A Direct Empirical Proof of the Existence of Dark Matter

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Collaborators

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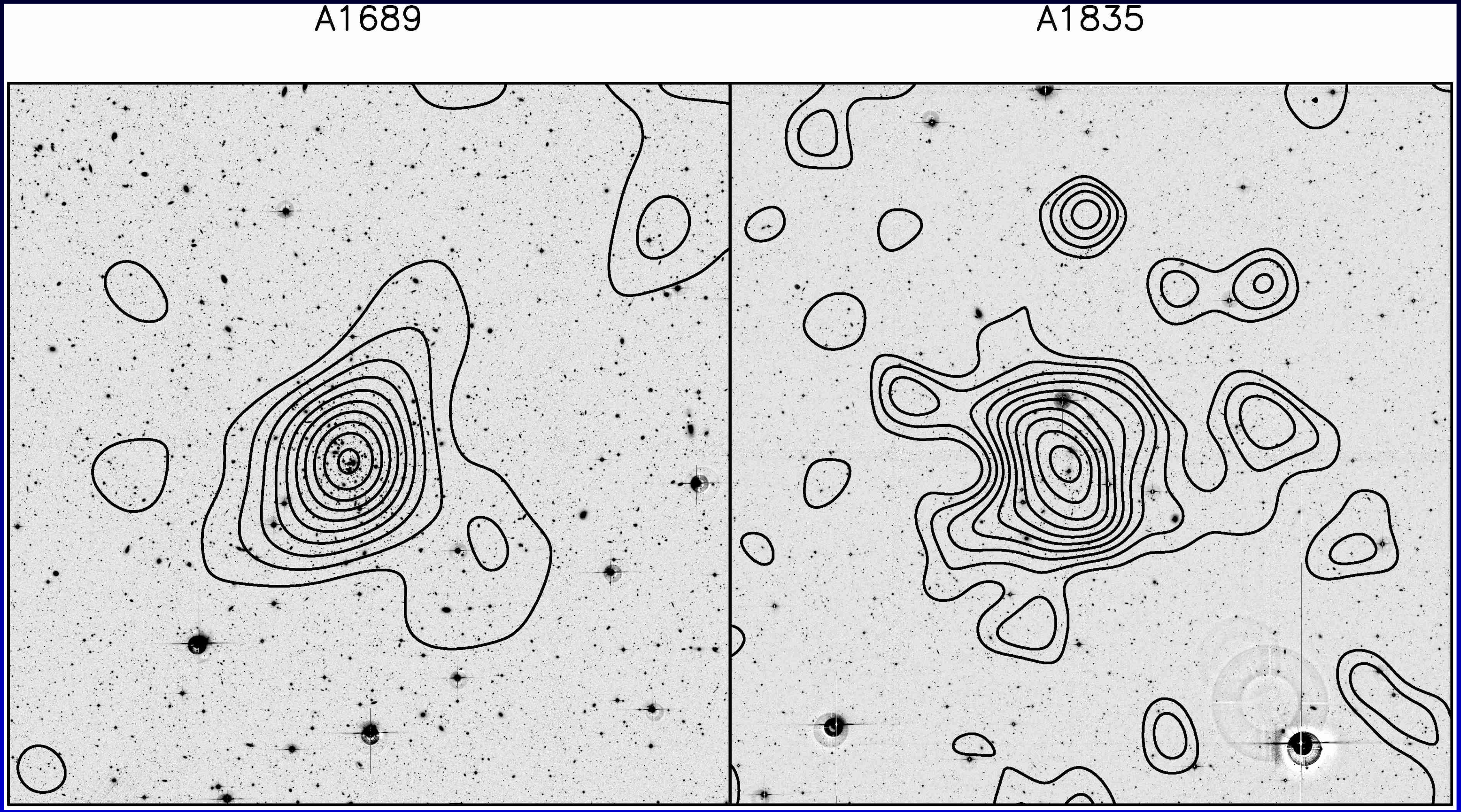
Excess of gravity in clusters

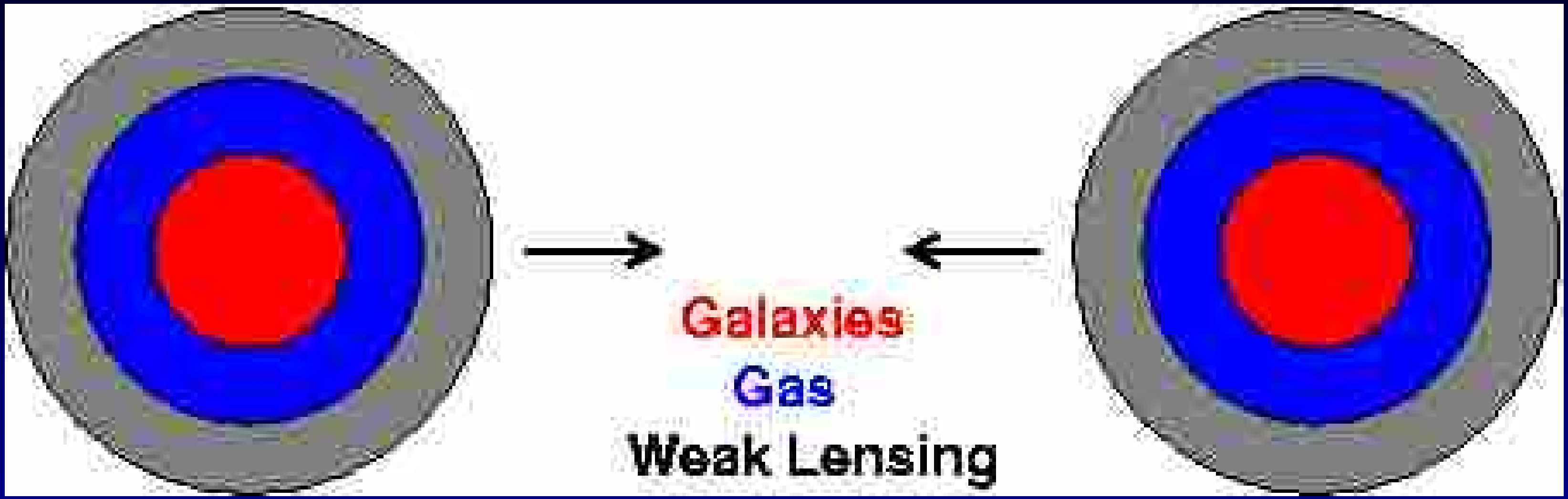
- Zwicky (1933) pointed out that the Coma cluster had a virial mass $> 100\times$ larger than the luminous matter in the cluster galaxies.
- Concluded that either gravity is non-Newtonian or the bulk of the mass of the cluster is made from non-luminous matter.
- Discovery of the X-ray plasma reduces the gravity excess to $\sim 6 - 10\times$ Newtonian gravity from luminous matter.
- Assumption of dark matter due mostly to lack of compelling non-Newtonian gravity theory.

A1689 and A1835

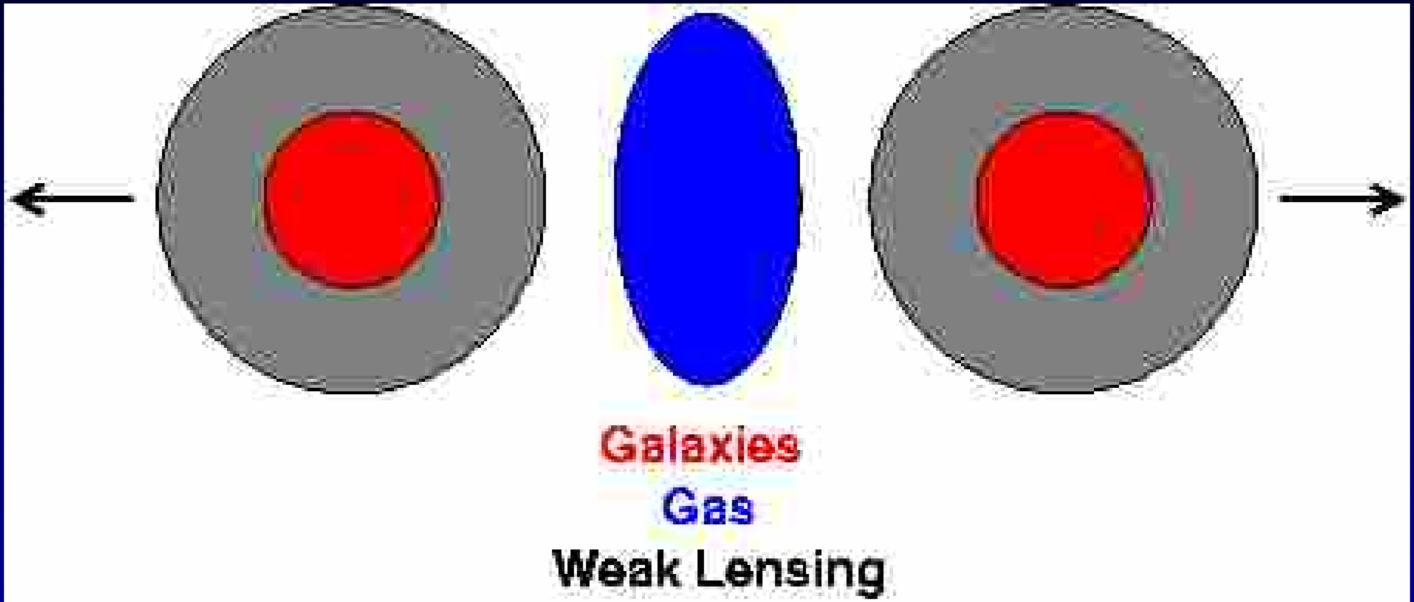


Clowe and Schneider (2001,2002)

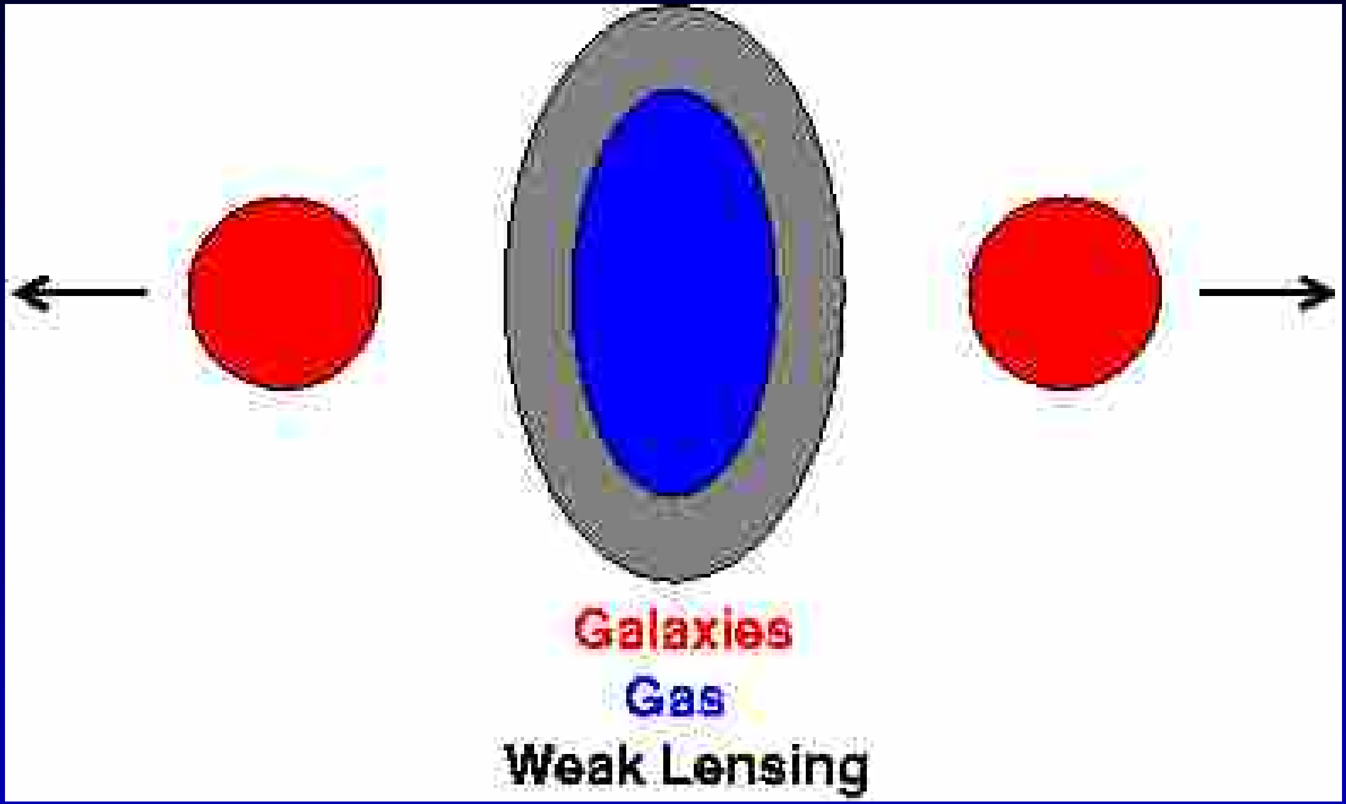
System before impact



System after impact with dark matter



System after impact with alternative gravity



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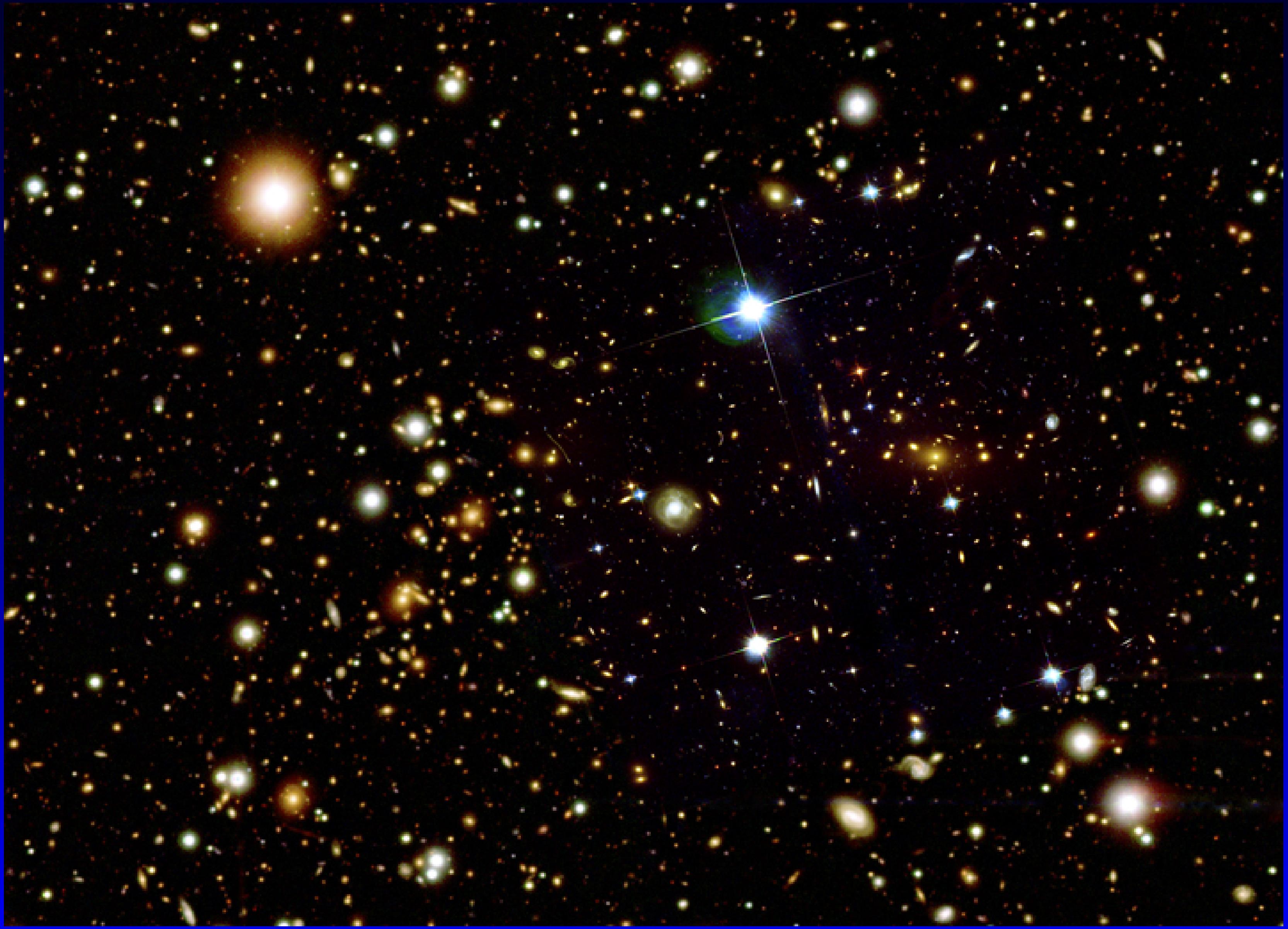
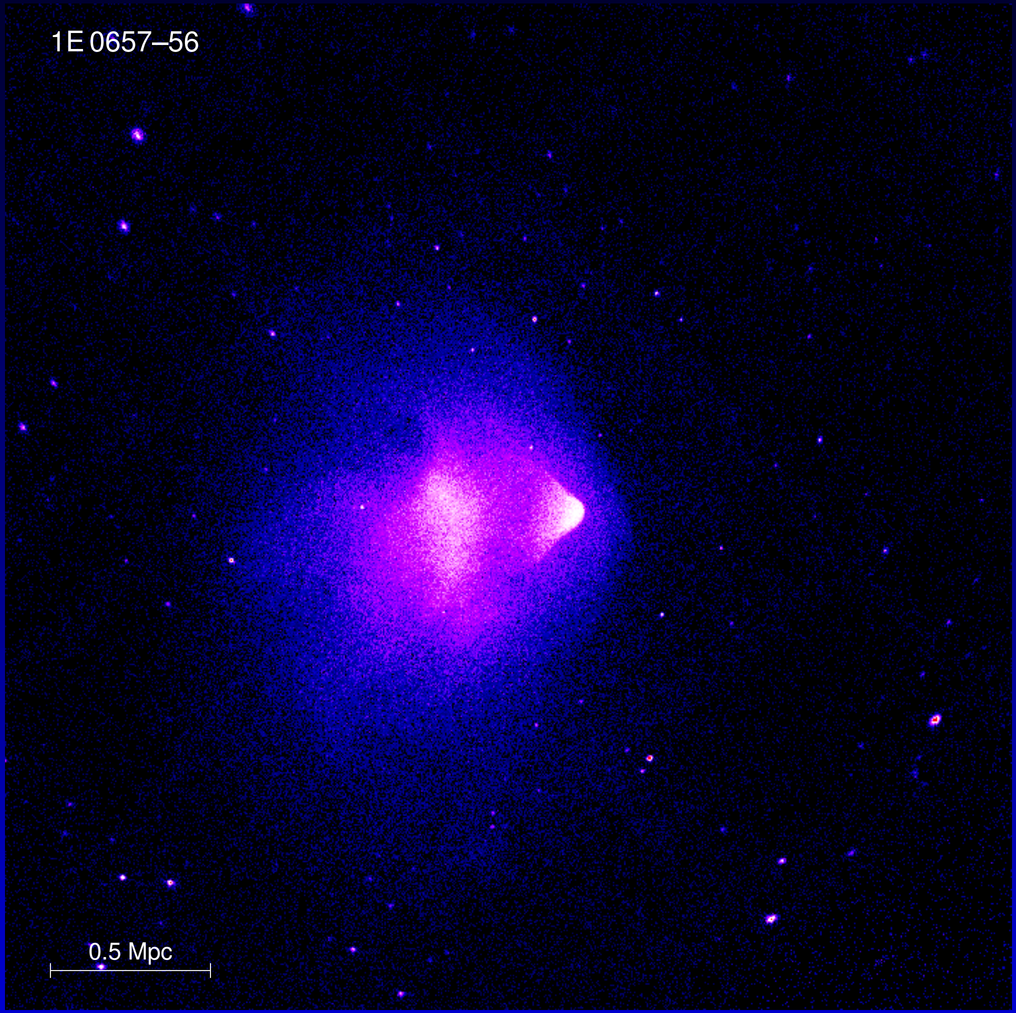
- "Mass sheet" degeneracy $\kappa_{\rm true} = (1-\lambda)\kappa_{\rm obs} + \lambda$

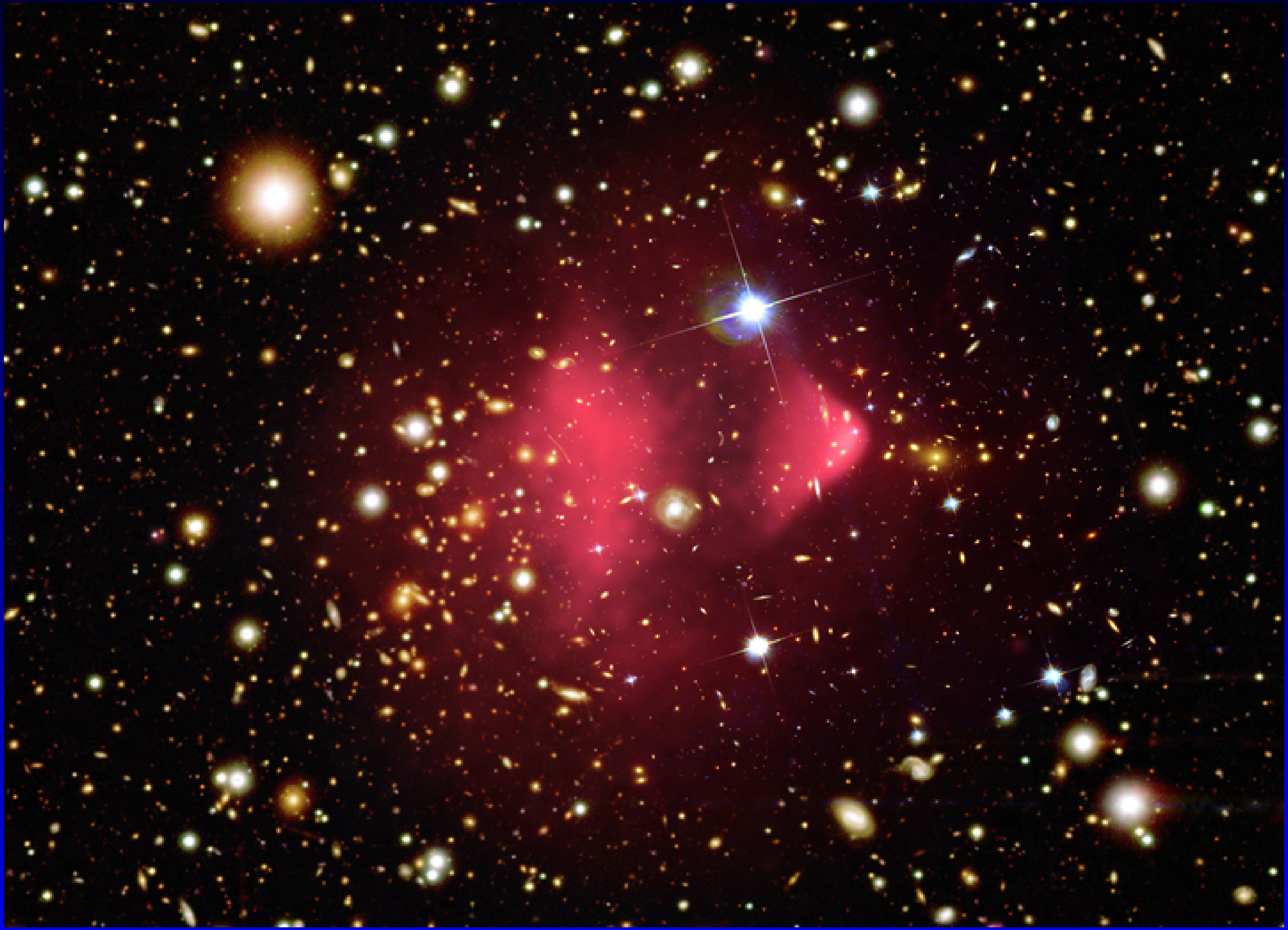
1E0657-556



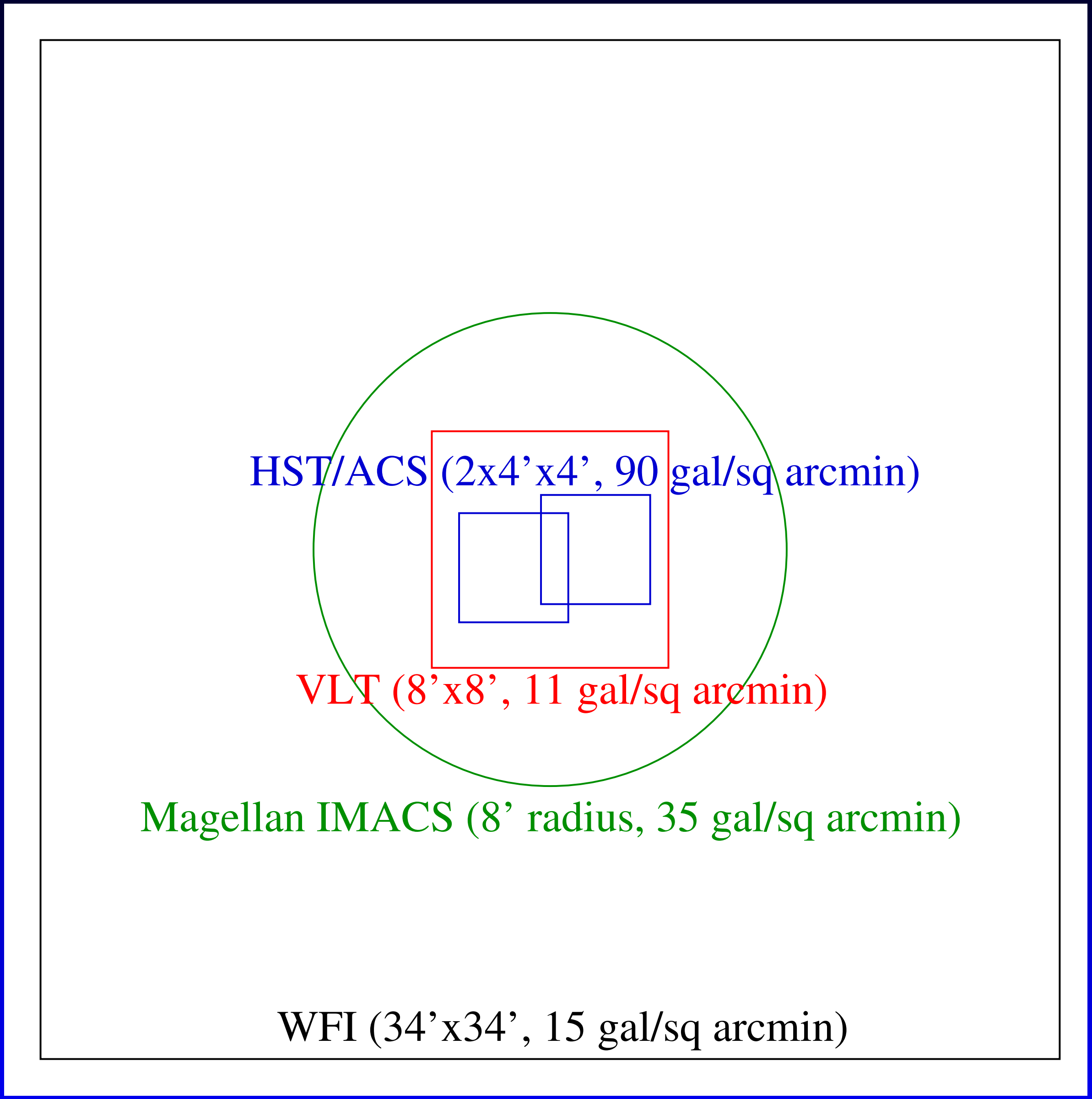
500 ks Chandra observation



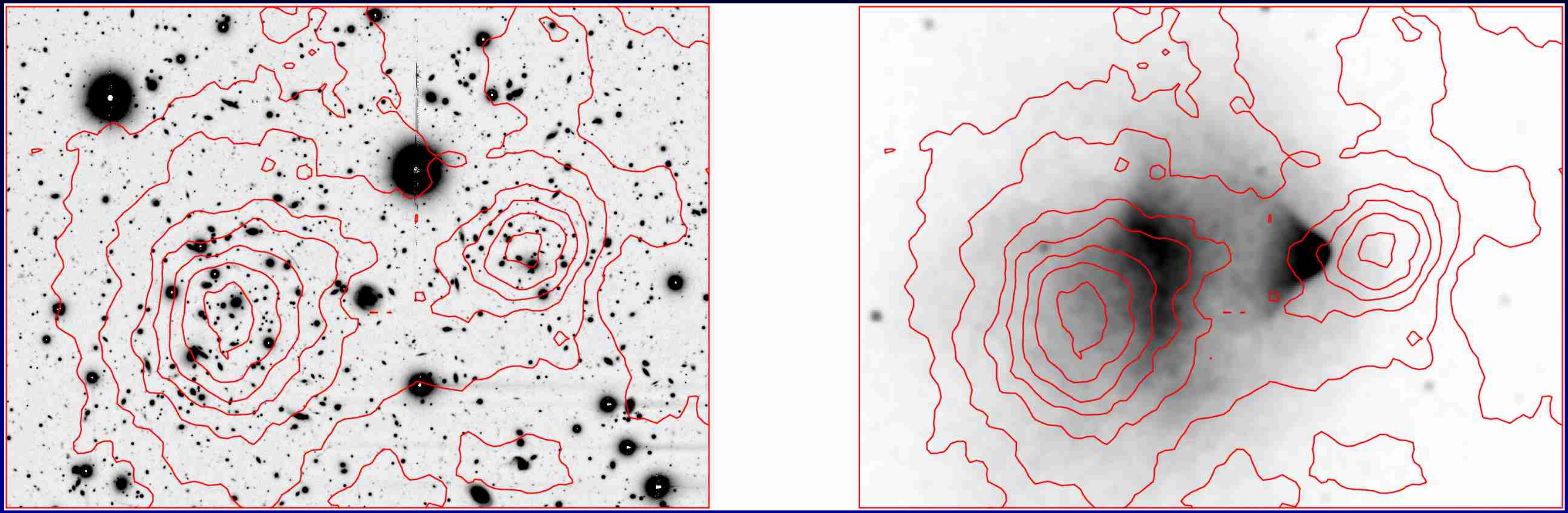
X-ray — galaxy offset



Weak lensing images



Weak lensing reconstruction



Sources of error

- PSF smearing correction
- Intrinsic ellipticity of background galaxies
- Projection of unrelated mass structures
- “Mass sheet” degeneracy
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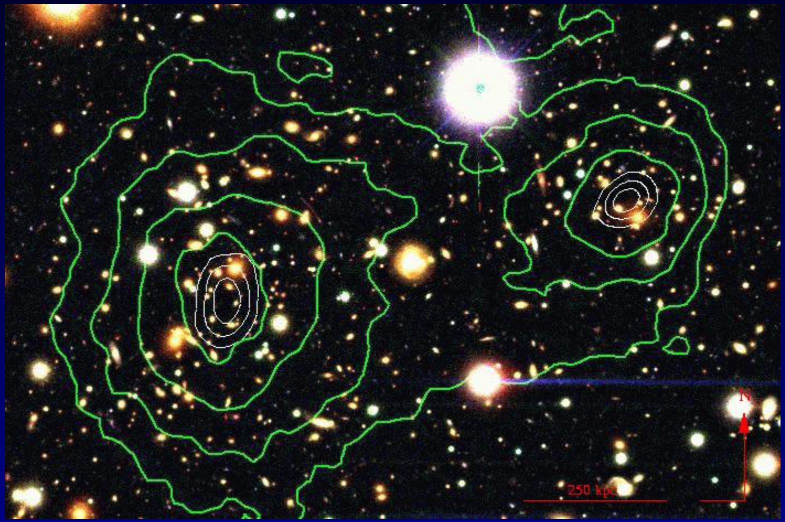
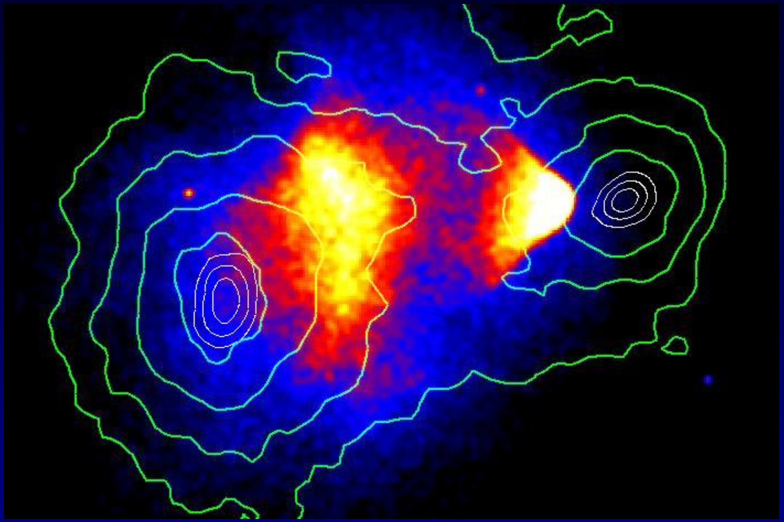
Mass centroid errors





Weak lensing results

- 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.
- Both mass peaks are offset from the X-ray peaks at $\sim 8\sigma$ significance.
- The X-ray gas is detected as a minor perturbation to the cluster gravitational potential.
- Subcluster has mass-to-light ratio of 0.95 ± 0.2 as compared to the main cluster.

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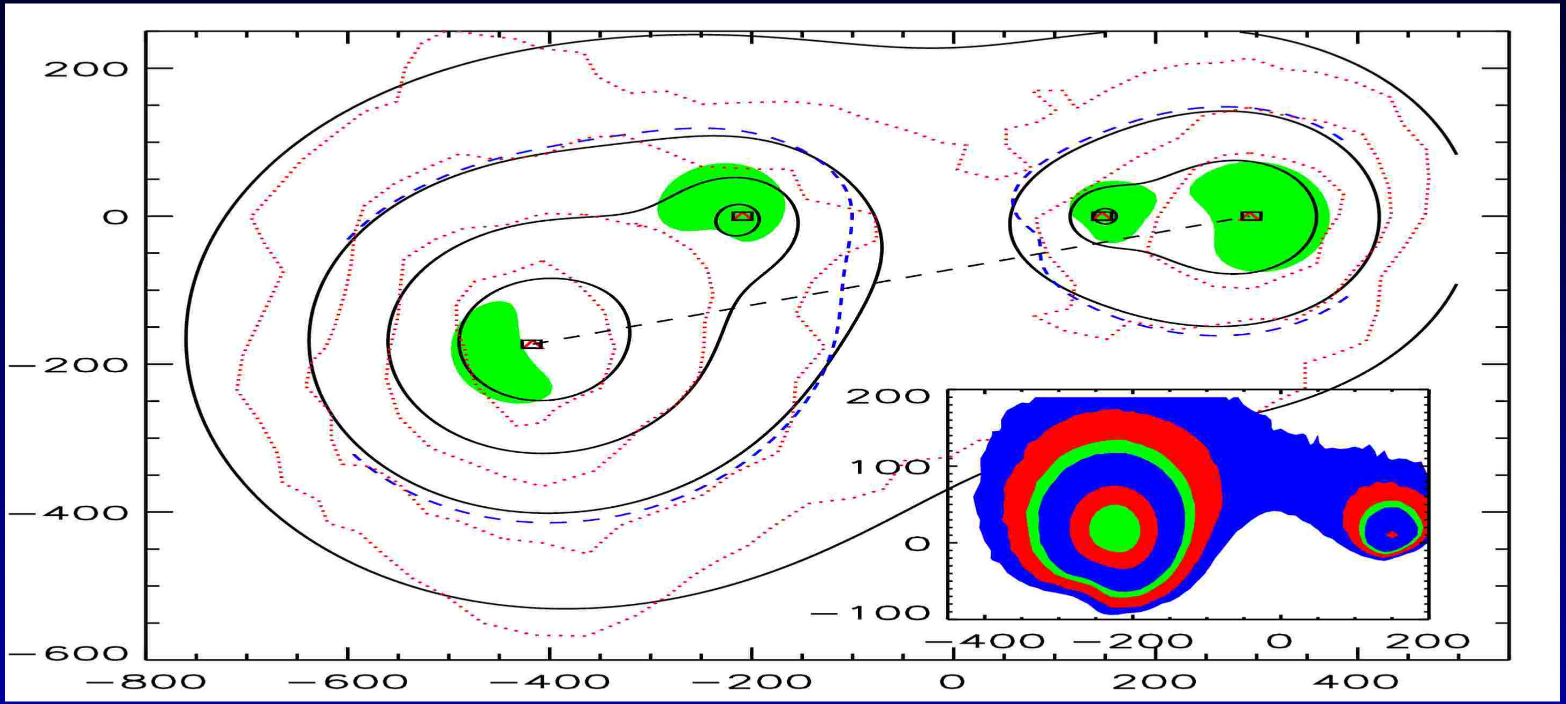
- lensing strength in normal systems from galaxies to clusters $\propto$ baryonic mass
- Even in an alternative gravity scenario, the universe must have a significant fraction ($> 70\%$) in dark matter.

TeVeS model, Angus et al, 2006, submitted



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		

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- 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 $1 - 100 \mathrm{cm}^2 \mathrm{g}^{-1}$ have been proposed to alleviate problems with CDM (cuspy cores, excess small halos) (Spergel & Steinhardt 2000).

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- No loss of mass from subcluster during interaction gives $\frac{\sigma}{m} < 0.7\mathrm{cm}^2\mathrm{g}^{-1}$.

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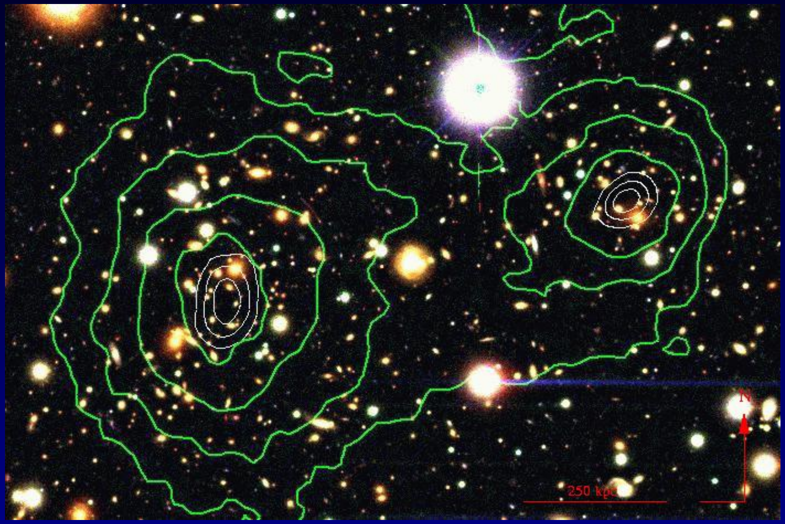
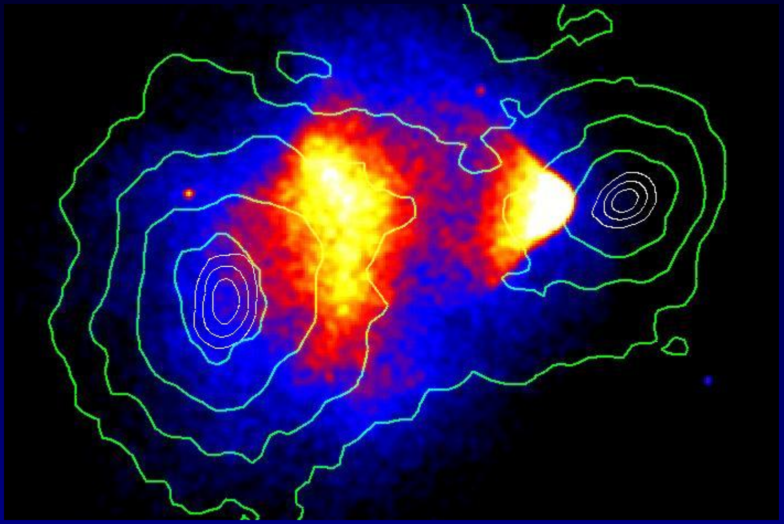
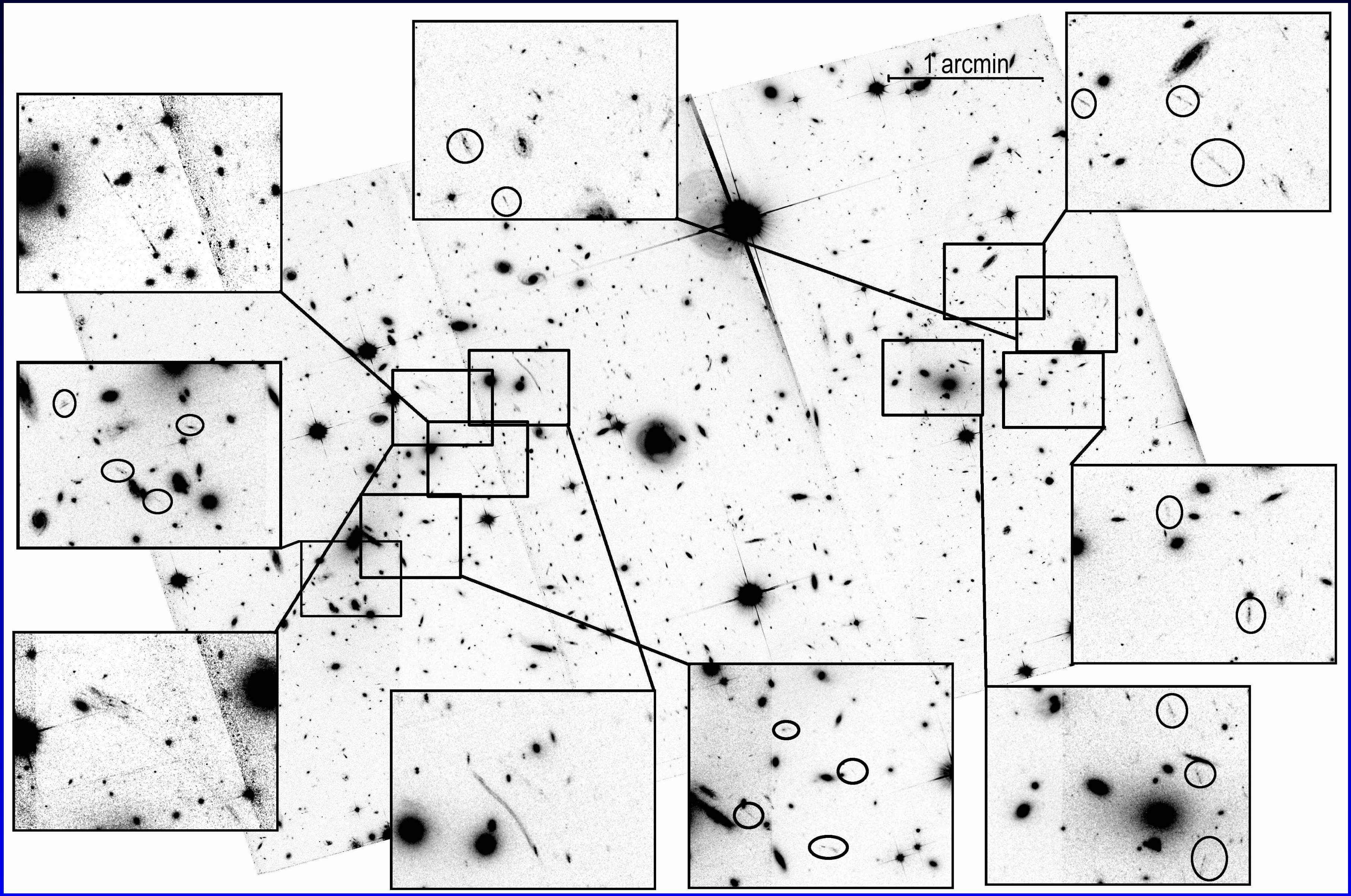
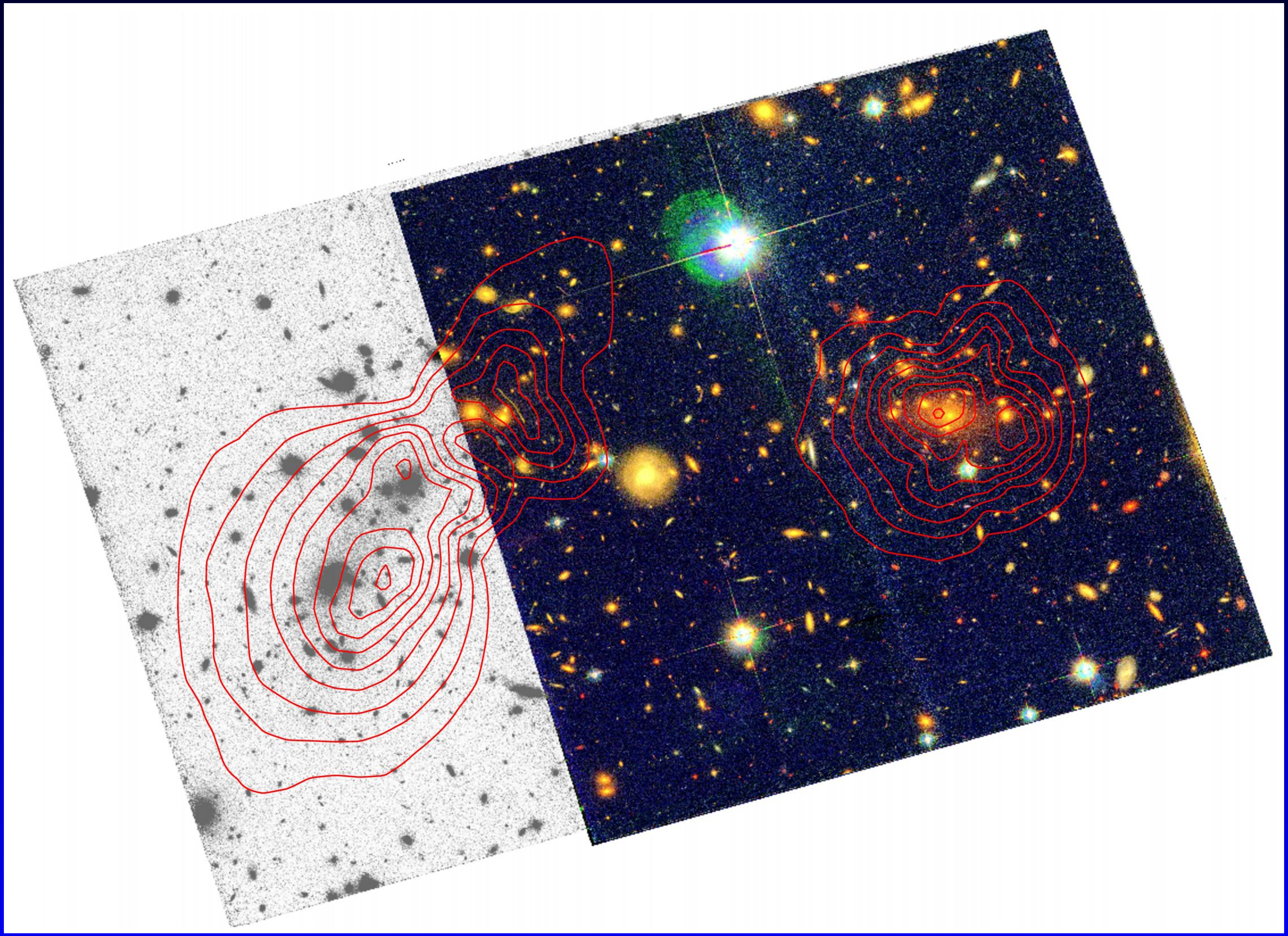




Strong lensing



Strong + weak lensing



Conclusions

- Studies of interacting clusters provide direct proof 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 1E0657-556 merger gives an upper limit of $3(0.7)\mathrm{cm}^2\mathrm{g}^{-1}$ for SIDM.

Future work

- We hope to reduce the SIDM upper limit using the observed strong lensing.
- Creating high resolution N-body simulations, including baryonic gas, to compare with the observations.
- 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.
- Extend to other merging cluster systems.