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

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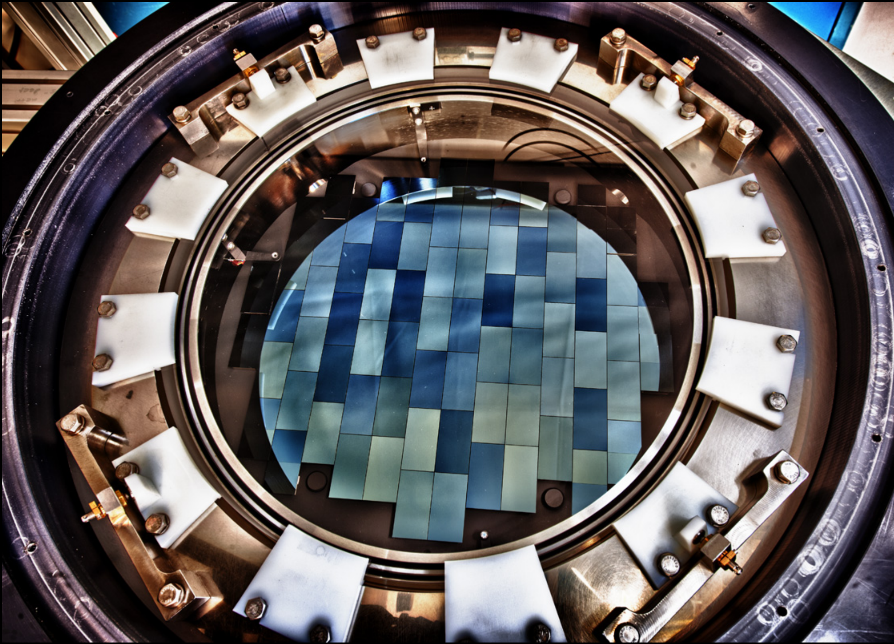
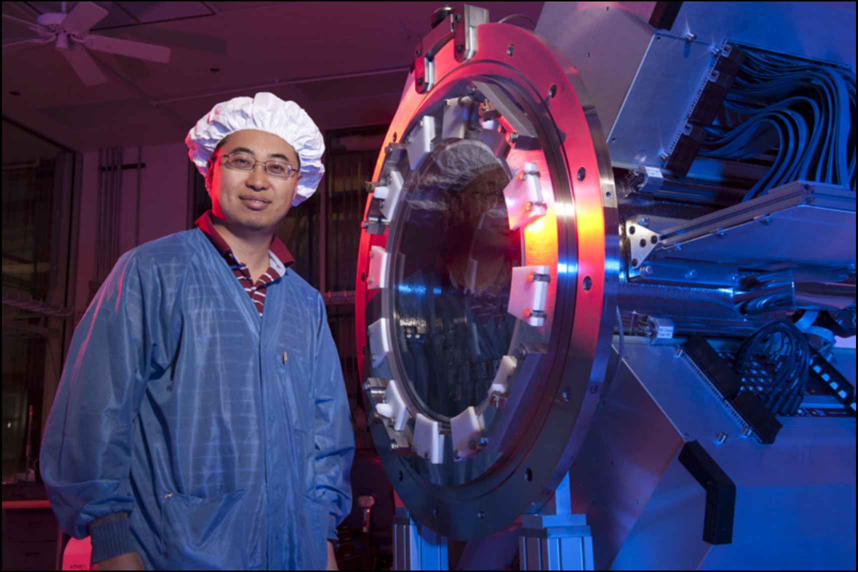
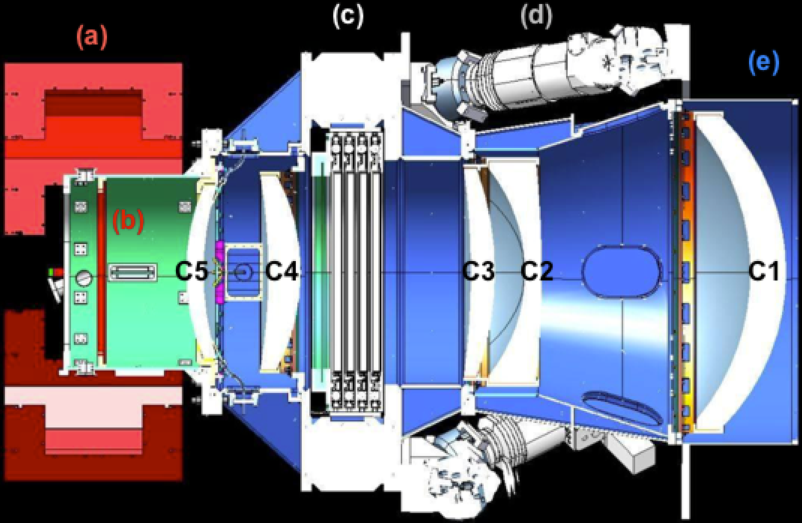
Find the presentation at https://tinyurl.com/y7w542eb





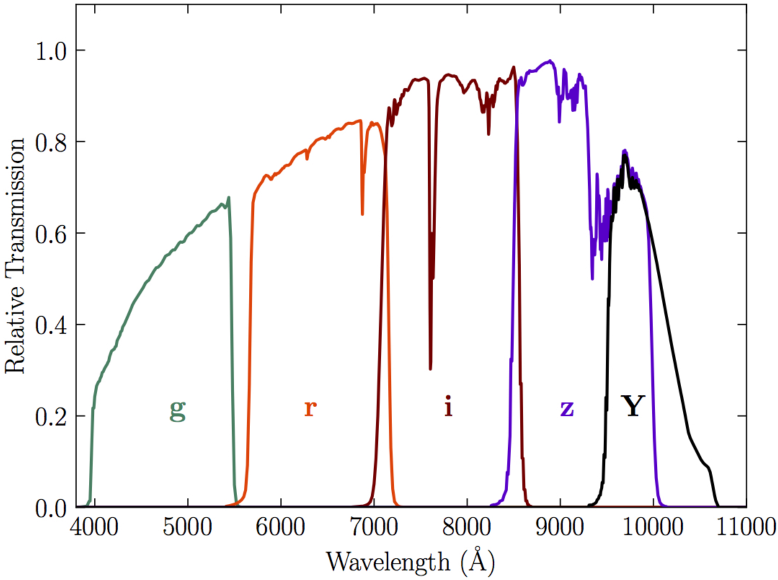
Detector

- Detector has 62 chips ('CCDs')
- Each CCD is 3 cm by 6 cm and has $2048x4096 = 8$ megapixels
- Total of 500 megapixels.
- Each pixel is 15 microns square.
- The CCDs are unusually thick $\implies$ more infrared light captured.
- Why do we want to capture infrared light?

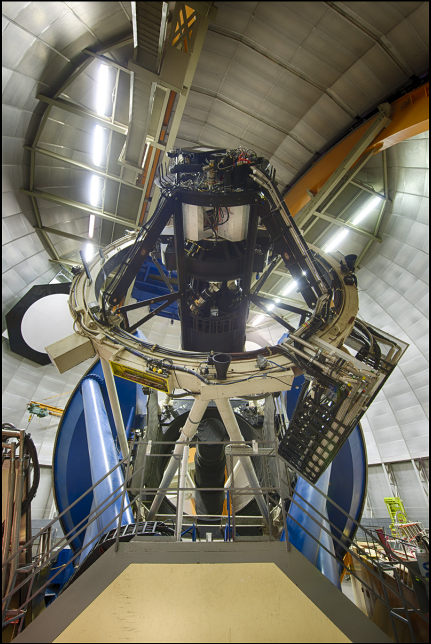

(a)
(b)
(c)
(d)
(e)
C5
C4
C3
C2
C1

DECam

- Detector is part of a camera called 'DECam'.
- Built in part at University College London.
- Five lenses - largest is 1m diameter.
- Five filters: green, red, and three infrared colours.



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



The Telescope

- The DECam camera is attached to the Victor Blanco Telescope at the Cerro-Tololo Inter-American Observatory in Chile
- 4m main mirror; $10m^2$ 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; $3deg^2$ area.
- 0.26 arcsec per pixel ('pixel scale').

Dark Energy Survey

- The camera is being used as part of a survey to collect information about the locations of many distant galaxies.
- We only care about distant galaxies. Milky Way stars, comets, nearby galaxies and so on are actually bad for us (as they block our view of distant objects).
- We only do statistical analysis on the data - we don't actually care about the details of any one particular object.
- Survey lasts six years - year six is just starting.
- Survey covers one-fifth of the entire celestial sphere.
- Each patch imaged ten times with each of the five filters.
- Each exposure is 90 seconds.
- TODO: What magnitude?

Dark Energy Survey

- The project involves over 400 scientists at 25 institutions in 7 countries.
- Funding is primarily from the U.S. Department of Energy.
- U.K. institutions are UCL and the Universities of Cambridge, Edinburgh, Portsmouth, Sussex and Nottingham.

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 place it properly 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 $\implies$ 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 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

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

Cosmological questions that we don't work on

- How big is the Universe?
- What caused the Big Bang?
- Are there other Universes?

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

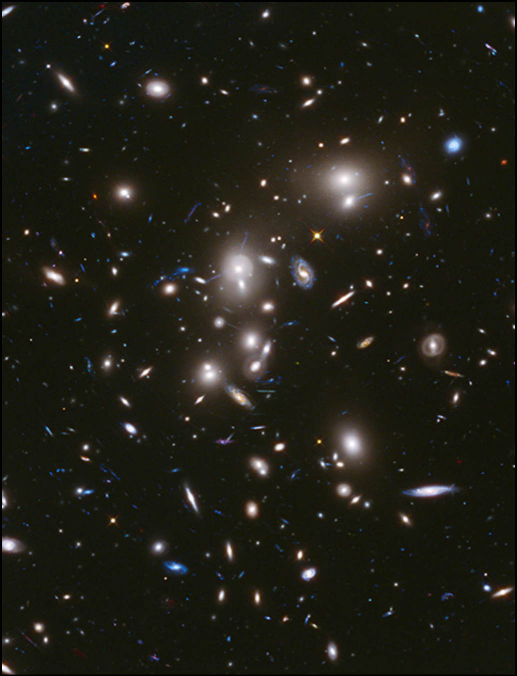
First principles

There is strong evidence that:

- There was a Big Bang - an initial hot and dense state - and the Universe has been expanding ever since.
- The Universe is more-or-less the same everywhere and we are not in a ‘special’ location.
- Einstein’s theory (‘General Relativity’) correctly describes how gravity works.

So how can we answer these comological 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.



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.

So here's the plan

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

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

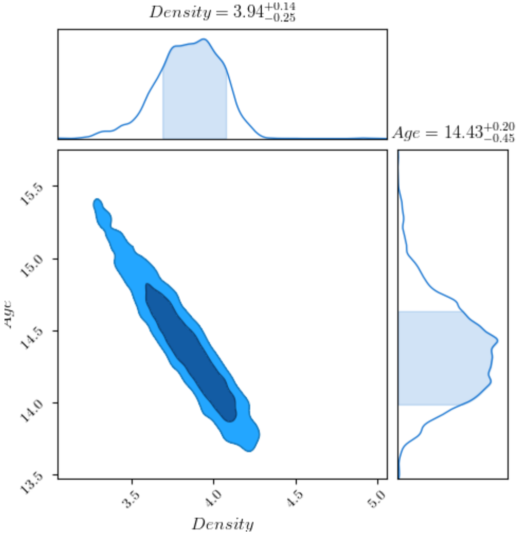
- You have been given some real galaxy positions as well as some random positions.
- Calculate how much clustering.
- Compare your results to the theoretical results.
- How old is the Universe? What is the density of matter?

Conclusions of the exercise

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

Comments

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



$Density = 3.94^{+0.14}_{-0.25}$
$Age = 14.43^{+0.20}_{-0.45}$
Age
15.5
15.0
14.5
14.0
13.5
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, empty space has a mass of 9 g per Jupiter volume.

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
DES book
DES public data
Systematic errors?
CMB