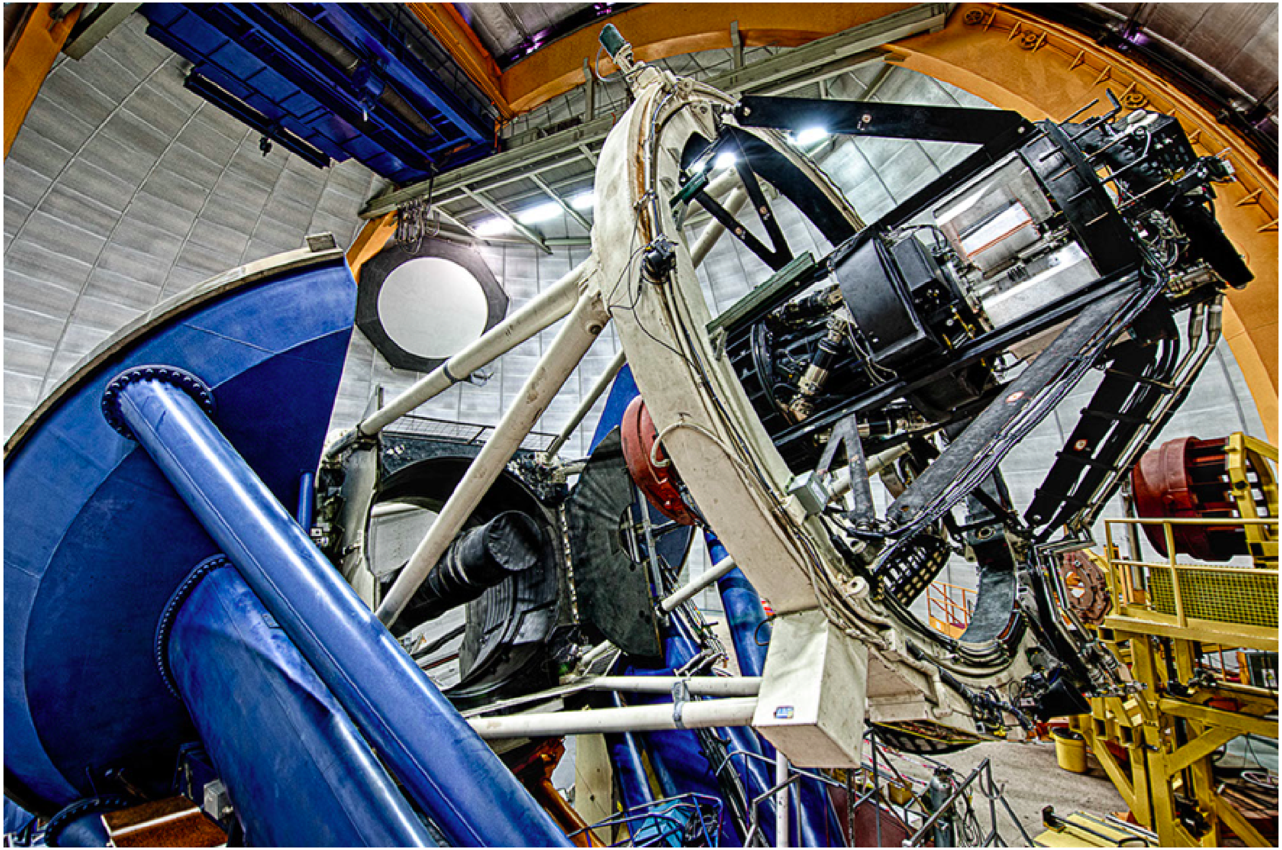
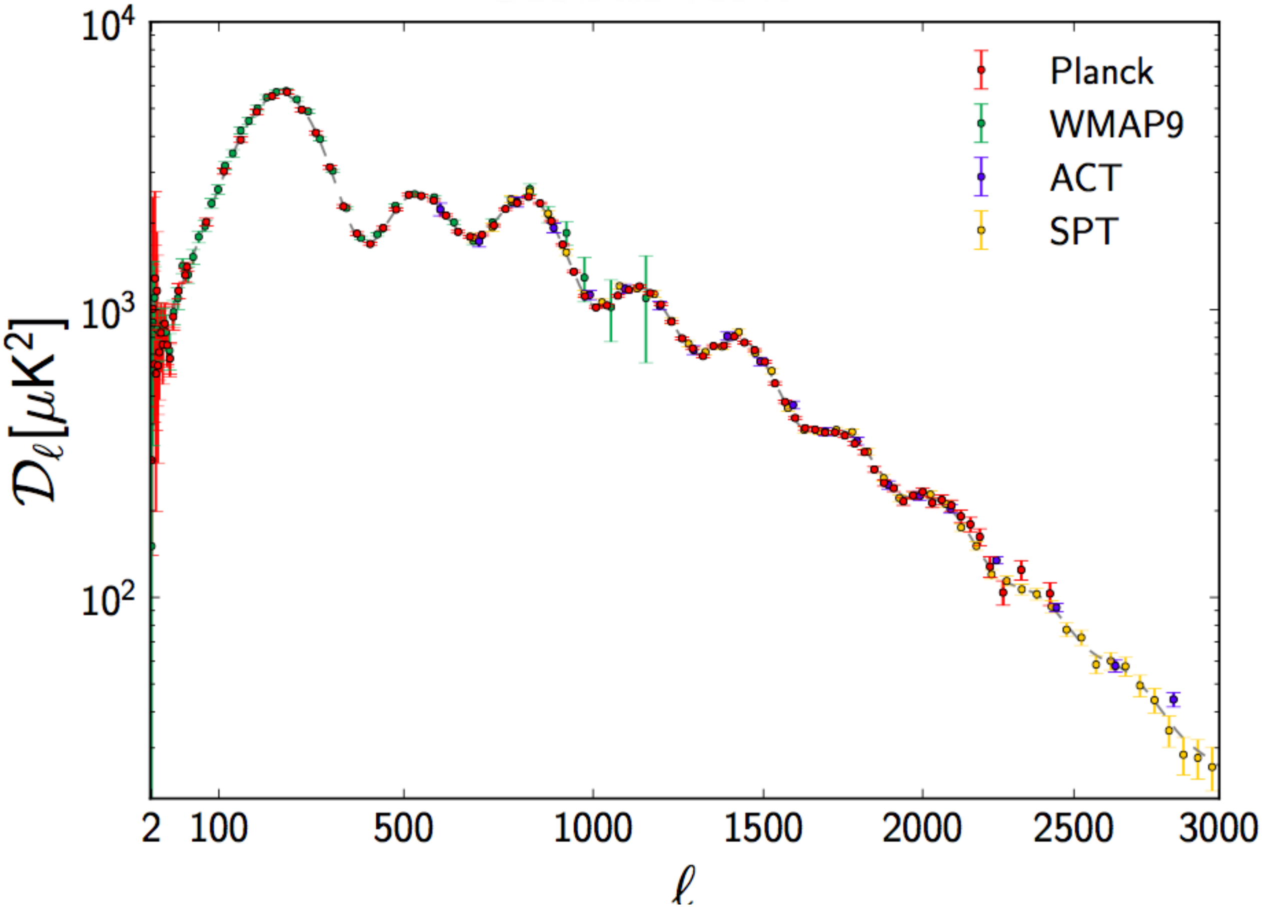
An Overview of the Dark Energy Survey



James Annis,

Center for Particle Astrophysics, Fermilab
International Conference on New Frontiers in Physics,
Orthodox Academy of Crete, September 5, 2013

Context: the seven peaks of Planck



The observed radiation temperature angular power spectrum. Planck measured 7 peaks, ACT and SPT several more. There is information in both the location of the peaks and in their amplitudes. From Planck I.

Observational cosmology from Plank

Technical

θ_{sound}	0.596724°	±0.00038°	angular size of sound horizon
r_{sound}	147.70	±0.63 Mpc	physical size of sound horizon
z_{sound}	1059.43	±0.64	redshift to sound horizon

The FRW metric has a free function of time, the scale factor a(t). We most often use the observable redshift, z, where $a = (1+z)^{-1}$. The Hubble parameter is the ln derivative of a(t): H = d/dt ln(a).

Cosmology

Age	13.796	±0.058 Gyr	age of the universe
H_0	67.9	±1.5 km/s/Mpc	size scale of the universe
Ω_k	-0.0010	±0.0065	geometry of the universe

The global geometry of the universe is Euclidean. (!)

Matter content

Ω_ν	<0.00024		total neutrino density
Ω_b	0.0497	±0.0007	normal matter density
Ω_m	0.307	±0.019	total matter density
Ω_λ	0.693	±0.019	dark energy density
w	-1.13	±0.24	dark energy equation of state

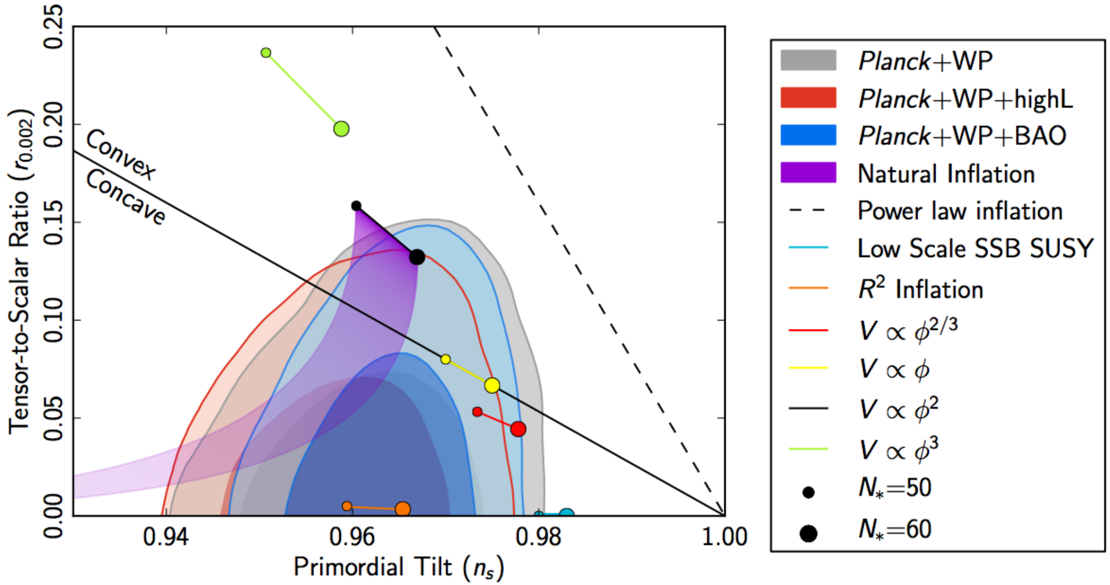
Distances in cosmology:
$D = c \int_0^z dz' H(z)^{-1}$, *where*

$$H^2(z) = H_o^2[\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\lambda(1+z)^0]$$

though if dark energy isn't a cosmological constant, the Ω_λ *term becomes* $\Omega_\lambda e^{-3\int_0^z d\ln(1+z')[1+w(z')]}$

The lack of a distance to the CMB is due to a degeneracy: the acoustic scale is a ratio $r_s/D(r_s)$, where $r_s = \int_{z_s}^{\infty} c_s H(z)^{-1} dz$ and $D(r_s) = \int_0^{z_s} H(z)^{-1} dz$. This can be broken using galaxy based BAO observations. Thus for Ω_k, Ω_ν, and w, CMB+BAO constraints were used.

The universe is Euclidean? Why is that?? inflation physics from Planck



The pragmatic working hypothesis is inflation- inflating away the initial curvature. The Planck data is consistent: there are nearly scale invariant spectrum (n_s = 0.960 ±0.007) and nearly Gaussian fluctuations ($f_{NL}{}^{local}$ = 2.7 ±5.8; Gaussian to 0.01%). (From Planck XXII and Planck XIV).

What underlies the inflation paradigm? Planck prefers the simplest inflationary models - single fields and slow rolls.

The model in the center of the Planck constraints is R^2 inflation, a gravitational solution motivated by including semi-classical quantum effects- a prediction, actually, pre-Guth (Starobinsky 1980). This needs no new interaction, which is a pleasingly minimal extensions to the SM. If one prefers to add no new scalar field one can design a Higgs inflation that suffices (e.g., Gorbunov; Bezrukov).

Dark energy I

After the horizon and flatness problems, solved by inflation, the biggest problem is the nature of dark energy.

Planck narrowed down parameter space, but we learned little.

In fact- we now understand the matter dominated phase of the universe at $z=1000$ better than we do the universe about us at $z = 0$.

Part of the solution is mapping the structure we see at $0 < z < 1.0$;, our contribution is the Dark Energy Survey.

The Dark Energy Survey

- Stage III dark energy project using 4 complementary techniques from imaging:
  - i supernova
  - ii large scale structure
  - iii clusters of galaxies
  - iv weak lensing
- Two multiband surveys
  - i 5000□° g,r,i,z,y bands to 24th magnitude
  - ii 30□° g,r,i,z band time domain survey, weekly visits, 5 month seasons over 5 years
- 500 megapixel camera & optics, DECam (Fermilab & collaboration)
- new data reduction system for DECam (NCSA & collaboration)
- 4m Blanco telescope for 525 nights over 5 years (NOAO/NSF)
- astronomical community has access to Blanco/DECam for ≈250 nights/year

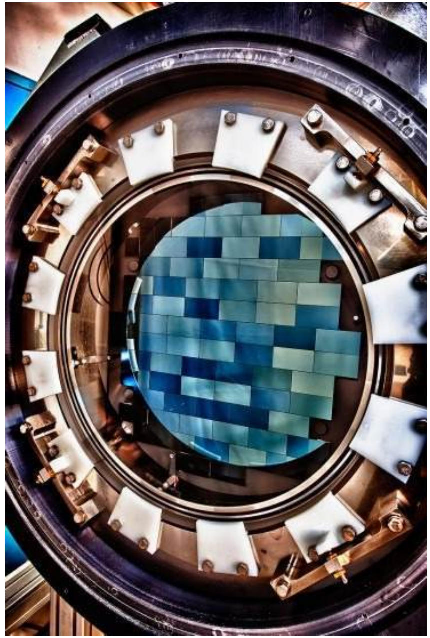


Figure 1: DECam focal plane CCDs- 62 full depletion LBNL ccds with very high red quantum efficiency. (photo credit: Fermilab)

The telescope simulator and DECam

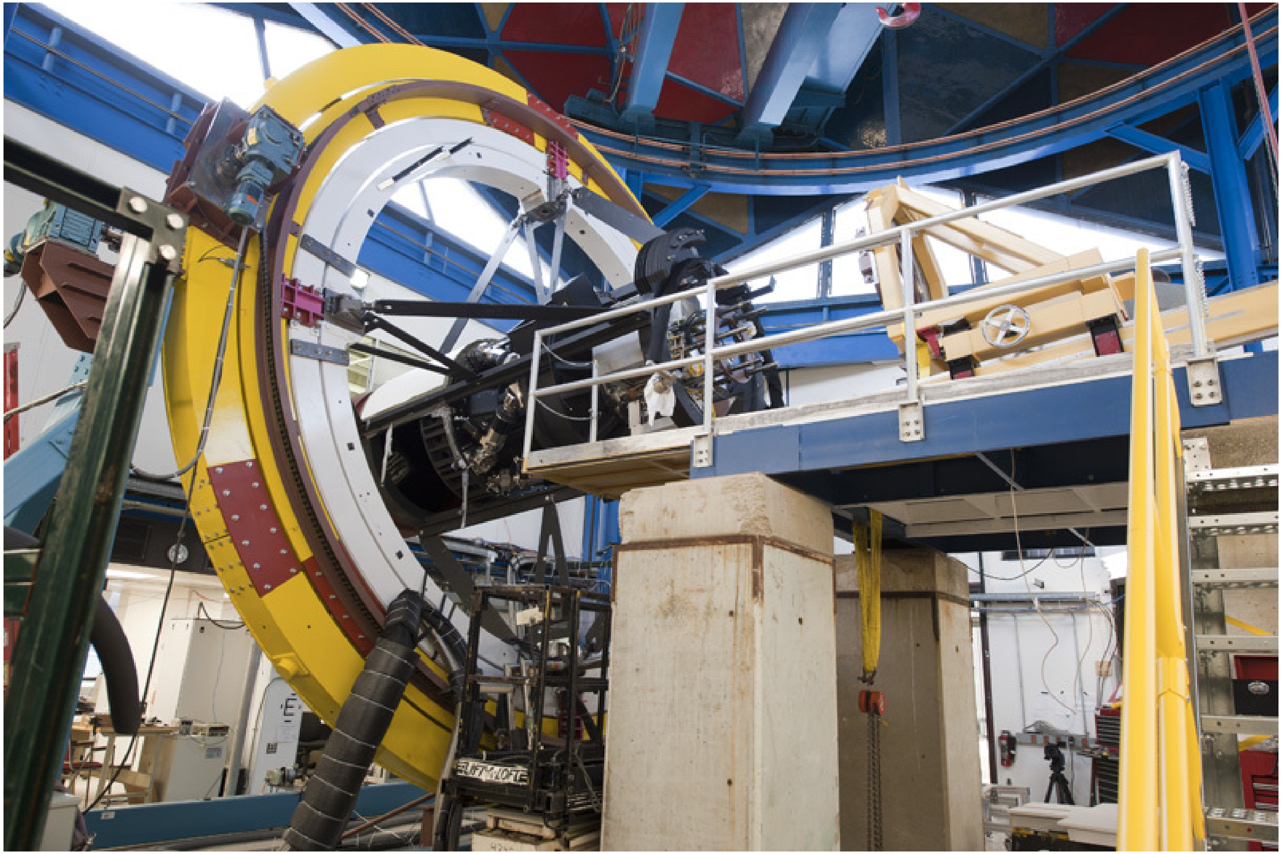


Figure 2: (photo credit: Fermilab)

Instead of a long commissioning at the telescope in Chile, we constructed a telescope simulator at Fermilab and commissioned there. Cooling the focal plane in a moving 3-d environment needed testing.

DECam on the Blanco telescope

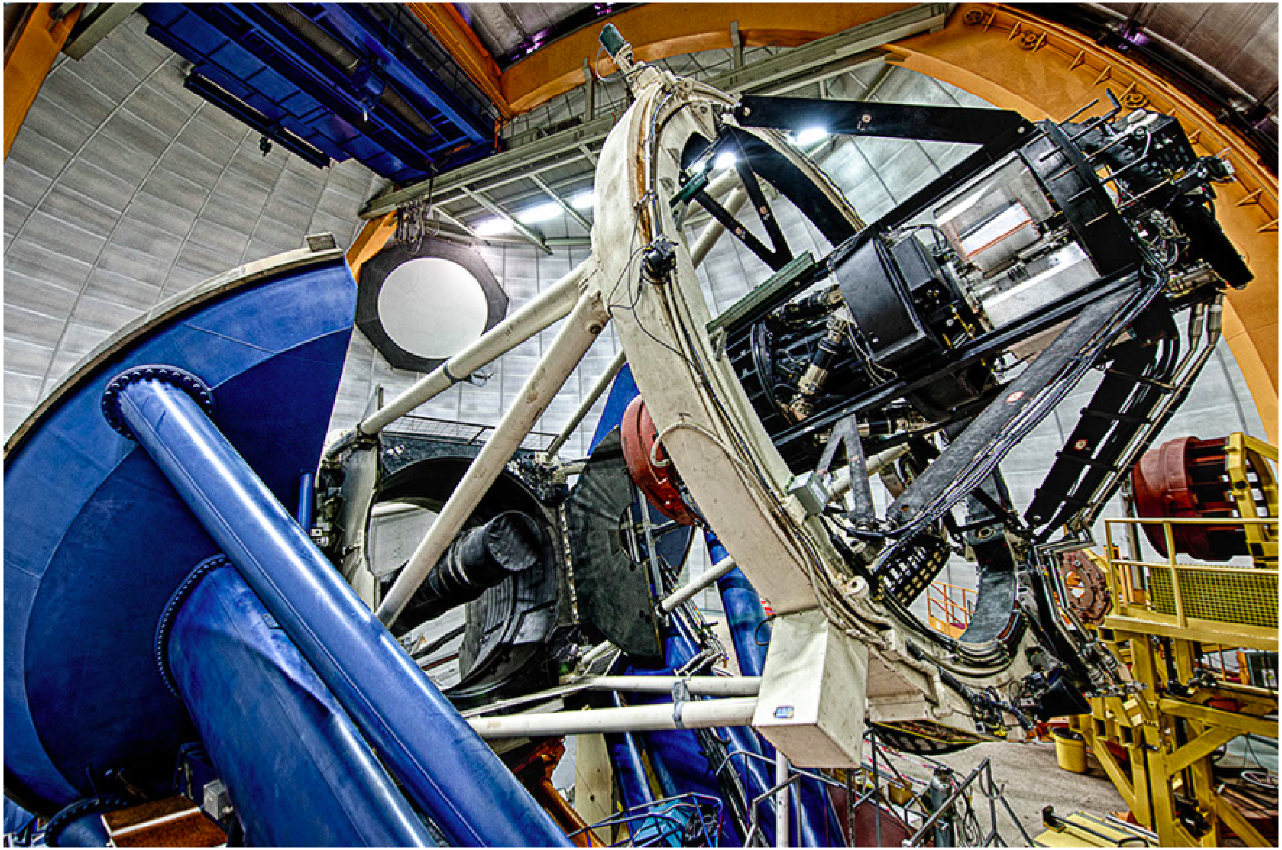


Figure 3: (photo credit: Fermilab)

During the 2012-2013 observing season we installed, commissioned and operated DECam on the Blanco. Much of the time was spent learning how to operate the performance of the essentially rebuilt telescope at the level we need for our data quality standards.

The telescope

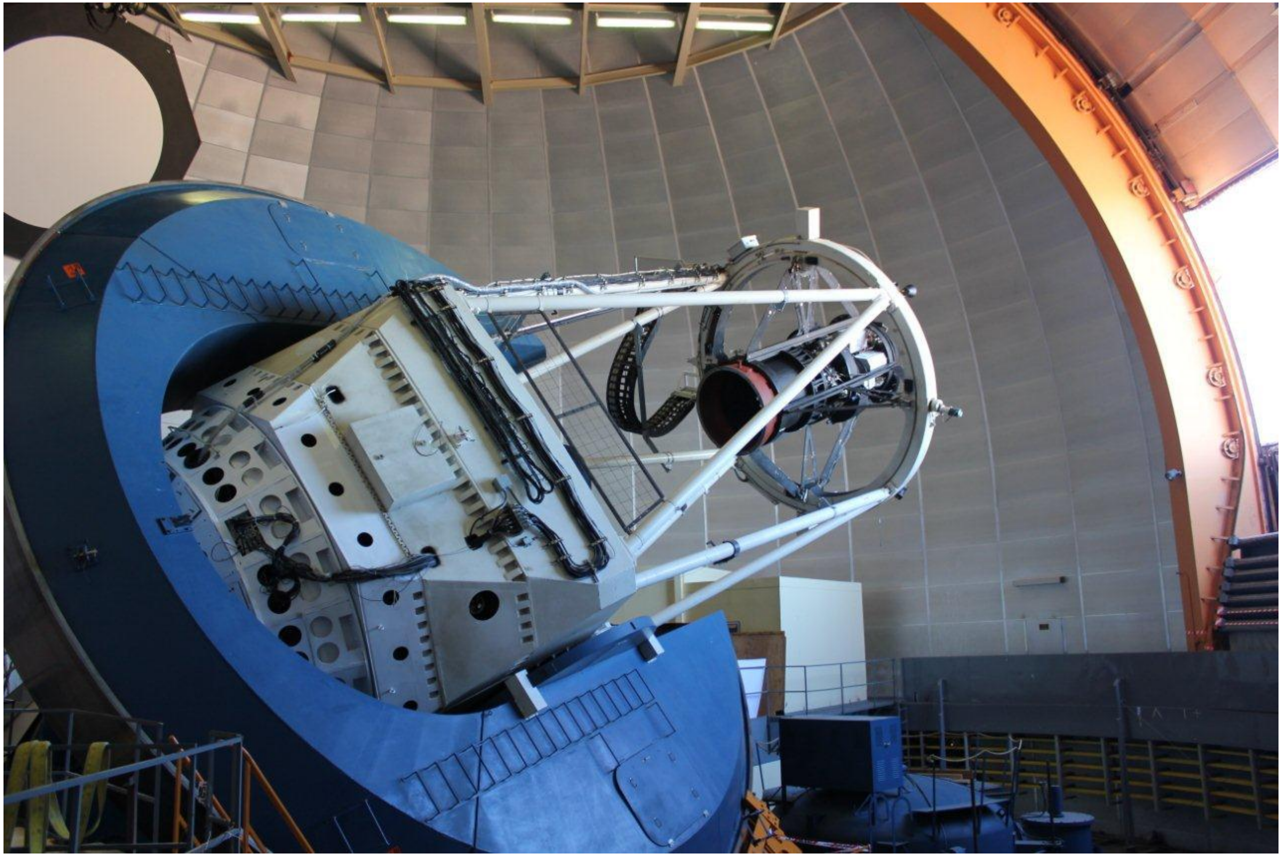


Figure 4: (photo credit: W. Percival)

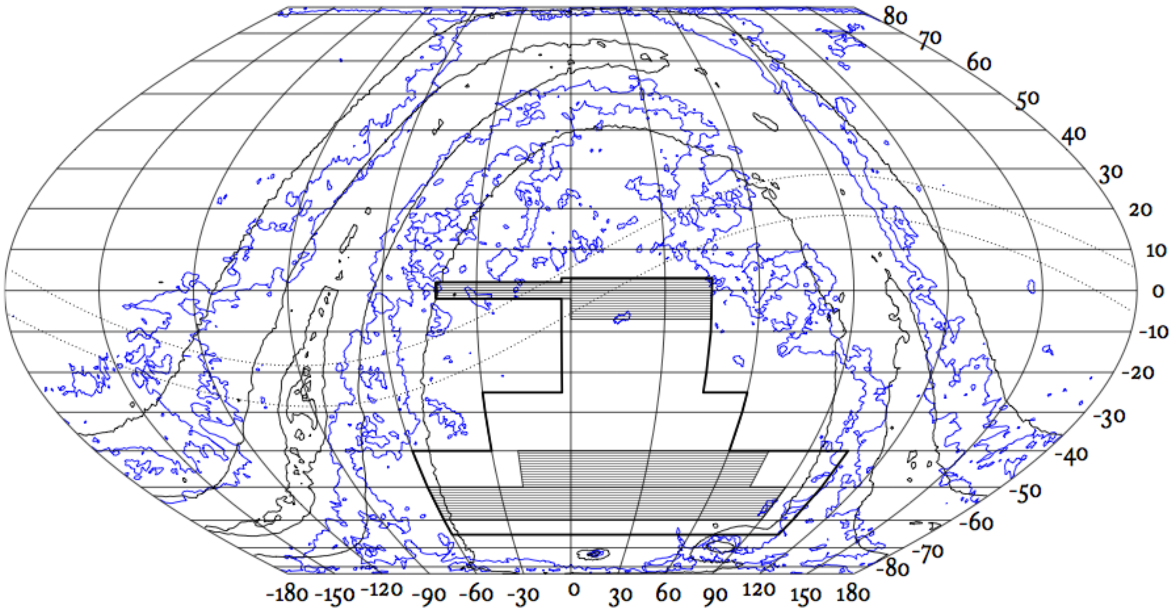
The Blanco 4^mtelescope is a 70^s era design with a beautiful primary mirror.

The mountain

Figure 5: (photo credit: T. Abbott

The Blanco operates on Cerro Tololo in Chile, south of the Atacama. The site has very good seeing, necessary for our lensing.

The DES footprint



We have to avoid the Milky Way, of course. This first year we will do the shaded areas twice as deep as in the standard strategy in order to improve calibration and maximize science output.

This is an equal area putnins4 projection of the entire sky.. Black: star densities are at x10, x30, x100, x233 times galactic south pole values. Blue: galactic dust caused extinction, i-band, at 0.25 and 0.5 mags.

Supernova

SNe are standardizable candles; they measure a geometric distance $D_L = (1+z)D$, where $D = c\int_0^z dz' H(z)^{-1}$.

The DES will obtain well sampled light curves for ~4000 SNe Ia at 0.1 < z < 1.1. (Bernstein, Kessler, Kuhlmann et al. 2012

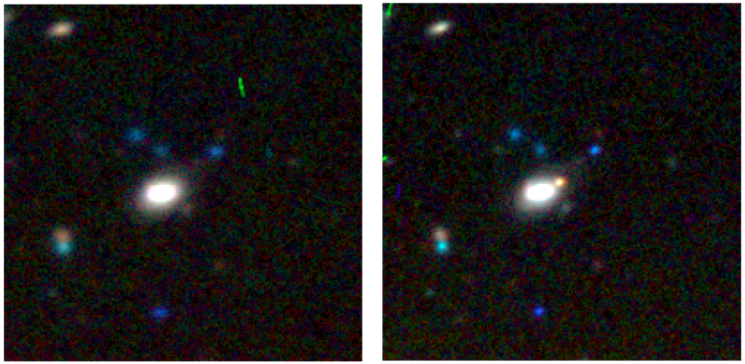


Figure 6: First DES SN. Left, Nov 7, 2012. Right Dec 15, 2012: AAT places it at z=0.2

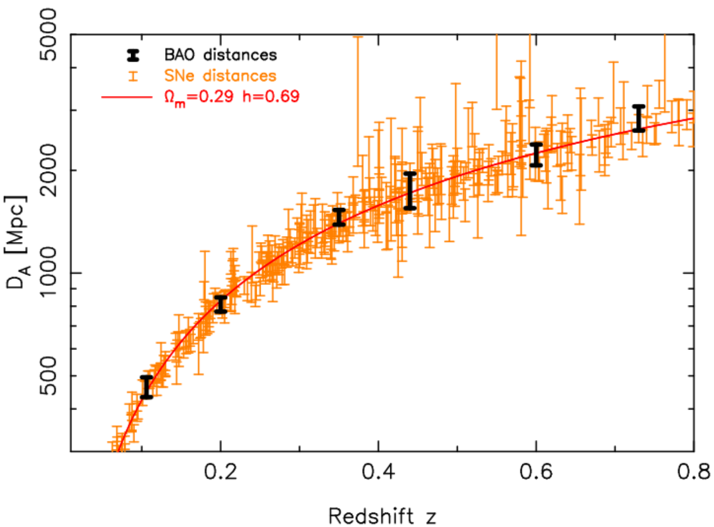


Figure 7: BAO distances superimposed on world supply of SN distances. The BAO in order from left to right: 6dFGS, two SDSS LRG points, three WiggleZ points. From Blake, Kazin, Beutler et al 2011.

SNe distances are similar to BAO in that they are purely geometrical, H(z).

Large scale structure

The galaxy distribution allows measurement of the matter power spectrum in photometric redshift shells, and a form of BAO measurements where only angular modes are used allows $D_A = (1+z)^{-1}D$, where $D = c\int_0^z dz' H(z)^{-1}$.

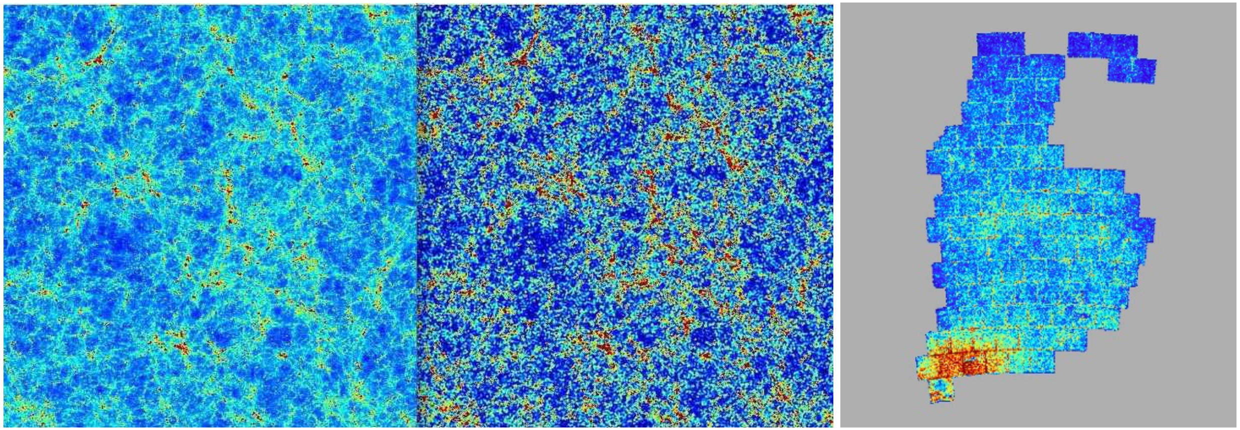


Figure 8: Left: dark matter distribution. Middle, galaxies in a redshift slice at z=1 on the right, both 7°on a side. Simulations from the MICE project. Right: Object map from the DES science verification data. The glow on bottom left is the edge of the LMC. Anne Bauer

These techniques should be considered platforms for a variety of experiments- in LSS, BAO, magnification, and non-Gaussianity.

In the inflationary paradigm, microscopic quantum fluctuations are the seeds of all the structure we see in the CMB and traced by collapsed objects like galaxies and clusters of galaxies. The standard class of single-field, slow-roll inflation models predict nearly zero non-Gaussianity, where other models of inflation predict detectable non-Gaussianity. A detection of primordial non-Gaussianity would rule out single-field slow-roll models, and that increasingly tight upper limits will rule out many other models. The non-Gaussianity limits from galaxy power-spectra are useful as a completely independent cross-check of (usually better) CMB limits.

Dark energy II

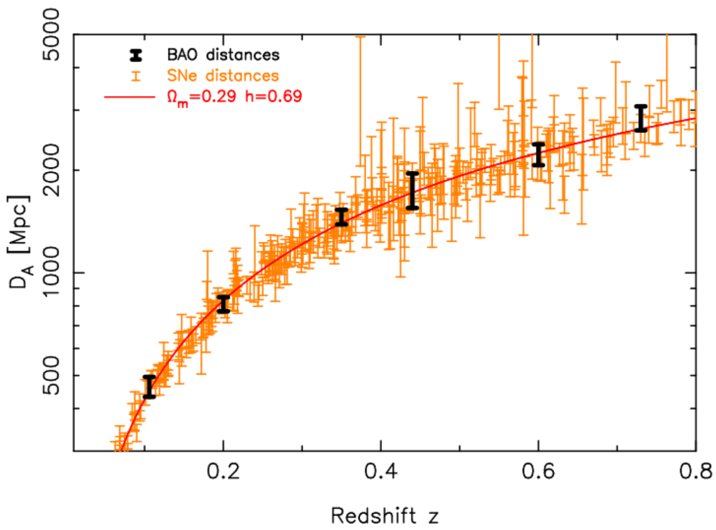


Figure 9: BAO distances superimposed on world supply of SN distances. The BAO in order from left to right: 6dFGS, two SDSS LRG points, three WiggleZ points. From Blake, Kazin, Beutler et al 2011.

If we have distance measurements from SN and BAO at a variety of redshifts, do we need more?

If the dark energy is a cosmological constant, the problem for us reduces to measuring w=1.

Following the idea of simplicity- Slepian, Gott, and Zinn (2013) suggest the simplest model of DE has the same mechanism as inflation. Inflation is likely a scalar field slowly rolling down its potential; if the dark energy is also a scalar field in slow-roll, w+1 evolves with redshift proportionally to $H(z)^{-2}$.

Do we need more? Other than cross checking for systematics- no.

Dark energy III

But following the situation in inflation- dark energy could be a gravitational effect. Since GR has gravity = geometry and geometry = mass-energy, perhaps the dark energy is an incomplete description of how matter determines geometry.

Modifications to gravity introduce new propagating degrees of freedom, mediating fifth forces. Fifth forces are highly constrained in solar system and laboratory measurements. These are called $f(R)$ theories; they derive from modified actions introduced by Starobinsky (1980), the same paper of R^2 inflation (!). Successful modified gravity models exhibit "screening mechanisms". Dynamics of the new degrees of freedom are rendered irrelevant at short distances and only become free at large distances or low densities: chameleon range < 3 Mpc; Vainshtein screening can be tested on large scales.

See, for example, the talks at the Novel Probes of Gravity and Dark Energy Workshop `https://sites.sas.upenn.edu/novelprobes/`

The difference is that a scalar field is globally smooth and only affects gravitational growth of structure through H(z). The geometrical techniques like supernova and BAO measure H(z); H(z) can then be used to predict the growth of structure.

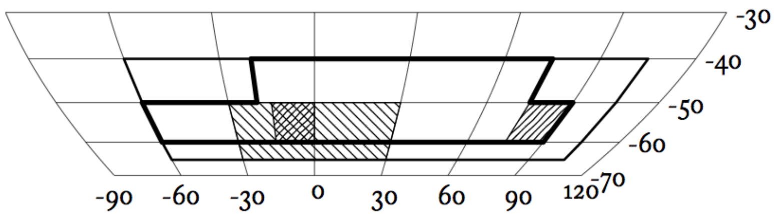
Smooth dark energy models slow the growth of structure in highly predictable ways.

Cluster counts

The counts of clusters of galaxies as a function of mass and redshift, along with their spatial distribution and spatial profiles are measurements of the growth of structure in the universe: fluctuations grow as $\ddot{\delta} + 2H\dot{\delta} - 4\pi G\rho_M\delta = 0$ allowing the growth function G(a) to be defined, $G(a) \equiv \delta(a)/\delta(a=1)$.

There are issues in cluster counting, mostly related to measuring the mass of clusters. The most promising avenues are to find the cluster in the optical and put them onto a mass scale using stacked weak lensing or stacked Sunyaev-Zeldovich signal.

The DES is deep enough to build optical cluster catalogs complete to z=1.



The medium-lined trapezoid is the completed SPT-SZ area (2500 sq-degree at 17μK-arcmin depth). the eastern small hatched area is the SPT-E deep area (100 sq-degree at 13μK-arcmin), the western small hatched area is the SPT-W/SPTpol deep area (100 sq-degree at 12μK-arcmin/ 6μK-arcmin) The larger hatched area is the ongoing SPTpol survey (500 sq-degree at 8μK-arcmin). SPT data The 2013 area covers 1520 sq-degrees of SPT-SZ, all of the deep fields, and 340 sq-degrees of SPTpol.

Highly predictable ways:

"We adopt the halo mass function of Tinker 2008

$$\frac{d\bar{n}}{d\ln M} = f(\sigma)\frac{\bar{\rho}_m}{M}\frac{d\ln\sigma^{-1}}{d\ln M},$$

where $\sigma^2(M,z)$ is the variance of the density field in a spherical region with mean (present-day) matter density ρ_m encircling a mass M. The function $f(\sigma)$ is thought to be universal to the changes in redshift and cosmology. Tinker et al parameterize this as

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right]e^{-c/\sigma^2},$$

The function $f(\sigma)$ is overdensity dependent, and fitting parameters are given in table 2 of Tinker2008. For our chosen $\Delta = 200$, the function becomes:

$$f(\sigma) = 0.186\left[\left(\frac{\sigma}{2.57}\right)^{-0.147} + 1\right]e^{-1.19/\sigma^2}$$

..."

Clusters and weak lensing

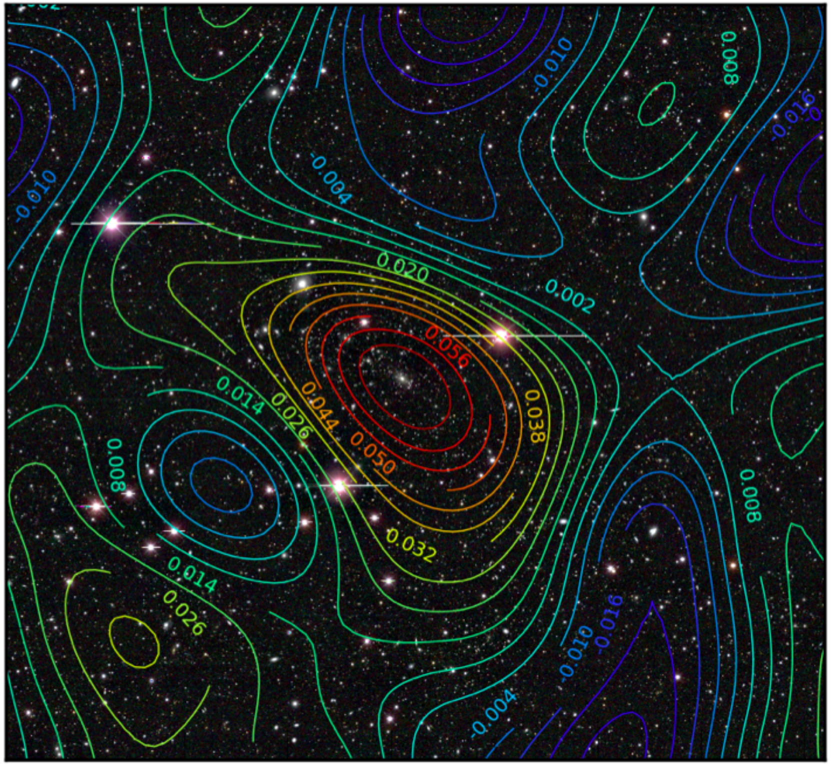


Figure 10: Cluster RXJ2238 at z=0.35 Preliminary cluster mass map from DES SV data . Peter Melchior.

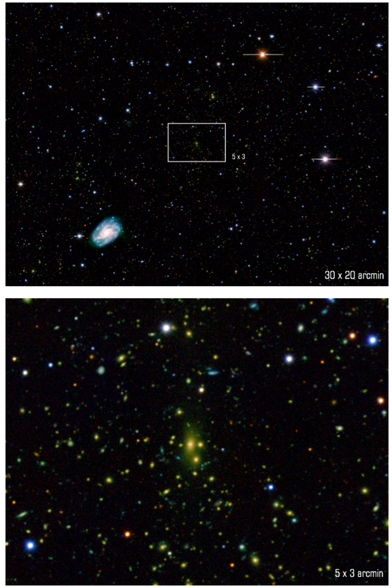
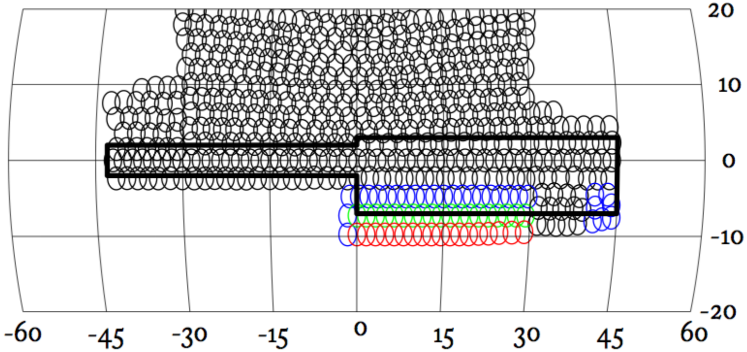


Figure 11: Finding a cluster-the same cluster seen at different angular scales. Peter Melchior and the cluster WG

Weak Lensing

Shear-shear correlation functions directly measures the distribution of dark matter in the universe. Shear-galaxy correlation functions measure the relationship between the galaxy and dark matter distributions. These are $G(a)$ measurements.

In the parameterized post-Newtonian approach, $ds^2 = -(1+2\Psi)dt^2 + a^2(1+2\Phi)dx^2$, there is a Newtonian dynamical potential Ψ which non-relativistic particles feel, and a space curvature potential Φ which additionally deflects photons. Weak lensing surveys measure Φ by measuring the mass estimated via light deflection, redshift surveys measure Ψ via measuring the motion of galaxies in potential wells.



BOSS survey plates on the DES northern year one area. EBOSS plates are similar,and a WiggleZ survey is in the area. These are spectroscopic redshift surveys well matched to DES imaging. EBOSS, for example, plans 180 deg^{-2} emission line galaxy targets in the 0.6<z<1 range, 110 deg^{-2} QSO targets at z >0.9, and 50 deg^{-2} LRG targets at 0.6<z <0.8.

Dark energy IV:
geometric distance vs growth of structure

Measurements of the growth of structure via clusters, weak lensing, and the velocity field can be used to show consistency or disagreement with that predicted from the H(z) derived cosmology.

If disagreement, we can rule out scalar fields and the daunting cosmological constant as explanations for dark energy.

Weak lensing technology

Measuring the weak lensing signal is the driving technological challenge in the DES.

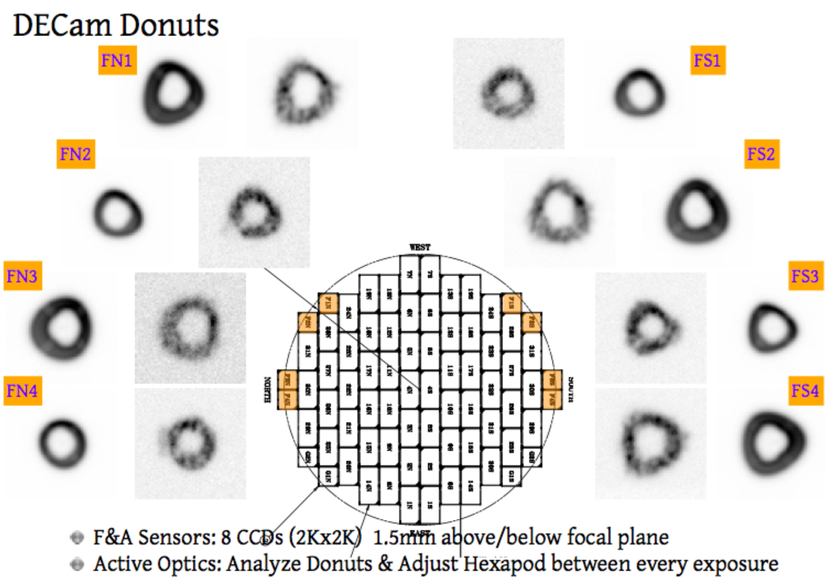


Figure 12: The donut analysis. Aaron Roodman

We monitor the alignment of the camera with the optical axis by watching out of focus stars around the edge of the focal plane and comparing donuts computed from optical models with the observed donuts. Our ability to correct, both in hardware and software, will improve with experience.

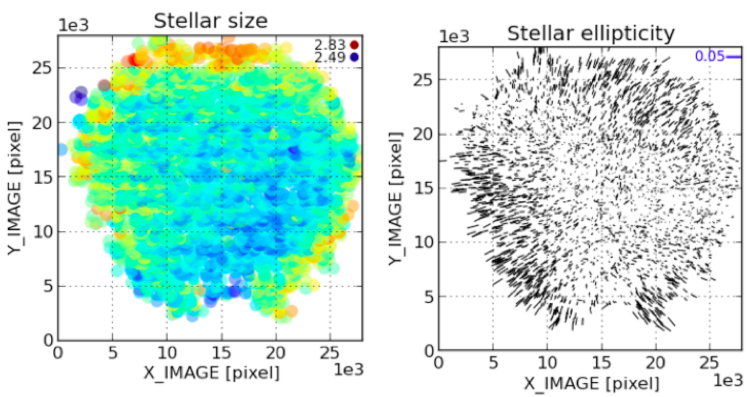


Figure 13: PSF size, left, and ellipticity maps, right, from the cluster weak lensing study in the DES SV data. Peter Melchior and the cluster WG

Supporting technologies

There are several technologies that underlie the science platforms described above:

i) an extensive photometric redshift program: our ability to turn precision 5-band photometry into redshifts accurate at Δz = 0.01-0.05 depends on spectroscopic training samples and, likely, redshift-object correlation techniques.

The weak lensing in particular is sensitive to catastrophic mis-estimates of redshift

ii) an extensive simulation program: starting from N-body simulations galaxies are added, weak lensing effects are added, and the simulation observed. We depend on the simulations to understand the observed data set.

This is new in astronomy

iii) blind analyses for the cosmology measurements

This is new in astronomy

iv) a large science collaboration

   (a) > 200 scientists

   (b) US, UK, Spain, Brazil, Germany, Switzerland

This type of collaboration follows the path of the SDSS collaboration; the DES is in many ways the southern descendant of the SDSS

Summary: the DES

- Stage III dark energy project using 4 complementary science platforms from imaging:
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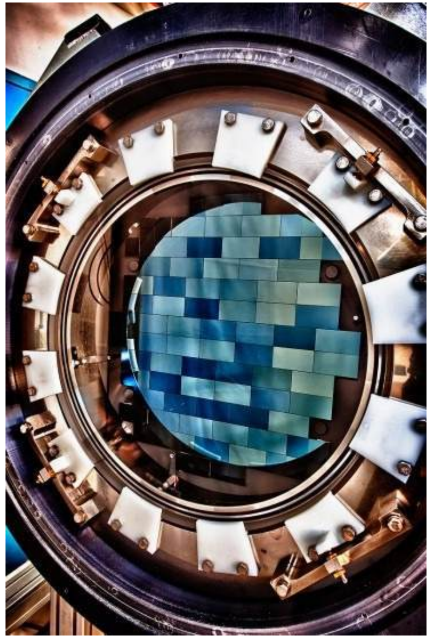

Figure 14: DECam focal plane CCDs- 62 full depletion LBNL ccds with very high red quantum efficiency.

Observations began August 31, 2013.