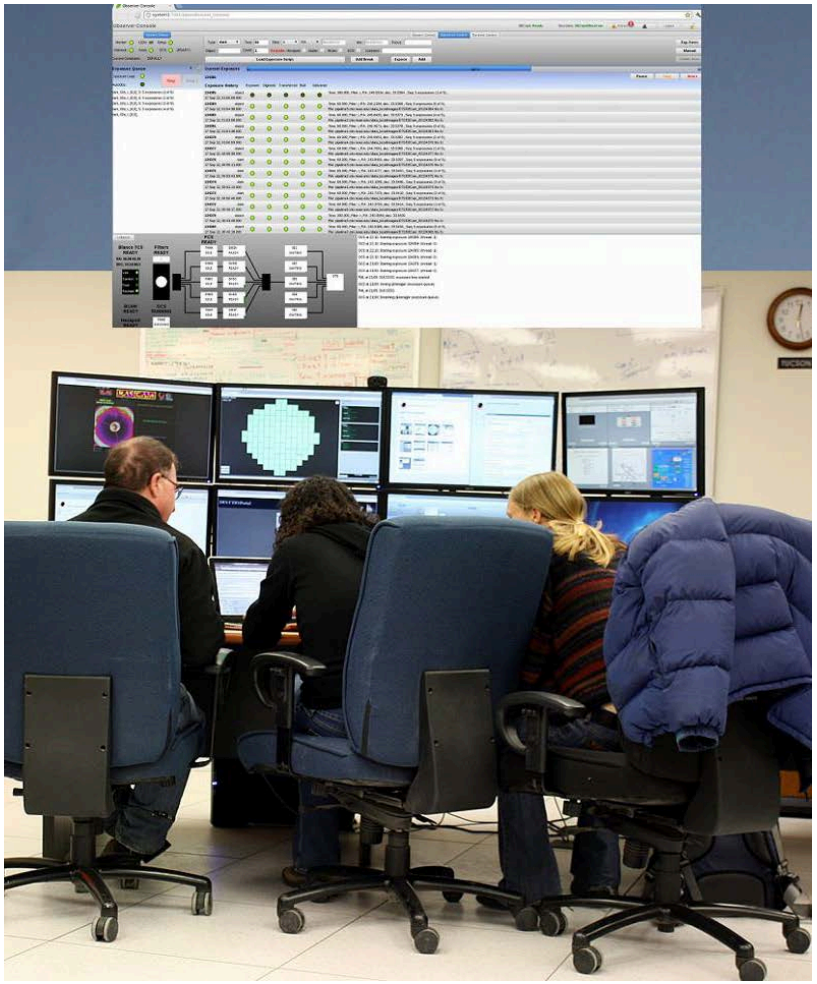
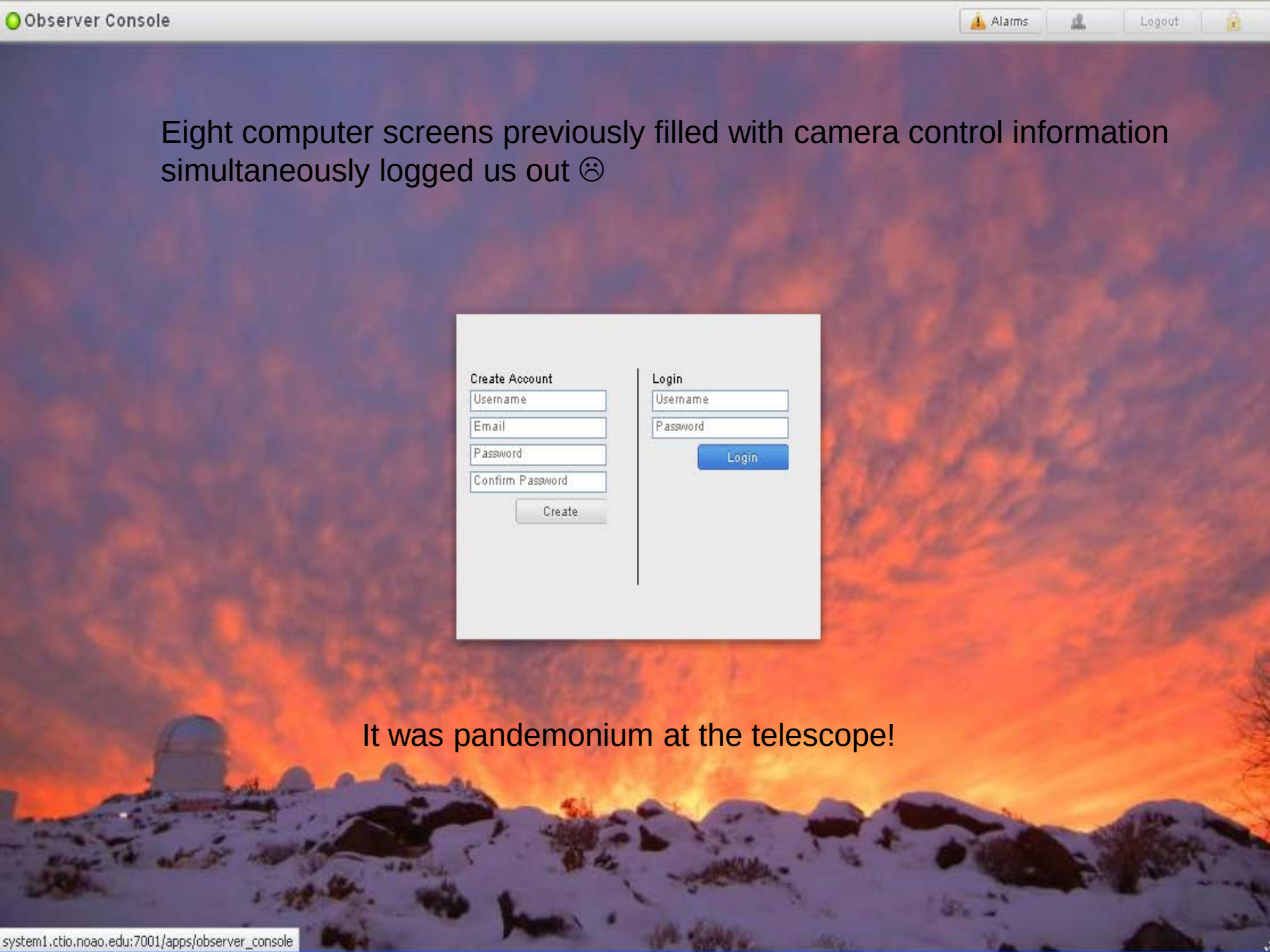
Preface



- Eight years of preparation and construction &
- Just before Midnight on September 12, 2012
- With a dozen scientists and engineers peering at the controls and many more connected by computer
- We engaged the “Start Exposure” button telling DECam to take images “1st Light” on the sky.



Eight computer screens previously filled with camera control information simultaneously logged us out ☹

It was pandemonium at the telescope!

The Dark Energy Survey

DARK ENERGY SURVEY

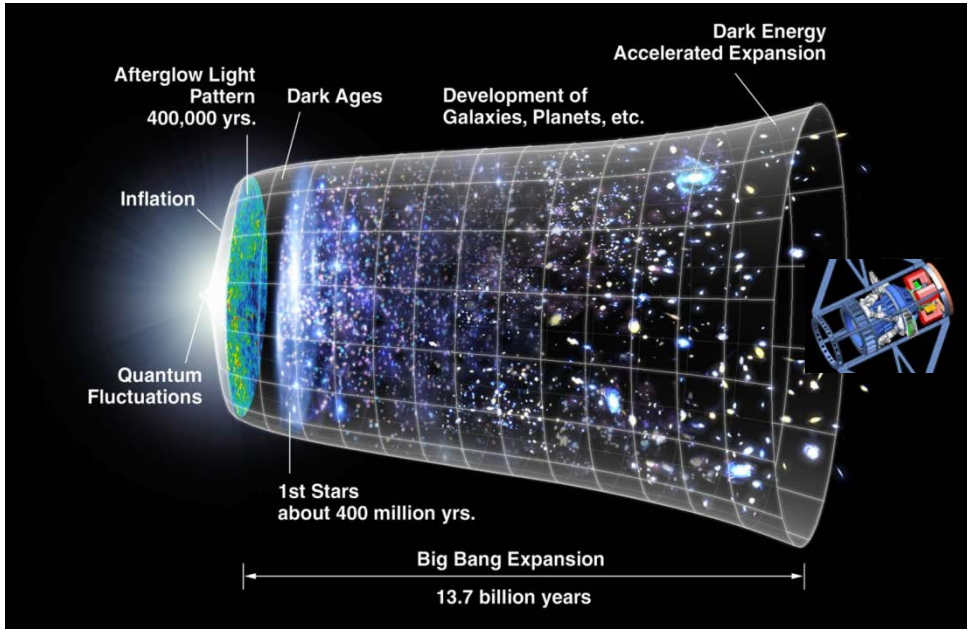
Outline

- Cosmology and the physics of the accelerating expansion of the Universe
- Dark Energy Camera Construction & Commissioning
- First Results from Dark Energy Survey "Science Verification"
- What's happening tonight?
- What we can expect in Dark Energy Survey in 5 years

Tom Diehl
Fermi National Accelerator Laboratory
September 11, 2013

Cosmology

A quick Introduction so that I can explain this picture of the Universe.



Topics

- Discovery of “The Expanding Universe”
- Cosmic “Noise”
- Type 1a supernovae and discovery of the accelerating expansion
- Dark Energy & Dark Matter

Hubble's Discovery

DARK ENERGY SURVEY

- Edwin Hubble discovered that more distant objects were receding faster (plot on right).
- Cosmologists interpreted this data to mean the Universe started at a smaller size and is expanding.
- The expansion slows down over time because of the gravitational pull of the matter in it.

Edwin Hubble (1929)
Studied Cepheid Variable Stars in nearby galaxies

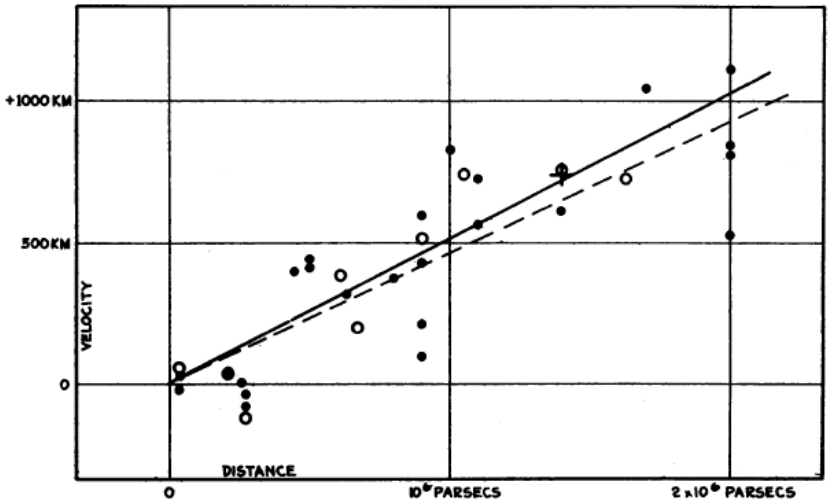


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

- Eventually named the "Big Bang". Then the Universe is expected to either, depending on the amount of matter, expand indefinitely or inevitably contract in a "Big Crunch".

Cosmic Microwave Background Radiation

DARK ENERGY SURVEY

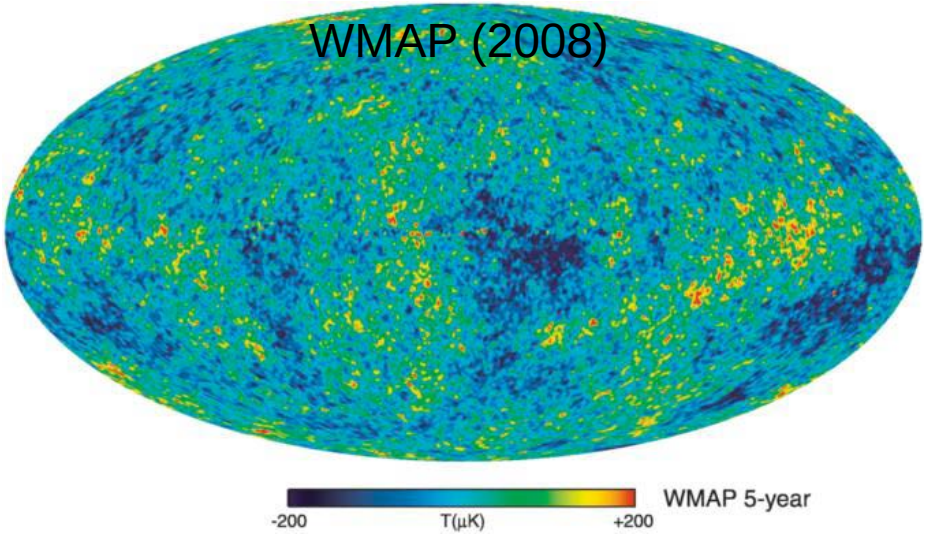
- When the Universe was small and young it was filled with a mixture of light nuclei, electrons, and photons in thermal equilibrium. It wasn't transparent. As it expanded it cooled some more …
- CMB Radiation was discovered in 1965 at Bell Labs Holmdel using a LHe-cooled receiver. "Big Bang" becomes accepted. Penzias and Wilson won Nobel Prize in Physics in 1978.
- This lead to a series of experiments to measure the CMB and refinement of the cosmological theory.
- COBE satellite project discovered anisotropy in CMB. Smoot and Mather won the Nobel Prize in Physics in 2006. They found <T>=2.73 K and dT~0.000001 K

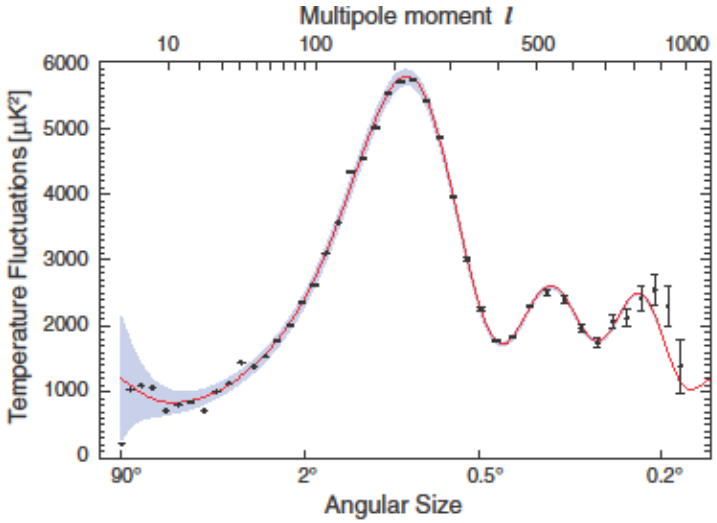
"A Measurement of Excess Antenna Temperature at 4080 Mc/s", Penzias and Wilson (1965).

- See references in Dicke et al., ApJ, v142, p.414-419 (1965), published concurrently with the discovery paper by Penzias and Wilson.

Temperature Map of the CMB Radiation

- WMAP (2008) improved over COBE
- Characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves in the photon-baryon fluid can travel just before Hydrogen recombination: sound horizon $s \sim c_s t_{ls}$
- Planck satellite makes further improvements (2013)

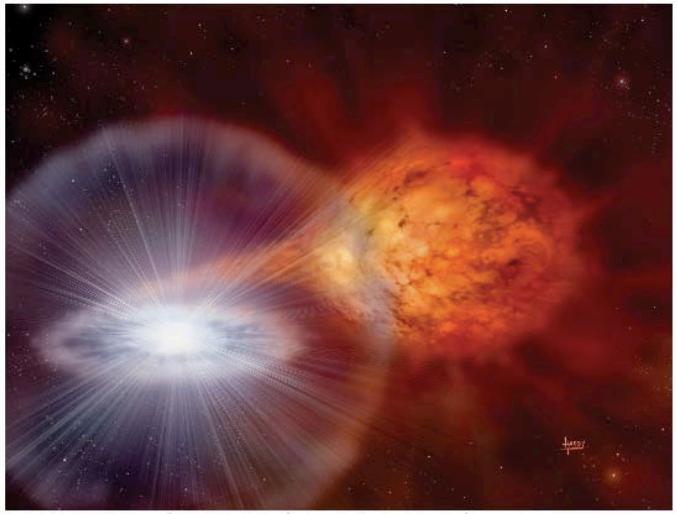




Type 1a Supernovae

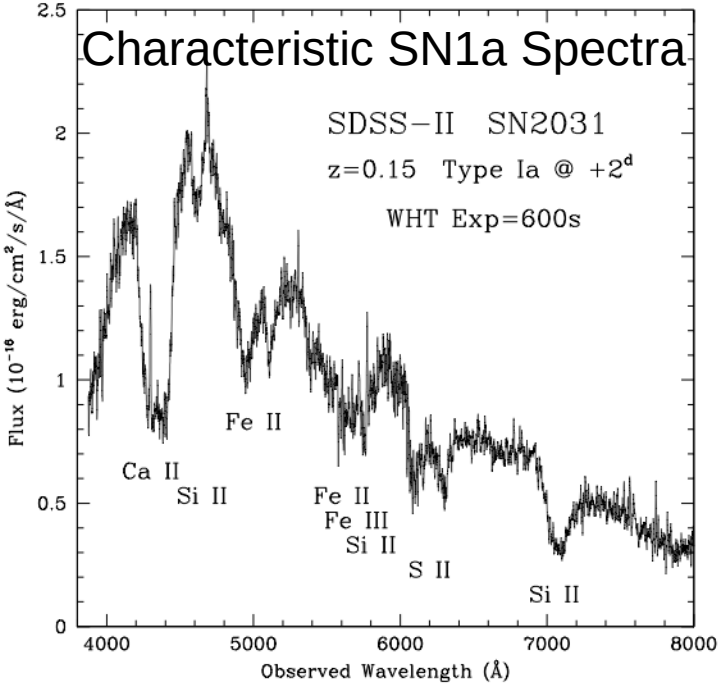
DARK ENERGY SURVEY

- A “white dwarf” star has M < 1.44 solar masses ($M_\odot$), the “Chandrasekhar Limit”
- Made of C and O and degenerate electrons but with insufficient density to fuse them. It just cools down unless it has a source of additional material, say another star.
- When mass becomes near the CL the star fuses the C and O into ^{56}Ni in a matter of seconds.
- The heat cannot escape so the star explodes. Then ^{56}Ni –> ^{56}Co –> ^{56}Fe



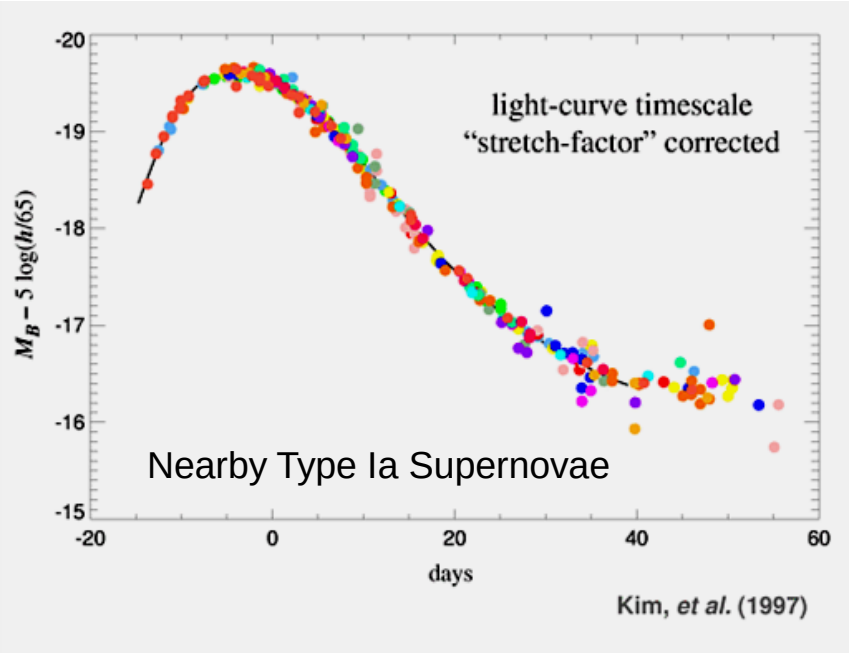
Artist’s rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

Image courtesy of David A. Hardy. © David A. Hardy/www.astroart.org



Type 1a Supernovae

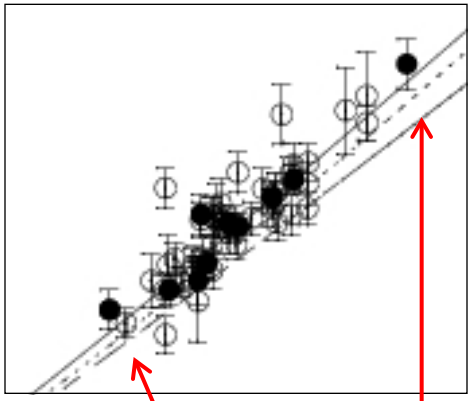
DARK ENERGY SURVEY

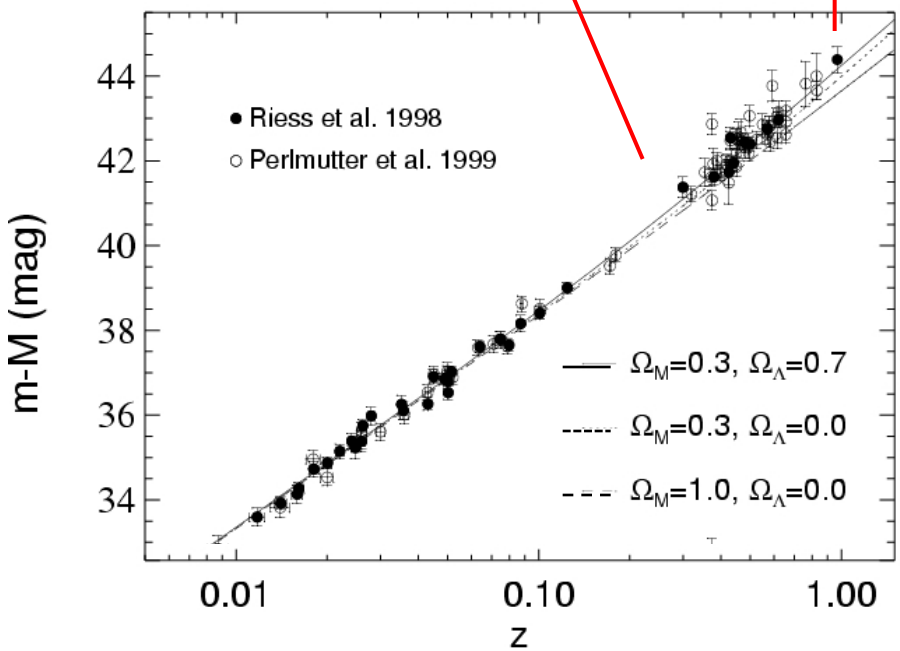


- Because the explosion occurs near the "CL", it has a characteristic brightness (determined by the ^{56}Ni).
- After some corrections it is a "Standard Candle" and the brightness can be used to determine the distance.

- In 1998 two teams were studying the distance and redshift of Type 1a SNe using the Blanco 4m Telescope at Cerro Tololo in Chile.
- The strange thing they discovered is that distant SN were dimmer than they were expected to be based on their redshifts.

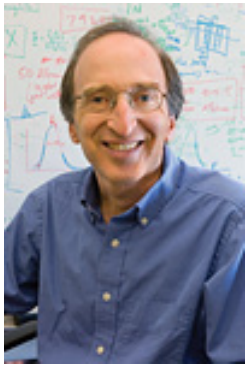
Type 1a Supernovae





- To left, the upper line is expectation for accelerating Universe. The middle and lower lines are decelerating.
- The two teams claimed that the Universe was accelerating. The mysterious effect is named “Dark Energy”

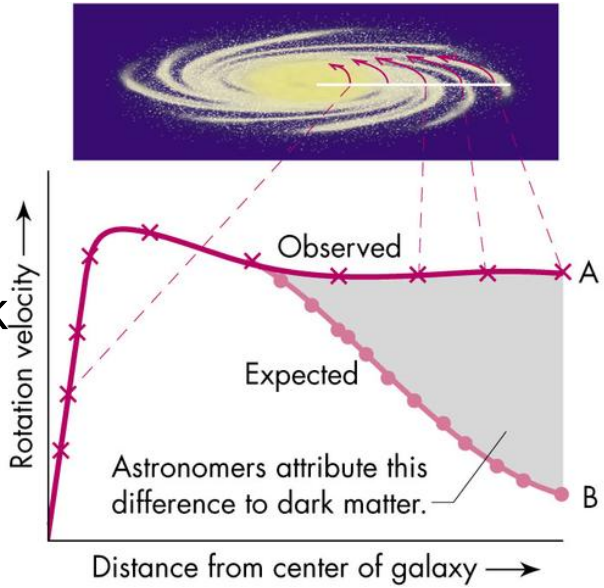
Saul Perlmutter, Adam Reiss, and Brian Schmidt won Nobel Prize in physics in 2011.

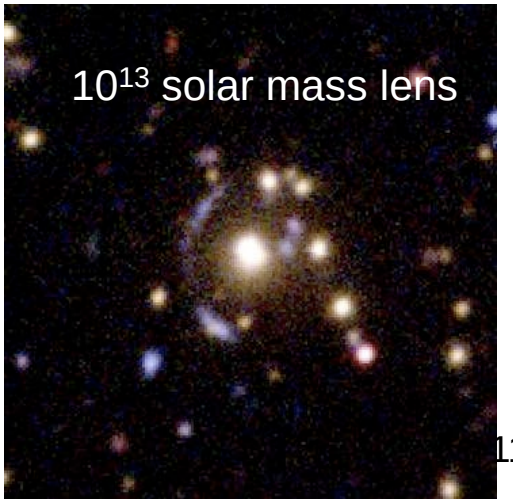


Meanwhile: Evidence for Dark Matter

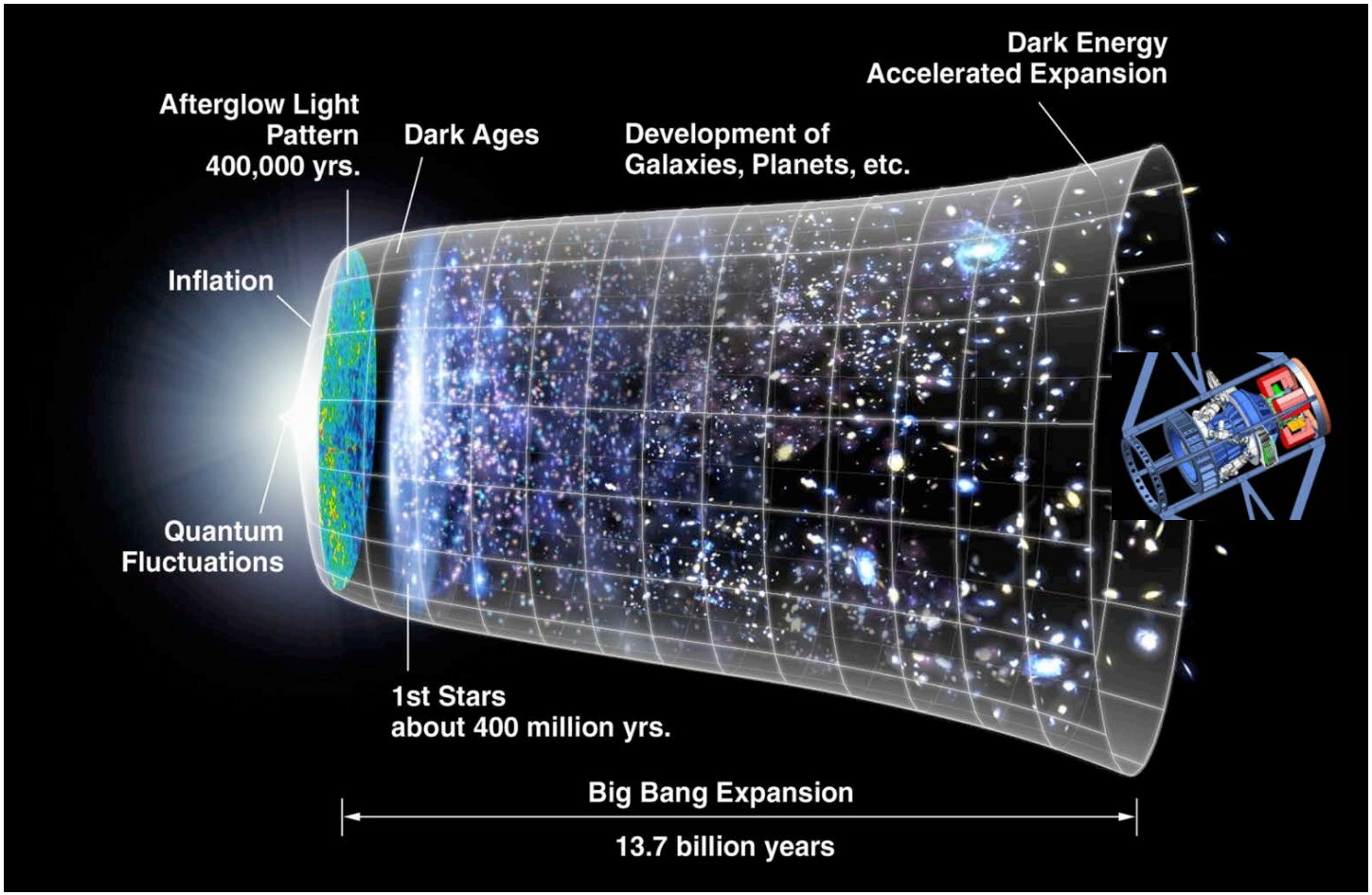
DARK ENERGY SURVEY

- Gravitationally bound clusters
  - Fritz Zwicky realized that the dispersion of velocities of galaxies in the Coma Cluster was consistent with much more mass than was seen in them. He coined the term “dark matter” (1933).
- Rotation Curves of Spiral Galaxies
  - Vera Rubin and collaborators (1970’s and 80’s) studied the rotation curves of spiral galaxies. Again, more mass is present than is seen.
- Strong Gravitational Lensing
  - Usually credited to Einstein, Zwicky described the possibility in 1937.
  - Allows a direct determination of the mass of the lens (visible plus dark matter).

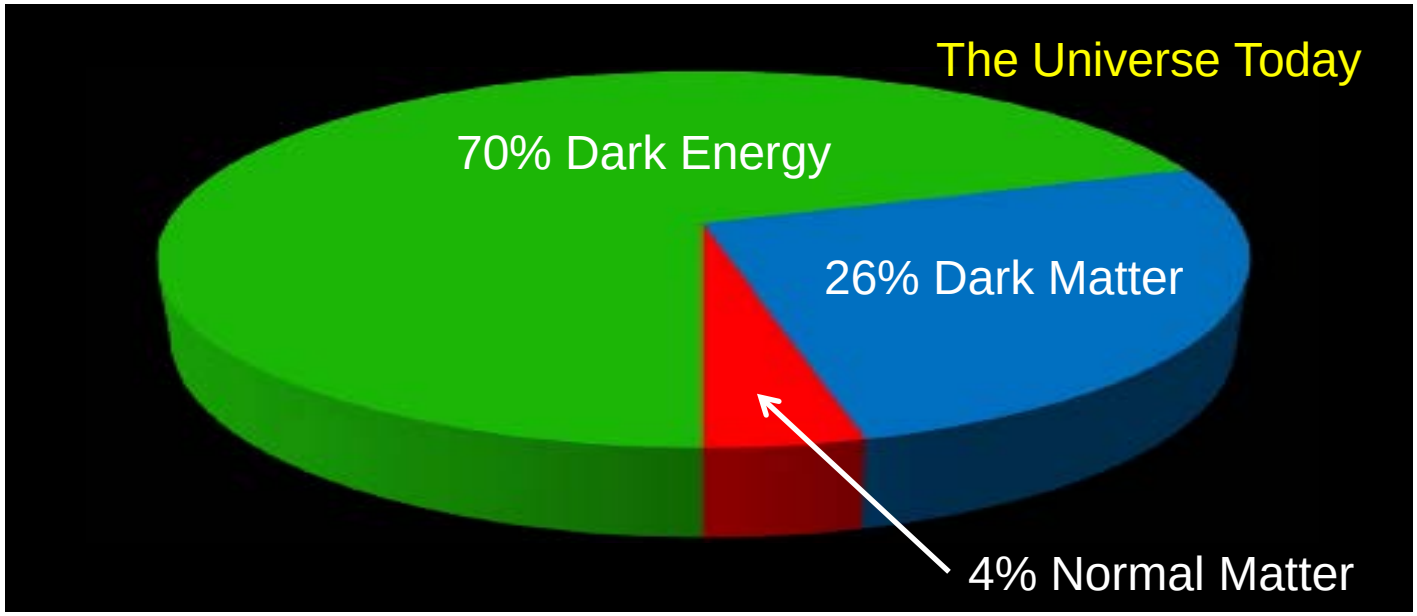




The “Standard Model” of Cosmology



The “Standard Model” of Cosmology



- In the past: In a given volume the same amount of Dark Energy but more dark matter and normal matter. Matter makes up a bigger piece of the pie.
- In the future: In a given volume the same amount of Dark Energy but less dark matter and normal matter. Dark Energy makes up an even bigger slice.

Dark Energy Theories

- We don't know the physics behind "Dark Energy".
- Four dominant classes of "theories"
  - "Cosmological Constant": Even the "vacuum" of space has a constant energy. More Space => More "Dark Energy". But we don't know how this works. When we try to calculate it at QM level we get an answer with 10^120 times more energy than is present.
  - Quintessence: Dark Energy is a (very light) field in space (with energy like that in a compressed spring) that changes with time. The potential energy causes an acceleration.
  - Other: we are detecting a "local effect" because we live in a "void".
  - Maybe General Relativity (Gravity) isn't correct on cosmological scales.
- Measuring the effect of Dark Energy with multiple techniques in the same experiment may provide the clues we need to pick among these.

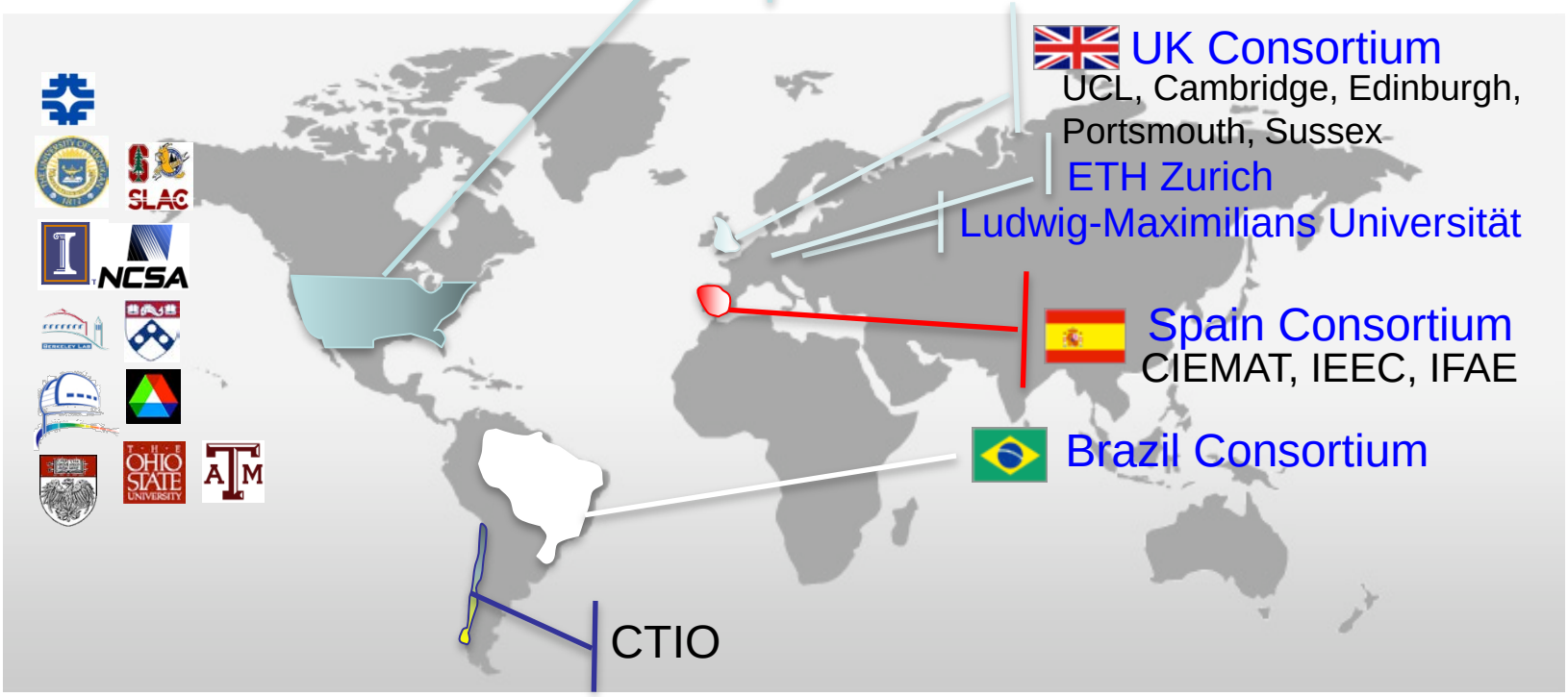
DES Collaboration

Astronomers, Cosmologists, High Energy Physicists

DARK ENERGY SURVEY

Started in 2003, DES is now an international collaboration of ~200 scientists from 27 institutions

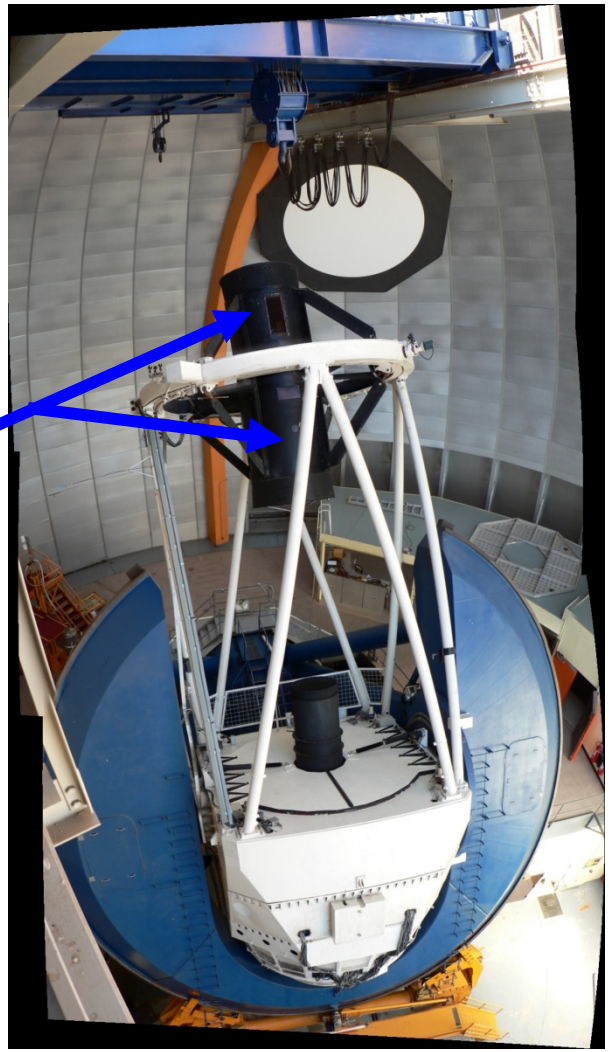
Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa-Cruz/SLAC/Stanford Consortium, Texas A&M



The Dark Energy Survey (DES)

DARK ENERGY SURVEY

- The General Idea:
  - Perform a 5000 sq. deg. survey of the galaxies in the southern galactic cap, also perform a SN survey
  - Measure dark energy with 4 complementary techniques
- Need a New Instrument:
  - Replace this 64 Mpix camera with a new 570 Mpix camera that has 3 sq-deg field of view.
- Take 525 nights to perform the survey
- Time scale:
  - R+D & Planning & Reviews 2003-2008 – skip this part
  - Instrument Construction 2008-2011 – touch lightly
  - Installation during 2012
  - First light …



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

DECam Overview

Spider/Cage

Barrel

Optics:Lenses

Optics:Filters

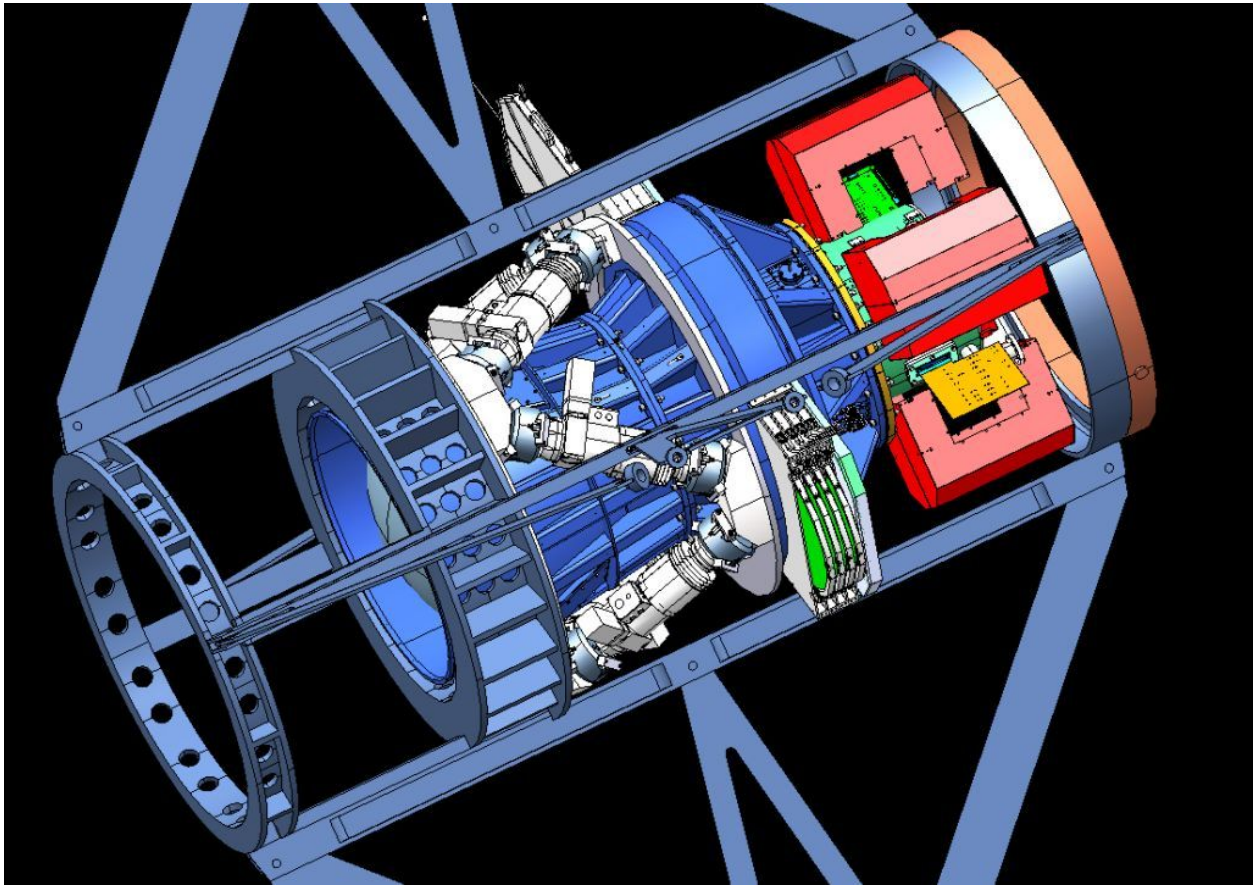
Shutter

Hexapod

CCDs

Electronics

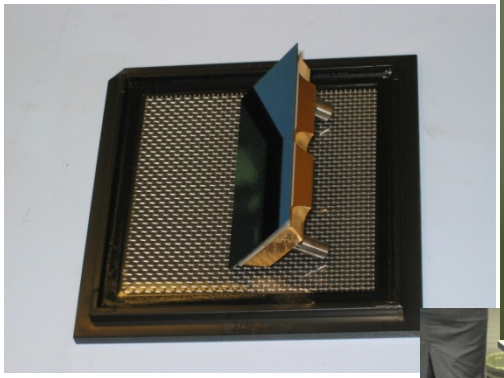
Controls

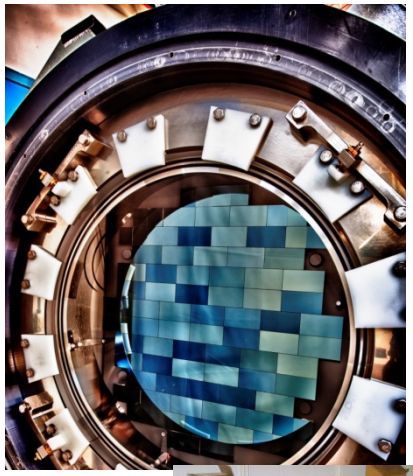


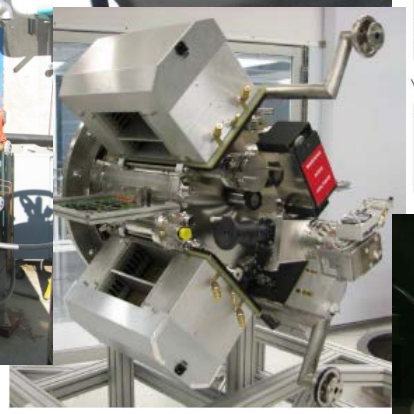
Sure – it's just a camera, BUT

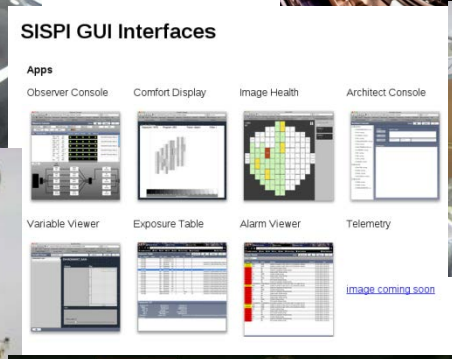
Dark Energy Camera Parts (2008-2012)

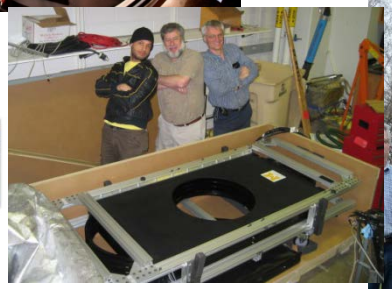
DARK ENERGY SURVEY







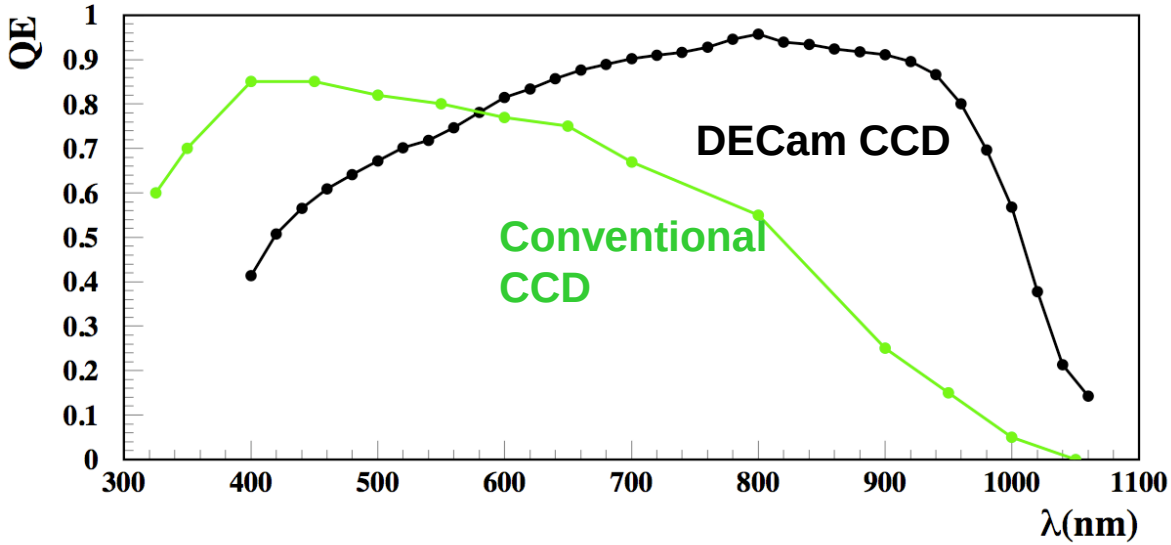


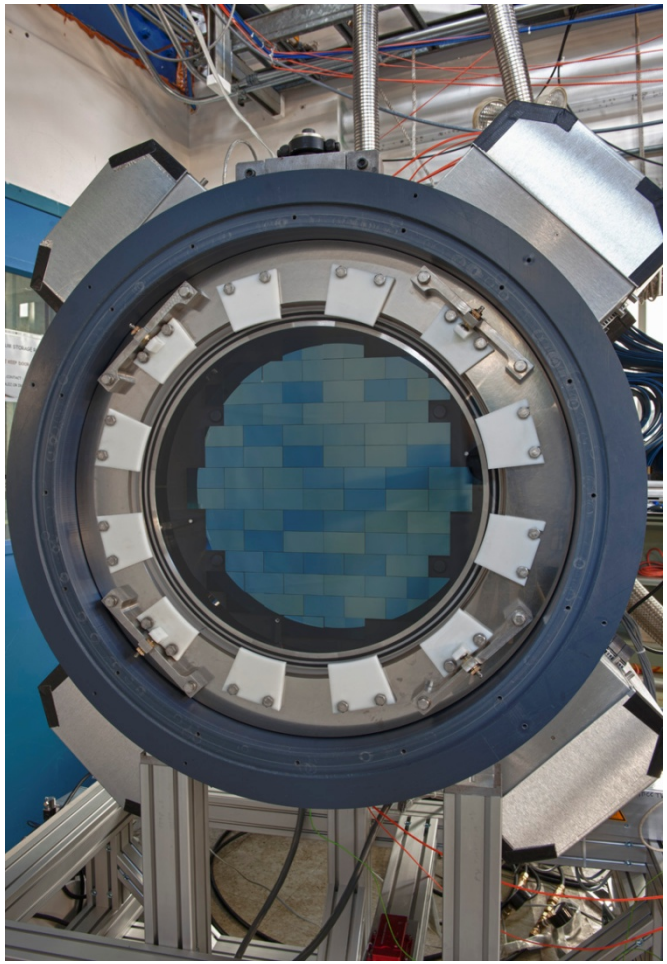


This makes the DECam Powerful

DARK ENERGY SURVEY

- Telescope w/ 4m primary mirror
- Large (45 cm diameter) Focal Plane, 2 deg across
- 74 High “Quantum Efficiency” CCDs, especially good in the near-infrared wavelengths.
- 570 Mpix readout in17s.

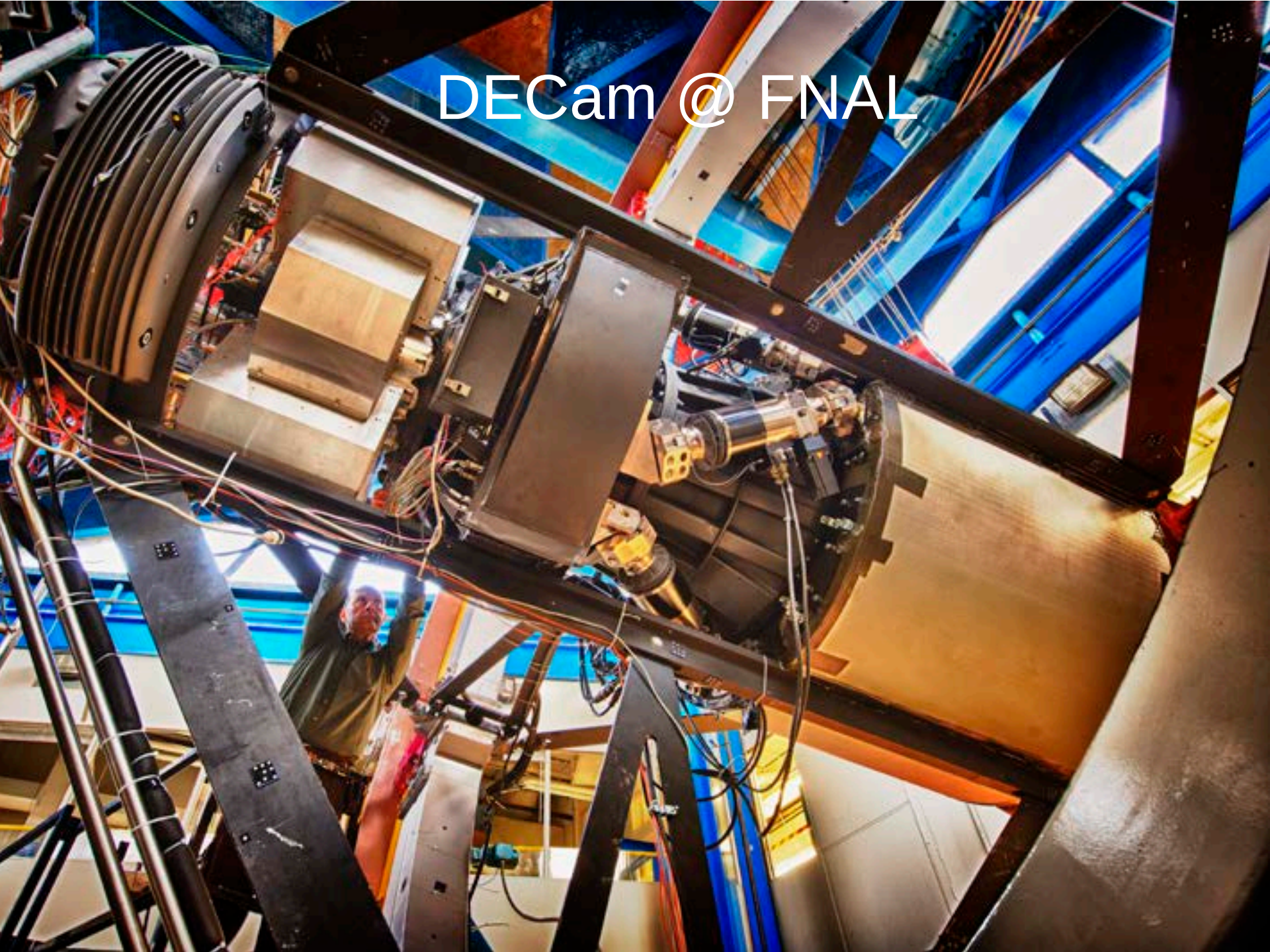




A “Telescope Simulator” at FNAL

DARK ENERGY SURVEY

DECam @ FNAL



Testing the camera in different positions!

(this is not how they move the telescope)

Shipping DECam

f/8 handling
9/17/10
Left FNAL
for NYC

- Many “Shipments”
- Components were sent to Chile by air or by boat depending on their value, size, and fragility.
- Shipping occurred from Sept. 2010 to Nov. 2011. The last piece to arrive was the camera.
- When the camera is on the plane you just can’t do anything about it but worry.

10/8/10
through
Panama
Canal
to SFO

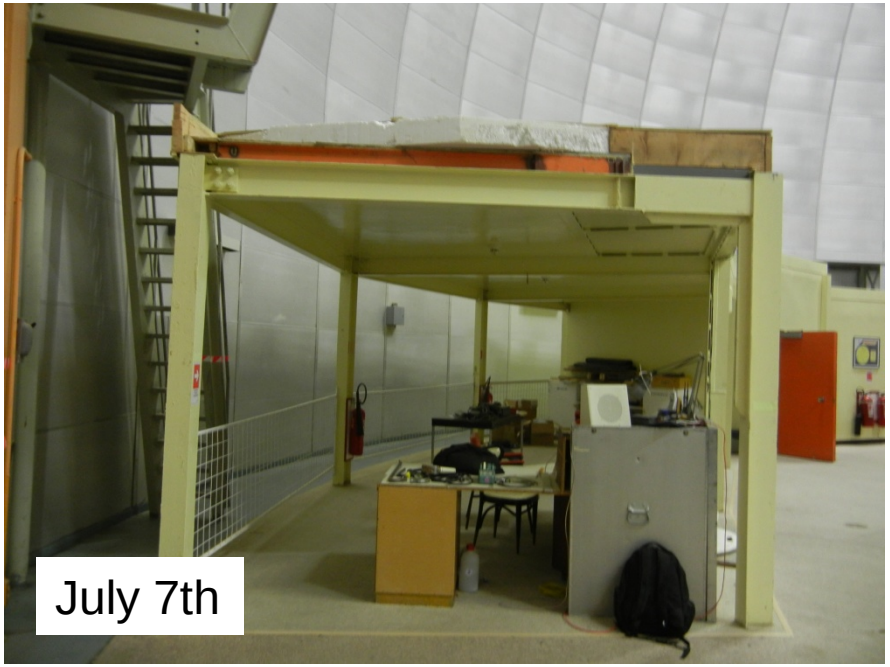
Somehow,
by boat,
10/17/10
Arrived in
Chile.

10/19/10
At CTIO

July 2011: LN2 Cooling installation at CTIO

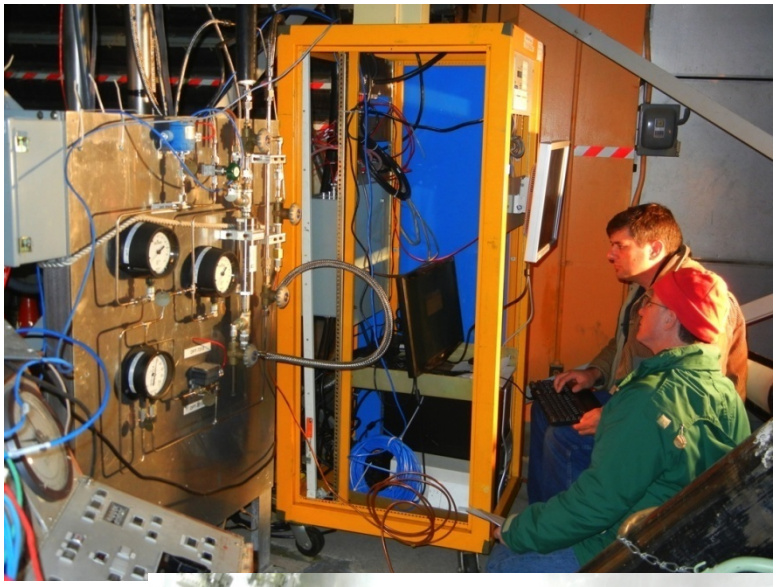
DARK ENERGY SURVEY

- Five of us went to Chile
- July 7-21 LN2 tank (cools the CCDs) and piping was installed on console roof in the dome,
- LN2 circulated to Coude room (where imager will be serviced and tested)



July 2011: LN2 Cooling installation at CTIO

DARK ENERGY SURVEY



It worked! frost on the bypass!

DARK ENERGY SURVEY

By Jan. 2012

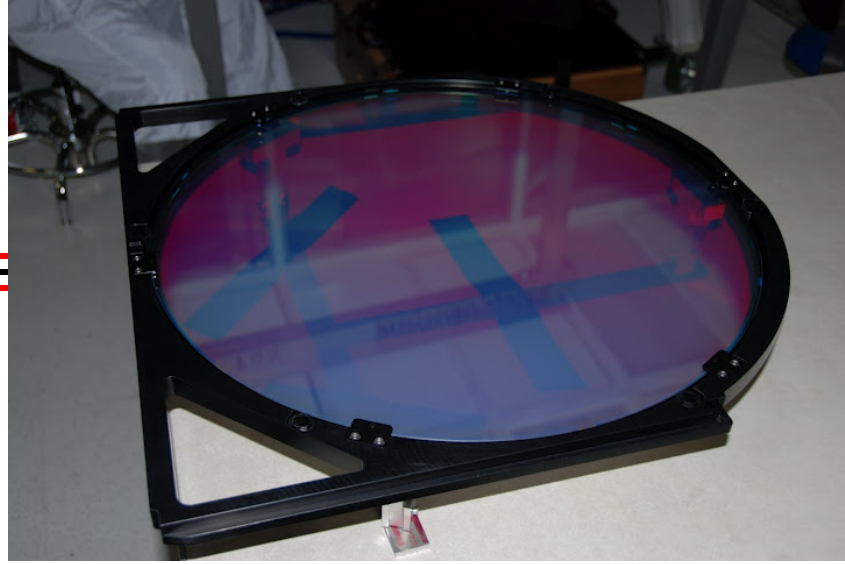
We make sure individual components work.

Camera re-assembly starts.

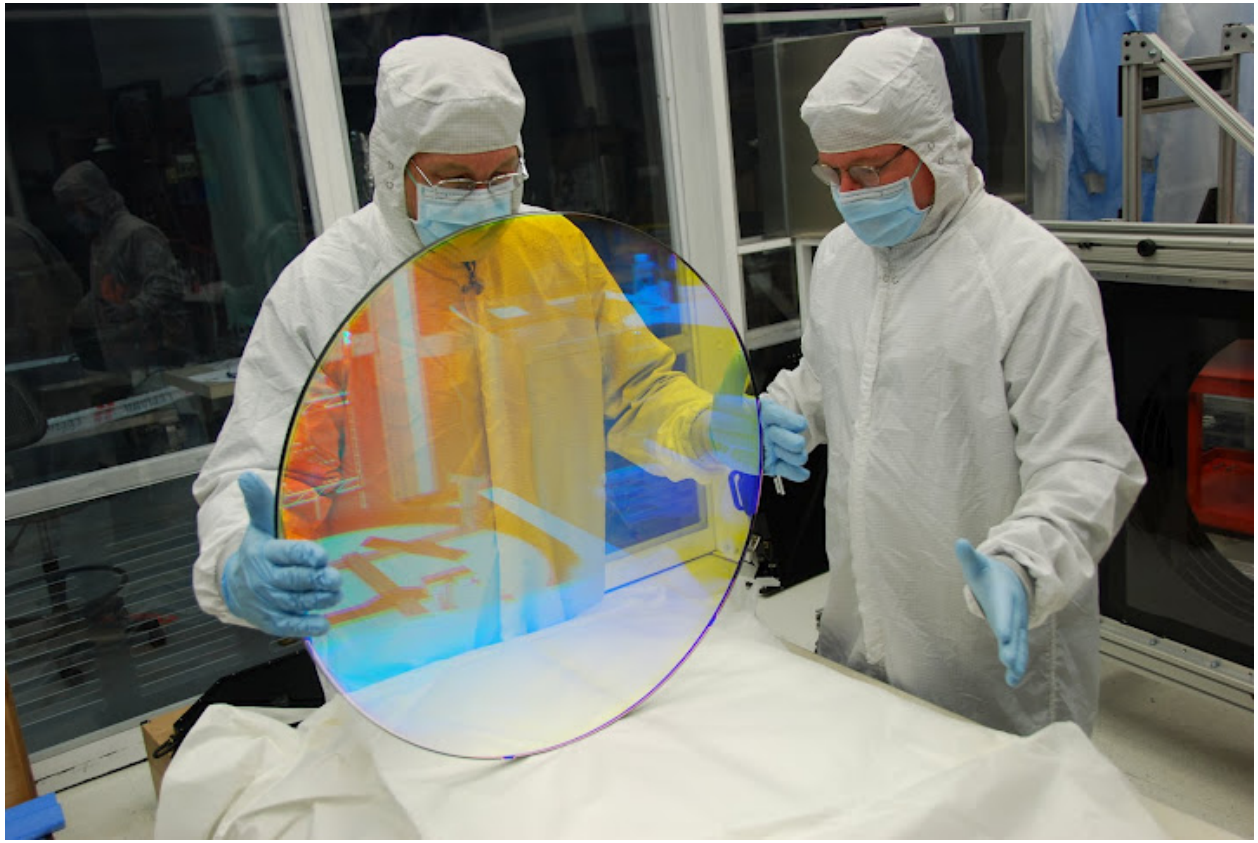
December 2011

- The imager had arrived at CTIO in late November 2011.
- It appeared to have survived shipping but … we are worried ☹
- Yes, All the CCDs are OK!
- Tremendous relief ☺

January March 2012

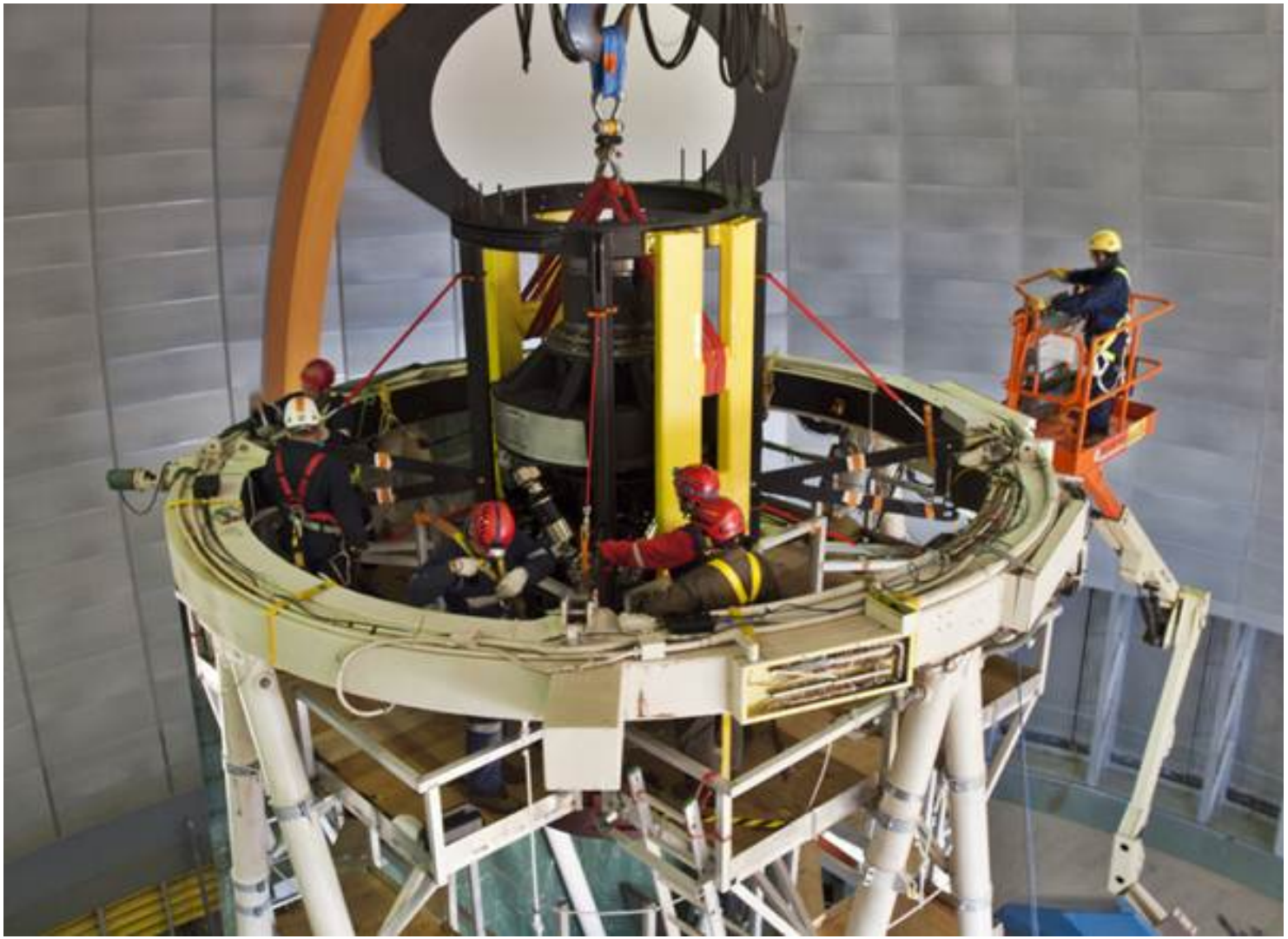


- Handling the World's Largest astronomical filters (r-band below & i-band right).
- Feb 20th telescope shutdown starts. Take out old camera and Cage



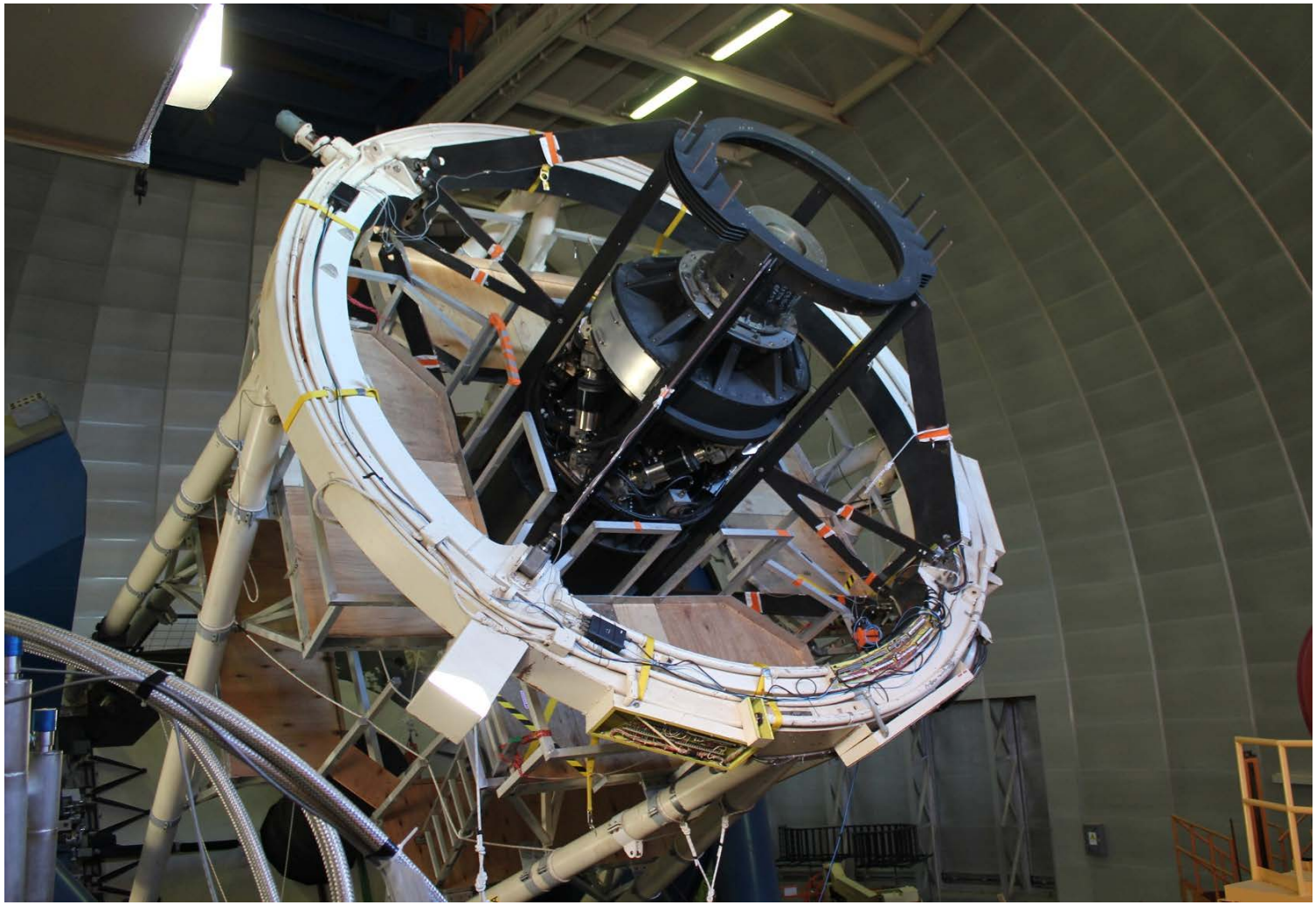
DARK ENERGY SURVEY

Installation of the DECam cage, and optical barrel! May 2012



The telescope moves once more but with dummy imager: June 2012

DARK ENERGY SURVEY

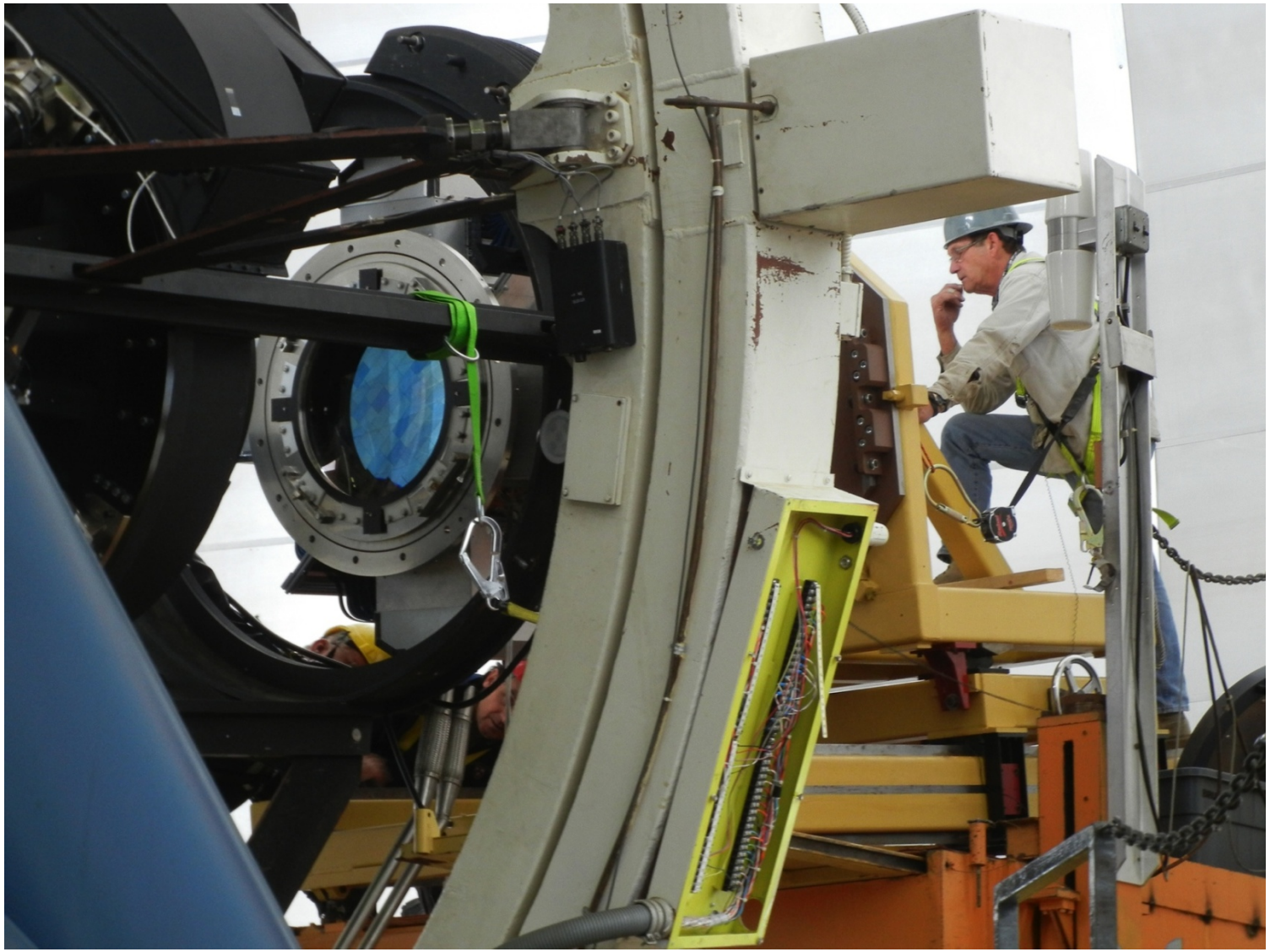


Attaching the Imager to DECam: Late August 2012

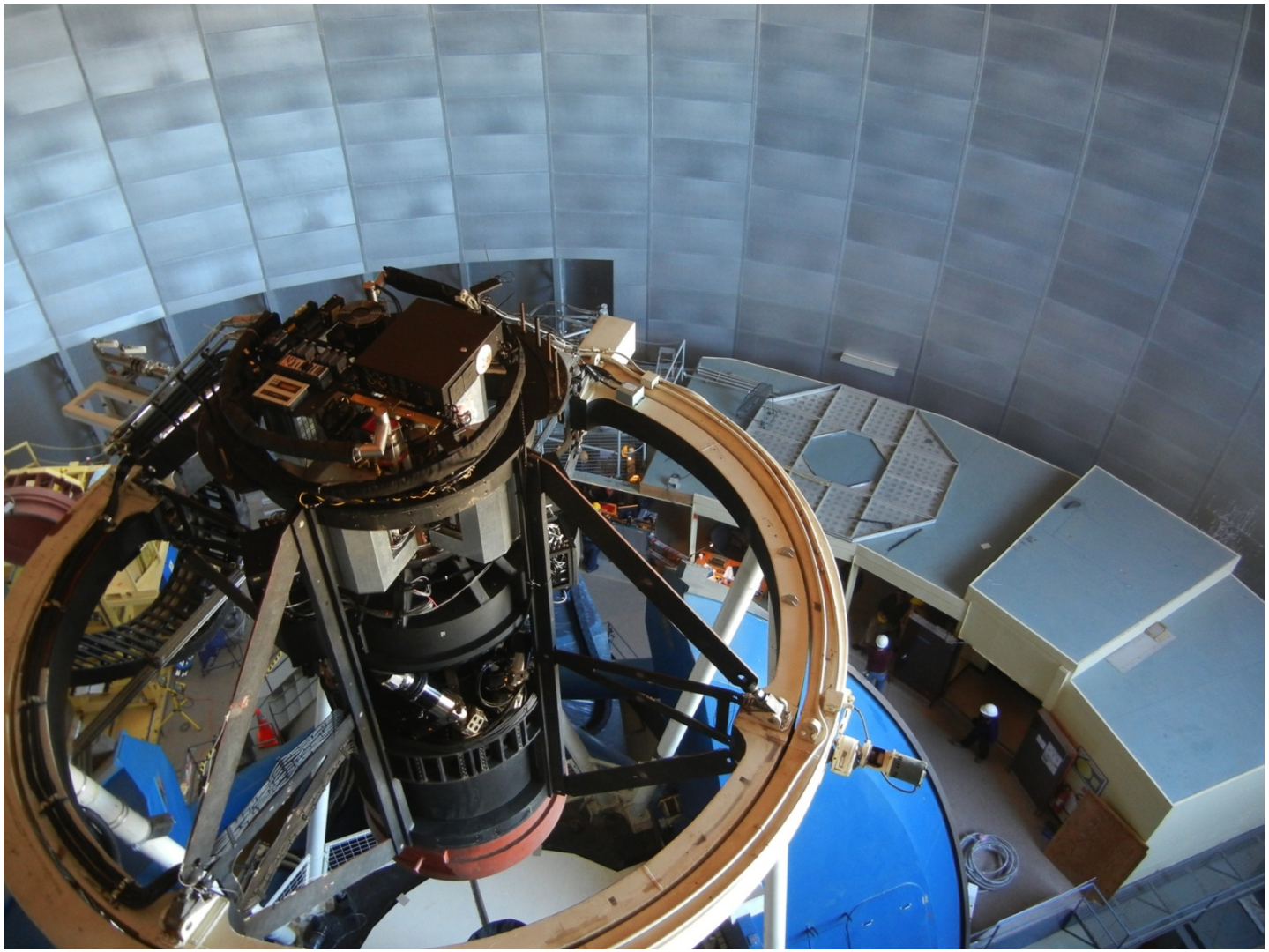
DARK ENERGY SURVEY

Attaching the Imager to DECam: Late August 2012

DARK ENERGY SURVEY



First Flight! Sept. 2012.
Nothing fell off!



A Mountaintop in Chile

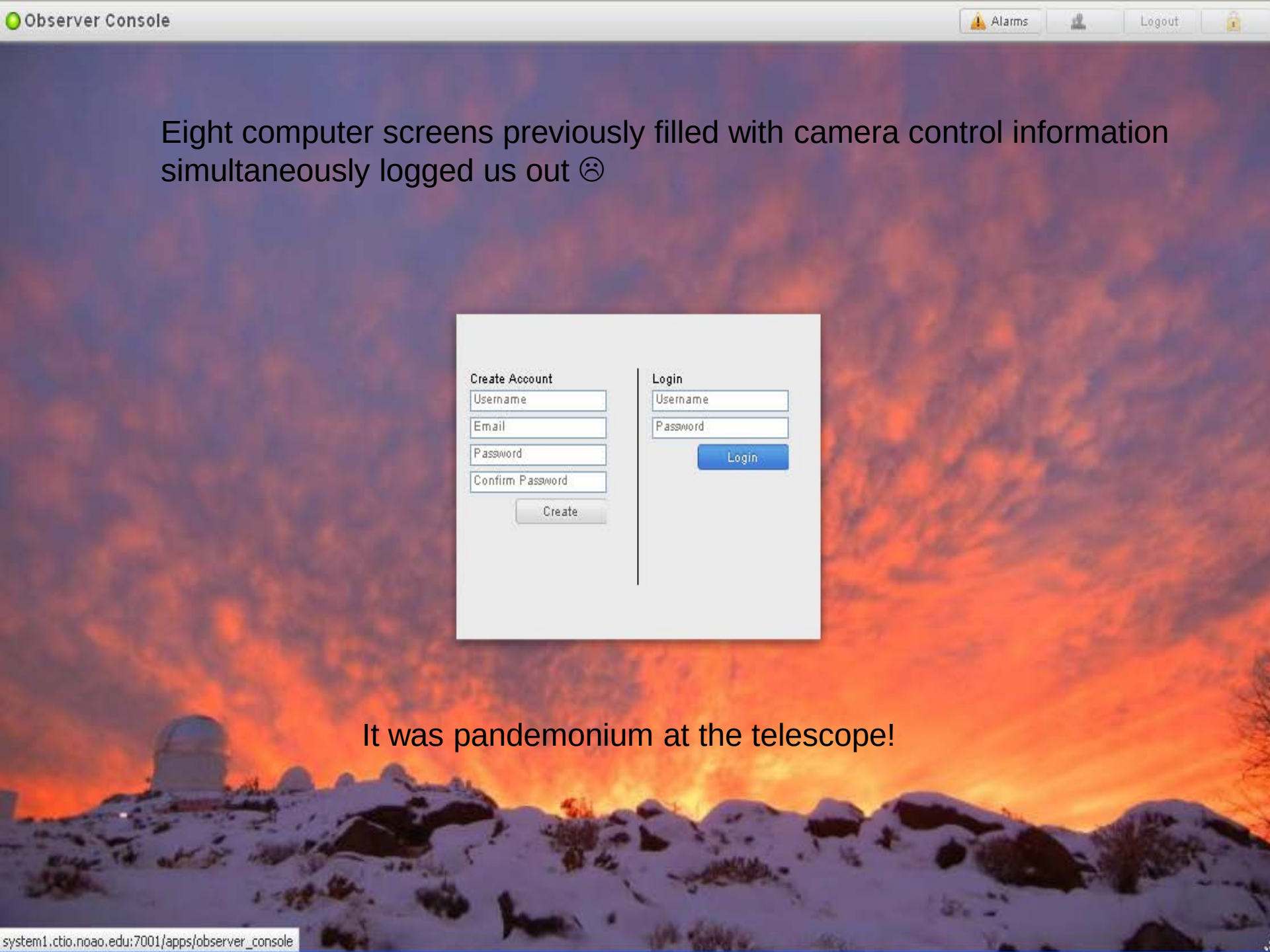
Cerro Tololo (altitude 2200m)

Mountaintop Critters [1]

DARK ENERGY SURVEY

Mountaintop Critters [2]

Room Mates

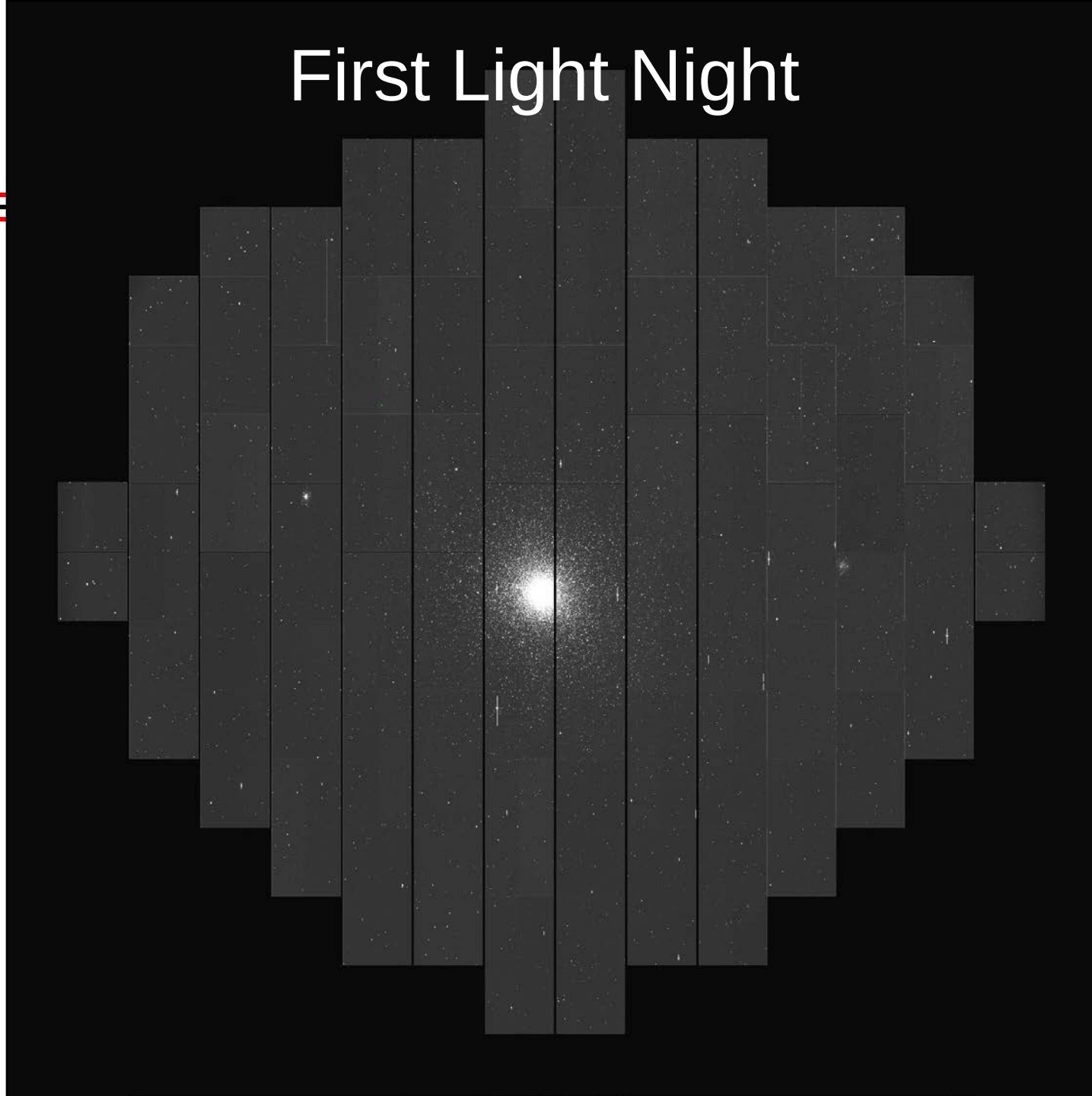


Eight computer screens previously filled with camera control information simultaneously logged us out ☹

It was pandemonium at the telescope!

First Light Night

- It took us <1 hr to get our 1st focused image. PSF 0.8” FWHM across the focal plane.
- One of first objects we looked-at is a globular cluster called 47 Tuc



First Light Night

DARK ENERGY SURVEY

Fornax Galaxy Cluster in "3-colors"

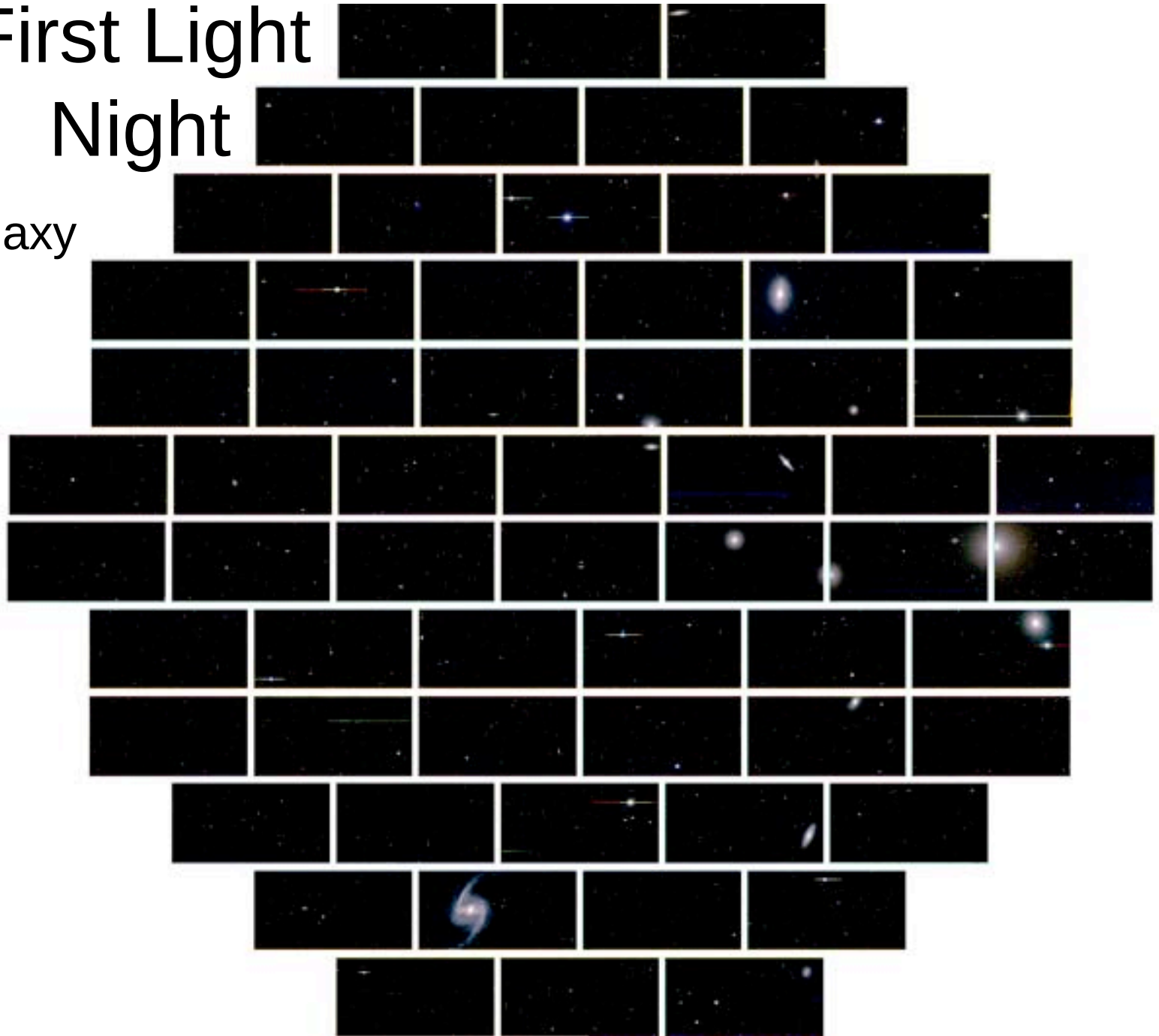


Image from Marcelle S.-S.

“The Great Barred-Spiral Galaxy” NGC1365

56 Million LY away

Image Credit: M. Murphy and N. Kuropatkin

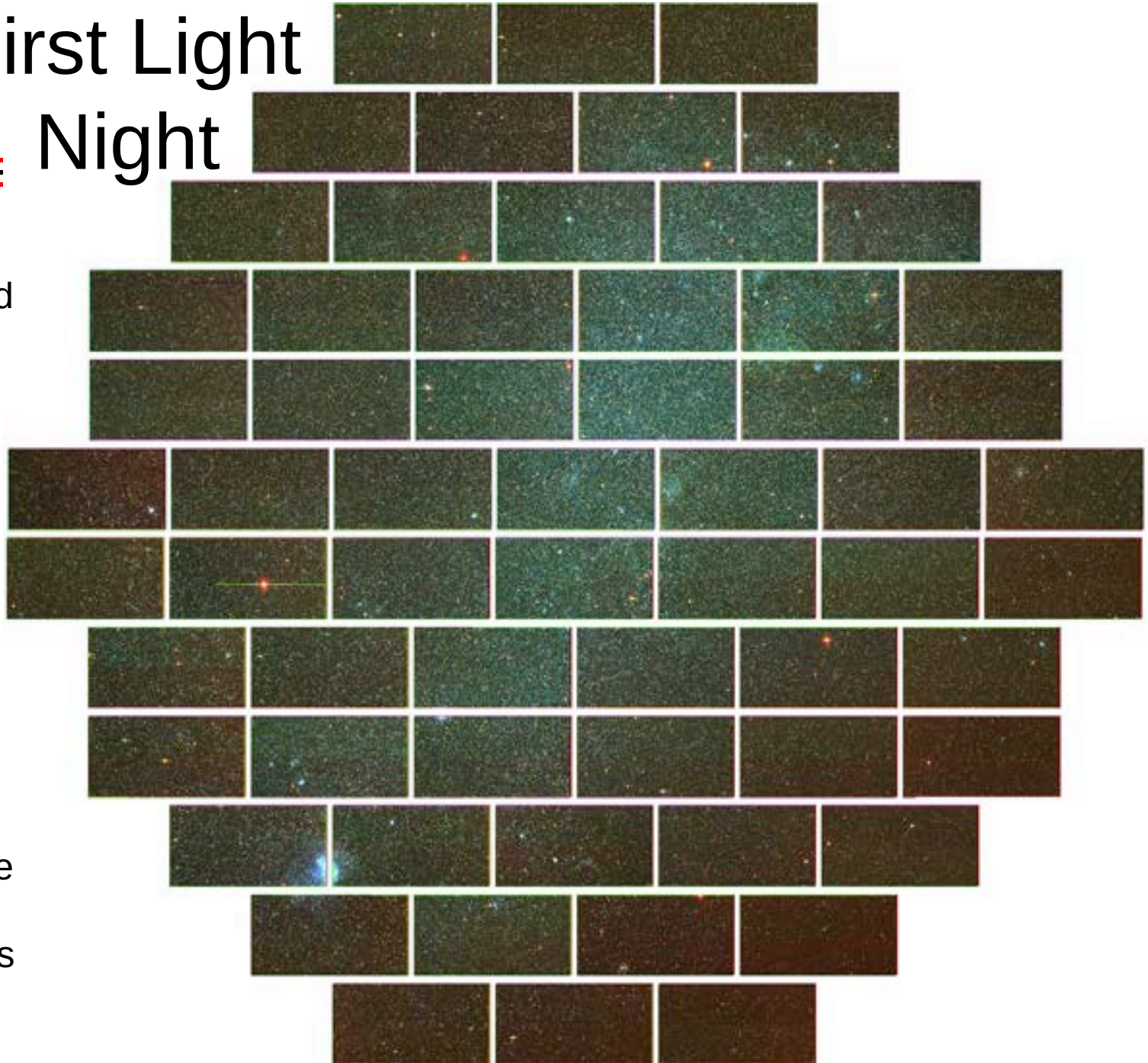
Also See darkenergydetectives.org/

Also Also See www.darkenergysurvey.org/dark-energy-camera-mosaic/

First Light Night

DARK ENERGY SURVEY

The Small Magellanic cloud (a dwarf galaxy that lies about 200,000 light years from Earth, and is a satellite of our Milky Way galaxy)



Hardest part of first light was to find targets large enough to show off the enormous field of view!

Blanco Telescope, and Southern sky. Small and Large Magellanic clouds

Photo Credit: Reidar Hahn

Dedication Nov. 2012

DARK ENERGY SURVEY

Dedication Nov. 2012

Commissioning and Science Verification

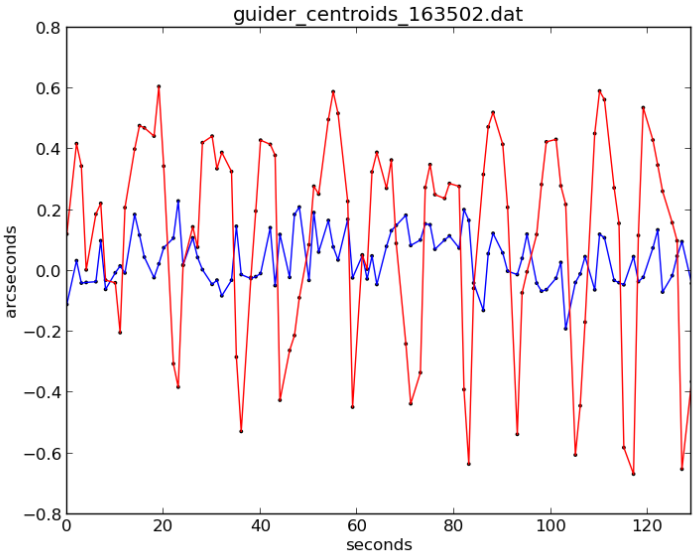
DARK ENERGY SURVEY

- From First Light through late October 2012 we implemented & tuned-up the camera systems
- On November 1st DES and NOAO and "Community" astronomers started to use the new instrument to try do science with the images
- "Community Users" are generally very happy with DECam and the control software, and pleased with the images from it.
  - ***This continues to be true.***

Commissioning and Science Verification

DARK ENERGY SURVEY

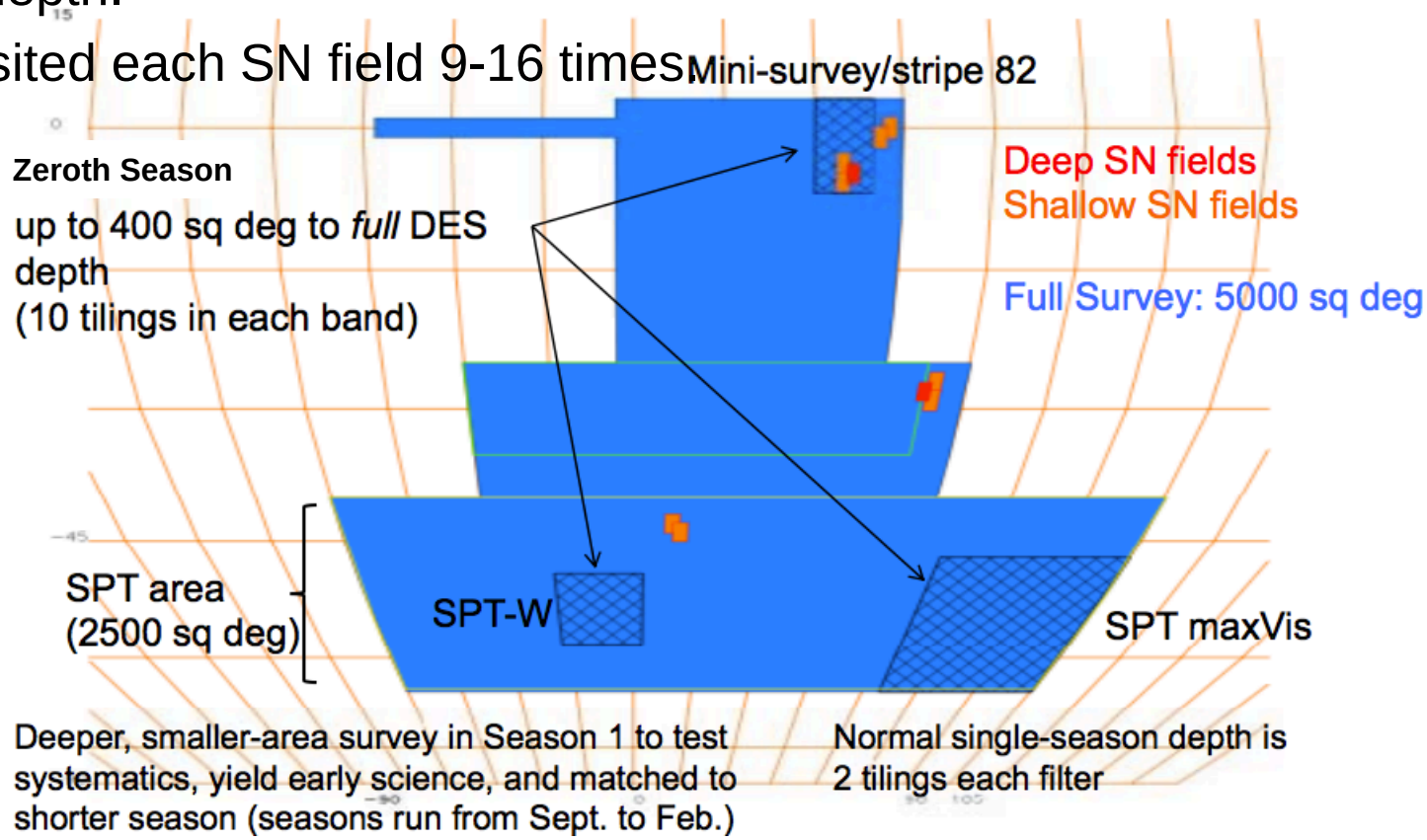
- But by the end, on November 24th, of “Science Verification” we all understood that more work was needed to improve the telescope performance
- From early December through the third week of February there were improvements to “pointing”, “offsets”, & “tracking”.
- We learned a lot about how telescopes work through our interaction with the telescope experts at NOAO!
- We named this “DES Season 0”



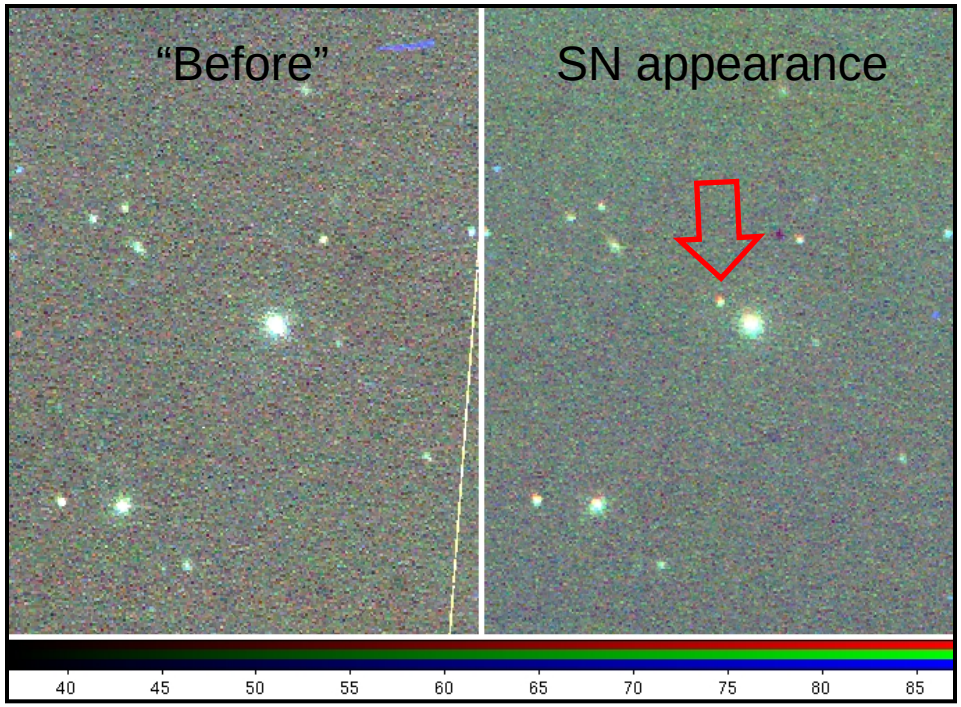
Survey Fields in Season 0

DARK ENERGY SURVEY

- Because we had a short season and spent a lot of observing time on engineering, we imaged a subset of the full DES area. We observed 23 full nights and 33 half-nights. 23,900 exposures in ~250 sq-deg to full DES depth.
- We visited each SN field 9-16 times



Supernovae “Difference Imaging”



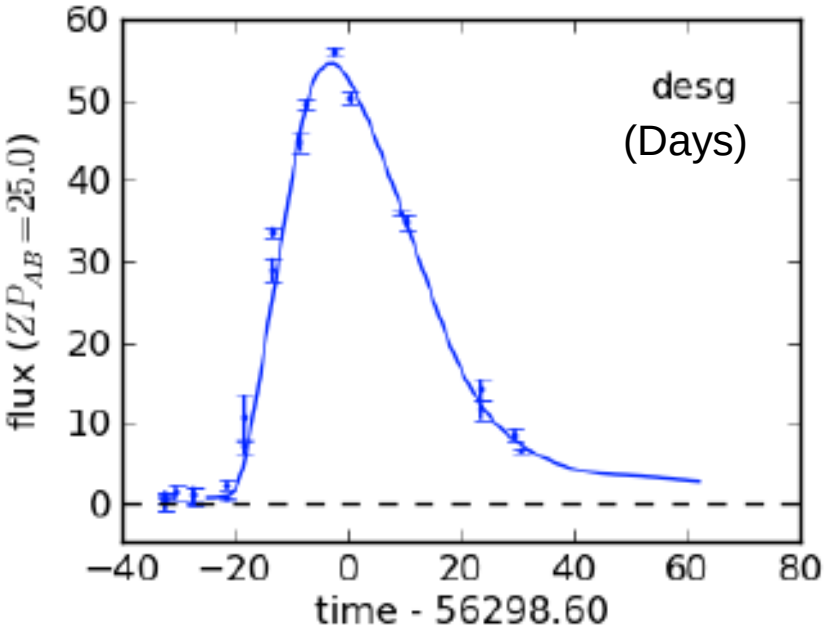
- Subtract a “template image” from the new image made for that field to make a “difference image”.
- The SNa appear as new objects in the “difference image”.
- See the SN a short distance away to upper left from the host galaxy

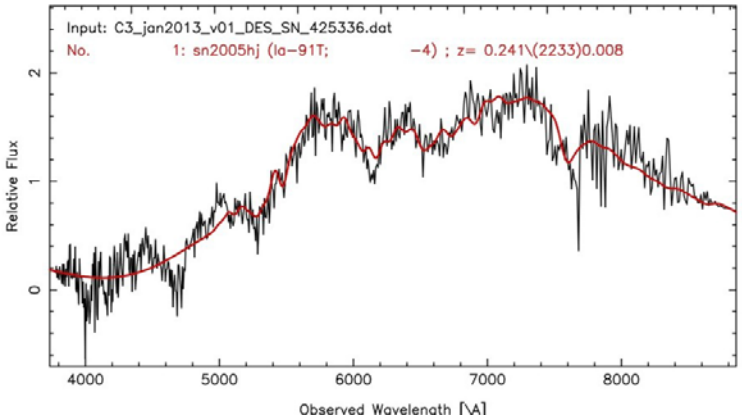
SN in Season 0

DARK ENERGY SURVEY

- Over the course of a few weeks we build up a “light curve”. Brightness of SN1a has a characteristic rise and fall time.
- 176 SNae candidates
- 16 SNae candidates z >1 discovered in Season 0
- Analysis of the light curve suggested 5 of those are Type 1a and all 5 were subsequently confirmed through spectroscopic follow-up

DES12C3a (z=0.241)

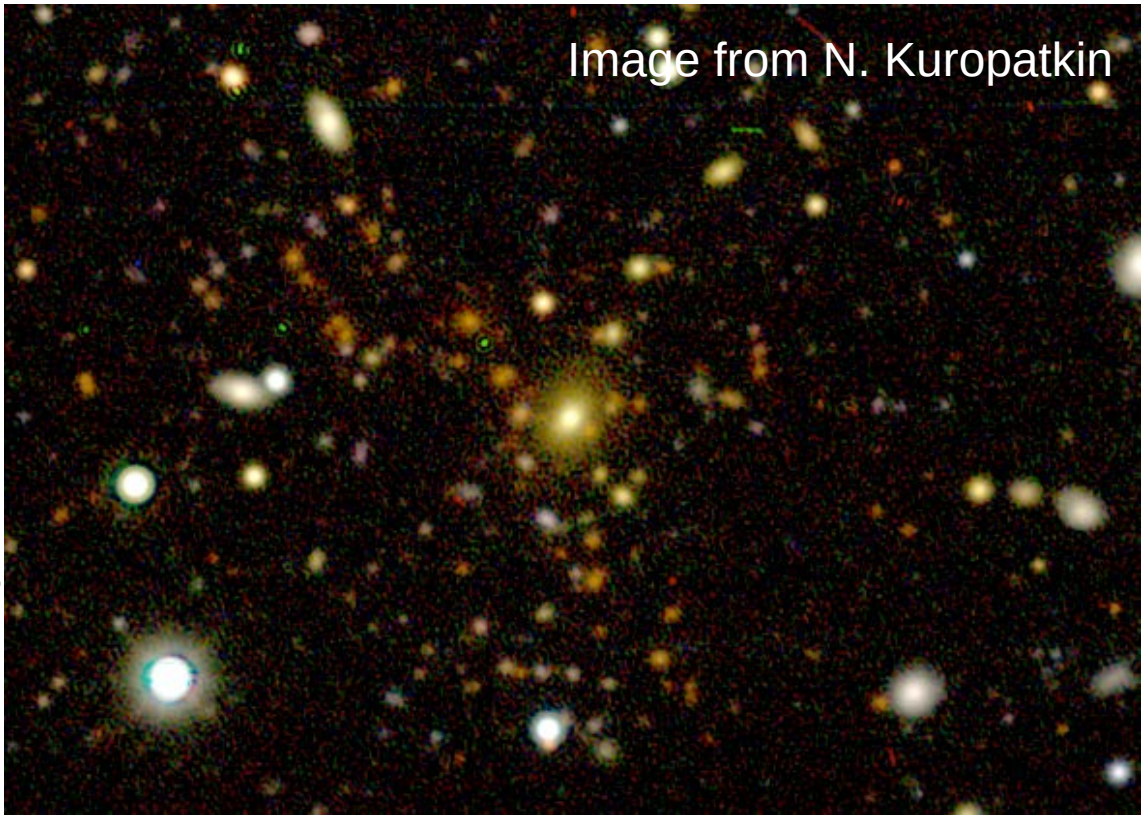




Galaxy Clusters

- Galaxy Clusters are the largest gravitationally bound structures that we know of.
- Composition
  - ~79% Dark Matter
  - ~20% hot diffuse gas
  - ~1% galaxies (stars)
- # vs. mass and redshift depends on how much Dark Energy there is (was)

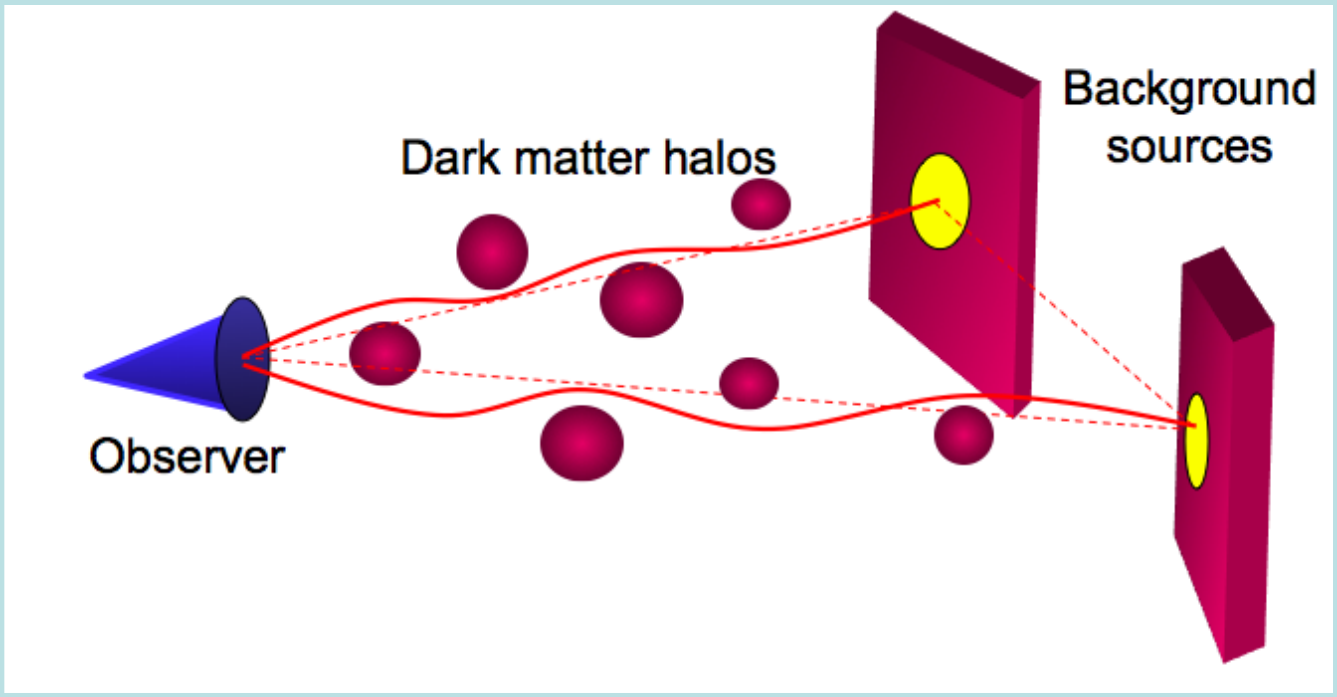
Image of a galaxy cluster (or is it 2 clusters)



10^{13} to 10^{14} solar masses

DES Weak Gravitational Lensing

DARK ENERGY SURVEY



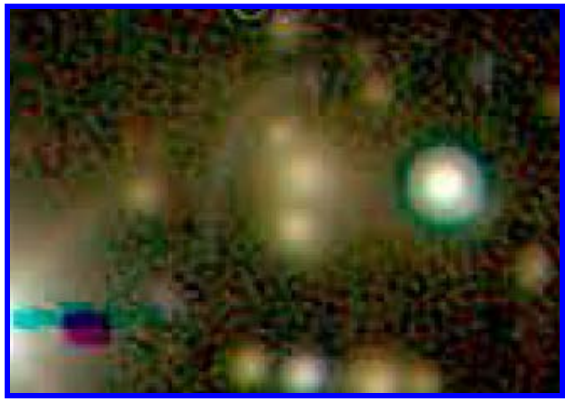
- Photons (light) are affected by gravity.
- The observed shape of a distant object is changed through the accumulated effects of passing close to matter along the line of sight.

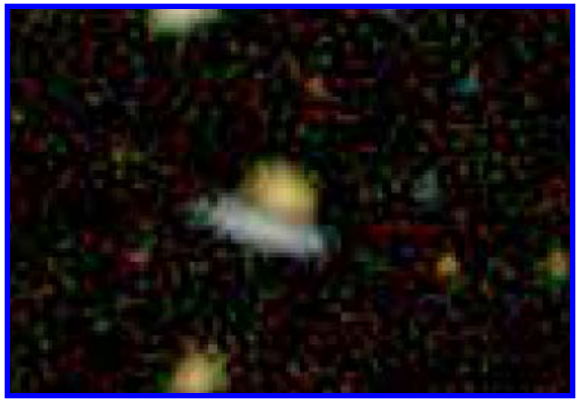
In special cases with a very massive object in LOS

"Strong" Gravitational Lensing

DARK ENERGY SURVEY

These are some of the dozens of candidates from Y0





- The distant sources can appear as "Einstein Rings", "Einstein Crosses", or arcs
- And are typically magnified by 10-100x so …

- Lenses are sometimes called "Einstein's Telescopes"

Please see “Wine and Cheese” from Marcelle Soares-Santos (FNAL) titled “Early Science Results from DES” on Friday October 25th at 4:00 PM.

DES Weak-lensing Map of Galaxy Cluster
courtesy of P. Melchior (OSU)

Since the end of SV data

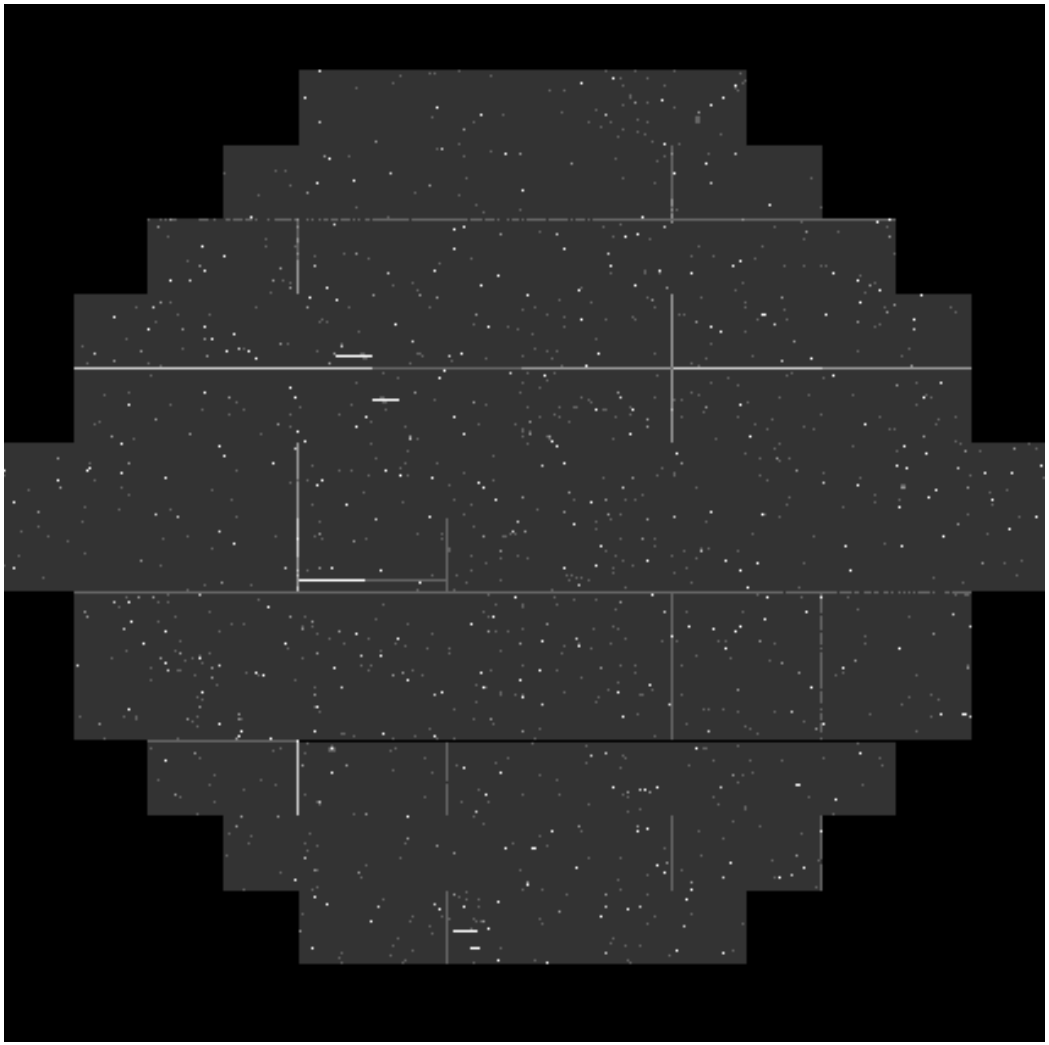
- During this spring & summer we “hardened” those parts that were vulnerable to failure so that we’d need to perform less maintenance and there would be decreased downtime.
- We are still making improvements from time to time
- Continued work on improving the “seeing”

On August 31, 2013 this observing team started DES “Year 1”

First DES Yr1 Image (8/31/2013 at 23:55 local time)

DARK ENERGY SURVEY

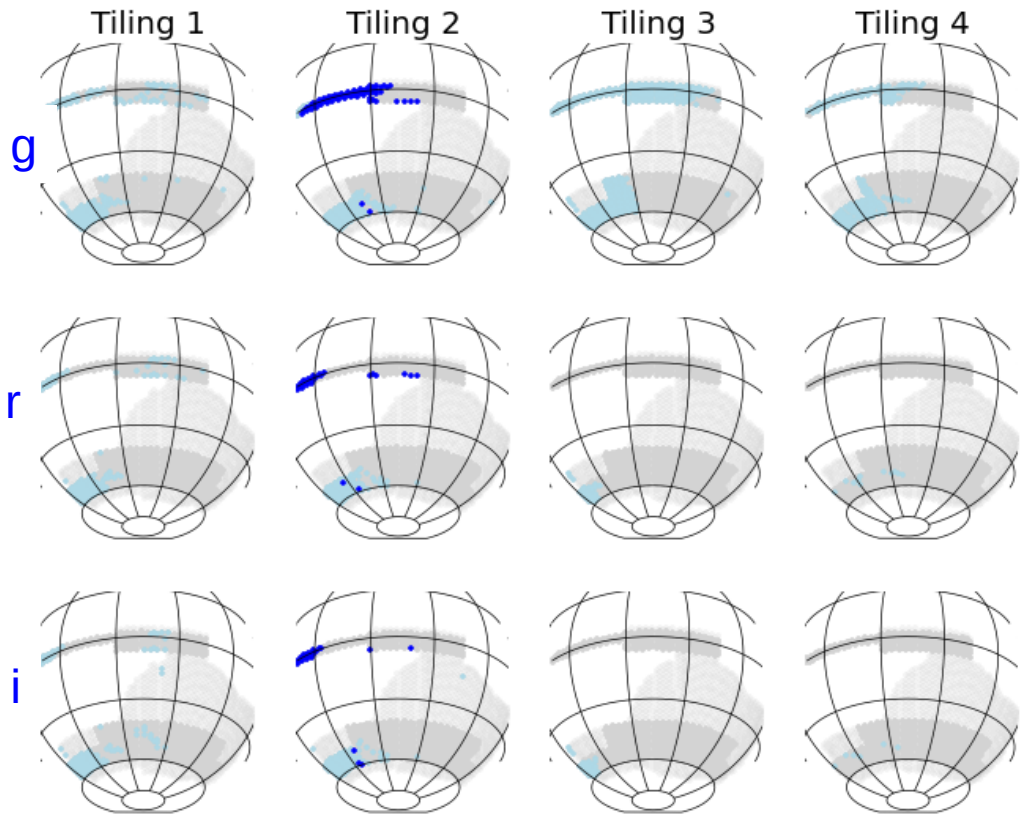
- Image 229250 was transferred to NCSA in Urbana where
- DES “Data Management” processed it and made a catalog of the stars and roughly 100,000 galaxies that can be identified in it.



How are we doing this year?

DARK ENERGY SURVEY

- DES Year 1 now has 11 nights of operations
- The weather could have been better so far. Six nights have been very cloudy.
- SN fields visited at least twice each.
- WF survey: (right) dark blue means done last night, light blue means done previously. Grey means not done.



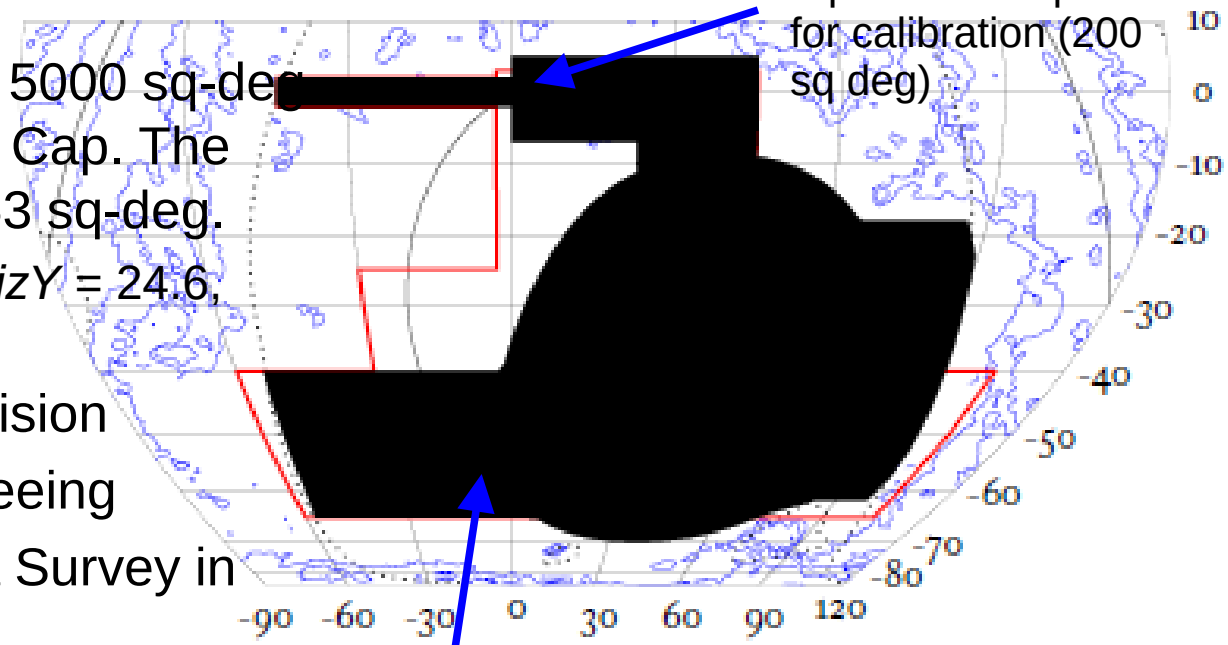
Map current on Wednesday Morning 9/11/13
Only the g,r,i-band filters shown.

DES Survey Parameters

DARK ENERGY SURVEY

- On our way towards 525 nights in the months from Aug. 2013 to Feb. 2013 to 2018.
- The Wide-field survey is 5000 sq-deg of the Southern Galactic Cap. The whole sky (4π) has 41253 sq-deg.
  - 300M Galaxies: 10σ *grizY* = 24.6, 24.2, 24.4, 23.8, 21.5
  - 2% photometric precision
  - 0.9" FWHM i-band seeing
- A 30 sq-deg Supernova Survey in 10 fields
  - If field not observed in 10 nights or anytime the "seeing" is poor.
  - Fields repeated typically every 4-10 nights. Discover ~4000 SN1A.

Survey Field



Overlap with SDSS equatorial Stripe 82 for calibration (200 sq deg)

Overlap with South Pole Telescope Survey (4000 sq deg) & Vista VHS Survey

Dark Energy Summary

DARK ENERGY SURVEY

Galaxy Clusters

- ~100,000 clusters to z>1
- Synergy with SPT
- Sensitive to growth of structure and geometry

Weak Lensing

- Shape measurements of 200 million galaxies
- Sensitive to growth of structure and geometry

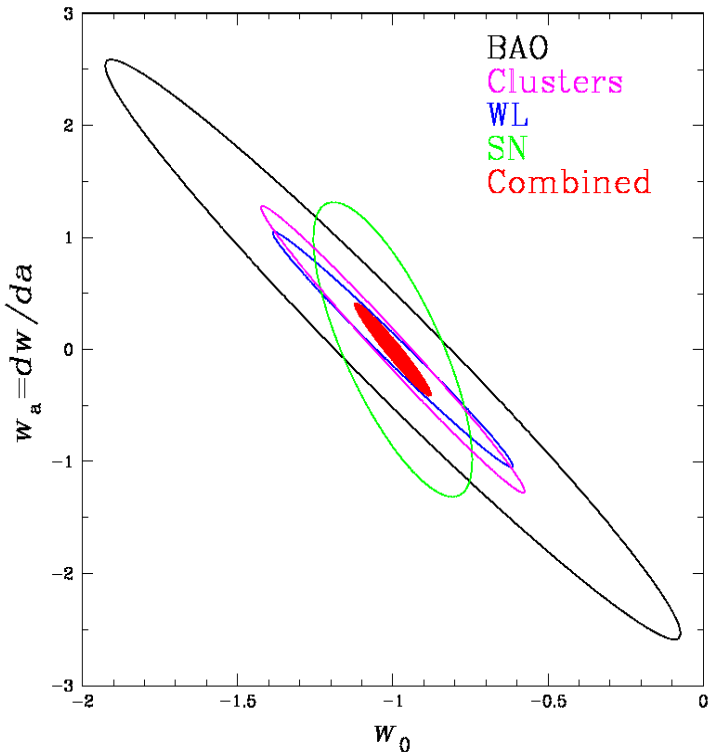
Baryon Acoustic Oscillations

- 300 million galaxies to z = 1 and beyond
- Sensitive to geometry

Supernovae

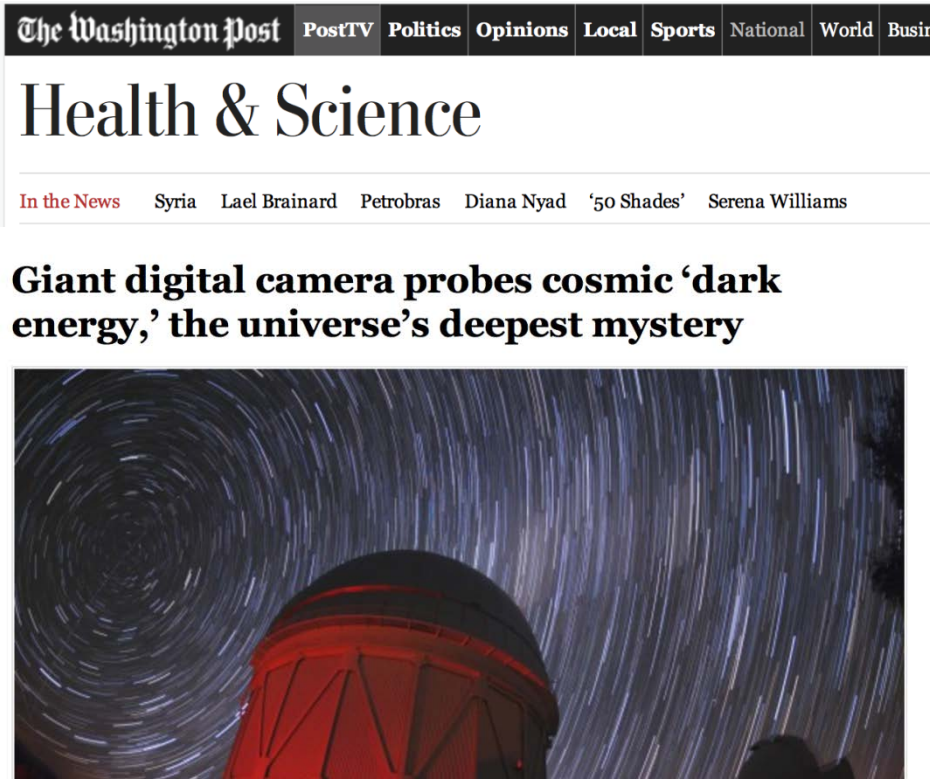
- 30 sq deg time-domain survey
- ~4000 well-sampled SNe Ia to z ~1
- Sensitive to geometry

Forecast Constraints on DE Equation of State



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

Summary


The Washington Post PostTV Politics Opinions Local Sports National World Busi

Health & Science

In the News Syria Lael Brainard Petrobras Diana Nyad '50 Shades' Serena Williams

Giant digital camera probes cosmic 'dark energy,' the universe's deepest mystery

Web page: www.darkenergysurvey.org

"Dark Energy Survey" has friends on Facebook

- We built DECam because we needed a new instrument to obtain a deep, wide field map of part of the Universe.
- These unprecedented data, analyzed with multiple techniques, may provide the clues that allow us to sort out the physics of cosmic acceleration.
- It's taken 10 years to get to this point. So far, so good.

Acknowledgements and appreciations:
CTIO staff, Alistair Walker,
Marcelle Soares-Santos, Brian Nord
Carlos Cuhna, Eric Suchyta, Kyle Barbary, Josh Frieman
Chris d'Andrea
& the rest of the DES Collaboration

Extras

Biggest Camera?

DARK ENERGY SURVEY

	Blanco DECam	CFHT MegaCam	WIYN O.D.I.	Subaru HyS.C.	PanStarrs *1	LSST	Yerkes
Year	2012	2003	2013+	2012	2009	2022+	1909
Filters	**62 cm diameter**	30 x 30 cm	42 x 42 cm	60 cm diameter		75 cm diameter	
Shutter	**60 cm diameter**		45 x 45 cm	58 cm diameter?	48 x 48 cm		
Primary Mirror	3.9m	3.6m	3.5m	**8.2m**	1.8m	6.5m	40” lenses 300 lbs
1st Lens Corrector	**0.98 m 176 kg**	0.8m	0.59m 36 kg	0.82 m	0.6 m	1.55 m	
Focal Plane	45 cm	25 x 25 cm	40.5 x 41.5 cm	**48 cm diameter**	40 cm	60 cm diameter	6 in.
Pixels	520 M	340 M	971 M	1.0 B	**1.4 B**	3.2 B	Plates
F.O.V.	3 deg^2	1 deg^2	1 deg^2	1.8 deg^2	**7 deg^2**	9.5 deg^2	100 deg^2
Etendue AΩ	~32	~8	~8	**95**	~12	~340	~200
Time to “do a DECam”	1	~10	~10	0.5	~4	~0.1	~1000

Biggest Camera?

DARK ENERGY SURVEY

	Blanco DECam	CFHT MegaCam	WIYN O.D.I.	Subaru HyS.C.	PanStarrs *1	LSST	Yerkes
Year	2012	2003	2013+	2012	2009	2022+	1909
Total weight	6000 lbs	1325 kgs	2500 lbs			2800 kgs	
Readout time	25 sec						

End Extras

Camera Installation Team

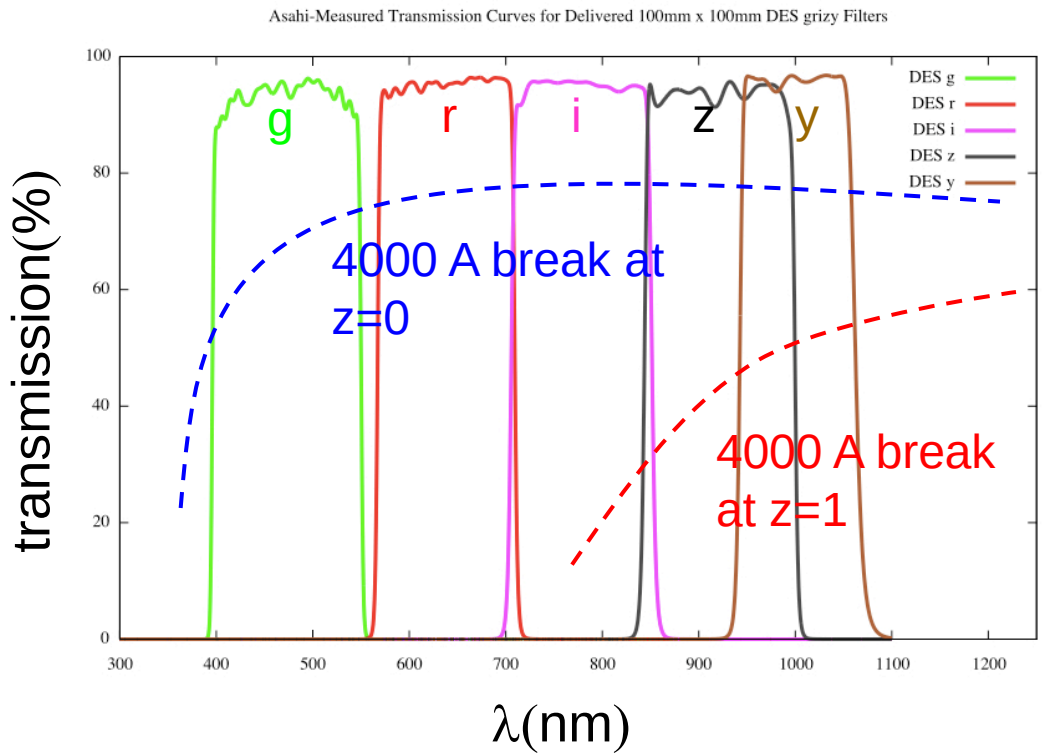
DES Filters & Photometric Z's

DARK ENERGY SURVEY

- Measure relative flux in *grizY filters* and track the "4000 Angstrom break"
- Estimate individual galaxy redshifts with accuracy $\sigma(z) < 0.1$ (~0.02 for clusters)
- Filters were produced by Asahi Spectra (Japan)

i-band (left) z-band (right)

Elliptical galaxy spectrum

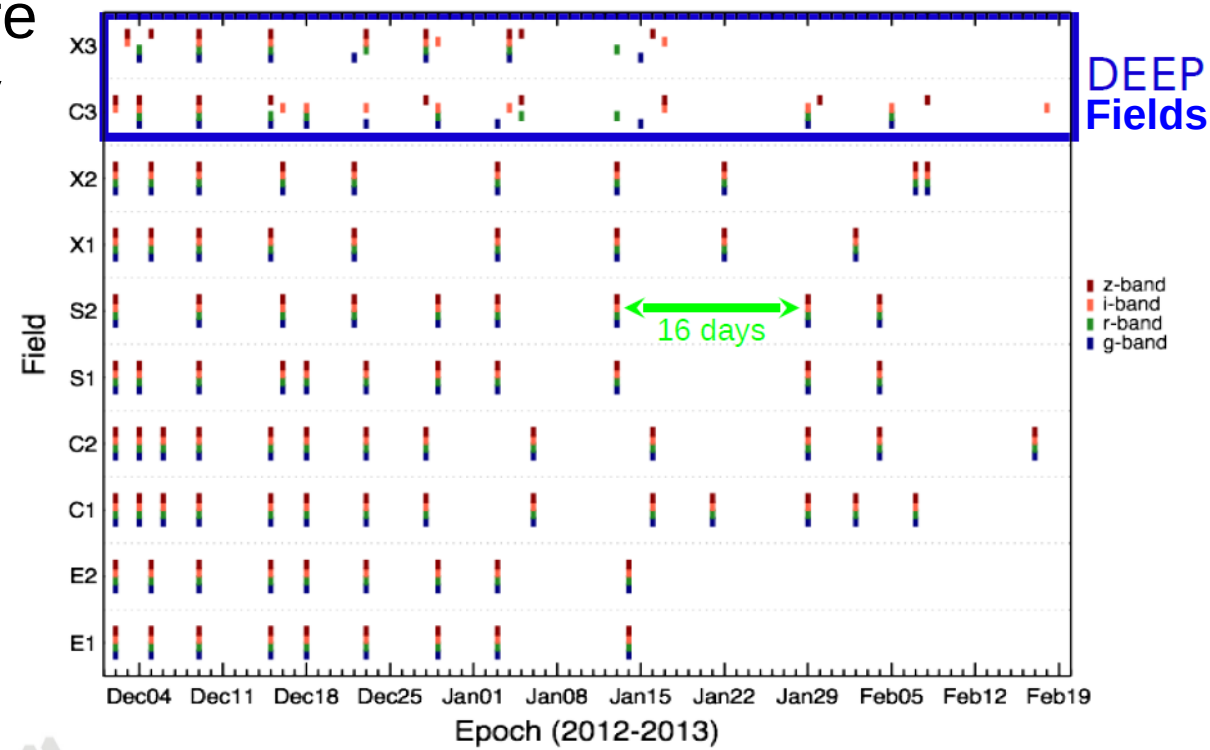


World's biggest astronomical filters (60 cm diameter)

DES Supernovae Survey Y0

DARK ENERGY SURVEY

- SN measurements are sensitive to geometry (expansion of the volume) but not to gravity.
- Roughly 10% of the time will be spent on 10 fields that we will visit at least every 4-10 nights.
- Identify 4000 new SN1a by the end of the survey.

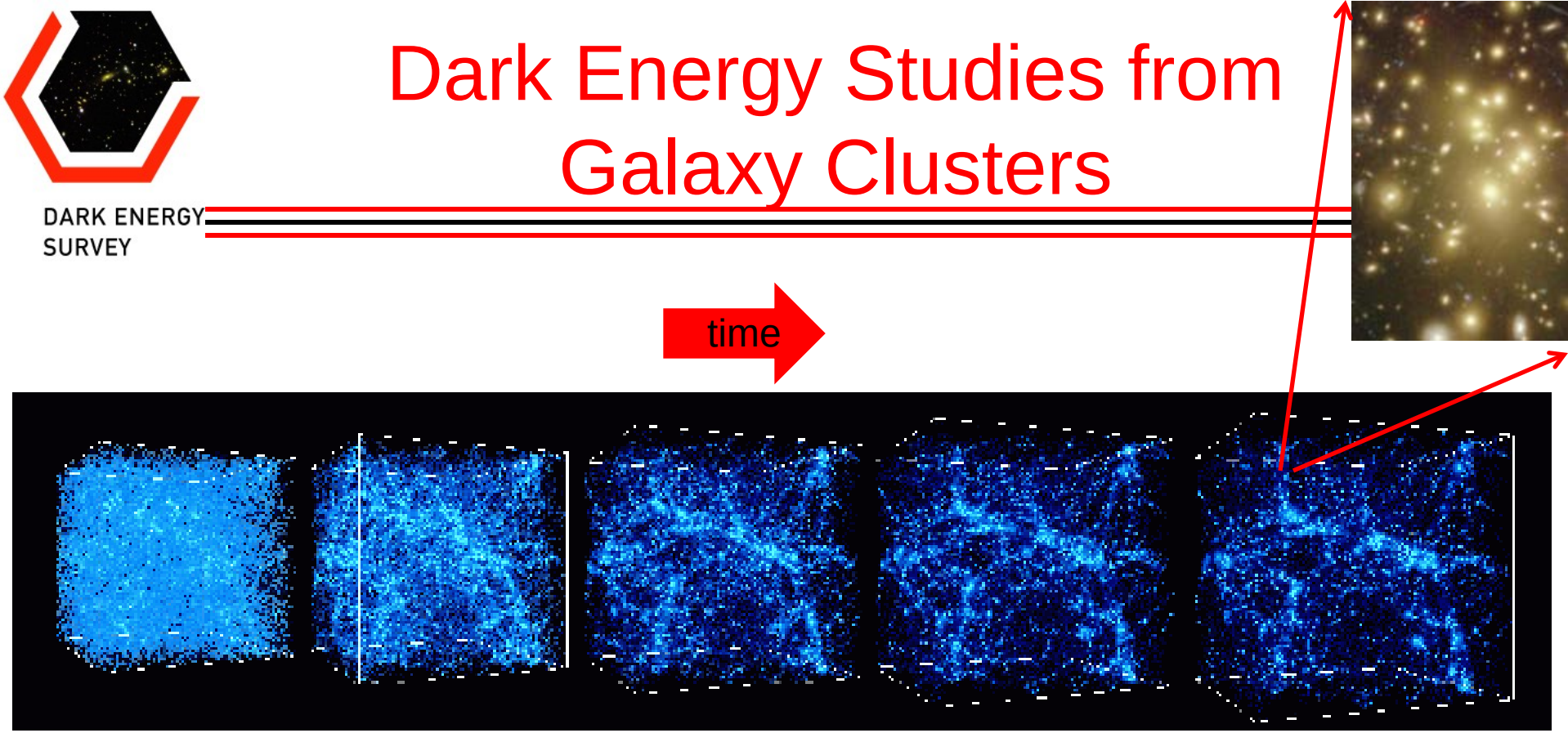


Extra Science

- Neutrino mass (see Ofer) 0911.5291 Thomas
- Quasars
- Strong Lensing
- Milky Way
- Galaxy Evolution
- Check working groups

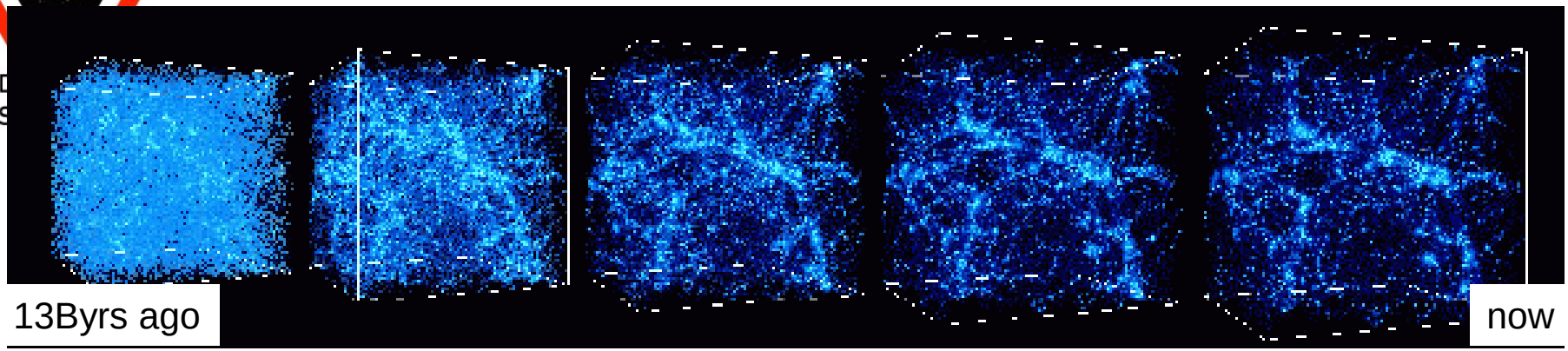
Dark Energy Studies from Galaxy Clusters

DARK ENERGY SURVEY



- The number of galaxy clusters formed as a function of time depends on the amount of matter (gravity) in competition with expansion (dark energy).

Four ple ways to measure the effects of Dark Energy



The Dark Energy Survey will measure the effects of Dark Energy and Dark Matter 4 different ways and by combining the results we hope to get a better understanding of what they are

Gravity and Expansion

1) Count the Galaxy Clusters as a function of time
2) Measure the distortion due to galaxy clusters and clumps of dark matter (Lensing)

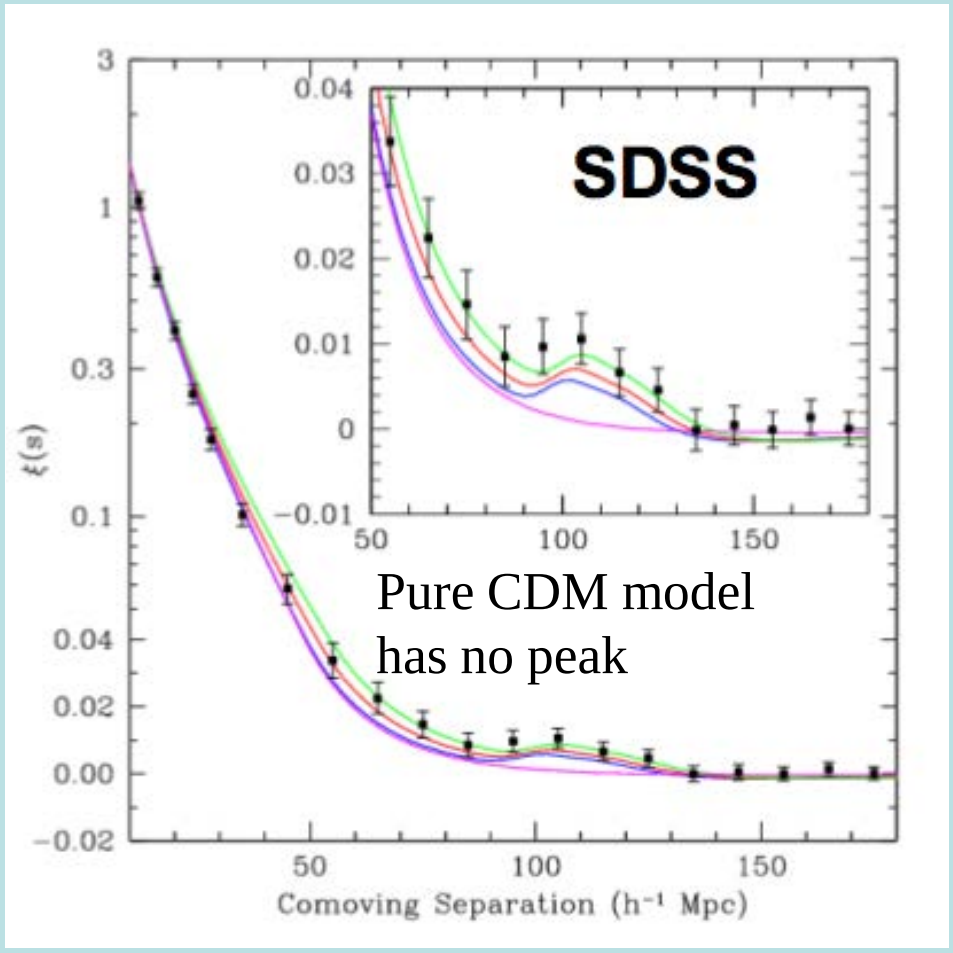
Expansion

3) Measure the space between galaxies as a function of time
4) Use Supernovae to measure the expansion rate

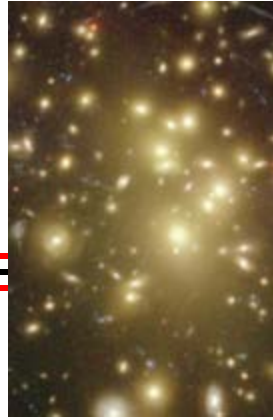
DES LSS/BAO

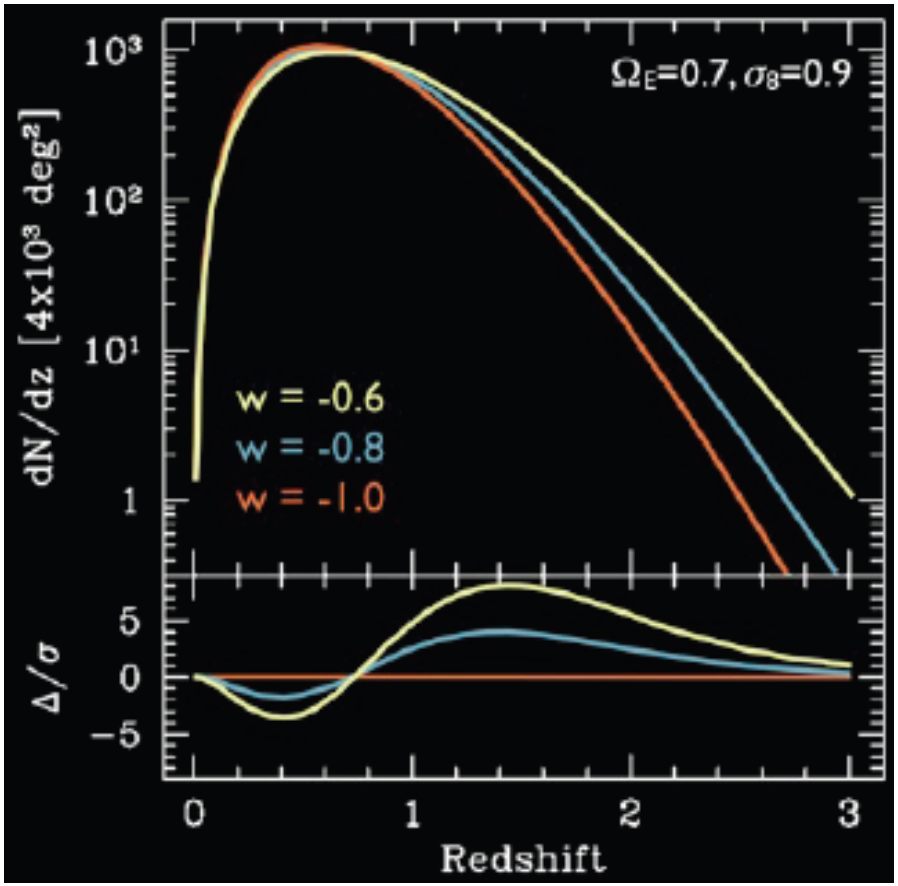
- CMB measures a snapshot of density fluctuations in the early Universe (z~1100).
- The density fluctuations are also imprinted into the distribution of galaxies. The size scale is ~100 Mpc.
- We'll measure it at 0<z<1.5 for $3x10^8$ galaxies.
- Sensitive to geometry (expansion of the volume) but not to gravity.

2 –point correlation vs. angular size



Dark Energy Studies from Galaxy Clusters





- We'll discover 100 thousand galaxy clusters
  - Test the growth rate of structure vs. geometry.
  - Pits gravity vs. the expansion rate of the volume.
- Overlap with South Pole Telescope measures the mass but not the distance using a shift of the CMB
  - Independent mass crosscheck

Terminology: Red Shift (z)

DARK ENERGY SURVEY

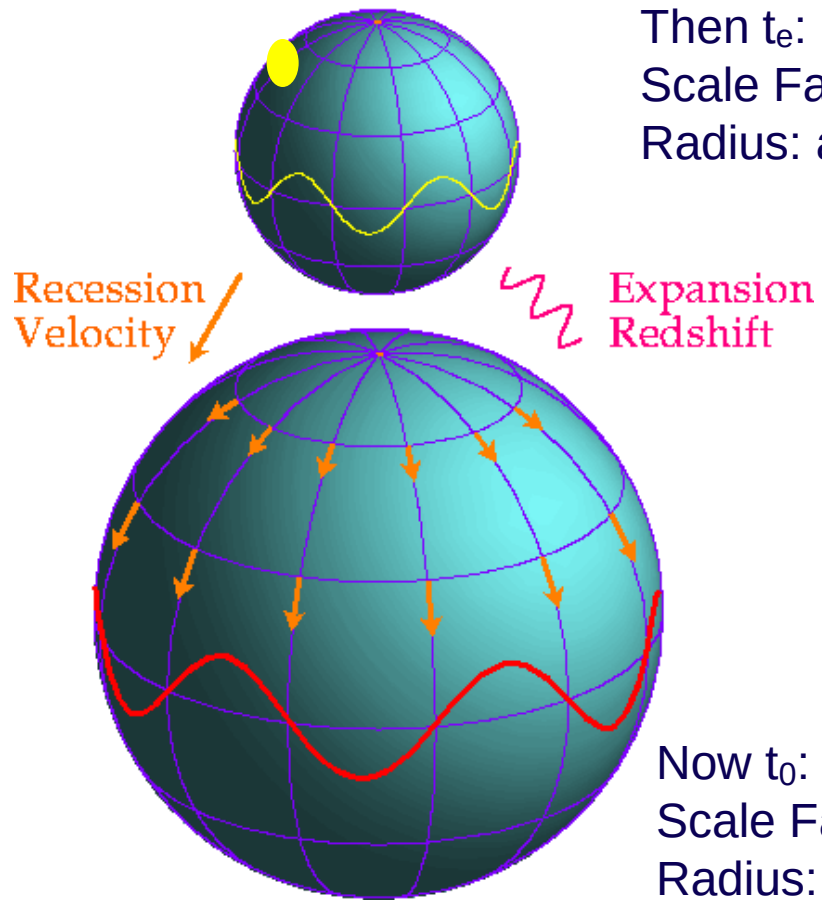
- A measure of age and distance.
  - z = 0 is here and now
  - z ~ 1100 for the oldest and most distant photons (CMB) that we see.
- For scale factor a and wavelength λ:

$$1+z = a(t_0)/a(t_e)$$
$$= \lambda(t_0)/\lambda(t_e)$$

- Redshift vs. distance relationship depends on the cosmology

2-D Analogue

Cosmological Expansion



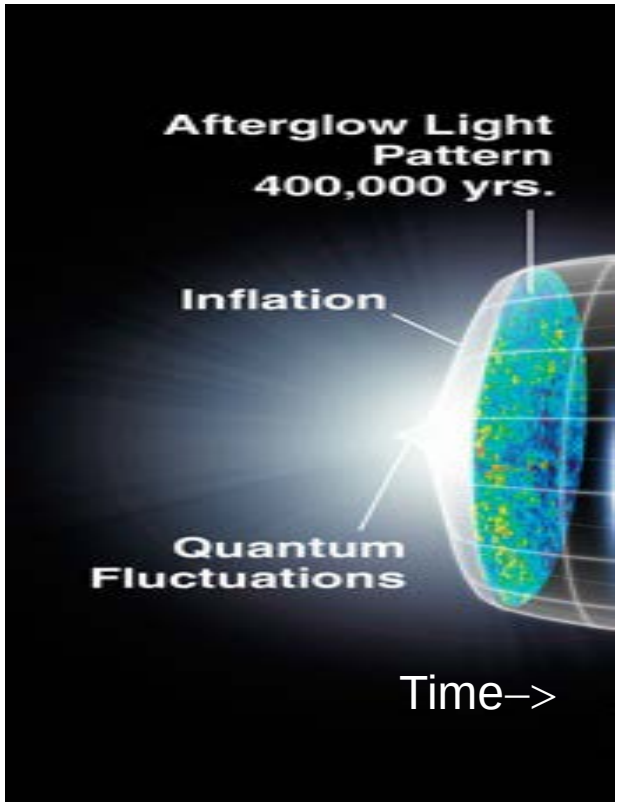
Omega Centauri

- The largest globular cluster in the Milky Way is15800 light-years away
- Might be the remnant of a dwarf galaxy captured by the M.W.
- Several million stars
- 12 billion years old
- Appears about as large as the full Moon but much fainter

Inflation (1980)

DARK ENERGY SURVEY

- Big Bang gives us the microwave background radiation but cannot explain why it is so uniform. This is called "The Horizon Problem"*.
- That is: parts of the Universe that should have been out of "causal contact" with each other are homogeneous
- In 1980 A. Guth theorized that an exponential expansion 10^{-36} s after the Big Bang blew-up the previously causally-connected Universe.
- Models for inflation (beyond the scope of this talk)



*Other problems: No Magnetic monopoles, flatness problem (Ω=1).