Lensing Basics:
I. Introduction

Sherry Suyu

Academia Sinica Institute of Astronomy and Astrophysics

University of California Santa Barbara

KIPAC, Stanford University

November 5, 2012

@ XXIV Canary Islands Winter School of Astrophysics

What is lensing?

Optical Lensing

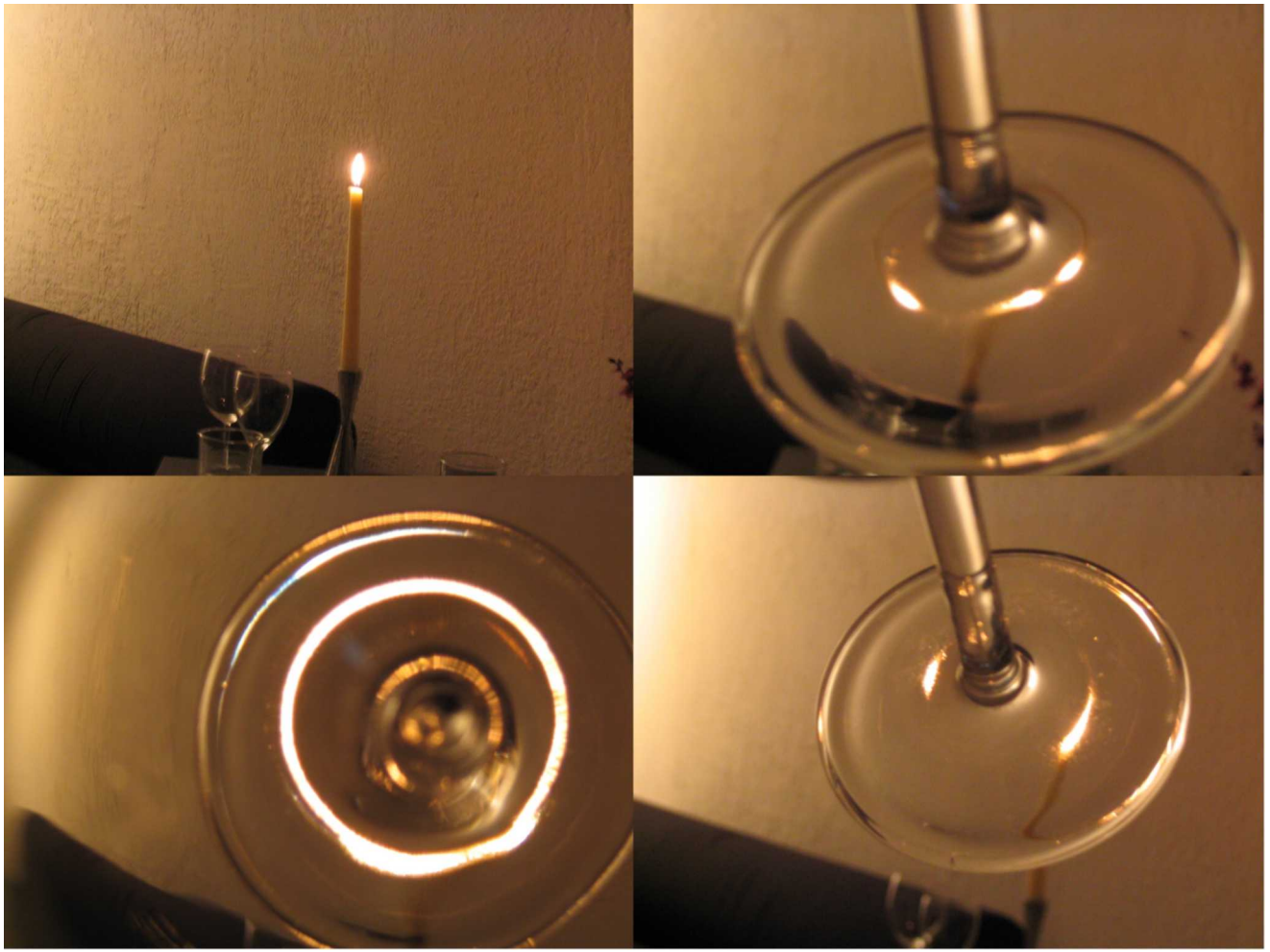
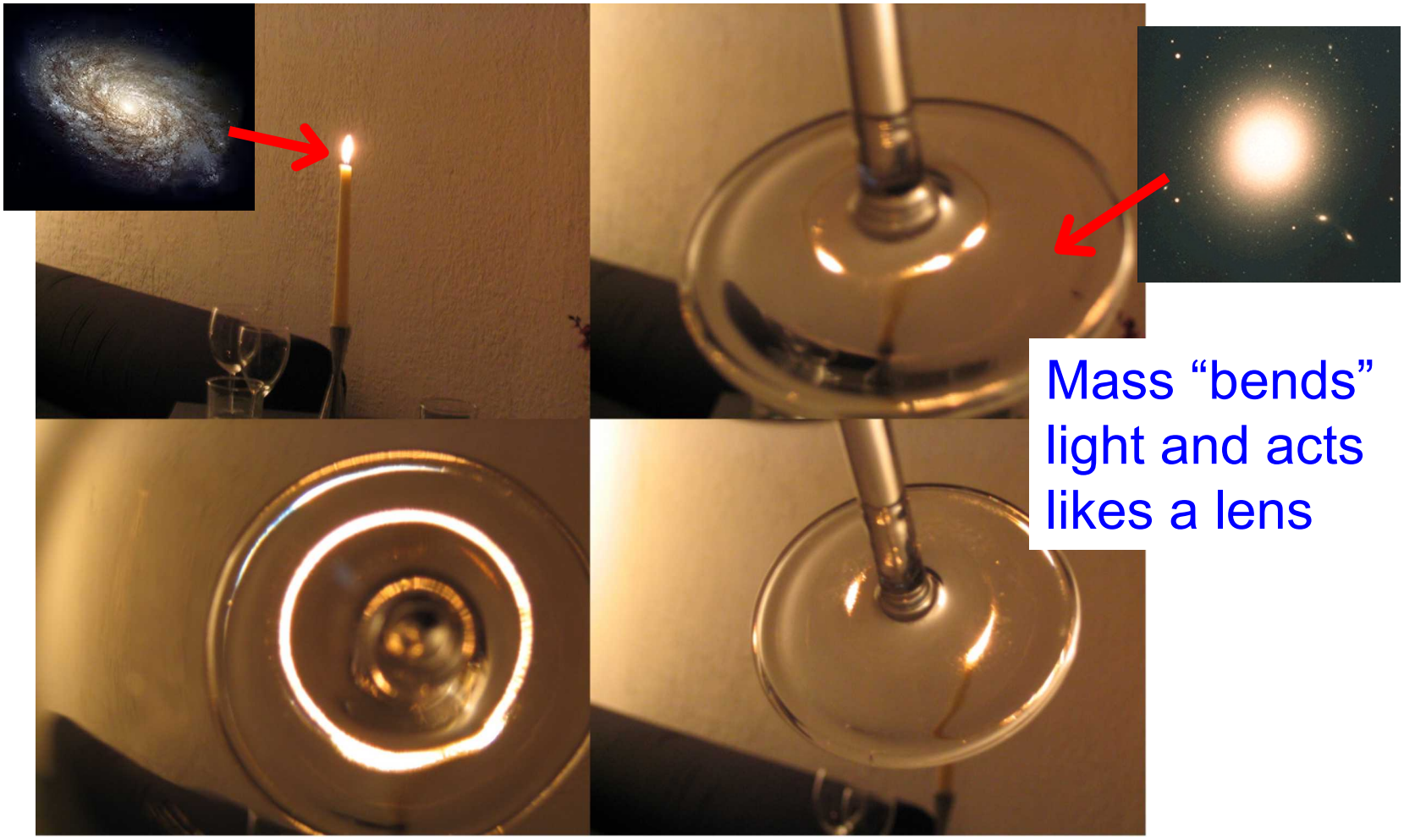


Image Credit: P. J. Marshall

Gravitational ~~Optical~~ Lensing

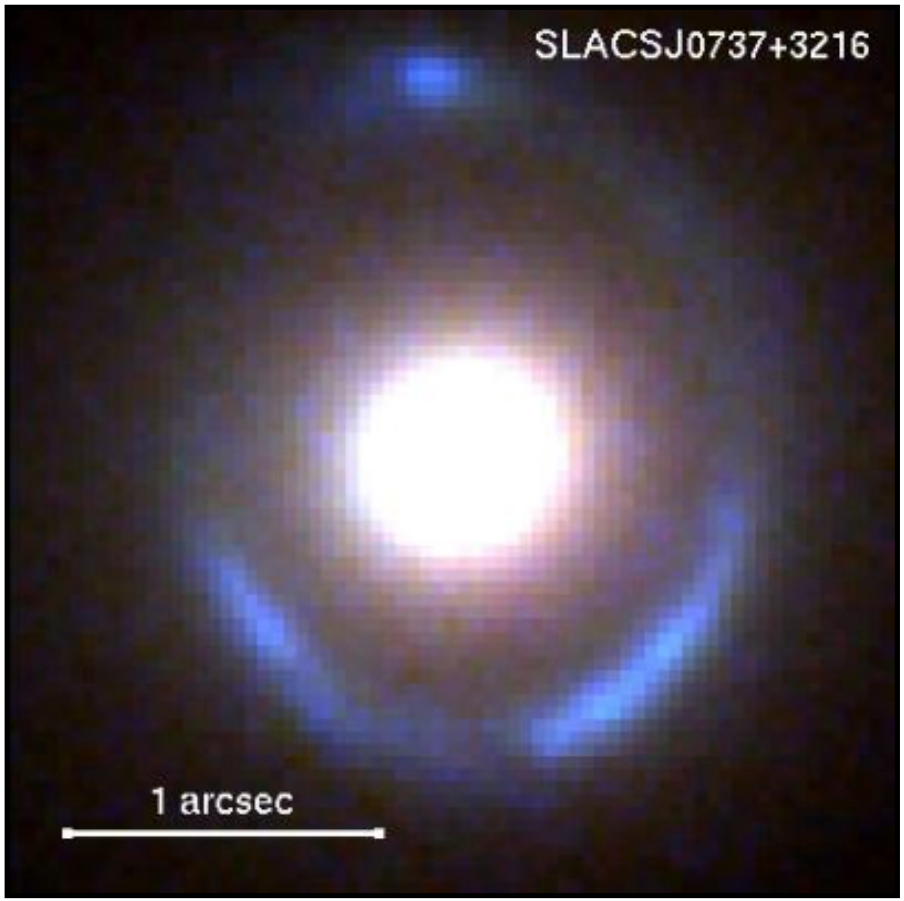


Mass “bends” light and acts likes a lens

Image Credit: P. J. Marshall

Gravitational Lens

HST image: SLACSJ0737+3216

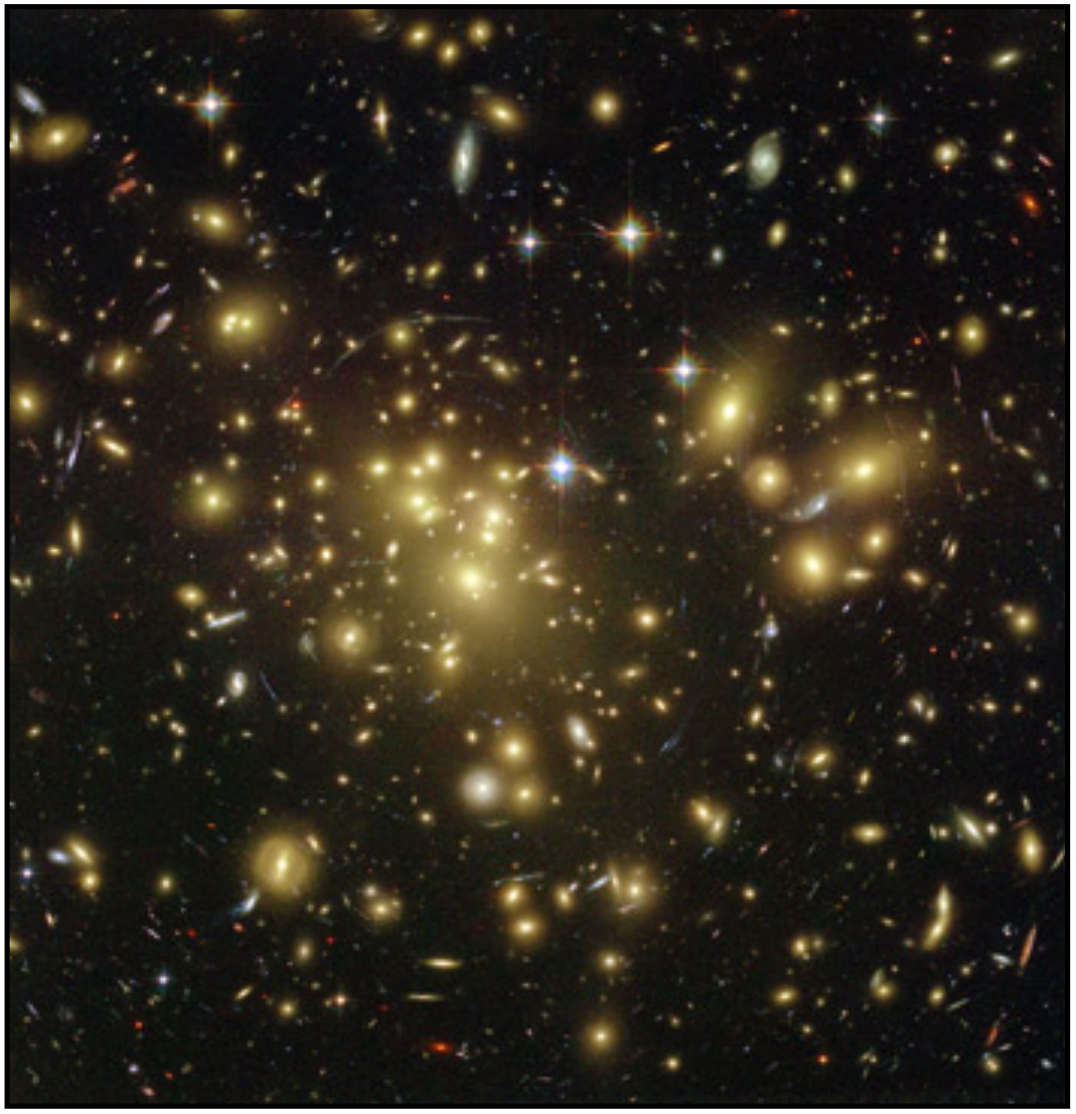


Marshall et al. (2007)

Image Credit: P. J. Marshall

Giant Lenses in the Sky

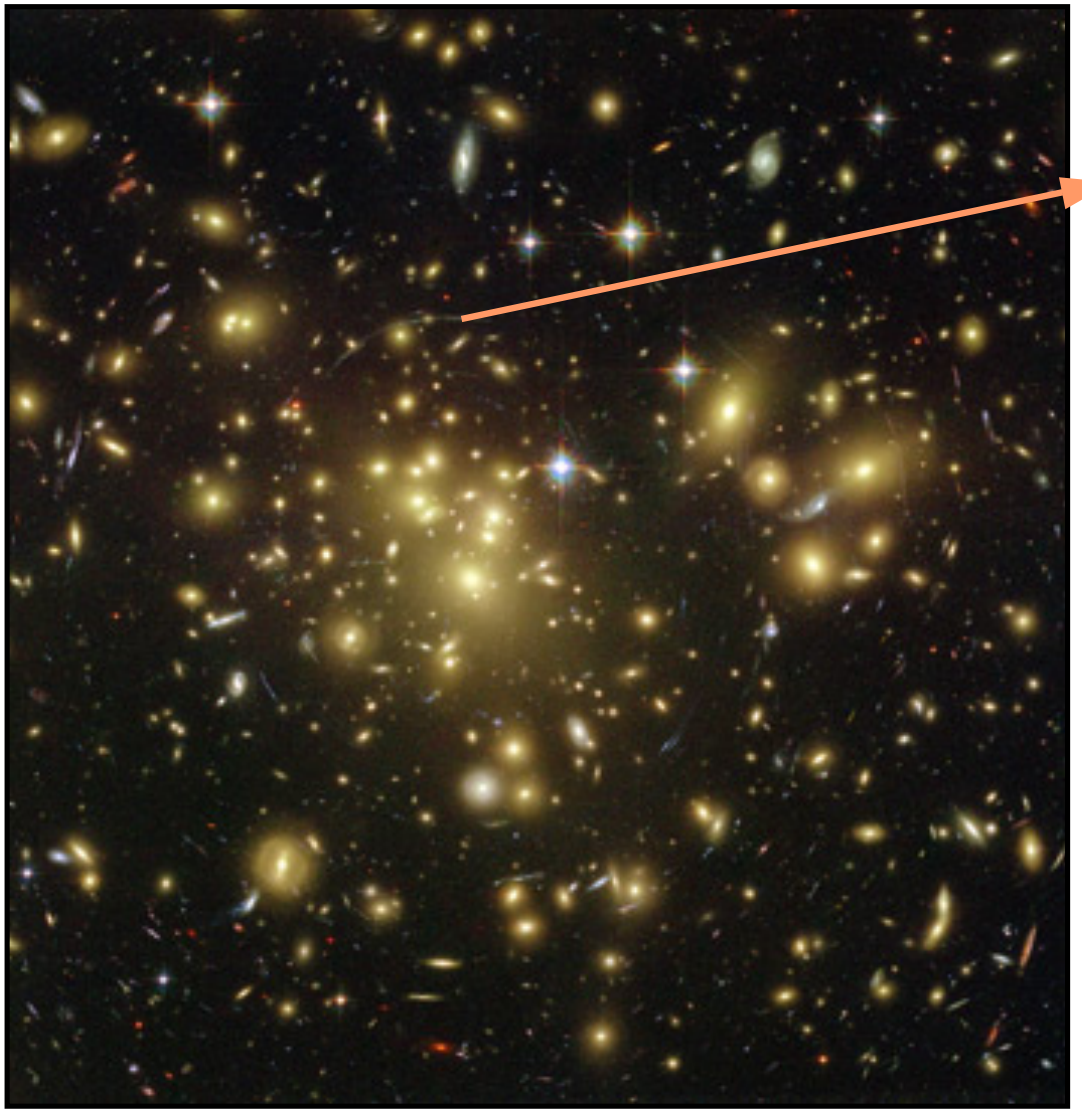
Galaxy
Cluster
Abell 1689



[Image credit: NASA, Benitez et al.]

Giant Lenses in the Sky

Galaxy Cluster Abell 1689

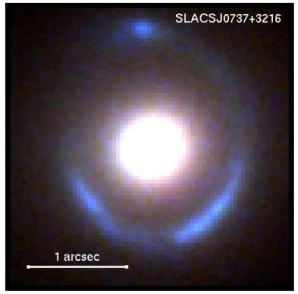


Multiple images of background source form giant arcs

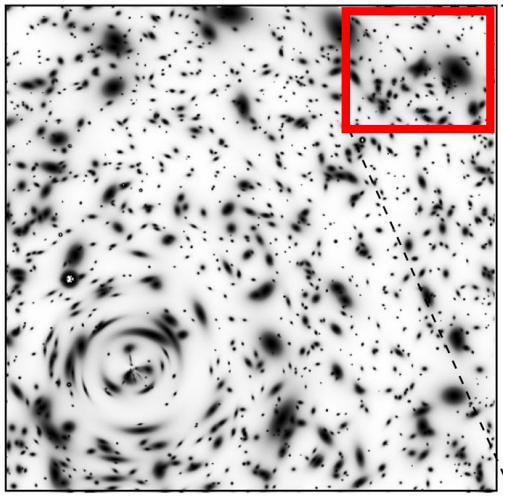
[Image credit: NASA, Benitez et al.]

Three regimes

Strong lensing:
- multiple images of background source
- images are strongly distorted into rings/arcs

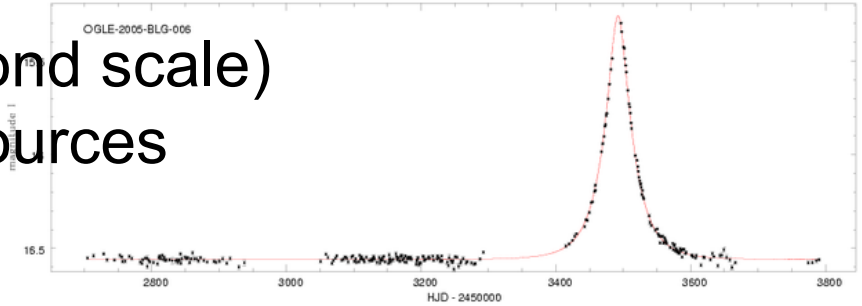


Weak lensing:
- weak distortions of singly imaged background sources

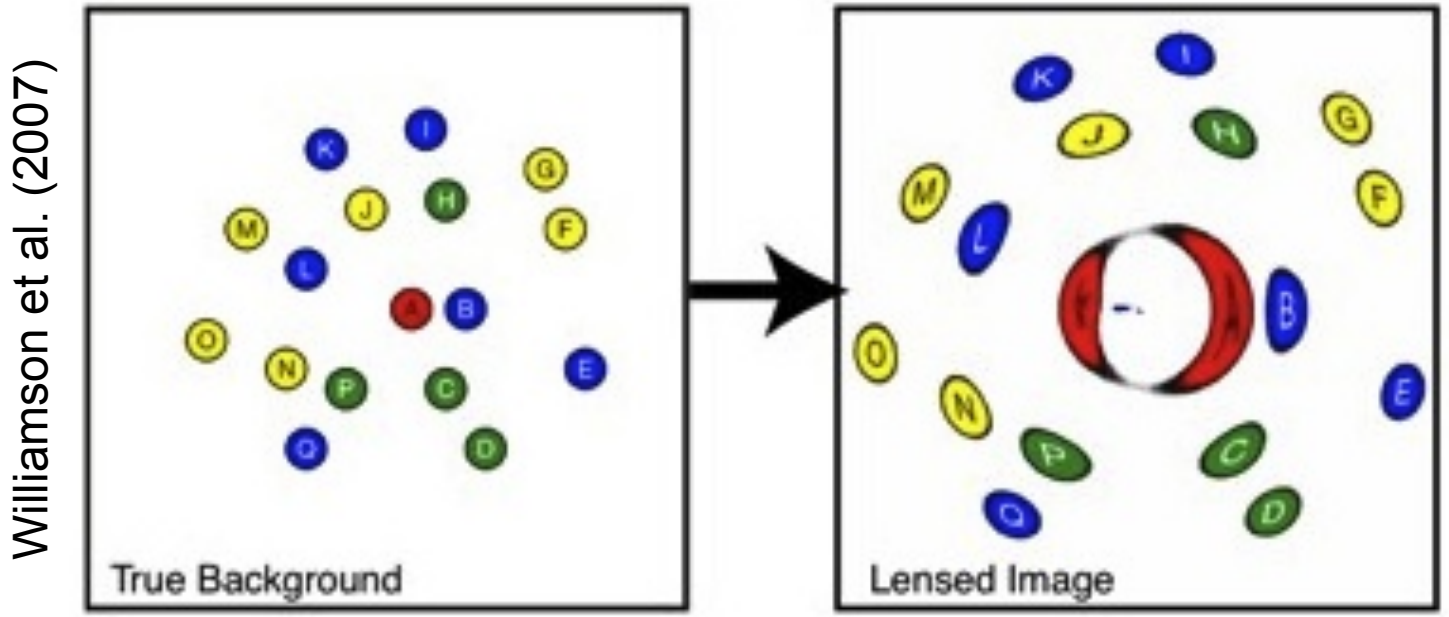


[Mellier 1999]

Microlensing:
- lensing by stars (micro-arcsecond scale)
- magnification of background sources



Recap



H is an example of

i) strong lensing
ii) weak lensing
iii) strong or microlensing
iv) None of the above

A is an example of

i) strong lensing
ii) weak lensing
iii) strong or microlensing
iv) None of the above

Brief history of lensing

Deflection Predictions

Newtonian theory of gravitation:

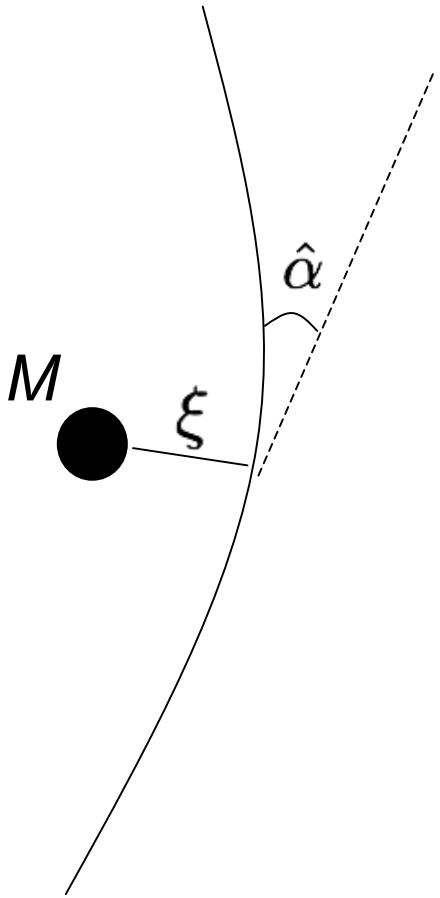
test particle with velocity *v* moving past an object of mass *M* is deflected by

$$\hat{\alpha} = 2GM/(v^2\xi)$$

if light treated as particles

$$\hat{\alpha_{\rm N}} = 2GM/(c^2\xi)$$

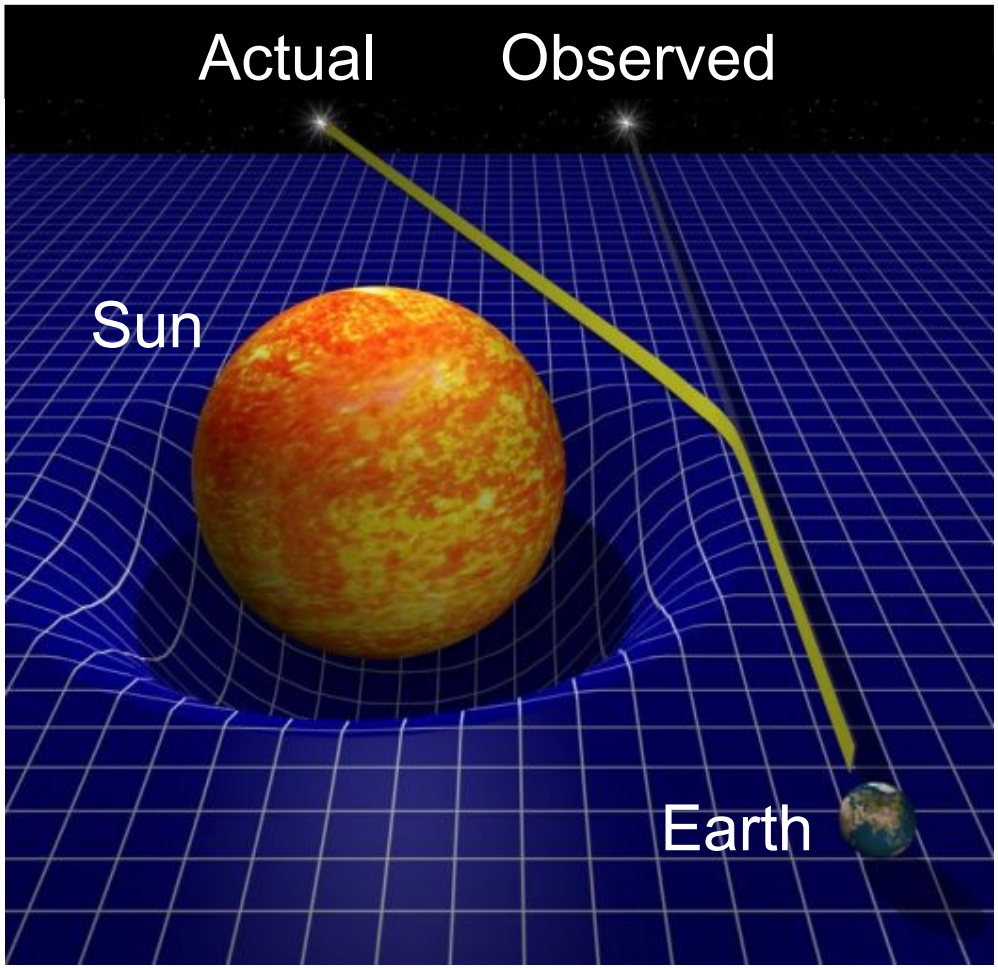
[Mitchell 1784; Soldner 1804]



Einstein's general theory of relativity:

$$\hat{\alpha_{\rm E}} = 4GM/(c^2\xi) = 2\hat{\alpha_{\rm N}}$$

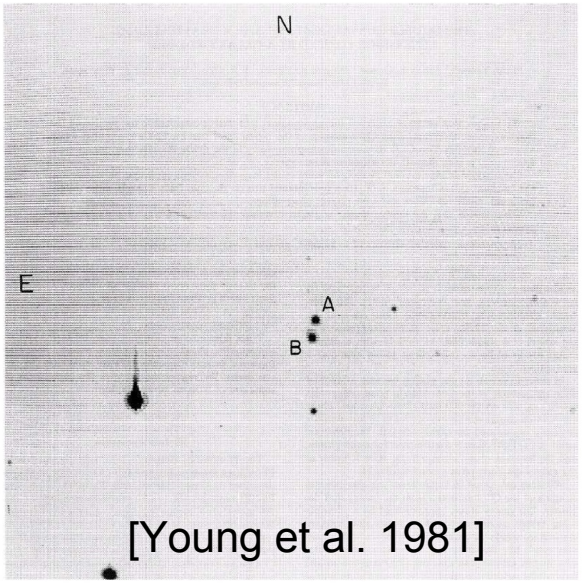
Deflection Detection



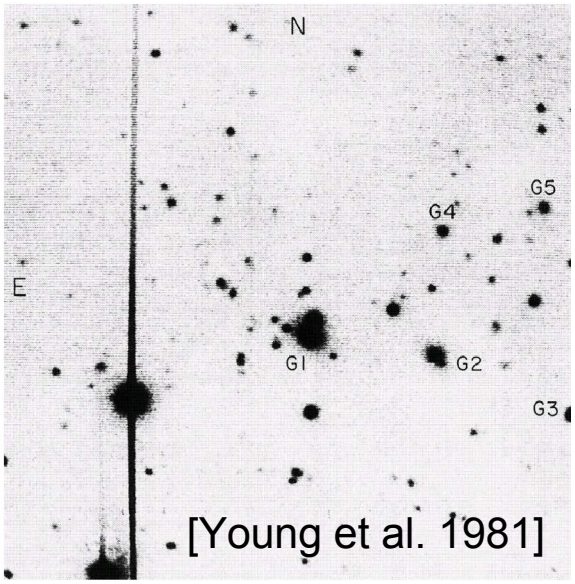
Measure the deflection of background stars by the sun during a total solar eclipse

In 1919, Arthur Eddington and collaborators measured the positions of stars near the sun, and confirmed Einstein's predictions

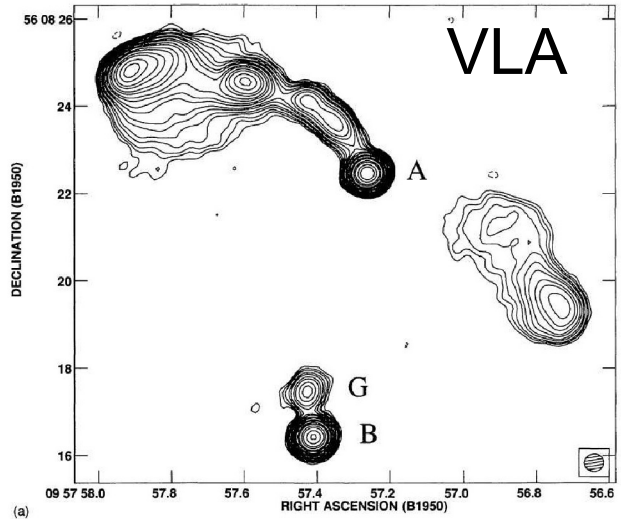
First detection of strong lensing:



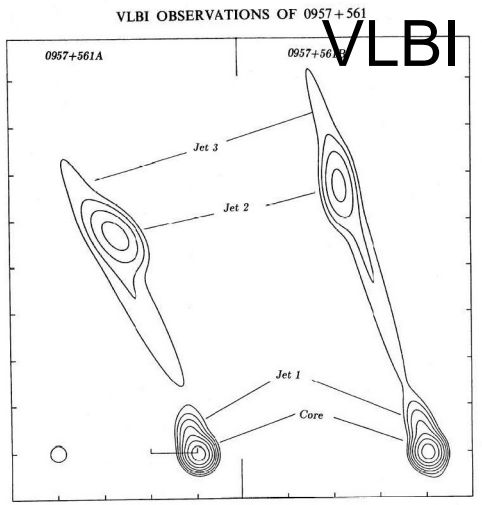
[Young et al. 1981]



[Young et al. 1981]



[Harvanek et al. 1997]

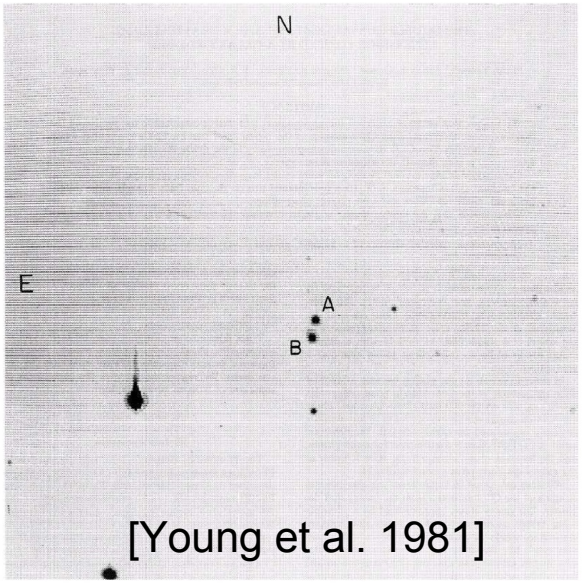


[Gorenstein et al. 1988]

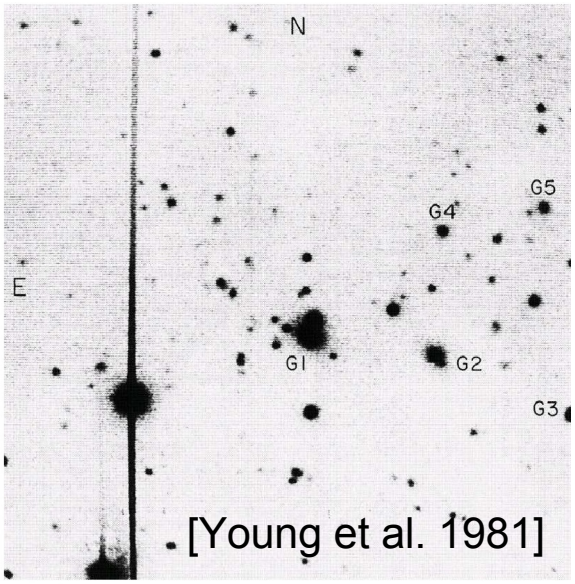
The gravitational lens 0957+561

Walsh, Carswell & Weymann (1979) discovered a pair of quasars separated by ~6”

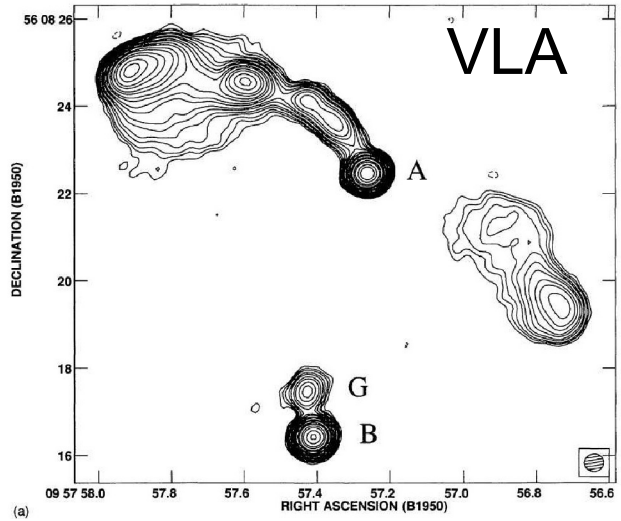
First detection of strong lensing:



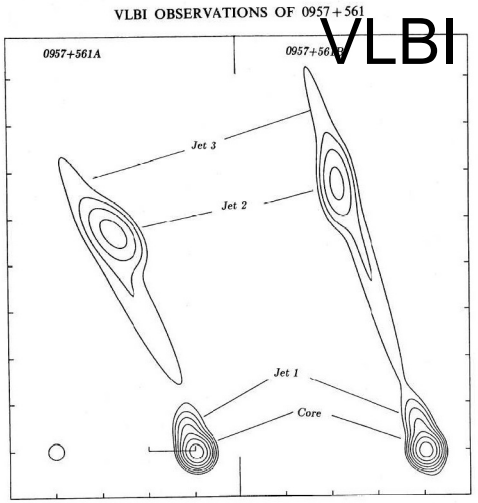
[Young et al. 1981]



[Young et al. 1981]

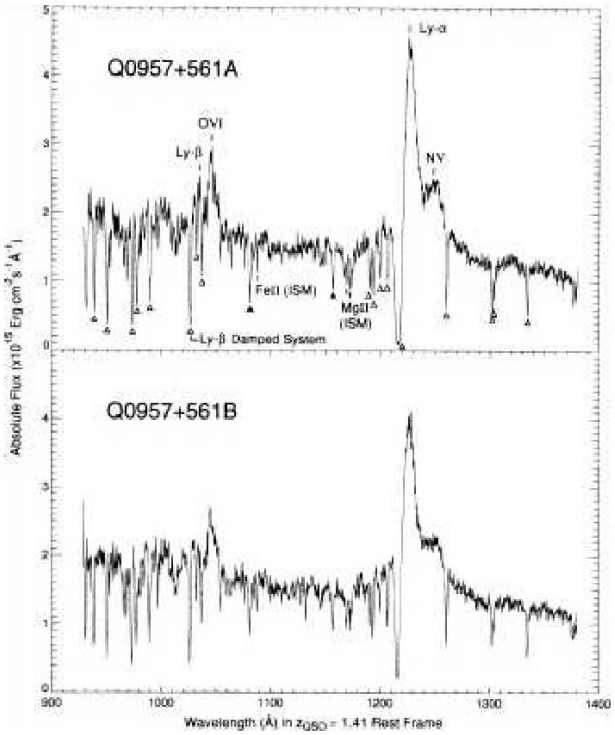


[Harvanek et al. 1997]



[Gorenstein et al. 1988]

The gravitational lens 0957+561

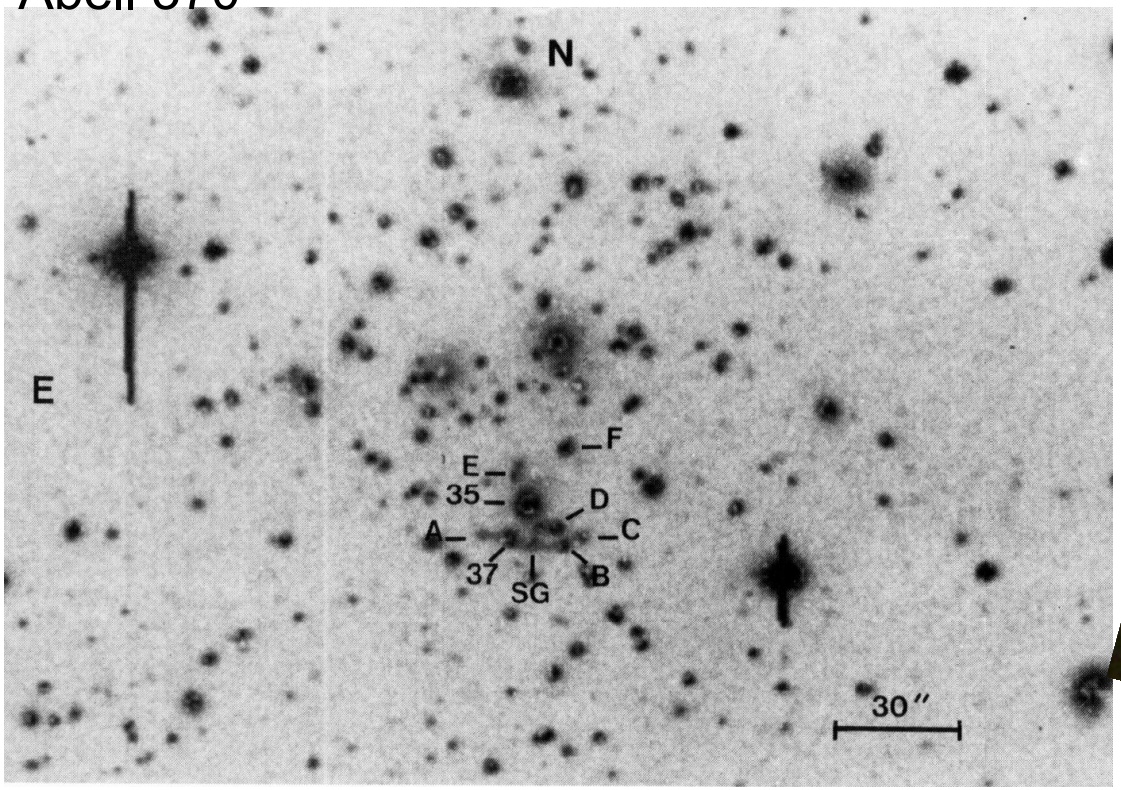


[Michalitsianos et al. 1997]

identical spectra!

Discovery of giant luminous arcs

Abell 370



[Soucail et al. 1987]

Image credit: CFHT

Lynds & Petrosian (1986) and Soucail et al. (1987) independently discovered elongated, curved features around two clusters of galaxies

Discovery of giant luminous arcs

HST ACS image of Abell 370:

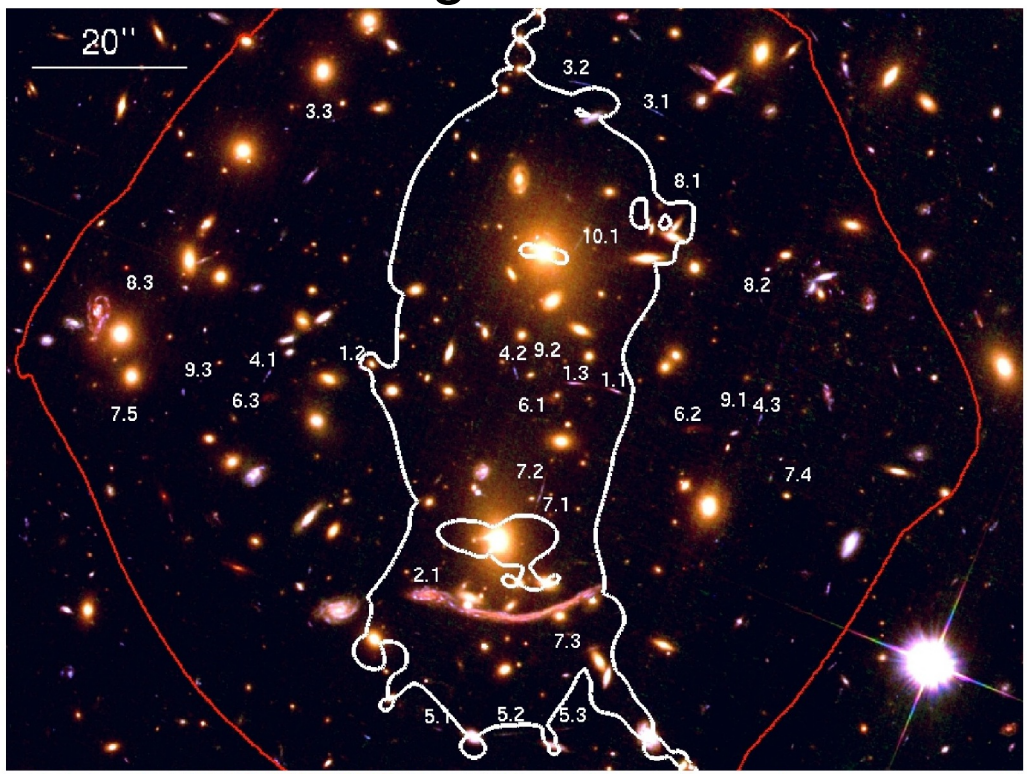
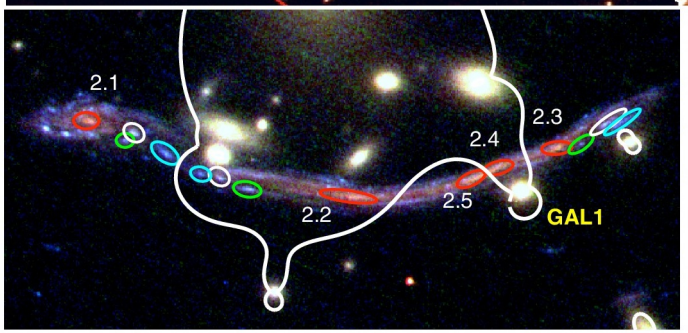
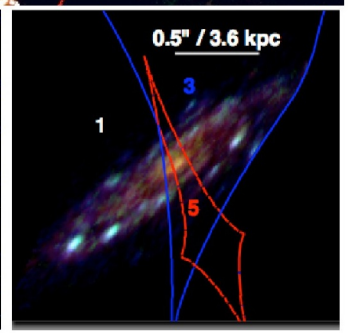


Image credit: CFHT

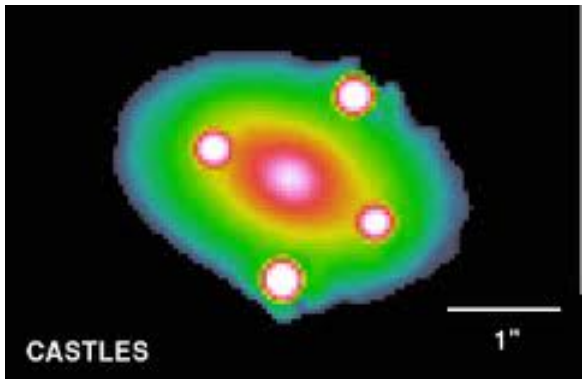




[Richard et al. 2010]

Quasar microlensing

QSO 2237+0305



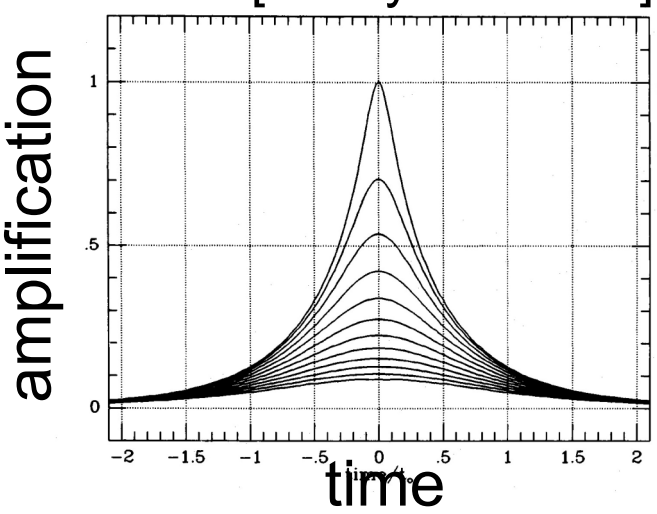
[CASTLES]

- In 1989, the microlensing effect was detected in QSO 2237+0305 [Irwin et al. 1989]
- Stars in the lens galaxies changes the magnifications of the quasar images
- The magnification varies over time since the quasar, lens and observer are not stationary (stars orbit in galaxies)
- The flux variations due to microlensing should be uncorrelated between the different quasar images [Chang & Refsdal 1979, 1984; Paczynski 1986; Kayser et al. 1986; Schneider & Weiss 1987]
- In contrast, flux variations due to intrinsic quasar variability are correlated / delayed

Galactic microlensing

Theory

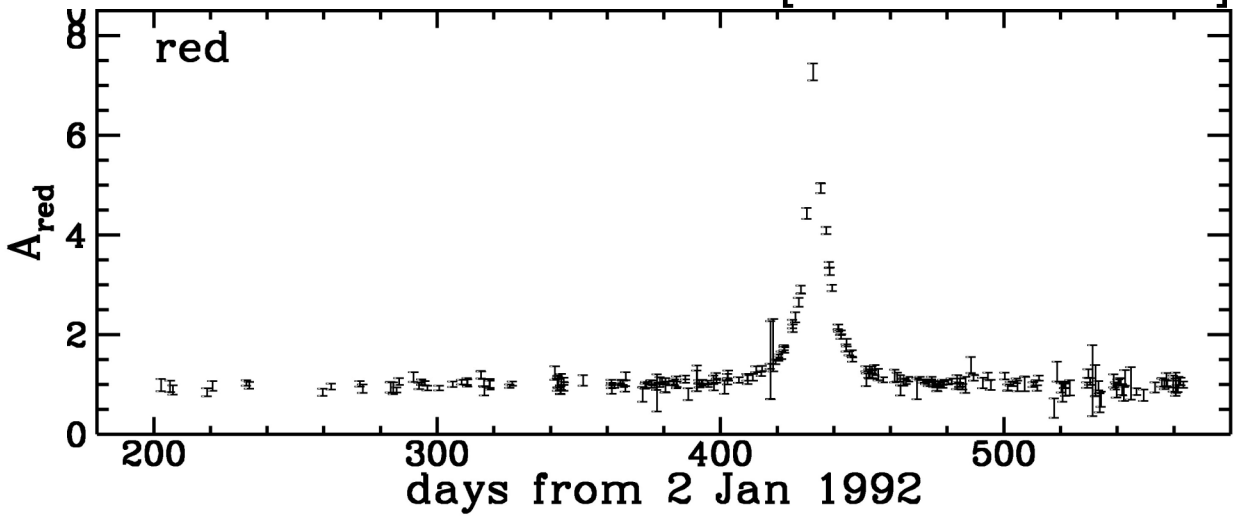
[Paczynski 1986]



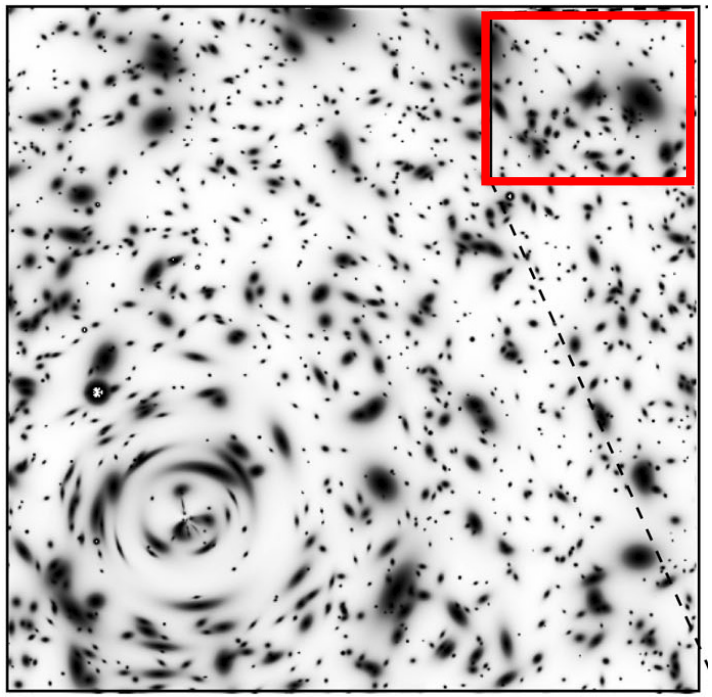
- stars of the Milky way act as lenses for other stars or extragalactic sources
- characteristic light curves of star
- First galactic microlensing events toward the LMC reported in 1993 by two groups Alcock et al. and Aubourg et al.

Observations

[Alcock et al. 1993]



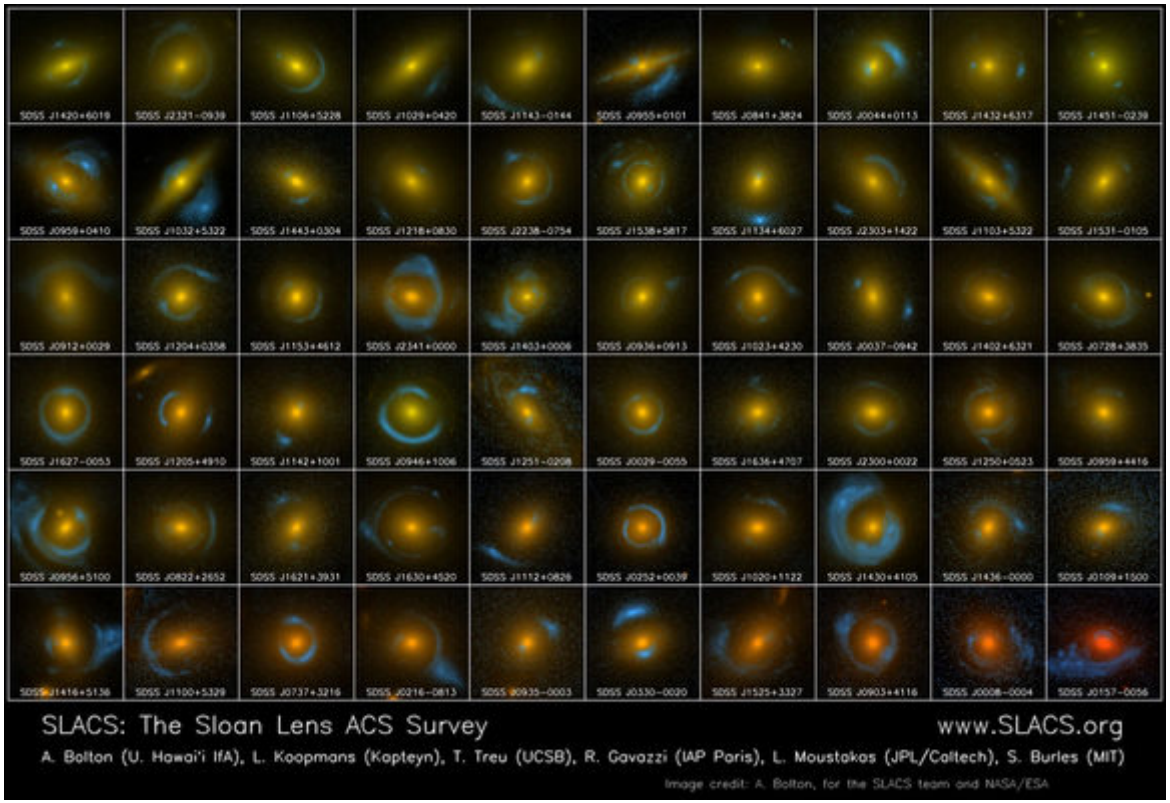
Weak lensing



[Mellier 1999]

- lensing distortion weaker than than intrinsic shape
- measure the shapes of galaxies over local ensembles
- mean distortion of ensemble yields a measure of lens strength
- this weak gravitational lensing effect was first detected in two galaxy clusters by Tyson, Valdes & Wenk (1990)
- even weaker lensing around individual galaxies was discovered by Brainerd et al. (1996)

Years/decades later

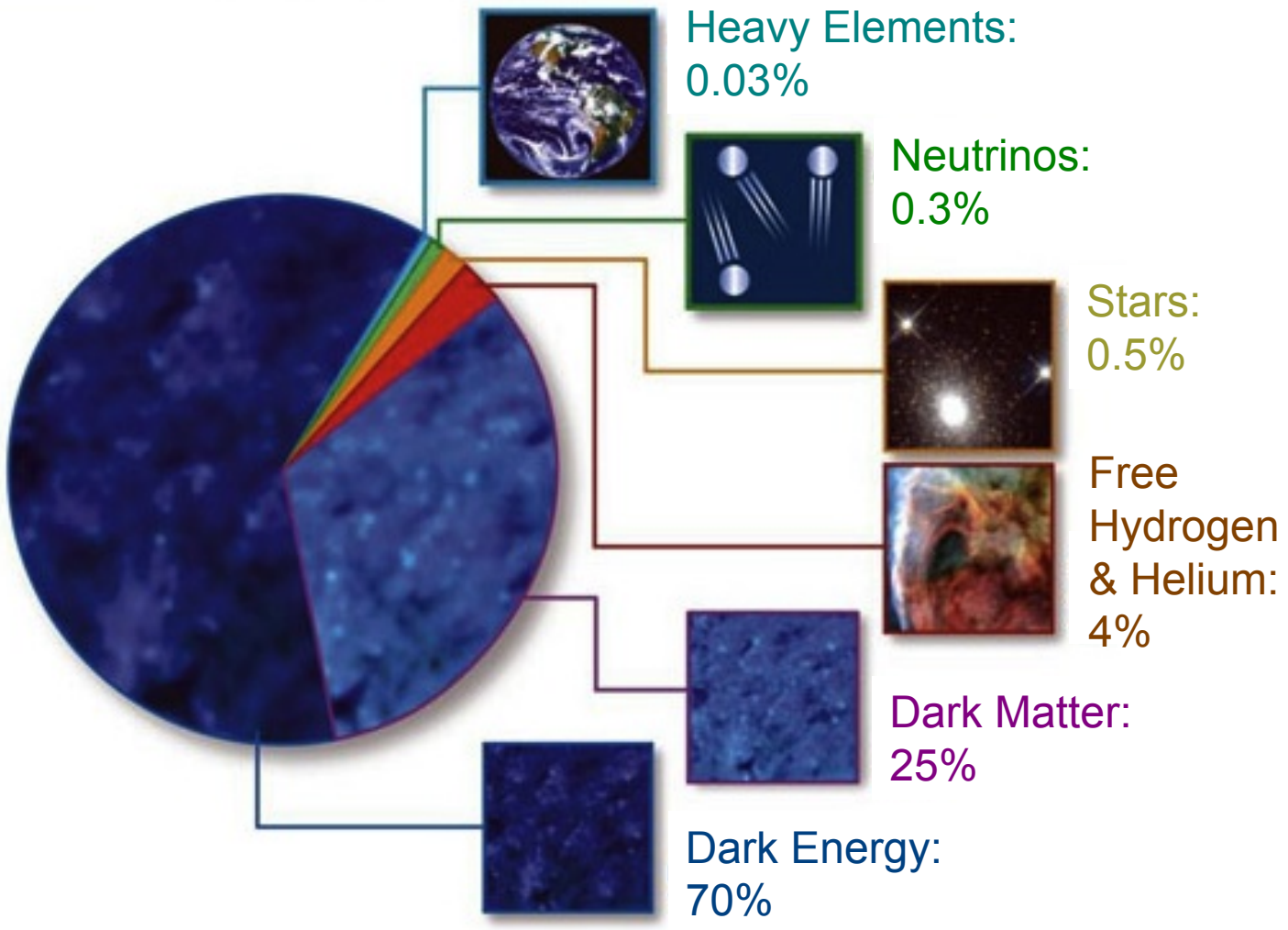


- Radio, optical imaging and spectroscopic surveys in recent years have led to an explosion in the discovery of lens systems
- Hundreds of strong lens systems now known

There are now a multitude of studies in the astrophysics literature based on strong, weak and/or microlensing

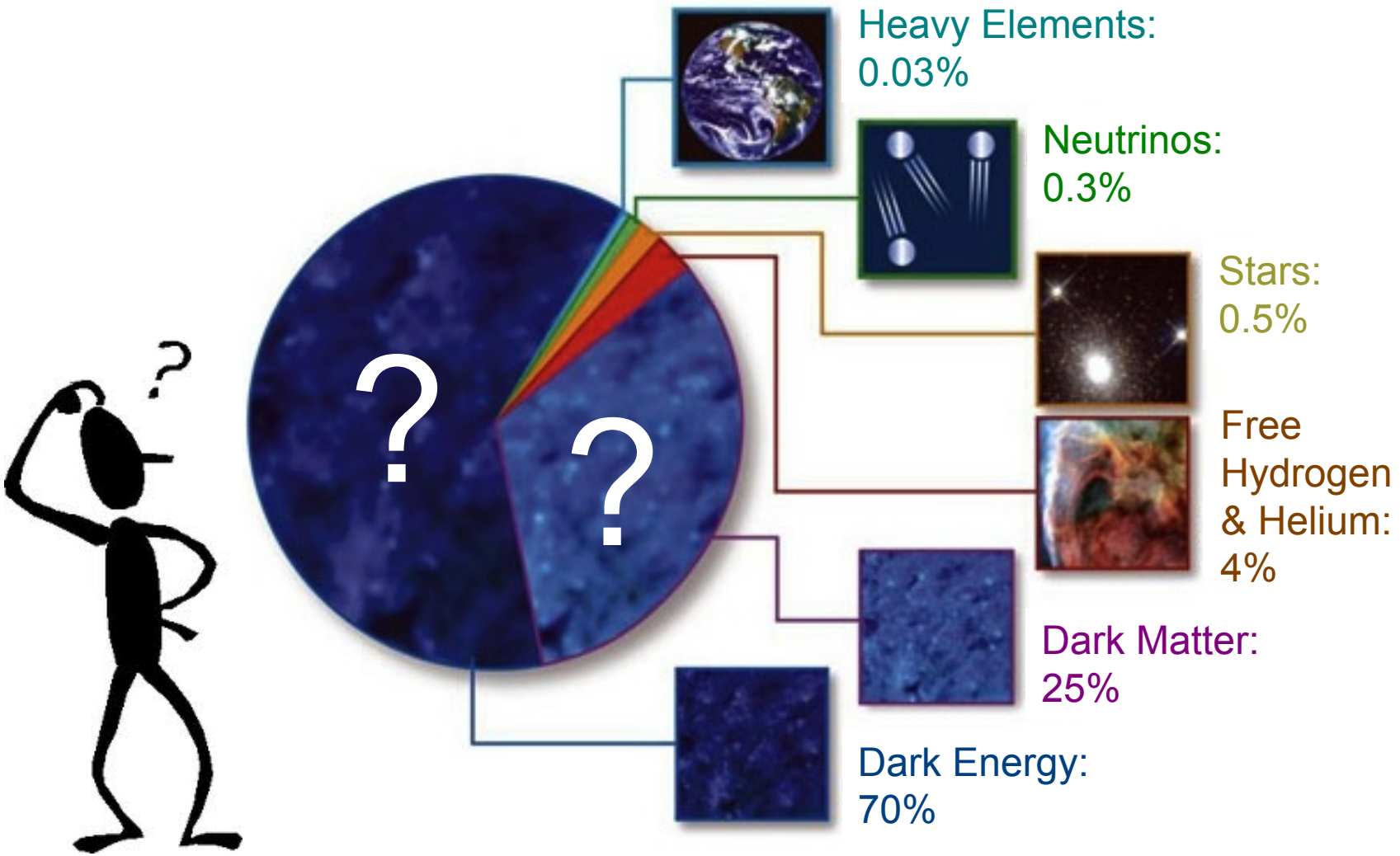
Why use lensing?

Composition of the Cosmos



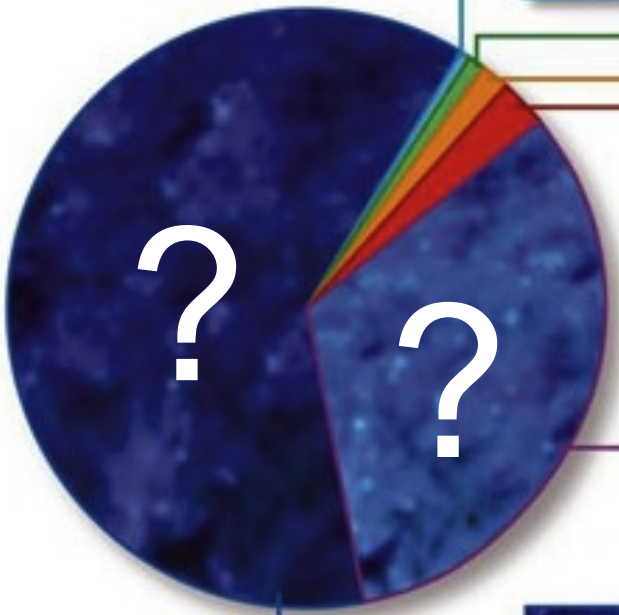
Credit: LSST

Composition of the Cosmos



Credit: LSST

Composition of the Cosmos



Heavy Elements:
0.03%

Neutrinos:
0.3%

Stars:
0.5%

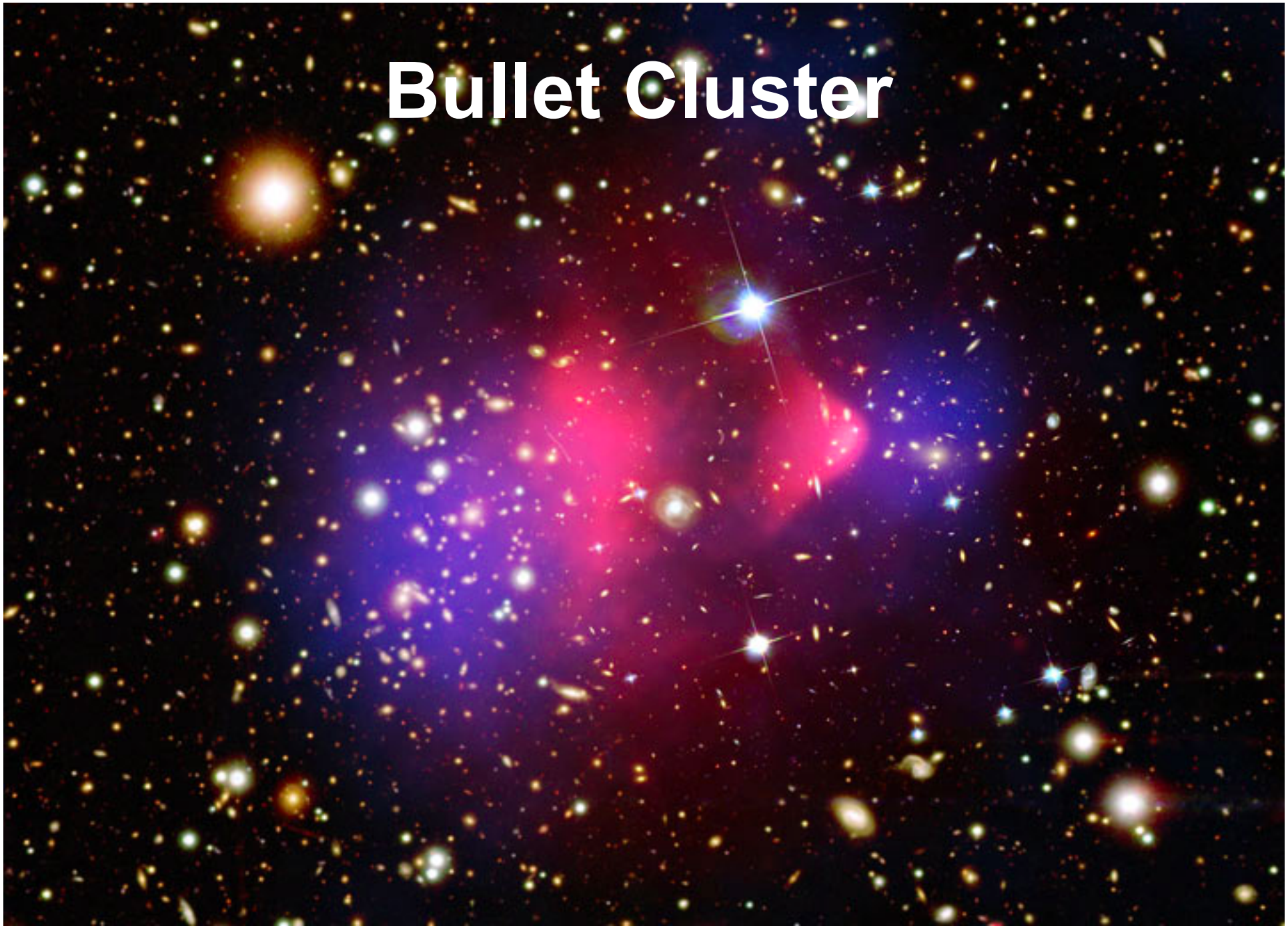
Free
Hydrogen
& Helium:
4%

Dark Matter:
25%

Dark Energy:
70%

Lensing is a powerful probe of the dark components

Bullet Cluster



[Clowe et al. 2006; Bradac et al. 2006]

Dark Matter

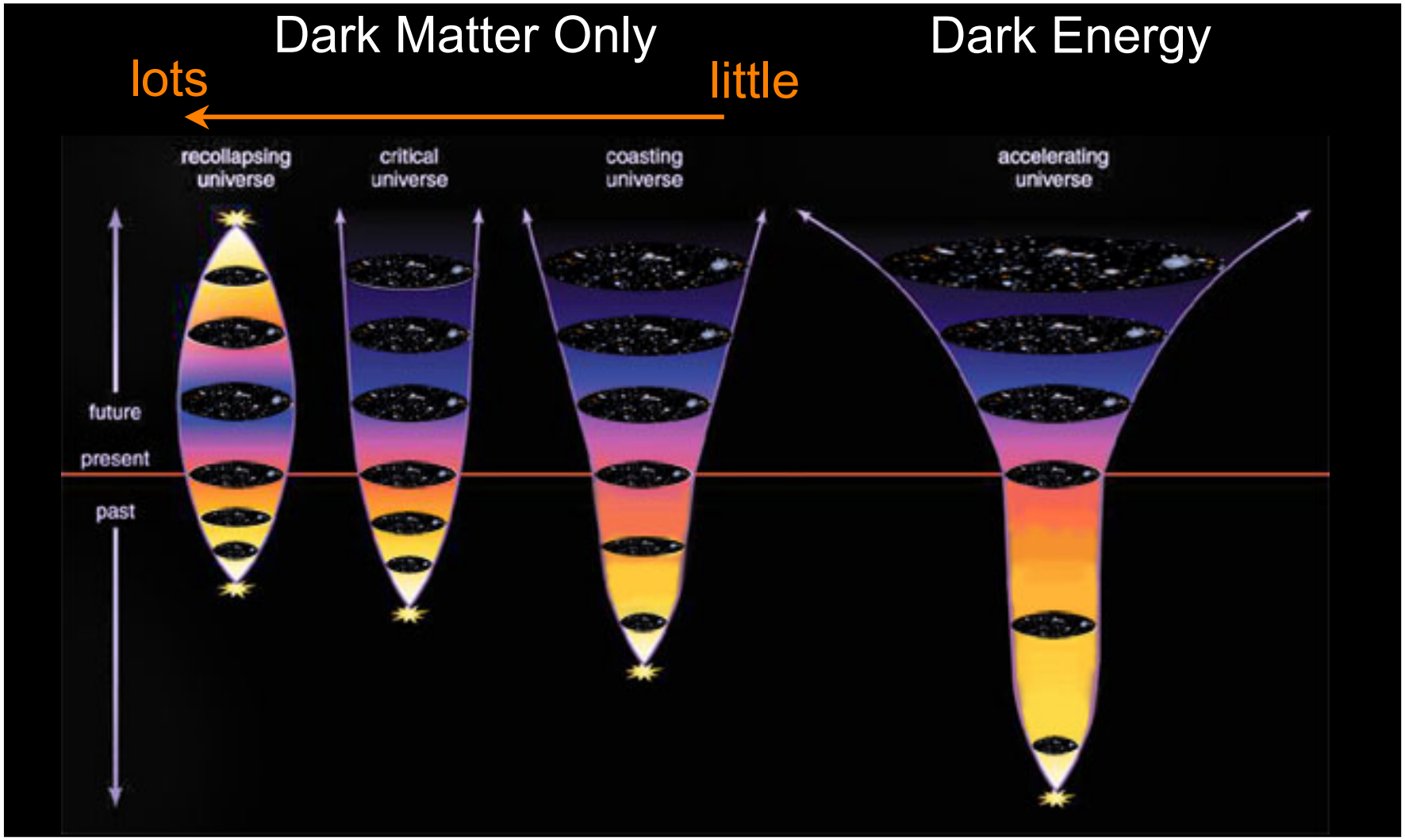
Lensing is excellent for

- measuring properties of dark matter halos of galaxies, groups of galaxies, and clusters of galaxies [e.g., Auger et al. 2010, Suyu & Halkola 2010, Natarajan et al. 2009; Mandelbaum et al. 2006; Newman et al. 2012]
  Important for understanding galaxy formation & evolution

- Detecting dark matter substructure and measuring the substructure mass fraction [e.g., Dalal & Kochanek; Fadely et al. 2012; Vegetti et al. 2012]
  Important for resolving the Missing Satellite Problem

Fate of the dark Universe

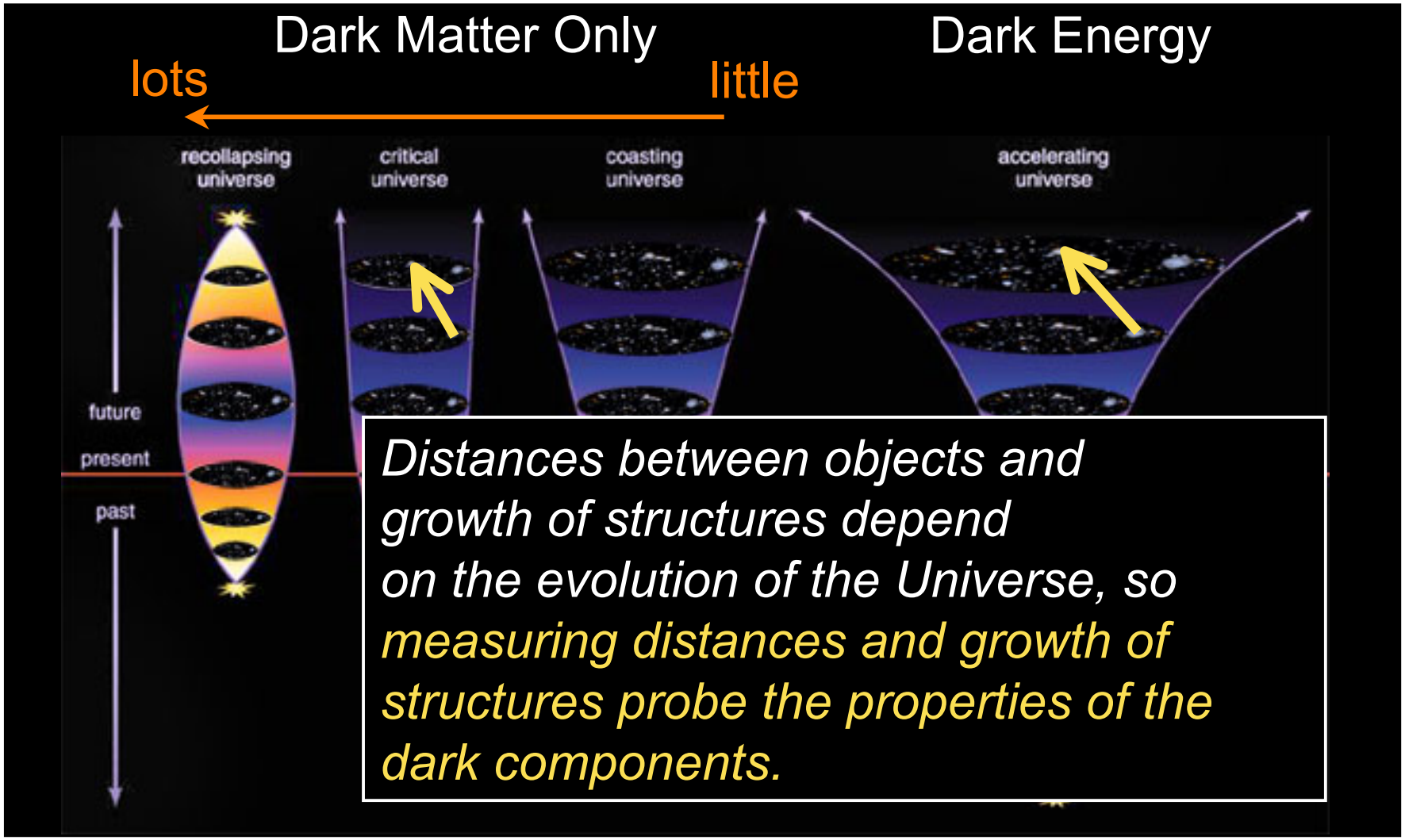
Dark energy and dark matter determine fate of Universe



Credit: LSST

Fate of the dark Universe

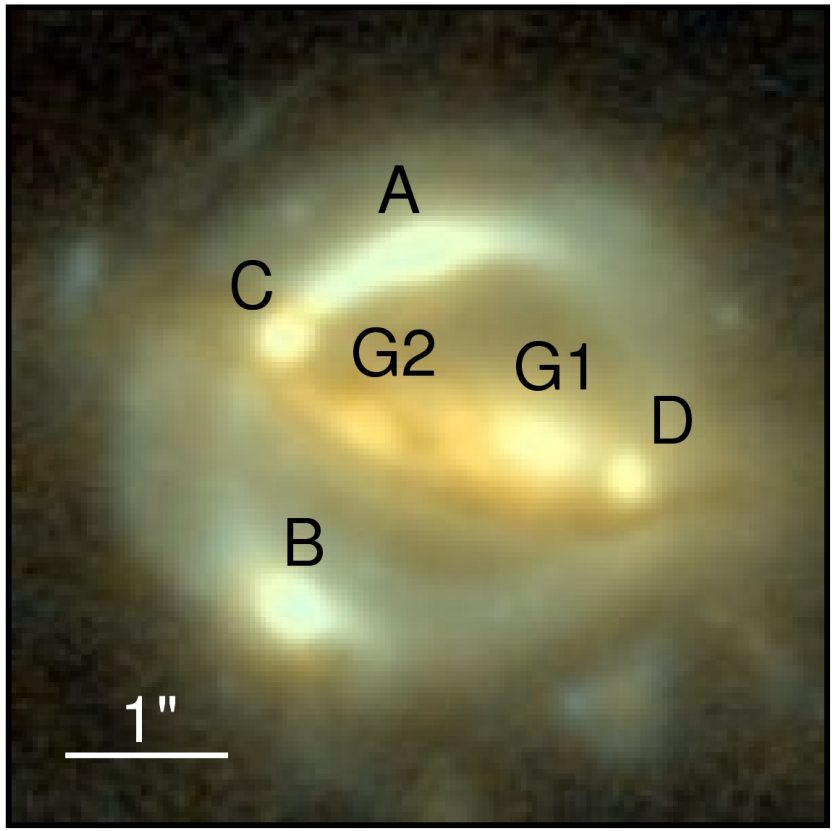
Dark energy and dark matter determine fate of Universe



Credit: LSST

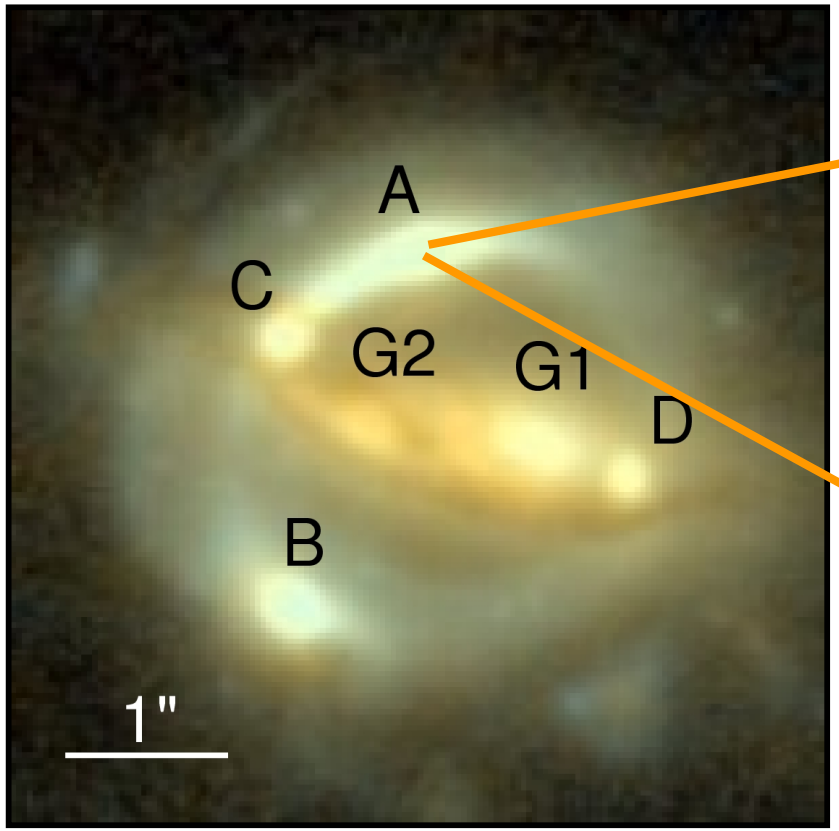
Measuring distance with lensing

B1608+656



Measuring distance with lensing

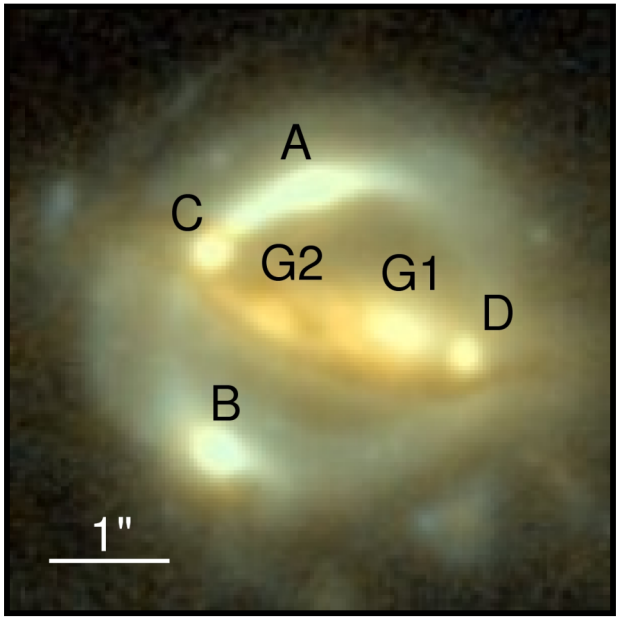
B1608+656



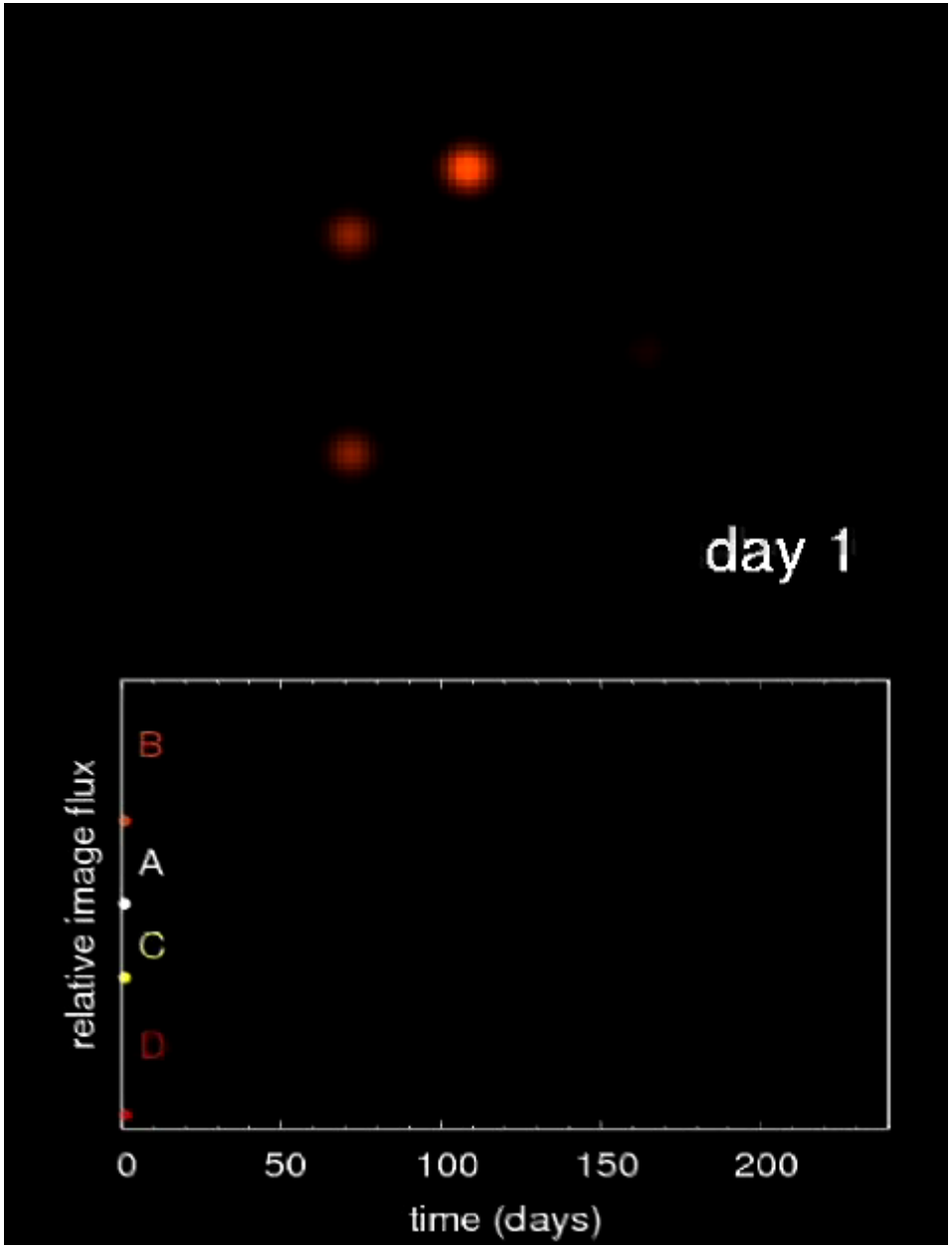
Active galactic nucleus (AGN) in the source:

Light emitted from AGN changes in time (“flickers”)

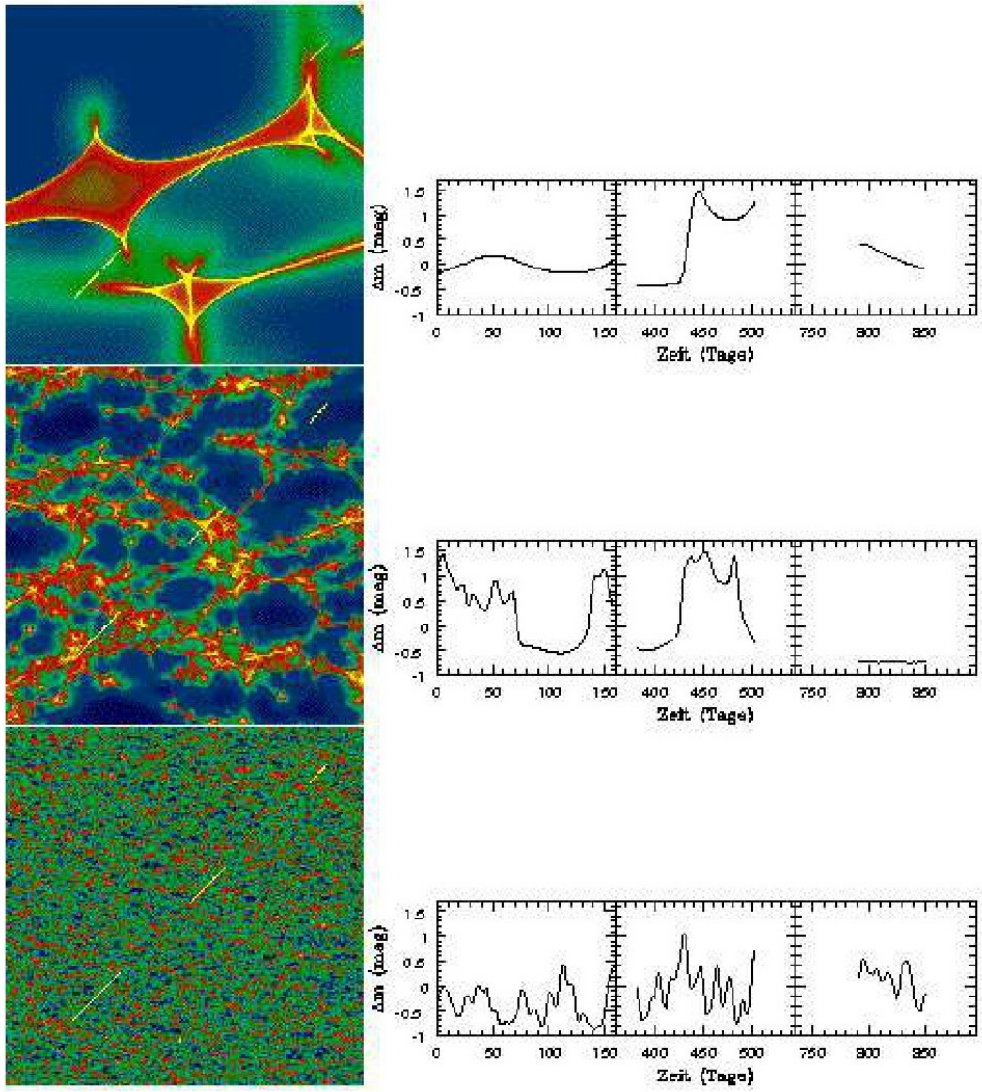
Gravitational Lens Time Delays



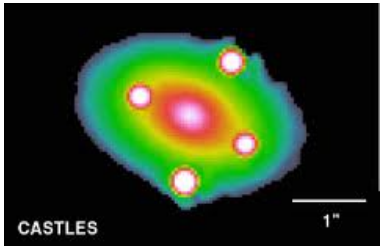
With a lens mass model, the delays can be converted to a distance measurement [e.g., Fadely et al. 2010; Suyu et al. 2010, 2012]



Quasar accretion disk size



[Wambsganss et al. 2000]



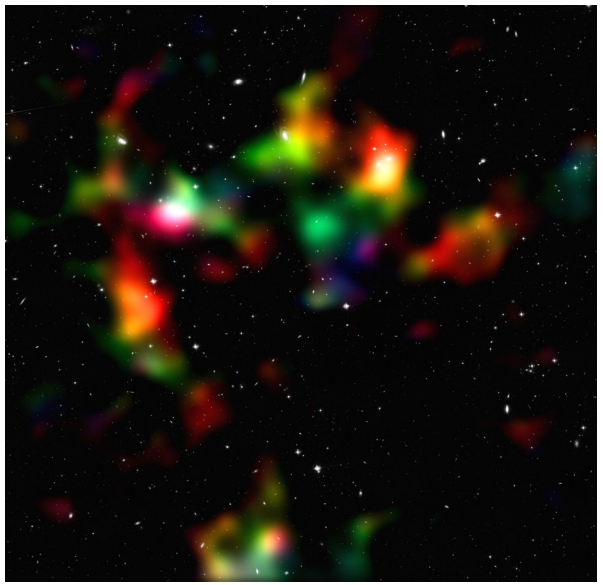
Microlensing variability depends on mass of the microlenses (stars) and source size

Microlensing of lensed quasar is a powerful way to measure the size of the quasar accretion disk [e.g., Wambsganss et al. 2000; Morgan et al. 2008; Morgan et al. 2010]

Cosmology with weak lensing

Weak lensing by large-scale structure

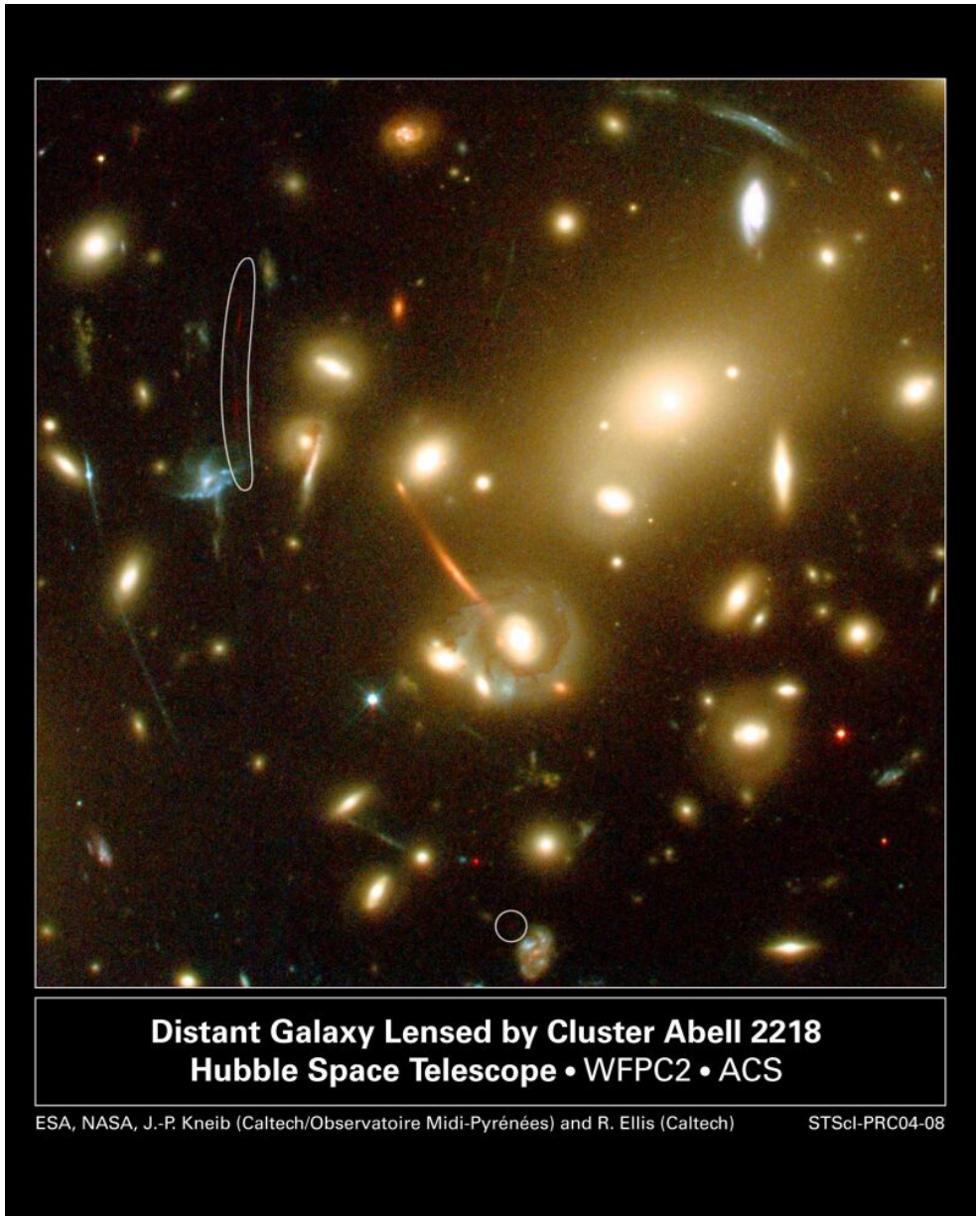
- sensitive to the matter density parameter and normalization of density fluctuations
- independently confirmed existence of dark energy [e.g., Schrabback et al. 2010]



Galaxy cluster abundances and masses provides a cosmological probe. [e.g., Benson et al. 2011]. Weak lensing provides absolute mass calibration [e.g., von der Linden et al. 2012; Applegate et al. 2012;]

Gravitational lensing in galaxy cluster Abell 2218. NASA, A Fruchter and the ERO Team (STScI).

Cosmic telescope



Lensing arcs are highly magnified (~10-100) background sources

Galaxy clusters are nature's cosmic telescope to observe baby galaxies [e.g., Kneib et al. 2004; Swinbank et al. 2009; Jones et al. 2010; Bradac et al. 2012; Hall et al. 2012]

Planet searches

Star and planet act as microlenses