Measuring Dark Matter and Dark Energy with Gravitational Lensing

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Outline

- Gravitational Lensing
- Dark Matter
  - What was known before lensing
  - Measurements using lensing
- Dark Energy
  - The little bit we know
  - Lensing and Dark Energy
  - Dark Energy Survey, *Preliminary* results
- LSST

Do not Bodies act upon light at a distance, and by their action bend its Rays; and is not this action (caeteris paribus) *strongest at the least distance?*

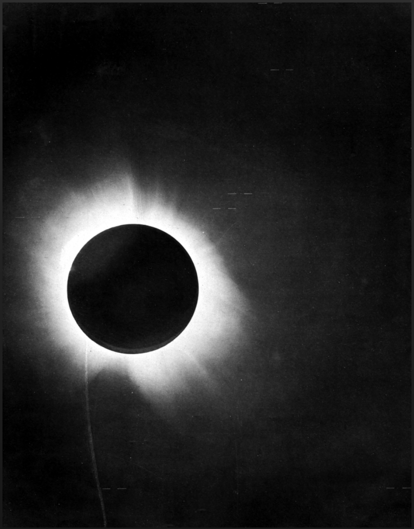
- Isaac Newton (Query I, Opticks, 1704)

Gravitational Lensing

- Newton's first Query, Opticks, 1704
  - One can naively "cancel" the zero masses and predict the effect
- Einstein 1911
  - Equivalence principle
  - Observers in free fall experience an inertial frame. The light appears to follow straight lines: the light falls with them.
- Einstein 1915
  - Full result from general relativity, factor of two larger

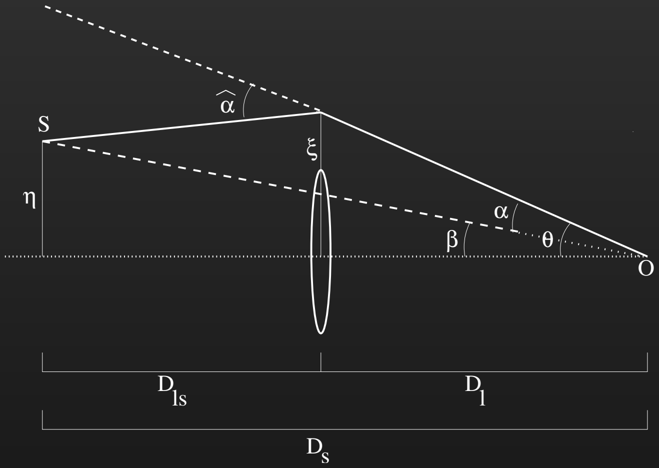
1919 Eclipse

- Einstein predicted the light from background stars would be deflected as it passes near the sun.
- Eddington and colleagues observed the 1919 eclipse looking for the effect.
- The locations of stars with known positions were measured, and found to have moved



Dyson, Eddington, Davidson 1919

Lensing Geometry



For a point mass lens, the deflection depends on impact prameter and mass as

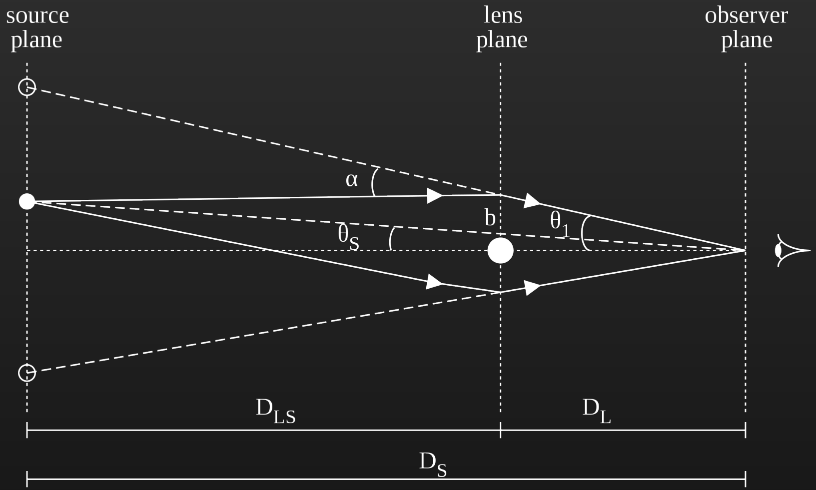
$$\alpha \propto \frac{M}{b}$$

Twin Quasar 0957+0561

- Two quasars discovered in 1979 (Walsh, Carswell, Weyman)
- Extremely close together, nearly identical spectrum and redshift
- Time variations in image A appear in image B also, but 14 months later.
- Two images of the same object!

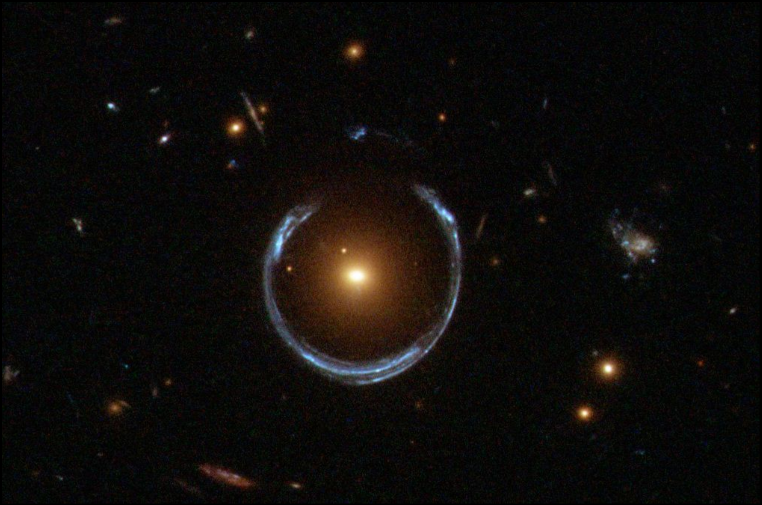
ESA/Hubble & NASA

Twin Quasars: Can infer α



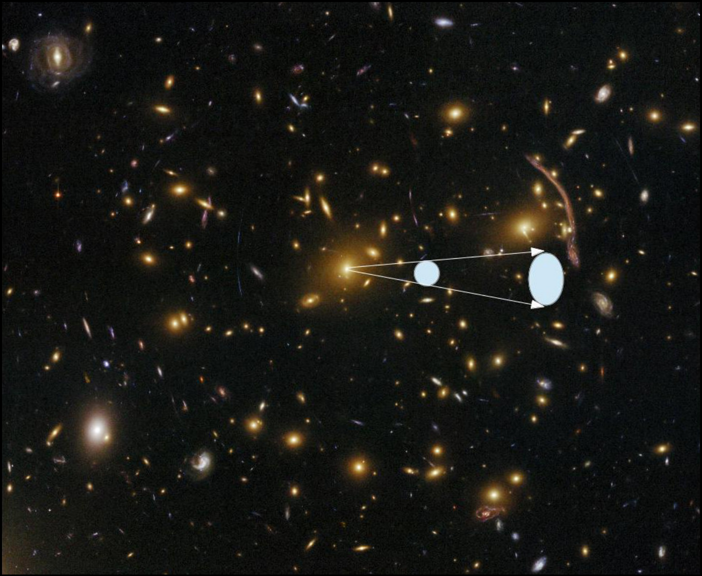
User Krishnavedala, *wikipedia*

Einstein Ring: The “Horseshoe”



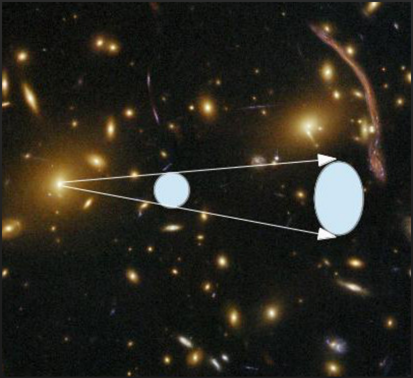
ESA/Hubble & NASA

Shear Illustration



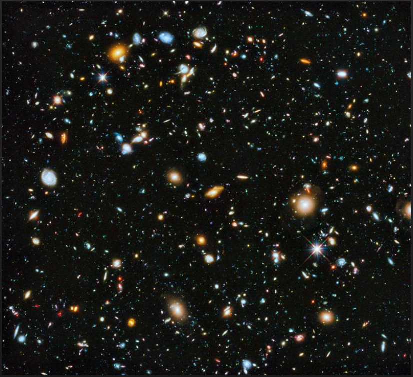
Shear Illustration

- The shape of extended background sources is changed.
- The differential deflections across the surface of the background image produces a shear.
- For strong lensing a round source becomes a "banana"
- For weak lensing a round source becomes slightly elliptical



Tangential Shear

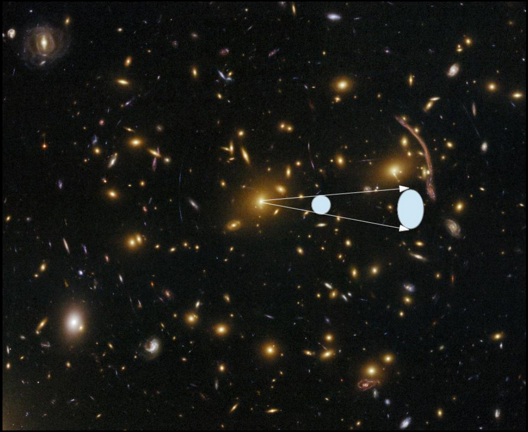
Weak Lensing



NASA/ESA, Teplitz et al.

- Strong lensing requires special, fortuitous alignments. Not that useful as a general tool
- But everything is lensed slightly, and the tangential shear pattern is imprinted all over the sky.
- Taking a statistical approach, we can study the mass distribution around any set of objects.

Weak Lensing: Tangential Shear



$$\bar{e}_T(R) \propto \bar{\Sigma}(< R) - \bar{\Sigma}(R)$$

Dark Matter

Dark Matter

Dean Rowe

- Fritz Zwicky 1933
- He found the galaxies in the Coma cluster were moving far too fast.
- Assuming equilibrium (good to factor of two) he calculated the binding mass is ~ 100 times the mass in stars

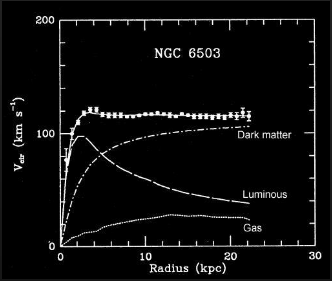
The observation of such gravitational lens effects promises to furnish us with the simplest and most accurate determination of nebular masses.

- Fritz Zwicky, 1937

Dark Matter: Galaxy Rotation Curves

- Rubin studied the rotation curves of galaxies in the 70s
- The light density falls exponentially with radius.
- The mass density implied by the velocities falls like a power law
- Extrapolation seemed to imply the mass continued well beyond the region of visible stars

NASA/ESA/V. Peris



Begeman, Broels and Sanders (1991)

Cold Dark Matter (CDM)

- Some form of matter that does not significantly emit or absorb light
- Cold: $v \ll c$
- Favored idea is an elementary particle, weakly interacting
- So far CDM successfully explains most observations, and has been predictive

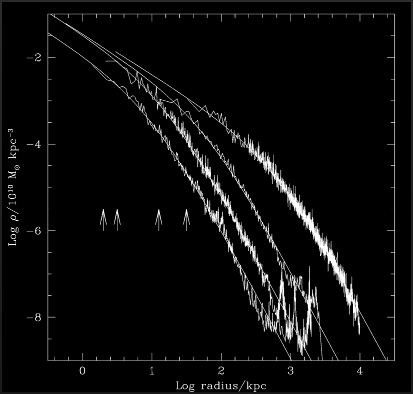
Early Successes of CDM

- Explains rotation curves of galaxies
- Explains the dynamics of galaxy clusters
- Explains the large scale distribution of galaxies: without it we would predict a wildly different universe
- Essential component needed to explain the cosmic microwave background

Predictions of CDM

- "Universal" radial profile of gravitationally bound dark matter structures, "halos" (NFW, simulations)
  - Running power law with one free parameter for shape
  - Mass extends orders of magnitude farther beyond visible portion of galaxy, merges with neighbors
- Dark matter should be distributed smoothly throughout the universe
  - Unlike dissipative baryons that collapse to more compact objects

Predictions of CDM



Navarro, Frenk, White 1996

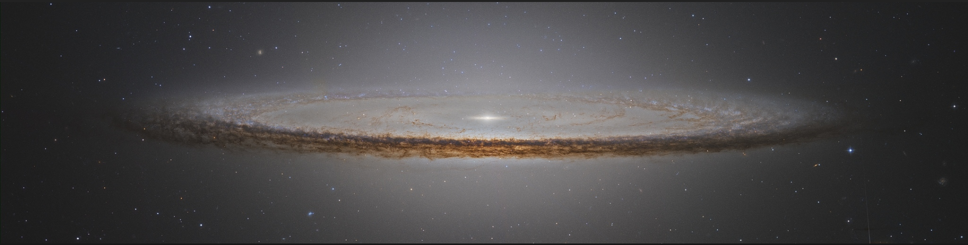
- "Universal" radial profile of gravitationally bound dark matter structures, "halos" (NFW)
- Running power law with one free parameter for shape
- Mass extends orders of magnitude farther than visible portion of galaxy, merges with neighbors
- Dark matter distributed smoothly throughout the universe, unlike dissipative baryons clumped in galaxies.

  1pc = 3.2 ly

Limits of dynamical approaches

- visible tracers are required
- cannot trace out the orbits, the timescales are too long
- assumptions must be made about the dynamical state of the system
- limits the scale over which it this can be used

Scale 10 kpc



NASA/ESA/V. Peris

Weak Lensing is a Better Option

- The weak effect can be observed anywhere
- The distribution of matter can be studied on a large range of scales
  - galaxies, galaxy clusters, bound objects
  - structure on the largest scales in the universe

NASA/ESA

Weak Lensing Limitations

- The effect is very weak, percent level change in ellipticity
- Statistical approach is required: average signal from many lenses and many background sources
- But these are unimportant limitations. The theory doesn't predict anything about individual objects anyway: these are messy systems with a complicated history

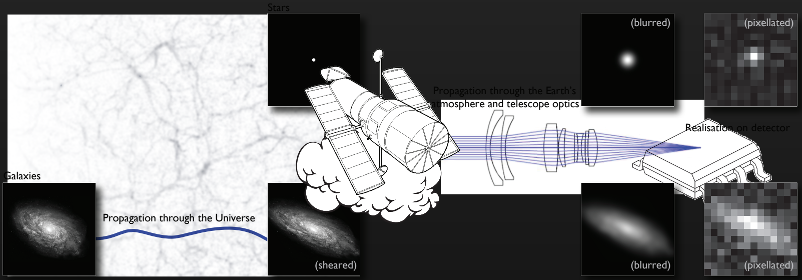
Weak Lensing: The Program

1. Identify lenses, such as galaxies or cluster of galaxies
2. Identify background sources and measure their ellipticities (that's the hard part!)
3. Average the ellipticities of background galaxies
4. Average over lots of lenses
5. Infer the mean radial distribution of mass

MASIL Imaging Team

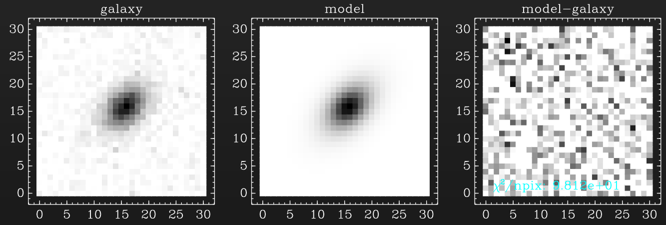
Shear Measurement

- Shear induces ellipticity
- Ellipticity is also altered by the atmosphere, the optics of the telescope, and the pixelization.
- These effects we call the Point Spread Function (PSF), must be modeled by studying stars.
- Surprisingly, the noise is the biggest problem: All naive ellipticity measures are biased in the presence of noise.



Ellipticity Measurement

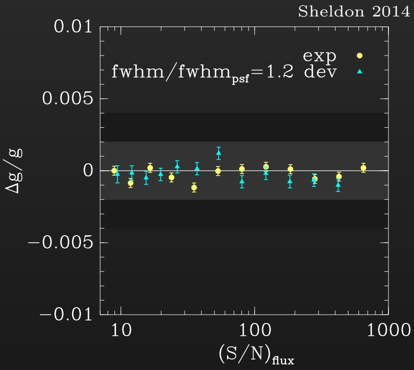
- Find the elliptical model that best fits the image
- In the presence of of noise, the best ellipticity yields a biased shear estimate: $\sim 10\%$ for faint galaxies!
- Need to measure shear to 0.1%.



Unbiased Shear Measurement

- In 2014 the first unbiased estimator was derived (Bernstein & Armstrong, 2014): theoretical only
  - Using Bayesian principles: prior informatioin required from low-noise data.
  - Forget about individual galaxy, estimate shear of population
- I developed an implementation for use on real images.

First Unbiased Shear Estimator



- Image simulations
  - Galaxies
  - PSF
  - noise
- Tested shear recovery for different galaxy types and noise levels
- Unbiased at the level required for current and future surveys.
- Published (Sheldon 2014)

Dark Matter Distribution in Galaxies and Clusters

Dark Matter Distribution

- The program:
  1. Identify lenses (galaxies or clusters)
  2. Identify background source galaxies.
  3. Measure the ellipticities of the source galaxies
  4. Average the ellipticities of background galaxies.
  5. Further average over many lenses
  6. Interpret in terms of the mean surface mass density Σ

$$\bar{e}_T(R) \propto \overline{\Sigma}(< R) - \overline{\Sigma}(R)$$

Sloan Digital Sky Survey

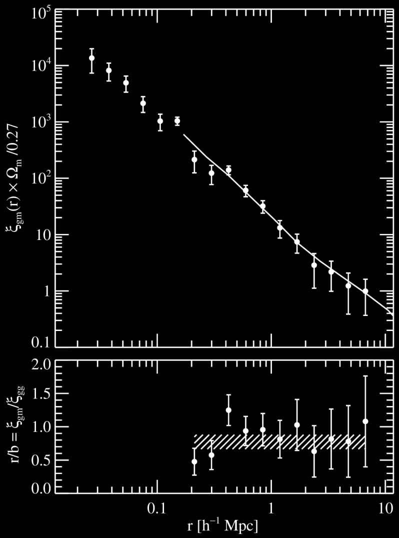
- 2.5 Telescope at Apache Point New Mexico
- Imaged 10,000 sq. deg. in the northern sky through 5 filters, 126 Mpixel camera
- Imaging taken from 1999-2009
- Spectroscopy and redshifts for 1 million galaxies used as lenses
- 50 million faint background galaxies used as sources

SDSS Telescope

Whirlpool Galaxy, SDSS/Robert Lupton

Mass Distribution Around Galaxies

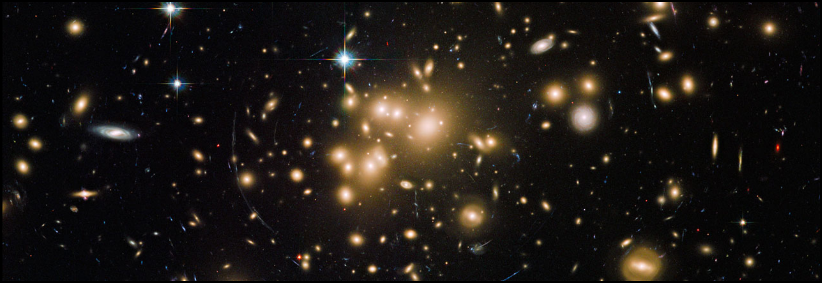
- Mean mass density in radial bins
- Min radius 20 kpc max 10 Mpc (1pc = 3.2ly)
- Light concentrated within 10 kpc
- About 100 times more mass than in stars
- On large scales looks like distribution of galaxies: neighbors



Sheldon et al. 2004

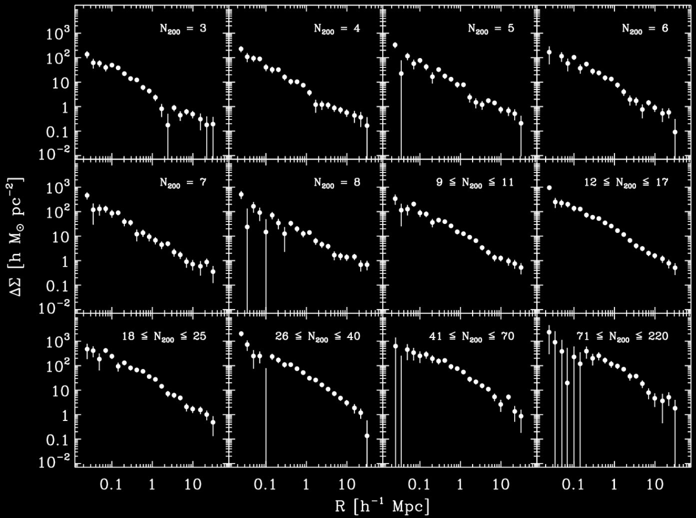
Galaxy Clusters

- More useful than galaxies for learning about Dark Matter
  - 100-1000 times more massive than galaxies: higher signal
  - 10 times larger in extent: better resolution in radius to study the mass profile



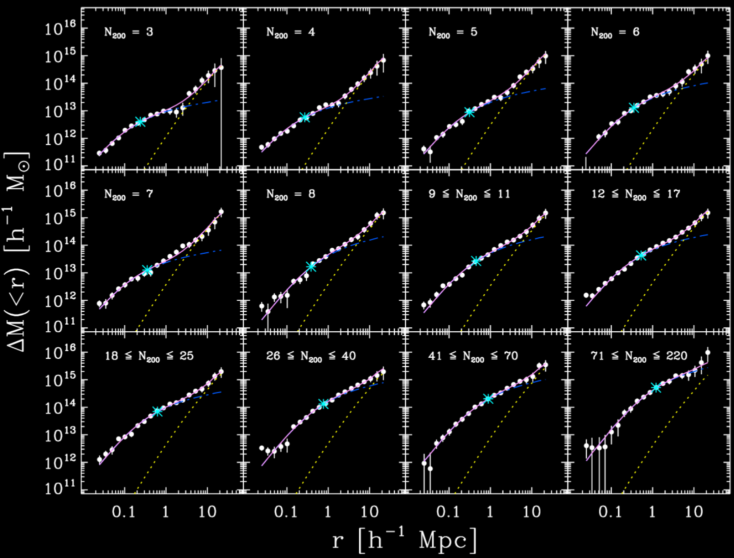
NASA/ESA

Mass Distriution in and around Galaxy Clusters



Sheldon et al. 2009

Interpretation in Terms of Universal Profile



Sheldon et al. 2009

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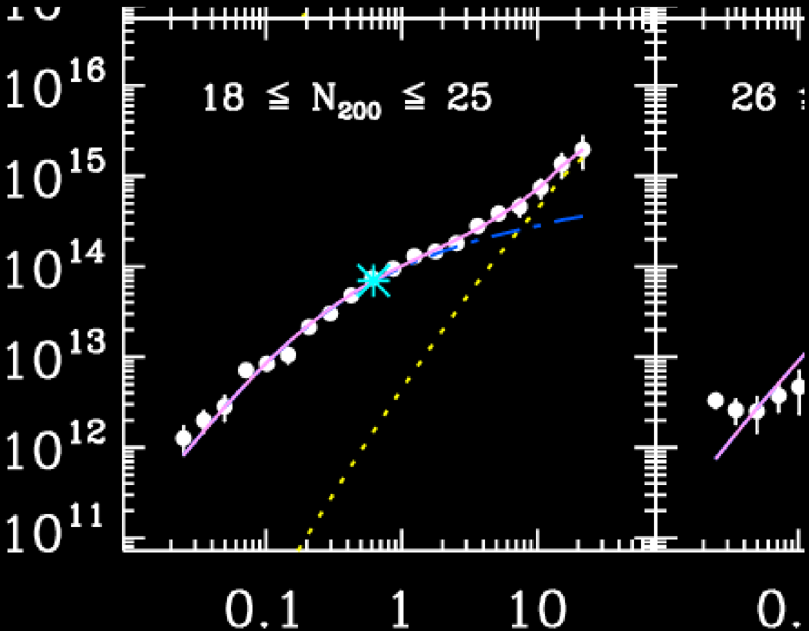
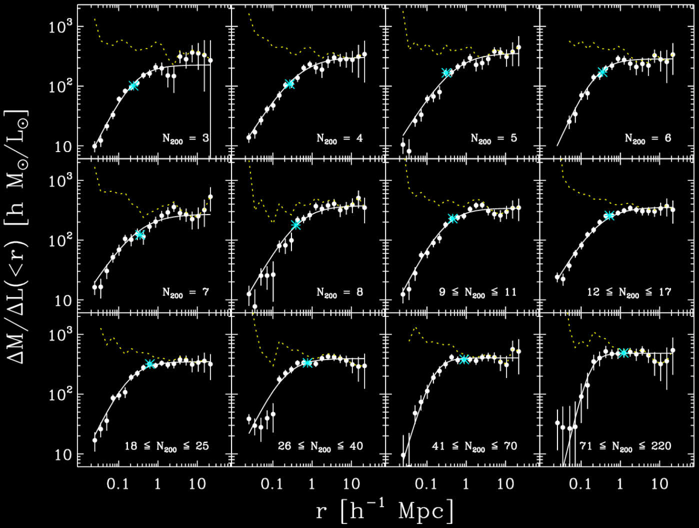


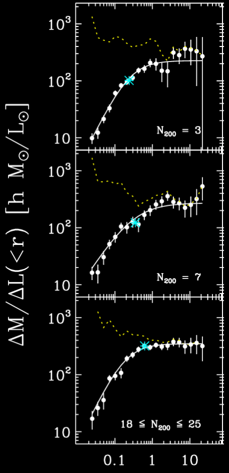
Mass-to-light Ratio: CDM Predicts Light Should be More Concentrated



Sheldon et al. 2009

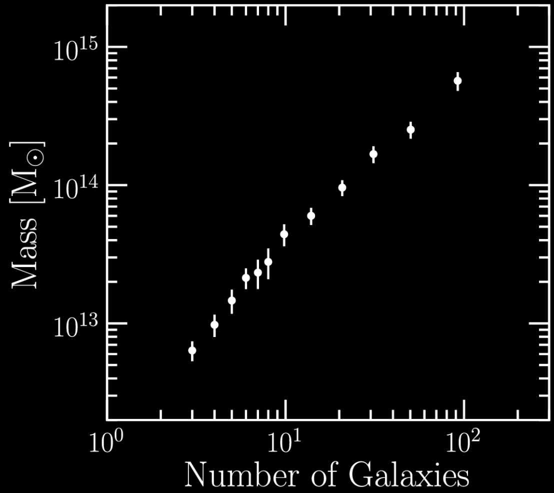
Mass-to-light Ratios and Ω_m

- M/L reaches constant at large radius, same for all samples
- Universal M/L
- Multiply by the luminosity density in the universe to get the universal mass density
  $\rho_m = \bar{\ell} \times M/L$
- Express as fraction of the universal energy density
- $\Omega_m b_{M/L}^{-2} = 0.20 \pm 0.03$



Sheldon et al. 2009

Total Mass in the Cluster



Johnston, Sheldon et al.

Cosmological Parameters

- CDM also predicts dN/dM, the number of objects of a given mass, and this depends on Ω_m.
  - We know dN/dn_{gals} and $M(n_{gals})$!
  - Combine dN/dn_{gals} and $M(n_{gals})$ to get dN/dM and infer Ω_m (Rozo et al. 2010)

$$\Omega_m = 0.28 \pm 0.07$$

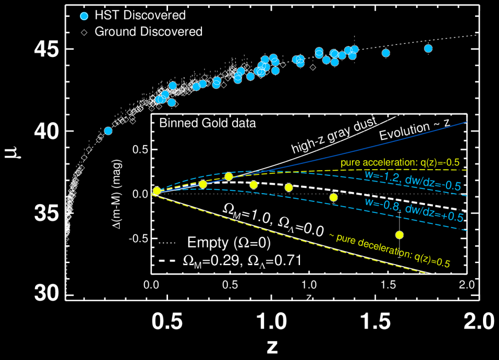
- Combine Mass/Number radial profiles with galaxy clustering (Tinker et al. 2012)

$$\Omega_m = 0.29 \pm 0.03$$

Dark Energy

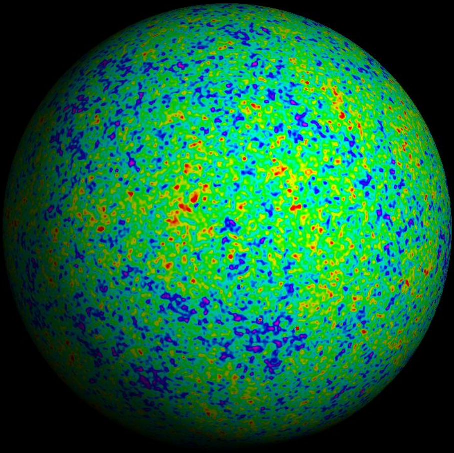
Dark Energy

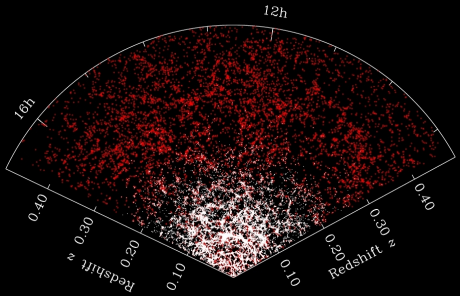
- Astronomers tried to predict the brightness of a standard candels at a known redshifts (type Ia Supernovae)
- They got the wrong answer assuming the universe is homogeneous and filled with normal matter
- Most easily explained if the universal expansion is accelerating.



Riess et al. 2007

The universe *is* homogeneous





WMAP (M. Tegmark), SDSS Galaxies (M. Blanton)

Dark Energy Equation of State

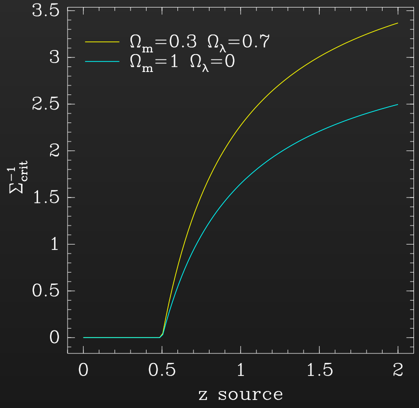
- The universe seems to be accelerating
- The simplest approach is to add a term to Einstein's equations
  - Cosmological Constant
  - Or maybe exotic stuff. Simplest model is uniform field with

$$p = w\rho$$

  - Cosmological Constant has $w = -1$
  - Current constraints $w \sim -1 \pm 0.1$

Using Lensing to Measure Dark Energy

- Lensing is geometrical, depends on the distances to all components of the lens system
- Look at the dependence of the shear effect as a function of the source redshift
- Current lensing data does not probe a sufficent volume of the universe



Dark Energy Survey (DES)

Image: Brian Nord, FNAL

- Imaging survey of 5000 square degrees in the southern sky in Chile. 5 optical filters
- New 500 Megapixel camera
- About 7 times the volume of SDSS: Study lensing as a function of cosmic time $\Rightarrow$ dark energy
- First light Fall 2012, survey start Aug. 31, 2013, end 2018.
- Study Dark Energy using weak lensing, galaxy clusters, large scale structure and supernovae.
- Measure w to ± 0.02

NGC 1398, Erin Sheldon, Martin Murphy

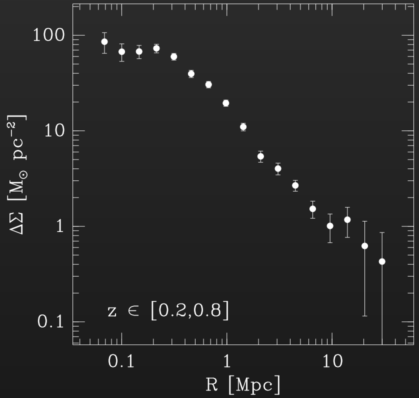
DES at BNL

- I've been working on DES since 2003
- I am a builder and associate member with data rights for self, postdoc, students.
- Co-convener of weak lensing working group
- Responsible for one of the two shear measurement codes
- Leading the effort to measure lensing around galaxy clusters
- Andres Plazas BNL postdoc worked on detector characterization and weak lensing of galaxy clusters

Image: Erin Sheldon

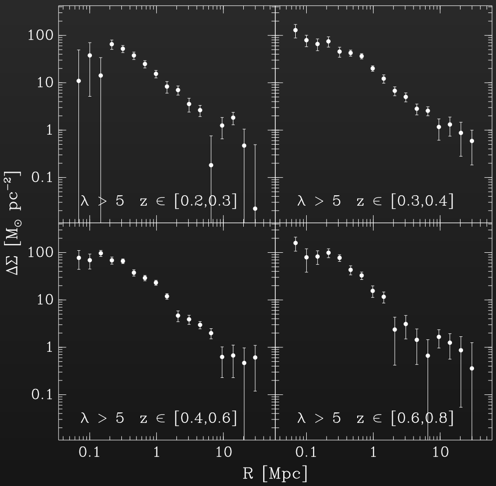
Preliminary Lensing Results from DES

- Results from science verification period
- 3% of final data
- Mean lensing signal for 12,000 galaxy clusters found using the RedMapper algorithm



Lensing as a Function of Cosmic Time

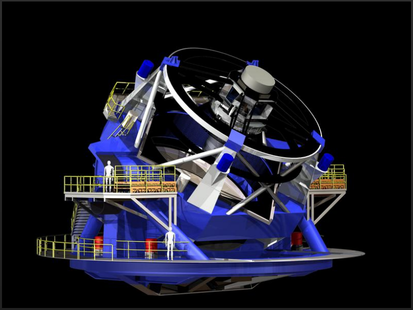
Binned by redshift, or cosmic time. Not possible with SDSS

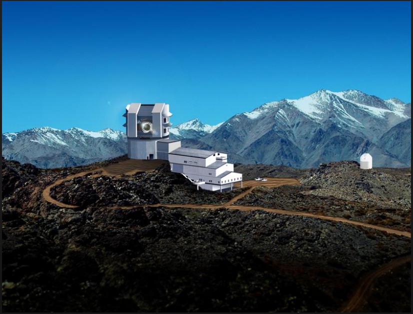


DES: Future Work

- Process more data!
- The codes are vetted, good enough for studies on early data
- Look in detail at the dark matter profiles: Do they evolve over time as predicted by CDM?
- Cosmological analysis requires more data. Approximately 2 years timescale.

The Long View: LSST

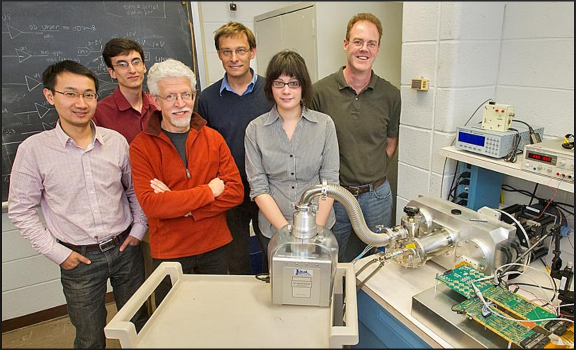




- Large Synoptic Survey Telescope (LSST)
- New 3.2 Megapixel camera, the world's largest
- New 8.4 Meter telescope
- Survey half the sky; 1000 visits per field over 10 years, each with depth of DES
- Entering construction phase; First light 2020

LSST

- BNL has been involved since 2004
- BNL Instrumentation responsible for CCDs, electronics and rafts.



Some BNL LSST Folks

LSST

- I am transitioning to LSST from DES work, full time by 2019
- I am incorporating my shear code into the LSST framework now.
- Raw shear sensitivity of LSST is ~ 5 times that of DES, with more leverage over cosmic time
- Constrain w to the sub-percent level.
- Study time dependence of dark energy properties: is w constant?

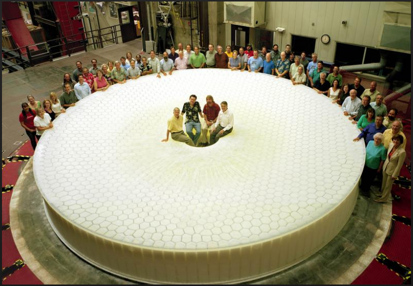


Image: LSST Collaboration

Summary

- Predictions of Cold Dark Matter theory confirmed
  - The distribution of mass in galaxies and clusters follows a "universal profile"
  - Universal profile is a running power law, no exponential cutoff like the light
  - Dark Matter is distributed smoothly throughout the universe, not bound in compact clumps like the disspiative baryonic material
- With DES, lensing will mature as a probe of Dark Energy
- This work will culminate in LSST