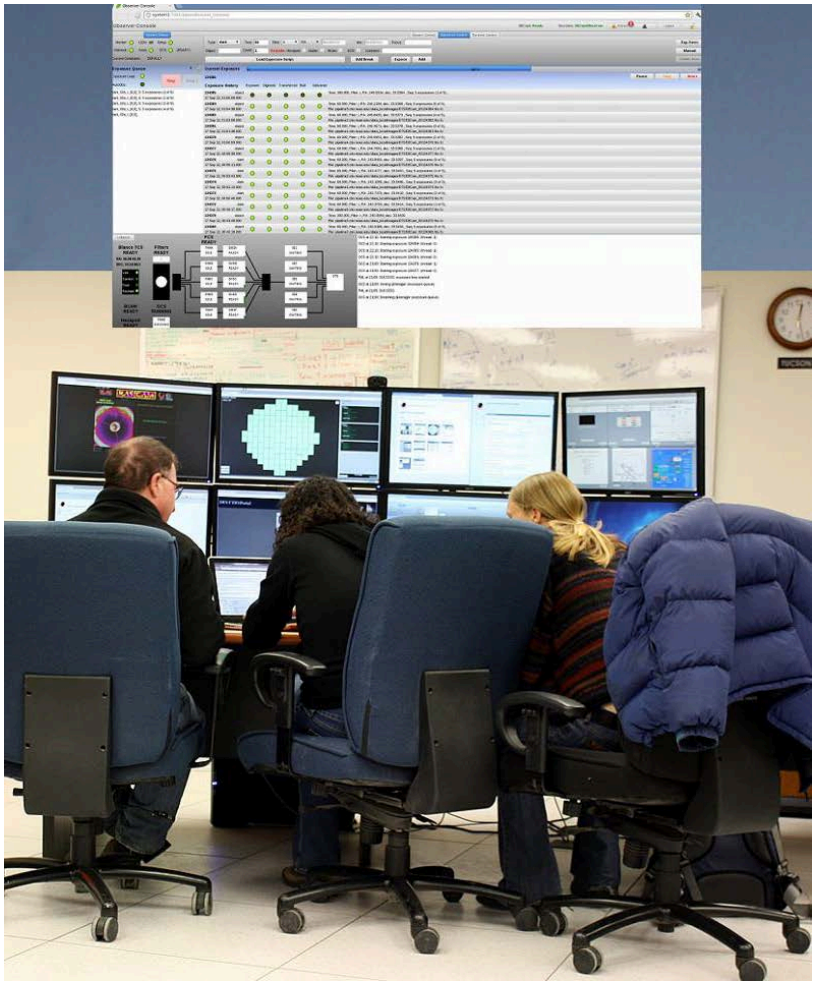
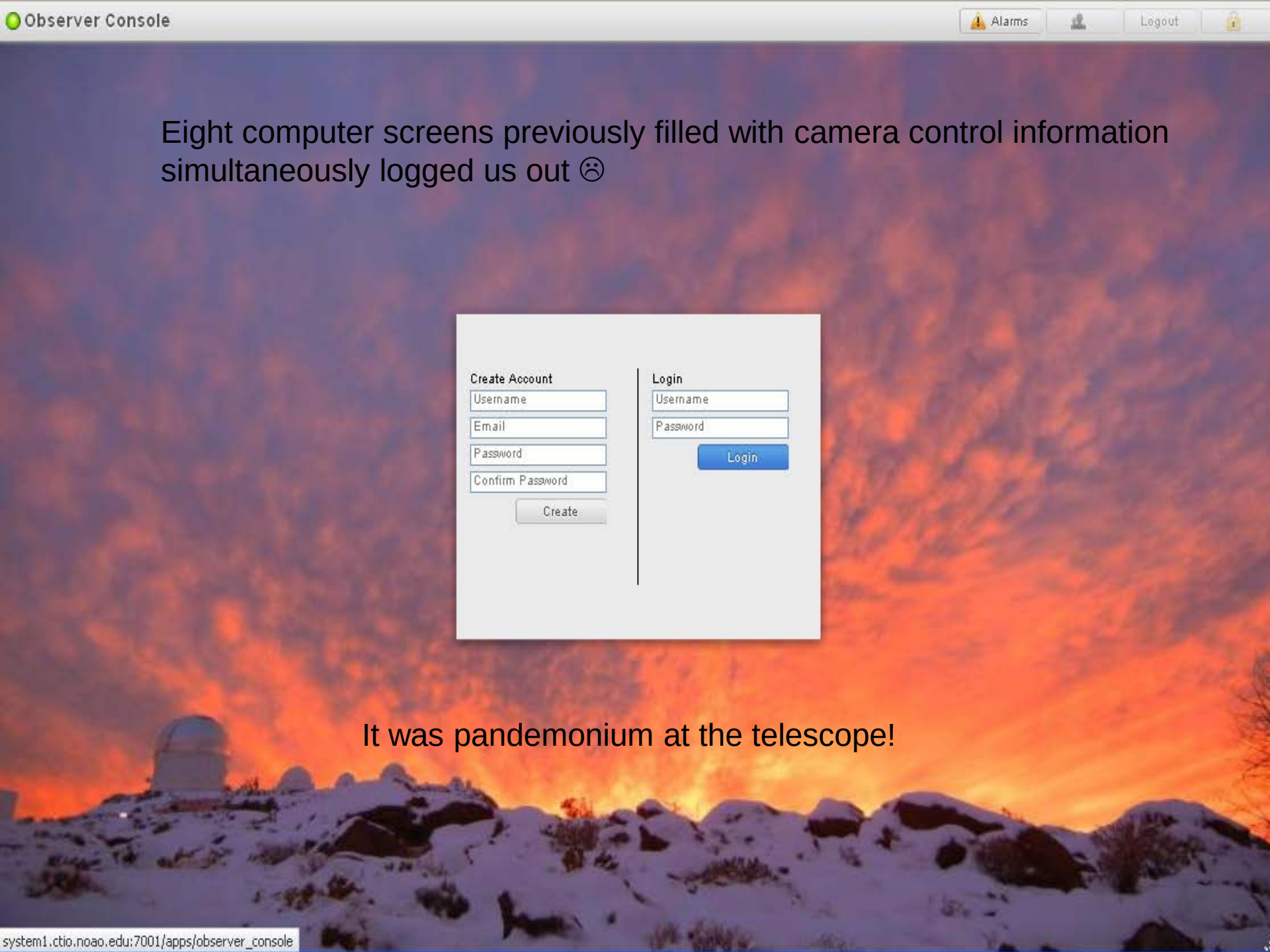
DARK ENERGY SURVEY

# 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

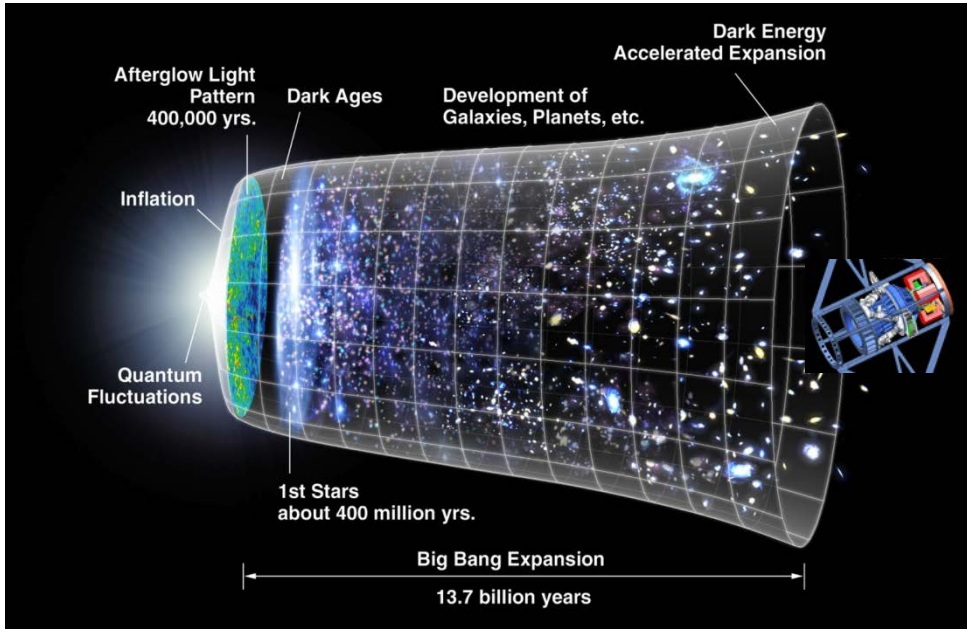
## Outline

- Cosmology and the physics of the accelerating expansion of the Universe
- Dark Energy Camera Construction & Commissioning
- First Light (2012)
- 2 Seasons of Observations
- Sample of the 1st DES Science Results

Tom Diehl (Fermilab)
@ NIU
November 21, 2014

# 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 much smaller size and is expanding with time.
- 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

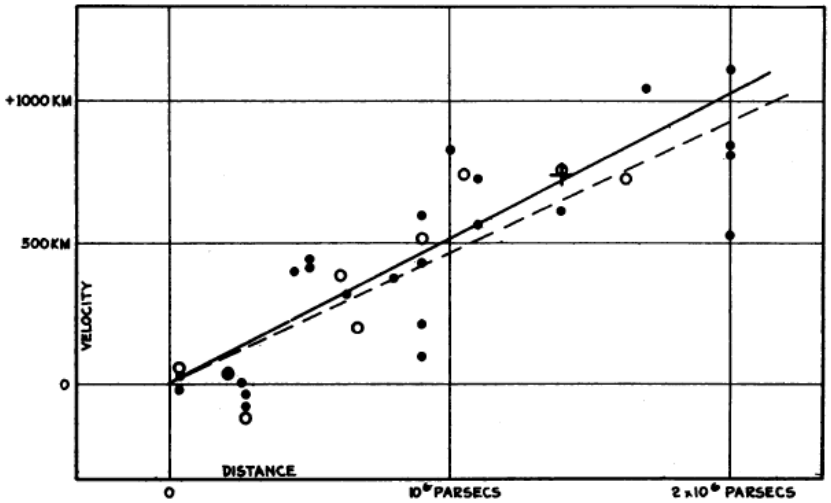



FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

- Cosmologists spent decades debating measurements of the *Cosmic Distance Scale* that determined the rate of Hubble Expansion 67.8 ± 0.8 km/s/Mpc (Planck 2013)

# Cosmic Microwave Background Radiation

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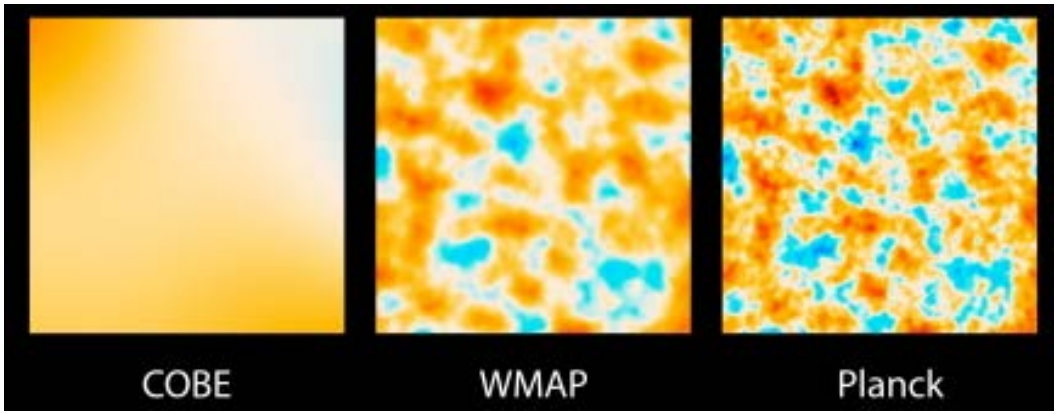
- CMB Radiation was discovered in 1965 at Bell Labs Holmdel using a LHe-cooled receiver. “Big Bang” (as opposed to “Steady State” becomes accepted. Penzias and Wilson won Nobel Prize in Physics in 1978.
- When the Universe was small and young it was filled with a mixture of light nuclei, electrons, and photons in thermal equilibrium. It wasn’t transparent. As it expanded it cooled some more …
- A series of experiments measured the CMB to more precision.
- 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

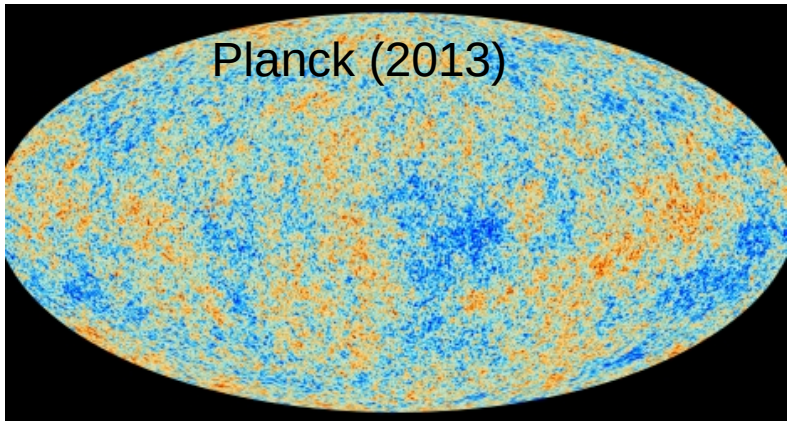

“A Measurement of Excess Antenna Temperature at 4080 Mc/s”, Penzias and Wilson (1965).

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

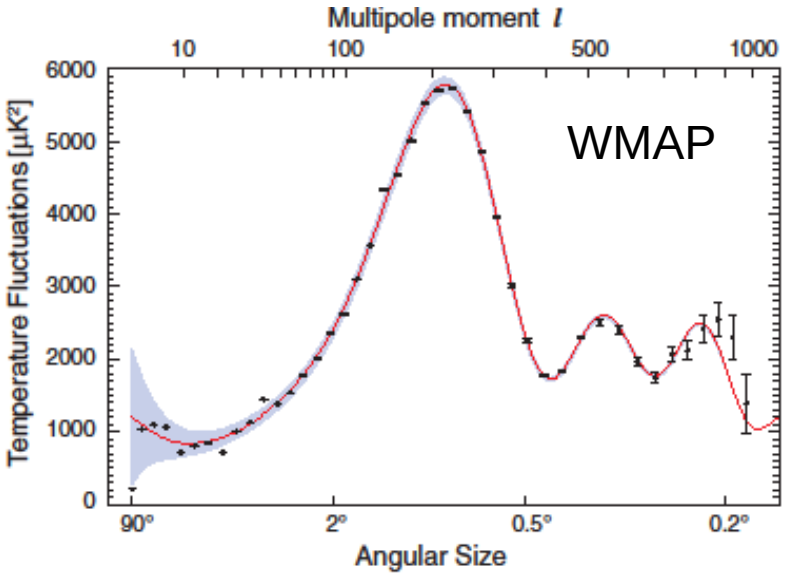
# Temperature Map of the CMB Radiation WMAP (2008) Planck (2013)

DARK ENERGY SURVEY



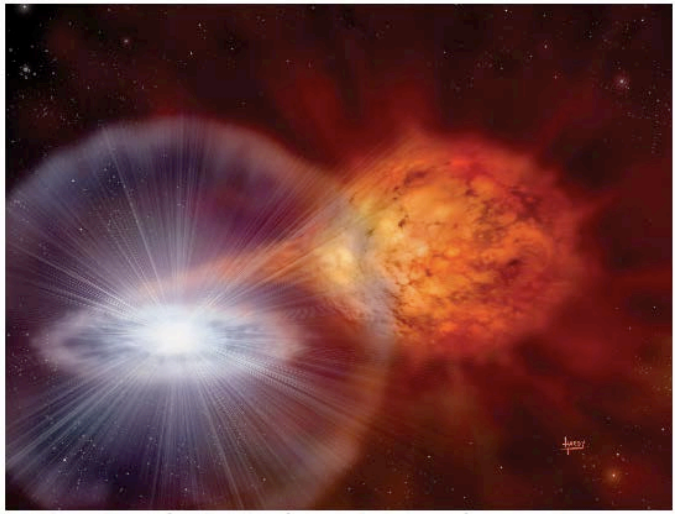

- Characteristic angular scale, ~ 1 degree on the sky, set by the distance sound waves in the photon-baryon fluid traveled just before Hydrogen recombination: sound horizon $s \sim c_s t_{ls}$



# Type 1a Supernovae

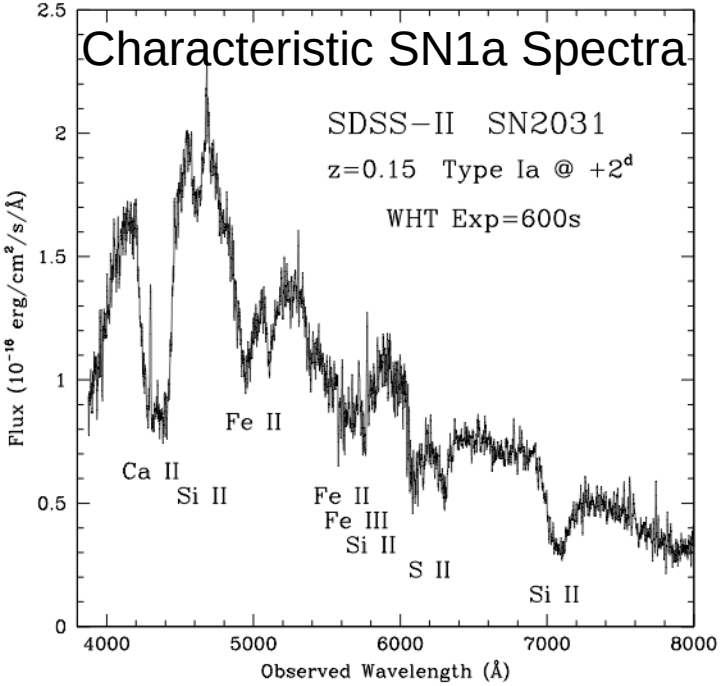
DARK ENERGY SURVEY

- A “white dwarf” star has M < 1.44 solar masses ($M_\odot$), the “Chandrasekhar Limit”
- Made of C and O ions and but with insufficient density to fuse them. It can’t contract any further because of electron degeneracy. It cools down unless another source of mass …
- 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 $^{56}Ni$ –> $^{56}Co$ –> $^{56}Fe$

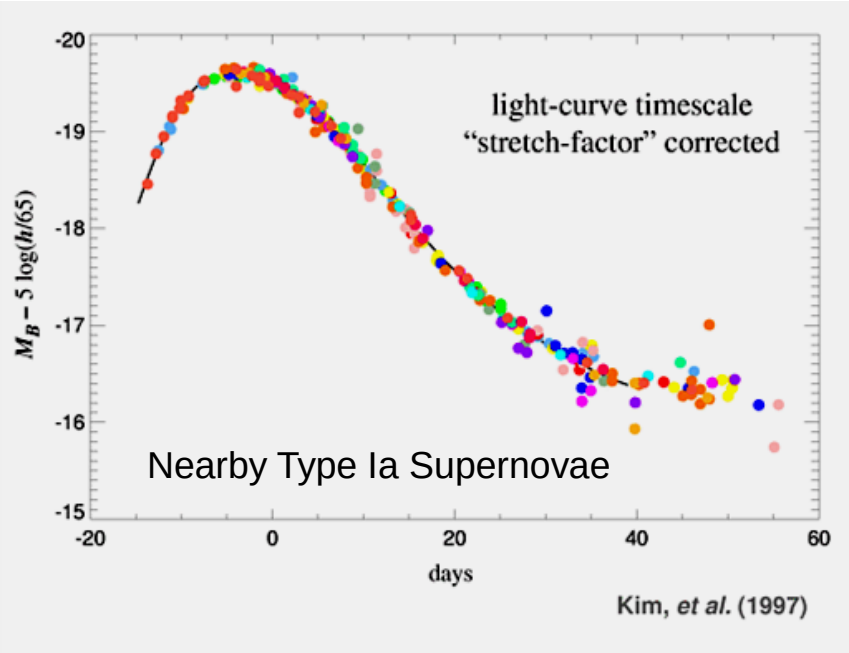


Artist’s rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly-degenerate.

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



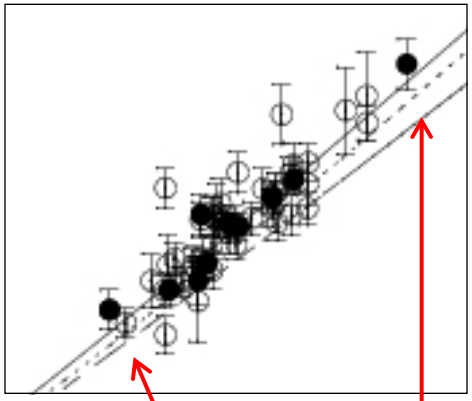
# Type 1a Supernovae

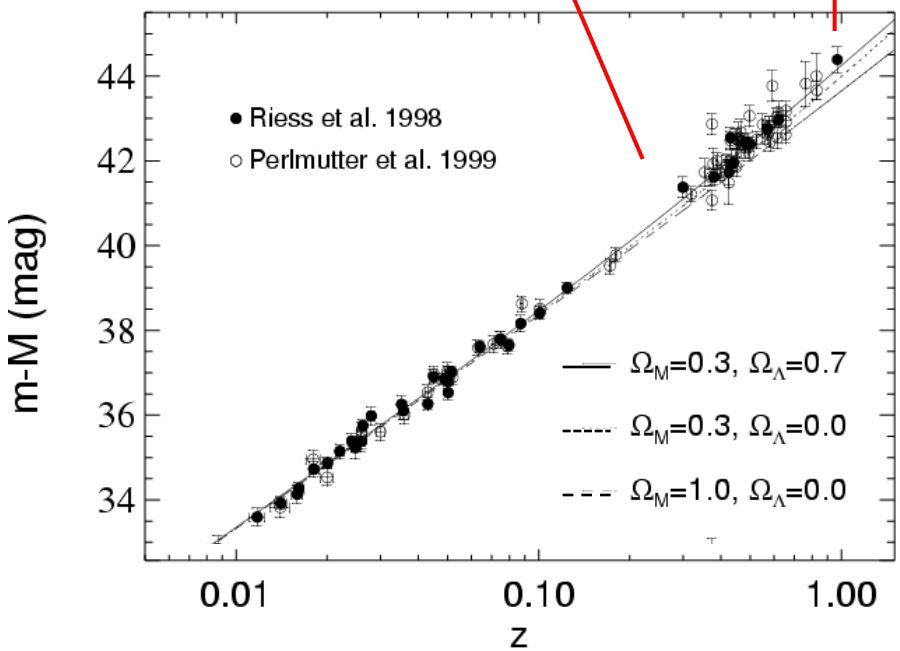



- Because the explosion occurs near the "CL", it has a characteristic brightness (determined by the $^{56}$Ni).
- After some corrections it is a "Standard Candle" and the brightness can be used to determine the distance.

- 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.

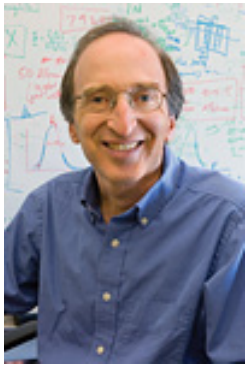
# Type 1a Supernovae






- 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”

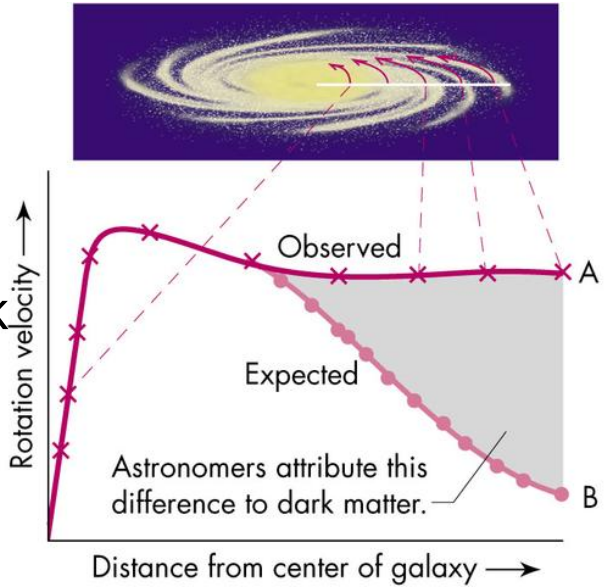
Saul Perlmutter, Adam Reiss, and Brian Schmidt won Nobel Prize in physics in 2011.

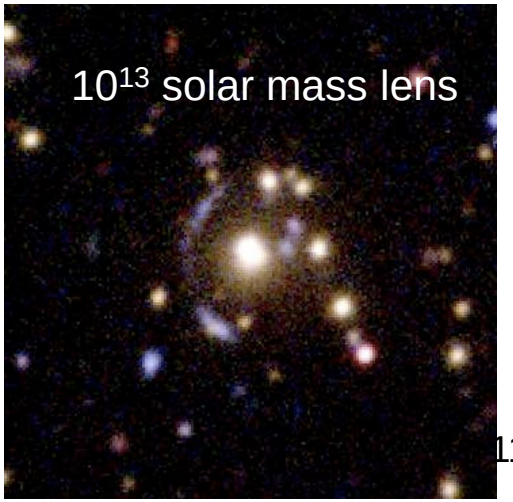


# Meanwhile: Evidence for Dark Matter

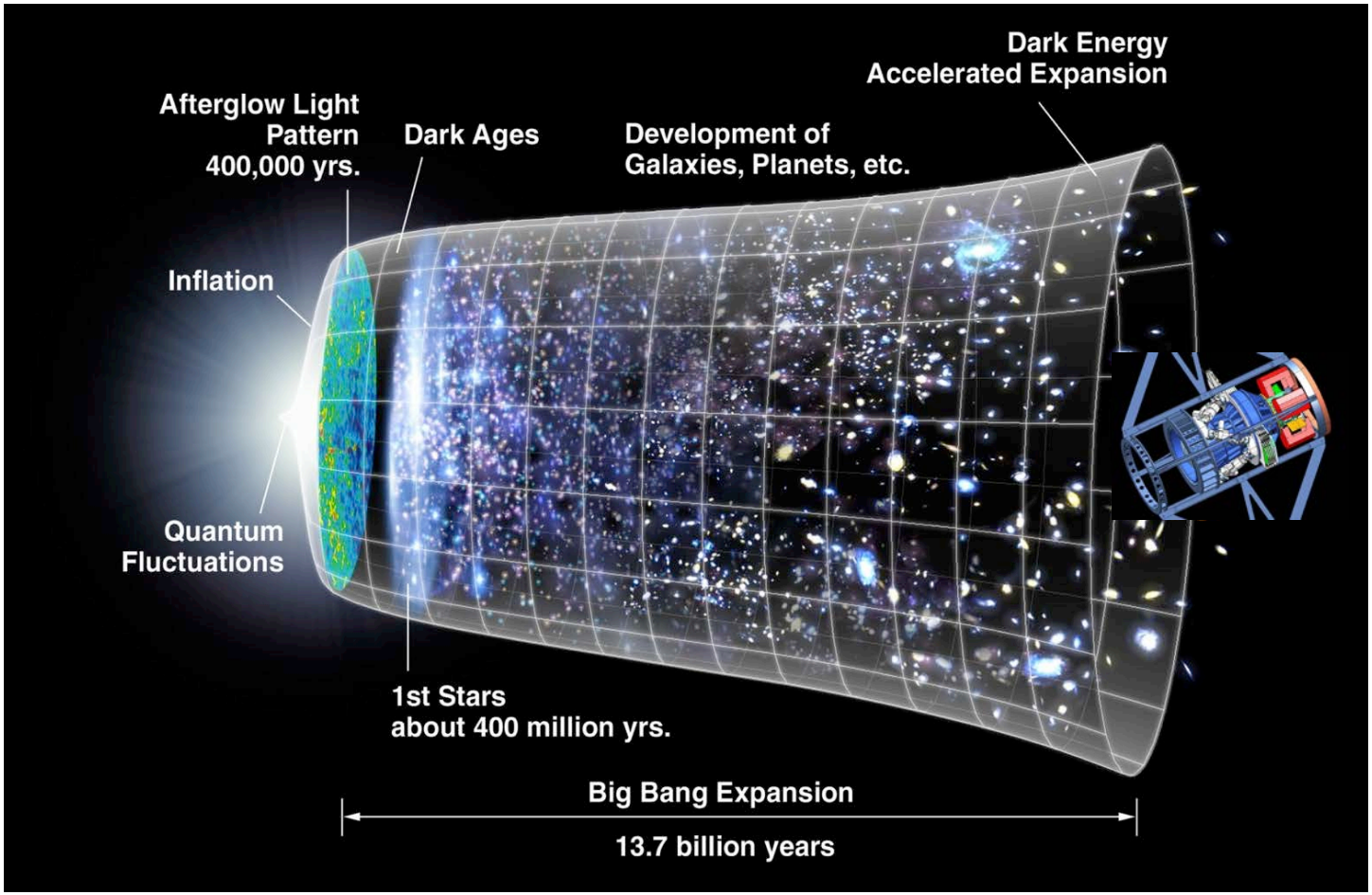
DARK ENERGY SURVEY

- 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).

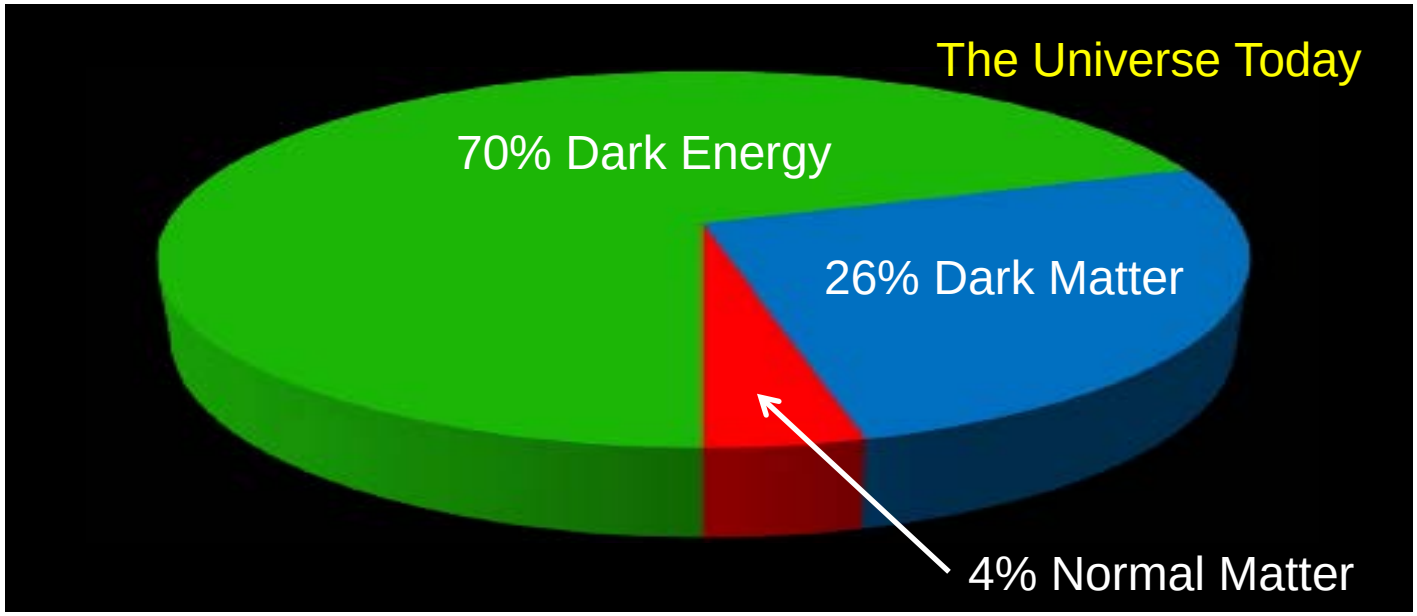


# The “Standard Model” of Cosmology



# The “Standard Model” of Cosmology: Present Energy Distribution




- 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 which is correct

- Four dominant classes of "theories"
  - "Cosmological Constant": 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, with known particles, we get an answer with 10^120 times more energy than is present. In this model dw/dt = 0.
  - 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. dw/dt>0
  - Other: we are detecting a "local effect" because the <u>Universe within our horizon</u> is lower than average density…a "void". No dark energy.
  - Maybe General Relativity (Gravity) isn't correct on cosmological scales. Anti-gravity? Extra-dimensions and even more fantastic ideas.
- Measuring the effect of Dark Energy with multiple techniques in the same experiment will provide clues.

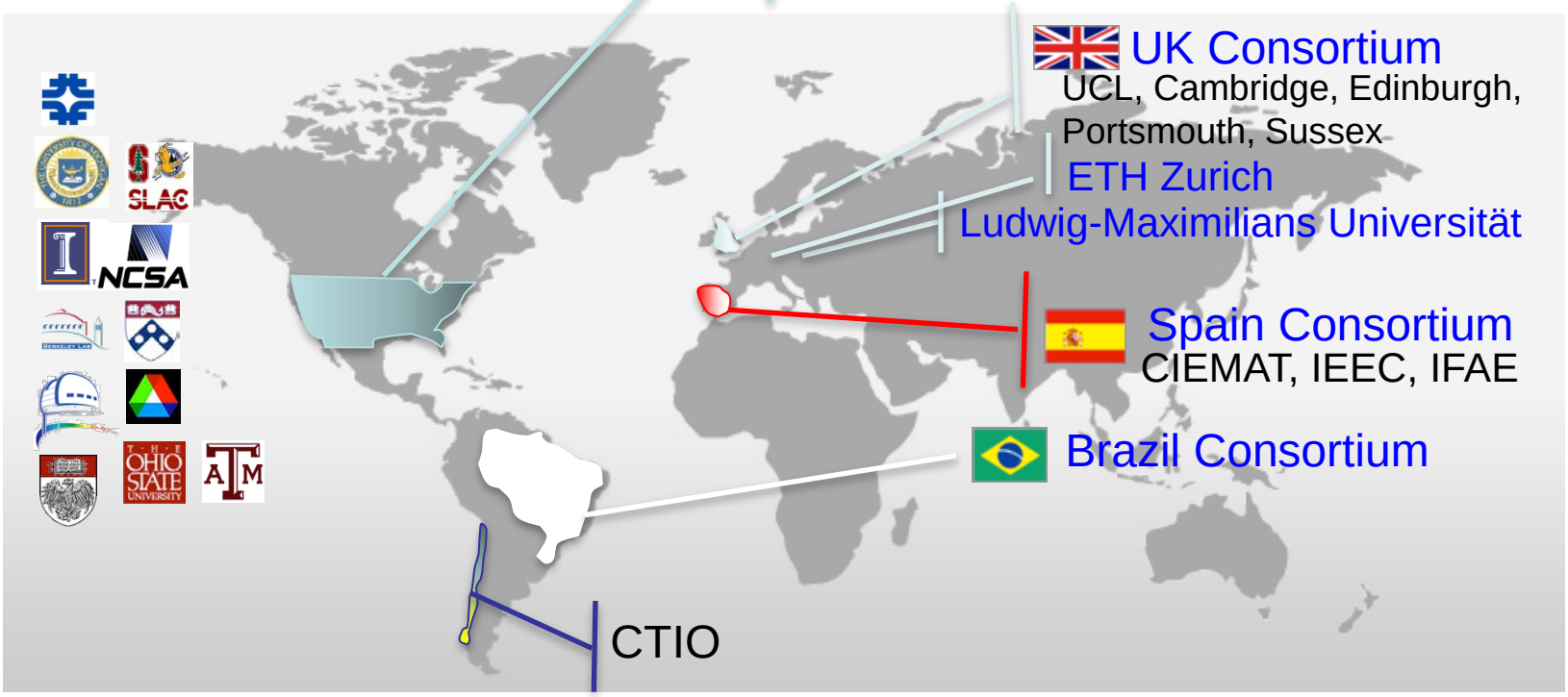
# DES Collaboration

Astronomers, Cosmologists, High Energy Physicists

DARK ENERGY SURVEY

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

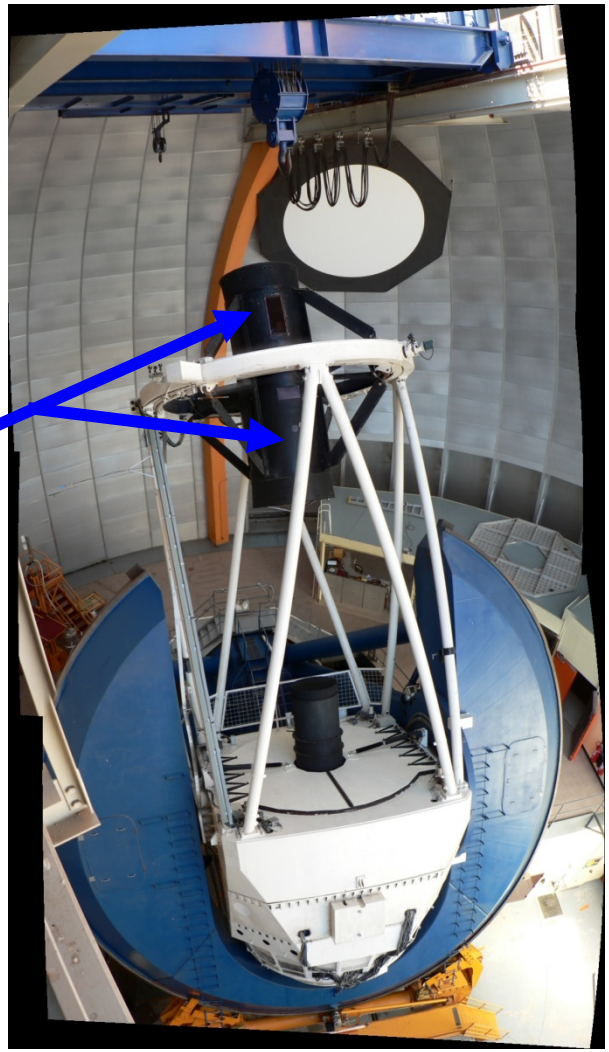
Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Laboratory, Ohio State University, Santa-Cruz/SLAC/Stanford Consortium, Texas A&M



# 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.
- Timeline:
  - R+D & Planning & Reviews 2003-2008
  - Instrument Construction 2008-2011
  - Installation during 2011 & 2012
  - Survey 2013-2019



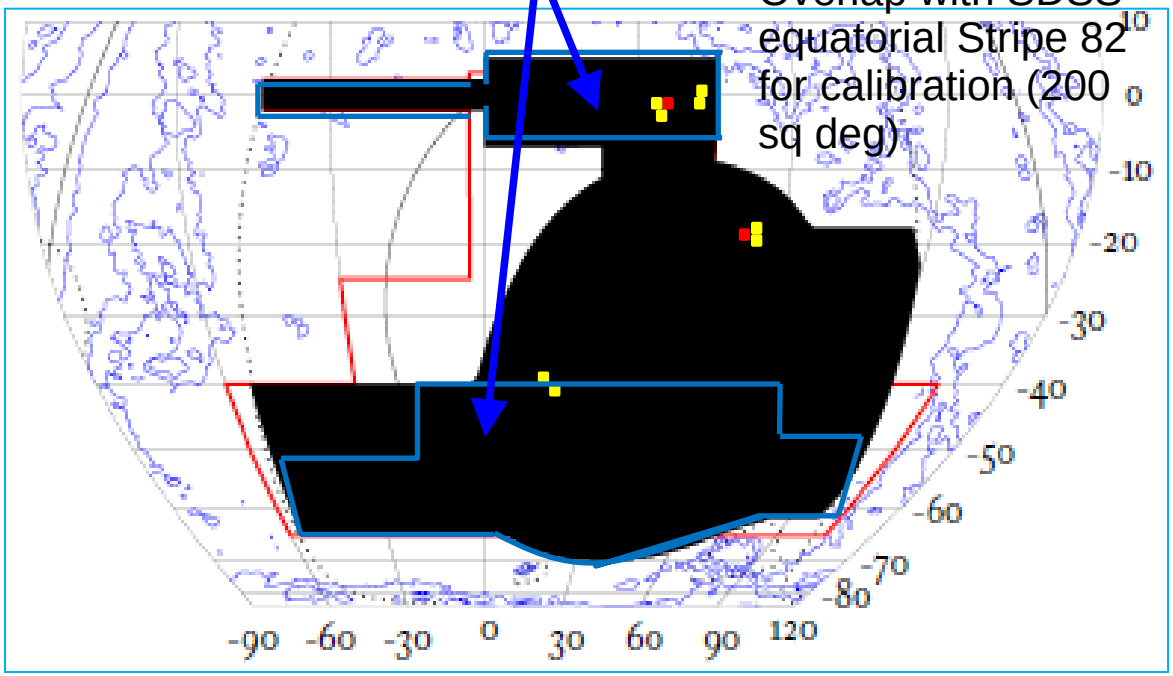
Use the Blanco 4M Telescope at the Cerro-Tololo Inter-American Observatory (CTIO)

# DES Survey Parameters

DARK ENERGY SURVEY

- In 525 nights during the months from Aug. to Feb. in 2013 to 2019.
- A 30 sq-deg Supernova Survey in 10 fields
  - Fields repeated observed typically every 4-10 nights.
- Wide-field survey is 5000 sq-deg of the Southern Galactic Cap. 5 filters.
  - The whole sky ($4\pi$) has 41253 sq-deg.

Survey Fields Y1




Full Survey Field

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

# Dark Energy Techniques

DARK ENERGY SURVEY

## Supernovae

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

## Galaxy Clusters

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

## Weak Grav. Lensing

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

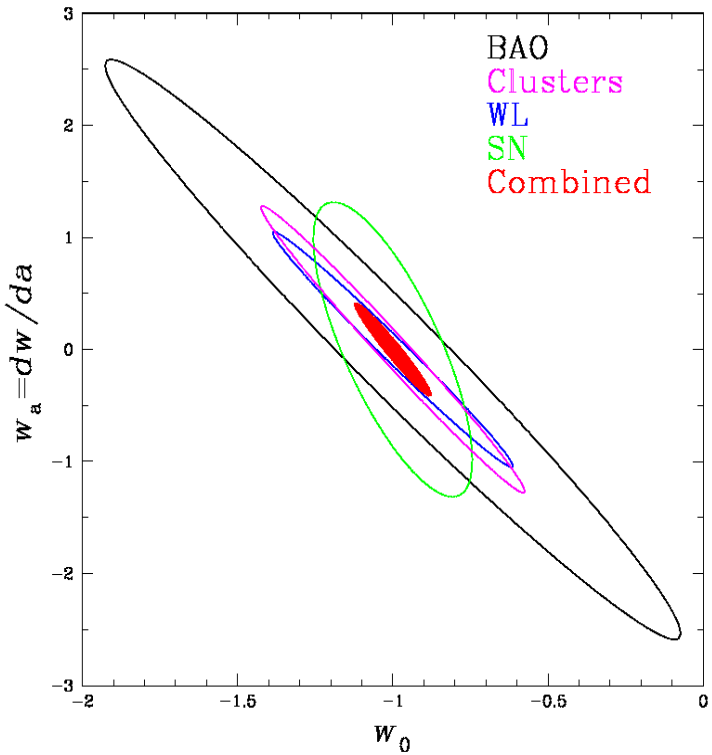
## Baryon Acoustic Oscillations

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

## Strong Lensing

Special cases sensitive to geometry

Forecast Constraints on DE Equation of State from DES




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

# DECam Overview

Spider/Cage

Barrel

Optics:Lenses

Optics:Filters

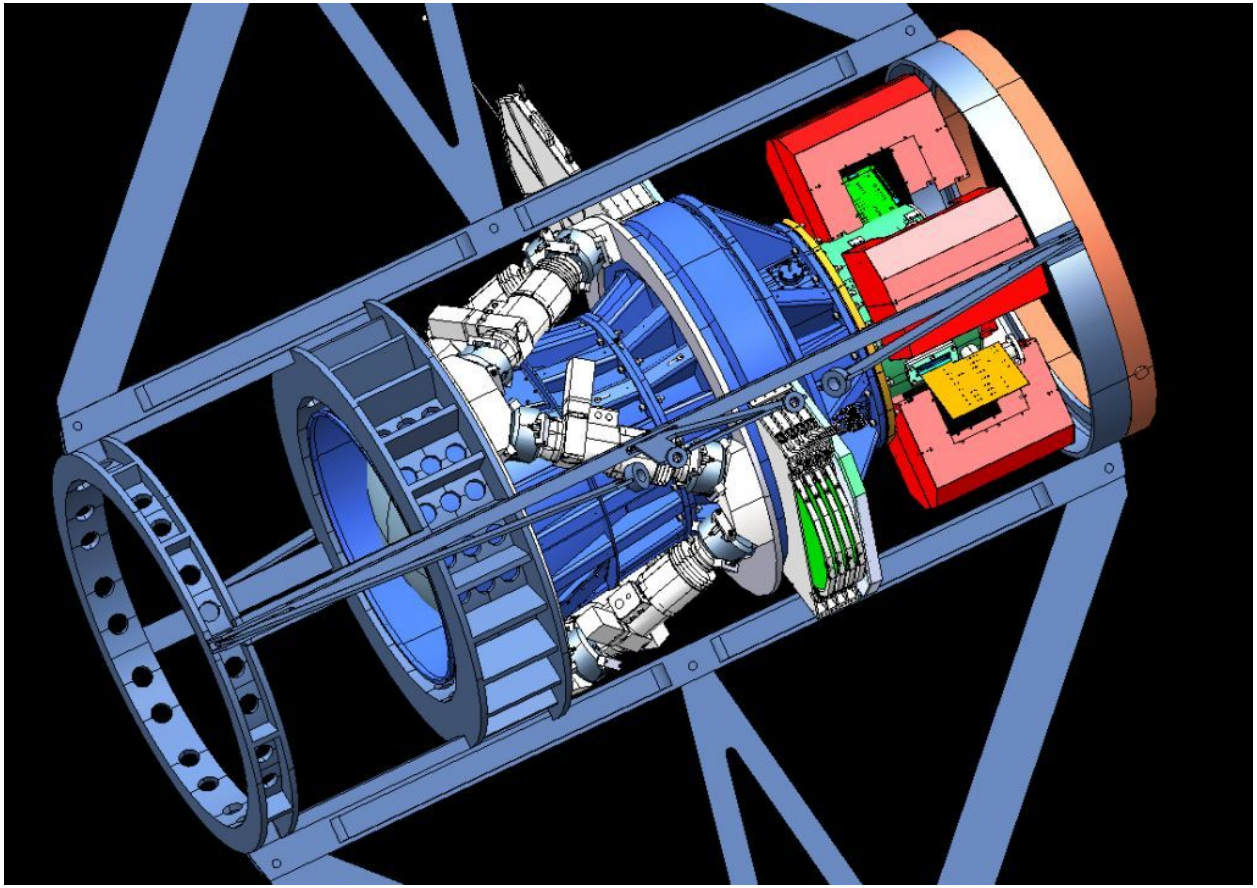
Shutter

Hexapod

CCDs

Electronics

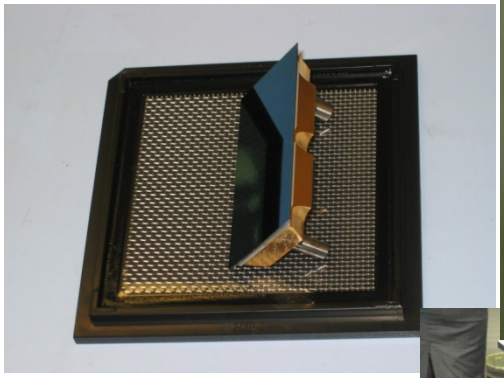
Controls

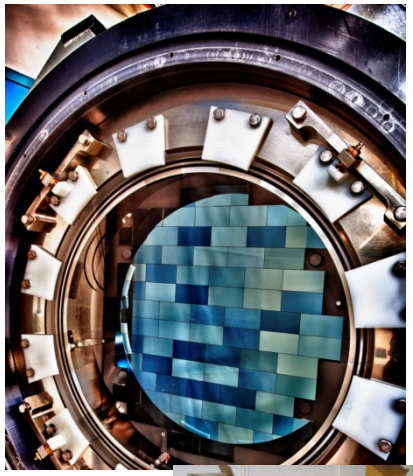


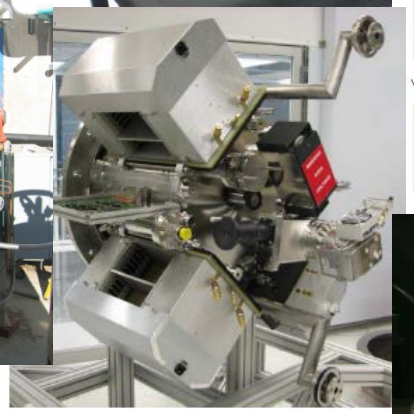
Sure – it's just a camera, BUT

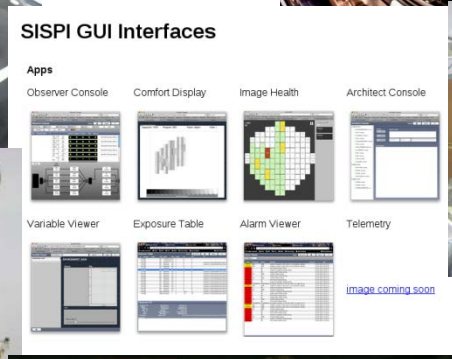
# Dark Energy Camera Parts (2008-2012)

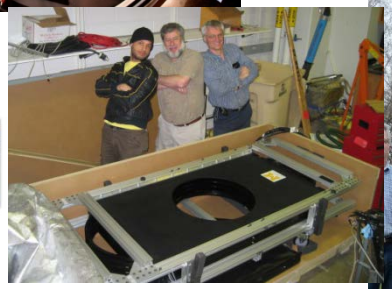
DARK ENERGY SURVEY







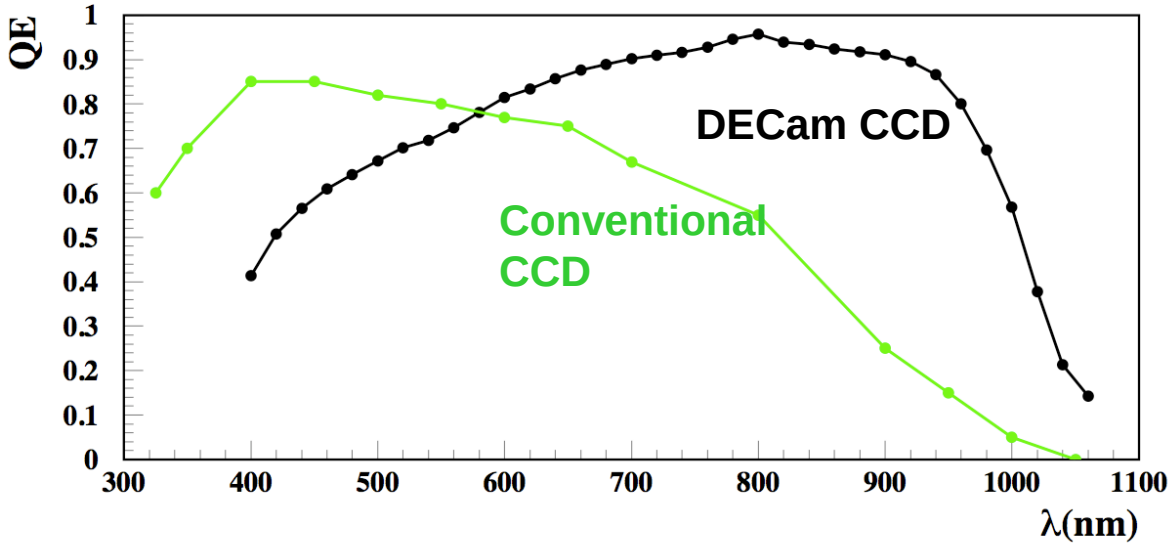


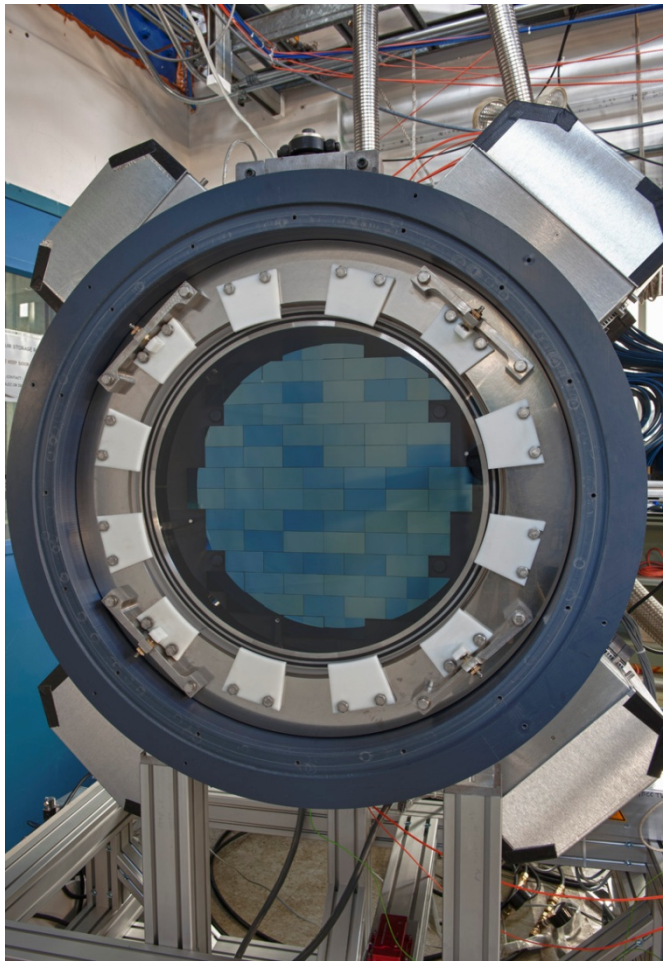



# This makes the DECam Powerful

DARK ENERGY SURVEY

- Blanco 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 in 20s.

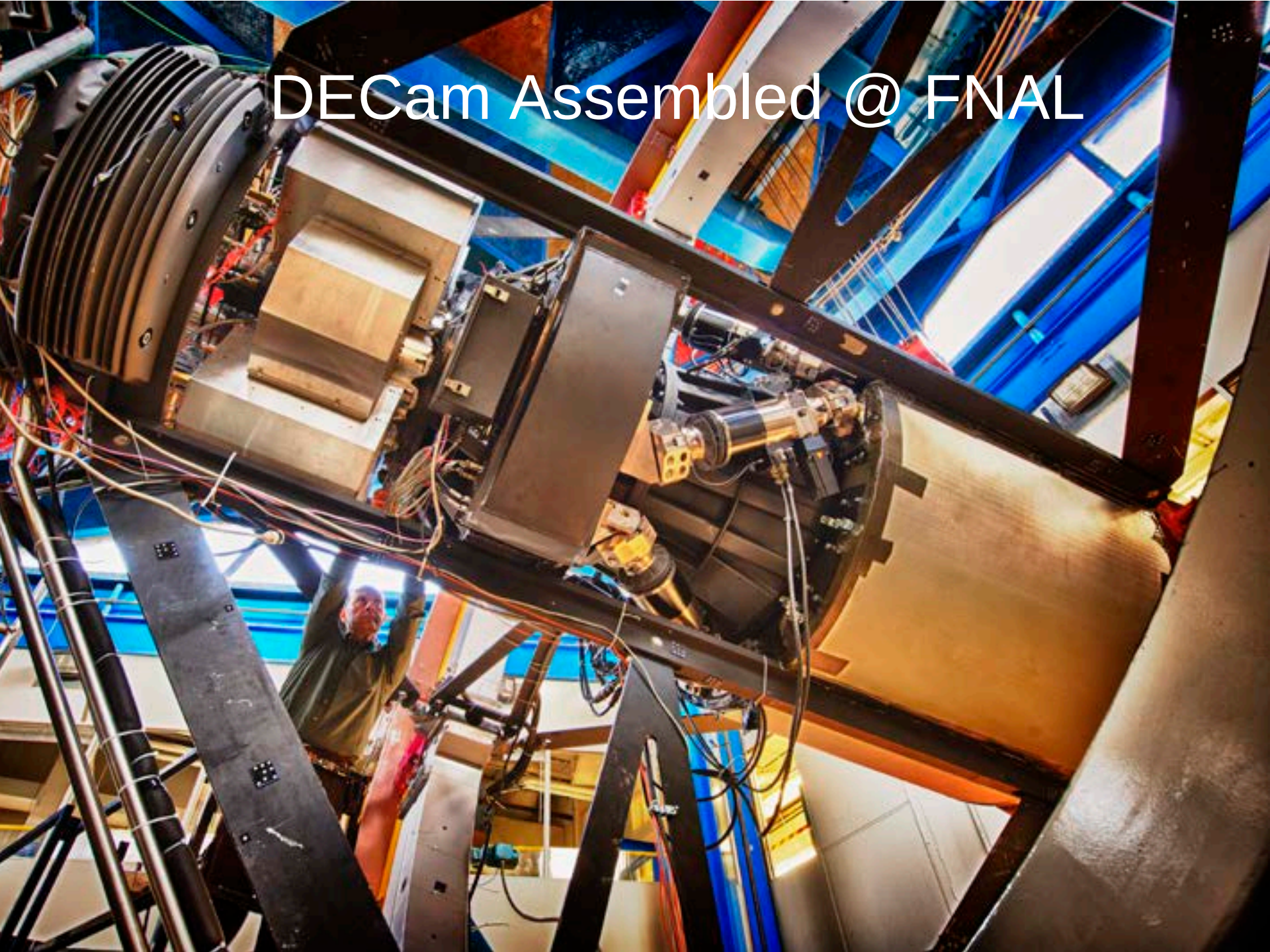


# A “Telescope Simulator” at FNAL (2011)

DARK ENERGY SURVEY

# DECam Assembled @ FNAL



# 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.

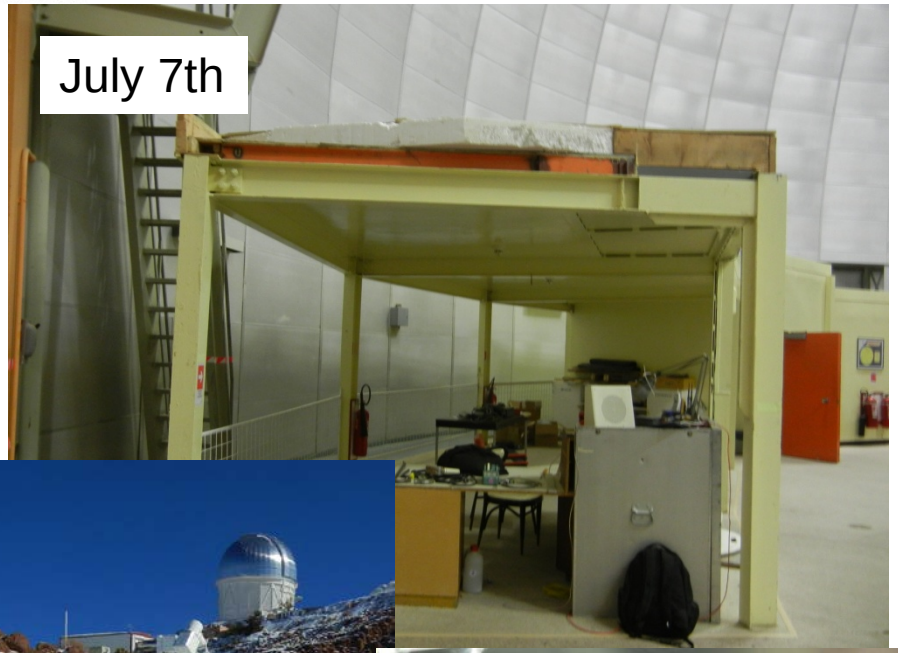
10/8/10
through
Panama
Canal
to SFO


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

10/19/10
At CTIO

# July 2011: LN2 Cooling installation at CTIO

DARK ENERGY SURVEY




DARK ENERGY SURVEY

# By Jan. 2012

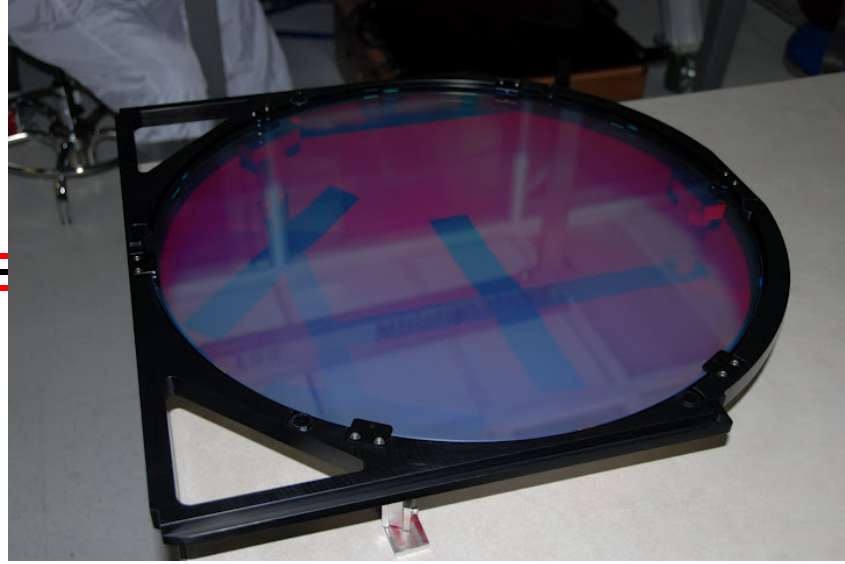
We make sure individual components work.

Camera re-assembly starts.

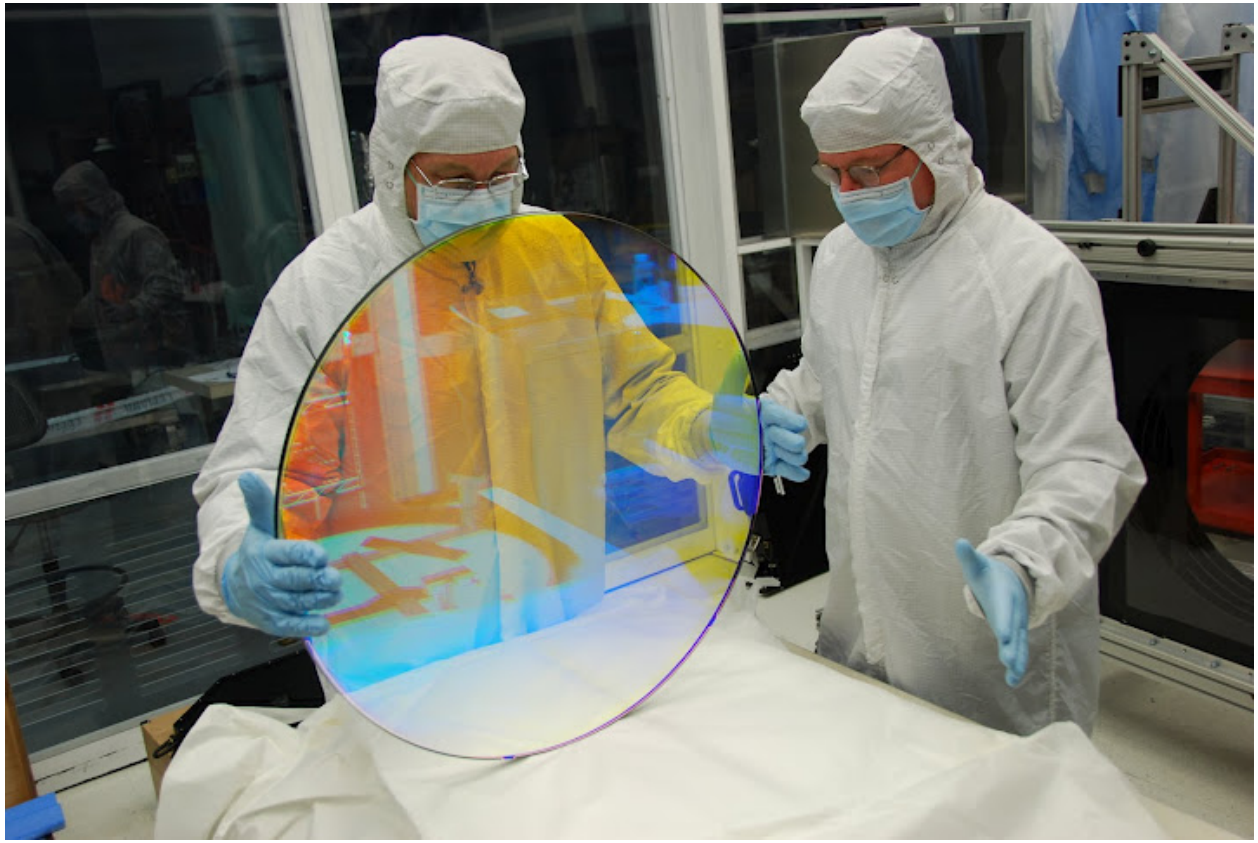
# December 2011

- 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

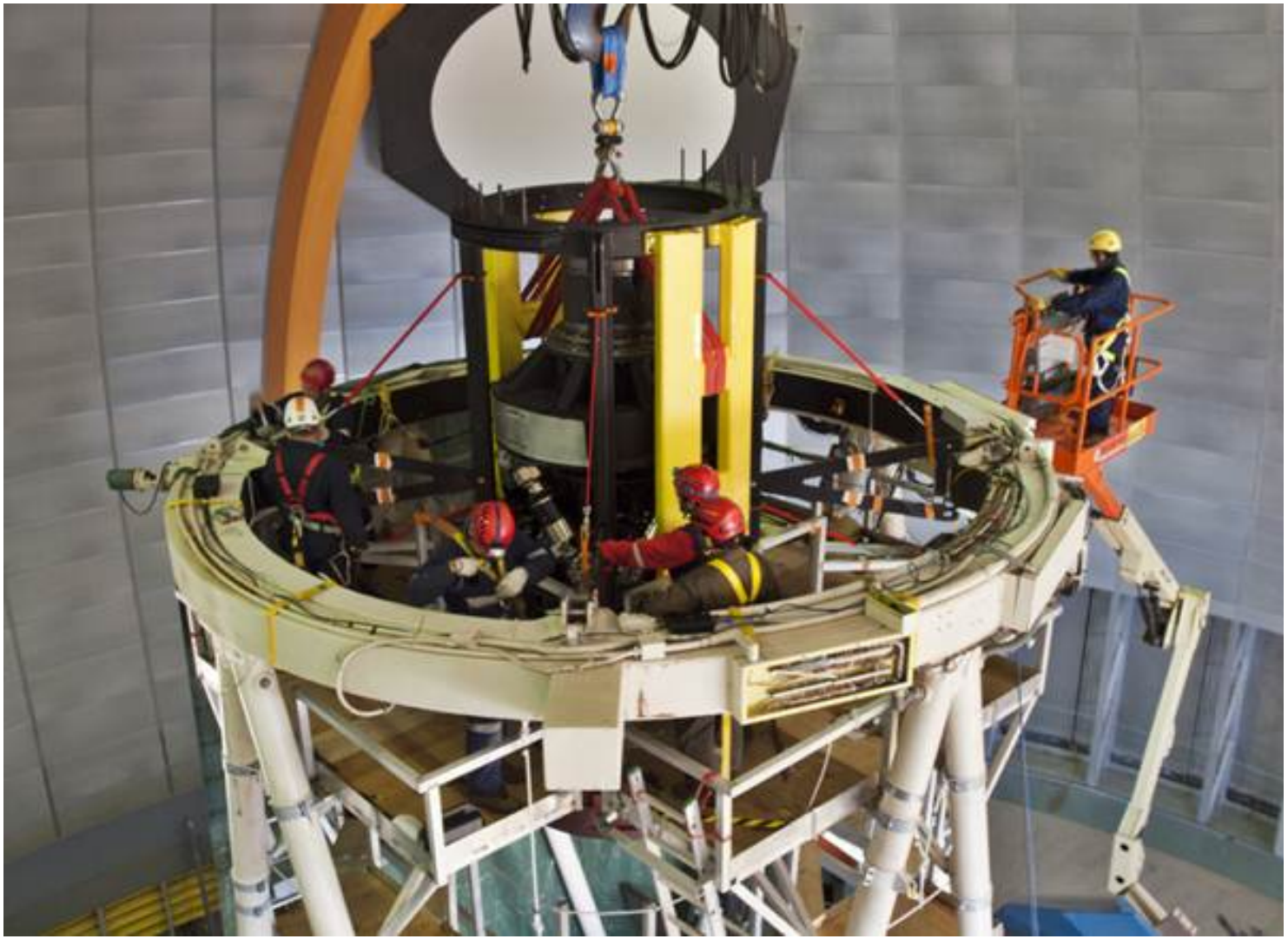


- Handling the World's Largest astronomical filters (r-band below & i-band right).
- Feb 20th telescope shutdown starts. Take out old camera and Cage



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

DARK ENERGY SURVEY

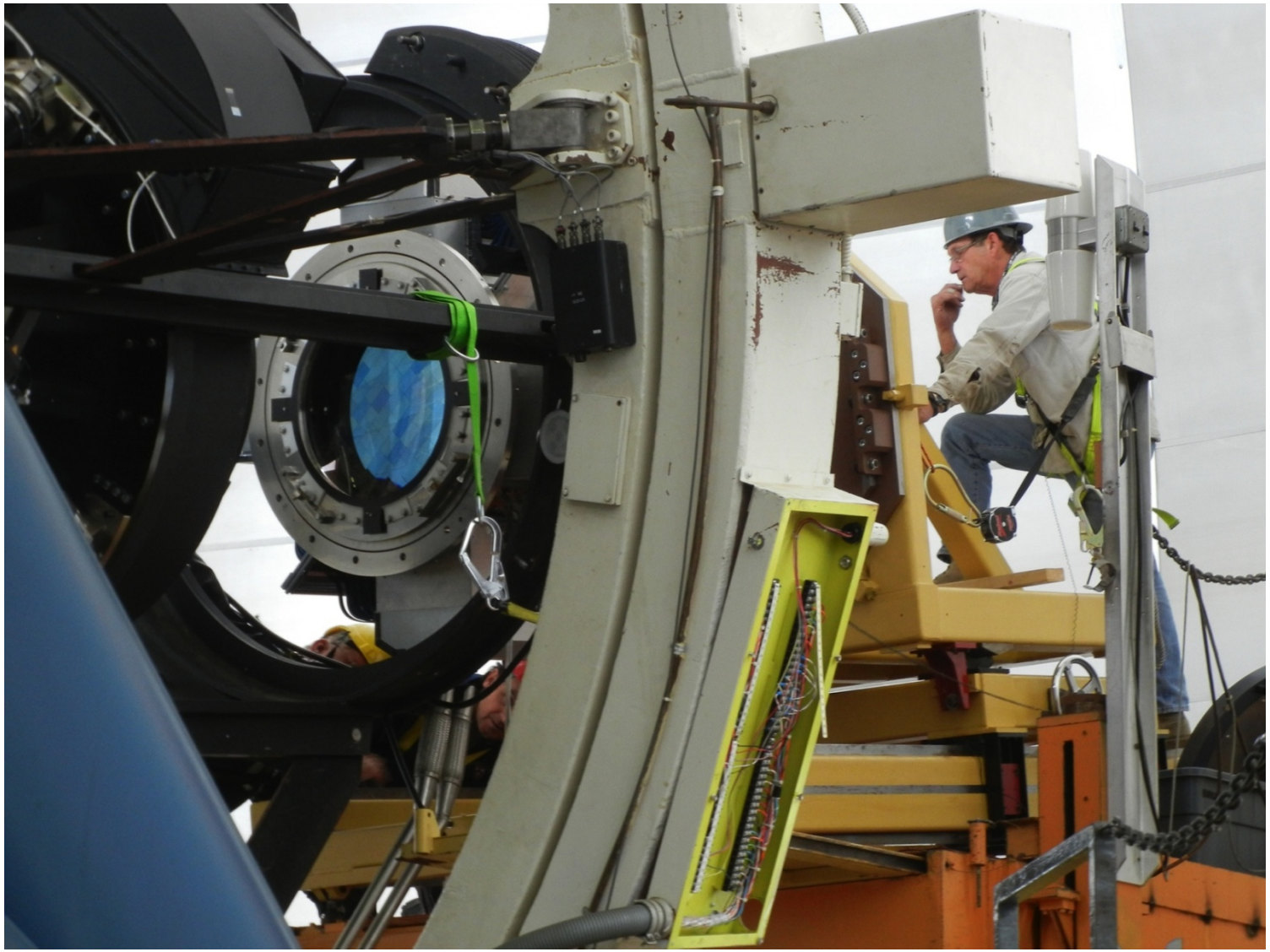


# Attaching the Imager to DECam: Late August 2012

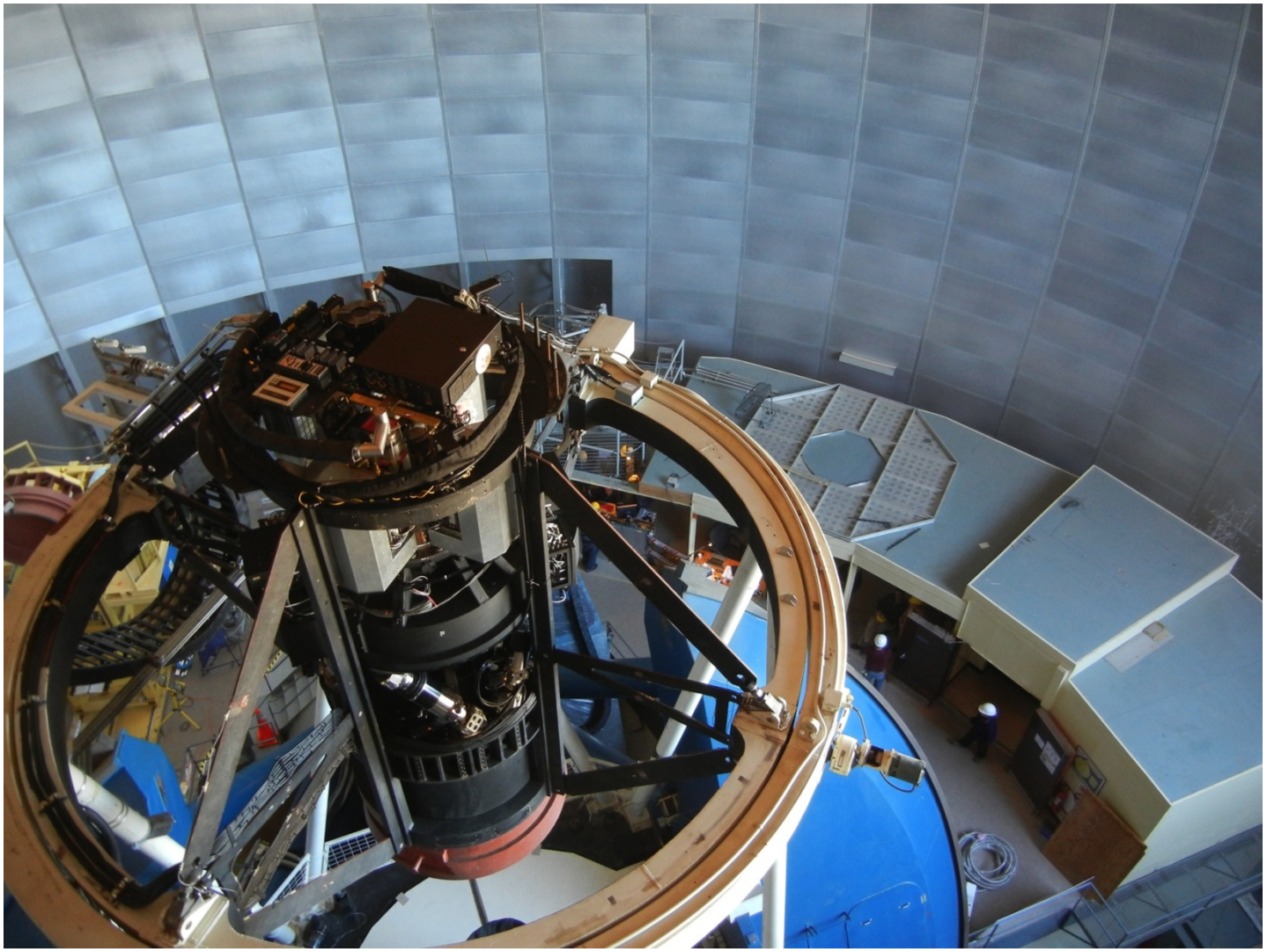
DARK ENERGY SURVEY

# Attaching the Imager to DECam: Late August 2012

DARK ENERGY SURVEY



# First Flight! Sept. 2012.
# Nothing fell off!



# Interlude
# A Mountaintop in Chile

Cerro Tololo (altitude 2200m)

# Mountaintop Critters [1]

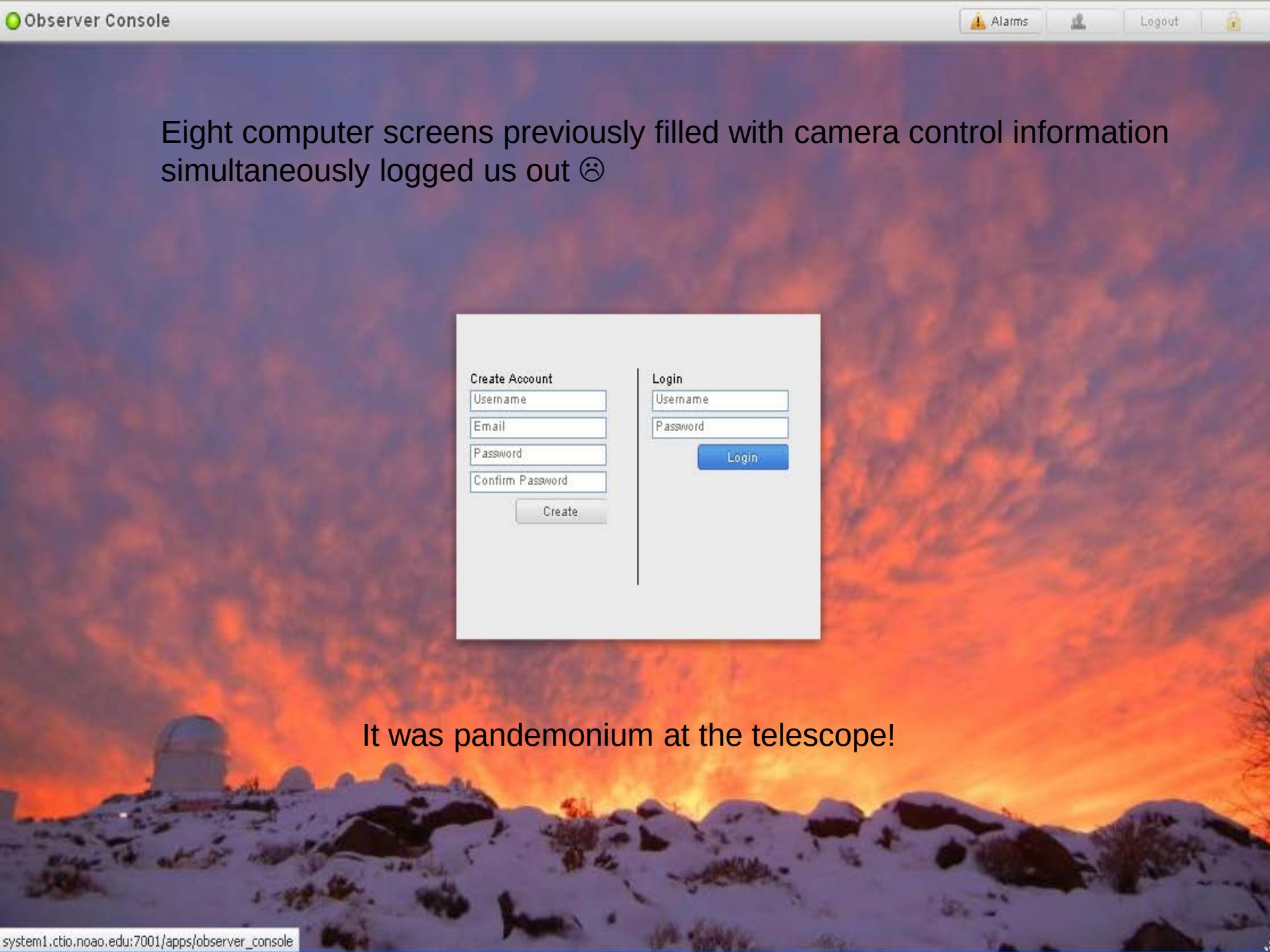
DARK ENERGY SURVEY

# Mountaintop Critters [2]

## Room Mates

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

Photo Credit: Reidar Hahn

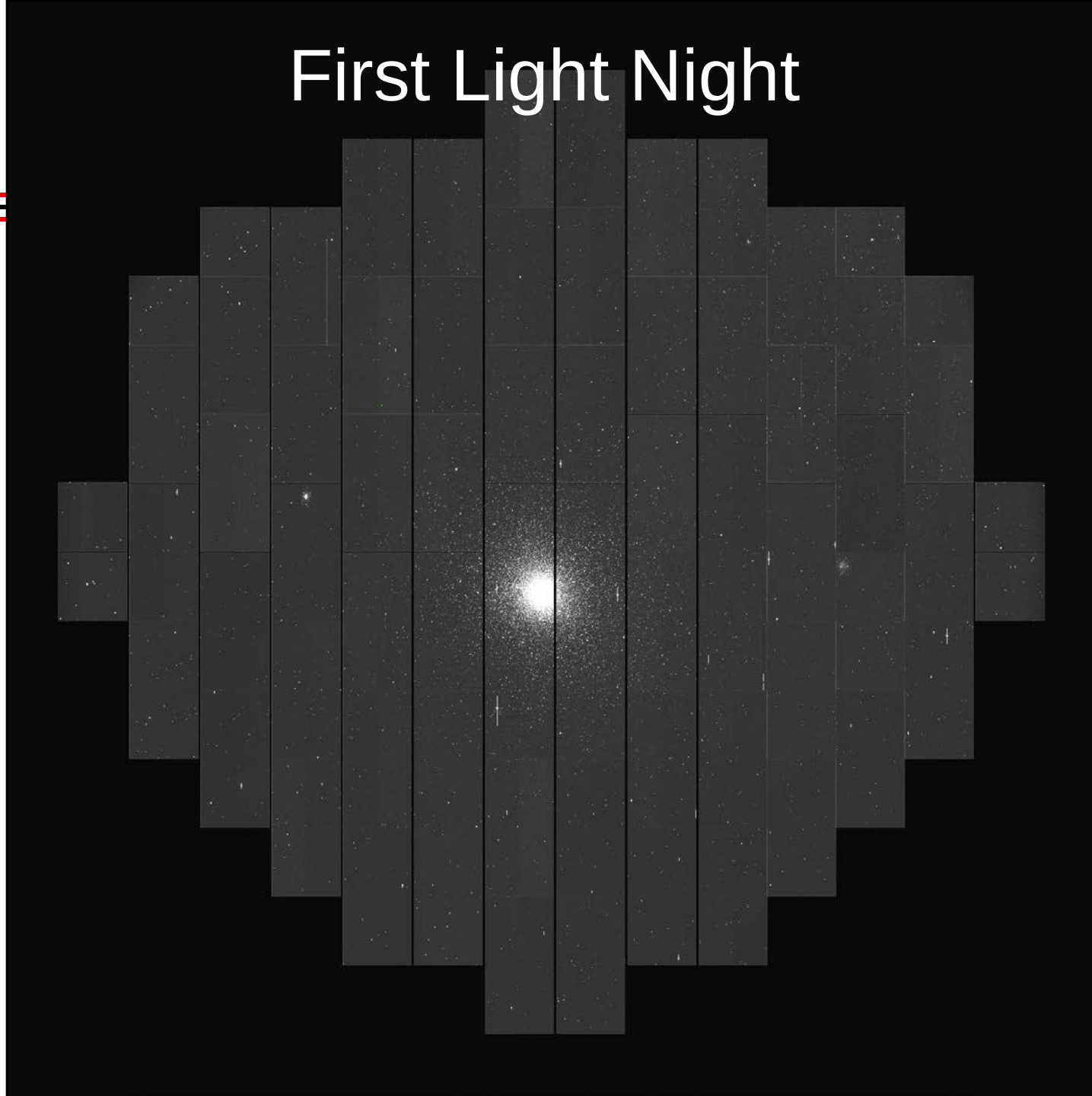



Eight computer screens previously filled with camera control information simultaneously logged us out ☹

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"

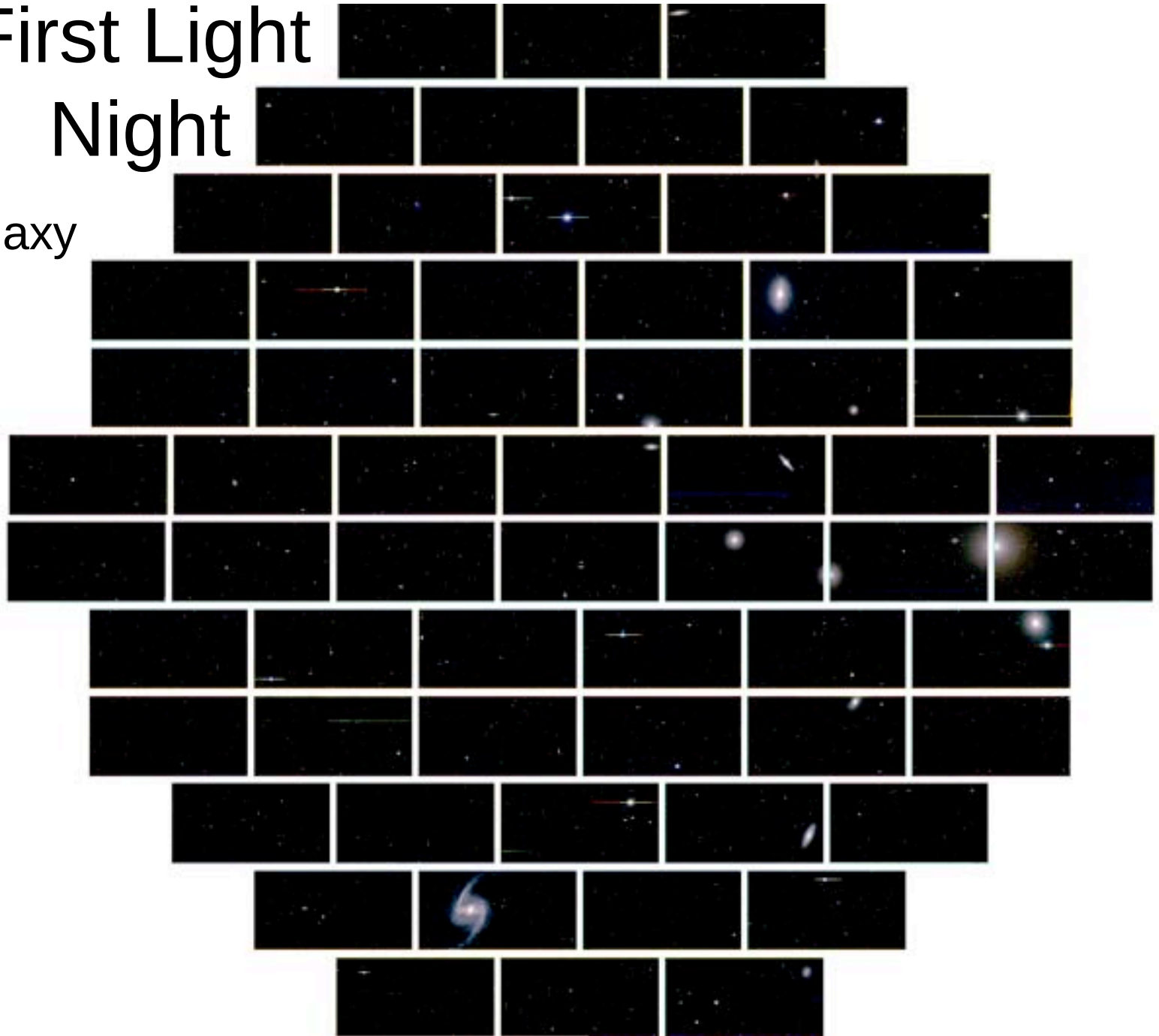


Image from Marcelle S.-S.

# “The Great Barred-Spiral Galaxy” NGC1365

56 Million LY away

Image Credit: M. Murphy and N. Kuropatkin

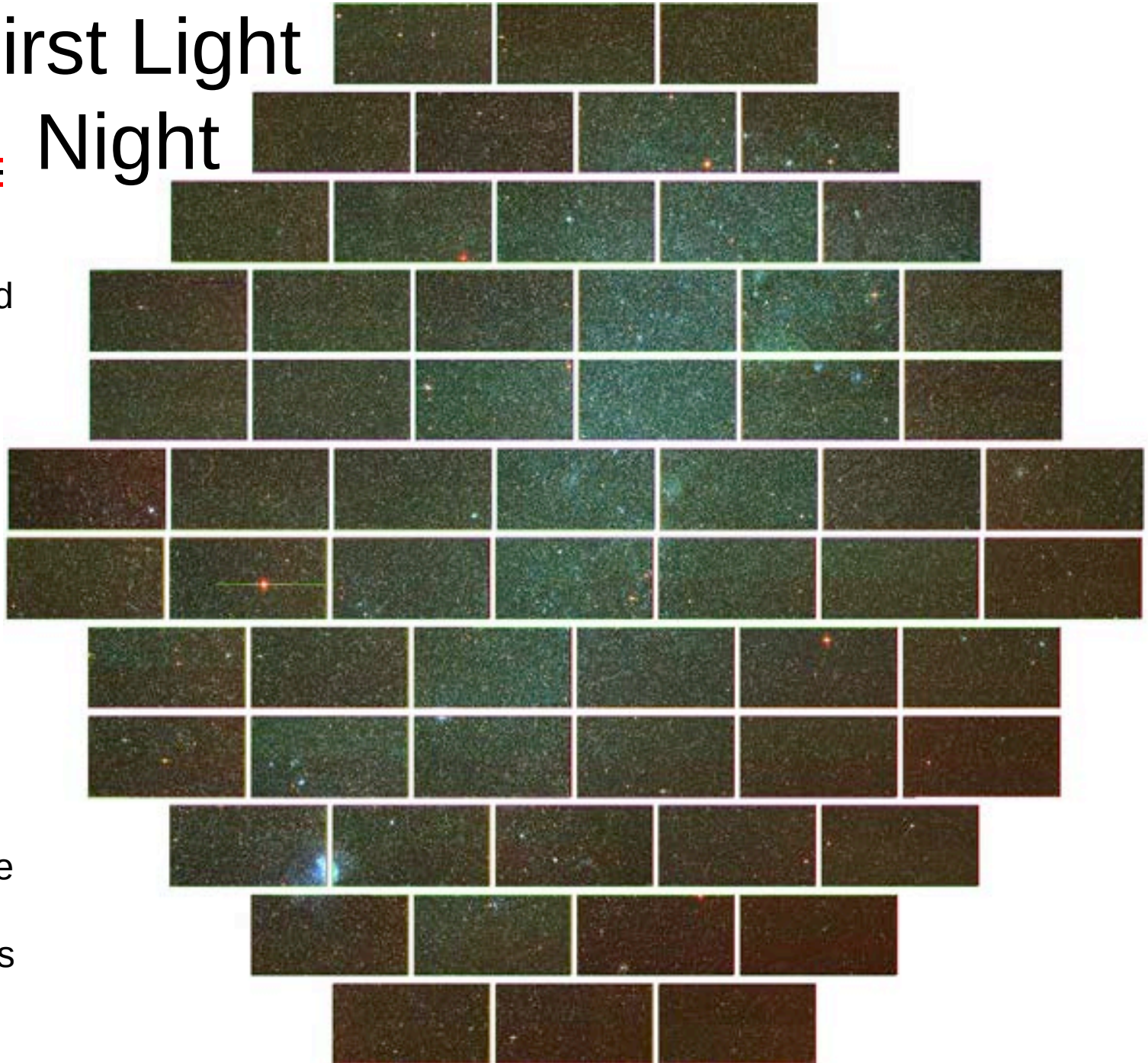
Also See darkenergydetectives.org/

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!

# Commissioning and Science Verification

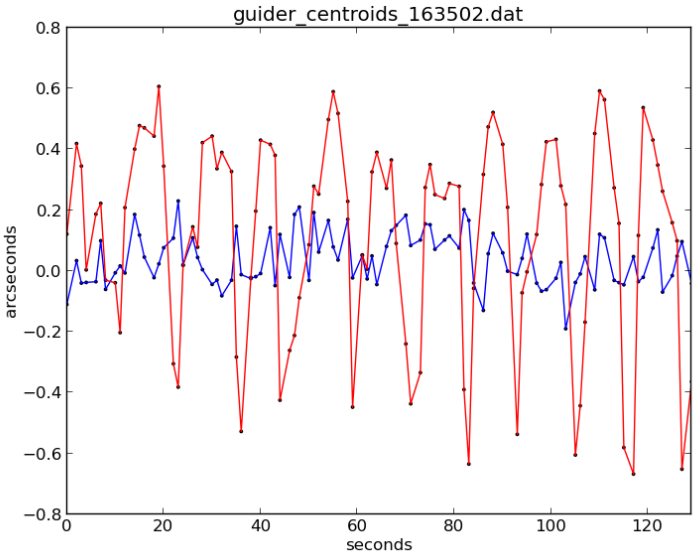
DARK ENERGY SURVEY

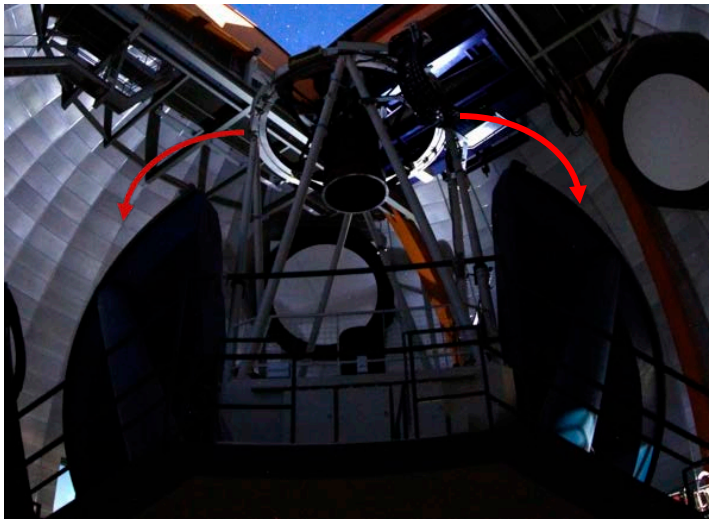
- From First Light through late October 2012 we implemented & tuned-up the camera systems
- On November 1st DES and NOAO and "Community" astronomers started to use the new instrument to try do science with the images
- "Community Users" are generally very happy with DECam and the control software, and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

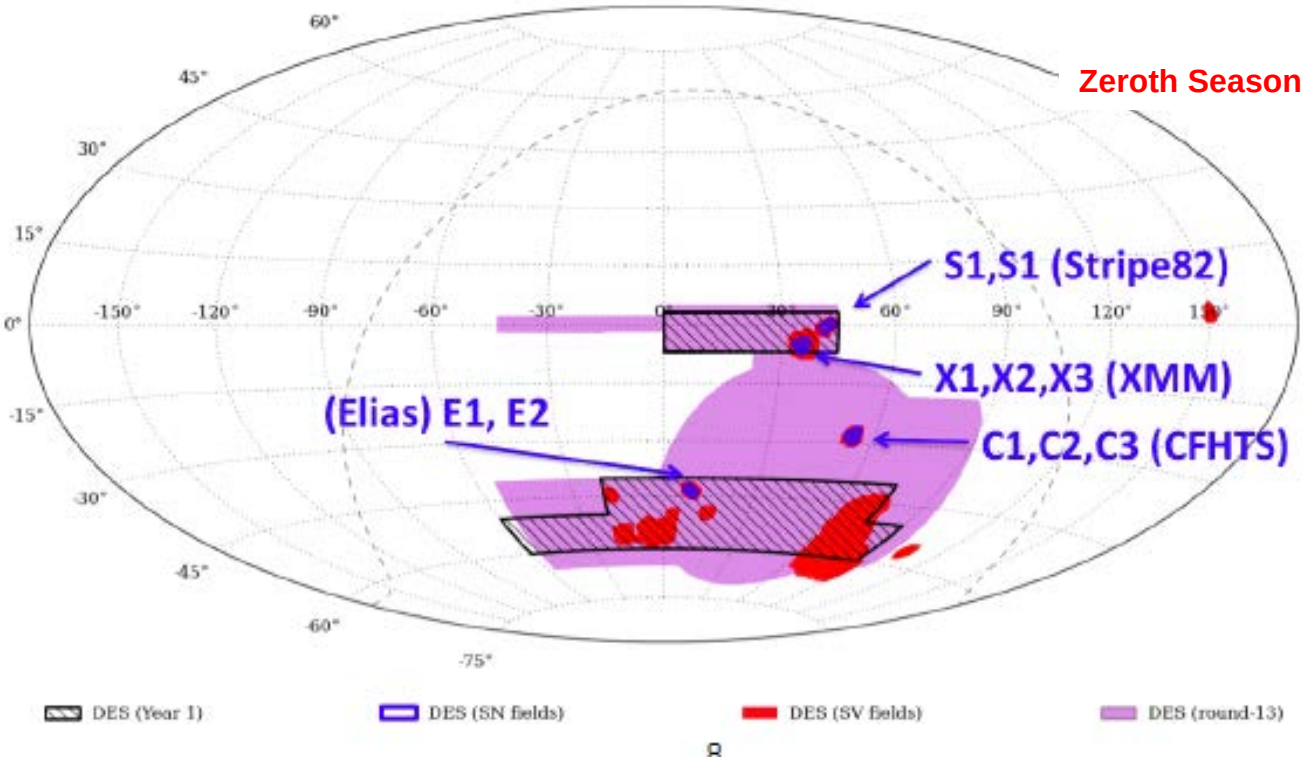


# Survey Fields in Season 0

DARK ENERGY SURVEY

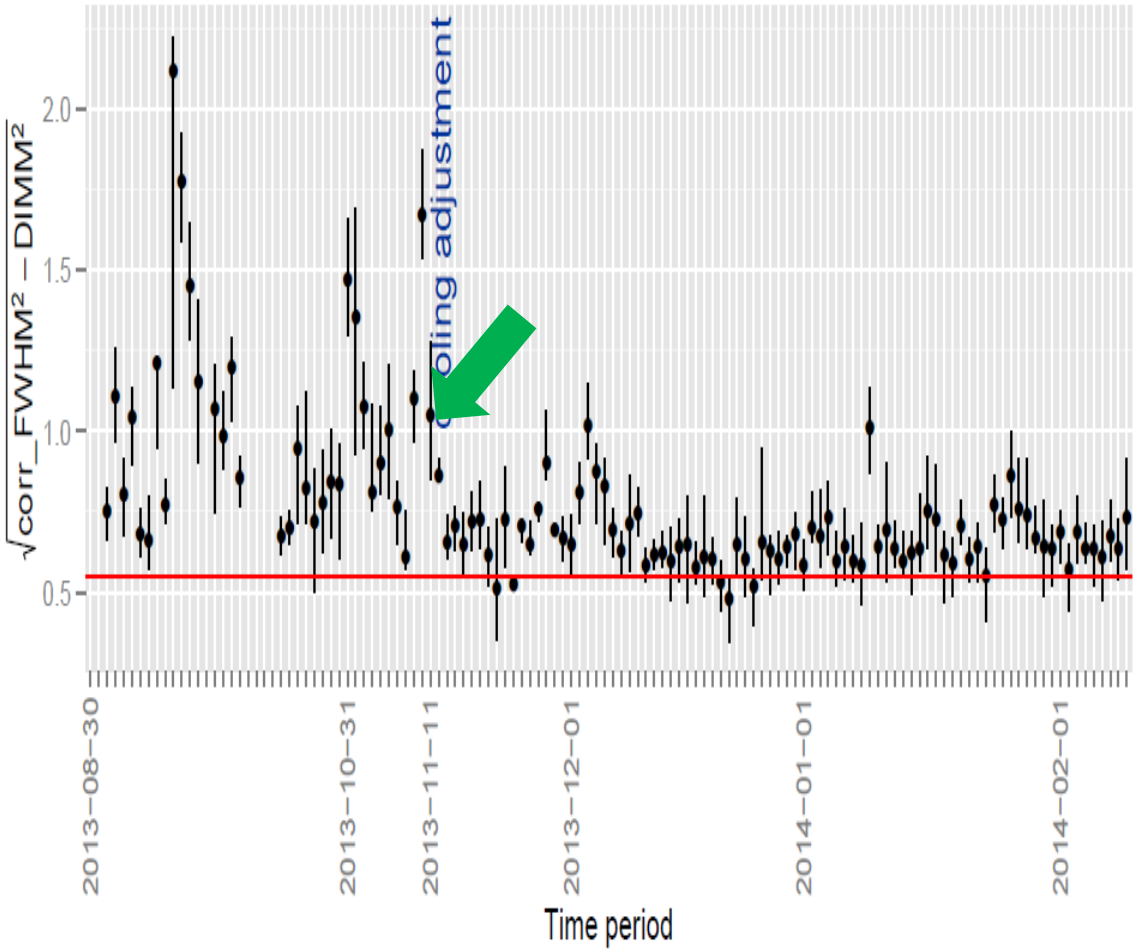
- DES SV was 23 full nights and 33 half-nights and experts spent a lot of the observing time on engineering tasks. We imaged a 250 sq-deg subset (red area) to full DES depth. The full DES area (purple), Y1 and Y2 fields also shown. We visited each SN field 9-16 times (blue area).
- Then more trips to “harden” DECam against vulnerabilities.



# DES Year One

DARK ENERGY SURVEY

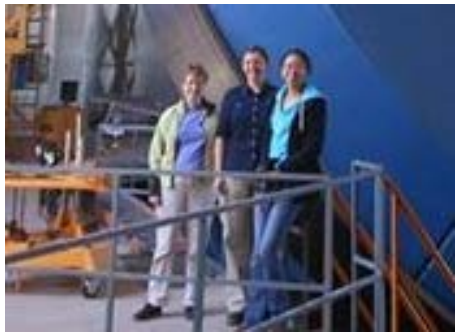
- Year 1 Observing started Aug. 31, 2013
- Slow start – weather OK, not great but … seeing achieved was poor compared to expectations (red line)
- Chile trip in late October.
- On Nov. 11 CTIO fixed the Dome floor cooling and made the primary mirror cooling more aggressive. Nightly Temperature change dT/dt improved at about the same date.

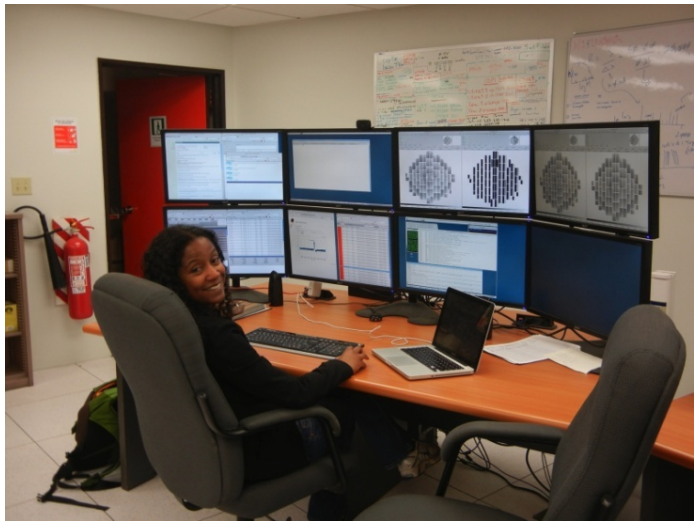


# Observing For DES

DARK ENERGY SURVEY

- Observing is done at the mountain by DES Collaborators usually in teams of 2-3 grad students, post-docs, and a few experienced astronomers
- Observing is computer-automated as we can make it.
- Supported remotely by “experts”.

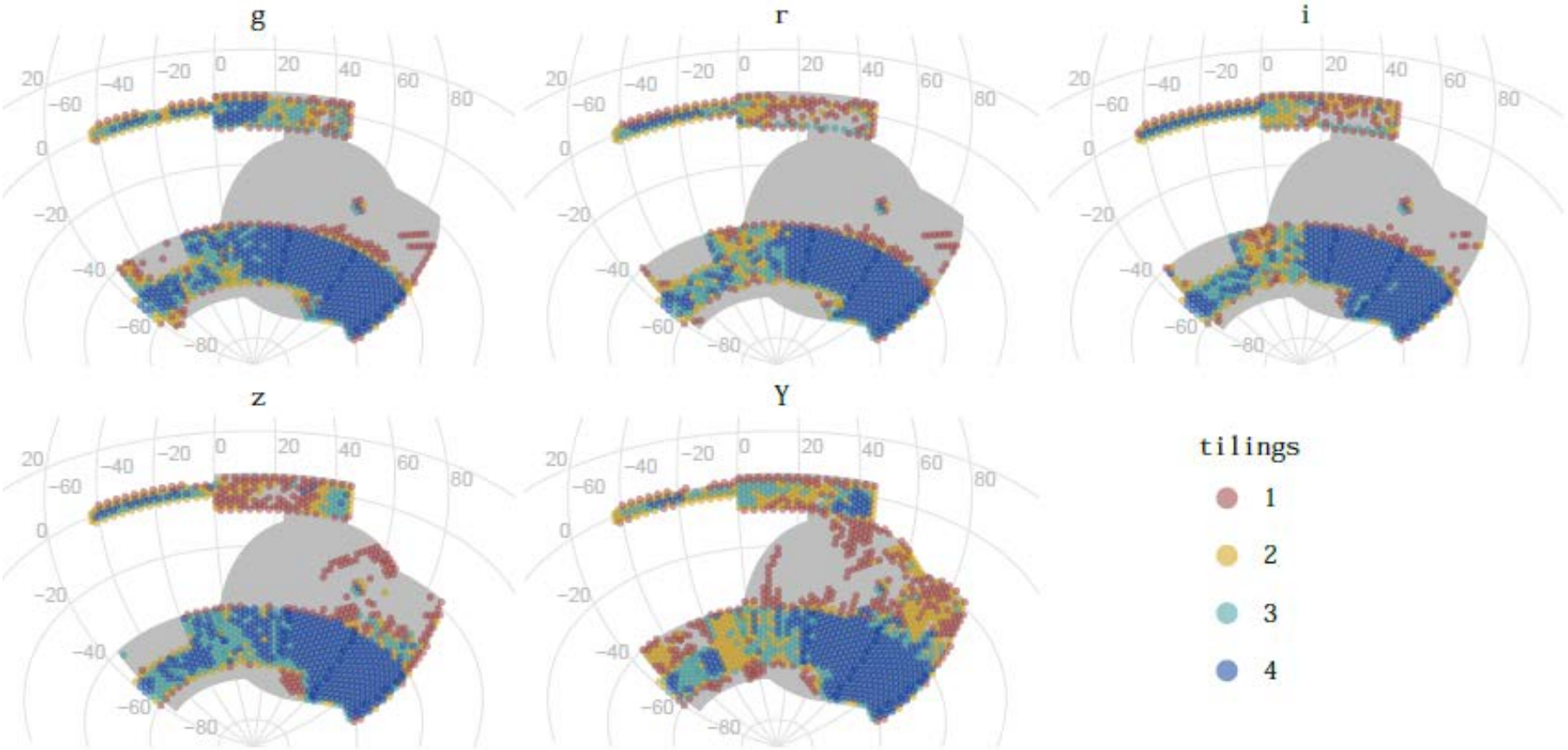




# DES Year One: Wide Field

DARK ENERGY SURVEY

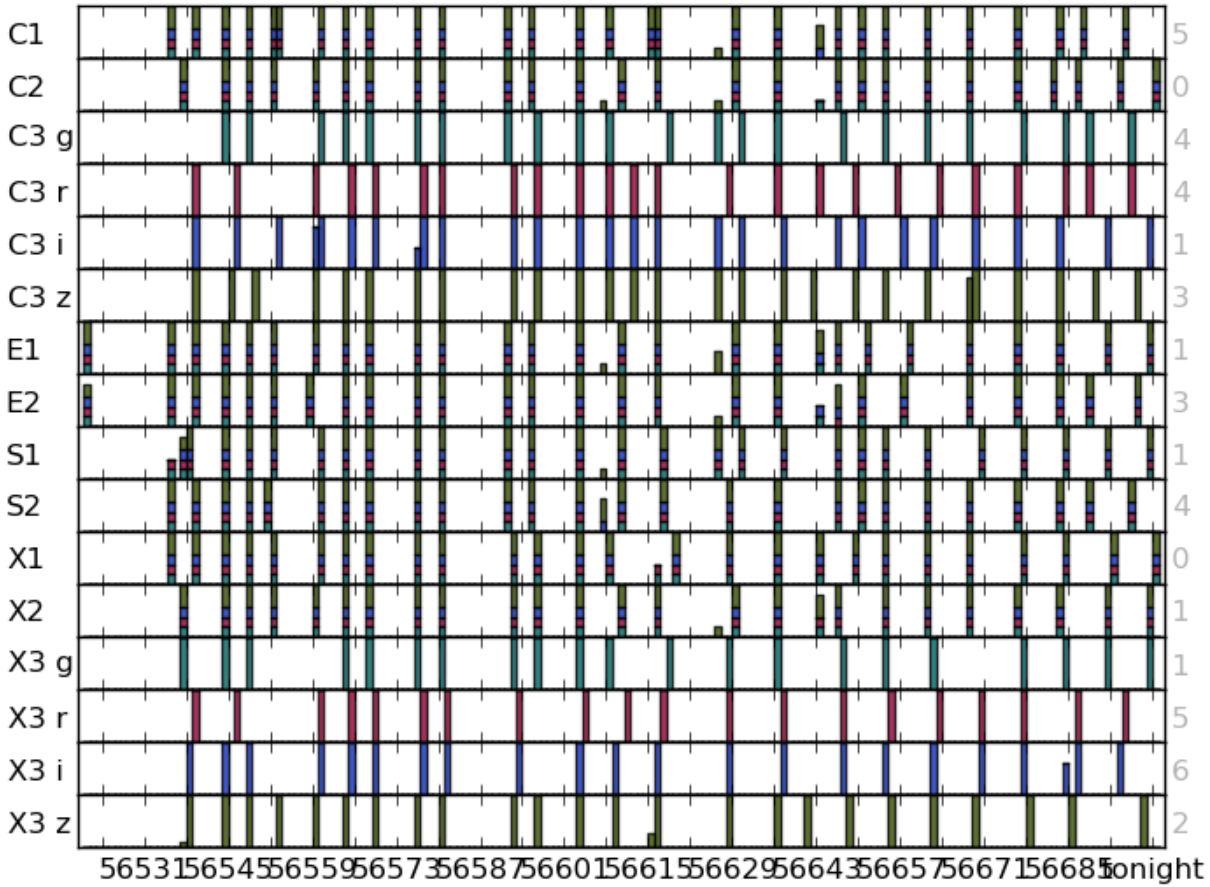
- In 105 Nights we got 14,500 good images in the Wide Field Survey area.
- This was ~10% short of what we need to average for each of 5 years.



# DES Year One: SN Survey

DARK ENERGY SURVEY

- SN “Cadence” (RHS) shows when we observed each SN field from start to end of Y1.
- We visited each SN field with a median interval of 6.5 nights.
- 2565/2699 SN exposures “good” (95%)
- 800 T1a SNae?

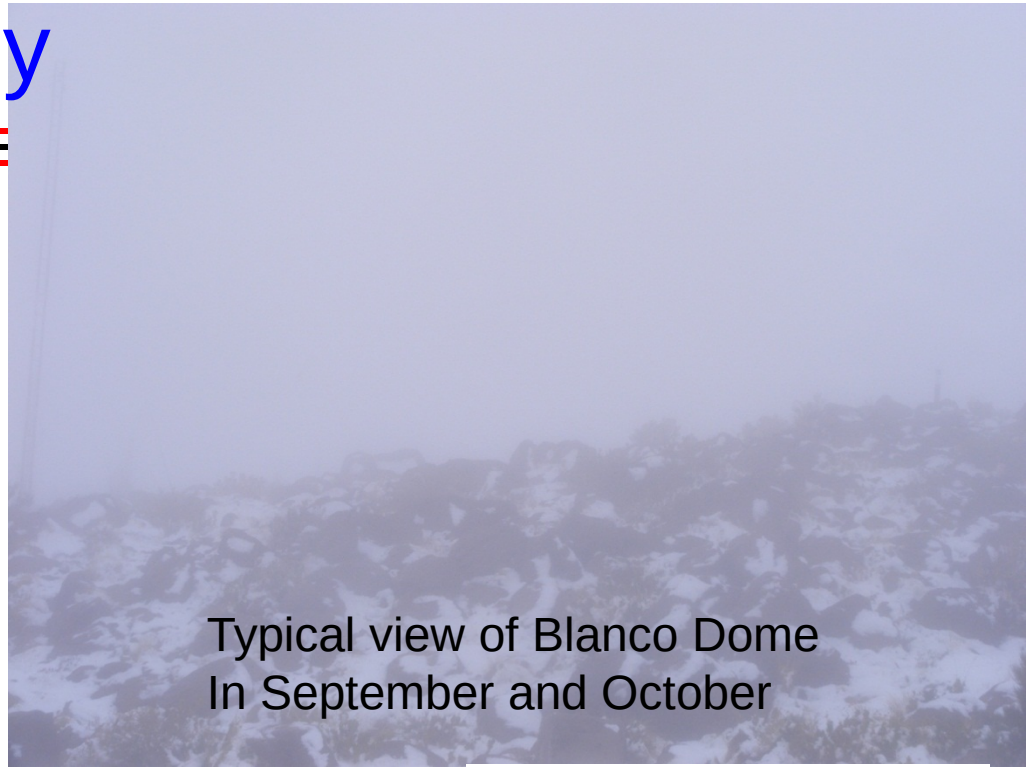


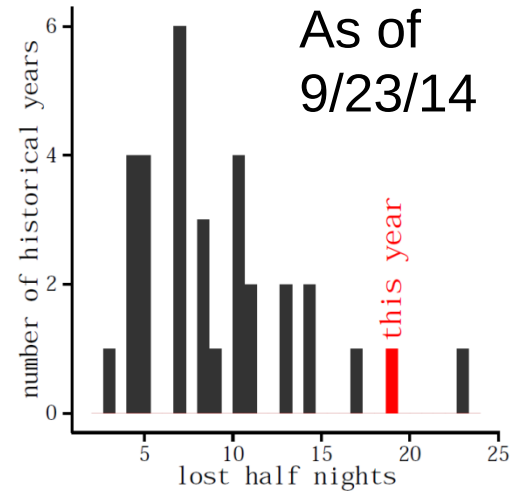

Now go off and analyze the data!

# DES Year 2: Wide Field Survey

DARK ENERGY SURVEY

- Year 2 Observing started Aug. 15, 2014
- Fast start! Records for best "seeing" in all bands in 1st few days.
- Then – cloud problems. Through Oct 31 we didn't even bother to open the dome 33% of time.
- When we did open, ~ 70% of the data was good ☹
- Appears Y2 turned around on Nov. 11th : 8 great nights in a row (and counting).
- Many DES record bests broken.

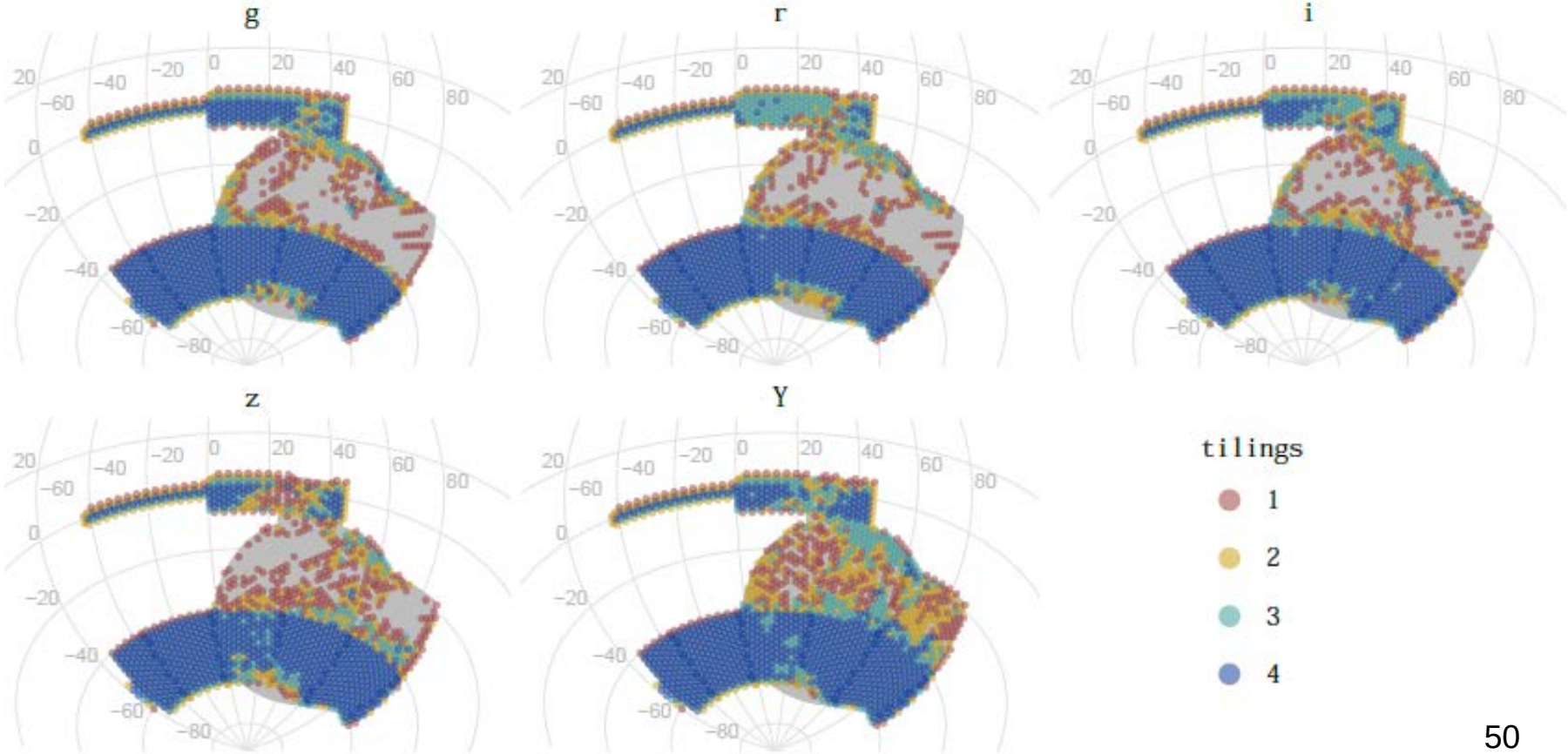


# DES Year Two: Wide Field

DARK ENERGY SURVEY

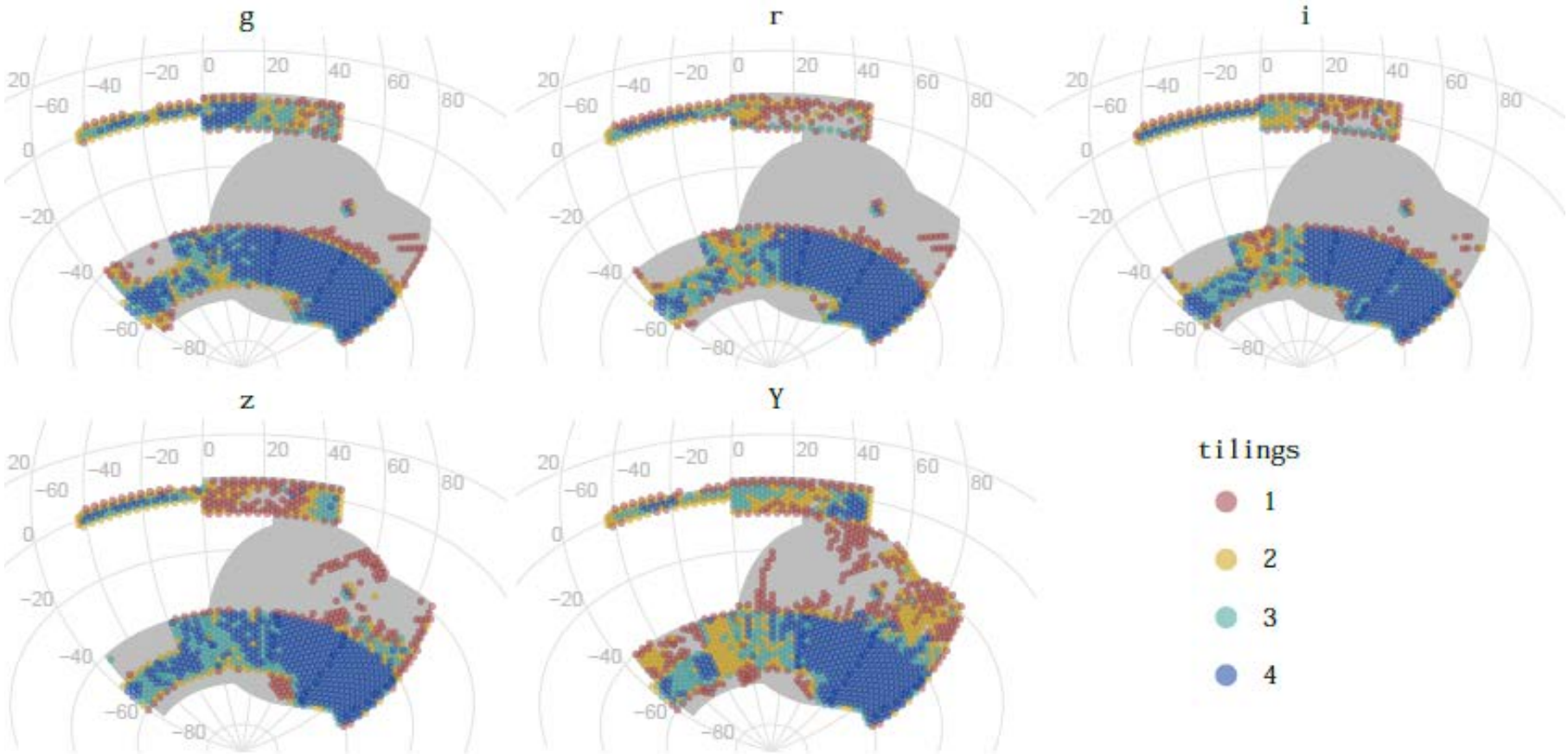
- 61 nights into Y2 we've got ~7,500 good images in the Wide Field Survey area. Y2 will finish in mid-February 2015.



# DES Y1 vs. Y2: Wide Field

DARK ENERGY SURVEY

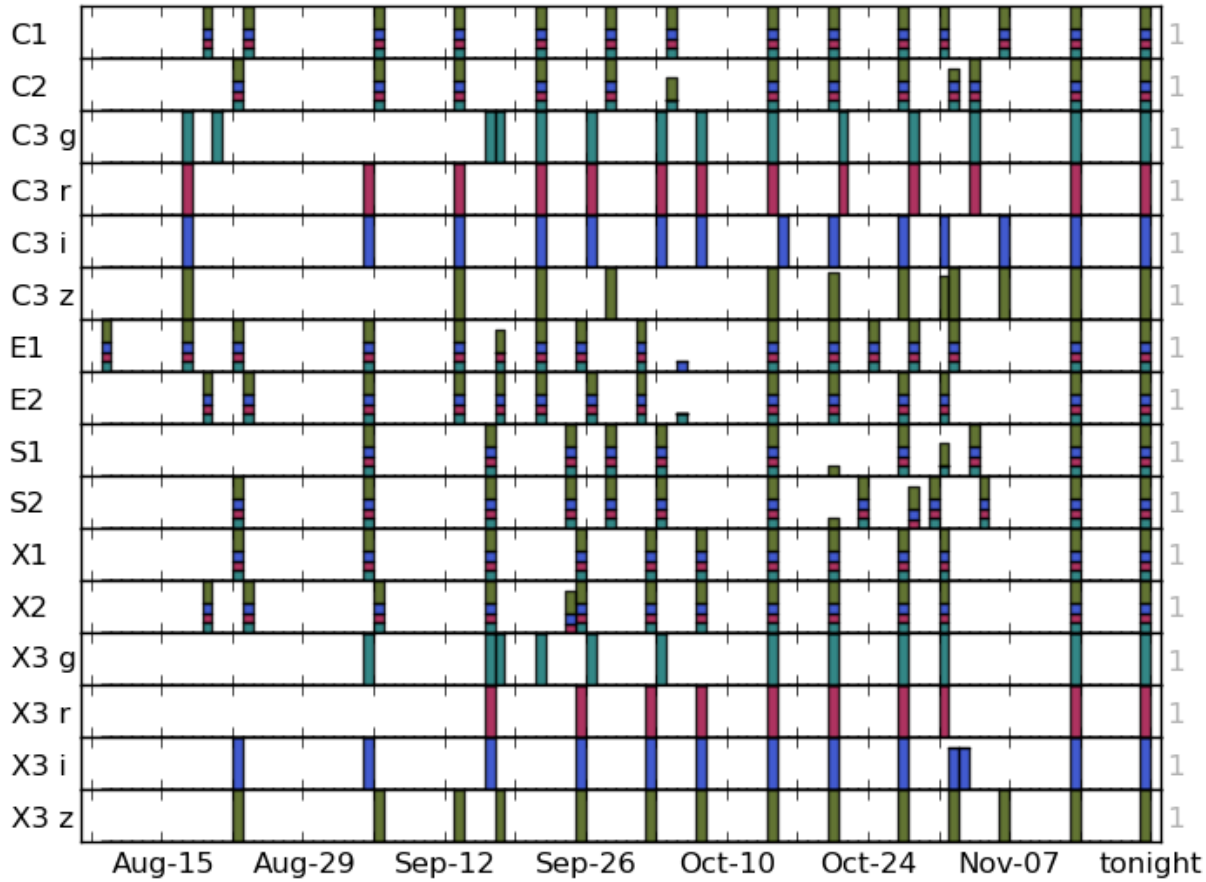
- Blinking Back-and-forth emphasizes the progress since end of Y1.



# DES Year Two: SN Survey

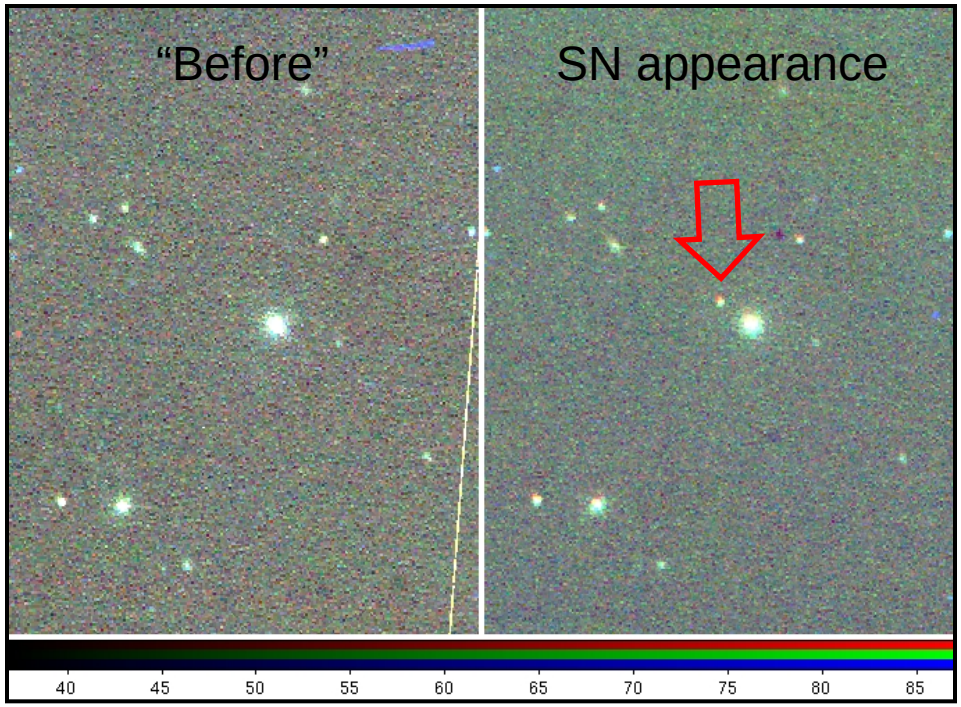
DARK ENERGY SURVEY

- SN “Cadence” (RHS) shows when we observed each SN field from start to end of Y2.
- Bigger gaps in Y2 than in Y1
- Note 11/11 & 11/18 we got all SN data in one night! Data “too good” ?&^%$#@



# Supernovae “Difference Imaging”

DARK ENERGY SURVEY




- 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

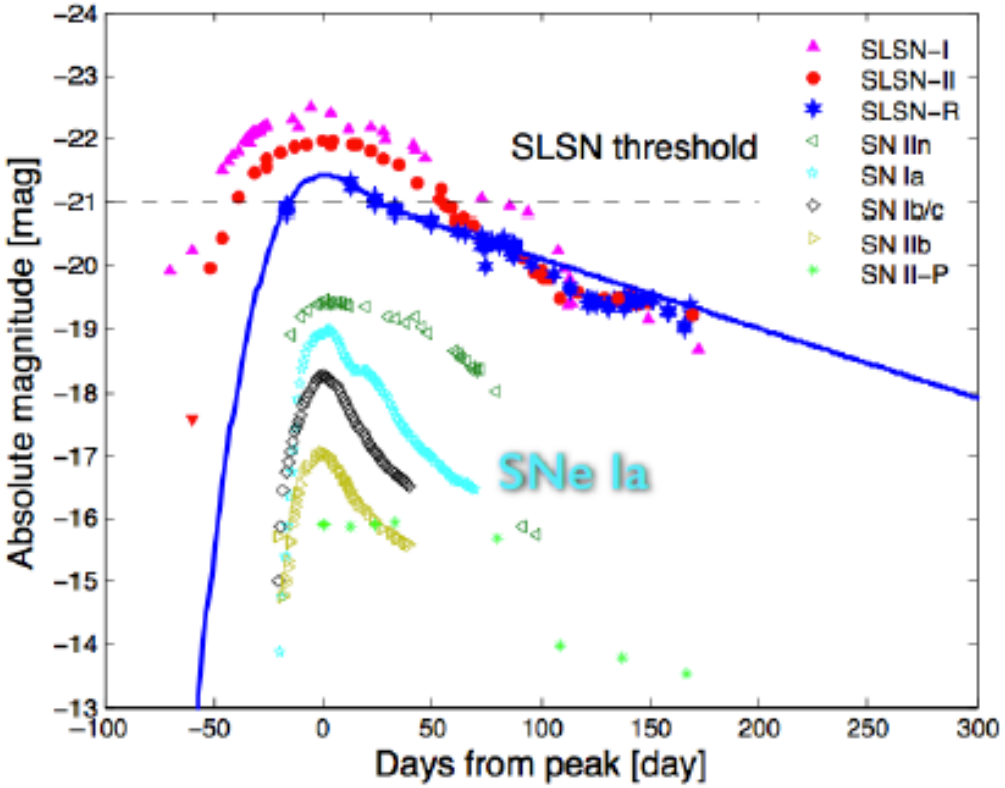
# Superluminous SNe (SLSNe)

SLSNe classes, Gal-Yam 2012 [review]:

SLSN-I
- hydrogen free
- Spin down Magnetar interactions
- 9 events

SLSN-II
- hydrogen rich surrounding
- CSM interactions
- 7 events

SLSN-R
- hydrogen free
- death of >100$M_\odot$ stars
- Pair-Instability / radioactive $^{56}$Ni
- 2 events




TOTAL: 18 events

TOTAL(updated): ~40

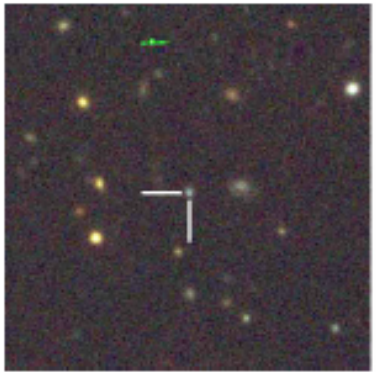


Slide from A. Papadopolous (U. Portsmouth, U.K.)

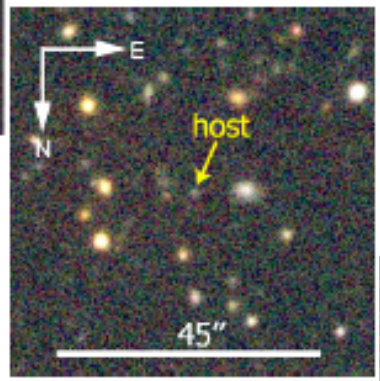
# DES13S2cmm a Superluminous SN

Peak Brightness:

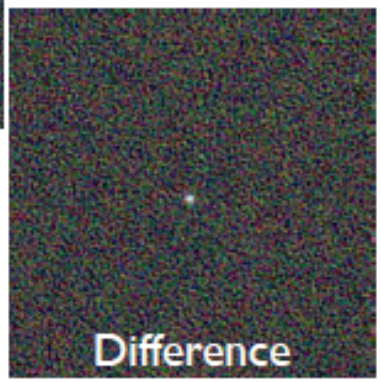
- 28-September-2013

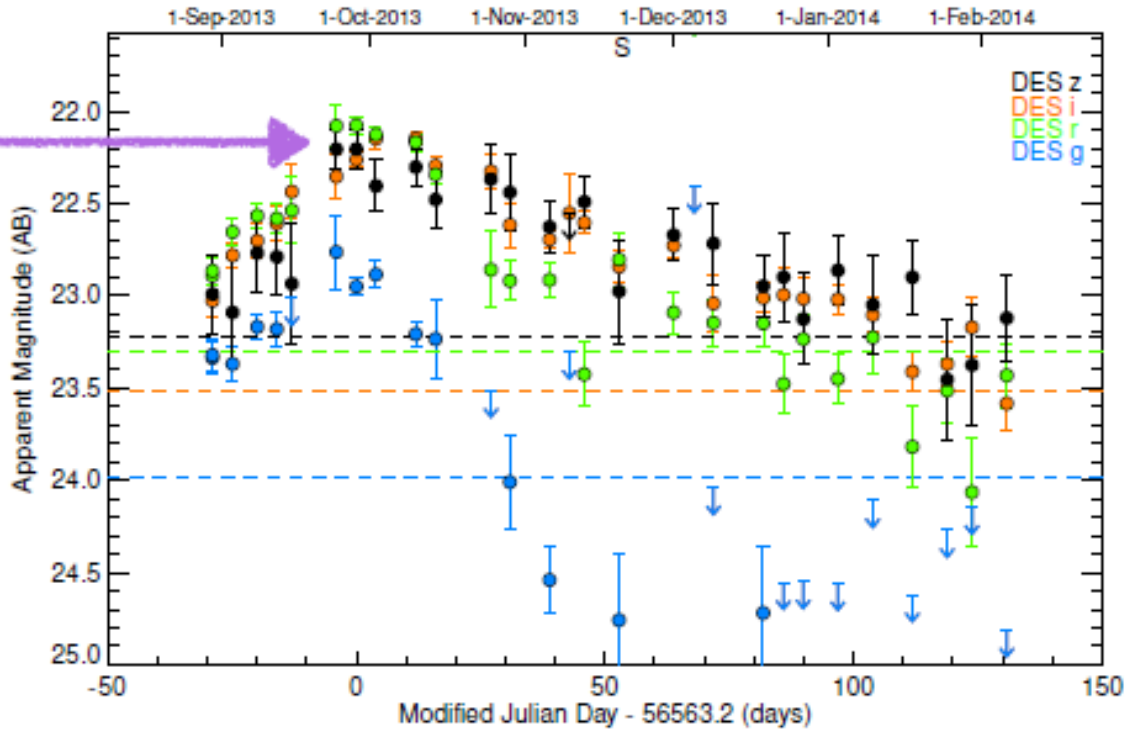


Search




Template




SLSNe Candidate:

- ~30 days rise time
- $z_{photo} = 0.83 \pm 0.13$
- $M_U < -21.6$
- Zspec=0.663±.001

Best Fit to light-curve is "Spinning-Down Magnetar" but SLSN-R not ruled-out.

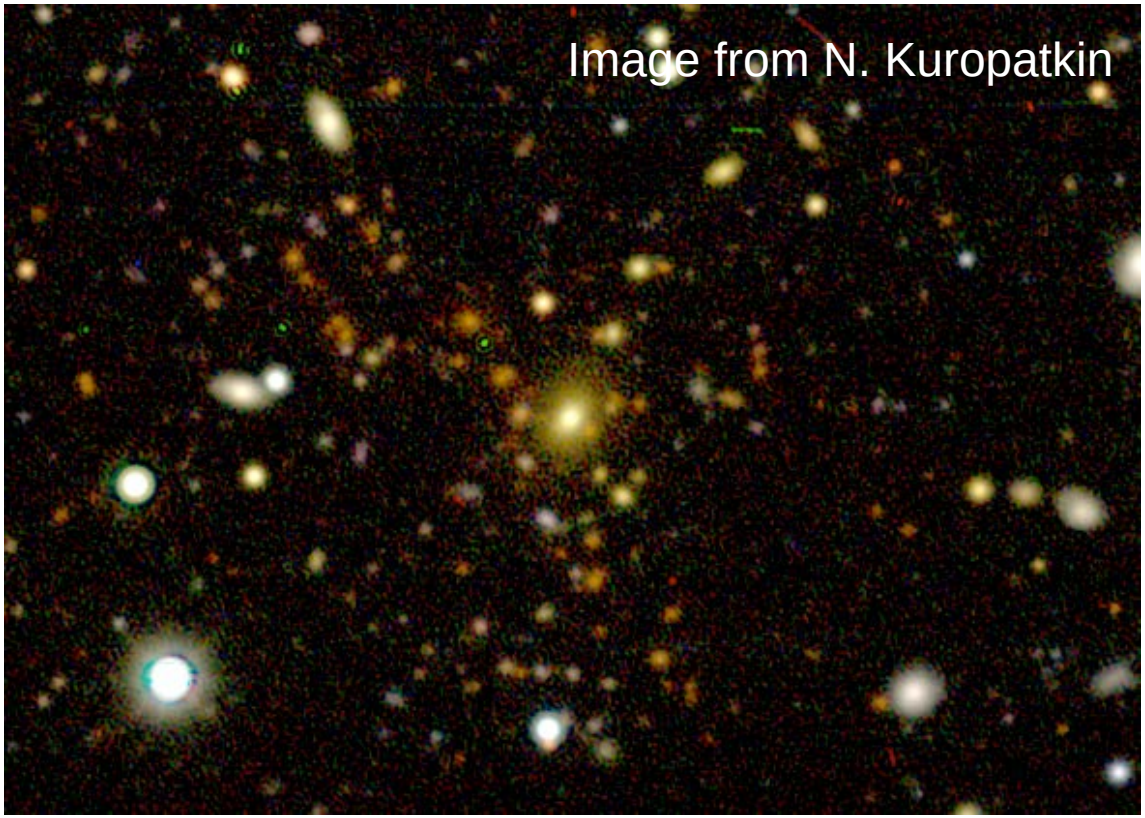


Slide from A. Papadopolous (U. Portsmouth, U.K.) submitted to MNRAS

# 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 z depends on how much Dark Energy there is (was)
- 1200-5000 clusters in SVA1

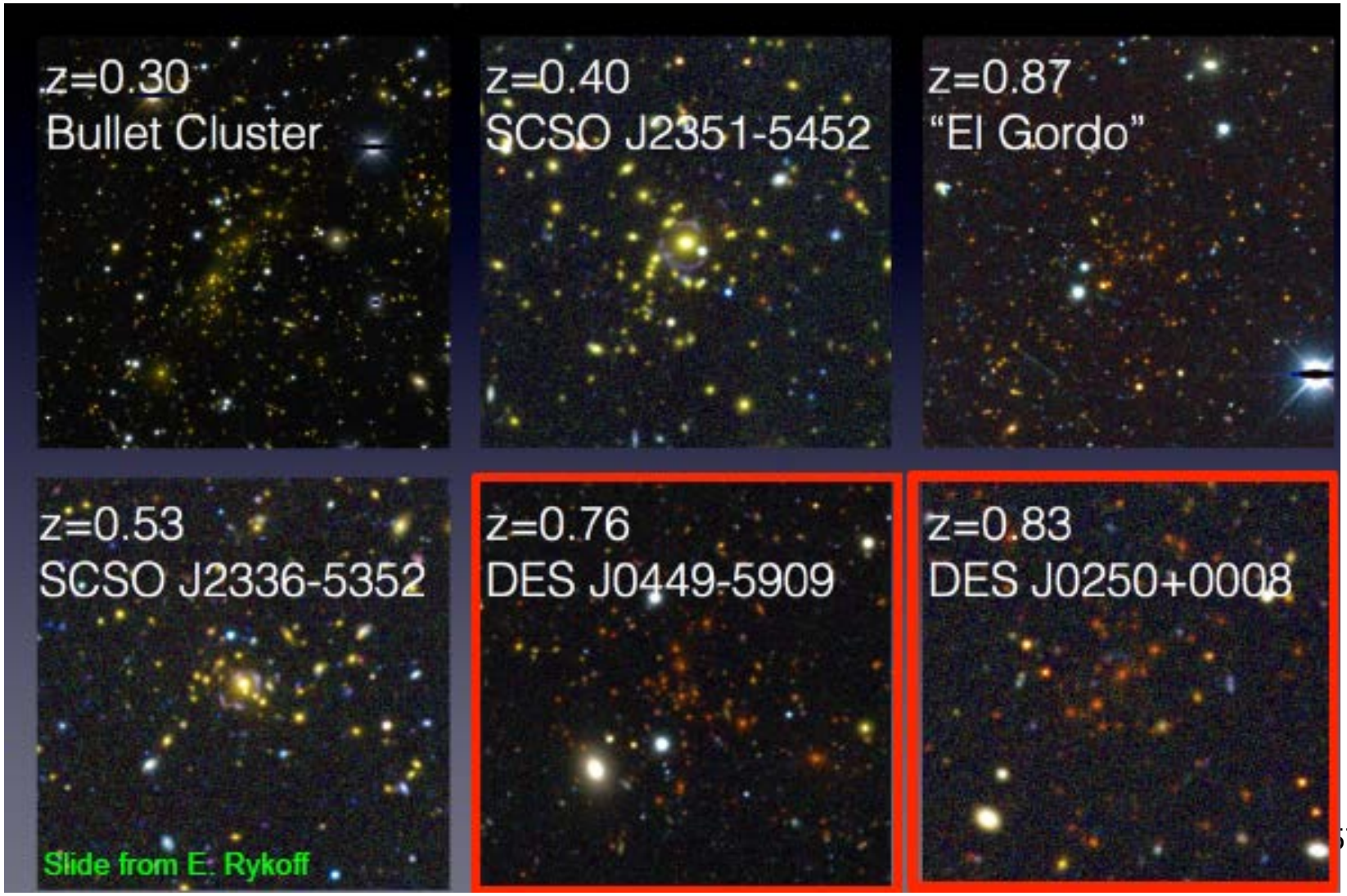
Image of a galaxy cluster
(or is it 2 clusters, one behind the other?)




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

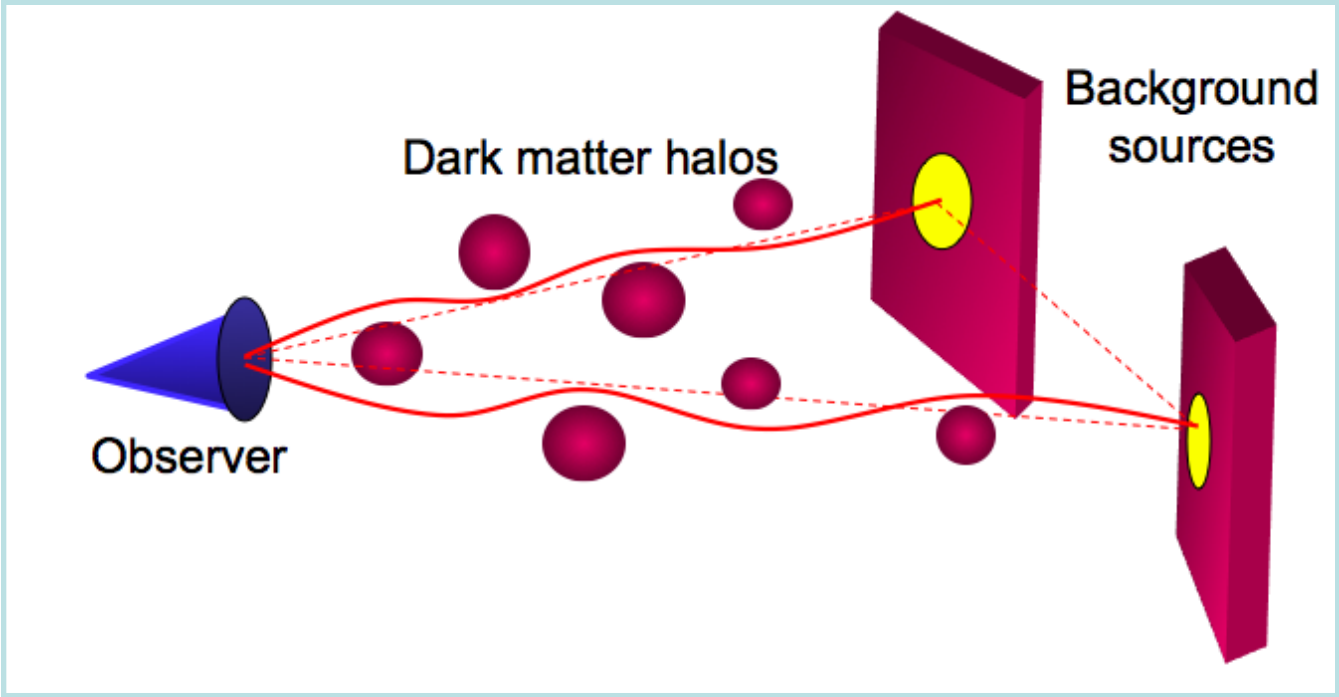
# More (High-z) Galaxy Clusters

DARK ENERGY SURVEY



# DES Weak Gravitational Lensing

DARK ENERGY SURVEY



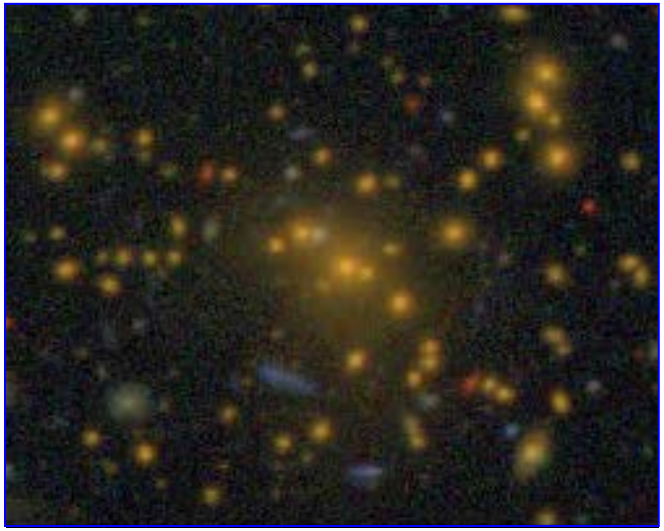

- Photon (light) trajectories are curved by gravity.
- The observed shape of a distant object is changed through the accumulated effects of passing close to matter along the line of sight.

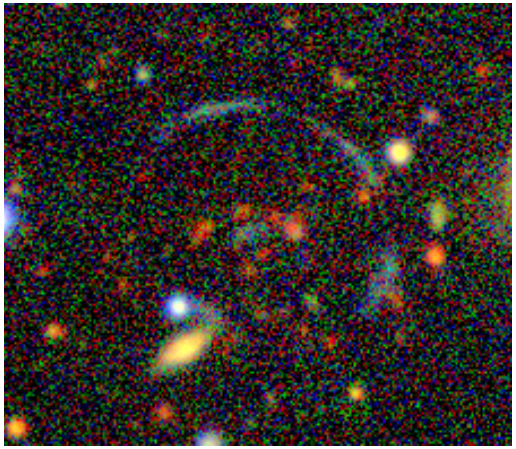
# In special cases with a very massive object in LOS

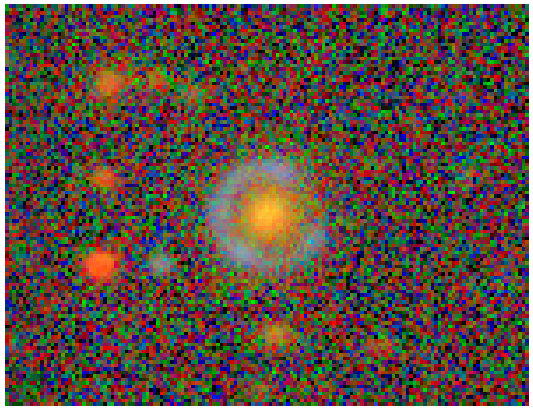
# "Strong" Gravitational Lensing

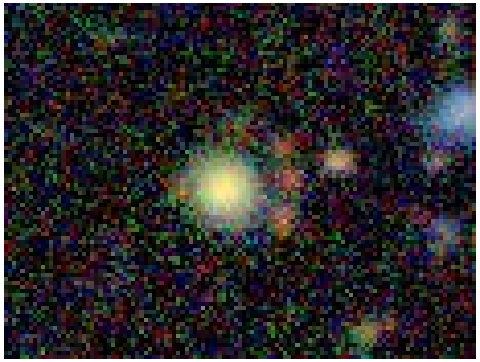
DARK ENERGY SURVEY

These are some of the dozens of candidates from SV





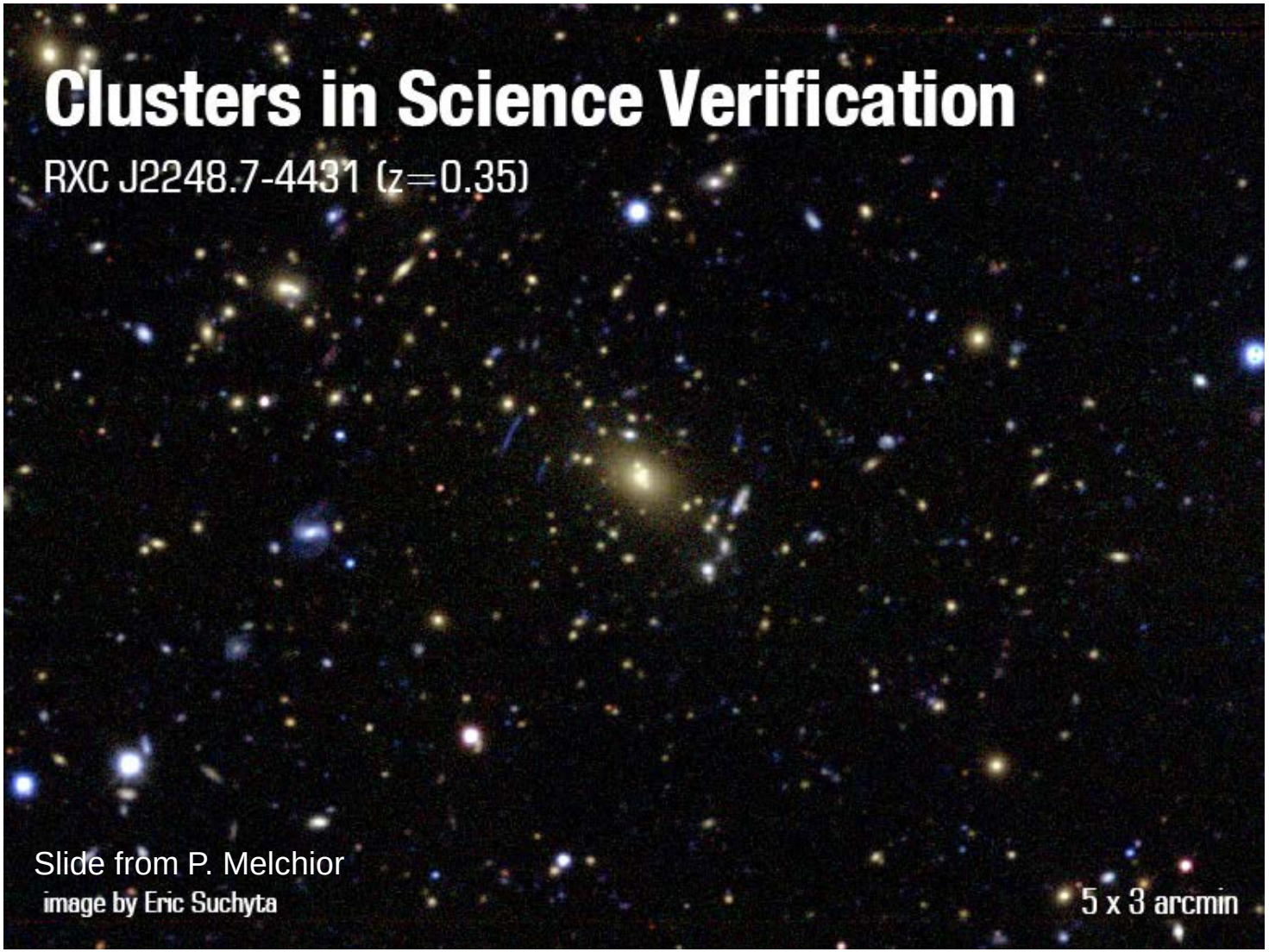




- The distant sources can appear as "Einstein Rings", "Einstein Crosses", or just simply arcs
- And are typically magnified by 10-100x so …"Einstein's telescopes"
- Special cases with more than on source (arc) may provide dark energy constrains."

# DES Galaxy Clusters and Weak-Gravitational Lensing

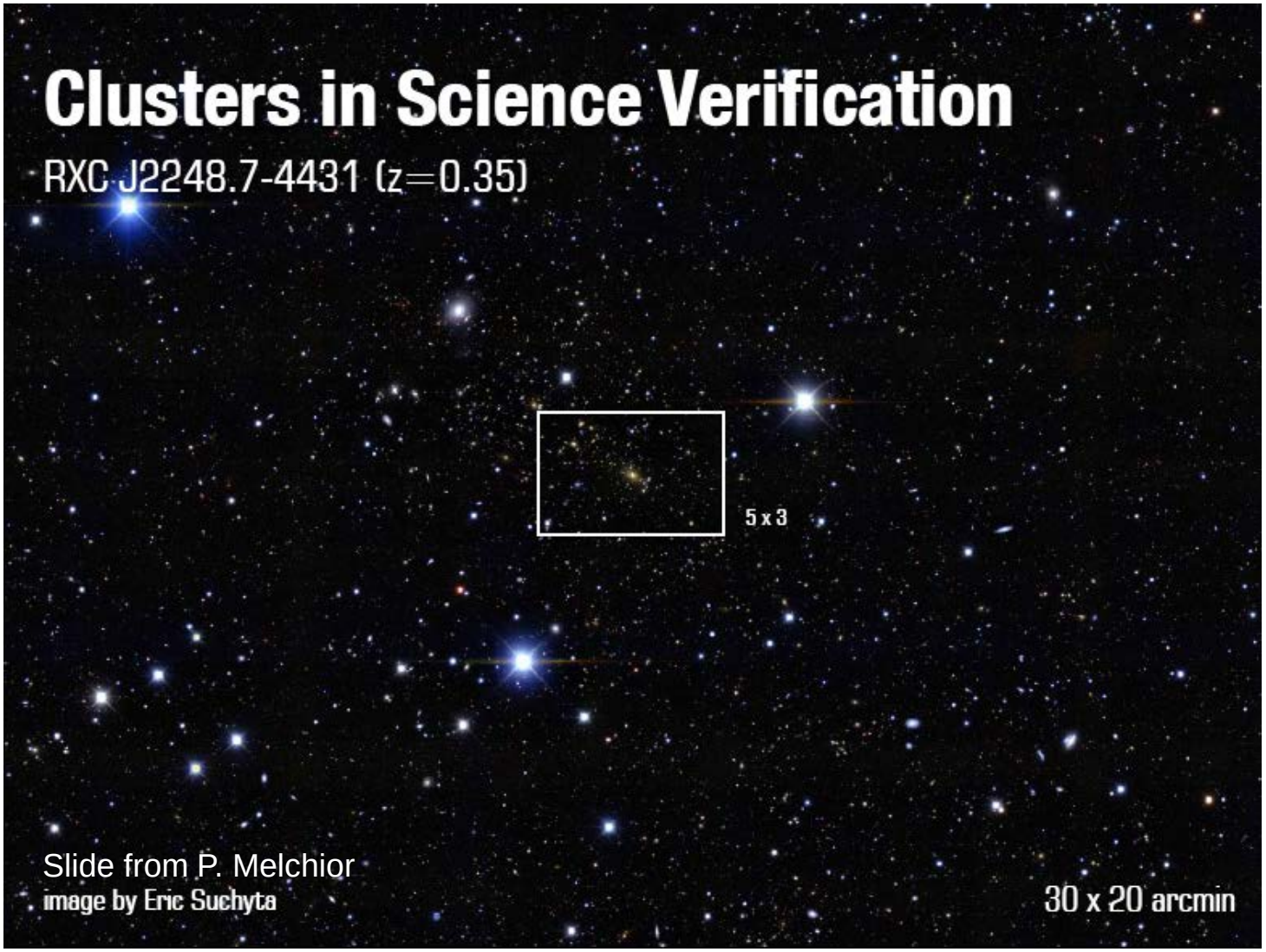
DARK ENERGY SURVEY




Slide from P. Melchior

# DES Galaxy Clusters and Weak-Gravitational Lensing

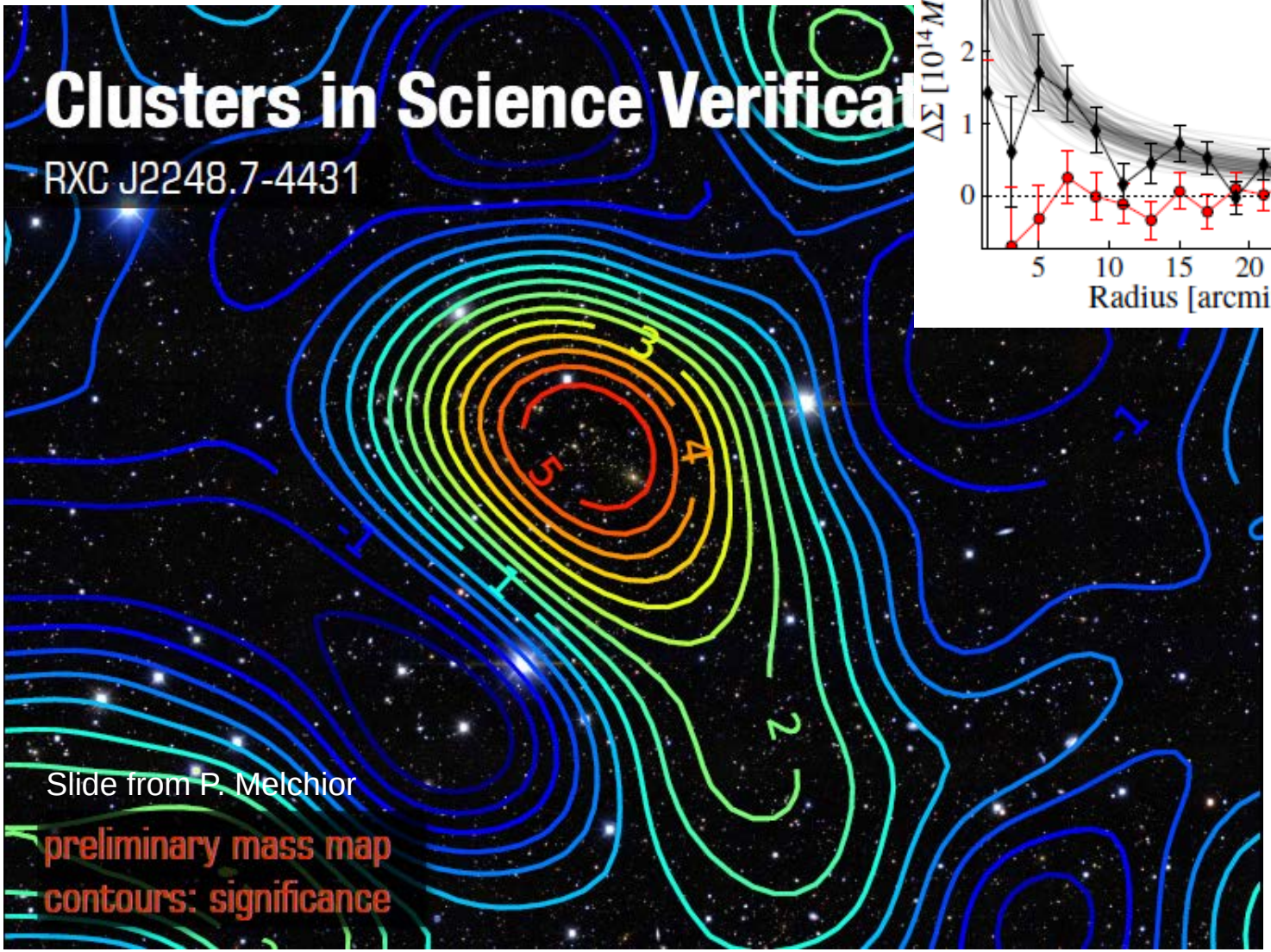
DARK ENERGY SURVEY

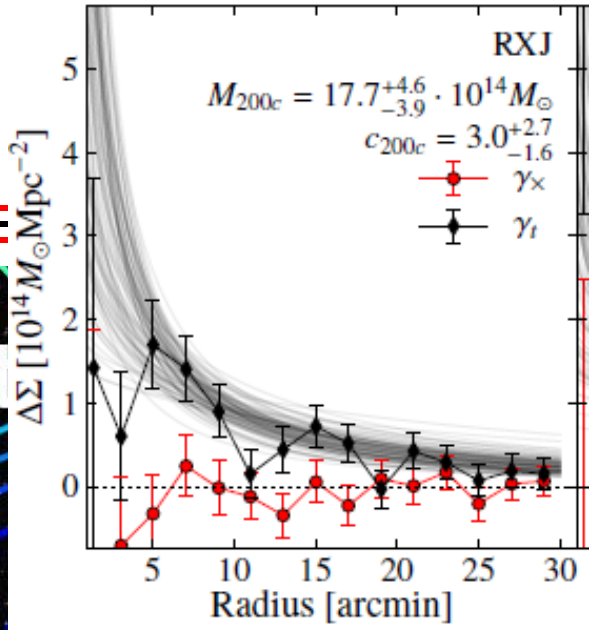



Slide from P. Melchior
image by Eric Suchyta

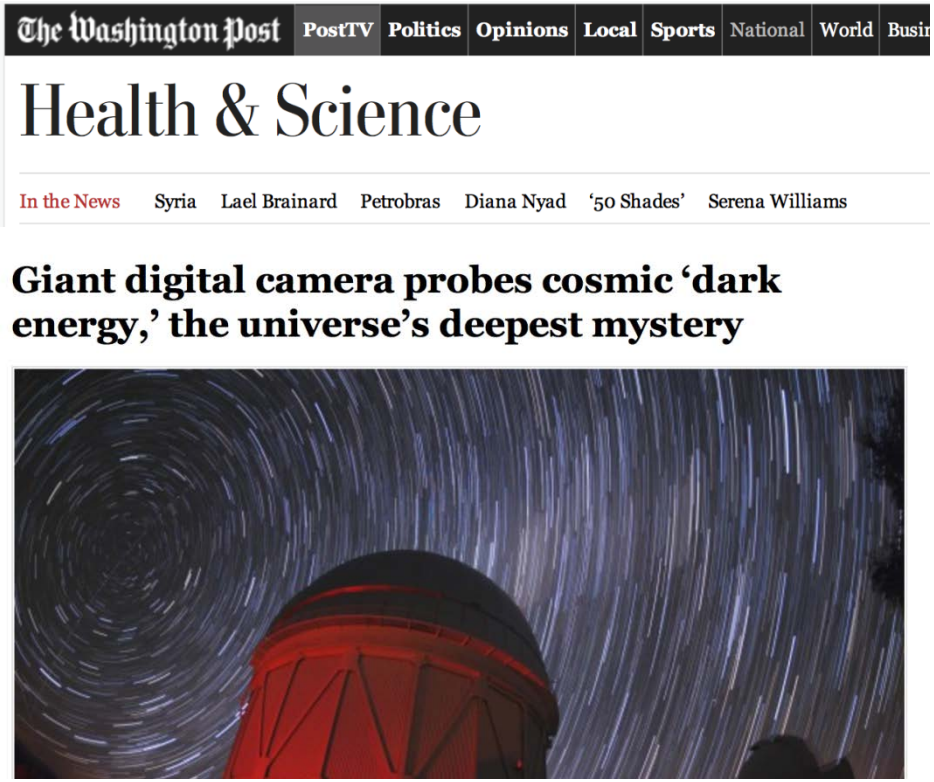
# DES Galaxy Clusters and Weak-Gravitational Lensing

DARK ENERGY SURVEY



# Summary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**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.

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Brenna Flaugher
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