Can the World's Largest Digital Camera Answer Cosmological Questions?

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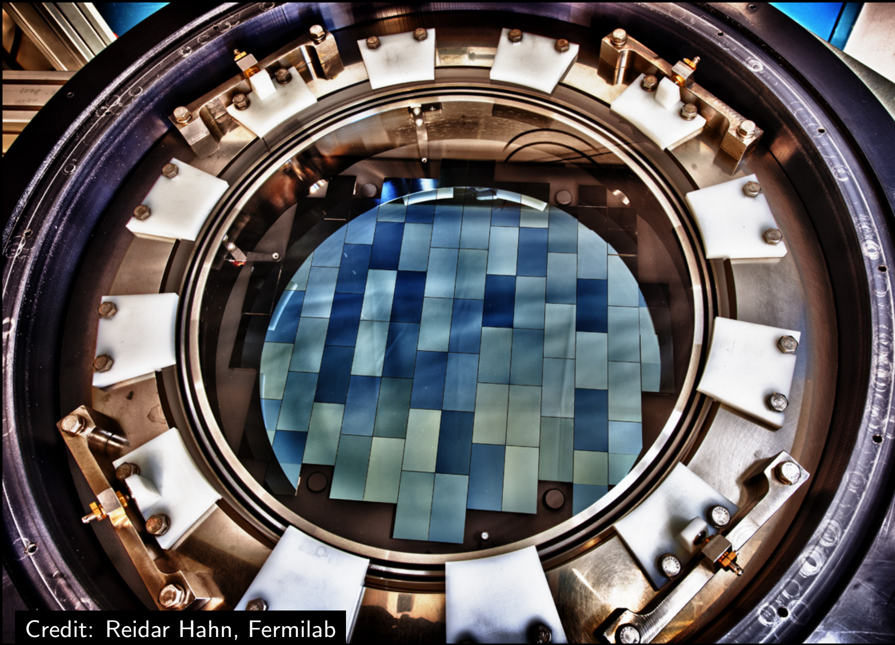
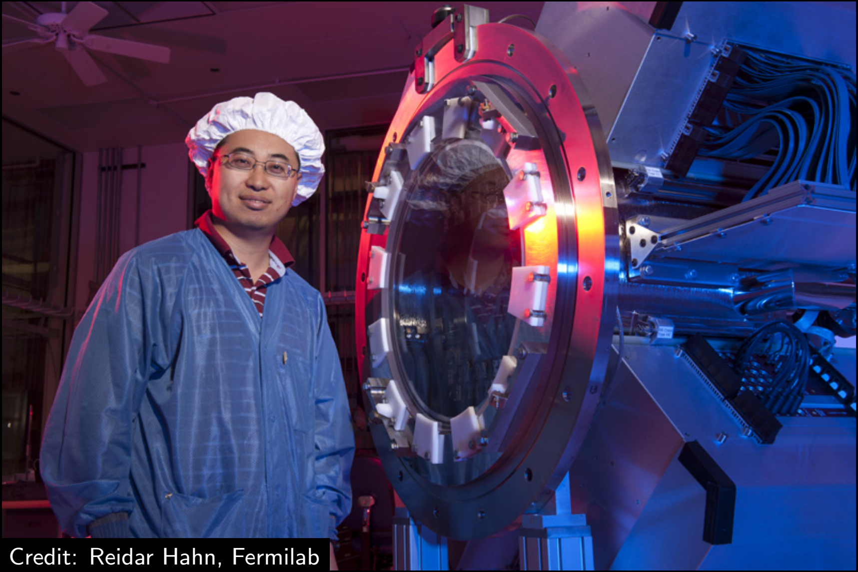
Find the presentation at https://tinyurl.com/y7w542eb



Credit: Reidar Hahn, Fermilab



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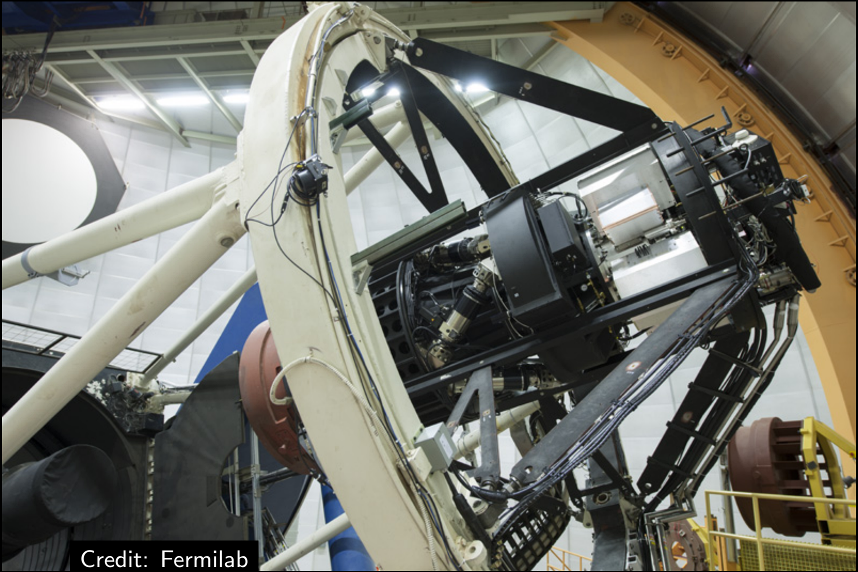
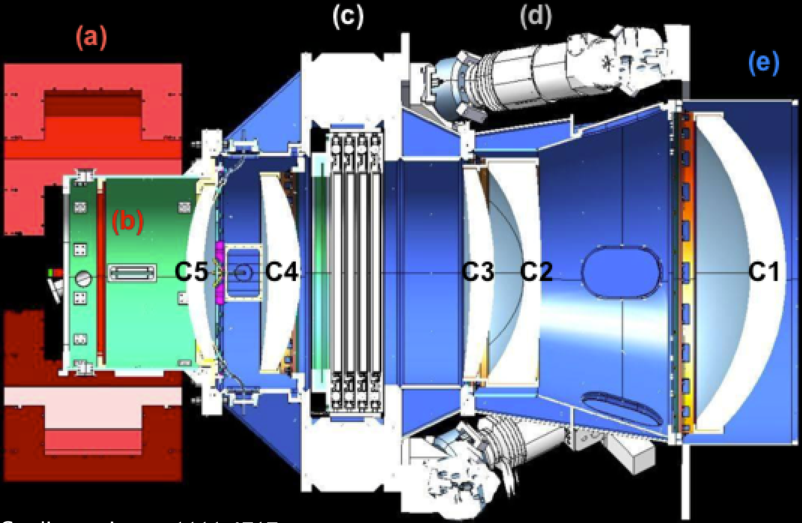
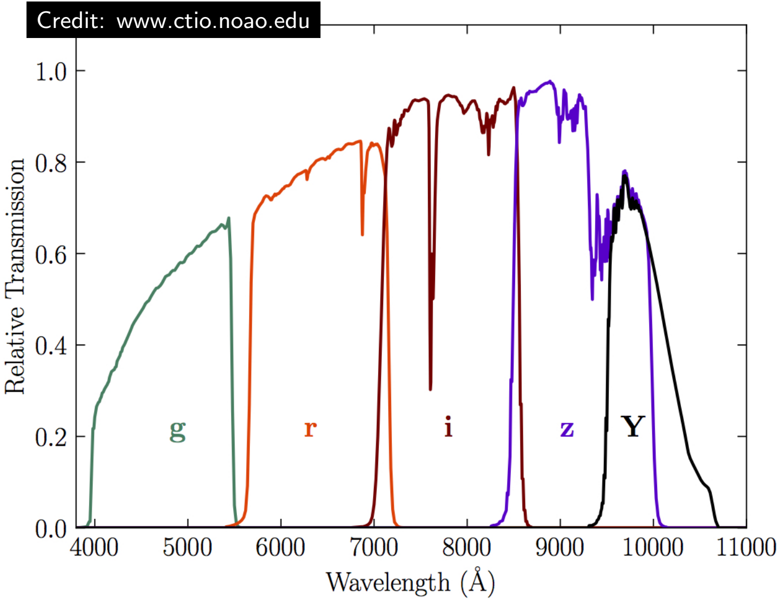

Credit: Fermilab

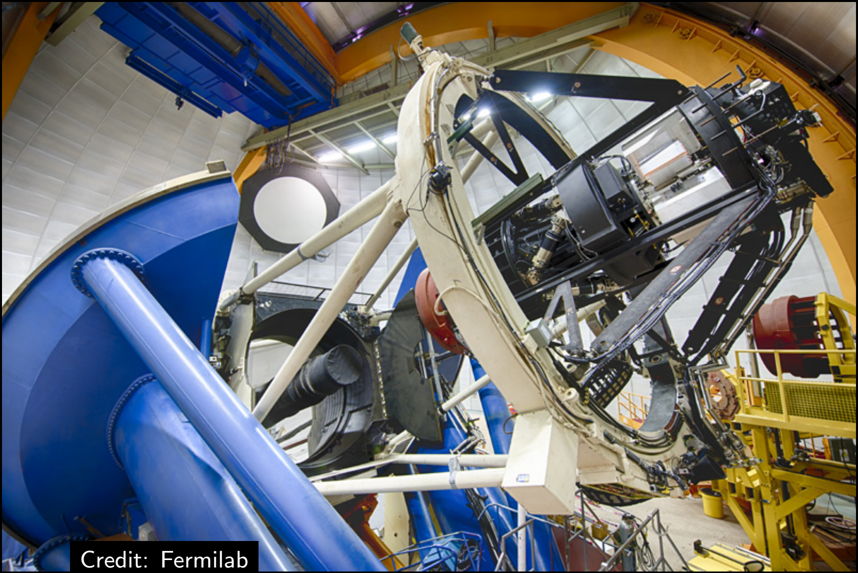


Credit: arxiv.org 1111.4717



Credit: www.ctio.noao.edu
Relative Transmission
1.0
0.8
0.6
0.4
0.2
0.0
4000
5000
6000
7000
8000
9000
10000
11000
Wavelength (Å)
g
r
i
z
Y

Credit: Reidar Hahn, Fermilab


Credit: Fermilab

The Telescope

- The DECam camera is attached to the Victor Blanco Telescope at the Cerro-Tololo Inter-American Observatory in Chile
- 4 m main mirror; 10 m^2 collecting area
- First light 1976; largest Southern Hemisphere telescope until 1998
- At 2200 m altitude
- Ritchey-Chrétien design

Optical system: Telescope plus camera

- The camera is at prime focus.
- f2.7
- Field of view: 2 deg diameter; 3 deg^2 area.
- 0.26 arcsec per pixel ('pixel scale').

Credit: Erin Sheldon, DES

Dark Energy Survey

- The camera has been used as part of a survey to collect information about the locations of many distant galaxies.
- Expect to see 300 million galaxies.
- We only do statistical analysis on the data - we don't actually care about the details of any one particular object.

Dark Energy Survey

- Survey lasts six years - final year has recently ended.
- Survey covers one-eighth of the celestial sphere.
- Each patch imaged ten times with each of the five filters.
- Each exposure is 90 seconds.

Cosmological redshift

- It's easy to measure the sky coordinates RA and DEC of each object.
- But we also want to know how far away the object is, to determine its place in three-dimensional space.
- The expansion of the Universe 'stretches' lightwaves, making the wavelength longer (redder). This is 'cosmological redshift'.
- From the redshift we can infer the distance (more redshift $\Longrightarrow$ more distant).

Photometric redshifts

- If we could point a spectrograph at each object, then we could precisely measure the redshift noting how much the spectral lines have shifted.
- This would take too long!
- But we get some (very coarse) spectral (i.e. colour) information by measuring the brightness through each of the five filters.
- From this we can get a 'good enough' estimate of the redshift.
- What can go wrong: small old nearby red galaxy and large old distant blue galaxy are indistinguishable.

Why a survey?

- So what do we do with all these galaxy positions?

Cosmology

- Cosmology is the study of the Universe on its largest scales.

Cosmological questions

1. Did the Universe have a beginning and if so old is it now?
2. Is the Universe expanding and if so how fast?
3. What types of matter and energy predominate in the Universe and what are their densities?
4. What is the mass of the neutrino?

Cosmological questions that we don't work on

1. How big is the Universe?
2. What caused the Big Bang?
3. Are there other Universes?

We (currently) have no tools to use to answer these questions.

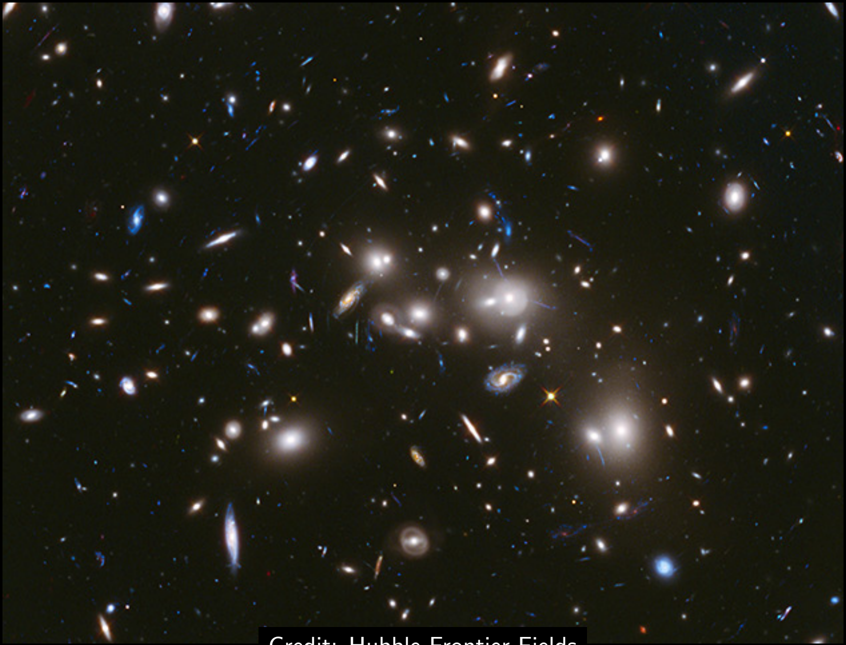
First principles

There is strong evidence that:

1. There was a Big Bang - an initial uniformly hot and dense state - and the Universe has been expanding ever since.
2. The Universe is more-or-less the same everywhere and we are not in a 'special' location.
3. Einstein's theory ('General Relativity') correctly describes how gravity works.
4. The overall geometry of the Universe is 'flat': keep going in a straight line and you won't return home.

So how can we answer these cosmological questions?

- One main method is to look at how ‘clustered’ galaxies are.
- Galaxies aren’t randomly distributed through space - instead, they cluster together under the influence of gravity.



Credit: Hubble Frontier Fields

Clustering

- The older the Universe, the longer time gravity has had to operate, so the more clustering.
- The more stuff in the Universe, the more gravity, so the more clustering.
- The two effects are similar but distinguishable.
- The idea to look at clustering is due to Jim Peebles (Nobel prize in physics 2019).

So here's the plan

1. Agree on a definition of clustering.
2. Theoretical astrophysicists calculate how much clustering they would expect for a range of ages and densities.
3. Astronomers measure how much clustering there actually is.
4. We match the results to see which age/density combination makes theory equal observation.

Credit: www.kingsnews.org

Definition of clustering

- Measure the distance between each pair of objects. Expect to see lots of pairs with small separation.
- Draw a histogram of the results.
- Repeat using randomly positioned objects.
- Look at the percentage difference between the two histograms.

Calculating how much clustering we would expect in theory

- Details of this are beyond the scope of this talk.
- See Dodelson's book *Modern Cosmology* for details.
- Ingredients: theory of gravity, interactions between light and electrons and between electrons and protons (important in early Universe).
- Mathematical tools: Perturbation theory, Fourier analysis.
- Can check the results using computer simulations.

Exercise: You are the Cosmologist

- Some of you have been given some real galaxy positions and some of you have been given some random positions.
- Calculate how much clustering.
- Compare your results to the theoretical results.
- How old is the Universe? What is the density of matter?

Exercise answers

Bin	Data Count	Random Count
0 - 50	7	3
50 - 100	14	7
100 - 150	21	19
Over 150	13	26

Exercise answers

Bin	Data Count	Random Count	Percentage Difference
0 - 50	7	3	133%
50 - 100	14	7	100%
100 - 150	21	19	10.5%
Over 150	13	26	

Clustering tables created from theory

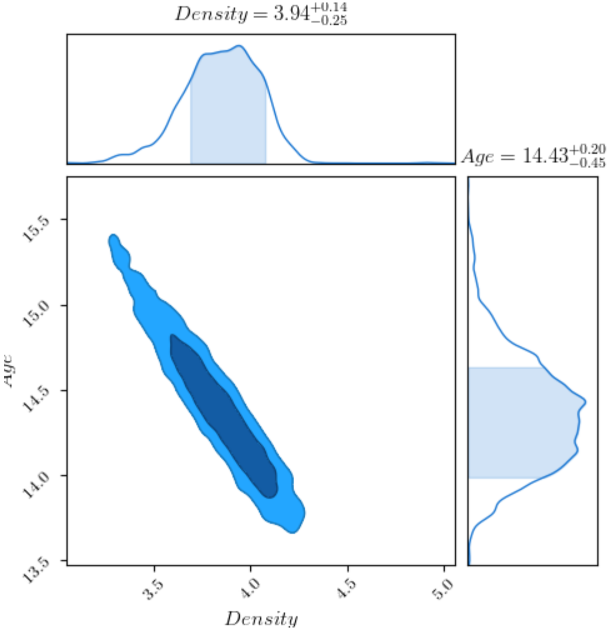
	Density = 3g per Jupiter Volume		Density = 5g per Jupiter Volume		Density = 7g per Jupiter Volume	
Age = 16 billion y	0-50 50-100 100-150	133.5% 100.4% 14.9%	0-50 50-100 100-150	153.2% 120.6% 16.1%	0-50 50-100 100-150	184.2% 140.7% 19.7%
Age = 14 billion y	0-50 50-100 100-150	123.7% 91.1% 11.7%	0-50 50-100 100-150	142.9% 109.0% 9.3%	0-50 50-100 100-150	162.3% 129.6% 9.7%
Age = 12 billion y	0-50 50-100 100-150	112.1% 79.9% 5.0%	0-50 50-100 100-150	132.7% 100.2% 5.1%	0-50 50-100 100-150	154.0% 120.4% 6.0%

Conclusions of the exercise

- Universe is about 14 billion years old.
- Density of matter is about 4 g per Jupiter volume.

Redshift

- Why was it important that all the galaxies have the same redshift?



$Density = 3.94^{+0.14}_{-0.25}$
$Age = 14.43^{+0.20}_{-0.45}$
15.5
15.0
14.5
14.0
13.5
Age
3.5
4.0
4.5
5.0
Density

What types of stuff?

- Our actual analysis is more complicated.
- The theoreticians actually create clustering graphs for a huge range of densities for different possible types of ‘stuff’.

Dark matter

- They include the possibility that some of the matter doesn't interact with light.
- Such 'dark matter' doesn't cluster as easily as ordinary matter. (Why not?)
- This gives a recognisable signature in the clustering graph.

Dark energy

- They also include the possibility that empty space itself has some mass.
- This mass is called ‘dark energy’.
- This mass is everywhere, and can’t cause clustering.

Conclusions

- If we throw all these stange things into the range of possibilities, then we find that the best match to the observed clustering is:
- Age of Universe = 14 billion years (as before).
- Of the 4.3 g per Jupiter volume of matter, only 0.7 g is normal matter (basically hydrogen and helium) and 3.6 g is dark.
- As well, there is an additional 9 g per Jupiter volume that is simply the mass of empty space.

Dark Energy

- Dark energy is not well understood.
- Normally you must expend energy to increase a volume (think of the piston on a steam locomotive).
- But dark energy *increases* as space expands. Thus we say that dark energy has a *negative* pressure.

Cosmic acceleration

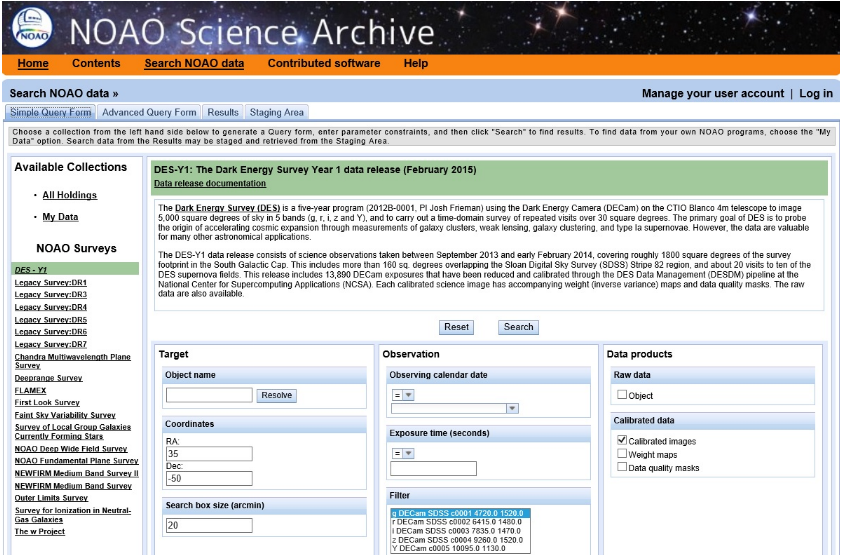
- Analysis of the Dark Energy Survey results shows that this pressure is exactly the negative of the energy density (the two quantities have the same units).
- This negative pressure causes an *acceleration* in the expansion of space.
- This acceleration was first observed in the 1990s.
- The accelaeration has been slowly building for the last five billion years.
- This will dominate the future Universe - in the distant future our galaxy will have no near neighbours.

Further reading

- Harrison, *Cosmology*, Cambridge University Press, 2nd ed 2000. Historical cosmology and the philosophy of cosmology as well as modern theory. Non-mathematical.
- Hawley & Holcomb, *Foundations of Modern Cosmology*, OUP, 2005. Undergraduate textbook.
- Dodelson, *Modern Cosmology*, Academic Press, 2003. Introduction to the mathematical theory; requires undergraduate physics preparation.

Images are publicly available

- Go to `http://archive.noao.edu/search/query/survey/desy1`
- Set coordinates to (say) RA = 35, DEC = -50; Search box size = 20; choose a filter colour and check ‘Calibrated images’. Then ‘Search’.
- On the next page click on ‘Retrieve’.
- This will download a file ($\sim$ 300 Mb) that you can view with DS9.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Legacy Survey:DR4
Legacy Survey:DR5
Legacy Survey:DR6
Legacy Survey:DR7
Chandra Multiwavelength Plane Survey
Deeprange Survey
FLAMEX
First Look Survey
Faint Sky Variability Survey
Survey of Local Group Galaxies Currently Forming Stars
NOAO Deep Wide Field Survey
NOAO Fundamental Plane Survey
NEWFIRM Medium Band Survey II
NEWFIRM Medium Band Survey
Outer Limits Survey
Survey for Ionization in Neutral-Gas Galaxies
The w Project
DES-Y1: The Dark Energy Survey Year 1 data release (February 2015)
Data release documentation
The Dark Energy Survey (DES) is a five-year program (2012B-0001, PI Josh Frieman) using the Dark Energy Camera (DECam) on the CTIO Blanco 4m telescope to image 5,000 square degrees of sky in 5 bands (g, r, i, z and Y), and to carry out a time-domain survey of repeated visits over 30 square degrees. The primary goal of DES is to probe the origin of accelerating cosmic expansion through measurements of galaxy clusters, weak lensing, galaxy clustering, and type Ia supernovae. However, the data are valuable for many other astronomical applications.
The DES-Y1 data release consists of science observations taken between September 2013 and early February 2014, covering roughly 1800 square degrees of the survey footprint in the South Galactic Cap. This includes more than 160 sq. degrees overlapping the Sloan Digital Sky Survey (SDSS) Stripe 82 region, and about 20 visits to ten of the DES supernova fields. This release includes 13,890 DECam exposures that have been reduced and calibrated through the DES Data Management (DESDM) pipeline at the National Center for Supercomputing Applications (NCSA). Each calibrated science image has accompanying weight (inverse variance) maps and data quality masks. The raw data are also available.
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Target
Object name
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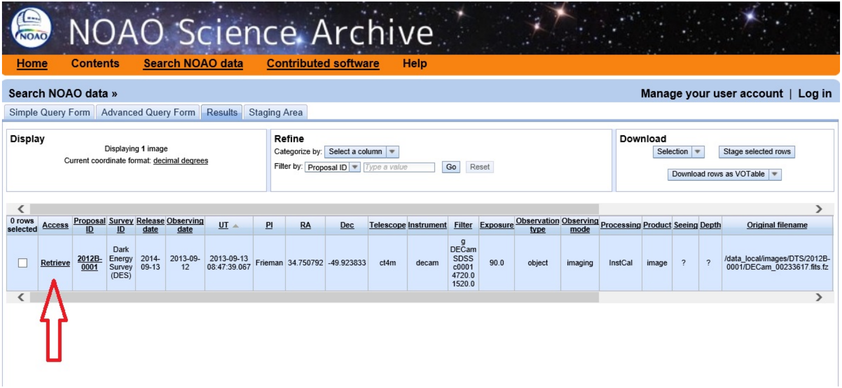
Data products
Raw data
Object
Calibrated data
Calibrated images
Weight maps
Data quality masks



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☐	Retrieve	2012B-0001	Dark Energy Survey (DES)	2014-09-13	2013-09-12	2013-09-13 08:47:39.067	Frieman	34.750792	-49.923833	ct4m	decam	g DECam SDSS c0001 4720.0 1520.0	90.0	object	imaging	InstCal	image	?	?	/data_local/images/DTS/2012B-0001/DECam_00233617.fits.fz

Other uses of the data

- The images capture everything in the sky (stars, galaxies, solar system objects, cosmic rays, airplanes, etc.)
- Non-cosmologists are using the images e.g. to search for planet 9.

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