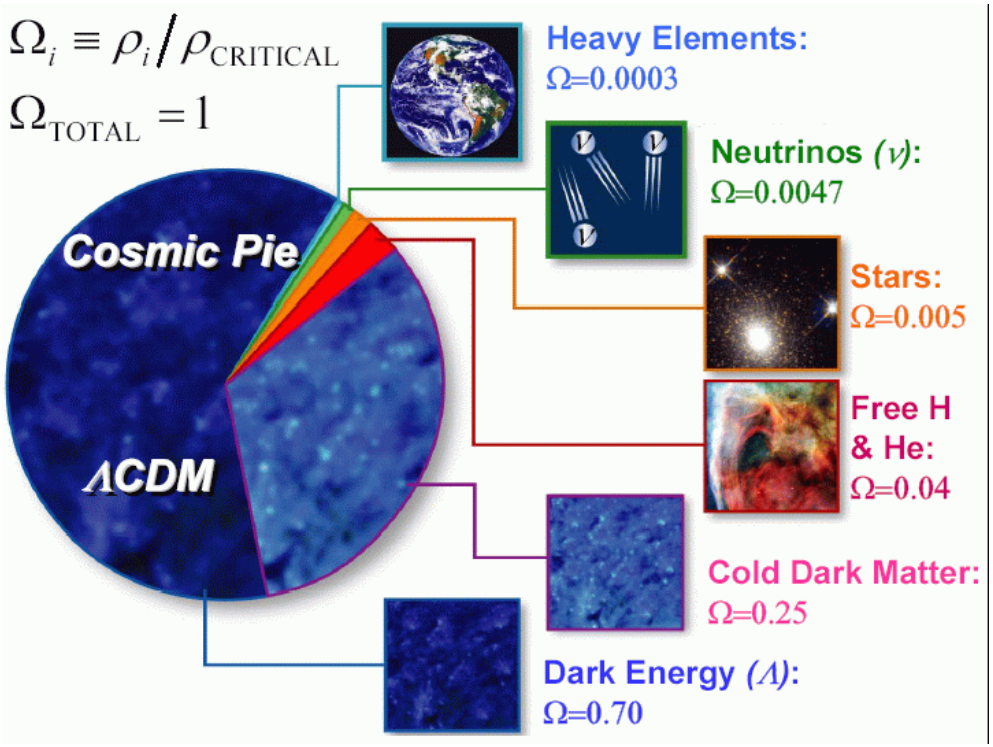
Dark Energy Survey (DES) Motivation

DARK ENERGY SURVEY



Dark Energy is the dominant constituent of the Universe
Dark Matter is next

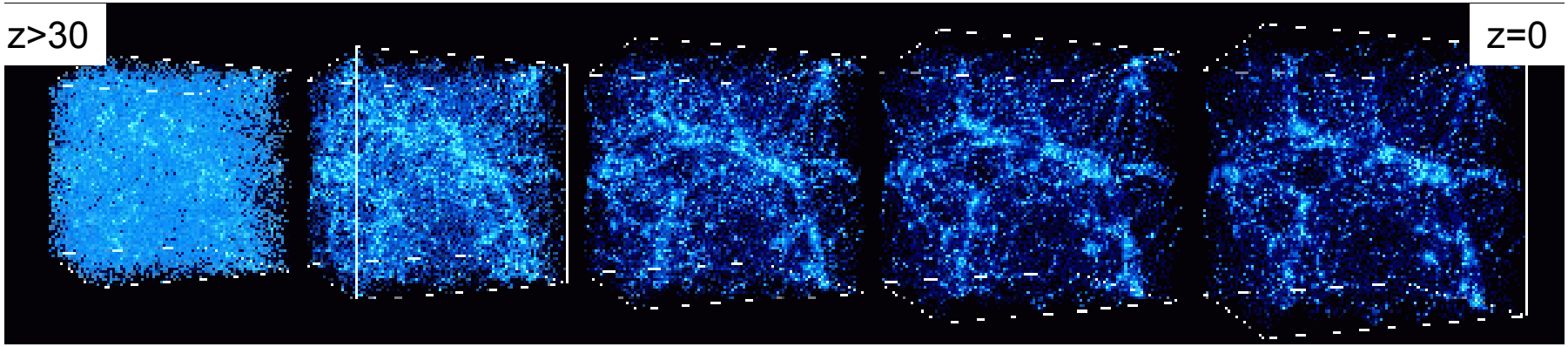
95% of the Universe is in Dark Energy and Dark matter for which we have no understanding

1998 and 2003 Science breakthroughs of the year

Probes of Dark Energy: Map the cosmological density field

DARK ENERGY SURVEY

DES will use 4 complementary techniques to characterize dark energy



Expansion and gravity

1. Count the Galaxy Clusters as a function red shift and cluster mass
2. Measure the distortion in the apparent shape of galaxies due to intervening galaxy clusters and associated clumps of dark matter (weak lensing)

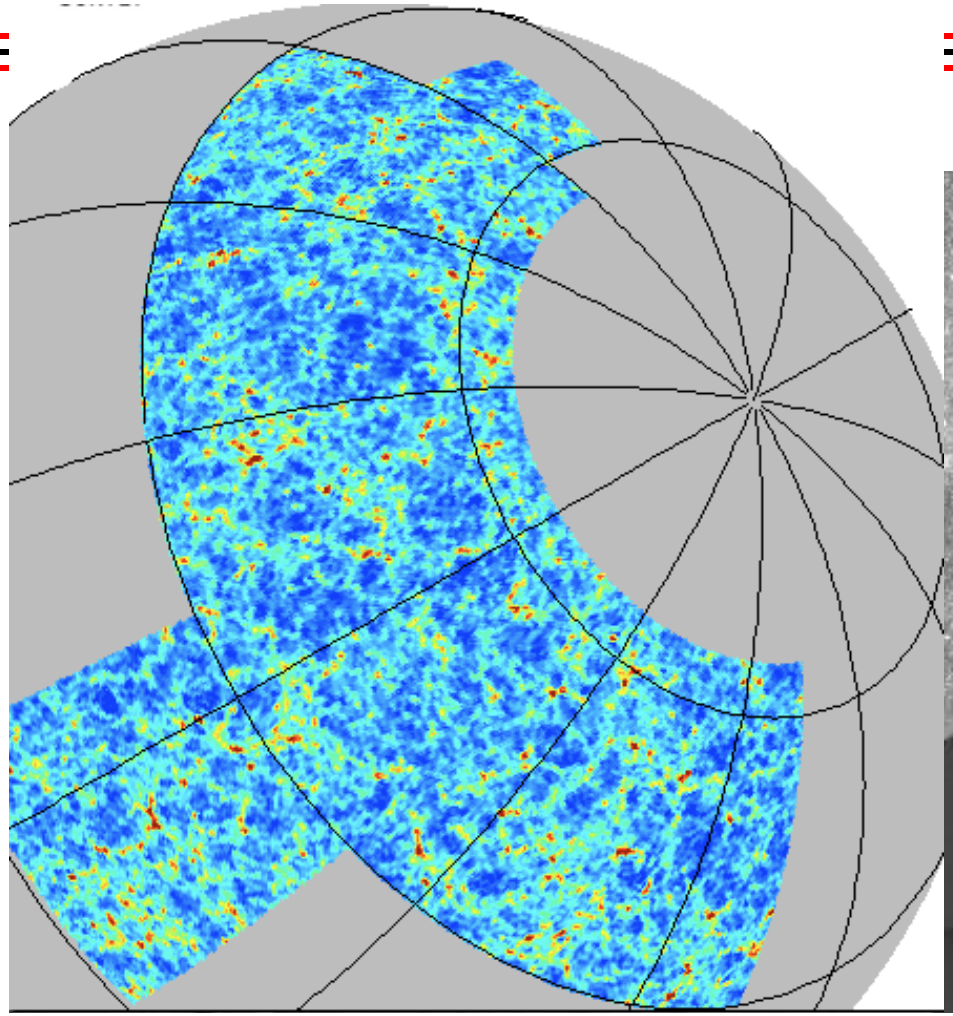
Expansion

3. Measure the spatial clustering of galaxies as a function of red shift (Baryon Acoustic Oscillations)
4. Use supernovae as standard candles to measure the expansion rate

The Dark Energy Survey Science

DARK ENERGY SURVEY

- Two multiband surveys:
  5000 deg^2 *g, r, i, Z,Y* to *i~24*
  9 deg^2 repeat (SNe)
- Observe:
  ~300M galaxies
  ~30K galaxy clusters
  ~2K SNe Ia
- DES Forecast: use the 4 techniques to improve the Dark Energy Task force Figure of merit by 4.6x



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

The Dark Energy Survey (DES)

DARK ENERGY SURVEY

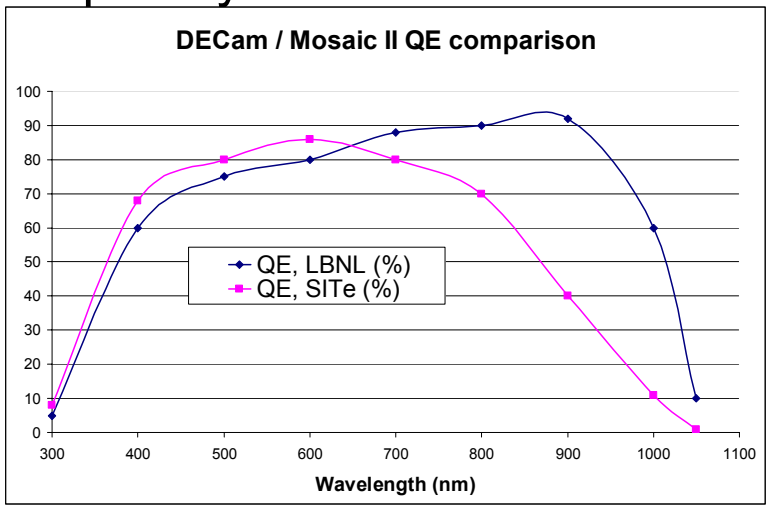
- New Instrument (DECam):
  - Replace the PF cage with a new 2.2 FOV, 520 Mega pixel CCD camera + optics
- Time scales:
  - CD2/3 approved in 2008
  - Inst. Construction 2008-2011
  - Survey: 525 nights during Oct.–Feb. 2011-2016
- Funding:
  - DOE, NSF, STFC (UK), Ministry of Education and Science (Spain), FINEP (Brazil), and the 11 Collaborating Institutions

Use the Blanco 4M Telescope at the Cerro-Tololo Inter-American Observatory (CTIO)

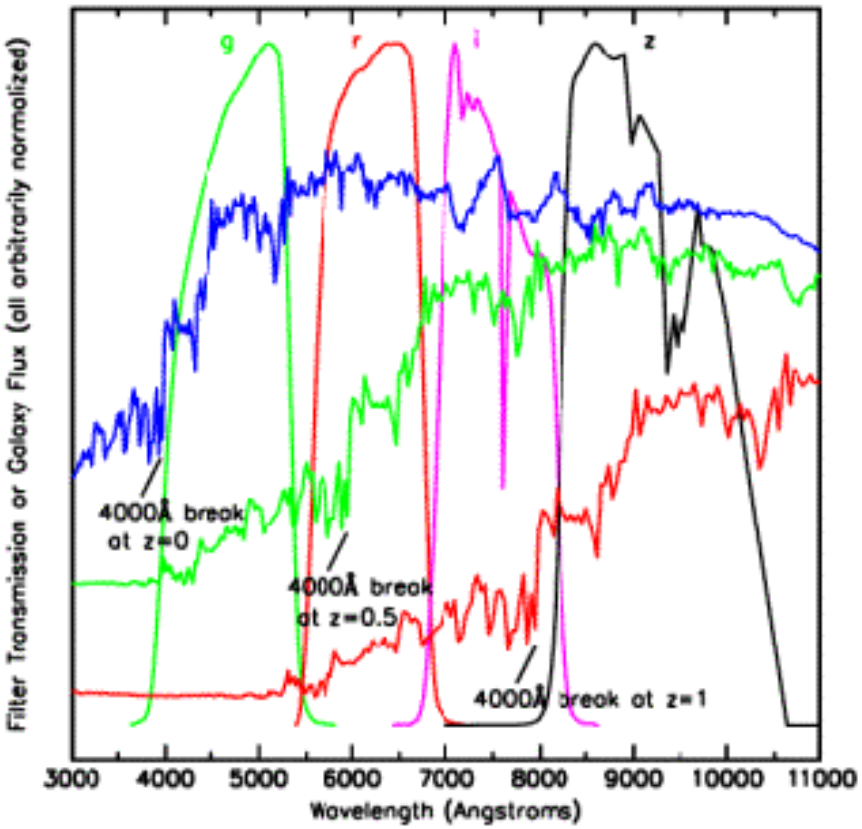
Photometric Redshifts

DARK ENERGY SURVEY

- Measure relative flux in multiple filters: track the 4000 A break
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Good detector response in *z* band filter needed to reach z~1 : Use thick CCDs developed by LBNL

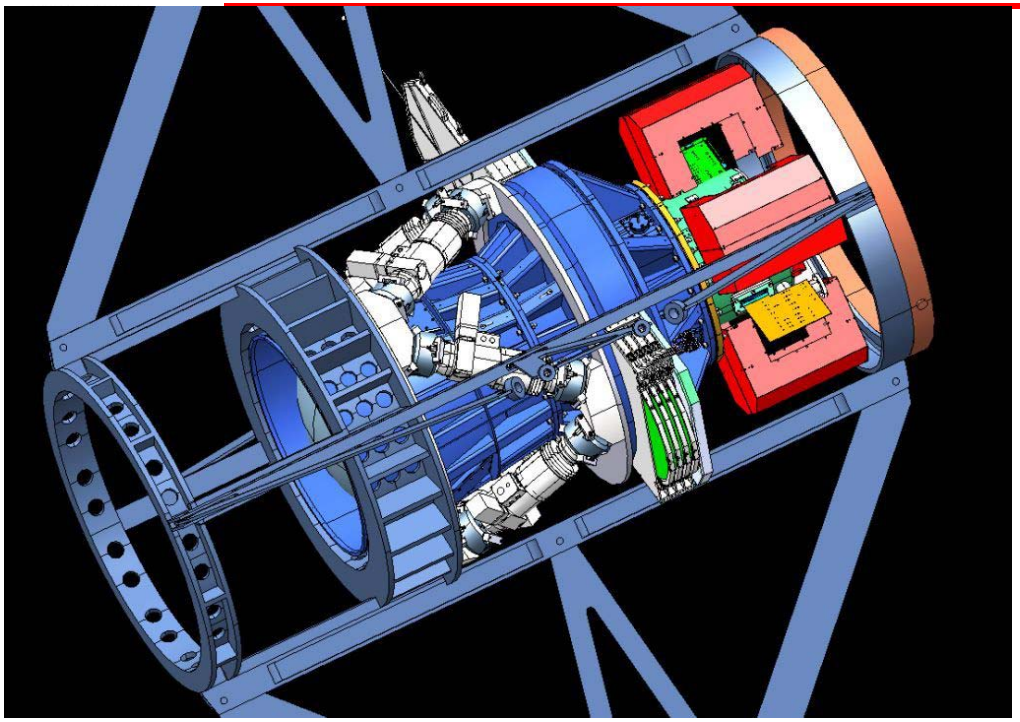


Elliptical galaxy spectrum

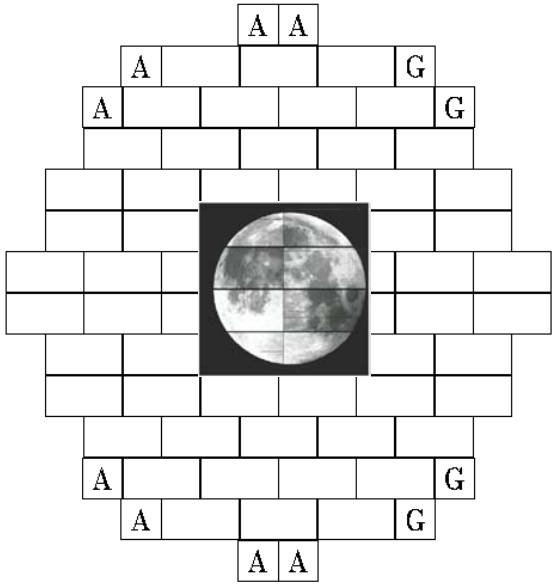


The DES Instrument: DECam

DARK ENERGY



DECam Focal Plane



- Hexapod provides focus and lateral alignment
- red sensitive CCDs (from LBNL)
- g,r,i,Z,Y filters
- low noise electronics (readout with < 10 e noise!)
- cryogenic (LN2) cooling system

3 sq. deg. field of view (~ 0.5 meter diameter focal plane)

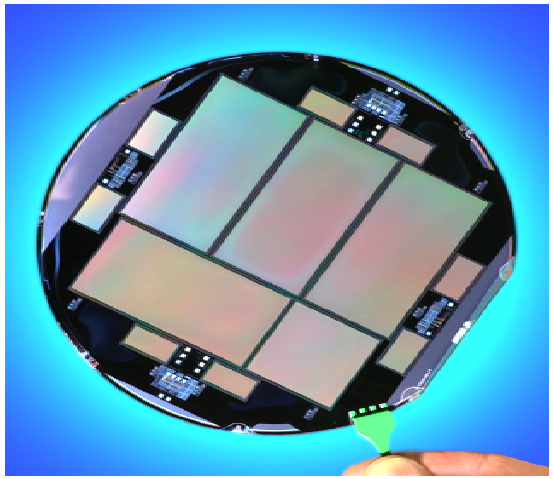
62 2kx4k Image CCDs: 520 MPix

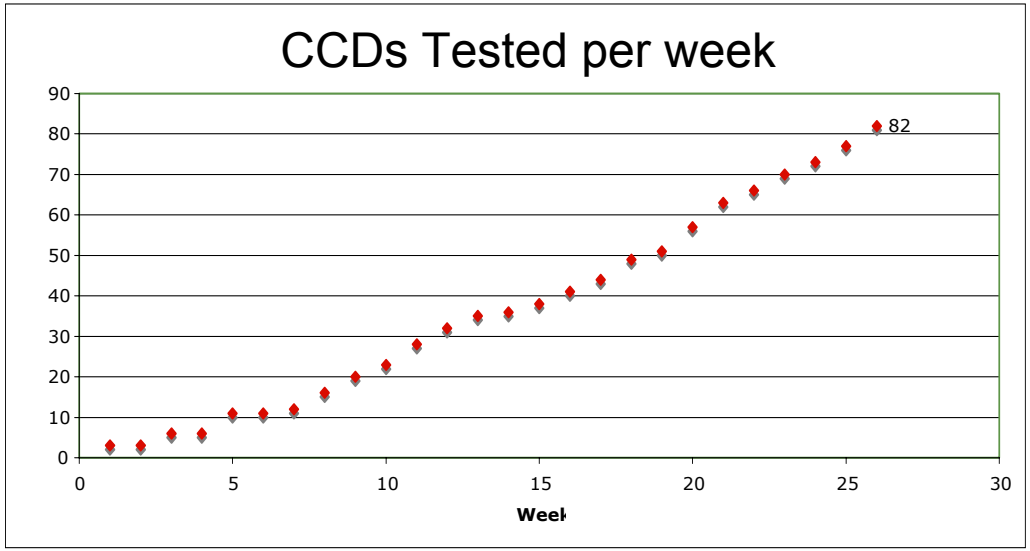
8 2kx2k Alignment/focus CCDs

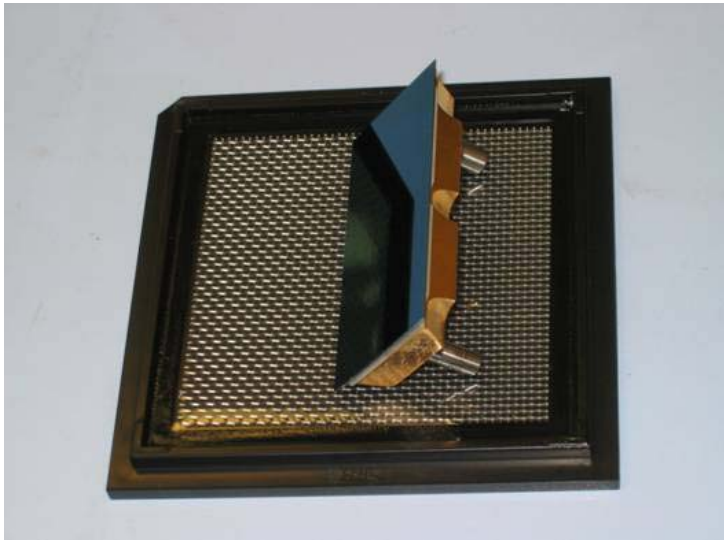
4 2kx2k Guide CCDs

CCD Packaging and Testing (At Sidet)

DARK ENERGY SURVEY







On schedule and yield is consistent with the baseline:

82 CCDs packaged and tested (started with lower quality devices to test the process)

As of 6/15/09 19 are Science Grade and ready for the focal plane!

Telescope Simulator (ready in early 2010)

DARK ENERGY SURVEY

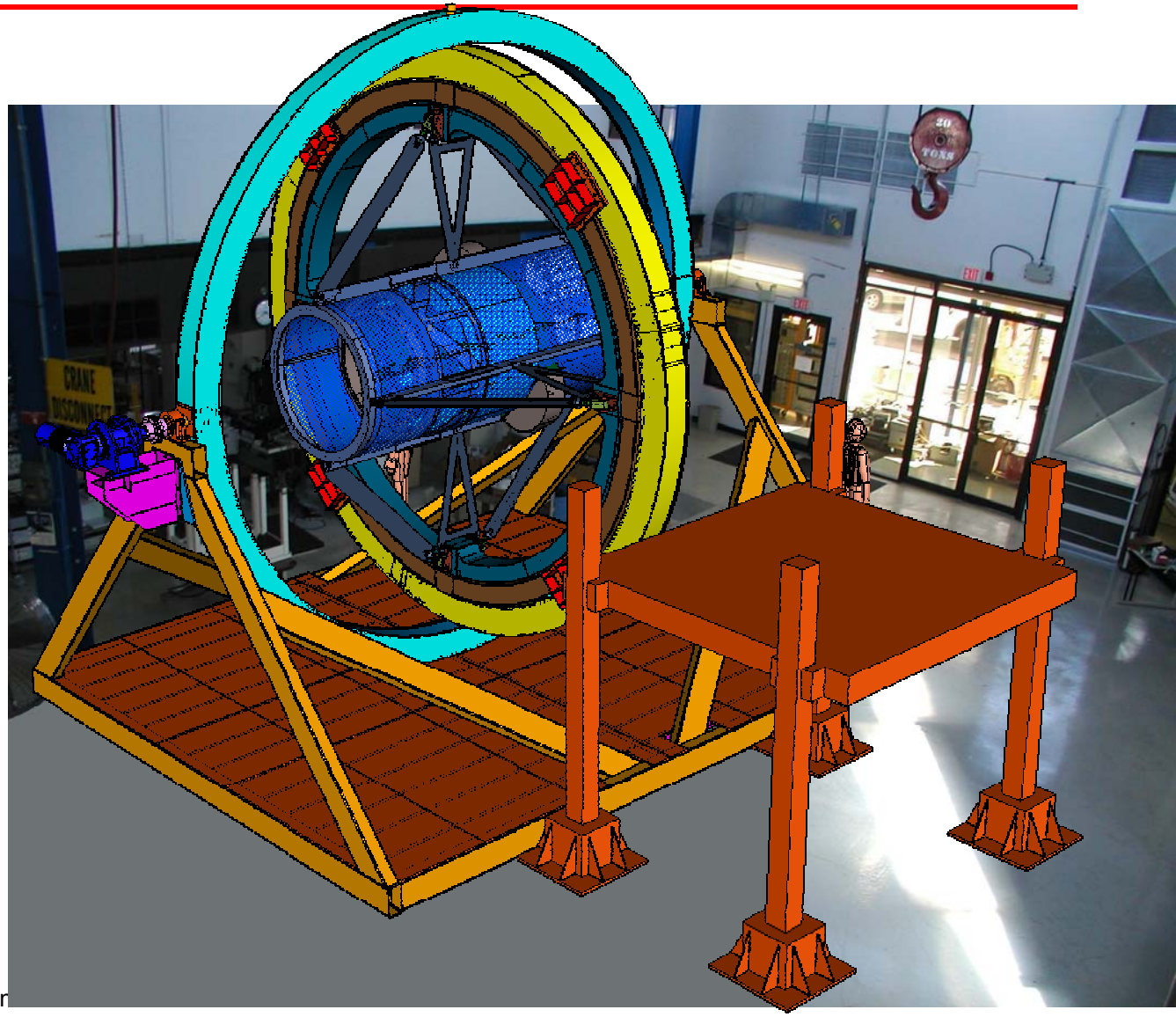
All DECam systems (except optics) will be integrated at Fermilab

Will test installation and operation in all orientations.

Inner two rings match top end of the telescope

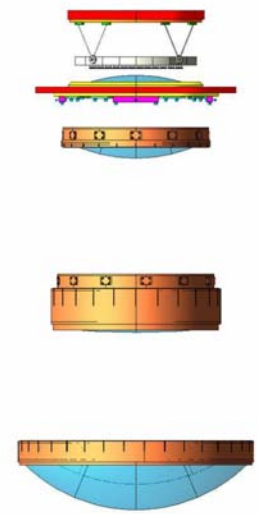
Outer two allow positioning in all orientations.

Design uses as many of the existing fabrication prints as possible



Optics Fabrication is in Progress in Europe

DARK ENERGY SURVEY



Design:

5 lenses, 2 aspheric surfaces

C1 is ~ 1m diameter, C5 is ~ 0.5m

Polishing contract awarded in April 2008 (~ 1.6 M pound grant to UCL from STFC). Est. Delivery to UCL Dec. 2009

UCL will install the lenses in the barrel provided by Fermilab and ship directly to Chile

C1 blank inspection

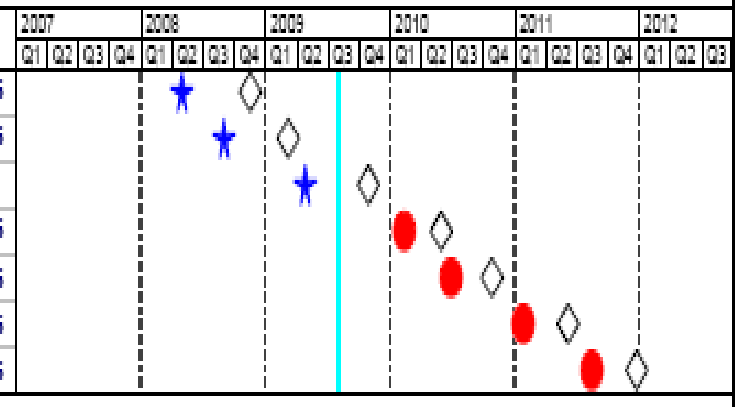
Milestones

DARK ENERGY SURVEY

- Level 1 Milestones: 7 (~ 1 every 6 months) tracked by DOE-OHEP
  - Three completed on or ahead of schedule. On track to complete the next one
- Level 2 Milestones: 56 (~ 1/6 months per WBS section) – tracked by Fermilab and DOE Site office

DECam L1 Milestones
Sorted By Baseline Start Date

WBS	Task Name	Baseline Start	Start	Baseline Variance
1.4.1.12.8	L1 - All Lens Blanks Complete	8/18/2008	1/31/2008	-27.6 wks
1.2.2.10.14	L1 - v2 CCD Processing and Packaging Review Complete	12/8/2008	6/2/2008	-25.8 wks
1.2.2.10.16	L1 - CCD's From 30th Production Wafer Delivered To FNAL	7/31/2009	1/26/2009	-26 wks
1.2.2.10.15	L1 - 128 CCD's Tested and Graded	3/1/2010	11/12/2009	-13.8 wks
1.5.2.12.1.13	L1 - Prime Focus Cage Complete	7/28/2010	3/29/2010	-16.8 wks
1.5.2.14.8	L1 - Camera and Telescope Simulator Tests Complete	3/7/2011	10/27/2010	-17.2 wks
1.1.6.16	L1 - Acceptance Testing Complete	9/24/2011	5/16/2011	-18.2 wks



Forecast delivery to CTIO has slipped from Dec. 2010 to Feb. 2011 (8 weeks) since the CD-2 review in Jan. 08.

Open Diamond = Baseline MS Date
Solid Red Circle = Forecast MS Date
Blue Star = Completed MS

Conclusions

- DECam Project is on schedule for delivery to CTIO in Feb. 2010
- Estimated cost to complete is consistent with Baseline cost + contingency
- $35M Total Project Cost
  - $16M spent
  - $14M of work and $5M contingency remaining

May 2008: 15 Engineering grade and 20 mechanical grade CCDs installed in prototype imager with preproduction electronics

DECam is on track for 'First light' (beginning of science observations) in September 2011

DARK ENERGY SURVEY

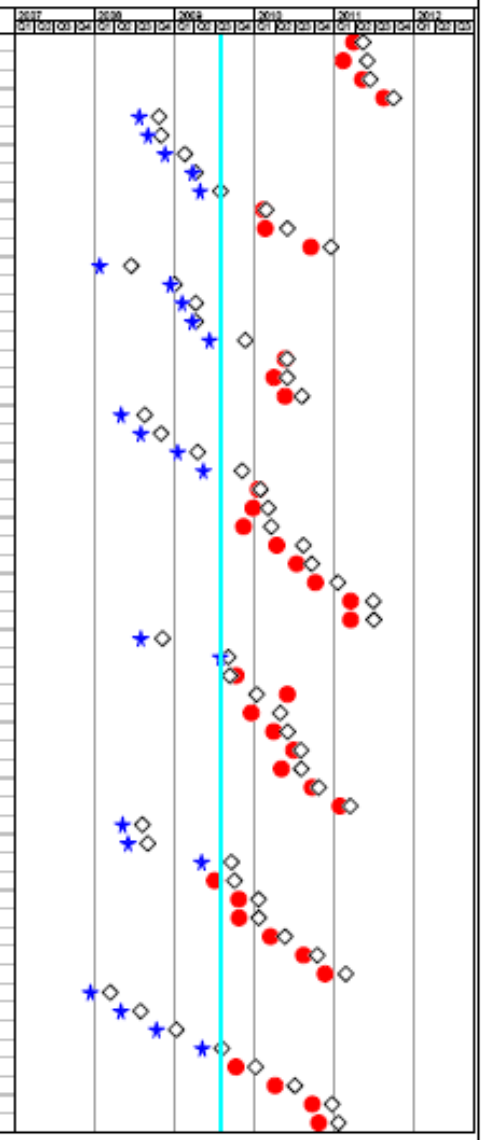
Cerro Tololo Inter-American Observatory

Extras

56 L2 milestones: Tracked by Fermilab and DOE site office

DECam L2 Milestones
Sorted By WBS & Baseline Start Date

WBS	Task Name	Baseline Start	Start	Baseline Variance
1.1.4.1.14	L2 - Integration Plans Ready For Delivery to CTIO	2/11/2011	12/28/2010	-5.8 wks
1.1.5.3	L2 - Corrector Arrives at CTIO	3/2/2011	11/11/2010	-14.2 wks
1.1.5.6	L2 - Camera and Prime Focus Cage Arrive at CTIO	3/15/2011	2/7/2011	-5 wks
1.1.5.13	L2 - Acceptance Testing Complete	7/1/2011	5/16/2011	-6.4 wks
1.2.1.10.5	L2 - Cold probe yield known for Lots 2C, 2D thinned wafers	7/22/2008	4/23/2008	-12 wks
1.2.2.10.9	L2 - v2 CCD Processing and Packaging Review Complete	8/1/2008	6/2/2008	-8.2 wks
1.2.1.10.6	L2 - Yield Estimate Based on Wafer processing R&D Complete	11/17/2008	8/19/2008	-12.6 wks
1.2.2.10.10	L2 - Design of v1 Guide and Focus Fixtures Complete	1/5/2009	12/23/2008	-0.4 wks
1.2.2.10.11	L2 - CCD's From 30th Production Wafer Delivered To FNAL	4/30/2009	1/26/2009	-13.4 wks
1.2.2.10.13	L2 - 128 CCD's Tested and Graded	11/25/2009	11/12/2009	-1.6 wks
1.2.2.10.12	L2 - CCD's From 60th Production Wafer Delivered To FNAL	3/2/2010	11/20/2009	-12.8 wks
1.2.2.10.17	L2 - Final Contingency CCD's at FNAL	9/17/2010	6/16/2010	-12.8 wks
1.3.1.13.5	L2 - CCD readout review - go ahead for V2	3/18/2008	10/26/2007	-18.6 wks
1.3.1.4.13	L2 - First Shipment of v2 Clock Cards Sent From Madrid	10/2/2008	9/12/2008	-2.6 wks
1.3.1.3.11	L2 - Vacuum Interface Boards v3 Ready For Testing	1/6/2009	11/5/2008	-7.2 wks
1.3.1.7.11	L2 - v1 Master Control Board testing Complete at Barcelona	1/7/2009	12/22/2008	-1 wk
1.3.2.12.5	L2 - Production Electronics Review Complete	8/21/2009	3/10/2009	-22.8 wks
1.3.2.4.9	L2 - Vacuum Interface Boards For Camera Tests Complete	3/1/2010	2/19/2010	-1 wk
1.3.2.8.1.12	L2 - DES Front End Electronic Production Complete	3/1/2010	12/30/2009	-7.8 wks
1.3.2.12.7	L2 - Front End Electronics Work Complete	5/7/2010	2/19/2010	-10.8 wks
1.4.1.12.7	L2 - All Lens Blanks Complete	5/19/2008	1/31/2008	-15.2 wks
1.4.3.4	L2 - Lens Polishing Contract Awarded	8/1/2008	4/30/2008	-12.4 wks
1.4.3.8	L2 - Review of Coating Plan	1/16/2009	10/15/2008	-11.8 wks
1.4.3.11	L2 - Intermediate Review of Polishing and Coating Progress	8/7/2009	2/10/2009	-24.8 wks
1.4.6.6	L2 - Ready To Order Filters	10/29/2009	10/19/2009	-1.6 wks
1.4.3.20	L2 - Factory acceptance of lenses before coating	12/4/2009	9/25/2009	-9.4 wks
1.4.7.4	L2 - Ready To Install Cells On Lenses at UCL	12/18/2009	8/13/2009	-17.3 wks
1.4.3.28	L2 - Final Lens Shipped To University College London	5/14/2010	1/11/2010	-17.4 wks
1.4.7.7	L2 - Barrel and C5 Cell Arrive At UCL From Fermilab	6/29/2010	4/12/2010	-9.6 wks
1.4.5.5	L2 - First Lens Installed In Barrel	10/18/2010	7/7/2010	-14.2 wks
1.4.6.12	L2 - Filters Complete	3/30/2011	12/15/2010	-13.8 wks
1.4.7.11	L2 - Corrector Assembly and Alignment Testing Complete	4/1/2011	12/15/2010	-14.2 wks
1.5.1.1.18	L2 - Preliminary Stray Light Analysis Complete	8/8/2008	4/30/2008	-13.4 wks
1.5.1.6.9	L2 - Prototype Imager Tests Complete	6/4/2009	4/29/2009	-5.1 wks
1.5.2.12.1.4	L2 - Design Review Of Prime Focus Cage & F/8 Plans Complete	6/12/2009	7/9/2009	3.6 wks
1.5.2.10.1.4	L2 - Barrel ready for telescope simulator	10/12/2009	3/1/2010	18.6 wks
1.5.2.10.1.11	L2 - Procurement of Barrel For UCL Complete	1/27/2010	9/17/2009	-17.4 wks
1.5.2.2.1.11	L2 - Imager Vessel Ready for CCD Installation	3/3/2010	12/29/2009	-8.5 wks
1.5.2.12.1.12	L2 - Prime Focus Cage Complete	5/3/2010	3/29/2010	-4.8 wks
1.5.2.4.4.4	L2 - Imager Shipping Container Design Complete	5/3/2010	2/2/2010	-12.8 wks
1.5.2.3.1.6	L2 - Camera Testing With CCD's Complete	7/29/2010	6/22/2010	-4.2 wks
1.5.2.14.7	L2 - Telescope Simulator Tests Complete	12/14/2010	10/27/2010	-6.2 wks
1.6.1.1.5	L2 - Conceptual Design of Infrastructure Software Complete	5/7/2008	2/7/2008	-12.8 wks
1.6.13.4	L2 - SISPI Subsystems Requirements Documents Complete	6/1/2008	3/3/2008	-12.4 wks
1.6.13.6	L2 - SISPI Subsystem Prototypes Complete	6/18/2009	2/2/2009	-19.4 wks
1.6.6.6	L2 - Image Acquisition and Data Transport Complete	7/2/2009	4/3/2009	-12.6 wks
1.6.4.5	L2 - Image Stabilization Control System Complete	10/20/2009	7/22/2009	-12.4 wks
1.6.1.5.4	L2 - SISPI Application Software (System Level) Complete	10/21/2009	7/23/2009	-12.4 wks
1.6.12.3.4	L2 - System Software Integration Complete	2/19/2010	12/14/2009	-8.6 wks
1.6.12.4.6	L2 - SISPI Subsystem Integration and Tests at FNAL Complete	7/16/2010	5/14/2010	-8.4 wks
1.6.12.8	L2 - SISPI Integration at CTIO Complete	11/24/2010	8/20/2010	-13.2 wks
1.7.3.4.5	L2 - Level 3 Test Images Complete	12/12/2007	9/13/2007	-12.4 wks
1.7.3.4.10	L2 - Image Simulation Level 3 Complete	4/29/2008	1/30/2008	-12.8 wks
1.7.3.2.7	L2 - Level 4 Final Catalogs Complete	10/9/2008	7/11/2008	-12.6 wks
1.7.3.4.18	L2 - Image Simulation Level 4 Complete	5/8/2009	2/5/2009	-12.8 wks
1.7.3.2.13	L2 - Level 5 Final Catalogs Complete	10/9/2009	7/9/2009	-12.2 wks
1.7.1.6	L2 - Final Observing Plan Complete	4/4/2010	1/4/2010	-12.6 wks
1.7.3.4.24	L2 - Image Simulation Complete	9/21/2010	6/23/2010	-12.4 wks
1.7.5.2	L2 - Survey Strategy Complete	10/20/2010	7/22/2010	-12.6 wks



Open Diamond = Baseline MS Date

Solid Red Circle = Forecast MS Date

Blue Star = Completed MS

23 completed on or ahead of schedule

Now we are in the hard part. Forecast delivery to CTIO has slipped from Dec. 2010 to Feb. 2011 (8 weeks) since the CD-2 review in Jan. 08.

DES Participating Institutions

DARK ENERGY SURVEY

- **Fermilab**
- **University of Illinois at Urbana-Champaign**
- **University of Chicago**
- **Lawrence Berkeley National Laboratory**
- **University of Michigan**
- **NOAO/CTIO**
- **Spain-DES Collaboration:**
  Institut d'Estudis Espacials de Catalunya (IEEC/ICE), Institut de Fisica d'Altes Energies (IFAE), CIEMAT-Madrid:
- **United Kingdom-DES Collaboration:**
  University College London, University of Cambridge, University of Edinburgh, University of Portsmouth, University of Sussex
- **The University of Pennsylvania**
- **Brazil-DES Consortium**
- **The Ohio State University**
- **Argonne National Laboratory**

12 participating institutions and >100 participants

DES Funding from DOE, NSF, STFC (UK), Ministry of Education and Science (Spain), FINEP (Brazil), and the Collaborating Institutions

DES Forecasts: Power of Multiple Techniques

DARK ENERGY SURVEY

$w(z) = w_0 + w_a(1-a)$

Assumptions:

Clusters:

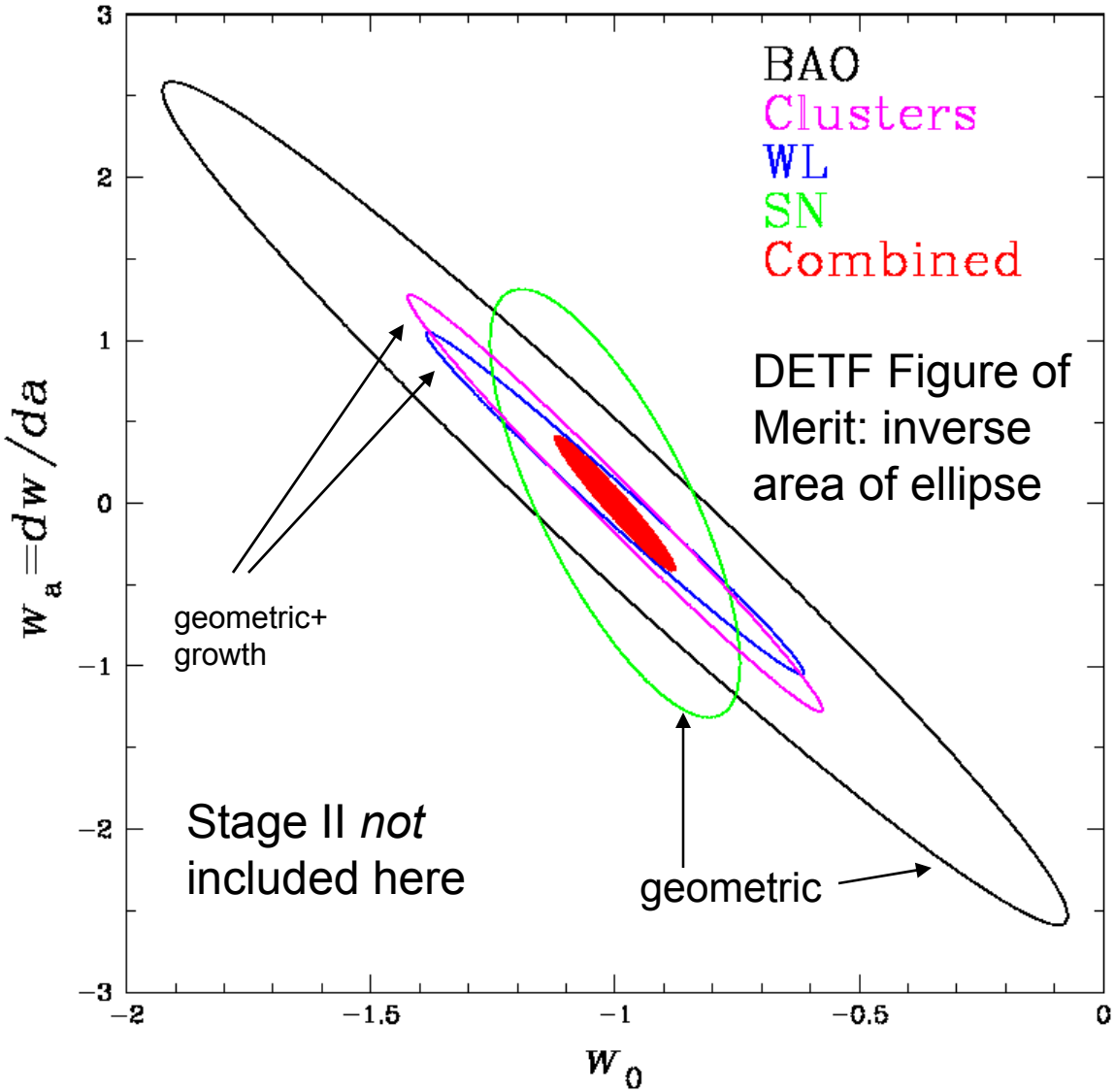
σ_8=0.75, z_{max}=1.5,
WL mass calibration

BAO: ℓ_{max}=300
WL: ℓ_{max}=1000

Statistical+photo-z systematic errors only

Spatial curvature, galaxy bias marginalized, Planck CMB prior

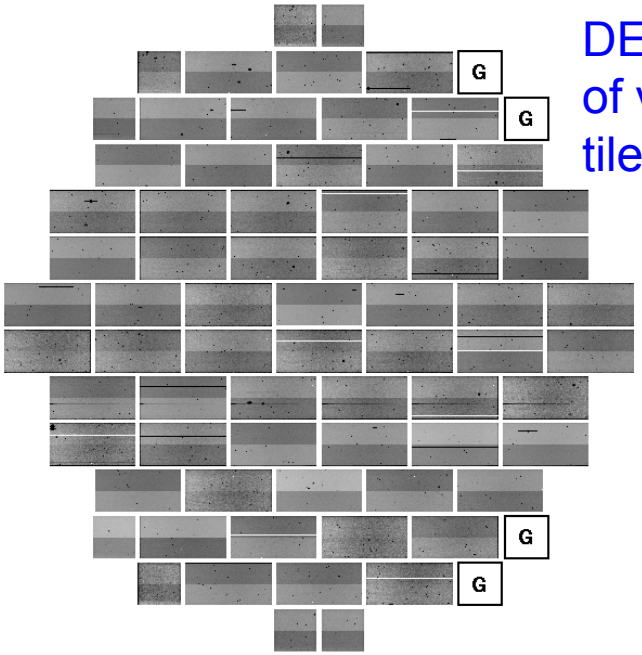
Factor 4.6 relative to Stage II



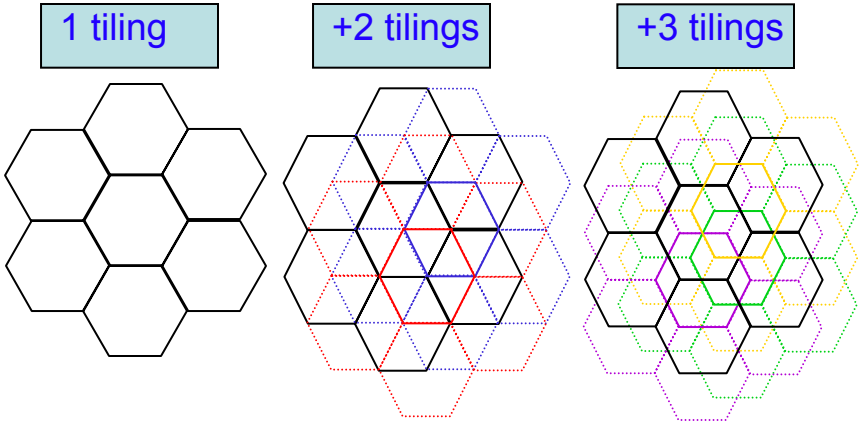
Survey Planning

DARK ENERGY SURVEY

- Determination (simulation) of an efficient observing strategy
  - Optimize for excellent photometric calibrations
- Simulation of mock raw DECam survey images, including galaxies and stars, and instrumental effect
- Status: On schedule



DECam 3 deg^2 field of view (= 1 hex = 1 tile = 1.1 GB)



- DES "tiles" 5000 deg^2 of sky at a rate of 2 times per year in each of 4 filters, constraints on DE possible after two years

Forecast Constraints

DARK ENERGY SURVEY

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	DETF FoM $[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.

- DES+Stage II combined = Factor 4.6 improvement over Stage II combined
- Large uncertainties in systematics remain, but FoM is robust to uncertainties in any one probe, and we haven't made use of all the information.
- Further detail of these forecasts is contained in the Dark Energy Science Program.

On-Sky Tests

DARK ENERGY SURVEY

- DECam runs on the 1m at CTIO provide calibration information and a test bed for DECam hardware
- October 2008
  - 1 DECam CCD
  - with Monsoon electronics
  - in a small test dewar
  - on the CTIO 1m (next to the Blanco)
  - VRI filters
- Next run is June 09, proposal submitted for following semester

Cluster of Galaxies: Largest gravitationally bound objects

Size ~ 10^{25} cm ~ Megaparsec (Mpc); Mass ~ 10^{15} Msun

DARK ENERGY SURVEY

What is the cluster redshift?

What is the cluster mass?

not completely different from jet clustering in collider physics but also have depth (red shift) info.

SDSS data

DES Timeline

DARK ENERGY SURVEY

- 2004: Fermilab and National Optical Astronomy Observatory (NOAO) approvals
- 2005: Nov. DOE approved CD-0 (Mission Need) for a ground based DE project
- 2006: P5 and the Dark Energy Task Force
  - Dark Energy Task Force report recommended projects like DES
  - P5 recommendation to proceed with DES. Reiterated this in 2008
- 2007: Oct. CD-1 approval
- 2008: May CD2/3a approval (Baseline and long lead procurements start for $35M project)
- 2008: Oct. CD-3b (construction) approval
- 2009: July Status review by NSF and DOE
- 2011: Start of observations!

I. Clusters and Dark Energy

DARK ENERGY SURVEY

- Requirements
  1. Understand formation of dark matter halos
  2. Cleanly select massive dark matter halos (galaxy clusters) over a range of redshifts
  3. Redshift estimates for each cluster
  4. Observable proxy that can be used as cluster mass estimate

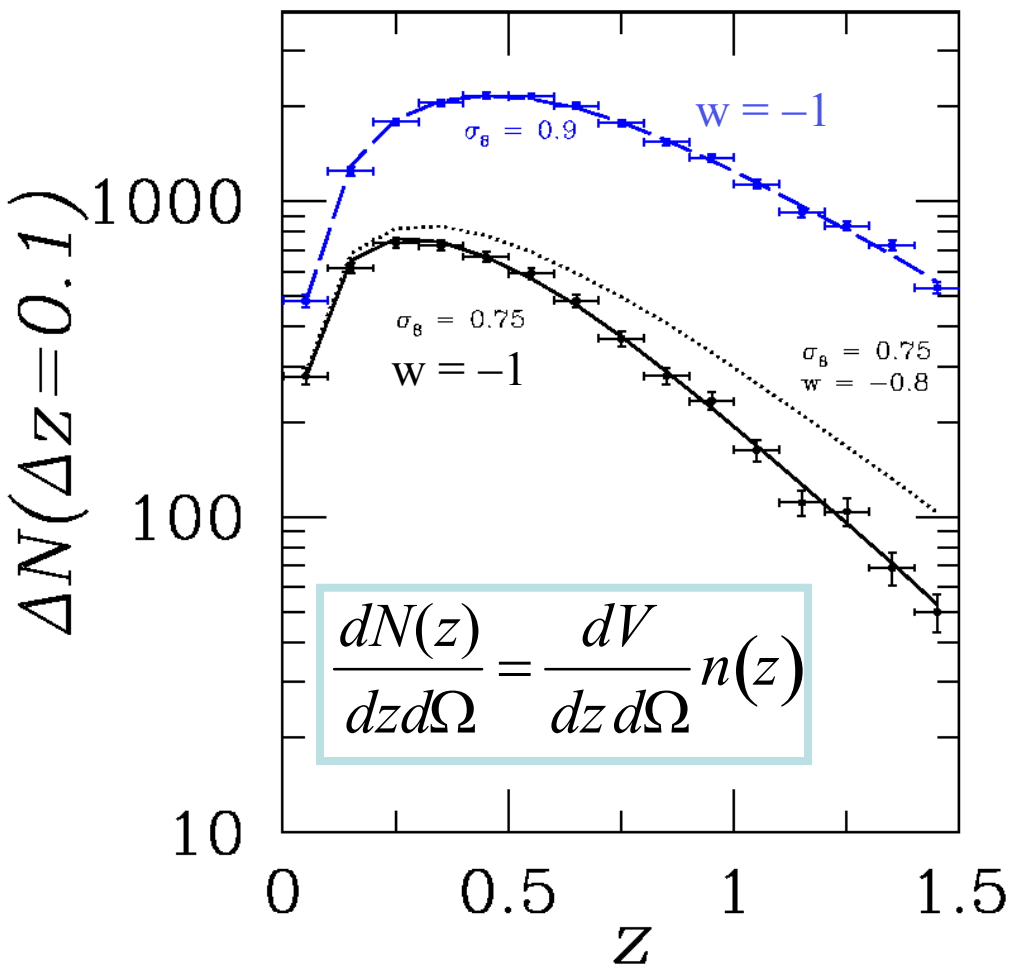
     g(O|M,z)

Primary systematics:

Uncertainty in *g* (bias & scatter)

Uncertainty in *O* selection fn.

Number of Clusters vs. Redshift



$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega} n(z)$$

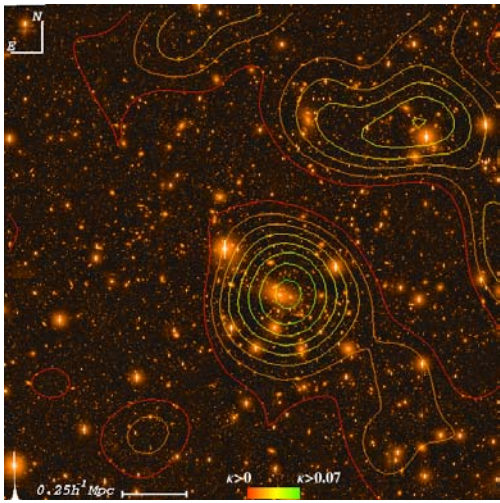
Cluster Cosmology with DES

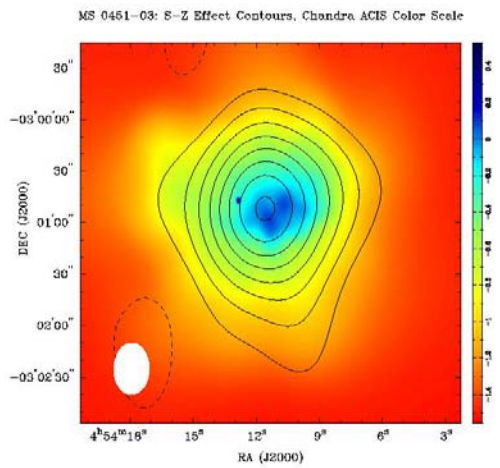
DARK ENERGY SURVEY

- 3 Techniques for Cluster Selection and Mass Estimation:
  - Optical galaxy concentration
  - Weak Lensing
  - Sunyaev-Zel'dovich effect (SPT)
- Cross-compare these techniques to reduce systematic errors
- Additional cross-checks:

  shape of mass function N(M,z)

  cluster spatial correlations $\xi_M(r;z)$





10-m South Pole Telescope (SPT)

DARK ENERGY SURVEY

Sunyaev-Zel'dovich effect (SZE)

Compton upscattering of CMB photons
by hot gas in clusters

- nearly independent of redshift
  - can probe to high redshift
  - need ancillary redshift measurement from DES

DES survey area encompasses
4000 sq. deg. SPT SZE Survey
Survey; SPT collecting data *now*

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