Clusters and Lenses: Analyzing Ten Gravitational Lensing Systems Discovered in the Sloan Digital Sky Survey

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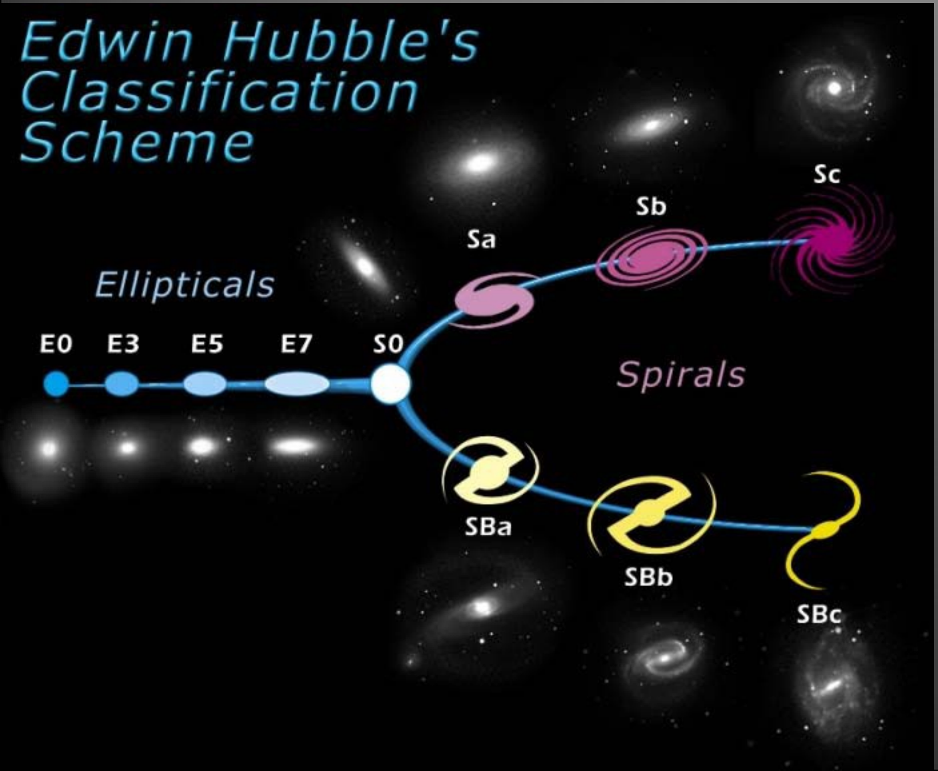
Outline

1) Introduction to the astrophysics
2) The data and how it was taken
3) Properties of the galaxy clusters
4) Properties of the gravitational lenses
5) Initial cosmological conclusions

1) The Astrophysics

What is a galaxy cluster?

- Collection of galaxies
- Dark matter

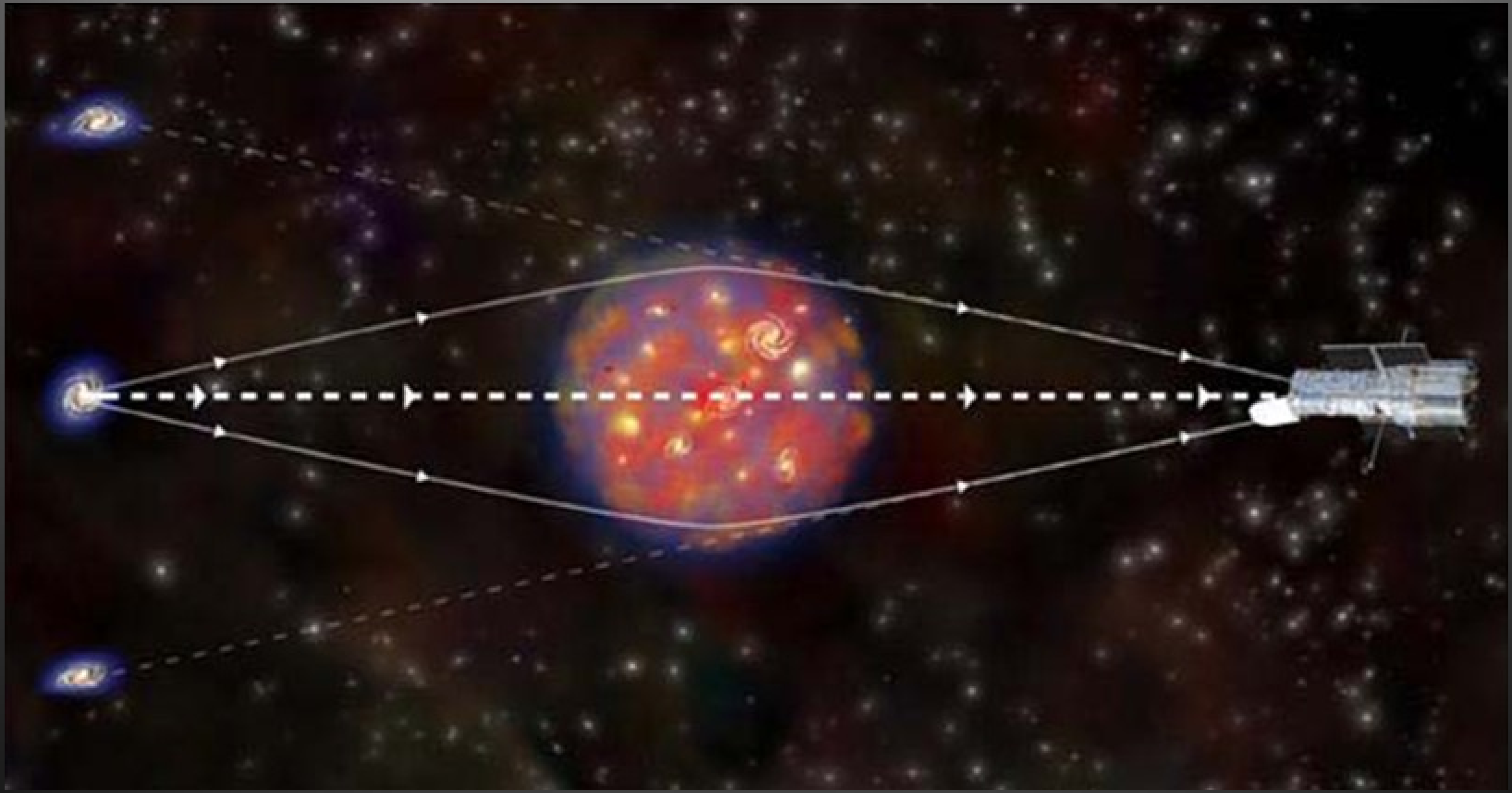


(Penn State University)

Abell 2255 (SDSS.org)

What is a gravitational lens?

- System where light bends due to presence of mass
- Effect of General Relativity (light follows curvature)



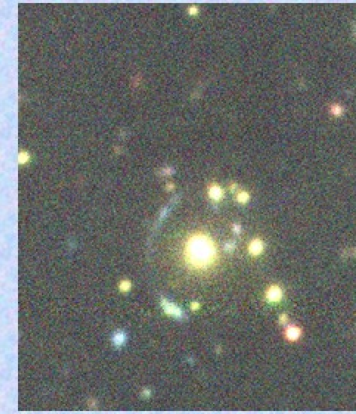
(NASA/CXC/M.Weiss)

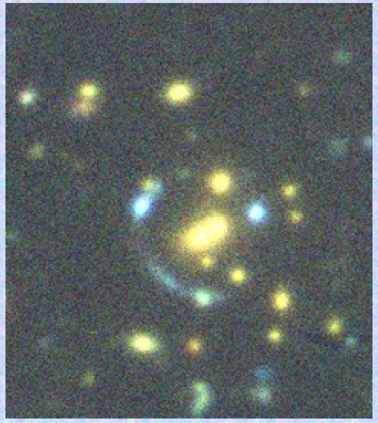
2) The Data

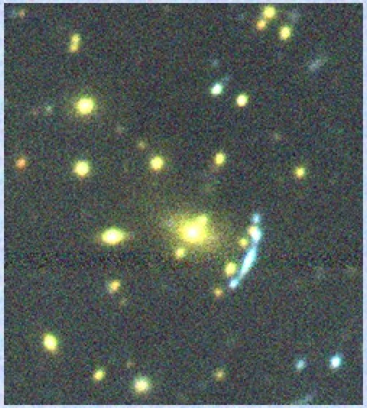
The ten systems

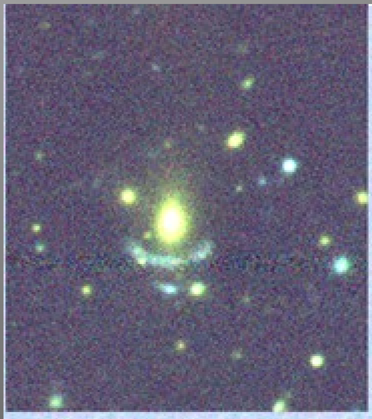
- Color images from g,r,i filters
- Found in Sloan Digital Sky Survey
- Follow-up data taken at WIYN telescope
- Each includes a blue arc and a galaxy cluster

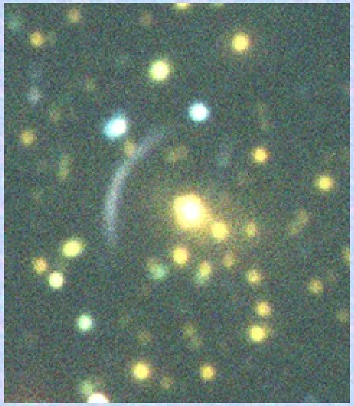

SDSS J1537+6556


SDSS J0901+1814


SDSS J0900+2234

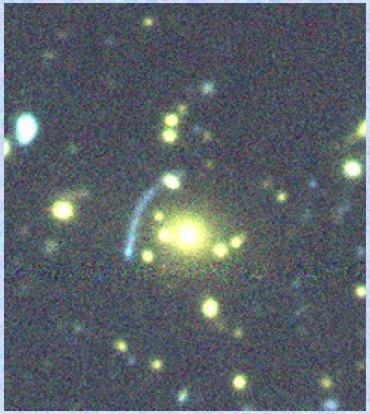

SDSS J0957+0509

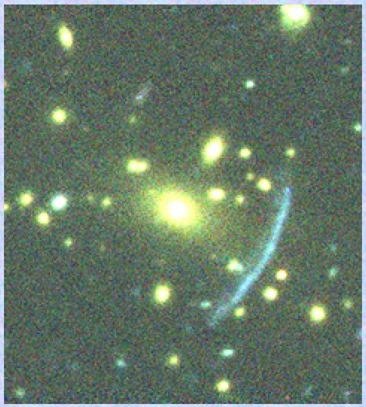

SDSS J1511+4713


SDSS J1209+2640


SDSS J1038+4849

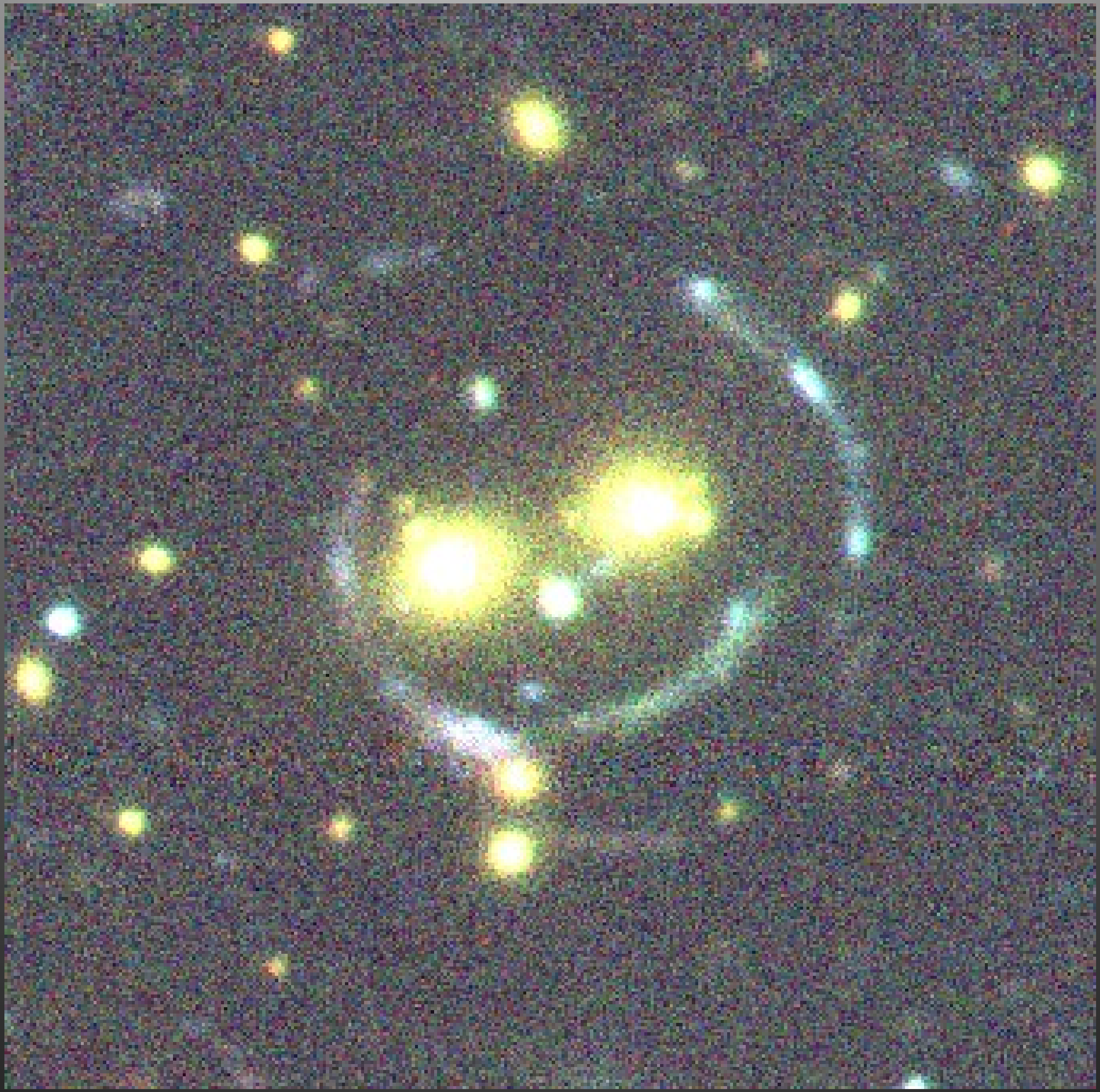

SDSS J1318+3942


SDSS J1439+3250


SDSS J1343+4155

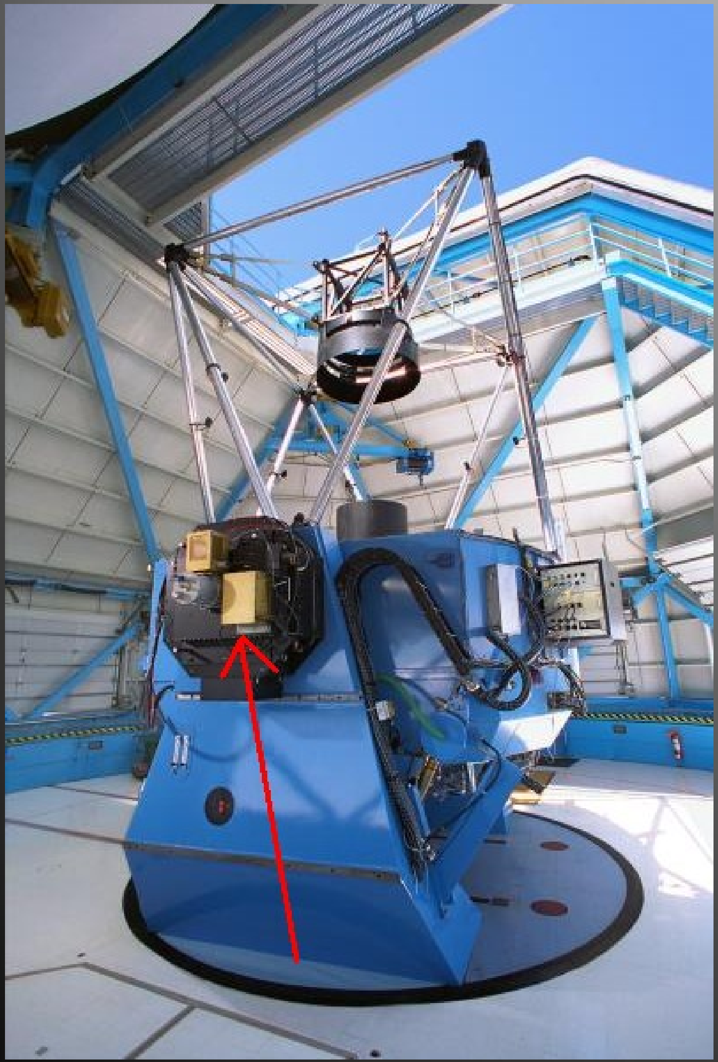
SDSS J1209+2640
The Richest Cluster

SDSS J1038+4849
The Happiest Cluster



The telescopes

The Wisconsin-Yale-Indiana-NOAO (WIYN) Telescope



NOAO/AURA/NSF

The Sloan Digital Sky Survey (SDSS) Telescope

SDSS.org

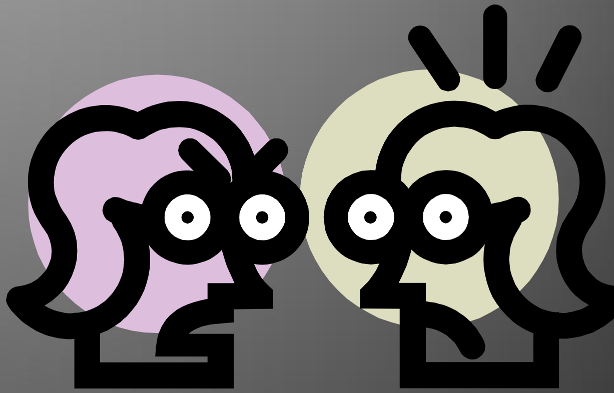
3) Properties of the Galaxy Clusters

How do we find galaxy clusters?

MaxBCG Method for Finding Galaxy Clusters
(Koester et al. 2007)

Look for:

(1)Groups of galaxies where density increases near center
(2)Constant color
(3)Central Brightest Cluster Galaxy (BCG)



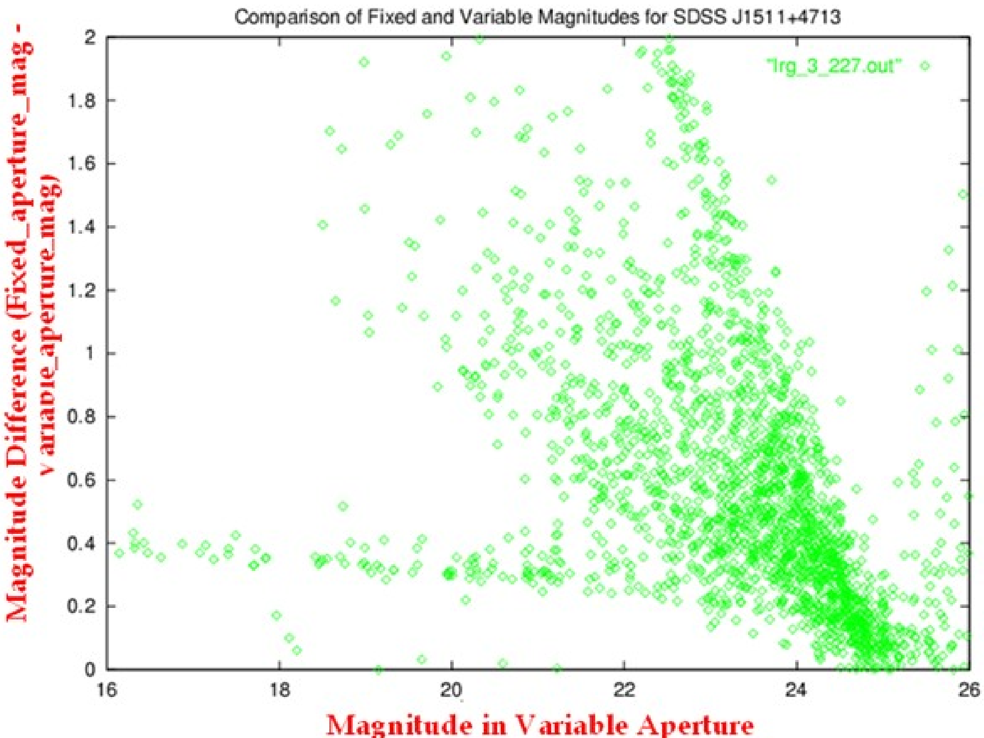
Defining a cluster galaxy

Counting Galaxies – Quantifying Richness

- N_{gals}, number within 1 Mpc

Used Fortran program to find objects that were:

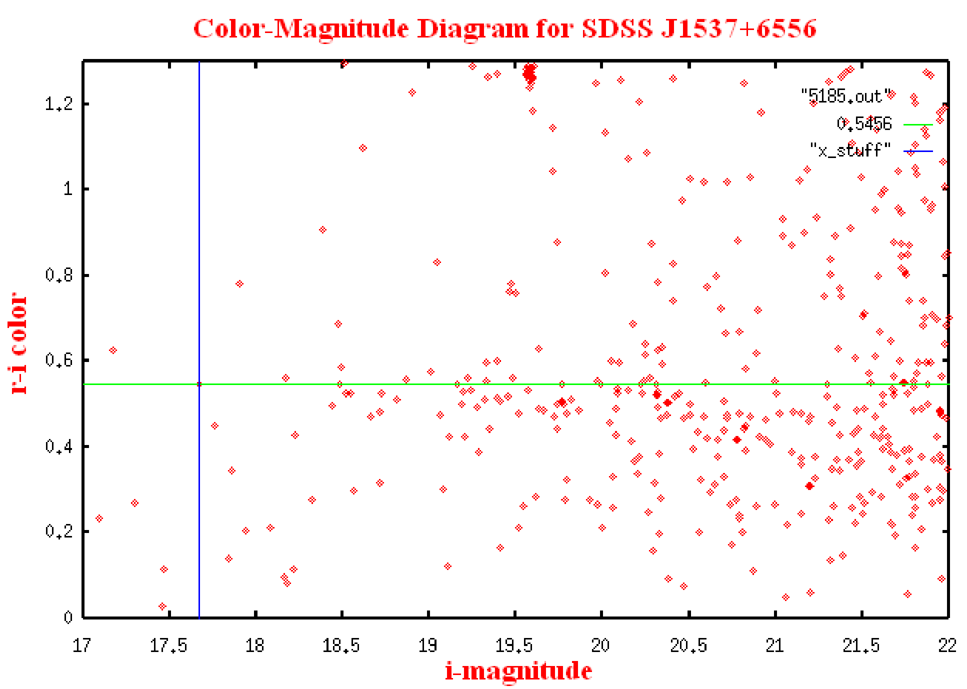
A. Galaxies, not stars
B. Within 1 Mpc of BCG
C. Within 2σ of particular color
D. At least as bright as 0.4L* (min brightness criterion)



A. Galaxy-Star Separation

Find stellar locus by plotting magnitude difference vs. variable aperture magnitude

C. Selecting Cluster Members



Results for N_{gals}

Object	N_{gals}
SDSS J1511+4713	26
SDSS J0901+1814	6
SDSS J1439+3250	50
SDSS J0900+2234	13
SDSS J0957+0509	21
SDSS J1537+6556	15
SDSS J1038+4849	15
SDSS J1318+3942	21
SDSS J1209+2640	59
SDSS J1343+4155	23

Finding N_{200}

Radius of sphere within which $\rho = 200\rho_c$ (Hansen et al. 2005)

$$r_{200} = 0.156(N_{gal}^{0.6})h^{-1}Mpc$$

$$\rho_c(z) = \frac{3H(z)^2}{8\pi G}$$

Object	r_{200} (h^{-1}Mpc)	N_{200}
SDSS J1511+4713	1.10	30
SDSS J0901+1814	0.457	3
SDSS J1439+3250	1.63	71
SDSS J0900+2234	0.727	12
SDSS J0957+0509	0.969	20
SDSS J1537+6556	0.792	14
SDSS J1038+4849	0.792	12
SDSS J1318+3942	0.969	18
SDSS J1209+2640	1.80	108
SDSS J1343+4155	1.02	22

Finding M_{200}

M_{200} (Johnston et. al. 2007). N_{200} from MaxBCG catalog, mass found from weak lensing.

$$M_{200}(N_{200}) = M_{200|20}\left(\frac{N_{200}}{20}\right)^{\alpha_N}$$

Object	M_{200} ($10^{14}h^{-1}M_\odot$)
SDSS J1511+4713	1.48 ± 0.665
SDSS J0901+1814	0.0776 ± 0.0349
SDSS J1439+3250	4.45 ± 2.00
SDSS J0900+2234	0.458 ± 0.206
SDSS J0957+0509	0.880 ± 0.396
SDSS J1537+6556	0.557 ± 0.251
SDSS J1038+4849	0.458 ± 0.206
SDSS J1318+3942	0.769 ± 0.346
SDSS J1209+2640	7.62 ± 3.43
SDSS J1343+4155	0.994 ± 0.447

Finding Velocity Dispersion

$$\langle \ln \sigma_v \rangle = A + B \ln\left(\frac{N_{200}}{25}\right)$$

Velocity dispersion (Becker et. al. 2008)

Object	σ_v (velocity dispersion) (km/s)
SDSS J1511+4713	652 ±183
SDSS J0901+1814	461 ±144
SDSS J1439+3250	832 ±213
SDSS J0900+2234	434 ±138
SDSS J0957+0509	291 ±102
SDSS J1537+6556	636 ±180
SDSS J1038+4849	540 ±161
SDSS J1318+3942	159 ±63
SDSS J1209+2640	720 ±195
SDSS J1343+4155	612 ±176

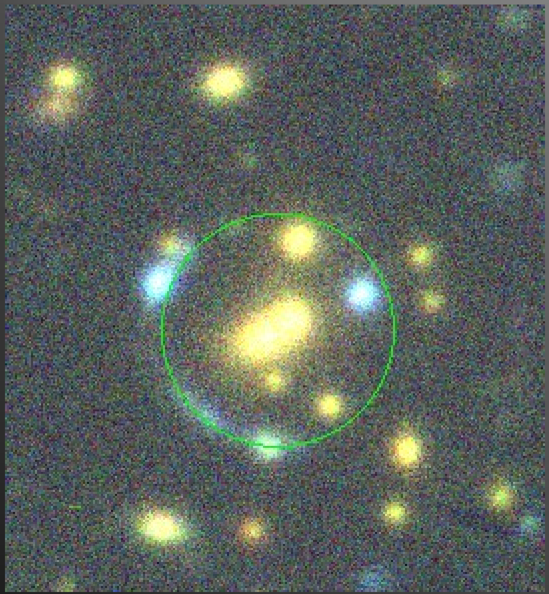
- Found σ_v from spectroscopy in N_{200} bins.

4) Properties of the Gravitational Lenses

Modeling the lens as a sphere

Einstein Radius

- Describes size of gravitational lens. For a perfect circle (Einstein ring) this is the radius of the ring.



SDSS J0900+2234

Object	Einstein Radius (arcsec)
SDSS J1511+4713	5.4 ± 0.5
SDSS J0901+1814	6.9 ± 0.7
SDSS J1439+3250	7.4 ± 0.7
SDSS J0900+2234	8.0 ± 0.8
SDSS J0957+0509	8.2 ± 0.8
SDSS J1537+6556	8.5 ± 0.9
SDSS J1038+4849	8.6 ± 0.9
SDSS J1318+3942	9.1 ± 0.9
SDSS J1209+2640	11 ± 1.1
SDSS J1343+4155	13 ± 1.3

Properties of the lens

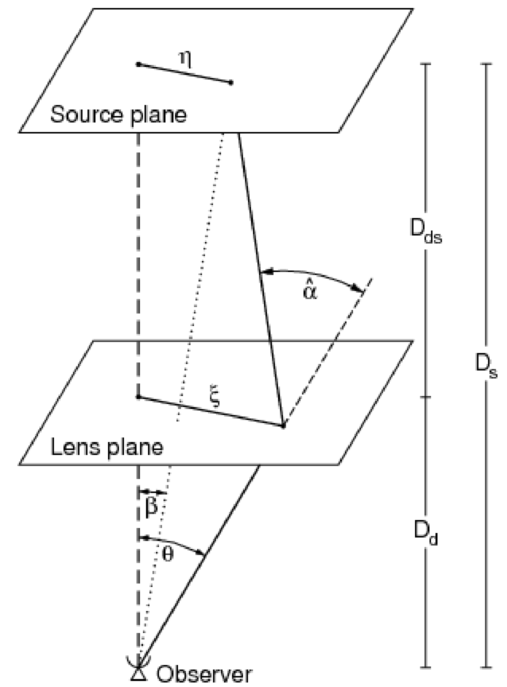
Einstein radius

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ds}}{D_s D_d}}$$

Lens Mass

$$M = \theta_E^{\,2}\left(\frac{c^2}{4G}\frac{D_d D_s}{D_{ds}}\right)$$

Narayan & Bartelmann (1997)



Object	Mass within Einstein Radius ($10^{12}h^{-1}M_\odot$)
SDSS J1511+4713	6.3 ± 1.2
SDSS J0901+1814	5.5 ± 1.1
SDSS J1439+3250	7.4 ± 1.4 – 10.0 ± 1.9
SDSS J0900+2234	11 ± 2.2
SDSS J0957+0509	12 ± 2.3
SDSS J1537+6556	8.7 ± 1.8
SDSS J1038+4849	15 ± 3.1
SDSS J1318+3942	12 ± 2.4
SDSS J1209+2640	36 ± 7.2
SDSS J1343+4155	24 ± 4.8

Velocity Dispersion

$$\sigma_v = \sqrt{\frac{\theta_E c^2}{4\pi} \frac{D_s}{D_{ds}}}$$

Narayan & Bartelmann (1997)

Object	Einstein Radius (arcsec)	Mass enclosed within Einstein radius ($10^{12} h^{-1} M_\odot$)	Velocity Dispersion (km/s)
SDSS J1511+4713	5.4 ± 0.4	6.3 ± 1.0	631 ± 29.2
SDSS J0901+1814	6.9 ± 0.1	5.5 ± 0.2	564± 26.6
SDSS J1439+3250	7.4 ± 0.5	7.4 ± 1.0 – 10.0 ± 1.3	596 ± 28.2 - 708 ± 33.5
SDSS J0900+2234	8.0 ± 0.0	11 ± 0.1	648 ± 32.4
SDSS J0957+0509	8.2 ± 0.1	12 ± 0.4	680 ± 33.2
SDSS J1537+6556	8.5 ± 0.5	8.7 ± 1.0	715 ± 37.9
SDSS J1038+4849	8.6 ± 0.4	15 ± 1.3	780 ± 40.8
SDSS J1318+3942	9.1 ± 0.5	12 ± 1.2	336 ± 16.6
SDSS J1209+2640	11 ± 0.5	36 ± 3.4	691 ± 34.6
SDSS J1343+4155	13 ± 0.6	24 ± 2.1	371 ± 18.6

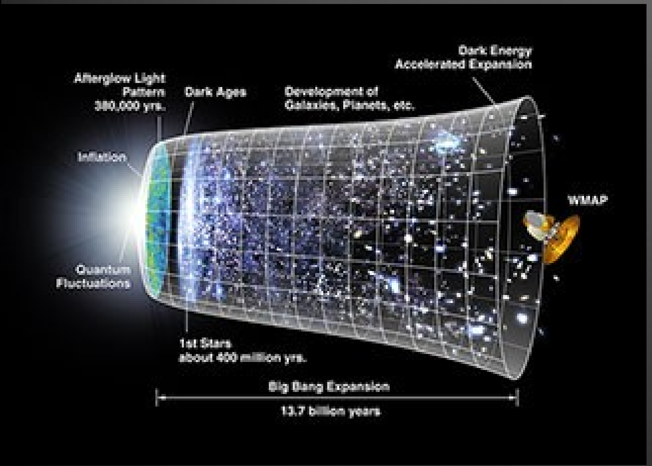
5) Initial Cosmological Conclusions

ΛCDM

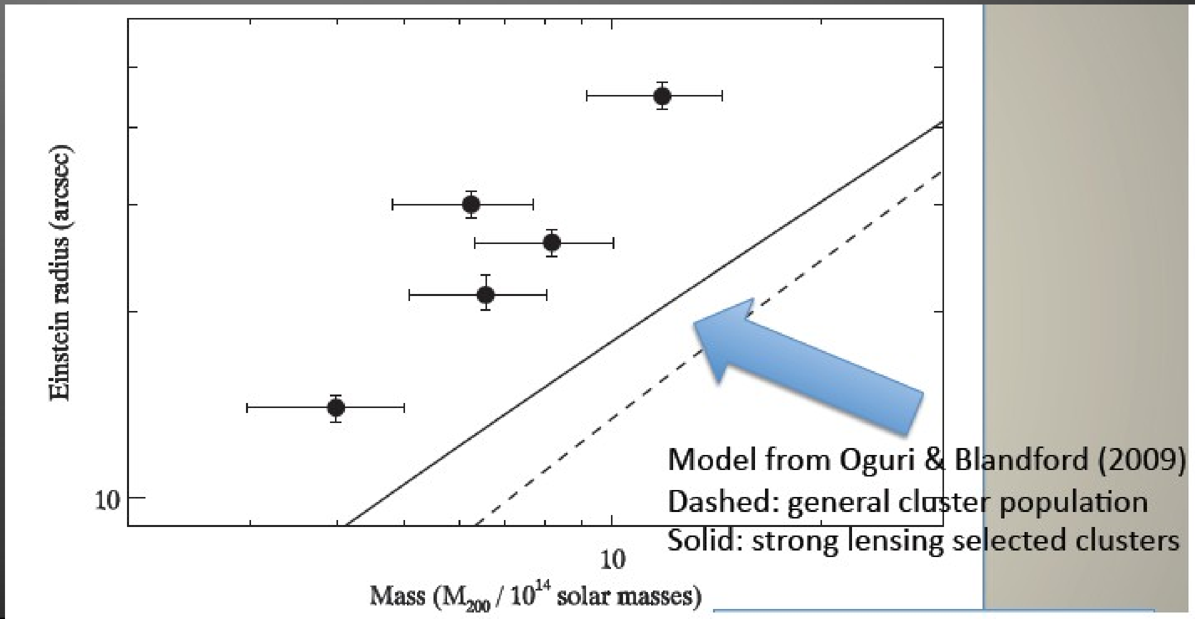
- Standard model of cosmology
  - Cosmological principle
  - Expansion of universe with Big Bang, cosmological redshift
  - Flat spatial geometry
  - Cosmological constant
  - Dark matter cold, non-baryonic, dissipationless (cannot cool by radiating), collisionless

A Disagreement with ΛCDM?

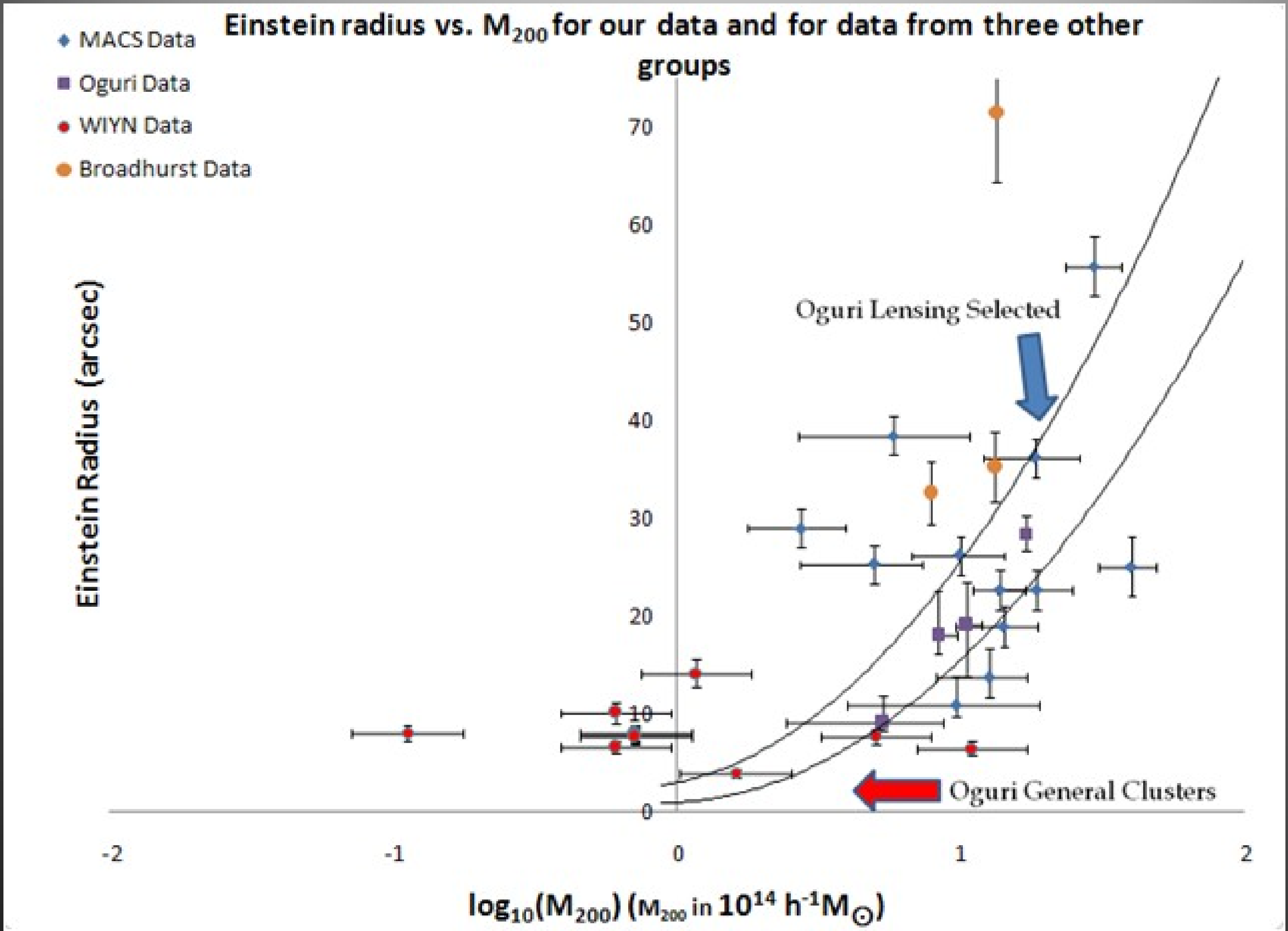
Gralla et. al. 2010



NASA/WMAP Science Team



A Disagree-ment with ΛCDM?



- Higher than expected concentrations: Cluster cores collapsing faster than we thought? Why? (Broadhurst and Barkana 2008)

Conclusion

- We studied ten galaxy clusters and gravitational lenses
- Found richness and mass of clusters
- Found size and mass of lenses
- Found that current predictions for Einstein radius as a function of cluster mass do not match data

Acknowledgements

- Fermilab Graduate Student Association
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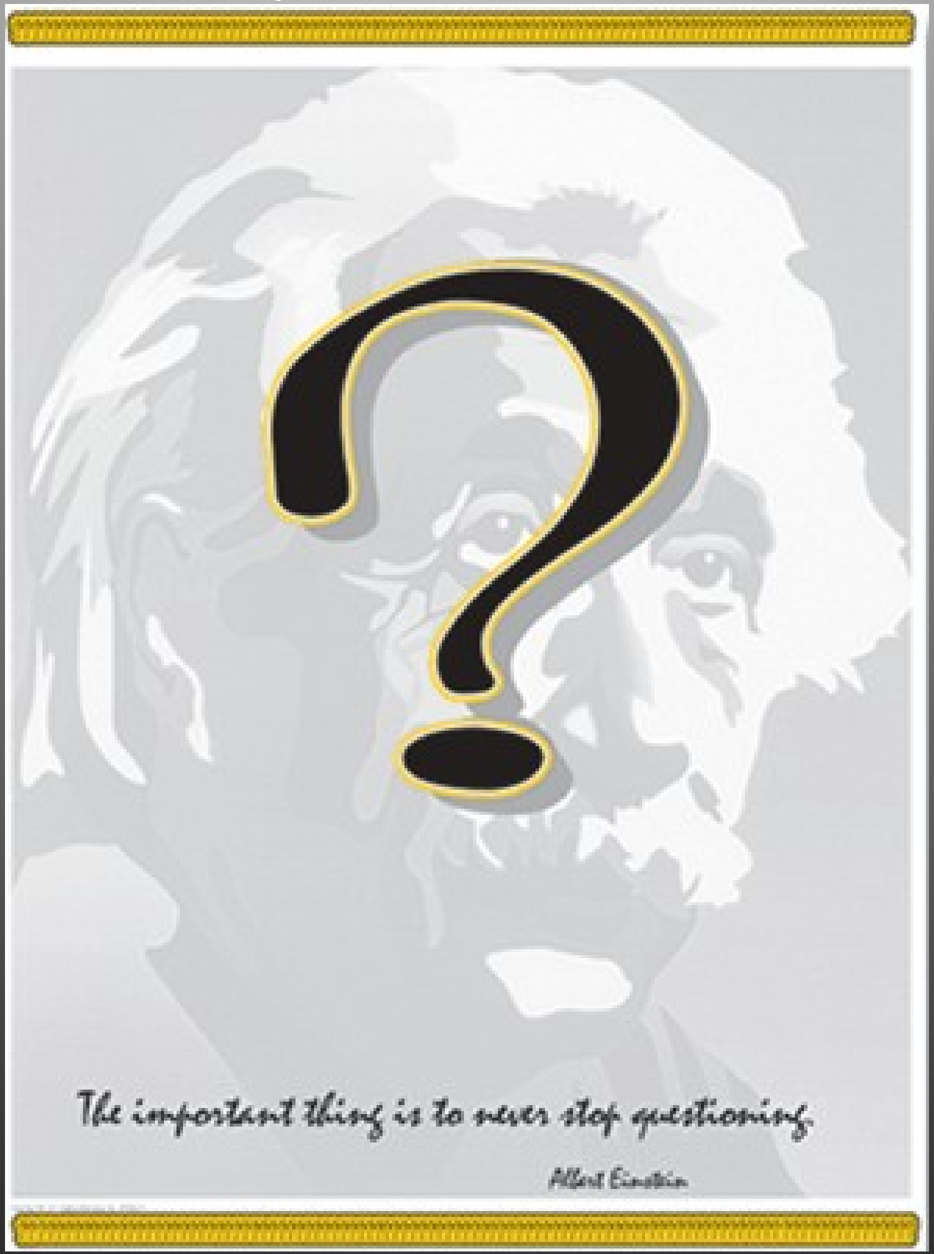
- The Fermilab Experimental Astrophysics Group
- Dr. Laurence Lurio and the NIU Department of Physics

Questions?



http://catalog.instructionalimages.com/einsteinquestion-pi-27.html