I. Structure formation and cluster dynamics

Maxim Markevitch (NASA GSFC)

July 7, 2014

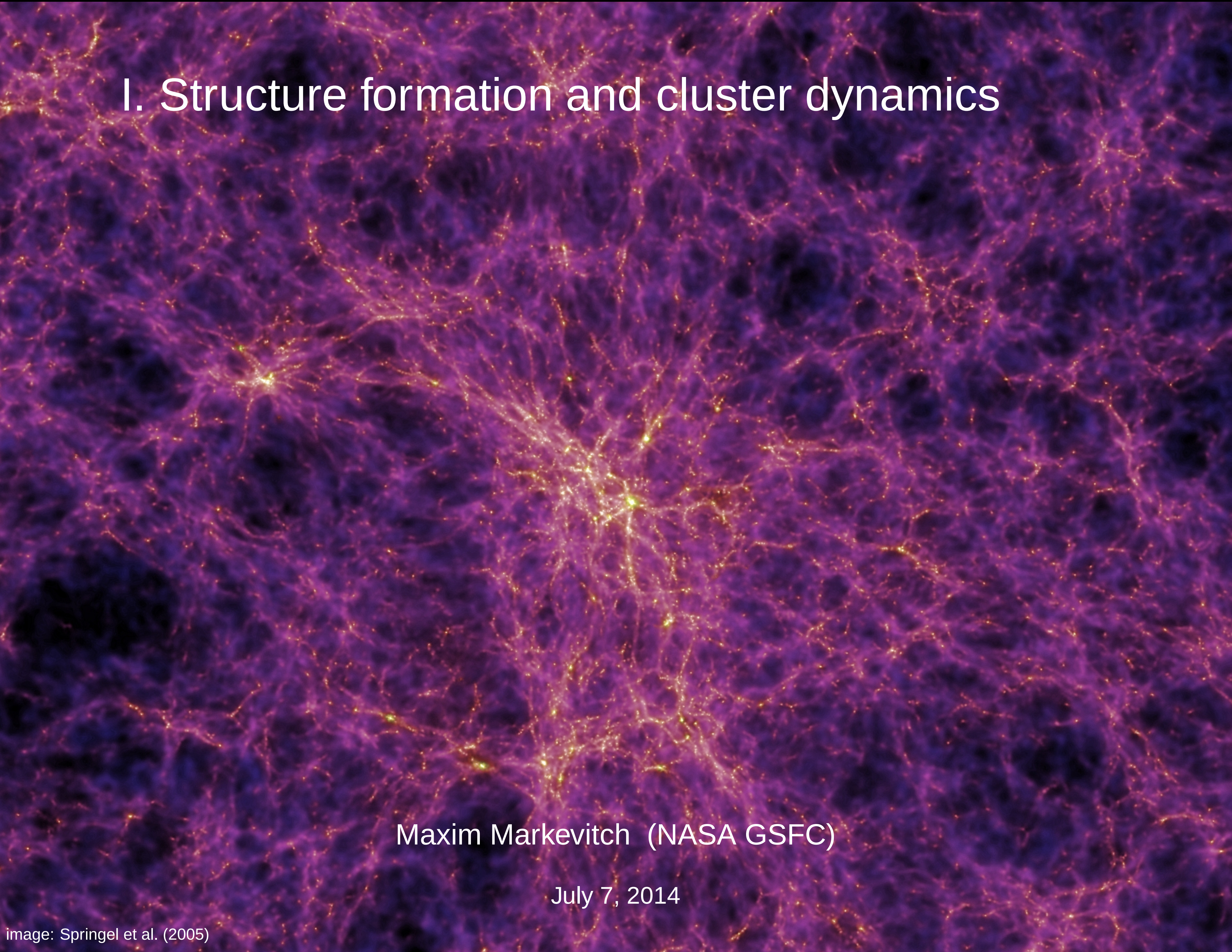
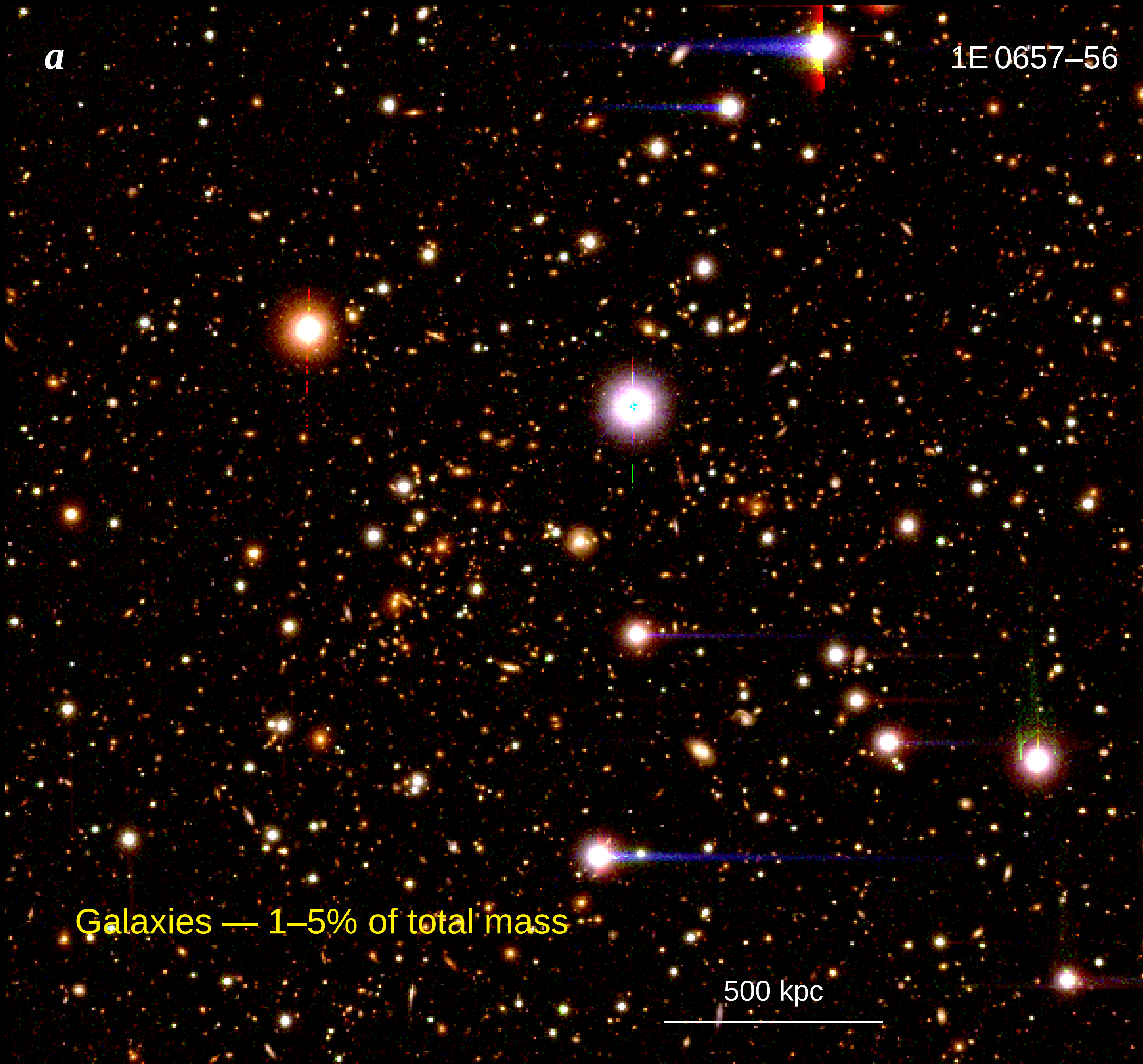
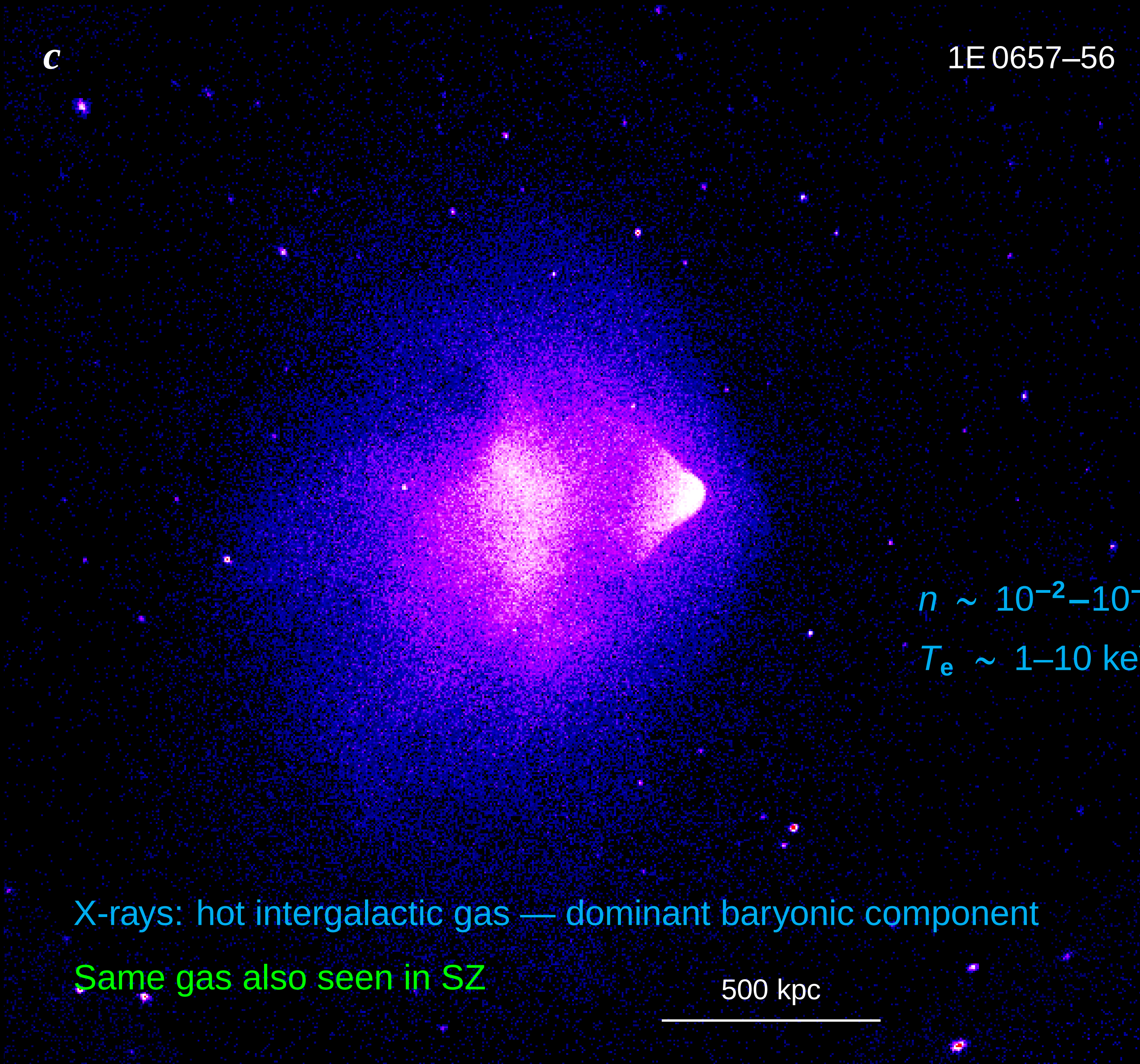


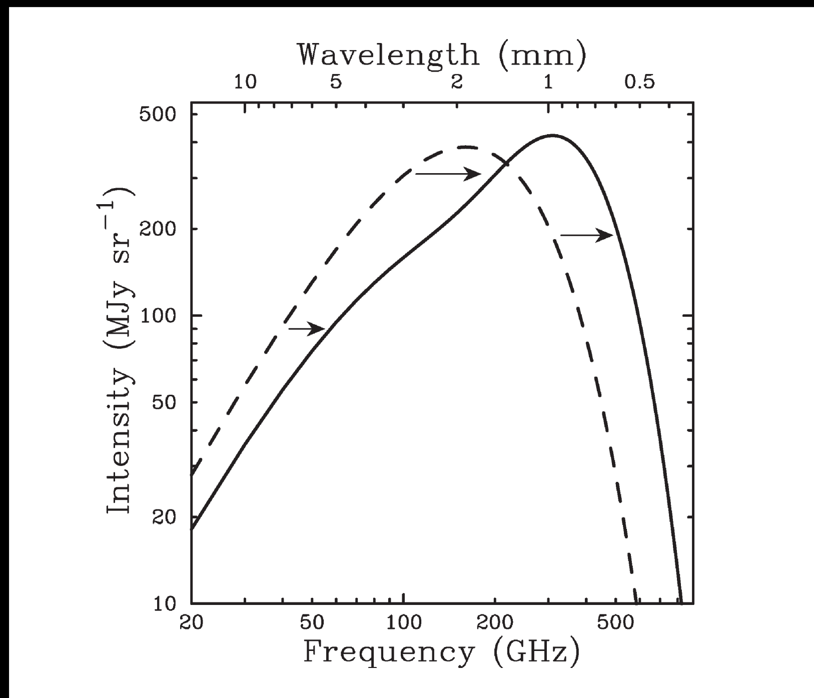
image: Springel et al. (2005)

movie: LSS formation, Springel et al. (2005)


a
1E 0657–56
Galaxies — 1–5% of total mass
500 kpc


c
1E 0657–56
$n \sim 10^{-2}$–10^{-3} cm^{-3}
$T_e \sim$ 1–10 keV
X-rays: hot intergalactic gas — dominant baryonic component
Same gas also seen in SZ
500 kpc

Sunyaev-Zeldovich effect

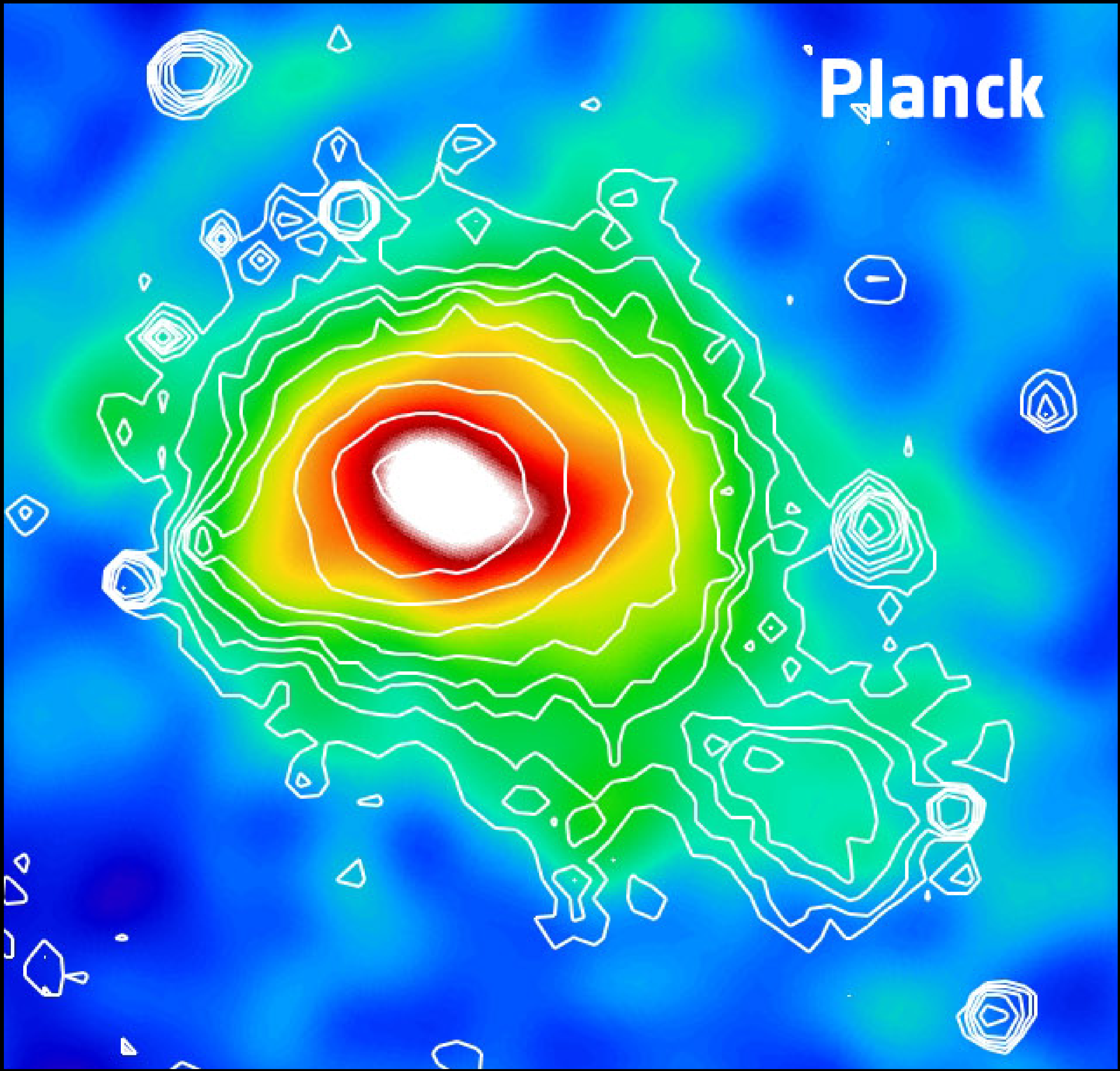


Sunyaev & Zeldovich (1972): inverse Compton scattering of 2.7K CMB photons on hot electrons of the ICM

Decrease in CMB brightness at $\nu \lesssim$ 220 GHz, increase in brighness at higher ν

Signal proportional to $\int n_e T_e dl$

Coma in SZ (Planck Collab. 13)



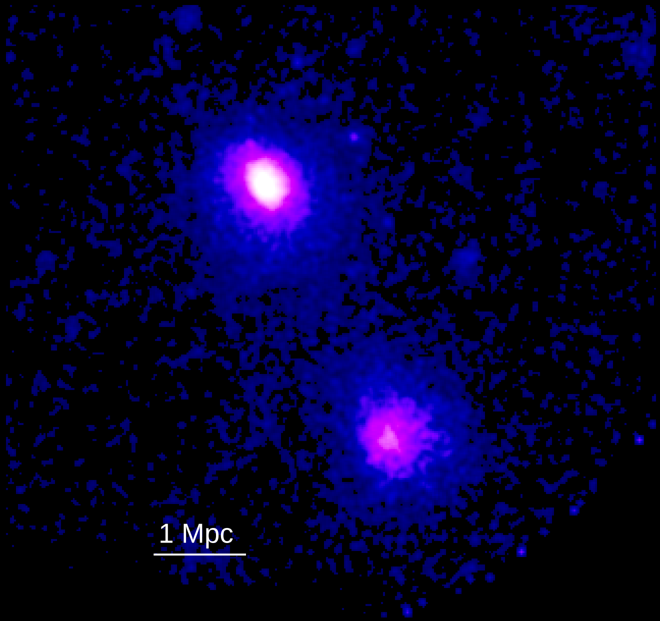

b
Total mass from lensing — 85% dark matter
500 kpc

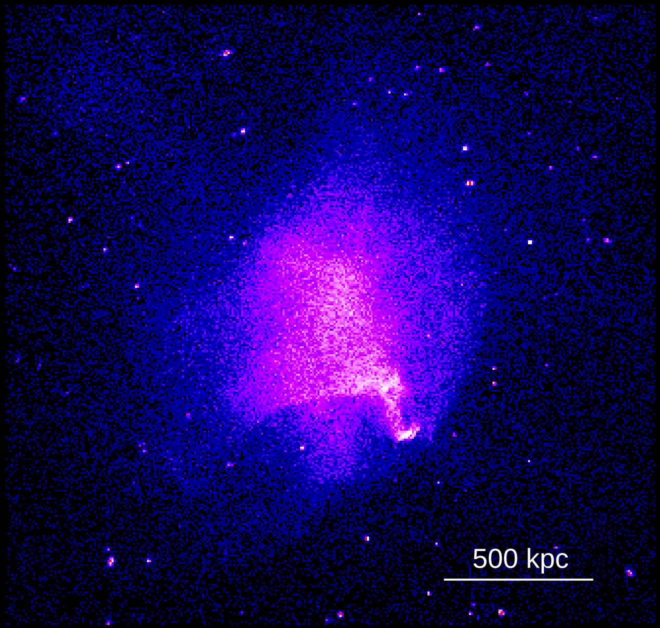
Cluster mass budget:

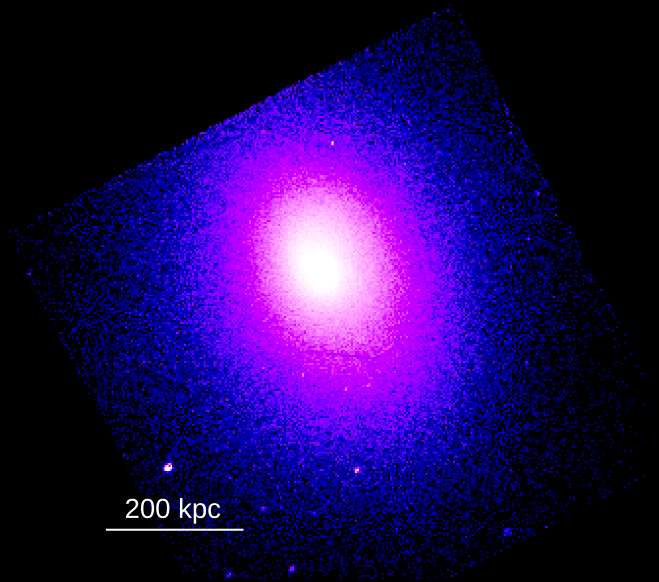
- 1–3% of mass in stars
- 10–20% in hot gas
- 80–90% in dark matter ($M \sim 10^{15}\ M_{\odot}$)

(will consider various methods to determine cluster mass below)

Clusters form via mergers:







Mergers are the most energetic events since the Big Bang:

$E_{\mathbf{kin}}$ up to $\sim 10^{\mathbf{63-64}}$ ergs

Unique laboratory of cluster physics:

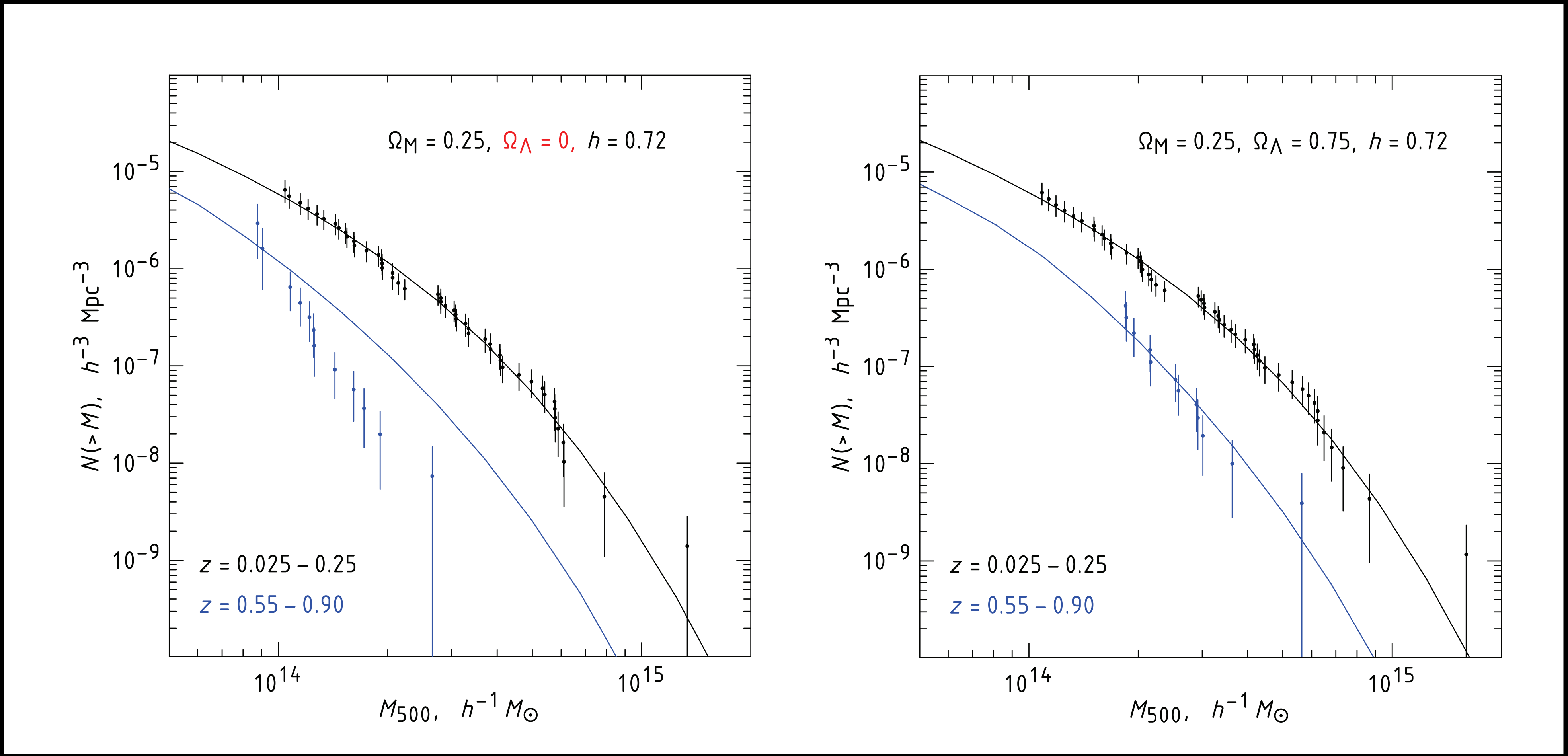
shocks, “cold fronts”, gasdynamic instabilities, turbulence;

particle acceleration, dynamic effects of magnetic field;

nature of dark matter

Clusters are sensitive cosmological probes

Growth of clusters test

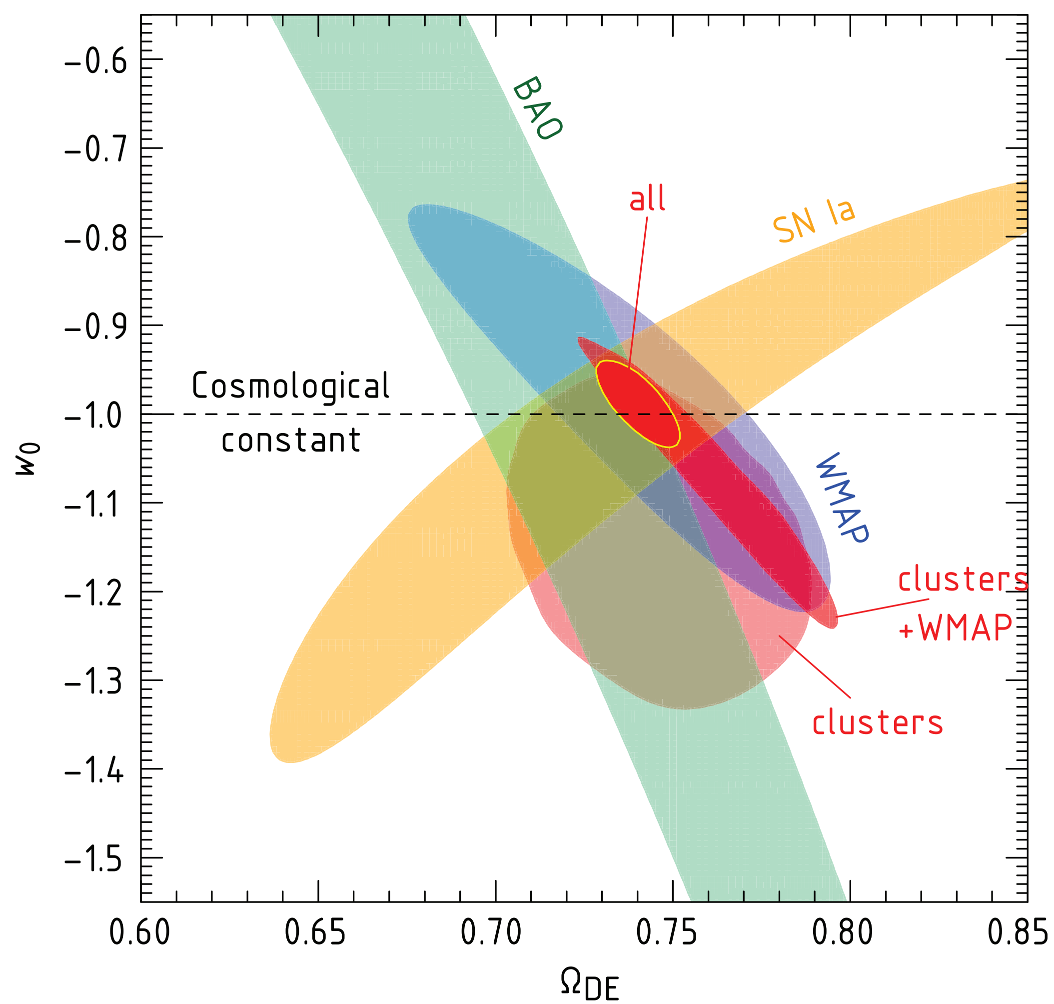


Ω_m = 0.25, Ω_Λ = 0 (wrong geometry)

ΛCDM (correct geometry & evolution)

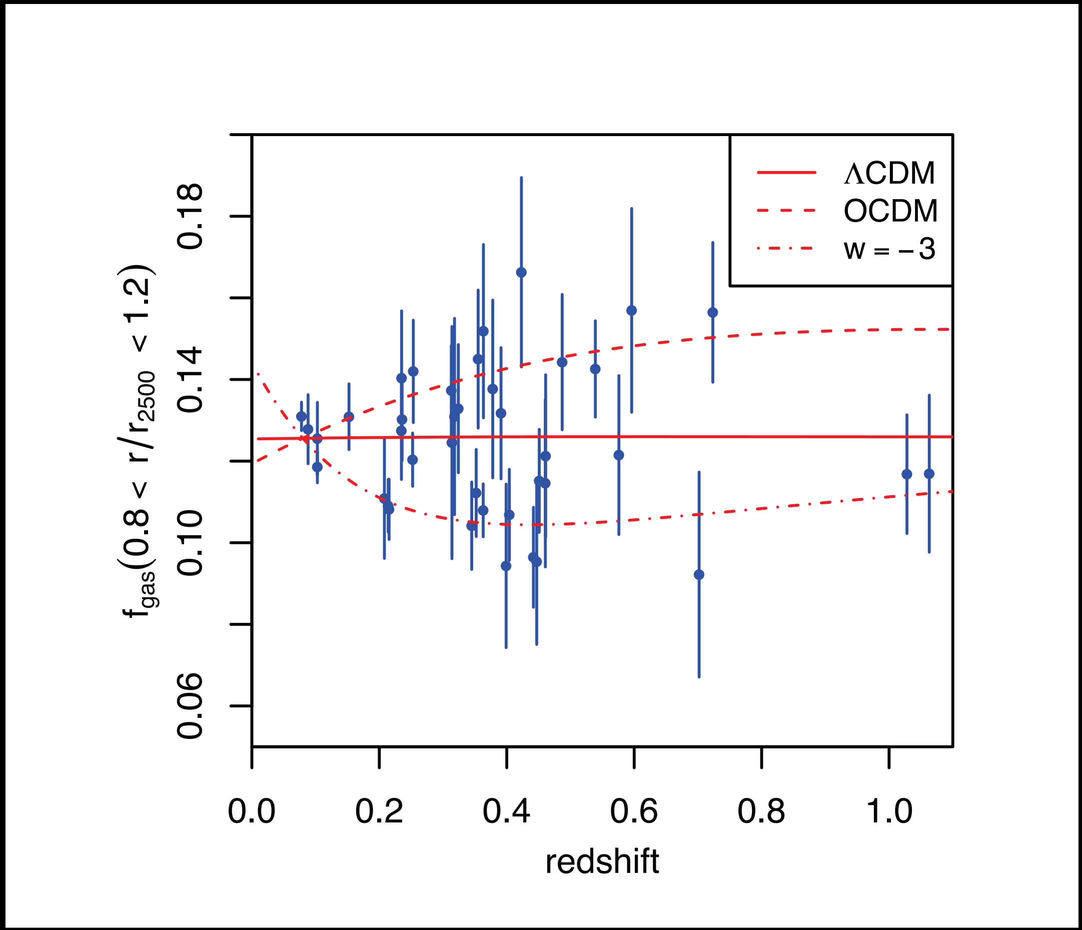
Sunyaev 71; Press & Schechter 74; ...; Vikhlinin et al. 09

Growth of clusters test



Vikhlinin 09

Baryon fraction test



Mantz 14

Clusters should have a representative sample of matter components

True $f_{gas} \equiv M_{gas} / M_{total}$ = const $\rightarrow$ test of geometry of the Universe

(Sasaki 96; Rines 99; Allen 02, 04; Mantz 14)

How to determine a cluster total mass

1. Galaxy velocity dispersion and virial theorem
2. X-ray hydrostatic equilibrium
3. Gravitational lensing

Zwicky (1933, 1937): Universe is dominated by “missing mass”

- Total mass of a galaxy cluster ~ 100 times the mass in stars
- “Missing mass” is not concentrated in galaxies

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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

How to determine a cluster total mass

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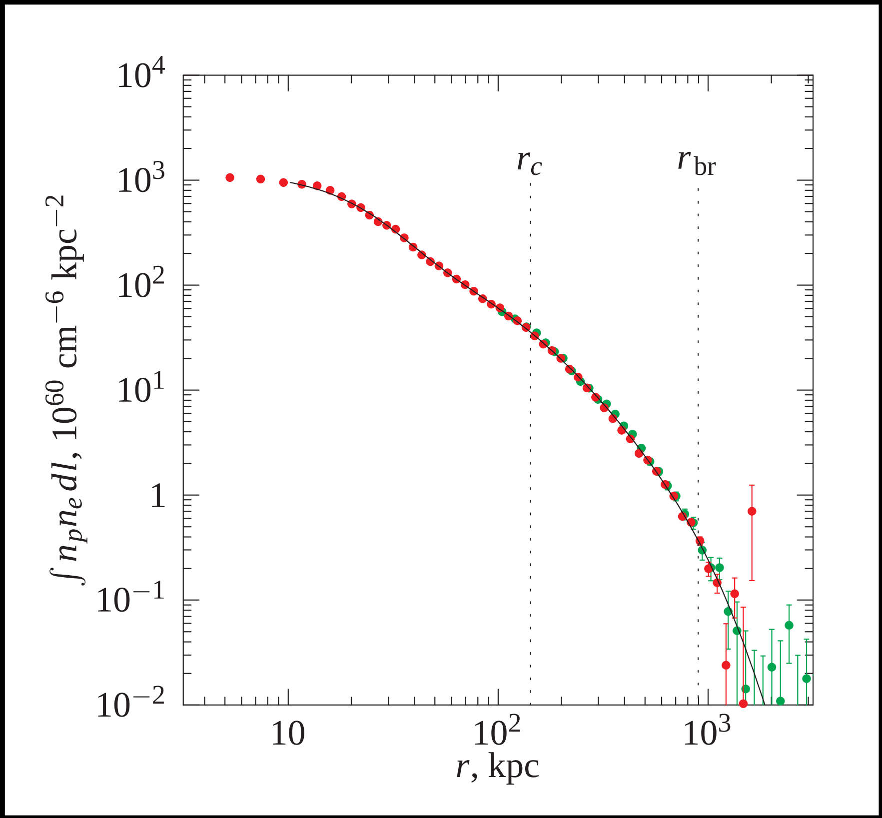
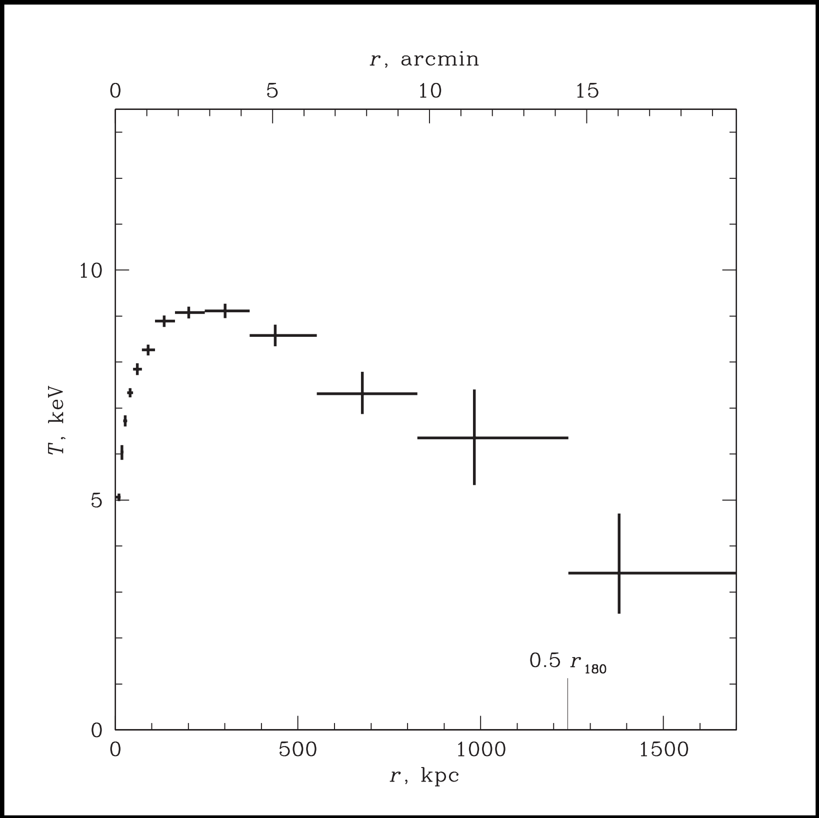
Typical X-ray brightness profile



Typical *T* profile



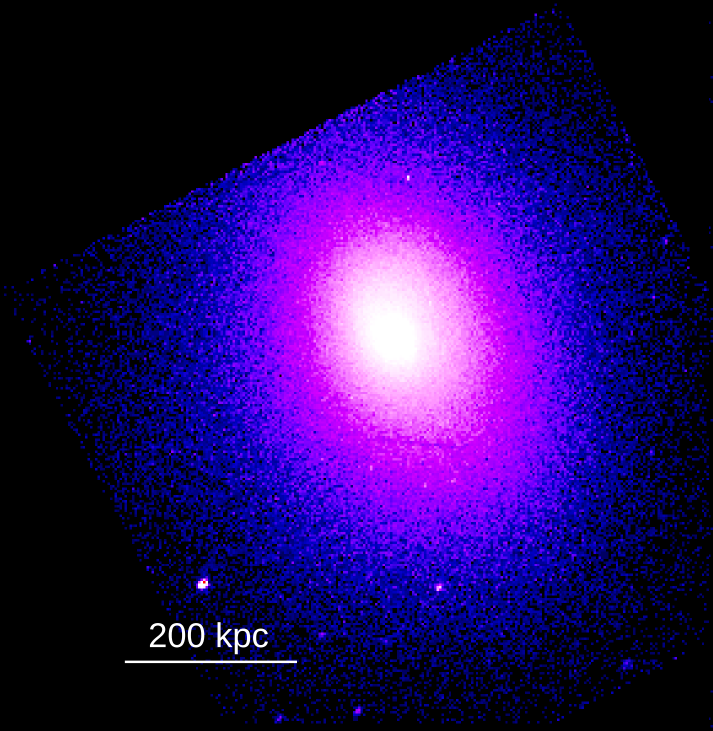
Assuming that gas is at rest and supported only by its thermal pressure in the cluster's grav. potential (hydrostatic equilibrium),

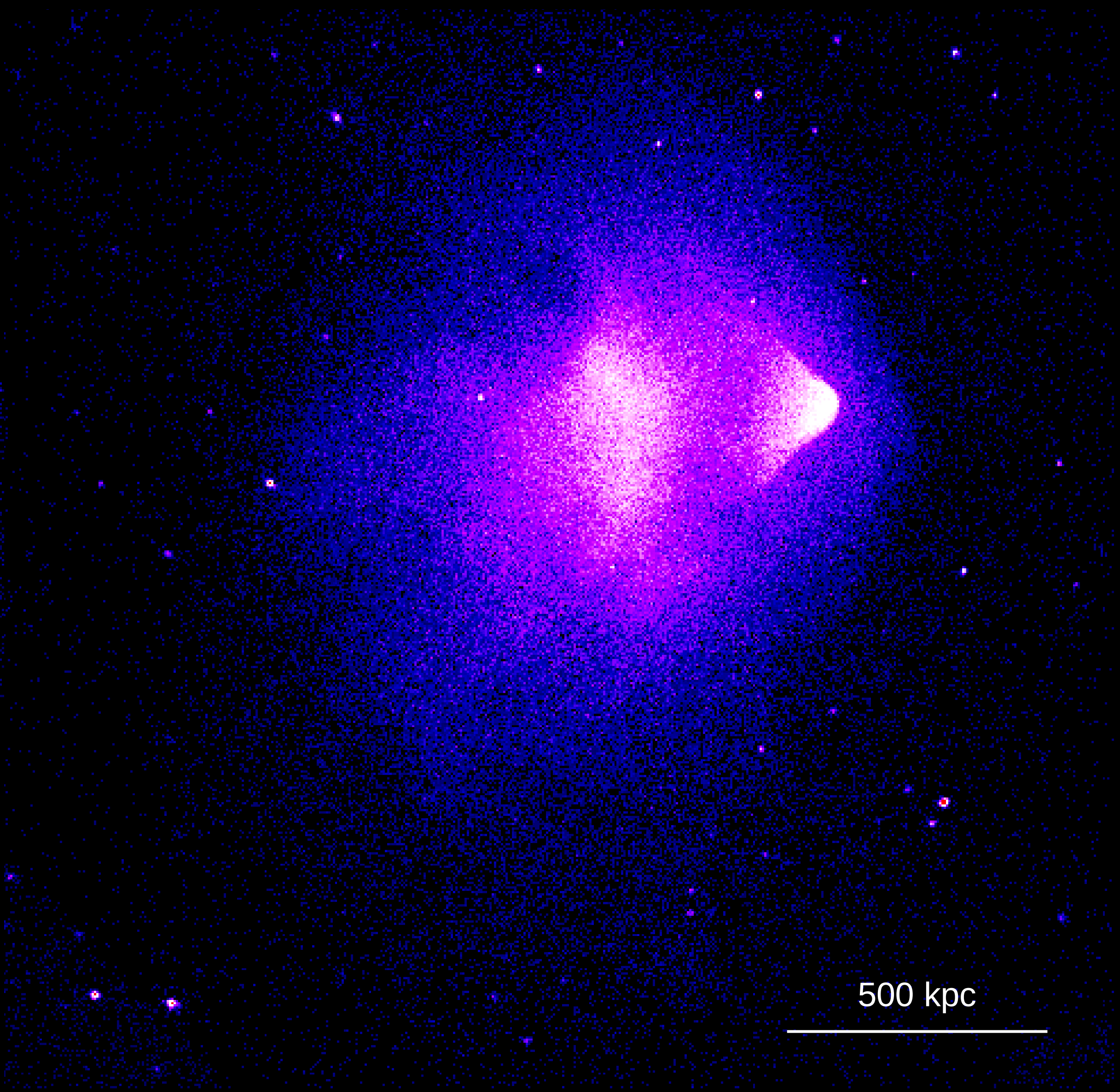
$$\nabla p = - \rho_{gas} \nabla \Phi$$

$p = \rho_{gas} T$ from X-rays or SZ; ρ_{gas} from X-rays $\rightarrow$ total mass profile

In equilibrium (possibly)

Not in equilibrium





How to determine a cluster total mass

1. Galaxy velocity dispersion and virial theorem
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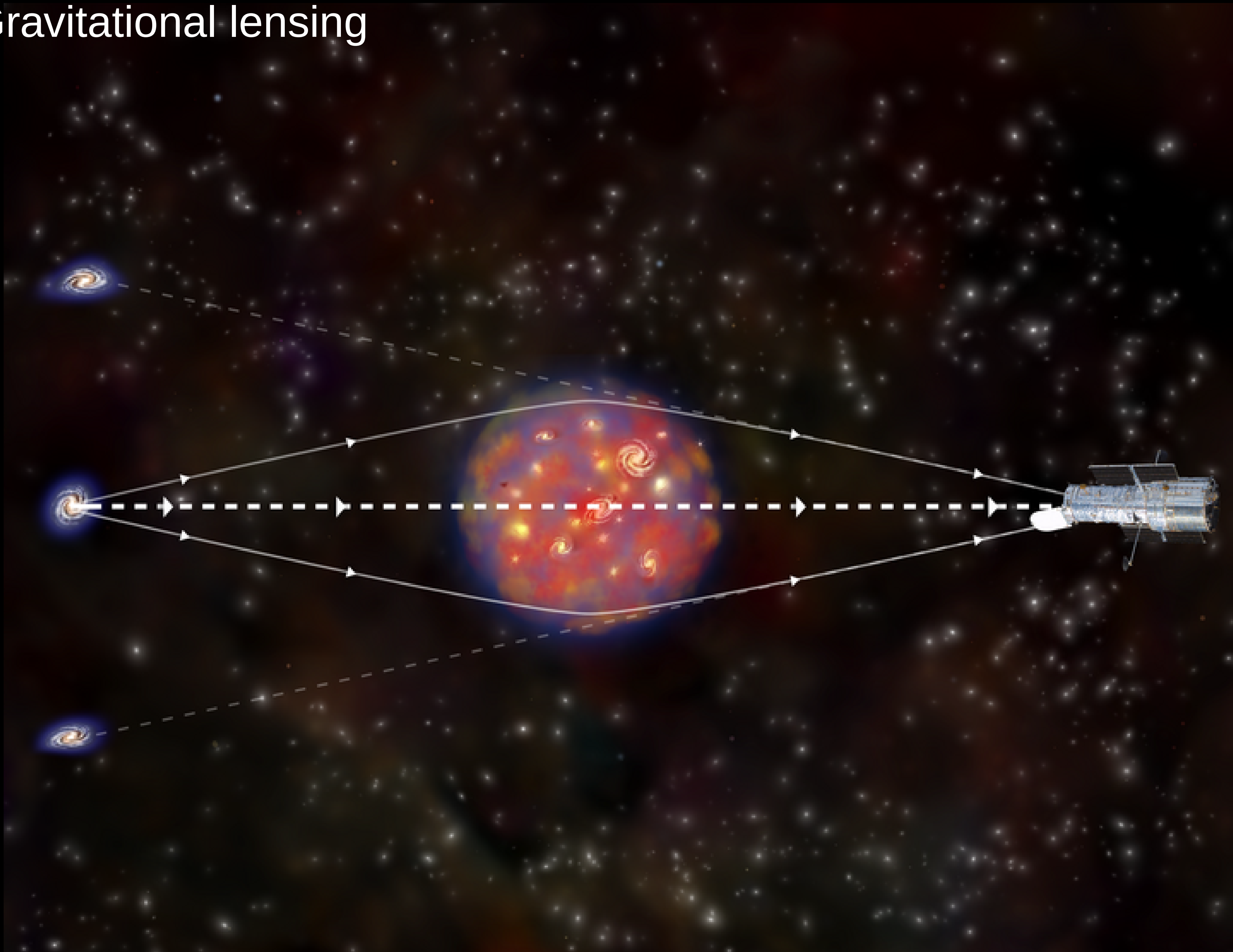
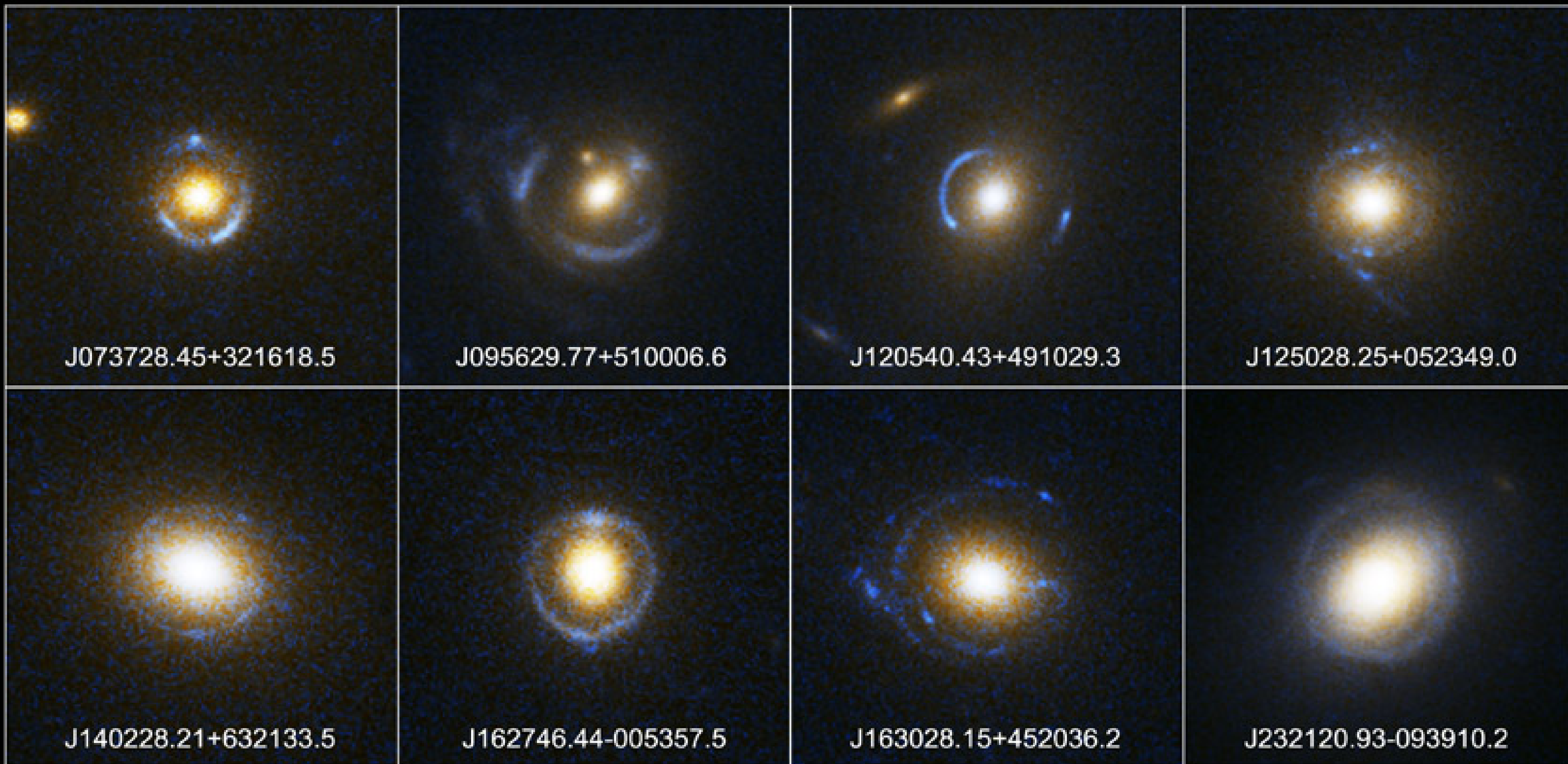
Gravitational lensing



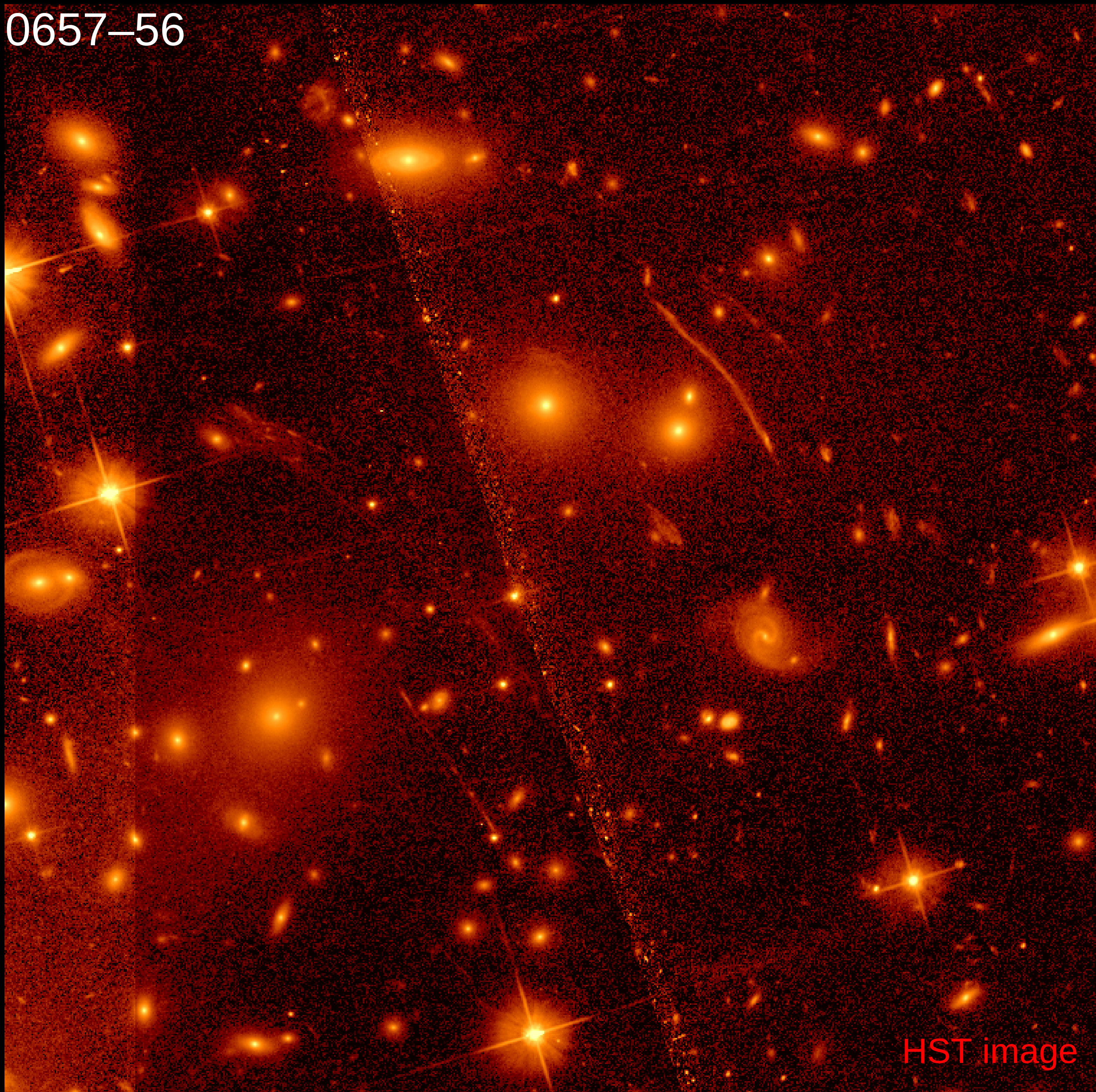


Einstein Ring Gravitational Lenses

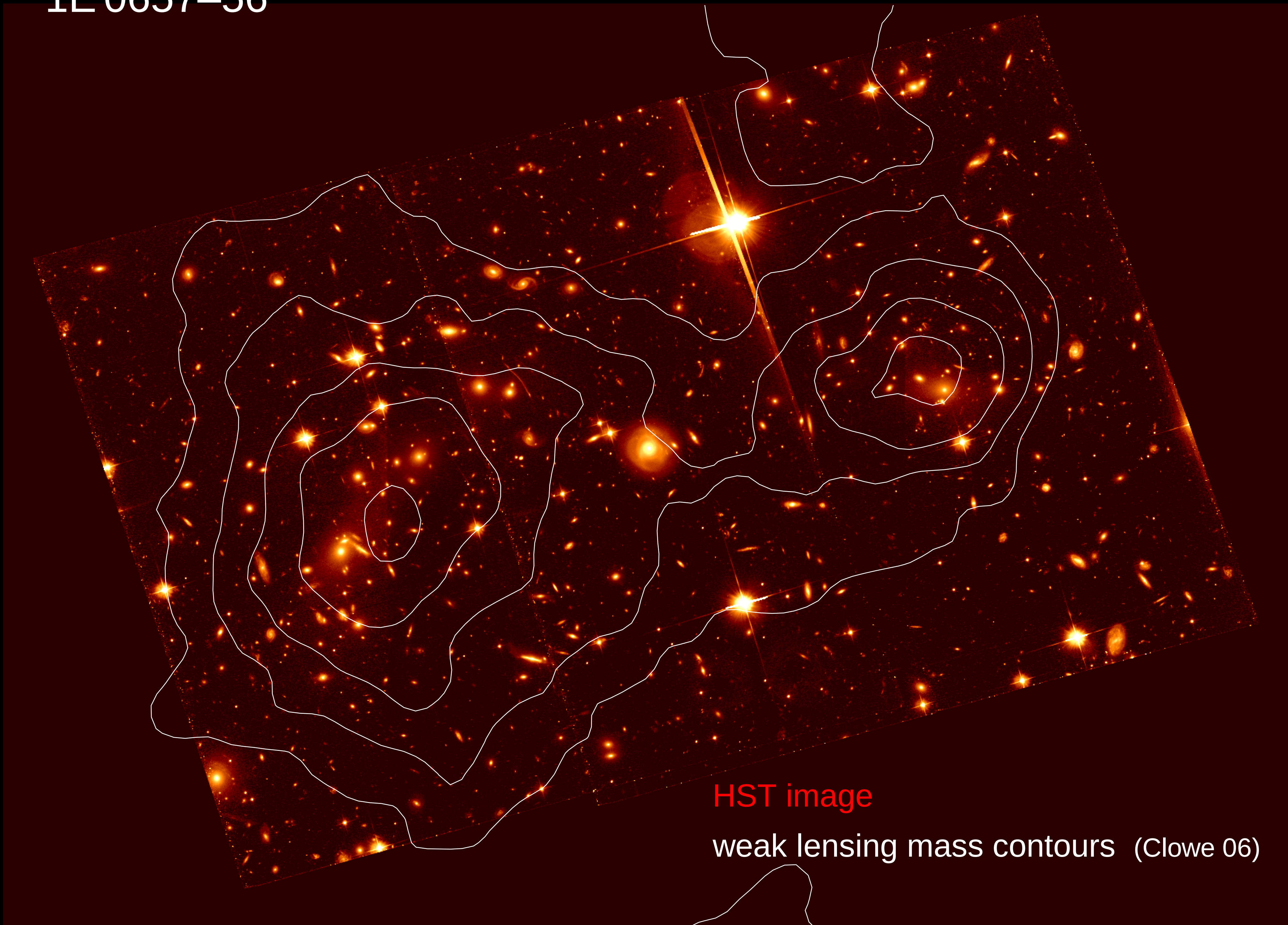
Hubble Space Telescope • Advanced Camera for Surveys

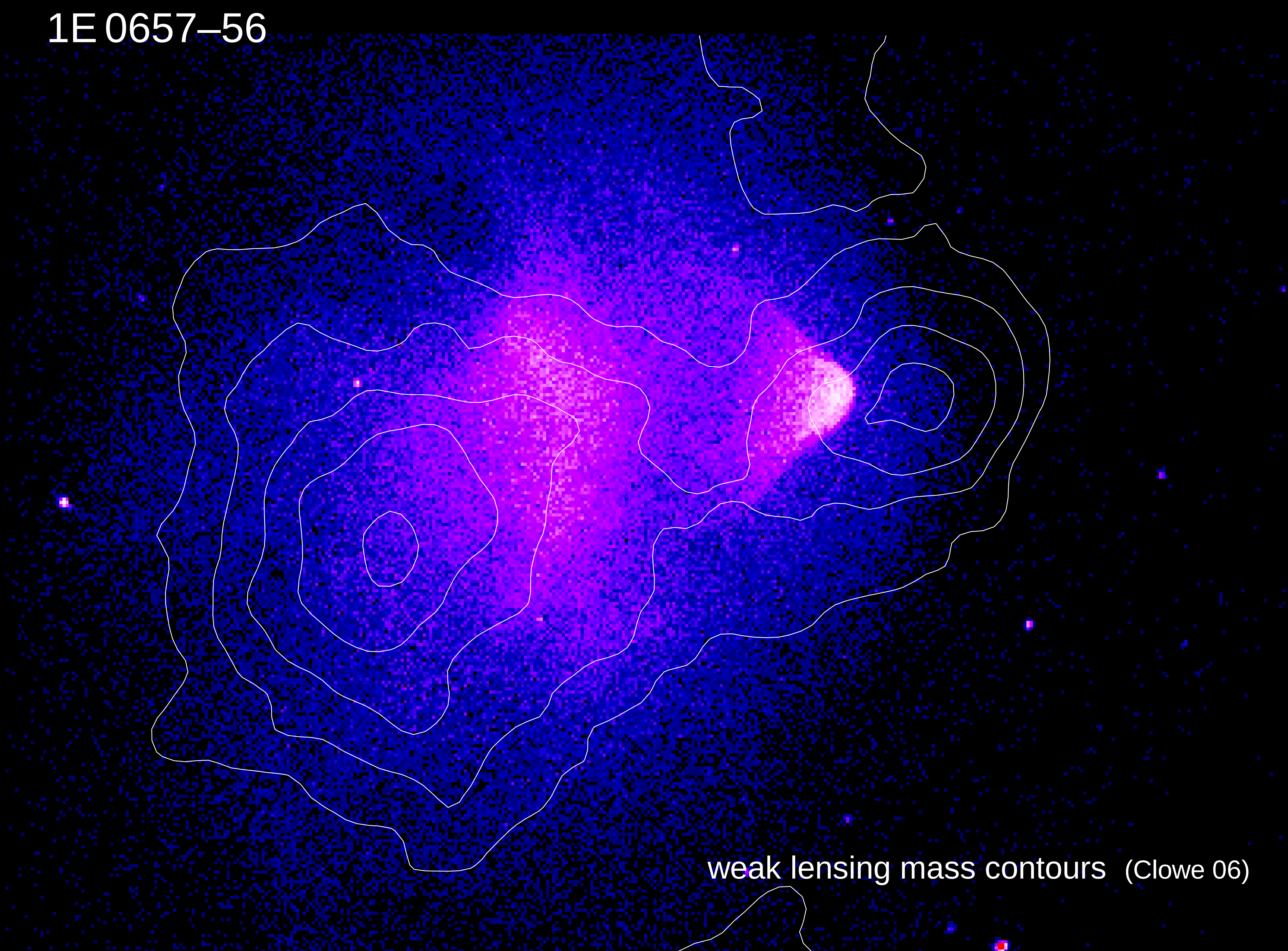
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32


1E 0657–56
HST image

1E 0657–56




1E 0657–56
weak lensing mass contours (Clowe 06)

1E 0657–56

most of visible mass is in hot gas, but grav. potential peaks are elsewhere

→   there is something else — dark matter exists! (Clowe 04, 06)

image from 2006 NASA / Chandra press release

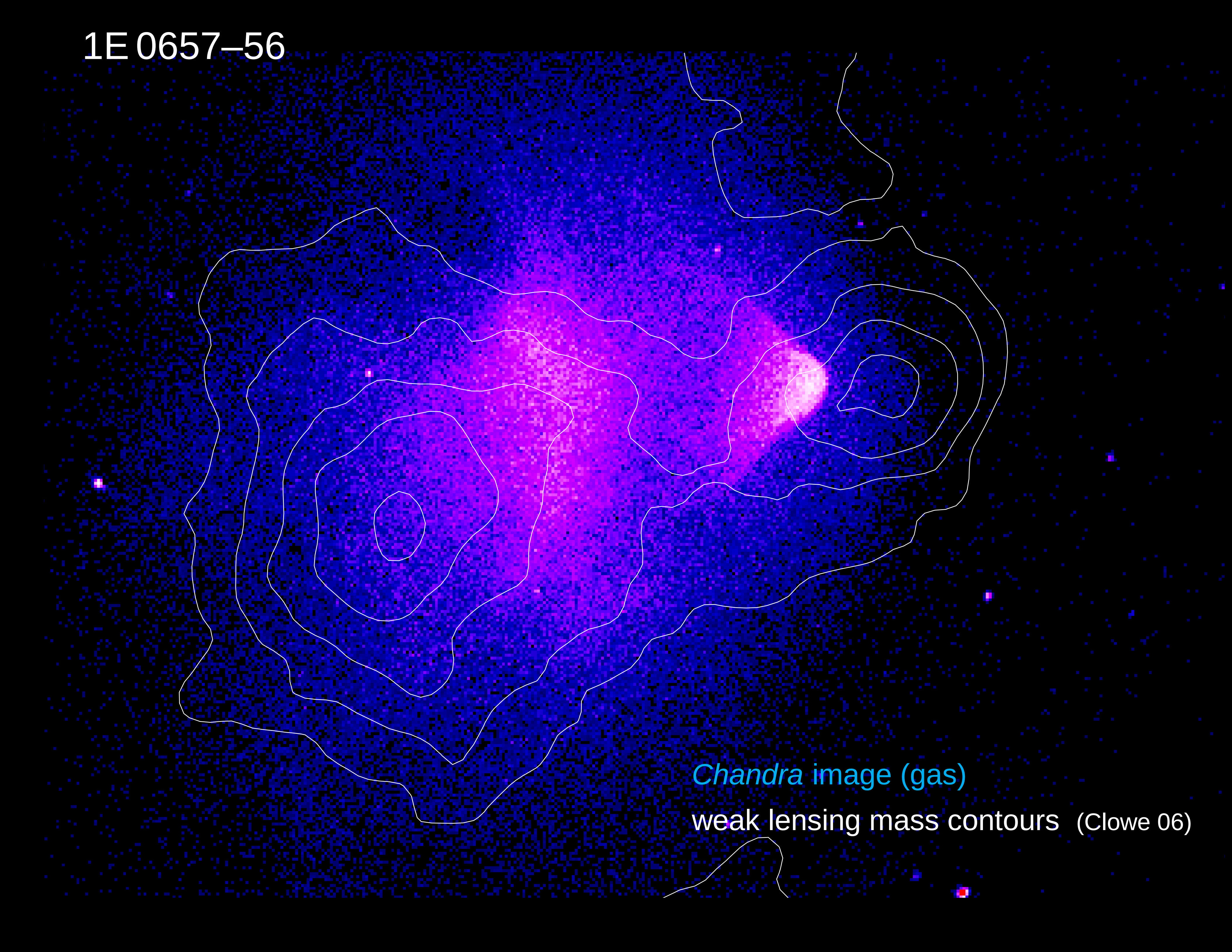
Nature of dark matter

Self-interacting Dark Matter?

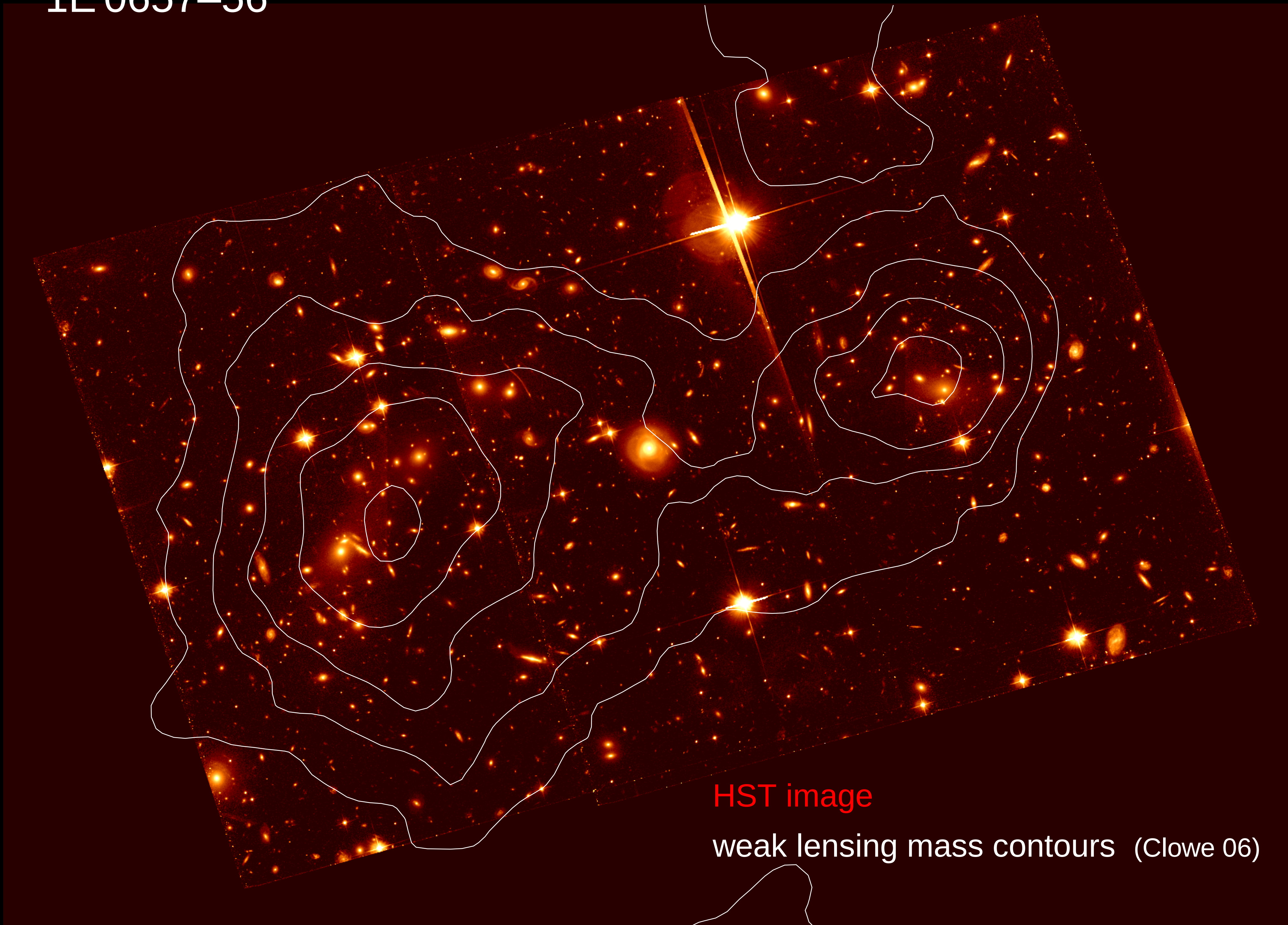
SIDM with $\sigma/m \sim 0.5\text{–}5\ \mathrm{cm}^2\,\mathrm{g}^{-1}$ was proposed to explain problems in standard CDM:

- Central cusps in dwarf galaxies
- Too many surviving small-mass subhalos within large halos

(Spergel & Steinhardt 00; Davé et al. 01)


1E 0657–56
Chandra image (gas)
weak lensing mass contours (Clowe 06)

1E 0657–56



HST image

weak lensing mass contours (Clowe 06)

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

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Observational evidence:

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The best constraint comes from method 4 (Markevitch et al. 04; Randall et al. 08)

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

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

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

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

- $m = m_p \quad \rightarrow \quad \sigma < 2 \times 10^{-24}$ cm^{-2}
  - strong interactions $\sim 10^{-24}$ cm^{-2}
- $m = 1$ eV $\quad \rightarrow \quad \sigma < 2 \times 10^{-33}$ cm^{-2}
  - neutrino-neutrino interaction from SN 1987a: $\sigma < 10^{-35} - 10^{-25}$ cm^{-2}

Warm Dark Matter

would help explain cores of dwarf galaxies and lack of Milky Way satellites

Sterile neutrino? (Dodelson & Widrow 94)

- From astrophysical considerations, $m_s > 0.5$ keV
- Decays into a photon $E = m_s / 2$ and a standard neutrino
- Decay rate is such that it may be detectable from galaxy clusters, etc.

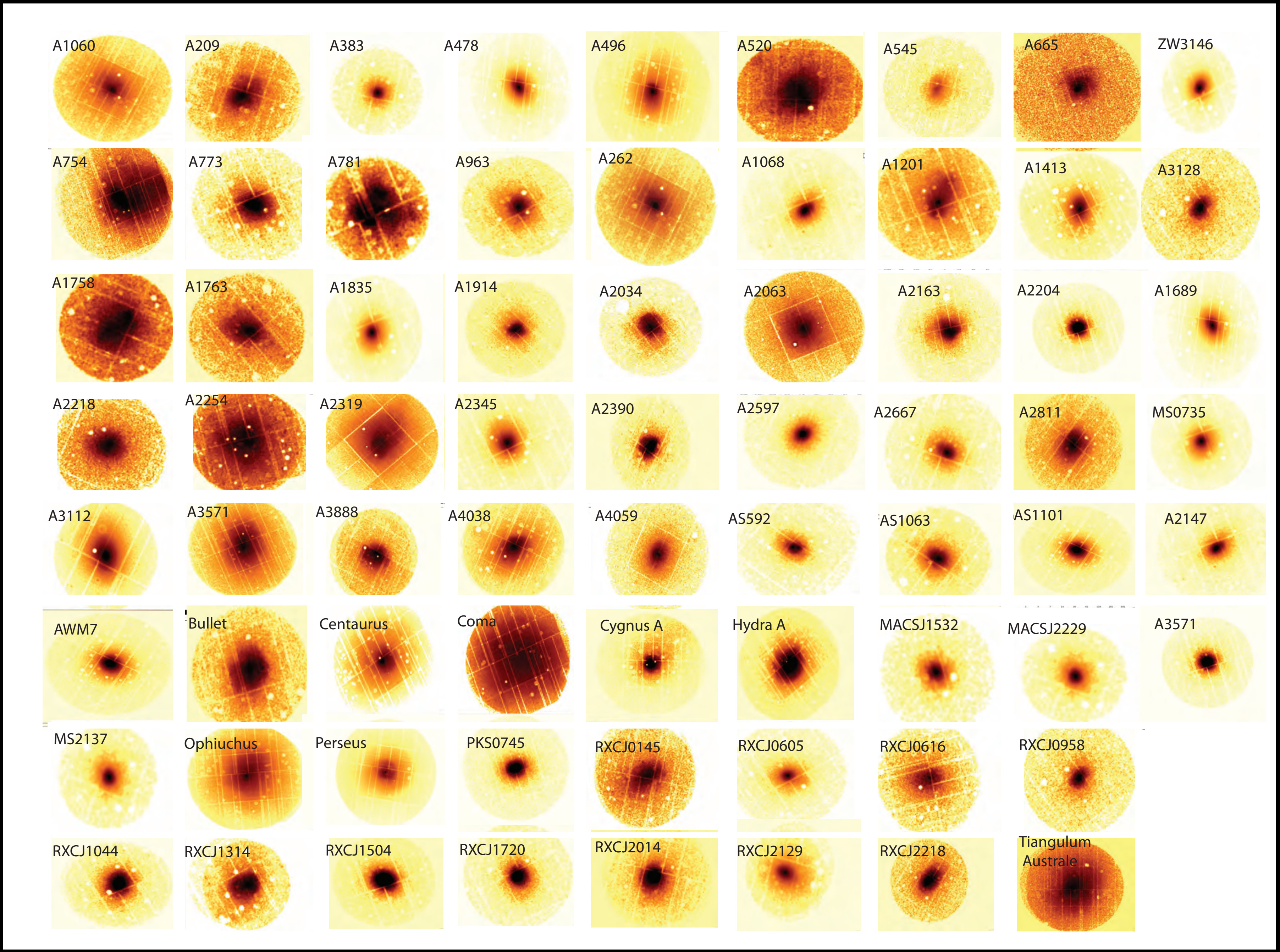
Has emission from warm dark matter been detected?

Detection of an unidentified emission line in the stacked X-ray spectrum of galaxy clusters

E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Loewenstein, S. Randall

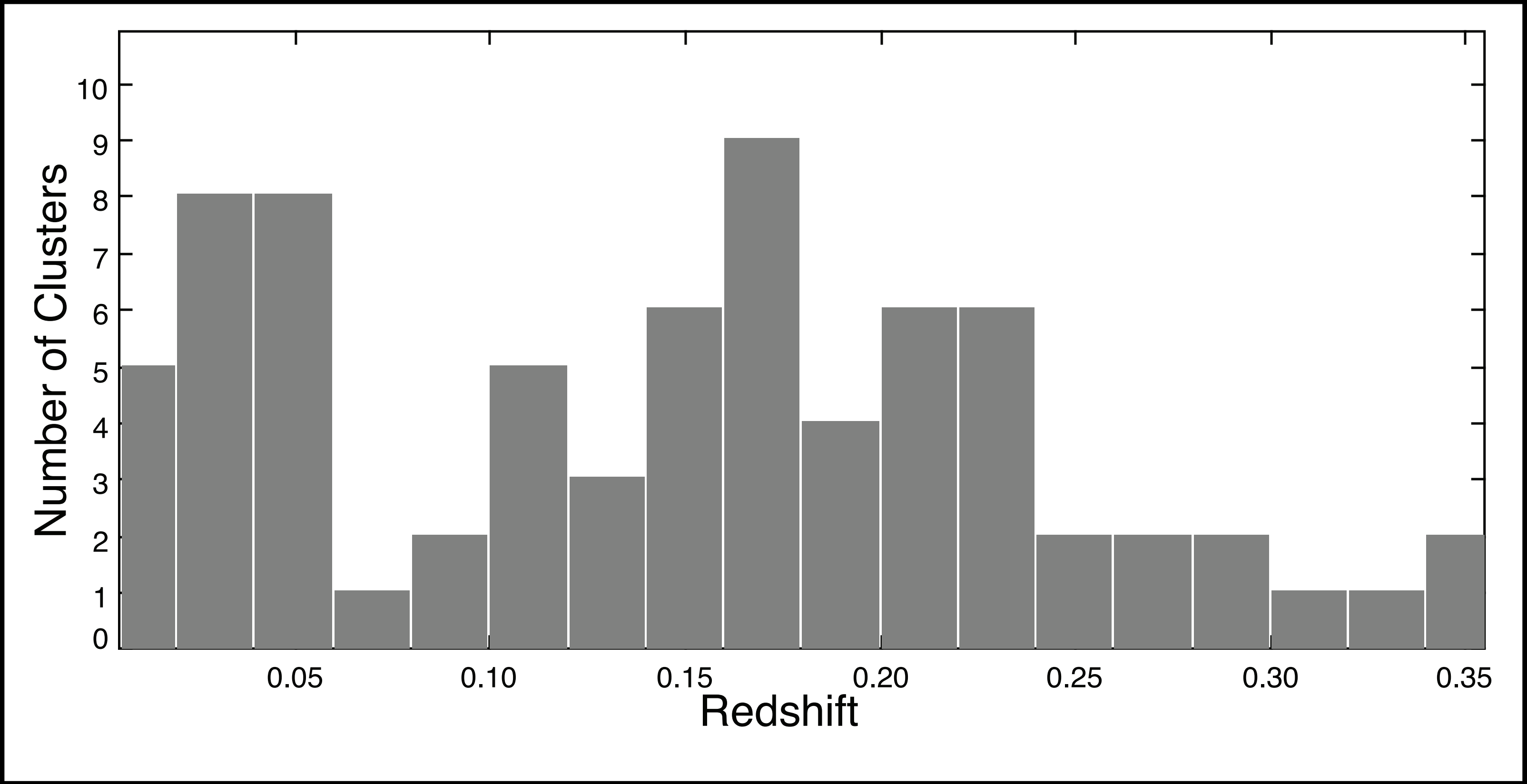
arXiv:1402.2301

Bright XMM clusters

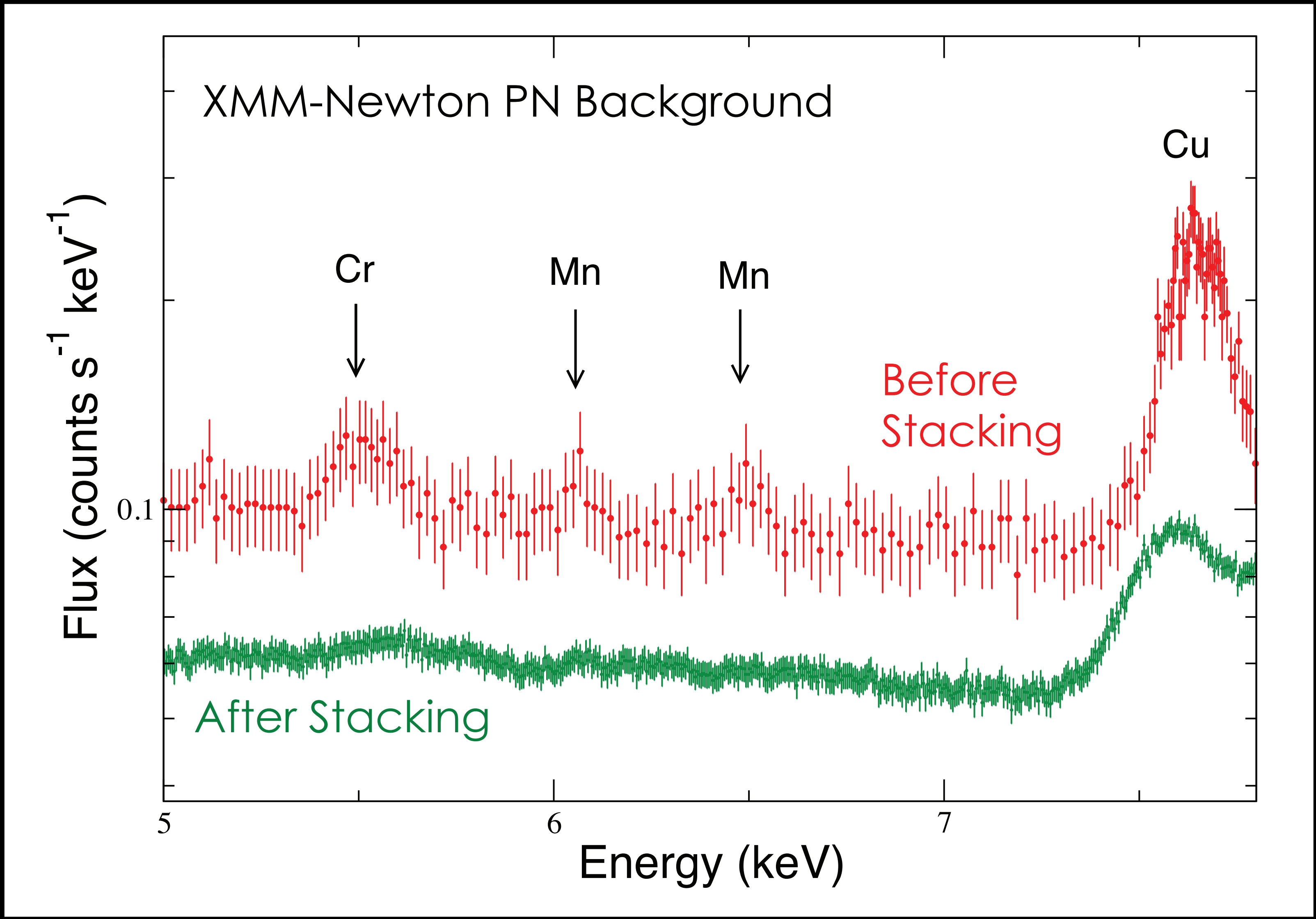


Stacked XMM spectra (MOS and PN) of 73 bright galaxy clusters,

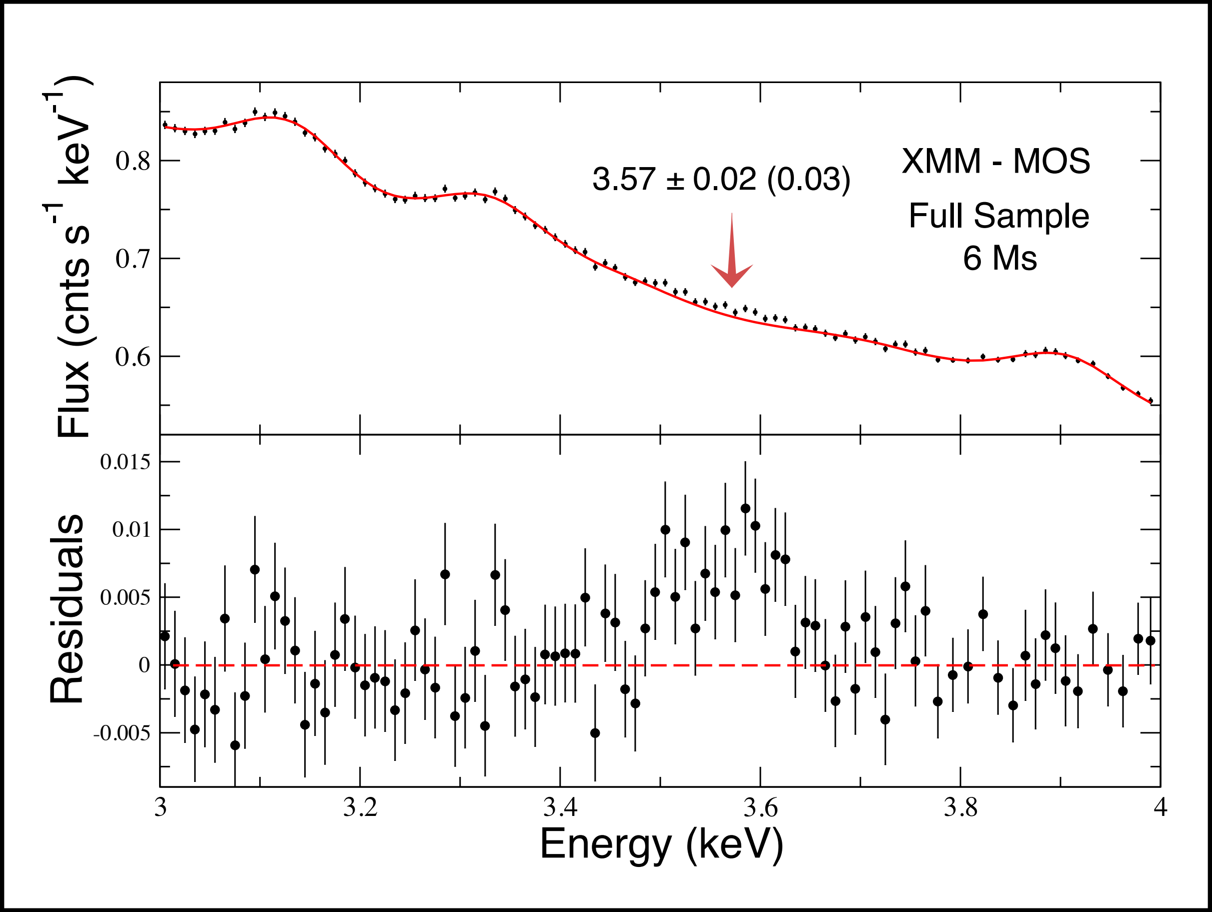
blue-shifted to the same cluster rest frame



Detector features smeared

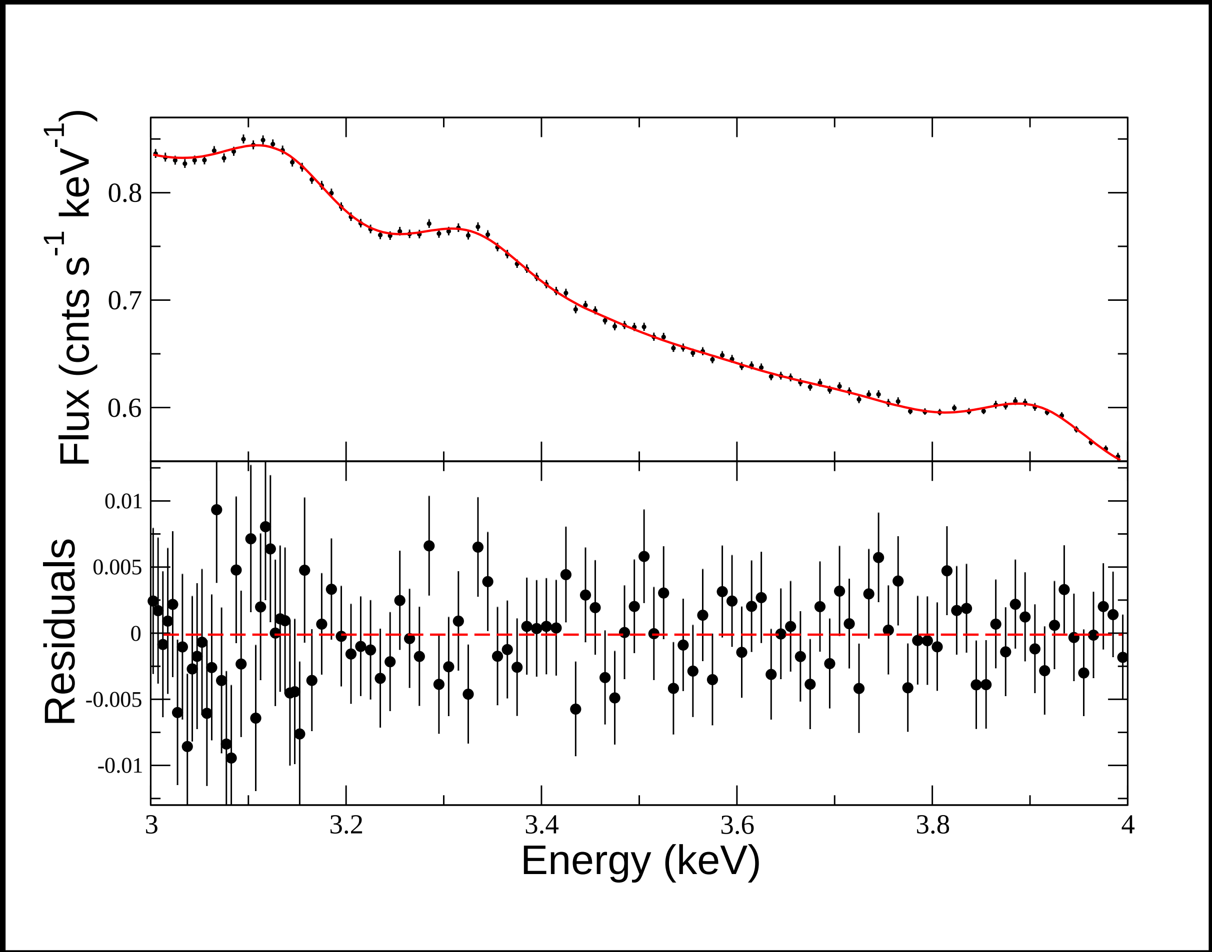


Line in stacked XMM spectra, full cluster sample



No line added

Line in stacked XMM spectra, full cluster sample



Gaussian line added

Line detected at consistent energy at $>3\sigma$ in 5 statistically indepentent spectra:

MOS: Perseus, Coma+Centaurus+Ophiuchus, distant subsample

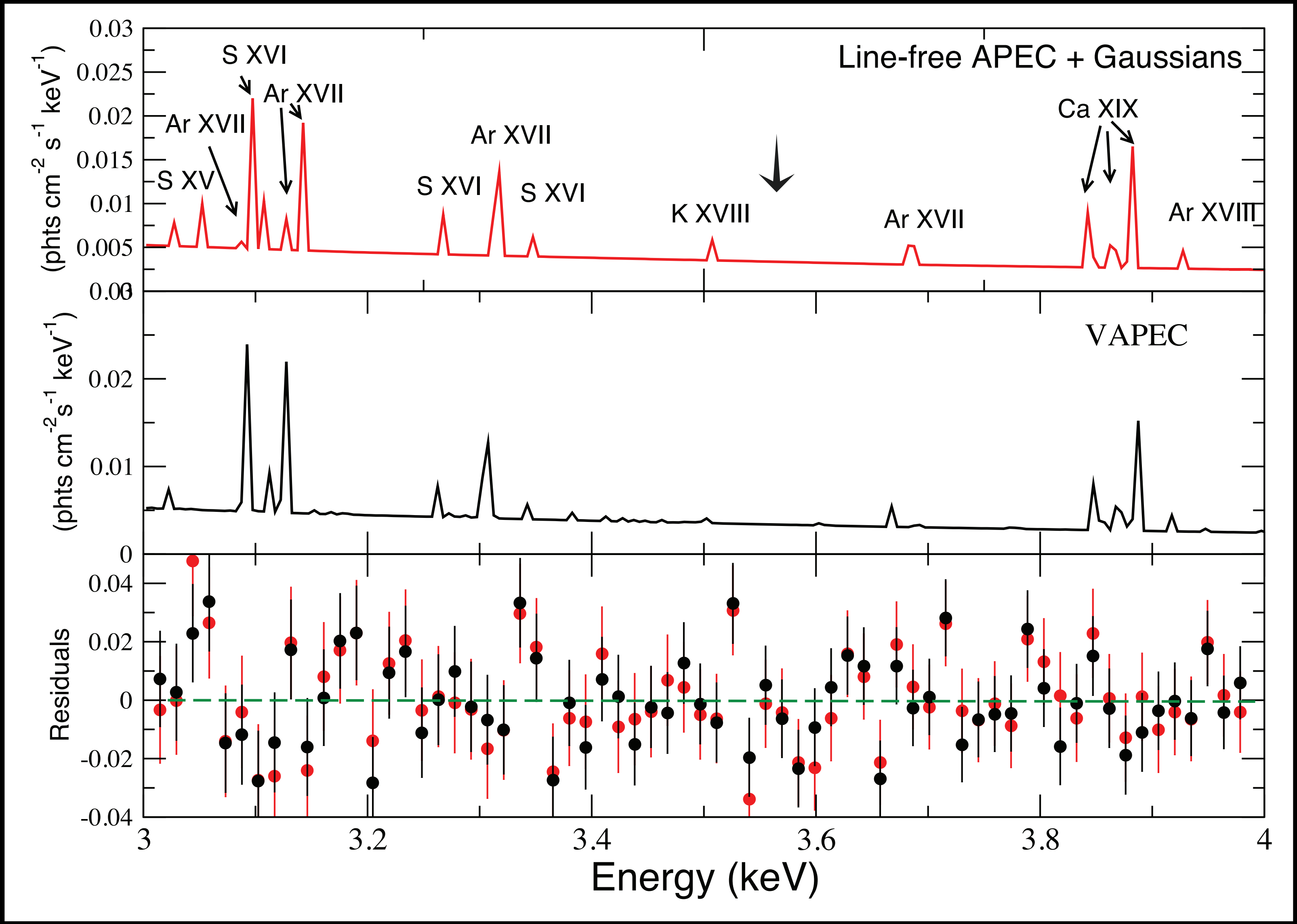
PN: distant subsample

ACIS-I: Perseus

Line is very faint – equivalent width $\sim$1 eV, or $\sim$1% bump over the continuum

at the limit of CCD detector capabilities

The crowded spectral interval



- CCD energy resolution: FWHM ~ 100 eV

Prediction for *Astro-H*