Fermilab Dark Energy Program

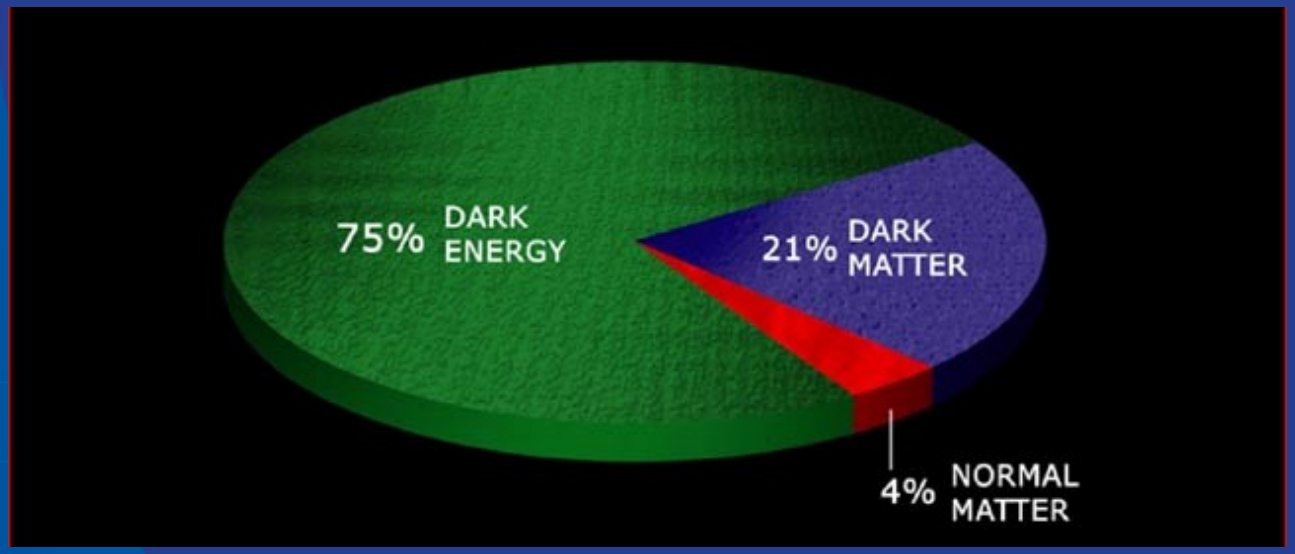
Josh Frieman

- Introduction and Motivation
- Dark Energy Survey
- Sloan Digital Sky Survey Results
- Future Projects

Dark Energy

- 1990's: growing circumstantial evidence (ΛCDM) FNAL theory
- 1998: SN discovery of cosmic acceleration
- 1998-2010: confirmation via CMB, LSS, SN surveys

SDSS SDSS-II



Goals for 2010 Decade

- What is the physical cause of cosmic acceleration?
  - Dark Energy or modification of General Relativity?
    - If Dark Energy, is it Λ (the vacuum) or something else?
      - What is the DE equation of state parameter *w*?

- Addressing these questions likely to have profound impact on our understanding of fundamental physics
- Given high priority by P5, DETF, PASAG, Astro2010
- Will require multiple, complementary approaches
- Our program is well aligned with these goals

www.darkenergysurvey.org

The Dark Energy Survey

- Stage III DE project using 4 complementary* techniques:
  - I. Cluster Counts
  - II. Weak Lensing
  - III. Large-scale Structure
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 30 deg^2 repeat (SNe)
- Build new 3 deg^2 FOV camera and Data management system

Survey 2012-2017 (525 nights)

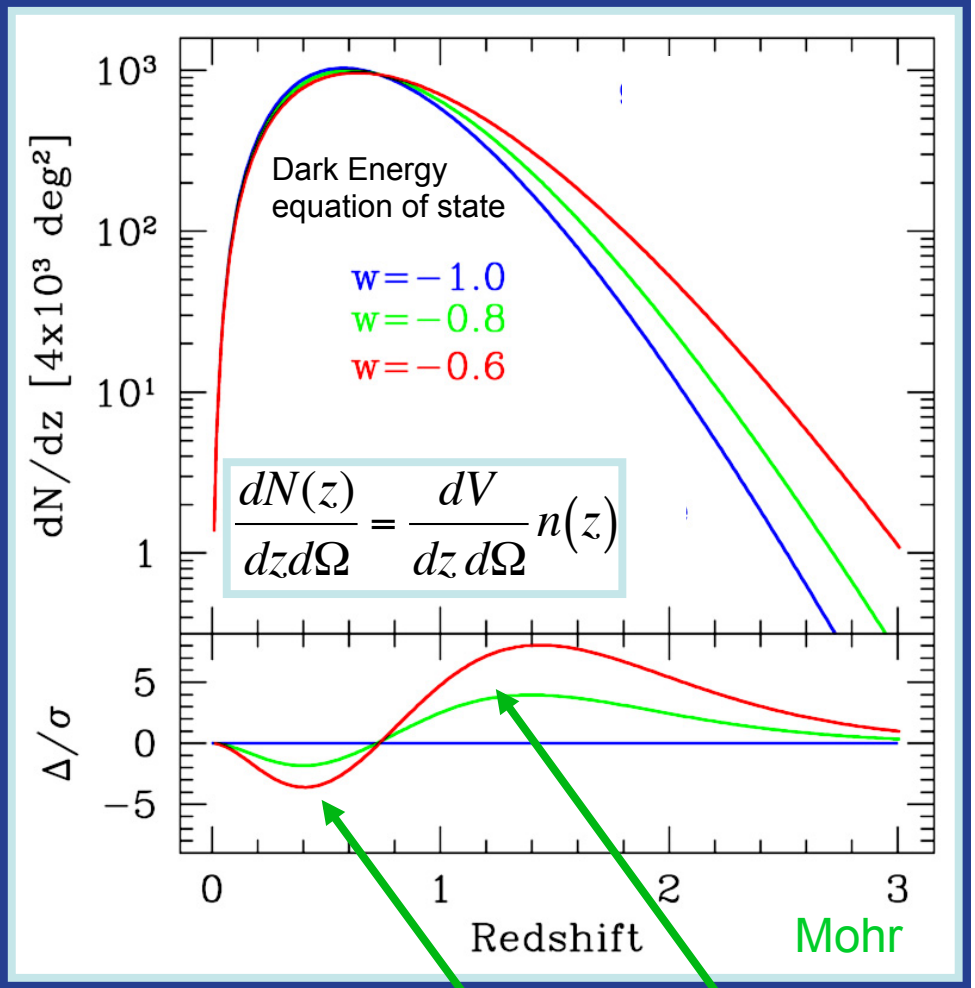
Blanco 4-meter at CTIO

*in systematics & in cosmological parameter degeneracies
*geometric+structure growth: test Dark Energy vs. Gravity

I. Clusters

- Elements of the Method:
  - Formation and abundance of dark matter halos *n(M,z)* robustly predicted by N-body simulations
  - Clusters are proxies for massive halos and can be identified optically to redshifts z>1
  - Galaxy colors provide photometric redshift estimates for each cluster
  - Variety of observable proxies for cluster mass: optical richness, SZ flux decrement, X-ray luminosity, weak lensing mass
  - Cluster spatial correlations cross-check mass estimates

Number of clusters above mass threshold



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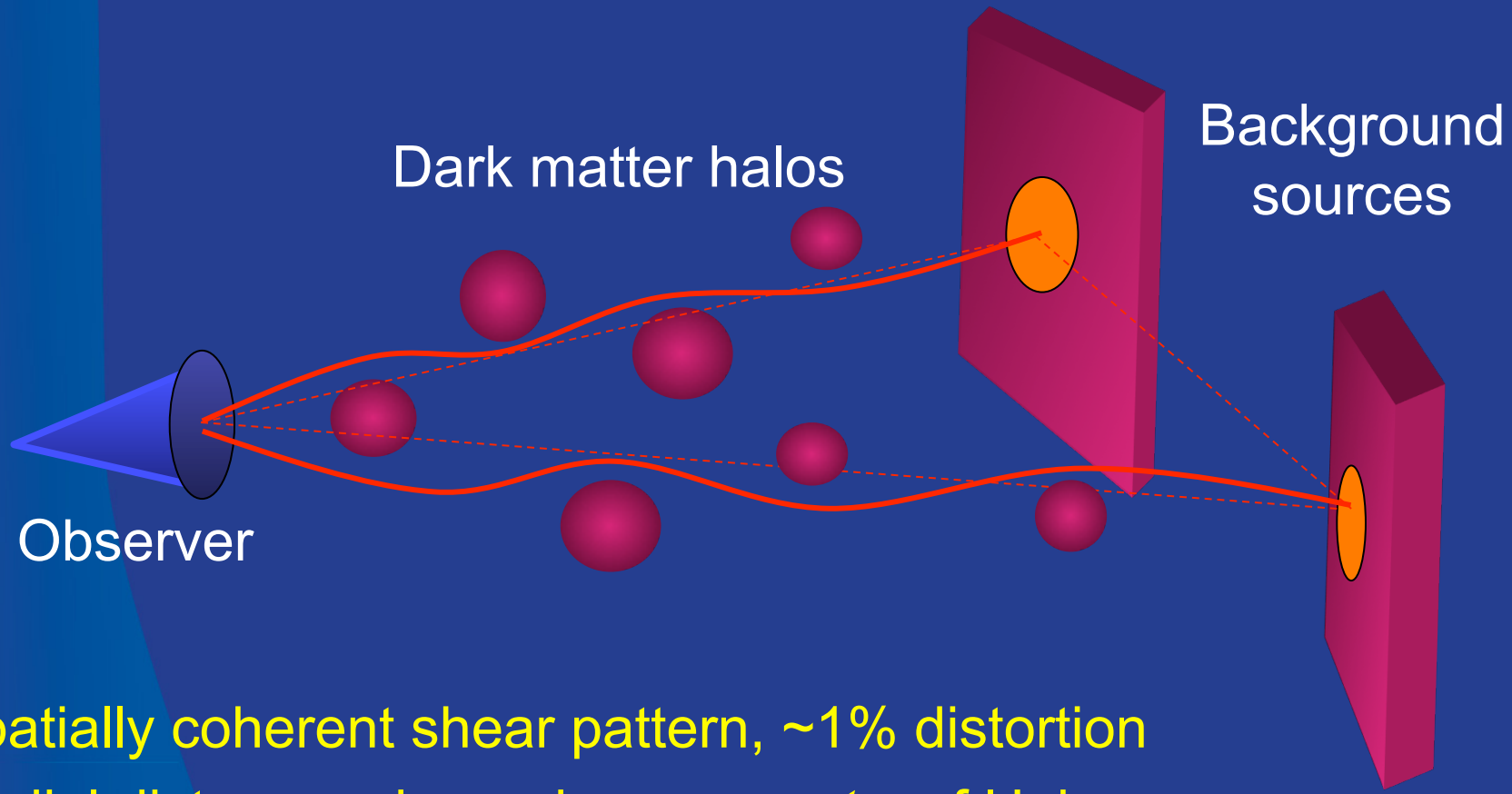
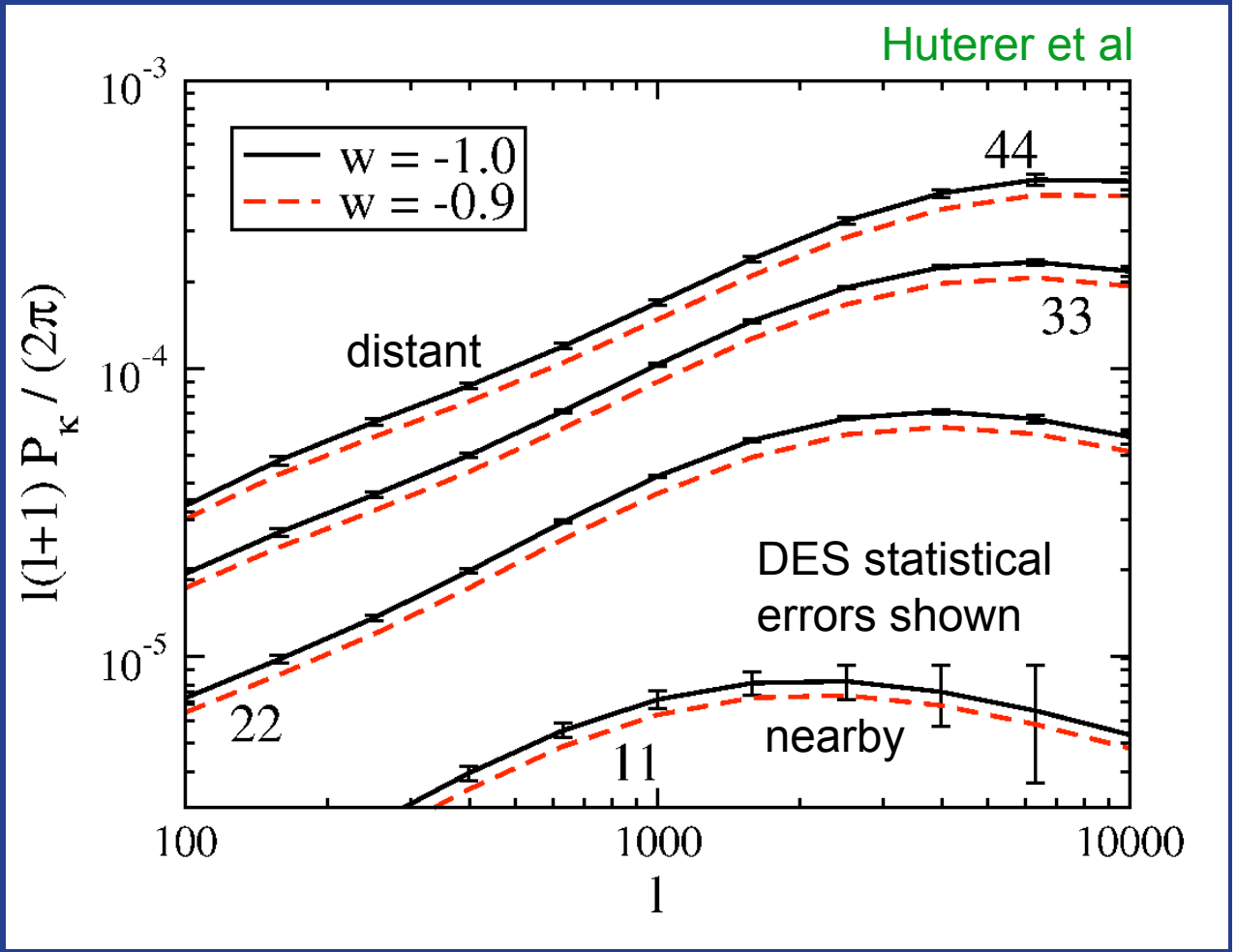
II. Weak Lensing: Cosmic Shear



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

Weak Lensing Tomography in DES

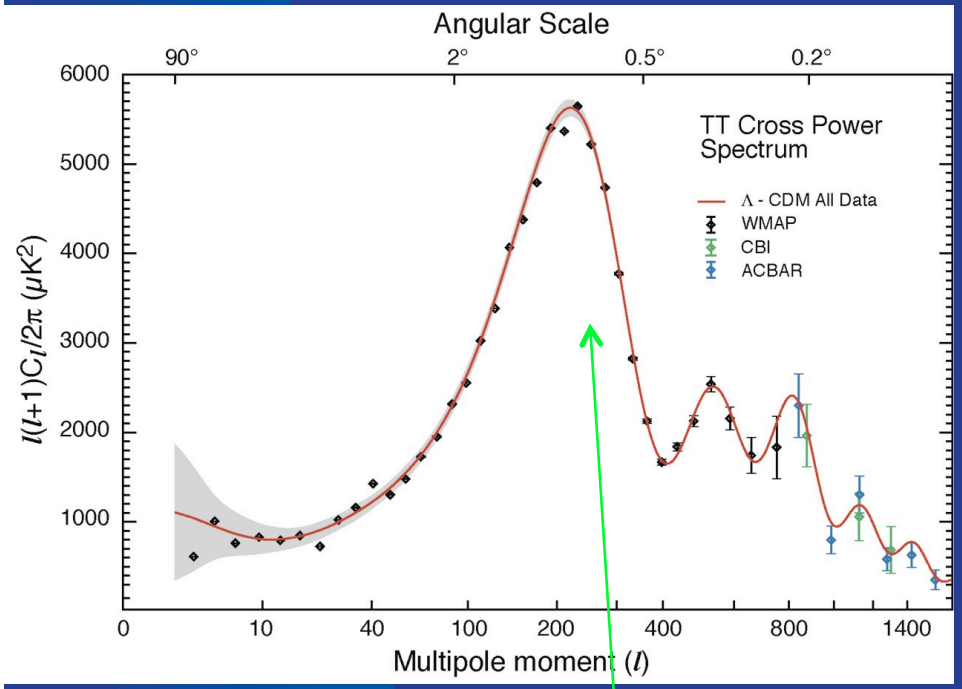
- Cosmic shear angular power spectrum in 4 redshift slices
- Shapes of ~300 million well-resolved galaxies with $\langle z \rangle = 0.7$
- Improved telescope, new optical corrector, active alignment system should deliver improved image quality for galaxy shape measurements



Factor ~30 greater area than CFHTLS

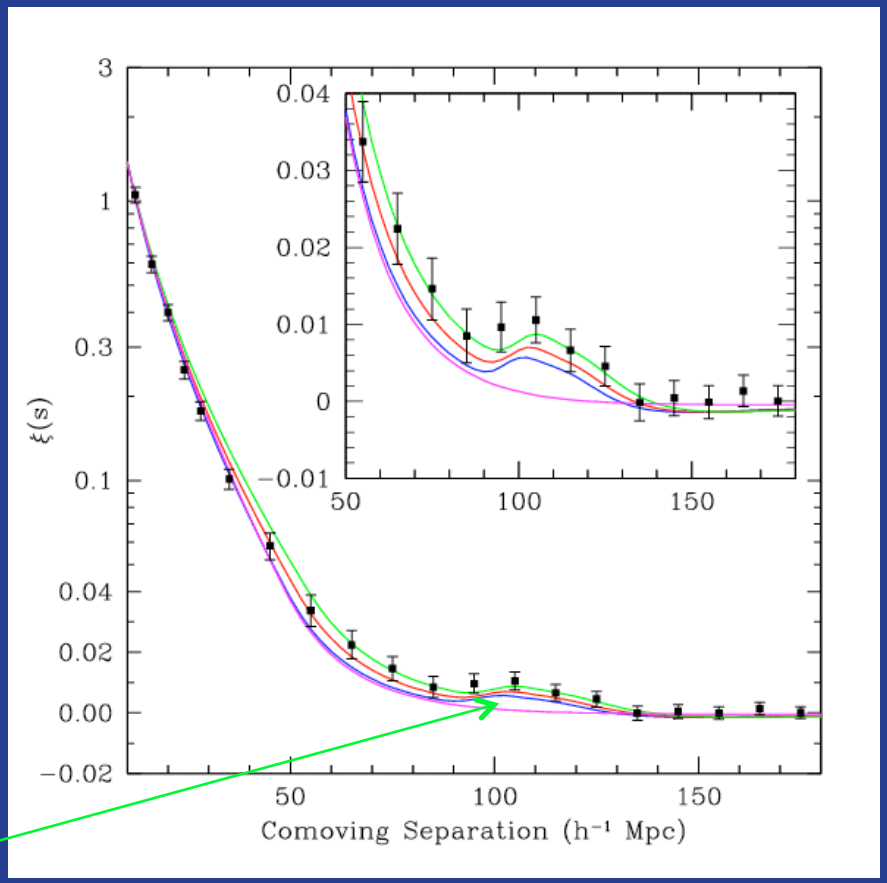
III. Large-scale Structure

CMB angular power spectrum



Bennett, et al

SDSS galaxy correlation function



Eisenstein et al

Baryon acoustic oscillations (BAO)

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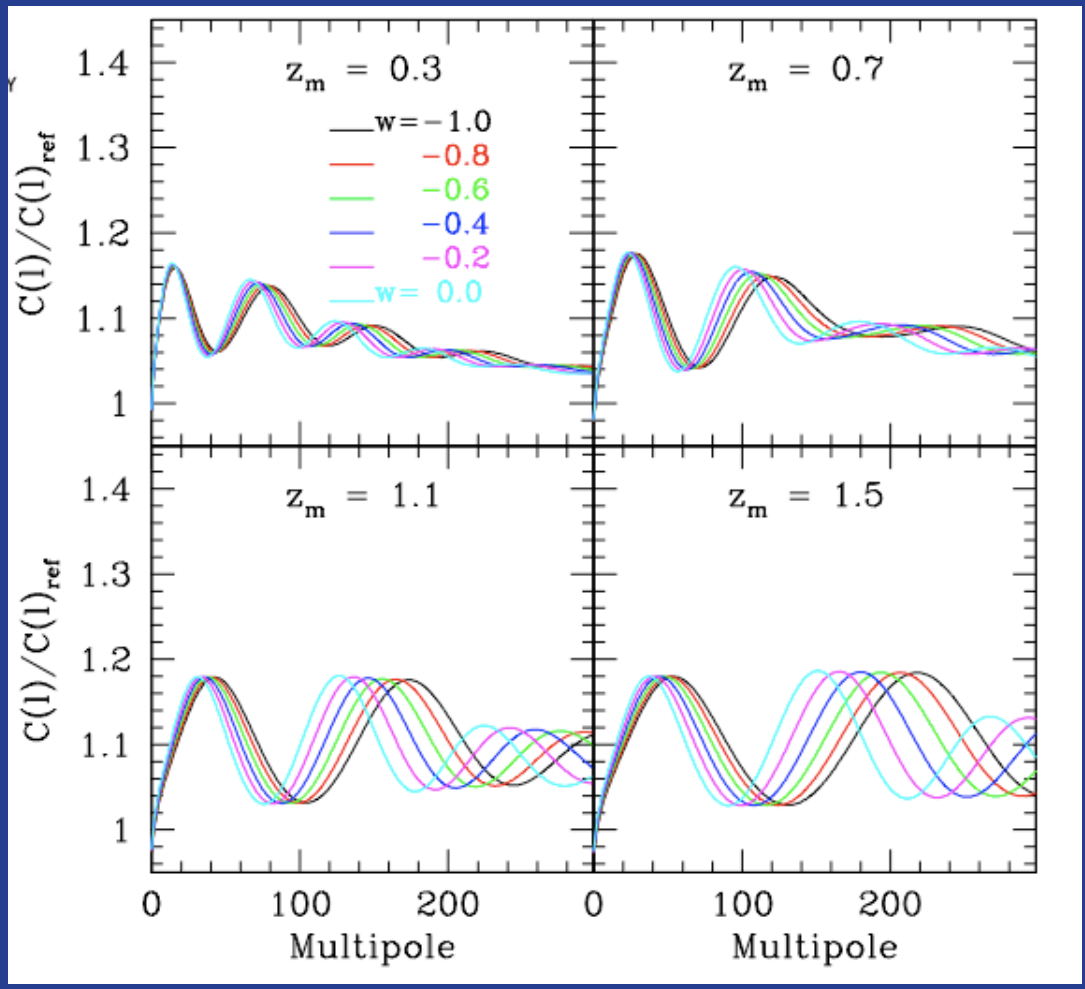
BAO Tomography in DES

Galaxy angular power spectrum in redshift bins (relative to model without BAO)

Probe to much higher redshift than SDSS galaxies



Fosalba & Gaztanaga

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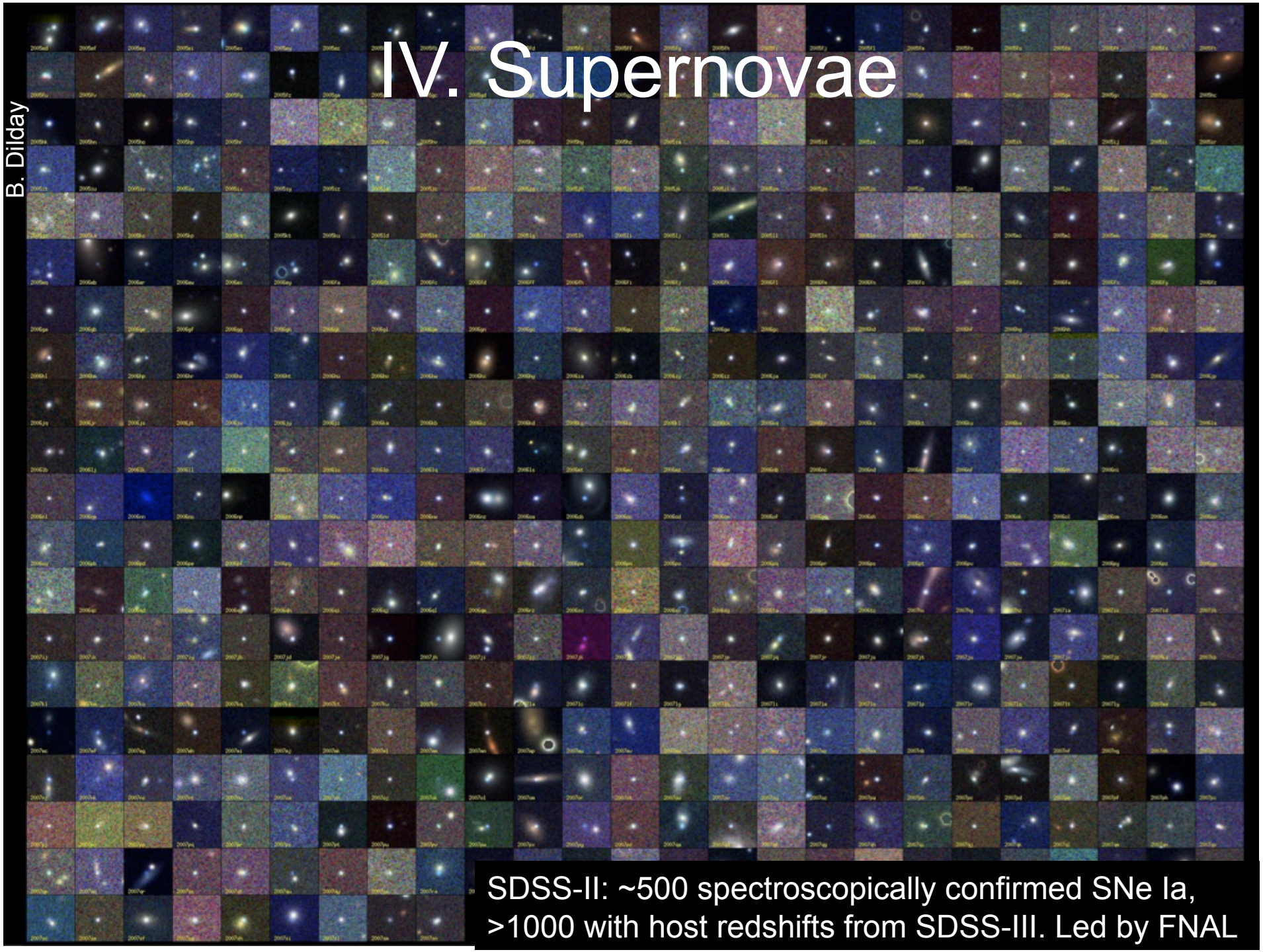
IV. Supernovae



B. Dilday

SDSS-II: ~500 spectroscopically confirmed SNe Ia, >1000 with host redshifts from SDSS-III. Led by FNAL

IV. Supernovae

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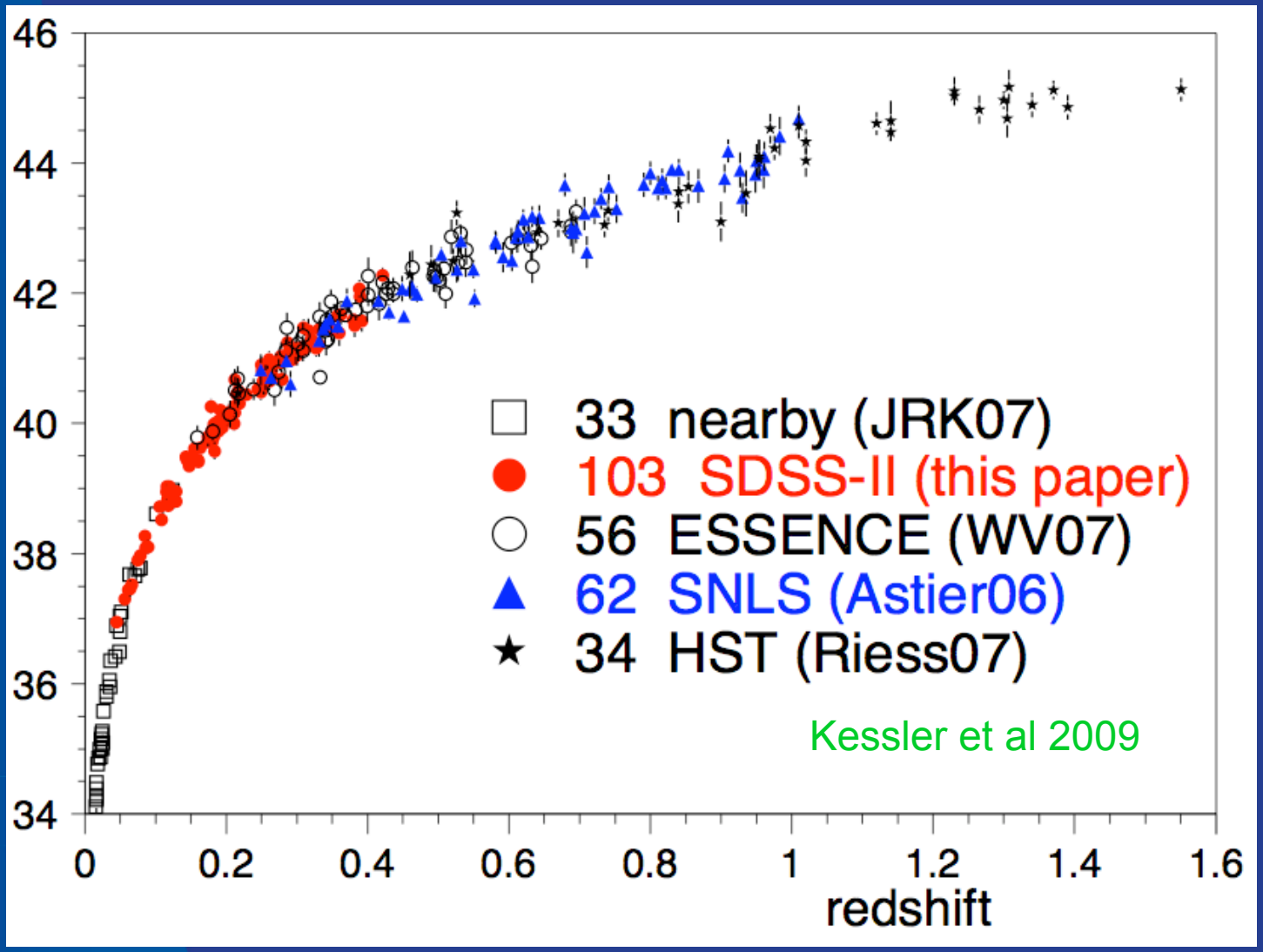
Supernova Hubble Diagram



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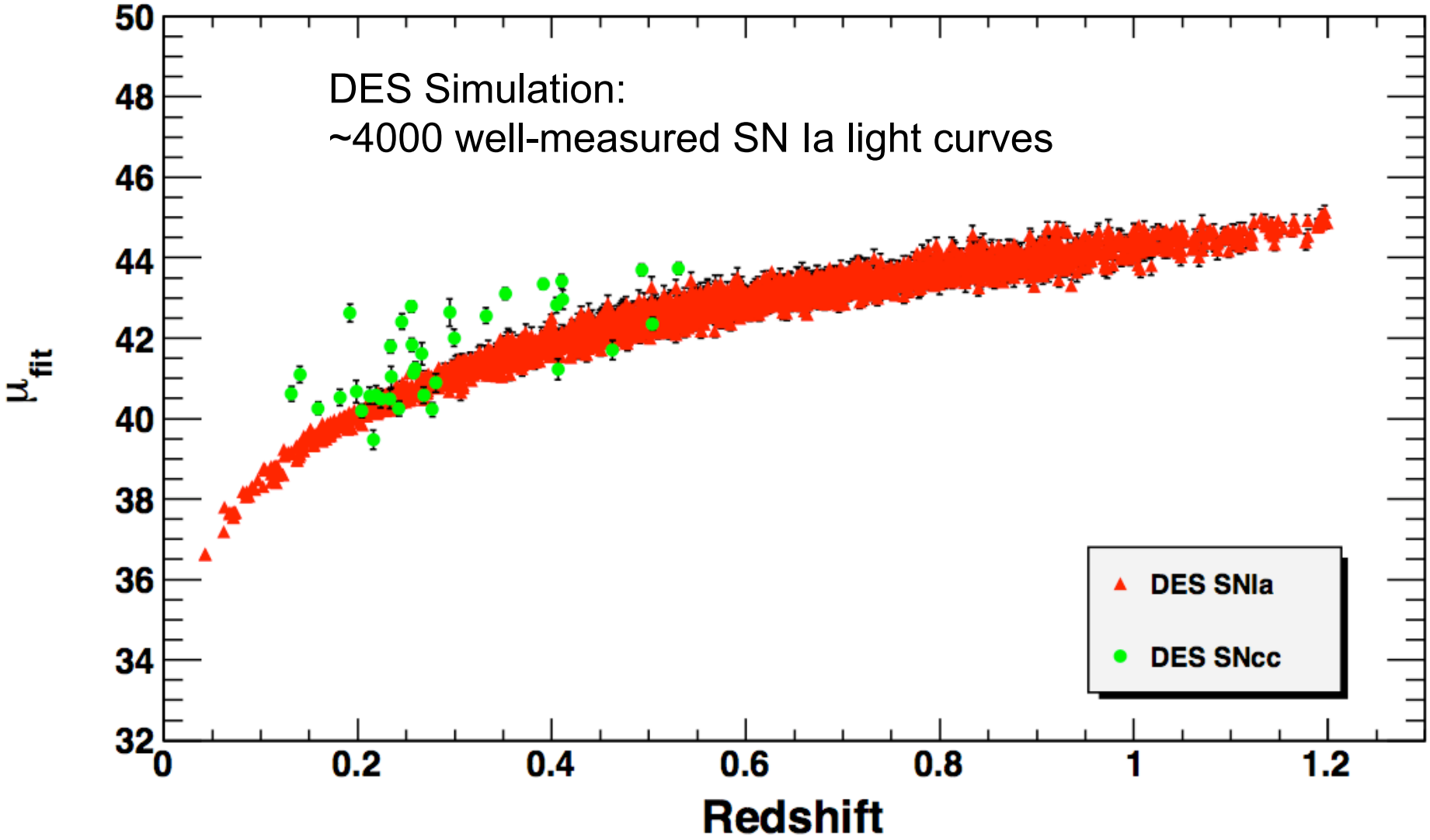
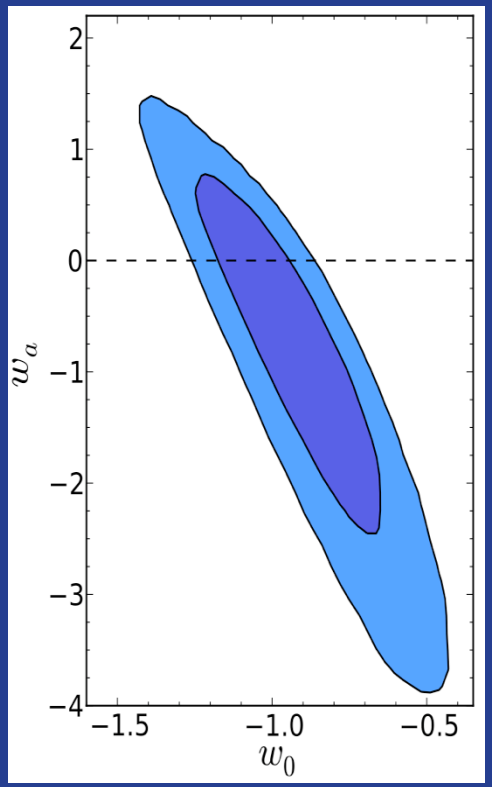


DES Science Summary

Four Probes of Dark Energy

- Galaxy Clusters
  - ~100,000 clusters to z>1
  - Synergy with SPT
  - Sensitive to growth of structure and geometry
- Weak Lensing
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- Supernovae
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Current Constraints on DE Equation of State



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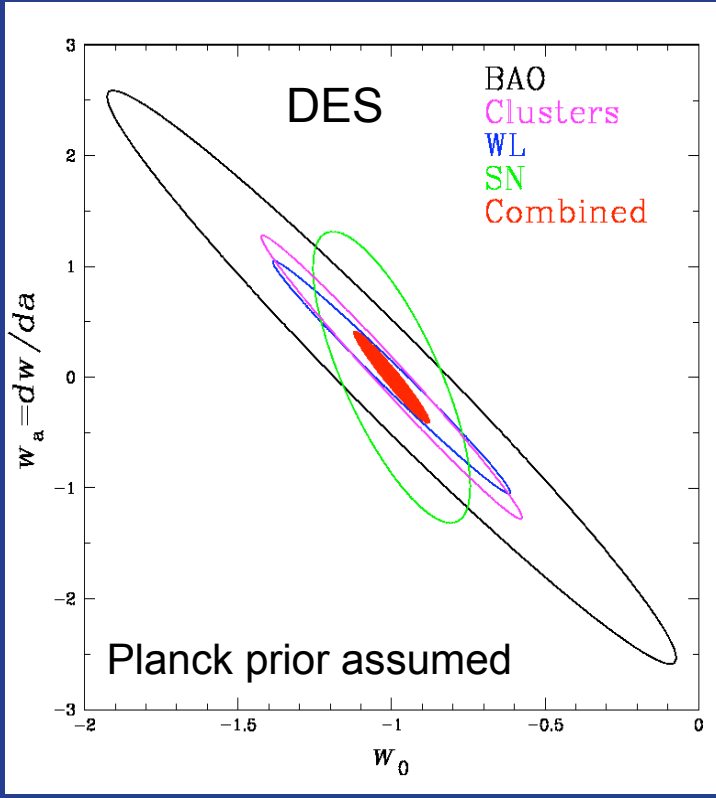
Forecast Constraints on DE Equation of State



Factor 3-5 improvement over Stage II DETF Figure of Merit

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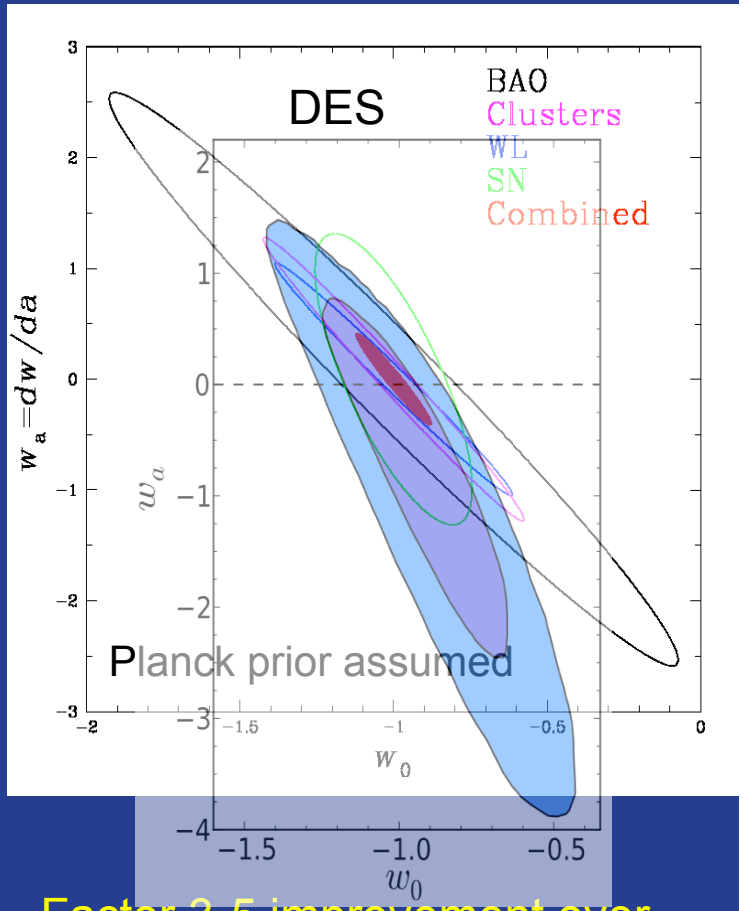

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The DES Collaboration

Fermilab
University of Illinois at Urbana-Champaign/NCSA
University of Chicago
Lawrence Berkeley National Lab
NOAO/CTIO
DES Spain Consortium
DES United Kingdom Consortium
University of Michigan
Ohio State University
University of Pennsylvania
DES Brazil Consortium
Argonne National Laboratory
SLAC-Stanford-Santa Cruz Consortium
Universitats-Sternwarte Munchen
Texas A&M University
plus Associate members at: Brookhaven National Lab, U. North Dakota, Paris, Taiwan

Over 120 members plus students & postdocs

Funding: DOE, NSF, UK: STFC, SRIF; Spain Ministry of Science, Brazil: FINEP, FAPERJ, Min. of Science; Germany: Excellence Cluster; collaborating institutions

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DES-Brazil Dark Energy Survey
LMU
Fermilab

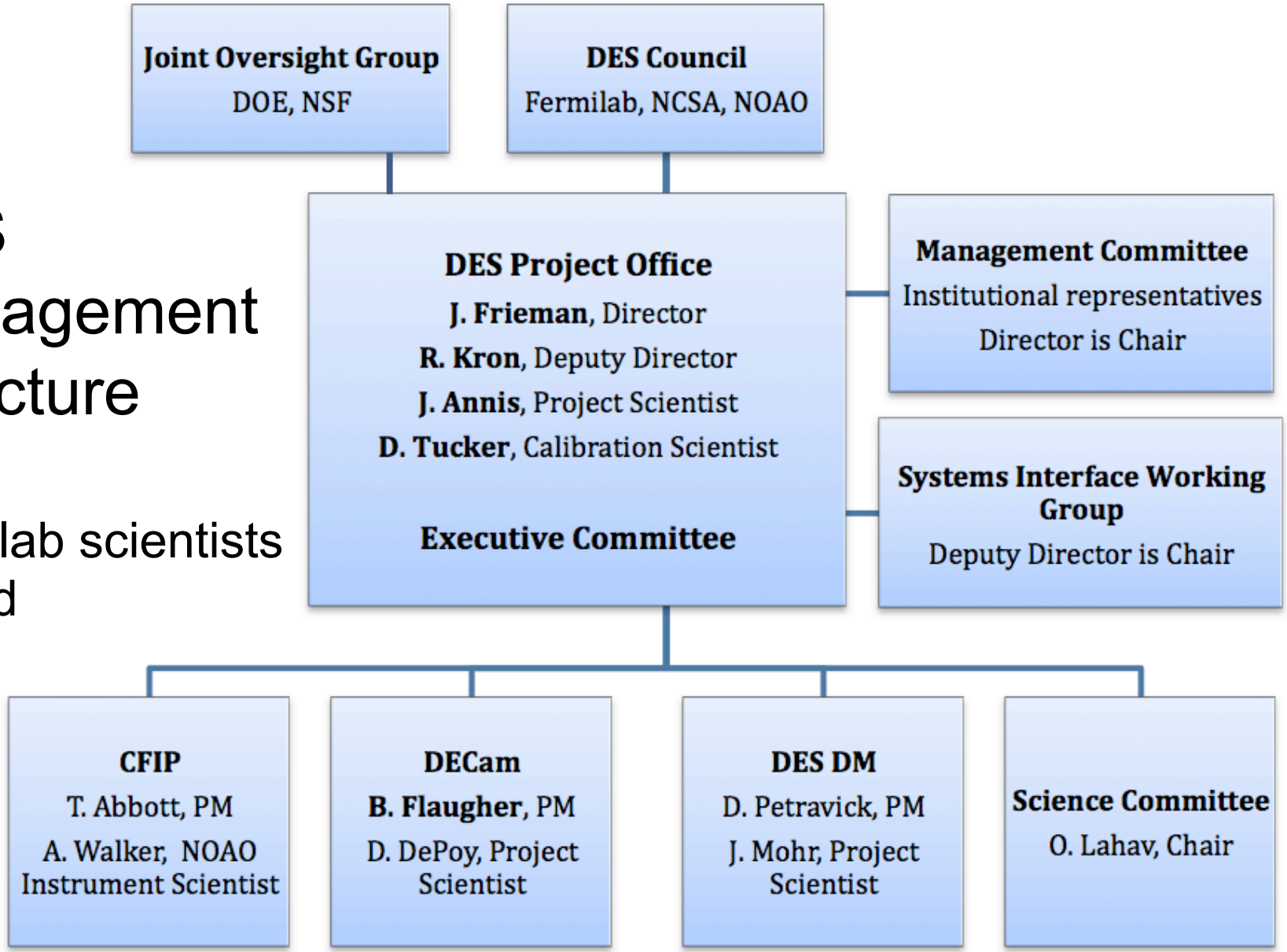
Project Structure & Timeline

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

    - Project initiated 2003
    - DECam R&D 2004-9
    - Camera construction 2008-11; currently ~93% complete
    - Final construction, testing, integration now on-going
    - Ship components to Chile: Sept. 2010-Sept. 2011
    - Installation: Jan.-Dec. 2011 (main install: Nov-Dec.)
    - First light on telescope: Jan. 2012
    - Commissioning: Jan.-April 2012
    - Survey: Sept. 2012-Feb. 2017 in 5x105-night seasons

DES Management Structure

Fermilab scientists in bold



Fermilab Leadership Roles in DES

- DES Project Management
- Survey Strategy
- Calibration
- Data Coordination & Validation
- DECam Project Management
- DECam Construction, Testing, Integration
- Mechanical & Electrical Design & Engineering
- Image simulations
- Installation & Commissioning by DECam team
- DECam operations support
- Computing: Secondary archive
- Science Working Groups (co-lead 4 of 11, active in others)

Currently ~11.5 FTE scientists on DES. Many played key roles in SDSS & SDSS-II and are also wrapping up SDSS analyses (supernovae, clusters, weak & strong lensing, Milky Way dark matter halo structure)

DES Institutions & Scientists are playing critical roles

- LBNL: CCD development & processing, SN strategy, LSS simulations
- Ohio State: SISPI (instrument software: control, DAQ), WL simulations
- U. Illinois: Data Management, SISPI
- U. Michigan: Filter changer, optical design, LSS simulations, preCAM telescope
- SLAC/Stanford: RASICAM cloud camera, calibration, alignment, LSS simulations
- Argonne: preCAM, calibration, F/8 handling system, SN simulations
- Penn: Weak Lensing pipeline & testing
- Brookhaven: Weak Lensing pipeline & testing
- Chicago: SN simulations, photo-z, LSS & WL simulations, multi-CCD test vessel
- United Kingdom: Optical corrector, Science Committee chair
- Spain: Front-end electronics, data quality testing
- Munich: Data Management science lead, data quality
- CTIO: Telescope improvements, installation, commissioning, operations
- Texas A&M: DECam, throughput calibration system, preCAM telescope work
- Brazil: Quick Reduce software, Science Portal

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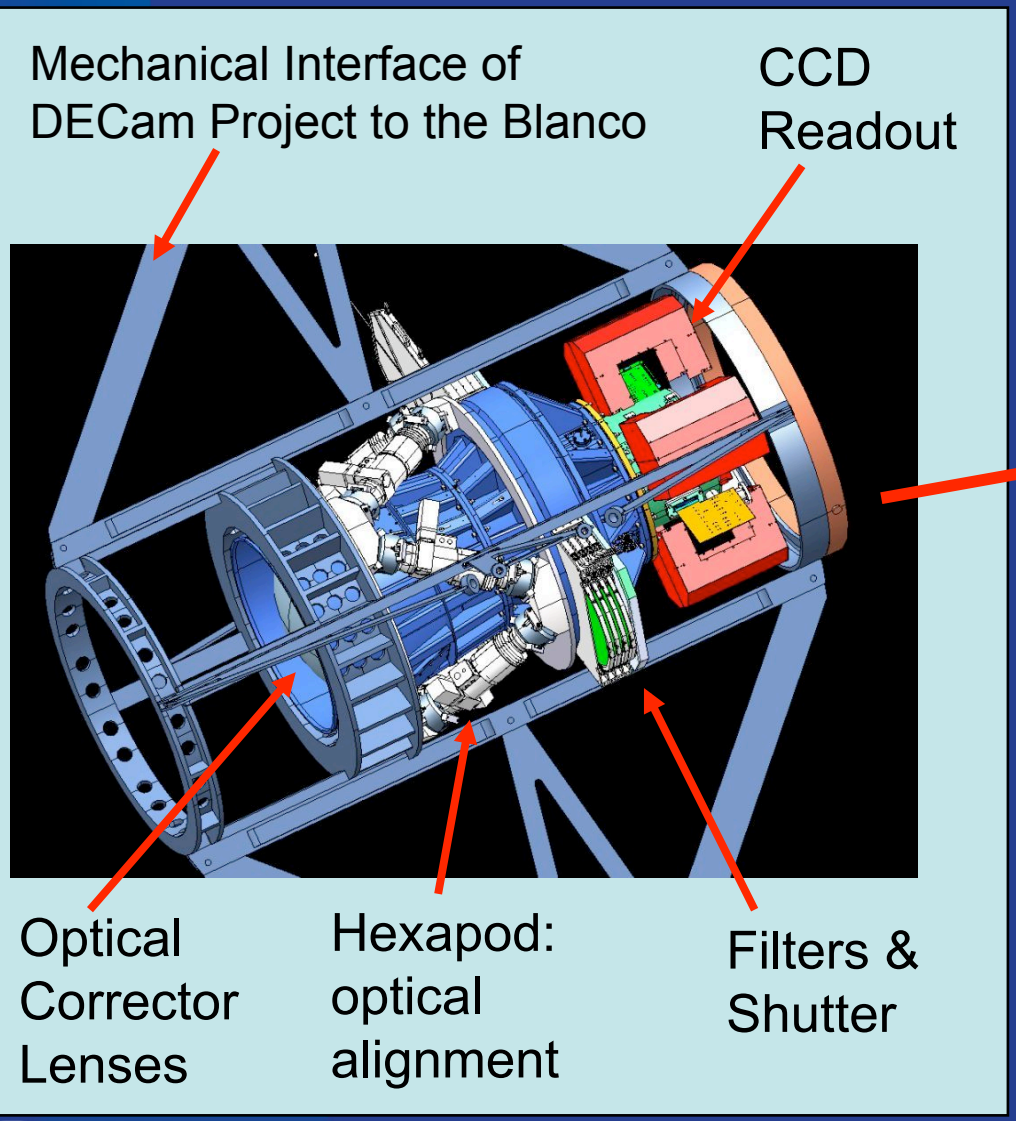
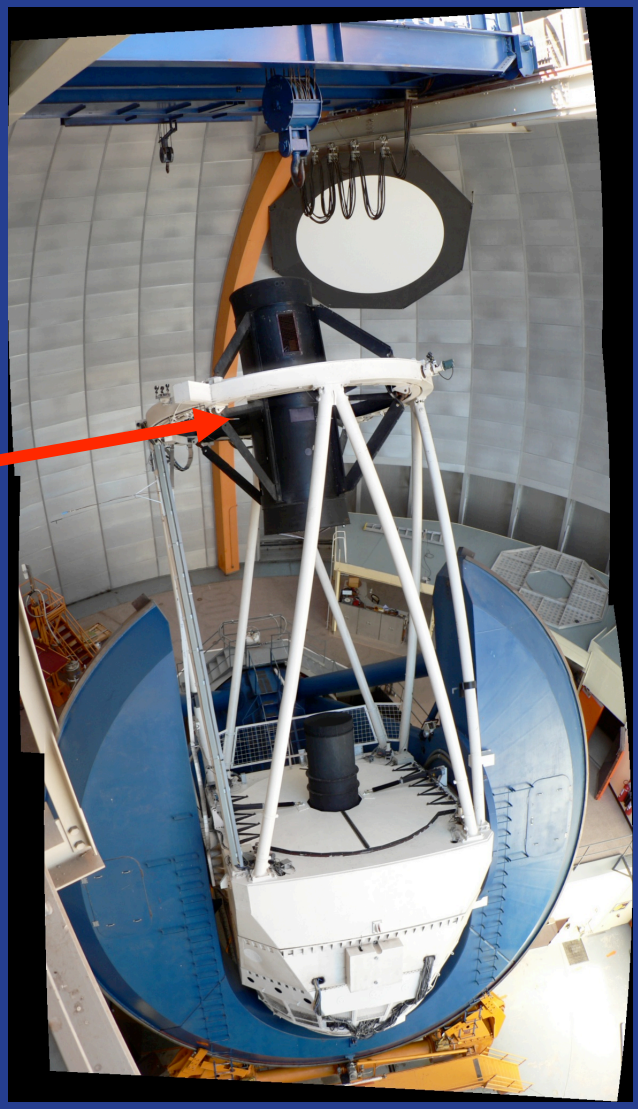
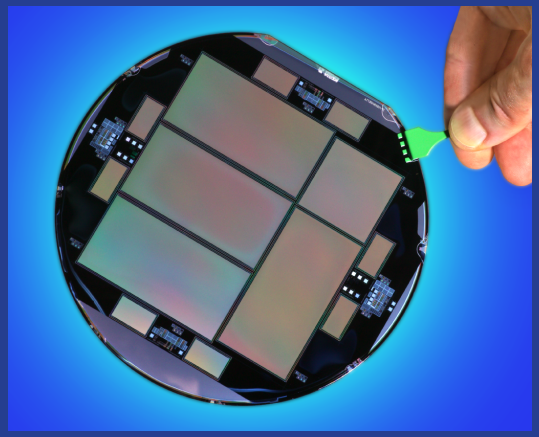
DES Instrument: DECam

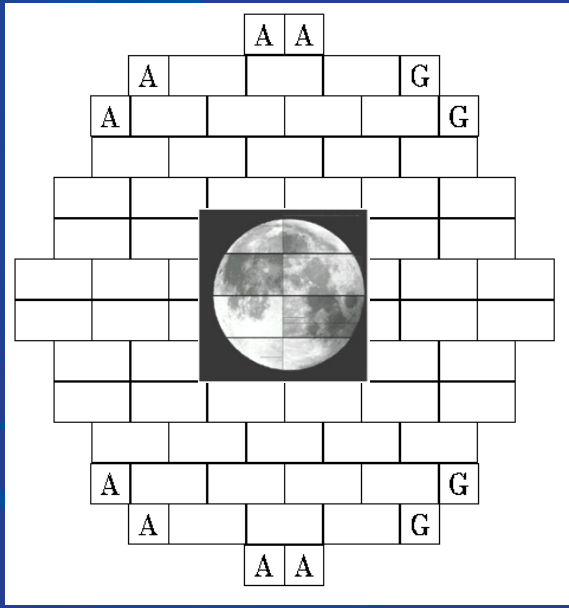


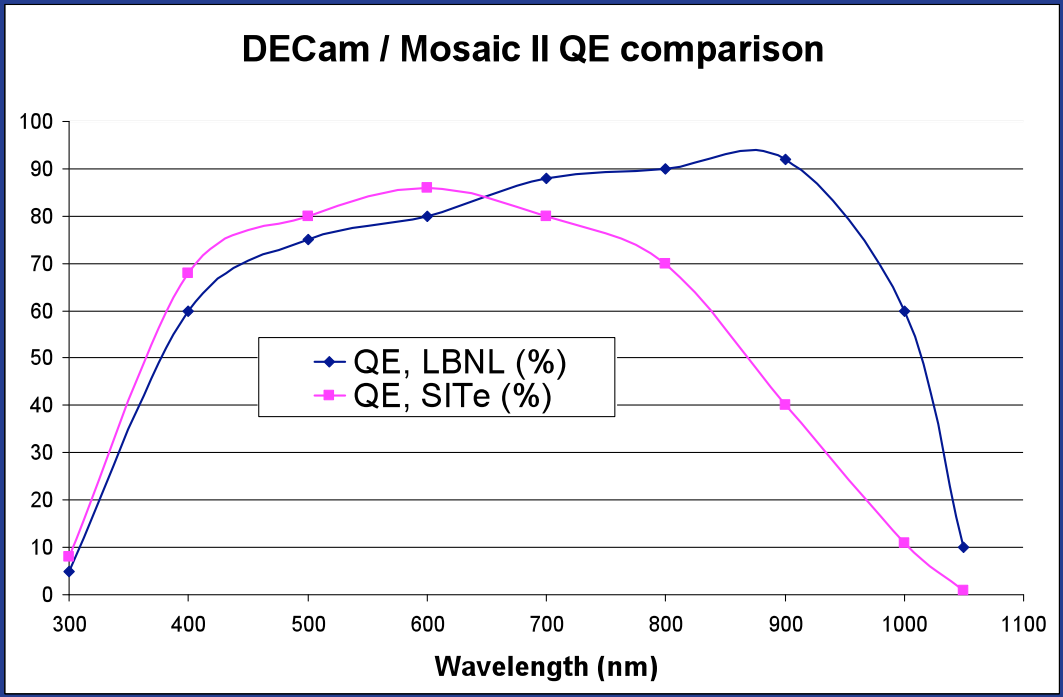


DECam CCDs



- 62 2kx4k fully depleted CCDs: 520 Megapixels, 250 micron thick, 15 micron (0.27”) pixel size
- 12 2kx2k guide and focus chips
- Excellent red sensitivity
- Developed by LBNL
- Processed at DALSA, LBNL
- Packaged and tested at FNAL





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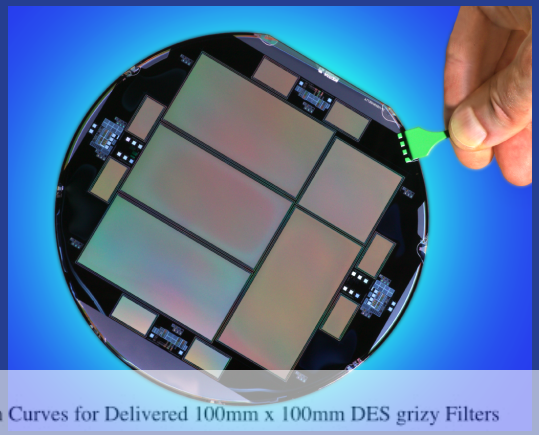
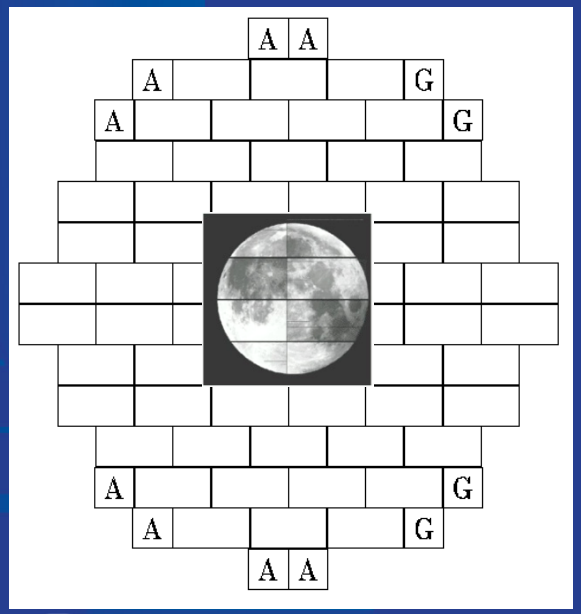
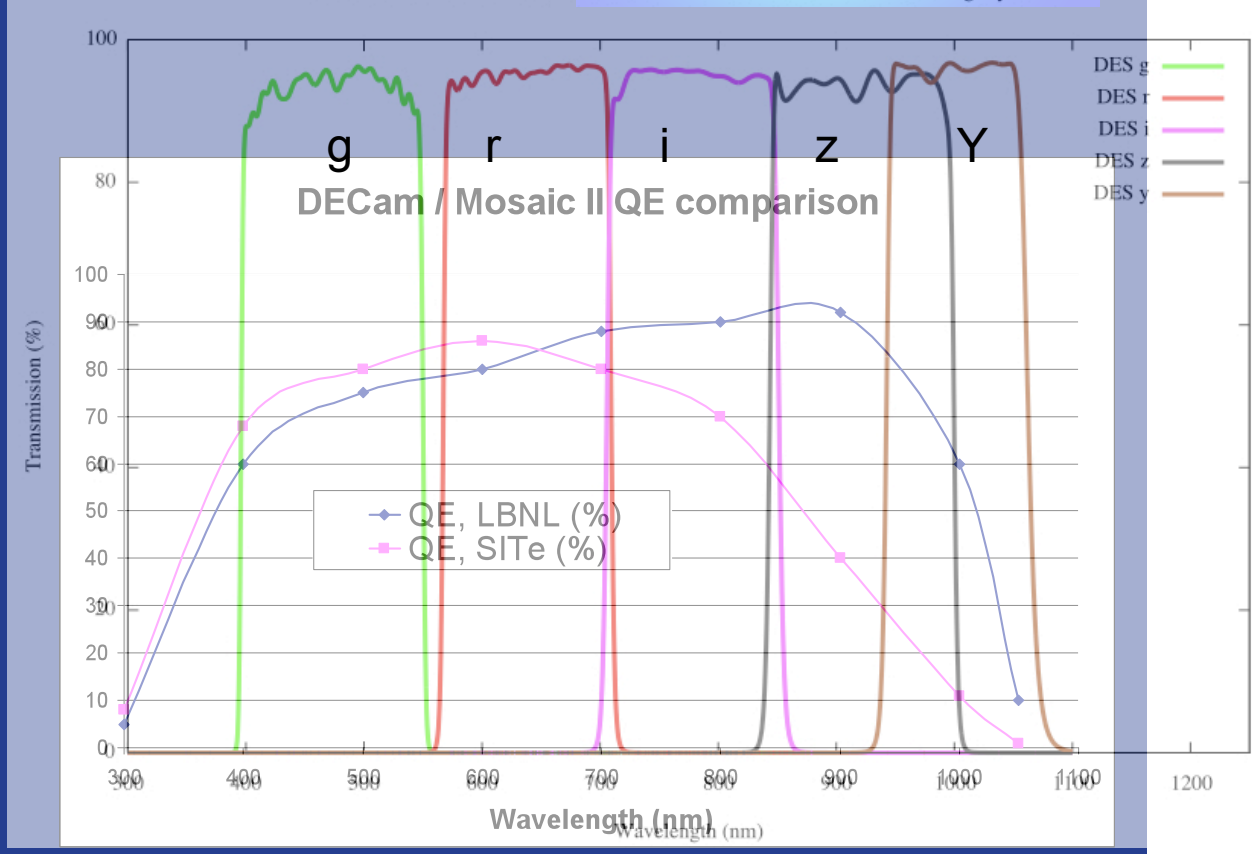
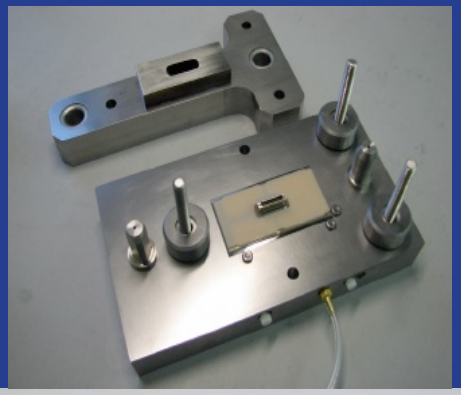


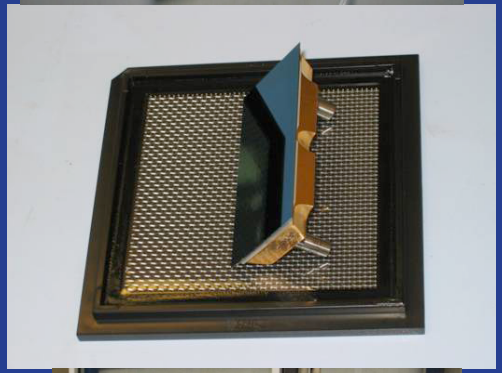


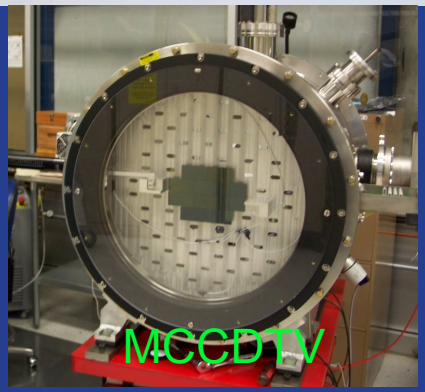


CCD Packaging and Testing at Fermilab

- Led by Fermilab Scientists Diehl and Estrada
- Fermilab engineer designed the CCD package with production line assembly in mind (from FNAL and LHC silicon vertex detectors)
- Operations in 2 clean rooms at Si Det
- Built on FNAL technical resources & expertise (ME, EE, SVD construction at Si Det)
- Production Packaging Nov. 2008-Oct. 2010
  - 270 2kx4k CCDs packaged and tested
  - 124 are Science Grade, ready for the focal plane
  - 62 + 10 spares are required
- Also have 26 science grade 2kx2k devices; need 12 plus spares.
- Mean # bad pixels = 0.12%
- Camera extensively tested with engineering-grade CCDs



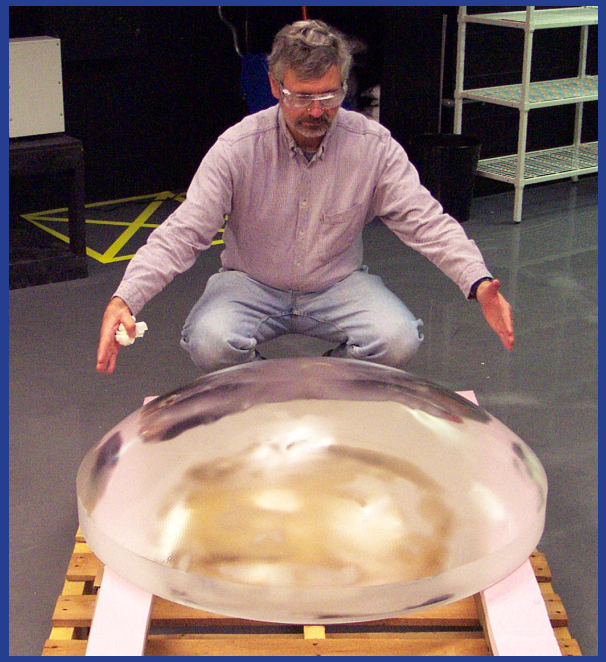


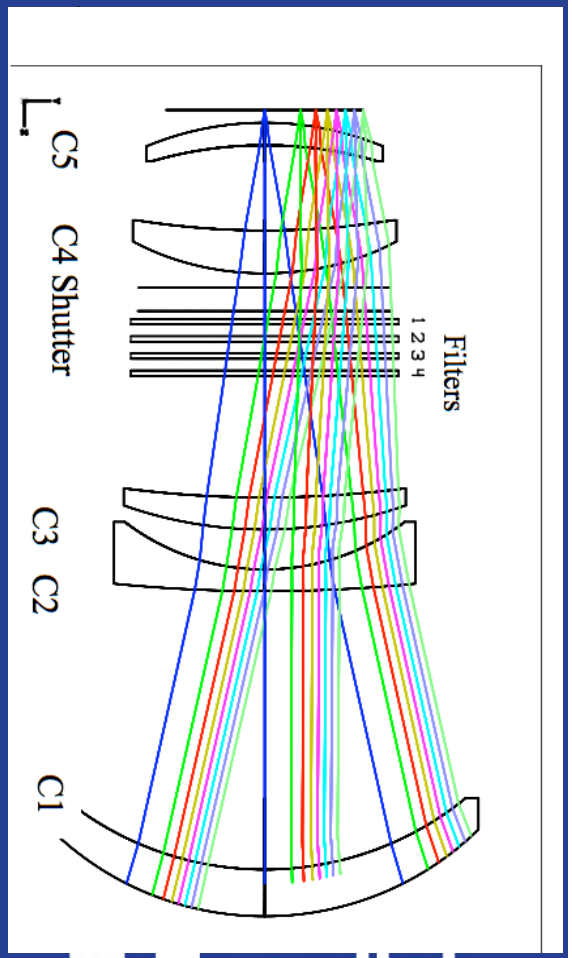


Optics

- Field of view: 2.2^{o} diameter (3 sq deg)
- Lenses being aligned in cells and barrel at University College London prior to shipping to Chile
  - Fermilab contributed to optical design in partnership with Universities

S. Kent (FNAL)

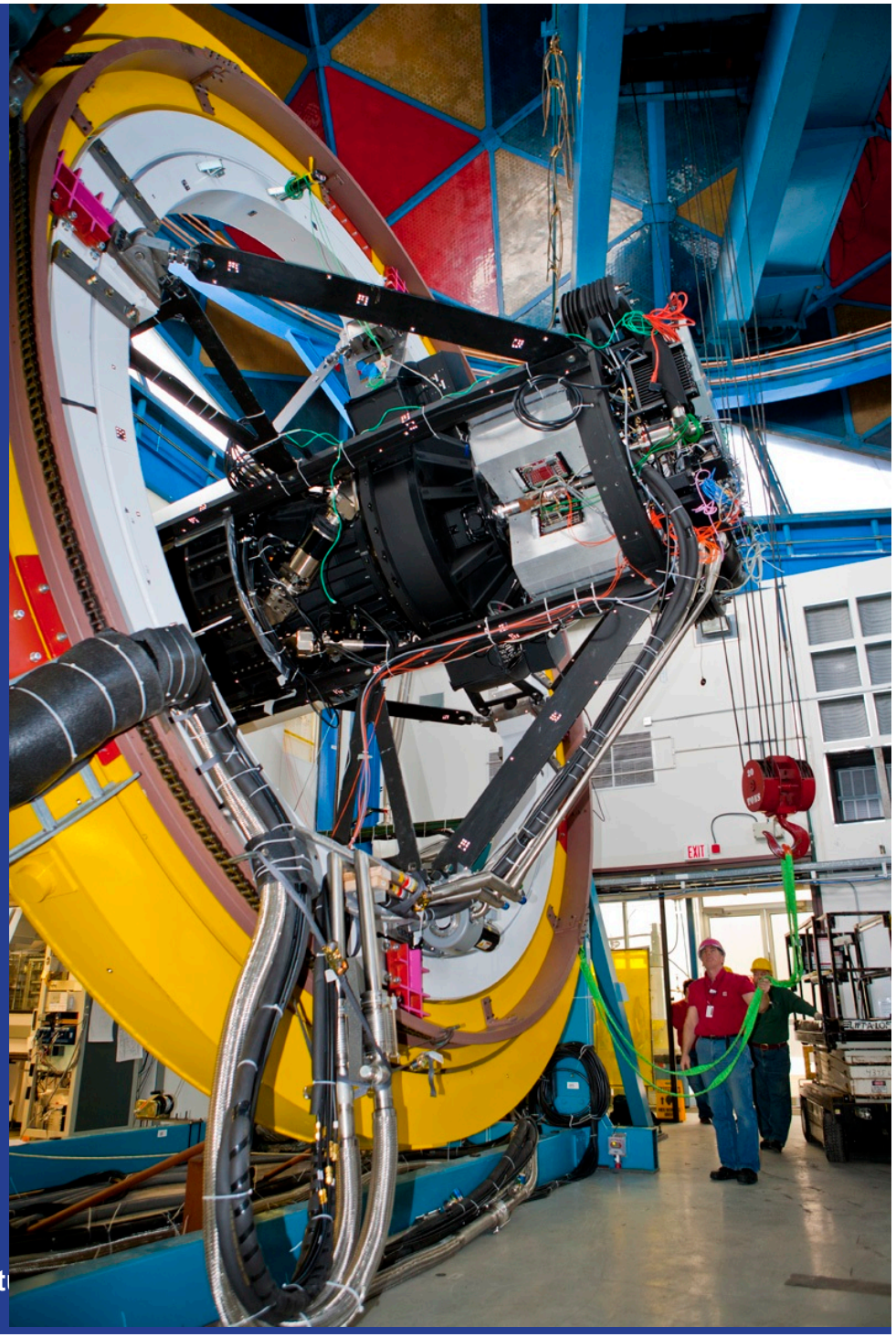




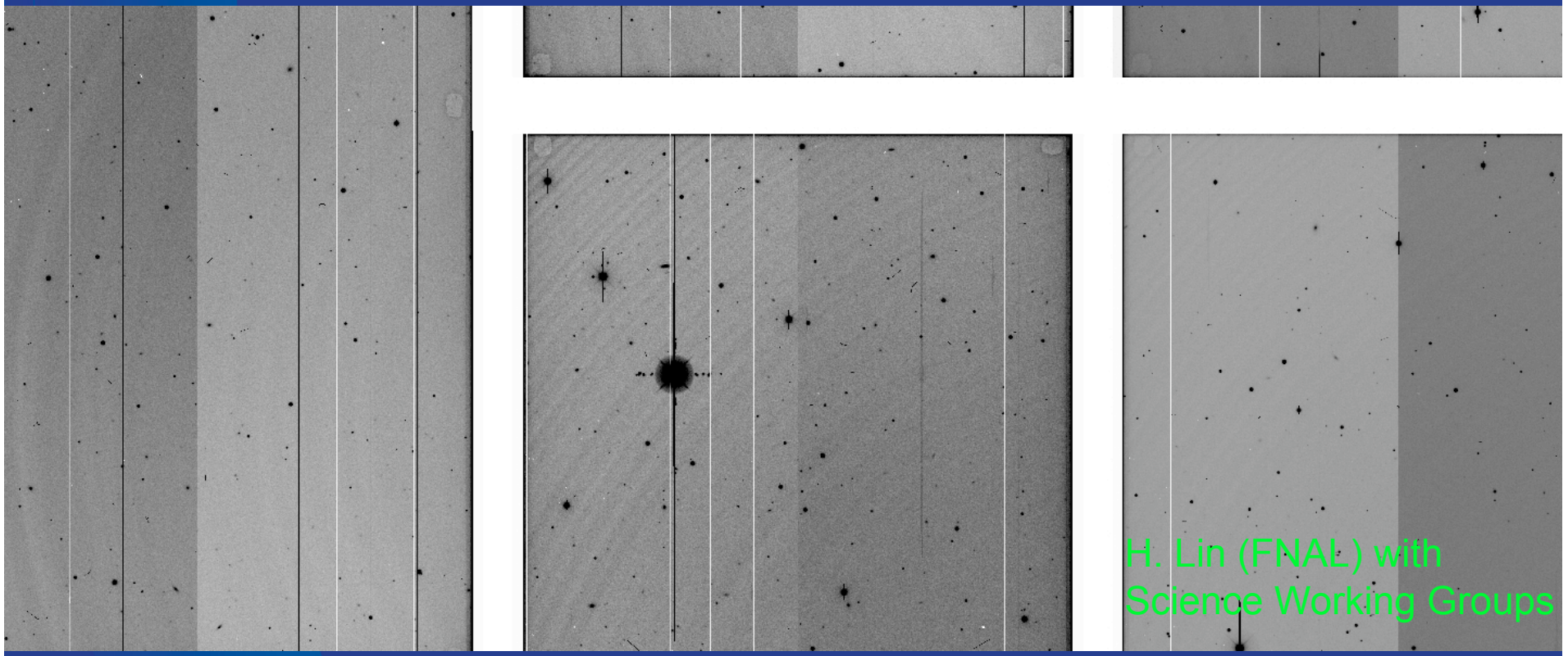
Telescope Simulator at Fermilab

- Enabled early acceptance testing of DECam components, testing of operations and installation procedures prior to shipping to CTIO, and interleaving of testing, shipping, installation of different components

- Summer 2010-Spring 2011



DECam Image Simulations:
test Data Management System

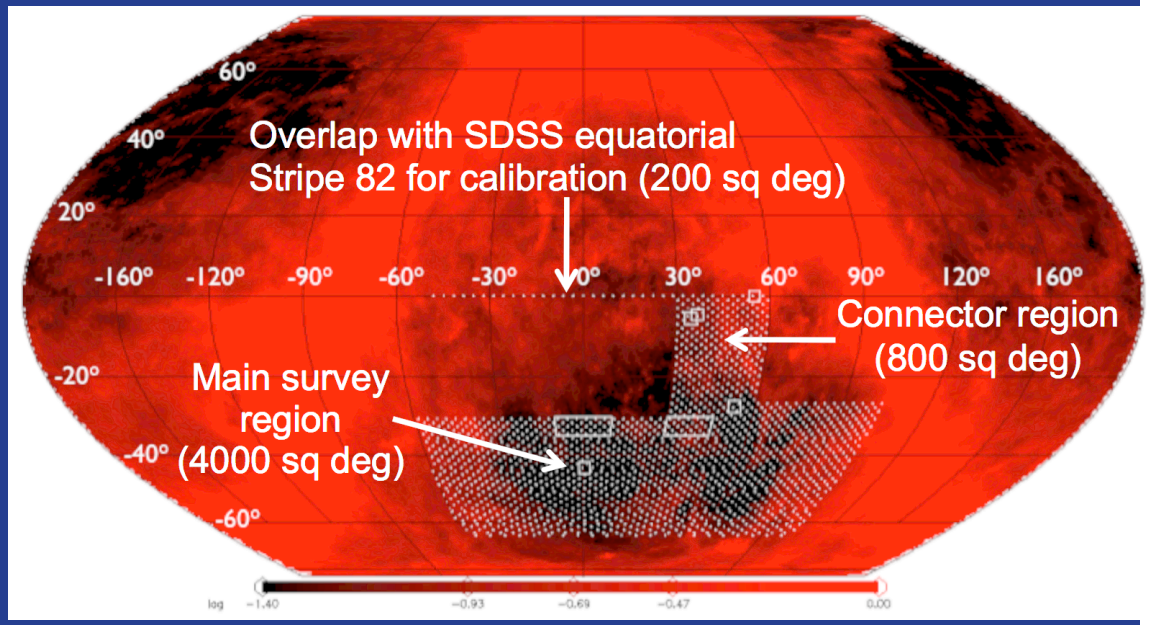


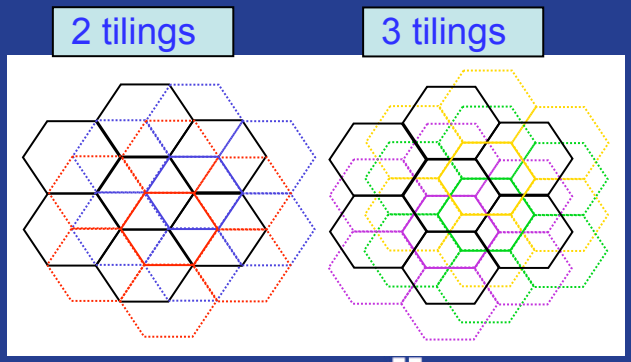
Note bright star artifacts, cosmic rays, cross talk, glowing edges, flatfield ("grind marks", tape bumps), bad columns, 2 amplifiers/CCD

DES Observing Strategy

Survey Area 5000 sq deg

- 80-100 sec exposures
- 2 filters per pointing (typically)
  - *gr* in dark time
  - *izy* in bright time
- Multiple overlapping tilings to optimize photometric calibration
- 2 survey tilings/filter/year
- Optimize Dark Energy science within the allotted 525 nights, based on simulations
- Observing Plan: DES Project Scientist J. Annis (FNAL)





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DECam Progress

- F/8 2ndary mirror handling system installed at CTIO in Jan. 2011
- New cloud camera shipped to Chile, will be installed June.
- Installation of DECam cooling system starts July.
- Science-grade CCDs being installed in DECam now, then will ship imager to Chile for Sept arrival.
- Integration & Installation Workshop and Review held in Chile in April.
- DES Directors' Review held at FNAL May 10-11.
- UCL aligning optics in cells and barrels, will arrive CTIO mid-Sept.
- Asahi (Japan) has produced 2 filters (i and z), are currently completing a third (y), and have recovered from aftermath of the tsunami. If there are rolling blackouts during peak summer air-conditioning use, it could stretch out delivery of last 1 or 2 filters to early Fall.
- Currently on schedule for installation on the telescope to start Nov. 1.


DES i and z filters at Asahi

DES Operations

- Although CTIO will be in charge of installation and commissioning (FY12) and will operate the instrument (FY12-17), substantial participation by FNAL scientists, engineers, technicians and by the collaboration will be *critical* to the success of these activities.

- Once DECam components are checked out in the Blanco dome and ready to install, they move from DOE DECam project funding to DOE DES operations support. FY11: both DECam project and operations support. FY12 and beyond: (mostly) DES operations. NSF supports CTIO observatory ops. Proposal submitted May 2 to NSF for Data Management operations at NCSA.

DES and mentoring at Fermilab

- Since the project began, DES scientists at Fermilab have mentored:
  - 23 high school students, both summer and academic-year internships (including quarknet)
  - 3 high school teachers
  - 10 undergrad students, from local colleges to UC Berkeley to S. America
    - Andres Plazas: undergrad from Colombia, now grad student at Penn
  - 5 graduate students, at both masters and PhD level
    - Marcelle Soares-Santos: earned PhD from U. Sao Paulo working with FNAL scientists on clusters, now starting FNAL postdoc
  - Tom Carter, on sabbatical from College of Du Page
- CCD lab at ICFA instrumentation school in 2010: trained 80 students

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EXECUTIVE OFFICE OF THE PRESIDENT
OFFICE OF SCIENCE AND TECHNOLOGY POLICY
WASHINGTON, D.C. 20502

Dr. Juan Estrada
2685 Stoneybrook Lane
Aurora, IL 60502

Dear Dr. Estrada,

I am writing to express my warmest congratulations on your selection for a Presidential Early Career Award for Scientists and Engineers. Your accomplishments at this early stage of your career highlight your extraordinary potential to catalyze the kinds of scientific and technological advances that have long been at the core of this nation's strength. Your promise as a leader stands out among your peers and places you in a position of great opportunity and responsibility—a position I feel confident you will fully embrace. America is counting on you to elevate its place in the world, both directly through your accomplishments and by inspiring others.

I applaud your energy and ambition and look forward to your achieving even greater goals in the years to come.

Sincerely,

John P. Holdren

John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

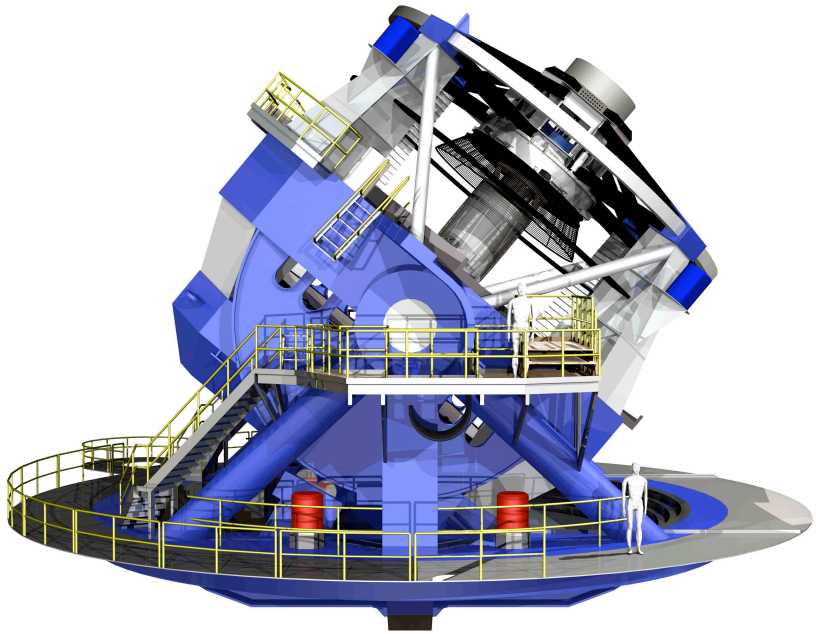
Dark Energy Beyond DES

- LSST
- DESpec
- BigBOSS
- 21-cm

exciting science opportunities to further improve Dark Energy constraints

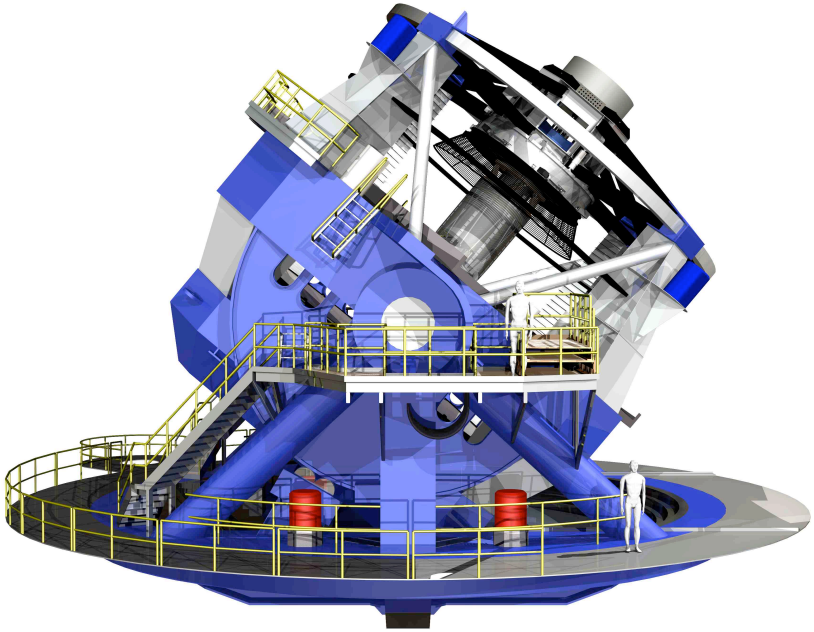
Large Synoptic Survey Telescope

- Dedicated 8.4m telescope on Cerro Pachon (next to Tololo)
- Gigapixel camera with 10 sq deg FOV
- Top-ranked ground project in Astro 2010
- SLAC is DOE managing institution for the camera
- NSF project (telescope, site, data management) will be managed by LSST Corp.
- Director's Review at SLAC now
- PDR will happen at NSF



Large Synoptic Survey Telescope

- Fermilab has joined LSST
- Fermilab in excellent position to help LSST succeed:
  - SDSS/DES survey heritage
  - Data acquisition system
  - Data management software
  - Science analysis
  - Si Det infrastructure and expertise: industrial-scale silicon-based instrumentation for accelerator and non-accelerator experiments
- Modest effort until DECam ramps down
- Will work with SLAC and LSST Corp to define roles



Dark Energy Spectrograph: DESpec

- Upgrade of DES currently under study:
  - multi-object prime focus spectrograph for the Blanco 4m, interchangeable with DECam
  - improved redshift precision (by a factor ~300) for ~10% of DES galaxies
  - Use DECam infrastructure (cage, barrel, hexapod, most optics, spare CCDs,…): substantial cost saving
  - 20 low-cost spectrographs, 4000 robotically positoned fibers
- Increased *z* precision would enhance Dark Energy science reach of DES by factor ~several, especially testing DE vs. modified gravity
- Enhance DE science reach of LSST
- Preliminary design and science studies underway

BigBOSS

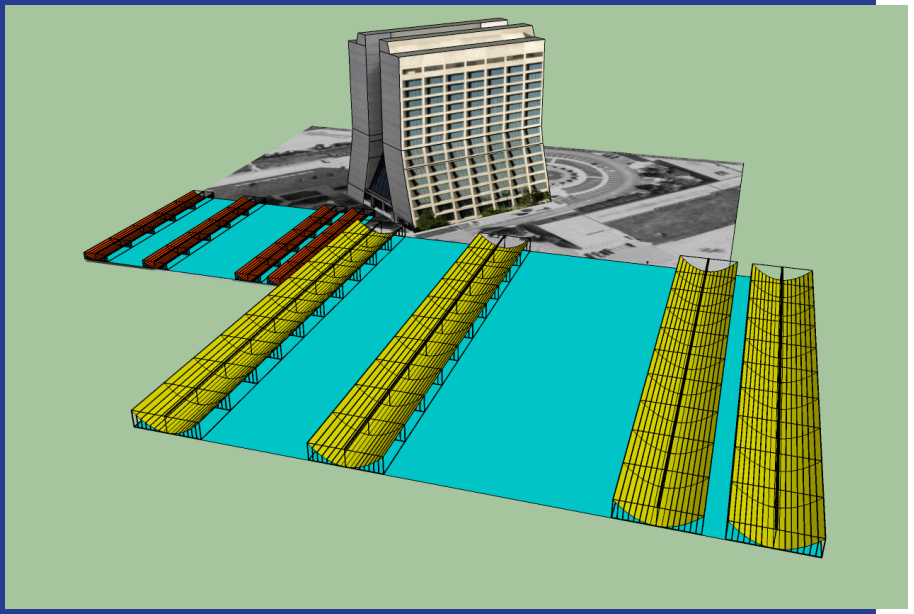
- LBNL-led concept for multi-object spectrograph for the NOAO Kitt Peak 4-meter telescope to carry out a massive BAO survey
- Follow up targets from PanSTARRS-I and WISE (sky overlap with DES or LSST small but potentially useful)
- NOAO agreed to award telescope time in exchange for delivery of the instrument (similar to DES). Construction not yet funded. Includes FNAL scientists Annis, Kent, and Diehl.
- Fermilab could contribute:
  - mechanical modeling of the telescope (solid model, stray light analysis, …): Blanco and Mayall essentially identical
  - Optical corrector: design, management of fabrication, alignment
  - CCD packaging and testing
  - Test the instrument using the Telescope Simulator

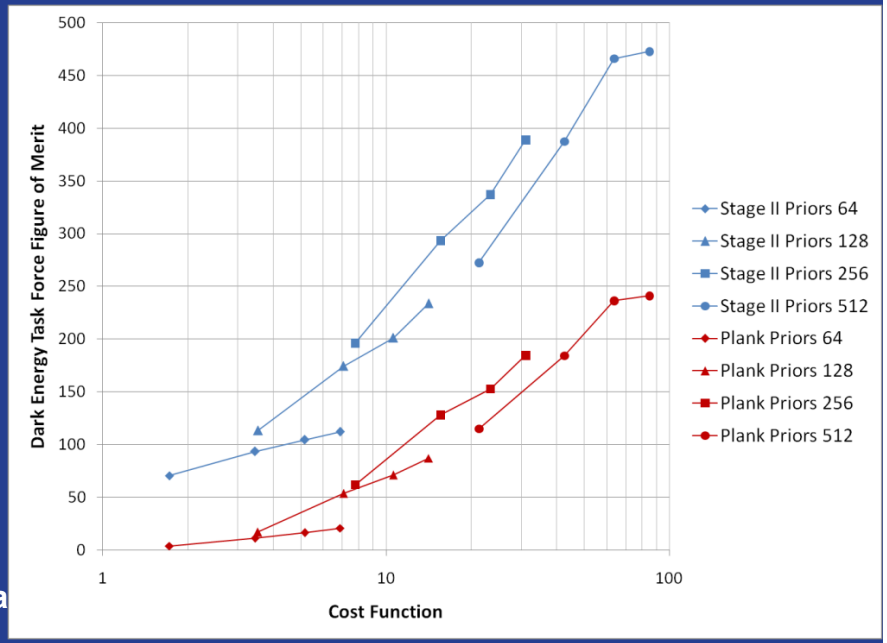
DESpec and BigBOSS

- Both projects involve 4000-5000-fiber spectrographs on 4m telescopes, with related science goals.
- DE reach increases with survey area, so ideally would survey both north (BB) and south (DESpec).
- Similar survey power (area/depth per unit time) for the two concepts: BB larger FOV, DESpec higher fiber density.
- DESpec could cover entire survey areas of DES and LSST, maximizing synergistic science (weak lensing+redshift distortions).
- DESpec would reuse much of the DECam infrastructure, resulting in cost savings.
- NSF AST will carry out Portfolio Review 2011-12, which will consider the future of the NOAO 4m telescopes.

21cm Cylindrical Radio Telescope

- Medium size dark energy project
  - 3-D radio intensity map of the hydrogen hyperfine transition at 1.42 GHz
  - Measure BAO at large redshifts ($z = 0.7 – 1.8$)
  - Extract 21 cm signal from foregrounds (galactic synchrotron emission, radio point sources)
- New technology that merges
  - simple radio reflectors
  - inexpensive room temperature low noise amplifiers ($T_{sys} < 35K$)
  - low cost, large scale computing (FGPAs and GPUs)





U.S. DEPARTMENT OF ENERGY

Fermilab and 21cm

- Technology well aligned to Fermilab expertise:
  - large data acquisition systems (collider detectors)
  - digital signal processing (collider detectors, accelerator control)
  - radio frequency technology (accelerators)
  - Heritage in sky surveys (SDSS, DES)
  - Management expertise in medium and large scale projects

- Fermilab contributions to date:
  - Site selection measurement
  - In-depth requirement study
  - Sky map simulation software
  - Initial foreground removal algorithms designed and simulated
  - Initial proposal written
  - Hosted collaboration meeting
  - Science workshop held

Next steps for this collaboration/project currently unclear. Current FNAL effort on hold.

Conclusion

- DES poised to take the next step in understanding the nature of dark energy, ramping up operations this year.
- Combination of Fermilab technical and scientific expertise and infrastructure with strengths of partner institutions enables this kind of project.
- DES entering critical phase, and timely operations support will be essential for success.
- Fermilab can make significant contributions to future DE projects, exploiting its infrastructure and technical expertise, building on its experience with SDSS and DES.
- Given limited resources, choices will have to be made, based on compelling science, the ability to make unique, critical contributions, and alignment with national priorities.