Cosmology with Galaxy Surveys

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About This Lecture

- The target audience is students with some background in physics and who hopefully were present for Paul Stankus' talk on cosmology
- My goal is to introduce basic concepts and give some examples
- Feel free to ask questions, *I don't care if I get through all of the material*
- In the interest of pedagogy, I ask those in the room with PhDs to please refrain from commenting or asking questions :)

Outline

- Very brief introduction to cosmology
- Optical astronomy and galaxy surveys
- How we learn about cosmology using galaxy surveys
- Two examples

Cosmology

Introduction to Cosmology

- I'm building off of Paul's lecture on cosmology.
- I'll focus on the main topics pertaining to galaxy surveys
- What makes up the universe? What can we see?
- Where is it all? How is matter distributed?
- What is the history of the universe?
- Can we explain what we see? Is what we see consistent with our understanding of fundamental physics?

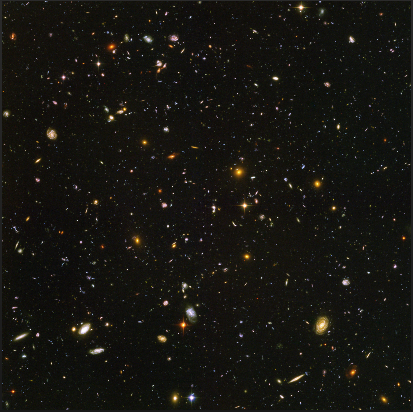
What Makes Up the Universe?

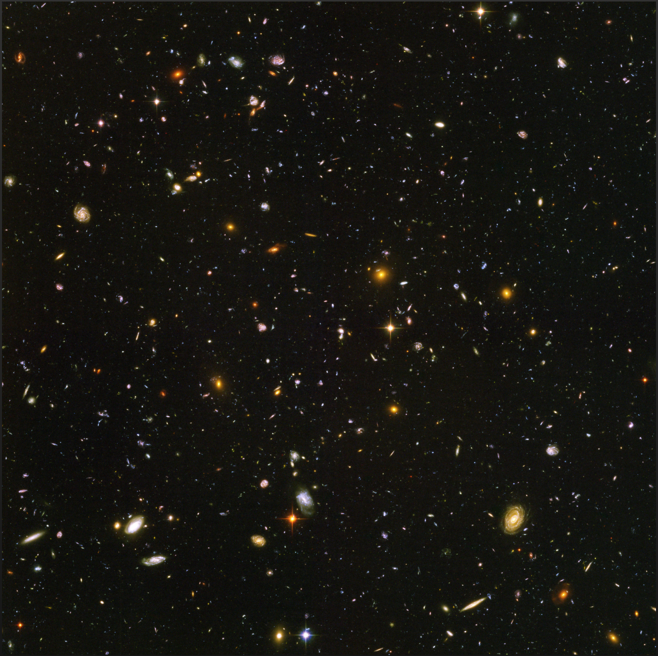
- Particles – people – planets – stars – galaxies
- What is the composition of distant objects?
- What is the mass density of the universe?
- What fraction of the mass in the universe is dark matter?

DES/Erin Sheldon

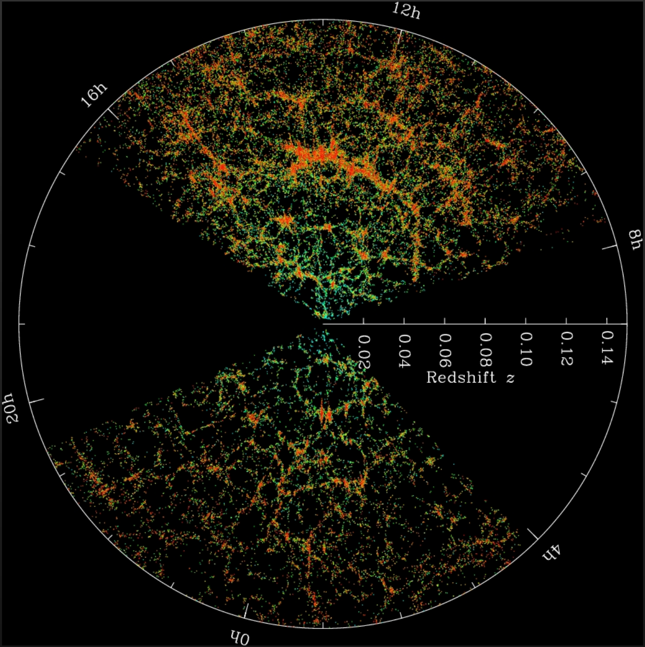
How is matter distributed?

- Where are the galaxies and dark matter in the universe, over large scales?





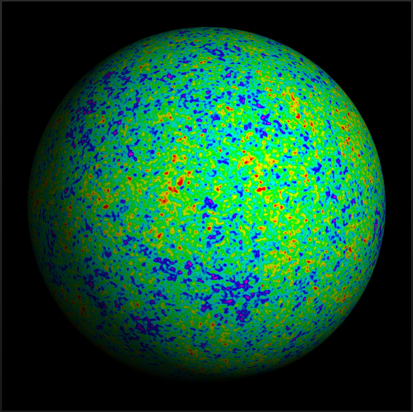
Hubble UDF



SDSS Galaxy Locations (M. Blanton)

What is the history of the universe?

- The universe is expanding
- Long ago the universe was extremely hot and dense
- The Cosmic Microwave Background is the relic light from a few hundred thousand years after the big bang (recall Chris Sheehy's talk)
- How did the visible universe evolve, from formation of the first nuclei to stars to the large scale structure of the universe?



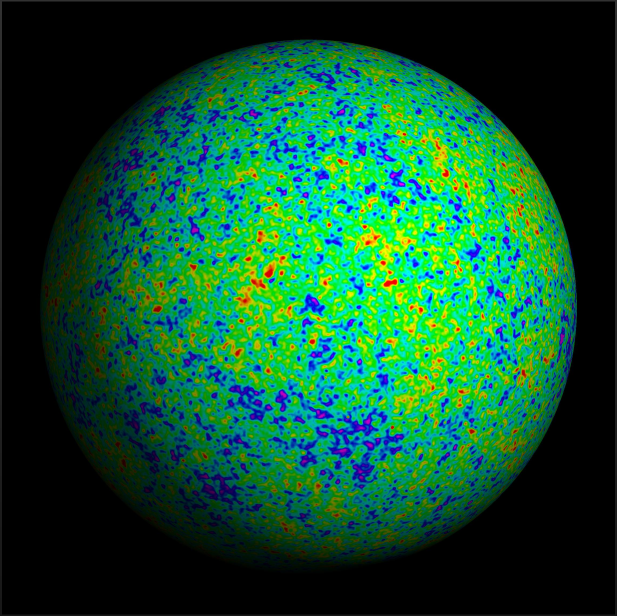
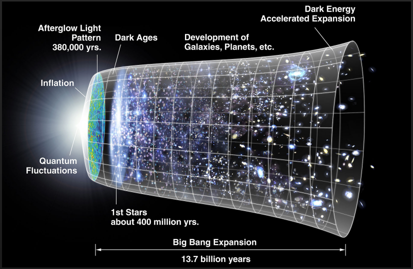


Image of the universe 300,000 years after the big bang (Tegmark, WMAP)

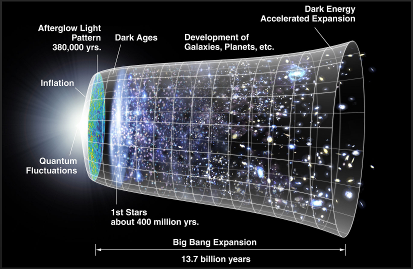
What is the history of the universe?

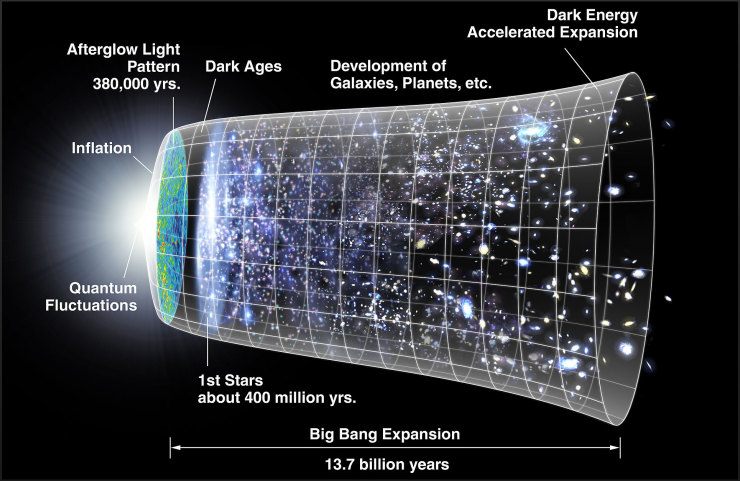
- The universe is expanding. Galaxies farther away from us moving away faster and their light is redshifted
- That is our view, but you would see the same thing from any other galaxy in the universe
- We can get an estimate of distance from the velocity/redshift.
- Because we see these galaxies as they were far back in time, the history is tied to the question of where things are.



What is the history of the universe?

- We expected the expansion to decelerate.
- The measurements indicated it *did* decelerate for a long time, but then began to accelerate!
- This mystery is called Dark Energy





Model of the expansion history (WMAP)

Optical Astronomy and Galaxy Surveys

Optical Astronomy and Galaxy Surveys

- It all starts with taking pretty pictures
- Optical means visible light, but we also use near infrared and ultraviolet.
- We call it a survey when the observations cover a large contiguous part of the sky, nearly uniformly.
- When the goal is mainly to study galaxies, we call it a galaxy survey. We don't look toward the milky way because it is mostly opaque and blocks our view of distant galaxies.

NASA, S. Smartt, D. Richstone

Optical Astronomy

- We use telescopes with cameras mounted on them.
- The primary detectors in astronomical cameras are CCDs, similar to the device in your phone.
- The raw data is an array of pixel values

Dark Energy Survey, color image Erin Sheldon

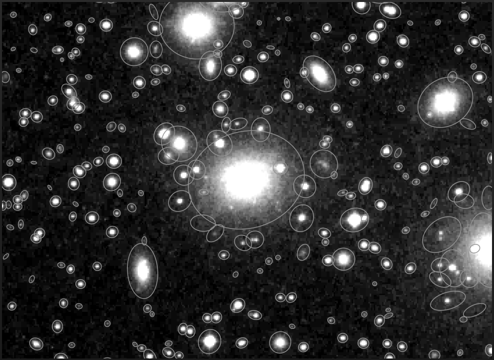
Optical Astronomy

- The color comes from combining images taken though red, green, and blue filters

Dark Energy Survey, color image Erin Sheldon

Optical Astronomy

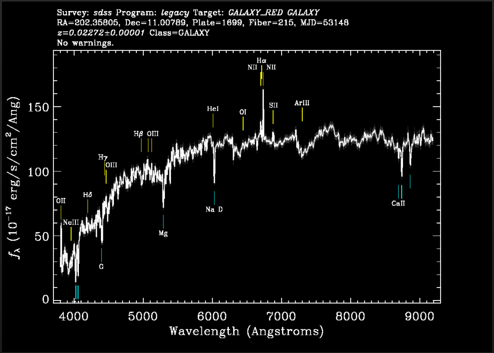
- We use software to identify objects in the images
- We then measure properties of each object, for example
  - Location
  - Brightness
  - Size
  - Ellipticity



Source Extractor (Bertin)

Optical Astronomy

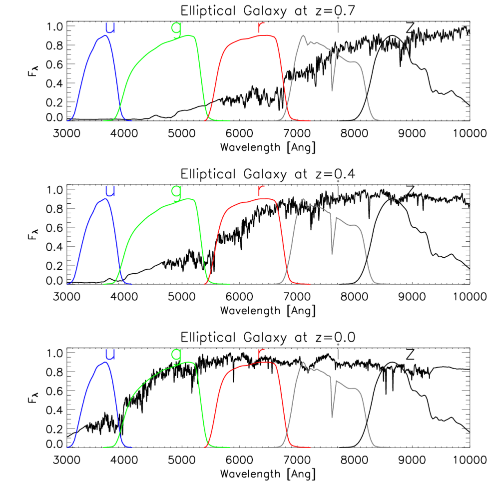
- Once we find objects, we can do additional observations
- One of the most interesting is to get a spectrum, also usually in the optical/near infrared
- Can learn about the chemical composition of the object
- For galaxies, can also get the redshift and thus a measure of *distance*



Galaxy spectrum (SDSS)

Optical Astronomy

- It is too time consuming to measure a full spectrunm for every object
- We instead estimate redshifts statistically based on measurements through different colored filters
- This is a *statistical* measure of distance



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Galaxy photometric redshift (Padmanabhan)

Optical Astronomy

- Thus we have a some basic measurements from optical data. For each object we can measure (among other things)
  1. Location on the sky
  2. Brightness
  3. Color
  4. Size
  5. Ellipticity
  6. Distance (velocity/redshift)

Cosmology with Galaxy Surveys

Cosmology with Galaxy Surveys

- How can we learn about cosmology from these measurements?
- First let's discuss what the theory can predict.

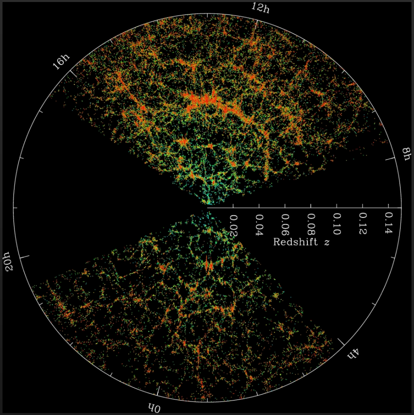
What Theory Predicts

- The theory is gravity (general relativity) with dark matter, dark energy, and normal matter.
- The theory can predict (among other things):
  - How the universe expands over time.
  - How the light from distant galaxies is redshifted
  - How the matter within the universe reacts to gravity, known as “clustering”.

What Theory Predicts

- How the universe is expanding
  - For two given galaxies, the distance between changes over time $|\Delta\vec{r}(t)| = |\vec{r}_1 - \vec{r}_2|(t)$
  - The relative velocity between galaxies is larger for more separated galaxies
- How the light from distant galaxies is redshifted $z(|\Delta\vec{r}|)$
- How the matter within the universe reacts to gravity over time. Gravity pulls matter together, and the density field in the universe evolves $\rho(\vec{r}, t)$

Gravity Pulls Everything Together: Clustering



Show Movie Mellenium Simulation
Show Movie Feng Yu

What Theory Predicts

- Expansion history: $|\Delta\vec{r}(t)|$
- Redshift: $z(|\Delta\vec{r}|)$
- Density evolution: $\rho(\vec{r}, t)$
- Recall from Paul's lecture: Ω_m and Ω_Λ were basic parameters in the Freedman Equations describing the expansion of the universe.
- Using these measurements we can learn about the mean mass density in the universe Ω_m
- We can learn about the properties of dark energy, for example the density Ω_Λ

Distance, Redshift and Density

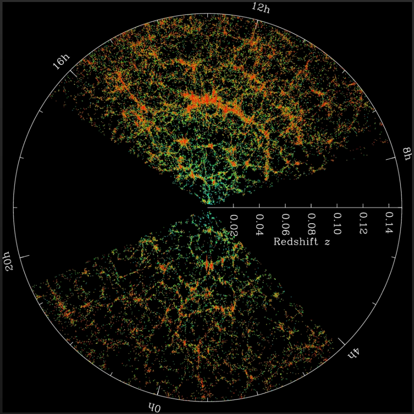
- The theory doesn't predict our particular universe
- The theory predicts *statistics* about these quantities
- Given the mean and variance of the mass density field, and the density of dark energy, it can predict
  - $\langle|\Delta\vec{r}(t)|\rangle$: Averaged over a large number of objects
  - $\langle z(|\Delta\vec{r}|)\rangle$
  - $\langle\rho(\vec{r_1})\rho(\vec{r_2})\rangle$: Correlation function

Cosmology with Distance, Redshift and Density

- I'll give two examples of how we do this in practice

Cosmology with Galaxy Surveys: Correlation Functions

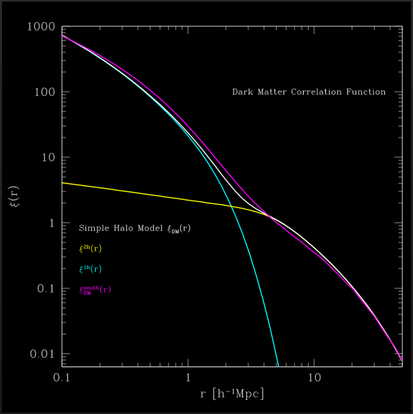
- The theory predicts the correlation function of dark matter $\langle \rho(\vec{r_1})\rho(\vec{r_2}) \rangle$
- For example, if a point in the universe has high density, a nearby point probably also has high density. Similarly for low density points.
- So there should generally be a positive correlation but it will decrease for points with larger separation.
- The amplitude increases over time because gravity pulls matter together, making it more spatially correlated



SDSS Galaxy Locations (M. Blanton)

Dark Matter Correlation Function

- The theory predicts the correlation function of dark matter $\langle \rho(\vec{r_1})\rho(\vec{r_2}) \rangle$
- Depends on the mean density and variance of the matter in the universe
- Evolution also depends on the dark energy
- Galaxies are only located at the highest density points, not ideal. But we can measure this better using gravitational lensing



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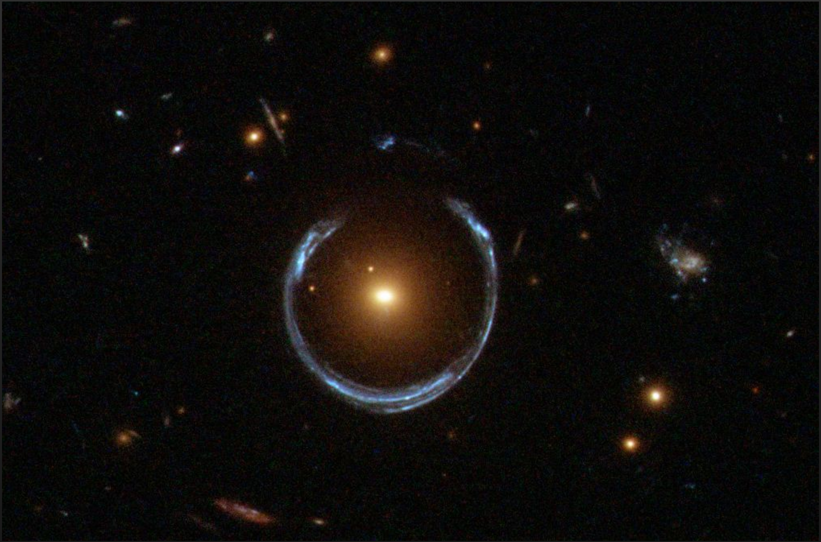
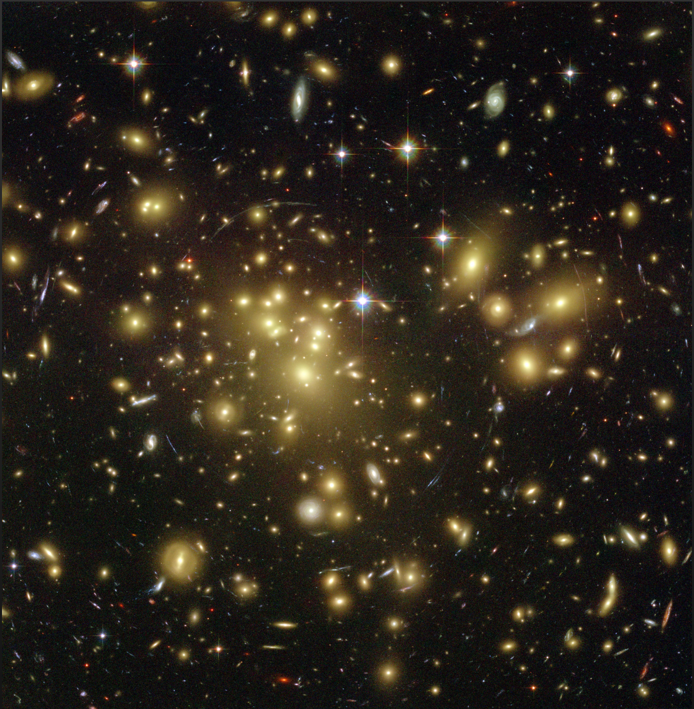
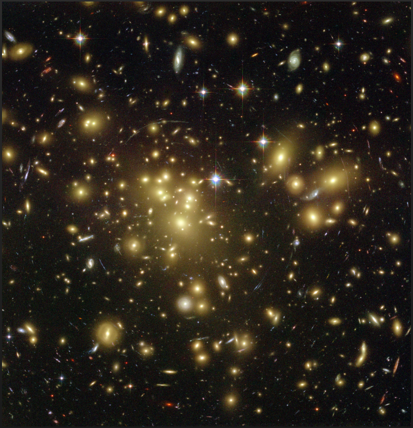


HST/NASA



Dark Matter Correlation Function

- The lensing from foreground masses causes correlations in the ellipticities of background galaxies
- Recall, the theory predicts the correlation function of dark matter $\langle \rho(\vec{r_1})\rho(\vec{r_2}) \rangle$
- We can measure the correlation function in the ellipticity $\langle e(\vec{\theta_1})e(\vec{\theta_2}) \rangle$
- The two correlation functions are directly related

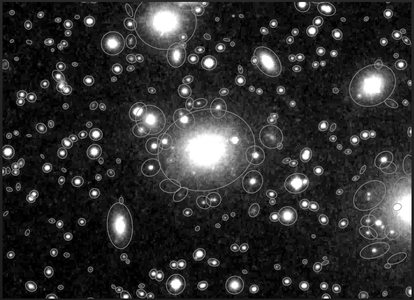


HST/NASA

Measuring Shear Correlation Function

1. Find Objects
2. Measure ellipticities
3. Correct for blurring by atmosphere and telescope
4. Measure the correlation function $\langle e(\vec{\theta_1})e(\vec{\theta_2})\rangle$
5. Statistically infer redshifts from images through different color filters

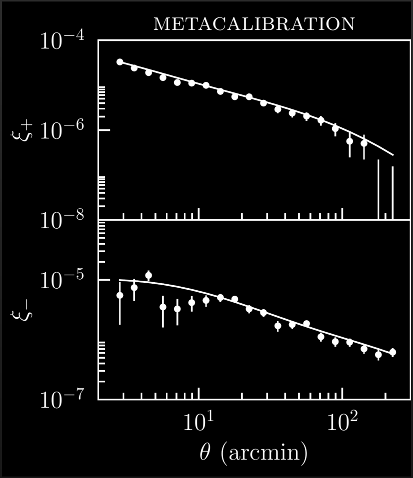
After 30 years we now have an algorithm to calibrate this measurement accurately (Sheldon & Huff 2017)



Source Extractor (Bertin)

Weak Lensing Shear Correlation Function

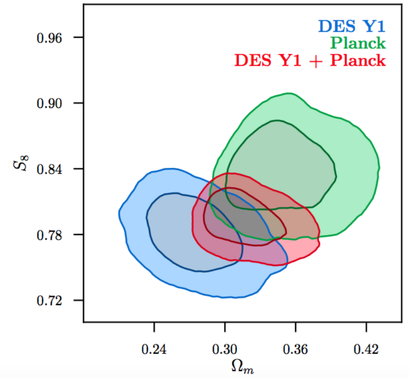
- Best measurement to date is from the Dark Energy Survey
- These results are from the first year of five.
- LSST, starting in a few years, will be even better.



Dark Energy Survey

Weak Lensing Shear And Cosmology

- DES constrains Ω_m, Ω_Λ and the mass variance very well.
- Agrees with the cosmic microwave background.
- Combining the two is even better.
- Soon we can start asking more interesting questions: Does the dark energy evolve or is it Einstein's cosmological constant? (see Paul's talk).



Dark Energy Survey

Cosmology with Galaxy Surveys: Distances and Redshift

- In terms of the expansion, it is the combination of $|\Delta\vec{r}(t)|$ and $z(|\Delta\vec{r}|)$ that is powerful
- Let's call this combination $D(z)$, the relationship between the distance and redshift.
- Typically one of the points is fixed on us, and the other is some distant galaxy. So $D(z)$ means the distance to some galaxy with known redshift z.
- We can measure z directly on a spectrum. The key is getting the distance.
- A good method is the standard candle.

Standard Candles

- If you know the intrinsic luminosity of an object, then you can calculate the distance from the *apparent brightness*
- $\ell = \frac{L}{4\pi d^2}$
- Type 1A supernovae are such objects.

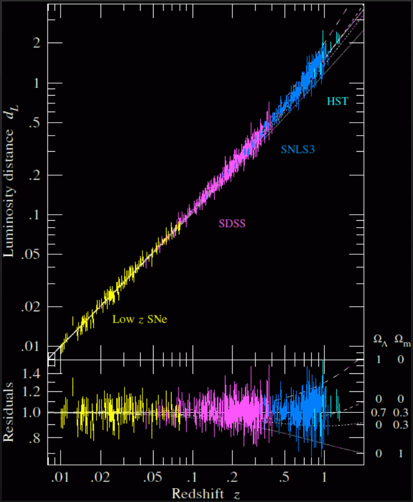
Type 1A Supernovae

- We can measure $D(Z)$ using galaxy surveys
  1. Take images of the sky, identify objects, measure their brightness
  2. Take more images, on a regular schedule
  3. Watch for a star to go Supernova in a distant galaxy: they get a lot brighter
  4. Get a spectrum and determine the redshift.
  5. Infer the distance
  6. Average over lots of these to get $\langle D(z) \rangle$

High-Z Supernova Search Team/HST

Type 1A Supernovae

- This is how Dark Energy was discovered
- No predictions without dark energy are consistent with the measurements
- Confirmed by other methods (BAO)



Summary

- With galaxy surveys we have made great discoveries such as the expansion of the universe, dark matter and dark energy.
- We can test our theory of the universe and measure the detailed properties of dark matter and dark energy.
- It all starts with pictures
- Expect exciting results in the near future!

DES/Erin Sheldon