



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
- ▶ Introduction 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



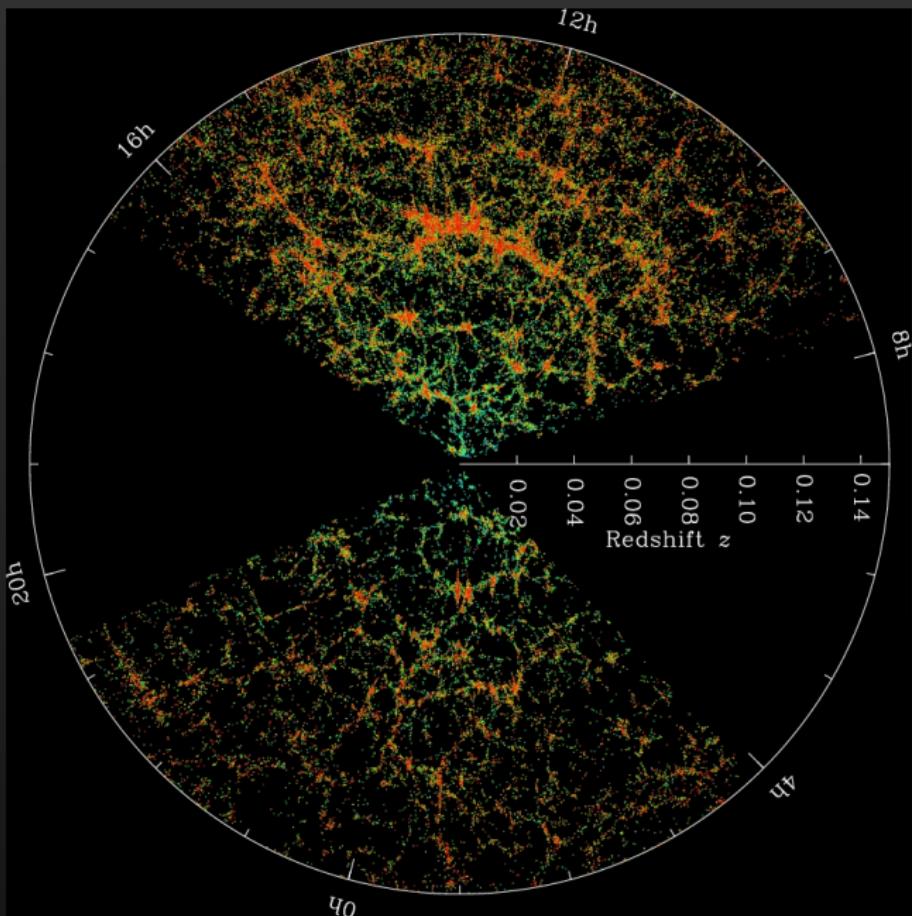
How is matter distributed?

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





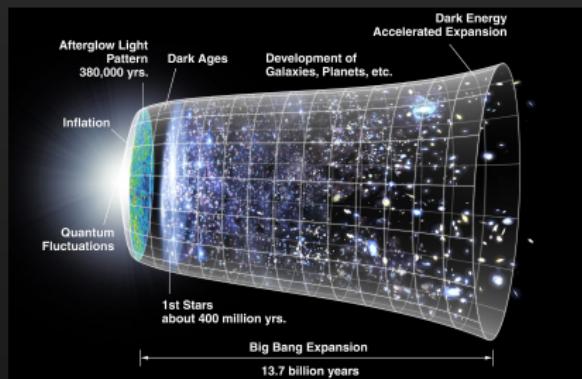
Hubble UDF



SDSS Galaxy Locations (M. Blanton)

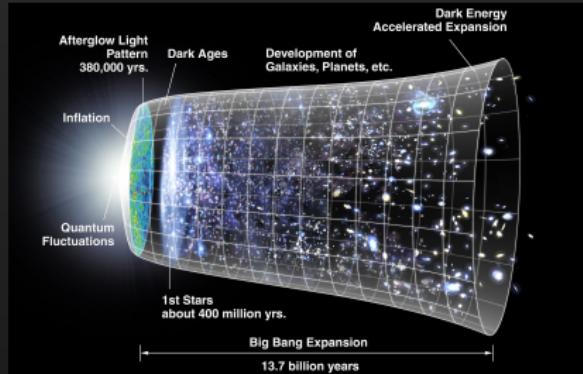
What is the history of the universe?

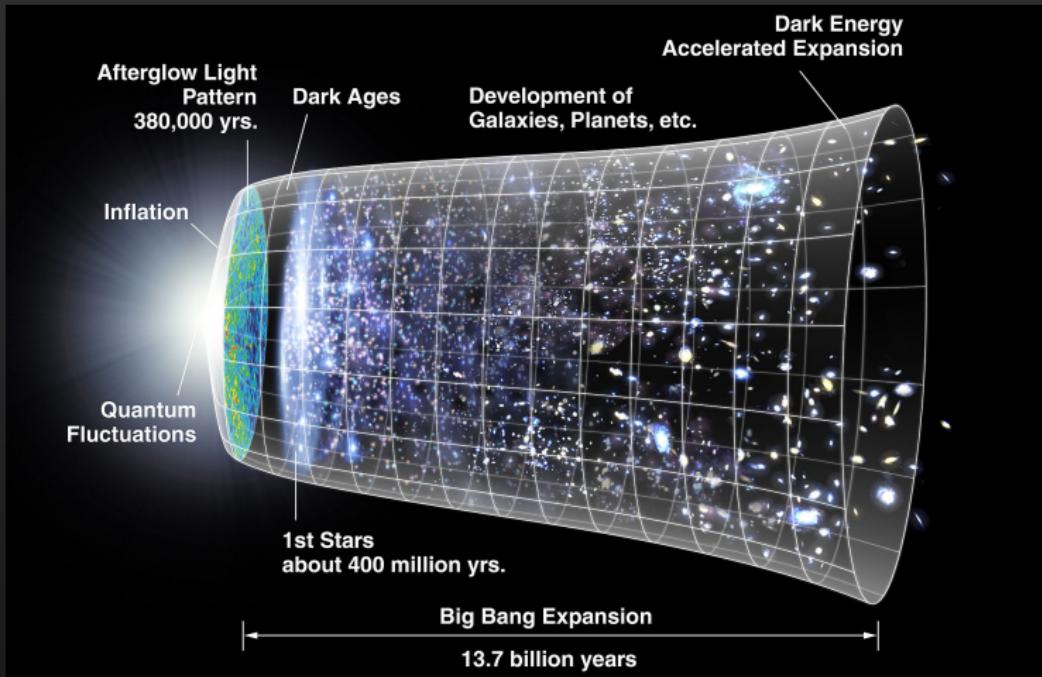
- ▶ The universe is expanding.
Galaxies farther away from us
moving away faster and their
light is redshifted
- ▶ That is our view, but you
would see the same thing
from any other galaxy in the
universe
- ▶ We can get an estimate of
distance from the
velocity/redshift.
- ▶ Because we see these galaxies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

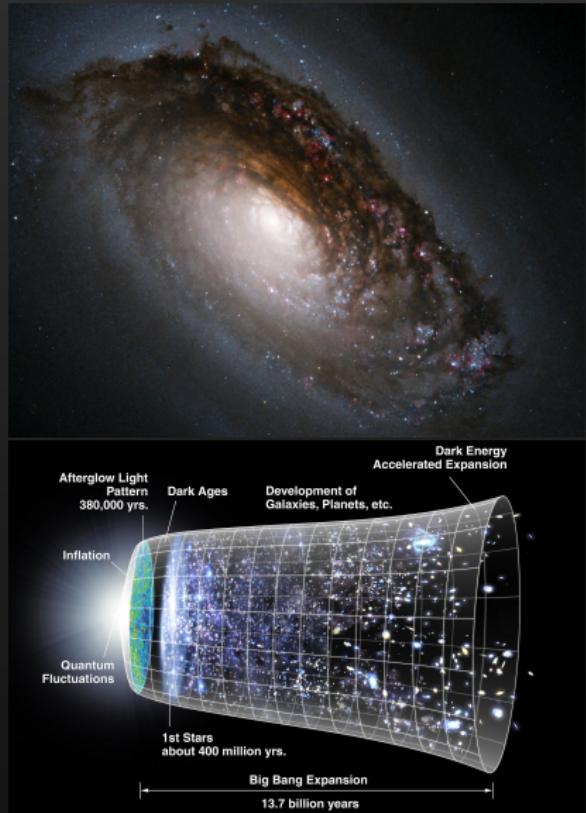




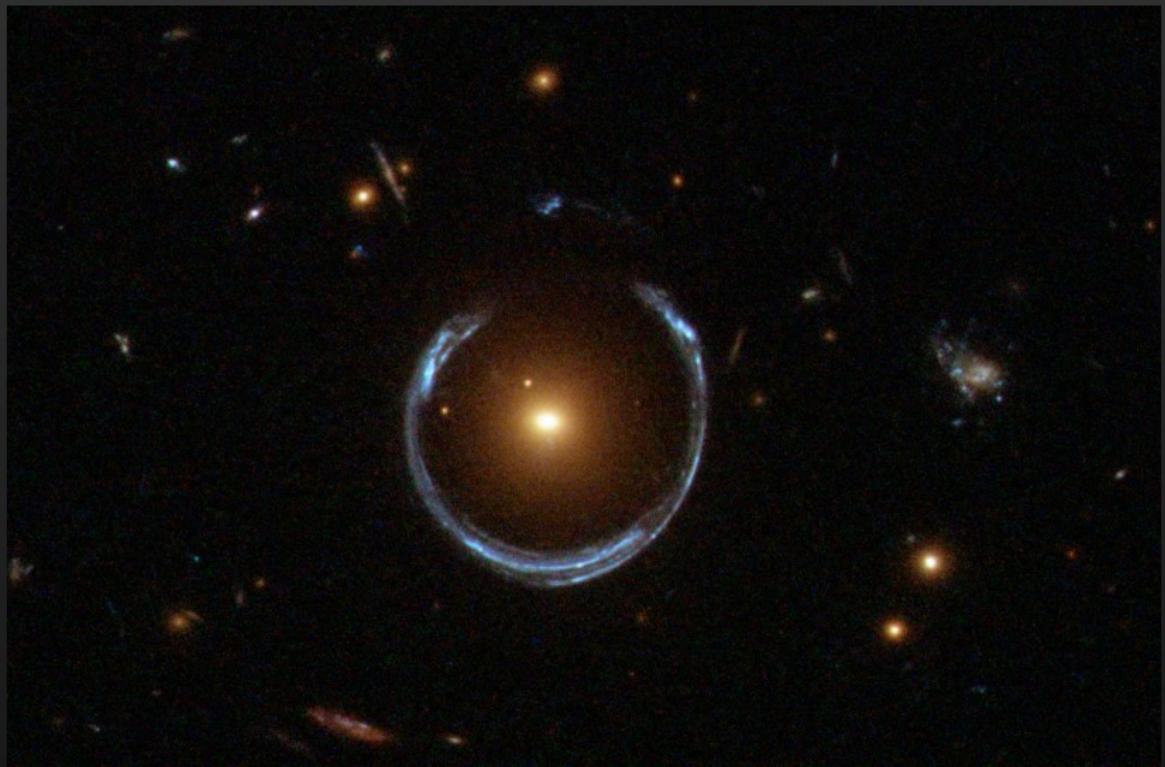
Model of the expansion history (WMAP)

The Big Mysteries We Want to Study

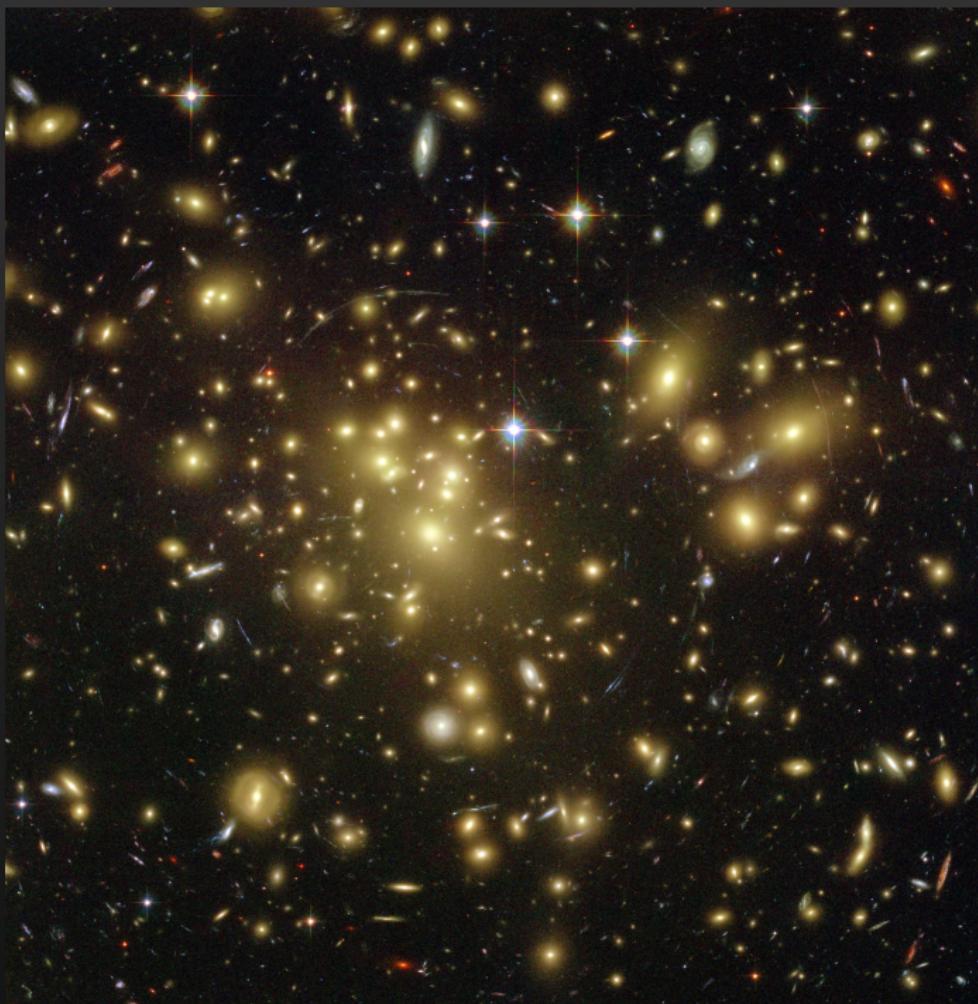
- ▶ What is the Dark Matter?
Where is it and how much is there?
- ▶ What is the Dark Energy?
What are its properties and how much is there?



Gravitational Lensing

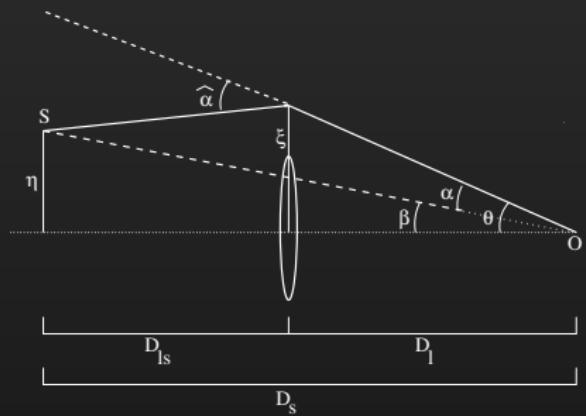


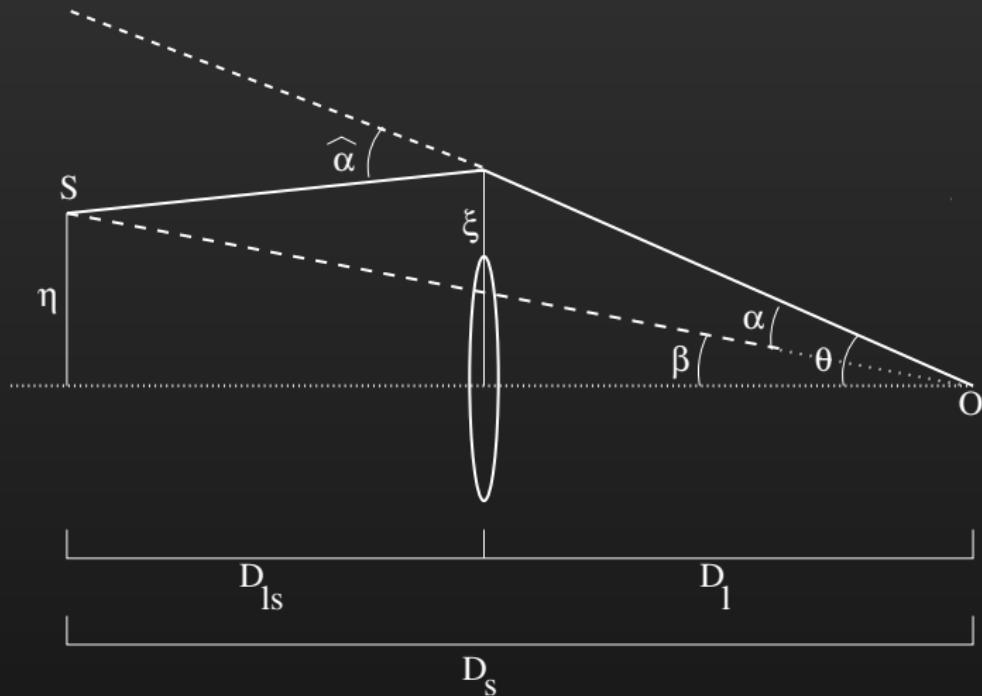
HST/NASA



Gravitational Lensing

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



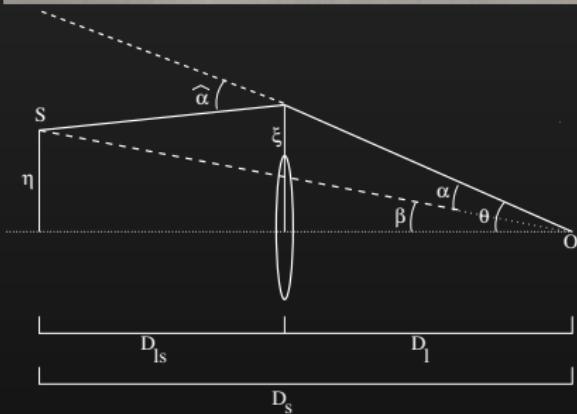
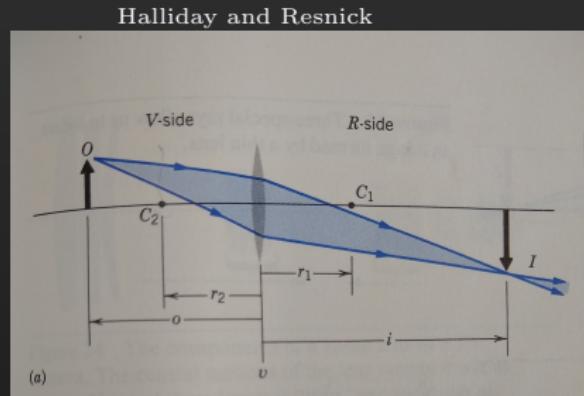


Gravitational Lensing Compared To Ordinary Lensing

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

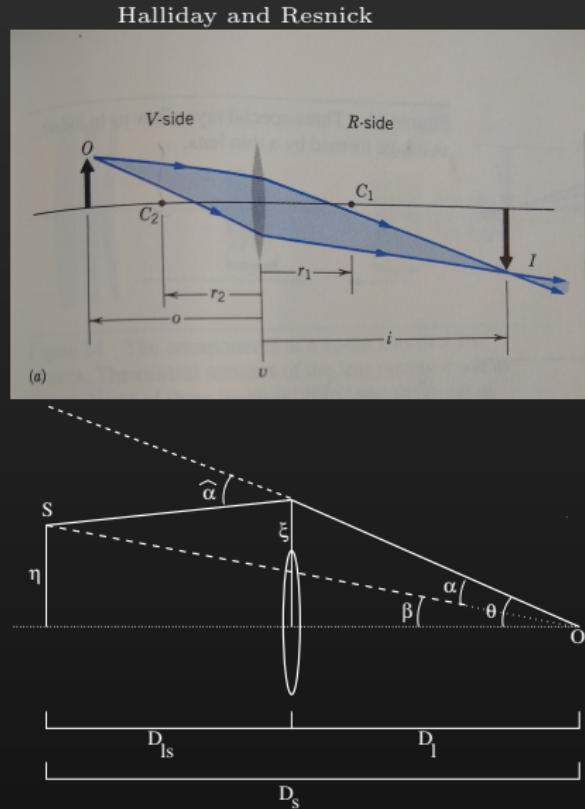
$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

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



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.

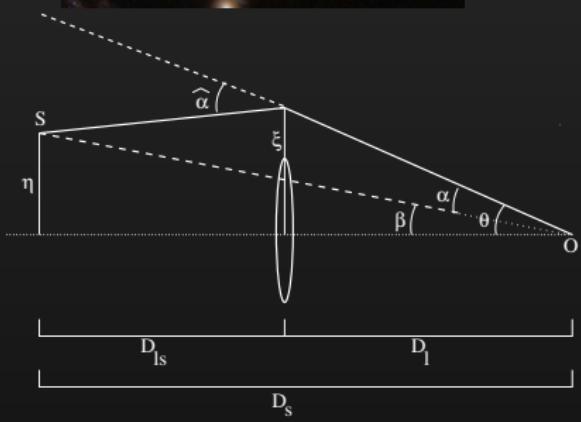




First Known Gravitational Lens: Two images of the same object (QSO 0957+0561, image HST/NASA)

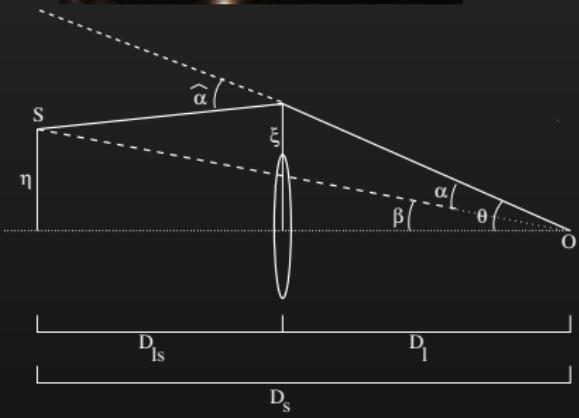
Using Gravitational Lensing

- ▶ 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.



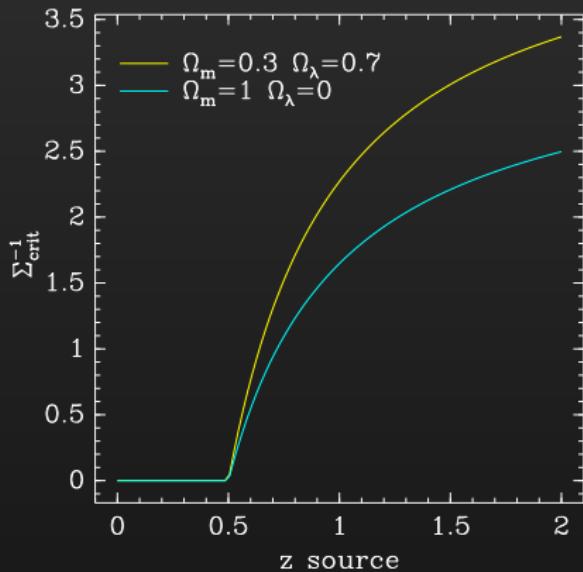
Using Gravitational Lensing

- ▶ 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



Using Gravitational Lensing

- ▶ In practice we really measure distance *ratios*, but that's useful as well.
- ▶ This shows how strong the lensing effect is for sources at different distances behind the lens



Practical Lensing Measurements

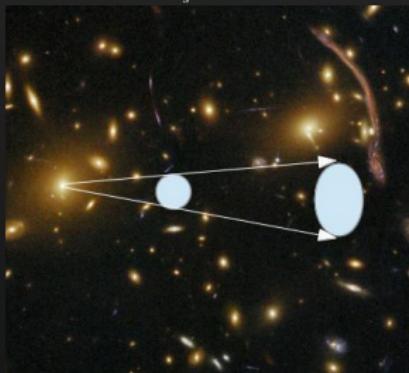
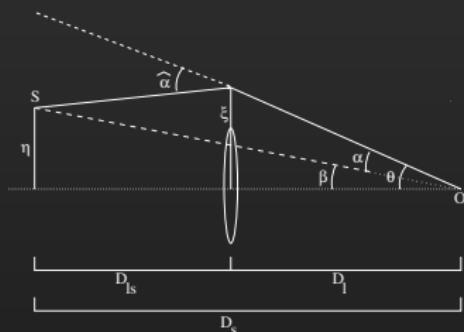
- ▶ These examples I've shown are extremely rare. Not that useful in general.
- ▶ But all objects in the universe are lensed by something. The effect is just small.
- ▶ We can use this pervasive “weak lensing” effect to measure the distribution of mass throughout the universe.



Dark Energy Survey, color image E. 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.



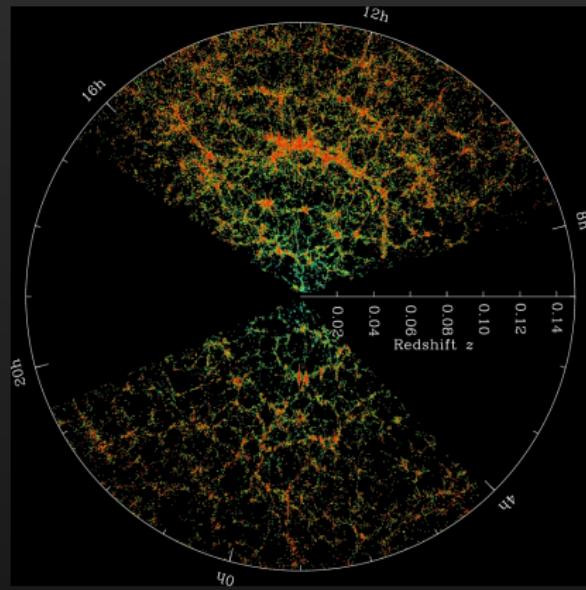
What Theory Predicts

- ▶ 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 Millennium Simulation

What Theory Predicts

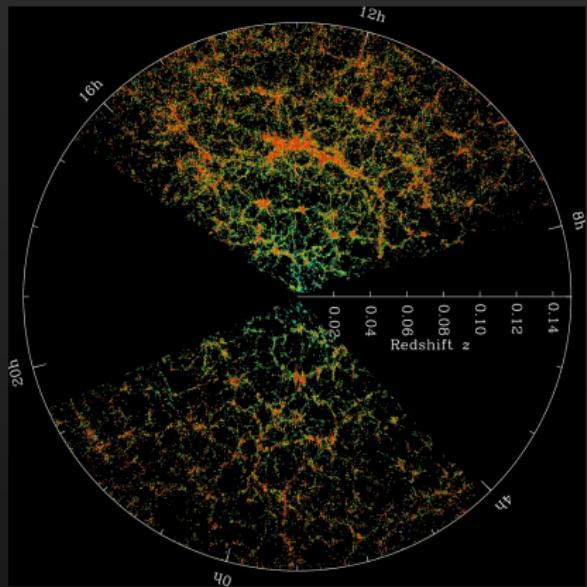
- ▶ Expansion history: $|\Delta\vec{r}(t)|$
- ▶ Redshift: $z(|\Delta\vec{r}|)$
- ▶ Density evolution: $\rho(\vec{r}, t)$
- ▶ Recall from Paul's lecture: Ω_m and Ω_Λ were basic parameters in the Freedman Equations describing the expansion of the universe.
- ▶ Using these measurements we can learn about 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
 - ▶ $\langle z(|\Delta \vec{r}|) \rangle$
 - ▶ $\langle \rho(\vec{r}_1)\rho(\vec{r}_2) \rangle \propto \xi(|\vec{r}_1 - \vec{r}_2|)$: Correlation function

Cosmology with Galaxy Surveys: Correlation Functions

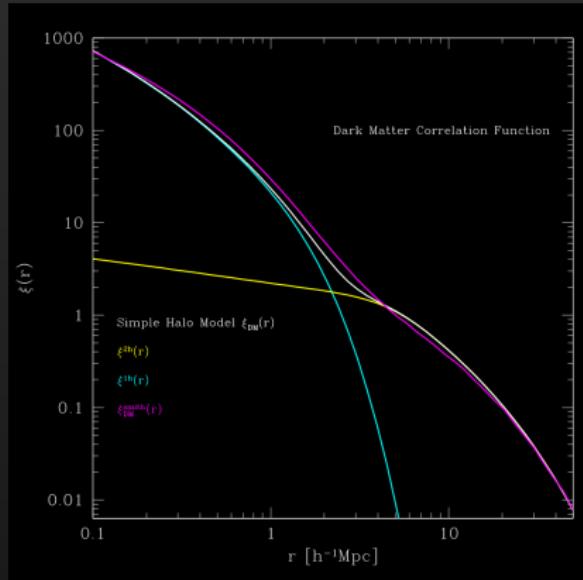
- ▶ The theory predicts the correlation function of dark matter
$$\langle \rho(\vec{r}_1)\rho(\vec{r}_2) \rangle \propto \xi(|\vec{r}_1 - \vec{r}_2|)$$
- ▶ For example, if a point in the universe has high density, a nearby point probably also has high density. Similarly for low density points.
- ▶ So 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

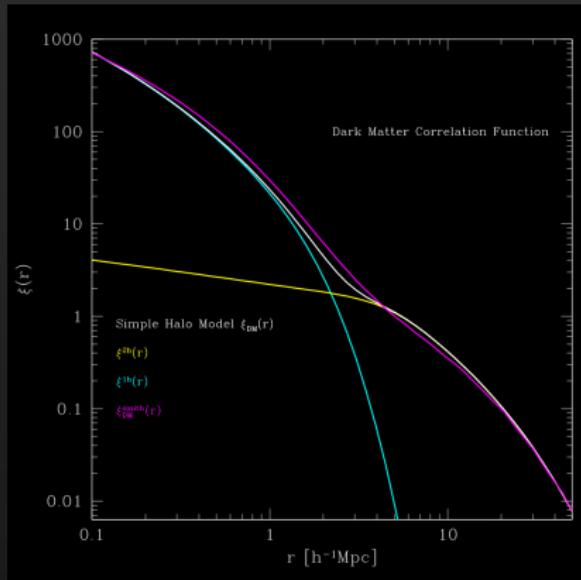
- The theory predicts the correlation function of dark matter
$$\langle \rho(\vec{r}_1)\rho(\vec{r}_2) \rangle \propto \xi(|\vec{r}_1 - \vec{r}_2|)$$
- Depends on the mean density and variance of the matter in the universe
- Evolution also depends on the dark energy
- Galaxies are only located at the highest density points, not ideal. But we can measure this better using gravitational lensing



A. Zentner

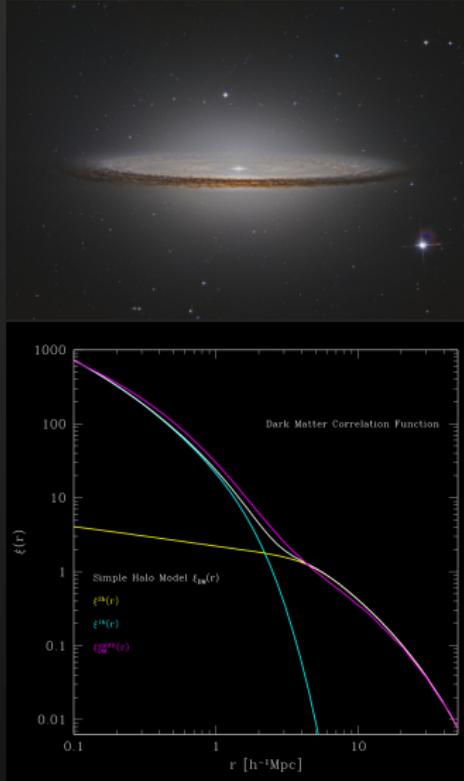
Dark Matter Correlation Function

- The lensing from foreground masses causes correlations in the ellipticities of background galaxies
- We can measure the correlation function in the ellipticity $\langle e(\vec{\theta}_1)e(\vec{\theta}_2) \rangle$
- Because the correlations in the ellipticities are caused by mass, this is closely related to the correlation function of the mass, which is what the theory predicts $\langle \rho(\vec{r}_1)\rho(\vec{r}_2) \rangle$



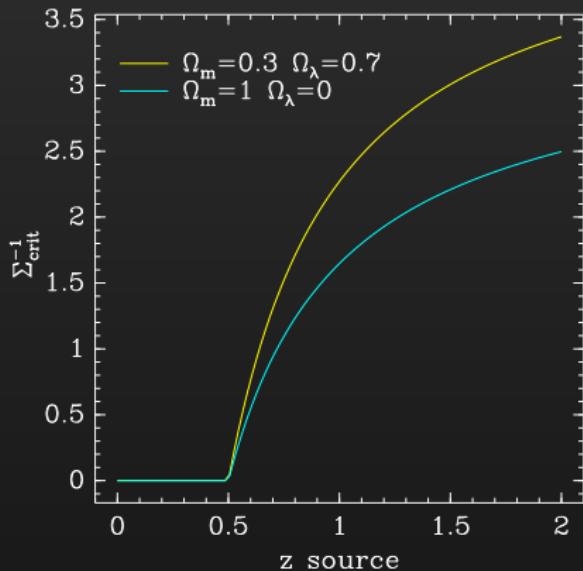
Dark Matter Correlation Function

- We can do a special measurement where we look specifically around foreground objects, rather than just correlating all shapes
- Then we measure the mean amount of mass in the lens, for example galaxies.
- Can we measure the dark matter in galaxies?



Using Gravitational Lensing

- ▶ Plus, with lensing we can re-measure the signal for objects at different *redshifts* learn about their *distances* from us.
- ▶ This is especially useful for studying Dark Energy



Dark Energy Survey

- ▶ We perform weak lensing measurements using data we take with the Blanco telescope in Chile
- ▶ We built a new camera specifically to do weak lensing and study Dark Energy



Blanco Telescope in Chile (D. Lang)

Dark Energy Survey

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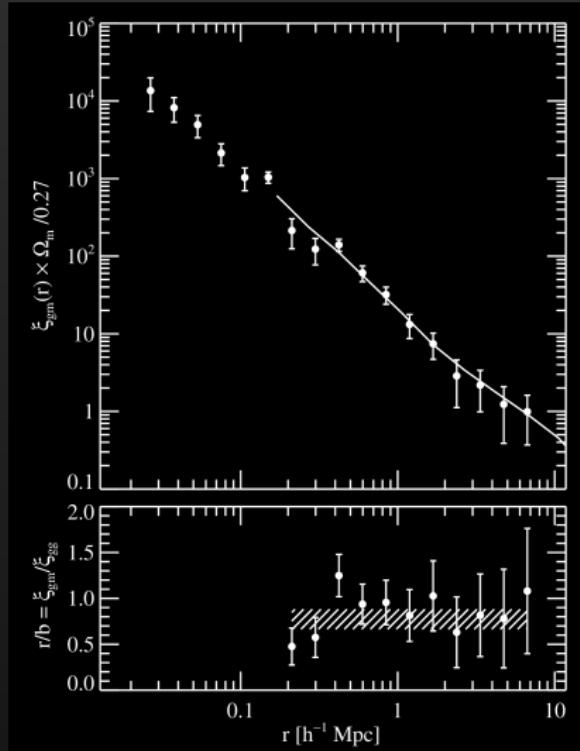
Blanco Telescope in Chile (B. Nord)



Dark Energy Survey (E. Sheldon)

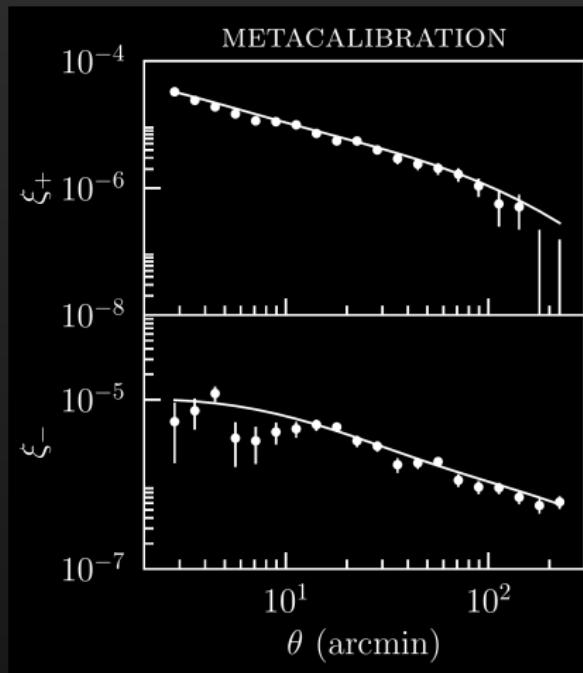
Dark Matter in Galaxies

- ▶ Measure the correlation of ellipticities with positions of galaxies
- ▶ If all the light were in stars only, the curve would be much steeper on small scales
- ▶ On large scales the signal is due to nearby objects, but the amplitude is way too high if the mass were only from stars
- ▶ In excellent agreement with prediction of cold dark matter theory



Weak Lensing Shear Correlation Function

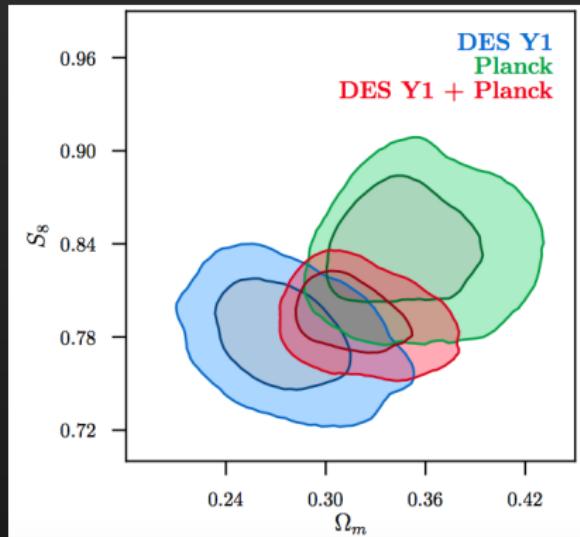
- ▶ Now just correlate the shapes, don't look around specific points $\langle e(\vec{\theta}_1) e(\vec{\theta}_2) \rangle$
- ▶ Recall this is related to the correlation function of the density field
 $\langle \rho(\vec{r}_1) \rho(\vec{r}_2) \rangle \propto \xi(|\vec{r}_1 - \vec{r}_2|)$



Dark Energy Survey

Weak Lensing Shear And Cosmology

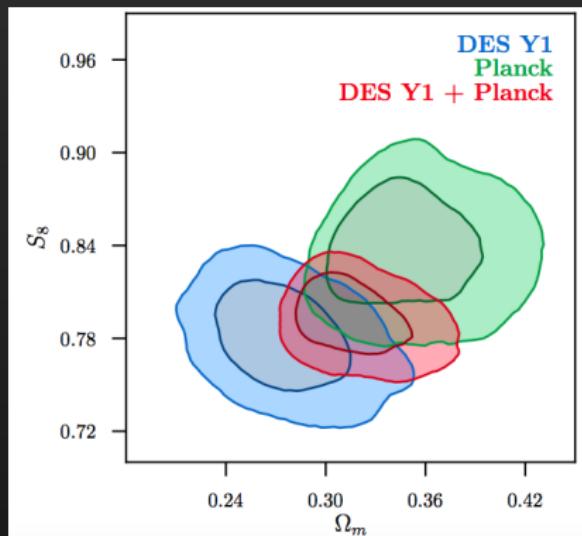
- ▶ DES constrains Ω_m , Ω_Λ and the mass variance very well.
- ▶ Agrees with the cosmic microwave background.
- ▶ Combining the two is even better.



Dark Energy Survey

Weak Lensing Shear And Cosmology

- ▶ At the end of this year we will have results from a lot more data.
- ▶ We will address some burning questions: Does the dark energy evolve or is it vacuum energy? (see Paul's talk).
- ▶ There are hints of discrepancy between measurements of the time right after the big bang and measurements now. Do we confirm these discrepancies?



Dark Energy Survey

Summary

- ▶ Lensing is a powerful tool to measure mass in the universe
- ▶ We can test our theory of the universe and measure the detailed properties of dark matter and dark energy.
- ▶ Expect exciting results in the near future!



DES/Erin Sheldon