Probing Cluster Masses with Gravitational Lensing

Sanghamitra Deb

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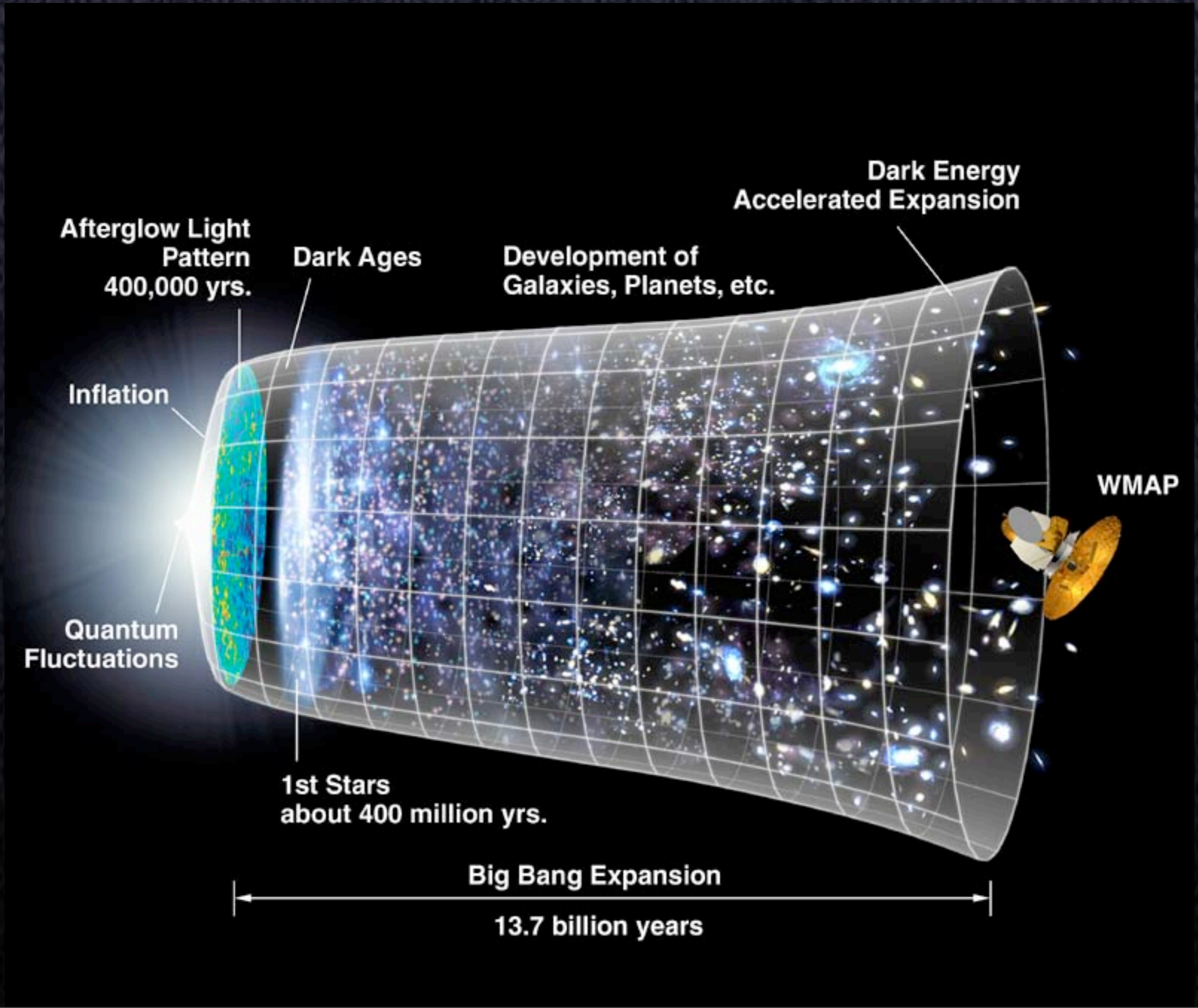
Looking Back ...



Galaxy Clusters : Formation

43 Mpc

4.3 Mpc

Andrey Kravtsov

http://cosmicweb.uchicago.edu

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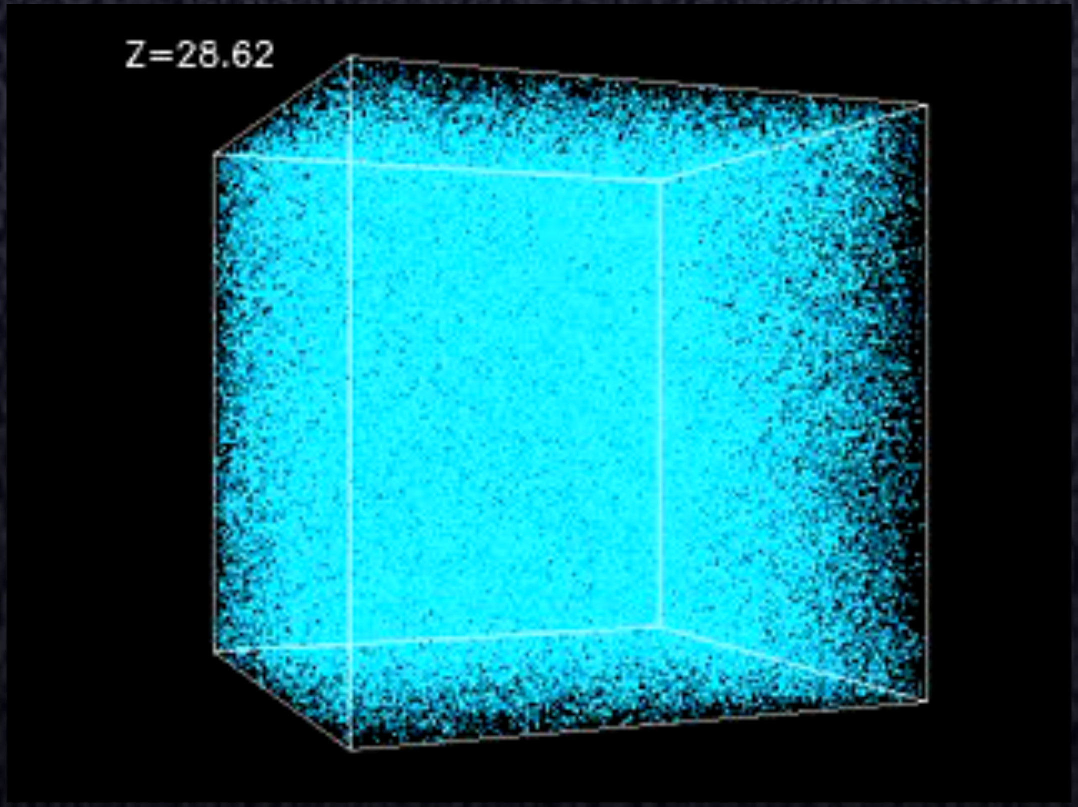
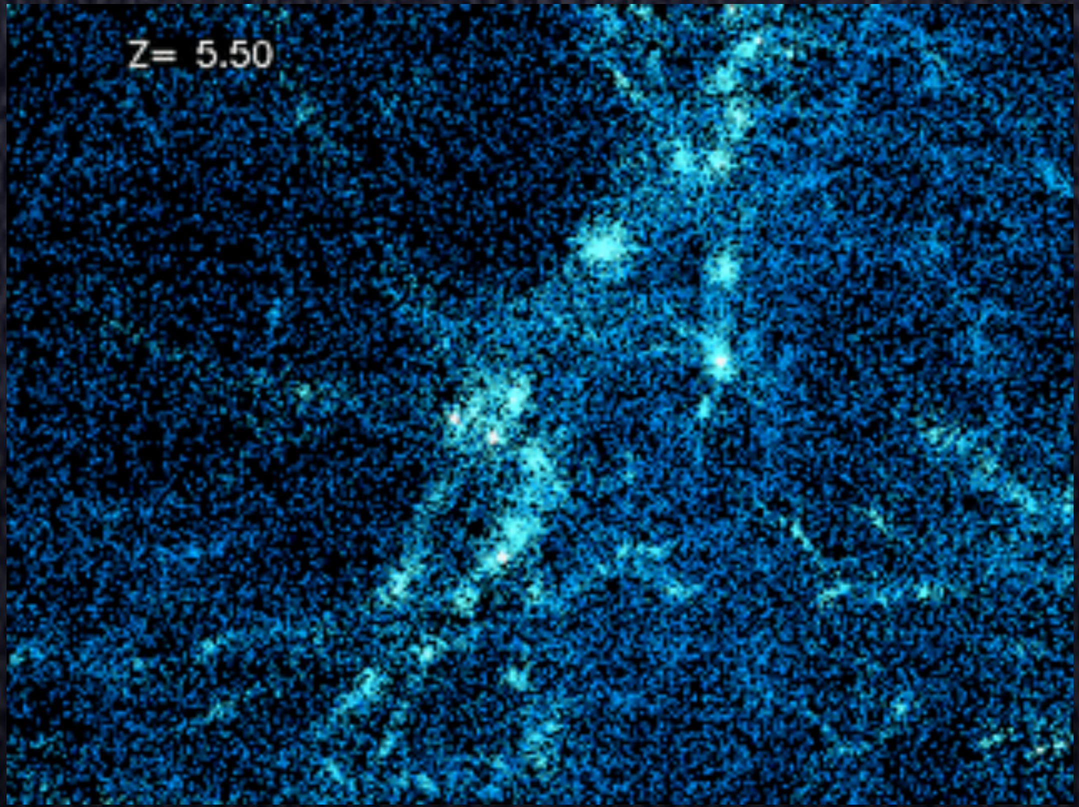


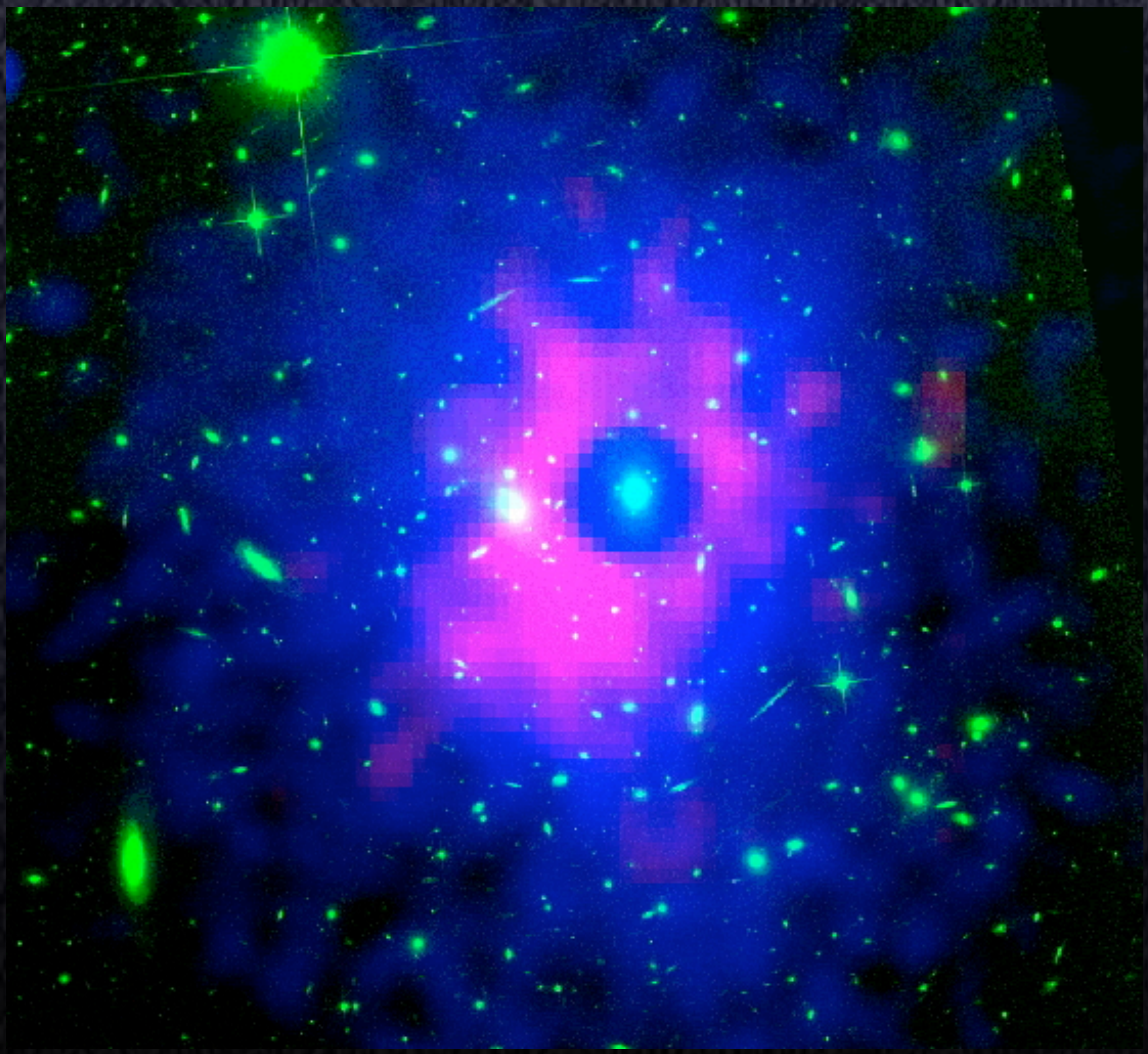
4.3 Mpc



Andrey Kravtsov

http://cosmicweb.uchicago.edu

Observing Clusters



galaxies: HST, optical observations

gas: Xray observations

gas: Sunyaev Zeldovich Effect

Galaxy Cluster RXJ1347-1145

http://chile1.physics.upenn.edu/gbtpublic/

What do we want to measure?

- Mass
- Substructure
- Morphology

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Why?

What do we want to measure?

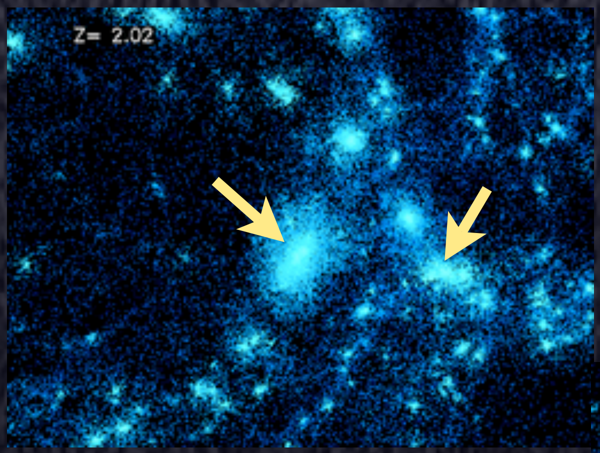
- Mass
- Substructure
- Morphology

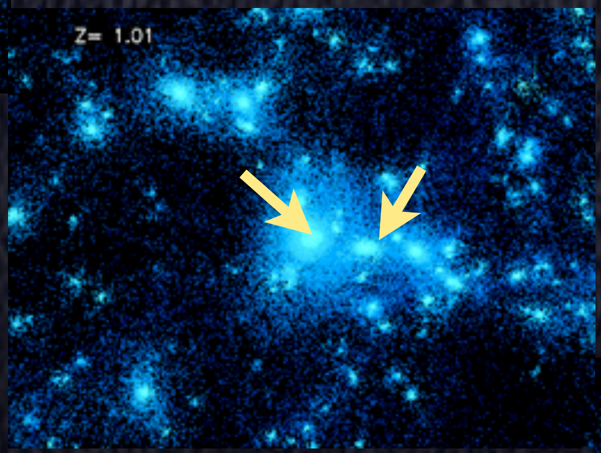
Why?

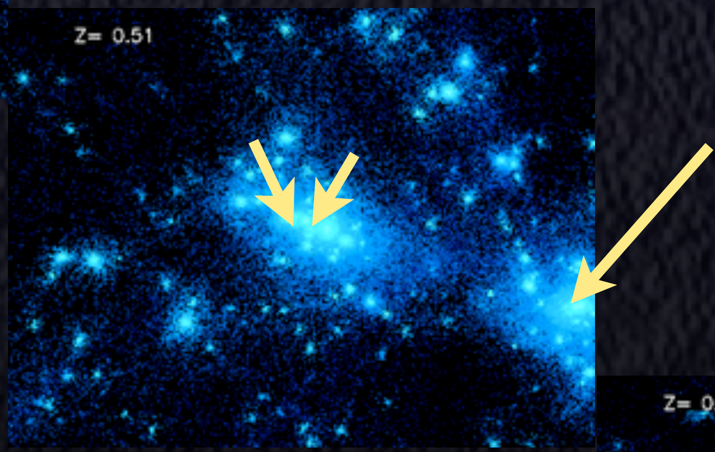
Test Predictions of LCDM cosmology in the local Universe.
Compare with the morphologies of gas and light.

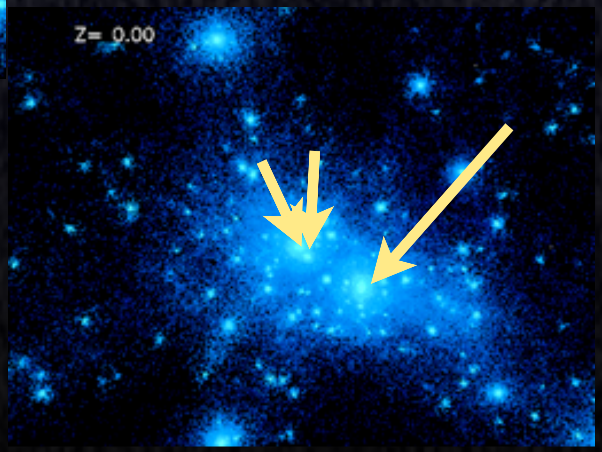
Substructure: Elliptical Halos

What is the distribution of cluster ellipticity?



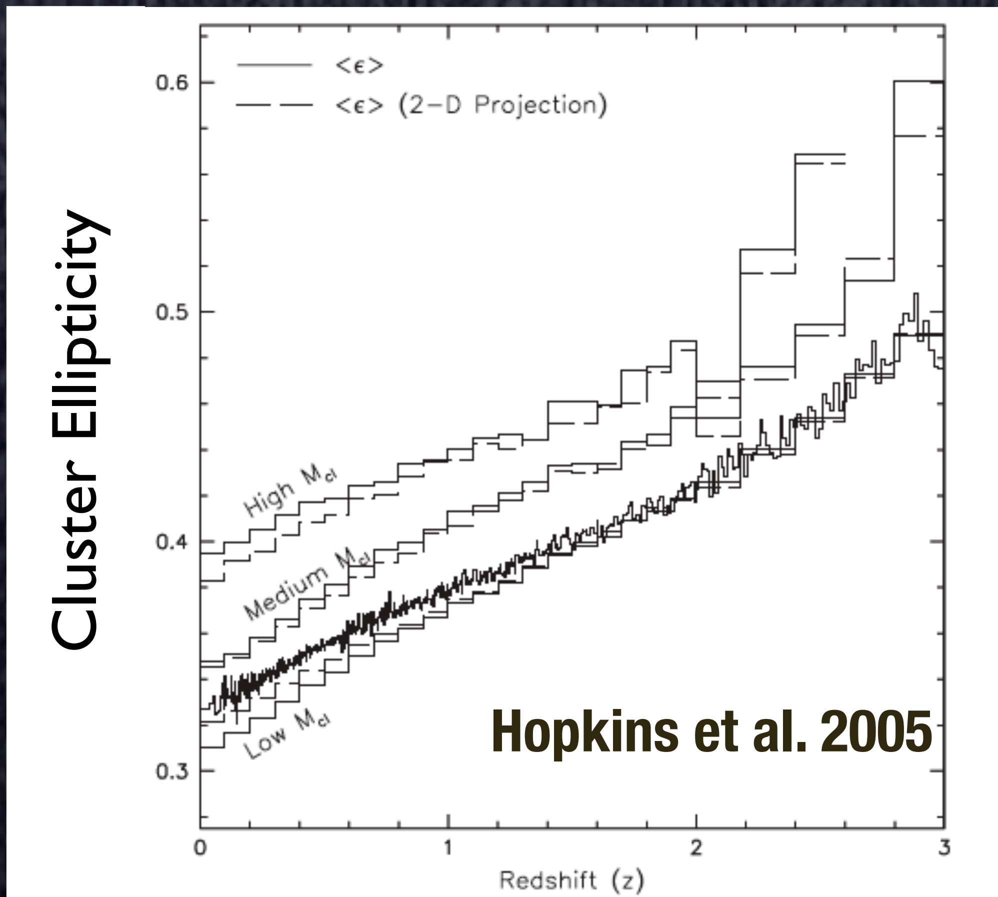


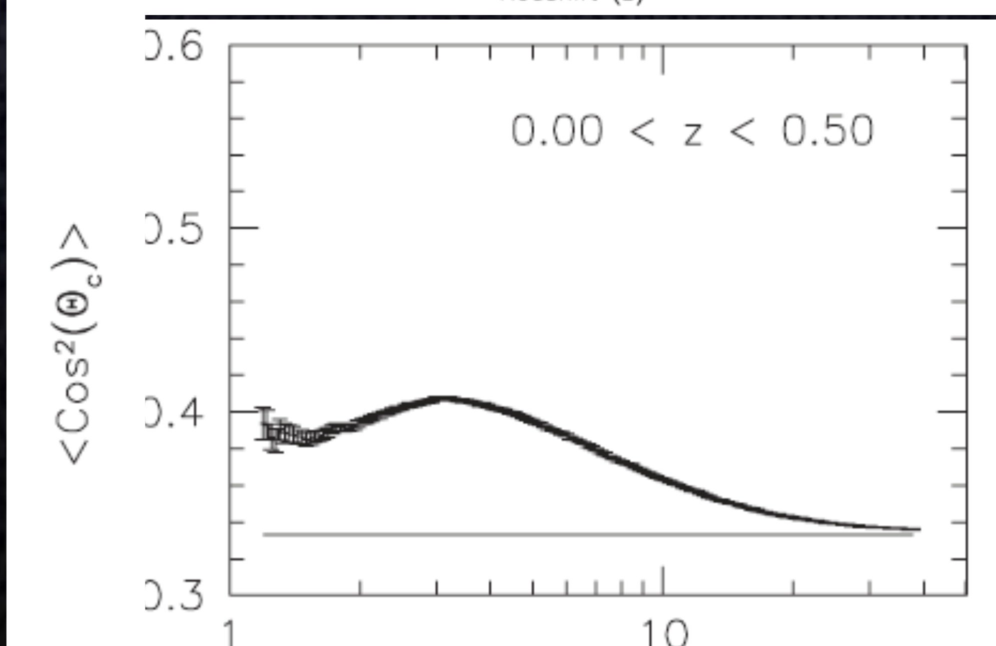




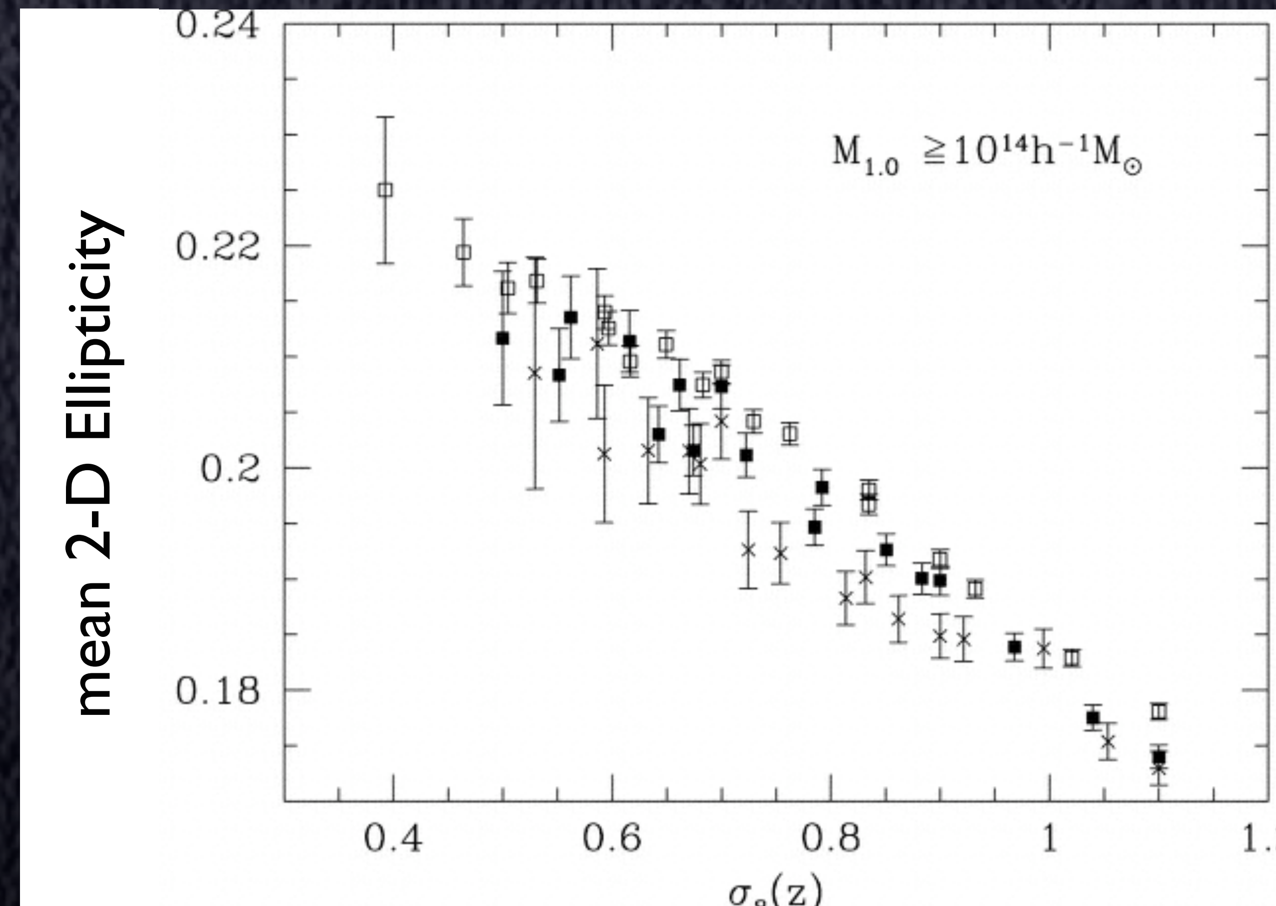
How does the distribution and alignment vary with redshift & mass?

Prediction from Simulations



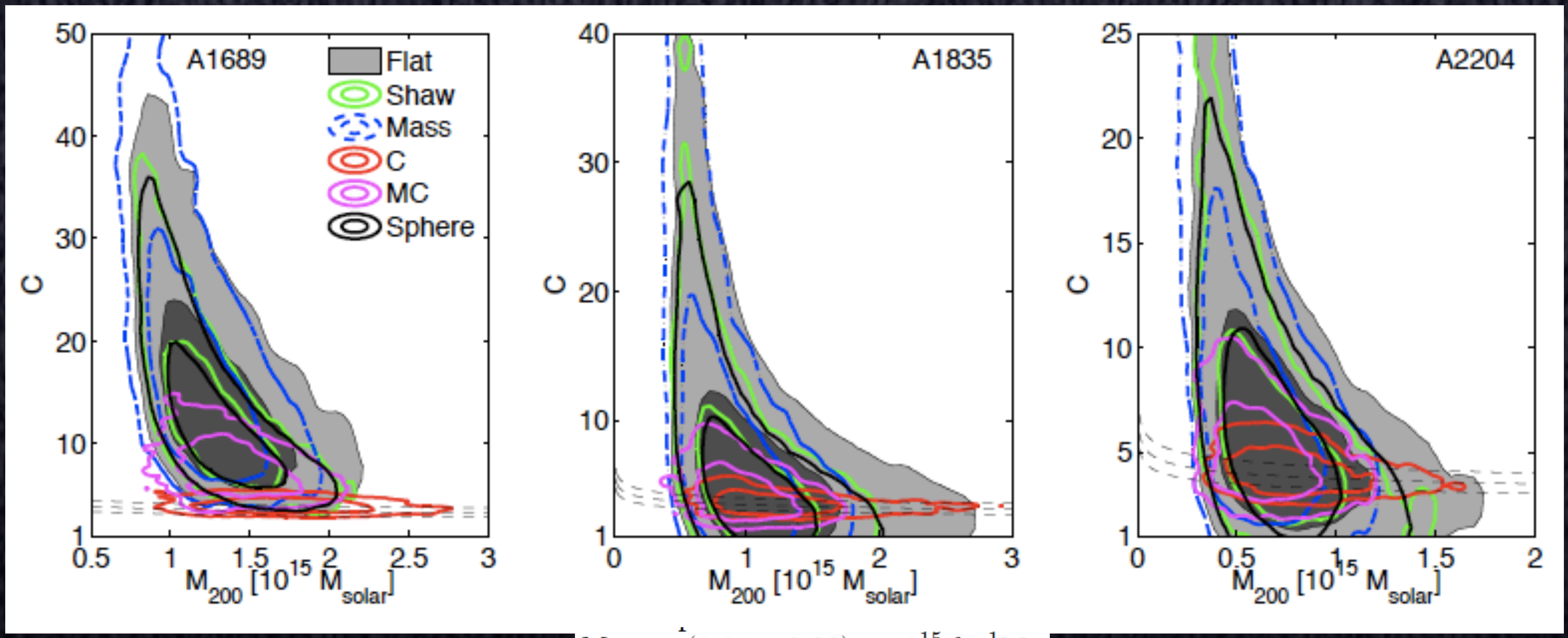


Pair separation (h Mpc)



Ho et al. 2006

Observations: Lensing



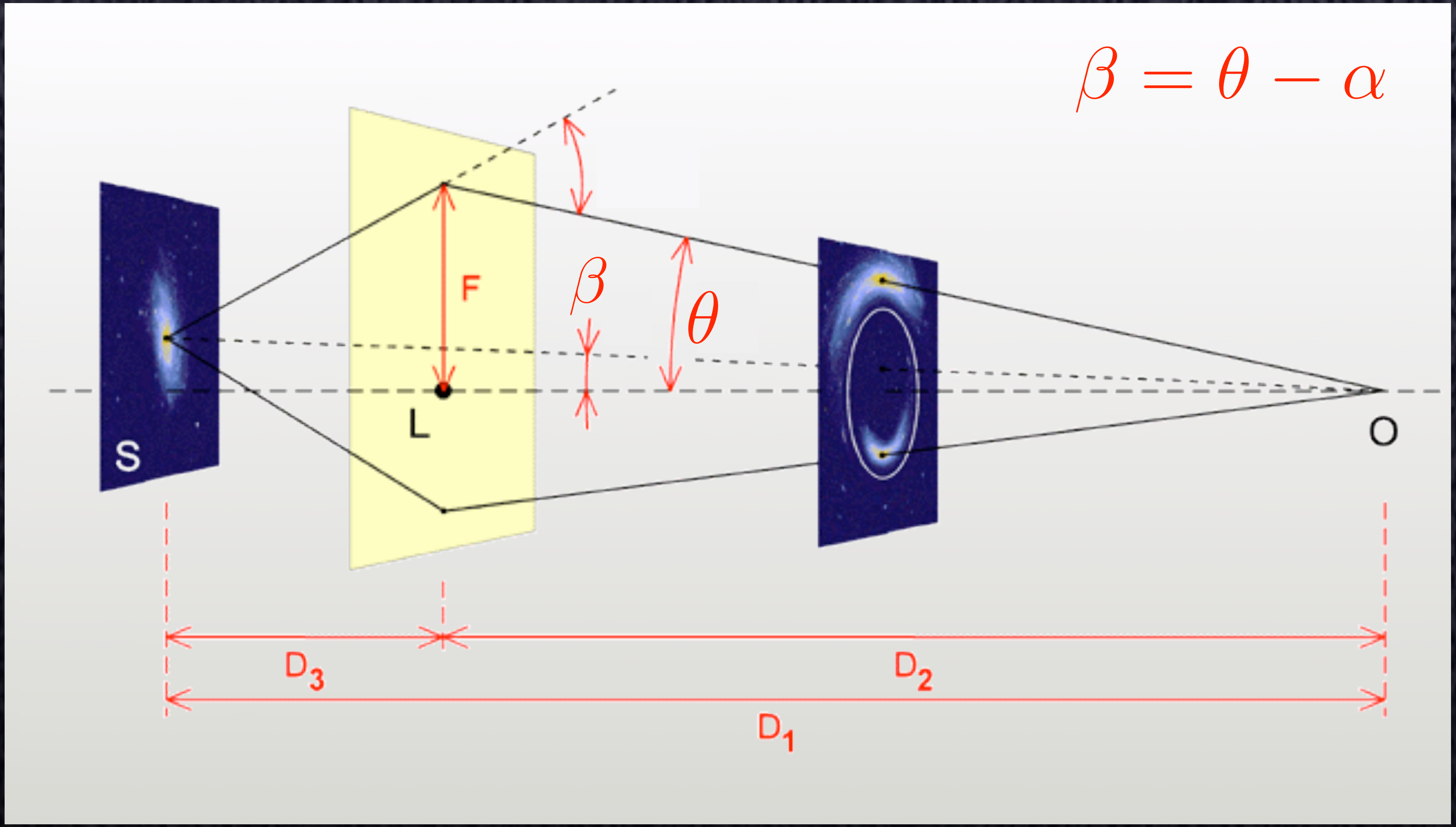
$M_{200} = (0.67 \pm 0.22) \times 10^{15}\ h^{-1} \mathrm{M}_\odot$

$$M_{200} = 200\rho_c$$

$$C = \frac{R_{200}}{R_s}$$

Corless & King 2008,2009

Gravitational Lensing



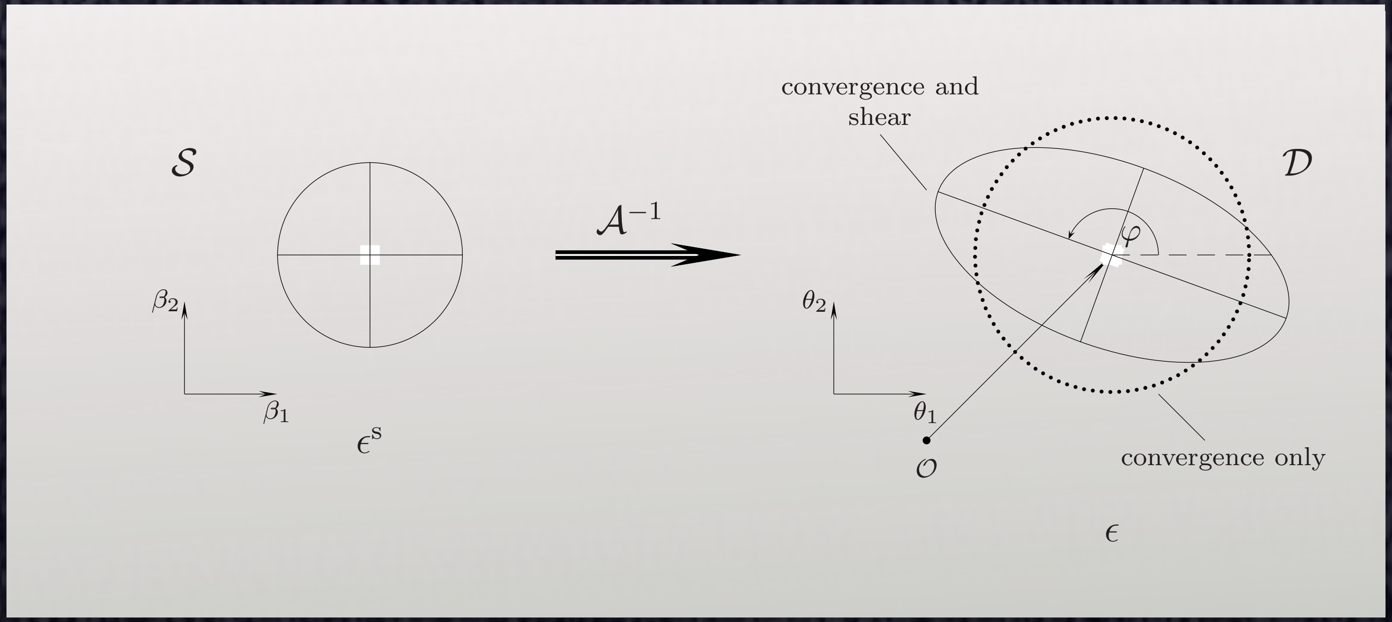
Dimension less surface mass density

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

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

Shape Distortions

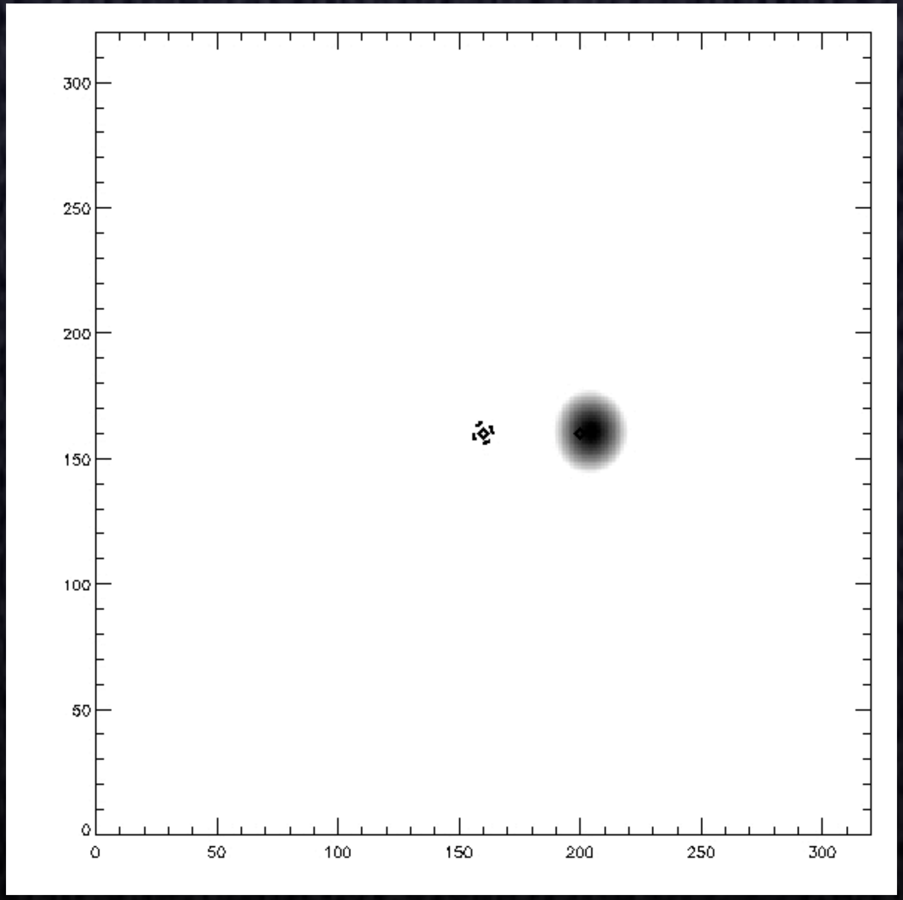
Critical Curves: det(A)=0



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

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

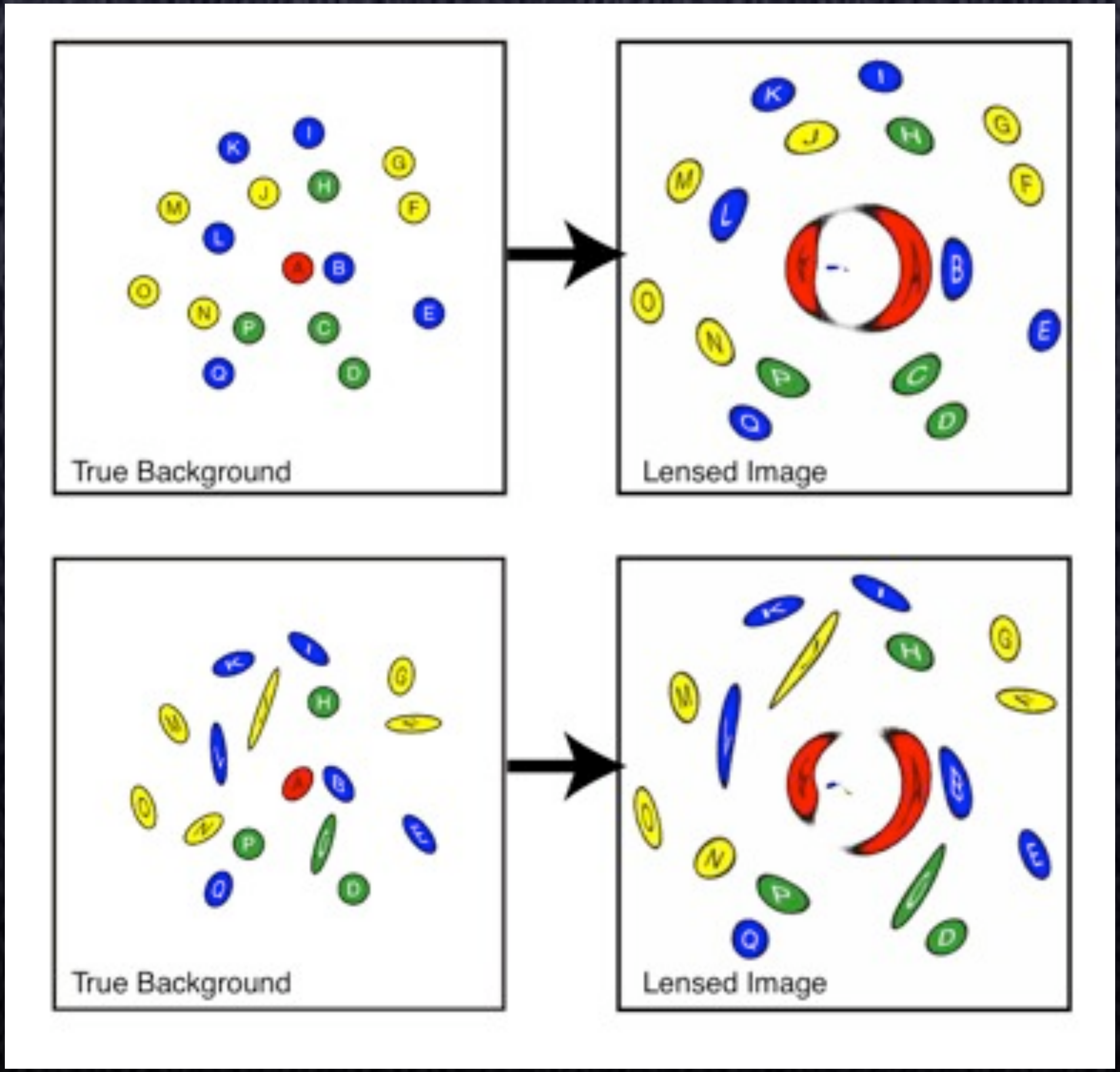
$$\gamma_2 = \psi_{,12}$$



Distortion Observables are Measured Ellipticities.

For semi-strong regime: $g = \gamma/(1-\kappa)$

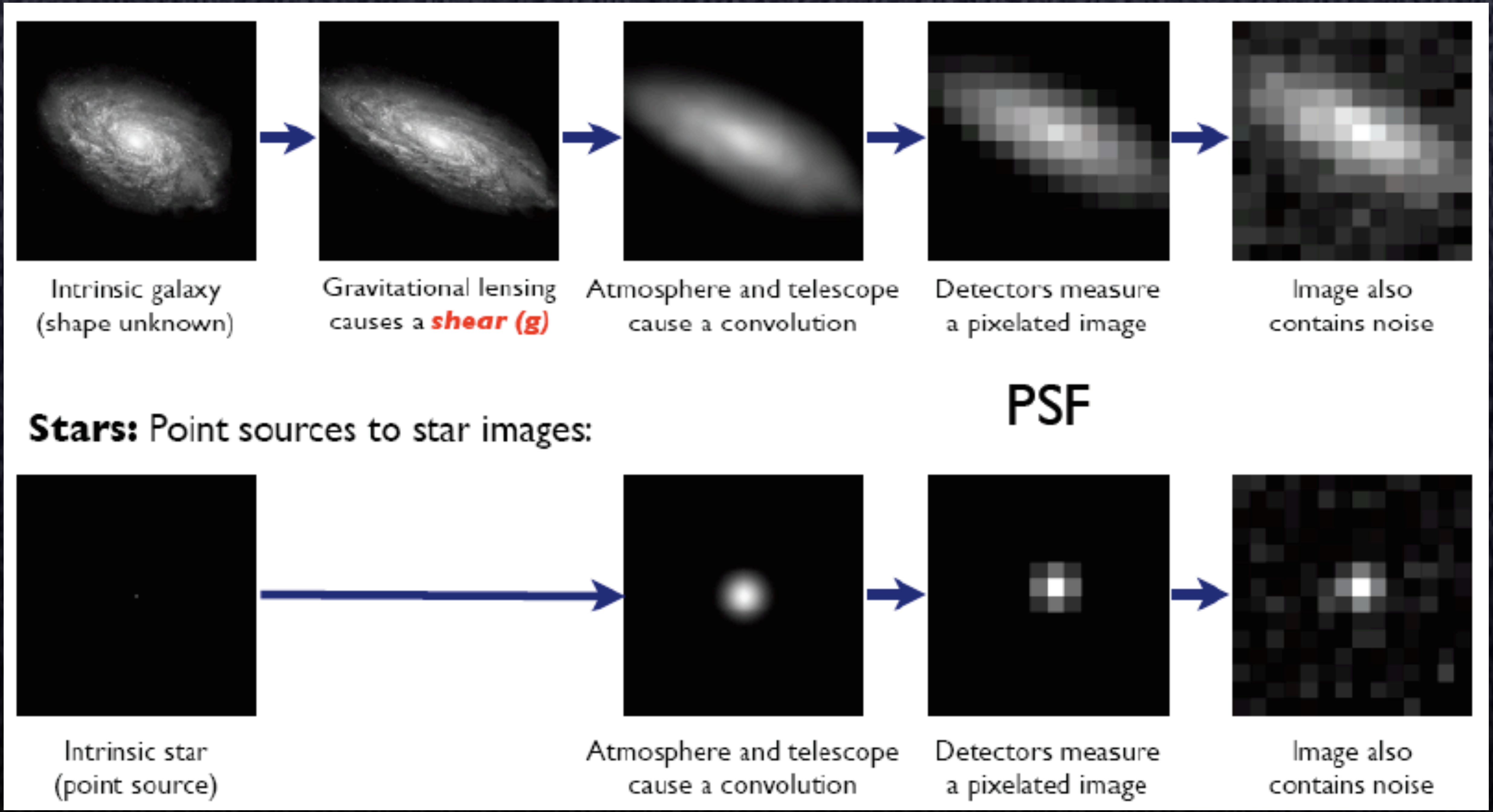
Weak Lensing



Williamson et al. 2007.

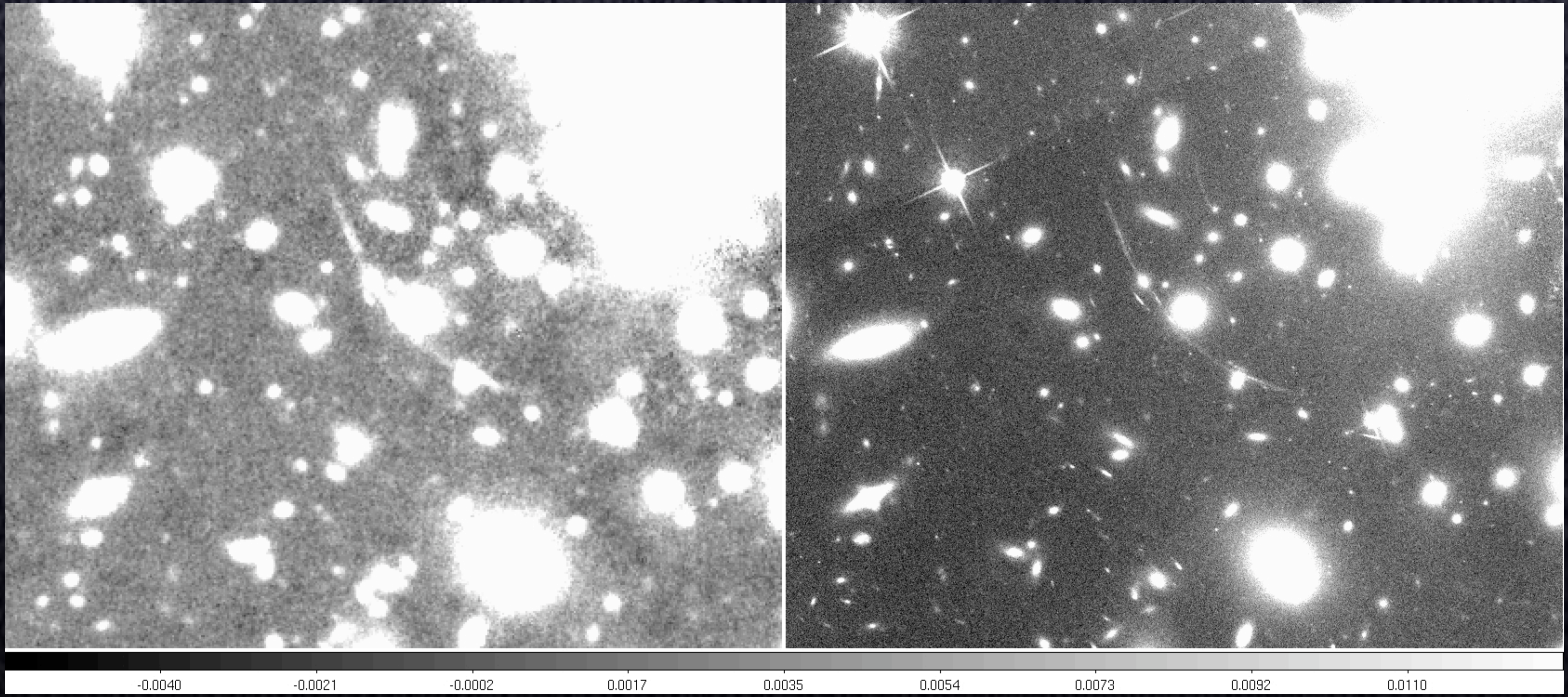
Weak lensing is a statistical measure of the distortion of background galaxies due to the intervening mass.

The shear signal

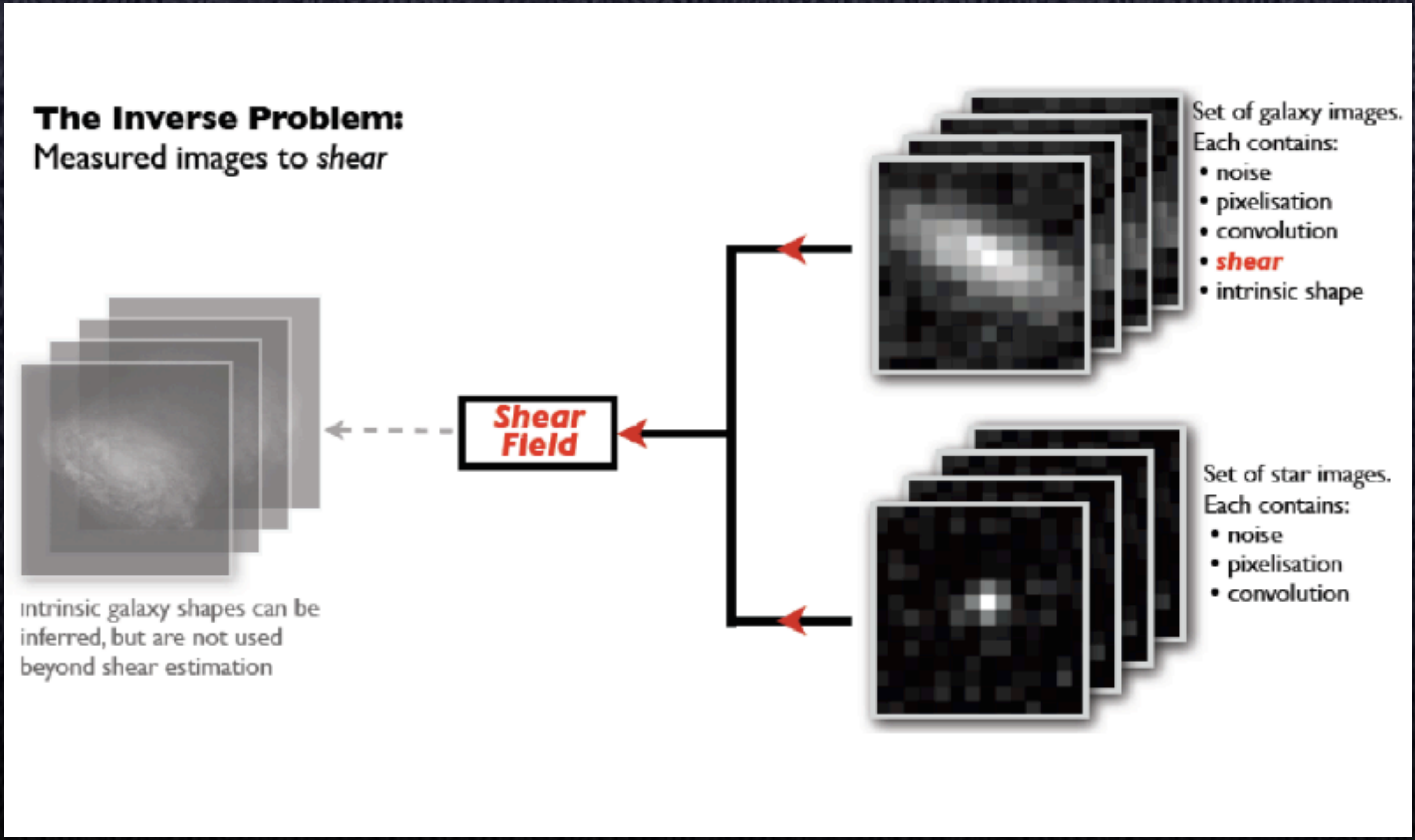


Catherine Heymans

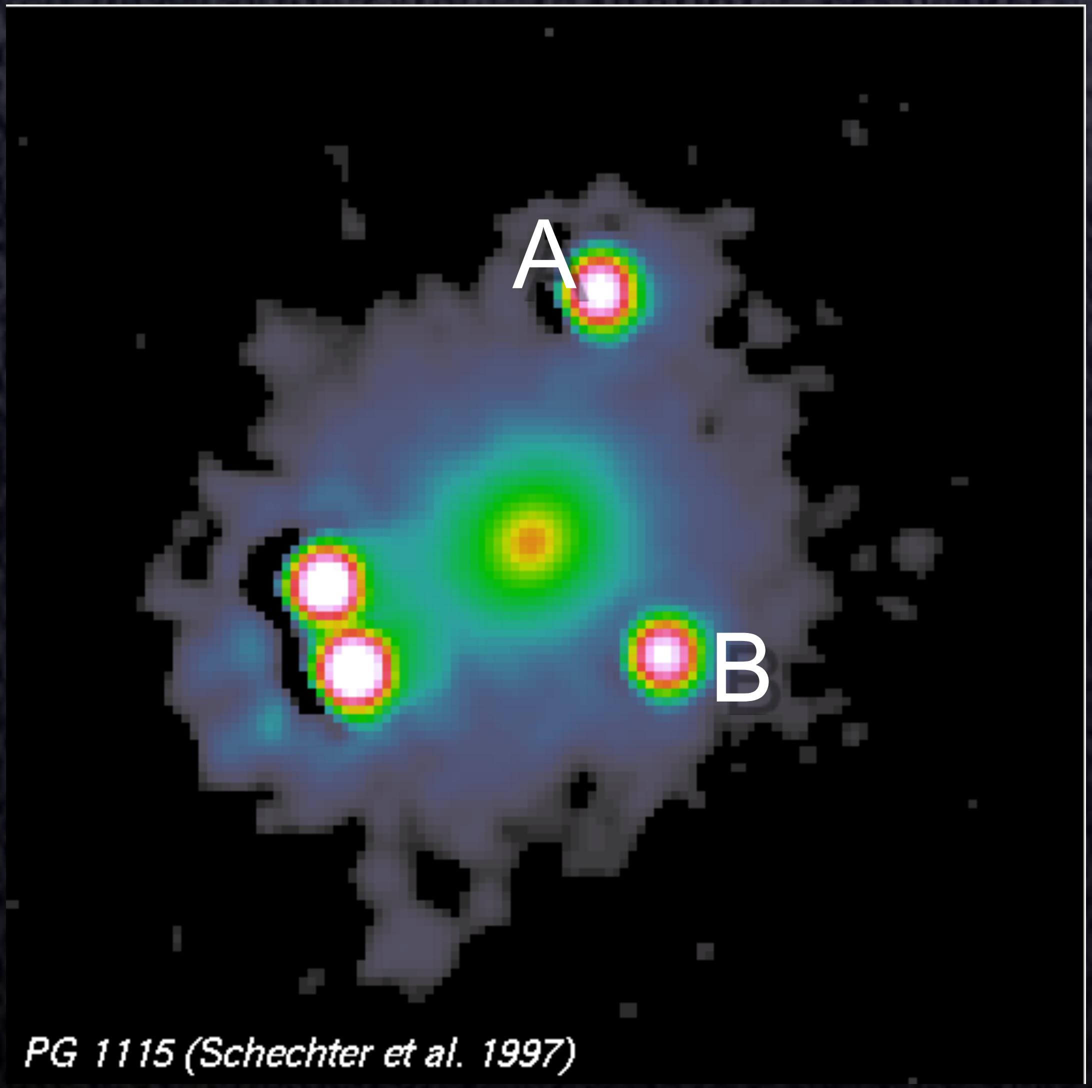
Comparison of Space vs Ground: A1689



Recovering the Shear



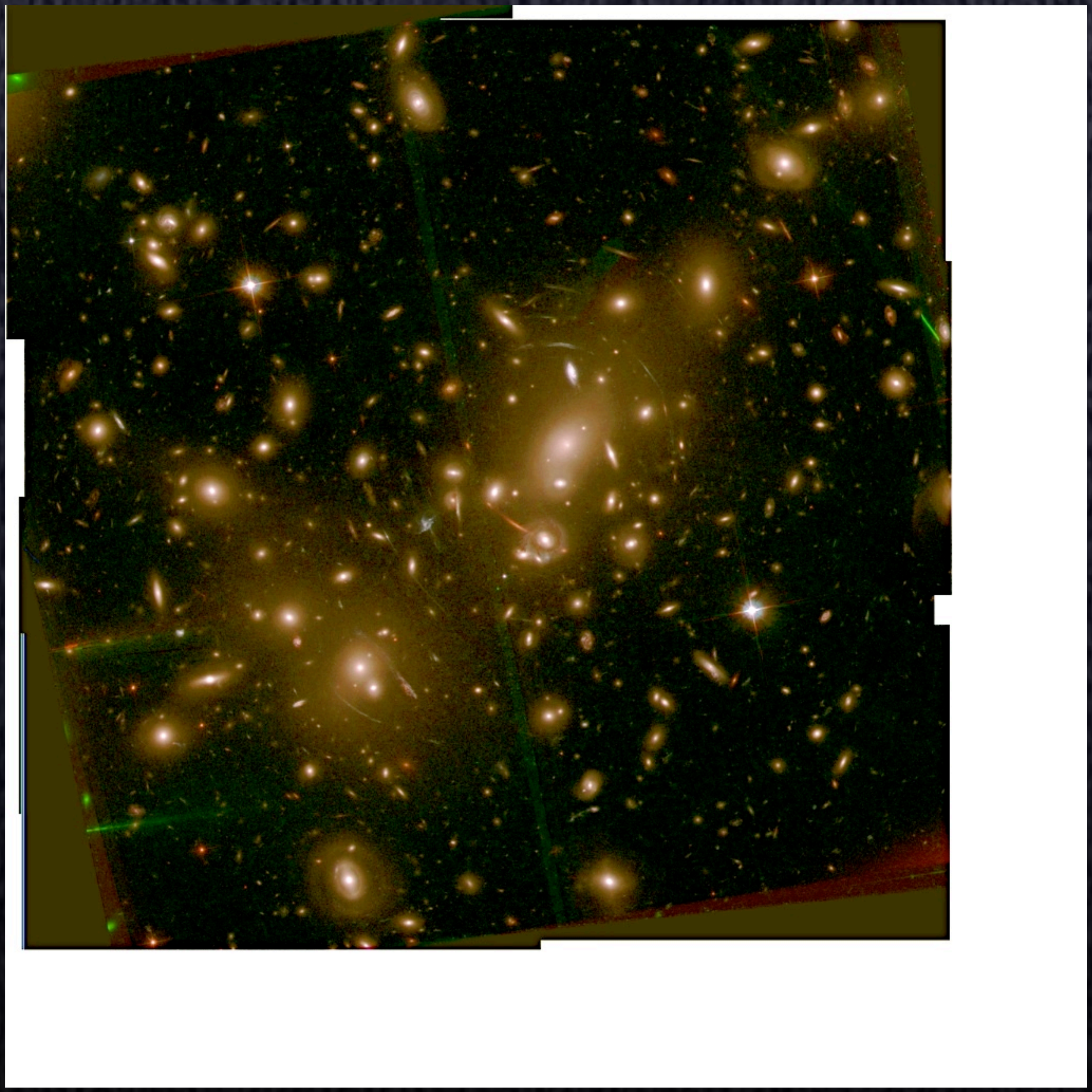
Strong Lensing



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

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

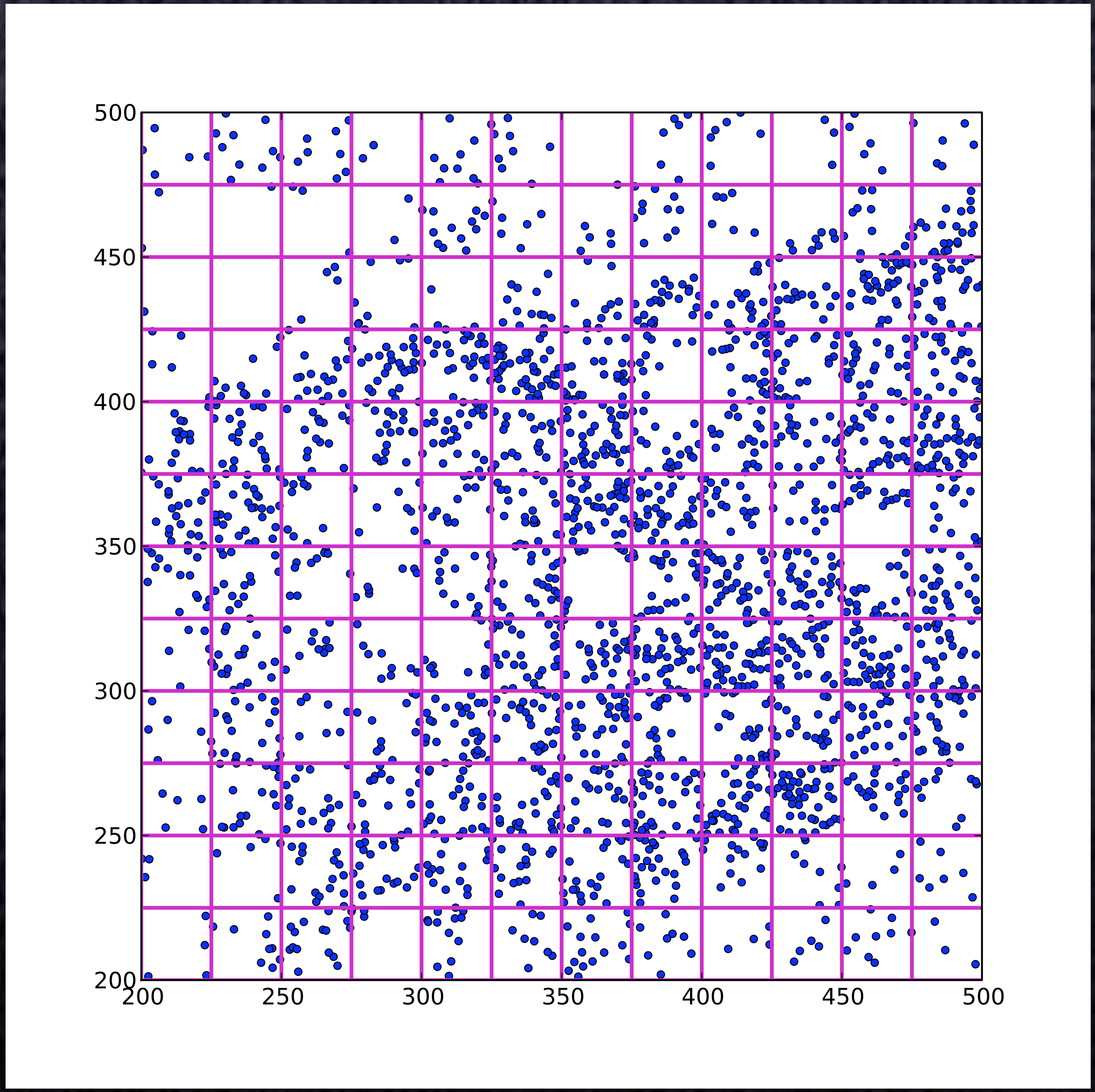
Parametric technique



Assumption: Light traces mass

- Place galaxy sized halos at the location of Cluster Members.
- Have one or more dark matter halos with free parameters that are fit from data.

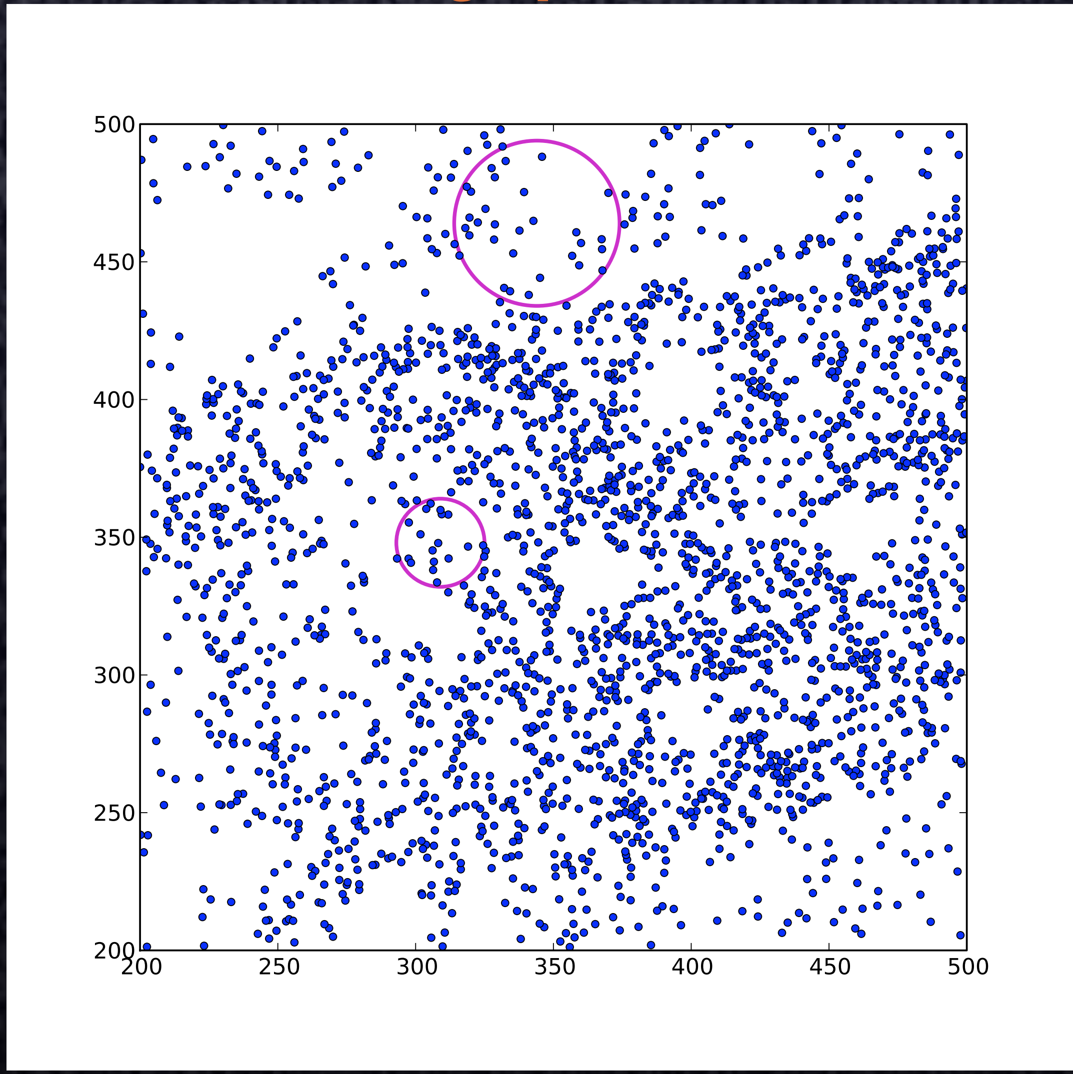
Grid Based Lensing

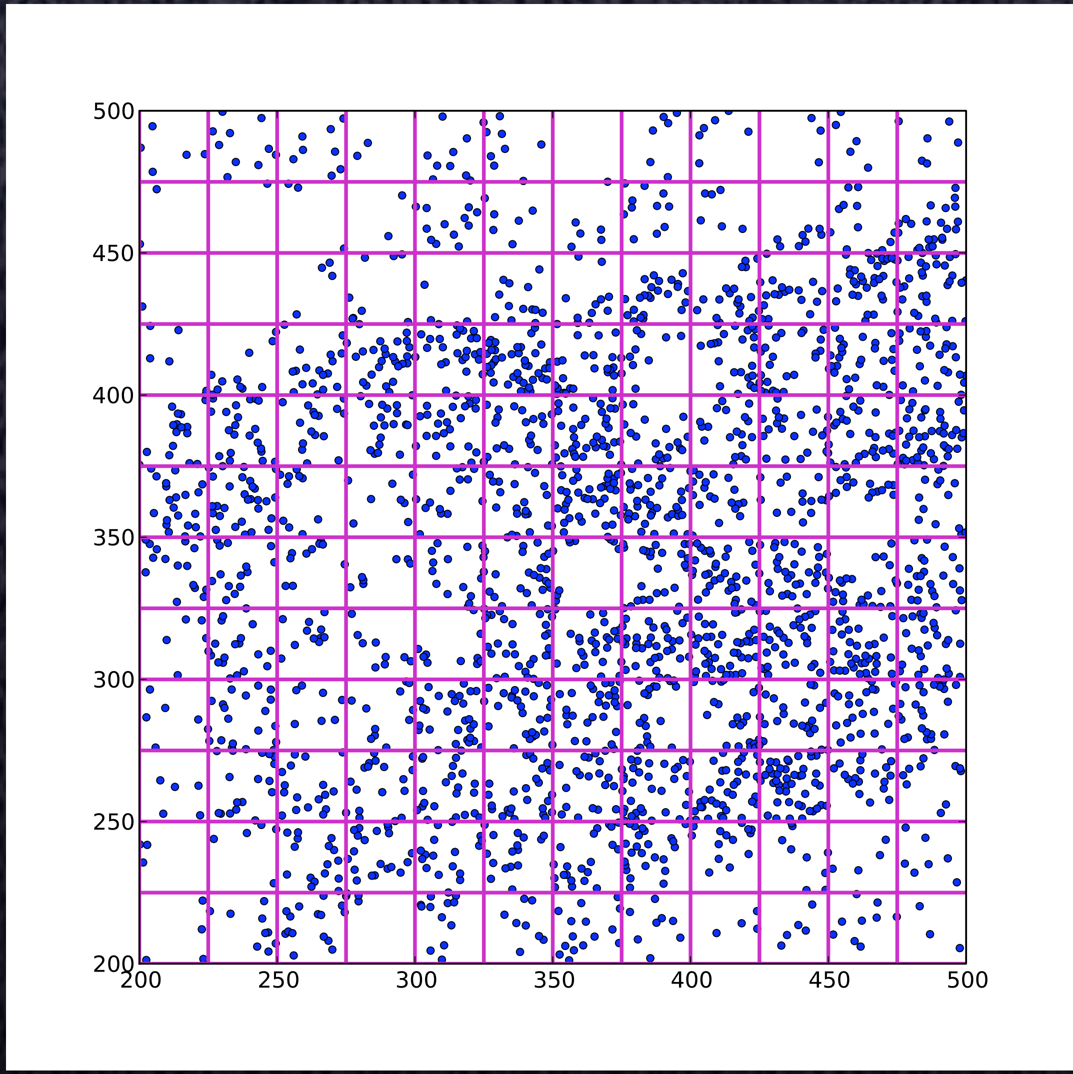


$$\langle \varepsilon \rangle = \gamma \xrightarrow{\text{Convolution}} \kappa$$

Particle Based Lensing

Particles-> lensed image positions

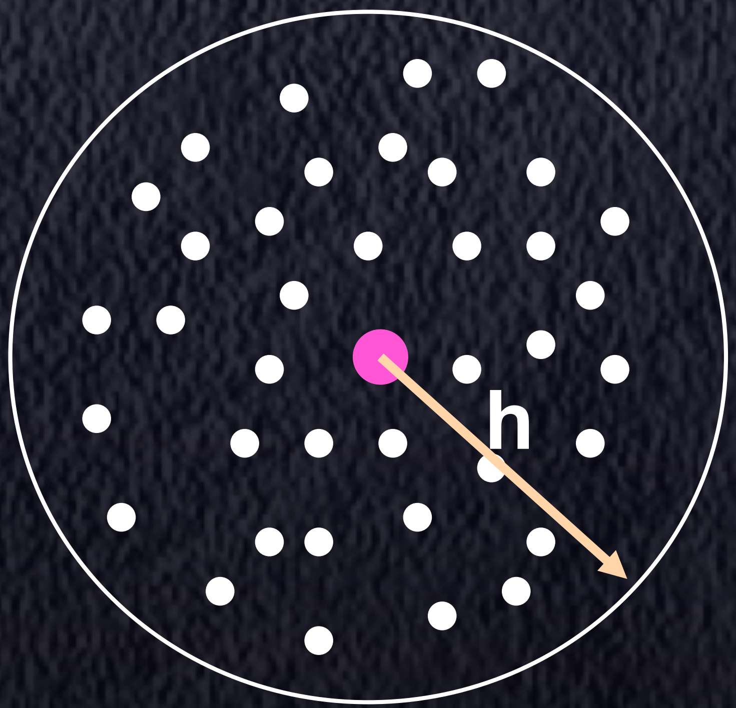




- Variable Resolution with the same complexity as finite differencing on a regular grid.
- No empty grid cells.

How does it work?

Taylor Expansion



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

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

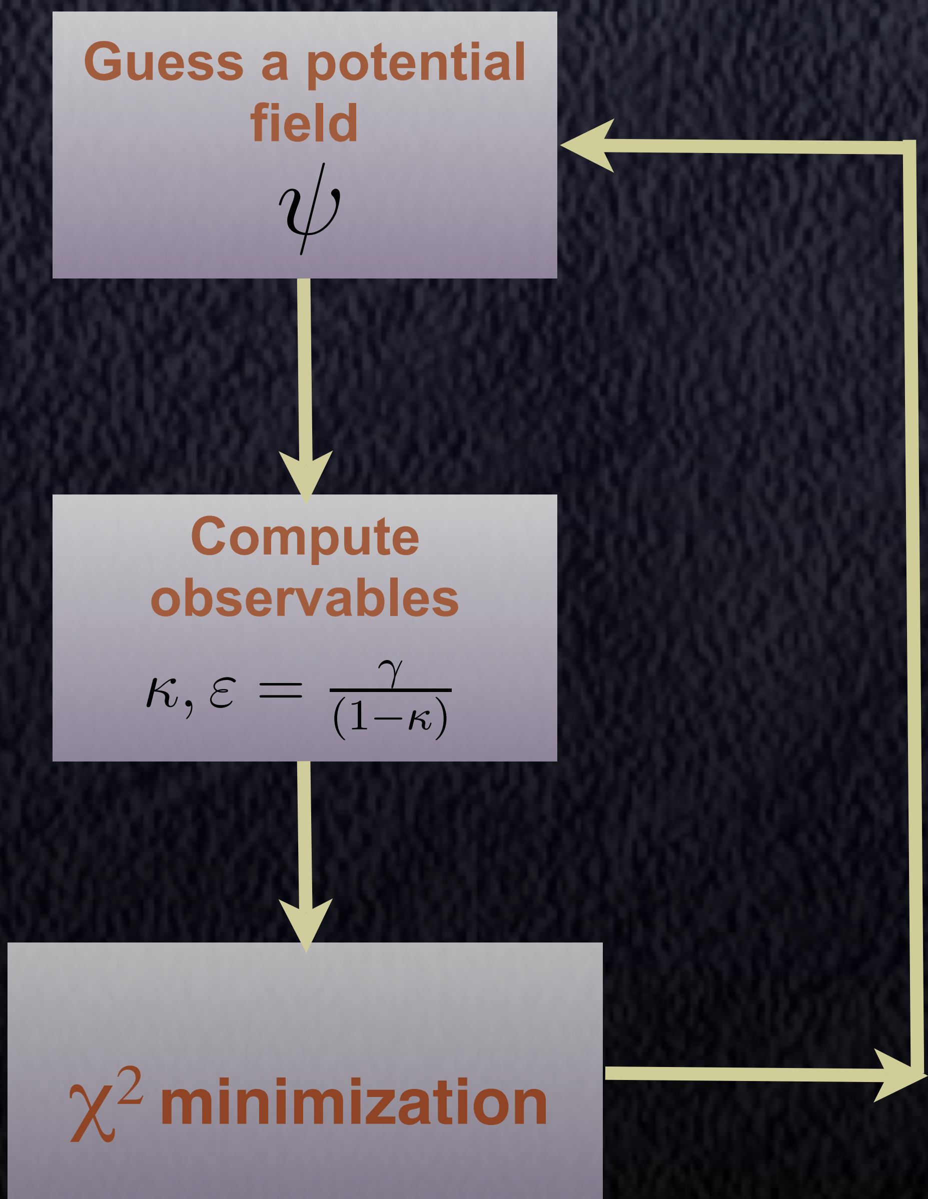
$$\psi_{n,jk} = D^{(jk)}_{nm}\psi_m$$

Similar to Finite Differencing on uniform grids

Reconstruction Procedure

Keep Iterating ...

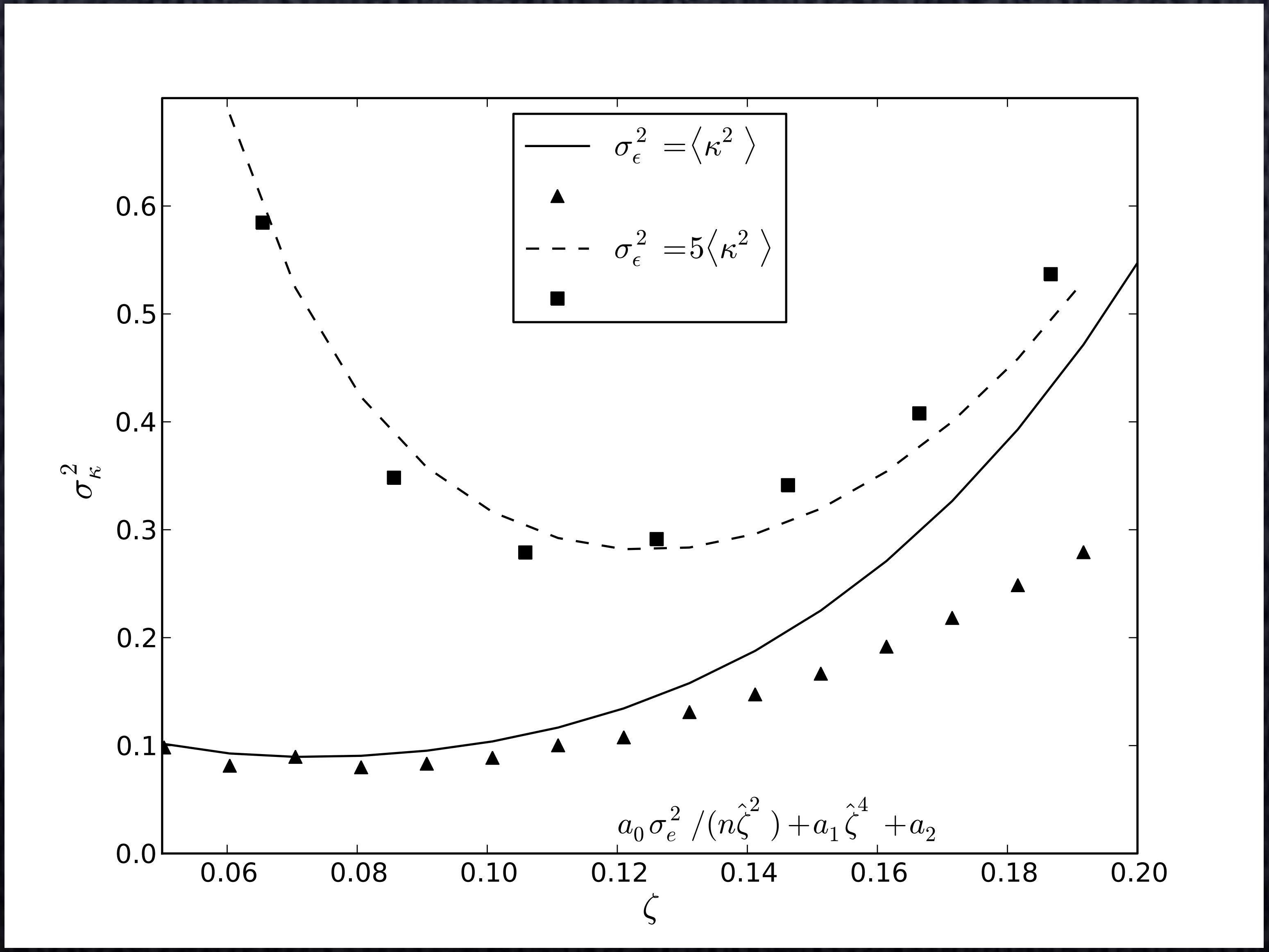
$$\chi^2_{\text{weak}} = \sum_i \frac{\left[\varepsilon_i - \frac{\gamma_i}{(1-\kappa_i)}\right]^2}{\sigma_i^2}$$



In case of weak lensing, a χ^2_{w} like this will fit best to noisy data

Smoothing the ellipticity field before minimization and using the full covariance matrix in the minimization

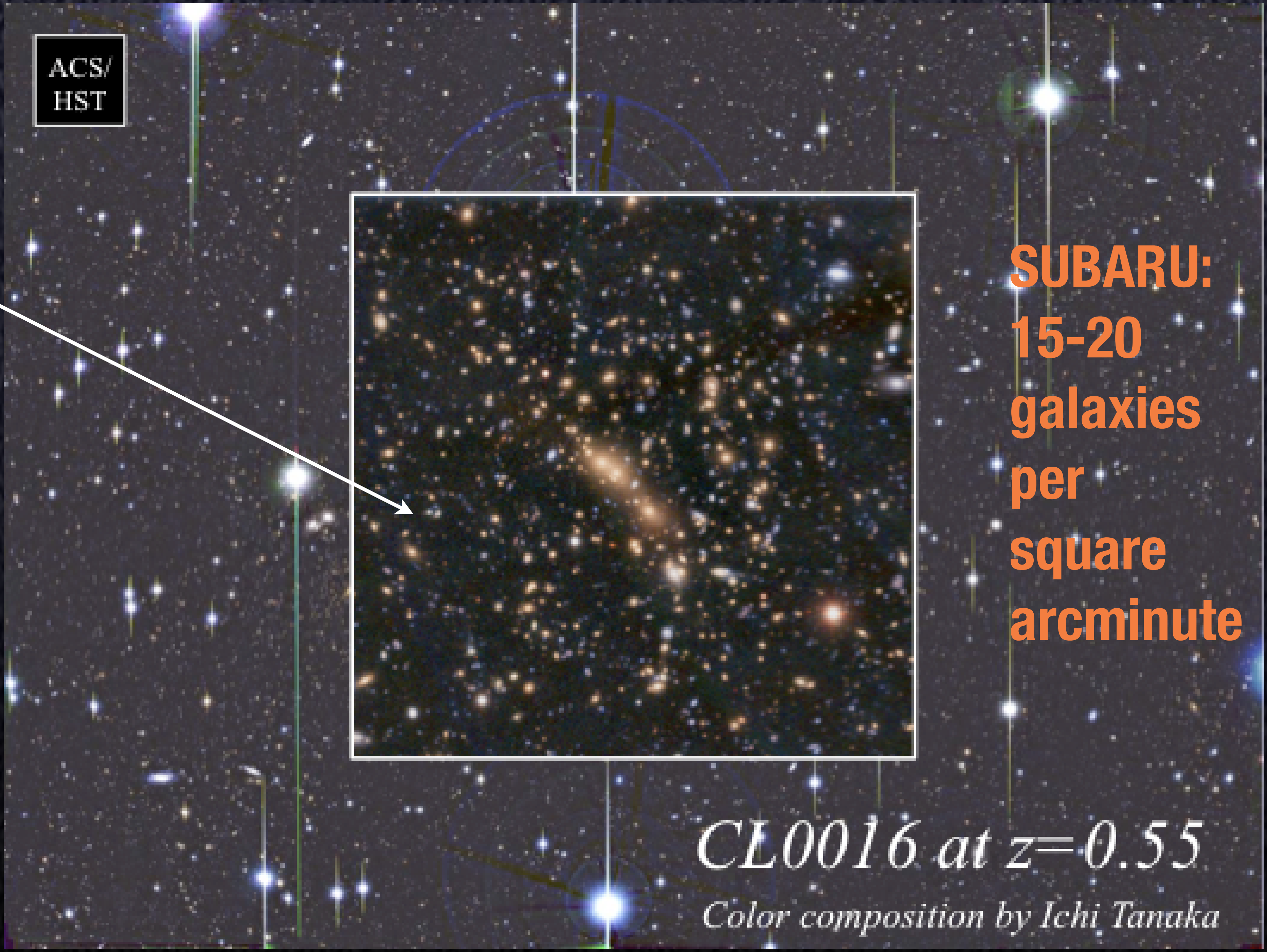
Choice of smoothing scale



$$\sigma_\kappa^2 = A_0\left(\frac{\zeta}{\lambda}\right)^4 + B_0\frac{\sigma_\varepsilon^2/\langle\kappa^2\rangle}{(\zeta)^2 n} + C_0$$

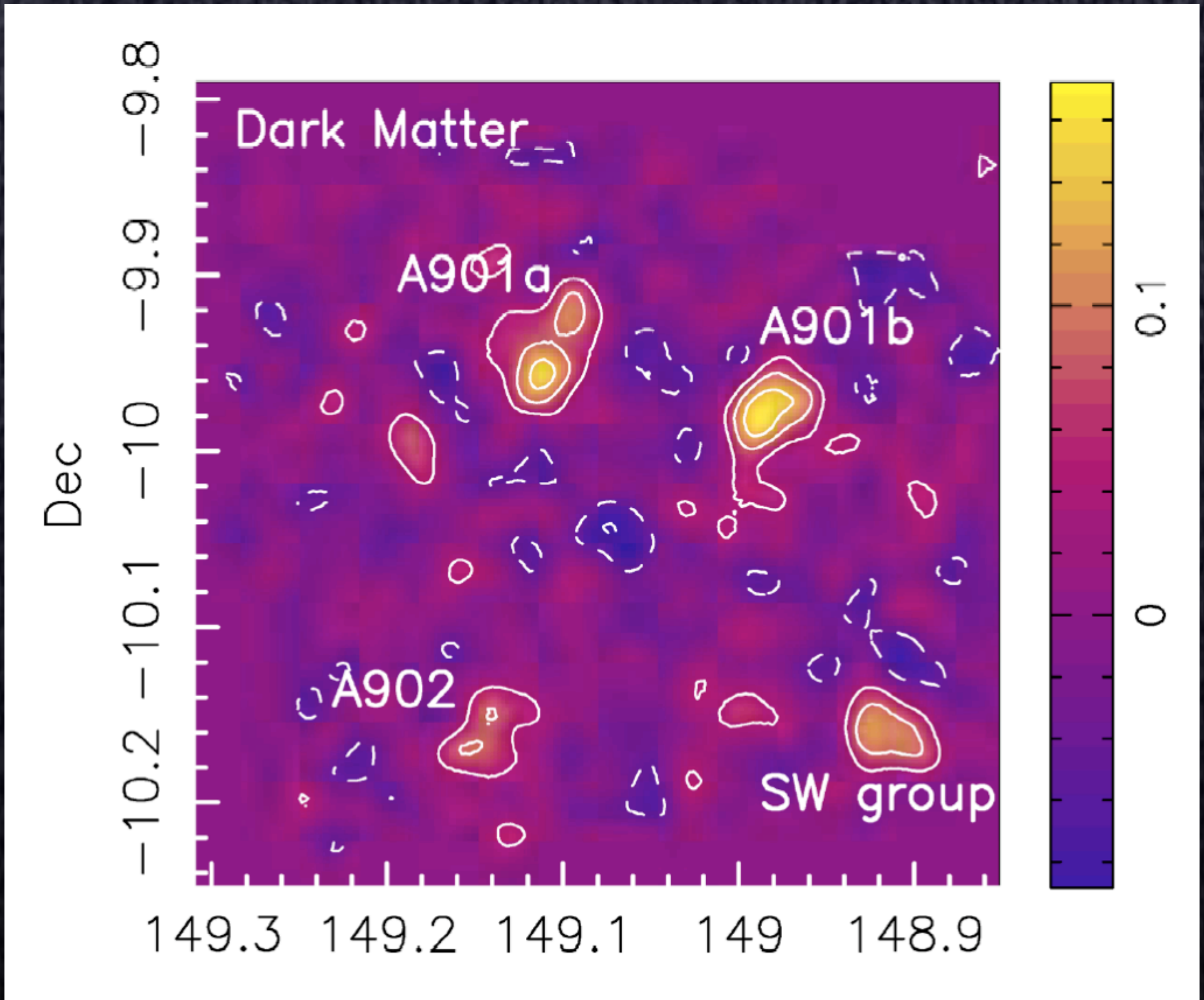
Heterogeneous Datasets

HST: 50-60 galaxies per square arcminute



SUBARU: 15-20 galaxies per square arcminute

Abell 901/902

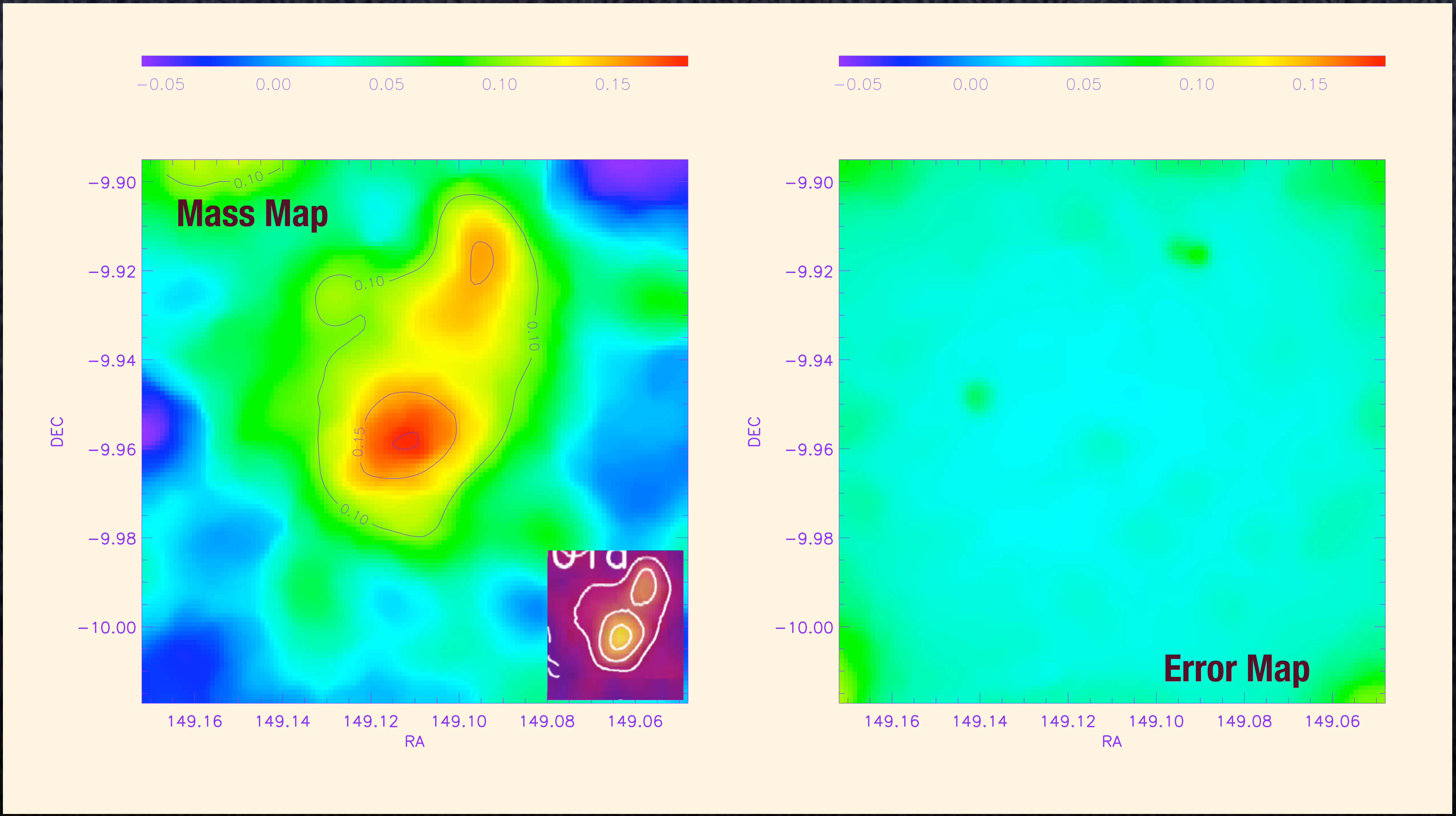


Heymans et. al. 2008.

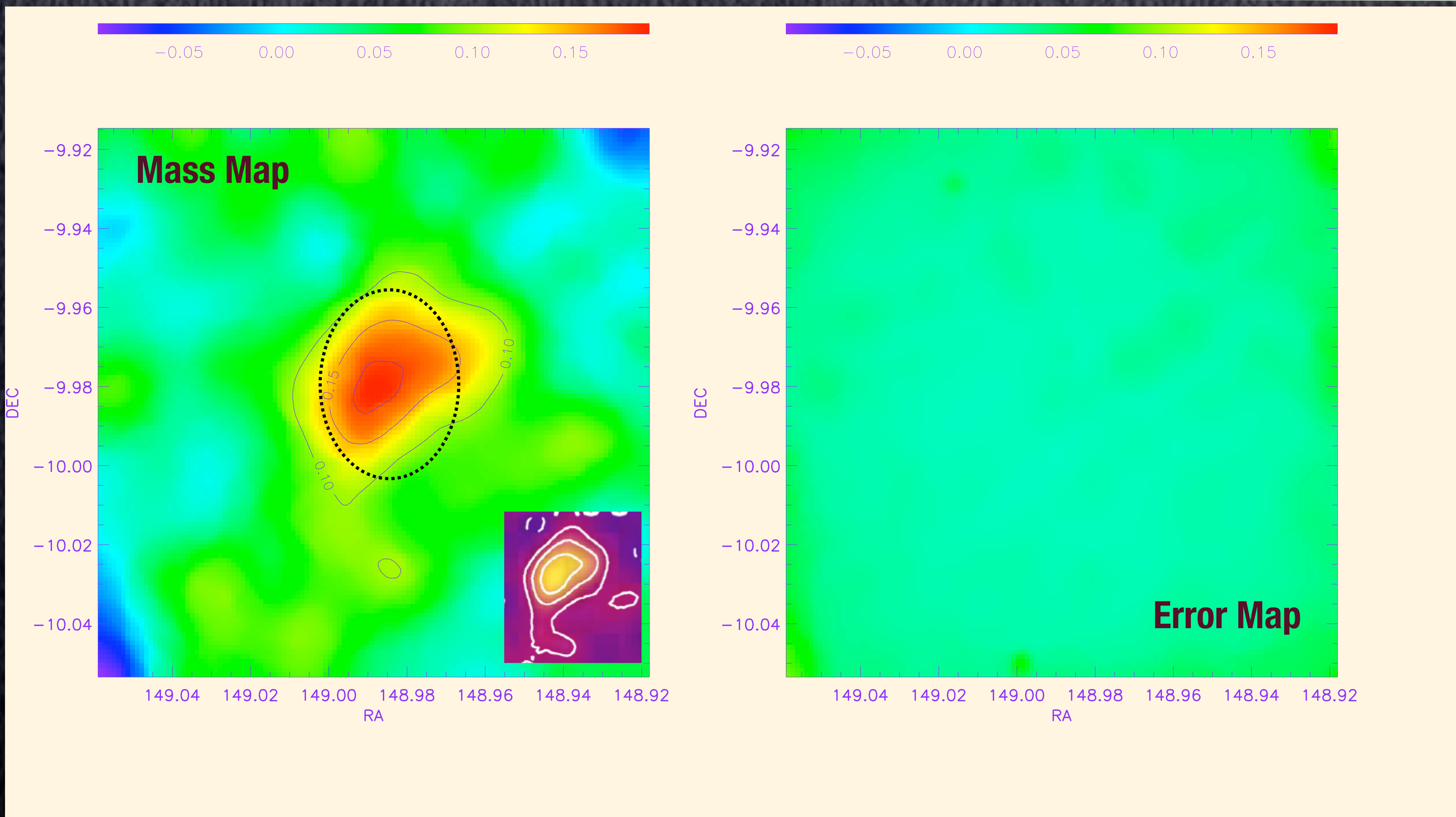
0.5 degree^2 fov
STAGES HST survey
60,000 background images.

A901a

From Deb et al. 2009



A901b

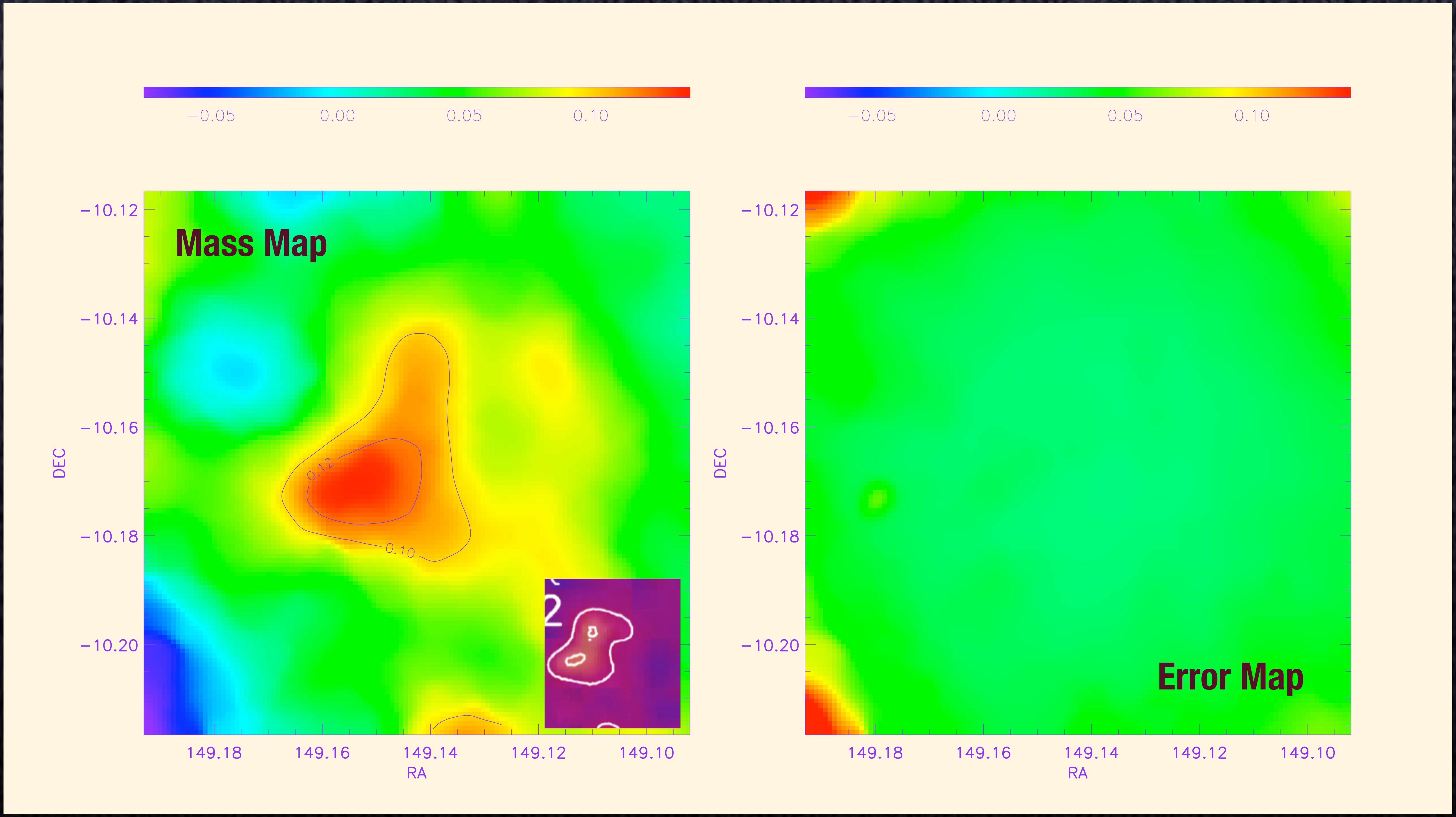


From Deb et al. 2009

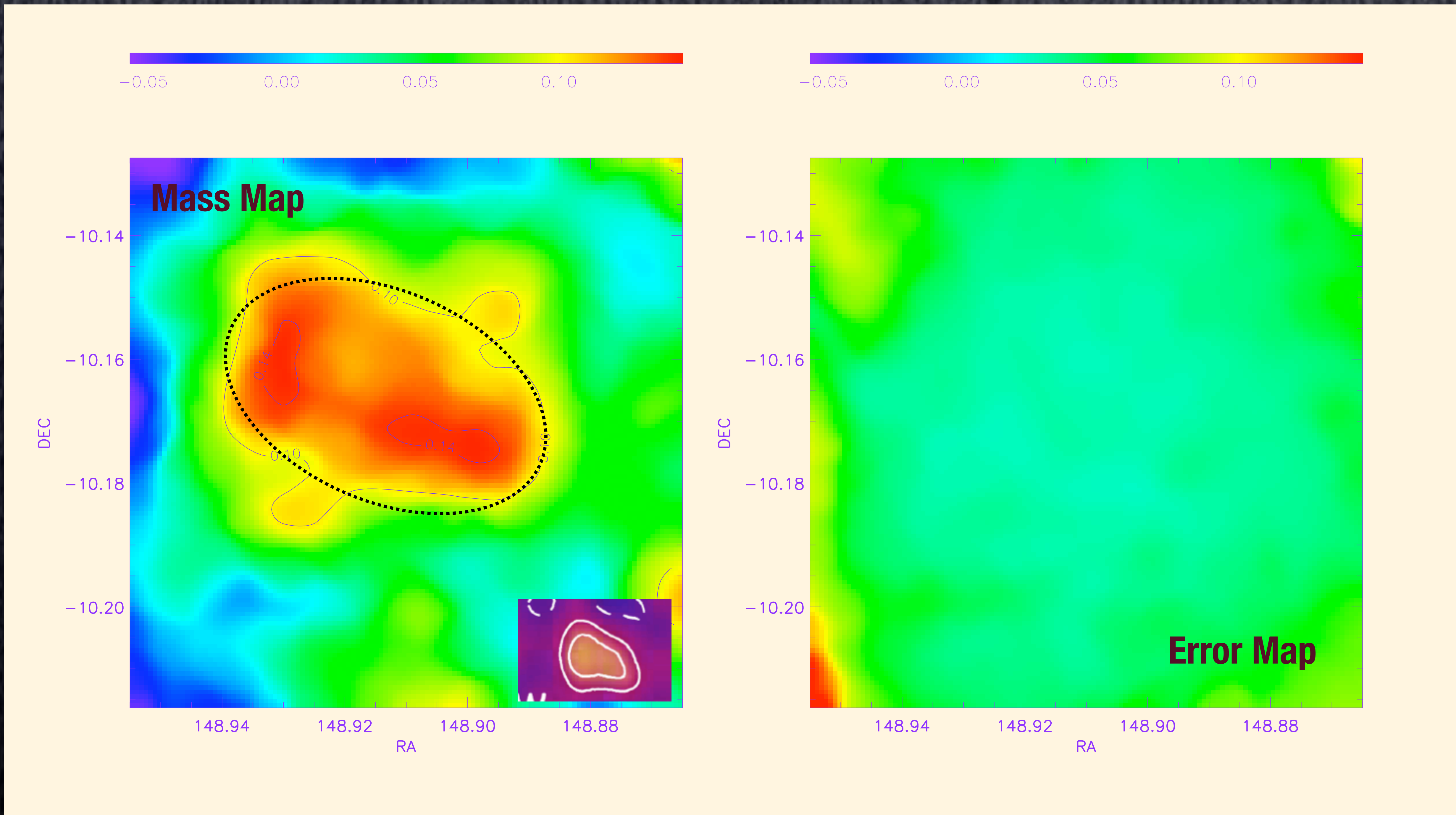
	Axis Ratio	Position angle
Non-Parametric:	$0.37^{+0.1}_{-0.1}$	$91.4^{+8.2}_{-8.2}$
Parametric:	$0.437^{+0.1}_{-0.087}$	$90.0^{+2.25}_{-2.25}$

A902

From Deb et al. 2009



Southwest Group

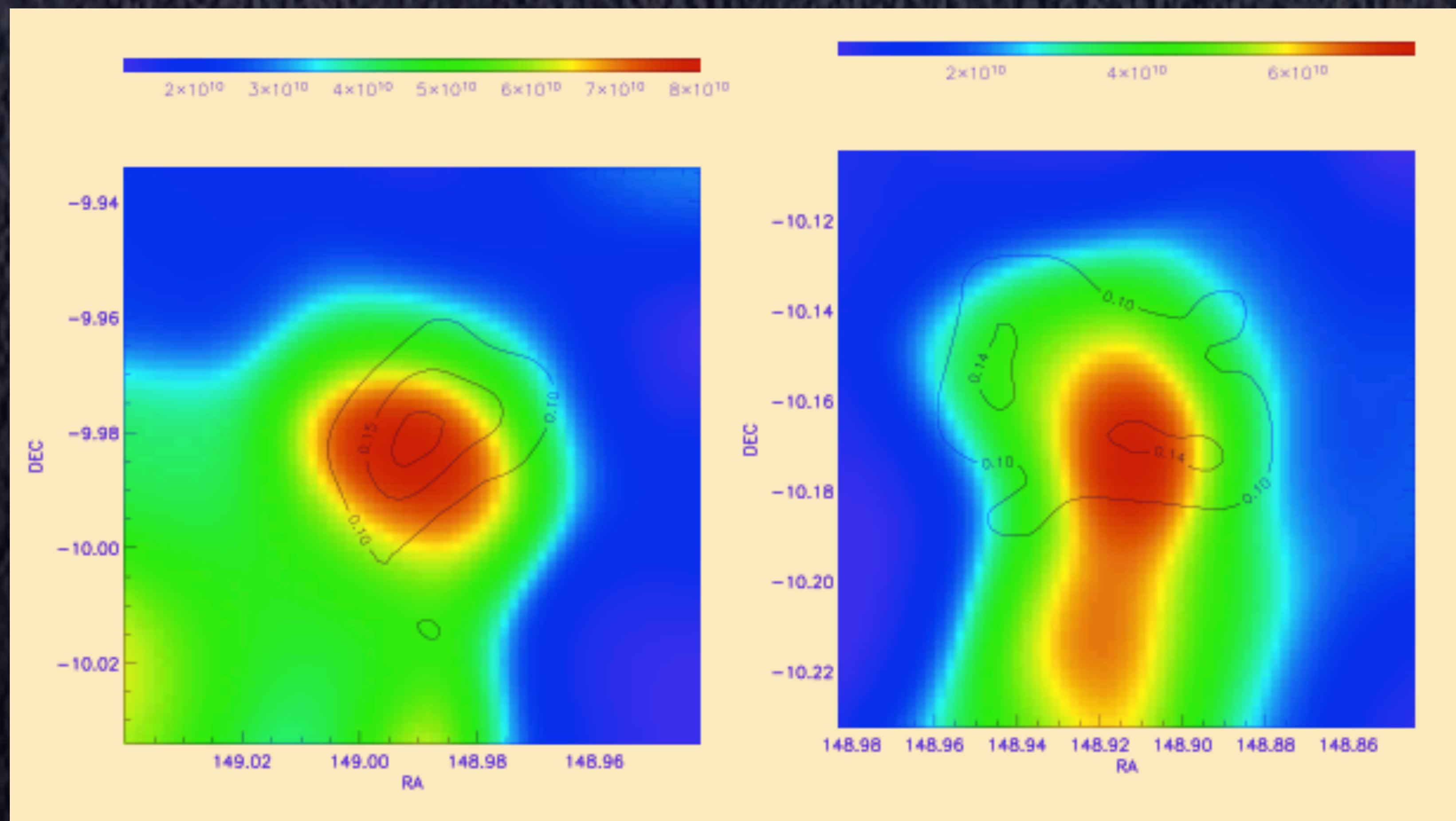


From Deb et al. 2009

	Axis Ratio	Position angle
Non-Parametric:	$0.54^{+0.08}_{-0.09}$	$120.0^{+4.8}_{-4.8}$
Parametric:	$0.42^{+0.18}_{-0.12}$	$180.0^{+7.73}_{-5.15}$

Dark Matter vs Light

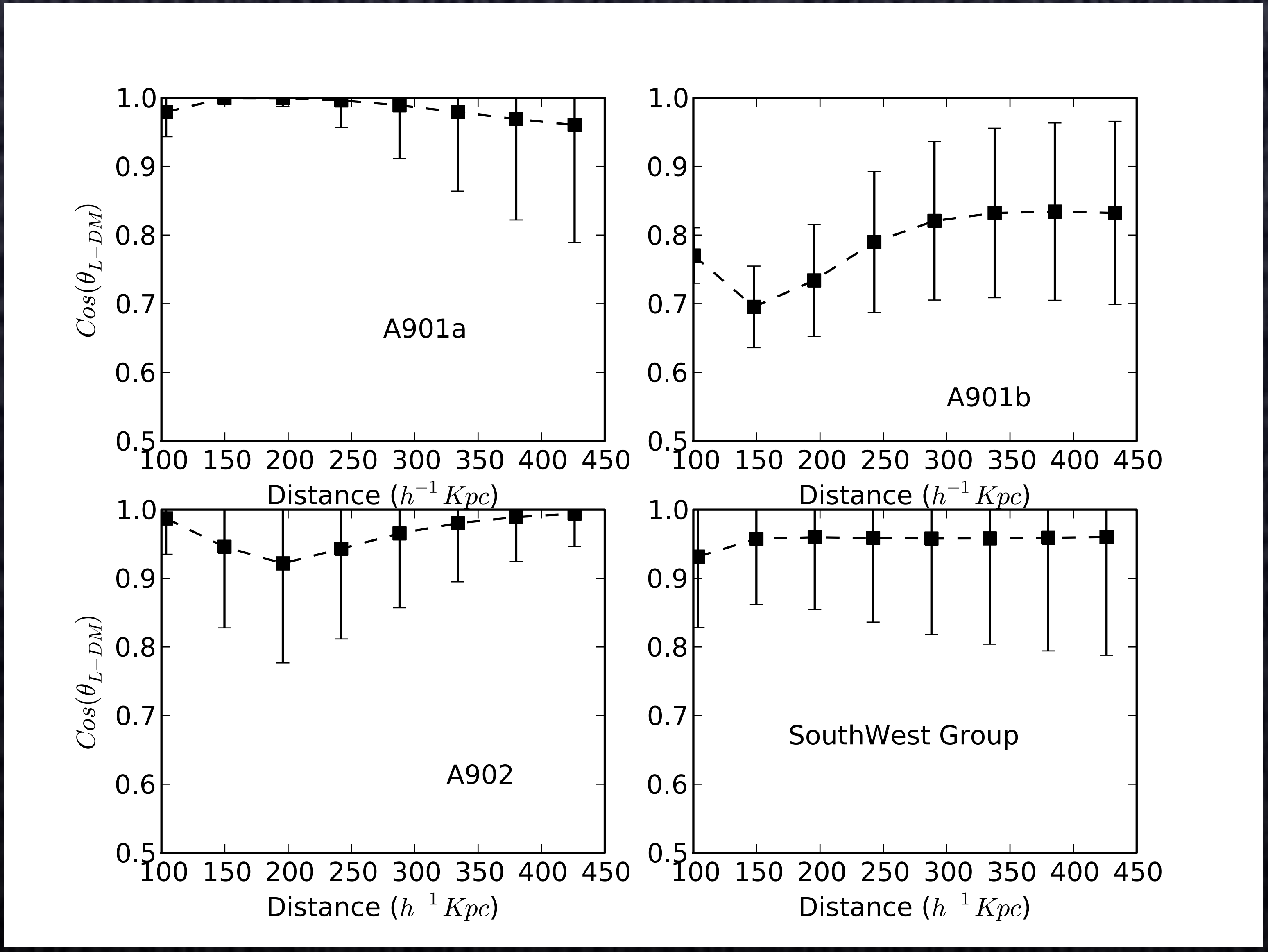
From Deb et al. 2009



Peak		f	α(degrees)
		Dark Matter: Non-parametric	
A901b	–	$0.37^{+0.1}_{-0.1}$	$91.4^{+8.2}_{-8.2}$
SW group	–	$0.54^{+0.08}_{-0.09}$	$120.0^{+4.8}_{-4.8}$
		Light Distribution	
A901b	–	$0.58^{+0.1}_{-0.09}$	$121.5^{+12.0}_{-12.0}$
SW group	–	$0.69^{+0.06}_{-0.05}$	$100.0^{+10.0}_{-10.0}$

Alignment between Light and Dark Matter

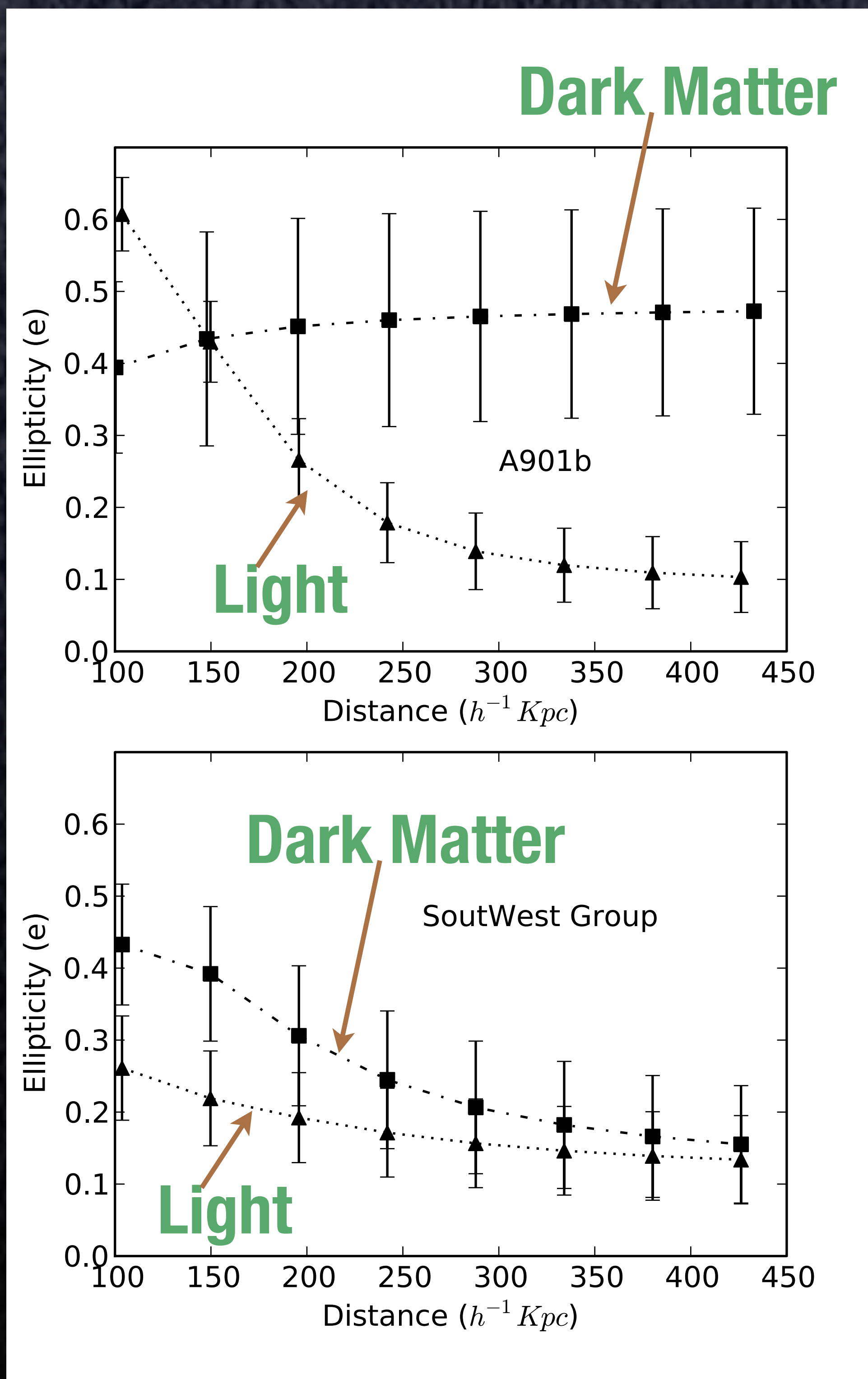
From Deb et al. 2009



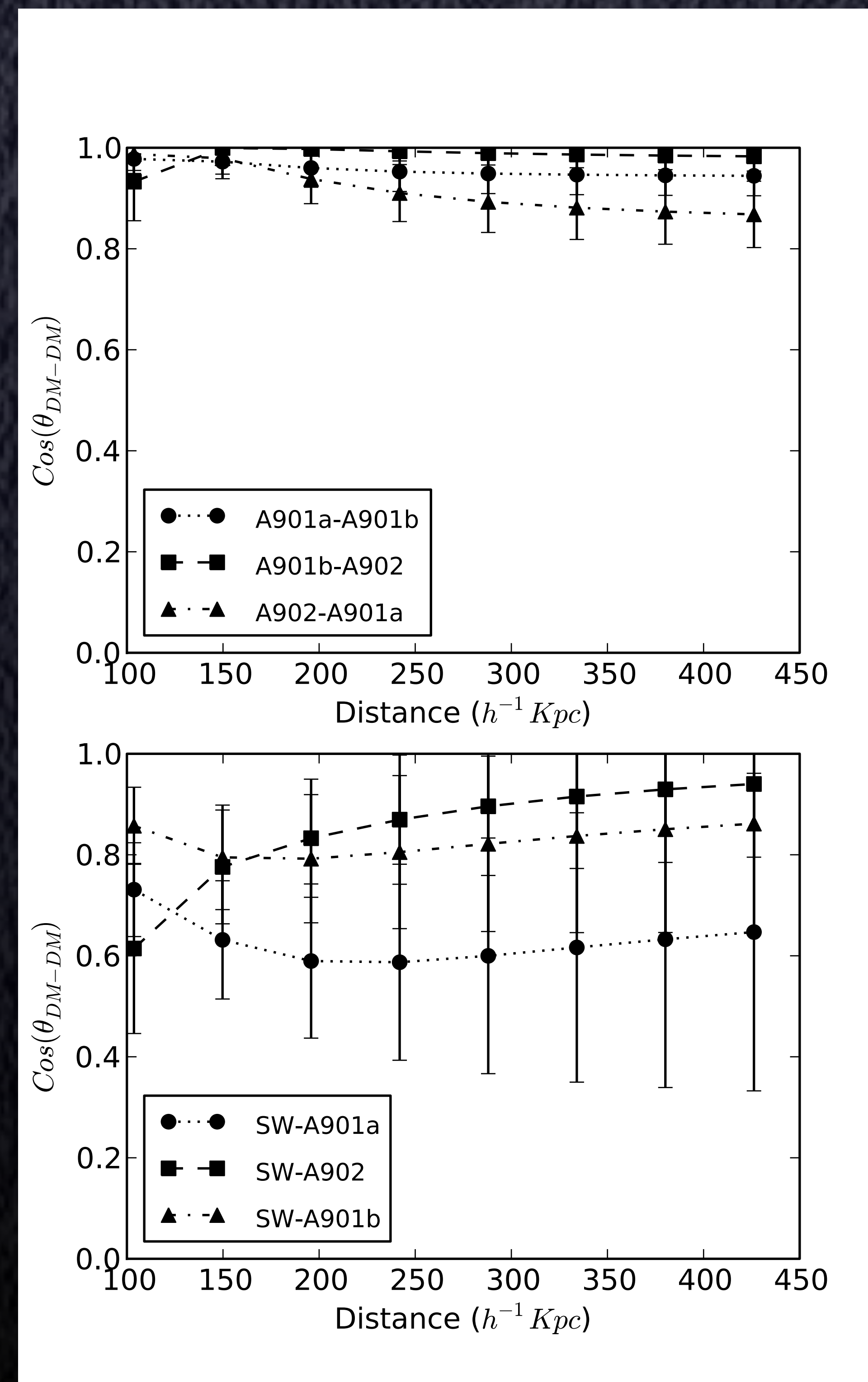
Radial dependence

From Deb et al. 2009

Ellipticity

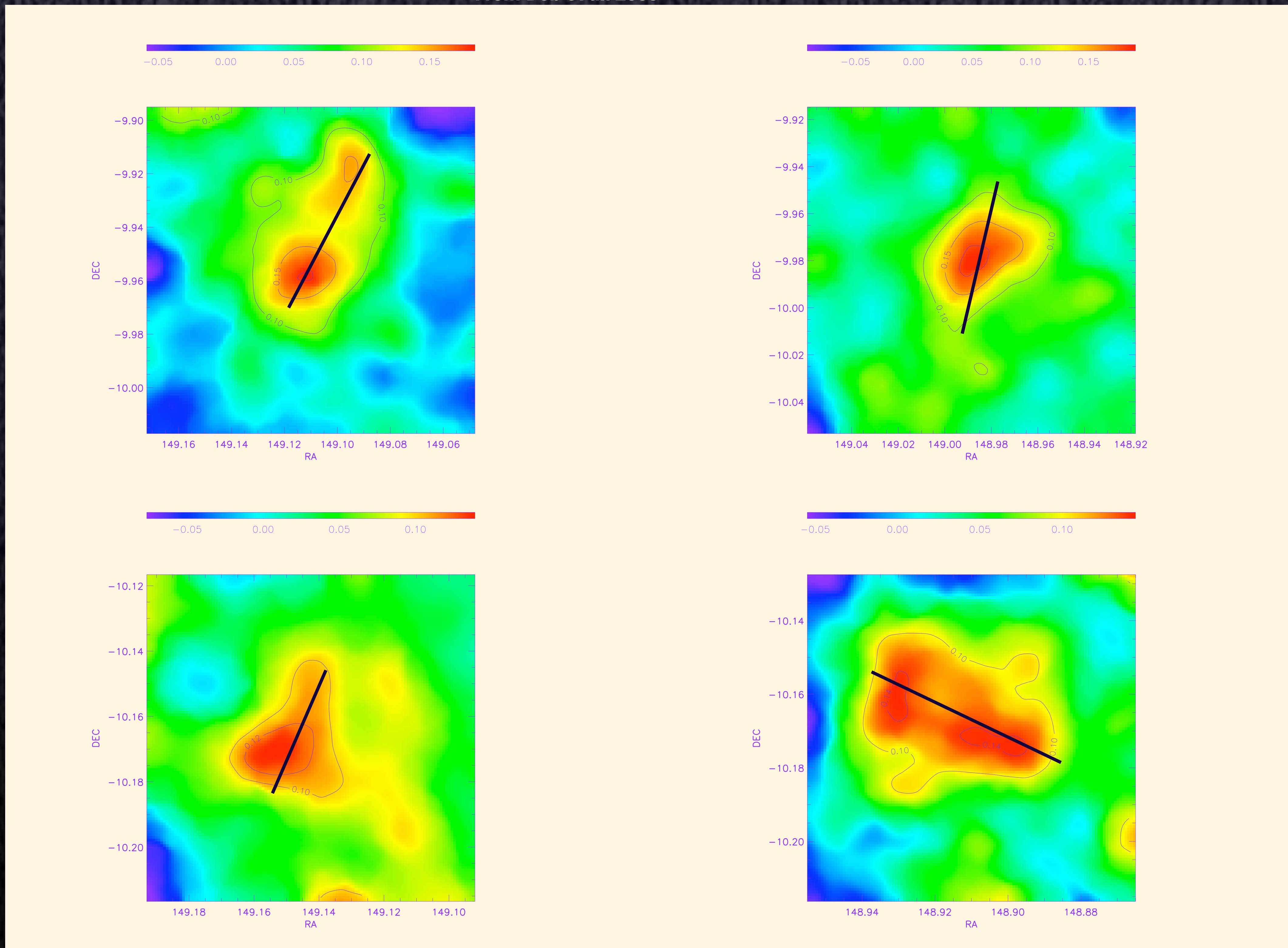


Alignment



Alignment

From Deb et al. 2009



Reconstruction Methods

Parametric:

Strong Lensing

GRAVLENS - Keeton et al., 2001

LENSTOOL - Jullo et al., 2007

Galaxy-Galaxy Lensing

Natarajan et al. 2005

Hybrid

LENSTOOL - Jullo et al., 2009

Non-Parametric

Strong Lensing

Jullo & Kneib 2009,

LENSPERFECT -Coe et al, 2008,2010 (Mesh Free)

Weak Lensing

Kaiser 1995, Seitz & Schneider 1995-2001

Strong+Weak Lensing

Finite Differencing Based

Bradac et al. 2004,

(ADAPTIVE) - Diego et al. , Cacciato et al.

Merten et al., Saha et. al. Pixelens

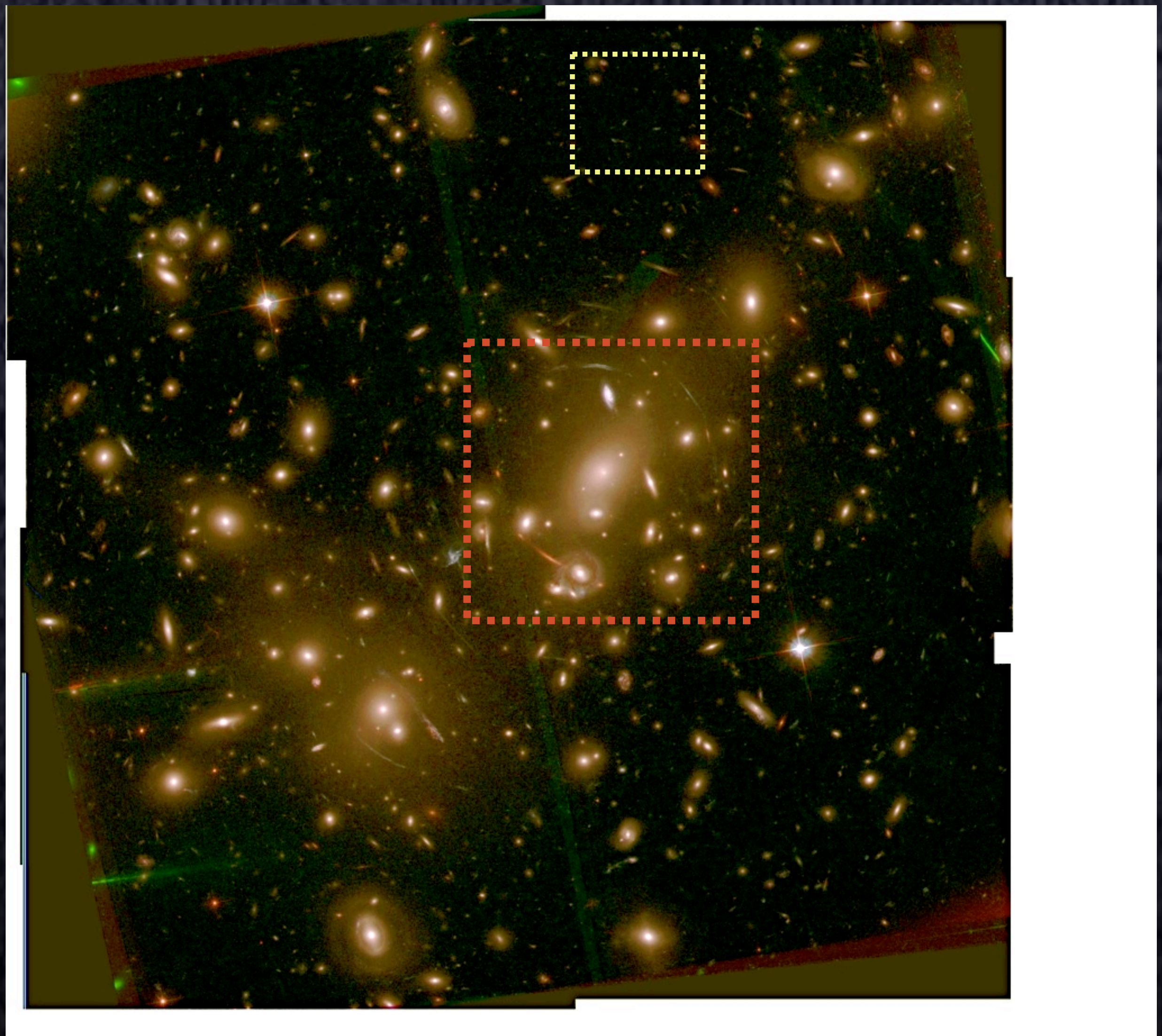
and more ....

Mesh-Free Technique

Particle Based Lensing (PBL)

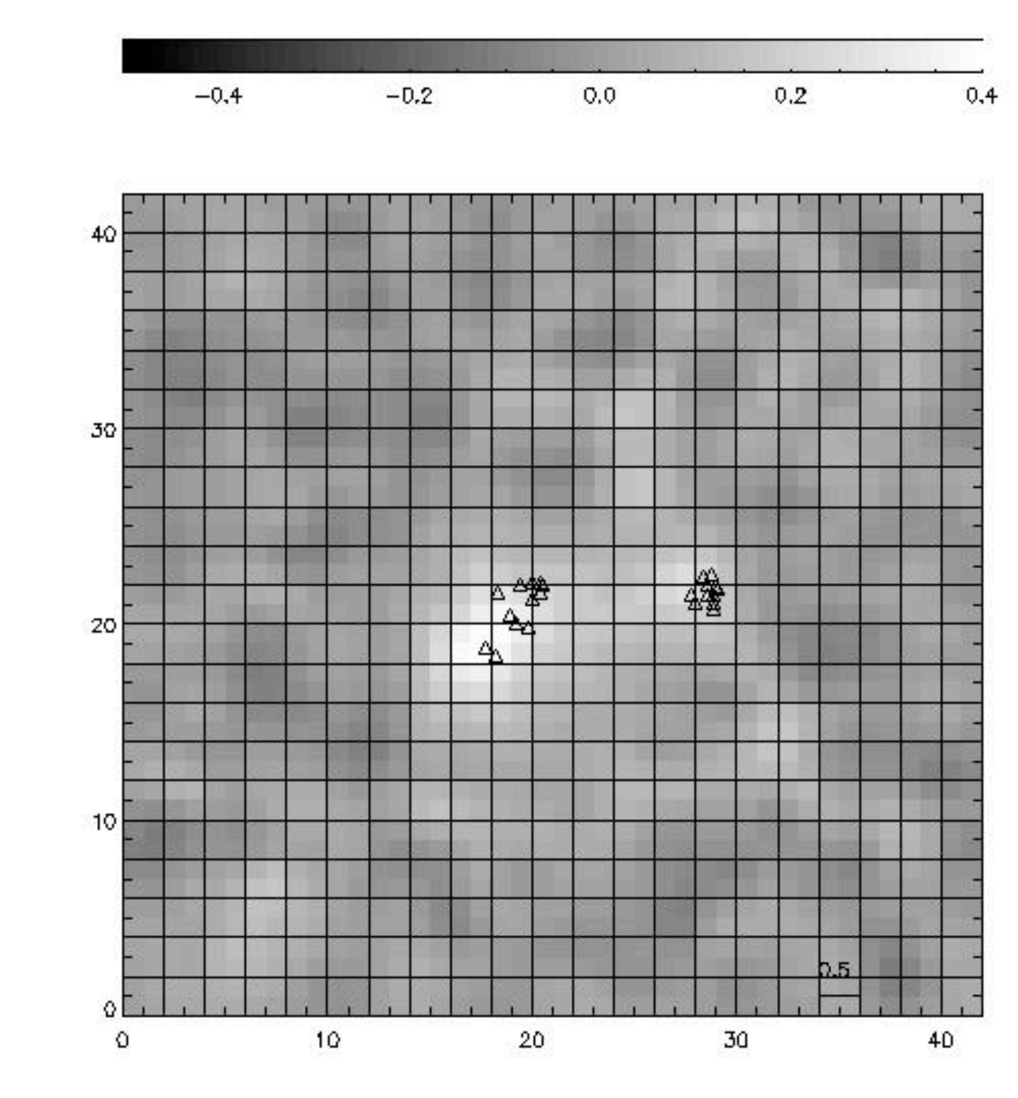
Deb et al. ,2008, 2009

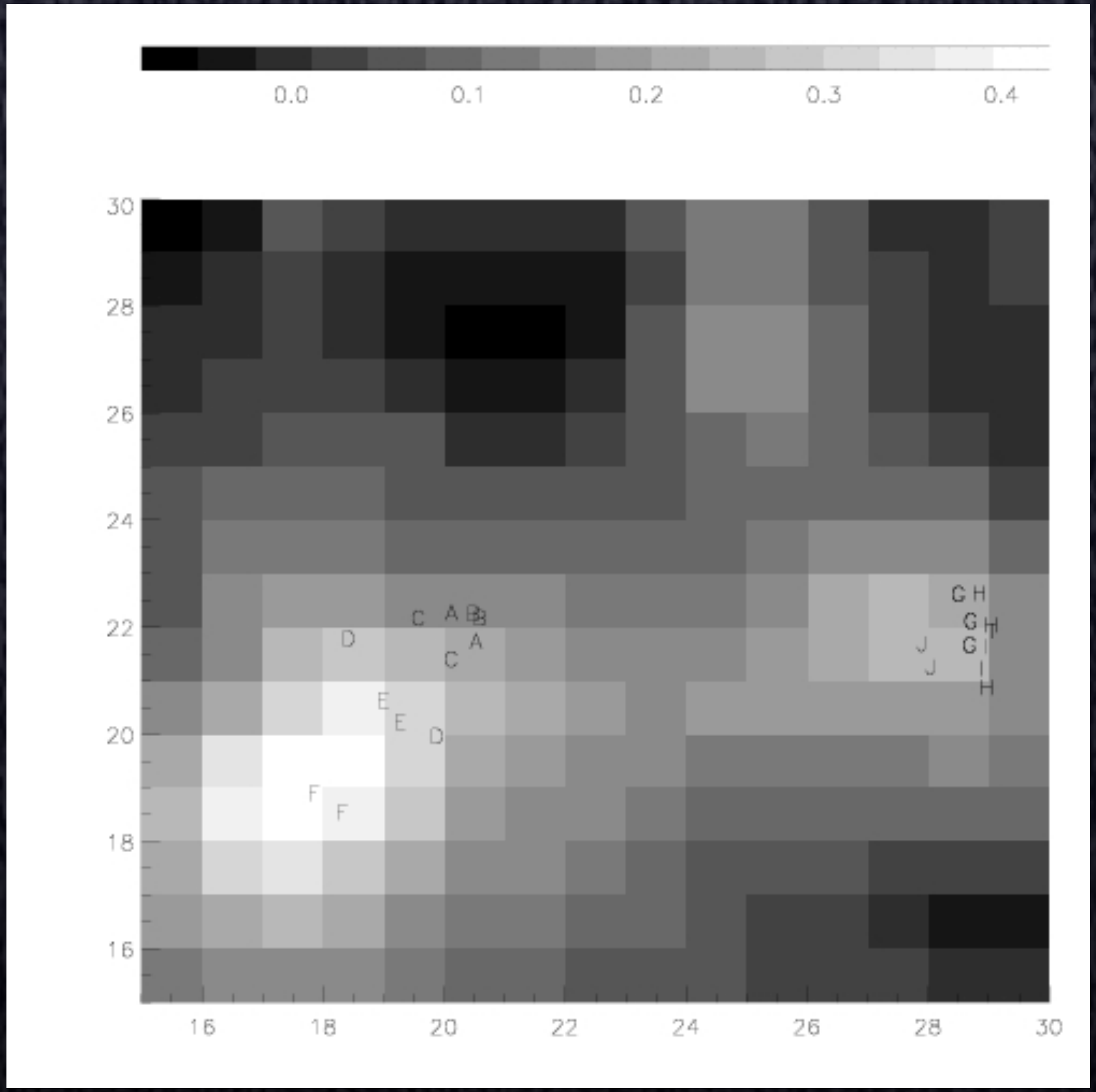
Strong+Weak Lensing: Challenges



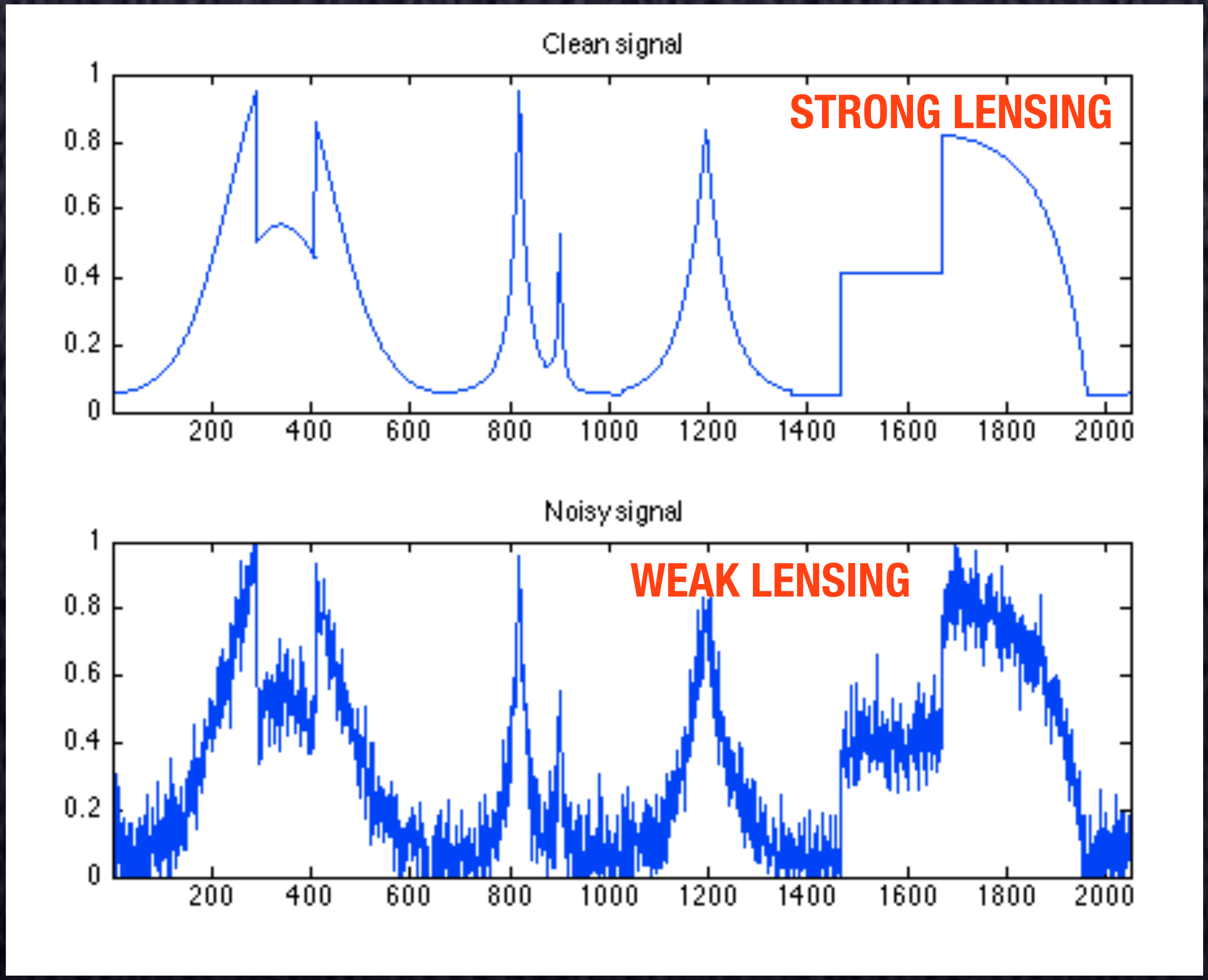
HST/ACS image of Abell 2218 (Sánchez et al. 2006)

Difference of Scales: Bullet Cluster





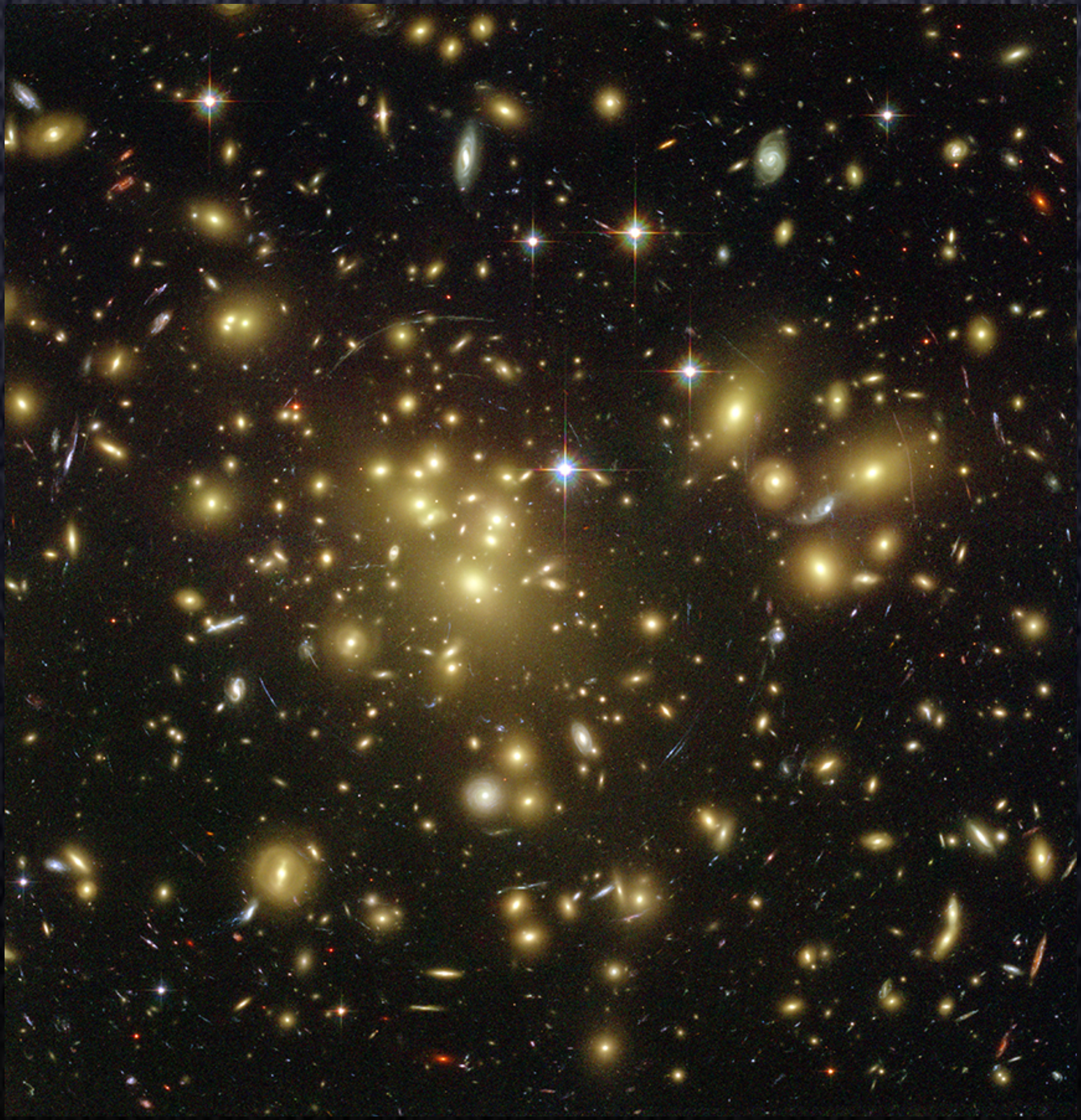
Strong+Weak Lensing



$$\chi^2 =$$

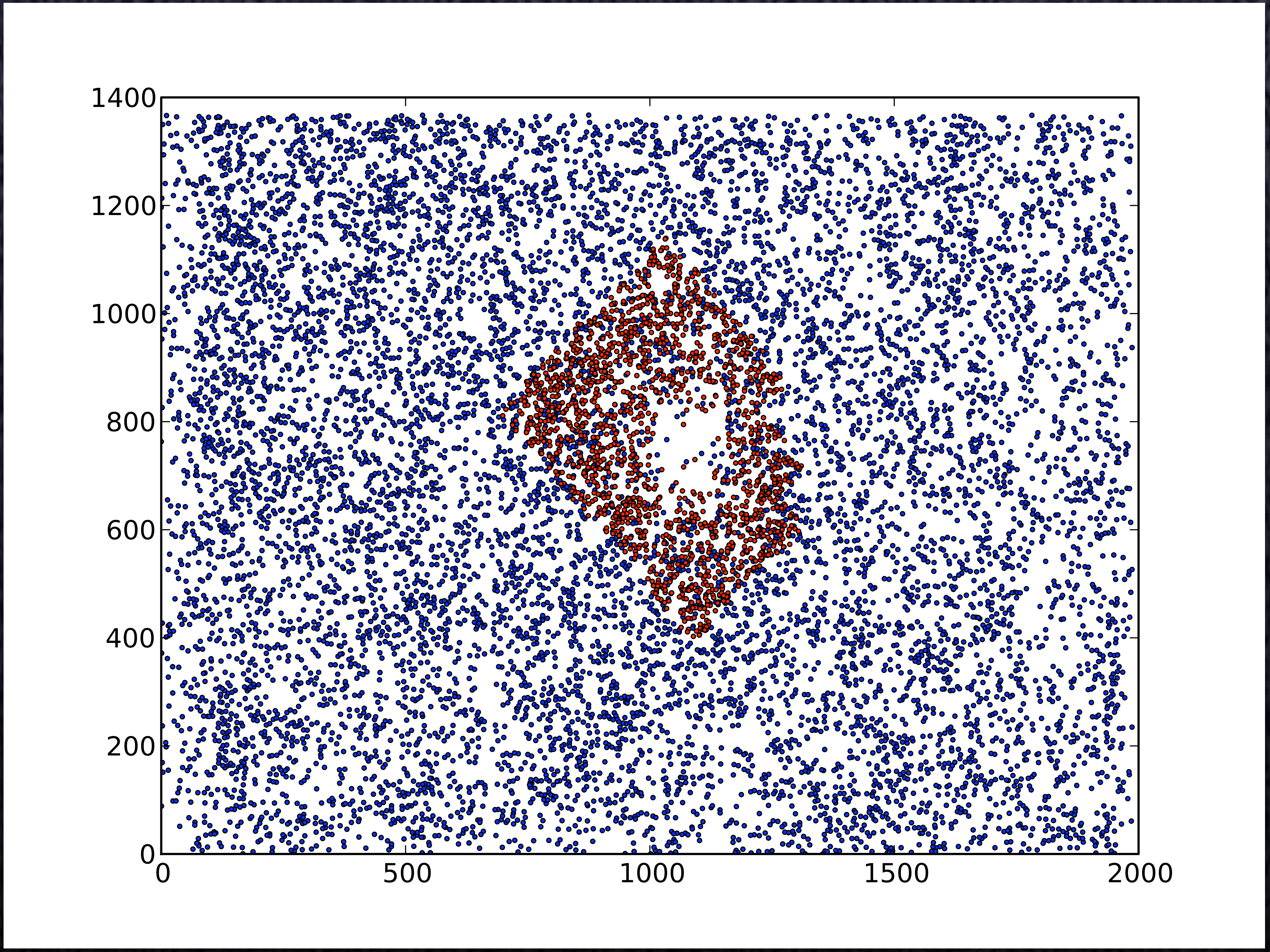
$$\sum_{mn}\left(\varepsilon^i_m - \frac{\gamma^i_m(\psi_m)}{1-\kappa_m(\psi_m)}\right) C^{-1}_{mn} \left(\varepsilon^i_n - \frac{\gamma^i_n(\psi_n)}{1-\kappa_n(\psi_n)}\right) + \sum_{i,pairs}\frac{\left((\boldsymbol{\alpha}^A(\{\psi\}) - \boldsymbol{\alpha}^B(\{\psi\}))Z(z_i) - (\boldsymbol{\theta}^A-\boldsymbol{\theta}^B)\right)^2}{\sigma_i^2}$$

A1689

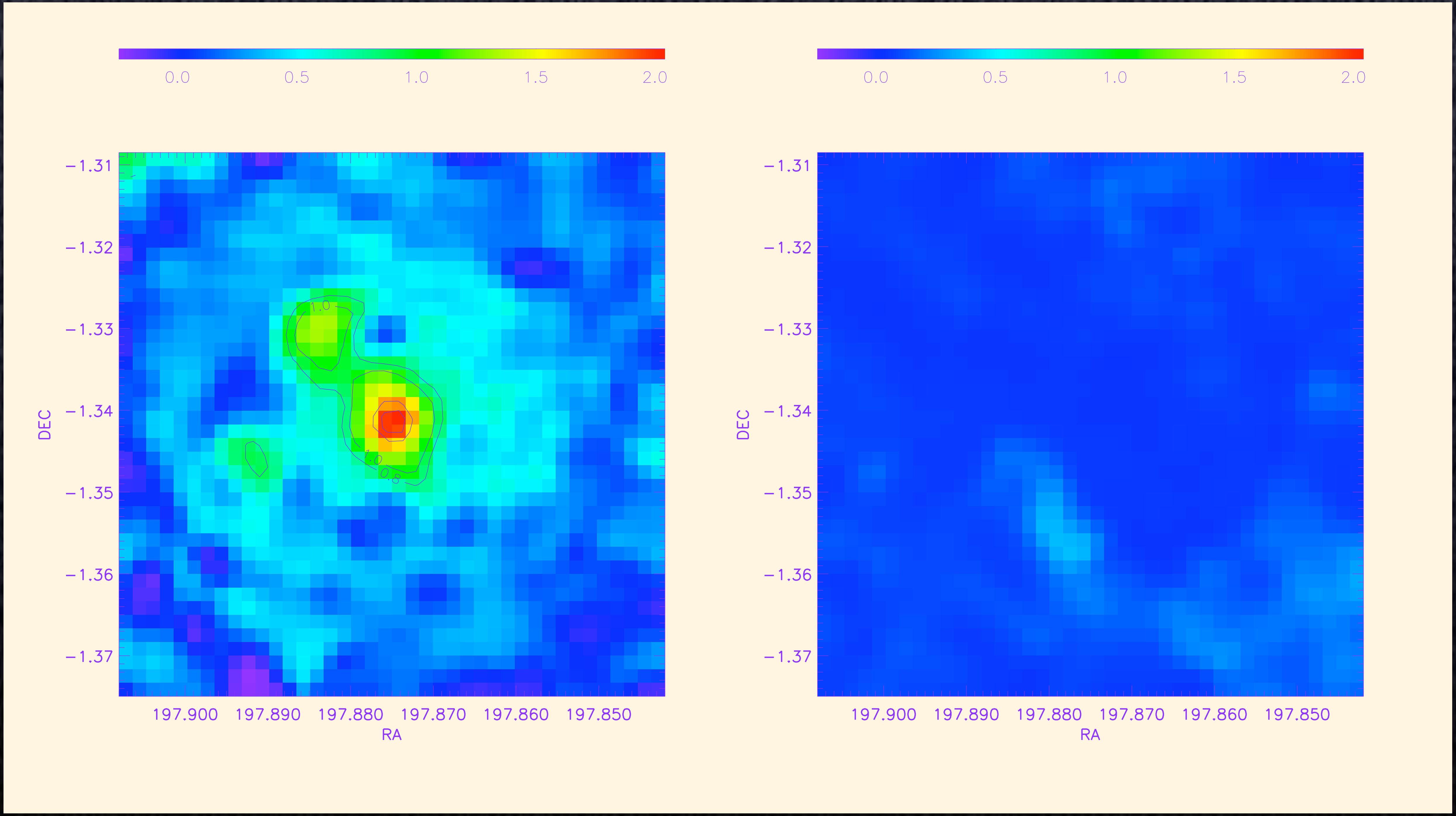


http://chandra.harvard.edu/photo/2008/a1689/

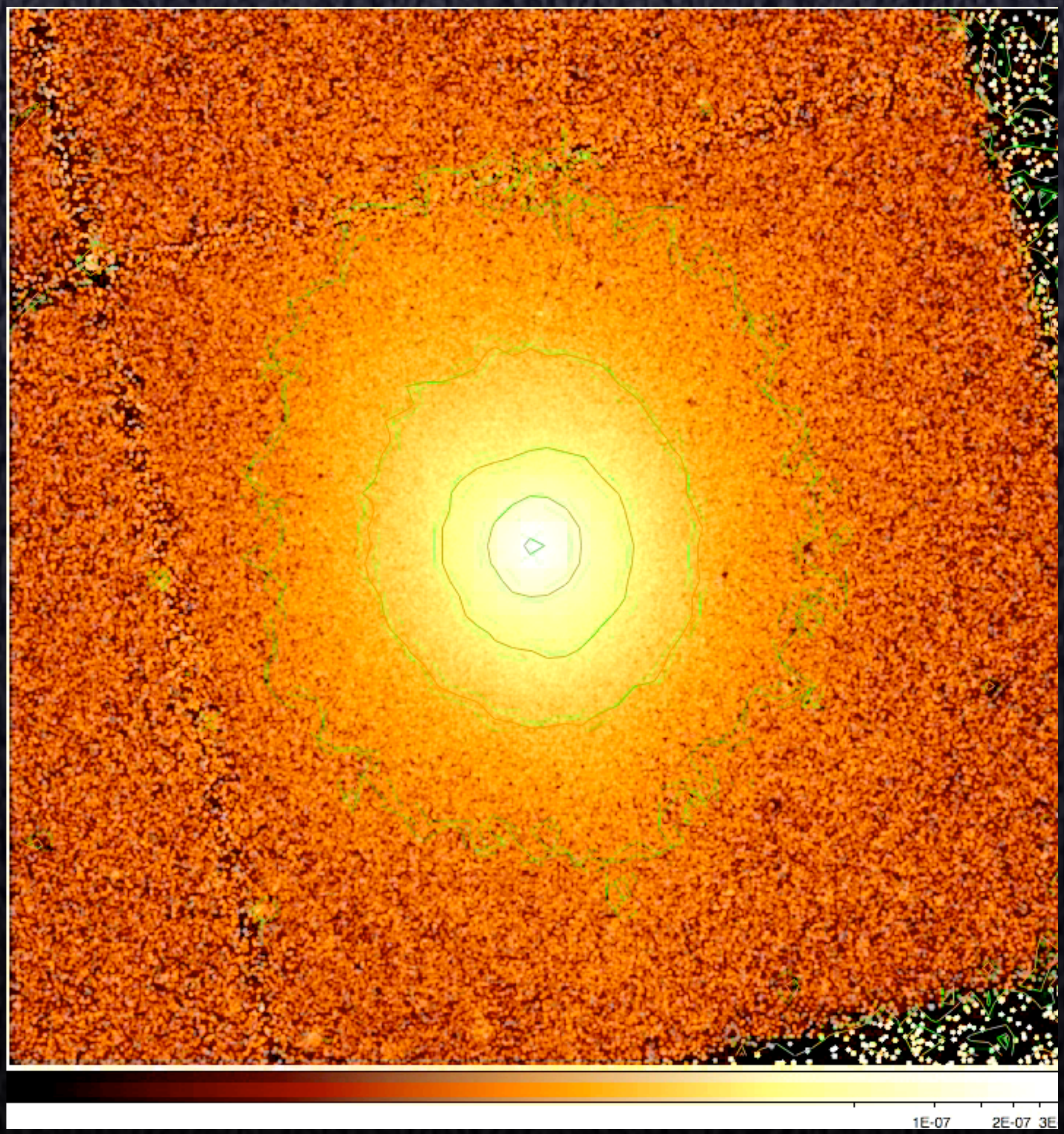
A1689: ACS+SUBARU

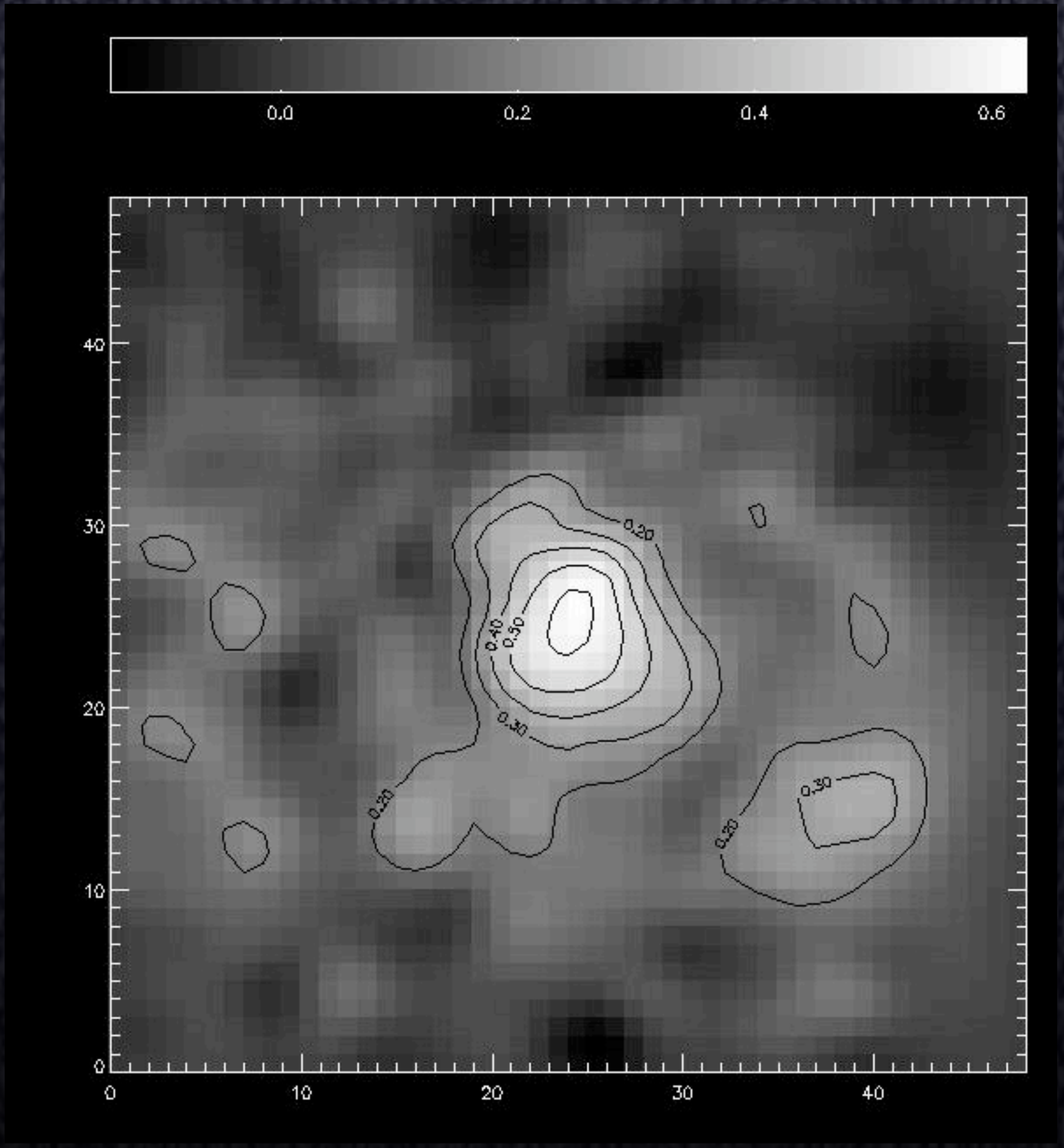


Mass Map


0.0
0.5
1.0
1.5
2.0
−1.31
−1.32
−1.33
−1.34
−1.35
−1.36
−1.37
DEC
197.900
197.890
197.880
197.870
197.860
197.850
RA
1.0
0.5
0.0
0.5
1.0
1.5
2.0
−1.31
−1.32
−1.33
−1.34
−1.35
−1.36
−1.37
DEC
197.900
197.890
197.880
197.870
197.860
197.850
RA

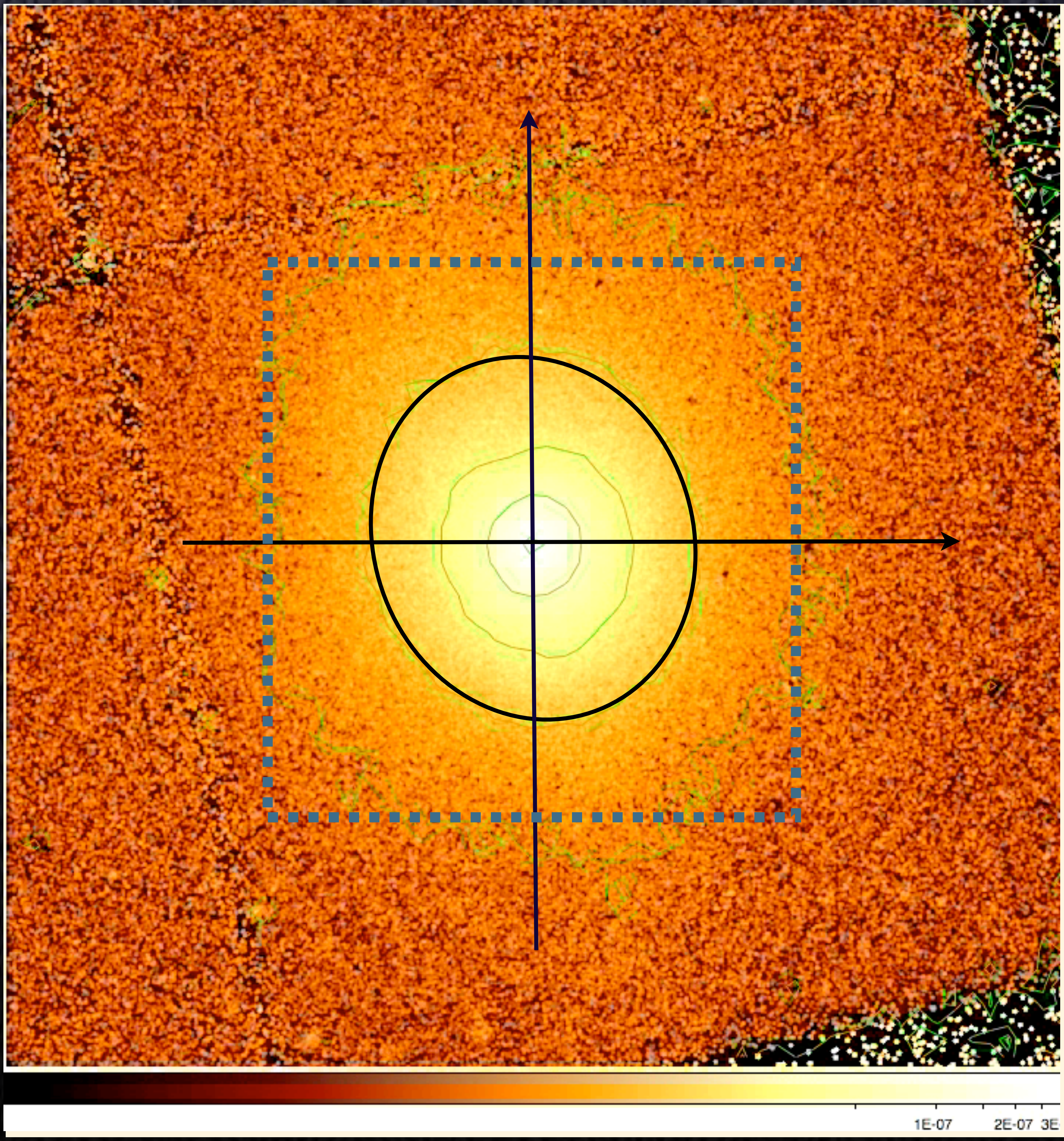
X-ray vs Weak Lensing

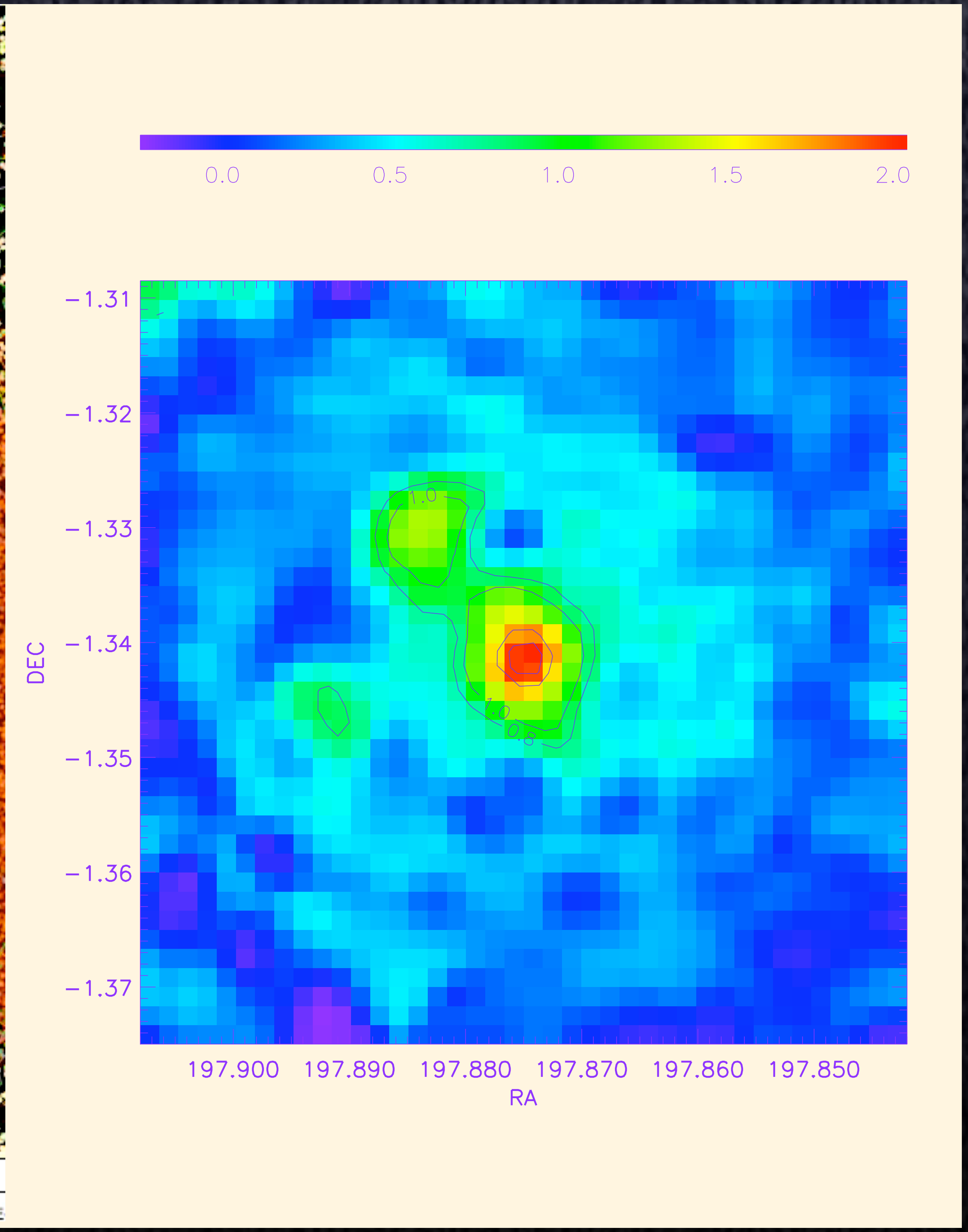




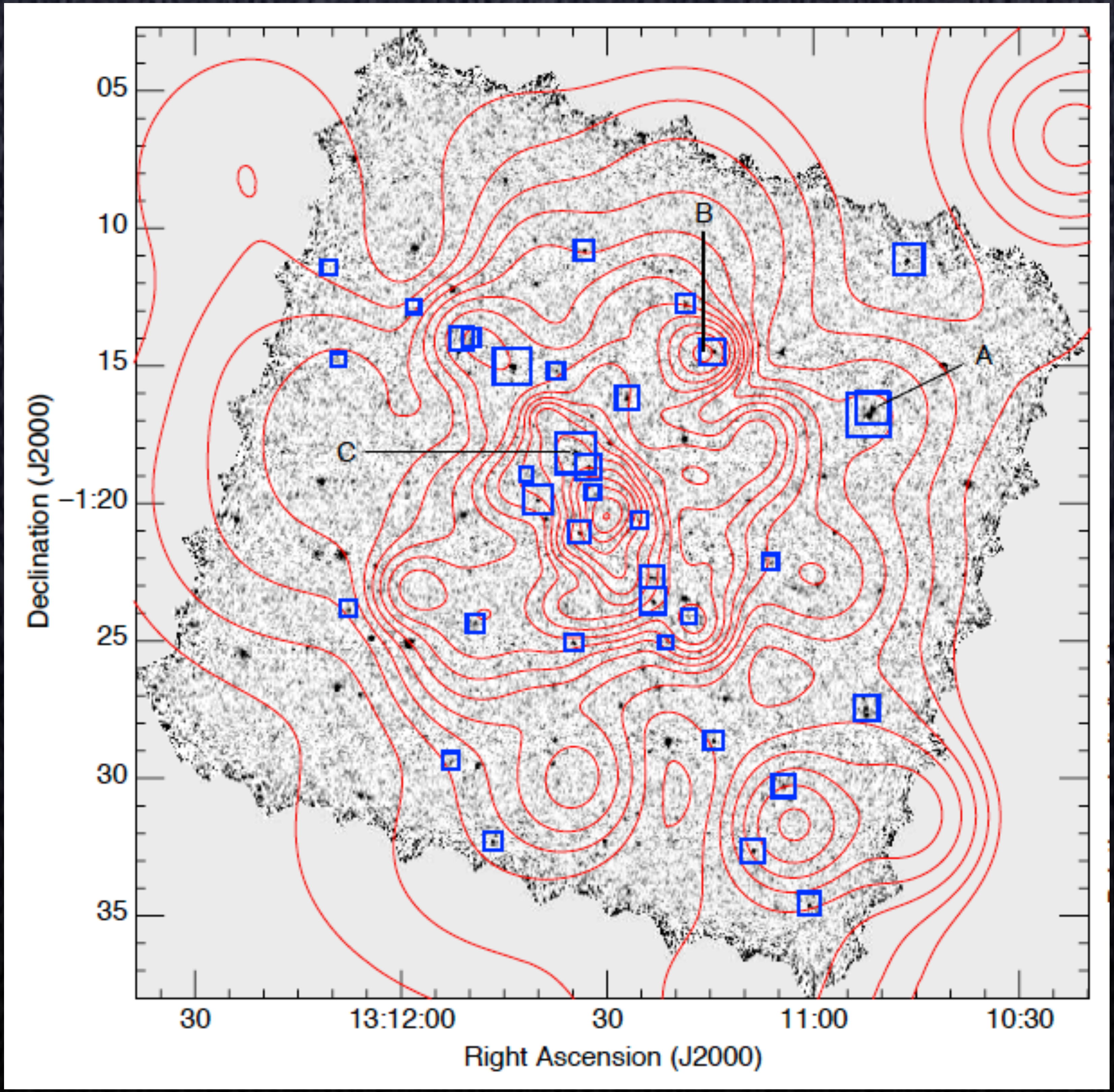
Sorensen et al. 2009

X-ray vs S+W Lensing





Recent Observations



Hershel Observations reveal an excess of 100 micron-selected galaxies extending ~6 Mpc in length along an axis that runs NE-SW through the cluster centre

Haines et al.
arXiv:1005.3811

Power Ratios

Moments of the mass distribution characterize the morphology and substructure in dark matter distribution.

$$a_m(r) = \int_{r'<r} \Sigma(\vec{r}') \, (r')^m \cos(m\phi') d^2\vec{r}',$$

$$b_m(r) = \int_{r'<r} \Sigma(\vec{r}') \, (r')^m \sin(m\phi') d^2\vec{r}'.$$

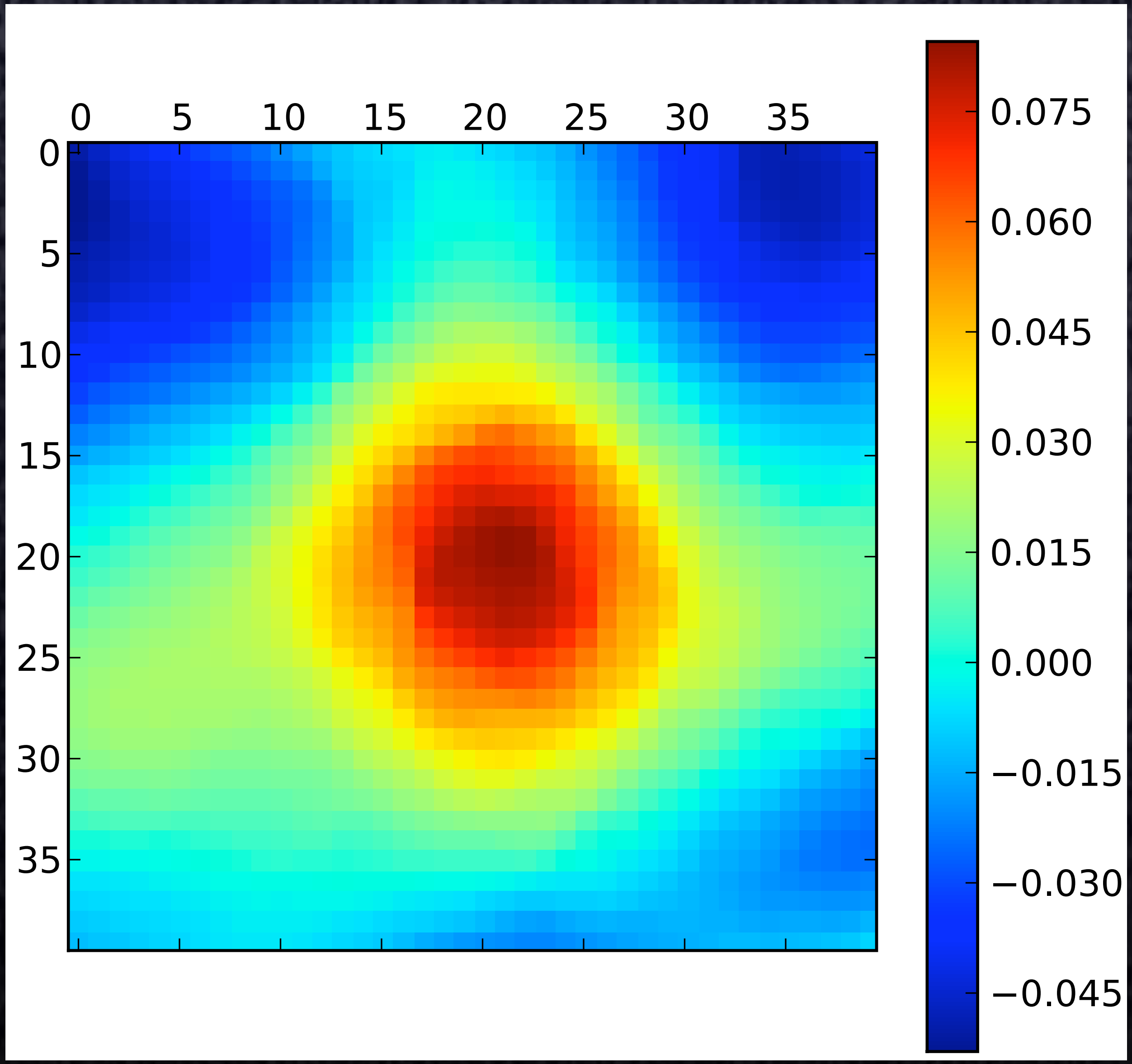
$$P_0 = [a_0 ln(R)]^2,$$

$$P_m = \frac{1}{2m^2 r^{2m}} \left(a_m^2 + b_m^2\right).$$

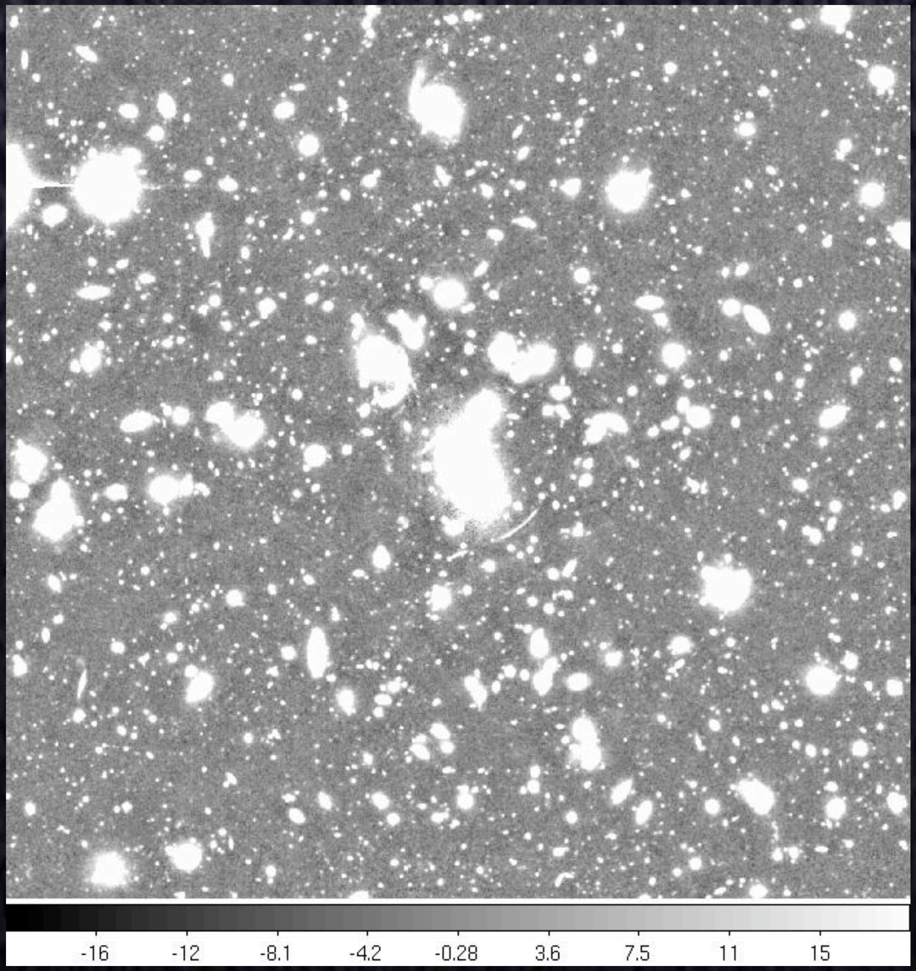
Power	X-ray	Lensing
P_2/P_0	$(6.68 \pm 0.27) \times 10^{-06}$	$(1.6 \pm 0.25) \times 10^{-5}$
P_3/P_0	$(3.71 \pm 1.12) \times 10^{-07}$	$(0.9 \pm 0.14) \times 10^{-5}$
P_4/P_0	$(6.42 \pm 2.65) \times 10^{-08}$	$(8.6 \pm 0.3) \times 10^{-5}$

Current Research

A2219: Optical vs Lensing mass reconstruction

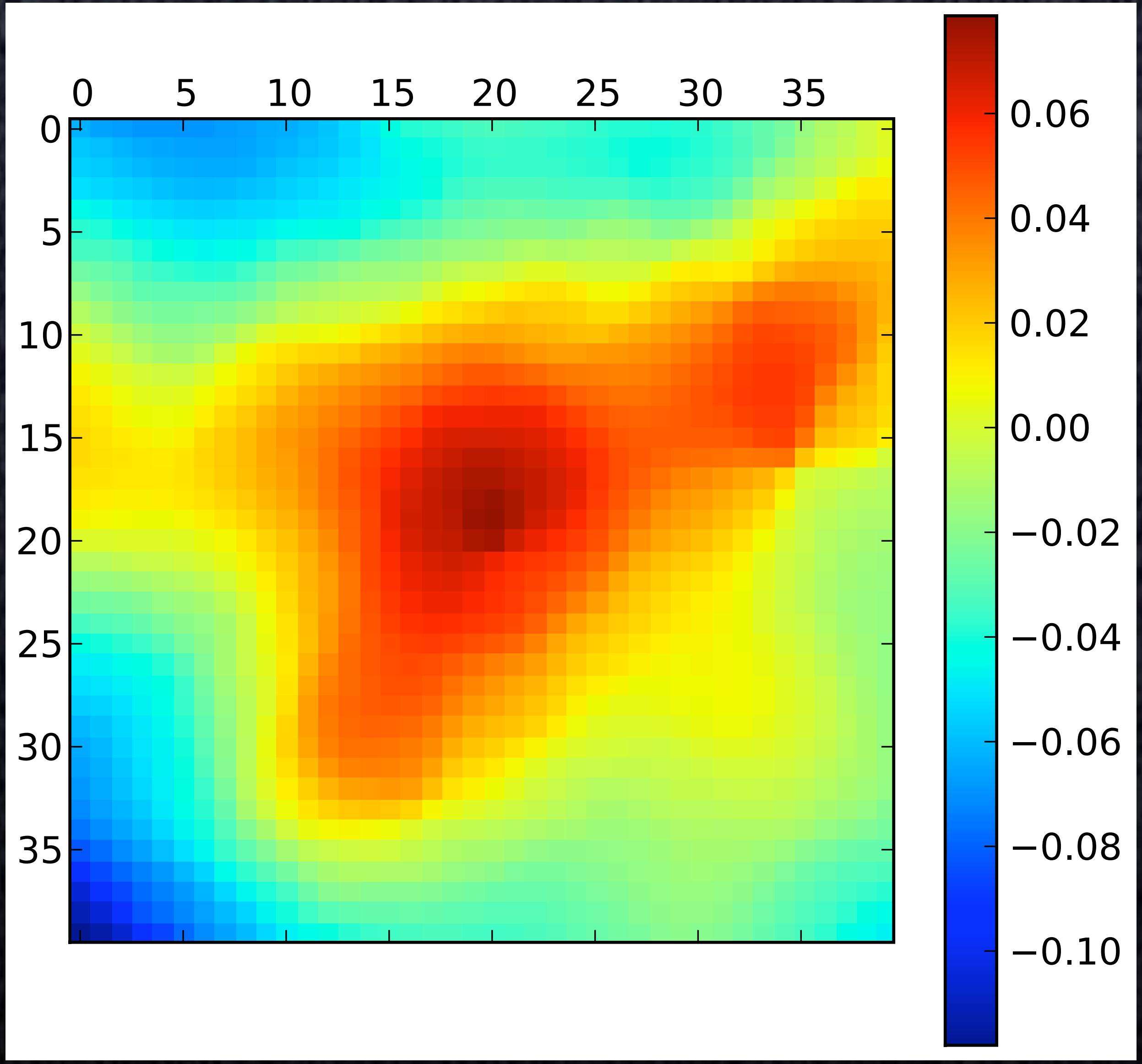


PRELIMINARY

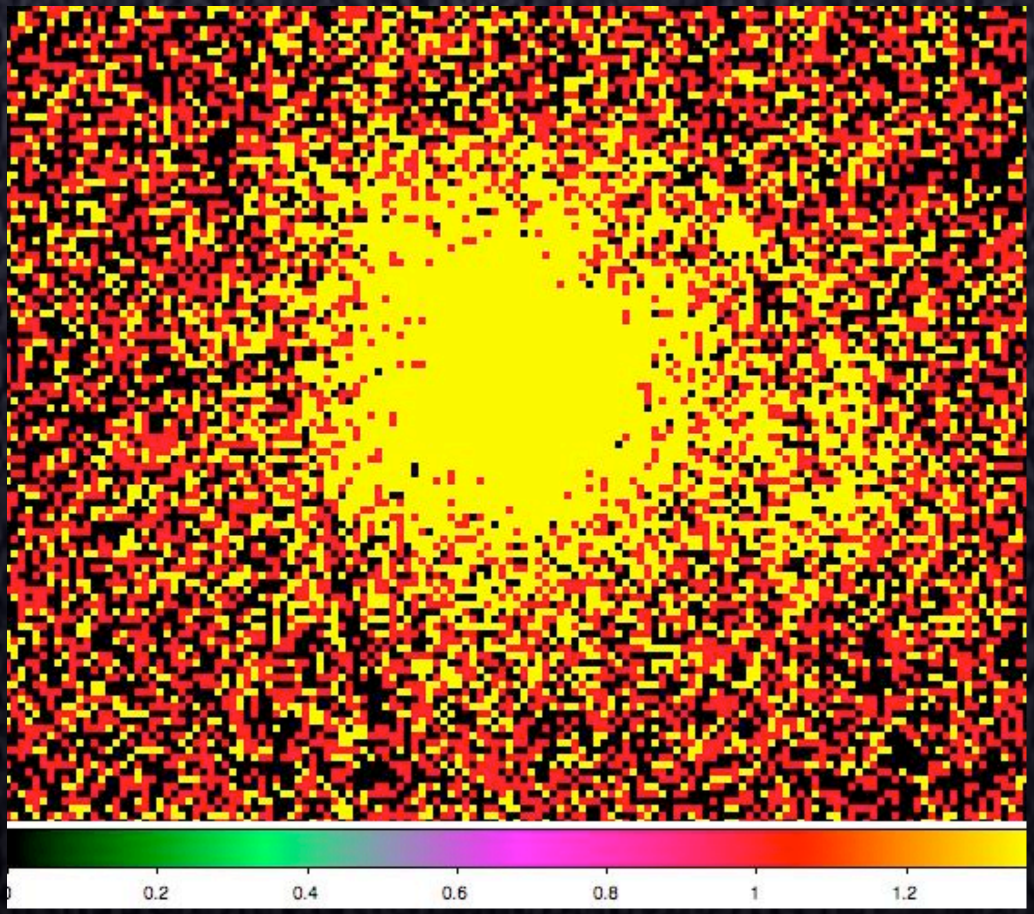


Current Research

A2261: X-ray vs Lensing mass reconstruction



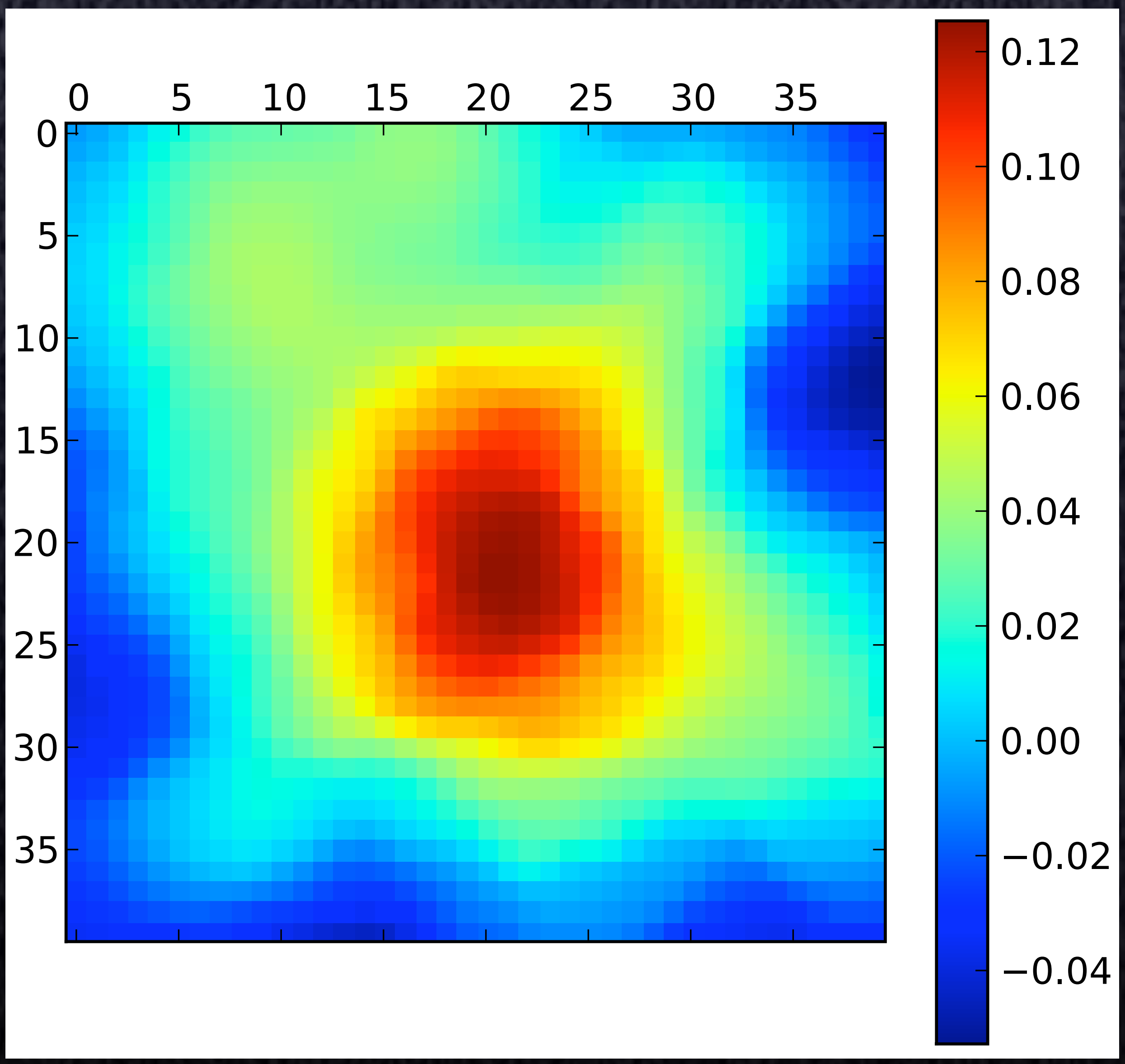
XMM Newton



PRELIMINARY

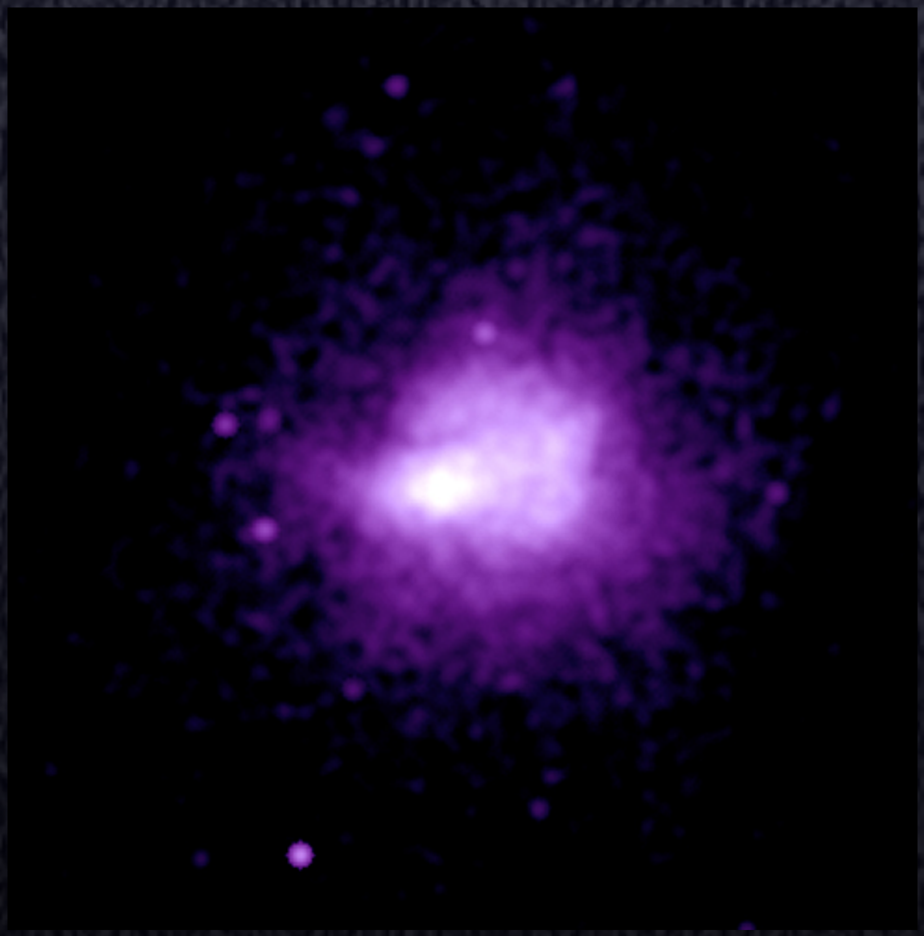
Current Research

A1914: X-ray vs Lensing mass reconstruction



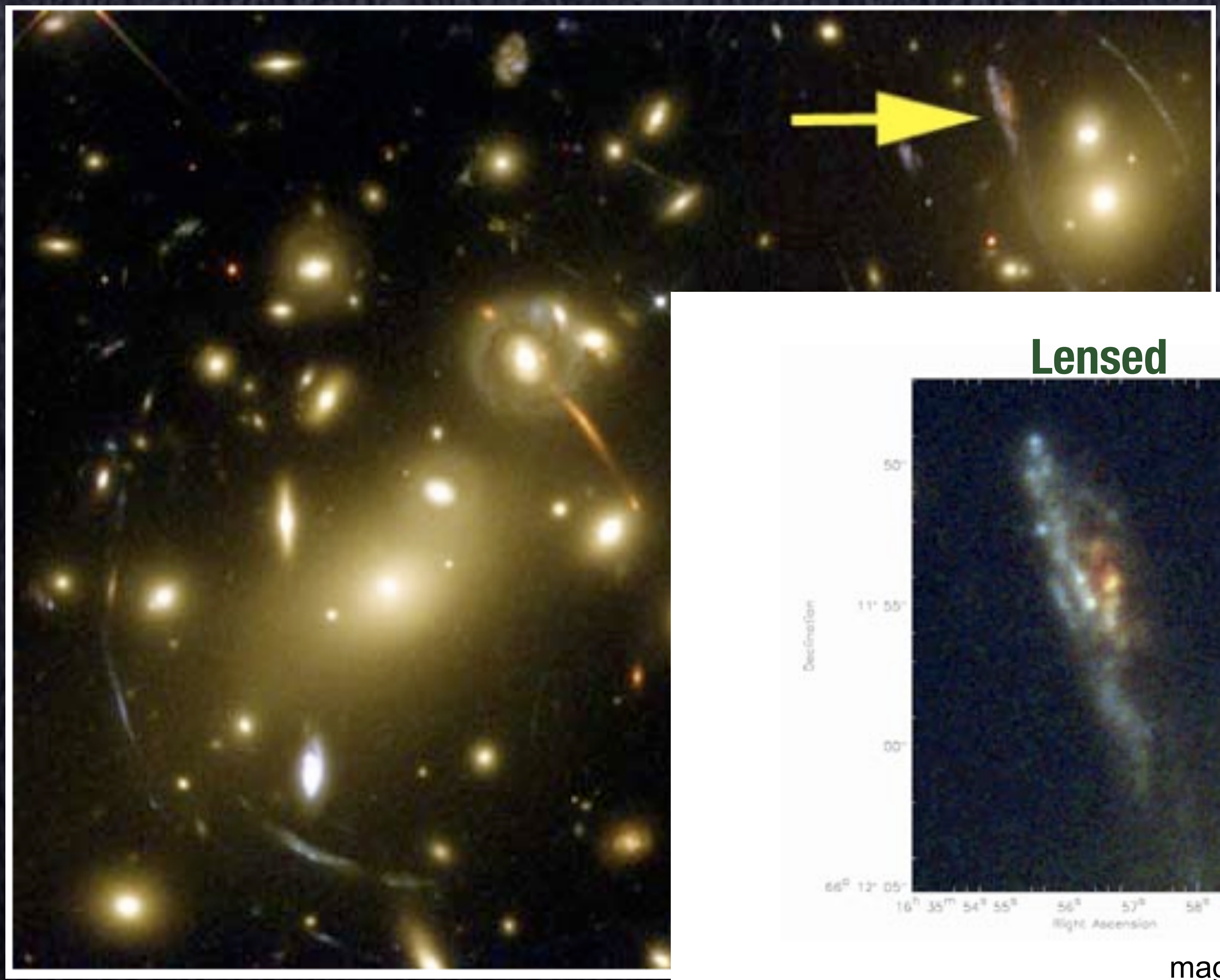
PRELIMINARY

Chandra data

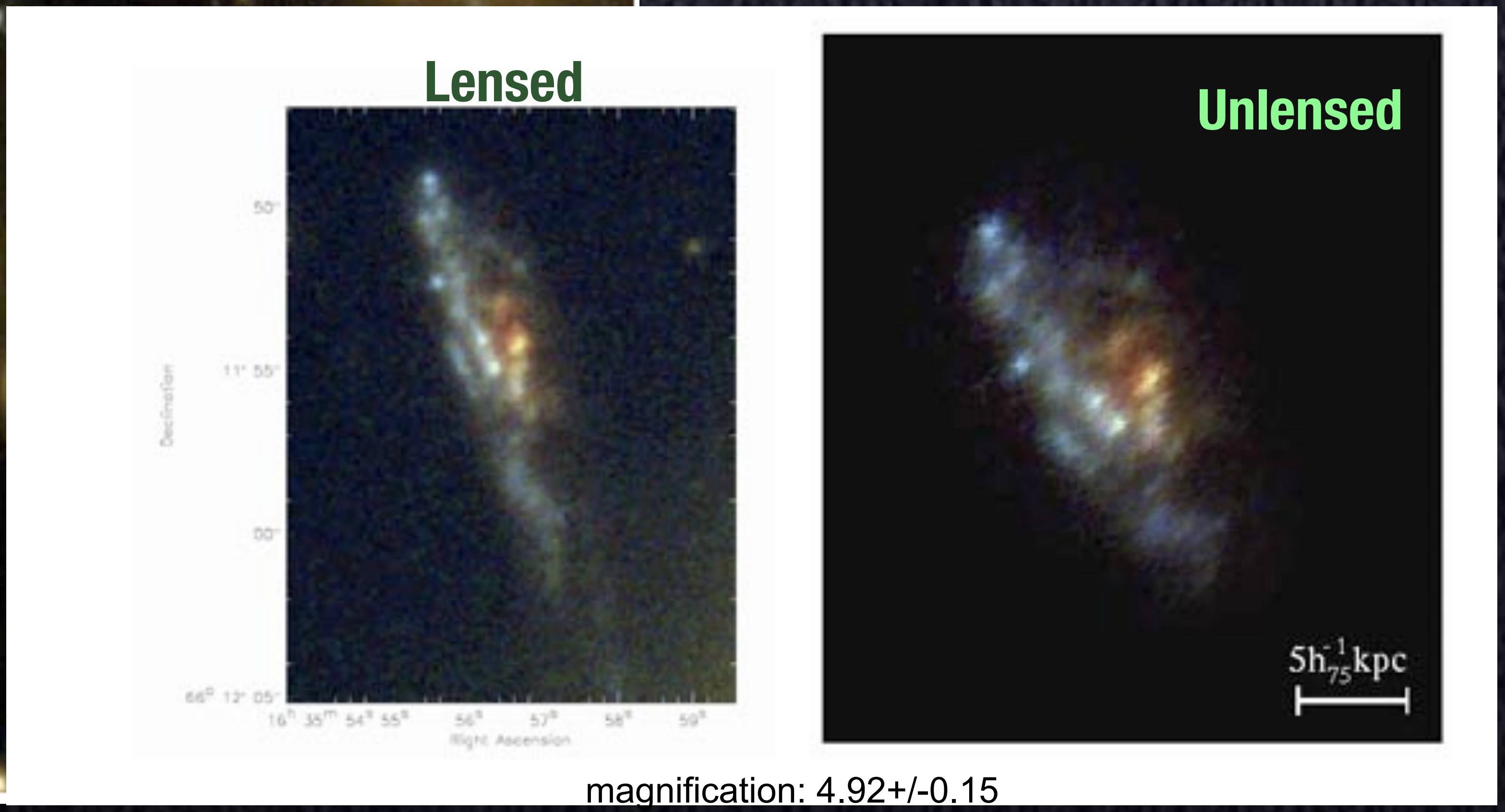


http://chandra.harvard.edu/photo/2006/clusters/

Application: Studying high redshift galaxies



Swinbank et al. 2006

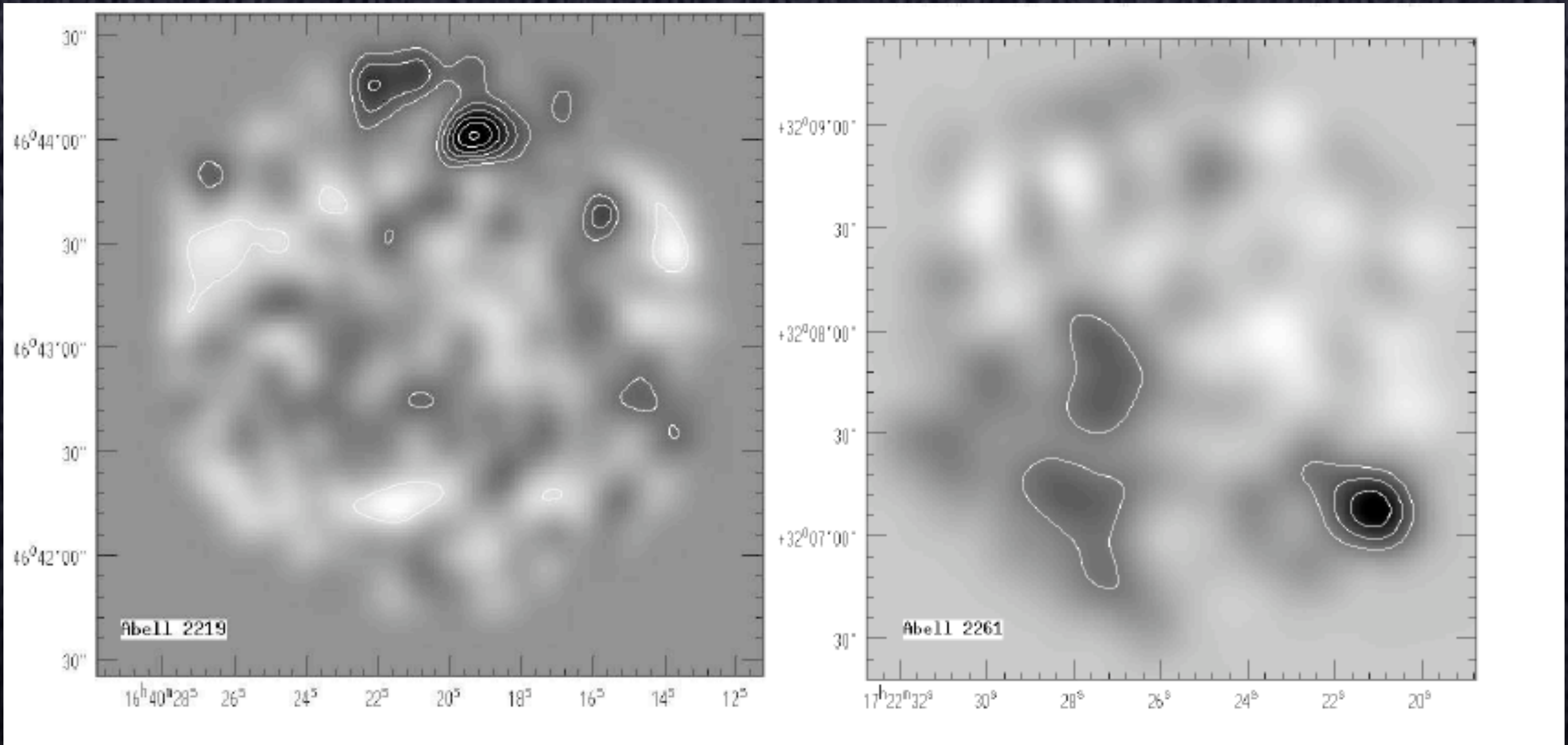


Lensed

z=1.034 → z=0.1

http://www.gemini.edu/node/100

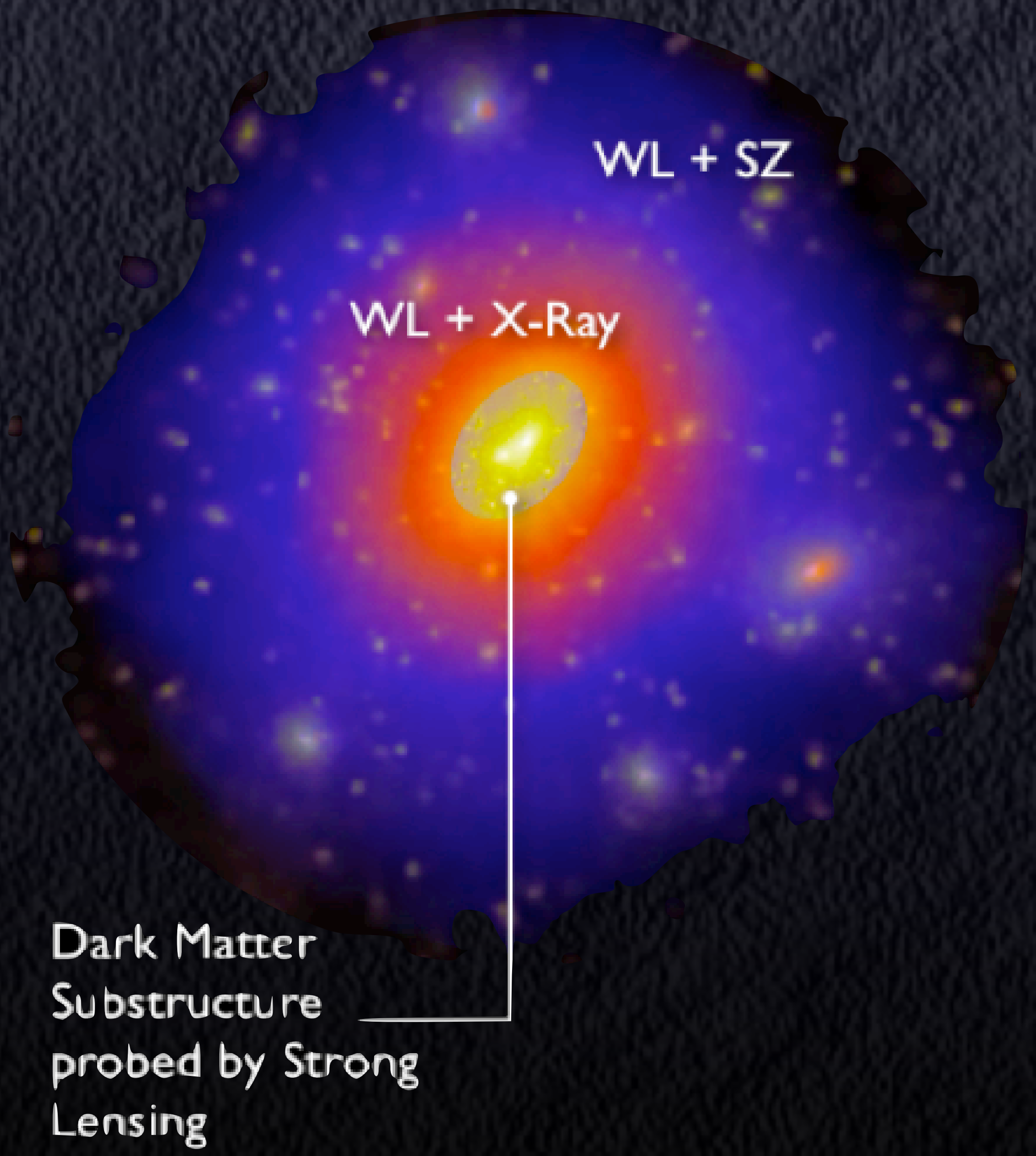
Sumilimeter Imaging



Cluster field images at 850 microns

Chapman et. al. 2000

Multiwavelength analysis



Multiwavelength shape analysis of galaxy clusters for the current sample of 20 clusters.

X-ray data: Chandra & XMM archival data
SZ data: Future plans of writing CARMA proposals with Dr. Morandi for some of these clusters.

Clusters are being discovered as we speak with SZ experiments like ACT/SPT. Lensing observations of these clusters will also increase this data set.

Summary

METHOD

Developed a non-parametric mass reconstruction technique “Particle Based Lensing” (PBL).

PBL is applied to compute mass maps of variable resolution and signal-to-noise.

RESULTS

- The ellipticity for the light distribution is smaller than the ellipticity of the dark matter distribution for A901b and the Southwest Group.
- A901a, A901b and A902 have strong alignment whereas the Southwest group is not aligned with the rest of the peaks.
- The gas distribution of A1689 is smoother than the dark matter distribution.

Future Research

Mutiwavelength analysis for a sample of 20 Supermassive Clusters.

Smoothing Ellipticities: Error Covariance

$$\varepsilon^i_{sm,p} = Q_{pq}\varepsilon^i_q \longrightarrow C^{\mathrm{MIN}}_{pq} = Q_{kp}Q_{kq}\sigma^2_q$$

Smoothing Ellipticities: Error Covariance

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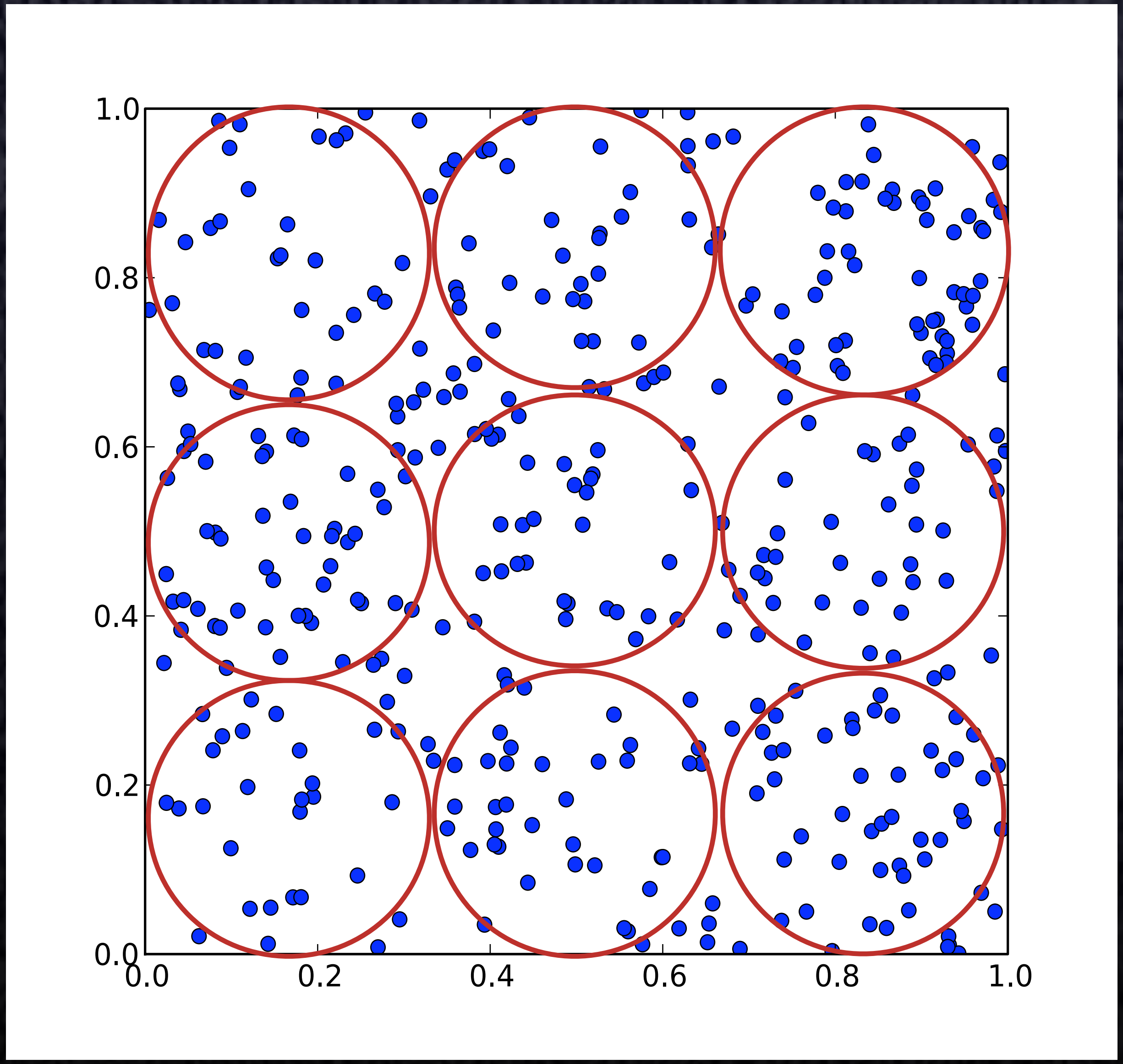
↓

singular

Smoothing Ellipticities: Error Covariance

$$\varepsilon^i_{sm,p} = Q_{pq}\varepsilon^i_q \longrightarrow C^{\mathrm{MIN}}_{pq} = Q_{kp}Q_{kq}\sigma^2_q$$

singular



Number of particles (background images) larger than the number of resolution units.

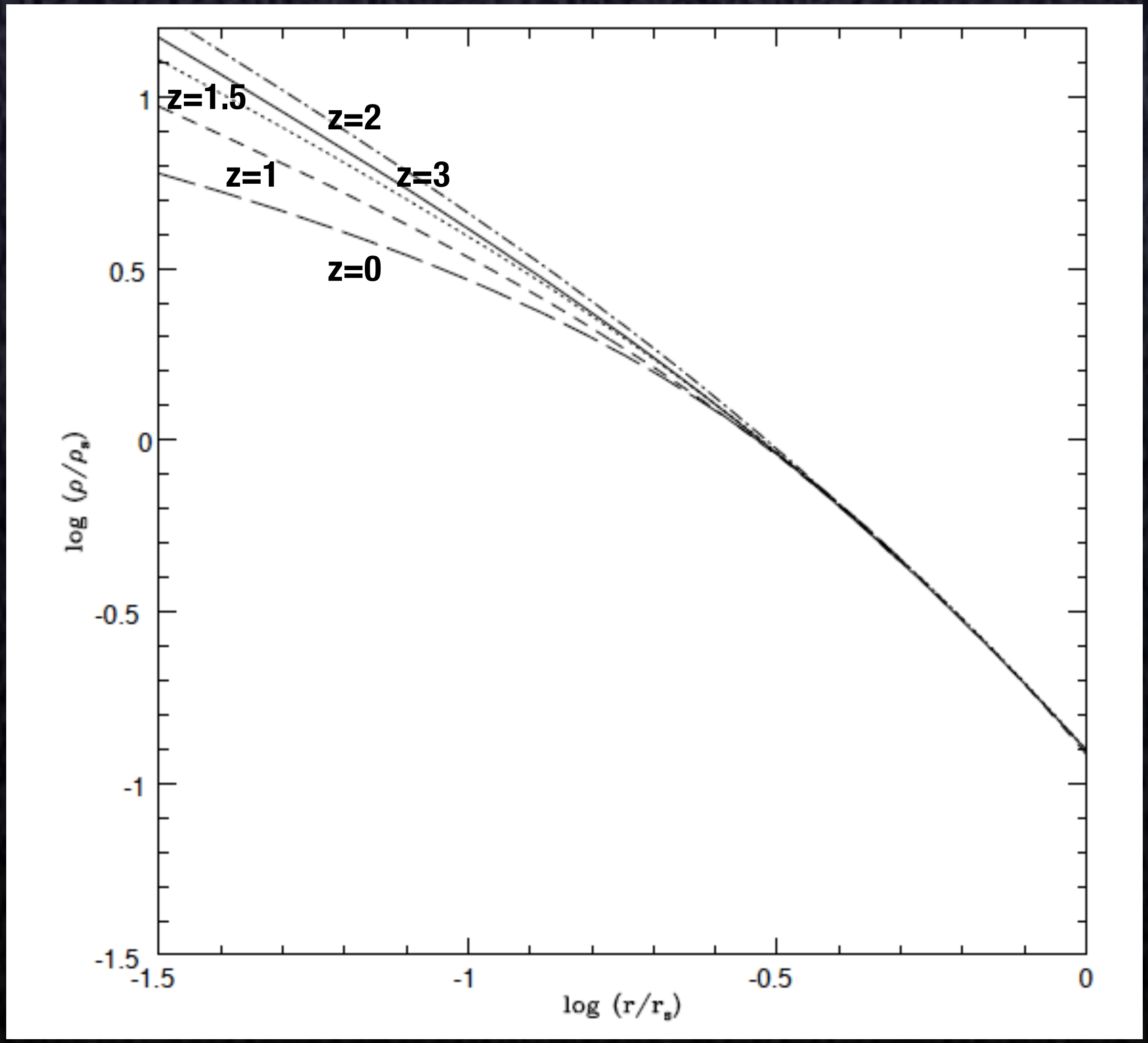
Ellipticity Observations: Triaxial NFW

$$\rho(R) = \frac{\delta_c \rho_c(z)}{\frac{R}{R_s}(1 + R/R_s)^2}$$

$\rho_c(z)$:critical density of the Universe

δ_c :characteristic overdensity of the halo

R_s : scale radius



Del Popolo et al. 2009

$$R^2 = \frac{X^2}{a^2} + \frac{Y^2}{b^2} + \frac{Z^2}{c^2}$$