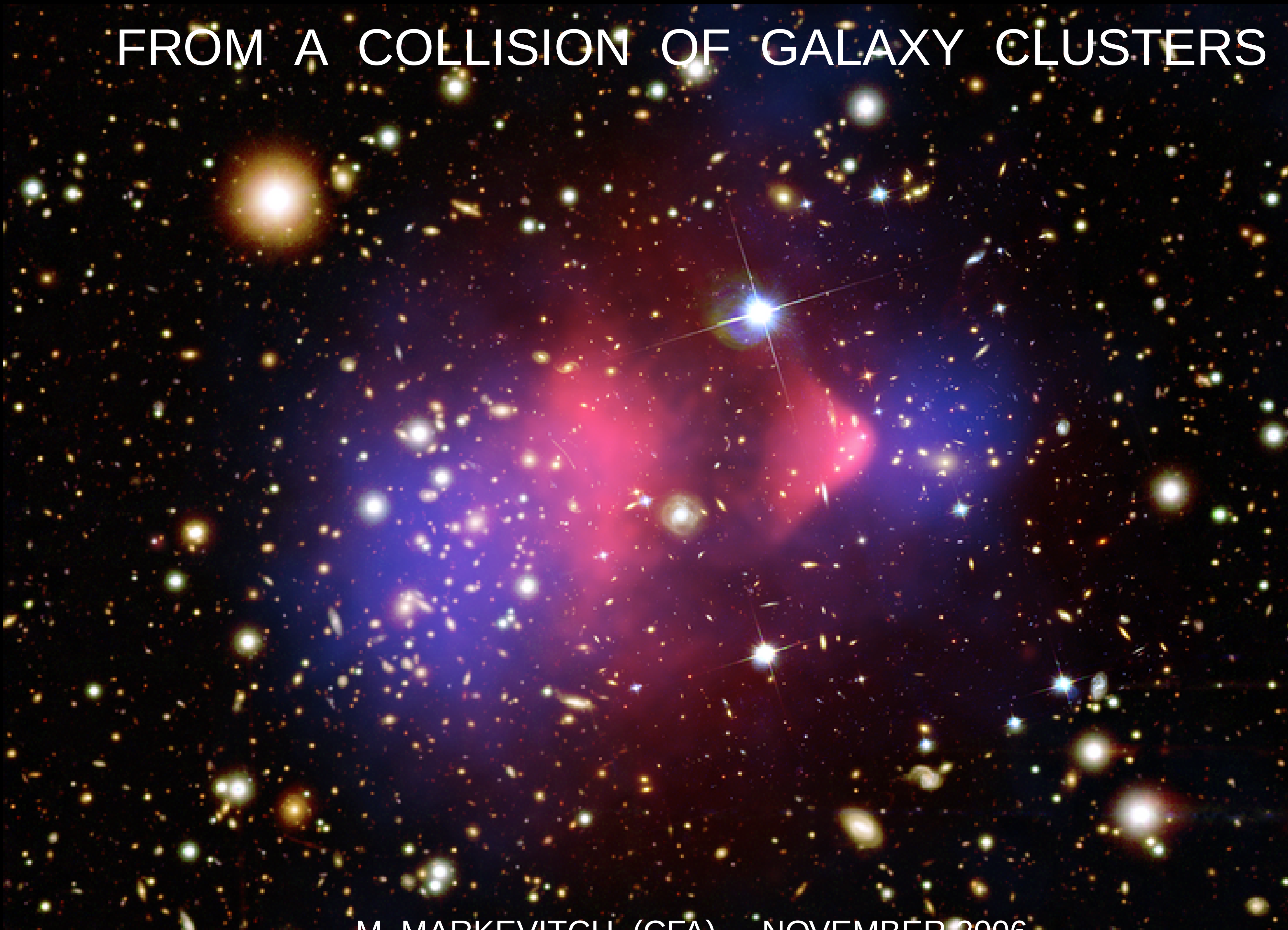
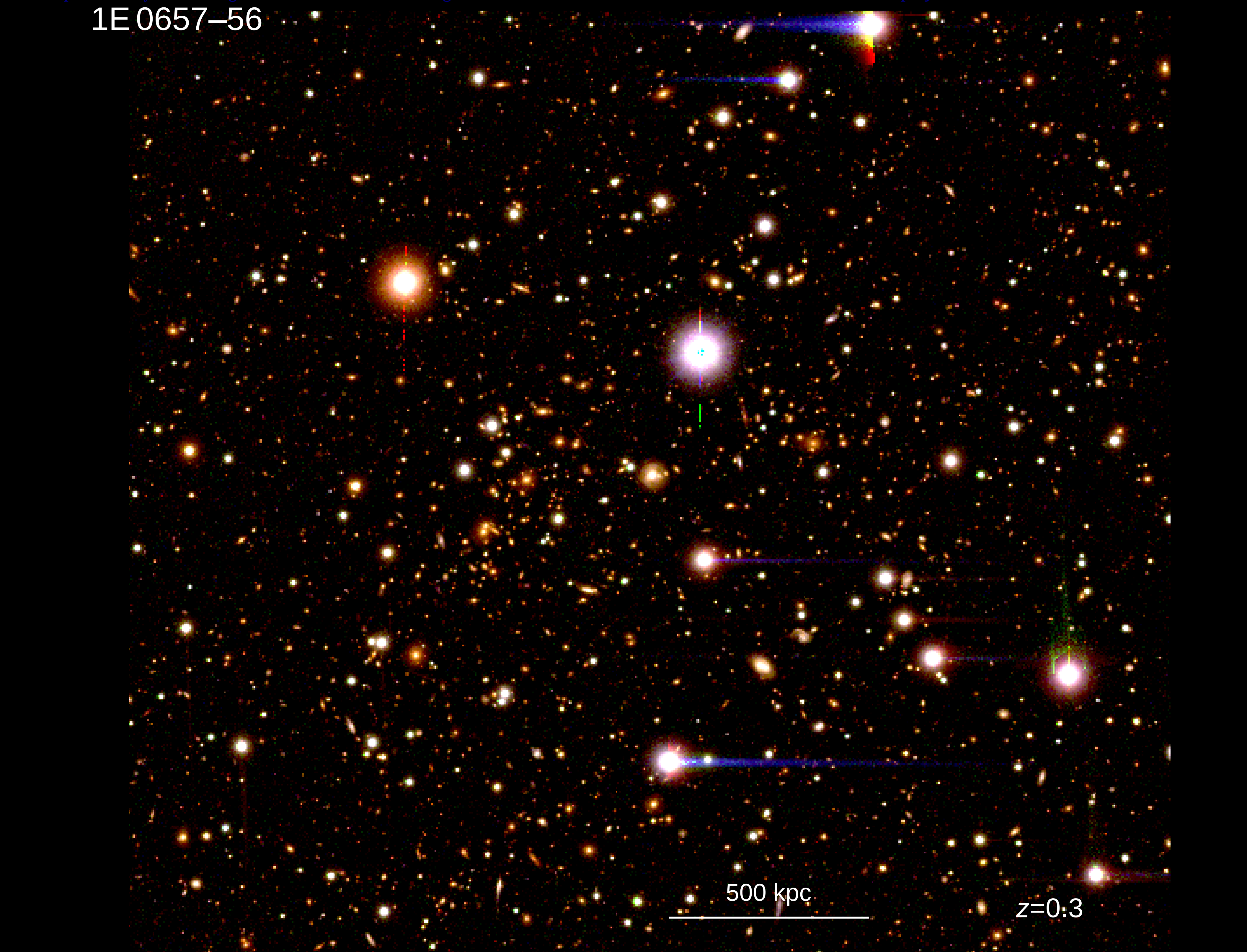
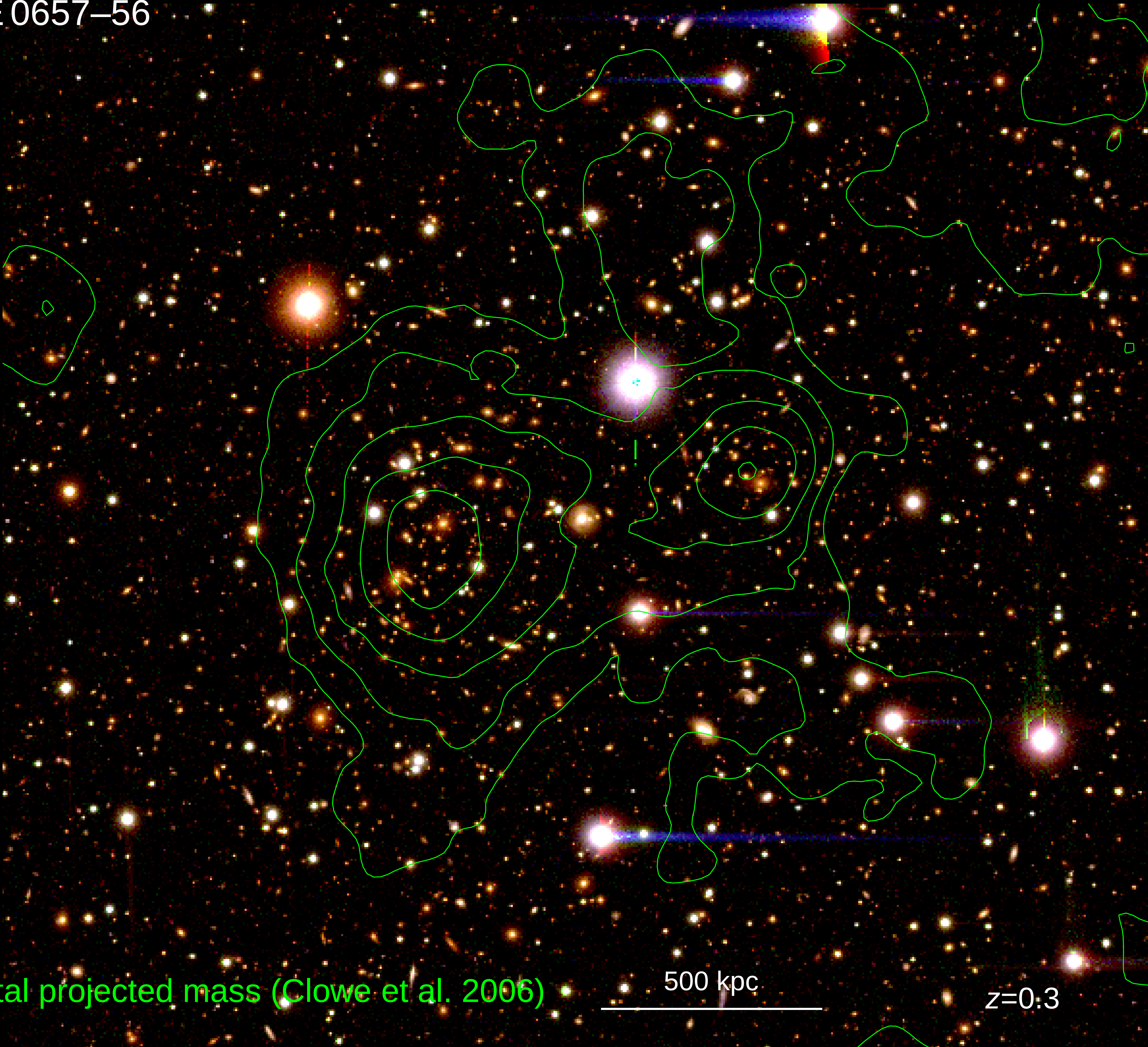
DARK MATTER EXISTENCE AND OTHER RESULTS FROM A COLLISION OF GALAXY CLUSTERS



M. MARKEVITCH (CFA) NOVEMBER 2006

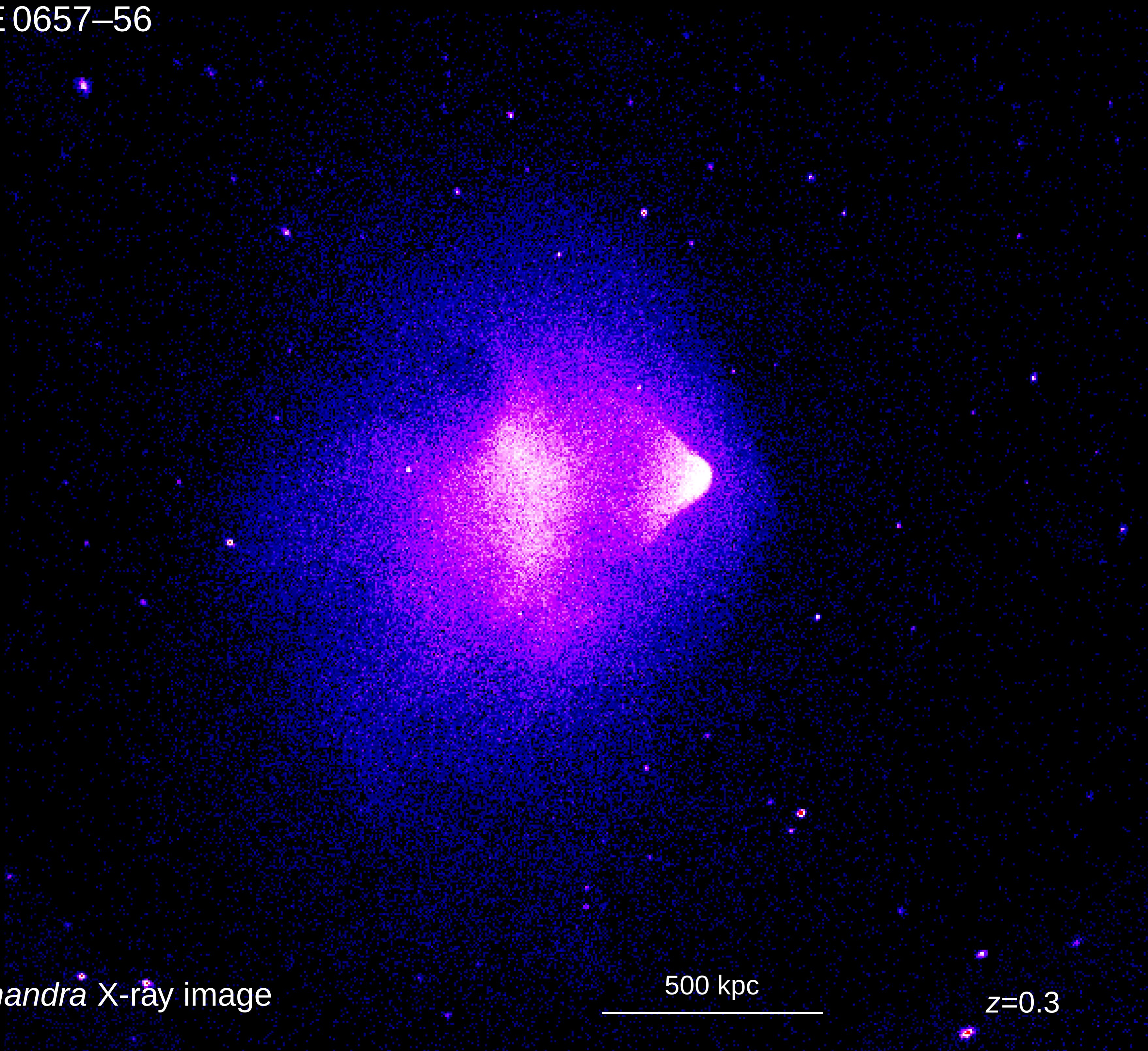

1E 0657–56
500 kpc
z=0.3

1E 0657–56



Total projected mass (Clowe et al. 2006)

1E 0657–56



Galaxy clusters contain:

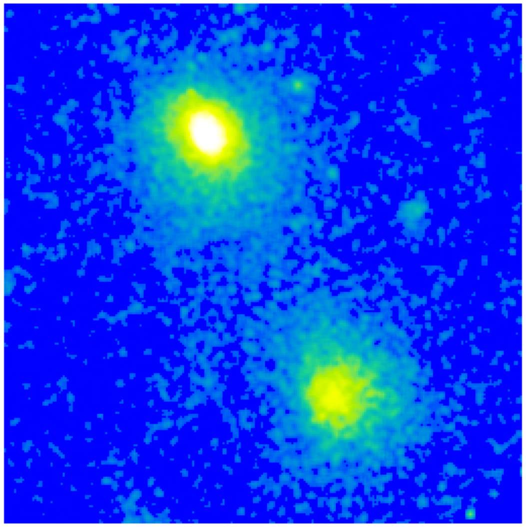
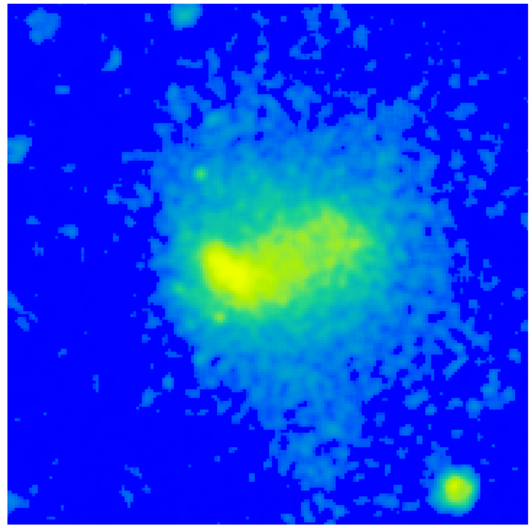
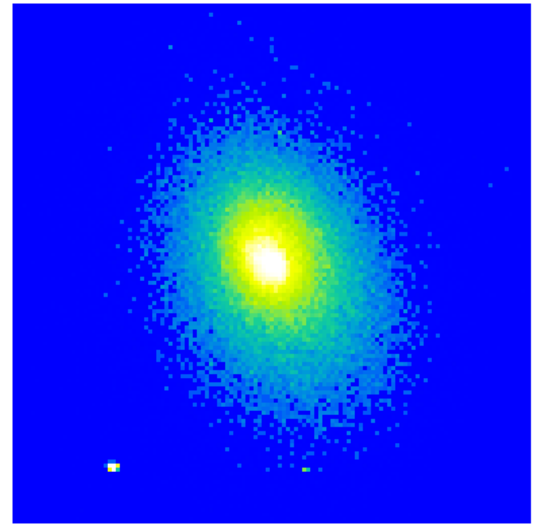
- **1–3% of mass in stars**
- **10–20% in hot gas ($\sim$ 10 keV, $\sim 10^{-3}$ cm^{-3}, optically thin for X-rays)**
- **80–90% in dark matter ($\sim 10^{15} M_\odot$)**

Plasma contains:

- **magnetic fields $B \sim 1\ \mu G$ $\rightarrow$ plasma collisionless, but "hot" ($\beta \equiv p/p_B \gg 1$)**
- **ultrarelativistic particles ($\gamma \sim 10^4$)**

Cluster mass function $N(M_{\rm tot})$ and baryon fraction $M_{\rm gas}/M_{\rm tot}$ — sensitive cosmological probes

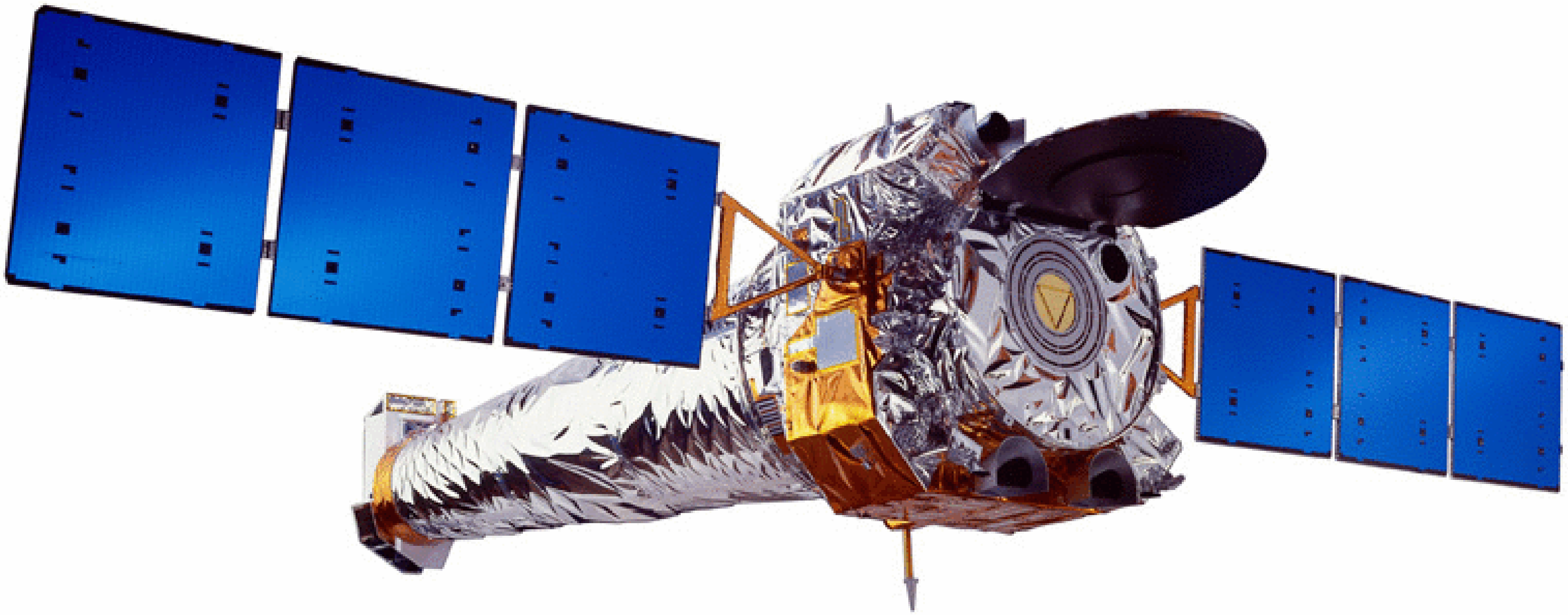
Cluster mergers

The most energetic events since the Big Bang:
two $10^{15} M_\odot$ clusters carry $E_{\rm kin} \sim 10^{63-64}$ ergs

Laboratory for studying intracluster plasma:
shocks, instabilities, ram pressure stripping, transport processes, relativistic particle accelertion, magnetic fields

Chandra X-ray Observatory

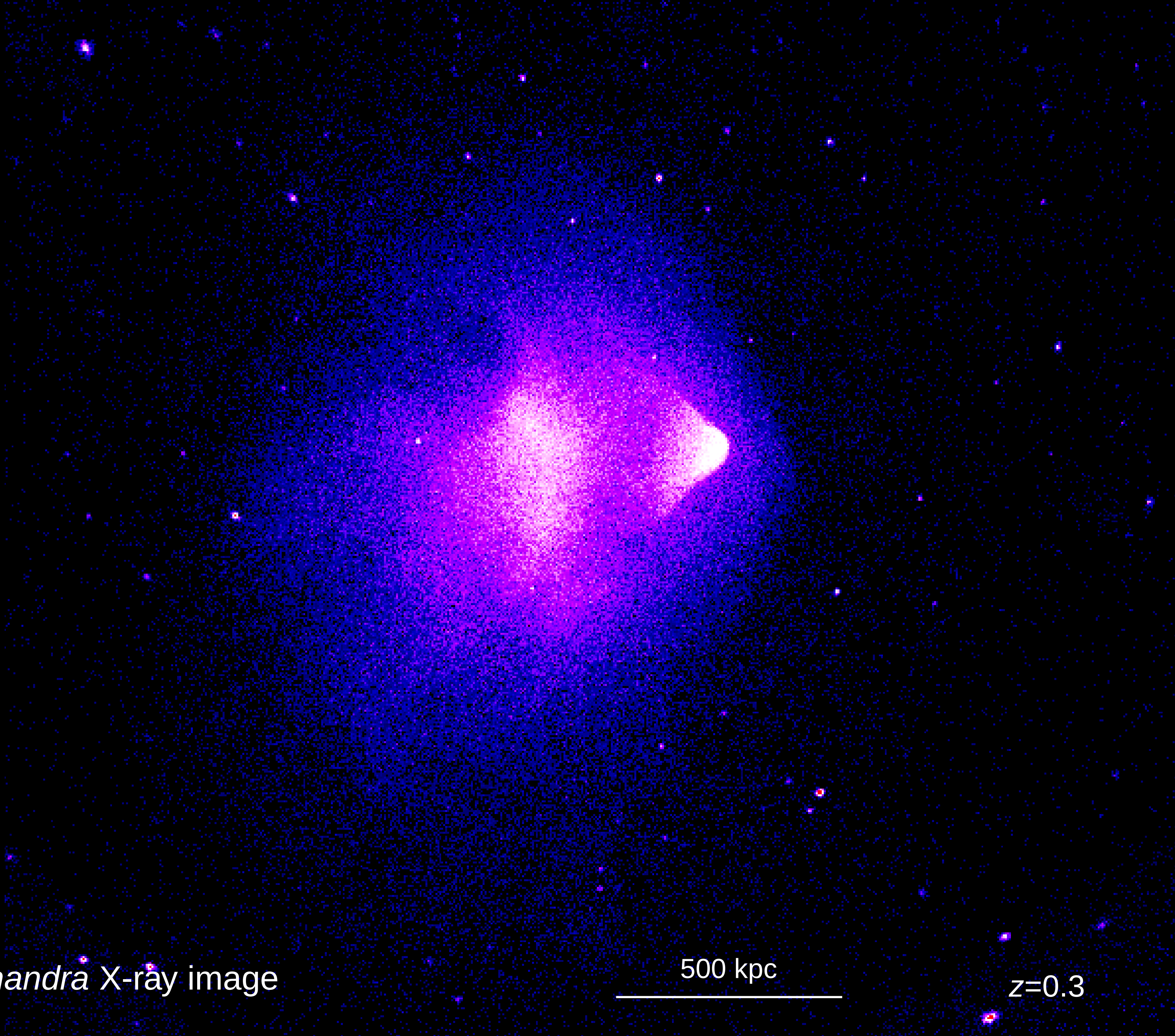


ACIS detector:

- **0.3 – 8 keV energy band**
- **16′ × 16′ FOV**
- **1″ on-axis angular resolution**

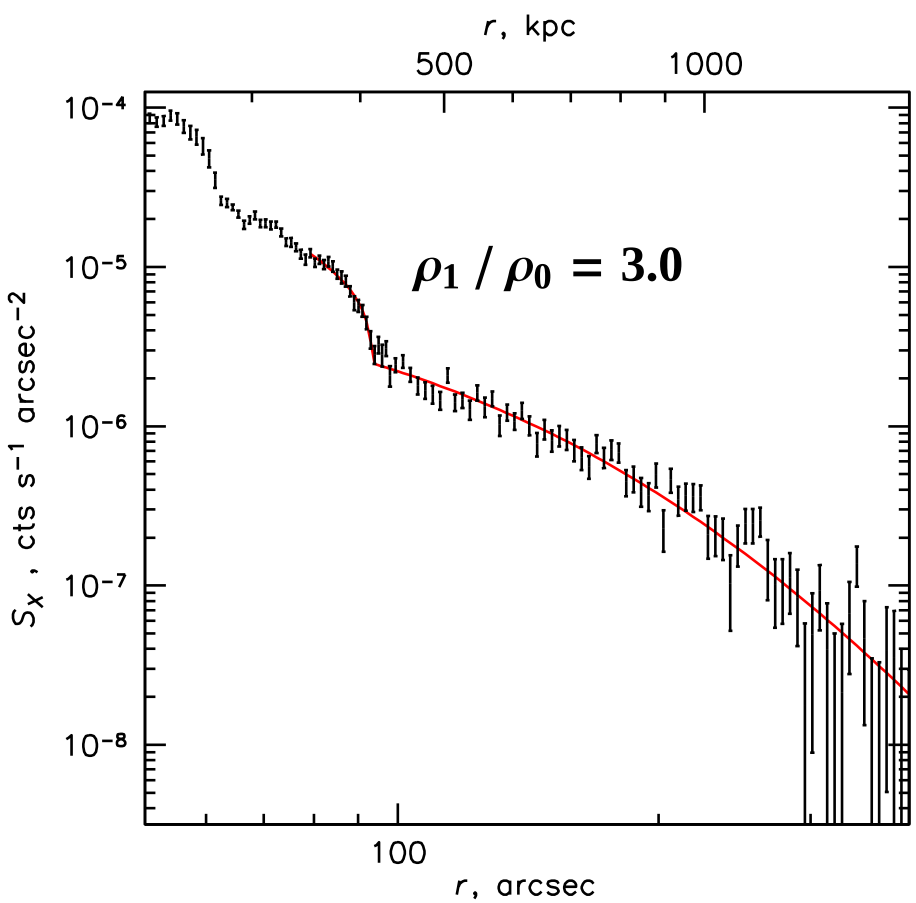
Shock front in 1E 0657–56

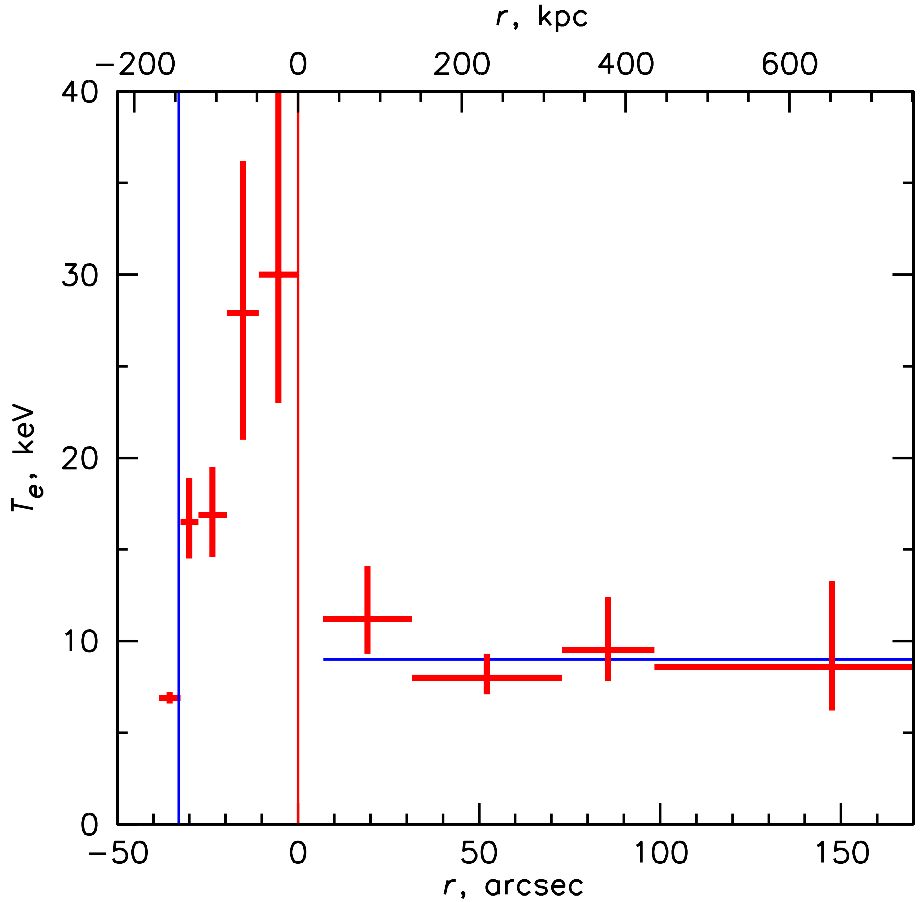
1E 0657–56



Chandra X-ray image

Textbook example of a shock front:





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

Testing alternative dark matter theories

Modified Gravity

MOND, TeVeS, others (Milgrom 1983, Bekenstein 2004):

- **No need for dark matter — gravity laws modified to mimic effects of DM**

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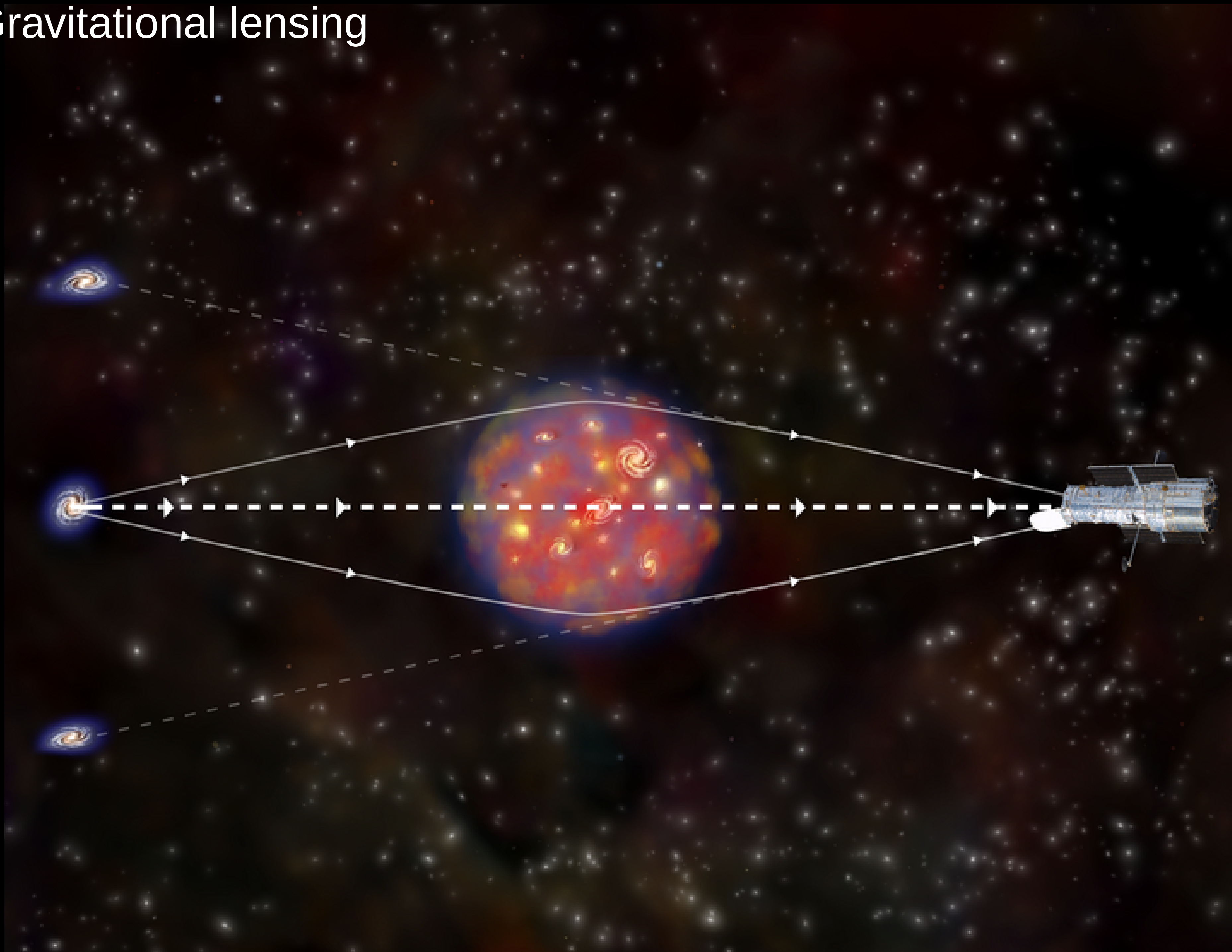
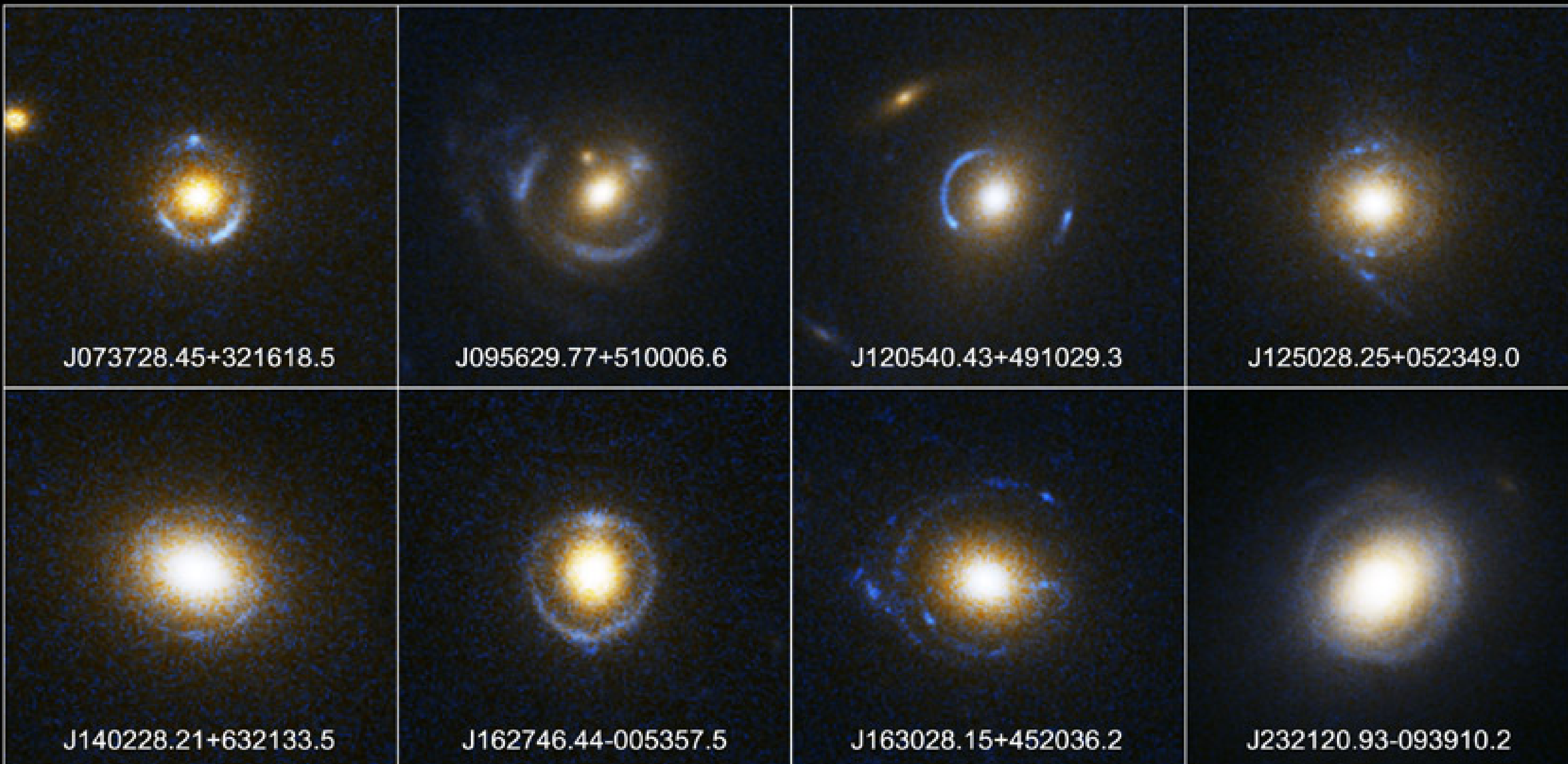
MOND, TeVeS, others (Milgrom 1983, Bekenstein 2004):

- **No need for dark matter — gravity laws modified to mimic effects of DM**

Can be falsified:
find an object where visible mass and center of gravity are spatially separated

Gravitational lensing





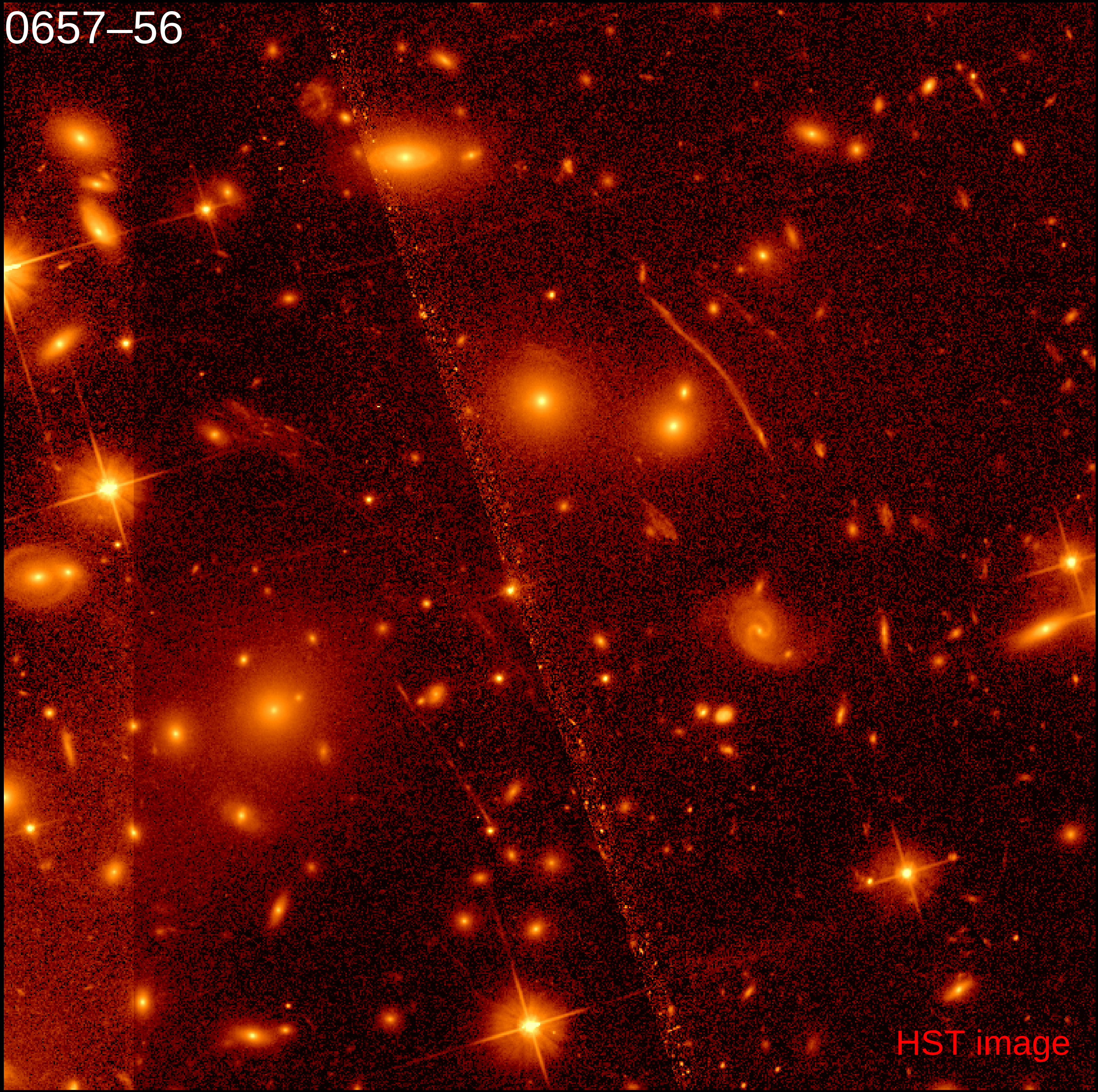
Einstein Ring Gravitational Lenses

Hubble Space Telescope • Advanced Camera for Surveys

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

STScI-PRC05-32

1E 0657–56



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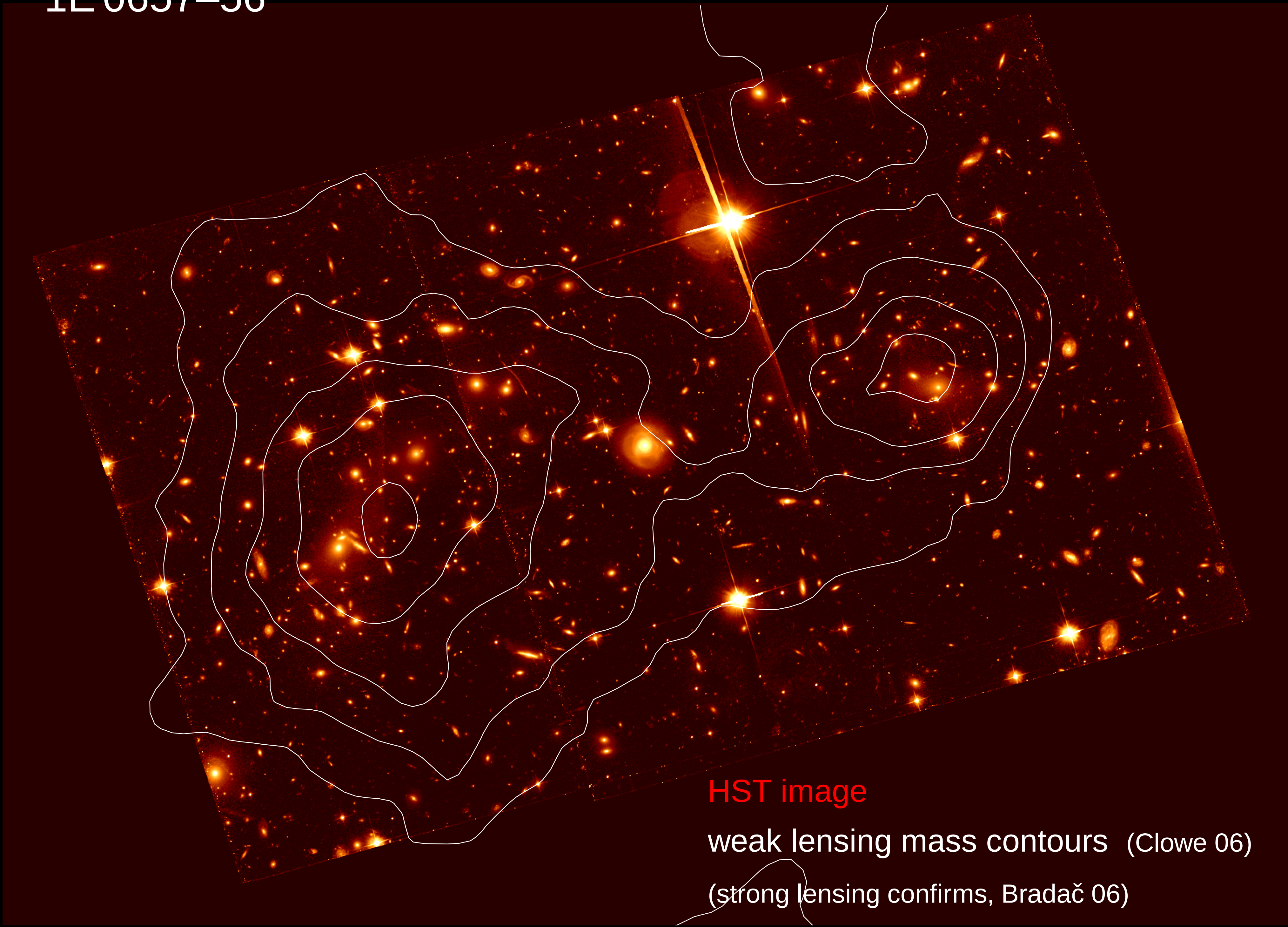
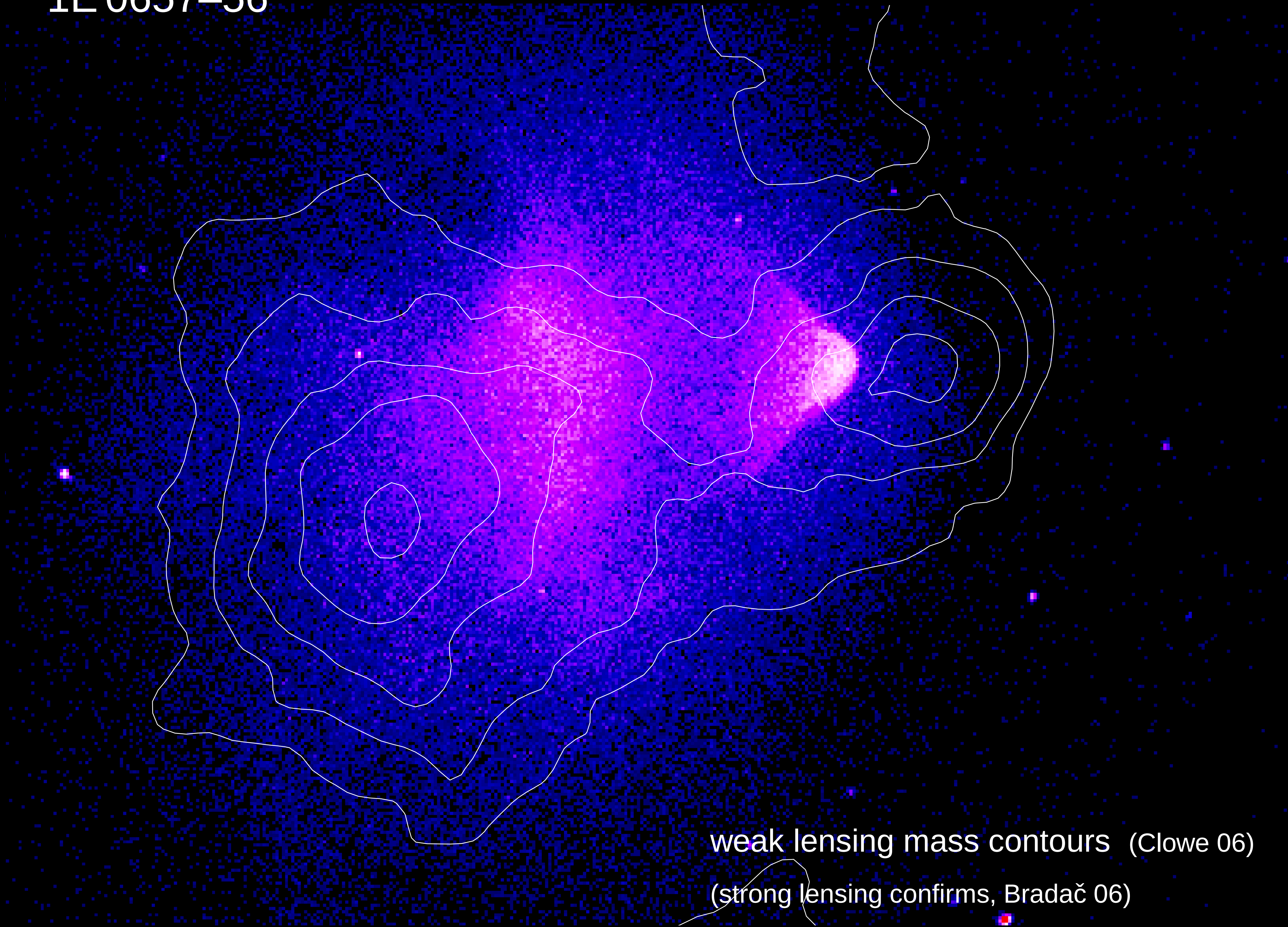


HST image

weak lensing mass contours (Clowe 06)

(strong lensing confirms, Bradač 06)

1E 0657–56

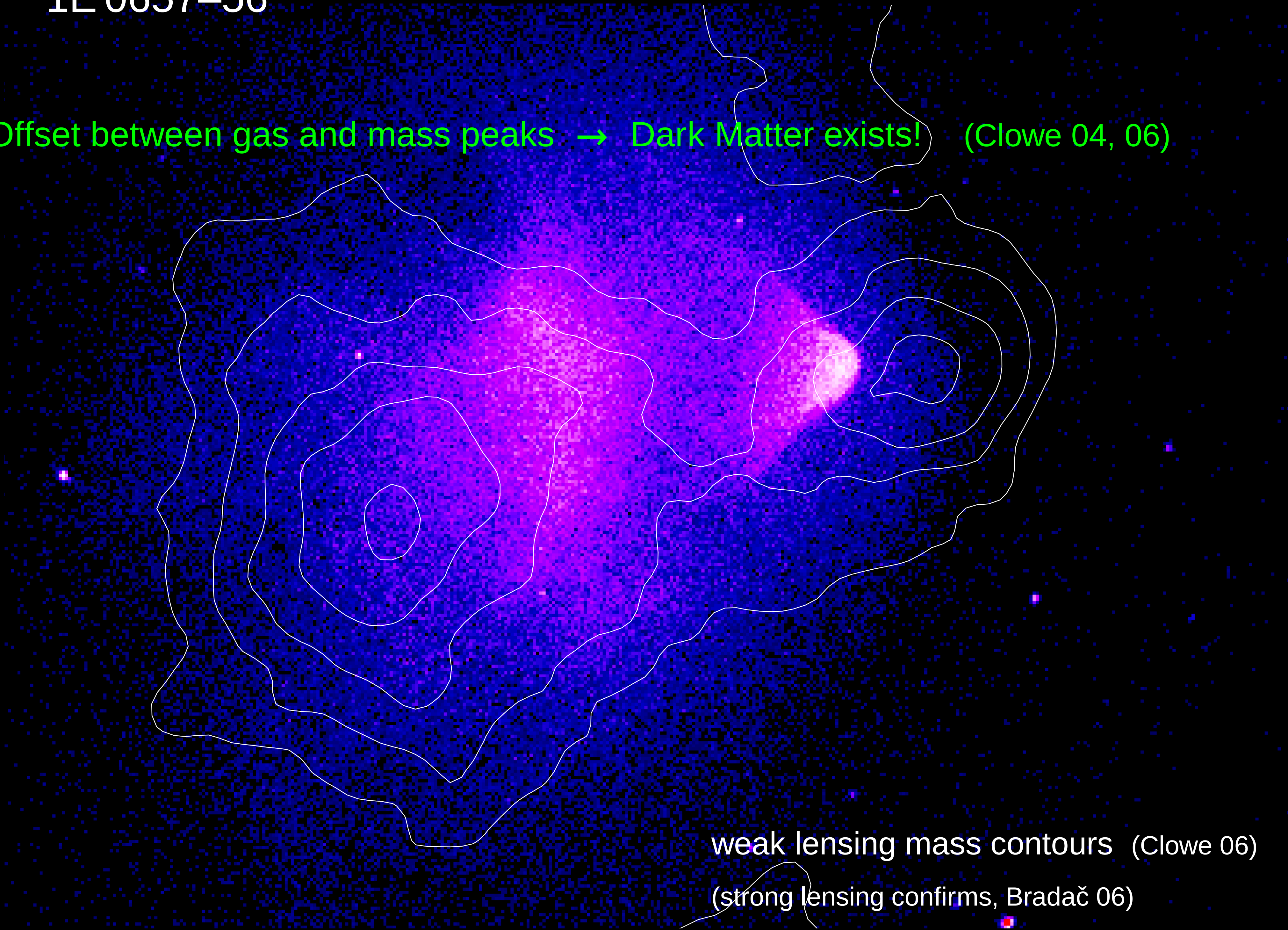


weak lensing mass contours (Clowe 06)

(strong lensing confirms, Bradač 06)

1E 0657–56

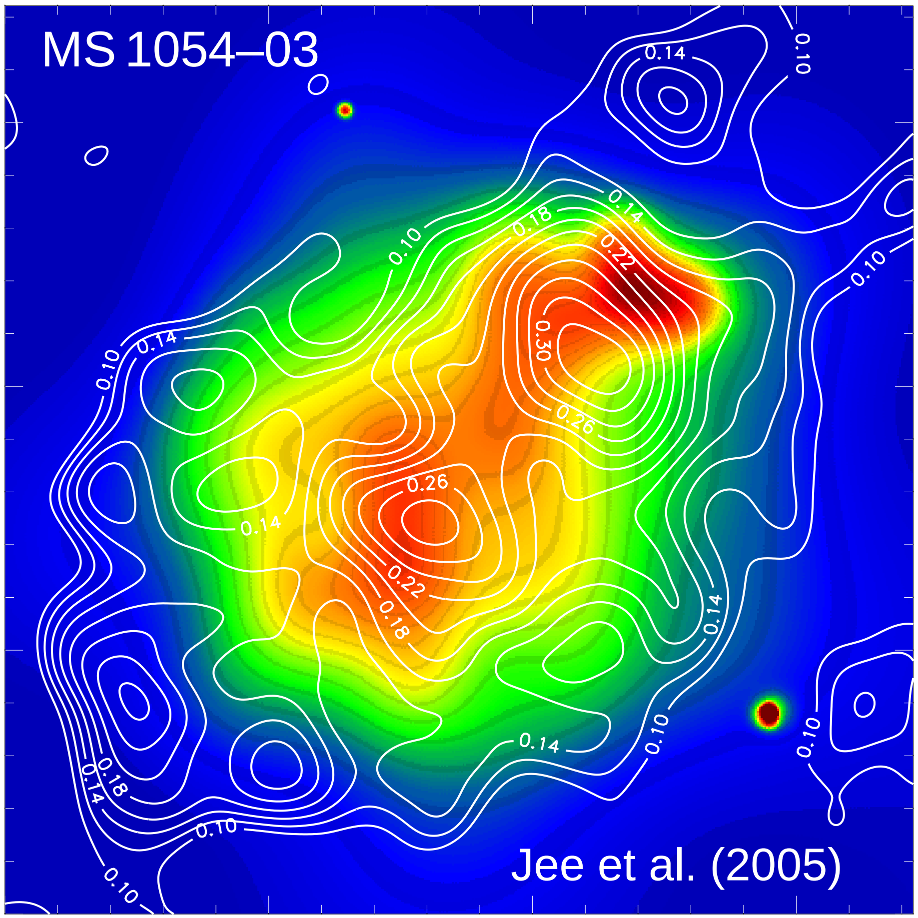
Offset between gas and mass peaks → Dark Matter exists! (Clowe 04, 06)

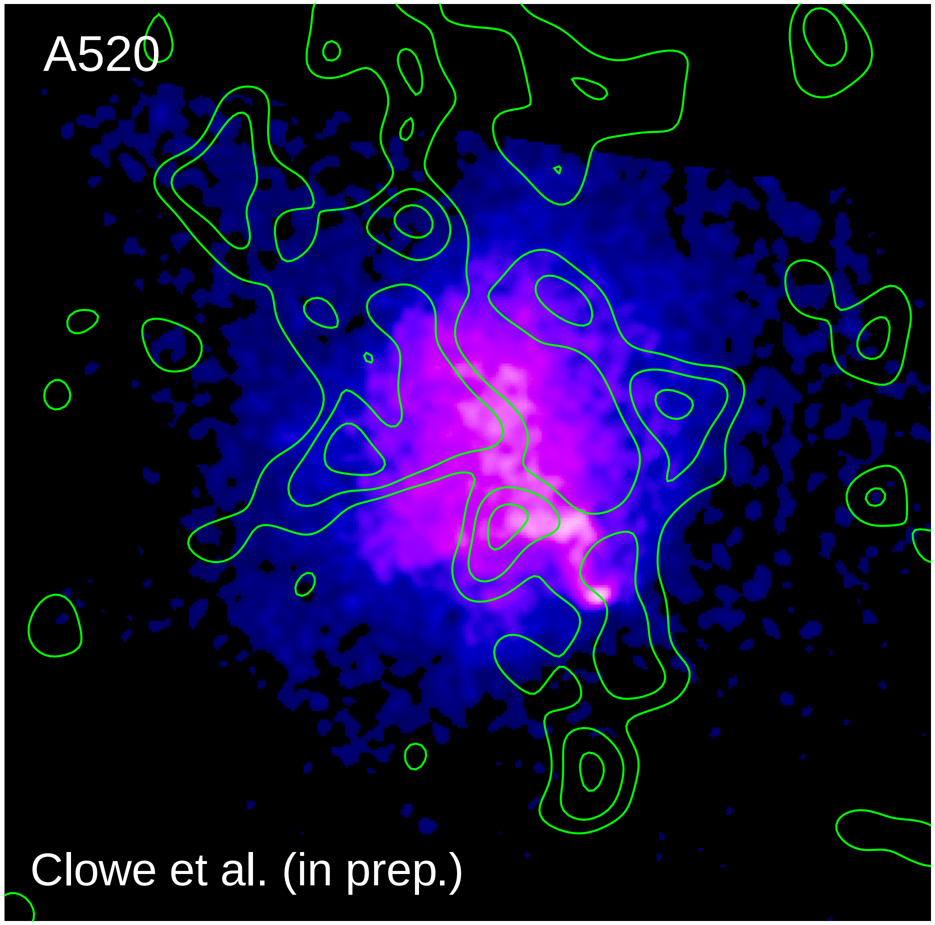


weak lensing mass contours (Clowe 06)

(strong lensing confirms, Bradač 06)

Other examples of gas – lensing mass offsets:





Gas mass — lensing mass offset:

- **proves that dark matter exists**
- **does not say anything about the nature of DM**
- **does not prove that gravity is Newtonian**

Self-interacting Dark Matter

SIDM with $\sigma/m \sim 0.5-5 \ \mathrm{cm^2\,g^{-1}}$ was proposed to explain problems in standard CDM:

- **Absence of central cusps in dwarf galaxies**
- **Too many surviving small-mass subhalos within large halos**

(Spergel & Steinhardt 2000; Davé et al. 2001)

Upper limits on σ/m from cluster mass peaks, evaporation of elliptical galaxy halos, ...

Direct constraint on cross-section from 1E 0657–56

Observational evidence:

1. **Offset between gas and dark matter clump**
2. **No offset between dark matter and galaxies**
3. **Subcluster's velocity not less than free-fall velocity**
4. **Subcluster's M/L ratio close to universal**

Direct constraint on cross-section from 1E 0657–56

Observational evidence:

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4. **Subcluster's M/L ratio close to universal**

The best constraint comes from method 4 **(Markevitch et al. 2004; Randall in prep.)**

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

Excludes almost all of interesting range — unless σ velocity-dependent

Direct constraint on cross-section from 1E 0657–56

Our limit: $\sigma/m < 0.7 \ \mathrm{cm}^2\,\mathrm{g}^{-1}$

- $m = m_p \quad \rightarrow \quad \sigma < 2 \times 10^{-24}\ \mathrm{cm}^{-2}$
  - strong interactions $\sim 10^{-24}\ \mathrm{cm}^{-2}$

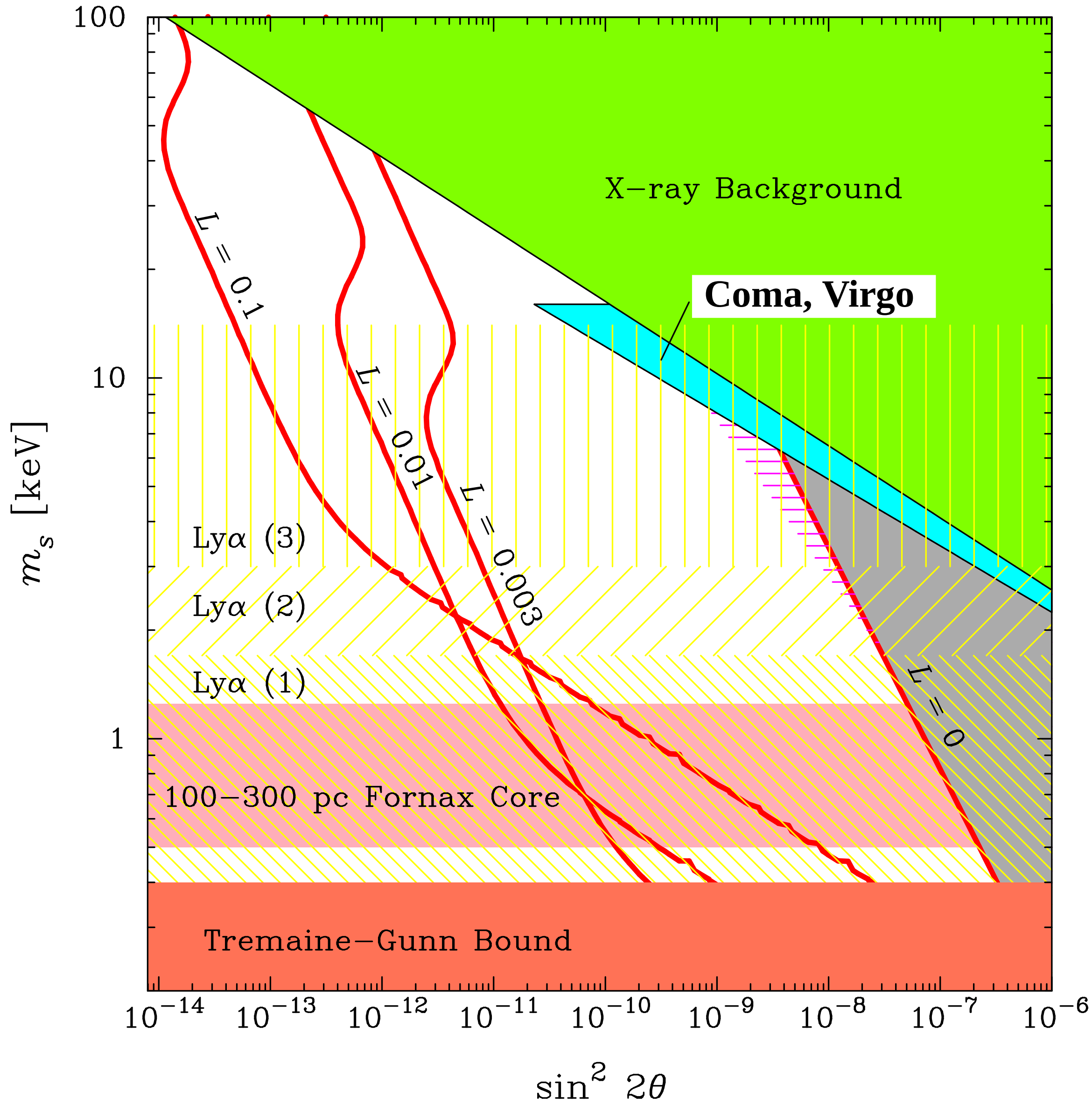
- $m = 1\ \mathrm{eV} \quad \rightarrow \quad \sigma < 2 \times 10^{-33}\ \mathrm{cm}^{-2}$
  - neutrino-neutrino interaction from SN 1987a: $\sigma < 10^{-35} - 10^{-25}\ \mathrm{cm}^{-2}$

Sterile neutrinos as Warm DM

- Does not interact with ordinary matter
- If $m_s \sim 1 - 10$ keV, can explain cores in dwarf galaxies and deficit of small halos
- Decays into active neutrino and photon $E_\gamma = m_s/2$

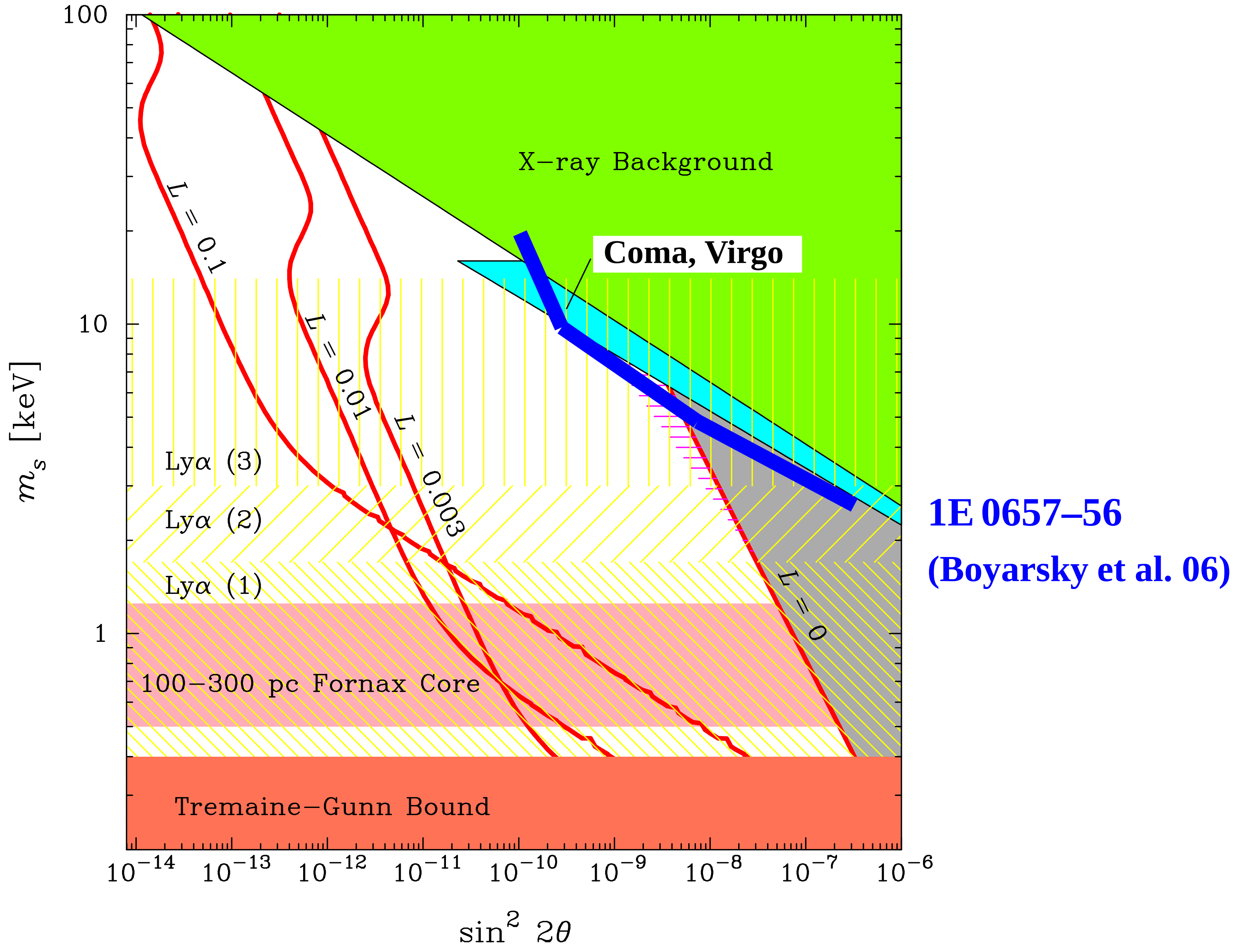
  → constraints from X-ray observations of CXB and clusters

Sterile neutrinos as Warm DM



Abazajian & Koushiappas (2006)

Sterile neutrinos as Warm DM



Abazajian & Koushiappas (2006)

Summary on exotic theories

MOND

SIDM

Sterile neutrino DM

Summary on exotic theories

~~MOND~~

SIDM

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Sterile neutrino DM still alive

Summary on exotic theories

~~MOND~~

~~SIDM~~ (or σ is velocity-dependent)

Sterile neutrino DM still alive

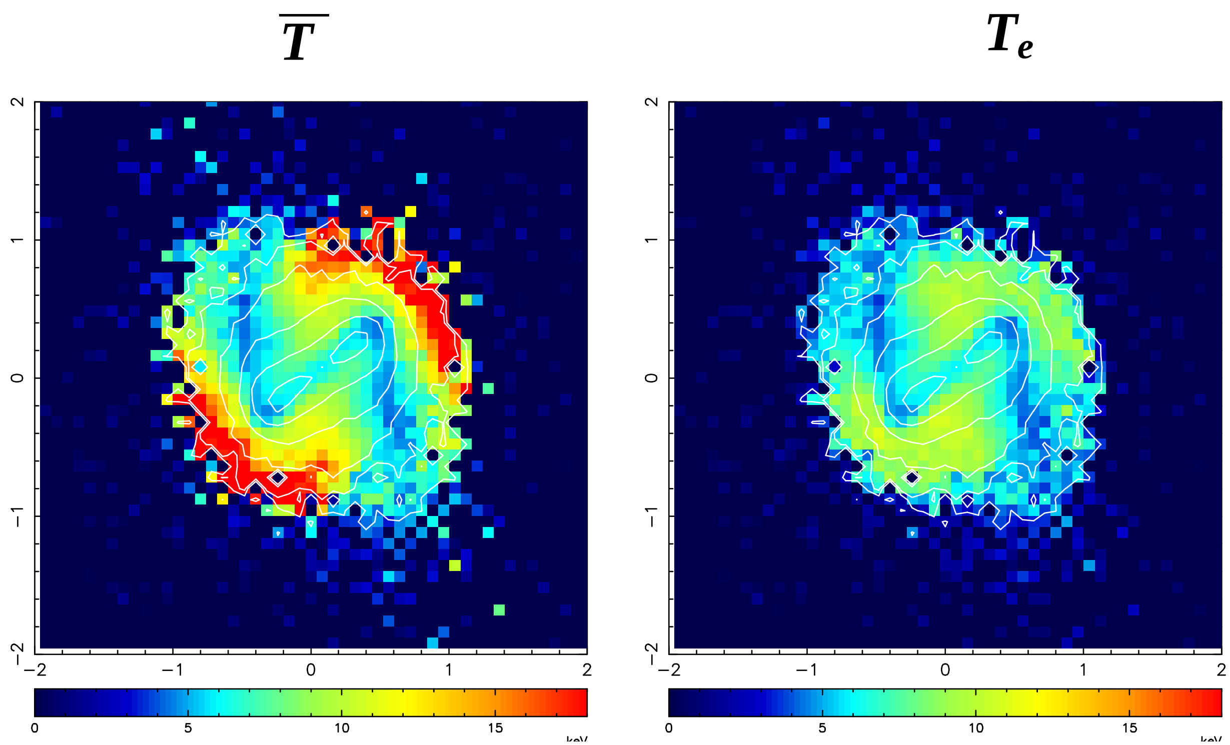
(Persistent strong / weak lensing mass discrepancy?)

Mainstream physics from cluster mergers

Electron-proton temperature equilibration

Electron-ion nonequilibrium

- **At shock, protons heated dissipatively**
- **Electrons heated adiabatically and then by collisions with protons on $t \sim \tau_{ep}$**



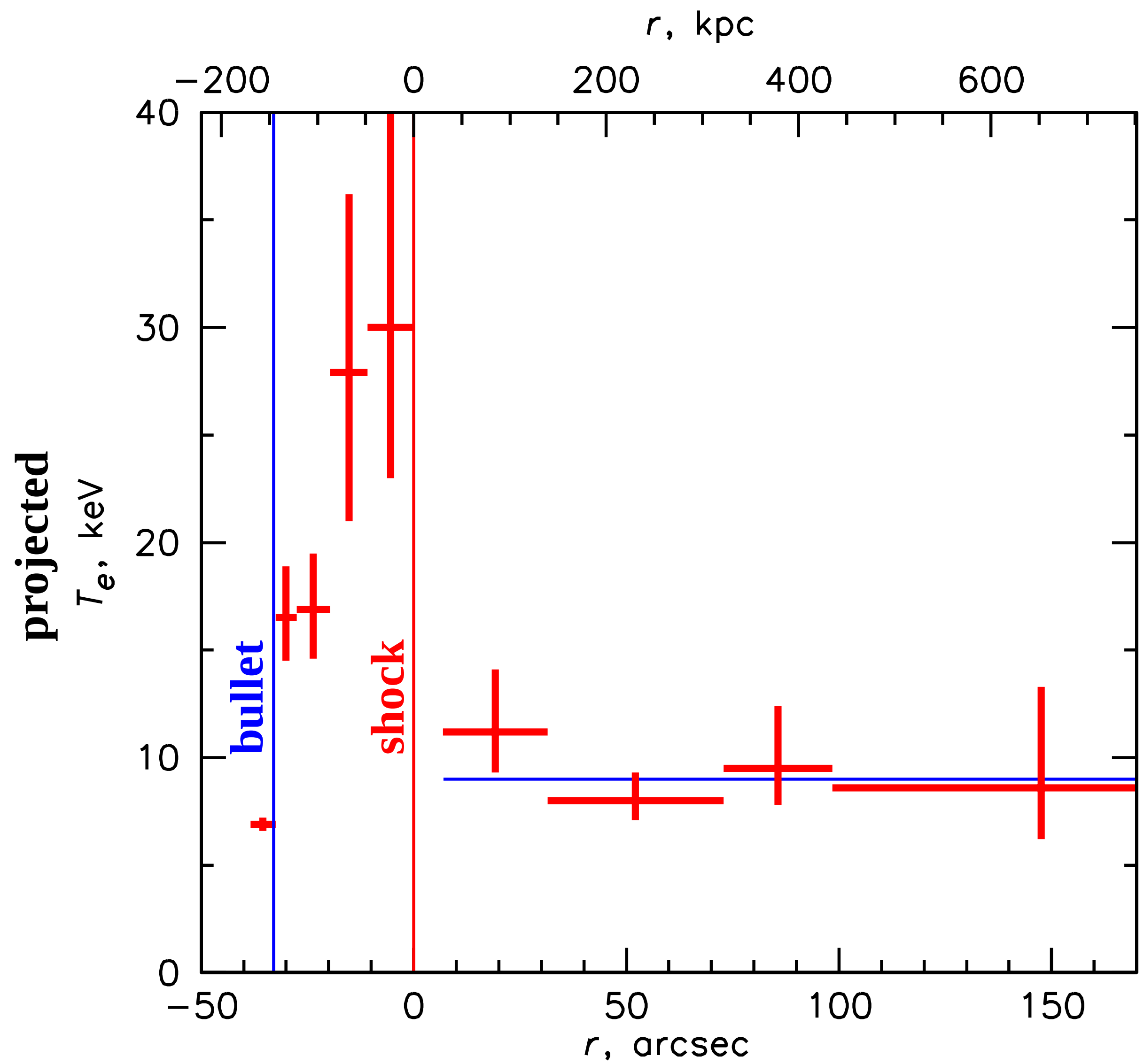
Collisional (Coulomb) τ_{ep} (simulations by Takizawa 1999)

In magnetized plasma, is electron-proton equilibration Coulomb?

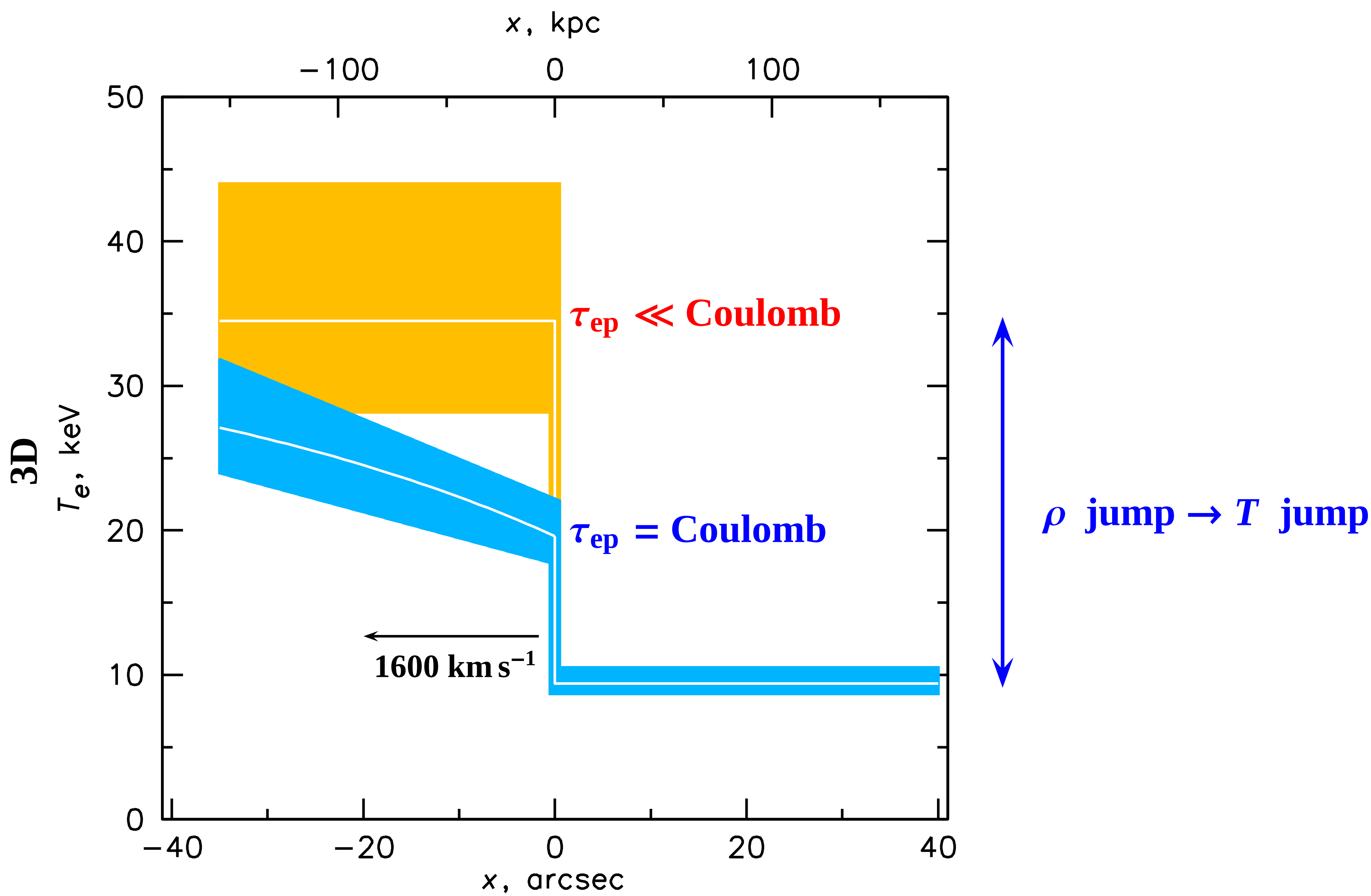
- **Cluster outer regions → errors in cluster masses?**

- **Supermassive black holes in AGN: advection-dominated accretion?**

Temperature across shock front in 1E 0657–56



Model predictions for shock in 1E 0657–56



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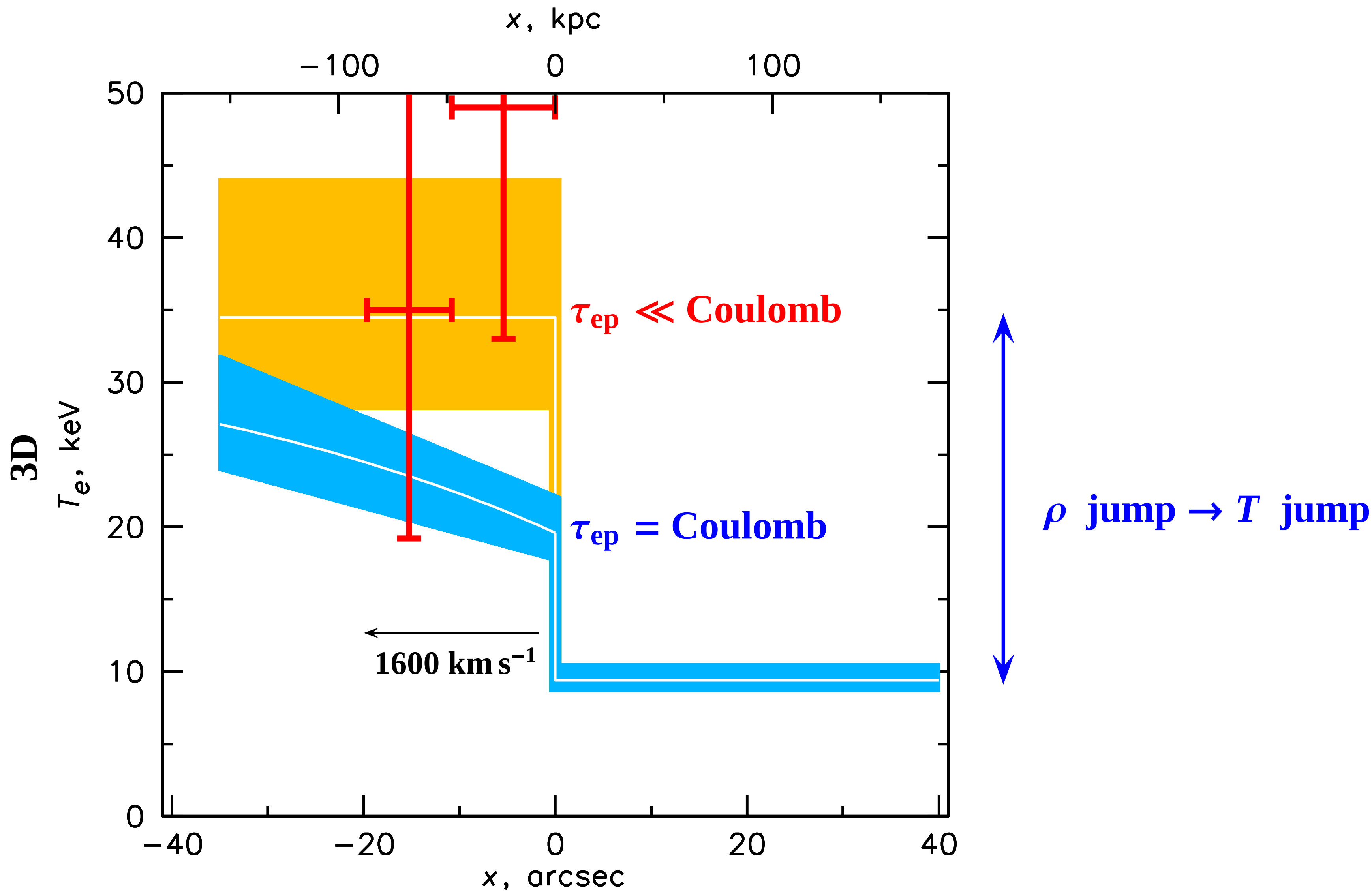
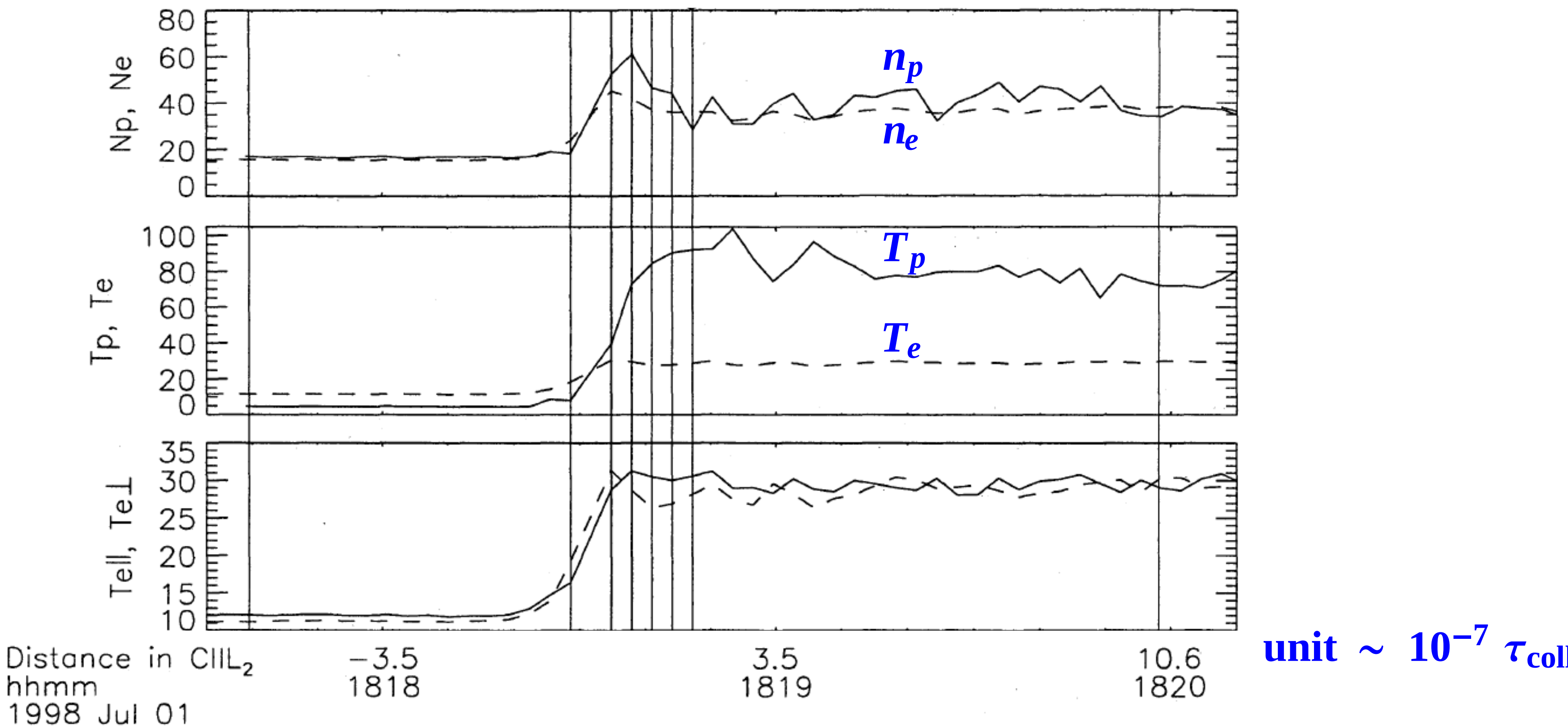


- **95% confidence: $\tau_{ep} \ll$ Coulomb**

Typical Earth's bow shock:

Hull et al. (2001)



Electrons are not heated at shock

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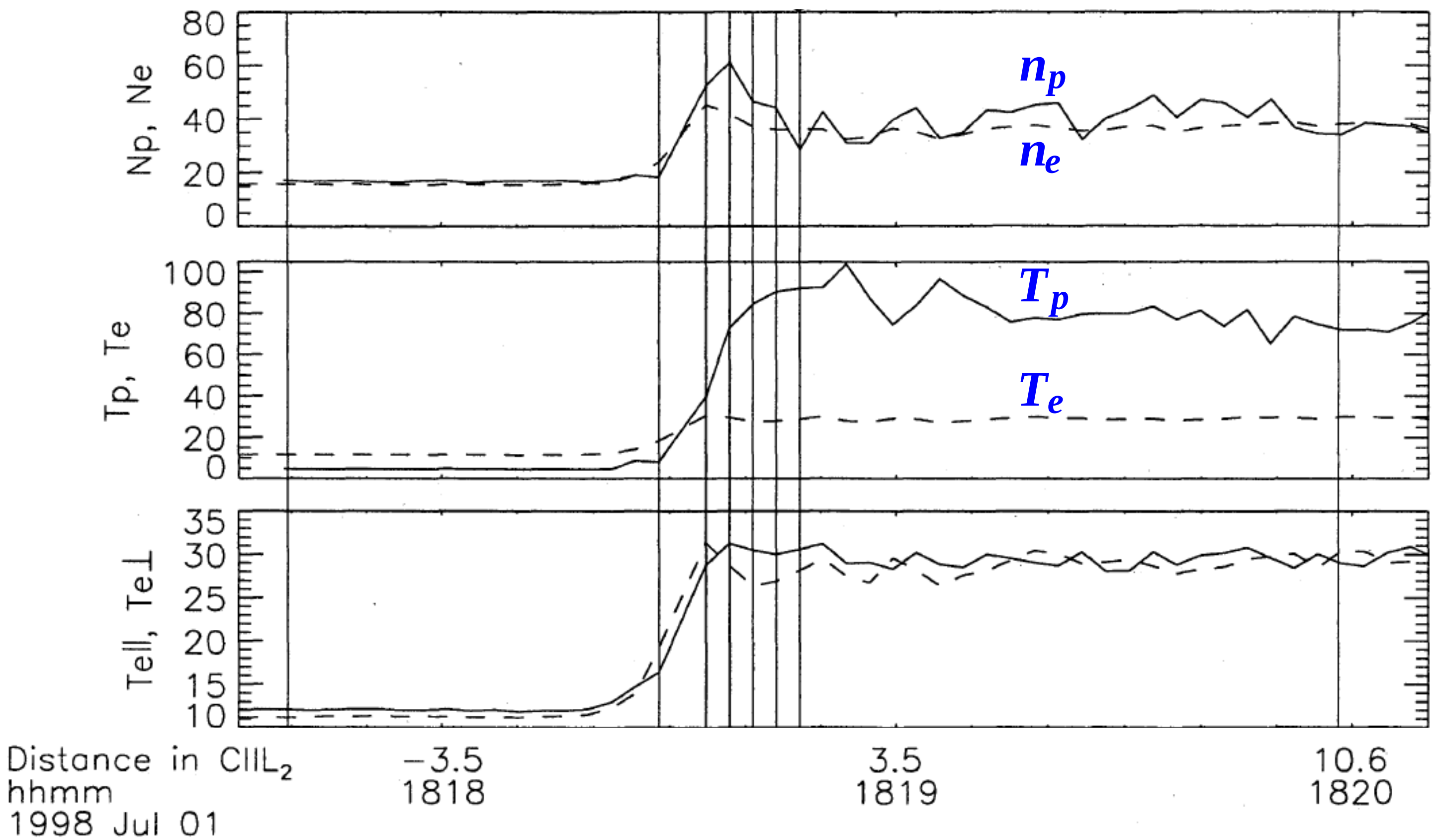

unit $\sim 10^{-7}\ \tau_{\rm coll}$

Electrons are not heated at shock

→ fast $T_e - T_p$ equilibration outside shocks

Summary

- **Dark matter exists!**
- **DM self-interaction cross-section** $\sigma/m < 0.7\ \mathrm{cm^2\,g^{-1}}$
  - **Excludes astrophysically interesting range (for velocity-independent** σ**)**
- **Sterile neutrino DM: improved constraints**
- **Electron-proton equilibration in plasma faster than Coulomb**
  - **First such test for any astrophysical plasma**