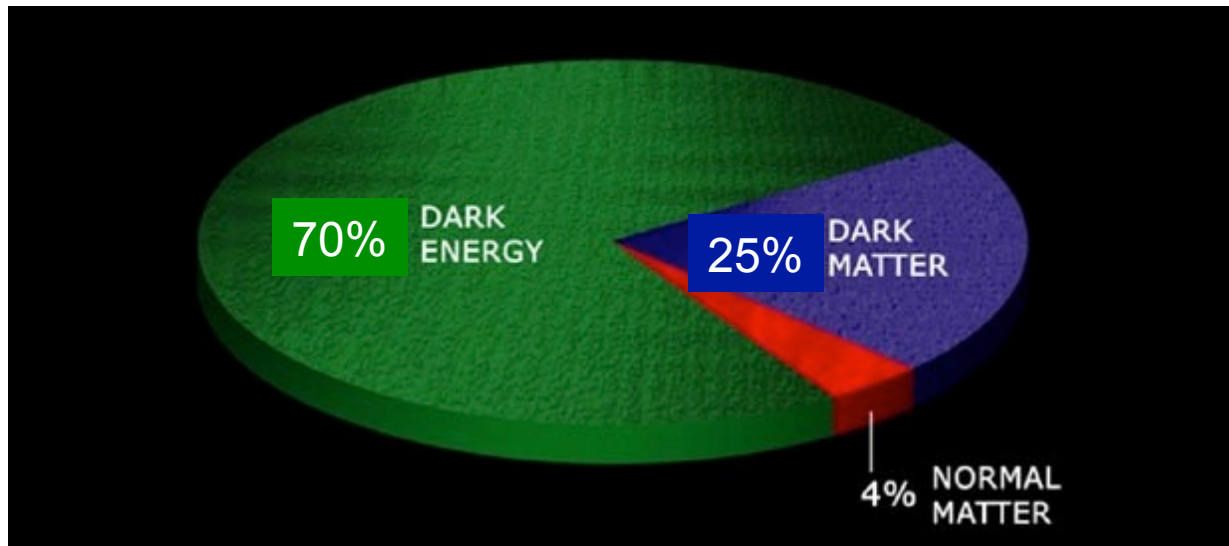


DES and the Fermilab Dark Energy Program



Josh Frieman
DOE Cosmic Frontier Program Review
September 17, 2013



Probing Dark Energy



What is the cause of cosmic acceleration?

Dark Energy (DE) or Modified Gravity?

If DE, is it Lambda or something else?

What is the value of the DE equation of state parameter $w = p_{DE}/\rho_{DE}$ and (how) does it evolve?

Addressing these questions likely to have profound impact on understanding of fundamental physics

Given high priority by P5, DETF, PASAG, Astro2010, Snowmass

Multiple, complementary methods required

Fermilab program well aligned with these goals

Fermilab Dark Energy Program



Dark Energy Survey (2013-2018) led by FNAL

Stage III Dark Energy Task Force (DETF) experiment; factor ~ 3 -5 improvement in Dark Energy precision (DETF Figure of Merit). Multiband images of 300M galaxies (5000 sq deg) and 4000 SNe. DECam on Blanco 4-m telescope at CTIO

Dark Energy Spectroscopic Instrument (DESI) (~ 2018 -2020) led by LBNL

Stage IV BAO+RSD experiment: 20-30M galaxy spectra to redshifts $z > 1$ over $\sim 15,000$ sq deg. Wide-field, multi-fiber spectrograph on Mayall 4-m telescope at KPNO.

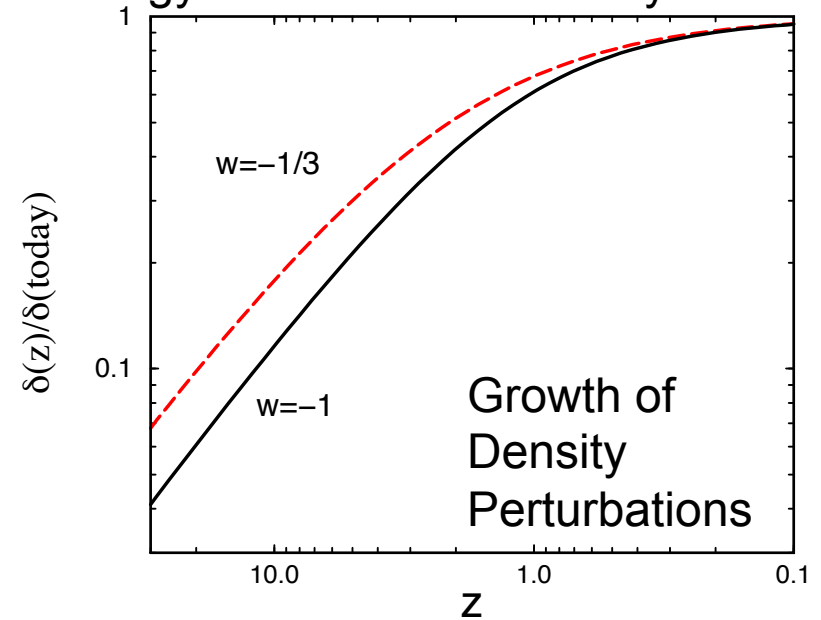
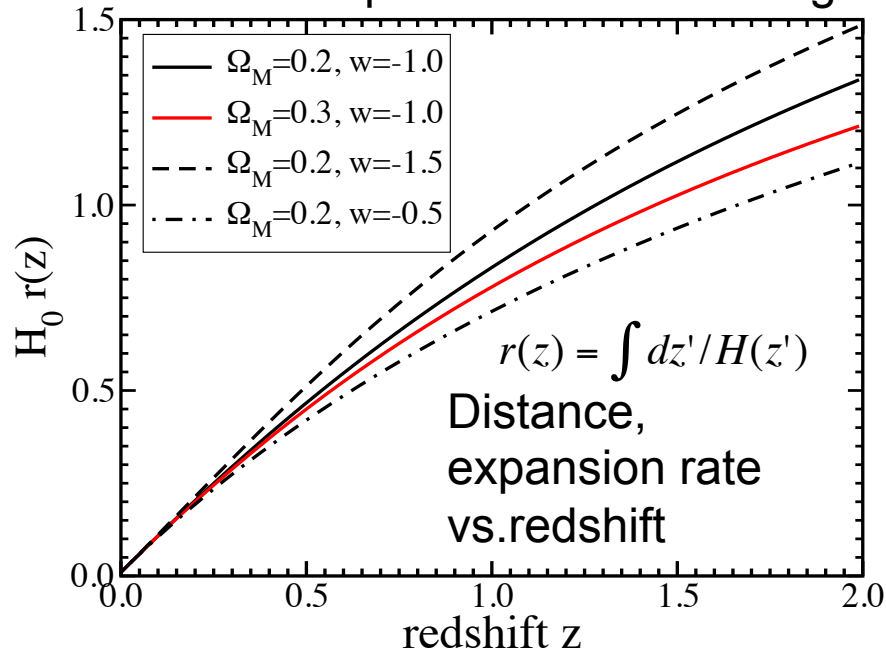
Large Synoptic Survey Telescope (~ 2020 -2030) led by SLAC

Stage IV imaging survey will use new 8.4-m telescope and wide-field camera on Cerro Pachon in Chile. Multiband images of ~ 3 B galaxies (18,000 sq deg) and tens of thousands of SNe.

What can we probe?



Require both to disentangle Dark Energy from Modified Gravity



DES, LSST { Weak Lensing cosmic shear
Supernovae
Clusters

DESI { Baryon Acoustic Oscillations
Redshift Distortions

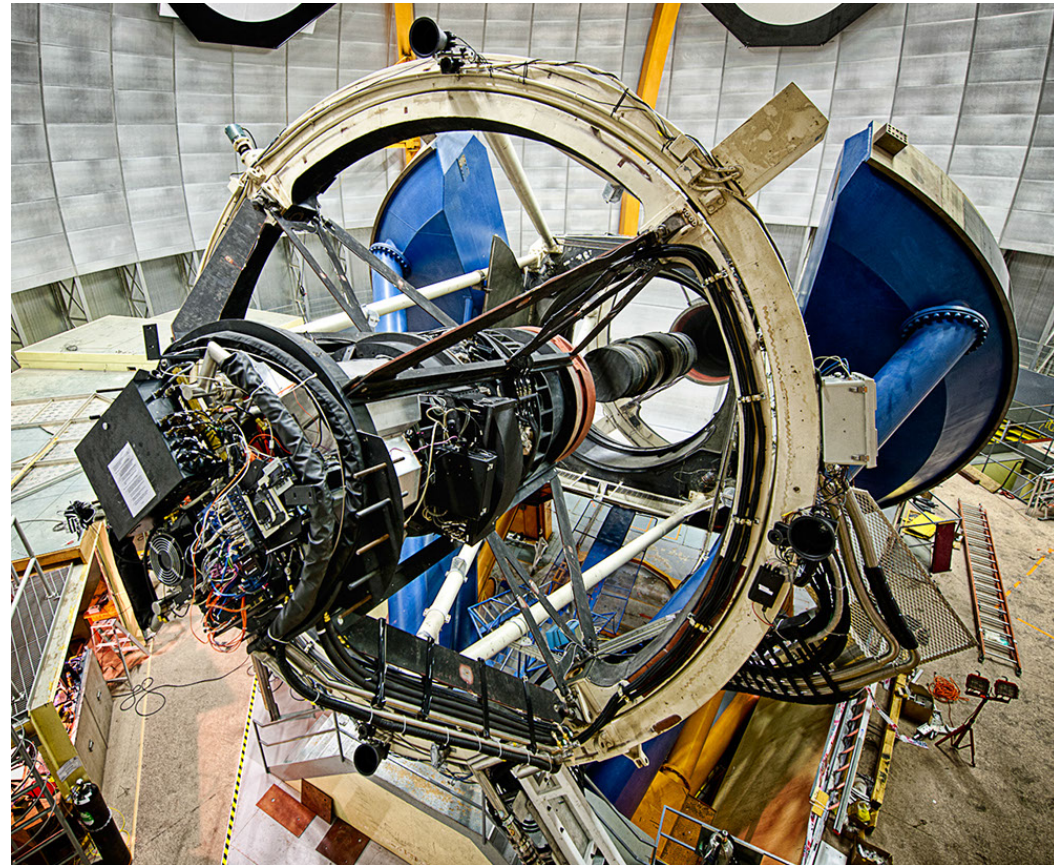
Distances+growth
Distances
Distances+growth
Distances and $H(z)$
Growth

The Dark Energy Survey



Survey project using 4 complementary techniques:

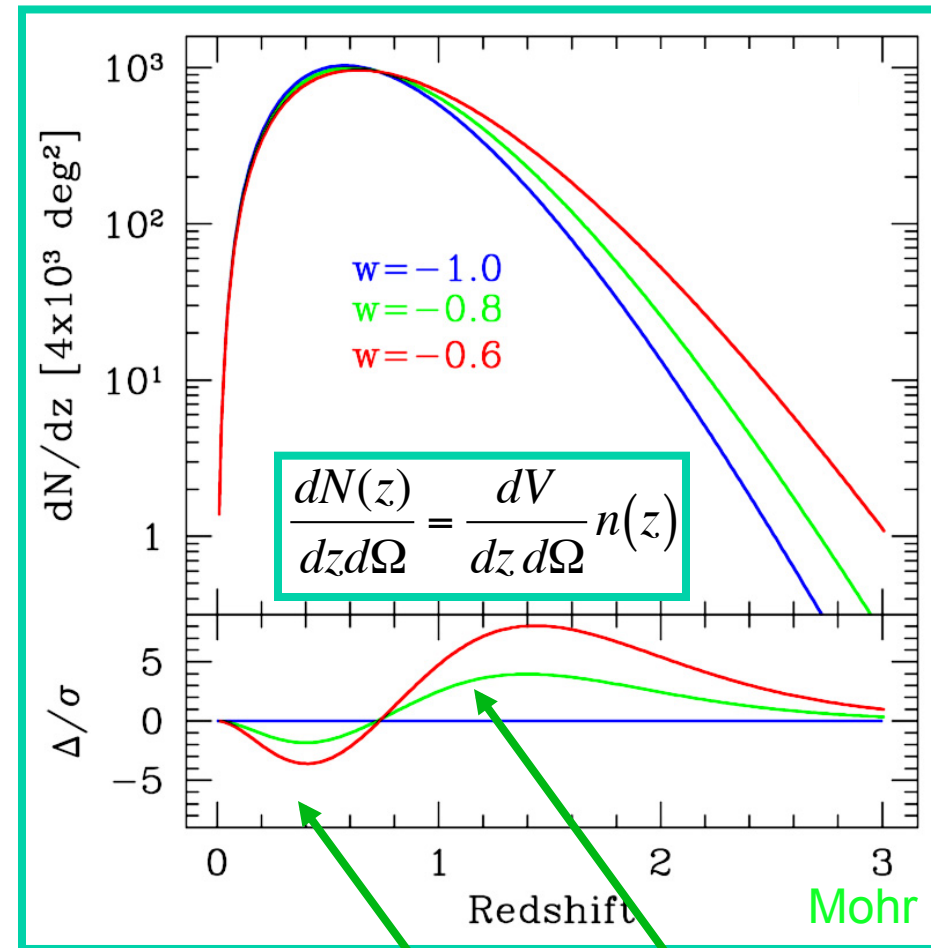
- I. Cluster Counts
- II. Weak Lensing
- III. Large-scale Structure
- IV. Supernovae
- Two multiband imaging surveys:
 - 5000 deg² *grizY* to 24th mag
 - 30 deg² repeat *griz* (SNe)
- New 3 deg² FOV camera on the Blanco 4m telescope
 - Survey 2013-2018 (525 nights)
 - Facility instrument for astronomy community (DES 30% time)



I. 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
- Multiple observable proxies O for cluster mass limits systematic errors: optical richness (DES), SZ flux decrement (SPT), weak lensing mass (DES), X-ray flux

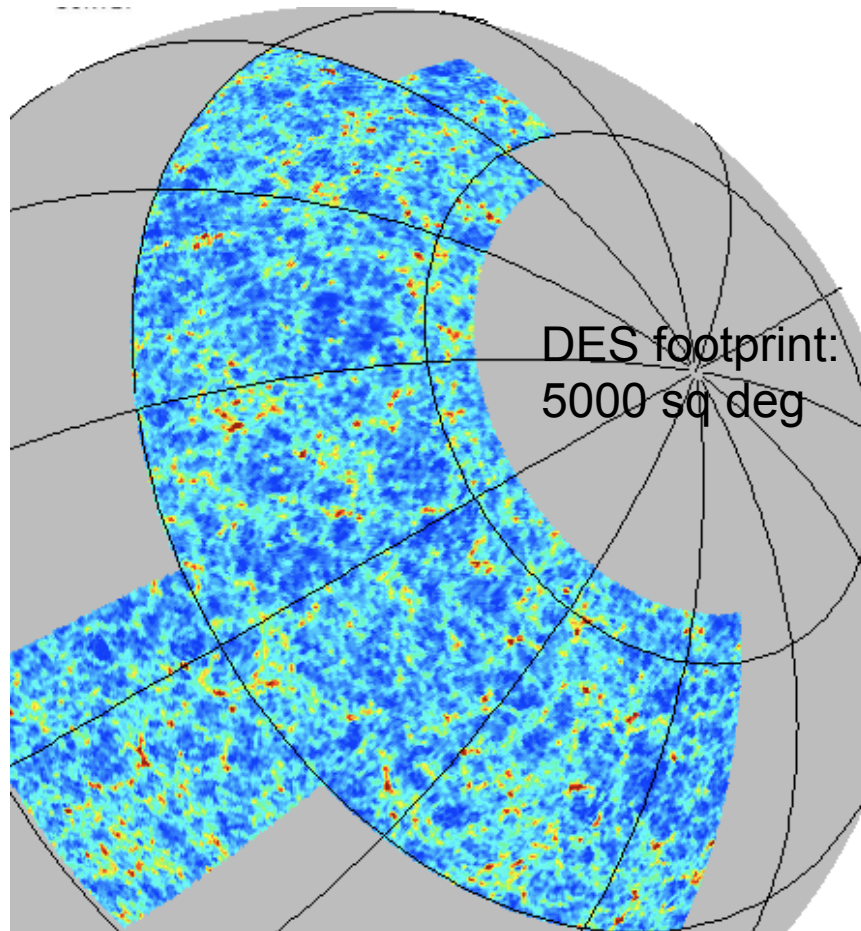


$$\frac{d^2 N}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int f(O,z) dO \int \underline{p(O|M,z)} \frac{dn(z)}{dM} dM$$

Volume

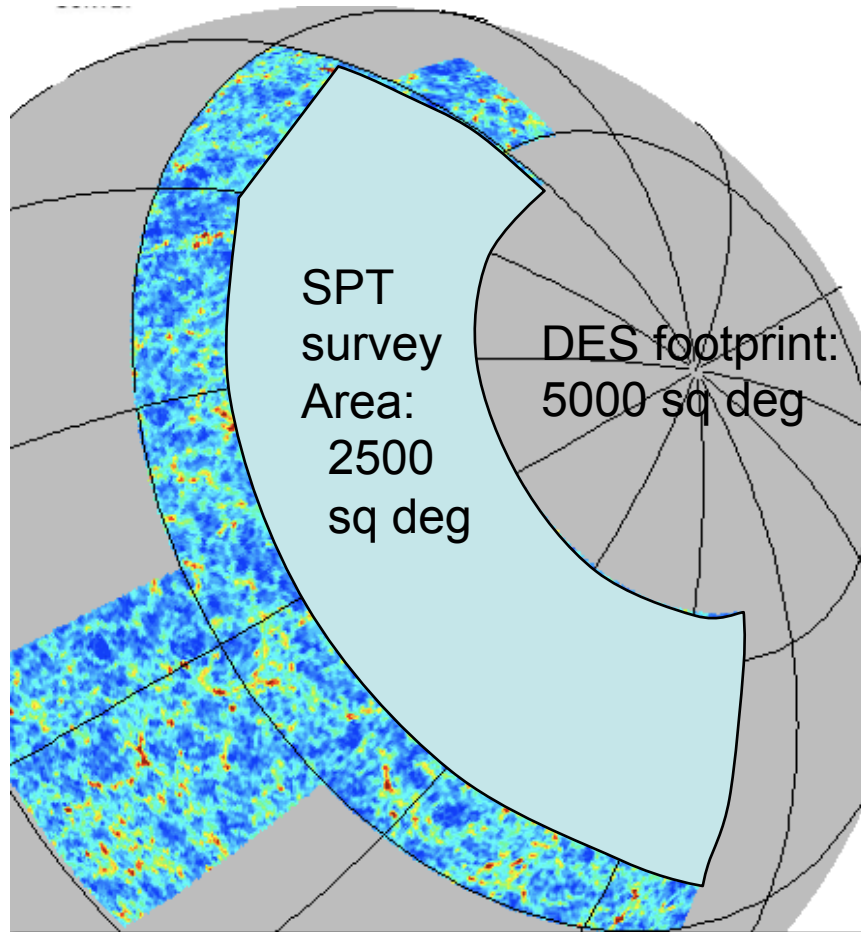
Growth 6

Synergy with South Pole Telescope



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

Synergy with South Pole Telescope



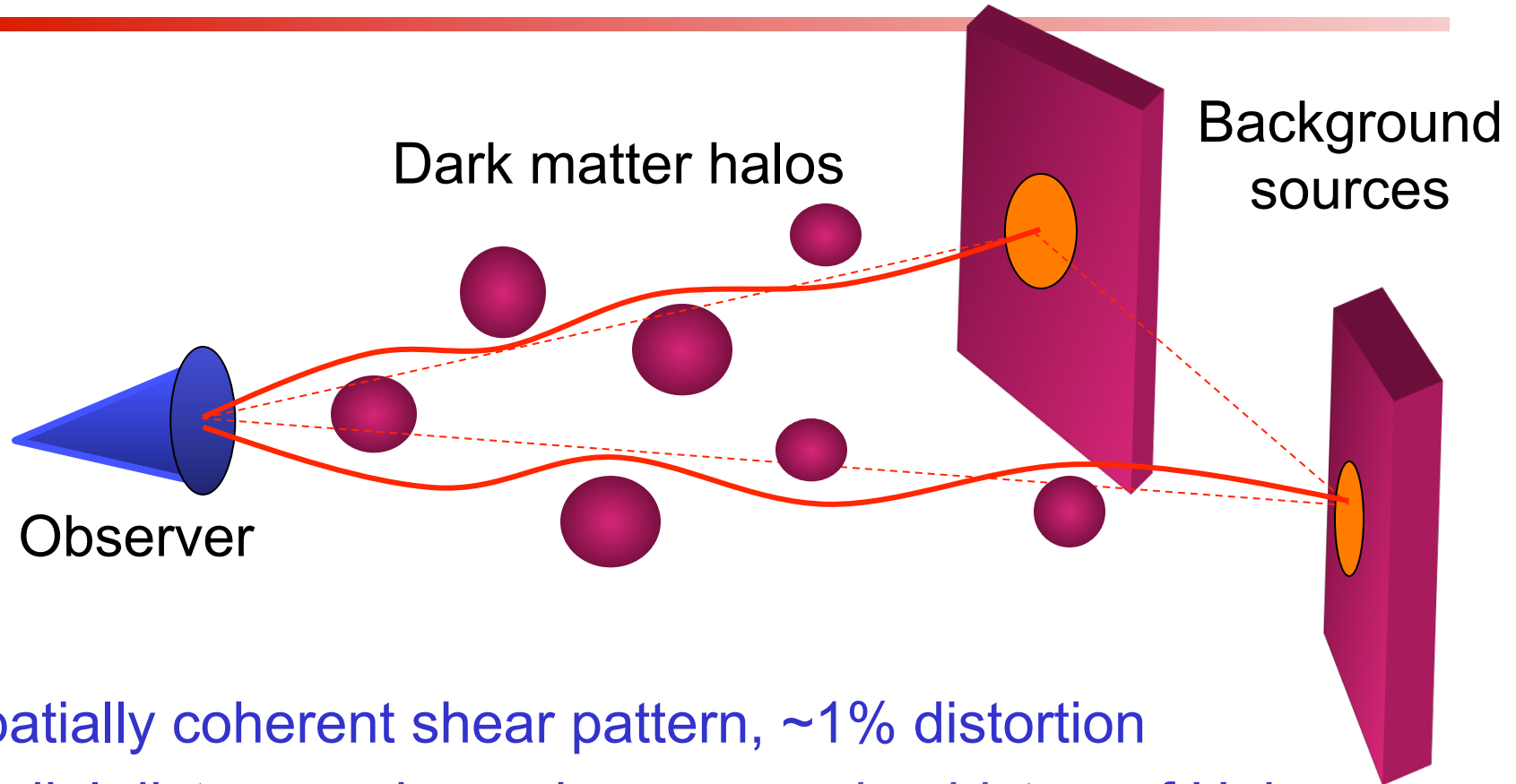
DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

DES-SPT Cross-correlations



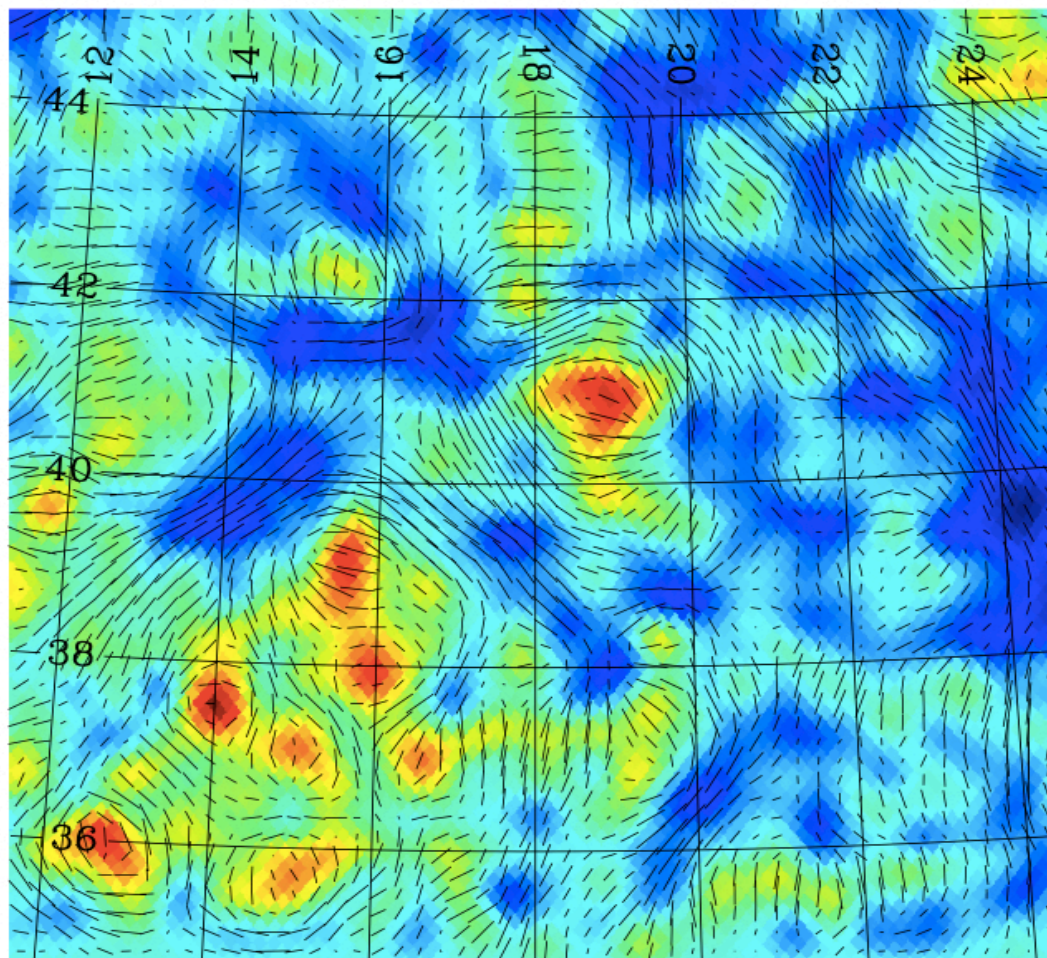
DES\SPT	κ Map	Temperature	SZ Source Profile	Lensing of Dipole
Galaxy Map	<u>1</u> Galaxy over-density and CMB kappa map LSS	<u>4</u> ISW and Diffuse SZ LSS	<u>7</u> <ul style="list-style-type: none"> • LRG: Th • Clusters: CI • Galaxies in SPT Selected Clusters, CI 	<u>10</u> Clusters: Th
Shear Map	<u>2</u> DES cosmic shear with CMB kappa map LSS/WL	<u>5</u> Might pick up ISW and Diffuse SZ	<u>8</u> This would probe $\langle \Phi \times \text{Pressure} \rangle$	<u>11</u> Might be interesting to think about this
Tangential Shear [g-g lensing; cluster lensing]	<u>3</u> Might be interesting to do "CMB kappa"-lensing	<u>6</u> Probes $\langle \Delta \Sigma \times \text{Pressure} \rangle$	<u>9</u> Cluster lensing of SZ-detected clusters: WL/CI	

II. Weak Lensing Cosmic Shear



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

Weak Lensing Mass & Shear



Tick marks: shear

Colors: projected
mass density

DES
Simulation

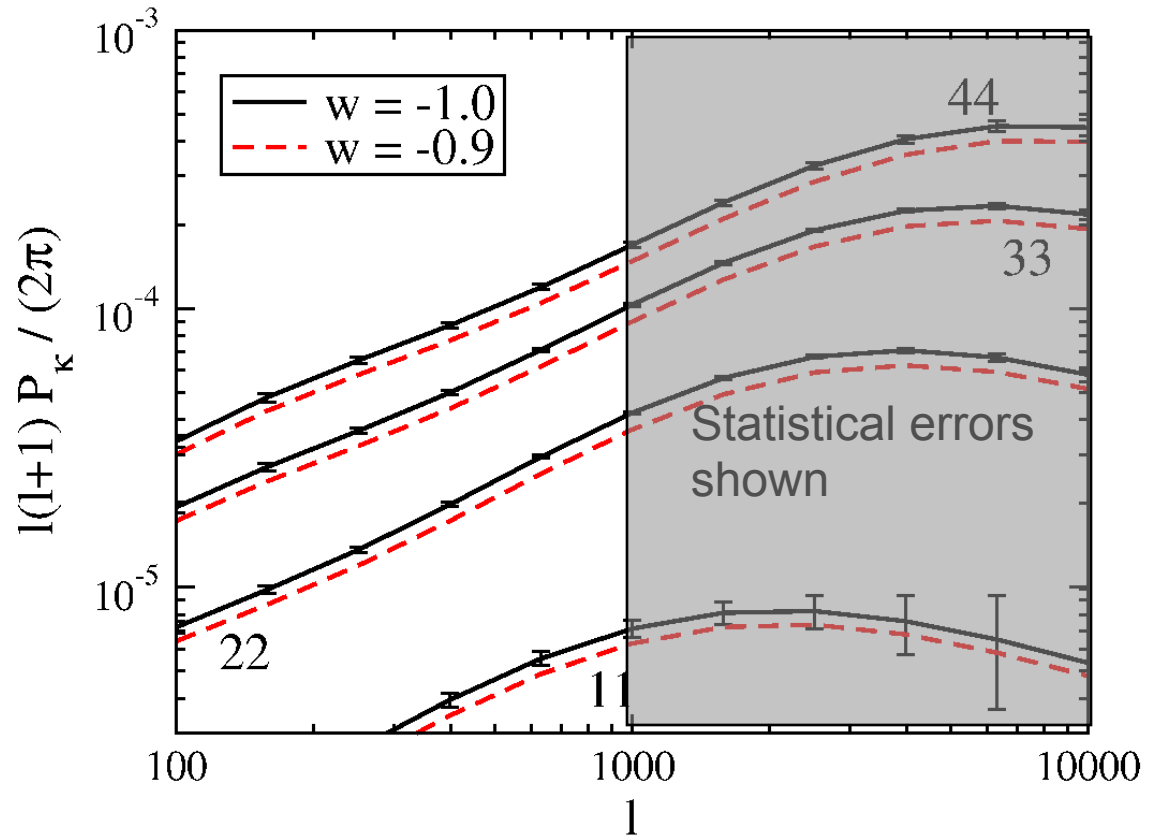
Becker,
Kravtsov,
etal

Weak Lensing Tomography



- 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

Expect $n_{\text{eff}} \sim 10/\text{arcmin}^2$ for median 0.9" PSF



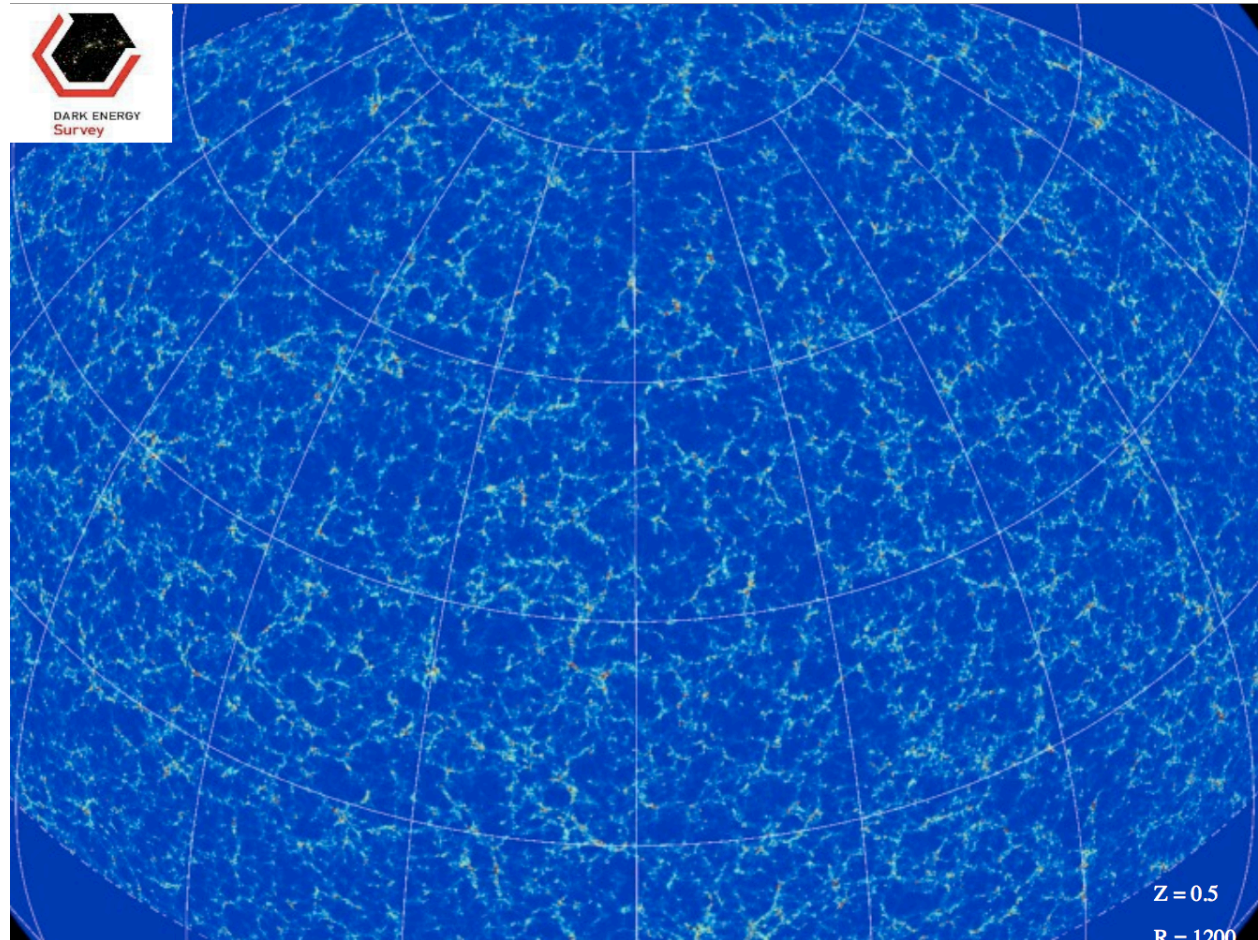
$$C_{\ell}^{x_a x_b} = \int dz \frac{H(z)}{D_A^2(z)} W_a(z) W_b(z) P^{s_a s_b}(k = \ell / D_A; z)$$

$$\Delta C_{\ell} = \sqrt{\frac{2}{(2\ell + 1) f_{\text{sky}}}} \left(C_{\ell} + \frac{\sigma^2(\gamma_i)}{n_{\text{eff}}} \right) \quad 12$$

III. Large-scale Structure



N-body
simulation
from DES
Barcelona
group



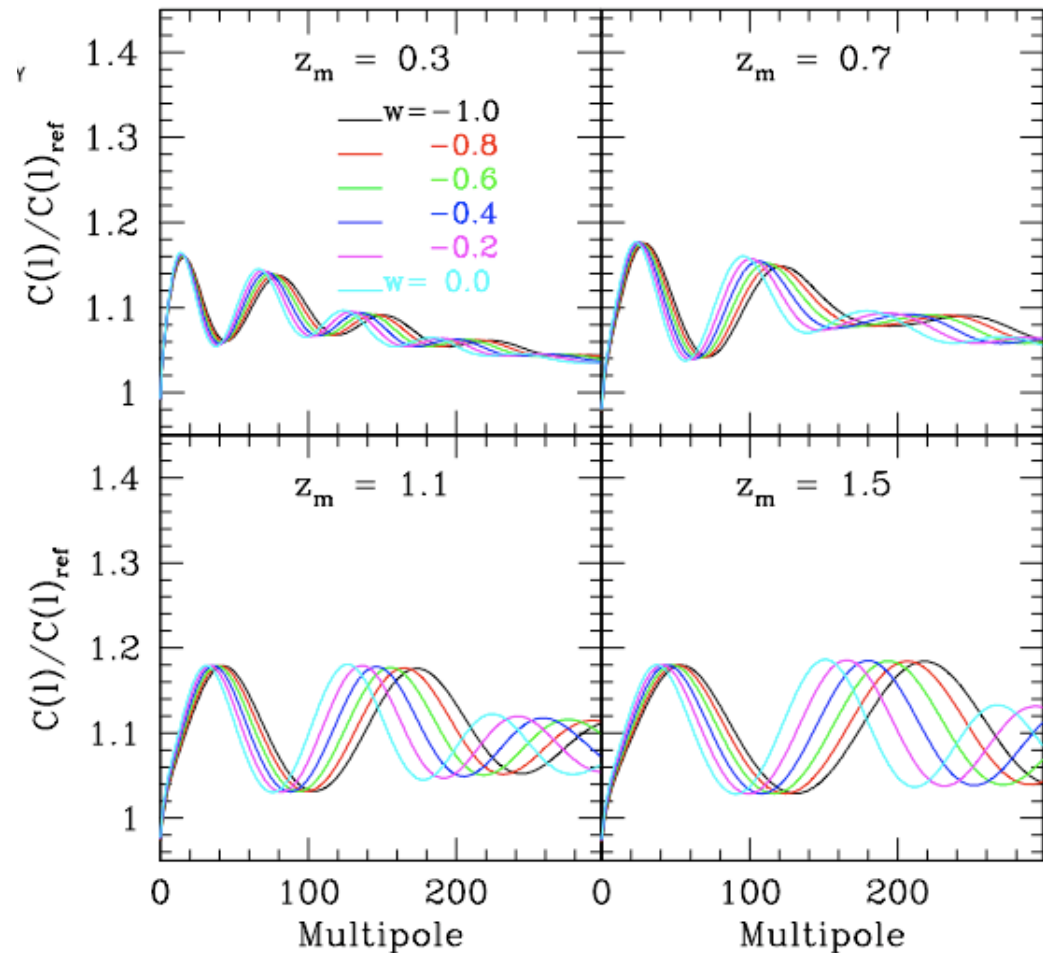
Baryon Acoustic Oscillations



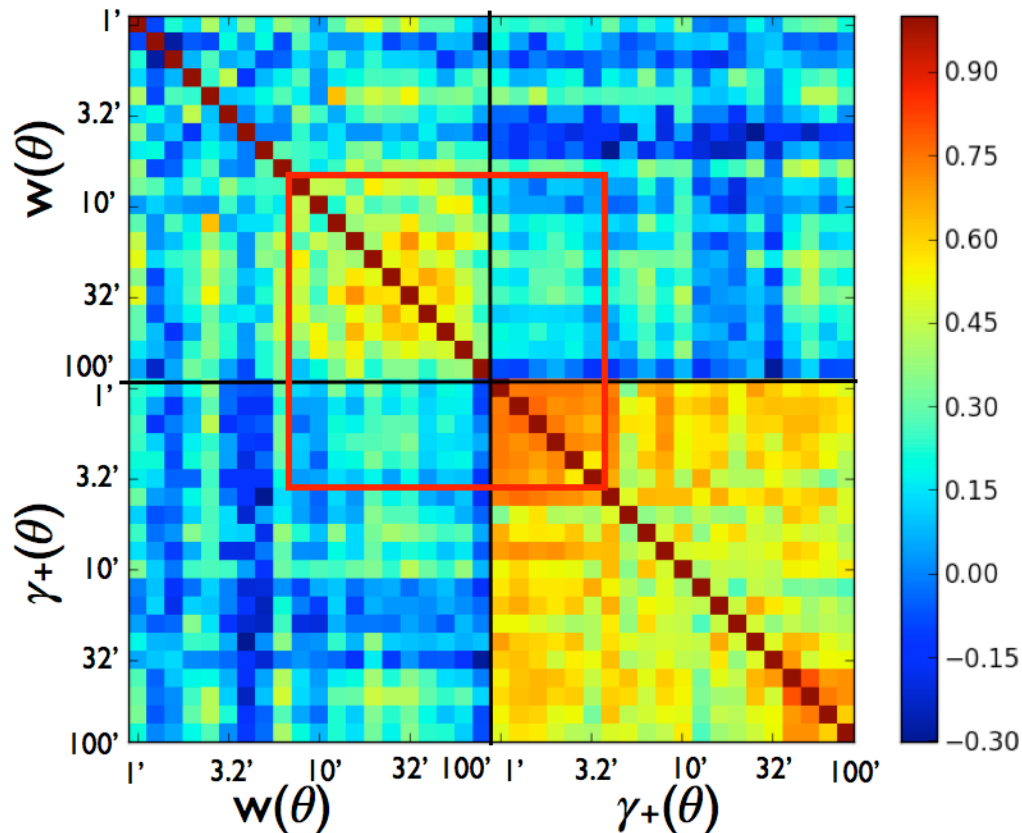
Galaxy angular
power spectrum
in photo-z bins
(relative to model
without BAO)

Photometric surveys
provide this angular
measure

Radial modes
require spectroscopy
(DESI)



Lensing-Clustering Covariance



IV. Supernovae

2005ff

2005fv

2005gb

2005fa

2005hc

2005hk

2005ik

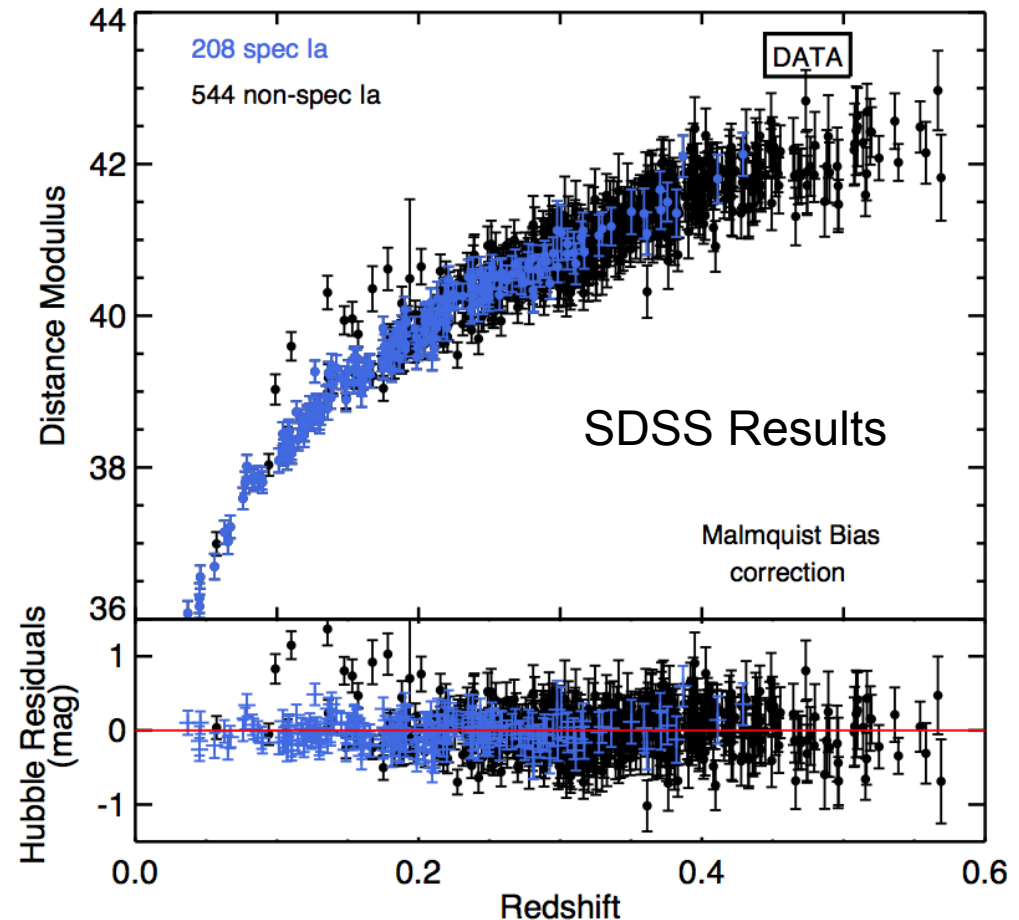
2005ir

SDSS-II: 500 spectroscopically confirmed SNe Ia,
>1000 with host redshifts from SDSS-III

Photometric SN Cosmology



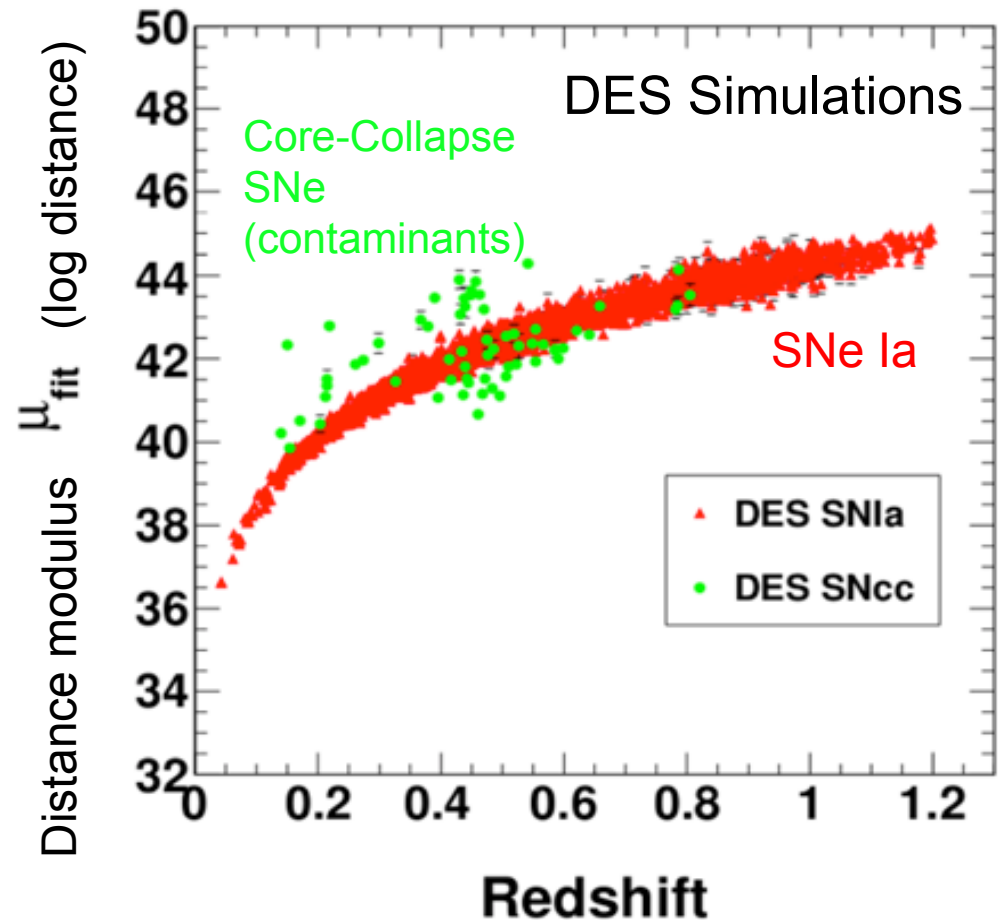
- Hubble diagram of SNe Ia: spectroscopic plus those classified photometrically that have host-galaxy redshifts
- DES will have host redshifts, plus SN spectra for a subsample



Photometric SN Cosmology



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



DES Science Summary



- **Galaxy Clusters**

- ~100,000 clusters to $z > 1$
- Synergy with SPT, VHS

- **Weak Lensing**

- Shape & magnification measurements of 200 million galaxies

- **Baryon Acoustic Oscillations**

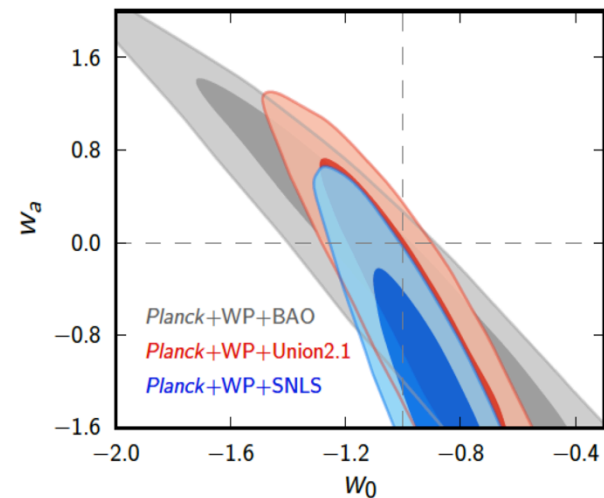
- 300 million galaxies to $z = 1$ and beyond

- **Supernovae**

- 30 sq deg time-domain survey
- ~4000 well-sampled SNe Ia to $z \sim 1$

Current Constraints on DE EOS

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



Ade, et al

DES Science Summary



- **Galaxy Clusters**

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- **Baryon Acoustic Oscillations**

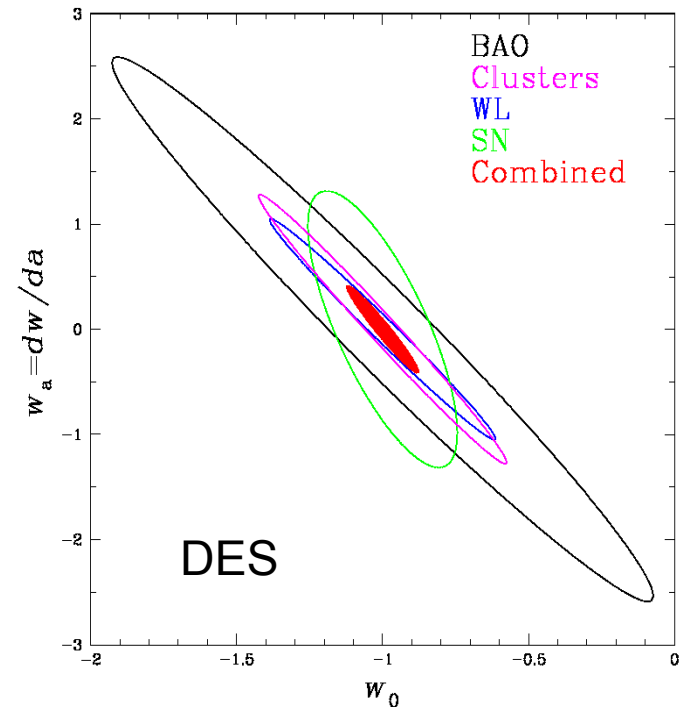
- 300 million galaxies to $z = 1$ and beyond

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Forecast Constraints on DE EOS

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DES Science Summary



- **Galaxy Clusters**

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- Synergy with SPT, VHS

- **Weak Lensing**

- Shape & magnification measurements of 200 million galaxies

- **Baryon Acoustic Oscillations**

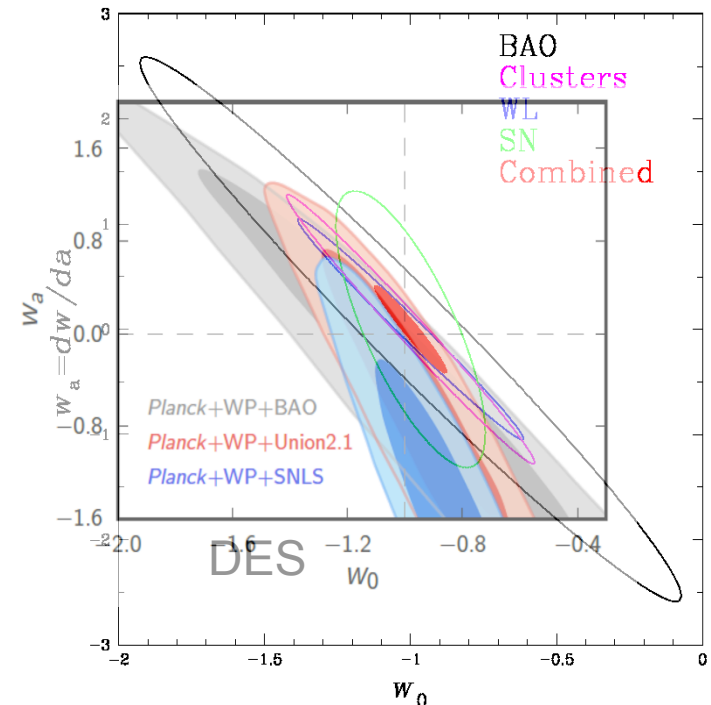
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Forecast Constraints on DE EOS

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



DES Collaboration



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
- Camera construction 2008-11; CD4 June 2012 (on-time, under budget)
- New Prime Focus Cage with corrector installed May 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 begun: Aug. 31, 2013 (105-night seasons Sept-Feb)
- Community observing with DECam since Dec. 2012

Fermilab Leadership Roles in DES

Construction

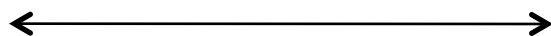
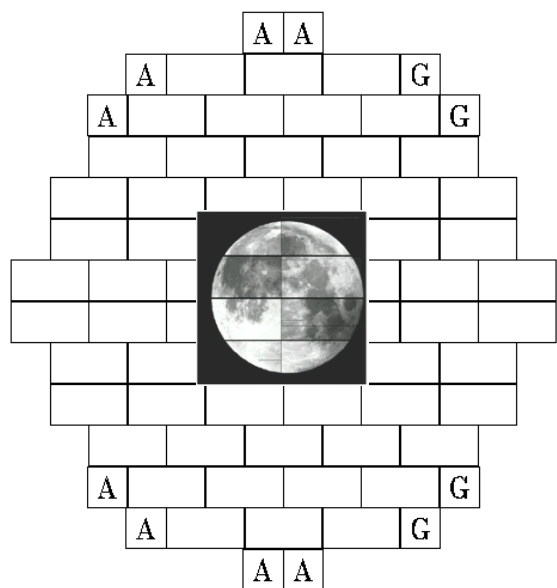
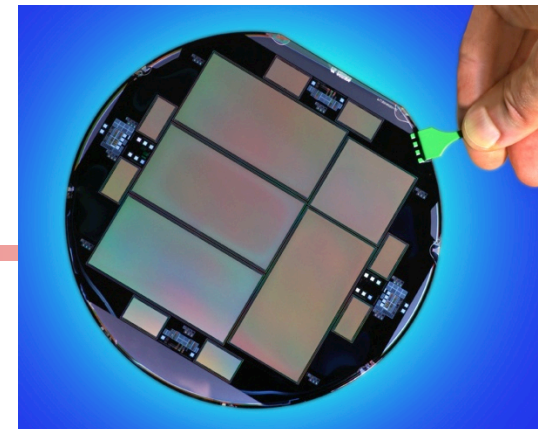
- DECam Project Management, Design, Engineering, Construction, CCD Testing & Packaging, Integration, Installation, Commissioning Flaugher, Merritt, Diehl, Estrada, Gutierrez, Kent
- Image Simulations & Testing Lin, Kuropatkin
- DES Project Management Frieman, Kron, Diehl (Peoples)

Operations

- Survey Strategy Annis, Kent, Nielsen
- Calibration Tucker, Kent, Wester
- Data Management Yanny, Buckley-Geer
- DECam Maintenance & Operations Diehl
- Analysis Computing framework Buckley-Geer, Dodelson
- Science Working Groups Buckley-Geer, Dodelson, Lin, Marriner, Yanny

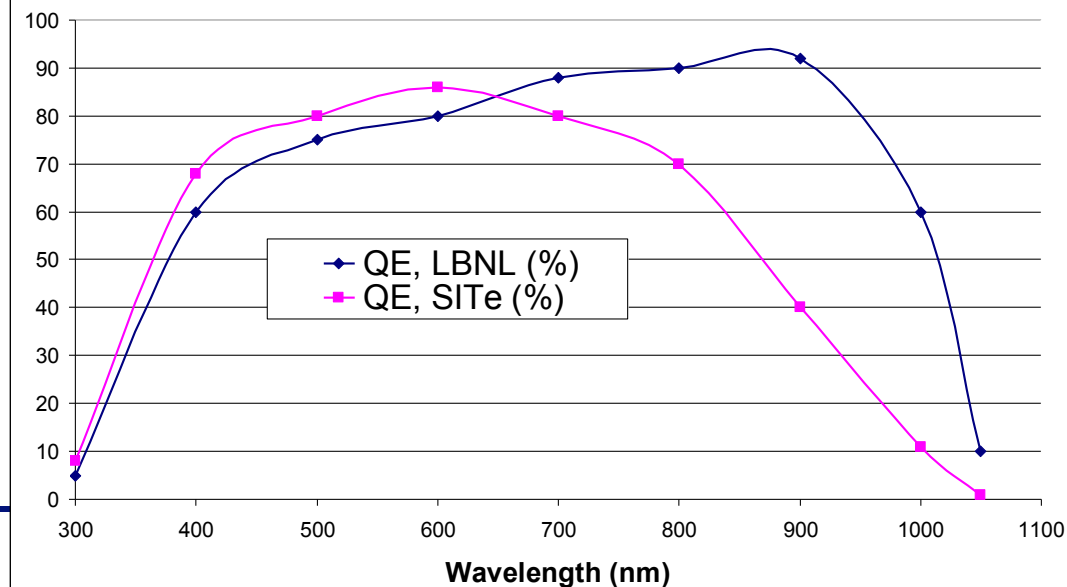
DECam CCDs

- 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 for high-z galaxies
- Developed by LBNL, packaged and tested at FNAL
- Total 570 Megapixels



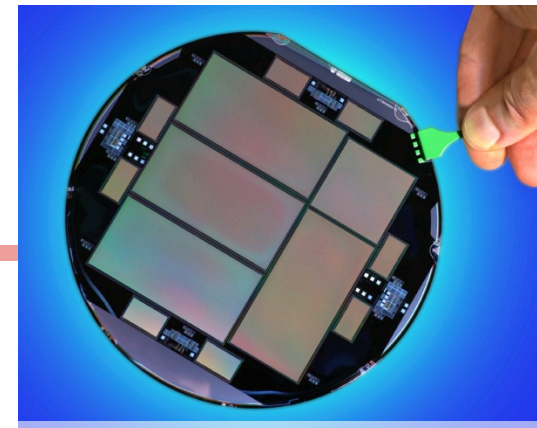
2.2 deg

DECam / Mosaic II QE comparison

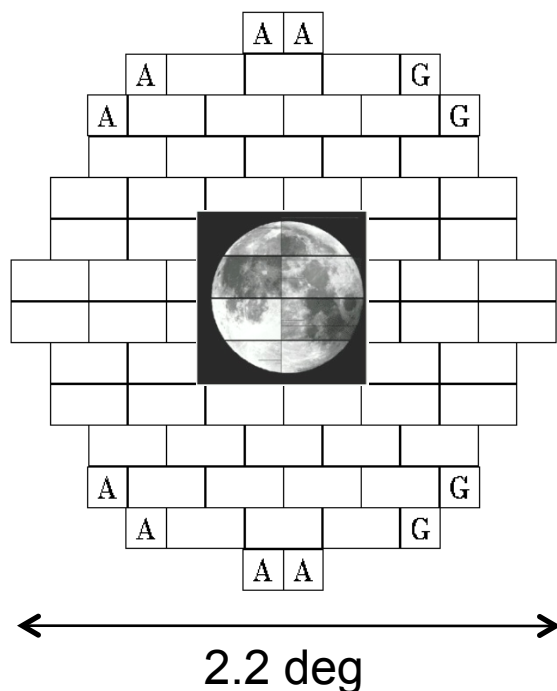
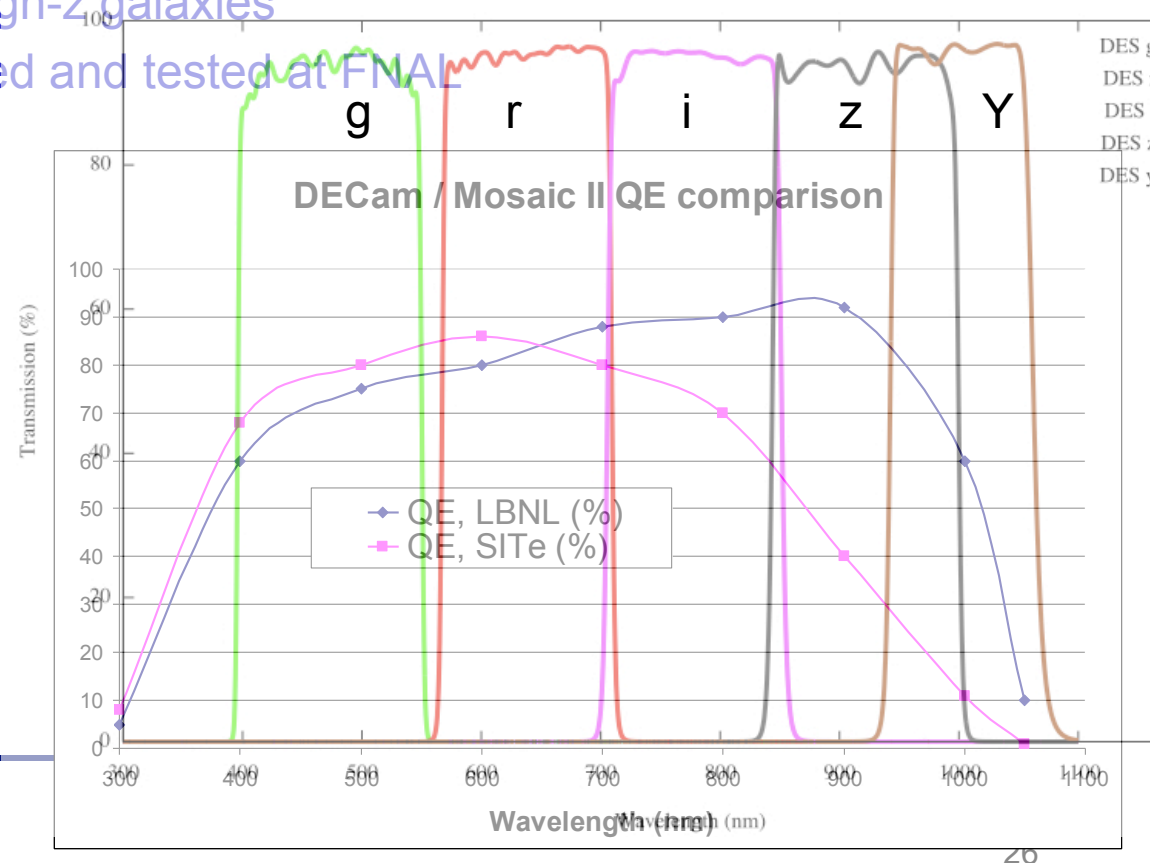


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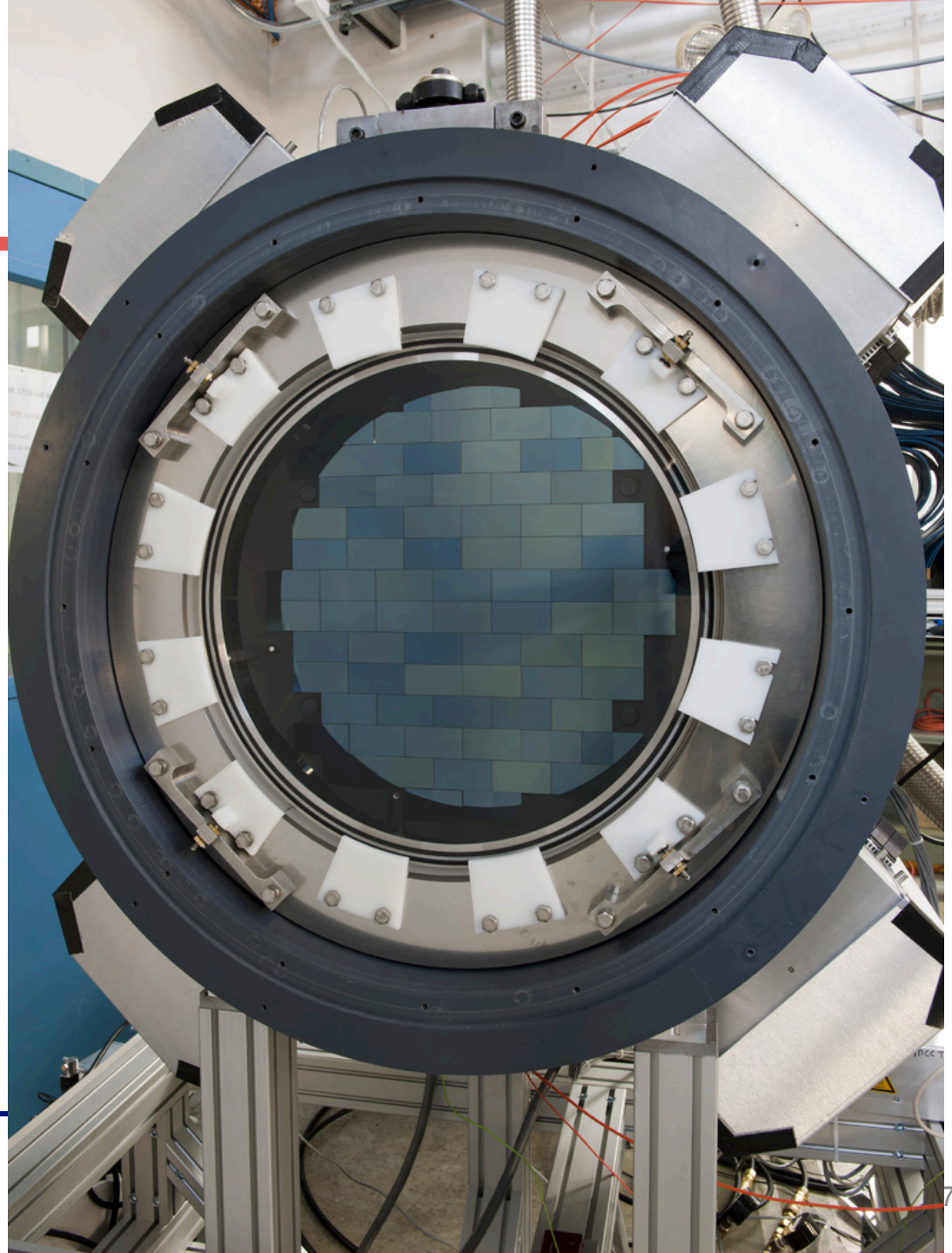


Asahi-Measured Transmission Curves for Delivered 100mm x 100mm DES grizy Filters

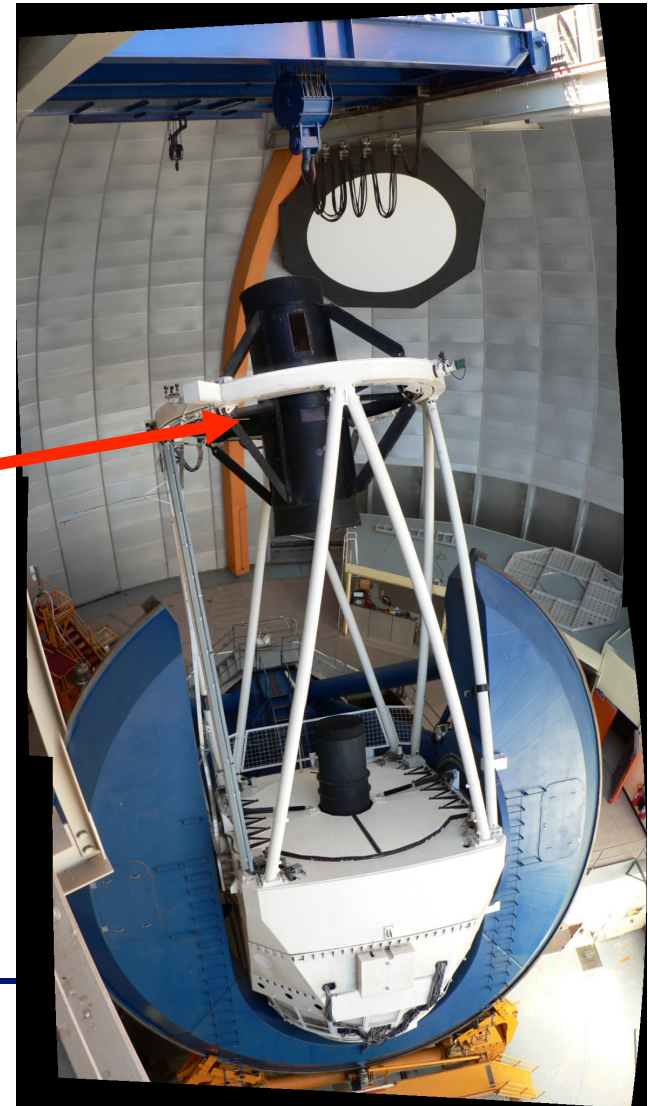
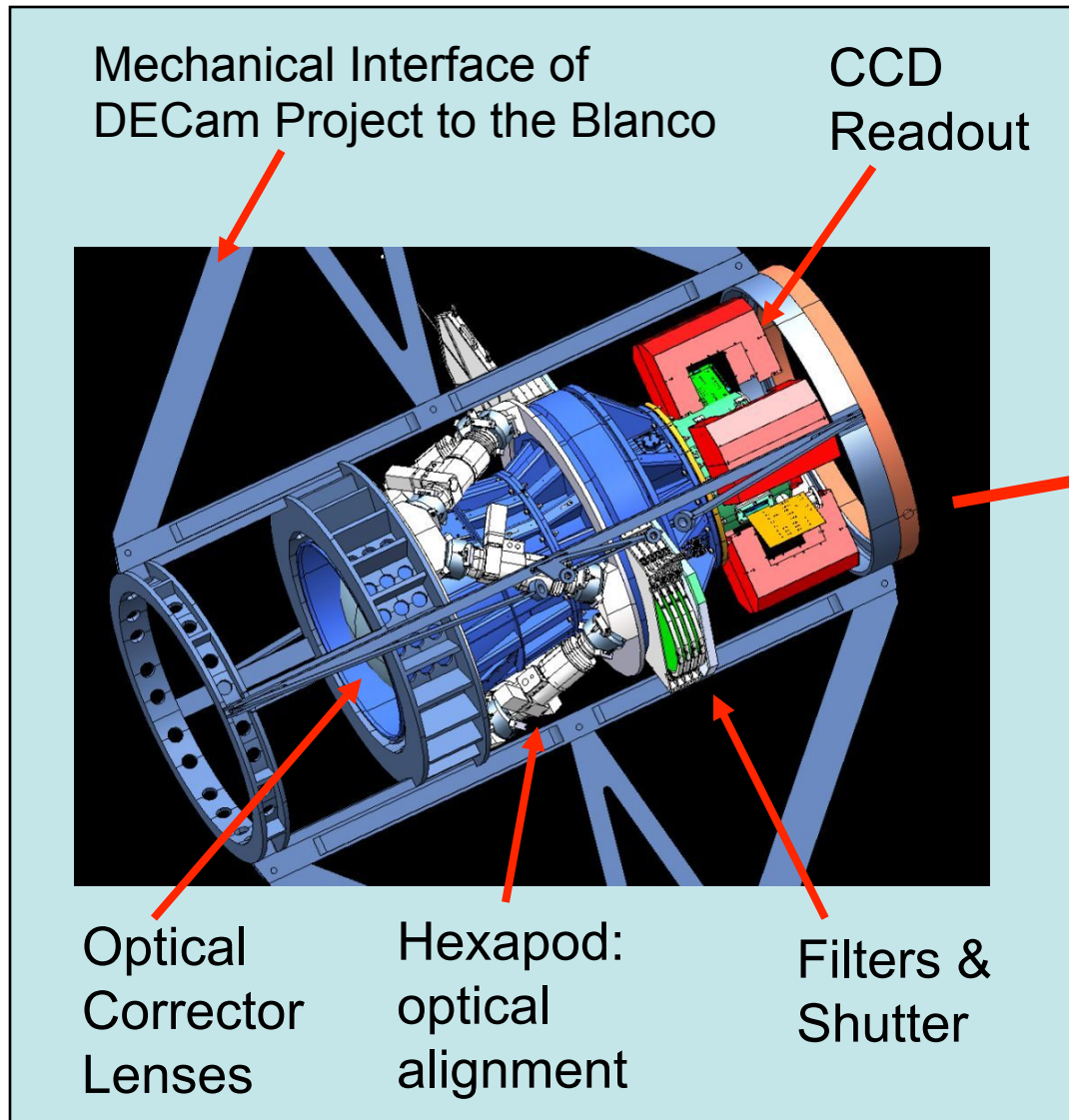


570-Megapixel DECam Imager

built by FNAL



Dark Energy Camera



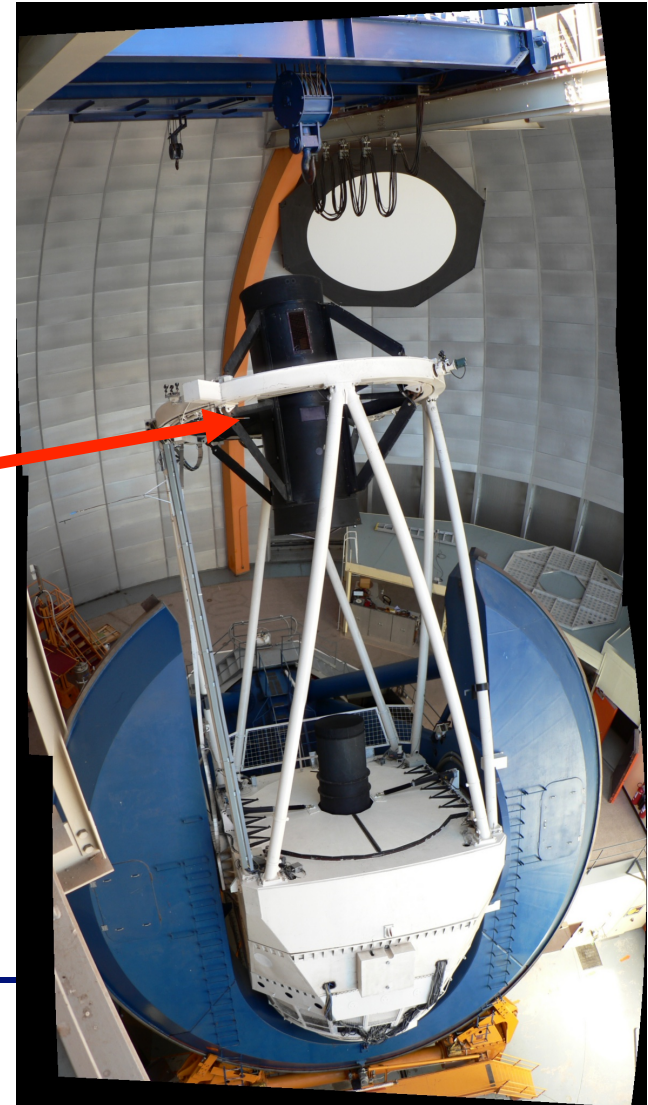
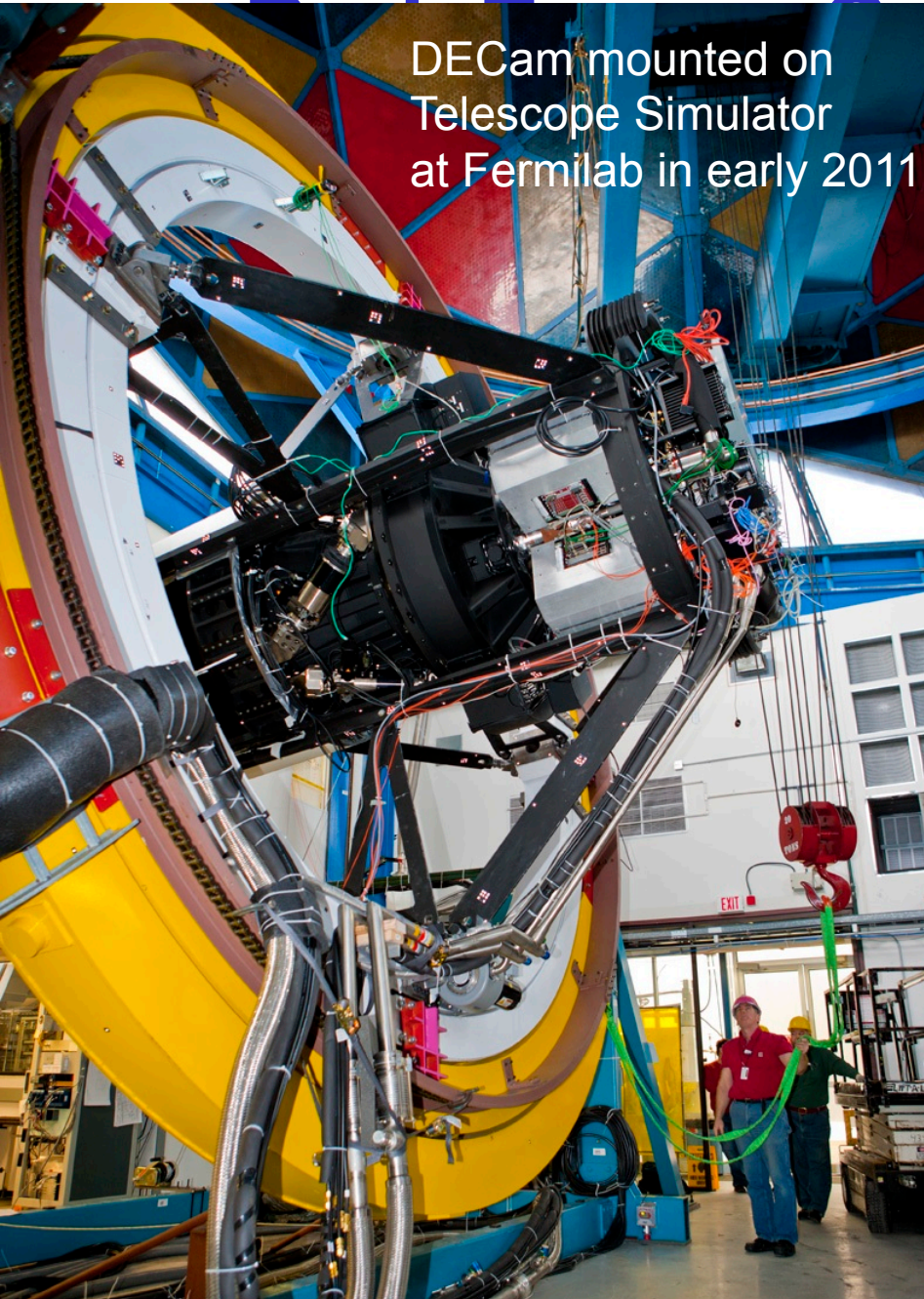
mera



DECam mounted on
Telescope Simulator
at Fermilab in early 2011

Med
DEC

Opt
Cor
Len



C1 Corrector Lens



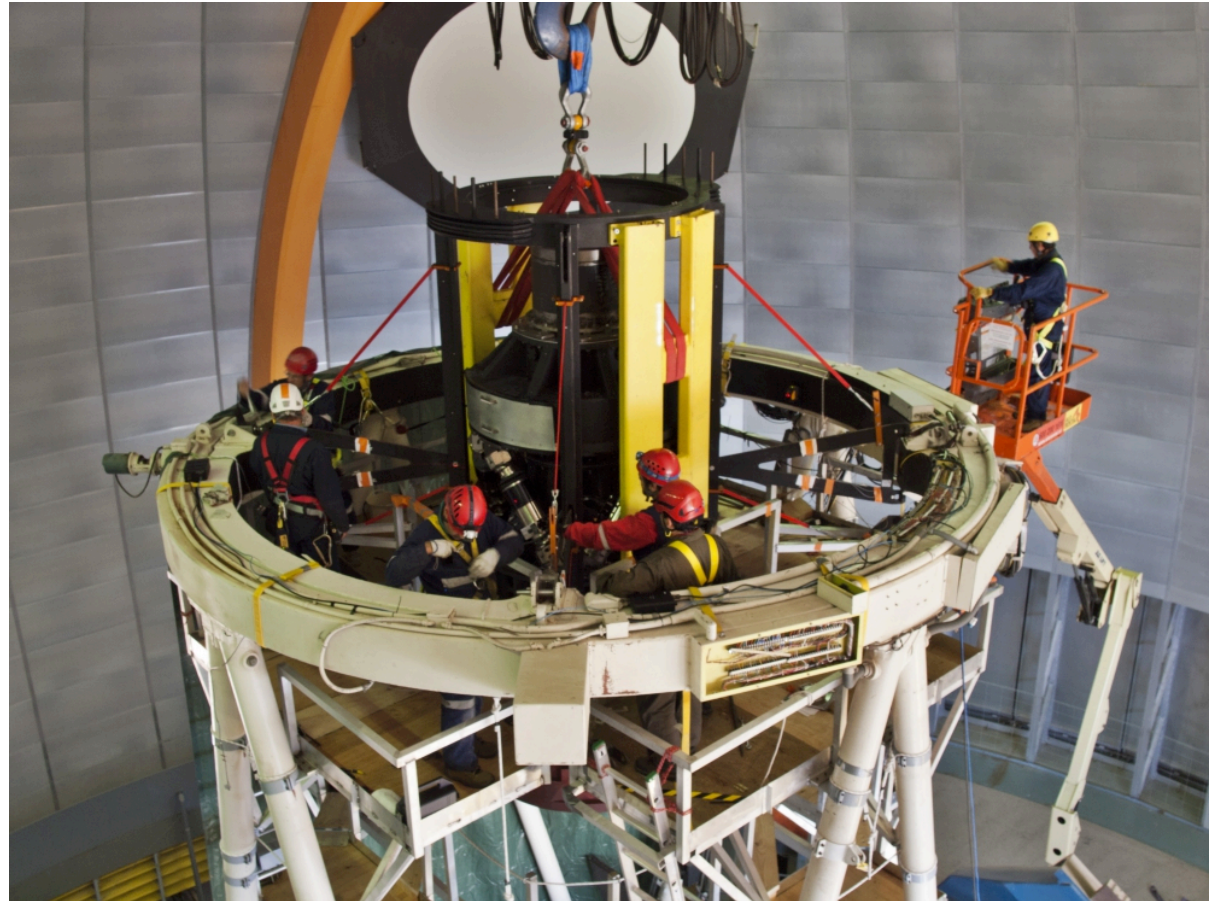
S. Kent



Prime Focus Cage Installation



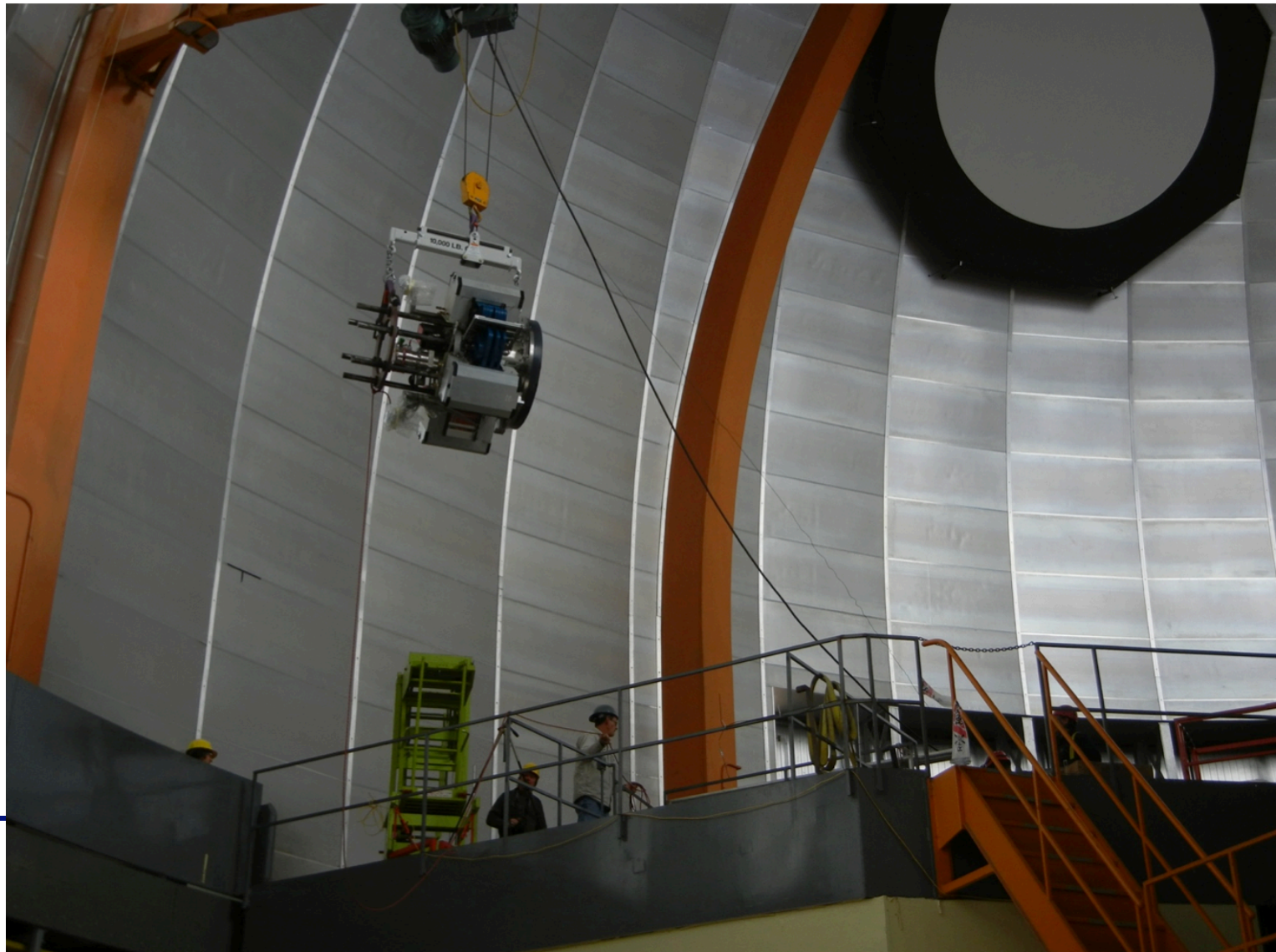
Early May
2012



Imager Installation



August
2012



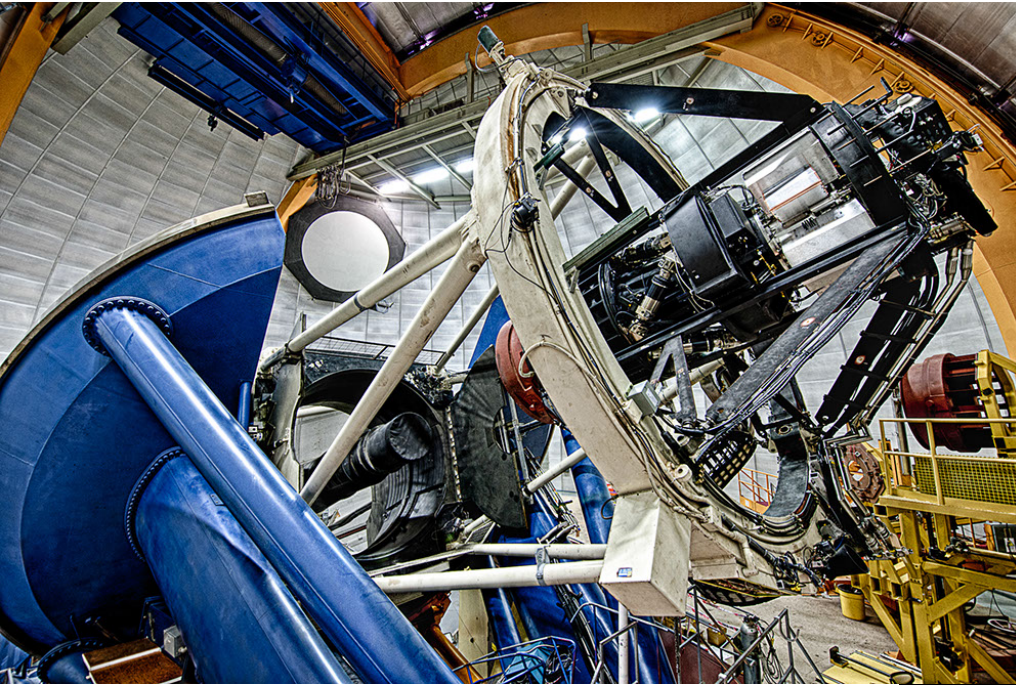
Imager Installation



August
2012



DECam First Light



September 12, 2012

Covered in 258 publications in 36 countries, plus Jay Leno's monologue

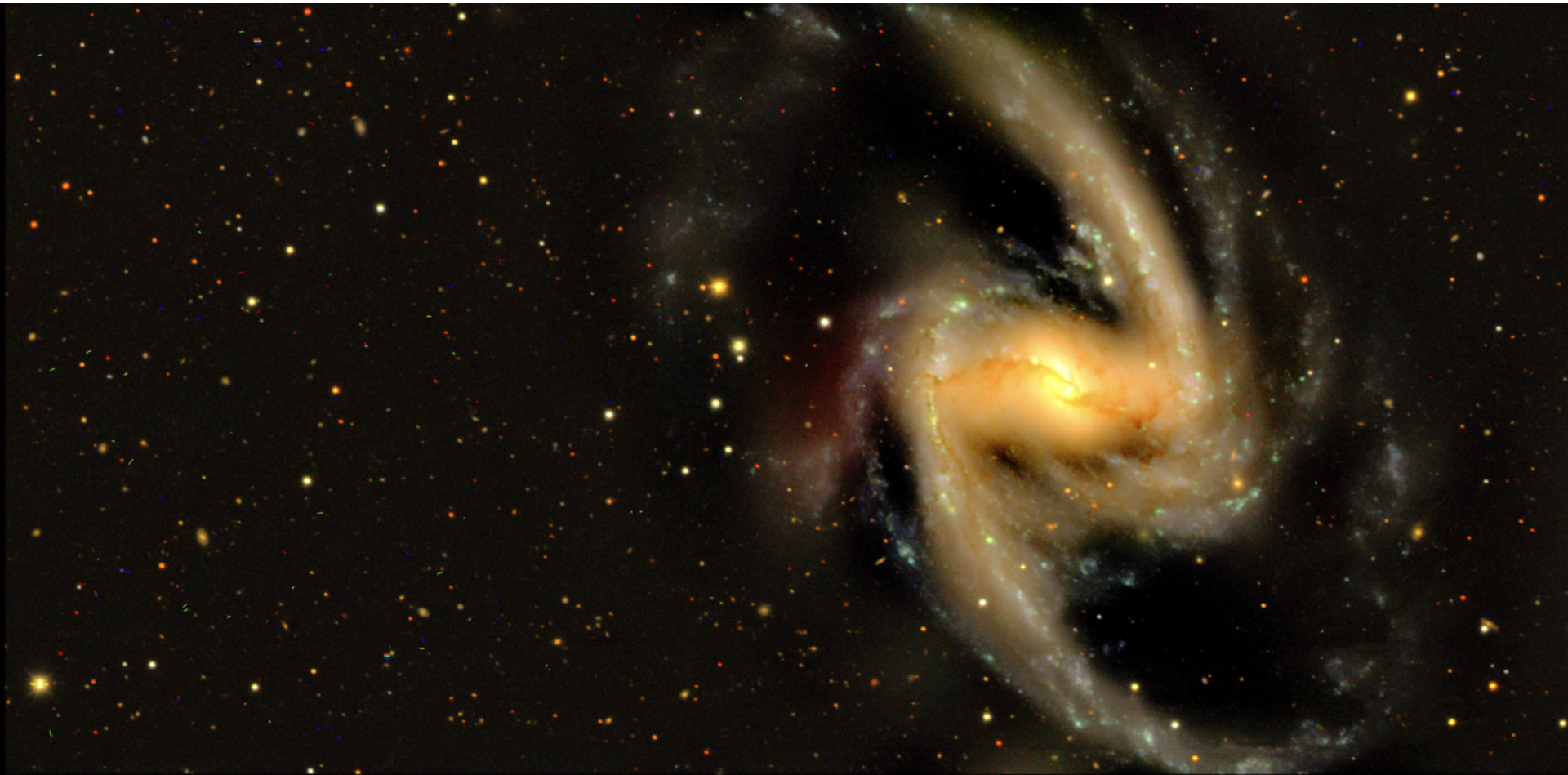
First Light Images



Fornax Cluster

0.8" images recorded within
first few nights of first light

First Light Images



NGC 1365 in Fornax

image from a single CCD



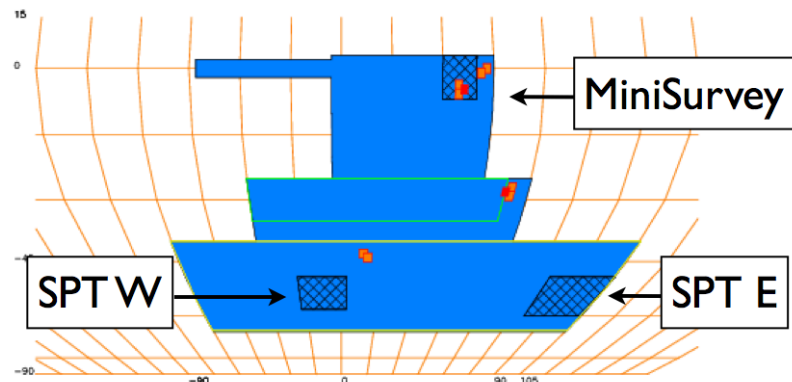
Led by G. Bernstein, K. Honscheid

SV Observations

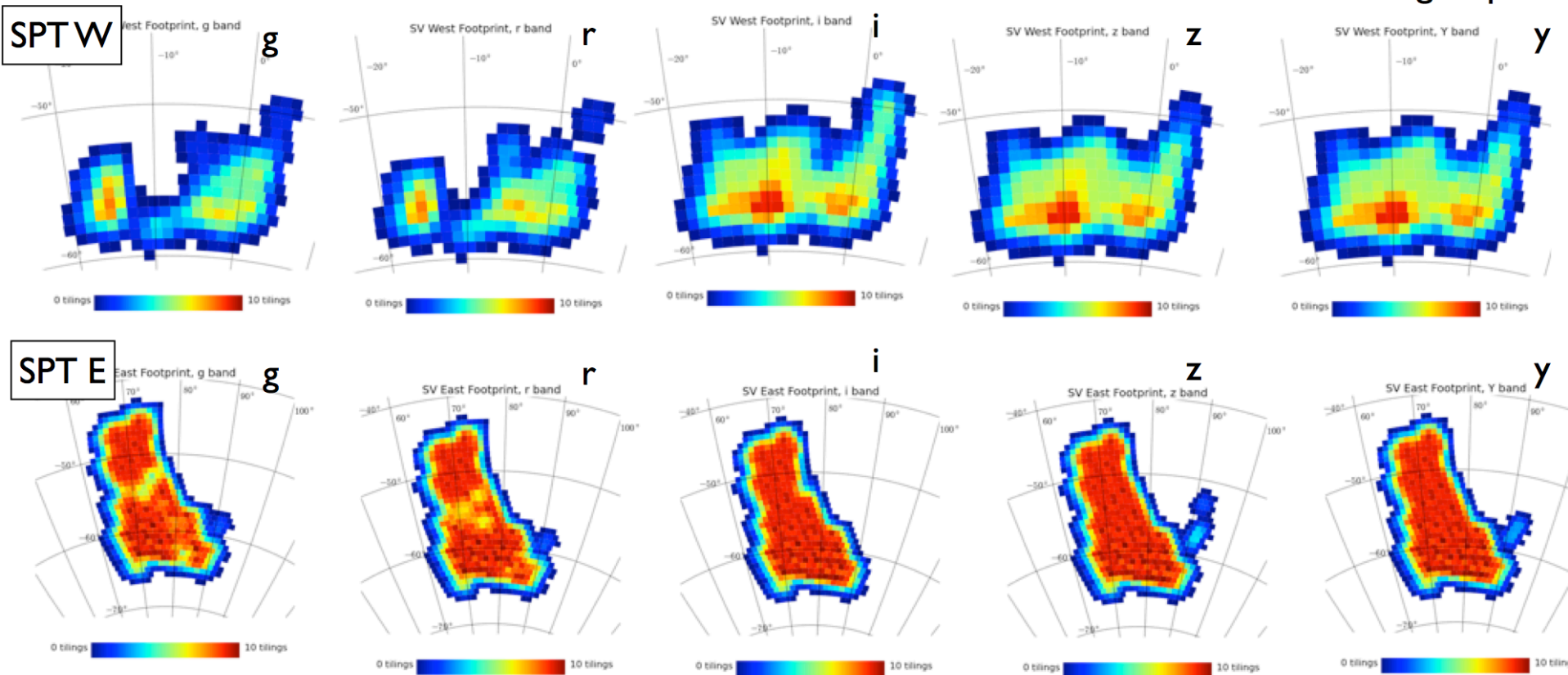
Nov. 2012-Feb. 2013

Field	Exposures	Deg ²	Tilings	Notes
Minisurvey	244	~30	~3	Inhomogeneous, poor IQ
SPT-W	322	~60	~3	Inhomogeneous, mostly izY.
SPT-E	2537	~157	10	Homogeneous depth, all exposures <1.3" FWHM

SV report (docdb 6985)



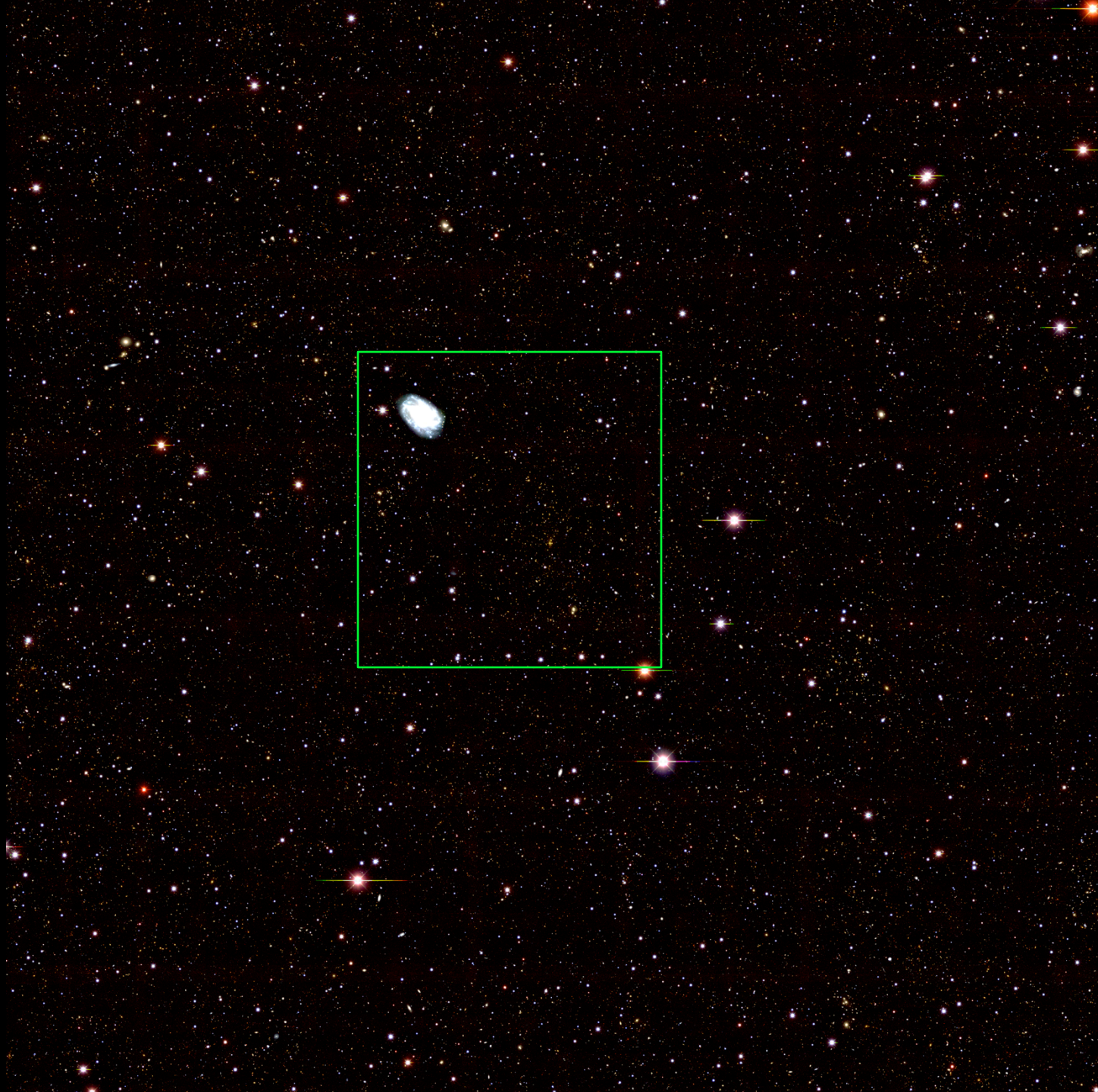
Number of tiling maps

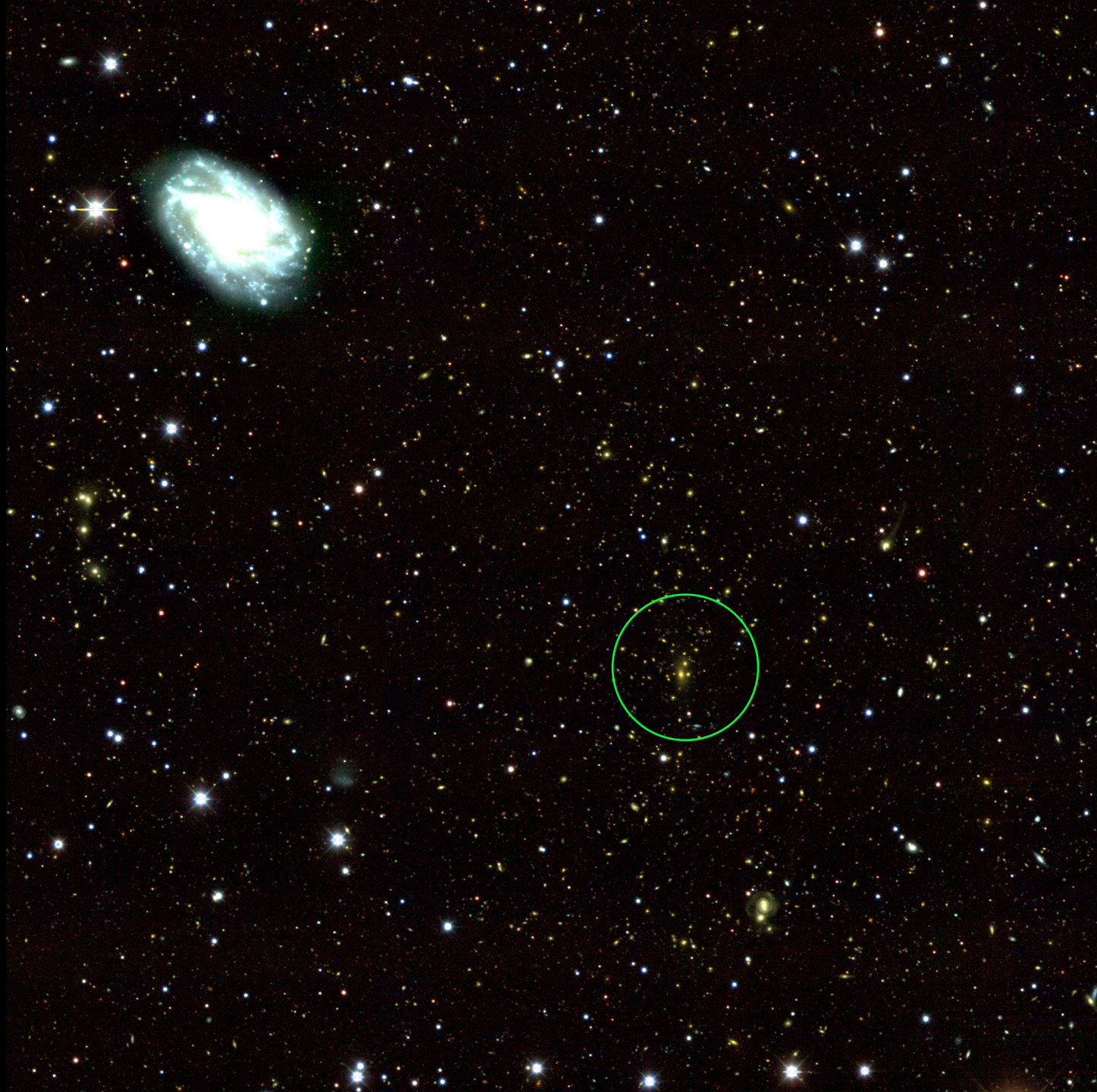




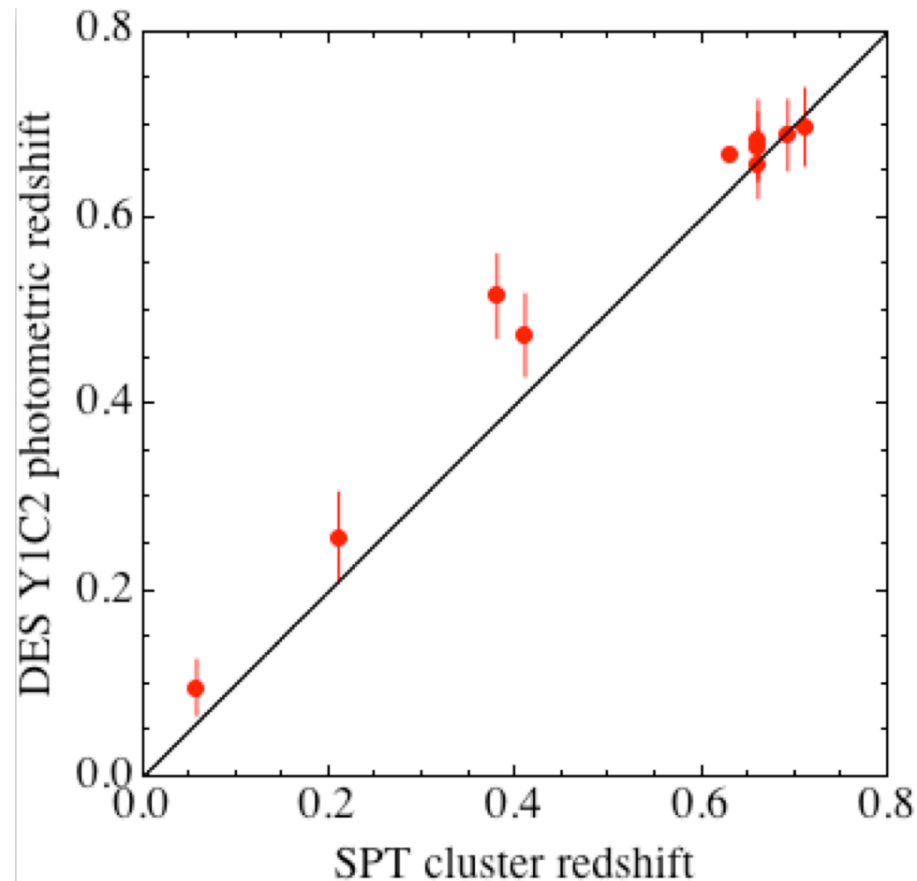
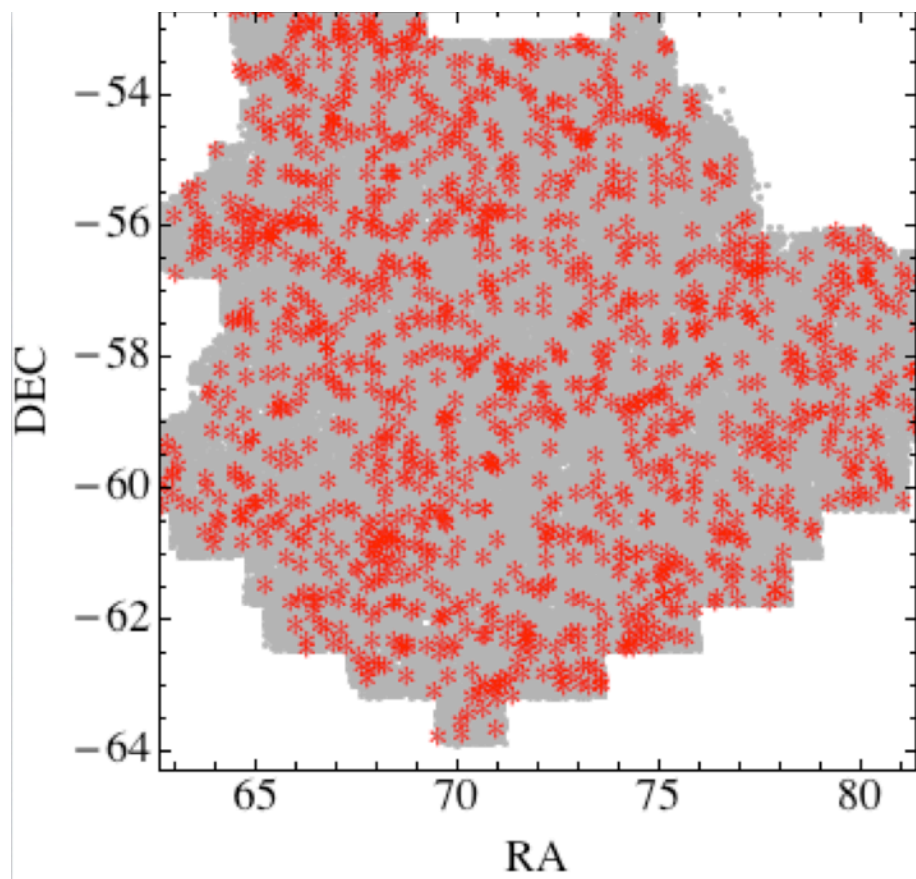
DES SV
1x1deg
grizY co-add
image of SPT
cluster
 $z=0.32$

~50,000 galaxies
in this image





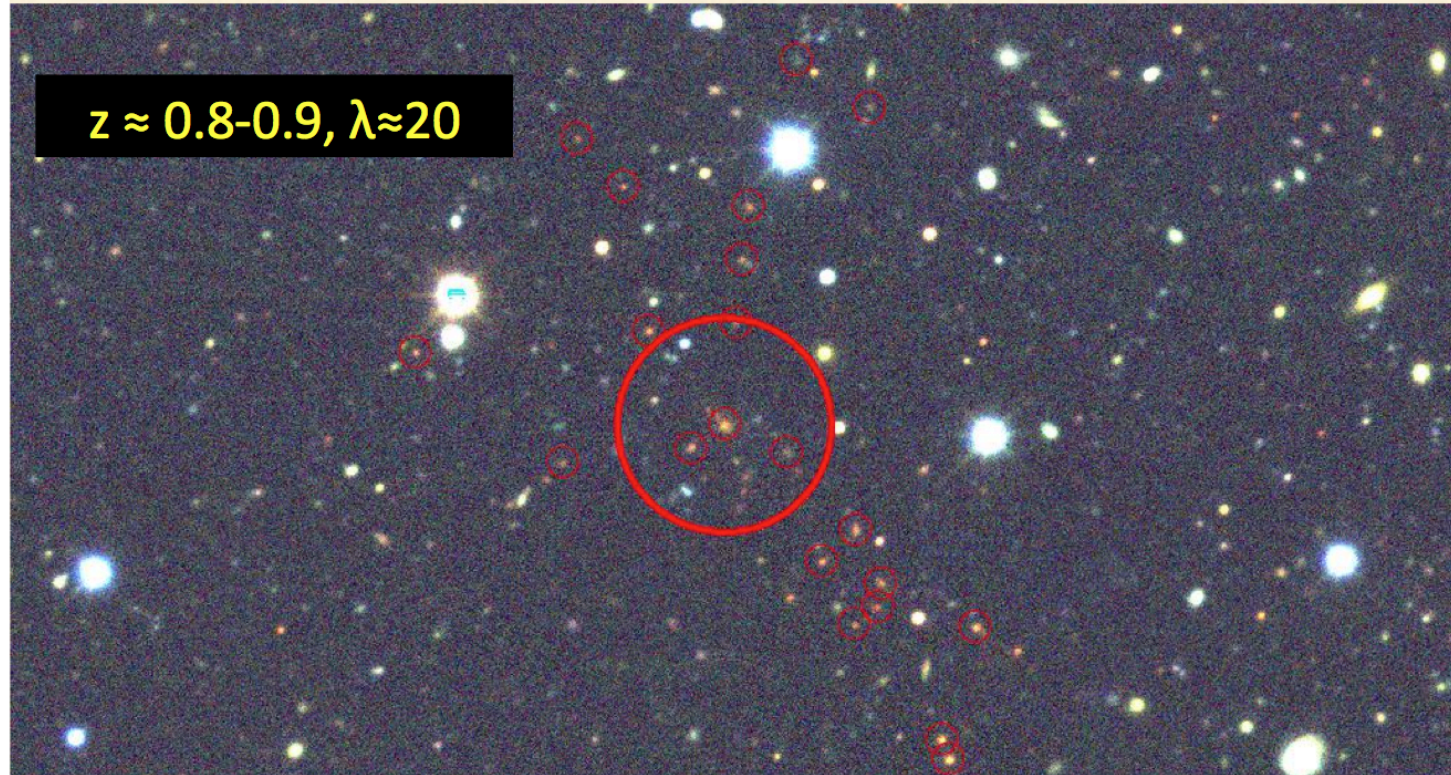
Identifying Clusters in SV



Voronoi Tessellation method

M. Soares-Santos, FNAL

High Redshift Cluster discovered by DES

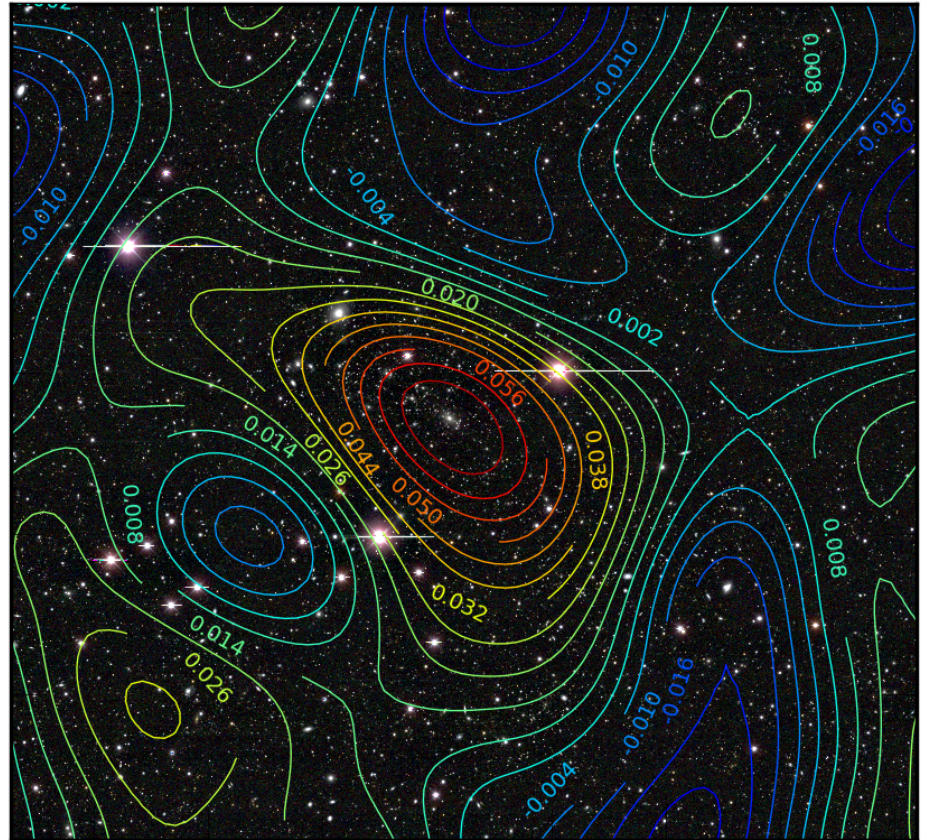


from DES Science Verification data in November

DES Cluster Weak Lensing

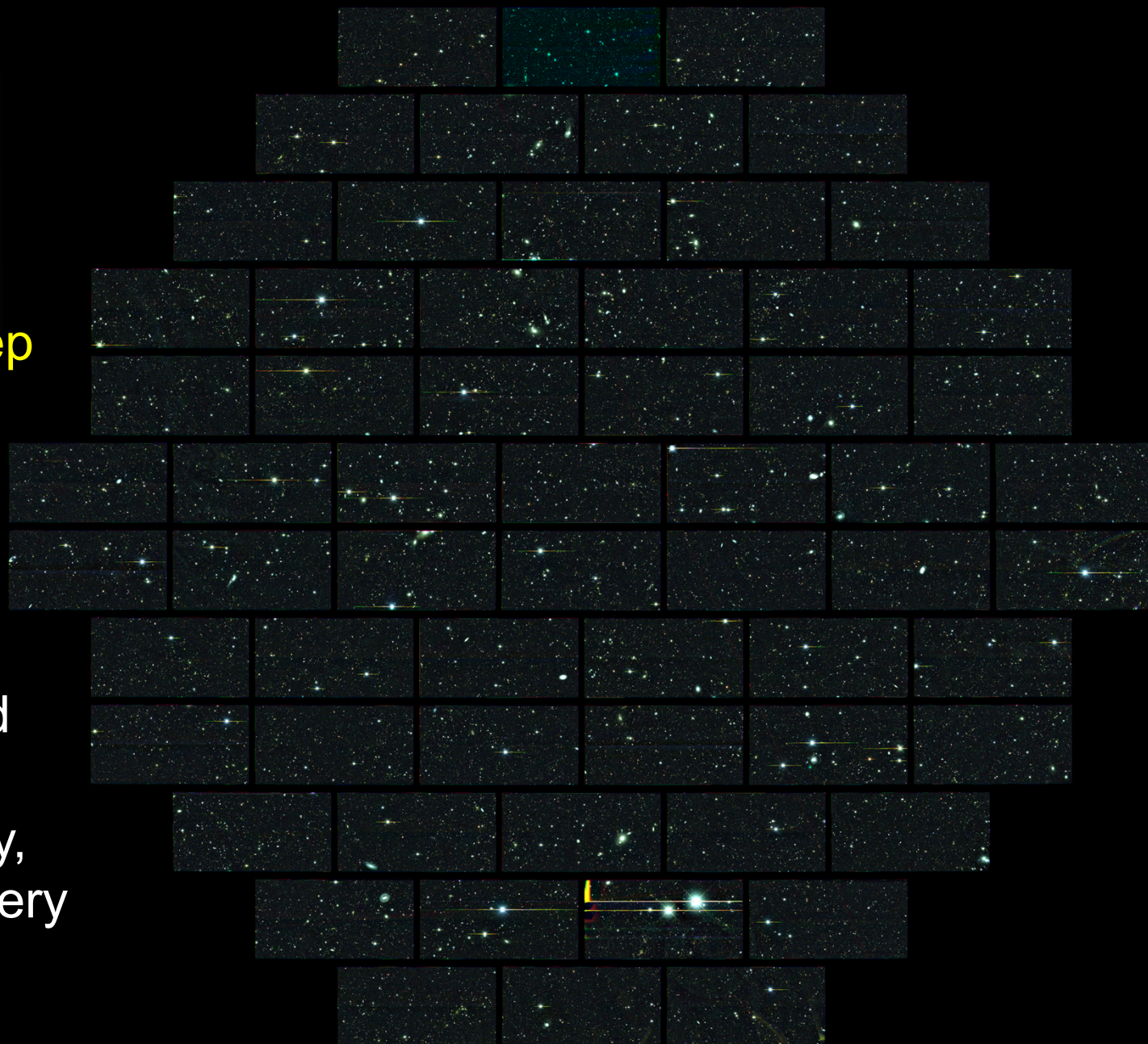


- Stacked (statistical) Weak Lensing cluster shear profiles will calibrate cluster mass-observable relations
- Preliminary cluster mass map from DES Science Verification data (OSU group)





DES SV composite image of deep SN field

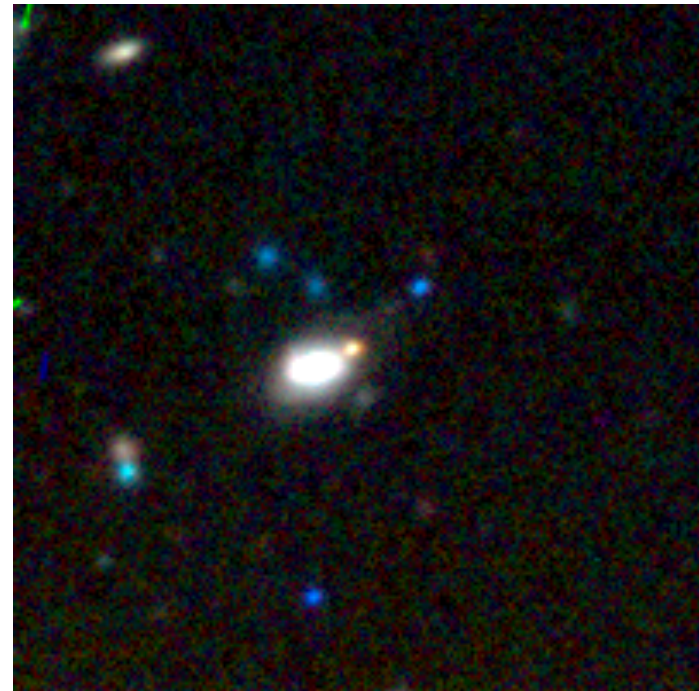


will be visited
many times
during survey,
resulting in very
deep co-add

First Confirmed SNe from DES



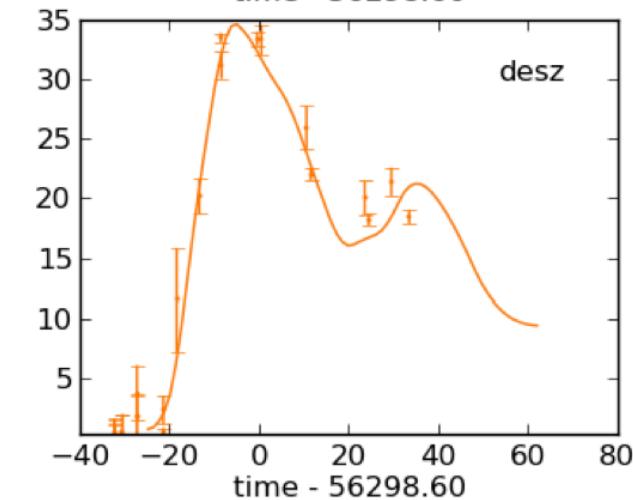
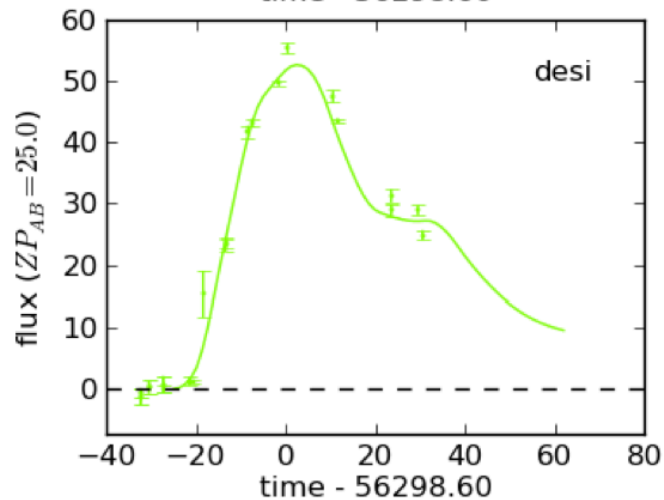
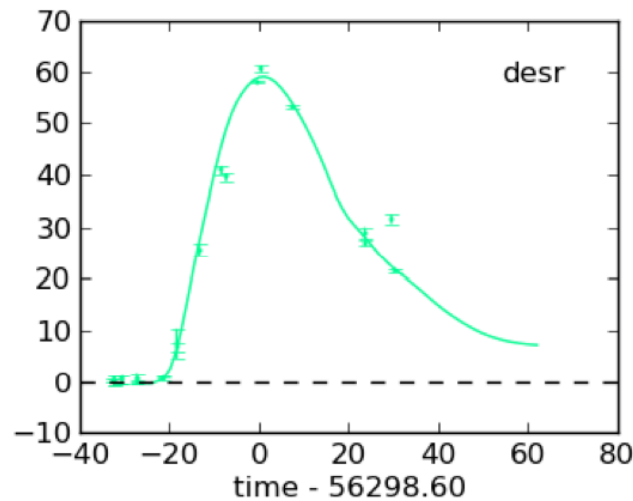
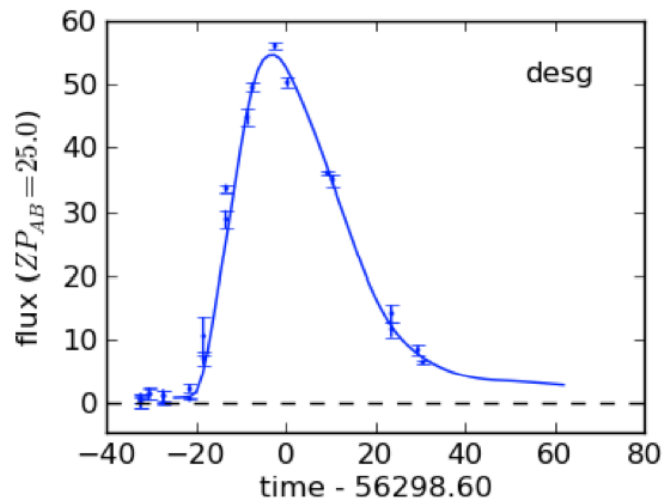
Nov. 7



Dec. 15

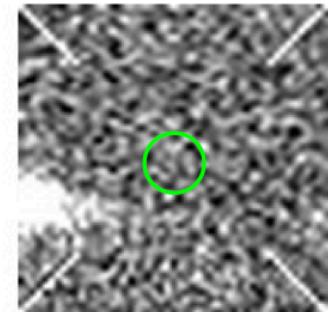
SN Ia at $z=0.2$ confirmed at AAO (100 nights awarded to OzDES for spectroscopic follow-up of SN fields)

Science Verification: Supernovae

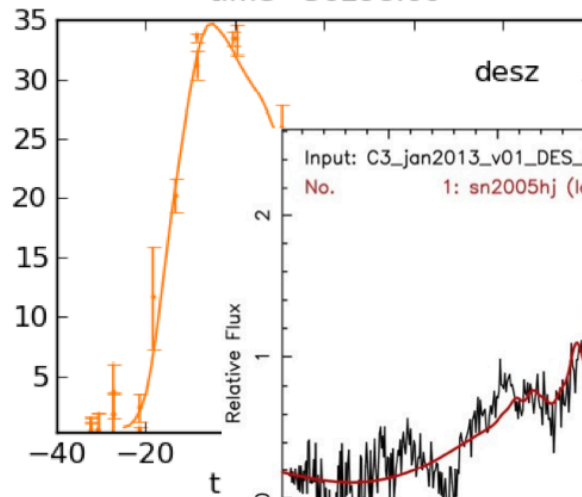
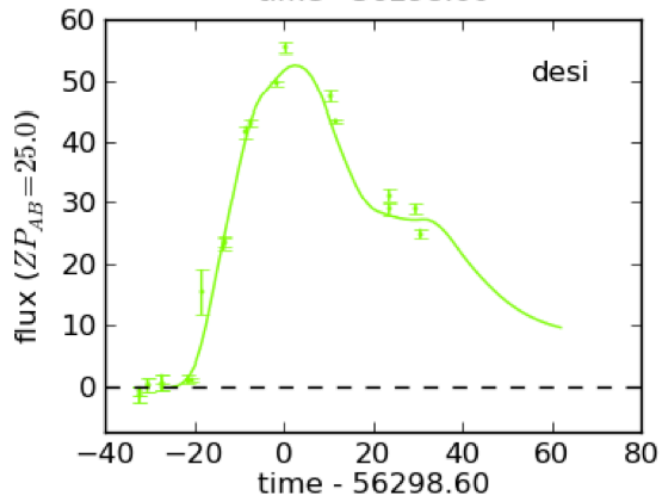
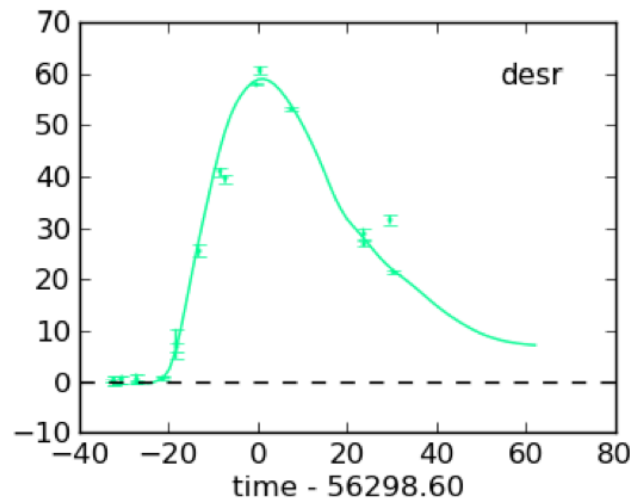
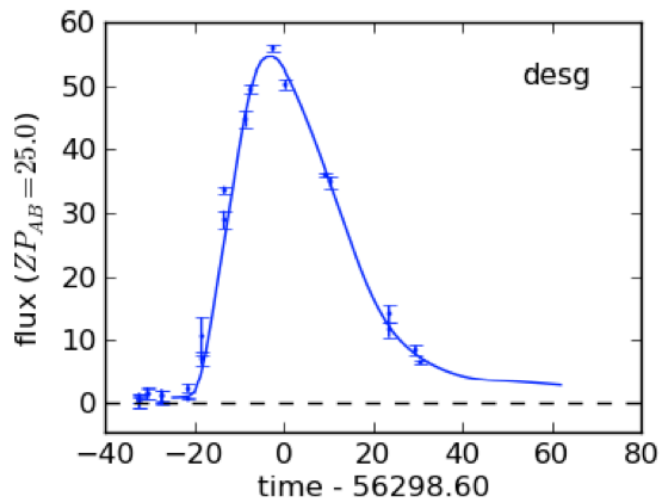


$z = 0.241$

DES12C3a
(642239)

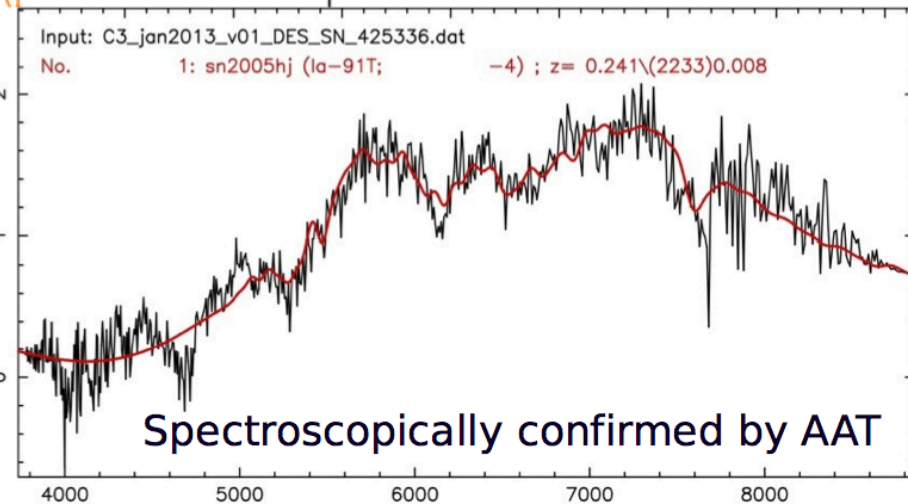
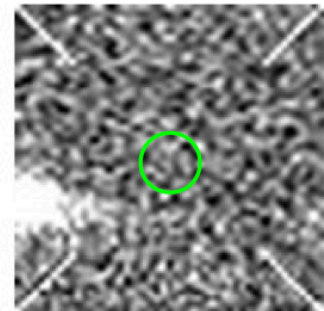


Science Verification: Supernovae

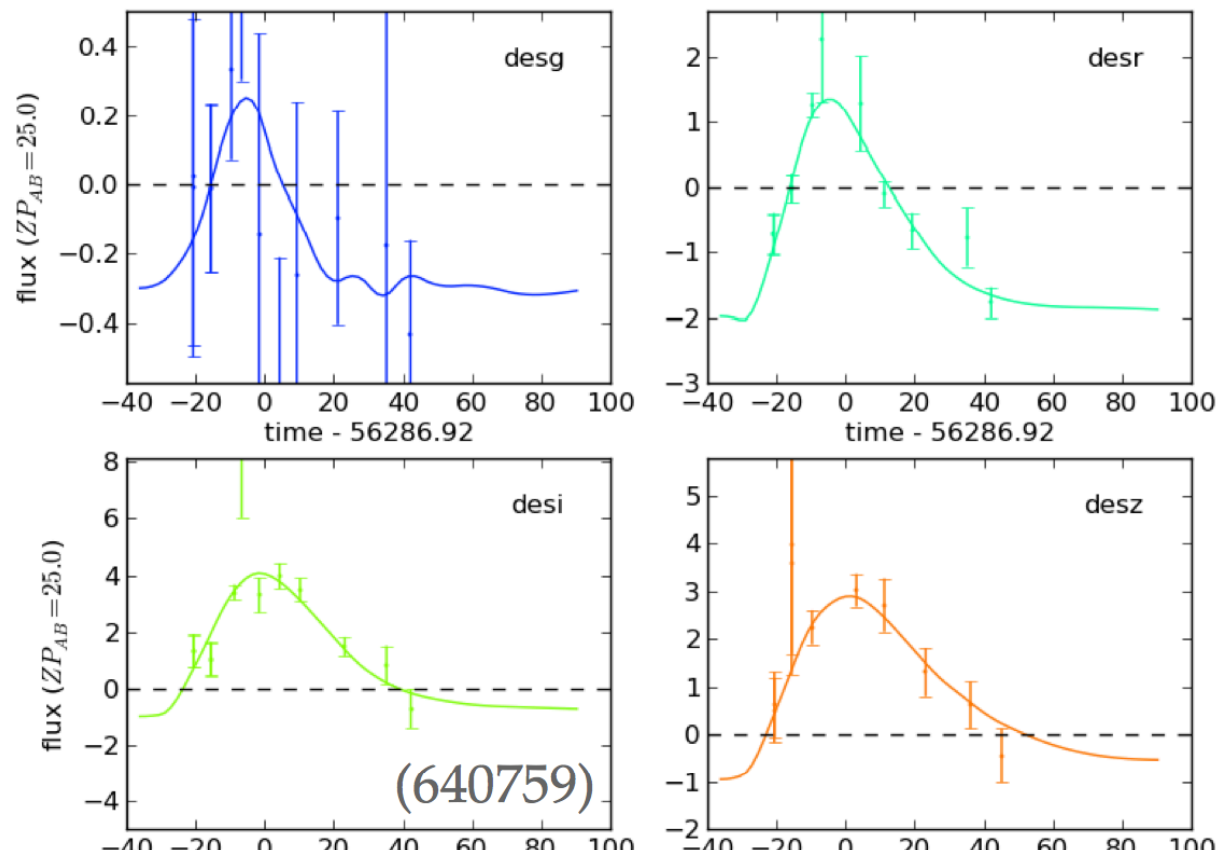


$z = 0.241$

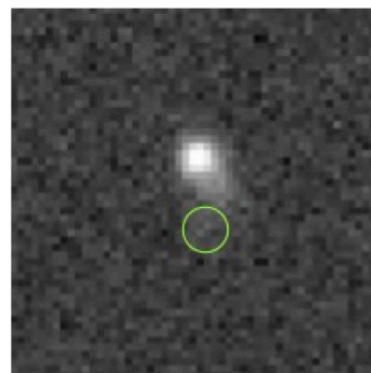
DES12C3a
(642239)



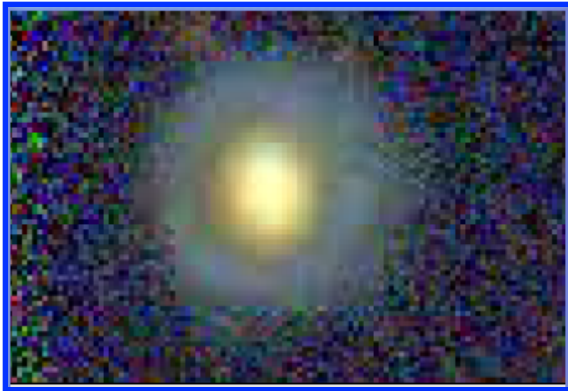
DES High-redshift SN candidate



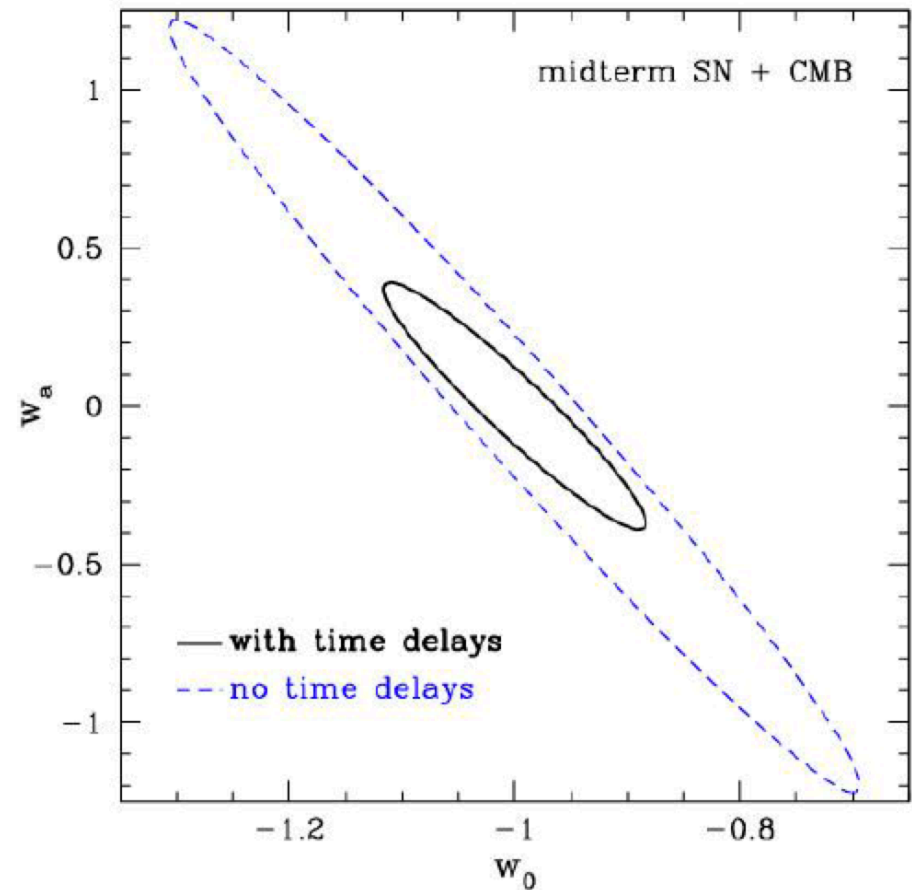
$z = 0.806$
from host spec-z
(VVDS)



Strong Lens Time Delays: new probe of Dark Energy



Strong Lens Candidates in DES SV



DES starts

Aug. 31, 2013



NATURE NEWS BLOG

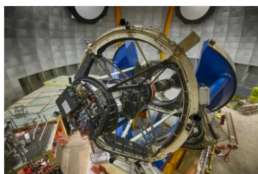
Dark energy survey launches

03 Sep 2013 | 19:25 BST | Posted by [Alexandra Witze](#) | Category: [Space and astronomy](#)

High in the Chilean Andes, a massive project to probe the nature of dark energy has begun.

The [Dark Energy Survey \(DES\)](#) launched on 31 August at the 4-metre Blanco telescope at the Cerro Tololo Inter-American Observatory. It is one of several new pushes to explore the physical properties of dark energy, the mysterious force that is driving the Universe to expand at an ever faster rate.

Over the course of 5 years, the DES will map 300 million galaxies over one-eighth of the night sky. Its backbone is a 570-megapixel digital camera (pictured).



The Dark Energy Camera photographs galaxies from its perch on the Blanco telescope in Chile.

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Stunning white animal is not a true albino but is merely a lighter color than the average giraffe.
- 

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Why are elephant poachers killing vultures? Because vultures circling in the sky alert wildlife authorities to the location of poachers' activities.
- 

Indelible 9/11 Pictures

See iconic images of the tragedy, as chosen by National Geographic photo editors. Warning: graphic content.

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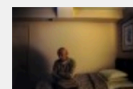
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Health & Science

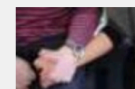
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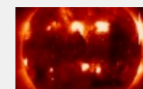
BLACKBERRY
FOR GOVERNMENT



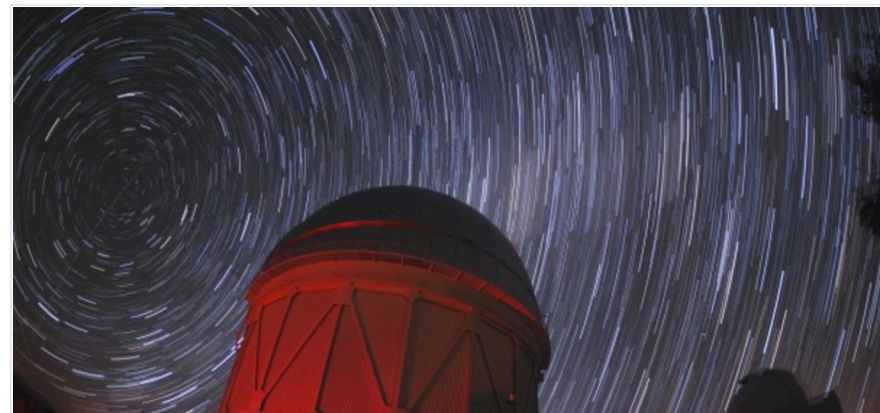
Homes for the taking: Liens, loss and profiteers



VIDEO | The ultimate dating experience



Giant digital camera probes cosmic ‘dark energy,’ the universe’s deepest mystery



Dark Energy Spectroscopic Instrument



- New Stage-IV Experiment
 - 5000-fiber, wide-field spectrograph to be built for the 4-m Mayall telescope at KPNO
 - 20-35M galaxy redshifts to probe Dark Energy via Baryon Acoustic Oscillations and Redshift Space Distortions
 - Recommended by Community Dark Energy report (Rocky-III, 2012)
 - fill the operational time gap between DES and LSST (and before Euclid), ~2018-2020
 - rich scientific program: dark energy, inflation, neutrino mass hierarchy
- Led by LBNL (you will hear details tomorrow)
- Fermilab is part of the collaboration, building on DES experience and capitalizing on infrastructure developed for DES.

Fermilab Contributions to DESI

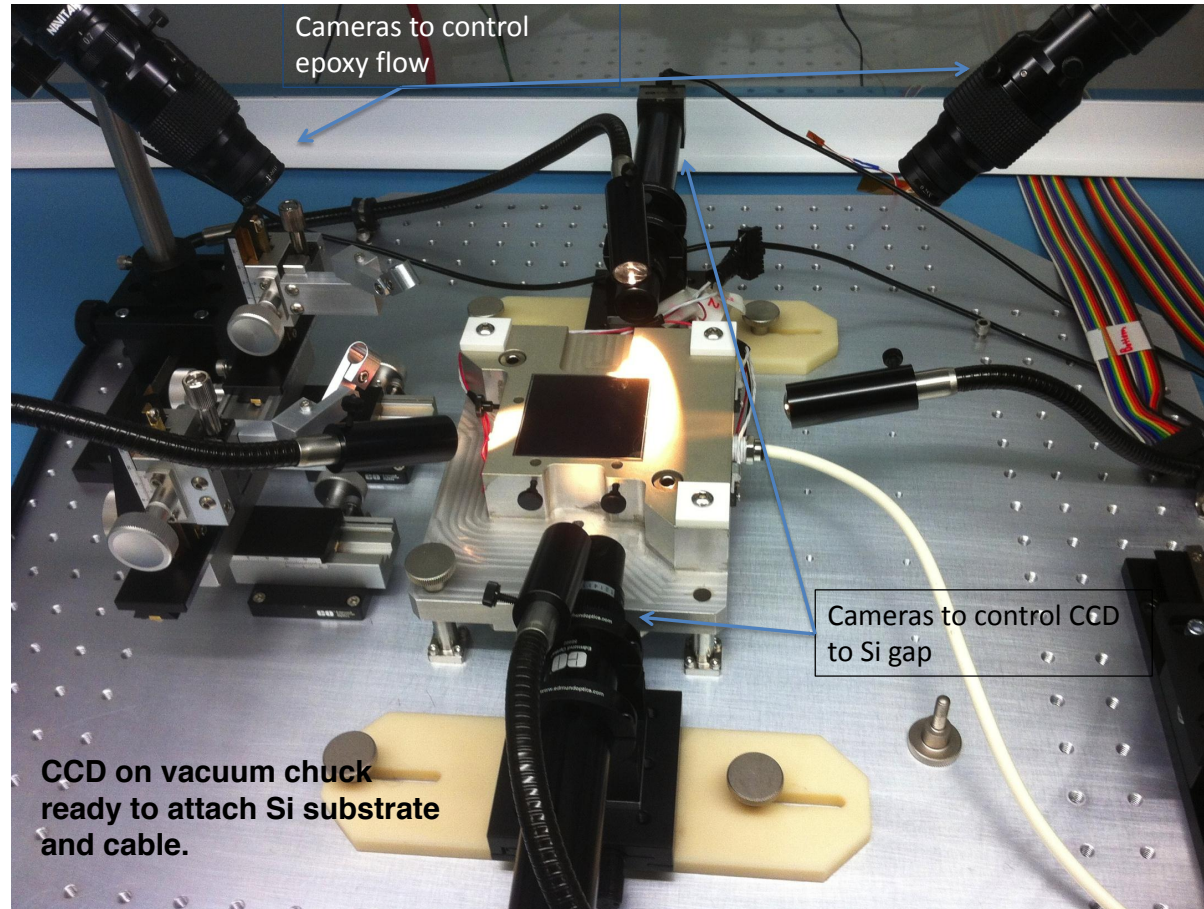


- Project management:
 - DESI Steering Committee: Flaughner, Kron
 - Inst. Rep and Chair of Spokesperson Search Committee: Flaughner
 - Leading development of Science Requirements: Kent
 - L2 manager for the Corrector Barrel: Gutierrez
 - L2 co-manager for Integration and Testing: Flaughner
- Technical:
 - CCD packaging and testing: Estrada
 - Corrector barrel: Gutierrez
 - On-line software: Buckley-Geer
 - Simulation framework for trade studies: Nord
 - Software analysis framework: Dodelson

DESI CCD Packaging & Testing at Fermilab

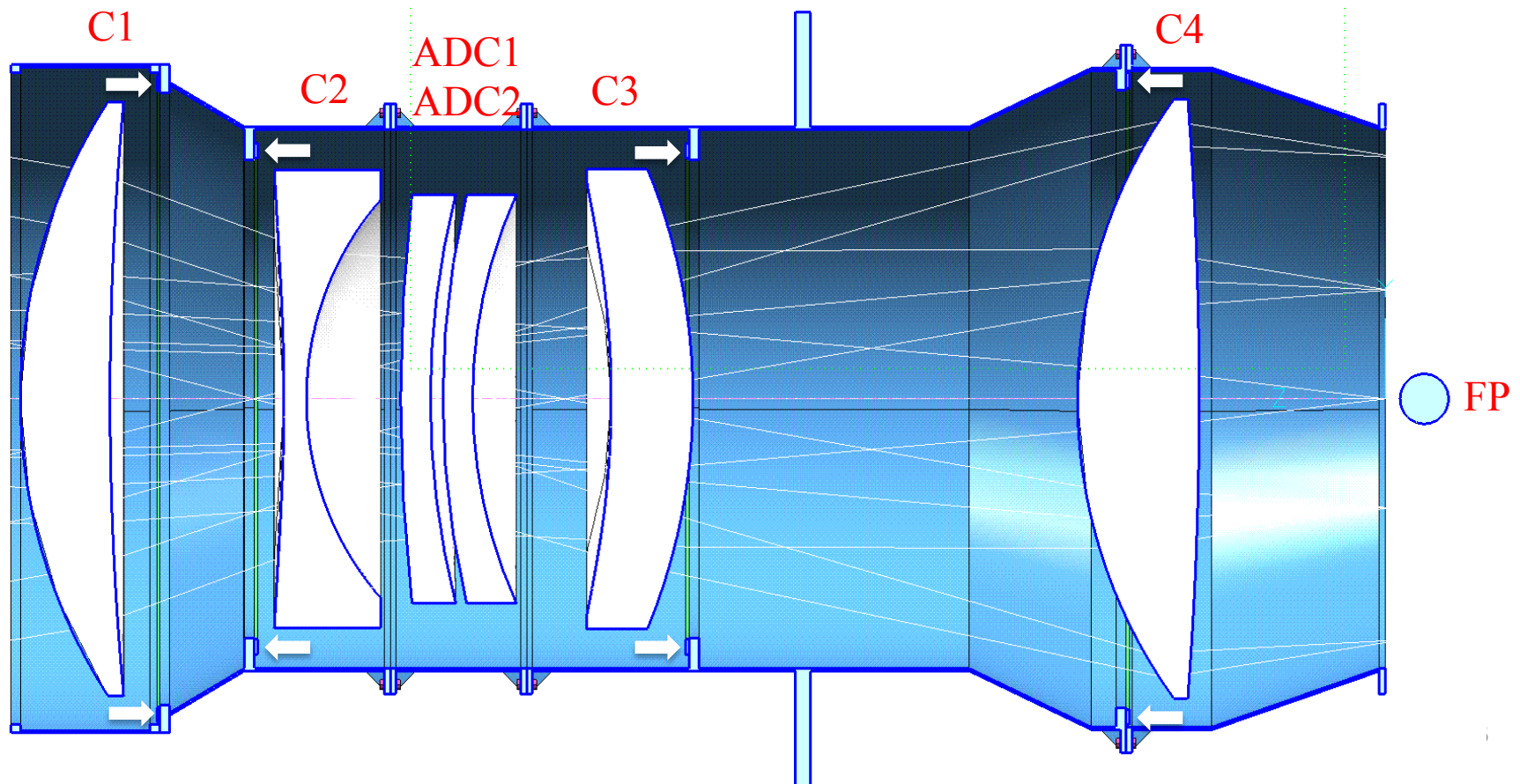


- Fermilab has constructed a CCD packaging station for DESI



Corrector Barrel conceptual Design

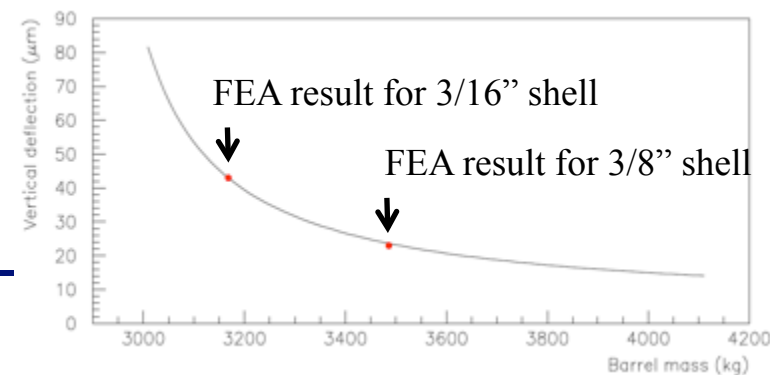
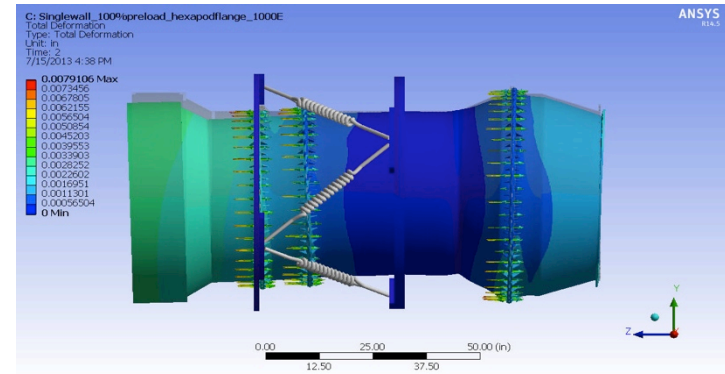
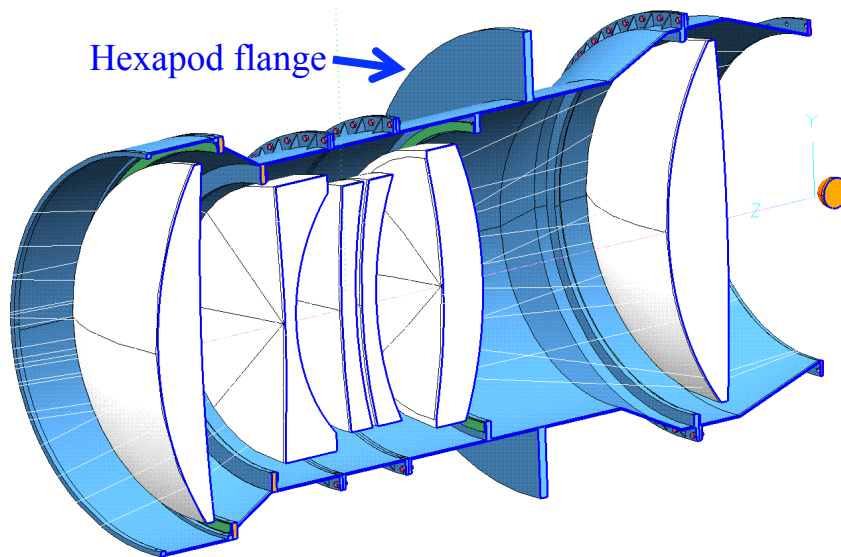
- DESI lenses will be mounted and aligned in the barrel using the proven techniques from DECam; white arrows show direction of installation and the room for alignment pins.



Corrector Design studies at FNAL

- Hexapod flange is located at the CG of the system. Finite element studies show the deflections for various design options.

Goal is to minimize weight while meeting stiffness requirements. This is for a 3/16 inch thick shell with preloaded bolts.



LSST @FNAL



- Engagement in science in the context of the Dark Energy Science Collaboration (DESC)
 - Leading Software Working Group in DESC with an eye towards building a set of tools
 - Running project tools on Open Science Grid
 - Exercising Project Software with an eye towards becoming a Level 3 Software Center
 - Available for CCD Testing
-

LSST Software Framework







- Builds on cosmoSIS (DES Analysis Framework)
- Working with DESC science WG's to define requirements (built after developing *use cases*)
- Requires integrating scientists in collaboration with computing professionals

The screenshot shows a web browser window displaying the 'Weak Lensing WG Use Cases' page. The browser's address bar shows 'rd.edu/display/LSSTDESC/Weak+Lensing+WG+Use+Cases'. The page has a dark blue header with navigation links like 'Analysis Group Use Cases' and 'Weak Lensing WG Use Cases', and a search bar. Below the header, the page title 'Weak Lensing WG Use Cases' is displayed, followed by a note: 'Added by Richard Dubols, last edited by Rachel Mandelbaum on Jul 18, 2013 (view change)'. The main content area lists use cases, with the first one being '1] Generate an instance of a distorted field of galaxies.' This section includes sub-headings for 'Goal', 'Task', 'Actors', 'Level', 'Preconditions', 'Post-conditions', and 'Description', each followed by a brief explanation of the requirement or process.

rd.edu/display/LSSTDESC/Weak+Lensing+WG+Use+Cases

tion > ... > Analysis Group Use Cases > Weak Lensing WG Use Cases Browse ▾ Scott Dodelson ▾ Q Search

 **Weak Lensing WG Use Cases**    Tools ▾

Added by Richard Dubols, last edited by Rachel Mandelbaum on Jul 18, 2013 (view change)

1] Generate an instance of a distorted field of galaxies.

Goal

Generating fields of stars and galaxies in PhoSim requires realistic galaxy catalogs as input.

Task

Generate an instance catalog for input into PhoSim. This could be either in the form of sheared images themselves or a recipe for how PhoSim should shear. If the images are already sheared, the task is to format them properly for input into PhoSim. If it is a recipe, the task is to format the algorithm properly for PhoSim to implement it correctly.

Actors

A scientist in the LSST Dark Energy Science Collaboration

Level

Low-level used for many different tasks.

Preconditions: What needs to have happened beforehand

There has to be some production of sheared images or a prescription of how to shear the images. In the former case, the input might be a set of postage stamps images.

Post-conditions: What will happen afterwards

This will feed into PhoSim as part of an input instance catalog, along with information about the camera and observing conditions.

Description: May include references to other, more basic use cases

There are many ways to generate sheared galaxies, ranging from adding constant shear to doing full ray tracing in an N-Body simulation. The

Concluding Remarks



- DES project made great progress in last 3 years
 - DECam completion on-time, under budget
 - Successful installation, commissioning, Science Verification
 - Data Management processing & serving data to collaboration
 - Successful start of survey operations & science analysis
- Over next 3 years, DES will take next step in understanding the nature of dark energy, with FNAL scientists in key operational & scientific roles.
- Combination of Fermilab technical, scientific expertise and infrastructure with strengths of partner institutions (national labs, Universities) enables this kind of project.
- Fermilab participating technically and scientifically in next-generation Dark Energy experiments (DESI, LSST), building upon the expertise developed for DES.

Extra Slides



Blanco Telescope at CTIO



- Excellent astronomical site in Chilean Andes:
 - Good seeing: $\sim 0.75''$ median for site
 - High, dry: high percentage of clear, photometric nights
- CTIO operated by National Optical Astronomy Observatory with funding from NSF Astronomy Division



Blanco 4-meter telescope



DARK ENERGY
SURVEY

DES Structure & Management

DES MOU between **NOAO**, **Fermilab**, and **NCSA** lays out institutional responsibilities and commits them equally to (a) successful deployment of DECam on the Blanco and (b) science goals of DES. DECam System (=Camera+Community Pipeline) delivered & accepted in exchange for 525 Blanco nights. Directors of these 3 institutions (or their delegates) form the DES Council.

Construction:

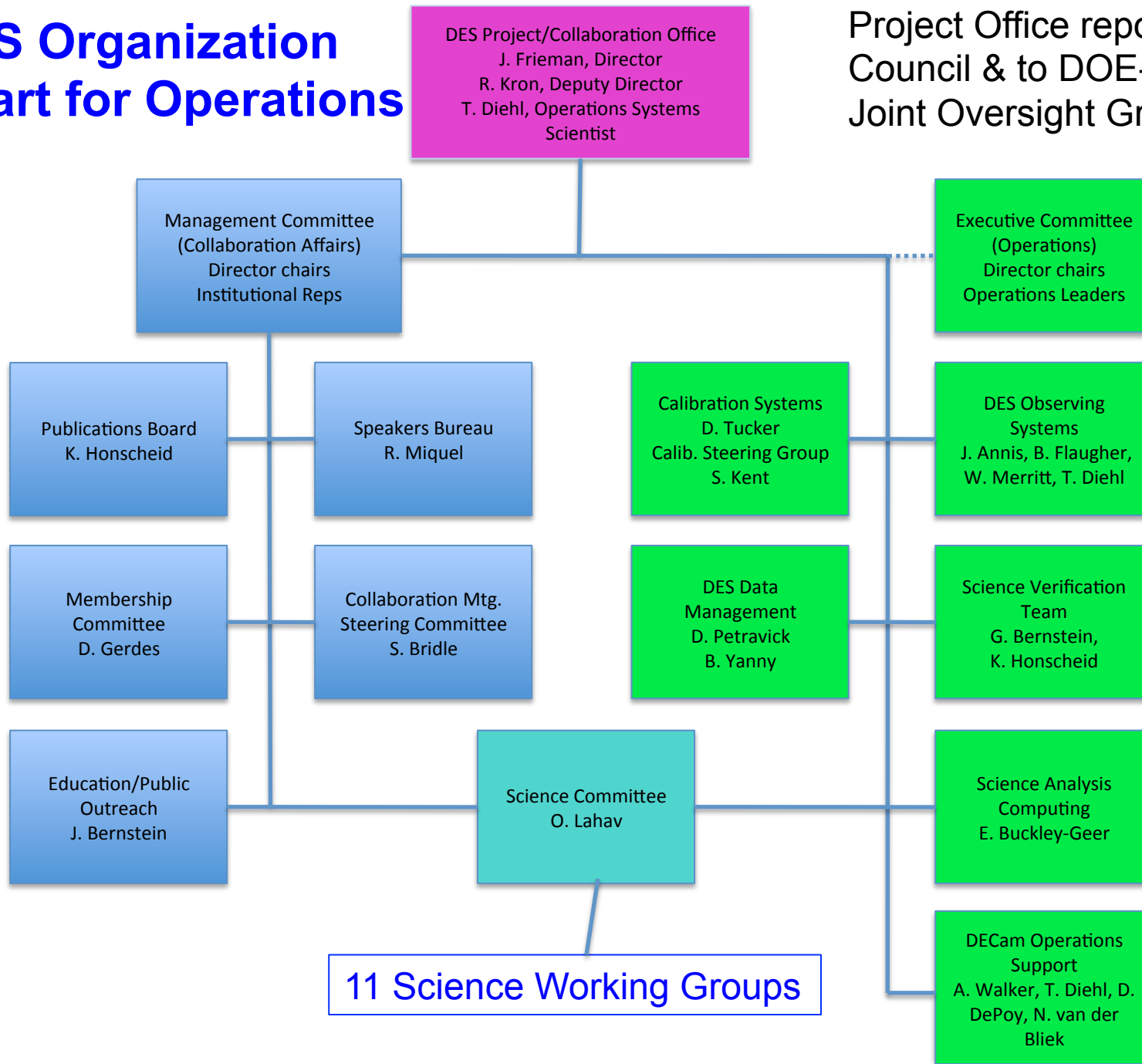
- DES Project comprised DECam Project (DOE/led by Fermilab), CTIO Facilities Improvement Project (NSF/NOAO), and DES Data Management Project (NSF/NCSA).

Operations:

- DES Project/collaboration operates the DES experiment, with support from DOE, NSF, and foreign & institutional partners.
- NOAO operates and maintains DECam and the Blanco for DES and the community; DES/Fermilab supports DECam maintenance.

DES Organization Chart for Operations

Project Office reports to
Council & to DOE-NSF
Joint Oversight Group

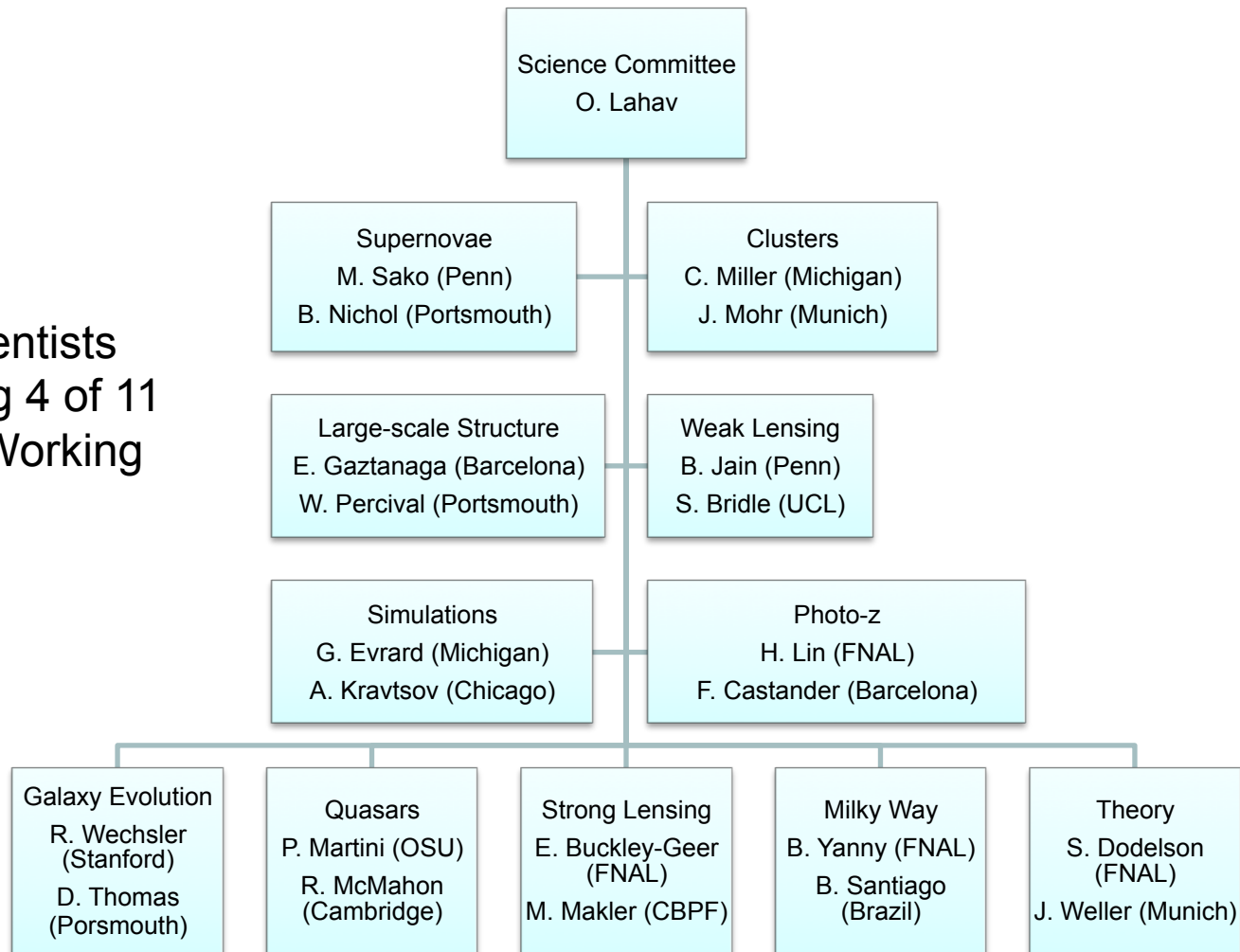




DES Science Working Groups

DARK ENERGY
SURVEY

FNAL scientists
co-leading 4 of 11
Science Working
Groups





Recent DES Reviews

DARK ENERGY
SURVEY

- May 2012 DOE-led Review: called for major project replan, backed by the 3 MOU institutions
- Aug. 2012: DES replan & response presented. Replan identified shortfall in support for DES Data Management (DESDM) operations at NCSA. Reviewers and agencies endorsed replan.
- Dec. 2012: NCSA submitted supplemental request to NSF AST for DESDM (\$830K supplement to \$8M 5-year grant).
- April 2013: Directors' Review
- May 2013: DOE-NSF Review of Operational Readiness plan:
 - “The DECam is working well and almost all performance goals and specifications were met during commissioning.”
 - recommended “in strongest possible terms” that NSF approve the supplemental request for DESDM. “This is the most pressing issue for the success of DES.”
 - “Planned operation costs are reasonable.”
 - “DES team has a viable plan for beginning the survey in September 2013”.
- July 2013: DESDM Supplemental proposal funded