Astronomical Observations of Dark Matter

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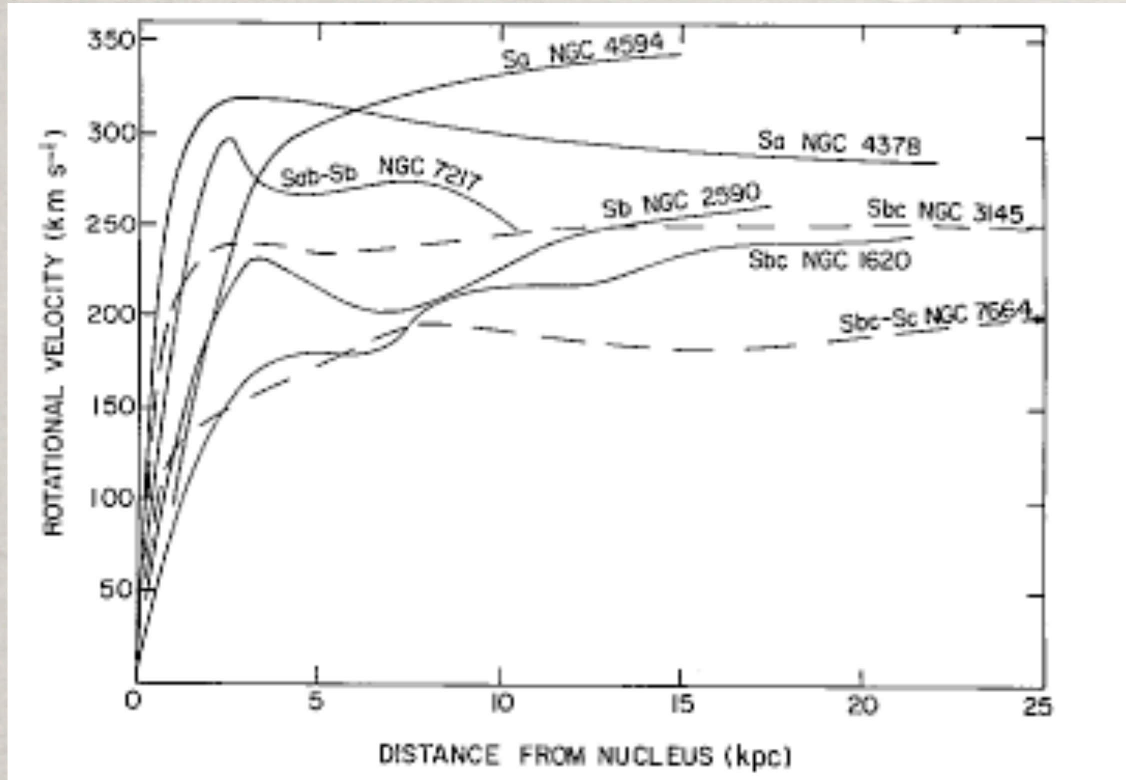
Astronomical Observations Used to Observe Dark Matter

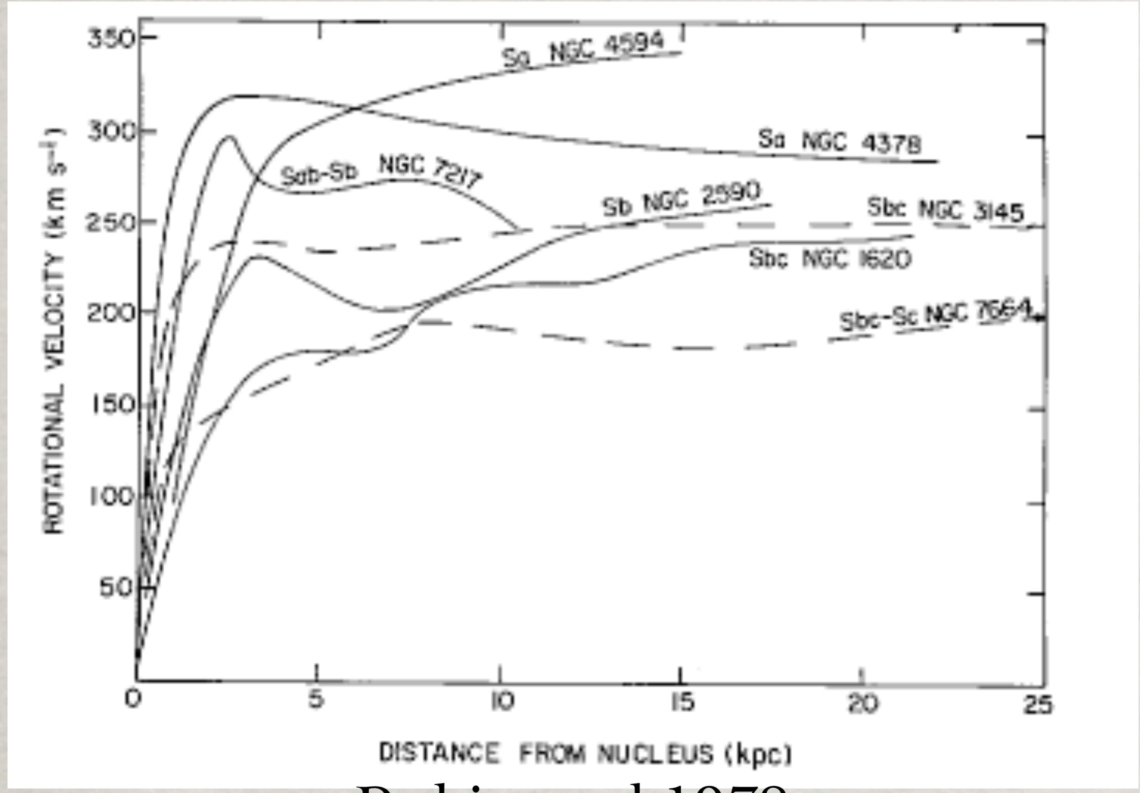
- spiral galaxy rotation curves
- elliptical galaxy velocity dispersions
- galaxy-galaxy gravitational lensing
- dwarf galaxies
- CMB
- formation of large scale structure
- galaxy cluster mass measurements
- merging galaxy clusters

Galaxy Observations

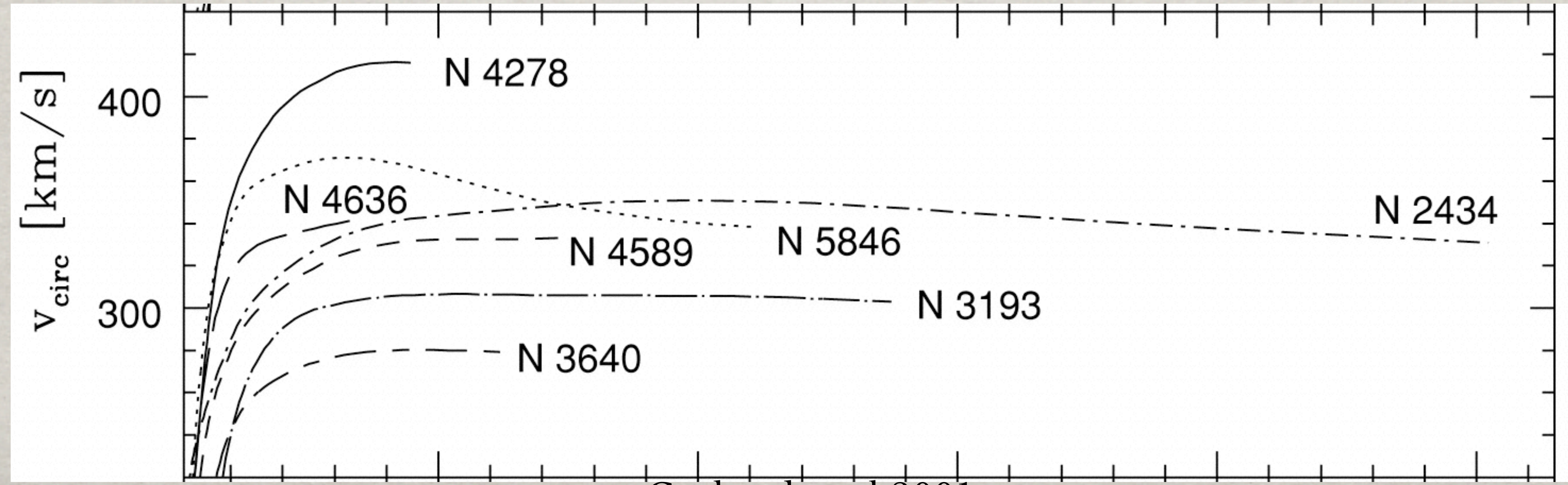


Rubin et al 1978

Galaxy Observations

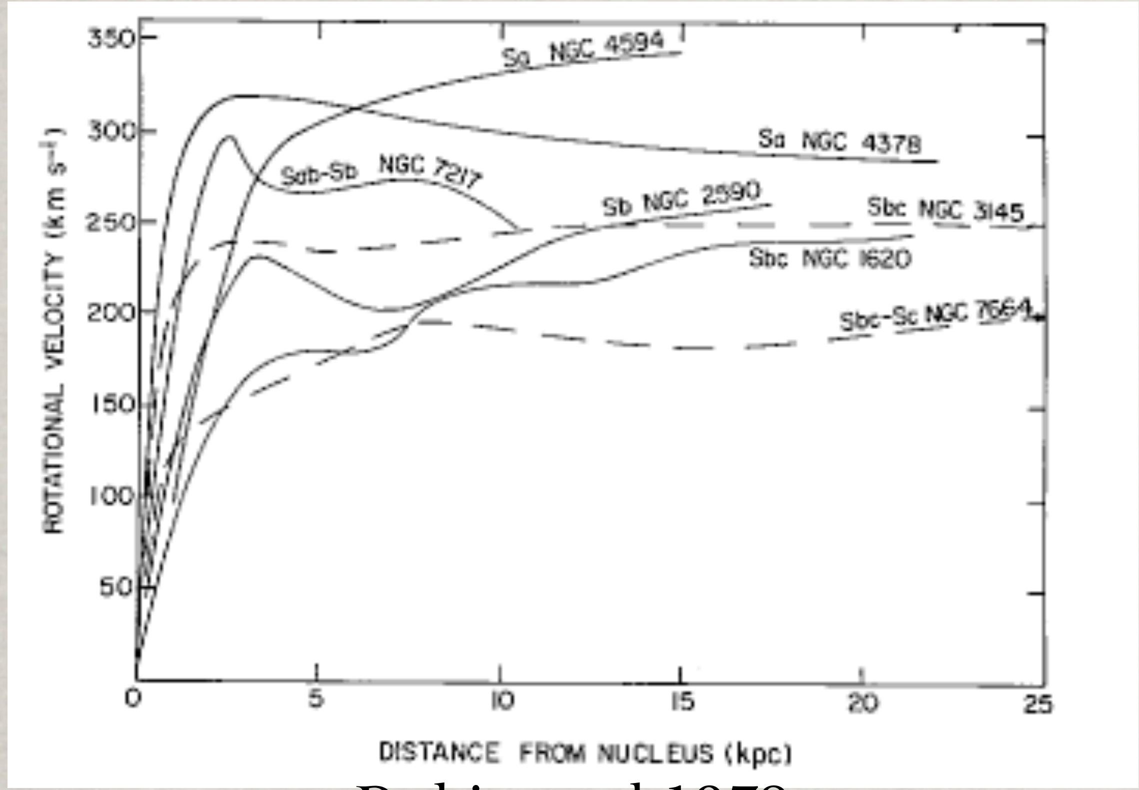


Rubin et al 1978

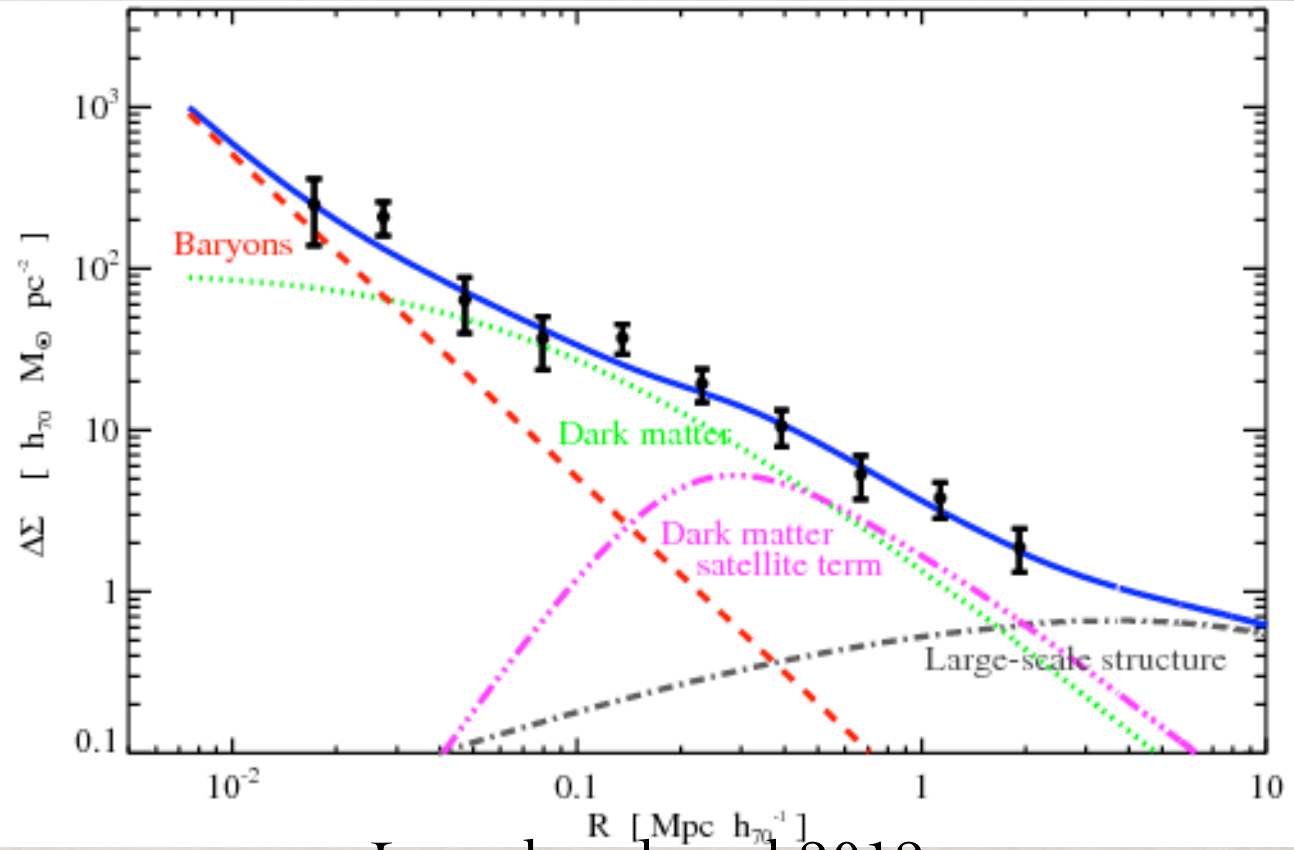


Gerhard et al 2001

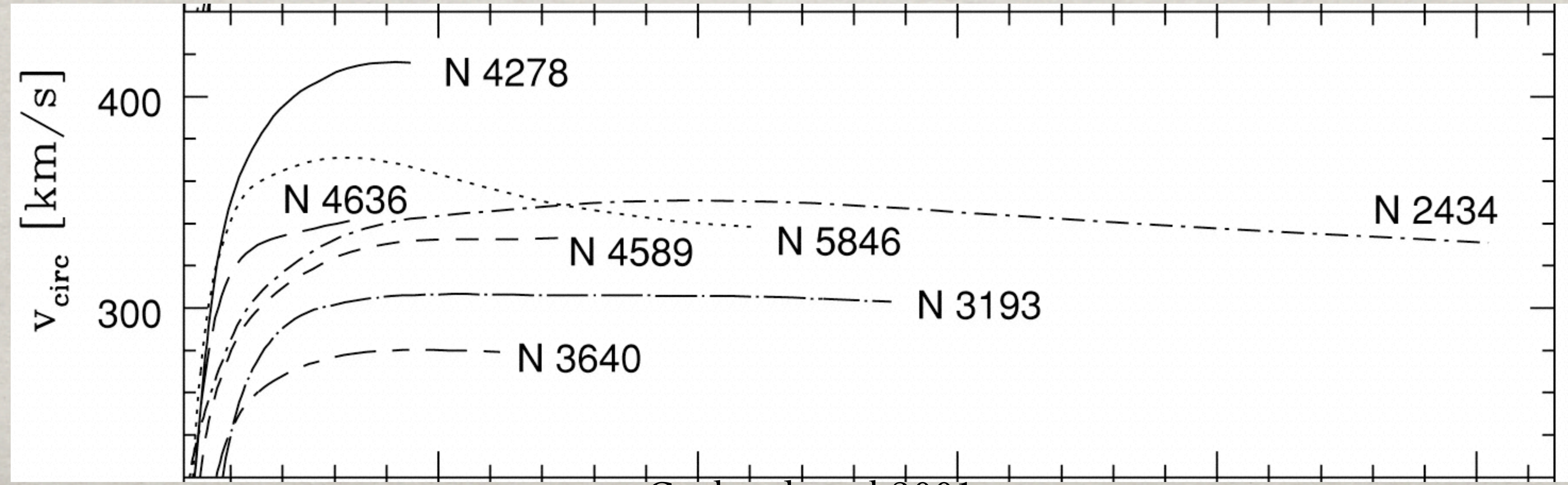
Galaxy Observations



Rubin et al 1978

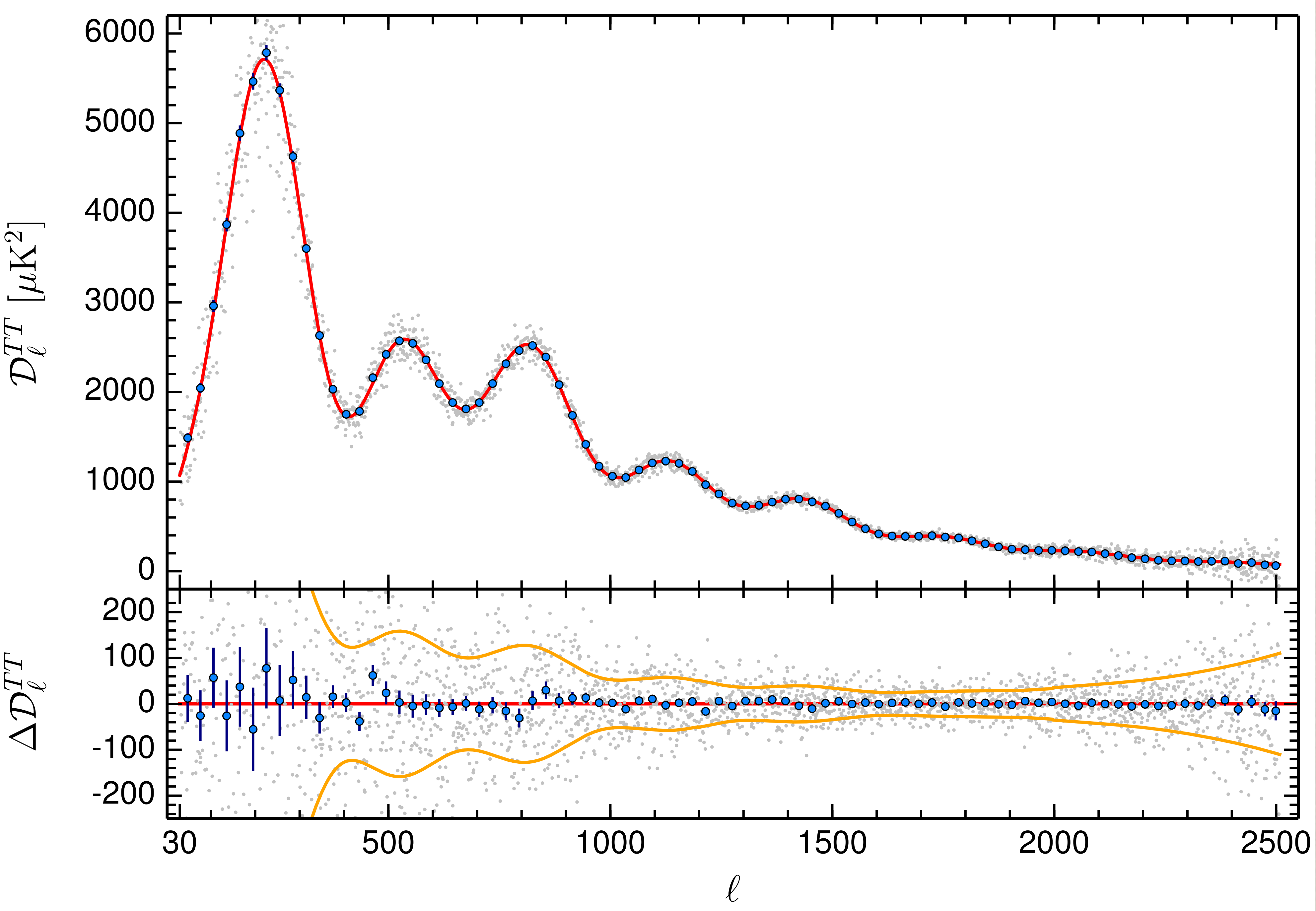


Leauthaud et al 2012



Gerhard et al 2001

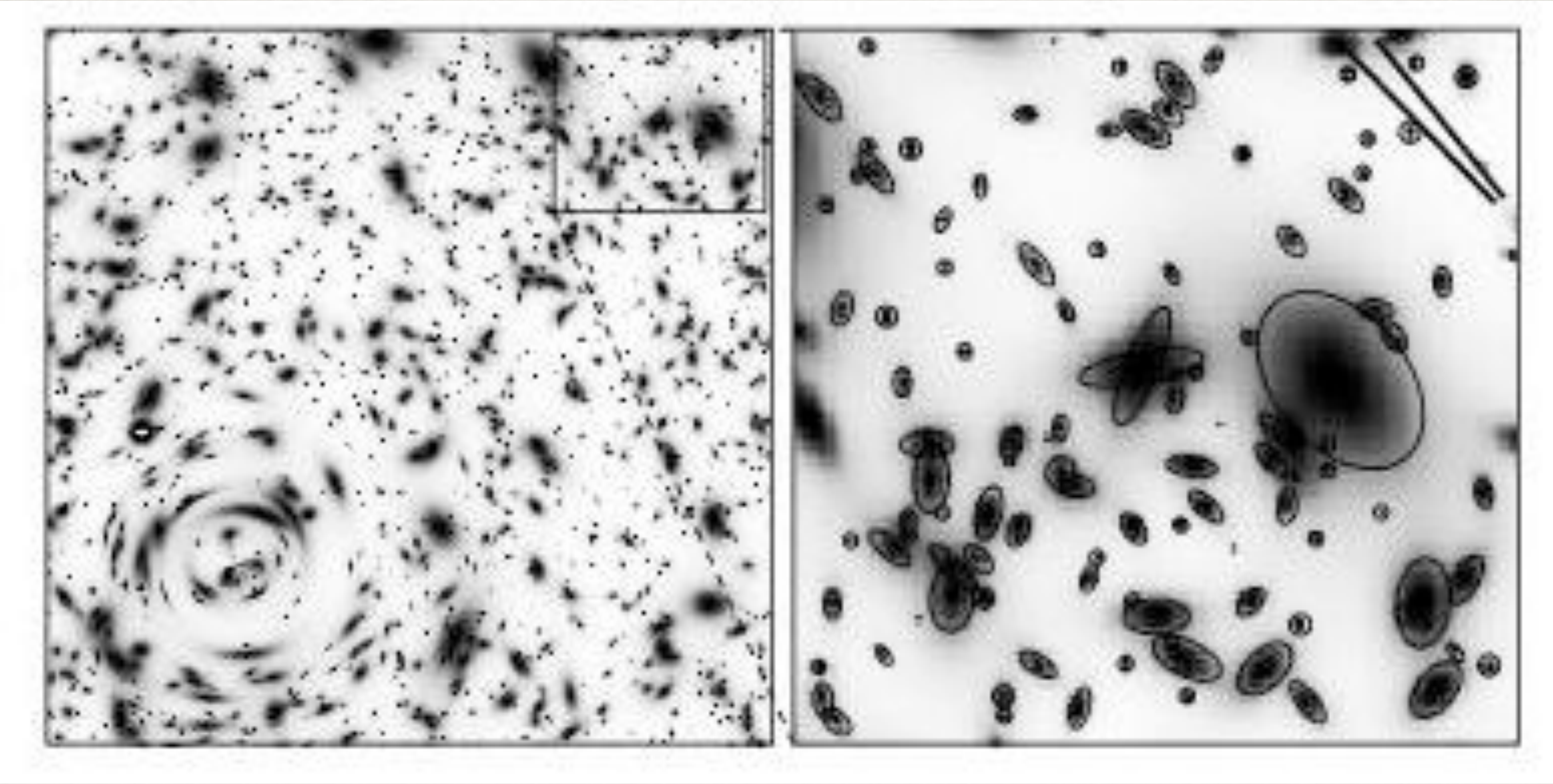
CMB



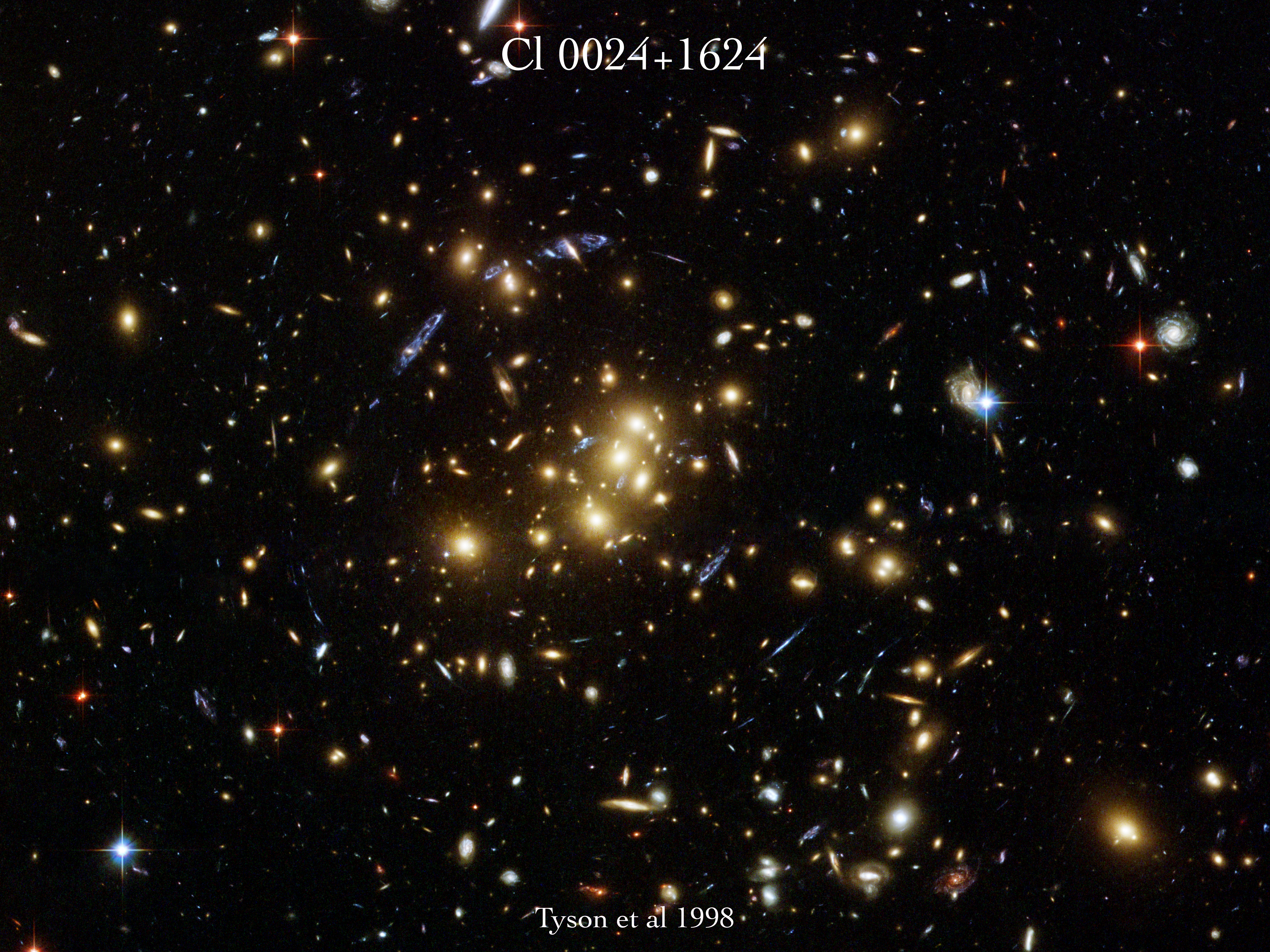
Aghanim et al 2016

Clusters of Galaxies

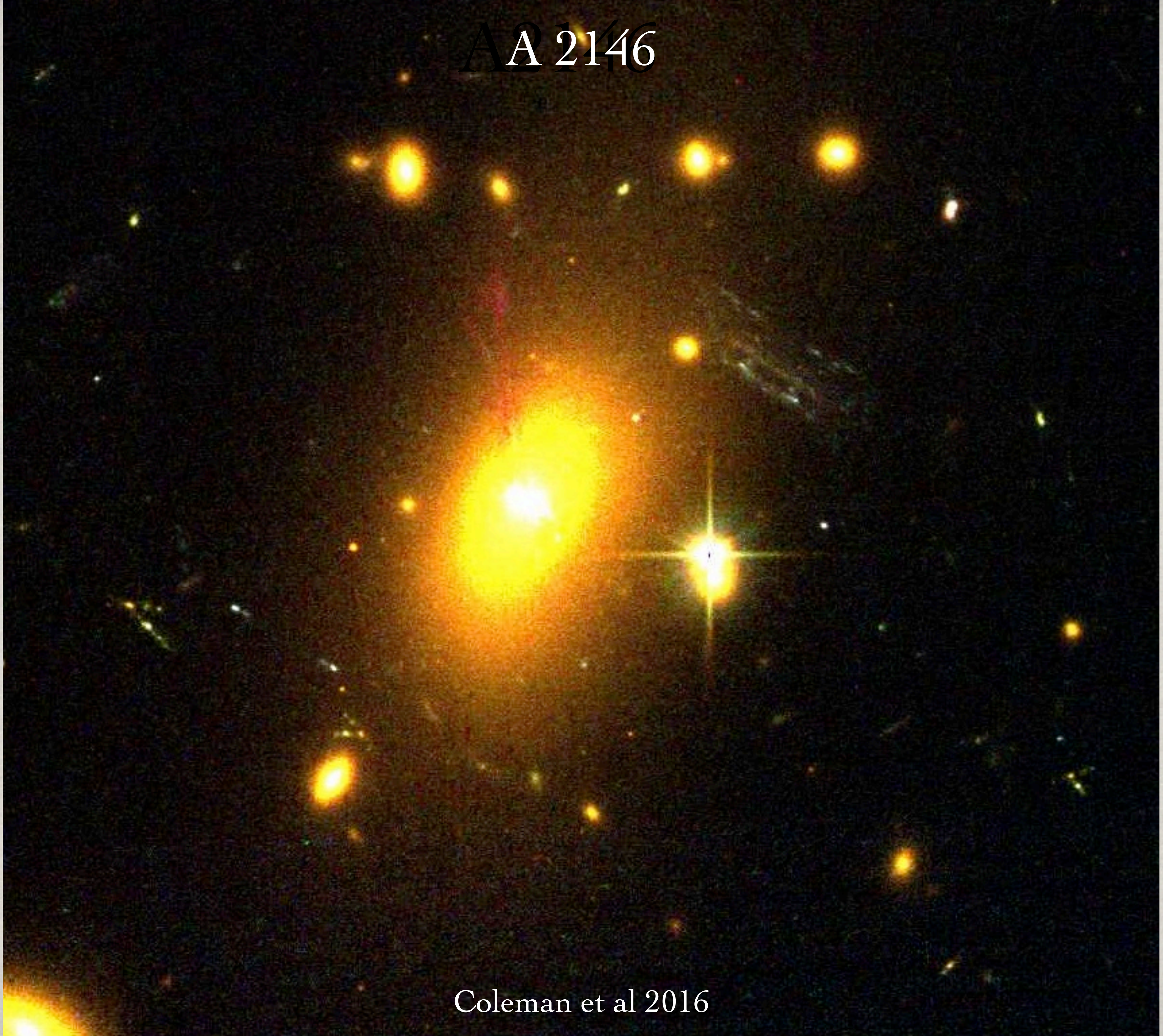
Lensing Simulation



Mellier 1999


Cl 0024+1624
Tyson et al 1998

A 2146



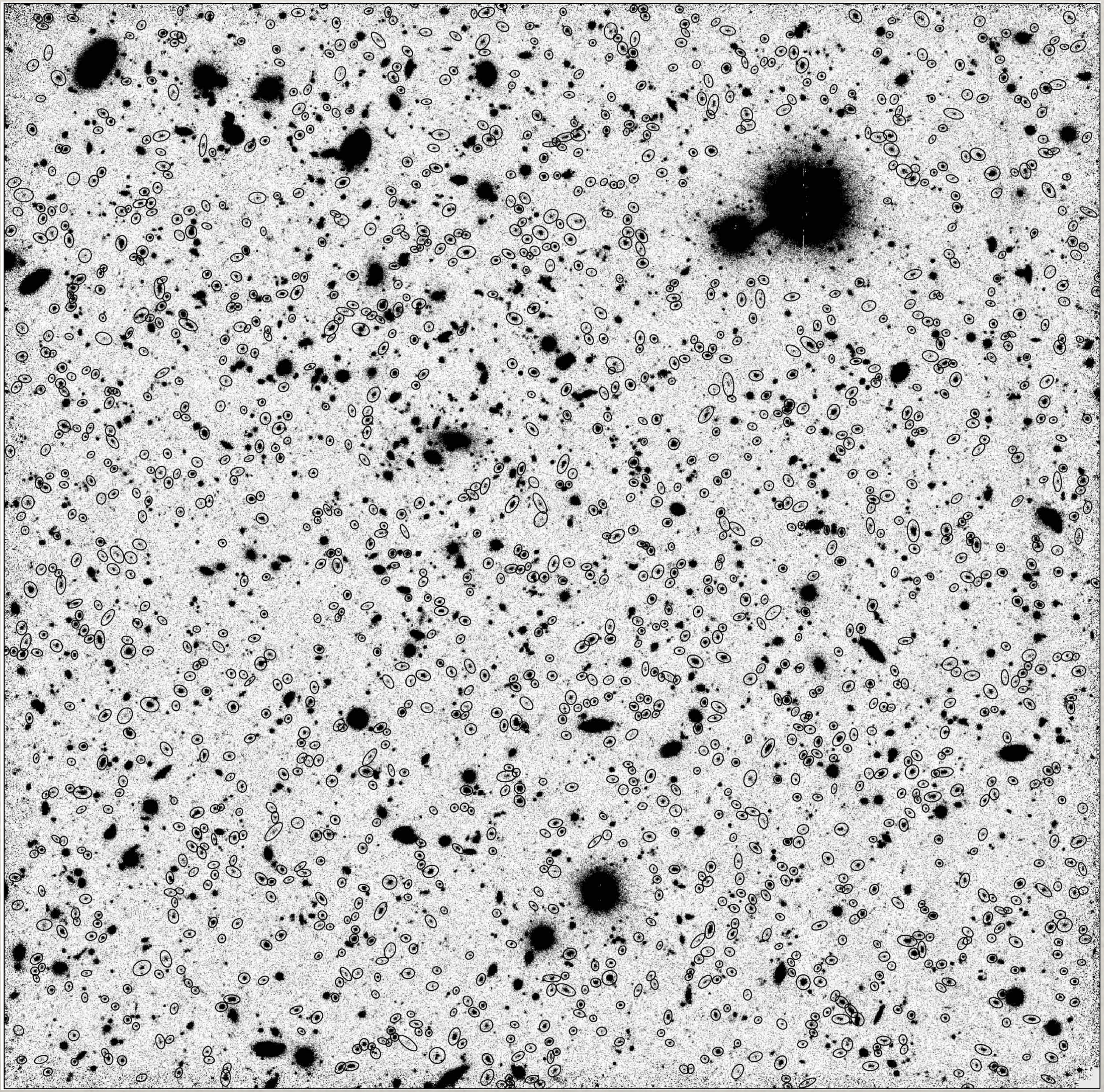
Coleman et al 2016

Weak Lensing Techniques

- Measure the galaxy ellipticities from the second moment of the surface brightness

- Correct ellipticities for image distortion and smearing by the Point Spread Function

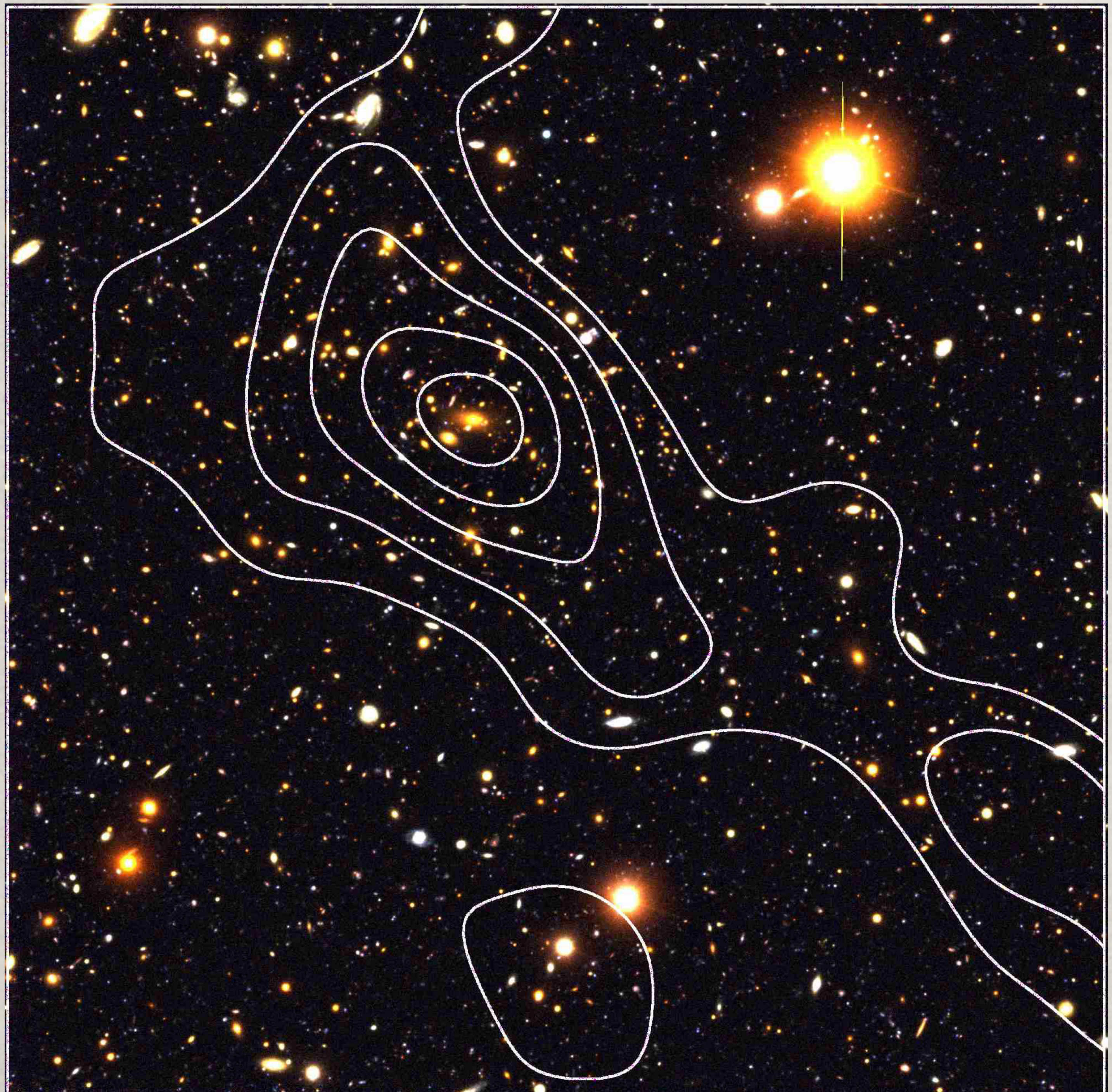
- Obtain a sparsely sampled, noisy measurement of the reduced shear g



- Measured reduced shear $g = \gamma/(1-\kappa)$
- Gravitational shear $\gamma = \left\{ \frac{1}{2}(\phi_{,11} - \phi_{,22}), \phi_{,12} \right\}$
- Convergence $\kappa = \frac{1}{2}\nabla^2\phi = \frac{\Sigma}{\Sigma_{\rm crit}}$
- can convert:

$$\vec{\nabla}\kappa = \left[\begin{array}{c} \partial\kappa/\partial x \\ \partial\kappa/\partial y \end{array} \right] = \left[\begin{array}{c} \partial\gamma_1/\partial x + \partial\gamma_2/\partial y \\ \partial\gamma_2/\partial x - \partial\gamma_1/\partial y \end{array} \right]$$

Reconstructed Surface Density

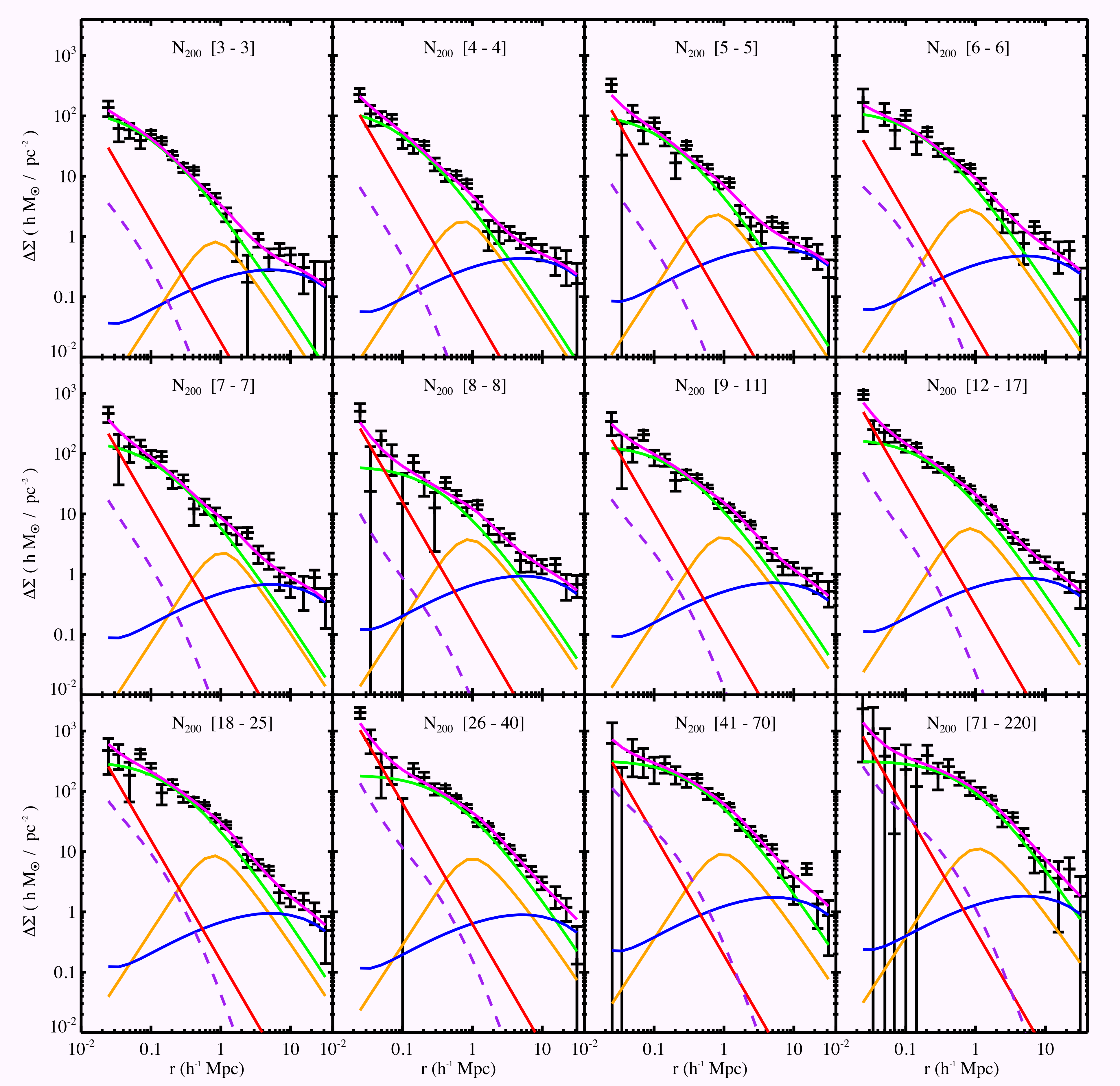


The white contours delineate regions of κ, or mass surface density

Weak Lensing Mass Measurements

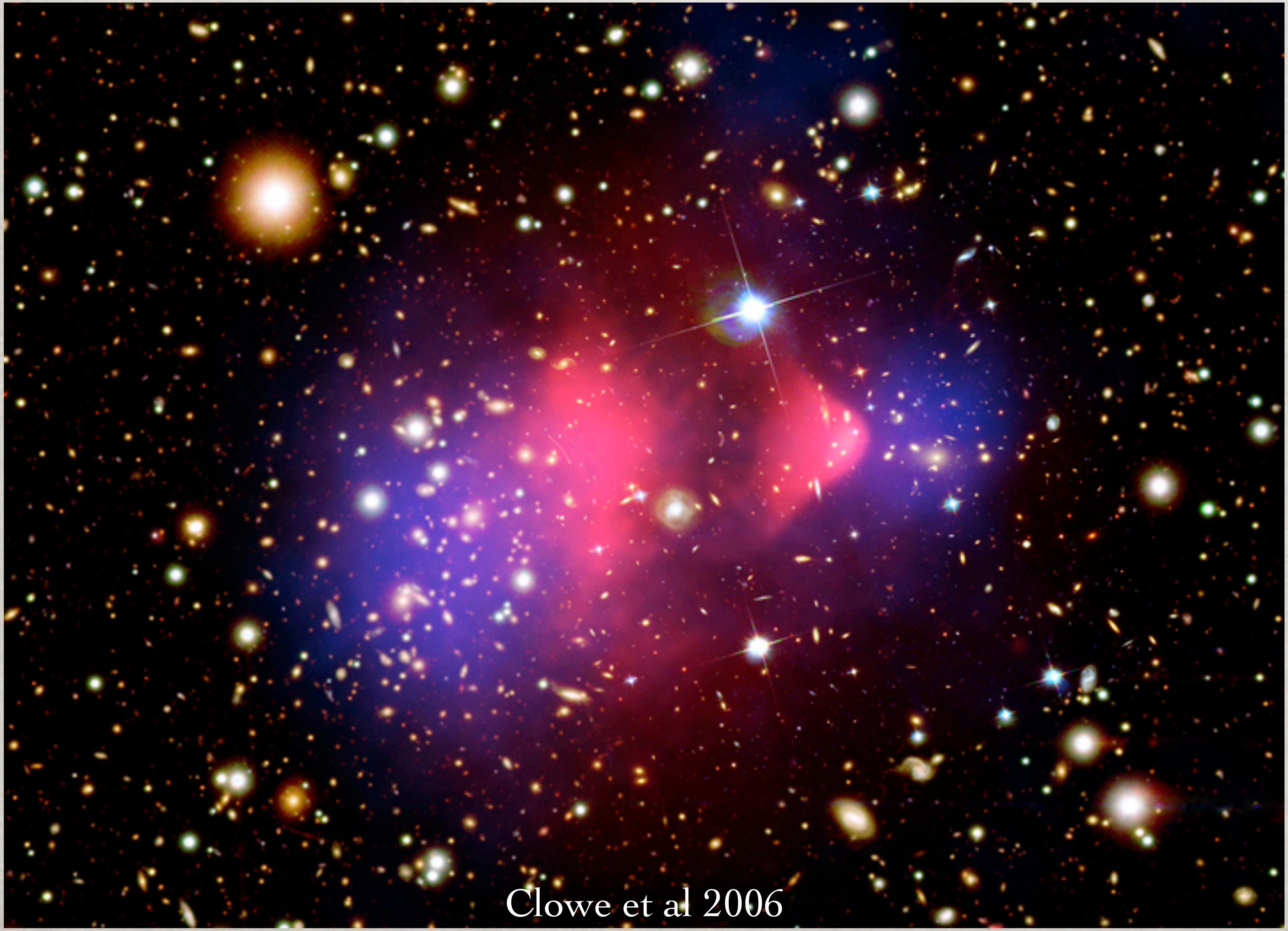
- Extremely noisy
  - 15-20σ measurement of 2-D mass best you can do
  - Conversion to 3-D mass has severe deprojection effects
  - Very sensitive to any additional mass along the line of sight

- No assumptions regarding dynamical state of the system



Johnston et al 2007

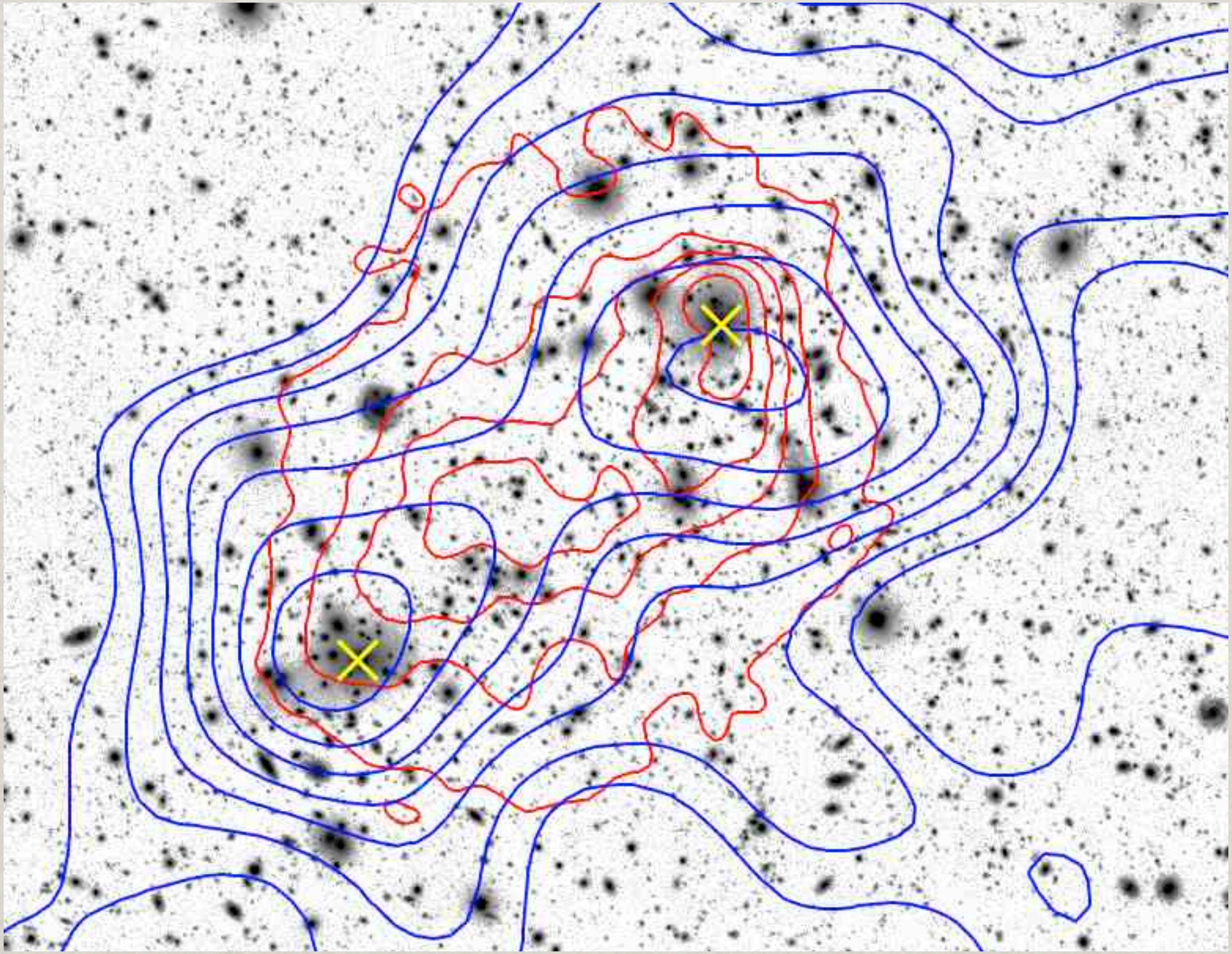
The Bullet Cluster



red = X-ray plasma

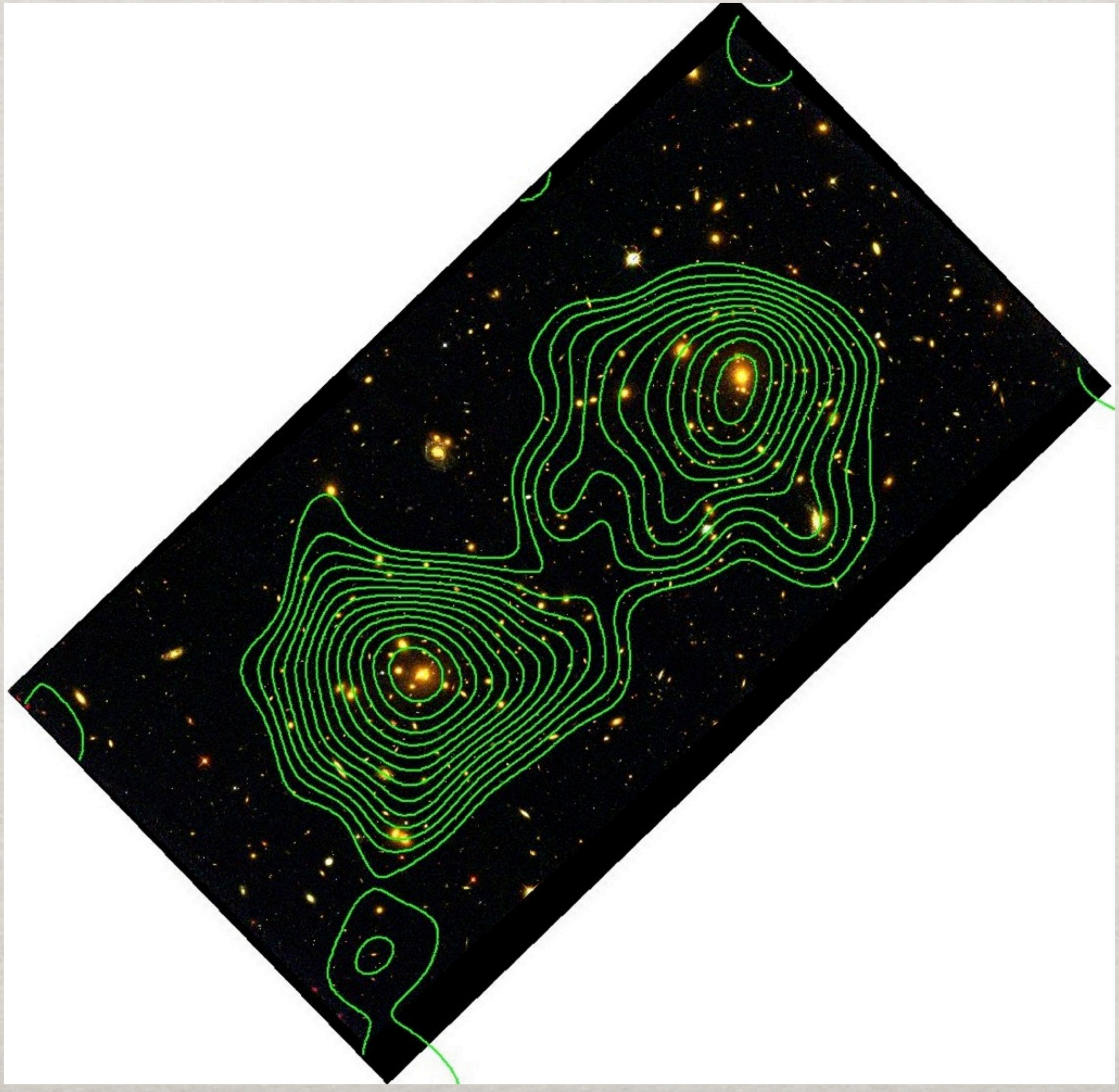
blue = weak lensing convergence

A1758N



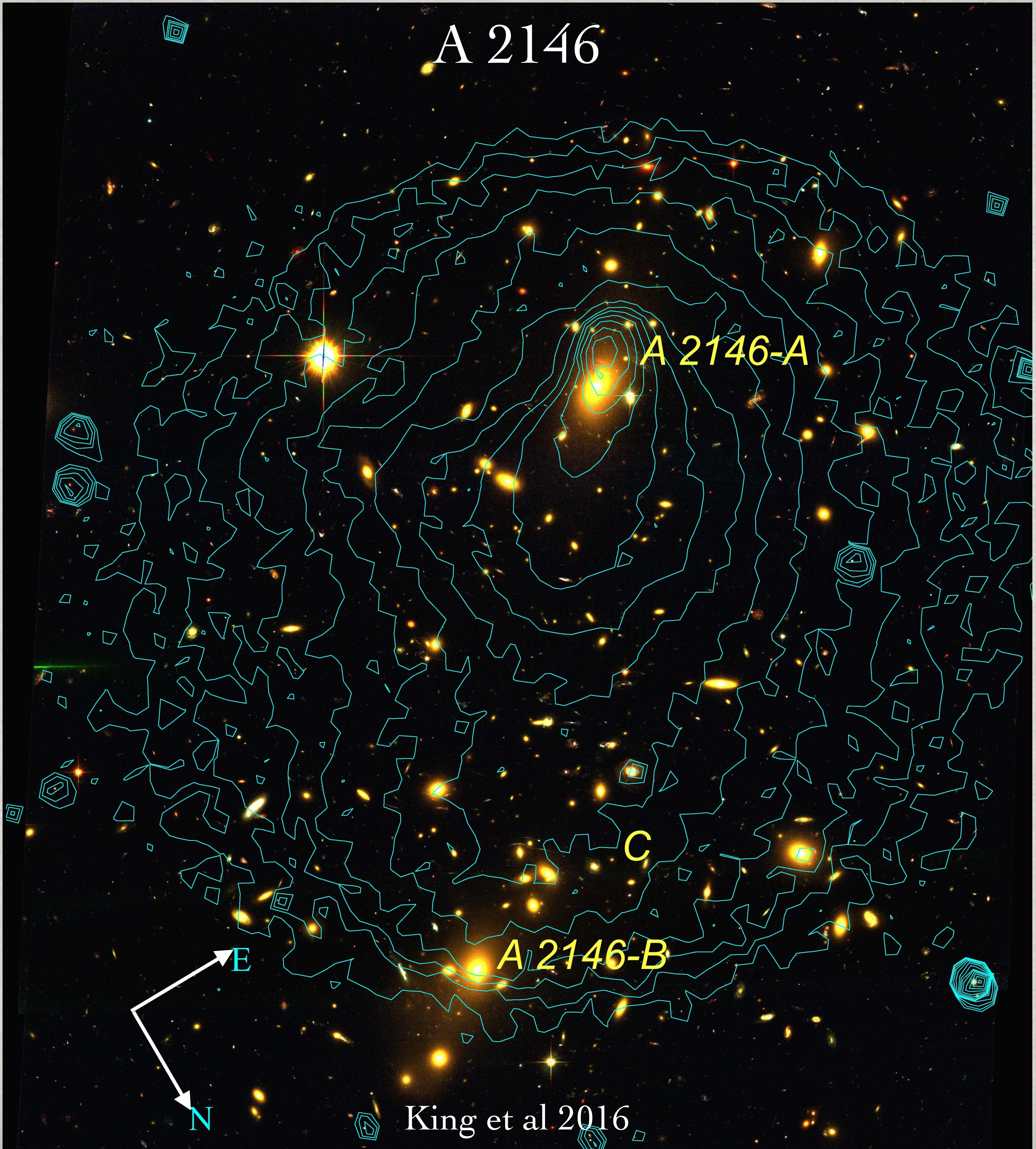
Ragozzine et al (2011)

A1758n (HST)

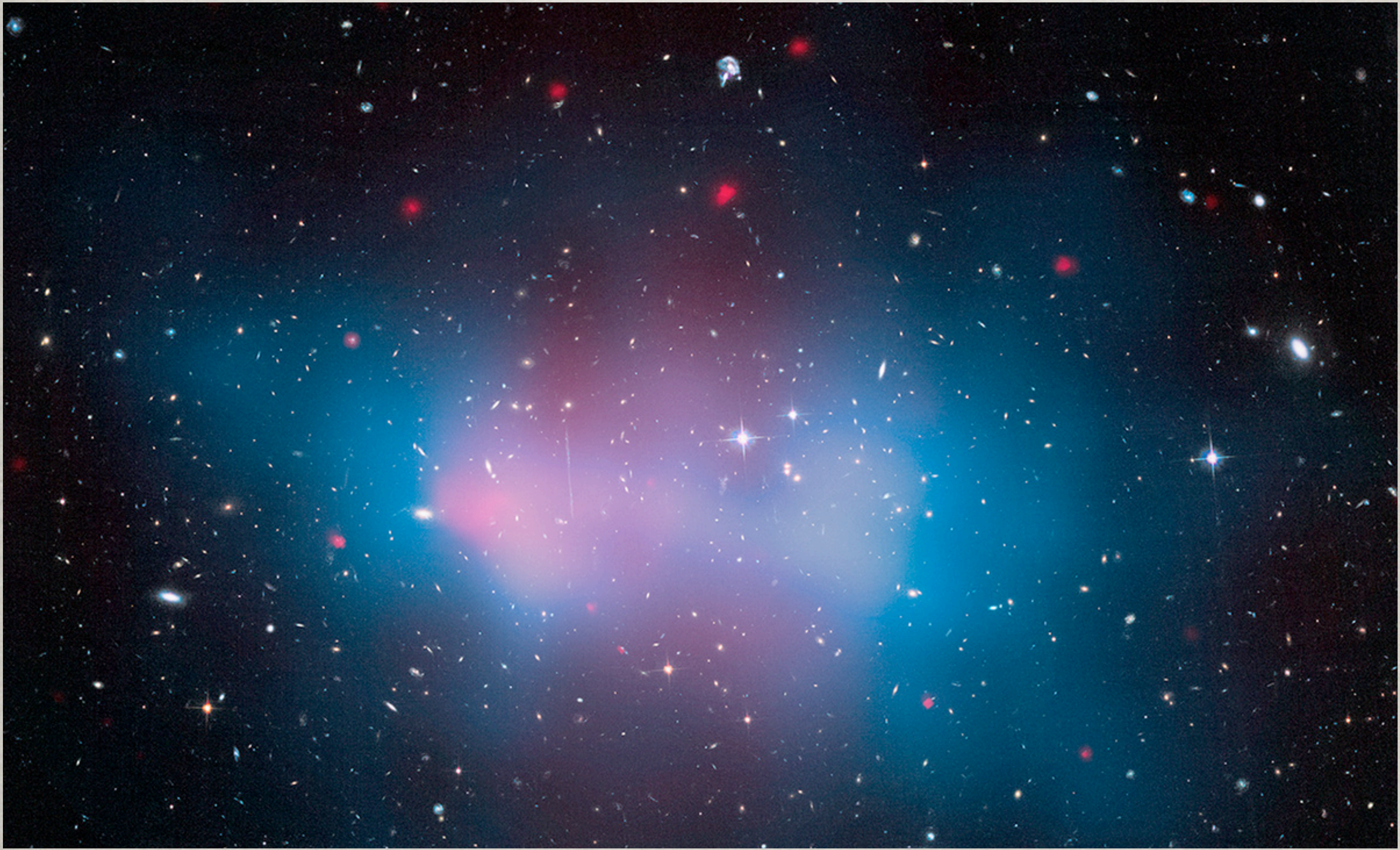


A2744

Merten et al (2011)

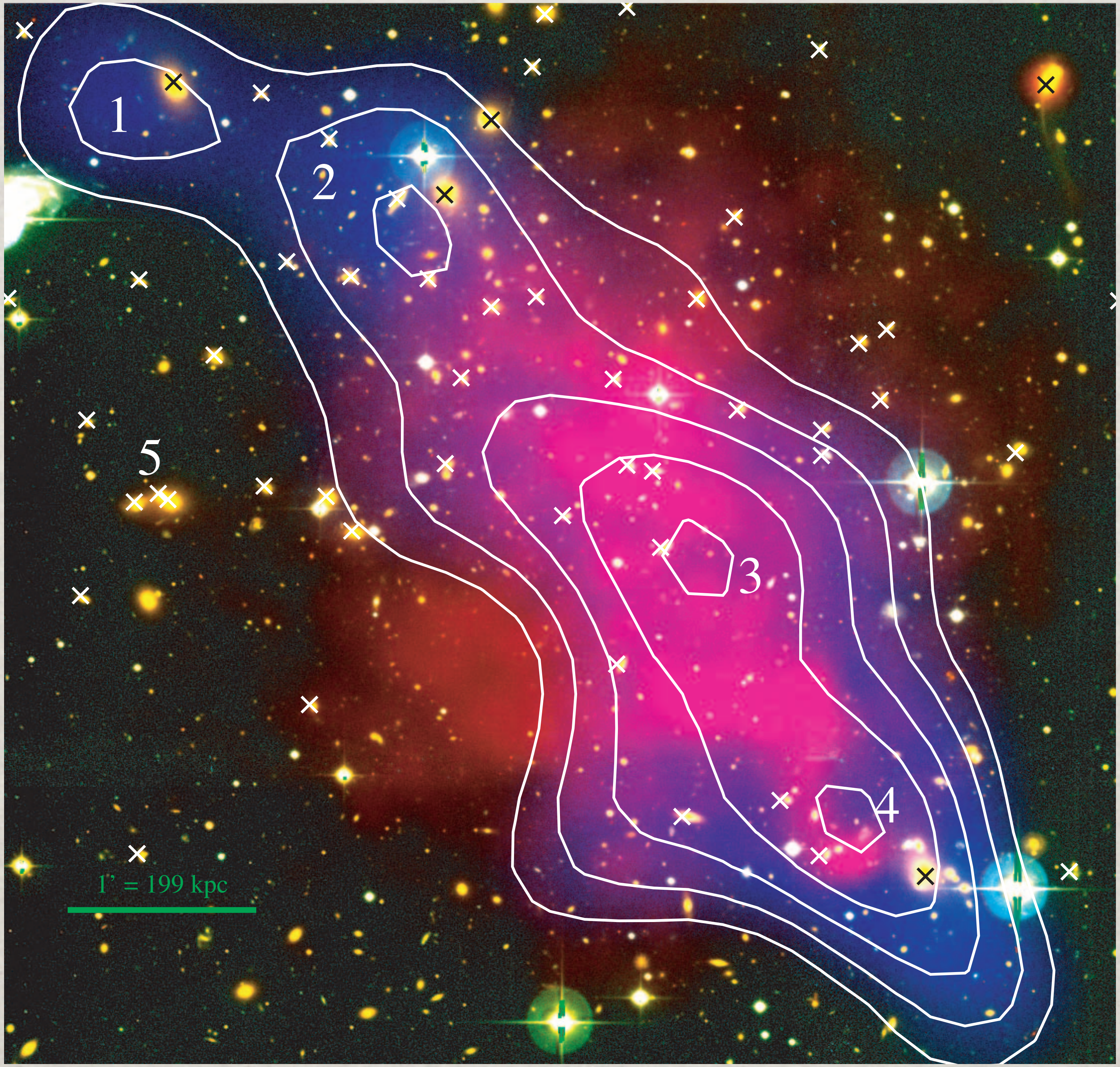

A 2146
A 2146-A
C
A 2146-B
E
N
King et al 2016

ACT-CLJ0102-4915

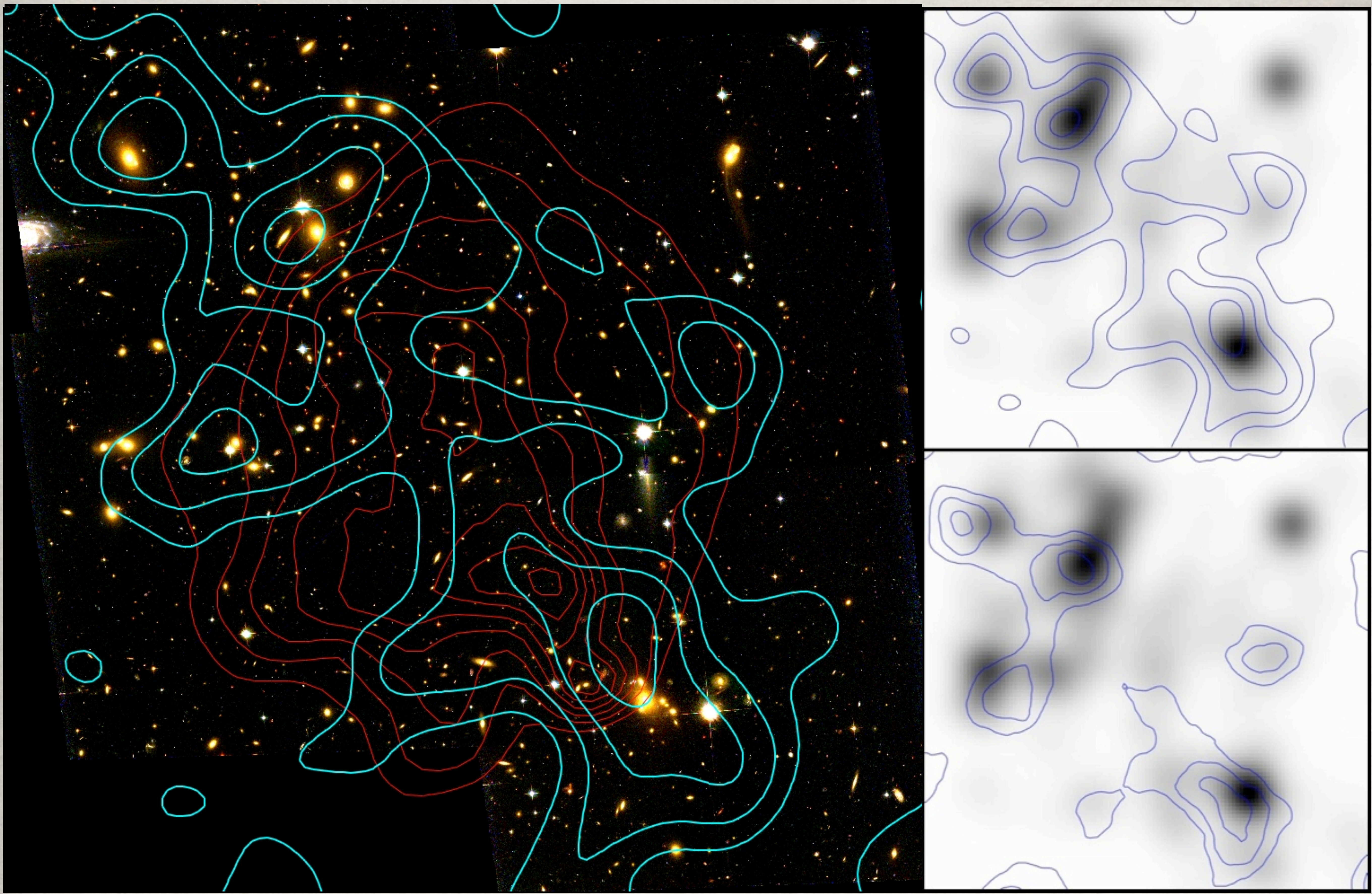


Jee et al 2014

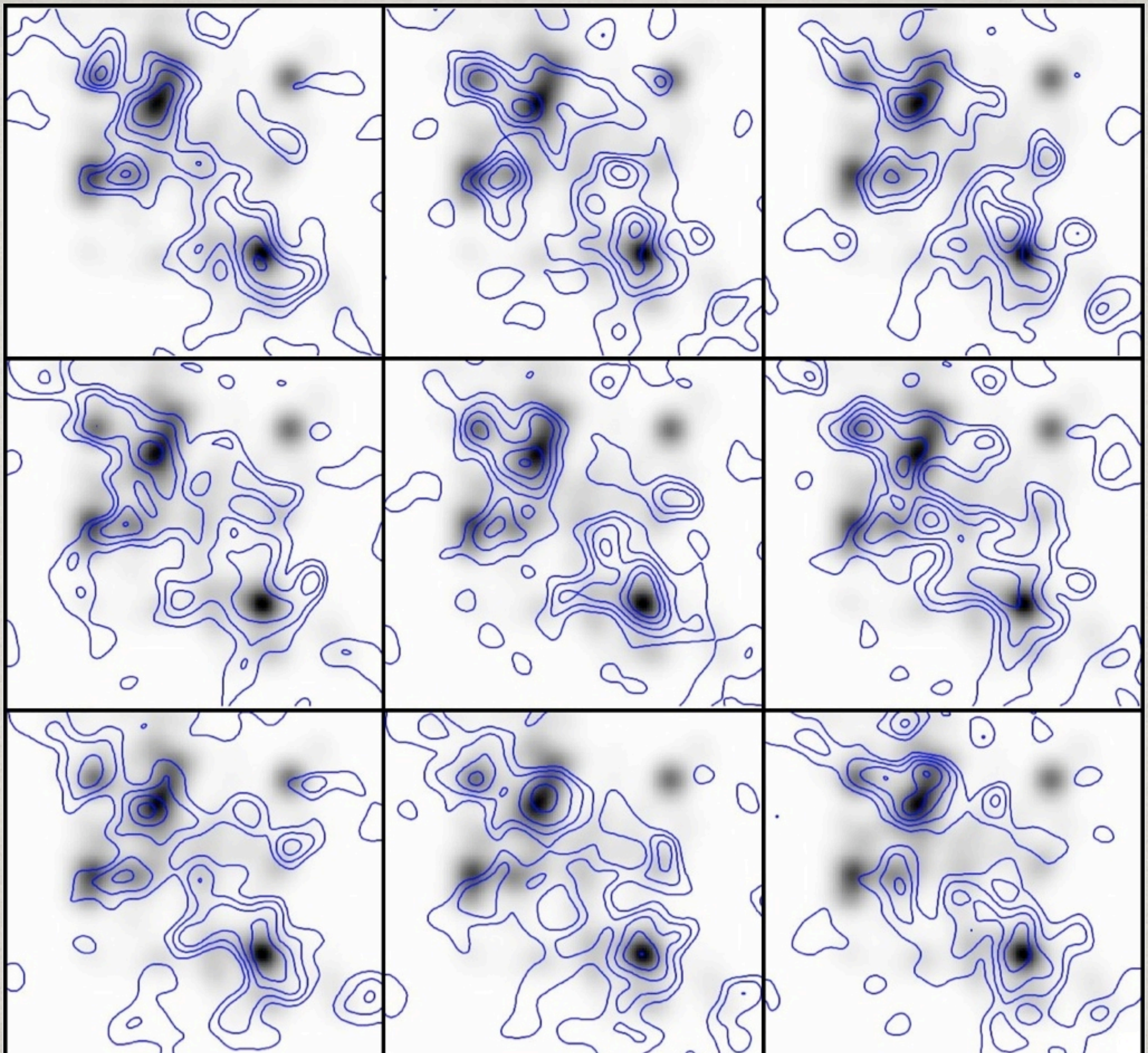
A520



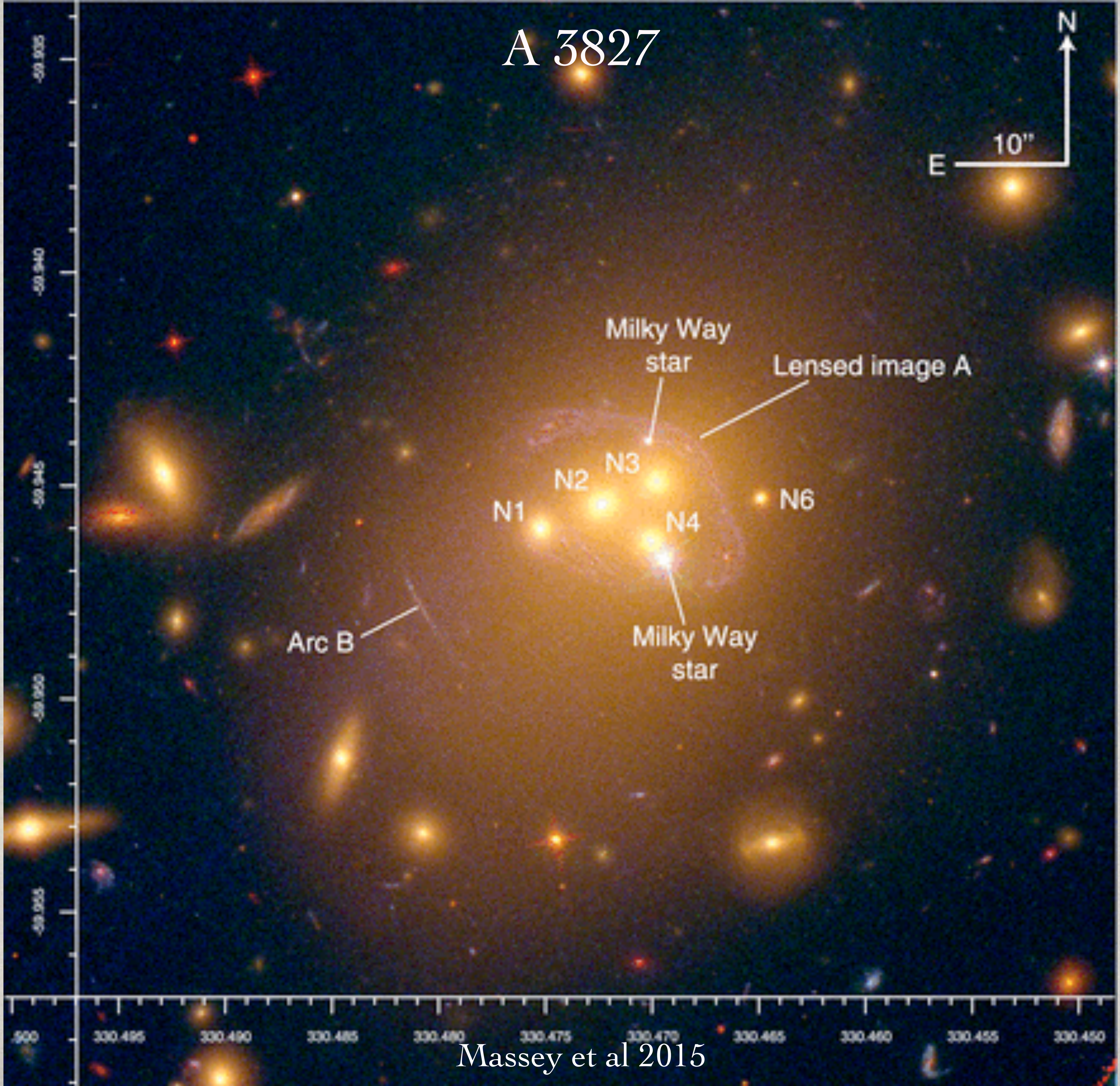
Mahdavi et al 2007



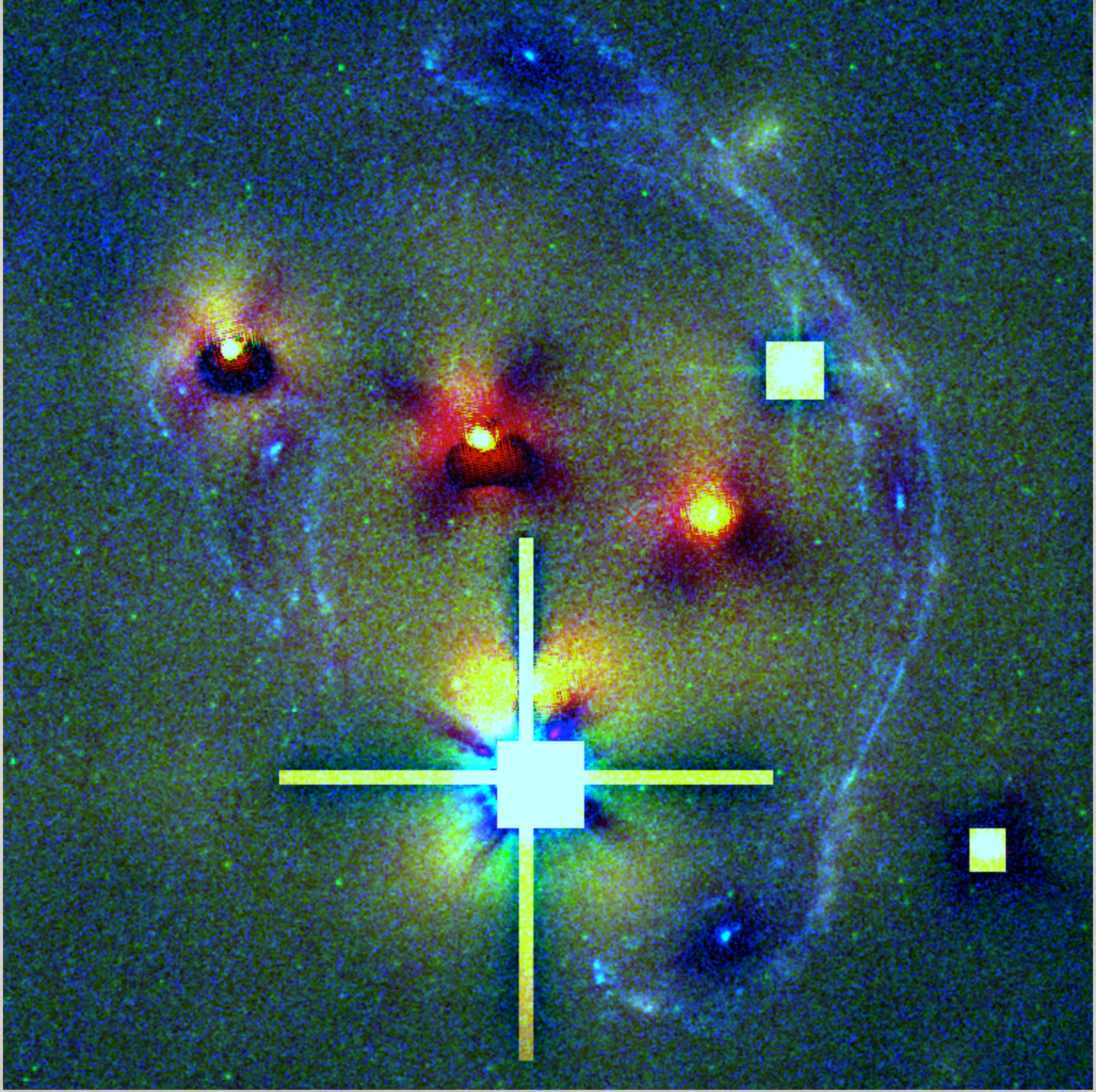
Clowe et al 2014

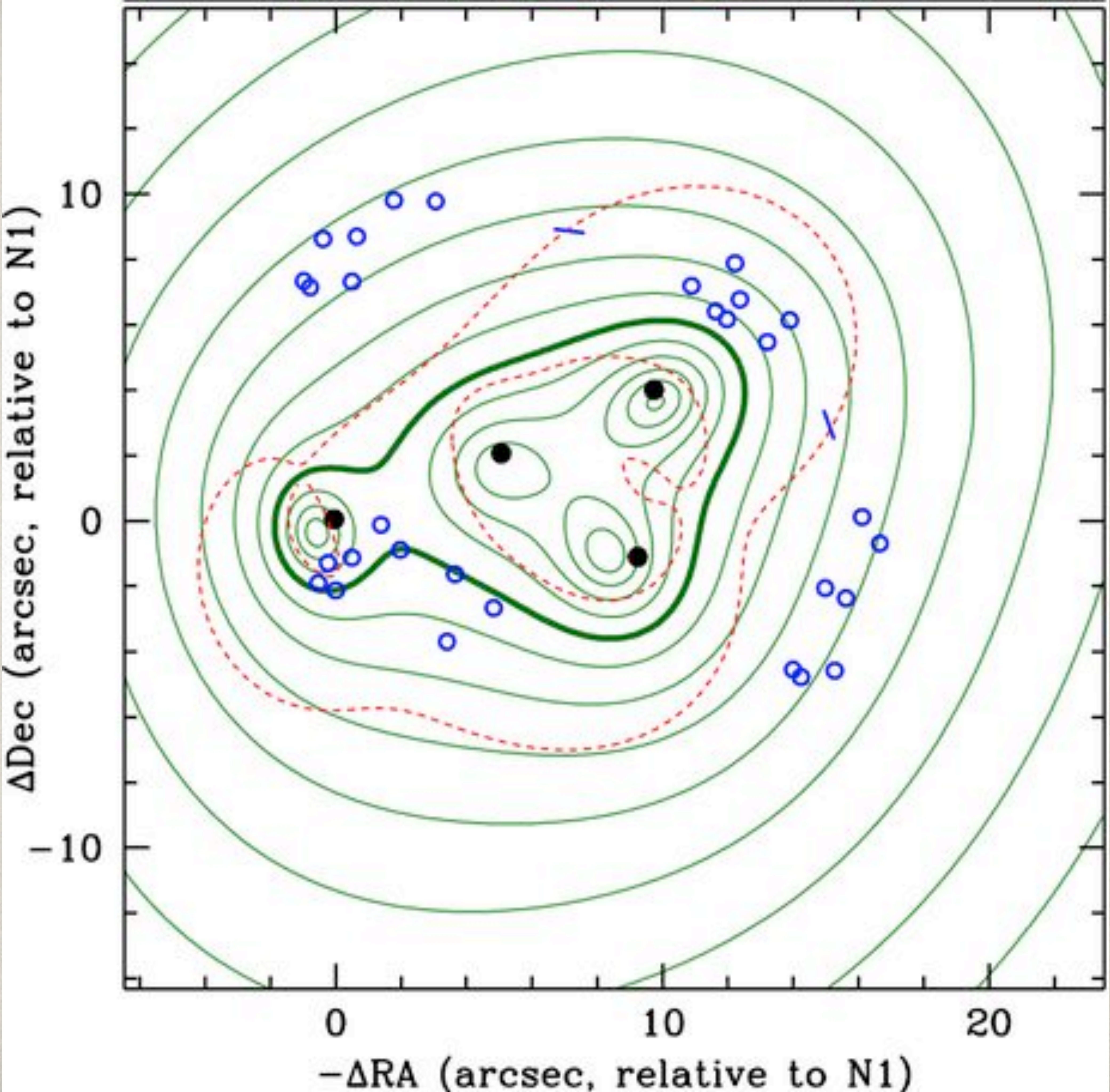


A 3827



Massey et al 2015





10
0
−10
ΔDec (arcsec, relative to N1)
0
10
20
−ΔRA (arcsec, relative to N1)

CDM Interaction Cross-Section

- Self-interacting dark matter with cross-sections 1-100 $cm^2\ g^{-1}$ have been proposed to alleviate problems with CDM (cuspy cores, excess small halos) (Spergel \&\ Steinhardt 2000).
- Simulations and theoretical studies have reduced the allowed range to 0.5-5 cm^2/g (Dave 2001; Ahn & Shapiro 2002).
- Agreement in position of dark matter and galaxy centroids in Bullet Cluster gives $\sigma/m < 1.25\ cm^2/g$.
- Offset between N1 galaxy and dark matter peak in A3827 implies $\sigma/m > 10^{-4}\ (t_{infall}/10^9\ \text{years})^{-2}\ cm^2/g$.
- Karlhoefer et al (2015) argue the A3827 offset gives a lower limit of $\sigma/m > 1.5\ cm^2/g$.

	Bullet cluster upper limit	A3827 lower limit $(t/10^9\ \mathrm{yr})^{-2}$	A3827 lower limit (upper)
cm^2/g	1.25	10^{-4}	1.5
b/GeV	2.23	1.78×10^{-4}	2.67
perch/stone (Brexit!)	3.14×10^{-2}	2.52×10^{-6}	3.77×10^{-2}
akaina/talent	3.48×10^{-10}	2.78×10^{-14}	4.18×10^{-10}
alen^2/Ørtug	2.84×10^{-3}	2.27×10^{-7}	3.41×10^{-3}

Summary

- Astronomical evidence for dark matter spans objects that span a range of 10^7 in mass and 10^4 in radius (plus the CMB)
- Most merging cluster systems obey the light-traces-mass CCDM paradigm
- In an independent ground based image and a multi-color ACS mosaic, we find no signs of the dark peak in A520. Jee, with the same data, argues one is still there
- The Bullet Cluster gives an upper limit on the collisional cross section of DM of 1.3(0.7) cm^2/g. A3827 gives a possible lower limit of 10^{-4} (1.5)cm^2/g
- Using alternative gravity models (TeVeS/MOND) reduces the amount of dark matter needed in clusters, but still at least 70% of a cluster's mass must be dark matter

MOND (TeVeS) Modeling

From Poisson's equation: $\nabla^2 \Phi = 4\pi G \rho$

Replace G by G_{eff}:

$$\frac{G}{G_{\text{eff}}} = \mu(x) = 1 - \left(\frac{1+\alpha x}{2} + \sqrt{\left(\frac{1-\alpha x}{2}\right)^2 + x} \right)^{-1}$$

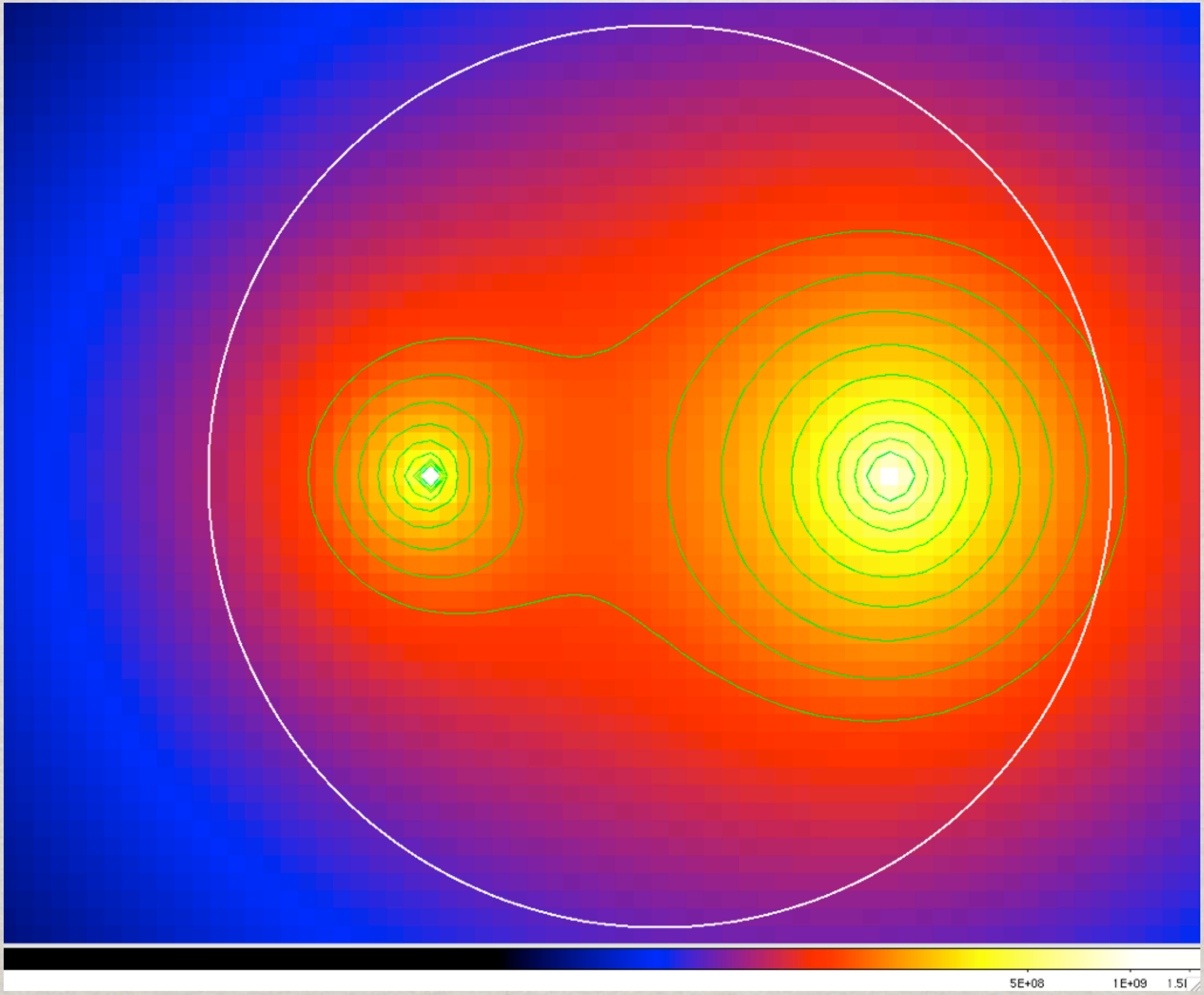
where $x = \dfrac{|\nabla \Phi|}{a_0}$

$\alpha = \infty$ unmodified gravity

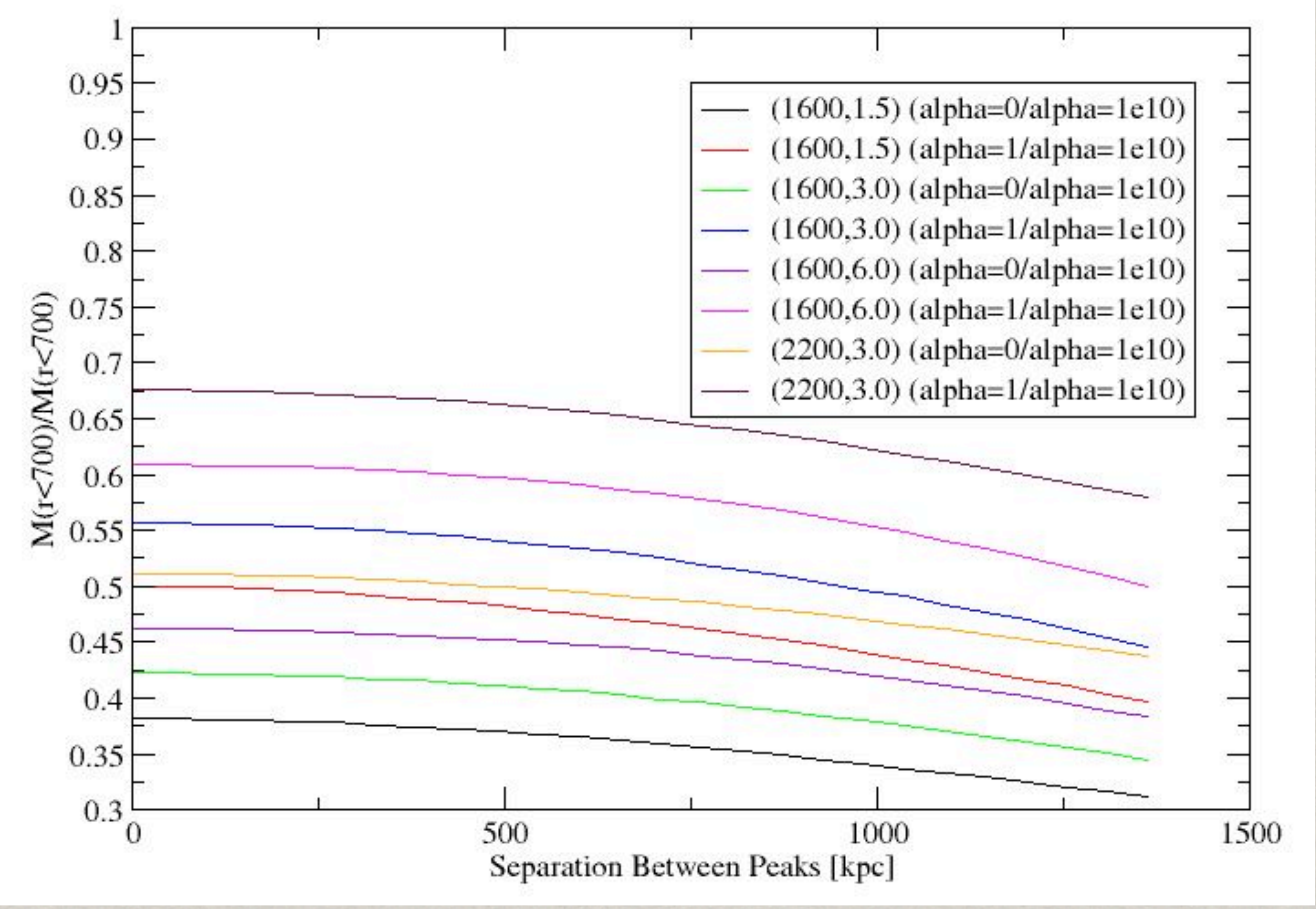
$\alpha = 0$ Bekenstein (2004) toy model

$\alpha = 1$ Better fit to Milky Way rotation curve (Famaey & Binney)

Effects of MOND



Changing Cluster Mass with Separation Distance



LOS Distance Effects in MOND

Inclination	Mass(Φ_{Angus}) $\alpha = 0$	$\alpha = 1$	$\alpha = \infty$	Mass(Φ_{NFW}) $\alpha = 0$	$\alpha = 1$	$\alpha = \infty$
0°	2.81	4.00	8.45	3.01	4.29	8.04
10°	2.80	3.98	8.45	3.00	4.27	8.04
20°	2.78	3.95	8.45	2.98	4.24	8.04
30°	2.74	3.90	8.45	2.93	4.19	8.04
40°	2.68	3.81	8.45	2.87	4.10	8.04
50°	2.58	3.68	8.45	2.77	3.96	8.04
60°	2.46	3.49	8.45	2.64	3.77	8.04