Weak Gravitational Lensing

Andean Cosmology School,
Universidad de Los Andes, Bogotá
Week 4, lecture 1
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Andrés Alejandro Plazas Malagón
andres.a.plazas.malagon@jpl.nasa.gov

Caltech Postdoctoral Scholar
Astrophysics and Space Sciences Section
NASA JPL-Caltech

Jet Propulsion Laboratory
California Institute of Technology

Overview of this week

- **First lecture:** Weak Gravitational Lensing (WL): history, basics, applications, systematics
- Second Lecture: The challenge of measuring shapes for WL, current and planned WL experiments
- Third Lecture: Charge-Coupled Devices: basics, characterization.
- Fourth Lecture: Instrumental signatures on astrophysical observables: photometry, astrometry, shapes.

Lecture 1: outline

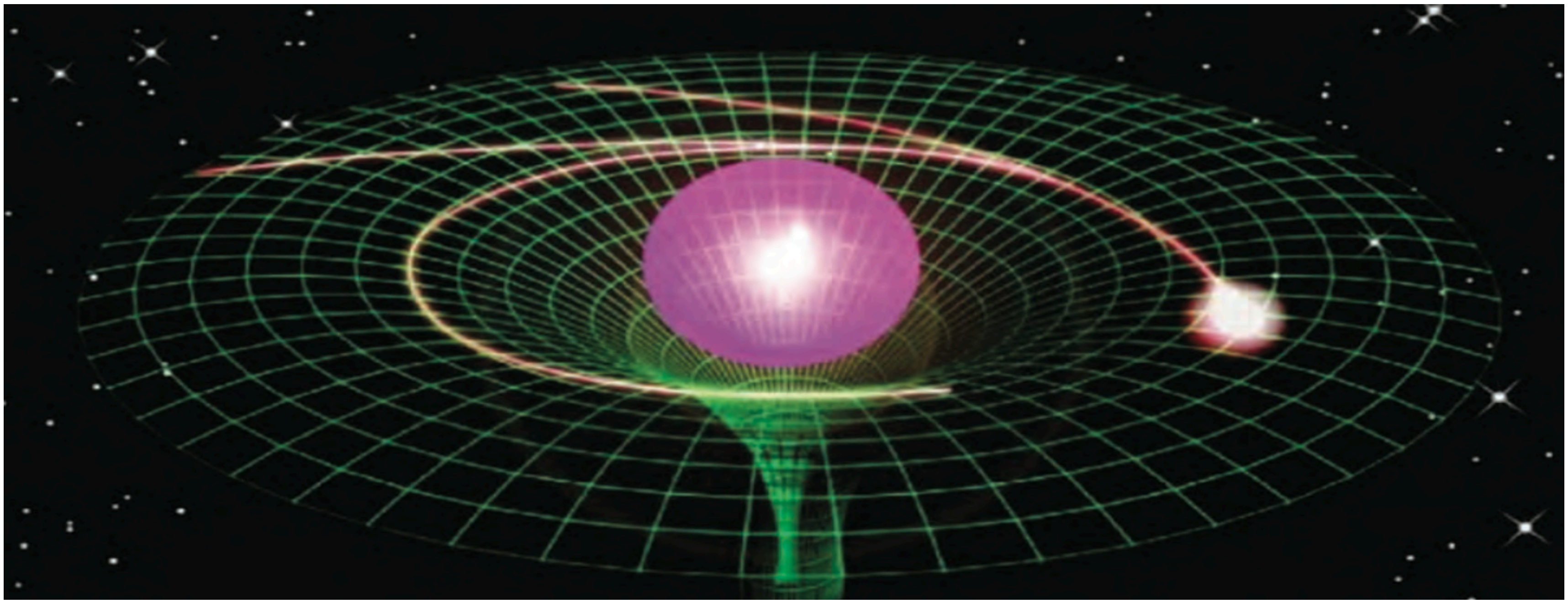
- **What is gravitational Lensing?**

- **Weak lensing: basics**

- **Applications and systematic errors**

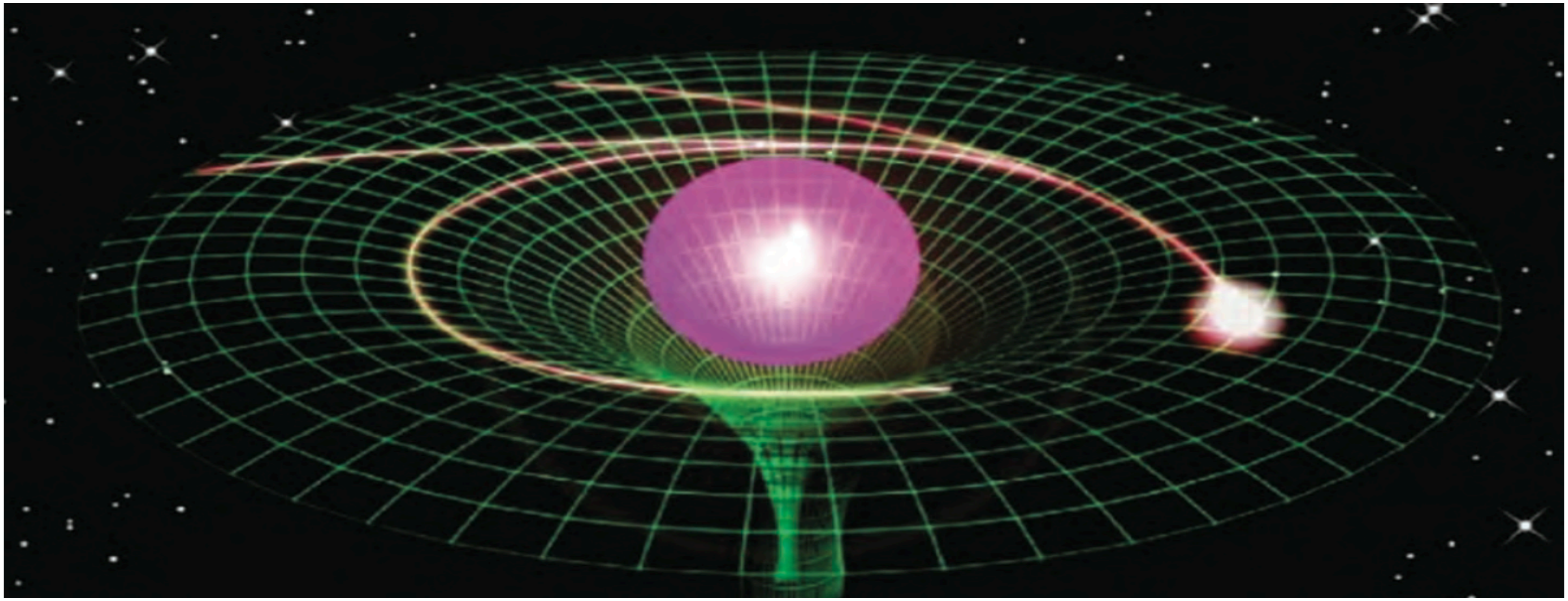
What is gravitational lensing?

- General Relativity predicts that spacetime is distorted due to the existence of matter-energy densities.
- **Gravitational lensing** is the deflection of light due to the effects of gravity (mass-energy).

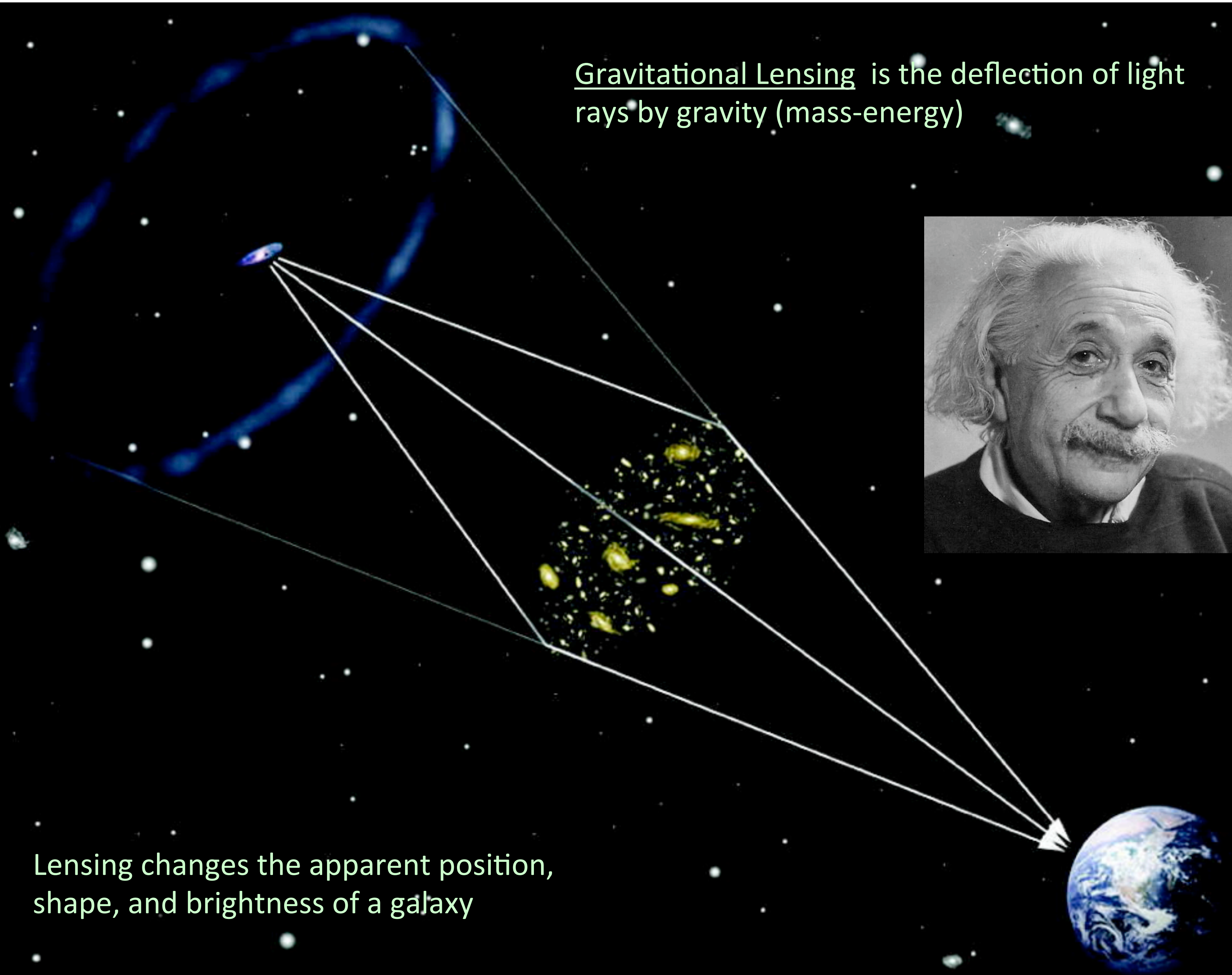


What is gravitational lensing?

- Lensing will produce multiple images, distortions, magnifications, and time delays



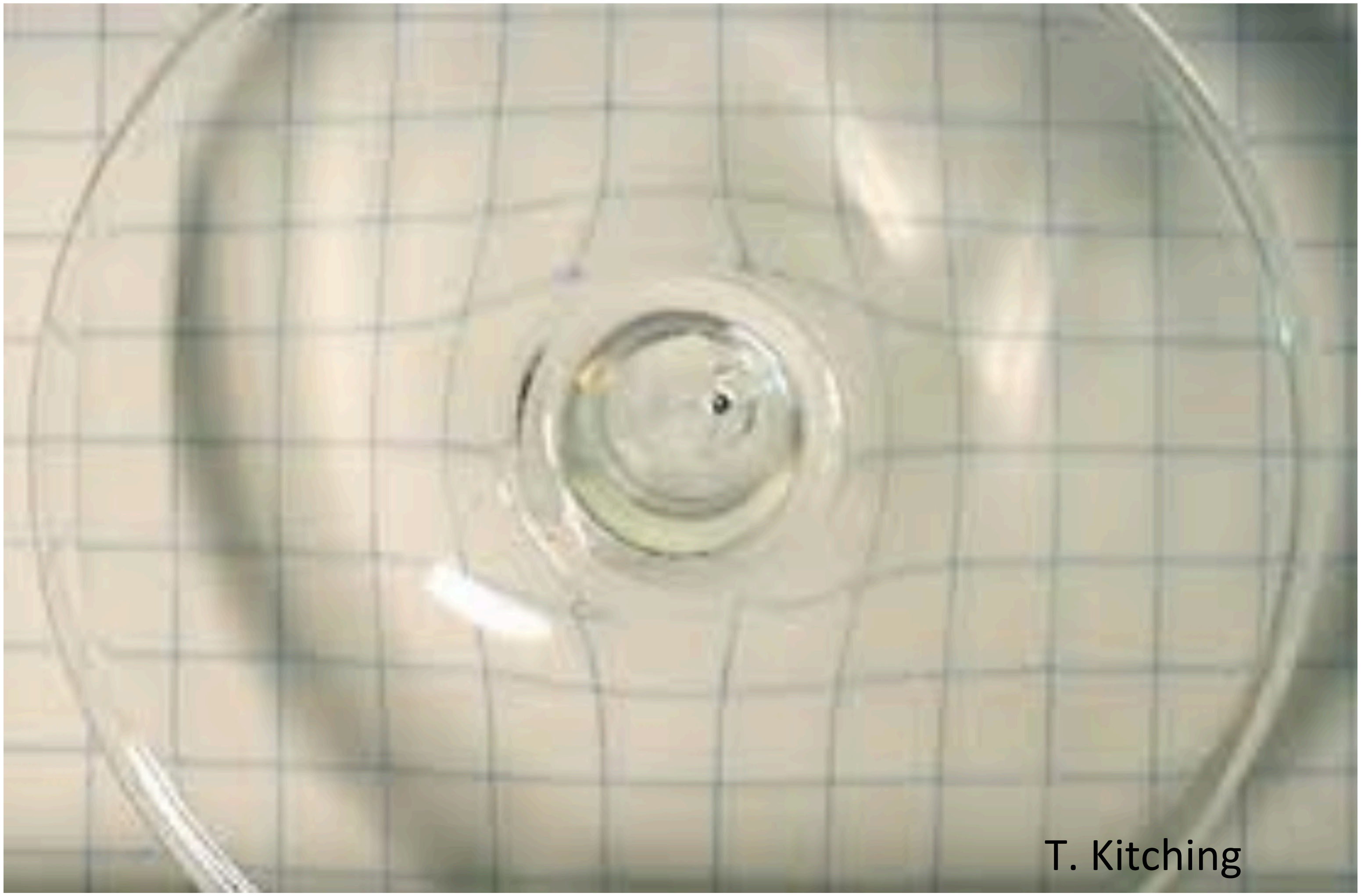
Gravitational Lensing is the deflection of light rays by gravity (mass-energy)



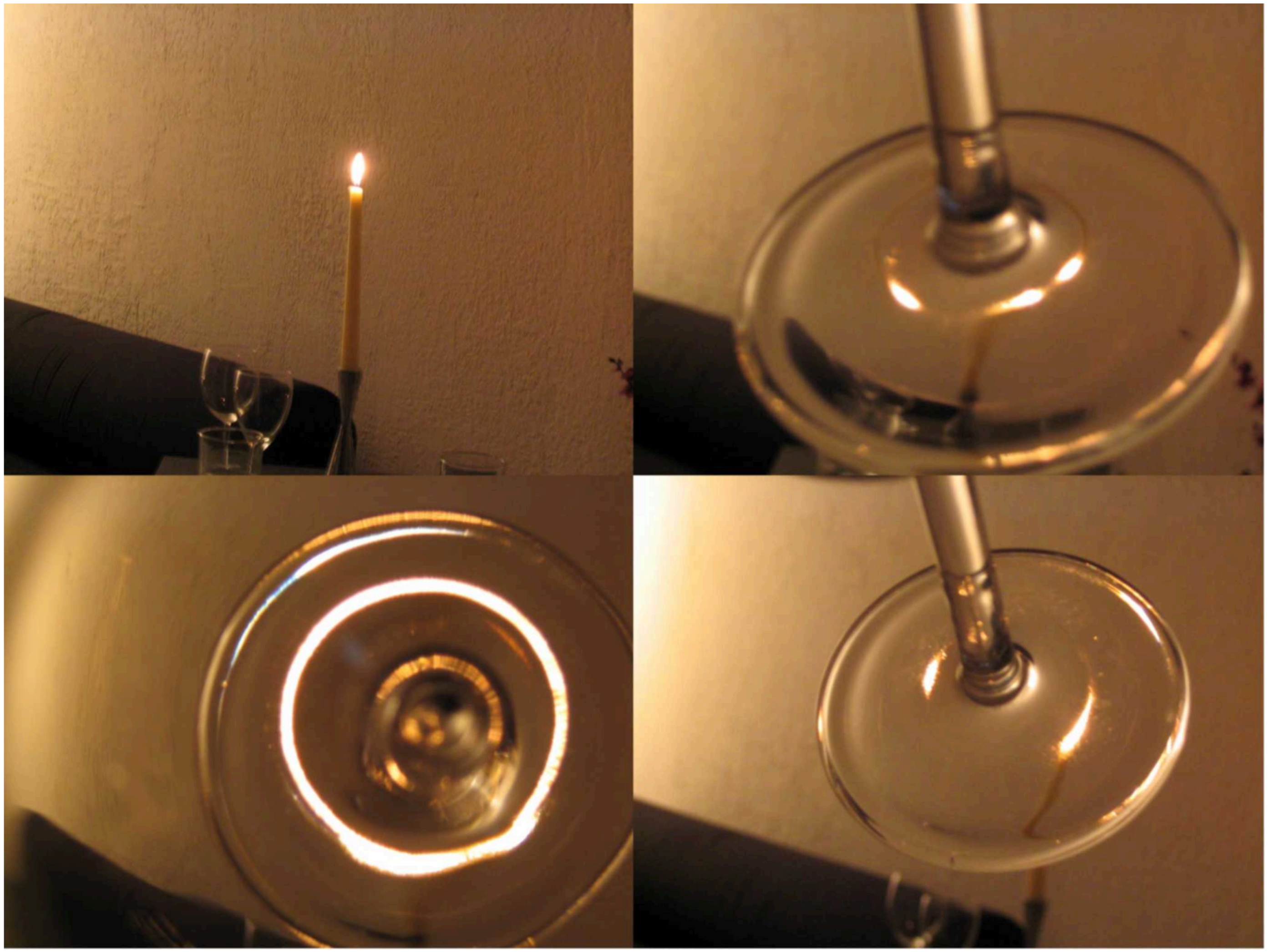
- Lensing changes the apparent position, shape, and brightness of a galaxy

An analogy

Analogous to the distortion of images produced by glass or a regular lens



An everyday analogy



-Mass deflects (“bends”) light like a regular lens.

*Depending on geometric configuration and nature of the lens:

- Full ring
- Giant arcs
- Multiple images
- Very small distortions

Credit: Phil Marshall

An everyday analogy

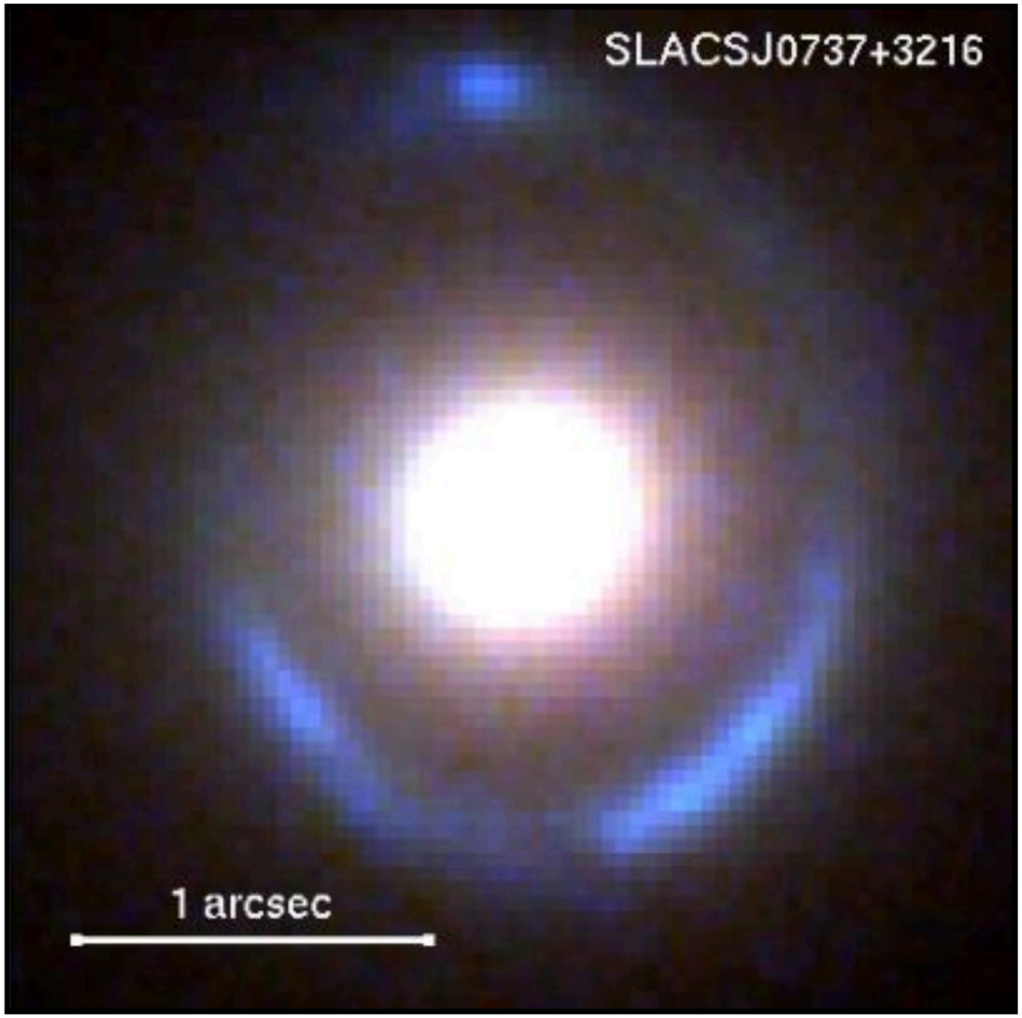


Image from the Hubble Space Telescope

Marshall et al. 2007

What is gravitational lensing?

Horseshoe Einstein Ring from Hubble

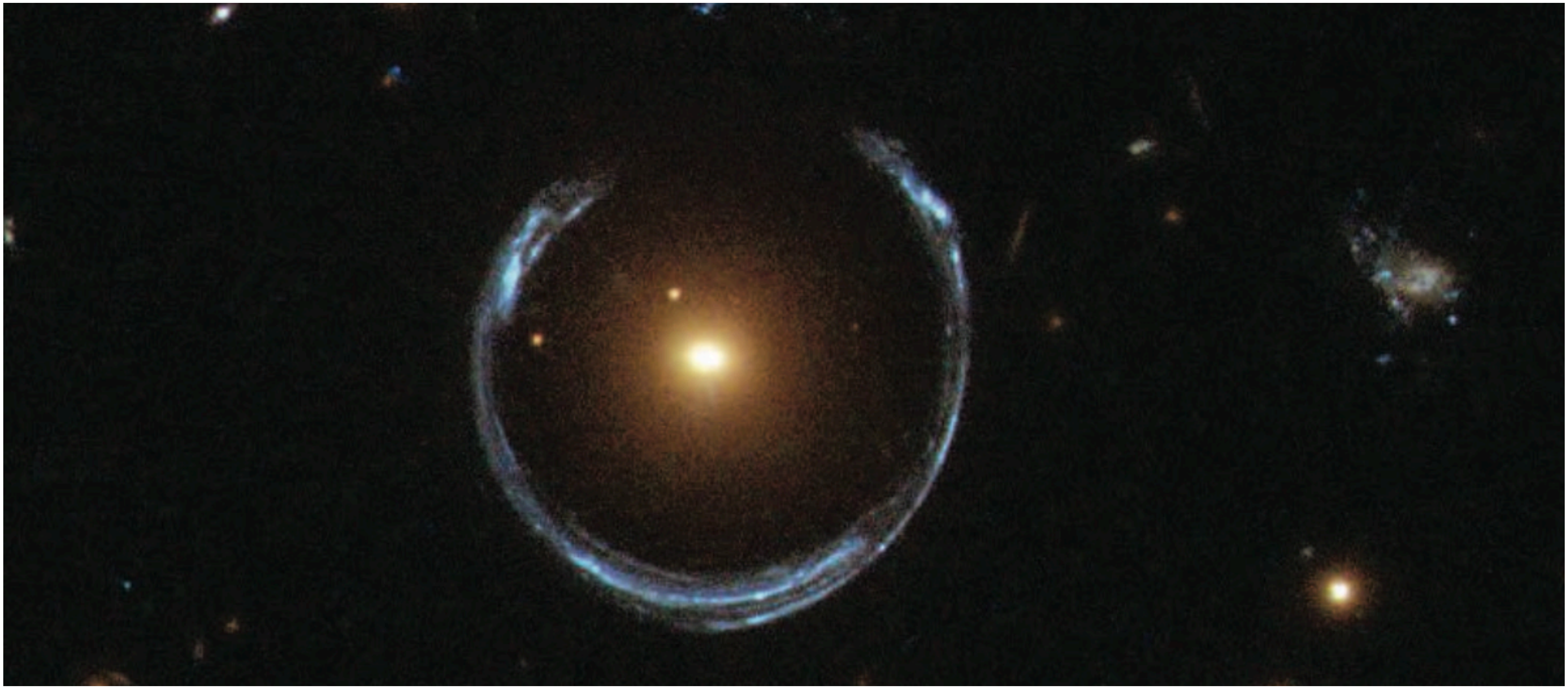
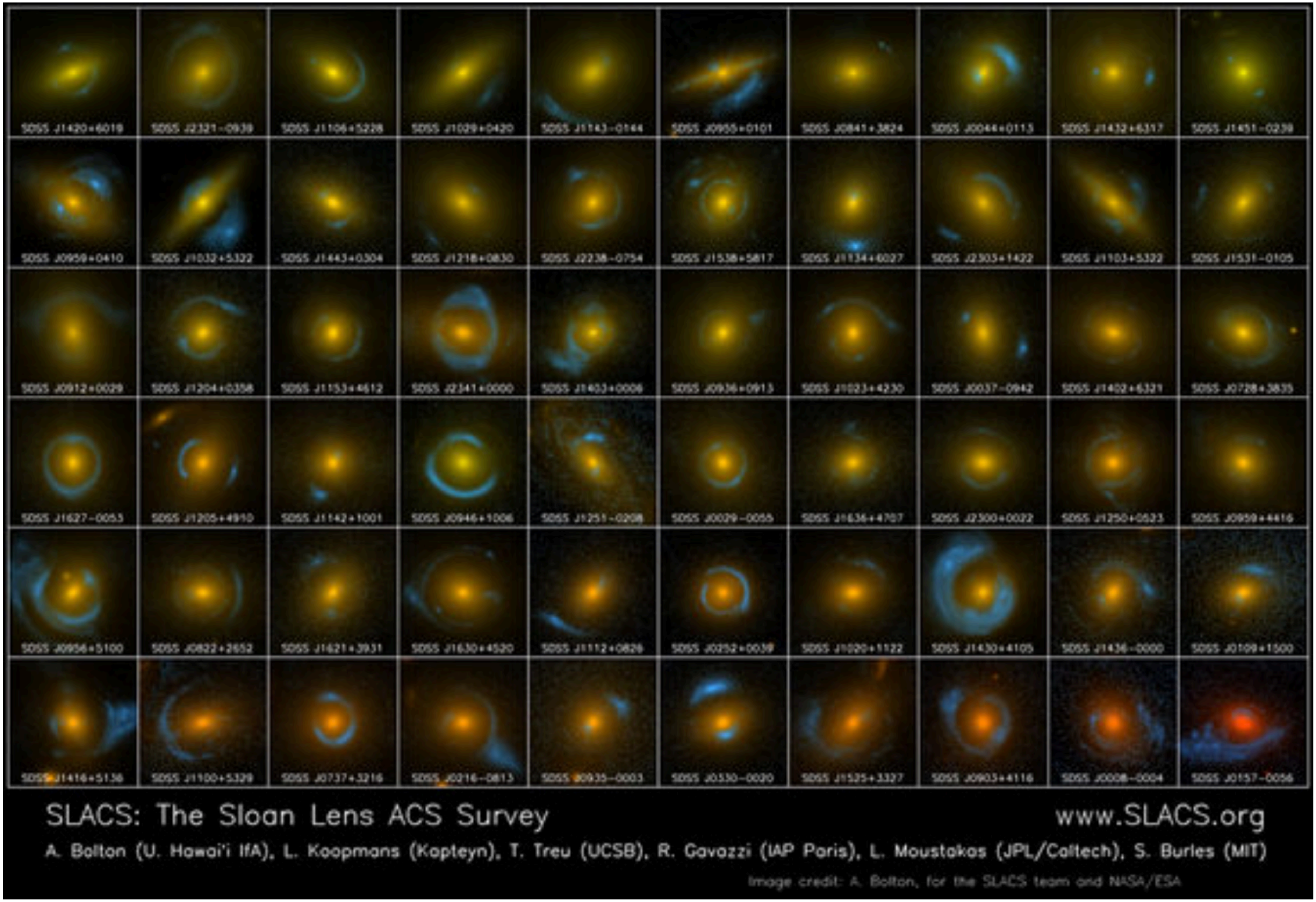


Image Credit: ESA/Hubble & NASA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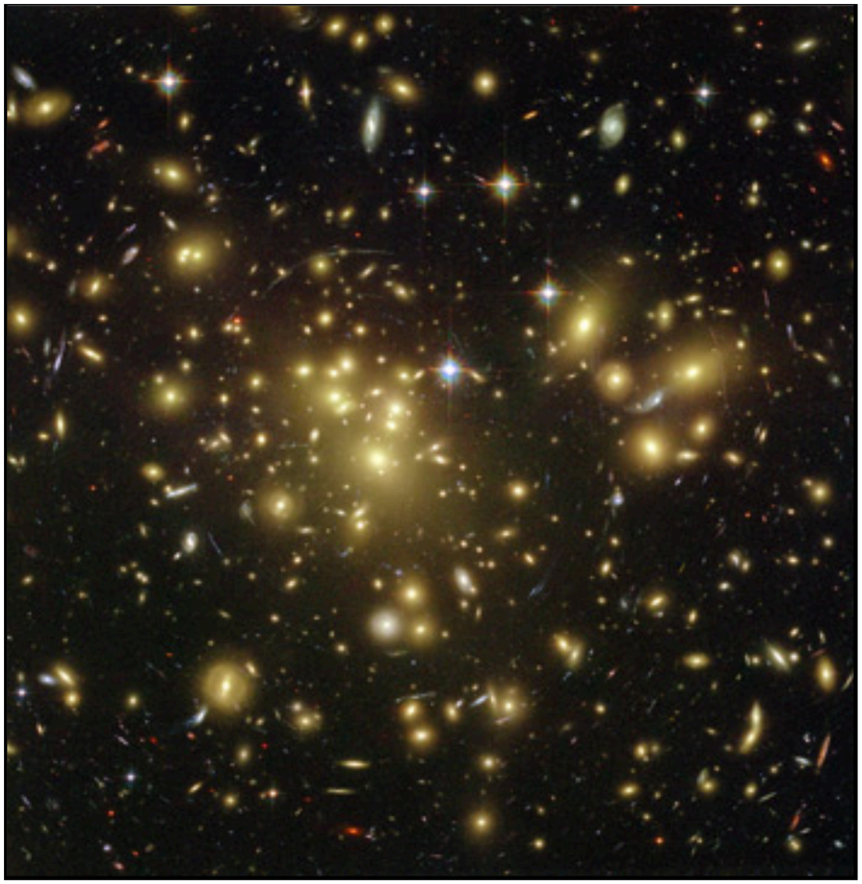
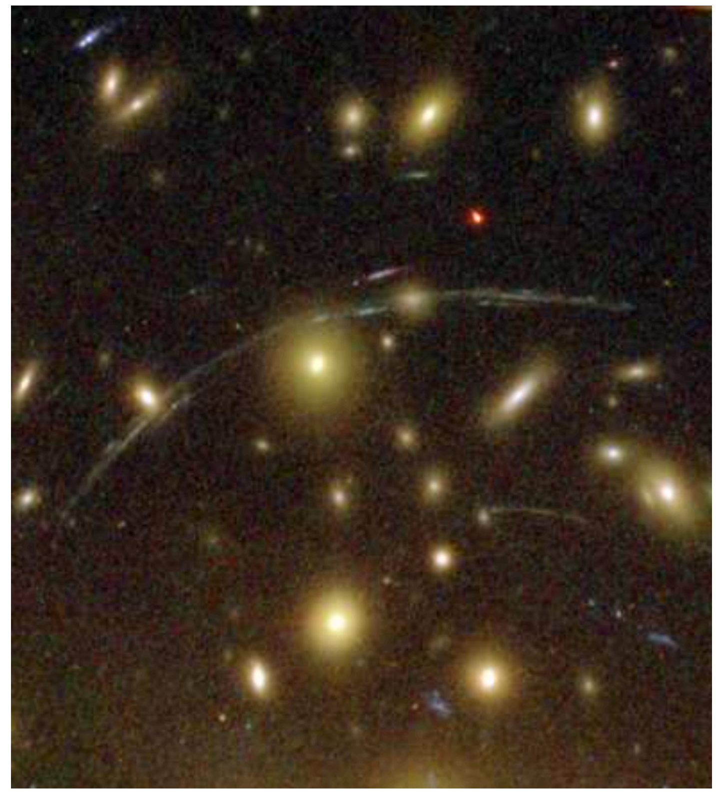
SDSS J1416+5136
SDSS J1100+5329
SDSS J0737+3216
SDSS J0216-0813
SDSS J0935-0003
SDSS J0330-0020
SDSS J1525+3327
SDSS J0903+4116
SDSS J0008-0004
SDSS J0157-0056
SLACS: The Sloan Lens ACS Survey
www.SLACS.org
A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)
Image credit: A. Bolton, for the SLACS team and NASA/ESA

What is gravitational lensing?

Abell 1689 is a galaxy cluster at z=0.183. The gravity of the cluster's trillion stars - plus dark matter - acts as a 2-million-light-year-wide 'lens' in space. This gravitational lens bends and magnifies the light of galaxies located far behind it, distorting their shapes and creating multiple images of individual galaxies.



[Image credit: NASA, Benitez et al.]

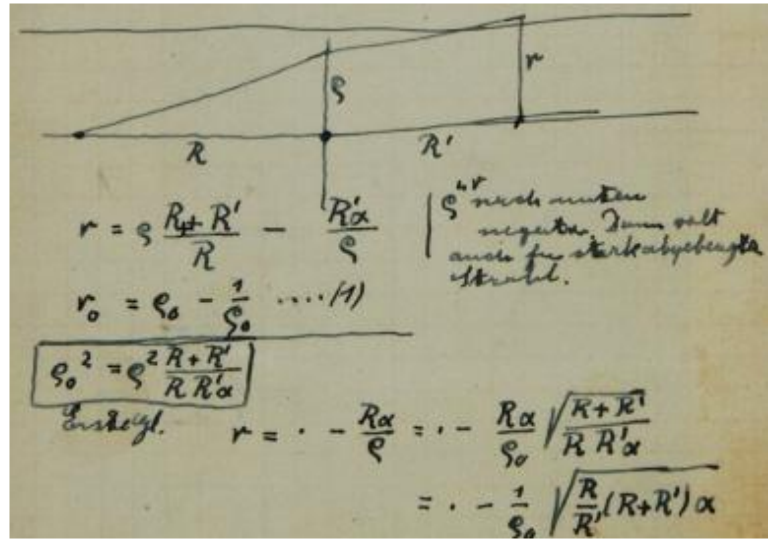


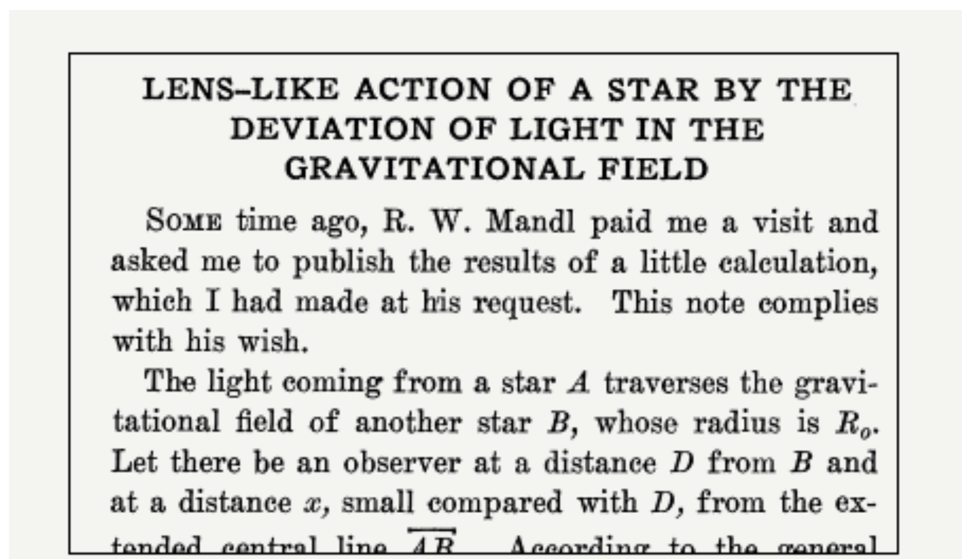
What is gravitational lensing?
Some history

- H. Cavendish (1731-1810): idea that gravity could deflect light
- J. Soldner (1776-1833): light is made of particles and Newtonian theory -> ray of light tangent to the Sun would deviate by 0.875 arcsecs.
- Einstein, in 1911, would independently reproduce Soldner's results. But GR was not complete yet…

What is gravitational lensing? Some history

- Einstein, in 1912, considers the idea of multiple images of a source by a foreground star. He won't publish his calculations until 1936 (Science), encouraged by a friend (R. Mandl).





LENS-LIKE ACTION OF A STAR BY THE DEVIATION OF LIGHT IN THE GRAVITATIONAL FIELD

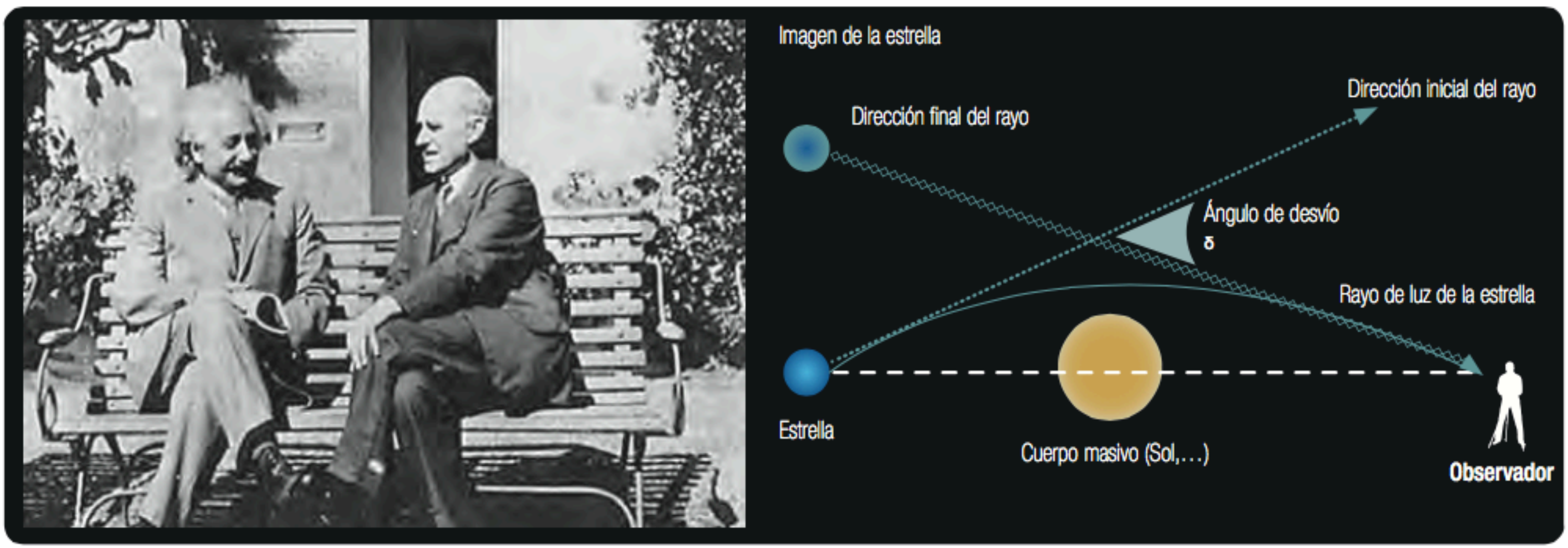
SOME time ago, R. W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request. This note complies with his wish.

The light coming from a star A traverses the gravitational field of another star B, whose radius is R_o. Let there be an observer at a distance D from B and at a distance x, small compared with D, from the extended central line $\overline{AB}$. According to the general

- O. Chwolson, in 1924, independently publishes the same results that Einstein derived in 1912.

What is gravitational lensing? some history

- GR is completed in 1915-1916. Rigorous calculation of the deflection angle by Sun gives an extra factor of 2 compared to Newtonian theory.
- Sir A. Eddington, in 1919, confirms this prediction during a Solar eclipse in Príncipe , Africa



What is gravitational lensing? some history

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

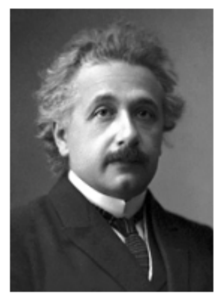
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

New York Times, November, 1919

-Einstein obtained world fame almost immediately.

-An English scientist (Eddington) confirmed the theory of a German scientist (Einstein). It was the times of the “Great War”.

The Nobel Prize in Physics 1921



Albert Einstein

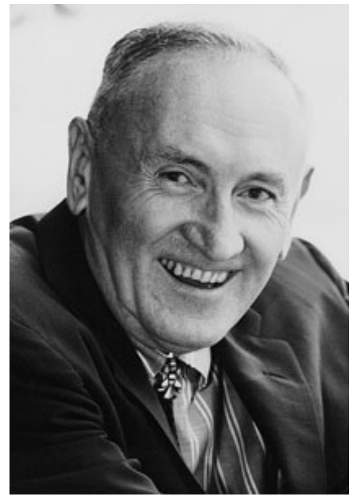
Prize share: 1/1

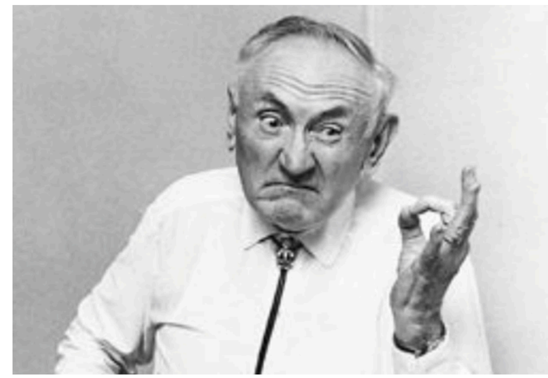
The Nobel Prize in Physics 1921 was awarded to Albert Einstein *"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"*.

Nobel prize: ‘services to Theoretical Physics…and the photoelectric effect’-> **CCDs! Lectures 3 and 4**

What is gravitational lensing? some history

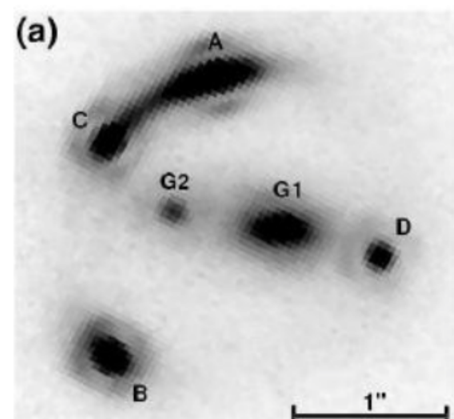
- F. Zwicky, 1937: galaxies, rather than stars, are more likely to act as lenses.





- S. Refsdal, 1964: time delay between multiple images could be used to estimate the Hubble constant.

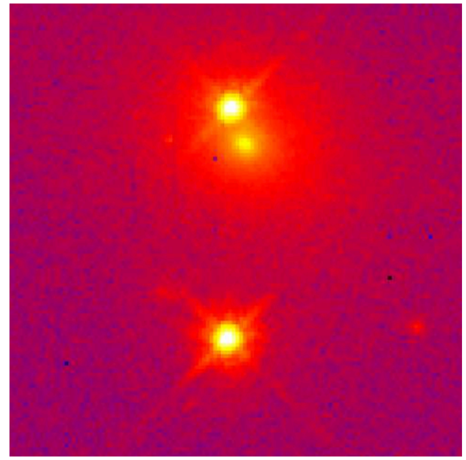
$$t = t_{\rm geom} + t_{\rm grav}$$

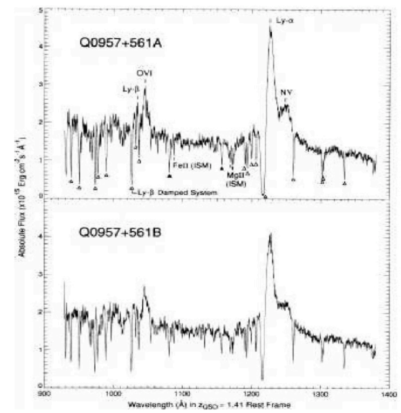


Koopmans et al. (2003)

What is gravitational lensing? some history

- Walsh, Carswell, & Weymann (1979): discovered **first example** of gravitational lensing, quasar QSO 0957+561A,B two images, A and B, separated by 6”

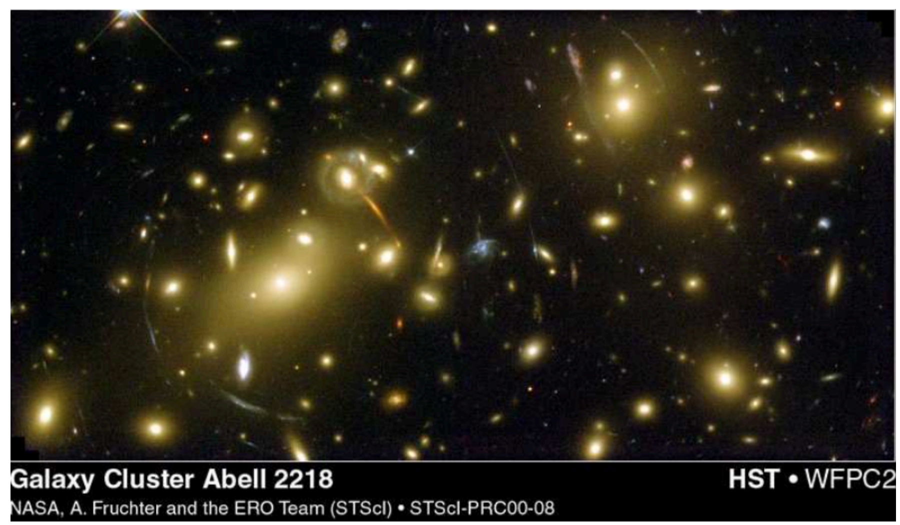




[Michalitsianos et al. 1997]

identical spectra!

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



Lensing arcs are highly magnified (~10-100) background sources: **cosmic telescope!**

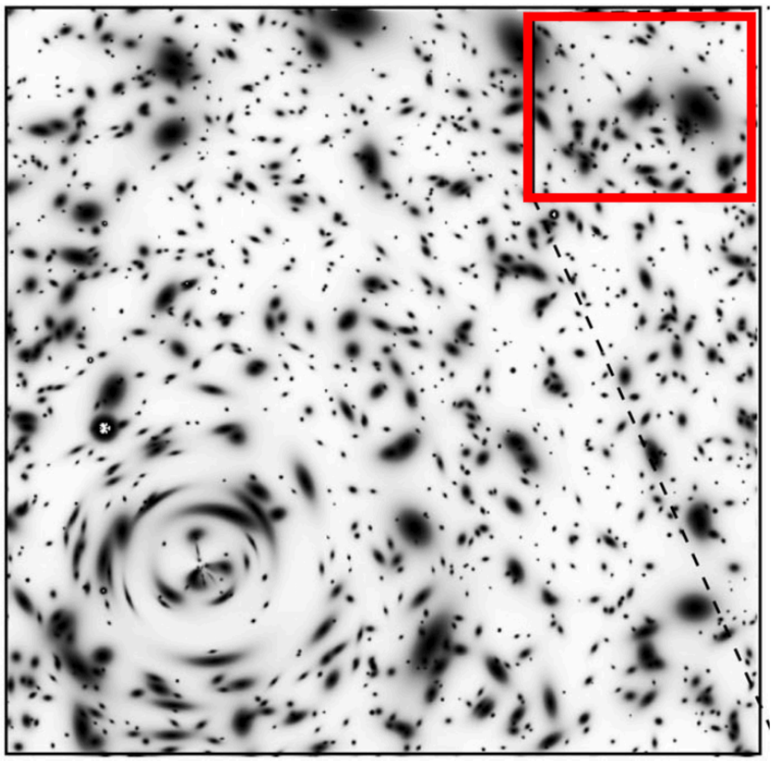
What is gravitational lensing? some history

- **Weak lensing about clusters and galaxies**

  -Distortion is weaker than intrinsic shape

  - First signal in **clusters** by Tyson, Valdes, and Wenk (1990)

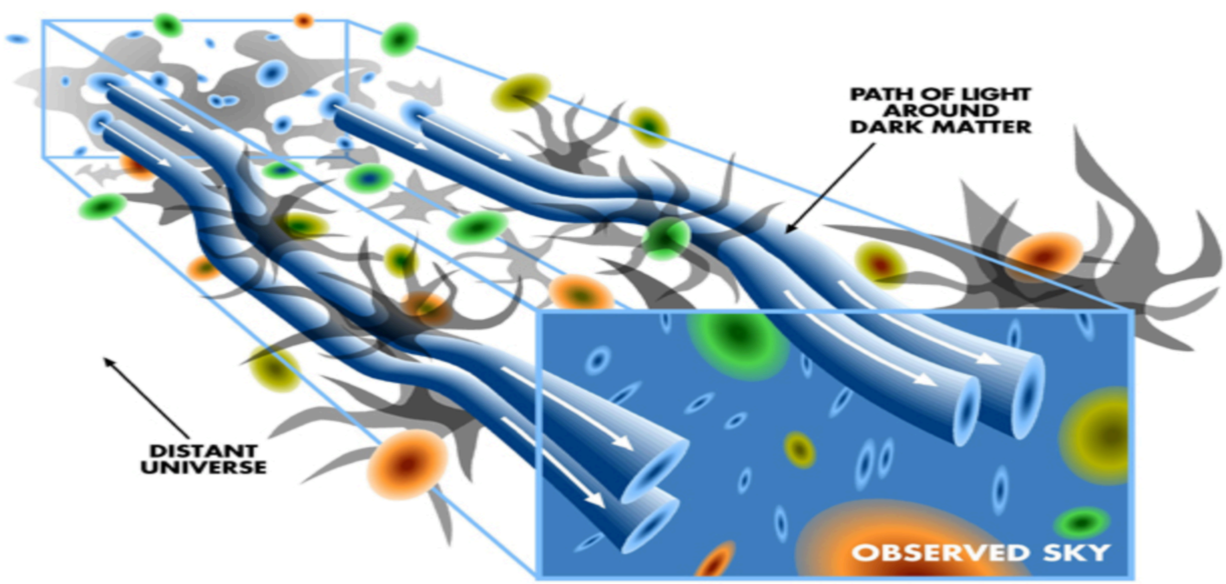
  - Brainerd et al. (1996): weaker signal around individual galaxies



[Mellier 1999]

What is gravitational lensing? some history

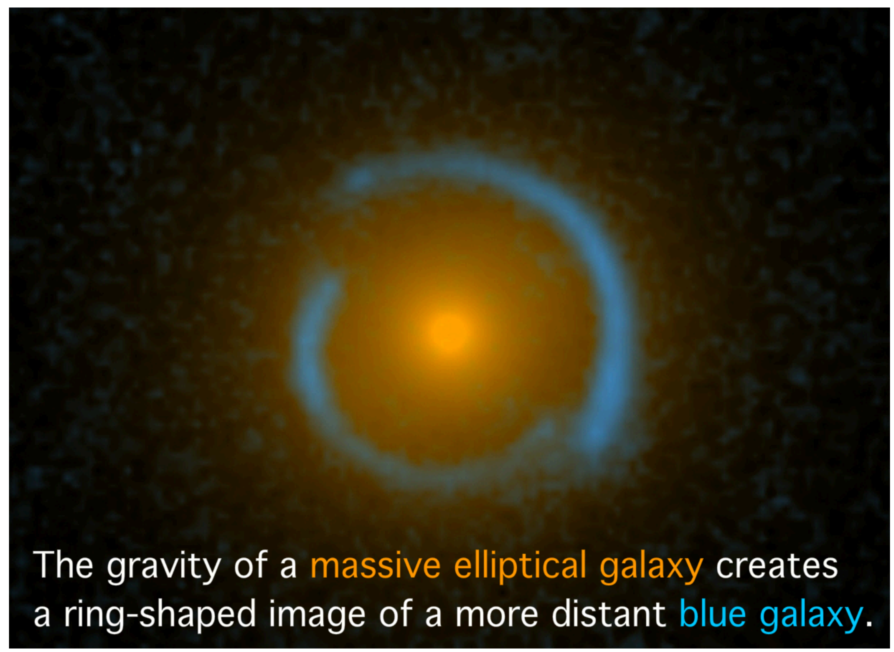
- Cosmic shear: weak lensing by the large scale structure of the Universe: **dark energy!**
- In 2000, four independent teams measured this signal (Kaiser et al. 200, Wittman et al. 2000, Van Waerke, Bacon et al. 2000)



Gravitational Lensing: strong, weak , and micro

- Depending on the spatial and mass scales, and the amplitude of the effect, we can in general talk about three regimes

-Strong Lensing: (almost) perfect alignment. There are multiple images of background and source. Or sometimes a ring: the Einstein Ring!



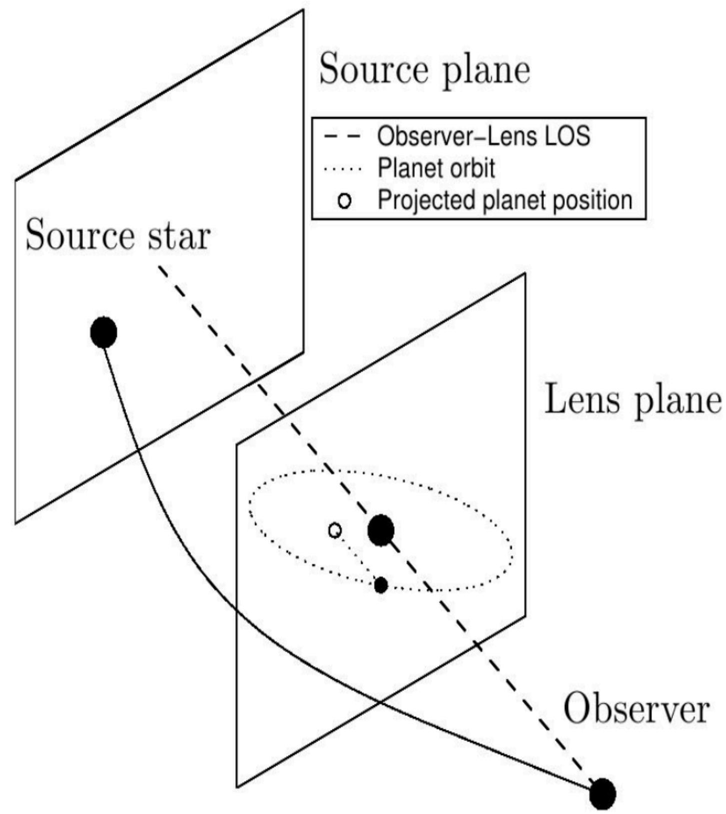
http://www.ifa.hawaii.edu/info/press-releases/Bolton7-08/lensing_animation.html

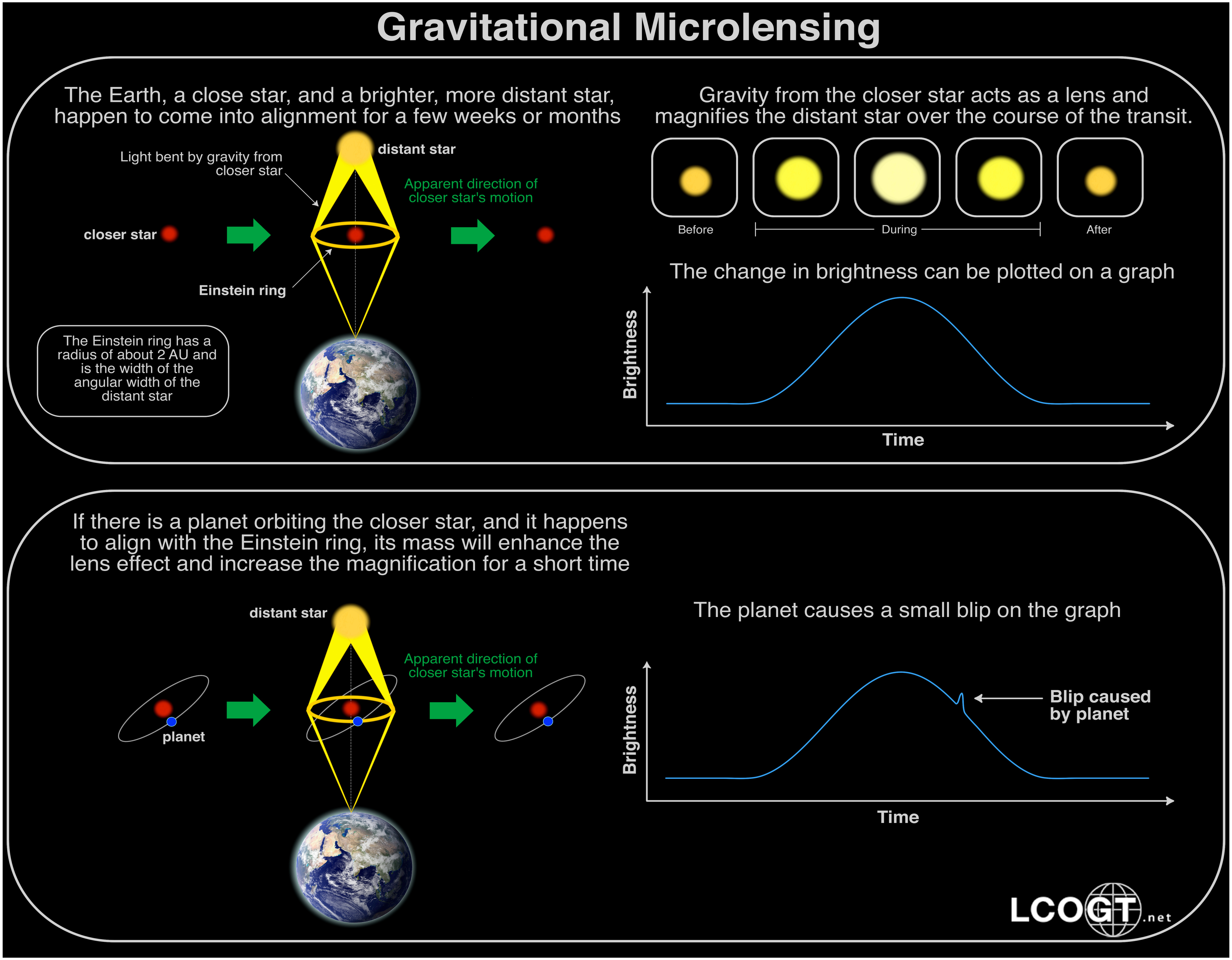
Microlensing

- lensing by stars or other object we can not see

(micro arcsecond scale)

- **magnification** of background sources
- Exoplanets!




Gravitational Microlensing
The Earth, a close star, and a brighter, more distant star, happen to come into alignment for a few weeks or months
Light bent by gravity from closer star
distant star
Apparent direction of closer star's motion
closer star
Einstein ring
The Einstein ring has a radius of about 2 AU and is the width of the angular width of the distant star
Gravity from the closer star acts as a lens and magnifies the distant star over the course of the transit.
Before
During
After
The change in brightness can be plotted on a graph
Brightness
Time
If there is a planet orbiting the closer star, and it happens to align with the Einstein ring, its mass will enhance the lens effect and increase the magnification for a short time
distant star
Apparent direction of closer star's motion
planet
The planet causes a small blip on the graph
Blip caused by planet
Brightness
Time
LCOGT.net

Weak Gravitational Lensing

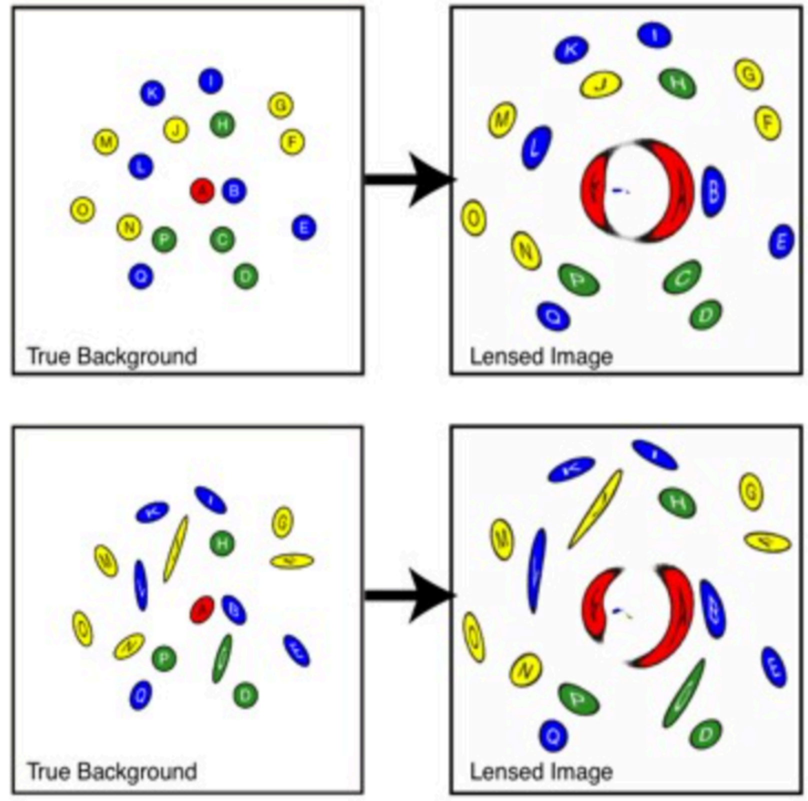
-Weak lensing:

The distortion of the galaxy shapes is of about 1% of the intrinsic ellipticity of the galaxies.

It is impossible to detect on an individual basis.

The dispersion of the intrinsic ellipticity distribution is called "shape noise"

Need millions of galaxies to average that shape noise down and **look for correlations.**



$$\sigma_{\rm shear} = \frac{\sigma_\gamma}{\sqrt{N}}, \sigma_\gamma \approx 0.3$$

Weak Lensing: basics

- Lensing is the deflection of light rays in the presence of massive bodies

The metric of a perturbed homogeneous, isotropic, and expanding Universe can be written as:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = \left(1 + \frac{2\Phi}{c^2}\right) c^2 dt^2 - \left(1 - \frac{2\Phi}{c^2}\right) dl^2$$

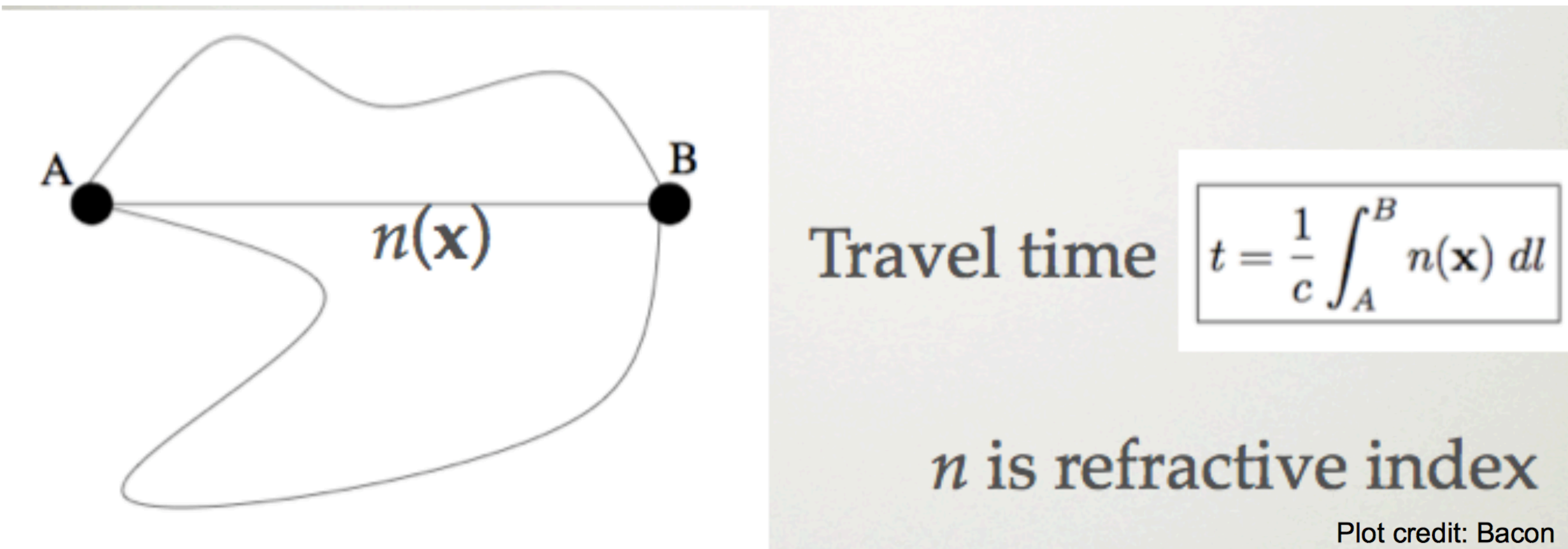
Φ: Newtonian potential. "Weak:" $\Phi/c^2 \ll 1$ For a cluster : $|\Phi| < 10^{-4} c^2 \ll c^2$

Photons satisfy **ds^2=0** (null geodesics): $t = \frac{1}{c} \int \left(1 - \frac{2\Phi}{c^2}\right) \mathrm{d}r$

The potential acts as a medium with variable refractive index: $n = 1 - 2\Phi/c^2$

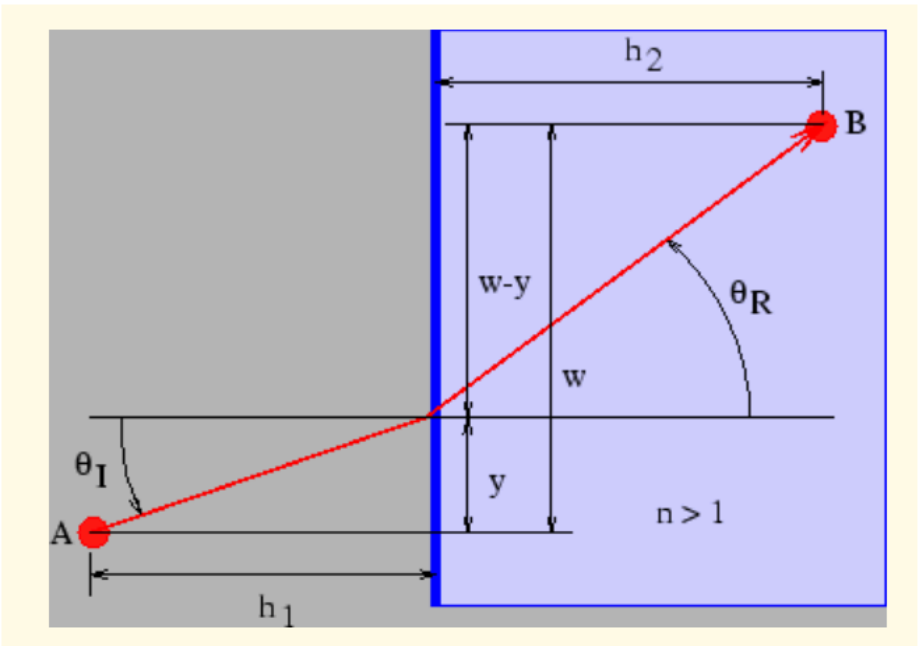
Weak Lensing: Fermat's Principle

Fermat's Principle:



The path taken by light rays between A and B is such that the time taken to transverse it is an **extremum**. We take the shortest solution.

Weak Lensing: Fermat'sPrinciple



$$t=[\{h_1^2+y^2\}^{1/2}+n\{h_2^2+(w-y)^2\}^{1/2}]/c.$$

Differentiate with respect to y and set to zero:

$$\frac{y}{\{h_1^2+y^2\}^{1/2}}=n\frac{w-y}{\{h_2^2+(w-y)^2\}^{1/2}}.$$

We obtain Snell's Law:

$$\sin\theta_I=n\sin\theta_R$$

Weak Lensing: Fermat'sPrinciple

Fermat Principle->Euler-Lagrange equations.

$$\delta \int_A^B n(\vec{x}(l))\mathrm{d}l = 0$$

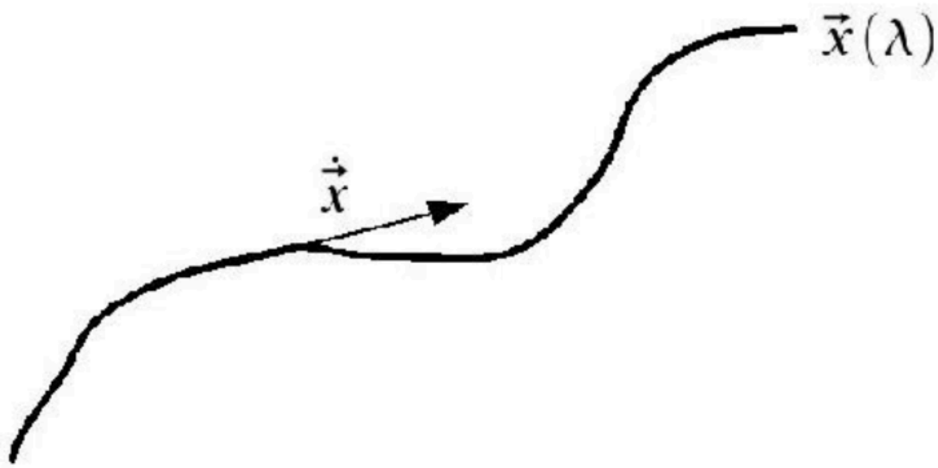
Curve parameterization: $\mathrm{d}l = \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| \mathrm{d}\lambda$ $\left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| = |\dot{\vec{x}}| = (\dot{\vec{x}}^2)^{1/2}$

So the Lagrangian in this case would be: $n[\vec{x}(\lambda)] \left|\frac{\mathrm{d}\vec{x}}{\mathrm{d}\lambda}\right| \equiv L(\dot{\vec{x}}, \vec{x}, \lambda)$

Weak Lensing: Fermat'sPrinciple

Euler-Lagrange Equations: $$\frac{\mathrm{d}}{\mathrm{d}\lambda}\frac{\partial L}{\partial \dot{\vec{x}}} - \frac{\partial L}{\partial \vec{x}} = 0$$

$$\frac{\partial L}{\partial \vec{x}} = |\dot{\vec{x}}|\frac{\partial n}{\partial \vec{x}} = (\vec{\nabla} n)|\dot{\vec{x}}| \; , \; \frac{\partial L}{\partial \dot{\vec{x}}} = n\frac{\dot{\vec{x}}}{|\dot{\vec{x}}|}$$



Weak Lensing: Fermat'sPrinciple

$$\frac{\mathrm{d}}{\mathrm{d}\lambda}(n\vec{e}) - \vec{\nabla}n = 0$$

$\vec{e} \equiv \dot{\vec{x}}$ Unit tangent vector to the path

$|\dot{\vec{x}}| = 1$ Normalizing the tangent vector

$$n\dot{\vec{e}} + \vec{e} \cdot [(\vec{\nabla}n)\dot{\vec{x}}] = \vec{\nabla}n \; ,$$

$$\Rightarrow n\dot{\vec{e}} = \vec{\nabla}n - \vec{e}(\vec{\nabla}n \cdot \vec{e})$$

Second term of r.h.s. is the derivative along the light path. So, whole r.h.s. is the gradient of n perpendicular to the light path

$\dot{\vec{e}} = \frac{1}{n}\vec{\nabla}_\perp n = \vec{\nabla}_\perp \ln n$ Since $n = 1 - 2\Phi/c^2$ and $\Phi/c^2 \ll 1$, $\ln n \approx -2\Phi/c^2$

$$\dot{\vec{e}} \approx -\frac{2}{c^2}\vec{\nabla}_\perp \Phi$$

Deflection angle: integral along light path

$$\hat{\vec{\alpha}} = \frac{2}{c^2}\int_{\lambda_A}^{\lambda_B} \vec{\nabla}_\perp \Phi \mathrm{d}\lambda$$