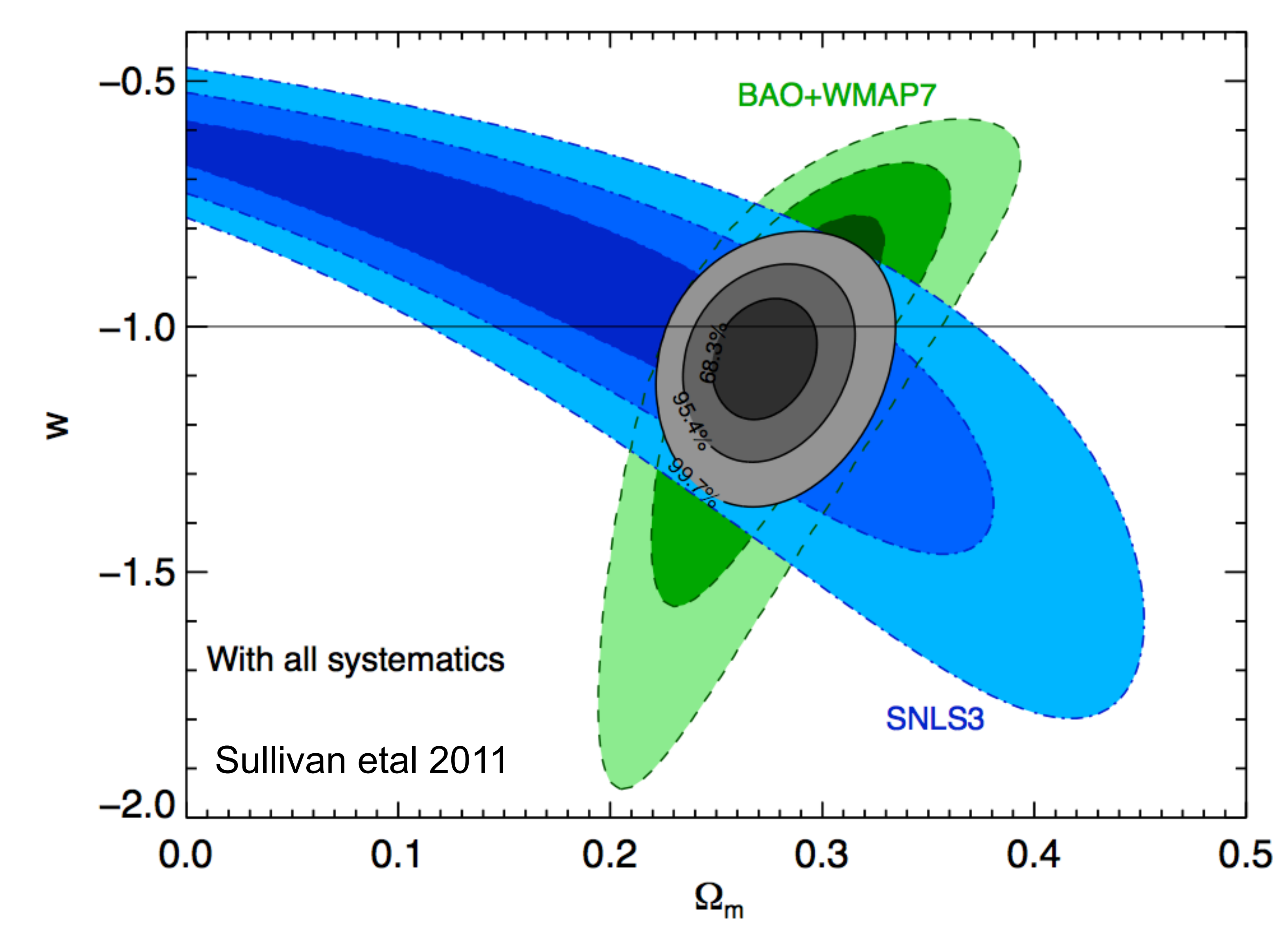
Combined probes and large-scale structure with the Dark Energy Survey

Joe Zuntz

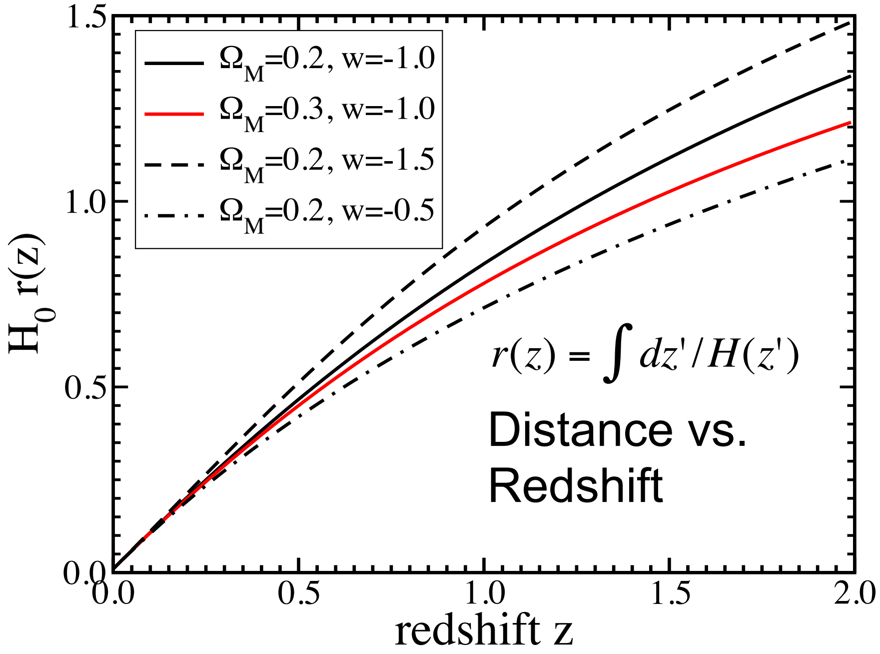
filling in for Josh Frieman

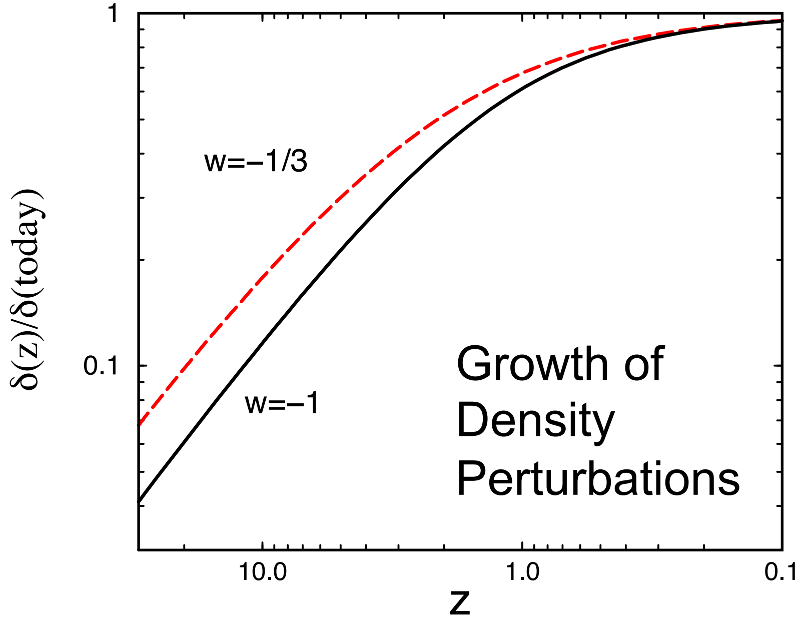


Recent Constraints from Supernovae, Cosmic Microwave Background Anisotropy (WMAP) and Large-scale Structure (Baryon Acoustic Oscillations, SDSS)

What can we probe?

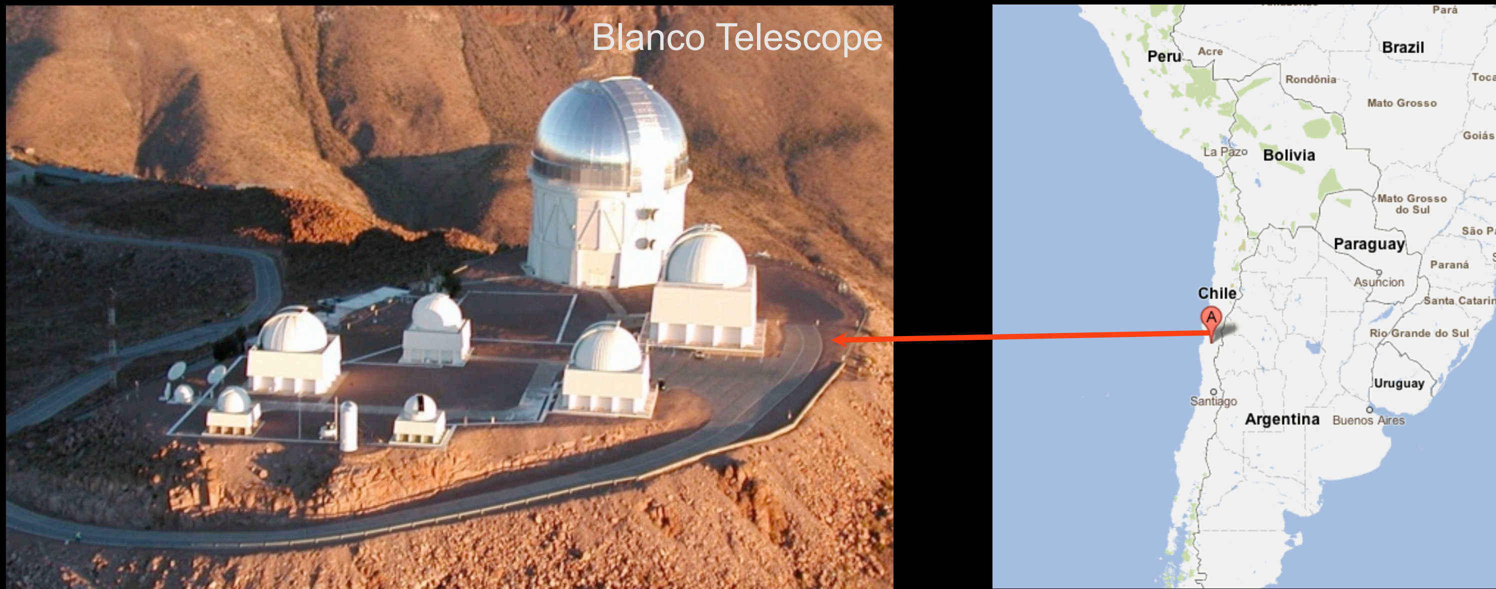
Require both to disentangle Dark Energy from Modified Gravity





- Weak Lensing cosmic shear — Distances+growth
- Supernovae — Distances
- Baryon Acoustic Oscillations — Distances and H(z)
- Cluster counting — Distances+growth
- Redshift Distortions — Growth

Blanco 4-meter Telescope at Cerro Tololo



Excellent astronomical site in Chilean Andes:

good seeing: ~0.75” median for site

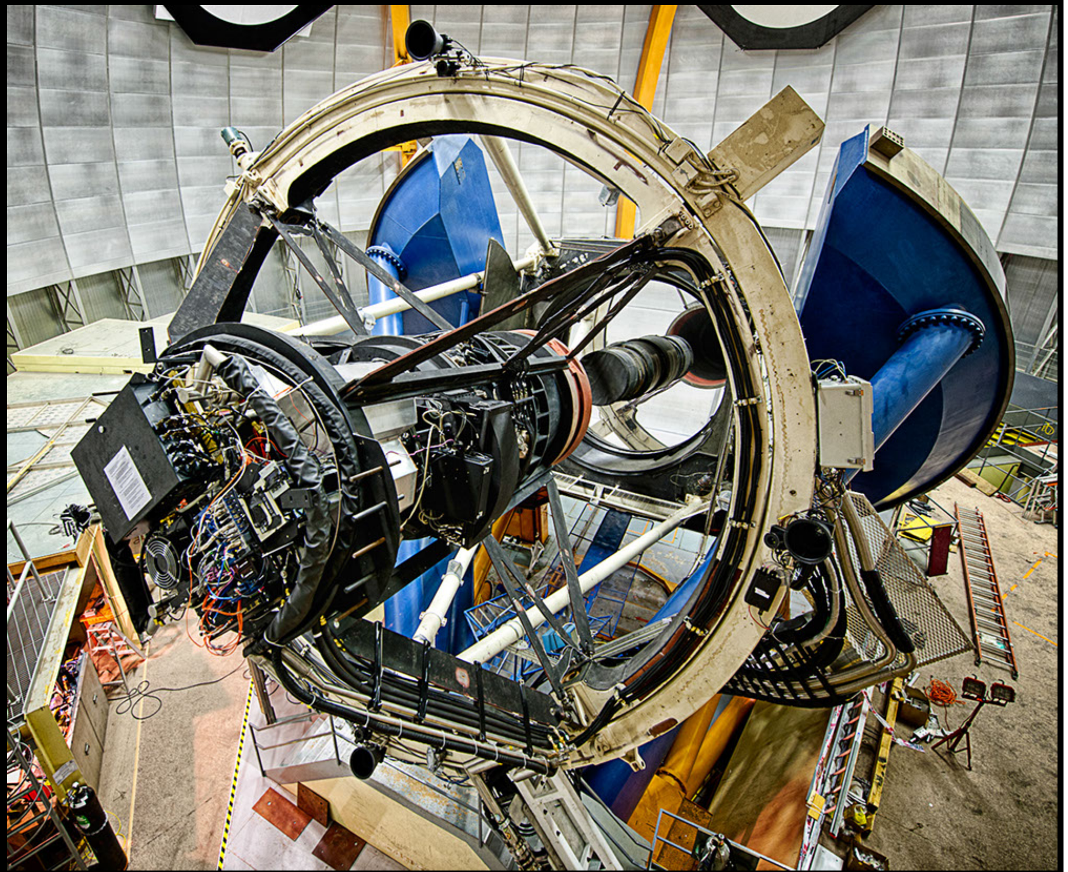
high, dry: high percentage of clear, photometric nights

Late 2003: NOAO Announcement of Opportunity for new facility instrument on the Blanco

The Dark Energy Survey

- Survey project using 4 complementary techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband imaging surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat *griz* (SNe)
- New 3 deg^2 FOV camera on the Blanco 4m telescope
  - Survey 2013-2018 (525 nights)
  - Facility instrument for astronomy community (DES 30% time)

DECam on the Blanco



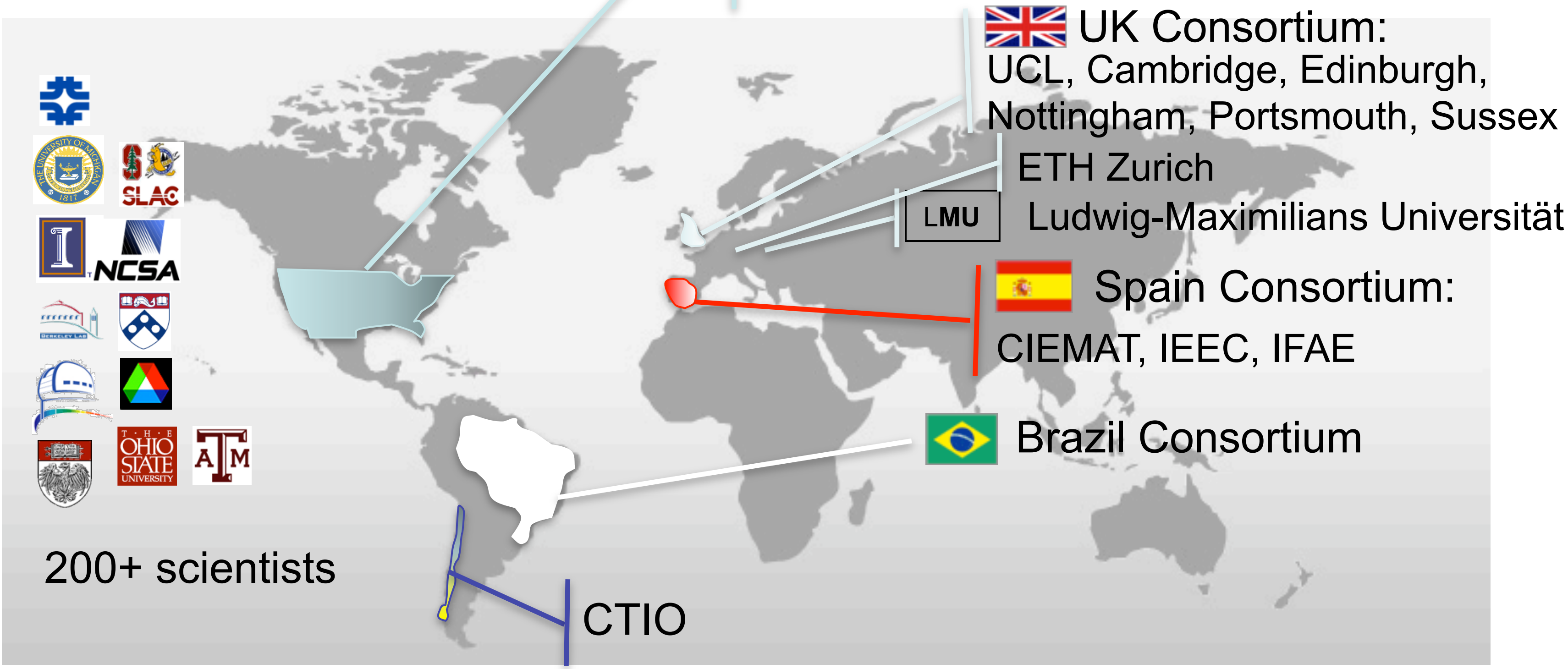
www.darkenergysurvey.org

DES Collaboration

DARK ENERGY SURVEY

Funding from DOE, NSF, foreign funding agencies, and DES institutions

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa-Cruz/SLAC/Stanford Consortium, Texas A&M



Project Structure & Timeline

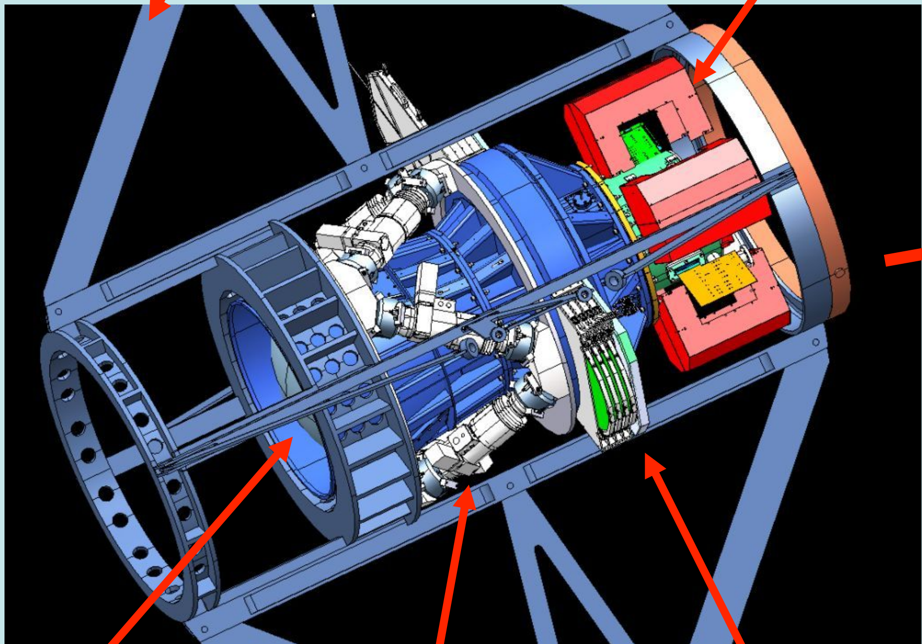
- 3 Construction Projects:
  - DECam (led by Fermilab; DOE support)
  - Data Management System (NCSA-led; NSF support)
  - CTIO Facilities Improvement Project (NSF/NOAO)

- NOAO Blanco Announcement of Opportunity 2003
- R&D, optical corrector elements
- Camera construction 2008-11
- New Prime Focus Cage with corrector installed May 2012
- Imager installalled August 2012
- First light with DECam on telescope: Sept. 12, 2012
- Commissioning: August-October 2012
- DES Science Verification: November 2012-Feb. 2013 (raw data public)
- Survey operations begin: Sept. 2013 (105-night seasons Sept-Feb)
- Community observing with DECam since Dec. 2012

Dark Energy Camera

Mechanical Interface of DECam Project to the Blanco

CCD Readout



Optical Corrector Lenses

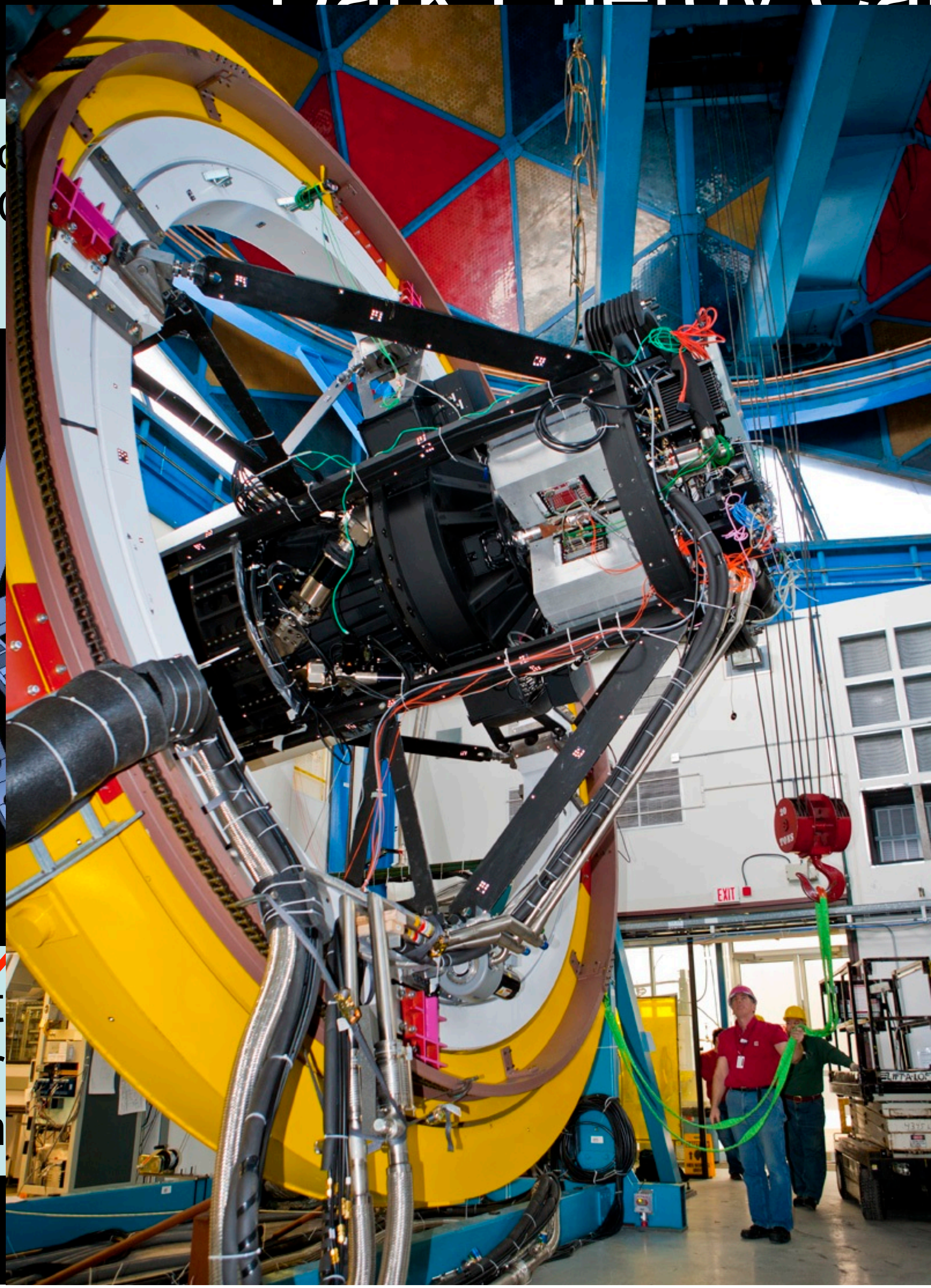
Hexapod: optical alignment

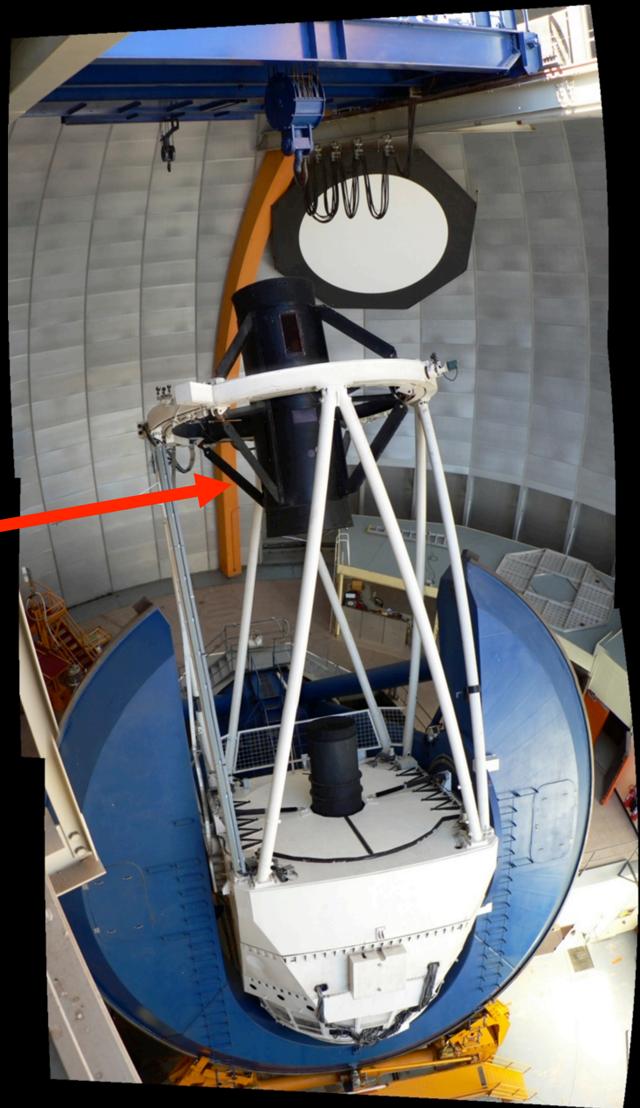
Filters & Shutter

Dark Energy Camera

Med
DEC

Opt
Cor
Len

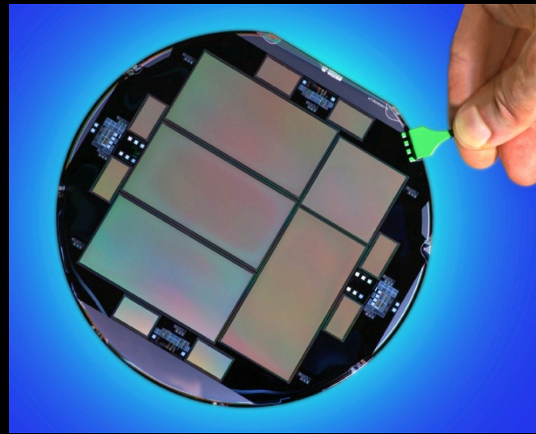




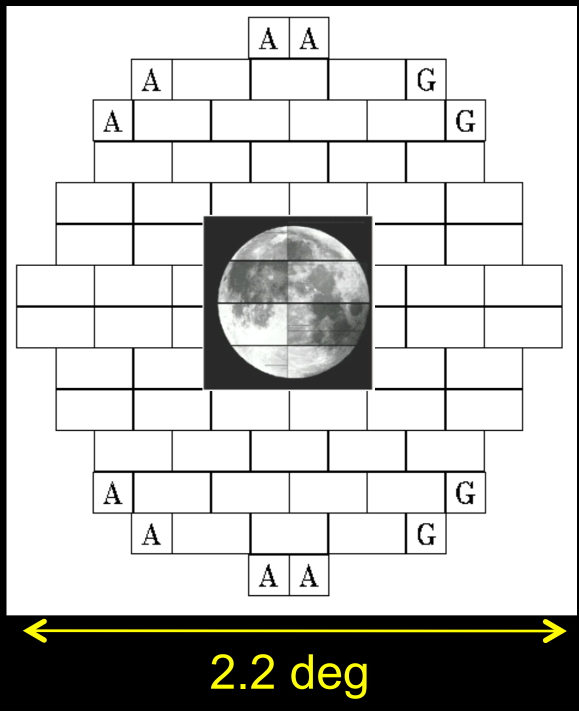
DECam mounted on
Telescope Simulator
at Fermilab in early 2011

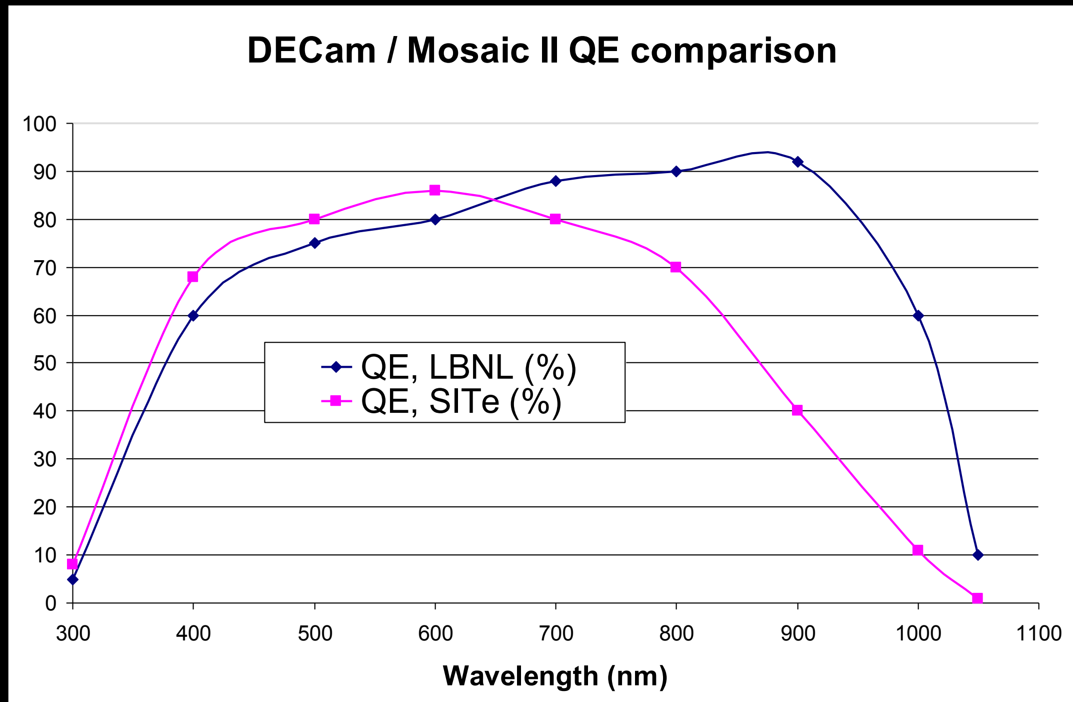
DECam CCDs

DARK ENERGY SURVEY



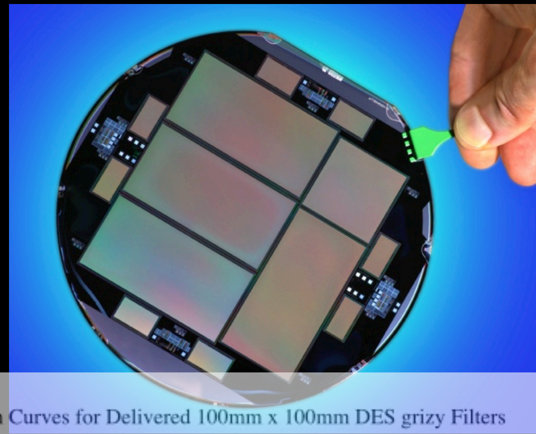
- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.264”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels





DECam CCDs

DARK ENERGY SURVEY



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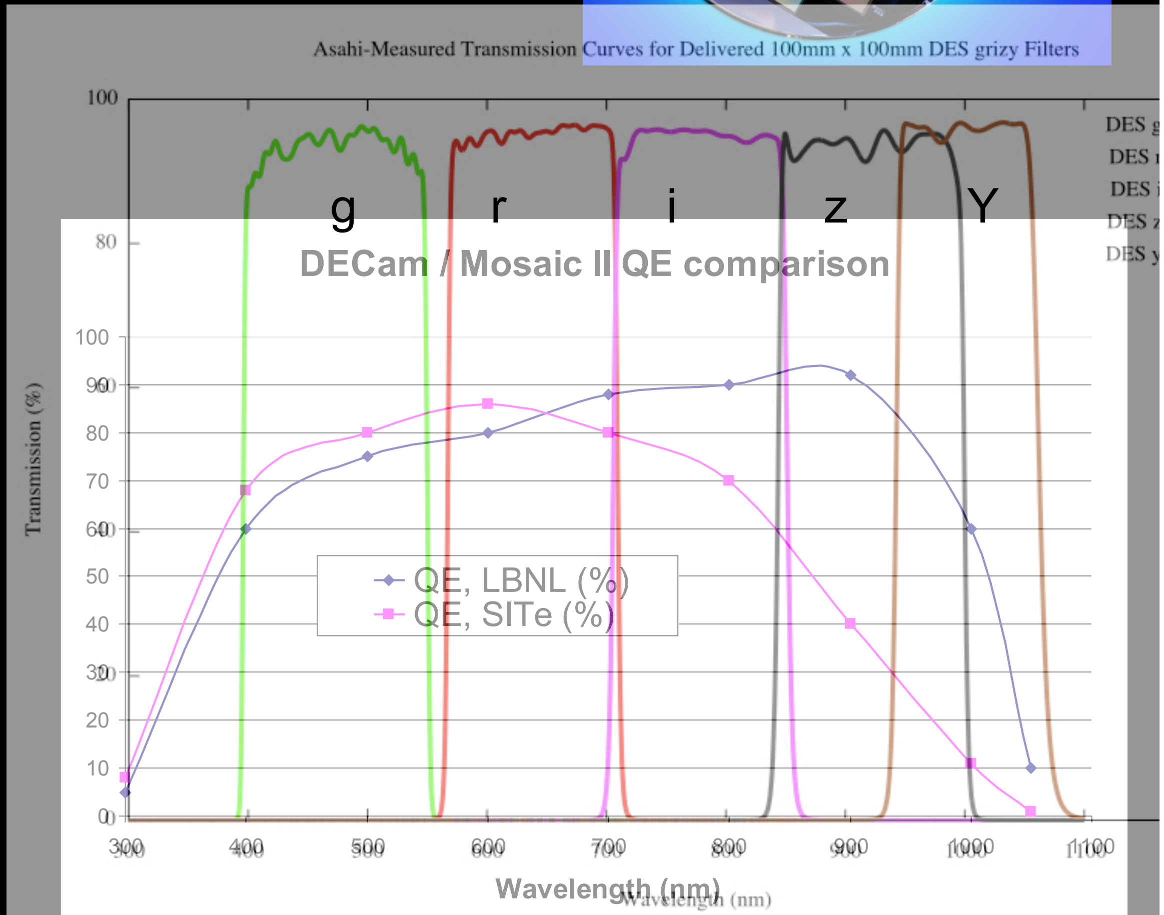
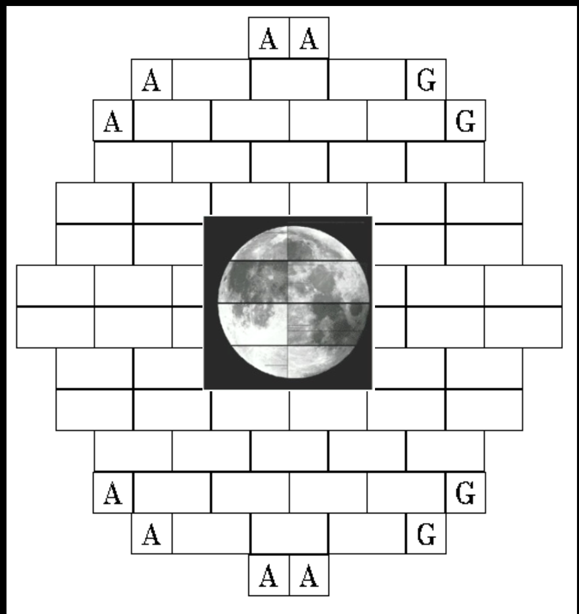
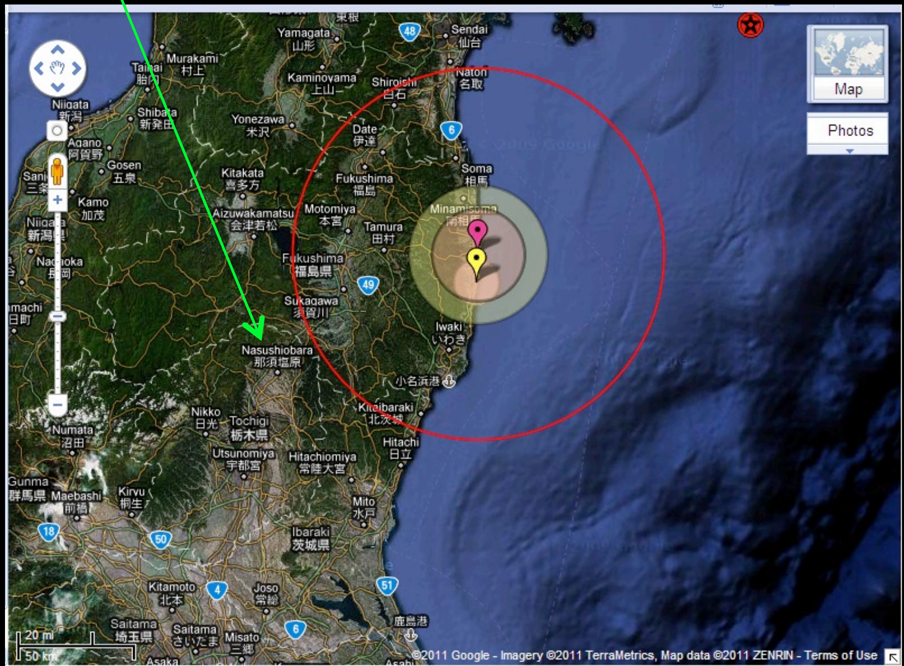


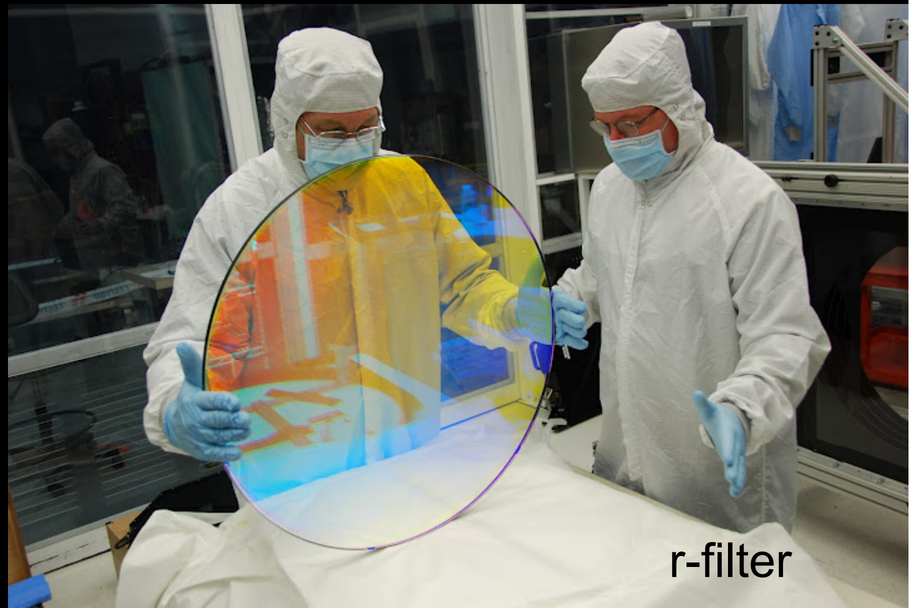


Asahi filters

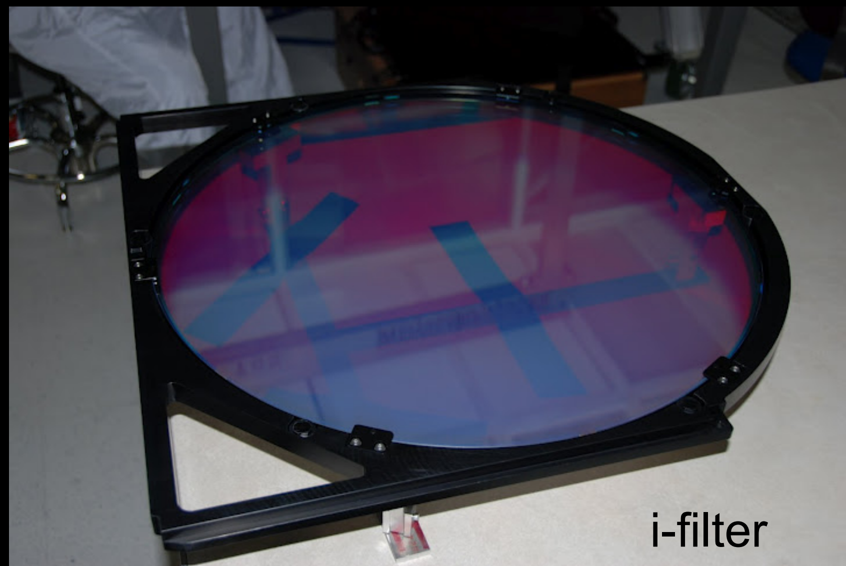
Filters

- 600 mm clear aperture, tight uniformity constraints, excellent throughput.
- Fabrication completed by Asahi within months of the tsunami in Japan.



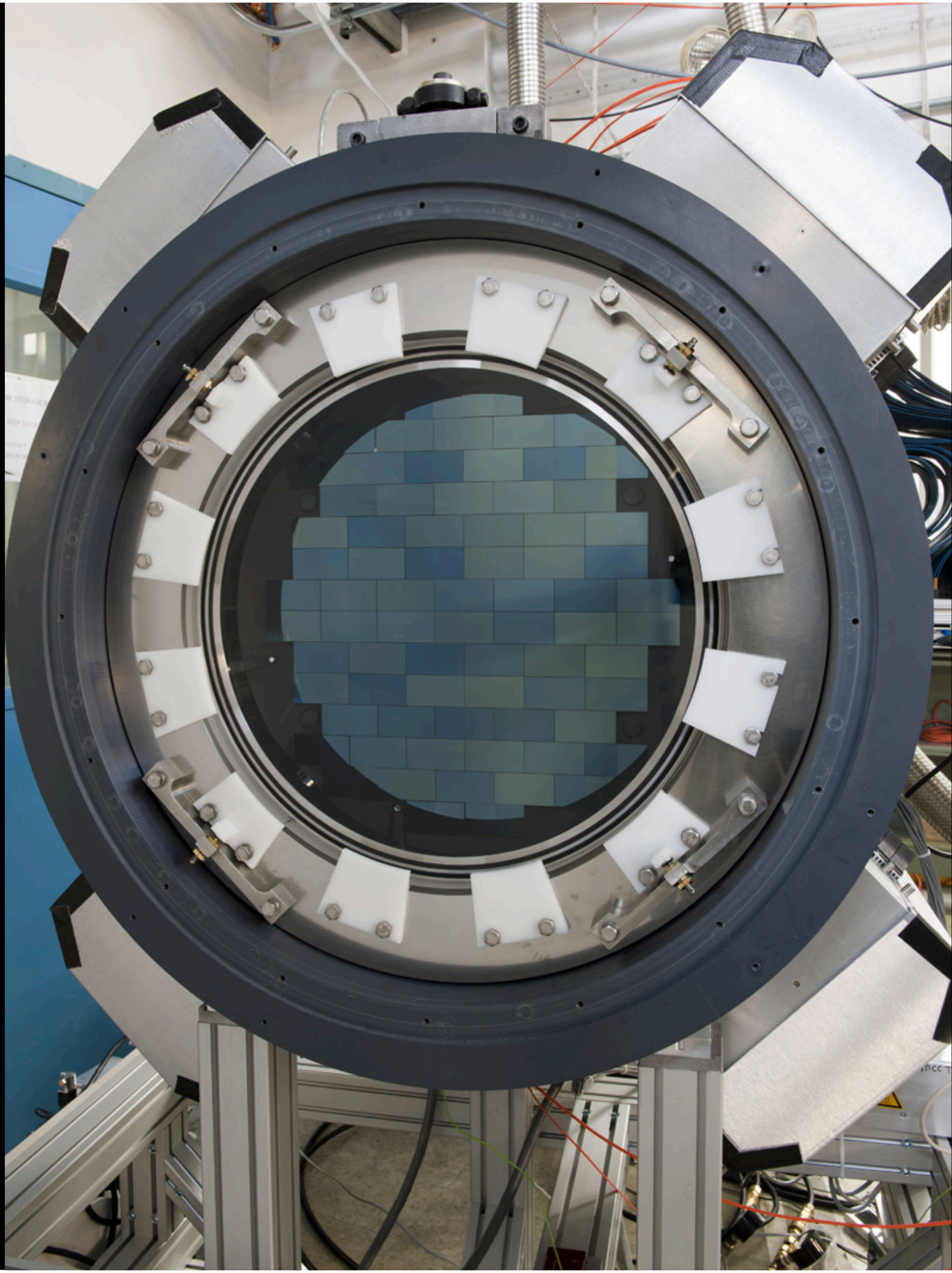


r-filter



i-filter

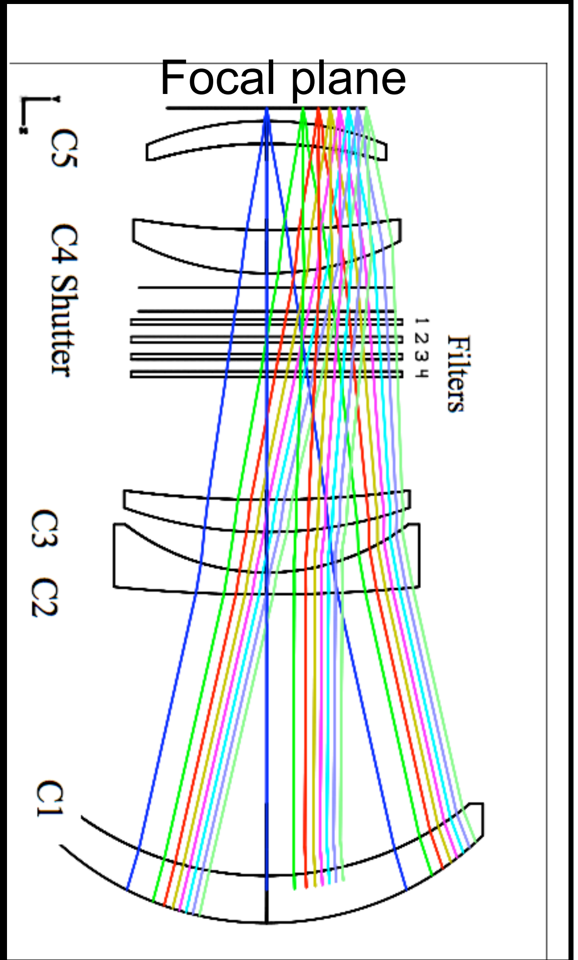
570-Mpix
DECam
imager



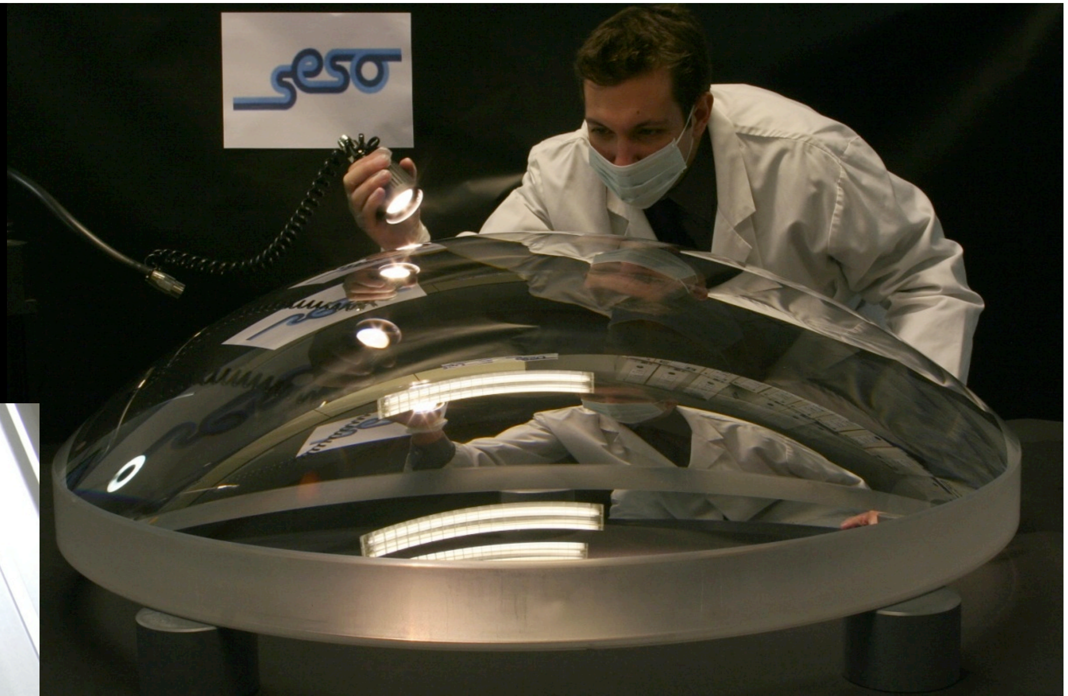
Optics

- Field of view: 2.2^{o} diameter
- Good image quality across FOV
- Optical elements aligned at UCL

S. Kent (FNAL)



DARK ENERGY SURVEY



C1 Lens

DARK ENERGY
SURVEY

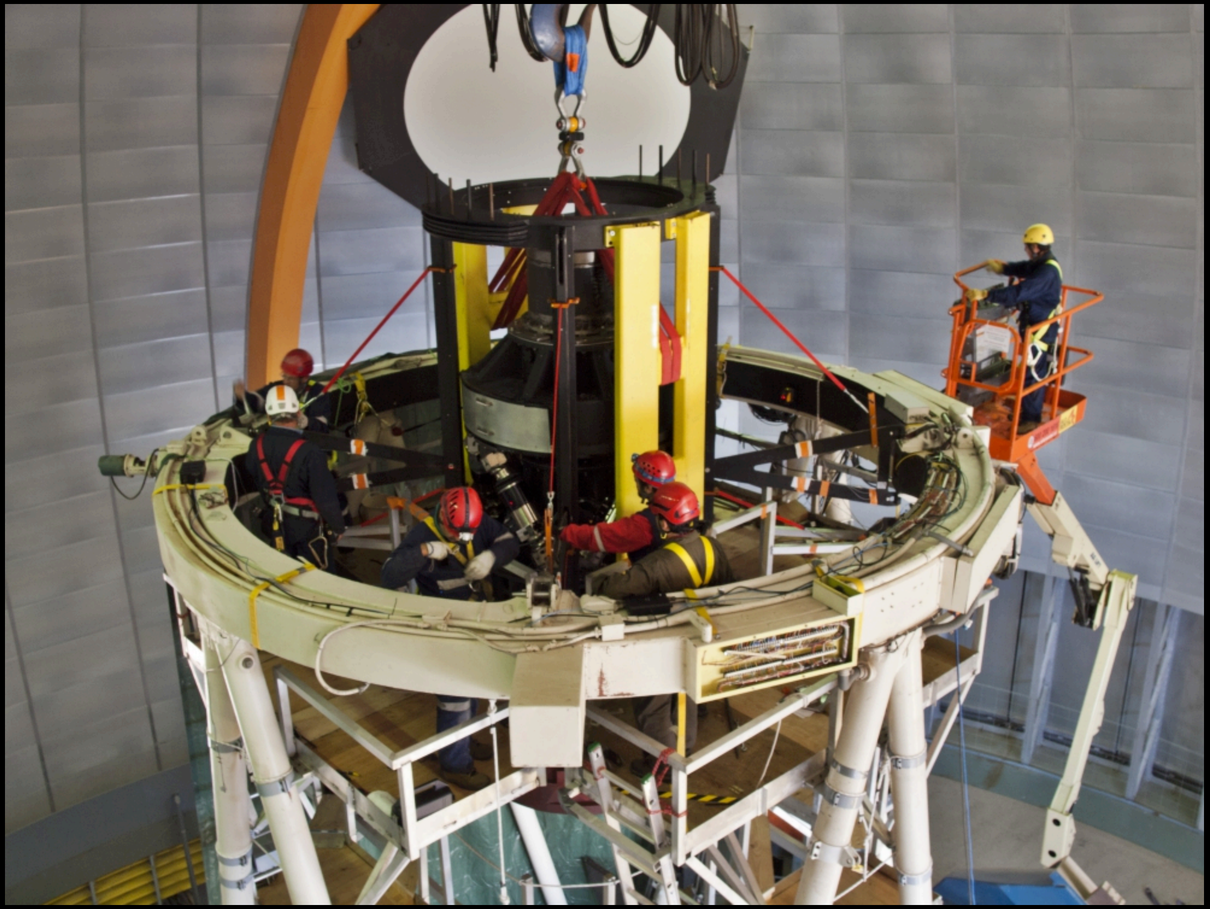
DARK ENERGY
SURVEY

DARK ENERGY SURVEY

DARK ENERGY SURVEY

DARK ENERGY SURVEY

DECam Prime Focus Cage Installed



early May 2012

Basic DES Observing Strategy

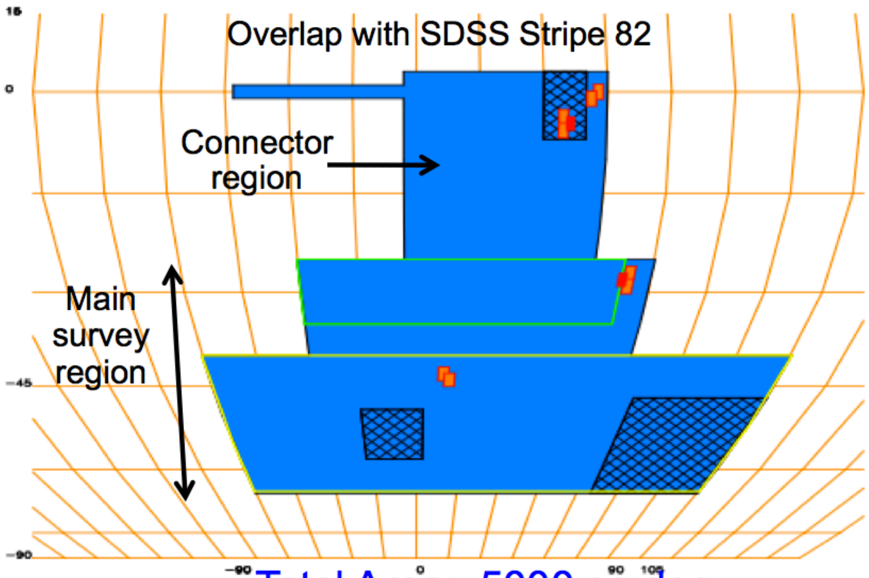
DARK ENERGY SURVEY

Observing Strategy

- 100 sec exposures (nominally)
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *izY* in bright time
- Multiple overlapping tilings (layers) to optimize photometric calibrations
- 2 survey tilings/filter/year
- Photometric Requirements (5-year)
  - All-sky internal: 2% rms (Goal: 1% rms)
  - Absolute Color: 0.5% (*g-r*, *r-i*, *i-z*); 1% (*z-Y*) [averaged over 100 objects scattered over FP]
  - Absolute Flux: 0.5% in *i*-band (relative to BD+17 4708)
- 5-year depth (co-added): ~24th mag for galaxies in i-band

Survey Area

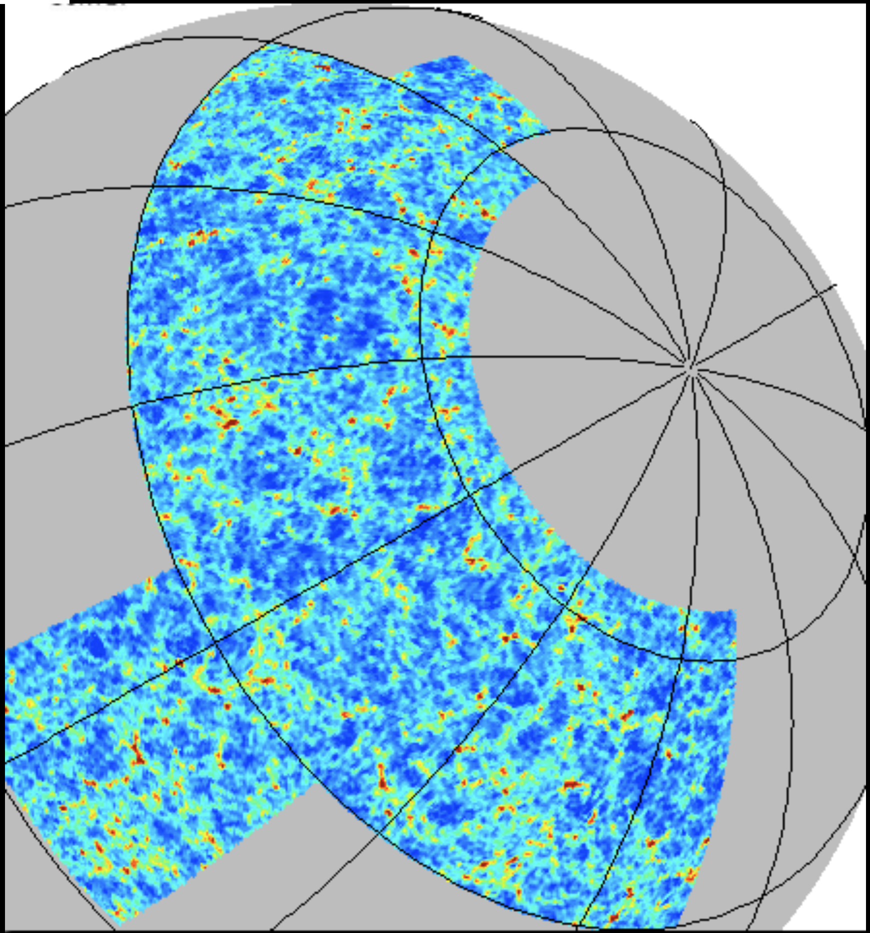
Credit: J. Annis



Total Area: 5000 sq deg

Synergy with South Pole Telescope

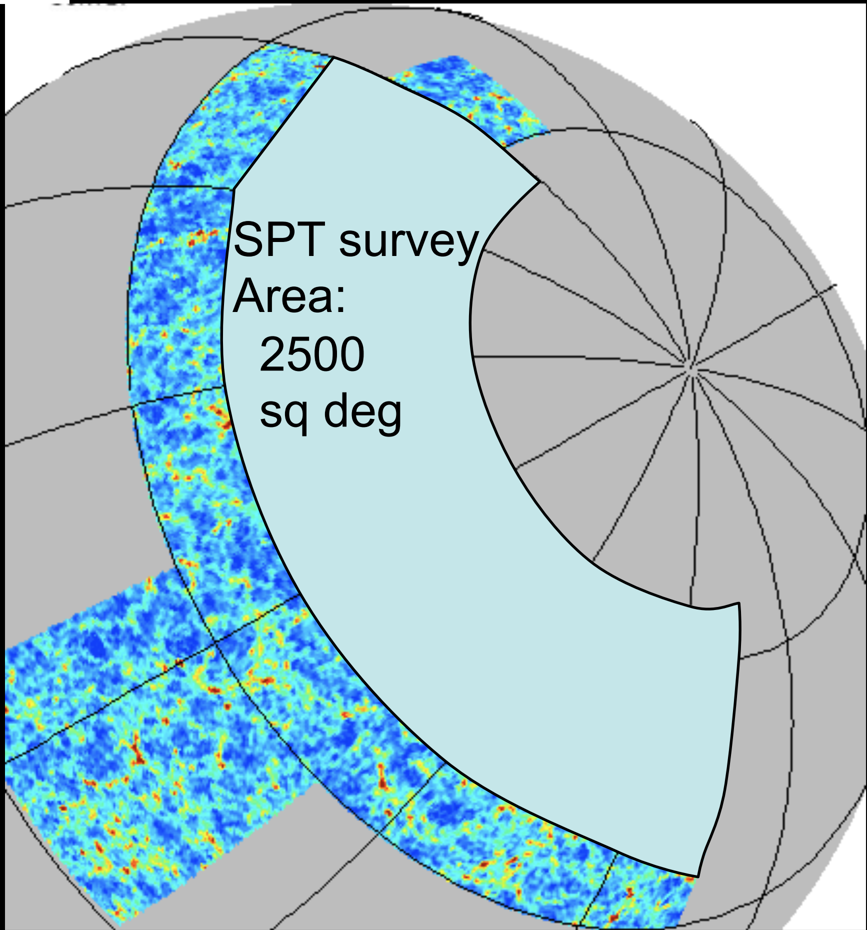
DES footprint: 5000 sq deg



DES survey area encompasses SPT Sunyaev-Zel’dovich Cluster Survey

Synergy with South Pole Telescope

DES footprint: 5000 sq deg

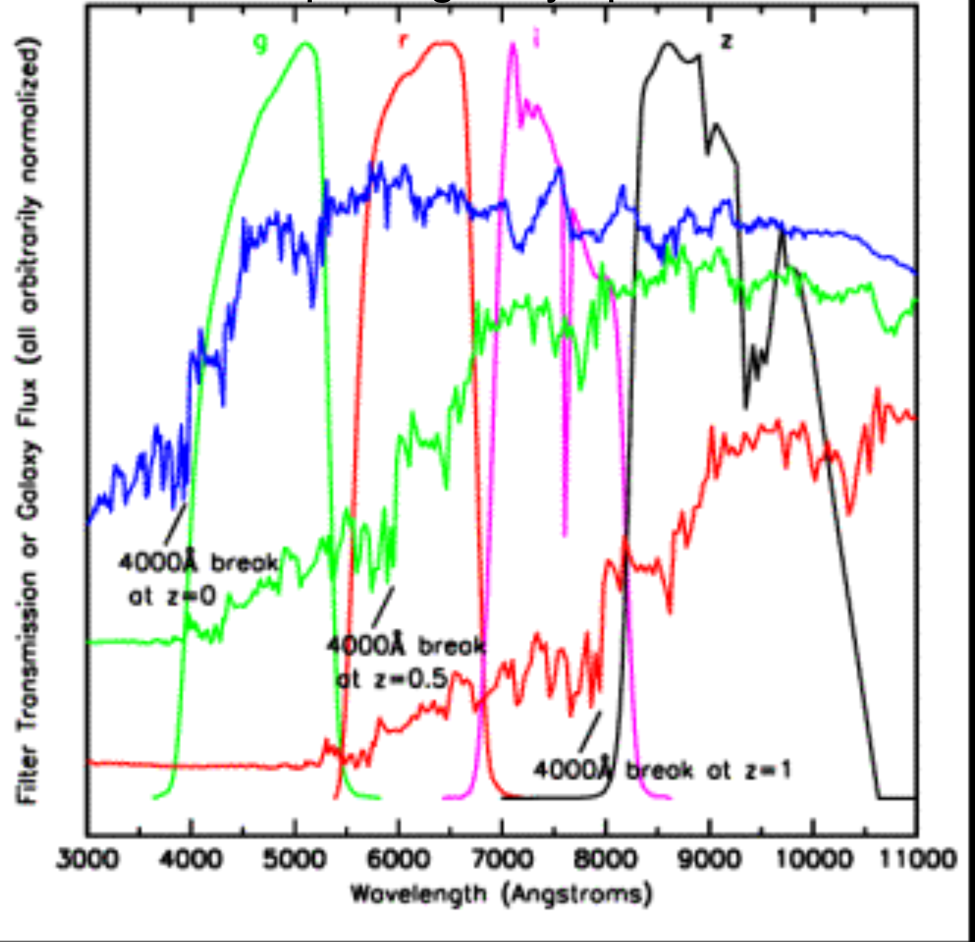


DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey
SZ flux correlates with cluster halo mass with ~10% scatter

Photometric Redshifts

- Measure relative flux in multiple filters (colors)
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Precision is sufficient for Dark Energy probes, *provided* error distributions well measured.
- Challenge: spectroscopic training & validation sets to flux limit of imaging survey (24^{th} mag DES, 25.5 LSST)

Elliptical galaxy spectrum



Galaxy Photo-z Simulations

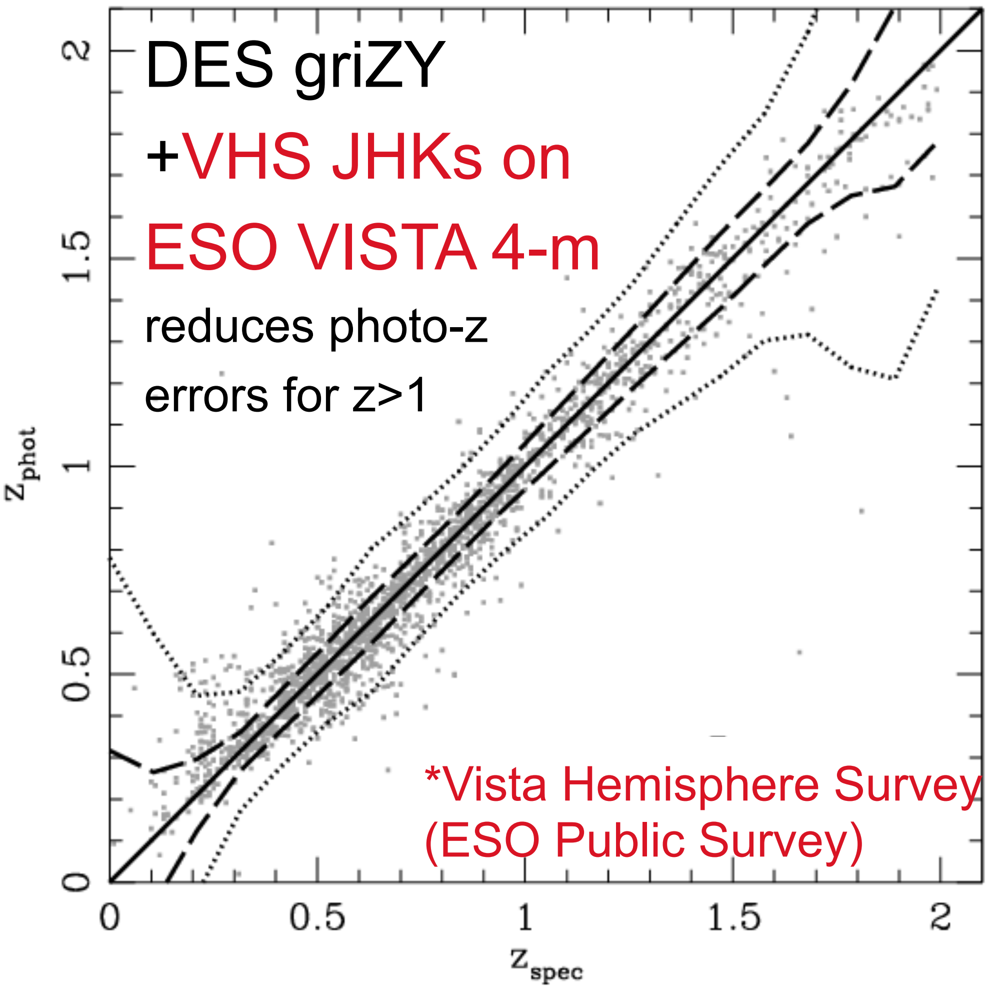
DES +VHS*

10σ Limiting Magnitudes

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

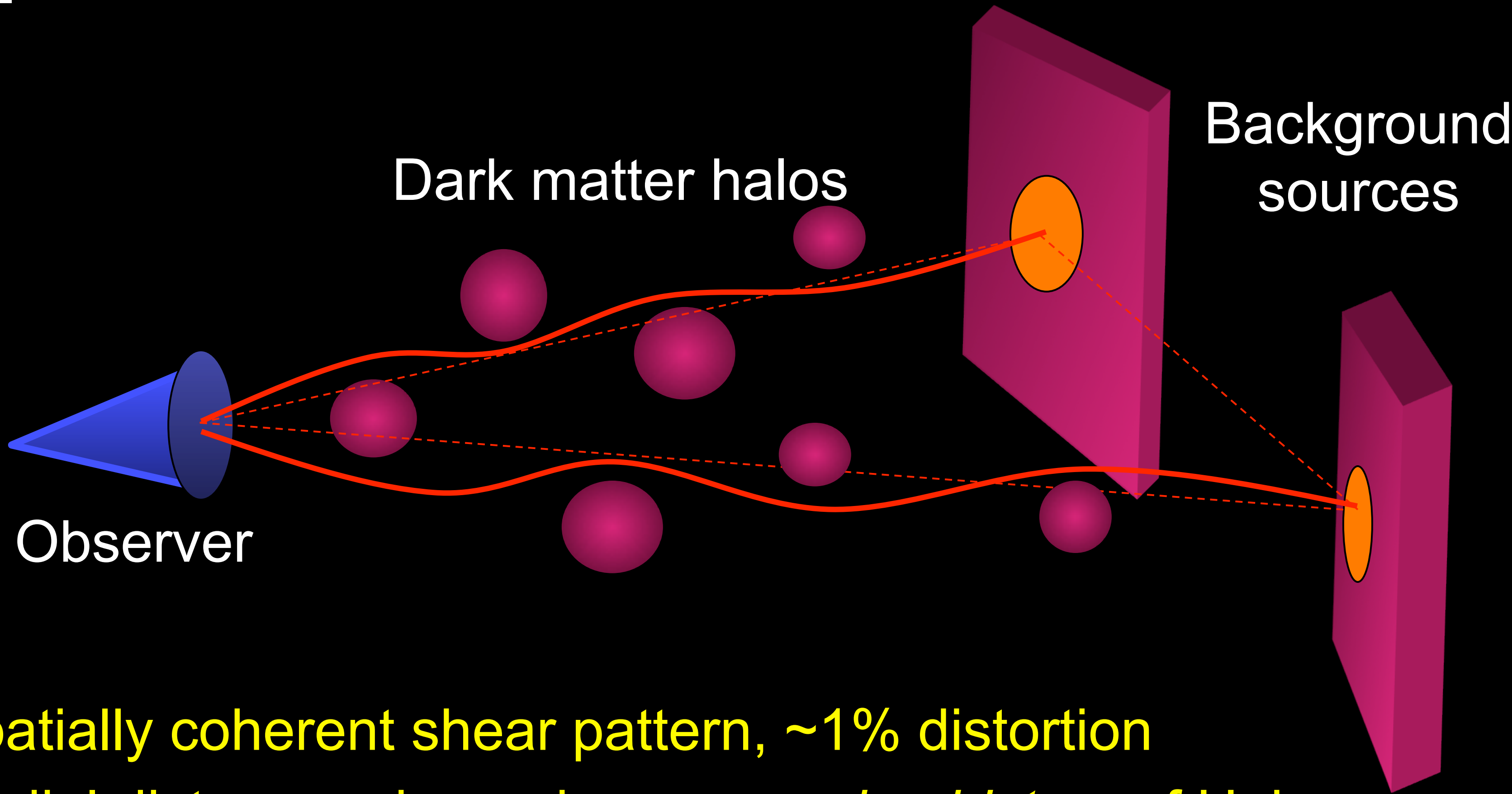
+2% photometric calibration error added in quadrature

Spectroscopic training sets comparable to DES depth exist, but not complete



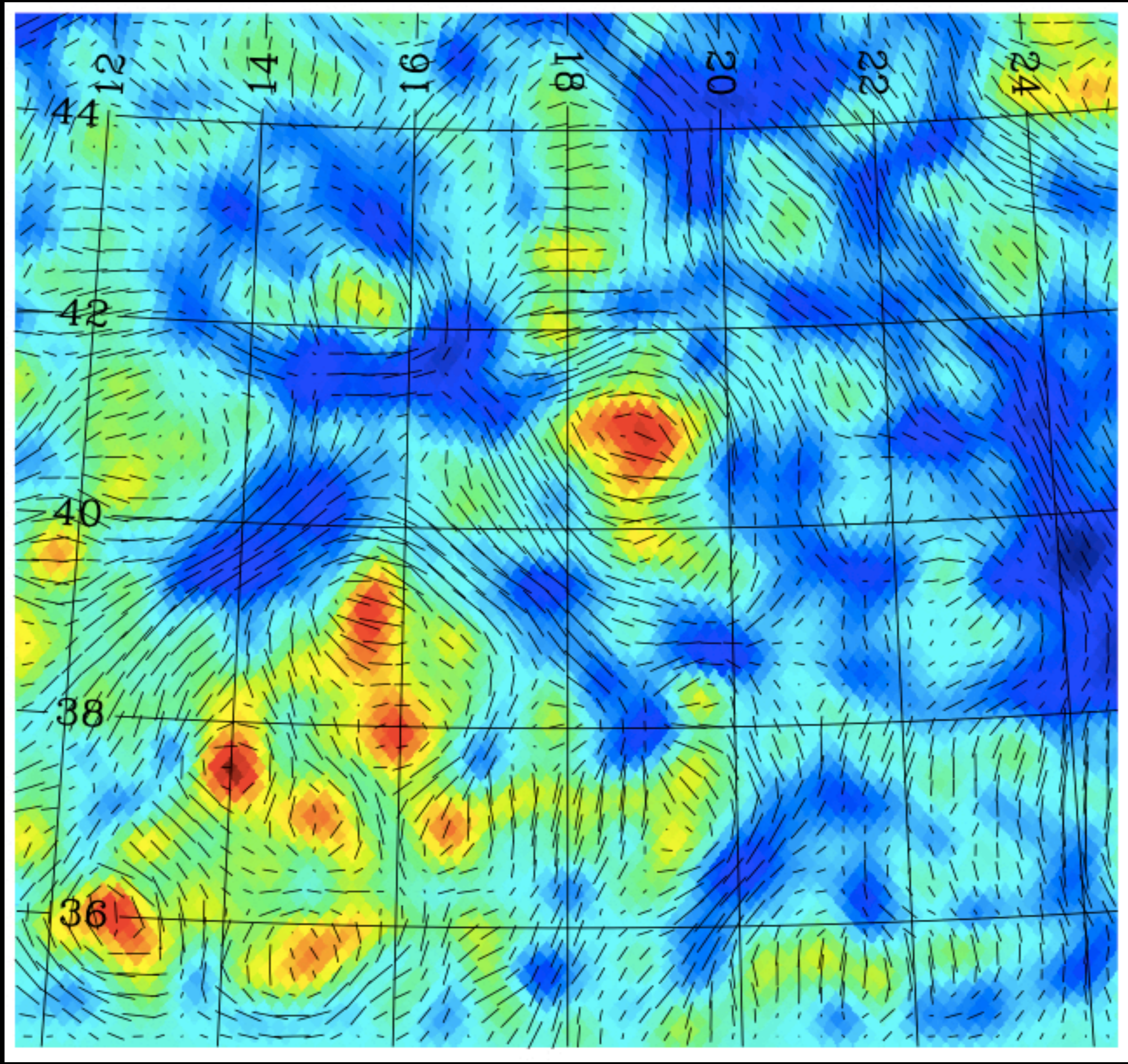
*Vista Hemisphere Survey (ESO Public Survey)

1 Weak Lensing: Cosmic Shear



- Spatially coherent shear pattern, ~1% distortion
- Radial distances depend on *expansion history* of Universe
- Foreground mass distribution depends on *growth* of structure

Weak Lensing Mass and Shear



Becker, Kravtsov, etal

Weak Lensing Tomography

DARK ENERGY SURVEY

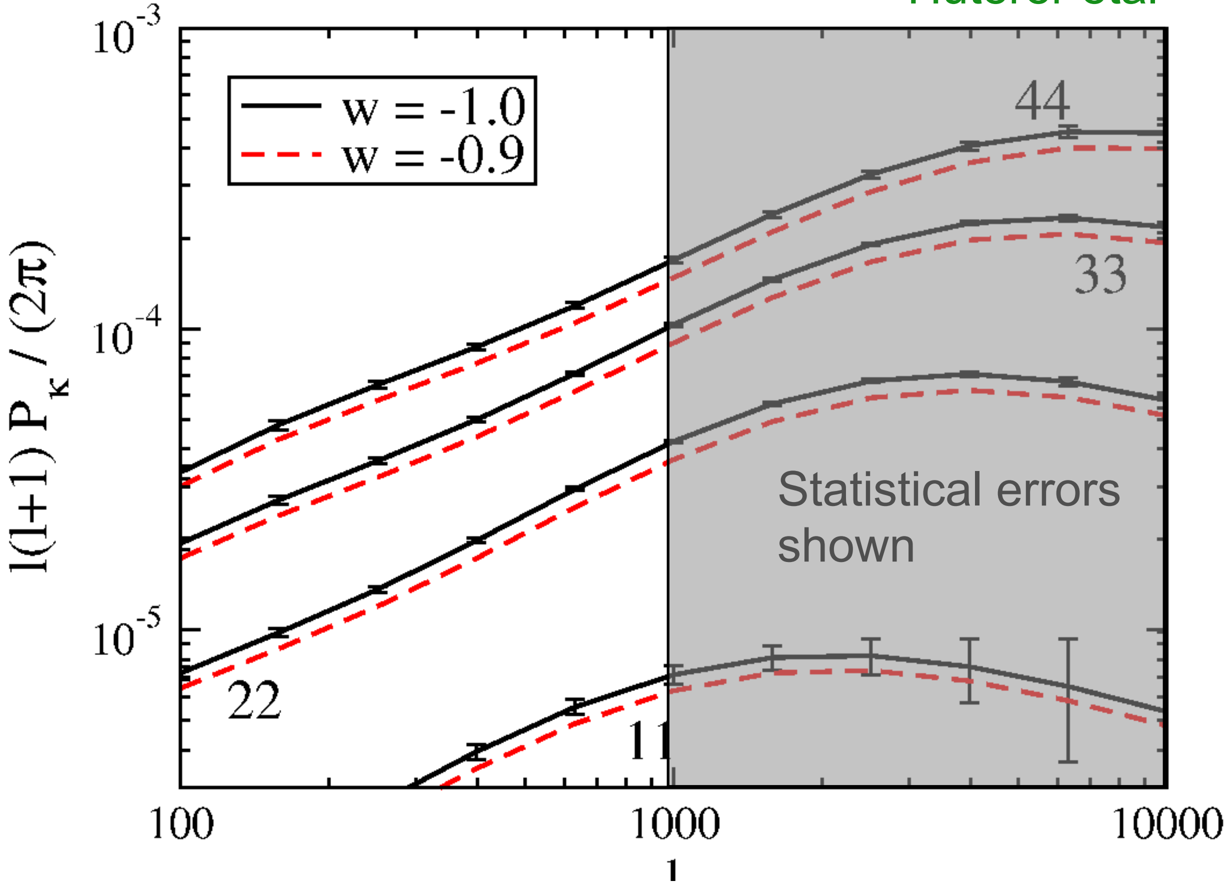
- Cosmic Shear Angular Power Spectrum in Photo-z Slices

- Shapes of ~200 million well-resolved galaxies, $\langle z \rangle = 0.7$

- Challenges:
photo-z's, intrinsic alignments, PSF anisotropy, shear calibration, nonlinear +baryon *P(k)* effects

- Extra info in bispectrum & galaxy-shear: robust

Huterer etal



Expect n_{eff}~10/arcmin^2 for median 0.9" PSF

$$C_\ell^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z) \qquad \Delta C_\ell = \sqrt{\frac{2}{(2\ell+1) f_{sky}}} \left(C_\ell + \frac{\sigma^2(\gamma_i)}{n_{eff}} \right)$$

DARK ENERGY SURVEY

Testing your theory with WL

Compute the 3D lensing power spectrum
$<(\Phi+\Psi)(\Phi+\Psi)>$

as a function of cosmological and any new parameters

In many theories including LCDM this can be directly related to the matter power spectrum. But not necessarily, so don't use blindly.

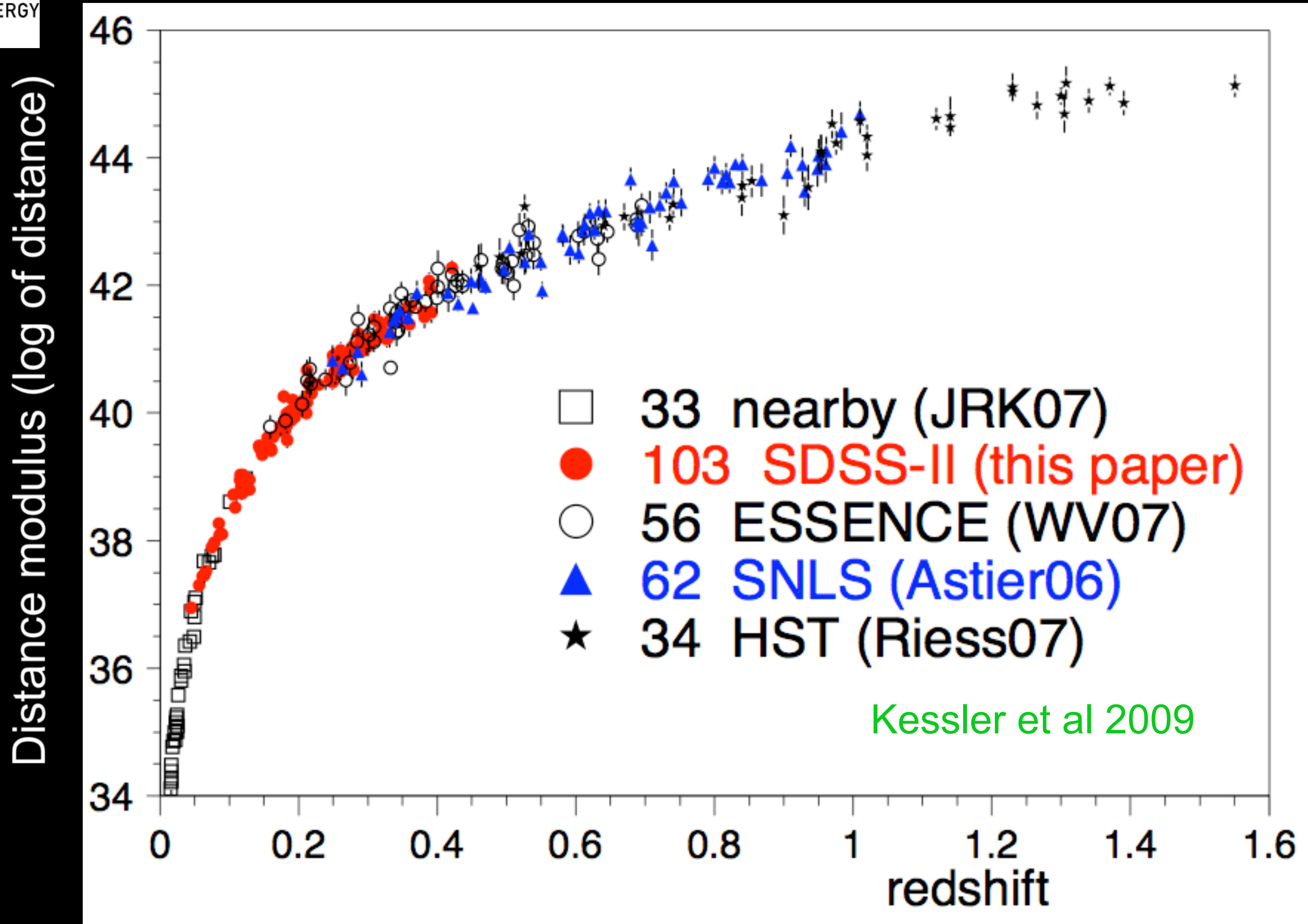
Aside: The Great 3 Challenge

DARK ENERGY SURVEY

Do you think you can measure the shapes of galaxies?

Prove it at the Great-3 challenge
http://great3challenge.info/

2 Supernova Hubble Diagram



DARK ENERGY SURVEY

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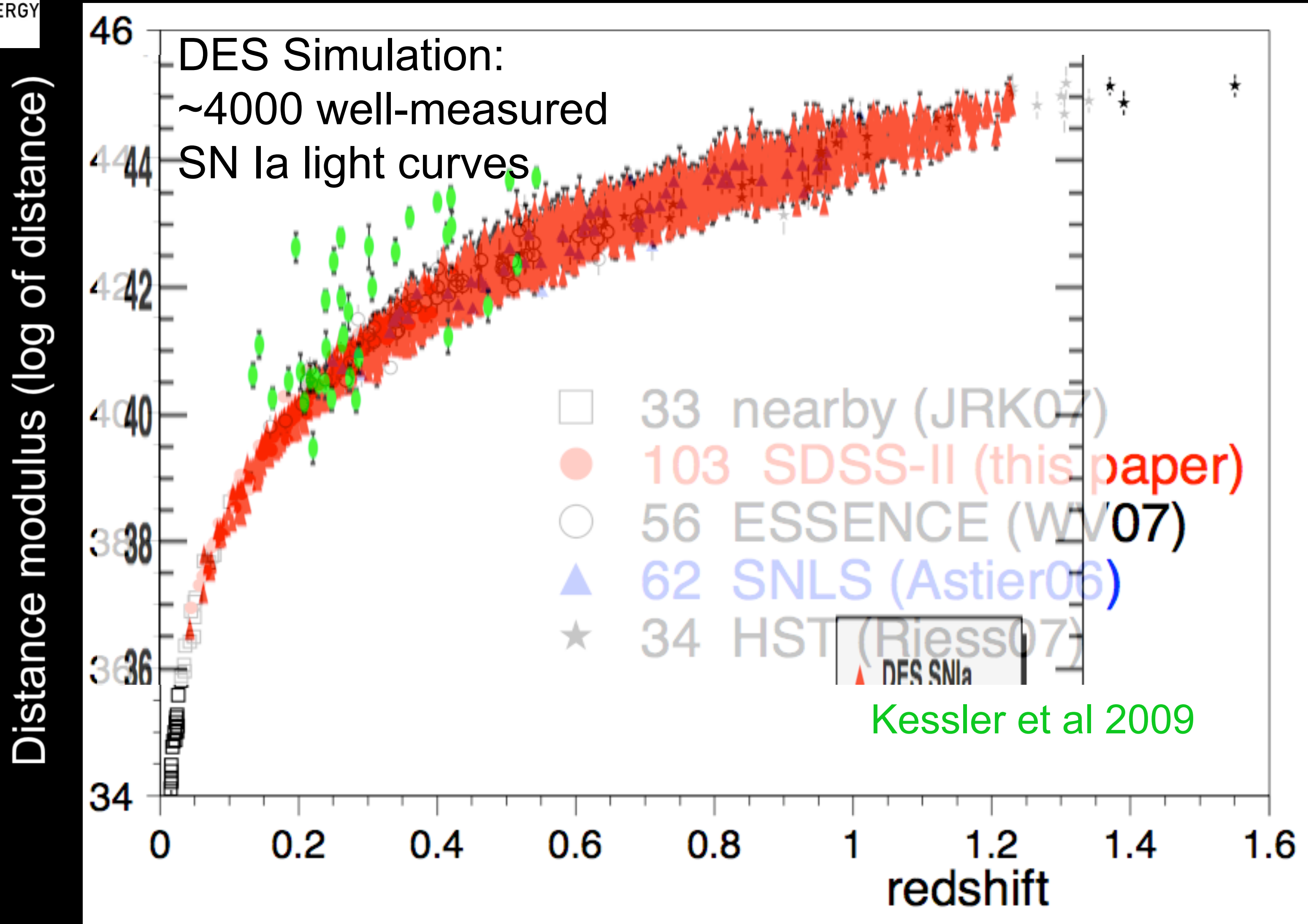
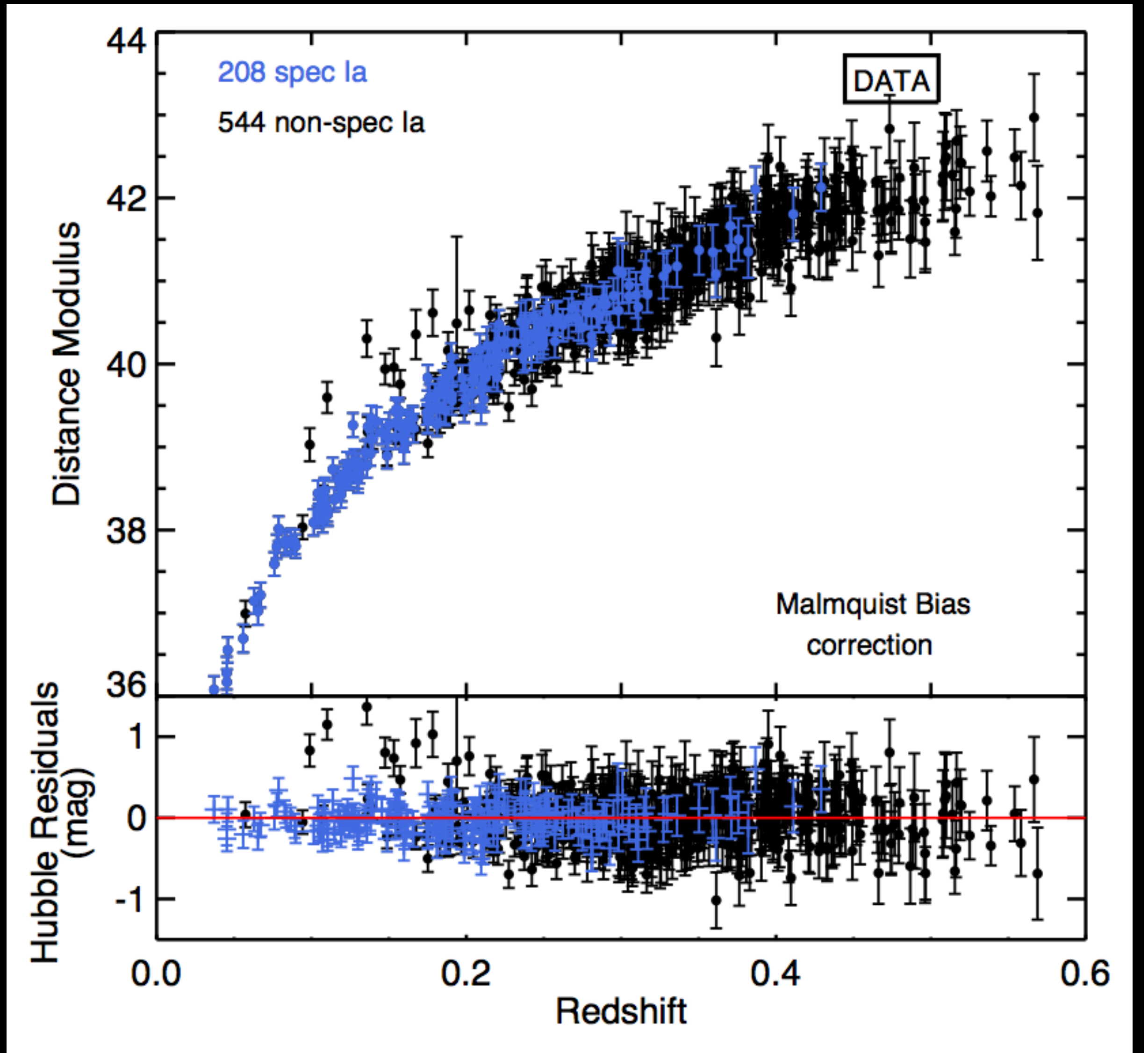


Bernstein, etal

Photometric SN Cosmology

- Hubble diagram of SDSS SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts
- DES will have host redshifts, plus SN spectra for a subsample



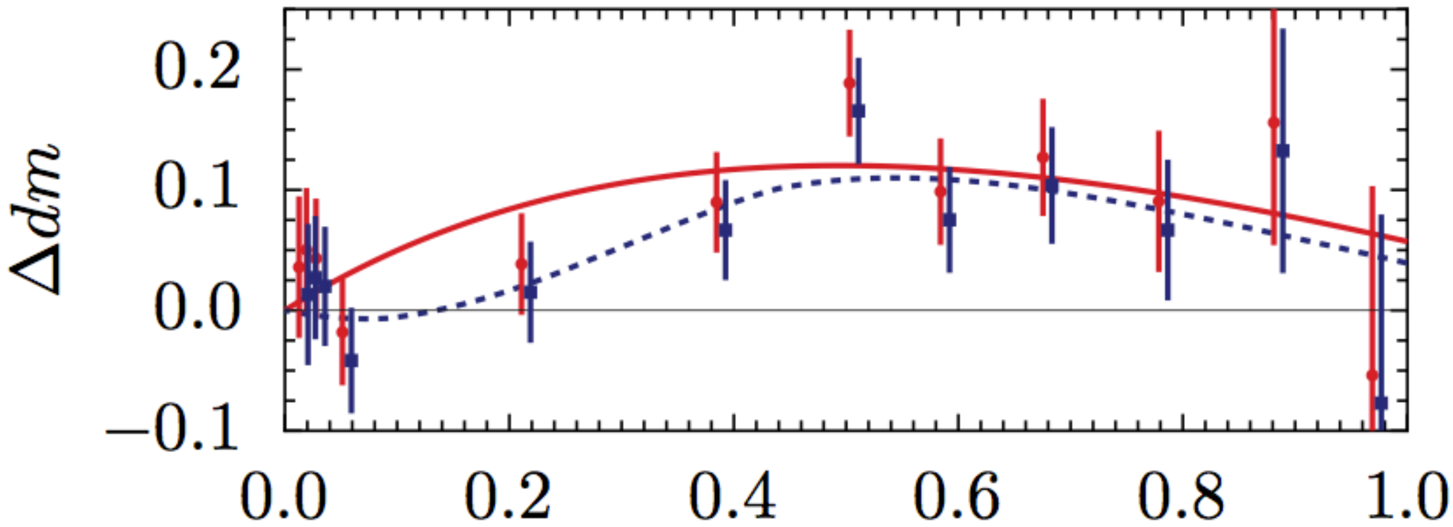
Campbell, etal

Testing your theory with SN

DARK ENERGY SURVEY

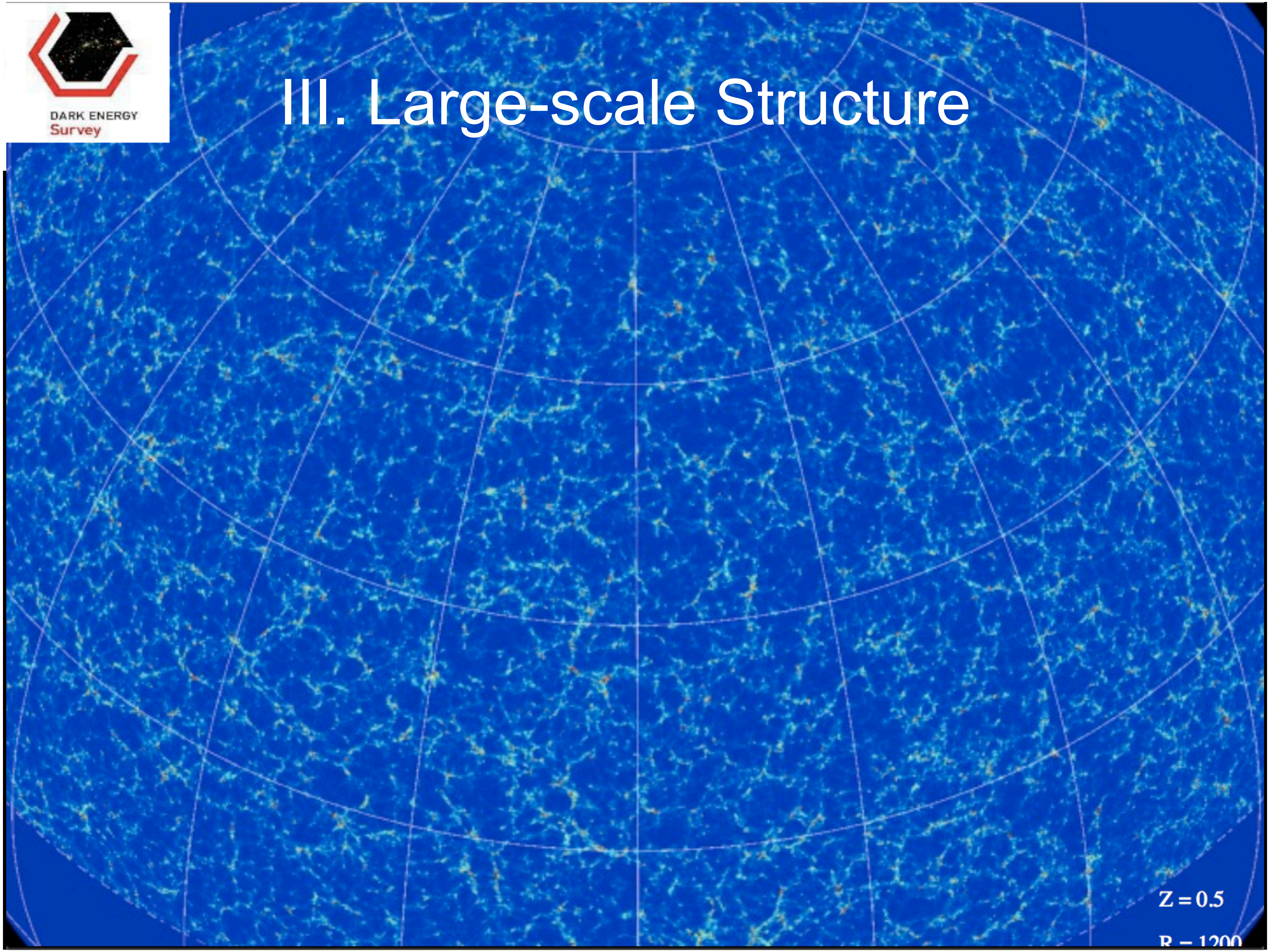
Compute the redshift-luminosity distance relation $d_L(z)$

as a function of cosmological and any new parameters. Error bars are theory dependent! Don't just blindly use the published covariance matrices! See March.



DARK ENERGY Survey

III. Large-scale Structure

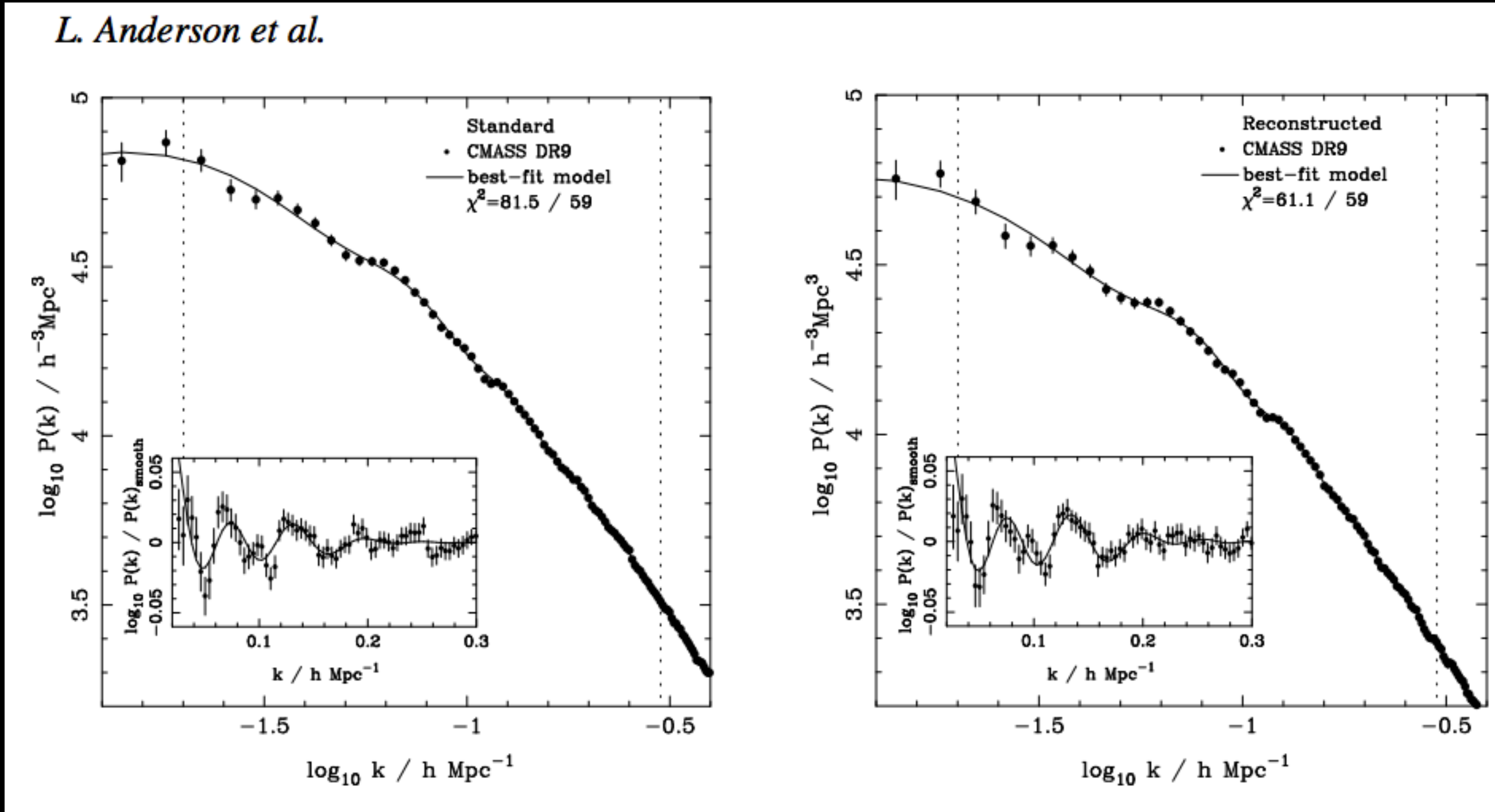


LSS observables

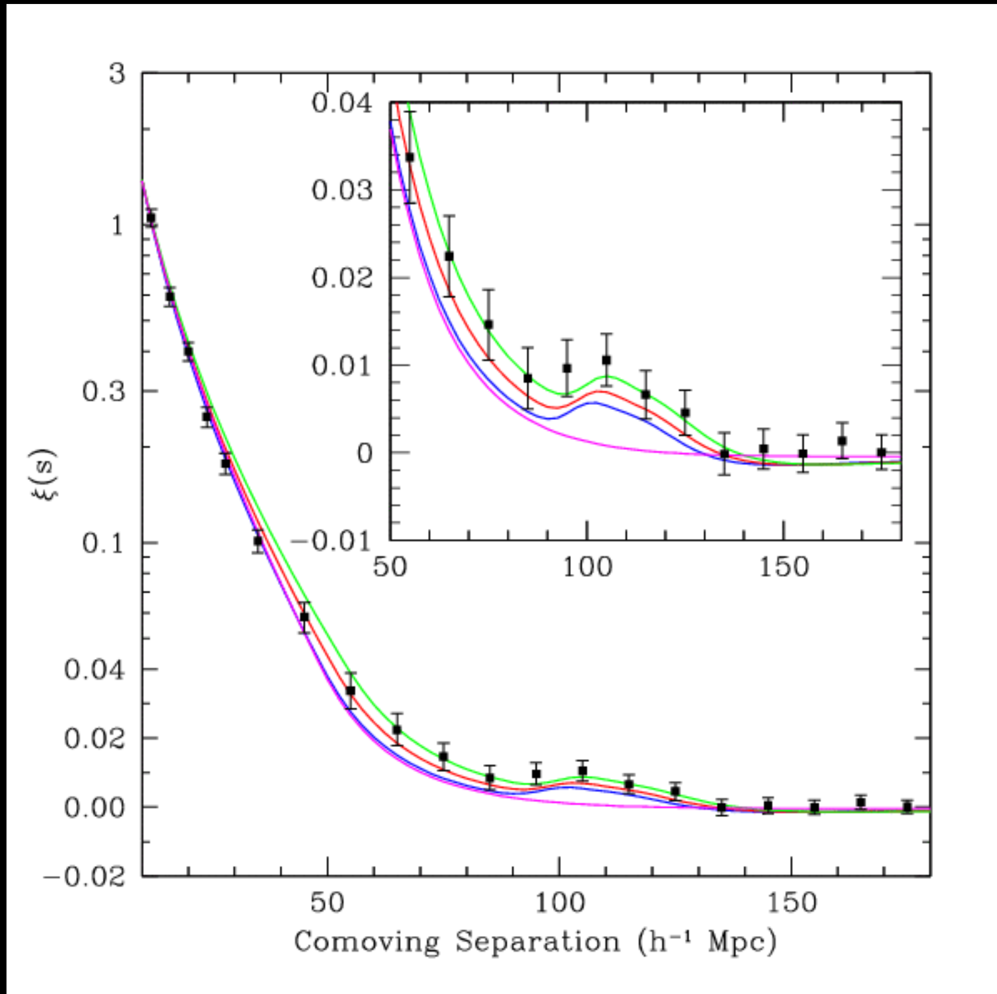
Galaxy $P_{3D}(k,z)$ → BAO position

Galaxy $C_l(z_{bin})$ → Shape

BOSS

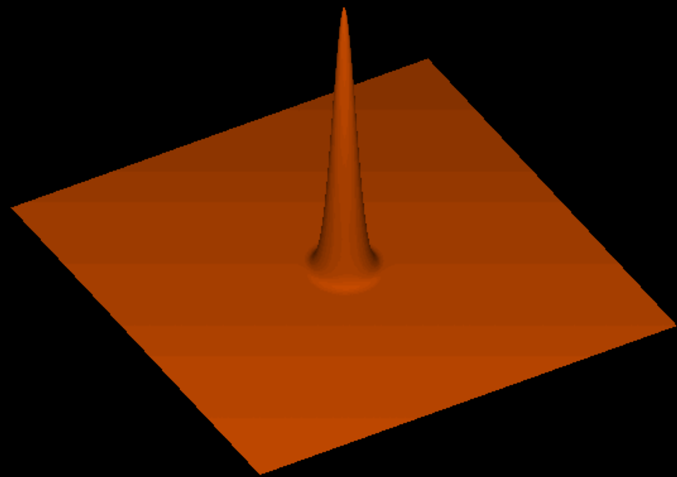

L. Anderson et al.
Standard
CMASS DR9
best-fit model
χ²=81.5 / 59
Reconstructed
CMASS DR9
best-fit model
χ²=61.1 / 59
log10 P(k) / h^-3 Mpc^3
log10 k / h Mpc^-1
log10 P(k) / P(k)smooth
k / h Mpc^-1

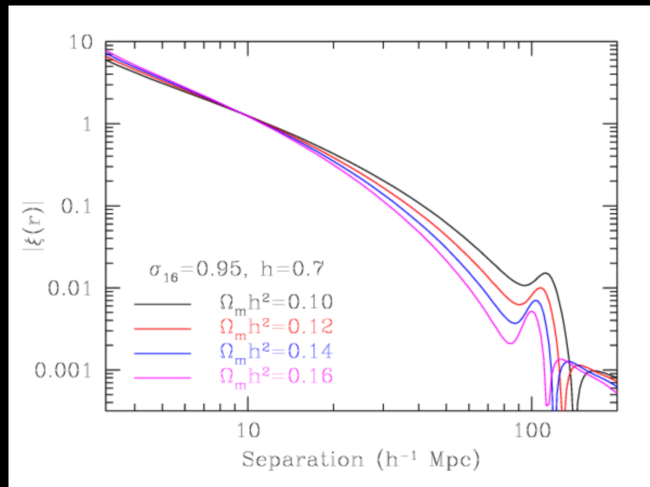
Correlation function



Baryon Acoustic Oscillations

- Each initial overdensity (in dark matter & gas) is an overpressure that launches a spherical sound wave.
- This wave travels outwards at 57% of the speed of light.
- Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.
- Sound speed plummets. Wave stalls at a radius of 150 Mpc.
- Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 150 Mpc.

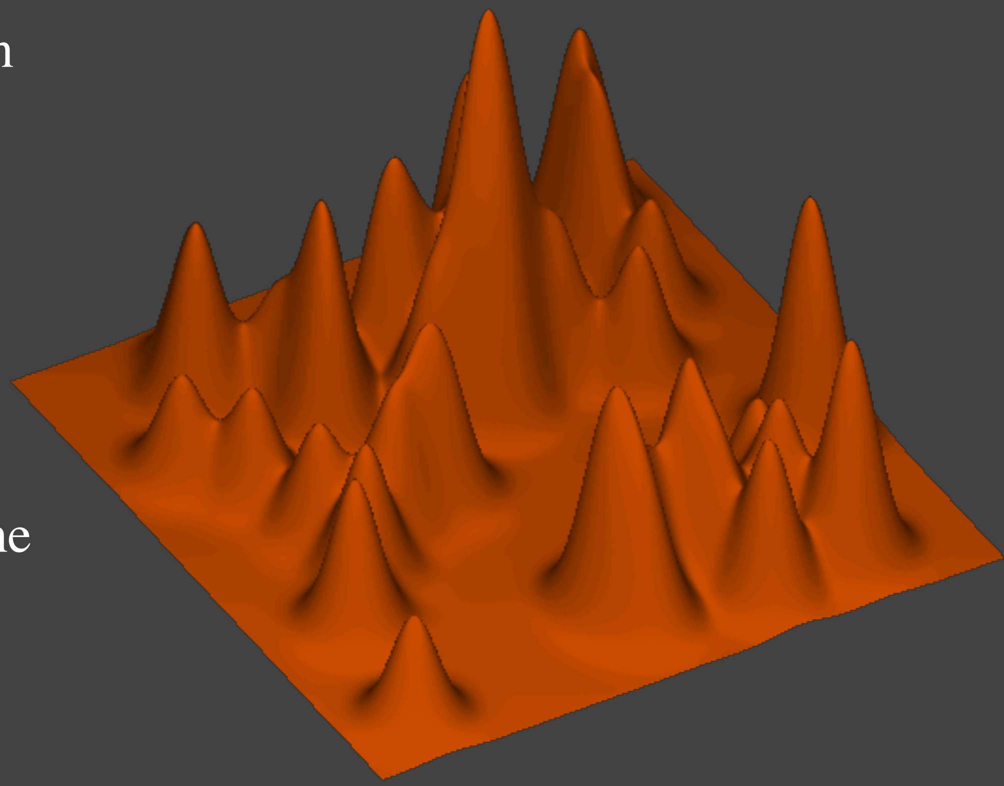




Eisenstein

A Statistical Signal

- The Universe is a super-position of these shells.
- The shell is weaker than displayed.
- Hence, you do not expect to see bullseyes in the galaxy distribution.
- Instead, we get a 1% bump in the correlation function.

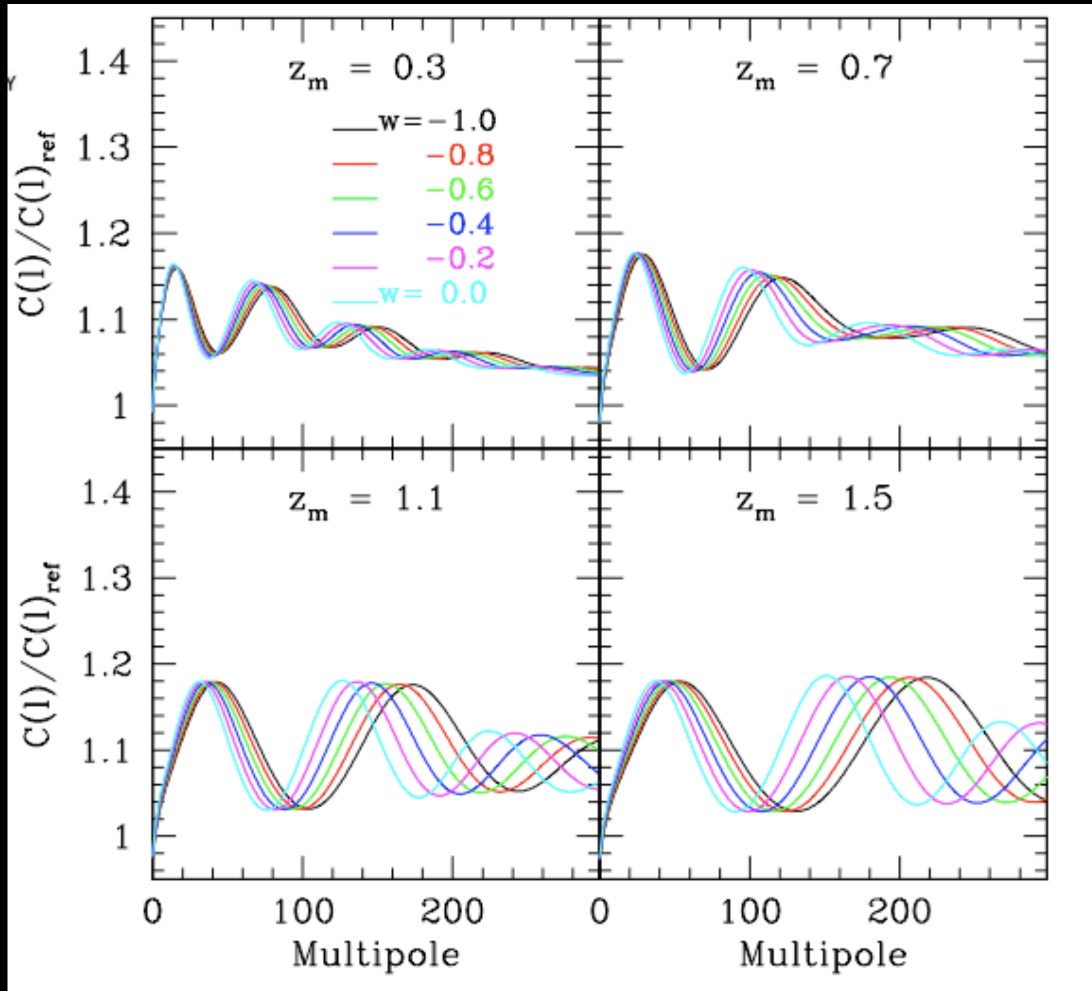


Photometric BAO

Galaxy angular power spectrum in photo-z bins (relative to model without BAO)

Photometric surveys provide angular measure

Radial modes require spectroscopy (DESI)



Fosalba & Gaztanaga

Angular Spectrum

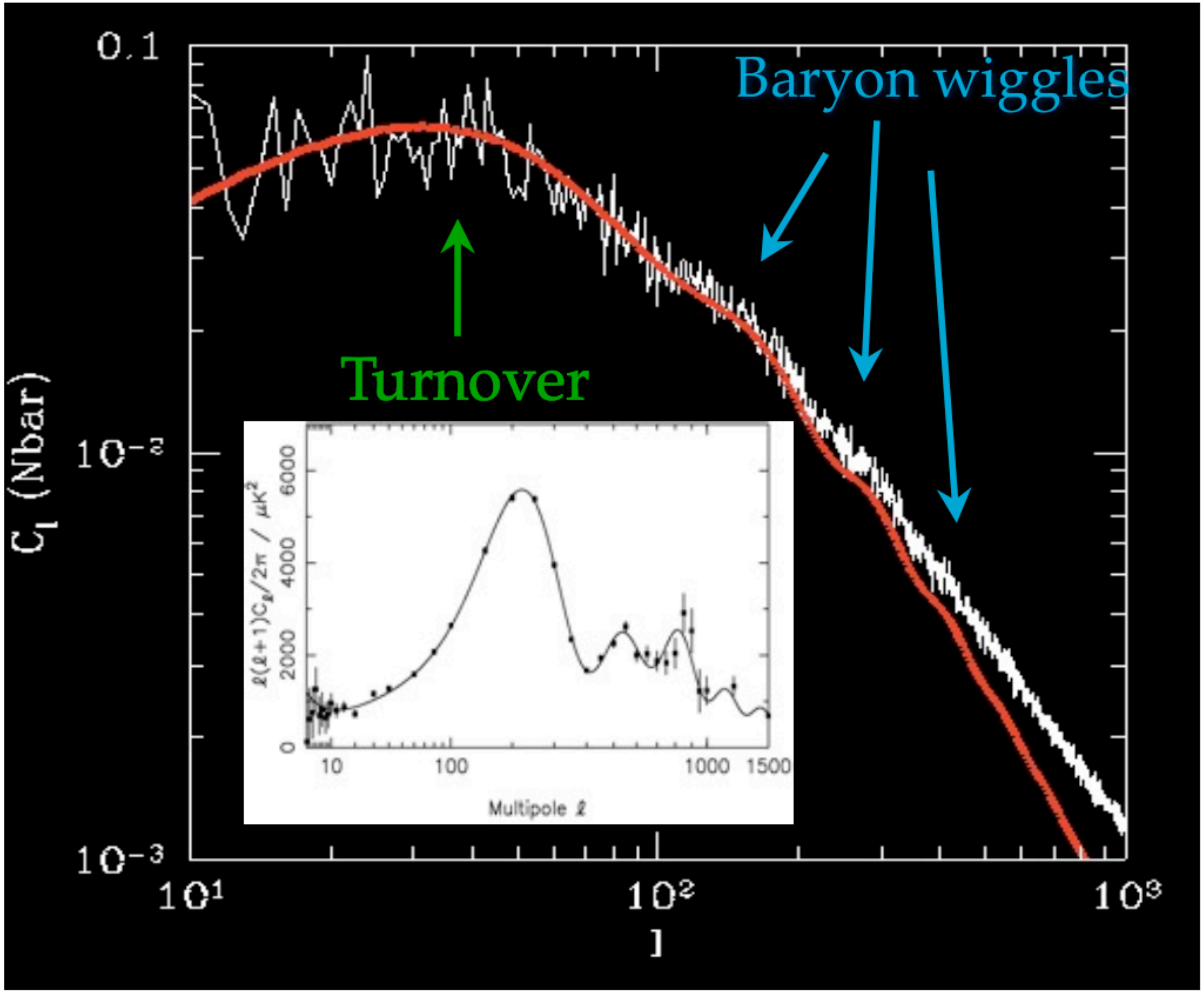
For single redshift slice:

z =0.9-1.0

Out of MICE Simulation

www.ice.cat/mice

Slide from E. Gaztanaga



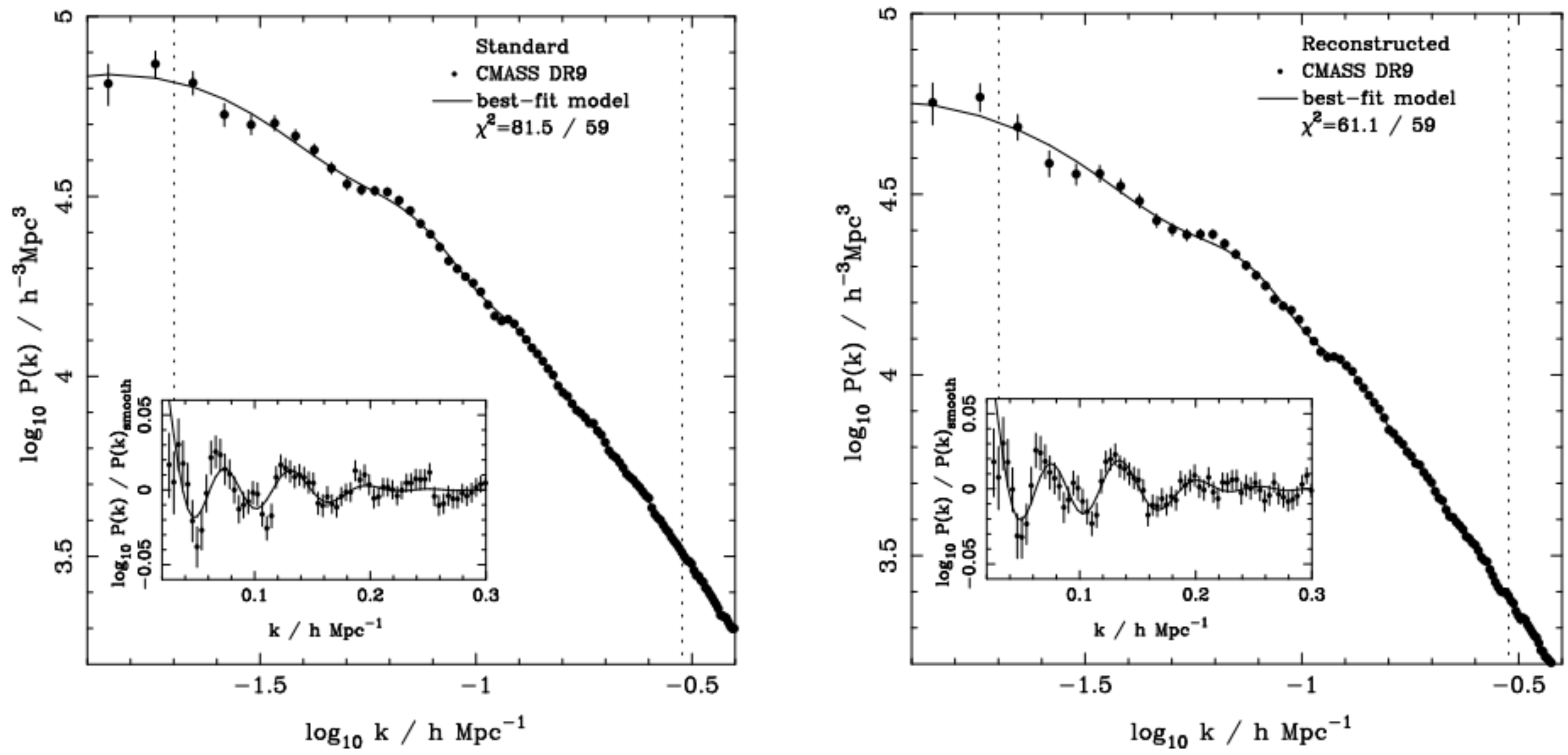
Measurements can provide both with:

1. BAO scale (DM & Baryon density)
2. distance to BAO scale (DE)

$$c\Delta z_{BAO} = r_{BAO} H(z) \qquad \Delta\theta_{BAO} = \frac{r_{BAO}}{d_A(z)}$$

BOSS

L. Anderson et al.



Issues with LSS P(k): NON-LINEARITY

- Major effect is galaxy "diffusion"
  - Reconstruction approaches for BAO
  - Modify galaxy positions by estimating motion
- Modelling approaches
  - Replicating simulations
  - Halofit & descendants – fitting functions with cosmology
  - 2nd order and higher approaches

Issues with LSS P(k): BIAS

- $\rho_g \neq \rho_m \neq \rho_{halo}$
- Linear on large scales
- HOD modelling
  - P(N|M) for central red galaxies and satellite blue
  - From correlation function within/between halos
  - See Zheng et al 04 for good intro
- What would people find persuasive?

Testing your theory with LSS

- BAO: Compute $d_A(z)$ for the specified redshifts
- P(k)/Cl: Compute matter power spectrum, run numerical simulations to get bias and non-linear power emulator(!)

4. Clusters

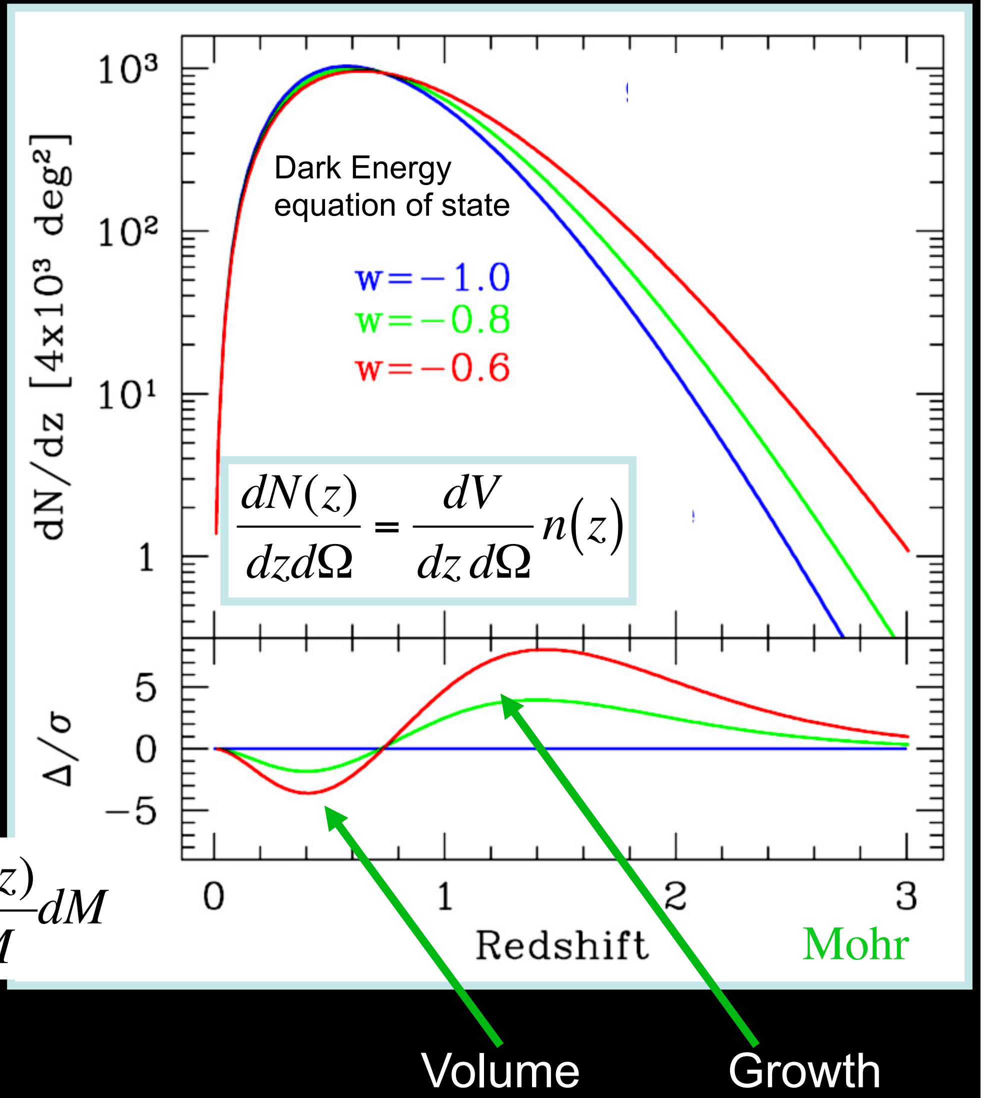
- Clusters are proxies for massive halos and can be identified optically to redshifts z>1

- Galaxy colors provide photometric redshift estimates for each cluster

- Challenge: determine mass-observable relation *p(O|M,z)* with sufficient precision

$$\frac{d^2N}{dz\,d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z)\,dO \int p(O\,|\,M,z)\,\frac{dn(z)}{dM}\,dM$$

Number of clusters above mass threshold



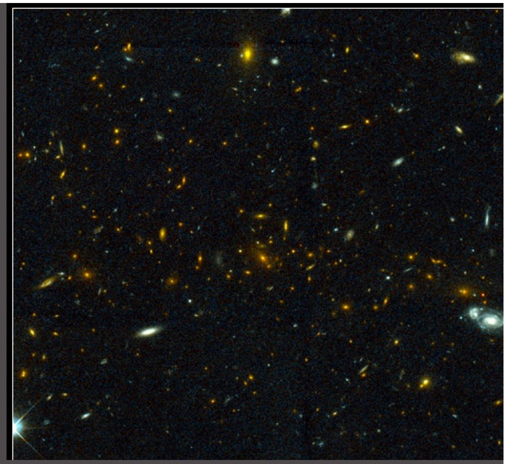
Cluster Mass Estimates

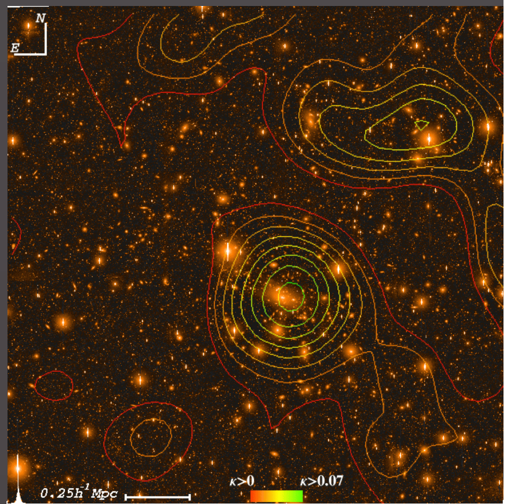
4 Techniques for Cluster Mass Estimation:

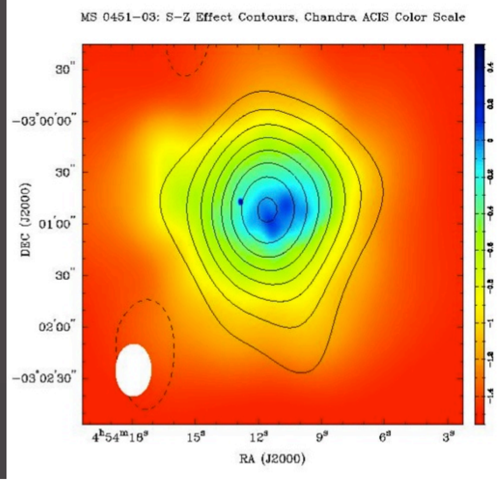
- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel' dovich effect (SZE)
- X-ray

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

  shape of mass function; cluster correlations

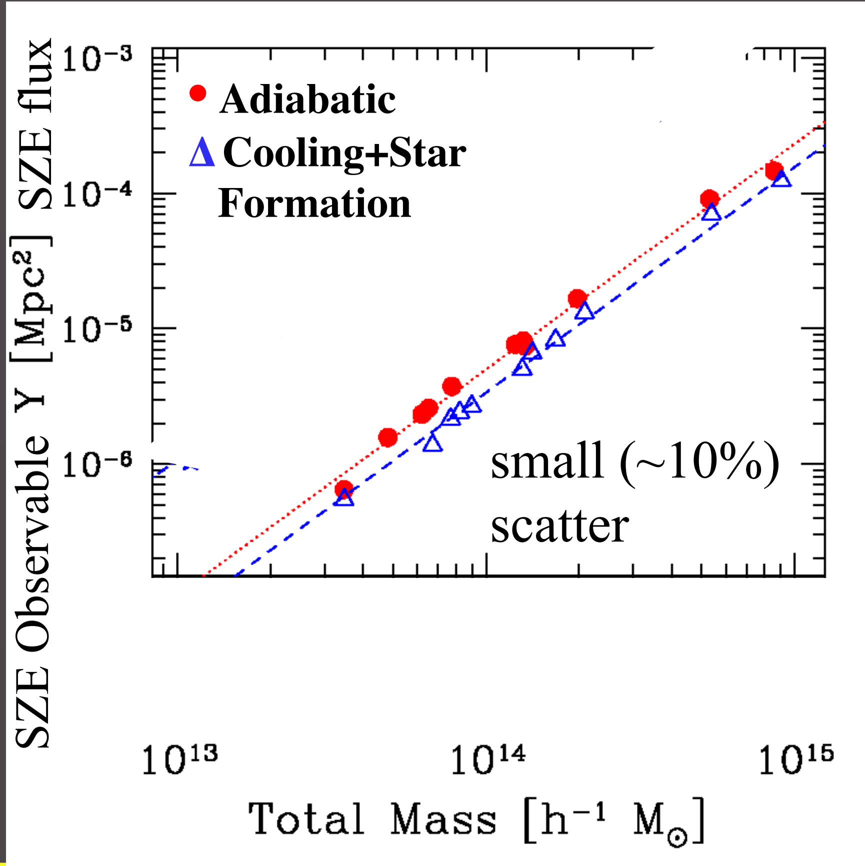






SZE vs. Cluster Mass: Progress toward Realistic Simulations

Kravtsov



Integrated SZE flux decrement depends only on cluster mass: insensitive to details of gas dynamics/galaxy formation in the cluster core → robust scaling relations

Nagai
Motl, etal

Testing your theory with Clusters

- You need $P(k,z)$ and dV/dz
- Then get $\sigma(M,z)$ from integral(s) of P
- Then procedure in Sahlen et al to compare with observations – not easy.

Combined Probes

Combined probes examples
CMB+DES

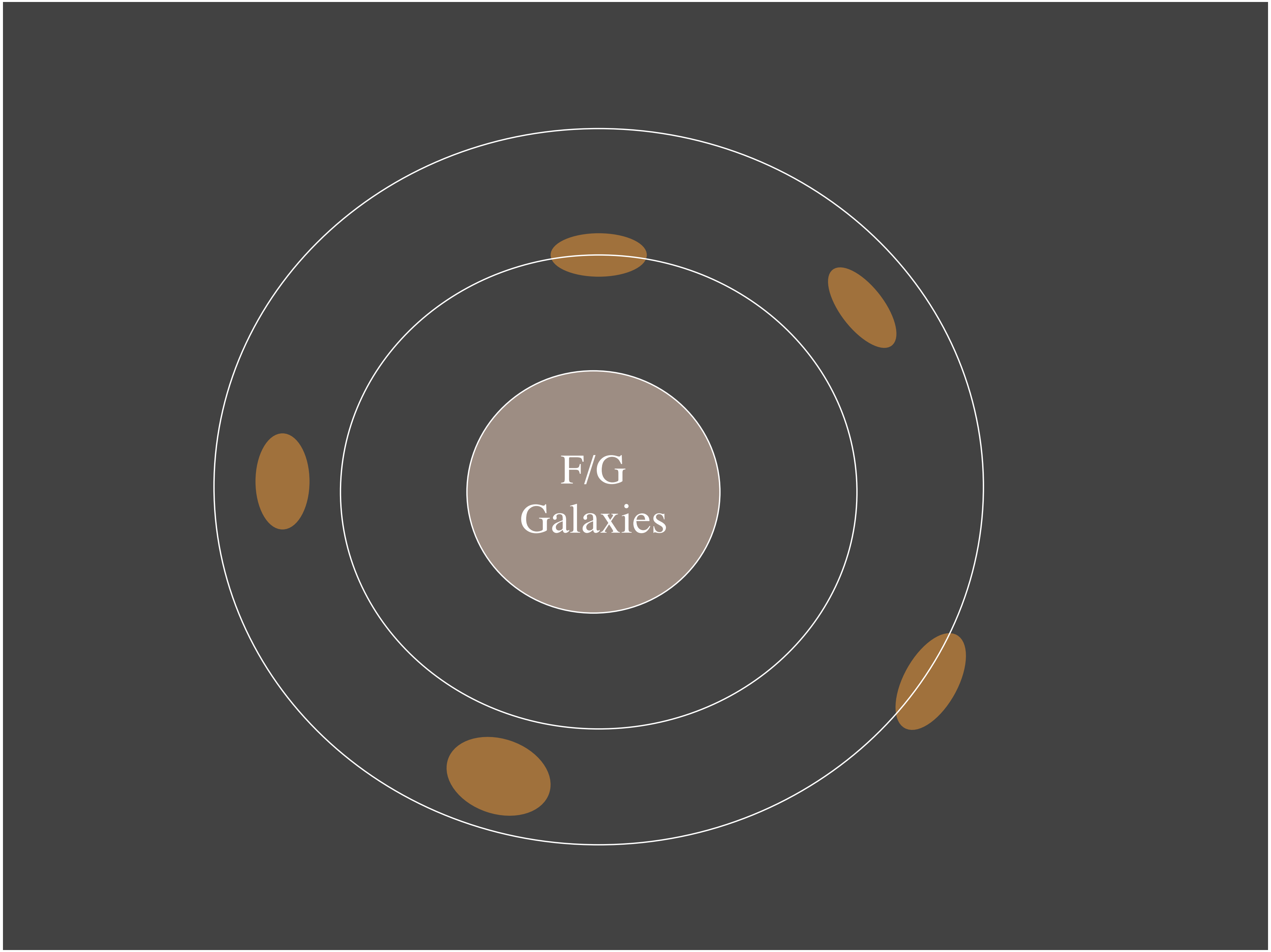
Galaxy map
Shear map
Tangential shear

X

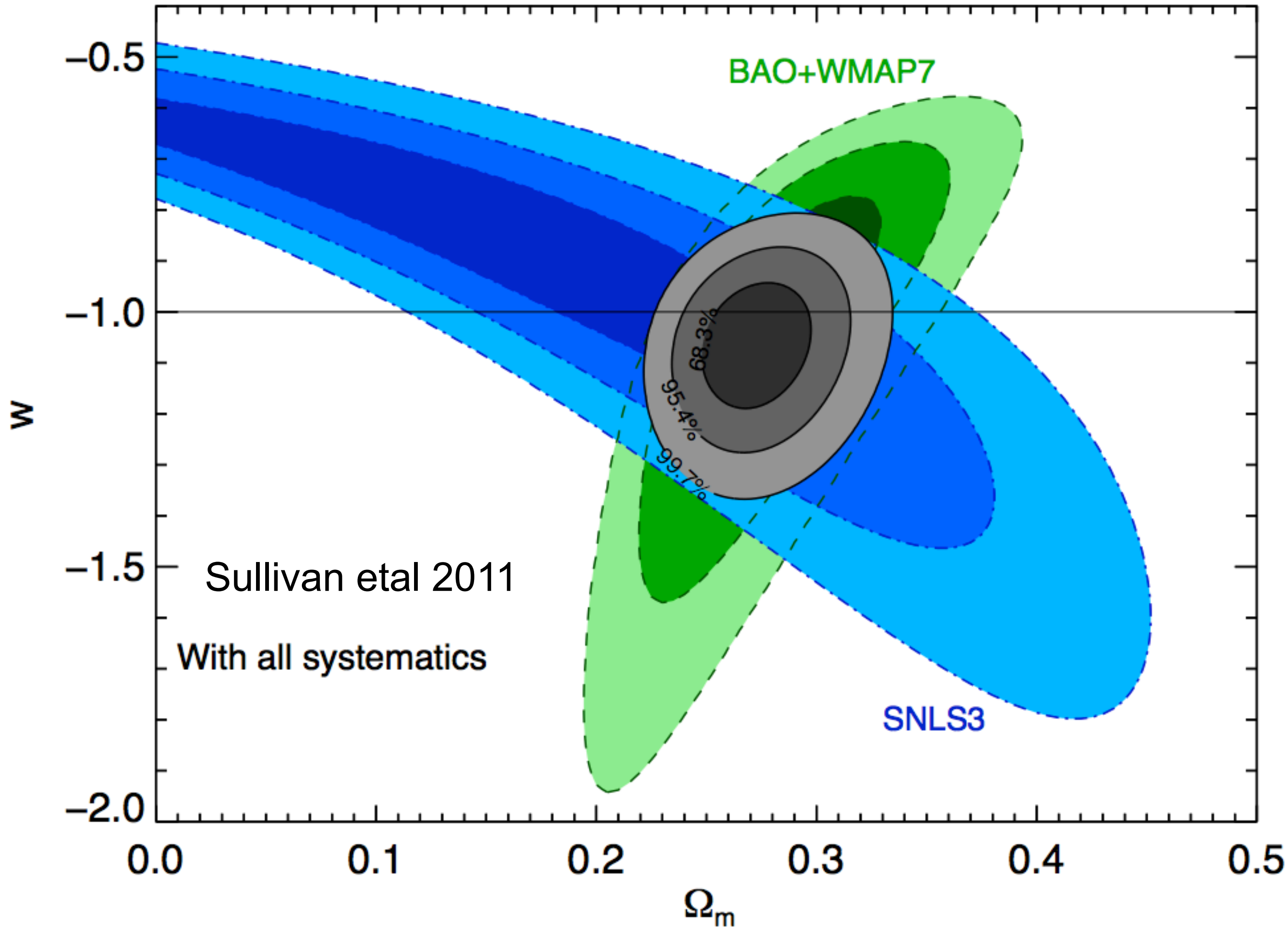
CMB Lensing
Temperature
SZ

Combined probes examples (Galaxy)-(Galaxy Lensing)

- Any correlation between galaxy positions and shears
- “Do galaxies point at other galaxies?”
- DES Focus Seljak & Yu
  - Select F/G galaxies → $P_g(k)$
  - Stack lensing around them galaxies → $P_m(k)$
- Find out bias for these galaxies!


F/G
Galaxies

Combined Probes



COMBINED PROBES

For late-time structure probes adding log-likelihoods is no longer good enough

Golden age of parameter estimation seems to be over

COMBINED PROBES

- Model consistency
  - Bias model, fiducial cosmo, … ?
  - Was data calibrated to LCDM?
- Theory covariance
  - Not as easy as CMB!
  - Emulation required
  - See Eifler et al
- Noise!

COMBINED PROBES

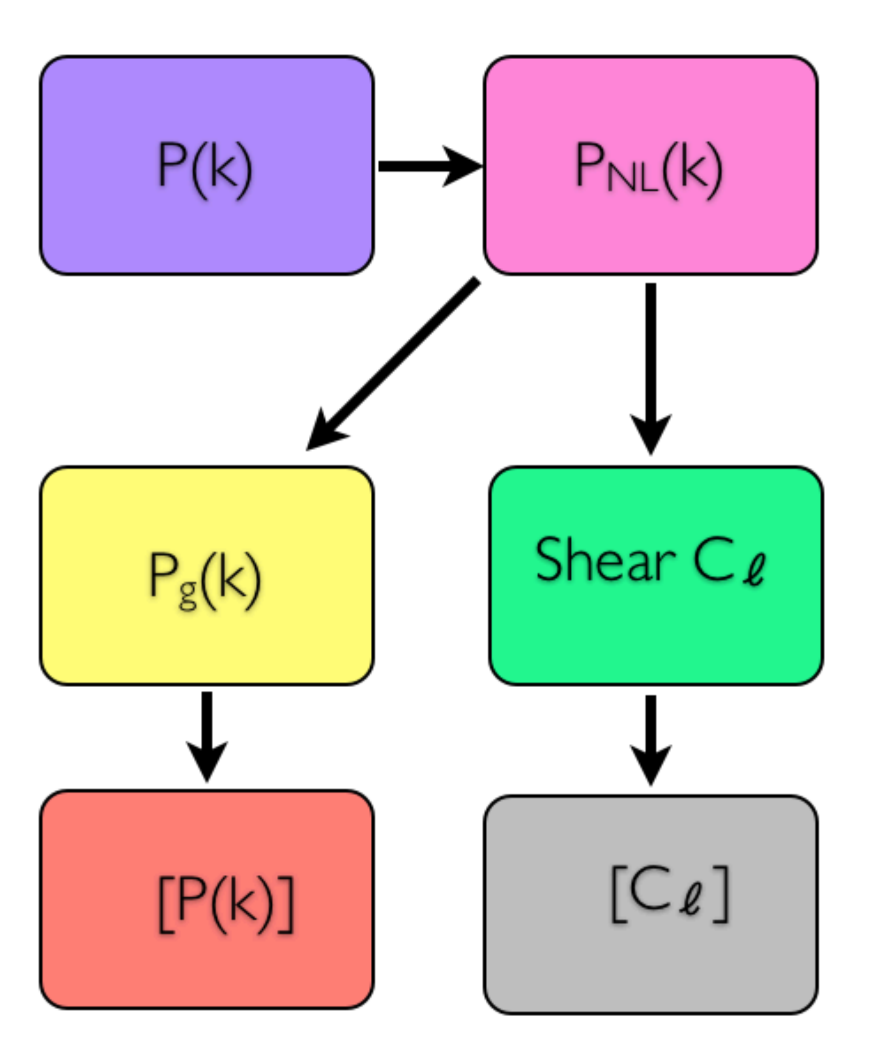
- Some of these problems are hard because they must be
- But some should be easy

COMBINED PROBES

- Advocating for plug-and-play cosmology
- Developing CosmoSIS w/ Fermilab
  – cross-language framework for parameter estimation

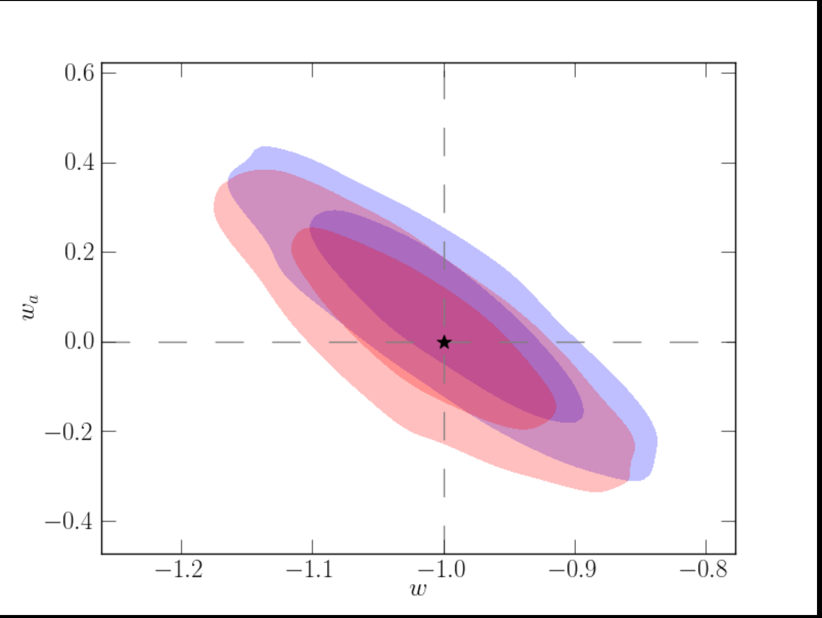
CosmoSIS

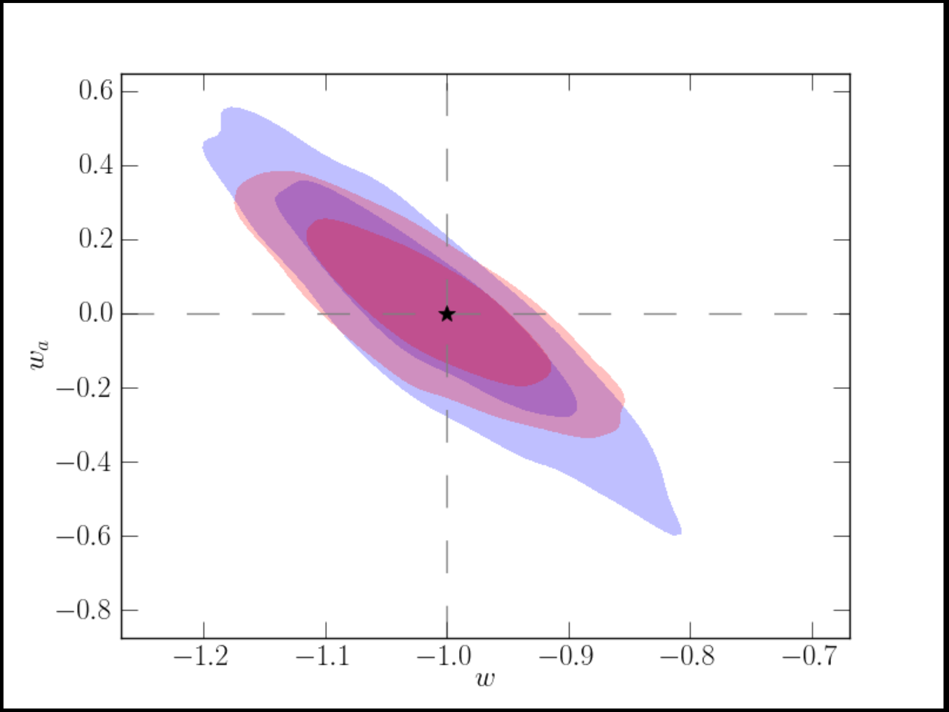
- Multiple methods can go in each box
- Should be easy to switch between them
- Make inputs/outputs clear
- With modular structure outputs are explicit
- Trivial to experiment with samplers & approximations



CosmoSIS examples

- Bias from mis-estimated intrinsic alignments





- Effect of marginalizing shape errors

DECam 1x1deg grizY co-add image of SPT cluster z=0.32

~50,000 galaxies in this image