Fermilab Dark Energy Program

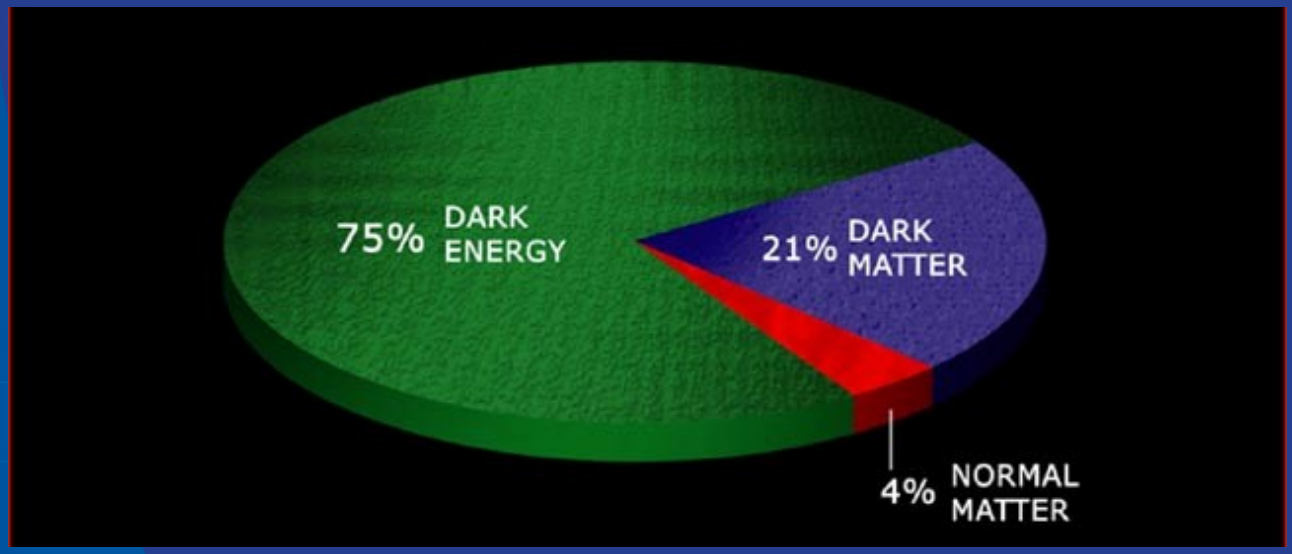
Josh Frieman

- 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. Baryon Acoustic Oscillations
  - IV. Supernovae
- Two multiband surveys:
  - 5000 deg^2 *grizY* to 24th mag
  - 15 deg^2 repeat (SNe)
- Build new 3 deg^2 FOV camera and Data management system

Survey 2012-2017 (525 nights)

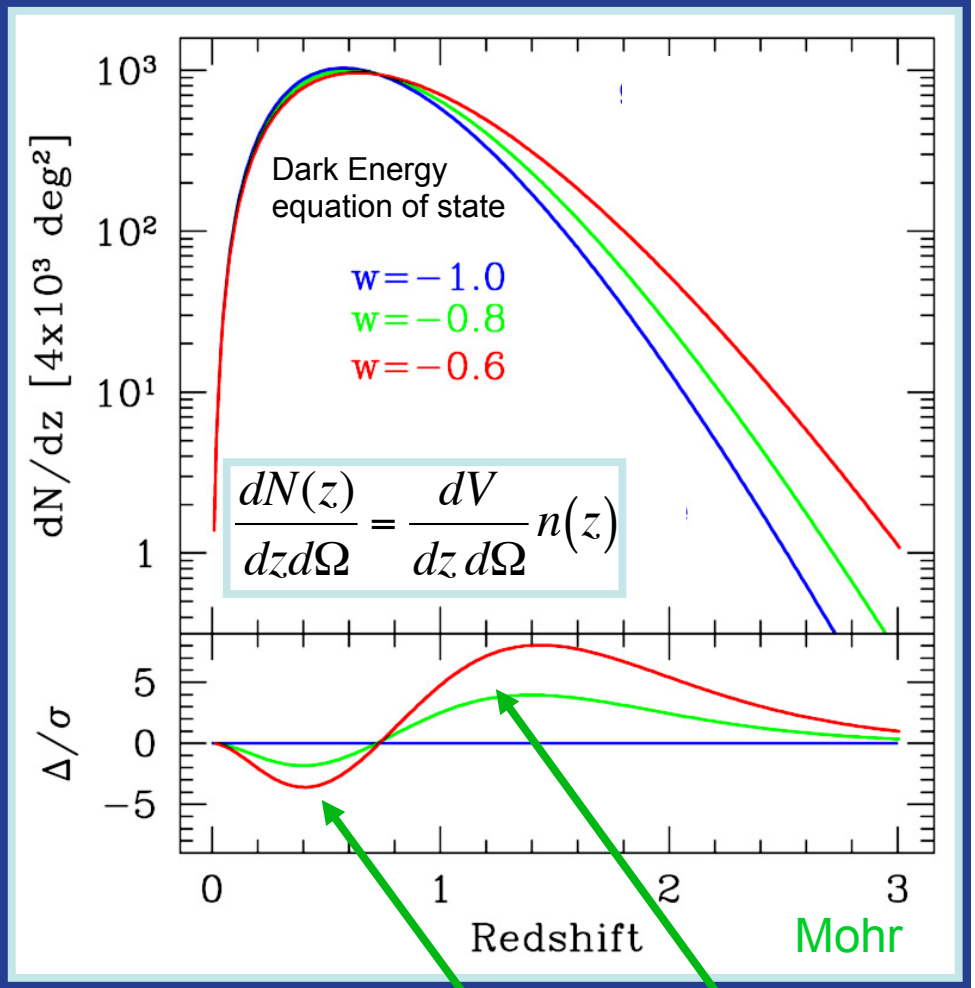
Blanco 4-meter at CTIO

*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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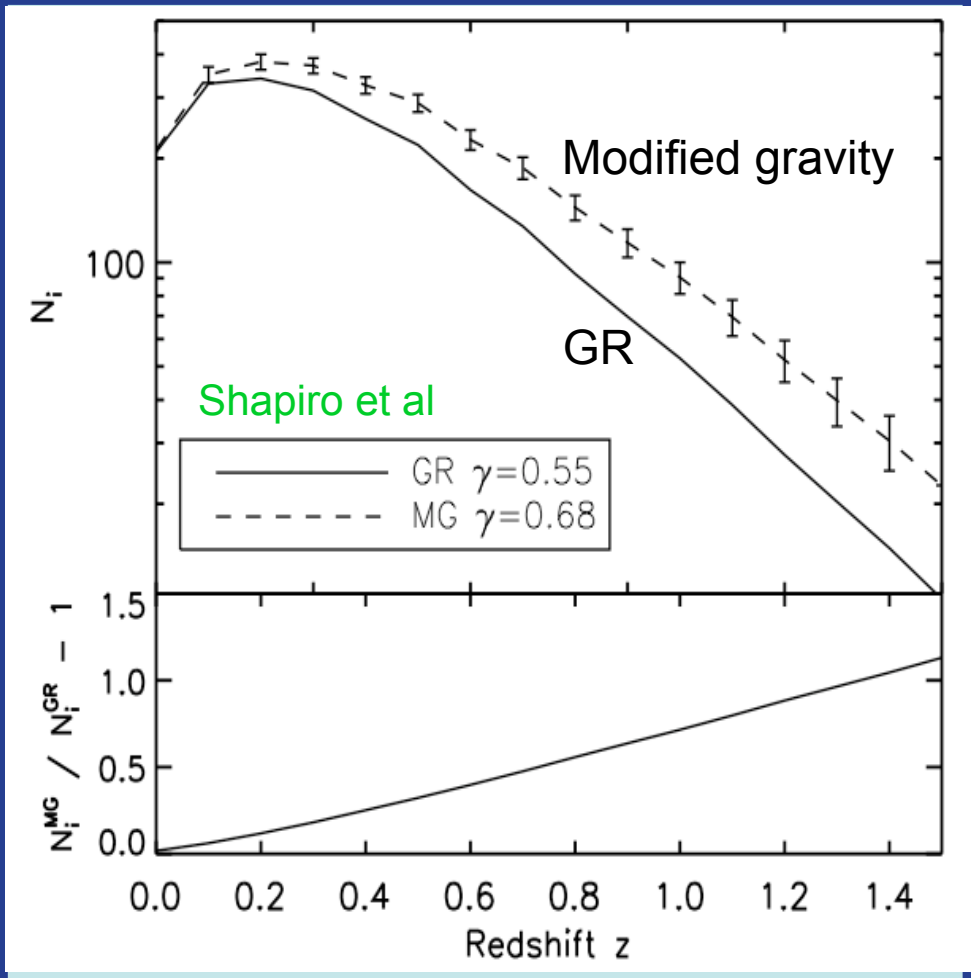


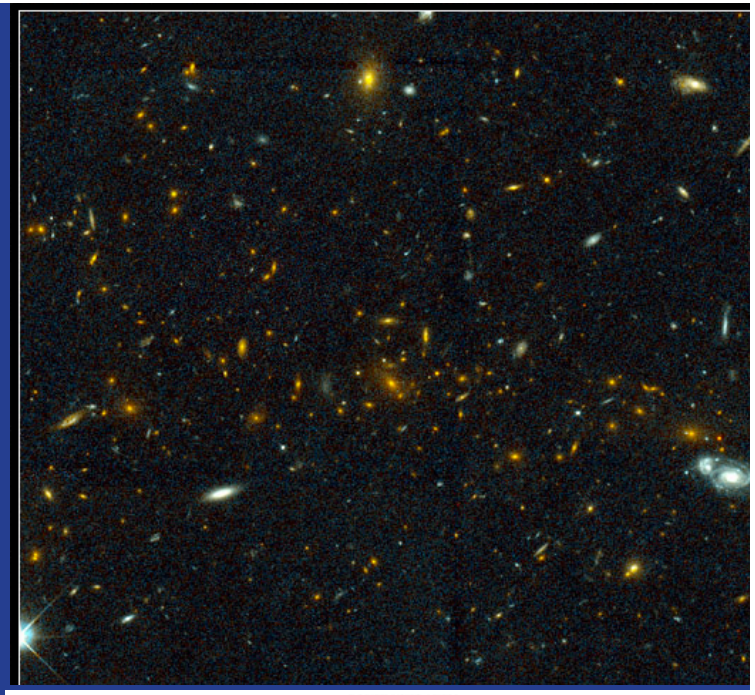
Finding Optical Clusters

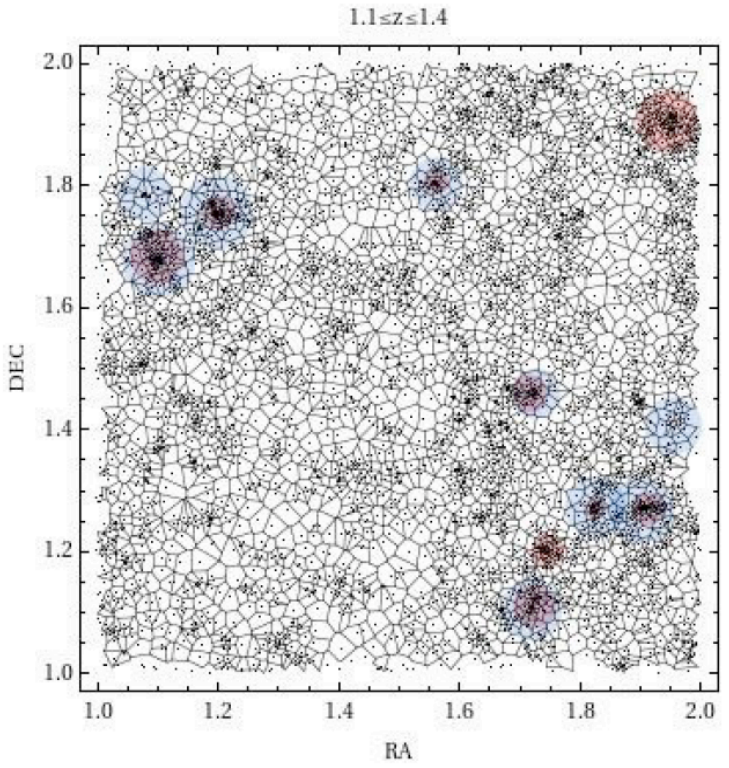
Fermilab group testing cluster-finding methods using SDSS and mock catalogs:

- MaxBCG method underlies SDSS cluster results
- Voronoi Tesselation
  - Completeness > 95%
  - Purity > 90%

- DES will extend to much higher redshift

Soares-Santos, Annis, etal





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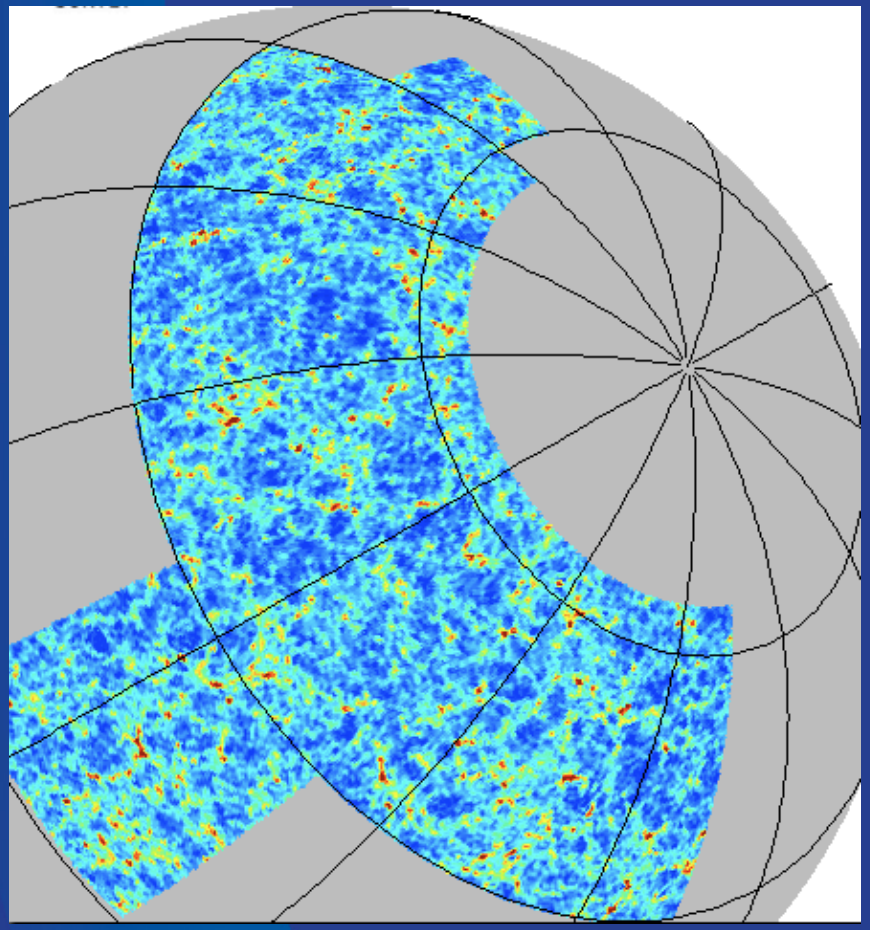
Synergy with South Pole Telescope

DES footprint: 5000 sq deg



DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey
Also partnering with VISTA Hempishere Survey (NIR): improve photo-z's

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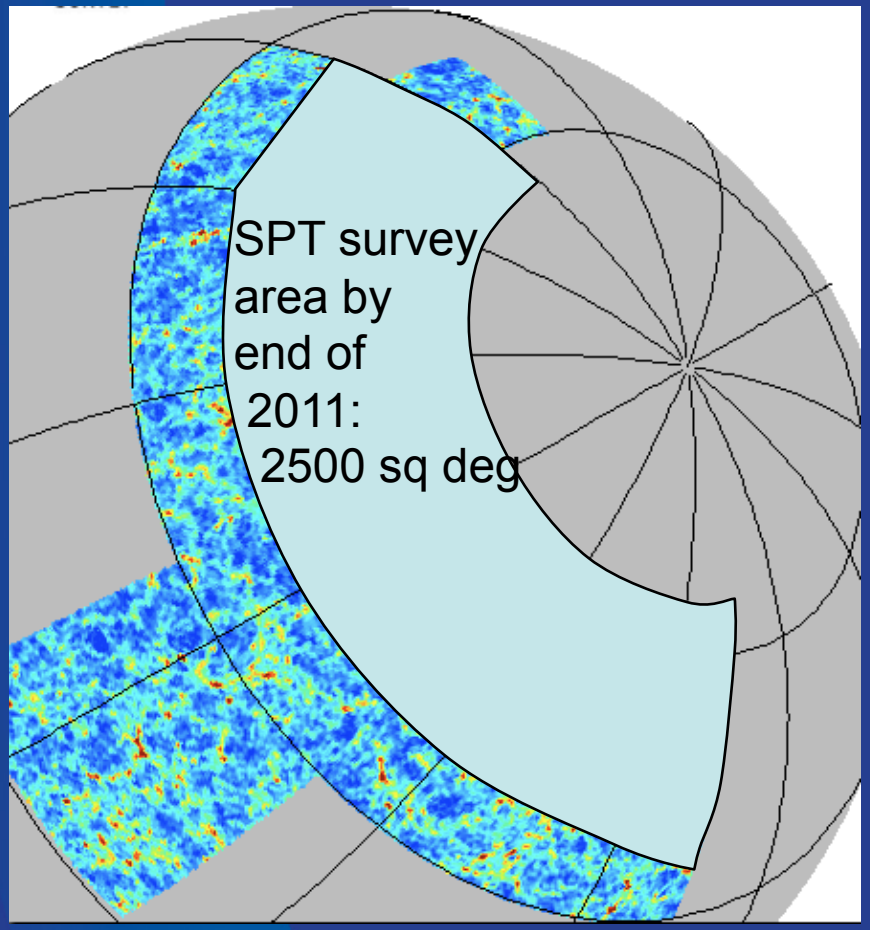
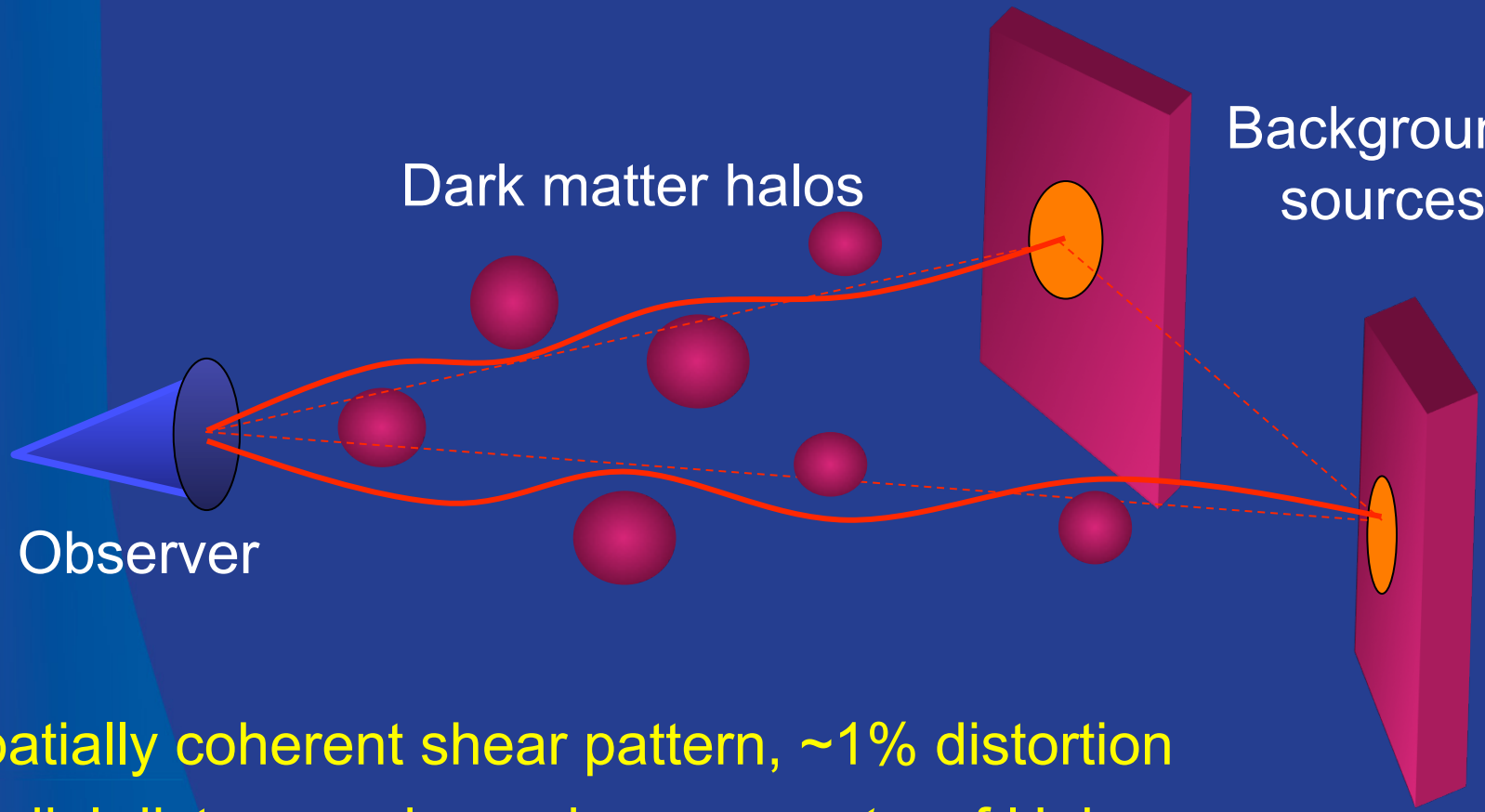


DES survey area encompasses SPT Sunyaev-Zel'dovich Cluster Survey

Also partnering with VISTA Hempishere Survey (NIR): improve photo-z's

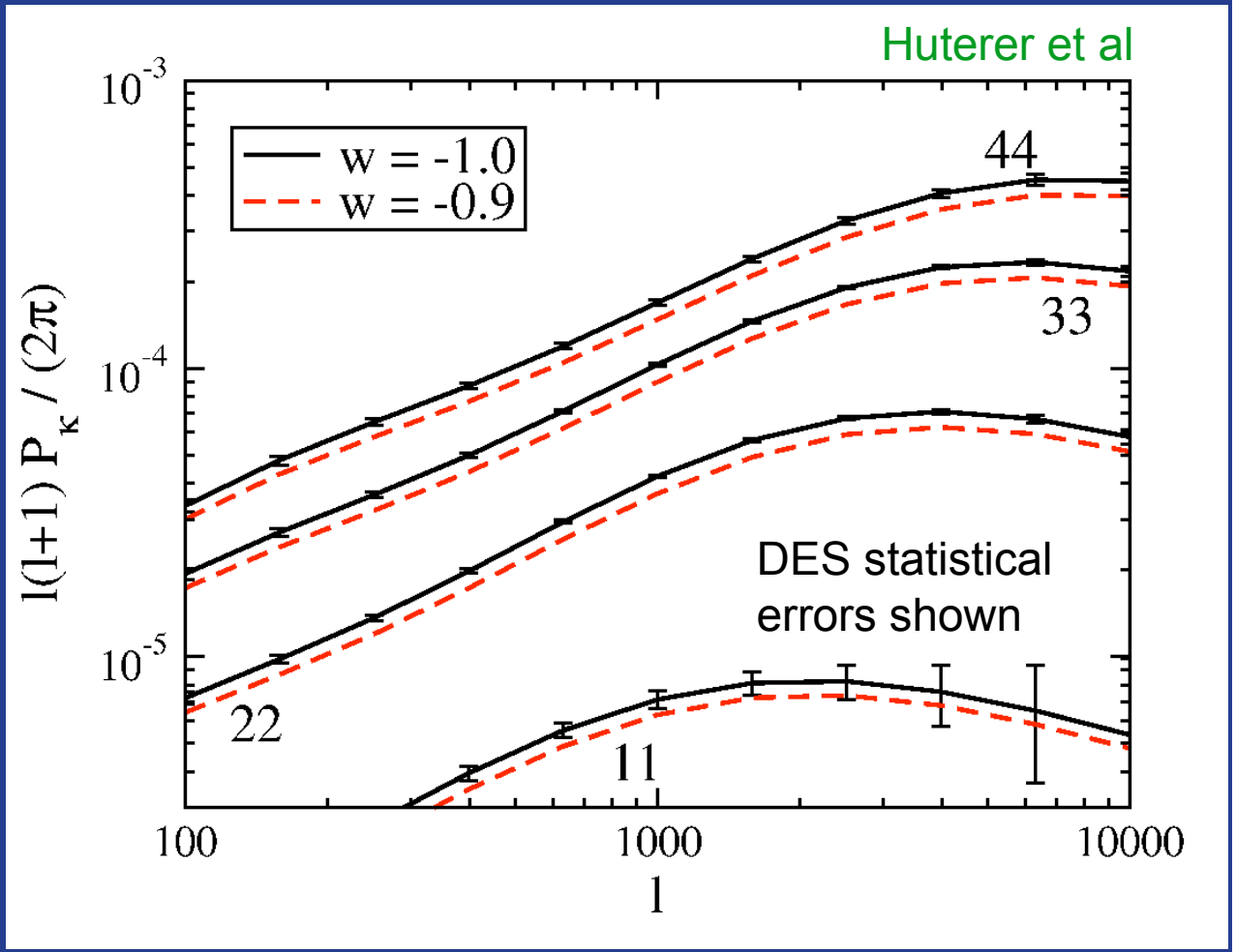
II. Weak Lensing: Cosmic Shear



- 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 photo-z slices
- Shapes of ~300 million well-resolved galaxies with $\langle z \rangle = 0.7$
- Improved telescope, new optical corrector, and active alignment system should deliver improved image quality for galaxy shape measurements



Factor ~30 greater area than CFHTLS

Sloan Bright Arc Survey

Identify lens systems in SDSS, follow up with HST, Spitzer,…

Constrain dark matter halos

Kubo et al, Diehl et al
Lin et al, Allam et al
Buckley-Geer et al
(FNAL)

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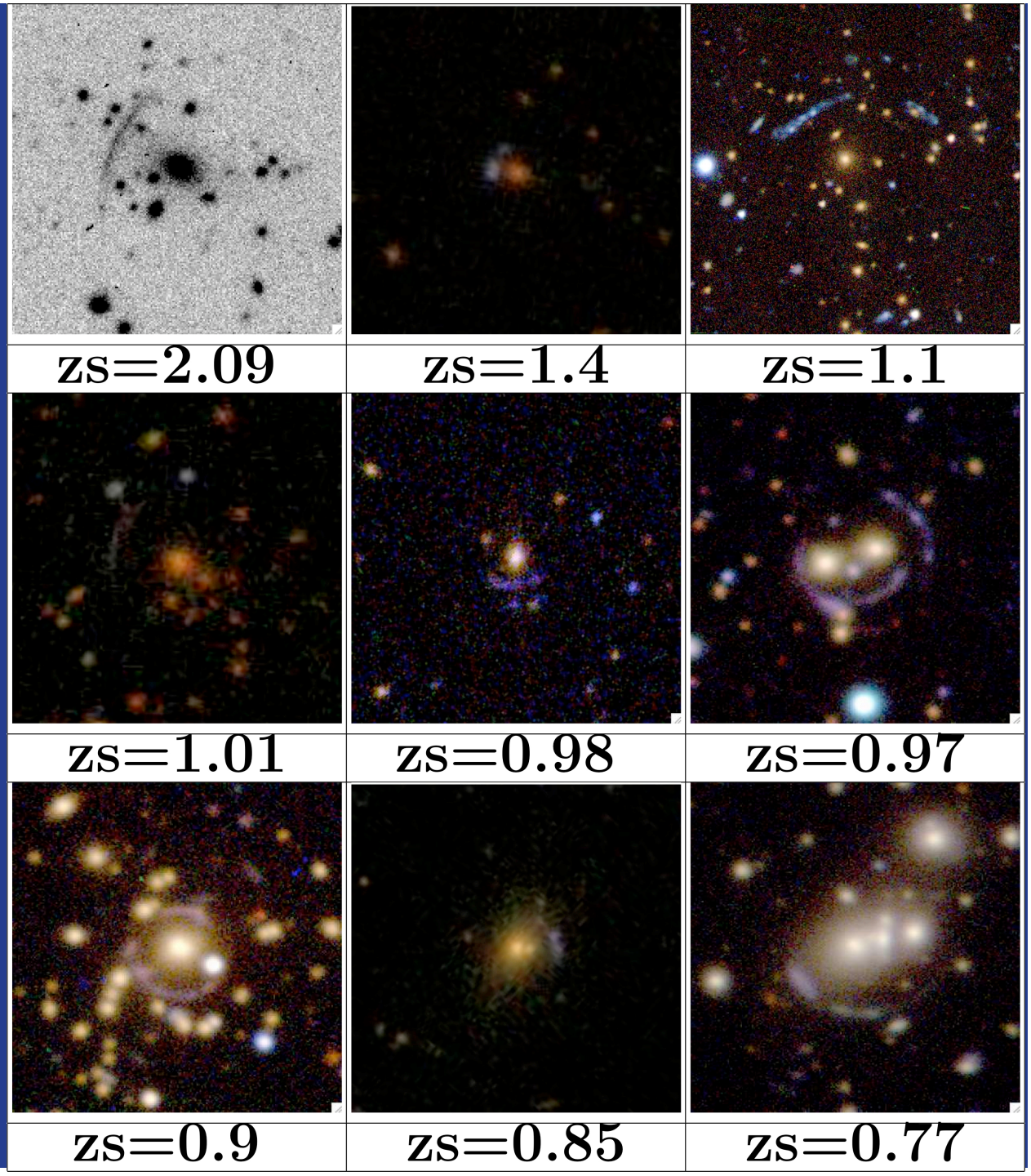
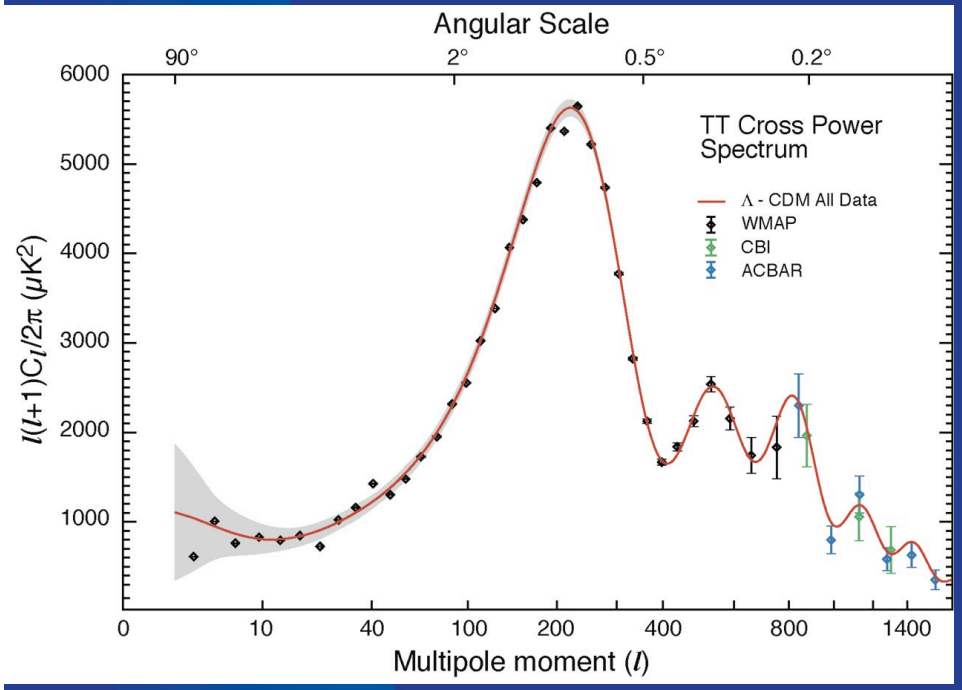


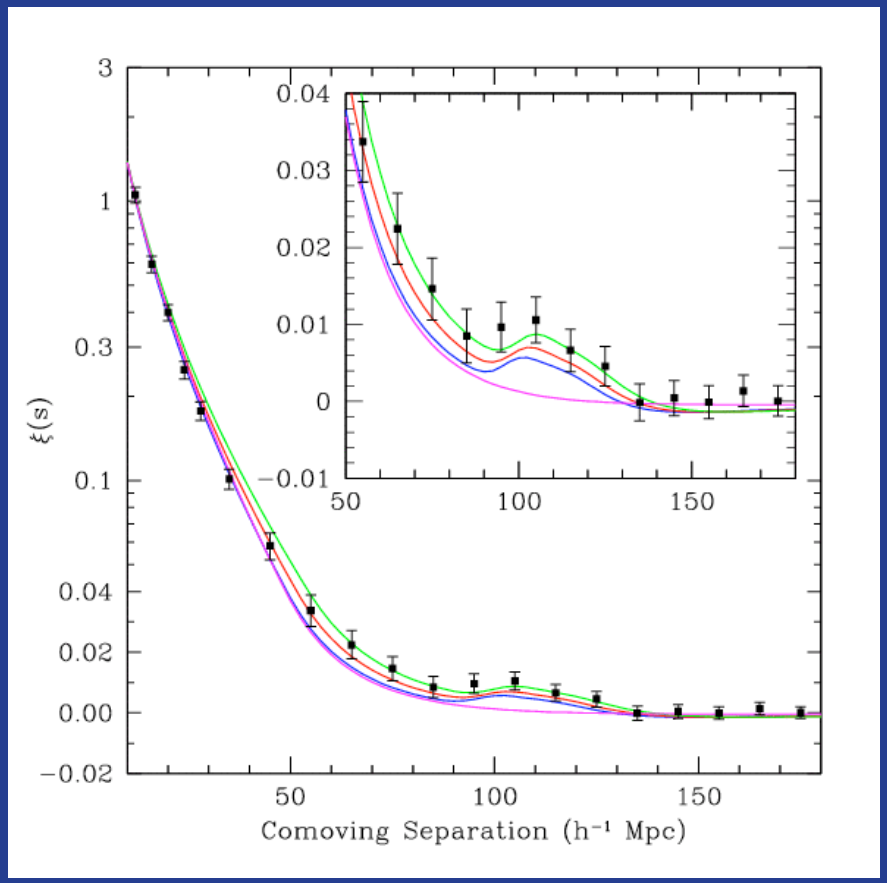
III. Baryon Acoustic Oscillations

CMB angular power spectrum



Bennett, et al

SDSS galaxy correlation function



Eisenstein et al

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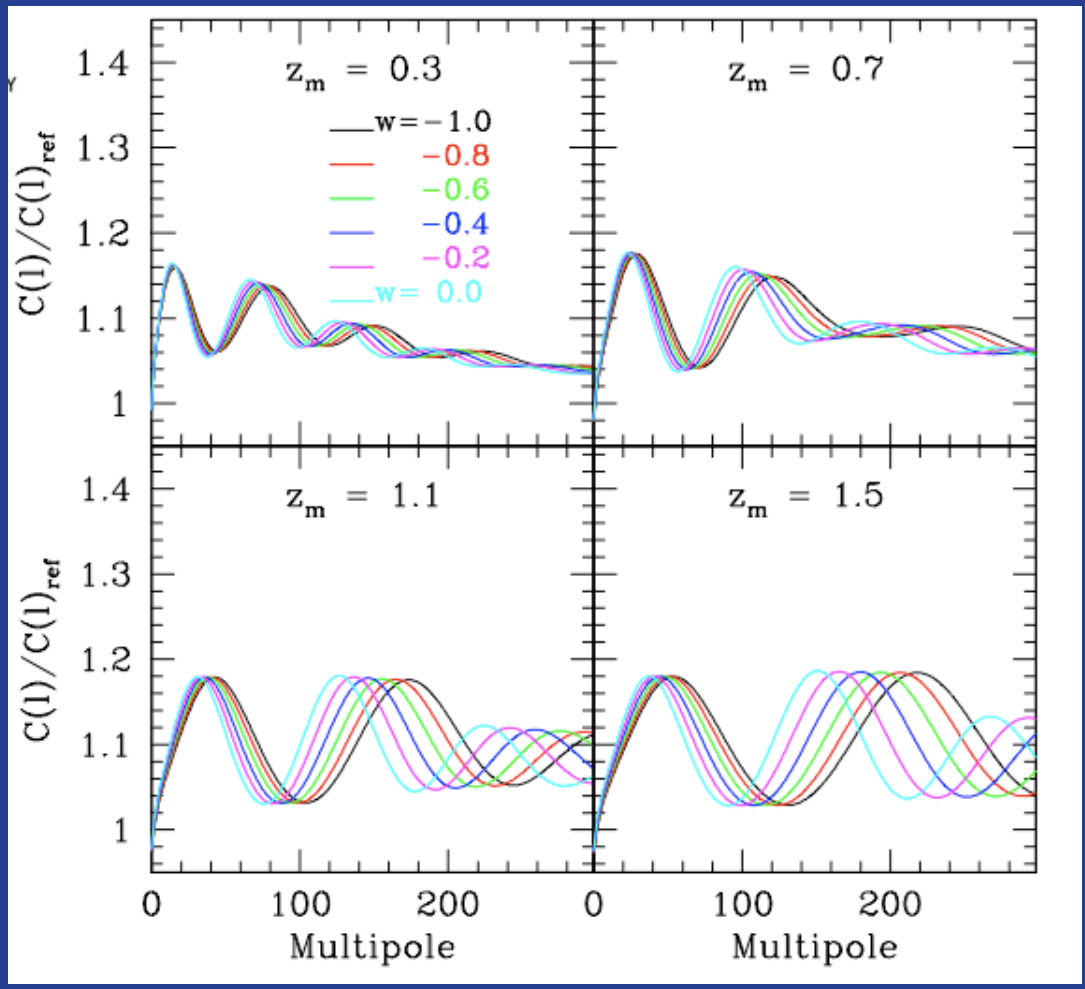
BAO Tomography in DES

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

Probe to much higher redshift than SDSS galaxies



Fosalba & Gaztanaga

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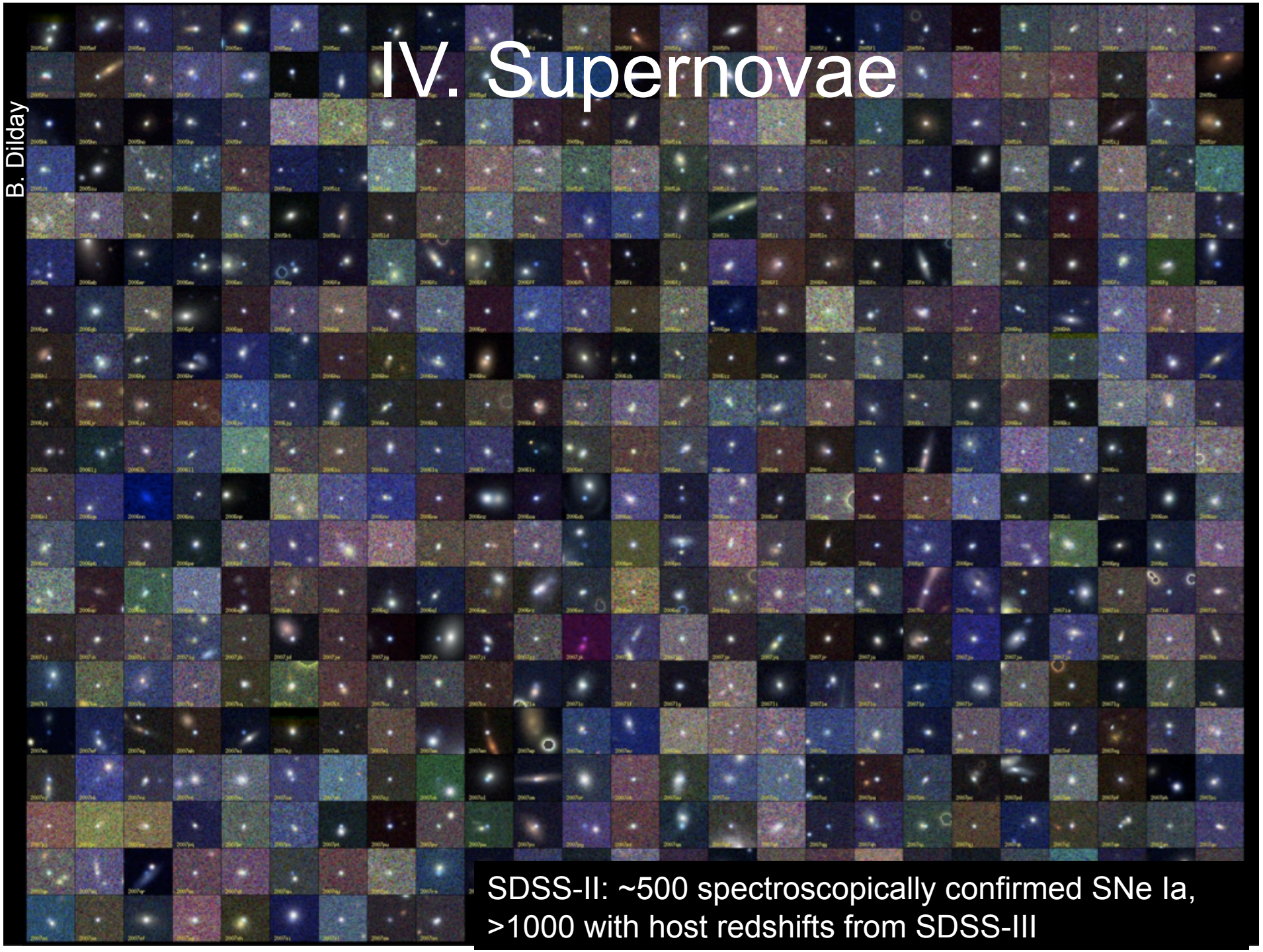
IV. Supernovae



B. Dilday

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

IV. Supernovae

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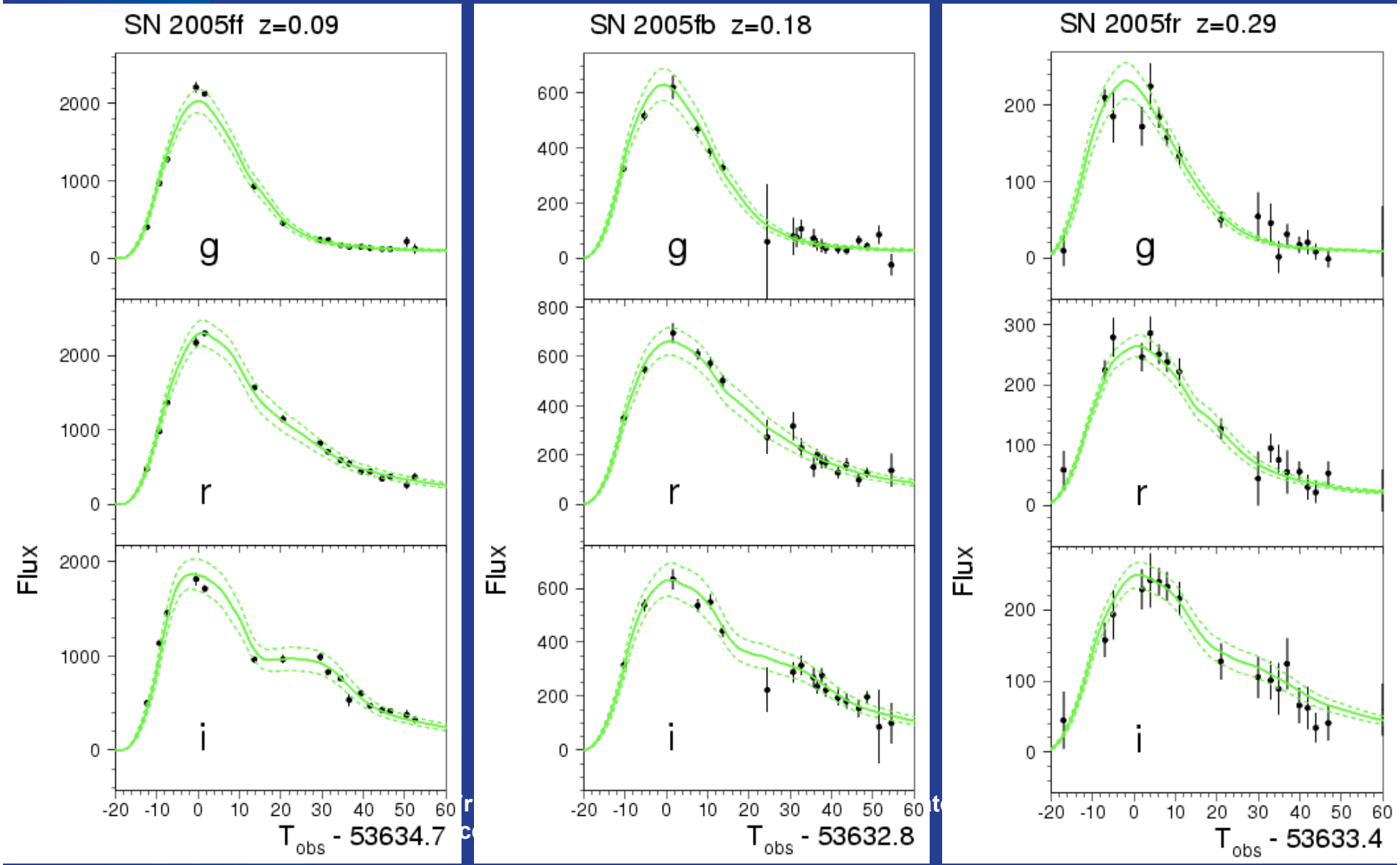
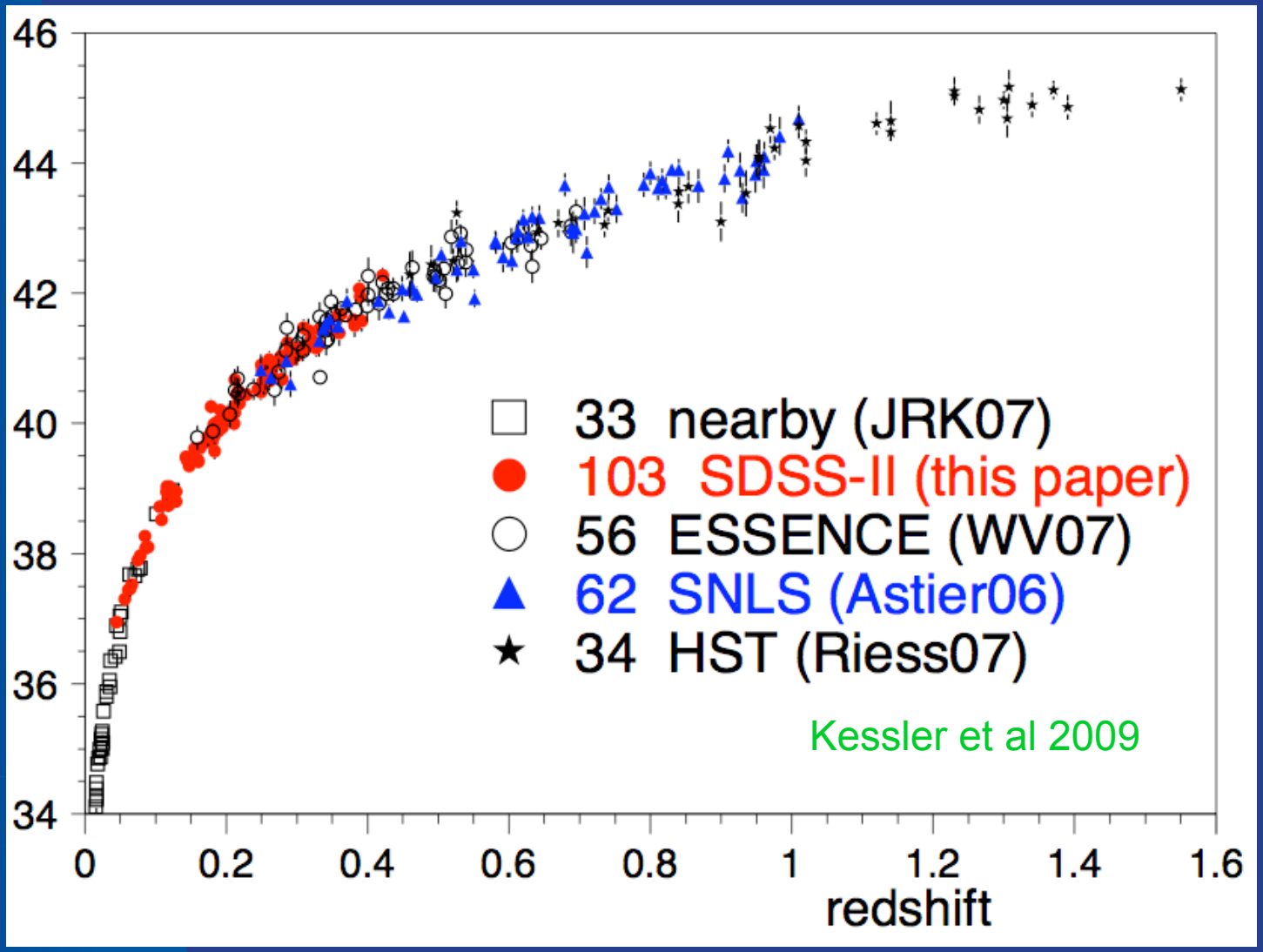
SN Ia Light Curves

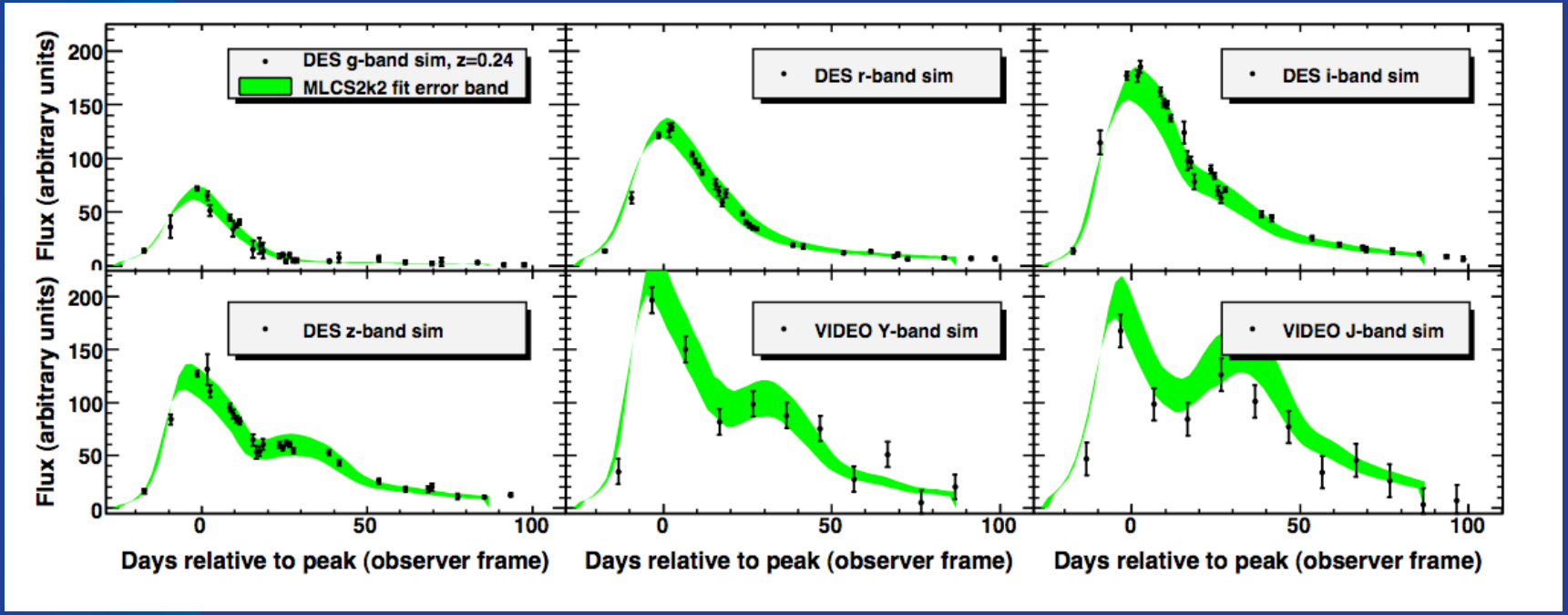
SDSS-II SN: Holtzman etal



Supernova Hubble Diagram

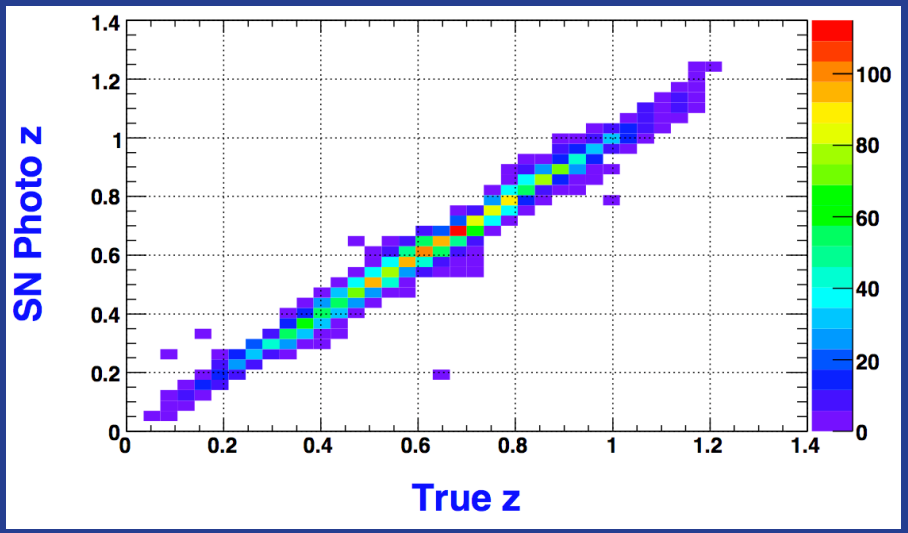


Supernovae in DES



Bernstein et al

- Broader redshift range than SDSS SN
- Higher S/N in red passbands than SNLS
- Add NIR from VISTA VIDEO survey
- Factor ~10x statistics vs. current samples



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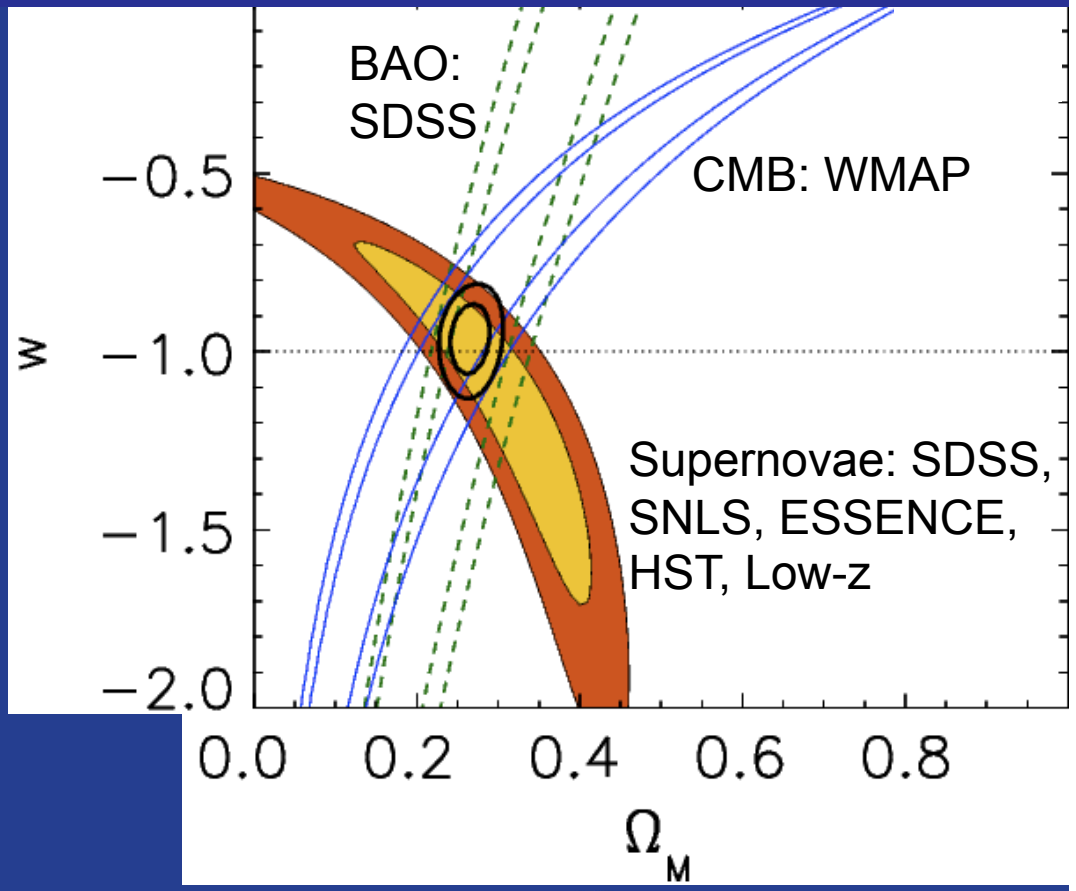
Current Constraints on Dark Energy

- ~10% precision on constant *w*
- Systematic errors (not shown) at least as large as statistical errors
- Constraints on time-dependent *w* or modifications of gravity are currently weak

Kessler et al 2009

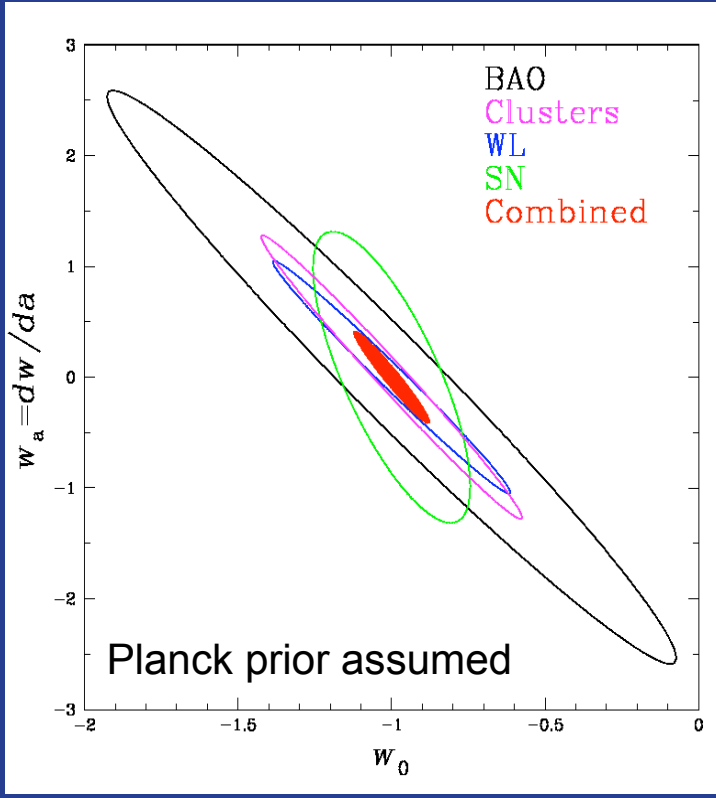


DES Science Summary

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**
  - >15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Forecast Constraints on DE Equation of State



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

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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, STFC, MEC, FINEP, Excellence Cluster, collaborating institutions

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DES-Brazil Dark Energy Survey

LMU

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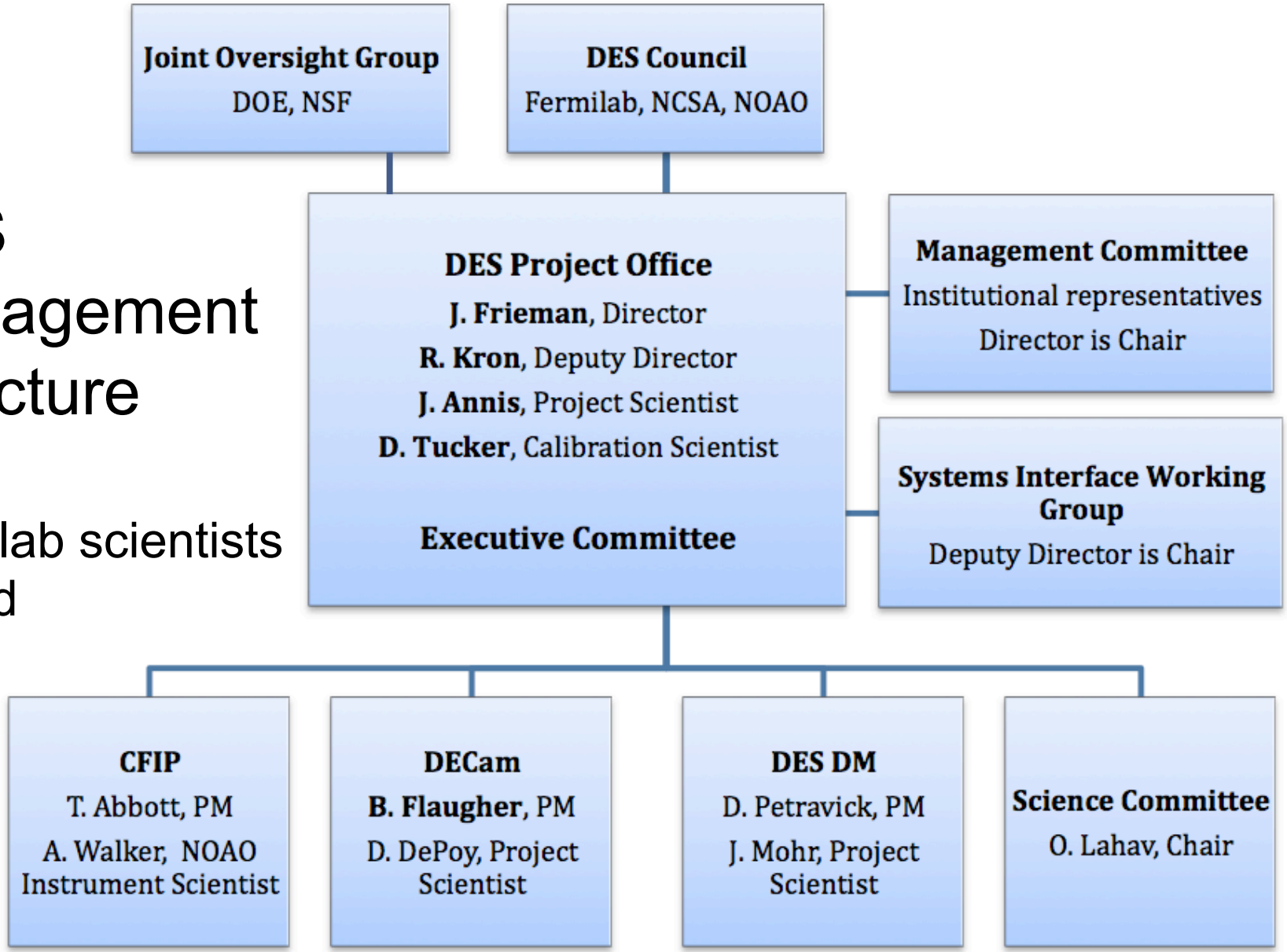
Project Structure & Timeline

- 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 2004-8
    - Camera construction 2008-11; currently ~80% complete
    - Final construction, testing, integration now on-going
    - Ship components to Chile: Sept. 2010-June 2011
    - Installation: Jan.-Oct. 2011 (imager Aug.-Oct.)
    - First light on telescope: Oct. 2011
    - Commissioning: Oct. 2011-Jan. 2012 (FY12)
    - Survey begins: 2012

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)

Fermilab Scientists on DES

S. Allam: Calibration, Strong Lensing
J. Annis: Project Scientist: Requirements, Survey Strategy & Observing Plan, Science Verification, Clusters
L. Buckley-Geer: Computing, SISPI, Strong Lensing Working Group co-chair
T. Diehl: CCD Packaging & Testing (L2 Manager), Telescope Simulator, Strong Lensing
S. Dodelson: Theory, Weak Lensing, Modified Gravity tests
J. Estrada: CCD Testing (L2 Manager), Cluster Correlations
D. Finley: Shipping, Integrated Schedule, Supernovae
B. Flaugher: DECam Project Manager
J. Frieman: DES Project Director, Spokesperson, Management Committee Chair
G. Gutierrez: Opto-mechanical alignment
S. Kent: Optical design, Calibration, Weak Lensing
R. Kron: DES Deputy Director, Systems Interface Working Group Chair, Operations plan
H. Lin: Image Simulations, Photometric Redshift WG co-chair, Data quality, Clusters, Lensing
J. Marriner: Supernova Working Group co-chair, supernova pipeline
W. Merritt: DECam Deputy Project Manager
J. Peoples: past Project Director, PreCAM management
V. Scarpine: CCD and DECam testing, weak lensing, clusters
A. Stebbins: Theory, Weak Lensing, Clusters
C. Stoughton: Image Simulations, Weak Lensing
D. Tucker: Calibrations Scientist, Strong Lensing, Milky Way
W. Wester: CCD electronics
B. Yanny: Data and Data Challenge Coordinator, Milky Way WG co-chair

Currently ~11.5 FTEs 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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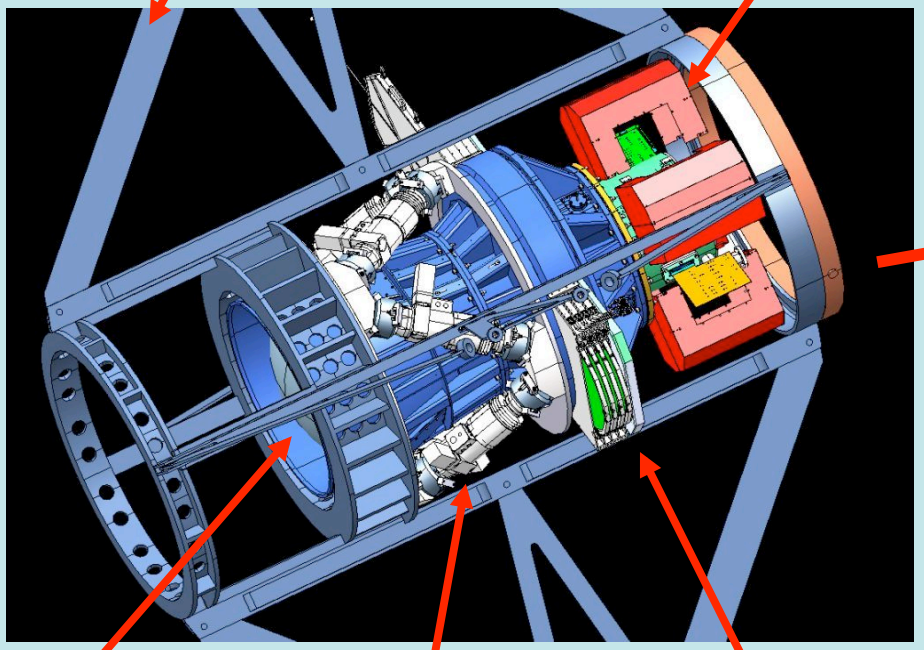
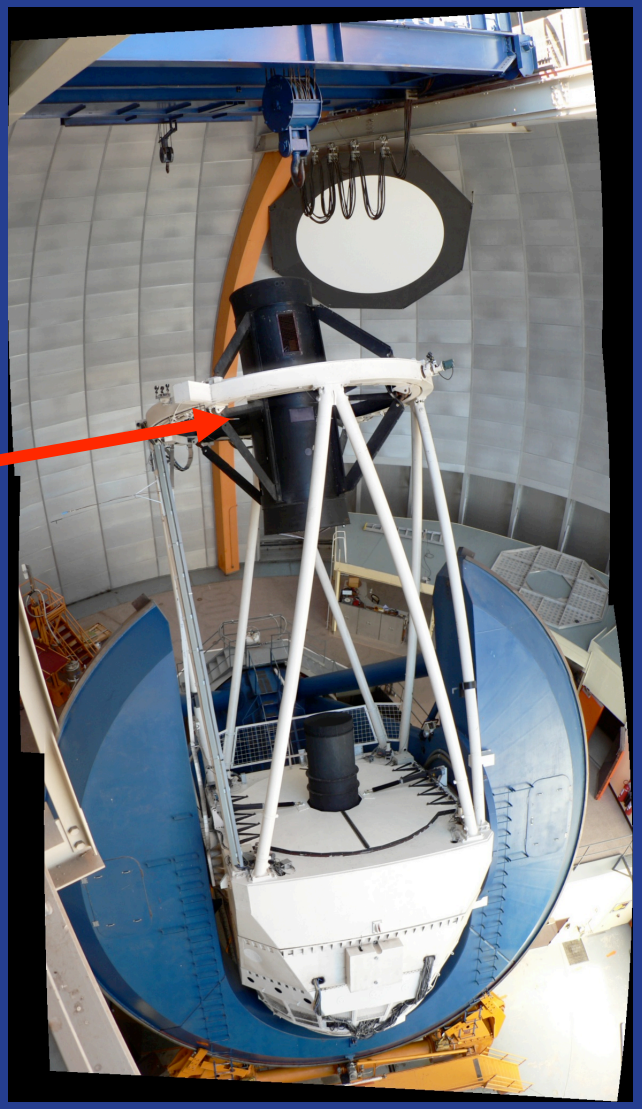
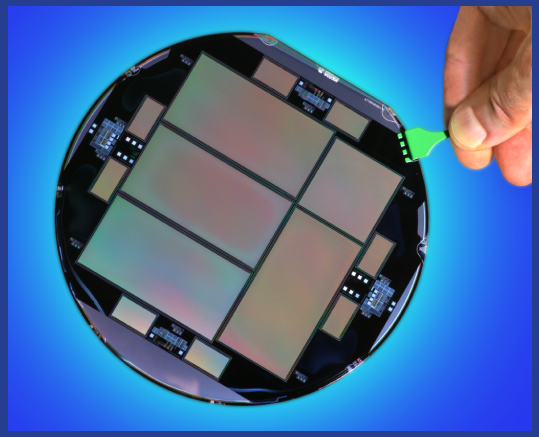
DES Instrument: DECam

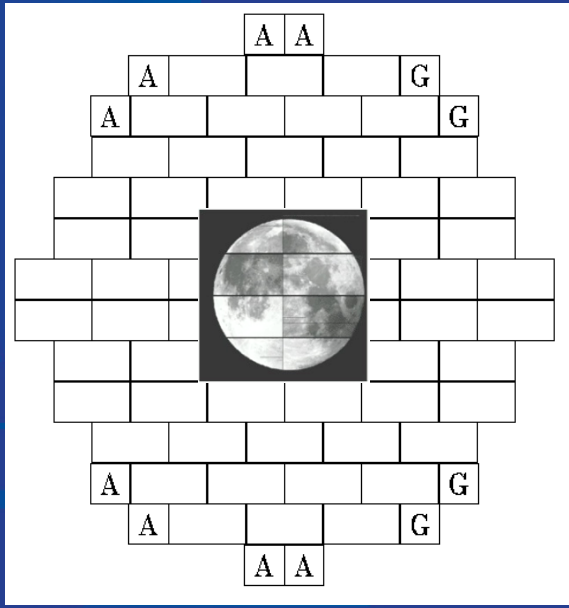


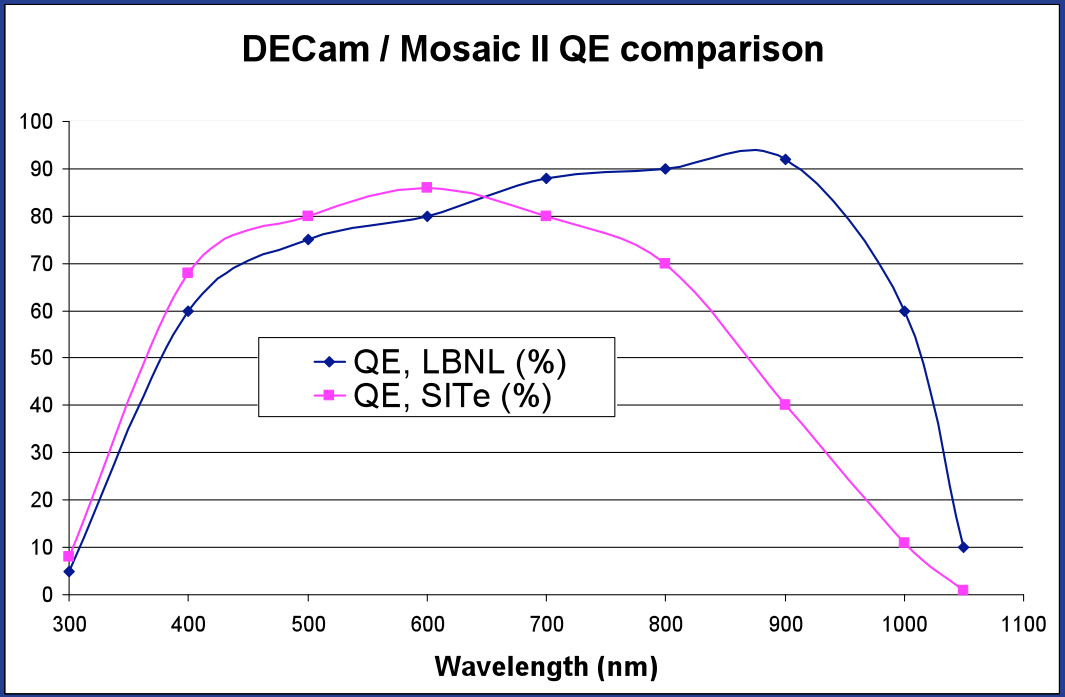


DECam CCDs



- 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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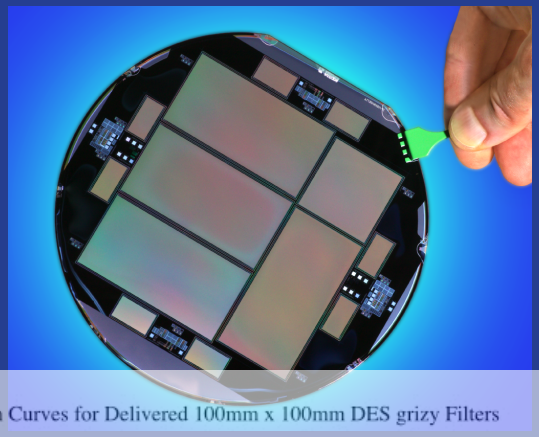

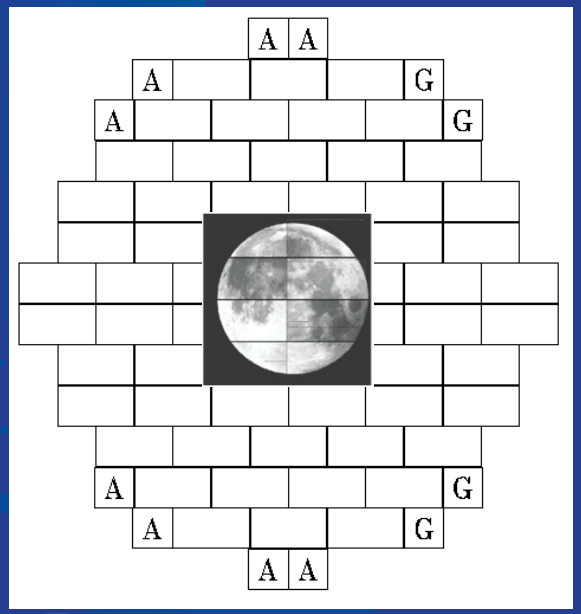

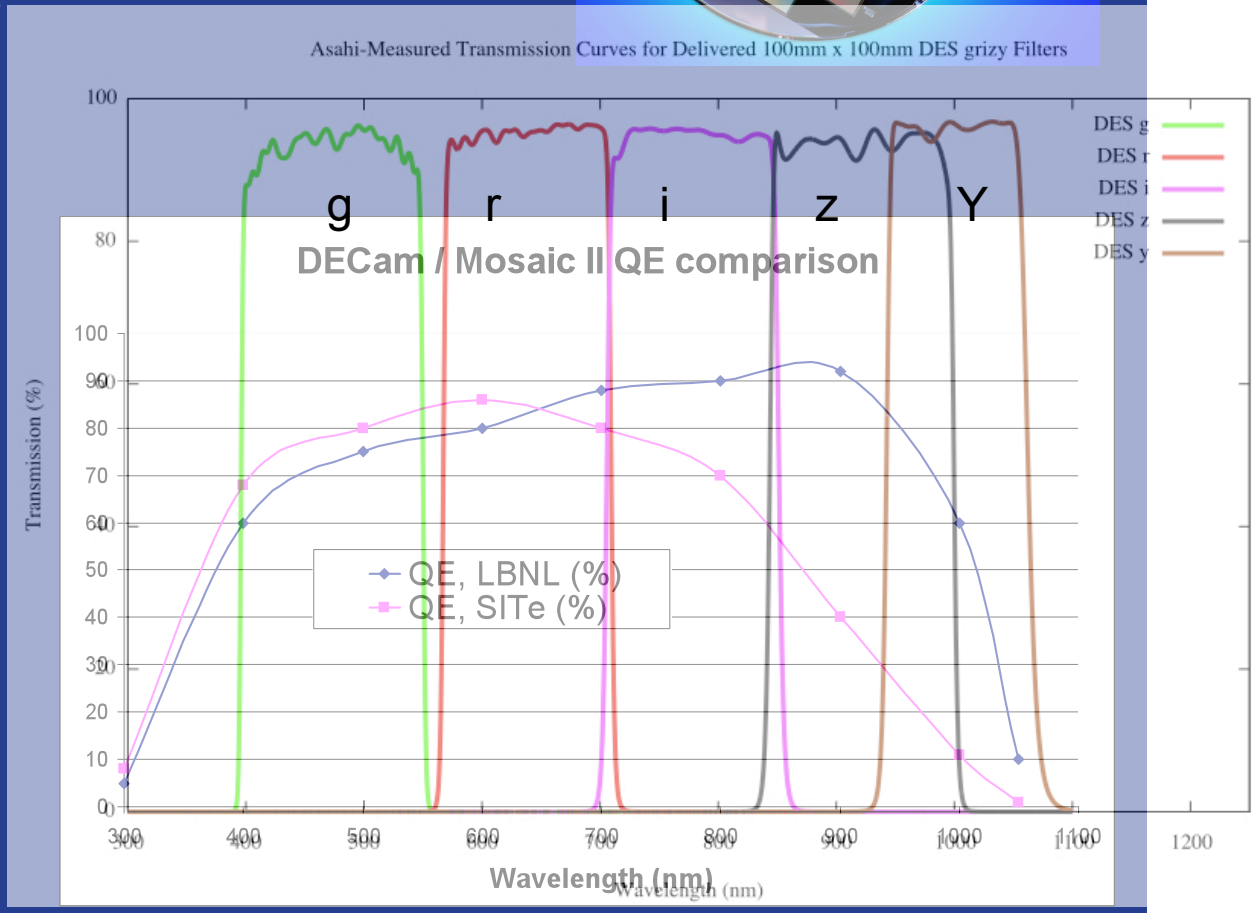

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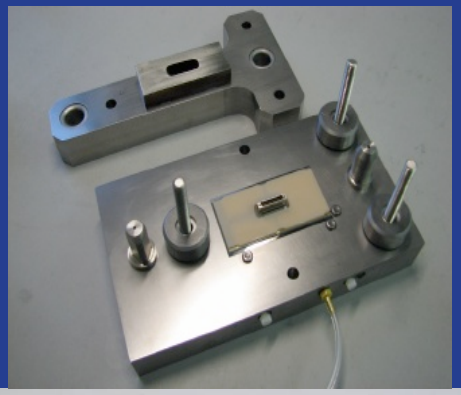
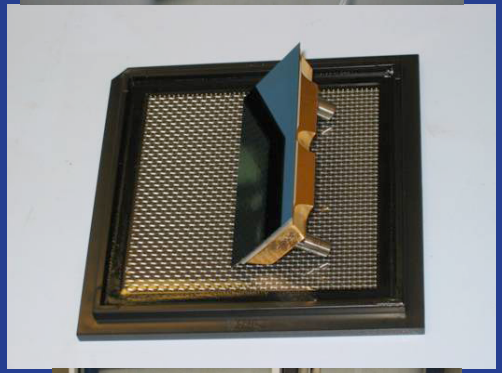
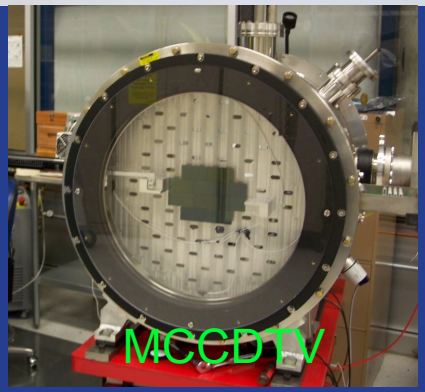
CCD Packaging and Testing at Fermilab

- 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
- Production Packaging started Nov. 2008
- As of 9/17/10:
  - 255 2kx4k CCDs packaged and tested
  - 115 are Science Grade, ready for the focal plane
  - 62 + 10 spares are required
  - Packaging will finish in a few weeks. Expect ~125 SG devices: spares in case of damage during final installation/shipping
- Also have 24 science grade 2kx2k devices; need 12 plus spares. Packaging of 2kx2k devices complete.







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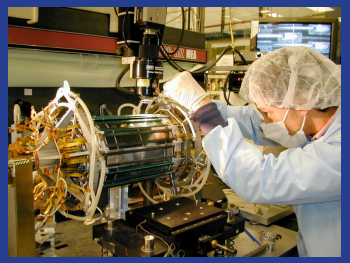
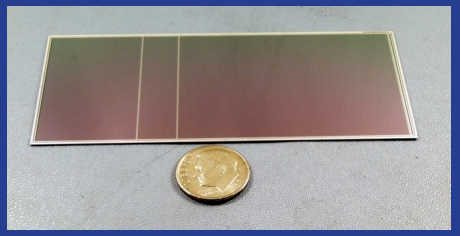
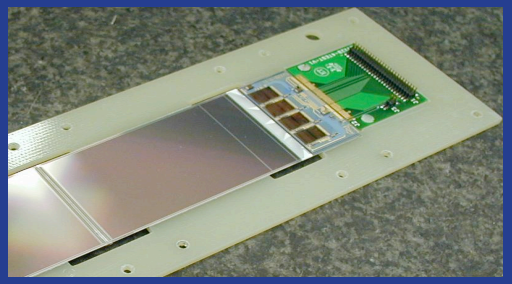
Exploiting Fermilab's Technical Resources

- DECam construction: natural extension of Fermilab expertise
  - PPD Mechanical Engineering Dept.
    - Structural and cryogenic experience
    - Silicon Vertex Detector design and construction
  - PPD Electrical Engineering Dept.
    - Silicon Vertex Detector experience, high-density low-noise electronics
  - CD Experimental Astrophysics group (EAG)
    - SDSS experience



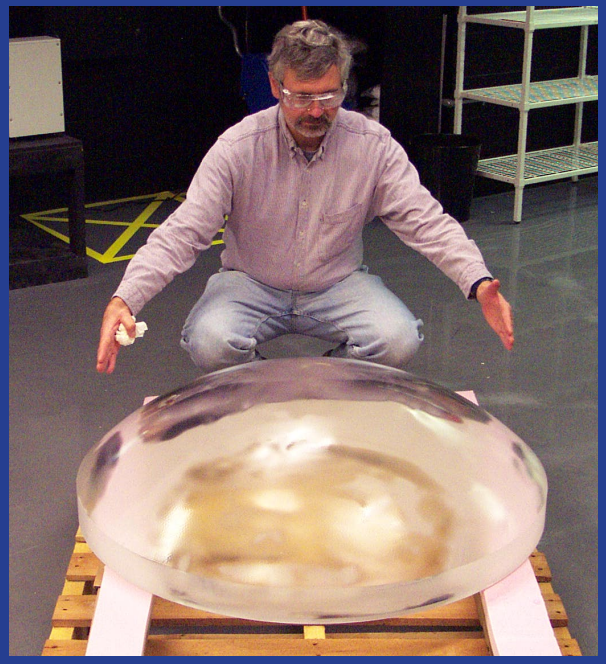


- Silicon Detector Facility (SiDet)
  - Experience from construction of SVDs for Collider experiments at Fermilab and LHC
  - Clean room space
  - Experienced technical staff
  - Extensive metrology facilities and experience
  - Micron precision assembly, wirebonding, thermal management

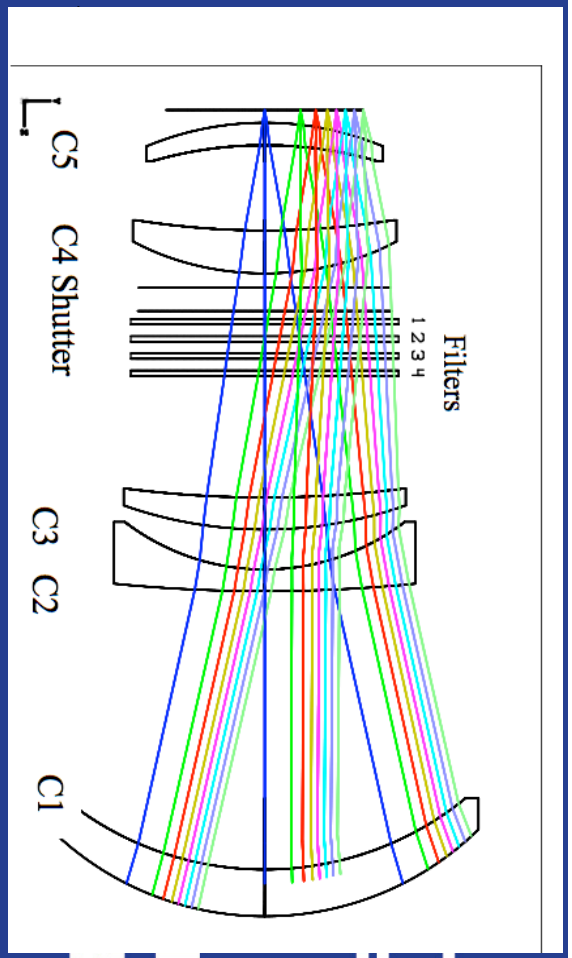


Optics

- Field of view: 2.2^{o} diameter
- Status
  - C2, C3, C5 delivered June, July
  - C1, C4 expected Oct. 2010
- Fermilab contributed to optical design in partnership with Universities

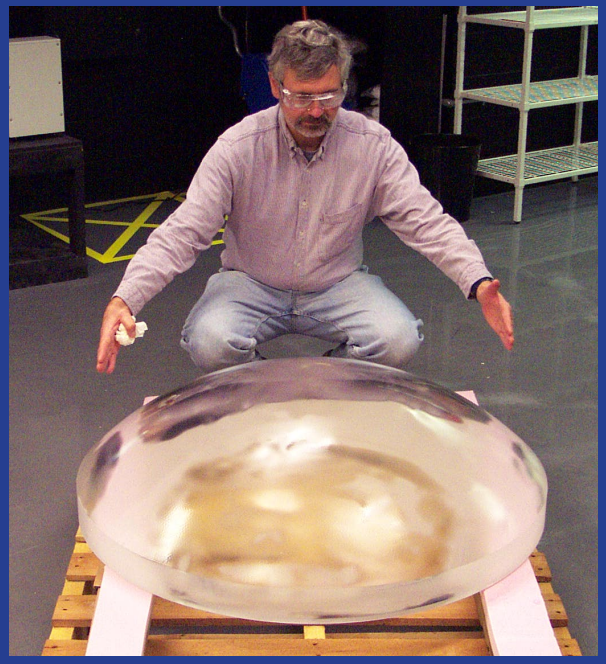


S. Kent (FNAL)



Optics

- Field of view: 2.2^{o} diameter
- Status
  - C2, C3, C5 delivered June, July
  - C1, C4 expected Oct. 2010
- Fermilab contributed to optical design in partnership with Universities



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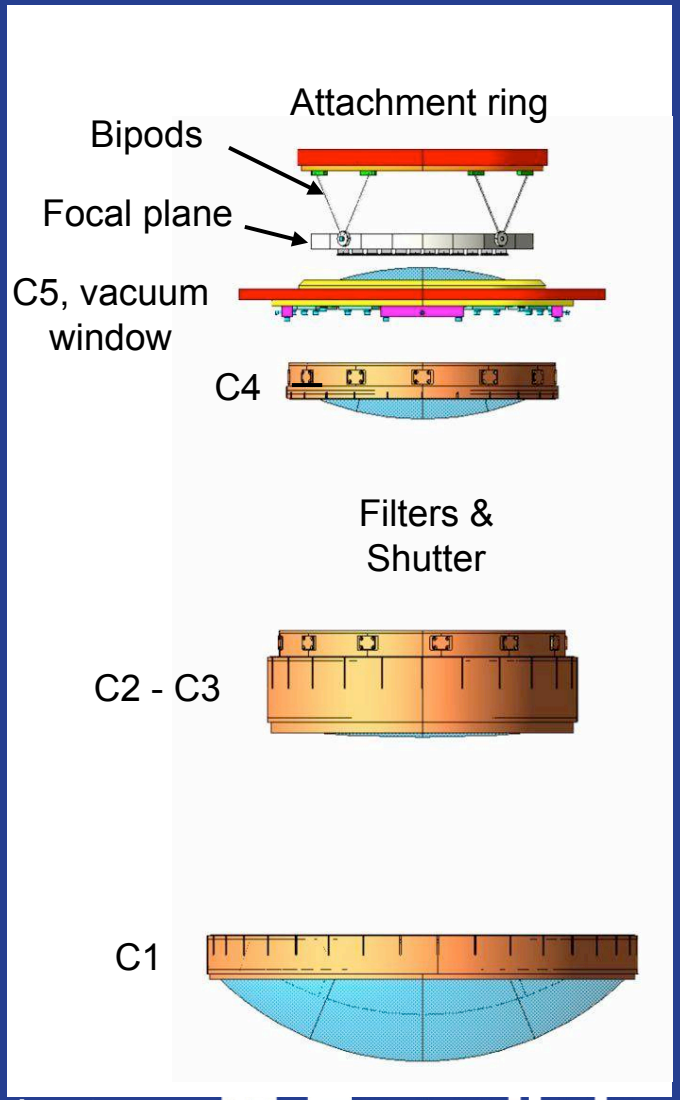

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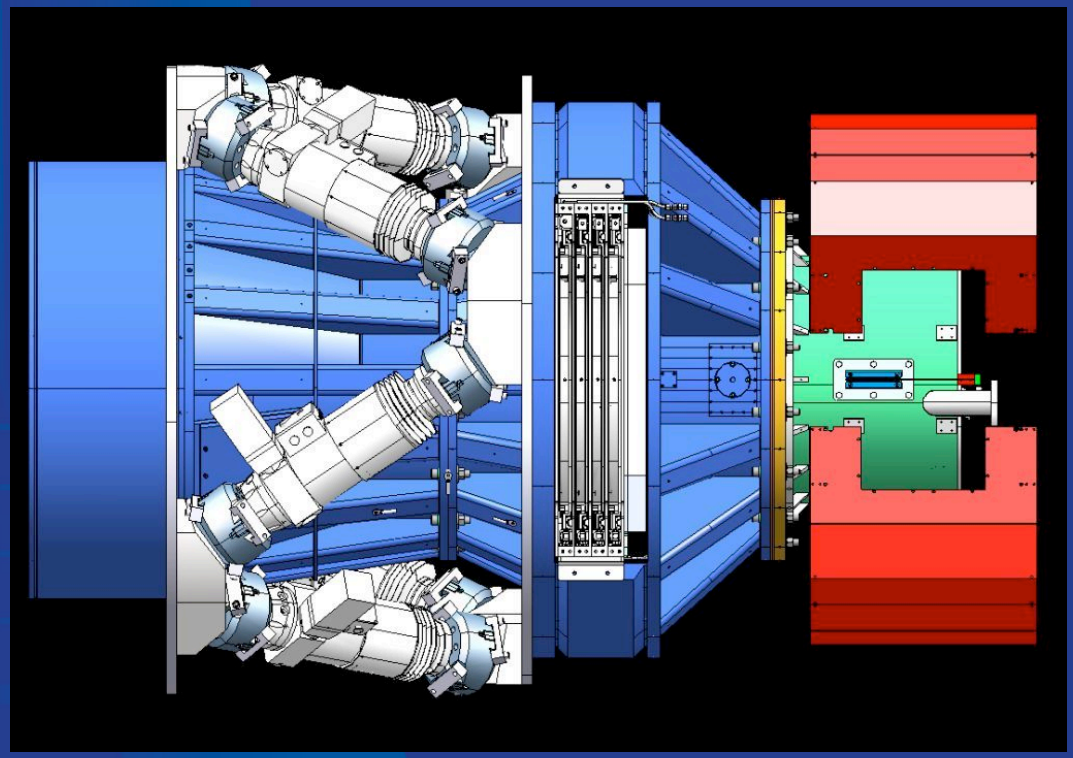
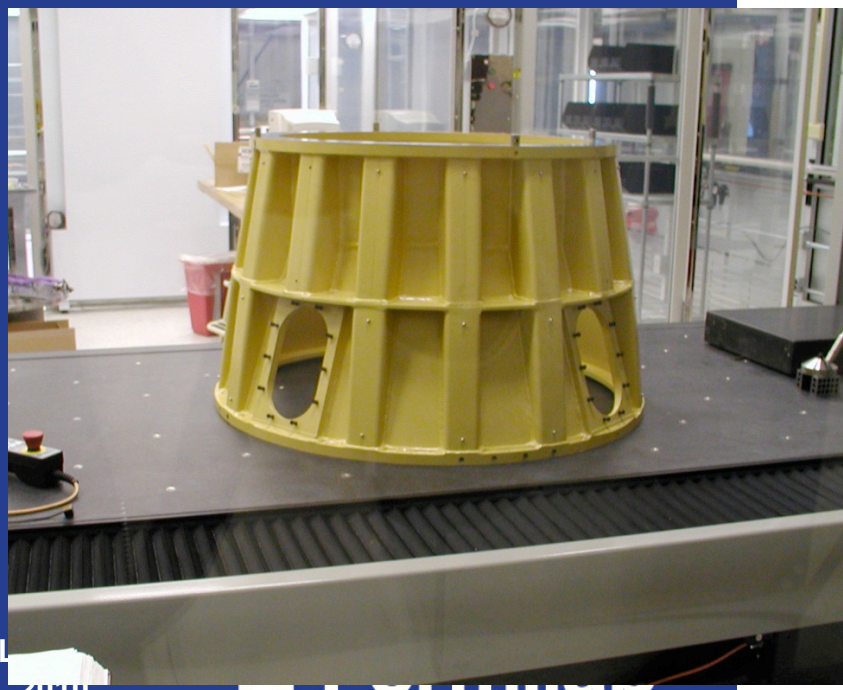
Fermilab

Fermilab mechanical engineering





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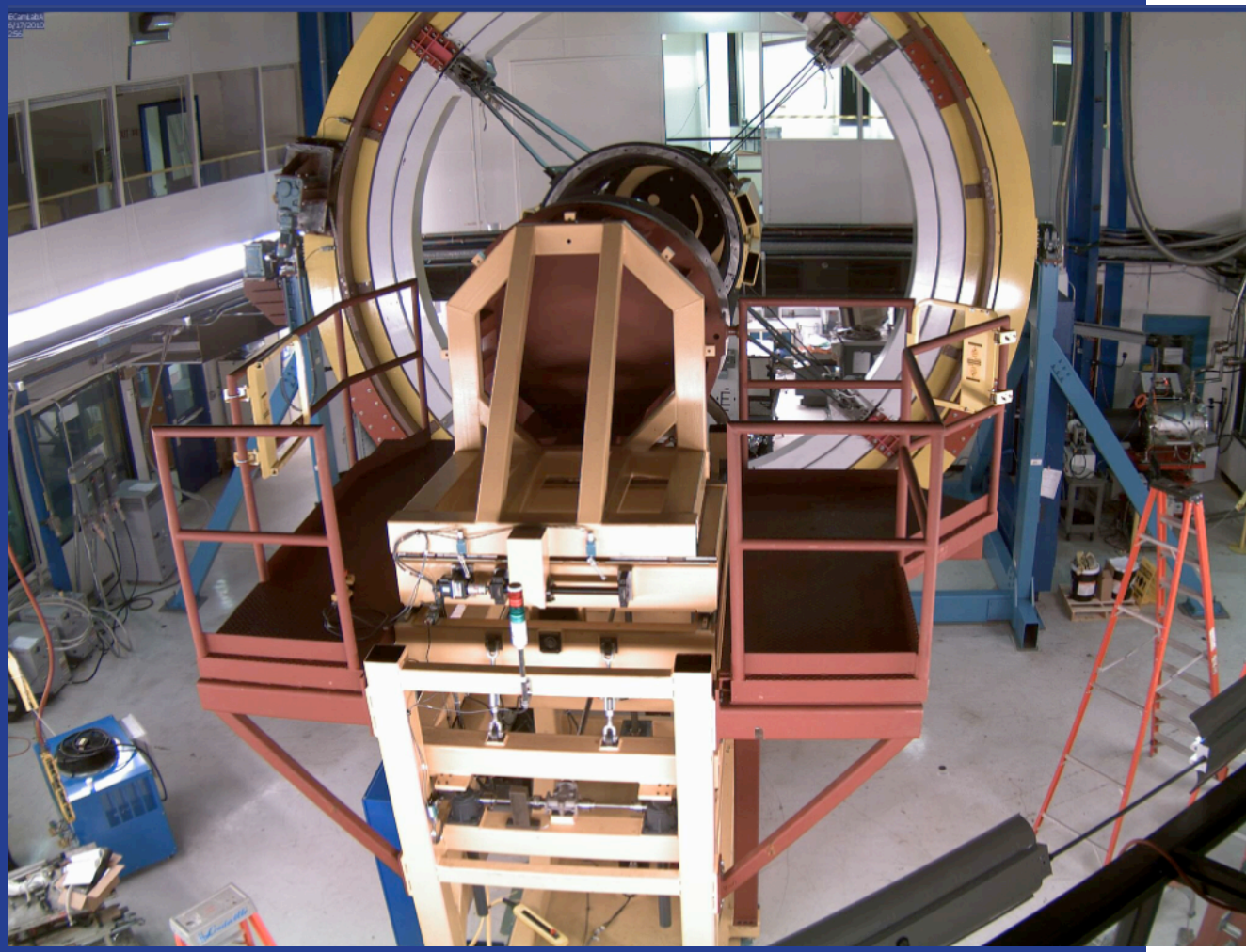
Telescope Simulator at Fermilab

- Enabling 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

http://decamlaba.fnal.gov



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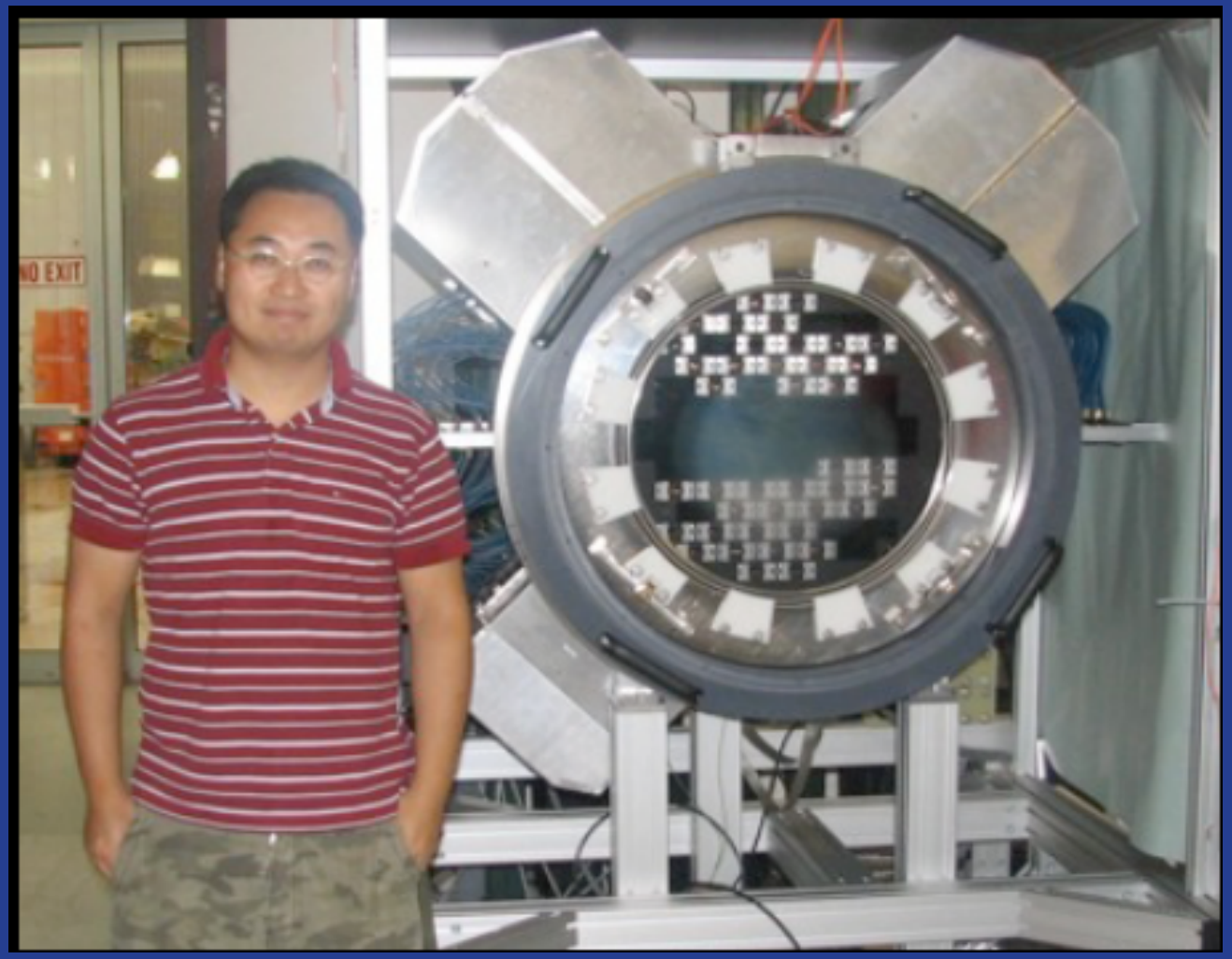
http://decamlaba.fnal.gov

DECam Vessel

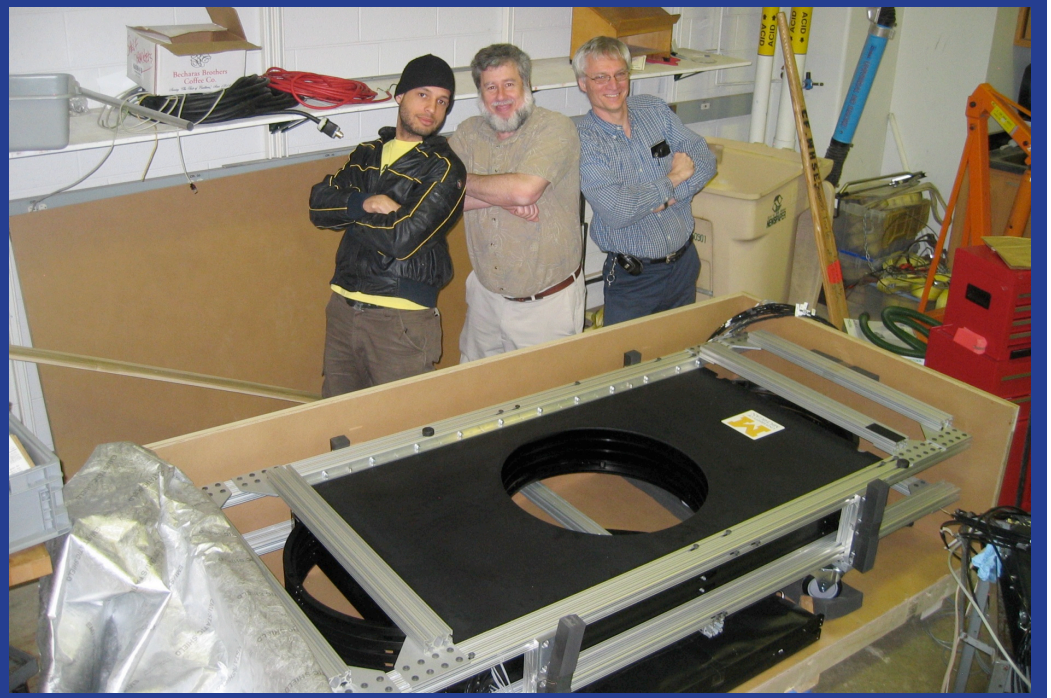
Fermilab postdoc Jiangang Hao with DECam

Focal plane populated with engineering-grade CCDs for testing



Major components delivered


Hexapod


Filter Changer: Michigan

Decam600

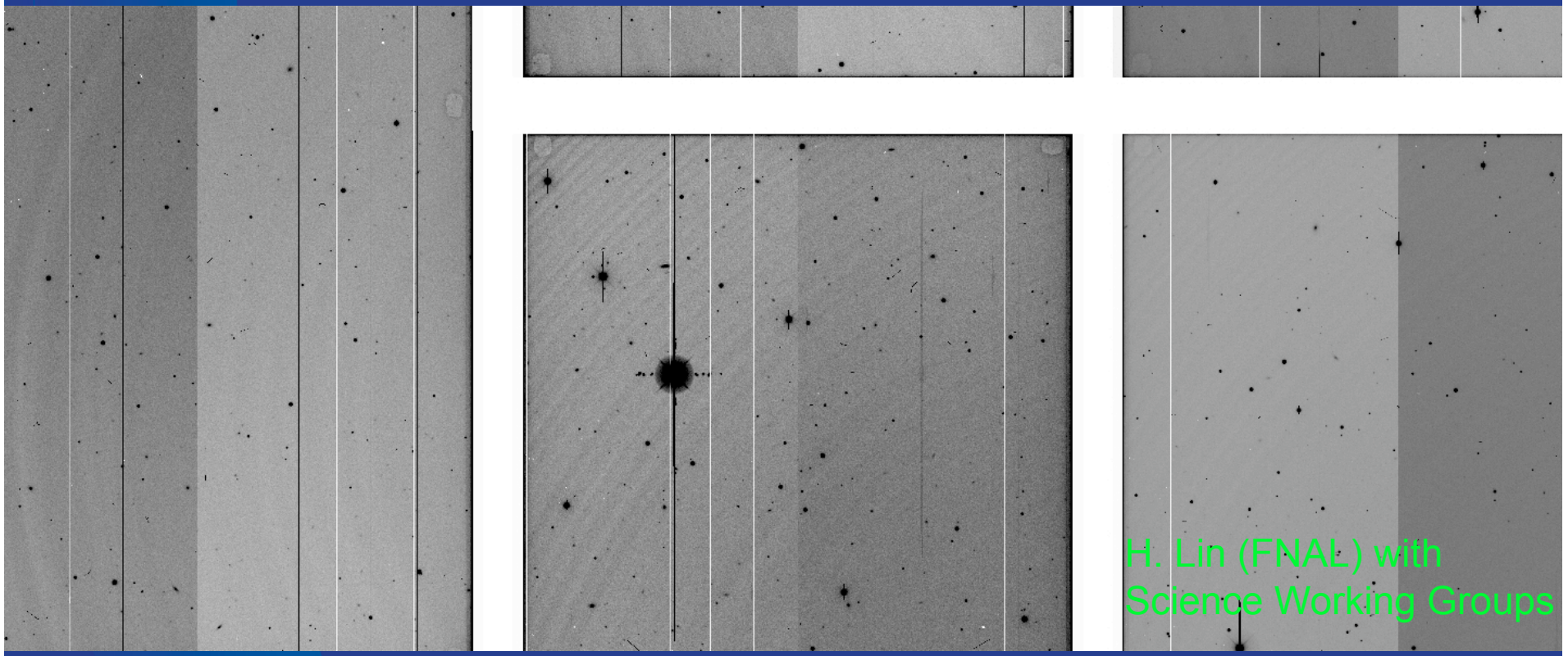
a Bonn Shutter for

the Dark Energy Survey camera

AIfA Instrumentation Group
Klaus Reif
(Vers. 1.0, April 2010)


Cloud Camera: SLAC

DECam Image Simulations:
test Data Management System



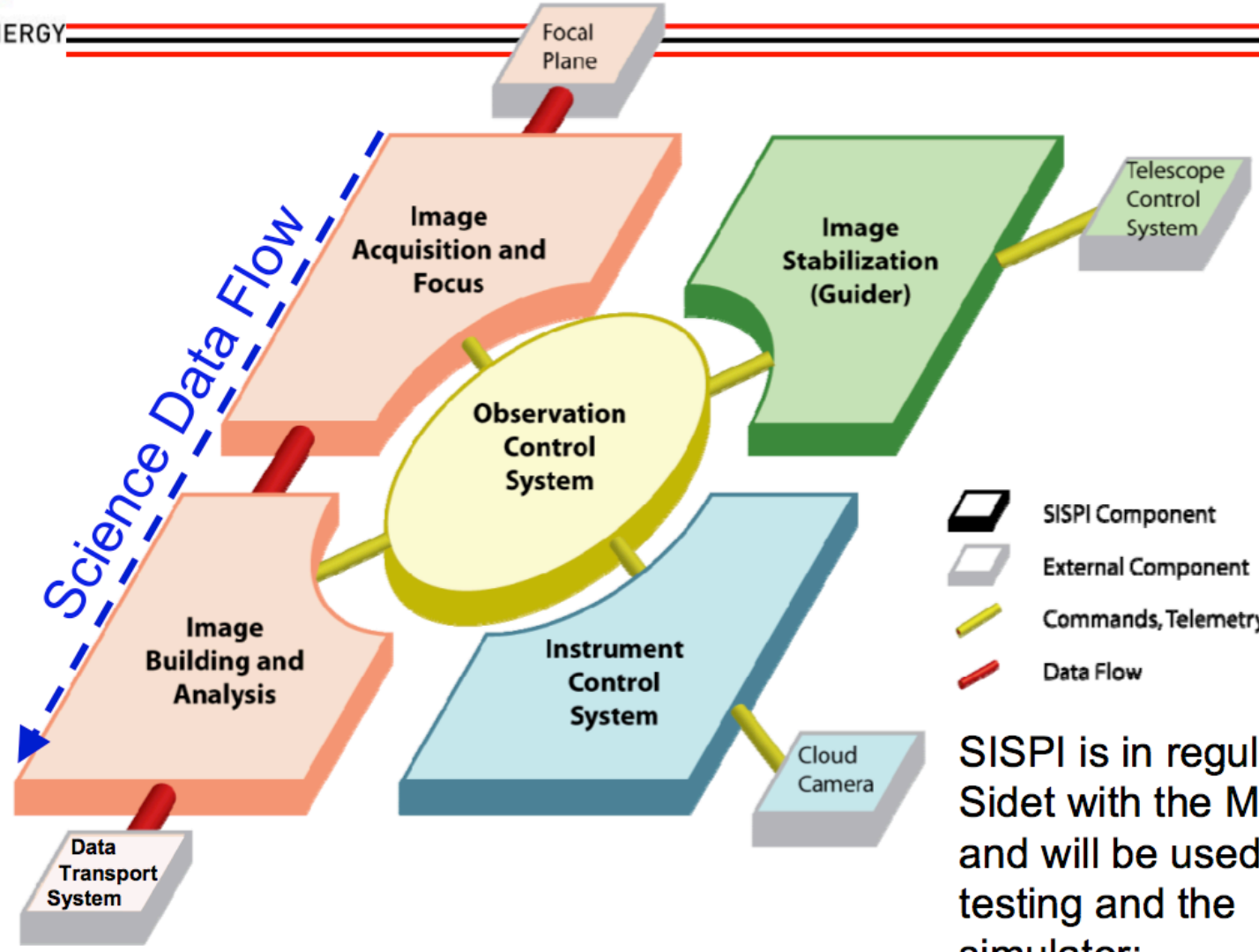
H. Lin (FNAL) with Science Working Groups

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

Survey Image System Process Integration (SISPI) WBS 1.6

UIUC, OSU, FNAL, CTIO, ANL, Spain, SLAC, Santa Cruz

DARK ENERGY SURVEY

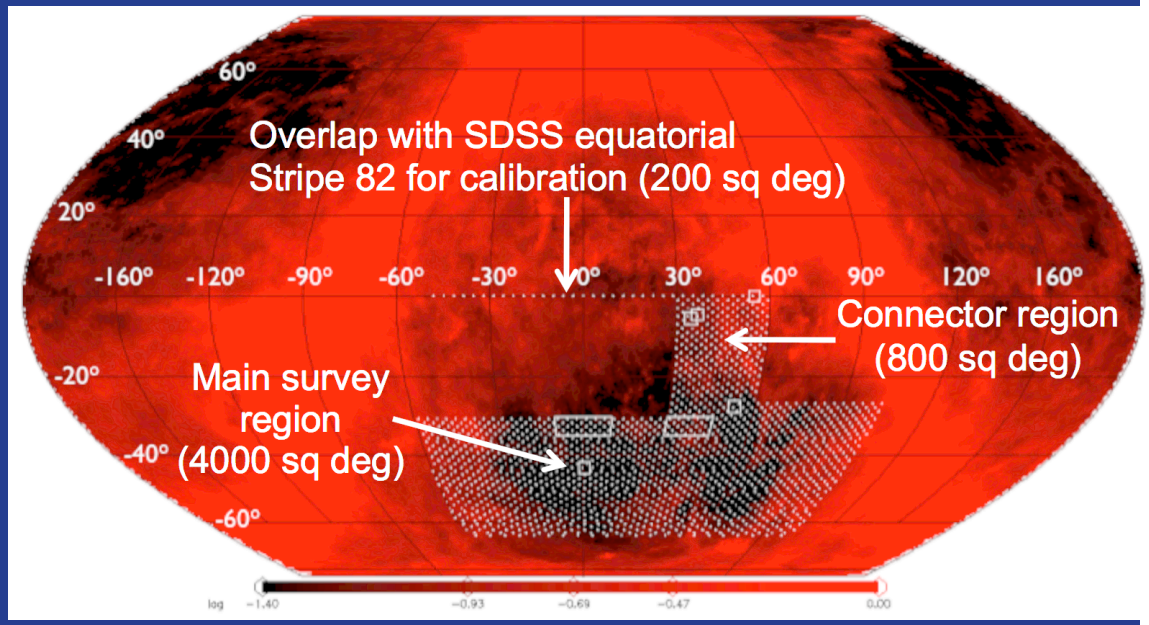


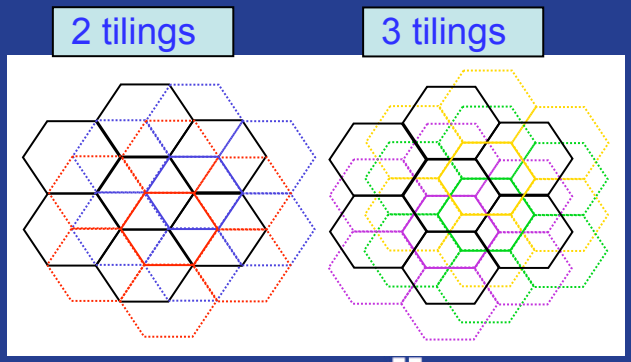
SISPI is in regular use at Sidet with the MCCDTV and will be used for imager testing and the telescope simulator:

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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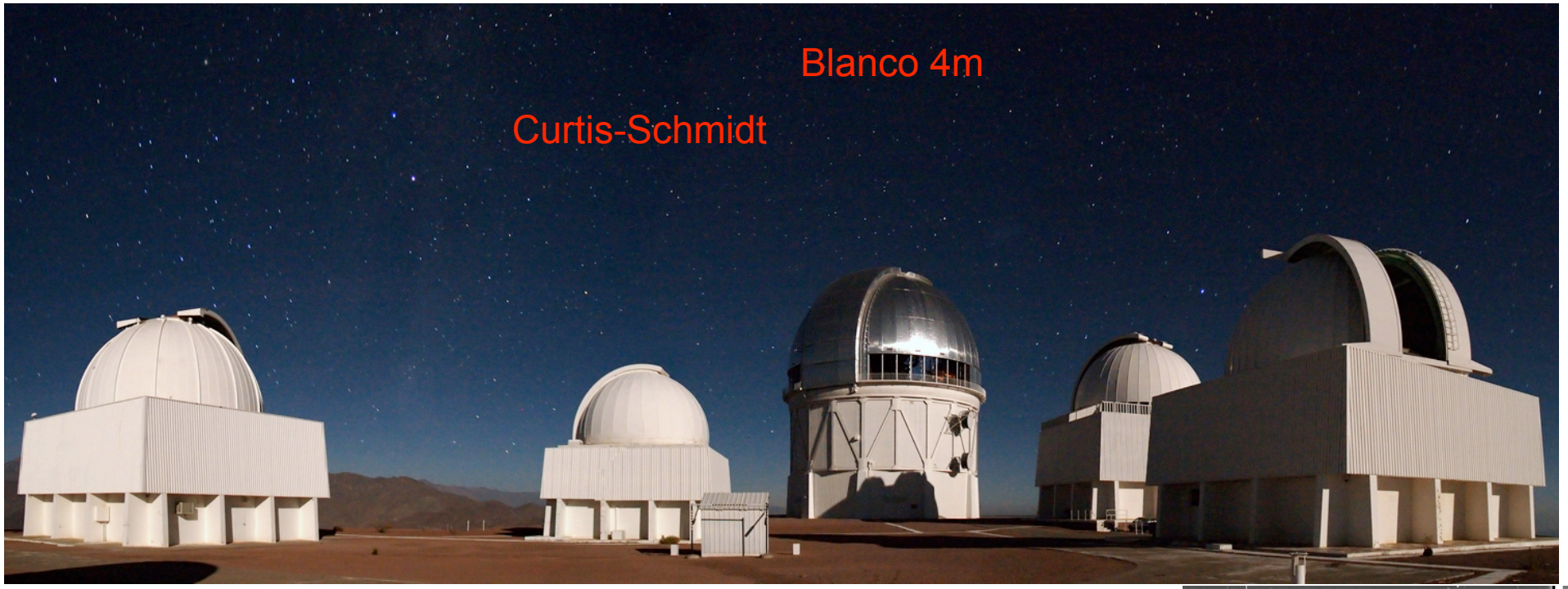
Fermilab



PreCAM:

- Calibration star network
- built by Argonne, uses 2 DECam CCDs
- Modifications to Curtis-Schmidt by Texas A&M
- Managed by J. Peoples and D. Tucker (FNAL)
- DES scientists from across the collaboration involved in commissioning


preCAM on the Curtis-Schmidt

DES Transition to Operations

- Over the next year, the three construction projects and the Science Working Groups will be integrated into a coherent whole, as we transition from hardware integration, software development, and testing to installation, commissioning, survey operations, and science analysis.
- We have reorganized DES Project management structure and created an Executive Committee to focus on integration. This structure will evolve further as we head into operations.
- The DES Memorandum of Understanding, Operations Plan, Operations Basis of Estimate, Installation Plan, and Commissioning Plan describe installation, commissioning, and operations activities and the institutional division of responsibilities.

DES Operations in FY11

- Although CTIO will be in charge of installation (FY11) 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 all these activities.
- Once DECam components are checked out in the Blanco dome and ready to install, they move from DECam project funding to DES operations support. For installation, operations must start in FY11.

FY11 operations request based on `bare bones' budget, with no contingency. Field Work Proposal in preparation at DOE request

FY11 Cost Estimates for DES Operations

Table 1. Operations Cost Request and Shortfall in $K

Requested	FY11 $K	Explanation
Technical Labor (PPD + CD)	1261	Camera support + Computing support
M&S (Technical) Equipment	475	Technical Equipment (Mostly Mirror Site)
M&S (Technical) Travel	510	Technical Travel
Non - Fermilab (Detailed in Table 2)	304	Travel & Technical Labor
Total Requested	**2551**	
Currently Budgeted (PPD + CD)	FY11 $K	
Technical Labor	629	
M&S	247	
Total Budgeted	**876**	
Shortfall	**1674**	

FNAL

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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  - Tom Carter, on sabba
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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

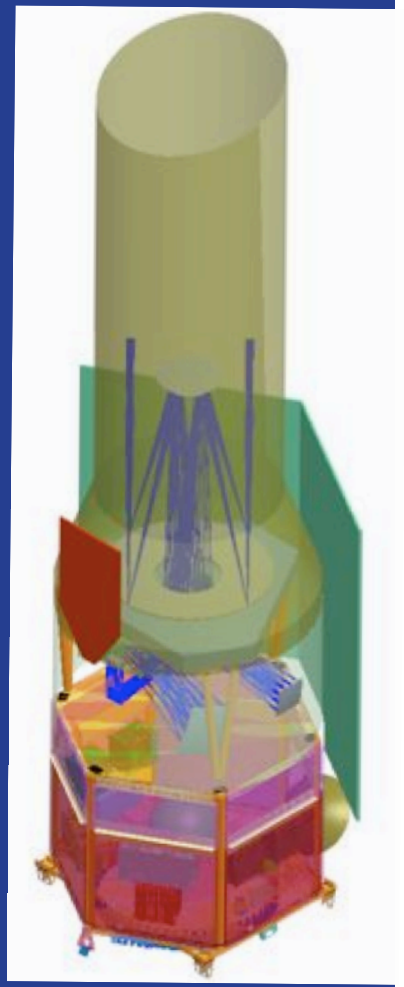
John P. Holdren
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

Options Beyond DES

- JDEM/WFIRST
- LSST
- DESpec
- BigBOSS
- CRT: 21 cm Intensity Mapping

JDEM/WFIRST

- WFIRST Astro2010 first-ranked space mission, based on JDEM-Omega design:
  - 1.5-m telescope, HgCdTe detectors for imaging & spectroscopy, 144 Mpixels
  - Weak Lensing, BAO, Supernovae
- Fermilab joined SNAP in 2003 (16 scientists), and was active in HW design, SW, science (e.g., calibration, electronics, shielding, weak lensing)
- Current Fermilab roles on JDEM:
  - S. Kent, Deputy Project Scientist
  - E. Gottschalk, Science Operations Center
    - Working closely with DOE lead lab LBNL
    - Potential spin-off to other projects



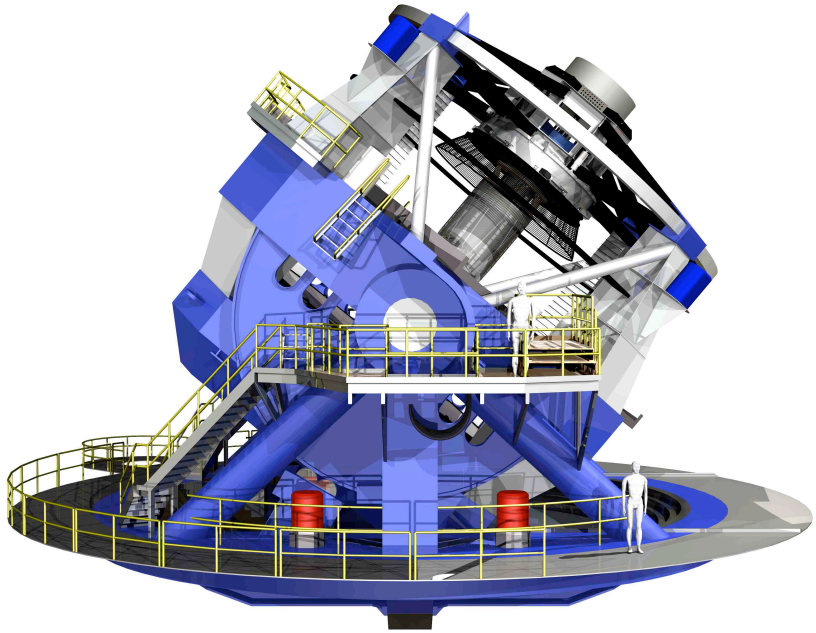
JDEM Ground System Computing
FY 10 Accomplishments

- Slitless spectroscopy prototype analysis algorithms
- Free database server software evaluations
- Discussions with NASA on architecture and ground system (w/ LBNL)
- ConOps Document for JDEM demonstration data processing system (with input from LBNL)
- Initial draft of Stakeholder requirements for JDEM demonstration data processing system (with input from LBNL)
- Data model prototype developed (FITS headers)
- Ground system preliminary cost estimates (input to LBNL)
- Slit spectroscopy simulation investigations
- JDEM Computing Team coordination meetings (with LBNL)

- Fermilab personnel: Gottschalk, Kent, E. Neilsen, I. Mandrichenko, J. Kowalkowski, V. Pavlicek, M. Paterno, V. Podstavkov, S. Fuess

Large Synoptic Survey Telescope

- Fermilab in excellent position to help LSST succeed:
  - SDSS/DES survey heritage
  - calibrations (DES synergy)
  - data management and access (build on SDSS, JDEM)
  - science analysis
  - Si Det infrastructure and expertise: industrial-scale silicon-based instrumentation for accelerator and non-accelerator experiments
- Fermilab in the process of joining LSST project
- Modest effort until DES ramps down



Dedicated 8.4m telescope,10 s.d. FOV
Top-ranked ground project in Astro 2010
SLAC is DOE lead on instrument

Dark Energy Spectrograph: DESpec

- Upgrade of DES currently under study:
  - multi-object prime focus spectrograph for the Blanco 4-m
  - 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 HETDEX-like spectrographs, 4000 fibers
- Enhance Dark Energy science reach of DES (LSS/BAO) by factor ~2-4
- Enhance DE science reach of LSST
- Preliminary design and science studies underway
  - Diehl, Flaugher, Kent, Kron (FNAL), DePoy (Texas A&M), Abbott (CTIO), DES Science Working Groups

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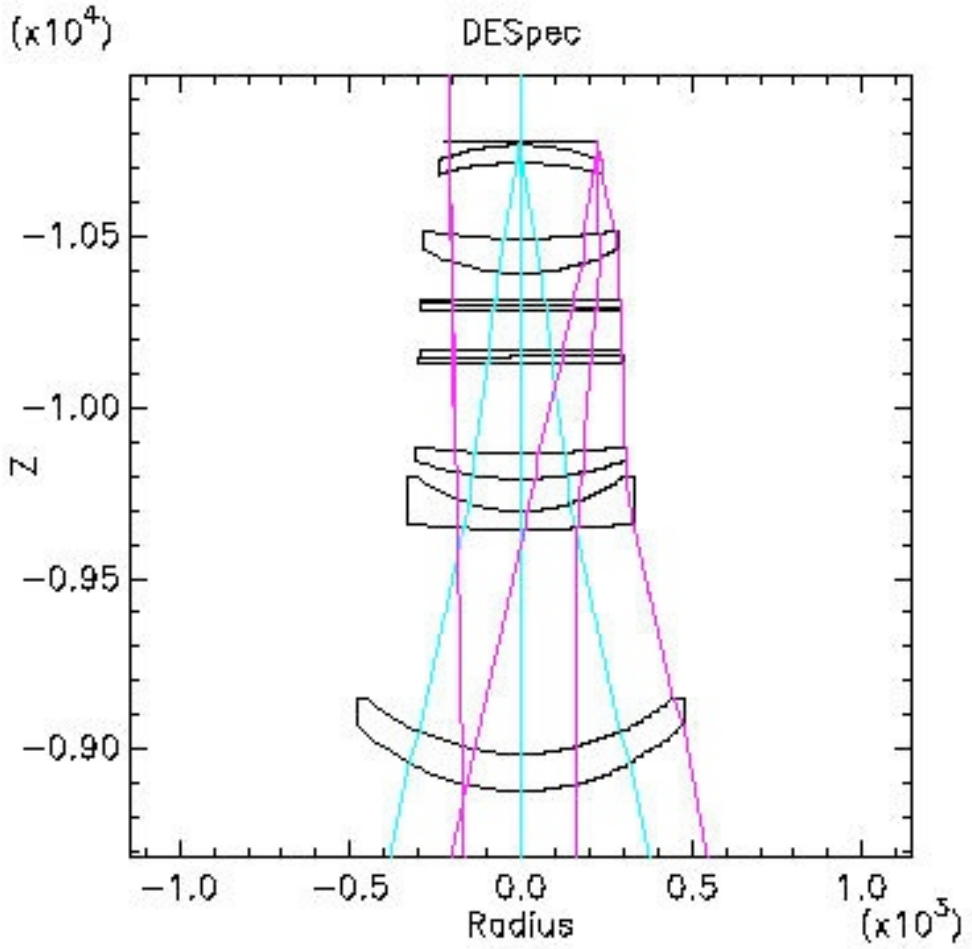
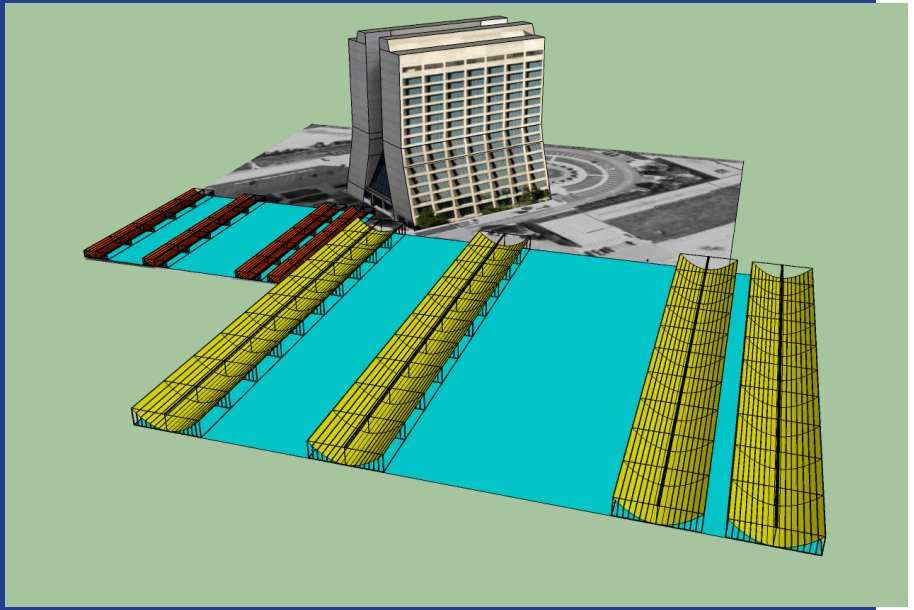


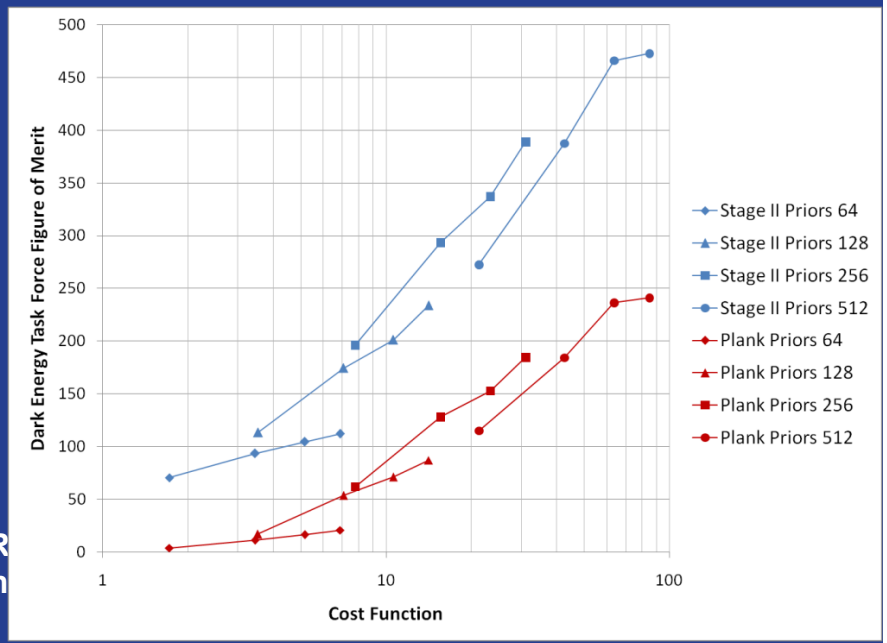
BigBOSS

- LBNL-led concept for multi-object spectrograph for the NOAO Kitt Peak Mayall 4-meter telescope to carry out a massive BAO survey
- Follow up galaxy and QSO (Ly-alpha forest) targets from PanSTARRS-I and WISE (sky overlap with DES or LSST small but potentially useful)
- Submitting survey proposal to NOAO Oct. 1. Includes Fermilab 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

21cm Cylindrical Radio Telescope

- Medium size dark energy project
  - 3-D radio intensity map (~10^9 pixels) 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)





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Fermilab and 21cm

- International collaboration with participants from 8 institutions
  - Carnegie–Melon, AUI (Morocco), CEA (Saclay), CITA (Canada), CSRIO (Australia), Fermilab, LAL (Orsay), University of Wisconsin
- Technology very well aligned to Fermilab's 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)
  - McGinnis, Marriner leading this effort, with FNAL theorists

Future Options

- Each of these projects offers exciting science opportunities and would further improve Dark Energy constraints
  - DESpec, BigBOSS, CRT focused on BAO
  - LSST focus on weak lensing, clusters, SNe
- Fermilab can make significant contributions to these projects, exploiting its infrastructure and technical expertise and 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.

Conclusion

- DES is poised to take the next step in understanding the nature of dark energy, ramping up operations in FY11.
- Combination of Fermilab technical and scientific expertise and infrastructure with strengths of partner institutions (national labs, Universities, foreign consortia) enables this kind of project.
- DES entering critical phase, and timely operations support to Fermilab and partner institutions will be essential for success.
- Exploring several `next-generation' options to make further progress on Dark Energy.