Gravitational Lensing and Dark Matter

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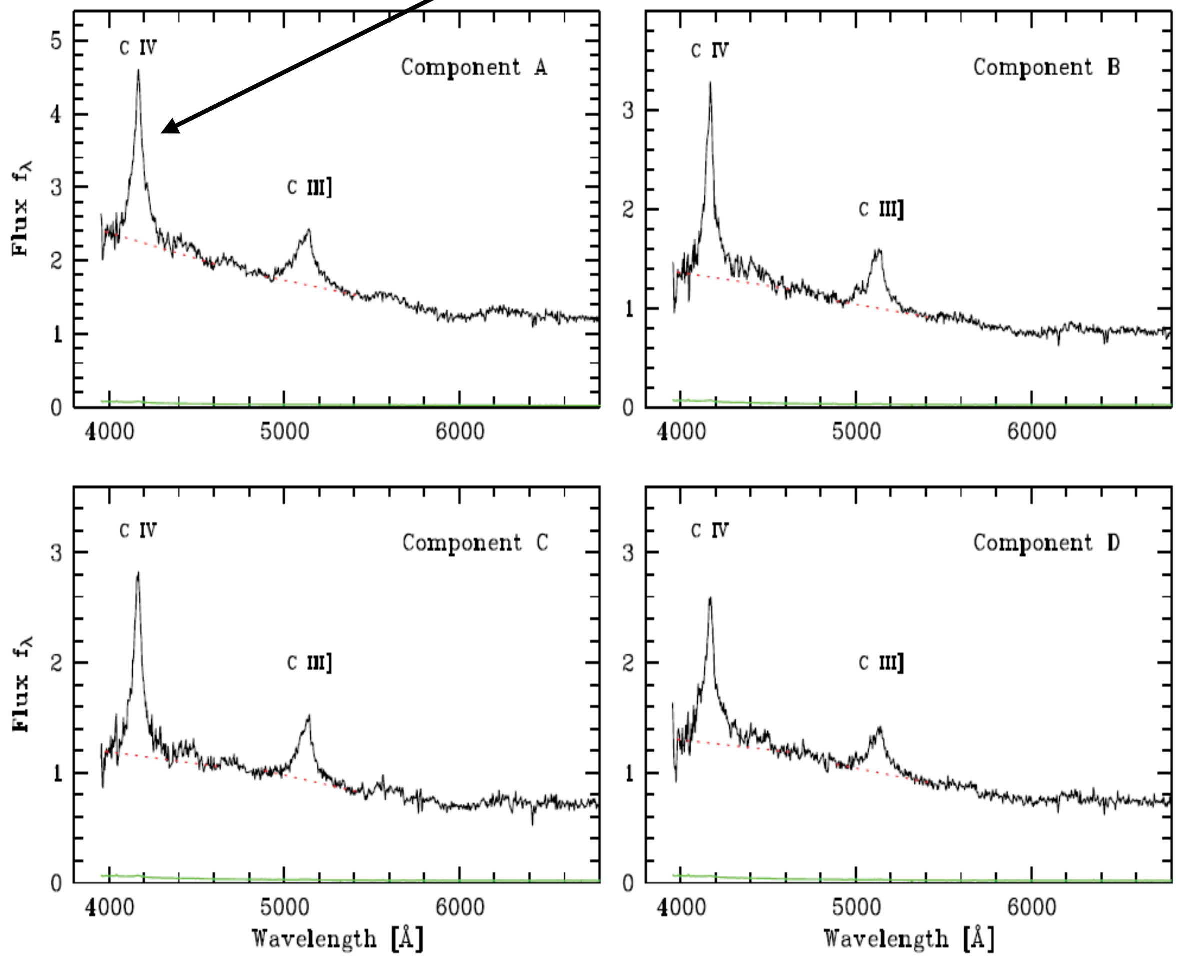
Multiple images: the « Einstein Cross»

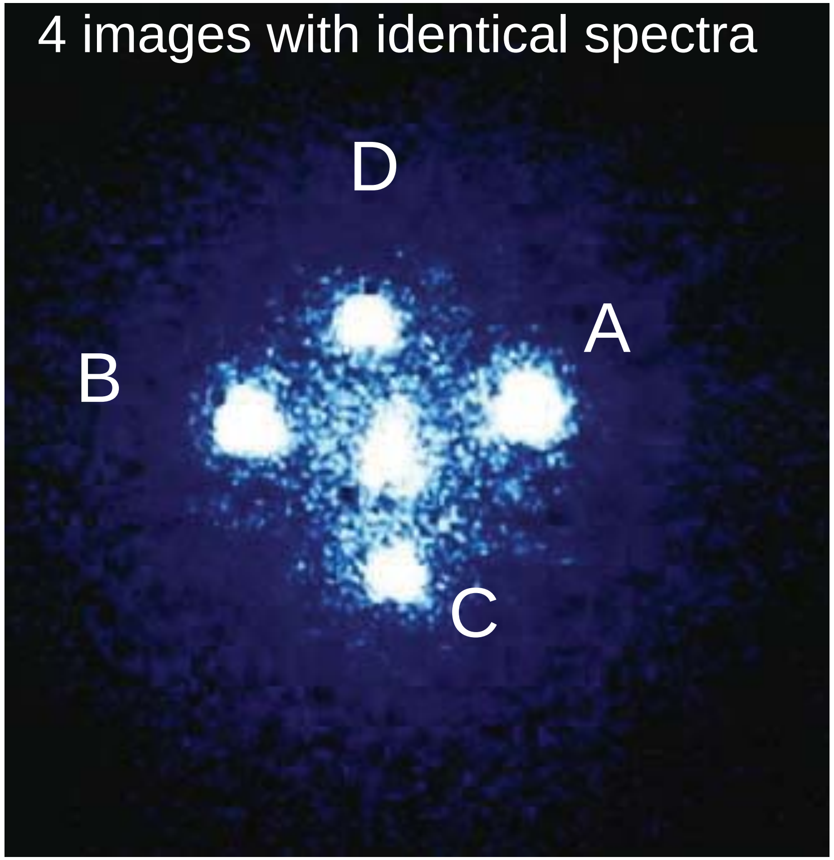
Galaxy 2227+030

Redshift z=0.0394

The « Einstein Cross»

CIV emission line at 154.9 nm observed 417.6 nm :z = 1.695

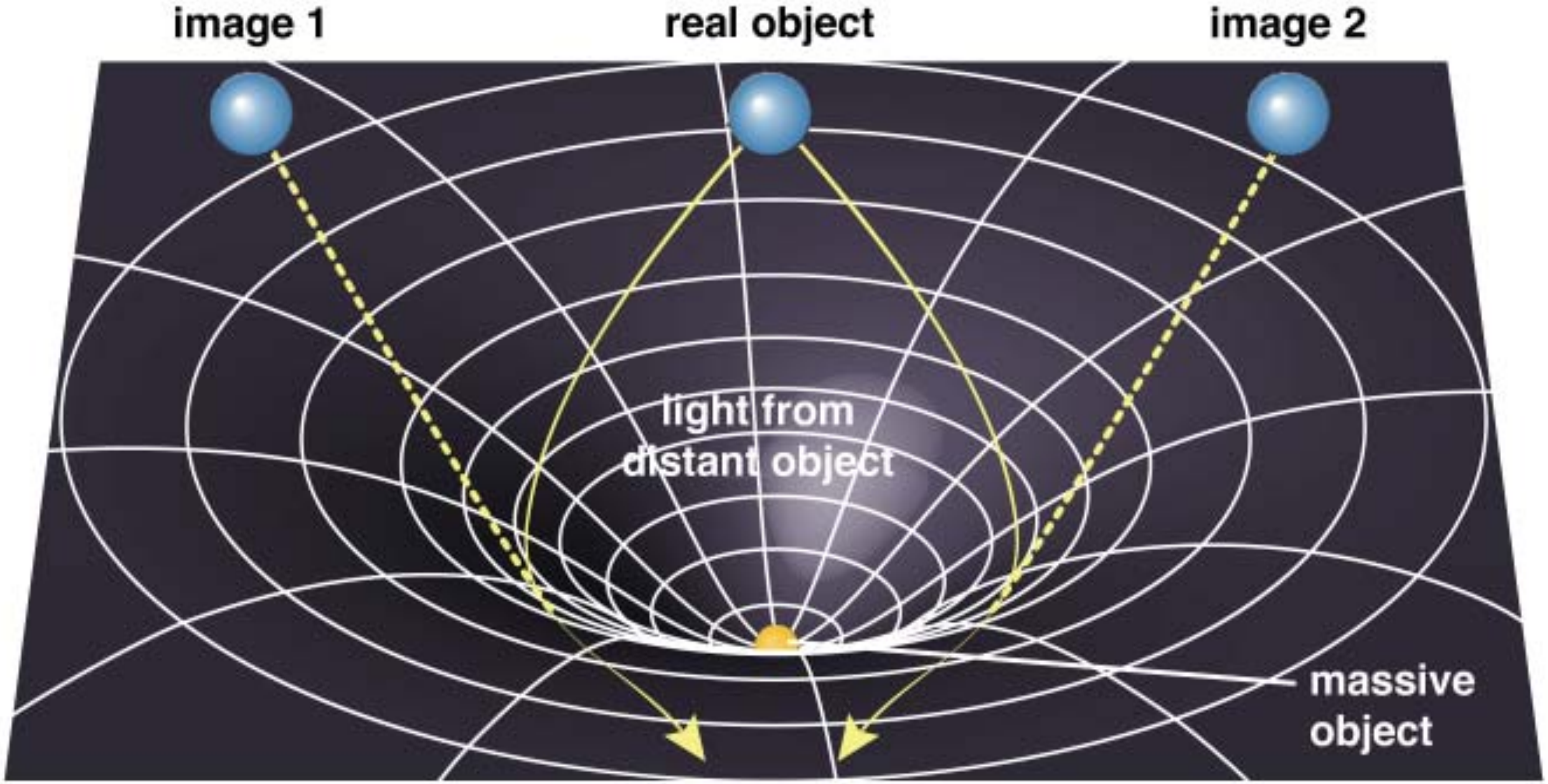




General relativity:

curvature of space time locally modified by mass condensation

Apparent position of a first image | Real image | Apparent position of a second image



Deflection of light, magnification, image multiplication distortion of objects : directly **depend on the amount of matter**

Gravitational lensing effect is **achromatic** (photons follow geodesics regardless their energy)

Gravitational Lensing

theory, concepts and definitions

Gravitational lensing: fundamental assumptions

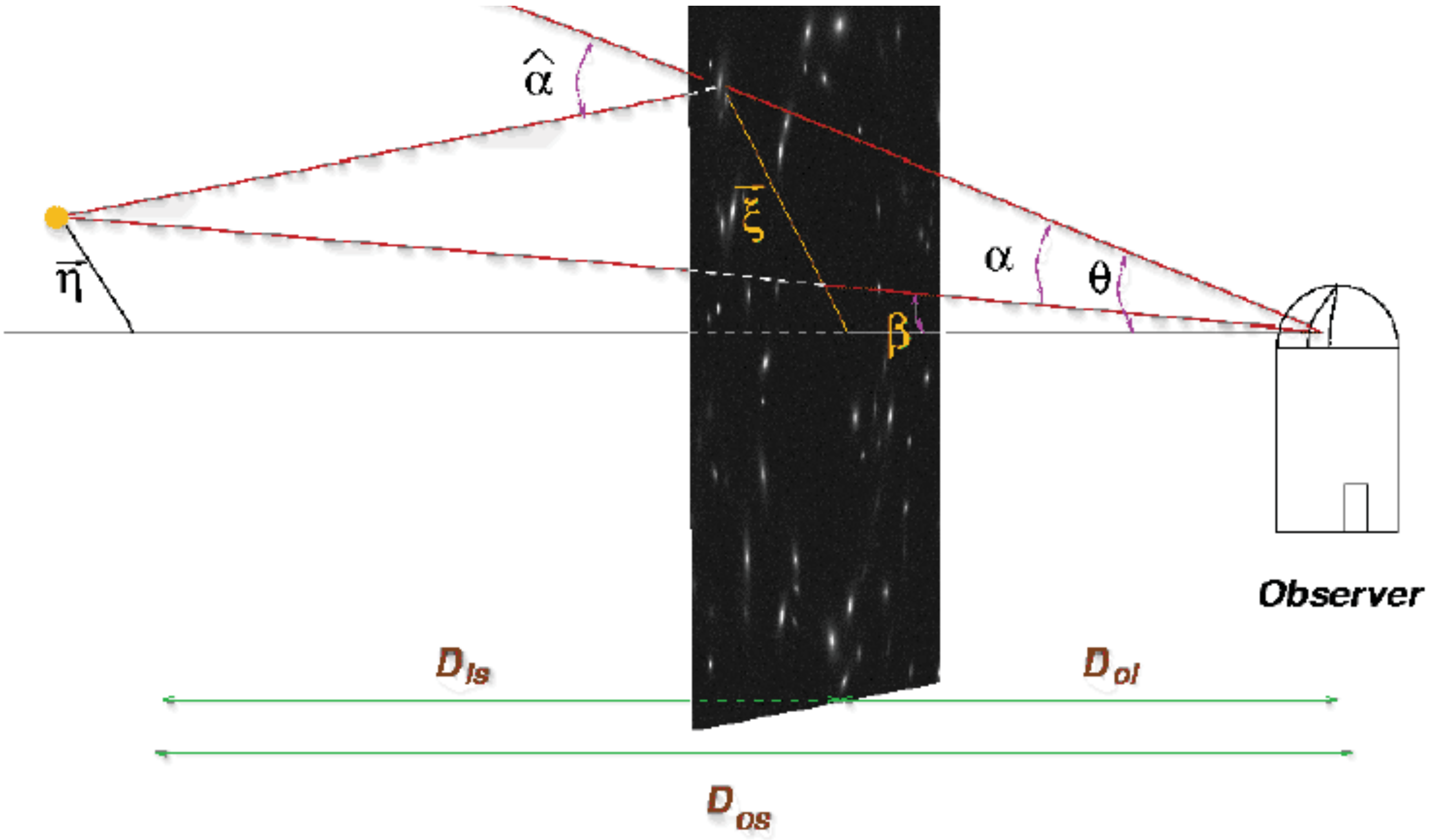
- Weak field limit: $\sigma^2 << c^2$
- Stationnary field: $t_{\mathrm{dyn}} \sim R_{\mathrm{lens}}/v >> t_{\mathrm{cross\text{-}photon}}$
- Thin lens approximation: $R_{\mathrm{lens}} << R_{\mathrm{bench}}$
- Small deflection angle:

  b = impact parameter ; R = Schwarzschild radius

  $\alpha = 4G\,M/bc^2 << 2G\,M/R_S c^2$

  $=> R_S << b$
- Transparent lens

Lens equation and deflection angle



$$\vec{\eta} = \frac{D_{os}}{D_{ol}}\vec{\xi} - D_{ls}\vec{\hat{\alpha}}\left(\vec{\xi}\right) \quad ; \quad \alpha = -\frac{2}{c^2}\int_S^O \nabla_\perp \Phi \, \mathrm{d}l$$

Deflection angle and mass density

$$\alpha = -\frac{2}{c^2}\int_S^O \nabla_\perp \Phi \, \mathrm{d}l$$

$$\alpha(\xi) = \frac{4G}{c^2}\int \frac{(\xi - \xi')\Sigma(\xi')}{|\xi - \xi'|^2}\,\mathrm{d}\xi'$$

where

- $\Sigma(\xi)$ is the projected mass density,
- ξ is a 2-dimensional vector in the lens plane and
- the integration is done over the lens plane.

Lens equation : spherical lens

- Lens equation

$$\vec{\eta} = \frac{D_{os}}{D_{ol}}\vec{\xi} - D_{ls}\hat{\vec{\alpha}}\left(\vec{\xi}\right)$$

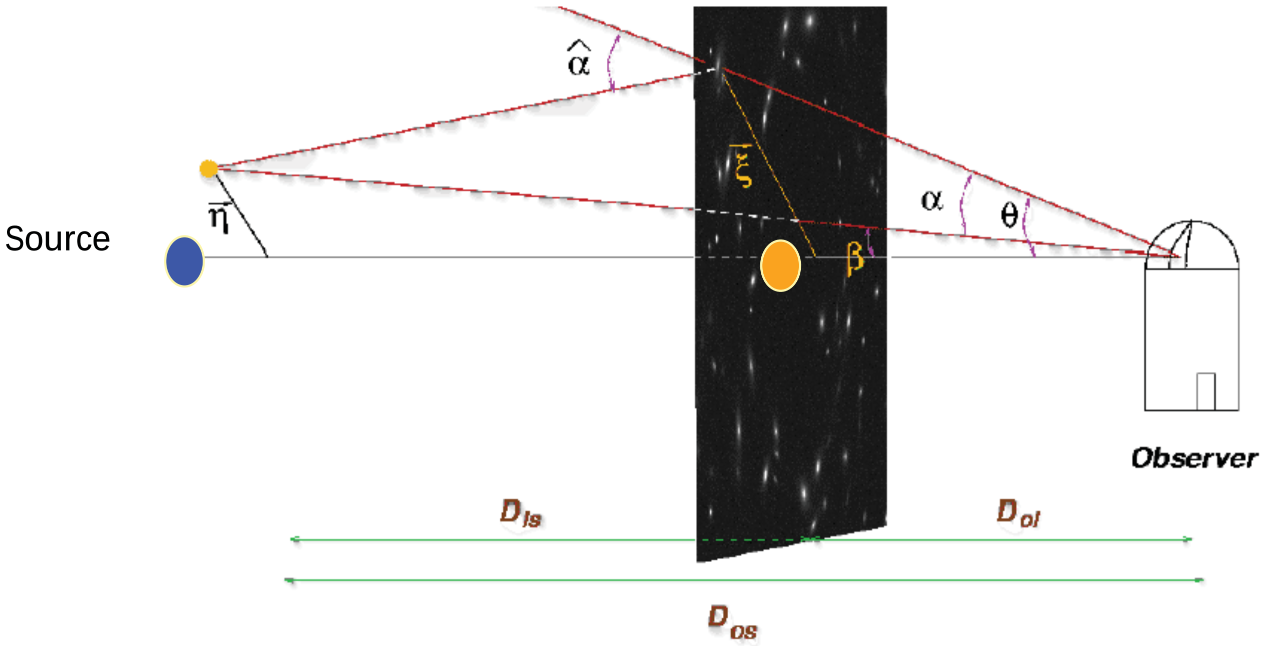
Setting $\vec{\eta} = D_{os}\vec{\beta}$ and $\vec{\xi} = D_{ol}\vec{\theta}$,

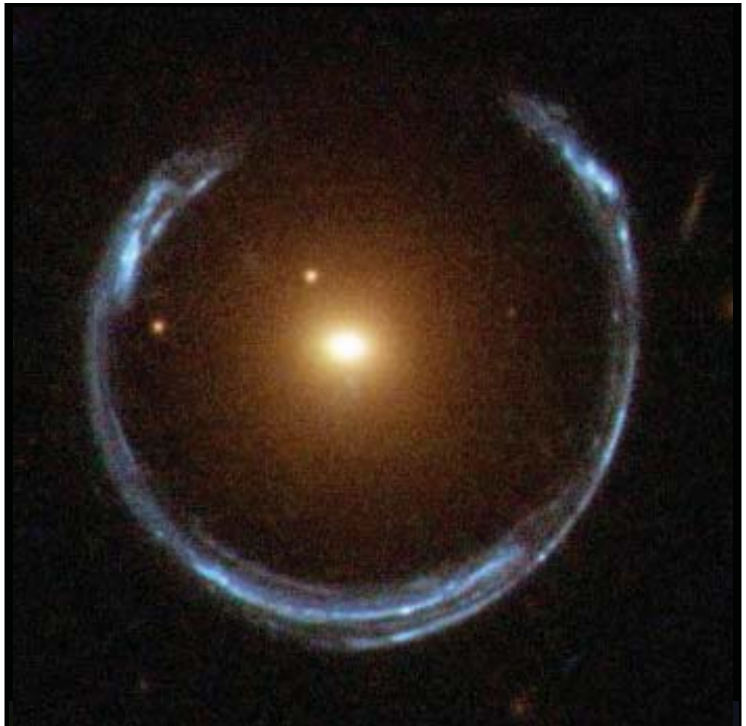
$$\vec{\beta} = \vec{\theta} - \vec{\alpha}\left(\vec{\theta}\right)$$

- Spherically symmetric lens

$$\beta = \theta - \frac{D_{ls}}{D_{os}D_{ol}}\frac{4GM\left(\theta\right)}{c^2\theta}$$

Perfect lens configuration
« Einstein ring »





Source-Lens-Observer perfectly aligned

Einstein ring

$$\theta_E = \left(\frac{D_{ls}}{D_{os} D_{ol}} \frac{4GM\left(\theta_E\right)}{c^2} \right)^{1/2}$$

<u>Typical values:</u>

- For a lens of 1 solar mass located at 1 AU and a source a 1 kpc

  θ_E= 0.003 arc-second

- For a lens of 10^{11} solar masses located at 100kpc and a source at 300 kpc

  θ_E= 1 arc-second

- For a lens of 10^{15} solar masses located at 1Gpc and a source at 3 Gpc

  θ_E= 30 arc-second (sensitive to cosmological parameters)

Convergence and critical density

- Convergence and critical density The gravitational convergence is a dimensionless surface masse density:

$$\kappa\left(\vec{\theta}\right) = \frac{\Sigma\left(D_{ol}\vec{\theta}\right)}{\Sigma_{cr}}$$

where Σ_{crit} is the *critical surface mass density*:

$$\Sigma_{cr} = \frac{c^2}{4\pi G}\frac{D_{os}}{D_{ol}D_{ls}}$$

that defined a "strength" of the lens. Strong lensing cases have $\Sigma > \Sigma_{cr}$

Magnification and distortion

$$\vec{\beta} = \vec{\theta} - \vec{\alpha}\left(\vec{\theta}\right) \qquad \alpha = -\frac{2}{c^2}\int_S^O \nabla_\perp \Phi \, \mathrm{d}l$$

- Jacobian of the lens mapping. Differentiting the lens equation

$$A\left(\vec{\theta}\right) = \frac{\partial \vec{\beta}}{\partial \theta} = \left(\delta_{ij} - \frac{\partial^2 \psi\left(\vec{\theta}\right)}{\partial \theta_i \partial \theta_j} \right) = M^{-1}$$

- Convergence, Shear

$$\begin{cases} \kappa = \frac{1}{2}\left(\psi_{,11} + \psi_{,22}\right) \\ \gamma_1\left(\vec{\theta}\right) = \frac{1}{2}\left(\psi_{,11} - \psi_{,22}\right) = \gamma\left(\vec{\theta}\right)\cos\left[2\varphi\left(\vec{\theta}\right)\right] \\ \gamma_2\left(\vec{\theta}\right) = \psi_{,12} = \gamma\left(\vec{\theta}\right)\sin\left[2\varphi\left(\vec{\theta}\right)\right] \end{cases}$$

Magnification and distortion

- Magnification, Convergence, Shear

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

$$\mathscr{M}^{-1} = (1-\kappa)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} - \gamma \begin{pmatrix} \cos(2\varphi) & \sin(2\varphi) \\ \sin(2\varphi) & -\cos(2\varphi) \end{pmatrix}$$

where $\gamma = \gamma_1 + \mathrm{i}\gamma_2 = |\gamma| e^{2\mathrm{i}\varphi}$

- Amplification amplitude

$$\mu = (\det A)^{-1} = \frac{1}{\left[(1-\kappa)^2 - |\gamma|^2\right]}$$

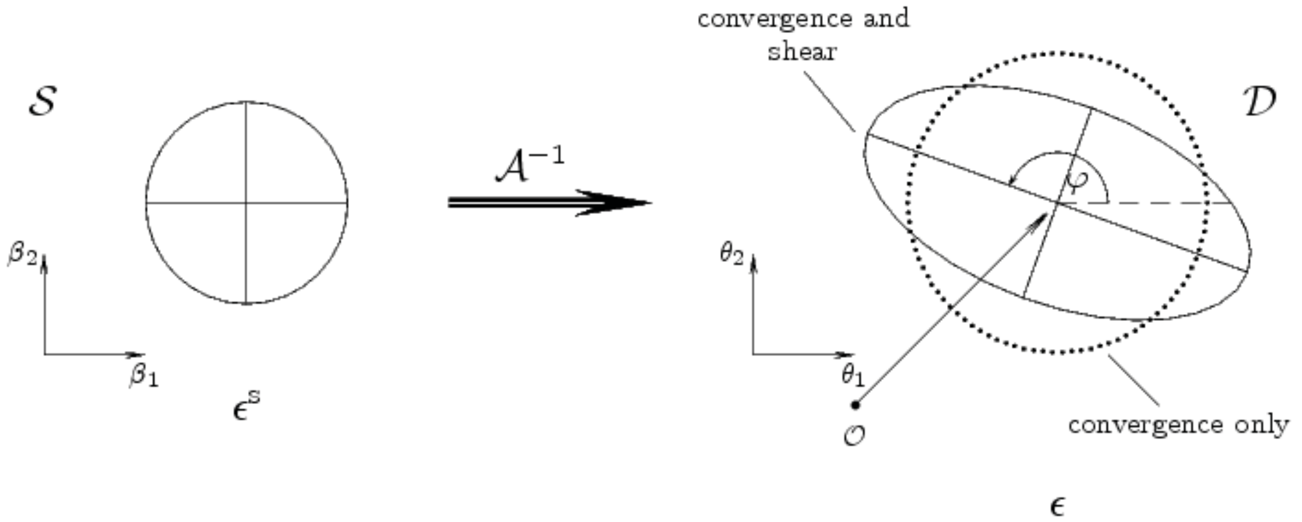
- Eigenvalues of $\mathscr{M}^{-1}$:

$$1-\kappa+\gamma \ , \ 1-\kappa+\gamma$$

Magnification and distortion

- Image and source From the magnification matrix,
  - κ expresses an isotropic magnification. It transforms a circle into a larger/smaller circle.
  - γ is an anisotropic magnification. It transforms a circle into an ellipse with minor and major axes :

$$b = (1-\kappa+\gamma)^{-1} \quad , \quad a = (1-\kappa-\gamma)^{-1}$$



From (reduced) shear to ellipticity

- Reduced shear Let us write the magnification matrix as:

$$A = \mathcal{M}^{-1} = (1-\kappa)\begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix}$$

where

$$g\left(\vec{\theta}\right) = \frac{\gamma\left(\vec{\theta}\right)}{1-\kappa\left(\vec{\theta}\right)} = g_1 + \mathrm{i}g_2 = |g|e^{2\mathrm{i}\varphi}$$

is the *reduced shear*. It directly provides the image ellipicity induced by lensing on a circular source:

$$\frac{b}{a} = \frac{1-|g|}{1+|g|}$$

as well as the orientation of the major axis, φ.

→ Measuring ellipticity=measuring gravitational shear

Caustic and critical lines

- Amplification amplitude

$$\mu = (\det A)^{-1} = \frac{1}{\left[(1-\kappa)^2 - |\gamma|^2\right]}$$

- critical lines corresponds to positions in the lens plane with $\det A = 0$

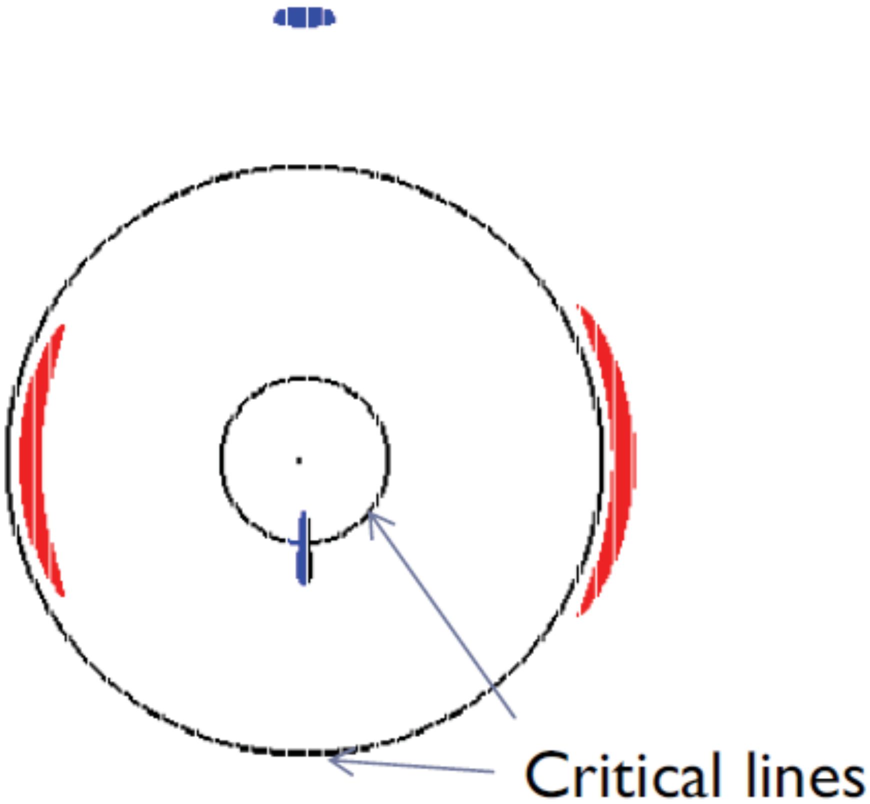
- the corresponding positions on the source plane are the caustic lines

- the positions of source points with respect to a caustic lines define de number of image multiplication and the source margnification

- when a source crosses a caustic line, its amplitication is almost infinity, and image pairs are formed

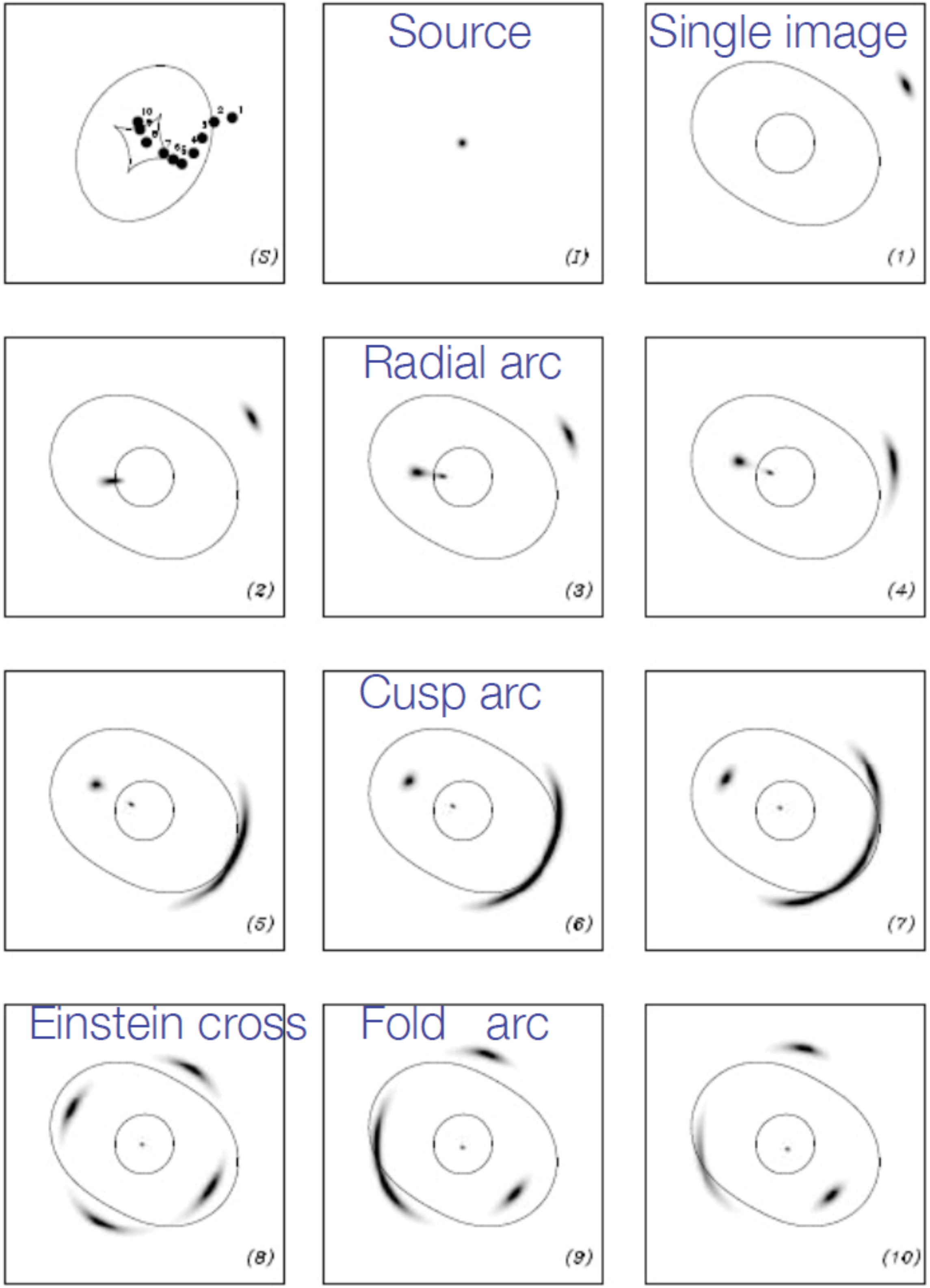
Caustic lines and critical lines

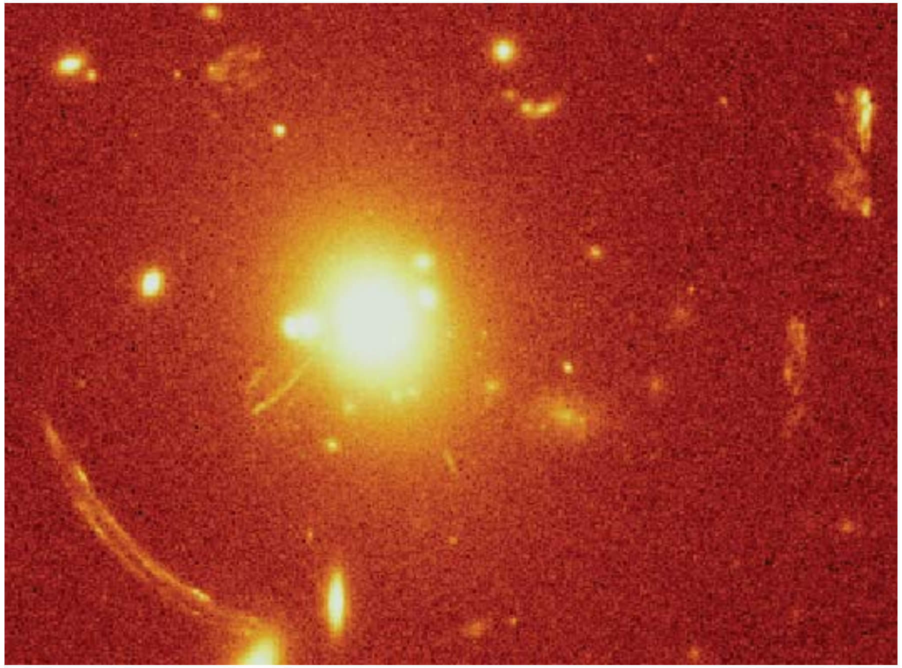
Circular potential with core



Caustic and critical lines

Elliptical potential with core

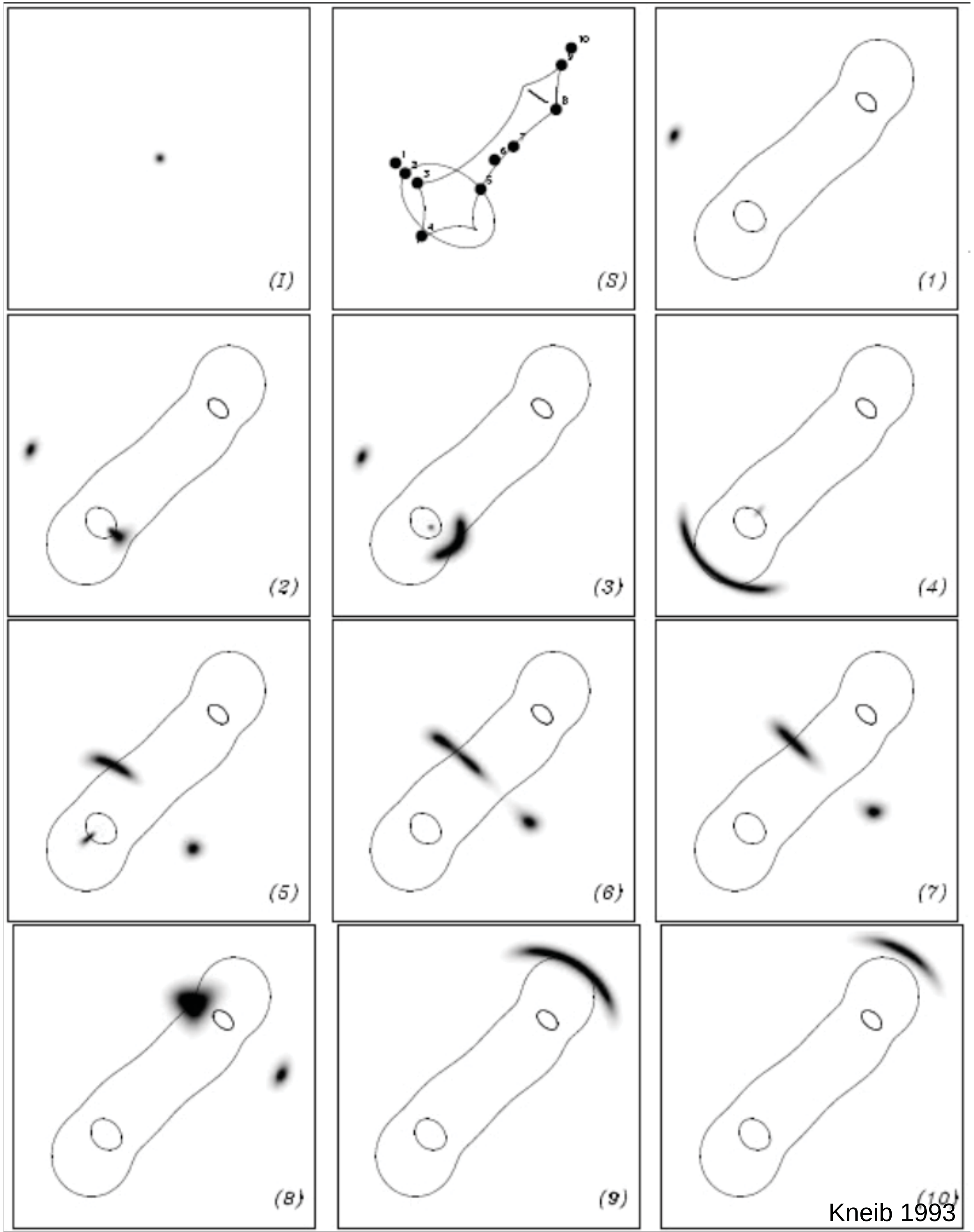




Kneib 1993

Caustic and critical lines

Bimodal potential with core

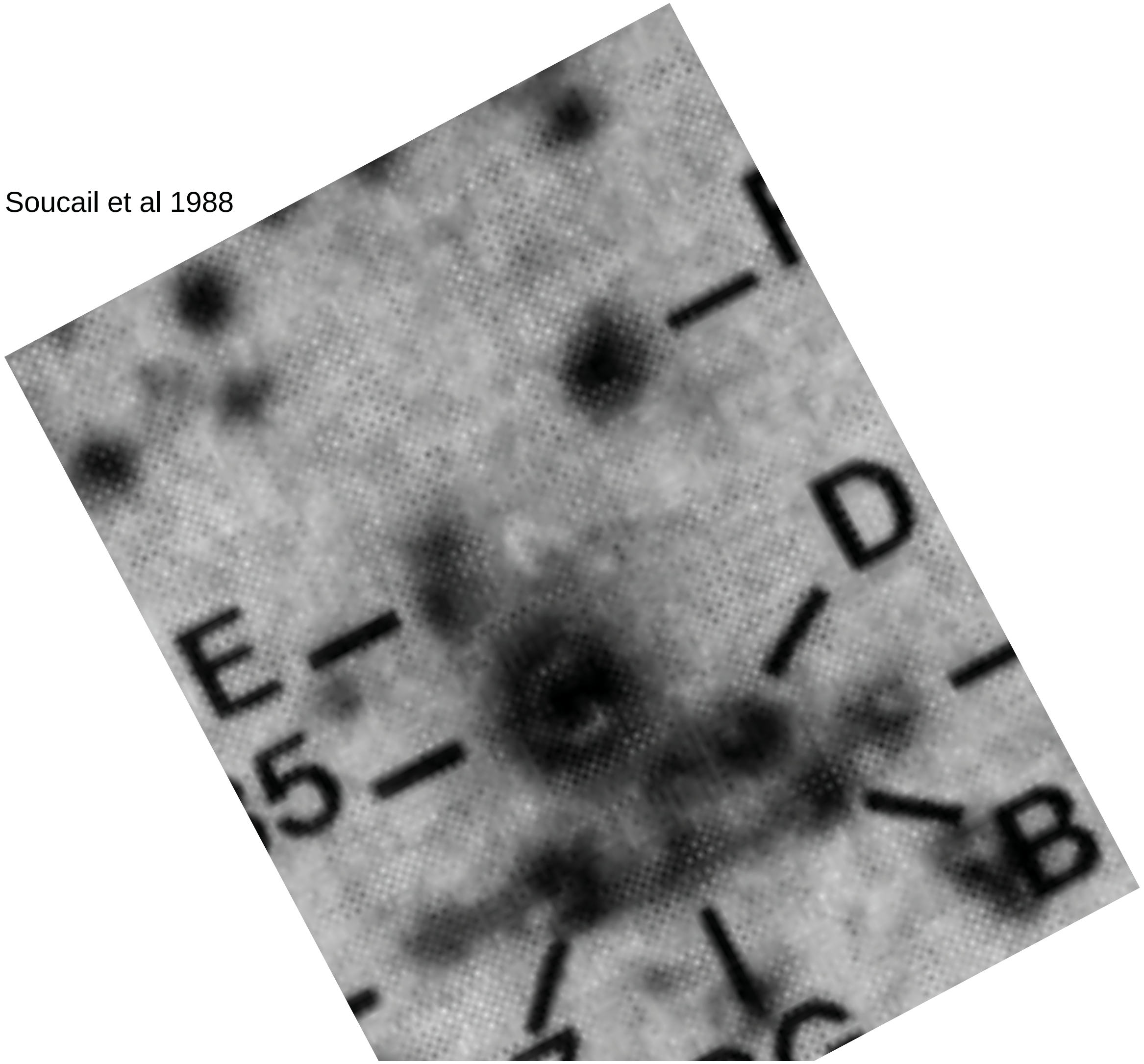


Kneib 1993

Dark matter with Strong Gravitational Lensing

Abell 370: first gravitational arc discovered

Soucail et al 1988



6 Sept. 1985 - A370 arc discovery

Very 1st image at CFHT Cass. focus

RCA 512x320 CCD 0.8'' /pixel,

10mn R-band , seeing 0.8''

Abell 370, HST/ACS ; credit NASA/ESA

Abell 370: first gravitational arc discovered

A spiral structure resolved at z=0.724

Abell 370, HST/ACS ; credit NASA/ESA

Abell 370: singular isothermal sphere model

Lens equation:

$$\boldsymbol{\theta}_S = \boldsymbol{\theta}_I - 4\pi \frac{\sigma^2}{c^2} \frac{D_{LS}}{D_{OS}} \frac{\boldsymbol{\theta}_I}{|\boldsymbol{\theta}_I|}$$

Effective potential:

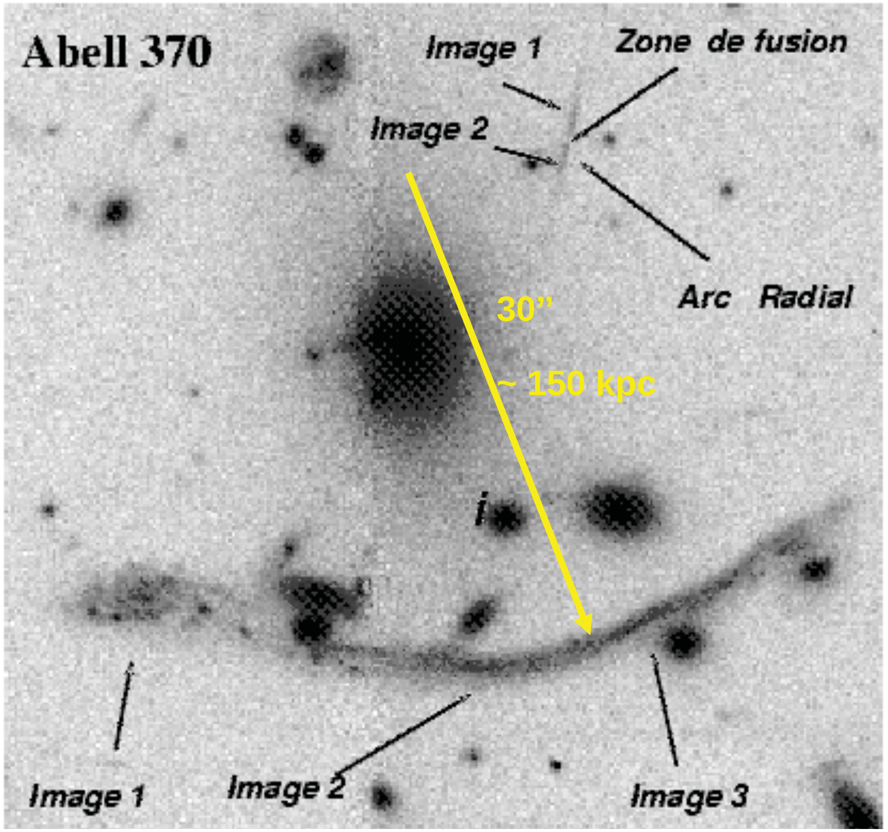
$$\varphi = 4\pi \frac{\sigma^2}{c^2} \frac{D_{LS}}{D_{OS}} r$$

Magnification matrix:

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 - 4\pi \frac{\sigma^2}{c^2} \frac{D_{LS}}{D_{OS}} \frac{1}{|\boldsymbol{\theta}_I|} \end{pmatrix}$$

Deflection angle:

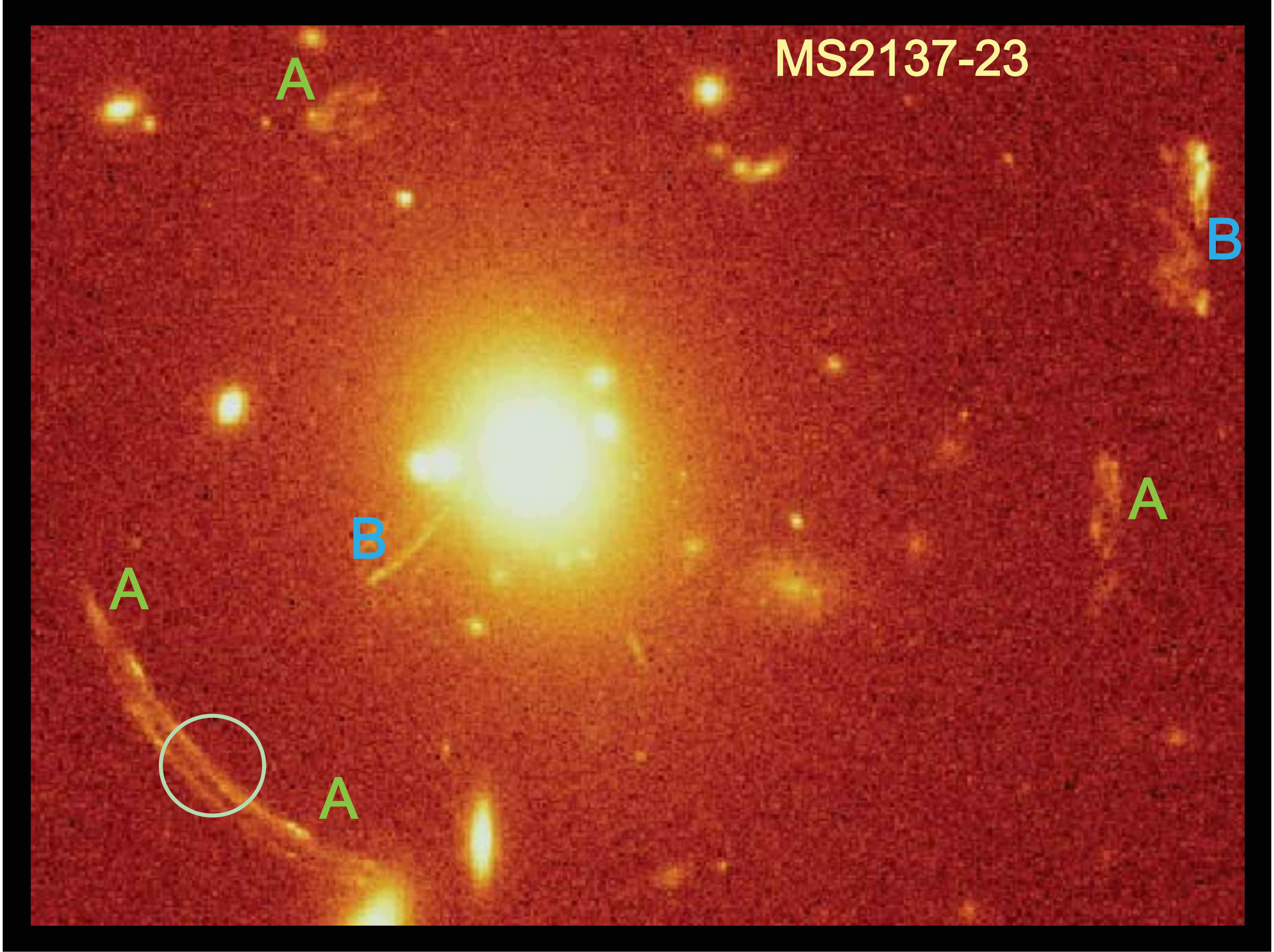
$$\theta_{SIS} = 4\pi \frac{\sigma^2}{c^2} \frac{D_{LS}}{D_{OS}} \approx 16" \left(\frac{\sigma}{1000 \mathrm{km.sec}^{-1}} \right)^2$$

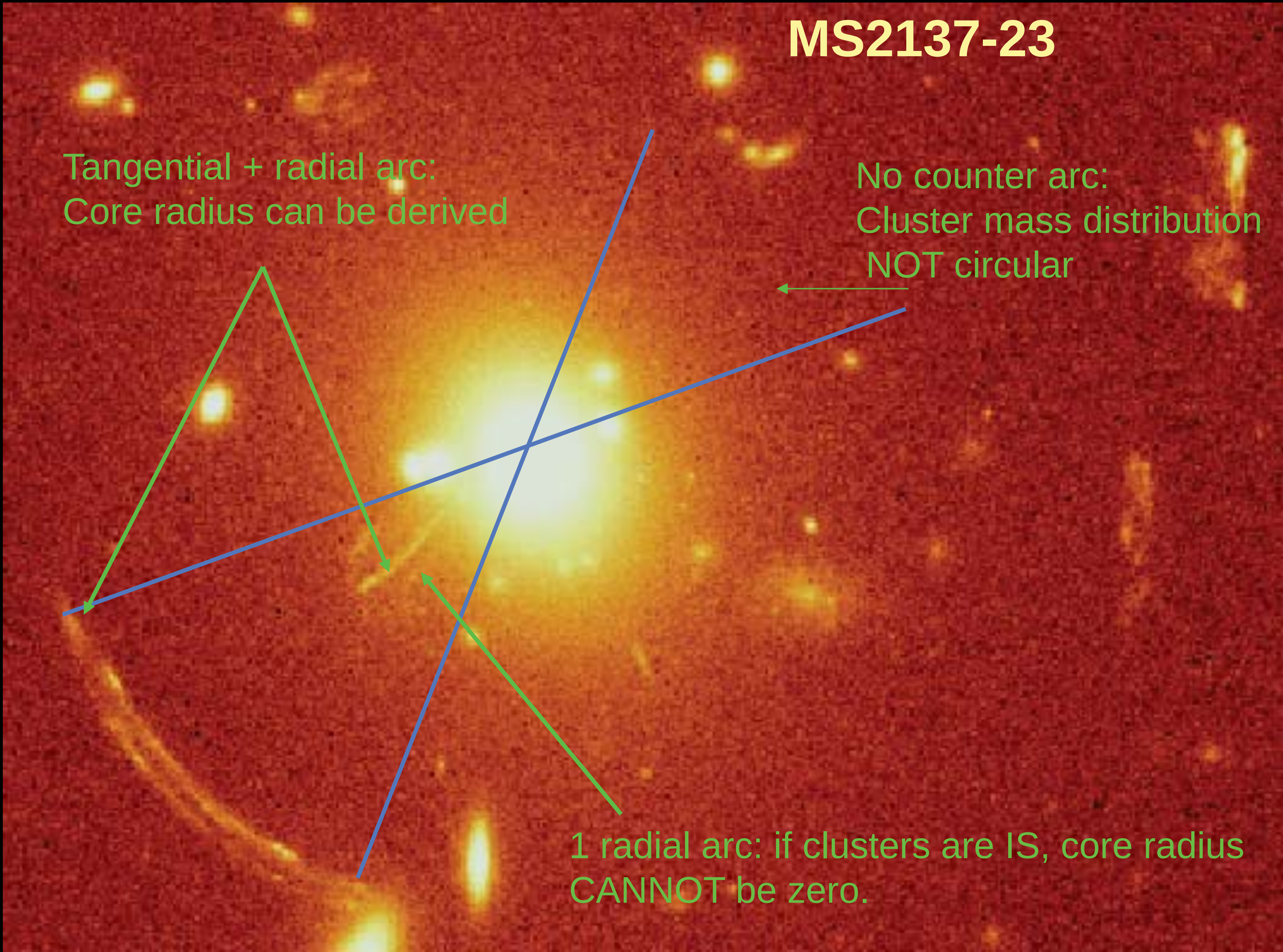


Kneib et al 94

Total mass inside the Einstein radius:

$$M(\theta) = 0.57 \times 10^{14}\ h^{-1}\ M_\odot \left(\frac{\theta}{30"} \right) \left(\frac{\sigma}{1000 \mathrm{km.sec}^{-1}} \right)^2$$


MS2137-23
A
A
A
A
B
B


MS2137-23
Tangential + radial arc:
Core radius can be derived
No counter arc:
Cluster mass distribution
NOT circular
1 radial arc: if clusters are IS, core radius
CANNOT be zero.

Modelling strong lenses

Constraints :

Method : mapping, inversion

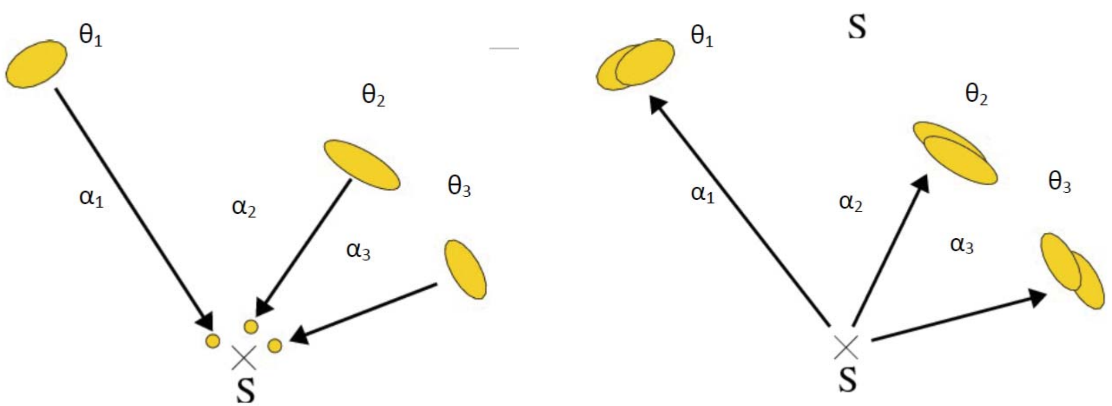
- The angular lens equation set the relation between each image position, $\theta_i^I, \theta_j^I, \theta_k^I, \ldots,$ and the unique position back in the source plane:

$$\theta^S = \theta_i^I - \alpha\left(\theta_i^I\right) = \theta_j^I - \alpha\left(\theta_j^I\right) = \theta_k^I - \alpha\left(\theta_k^I\right) = \ldots.$$

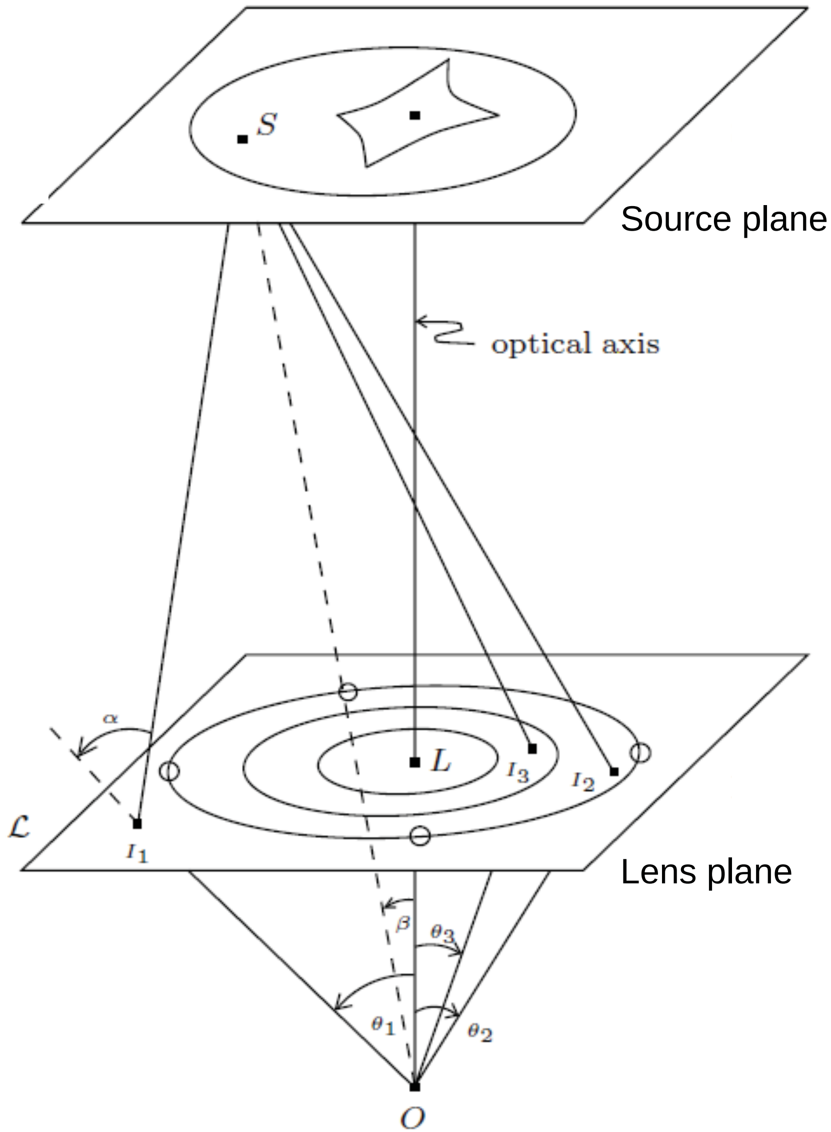
- The flux ratios between each image is an estimate of their magnification ratio:

$$\frac{F_i^I}{F_j^I} = \frac{|\mu_i^I|}{|\mu_j^I|} \quad ; \quad \frac{F_i^I}{F_k^I} = \frac{|\mu_i^I|}{|\mu_k^I|} \quad ; \quad \ldots$$

- When sent back to the source plane, the morphology of each un-lensed image should be identical.



Kneib 2012



MS2137-23 mass model

from critical lines analysis

$$\Phi(r,\theta) = \Phi_0 \sqrt{1 + \left(\frac{r}{r_c}\right)^2 (1 - \epsilon \cos 2\theta)} \, .$$

$$M^{-1} = \begin{pmatrix} 1 - \frac{1}{r}\frac{\partial \Phi}{\partial r} - \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \theta^2} & -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Phi}{\partial \theta}\right) \\ -\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Phi}{\partial \theta}\right) & 1 - \frac{\partial^2 \Phi}{\partial r^2} \end{pmatrix} .$$

Small ellipticity and small core radius: $\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial \Phi}{\partial \theta}\right) \sim 0$

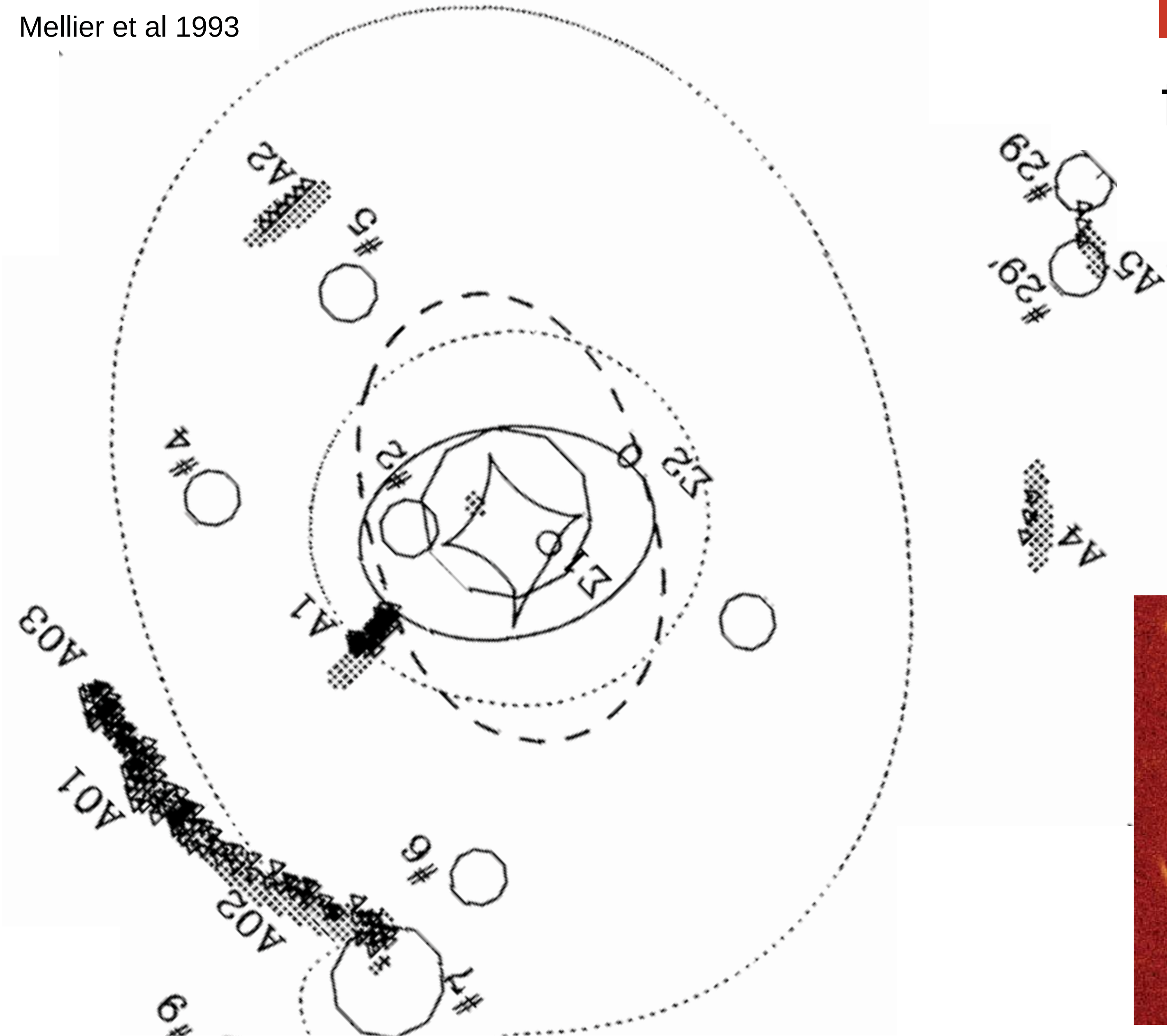
Tangential critical line: $1 - \frac{1}{r}\frac{\partial \Phi}{\partial r} - \frac{1}{r^2}\frac{\partial^2 \Phi}{\partial \theta^2} = 0 \, .$

Radial critical line: $1 - \frac{\partial^2 \Phi}{\partial r^2} = 0 \, .$

Mellier et al 1993

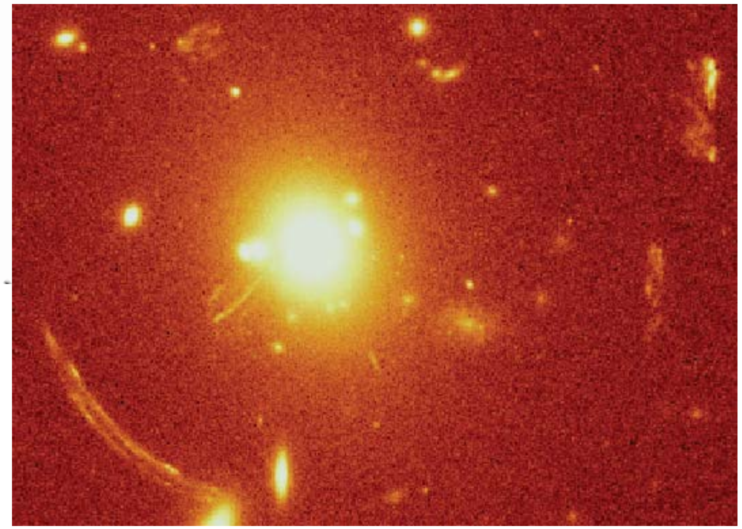
System	ϵ	θ	r_c	σ_{los} (km s^{-1})
Cluster model	$0.08^{+0.03}_{-0.03}$	$29°.5^{+9}_{-5}$	$8''^{+0.5}_{-2}$	1000
cD[a]	0.07 ± 0.04	$29°.5 \pm 5$	1.5 ± 1	350 ± 30[b]
Galaxy 7 model	0.04	8	$0''.27$	185
Galaxy 7[a]	0.07	8	...	230 ± 30[b]

Mellier et al 1993



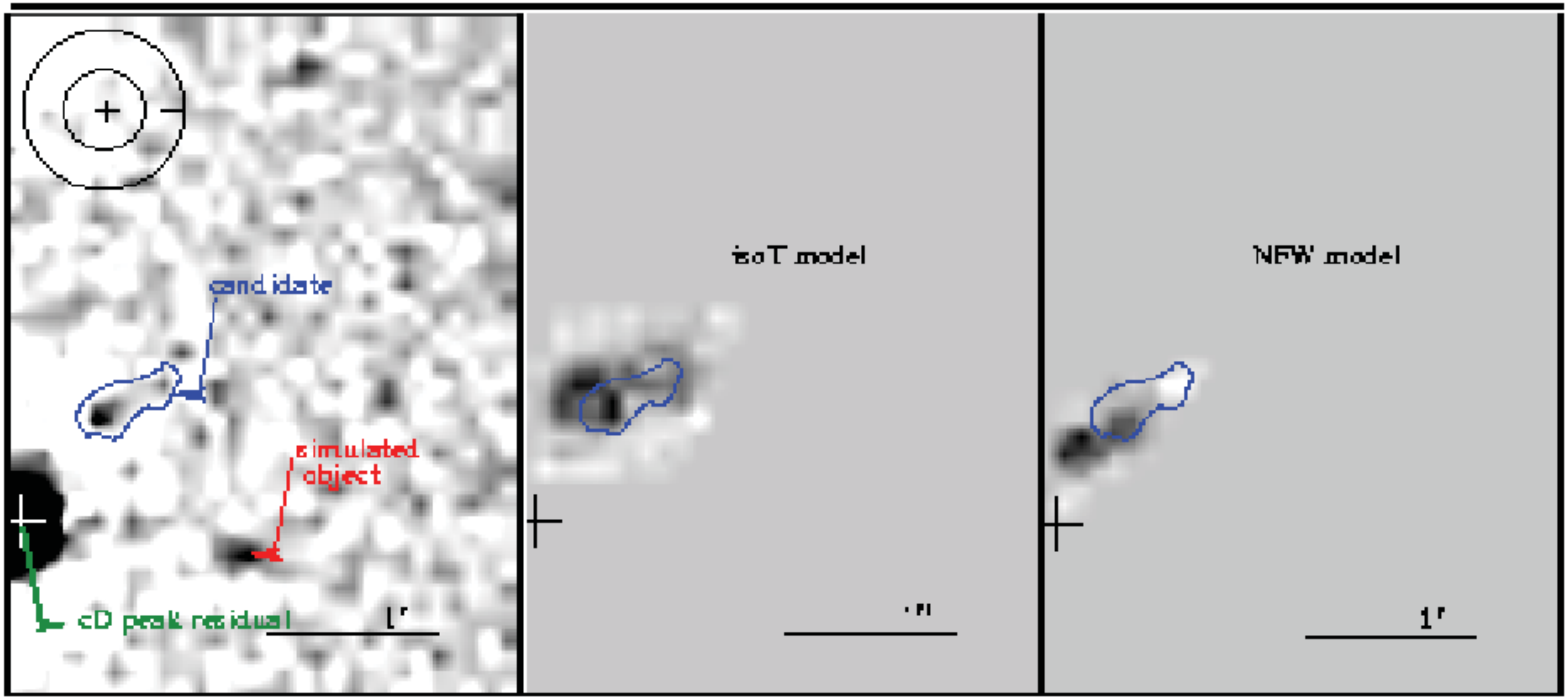
MS2137-23 mass model

from critical lines analysis and 2 sources



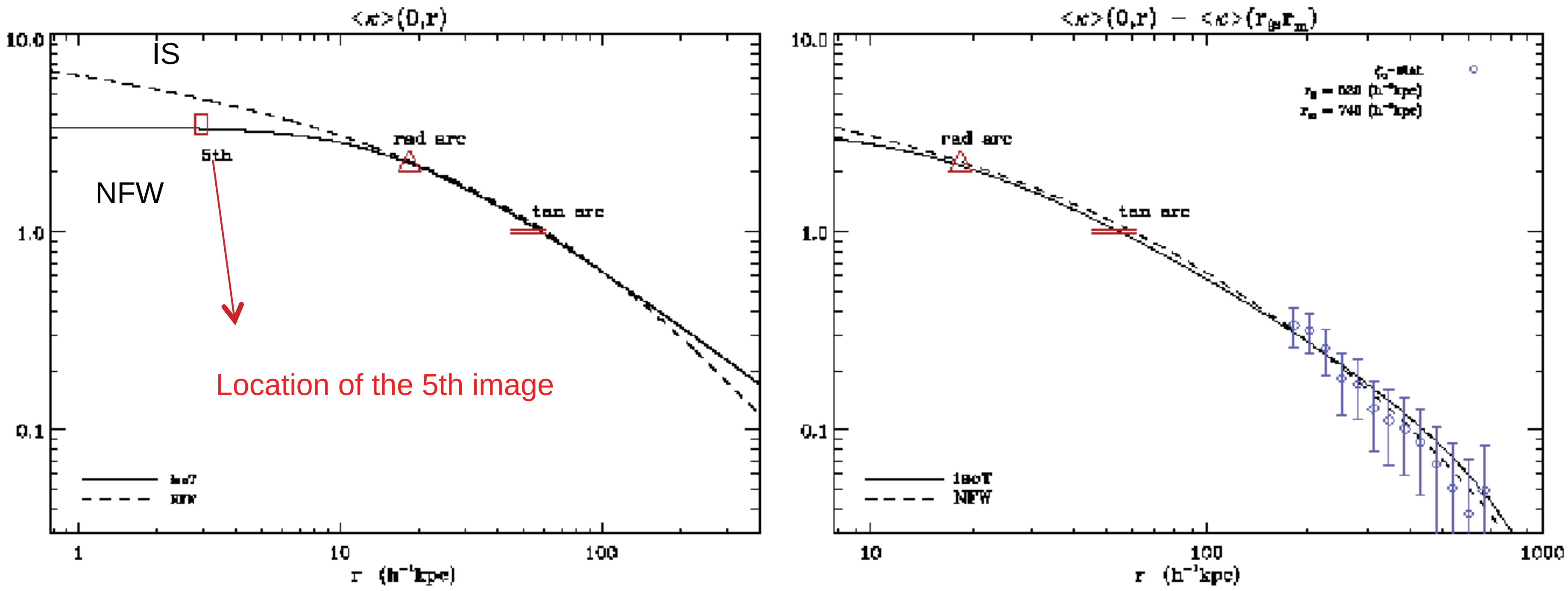
MS2137-23: position and shape of the 5th image: depend on the mass profile

Gavazzi et al 2004



MS2137-23: strong/weak with the 5th image

Even a lens configuration with 2 sources and a [radial+tangential] arc system cannot provide conclusive results on SIS vs NFW

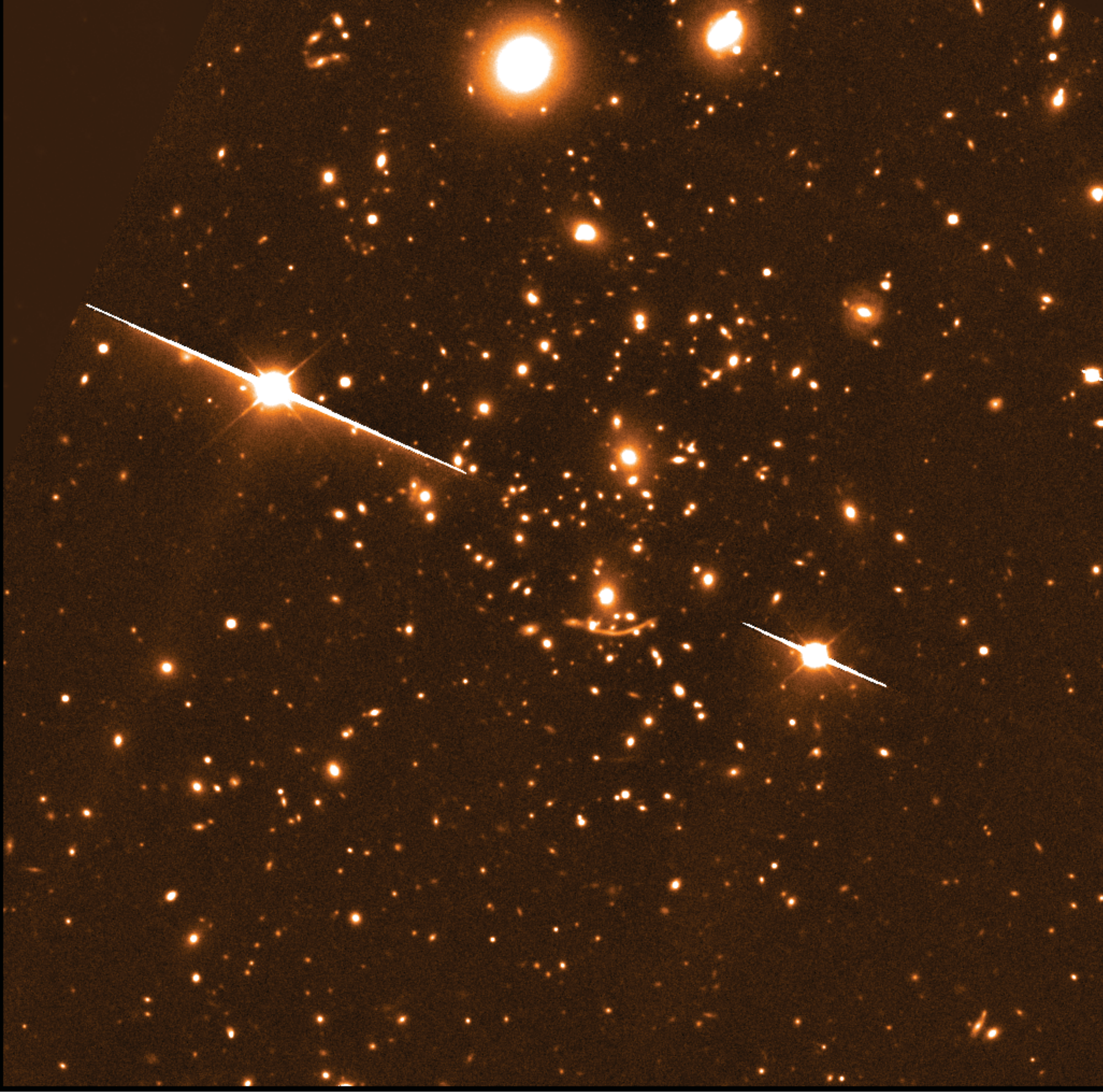


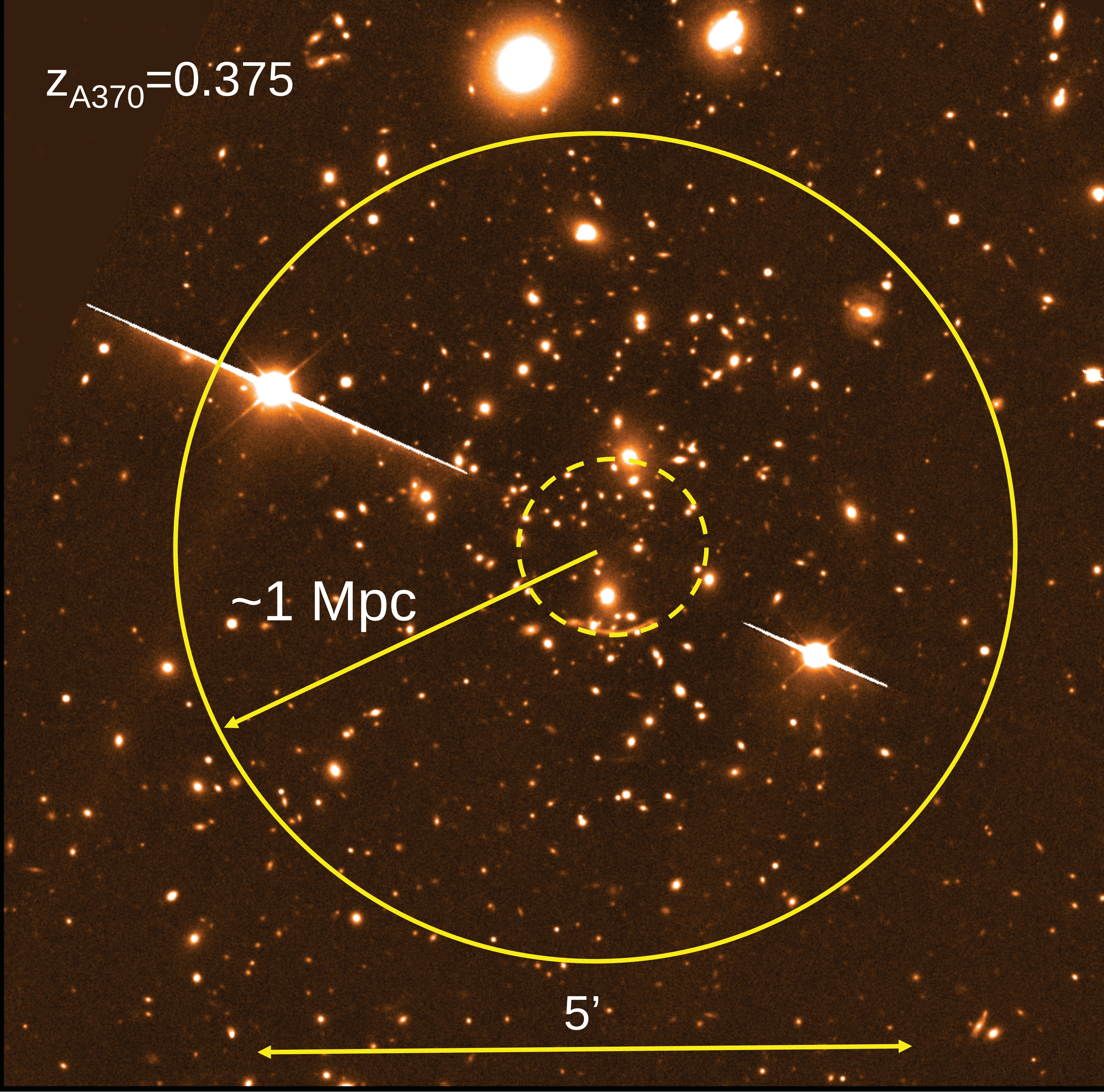
Conclusion: find the 5th image!

But not that obvious…if located under a very bright galaxy

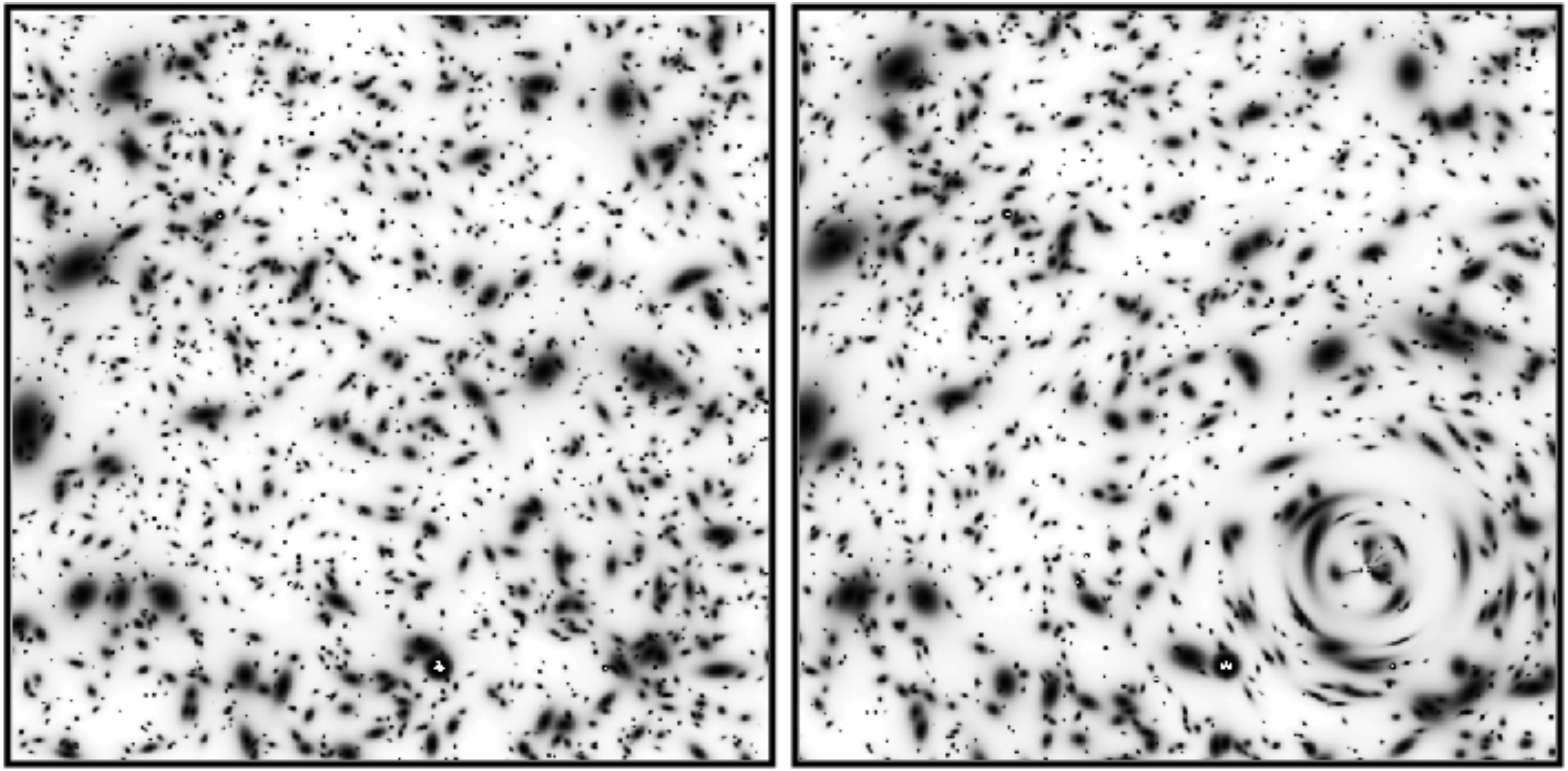
Gavazzi et al 2004

Dark matter with Weak Gravitational Lensing




z_{A370}=0.375
~1 Mpc
5’

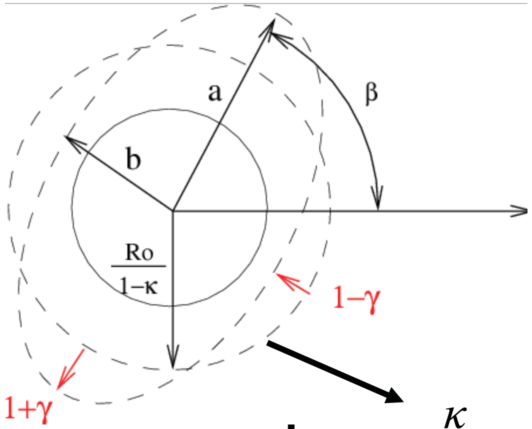
Beyond gravitational arcs:weak lensing

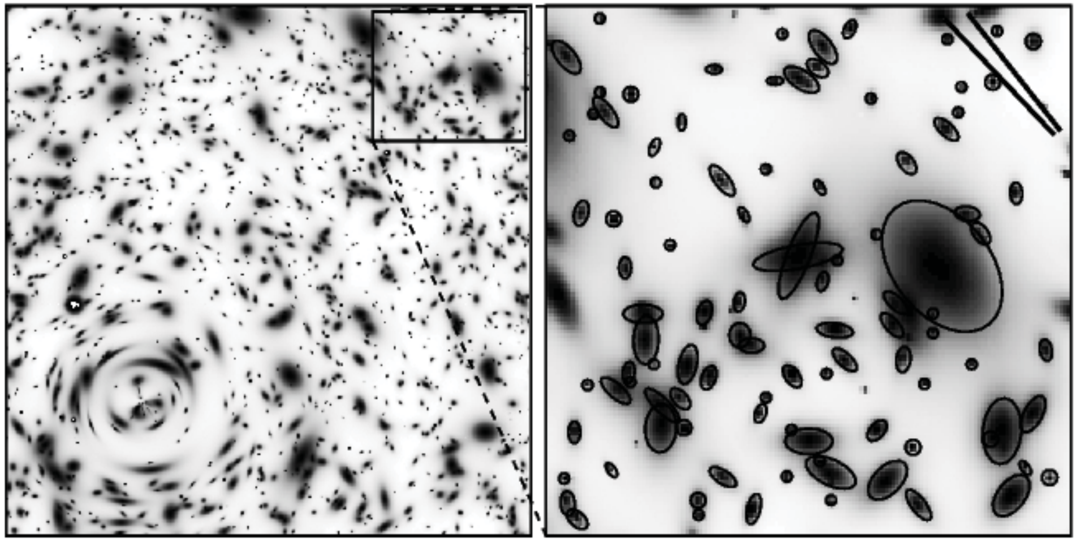


Melllier 1999

Simulation, lensing cluster : isothermal sphere at z=0.3

From ellipticity to shear





κ

$$M_{ij} = \frac{\int I(\boldsymbol{\theta})\, \theta_i\ \theta_j\ \mathrm{d}^2\theta}{\int I(\boldsymbol{\theta})\ \mathrm{d}^2\theta}$$

$$\boldsymbol{\delta} = \frac{2\gamma\ (1-\kappa)}{(1-\kappa)^2 + |\gamma|^2} = \frac{a^2 - b^2}{a^2 + b^2} \qquad \frac{a^2 - b^2}{a^2 + b^2}$$

$\boldsymbol{\delta} \sim\ 2\boldsymbol{\gamma}$ (weak lensing regime)

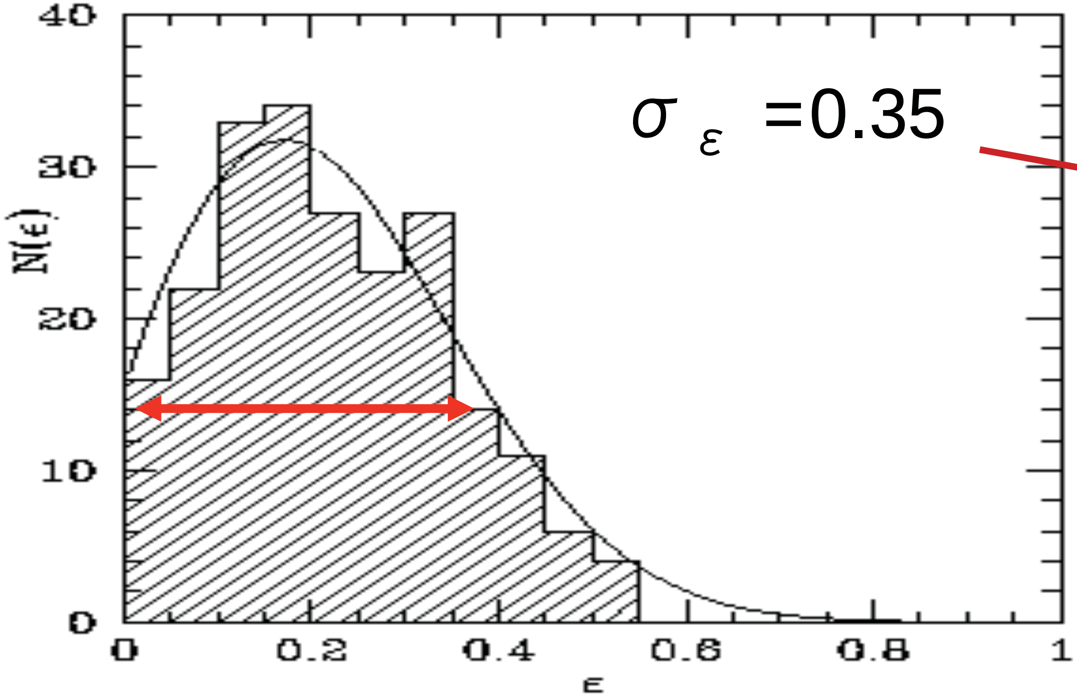
$= \ \boldsymbol{\varepsilon_s} + \ \boldsymbol{\varepsilon_i}$ + noise + systematics….

Reliability of results: depends on PSF analysis

Assume sources orientation is isotropic:

Weak lensing regime : $\delta \sim 2\gamma = \langle \varepsilon_{\text{Shear}} \rangle_\theta$ + noise + complications

Complication: galaxy ellipticity contaminates gravitational ellipticity



$\sigma_{\varepsilon} = 0.35$

$$E\left(\varepsilon^2\right) = \sum_{ij} \gamma_t(\theta_i)\ \gamma_t(\theta_j) + \delta_{ij}\frac{\sigma_\varepsilon}{2}$$

$$S/N = 10\left(\frac{n}{30\ \mathrm{arcmin}^2}\right)^{1/2}\left(\frac{\sigma_\varepsilon}{0.2}\right)^{-1}\left(\frac{\sigma_v}{600\ \mathrm{km/s}}\right)^2\left(\frac{\ln\left[\frac{\theta_2}{\theta_1}\right]}{\ln 10}\right)^{1/2}\langle\frac{D_{ls}}{D_{os}}\rangle$$

From shear to mass density

2D mass density map = Distortion (ellipticity) map

$$\kappa(\theta) = \frac{1}{\pi} \int \hat{F}^*(\theta - \theta')\,\gamma(\theta')\; \mathrm{d}\theta^2 + \kappa_0$$

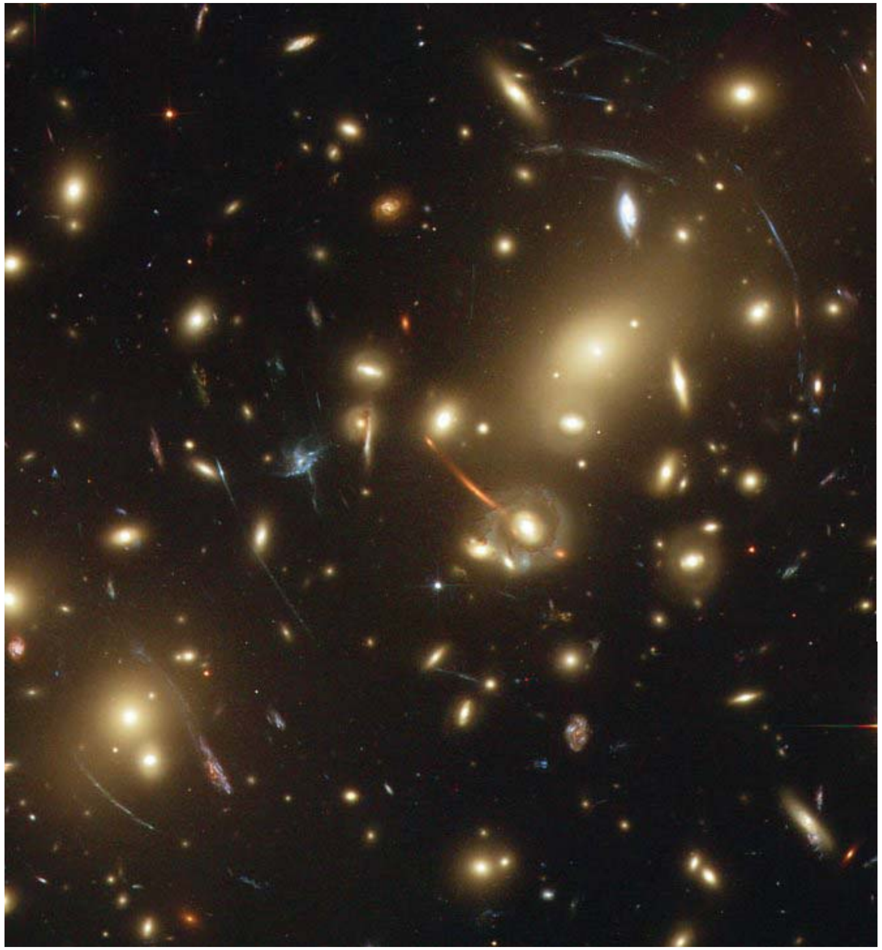
Application to real data. Sampling ellipticities on a grid:

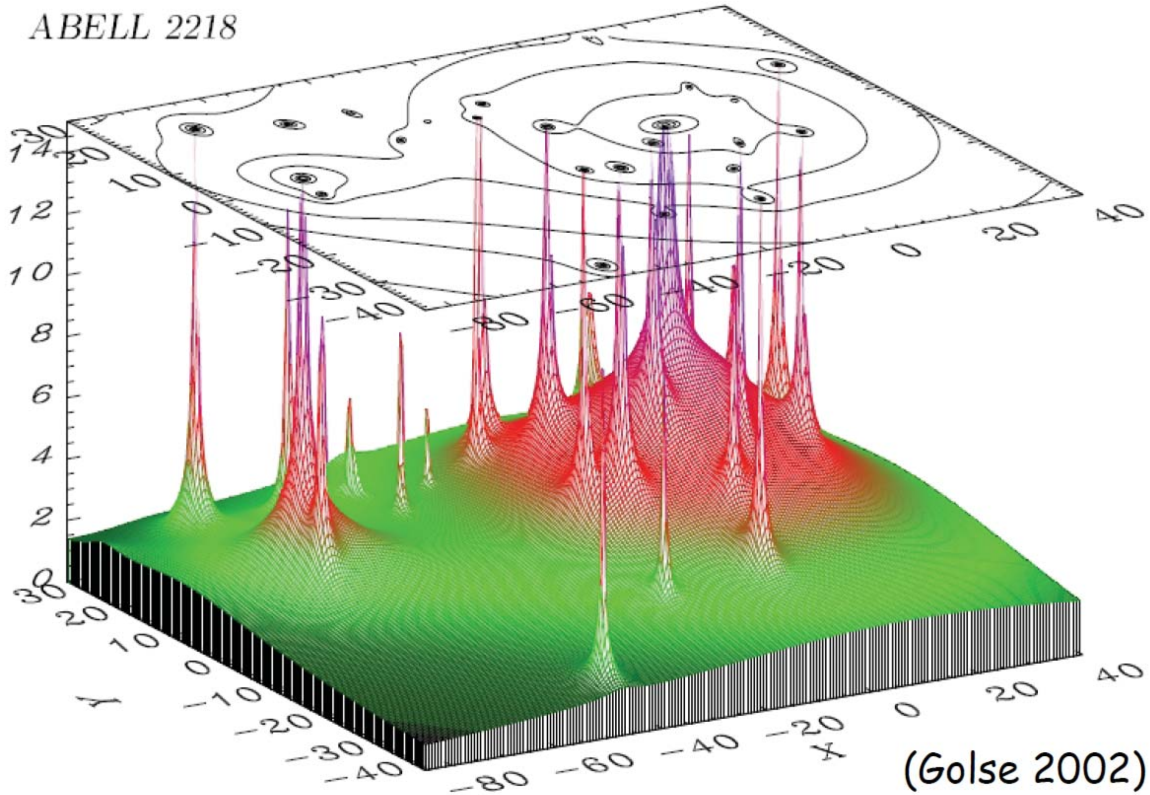
$$\Sigma(\theta) - \Sigma_0 = \Sigma_{critic} \frac{1}{\pi} a^2 \sum_{i,j} \Re\left(\hat{F}^*(\theta - \theta_{i,j})\,\bar{\varepsilon}(\theta_{i,j})\right)$$

where a is the distance between grid points

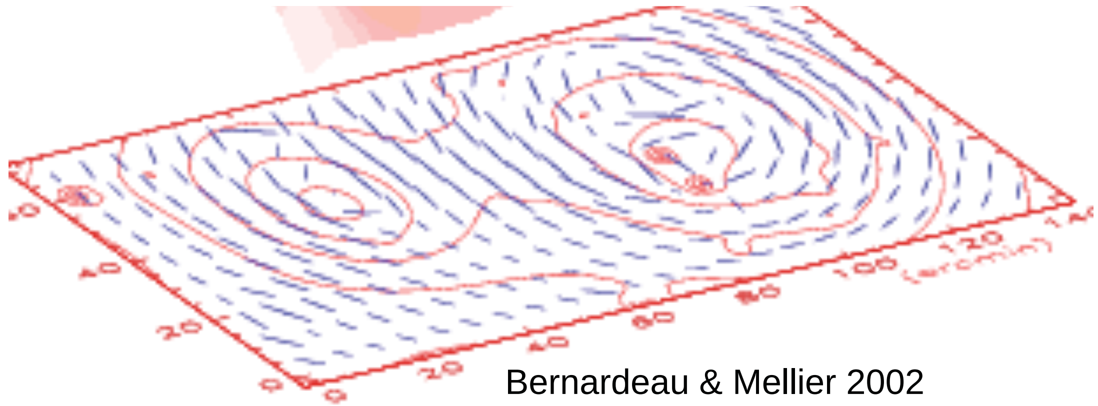
HST
Cluster of galaxies
Abell 2218, z=0.17

Mass reconstruction: Abell 2218





(Golse 2002)



Bernardeau & Mellier 2002


HST
Abell 1689
Light (galaxies)

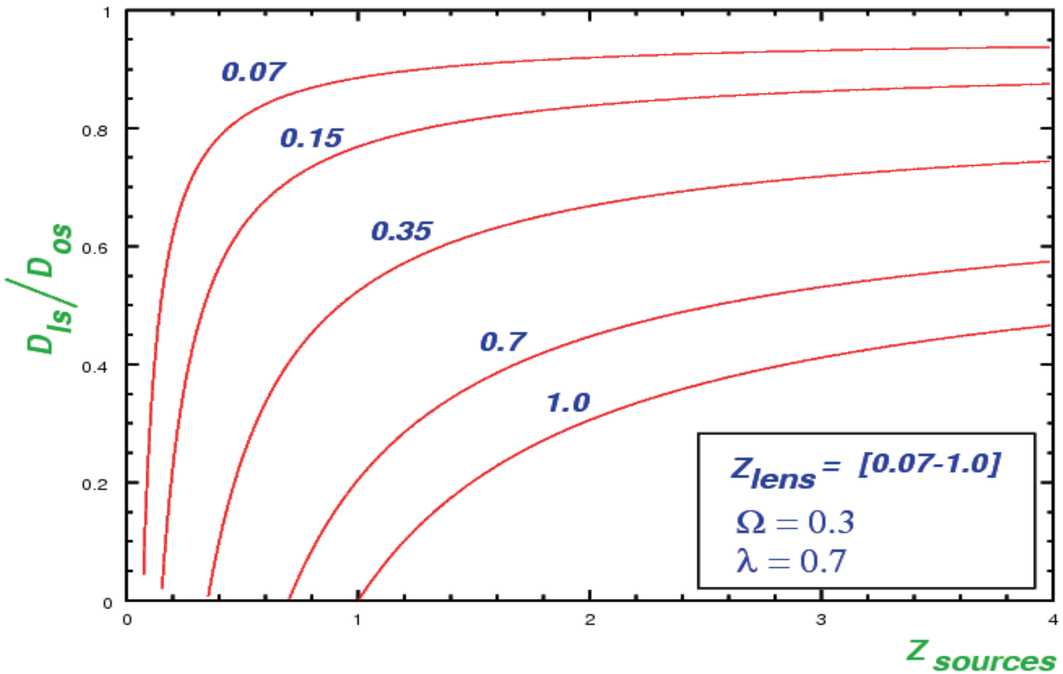

Abell 1689
Dark matter

Getting the absolute mass

- The mass reconstruction provides the shape of the projeted mass distribution but not the absolute scale.
- Need the redshift of the sources:

$$\kappa\left(\vec{\theta}, z\right) = \frac{\Sigma\left(\vec{\theta}\right)}{\Sigma_{critic}\left(z\right)} = \Sigma\left(\vec{\theta}\right)\frac{4\pi G}{c^2}D_{ol}\left[\frac{D_{ls}}{D_{os}}\right]$$

$$\gamma\left(\vec{\theta}, z\right) = \frac{4\pi G}{c^2}D_{ol}\left[\frac{D_{ls}}{D_{os}}\right]\gamma\left(\vec{\theta}\right)$$



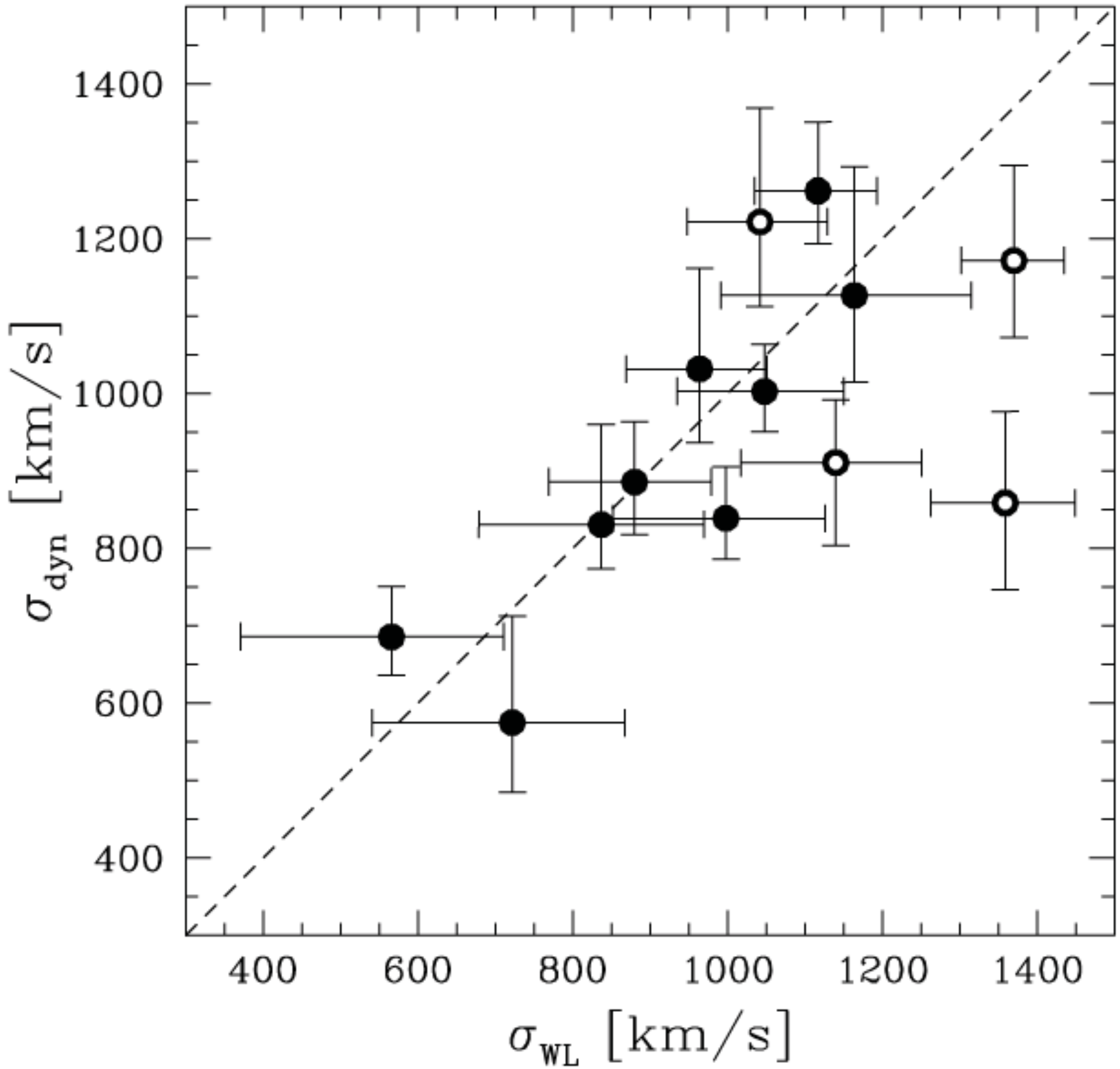
Redshift increasingly important as z_{lens} increases

Summary mass from cluster WL reconstruction

(1) Name	(2) σ_{WL} (km s^{-1}) SIS	(3) $M(<0.5h^{-1}$ Mpc) WL by aperture mass	(4) M_{2500}	(5) M_{500}	(6) M_{2500}^{NFW} WL using NFW profile fitting of the shear	(7) M_{500}^{NFW}	(8) M_{200}^{NFW}
A2390	1117^{+76}_{-82}	5.2 ± 0.6	2.4 ± 0.5	6.8 ± 1.5	2.9 ± 0.6	$9.2^{+2.0}_{-1.9}$	$14.6^{+3.1}_{-2.9}$
MS 0016+16	1164^{+151}_{-173}	7.9 ± 1.1	3.2 ± 0.7	15.8 ± 4.3	$4.2^{+1.4}_{-1.3}$	$16.0^{+5.3}_{-4.9}$	$27.0^{+9.0}_{-8.4}$
MS 0906+11	880^{+99}_{-111}	3.7 ± 0.7	1.6 ± 0.4	7.4 ± 1.5	1.5 ± 0.4	$4.4^{+1.2}_{-0.2}$	$6.7^{+1.8}_{-1.8}$
MS 1224+20	837^{+133}_{-158}	3.0 ± 0.9	1.0 ± 0.4	2.3 ± 1.2	0.8 ± 0.4	$2.1^{+1.2}_{-1.0}$	$3.2^{+1.8}_{-1.5}$
MS 1231+15	566^{+145}_{-195}	0.8 ± 0.6	0.4 ± 0.2	0.5 ± 0.5	0.4 ± 0.2	$0.9^{+0.5}_{-0.5}$	$1.3^{+0.7}_{-0.7}$
MS 1358+62	1048^{+102}_{-113}	4.3 ± 0.8	1.8 ± 0.4	5.6 ± 2.0	$1.8^{+0.6}_{-0.5}$	$5.5^{+1.9}_{-1.7}$	$8.5^{+3.0}_{-2.6}$
MS 1455+22	964^{+87}_{-95}	3.3 ± 0.7	1.2 ± 0.3	3.7 ± 1.2	$1.4^{+0.4}_{-0.3}$	$3.9^{+1.0}_{-1.0}$	$6.0^{+1.6}_{-1.5}$
MS 1512+36	722^{+145}_{-181}	2.1 ± 0.8	0.6 ± 0.3	2.5 ± 1.6	$0.7^{+0.4}_{-0.3}$	$1.8^{+1.1}_{-0.9}$	$2.8^{+1.6}_{-1.4}$
MS 1621+26	998^{+128}_{-146}	5.3 ± 1.0	1.7 ± 0.7	5.8 ± 2.0	$2.0^{+0.8}_{-0.6}$	$6.5^{+2.8}_{-1.9}$	$10.3^{+4.4}_{-3.0}$
A68	1036^{+89}_{-97}	4.4 ± 0.8	1.9 ± 0.4	4.8 ± 1.8	$1.8^{+0.5}_{-0.4}$	$5.6^{+1.6}_{-1.3}$	$8.6^{+2.5}_{-2.1}$
A209	898^{+92}_{-102}	3.9 ± 0.9	1.5 ± 0.6	5.7 ± 1.4	$1.5^{+0.5}_{-0.4}$	$4.3^{+1.4}_{-1.1}$	$6.6^{+2.1}_{-1.7}$
A267	1008^{+90}_{-99}	3.3 ± 0.6	1.5 ± 0.3	4.3 ± 1.4	1.4 ± 0.4	$4.0^{+1.2}_{-1.2}$	$6.2^{+1.9}_{-1.8}$
A383	701^{+138}_{-171}	2.6 ± 0.7	0.6 ± 0.3	3.7 ± 1.6	$0.6^{+0.4}_{-0.3}$	$1.6^{+0.9}_{-0.8}$	$2.3^{+1.3}_{-1.2}$
A963	844^{+99}_{-112}	2.7 ± 0.6	1.0 ± 0.3	3.1 ± 1.1	1.3 ± 0.4	$3.5^{+1.1}_{-1.0}$	$5.3^{+1.6}_{-1.5}$
A1689	1370^{+65}_{-68}	6.7 ± 0.7	3.7 ± 0.5	11.2 ± 1.8	$4.0^{+0.8}_{-0.7}$	$12.8^{+2.7}_{-2.3}$	$20.4^{+4.2}_{-3.6}$
A1763	1060^{+87}_{-95}	4.9 ± 0.7	2.3 ± 0.4	8.5 ± 2.2	2.3 ± 0.6	$7.0^{+2.0}_{-1.7}$	$11.0^{+3.0}_{-2.7}$
A2218	1042^{+87}_{-94}	4.5 ± 0.7	2.0 ± 0.5	4.6 ± 1.2	$1.6^{+0.5}_{-0.4}$	$4.7^{+1.5}_{-1.3}$	$7.1^{+2.3}_{-1.9}$
A2219	1074^{+82}_{-89}	5.0 ± 0.7	2.3 ± 0.4	7.7 ± 1.7	$2.0^{+0.6}_{-0.5}$	$5.9^{+1.7}_{-1.4}$	$9.2^{+2.7}_{-2.2}$
A370	1359^{+90}_{-96}	6.5 ± 0.9	3.1 ± 0.5	10.6 ± 2.5	$3.7^{+1.1}_{-0.9}$	$12.9^{+3.8}_{-3.2}$	$21.1^{+6.2}_{-5.3}$
CL0024+16	1140^{+111}_{-123}	5.5 ± 0.9	2.3 ± 0.5	7.4 ± 2.4	$2.7^{+0.9}_{-0.8}$	$9.1^{+3.2}_{-2.7}$	$14.7^{+5.1}_{-4.4}$

Hoekstra 2014

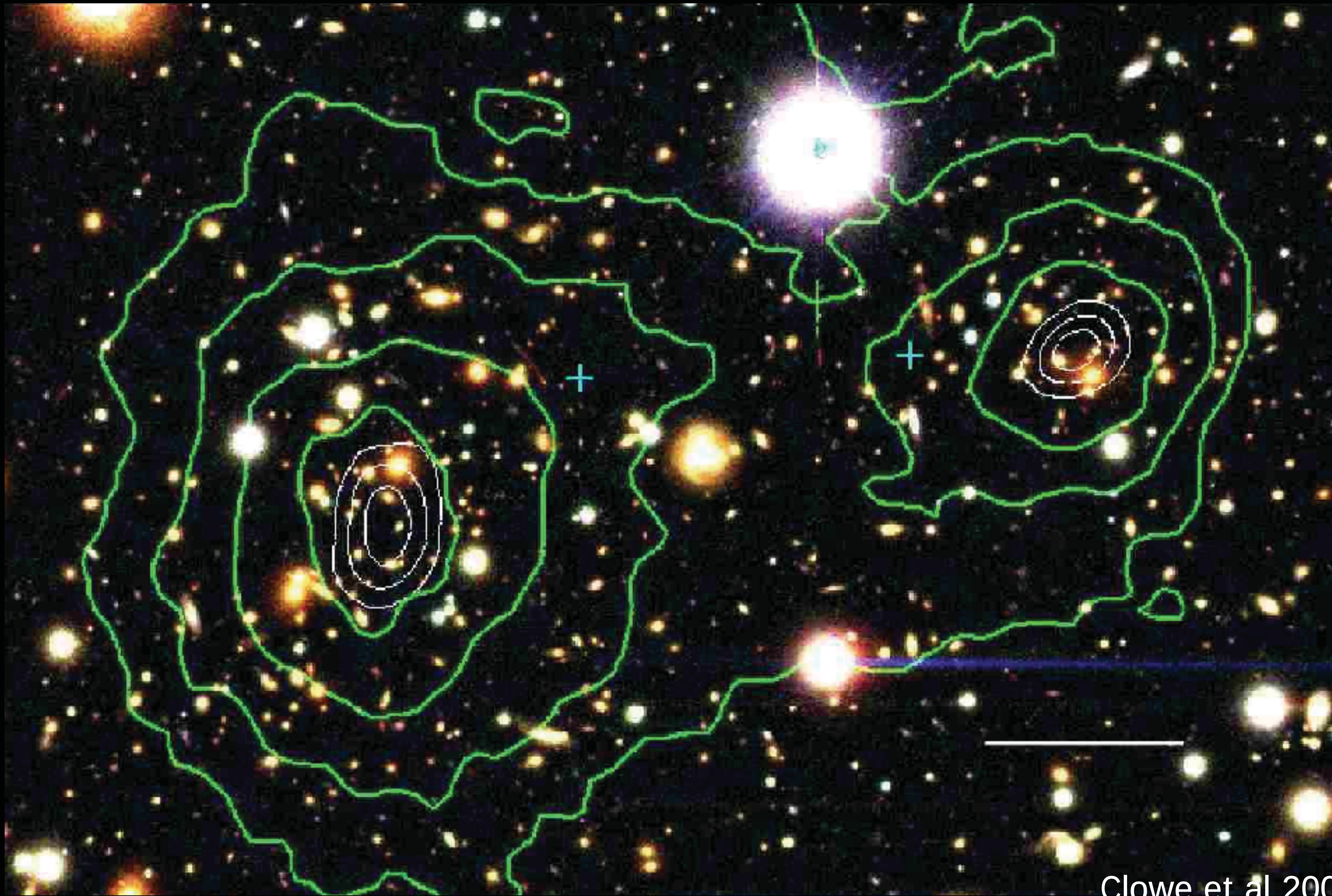
Summary mass from cluster WL reconstruction



Hoekstra 2014

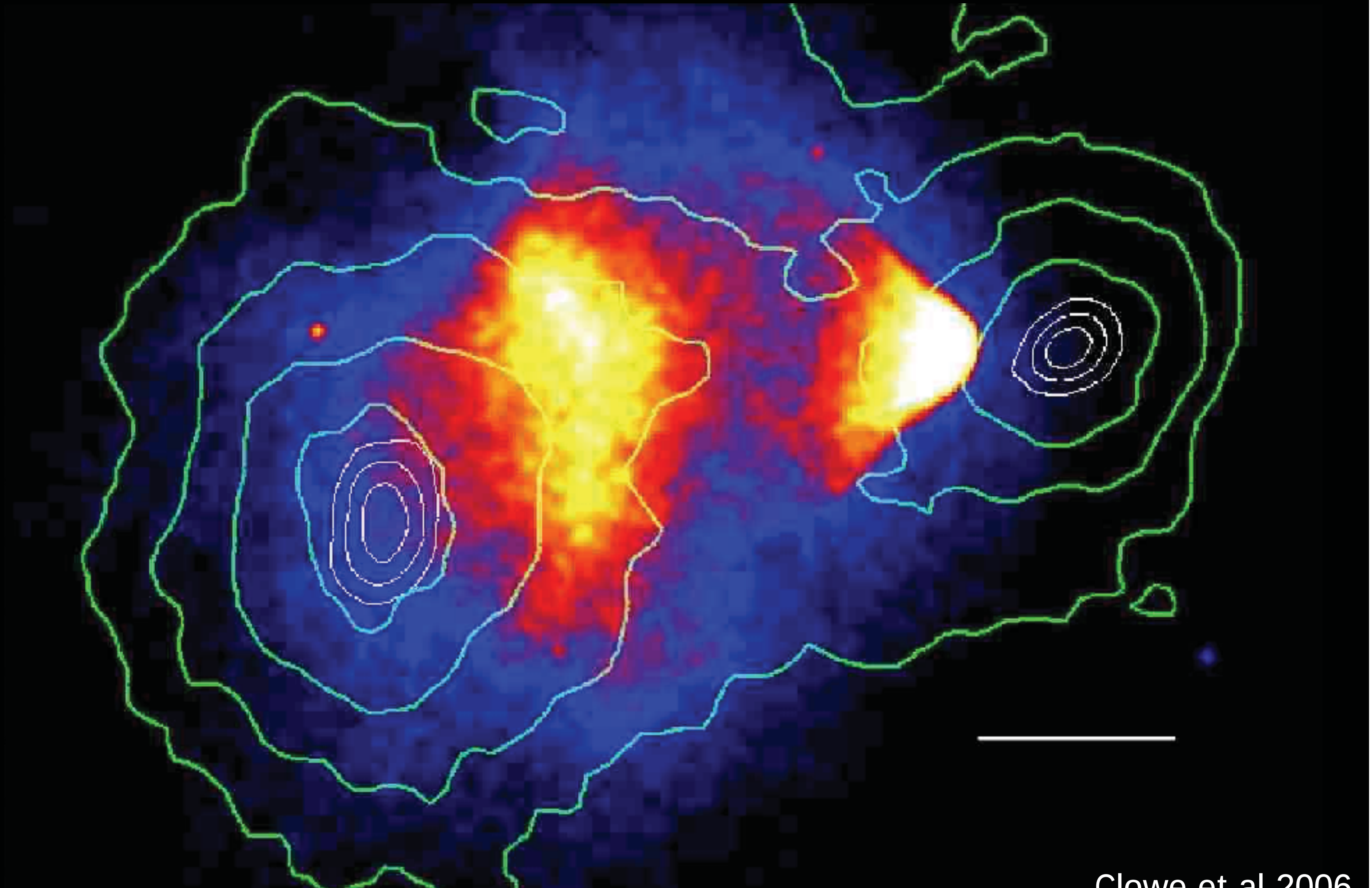
The Bullet cluster

Bullet cluster



Clowe et al 2006

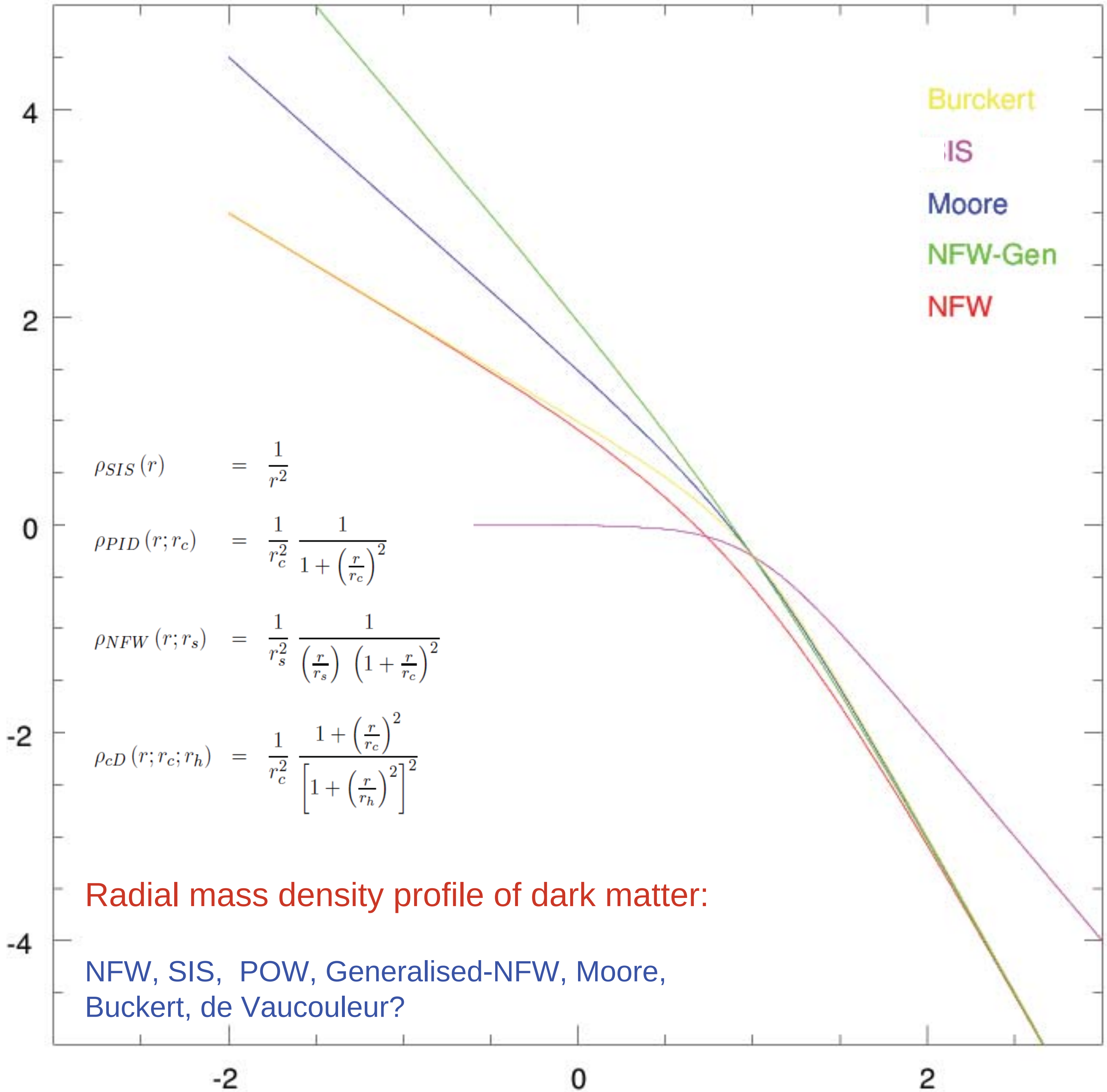
Bullet cluster



Clowe et al 2006

Mass reconstruction

Application to clusters of galaxies



$$\rho_{SIS}(r) = \frac{1}{r^2}$$

$$\rho_{PID}(r;r_c) = \frac{1}{r_c^2}\,\frac{1}{1+\left(\frac{r}{r_c}\right)^2}$$

$$\rho_{NFW}(r;r_s) = \frac{1}{r_s^2}\,\frac{1}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_c}\right)^2}$$

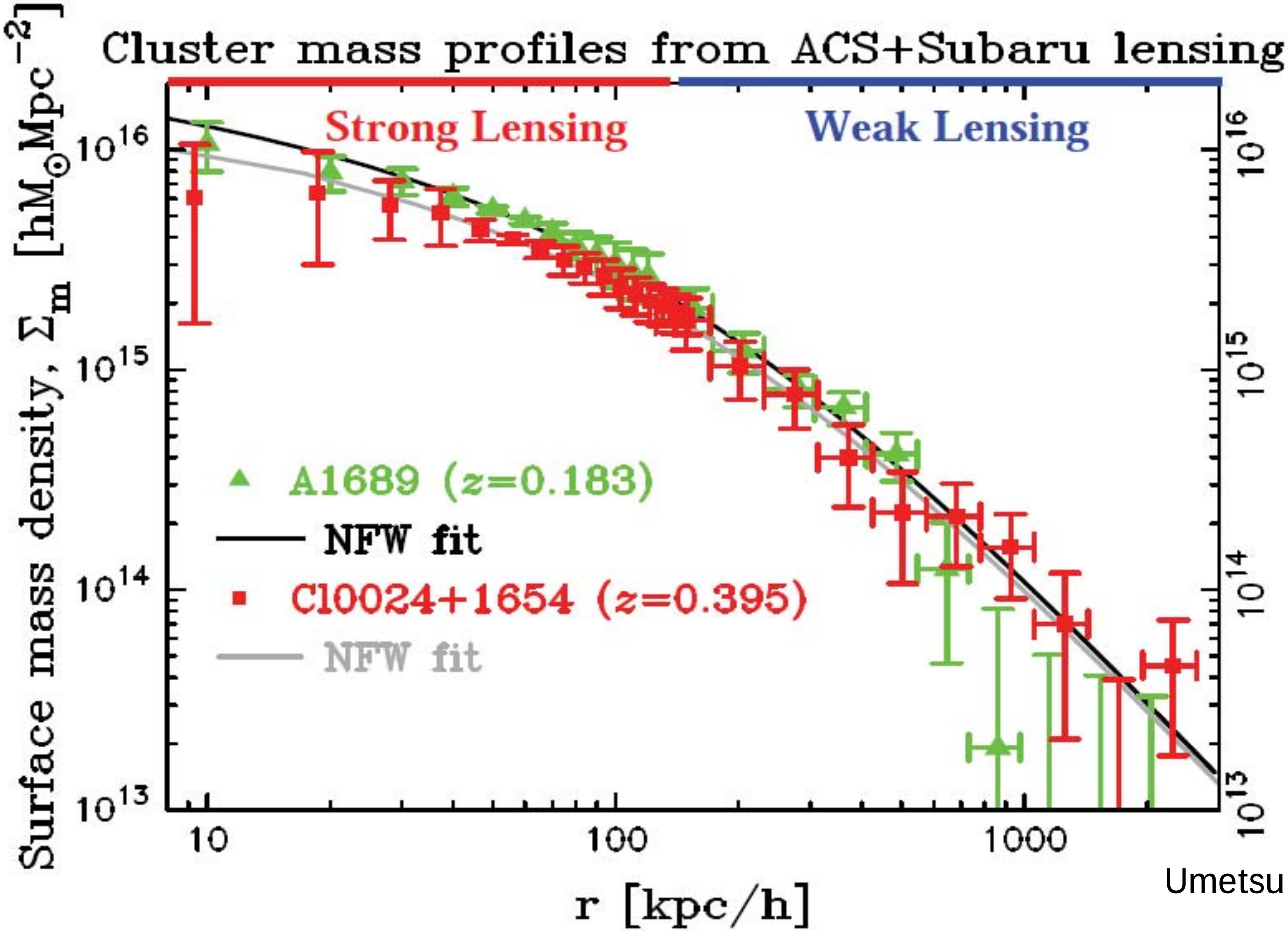
$$\rho_{cD}(r;r_c;r_h) = \frac{1}{r_c^2}\,\frac{1+\left(\frac{r}{r_c}\right)^2}{\left[1+\left(\frac{r}{r_h}\right)^2\right]^2}$$

Radial mass density profile of dark matter:

NFW, SIS, POW, Generalised-NFW, Moore,
Buckert, de Vaucouleur?

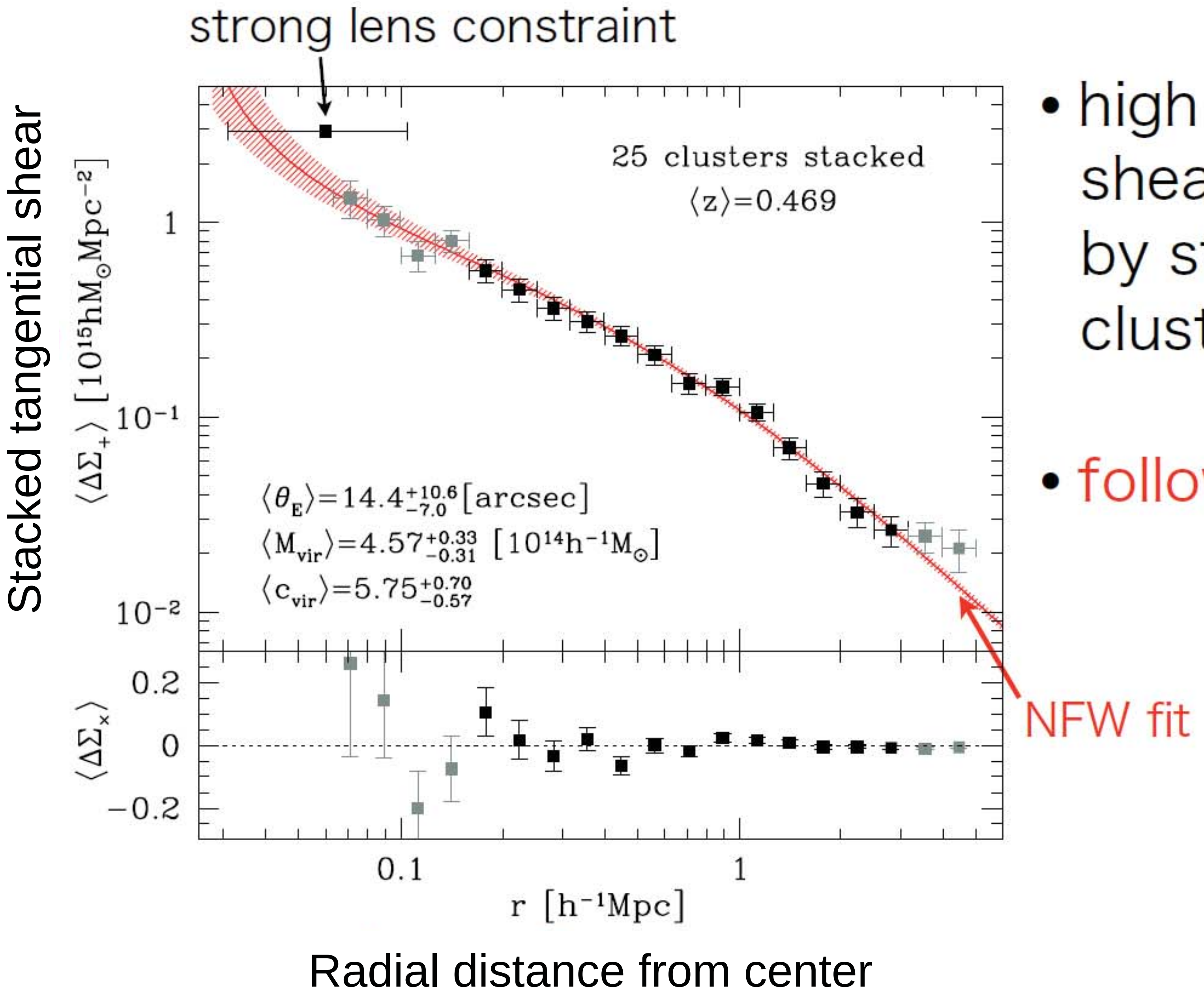
Cl0024+1654 + Abell 1689

Weak+strong lensing



Umetsu et al 2010

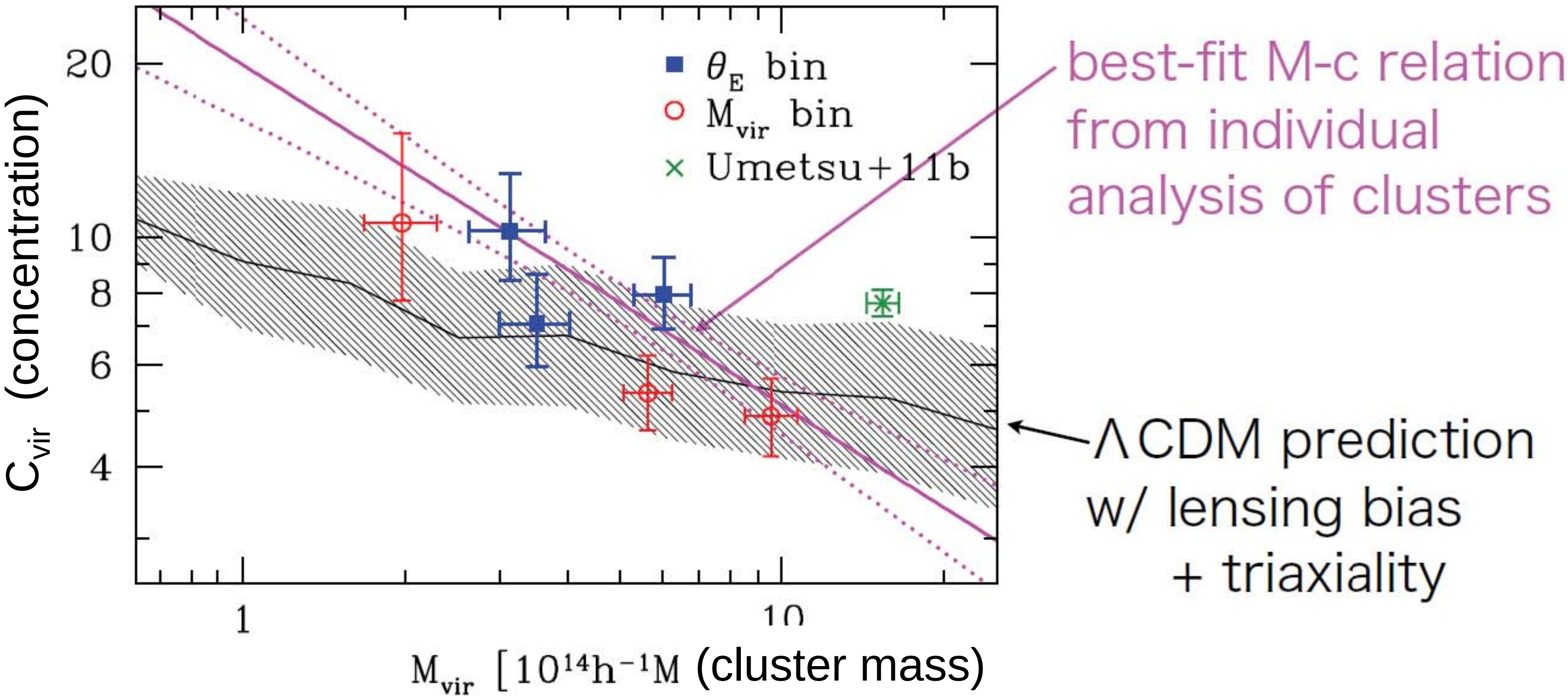
Stacking 25 lensing clusters



- high S/N lensing shear profile by stacking 25 clusters
- follow NFW well

Oguri 2012

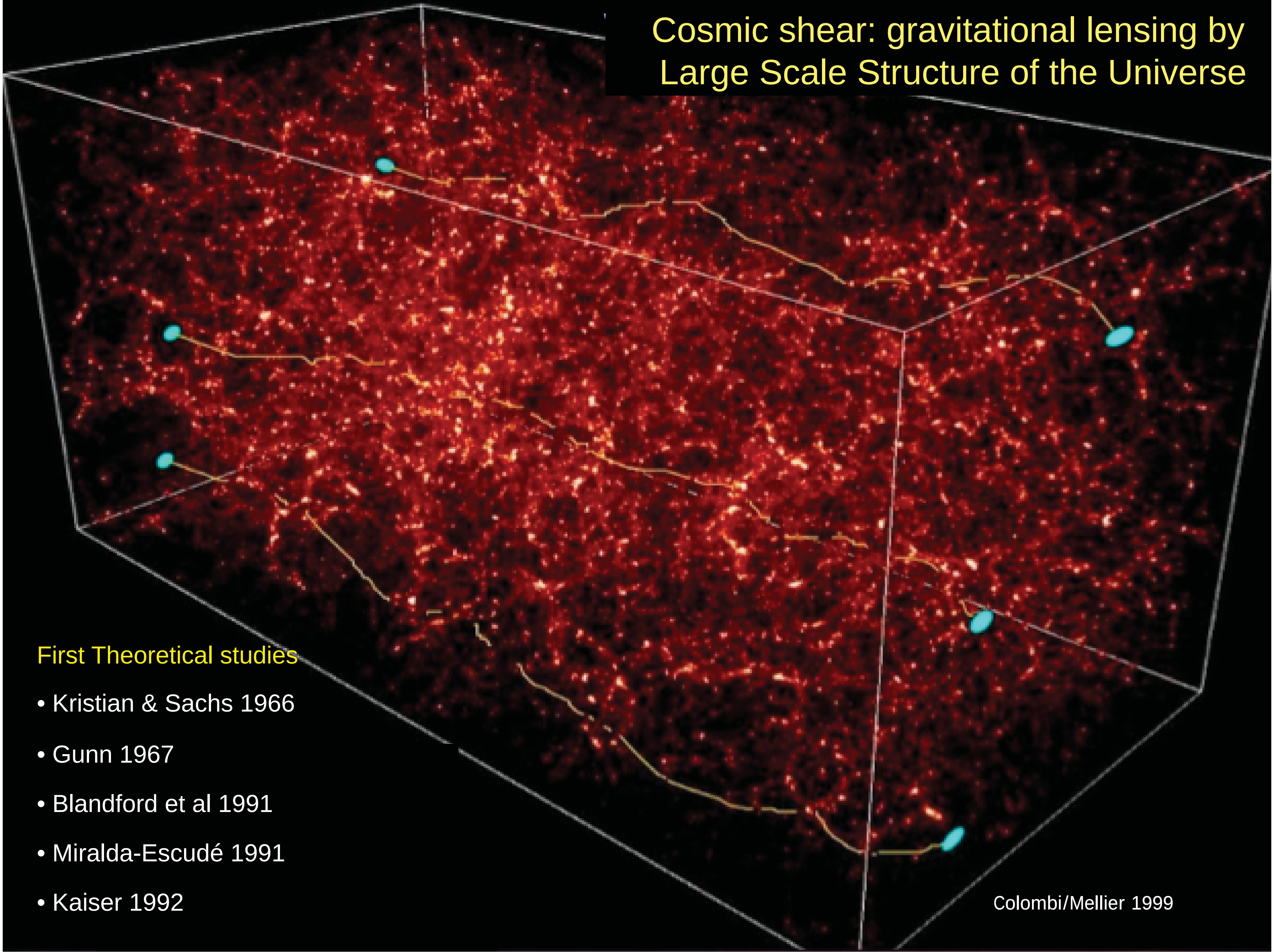
Stacking lensing clusters



Oguri 2012

Gravitational lensing by large scale structure: cosmic shear

Cosmic shear: gravitational lensing by Large Scale Structure of the Universe

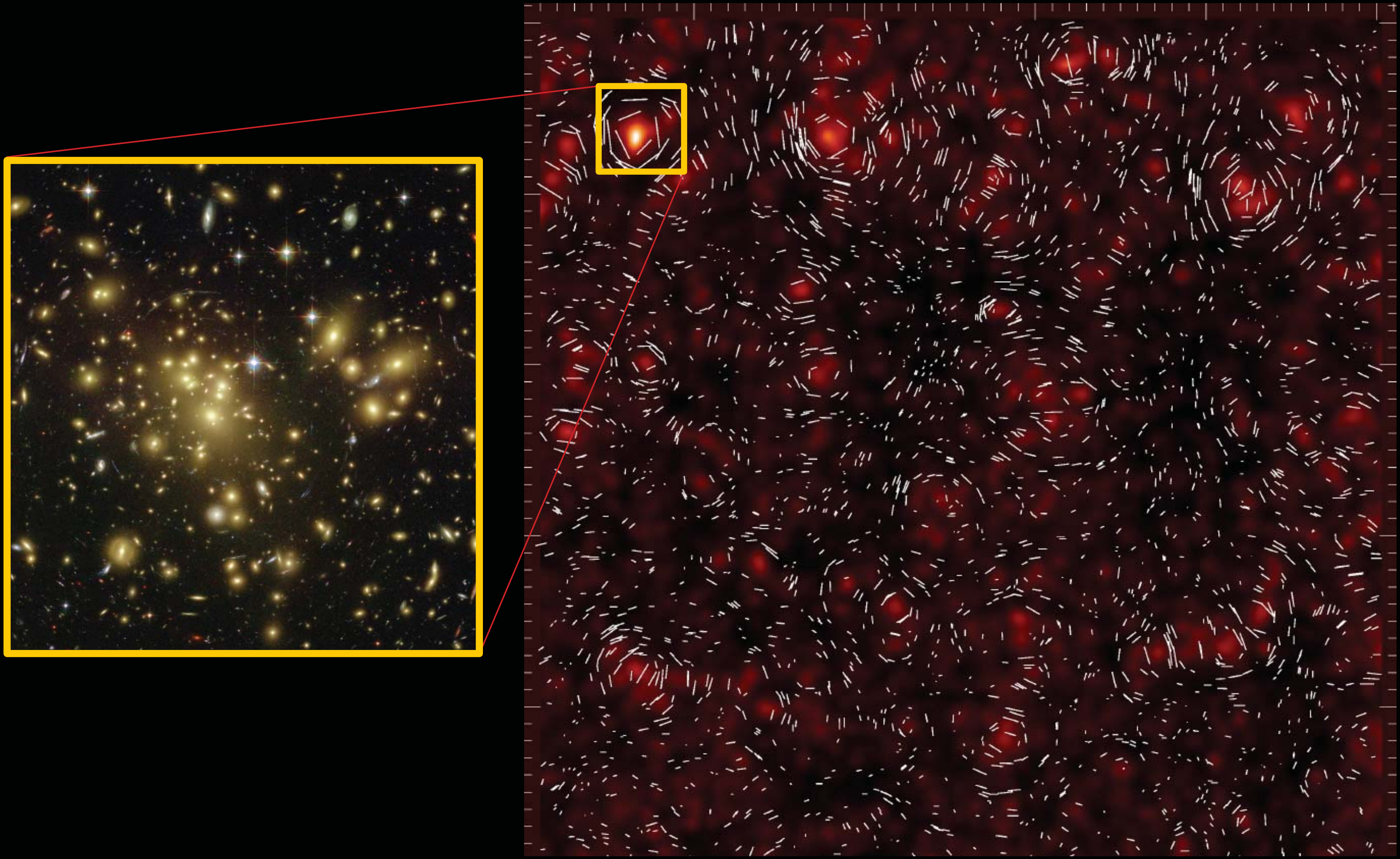


First Theoretical studies

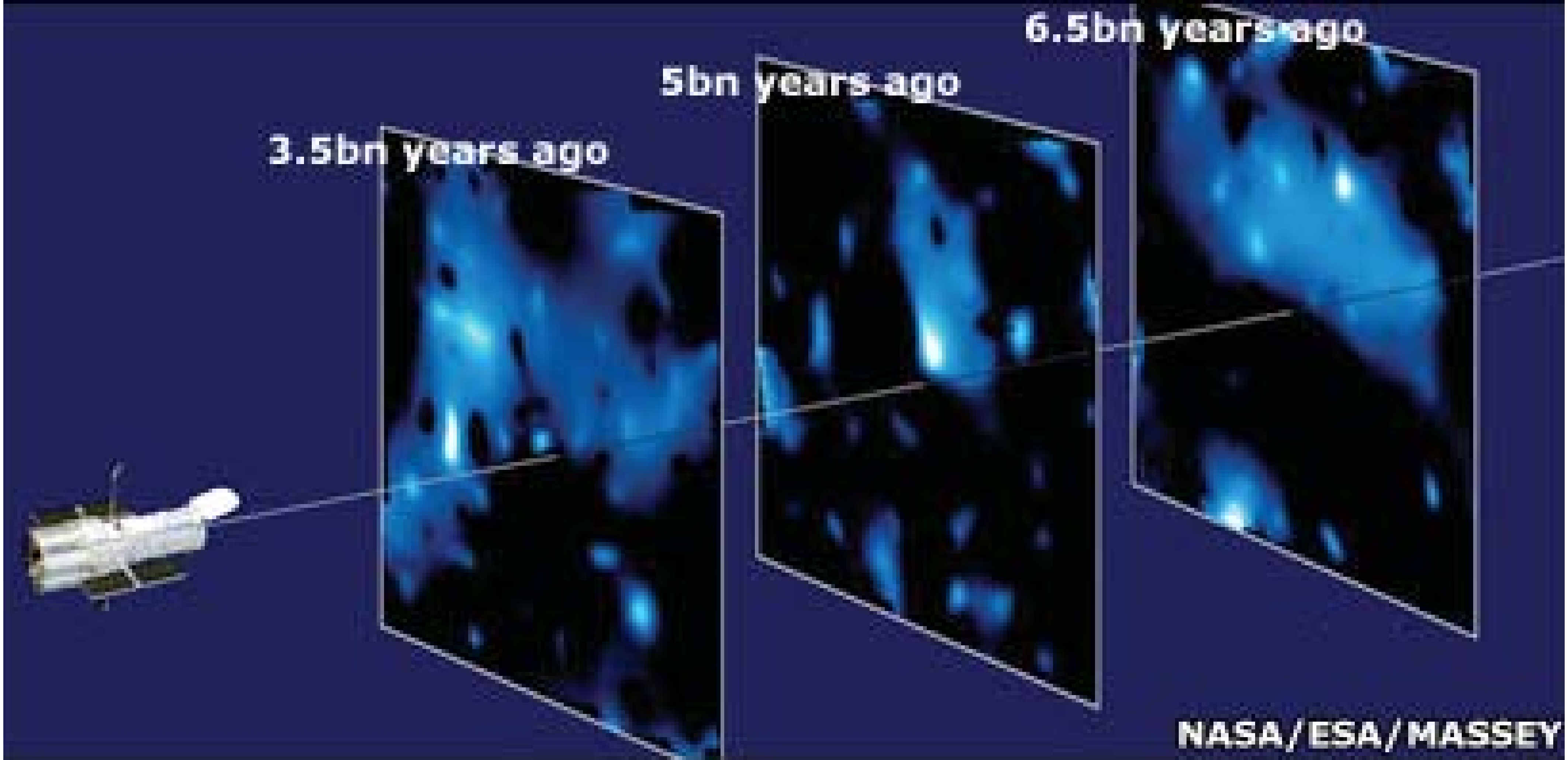
- Kristian & Sachs 1966
- Gunn 1967
- Blandford et al 1991
- Miralda-Escudé 1991
- Kaiser 1992

Cosmic shear: weak gravitational distortion

→ Projected on the sky: coherent ellipticity field



Most spectacular
Cosmic shear and tomography with HST

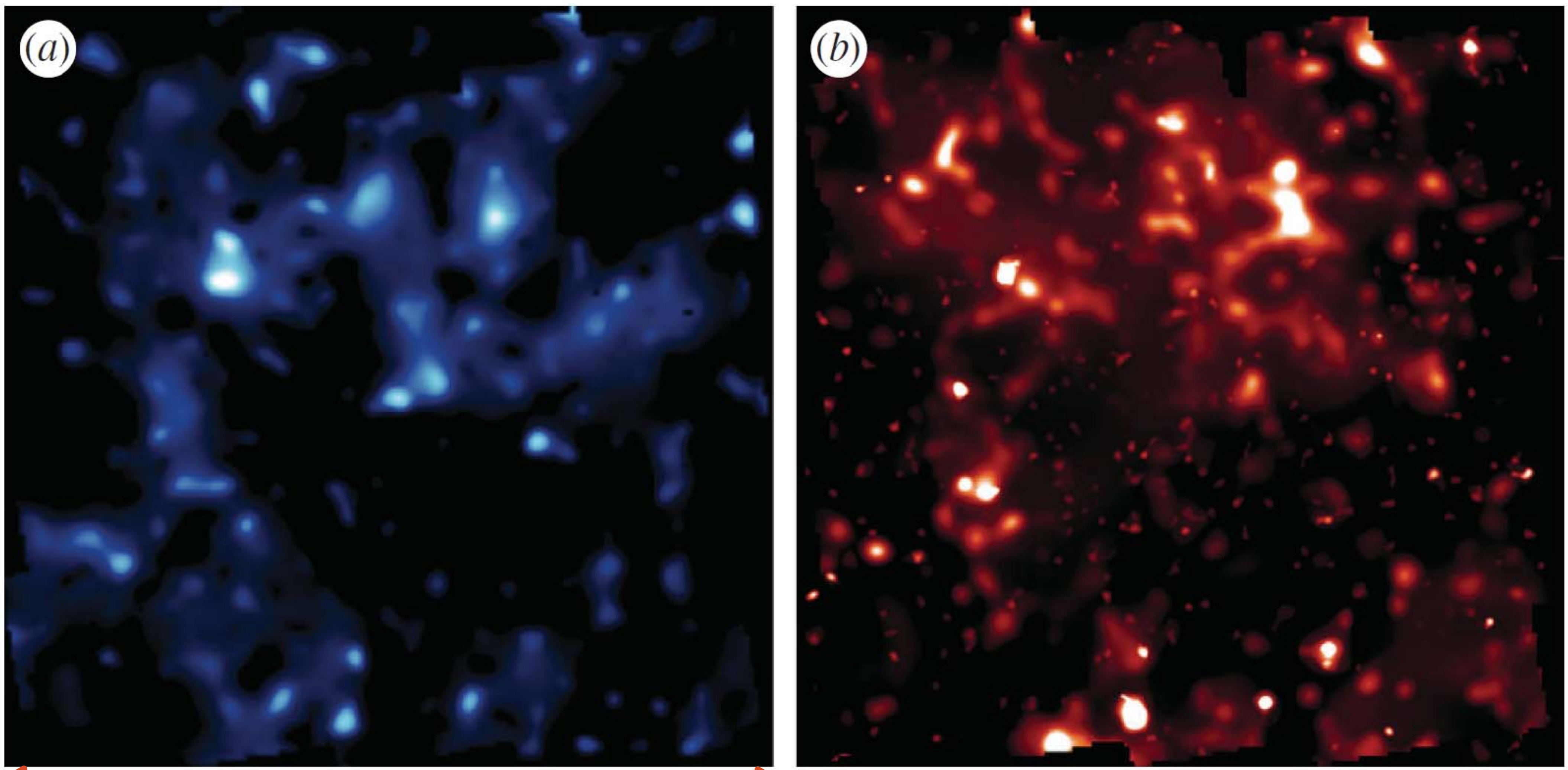


Massey et al 2007

Cosmic shear and tomography with HST

Dark matter

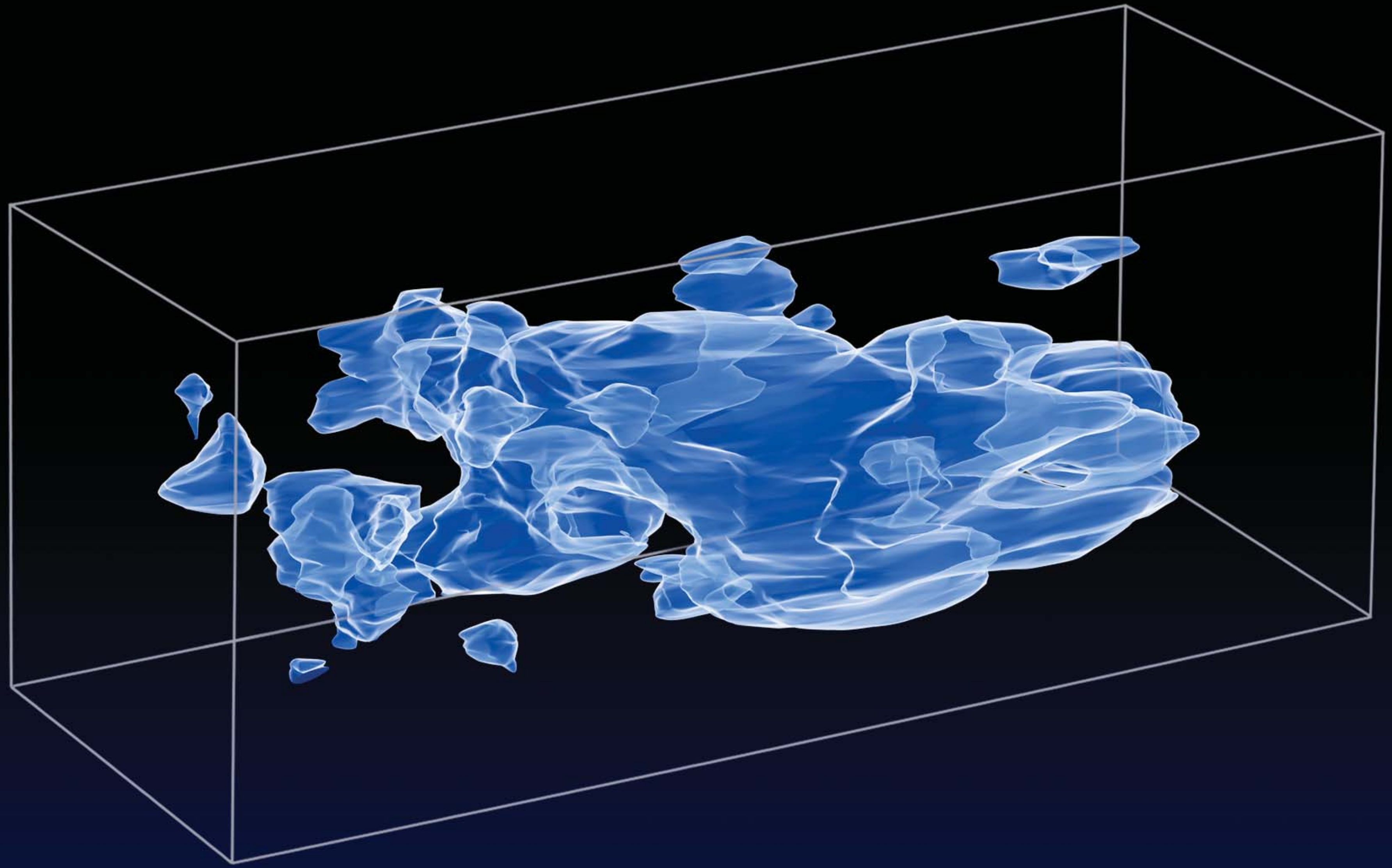
Light (galaxies)



1.2 deg.

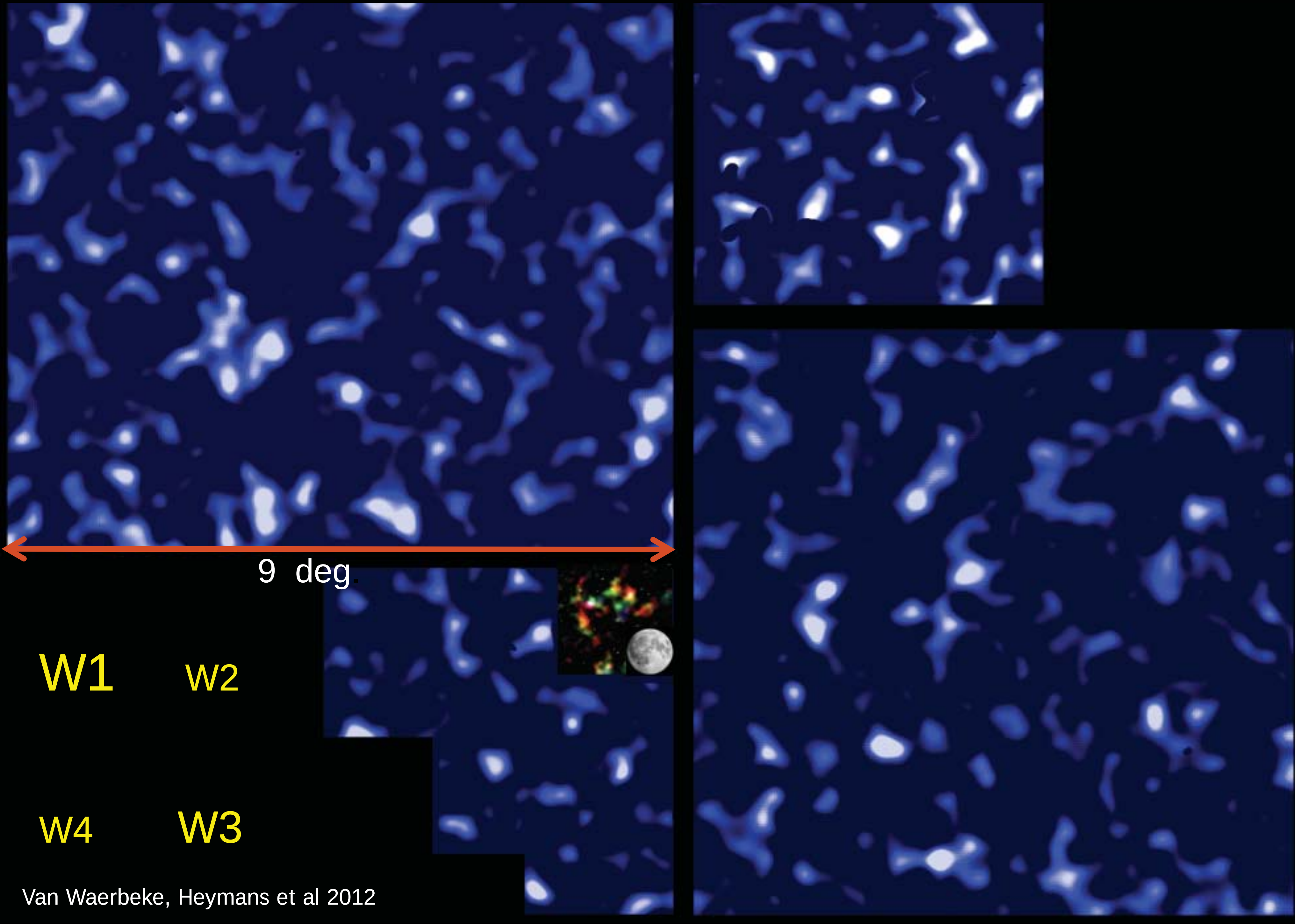
Massey et al 2007

Cosmic shear and tomography with HST



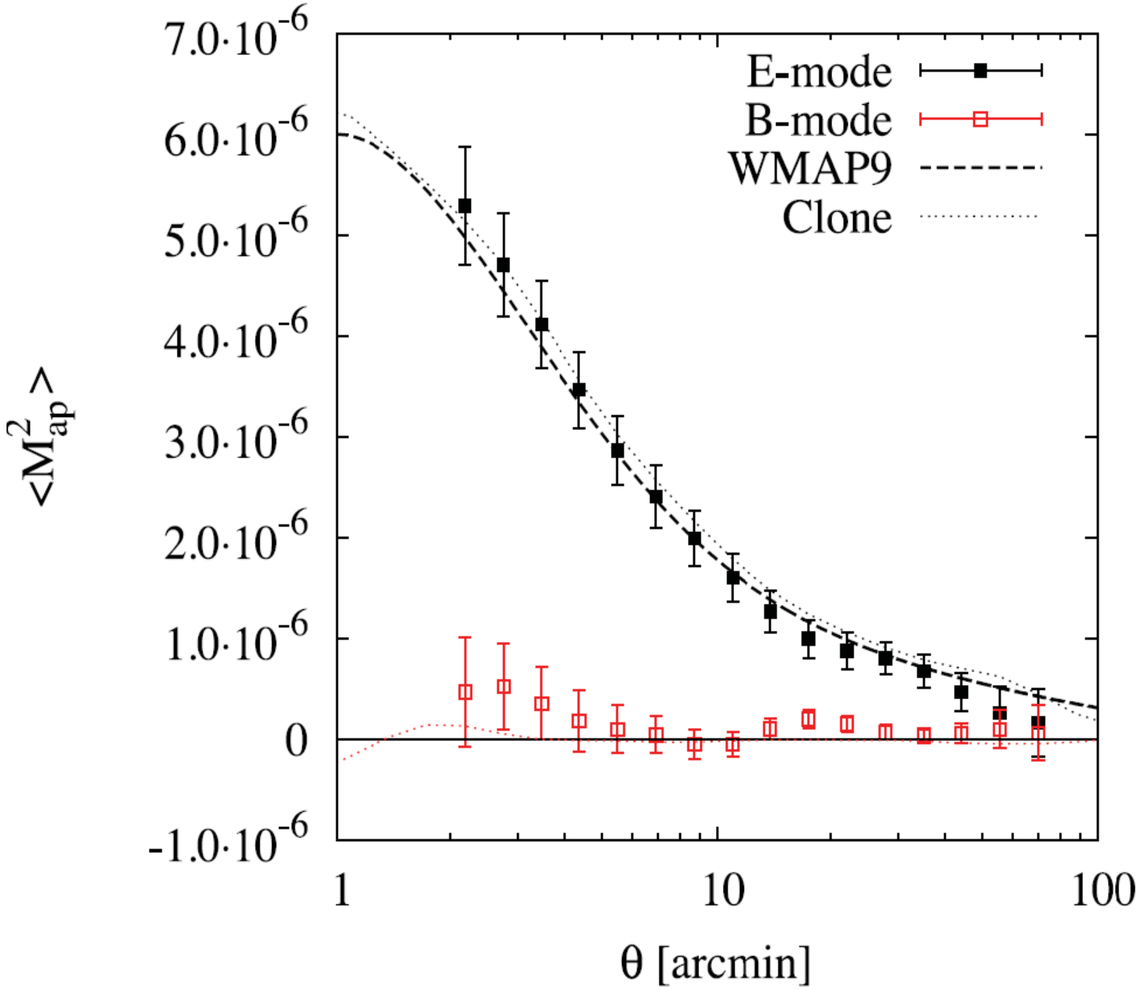
Massey et al 2007

CFHTLens - mass maps Wide fields

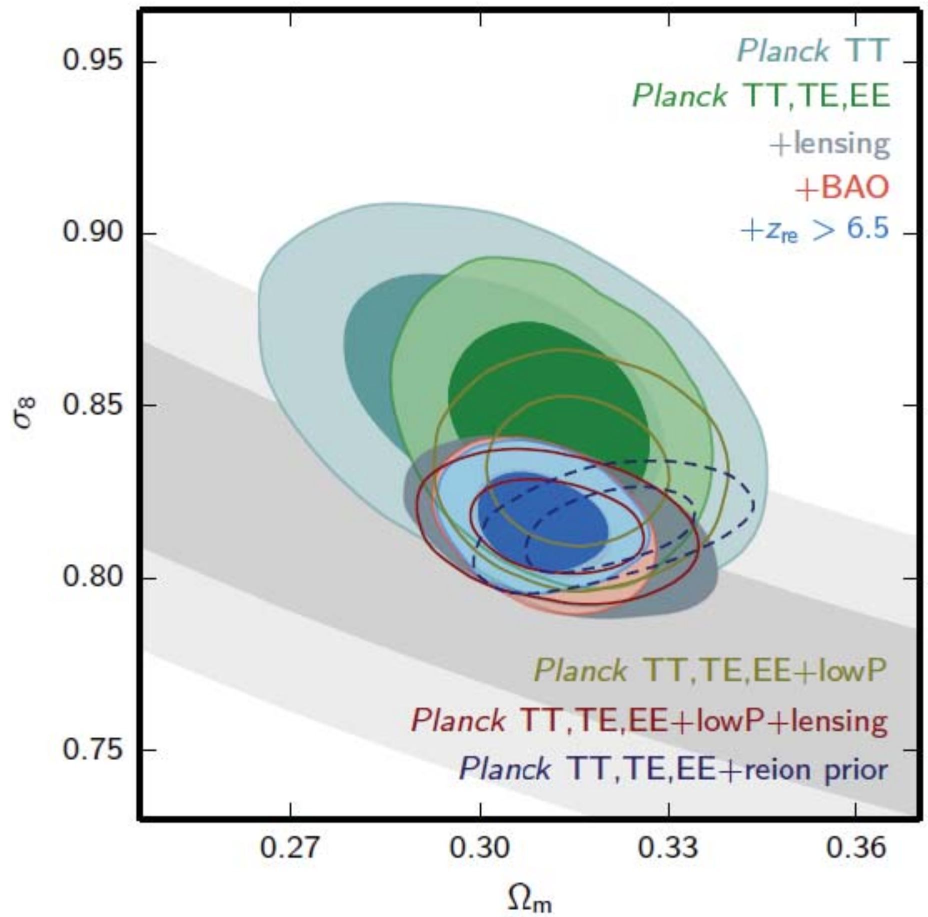


Van Waerbeke, Heymans et al 2012

CFHTLens - Cosmic shear signal



Fu et al 2014



Planck Collab. Planck 2015-XIII

Cosmology with WL ?

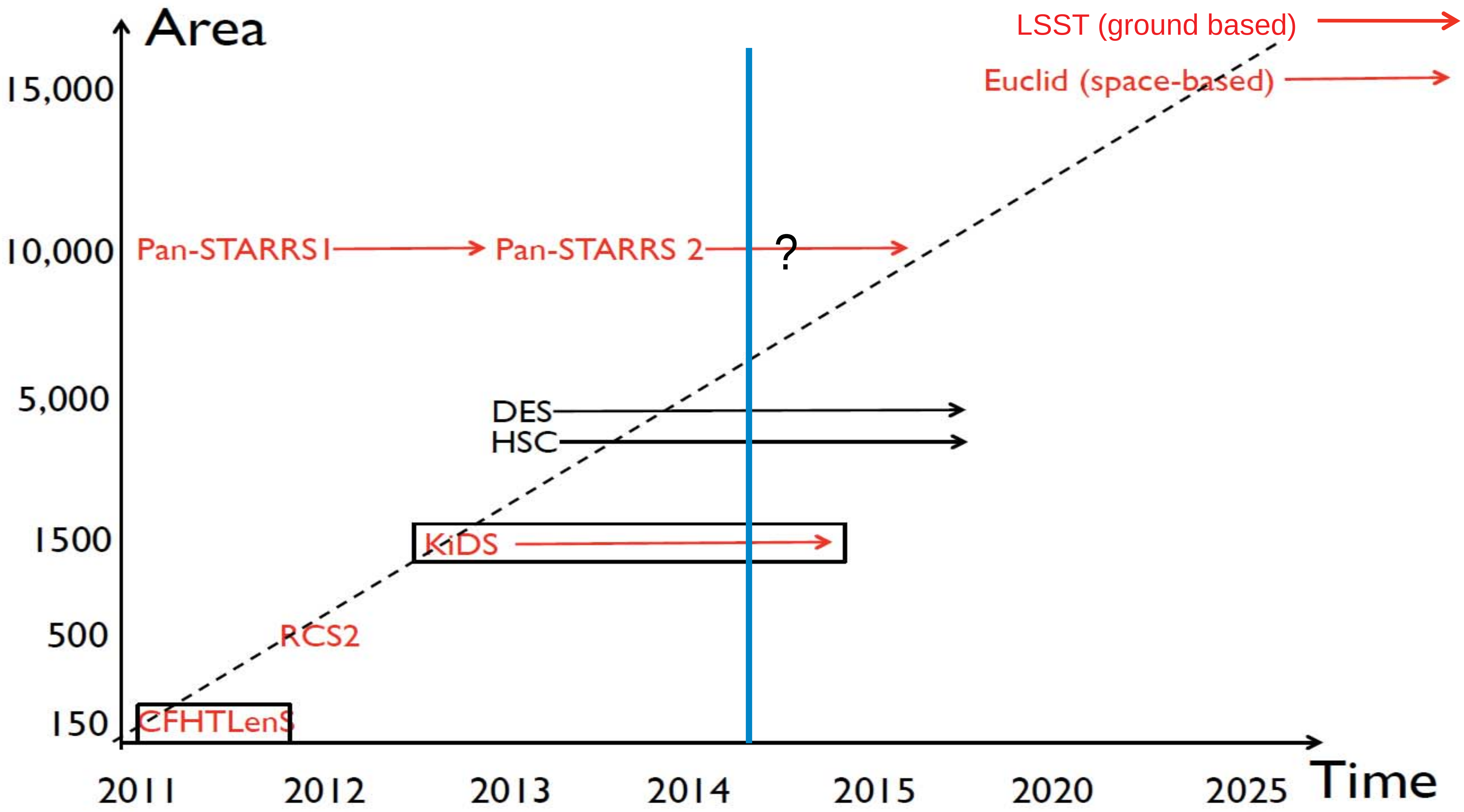
Weinberg et al 2013

Reference	Telescope/instrument	Area (deg^2)	Number of galaxies	Result
Bacon et al. (2000)	WHT/EEV-CCD	0.5	27k	$\sigma_8 = 1.5 \pm 0.5$ (@ $\Omega_m = 0.3$)
Van Waerbeke et al. (2000)	CFHT/UH8K+CFH12K	1.75	150k	Detection[a]
Wittman et al. (2000)	Blanco/BTC	1.5	145k	Detection[b]
Rhodes et al. (2001)	HST/WFPC2	0.05	4k	$\sigma_8 (\Omega_m/0.3)^{0.48} = 0.91^{+0.25}_{-0.30}$
Van Waerbeke et al. (2001)	CFHT/CFH12K	6.5	400k	$\sigma_8 (\Omega_m/0.3)^{0.6} = 0.99^{+0.08}_{-0.10}$ (95%CL)[c]
Hoekstra et al. (2002)	CFHT/CFH12K +Blanco/Mosaic II	53	1.78M	$\sigma_8 (\Omega_m/0.3)^{0.55} = 0.87^{+0.17}_{-0.23}$ (95%CL)
Refregier et al. (2002)	HST/WFPC2	0.36	31k	$\sigma_8 = 0.94 \pm 0.14$ (@ $\Omega_m = 0.3$, $\Gamma = 0.21$)
Bacon et al. (2003)	Keck II/ESI +WHT	1.6		$\sigma_8 (\Omega_m/0.3)^{0.68} = 0.97 \pm 0.13$
Brown et al. (2003)	MPG ESO 2.2m/WFI	1.25		$\sigma_8 (\Omega_m/0.3)^{0.49} = 0.72 \pm 0.09$[d,e]
Jarvis et al. (2003)	Blanco/BTC+Mosaic II	75	2M	$\sigma_8 (\Omega_m/0.3)^{0.57} = 0.71^{+0.12}_{-0.16}$ (2σ)
Hamana et al. (2003)	Subaru/SuprimeCam	2.1	250k	$\sigma_8 (\Omega_m/0.3)^{0.37} = 0.78^{+0.55}_{-0.25}$ (95%CL)
Rhodes et al. (2004)	HST/STIS	0.25	26k	$\sigma_8 (\Omega_m/0.3)^{0.46} (\Gamma/0.21)^{0.18} = 1.02 \pm 0.16$
Heymans et al. (2005)	HST/ACS	0.22	50k	$\sigma_8 (\Omega_m/0.3)^{0.65} = 0.68 \pm 0.13$
Massey et al. (2005)	WHT/PFIC	4	200k	$\sigma_8 (\Omega_m/0.3)^{0.5} = 1.02 \pm 0.15$
Hoekstra et al. (2006)	CFHT/MegaCam	22	1.6M	$\sigma_8 = 0.85 \pm 0.06$ @ $\Omega_m = 0.3$
Semboloni et al. (2006a)	CFHT/MegaCam	3	150k	$\sigma_8 = 0.89 \pm 0.06$ @ $\Omega_m = 0.3$
Benjamin et al. (2007)	Various[g]	100	4.5M	$\sigma_8 (\Omega_m/0.3)^{0.59} = 0.74 \pm 0.04$
Hetterscheidt et al. (2007)	MPG ESO 2.2m/WFI	15	700k	$\sigma_8 = 0.80 \pm 0.10$ @ $\Omega_m = 0.3$
Massey et al. (2007b)	HST/ACS	1.64	200k	$\sigma_8 (\Omega_m/0.3)^{0.44} = 0.866^{+0.085}_{-0.068}$
Schrabback et al. (2007)	HST/ACS	0.4	100k	$\sigma_8 = 0.52^{+0.11}_{-0.15}$(stat)$\pm 0.07$(sys)@ $\Omega_m = 0.3$[f]
Fu et al. (2008)	CFHT/MegaCam	57	1.7M	$\sigma_8 (\Omega_m/0.3)^{0.64} = 0.70 \pm 0.04$
Schrabback et al. (2010)	HST/ACS	1.64	195k	$\sigma_8 (\Omega_m/0.3)^{0.51} = 0.75 \pm 0.08$
Huff et al. (2011)	SDSS	168	1.3M	$\sigma_8 = 0.636^{+0.109}_{-0.154}$ @ $\Omega_m = 0.265$[h]
Lin et al. (2012)	SDSS	275	4.5M	$\sigma_8 (\Omega_m/0.3)^{0.7} = 0.64^{+0.08}_{-0.12}$[h]
Jee et al. (2013)	Mayall+CTIO/Mosaic	20	1M	$\sigma_8 = 0.833 \pm 0.034$[i]
Kilbinger et al. (2013)	CFHT/MegaCam	154	4.2M	$\sigma_8 (\Omega_m/0.27)^{0.6} = 0.79 \pm 0.03$

After first enthusiastic reactions: skepticism on reliability of WL data and cosmological interpretations: WL is a very hard (too hard?) technique

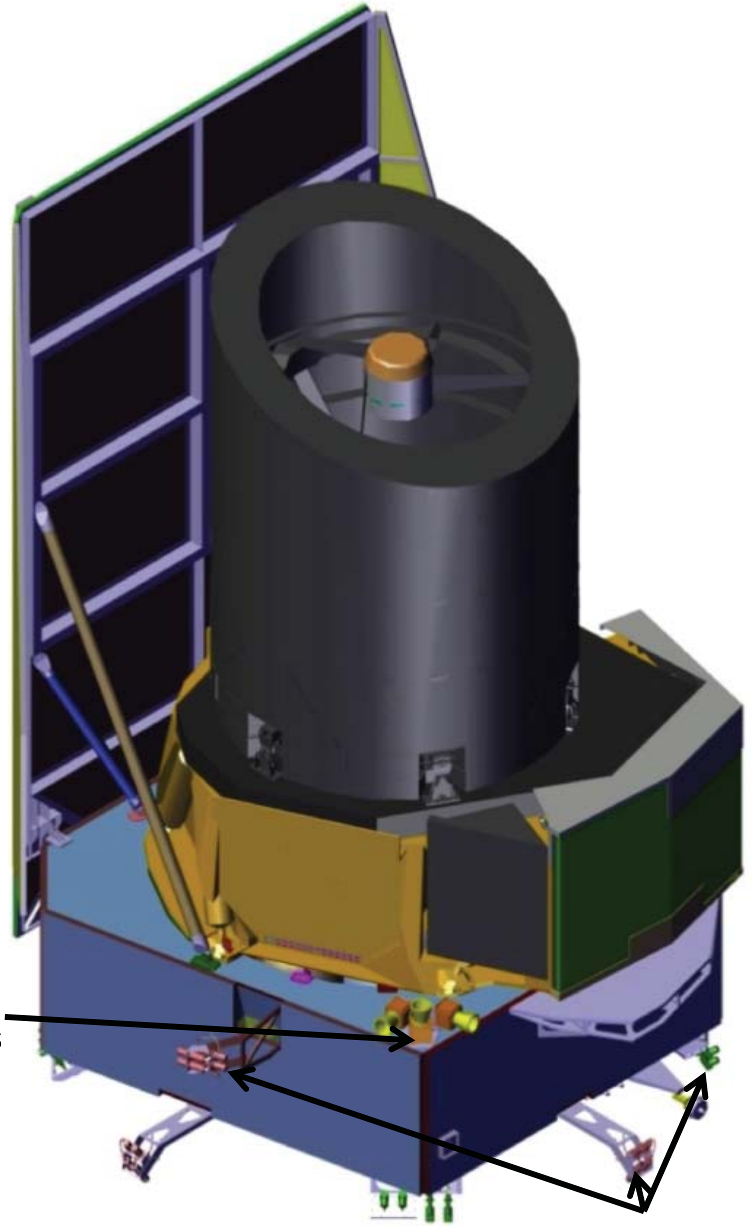
→ **… What Next ?**

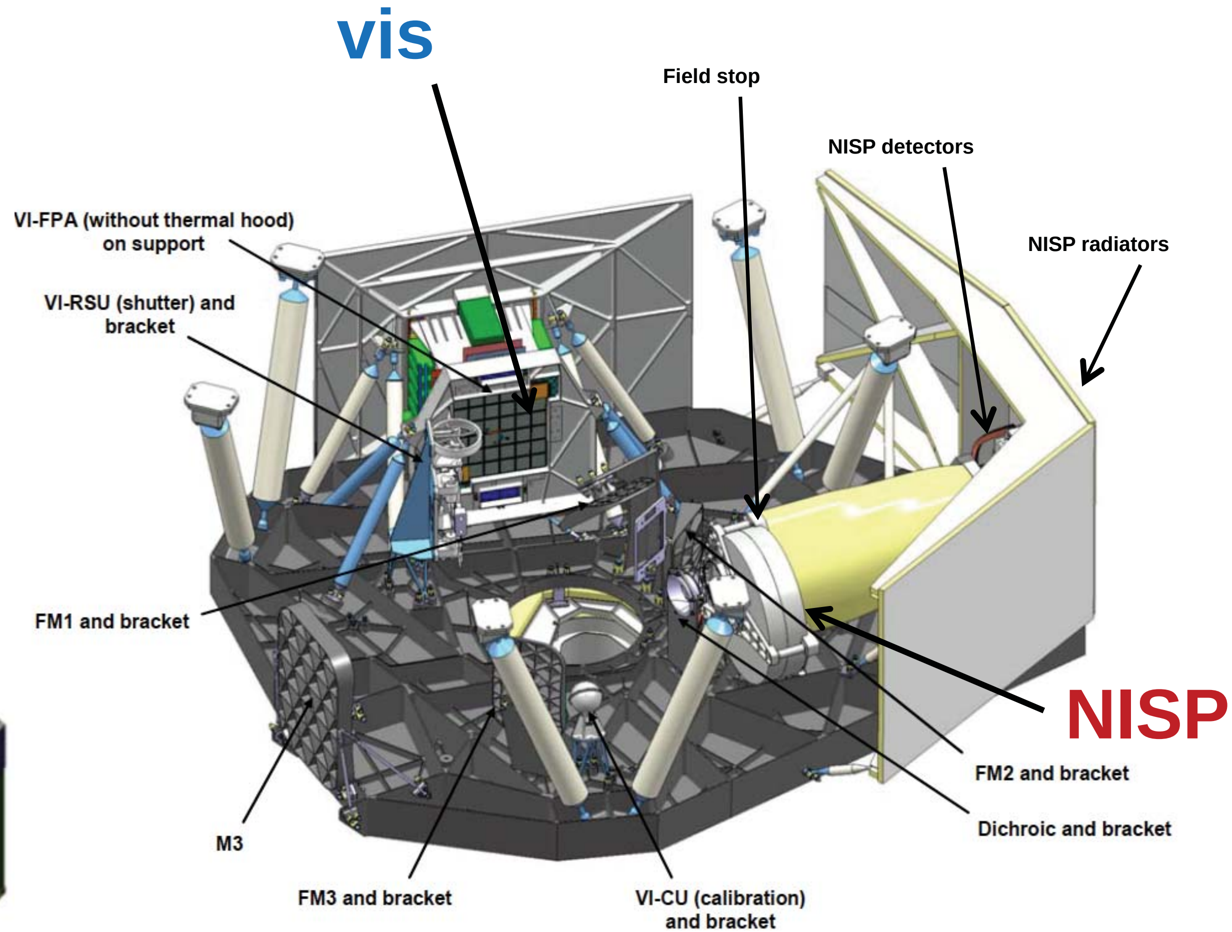
Future of cosmic shear surveys



Kitching 2014

Euclid





Common VIS and NIR FoV = 0.54 deg²

Pointing error along the x,y axes= 25mas over 700 s.

From Thales Alenia Space Italy, Airdus DS, ESA Project office and Euclid Consortium

Galaxy-lenses SLACS (~2010 - HST)

SLACS: The Sloan Lens ACS Survey www.SLACS.org

A. Bolton (U. Hawai'i IfA), L. Koopmans (Kapteyn), T. Treu (UCSB), R. Gavazzi (IAP Paris), L. Moustakas (JPL/Caltech), S. Burles (MIT)

Image credit: A. Bolton, for the SLACS team and NASA/ESA


SLACS
Euclid after 2months
(66 months expected)

Summary

Gravitational lensing

- Can probe the distribution of dark matter from galaxies to large scale structures of the Universe almost directly.
- Is an independent method, beside X-ray or dynamical ones
- Show evidence of dark matter in
    - MACHOS in our galaxy (microlensing: no time to discuss here)
    - Other galaxies (Strong lensing, Weak lensing)
    - Groups and Clusters of galaxies (SL, WL)
    - Superclusters of galaxies (WL)
    - Large Scale Structure (WL)

Summary

• Gravitational lensing confirms that a Universe without dark matter can hardly explain observations

• Modified gravity is still an option but not favoured

• Weak and/or Strong lensing data agree with NFW and SIS, but favours NFW-like radial profiles

• All data compatible with Lambda-CDM predictions

• Cosmic shear is detected, favours lambda-CDM, but detection and measurements very hard and systematics still an issue

• Likely : WL still have to improve

→ Much more statistics: number of galaxies, wave number

→ Improve shear measurement → space

→ Numerical simulations for baryon physics (small scales)