Using Gravitational Lensing to measure Dark Matter and Dark Energy in the Universe

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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
- Introductioin to Gravitational Lensing
- How we learn about cosmology using lensing
- Some examples

Cosmology

Introduction to Cosmology

- I'm building off of Paul's lecture on cosmology.
- I'll focus on the main topics pertaining to lensing
- 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?

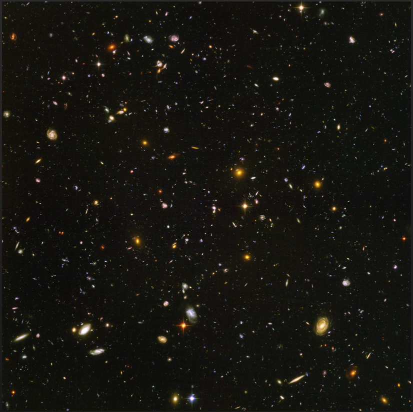
What Makes Up the Universe?

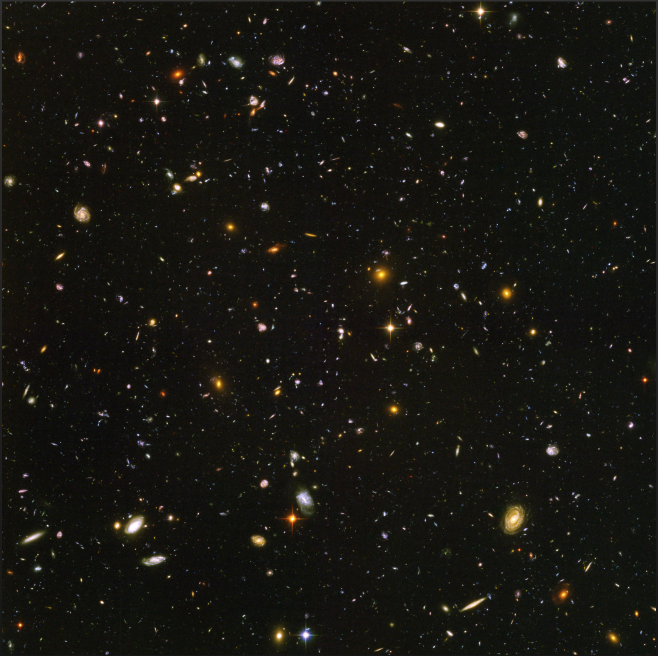
- Particles – people – planets – stars – galaxies
- What is the composition of distant objects?
- What is the mass density of the universe?
- What fraction of the mass in the universe is dark matter?

DES/Erin Sheldon

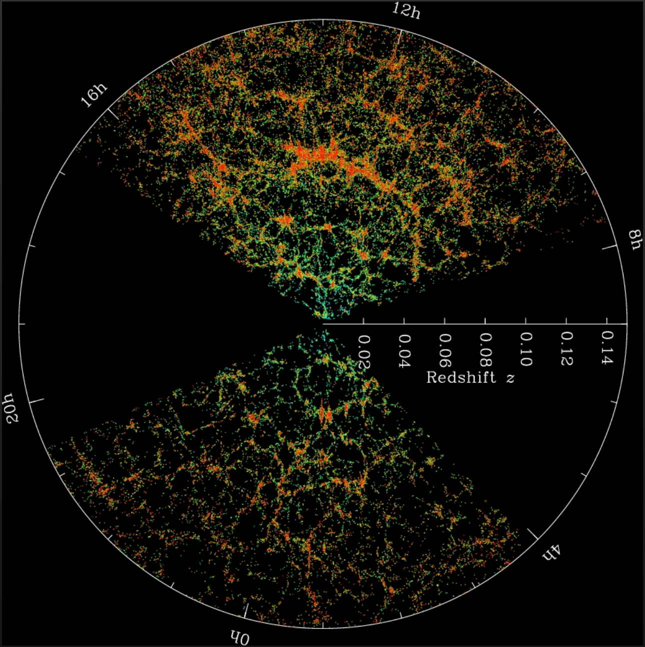
How is matter distributed?

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





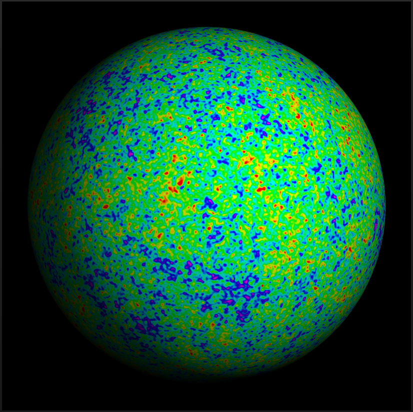
Hubble UDF



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 (CMB) is the relic light from a few hundred thousand years after the big bang
- All the structure we see today must have grown from the kind of fluctuations seen in this map, under the influence of gravity.
- Can we predict what we see today from CMB observations?



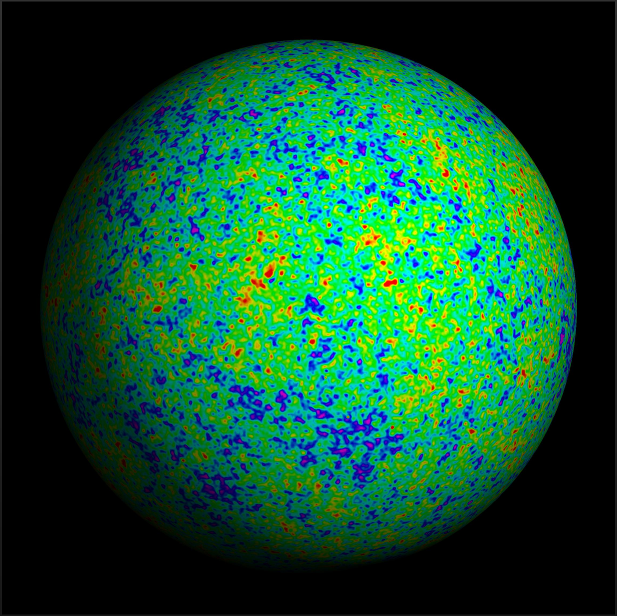
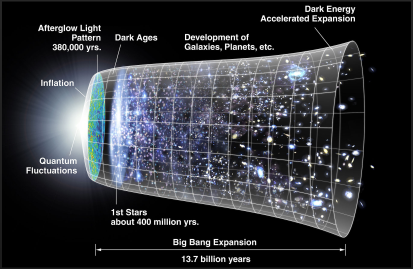


Image of the universe 300,000 years after the big bang
(Tegmark, WMAP)

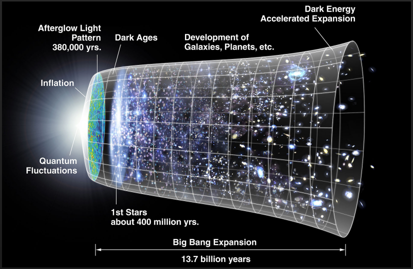
What is the history of the universe?

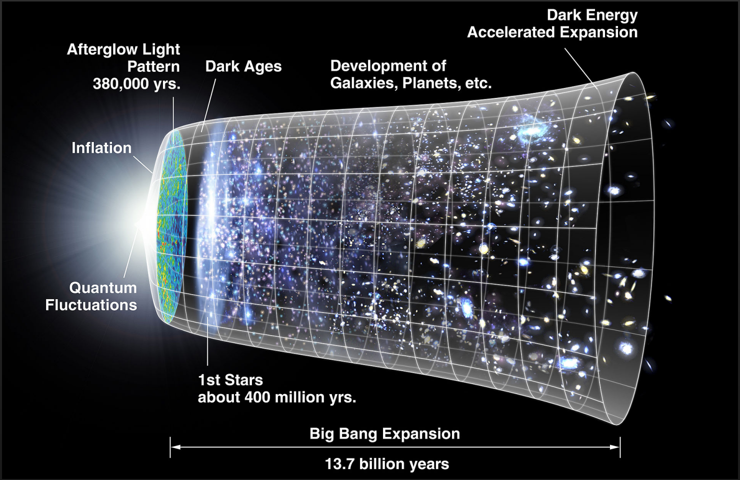
- The universe is expanding. Galaxies farther away from us moving away faster and their light is redshifted
- That is our view, but you would see the same thing from any other galaxy in the universe
- We can get an estimate of distance from the velocity/redshift.
- Because we see these galaxies as they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

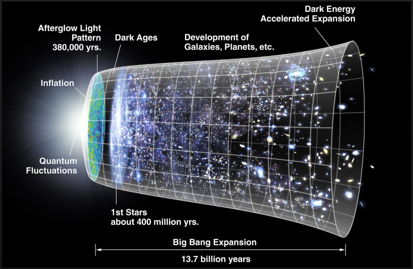




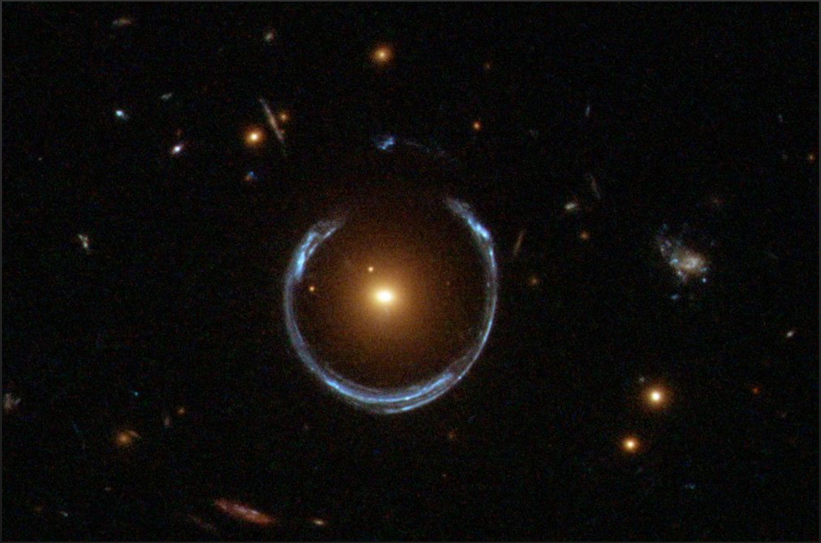
Model of the expansion history (WMAP)

The Big Mysteries We Want to Study

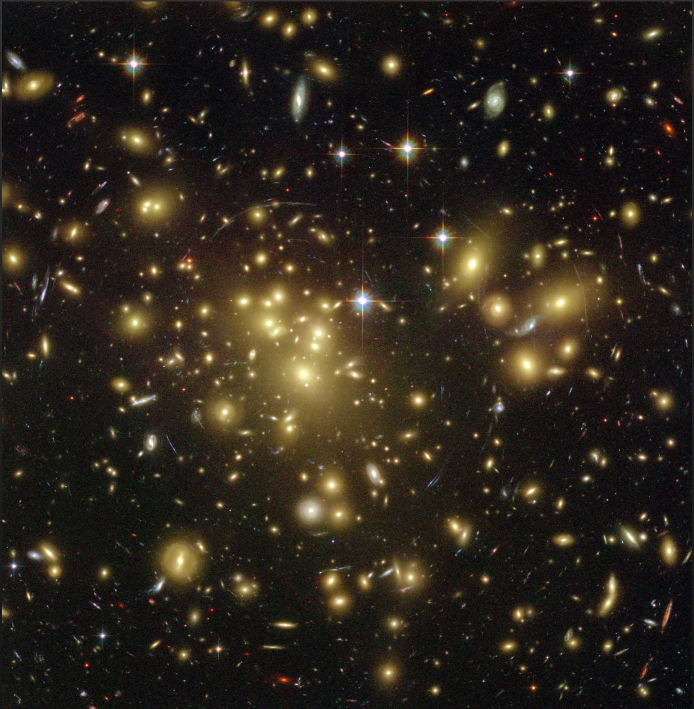
- What is the Dark Matter? Where is it and how much is there?
- What is the Dark Energy? What are its propeties and how much is there?



Gravitational Lensing

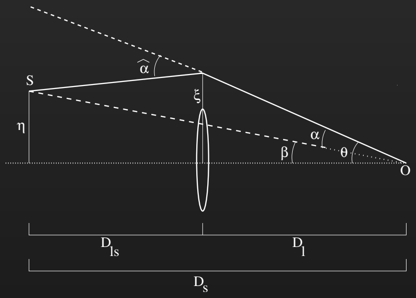


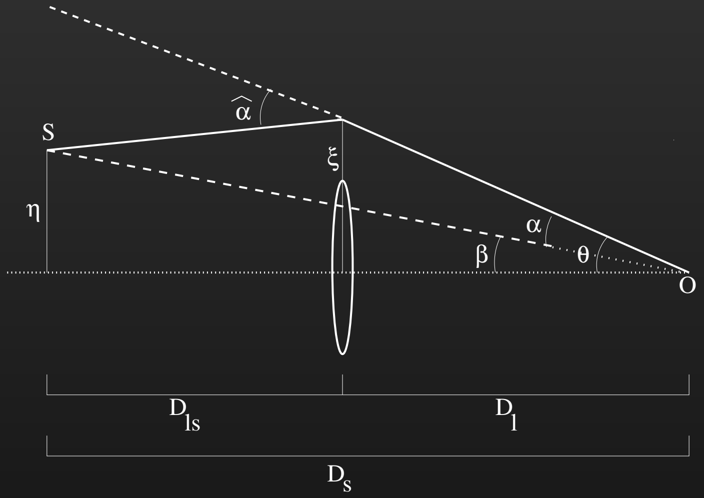
HST/NASA



Gravitational Lensing

- Gravitational lensing is the apparent bending of light rays as they pass massive objects

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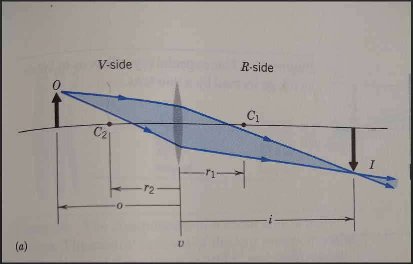
Gravitational Lensing Compared To Ordinary Lensing

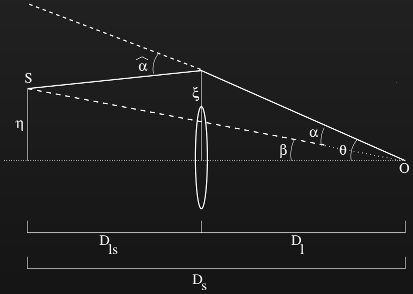
- Similar in that the magnification depends on the curvature of the lens and the distances.

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

$$m = \frac{i}{o}$$

Halliday and Resnick

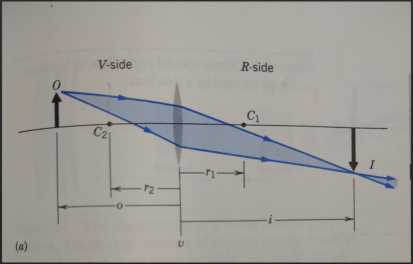


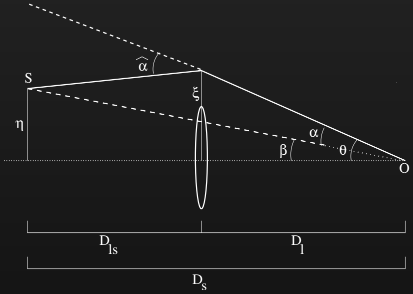


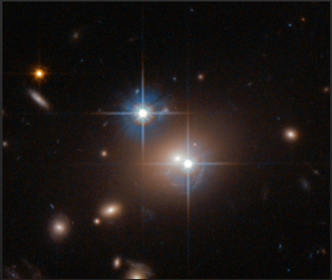
Gravitational Lensing Compared To Ordinary Lensing

- Difference: The effect is strongest for paths that go through the center of the lens (near the object)
- Difference: The image is not inverted
- Difference: Gravity is a long range force, so the effect is present even for paths far from the lens.
- Difference: When the rays pass near the center, you can see multiple images and rings even for simple lenses.

Halliday and Resnick



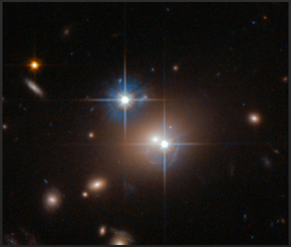


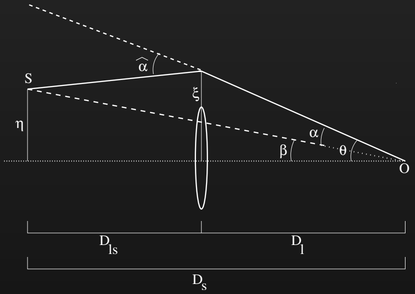


First Known Gravitational Lens: Two images of the same object (QSO 0957+0561, image HST/NASA)

Using Gravitational Lensing

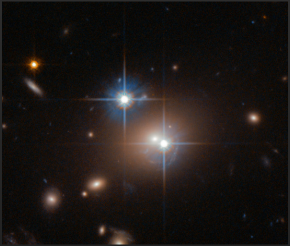
- The effect depends on the mass of the lens: we can measure the mass of the lensing object!
- Lensing is especially useful for measuring dark matter. The lensing effect is present even if we can't see the mass.

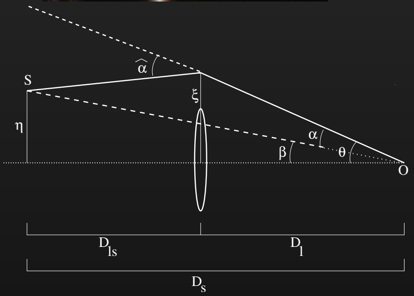




Using Gravitational Lensing

- The effect depends on distances from observer to lens and between lens and source.
- We can use lensing to infer distances.
- Farther distance means farther back in time, so we can probe the expansion history of the universe and measure the effects of Dark Energy
- In practice we really measure distance *ratios*, but that's useful as well.





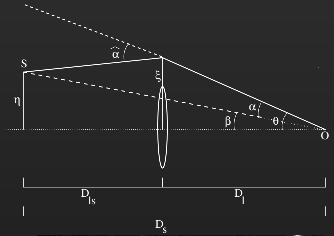
Practical Lensing Measurements

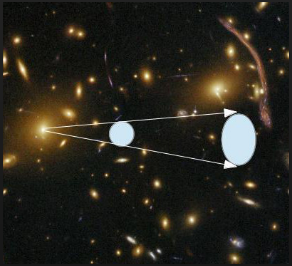
- These examples I've shown are extremely rare. Not that useful in general.
- But all objects in the universe are lensed by something. The effect is just small.
- We can use this pervasive "weak lensing" effect to measure the distribution of mass throughout the universe.

Dark Energy Survey, color image Erin Sheldon

Weak Lensing

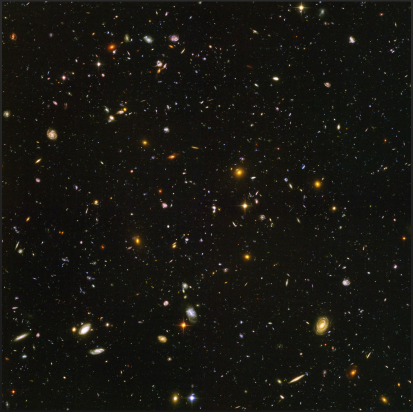
- A ray of light always looks like it came from a larger angle offset from the lens.
- But we don't know the original location, so that displacement isn't generally useful.
- However, rays are generally displaced radially, so the images of background galaxies get stretched a bit.
- This stretching we can measure, because it is coherent: all the galaxies get stretched tangentially around the lens, making a pattern.





Weak Lensing

- We can measure the stretching pattern of galaxies.
- But the effect is *super* weak. And galaxies are not round anyway, which is like extra noise on the measurement.
- We need to measure the ellipticities of millions of galaxies and look for *correlations* in their ellipticities.



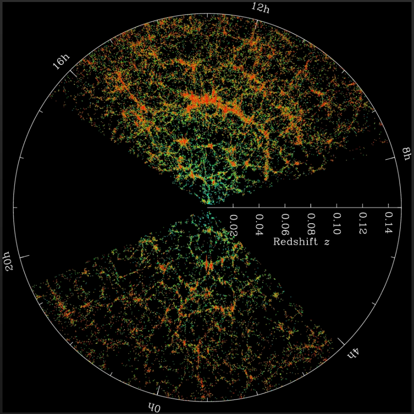
What Theory Predicts

- 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

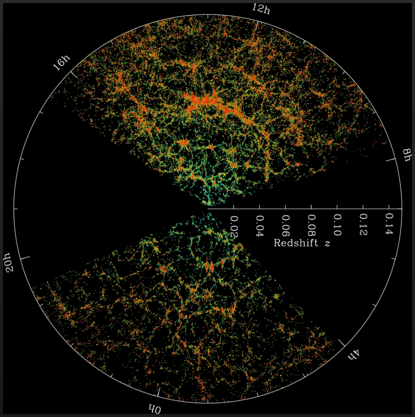
- The theory doesn't predict our particular universe
- The theory predicts *statistics* about these quantities
- Given the mean and variance of the mass density field, and the density of dark energy, it can predict
  - $\langle|\Delta\vec{r}(t)|\rangle$: Averaged over a large number of objects
  - $\langle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

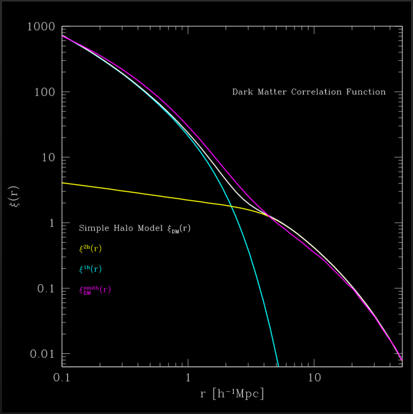
- The theory predicts the correlation function of dark matter $\langle \rho(\vec{r_1})\rho(\vec{r_2}) \rangle$
- For example, if a point in the universe has high density, a nearby point probably also has high density. Similarly for low density points.
- So there should generally be a positive correlation 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

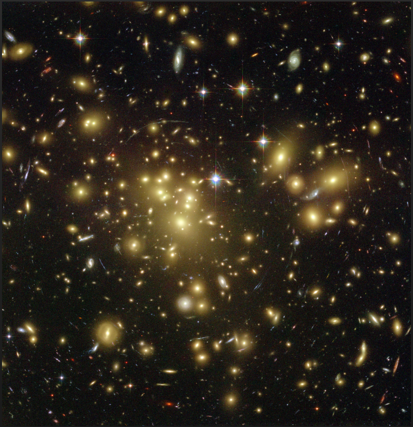
- The theory predicts the correlation function of dark matter $\langle \rho(\vec{r_1})\rho(\vec{r_2})\rangle$
- Depends on the mean density and variance of the matter in the universe
- Evolution also depends on the dark energy
- Galaxies are only located at the highest density points, not ideal. But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



A. Zentner

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

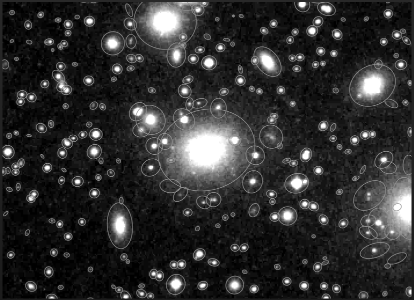


HST/NASA

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

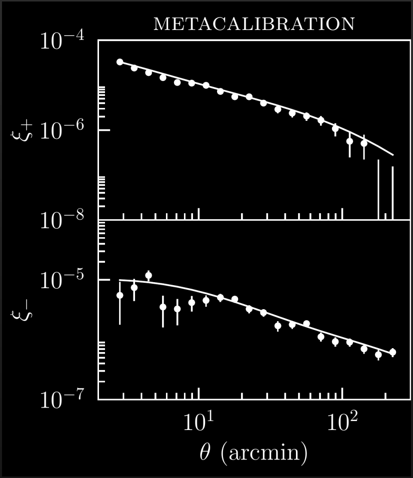
After 30 years we now have an algorithm to calibrate this measurement accurately (Sheldon & Huff 2017)



Source Extractor (Bertin)

Weak Lensing Shear Correlation Function

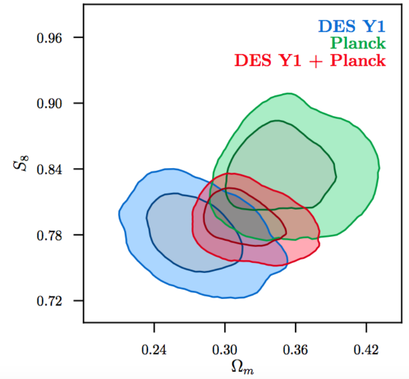
- Best measurement to date is from the Dark Energy Survey
- These results are from the first year of five.
- LSST, starting in a few years, will be even better.



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.

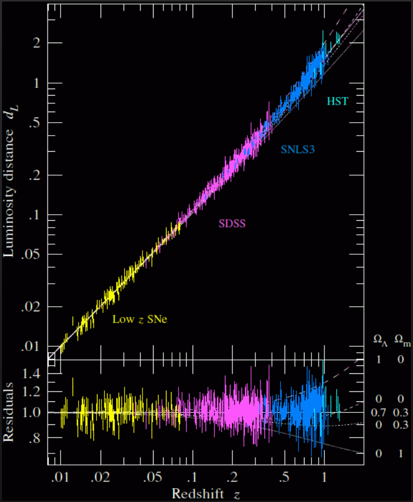
Type 1A Supernovae

- 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