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WHAT CAN WE LEARN FROM CLUSTER LENSING?

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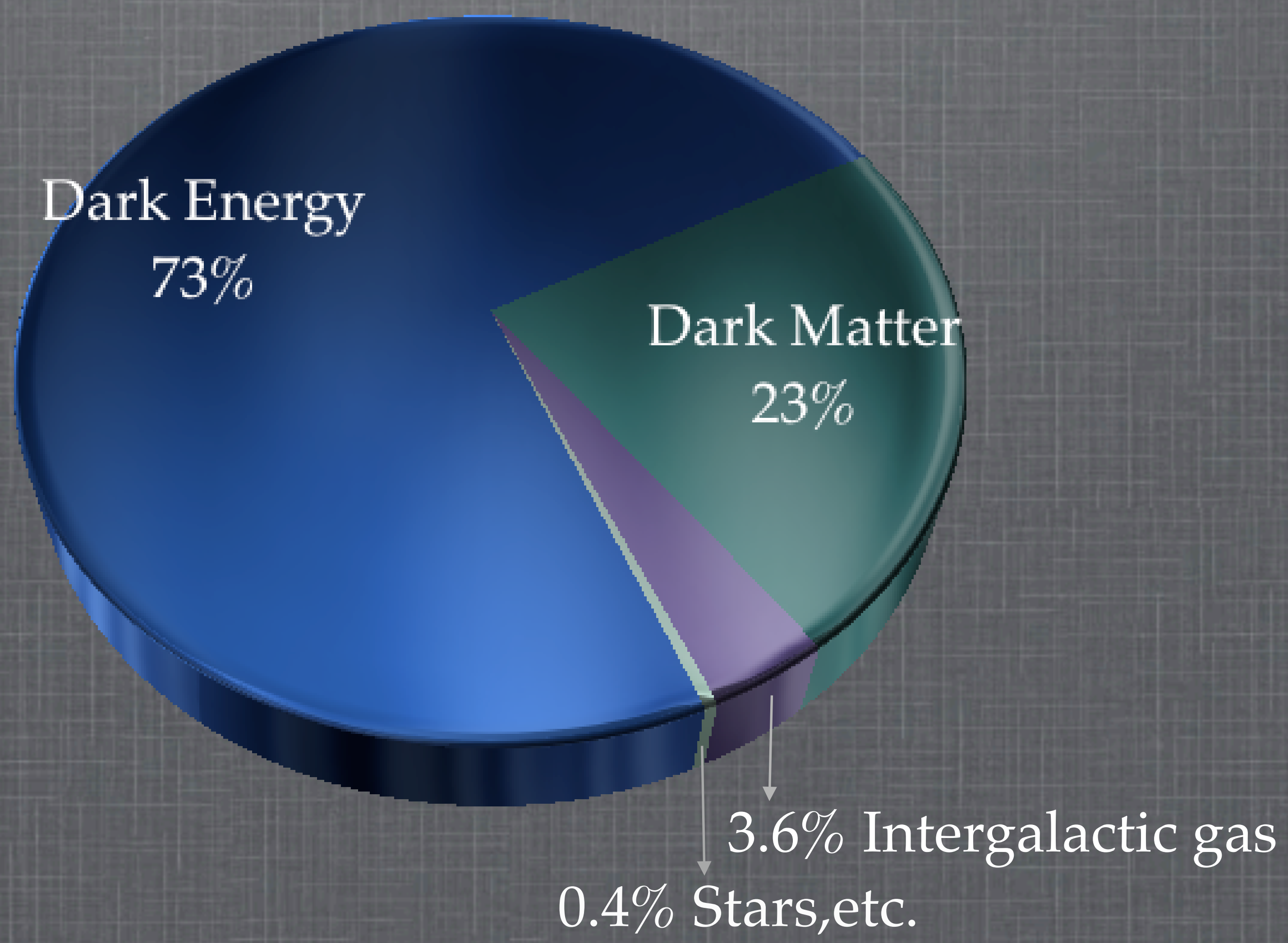
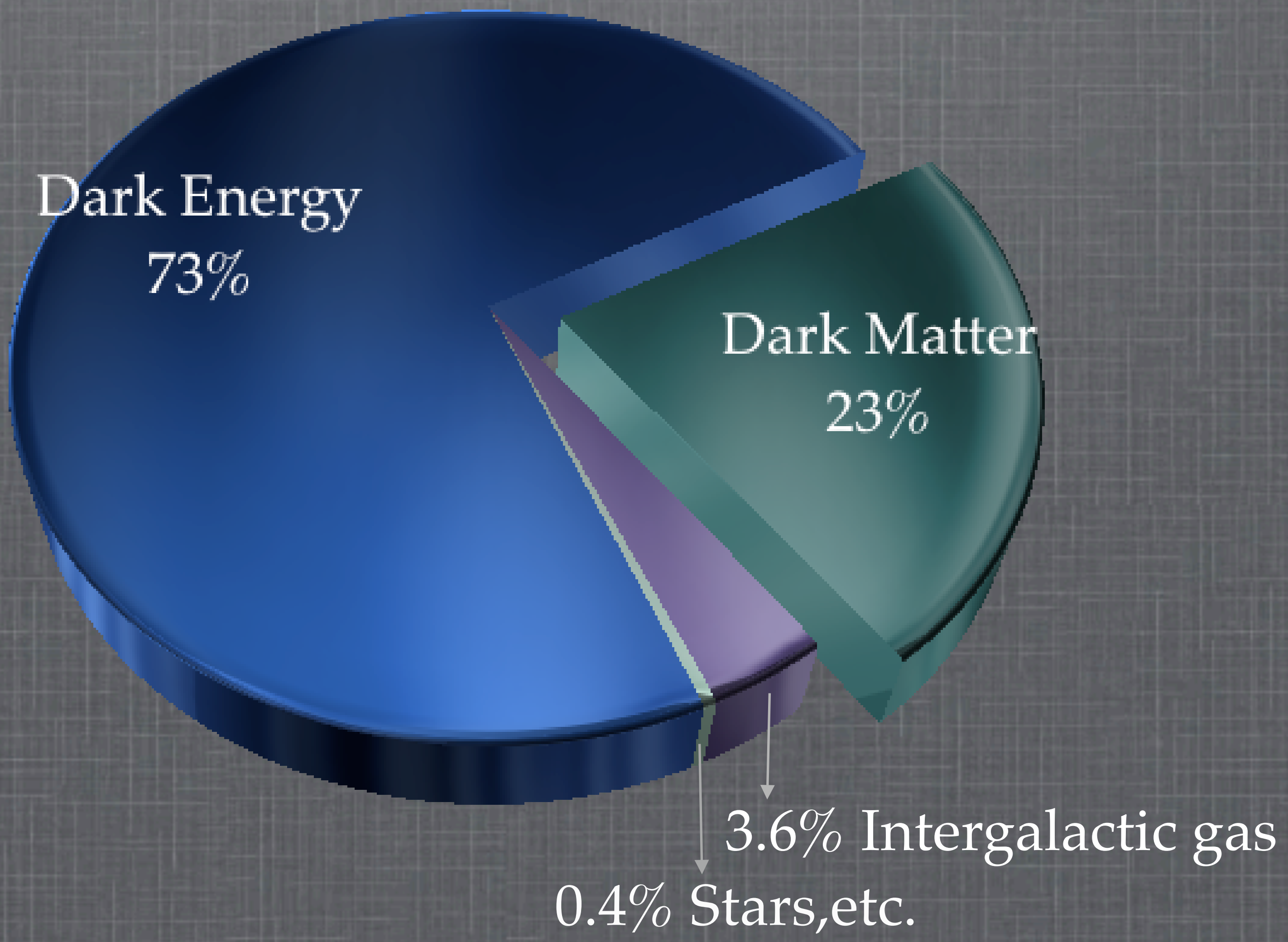
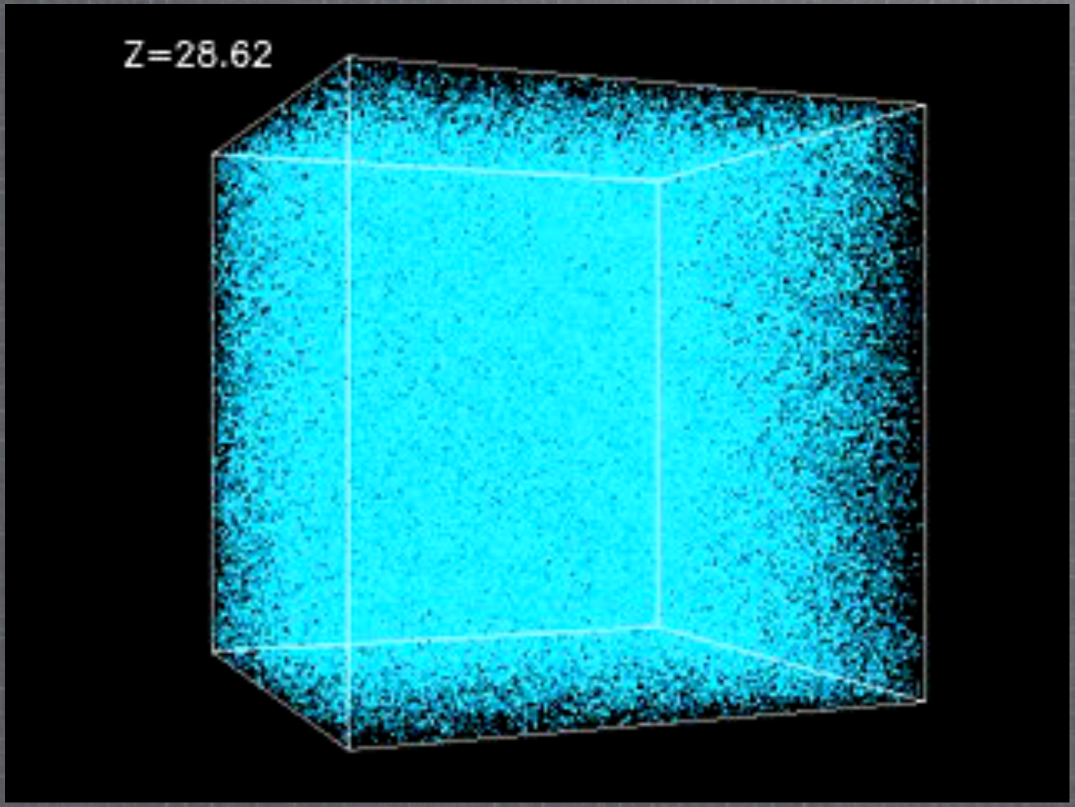
Introduction

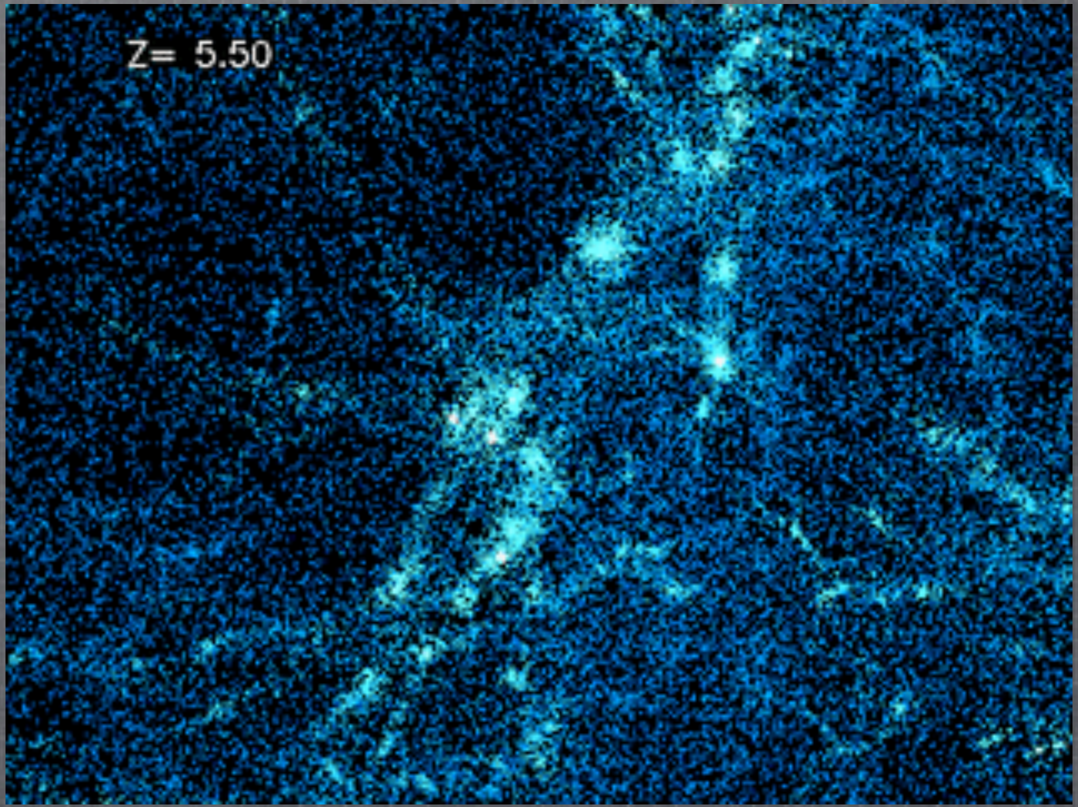


Introduction

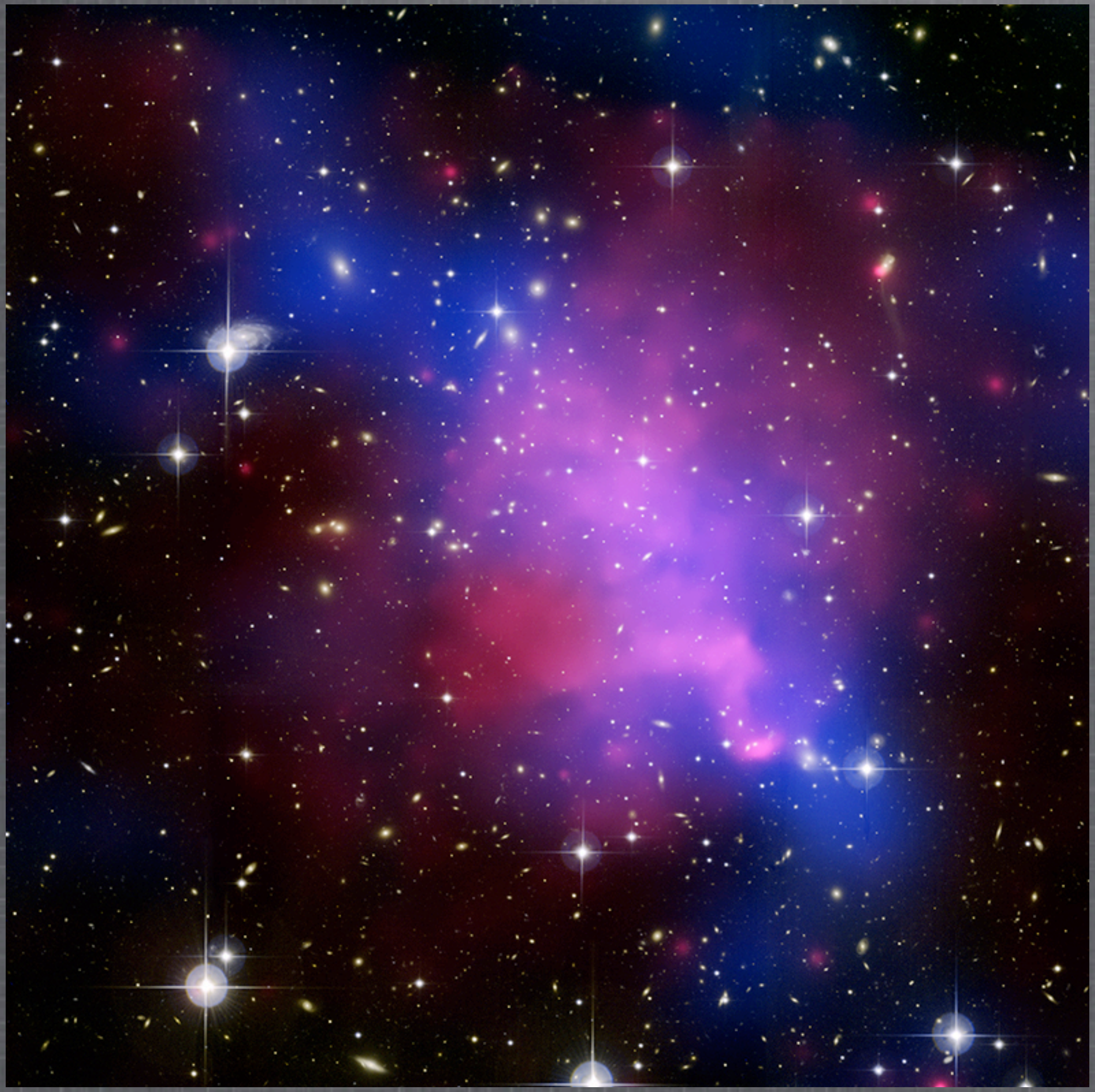


Why Clusters?





Why Clusters?

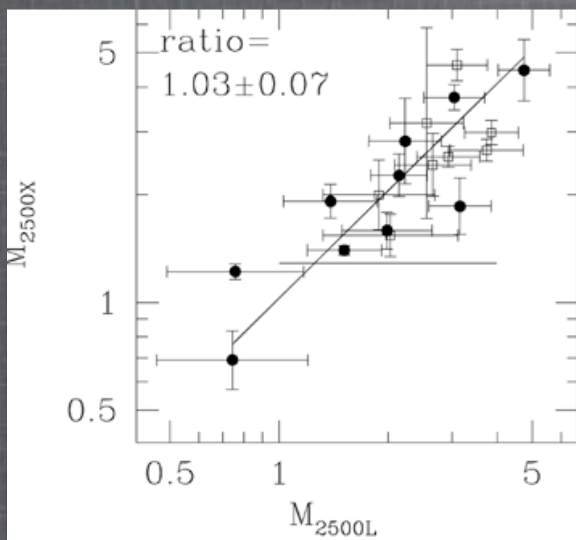


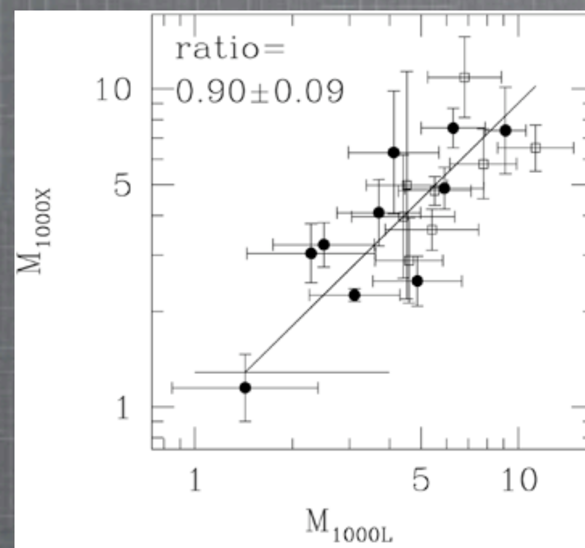
Abell 520: Where is the gas???

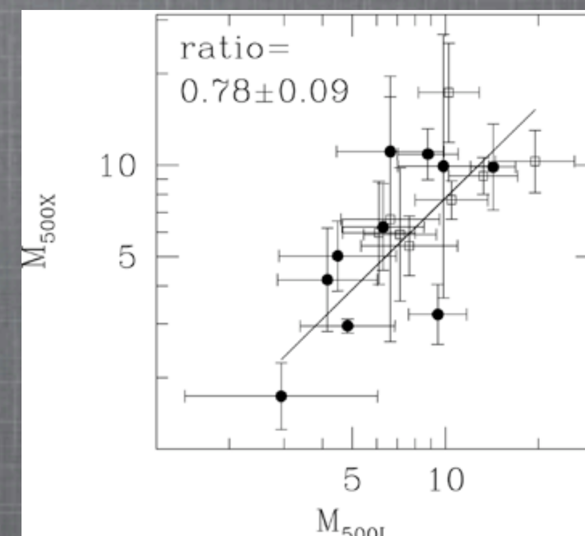
Where is the dark matter???

Credit: *X-ray: NASA/CXC/UVic./A.Mahdavi et al. Optical/Lensing: CFHT/UVic./A.Mahdavi et al.*

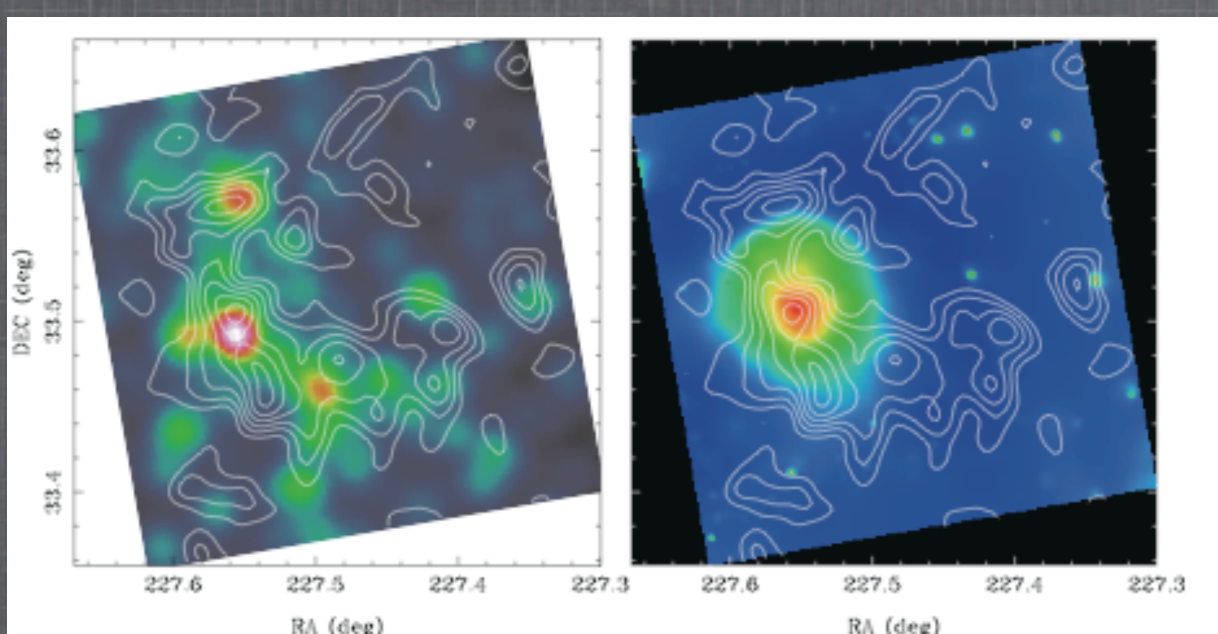
Why Clusters? Lensing+X-Ray





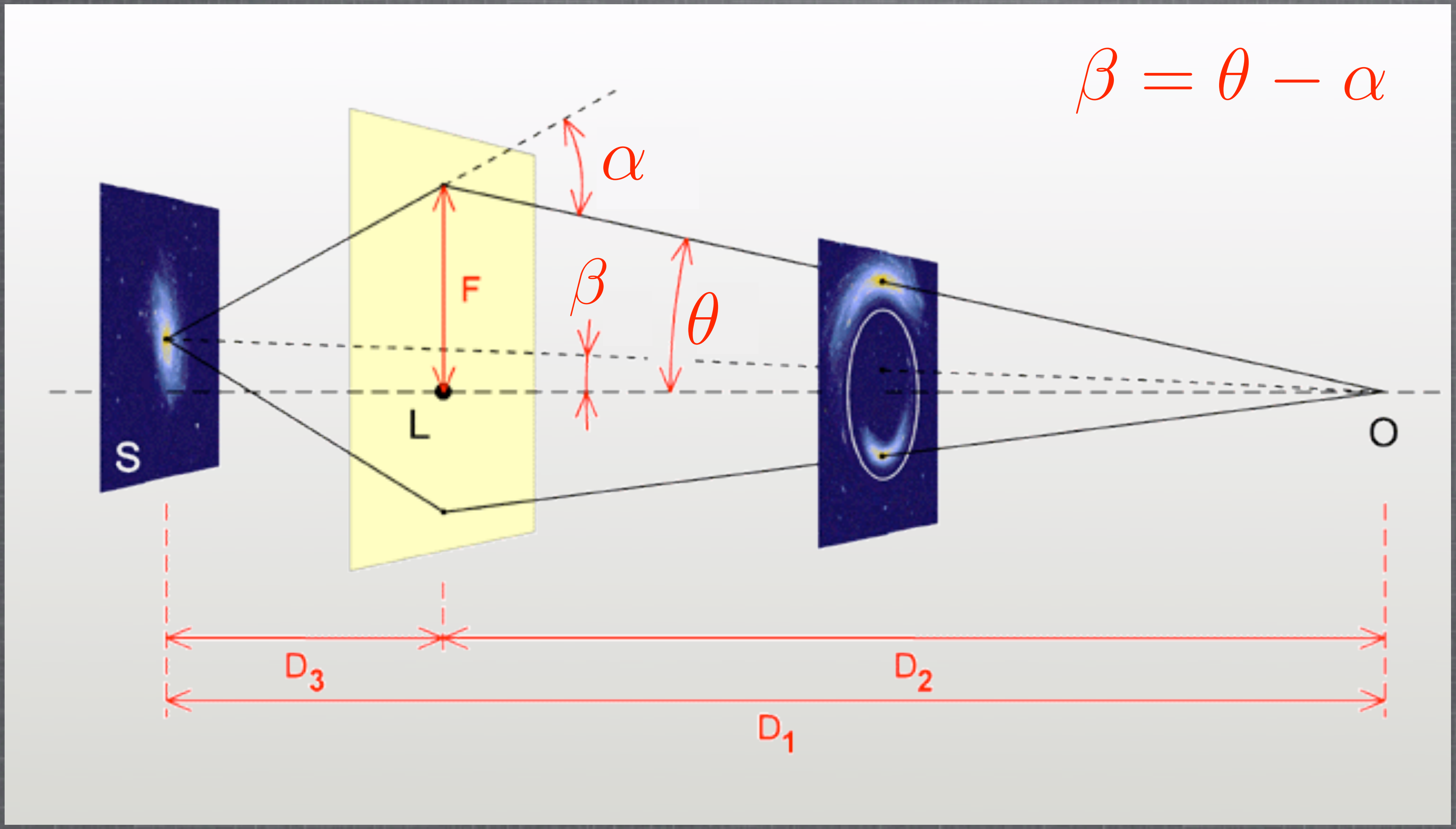


Mahdavi et al. (2008), Fig. 2. A composite of 18 clusters. The outer regions are presumably non-virialized, with M_X/M_lens < 1



Okabe & Umetsu (2008), Fig. 9. A2034, at z=0.11. While there
is only a single X-ray peak, there are genuine DM (and galaxy)
secondary peaks.

Lensing Basics

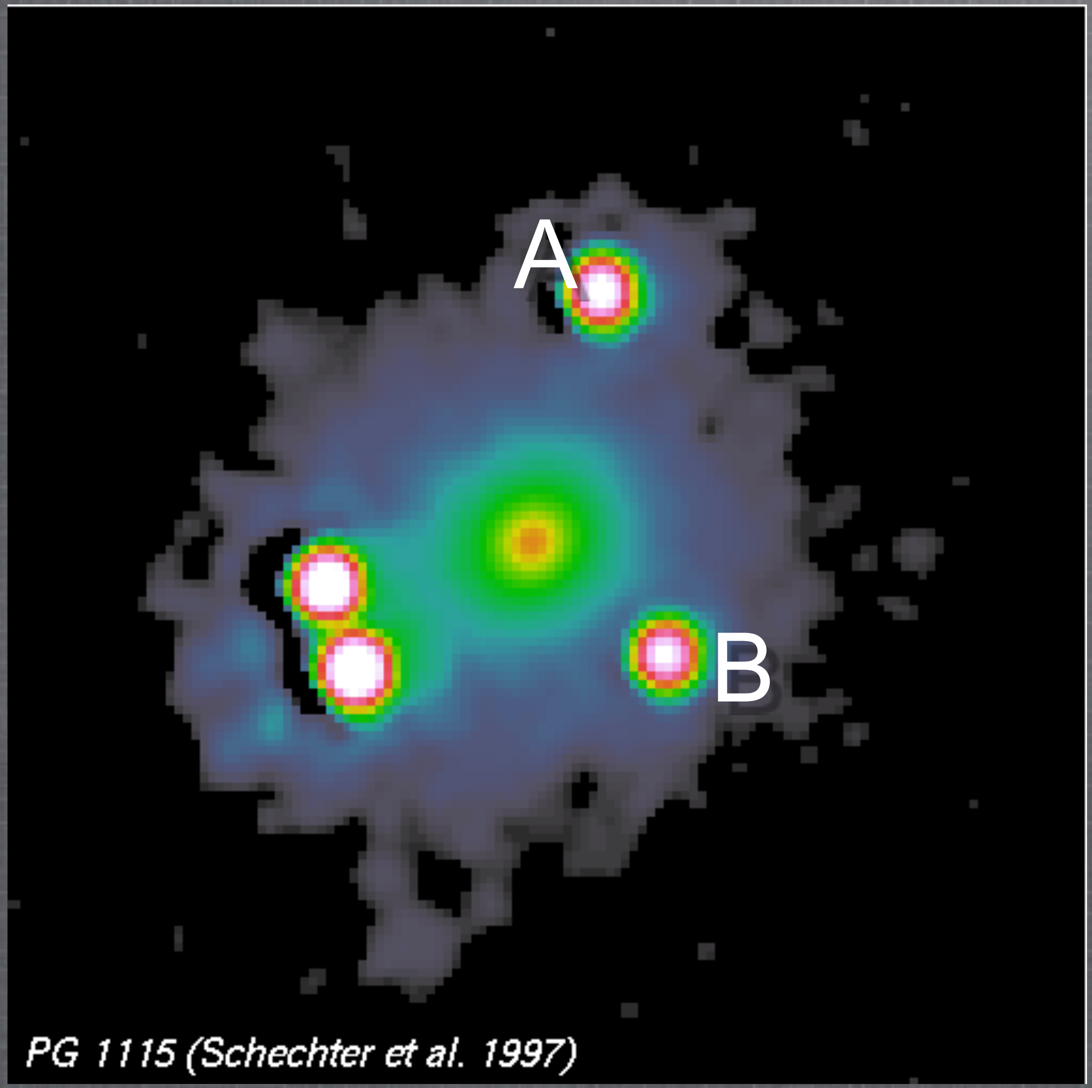


Dimension less surface mass density

$$\kappa = \frac{\Sigma}{\Sigma_{cr}}$$

Gravitational Lensing is co-ordinate transformation between the foreground (θ), and background positions(β)

Lensing Basics: Strong Lensing

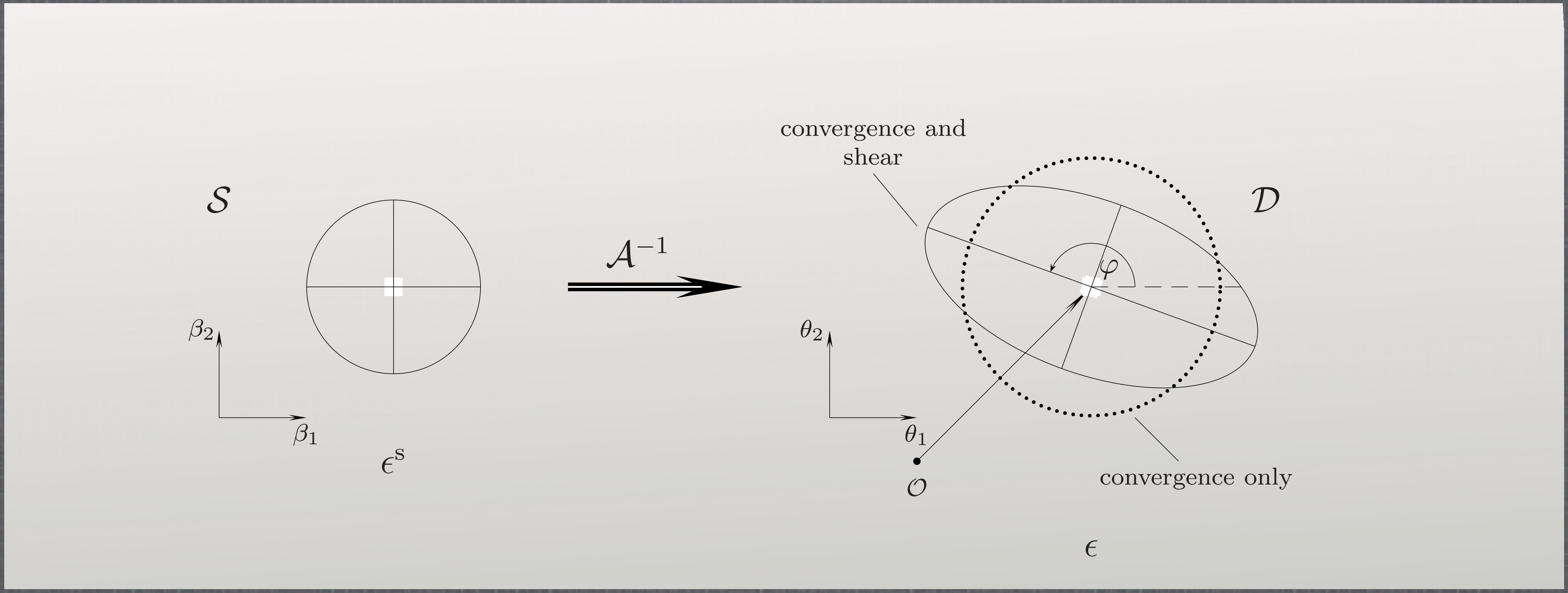


$$\alpha_i = \psi_{,i}$$

$$\alpha_A - \alpha_B = \theta_A - \theta_B$$

Lensing Basics: Shape Distortion

Shape Distortion= convergence + shear



$\gamma_1 = (\psi_{,11} - \psi_{,22})/2$

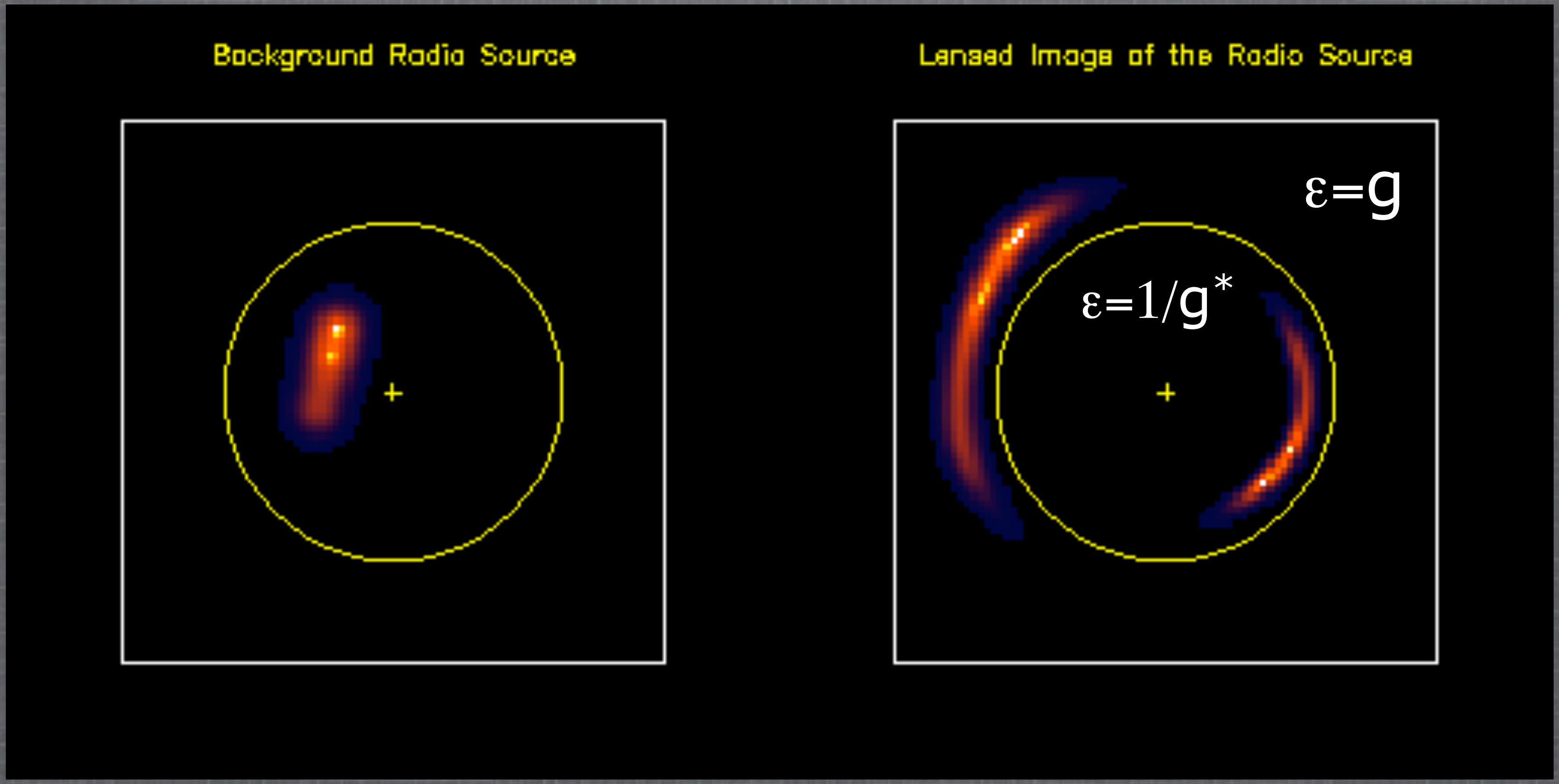
$\kappa = (\psi_{,11} + \psi_{,22})/2$

$\gamma_2 = \psi_{,12}$

Schneider,2005

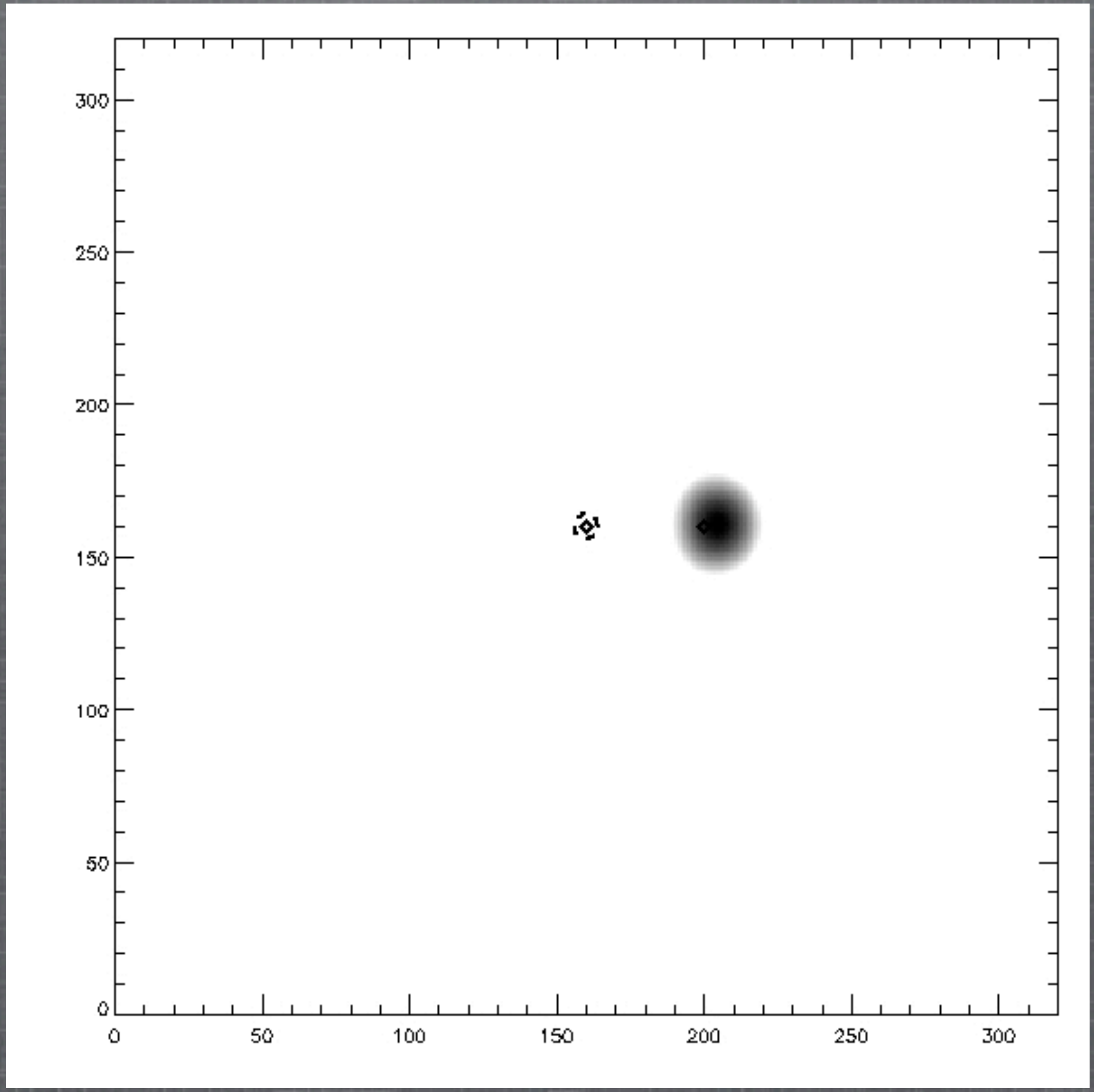
Ellipticities

Reduced shear : $g=\gamma/(1-\kappa)$

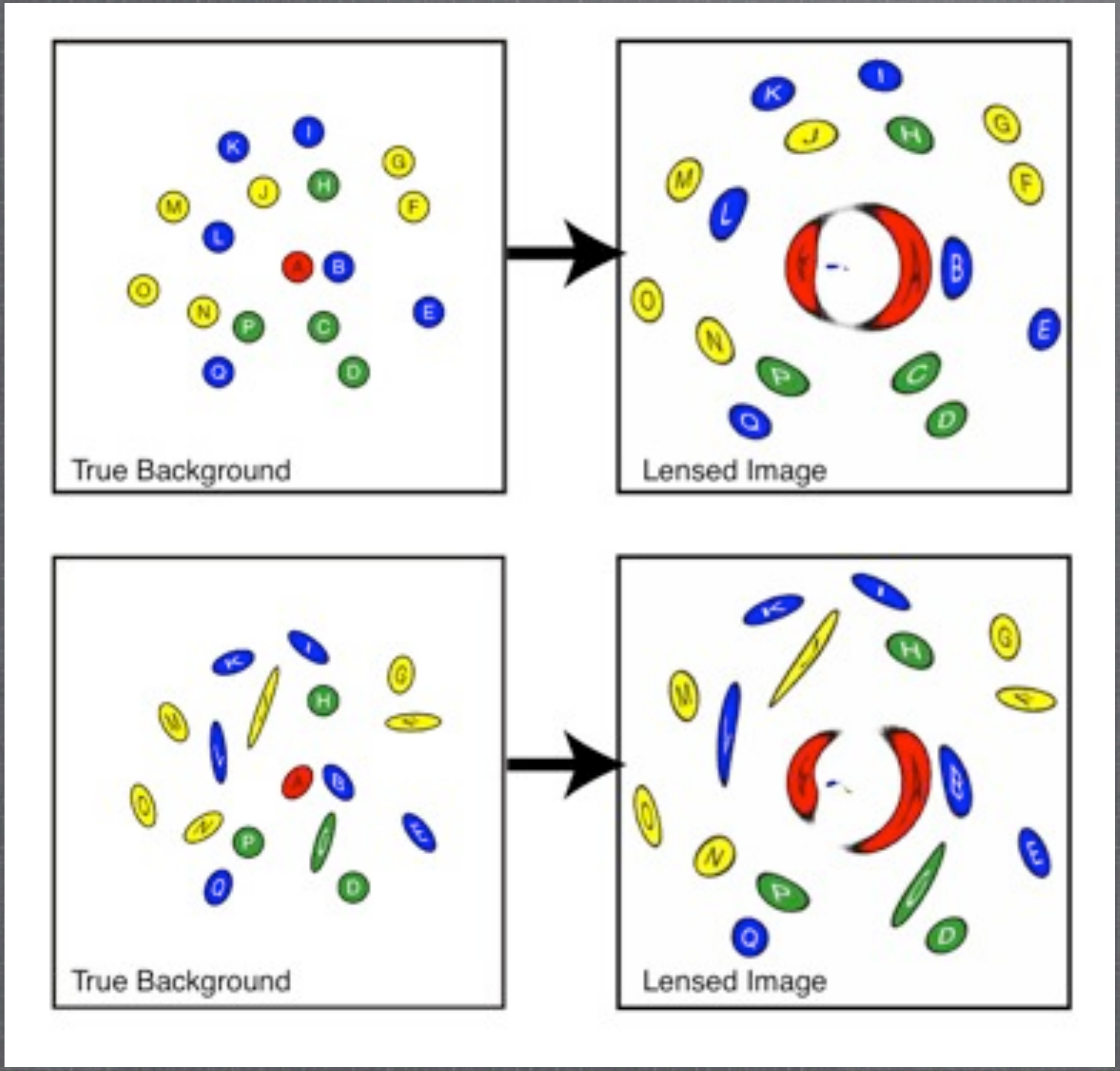


Critical Curves: det(A)=0

Lensing Basics: Shape distortions



Lensing Basics: Weak Lensing



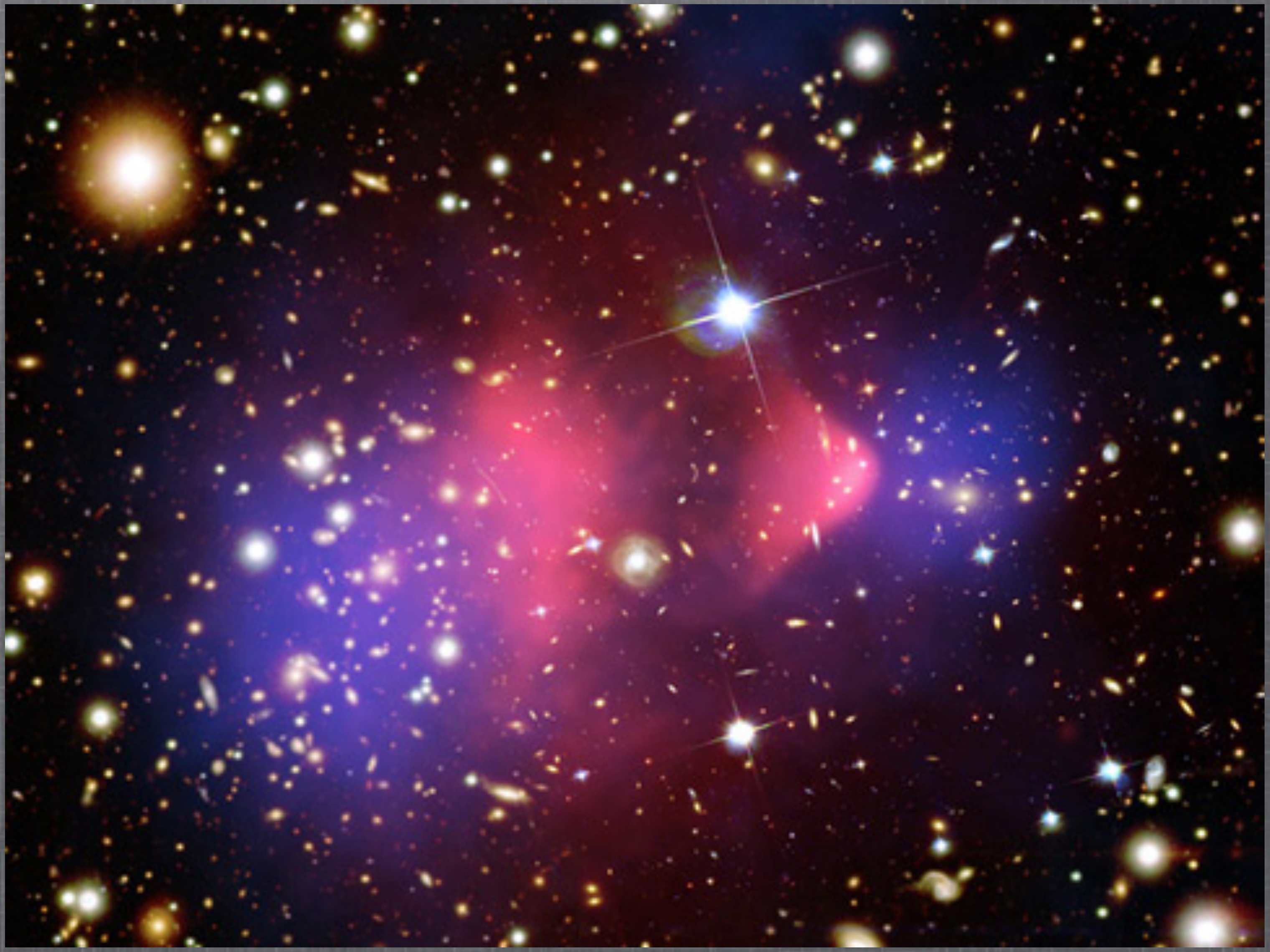
Weak lensing is a statistical measure of the distortion of background galaxies due to the intervening mass.

Williamson et al. 2008

Strong+Weak Lensing

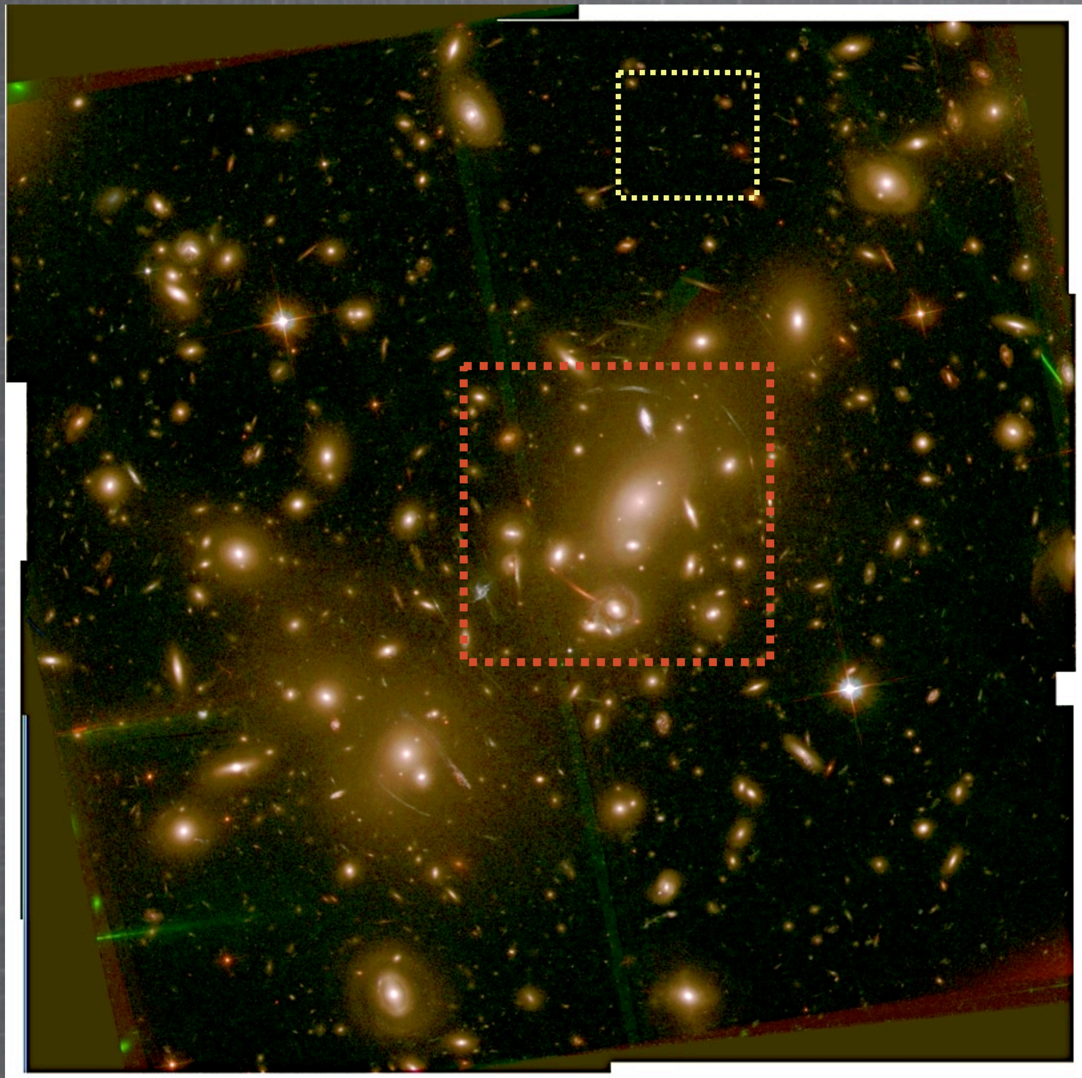
One of the most important results: "Bullet Cluster"

Dark matter well separated from the gas.

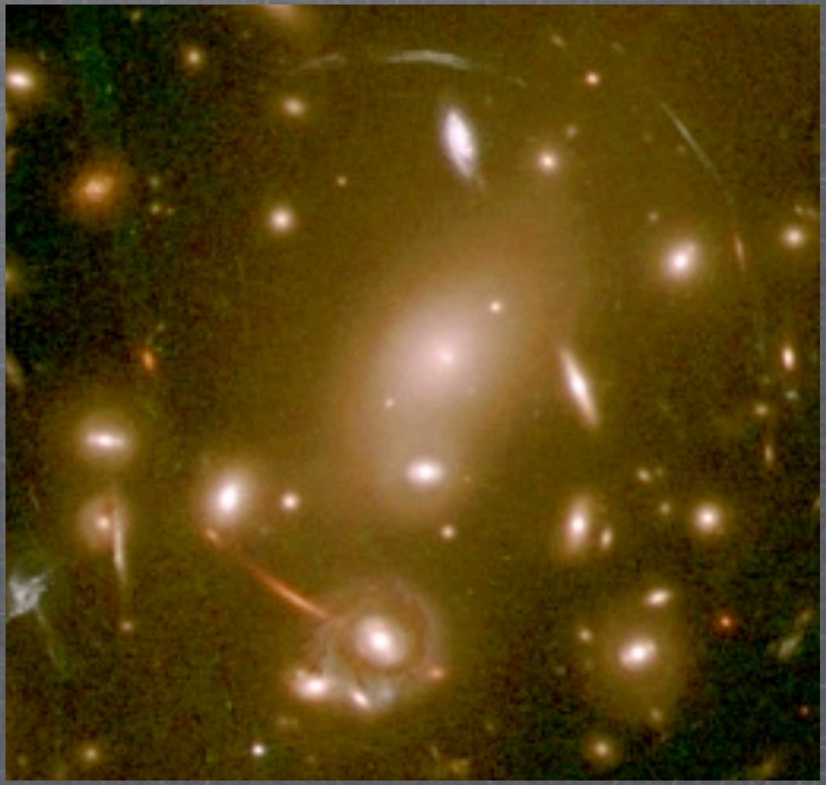


The "Bullet Cluster," 1E0657-56, Bradac et al. (2006) astro-ph/0608408

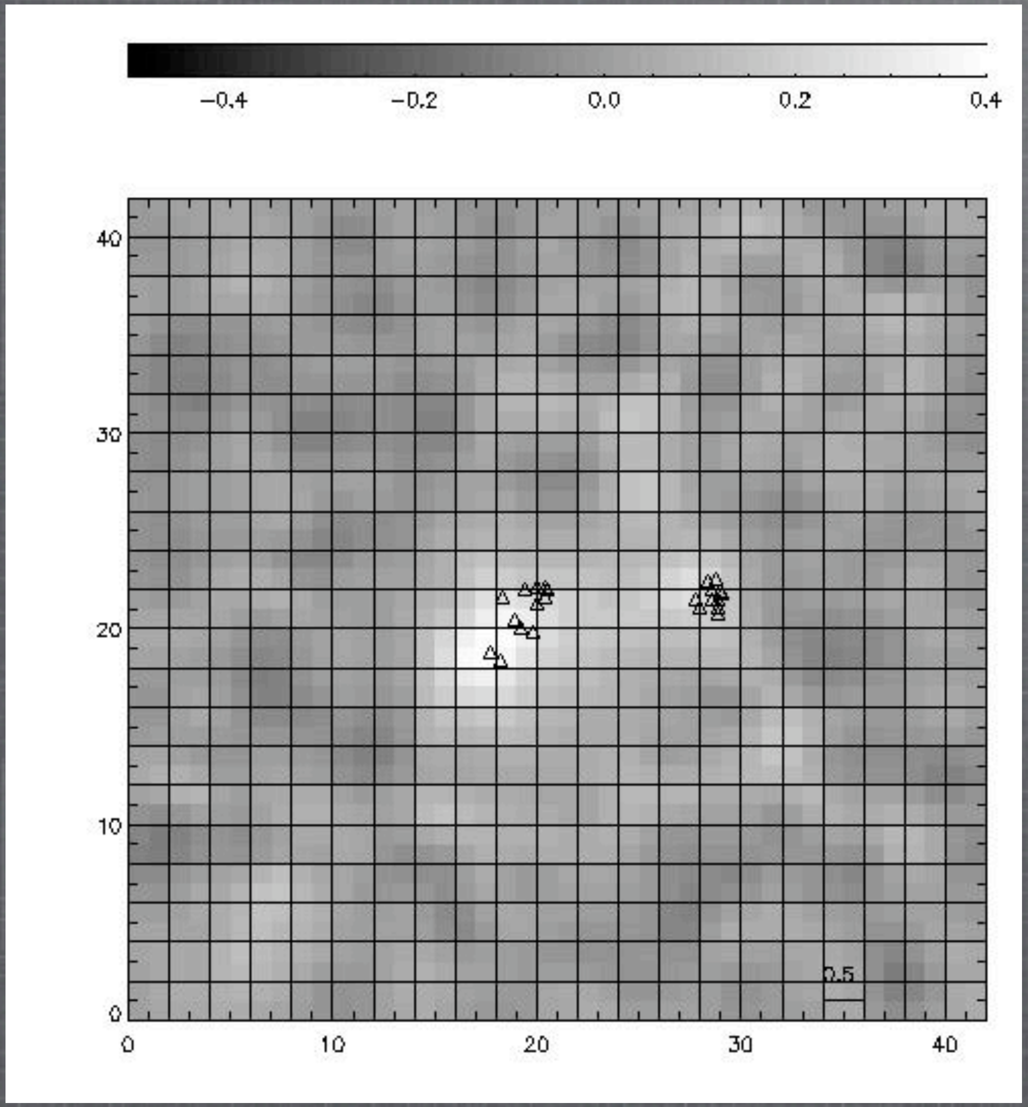
Strong+Weak Lensing

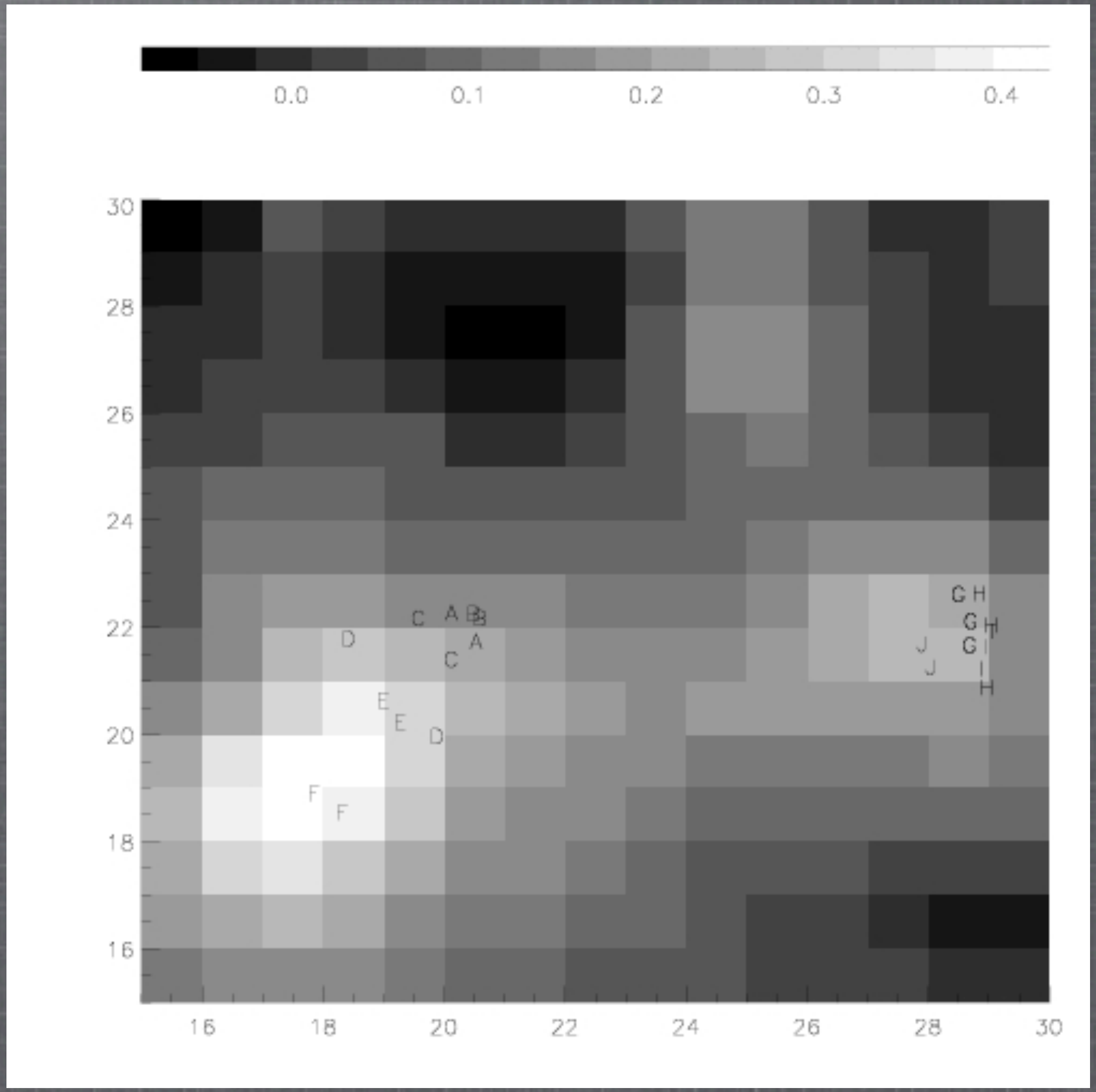


HST/ACS image of Abell 2218 (Sánchez et al. 2006)

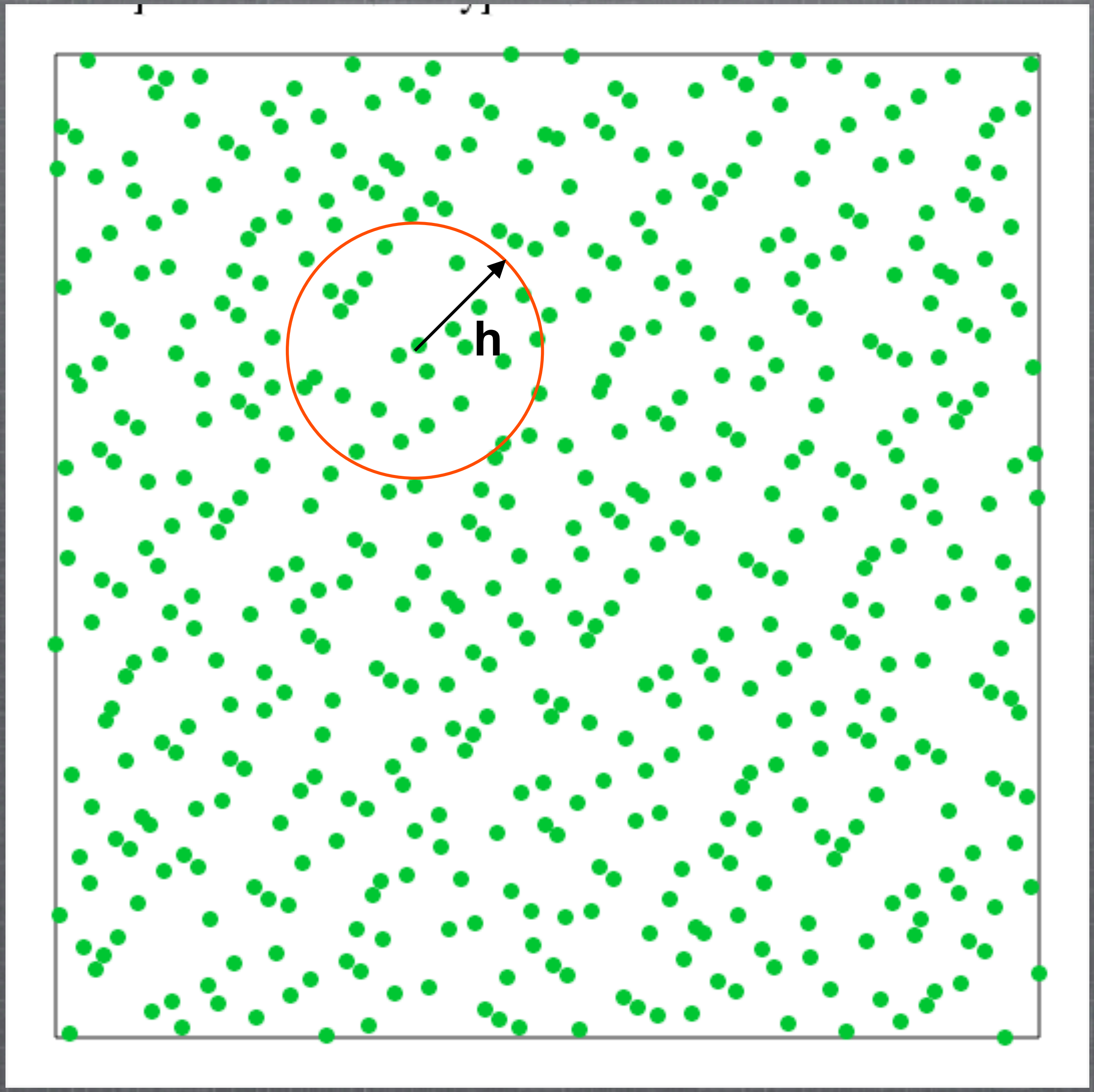


Strong+Weak Lensing

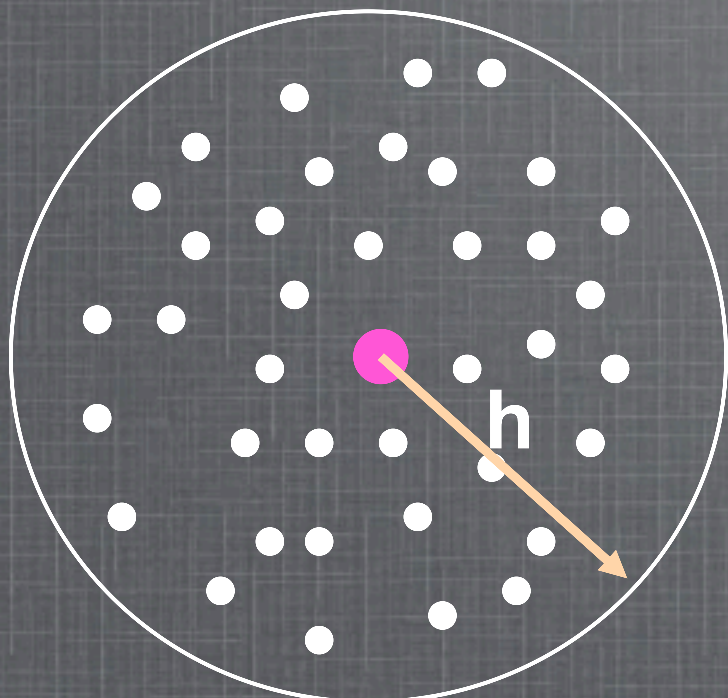




Particle Based Lensing



PBL: Method



Taylor Expansion

$$\psi(\boldsymbol{\theta}) = \psi_n + \theta_j \psi_{n,j} + \frac{1}{2}\theta_j \theta_k \psi_{n,jk} + \ldots$$

$$X^{(1)}_{nm} = \theta_{nx} - \theta_{mx}$$

$$X^{(2)}_{nm} = \theta_{ny} - \theta_{my}$$

$$X^{(3)}_{nm} = \frac{1}{2}\left(\theta_{nx} - \theta_{mx}\right)^2$$

$$\psi_{n,j} = D^{(j)}_{nm}\psi_m$$

$$\psi_{n,jk} = D^{(jk)}_{nm}\psi_m$$

PBL: Method

$$\psi(\boldsymbol{\theta}_m) = \psi_n + \sum_{\nu} D_{nl}^{(\nu)} X_{nm}^{(\nu)} \psi_l$$

The system of N equations are solved using a χ^2 minimization

$$\chi^2 = \sum_m \left(\psi_m - \psi_n - \sum_{\nu,l} D_{nl}^{(\nu)} X_{nm}^{(\nu)} \psi_l \right)^2 w_{nm}$$

Takes care of noisy data

The Weight

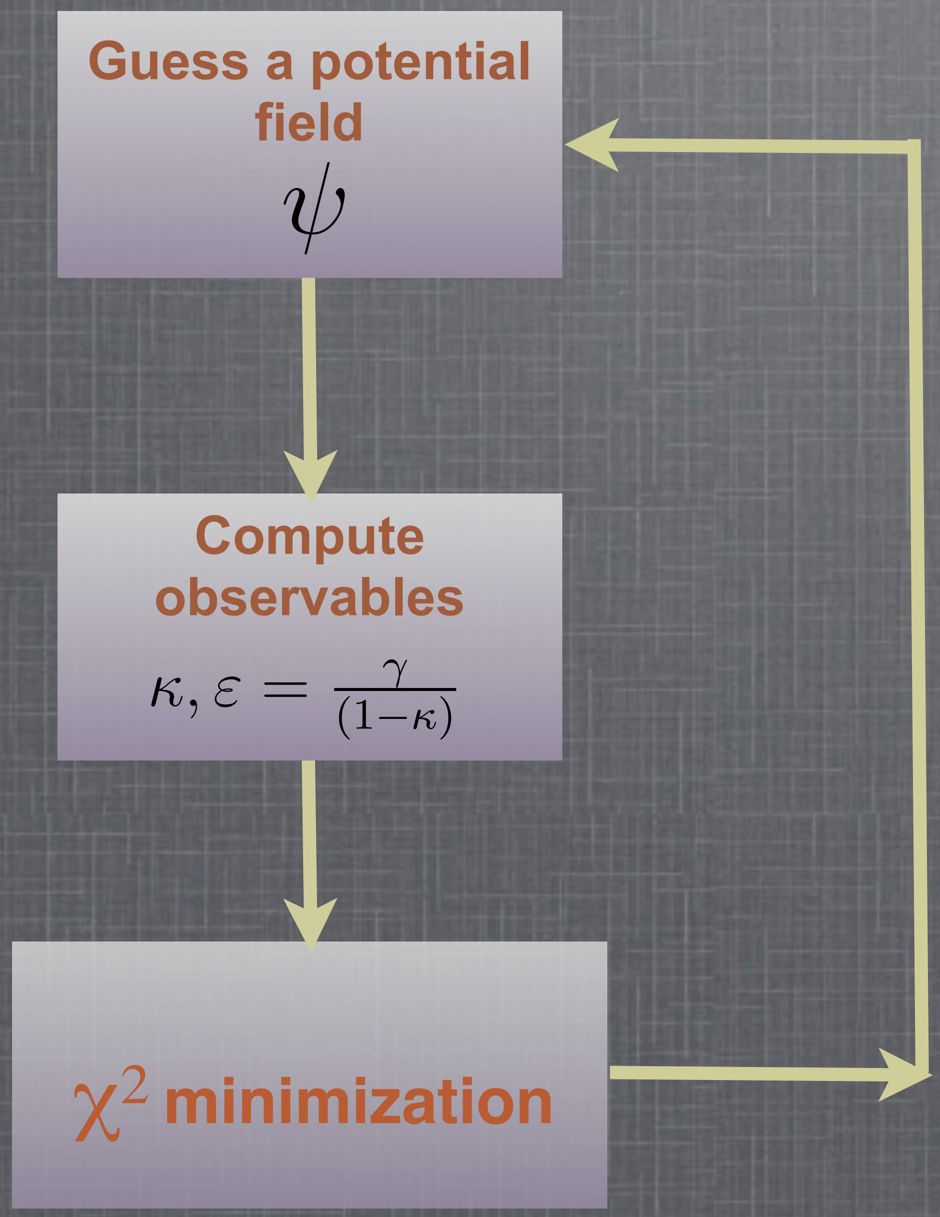
$$w_{nm} = w\left(\frac{|\theta_n - \theta_m|}{h_n}\right)$$

Gaussian weight function

$$w_{nm} = \mathrm{A}_n \exp\left(\frac{(\theta_n - \theta_m)^2}{h_n}\right)$$

Takes care of variable signal-to-noise

Reconstruction Procedure



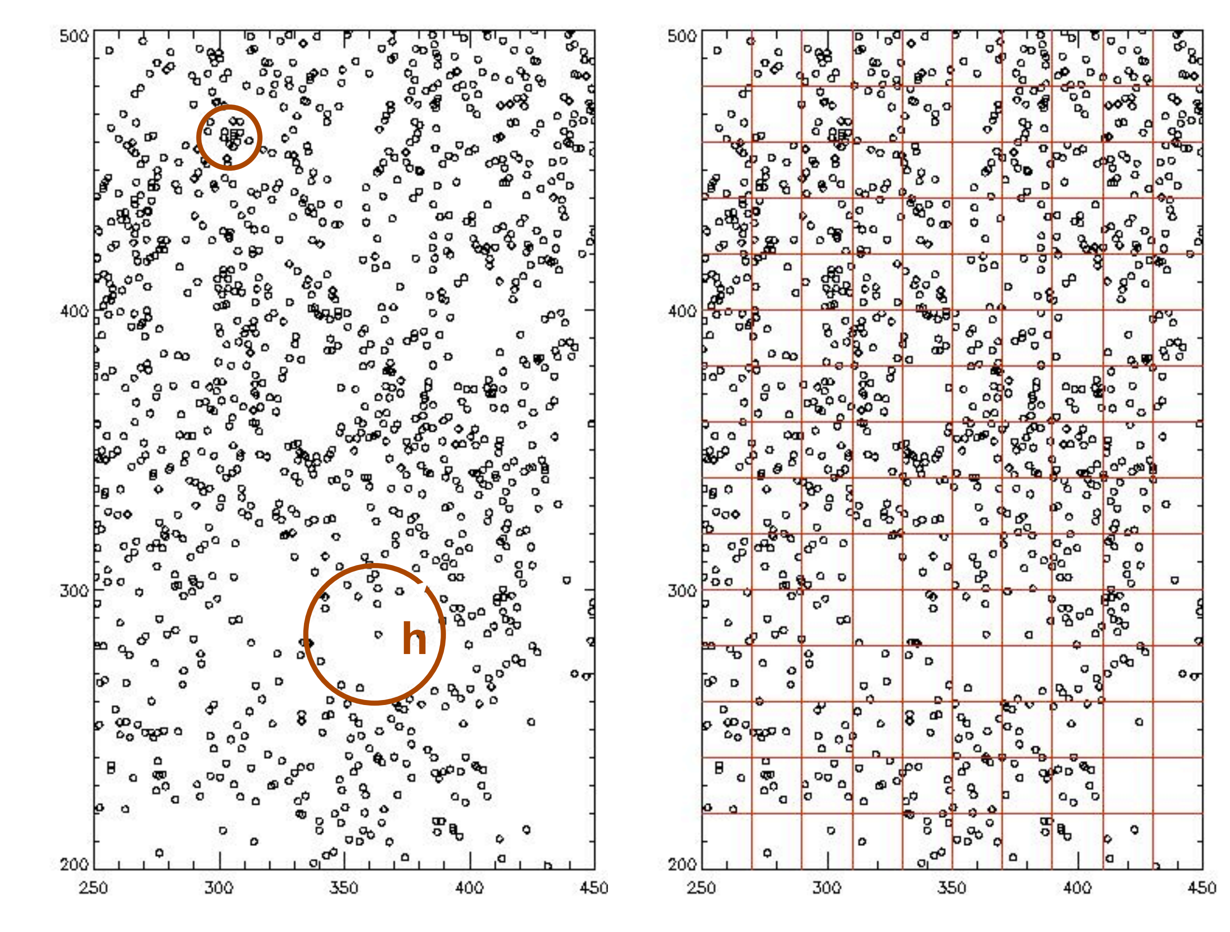
Keep Iterating ...

Reconstruction Procedure

$$\chi^2_{\text{weak}} = \sum_i \frac{\left[\varepsilon_i - \frac{\gamma_i}{(1-\kappa_i)}\right]^2}{\sigma_i^2}$$

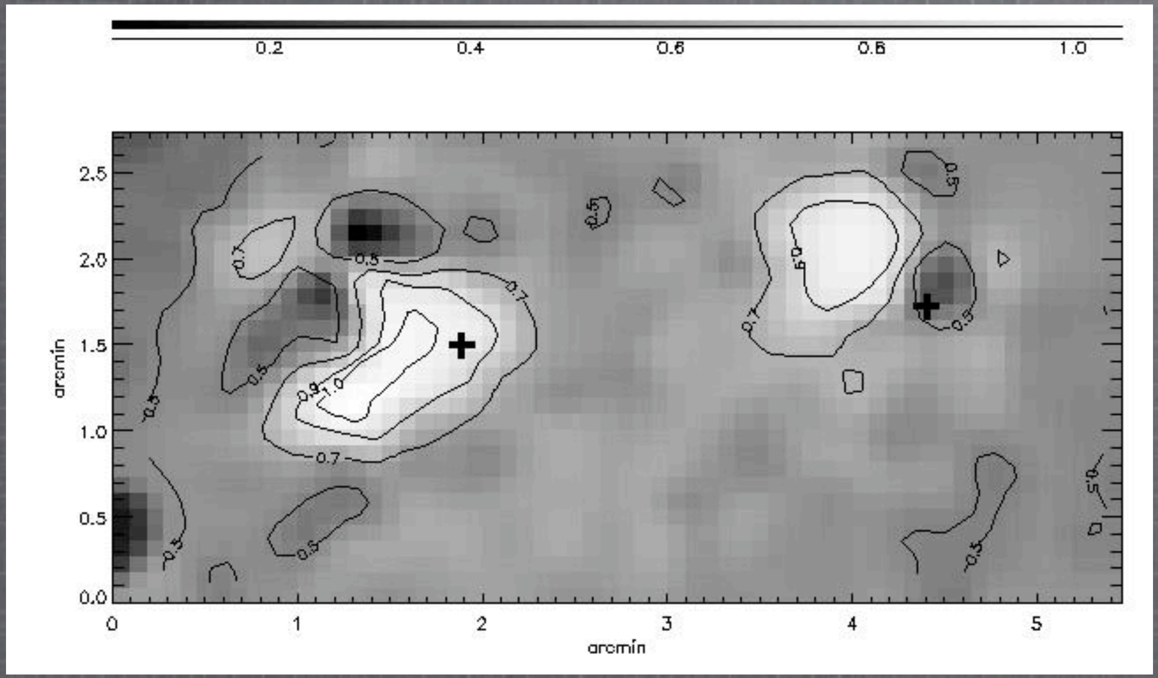
$$\chi^2_{\text{strong}} = \Sigma_i \eta[(\theta_i^A - \theta_i^B) - (\alpha_i^A - \alpha_i^B)]^2$$

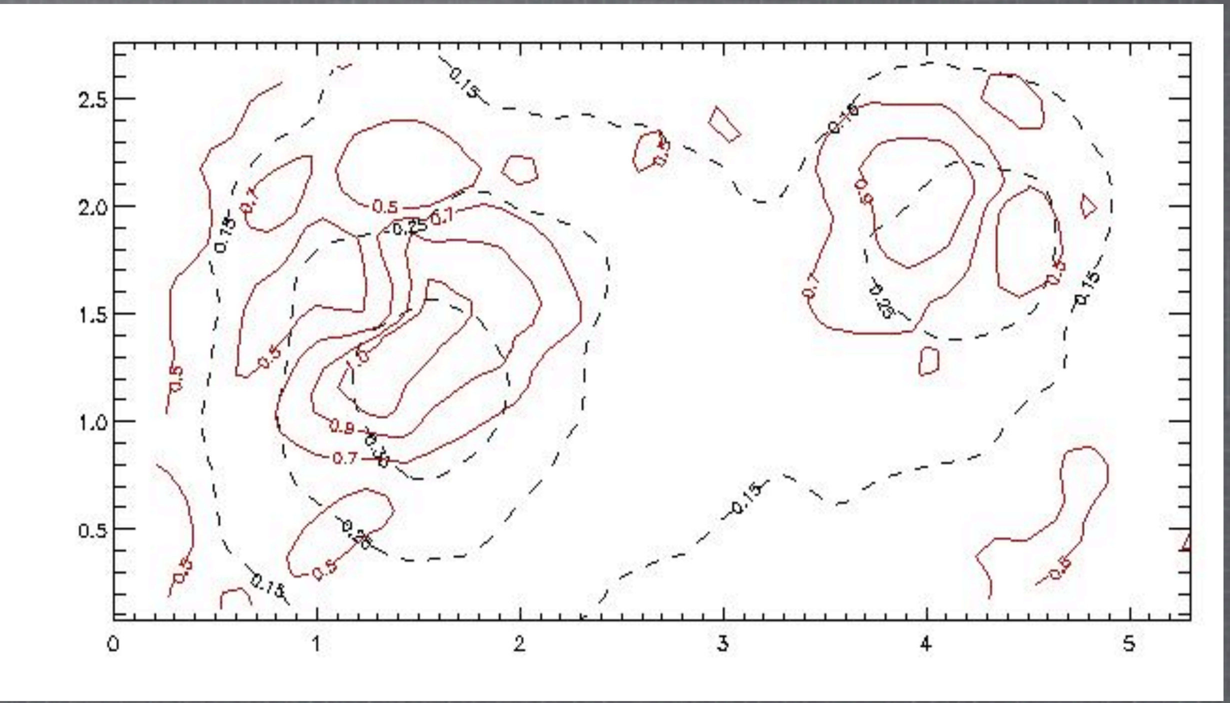
PBL vs. Gridding



- No empty grid cells.
- No direct regularization
- The amplitude A_n in the weight function facilitates inclusion of strong lensing signal.

Results

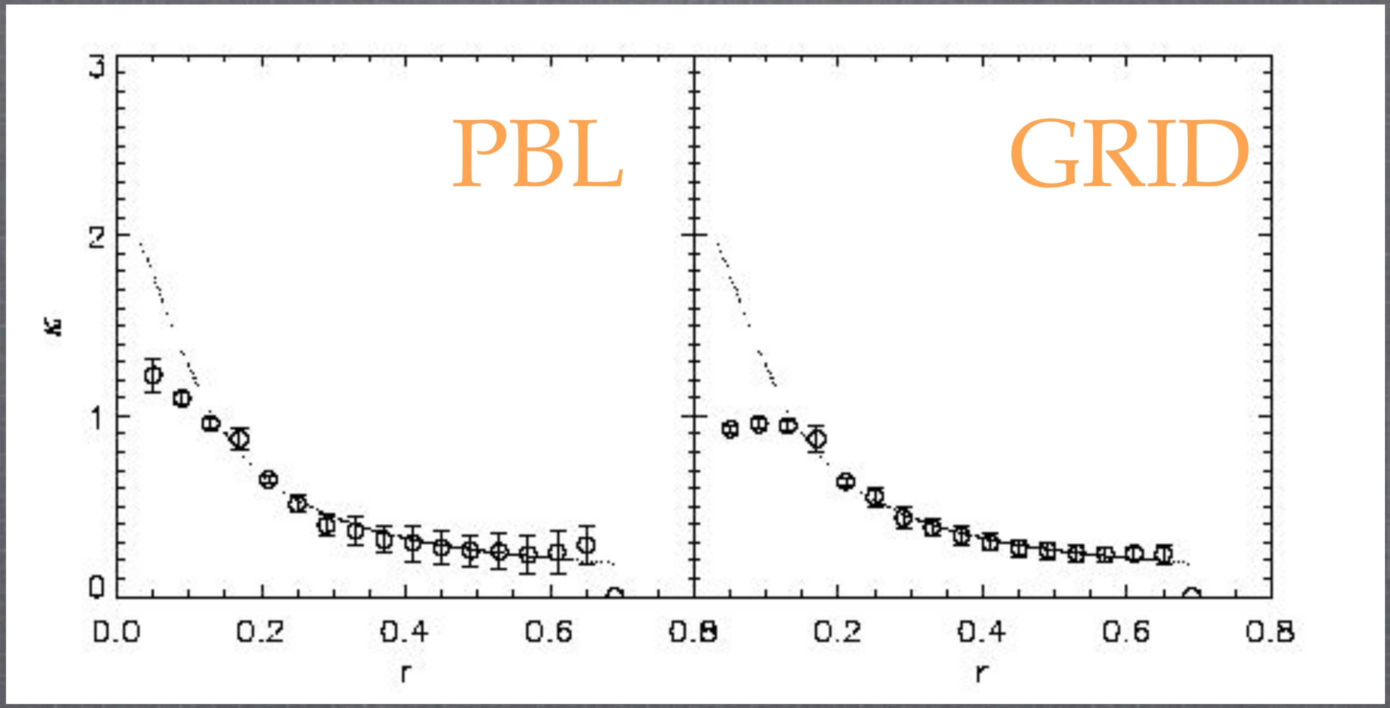




From Deb, Goldberg & Ramdass, 2008

Results

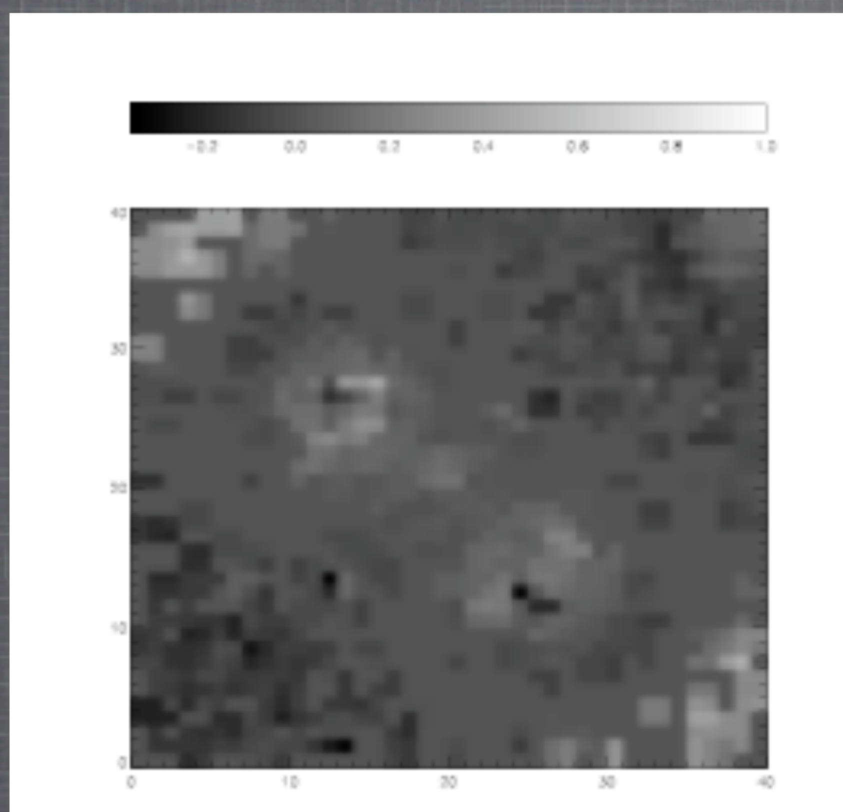
$$\kappa = \theta_E \frac{(\theta^2 + 2\theta_c^2)}{(\theta^2 + \theta_c^2)^{3/2}}.$$



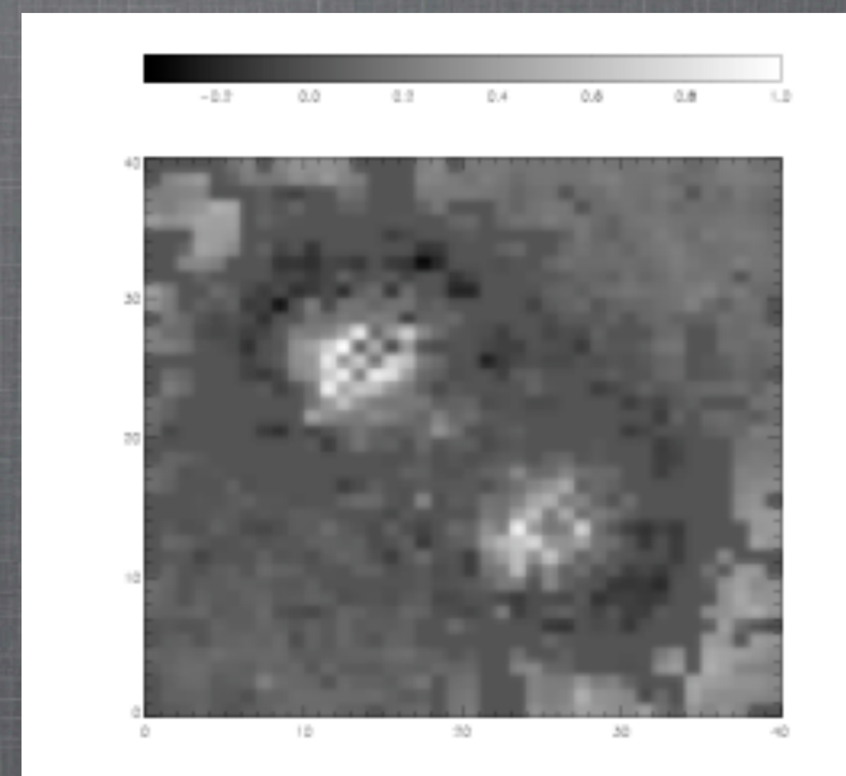
From Deb, Goldberg & Ramdass, 2008

Results

PBL



GRID



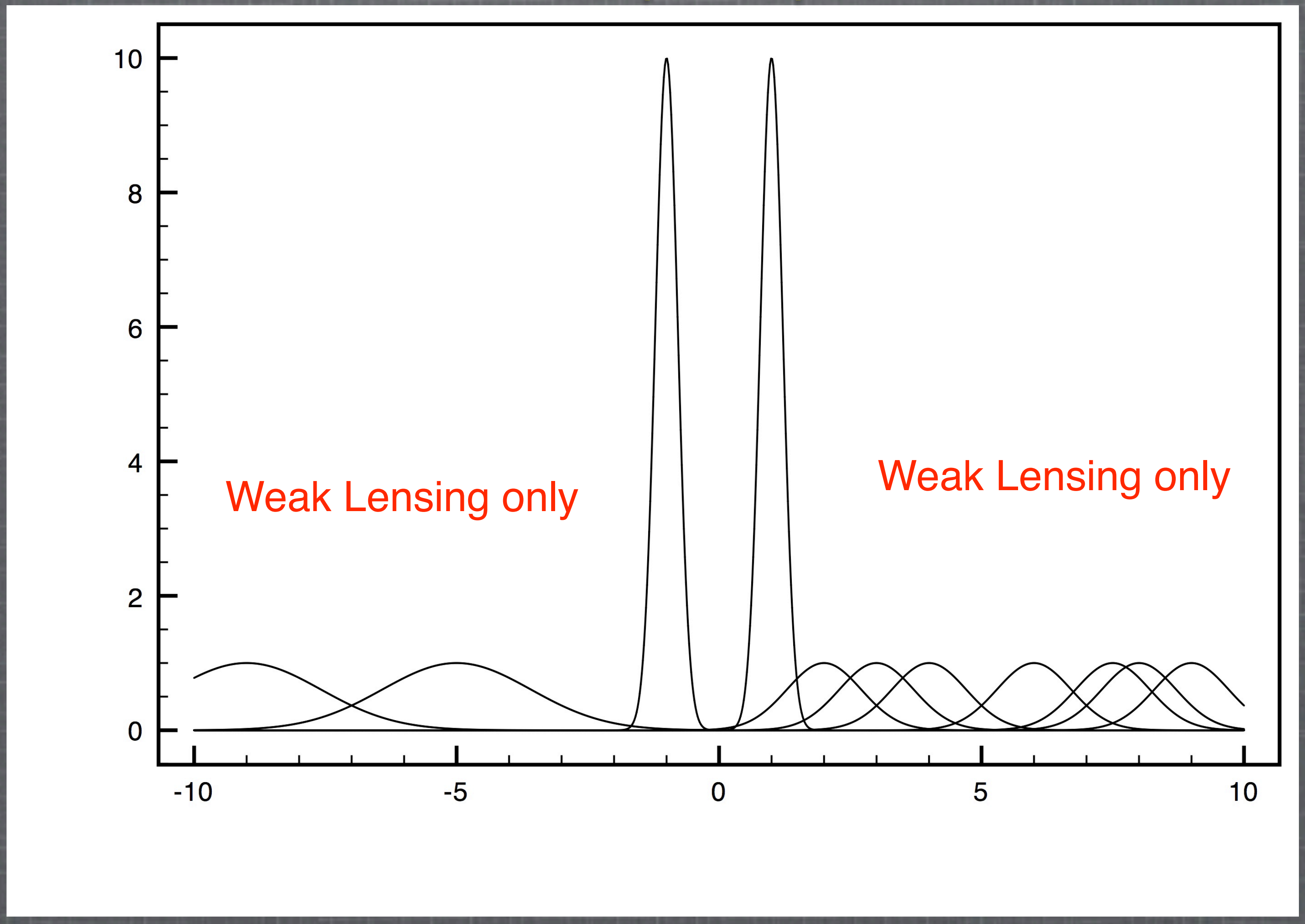
From Deb, Goldberg & Ramdass, 2008

Inclusion of strong lensing

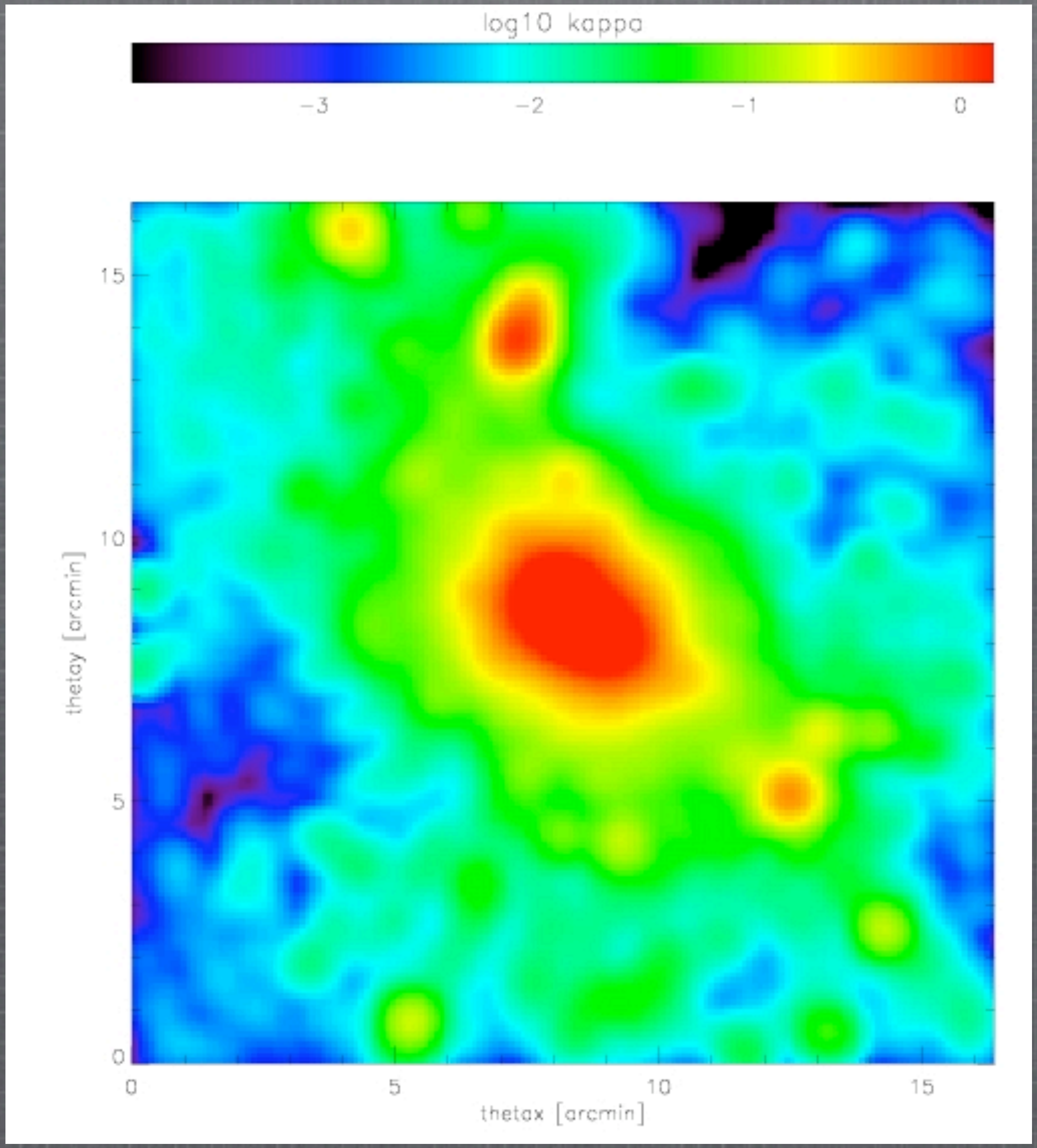
$$w_{nm} = \mathrm{A}_n \exp\left(\frac{(\theta_n - \theta_m)^2}{h_n}\right)$$

Strongly Lensed
(Multiple Images)

A_n

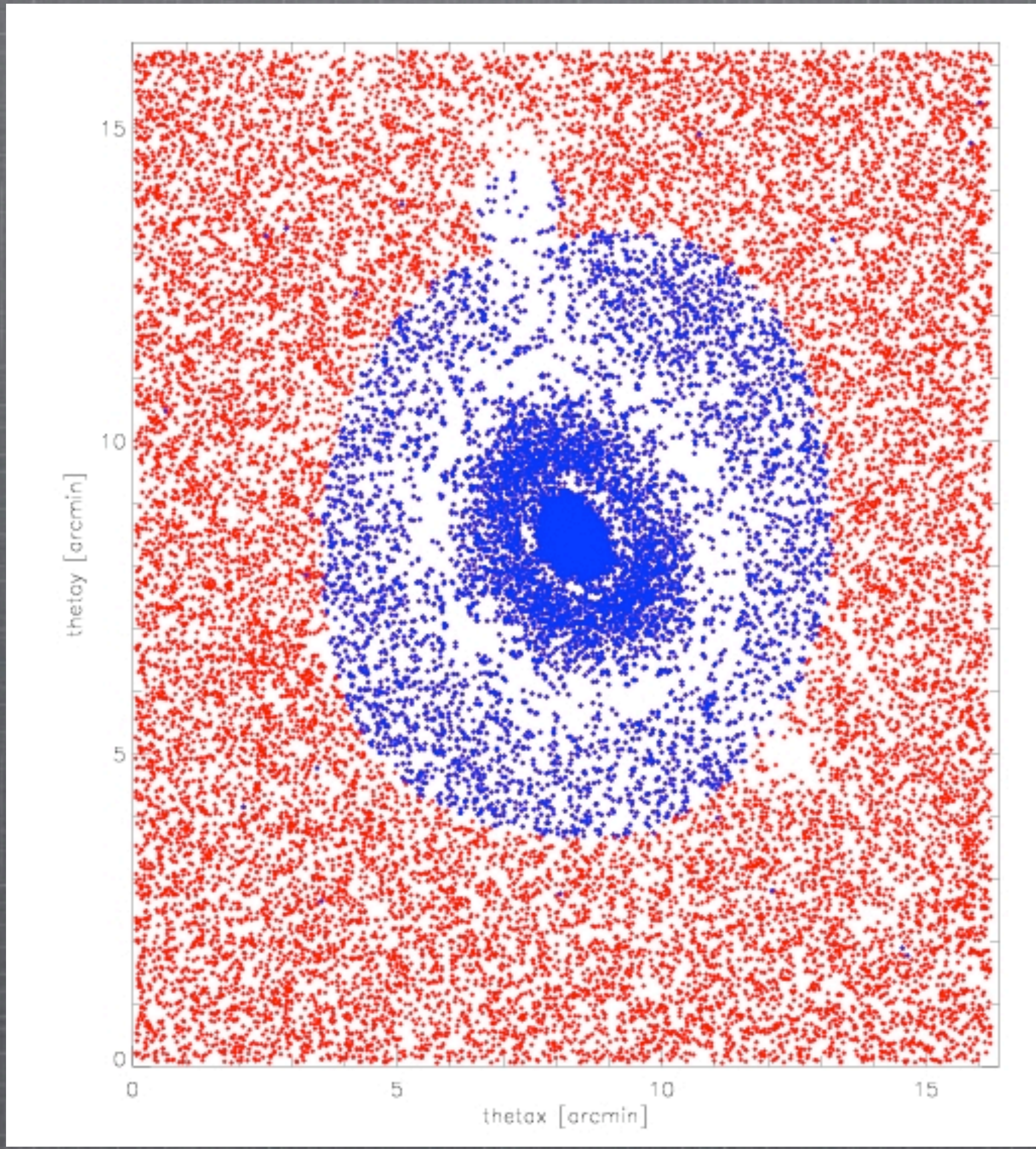


Simulations

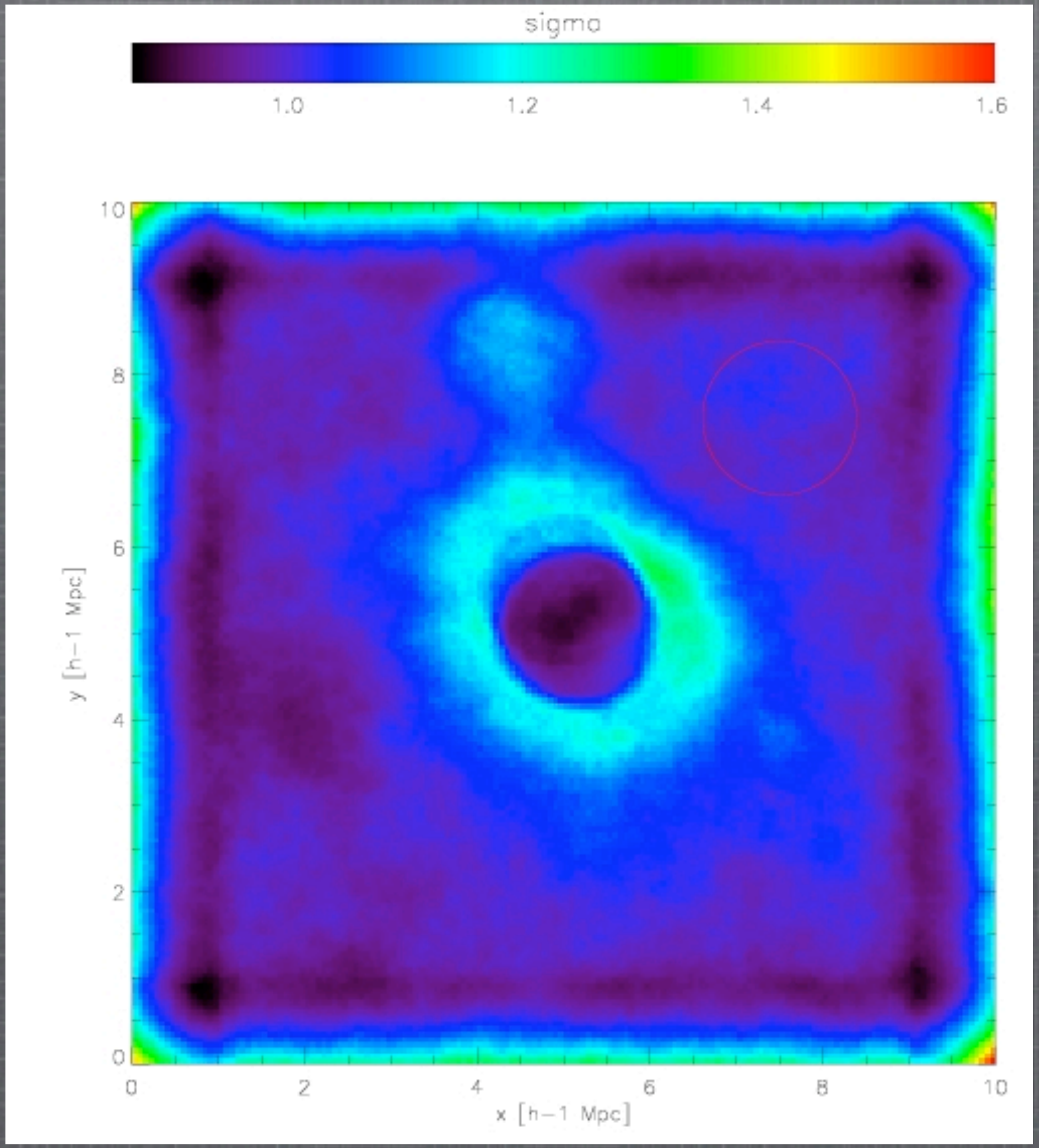


Simulations: Lensing

Red: weak
Blue: strong



Simulations: Noise

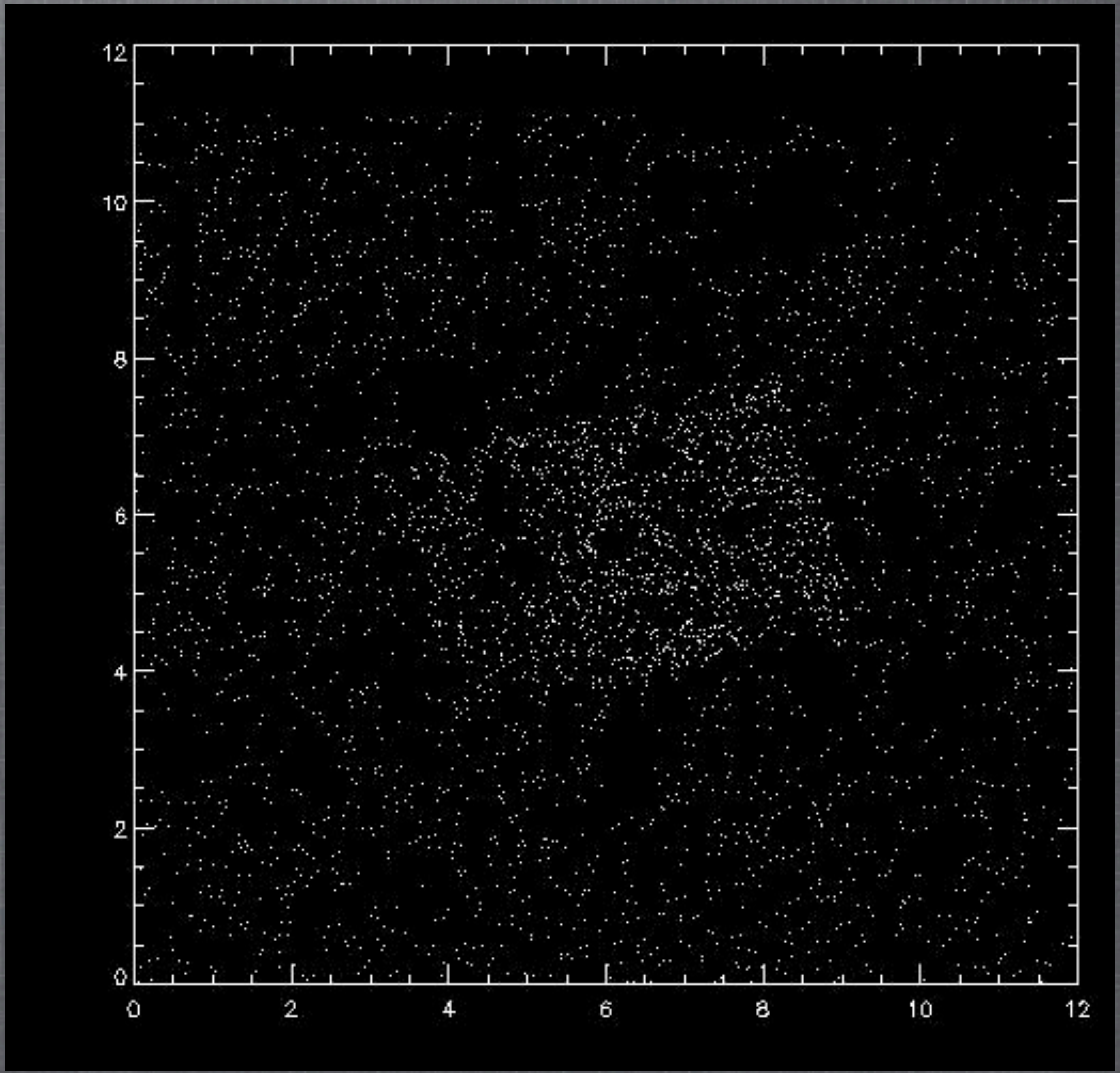


Bullet Cluster

The weak lensing data is from 3 different instruments:

- ESO/MPG wide field imager
- IMACS on Magellan
- ACS on HST

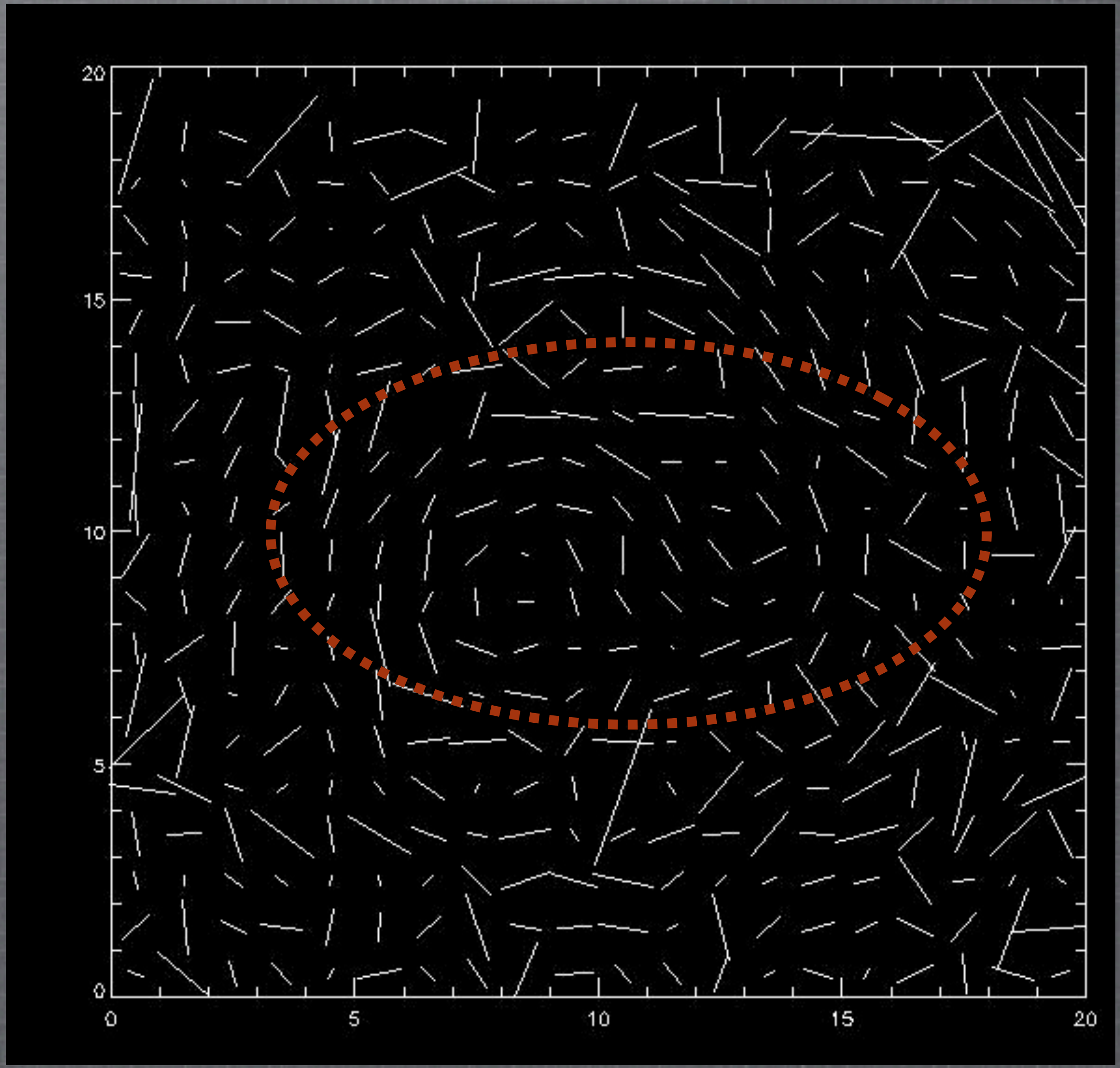
~6000 image galaxies: 12′ by 11′ fov (Clowe et al.,2006)



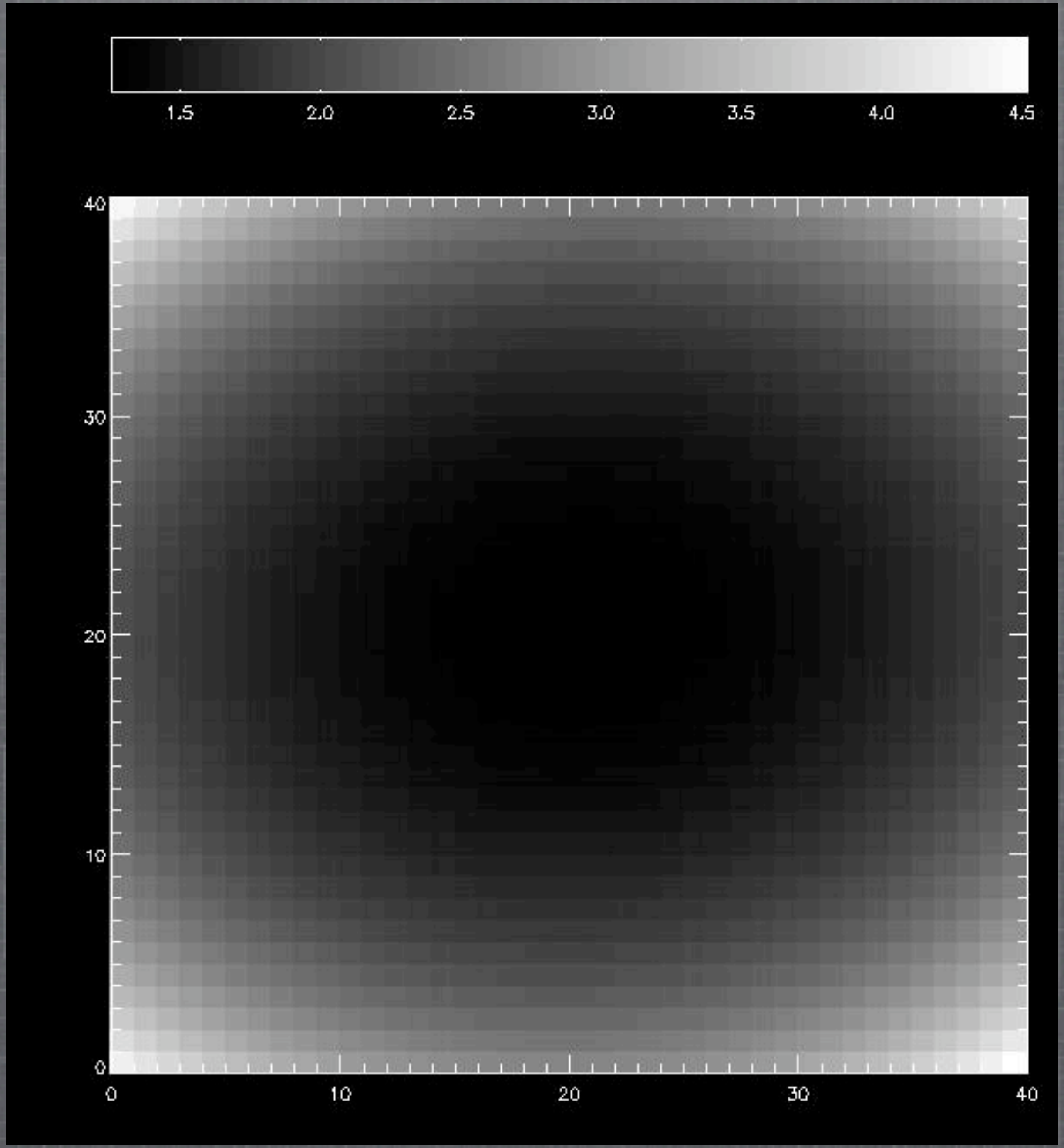
Choosing the length scale

A very coarse shear map of the bullet cluster.

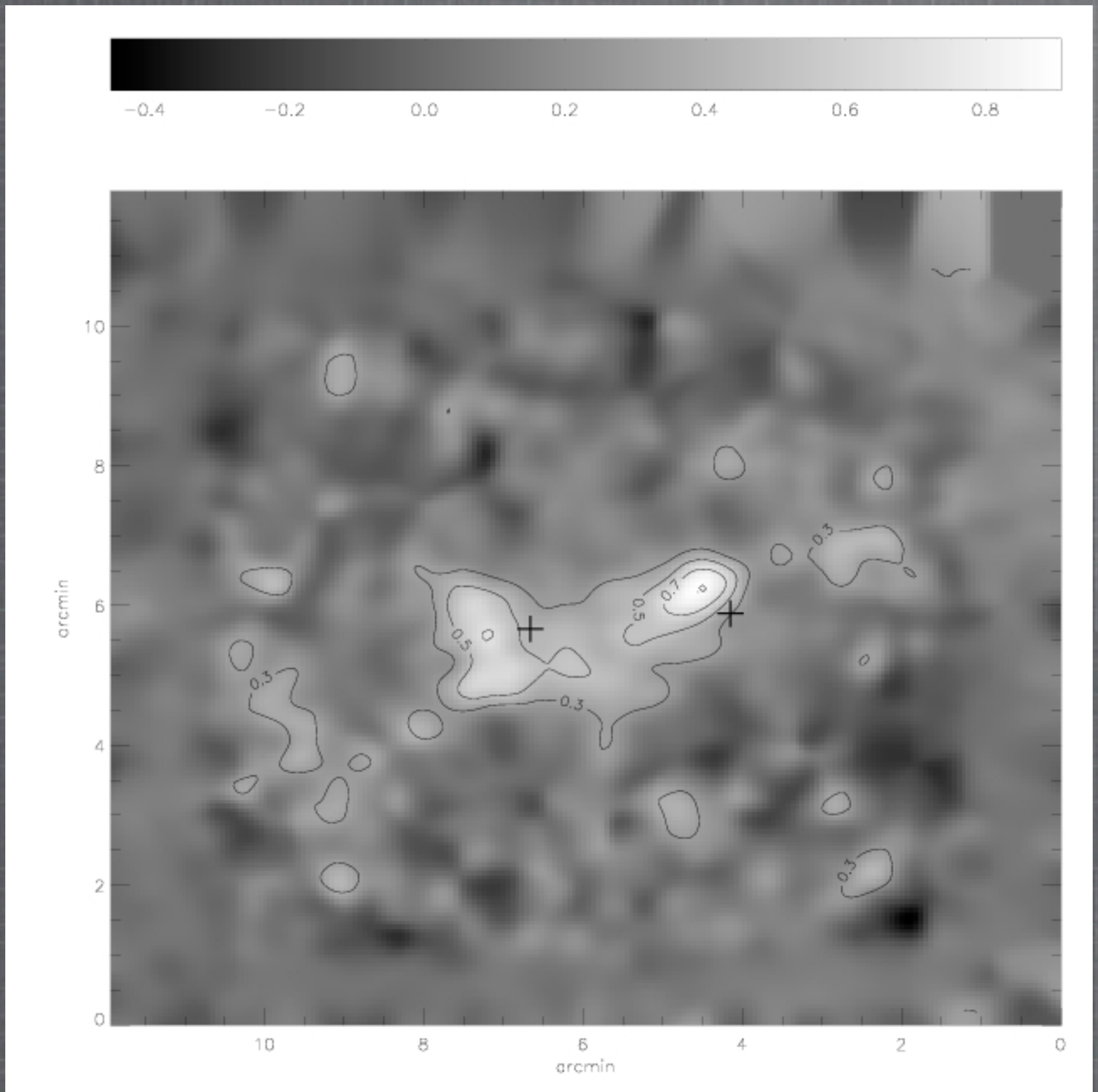
Even though the two peaks are not clearly visible, it is clear that the region outside the ellipse is primarily dominated by noise.

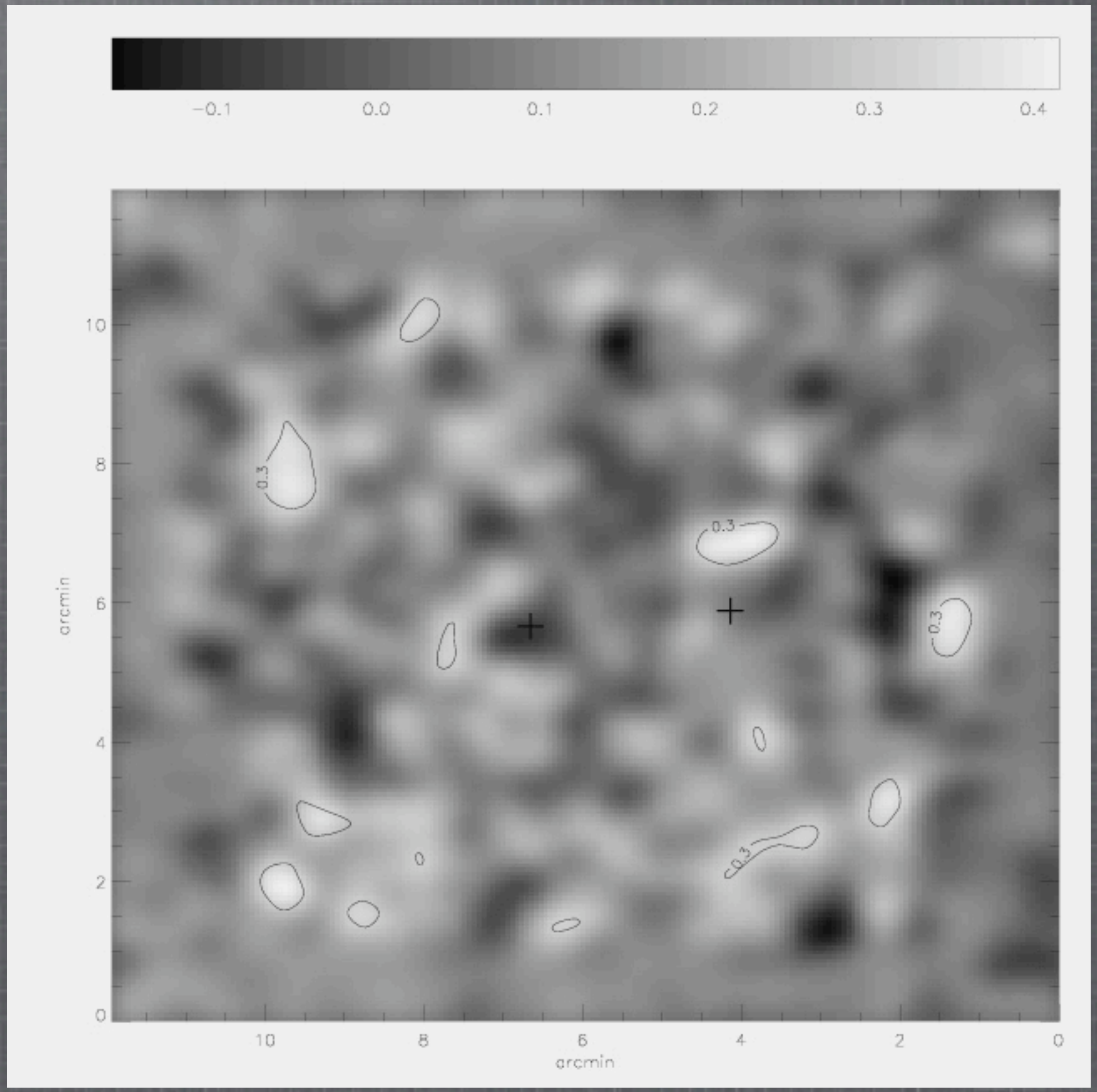


Choosing the length scale



Results: Bullet Cluster S+W

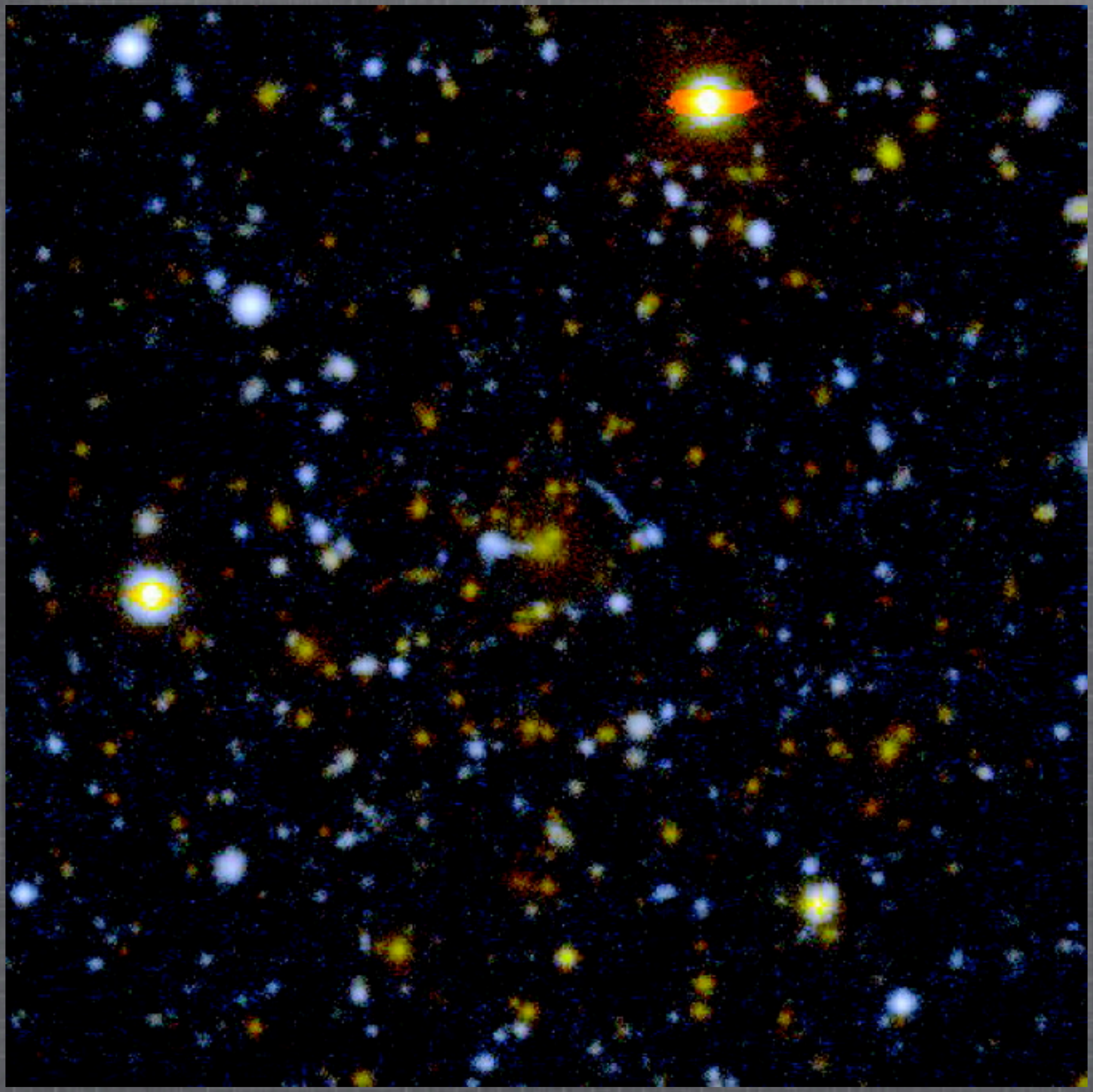


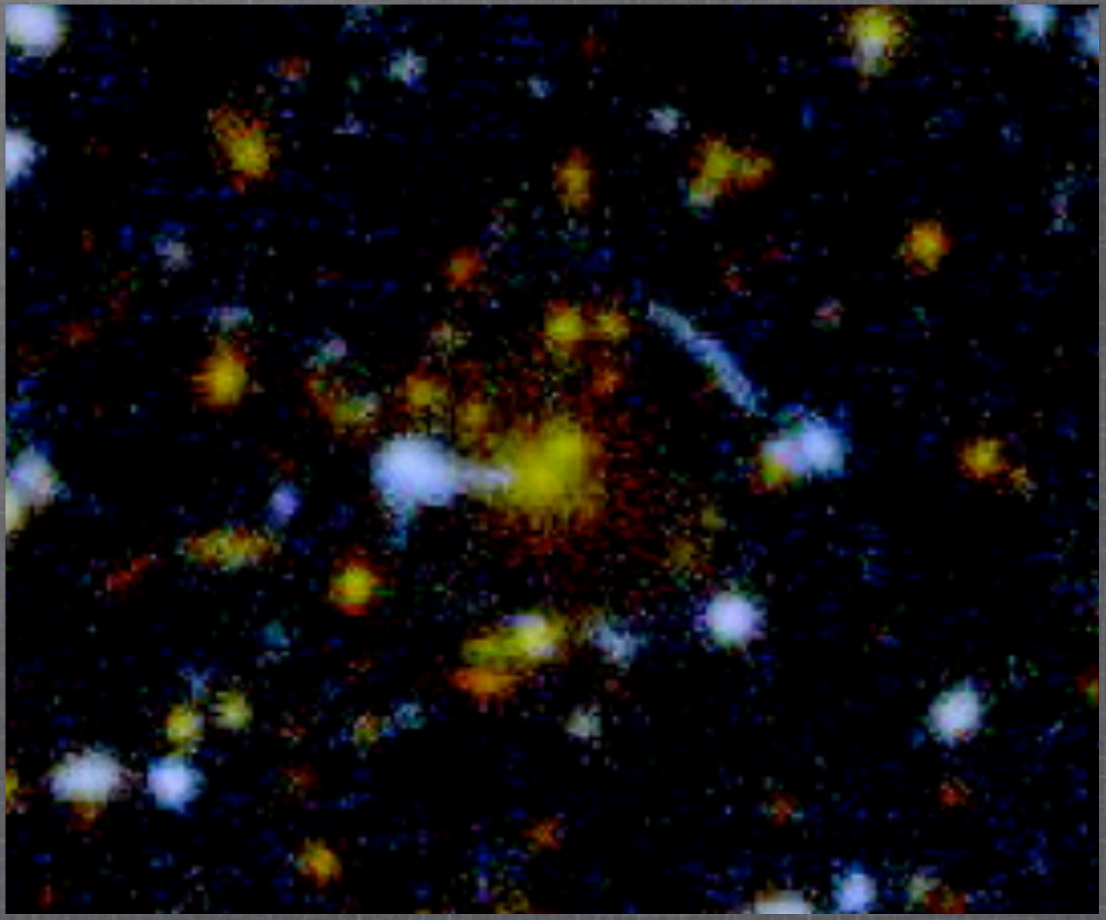


Deb et al. in prep

Arcs

DLSCL J1055.2−0503





Wittman et al.,2006

There is more Information

From a pair of strong lensing images we usually get 2 constraints from the positions.

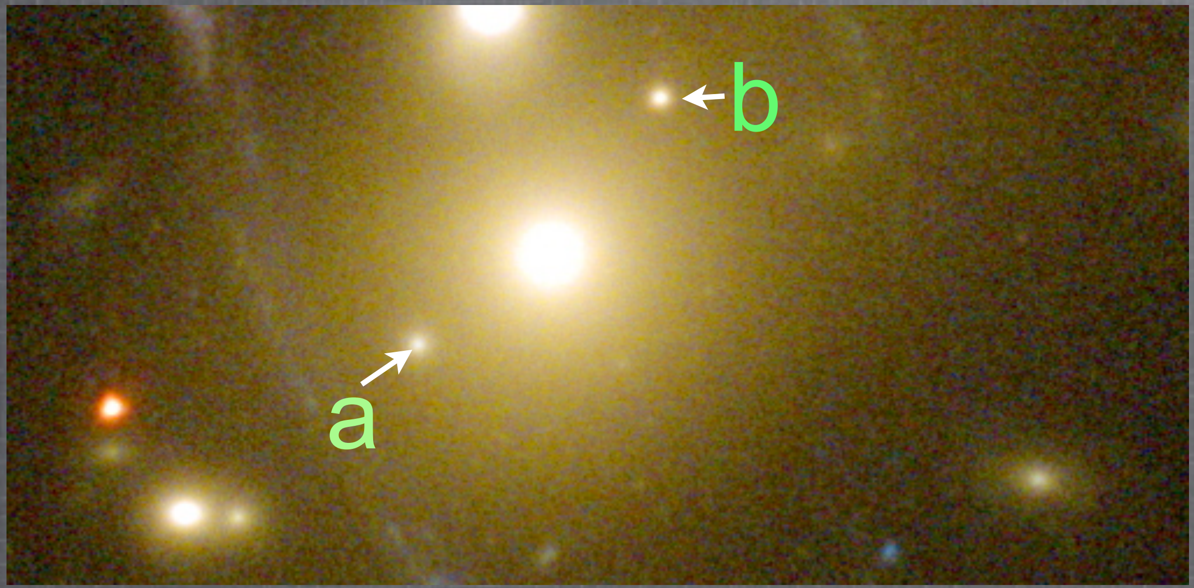
What if we had **5** constraints instead of **2**?

$$\left(\frac{S}{N}\right)_{new} \simeq \sqrt{\frac{5}{2}}\left(\frac{S}{N}\right)_{old} = 1.6\left(\frac{S}{N}\right)_{old}$$

Flux Ratio's ???: 1 constraint per pair

Ellipticity Differences: 2 constraints per pair

Ellipticity Differences



$$\varepsilon_a - \varepsilon_b = g_a - 1/g_b + O({\varepsilon^{(s)}}^4)$$

$$\varepsilon = \begin{cases} \dfrac{\varepsilon^{(s)} + g}{1 + g^* \varepsilon^{(s)}} & \text{for} \quad |g| \le 1 \\[2ex] \dfrac{1 + g {\varepsilon^{(s)}}^*}{{\varepsilon^{(s)}}^* + g^*} & \text{for} \quad |g| > 1 \end{cases}$$

Ongoing work

Characterizing error in PBL

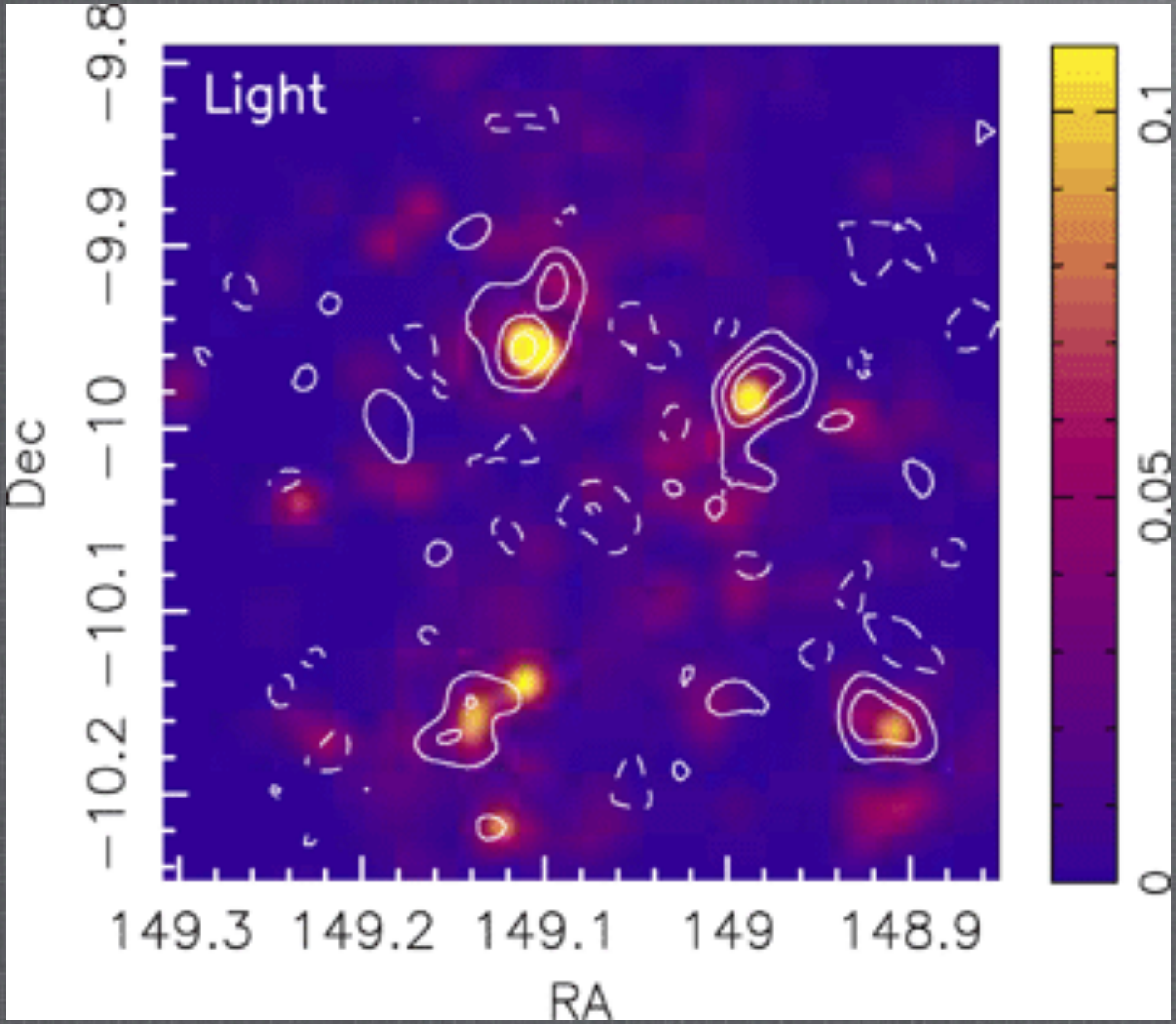
Given a number density of images and a measure of the noise,

What is the significance of detecting a dark matter peak with PBL?

What is the mass threshold for this peak detection?

Deb et al. in prep

Applications: A901/2



Heymans et al,2008

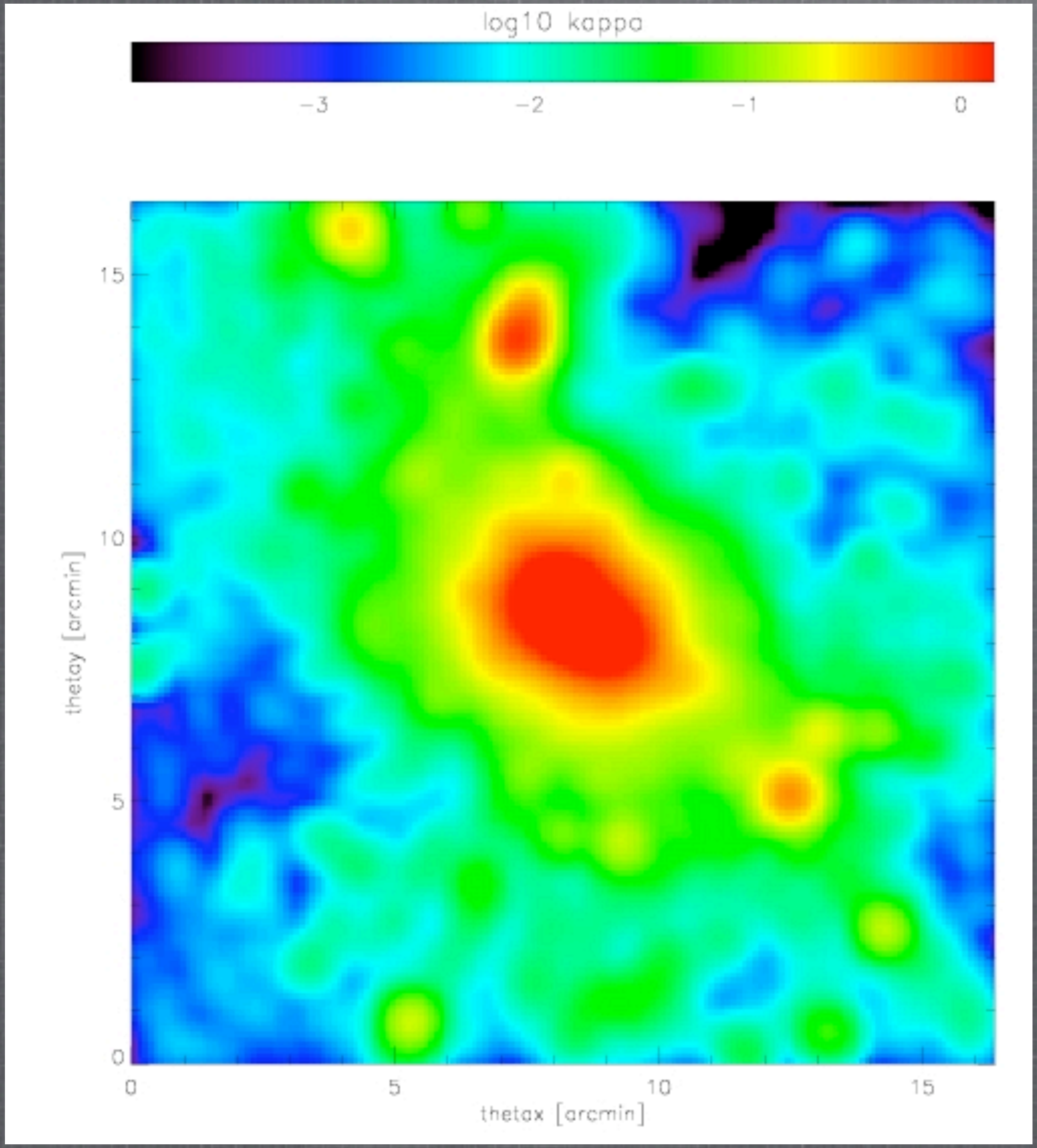
0.5 degree^2 fov
STAGES HST survey
60,000 background images.

Why do we care?

Find interesting substructure???

PBL can very easily incorporate strong lensing information. Thus if strong lensing observations are available for large fov's like this we will have an algorithm ready

Future Work



Compare observations and simulations.

- Measure substructure
- Measure shape

Conclusion & Remarks

PBL

PBL has measured mass peaks better than finite differencing schemes for a single peak and a double peaked system.

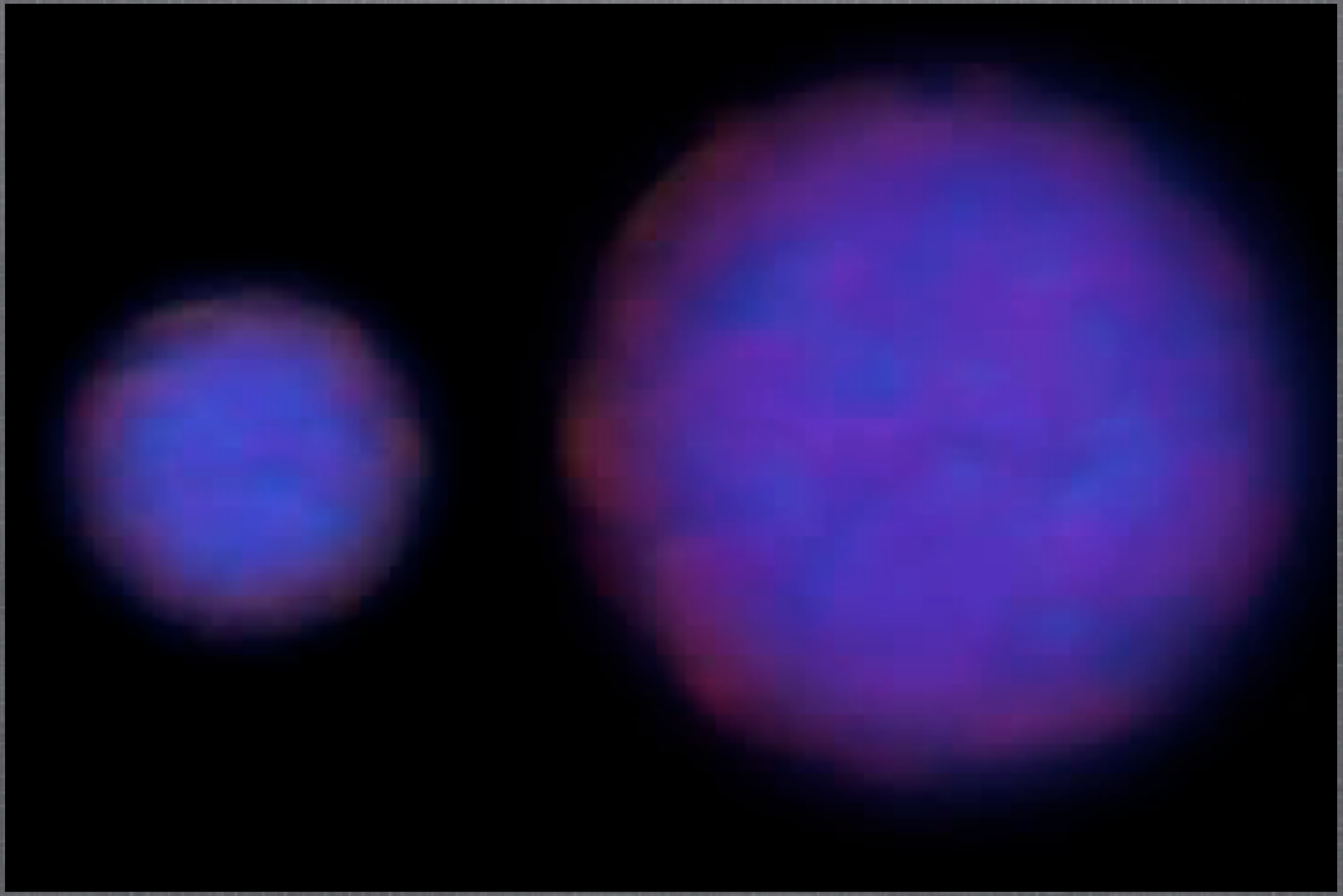
PBL is naturally designed to measure substructure.
Where does it stop?

Clusters

Galaxy clusters are measured with 4 different techniques: SZ,Optical, X-ray and lensing.

Each of these method probe a different property of the clusters. We should aim at doing a joint analysis of all of them to take advantage of the maximally available data set.

Thank You.



For Further Reading:

Reconstruction of Cluster Masses using Particle Based Lensing I: Application to Weak Lensing, S Deb, DM Goldberg, & VJ Ramdass, 2008, accepted to ApJ, arxiv/0802.0004

public codes: www.physics.drexel.edu/~deb/PBL.htm