Astr 102: Introduction to Astronomy

Fall Quarter 2009, University of Washington, Željko Ivezić

Lecture 15:

Observational Cosmology

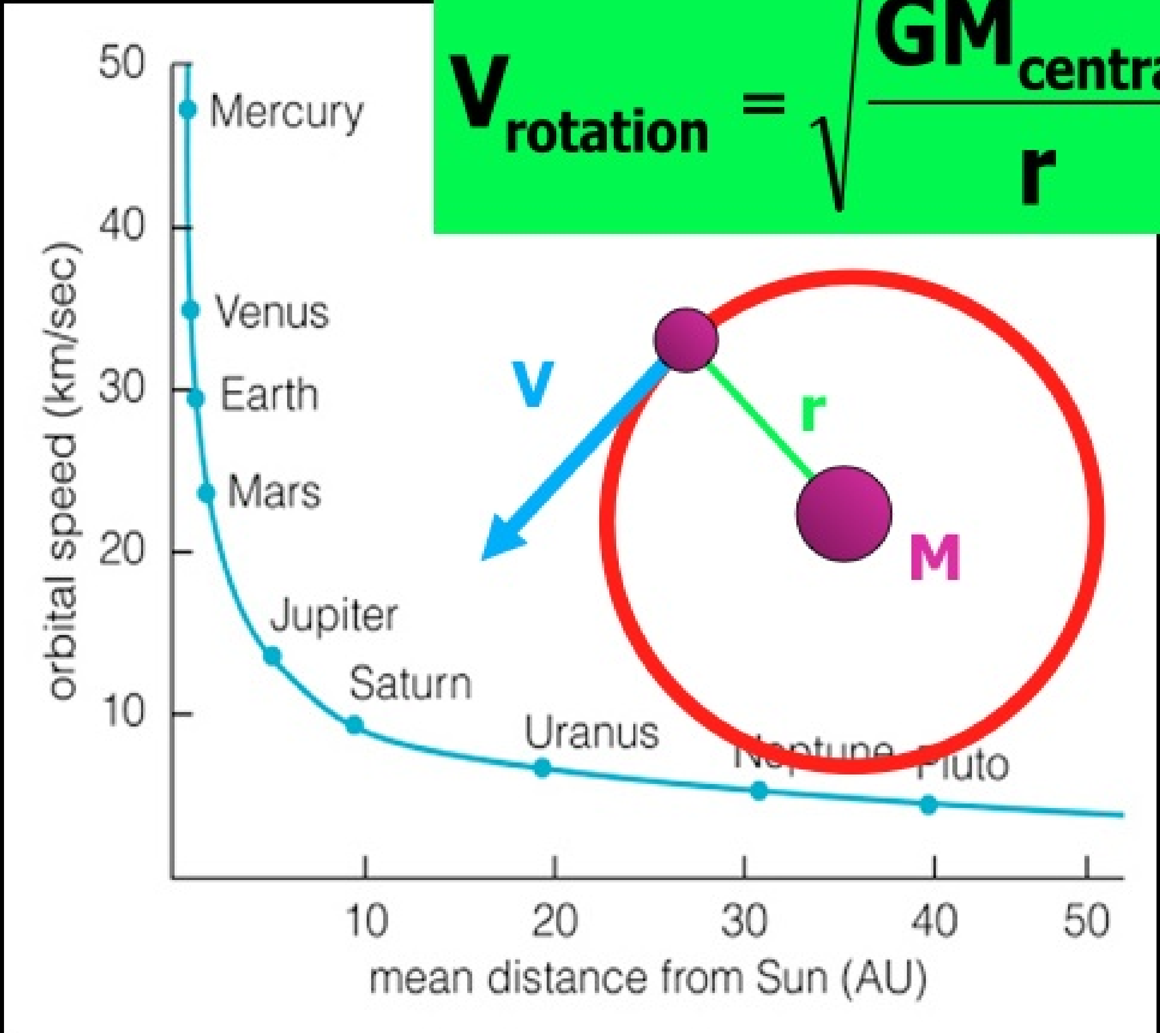
Outline

Observational Cosmology: observations that allow us to test our models for evolution of the whole Universe!

- **Dark matter: rotation curves**
- **Dark matter: gravitational lensing**
- **Gamma-ray bursts**
- Standard candles: supernovae (type Ia)
- Cosmic microwave background
- Nucleosynthesis
- Cosmological models

What can we learn from a rotation curve?

$$V_{rotation} = \sqrt{\frac{GM_{central}}{r}}$$



- Sun has all the mass, so $GM_{central}$ is constant with radius
- Velocity drops with increasing radius!

"Keplerian Rotation"

Rotation of Stars in the Disks of Spiral Galaxies

- Most stars in spiral galaxies are concentrated in fairly thin disks

- Stars move around the galaxy center – described by the rotation (circular velocity) curve $v_c(R)$

- The shape of rotation curve depends on the distribution of enclosed mass – e.g. for a point mass $v_c(R) \propto 1/\sqrt{R}$

- In general, $v_c(R) = R\, d\Phi(R)/dR$, where Φ is the gravitational potential (Φ follows from the mass density profile via Poisson equation)

- We know the disk light intensity profile; we can assume that mass is following light and predict $v_c(R)$ for an exponential disk; but...

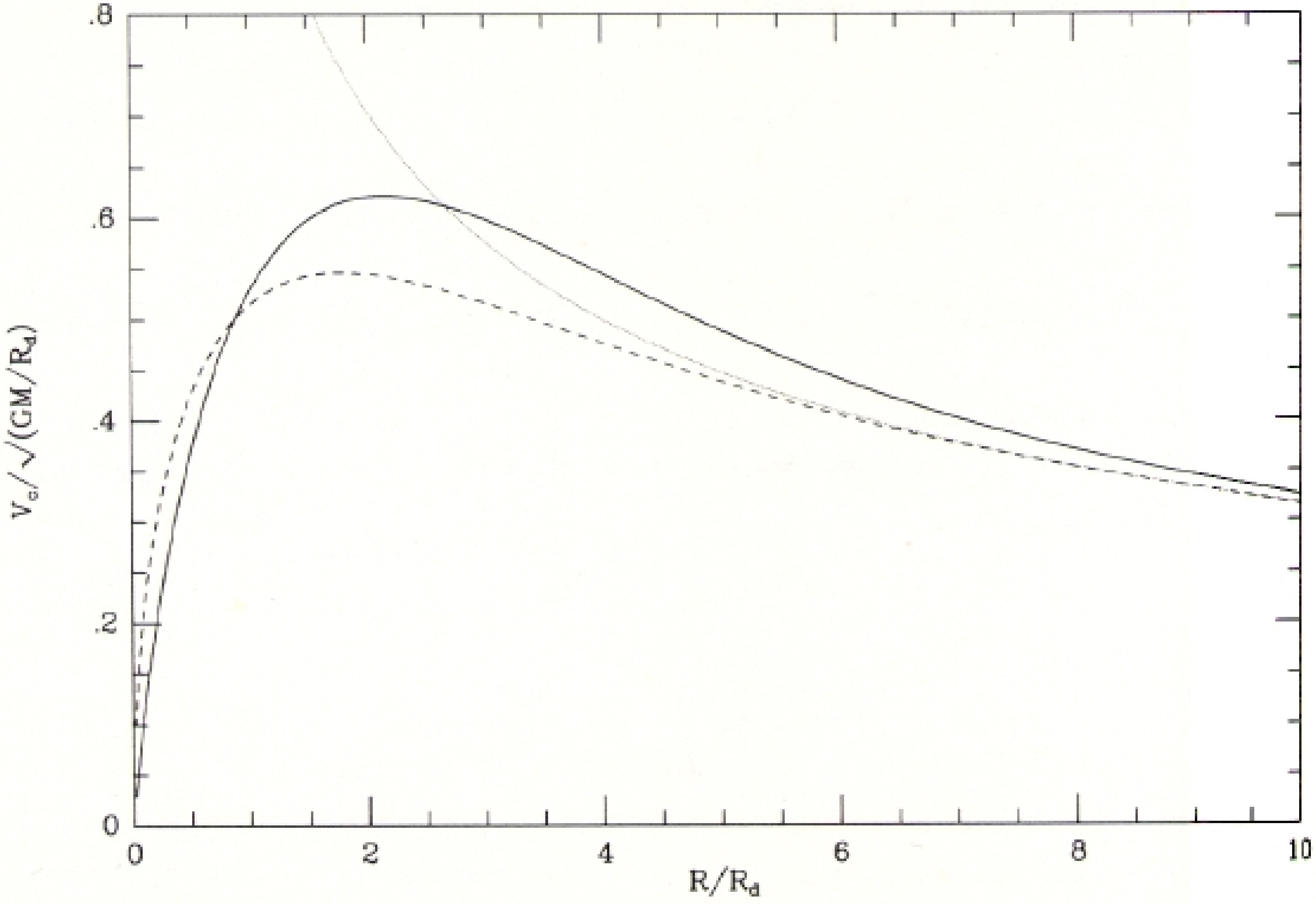


Figure 2-17. The circular-speed curves of: an exponential disk (full curve); a point with the same total mass (dotted curve); the spherical body for which $M(r)$ is given by equation (2-170) (dashed curve).

Rotation of Stars in the Disks of Spiral Galaxies

The prediction for rotation curve in an infinitely thin exponential disk (the previous slide) involves (somewhat) complicated Bessel functions. A much simpler, but still decent approximation is

$$v_c(R) = 0.876\sqrt{\frac{GM}{R_e}}\sqrt{\frac{r^{1.3}}{1+r^{2.3}}} \tag{1}$$

where R_e is the scale length ($I(R) \propto \exp(-R/R_e)$), and $r = 0.533R/R_e$.

Note that for $R >> R_e$, $v_c(R) \propto 1/\sqrt{R}$

FYI: if M is measured in solar masses ($M_\odot$), R in pc, v_c in km/s, then the gravitational constant is $G = 233$

What do we get from observations?

Measurements of the Rotation Curve

The circular speed can be determined as a function of radius by measuring the redshift of emission lines of the gas contained in the disk:

Hot stars ionize gas: hydrogen emission lines (e.g. H_α) in the optical

Neutral atomic hydrogen gas: hyperfine structure transition (due to flip in electron spin) leads to 21 cm radio line

H_α measurements

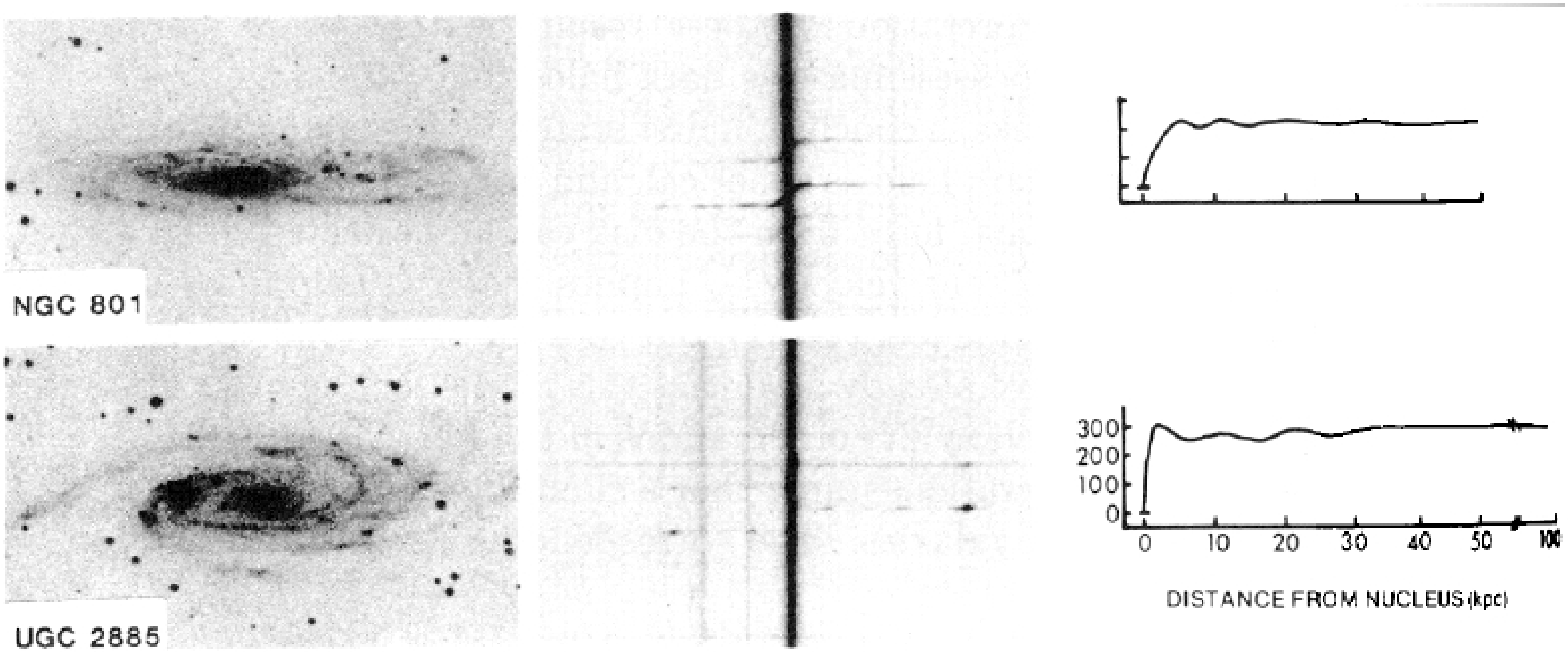
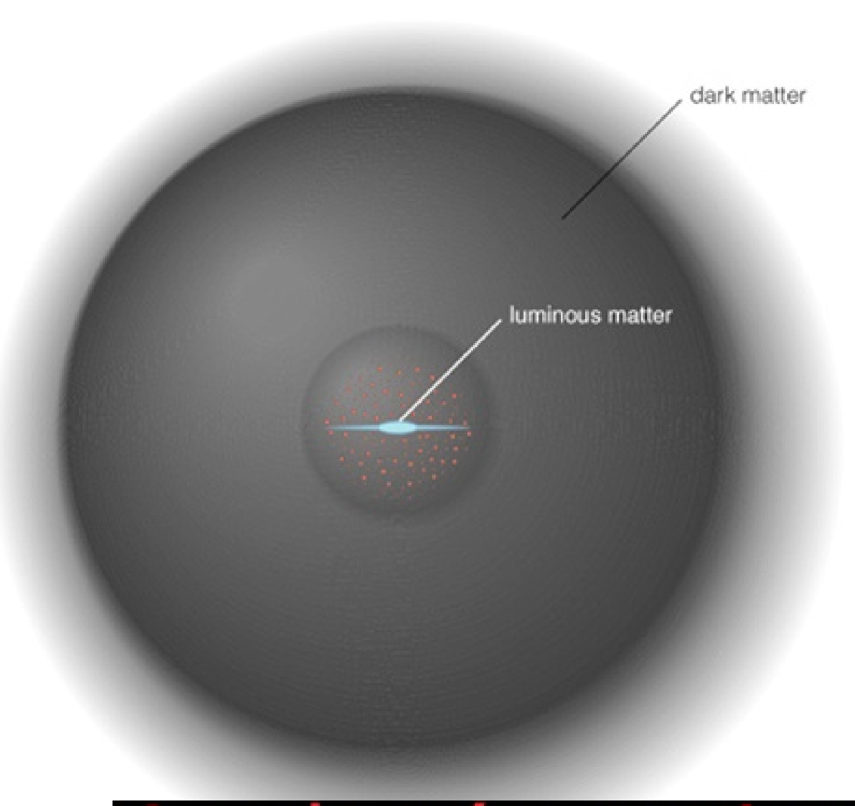
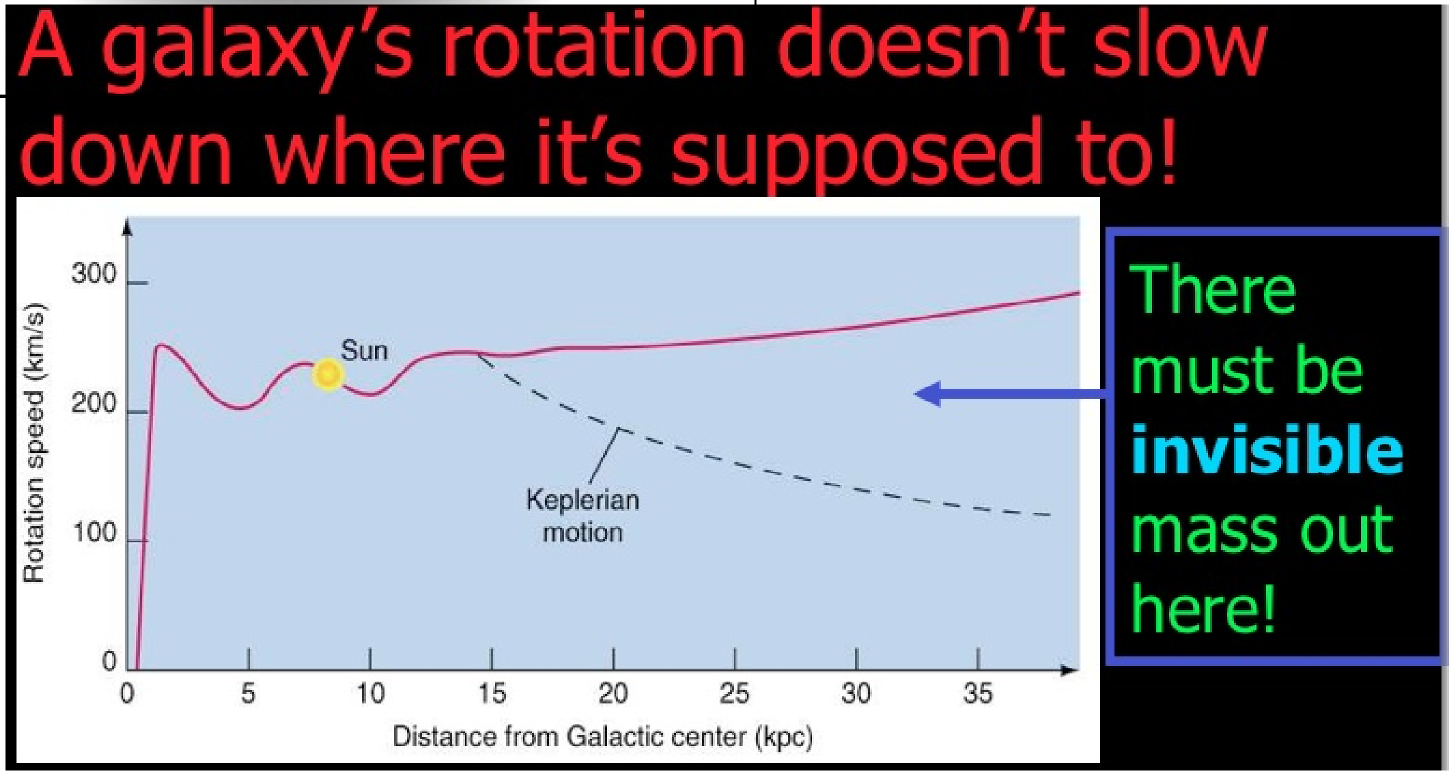


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.



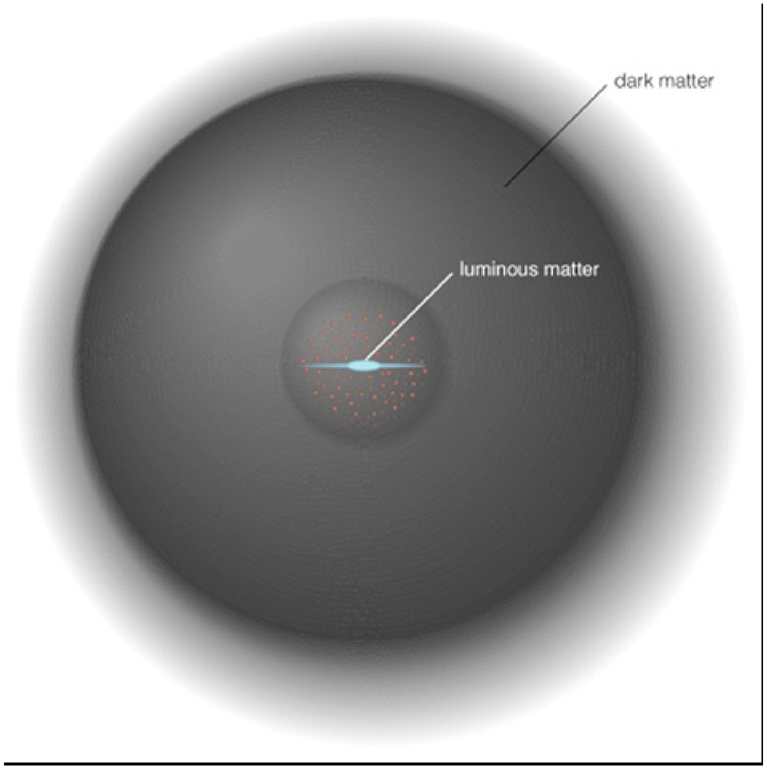
“Flat” rotation curves

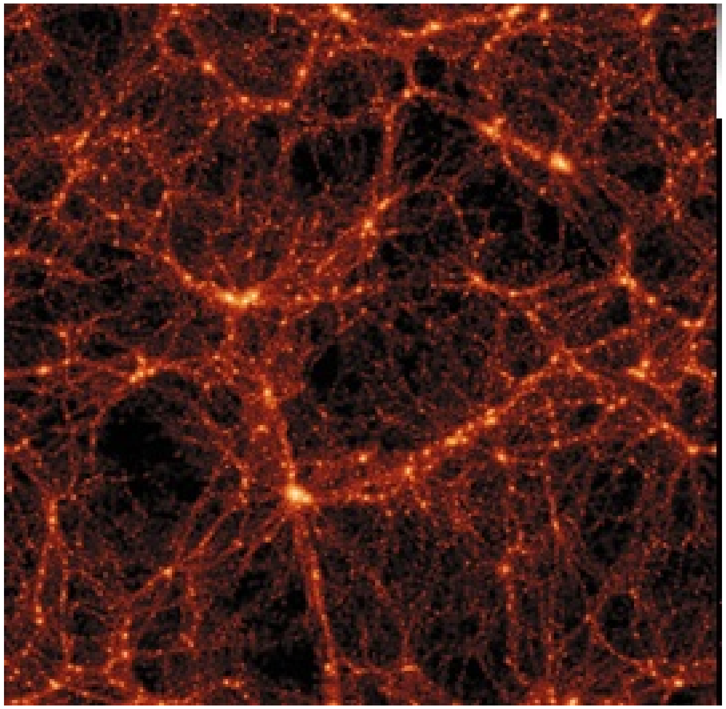
- The measurements show that rotation curves are “flat” – they are not approching the $v_c(R) \propto 1/\sqrt{R}$ behavior expected in the outer parts of disks
- Therefore, there must be an invisible galaxy component that is capable of producing gravitational force
- Earlier (1930’s) suggested by Fritz Zwicky, became an accepted view after Rubin’s work



A galaxy’s rotation doesn’t slow down where it’s supposed to!

There must be **invisible** mass out here!





“Flat” rotation curves

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- Therefore, there must be an invisible galaxy component that is capable of producing gravitational force
- While, in principle, this discrepancy could also be due to a different gravitational law (i.e. force that is not $\propto 1/R^2$), the modern data, including cosmic microwave background measurements, suggest that indeed that is a “dark matter” component contributing ∼5 more gravitational force than stars and gas combined!
- **Bottom left: theoretical prediction for dark matter distribution**

A simple analytical model for dark matter halos

$$\rho = \rho_0 \frac{a^2}{r^2 + a^2} \qquad \left(r \gg a \rightarrow \rho \sim r^{-2}\right)$$

$$M(r) = \int_0^r 4\pi \rho r^2 dr \qquad \text{(Bronstein No. 65)}$$

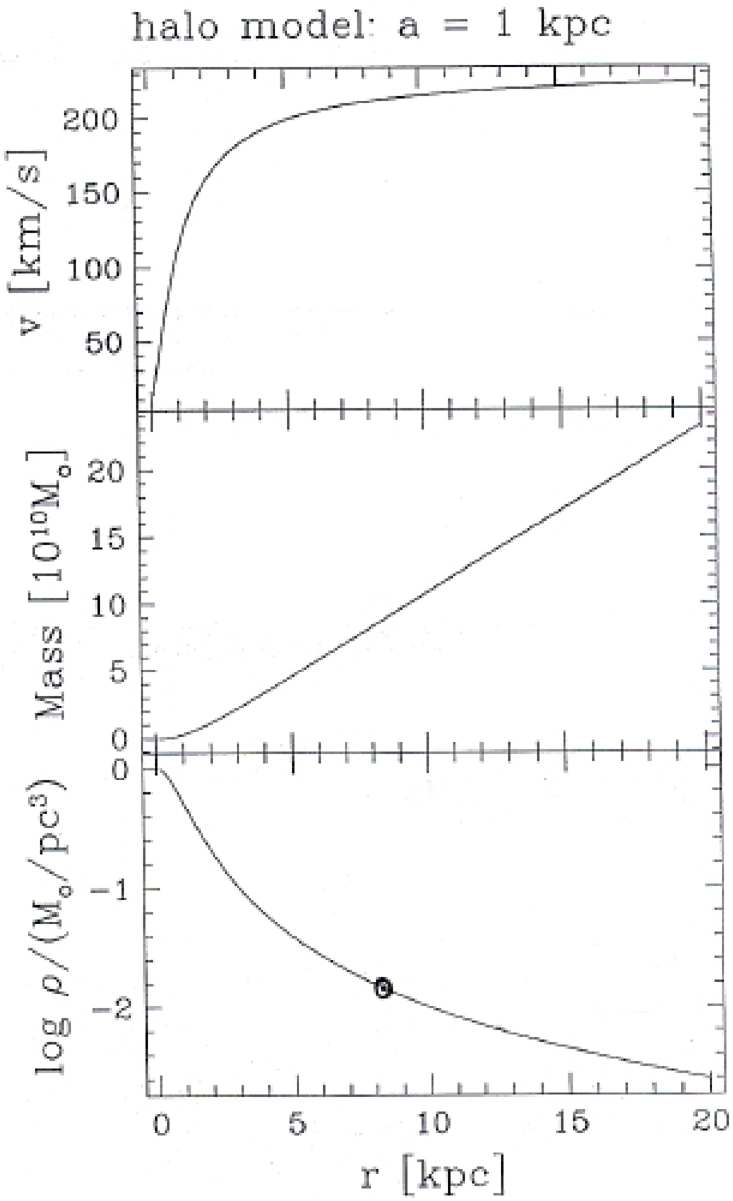
$$= 4\pi \rho_0 a^3 \left(\frac{r}{a} - \arctan \frac{r}{a}\right)$$

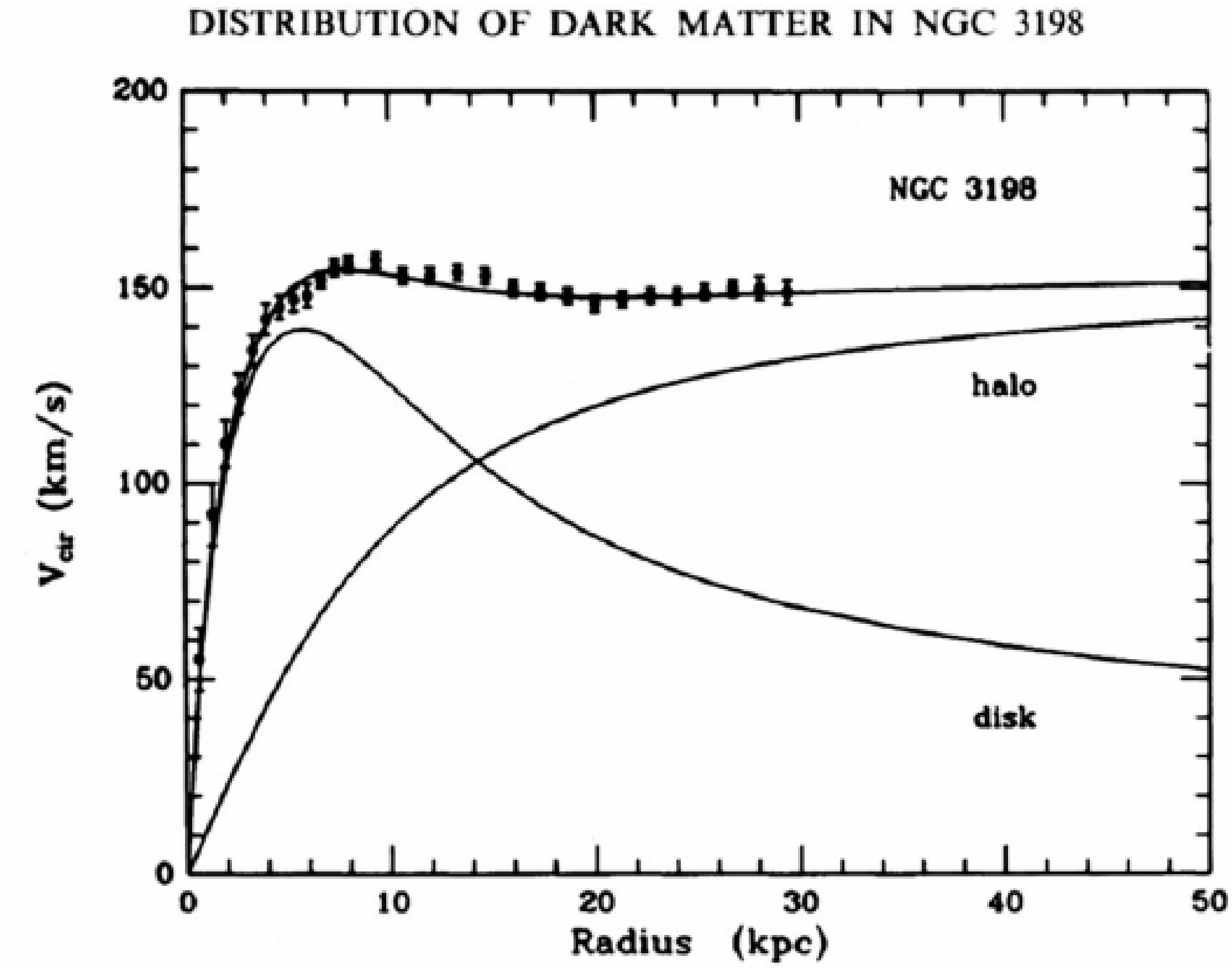
$$\text{circular velocity :} \quad v_c(r) = \sqrt{\frac{GM(r)}{r}}$$

$$v_c(r) = \left[4\pi G \rho_0 a^2 \left(1 - \frac{a}{r} \arctan \frac{r}{a}\right)\right]^{\frac{1}{2}}$$

$$r \gg a : \quad v_c \rightarrow \sqrt{4\pi G \rho_0 a^2} \simeq \text{const}$$

$$r \ll a : \quad v_c \rightarrow \sqrt{\frac{4\pi G \rho_0 a^2}{3}} \cdot \frac{r}{a}$$



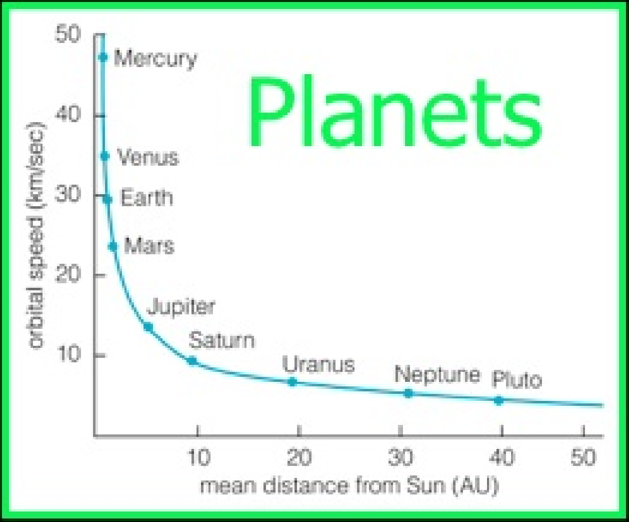


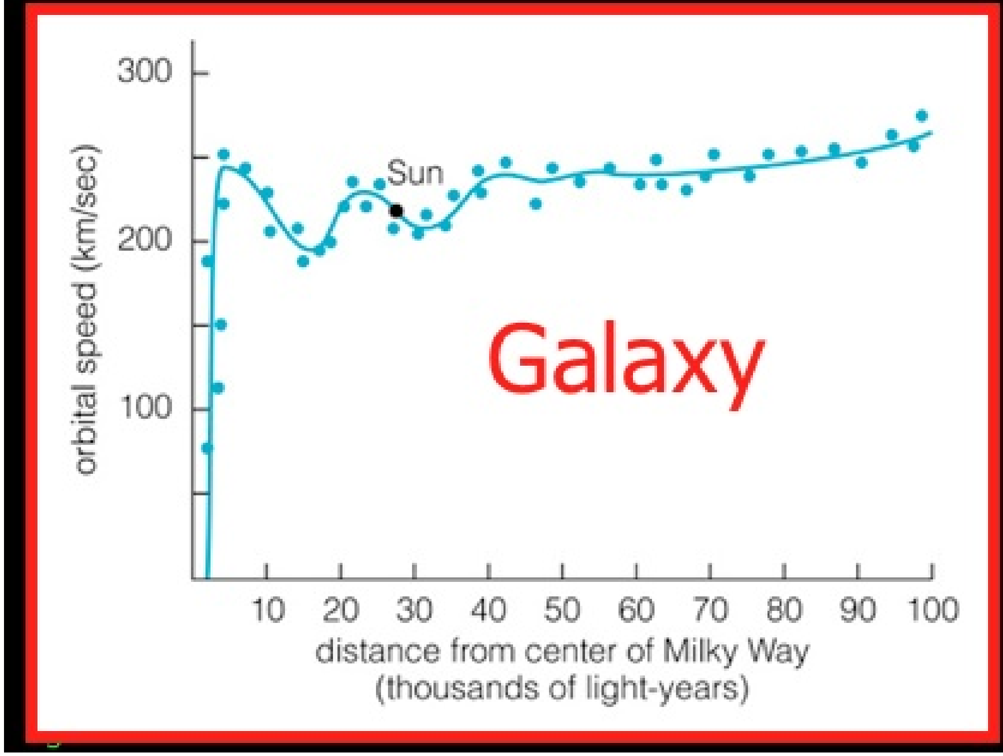
see: van Albada et al. ApJ 295, 305 (1985)

$$\Phi = \Phi_{halo} + \Phi_{disc} \Rightarrow v_c^2 = v_{c,halo}^2 + v_{c,disc}^2 \; (v_c^2 = r\frac{\partial \Phi}{\partial r})$$

Summary: gravitational evidence for dark matter

- Falls with radius because all the mass is at the center.
- No new mass at large radii.





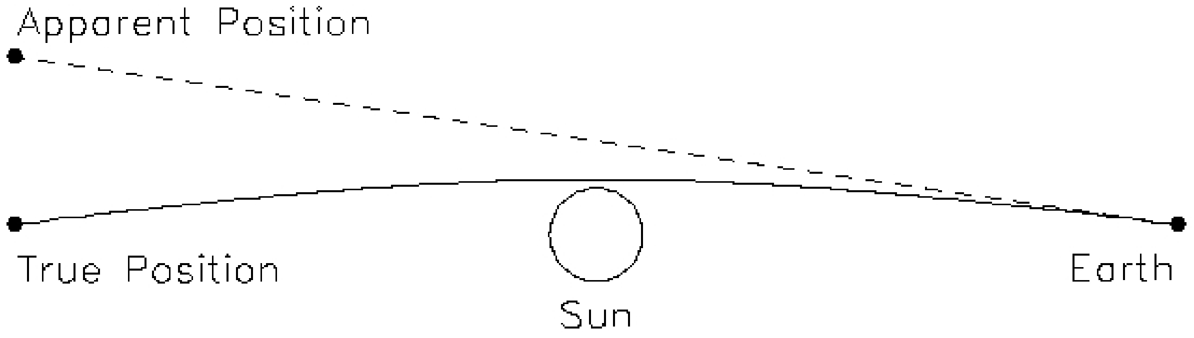
- Does NOT fall with radius!
- There must be more and more mass at large radii.

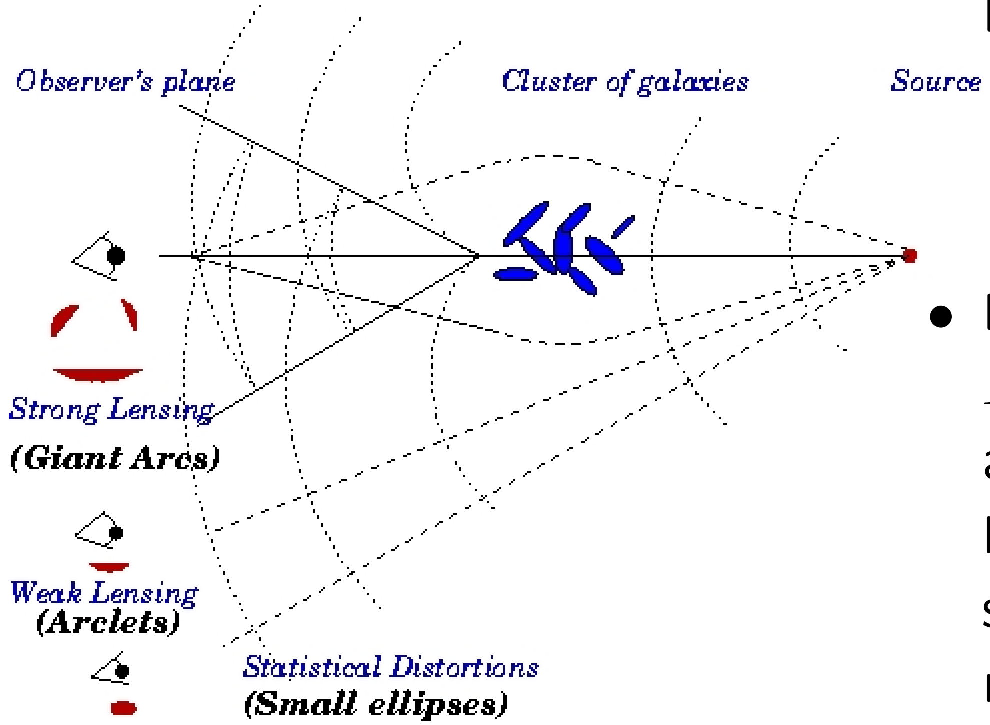
Deflection of light by gravitational field

- Einstein (1916) predicted that the path of a beam of light could be deflected by the force of gravity.
- Einstein's prediction of the deflection angle, α, for a spherically symmetric mass is:

$$\alpha = \frac{4G}{c^2}\frac{M(<b)}{b} = 1.75'' \frac{M(<b)/M_\odot}{b/R_\odot} \tag{2}$$

  where $M(b)$ is the total mass within a distance b from the center of the mass.
- Confirmed observationally by Eddington et al. (1920)
- If M is $\sim 10^{12}\ M_\odot$ (galaxy) and $b \sim 10$ kpc, then $\alpha \sim$ arcmin – significant deflections and distortions!



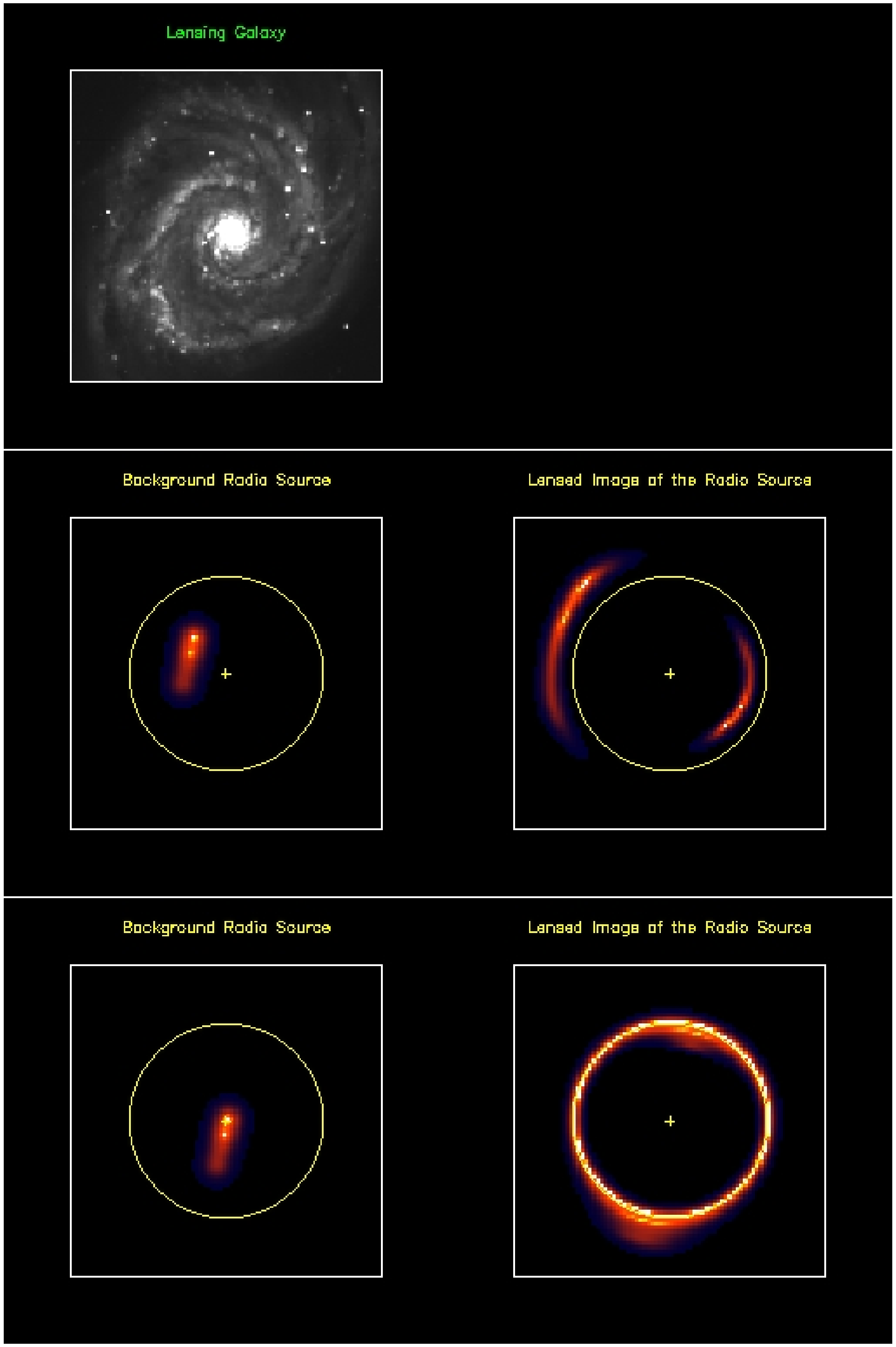


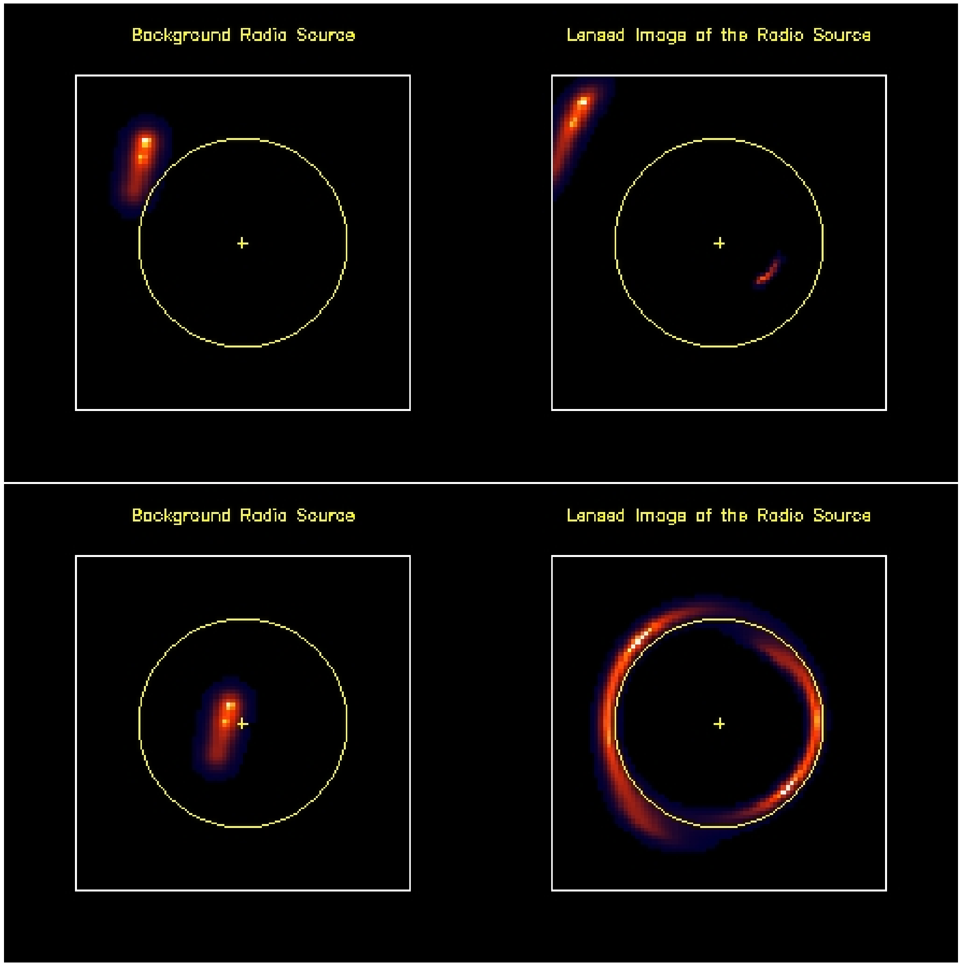
Lensing Regimes

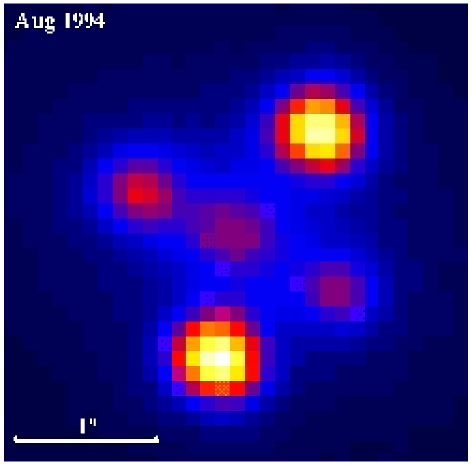
- A parameter that determines the morphology of lensed image is the Einstein angle:

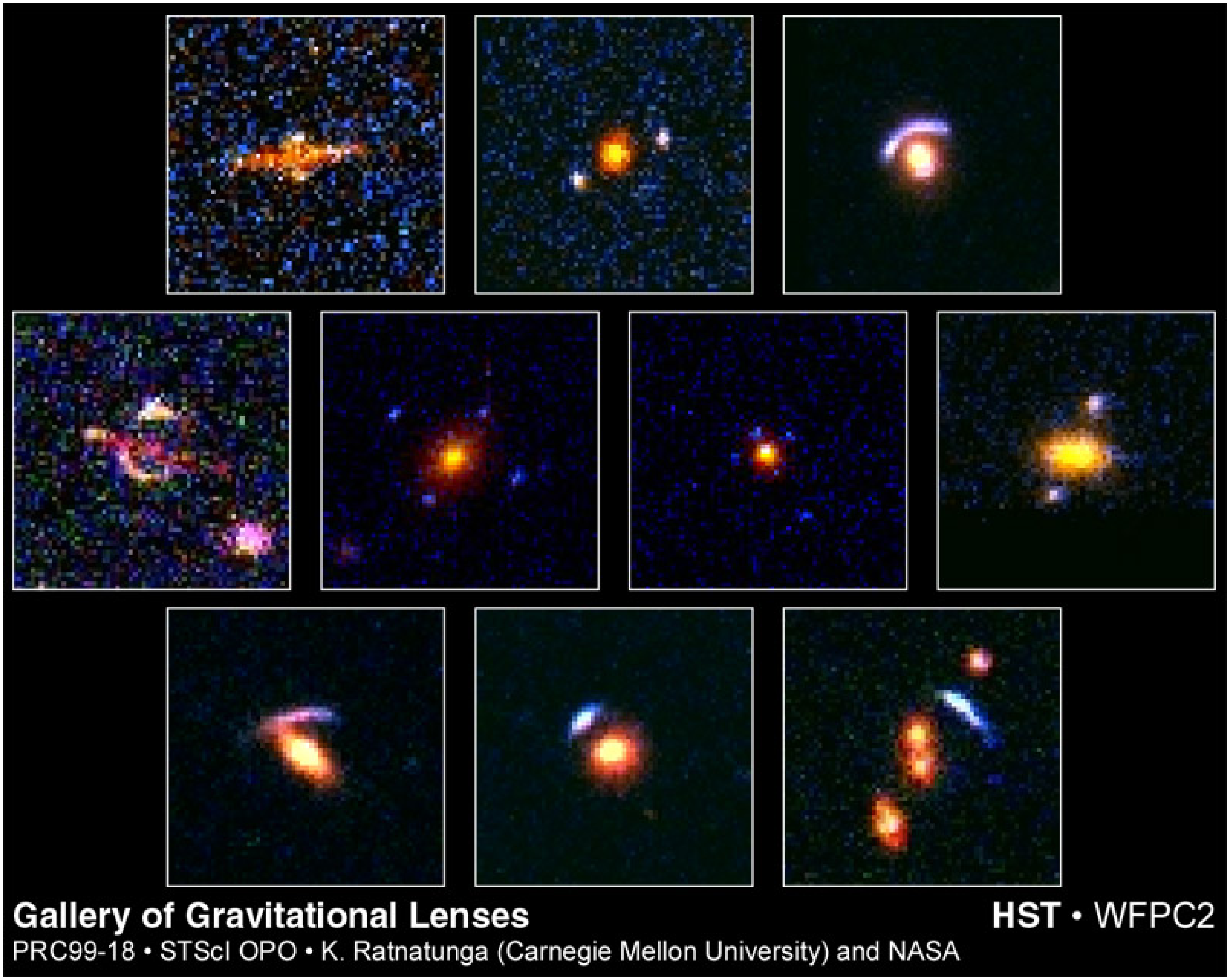
$$\theta_E^2 = \frac{4GM}{c^2}\frac{D_{LS}}{D_L D_S} \tag{3}$$

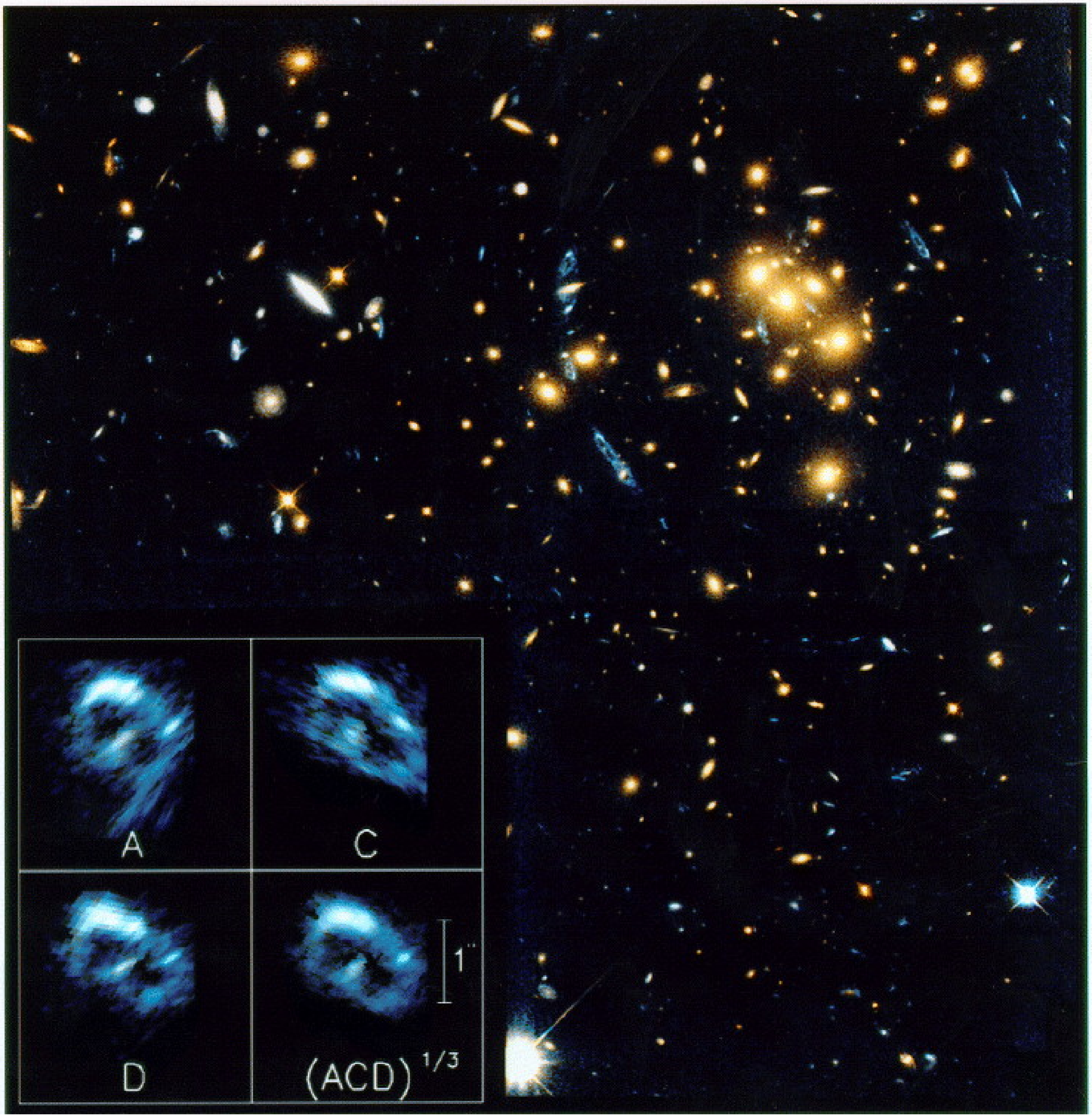
- Here, D_L is the distance to the lens, D_S is the distance to the source, and D_{LS} is the distance from the lens to the source (for Euclidean space $D_{LS} = D_S - D_L$, but for cosmological distances it is slightly different).
- Depending on D_S, D_L and lensing mass distribution, the lensed image can include multiple source images, rings, arcs
- Regimes: strong lensing, weak lensing, and statistical distortions


Lensing Galaxy
Background Radio Source
Lensed Image of the Radio Source
Background Radio Source
Lensed Image of the Radio Source


Background Radio Source
Lensed Image of the Radio Source
Background Radio Source
Lensed Image of the Radio Source


Aug 1994
1"


Gallery of Gravitational Lenses
HST • WFPC2
PRC99-18 • STScI OPO • K. Ratnatunga (Carnegie Mellon University) and NASA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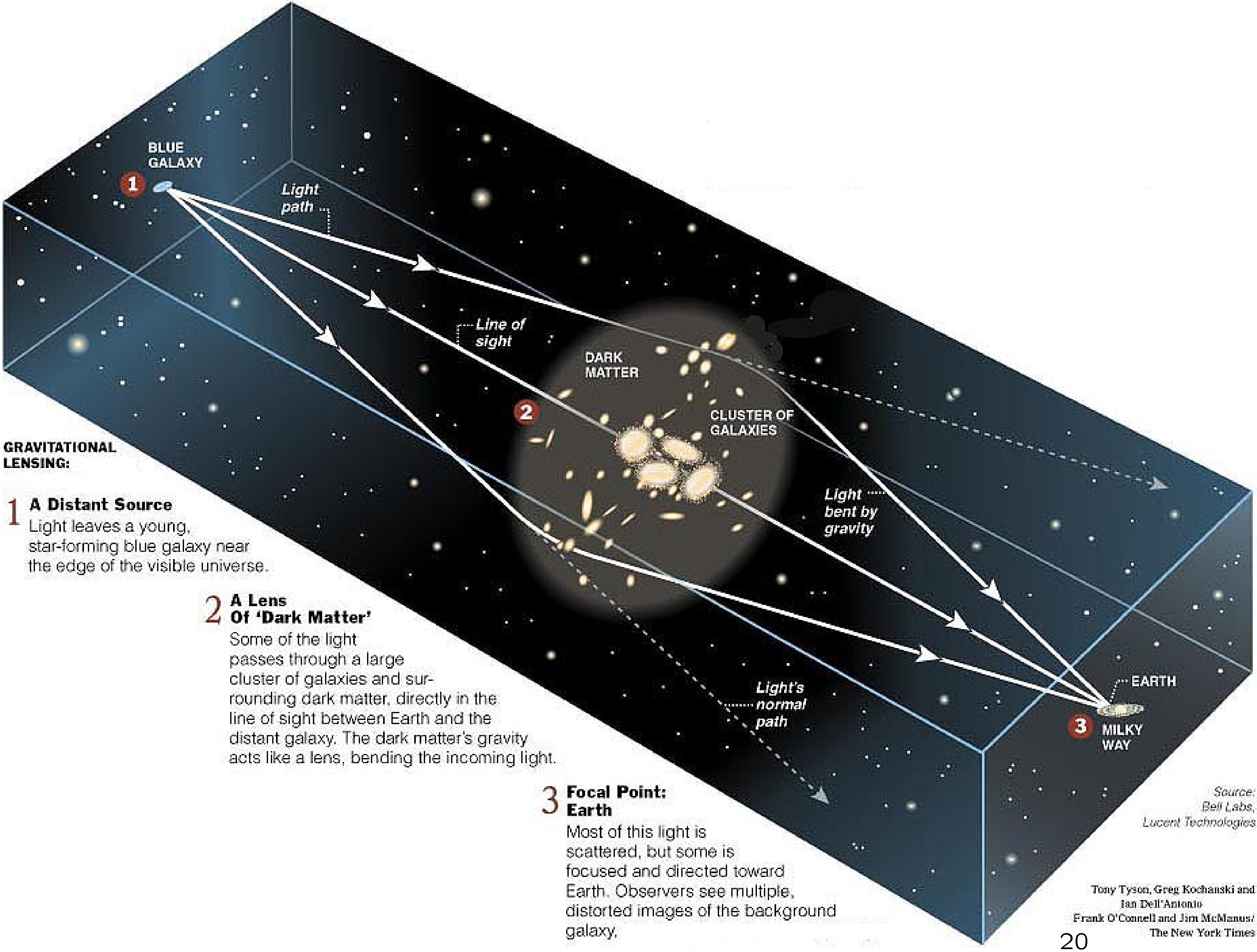


GRAVITATIONAL LENSING:

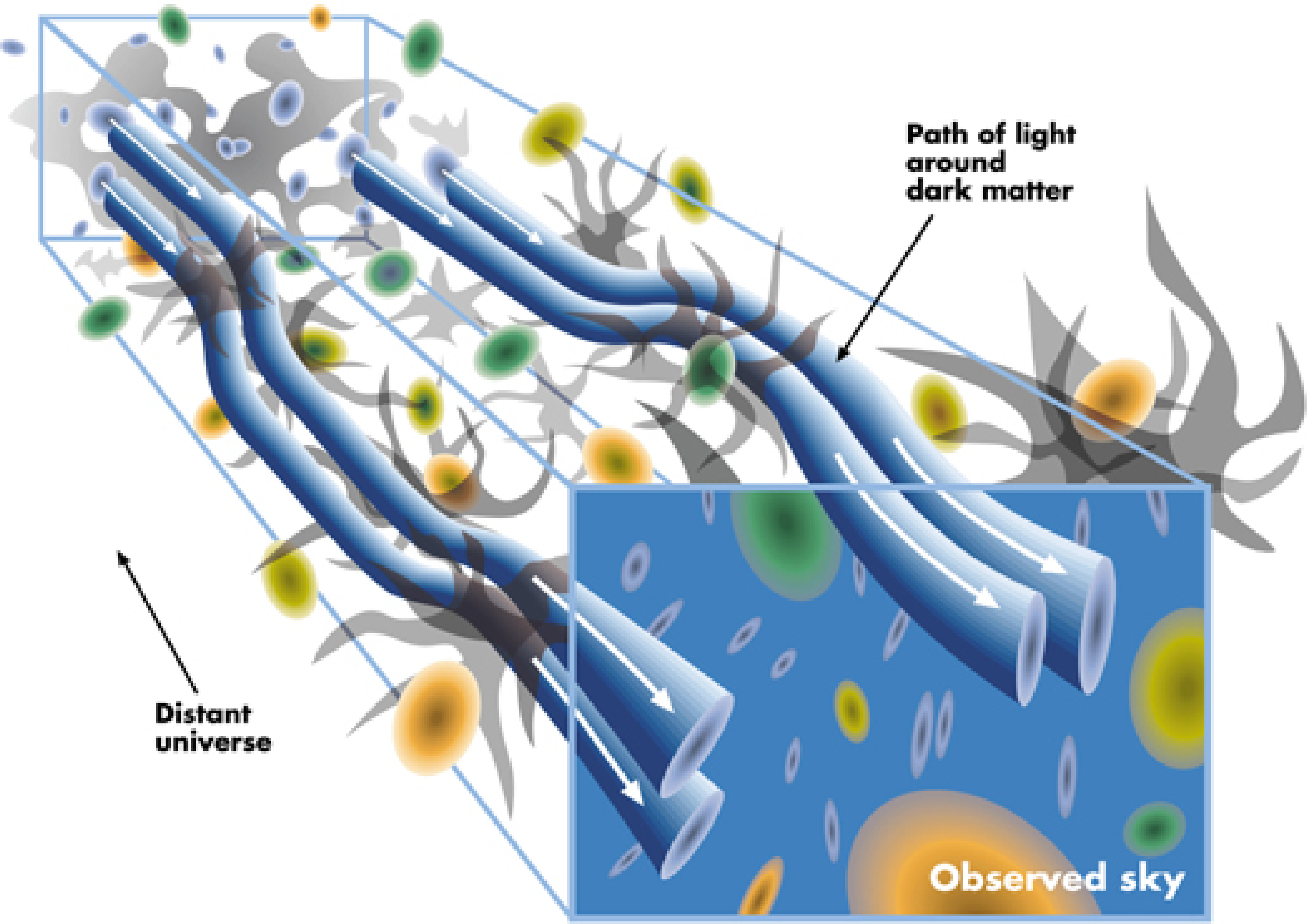
1 **A Distant Source**
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

2 **A Lens Of 'Dark Matter'**
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 **Focal Point: Earth**
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source: Bell Labs, Lucent Technologies

Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/The New York Times


Path of light
around
dark matter
Distant
universe
Observed sky

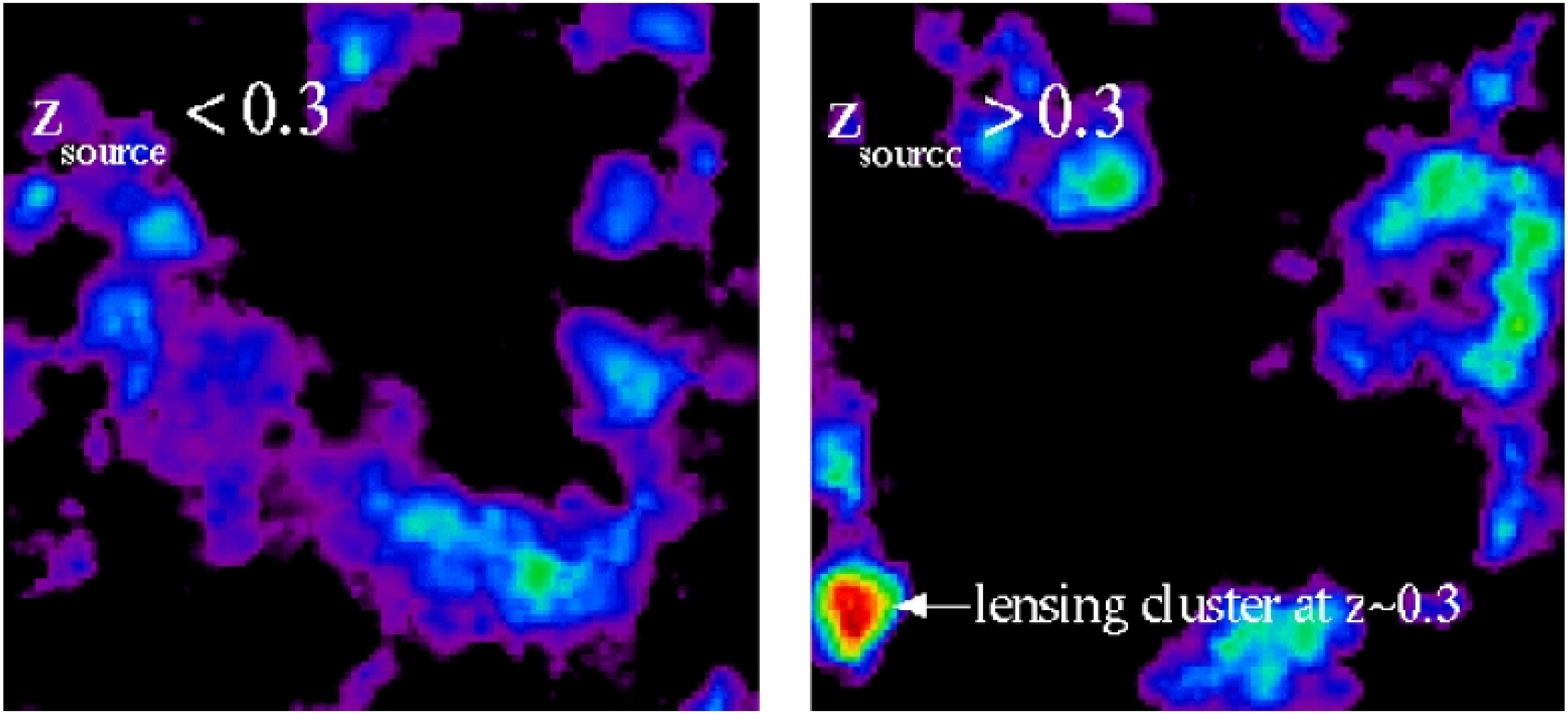
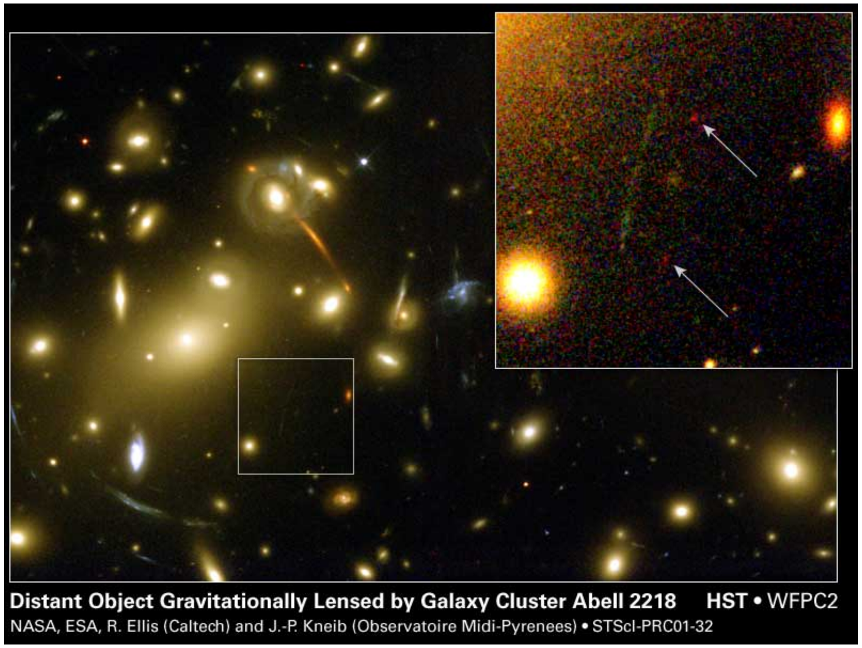


Figure 4. 3-D mass tomography from the Deep Lens Survey. These mass maps of a 40' field show two slices in redshift. Similar 3-D mass tomography has found clusters up to *z*=1.

Lensing Magnification

Distant Galaxy Lensed by Cluster Abell 2218 *HST* • WFPC2 • ACS

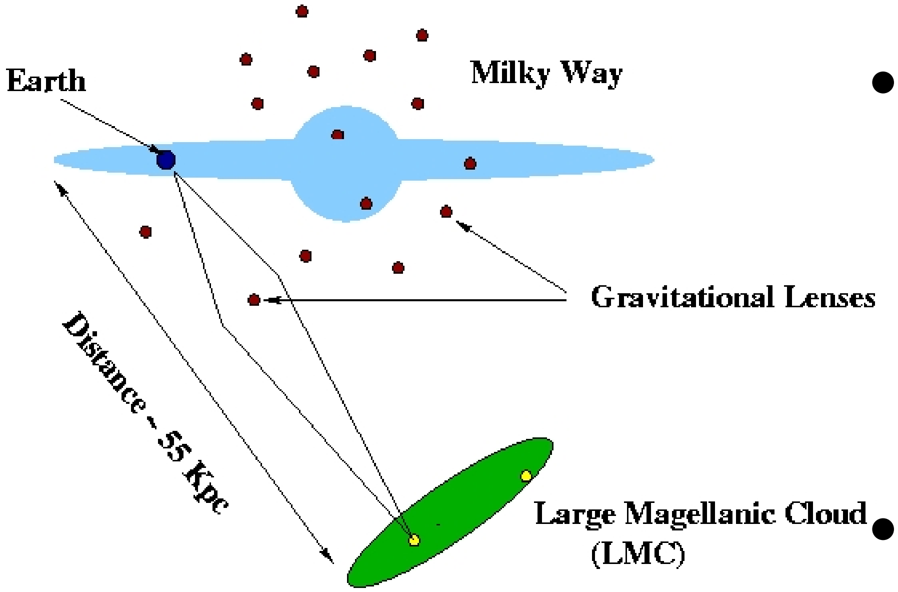
ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech)) STScI-PRC04-08

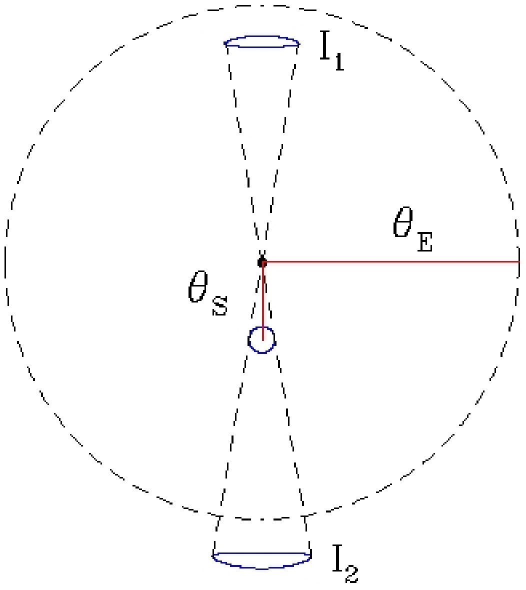


Distant Object Gravitationally Lensed by Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, ESA, R. Ellis (Caltech) and J.-P. Kneib (Observatoire Midi-Pyrenees) • STScI-PRC01-32

- Gravitational lenses are excellent probes of cosmological parameters
- Galaxy shear: tiny distortions of galaxy images. The future is in large faint samples – Large Synoptic Survey Telescope (LSST)!
- Gravitational lenses are giant telescopes: the magnification they provide allows detection of very distant galaxies
- Gravitationally lensed quasars allow studies of intergalactic medium and a direct determination of Hubble constant. How do we find such objects?





Microlensing

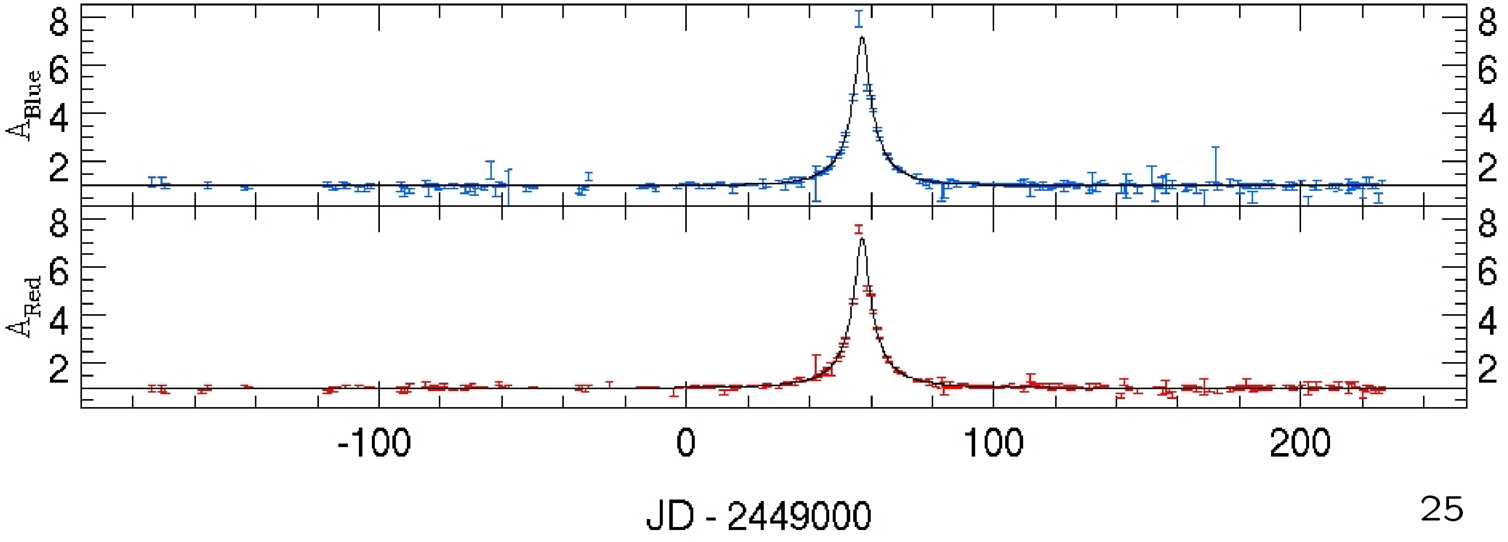
- The dark matter can be studies using a phenomenon called microlensing. This method was proposed in 1986 by Bohdan Paczynski, and is based on light magnification by a foreground compact dark object.
- With current telescopes the observer sees microlensing event as neither the splitting nor the distortion of the two images, but as one image (a blurring of the two microimages) that is brighter than the unlensed source.
- The magnification A by which the blurred combined image is brighter depends on the angular separation between the background source and the lens θ_S, compared to the angular size of the Einstein ring

Microlensing

- Magnification A is

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \tag{4}$$

  where $u = \theta_S/\theta_E$ (what is A for $\theta_S = 0$?)
- Paczynski's idea was implemented by three major surveys: OGLE, MACHO and EROS. Although the probability that a star is lensed is only $\sim 10^{-6}$, all three surveys reported detection of microlensing events in 1993.
- It seems today that this method is more useful for understanding stars in the Milky Way, than for characterizing dark matter.



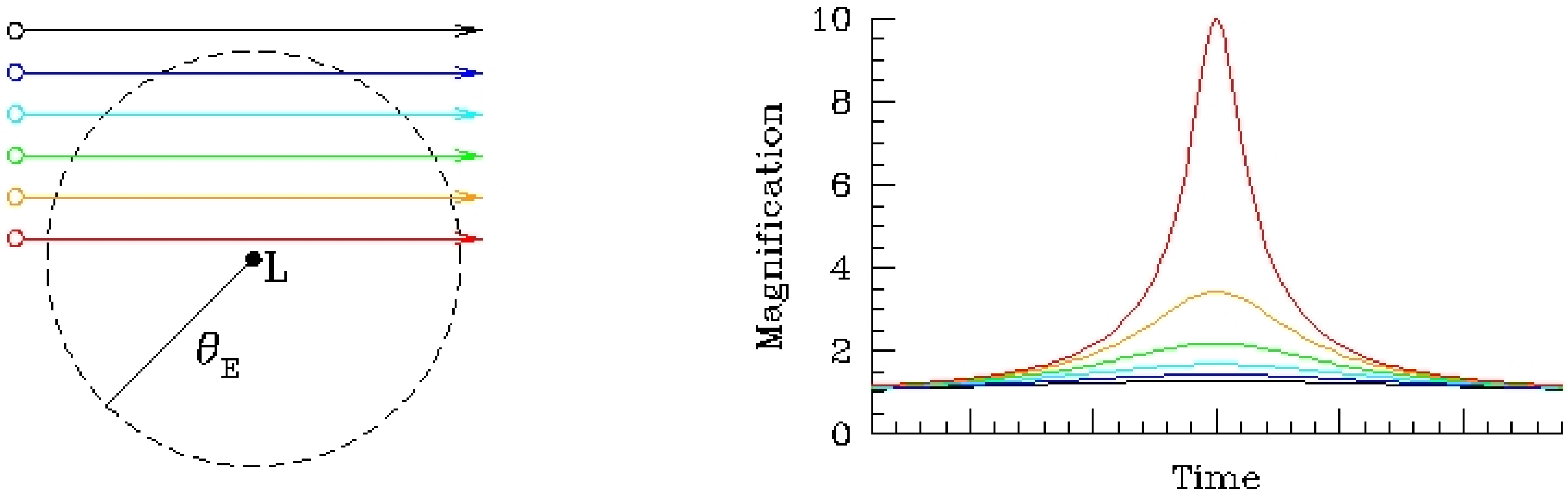


Fig. 4 --- Background source stars may pass behind the lens with different minimum angular separations. Those that pass closest to the lens (in projection on the sky) will experience the greatest magnification in their brightness. Sources that pass an angular distance from the lens equal to the Einstein ring radius θ_E will be magnified by a factor 1.34. The light curves (brightness of the sources as a function of time) are shown on the right for each of the possible paths shown on the left. Since each of the random possibilities for source position shown above is equally likely, each of the resulting light curves show below have equal probability. Click on figures for a zoom.

The length of time over which this takes place and thus the duration of the microlensing event depends on the mass of the lens, the speed of the source across the sky, and distances of the observer to the lens and source. Faster motion and smaller lens masses will produce shorter microlensing ``events." For stellar mass lenses traveling at speeds typical for stars in the Milky Way, microlensing events should last a few weeks to a few months. Since the focusing of the light rays is independent of wavelength, microlensing light curves are ``achromatic," that is, they have the same shape regardless of the filter in the telescope camera.

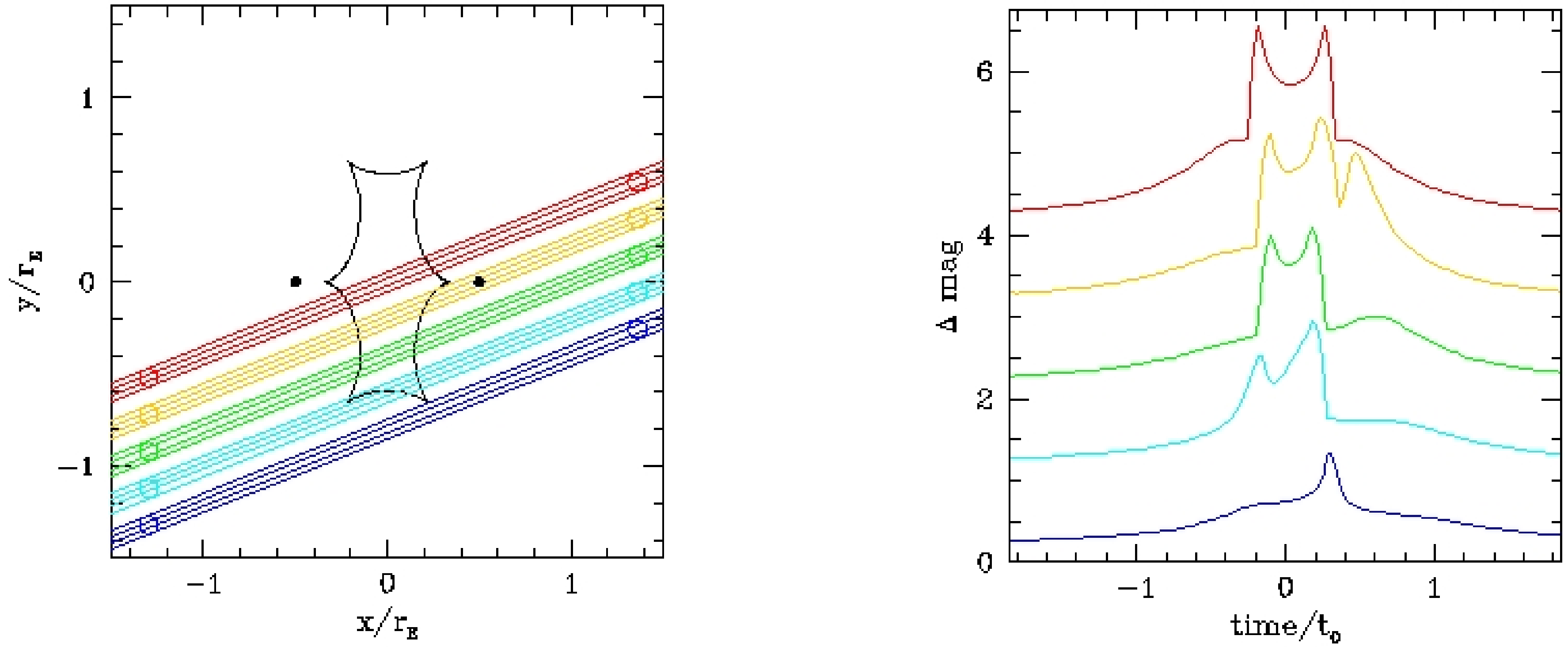
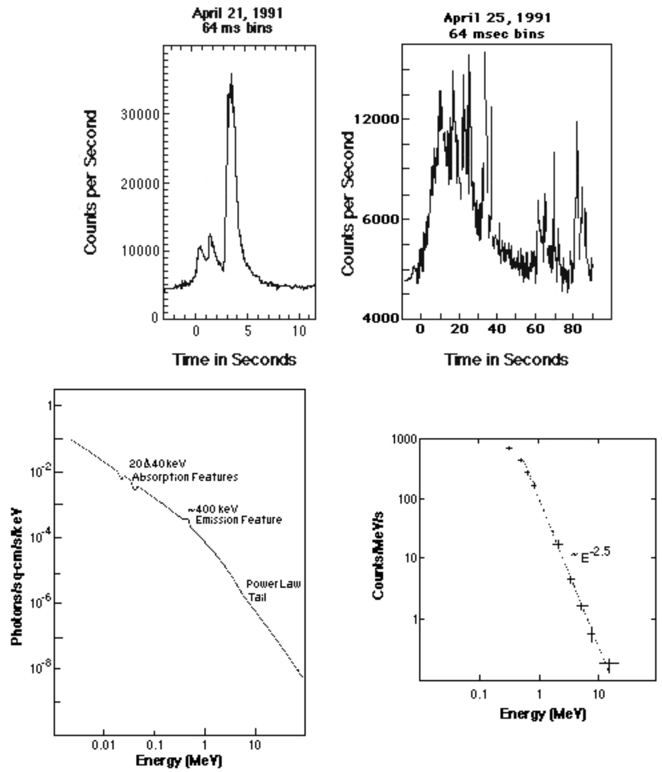
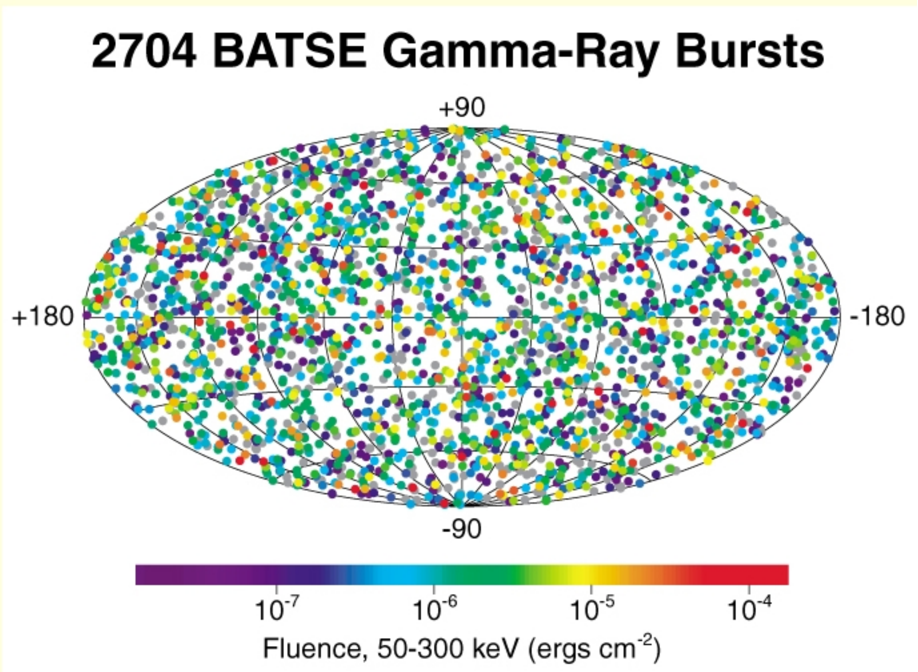


Fig. 9 --- Left: An equal mass double lens (two black dots) creates a caustic structure --- regions where the combined effect of both lenses is enormous --- shown here as the solid black line between the two lenses. Right: The light curves of sources passing behind this caustic structure will exhibit rapid increases of brightness at the moment of crossing. The exact light curve shape depends on the path (shown as the colored lines in the left-hand figure) that the source takes as well as on the mass ratio of the lens and their angular separation. Click on the figures for a zoom. (Adapted from Paczynski 1996.)

By carefully measuring the anomalous structure in a binary lens light curve, the ratio of the mass of one lens to the mass of its partner can be measured. One can also measure the angular distance between the lenses at the time the anomaly occurred as a fraction of their Einstein ring radii. Microlensing thus gives astronomers a way to determine which types of binary stars are common in our Galaxy.





Gamma-ray bursts

- Short-lived bursts of gamma-ray photons, the most energetic form of light. Discovered serendipitously in the late 1960s by U.S. military satellites.
- Until recently, it wasn't clear whether they originated in the Solar System, the Milky Way, or at cosmological distances! The arguments were nicely summarized in the Paczynski–Lamb debate (1995), modeled after the Shapley-Curtis 1920 debate.
- Today there is a growing consensus that most gamma-ray bursts are associated with supernovae in distant galaxies.
- For a recent review, see Meszaros (2002, astro-ph/0111170)