A Direct Empirical Proof of the Existence of Dark Matter

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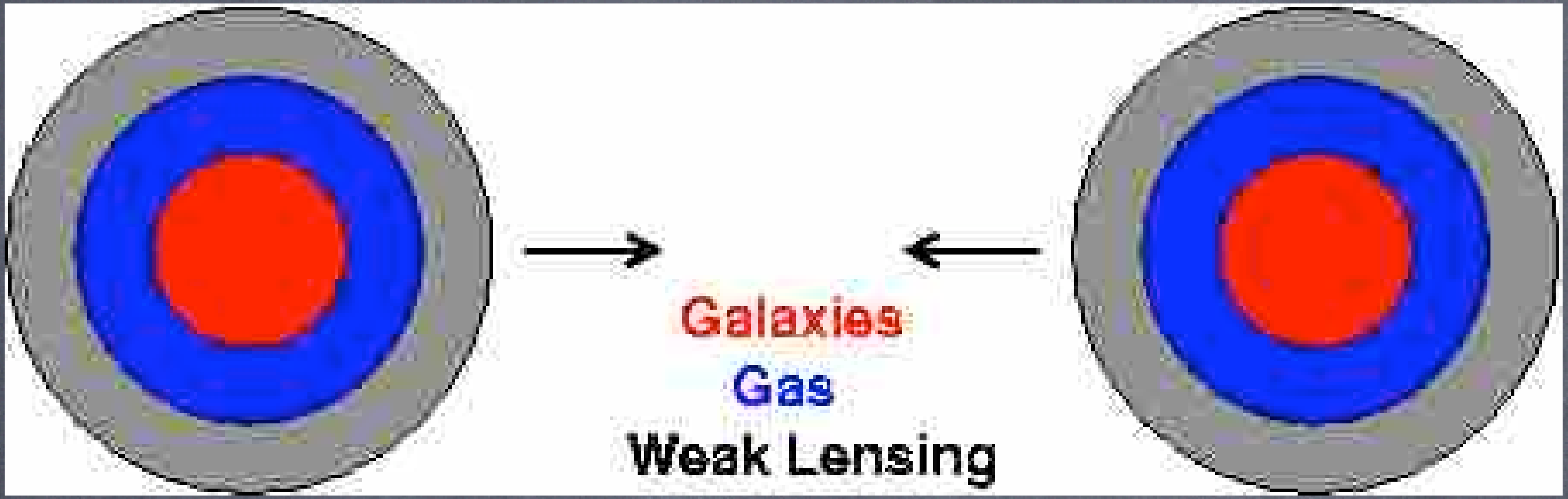
Excess gravity in clusters

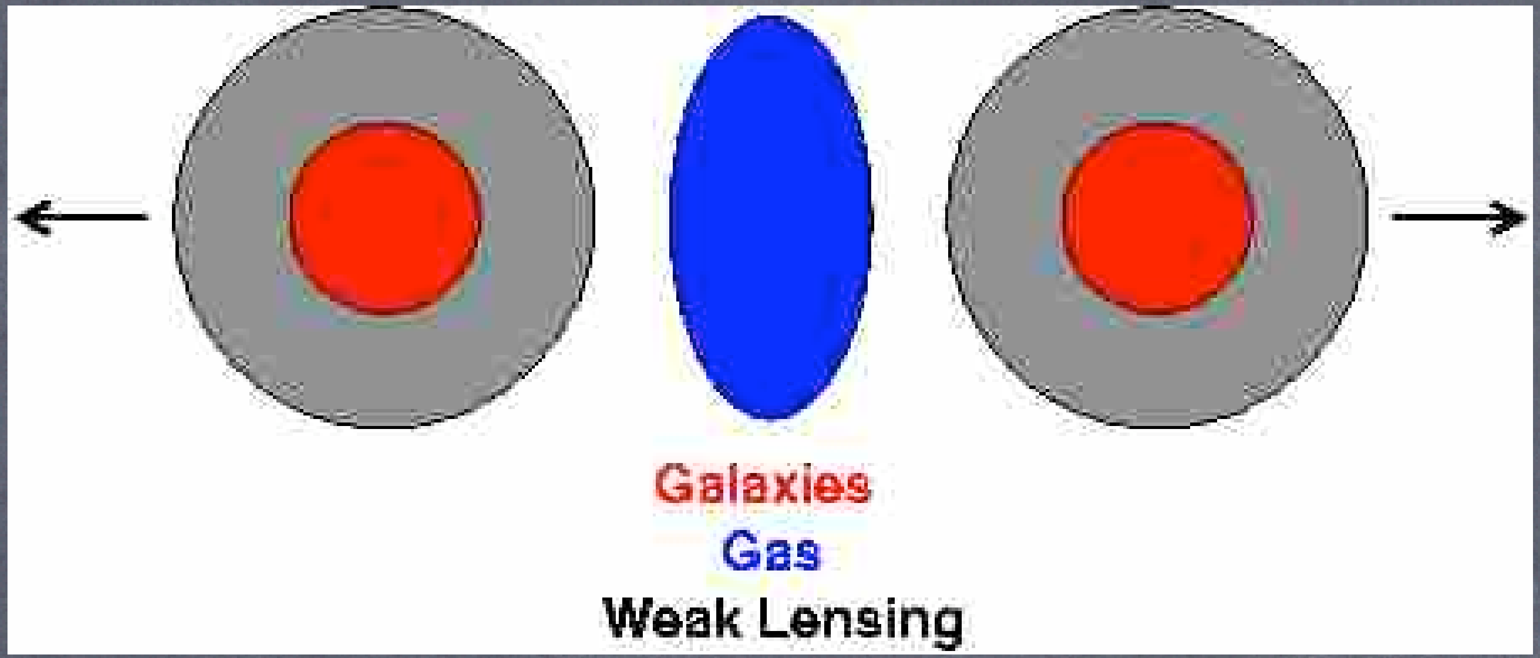
- Zwicky (1933) pointed out that the Coma cluster had a virial mass > 100× larger than the visible stellar matter
- Concluded that either the majority of the mass of the cluster was some type of non-luminous matter, or gravity was not Newtonian on these scales
- Discovery of the X-ray plasma reduces the gravity excess to 6-10× Newtonian gravity from visible matter
- Assumption of dark matter due mostly to lack of a compelling non-Newtonian gravity theory

Merging cluster system before impact



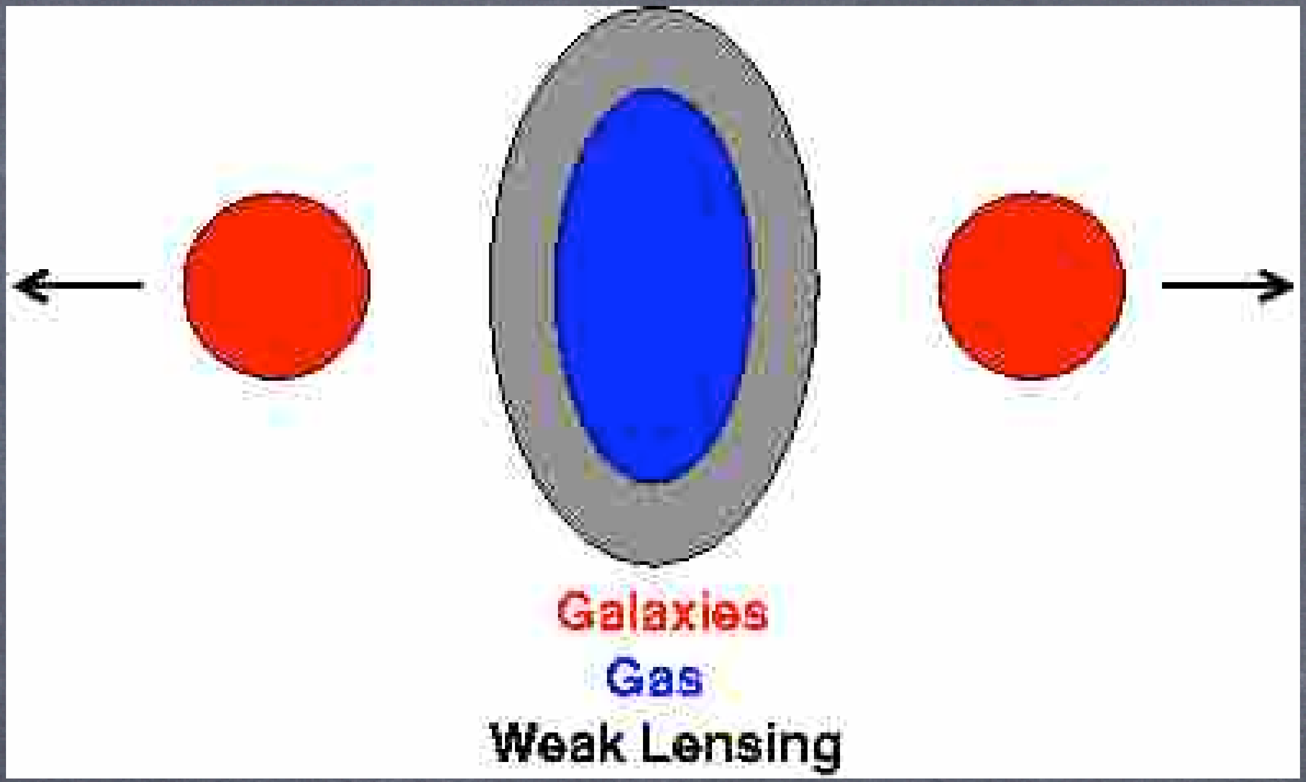
Galaxies, plasma, and any dark matter are all in the same place, so difficult to tell what generates the excess gravity

System after impact with dark matter



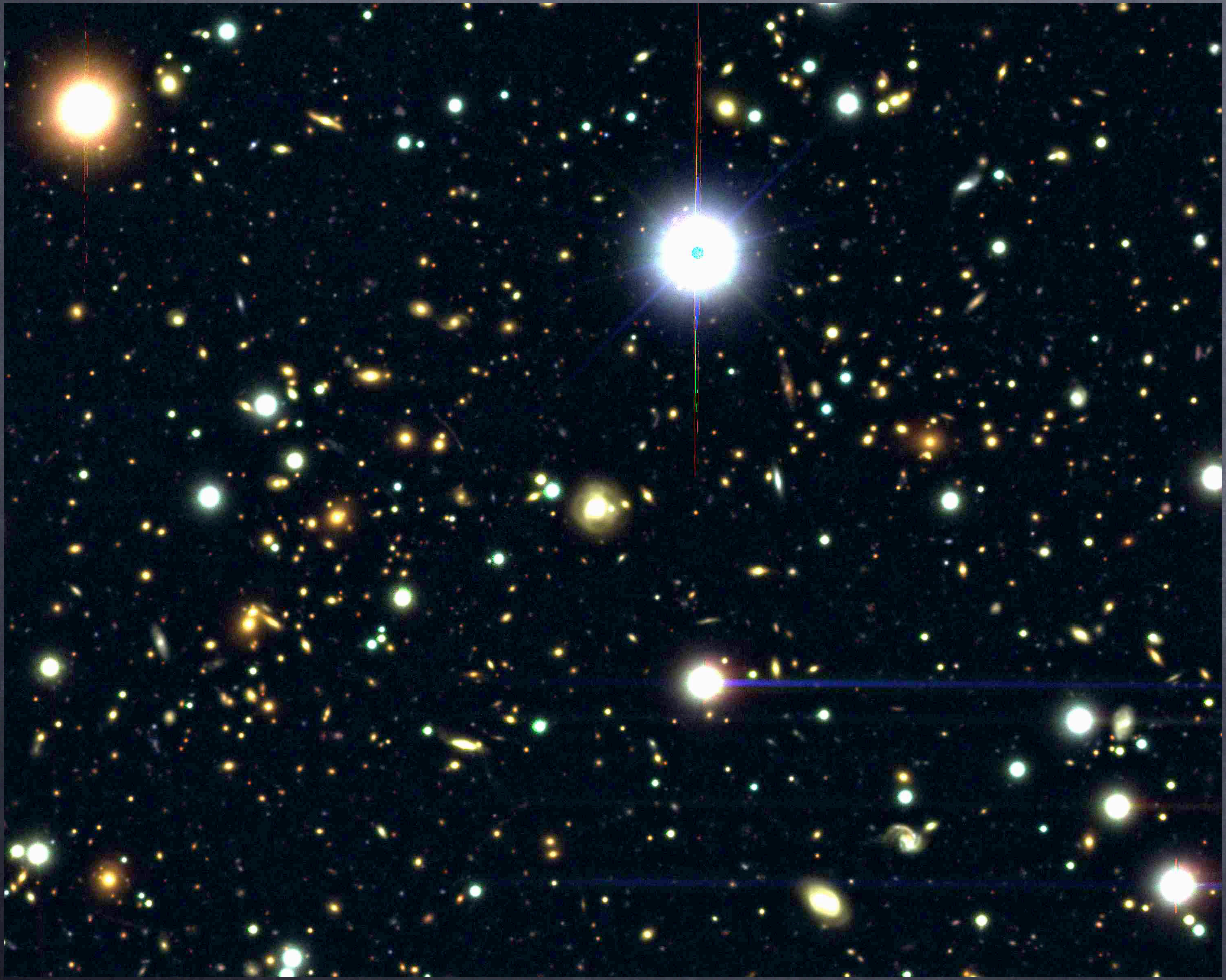
Plasma has separated from galaxies and dark matter, most of the mass and therefore most of the gravity is around the galaxies + dark matter

System after impact with alternative gravity



Plasma separated from galaxies, but the majority of the mass is now the plasma, so the gravity is mostly around the plasma

1E0657-558
“The Bullet Cluster”



Collaborators:

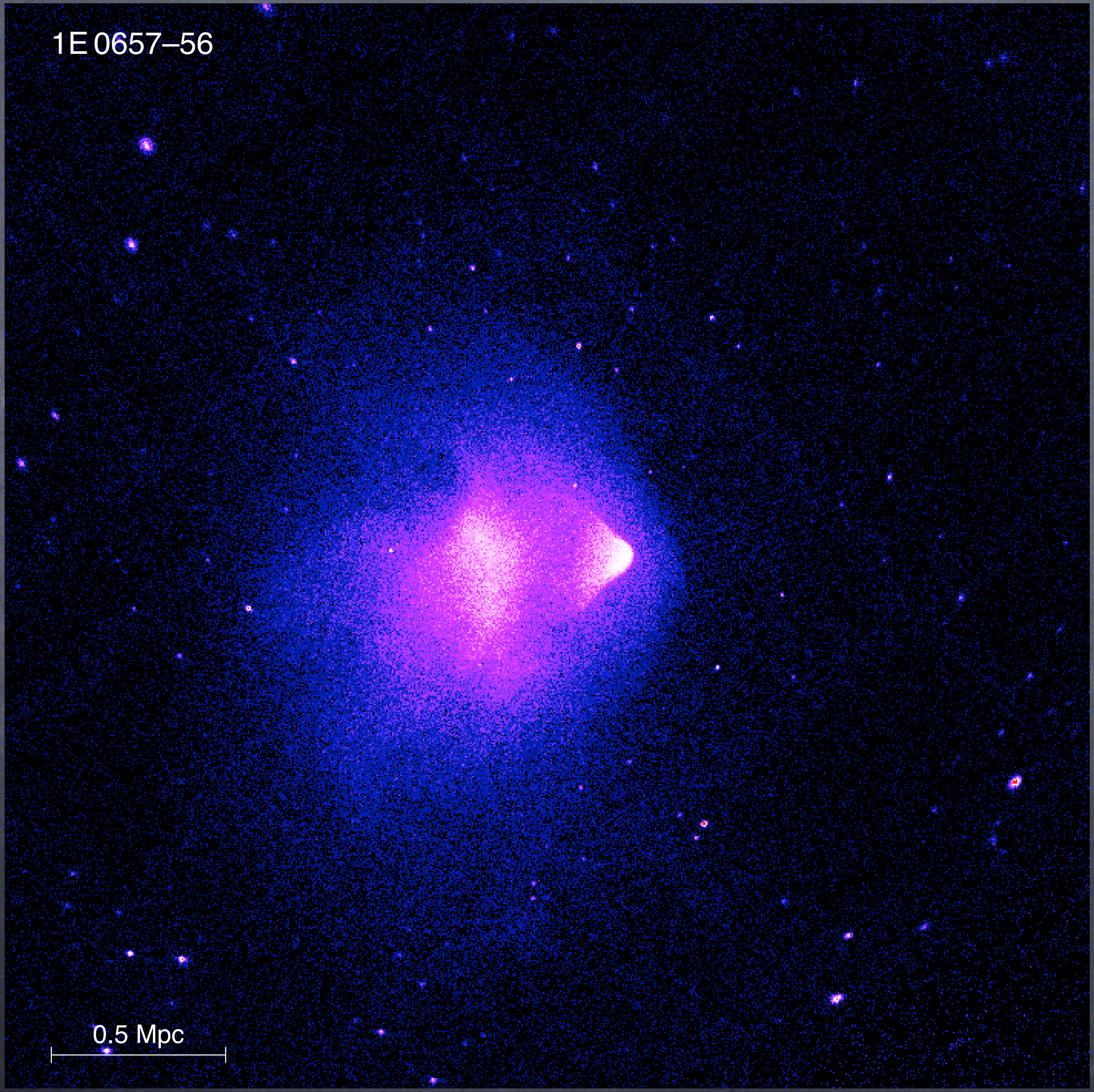
Stanford:
- M. Bradac

Harvard CFA:
- M. Markevitch
- S. Randall
- C. Jones Forman

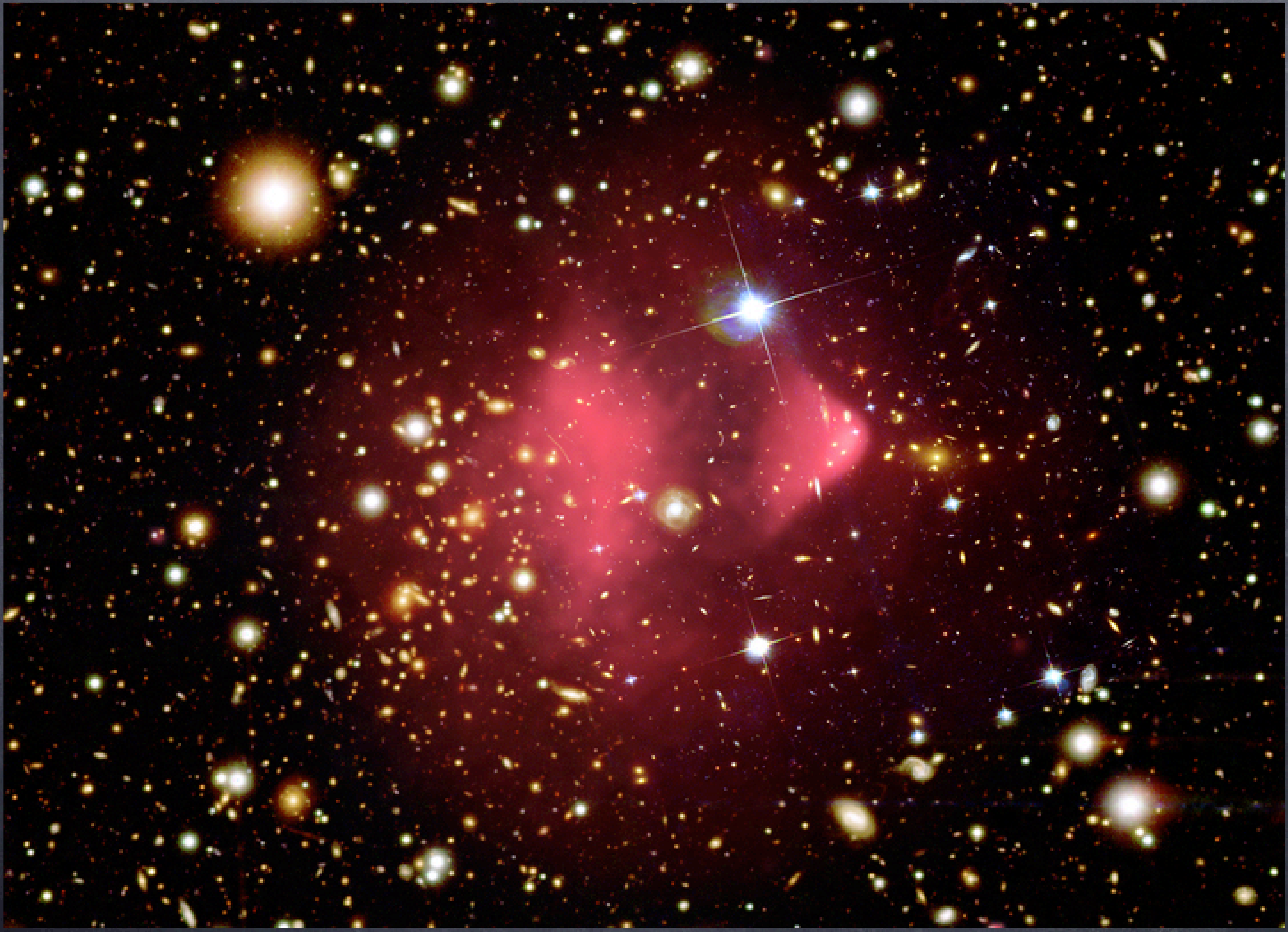
Arizona:
- D. Zaritsky

Florida:
- A. Gonzalez

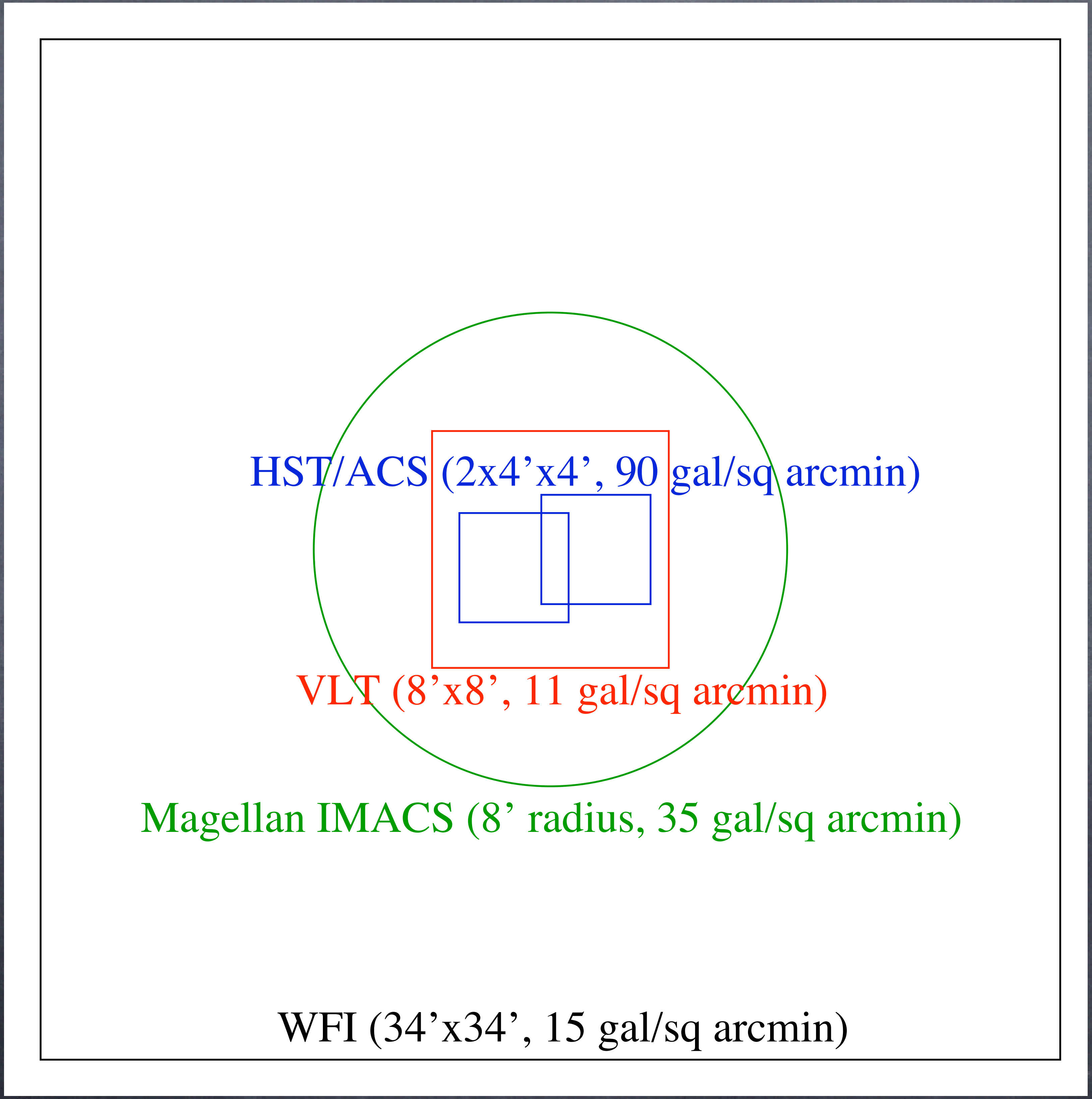
500 ks Chandra Observation



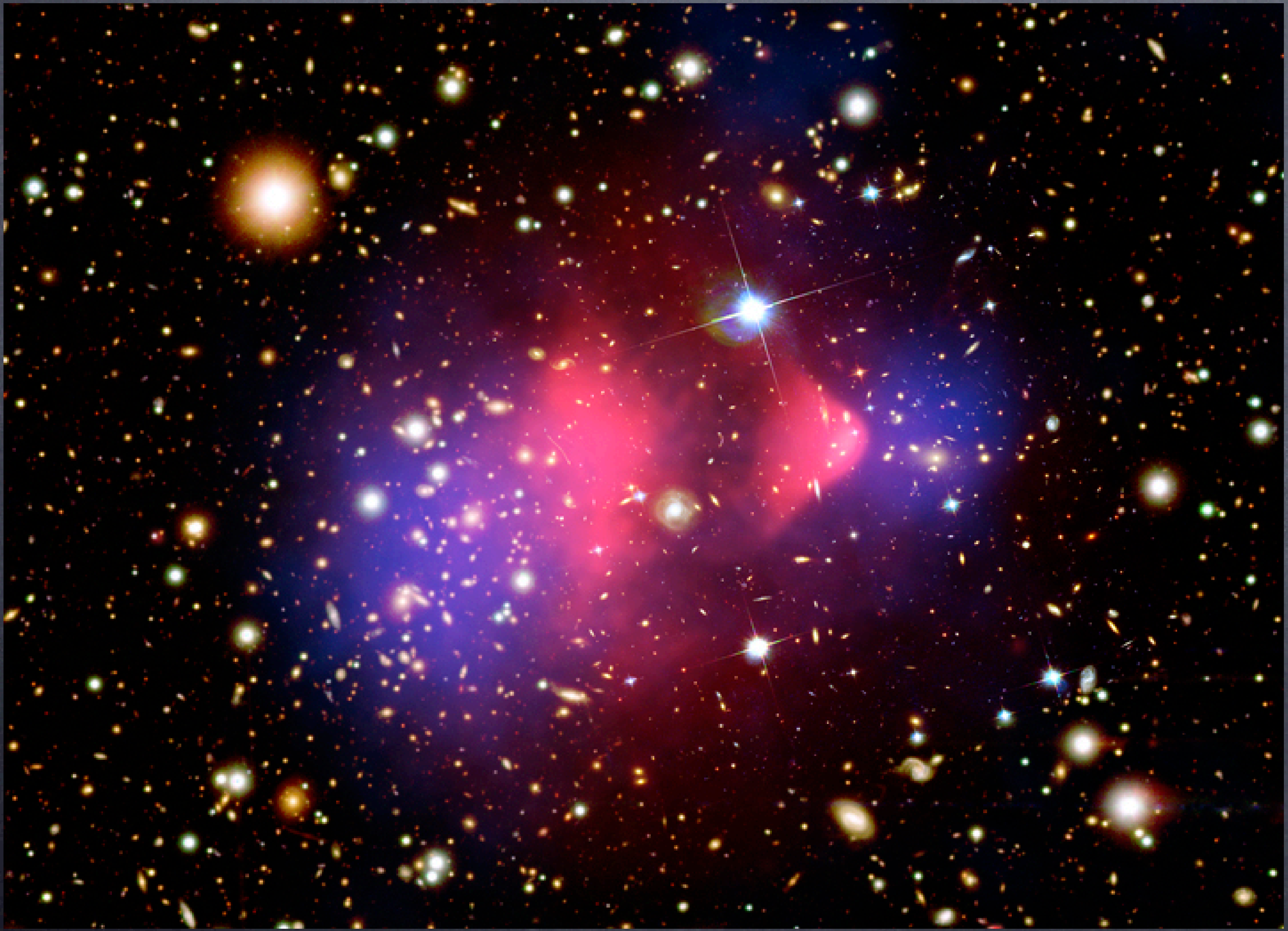
X-ray - Galaxy Offset



Optical Imaging



Weak Lensing Reconstruction



red = X-ray plasma

blue = weak lensing convergence

Sources of Error

- Intrinsic ellipticity of background galaxies
- Projection of unrelated mass structures
- "Mass sheet" degeneracy
- Unknown redshifts of background galaxies
- Assumption of mass profile family
- Assumption of spherical symmetry
- PSF smearing correction

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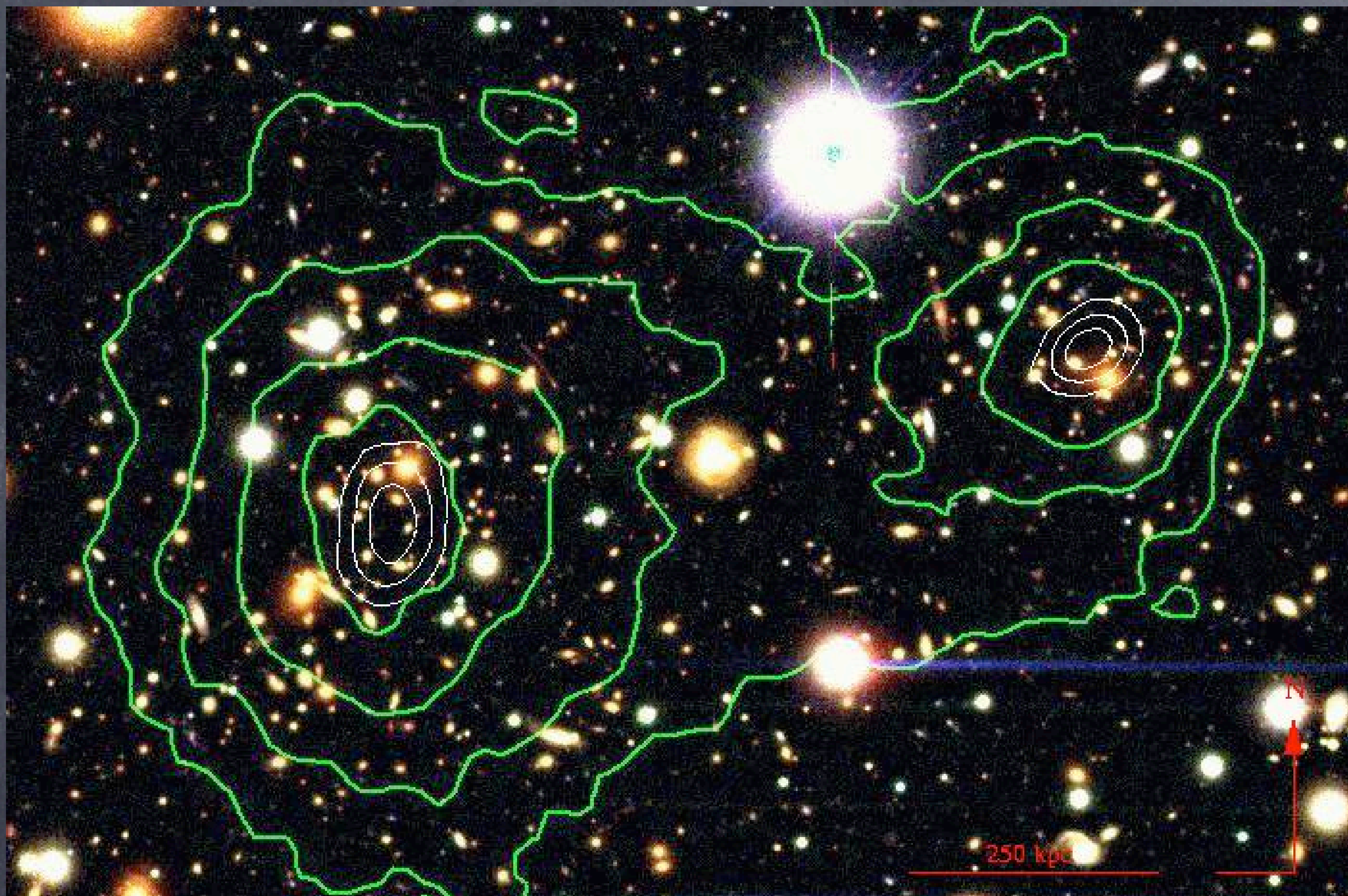
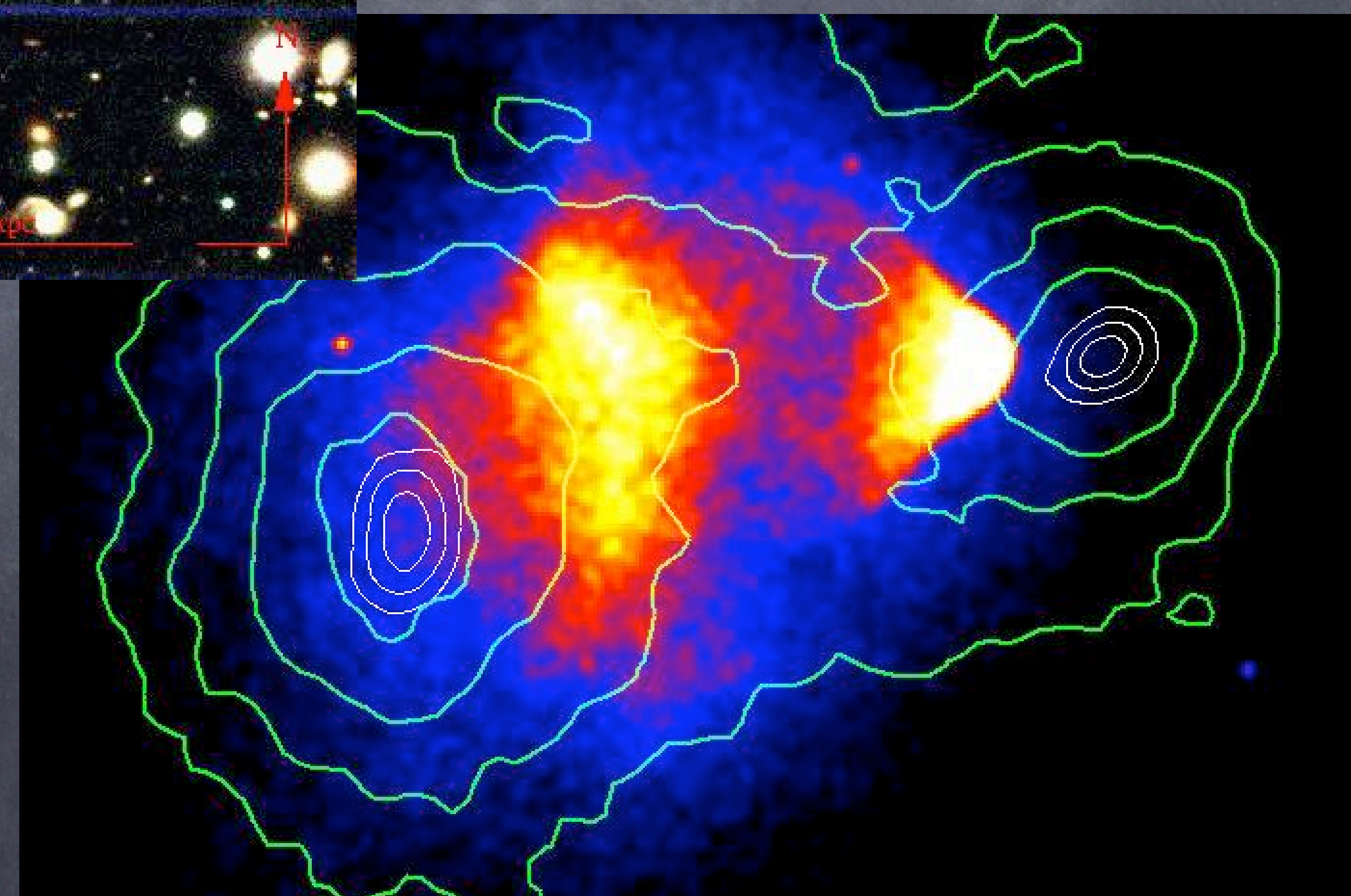
Mass Centroid Errors



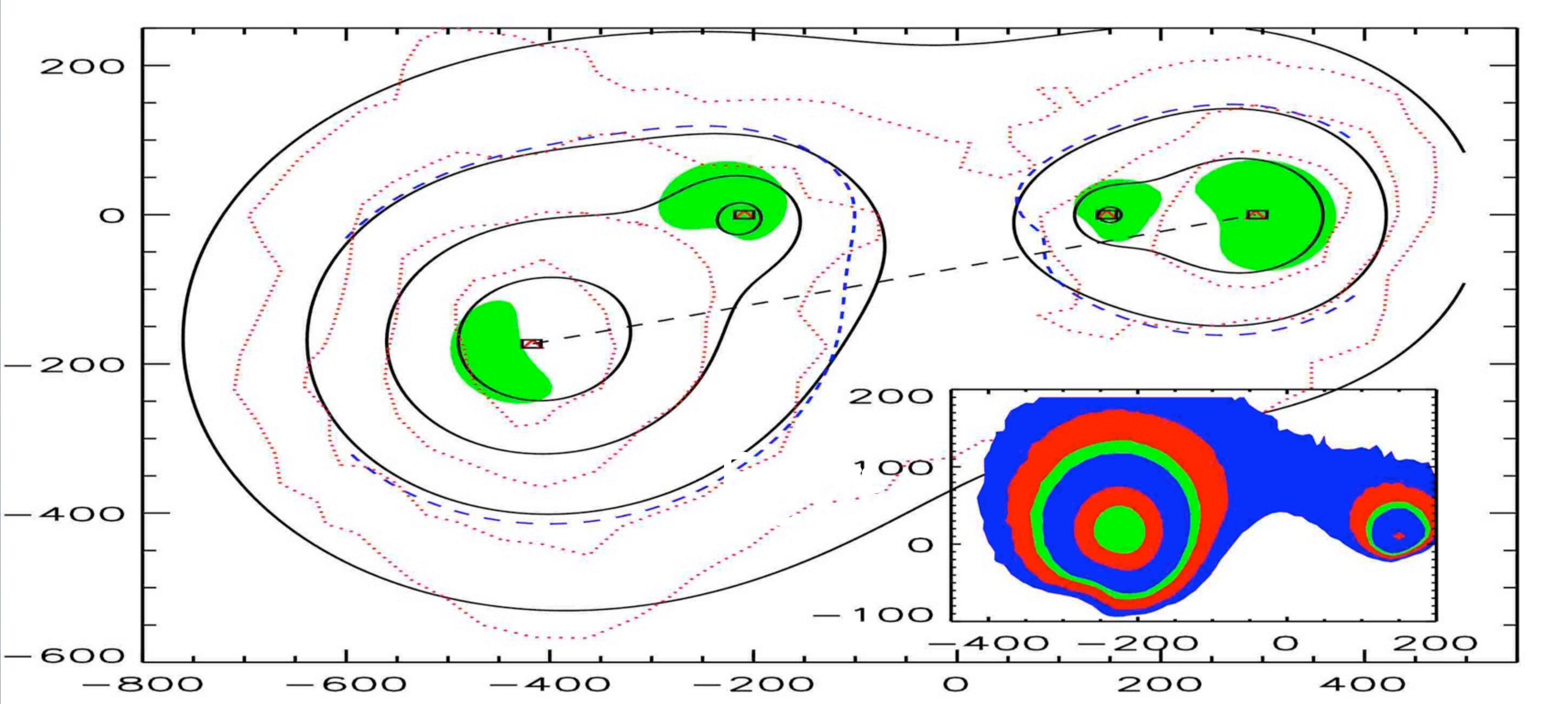


green = convergence
white = centroid errors

Implications for Gravity

- 85-90% of the baryons have been stripped from the subcluster and main cluster.
- γ measurements indicate the lensing potential is near the galaxies, not the gas, and the 4 baryonic peaks are not symmetric.
- The ratio of lensing strength to optical light consistent with normal clusters.
- Lensing strength in normal systems from galaxies to clusters $\propto$ baryonic mass.
- Even in an alternative gravity scenario, the universe must have a significant fraction (>70%) in dark matter.

TeVeS Model



μ	$M^{gas}_{m,x-ray}$	$M^{gas}_{s,x-ray}$	$M_{m,gal}$	$M_{s,gal}$	$\overline{\rho_m}$	$\overline{\rho_s}$
	r<100/180kpc	r<100/80kpc	r<250kpc	r<250kpc	$r < 100$	$r < 100$
GR	1.05/1.97	0.33/0.27	9.97	7.58	2.63	2.59
standard μ	0.97/1.79	0.29/0.24	9.0	6.78	2.26	2.34
simple μ	0.74/1.33	0.21/0.18	6.81	5.06	1.66	1.76
C06/B06	0.66/2.0	0.58/0.42	/28.0	/23.0		

Angus et al 2006, ApJ, 654, L13

Merger Velocity Problem?

- The total system is best fit with r_{200} = 2140 kpc, c = 1.9 at 11σ for the main cluster, r_{200} = 1000 kpc, c = 7.1 at 7σ for the merging subcluster.
- Infall velocity for the system is ~3000 km/s, X-ray shock velocity measured at ~4700 km/s
- System is likely seen with major axis in plane of sky -> WL underpredicts mass by ~30%
- Shock velocity not affected by gravity (Milos[2] et al), X-ray gas moving toward bullet (Springel & Farrar) -> true velocity 3000-3500 km/s

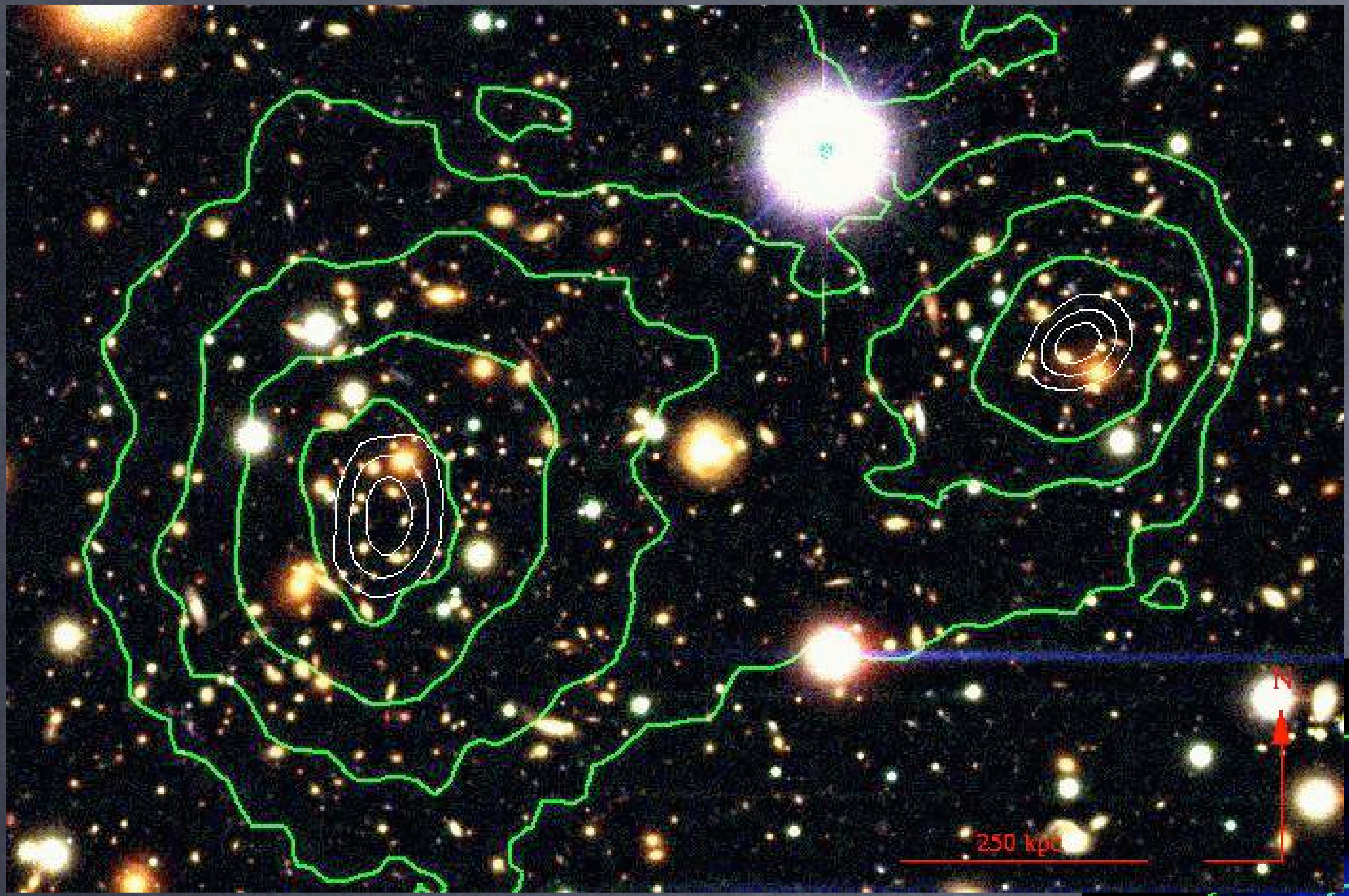
Constraints on Dark Matter

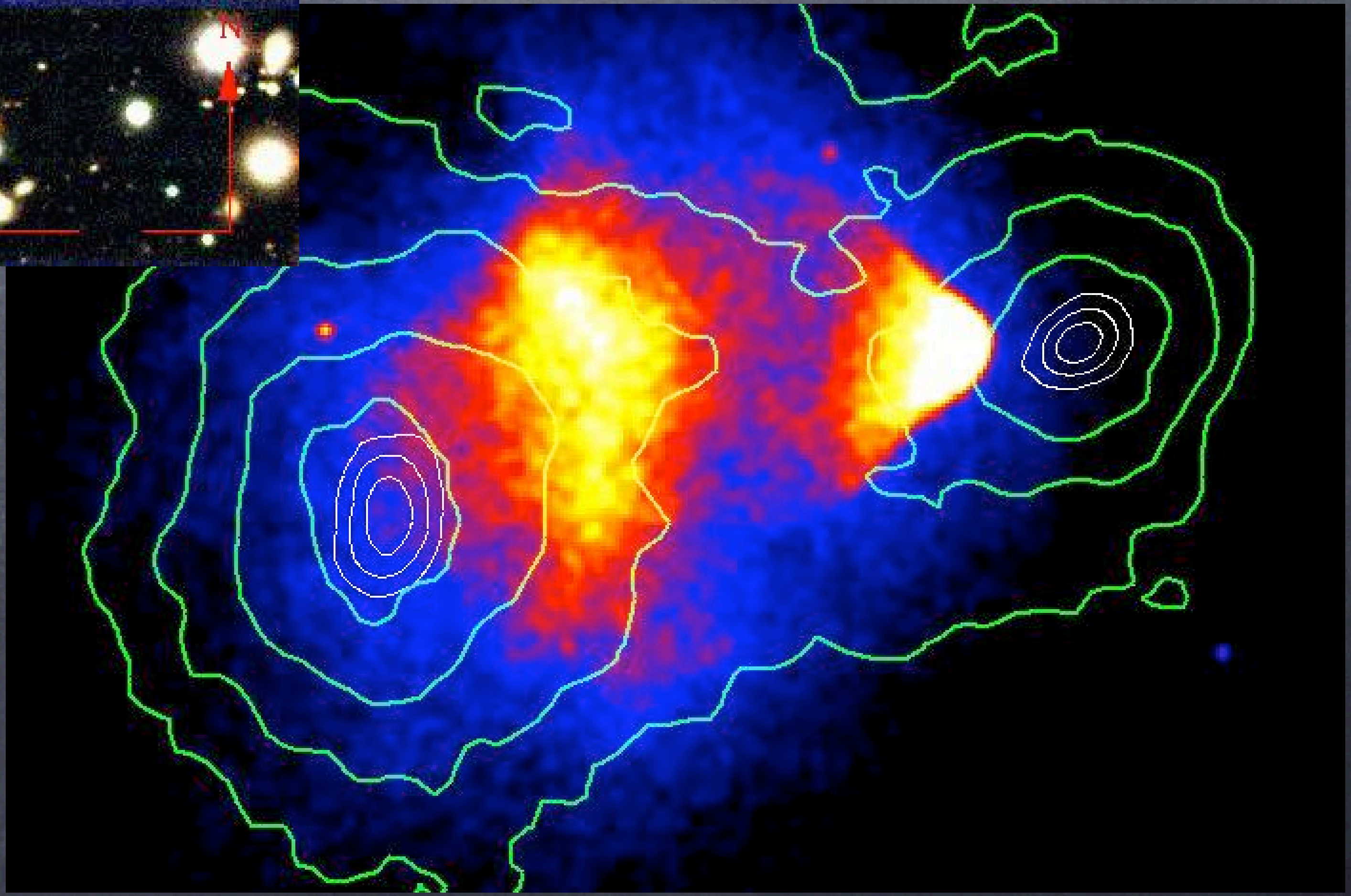
- Lensing measures gravity, so independent of the dynamical state of mass.
- BBN requires most of this mass is non-baryonic.
- The subcluster cannot have a core larger than 120 kpc, so neutrinos must have mass greater than 3.9 eV, which has been ruled out experimentally (eg Bonn et al 2002).

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 $cm^2\ g^{-1}$ (Dave 2001; Ahn & Shapiro 2002).
- Significant offset between subcluster X-ray gas core and dark matter peak gives $\sigma/m < 10\ cm^2\ g^{-1}$.
- Survival of the subcluster dark matter peak during interaction gives $\sigma/m < 3\ cm^2\ g^{-1}$.
- Agreement in position of dark matter and galaxy centroids gives $\sigma/m < 1.25\ cm^2\ g^{-1}$.
- No loss of mass from subcluster during interaction gives $\sigma/m < 0.7\ cm^2\ g^{-1}$.

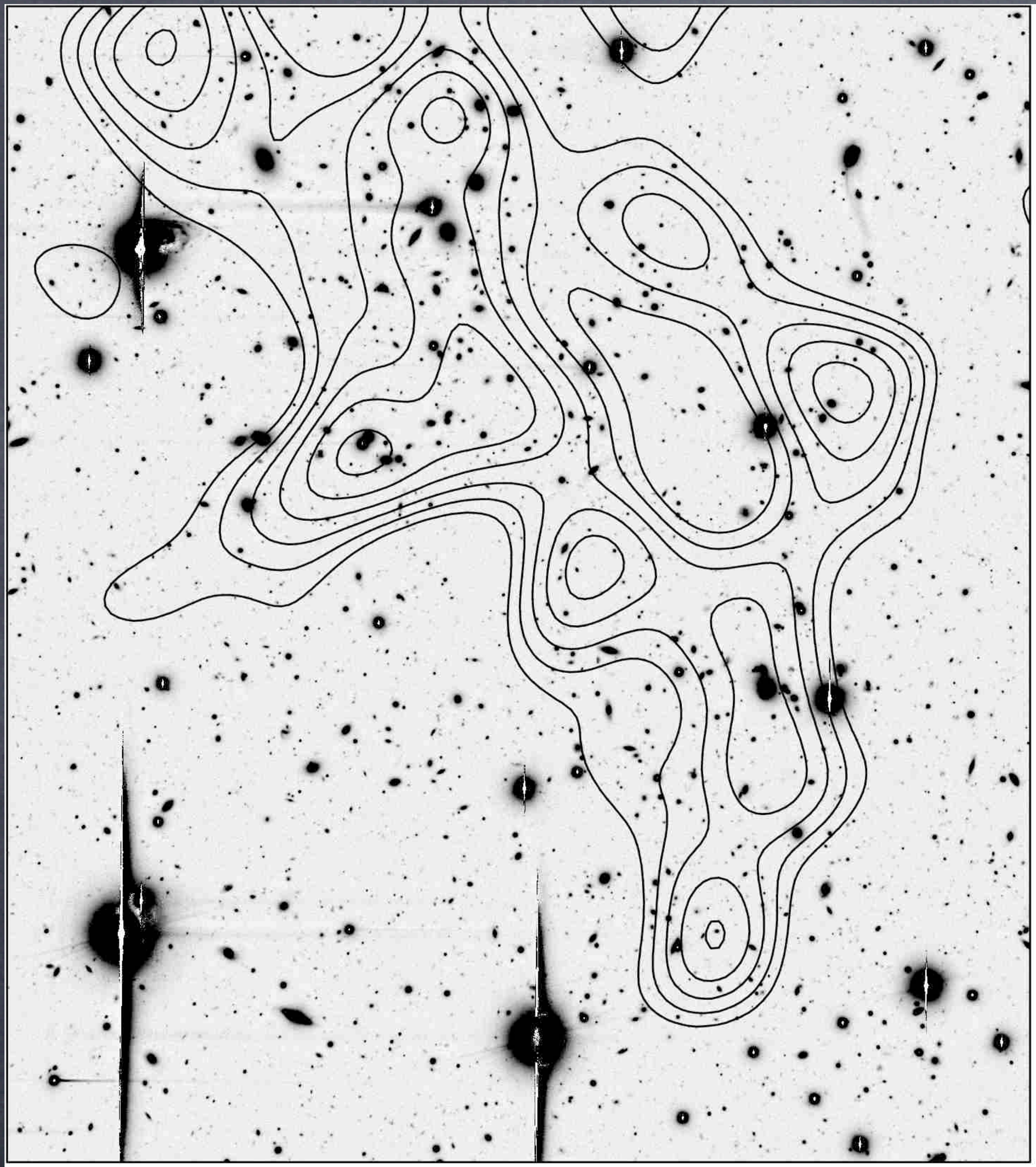
Projected Structures

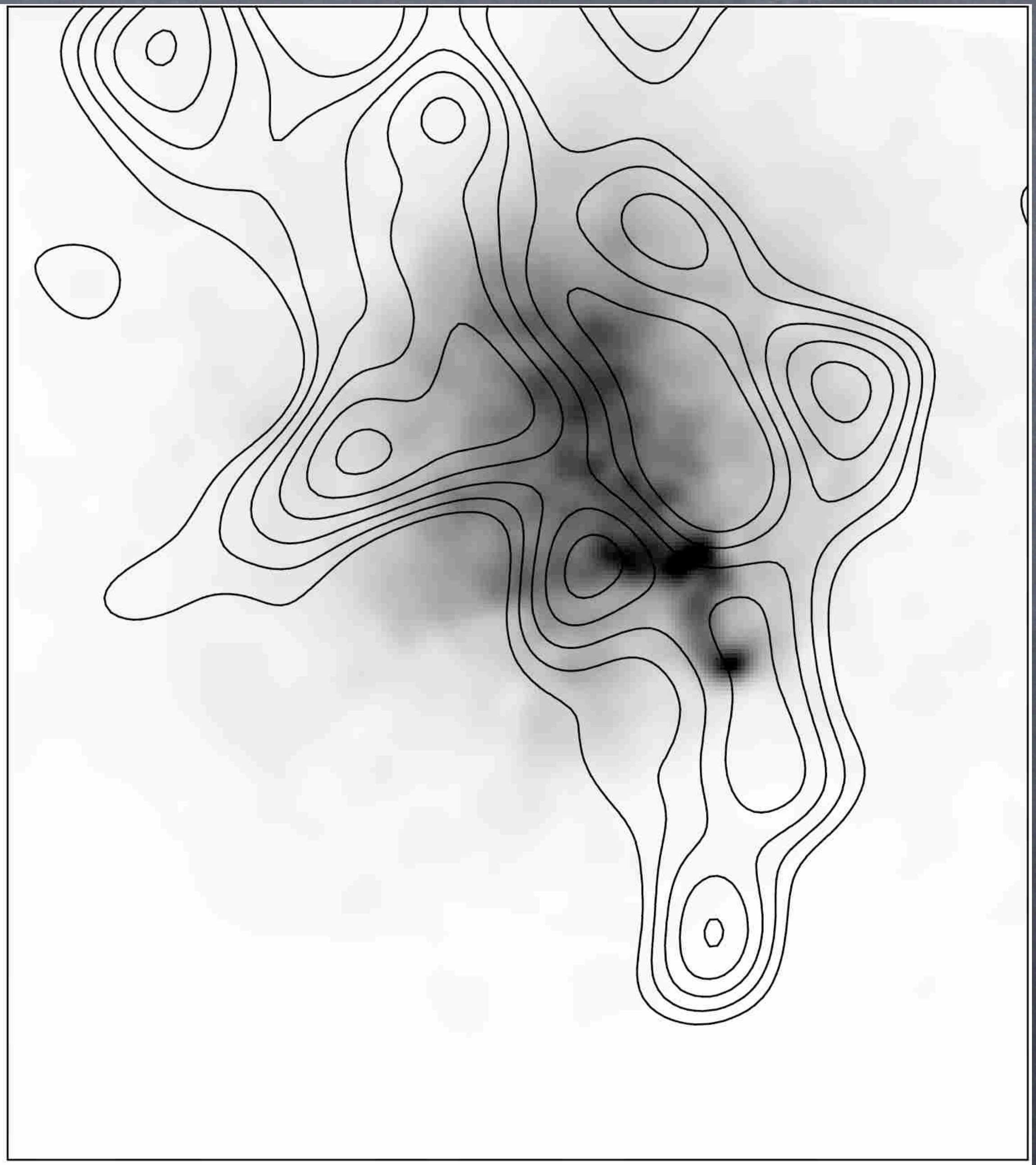




We do not see any structures in galaxies or X-rays which could cause the lensing signal other than the cluster

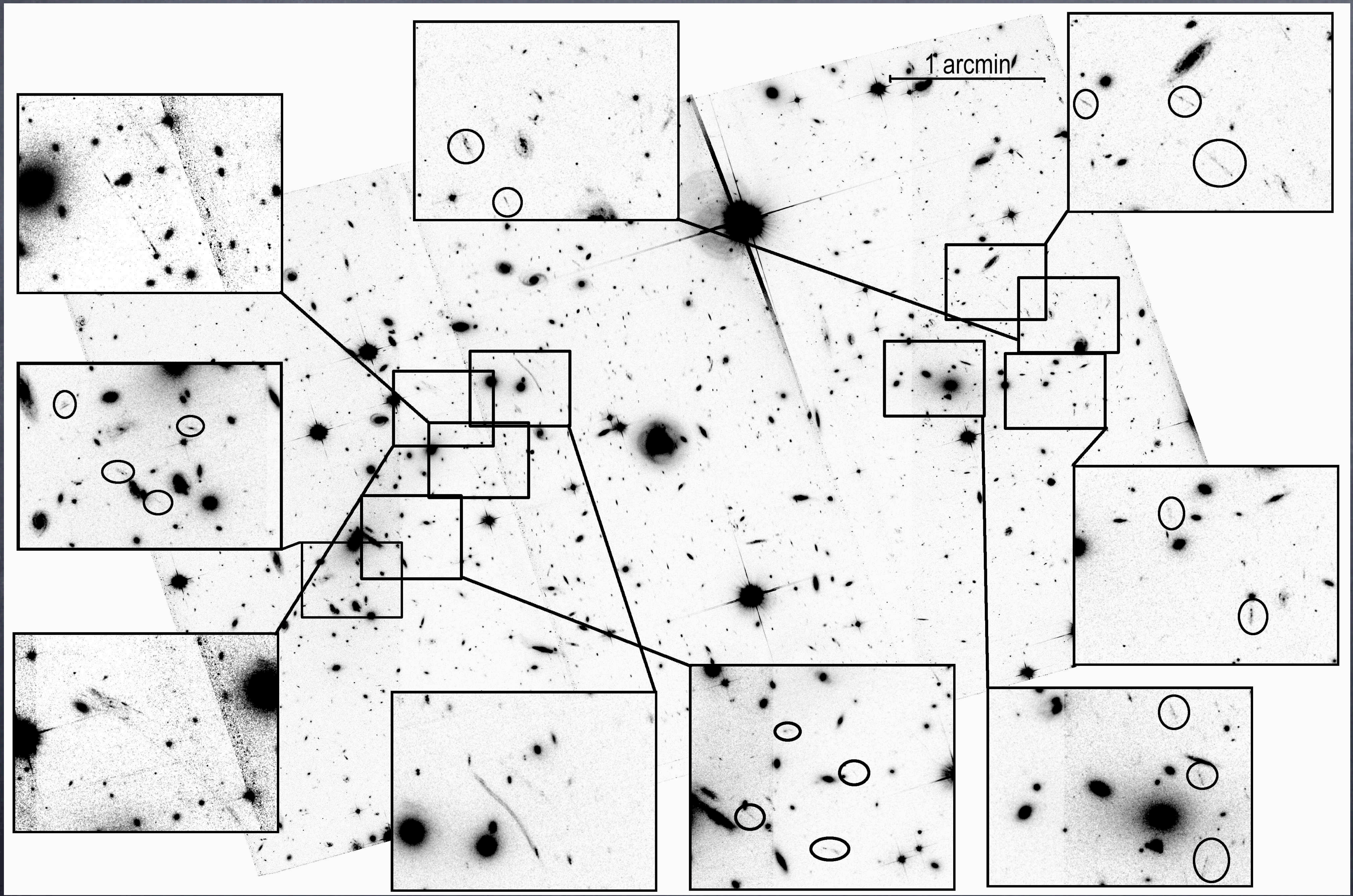
Another Example: A520

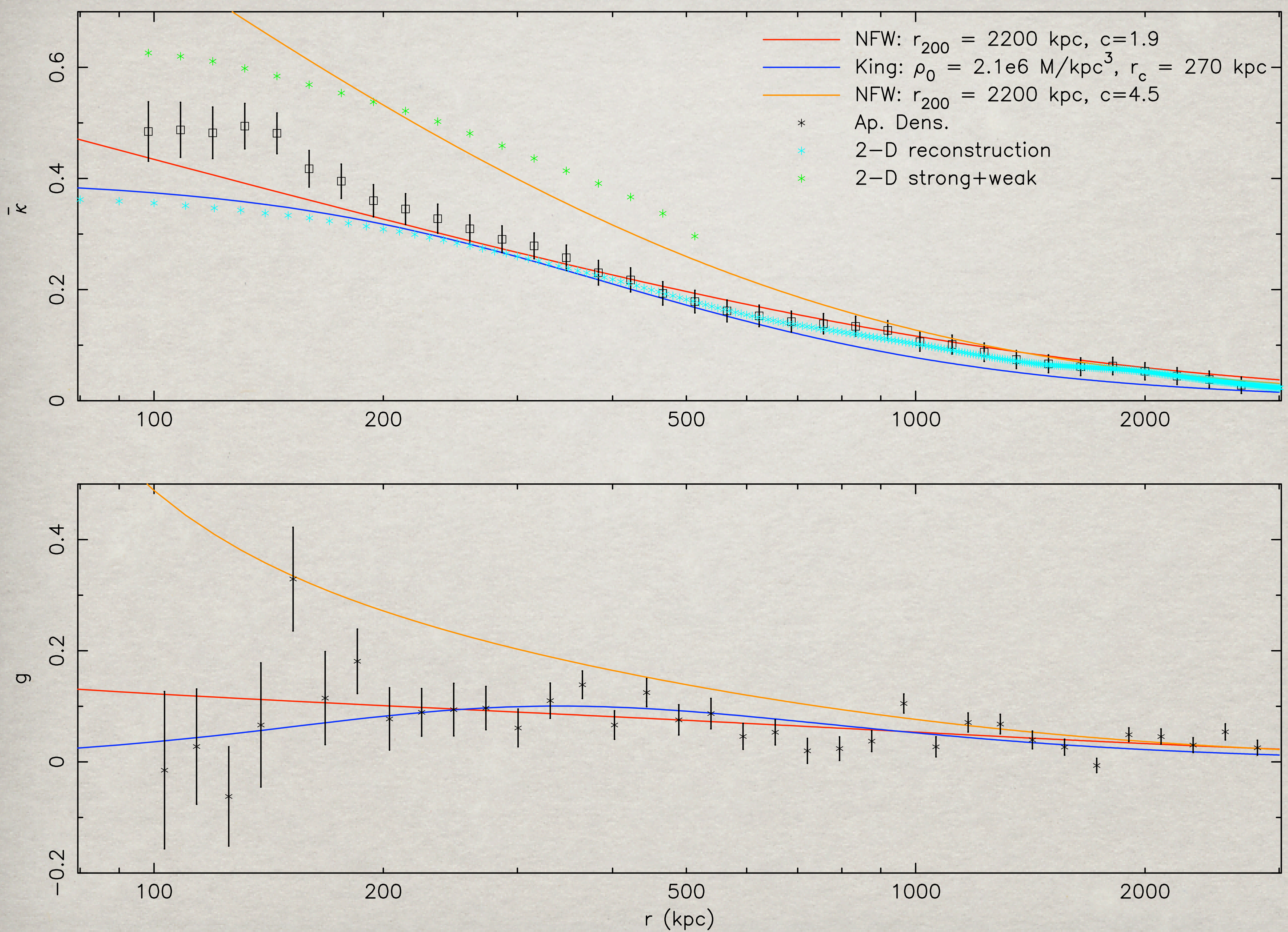




Much more complicated system, but lensing convergence location ≠ X-ray plasma location

Strong Lensing in the Bullet Cluster





NFW: r_{200} = 2200 kpc, c=1.9
King: ρ_0 = 2.1e6 M/kpc^3, r_c = 270 kpc
NFW: r_{200} = 2200 kpc, c=4.5
Ap. Dens.
2−D reconstruction
2−D strong+weak
$\bar{\kappa}$
0
0.2
0.4
0.6
g
−0.2
0
0.2
0.4
100
200
500
1000
2000
r (kpc)

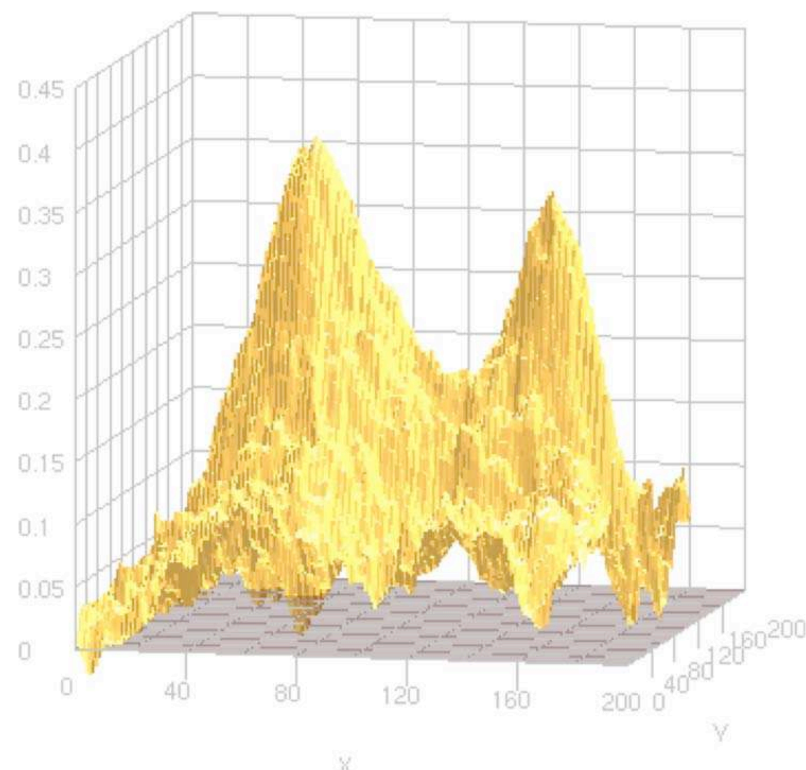
Conclusions

- Weak lensing provides a means to measure the mass of a cluster independent of its dynamical state.
- Studies of interacting clusters provide direct evidence that dark matter exists independent of any assumptions about gravity or cosmology.
- Small core radii of the dark matter peaks requires a neutrino mass higher than allowed by the β decay experiments.
- The survival of the subclump in the 1E0657-558 merger gives an upper limit of 1.25 (0.7) $cm^2\ g^{-1}$ for SIDM.

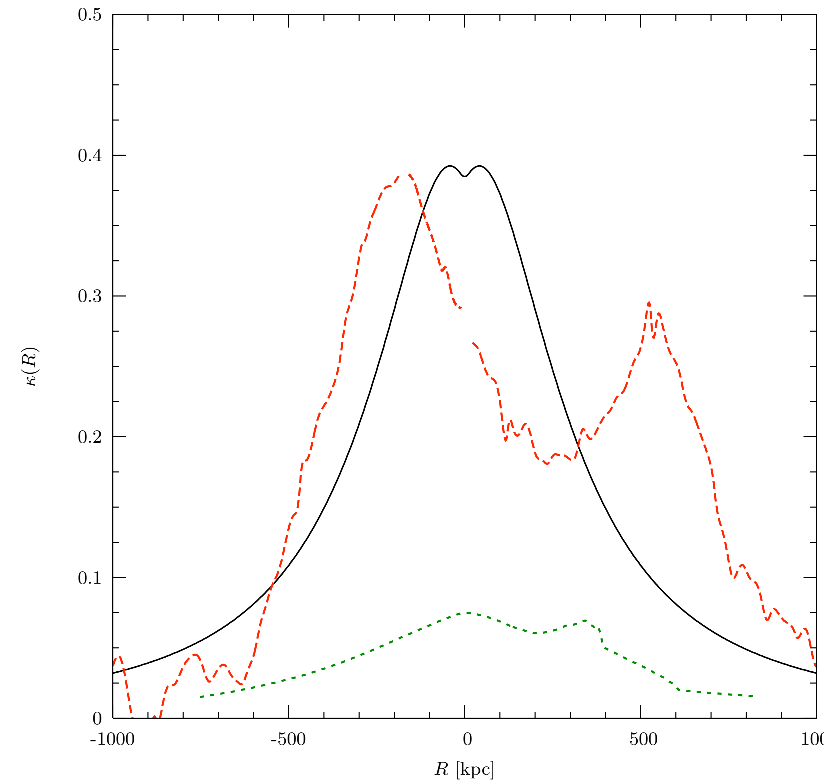
Future Work

- Spectroscopy of star-forming galaxies near the X-ray shock.
- Wide-field spectroscopy for better kinematics of both clusters and to detected projected structures/ filaments.
- Examine other merging systems to exclude conspiracy models that always accompany a sample of one.

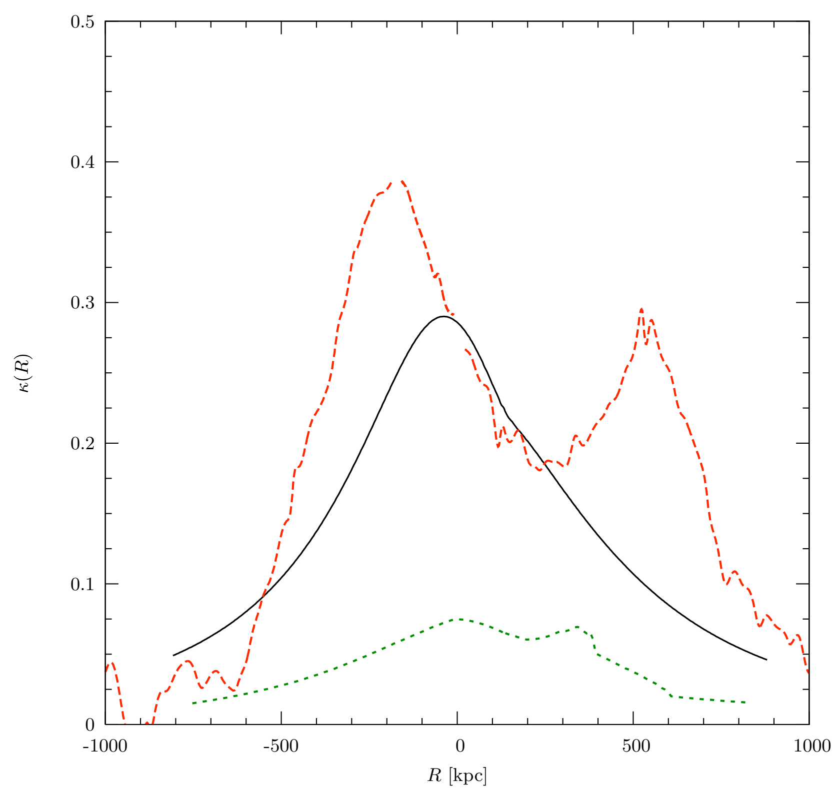
Brownstein and Moffat 2007



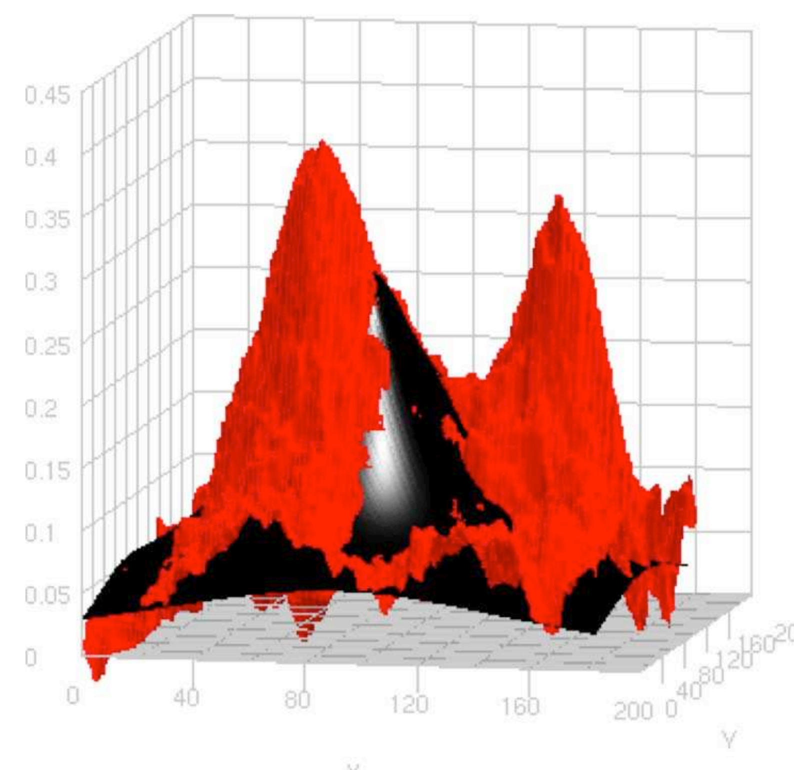
(a) 3D visualization of the κ-map
November 15, 2006 data release (Clowe *et al.*, 2006c)



(b) 0^{th}-order approximation – neglecting the subcluster



(c) Best-fit κ-model



(d) 3D visualization of the best-fit κ-model