Detailed Mass Map of CL 0024+1654 from Strong Lensing

Tyson, Kochanski, & Dell'Antonio (1998)

HST WFPC2 image of CL0024+1654

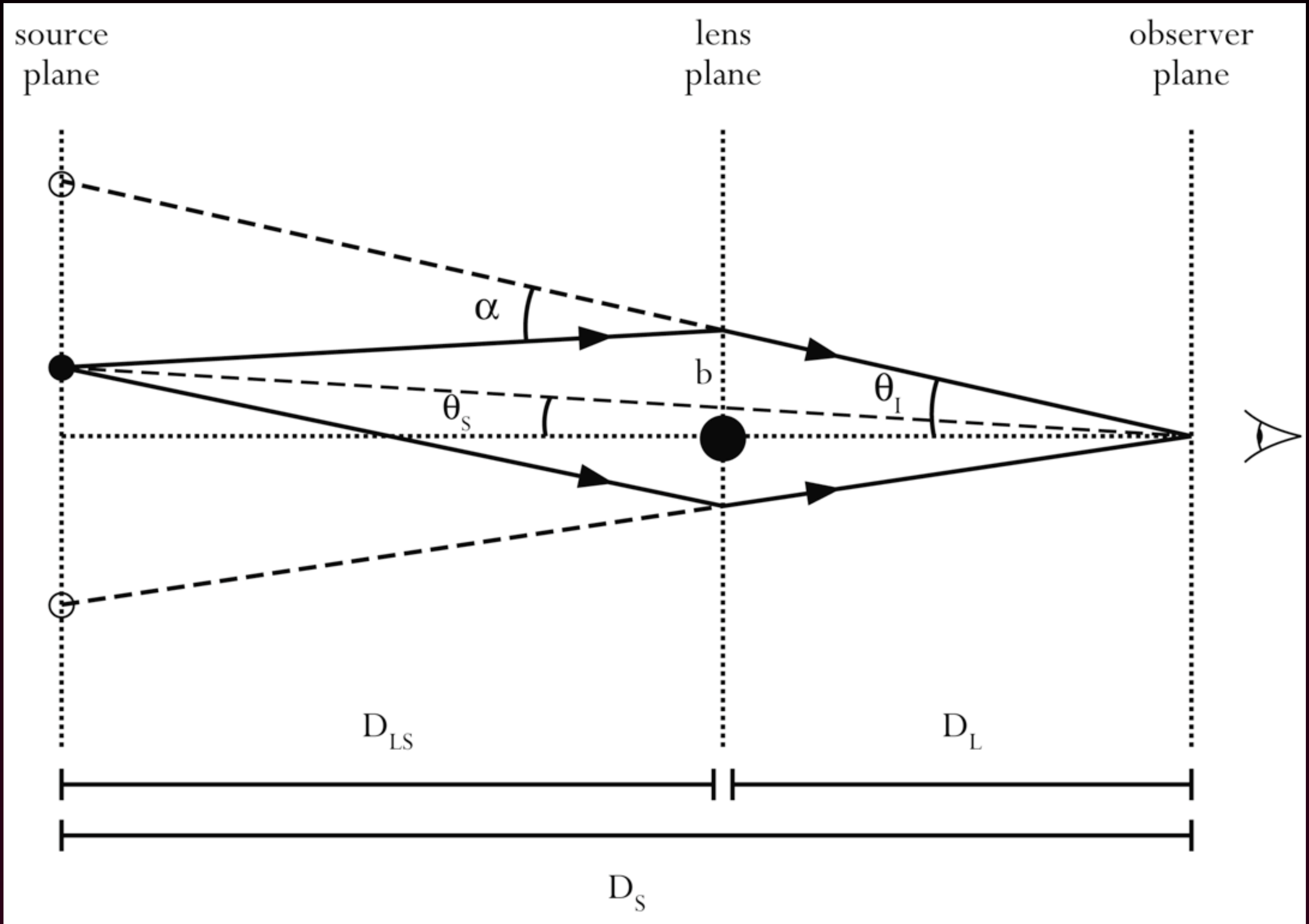
slides based on presentation by Yue Zhao

Rutgers Physics 690   February 21, 2008

Lensing Basics

$$\theta_E = \left(\frac{4GM}{c^2} \frac{d_{LS}}{d_L d_S} \right)^{1/2}$$

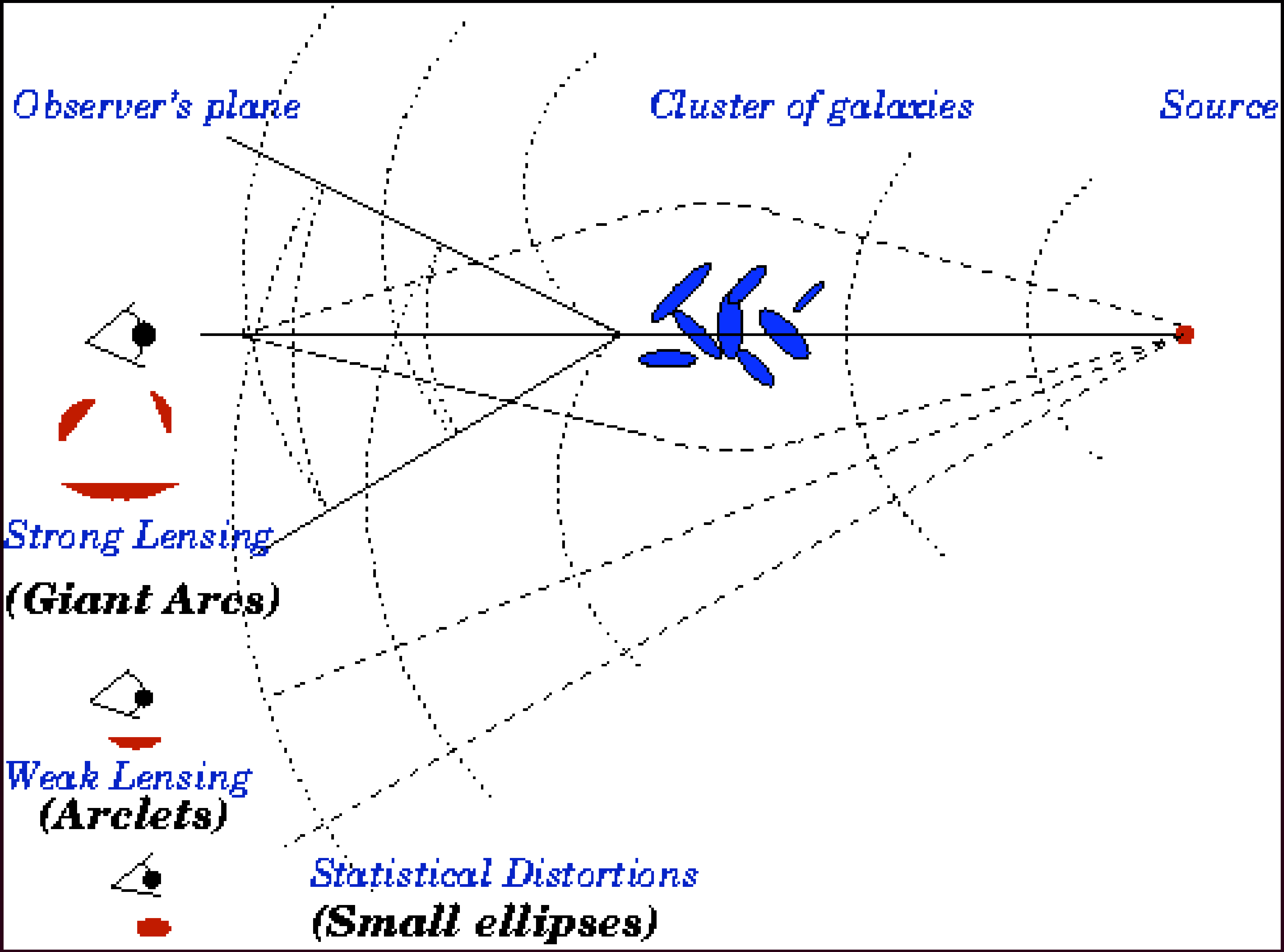
$$\theta_E = \left(\frac{M}{10^{11.9} M_\odot} \right)^{1/2} \left(\frac{d_L d_S / d_{LS}}{Gpc} \right)^{-1/2} arcsec$$



- microlensing:
  $M \sim M_\odot$ $d \sim$ kpc
  $\theta_E \sim$ milliarcsec
- galaxy lensing:
  $M \sim 10^{12} M_\odot$
  $d \sim$ Gpc
  $\theta_E \sim$ arcsec
- cluster lensing:
  $M \sim 10^{15} M_\odot$
  $d \sim$ Gpc
  $\theta_E \sim 30$ arcsec

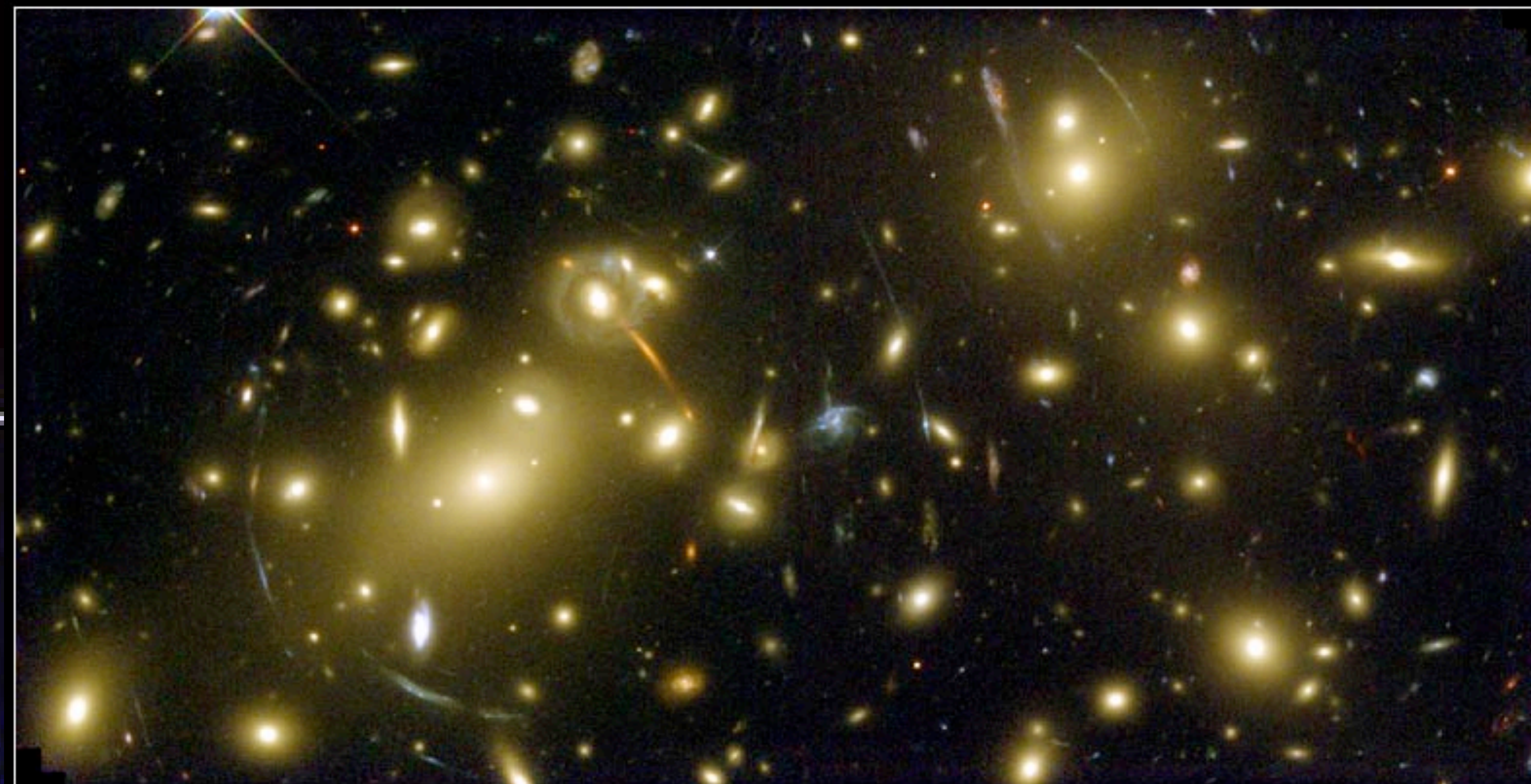
from Wikipedia, http://en.wikipedia.org/wiki/Einstein_radius

Lensing Regimes



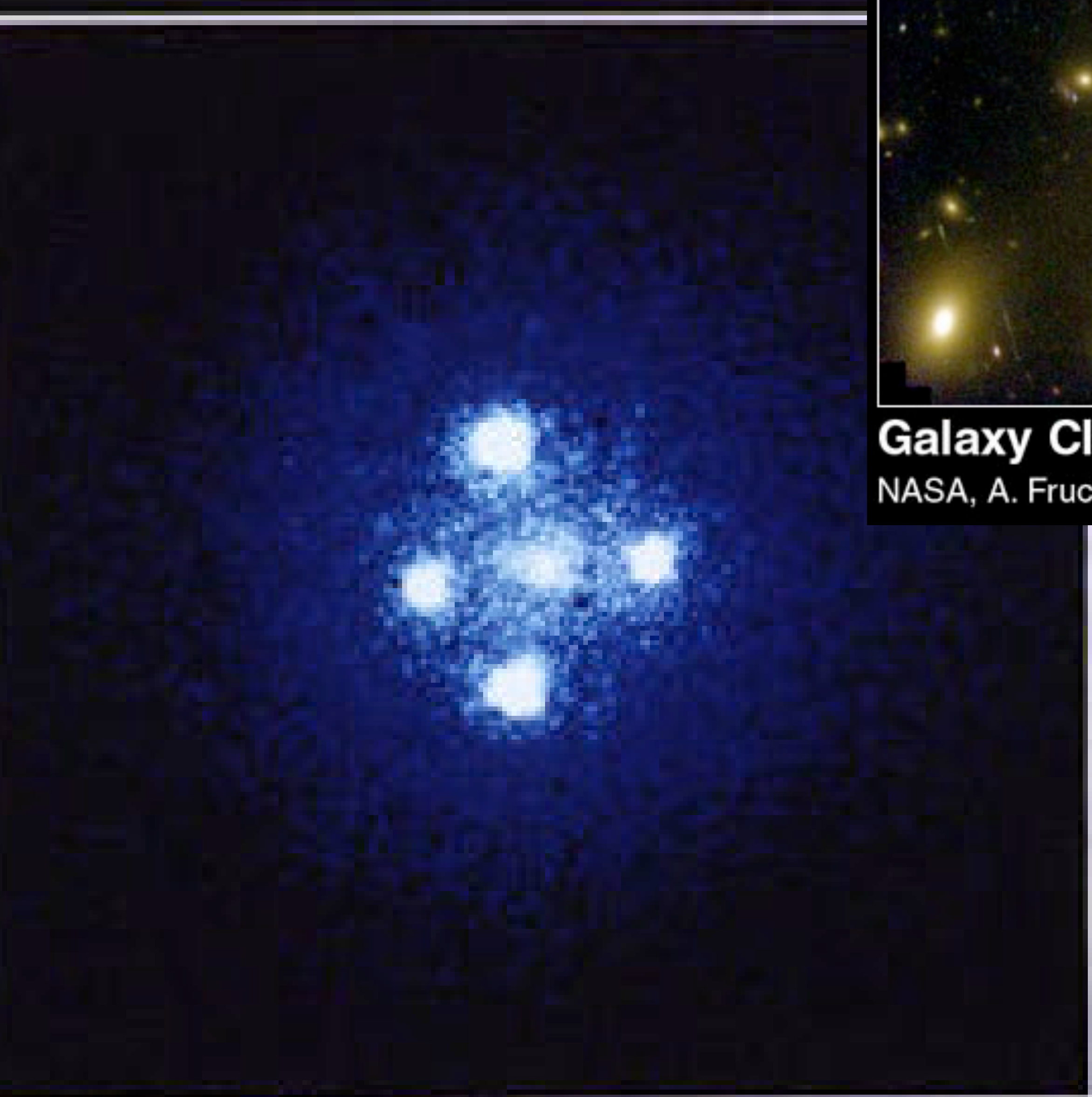
from Bhuvnesh Jain, http://www.hep.upenn.edu/~bjain/lensing.html

Strong Lensing



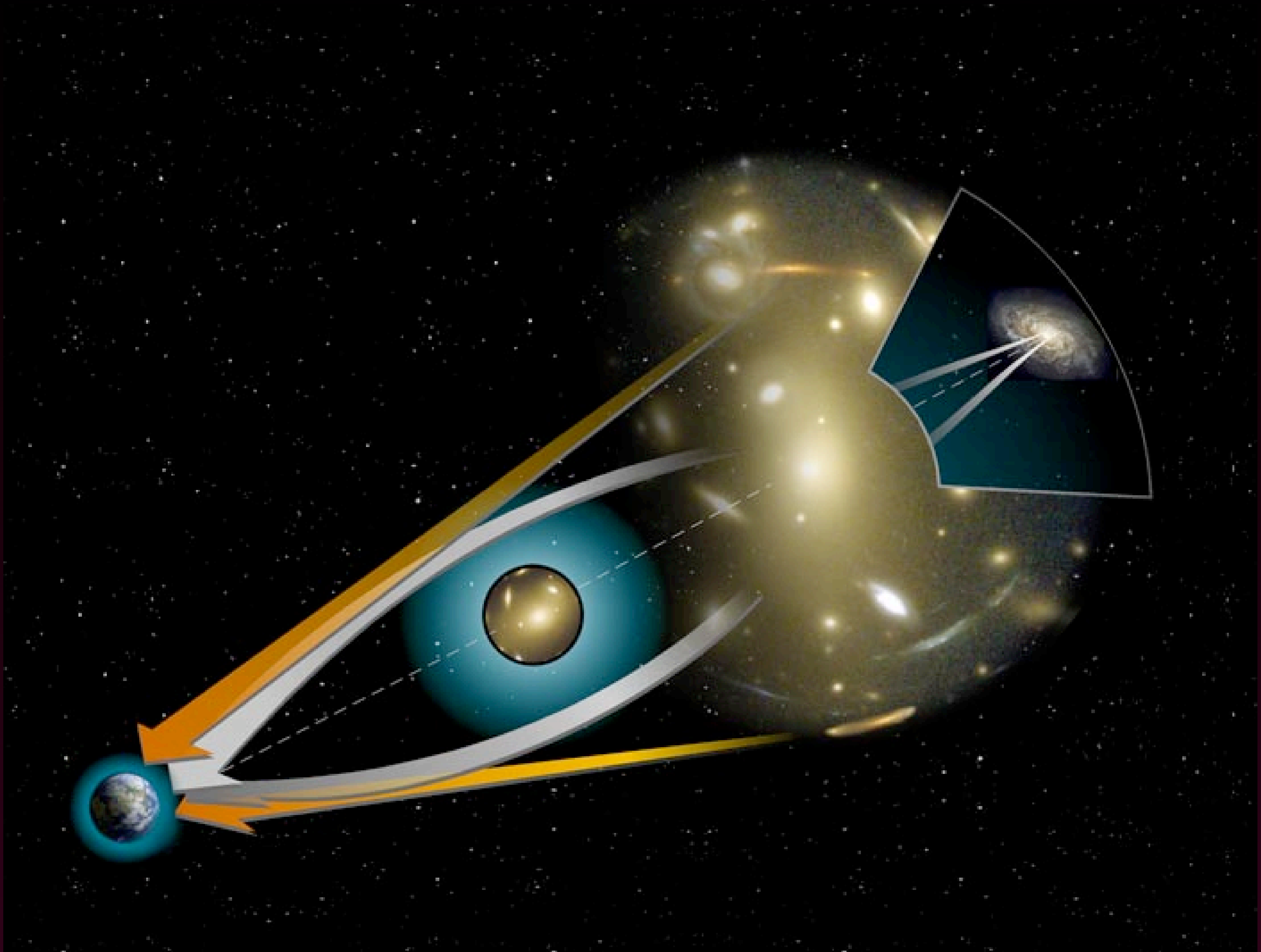
Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08



Gravitational Lens G2237+0305

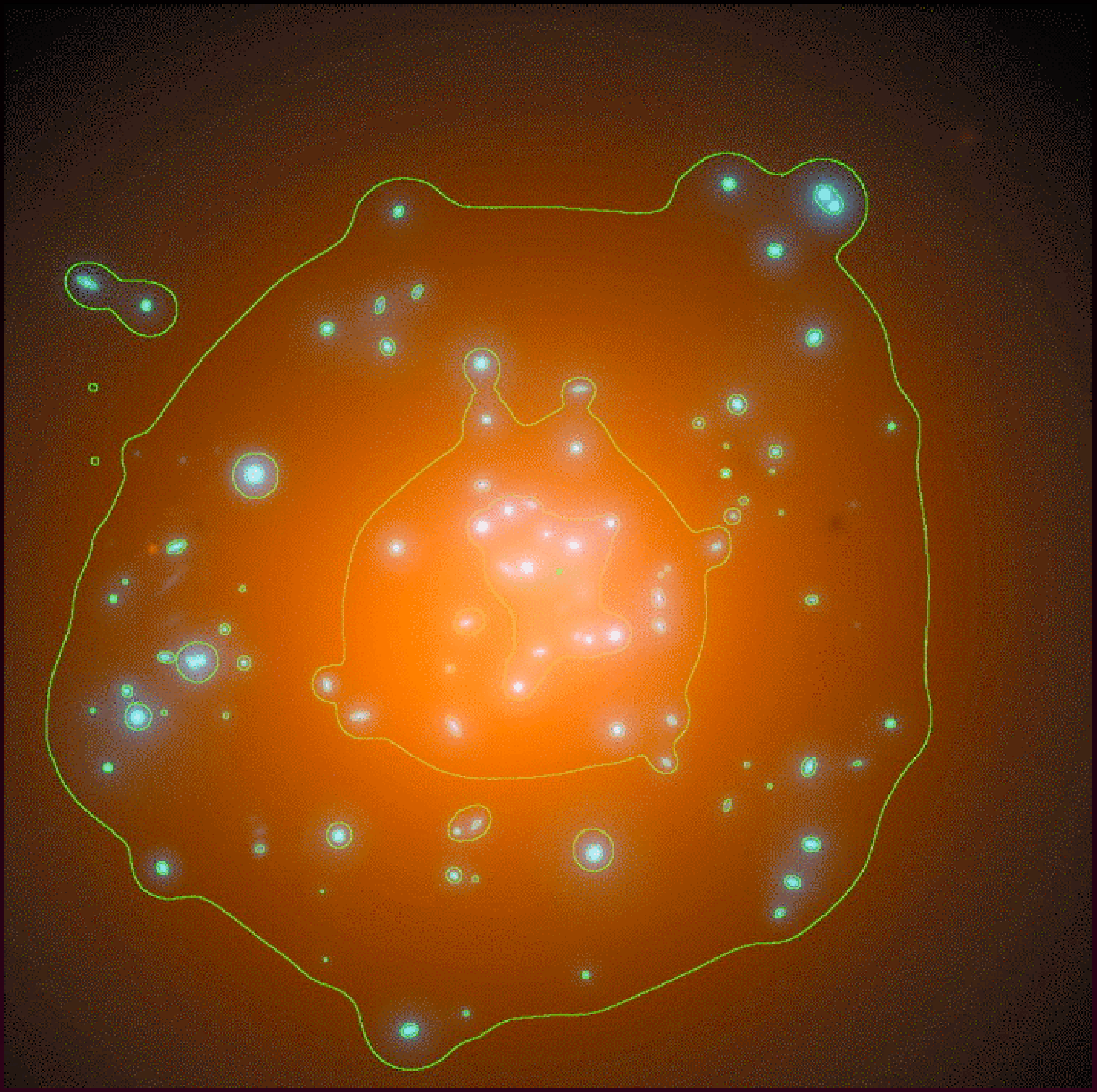
Cluster Lensing Arcs



CL 0024+1654

- rich cluster at z = 0.39
- one background galaxy multiply imaged
- complicated parametric model of the source and the lens
- ray trace model to match observed images and find best-fit parameters

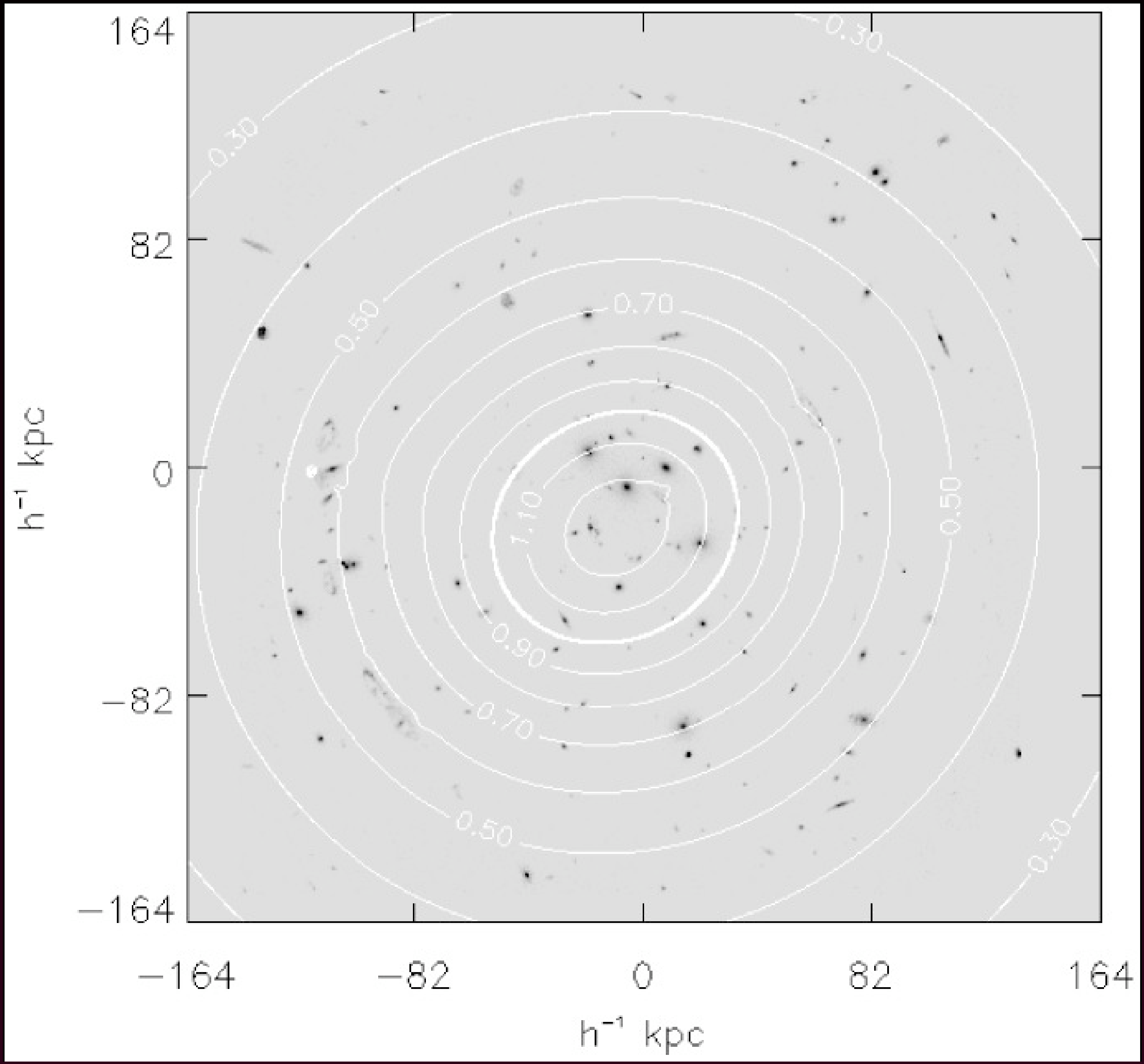
Mass model



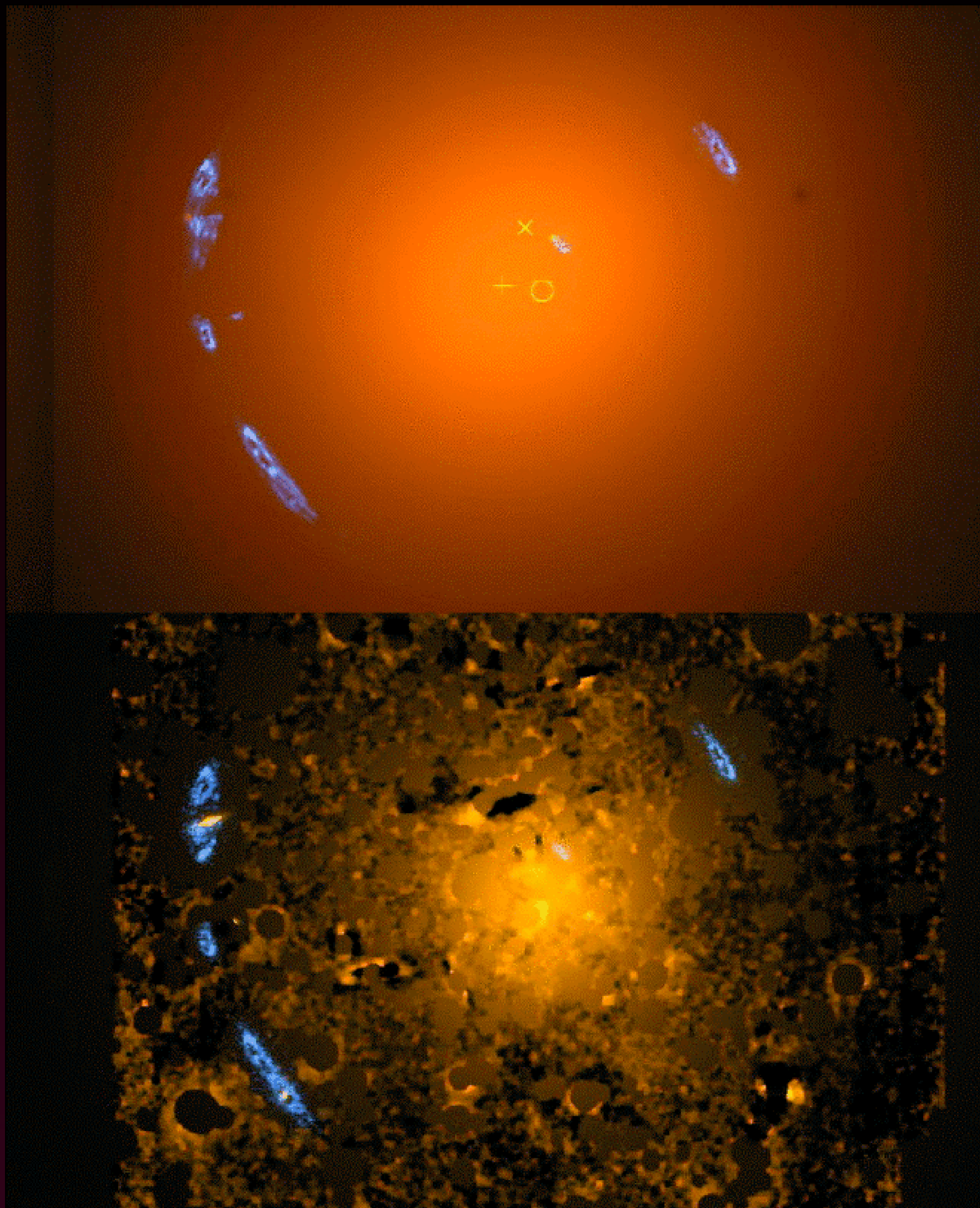
- blue points:
  visible galaxies
- orange:
  mass (dark matter), smooth, elliptical distribution
- contour:
  multiples of critical lensing surface density
- dark matter does not show massive infalling clumps

Mass versus Light

- dark matter contours superimposed on HST image
- on scales larger than 10 kpc, DM is smoothly distributed
- M/L ~ 300 for mass to *stellar* light ratio (gas not included)



Model versus Observation



- + DM center
  x total light center
  o diffuse light center
- blue arcs: reconstructed from model
- orange: diffuse light
- blue: observed arcs
- good agreement between model and observations

Core Concern?

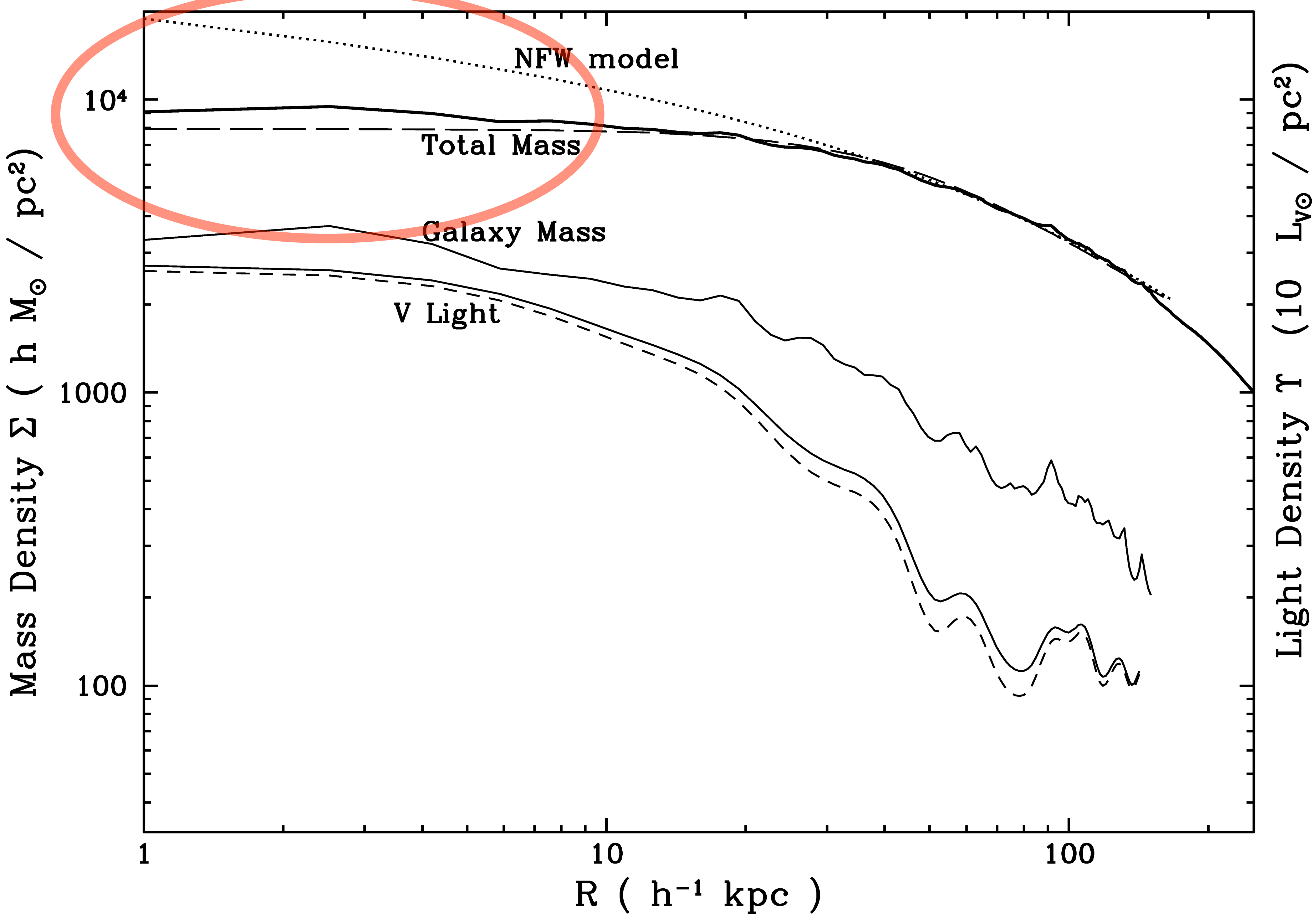
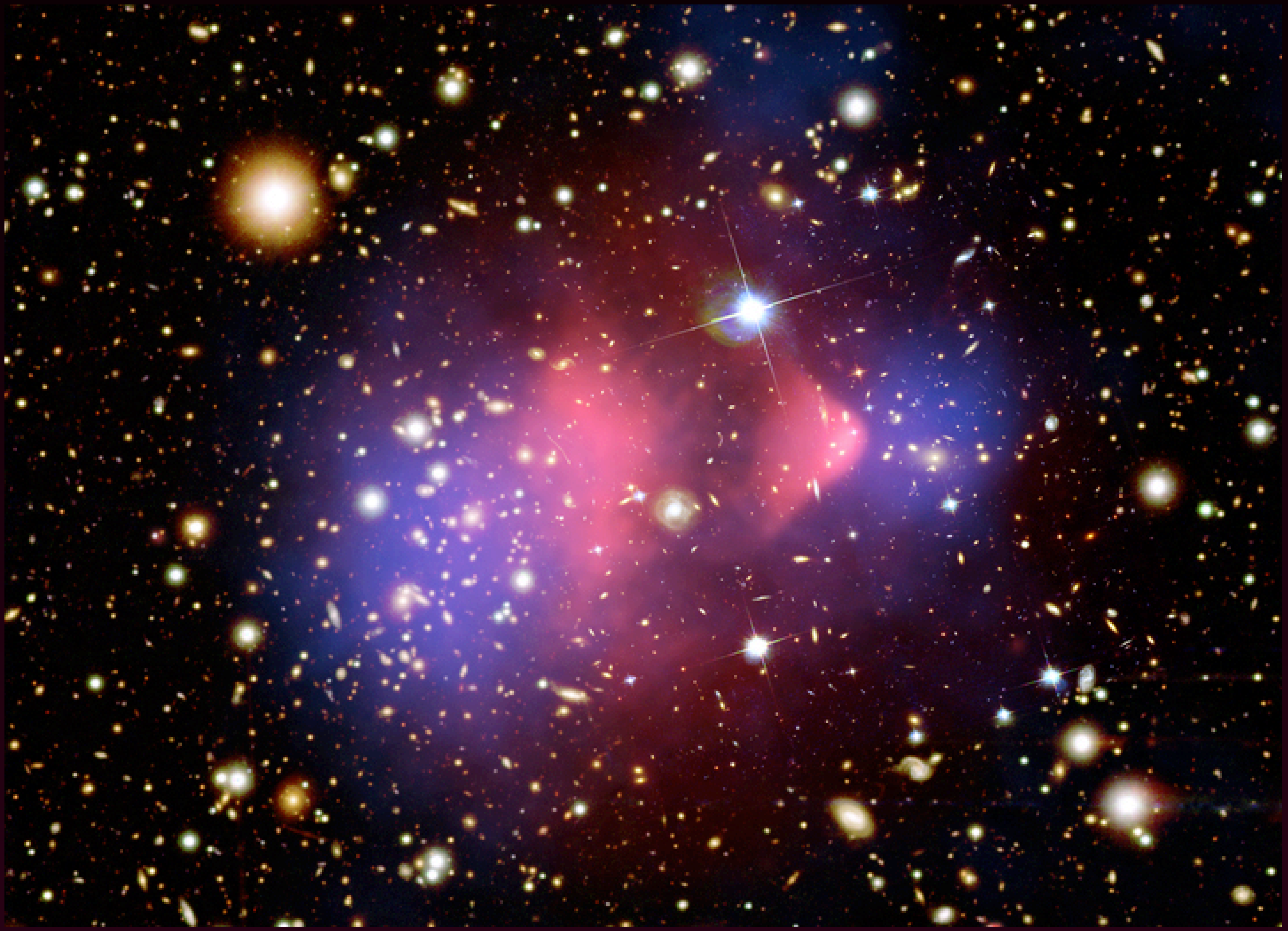


FIG. 4.—A radial plot of the mass density and light density. Total (*thick line*) and galaxy-only (*thin line*) components of the mass are shown. The dotted line is the best NFW fit discussed in the text, and the dashed line is the best-fit single PL model. The 35 h^{-1} kpc soft core in the mass is evident. A singular mass distribution is ruled out. The total rest-frame *V* light profile (*solid line*) and galaxy *V* light profile (*dashed line*), smoothed with a 5 h^{-1} kpc Gaussian, are also shown.

A Direct, Empirical Proof of the Existence of Dark Matter

Clowe et al. (2006)



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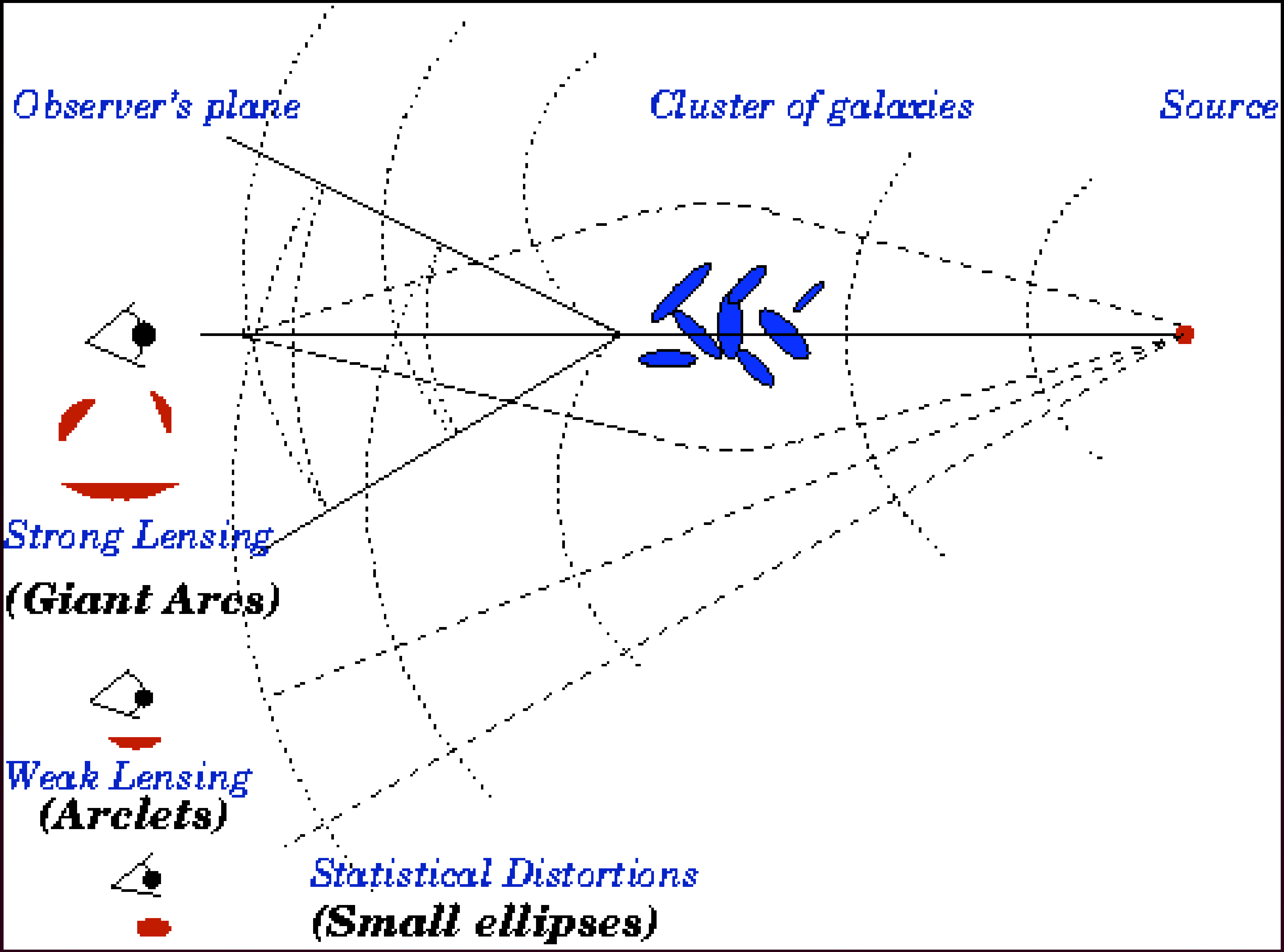
Dark Matter or Modified Gravity?

- If you find a system where observed baryons and inferred dark matter are spatially separated, then modified gravity hypotheses (like MOND) could be ruled out.

- In this paper, such evidence is reported, based on observations of a cluster collision in the "Bullet" cluster at $z = 0.296$. Clusters passed through each other, primarily on the plane of the sky, ~100 Myr ago.

- Observations
  - visible light (stars & galaxies)
  - X-rays (gas heated in cluster potential, shocked by collision)
  - total mass (reconstructed from weak lensing)

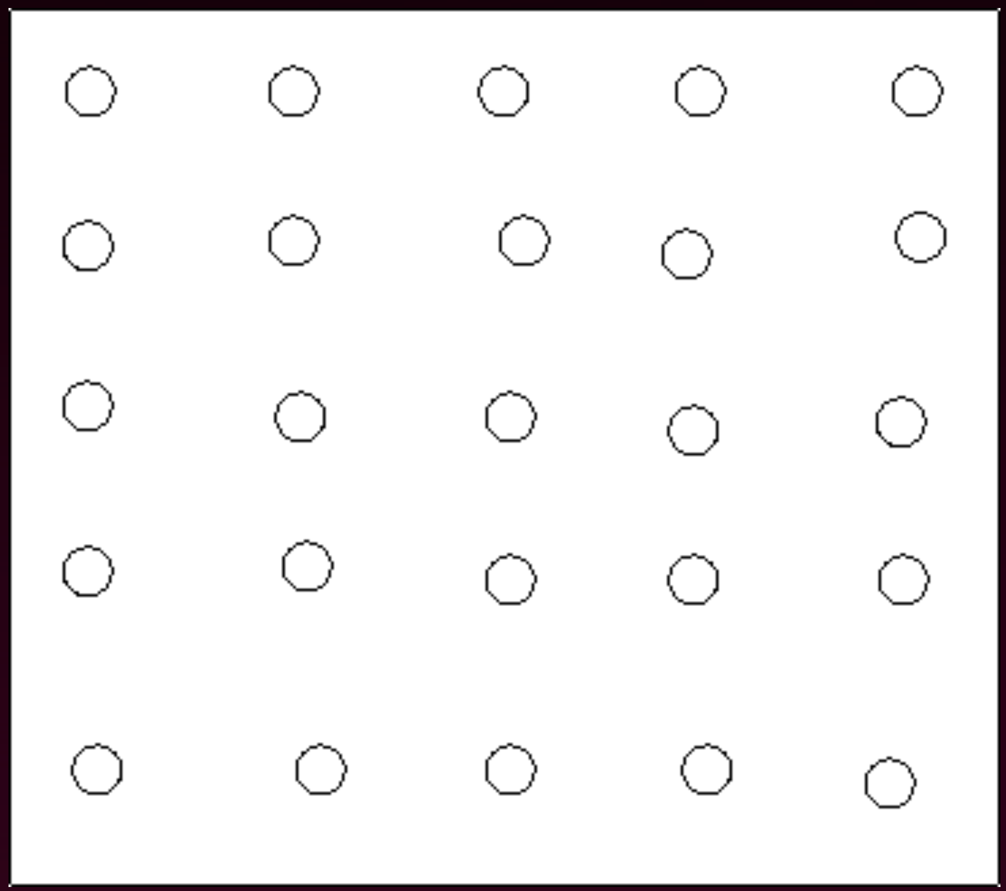
Lensing Regimes

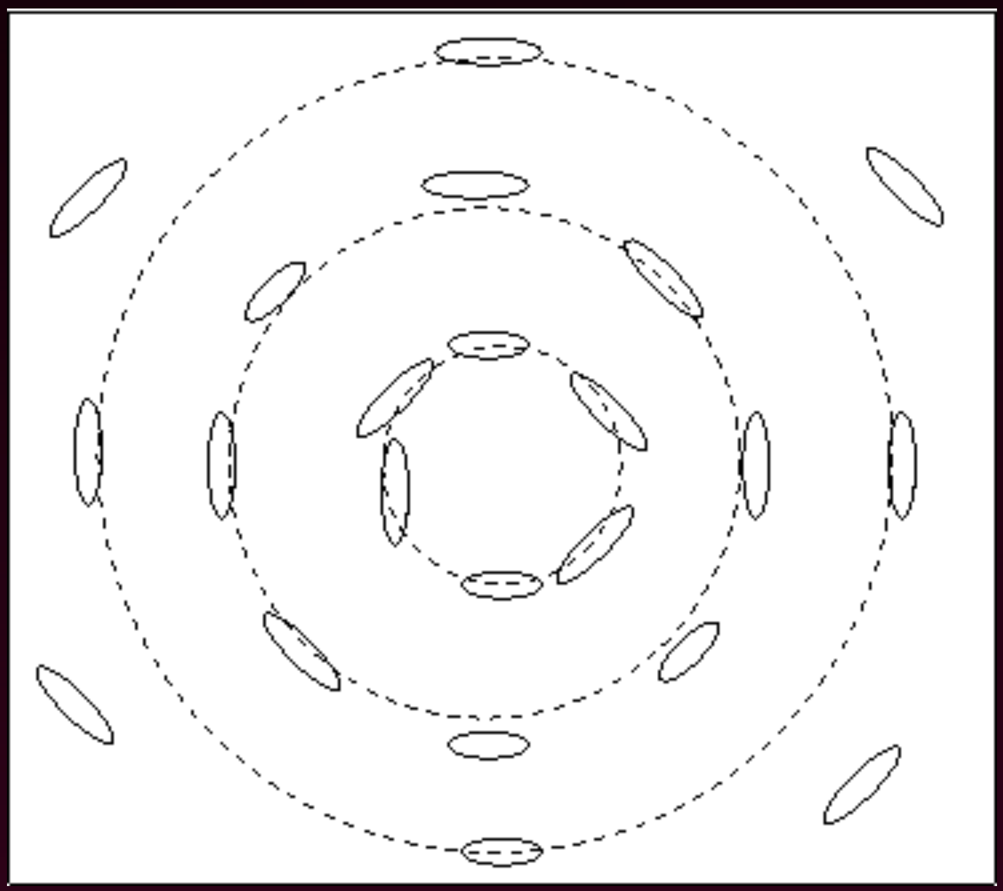


from Bhuvnesh Jain, http://www.hep.upenn.edu/~bjain/lensing.html

Weak Lensing

- even when the lens is not strong enough to form multiple images, background sources appear distorted
- if source sizes and shapes were known, we could deduce lens properties
- do this *statistically* by averaging many background sources, measure shear
- can be applied to clusters (this paper) and general large scale structure





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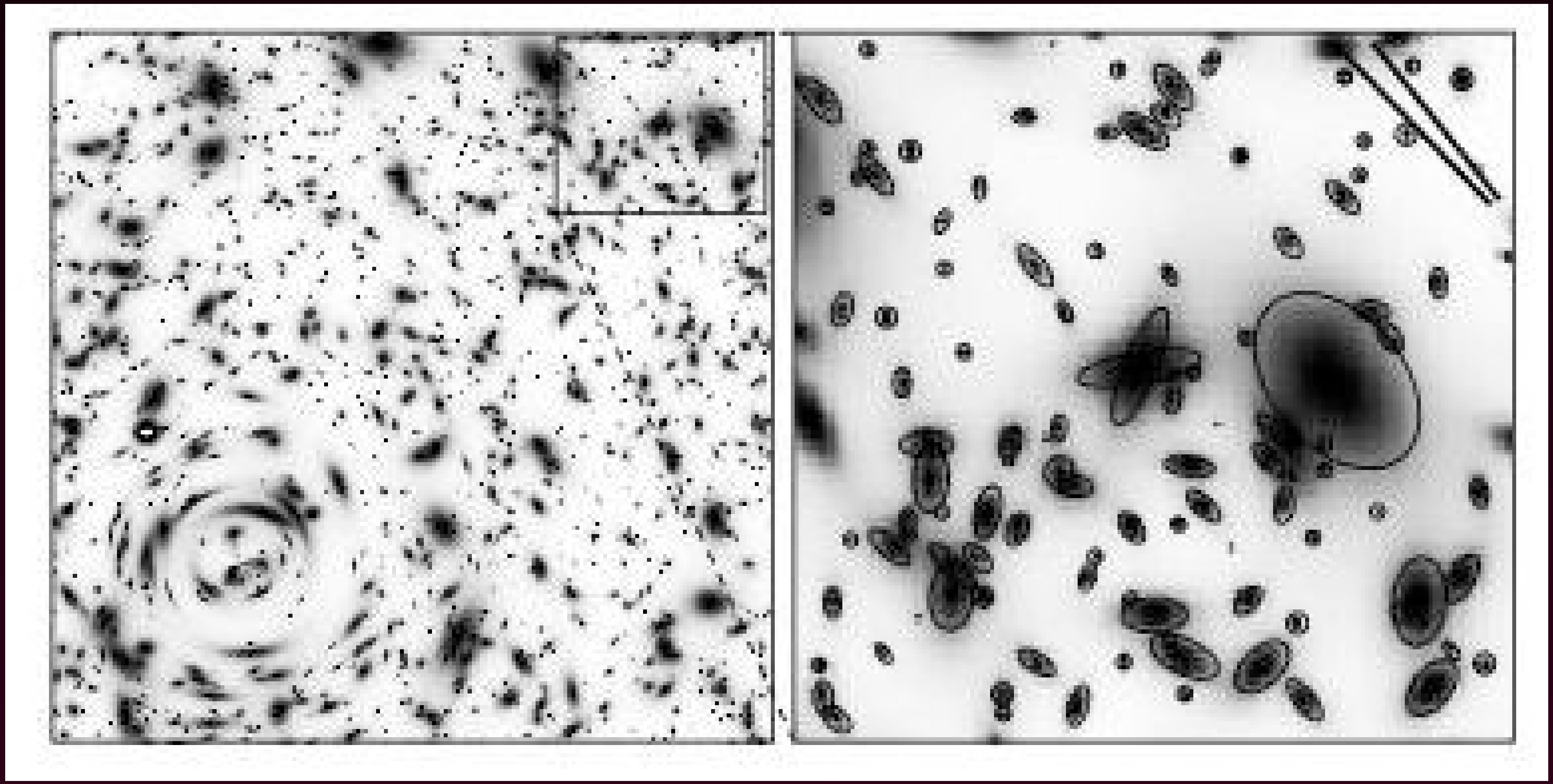


Results

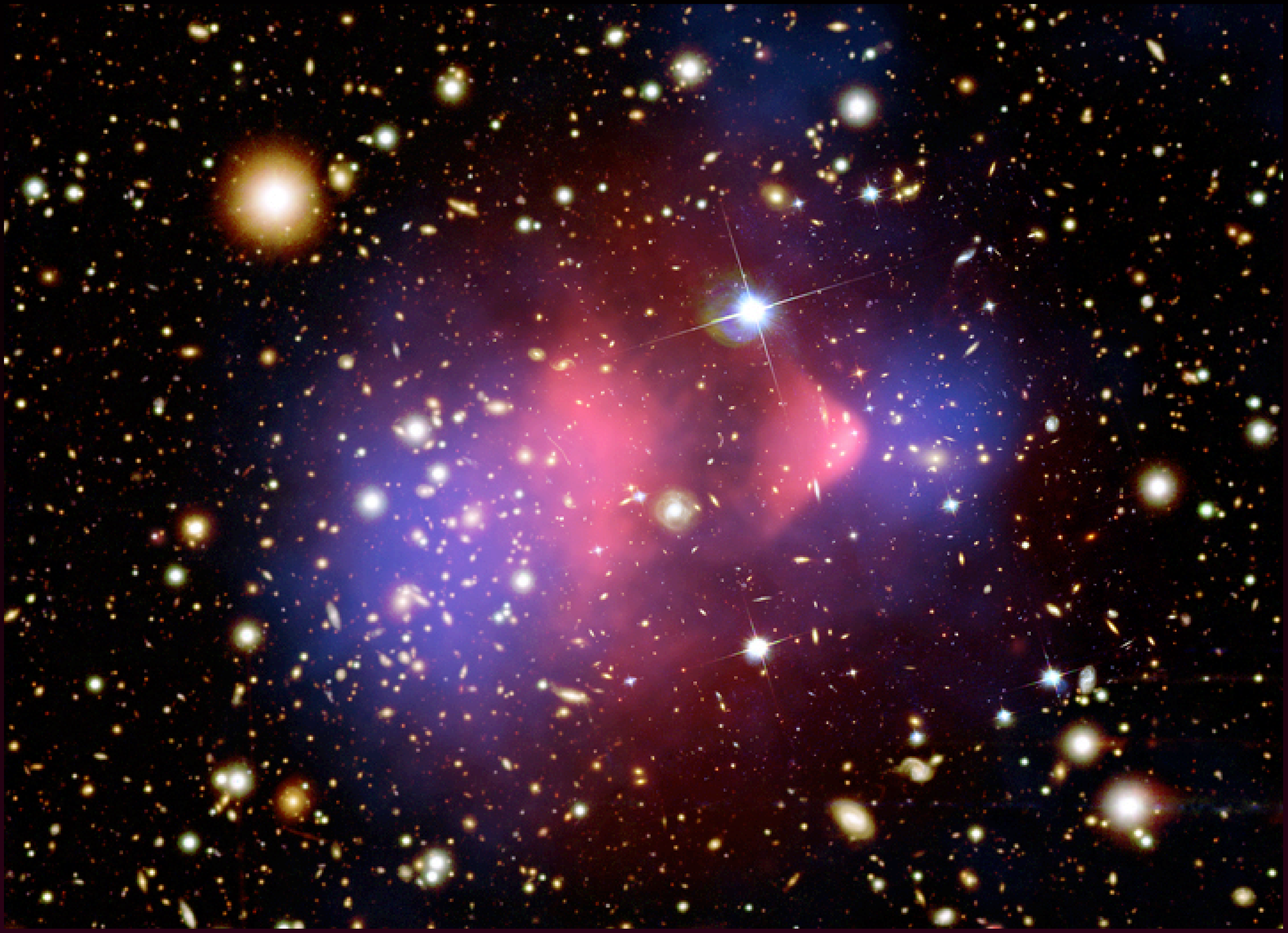
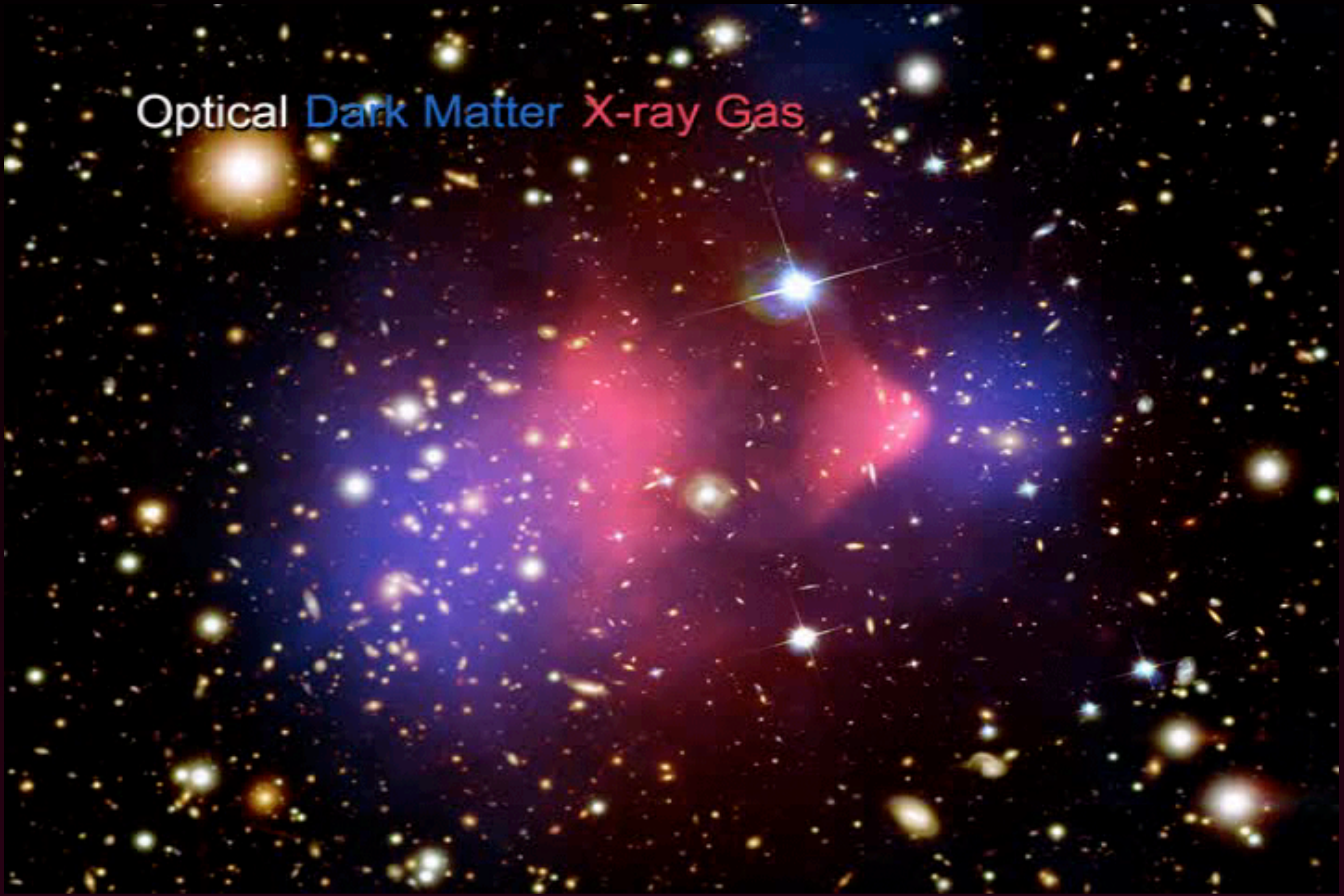


image: optical pink: X-ray gas blue: lensing mass

images and animations from http://chandra.harvard.edu/photo/2006/1e0657/index.html

Results



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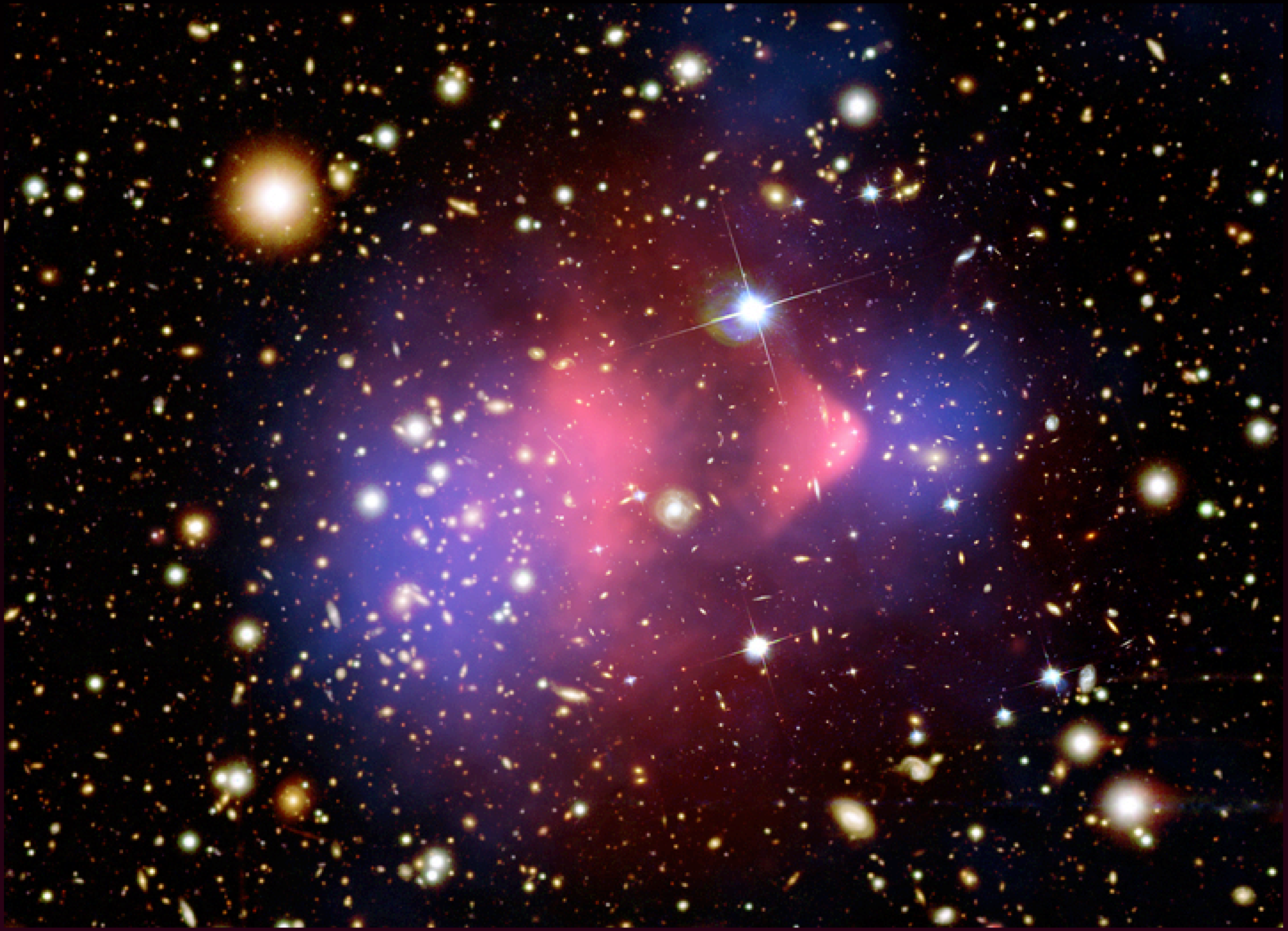
What's going on?



dark matter is collisionless while X-ray gas is not

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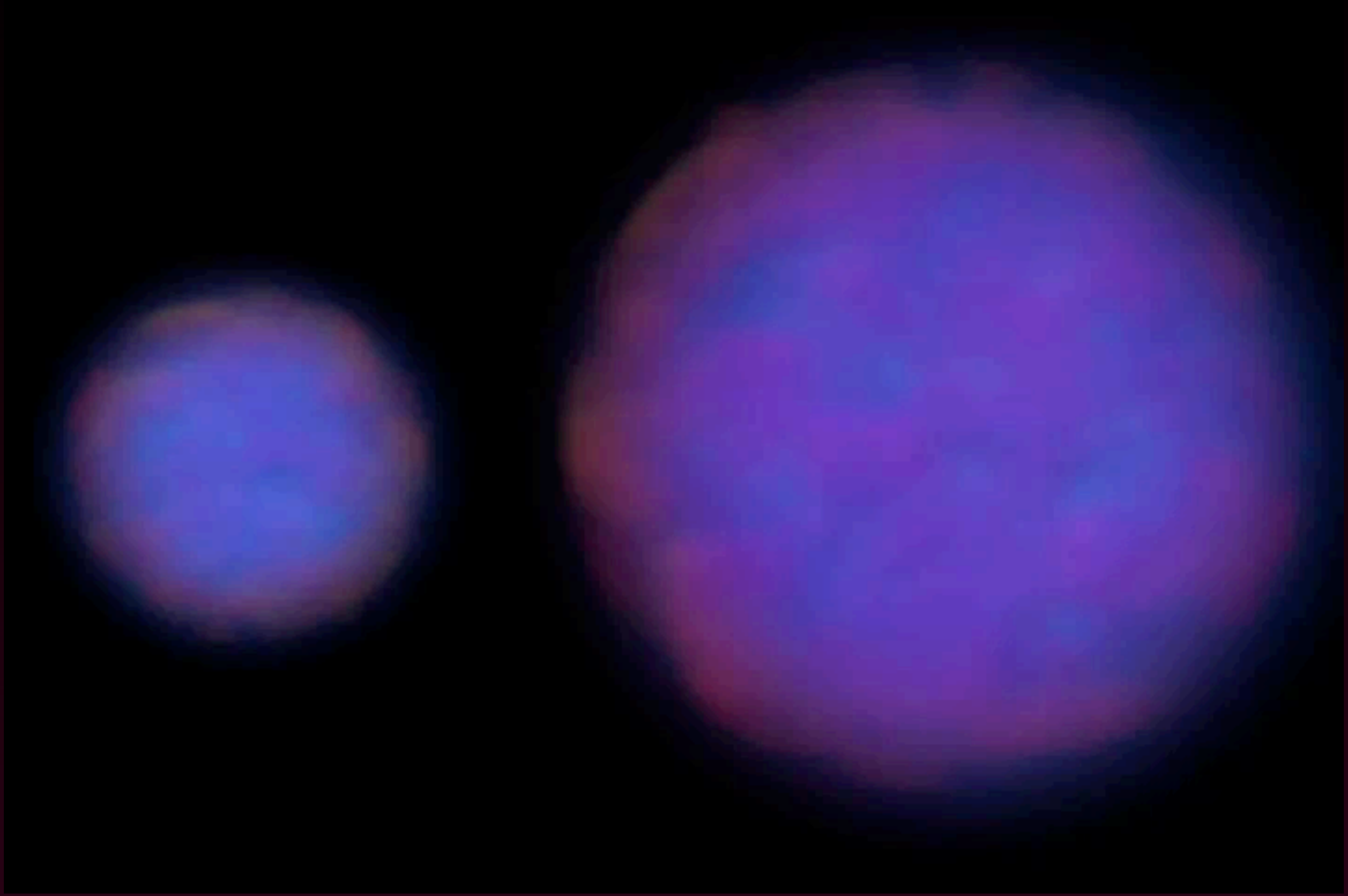

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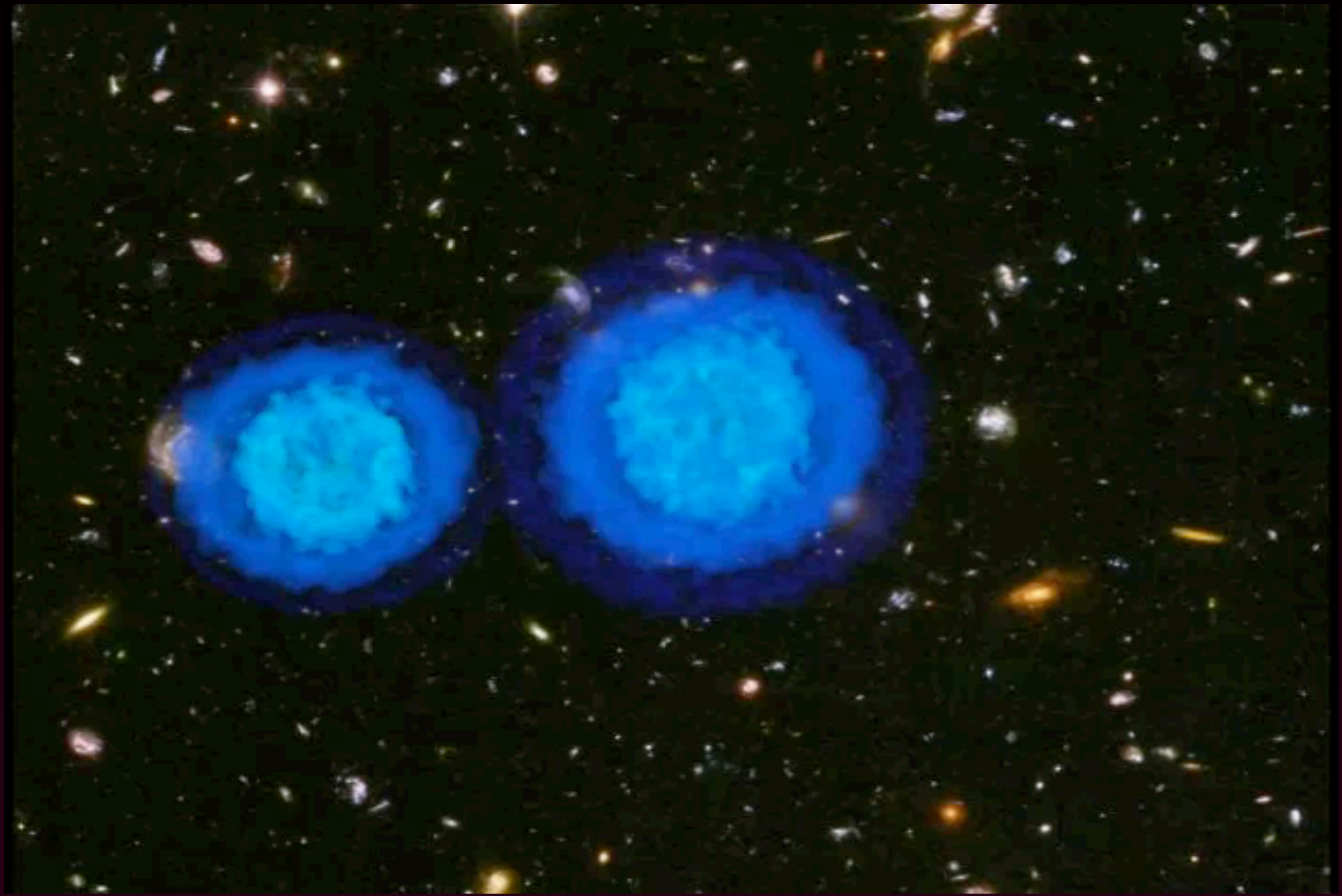

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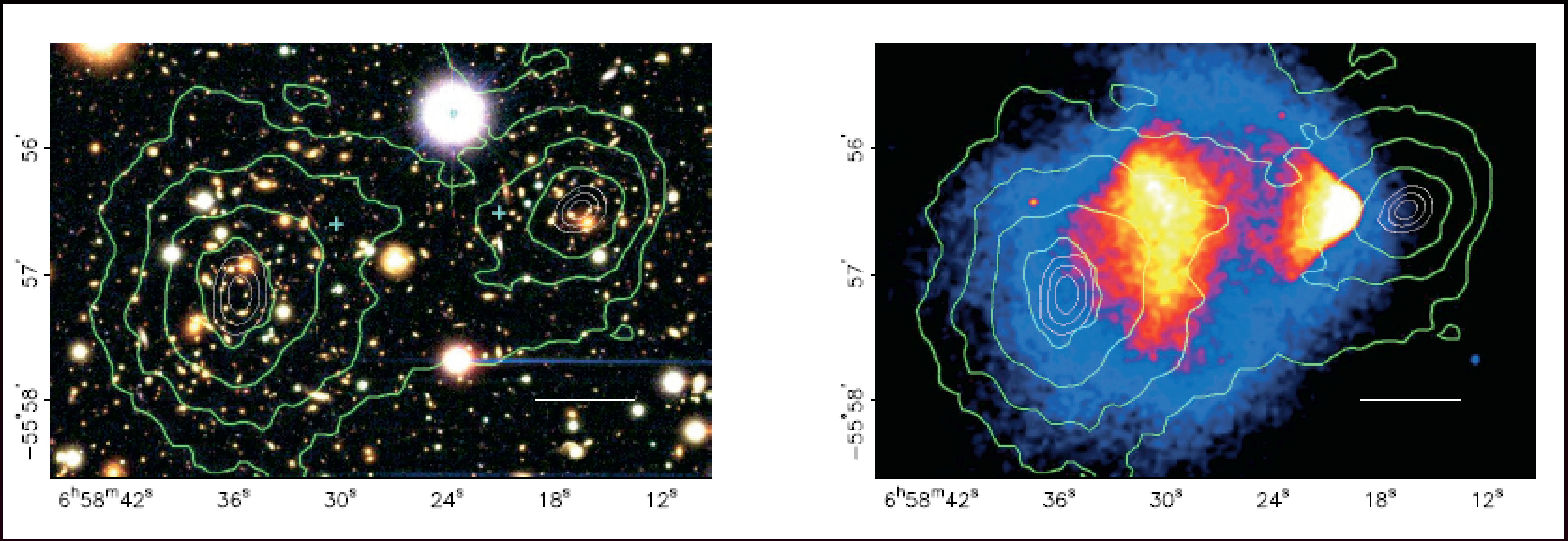
Dark and Light Offset



- total mass is concentrated like the galaxies are, not where the gas is, but $M_{total} : M_{gas} : M_{stars} \sim 70 : 10 : 1$
- spatial offset between gas peaks (+) and mass is very significant
- strongly favors DARK MATTER hypothesis over modified gravity