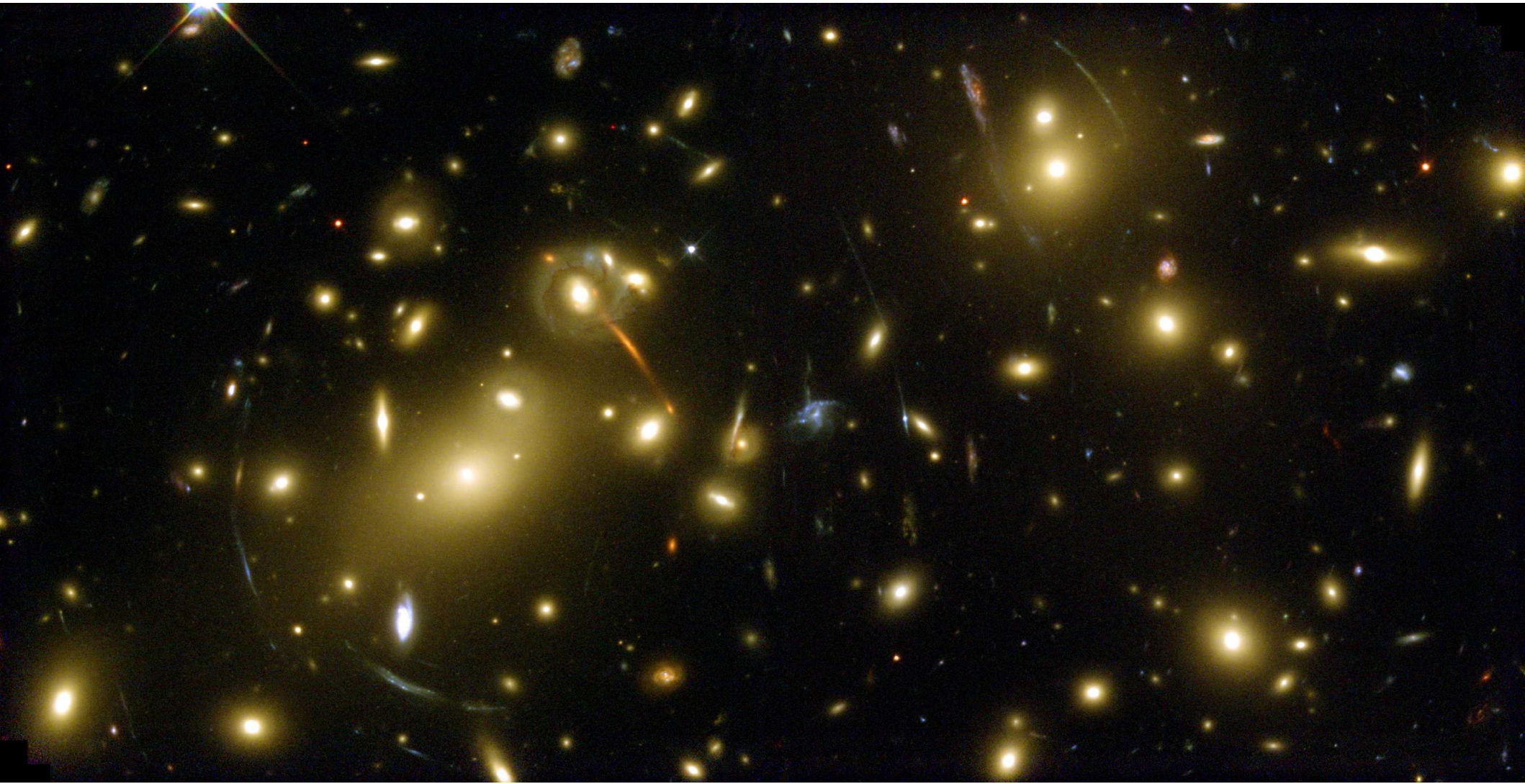
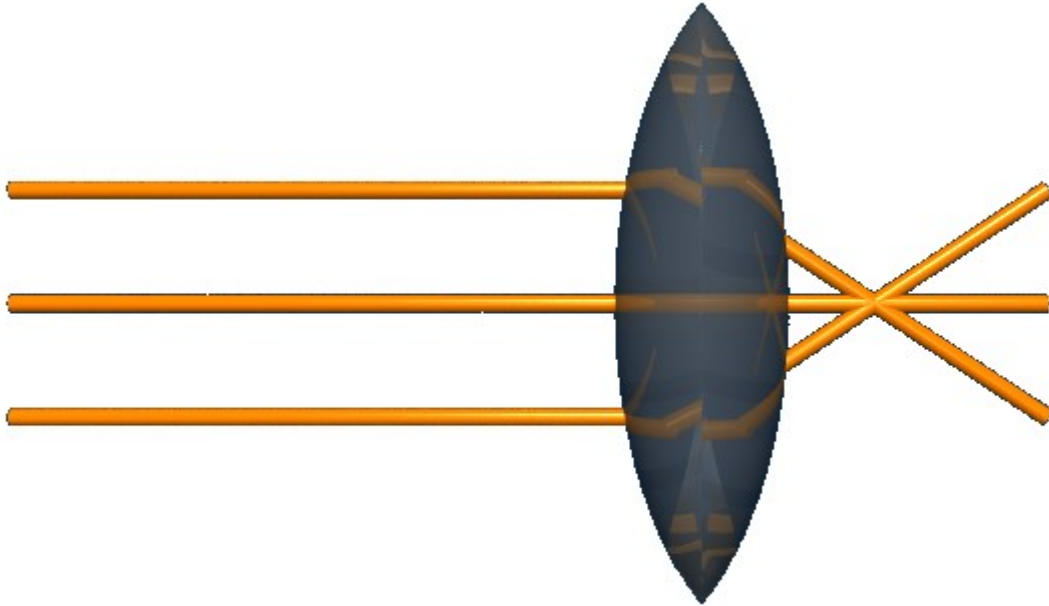


Gravitational Lensing

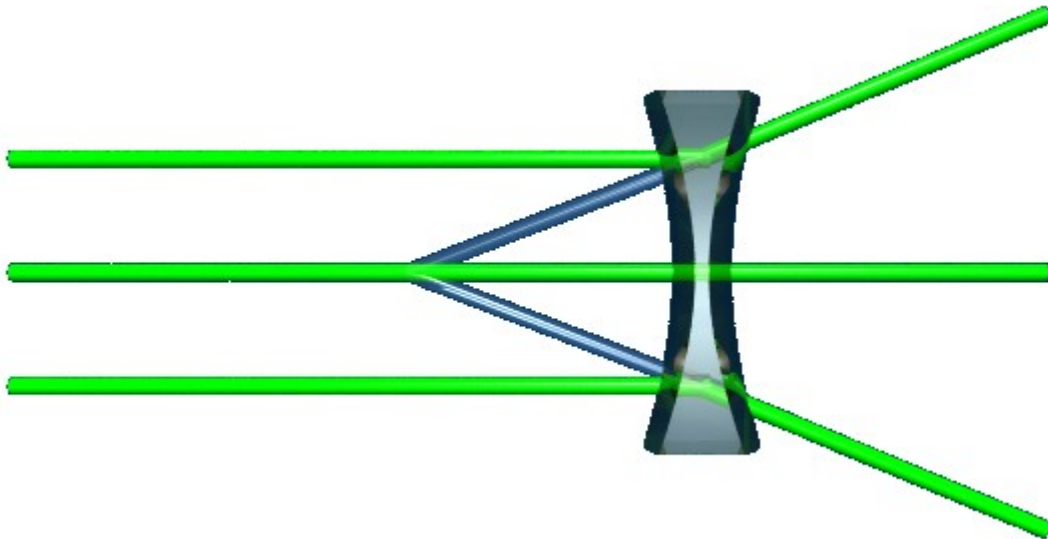
Physics 343, Lecture 11



Geometric Optics

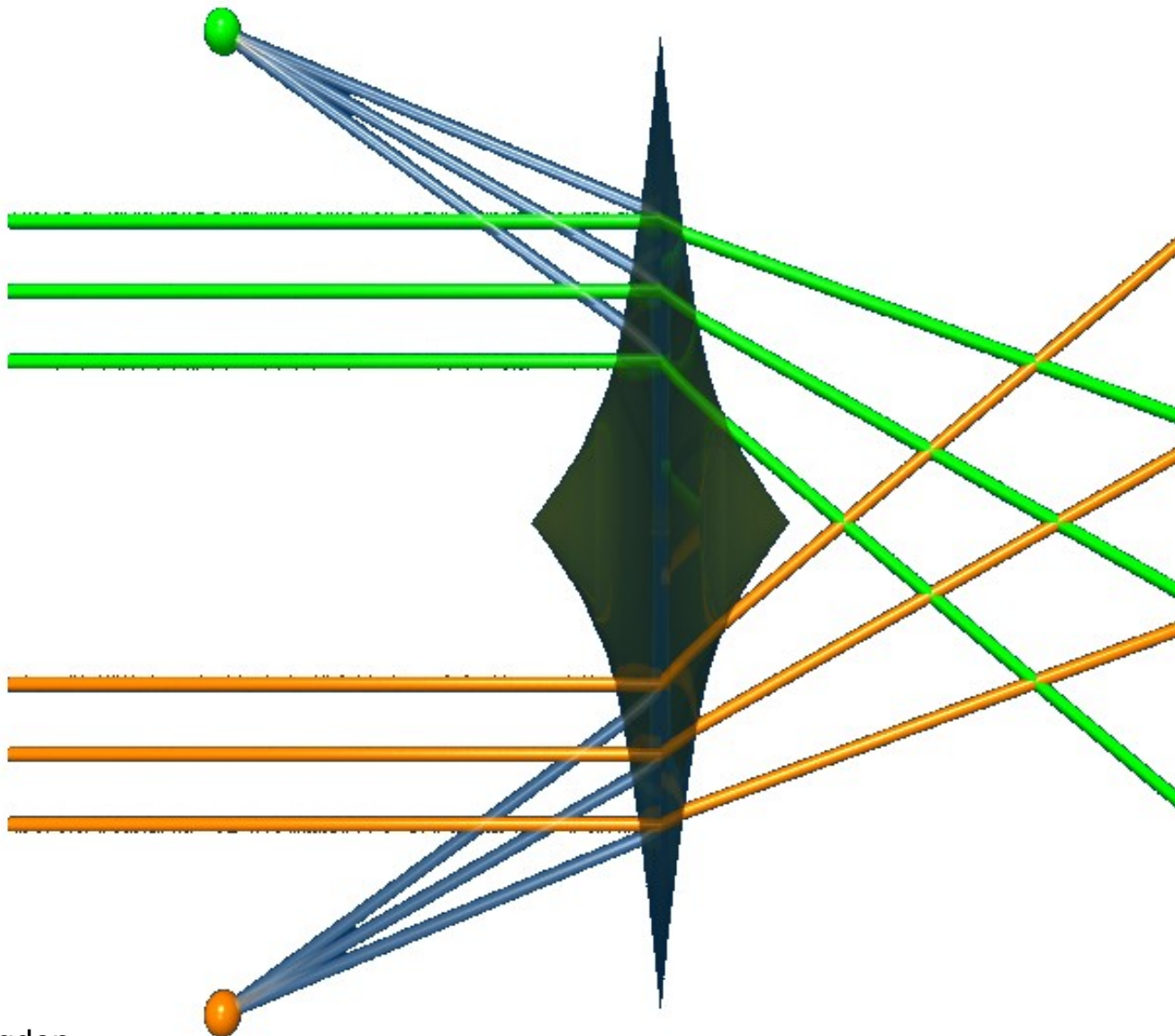


Converging Lens

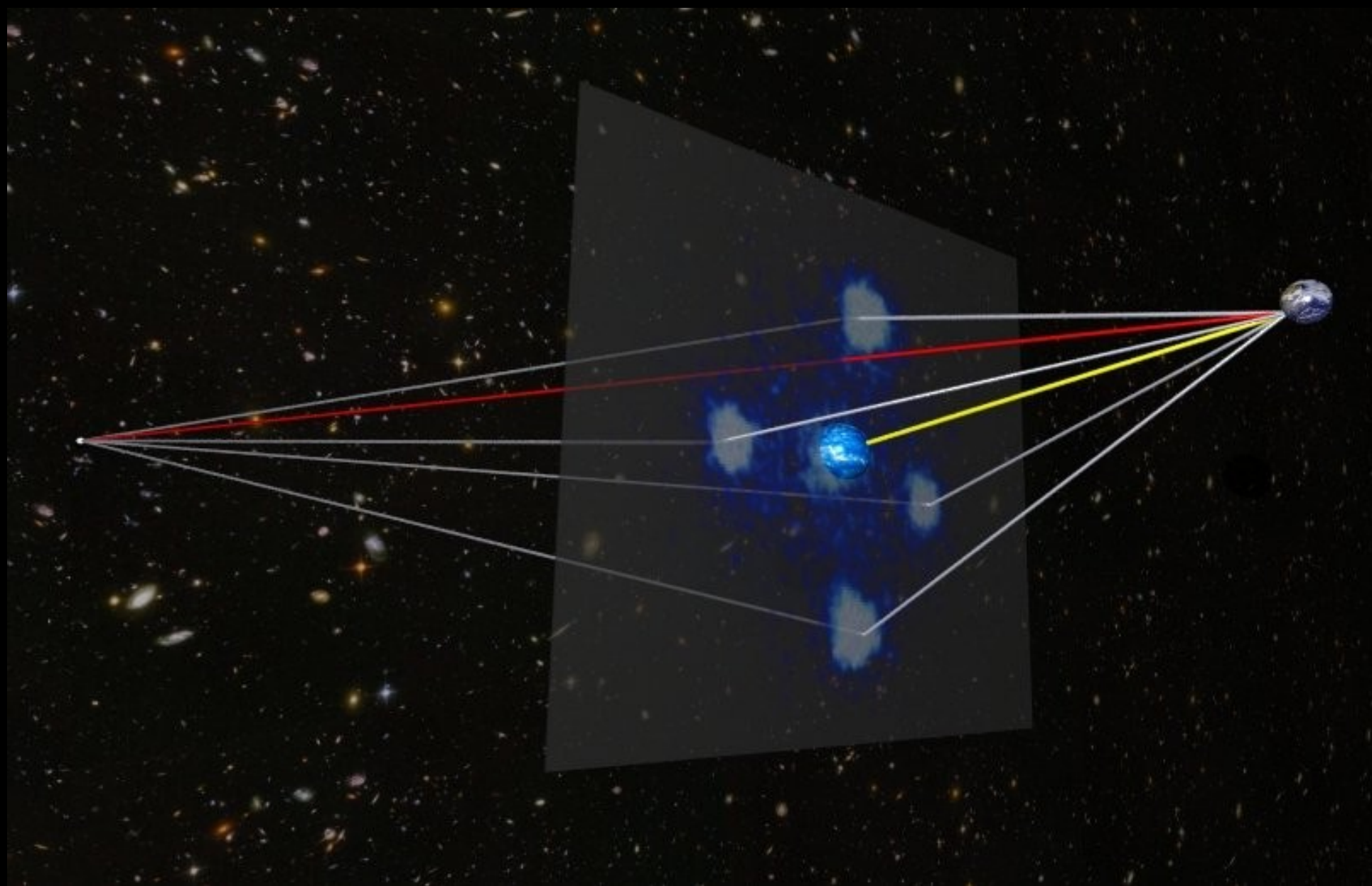


Diverging Lens

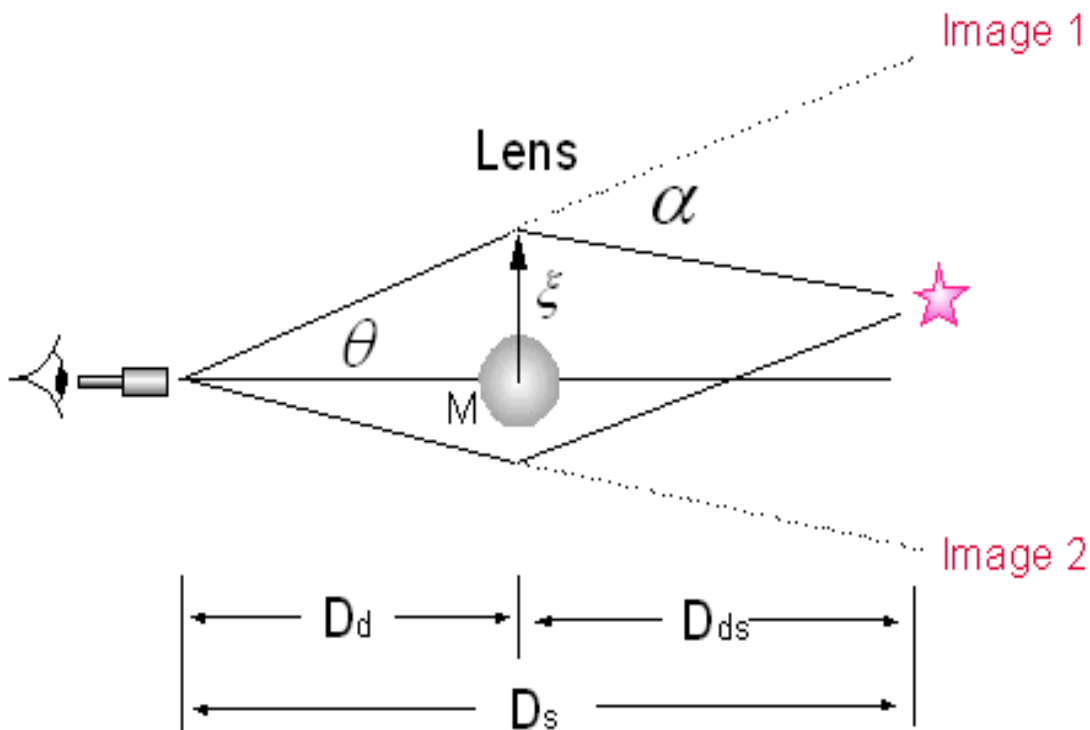
Gravitational Optics



Courtesy: Art Congdon



Basic Lensing Equations



- Deflection angle

$$\alpha = 4GM/\xi c^2$$

- Lens Equation

$$u = \theta - \nabla\phi$$

- Lens Potential

$$\nabla^2\phi = \kappa$$

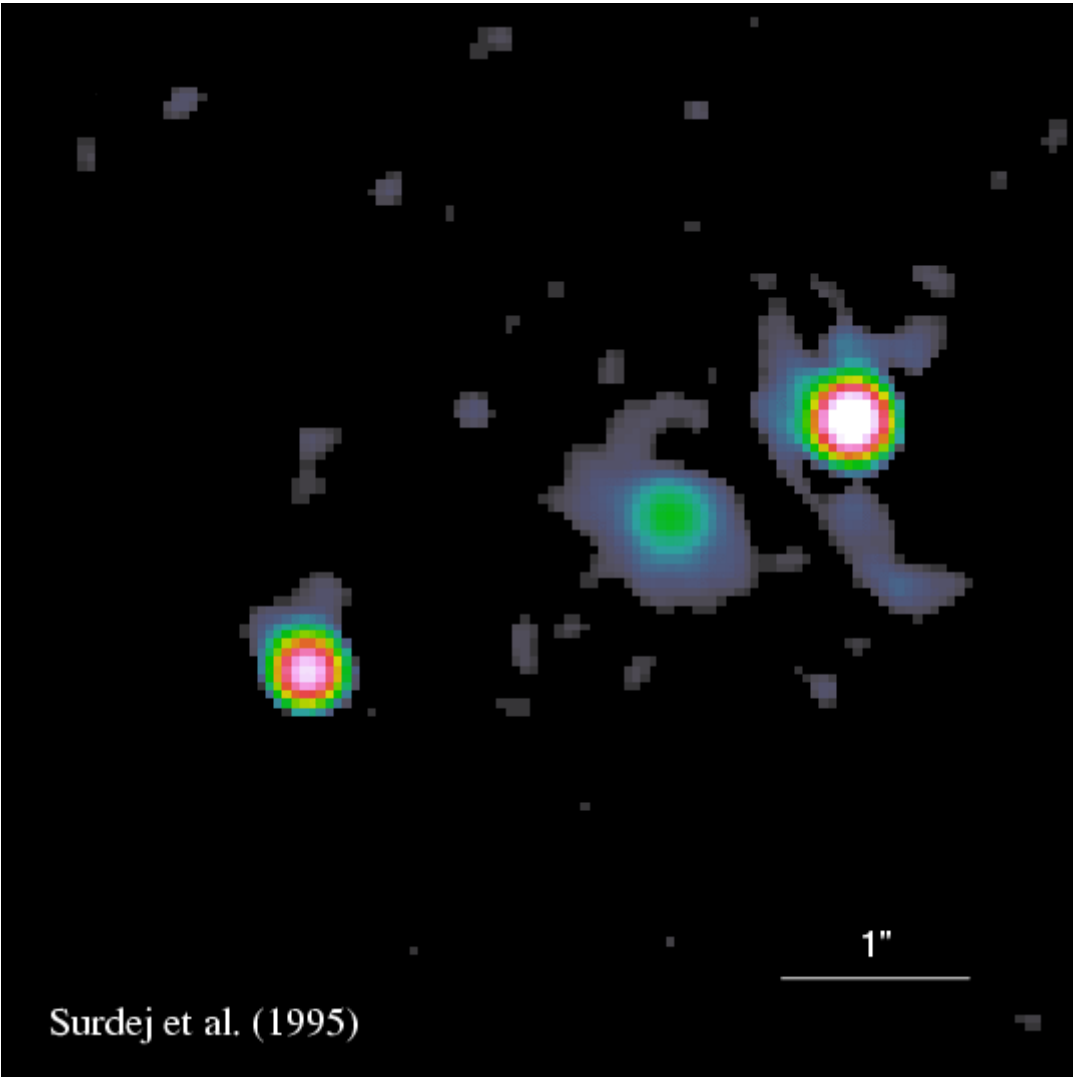
$$\kappa = \Sigma/\Sigma_{crit}$$

But thats not all!

Lensing magnifies images

$$\mathbf{M}^{-1} = \begin{pmatrix} 1 - \phi_{,xx} & -\phi_{,xy} \\ -\phi_{,xy} & 1 - \phi_{,yy} \end{pmatrix}$$

- Typically ~ Orders of a few times the unlensed flux
- Can many orders of magnitude

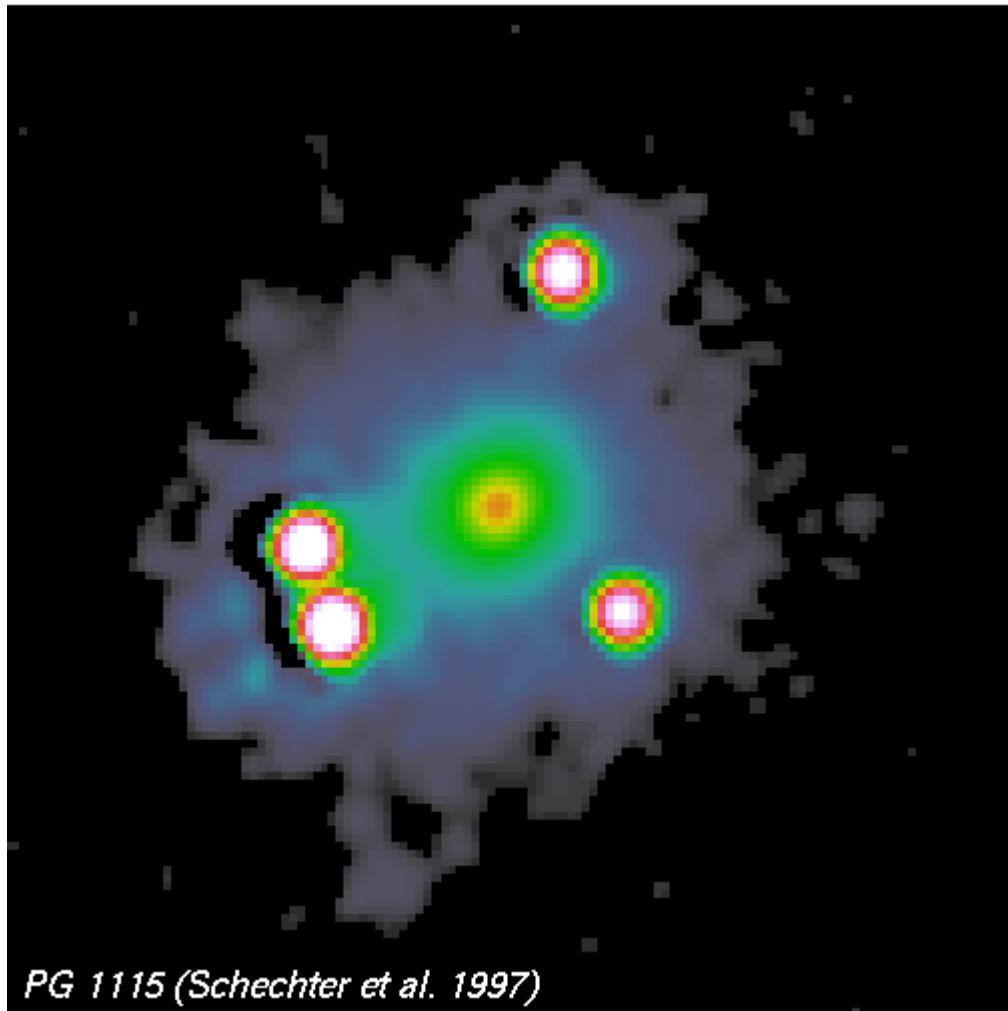


Surdej et al. (1995)

Three Regimes of Lensing

- Strong Lensing
- Weak Lensing
- Micro/Millilensing

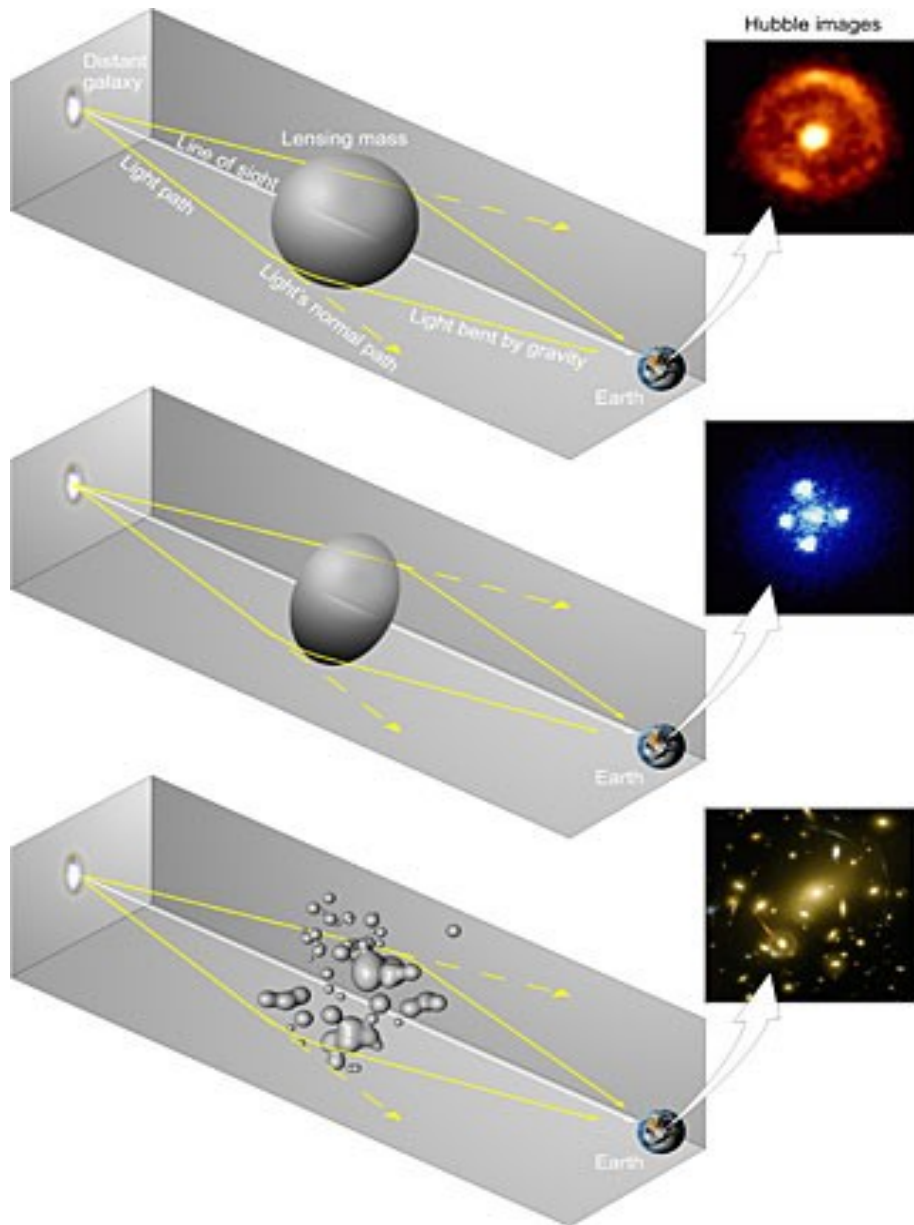
Three Regimes of Lensing



PG 1115 (Schechter et al. 1997)

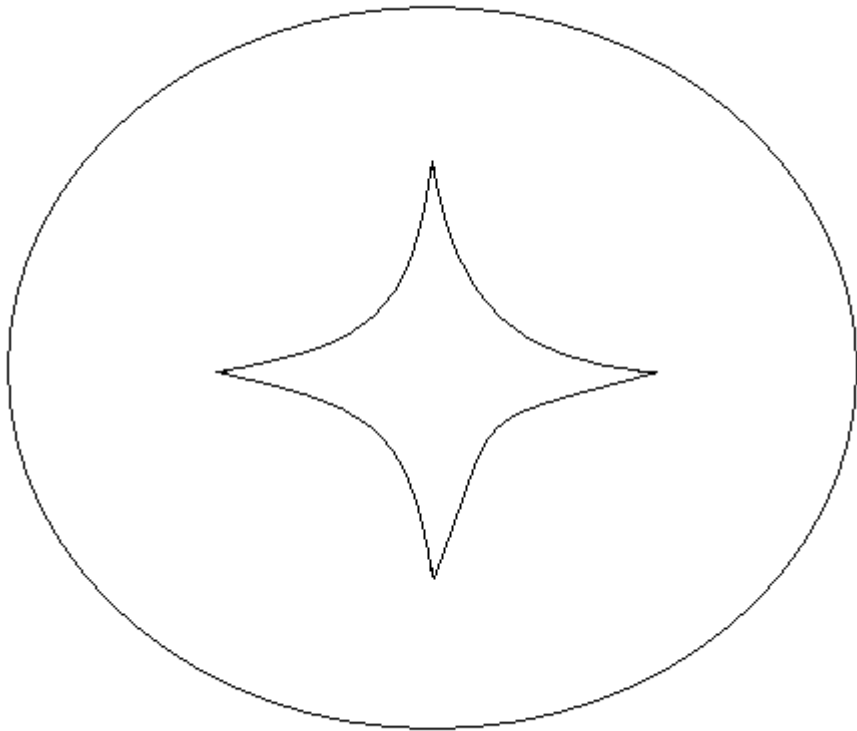
- **Strong Lensing**
 - Large deflections
 - Multiple images
 - Source magnification
- Weak Lensing
- Micro/Millilensing

Strong Lensing



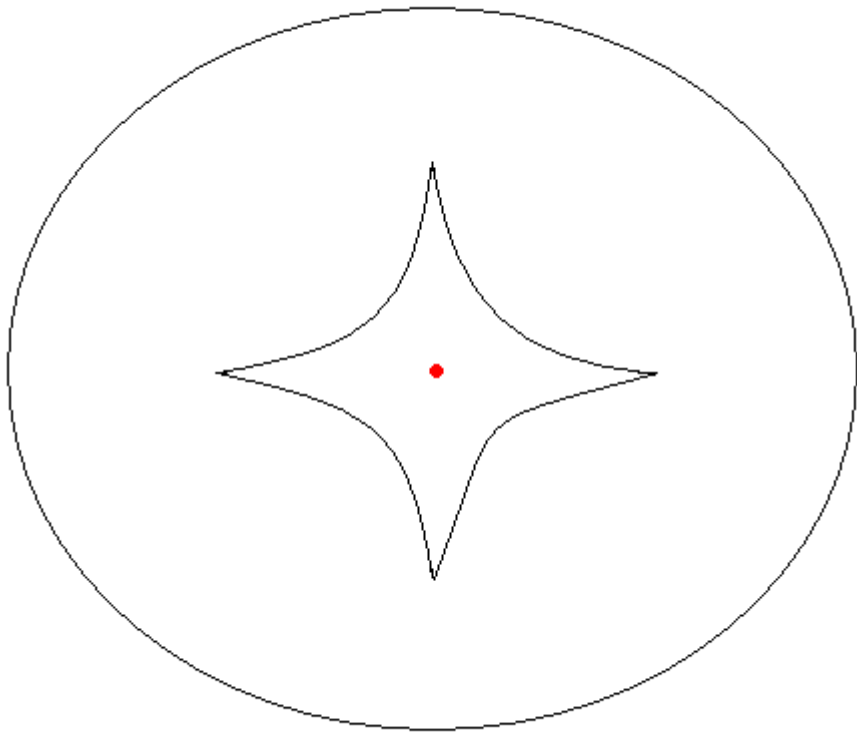
- Mass geometry determines type of images
- Source location determines number of images
- Models are often degenerate

Strong Lensing

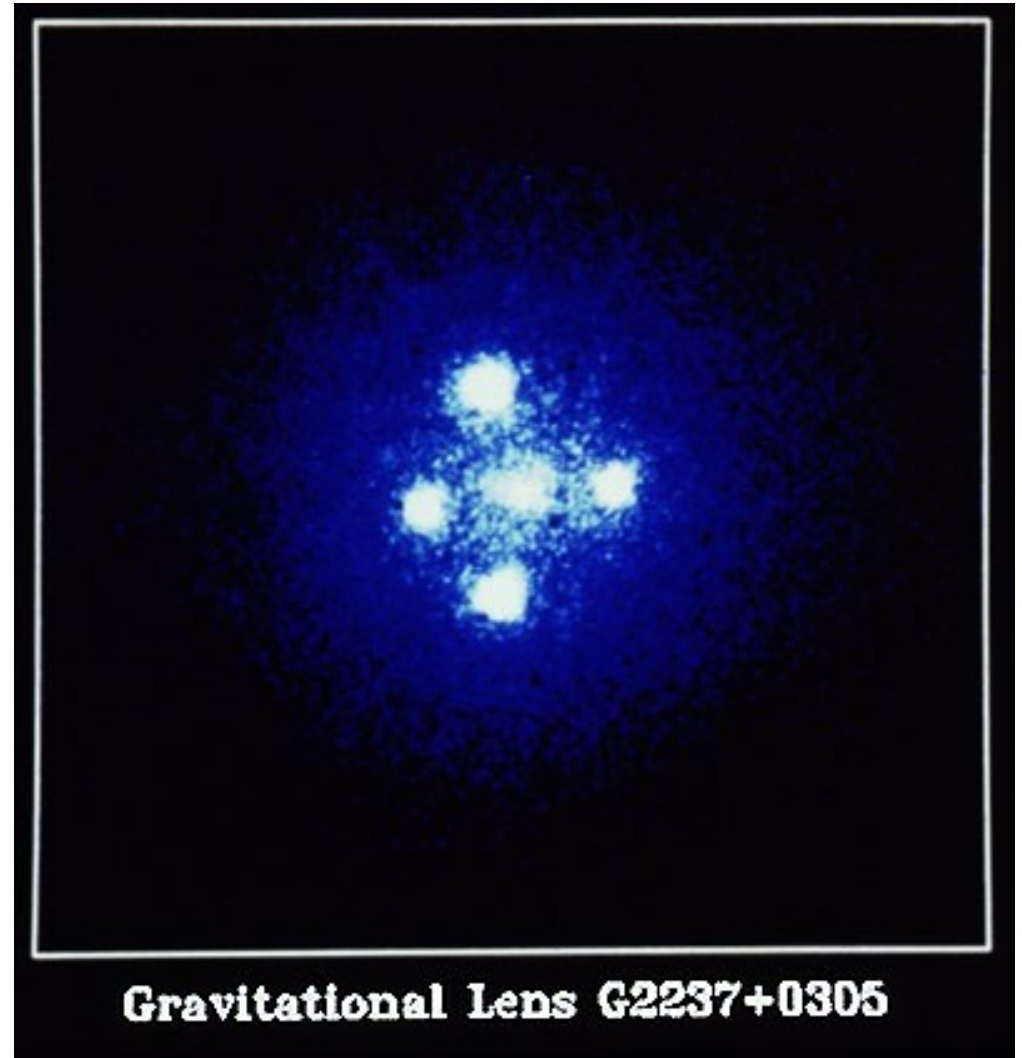
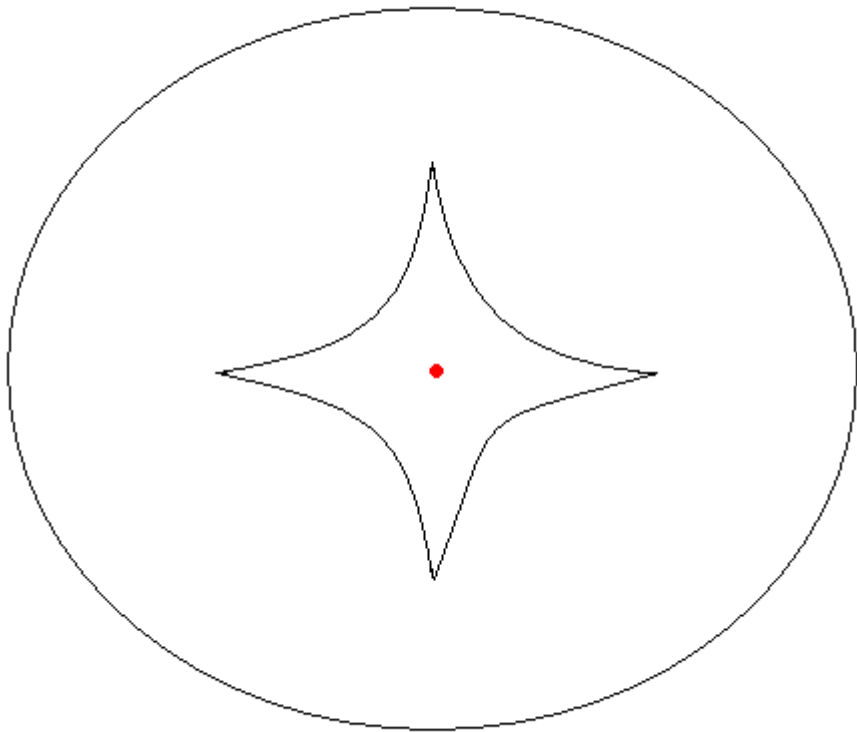


- *Caustics* are critical curves in source plane
- Define regions where source will produce specific image configurations
- Crossing changes image number by 2

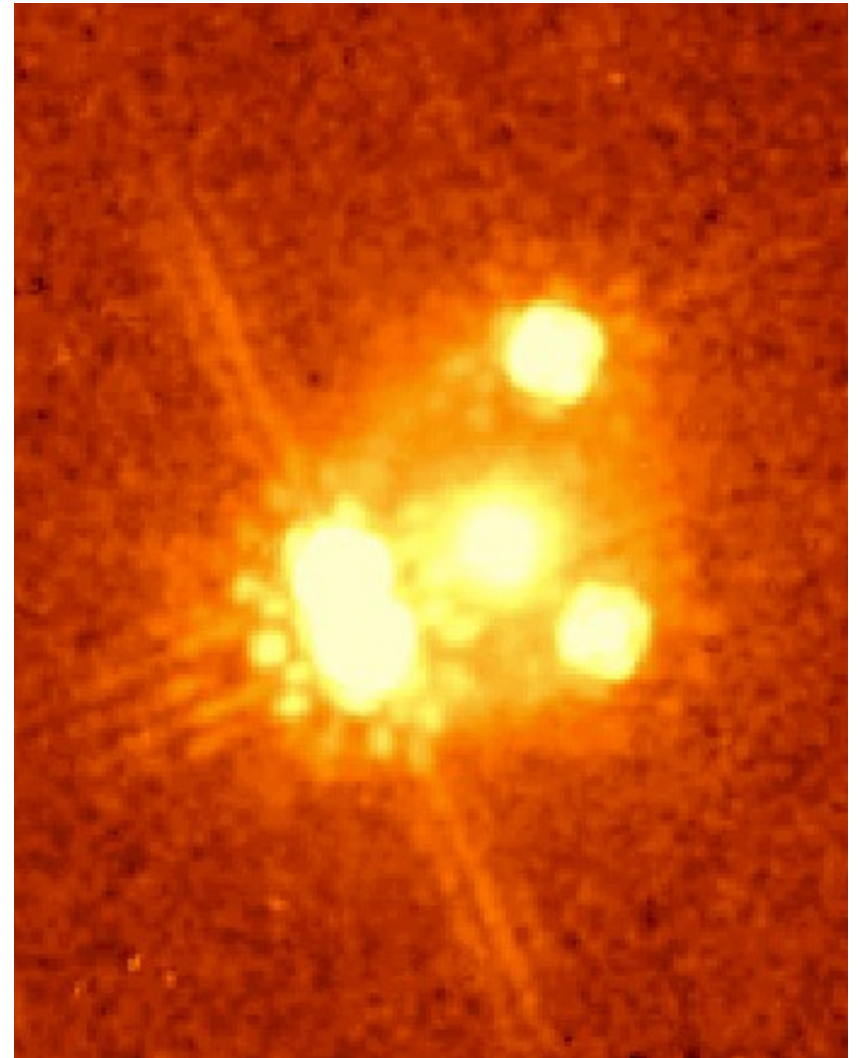
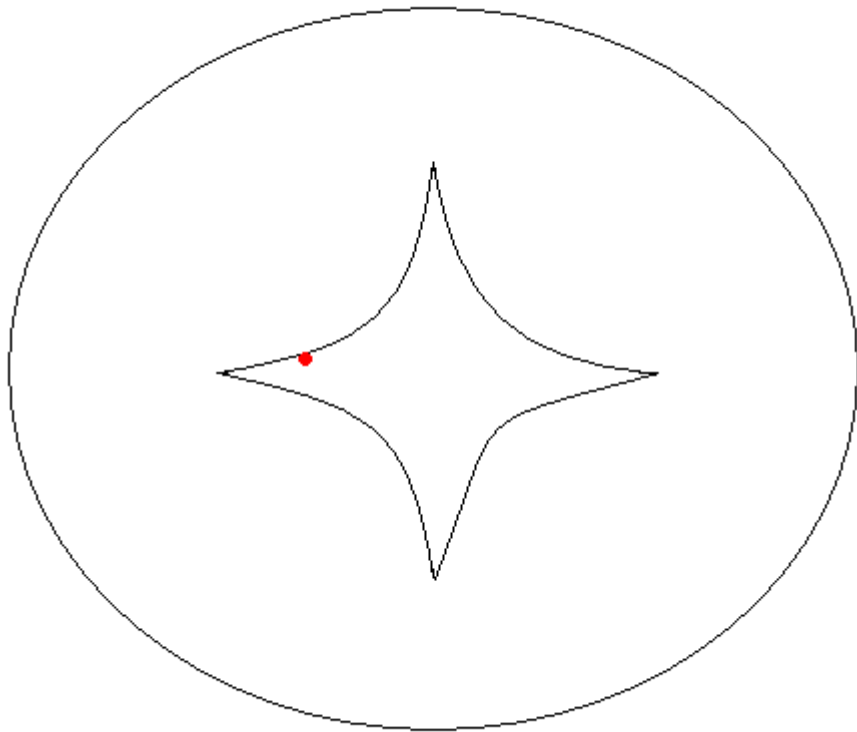
Strong Lensing



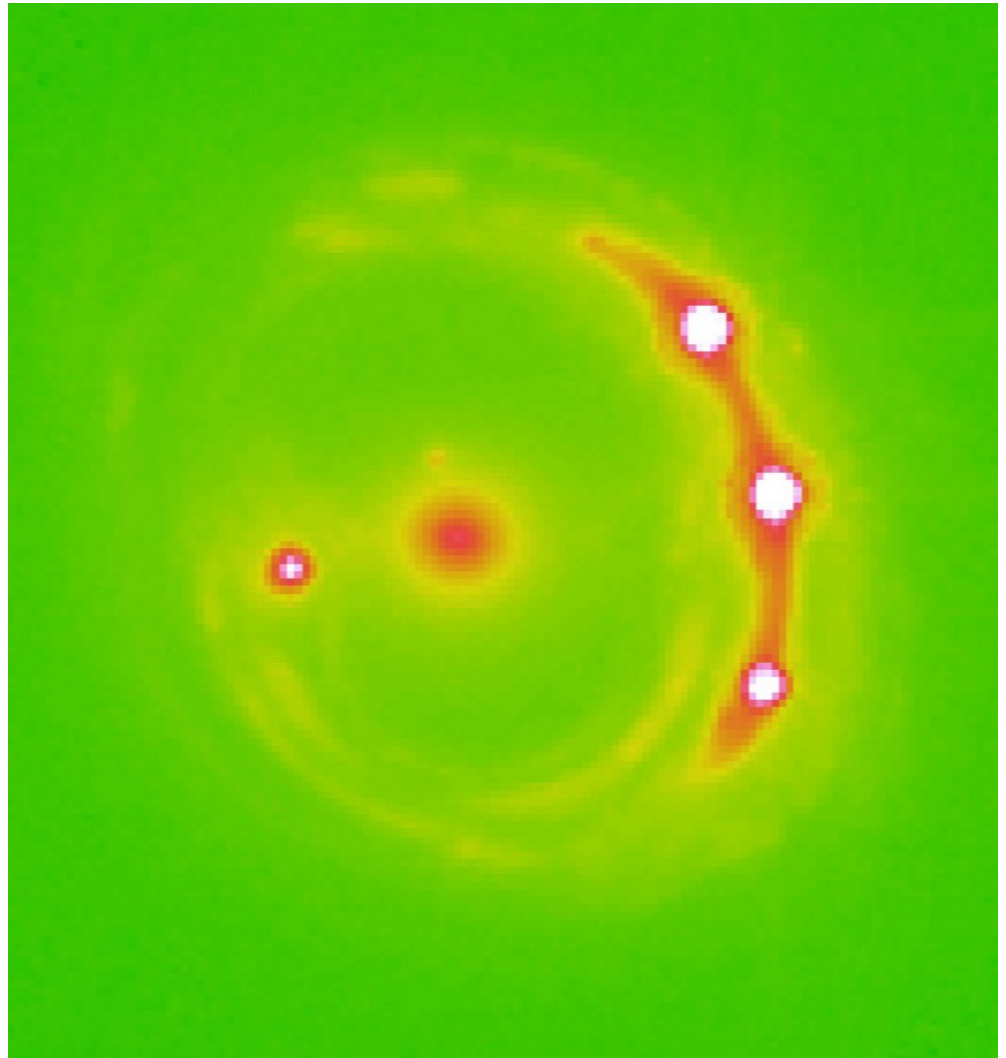
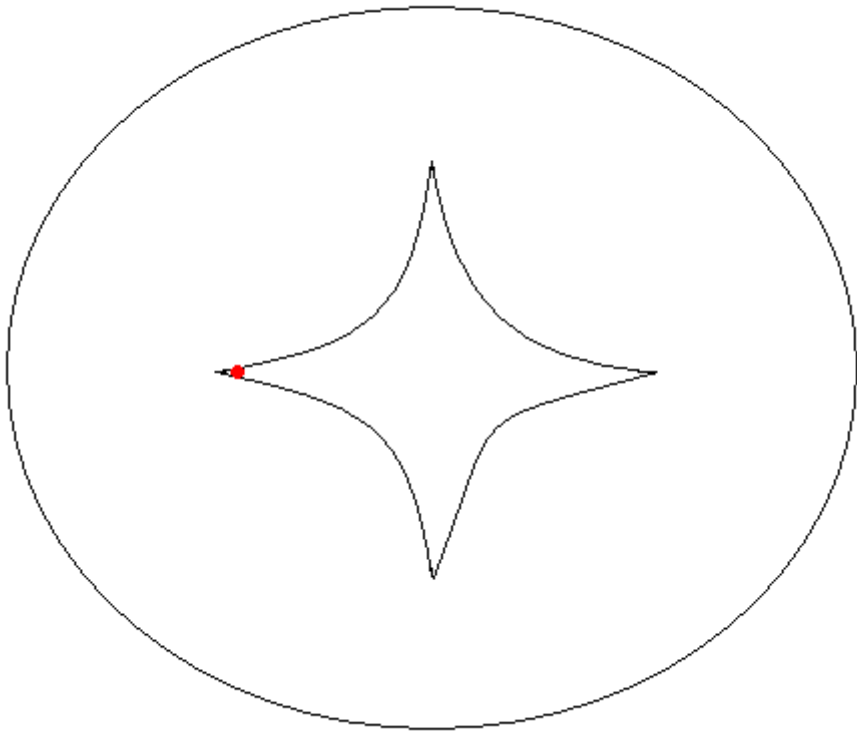
Strong Lensing



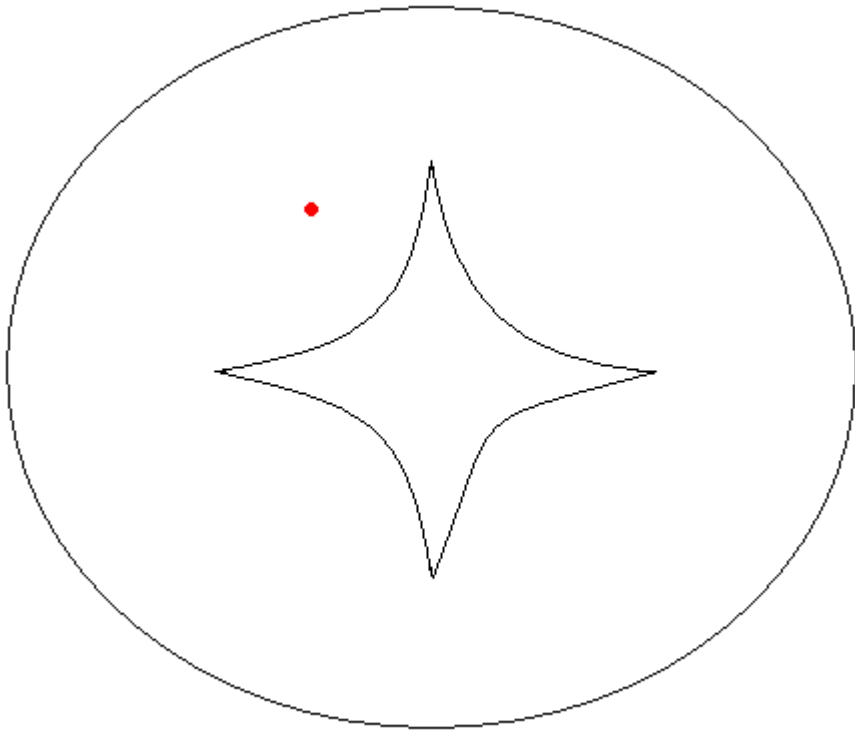
Strong Lensing



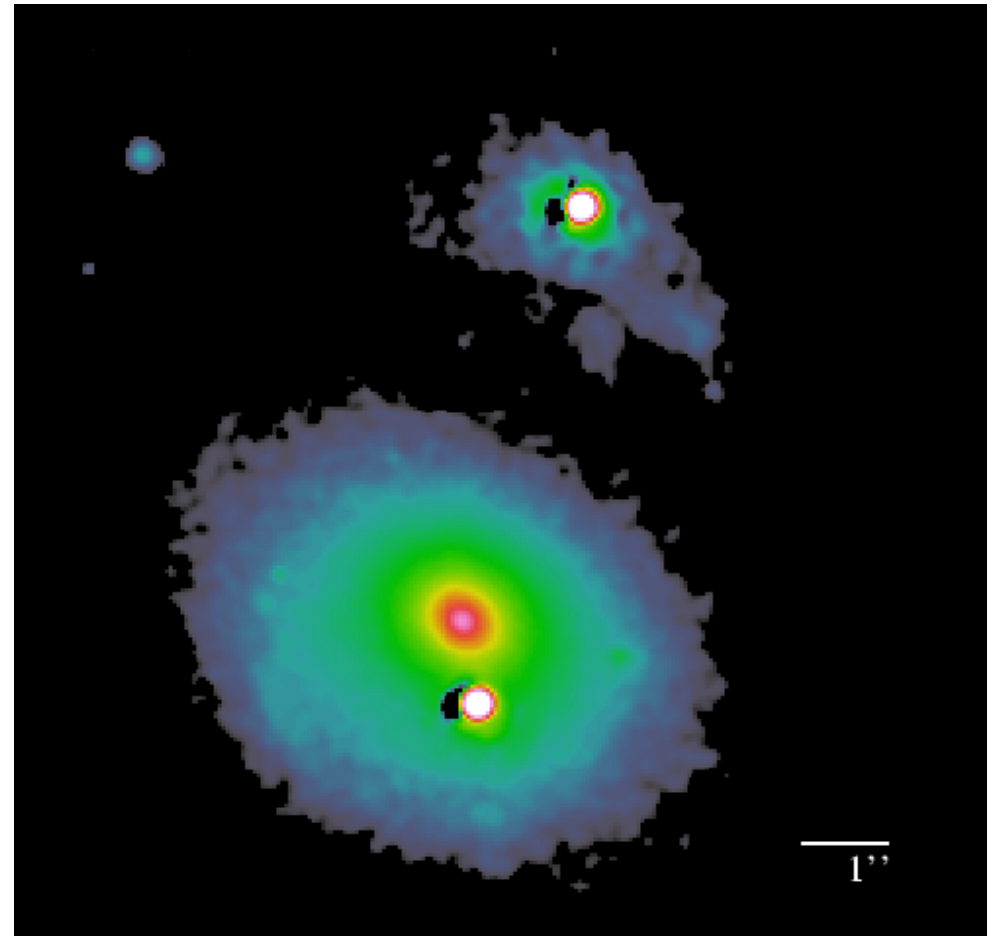
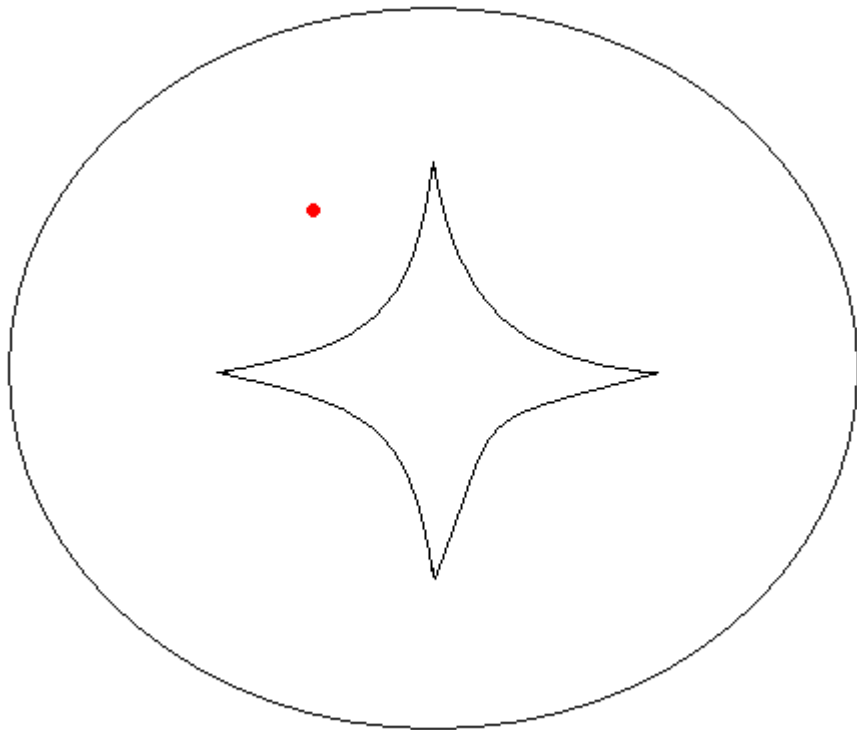
Strong Lensing



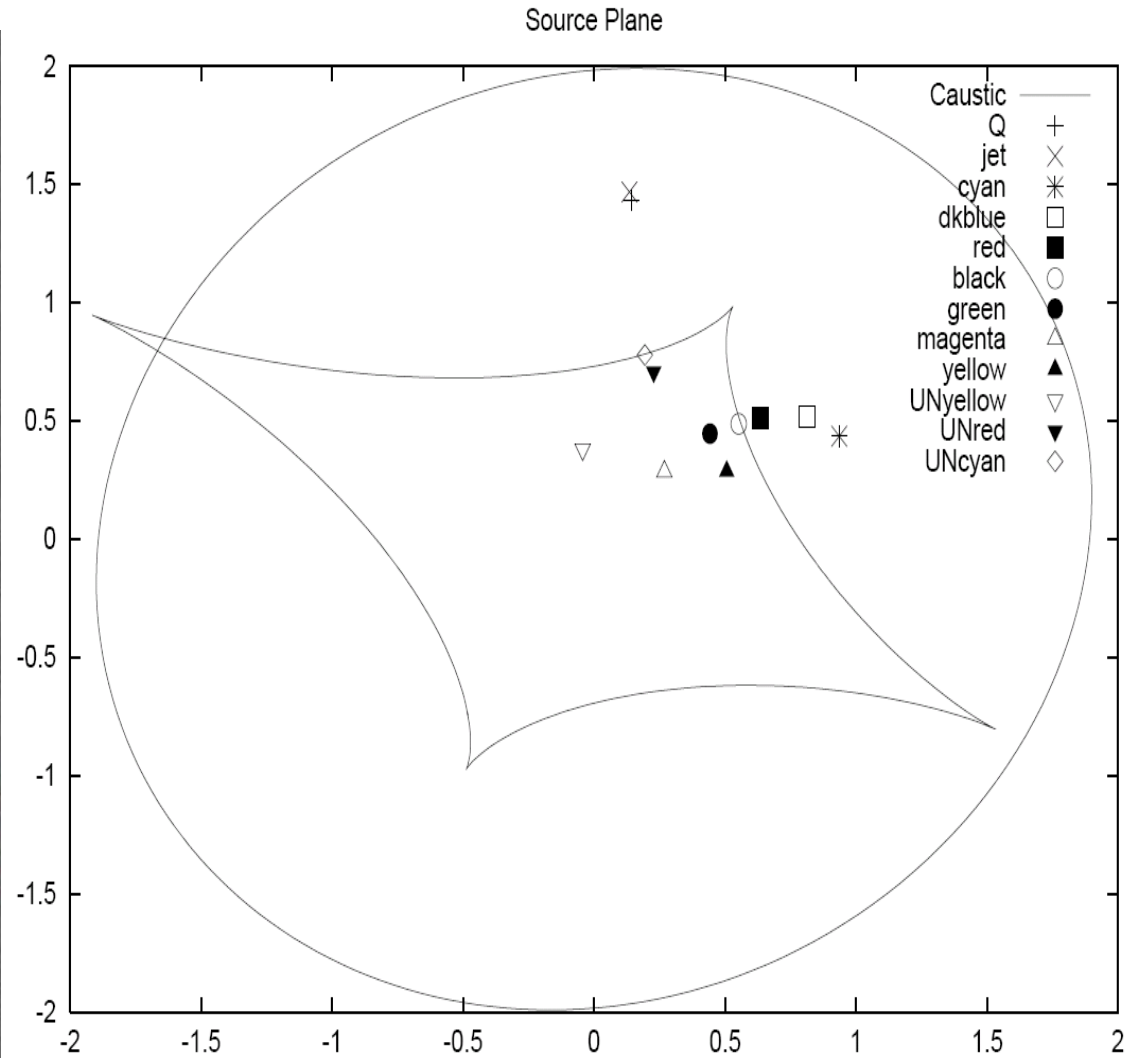
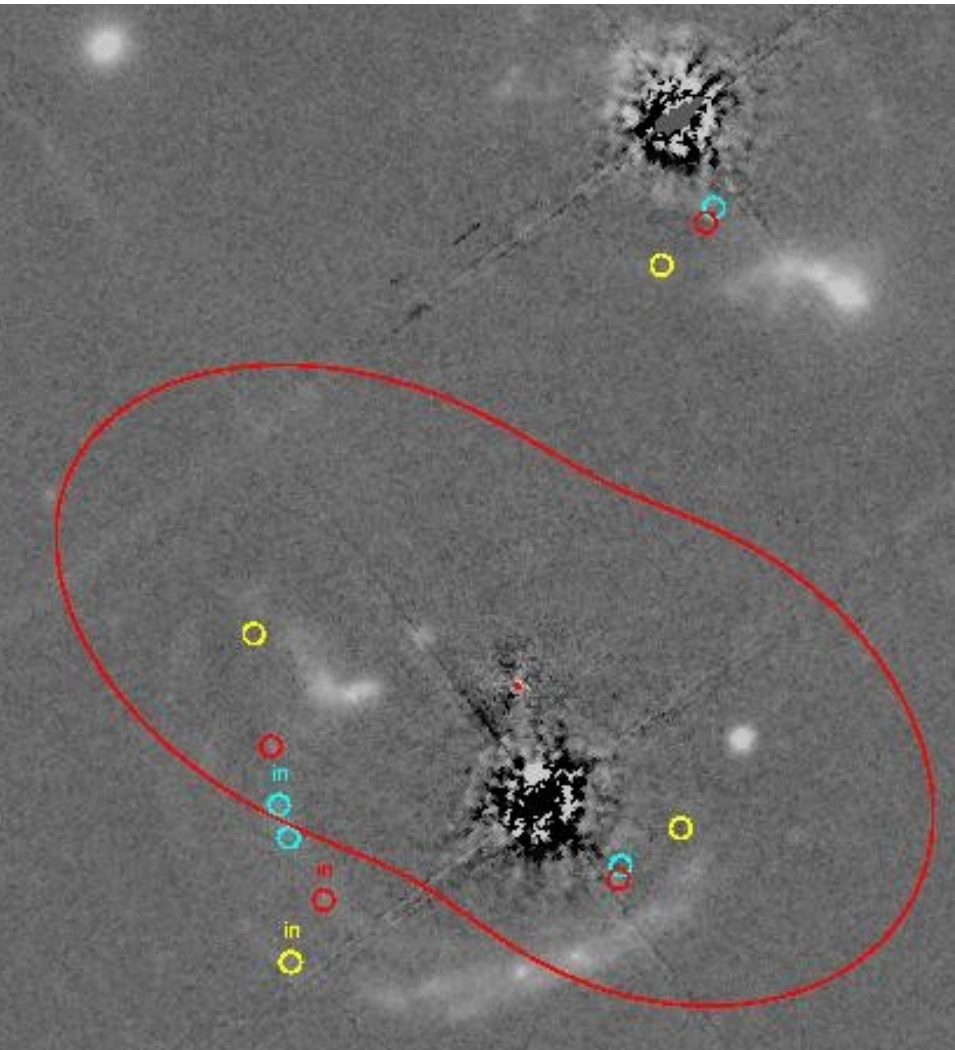
Strong Lensing



Strong Lensing



Q0957+561



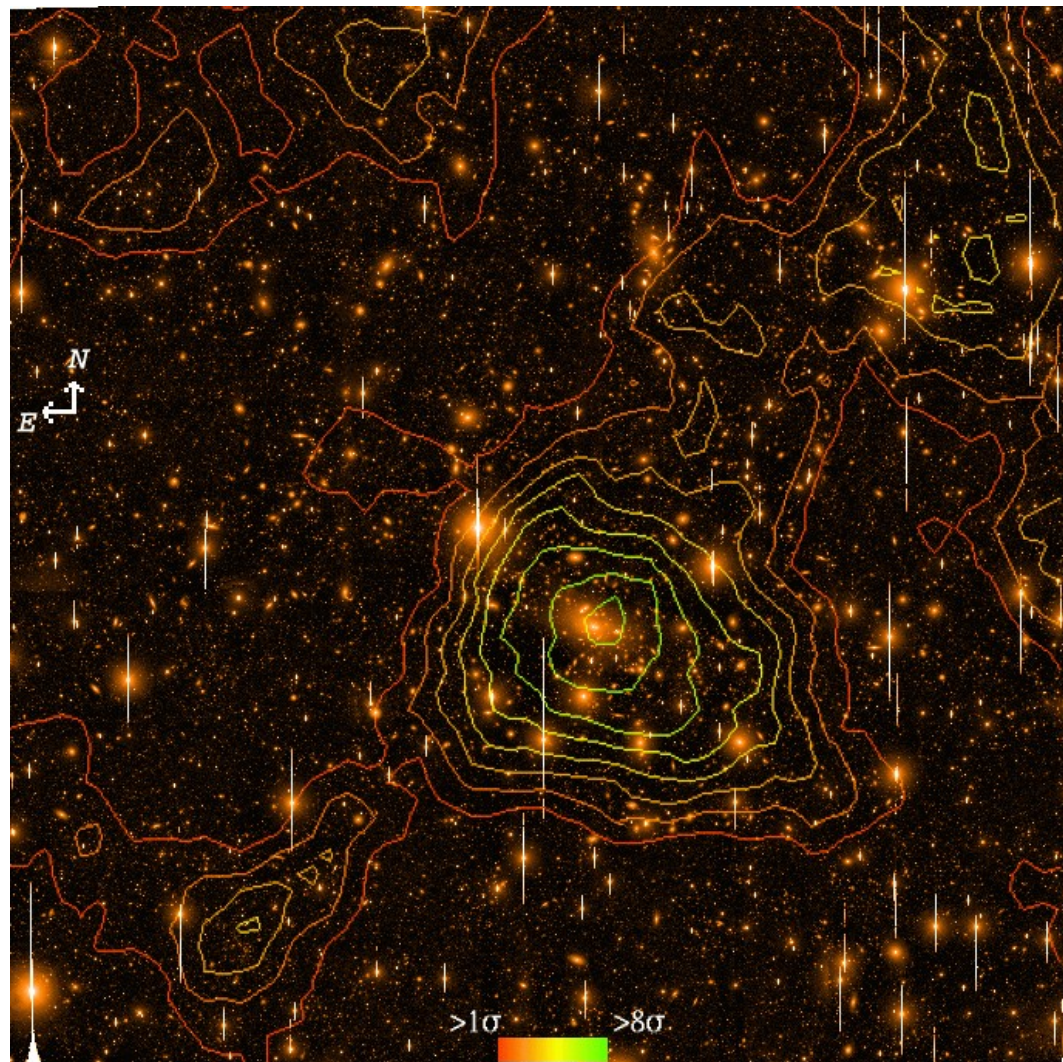
Three Regimes of Lensing



- Strong Lensing
- **Weak Lensing**
 - Tiny distortions of background galaxies
 - Statistical in nature
 - Large area mass maps
- Micro/Millilensing

Caveat: Not a weak lensing image!!!

Weak Lensing



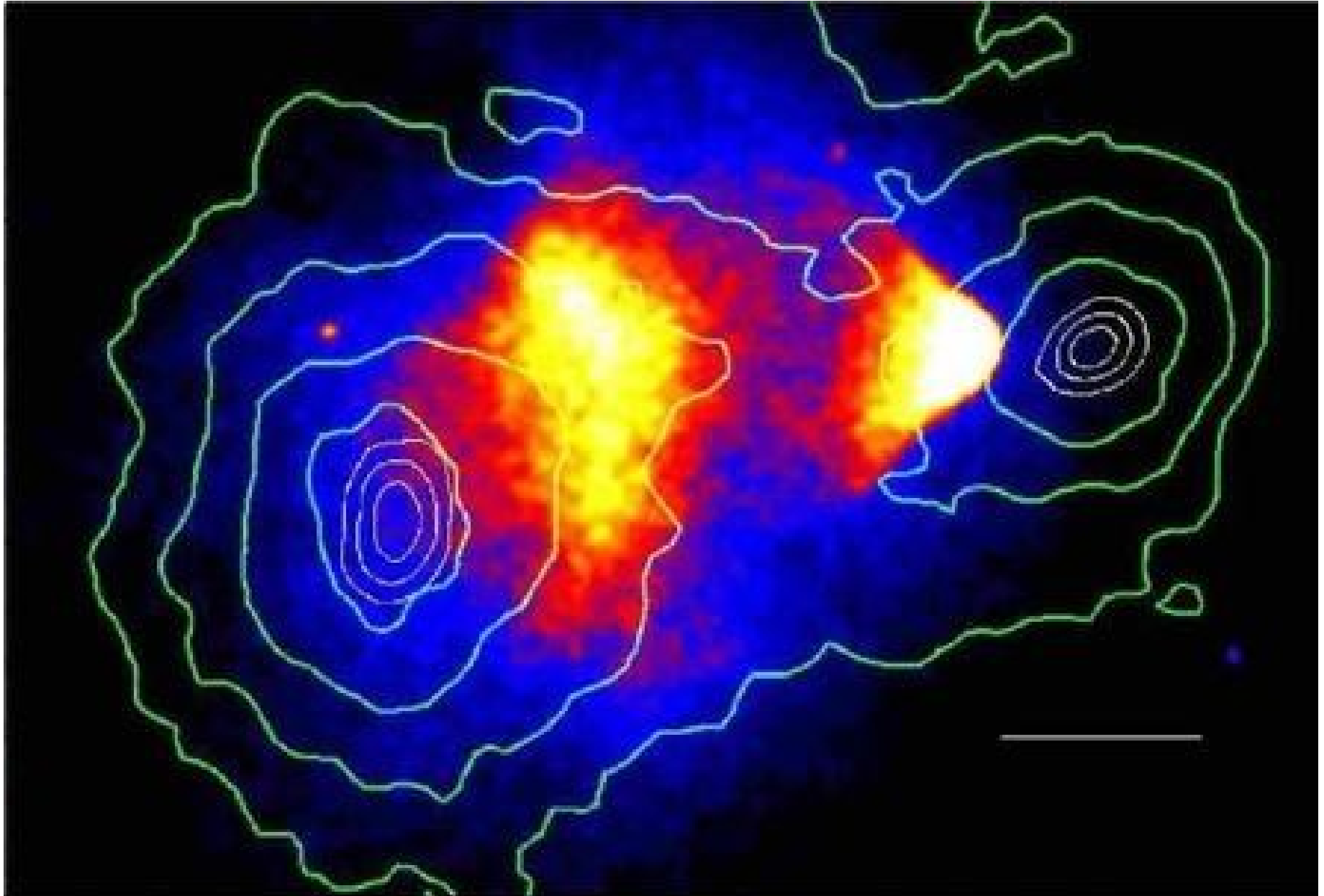
- Need deep images to recover sources
- Source redshifts are uncertain
- Source shapes are uncertain
- Crucial for some H_0 measurements

Smoking Gun !?!



Bullet Cluster- Clowe et al., 2006

Smoking Gun !?!



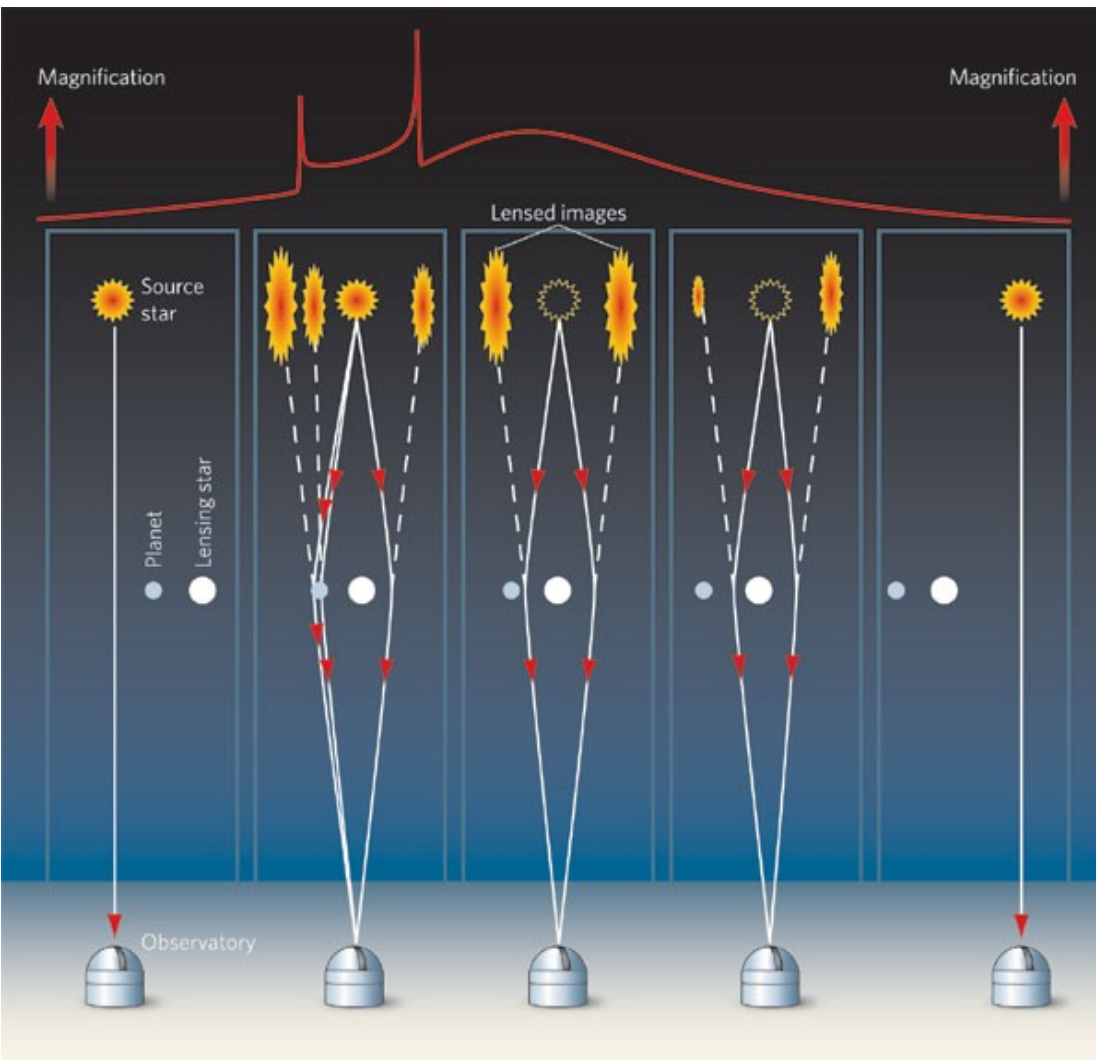
Bullet Cluster- Clowe et al., 2006

Three Regimes of Lensing



- Strong Lensing
- Weak Lensing
- **Micro/Millilensing**
 - Deflections on micro to milli arcsec scales
 - Sensitive to “substructure” in lenses
 - Detected through magnification

Micro/Millilensing



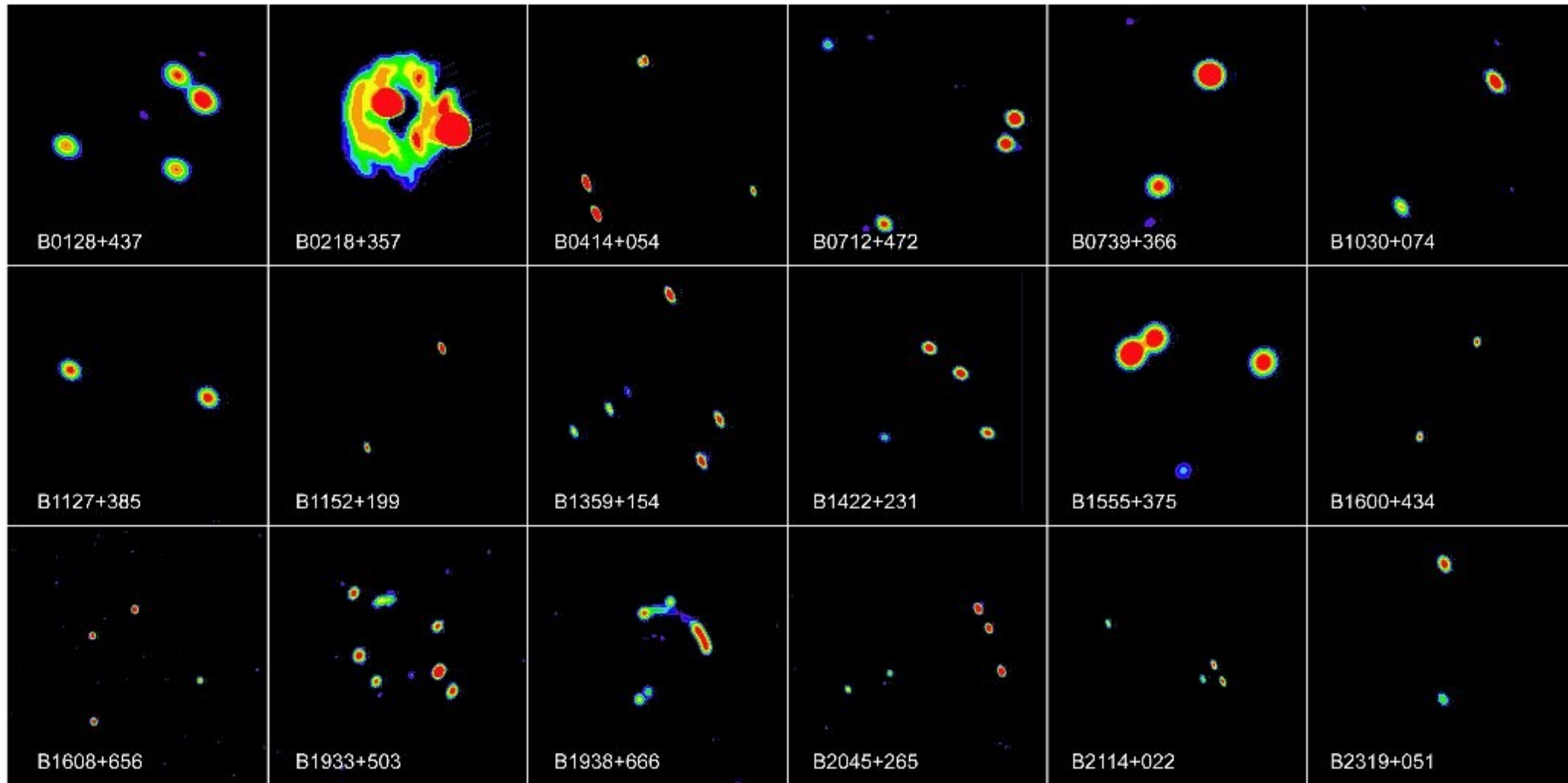
- Powerful and unique tool to detect hard to find objects
 - Exoplanets
 - Compact Objects
 - CDM Substructure
- Rapidly growing
 - Future surveys and instruments

Why Radio??



Image courtesy of NRAO/AUI and ALMA/ESO/NRAO/NAOJ

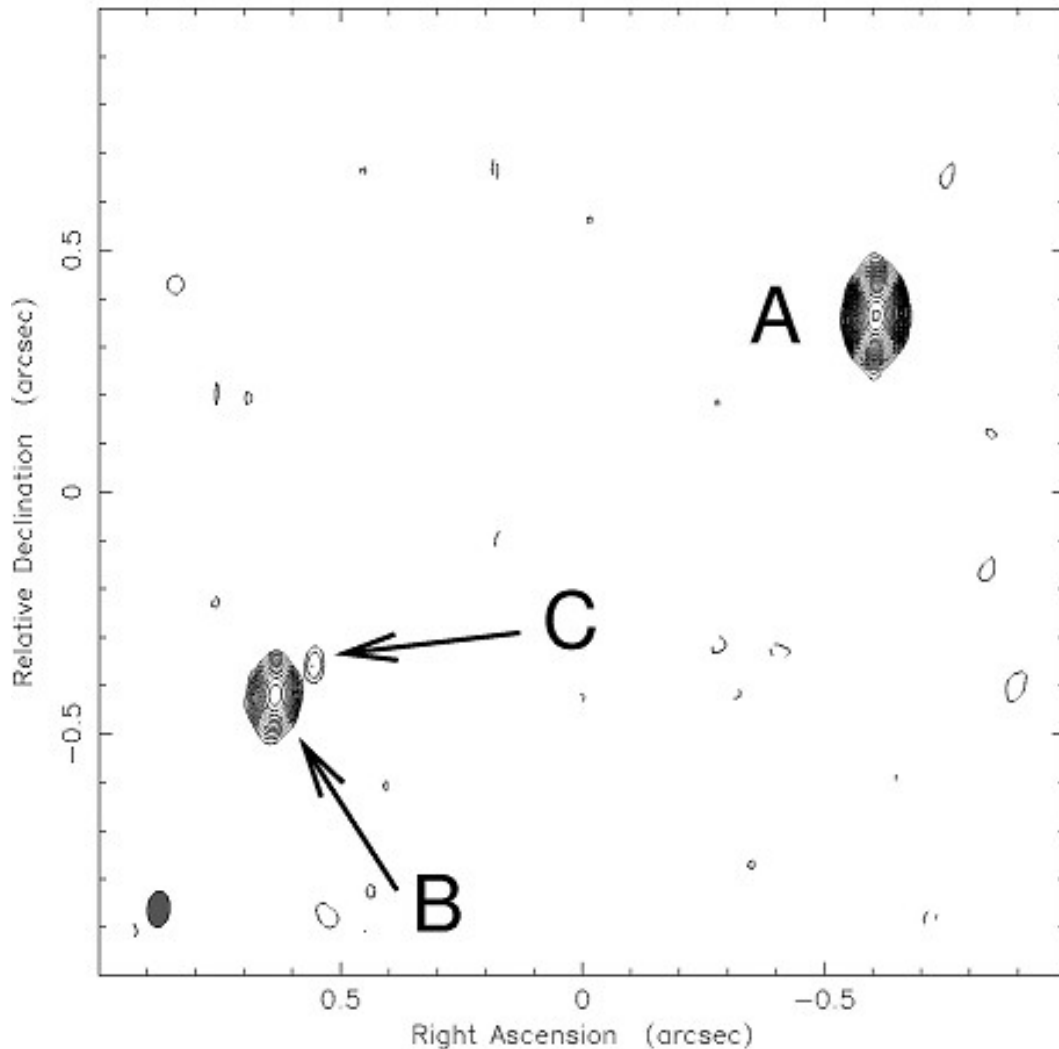
Surveys



- Discovery of many new lenses due to high angular resolution and fast image processing
- MIT-Green Bank, Parkes-MIT-NRAO, Jodrell Bank, CLASS: ~30% of known lenses

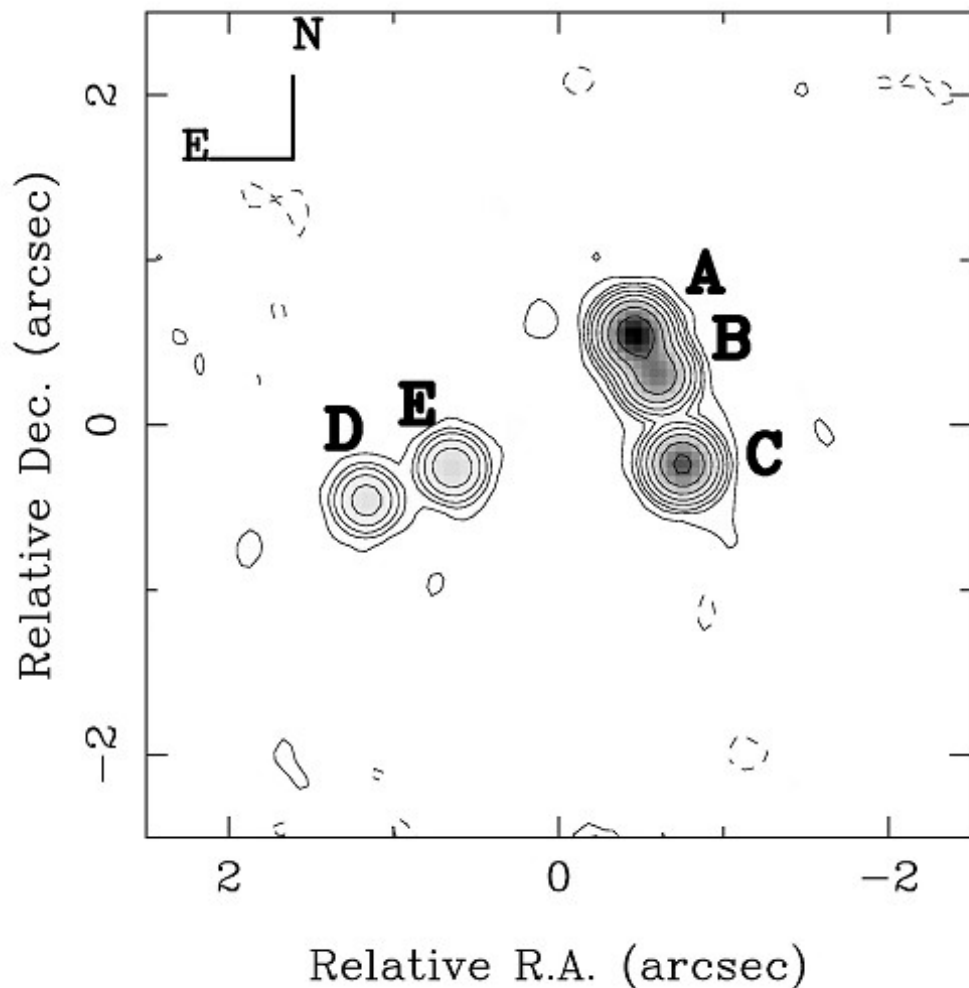
Central Images

Winn et al., 2003



- Lensing predicts odd numbers of images
- Central Images are highly demagnified
- Only two such images found in lens systems
- Radio crucial due to resolution and “low” radio emission in lens

Flux Ratio Anomalies

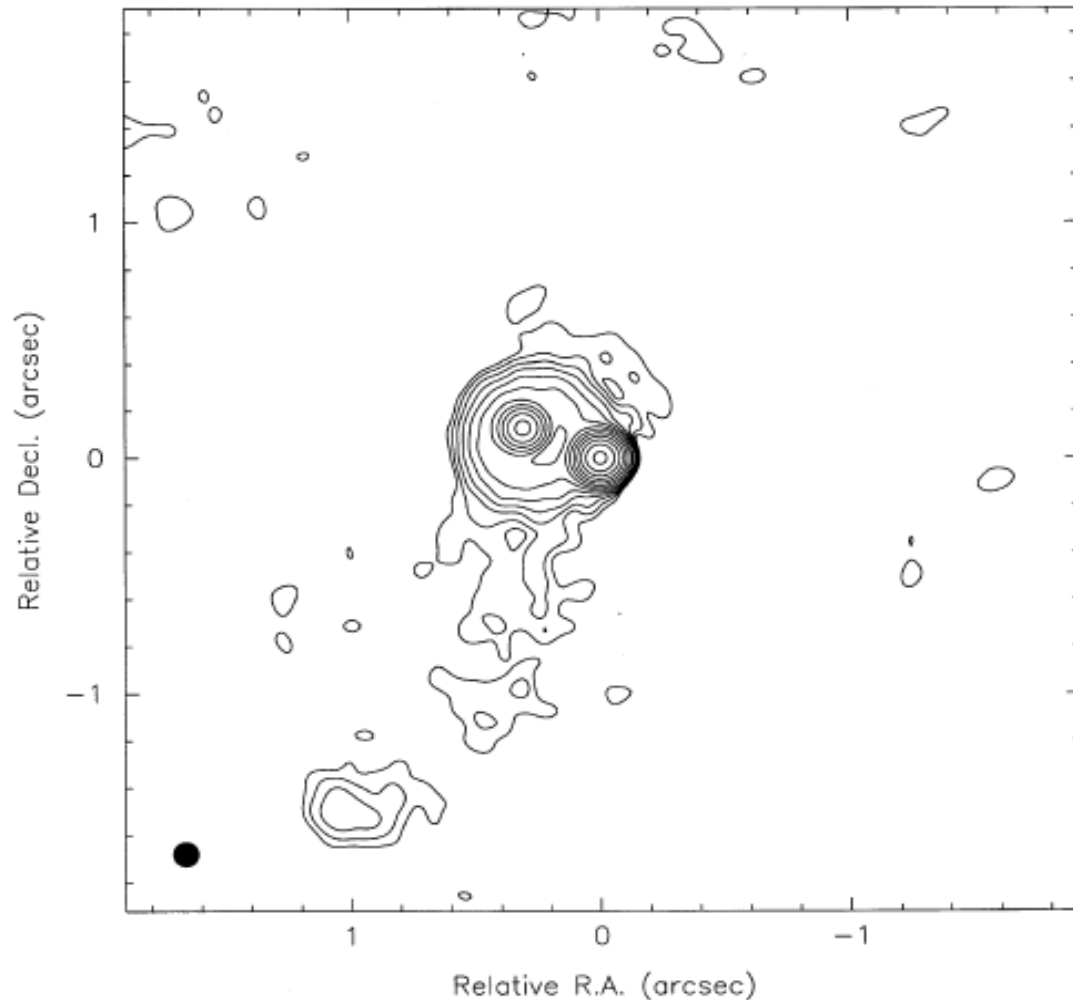


- Provides handle on size of stellar or substructure clumps
- Perturbations in magnification depend on source size
 - Radio sources are big
- Free from extinction concerns

Time Delays

Biggs et al., 1999

0218+357 VLA 14.915 GHz 18/11/92

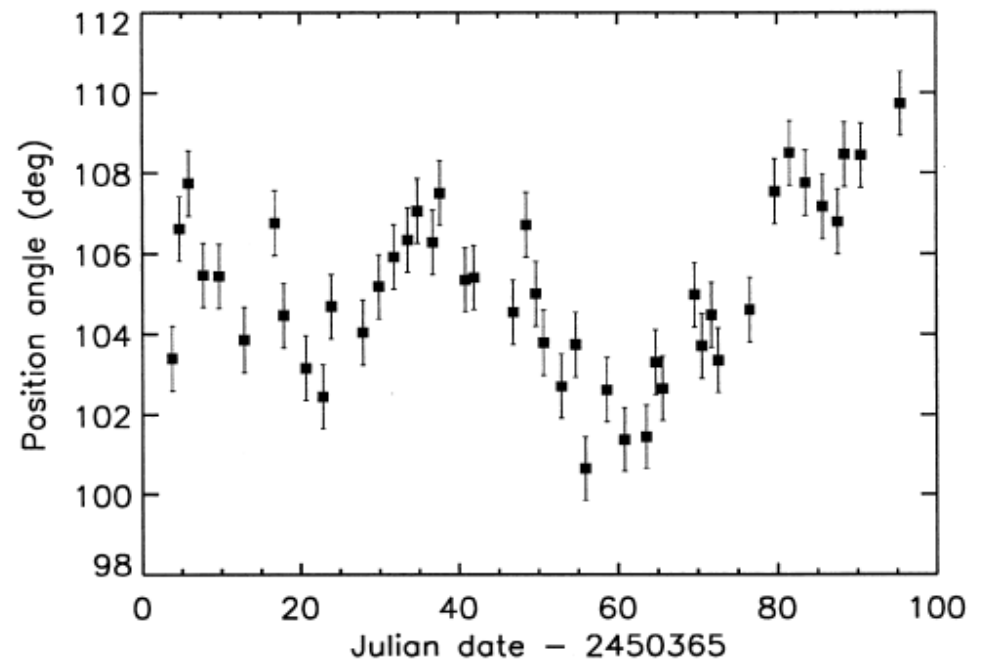
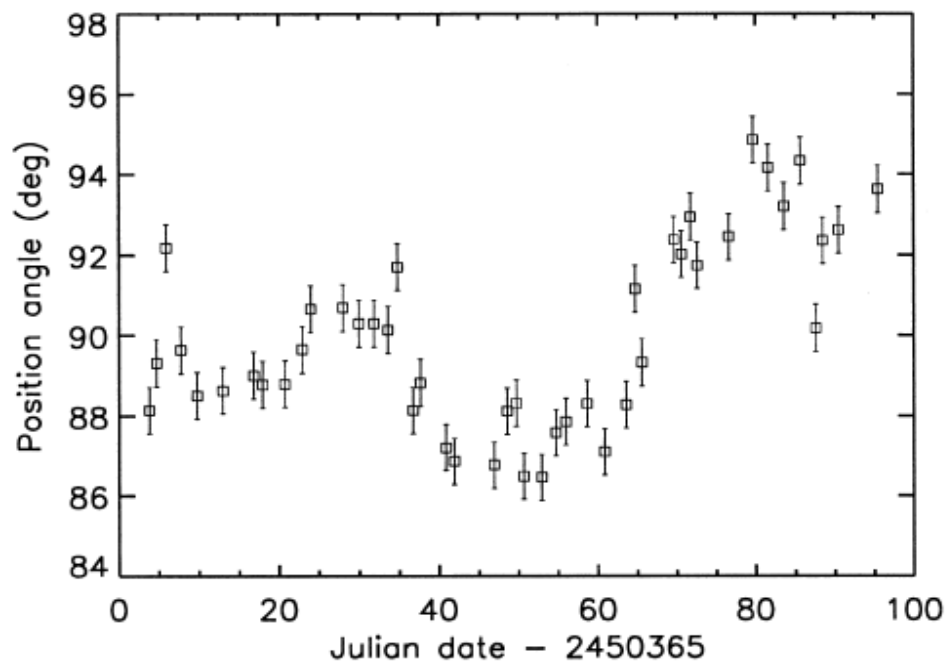
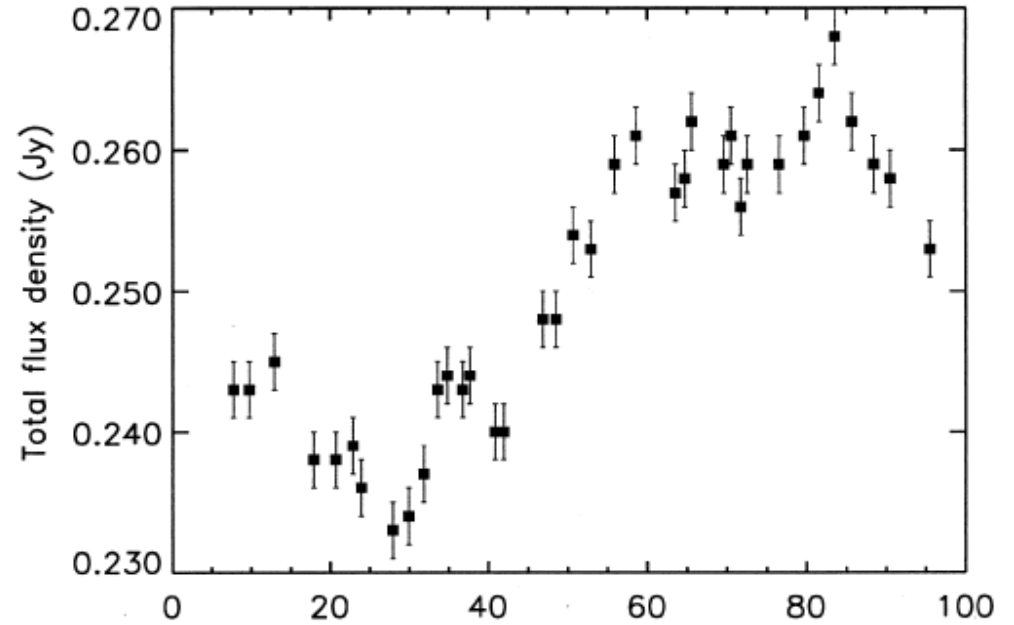
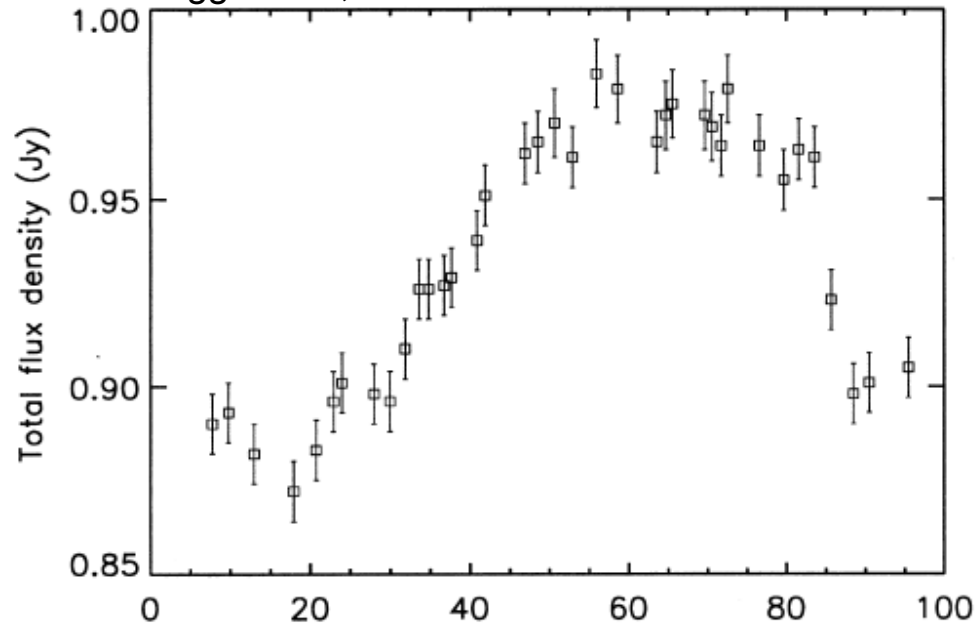


- Due to different light paths, images arrive at different times
- Time delays yield cosmological constraints, i.e. Hubble Constant
- Need good resolution
- Radio emission free from differential extinction concerns

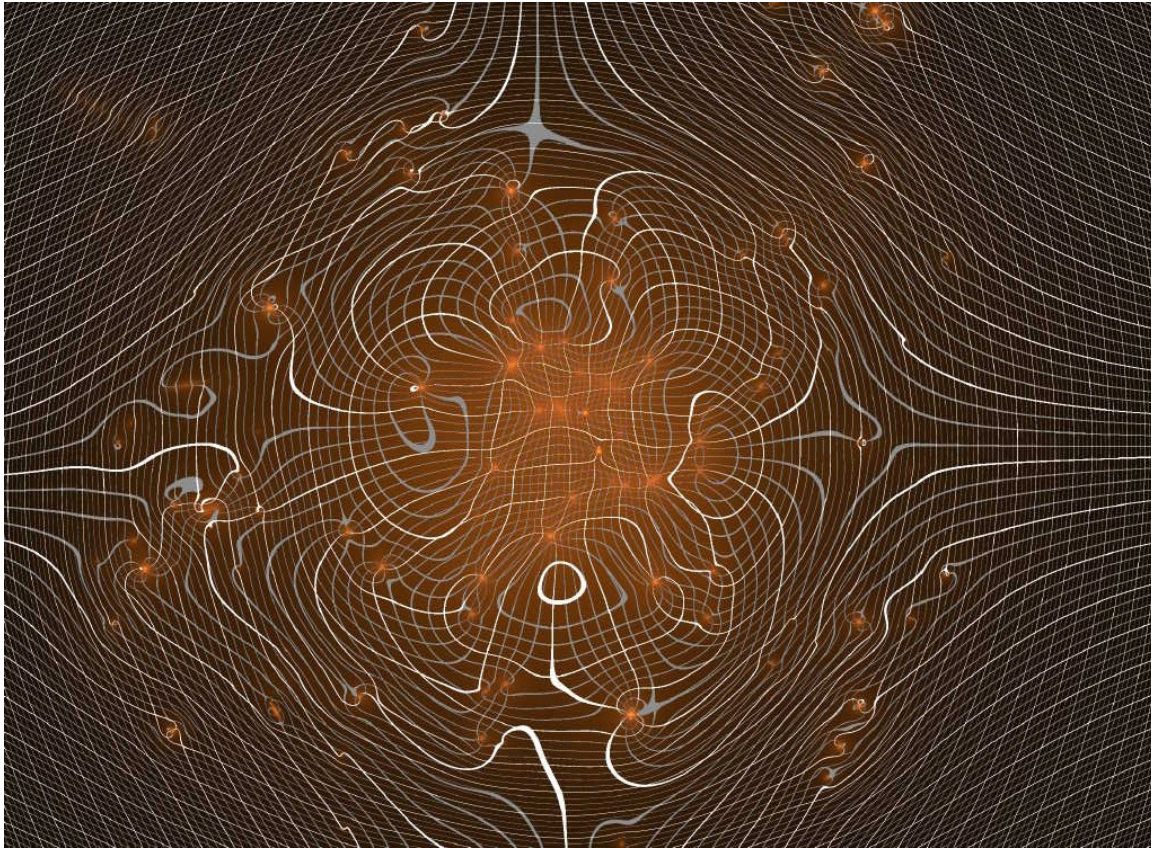
$$\Delta t_{ij} = \frac{1+z_l}{c} \frac{D_{ol} D_{os}}{D_{ls}} \left[\frac{1}{2} \left(|\vec{x}_i - \vec{u}|^2 - |\vec{x}_j - \vec{u}|^2 \right) - \left(\phi(\vec{x}_i) - \phi(\vec{x}_j) \right) \right]$$

Time Delays

Biggs et al., 1999



Summary



- Lensing is a vital tool for astrophysicist
 - Direct measurements of mass in lenses
 - Key role in answering big questions
- Radio measurements are important to lensing
 - Excellent resolution
 - Vital wavelengths for lensing science

Quiz

Quiz

The VLA has 27 dishes in its array.

How many baselines does the VLA have??