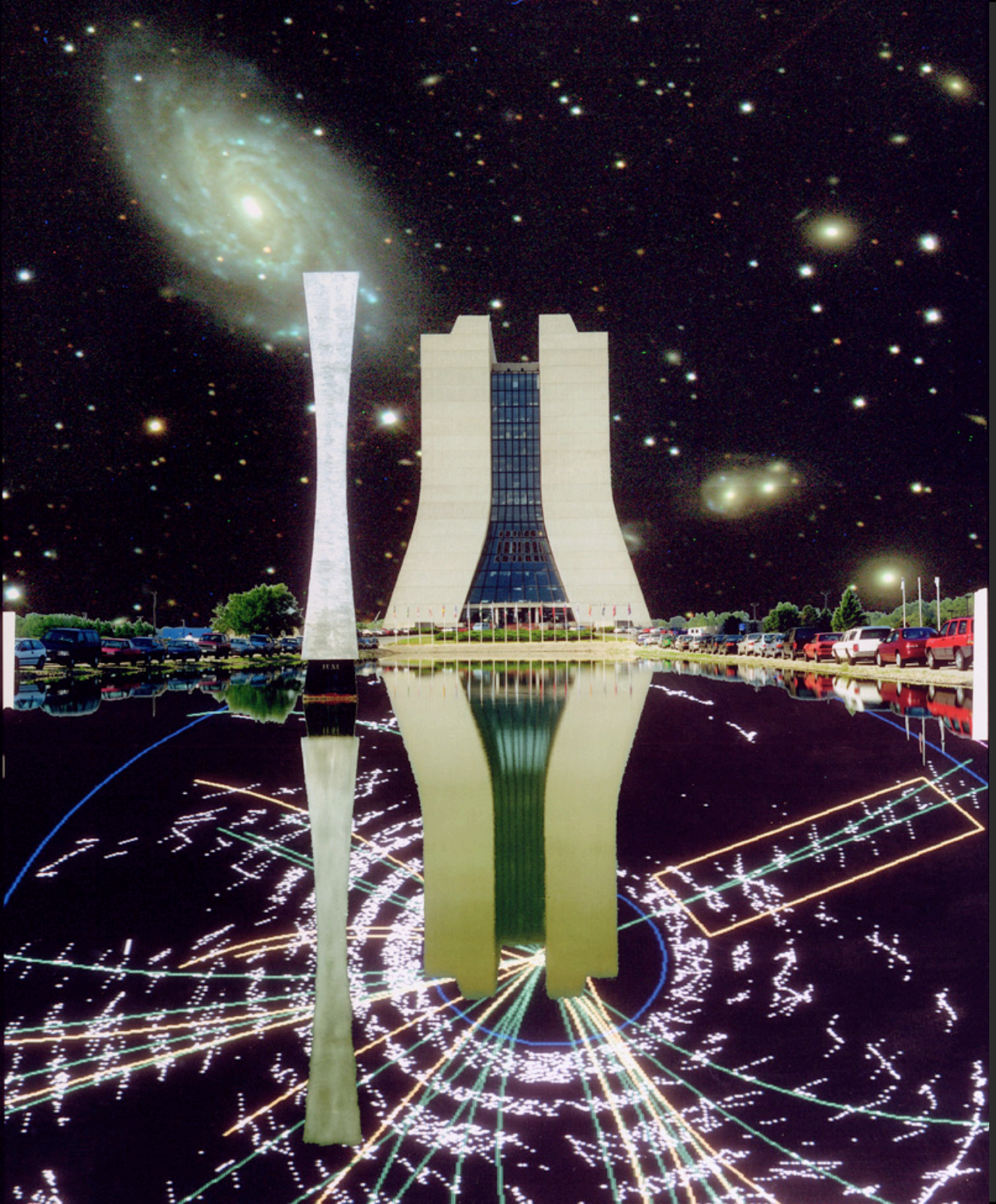
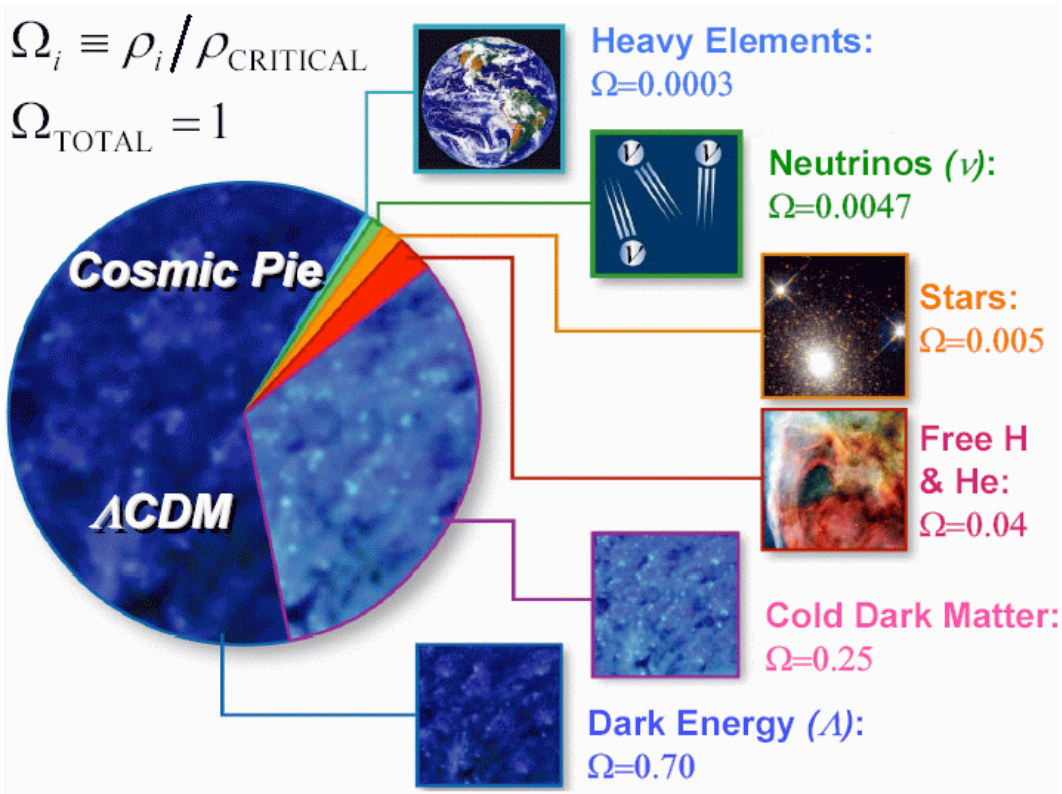


The Dark Energy Survey

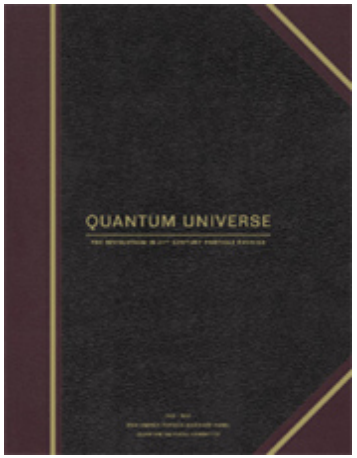
Fundamental Physics at Fermilab

James Annis
Experimental Astrophysics



The concordance universe

- is predominately dark.
  - 70% dark energy
  - 25% dark matter



Which leaves us with questions

- How can we solve the mystery of dark energy?
- What is dark matter?
- How did the universe come to be?

Questions that experimental astroparticle physics can help answer.

The Dark Energy Survey

DARK ENERGY SURVEY

Measure Dark Energy using four complementary techniques

- Cluster Counts
- Weak Lensing
- Baryon Acoustic Oscillations
- Supernovae

Survey Strategy

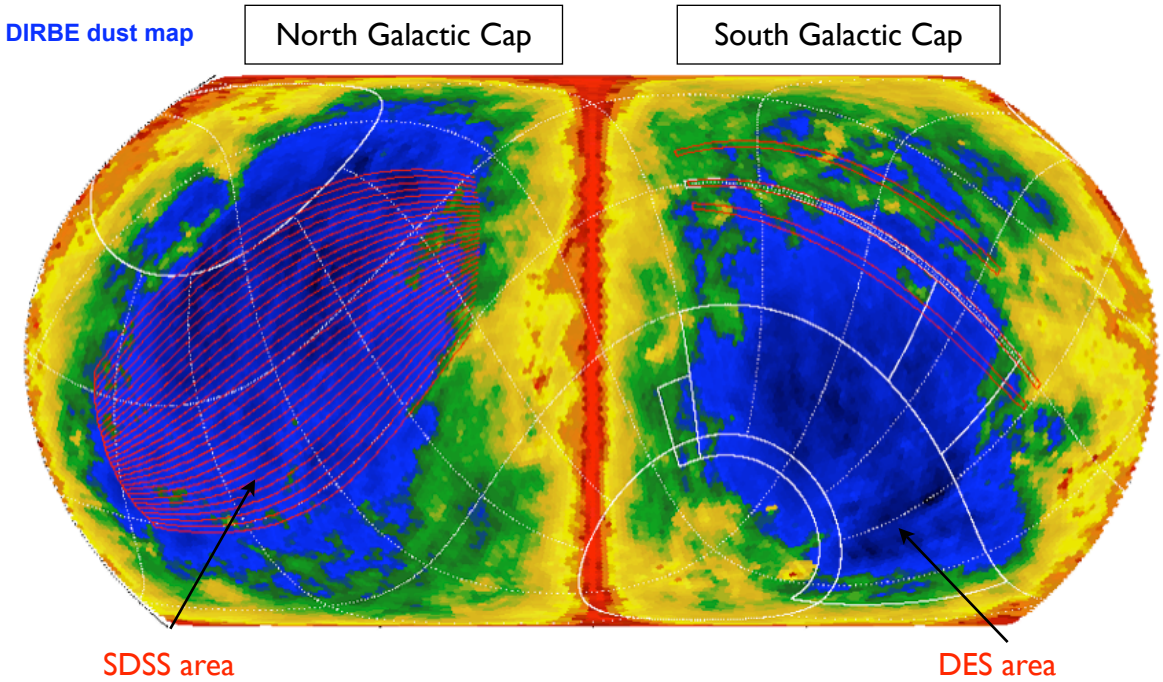
- 5 years of data taking 2010-2015
- 5000 sq-degrees
  - cover 4000 sq-degree SPT SZ survey
  - cover redshift surveys
  - 40 sq-degree time domain for SN
- Cover survey area multiple times/year
  - => substantial science after year 2

Telescope

- Use 30% of the NOAO/CTIO Blanco 4m

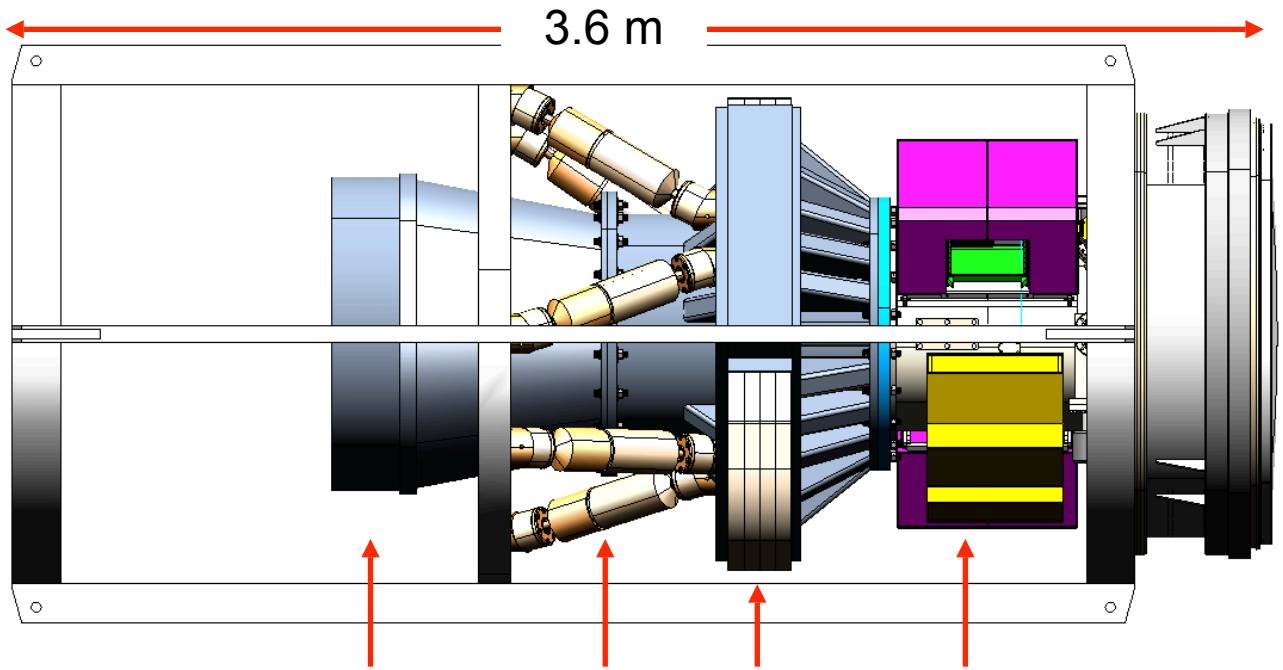
Instrument required

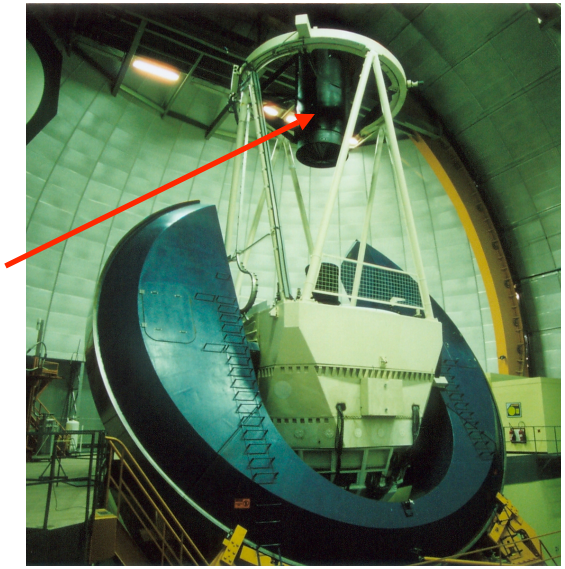
- DECam
  - 3 sq-degree camera to cover the area
  - high near-IR sensitivity to reach z = 1



g,r,i,z (10σ, galaxies) = 24.6, 24.1 ,24.3, 23.9
g,r,i,z (5σ, psf) = 26.1, 25.6, 25.8, 25.4

The Dark Energy Camera



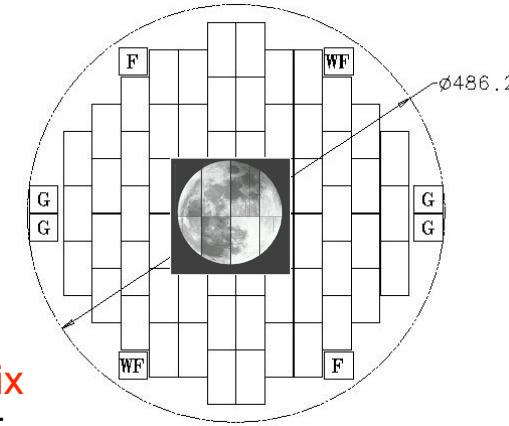


CTIO Blanco 4m telescope
Operated by NOAO for the NSF

Slides to follow

- Full depletion CCDs
- Very large focal plane
- Readout: 17s readout time, 10 e- noise
- 0.6mx0.6m glass filters: g,r,i,z
- Hexapod for focus, xy translation
- 5 element optical corrector

Focal plane:
62 2kx4k Image CCDs: 520 MPix
8 2kx2k Guide, focus, alignment



CCD Fabrication and Packaging

DARK ENERGY SURVEY

CCD Fabrication

- Follows SNAP fabrication model
- Dalsa delivers partially processed wafers to LBNL
- LBNL finishes processing wafers, tests, dices

CCD Packaging

- FNAL produces 4 side abuttable packaged CCDs

CCD Testing

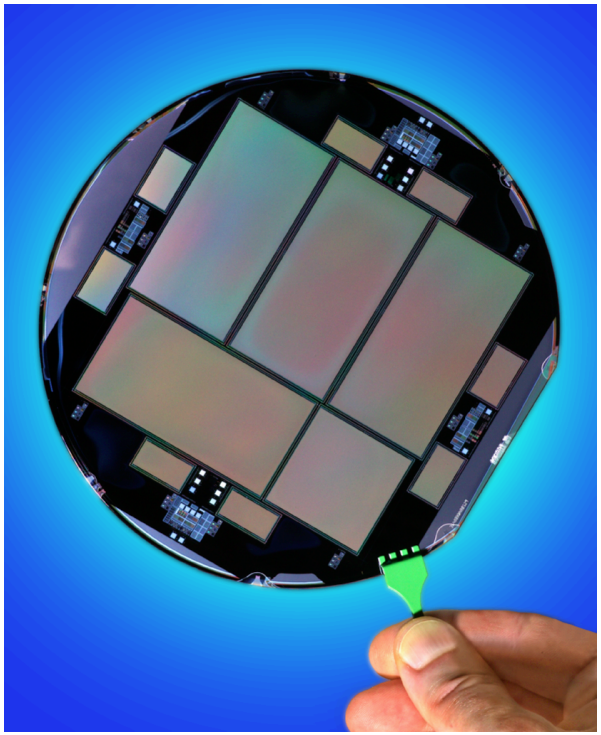
- FNAL tests and characterizes the CCDs

CCD Status

- Have 36 Eng. grade 2kx4k CCDs in hand and expect 20 more in July
- Potential science grade devices expected in Oct 2006
- In 2007 establish CCD processing and packaging yield

CCD yield is a cost and schedule driver

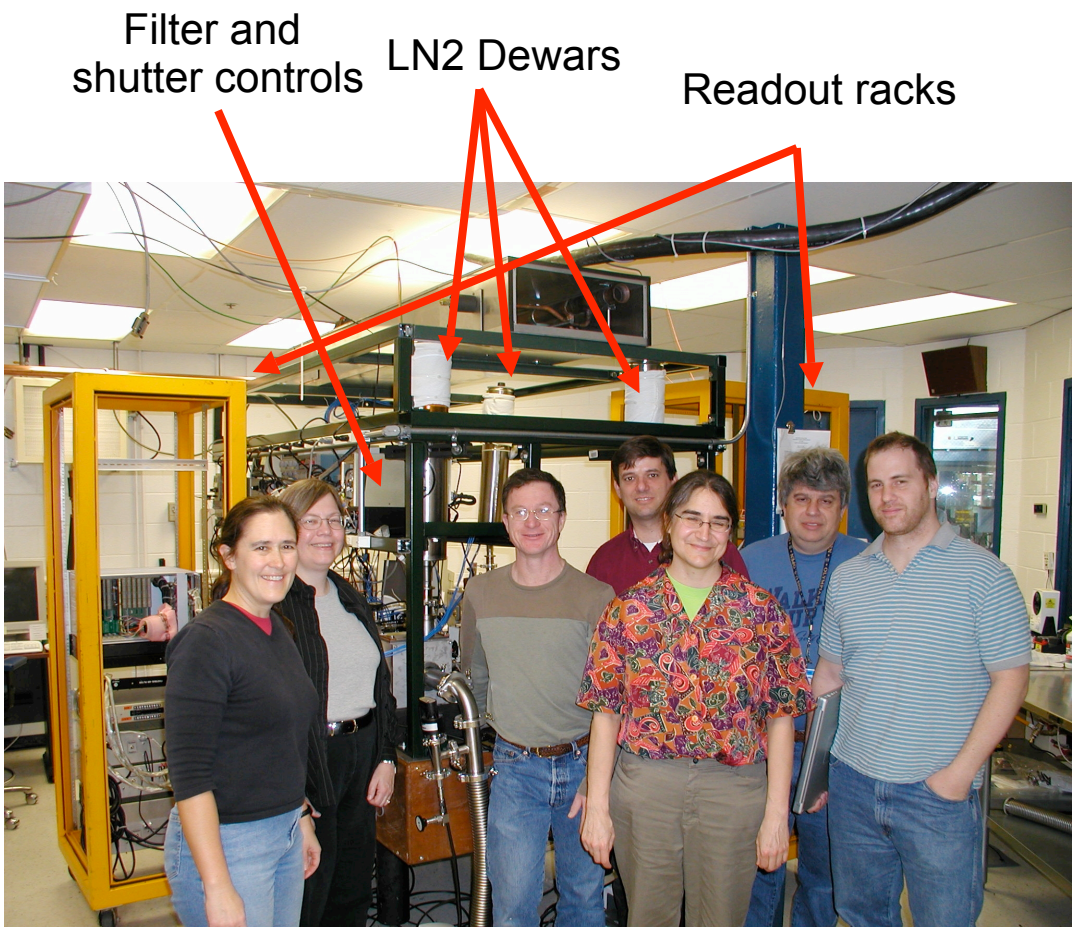
DES Wafers – June 2005!



CCD Testing Lab

- Over the last year we have created a CCD testing lab
- Contributions
  - Fermilab runs the main lab, in the old bubble chamber control room
  - Barcelona: remote analysis
  - NOAO: DA support
- 3 operational testing setups
  - 2 NOAO Monsoon systems
  - 1 Leach controller
- Flatness measuring engine
  - Micro-Epsilon Opto-NCDT 2400
- Quantum efficiency bench

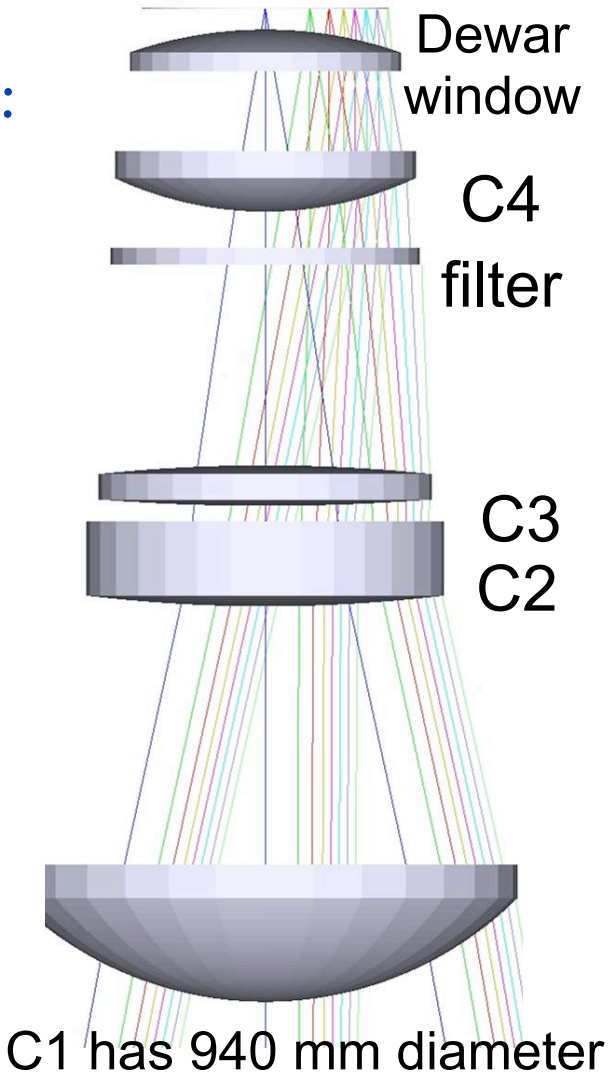
3 operational CCD testing setups



Part of Fermilab Team in the testing lab

Optical Corrector

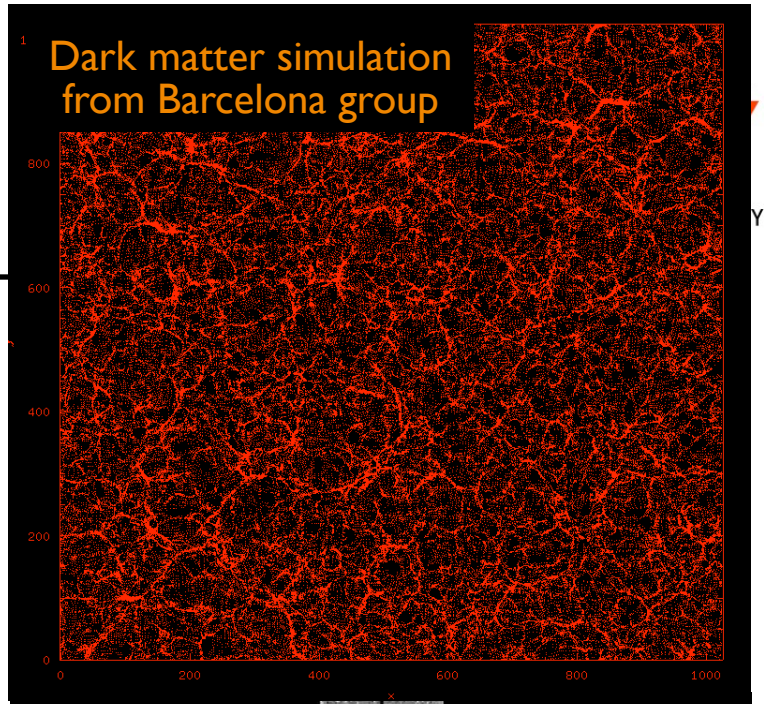
- International team to build the optical corrector:
  - Optics design complete (Michigan, FNAL, Chicago)
    - Image quality FWHM: ~ 0.33" (<0.4" required)
  - Glass blanks
    - Michigan, Chicago, and Portsmouth are providing the funds
  - Corrector polishing and construction
    - P. Doel at the Optical Science Lab (UCL) will manage the procurement and fabrication
    - UCL led a UK proposal submitted to PPARK for £1.5 million for corrector construction
  - Mechanical structures (Michigan, FNAL)
- Optics is the critical path
  - procurement is ~2.5 years
  - assembly and testing ~0.5 years

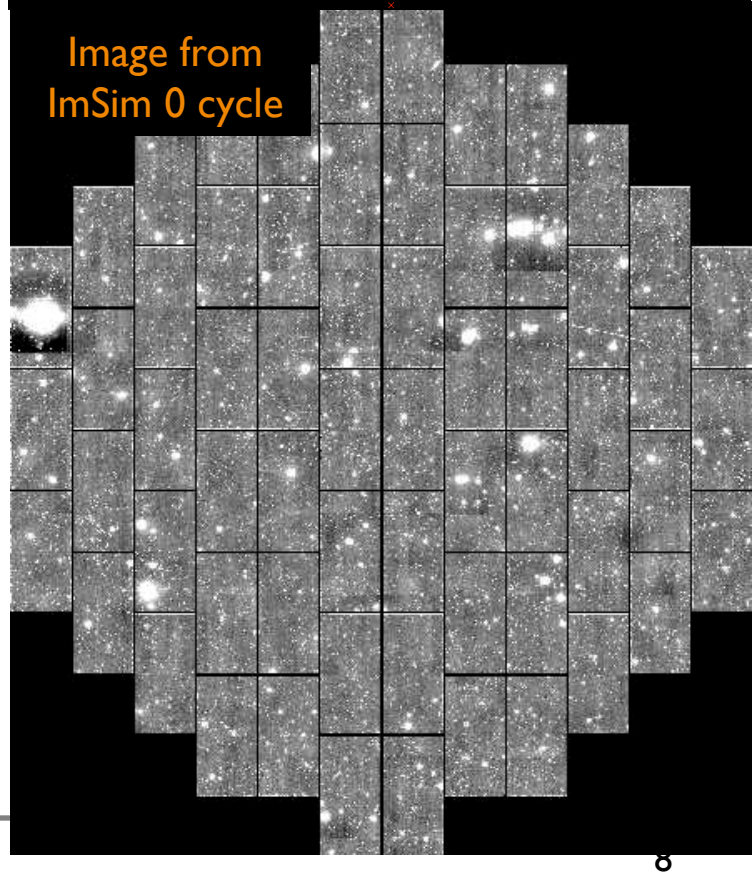


March 2006, the UK PPARC Council announced that it "will seek participation in DES"

DES Simulations

- Simulations central to science
  - goal: 1 year of imaging simulation in 2008
  - goal: 10x survey area of catalog simulation in 2008
- Simulation Design:
  - N-body for dark matter
    - Barcelona, Michigan
    - Chicago, NCSA exploring hydro codes
  - add galaxies
    - place SDSS galaxies onto DM particles (Chicago)
  - catalog level simulation of survey
    - wl shear, stars, instrumental effects (Fermilab)
  - image level simulation of survey
    - galaxy shapes, instrument point spread functions (Fermilab)
- Data Reduction Challenges
  - Provide connection to Data Management
- Status
  - Simulation round 0,1 are finished
  - Simulation round 2 is in progress





Key Projects

DARK ENERGY SURVEY

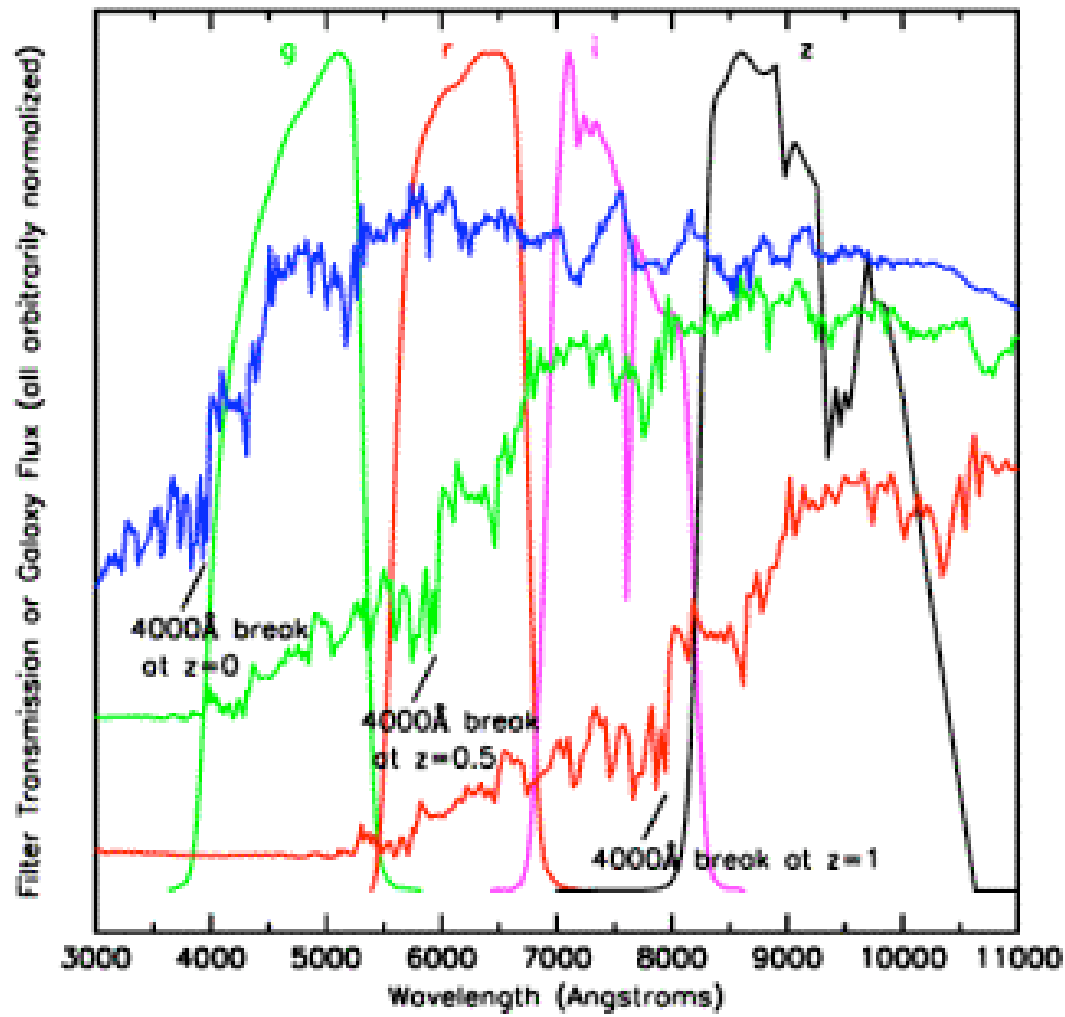
- The models for dark energy break into three broad classes
  - the cosmological constant
  - a new scalar field
  - a modification to gravity
- With the 2012 data release we will be able to address two simple questions...
  - Is dark energy the cosmological constant?
    - if w = -1 and dw/da = 0, probably
    - otherwise, NO
  - Is dark energy a modification to gravity?
    - if the growth of structure and geometric methods disagree, YES
- Our key projects include
  - Two probes using geometrical methods
  - Two probes using the growth of structure
  - Precision photometric redshifts supporting all four
  - Simulations underly our understanding of the measurements

Photometric Redshifts

- Measure the relative photon flux in the 4 filter *griz*: track the 4000 A break.
- Estimate individual galaxy redshifts with accuracy of $\sigma(z) < 0.1$ (0.02 for clusters).
- These precisions are sufficent for dark energy probes provided the error distributions are well measured.
- Photo-z working group co-led by Huan Lin (Fermilab)

Photometric redshifts are the key scientific technology of the Dark Energy Survey.

Elliptical galaxy spectrum



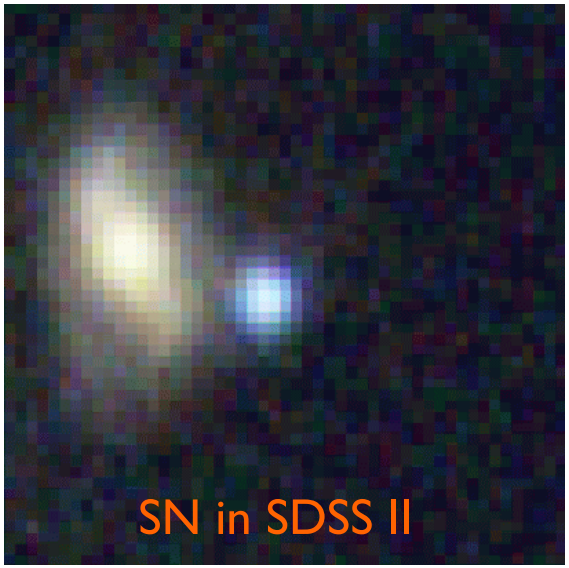
We need high red QE detectors to reach z > 0.7

Geometric Probe Key Projects

DARK ENERGY SURVEY

I. Supernovae

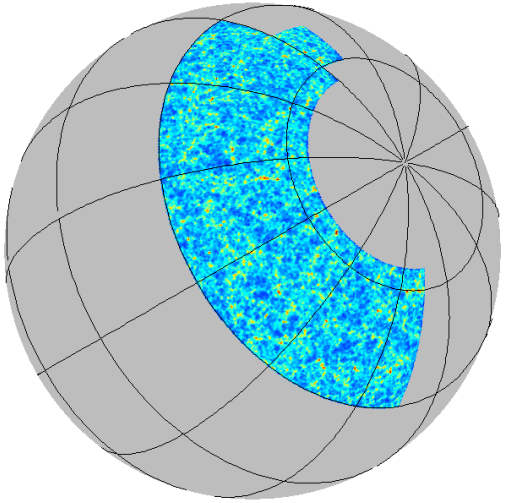
- Time domain survey
  - repeat observations of 40 sq-degrees
  - 10% of survey time
- ~1900 SN with well measured light curves
  - 0.25 <= z <= 0.75



II. Baryon Acoustic Oscillations

- Characteristic angular scale set by sound speed at recombination
- Method:
  - Break up sample into photo-z bins
    - 0.5 < z < 1.0 1.0< z < 1.5
  - Locate peaks in the correlation function
  - Compare to other redshifts
    - SDSS LRG at z=0.35
    - WMAP CMB at z=1300

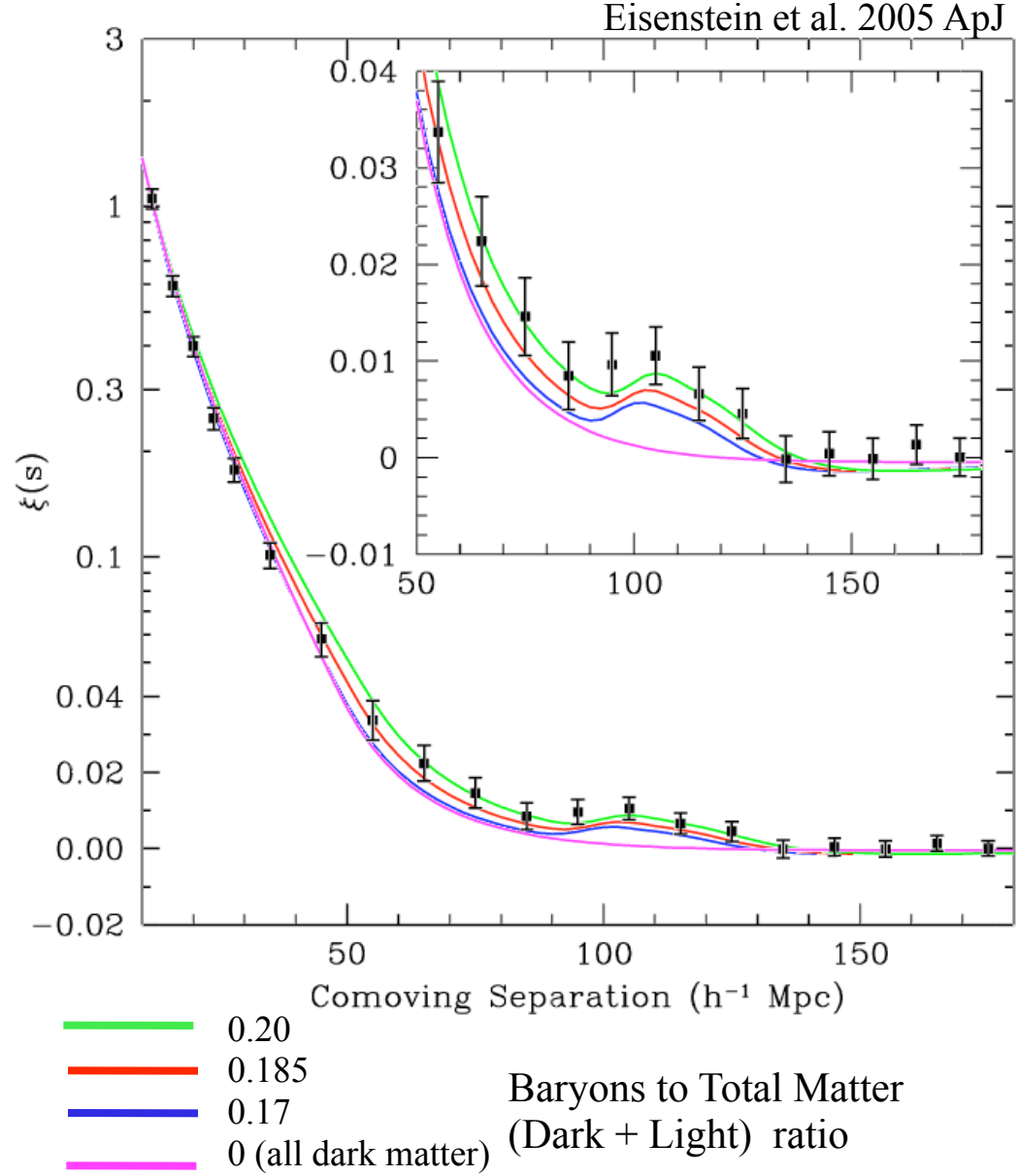
Galaxy distribution at z=0.1 and z=0.7



SDSS Baryon Acoustic Oscillations

- The SDSS discovered the baryon acoustic peak.
  - perhaps the most imporant SDSS result of all.
- The existence of the peak demonstrates
  - there is dark matter at z=1000, just as at z=0
  - there are baryons that interact with the photon plasma and evolve gravitationally
  - the ratio of these two types of matter is measured
  - and when combined with CMB acoustic peaks, we measure the curvature of the universe to be 0 within 1%.

Eisenstein et al. 2005 ApJ



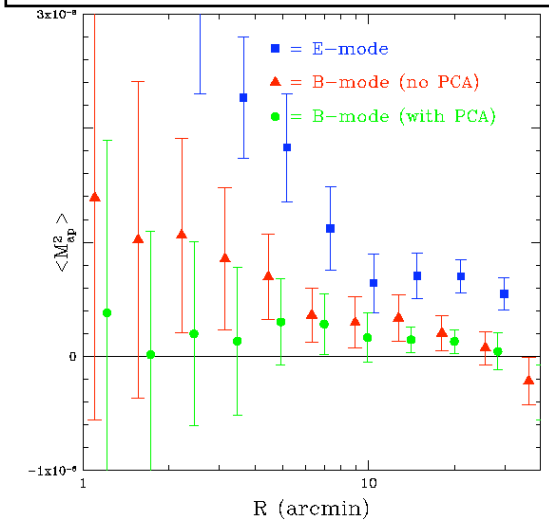
Growth of Structure Key Projects

DARK ENERGY SURVEY

III. Weak Lensing Tomography

- Statistical measure of shear pattern (~1% effect)
  - Break up sample into 4 photo-z bins
    - 300 million galaxies will have useful shapes
    - median redshift <z> = 0.7
  - Calculate the shear-shear power spectrum in each bin
    - there are several different experiments one can do
- Shear systematics under control at level needed

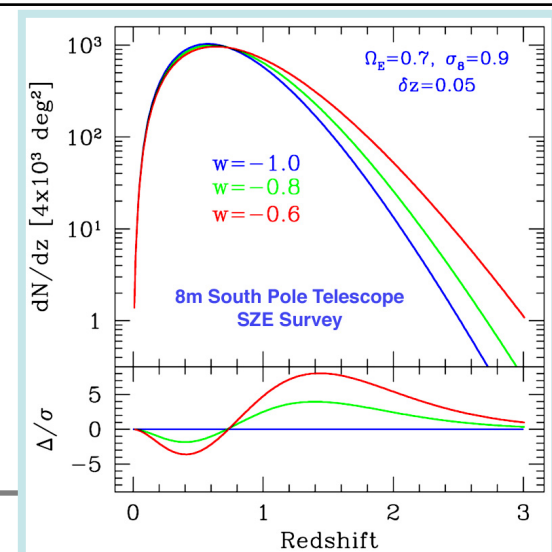
Published results from a 75 sq-degree WL survey using the existing camera on the Blanco 4-m. (Bernstein, et al 2006)



IV. Cluster Counting

- Use clusters are dark matter halo markers
  - cleanly select dark matter halos
  - measure redshifts for each cluster
  - calibrate an observable mass estimator
    - red galaxy clusters
    - weak lensing
    - Sunyaev-Zeldovich peaks in the SPT data
- Primary systematic uncertainty in bias and scatter of mass-observable relation
  - cross compare the observables

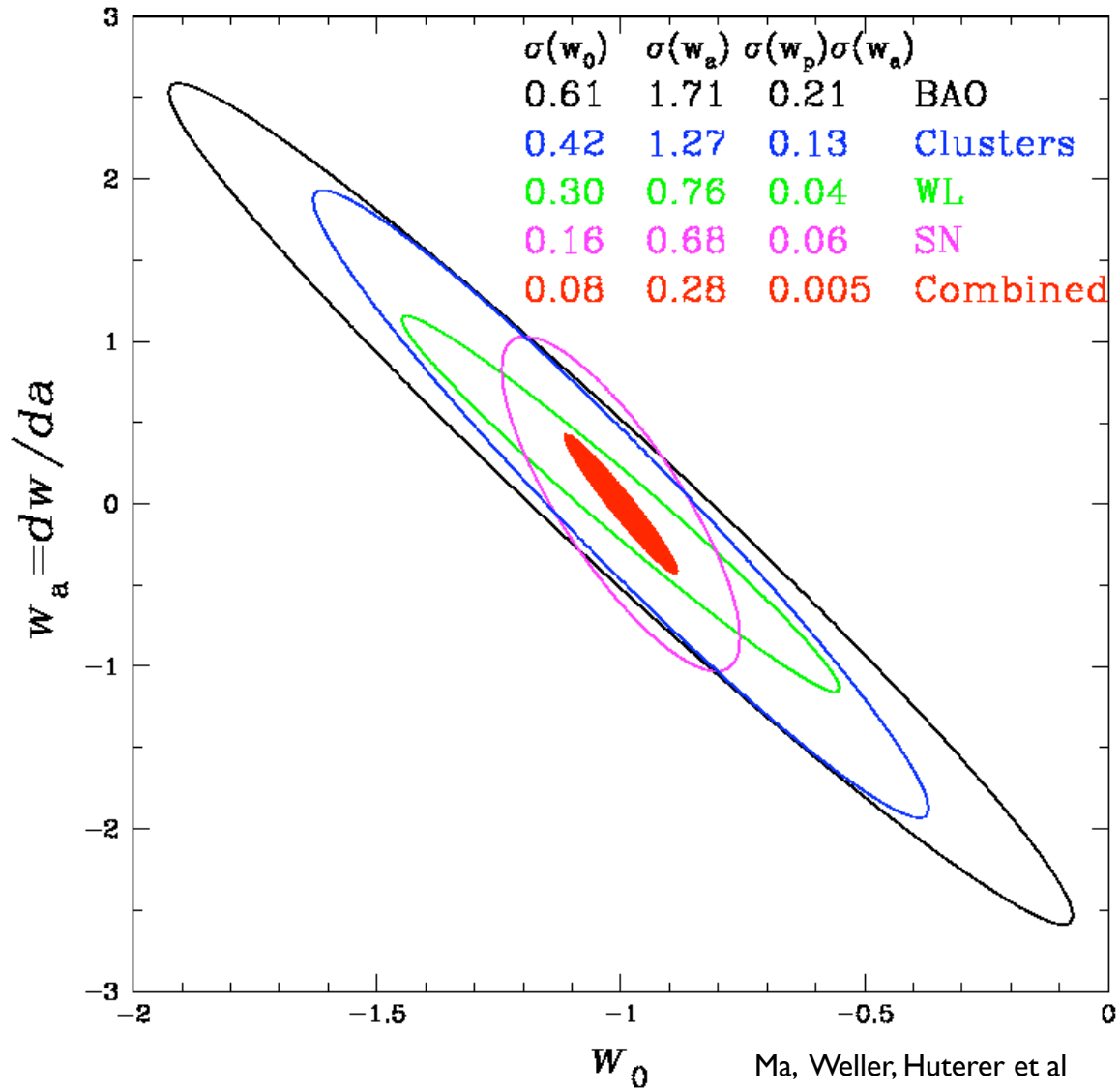
Number of clusters above mass threshold



DES Forecasts: Power of Multiple Techniques

DARK ENERGY SURVEY

- We evaluate each key project separately.
  - check for systematics
  - then we combine
- Assumptions
  - baryon acoustic oscillations
    - ℓ_{max} = 300
  - weak lensing
    - ℓ_{max}= 1000, no bispectrum
  - clusters
    - σ_8=0.75, z_{max}=1.5,
    - WL mass calibration,
    - no use of spatial clustering
  - systematic errors included:
    - photo-z
  - 6 parameter cosmology fit
    - including spatial curvature
  - galaxy bias marginalized over
  - Plank CMB prior



Ma, Weller, Huterer et al

DES and Fundamental Physics

- With the 2012 data release we will be able to address two simple questions...
- The models for dark energy break into three broad classes
  - the cosmological constant
  - a new scalar field
  - a modification to gravity
- Is dark energy the cosmological constant?
  - if w = -1 and dw/da = 0, probably
  - otherwise, NO
- Is dark energy a modification to gravity?
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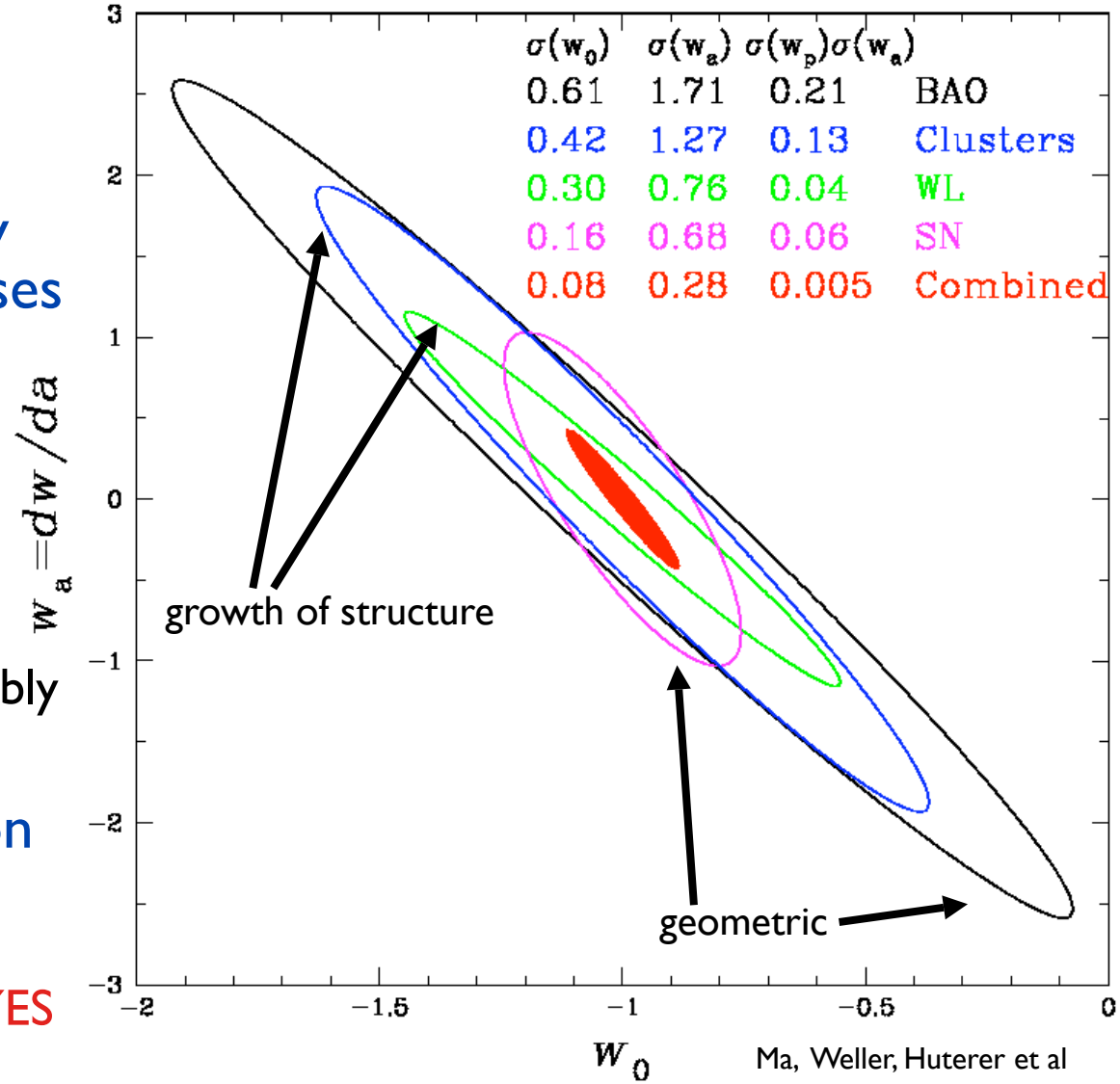
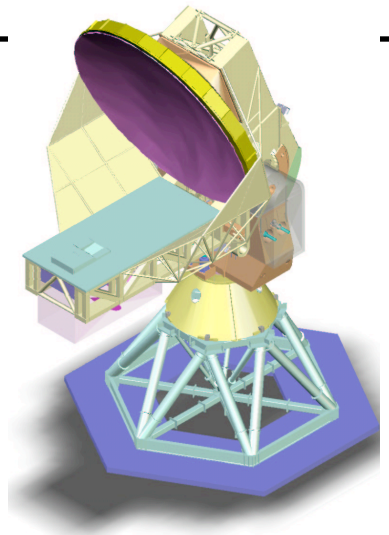


Ma, Weller, Huterer et al

Complementary Surveys

- The South Pole Telescope
  - 4000 sq-degree SZ survey
    - NSF funded- Antartica deployment Nov 2006
    - SZ effect measurements of ~20,000 clusters
      - hot gas in clusters compton scatters CMB photons
      - nearly independent of redshift



SPT

- VDES - VISTA DES (proposed)
  - 5000 sq-degree J,K survey
    - VISTA is a ESO telescope- first light 2007
    - Precision photo-z's to z=2 (from the DES z~1)

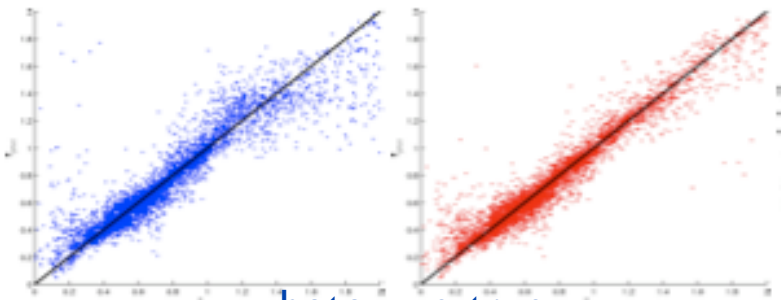


photo-z vs. true z

DES VDES

- Theoretical and Observational Studies of DE (proposed)
  - create and analyze a grid of cosmological simulations
    - SciDAC proposal led by Salman Habib (LANL)
      - collaboration includes Los Alamos, Fermilab, NCSA
    - Cosmological simulations for DE accurate to 1%

The DES Collaboration

DARK ENERGY SURVEY

Fermilab: J. Annis, H. T. Diehl, S. Dodelson, J. Estrada, B. Flaugher, J. Frieman, S. Kent, H. Lin, P. Limon, K. W. Merritt, J. Peoples, V. Scarpine, A. Stebbins, C. Stoughton, D. Tucker, W. Wester

University of Illinois at Urbana-Champaign: C. Beldica, R. Brunner, I. Karliner, J. Mohr, R. Plante, P. Ricker, M. Selen, J. Thaler

University of Chicago: J. Carlstrom, S. Dodelson, J. Frieman, M. Gladders, W. Hu, S. Kent, R. Kessler, E. Sheldon, R. Wechsler

Lawrence Berkeley National Lab: N. Roe, C. Bebek, M. Levi, S. Perlmutter

University of Michigan: R. Bernstein, B. Bigelow, M. Campbell, D. Gerdes, A. Evrard, W. Lorenzon, T. McKay, M. Schubnell, G. Tarle, M. Tecchio

NOAO/CTIO: T. Abbott, C. Miller, C. Smith, N. Suntzeff, A. Walker

CSIC/Institut d'Estudis Espacials de Catalunya (Barcelona): F. Castander, P. Fosalba, E. Gaztañaga, J. Miralda-Escude

Institut de Fisica d'Altes Energies (Barcelona): E. Fernández, M. Martínez

CIEMAT (Madrid): C. Mana, M. Molla, E. Sanchez, J. Garcia-Bellido

University College London: O. Lahav, D. Brooks, P. Doel, M. Barlow, S. Bridle, S. Viti, J. Weller

University of Cambridge: G. Efstathiou, R. McMahon, W. Sutherland

University of Edinburgh: J. Peacock

University of Portsmouth: R. Crittenden, R. Nichol, W. Percival

University of Sussex: A. Liddle, K. Romer

plus students

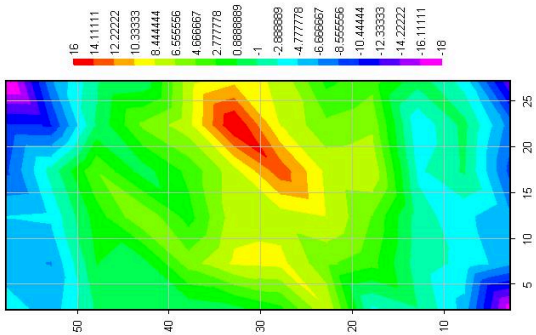
Fermilab Roles and Personnel

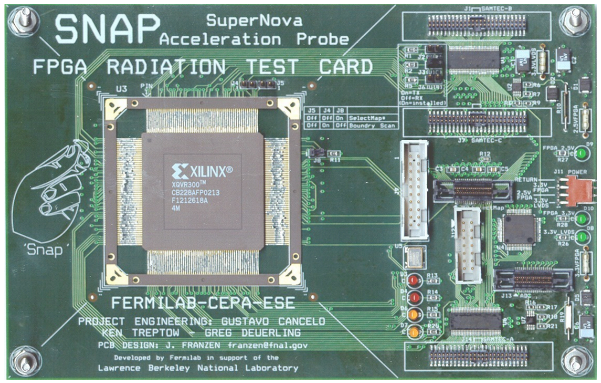
DARK ENERGY SURVEY

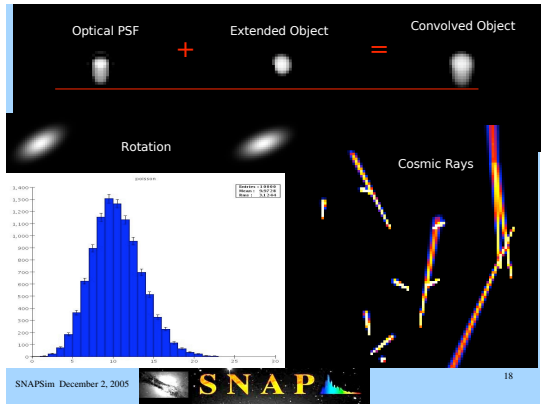
- Fermilab Roles
  - Project management
  - CCD packaging
  - CCD readout
  - CCD focal plane and vessel
  - Optical corrector barrel and optical corrector design
  - Cage and hexapod/alignment
  - Simulations
  - Calibrations
  - Science codes
- Scientists:
  - 12 experimentalists
  - 3 theorists
  - currently ~ 6 FTEs

SNAP at Fermilab

- Focal plane
  - warm-cold flatness testing
    - lowering T leads to CCD warping, middle low, edges high
- Electronics
  - Fermilab regulator IC (FRICO) ASIC
    - signal processing for IR chips, temperature and regulated voltage control for focal plane
  - Mass memory
    - flash for storage, FPGA for control
    - radiation damage testing
      - protons at Indiana University cyclotrons
      - ions at LBNL heavy ion facility
- SNAP Simulations
  - pixel level simulations
    - includes
      - detector physics
      - instrumental optical design
      - shapelet derived source shapes







The Dark Energy Survey

DARK ENERGY SURVEY

- The Dark Energy Survey has 4 key science projects (clusters, weak lensing, BAO, SN) and all are well matched to the DETF Report
  - The Dark Energy Task Force emphasizes that combinations of the four principal techniques
    - have substantially more statistical power,
    - much greater ability to discriminate among DE models,
    - more robustness to systematic errors
  - Our work on the techniques and on systematic errors will perhaps be our biggest contribution to the stage IV projects.
- The Dark Energy Survey is a modest, low-risk, near term project with high discovery potential.
  - DECam has made substantial progress over the last year
  - We continue to have success in attracting good collaborators
  - Next we need support as we move through the DOE approval process

Additional Slides

DECam Schedule

DARK ENERGY SURVEY

Dependent on DOE funding and international participation

Opportunity exists to capitalize on international interest in DES

DOE Critical Decision Process schedule

- FY06 Preconceptual R&D; CD1 Paper review Sept.06
- FY07 R&D, CD2 Review March 07, CD3 Review Sept. 07
- FY08 MIE Construction start
- FY09-10: Assemble and test camera vessel and corrector
  - Ship to Chile and install on Blanco , first DES observations Dec. 09

DECam Funding Need Profile

(then yr $, Overhead included)

DARK ENERGY SURVEY

$ M	FY07	FY08	FY09	FY10	TOTAL
ACTIVITY	R&D	CONST	CONST	CONST	
R&D FUNDS (DOE HEP)	4.1				4.1
DOE HEP MIE FUNDS		5.8	4.9	1.9	12.6
EXTERNAL (Foreign + Univ. Non DOE)	1.0	2.0	0.0	0.0	3.0*
TOTAL	5.1	7.8	4.9	1.9	19.7

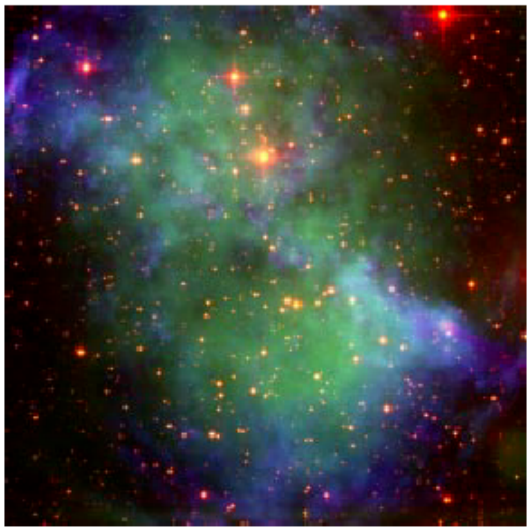
*Additional $1M in External funds in FY06, Total External Funds = $4M

- Total Project Cost: (FY07-FY10) = $19.7 M
- Total DOE Project cost: $16.7 M
- DOE Major Item of Equipment (MIE) total of $12.6 M includes M&S equipment ($7M), technical labor ($5.6M) and a total of ~35% contingency
- Scientists: ~ 6 FTEs now (11 Experimentalists + 3 Theorists)

Fermilab Personnel

- ~ 5 FTE Scientists, Associate Scientist
  - 5 PPD/HEP (Flaugher, Merritt, Diehl, Estrada, Grunendahl, Wester)
  - 5 CD/EAG (Annis, Lin, Kent, Stoughton, Tucker)
  - 1 CD (Buckley-Geer)
  - 1 AD (Scarpine)
- ~ 0.5 FTE Theorists (Frieman, Dodelson, Stebbins)
- ~ 3 FTE: Mechanical Engineers
- ~ 2 FTE ME and EE design and drafting
- ~ 4 FTE Electrical Engineers
- ~4 FTE ME and EE Technicians

DES CCDs



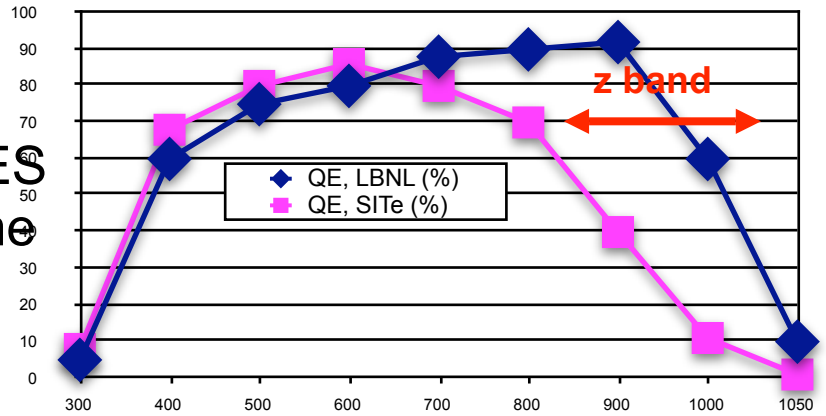
LBNL CCDs in use on WIYN telescope. From S. Holland et al, LBNL-49992 IEEE Trans. Elec. Dev. Vol.50, No 1, 225-338, Jan. 2003

LBNL Design: fully depleted 2kx4k CCDs

- QE> 50% at 1000 nm, 250 microns thick
- 15 μm pixels, 0.27"/pixel
- readout 250 kpix/sec, readout time ~17sec

LBNL CCDs are much more efficient than the SITE CCDs in Mosaic II at high wavelengths

To reach redshifts of ~1.3 DES will spend 46% of survey time in z –band



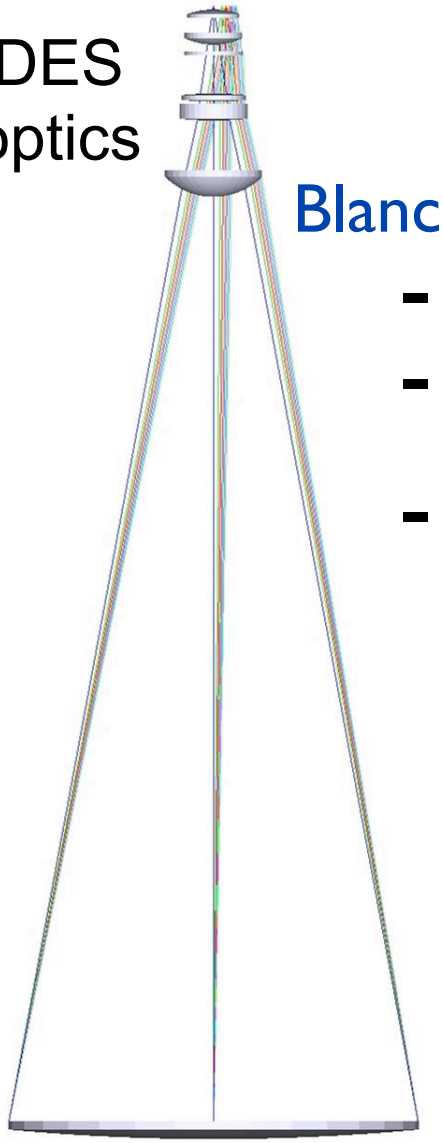
DES is the 1st production quantity application for LBNL CCDs

DES CCD design has already been used on telescopes in small numbers (3)

SNAP CCDs are the next generation, optimized for space

Telescope Primary Mirror

DES optics



Primary Mirror

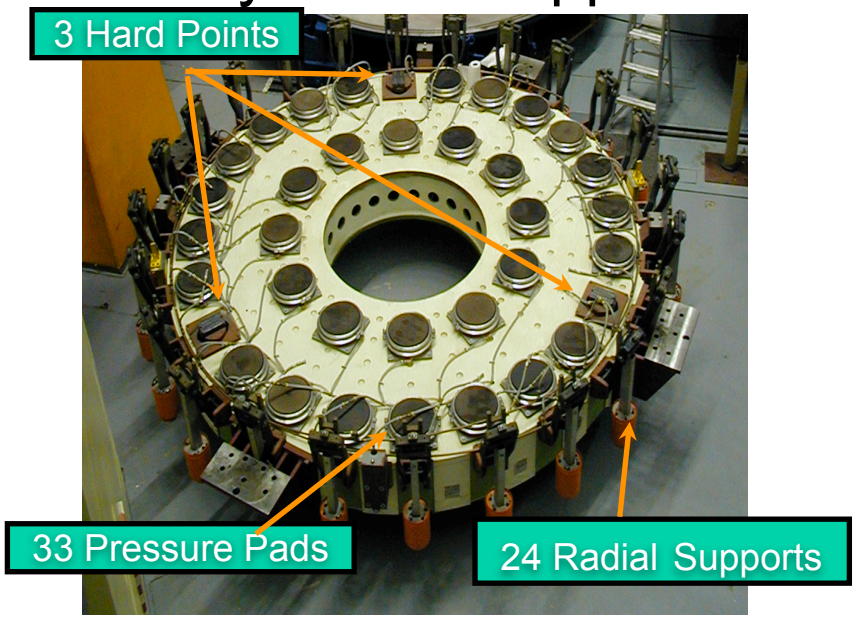
Blanco Primary mirror

- excellent figure: D80 <0.25”
- radial position controlled by counterweights
- Upgrades in Oct. 05 reduced the mirror motion from ~1.5mm to < 0.4mm, further reduction expected

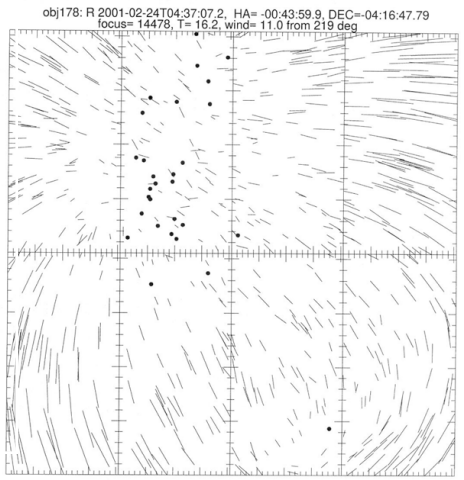
Ray tracing model of existing mirror, camera and corrector reproduces PSF patterns seen in data

In this model the primary was misaligned by 0.2 mm x and -0.7 mm y

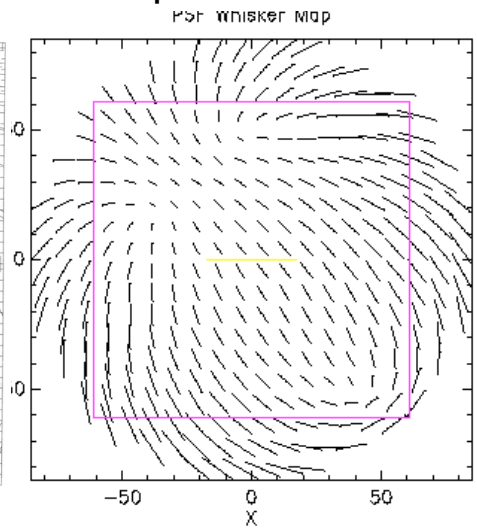
Primary Mirror Support cell



An observed PSF pattern



optical model

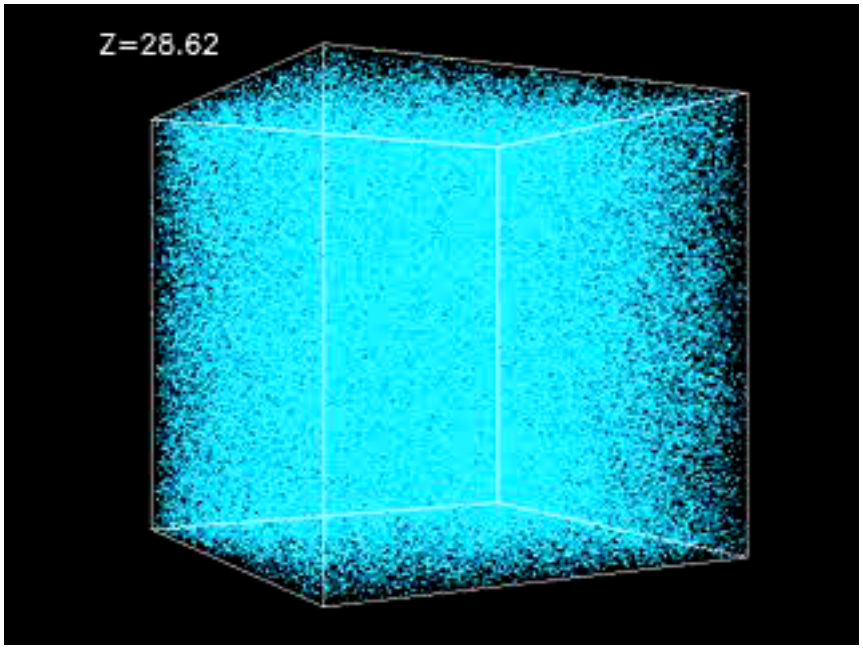


CCD Readout Electronics

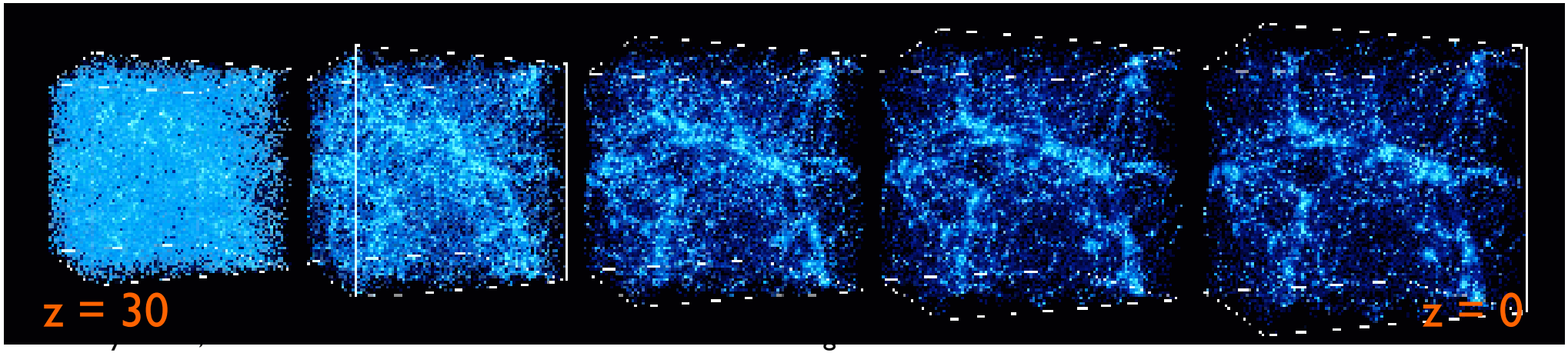
DARK ENERGY SURVEY

- International team to build the CCD readout electronics
  - FNAL, Barcelona, Madrid, UIUC
  - Spanish consortium has submitted a proposal that would enable them to lead the construction of the production front end electronics.
- Status:
  - UIUC funds used to purchase prototype readout systems
  - have already achieved 6.5e noise at 160 kpix/sec,
  - have a design that fits in 3 temp. controlled crates in PF cage
  - need to test readout of multiple CCDs

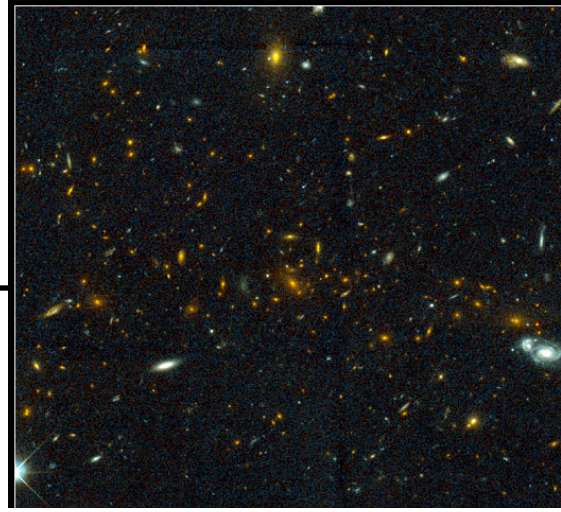
New Probes of Dark Energy

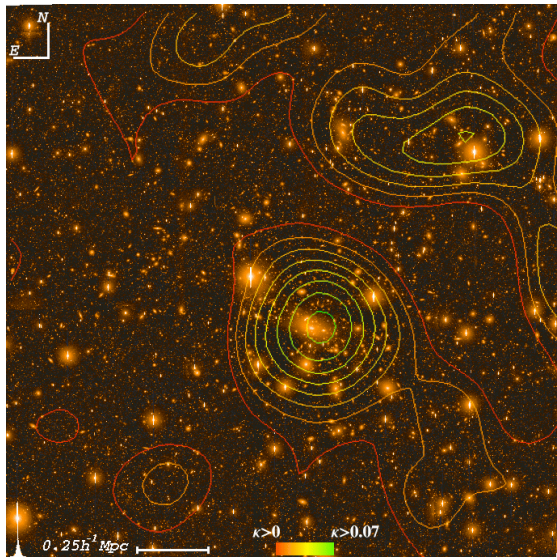


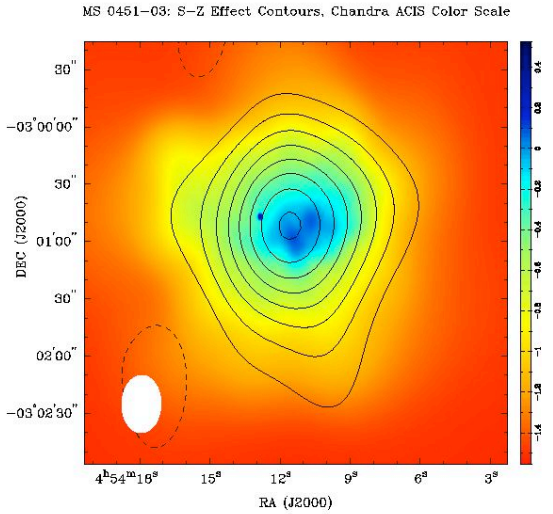
- The new probes rely on the growth of structure over time.
  - Rely on mapping the cosmological density field
  - Up to the decoupling of the radiation, the evolution depends on the interactions of the matter and radiation fields - **'CMB physics'**
  - After decoupling, the evolution depends only on the cosmology - **'large-scale structure in the linear regime'**.
  - Eventually the evolution becomes non-linear and complex structures like galaxies and clusters form - **'non-linear structure formation'**.



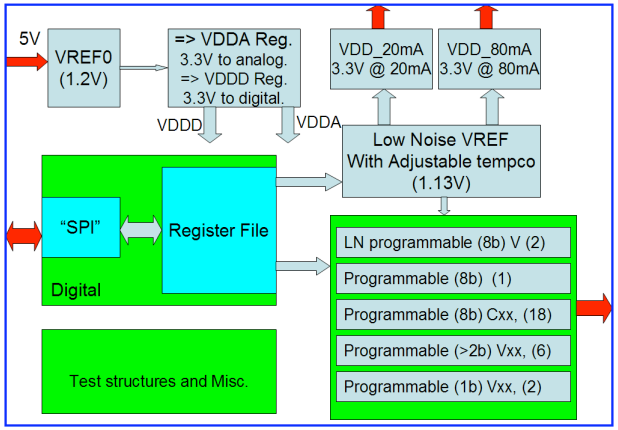
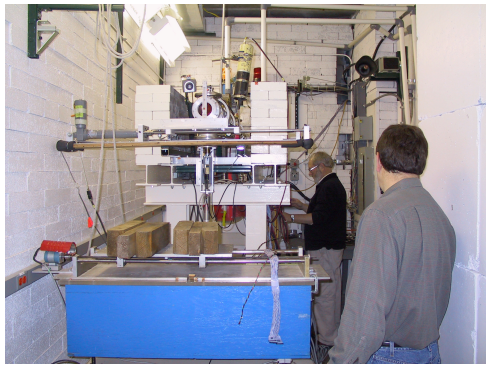
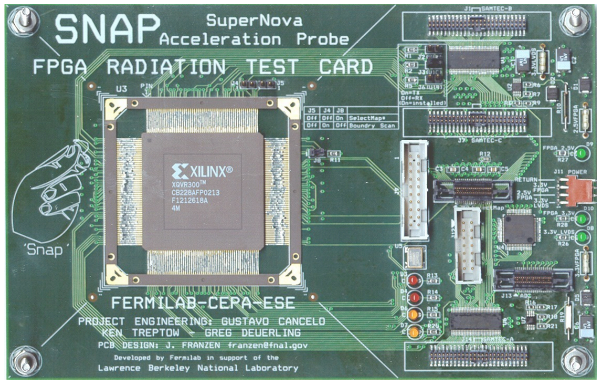
Mass Estimation







- 3 techniques for cluster selection and mass estimation
  - red galaxy clusters
  - weak lensing
  - Sunyaev-Zeldovich peaks in the SPT data
- We cross compare these techniques to reduce systematic errors
- Further consistency checks (or additional constraint power!)
  - cluster spatial correlation function
  - cluster mass function

SNAP at Fermilab II

- Focal plane electronics
  - Fermilab regulator IC (FRICO) ASIC
    - front end signal processing, clock and control for Raytheon IR chips
    - regulated voltages and bias, temperature control and regulation for entire focal plane
- Mass memory
  - flash memory
    - high density, low power
    - space radiation testing
      - protons at Indiana University cyclotrons
      - ions at LBNL heavy ion facility
  - FPGA
    - prototyping for memory interface/compression/error correction
    - space radiation testing