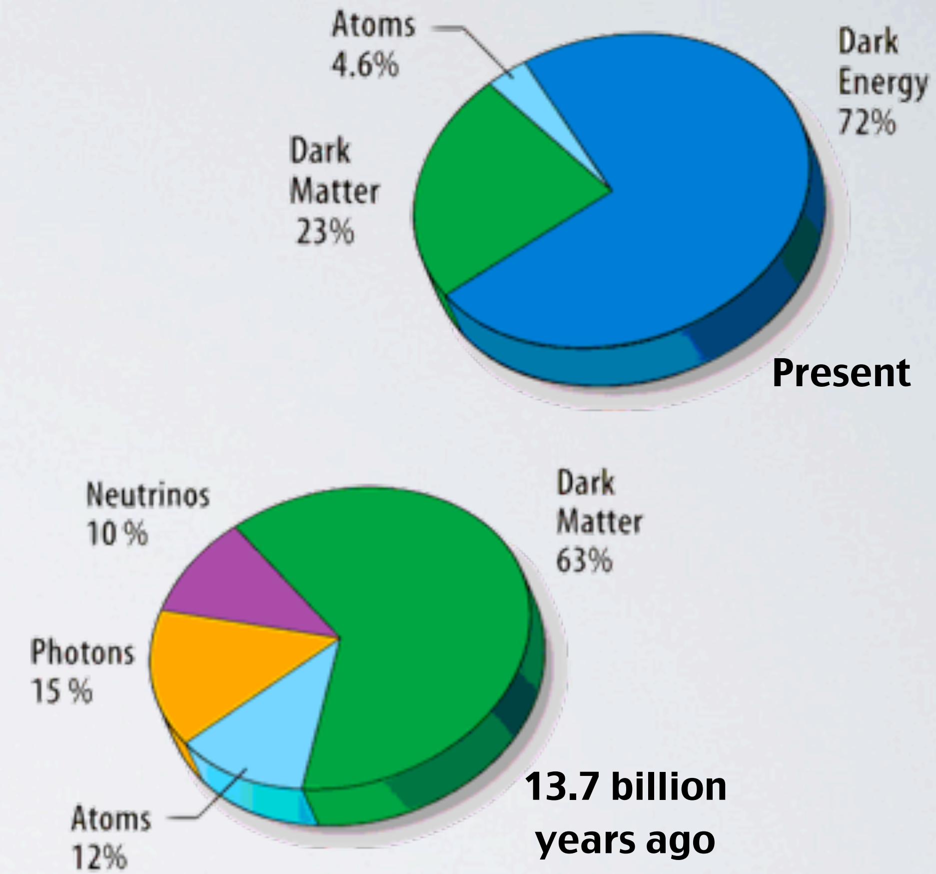
reported on the status of our SDSS Coadd cosmology analyses.

discussed how DES will allow for outstanding new measurements of dark energy.

argued that by analyzing this state of the art data set similar to DES, we can improve the current limits while getting ready for the upcoming survey.

DARK ENERGY & ACCELERATED EXPANSION





$$\ddot{a}/a = -(3p + \rho)$$

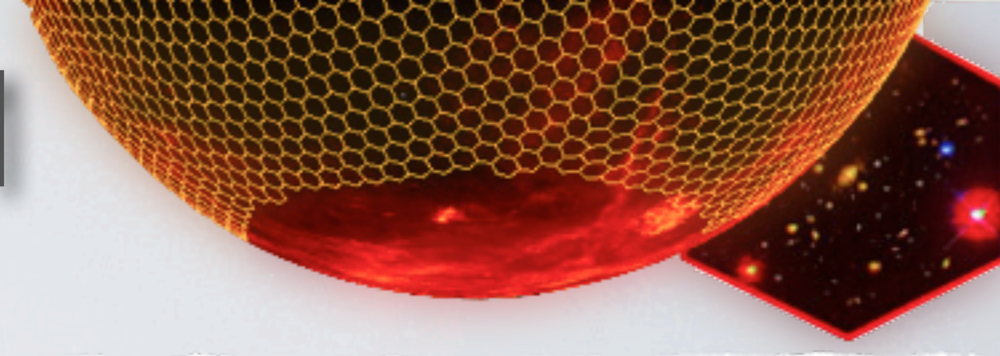
spacetime geometry (scale factor)

energy content (equation of state)

$$p = w(a)\rho$$

$$w(a) = w_0 + w_a(1 - a) + \cdots$$

QUANTUM VACUUM & DARK ENERGY



fractional energy densities

$$\Omega_\Lambda = 1 - \Omega_m - \Omega_k$$

Ω_m Matter energy density

Ω_k Geometrical curvature

Ω_Λ Dark energy density, if vacuum, $w_0 = w = -1,\ w_a = 0$

cosmological constant (Λ)

This is how well we know Dark Energy today. Combining **multiple probes** (Komatsu et al. 2010). ➤➤

$$w_0 = -\,0.93 \pm 0.12$$
$$w_1 = +\,0.38 \pm 0.65$$
$$\Omega_\Lambda = 0.72 \pm 0.02$$

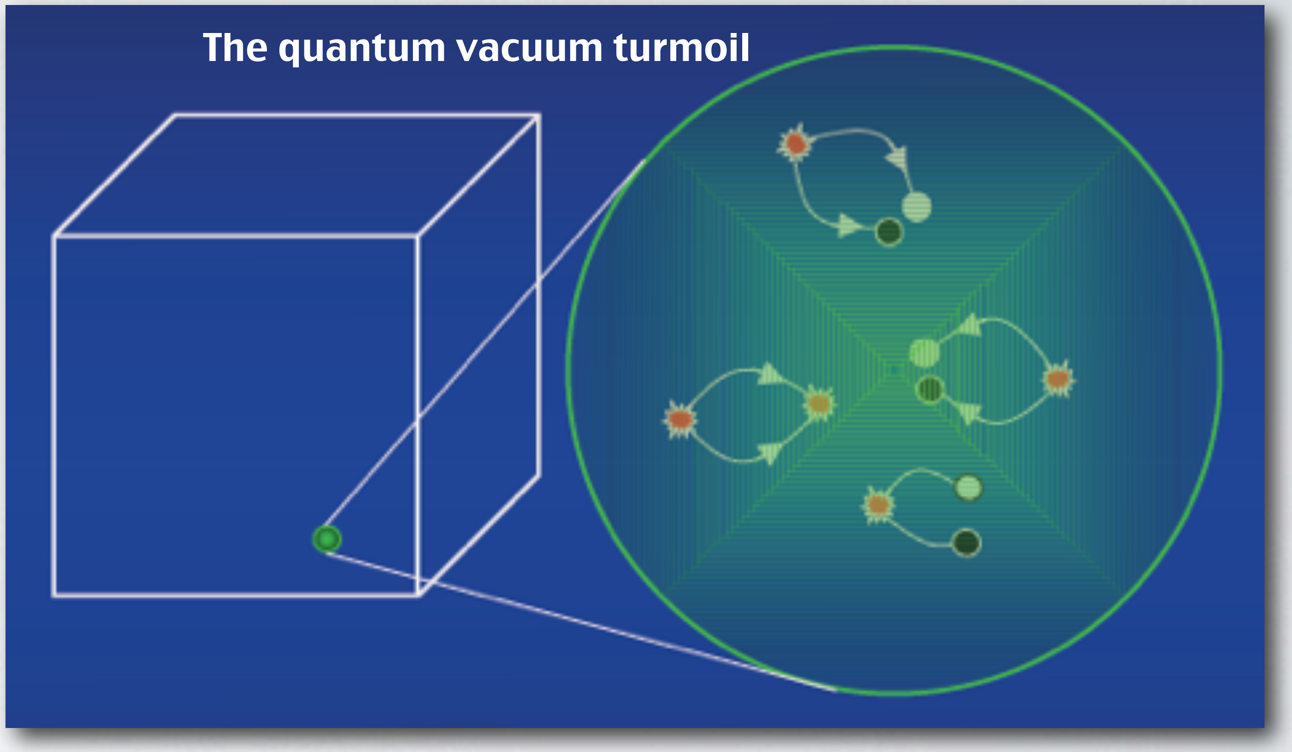
Equation of state consistent with ➤➤ **cosmological constant** !

What about the energy density? **Ask a theorist...**

COSMOLOGICAL CONSTANT PROBLEM

Simple calculation: $\Omega_\Lambda = 10^{120}$
Well, that can't be right.

Through some not yet understood mechanism (symmetry?) the vacuum energy is cancelled and Ω_Λ is identically zero.



➤➤ **Well, that can't be right either...**
We have measured ➤➤ $\Omega_\Lambda \simeq 0.7$

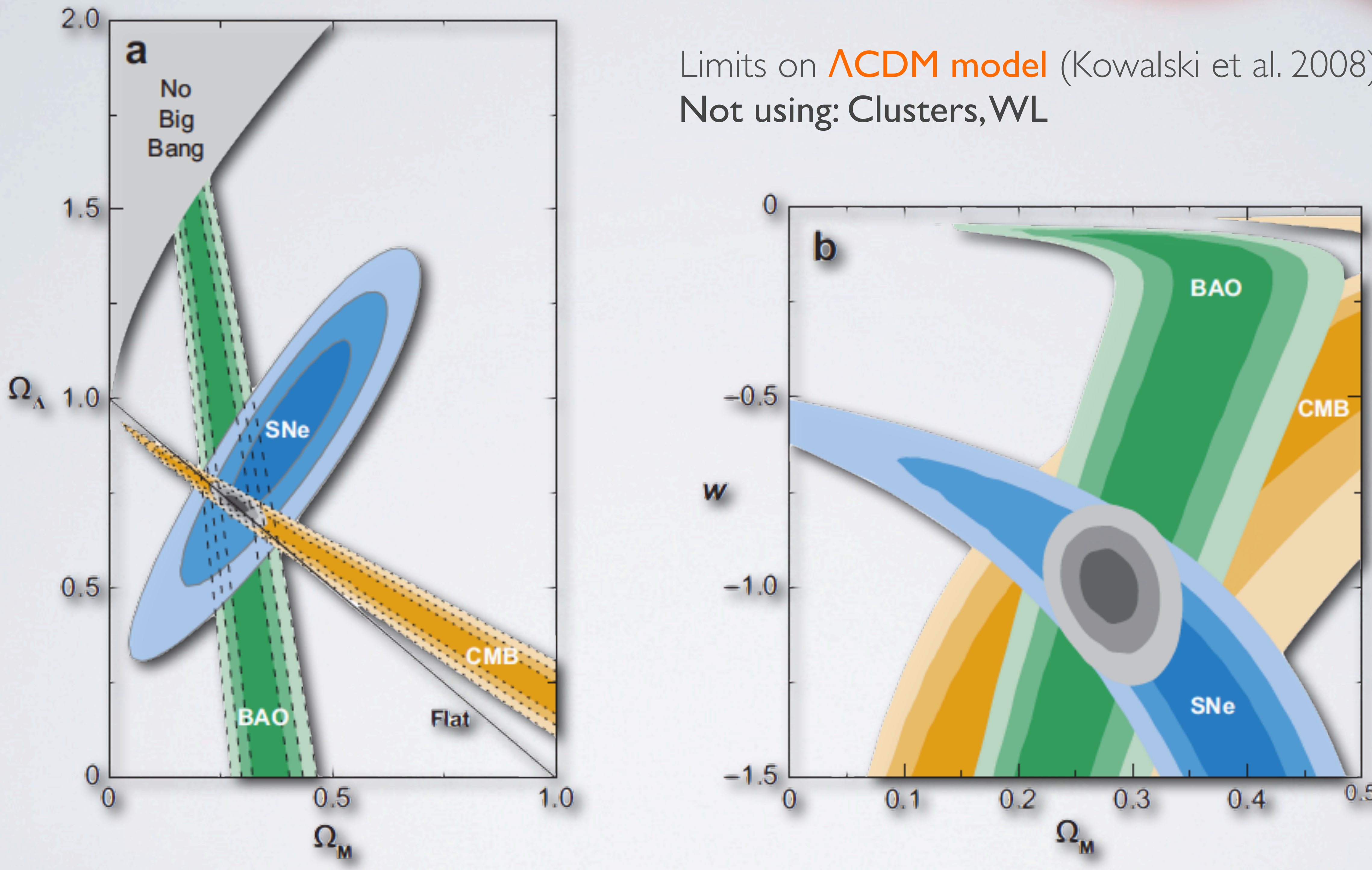
A CRISIS IN PHYSICS

Puzzle #1: Why so small?
Puzzle #2: Why so big?
Puzzle #3: What is the Physics?

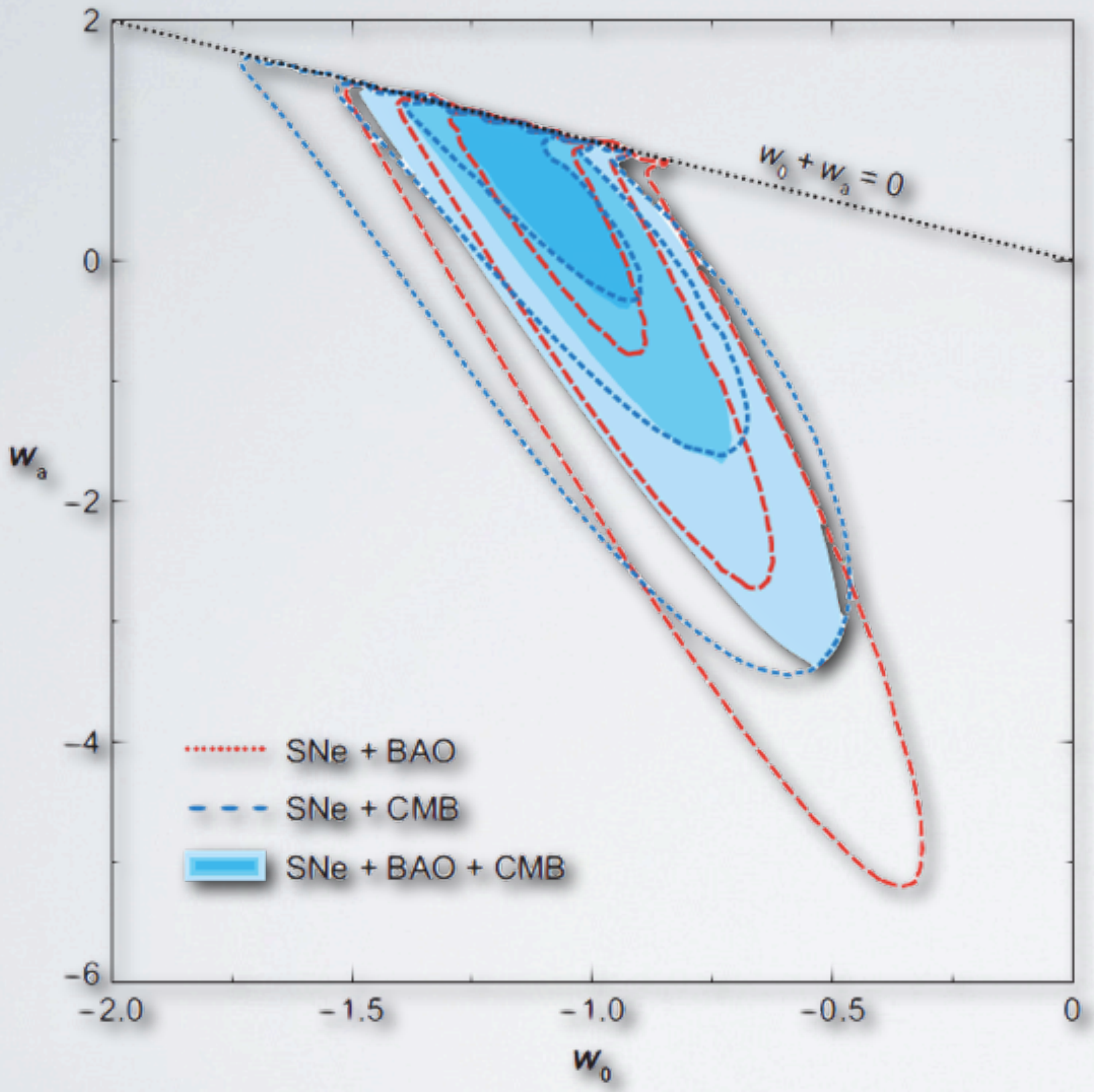
The nature of dark energy is arguably the most profound and outstanding problem of fundamental physics.

CURRENT LIMITS

Limits on ΛCDM model (Kowalski et al. 2008).
Not using: Clusters, WL



CURRENT LIMITS

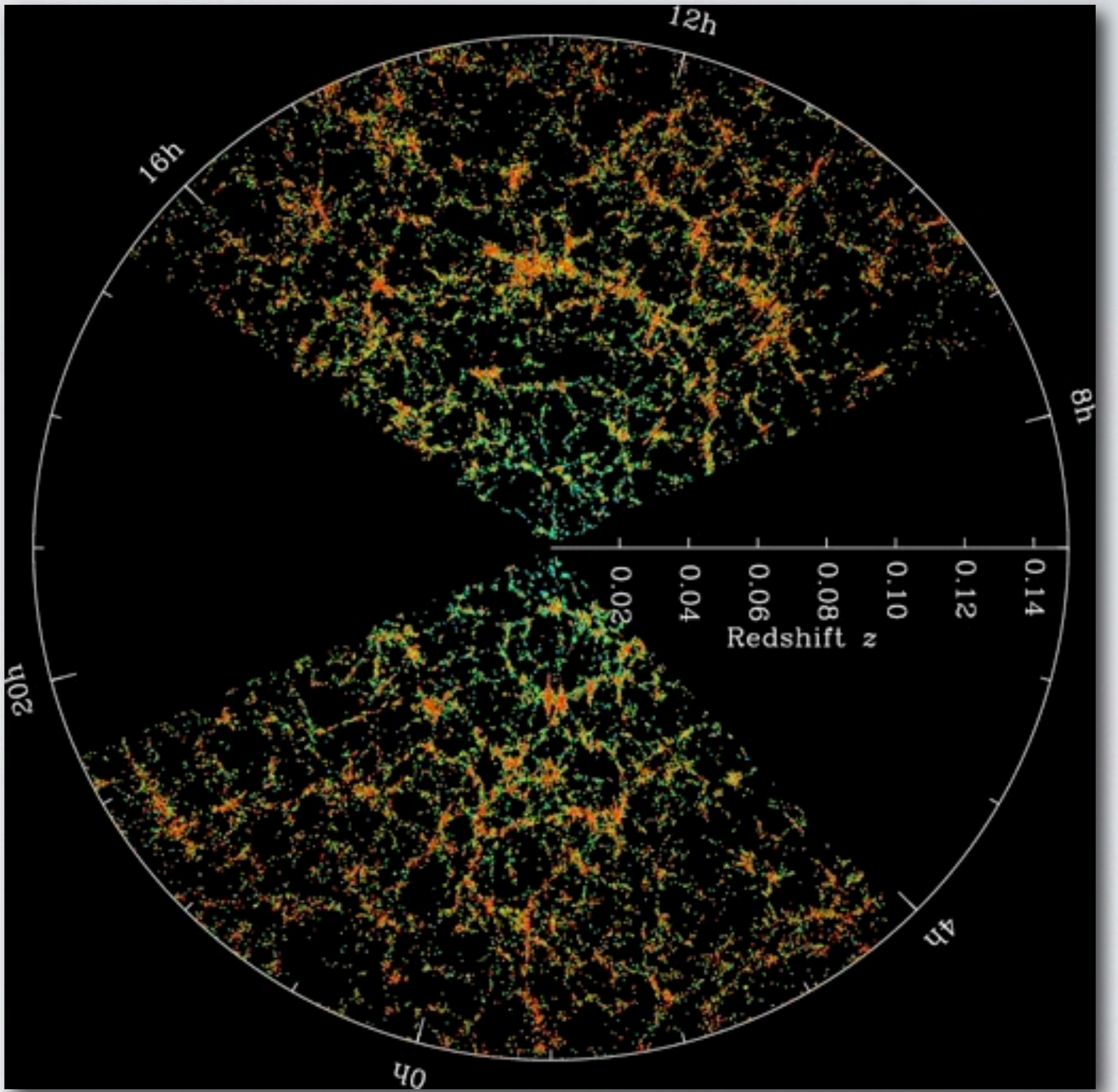


Constraints on **the two parameters** of the dark energy equation of state, in a flat universe. (Kowalski et al. 2008).

Not using: Clusters, WL.

DISTRIBUTION OF GALAXIES

Large scale structure in the northern and southern slices of the SDSS main galaxy redshift sample. The slice is 2.5 degrees thick and galaxies are color-coded by luminosity.



Stacked Shear Estimator

$$\Delta\Sigma = \frac{1}{2\mathcal{R}} \frac{\sum w_{l,s} \frac{e_t}{<\Sigma_c^{-1}>}}{\sum w_{l,s}}$$

estimator

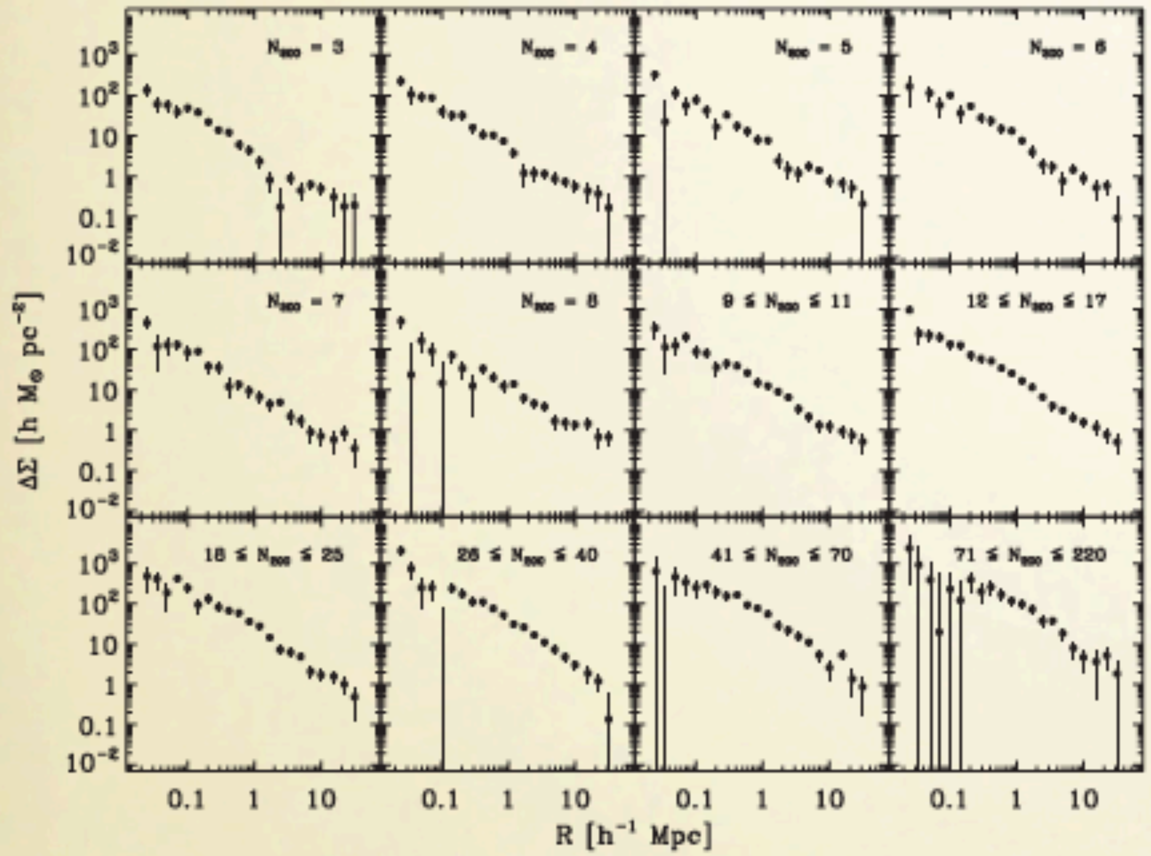
source redshift probablity distribution

$$P(z_{s_i}) = \frac{1}{\sqrt{2\pi\sigma_{ph}^2}} exp\left(\frac{-(z_{s_i}-z_{ph})^2}{2\sigma_{ph}^2}\right)$$

$$<\Sigma_{crit}^{-1}> \simeq \sum_{i=1}^{n} \Delta z_{s_i} P(z_{s_i}) \Sigma_{crit}^{-1}(z_{s_i}, z_{l_i})$$

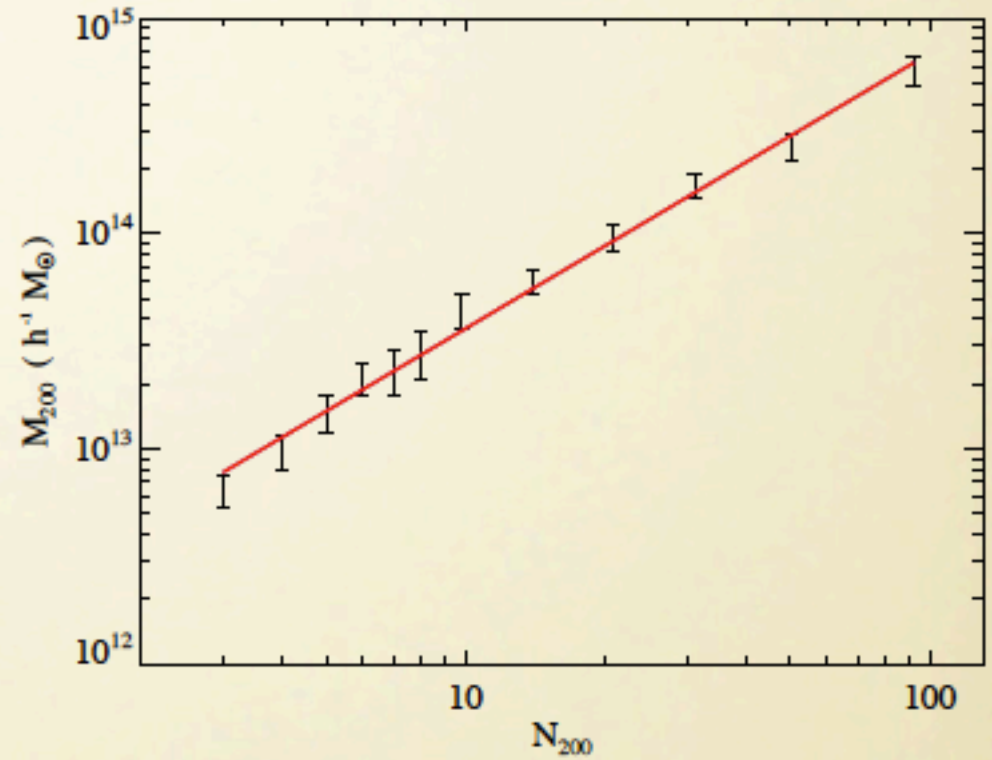
SDSS North is done, what's left?

SDSS North Stacked Clusters
0.1<z<0.3



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

Sheldon et al. 2007

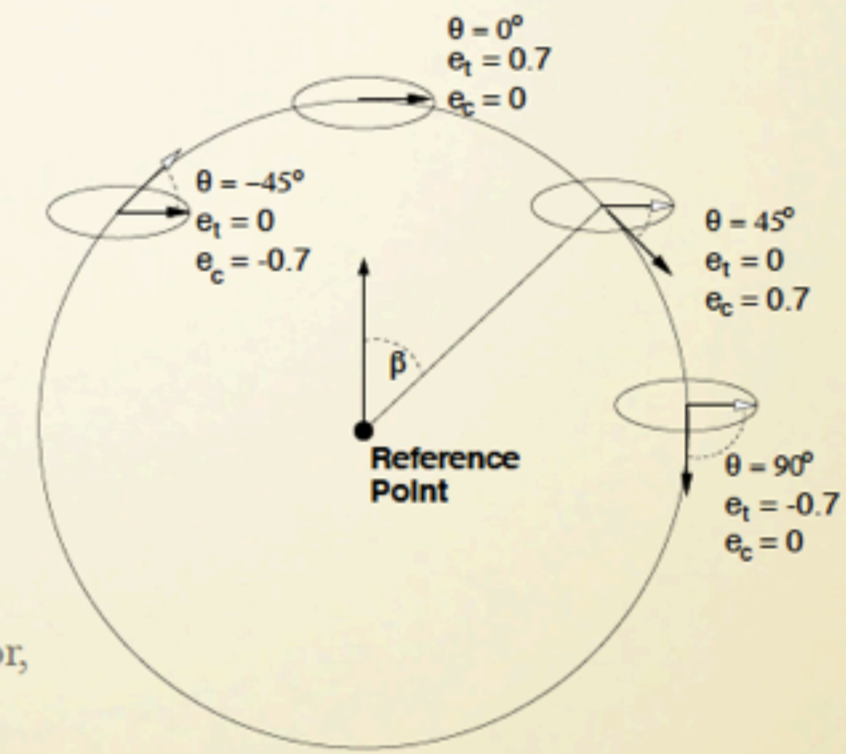


Johnston et al. 2007

Tangential Shear

$$\gamma_t = \frac{\bar{\Sigma}(\leq r) - \Sigma(r)}{\Sigma_{\text{crit}}}$$

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G}\frac{D_s}{D_l D_{ls}}$$

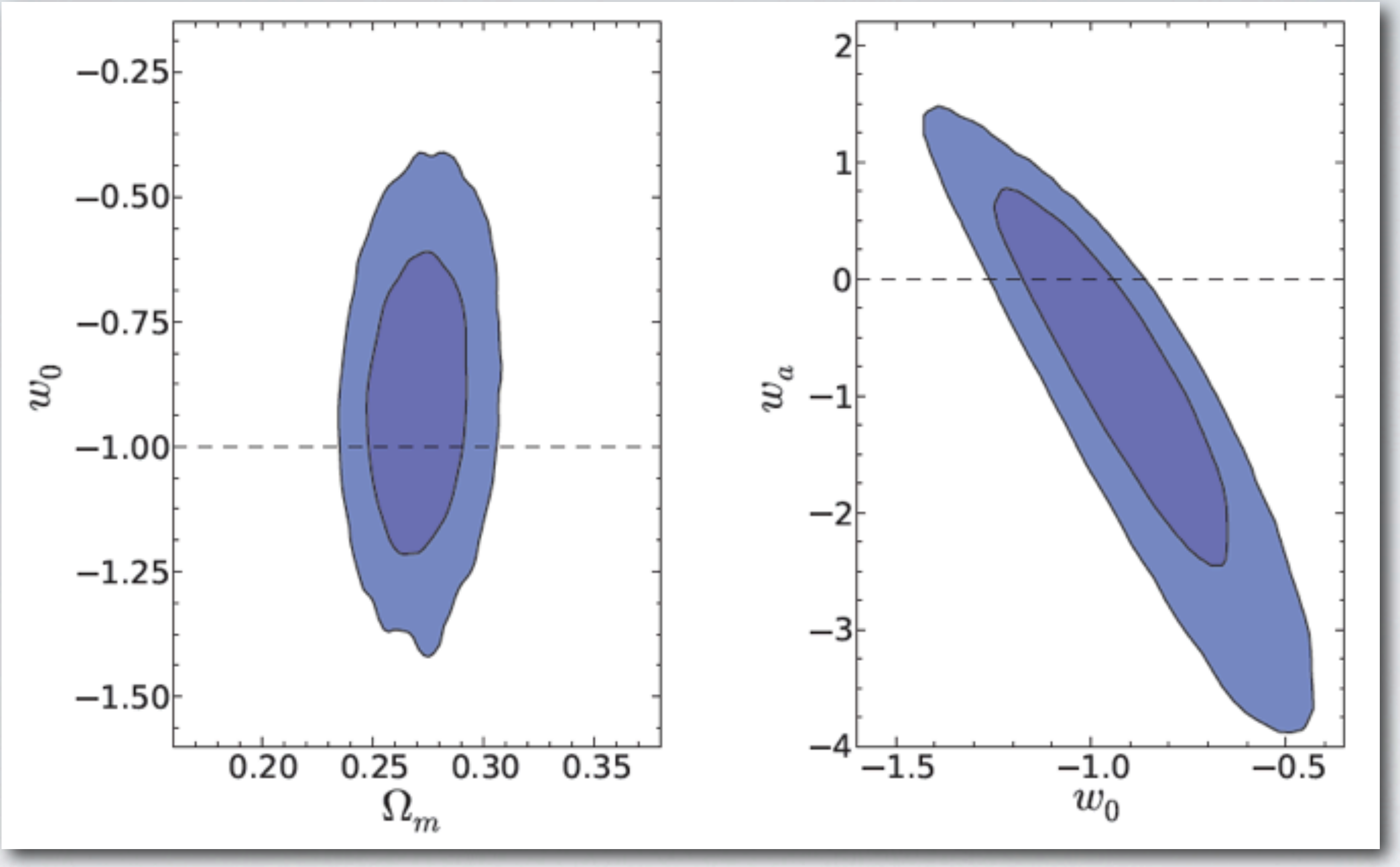


one galaxy ellipticity is a noisy shear estimator, need to average over many galaxies

$$\gamma_t = \frac{1}{2\mathcal{R}}\frac{\sum_i w_i e_{t_i}}{\sum_i w_i}$$

(shear estimator)

CURRENT RESULTS



Sullivan et al. 2011

STANDARD STARS

SDSS Stripe 82

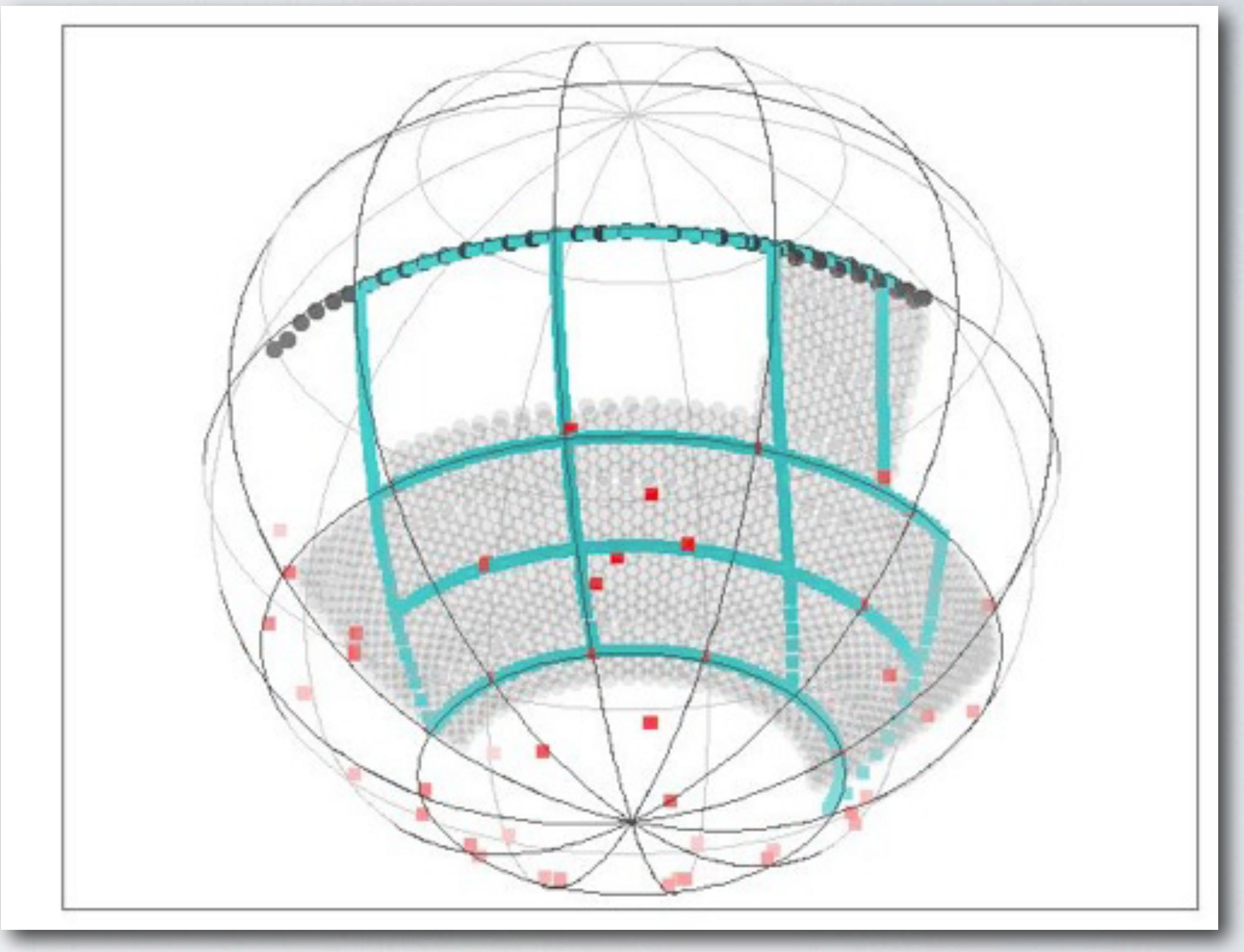
- r = 14.5-21
- # density ~ 4000 / sq deg
- area ~ 250 sq deg

PreCam

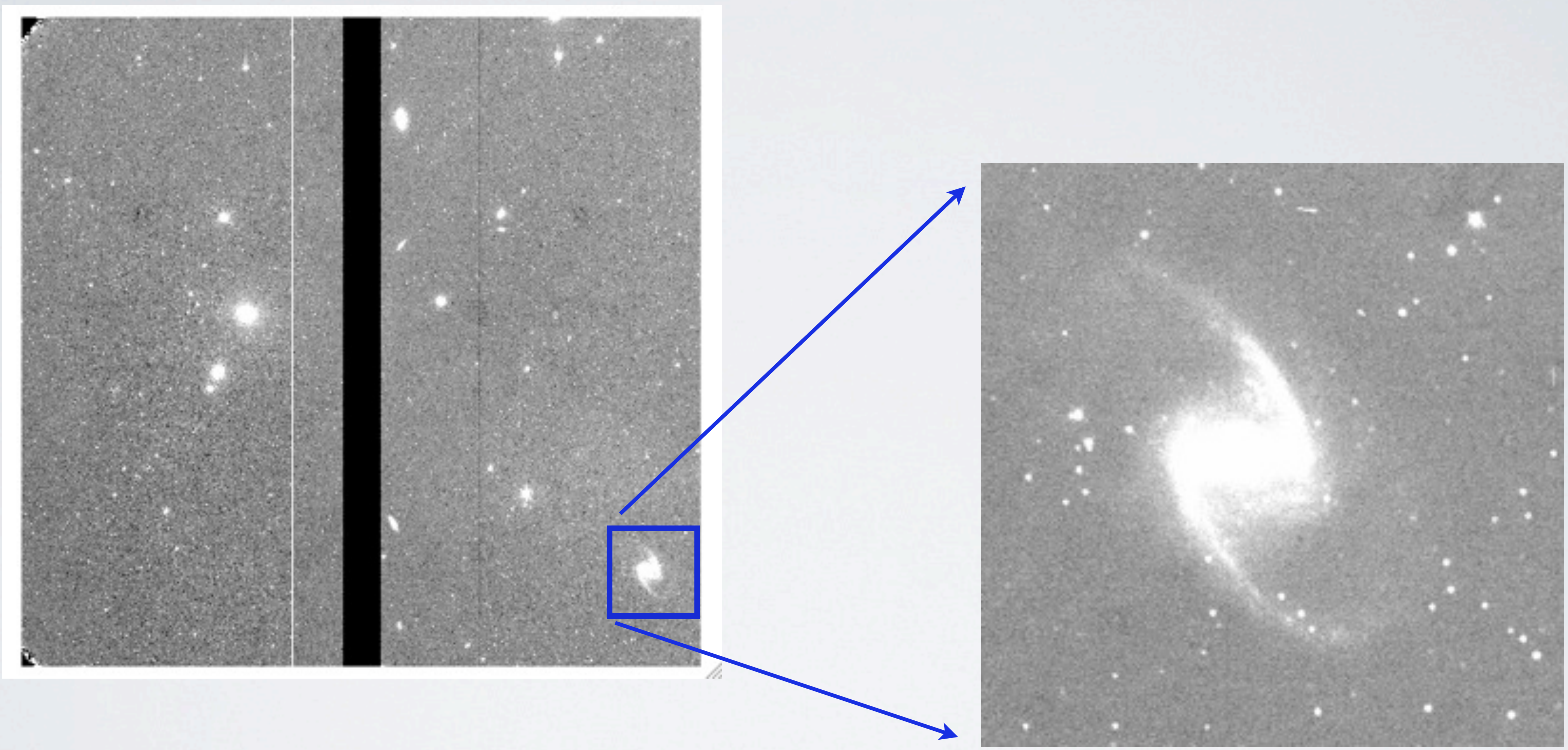
- r ~ 14.5-23
- # density ~200 / sq deg
- area ~ 500 sq deg

Southern u'g'r'i'z' Standards

- r = 9-18
- # density ~ tens per field
- Sixty 13.5'x13.5' fields



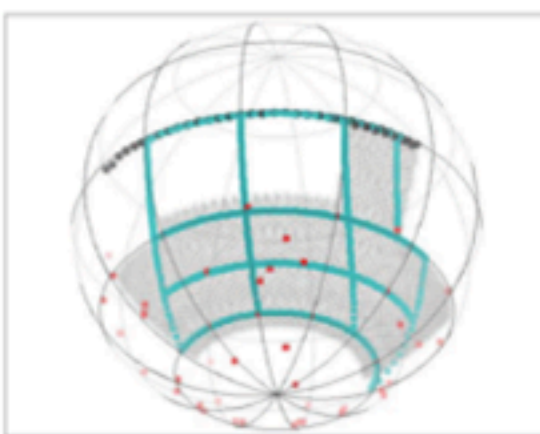
PRECAM IMAGE



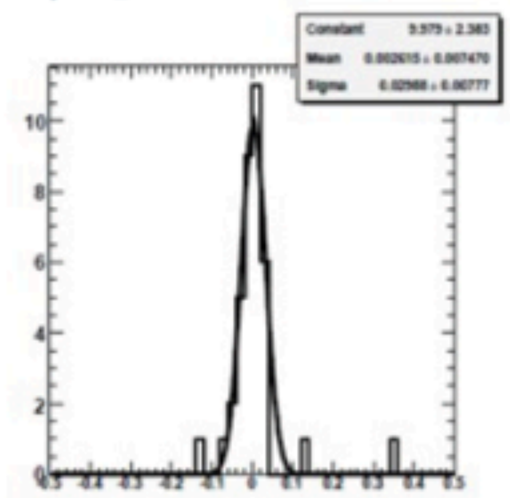
PRECAM OVERVIEW

PreCam: a "mini-DECam," camera developed & built at ANL

- Science motivation for pre-survey observations with DECam hardware:
  - 0.01 calibrated stars/image w/o PreCam, ~1000/image with PreCam
  - reach 2% photometry requirement faster, and better chance at 1% goal
  - possible 10% savings (~$1M!) in telescope time
- Test-bed for DECam hardware, software, and observing strategies
- PreCam science run and First Results, ~500 images/night
- From FNAL Director's Review: "Data from PreCAM plays a key role in the calibration." It is "imperative that PreCam…be finished before the end of the 2012-2013 observing campaign."



PreCam Grid overlaid on DES Footprint, with Standard Star Fields



i-band comparison to USNO standards on equator, σ=2-3.5%

Kyler Kuehn (ANL) and Jorge Briones (CTIO) during camera installation (Aug 30, 2010).

DOE Lab review, May 24-26,2011; K.Byrum 3