Cluster strong lensing as a probe of the high redshift Universe

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Chapters

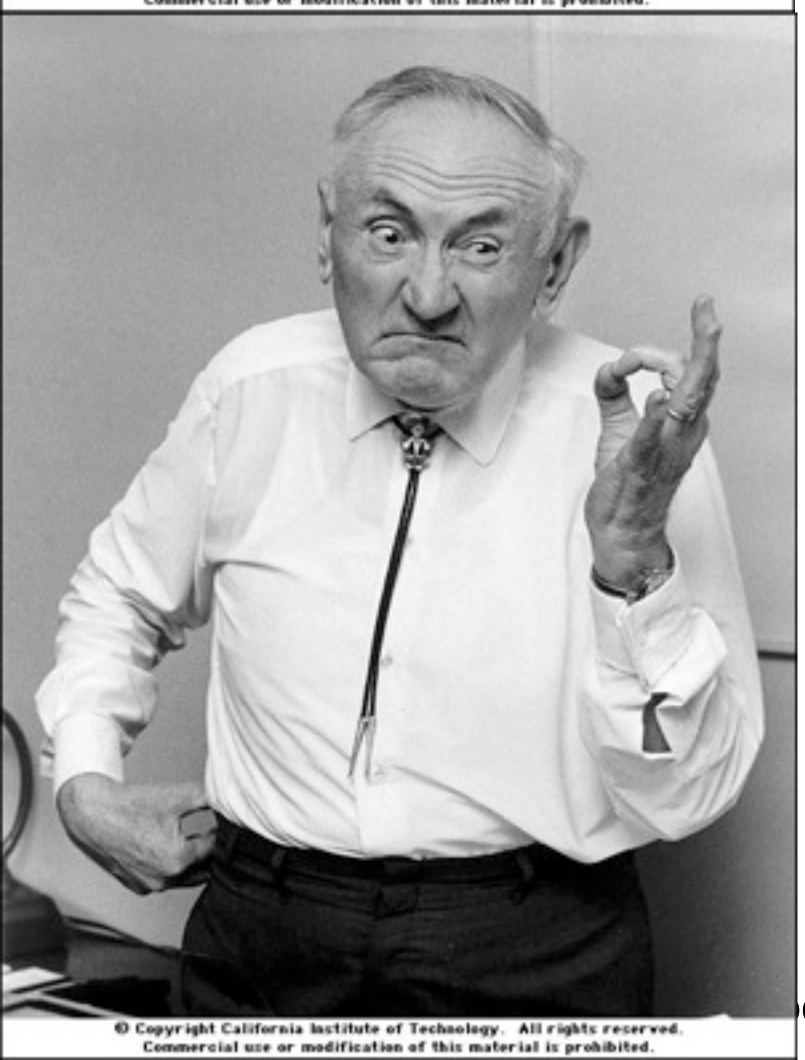
- Introduction on cluster strong lensing
- Strong lensing modeling techniques
- Using clusters to probe lensed distant galaxies (tomorrow!)

Outline Chapter 1 & 2

- Introduction on cluster strong lensing
  - A very brief history
  - Theory in relation to strong lensing in clusters

- Strong lensing modeling
  - constraints: multiple images, others
  - mass models
  - modeling technique and results

Brief history of cluster lensing



First account of Cluster lensing

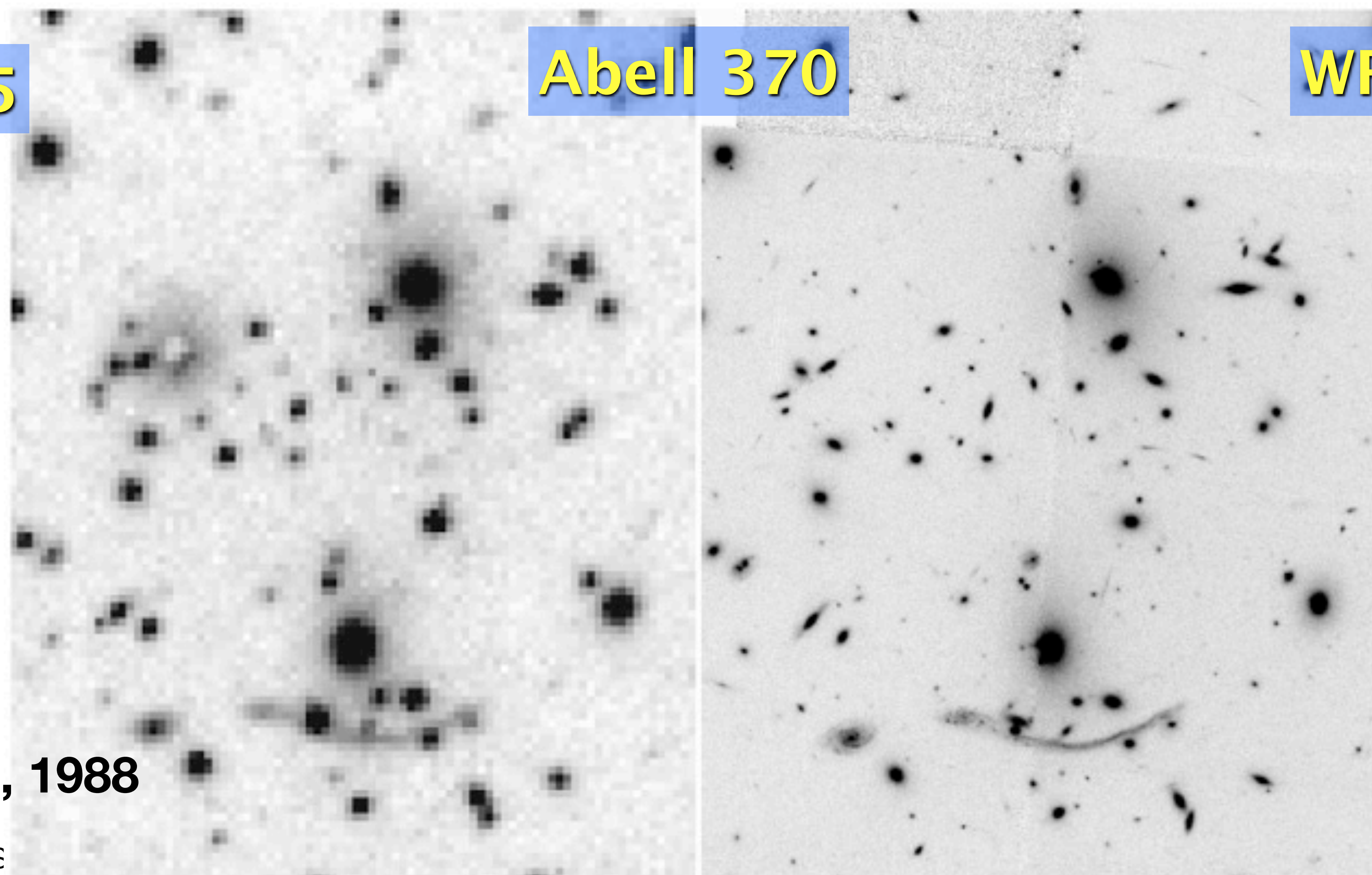
- 1933: Zwicky "discovered" DM in Coma cluster
- 1937: Zwicky's "vision": observation of gravitational lensing (by clusters) should allow to probe:
  - the Dark Matter distribution
  - study distant galaxies thanks to the magnification effects

25 years ago: 1st arc in cluster

- 1987 the first giant luminous arc discovered

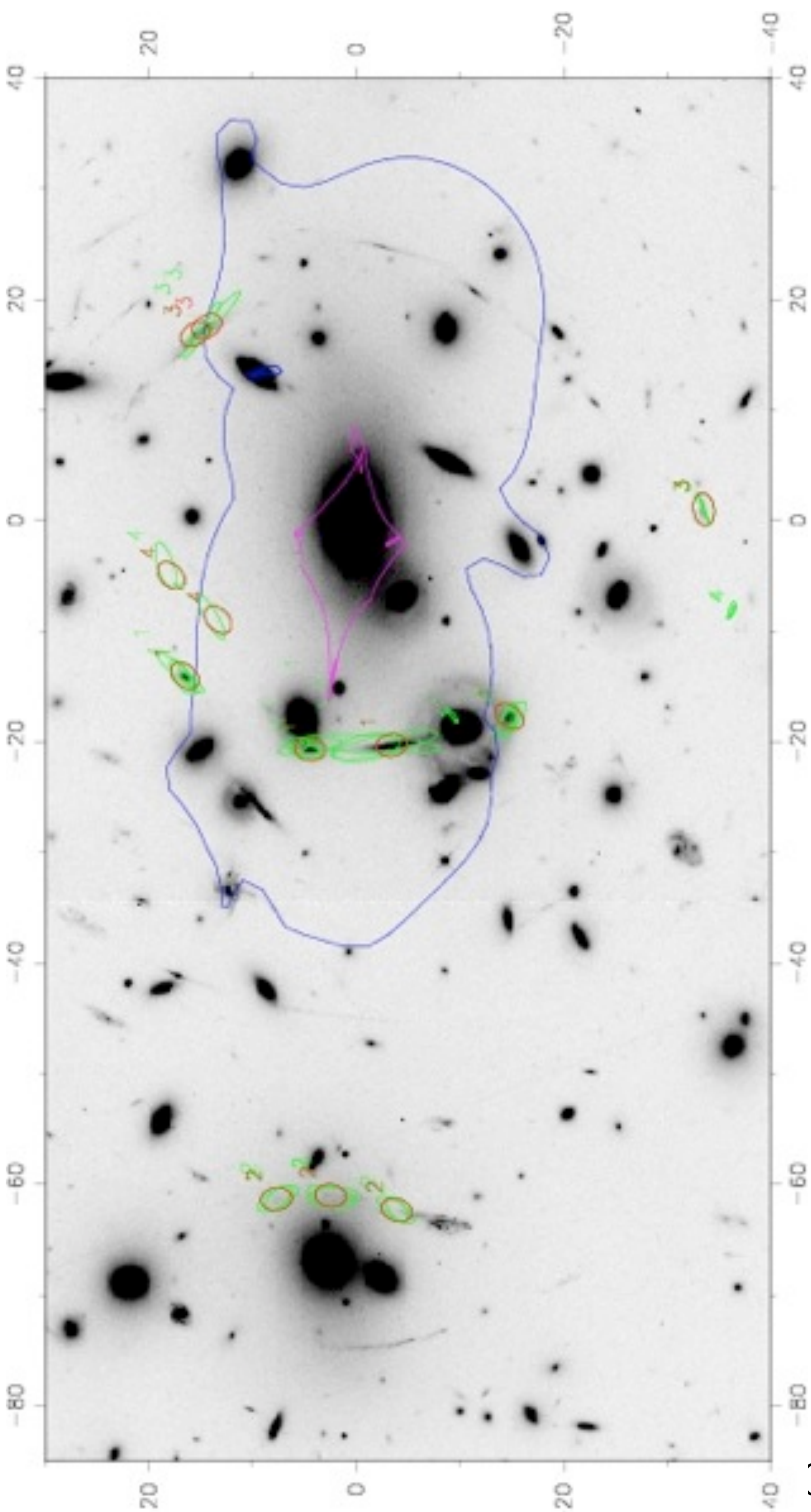
- **"Cluster are massive and *dense* enough to produce strong lensing - they must be filled with dark matter"**

- *Every massive cluster is a lens !!!*

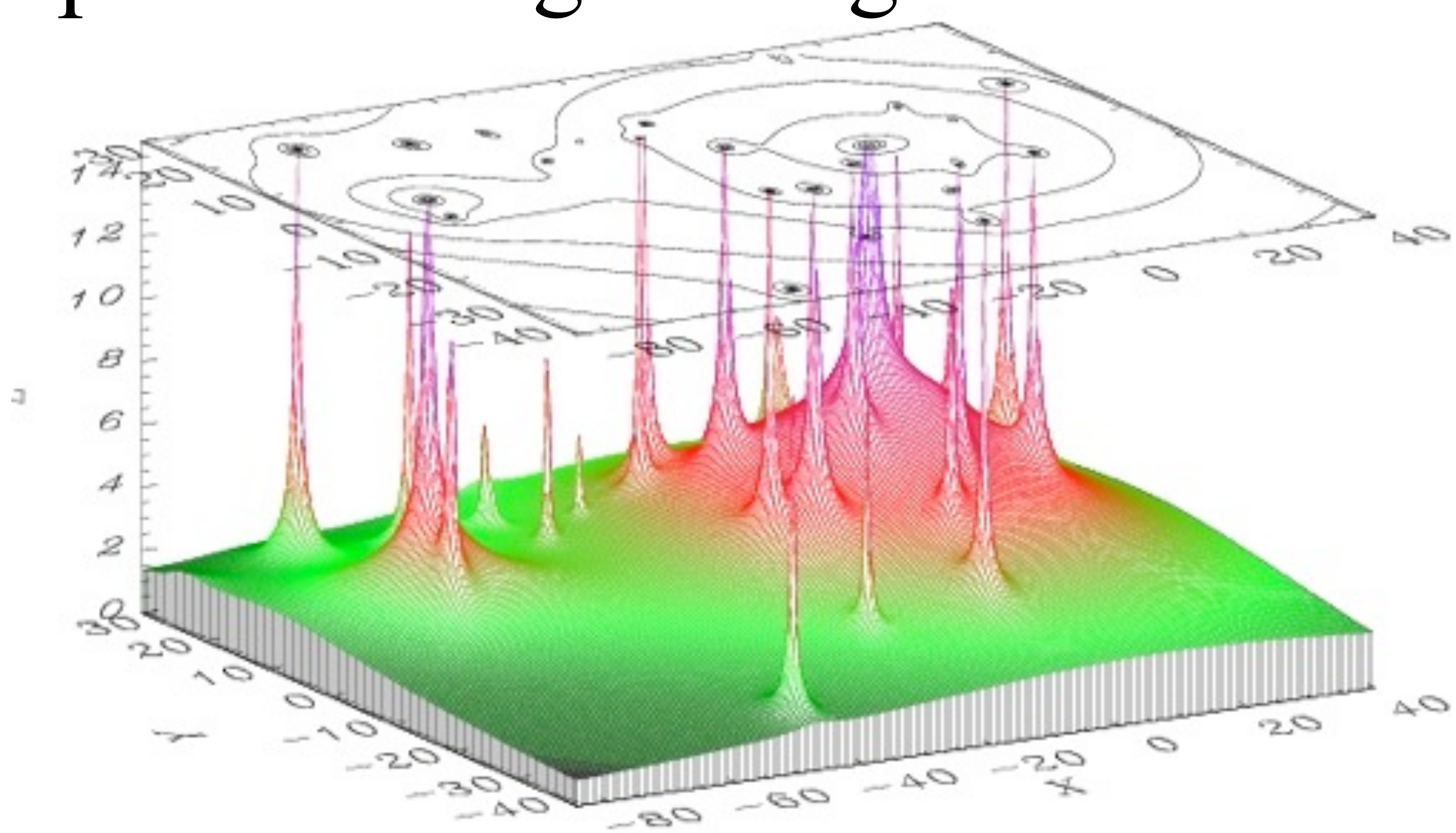


Soucail et al 1987, 1988

Different Mass Scale



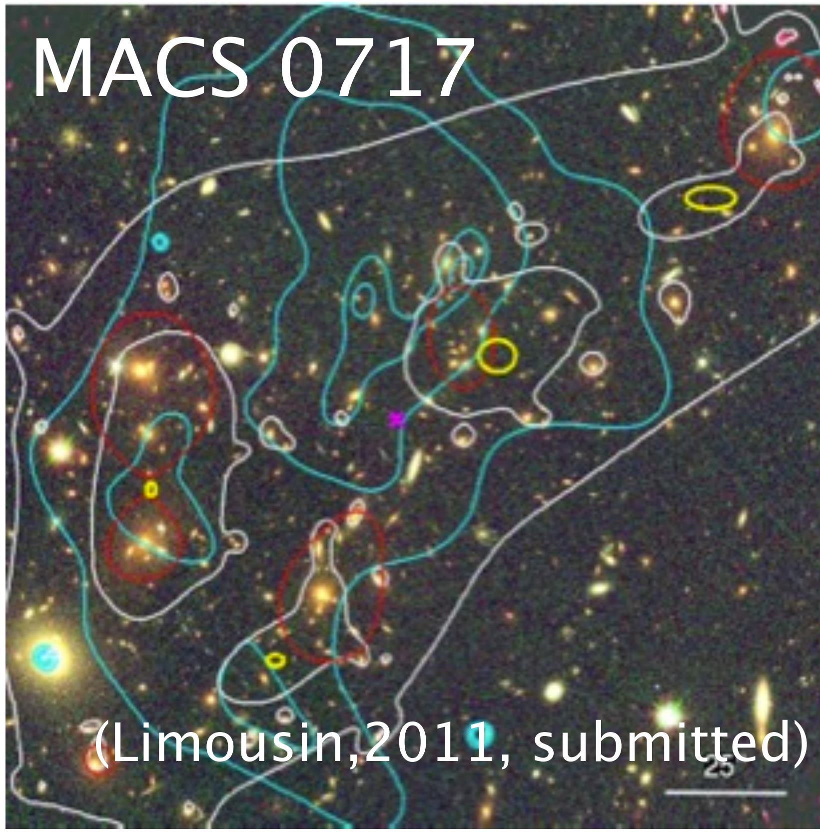
- Cluster Mass = DM + X-ray gas + Galaxies
- 1996: First parameterized lens model, involving various multiple image system
- *Requires to include galaxy scale mass* component using scaling relations

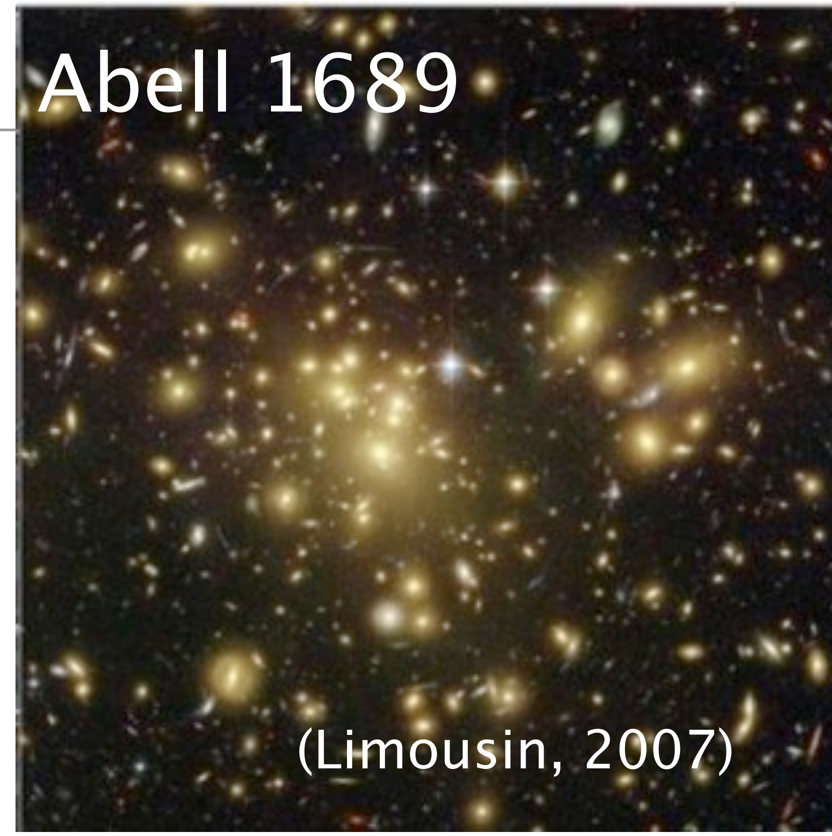


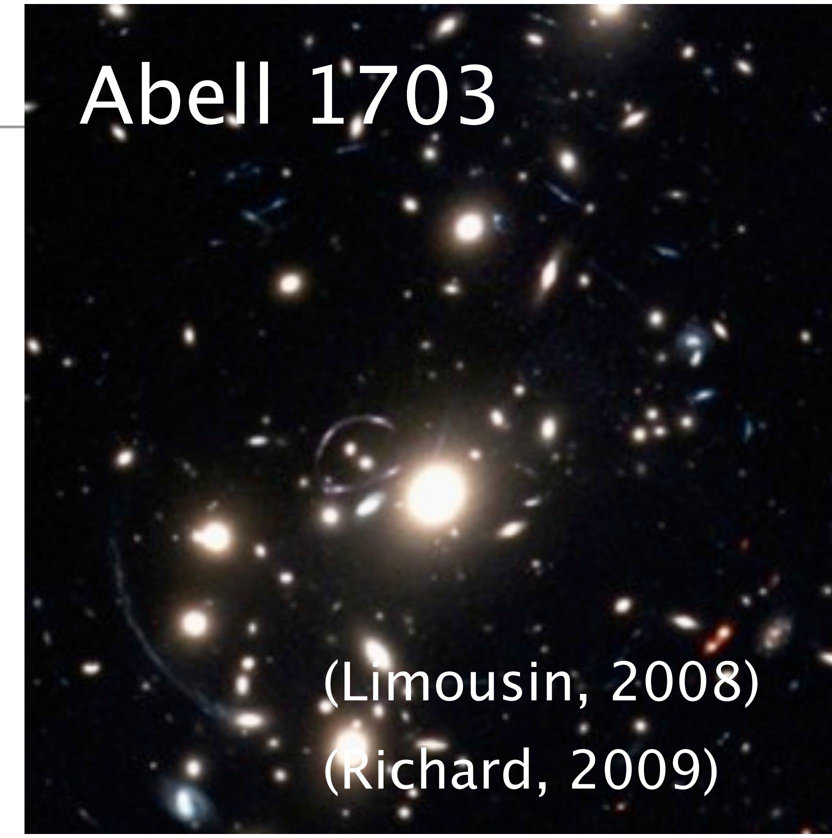
Kneib et al 1996, Golse et al 2002

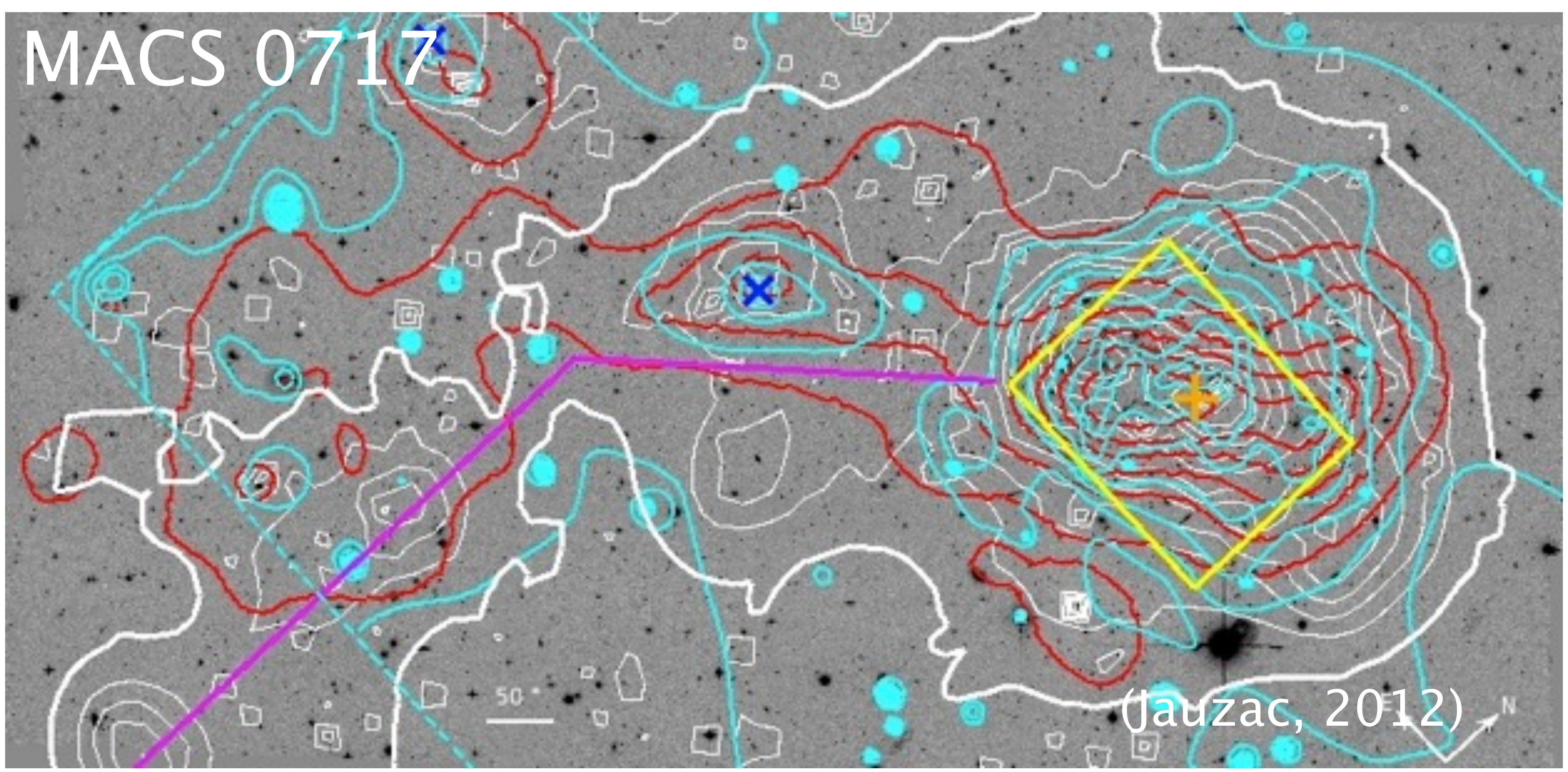
Many cluster lens mass models !

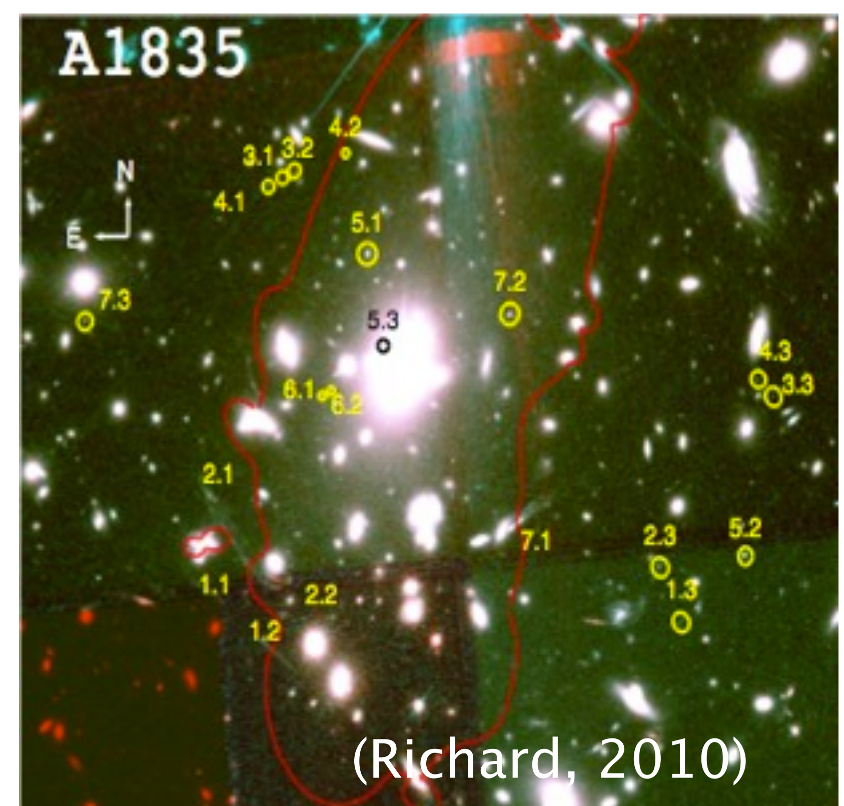
(here using LENSTOOL)

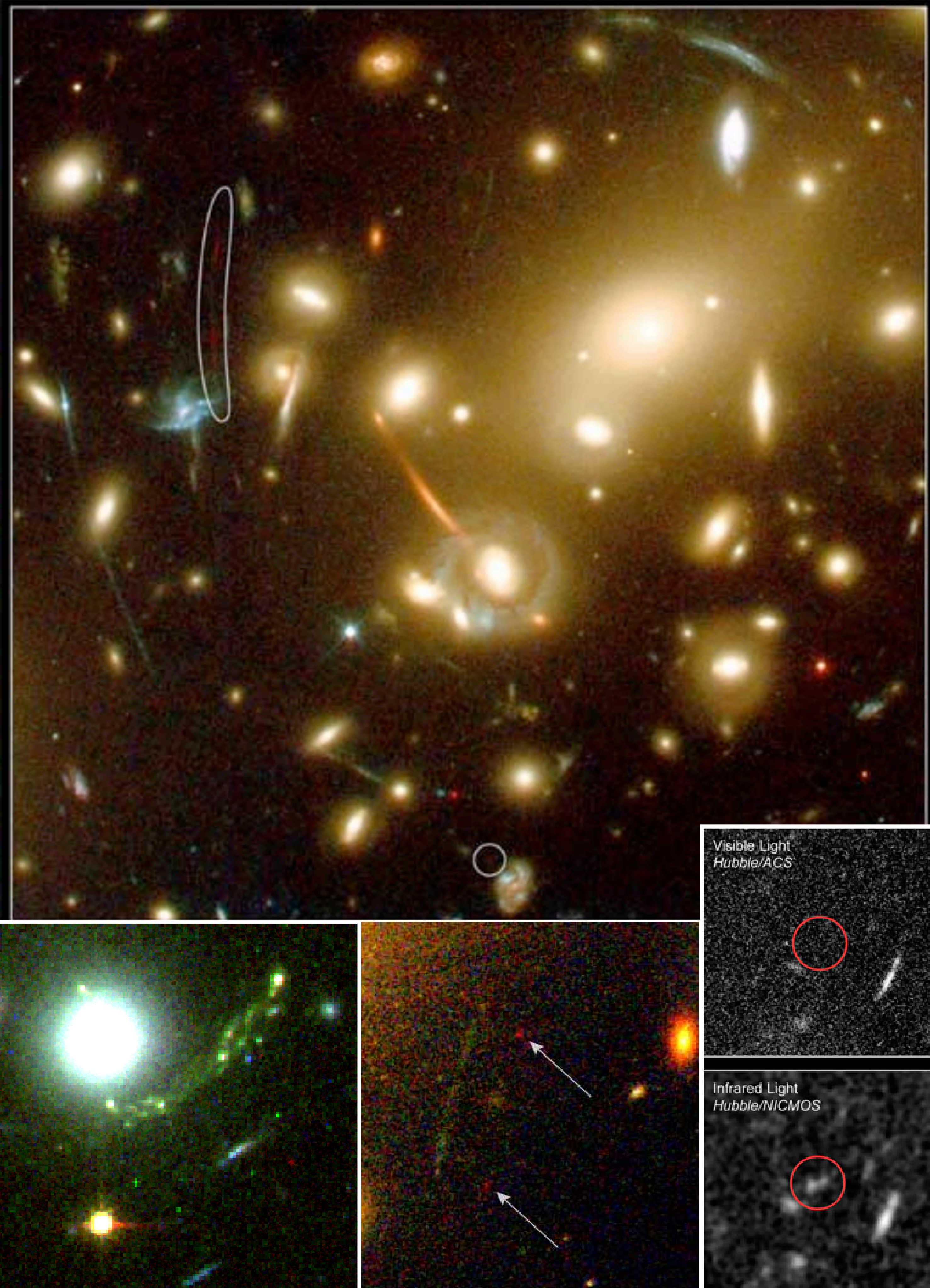












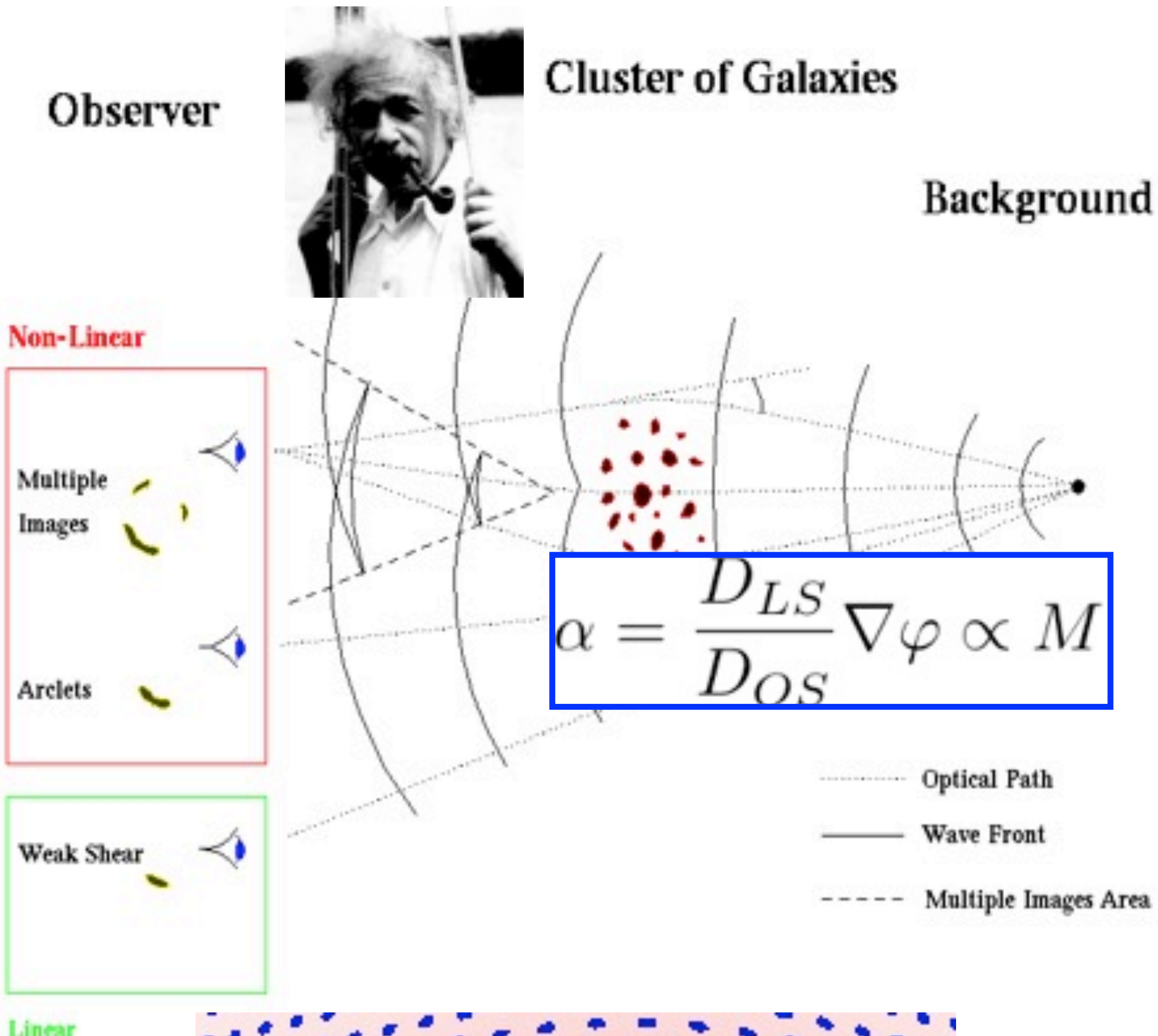
Cluster Lenses to study the distant Universe

Cluster Lenses as gravitational Telescopes:

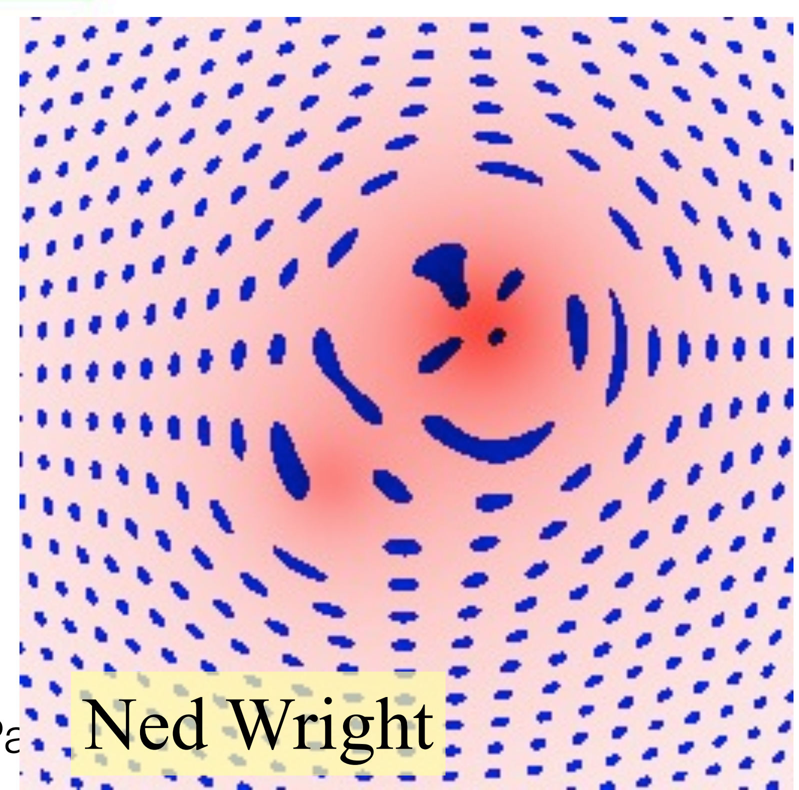
- **Franx** (1998): z=4.91 [ms1358]
- **Ellis**(2001): z=5.578 [a2218]
- Hu(2002): z=6.56 [a370]
- **Kneib**(2004): z~6.8 [a2218]
- Pello(2004): z=10.0? [a1835]
- Stark(2007): z~9.5? [survey]
- **Bradley**(2008): z~7.6 [a1689]
- Richard (2009): z=5.827 [a1703]
- Richard(2011): z=6.027 [a383]
- Bradley(2012): z~7 [a1703]
- Zheng(2012): z~9.6? [macs1149]
- Bradac(2012): z=6.74 [bullet]
- **z~11?**

Cluster Strong Lensing Basics

Cluster Lensing - Back to Basics



$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M$$



- **Basics of lensing:**
  - Large mass over-densities locally deform the Space-Time
  - – *A pure geometrical effect, no dependence with photon energy - depends on TOTAL MASS*
- **Lensing by (massive) clusters**
  - Deflection of ~10-50 arcsec
  - – *strongly lens many background sources => allow detailed mass reconstruction at different scales: cluster core, substructures, large scales*
  - – *~1 SL cluster-lens per ~10 sq. deg: potentially ~2000 to study, Probably only ~200 identified today, nearly 20 with "a good" (SL) mass model*

Lensing Equations

Lens Mapping:

Lensing Potential

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

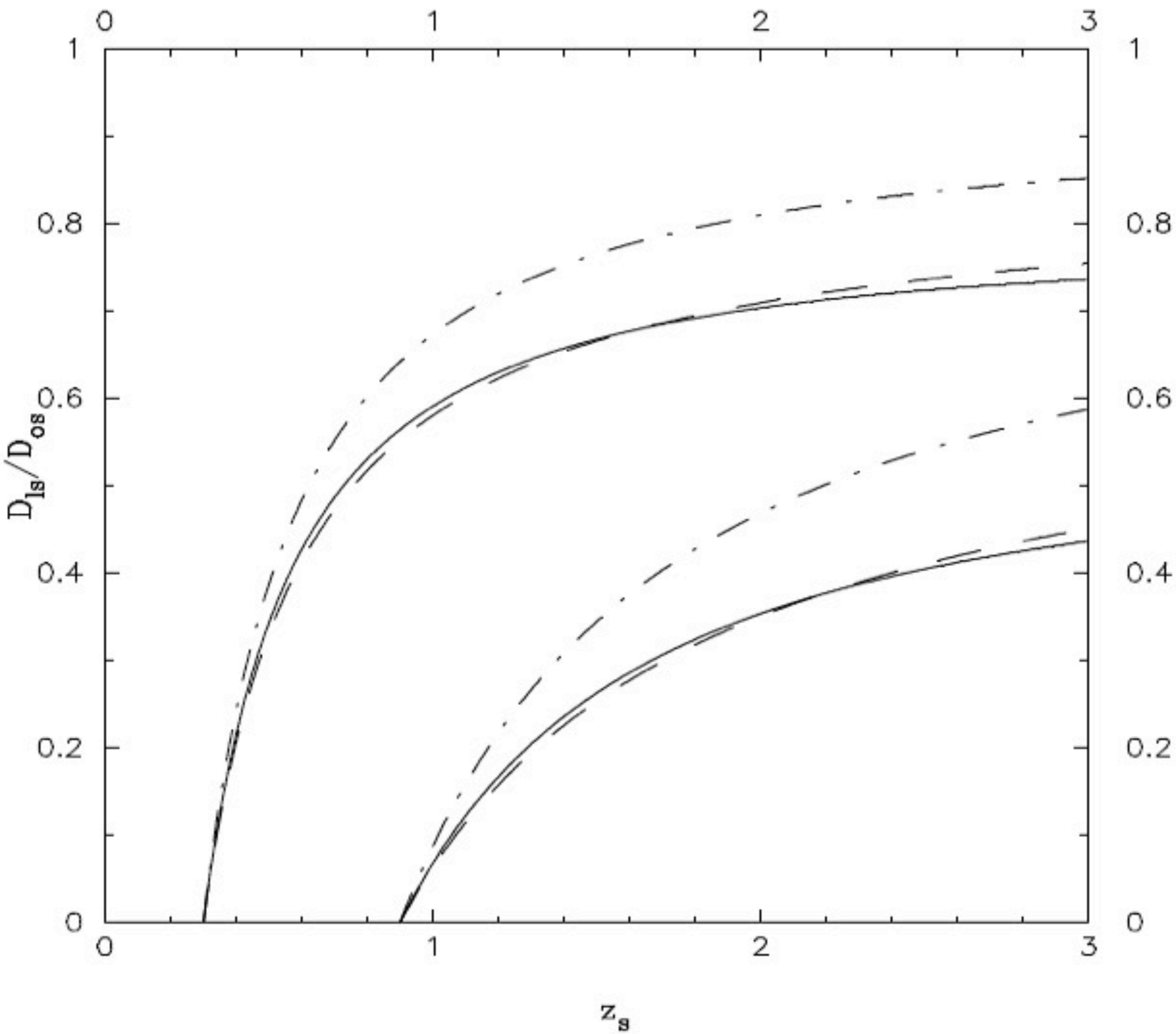
φ : lensing potential

⇒ Link with catastrophe theory

⇒ Parameters: Distances and Mass

⇒ Purely geometrical: *Achromatic effect*

Redshift and Cosmology



Lens Efficiency:

$$D_{LS}/D_{OS}$$

For a fixed lens redshift, the efficiency increase with source redshift

Weak cosmology dependence

Lensing Equations

Lens Mapping distortion (first order):

$$\frac{d\vec{\theta}_S}{d\vec{\theta}_I} = \mathcal{A}^{-1} = \begin{pmatrix} 1 - \partial_{xx}\varphi & -\partial_{xy}\varphi \\ -\partial_{xy}\varphi & 1 - \partial_{yy}\varphi \end{pmatrix}$$

In polar coordinates:

$$= \begin{pmatrix} 1 - \partial_{rr}\varphi & -\partial_r\left(\frac{1}{r}\partial_\theta\varphi\right) \\ -\partial_r\left(\frac{1}{r}\partial_\theta\varphi\right) & 1 - \frac{1}{r}\partial_r\varphi - \frac{1}{r^2}\partial_{\theta\theta}\varphi \end{pmatrix}$$

Lensing Equations

Amplification Matrix:

$$\mathcal{A}^{-1} = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

κ: convergence

$$\boxed{\kappa \;=\; \Delta\varphi/2 \;=\; \Sigma/2\Sigma_{crit}}$$

$$\Sigma_{\rm cr} = \frac{c^2}{4\pi G}\,\frac{D_{\rm s}}{D_{\rm d}D_{\rm ds}}$$

$$= 0.35\,{\rm g\,cm^{-2}}\left(\frac{D}{1\,{\rm Gpc}}\right)^{-1}$$

γ(γ1,γ2): shear vector

$$\boxed{\gamma_1 = (\partial_{yy}\varphi - \partial_{xx}\varphi)/2 \qquad \gamma_2 = \partial_{xy}\varphi}$$

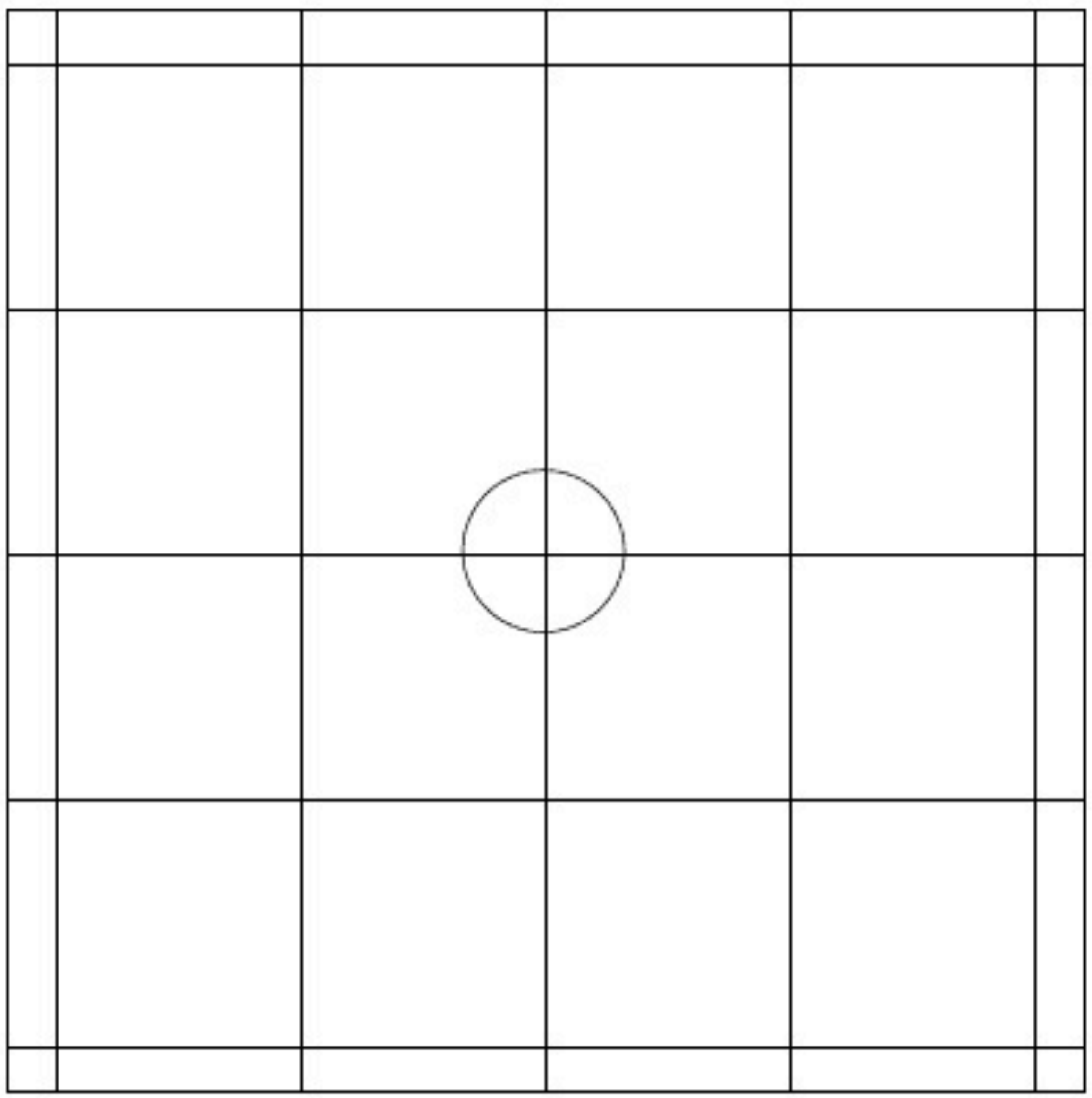
Reduced shear:

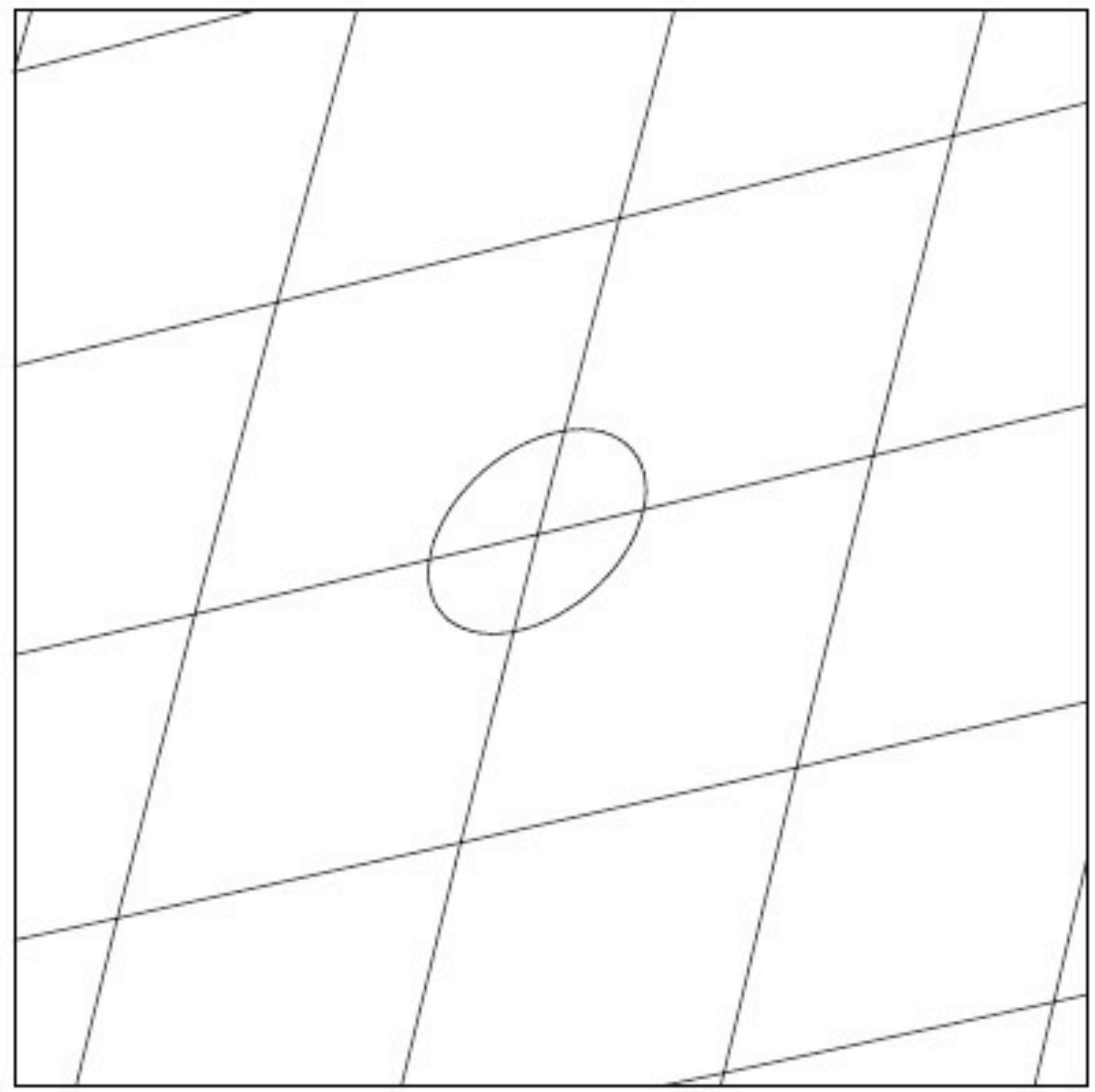
$$\boxed{g = \frac{\gamma}{1-\kappa}}$$

Lensing Equations

Plane transformation for constant κ and γ

Measured distortion: reduced shear $\boxed{g = \frac{\gamma}{1-\kappa}}$





Lensing Equations

Magnification: μ

Size Magnification
=> **Total flux** increase

$$\mu^{-1} = \det(\mathcal{A}^{-1}) = (1-\kappa)^2 - \gamma^2$$

Shear direction is independent of distance parameters:

$$\tan 2\theta_{shear} = \frac{2\partial_{xy}\varphi}{\partial_{yy}\varphi - \partial_{xx}\varphi}$$

Important properties for weak shear analysis &
direction of large arc = direction of the shear

Lensing Equations

Definition: Critical lines

Locus of the image plane where the determinant of the (inverse) magnification matrix is zero:

$$1 - \kappa = \pm\gamma \qquad\qquad (\mu = \infty)$$

Critical lines are closed curves and non over-lapping.

In general: 2 types of critical lines:

- tangential (external)
- radial (internal)

Lensing Equations

Definition: Caustic lines

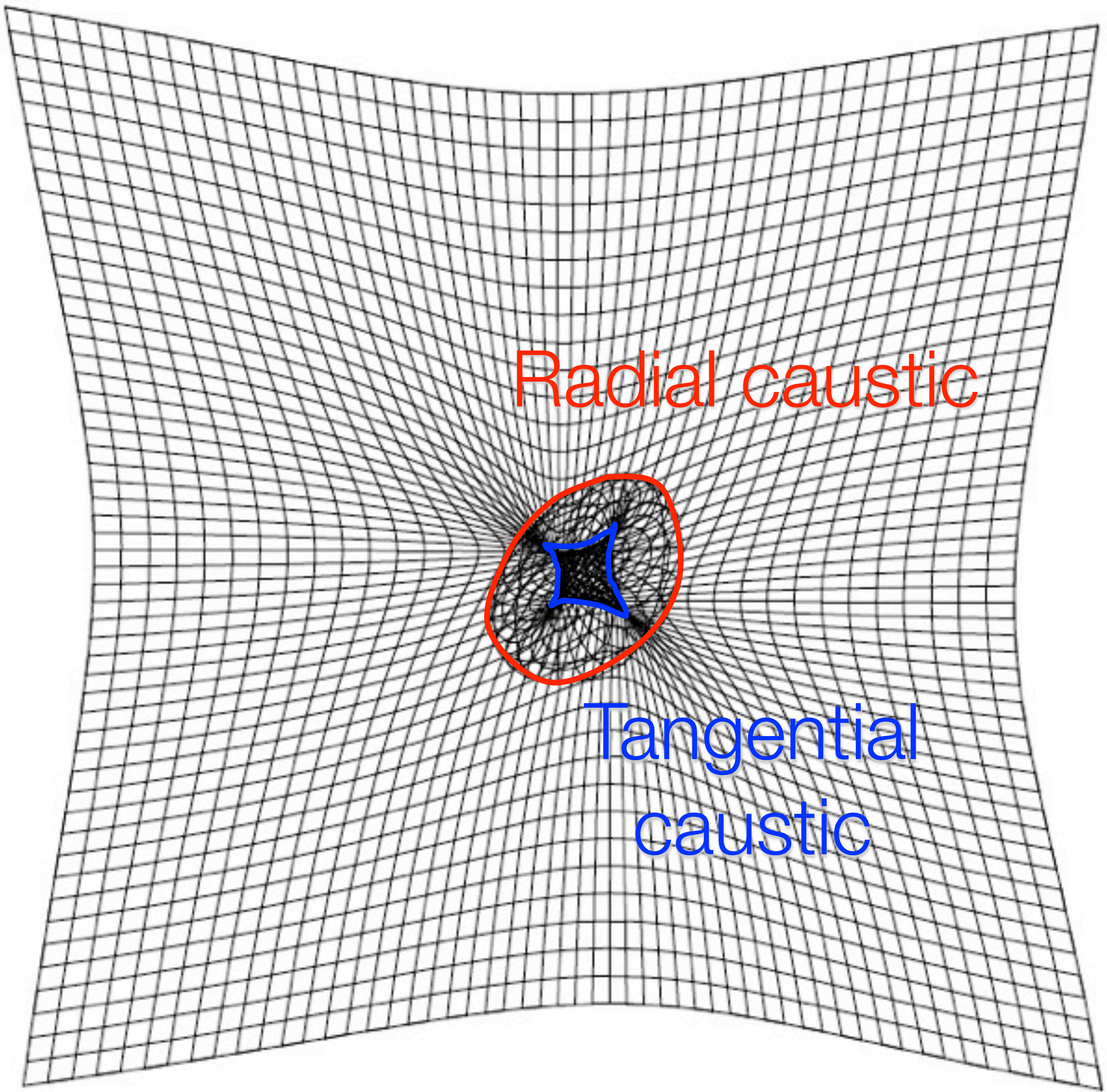
Transform of the critical lines in the source plane;

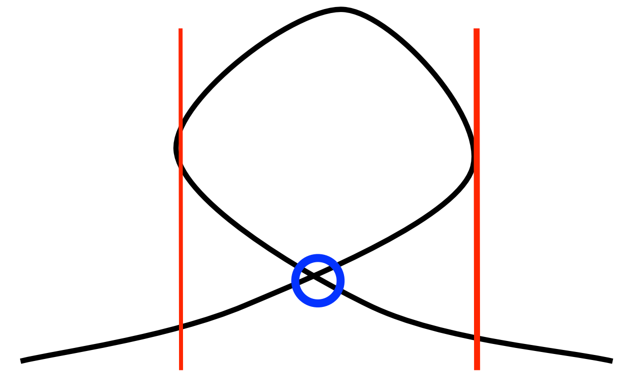
Caustic lines are delineating the regions with different number of multiple images: crossing a caustic lines adds 2 images

In general: 2 types of caustic lines:

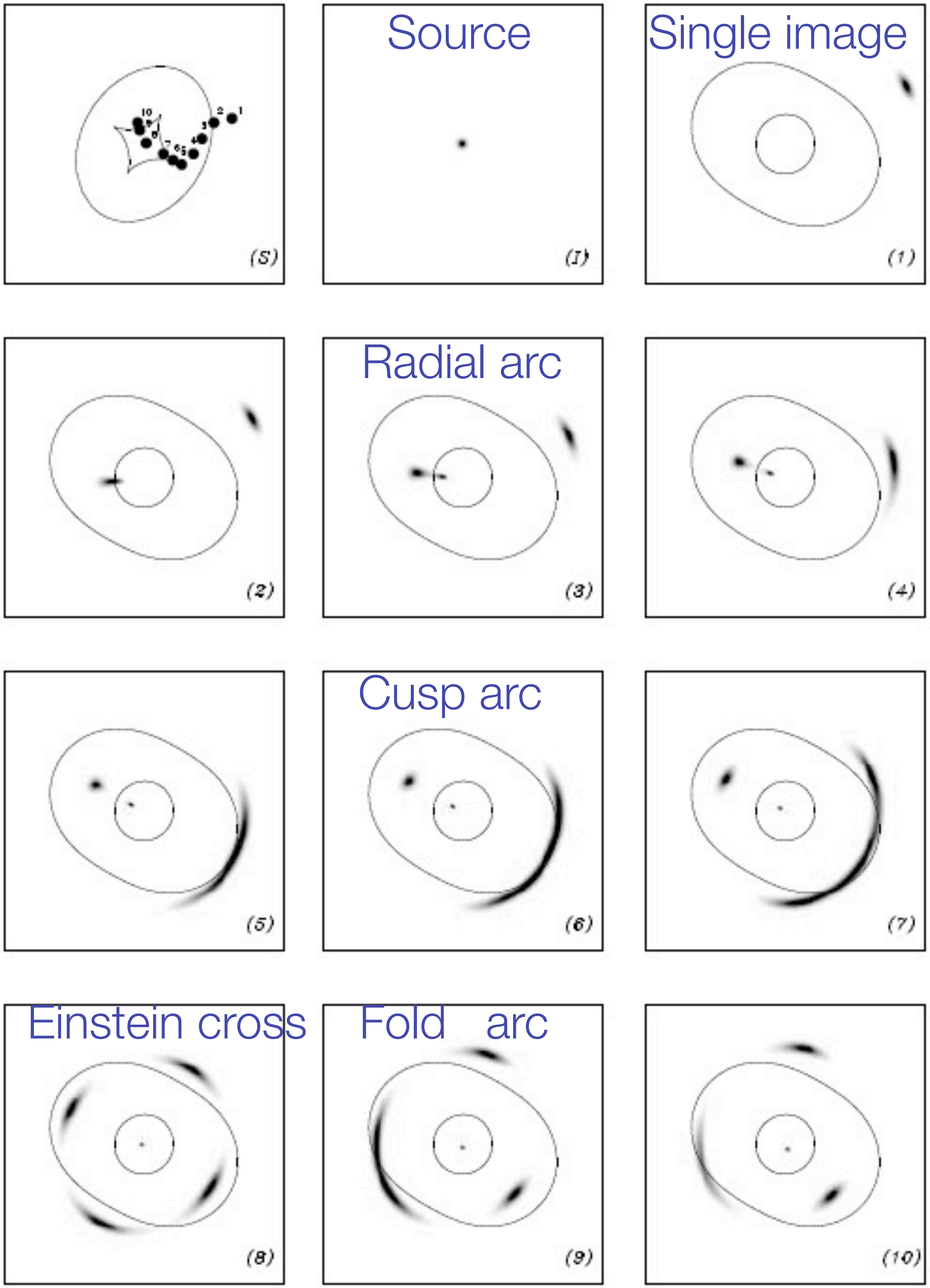
- tangential => diamond shape caustic [astroid]
- radial (usually larger than the tangential one if regular shape)

Lensing theory



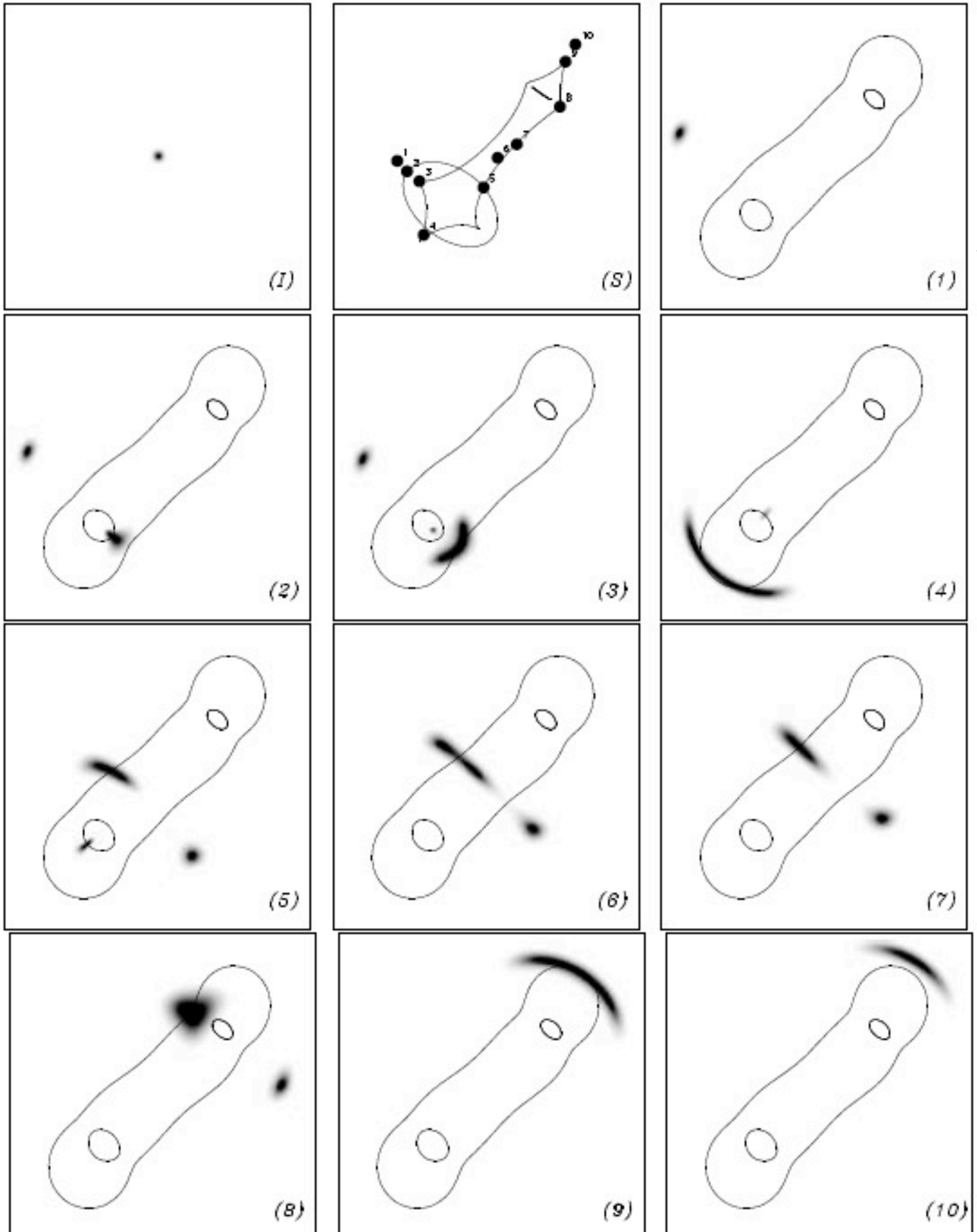


Transform of a regular image plane grid in the source plane



Lensing Theory

Multiple image configurations for a *non-singular elliptical mass distribution*



Lensing Theory

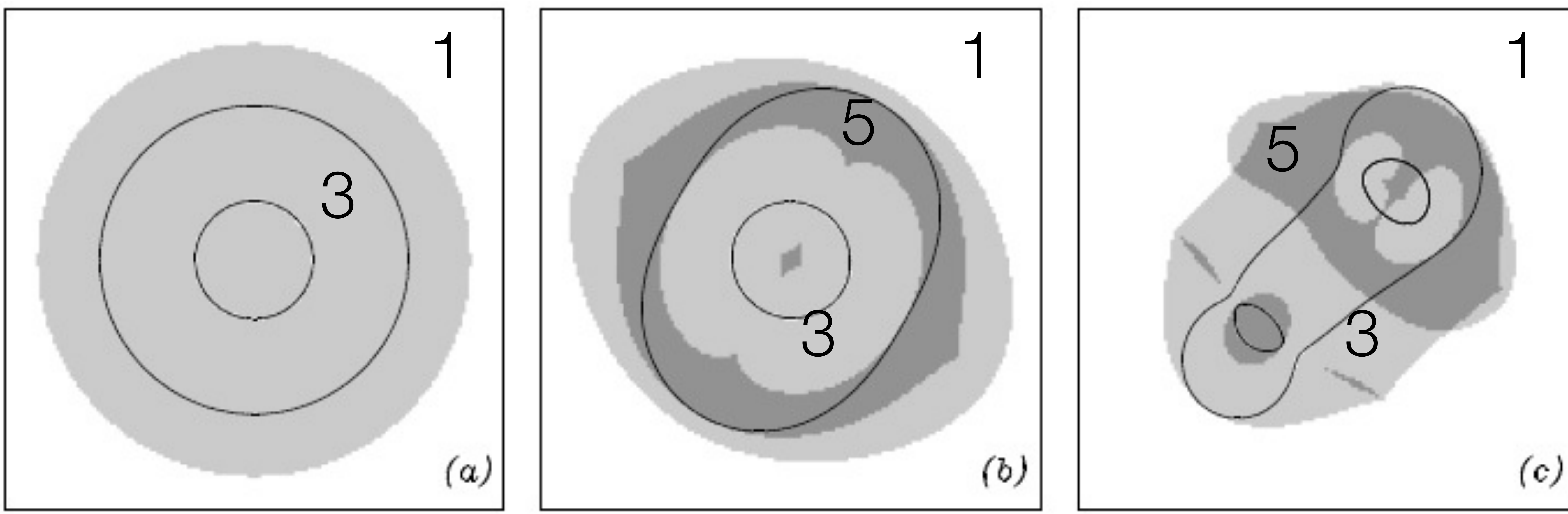
Multiple image configurations for a *bimodal mass distribution with similar mass clumps*

Lensing Theory

Multiple image region for:

Circular Elliptical Bimodal

mass distribution

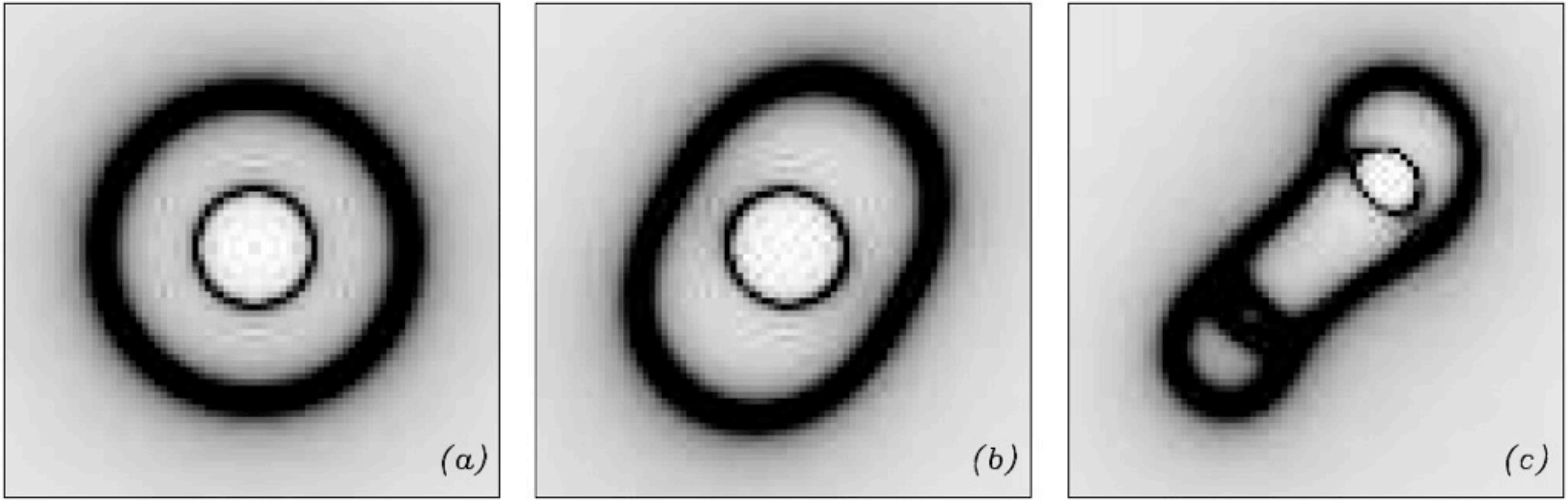


Lensing Theory

Amplification map for:

Circular Elliptical Bimodal

mass distribution

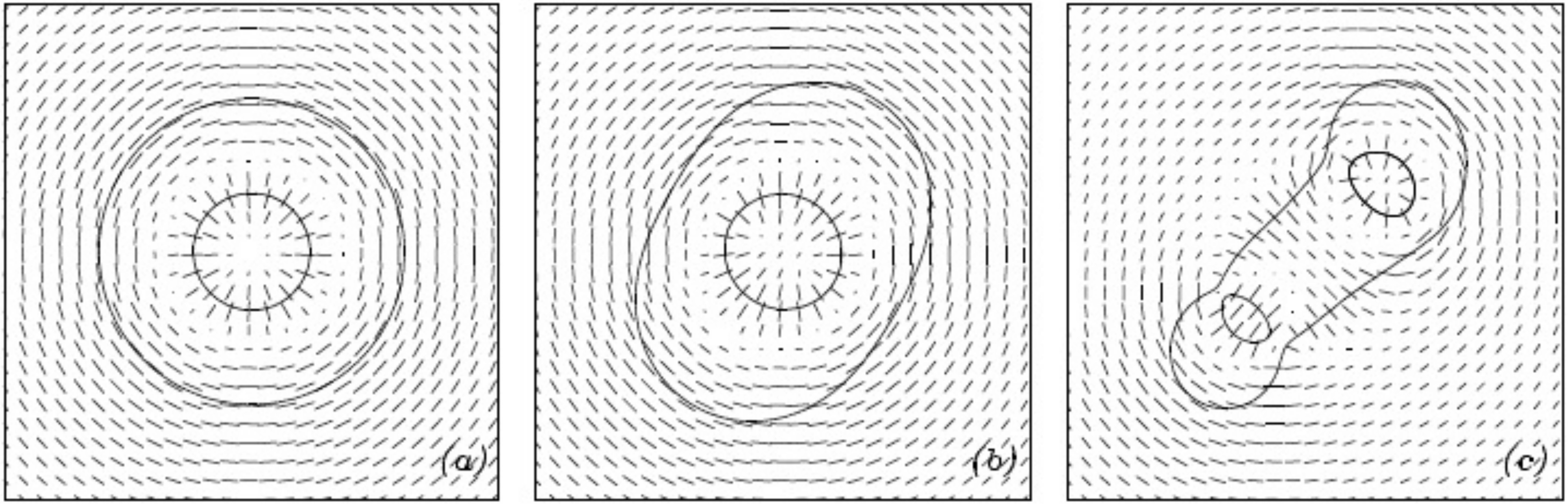


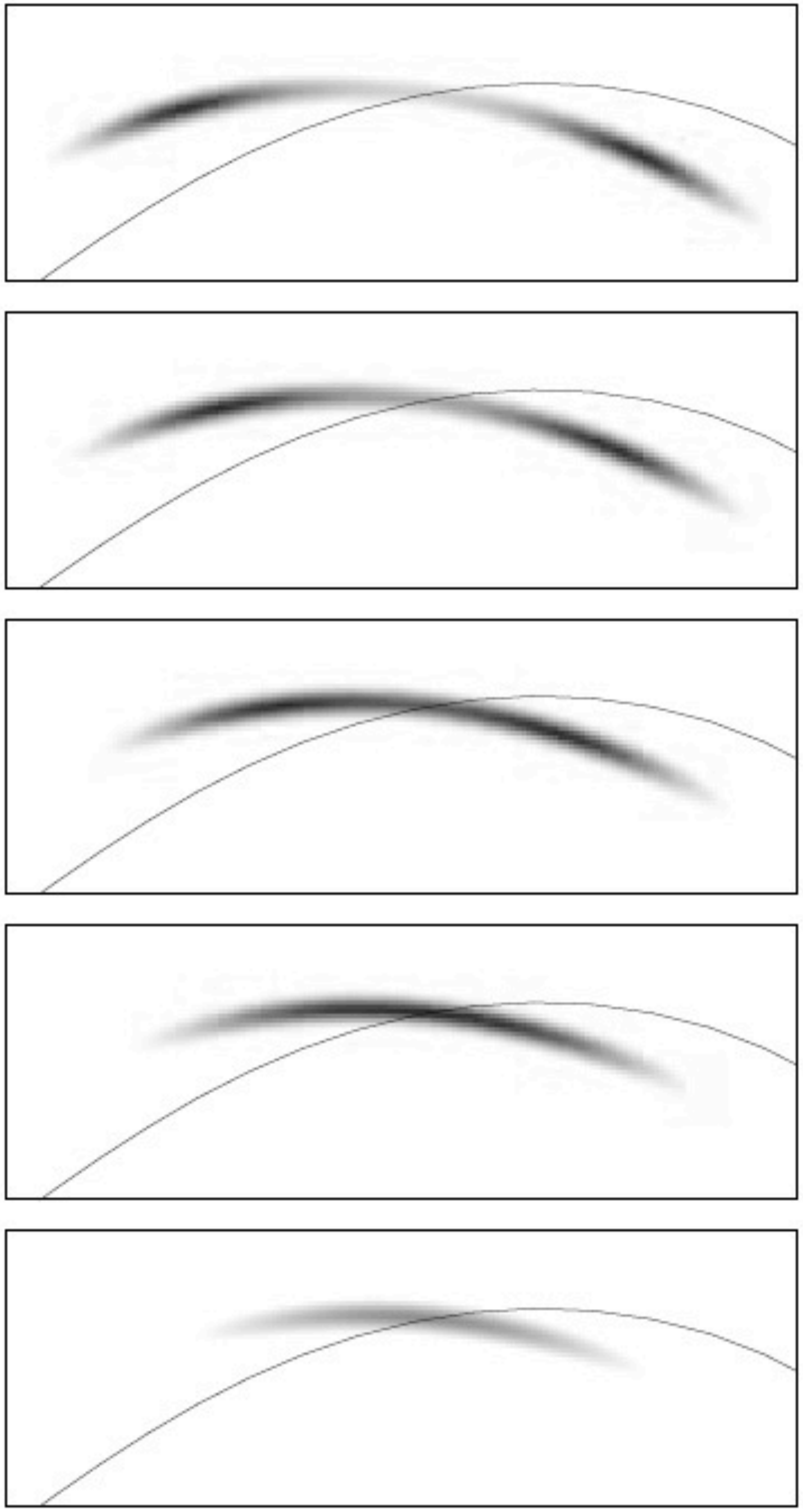
Lensing Theory

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***

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):

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

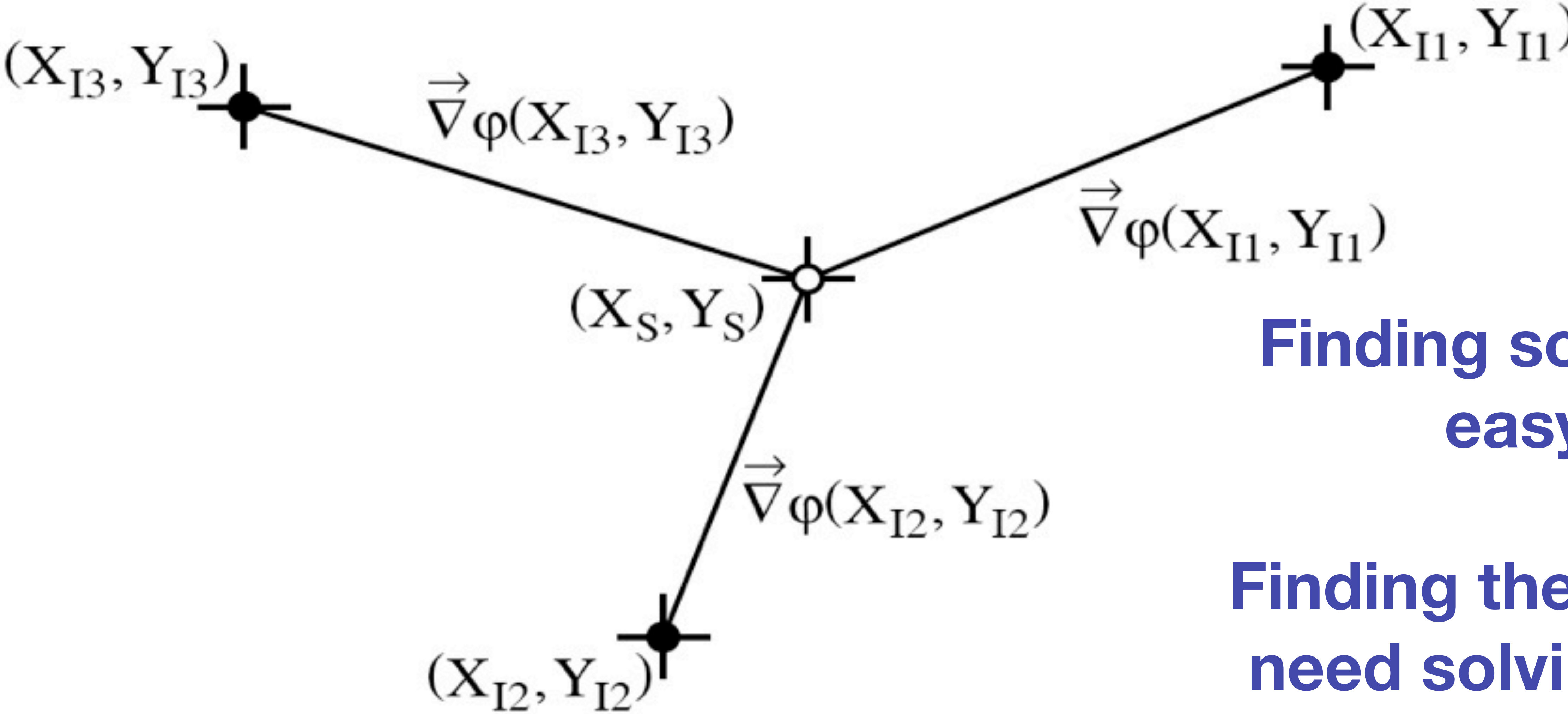
$$\approx 1.1 \times 10^{14}\, M_\odot \left(\frac{\theta_E}{30''}\right)^2 \left(\frac{D}{1\,\mathrm{Gpc}}\right)$$

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

Strong Lensing

Lensing equation have multiple solution (Strong lensing):

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

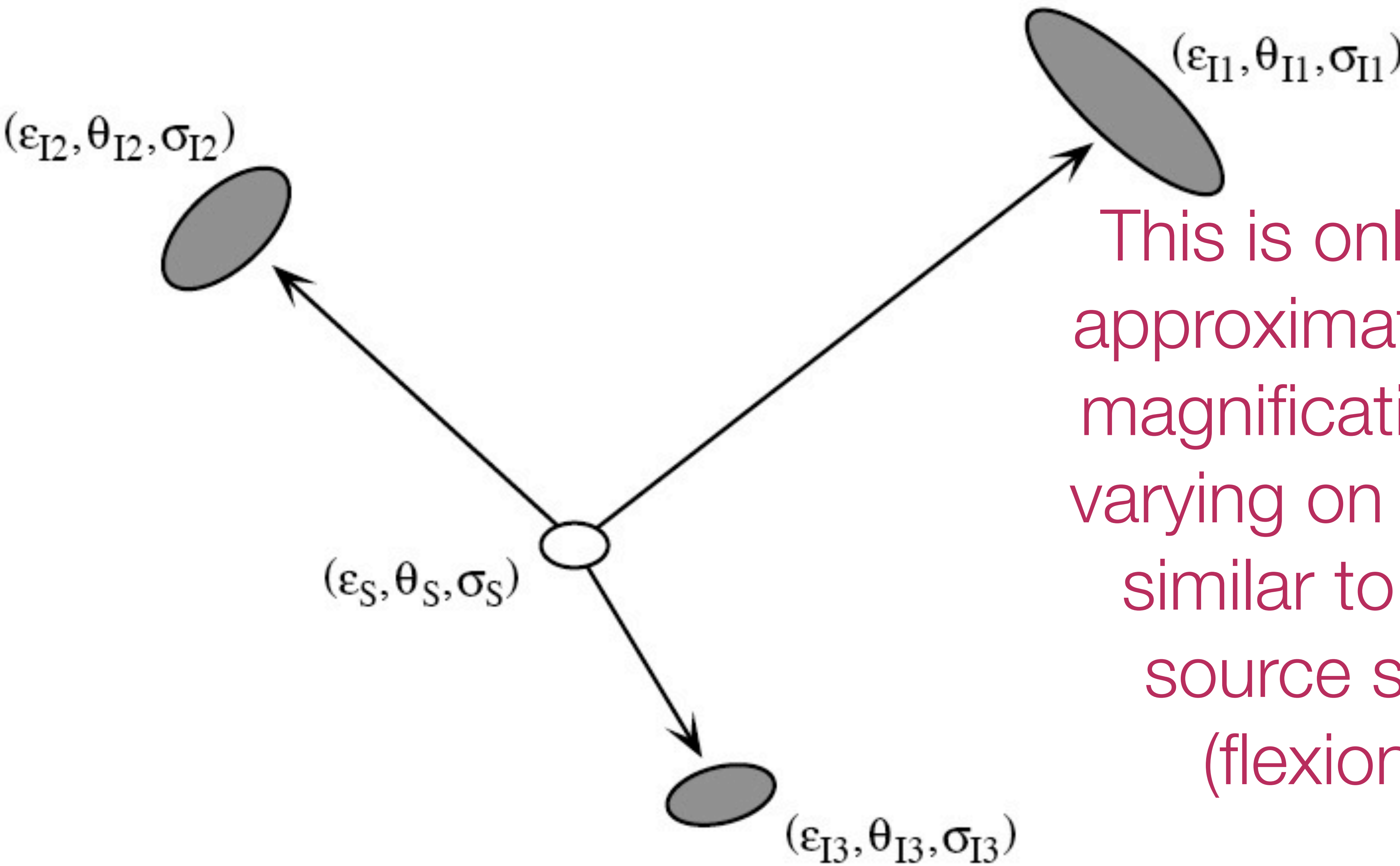


Finding source is easy!

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

Strong Lensing

Image shape are transformed depending on the local shear matrix

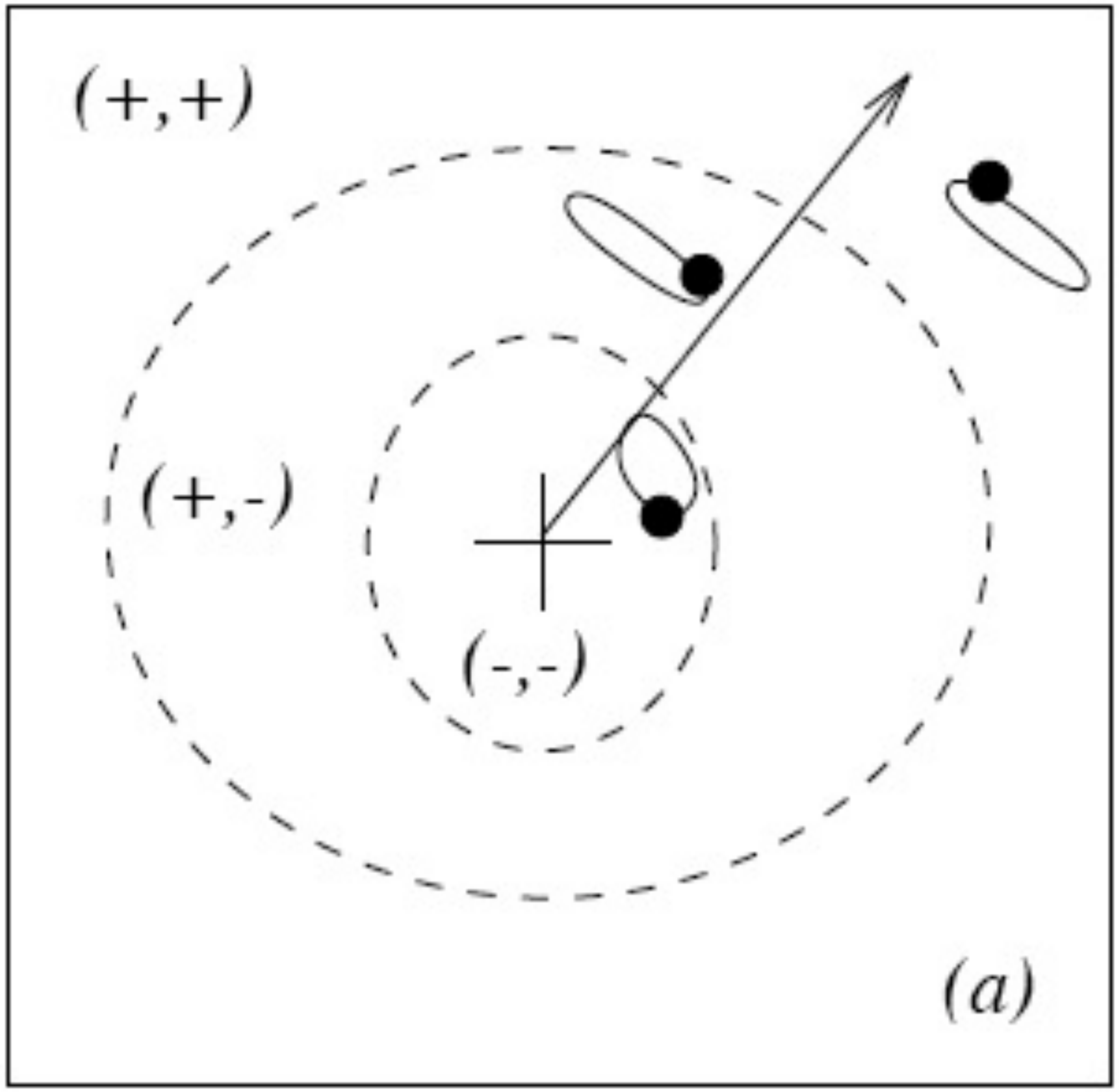


This is only an approximation if magnification is varying on scale similar to the source size (flexion)

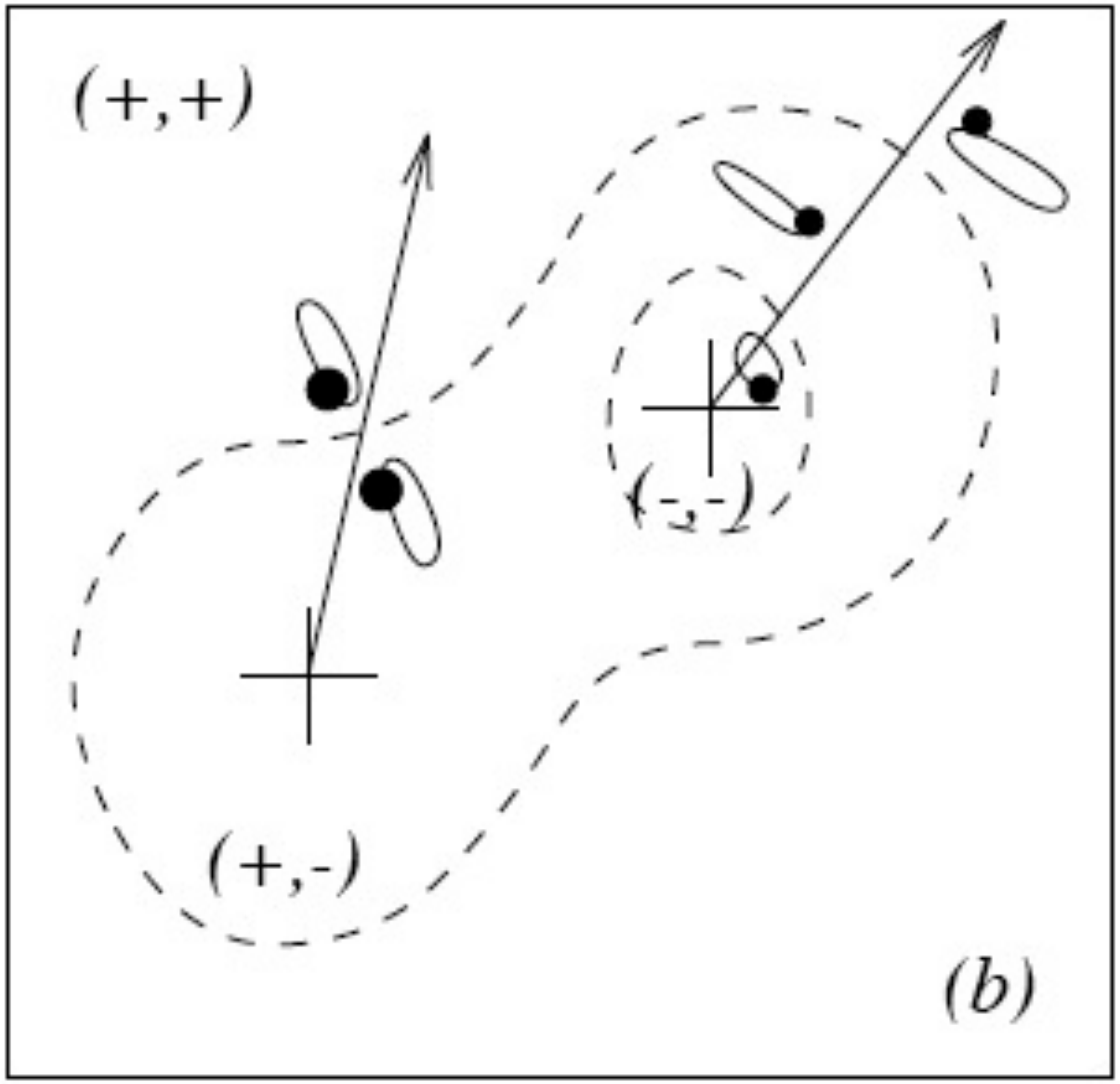
Strong Lensing

Image parity

Elliptical case

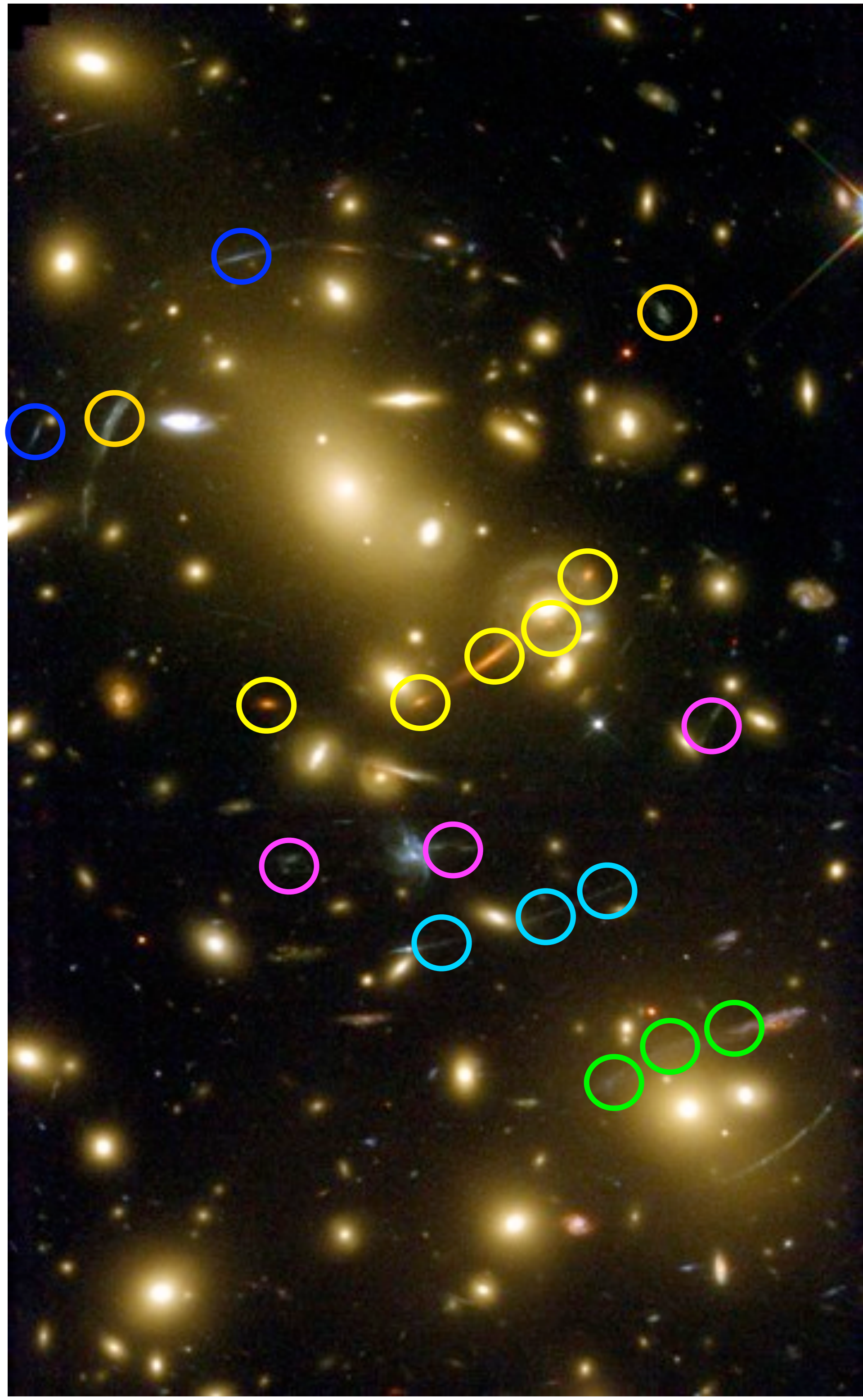


Bimodal case



Modeling

SL Cluster Modeling and Errors



Constraints:

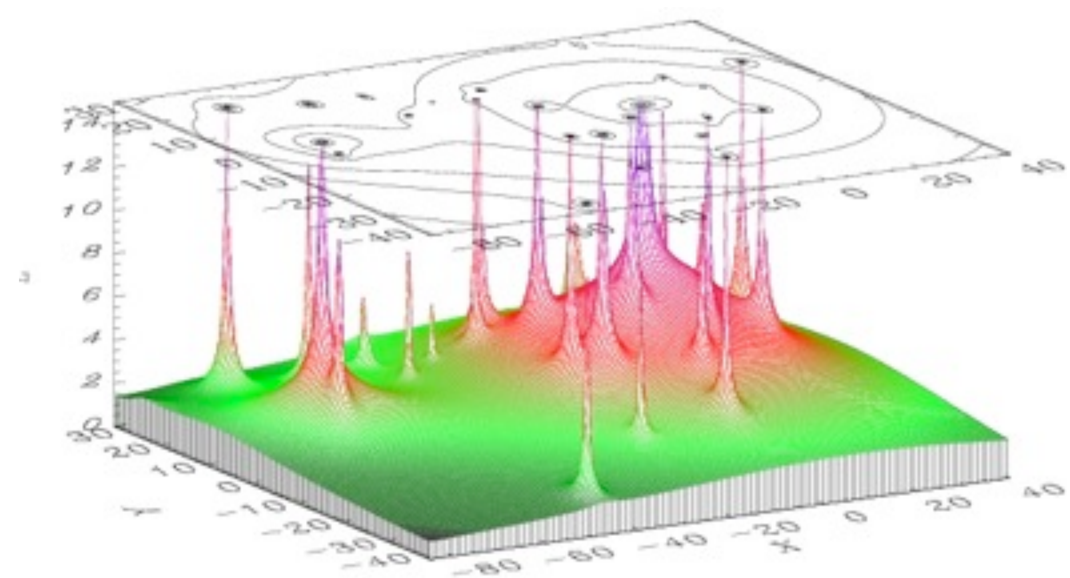
– Multiple images (position, redshift, flux, shape)
– Single images with known redshift
– Light/X-ray gas distribution

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

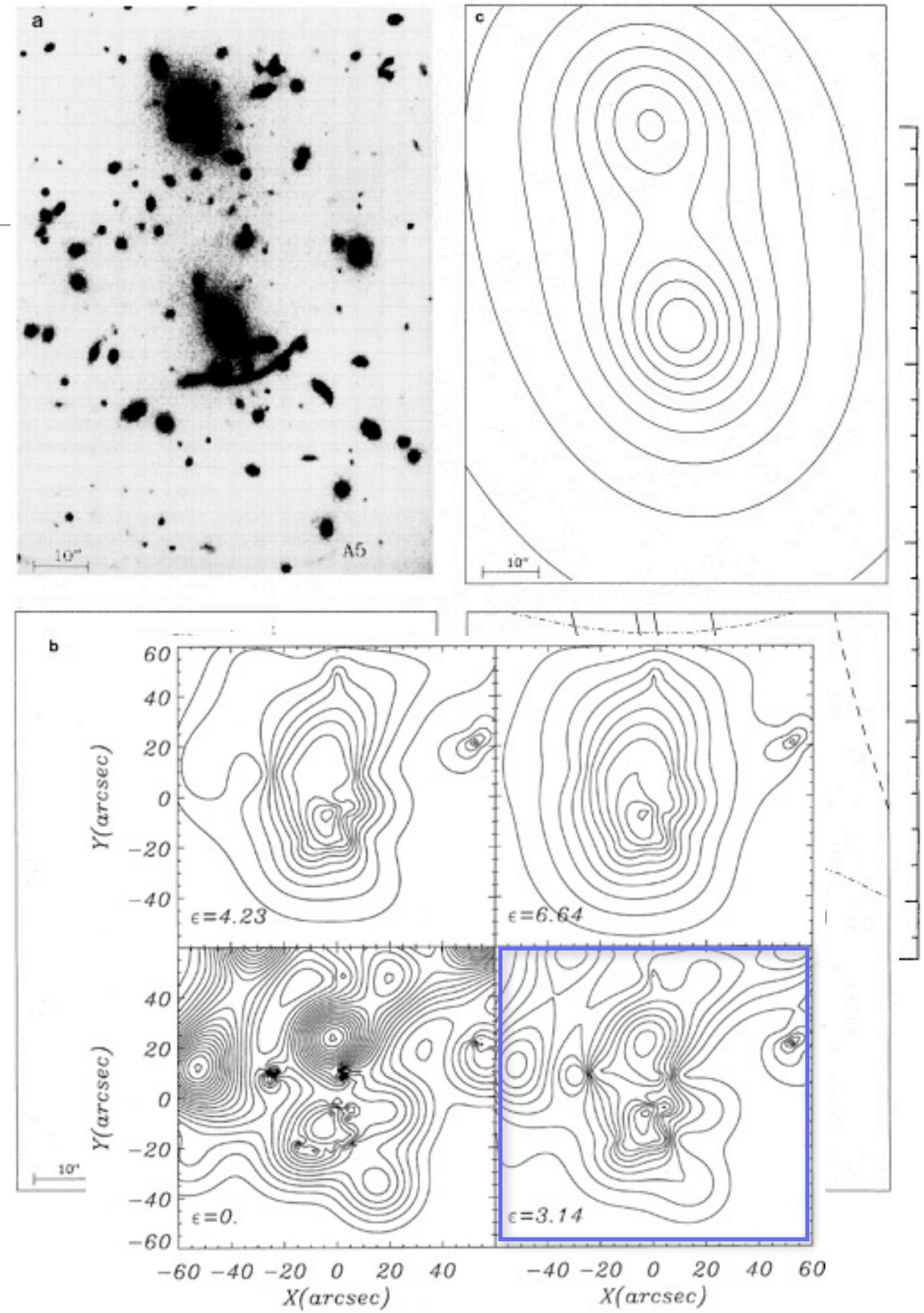
– e.g. Bayesian approach (robust errors)
– Not a unique solution: “most likely model and errors”
– *Predict amplification value and errors => cluster as telescopes*



Jullo et al 2007, Jullo & Kneib 2009
***LENSTOOL* public software http://www.oamp.fr/cosmology/lenstool**

strong lensing cluster models

- 1993: Kneib et al: A370
  - Bimodal mass distribution
- 1996: Kneib et al: A2218
  - Including galaxy halos
- 1998: Abdelsalam et al: A370
  - First non-parametric modeling
- 2002: Sand et al: MS2137-23
  - including velocity dispersion
- 2005: Broadhurst et al: A1689
  - 30 systems of multiple images
- 2005: Diego et al: A1689
  - Non parametric mass model (POSTER)
- 2007: Jullo et al: technical paper
  - MCMC cluster optimization
- 2009: Jullo & Kneib:
  - Multi-scale grid approach
- 2010: Coe et al: A1689
  - LensPerfect
- 2010: Morandi et al: z~0.2 clusters
  - Including Xray, SZ and triaxiality



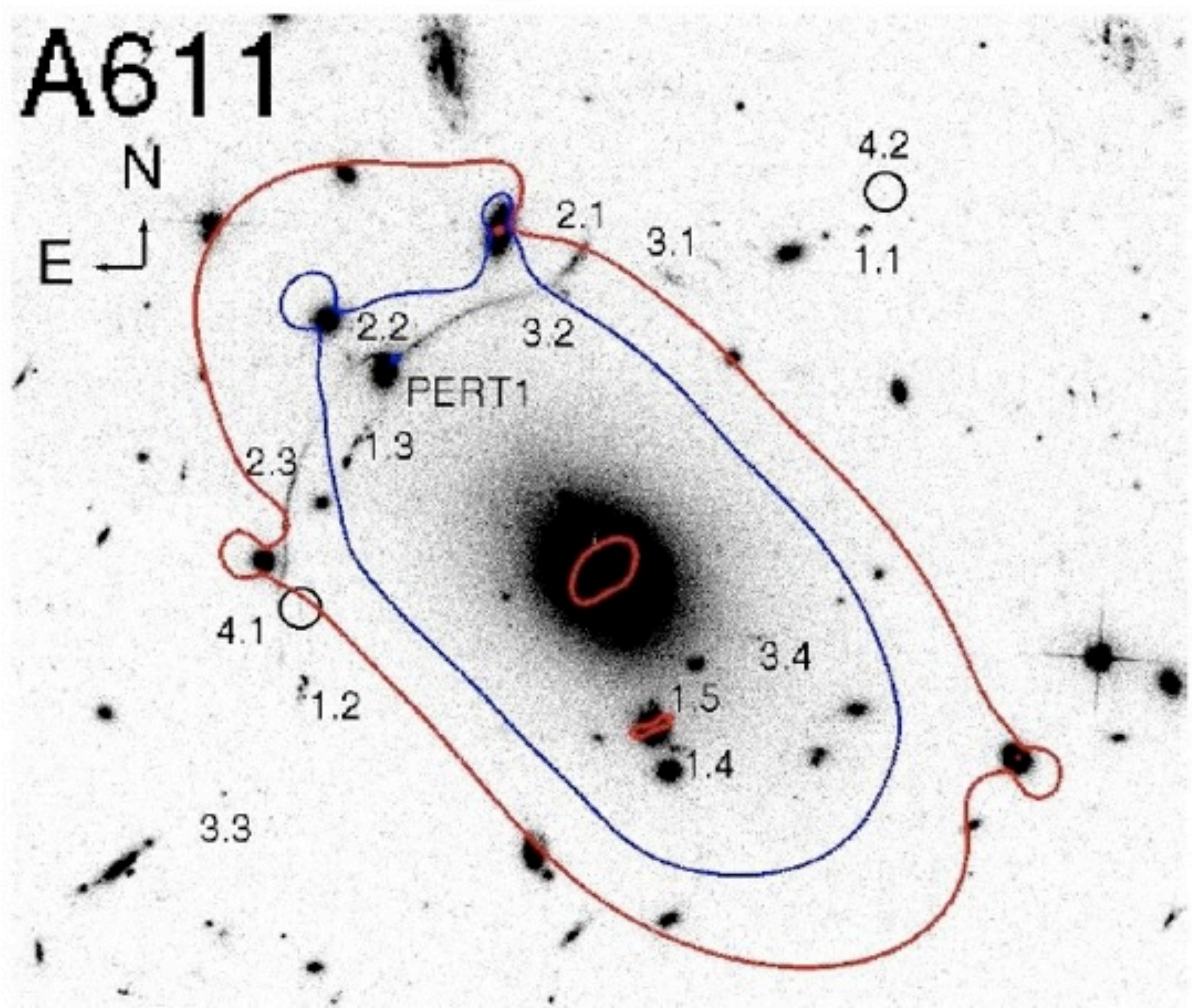
Cluster modeling

- 20+ LoCuSS clusters z ~ 0.2
Richard et al. 10

- 40+ MACS clusters z ~ 0.3-0.7
Ebeling et al. 07, Zitrin et al. 10 Richard et al in prep

- 20+ others in particular SDSS/ RCS2
e.g.Bayliss et al. 11

~ 100 clusters with lensing model !!!



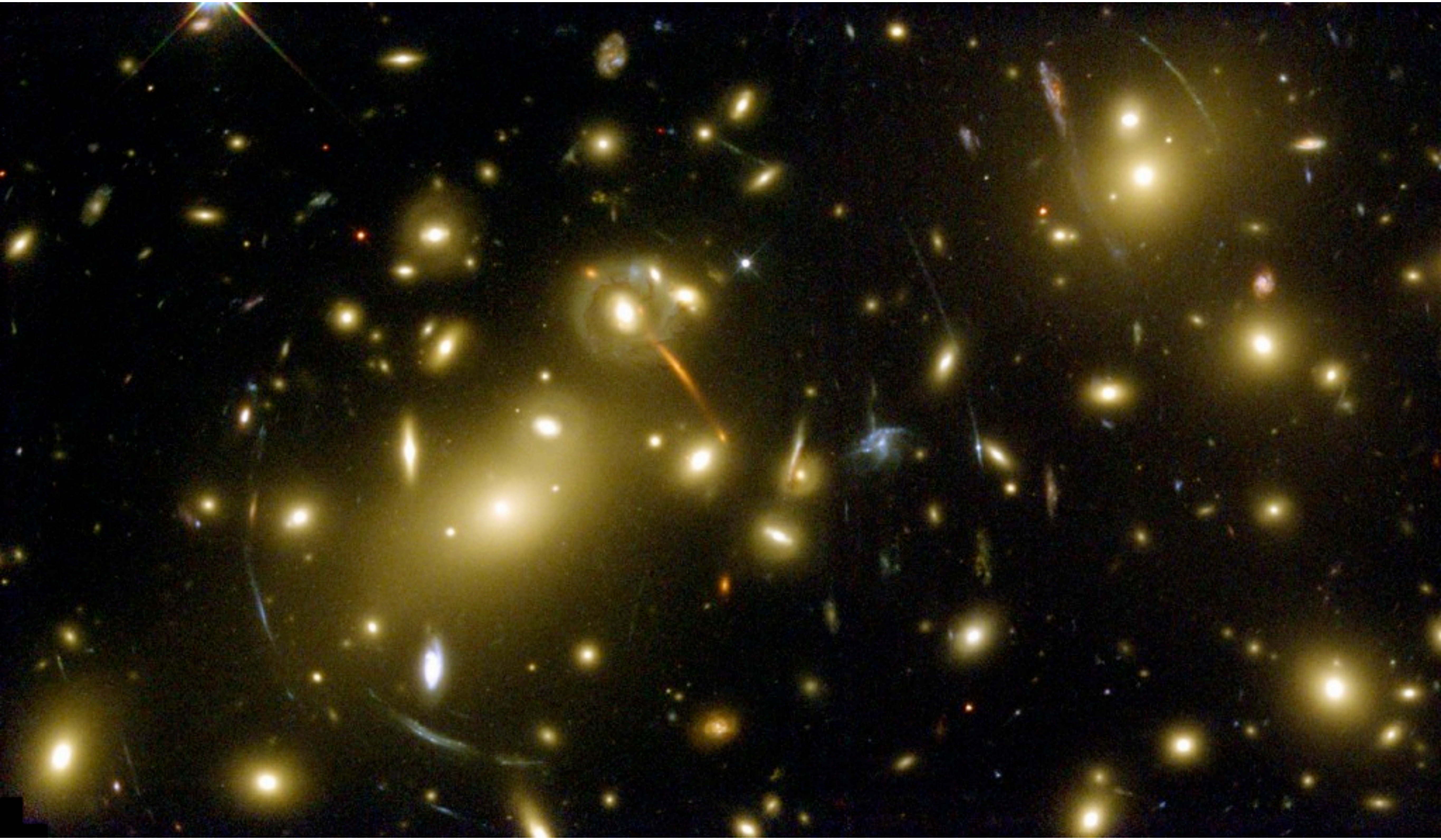
Modeling

- 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)
- Modeling confirmation/finding
- Still missing an automatic software for multiple image identification! Human eye is still the best!

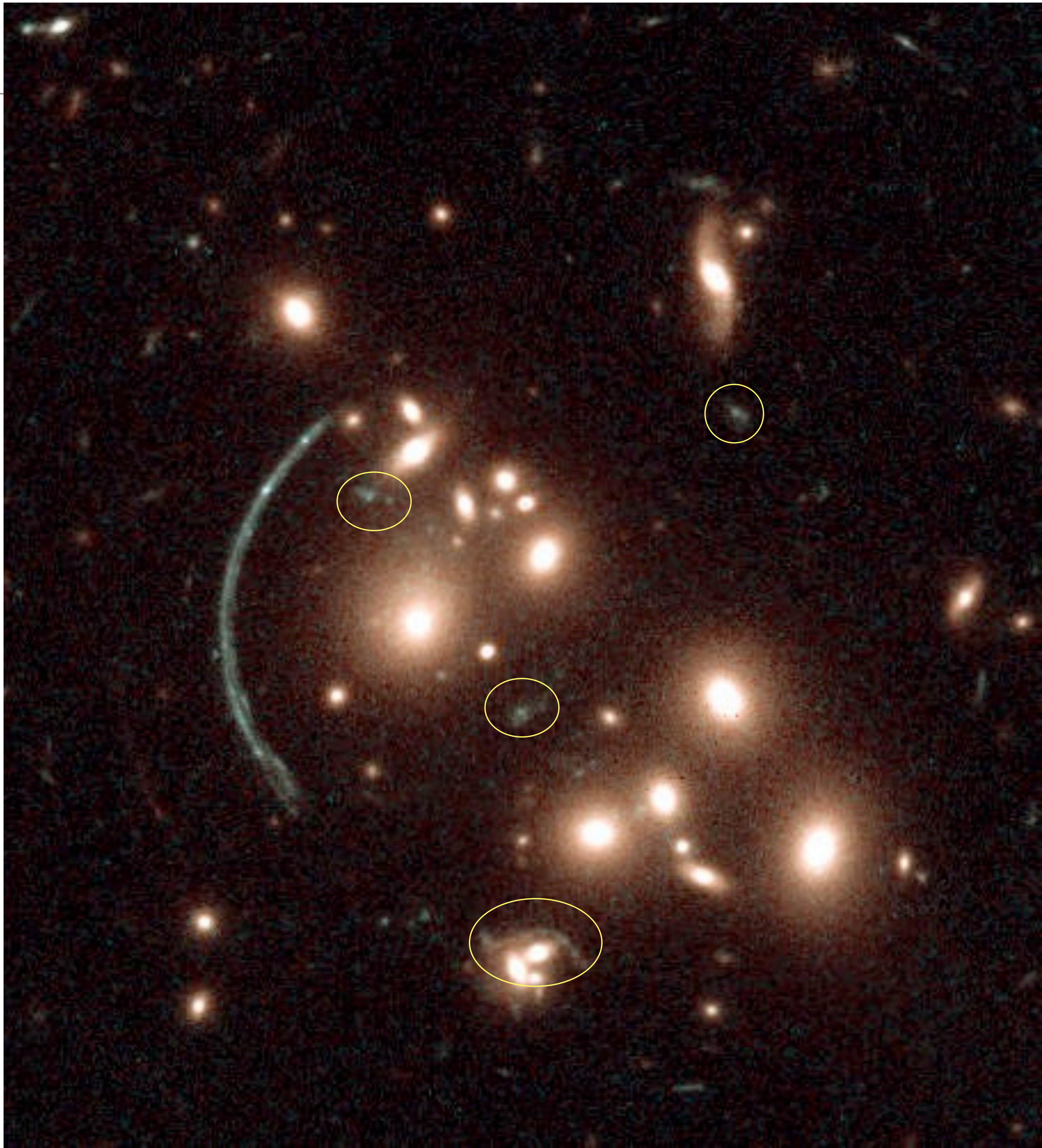
<u>Best strong lensing data:</u> *Hubble* (color) images



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

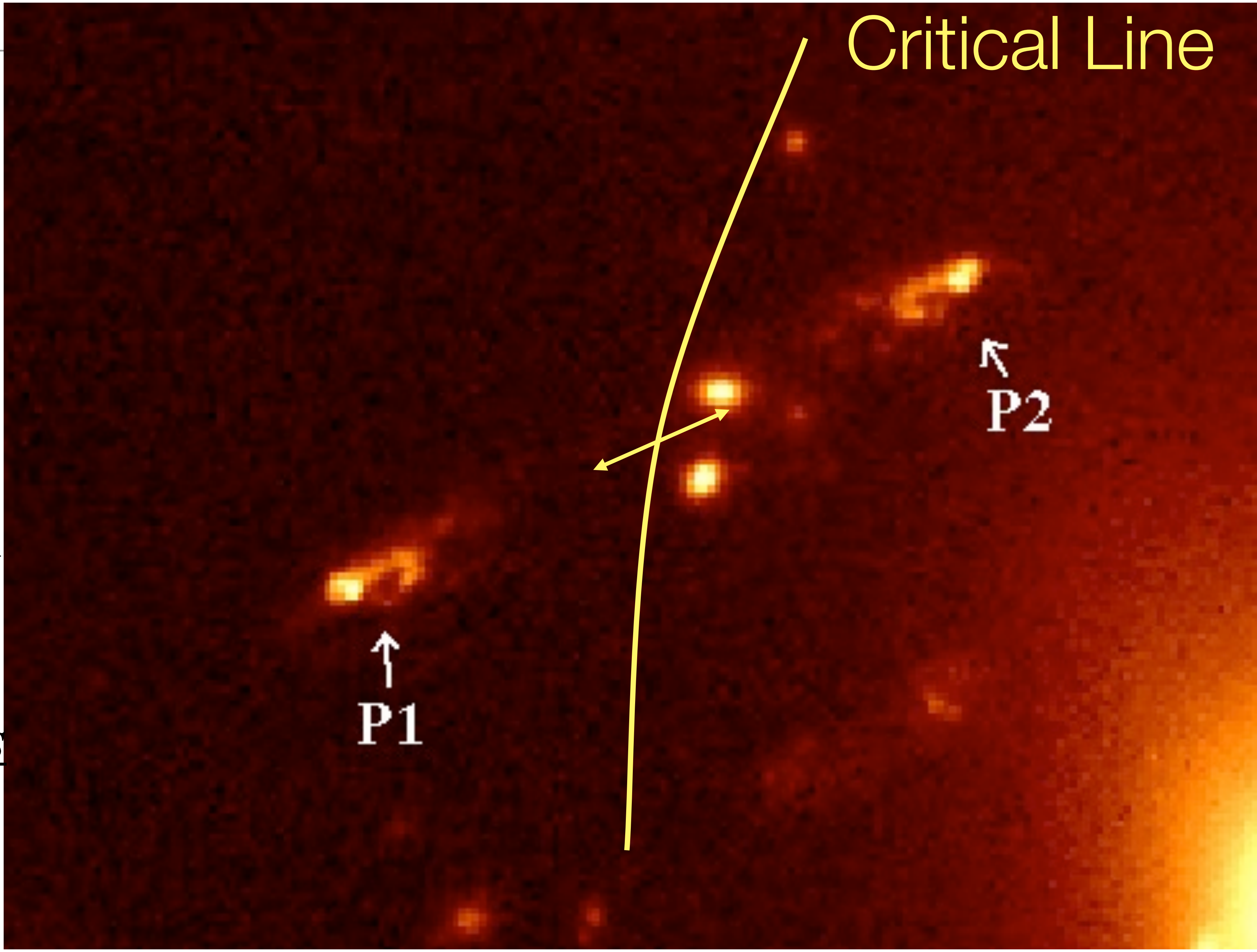


Giant arc in Cl2244-04, z=2.24, Septuple image

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.



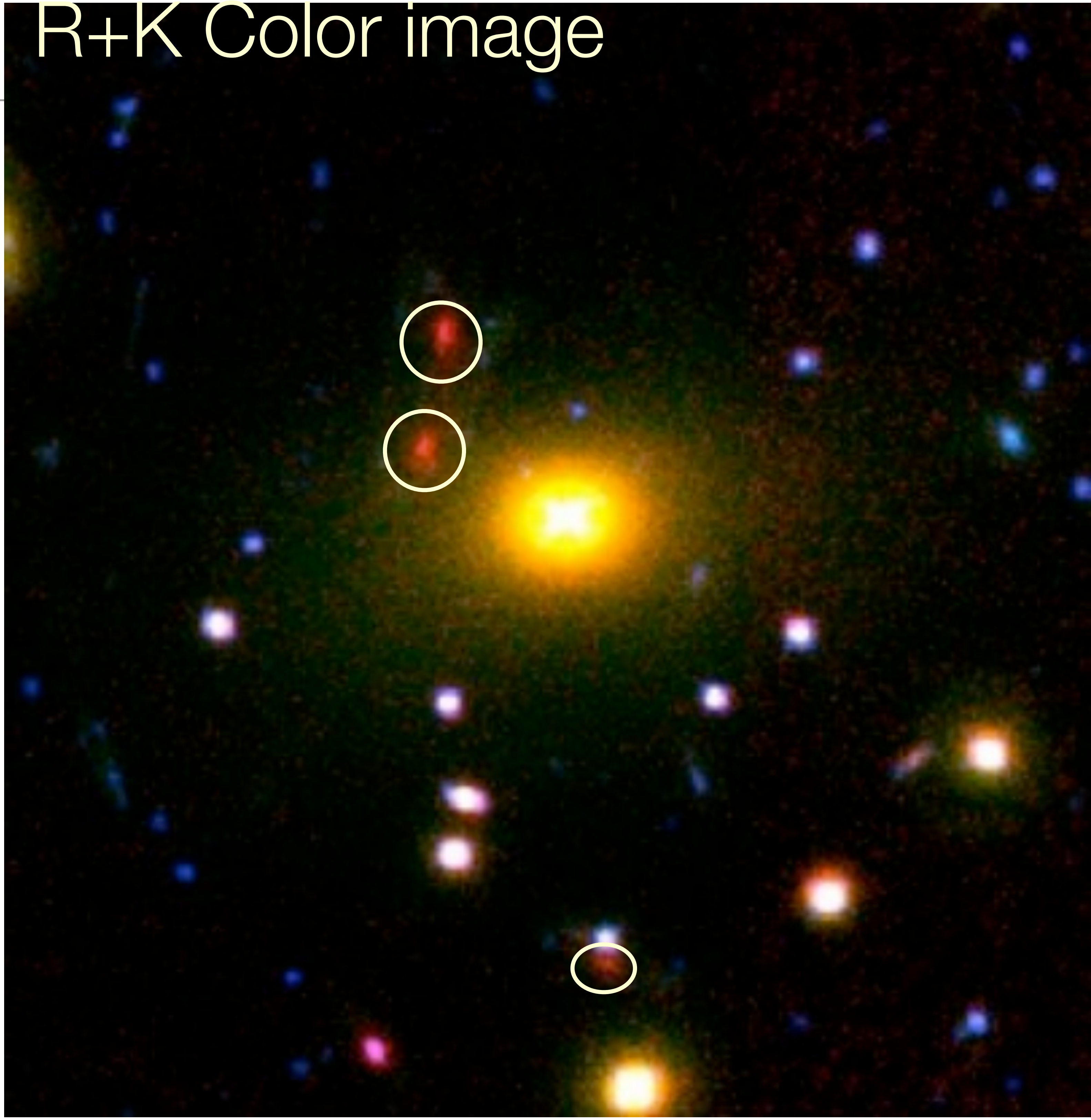
Lensed pair in AC114, z=1.86

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)**

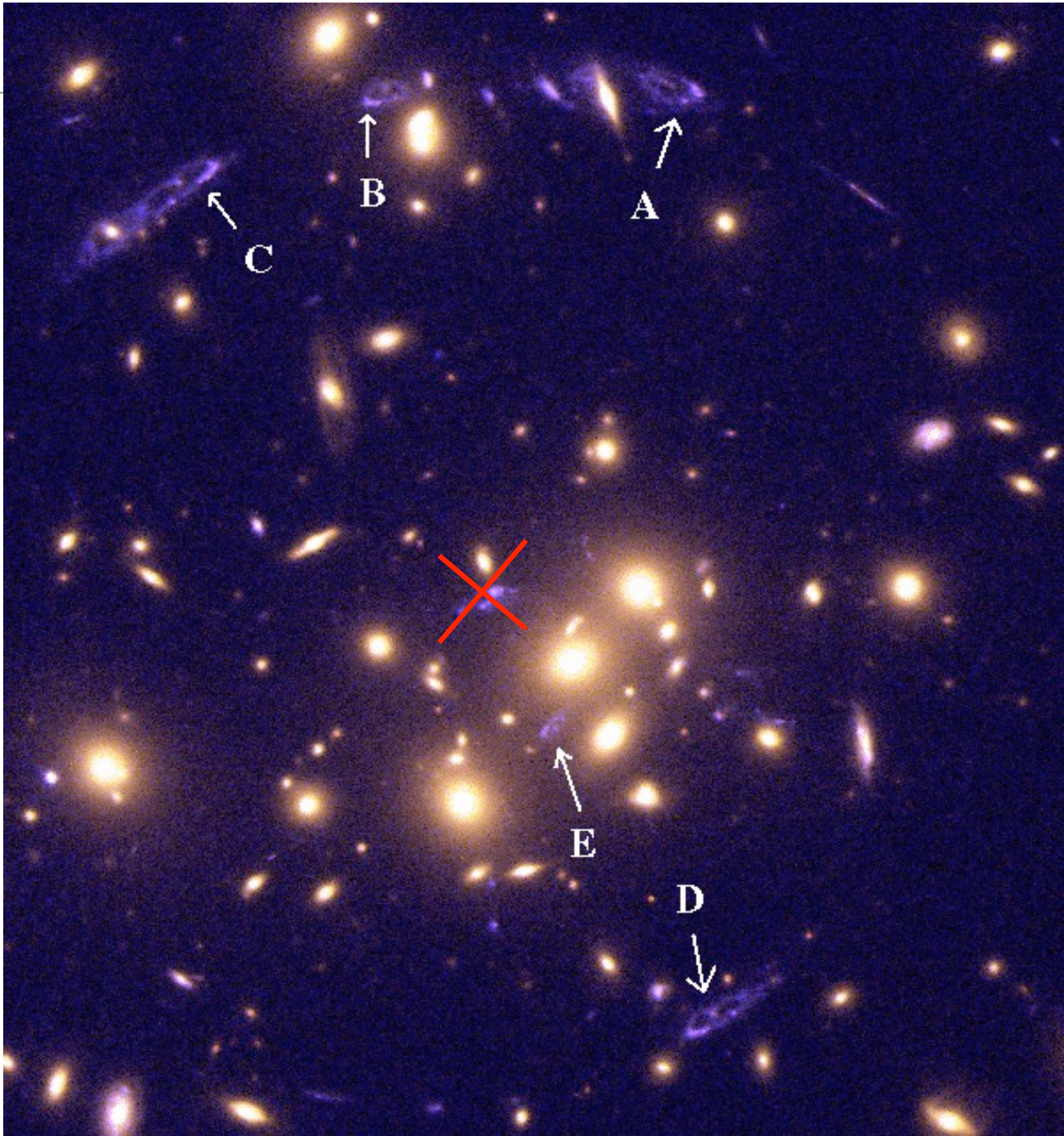


Abell 68: ERO triple image at z~1.6

How to identify multiple images ?

Color and Morphology:

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

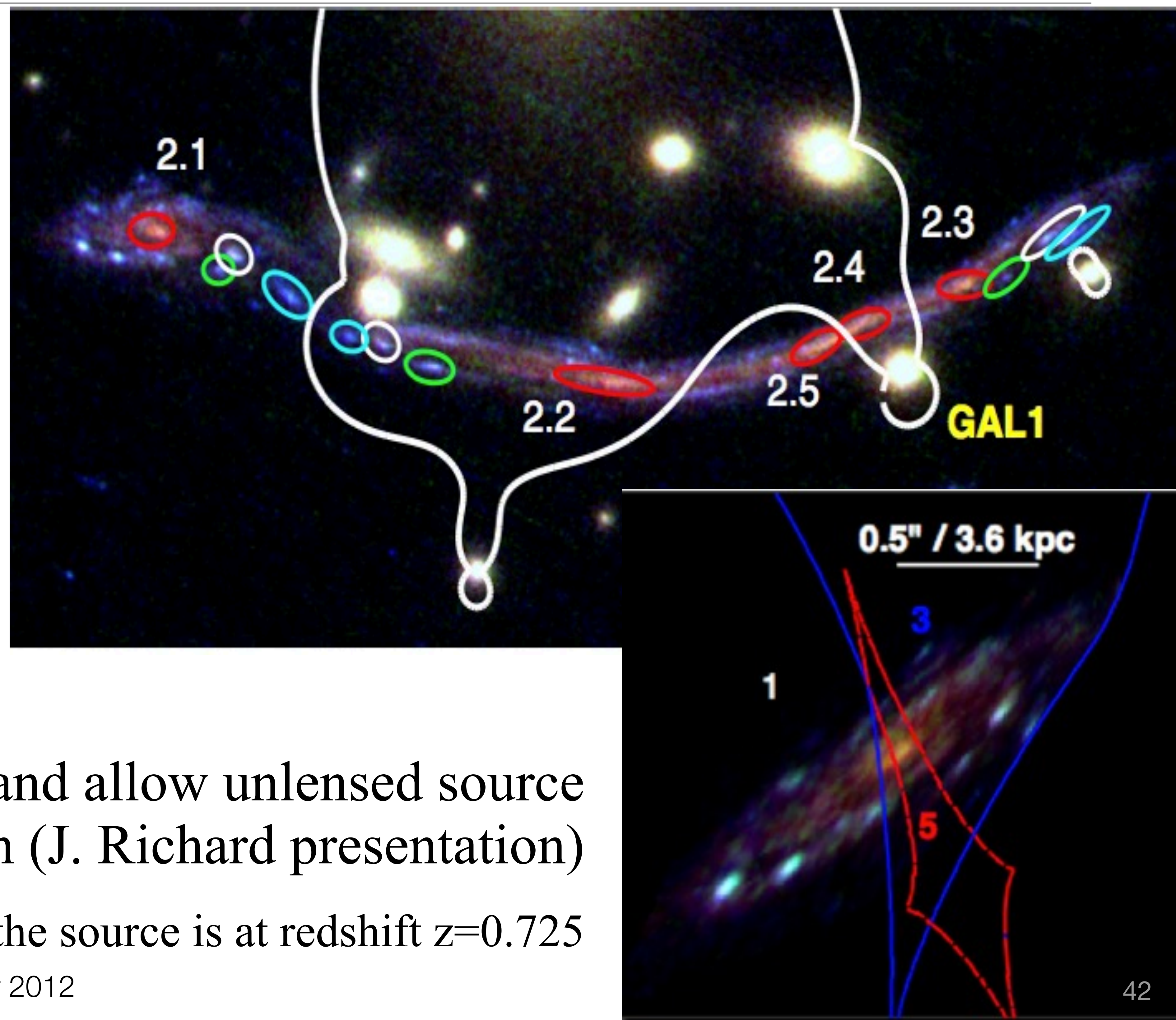


Quintuple arc (z=1.67) in Cl0024+1654 (z=0.39)

How to identify multiple images ?

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

HST multi-color images help understand giant arc morphologies…

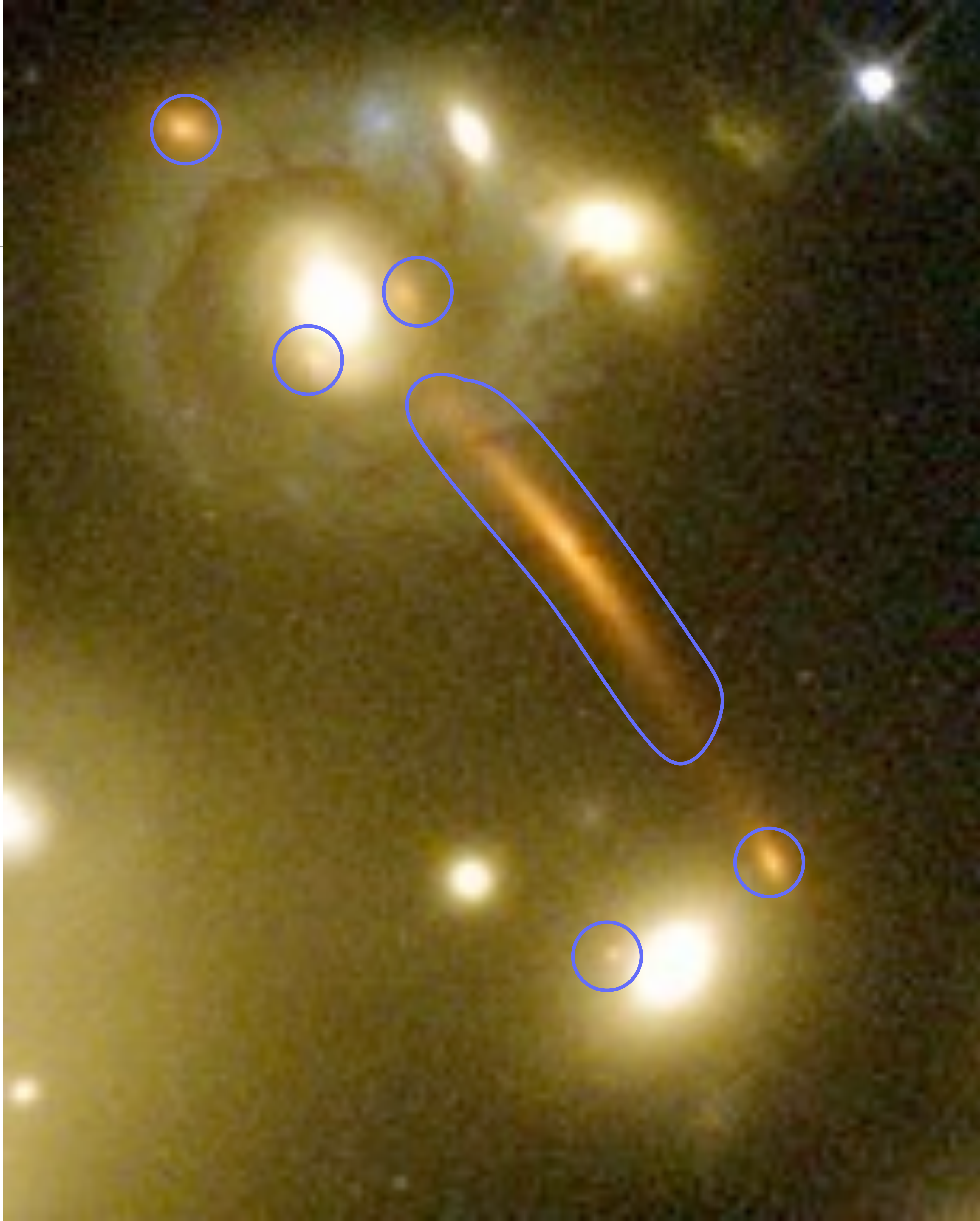


… and allow unlensed source reconstruction (J. Richard presentation)

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)

Modeling

- <u>Mass model parametrization</u>

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:

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

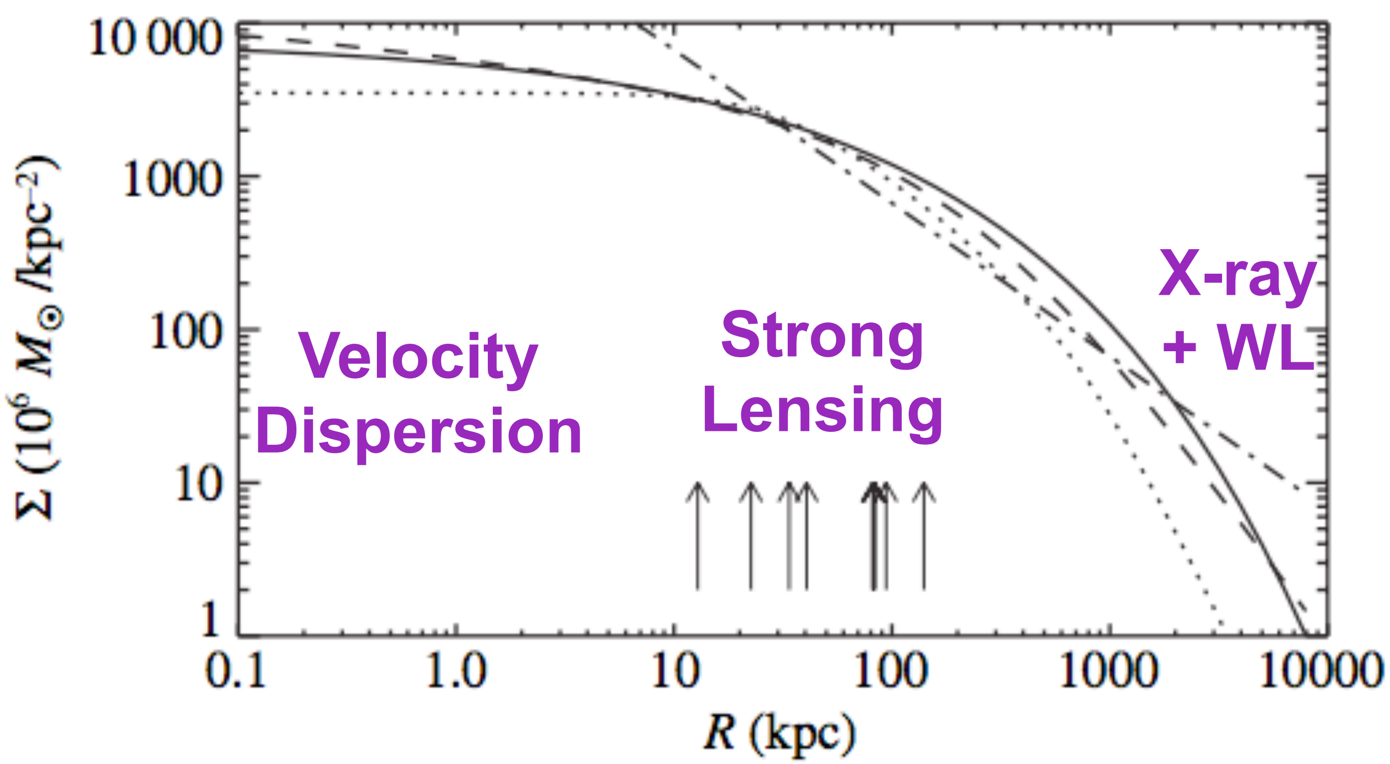
- Hence: $\frac{M}{L} \propto L^{\eta - 1/2}$

$\eta = 1/2$ 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?)

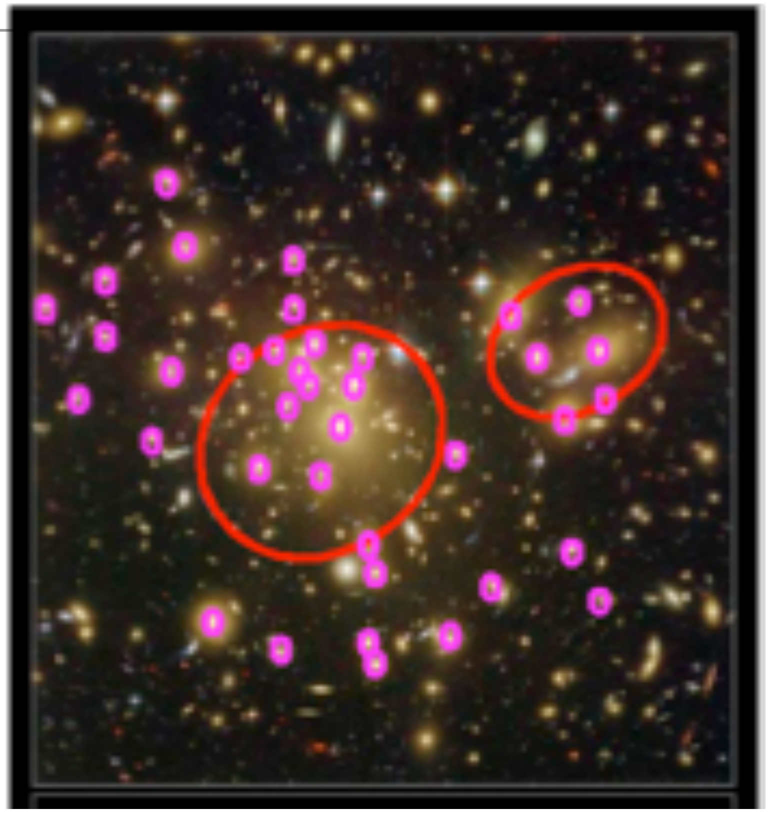


Additional data useful to constraints further the mass profile

Strong lensing modeling strategies

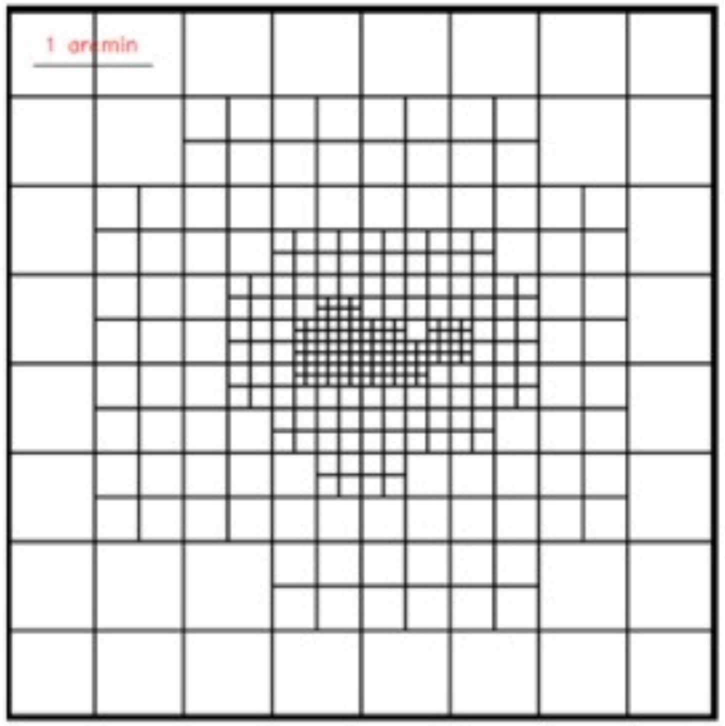
Observationally motivated models

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

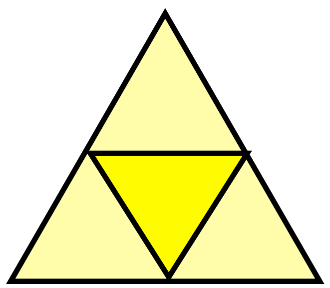


Grid-based models

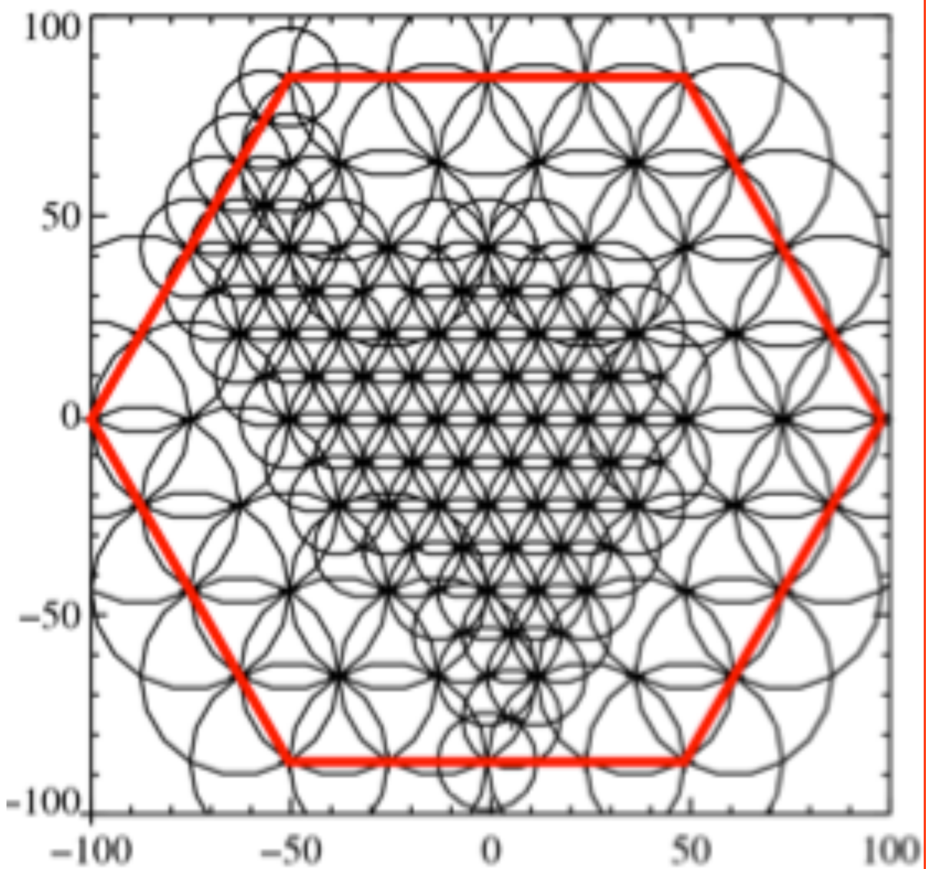
- Decomposition into pixels/clumps
- Complex clusters
- Lots of constraints
- Better fit with lots of constraints



Multi-Scale Grid Based Modeling



ACS field of A1689



More flexible "multi-scale" model:

- hexagonal/triangle padding- to match the natural shape of clusters
- Multi-scale: split triangles according to a mass density threshold
- Circular mass clump at each grid point:
  - Truncated isothermal profile with a core
  - size of the mass clump depends on the grid: r_core =grid-size
  - Truncation also depends on the grid: r_cut/r_core = 3
  - one free parameter for each clump
- Add galaxy-scale mass clumps
- MCMC optimized
- Easy extension to WL regime

Jullo & Kneib 2009

Grid-based models

Jullo & Kneib 2009

Linearized lensing quantities

$$\begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_M \end{bmatrix} = \begin{bmatrix} M_{11} & \dots & M_{1N} \\ \vdots & \ddots & \vdots \\ M_{M1} & \dots & M_{MN} \end{bmatrix} \begin{bmatrix} c_1 \\ \vdots \\ c_N \end{bmatrix}$$

with

$$M_{ij} = \alpha_i(|\theta_i - \theta_j|)$$

(i) grid geometry from *a-priori* known light map

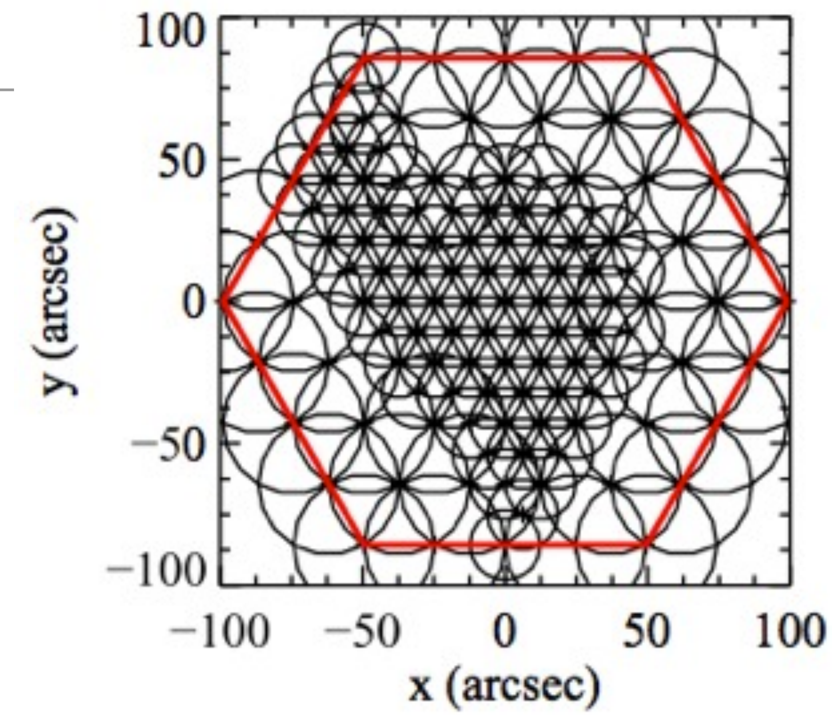
(ii) extended RBF to obtain smooth maps

(iii) mass must be positive (ie. $c_i > 0$)

(iii) extra data: galaxies in clusters with Sc Rel:

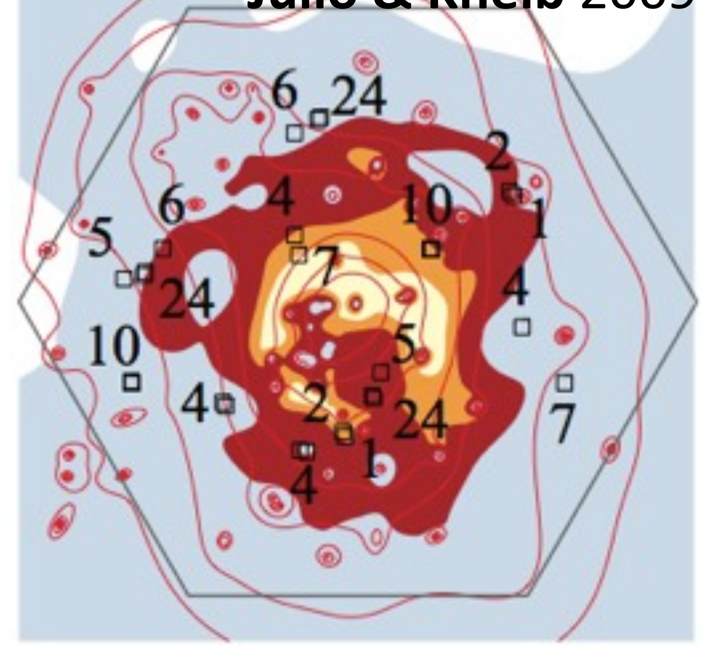
$$r_{\rm core} = r^{\star}_{\rm core}\left(\frac{L}{L^{\star}}\right)^{1/2}, \quad r_{\rm cut} = r^{\star}_{\rm cut}\left(\frac{L}{L^{\star}}\right)^{1/2}, \quad \sigma_0 = \sigma^{\star}_0\left(\frac{L}{L^{\star}}\right)^{1/4} \quad (13)$$

(iv) Likelihood exploration with Lenstool



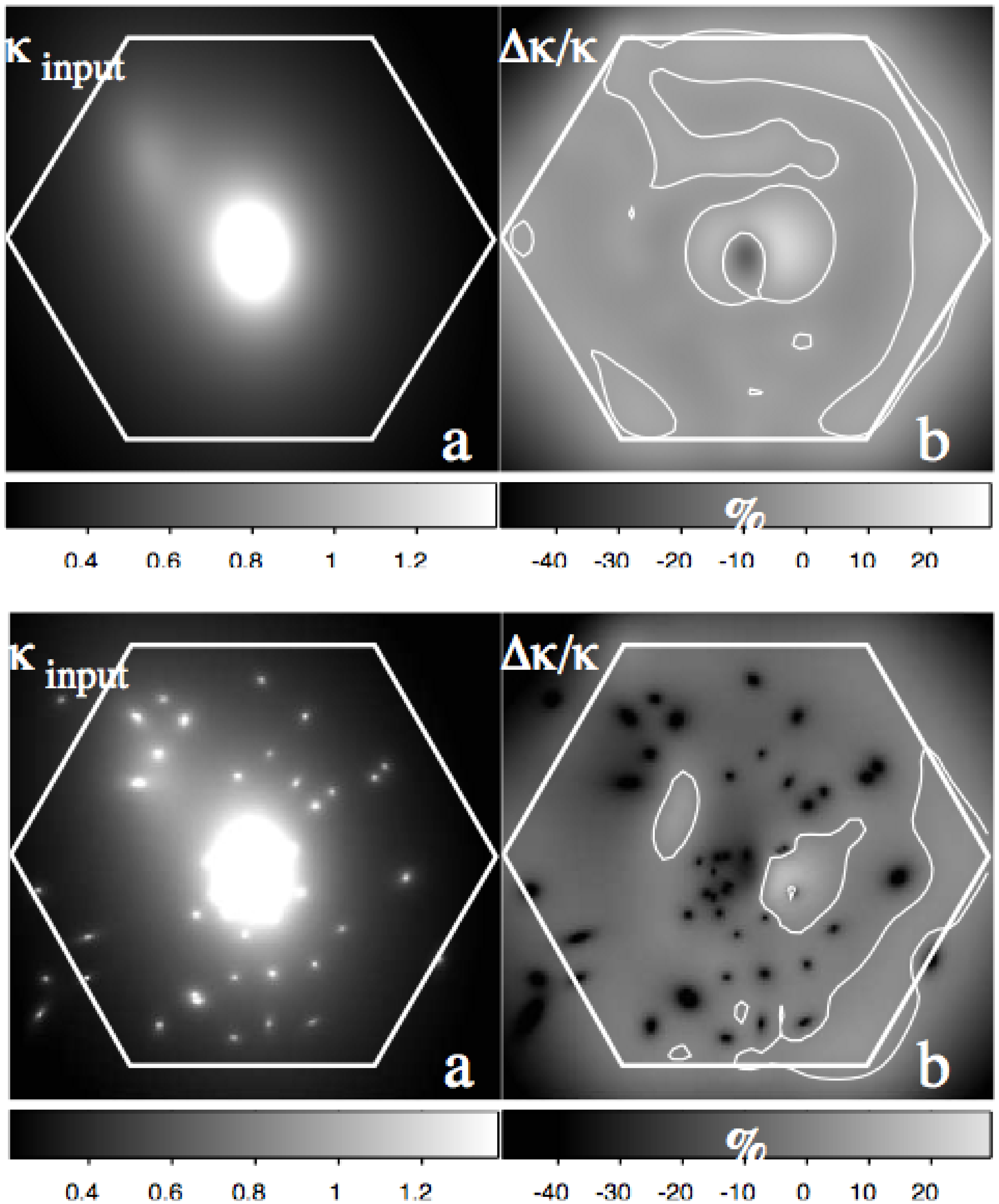
Abell 1689

Jullo & Kneib 2009

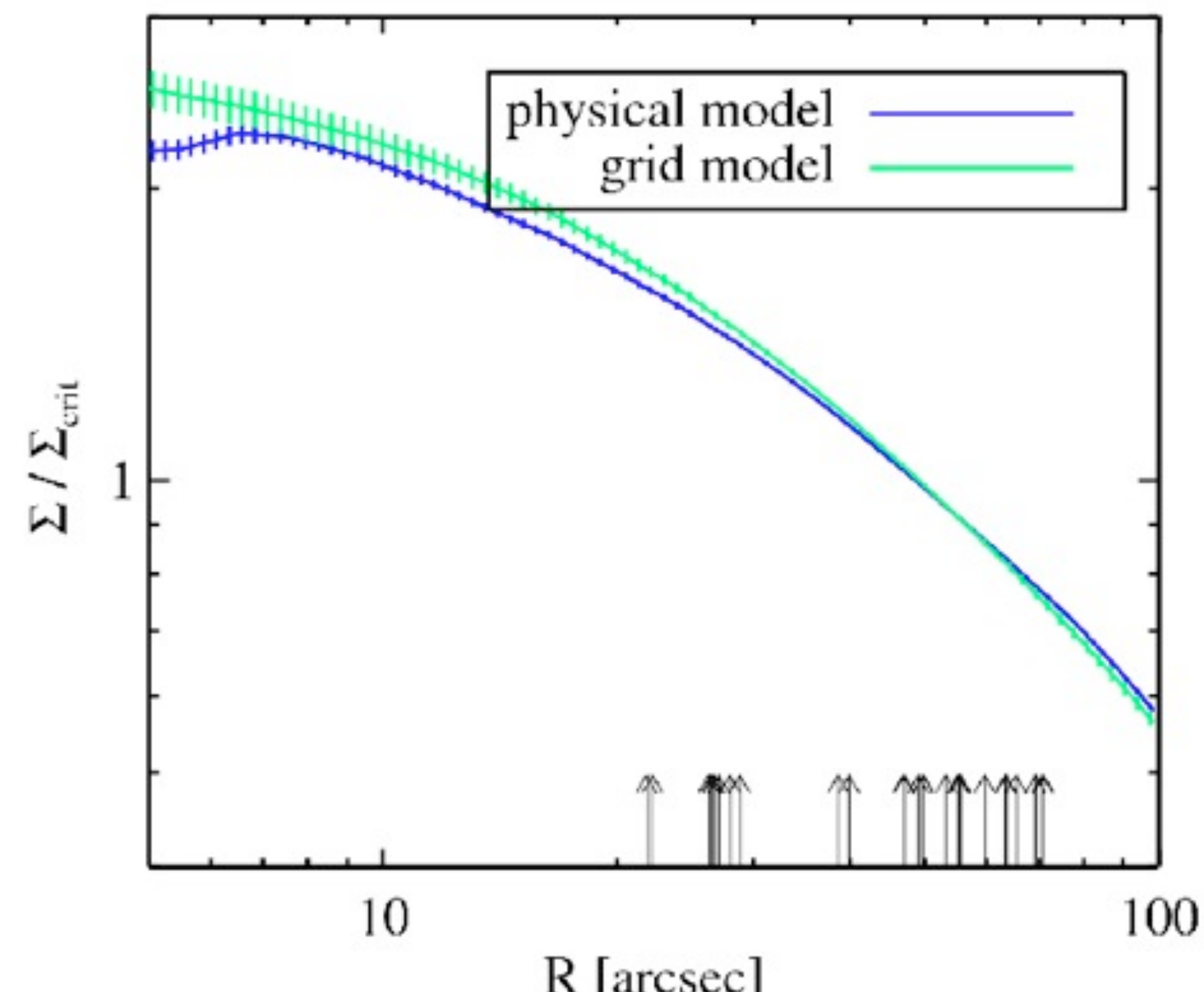


➔ **error estimates, Bayesian evidence to rank models**

Reconstructed mass profile



Multi-scale grid model adapt well to complex mass distribution but are not designed to match galaxy scale component - this needs to be modeled separately.



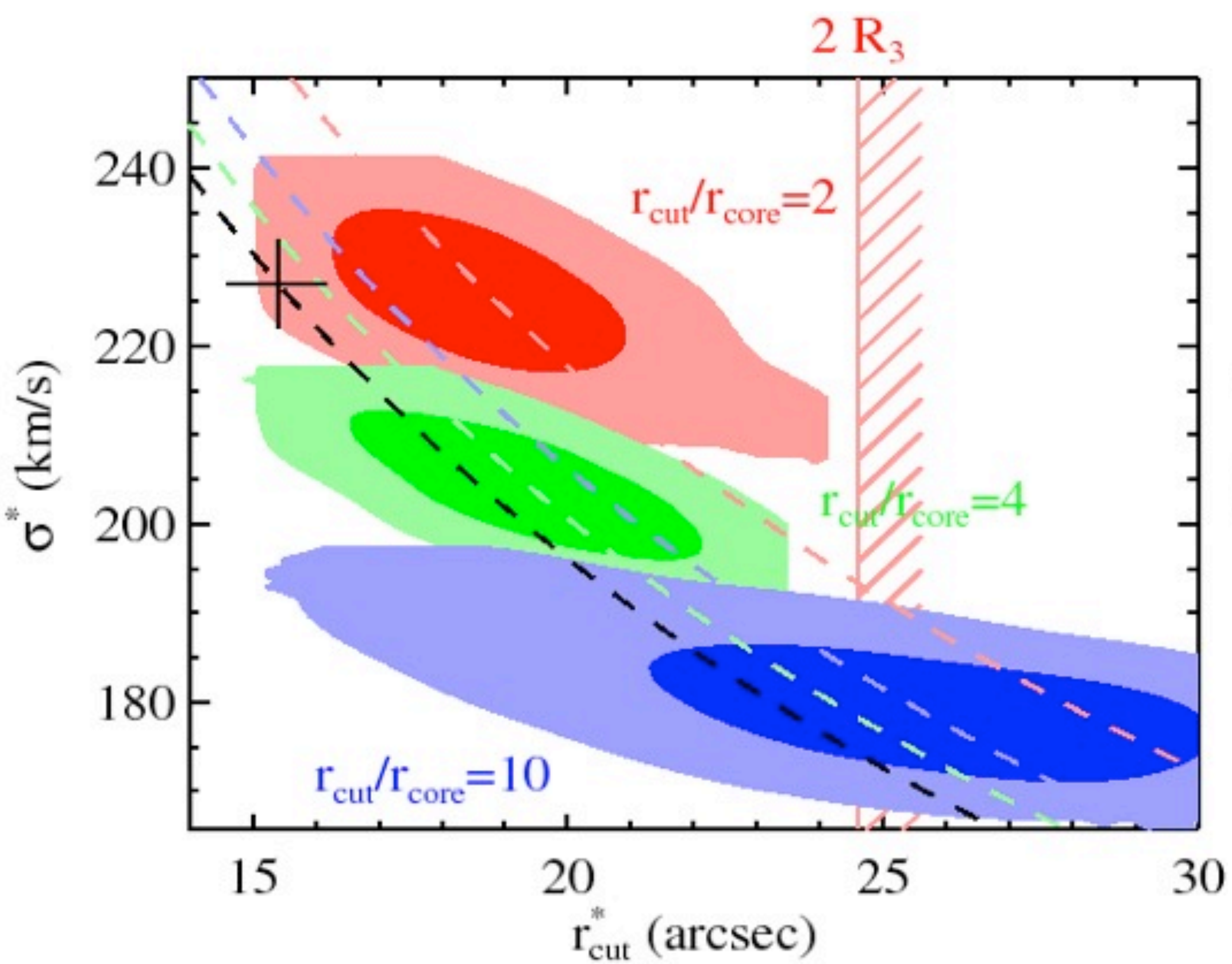
Jullo & Kneib 2009

Grid size – Galaxies degeneracy

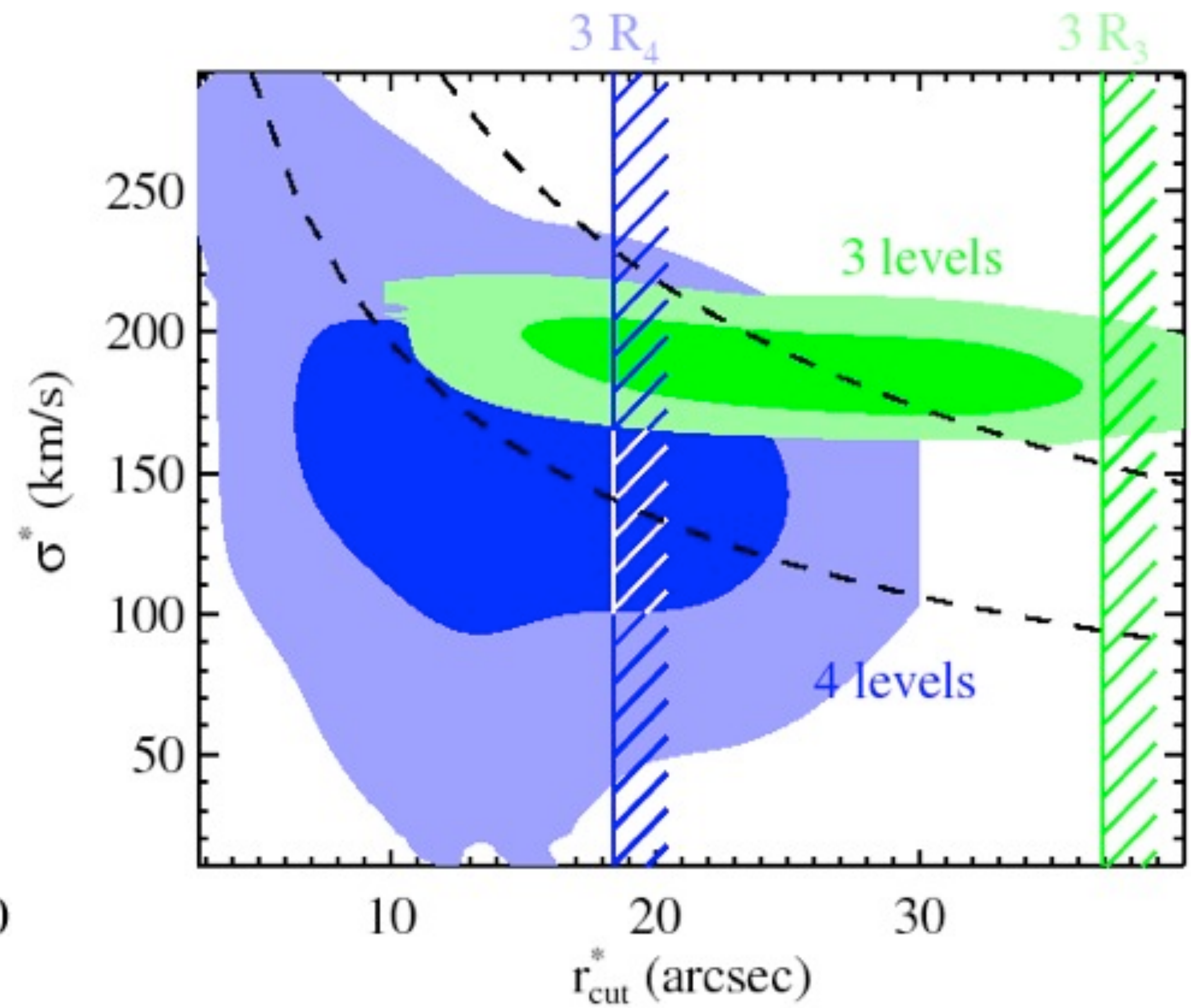
Jullo & Kneib 2009

Degeneracy between the multi-scale grid definition and cluster galaxies component

Changing the concentration of the grid clump



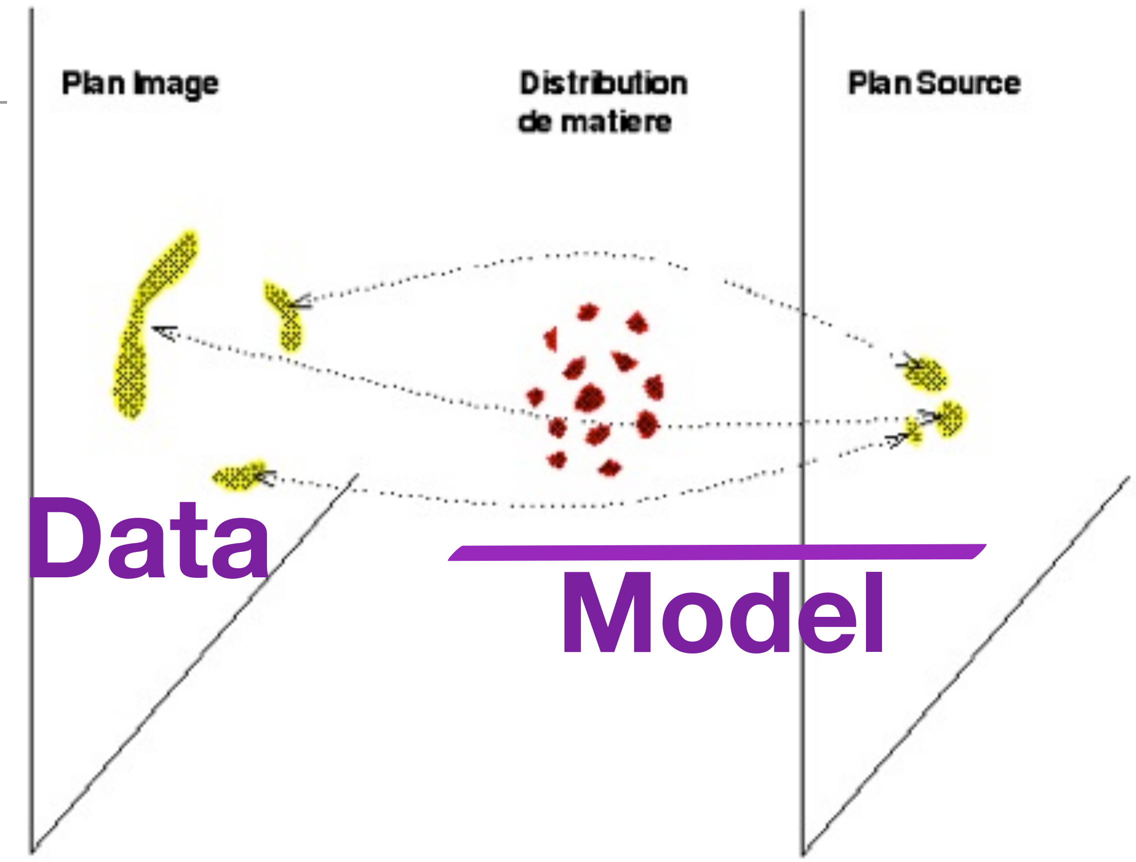
Changing the number of the grid levels



Modeling

<u>Likelihood estimator, optimisation</u>

Lens Modeling with Multiple Images



- **One system with N images:**

- # of constraints: 2N, 3N (image position+flux)
- # of unknown: 2, 3 (source position+flux)
- # of free parameter: 2(N-1), 3(N-1)

Double: 2, 3 Triple: 4, 6 Quad: 6, 9

- **η systems of N images:**

- # of free parameters: 2(N-1)η, 3(N-1)η
- *need to subtract number of unknown redshift !!*

A1689 with ACS ~30 triples: <120, <180

[=> deep JWST observations may reach ~1000]

⇒ parametric models have been favoured as there was generally a small number of constraints

⇒ Introduce other constraints:

critical line location and/or external constraints from X-ray observations or velocities (of stars in central galaxy)

Maximum Likelihood expressions

Likelihood of the *image positions* can be computed:

- in the source plane *[FAST no lens inversion needed, bad error estimate!]*
- or in the image plane *[better! real error estimate possible, SLOW]*

Source plane:

$$\chi^2_{S_i} = \sum_{j=1}^{n_i} \frac{[x^j_{\mathrm{S}}(\boldsymbol{\theta}) - < x^j_{\mathrm{S}}(\boldsymbol{\theta}) >]^2}{\mu_j^{-2}\sigma^2_{ij}}$$

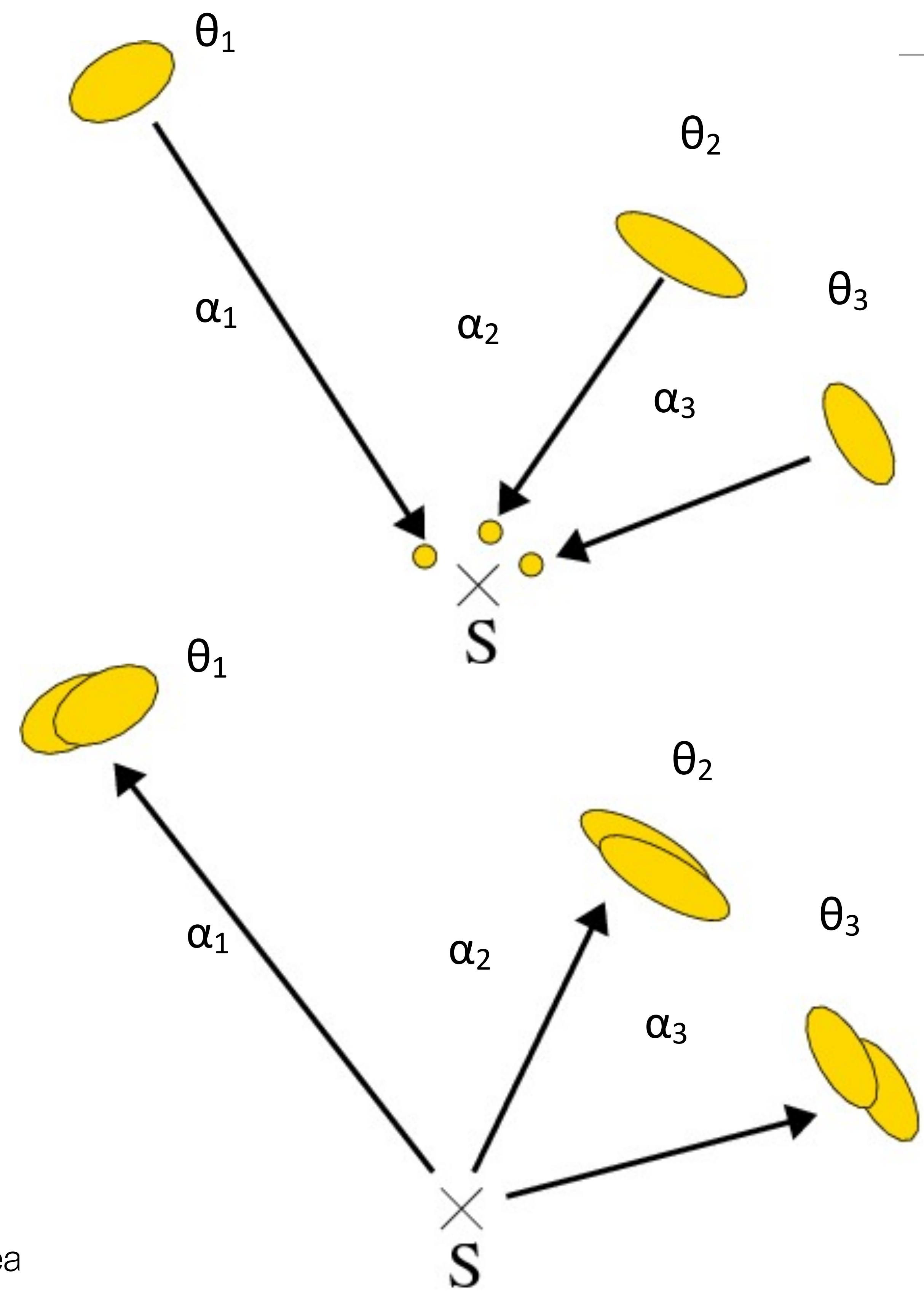
Image plane:

$$\chi^2_i = \sum_{j=1}^{n_i} \frac{[x^j_{\mathrm{obs}} - x^j(\boldsymbol{\theta})]^2}{\sigma^2_{ij}}$$

Jullo et al 2007

θ : **source, and model parameters**

Lens modeling strategy



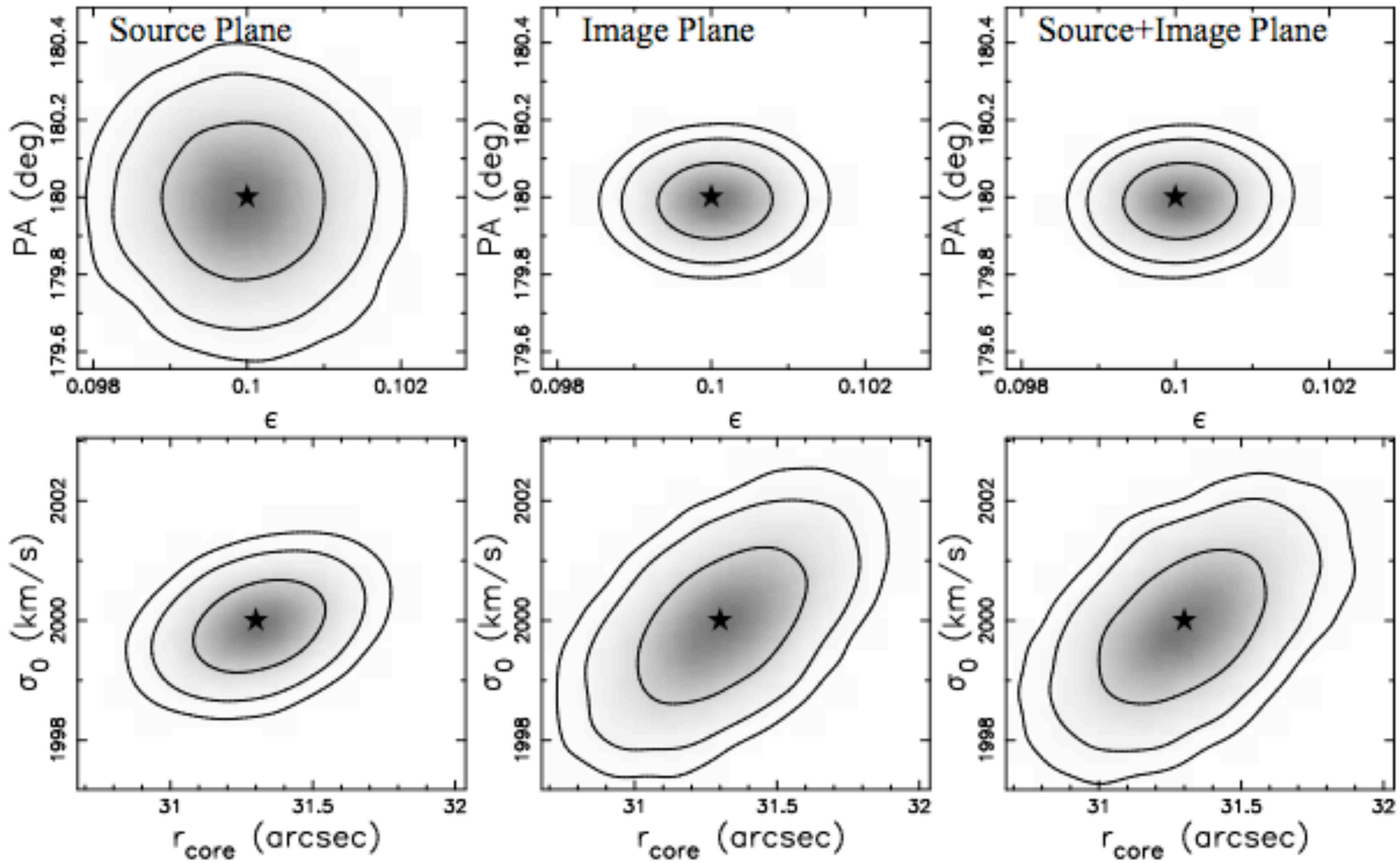
Identification of multiple image systems

Modeling strategy:
Source Plane
vs
Image Plane

The fit is good when the predicted and observed images overlap each others (within the positioning accuracy!)

Source vs. Image plane modeling

Julloet al 2007

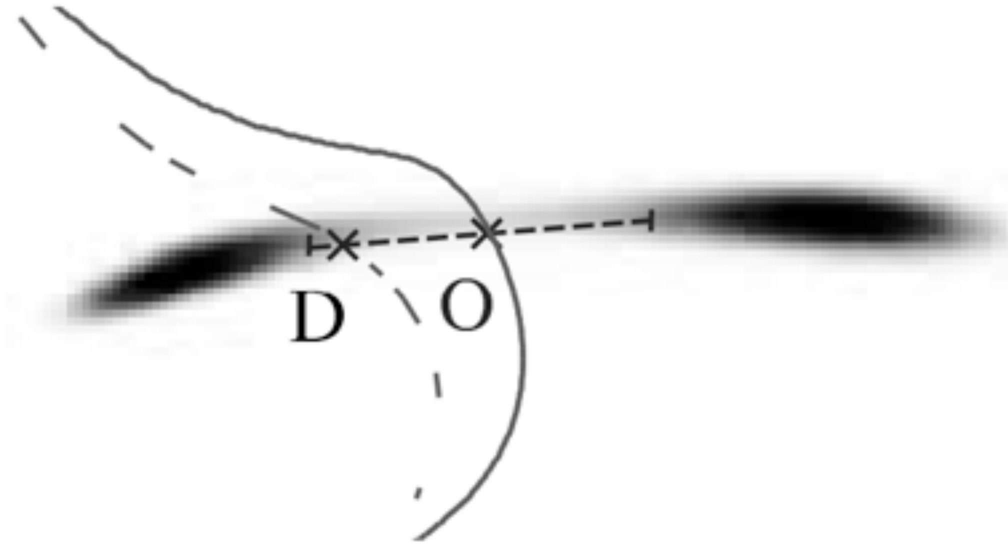


- Source plane only => bad error estimate, **possible bias in some parameters** (depending on the constraints)
- Source+image => ~10 times faster than image plane optimisation

Other (lensing) constraints

- Constrain from critical line position

$$\chi^2_{cl} = \frac{||\mathbf{O} - \mathbf{D}||^2}{\sigma^2_{cl}}$$



- Constrain from flux ratios

$$\chi^2_{flux} = \sum_{i=1}^{N} \frac{(f_i - f_i^{model})^2}{\sigma_i^2}$$

Although ideally, we would like to do the fitting at data pixel level !
Yet to be fully implemented.

Jullo et al 2007

Other constraints

- Single image constraint (effectively a penalizing term)

$$\chi^2_{single} = \sum_{j=1}^{n_k} \frac{[x_{single} - x^j(\boldsymbol{\theta})]^2}{\sigma^2_{single}}$$

Important ingredient to validate a model

Jullo et al 2007

- Non lensing constraints:
  - X-ray measurements
  - galaxy velocities (in particular cD galaxy)
  - ...

e.g. Morandi et al 2012

MCMC optimization (LENSTOOL)

Jullo et al 2007

- Bayesian approach (problem with many parameters, need for proper error estimates)
- Bayes Theorem

Likelihood Prior

$$\Pr(\boldsymbol{\theta}|D, M) = \frac{\Pr(D|\boldsymbol{\theta}, M)\Pr(\boldsymbol{\theta}|M)}{\Pr(D|M)}$$

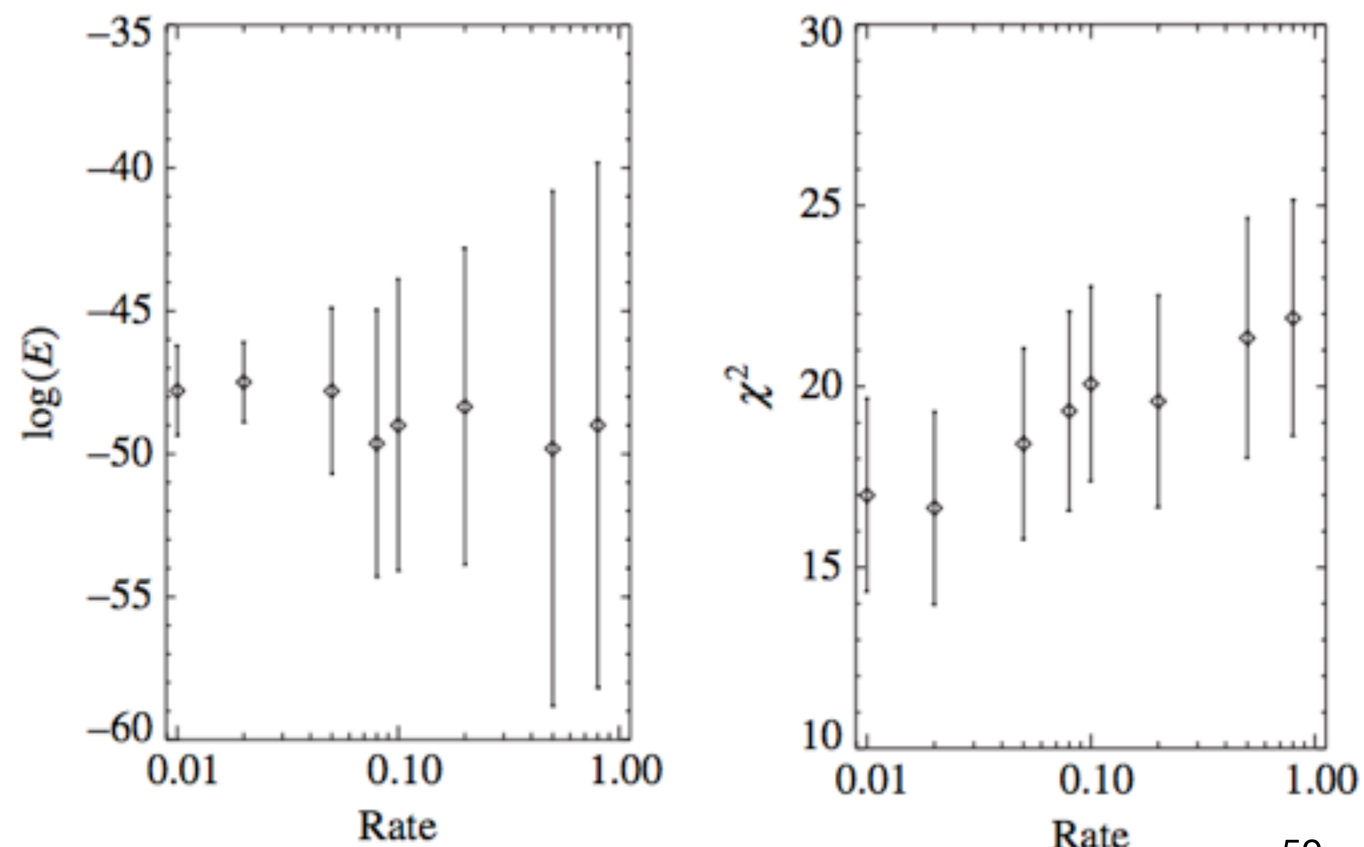
Posterior

evidence

- Use of selective annealing (rewrite of Bayes theorem) - control convergence speed

$$\Pr(\boldsymbol{\theta}|D, M) = \frac{\Pr(D|\boldsymbol{\theta}, M)^{\lambda}\Pr(\boldsymbol{\theta}|M)}{\Pr(D|M)}$$

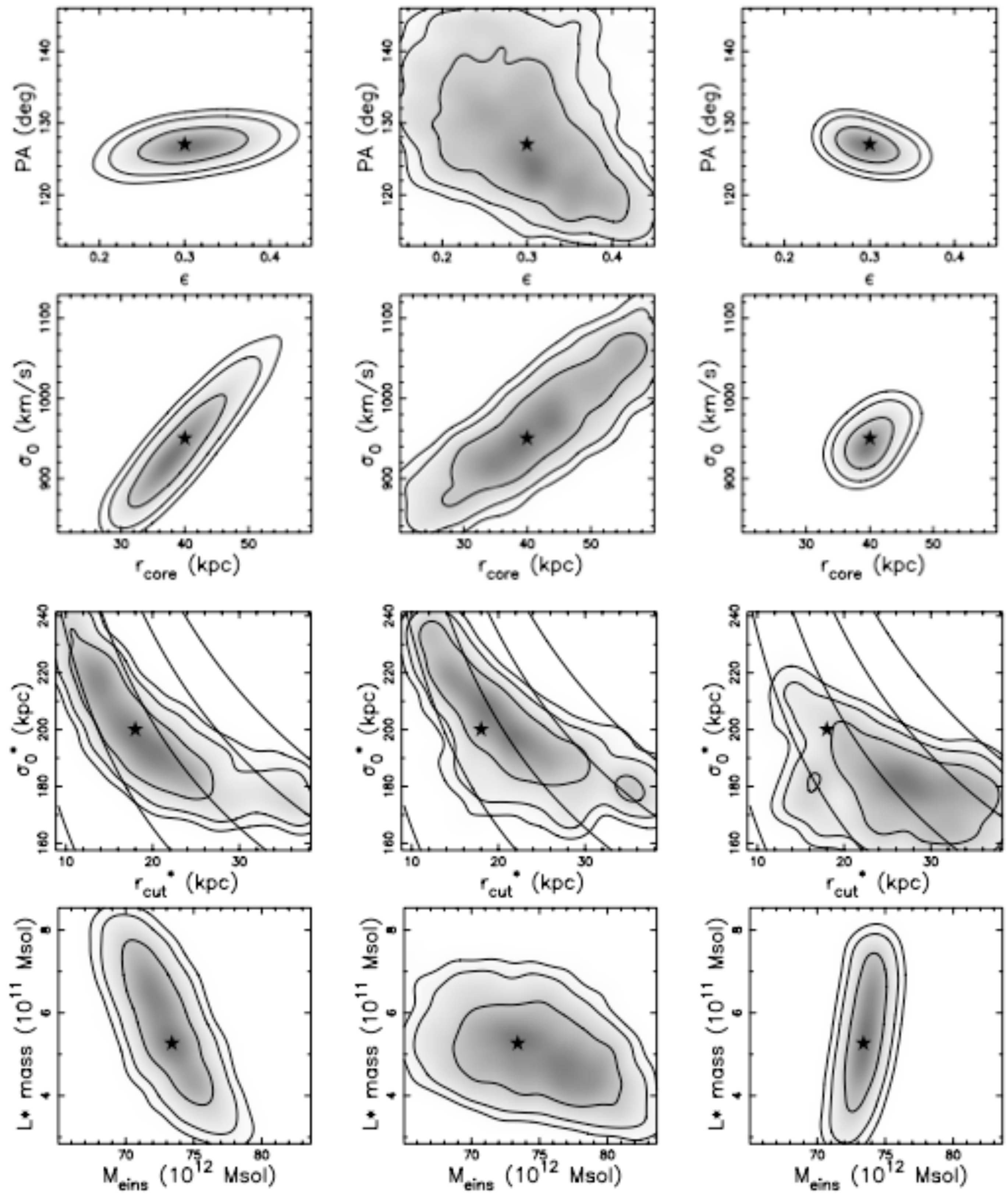
- Burning phase goes 0=>1 depending on the 'Rate' value
- 'Rate' does impact on the convergence
- Sampling phase to derive errors



MCMC optimization (LENSTOOL)

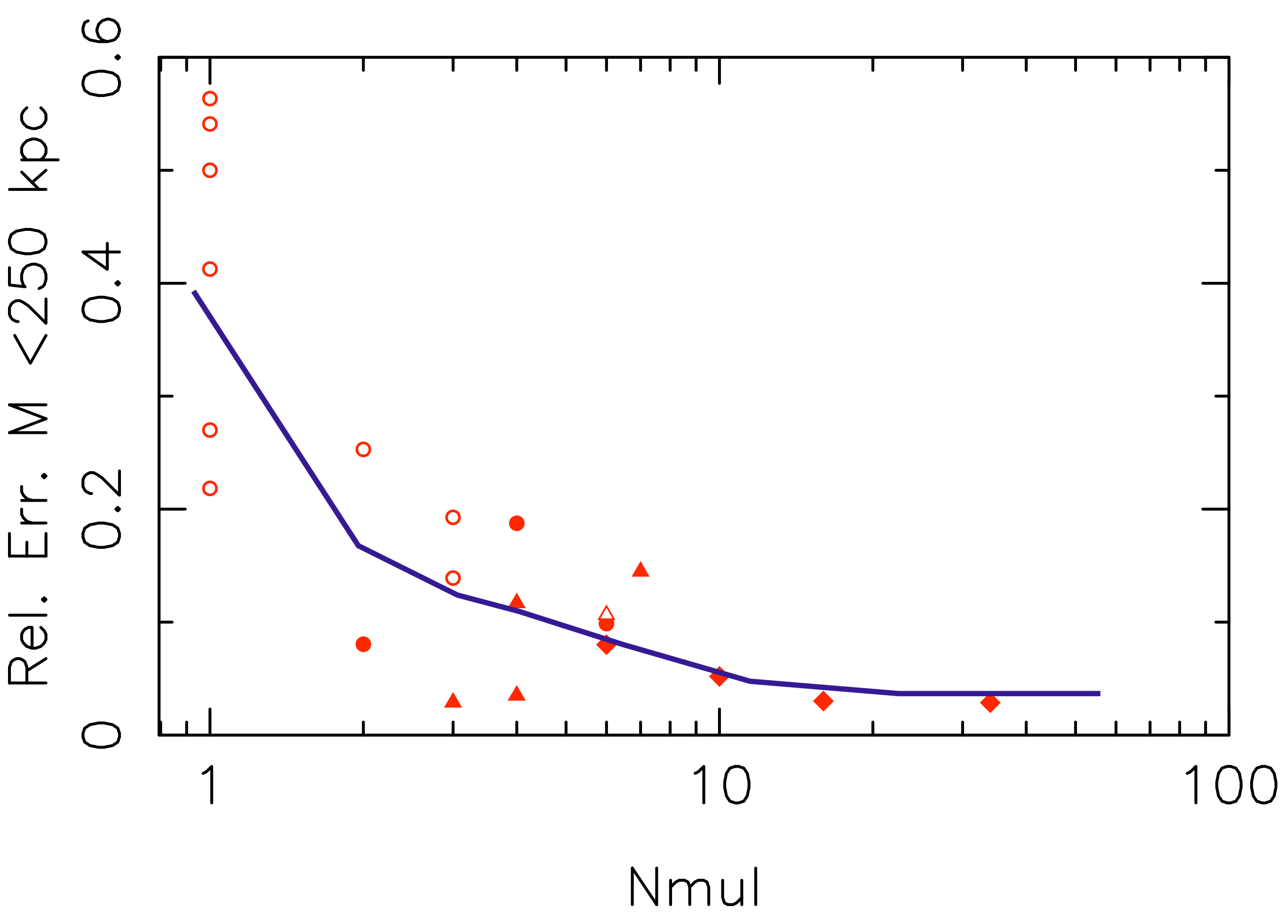
Jullo et al 2007

- Example of degeneracies for 3 different simulated clusters
- Easy parameter estimation
- Can include cosmological parameters in the optimization (Jullo et al 2010)



Cluster lens model accuracy ?

- Mass model accuracy depends on the number of multiple images.
- Mass accuracy limitations:
  - multiple images identification
  - redshift of multiple images
  - priors on the mass models (hence on the method used)
  - galaxy halos scaling relations
  - line of sight structures (can be modeled)

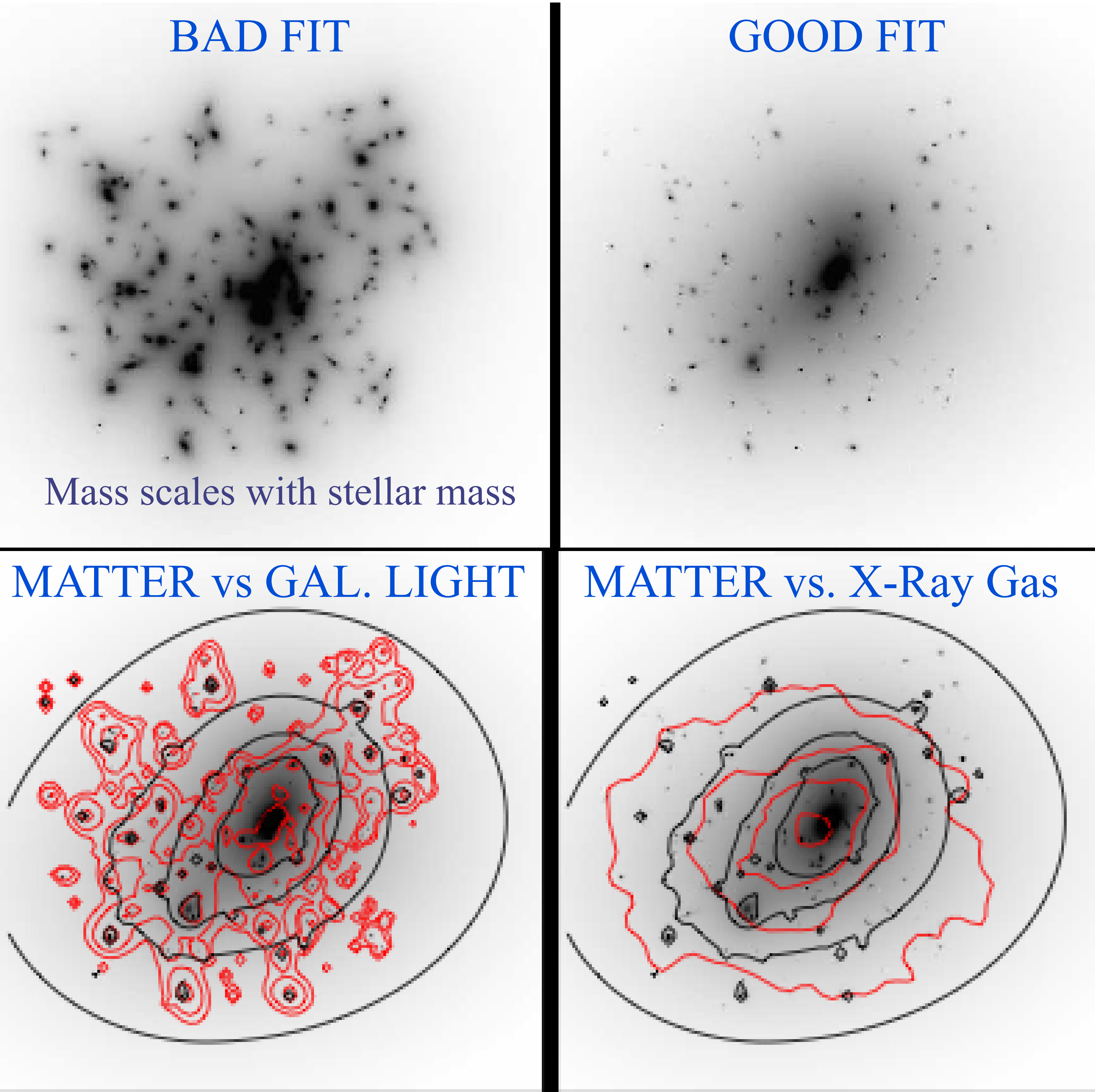


Modeling:
Mass Distribution Measurement

Mass Distribution Measurement

- Why do we measure cluster mass ?
- Central mass profile ? => learn about DM and baryon interactions
- Large scale mass profile and substructures ? => structure formation paradigm, halo models, filaments (use of with weak lensing)
- Case of mergers => probe nature of DM
- Comparison of the distribution of the different components => scaling relations, cluster thermodynamics
- Use cluster as telescopes

Where is the Matter in A2218?



Strong Lensing constraints in Abell 2218:

- Mass distribution proportional to the stellar mass produce a BAD FIT to the lensing data
- Require large scale mass distribution (cluster DM)
- Important difference between DM , Galaxy distribution and X-ray gas (different physics)
- But, scaling relation should exists

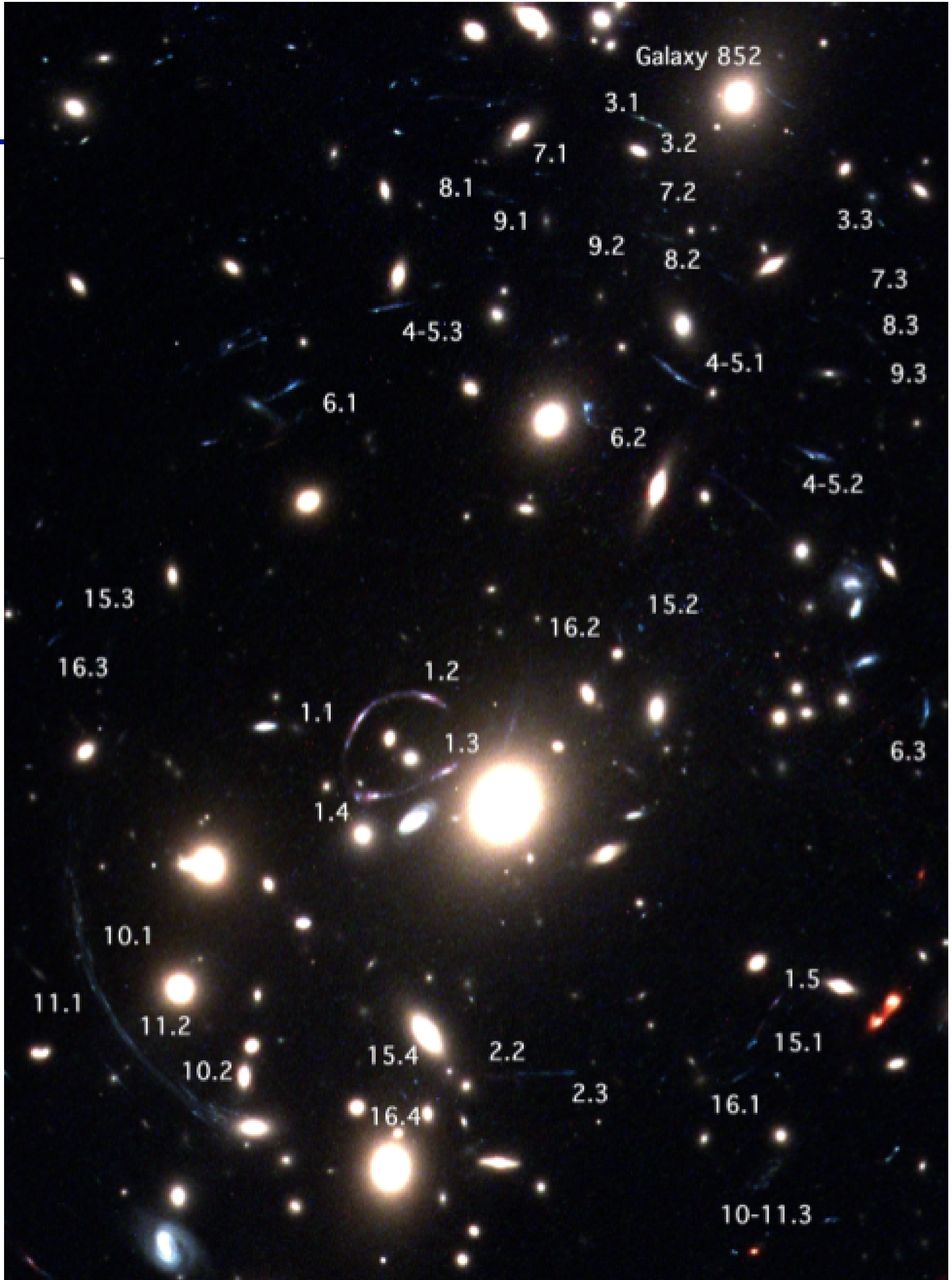
Eliasdottir et al. 2009

Deep = Many

Deep HST/ACS multi-band imaging of massive clusters provides **MANY** multiple images:
A1689 ~40 systems
A1703 ~20 systems
Standard parametric modeling have the RMS image position fit proportional to number of constraints = model too rigid!

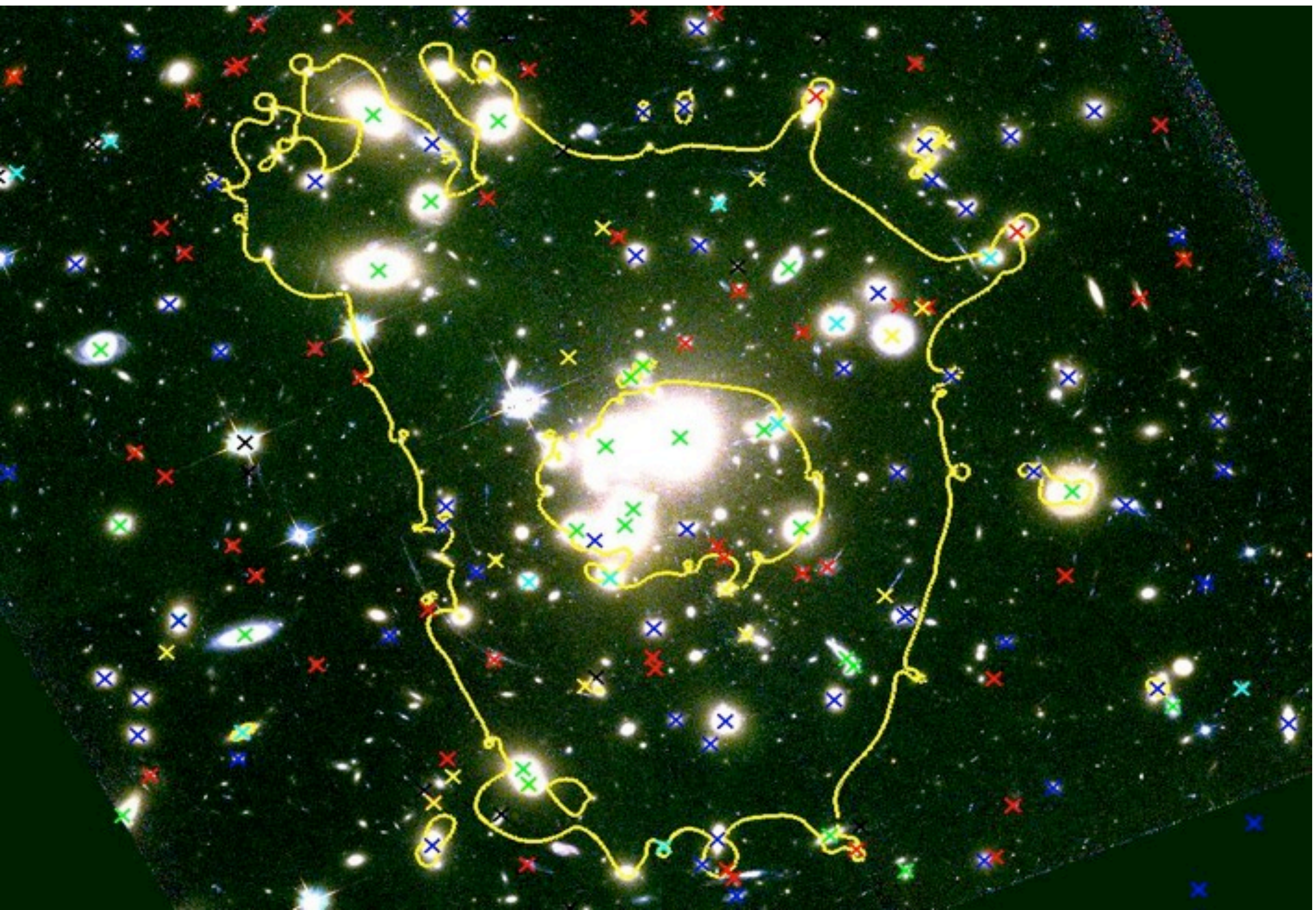
Need a change of paradigm in strong lensing mass modeling
⇒ Grid approach: Jullo & Kneib 2009
⇒ LensPerfect approach: Coe et al 2010

Limousin et al 2008. Richard et al 2009



The most massive cluster: Abell 1689

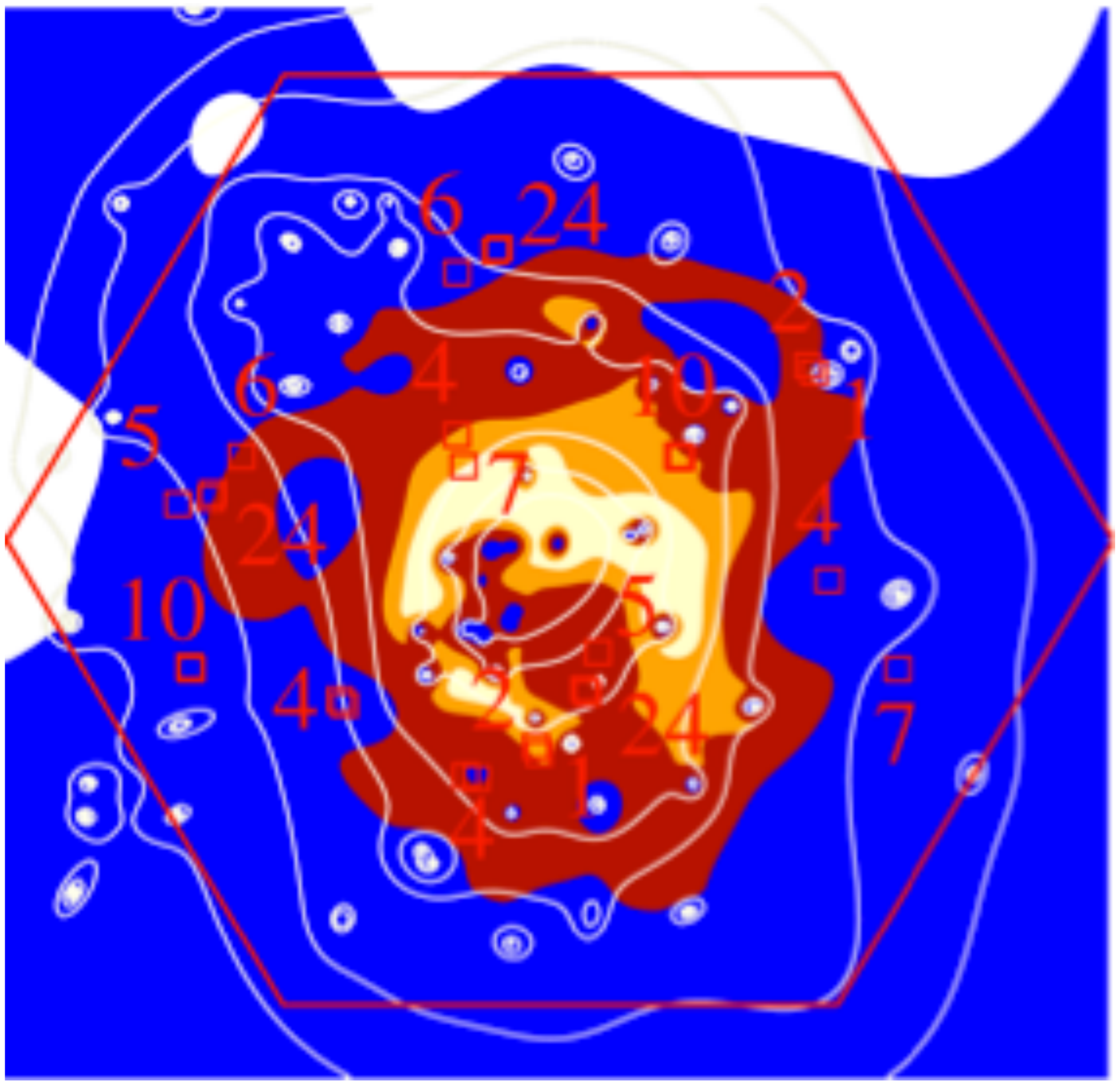
- Mass models form different groups w. or w/o weak lensing
- Massive spectroscopic surveys (2003-2006)
- 41 multiple image systems, 24 with spectro-z with $1.1<z<4.9$



Broadhurst et al 2005
Halkola et al 2007
Limousin, et al. 2007
Richard et al. 2007
Frye et al 2007
Leonard et al 2007
Jullo & Kneib 2009 …

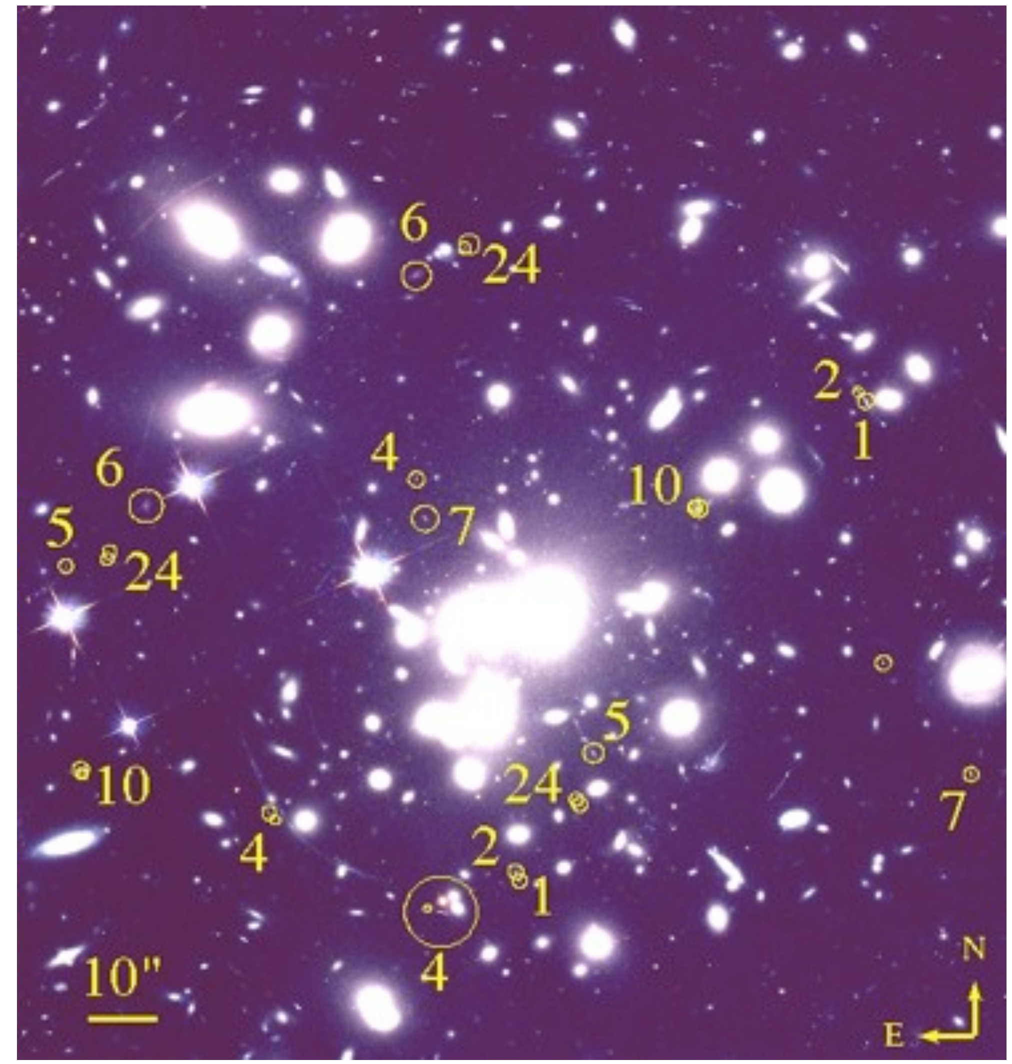
X KECK/LRIS
X VLT/FORS
X CFHT/MOS
X MAGELLAN /LDSS2
X Littérature

Multiscale-grid modeling of Abell 1689



Mass distribution and
S/N map (300,200,100,10)

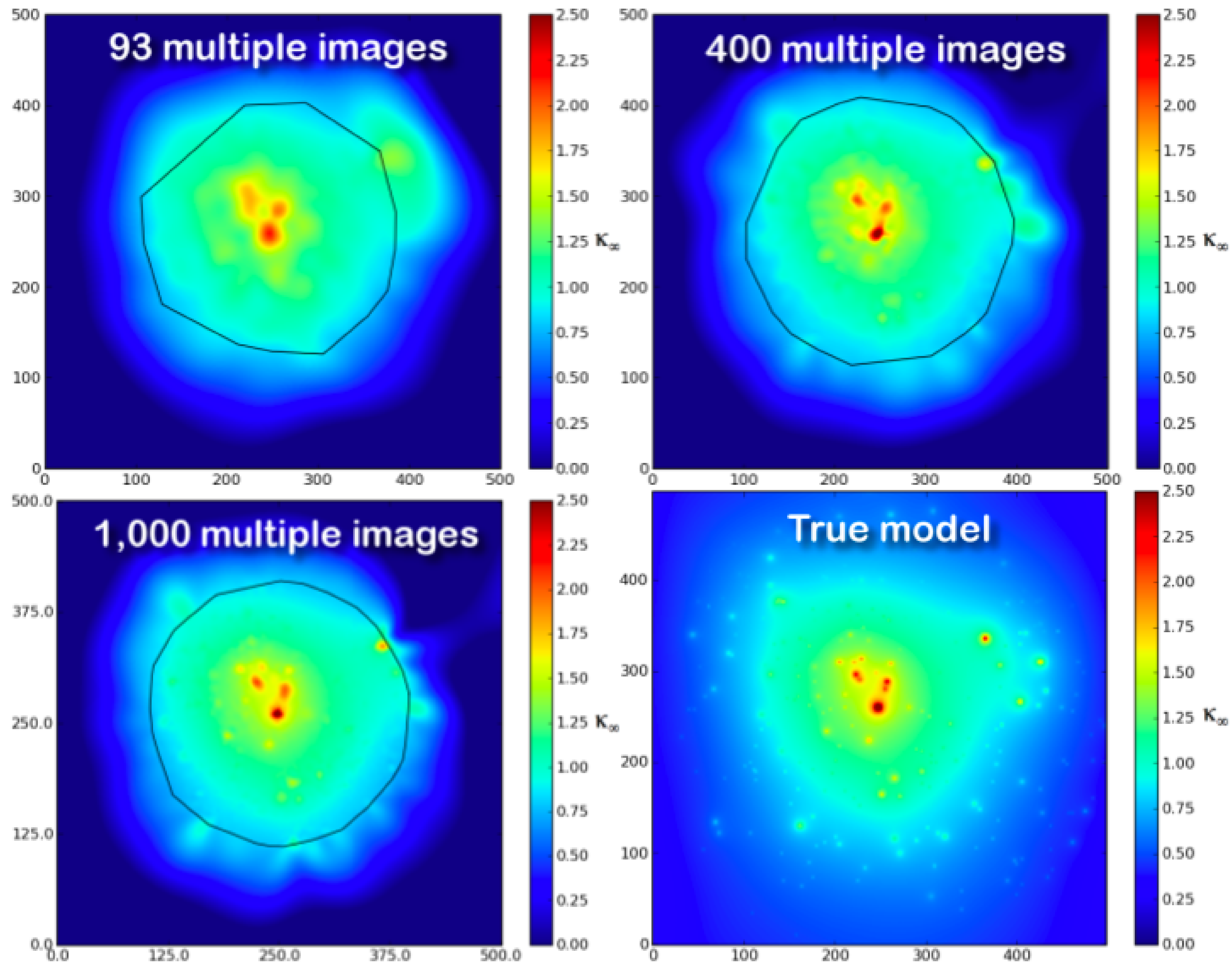
Jullo & Kneib 2009



- Mass map similar to Limousin et al 2007
- mean RMS = 0.22"
- RMS min = 0.09" max = 0.48" (sys6)
- Mass density uncertainty of a few %

LensPerfect - not yet perfect !

- **IDEA: Solve lensing equation perfectly using curl-free basis of function**
- However for a multiple image system, there is an infinity of solution depending on the source position
- What is the most likely “perfect model” ???
- Perfect model only converge if an infinity of constraints …

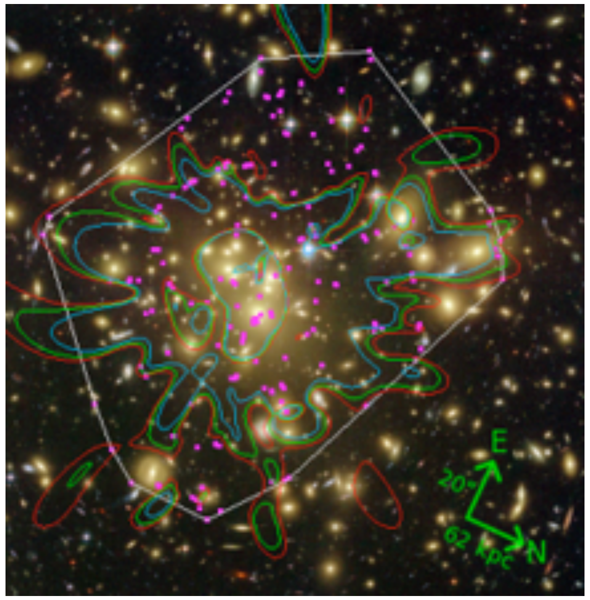


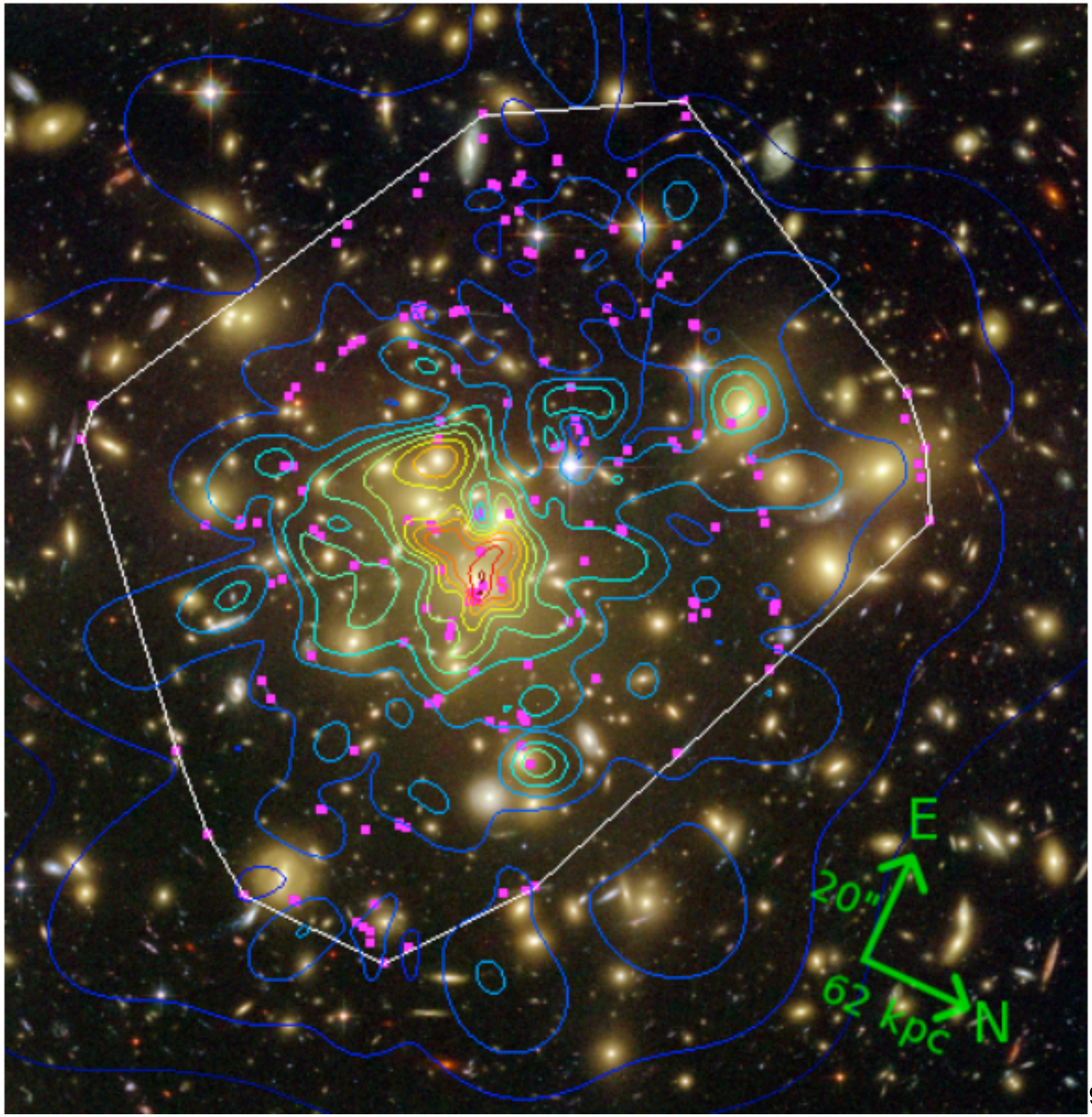
Coe et al 2008, Coe 2009

LensPerfect Application to A1689

- Highest resolution mass distribution map of a cluster (no prior on galaxy distribution => start to be sensitive to small galaxy scales)

- Very odd critical lines - due to limited information and thus limited mass scale





Mass Profile of Clusters (SL+Dynamics)

•DM simulation predicts a universal profile; what is observed in the inner core?

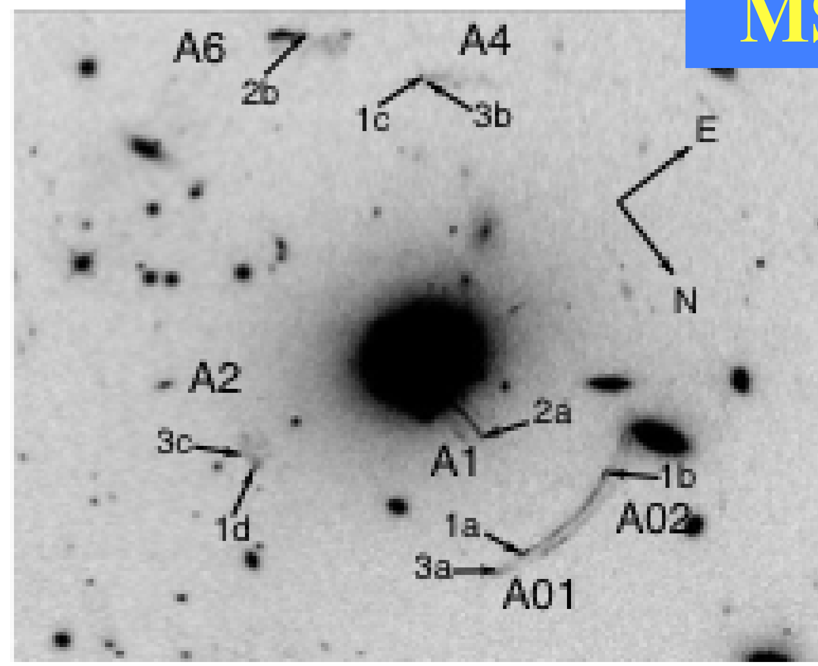
•Combination of strong lensing (radial and tangential arcs) + dynamical estimates from the cD galaxies

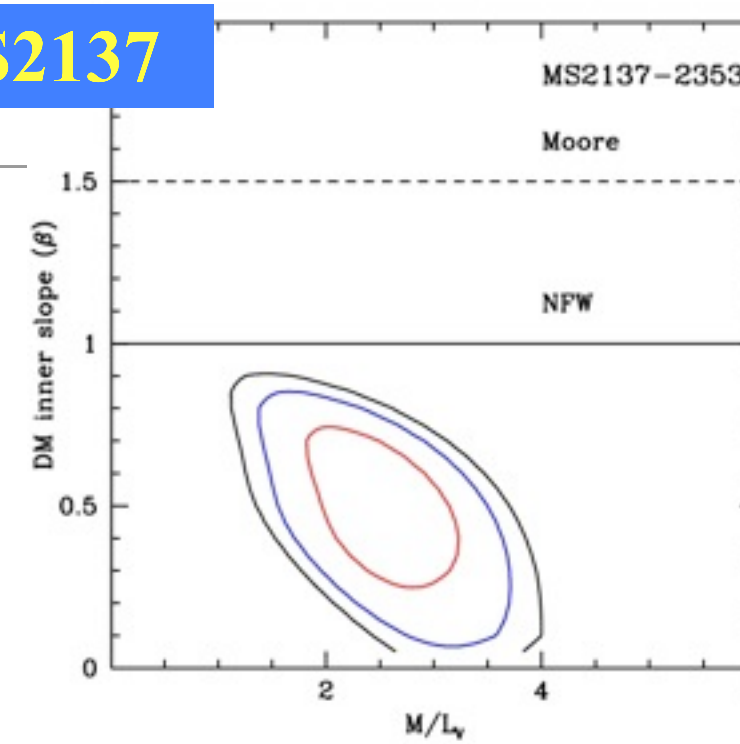
•Some degeneracies, but indication of a flatter profile than canonical NFW: -0.5<beta<-1

•“Flat” core found in other clusters (RCS0224, Cl0024)

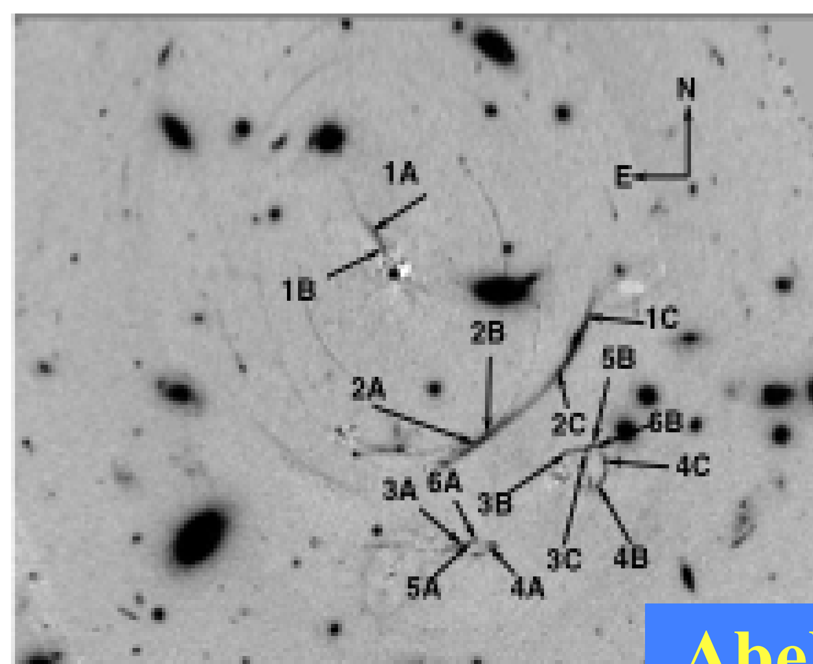
•Possibly probe DM & Baryon coupling?

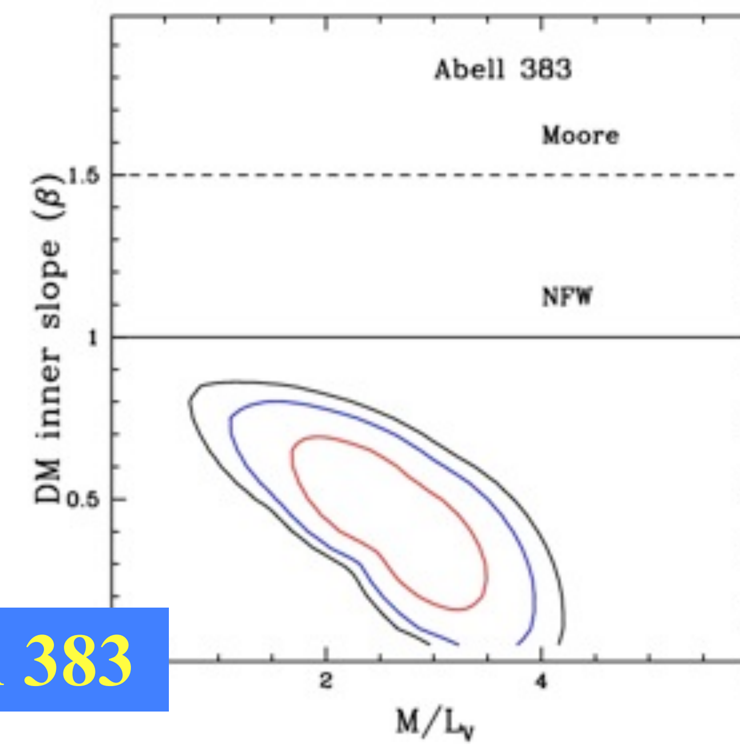
MS2137





New detailed modeling





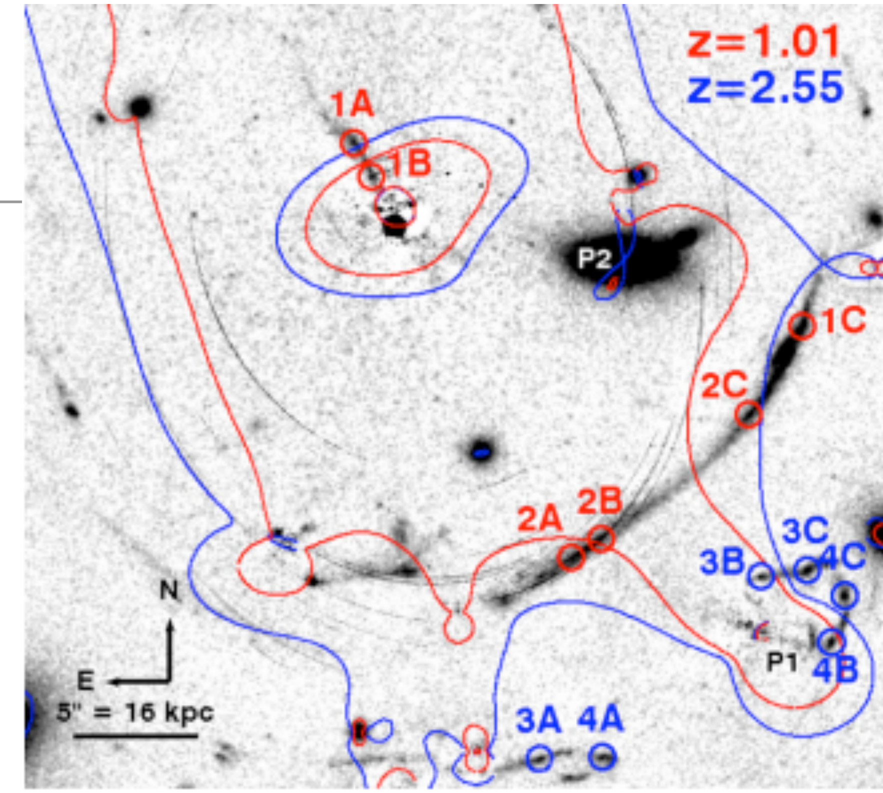
Abell 383

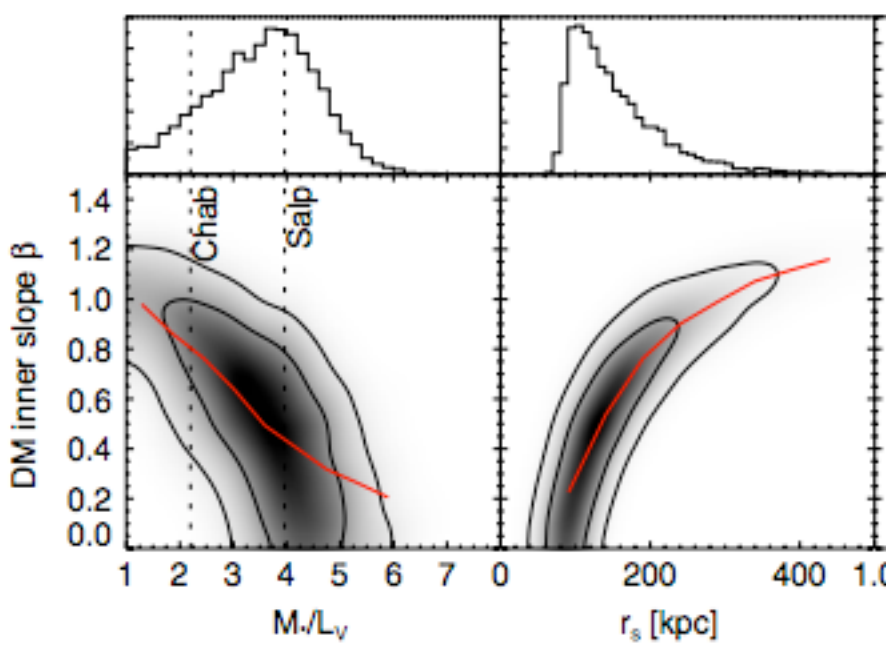
Sand, et al. 2007

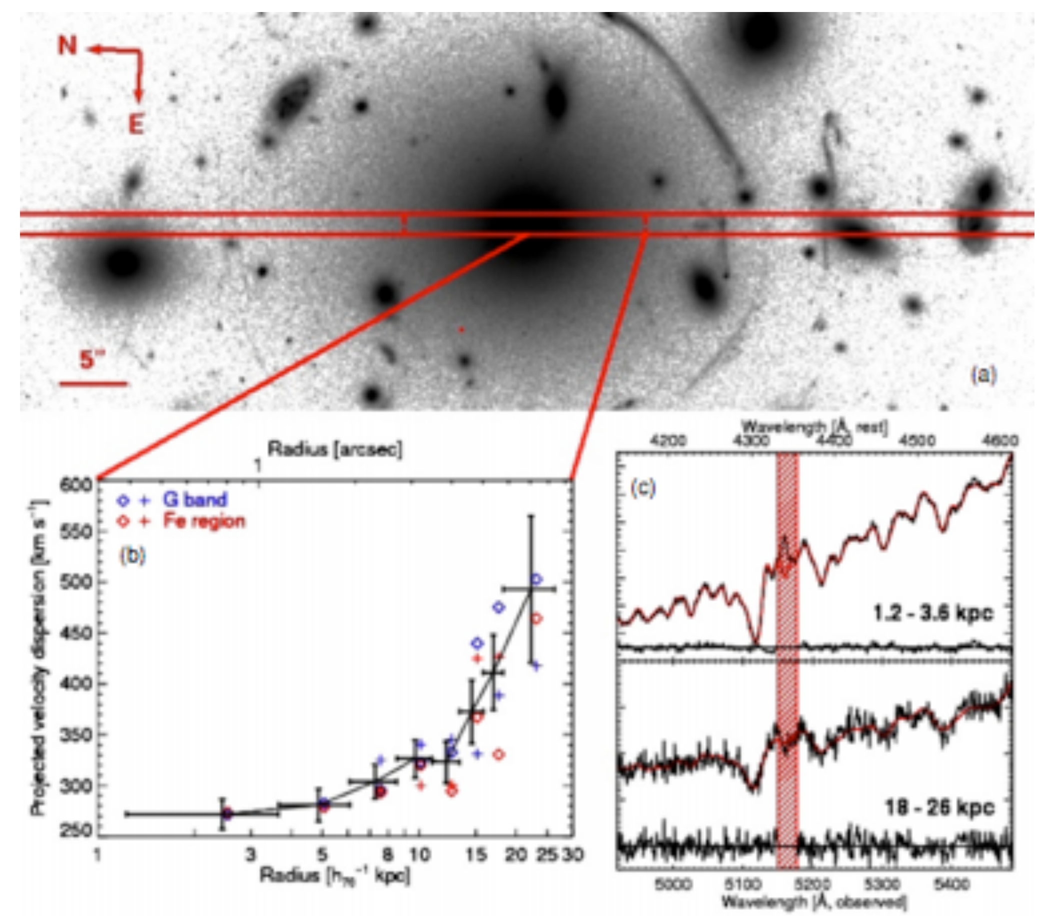
Mass Slope Measurement for Abell 383

Newman et al 2011

- Best measurement yet of velocity dispersion of stars in a cD galaxy!
- Best constraints on the inner slope profile of Dark Matter (slope shallower than -1) => limited by the knowledge of mass/ luminosity of stars
- in conflict with DM only simulation, but baryon/DM interaction are likely to be important.



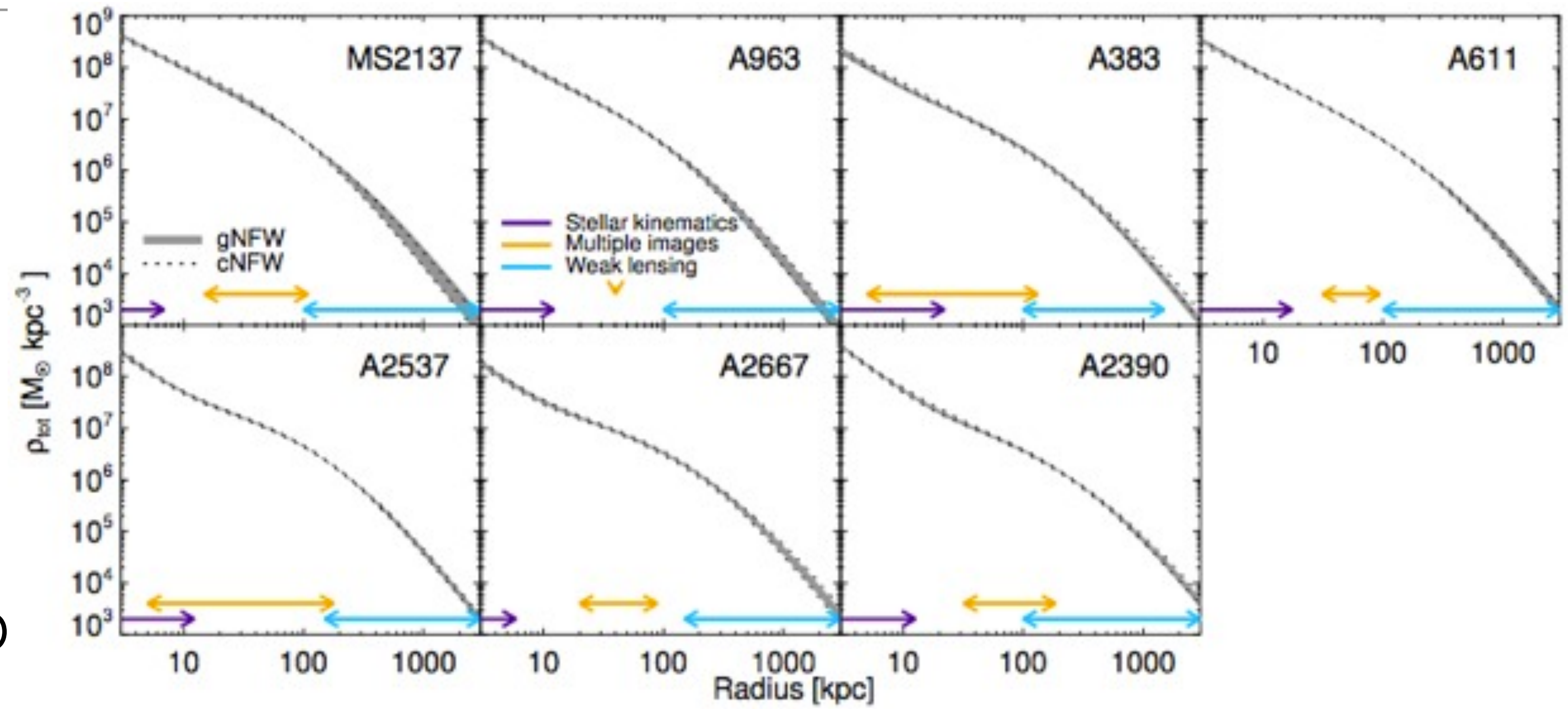




Mass Profile of Clusters (SL+Dynamics)

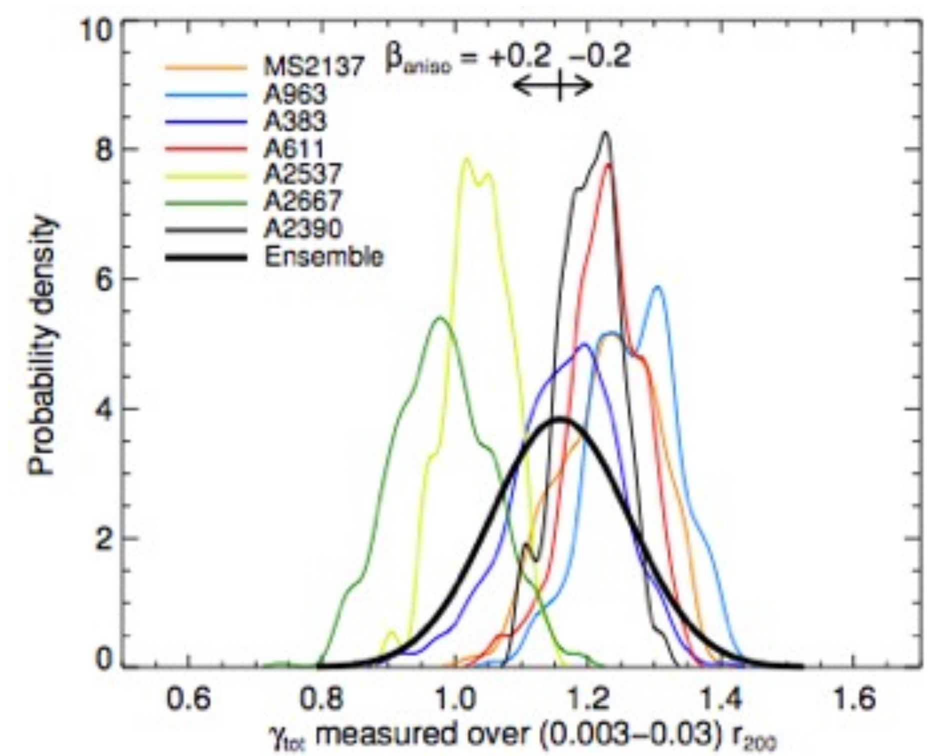
Newman et al. 2012

DM simulation predicts a universal profile; what is observed profile?



- Combination of strong lensing, weak lensing and dynamical estimates from the cD galaxies to measure ρ_{tot} between 3-3000 kpc.

- Sample of 7 galaxy clusters at redshift z ~0.25



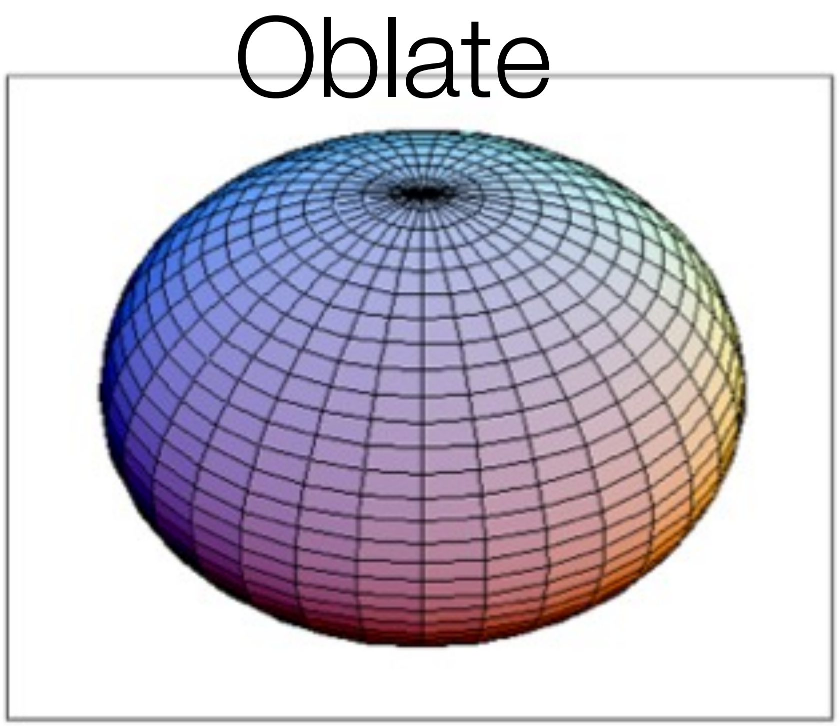
The slope of the density profile γ_{tot} ~ 1.16 is in agreement with DM simulations

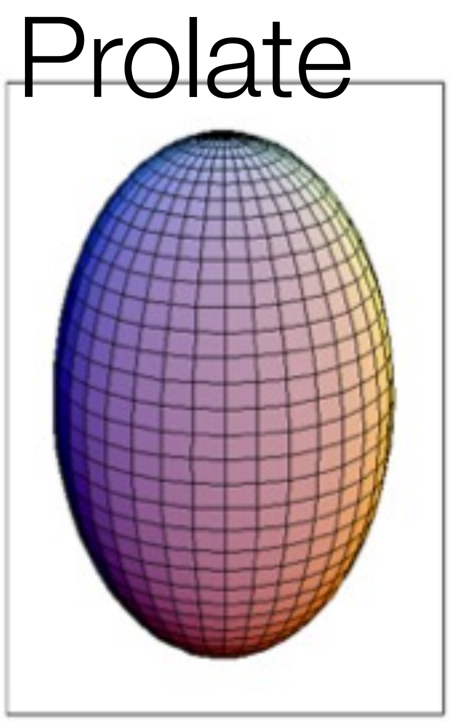
Cluster triaxiality

Dark matter halos are triaxial

Mass discrepancies when Lensing and X-ray estimates when a Spherical shape is assumed

Strong lensing clusters constitute a highly biased population of prolate halos with major axis aligned along the LOS (Oguri & Blandford 2009, Meneghetti et al. 2010)





Cluster triaxiality

Morandi, Pedersen & Limousin 2010a,b

Joint X-ray, SZ & Lensing analysis

X-ray flux

$$S_X = \frac{1}{4\pi(1+z)^4}\Lambda(T^*_{\rm proj}, Z)\int n_e n_p \, dz'$$

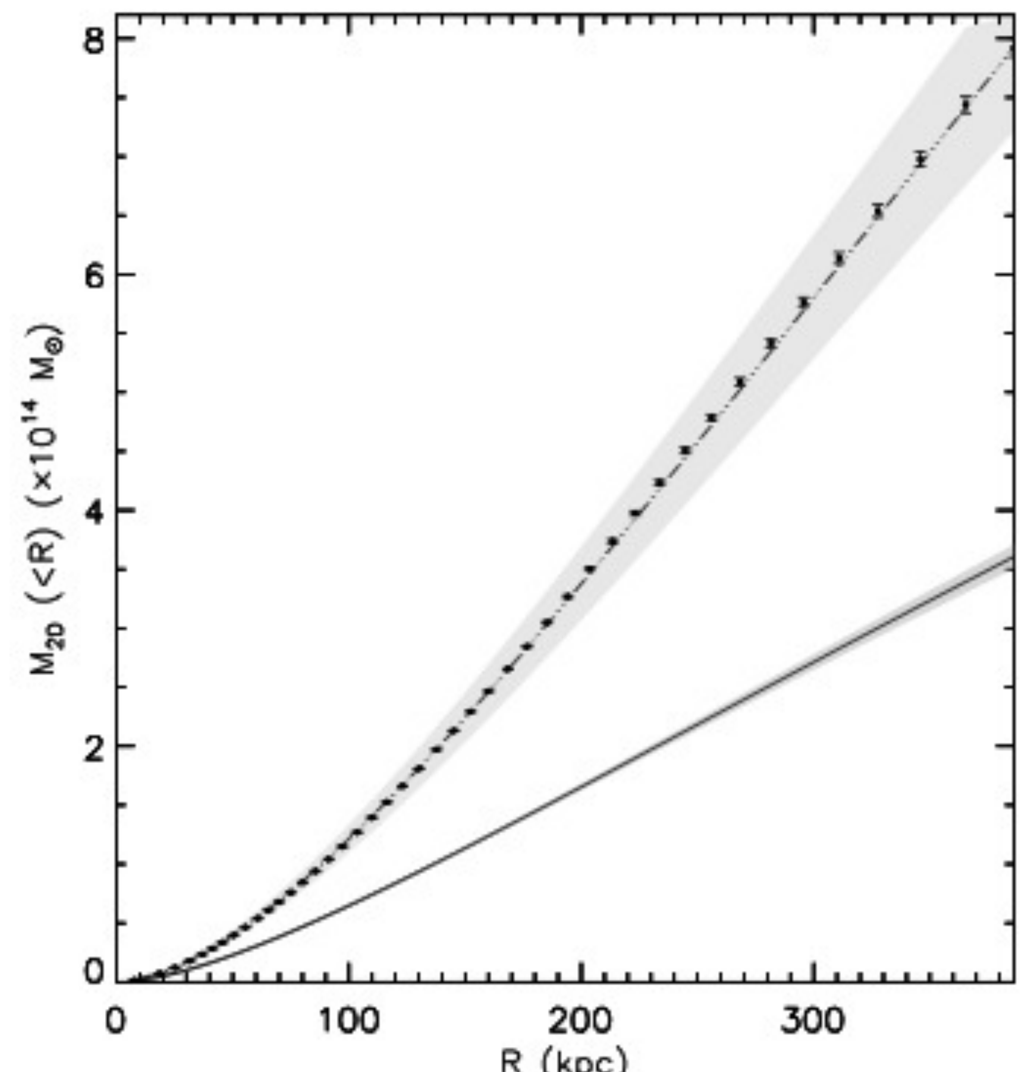
SZ effect

$$\frac{\Delta T(\nu)}{T_{\rm cmb}} = \frac{\sigma_T}{m_e c^2}\int P(\mathbf{r})\, f(\nu; T(\mathbf{r}))\, dz'$$

Lensing mass

$$\mathbf{\Sigma} = \int_{-\infty}^{\infty} \rho(R) dz'$$

→ Estimation of the 3D shape of the gravitational potential (DM)



Solving the Xray-Lensing mass discrepancy in MACS1423
Morandi et al. 2010

« Bullet Cluster » unusually strong mergers

1E0657 alias “the Bullet”

•Encounter of 2 massive clusters
•Significant offset between X-ray gas and lensing mass peaks
⇒ probably best evidence for « collision-less dark matter »
⇒ put constraints on DM/baryon interactions

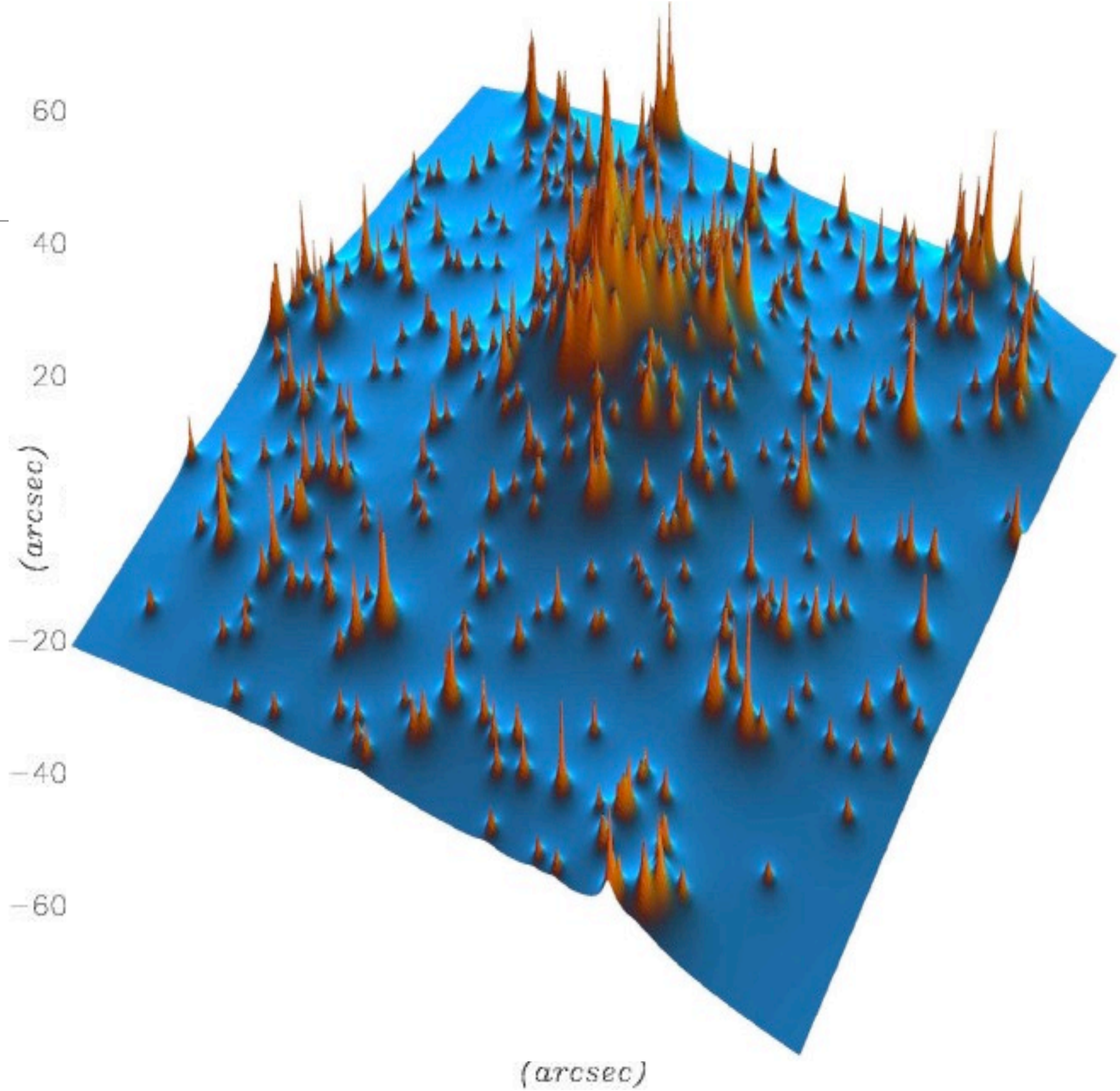
★ Bullet recently revisited (Paraficz et al 2012)

Clowe et al 2006,
Bradac et al 2006

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

Conclusion

- Strong Lensing in cluster is becoming a very mature technique to map the mass map in the core of clusters
- Require deep HST multi-color data, spectroscopy (8-10m => MUSE IFU)
- Finding multiple images is still a challenge
- With more multiple images, fitting model is harder, advanced model are needed as we go below the few % error on the mass model.
- Next steps:
  - Pixel level fitting of arcs/multiple image is the next step
  - Inclusion of other constraints galaxy FP, X-ray, WL => more physics & 3D

End of Chapter 1-2