Gravitational Lensing - 2

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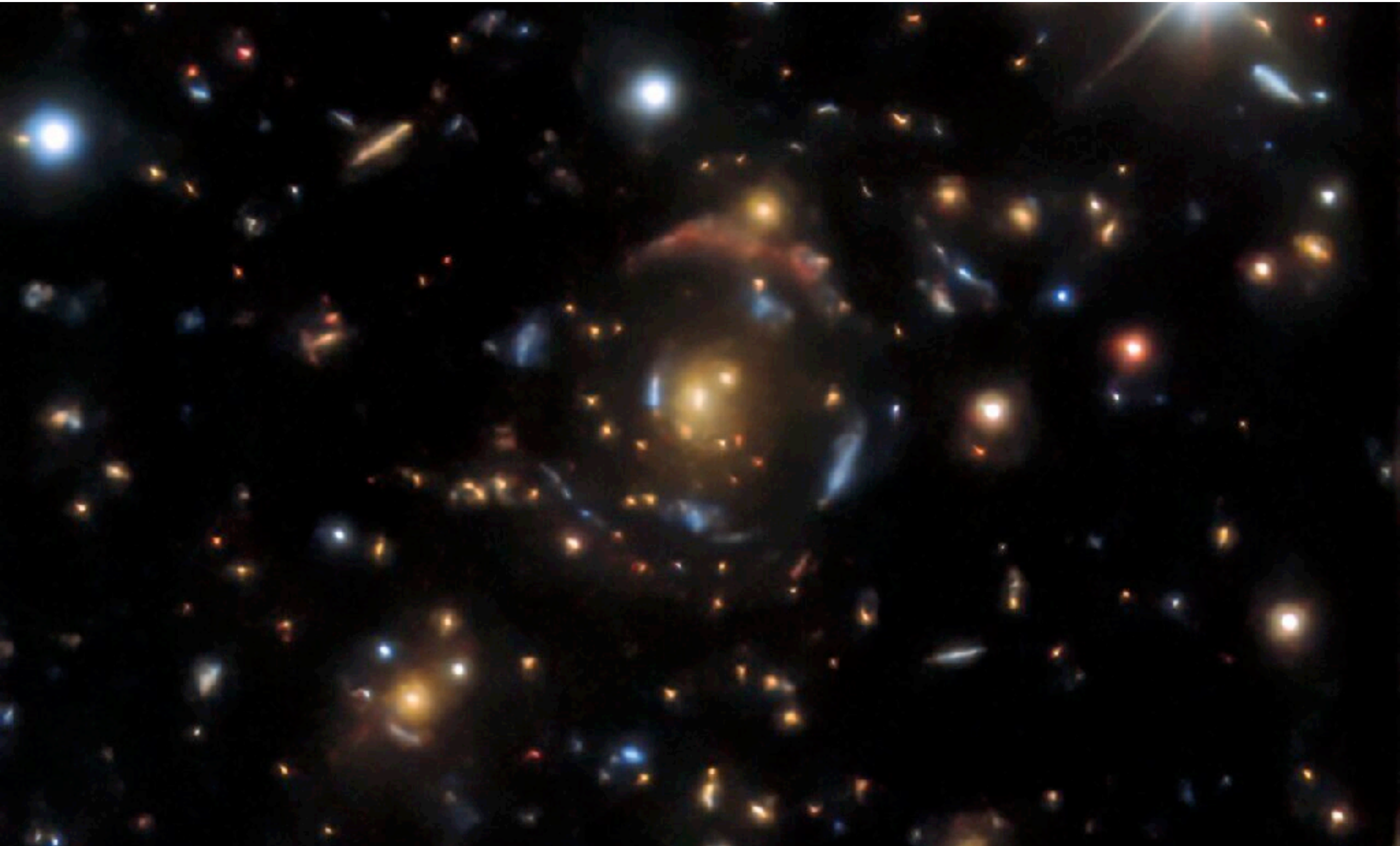
May 7, 2020

https://arxiv.org/abs/2005.04730

Artificial Intelligence finds more than 1,200 Gravitational Lensing Candidates In the DESI Legacy Imaging Survey



Quiz - 1

- How to explain the effect of gravitational lensing?
- Who had the first vision? How can it be useful?
- What is strong lensing? Is it common?
- What is weak lensing?
- What does mean “multiple images”?
- What are the main strong lensing configuration for an elliptical lens?
- What are the “critical lines”?
- What are the “caustic lines”?
- What is the Einstein radius?

Lensing Equations

Lens Mapping:

Lensing Potential

$$\vec{\theta}_S = \vec{\theta}_I - \frac{2\mathcal{D}}{c^2}\vec{\nabla}\phi_N^{2D}(\vec{\theta}_I) = \vec{\theta}_I - \vec{\nabla}\varphi(\vec{\theta}_I)$$

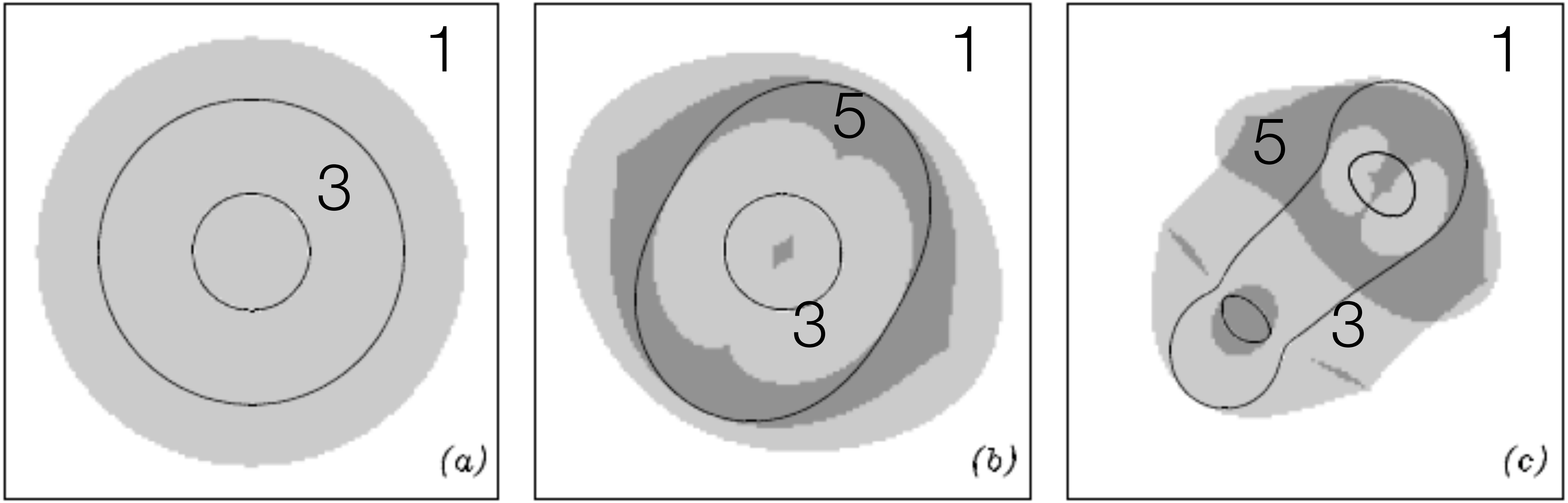
φ : lensing potential

⇒ Link with catastrophe theory

⇒ Parameters: Distances and Mass

⇒ Purely geometrical: *Achromatic effect*

Multiple image region for:
Circular Elliptical Bimodal
mass distribution

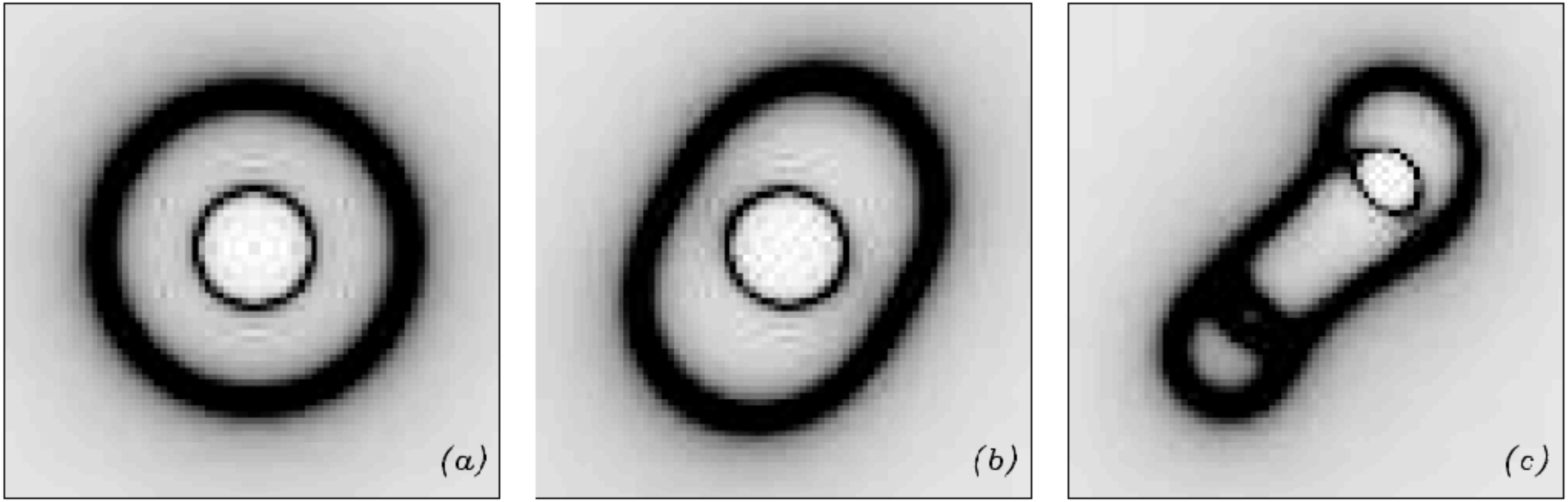


Lensing Theory

Amplification map for:

Circular Elliptical Bimodal

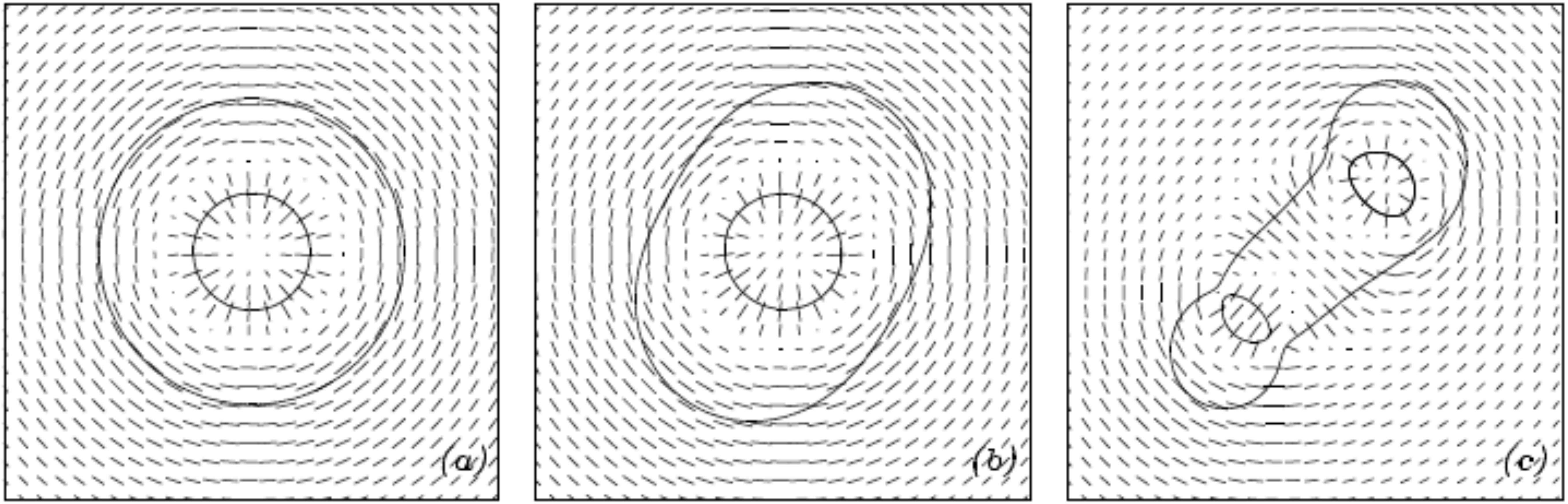
mass distribution

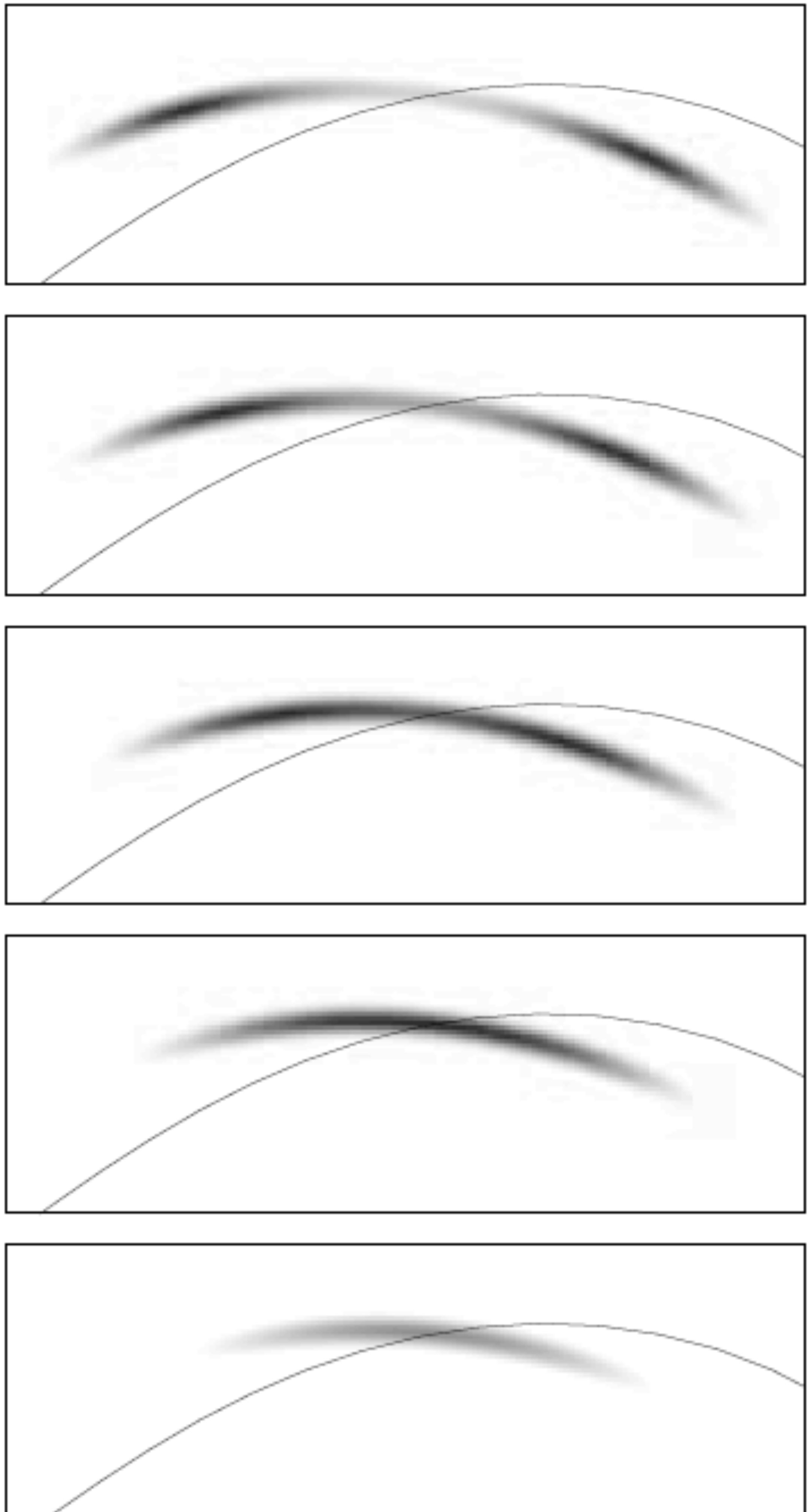


Shear field for:

Circular Elliptical Bimodal

mass distribution





Strong Lensing

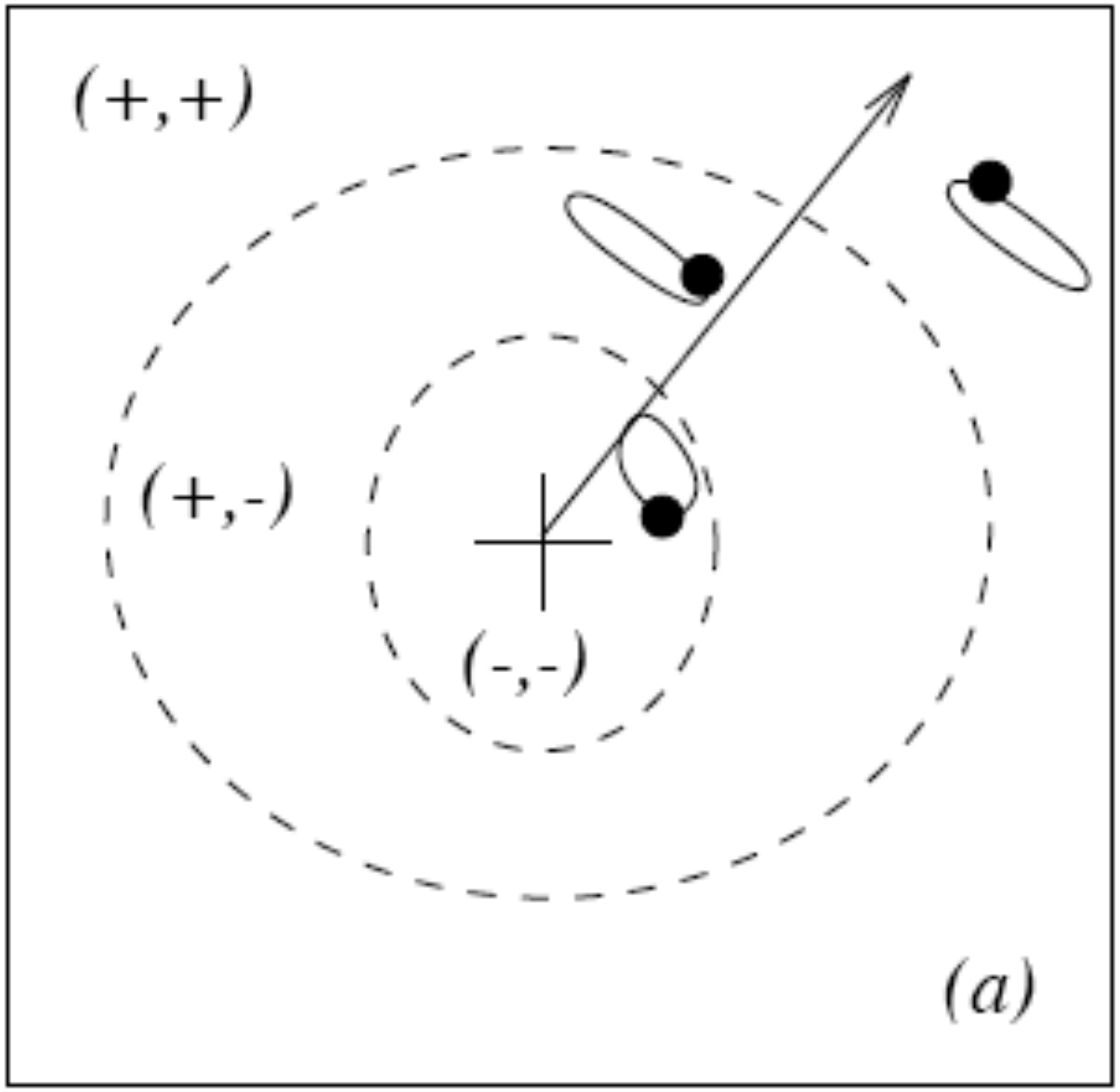
Schematic of image fusion on the critical line

Magnification is due to stretching of the image: ***surface brightness is conserved through lensing***

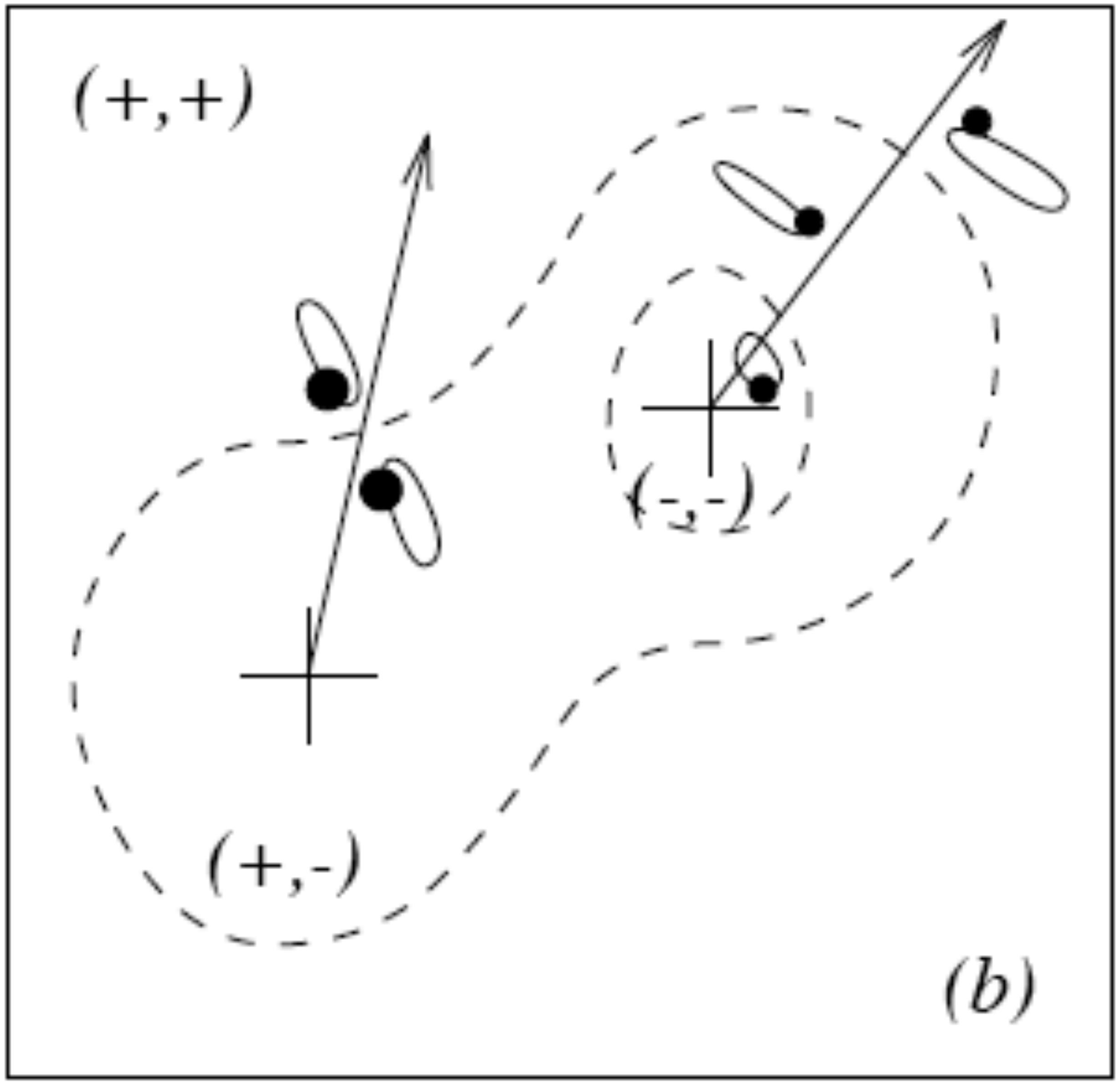
Strong Lensing

Image parity

Elliptical case



Bimodal case



Mass & Einstein Radius

Mass within the Einstein ring:

- mass as a function of lensing potential (circular case): $M(r) = \frac{c^2}{4G}\frac{D_{OS}D_{OL}}{D_{LS}} r\partial_r\varphi(r)$

- Mass within the tangential critical line (Einstein ring):

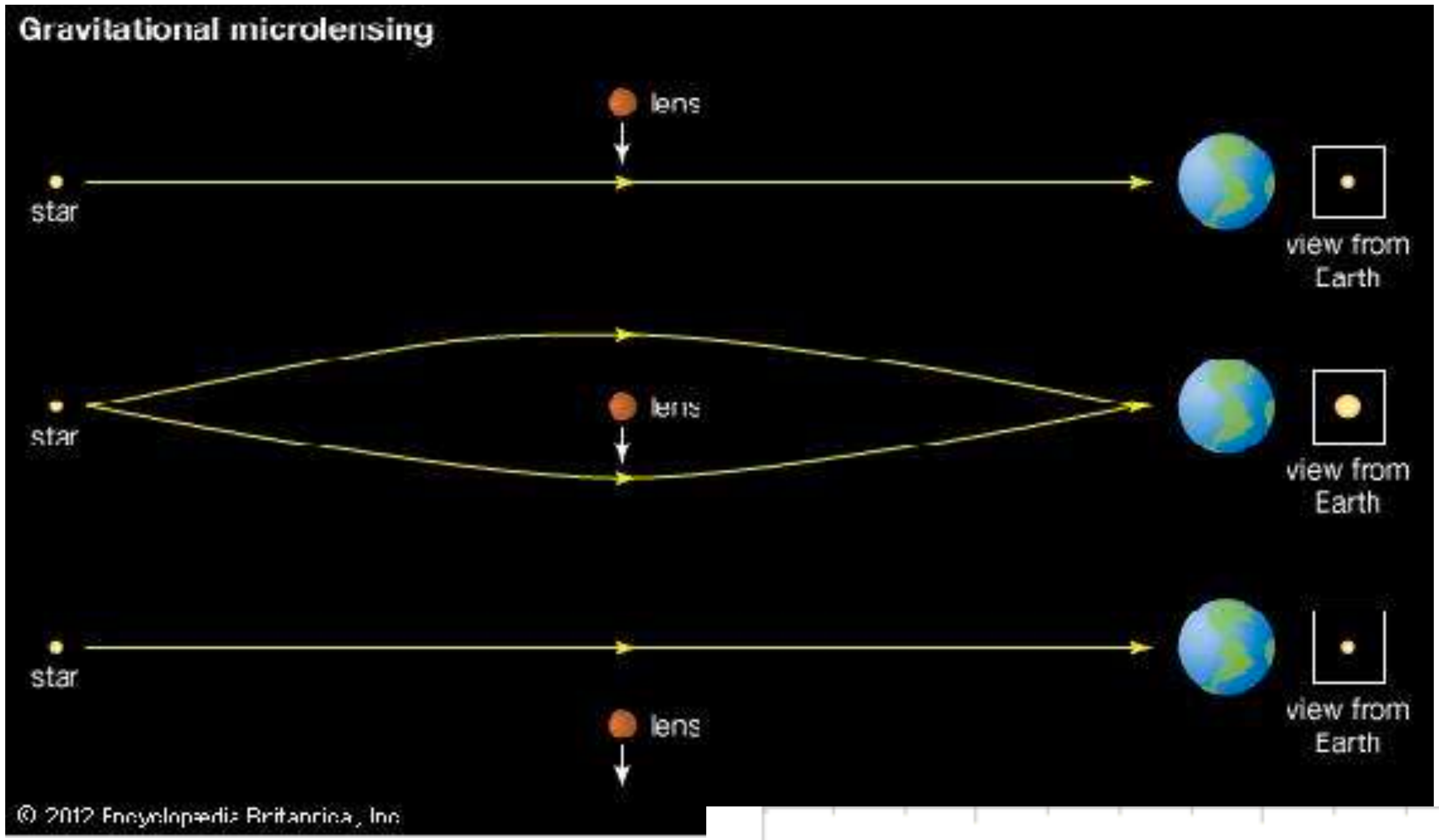
$$M(r_E) = \pi\Sigma_{crit} r_E^2$$

$$\approx 1.1 \times 10^{14}\, M_\odot \left(\frac{\theta_E}{30''}\right)^2 \left(\frac{D}{1\,\mathrm{Gpc}}\right)$$

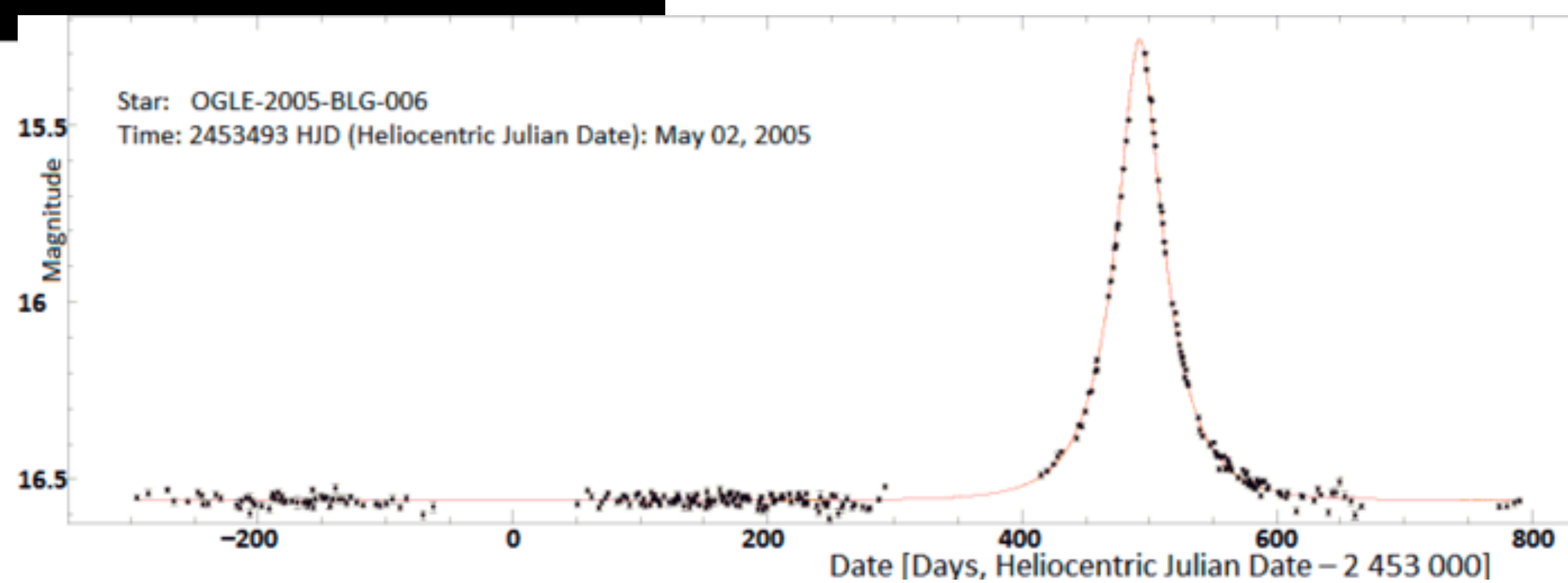
- Value of Einstein radius is not everything! Anisotropy is also very important.

Micro-Lensing

Micro Lensing



- Moving object lensing a distant star
- Achromatic effect
- search for DM in compact form (EROS, MACHO, OGLE projects)



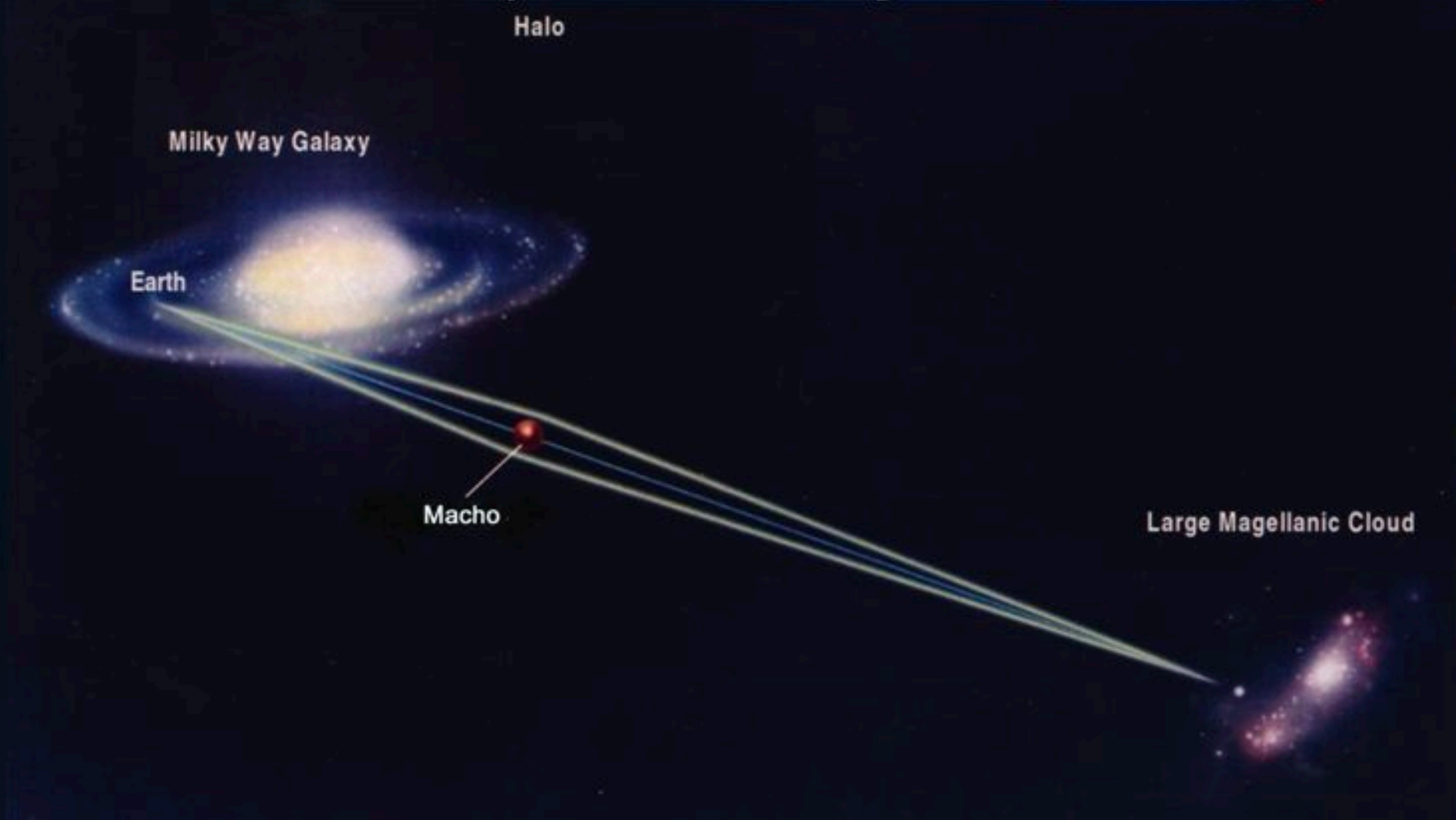
Micro Lensing - some numbers

- The lensing object is a point mass, Einstein radius is: $$\theta_E = \sqrt{\frac{D_{LS}}{D_S D_L} \frac{4GM}{c^2}}$$
- Let's define the relative distance: $$u = \frac{\theta_S}{\theta_E}$$
- The total magnification due to micro-lensing is: $$A(u) = \frac{u^2+2}{u\sqrt{u^2+4}}$$
- Time to cross the Einstein radius $$t_E$$
- Variation of the relative distance as a function of time: $$u(t) = \sqrt{u_{min}^2 + \frac{(t-t_0)^2}{t_E^2}}$$

Halo Dark Matter & Paczynski's Idea

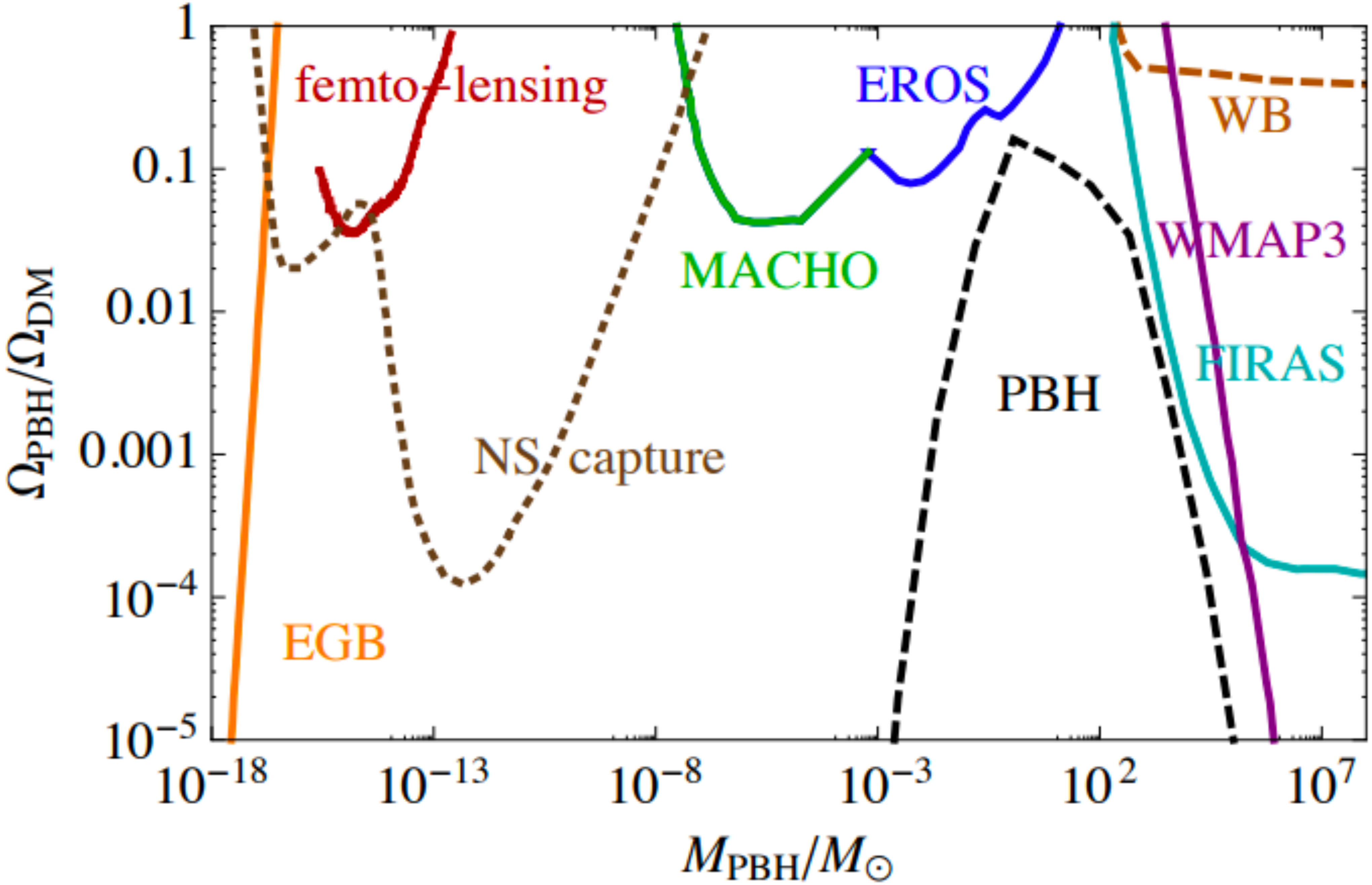
(Paczynski 1986)

- 20〜40 times more dark matter than visible mass.
- MAssive Compact Halo Objects (MACHOs) ←→ WIMPs



- MACHO can be observed by Microlensing.
- $\tau \sim 10^{-6}$ → need to observe 1M stars !

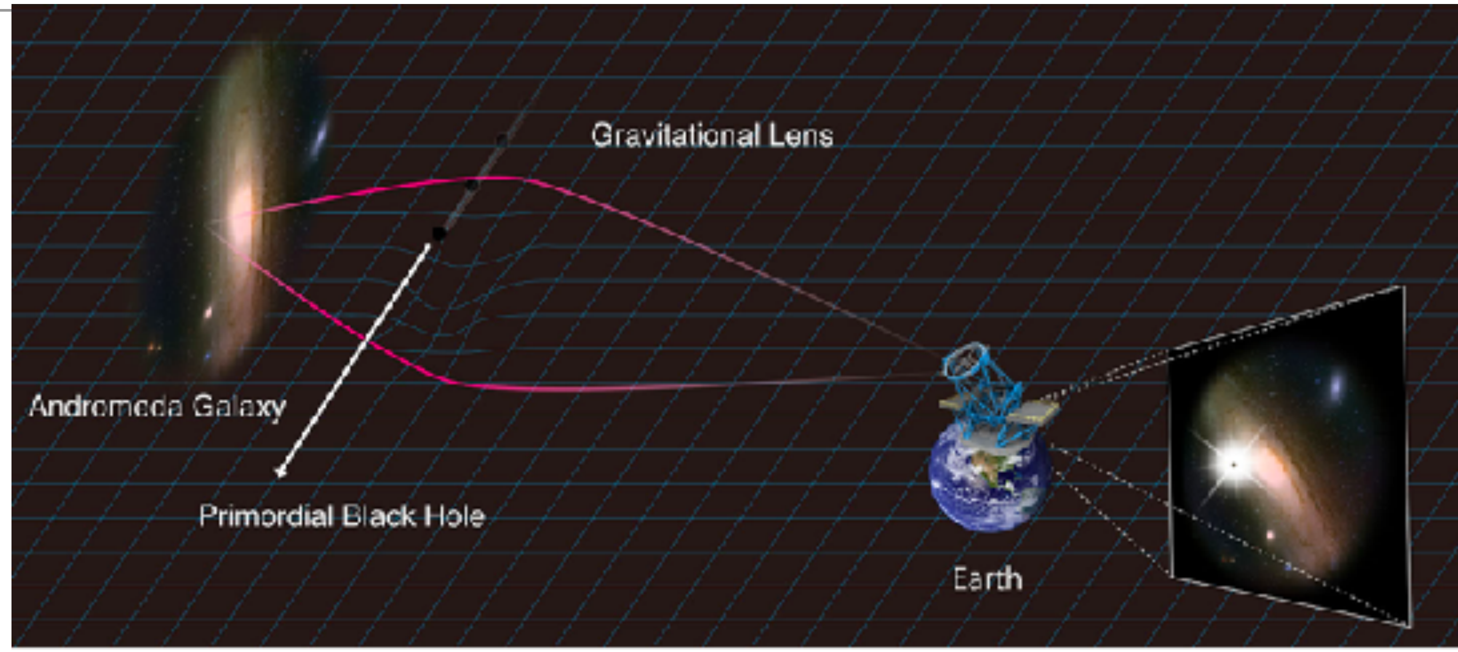
Constraints on the fraction of DM as compact object (BH)

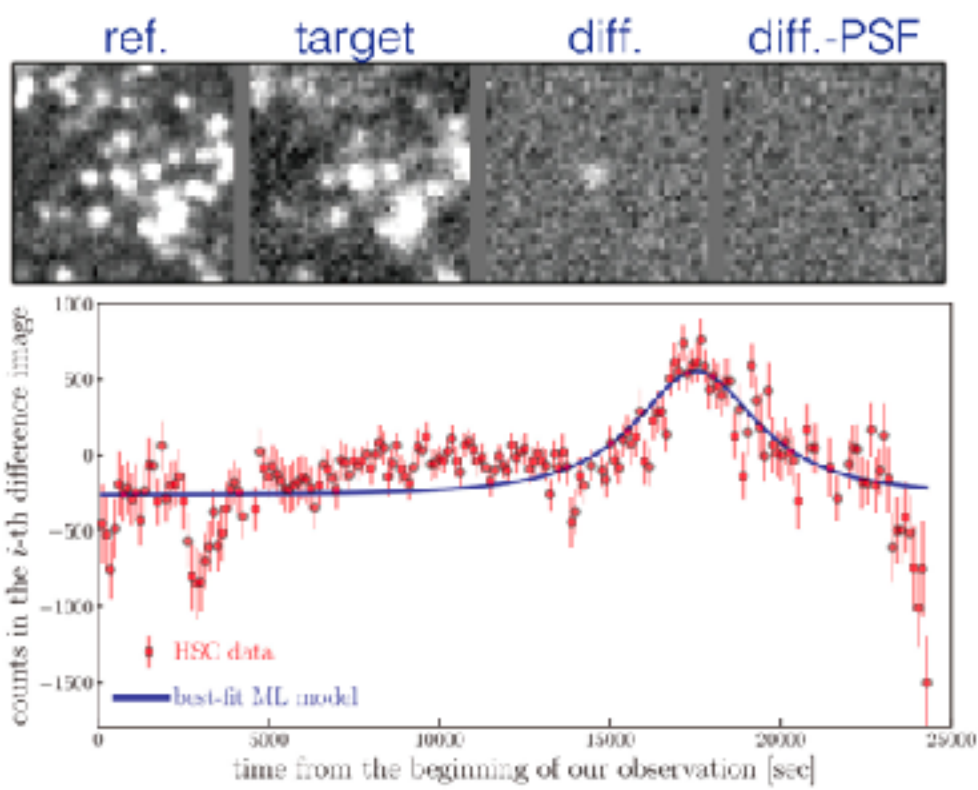


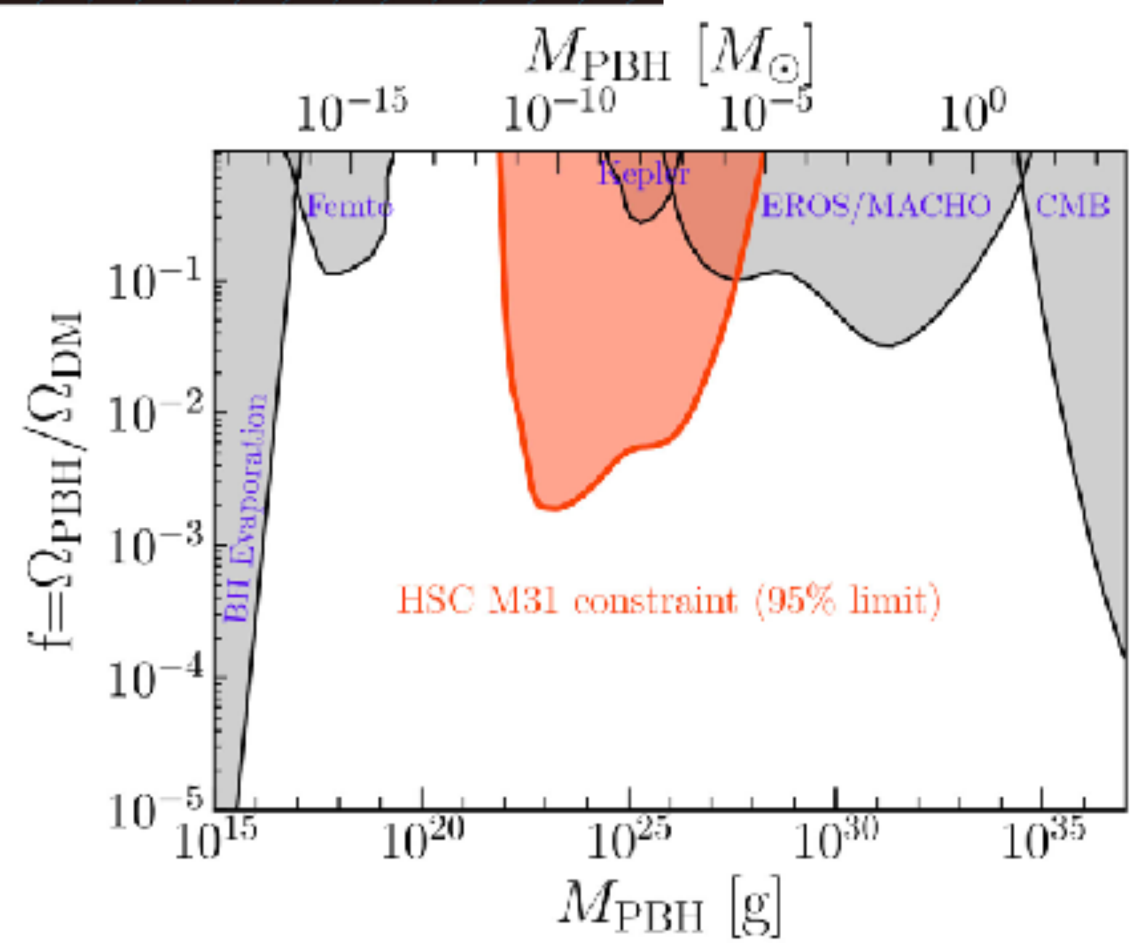
Garcia-Bellido et al 2017

2 April 2019: PBH constraints with HSC Microlensing

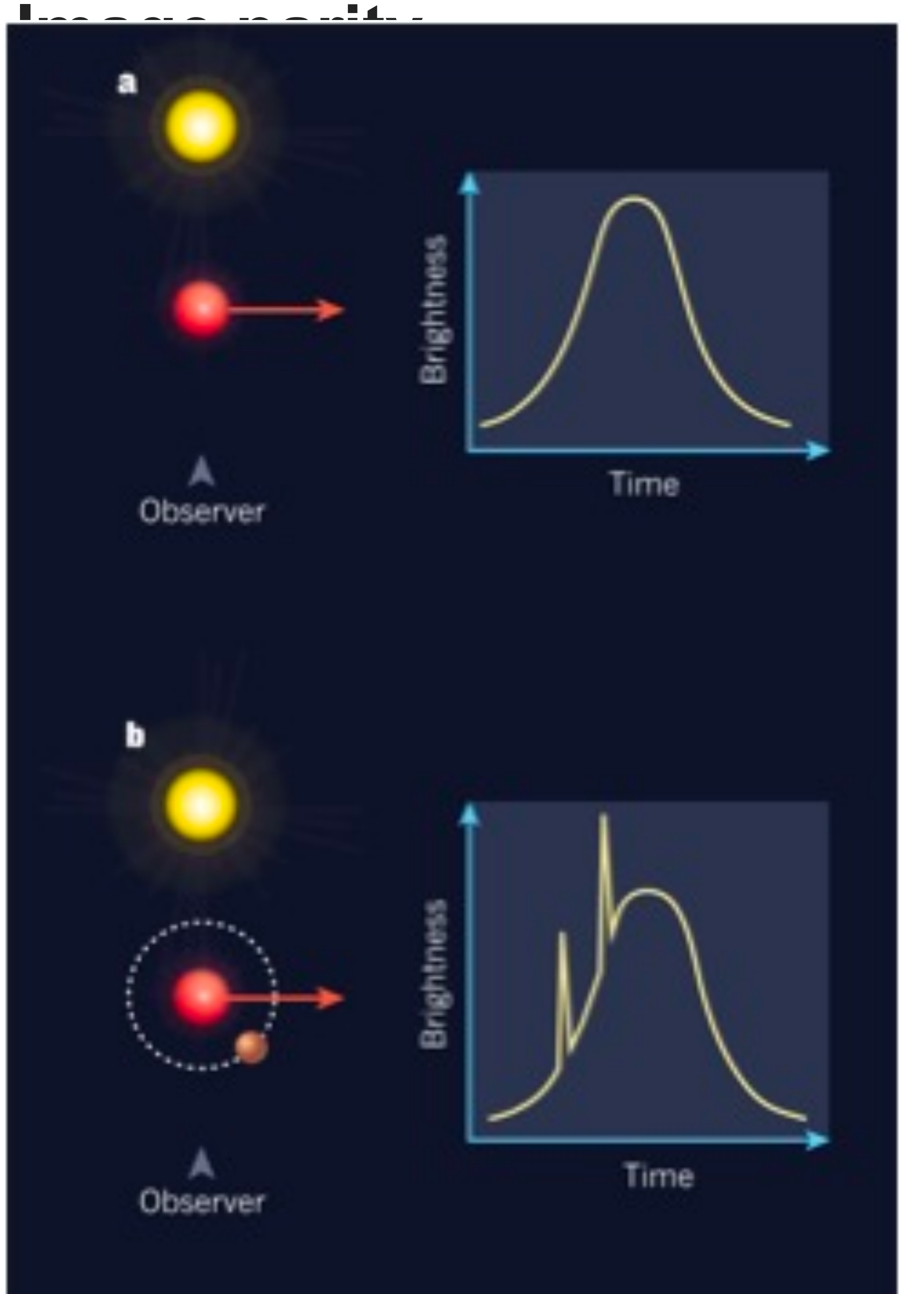
Niikural et al 2019 https://arxiv.org/abs/1701.02151

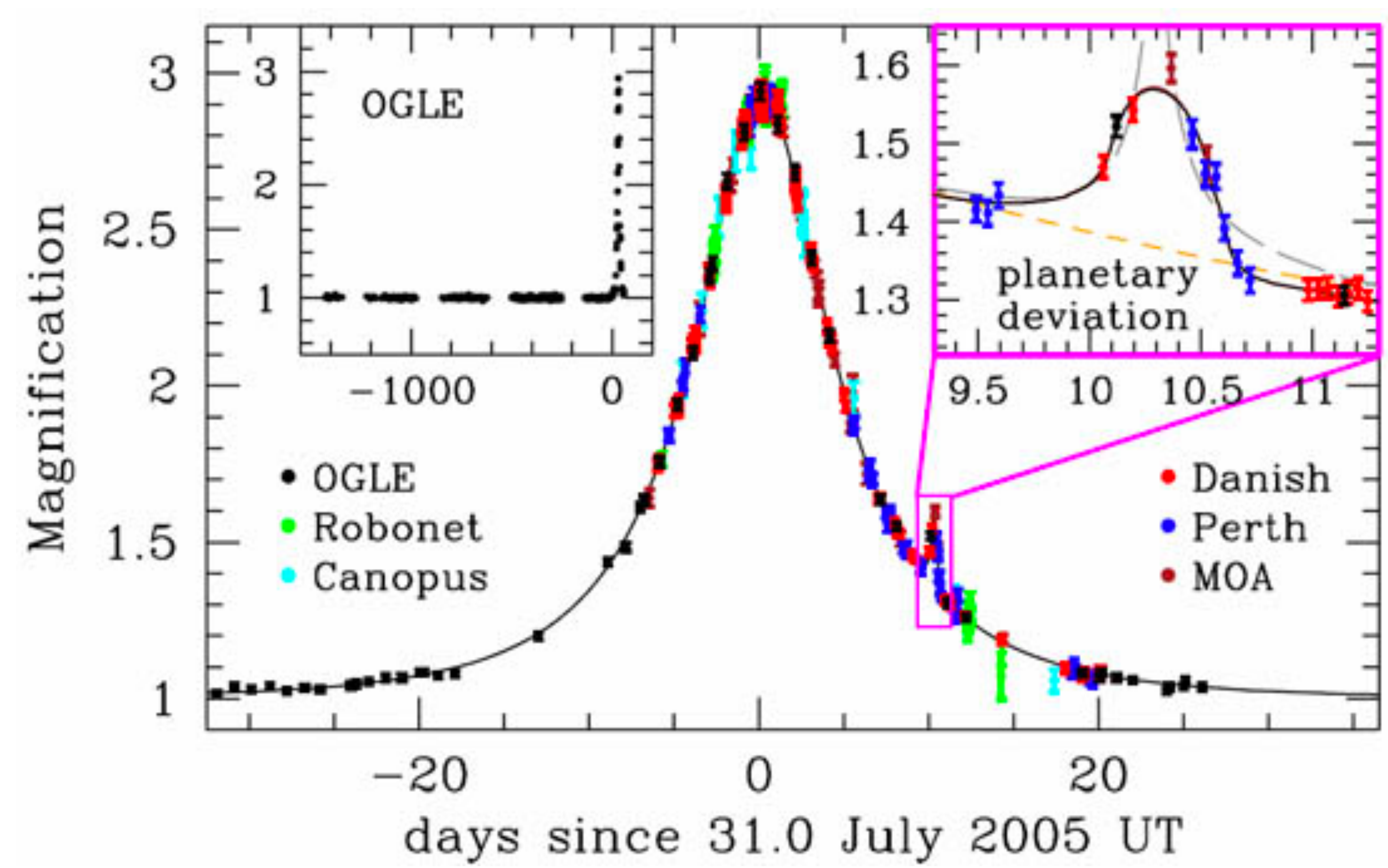






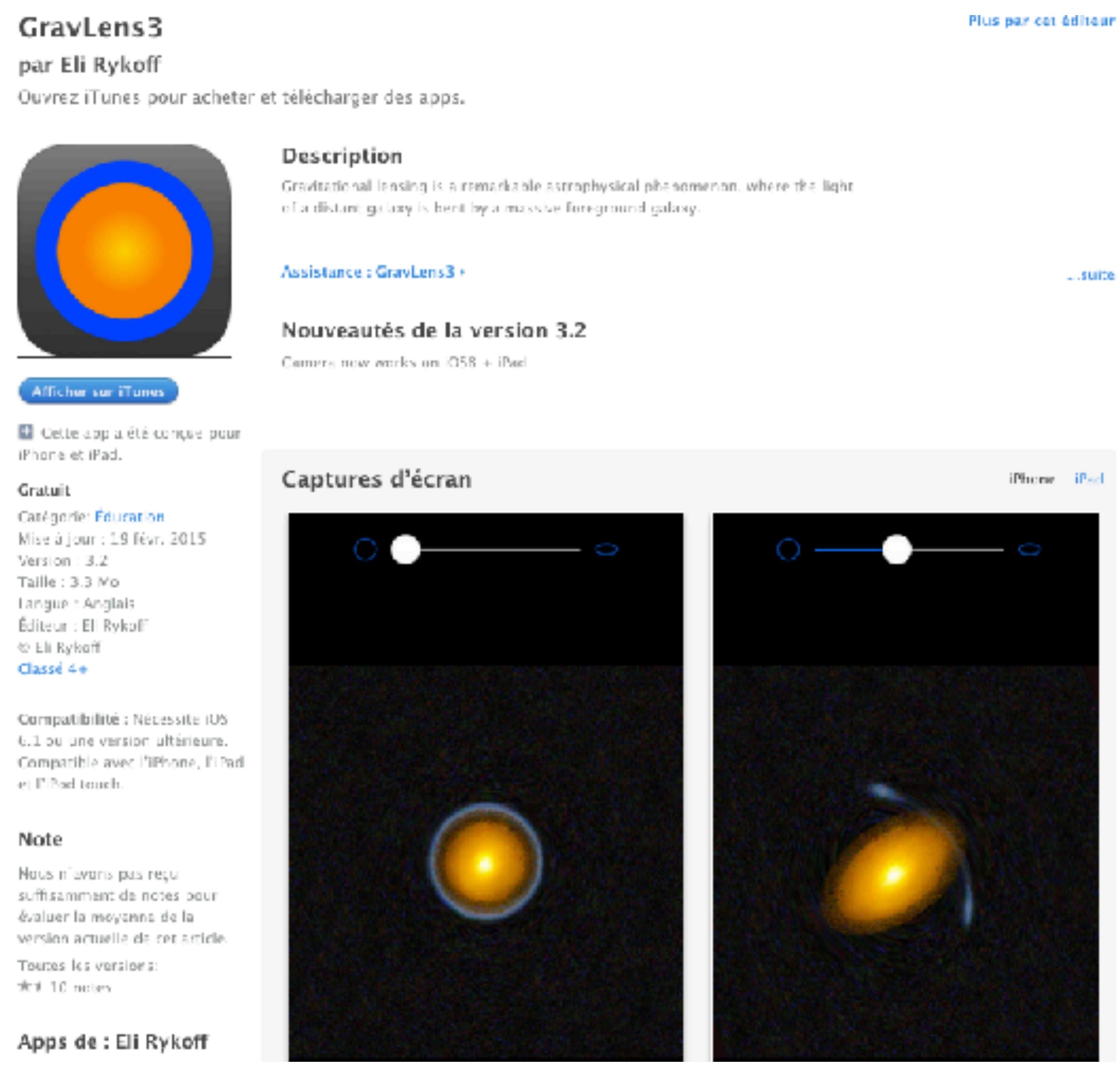
Micro Lensing by exo-planets



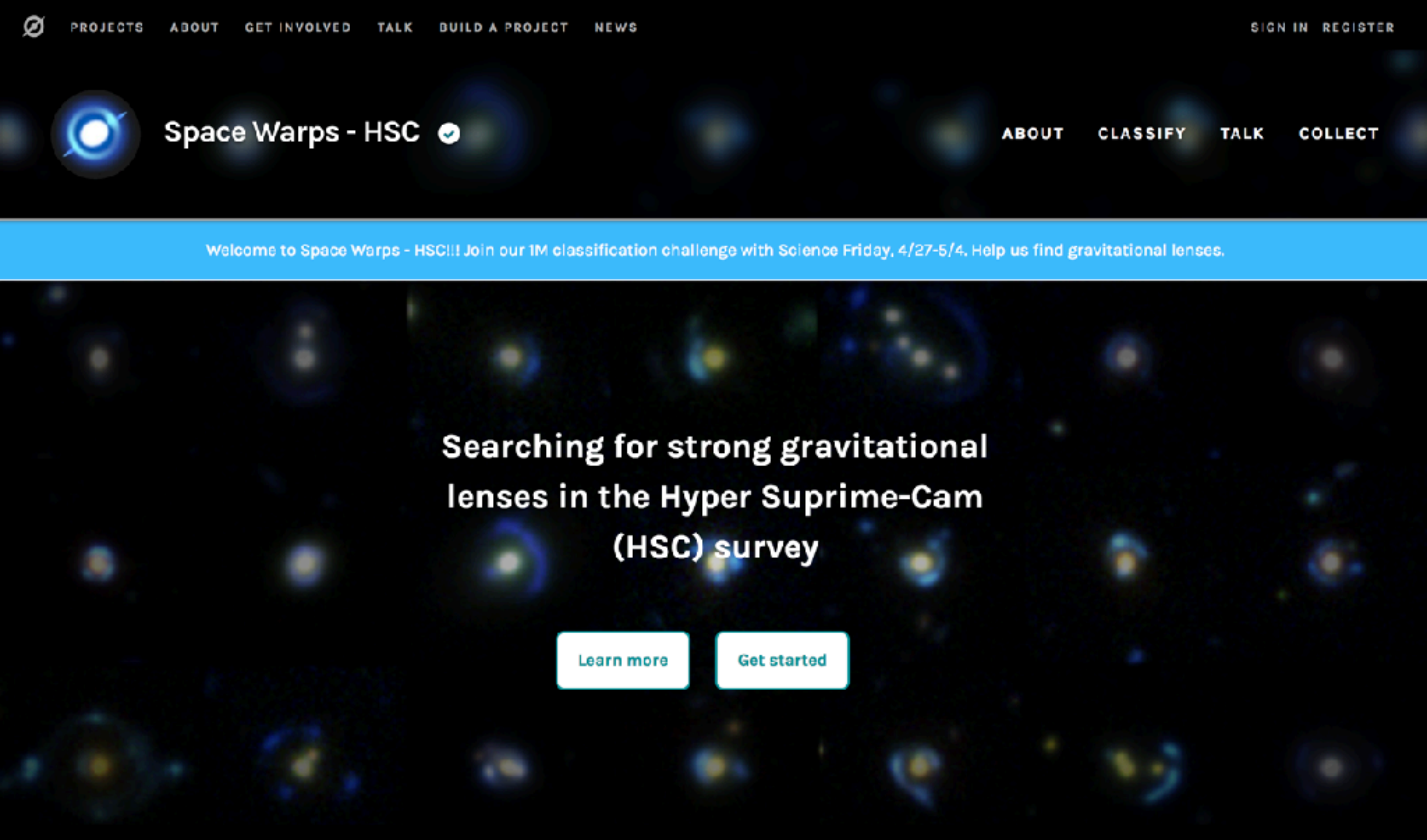


Lensing fun tools

- Gravitational Lensing iPhone App:



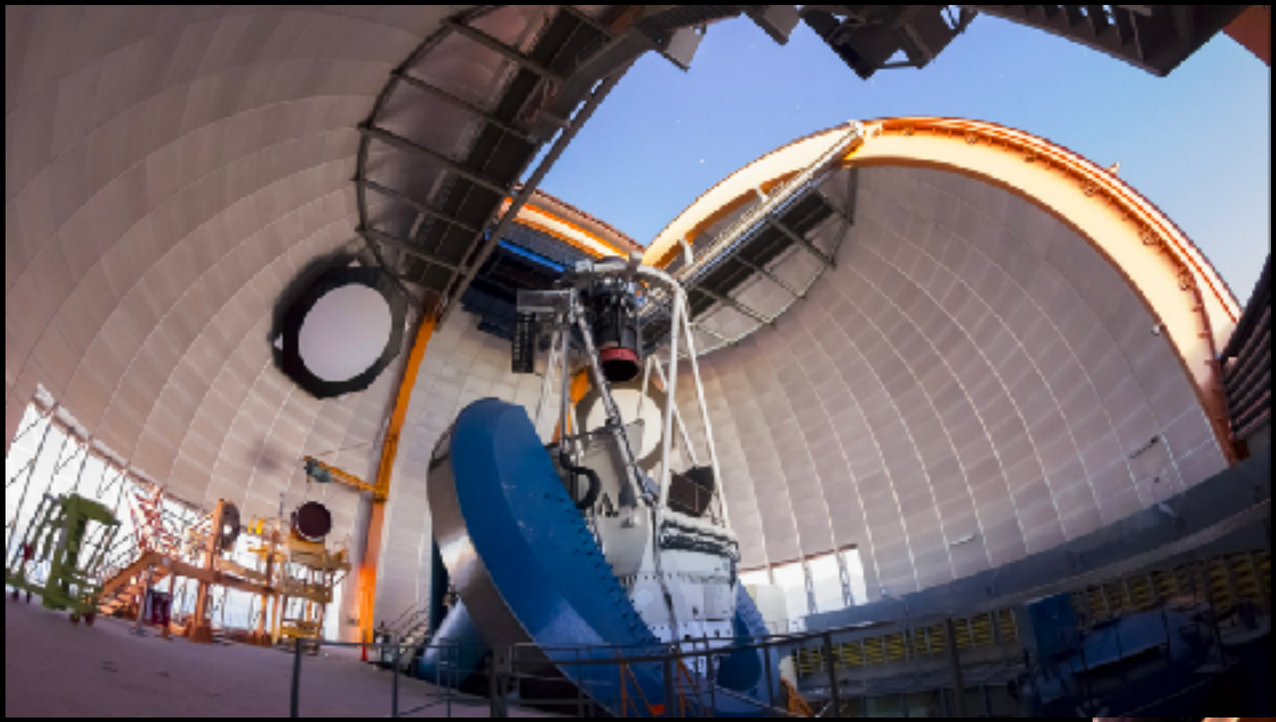
- SpaceWarps: Citizen science
  - https://spacewarps.org/



https://www.zooniverse.org/projects/aprajita/space-warps-hsc

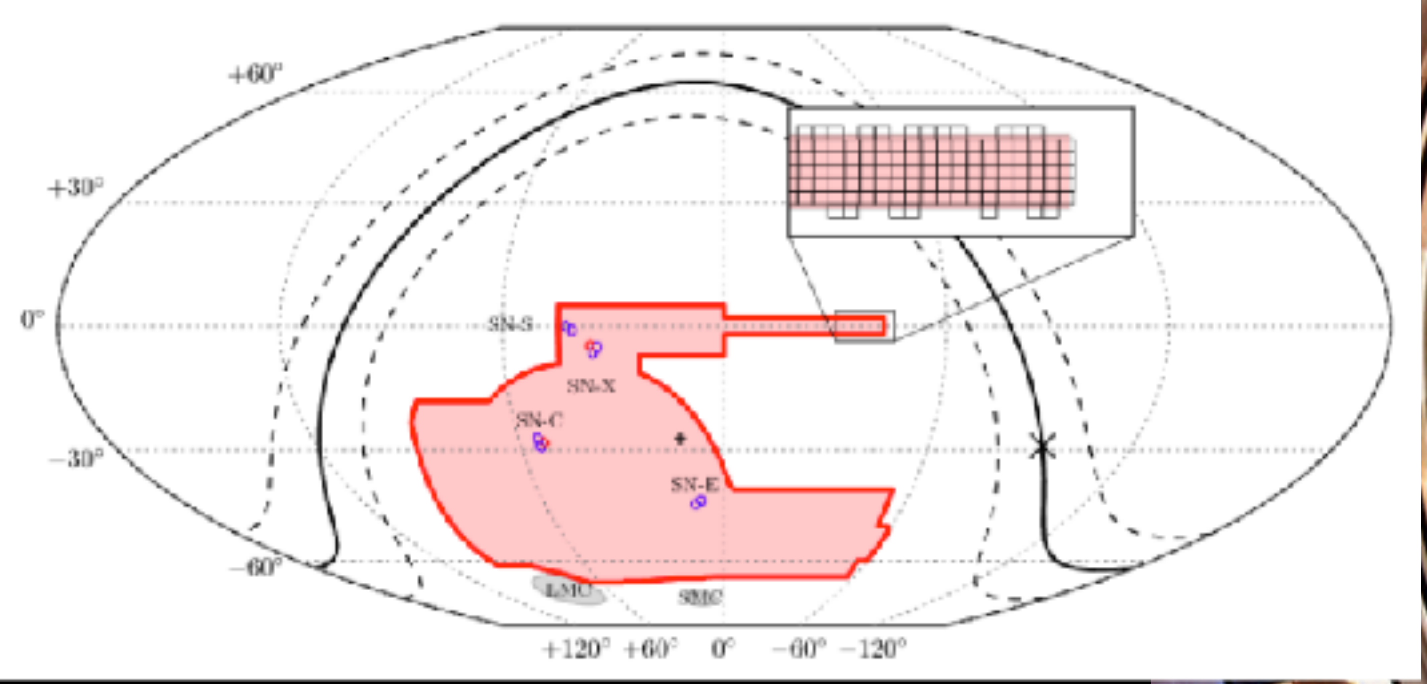
The DarkEnergy Camera of the 4m Blanco Telescope

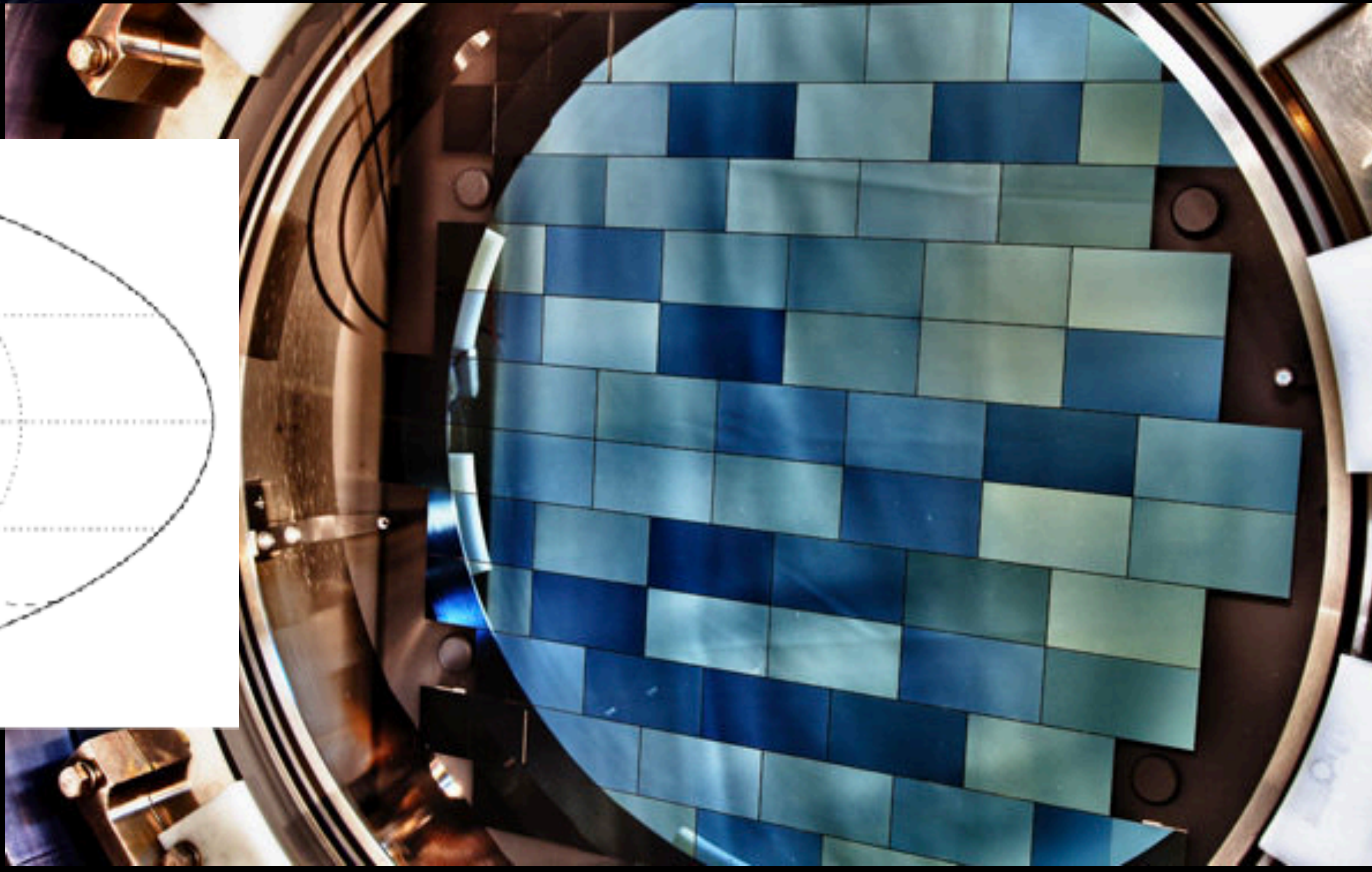
74 2k x 4k CCD detectors => 570 MPixel Camera



https://www.darkenergysurvey.org/

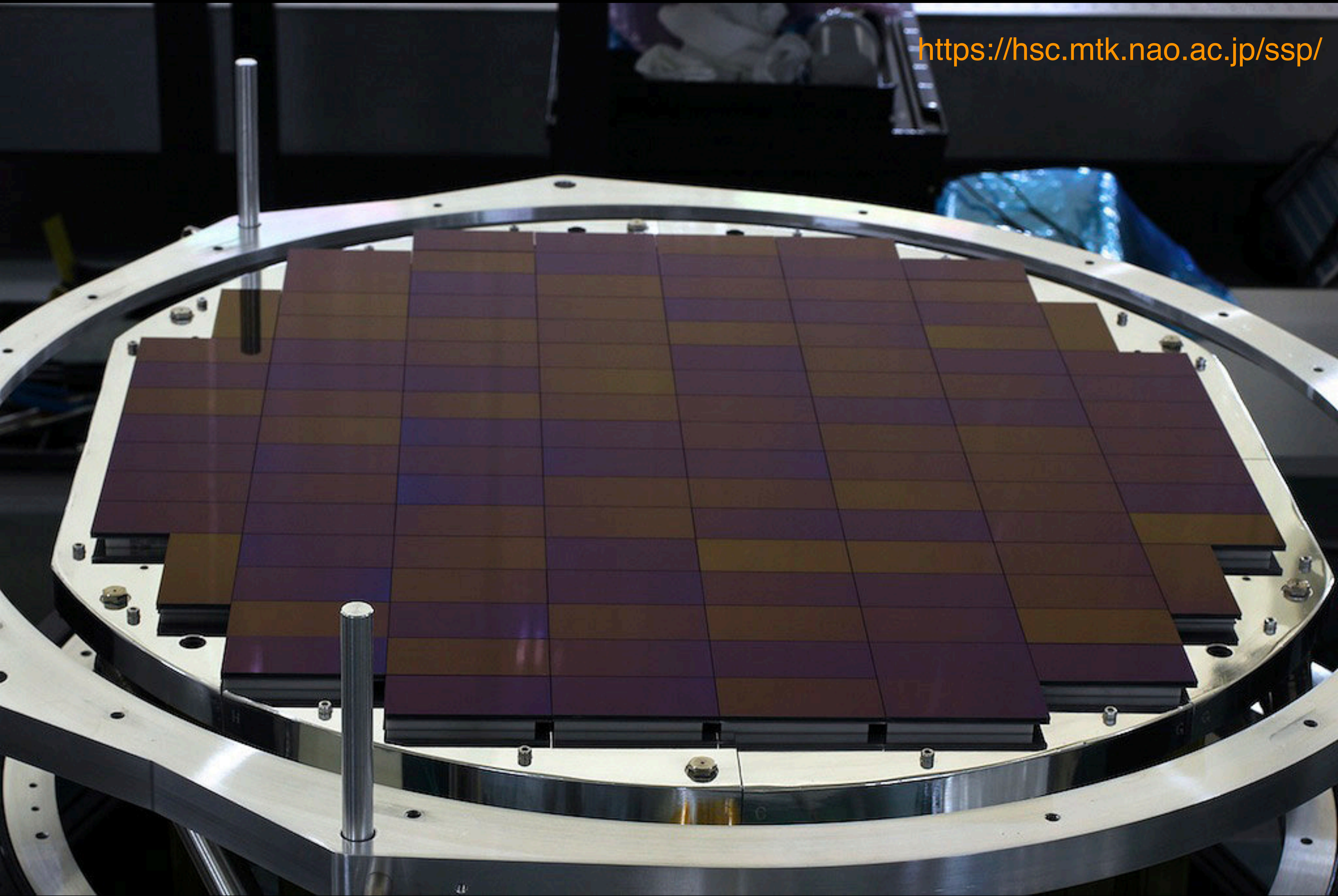
Data Release:
https://des.ncsa.illinois.edu/releases/dr2



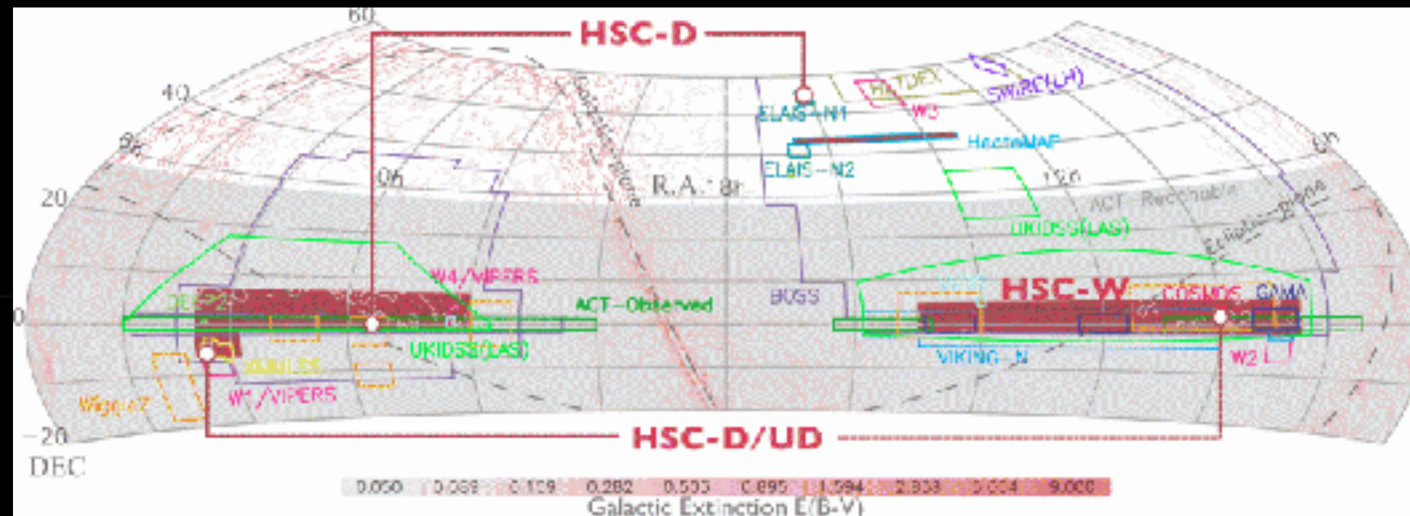


The Hyper Suprime Camera of the 8.2m Subaru Telescope

116 2k x 4k CCD detectors => 870 MPixel Camera



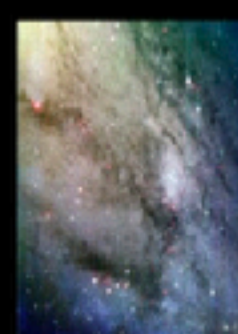
The Hyper Suprime Camera of the 8.2m Subaru Telescope



Typical Apparent Diameter of the Moon (0.5 degrees)

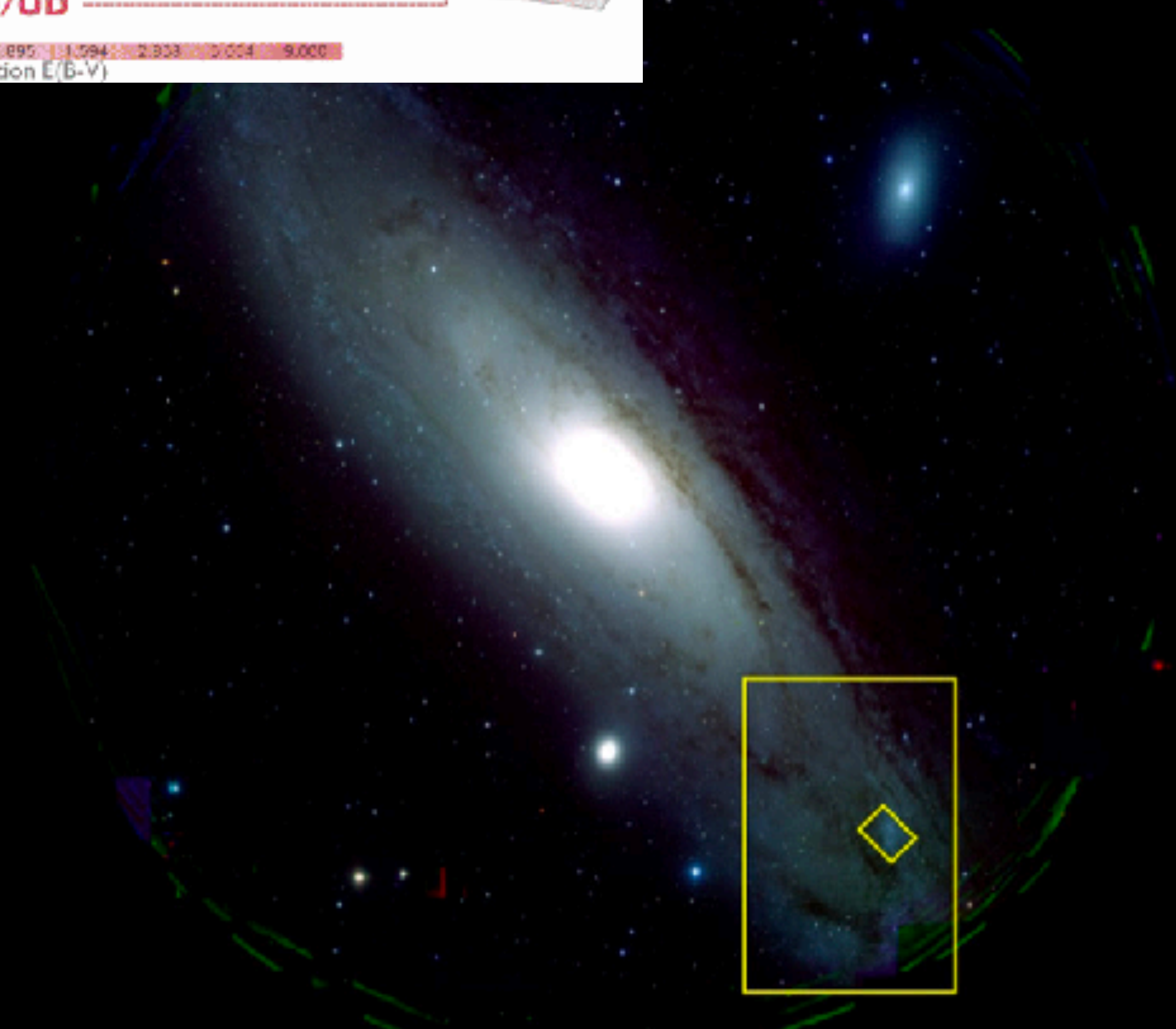
Suprime-Cam

First Light Release
January 1999



Suprime-Cam

Image Release
September 2001



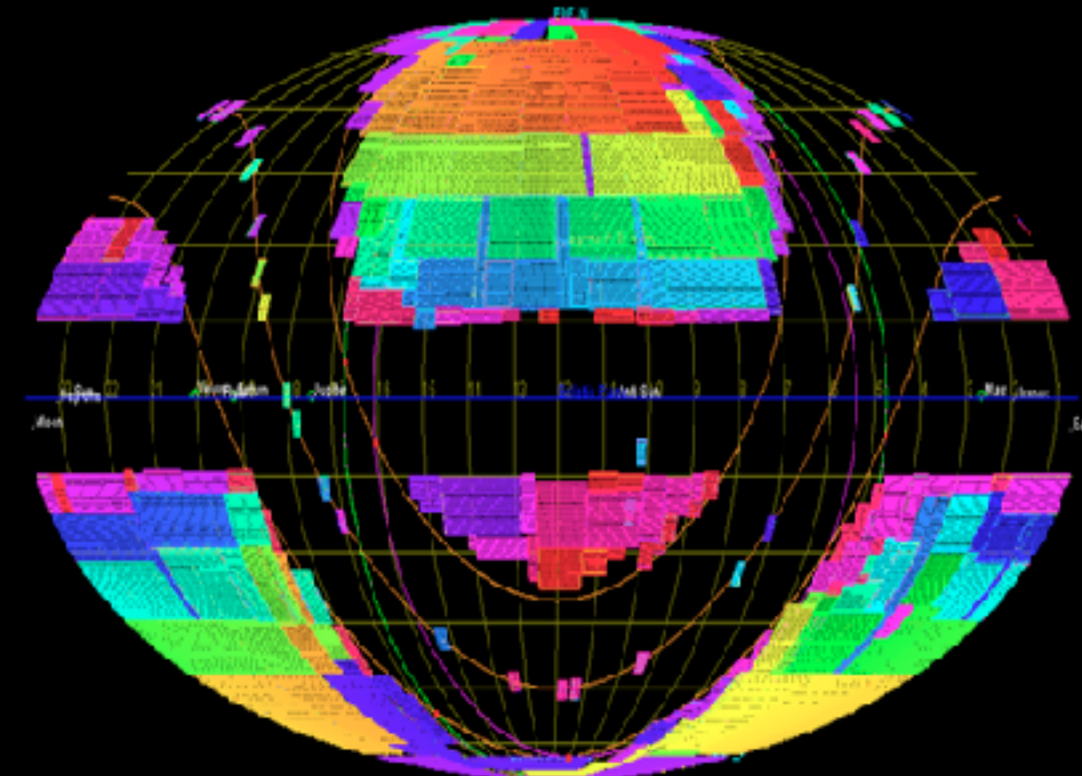
Hyper Suprime-Cam

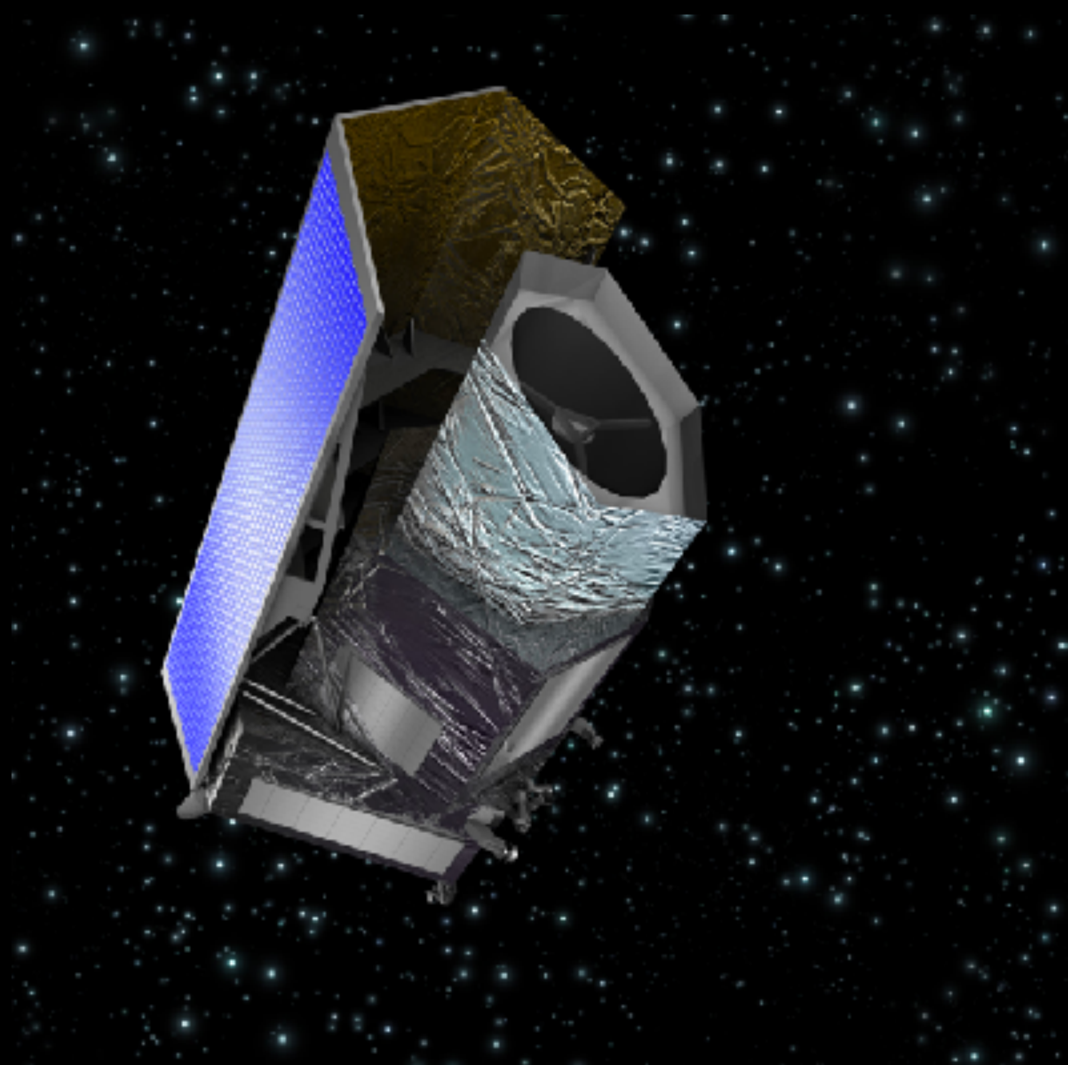
Image Release
July 2013

The largest camera in Space for the 1.2m Euclid Space Mission

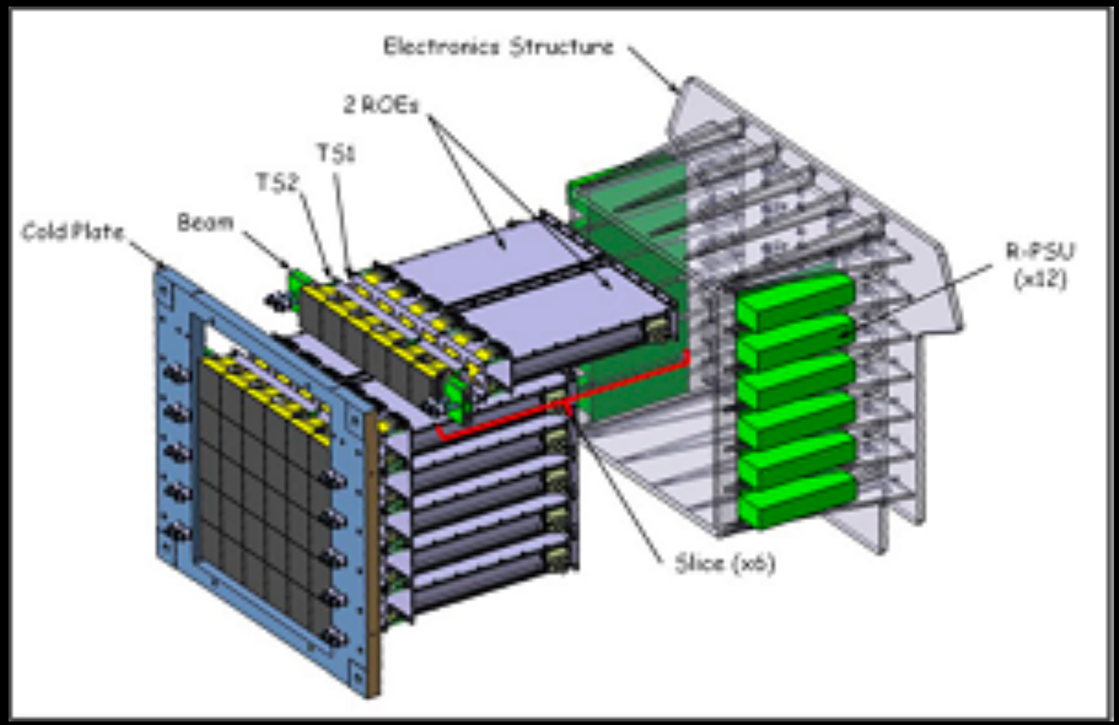
36 4k x 4k CCD detectors => 576 MPixel Camera

https://www.euclid-ec.org/





Launch this July 2023 !!!



The largest ever Camera constructed for the 8.4m LSST

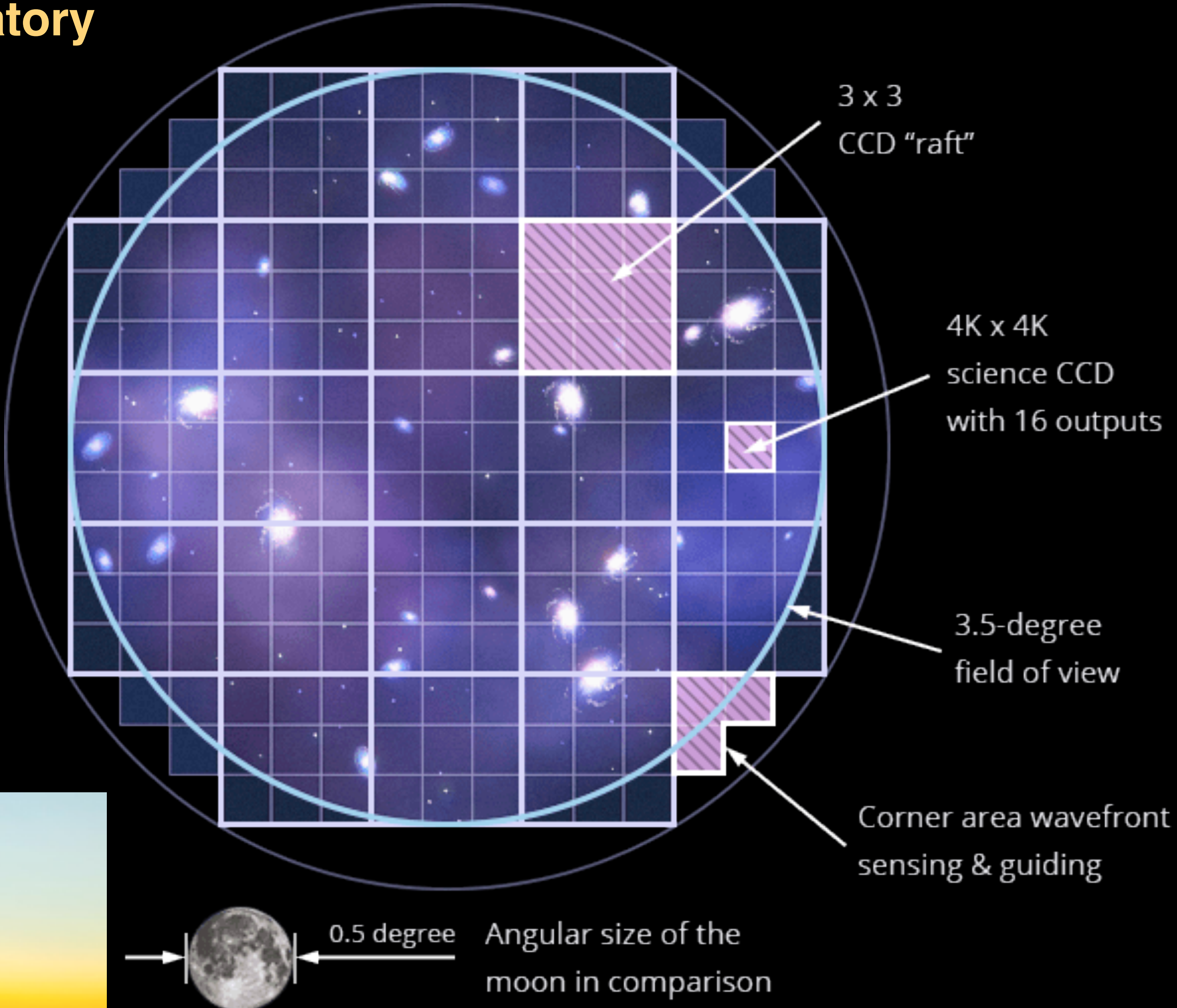
201 4k x 4k CCD detectors => 3.2 GPixel Camera

Renamed: the **Vera Rubin Observatory**

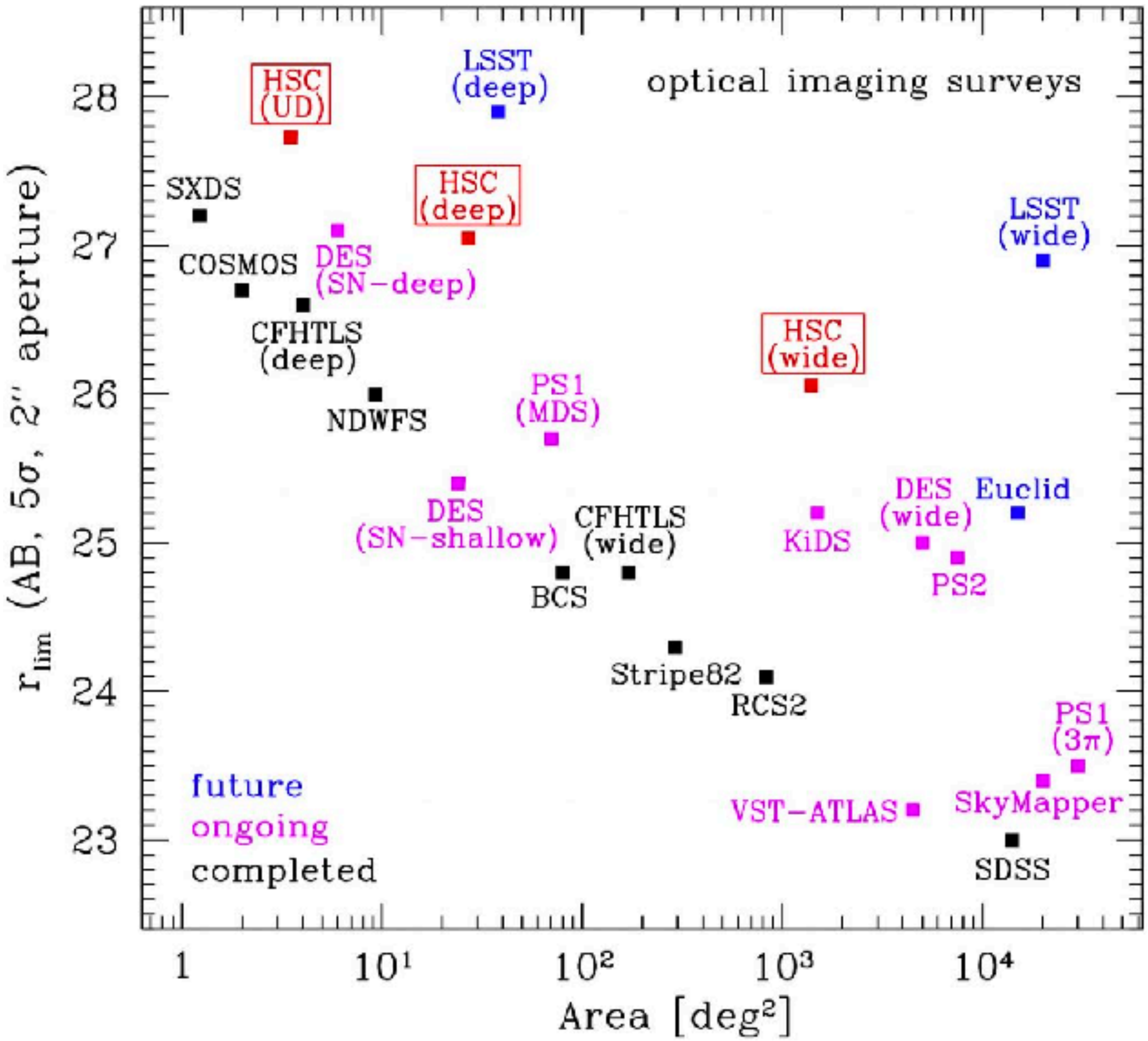
https://www.lsst.org/

First light in July 2024 !!!

Picture as April 2021



Weak Lensing Surveys



Outline

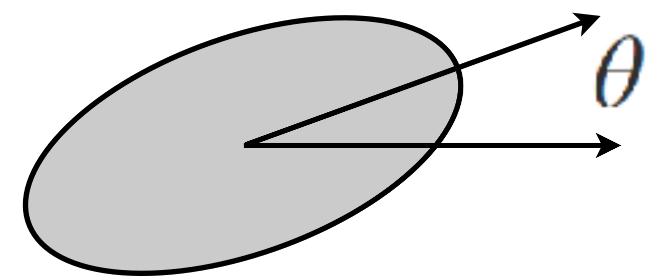
- Weak Lensing
- Modelling strategy of strong lens systems (focusing on cluster of galaxies)

Weak Lensing Basics

Weak Lensing

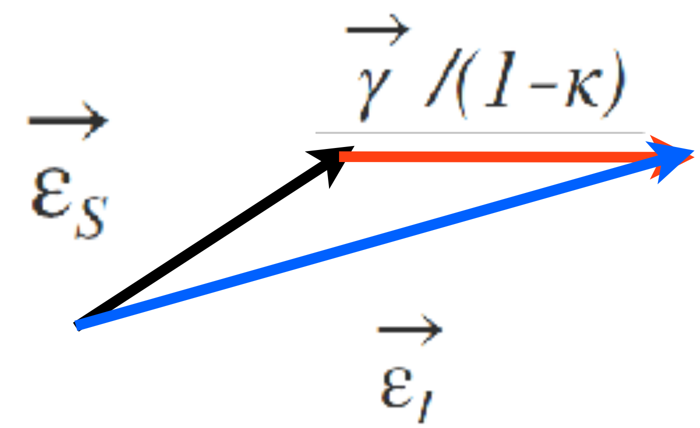
$$\varepsilon = \frac{a-b}{a+b}$$

- Background galaxies are distorted.
- To first order mass distribution is “shearing” the shape of a galaxy:
- a circle becomes an ellipse
- an ellipse is transformed in an other ellipse
- Can define a vector transform:



$$\vec{\varepsilon} = \begin{pmatrix} \varepsilon_1 = \varepsilon .\sin 2\theta \\ \varepsilon_2 = \varepsilon .\cos 2\theta \end{pmatrix}$$

$$\vec{\varepsilon_I} = \vec{\varepsilon_S} + \frac{\vec{\gamma}}{1-\kappa}$$



Weak Lensing

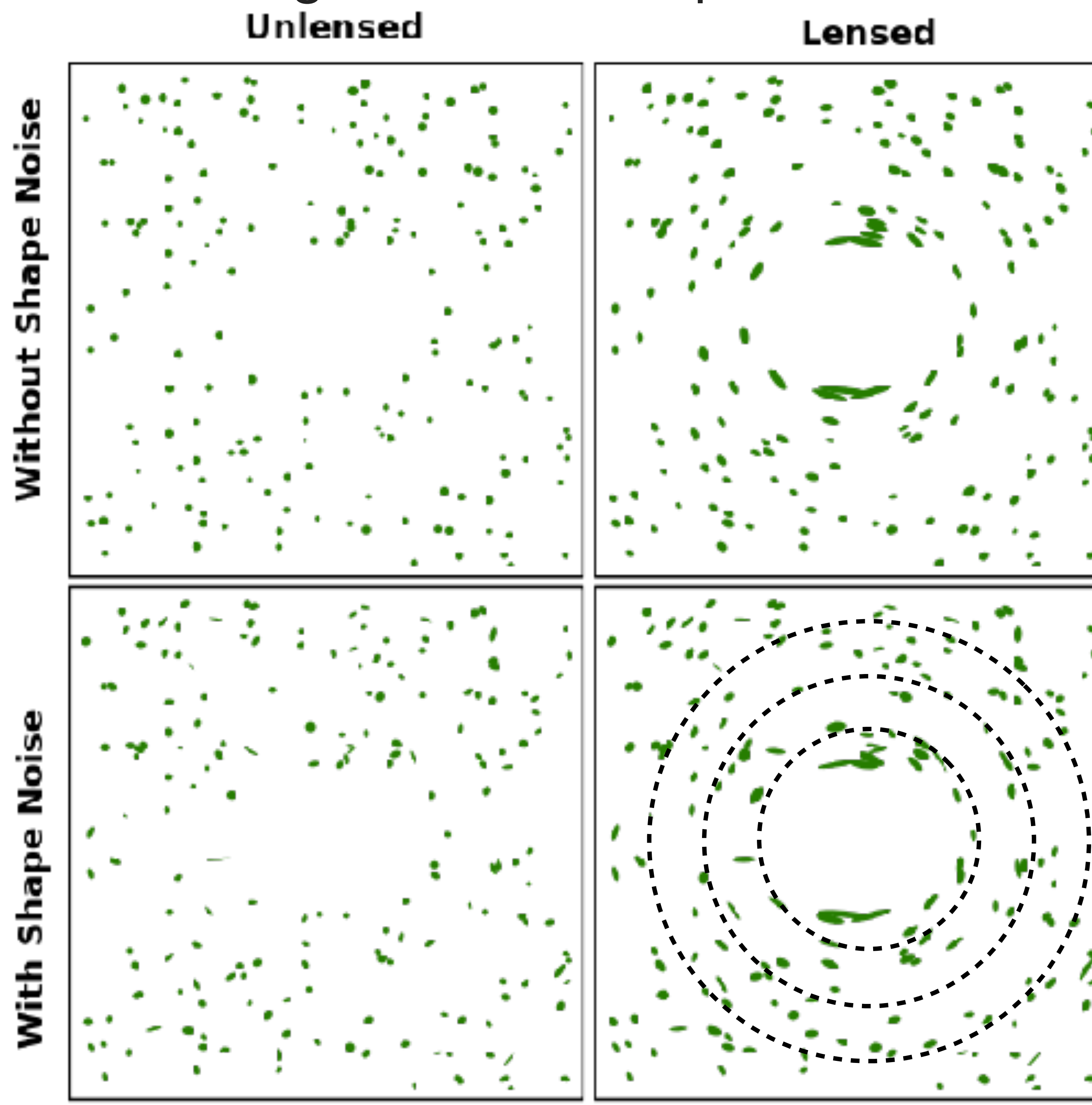
- Averaging over a number of galaxies and assuming the source ellipticities are randomly distributed:

$$< \vec{\varepsilon_I} > = \vec{0} + < \vec{\gamma} /(1-\kappa) >$$

- For a singular isothermal sphere:

$$\kappa(r) \sim \frac{1}{r}$$

$$\gamma(r) \sim \frac{1}{r}$$

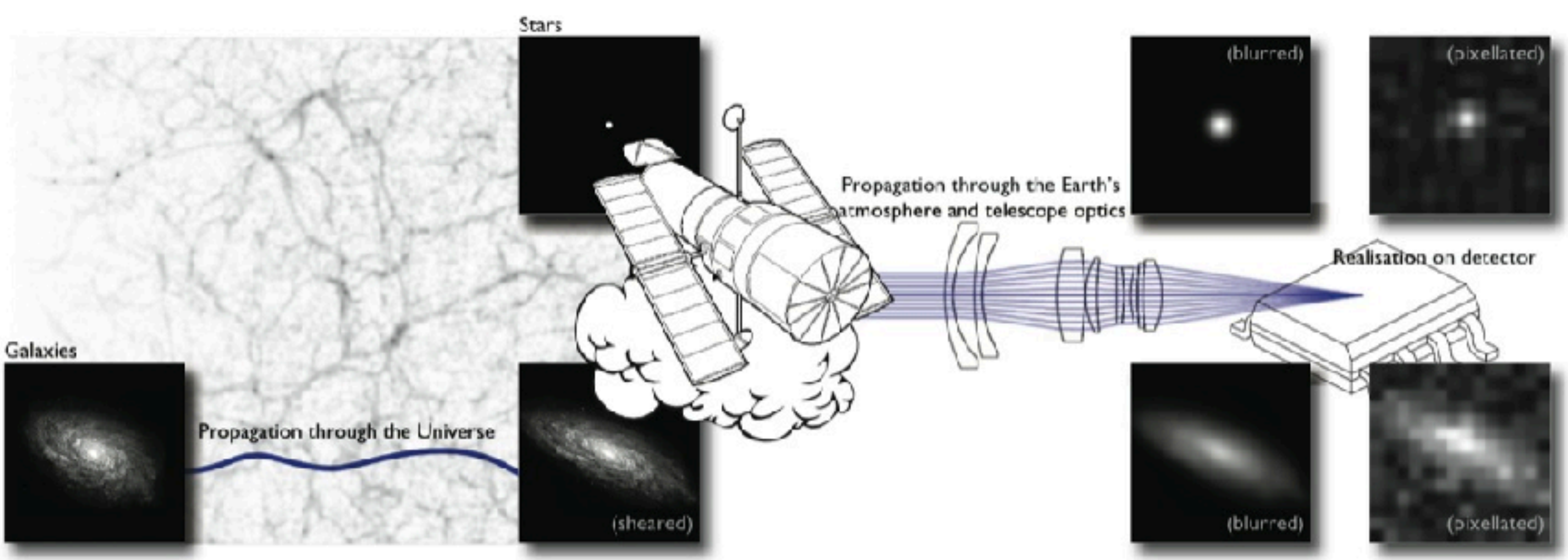


Weak Lensing measurements

- The challenge in weak lensing is to measure the ellipticities of galaxies with no bias

- m is the multiplicative factor ($<10^{-3}$)
- C is the additive constant ($<10^{-6}$)

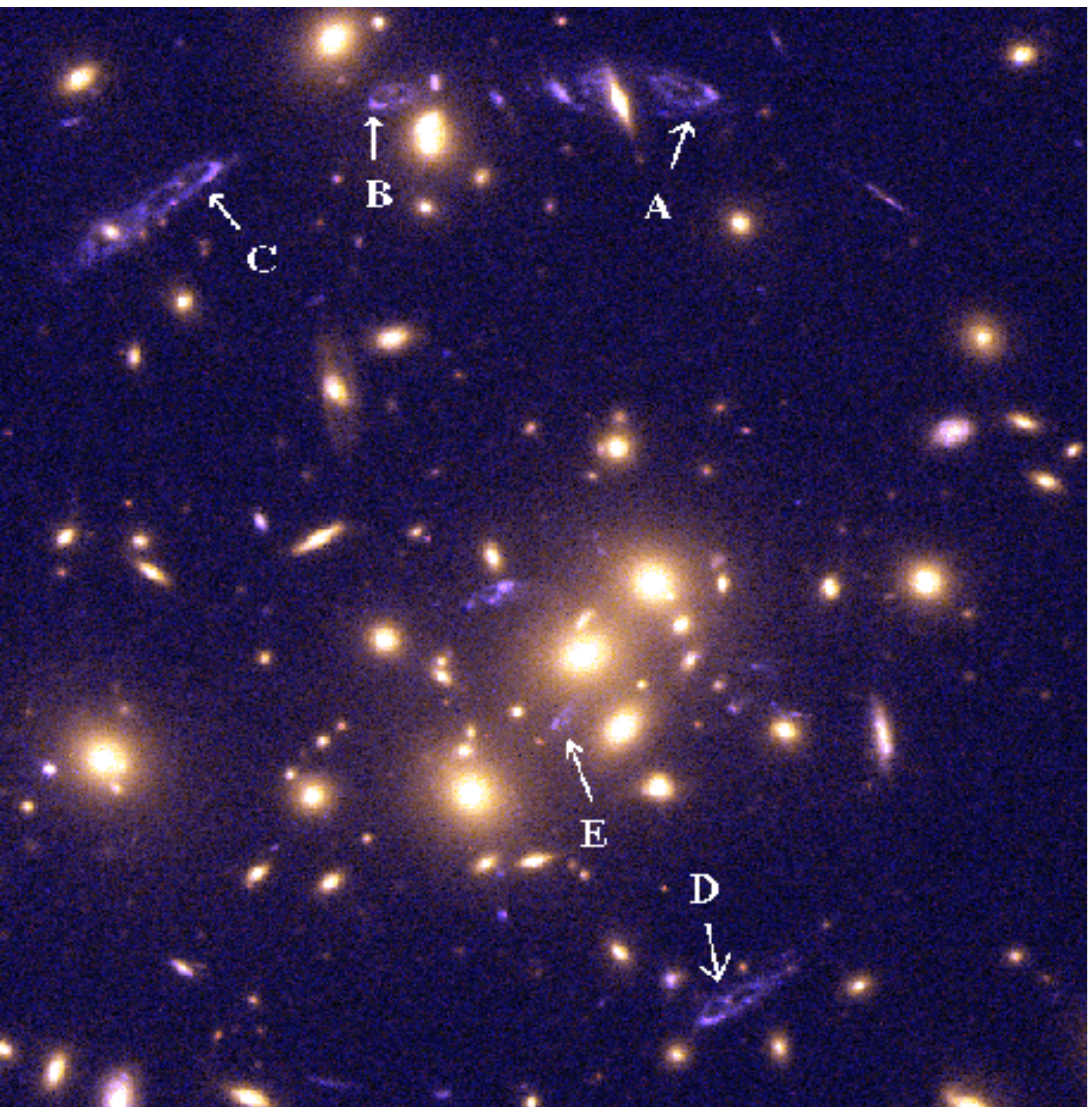
$$\varepsilon_{measured} - \varepsilon_{true} = m.\varepsilon_{true} + c$$

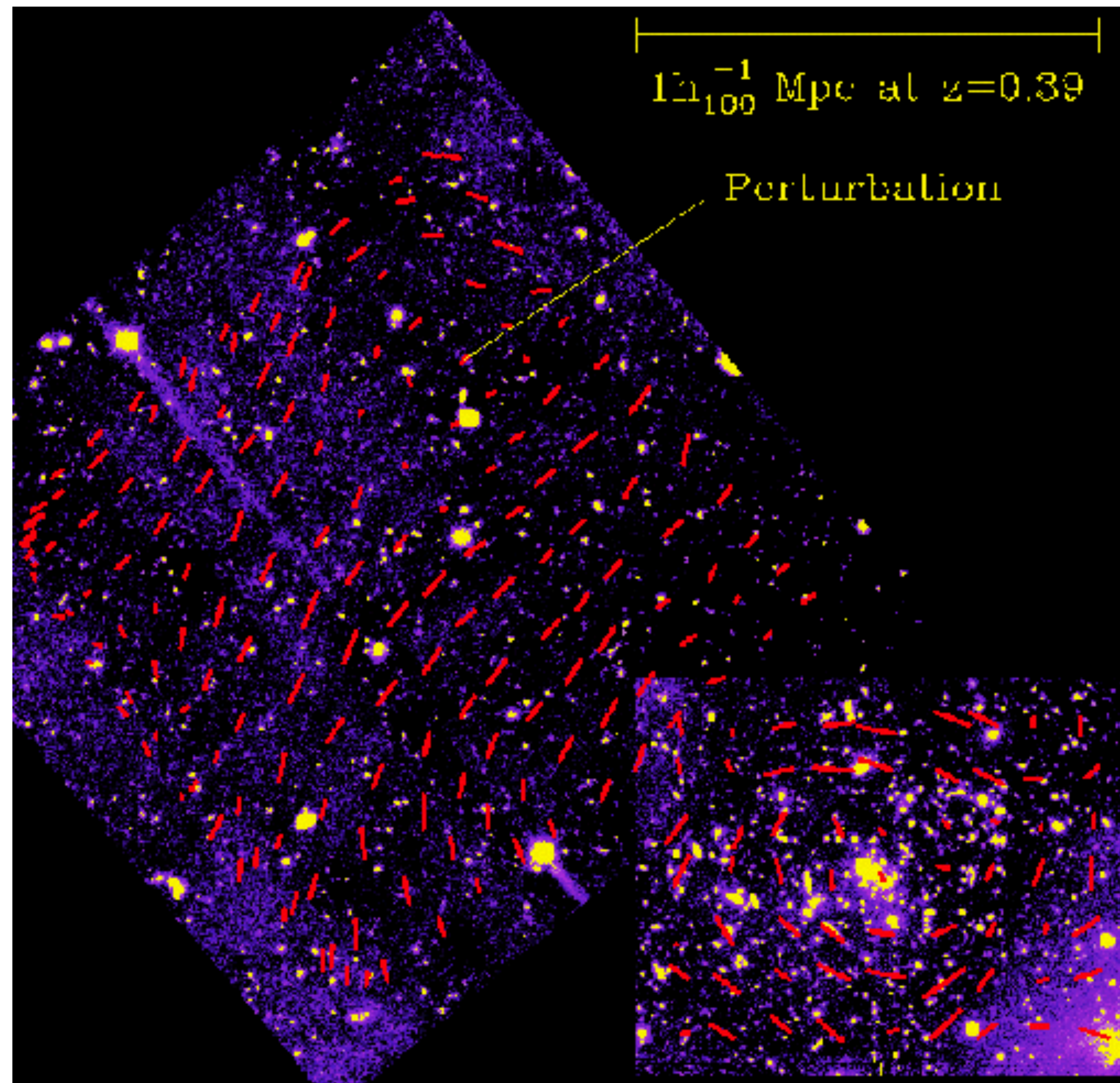


Coupling Strong and Weak Lensing

Absolute central mass

relative total mass and slope

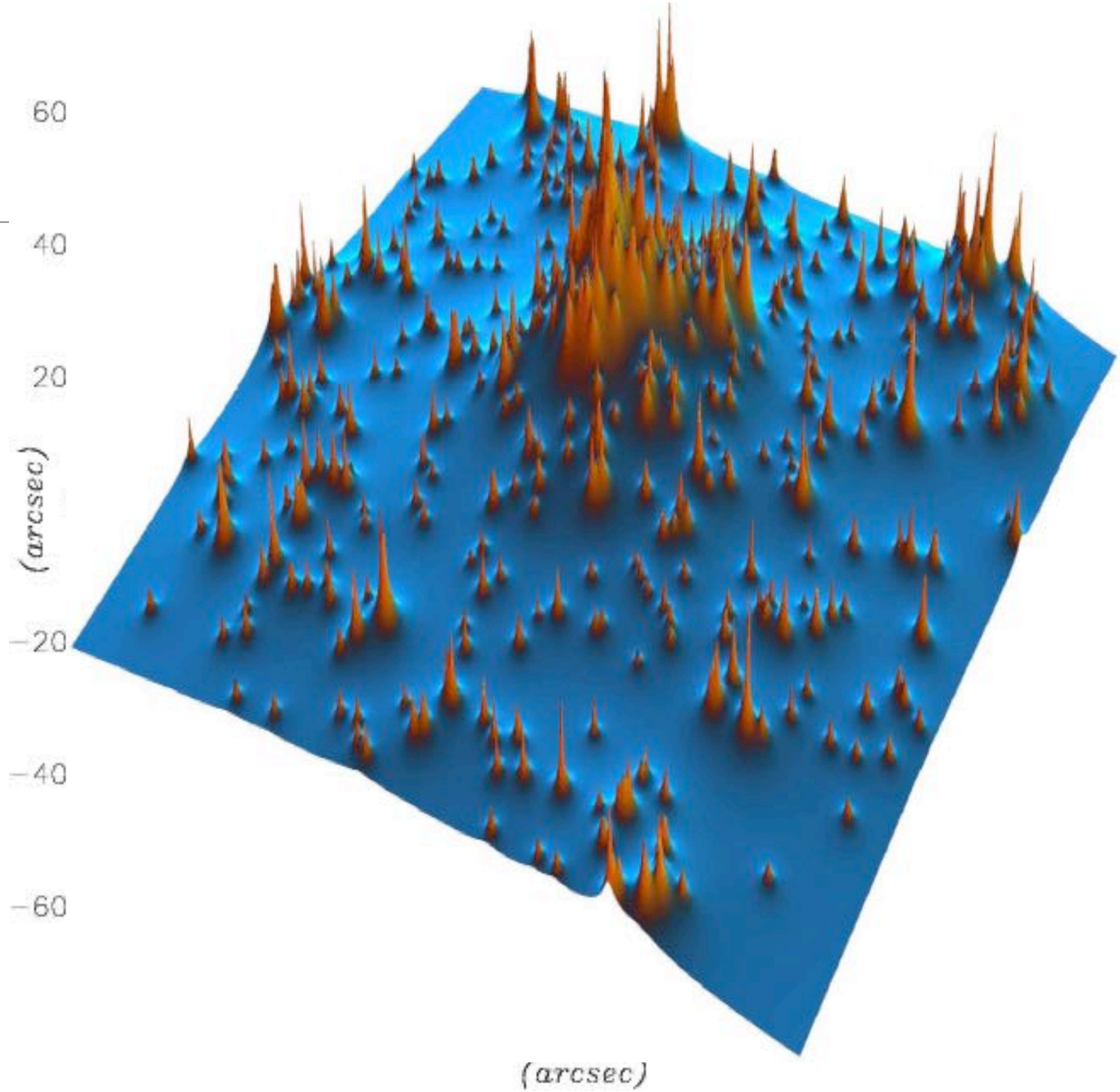




Cl0024+1654 HST wide field sparse mosaic

- **76 orbits, 38 pointings**
- **Probe regions up to ~5Mpc**

Aim: learn cluster physics of clusters by comparing with other mass estimates: X-ray, dynamics, learn on galaxy halo mass stripping



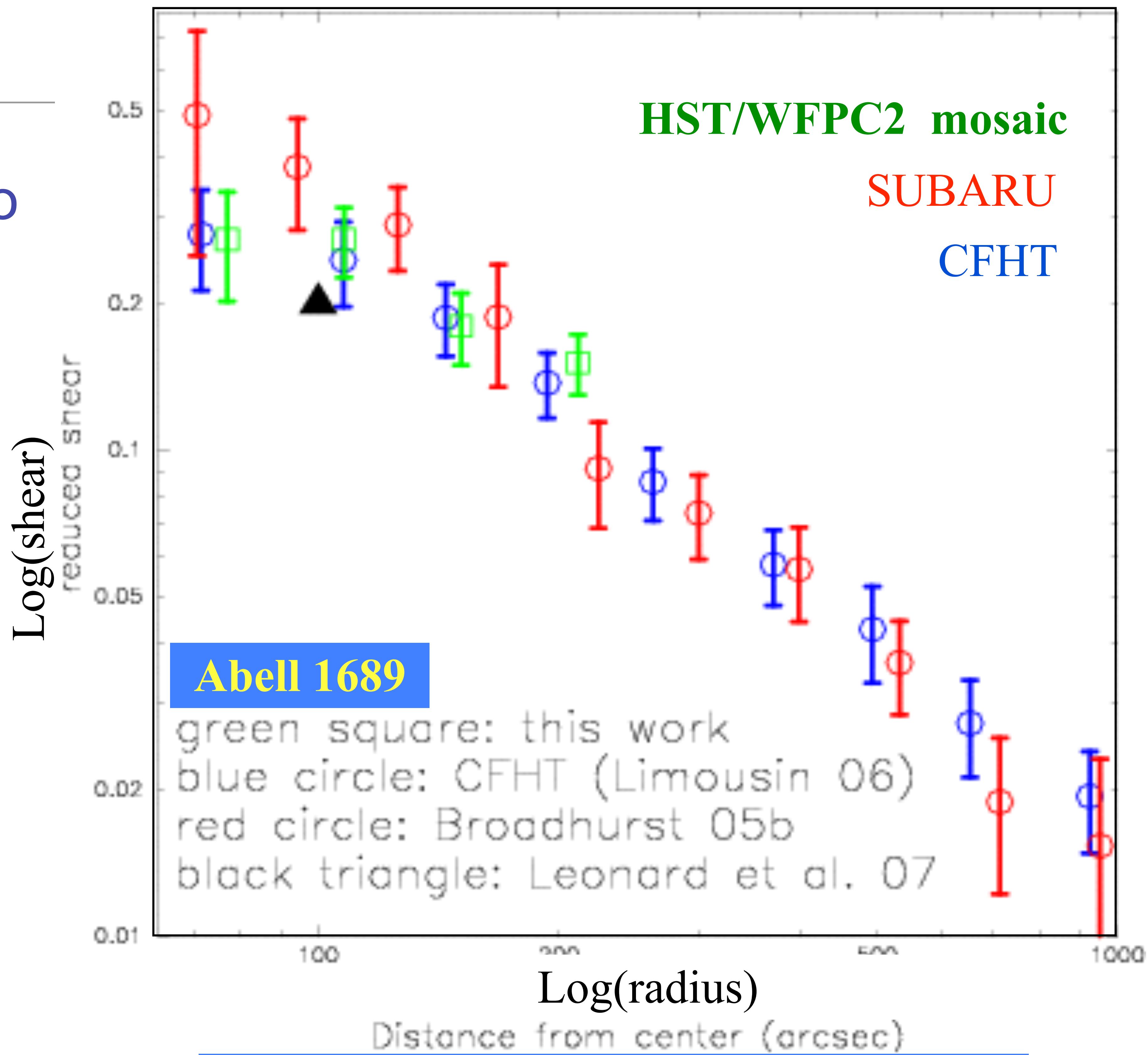
Treu et al 2003, Kneib et al 2003, Natarajan et al 2008

Mass Profile of Clusters (SL+WL)

- Background source selection is *critical* to accurately measure WL

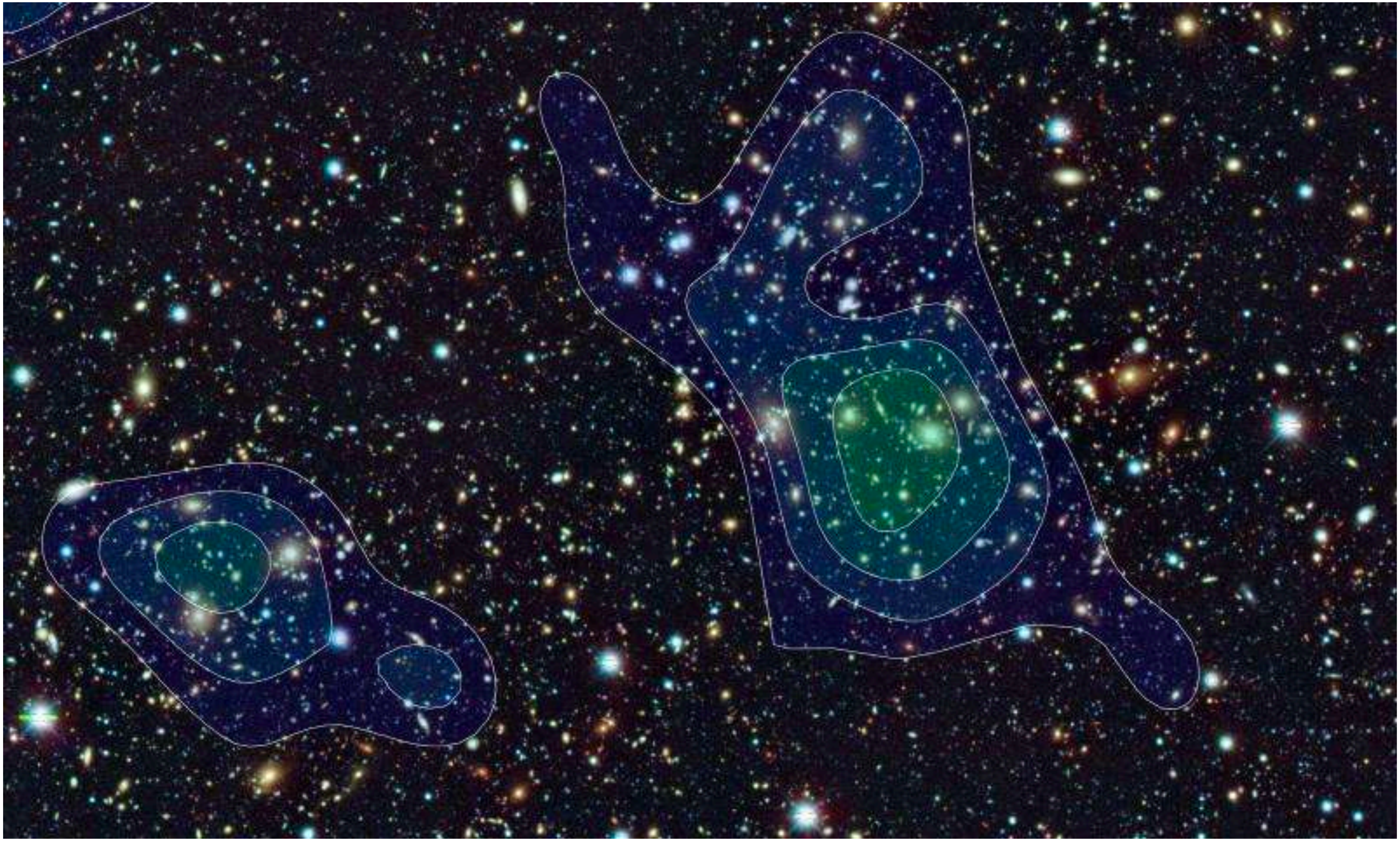
- Improved lensing constraints, revised concentration from c~15 to c~8

- Better agreement with numerical simulation predictions

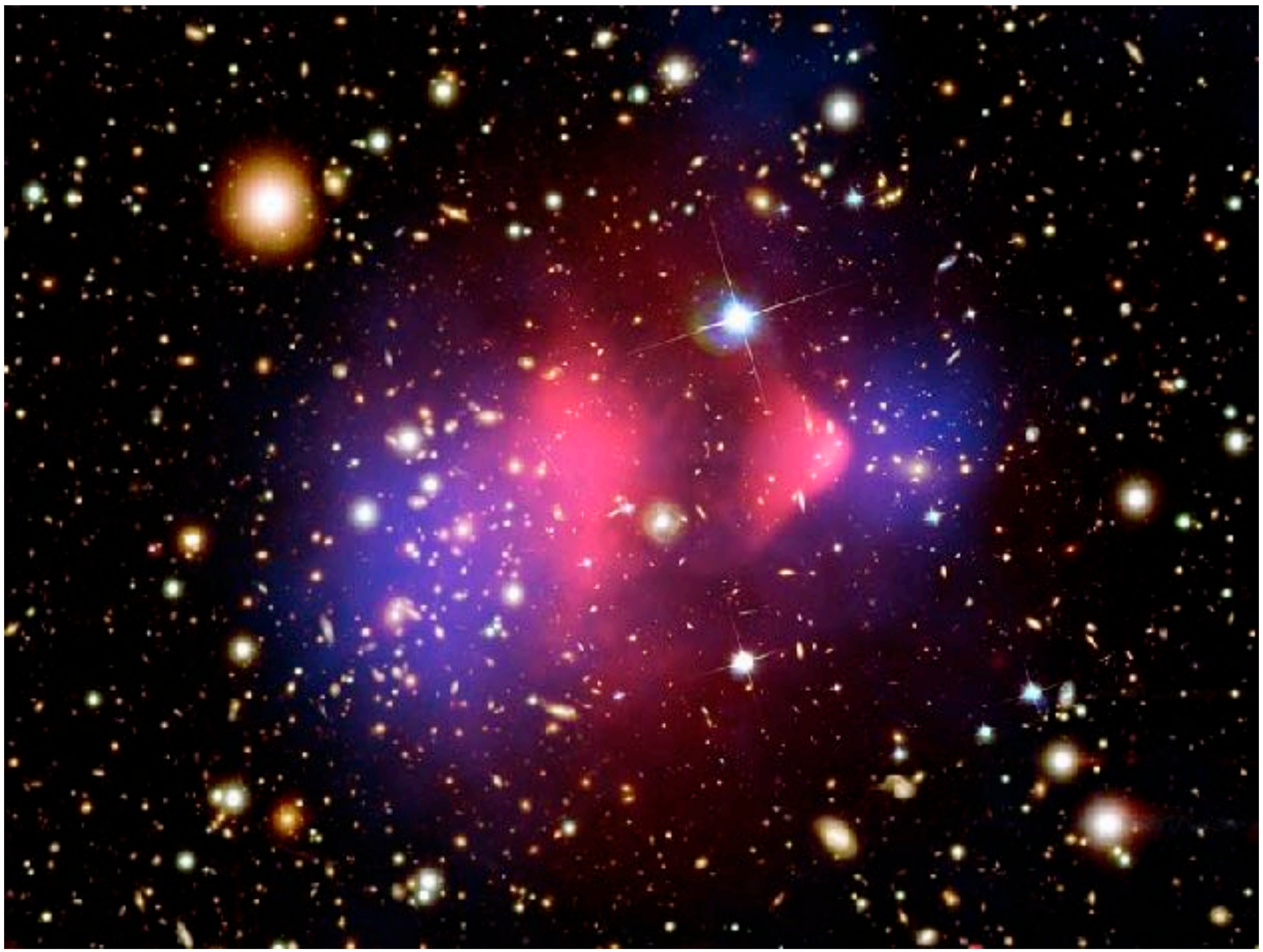


Limousin, et al. 2007, Dahle et al 2009

Weak lensing mass map
=> identify massive clusters



« Bullet Cluster »
unusually strong cluster mergers



1E0657 alias “the Bullet”

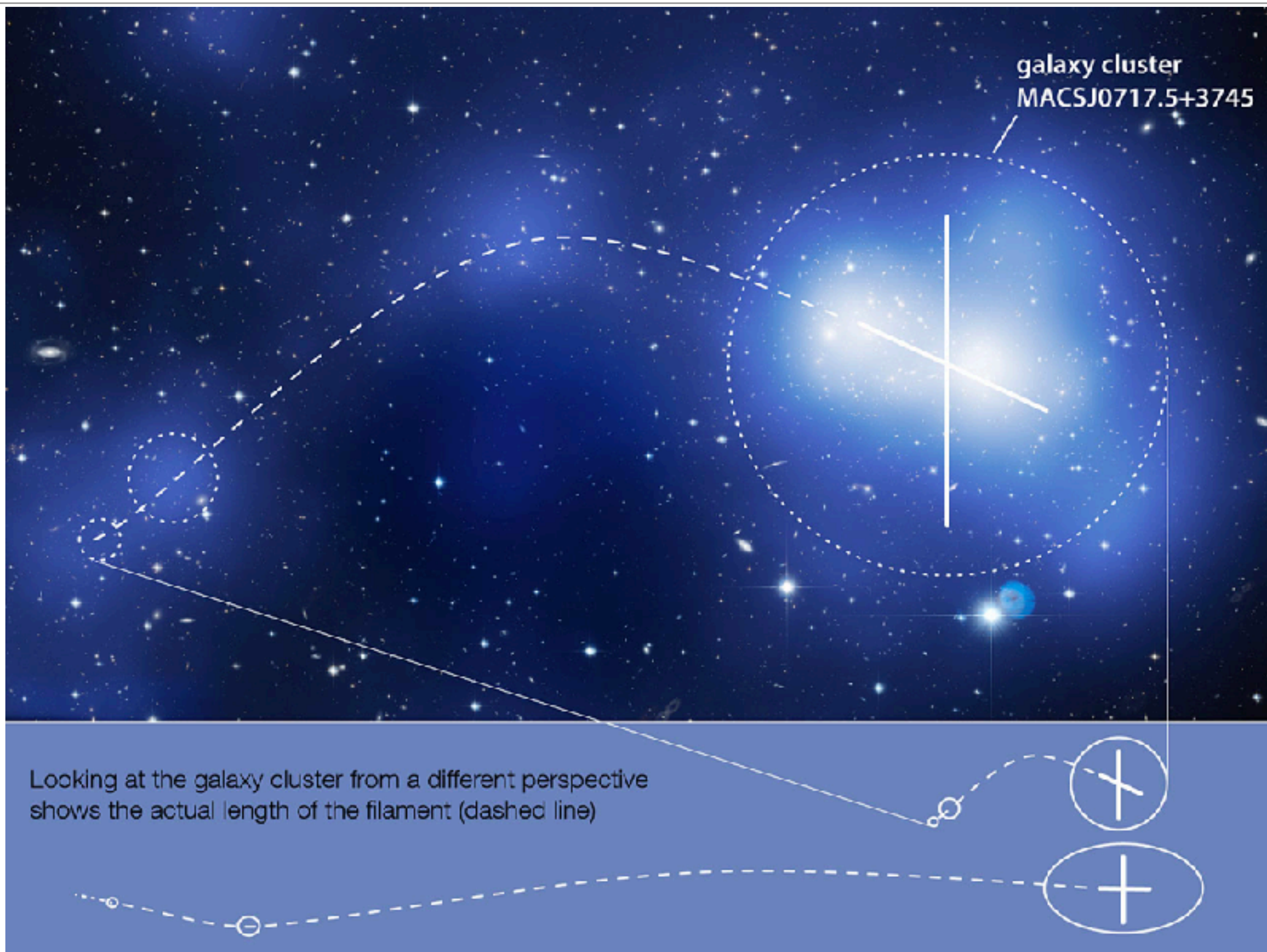
Clowe et al 2006,
Bradac et al 2006

- Encounter of 2 massive clusters
- Significant offset between X-ray gas and lensing mass peaks:

⇒ **best evidence for « collision-less dark matter »**
⇒ put constraints on DM/baryon interactions

Weak lensing filament detection

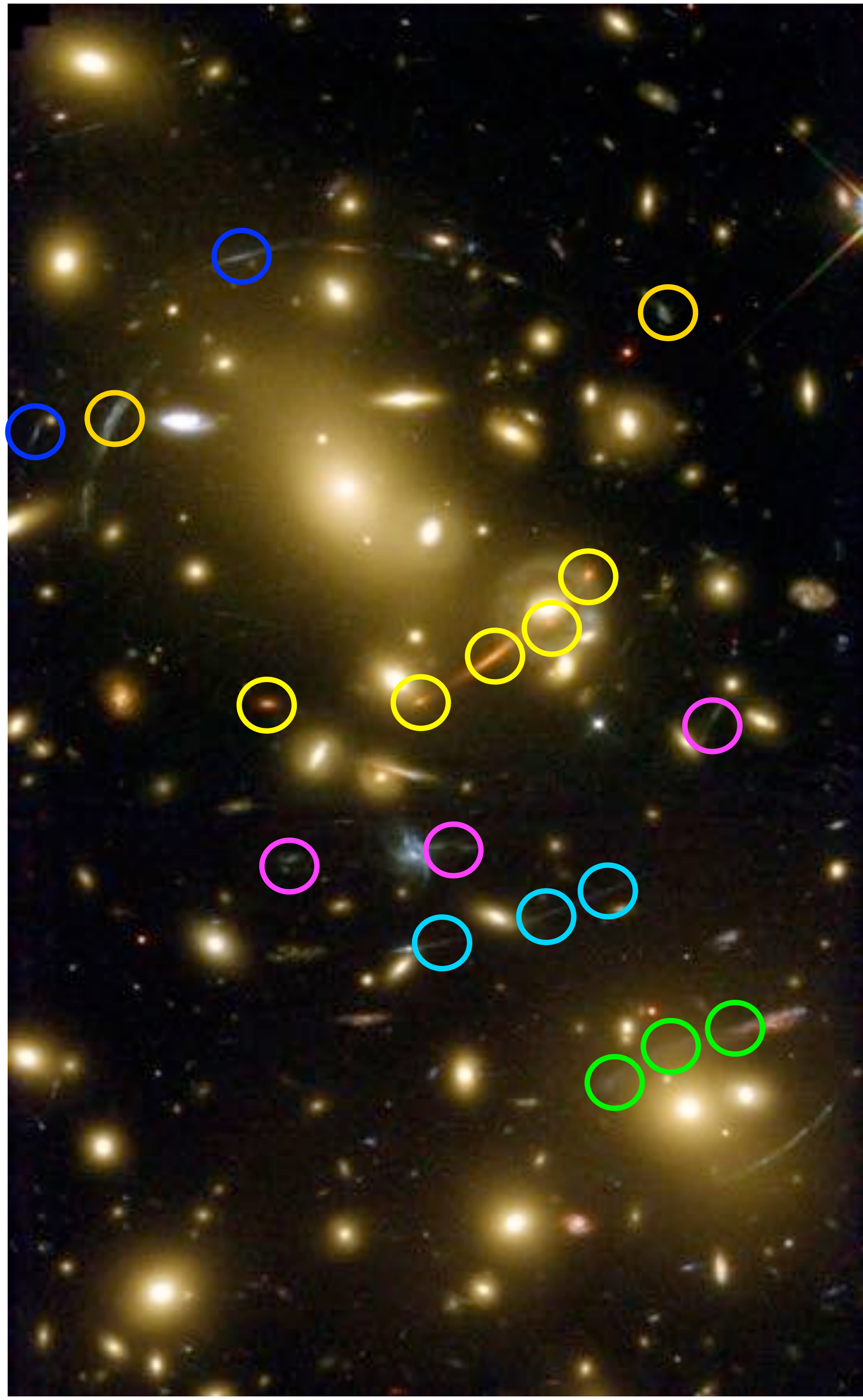
Jauzac et al 2012



Modeling Strong Lensing

SL Cluster Modeling and Errors

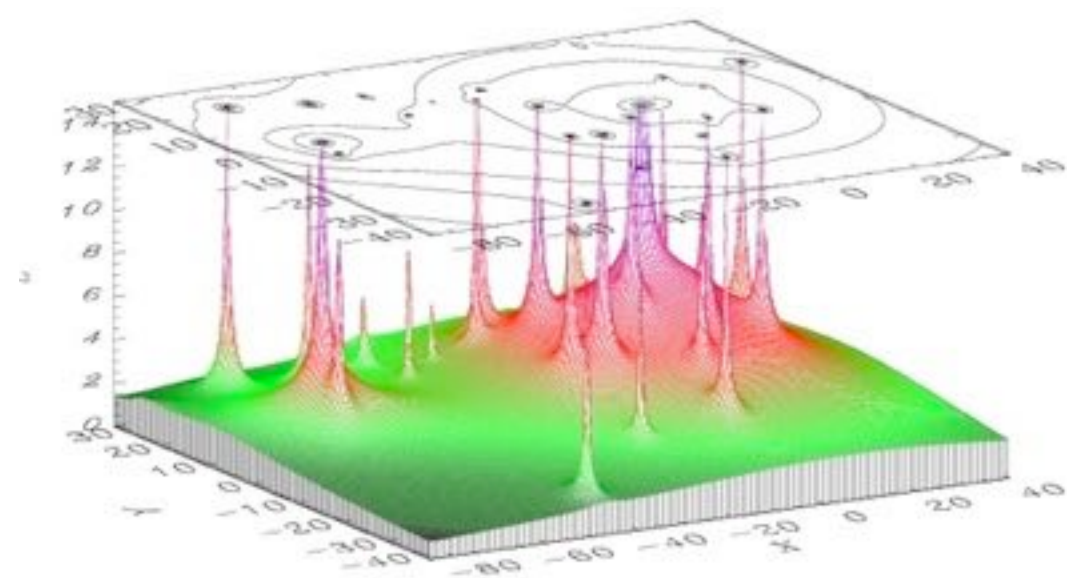
Abell 2218



Constraints:
- Multiple images (position, redshift, flux, shape)
- Single images with known redshift
- Light/X-ray gas distribution

Model parameterization
- Need to include **small scales**: galaxy halos (parametric form scaled with light)
- Large scale: DM/X-ray gas (parametric form or multi-scale grid)

Model optimization
- e.g. Bayesian approach (robust errors)
- Not a unique solution: "most likely model and errors"
- *Predict amplification value and errors => cluster as telescopes*

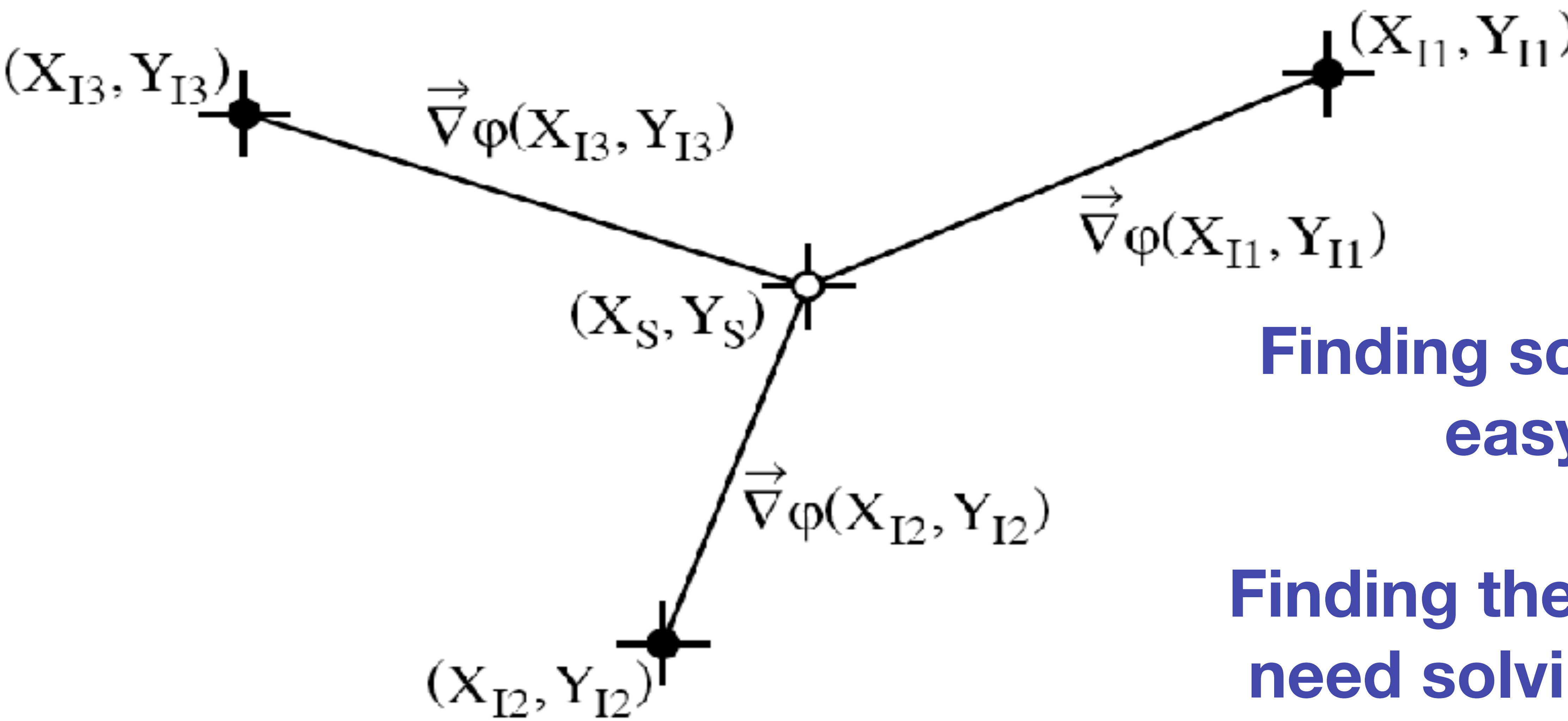


Jullo et al 2007, Jullo & Kneib 2009
***LENSTOOL* public software**
https://projets.lam.fr/projects/lenstool/wiki

Strong Lensing

Lensing equation have multiple solution (Strong lensing):

$$\theta_s = \theta_I - \nabla\varphi(\theta_I)$$

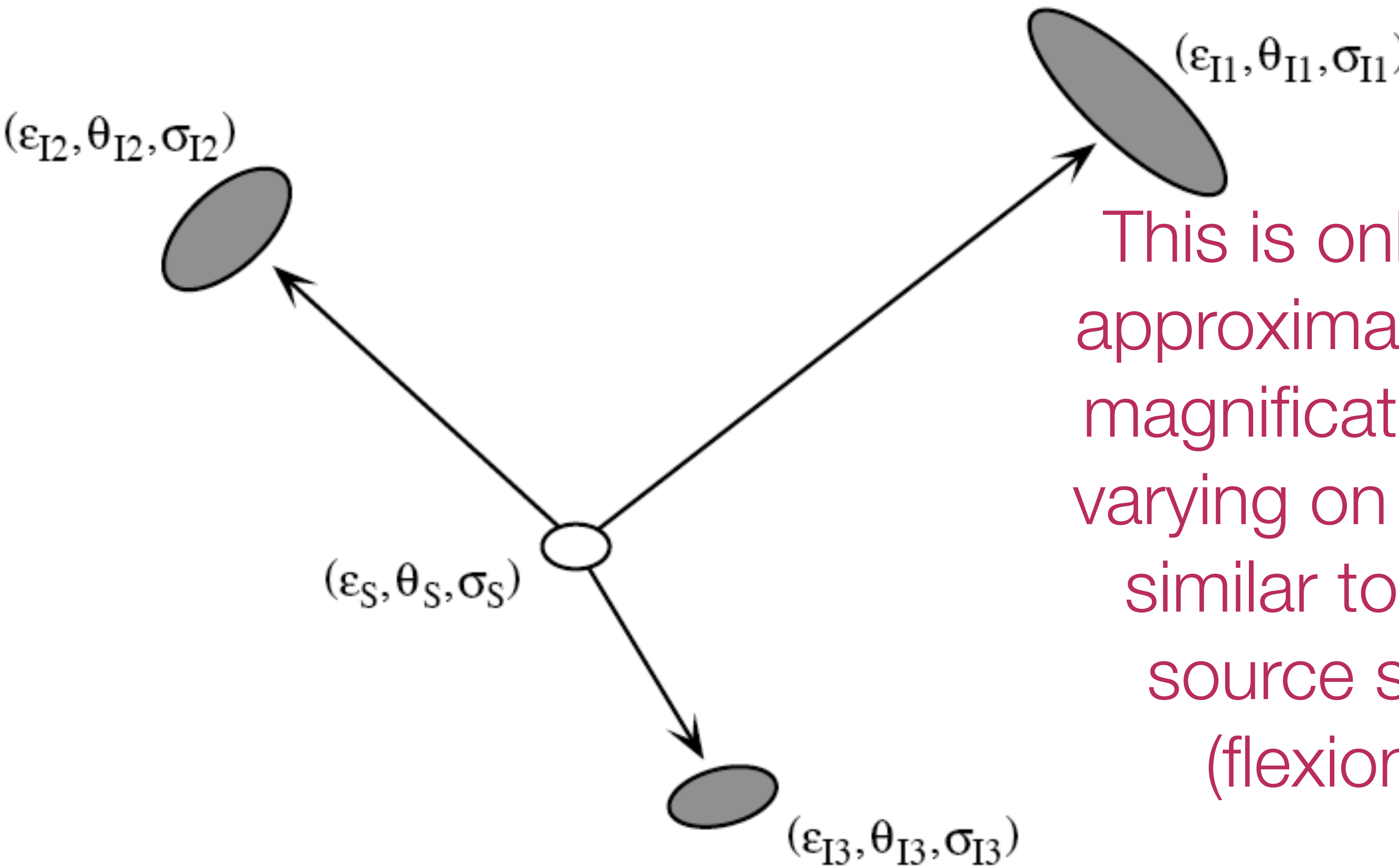


Finding source is easy!

Finding the images need solving a 2D equation (ray tracing)

Strong Lensing

Image shape are transformed depending on the local shear matrix



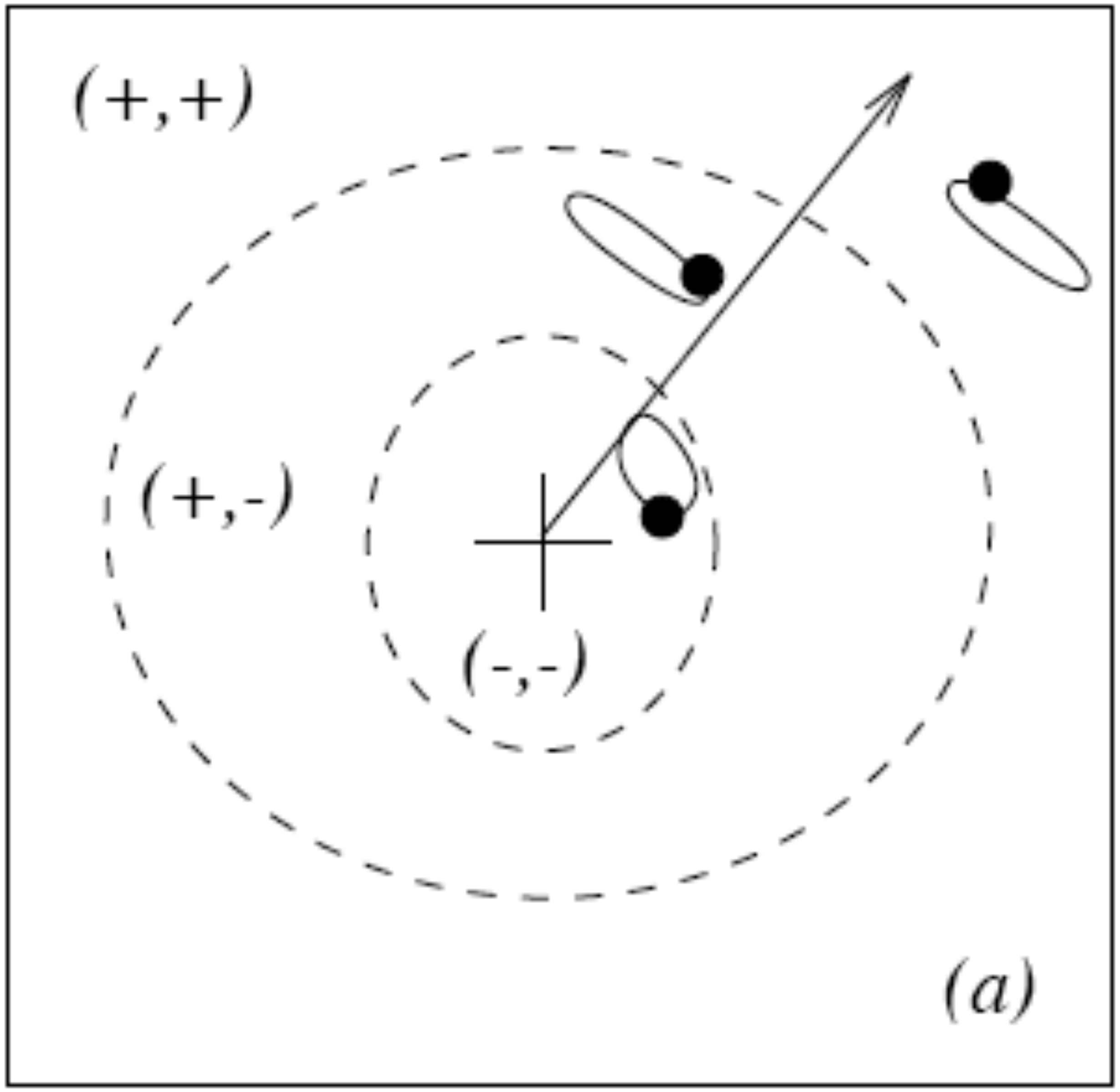
This is only an approximation if magnification is varying on scale similar to the source size (flexion)

Je

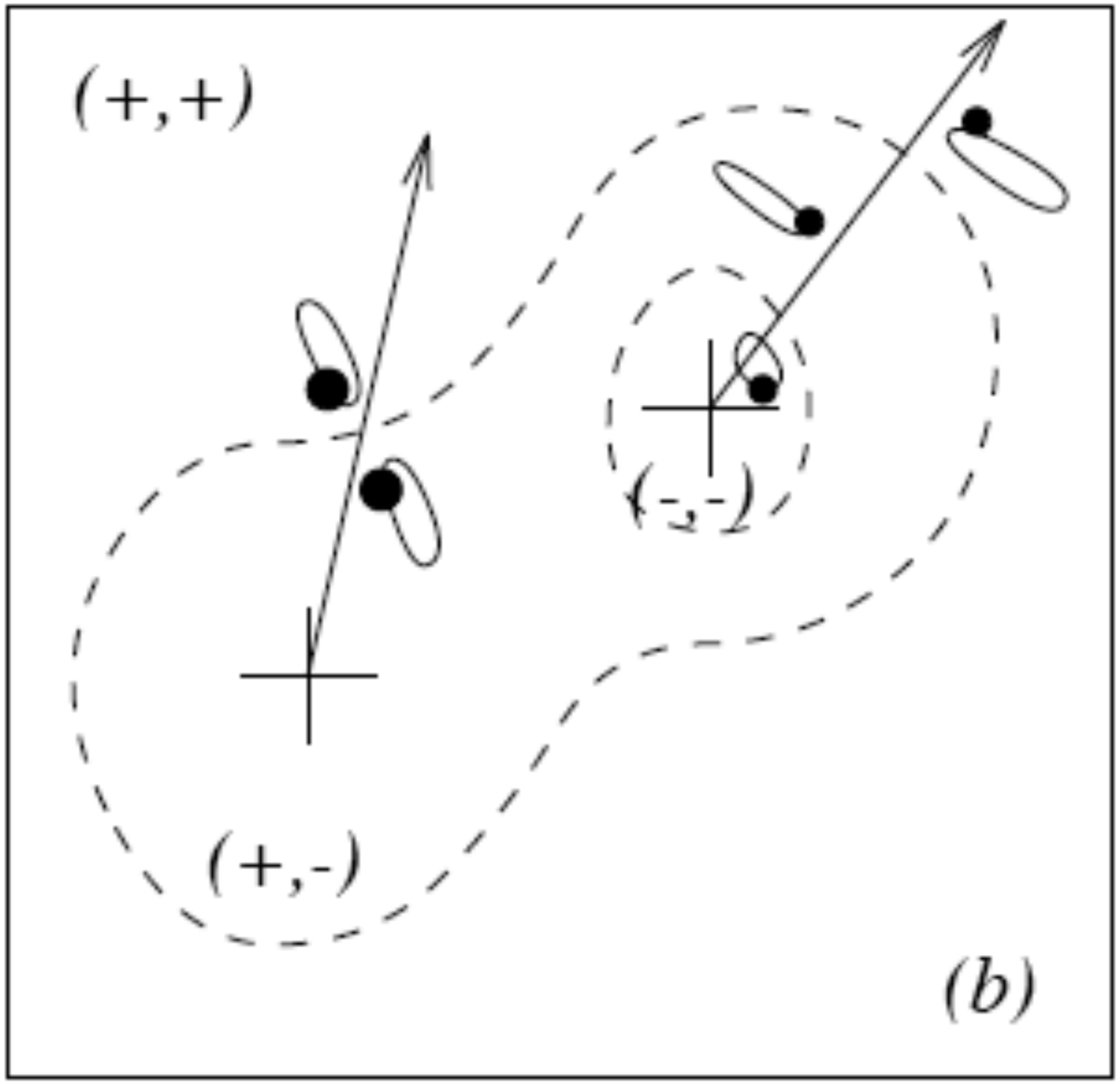
Strong Lensing

Image parity

Elliptical case



Bimodal case



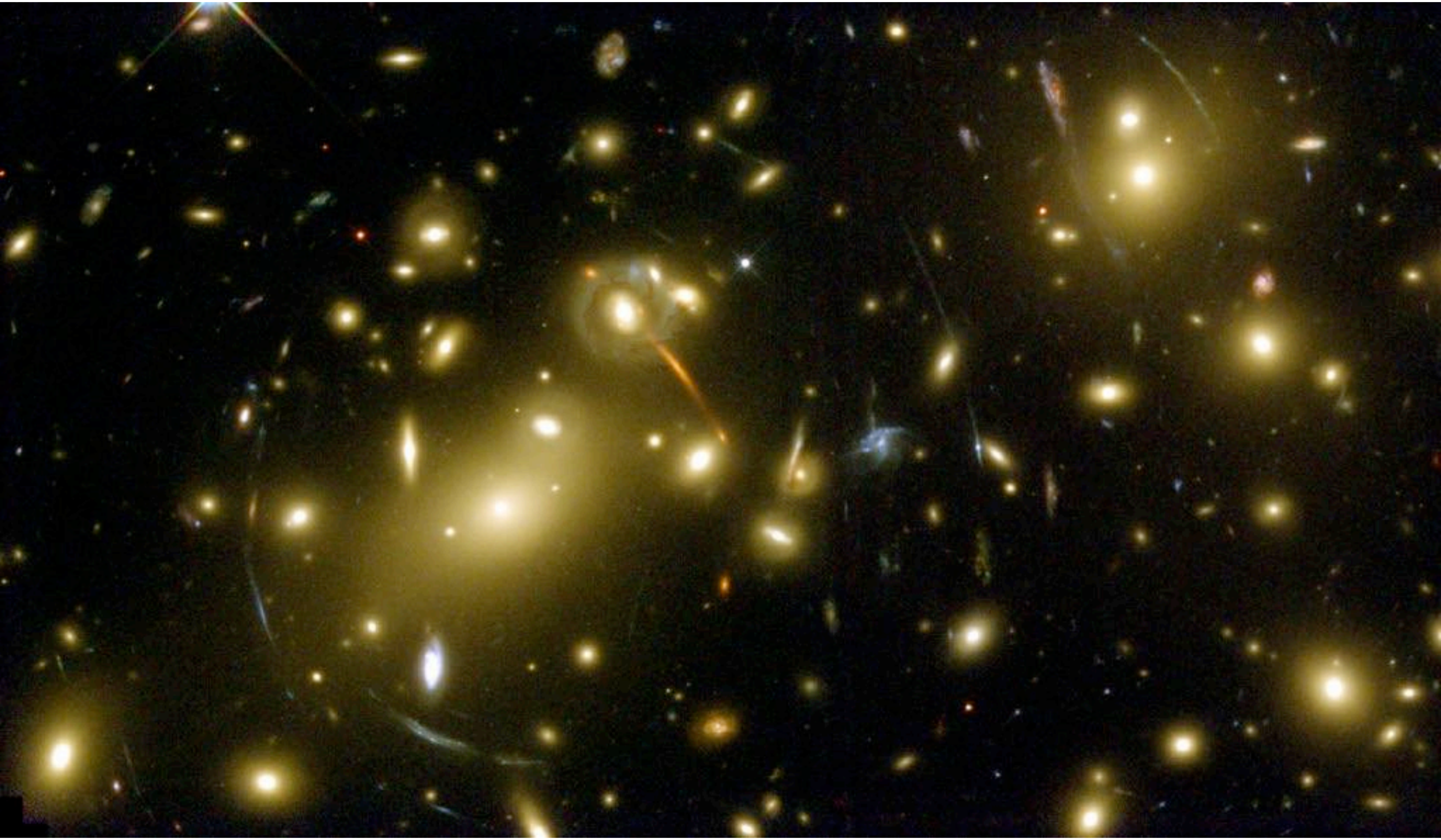
Modeling

- Finding Multiple images

Finding Multiple images

- Need GOOD (high-resolution) data
  - *Really this means HST quality data !*
- Morphology (should agree with rules of **image parity**)
- Color (could do from ground but hard)
- Spectroscopic confirmation (important for lensing strength)
- Modelling confirmation/finding
- Still missing an automatic software for multiple image identification! Human eye is still the best!

Best strong lensing data: *Hubble* (color) images

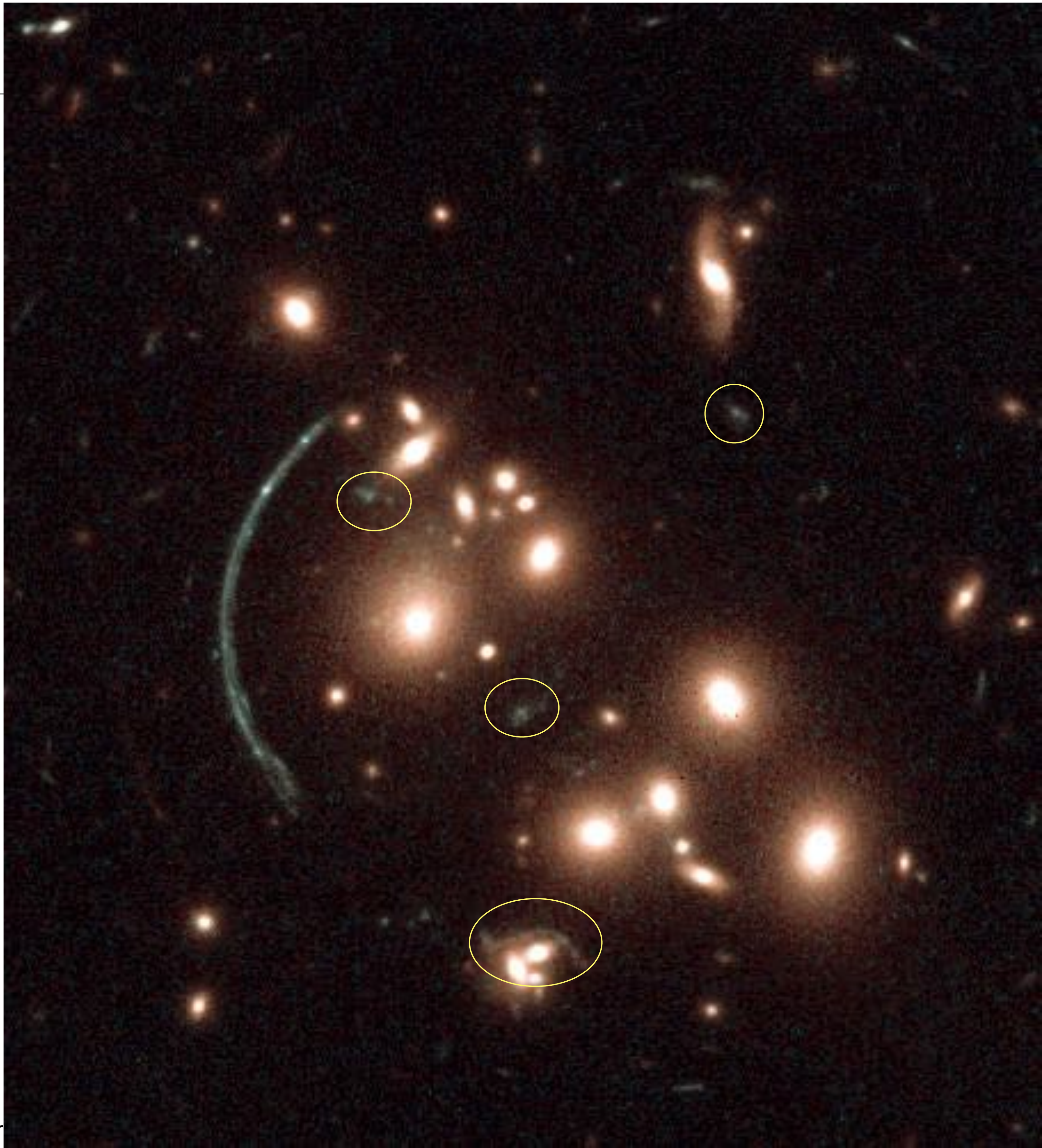


Abell 2218 at z=0.175

How to identify multiple images ?

Extreme distortion:
Giant arcs are the merging of 2 or 3 (or possibly more) multiple images

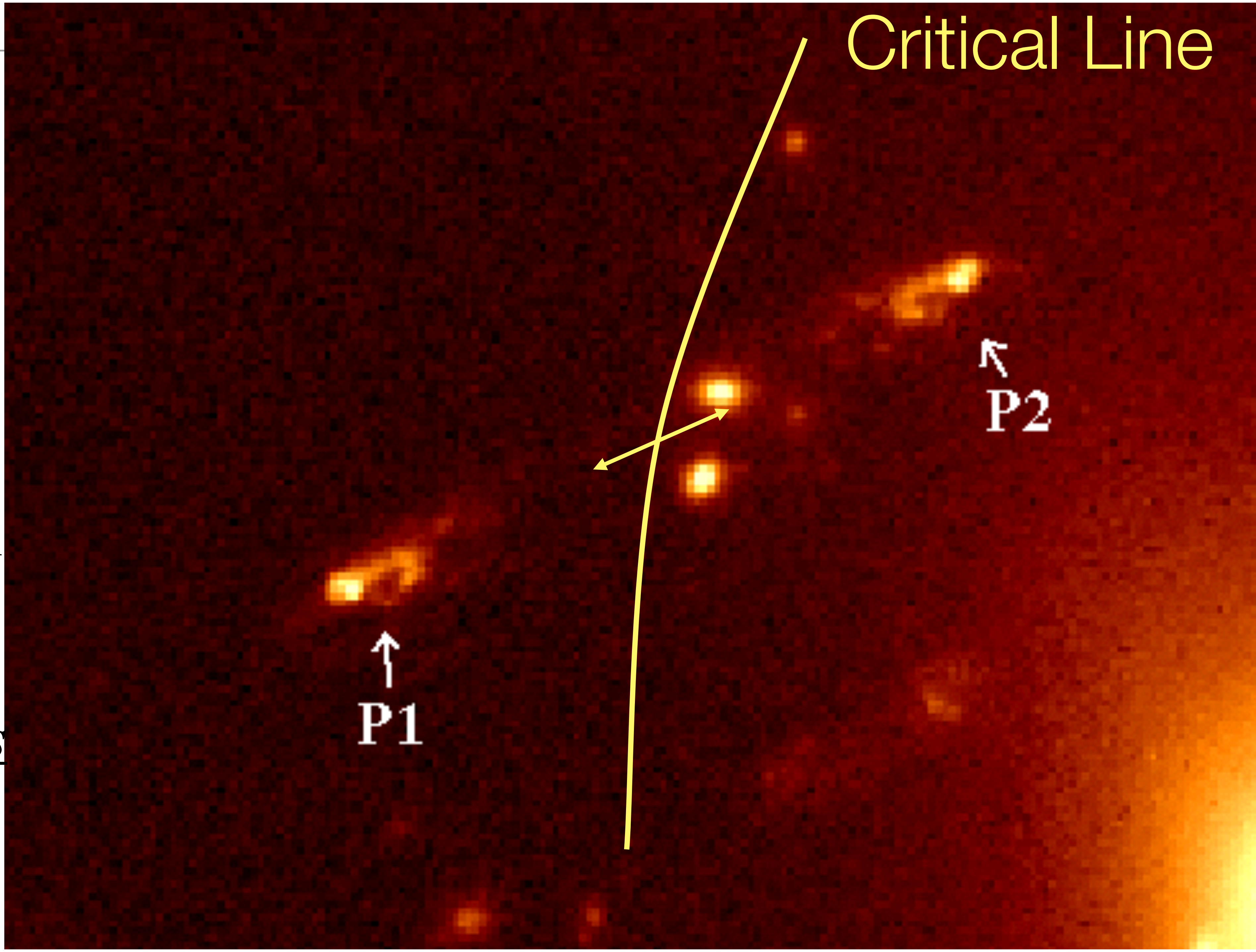
Giant arc in Cl2244-04, z=2.24, Septuple image



How to identify multiple images ?

Morphology: *Change of parity across a critical line.*

Note: lensing amplification is a gain in the angular size of the sources. Allow to *resolve distant sources* and study their size and morphologies.



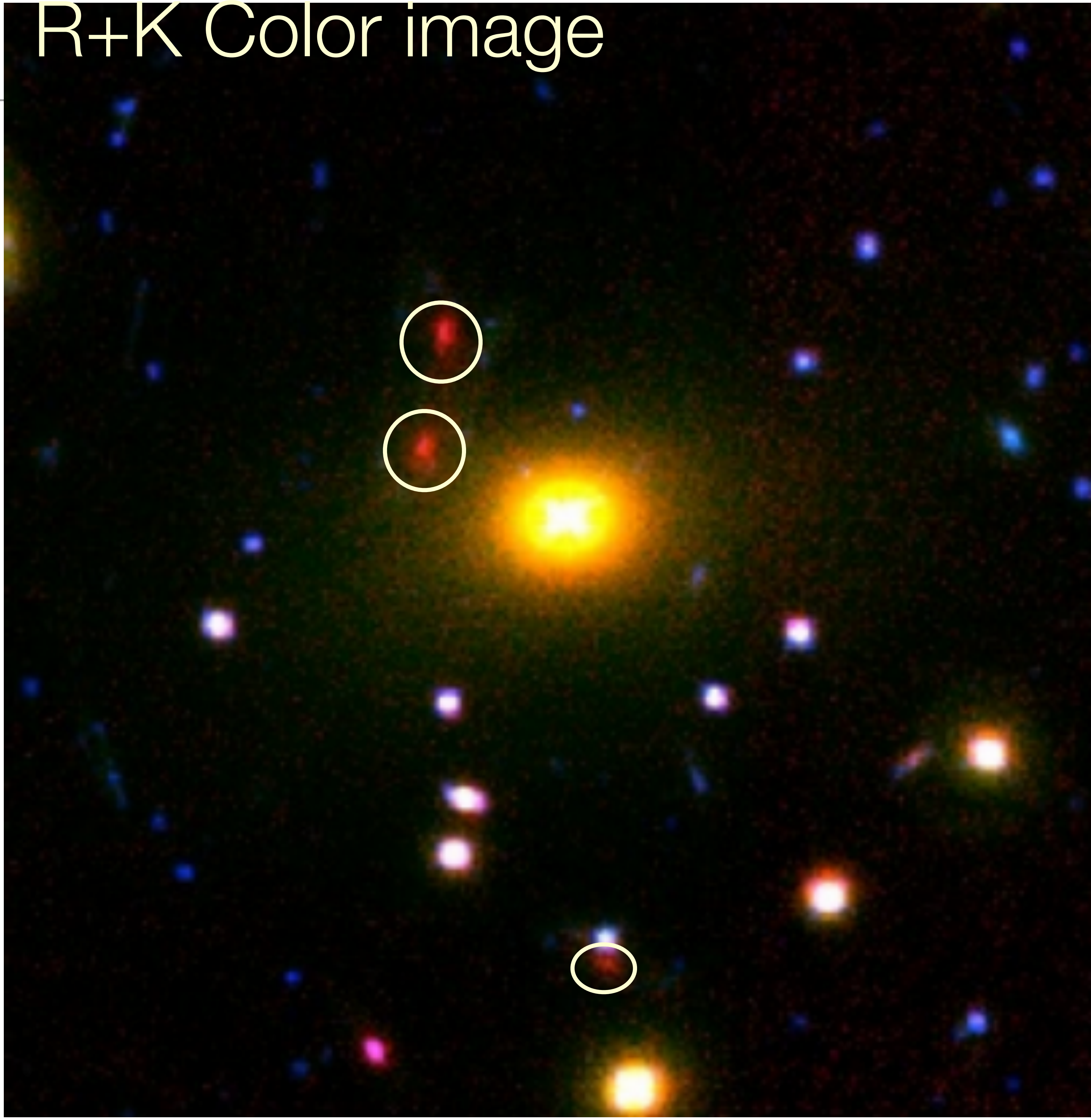
Lensed pair in AC114, z=1.86

How to identify multiple images ?

Extreme similar colors:

<u>Example</u> of a triple ERO system at z~1.6 (Smith et al 2002) lensed by Abell 68

Interest of magnification is to allow to resolved the morphology of these systems **(see Johan Richard presentation)**



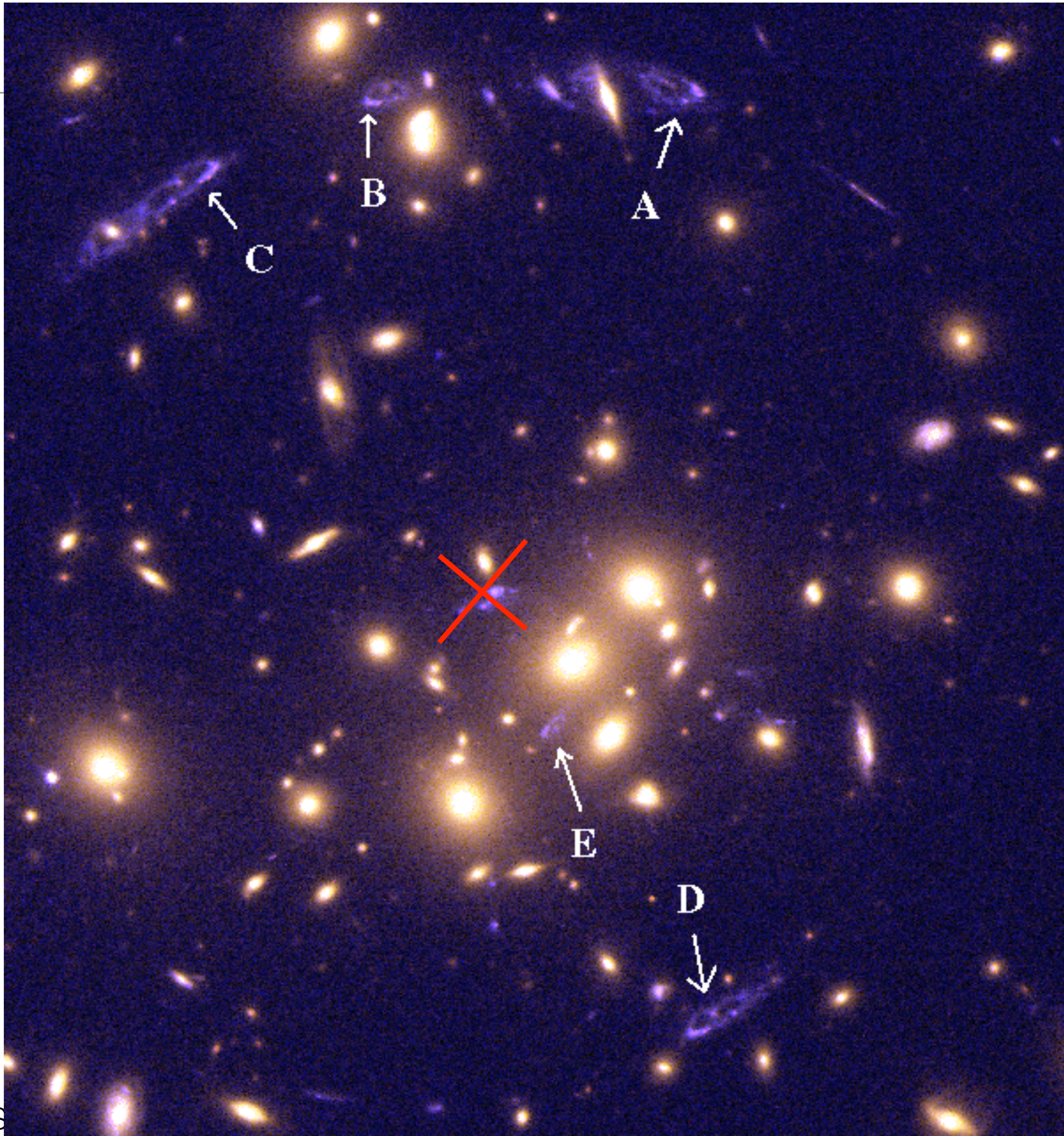
Abell 68: ERO triple image at z~1.6

How to identify multiple images ?

Color and Morphology:

Lens model can help for the identification when different solution are possible

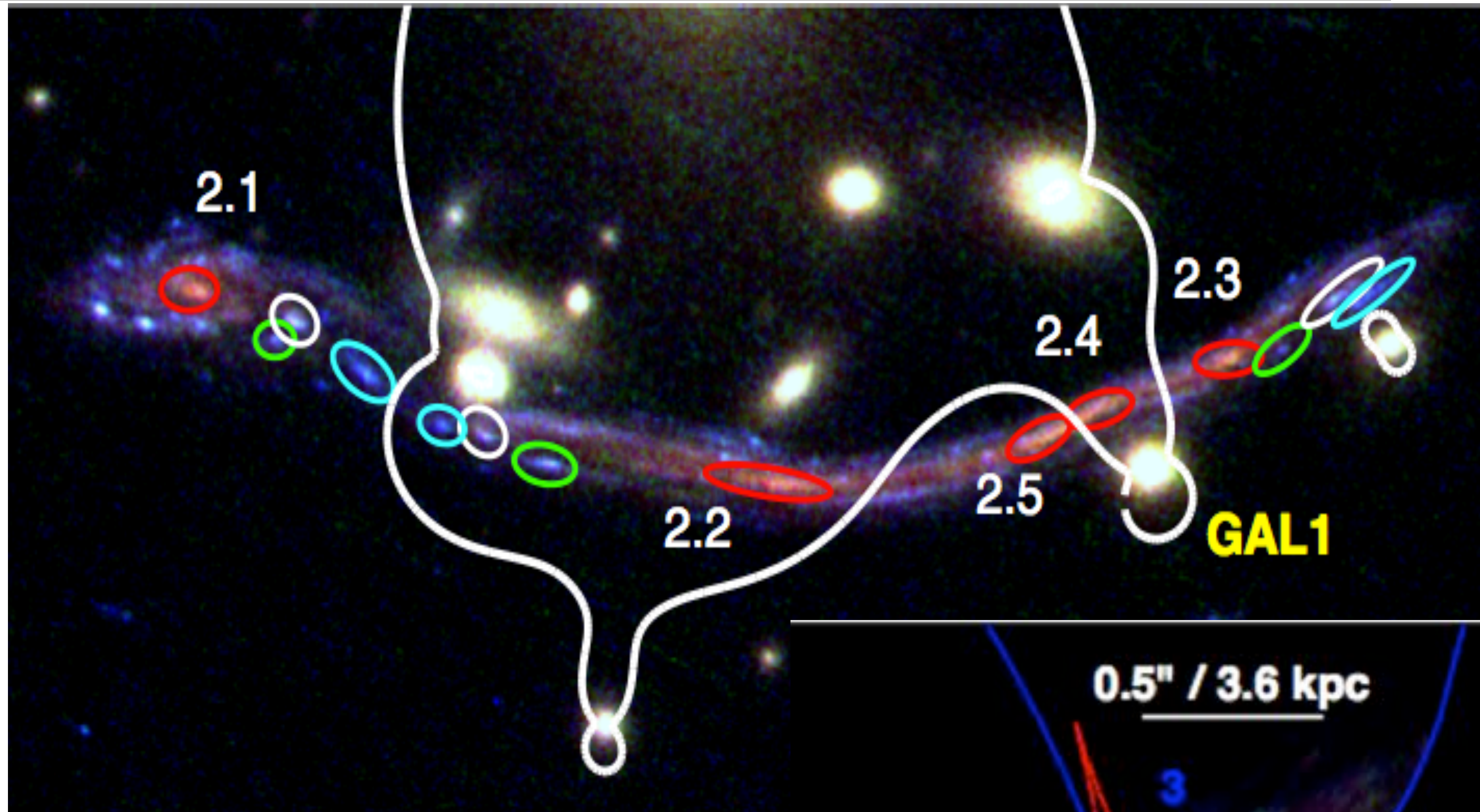
Quintuple arc (z=1.67) in Cl0024+1654 (z=0.39)

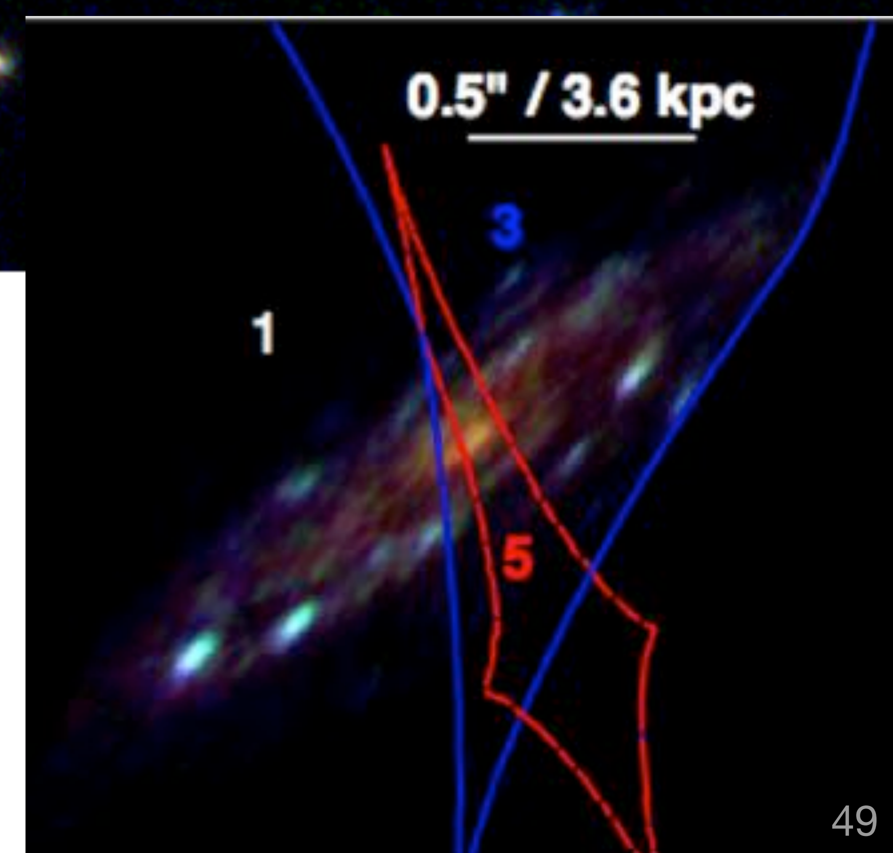


How to identify multiple images ?

Giant arc in Abell 370 by Richard et al., 2010

HST multi-color images help understand giant arc morphologies…



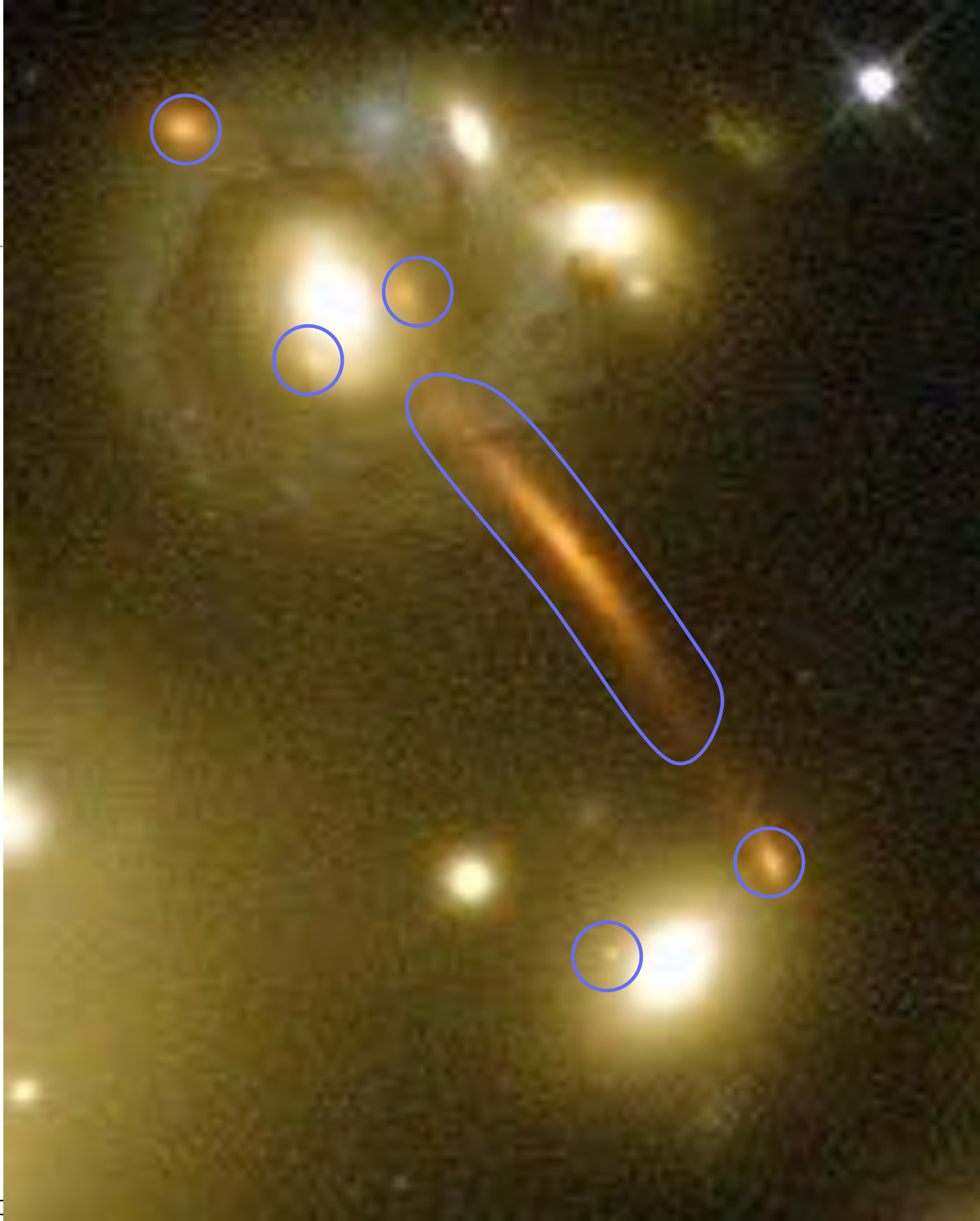


… and allow unlensed source reconstruction (Richard et al 2010)

Here the source is at redshift z=0.725

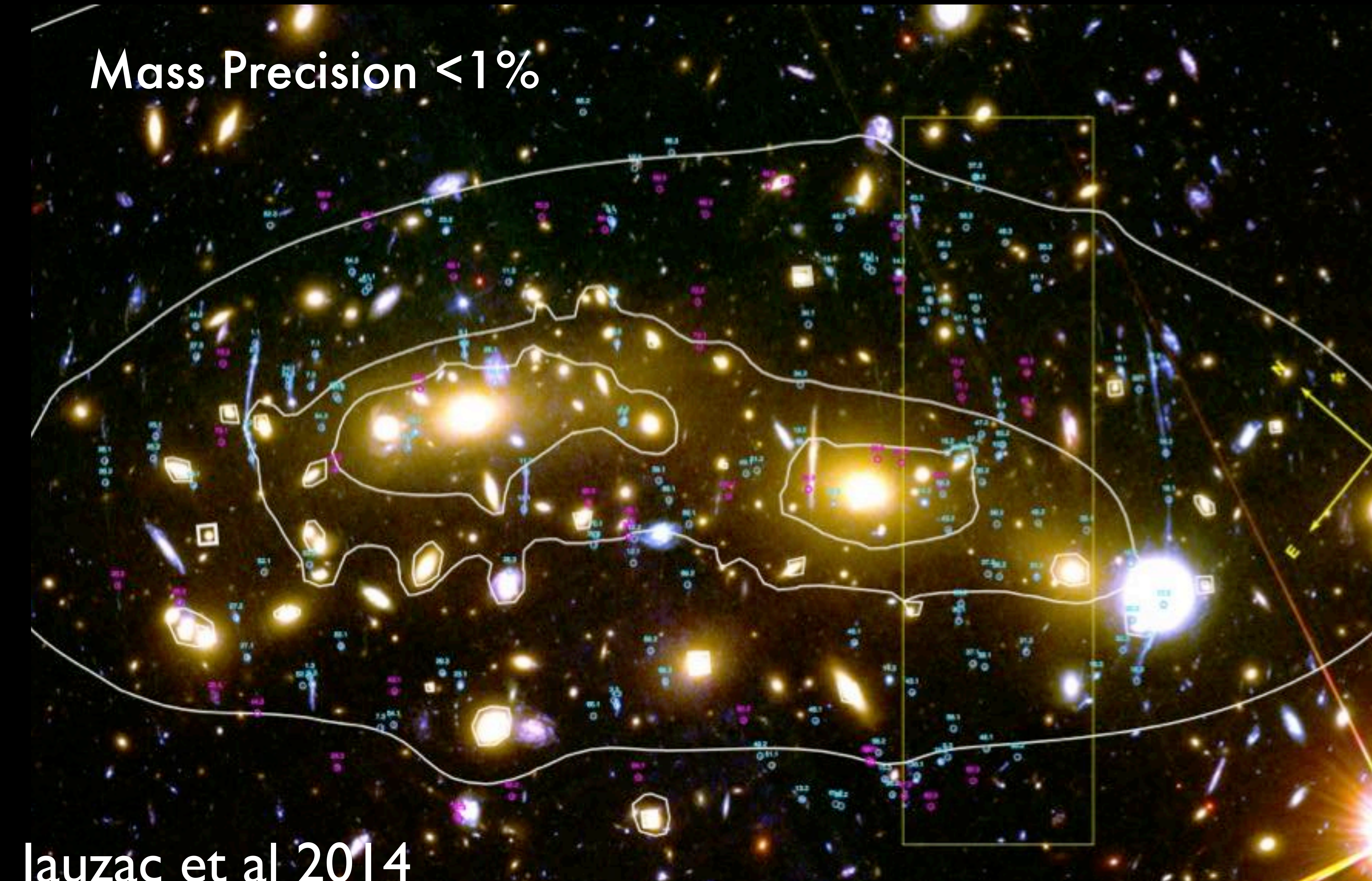
Strong Galaxy-Galaxy Lensing in Cluster

Cluster Galaxies are breaking arcs into smaller ones, adding new images of the lensed galaxy.



Abell 2218, arc at z=0.702, with 8 images identified (the arc is the merging of 2 images)

>200 Multiple Images in MACSJ0416



Modeling

- Which Mass Model?
- What Mass Model Parametrisation?

Singular Isothermal Sphere - 1

- To first approximation stars or other mass components are like particles in a gas.
- Let's consider an ideal gas: $$p = \frac{\rho k T}{m}$$
- The temperature T is related to the 1D velocity dispersion of the particles with: $$m\sigma_V^2 = kT$$
- Thus: $$p = \rho \sigma_V^2$$

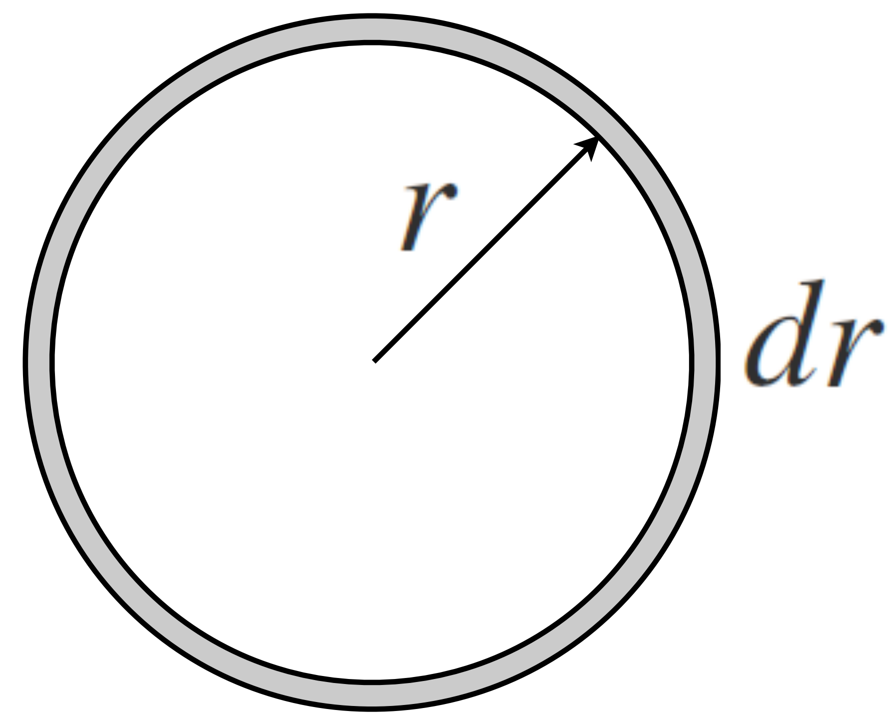
Singular Isothermal Sphere - 2

- Consider a spherical shell, its mass is:

$$dM = 4\pi r^2 \rho dr$$

- The gravitational force between the inside and the shell can be expressed as:

$$dF = -\frac{GM(r)dM}{r^2}$$



- The pressure is thus:

$$dp = \frac{dF}{4\pi r^2} = -\frac{GM(r)}{r^2}\rho dr$$

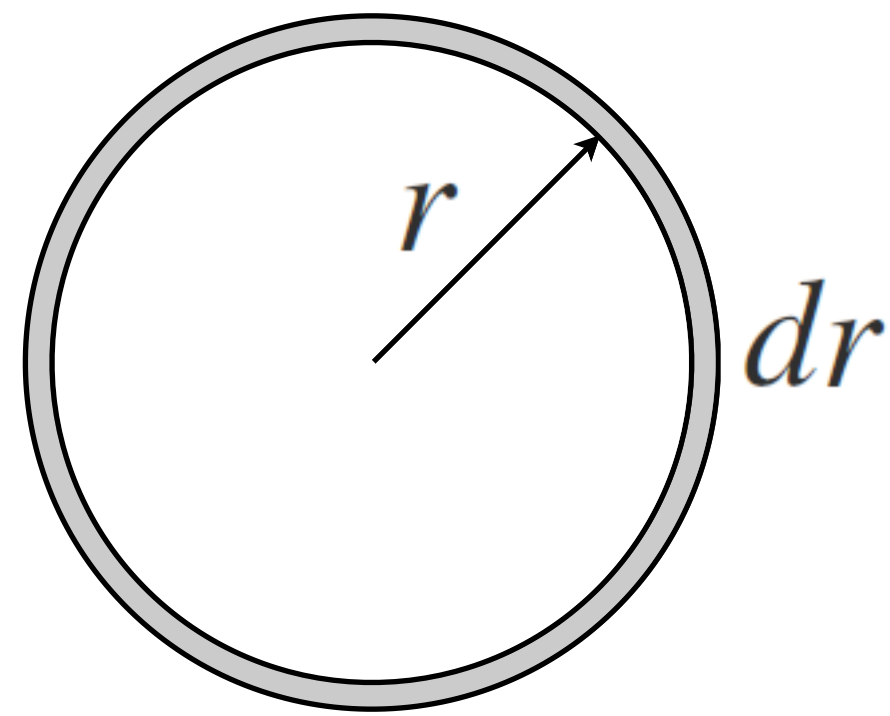
- One solution of this equation is:

$$\rho = \frac{\rho_0}{r^2} = \frac{\sigma_v^2}{2\pi G}\frac{1}{r^2}$$

Singular Isothermal Sphere - 3

- Total mass is thus:

$$M(r) = 4\pi\rho_0 r = \frac{2\sigma_V^2}{G} r$$



- Projected surface density:

$$\Sigma(R) = \frac{\sigma_V^2}{2G} \frac{1}{R}$$

- Issues:
  - Mass diverges at large radius
  - Mass density diverge at small radius

Truncated Isothermal Sphere with a core

- Adding a core (softening the central density spike):

$$\rho(r) = \frac{\sigma_V^2}{2\pi G} \frac{1}{r_c^2 + r^2}$$

- Truncating the profile at large radius:

$$\rho(r) = \frac{\sigma_V^2}{2\pi G} \left(\frac{1}{r_c^2 + r^2} - \frac{1}{r_{cut}^2 + r^2} \right)$$

- Pseudo isothermal profile:
  - Mass converge at large radius $\rho \sim r^{-4}$ $M_{tot} \sim \sigma_V^2 r_{cut}$
  - Mass density diverge at small radius $\rho \sim cste$

Navarro-Frenk-White (NFW) mass profile

- The NFW profile correspond to the 3D mass distribution of dark matter fitted to dark matter haloes identified in N-body simulations by Julio Navarro, Carlos Frenk and Simon White (1996, 1997).

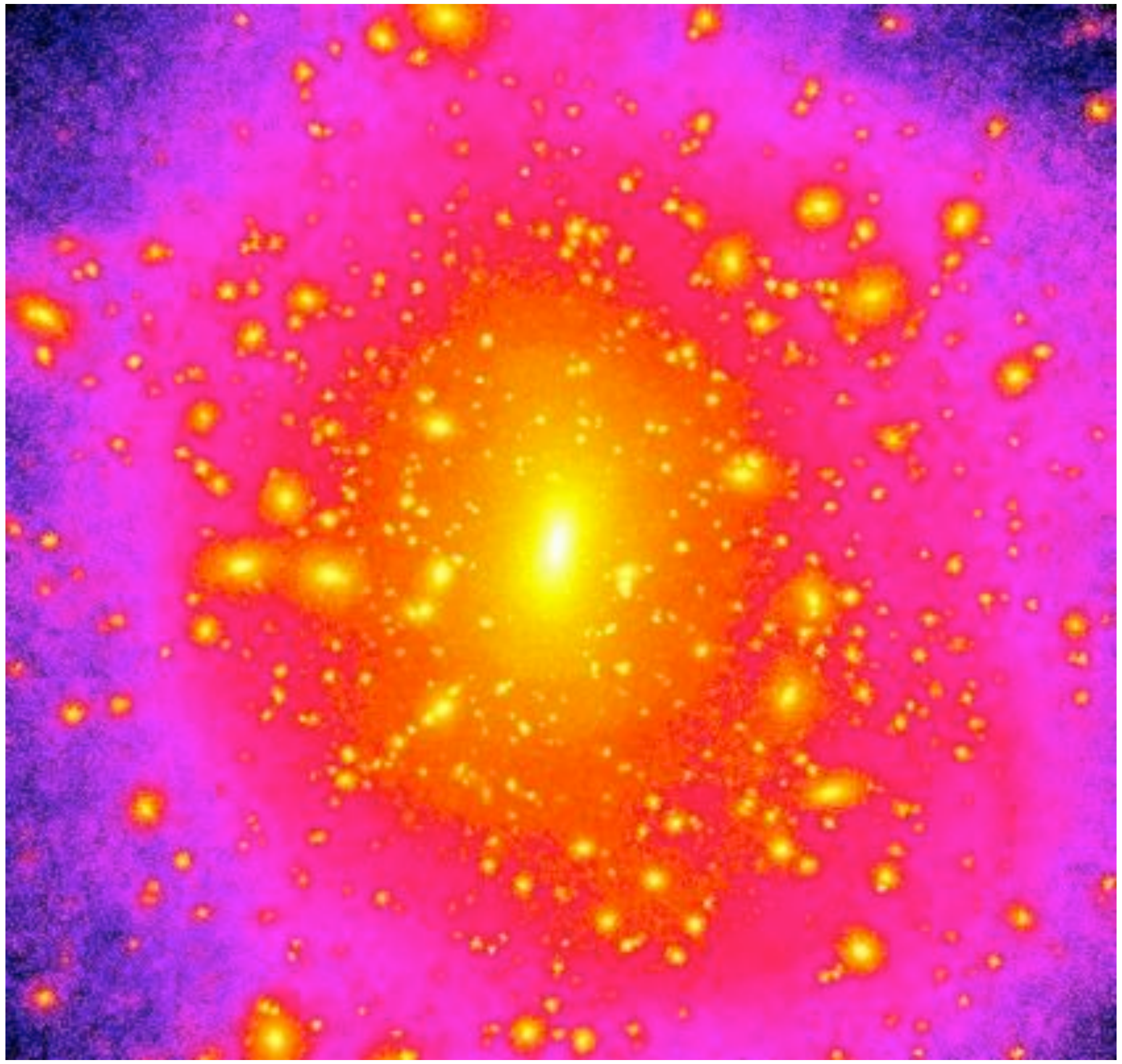
$$\rho = \frac{\rho_0}{r/r_s(1+r/r_s)^2}$$

- The NFW profile is one of the most commonly used model profiles for dark matter halos.
- However:
  - Mass diverges at large radius
  - Mass density diverge at small radius

More recent CDM-only Simulations

(e.g. Navarro et al. 2004; Diemand et al. 2004; Tasitsiomi et al. 2004 + others)

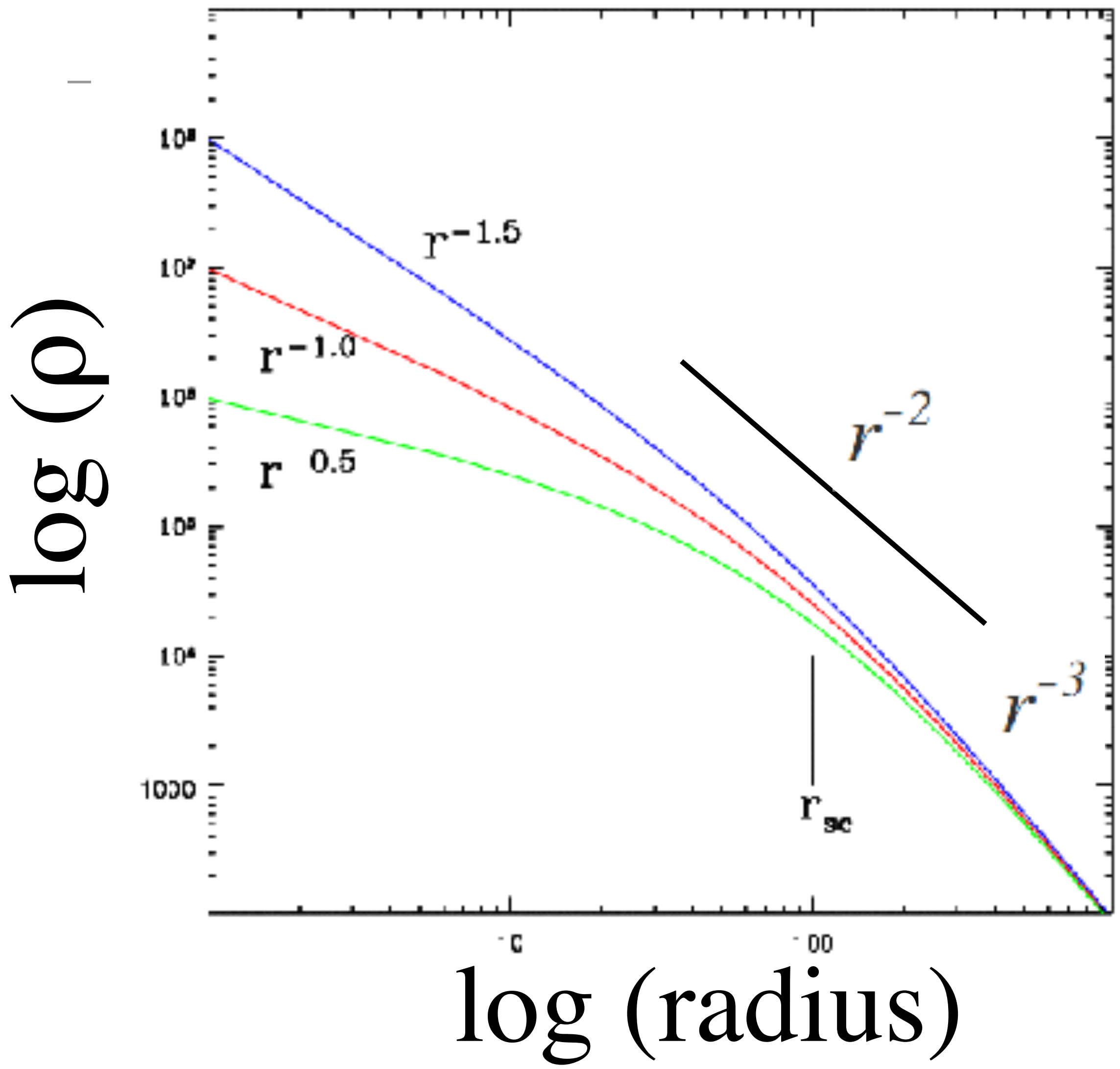
- Convergence achieved down to ~$0.003r_{vir}$…roughly the size of massive galaxies. Baryons are important for progress!!
- Density profiles obtained using different codes and initial conditions agree.
- The generalized NFW density profile is a good fit to simulations with β between 1.0 & 1.5. There is significant scatter.
- Sersic profiles seems to be an alternative to generalized NFW expression (Merrit et al 2005)

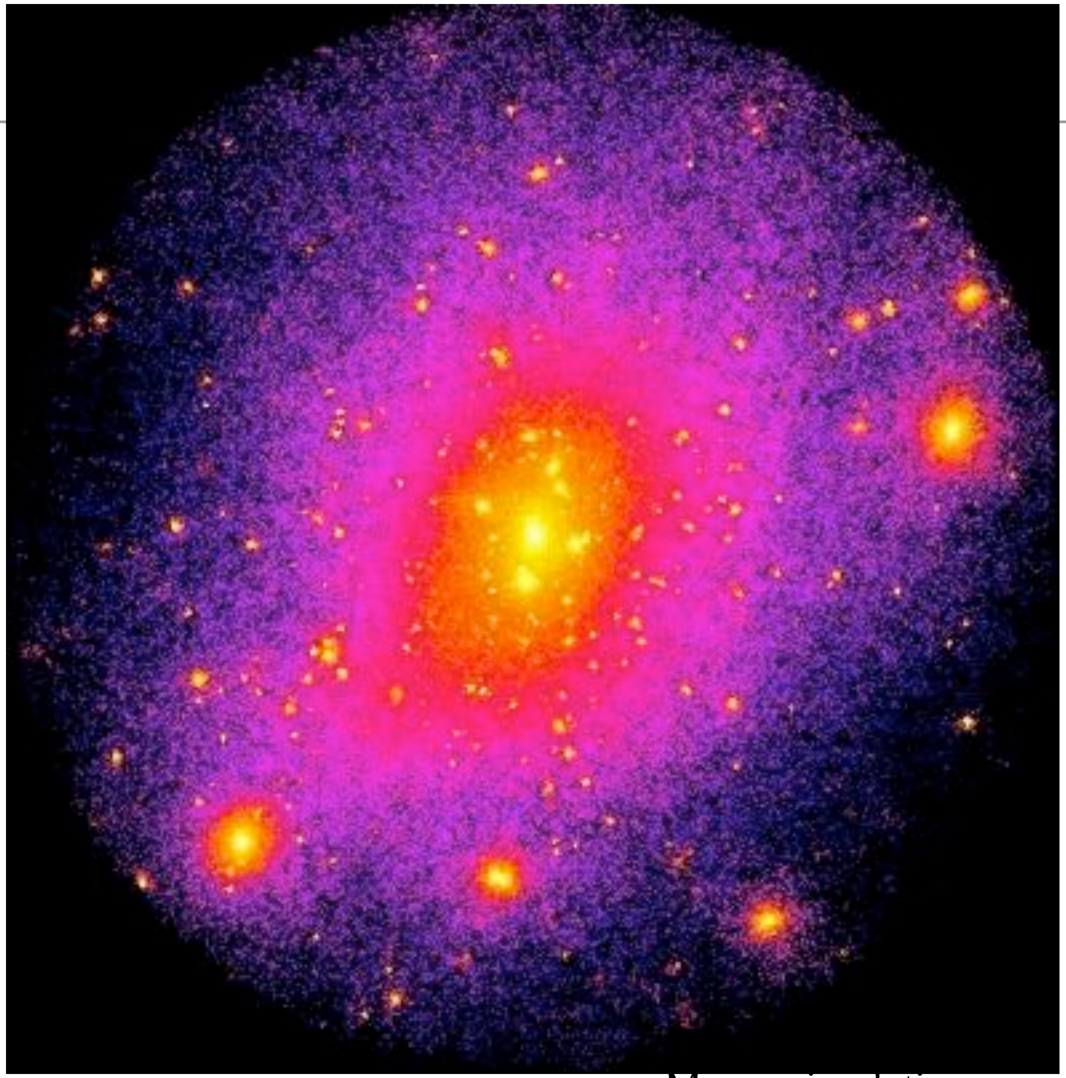


Generalized NFW

$$\rho = \frac{\rho_0}{(r/r_s)^{\beta}(1+r/r_s)^{3-\beta}}$$

Generalised NFW profile





Moore simulation

Inner profile: $\rho \propto r^{-\beta}$ NFW: $\beta \to 1.0$ Moore: $\beta \to 1.5$

What is the inner slope of cluster DM profiles?

What is the TOTAL density profile?

Mass model representation

- large scale cluster component+sum of galaxy halo components ([DM+gaz]+galaxy halos):

$$\phi_{tot} = \phi_{cluster} + \Sigma_i \phi^i_{halos}$$

Kneib et al 1996

- need to scale the galaxy halo components; for example for a PIEMD mass distribution:

$$\sigma = \sigma_* (\frac{L}{L_*})^{1/4} \qquad r_{cut} = r^*_{cut} (\frac{L}{L_*})^{\eta}$$

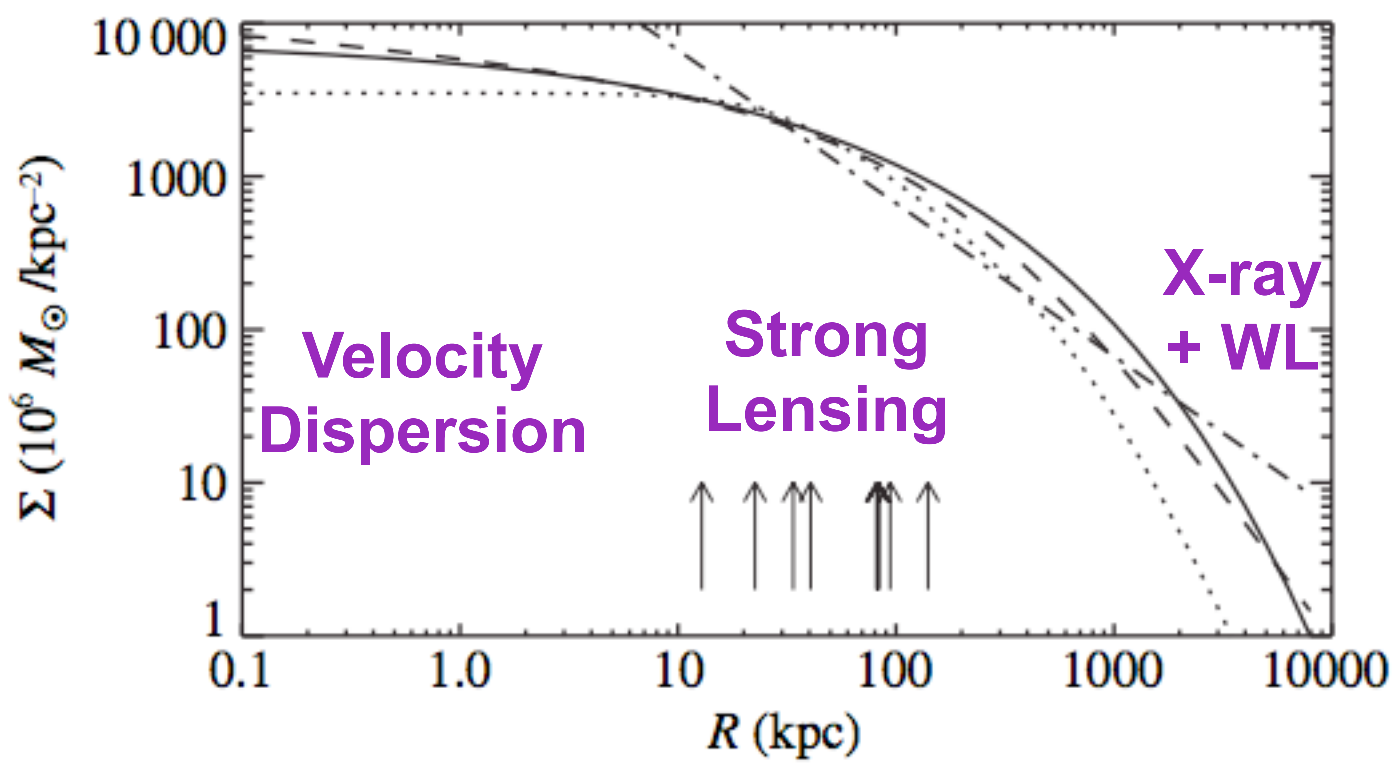
- Hence: $$\frac{M}{L} \propto L^{\eta - 1/2}$$

$\eta = 1/2$ Constant M/L

$\eta = 0.8$ FP scaling

Mass profile for a mass clump?

- Mass profile should match theoretical or numerical simulations in order to be close to reality (avoid Gaussian function for example):
  - isothermal model (singular => cored & truncated, circular =>elliptical): PIEMD
  - NFW model => gNFW, Sersic, Einasto (beware at infinite values, truncate?)

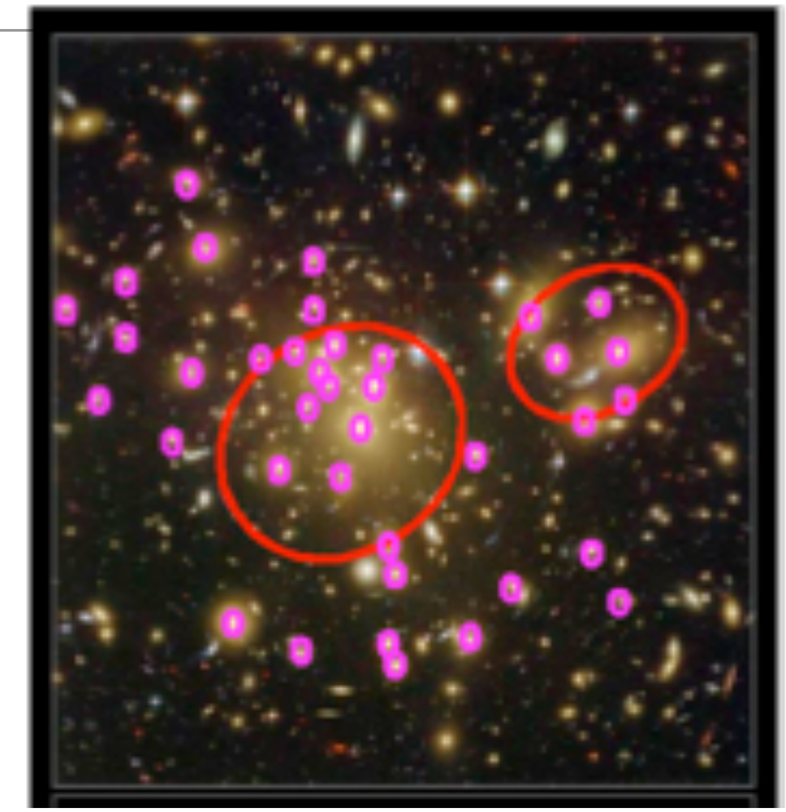


Additional data useful to constraints further the mass profile

Strong lensing modeling strategies

Observationally motivated models

- Decomposition into halos
- Simple clusters
- Few constraints
- Good fit with few constraints



Grid-based models

- Decomposition into pixels/clumps
- Complex clusters
- Lots of constraints
- Better fit with lots of constraints