Strong Gravitational Lensing

Utilizing Nature's Telescope for the Study of Galaxy Evolution

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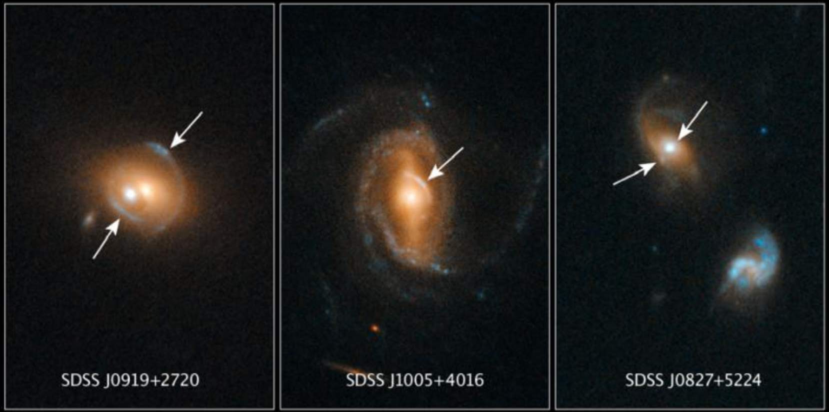
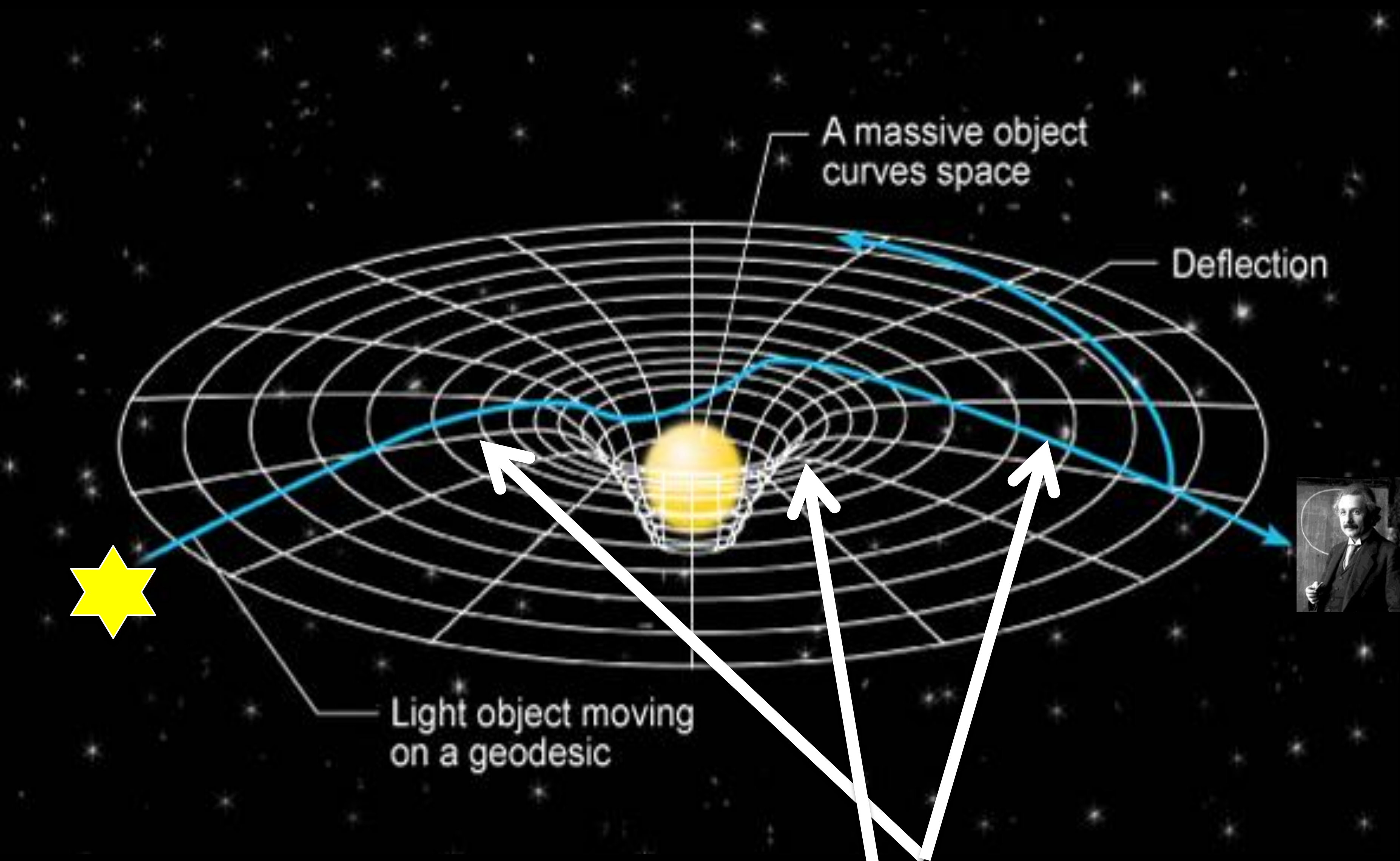
Outline

- Introduction to gravitational lensing
- What are the advantages of gravitational lensing?
- Some pretty pictures
- The science
- Sloan Lens ACS Survey
- Future prospects



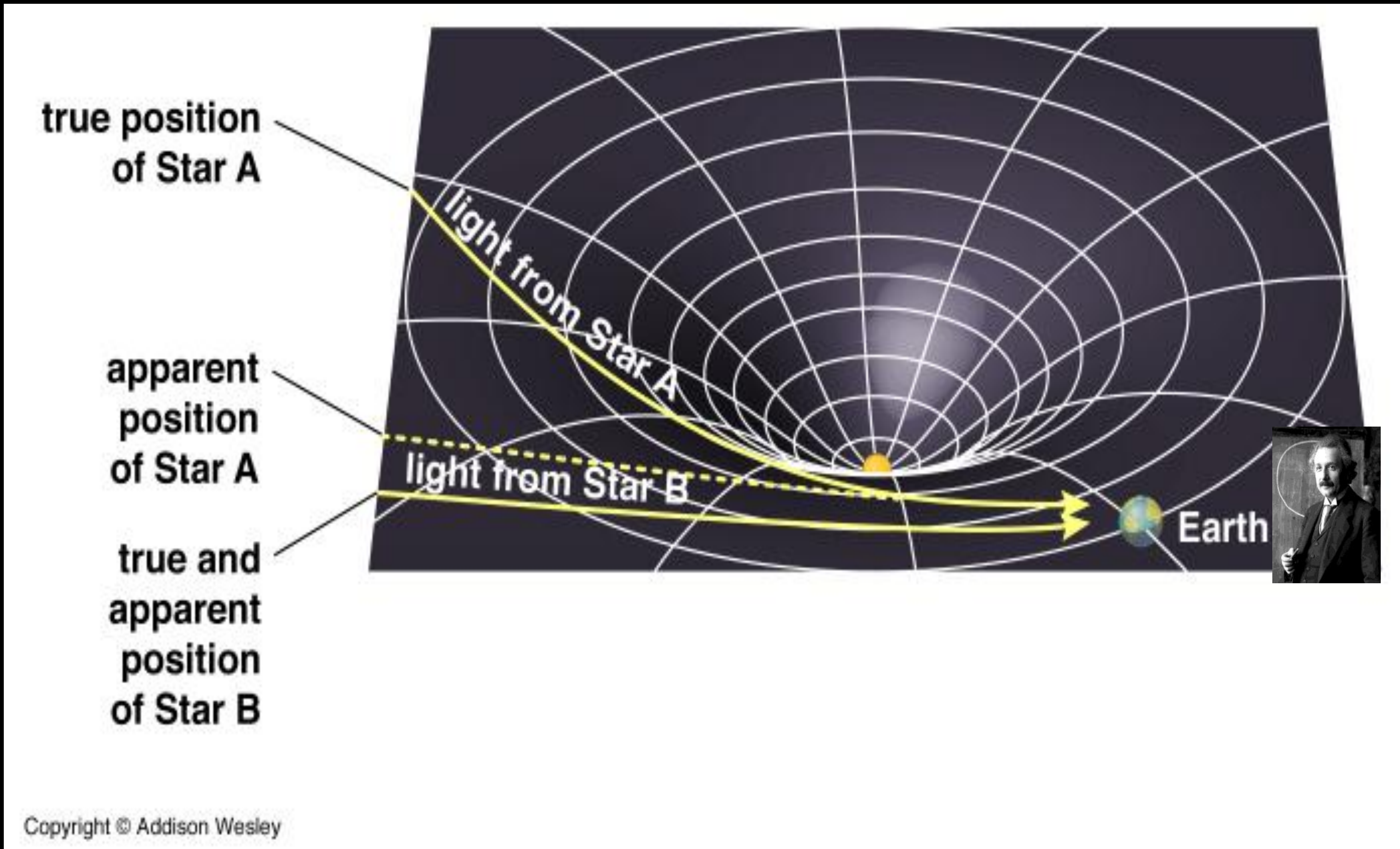
Predictions from the General Theory of Relativity



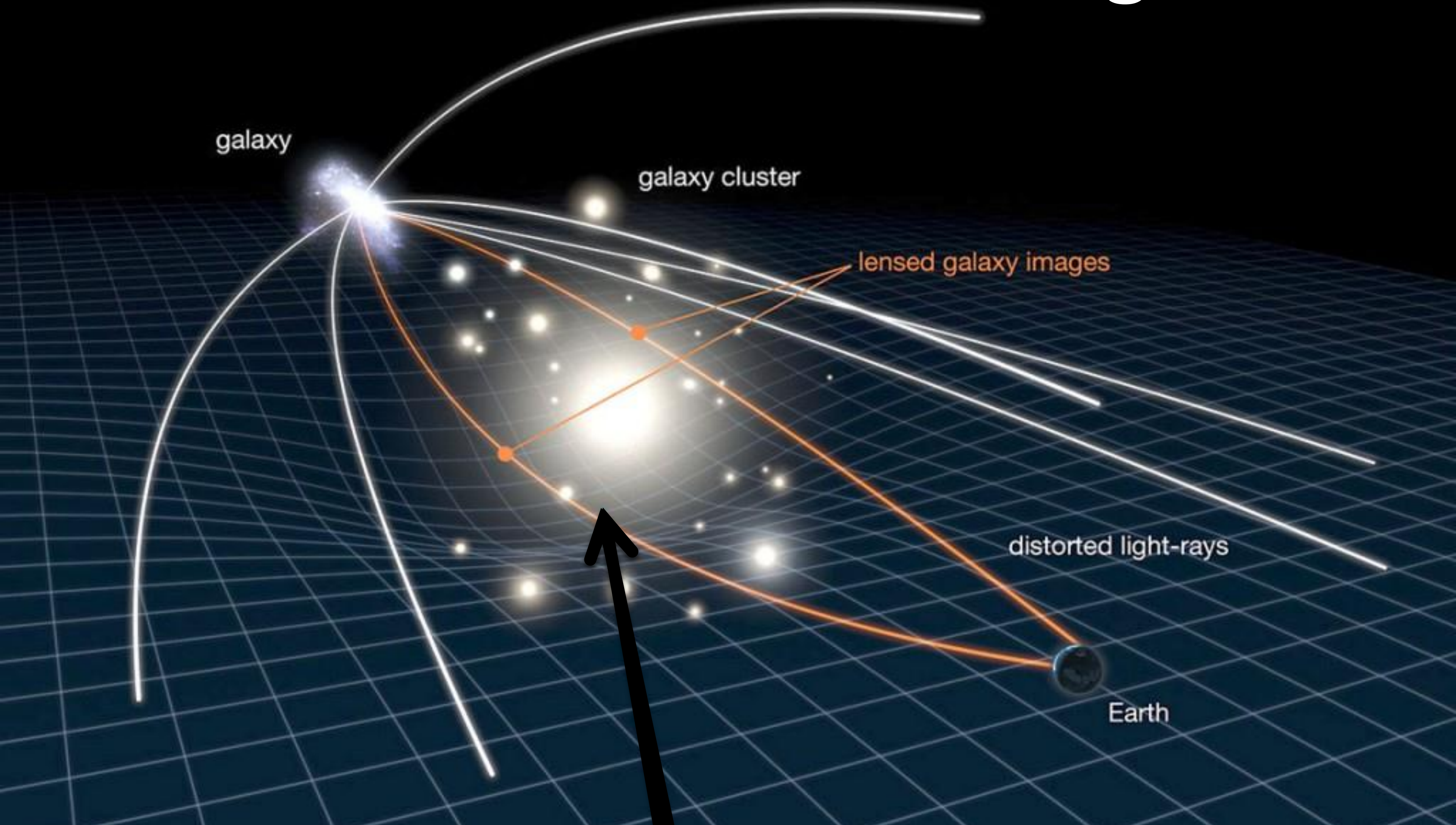
Geodesic = Shortest Path

Gravity = Curvature of spacetime

Predictions from the General Theory of Relativity

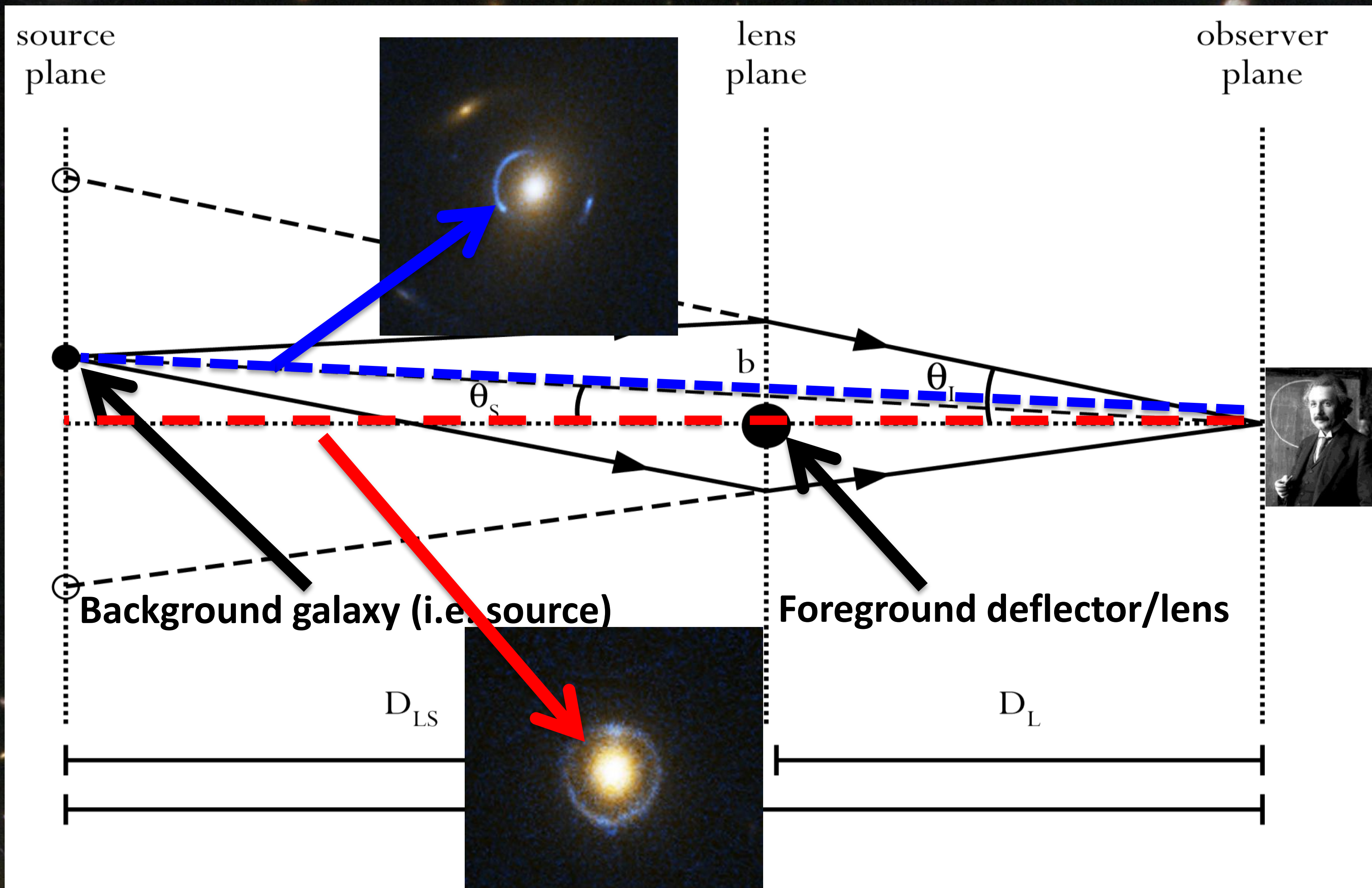


Gravitational Lensing



Larger curvature of spacetime = larger deflection

A Cross Section of a Gravitational Lens

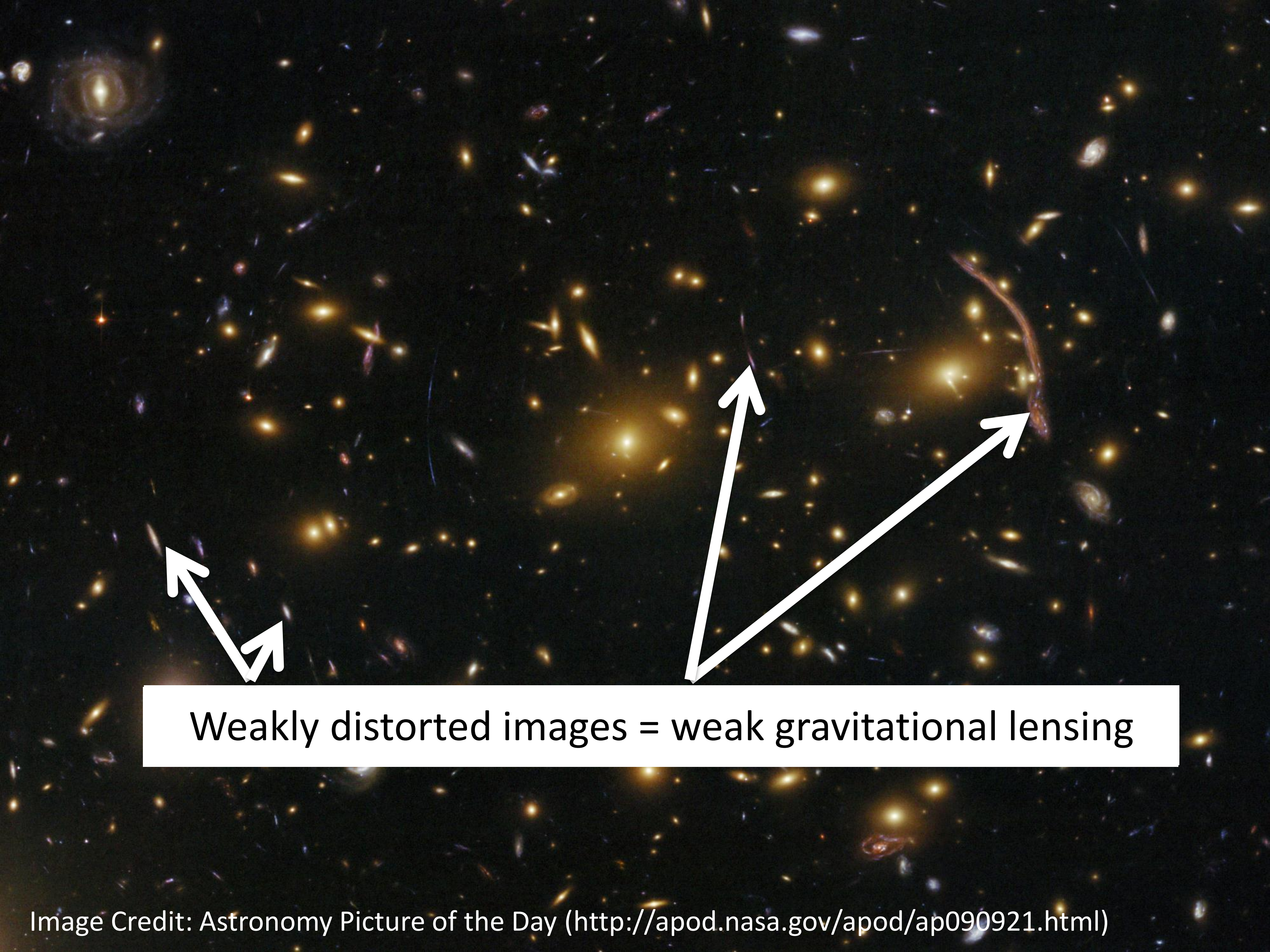


What Kind of Objects Act as Extragalactic Gravitational Lenses?

- A single galaxy (typically, bright and massive elliptical galaxies)

- A group of galaxies

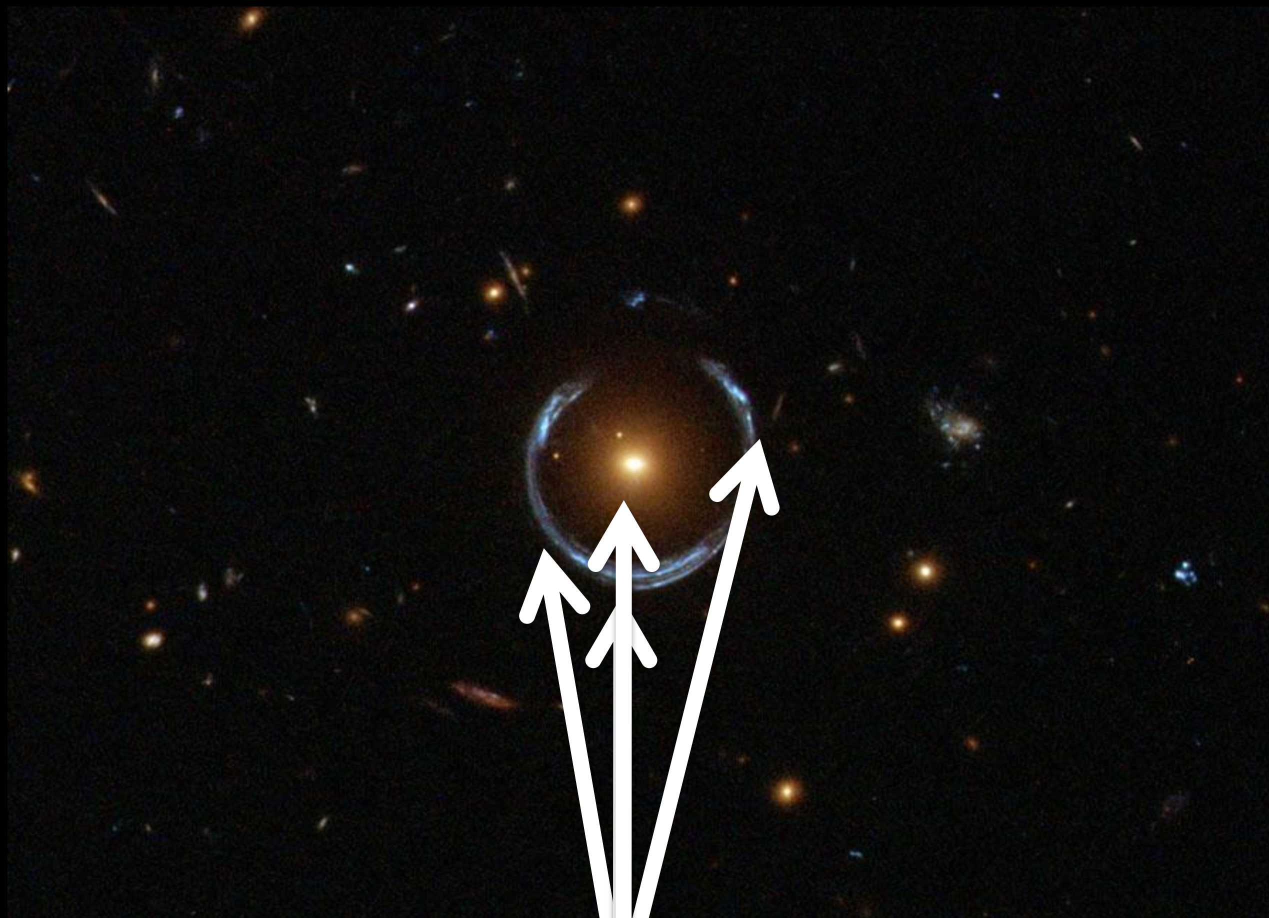
- A cluster of galaxies



Weakly distorted images = weak gravitational lensing

Image Credit: Astronomy Picture of the Day (http://apod.nasa.gov/apod/ap090921.html)

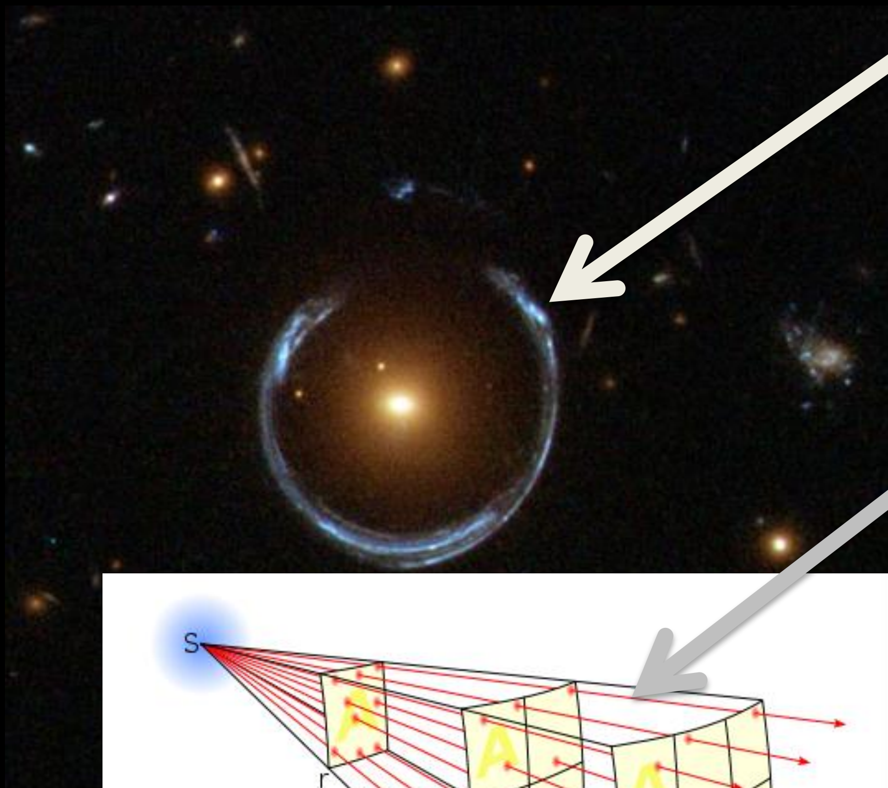
Advantages of Strong Gravitational Lensing

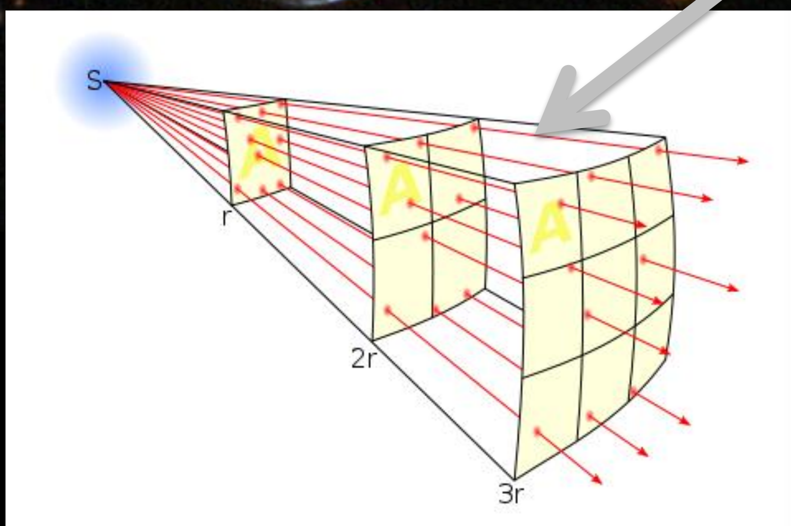


…we can measure the amount of mass that gives rise to the deflection → Even if the mass isn't all visible…

If we can measure the deflection of the light…

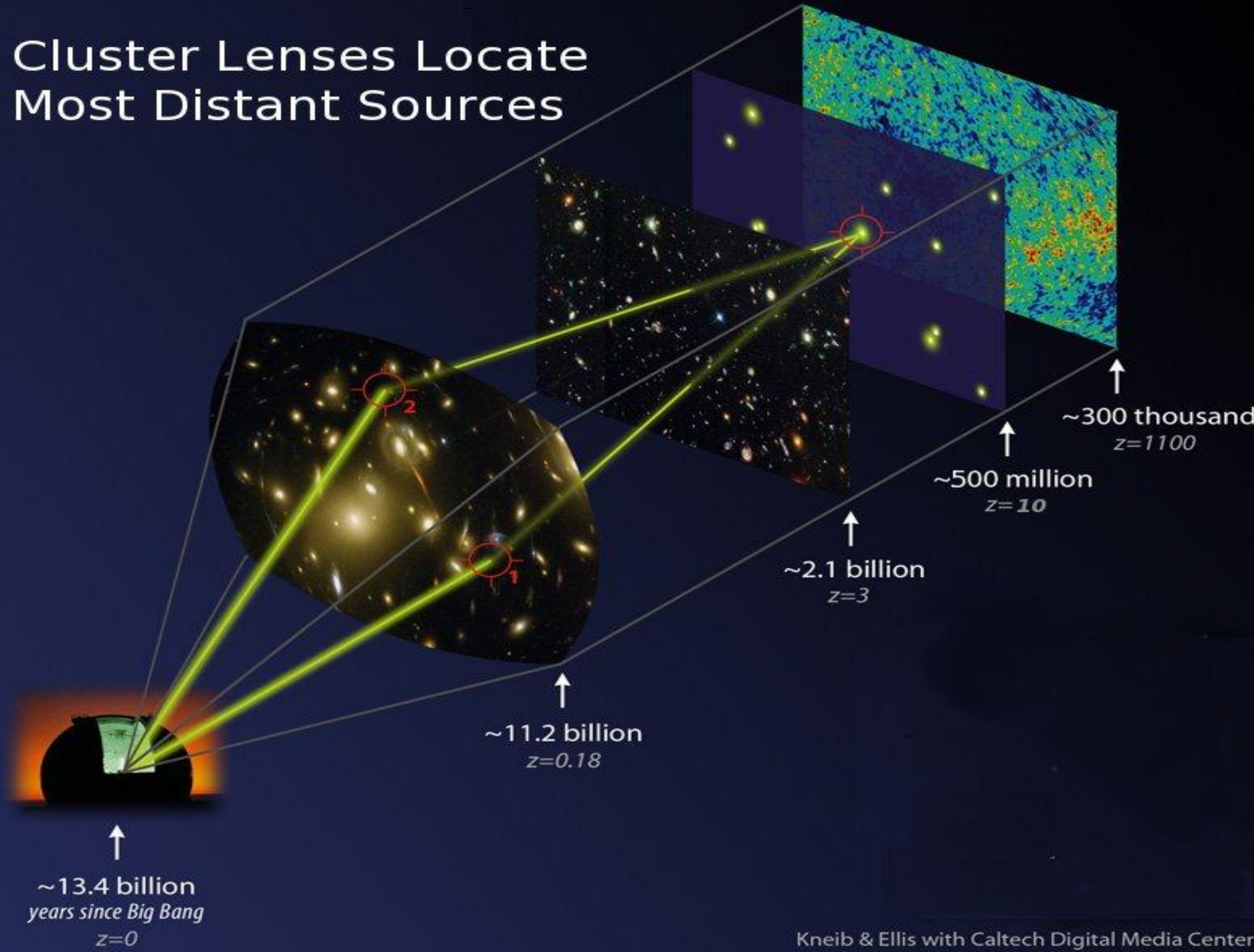
Advantages of Strong Gravitational Lensing Pt. 2





- Gravitational lensing magnifies the area of the background galaxy that we observe.
- But preserves *surface brightness*.
- **Surface brightness** = luminosity over a given area
- If the *observed area* of the background galaxy increases because of lensing…
- …*observed brightness* of the background galaxy increases too!

Cluster Lenses Locate Most Distant Sources



Kneib & Ellis with Caltech Digital Media Center

Horseshoe Einstein Ring

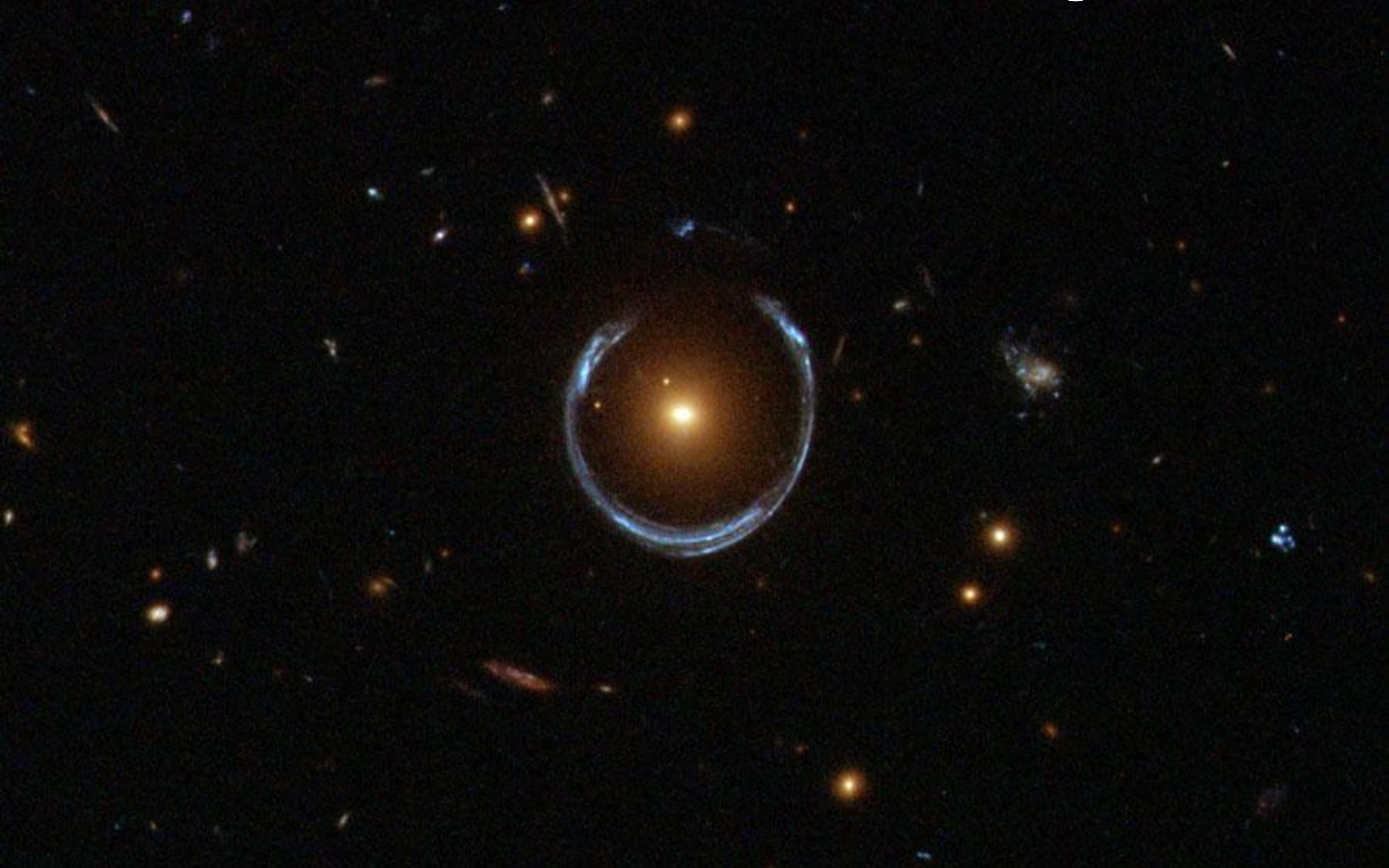


Image Credit: Astronomy Picture of the Day (http://apod.nasa.gov/apod/ap111221.html)

RCS2 032727: *Galaxy Cluster Gravitational Lens*

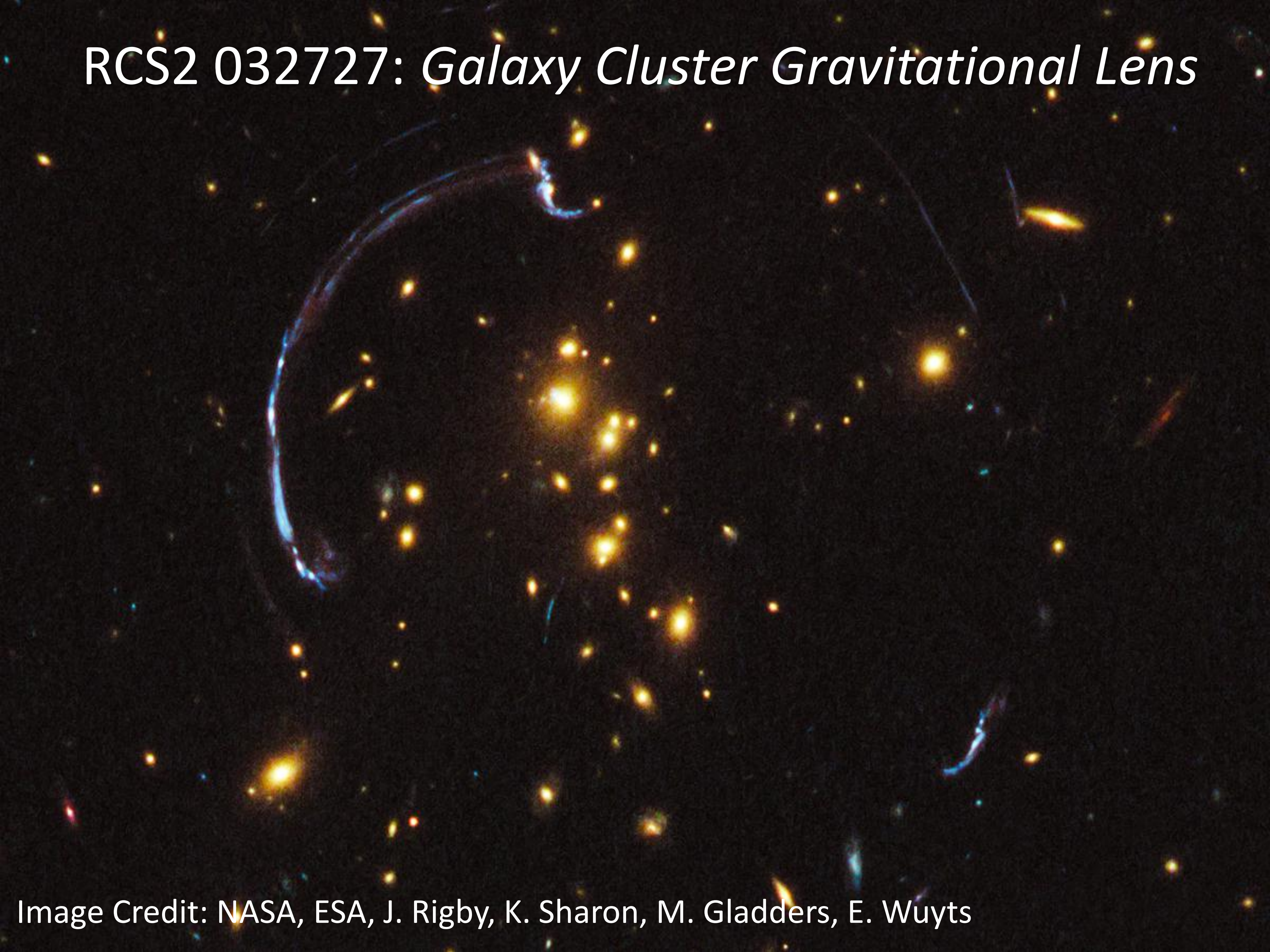


Image Credit: NASA, ESA, J. Rigby, K. Sharon, M. Gladders, E. Wuyts

SDSS J1004: *A Quasar Gravitational Lens*

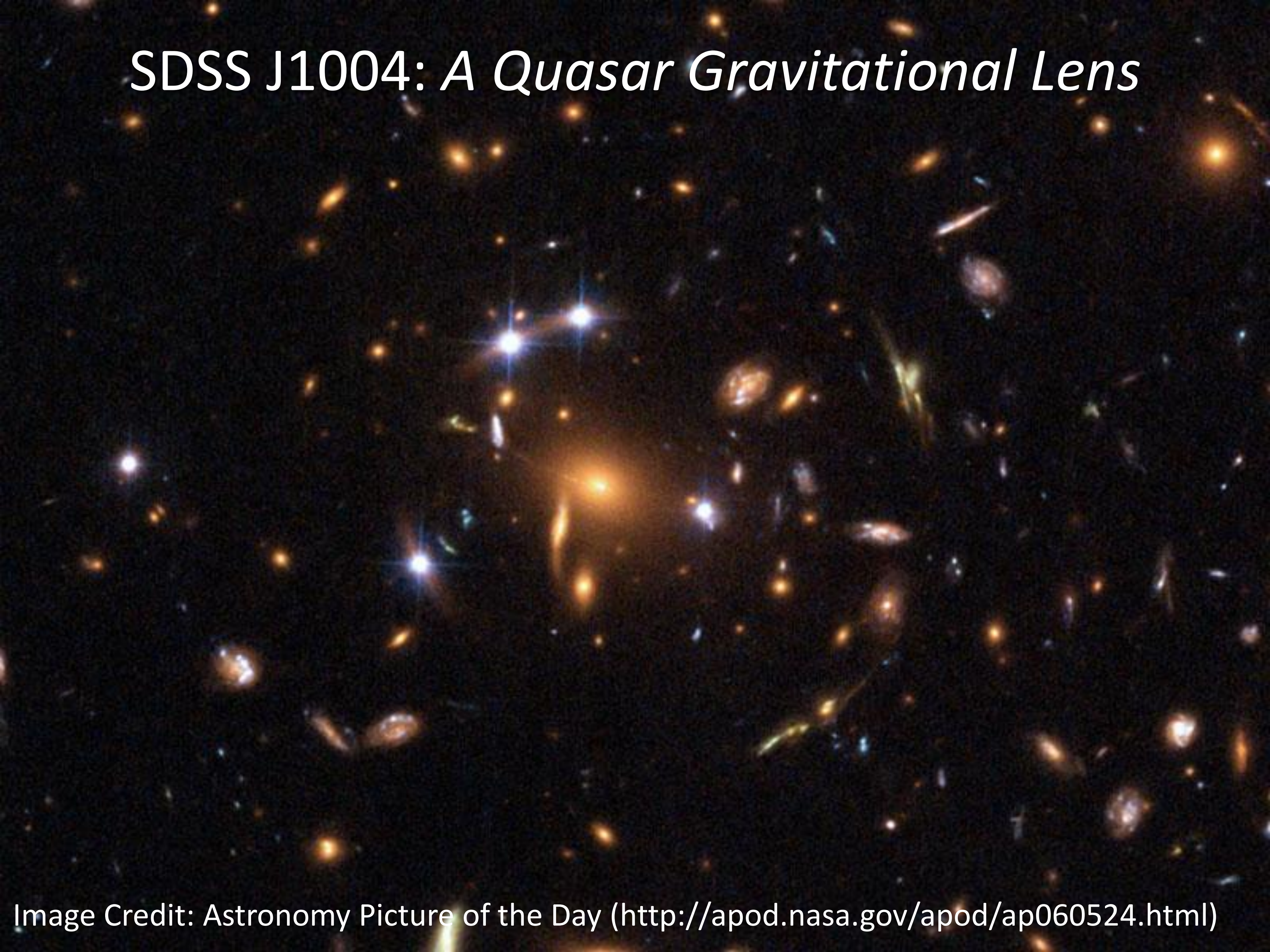


Image Credit: Astronomy Picture of the Day (http://apod.nasa.gov/apod/ap060524.html)

MACS J1206: *Galaxy Cluster Gravitational Lens*

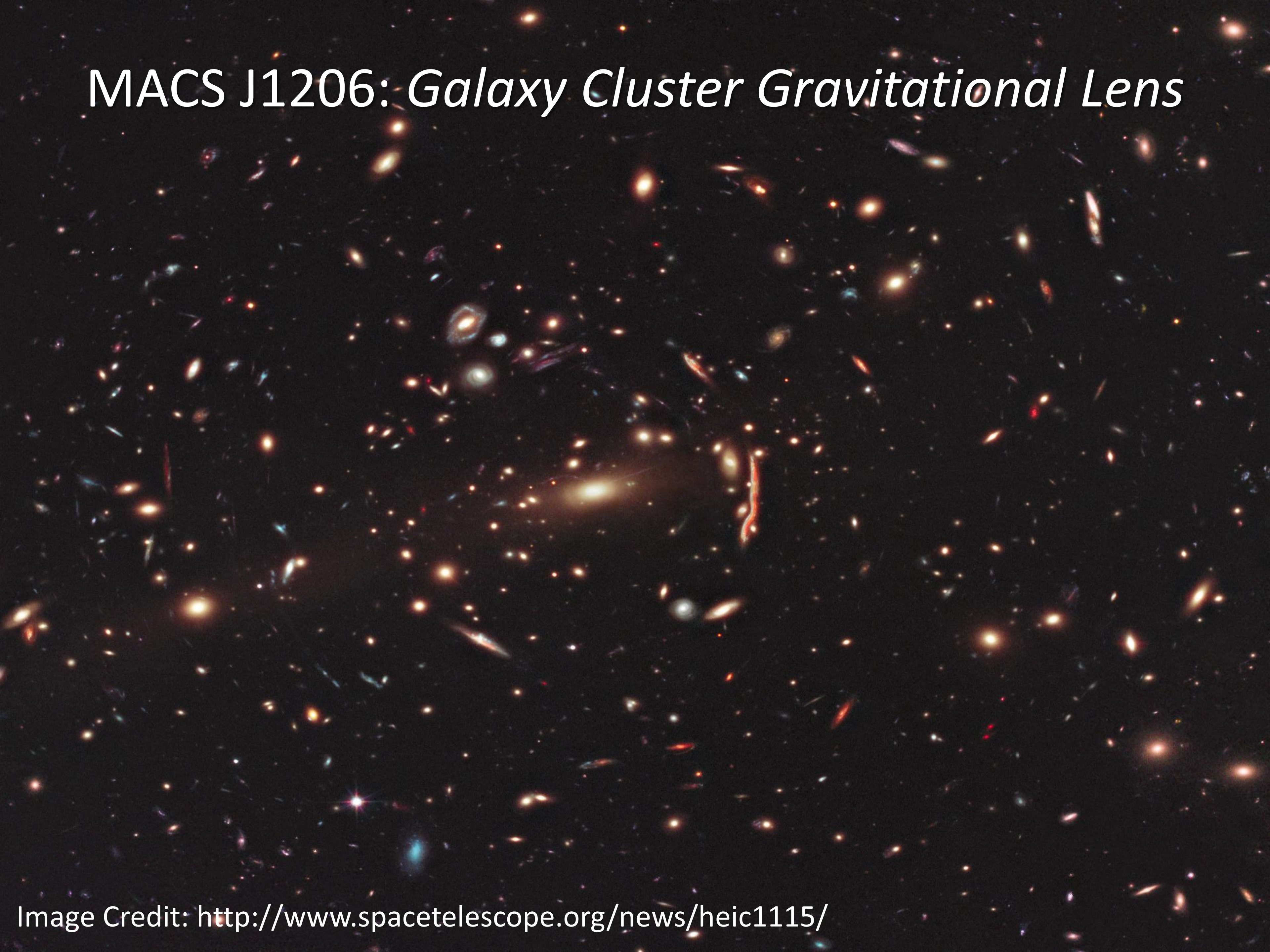
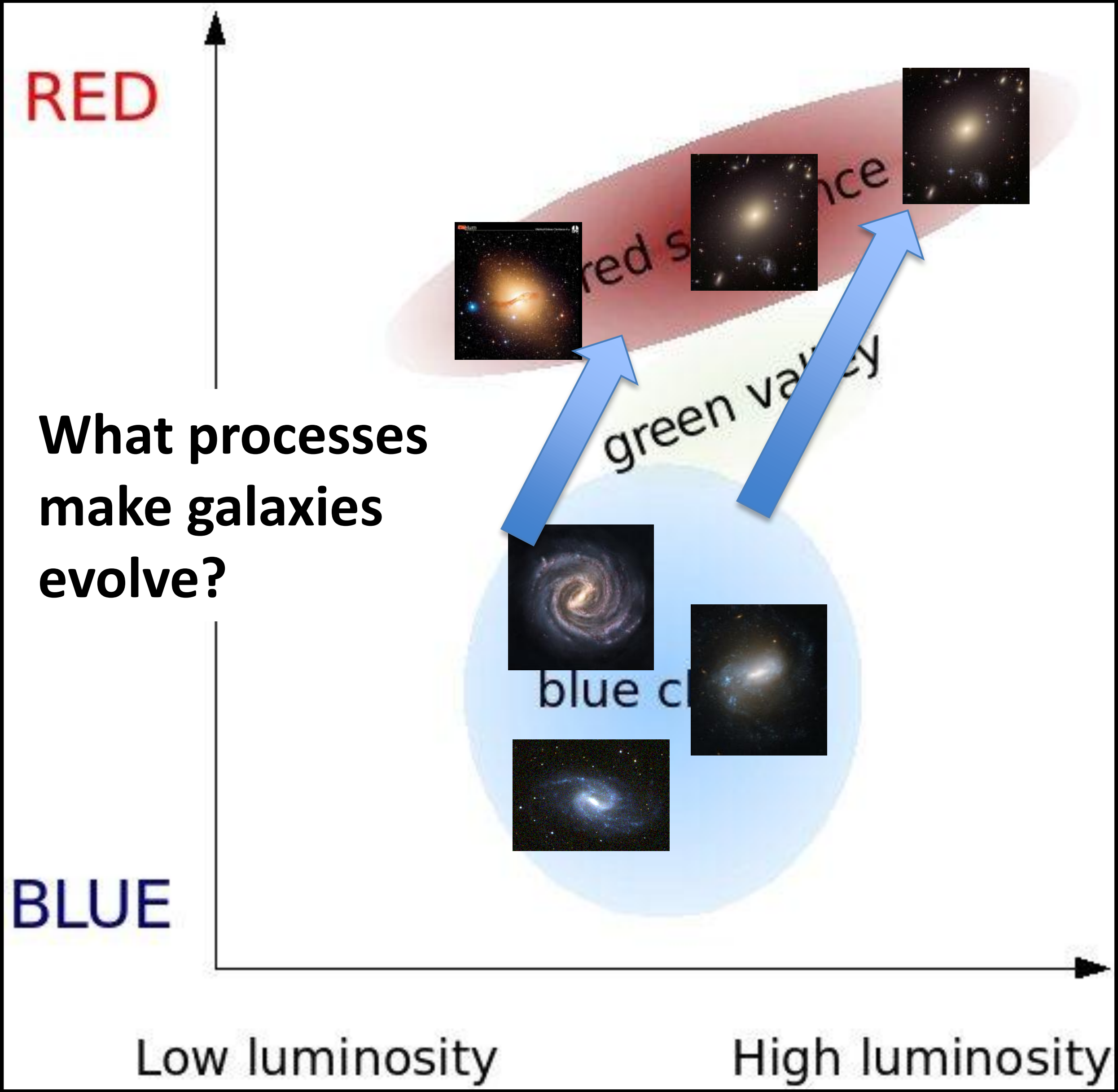


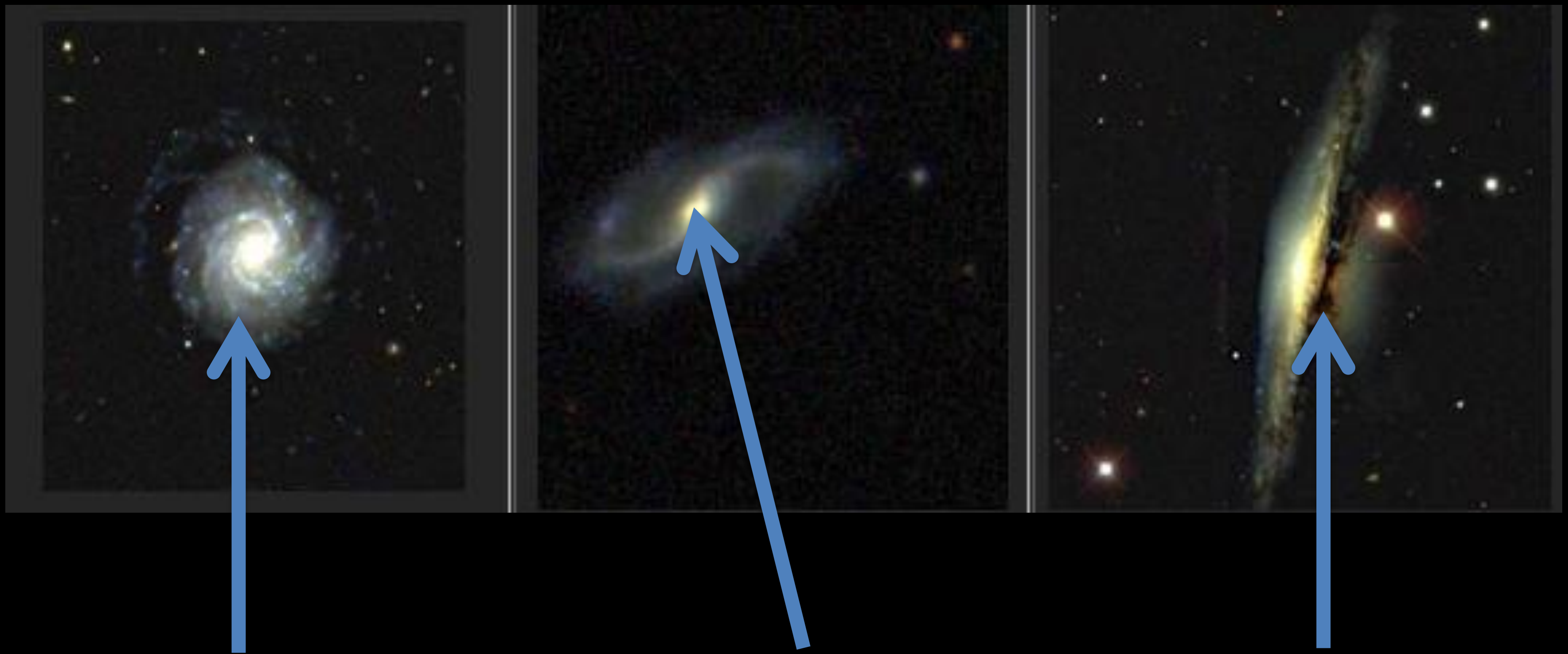
Image Credit: http://www.spacetelescope.org/news/heic1115/

Extragalactic Science

A Picture of Galaxy Evolution



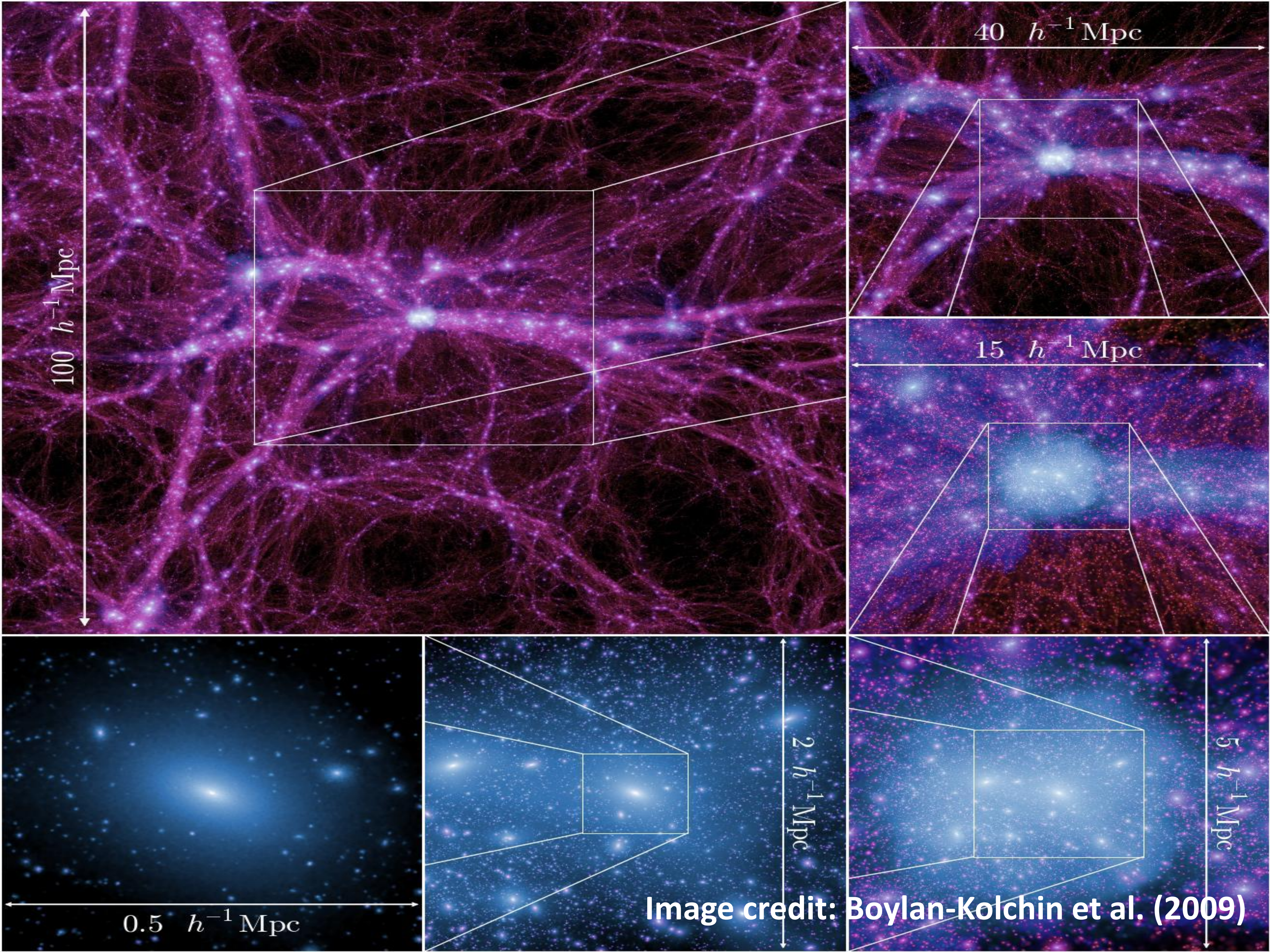
Evolution of Disk Galaxies



Flat, rotating disk of stars, gas and dust

Central bulge

A dust lane



100 h^{-1}Mpc
40 h^{-1}Mpc
15 h^{-1}Mpc
5 h^{-1}Mpc
2 h^{-1}Mpc
0.5 h^{-1}Mpc
Image credit: Boylan-Kolchin et al. (2009)

Theoretical models of galaxy formation and evolution

Observations of various galaxy populations at different cosmic times

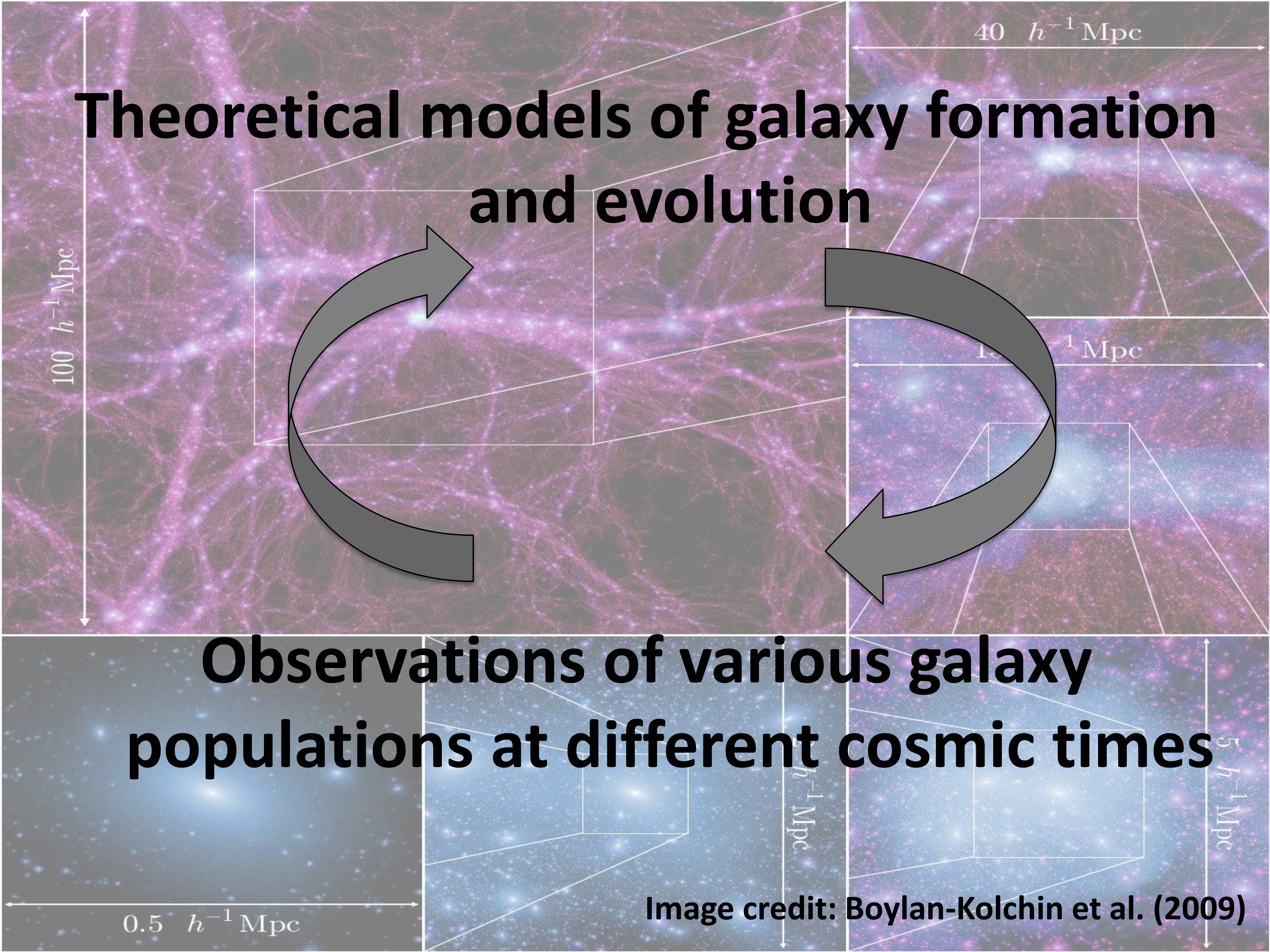
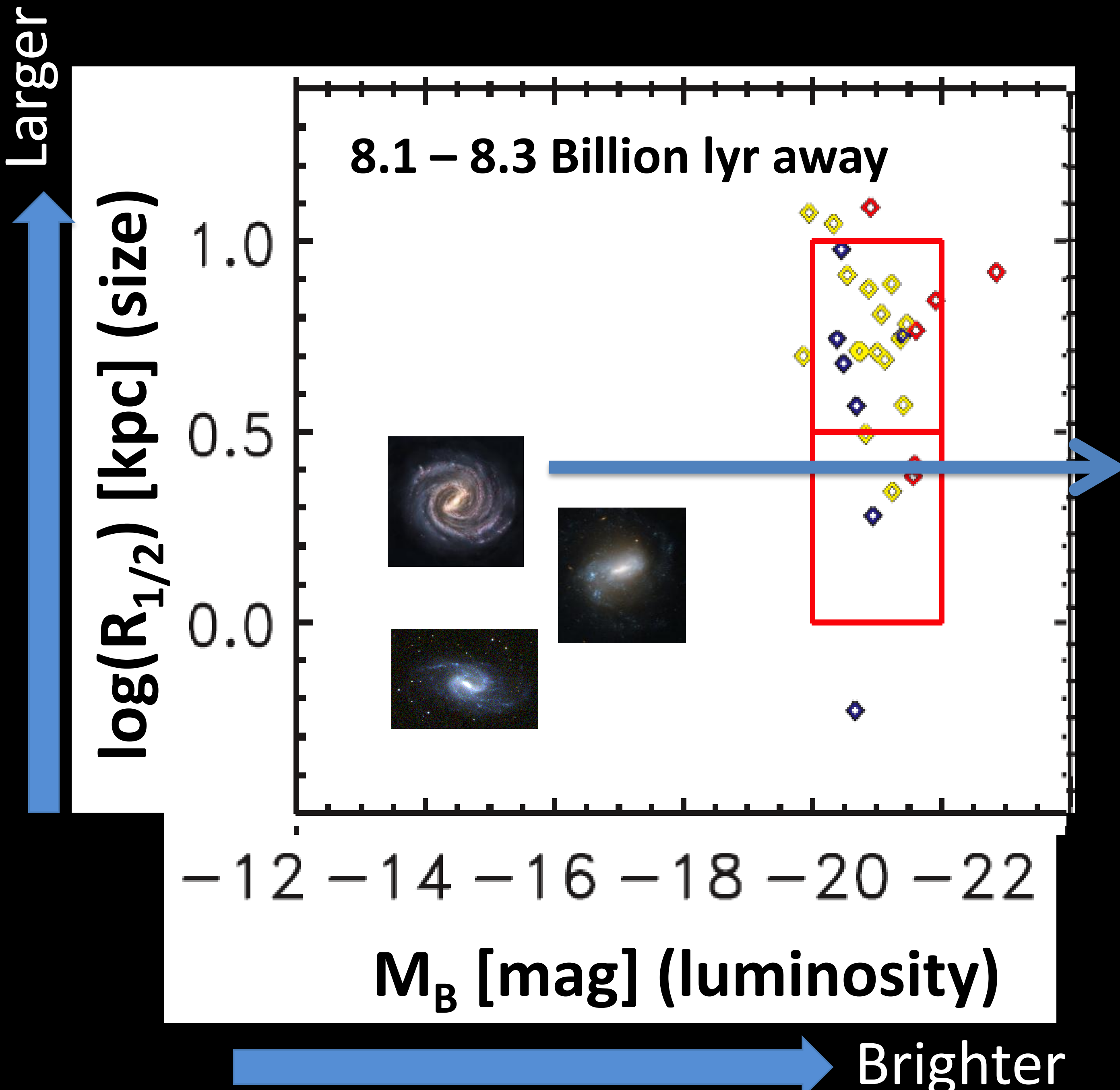


Image credit: Boylan-Kolchin et al. (2009)



Where did all the <u>small and faint</u> disk galaxies go?

- Faint and compact disk galaxies are abundant in the early universe.

- **PROBLEM:** We need a lot of telescope time to observe them <u>and</u> its hard to measure their properties accurately.

- Any model of galaxy evolution isn't complete without accounting for these numerous objects.

- We need to measure their properties first – then we can model their evolution.

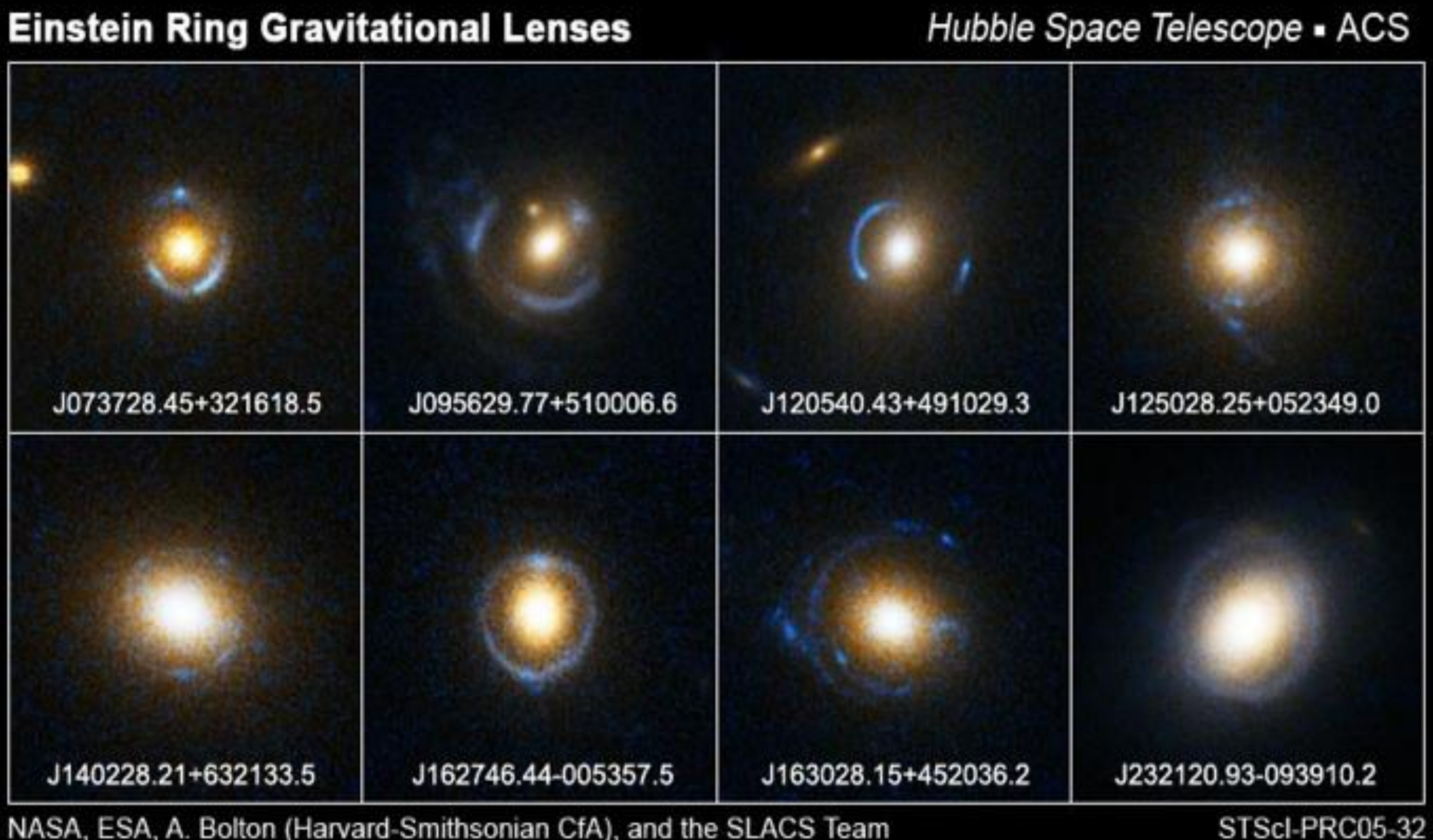
Q: How do we measure the properties of small and faint galaxies accurately?

A: Use the magnification advantage of gravitational lensing!

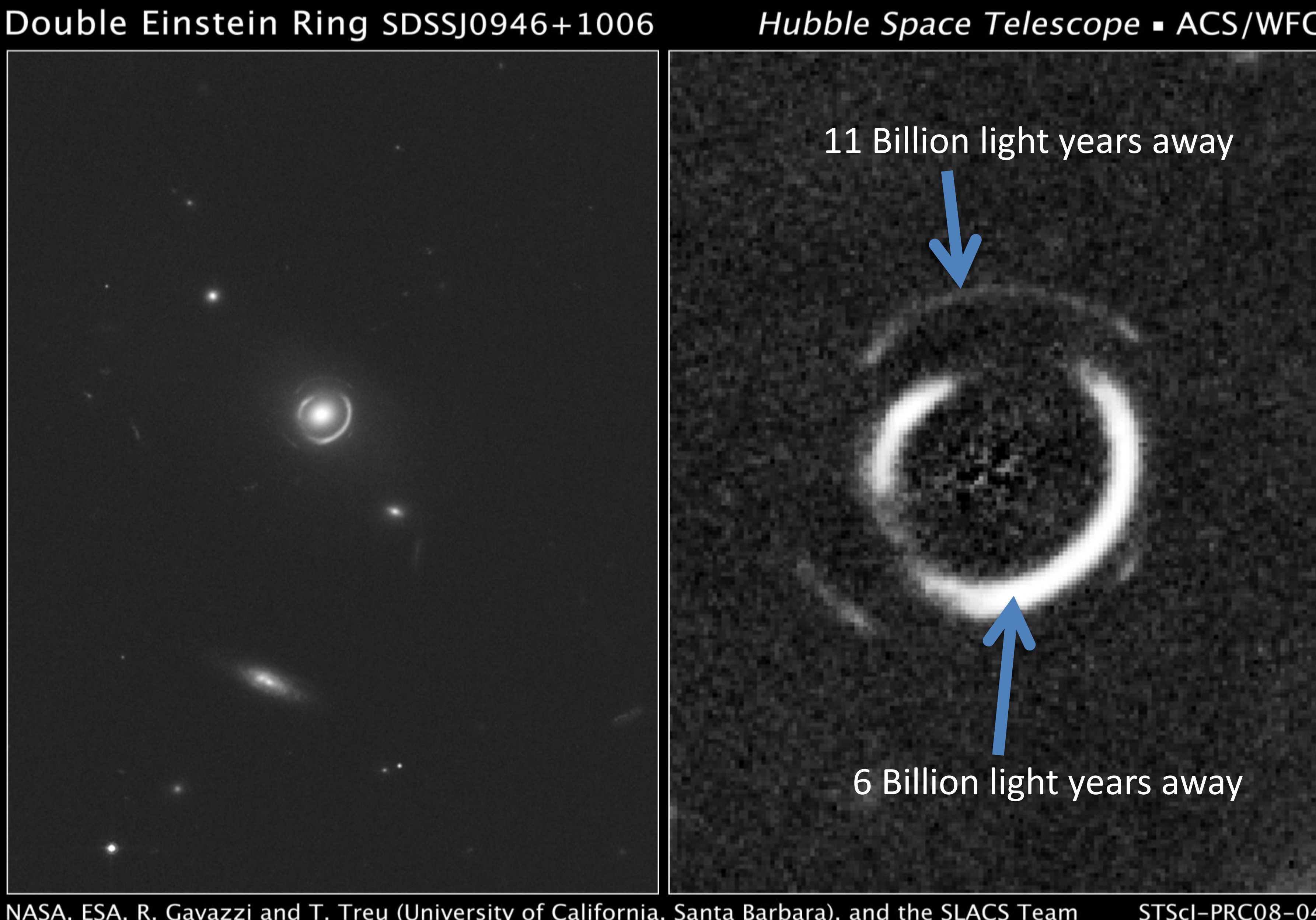
Sloan **L**ens **ACS** (SLACS) Survey

- One of the most comprehensive discovery surveys of gravitational lenses to date (Bolton et al. 2008).
- Two prong approach: *discovery* and *confirmation*.
- ***Discovery*** = From spectroscopy of almost a million galaxies from the Sloan Digital Sky Survey (SDSS, York et al. 2000).
- ***Confirmation*** = Imaging from the *Hubble Space Telescope* (Instruments: Advanced Camera for Surveys, Wide Field Camera 3 etc.).

SLACS Survey: Confirmation

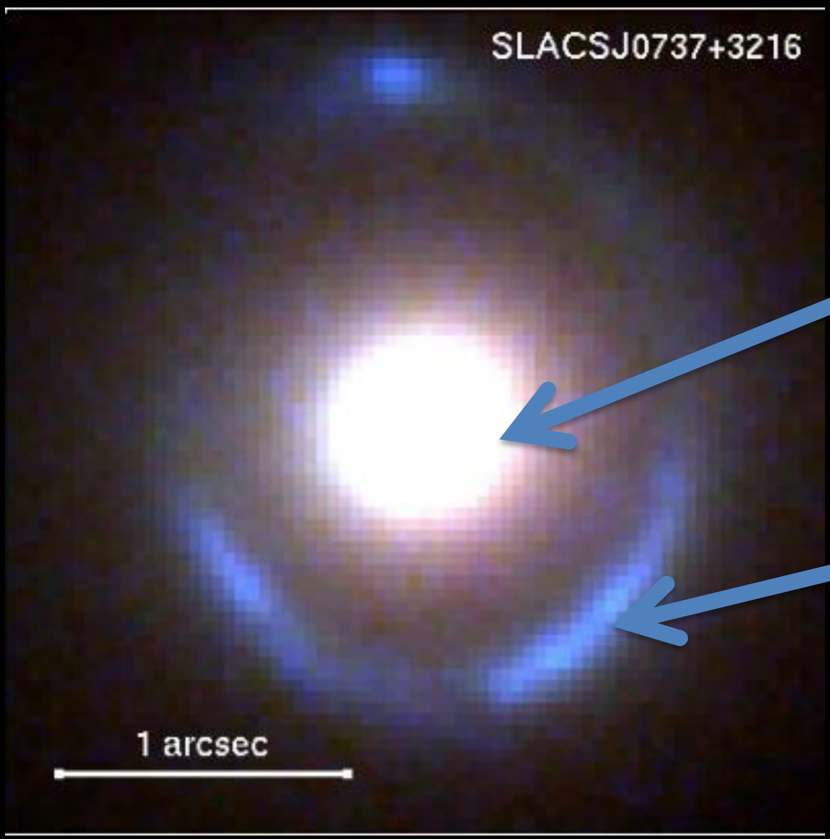


Bolton et al. 2008



Bolton et al. 2008

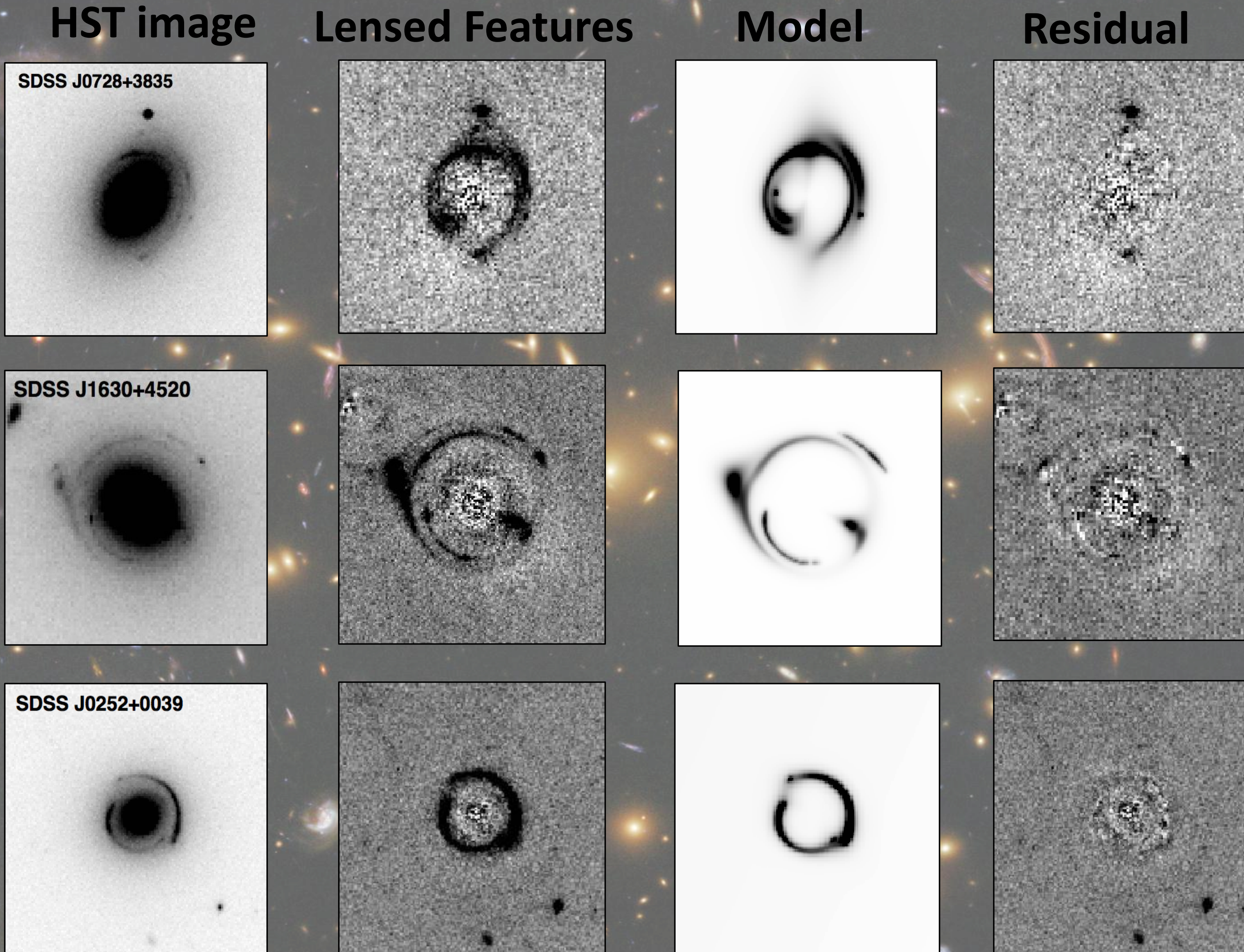
SLACS Survey: Overview



- About 85 gravitational lenses discovered to date (this is a lot!).
- The foreground lens is a single galaxy → usually an elliptical galaxy.
- The background galaxies are star forming → We see blue arcs…
- Background galaxies are located as far as 2.4 – 8.4 Billion light years away!

Taking a Gravitational Lens Apart…

LENSFIT (Peng et al. 2006)



Bandara et al. 2012

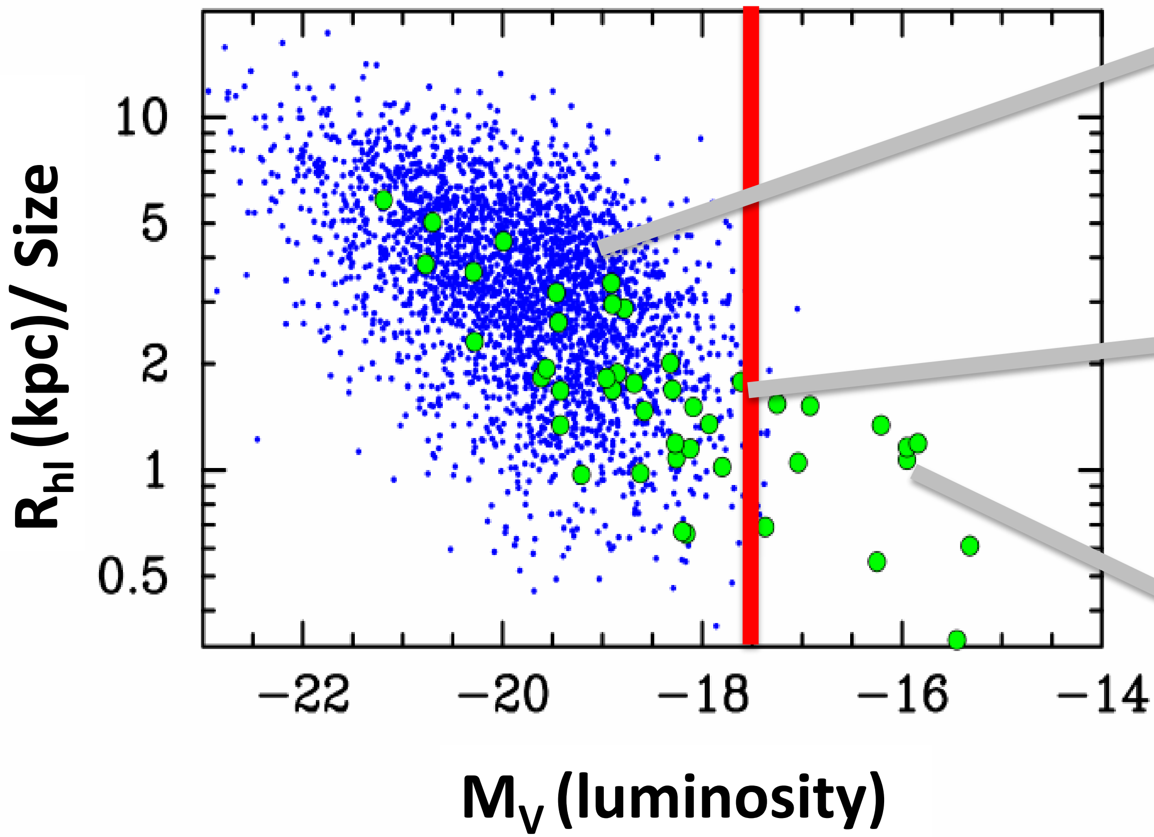
If they weren't gravitationally lensed, some of the background galaxies would look like this…

Bandara et al. 2012

How does strong gravitational lensing help us?

Larger

Disk galaxies as they were 4.3 – 6.6 Billion years ago…



Blue points = Galaxy measurements from GEMS survey (HST imaging)

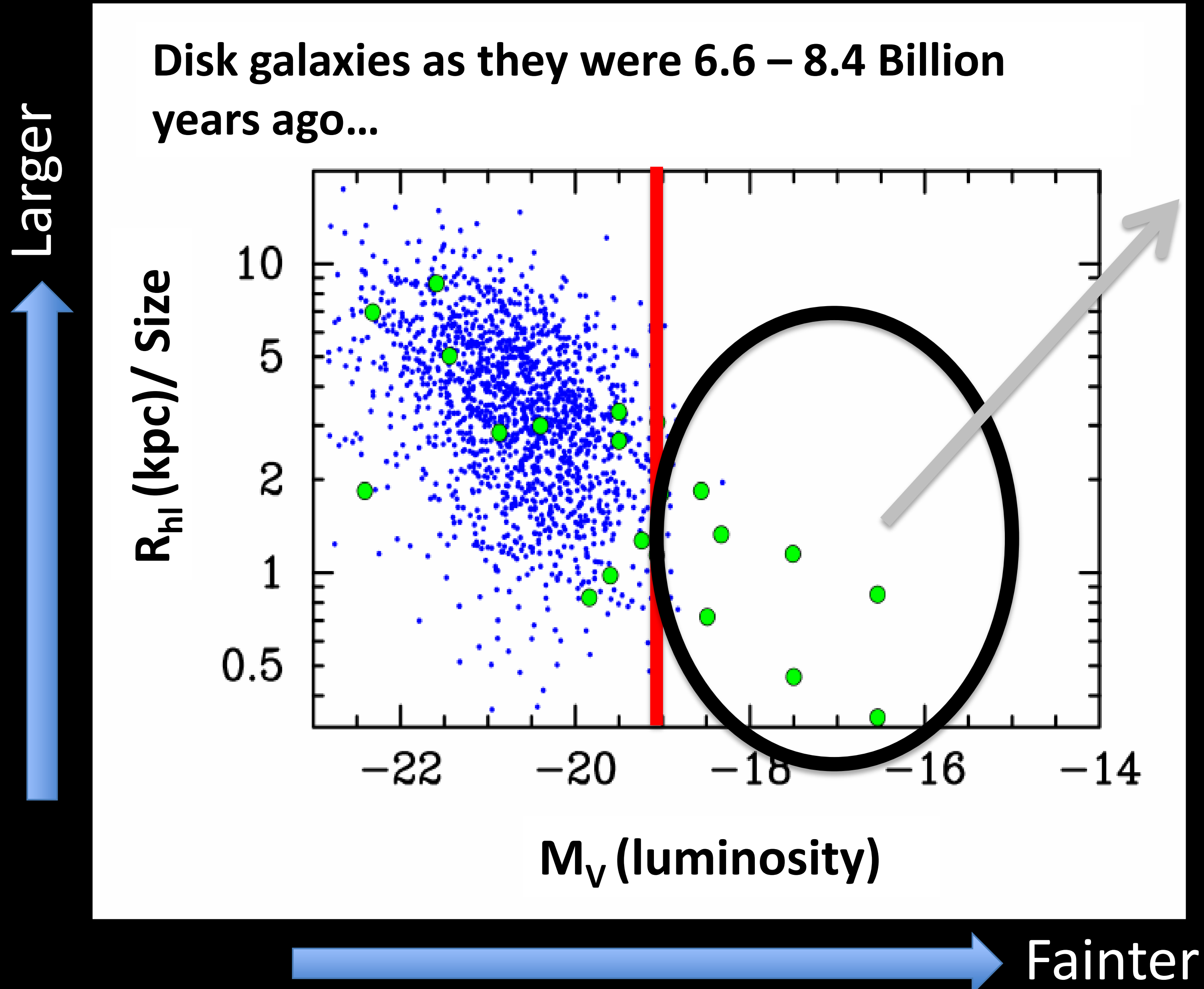
Red line = Typical sensitivity limit

Green points = Measurements of gravitationally lensed disk galaxies

Fainter

Bandara et al. 2012

Our study measures properties of disk galaxies that are at least 6 times fainter…



…and now we can start refining galaxy evolution models to reproduce the observations of small and faint galaxies.

Bandara et al. 2012

Current Samples of Strong Gravitational Lenses

TABLE 2
COMPARISON OF CHARACTERISTICS OF RECENT LENS SURVEYS

Name	Reference	Telescope	Bands	Area ($\deg^2$)	Depth mag	lens candidates	Confirmed /followed-up systems
AEGIS	Moustakas et al. (2006, 2007)	*HST*	V, I	0.18	$V = 28.75$	7	3/0
GEMS	This work	*HST*	V, z	0.22	$V = 28.25$	10	1/0
COSMOS	Faure et al. (2010)	*HST*	I	1.80	$I = 25.00$	88	4/18
CFHTLS-SL2S	Gavazzi et al., in prep	CFHT	u, g, r, i, z	170	$g = 25.47$	330	40/65
SDSS-SLACS	Bolton et al. (2006)	Sloan	spectroscopy	3732	$r = 17.77$	131	**85** /131

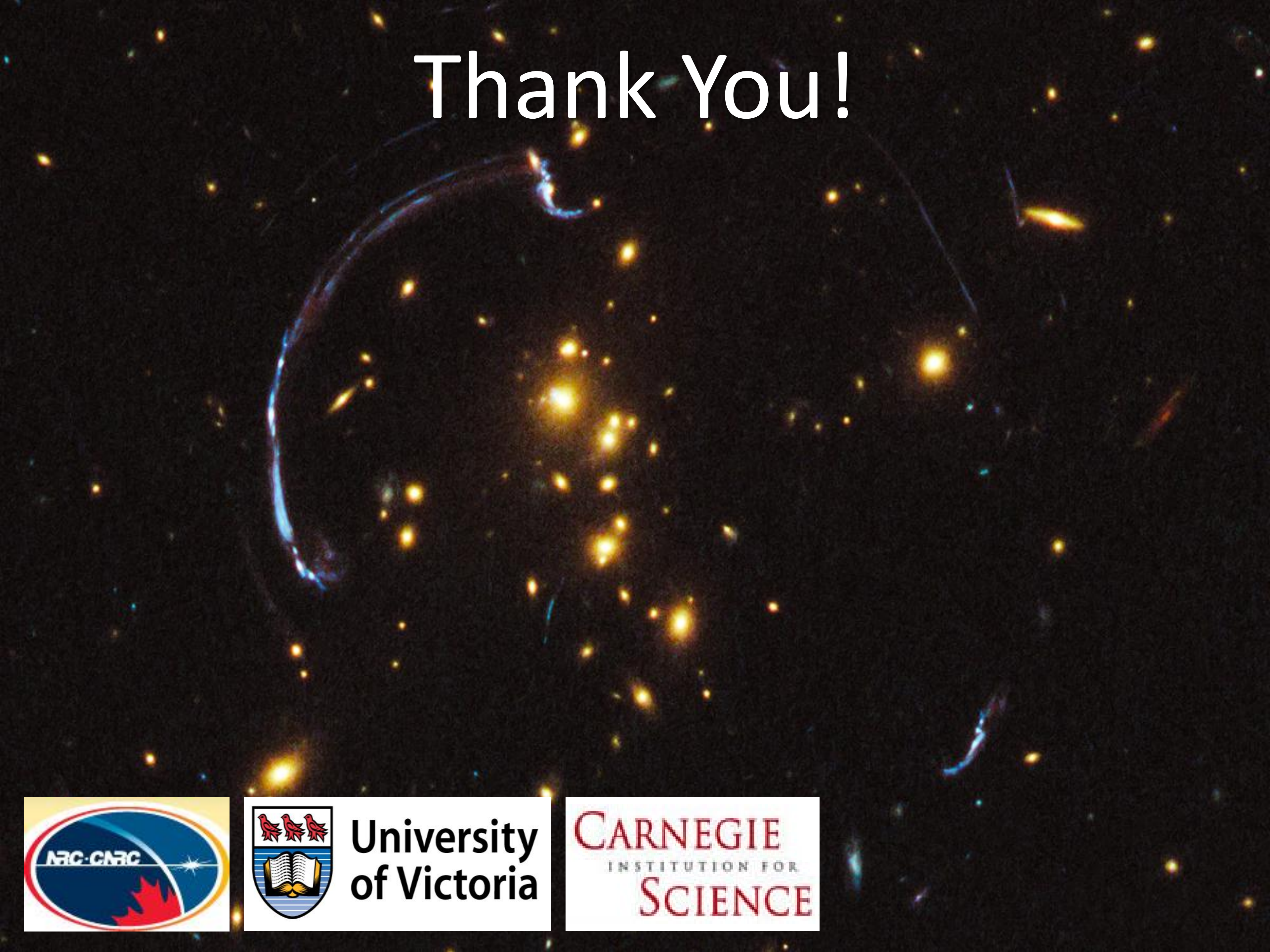
SDSSIII-BELLS Brownstein et al. (2012) Sloan spectroscopy 10000 45(6 months of data) 25/36

More et al. 2011

Future Prospects

- So much exciting science to be done!
- **Immediate prospects:** Larger samples ➔ High resolution imaging combined with complementary spectroscopy using instruments on 8 – 10 m class telescopes (such as Gemini North observatory, Very Large Telescope etc.)
- **Nearby prospects (~ next few years):** Follow-up observations with the newest suite of spectrographs on 8 – 10 m class telescopes.
- **Long-term prospects:** Larger samples of gravitational lenses to be discovered with the *Large Synoptic Survey Telescope (LSST)*, follow-up with next generation of extremely large telescopes (ex: *Thirty Meter Telescope*), follow-up with *James Webb Space Telescope*

Thank You!



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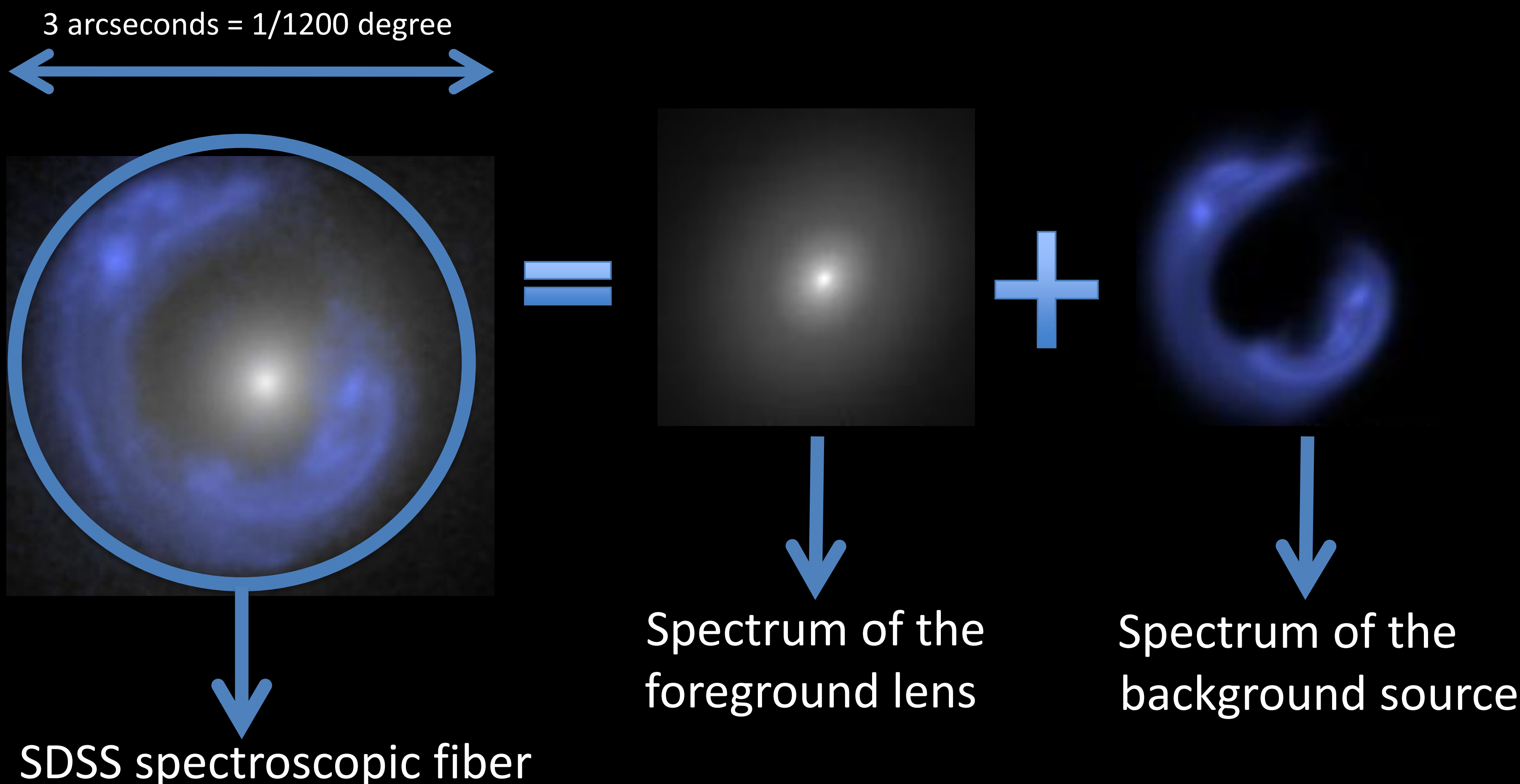
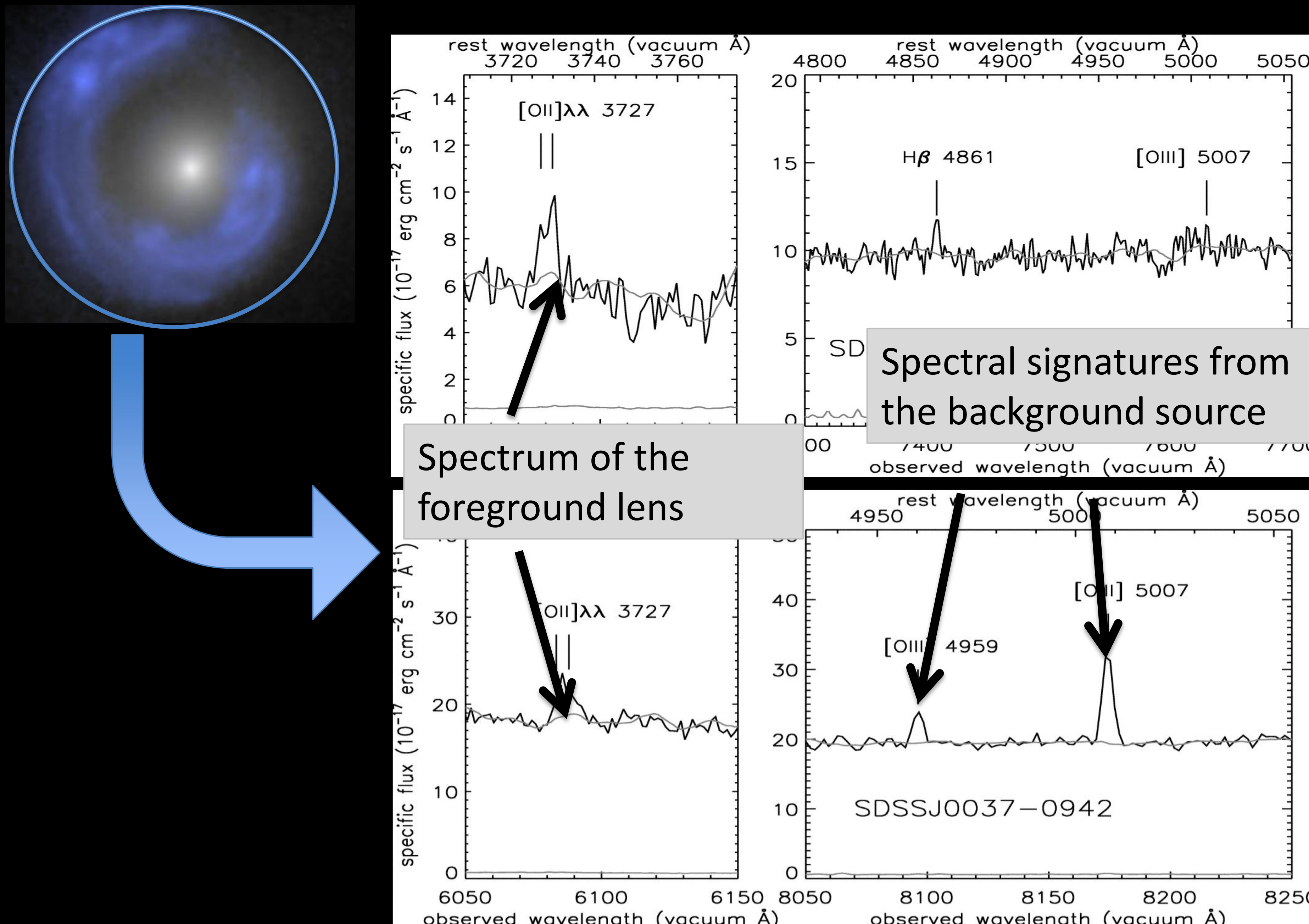
SLACS Survey: Discovery

- **Basic idea**: If a spectroscopic fiber covers an entire gravitational lens, the spectrum we see is a composite of the foreground and background objects.





Spectrum of the foreground lens
Spectral signatures from the background source
rest wavelength (vacuum Å)
observed wavelength (vacuum Å)
specific flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
[OII]λλ 3727
Hβ 4861
[OIII] 5007
[OIII] 4959
SDSSJ0037−0942