Direct evidence for dark matter and astrophysical bounds on its cross section

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ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

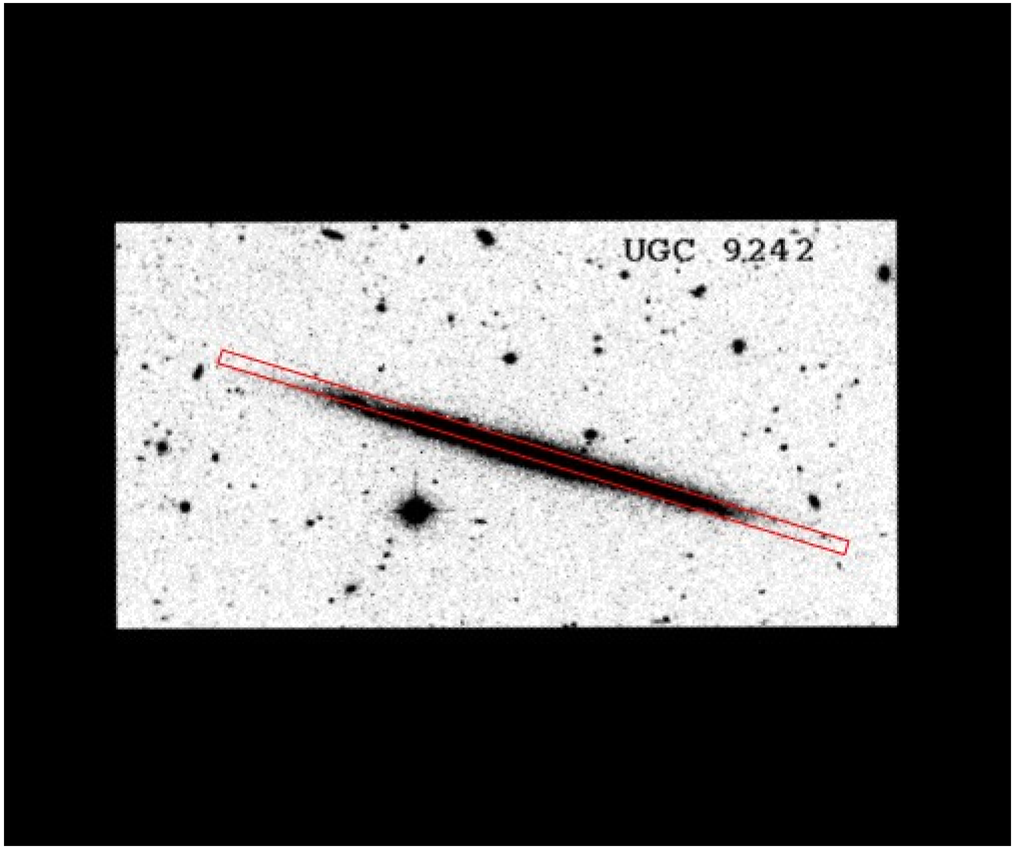
Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the

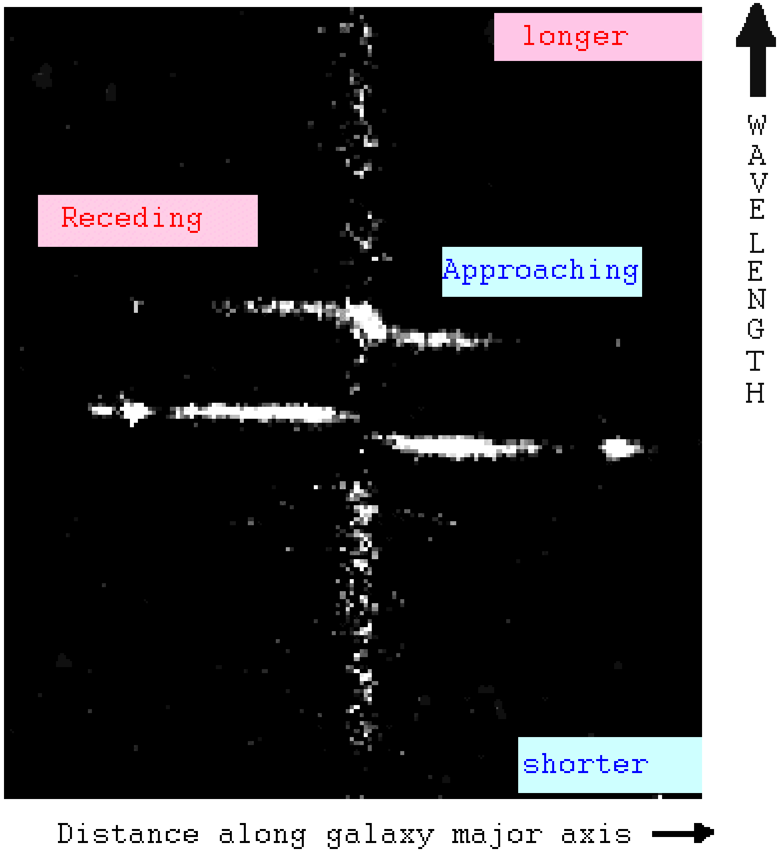
Mass in clusters

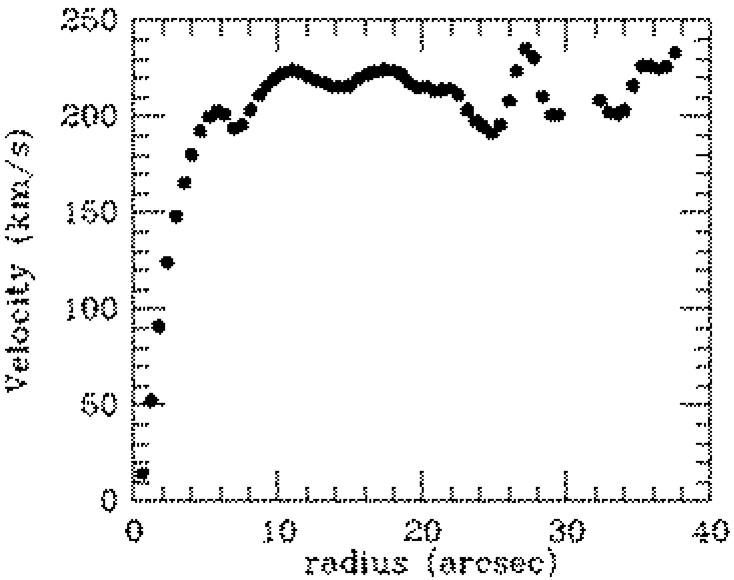
- Zwicky – 1933, 1937: total mass in clusters is 100 times larger than the visible mass
- Current inventory:
  - 1-3% in stars
  - 10-20% in gas (T~1-10 keV, optically thin)
  - 80-90% in dark matter (10^{15} Msun)

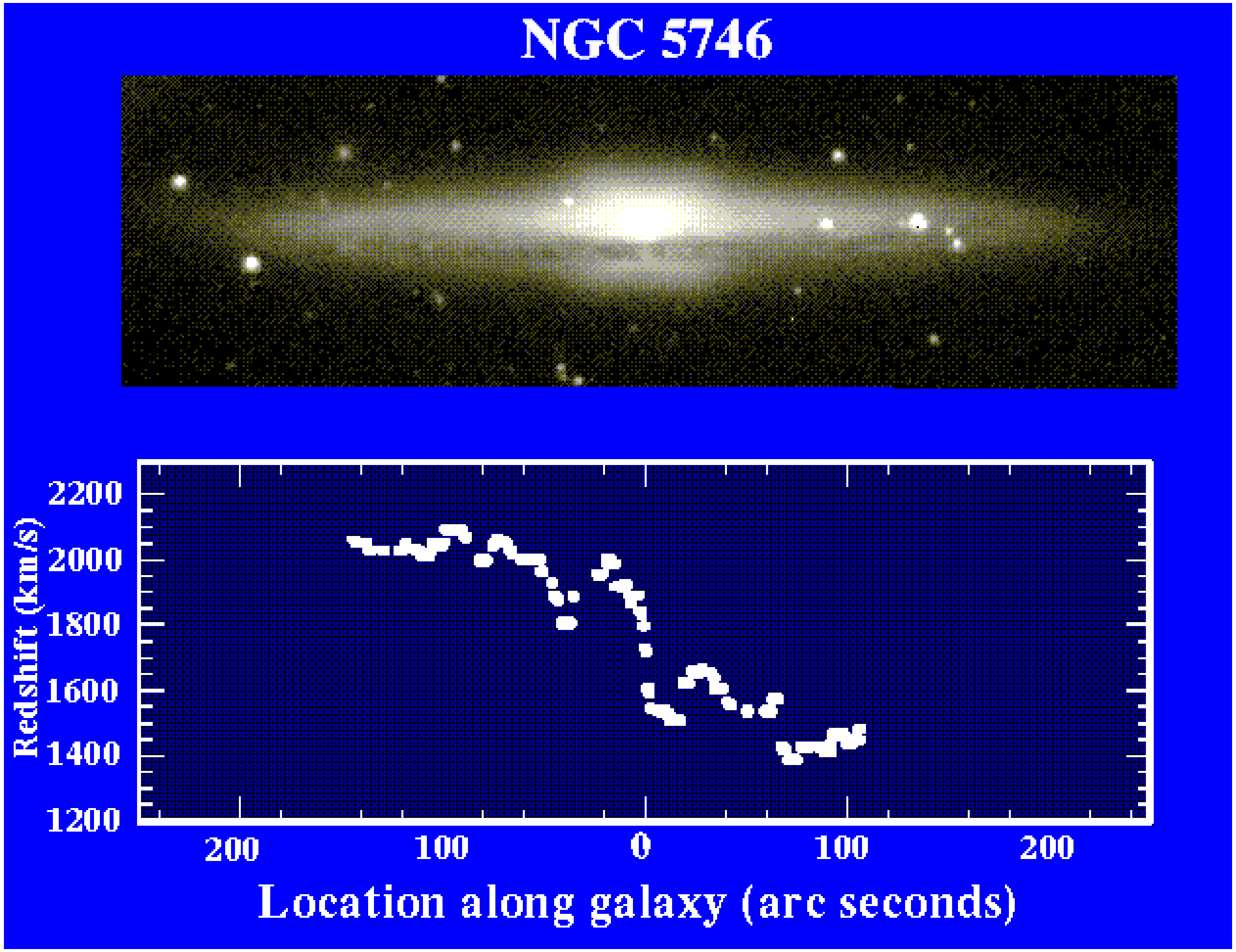
Galactic dark matter

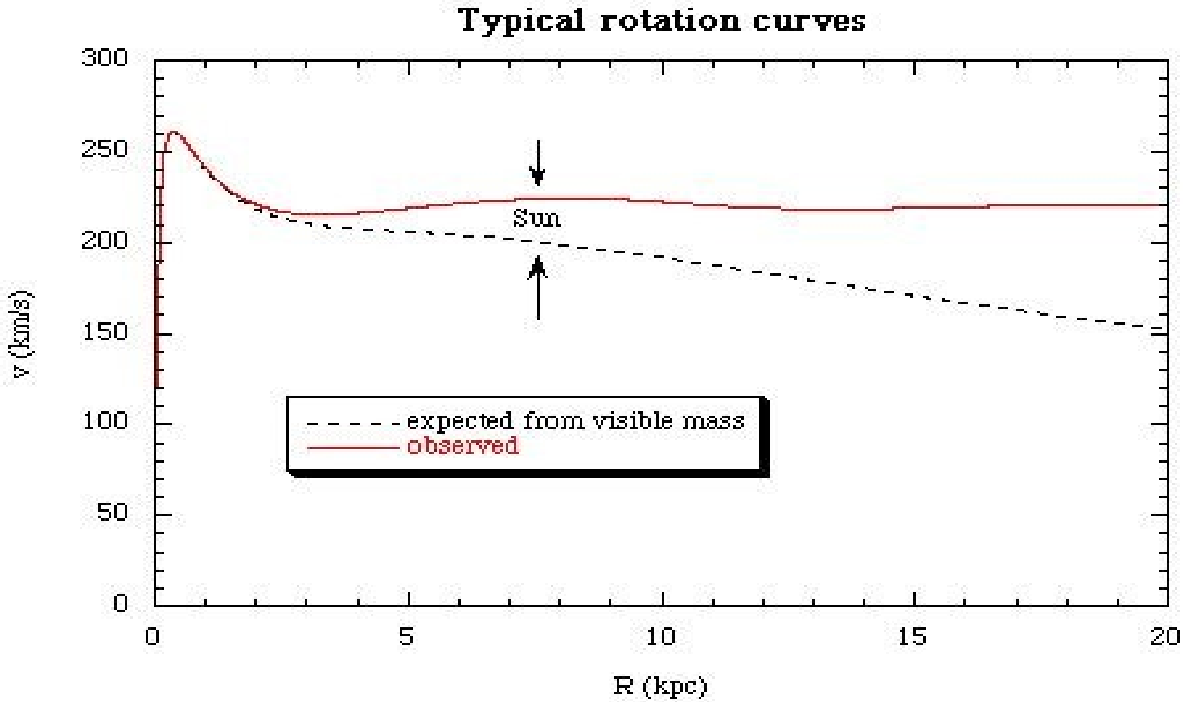


Galaxy rotation curve

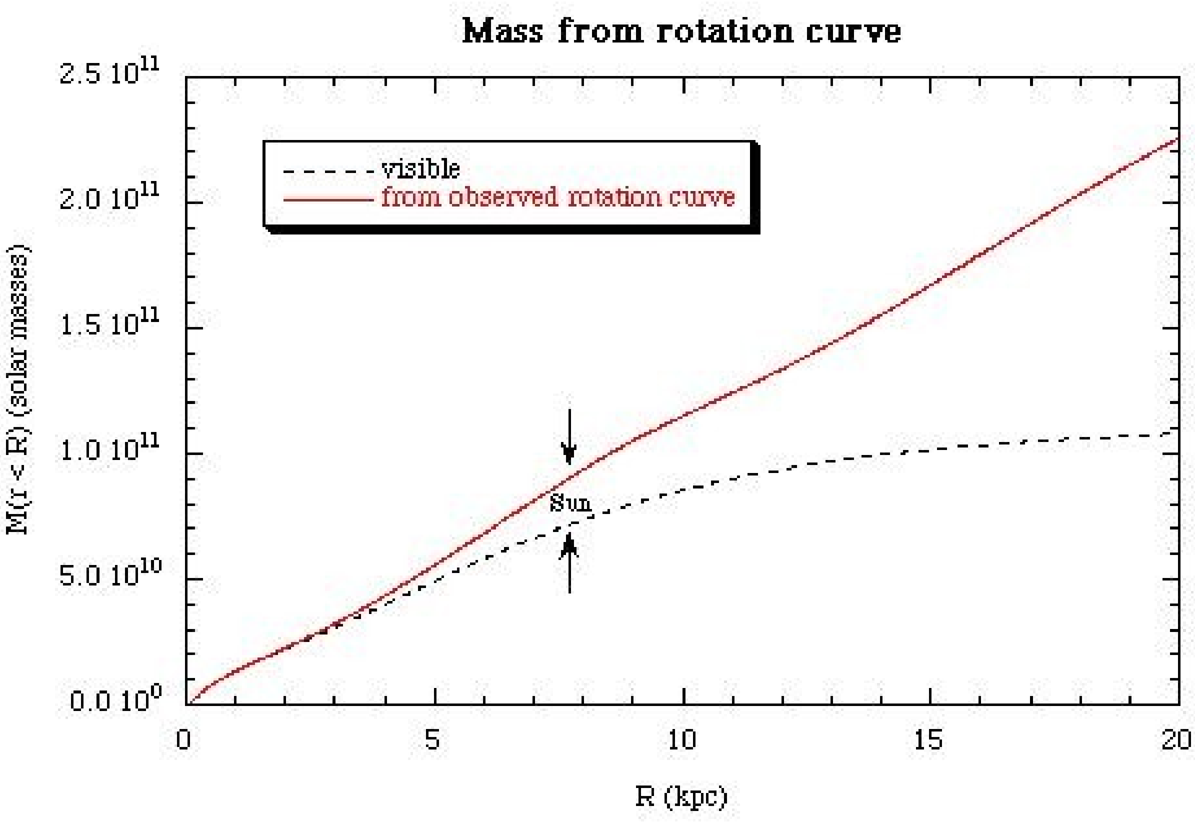





NGC 5746
Redshift (km/s)
2200
2000
1800
1600
1400
1200
200
100
0
100
200
Location along galaxy (arc seconds)



Mass estimate



Alternative explanation

- Assumption: Newtonian gravity works at large distances (Mpc scale)
- Can theory be modified to get rid od dark matter?
- Modified Newtonian Dynamics (MOND) – an attempt to do that

What is MOND?

$$\vec{F} = m \cdot \mu\left(\frac{a}{a_0}\right)\ \vec{a}$$

The additional function $\mu(x)=1$ for $x>>1$
and

$\mu(x)=x$ for $x<<1$

Proposed by M. Milgrom in 1981.

Rotation curves

$$F = \frac{GMm}{r^2} = m\mu\left(\frac{a}{a_0}\right)a$$

$$v = (GMa_0)^{1/4}$$

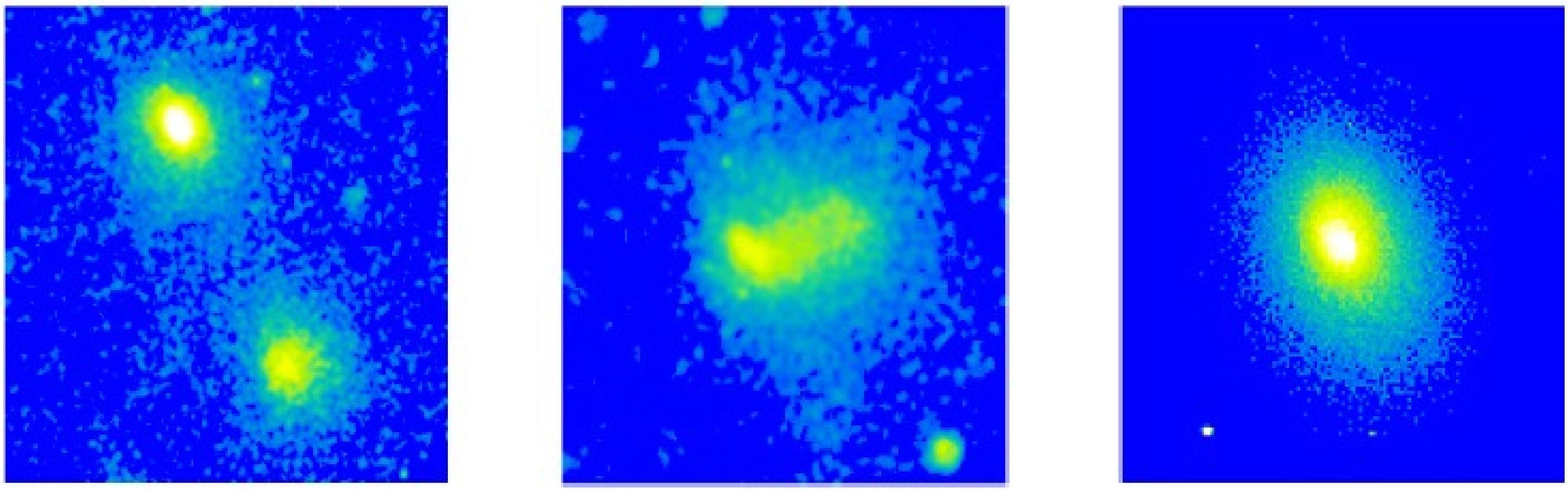
Milgrom found the constant using the
Tully Fischer relation.

$$a_0 = 1.2 \times 10^{-10}\mathrm{ms}^{-2}$$

MOND

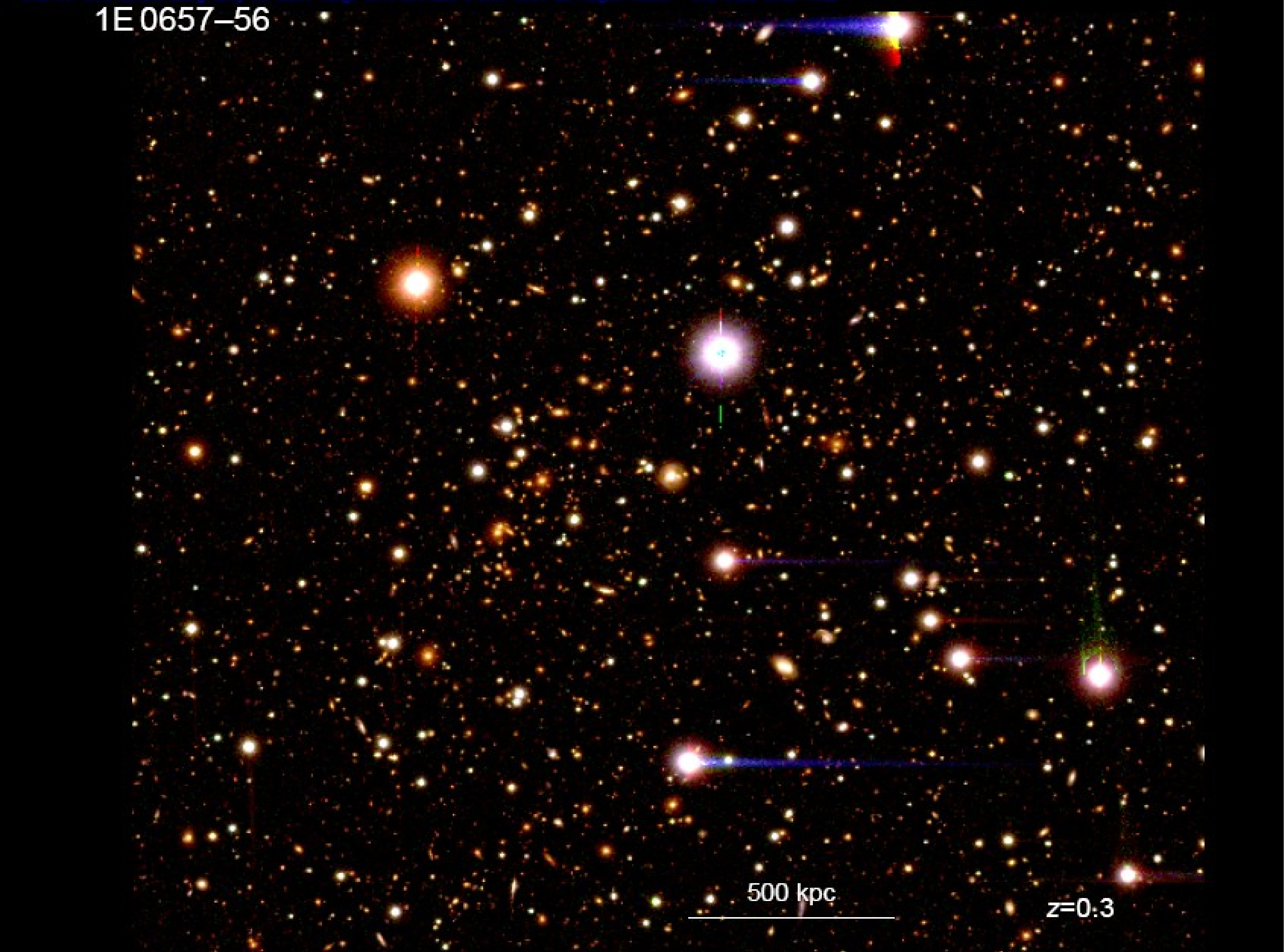
- Difficult to generalise to the general relativistic version
- A sussesful attempt – TeVeS
- Difficult to falsify in solar system
- Galaxy clusters and their dynamics
- May be consistent with the Pioneer anomaly

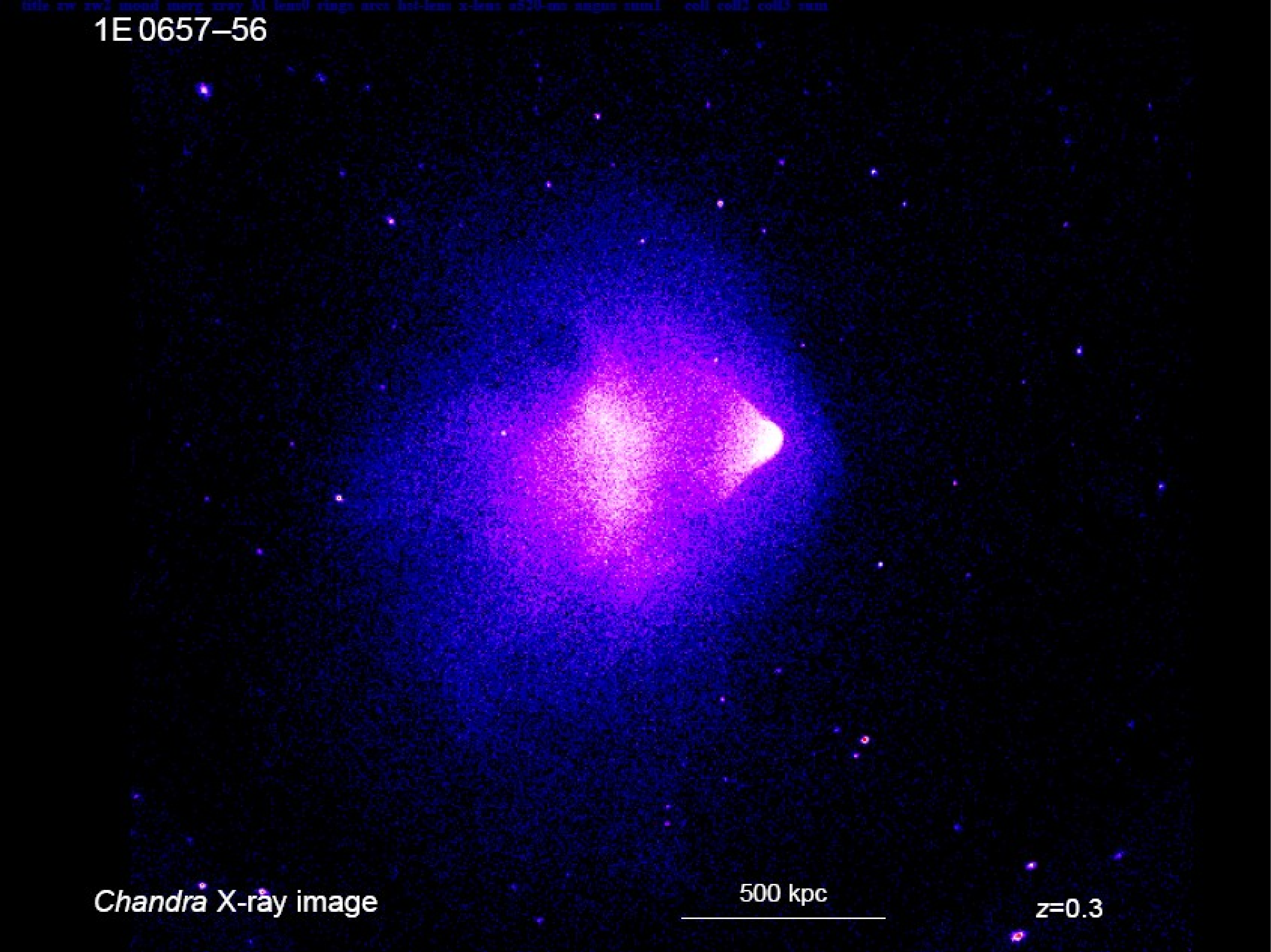
Cluster mergers



Timescale: up to a Gyr
energy: 10^{63-64} erg

Can dark matter and visible matter be separated in a merger?

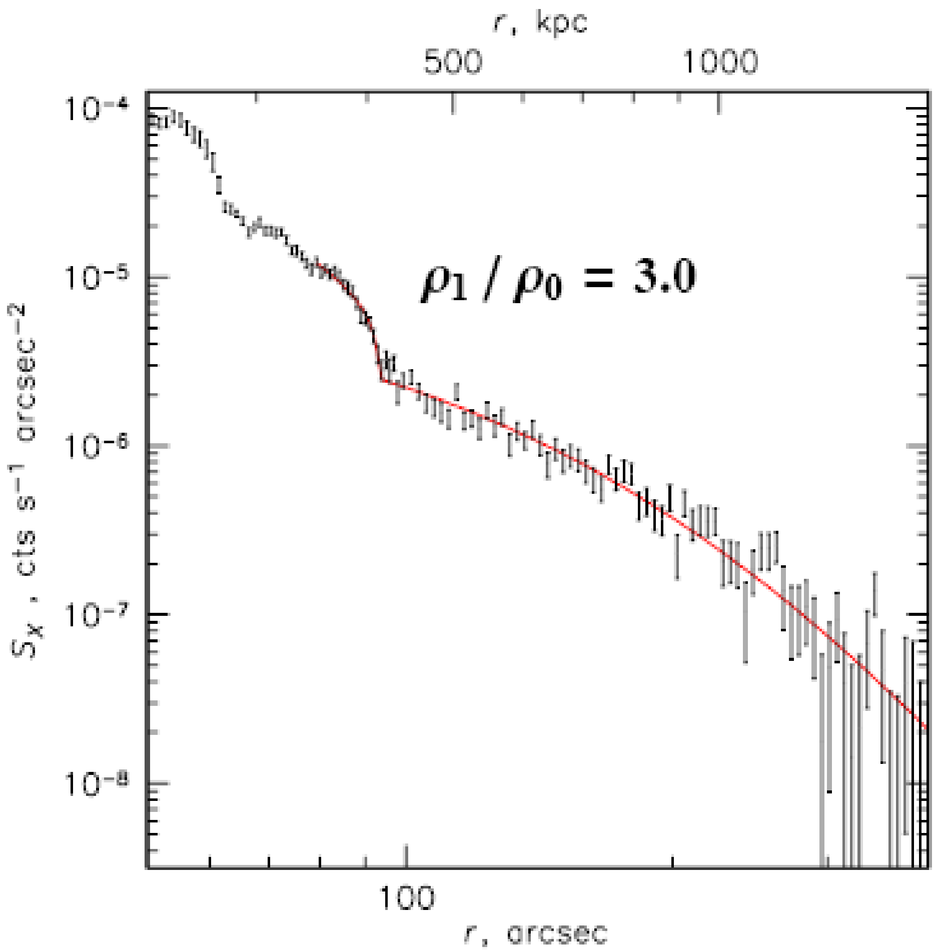

1E 0657–56
500 kpc
z=0.3

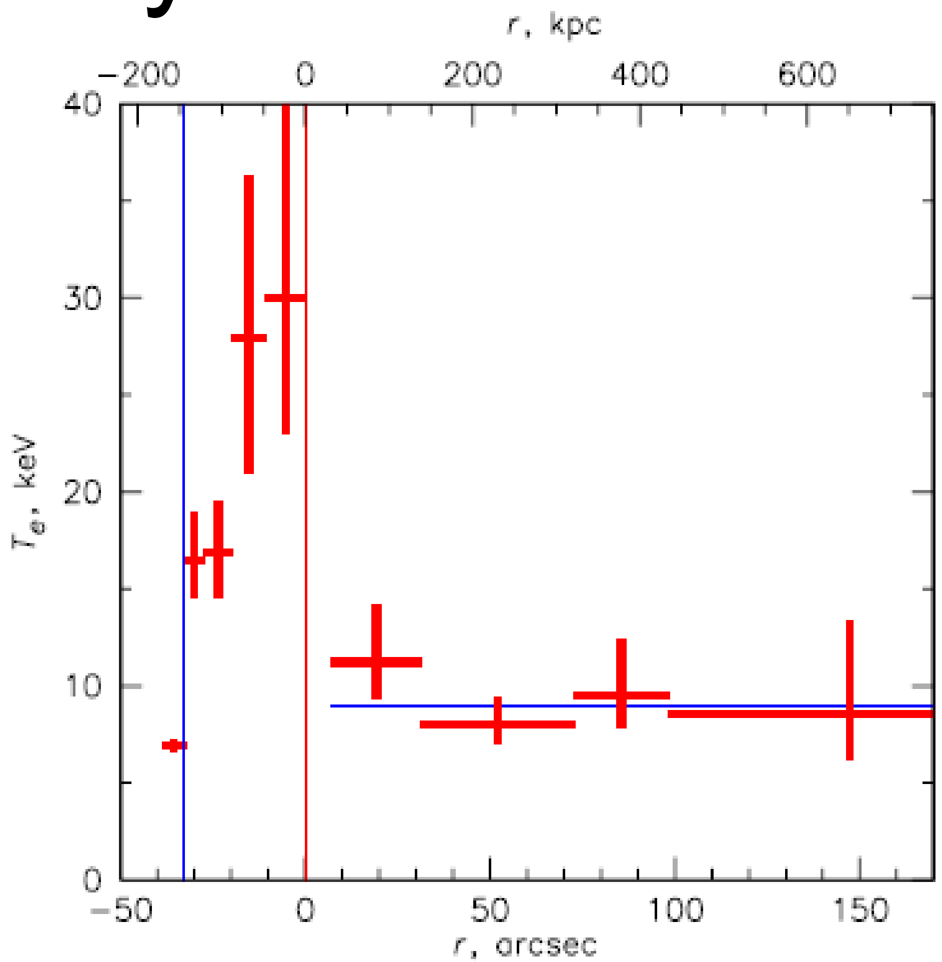

1E 0657–56
Chandra X-ray image
500 kpc
z=0.3

Gas density reconstruction

- Optically thin bremstrahlung spectrum
- Column density from intensity
- Total mass

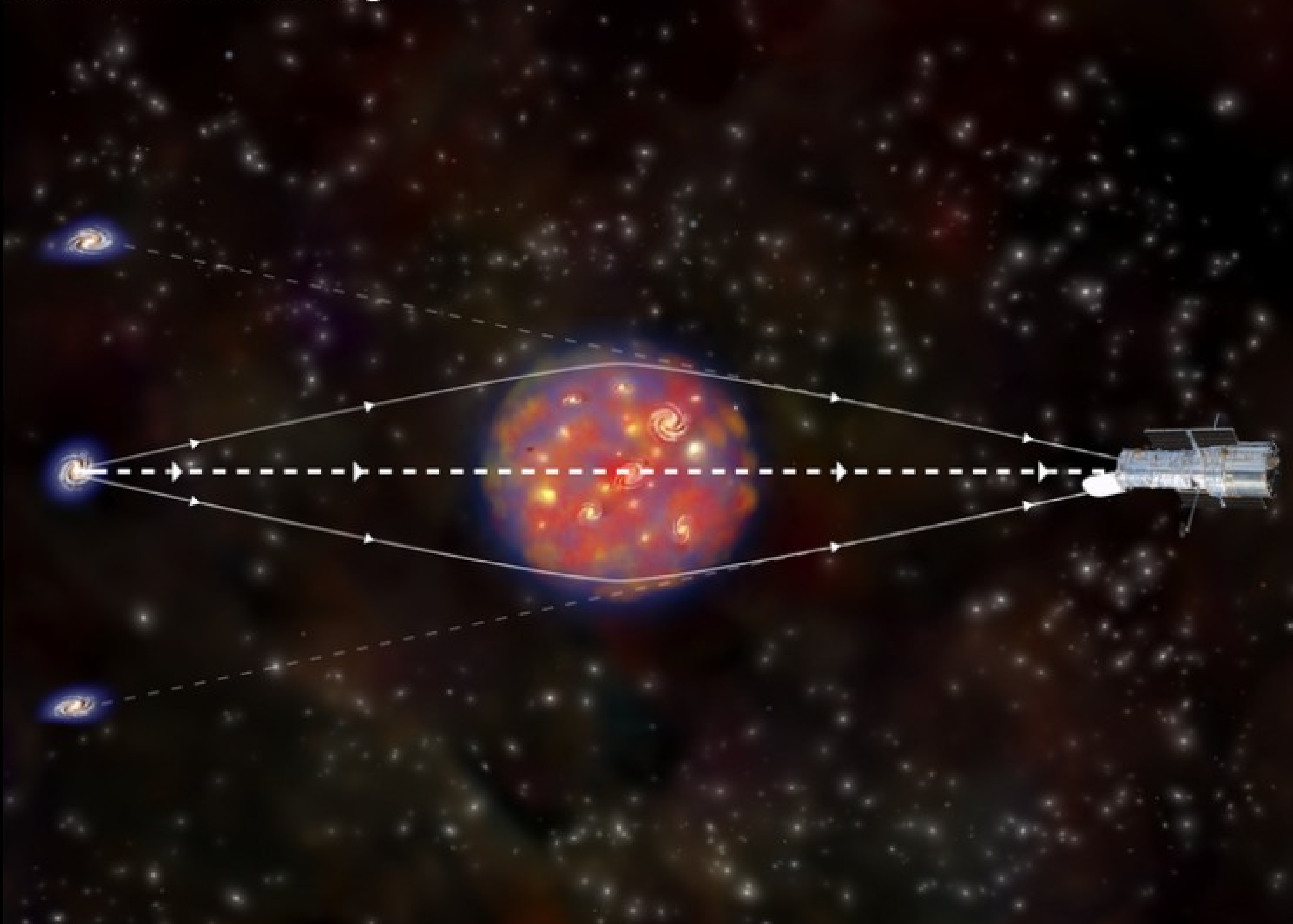
Shock analysis

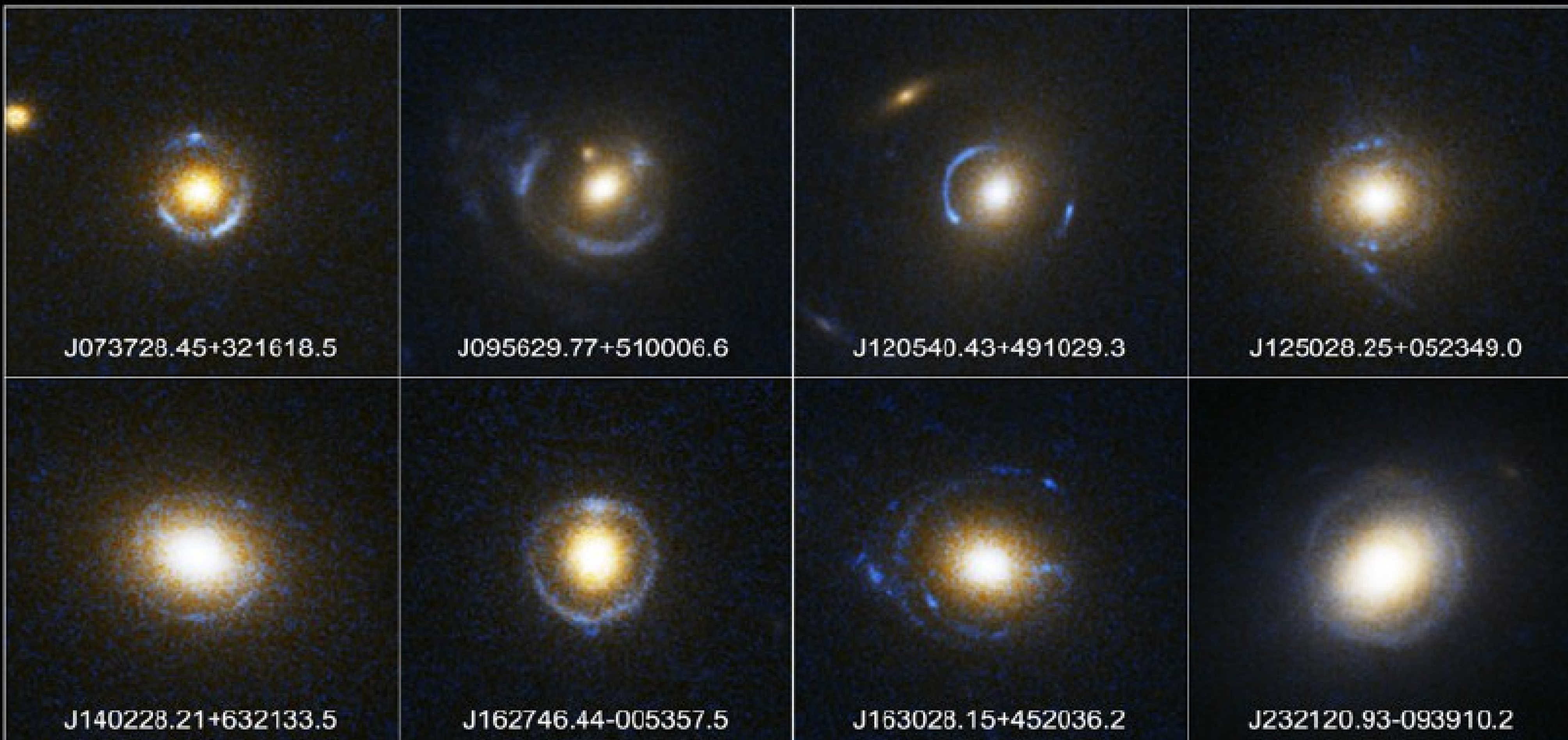




$M = 3.0 \pm 0.4$, shock $v = 4700$ km s^{-1}

Gravitational lensing





Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

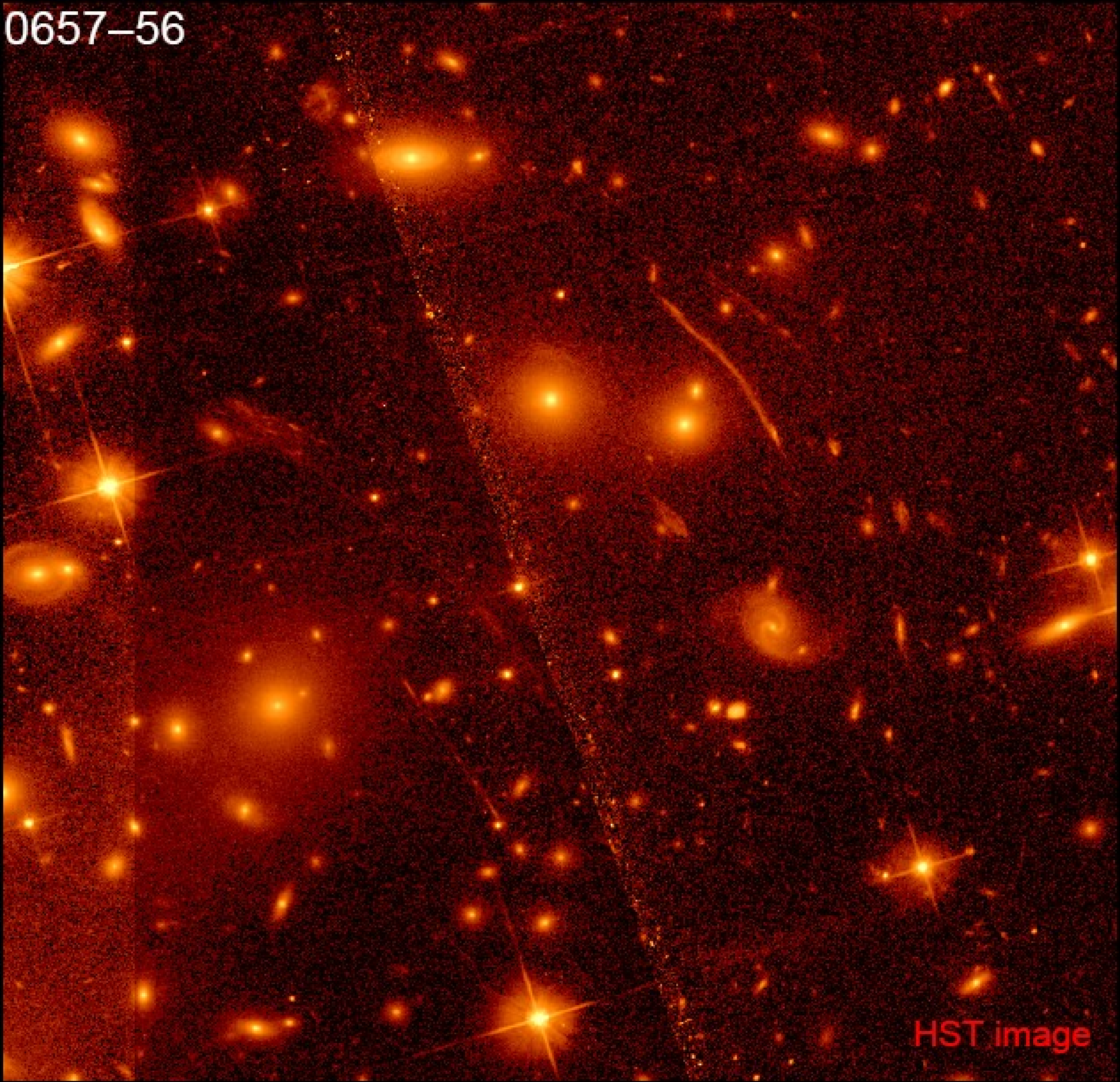
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

Mass reconstruction from lensing

- Find weak galaxies
- Determine shapes
- Find average shear
- Find arcs
- Average shear – average gravitational potential
- Potential - mass

1E 0657–56



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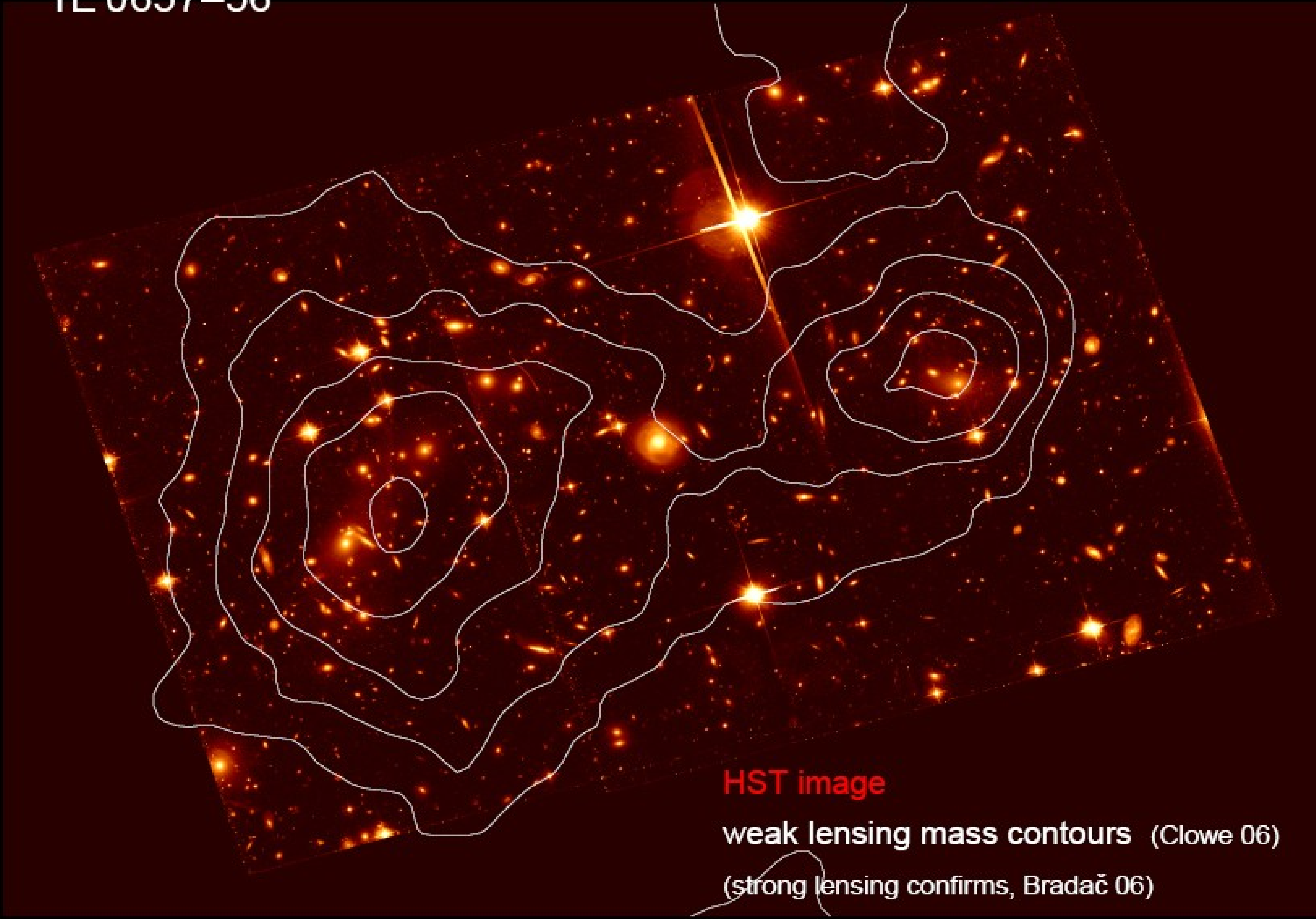


HST image

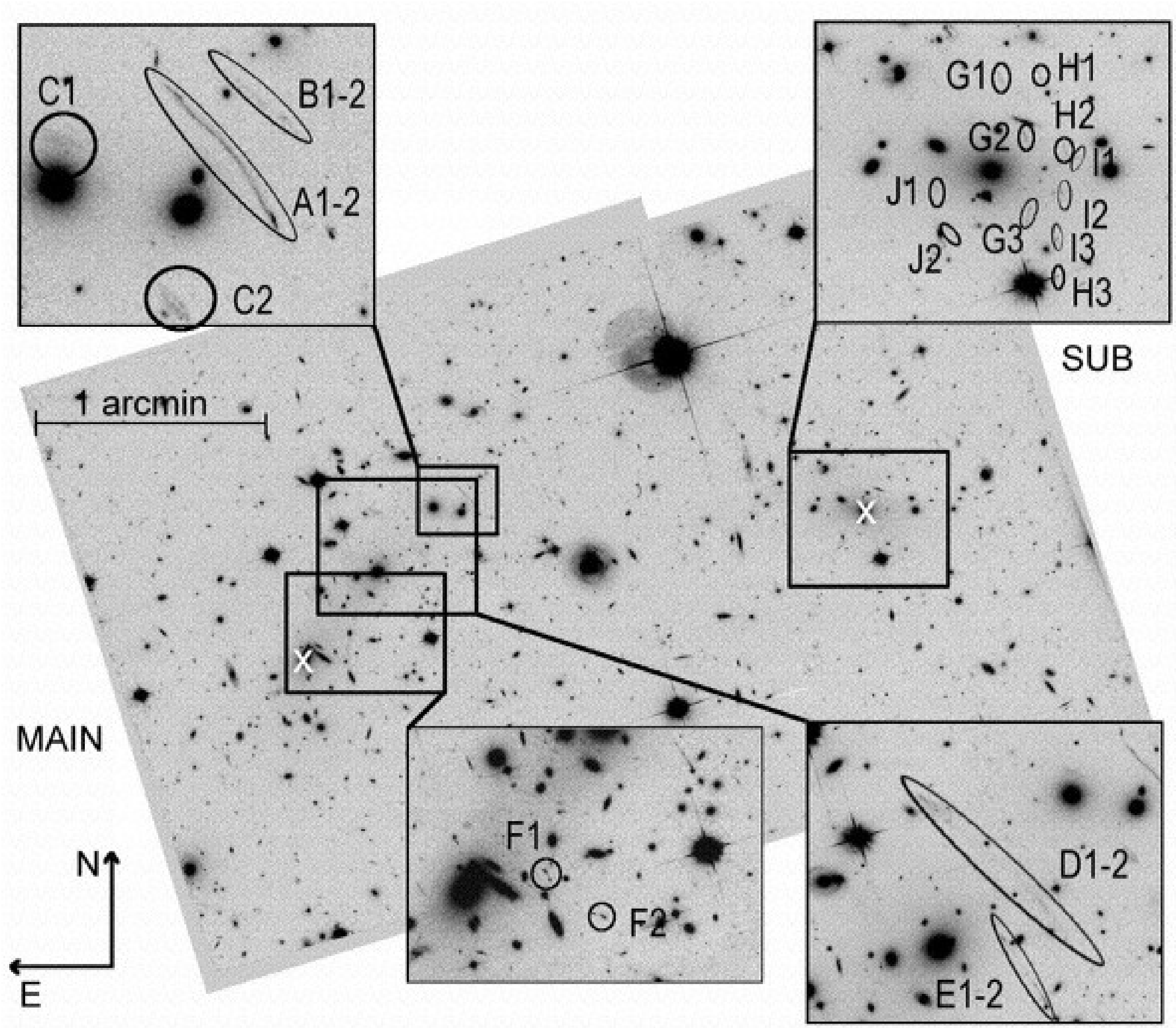
weak lensing mass contours (Clowe 06)

(strong lensing confirms, Bradač 06)

Strong lensing

- Find elongated arcs
- Find multiple images
- Deduce the underlying mass distribution

Strong lensing



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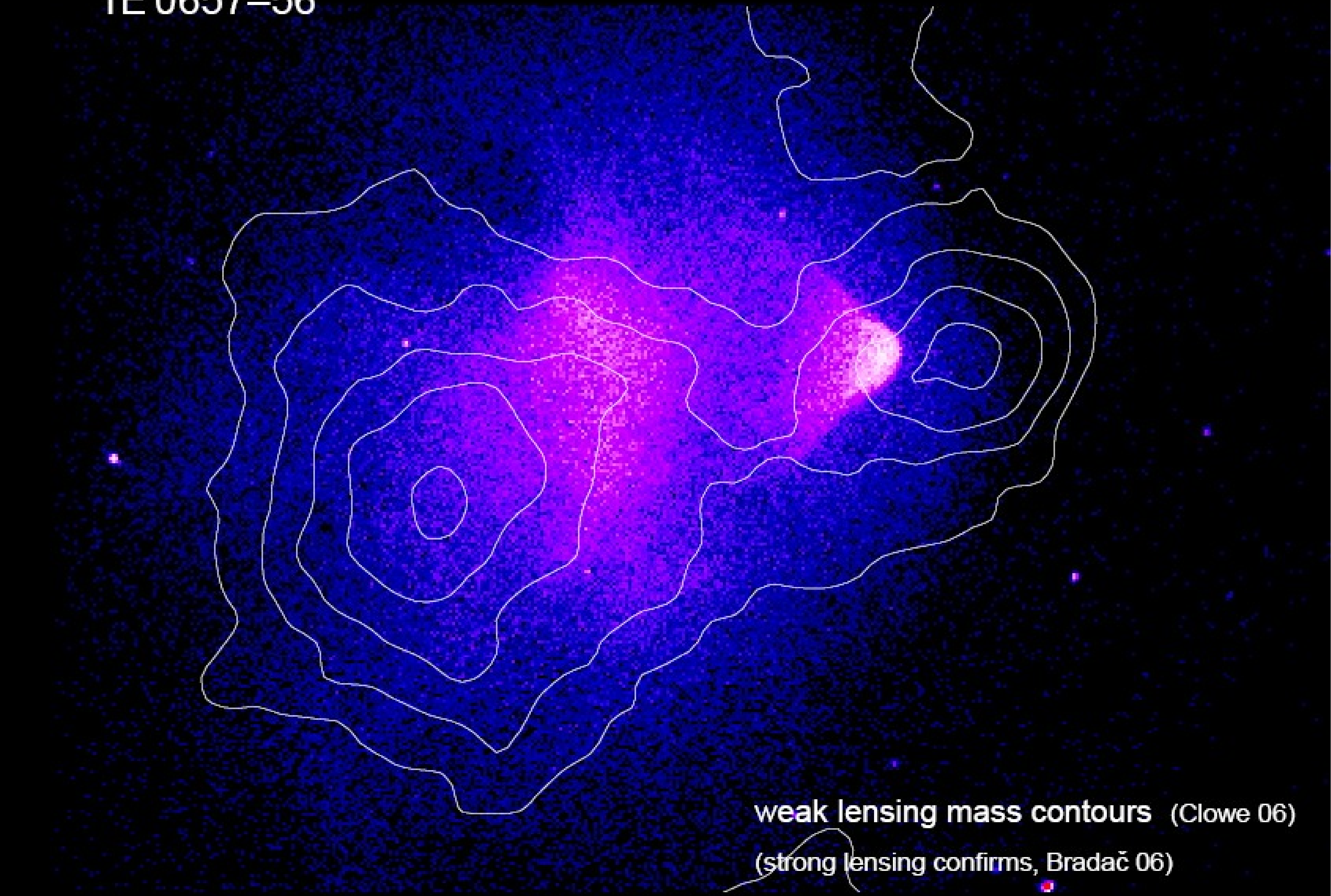
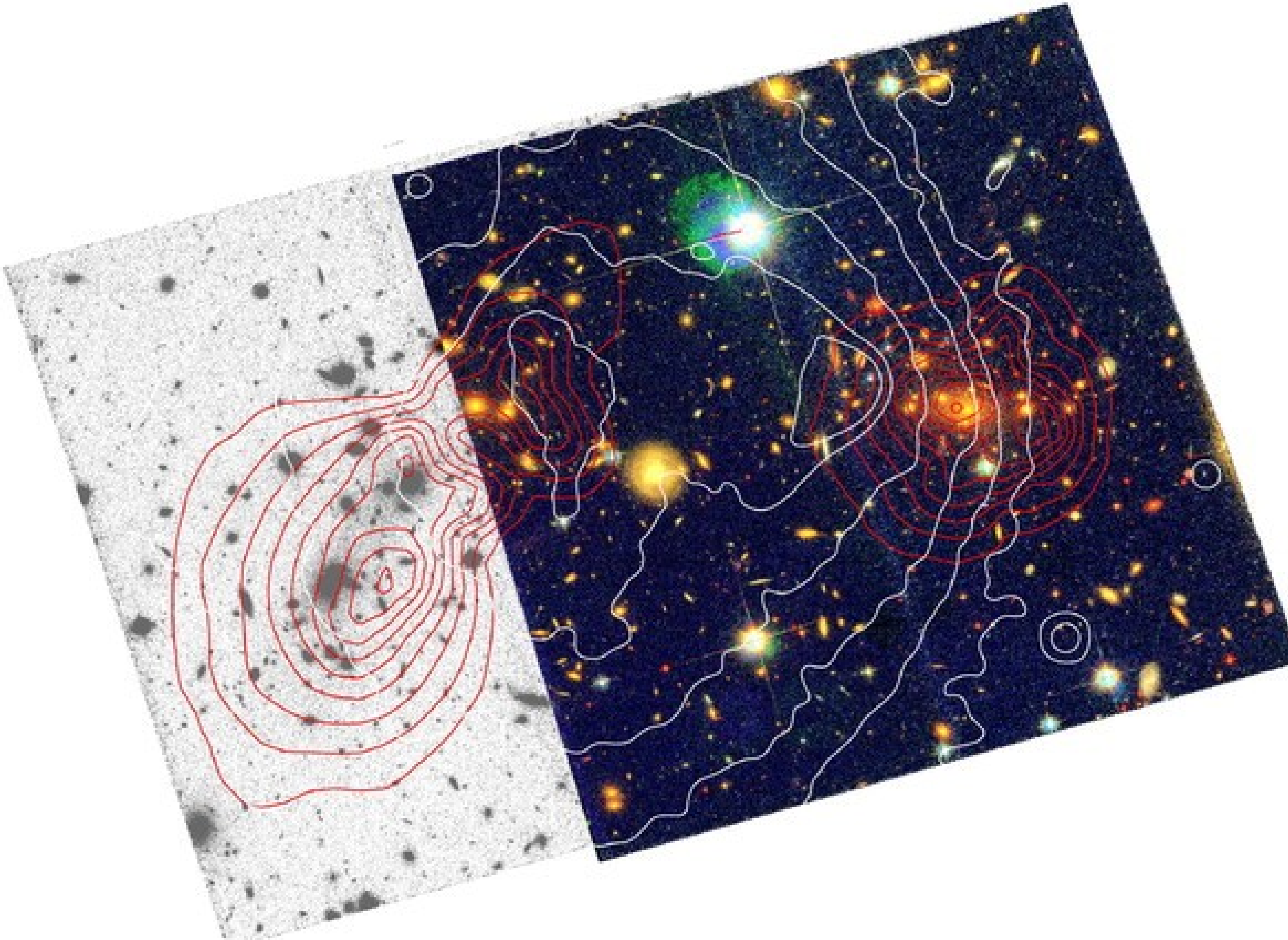

weak lensing mass contours (Clowe 06)
(strong lensing confirms, Bradač 06)

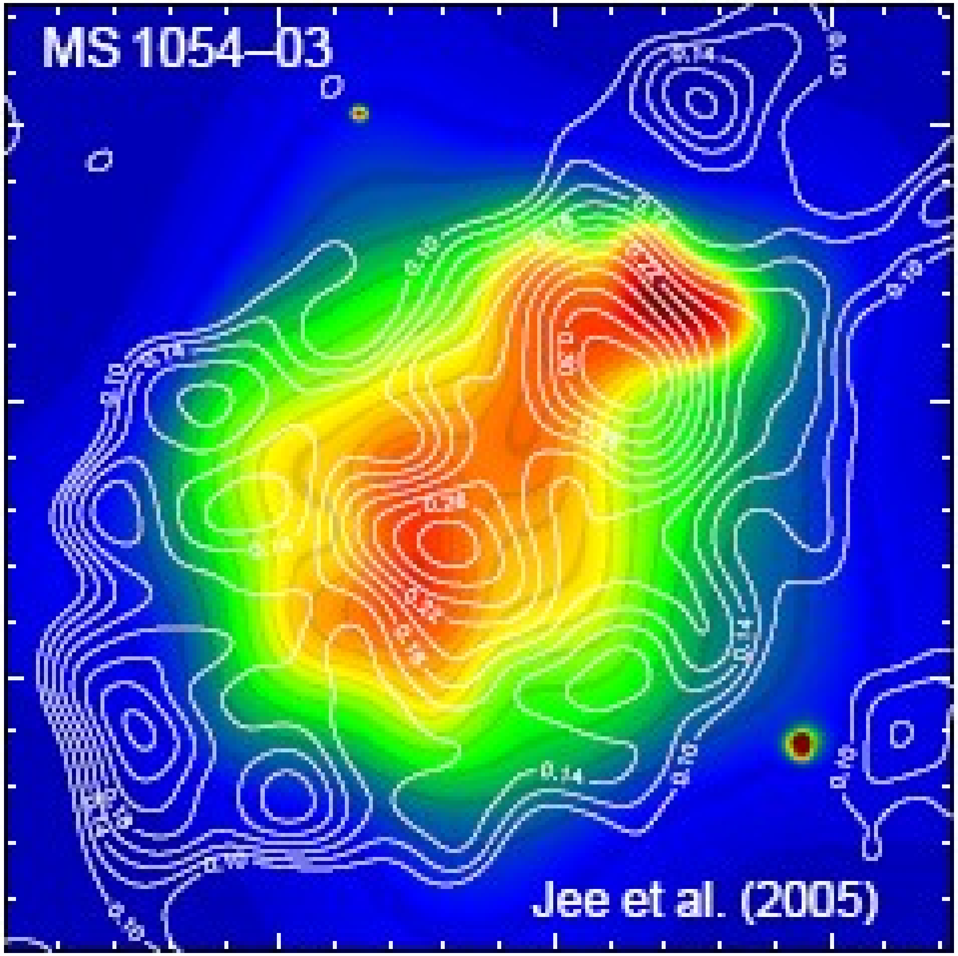


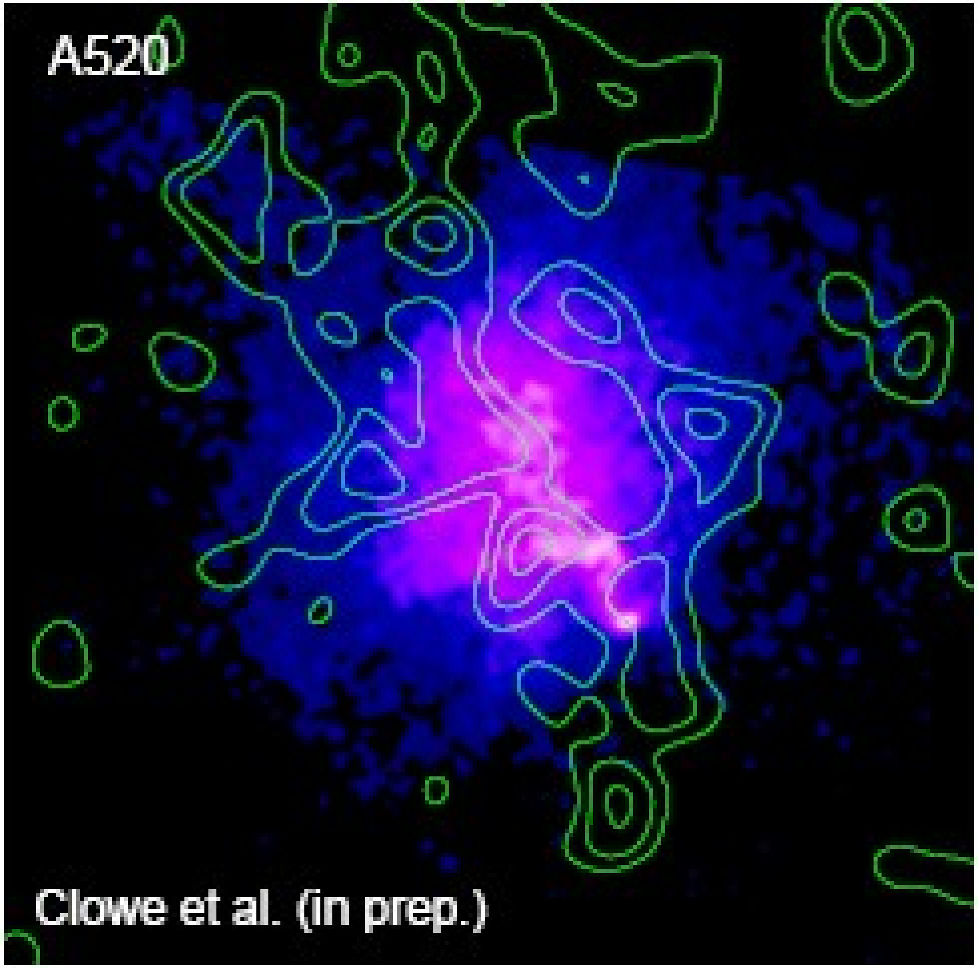
Mass distributions

- Dark matter and galaxies overlap
- Dark matter and hot gas are offset

- Galaxies and dark matter are colissionless
- Gas – collisional

Other examples





Offsets implications

- Dark matter exists
- Nature of DM is unknown
- Not a proof of the Newtonian nature of graviaty at large distances
- MOND unable to explain observations

DM self interaction

- No cusps in dwarf galaxies
- Sub-halos in large halos
- Self Interacting Dark Matter with

$$\sigma = 0.5 - 5\ \mathrm{cm}^2\mathrm{g}^{-1}$$

- Some upper limits from non-evaporation of halos, cluster mass peaks

Constraints on the cross section

Self interaction -opt. depth

- The optical depth of the DM of subcluster mus be small

$$\tau_s = \frac{\sigma}{m}\Sigma_s < 1$$

$$\frac{\sigma}{m} < 5\ \mathrm{cm^2 g^{-1}}$$

Subcluster velocity

- The velocity of subcluster from shock analysis
- Velocity is ~ free fall velocity
- Drag force

$$v - v_{ff} = \frac{p}{m}\frac{\sigma}{m}\Sigma_m$$

$$v - v_{ff} < 1000\ \mathrm{km\,s^{-1}} \Rightarrow \frac{\sigma}{m} < 7\ \mathrm{cm^2 g^{-1}}$$

Mass to light ratio

- Subcluster stripped off its mass while passing through
- Mass to light ratios nearly universal
- Less than 0.3 of the mass stripped

$$\chi \tau_m = \frac{\sigma}{m} \Sigma_m \left[1 - 2 \left(\frac{v_{esc}}{v_0} \right)^2 \right] < 0.3$$

$$\frac{\sigma}{m} < 0.7 \ \mathrm{cm}^2 \mathrm{g}^{-1}$$

Cross sections

- Assume that the cross section is velocity independent
- Protons; $m=m_p$

$$\sigma < 2 \times 10^{-24}\ \mathrm{cm}^2$$

- Neutrinos: m=1eV

$$\sigma < 2 \times 10^{-33}\ \mathrm{cm}^2$$

Black holes

- BH cross section
- BH masses below 0.01 mass of the Sun

Conclusions

- Dark matter exists
- Astrophysical bound on cross sections nearly excludes SIDM

Papers

Bradac, M., D.~Clowe, A.~H.~Gonzalez, P.~Marshall, W.~Forman, C.~Jones, M.~Markevitch, S.~Randall, T.~Schrabback, and D.~Zaritsky 2006. Strong and Weak Lensing United. III. Measuring the Mass Distribution of the Merging Galaxy Cluster 1ES 0657-558. Astrophysical Journal652, 937-947.

Clowe, D., M.~Bradac, A.~H.~Gonzalez, M.~Markevitch, S.~W.~Randall, C.~Jones, and D.~Zaritsky 2006. A Direct Empirical Proof of the Existence of Dark Matter. Astrophysical Journal648, L109-L113.

Markevitch, M., A.~H.~Gonzalez, D.~Clowe, A.~Vikhlinin, W.~Forman, C.~Jones, S.~Murray, and W.~Tucker 2004. Direct Constraints on the Dark Matter Self-Interaction Cross Section from the Merging Galaxy Cluster 1E 0657-56. Astrophysical Journal606, 819-824.

Clowe, D., A.~Gonzalez, and M.~Markevitch 2004. Weak-Lensing Mass Reconstruction of the Interacting Cluster 1E 0657-558: Direct Evidence for the Existence of Dark Matter. Astrophysical Journal604, 596-603.