Gravitational Lensing of the Largest Scales

Maruša Bradač

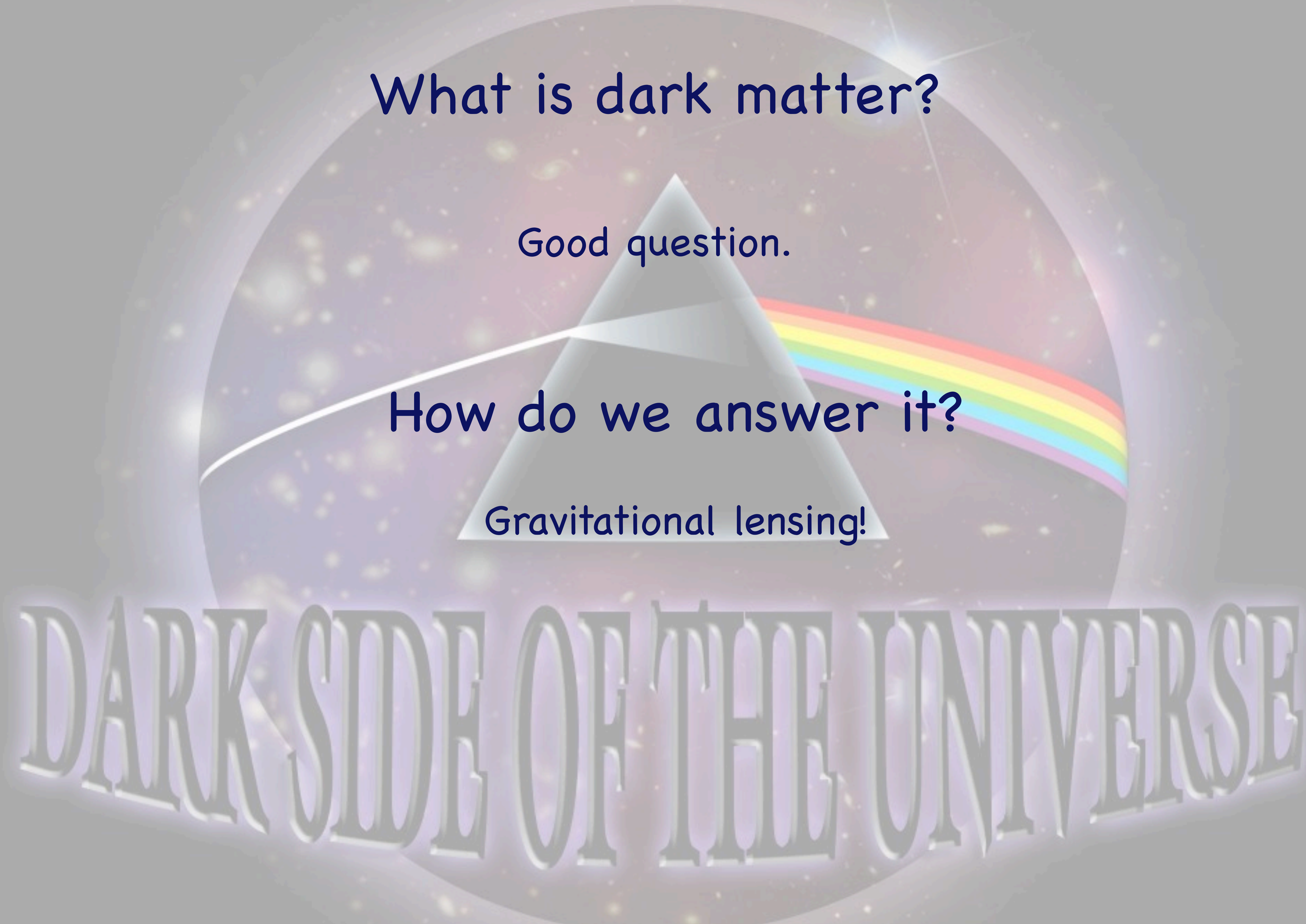
DARK SIDE OF THE UNIVERSE

What is dark matter?

Good question.

How do we answer it?

Gravitational lensing!



Why Clusters of Galaxies

* Because they are cool!!
* Studying empirical properties of dark matter
* Study the very tail of the mass function
* Great laboratory for studying the growth of structure -> dark matter and dark energy

Cluster mass reconstruction methods

* Simply parametrized:

  -> Simple, but limited

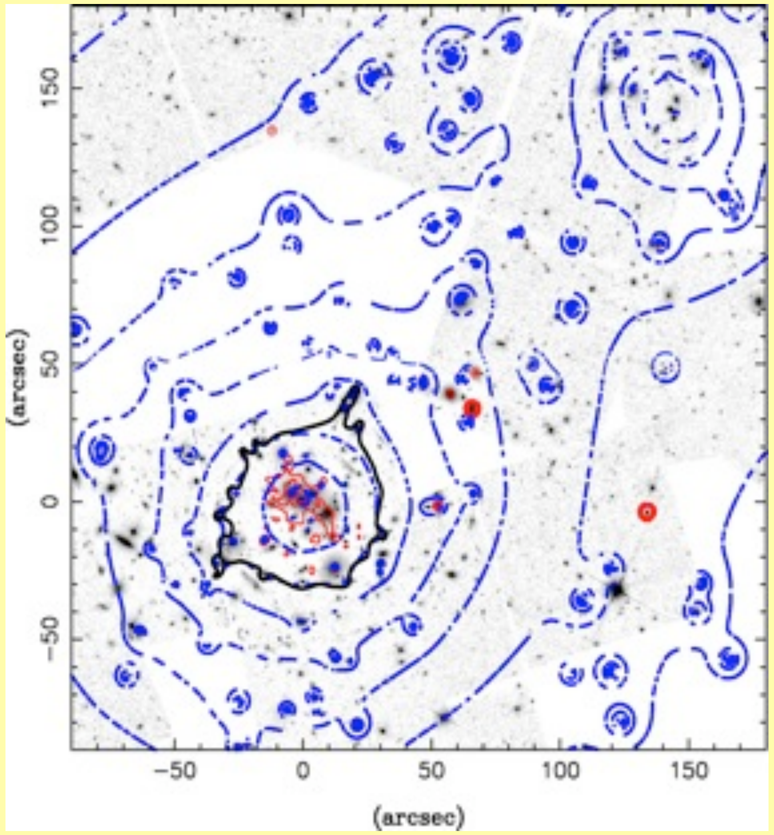
  -> Bayesian framework allows simple combinations of datasets and can be used to explore errors and degeneracies between parameters

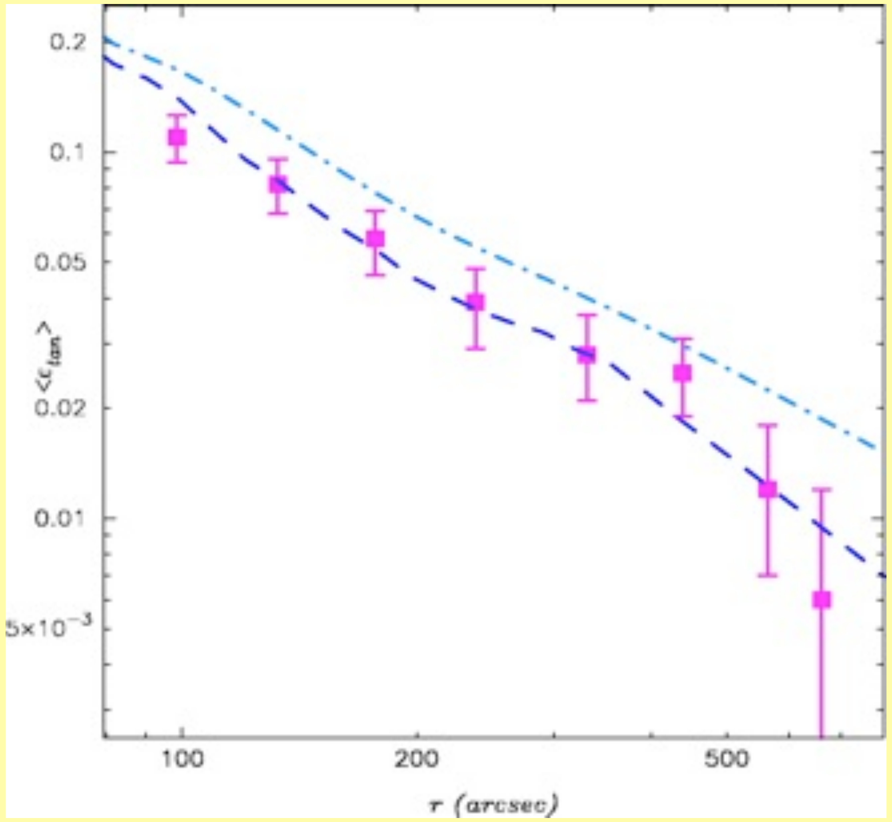
  -> LENSTOOL Kneib et al. 1993 - Jullo et al. 2007

  -> Natarajan et al. 1998 -> study galaxy properties

Cluster mass reconstruction methods

Strong + Weak Lensing: Cl0024 (Kneib et al. 2003)





With sparsely-sampled WFPC2 pointings, Kneib et al have measured the shear out to 5 Mpc.

A combined weak+strong lensing analysis indicates the density profile falls off like $\rho \propto r^{-n}$ with n>2.4.

Found a relatively high concentration parameter: c ~ 22

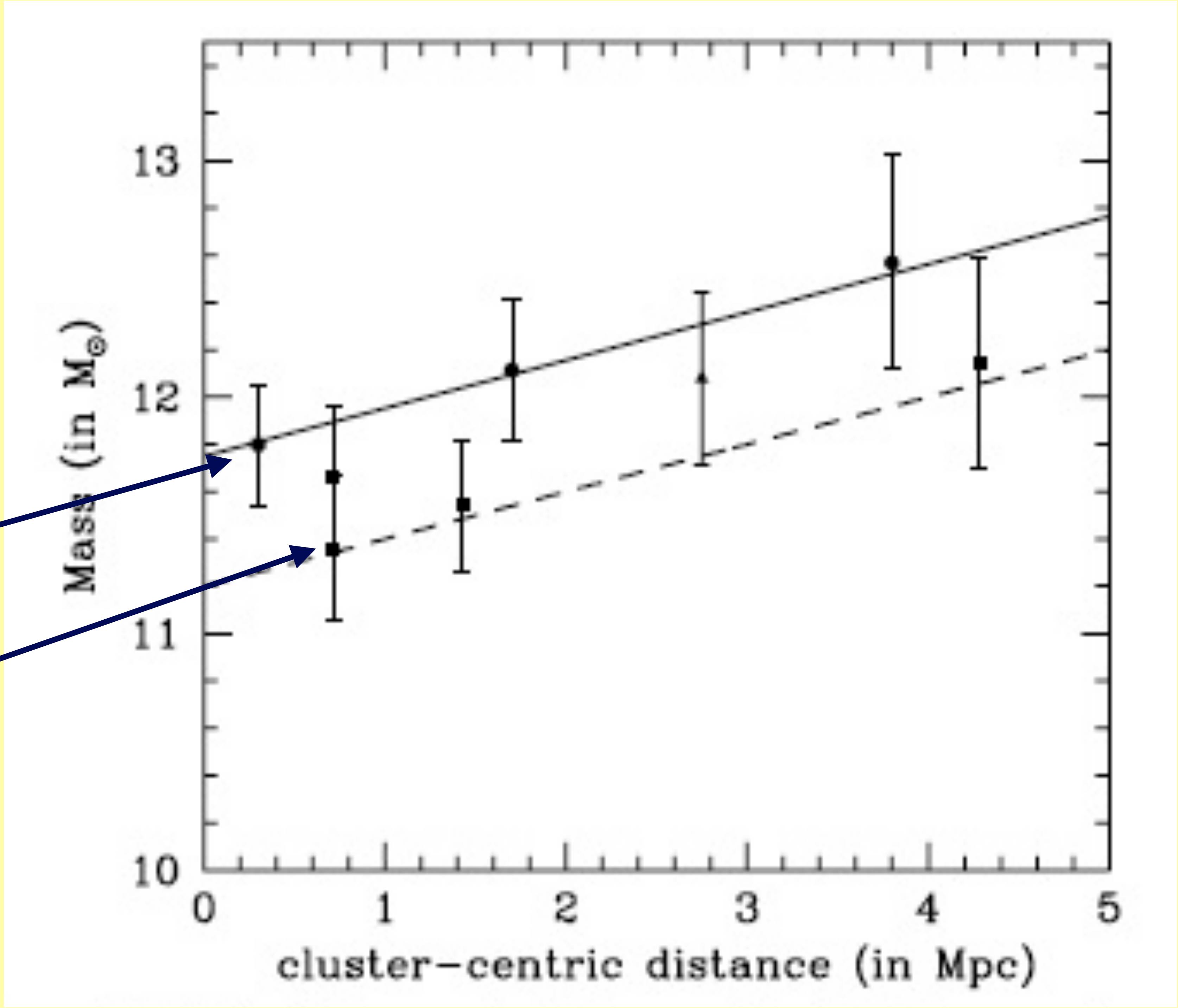
Cluster mass reconstruction methods

Cluster galaxies:

Mass of a halo that hosts an L* galaxy

Observations

Simulations



Natarajan et al. 2009

Cluster mass reconstruction methods

* Grid based

  -> Expect unexpected (the only way to explore merging clusters, maybe discover dark clumps)

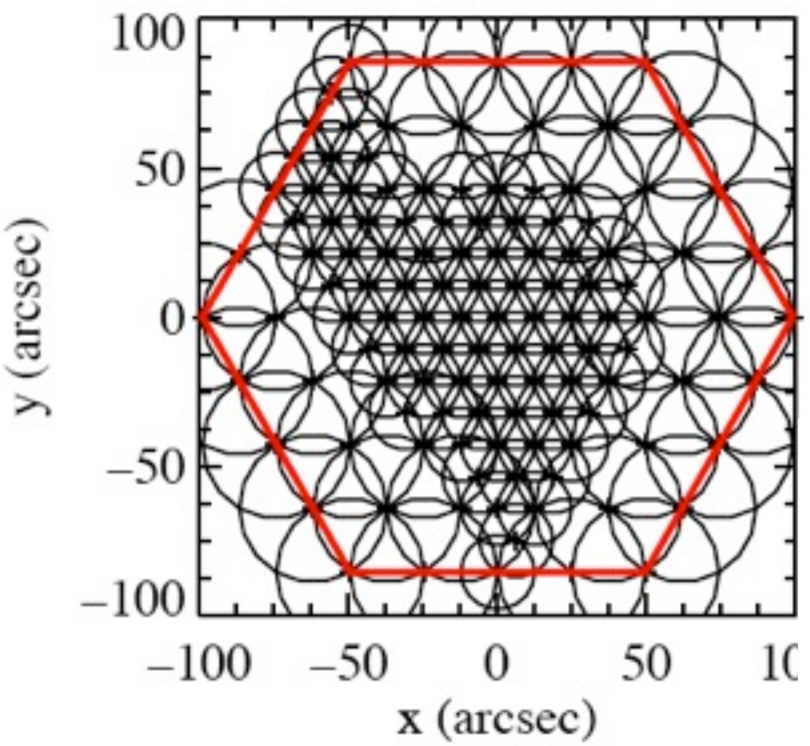
  -> Bayesian framework can be implemented, errors can be explored

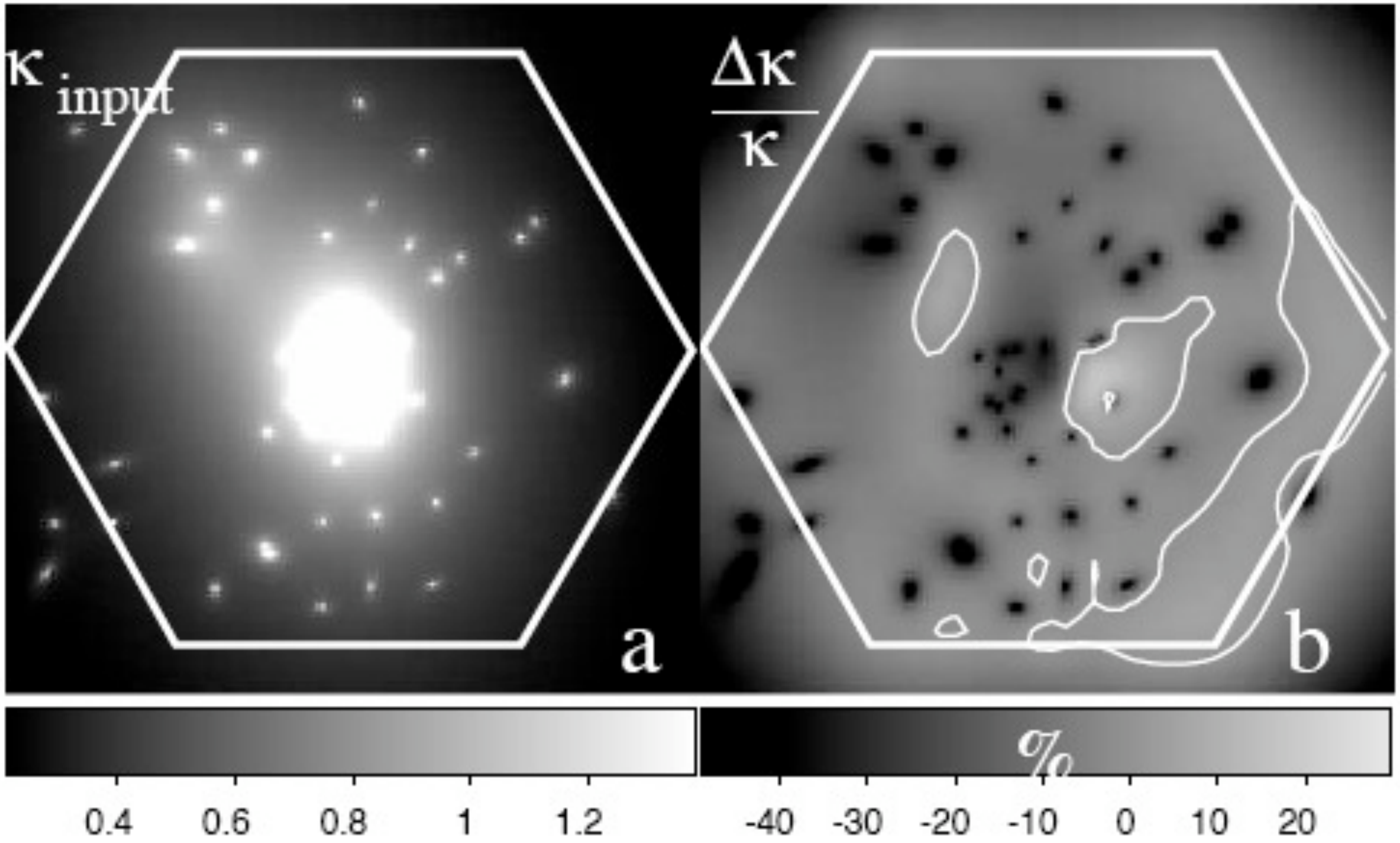
  -> Can be perfect (see D. Coe)

  -> Combination of observations possible (SL+WL Bradac et al. 2005)

  -> Multi-grid method

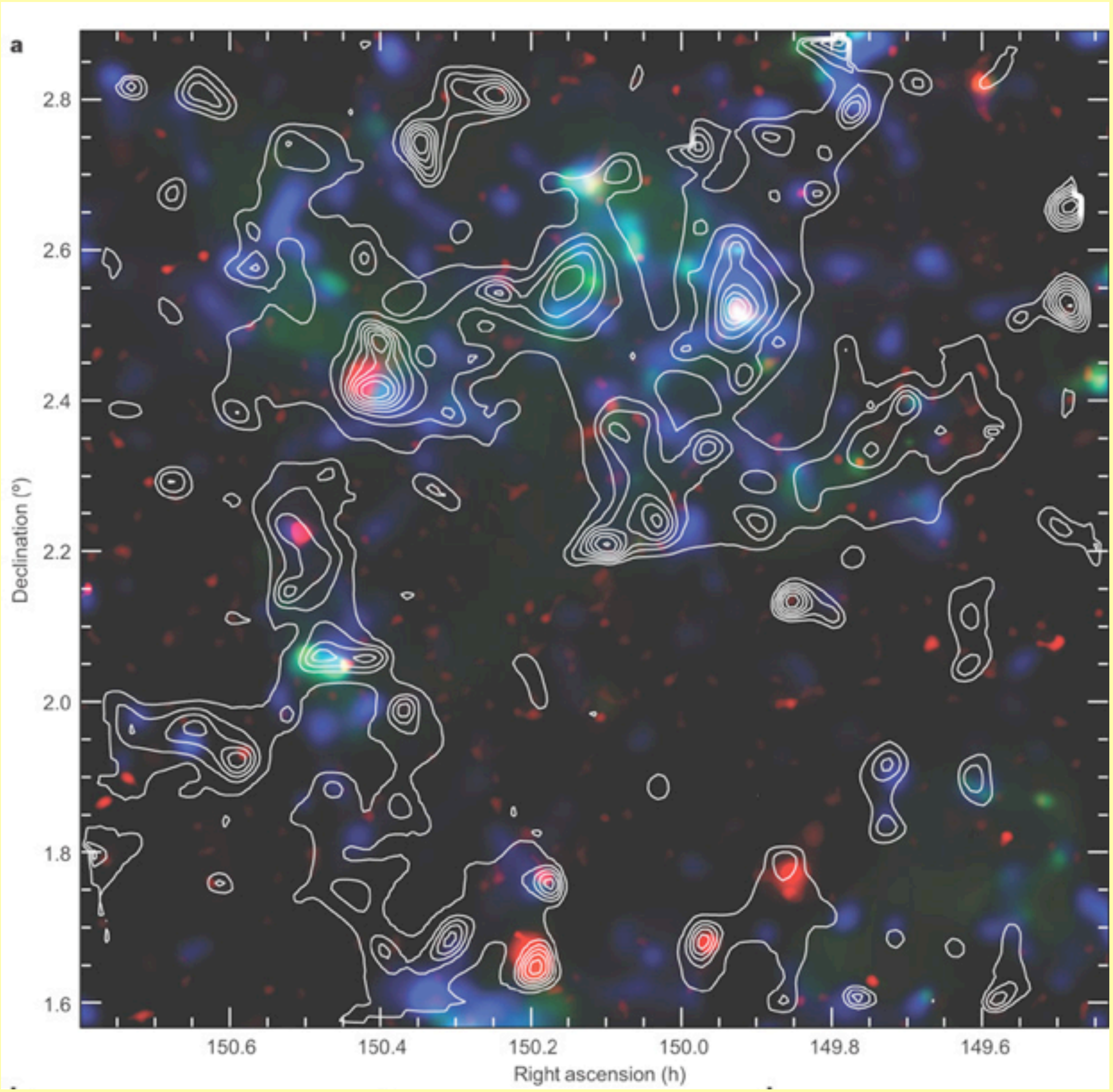
Cluster mass reconstruction methods





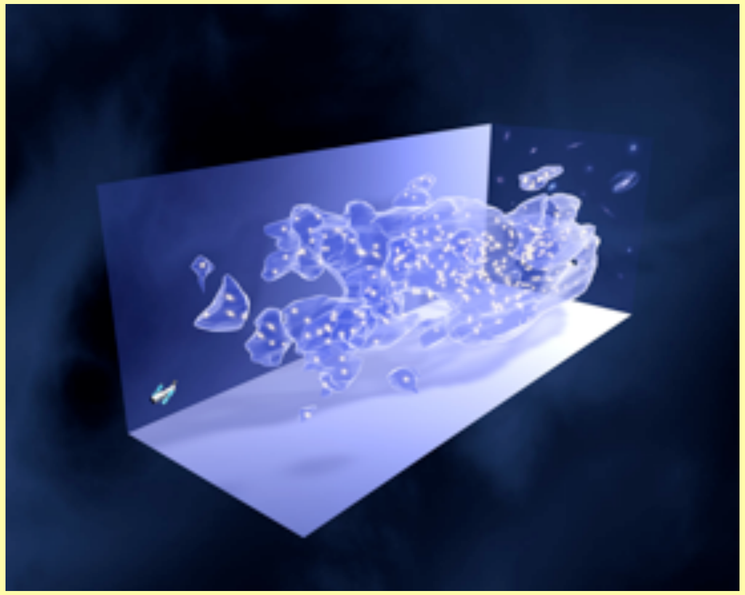
Jullo et al. 2008

Cluster mass reconstruction methods



Weak lensing (contours)

Stellar mass (blue)
galaxy density (yellow)
hot gas (red)



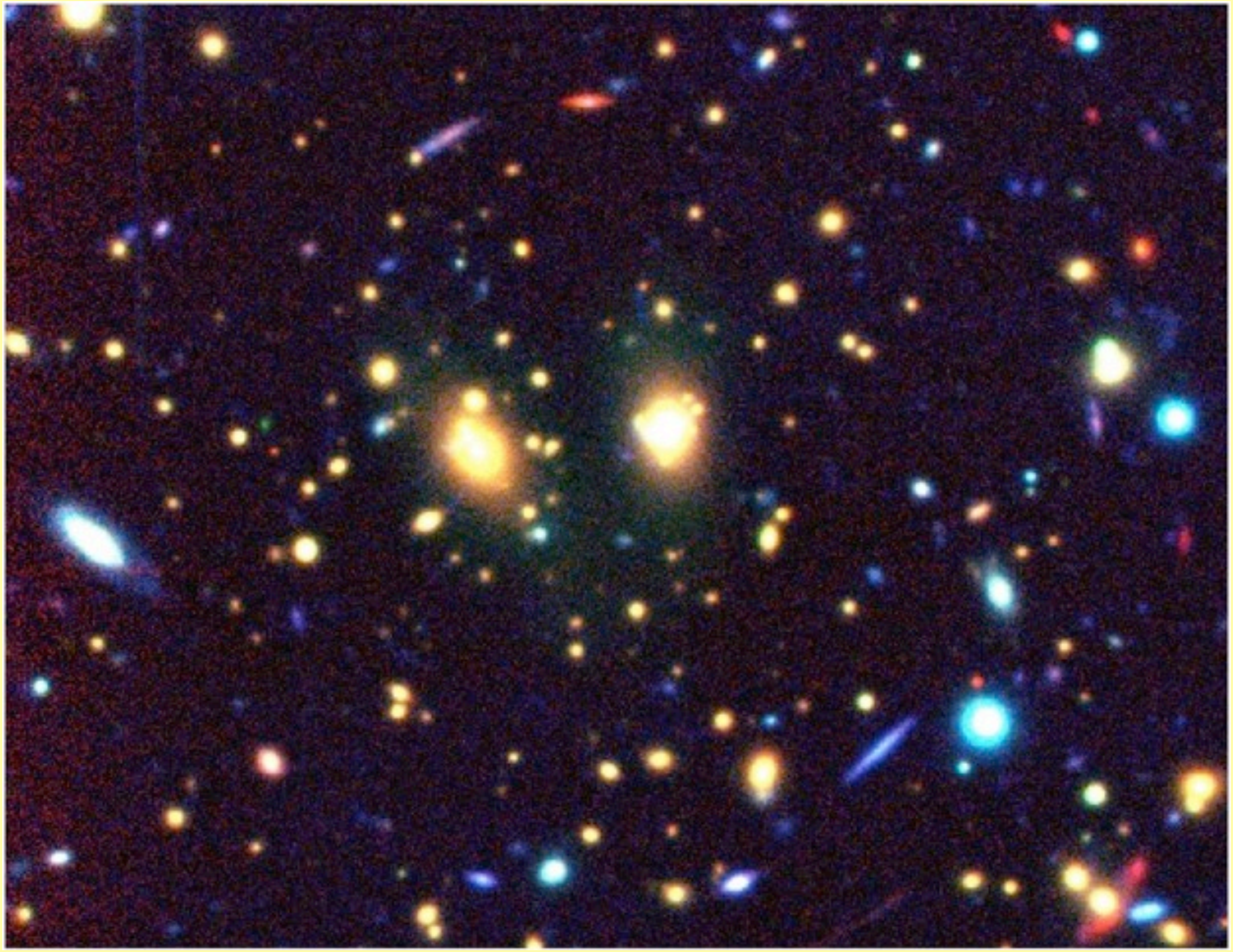
Massey et al. 2007

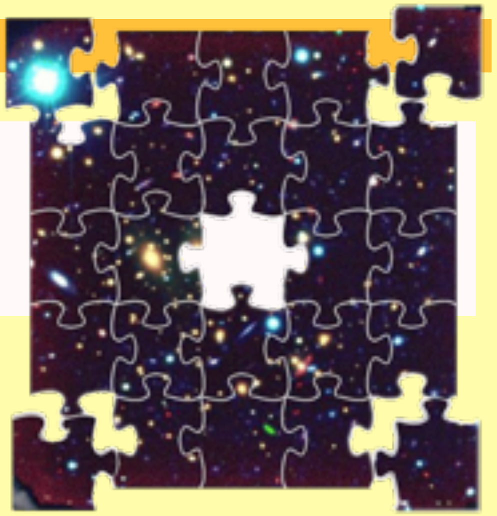
Dissecting galaxy clusters
Dark matter profile

RX J1347-1145

* One of the most luminous X-ray clusters known

* Post merger system





The Puzzle of RX J1347-1145

* Discovered by ROSAT, intrinsic bolometric X-ray luminosity

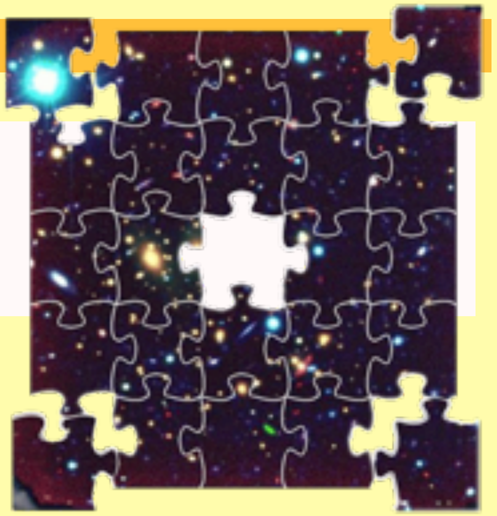
* $L_{bol} = 5\ 10^{45} h^{-2} erg s^{-1}$ from ASCA observations (Schindler et al. 1997 Schindler et al.1997)

* Large discrepancies between different mass estimates

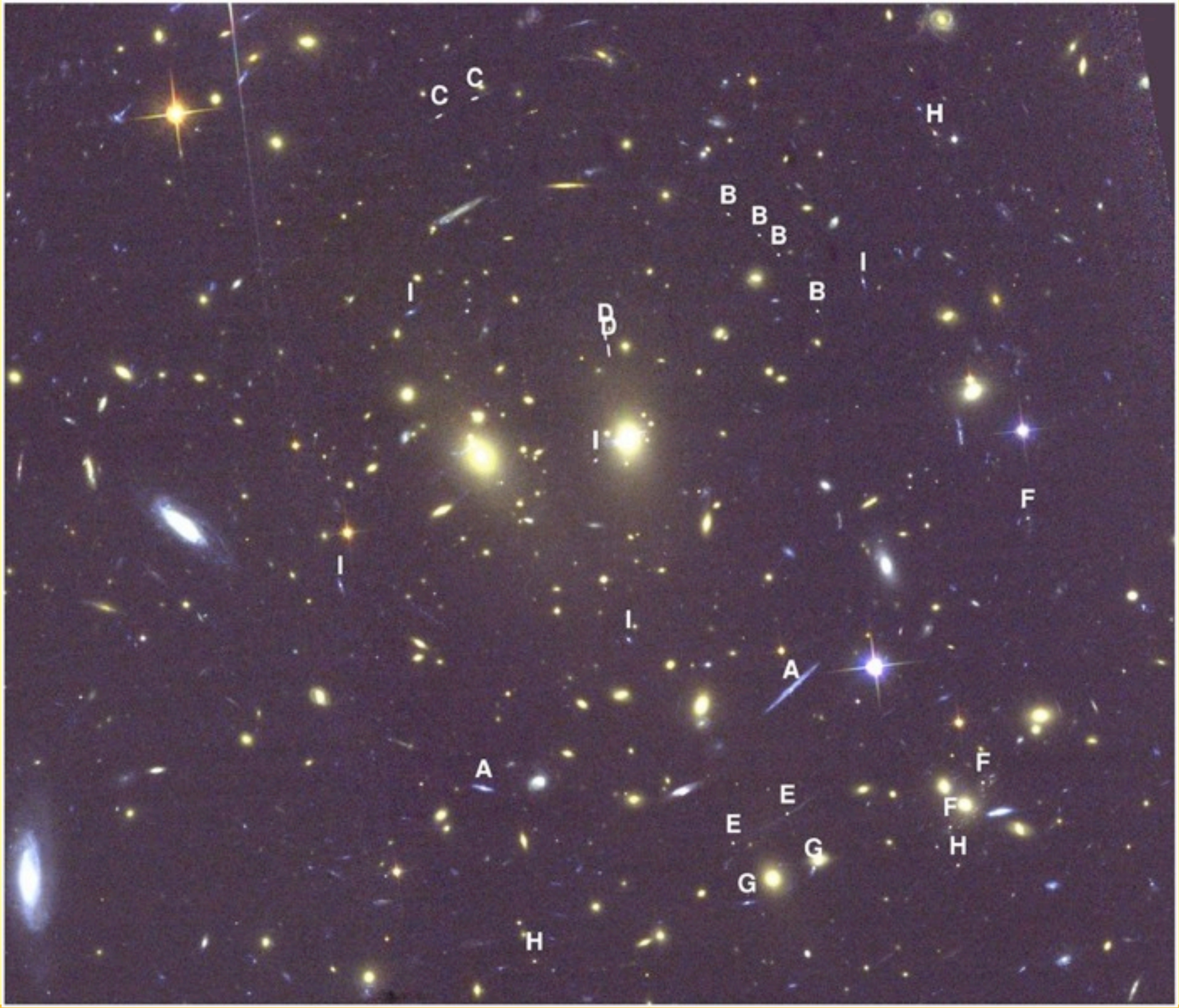
  ->Mdyn < Mstrong < Mweak ≅ MX - a factor of 3 between them.

  ->Ms+w ≅ MX (Bradač et al. 2005a)

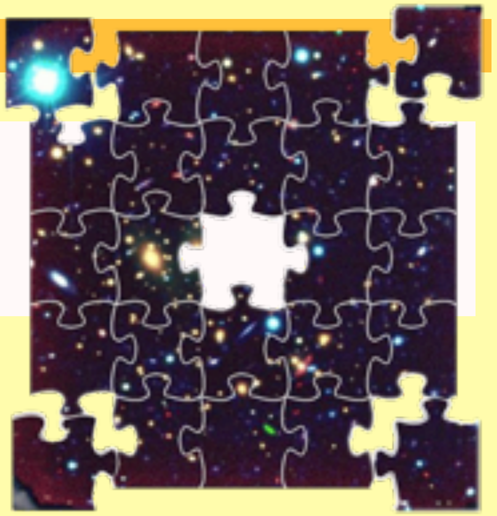
* New space based (ACS-HST) data (in addition VLT-FORS multicolour data in UBVRI bands, Ks band from ISAAC).



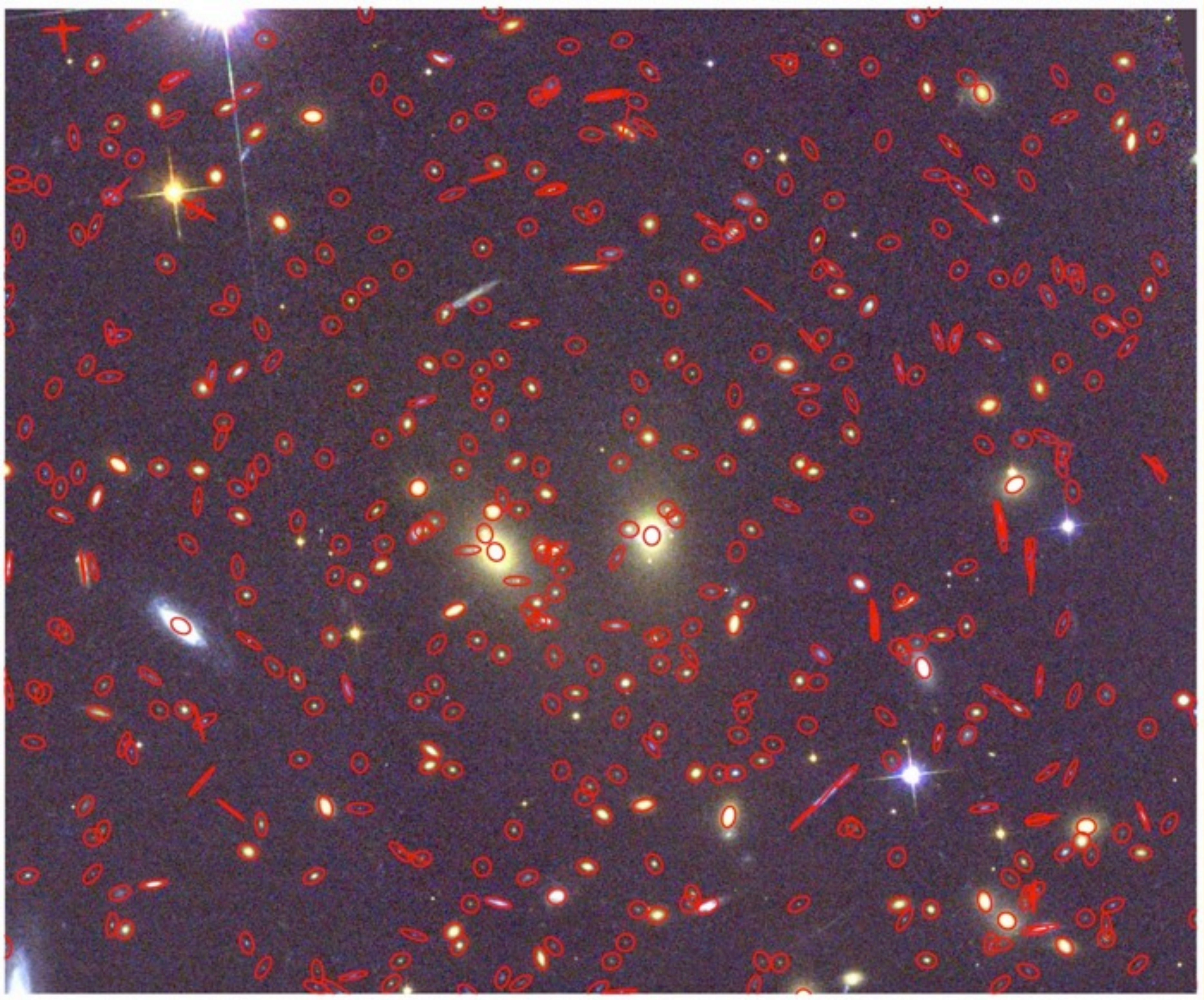
RX J1347-1145



Bradač et al. 2008

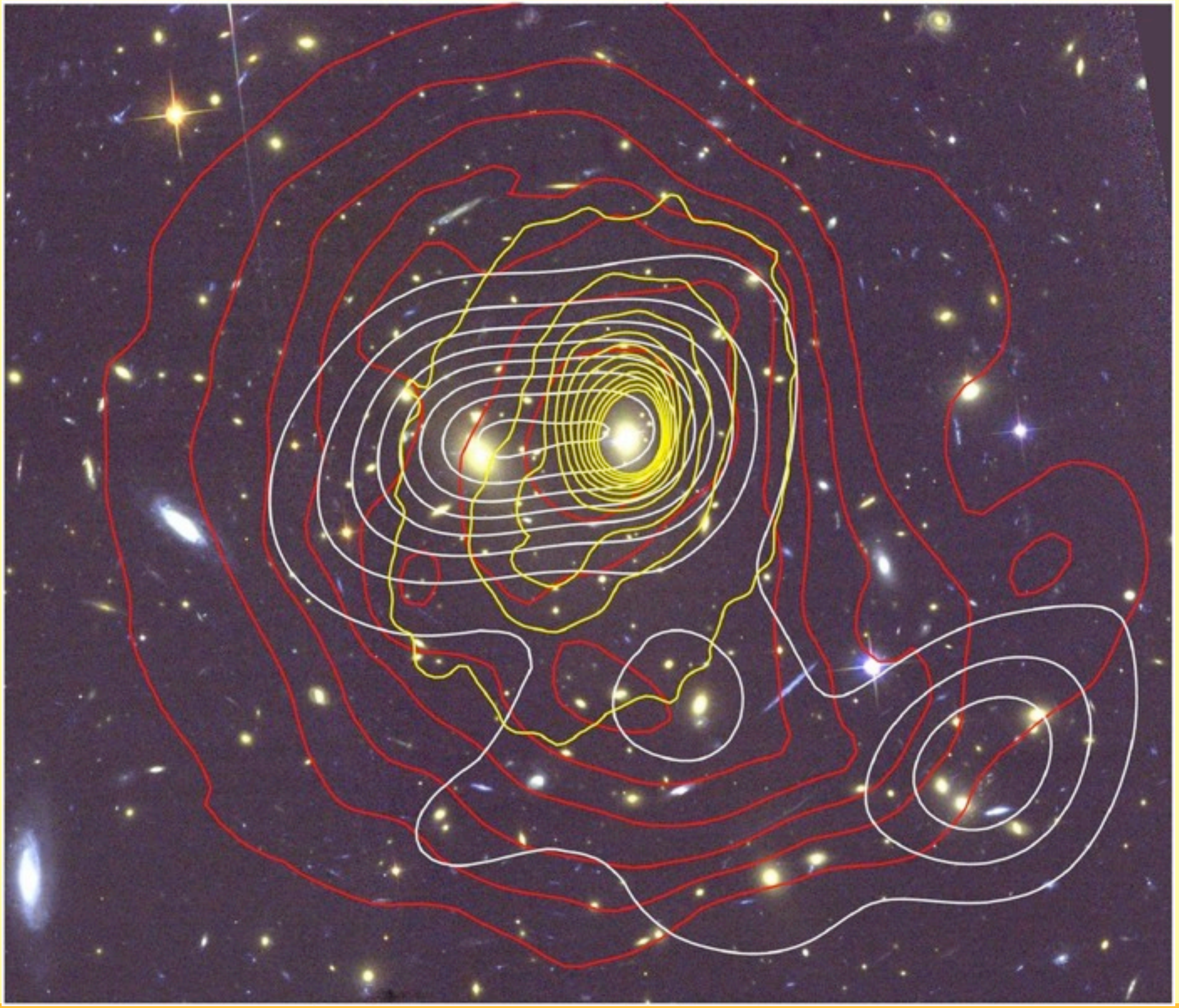


RX J1347-1145



Bradač et al. 2008

RX J1347-1145



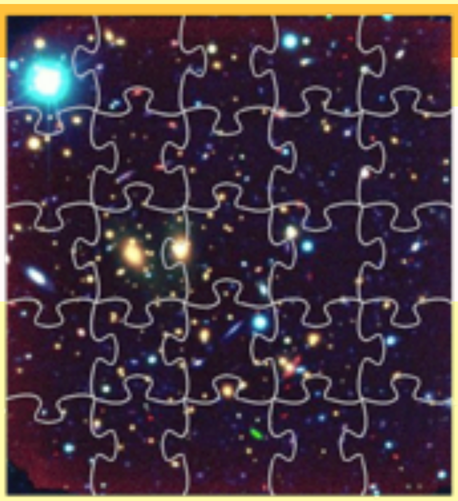
Total mass

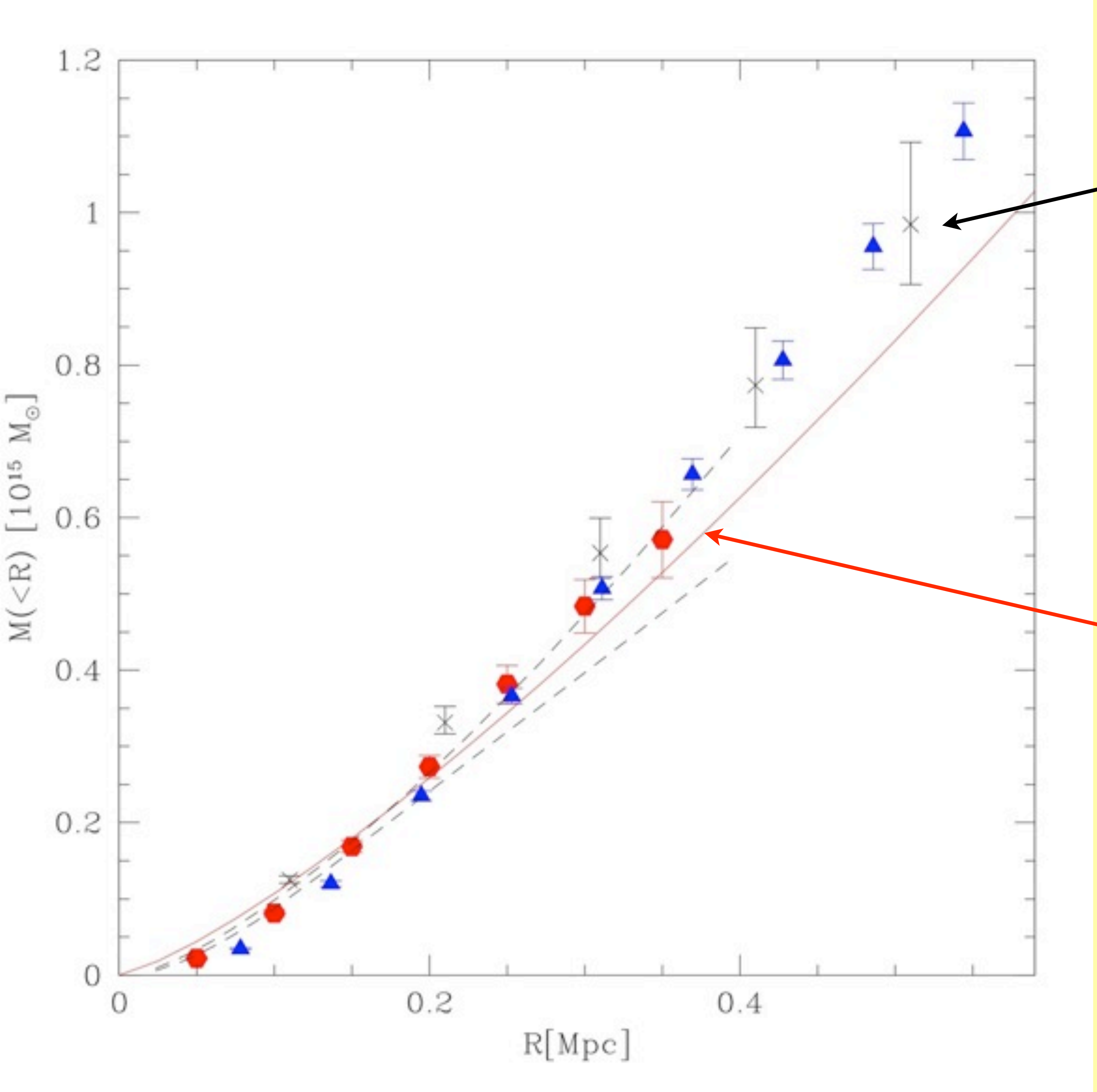
Gas

Stars

Bradač et al. 2008

RX J1347-1145 Mass Estimates





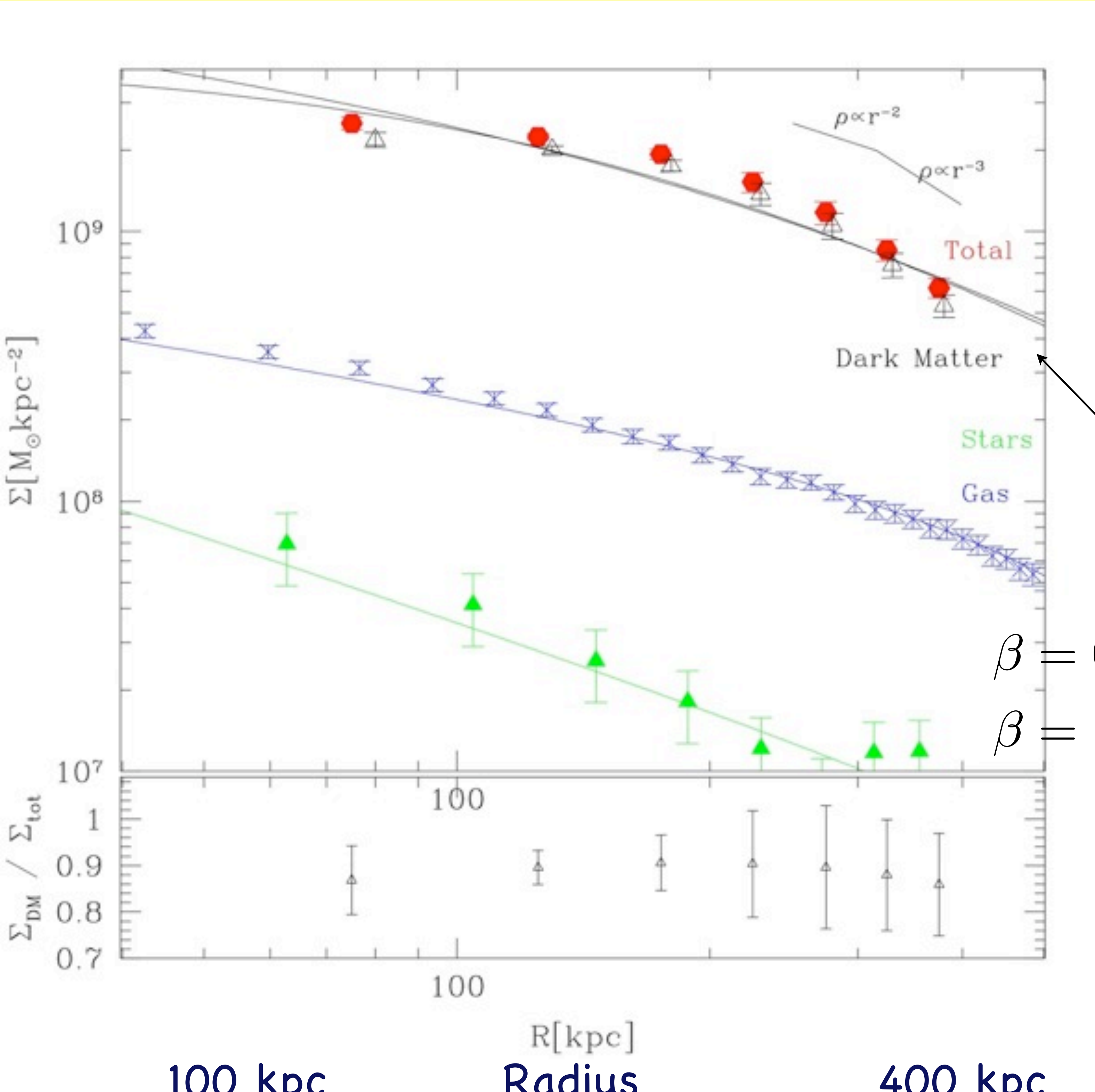
Xray

Strong+weak lensing

Bradač et al. 2008

Dissecting RX J1347-1145

Projected surface mass desity



Bradač et al. 2008

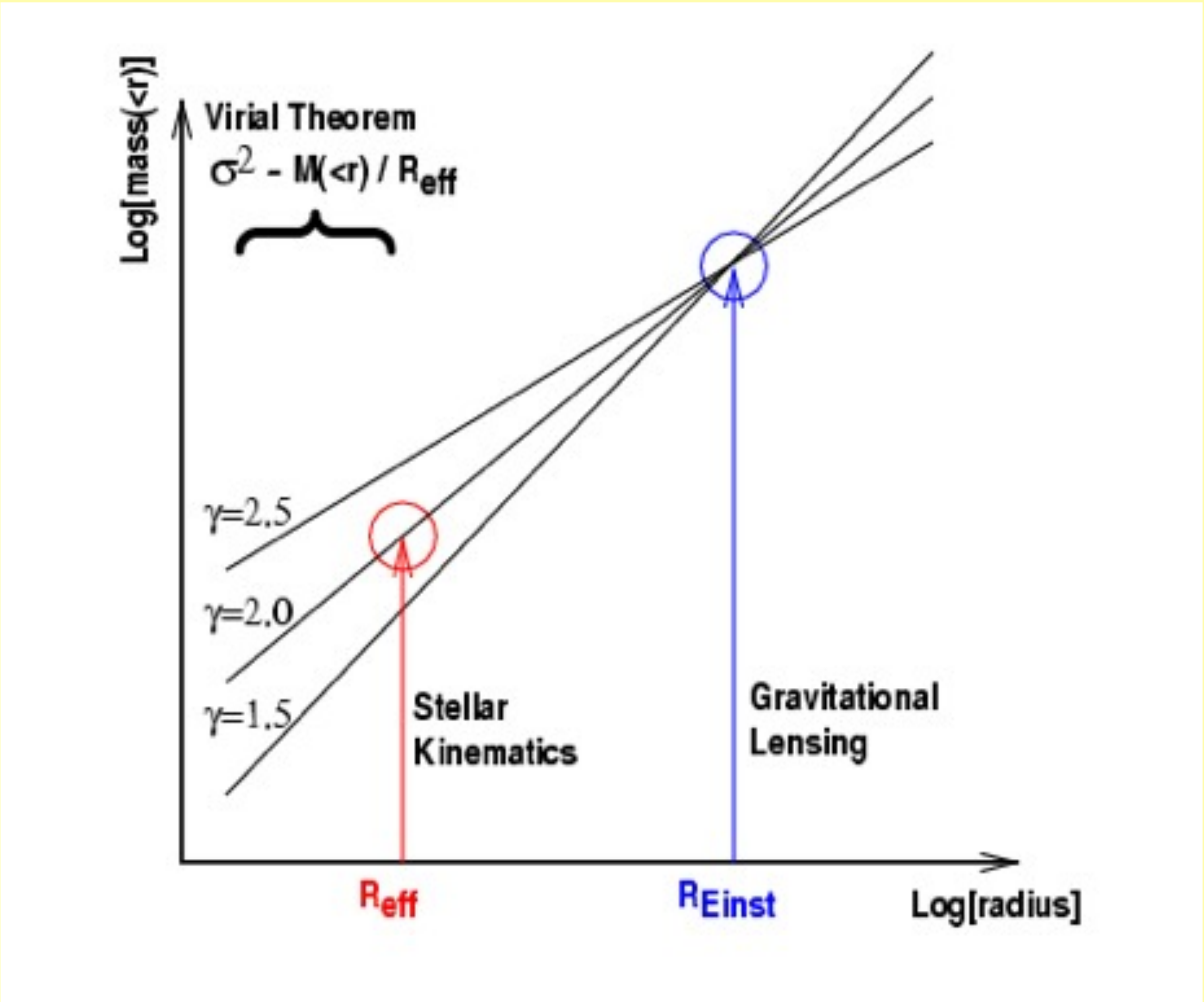
Fitting NFW profile to dark matter

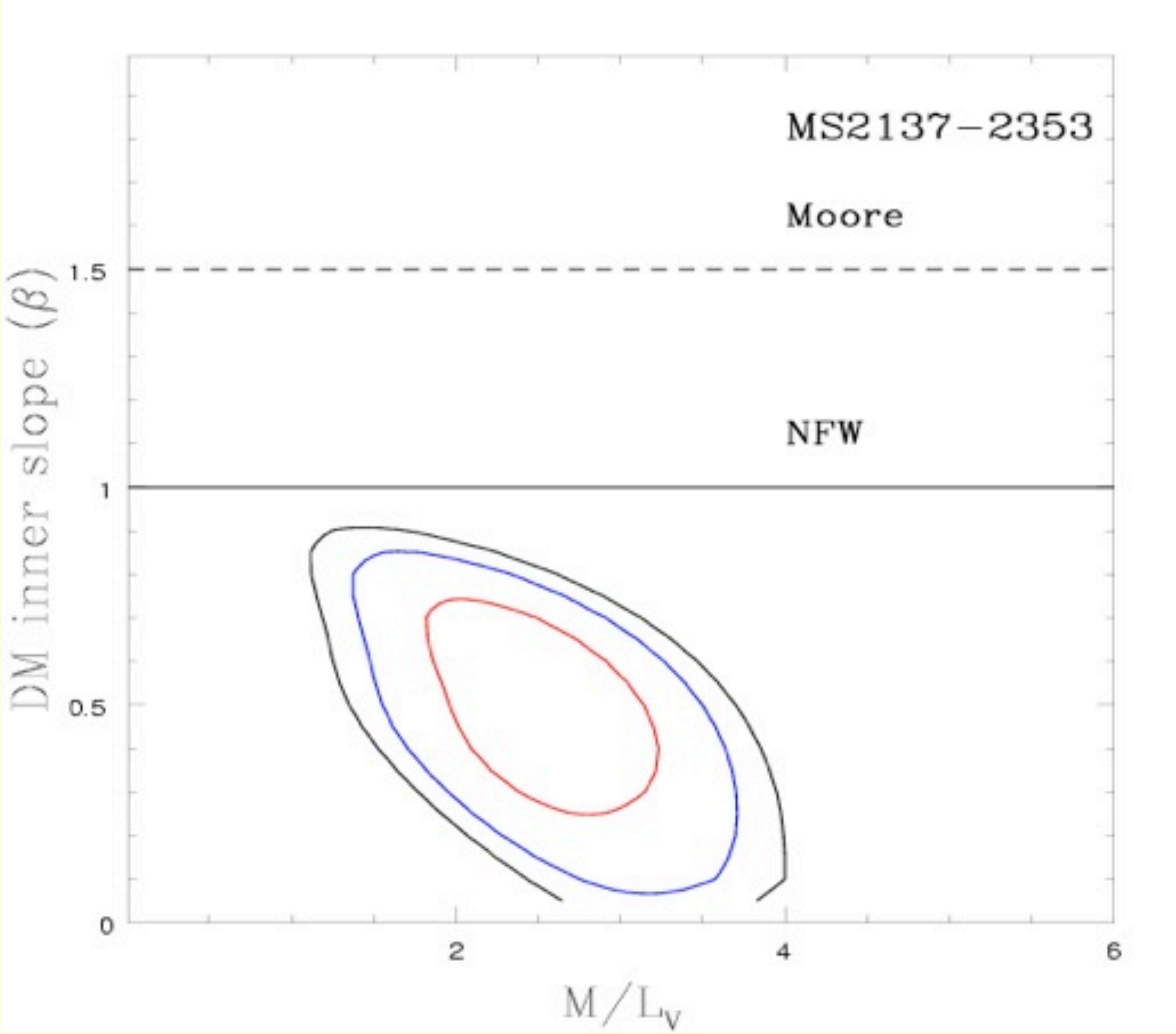
$$\rho_{\rm DM}(r) = \frac{\rho_{0,\rm DM}}{(r/r_{\rm s})^{\beta}(1+r/r_{\rm s})^{3-\beta}}$$

$$\beta = 0 \quad c_{200} = 15 \quad r_{200} = 2400\ \mathrm{kpc}$$

$$\beta = 1 \quad c_{200} = 6 \quad r_{200} = 2200\ \mathrm{kpc}$$

Cluster mass reconstruction methods





Constraints on Inner Slope with observationally motivated prior of r_{sc} =100-200 kpc

Sand et al 2008

Dissecting galaxy clusters

* Great way to probe dark matter profiles
* Analyses underway to include strong+weak+dynamics
* Need large sample of clusters, uniformly analysed

The Nature of Dark Matter
The Bullet Cluster
1E0657-56

The Bullet Cluster 1E0657-56

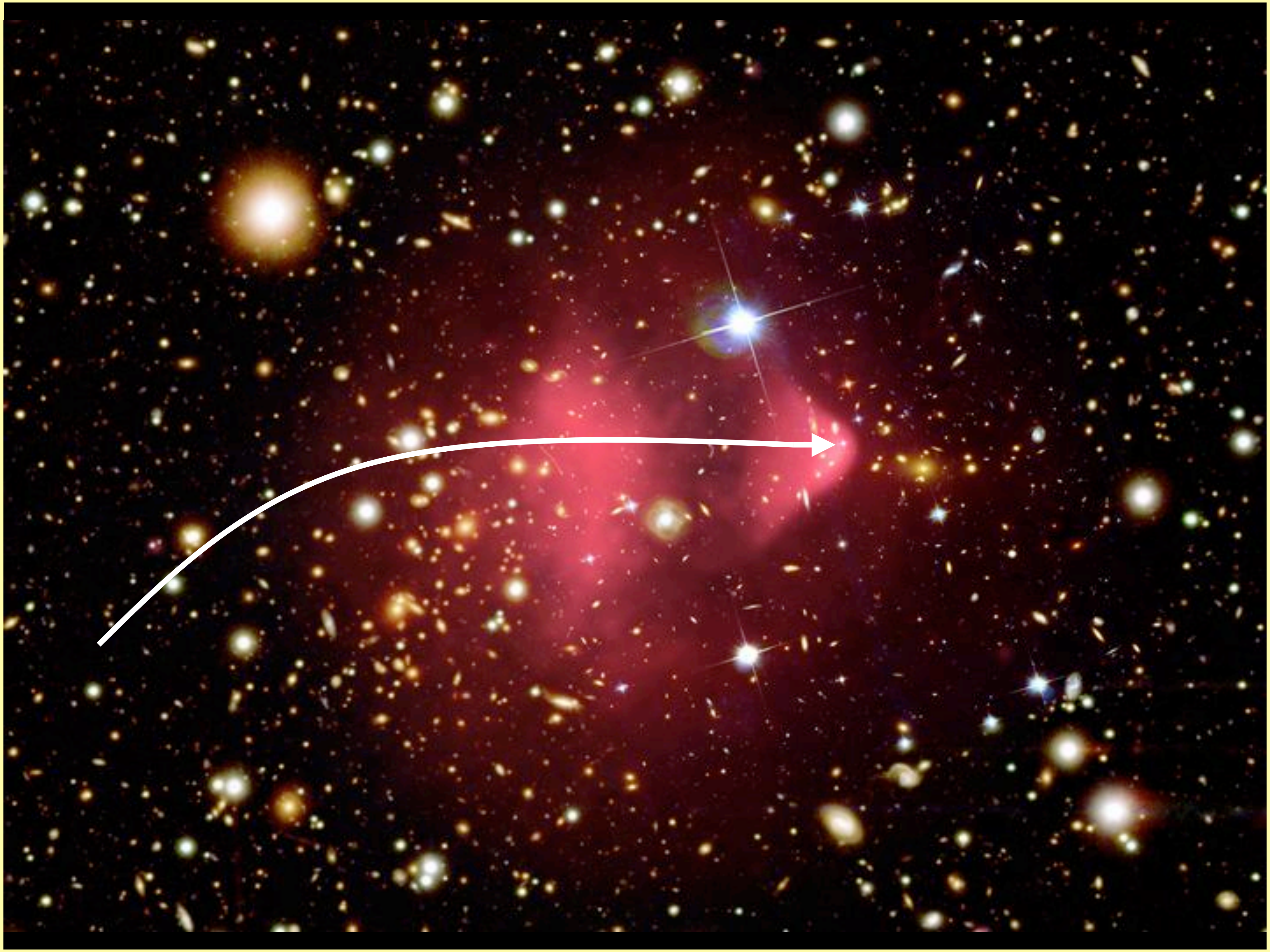
* One of the hottest and most luminous X-ray clusters known.

* Unique case of a major supersonic cluster merger occurring nearly in the plane of the sky ($i < 15°$, Markevitch et al. 2002).

* Using the gas density jump at the shock we derived a shock Mach number of 3.2 ± 0.8, which corresponds to a shock velocity 4500 ± 1000 kms^{-1}

* Subcluster velocity $\sim$2700 kms^{-1} (Springel & Farrar 2007)

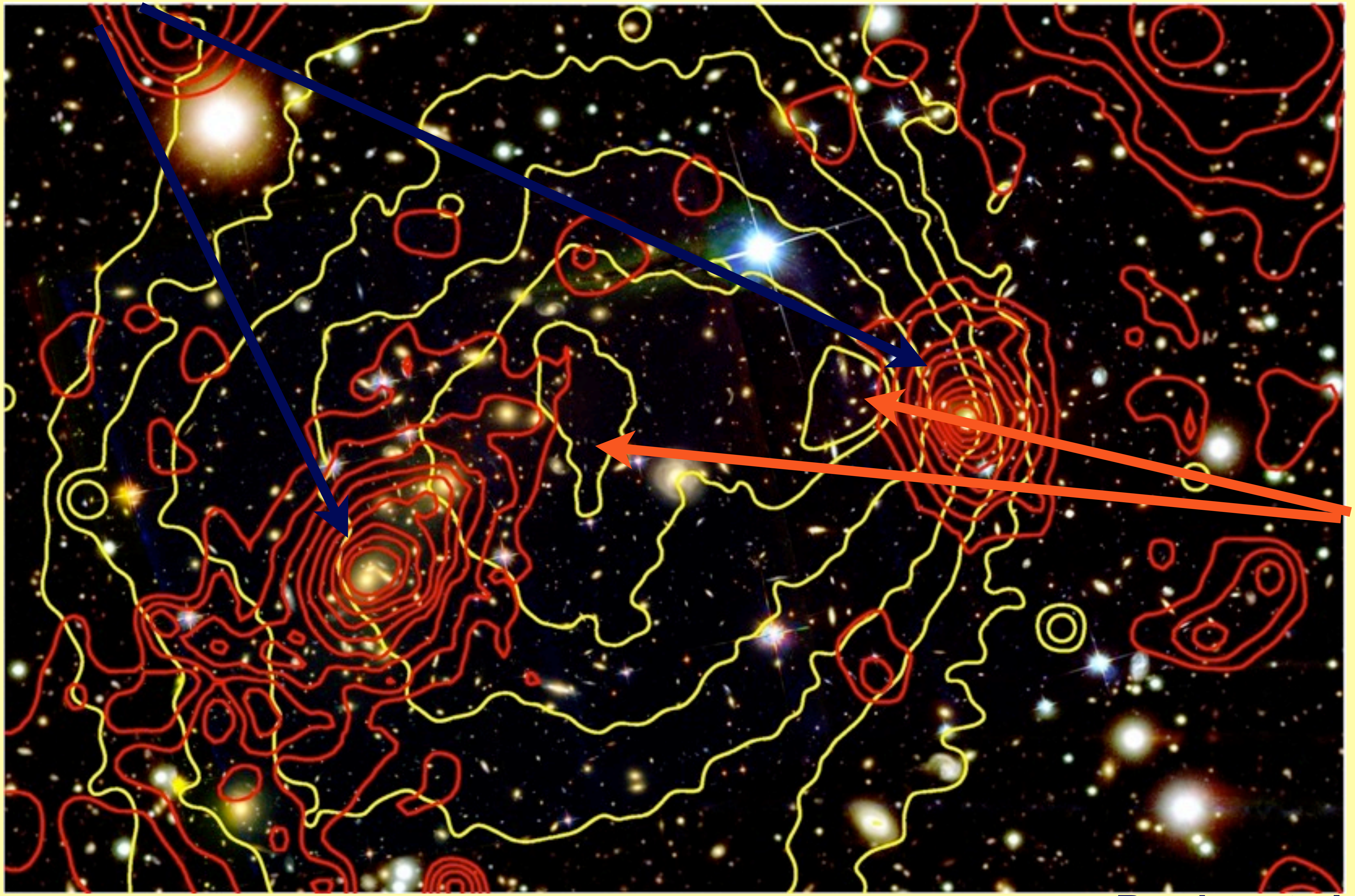
The Bullet Cluster 1E0657-56



Gravitational Lensing

1E0657-56: Strong and Weak Lensing

Total Matter

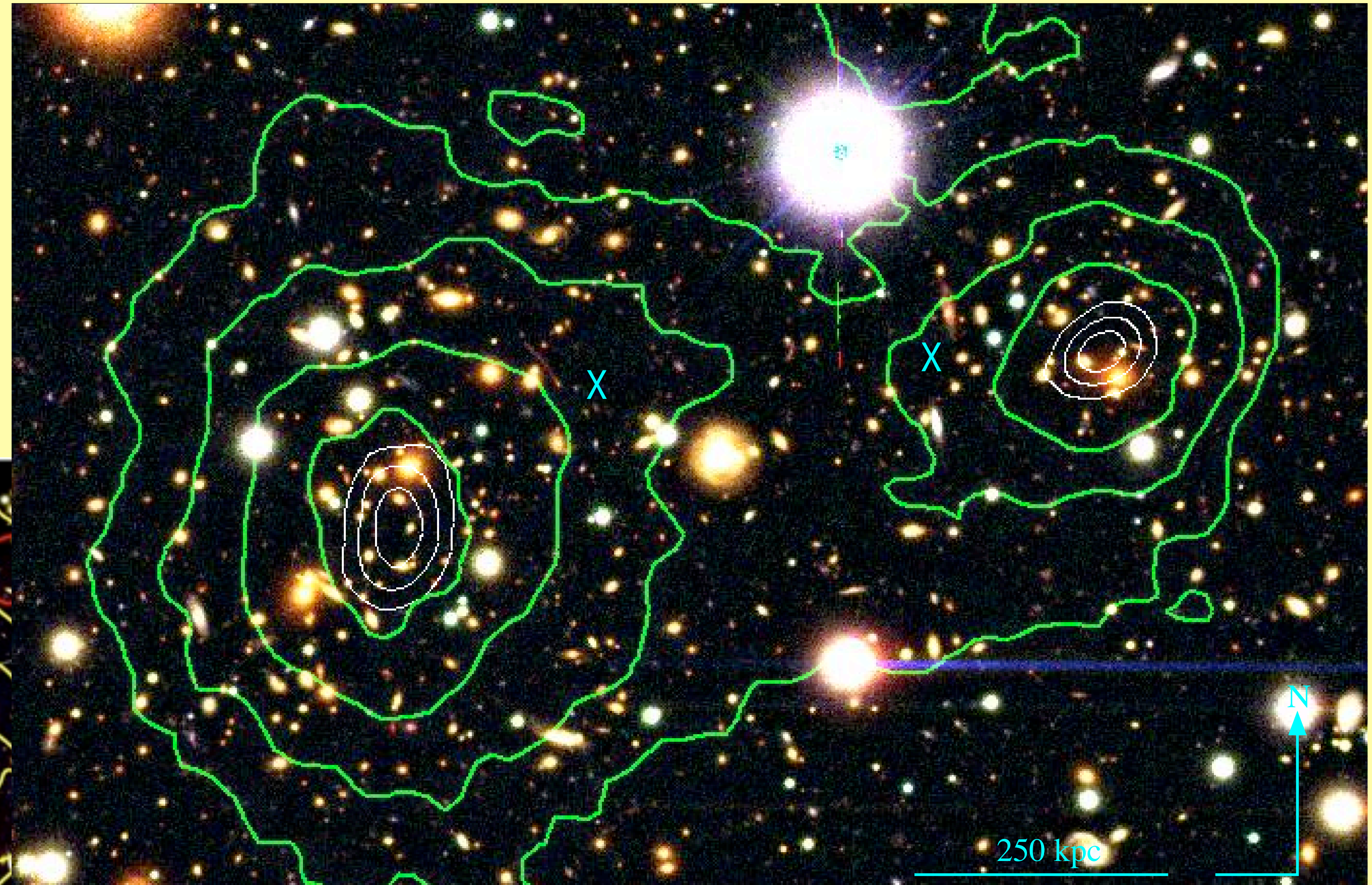


Gas

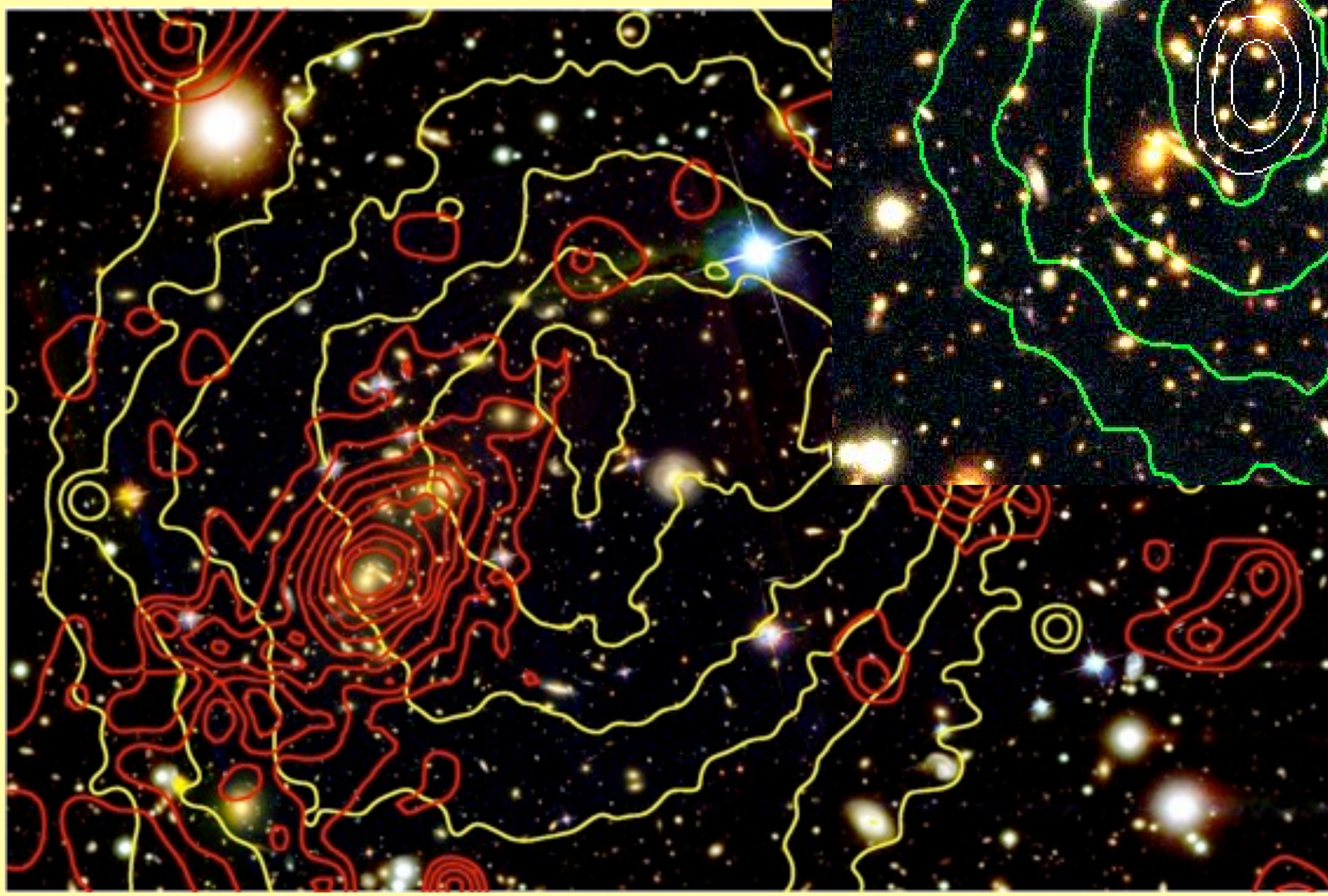
Bradač et al. 2009

1E0657-56: Strong and Weak Lensing

Only weak lensing



Strong and weak lensing

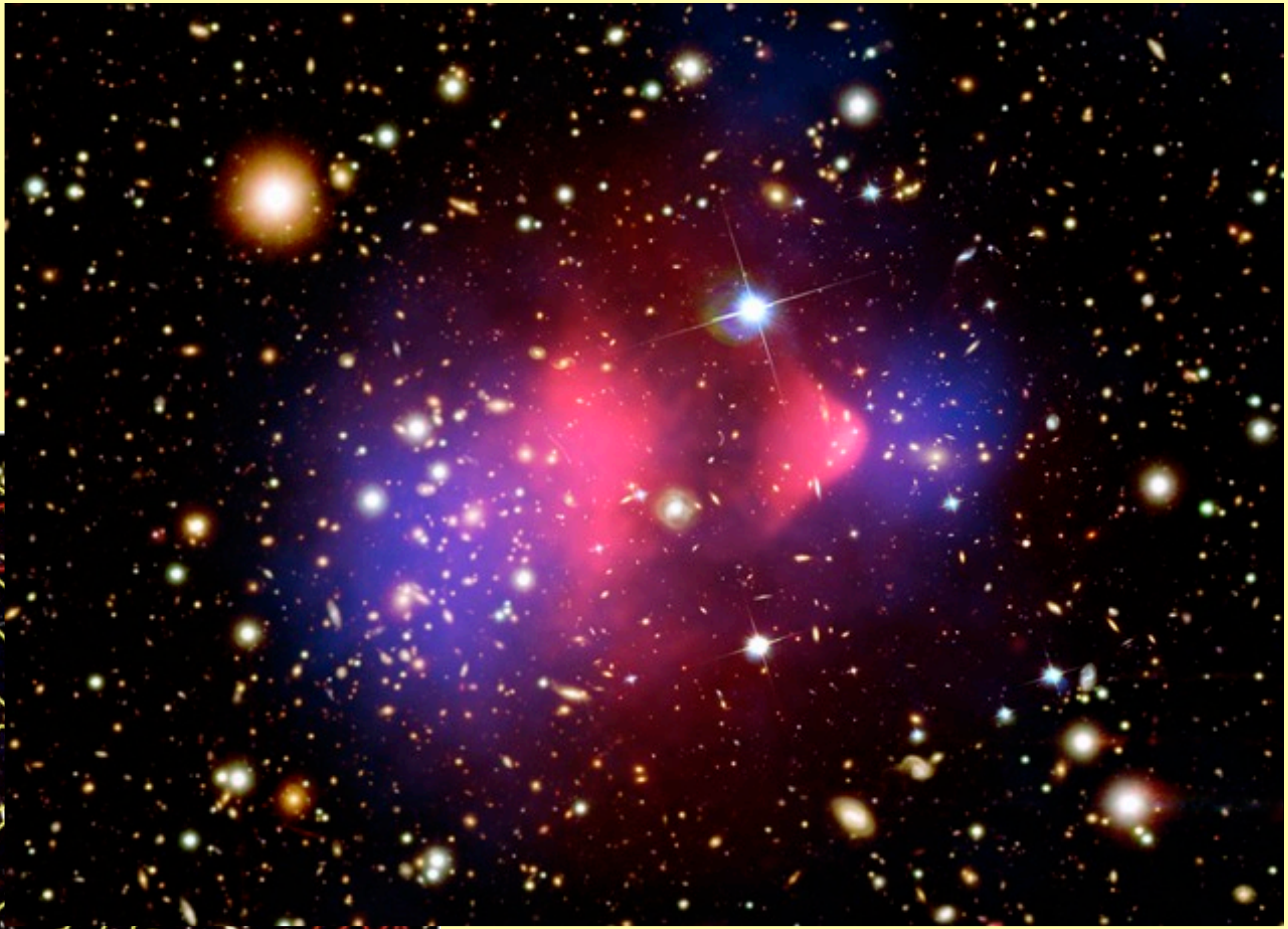


Clowe, MB et al. 2006

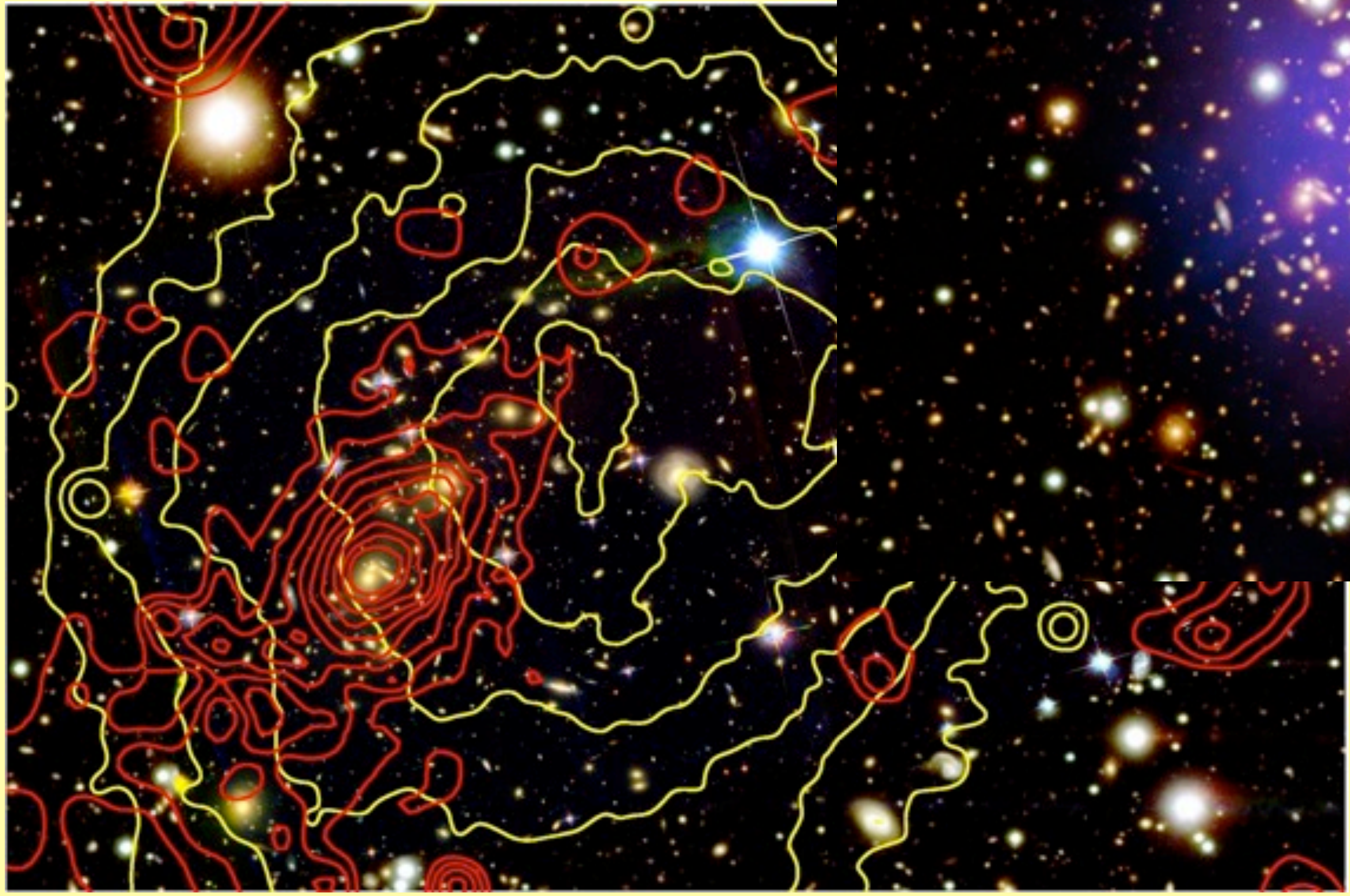
Bradač et al. 2009

1E0657-56: Strong and Weak Lensing

Only weak lensing



Strong and weak lensing



Clowe, MB et al. 2006

Bradač et al. 2009

Dark Matter Properties

* Combining the Chandra data with lensing mass maps -> place an upper bound on the dark matter self-interaction cross section $\sigma/m < 1\ \mathrm{cm^2 g^{-1}}$ = 1.8barn/GeV (Markevitch et al. 2004).

  -> Significant offset between subcluster X-ray gas core and dark matter peak gives $\sigma/m < 10\ \mathrm{cm^2 g^{-1}}$

  -> Survival of the subcluster dark matter peak during interaction gives $\sigma/m < 3\ \mathrm{cm^2 g^{-1}}$

  -> No loss of mass from subcluster during interaction gives $\sigma/m < 0.8\ \mathrm{cm^2 g^{-1}}$

* $\sigma/m < 0.7\ \mathrm{cm^2 g^{-1}}$ = 1.3barn/GeV (Randall et al.2008)

* SI dark matter $\sigma/m < 0.5 - 5\mathrm{cm^2 g^{-1}}$ (Davé et al. 2001).

Really Direct Evidence for Dark Matter?

* Adopting MOND gravity:

  ->Angus et al. (2006) - Can fit weak lensing surface mass density predictions with gas+2eV Neutrino model

  ->Still require > 70% of the mass to be hot non-baryonic matter

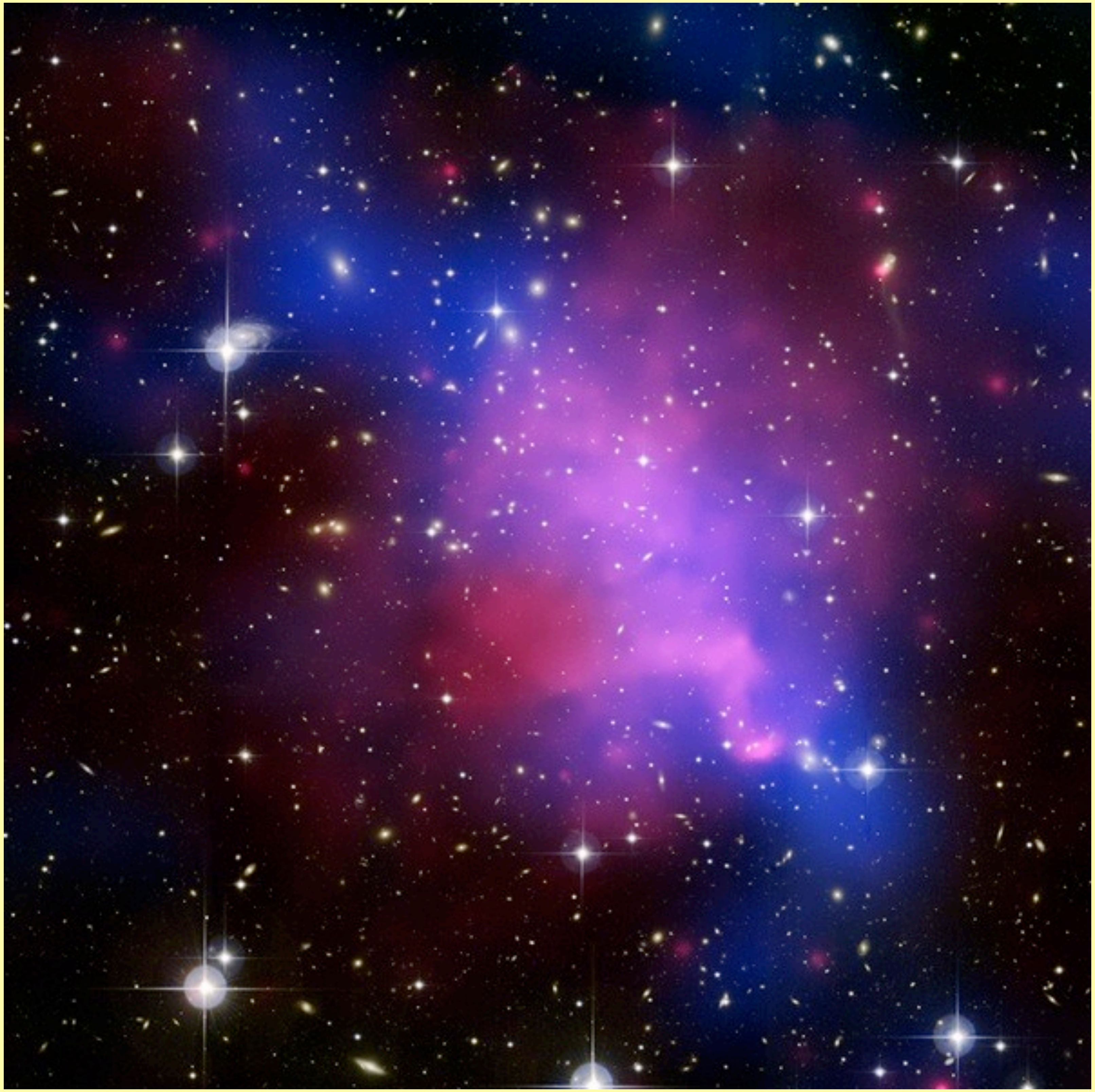
  ->Incompatible with strong+weak lensing analysis.

  ->Gas mass too low for the subcluster.

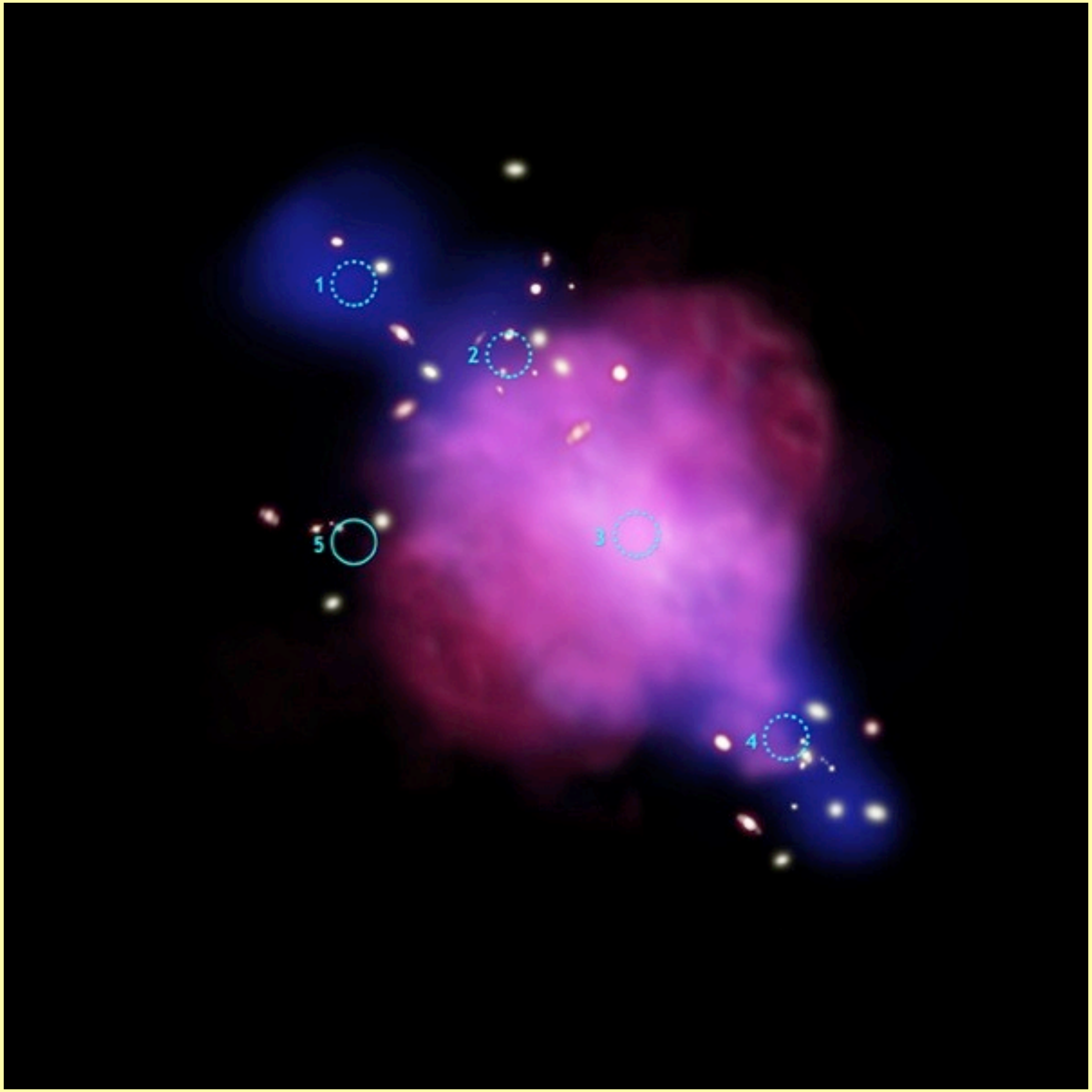
* Moffat (2006) - MOG to displace surface mass density peaks away from gas peaks - very unphysical profile.

The Nature of Dark Matter
Really collision-less?
Cosmic Train Wreck A520

A520 - Cosmic "Train Wreck"



A520 - Cosmic "Train Wreck"



A520 - Cosmic "Train Wreck"

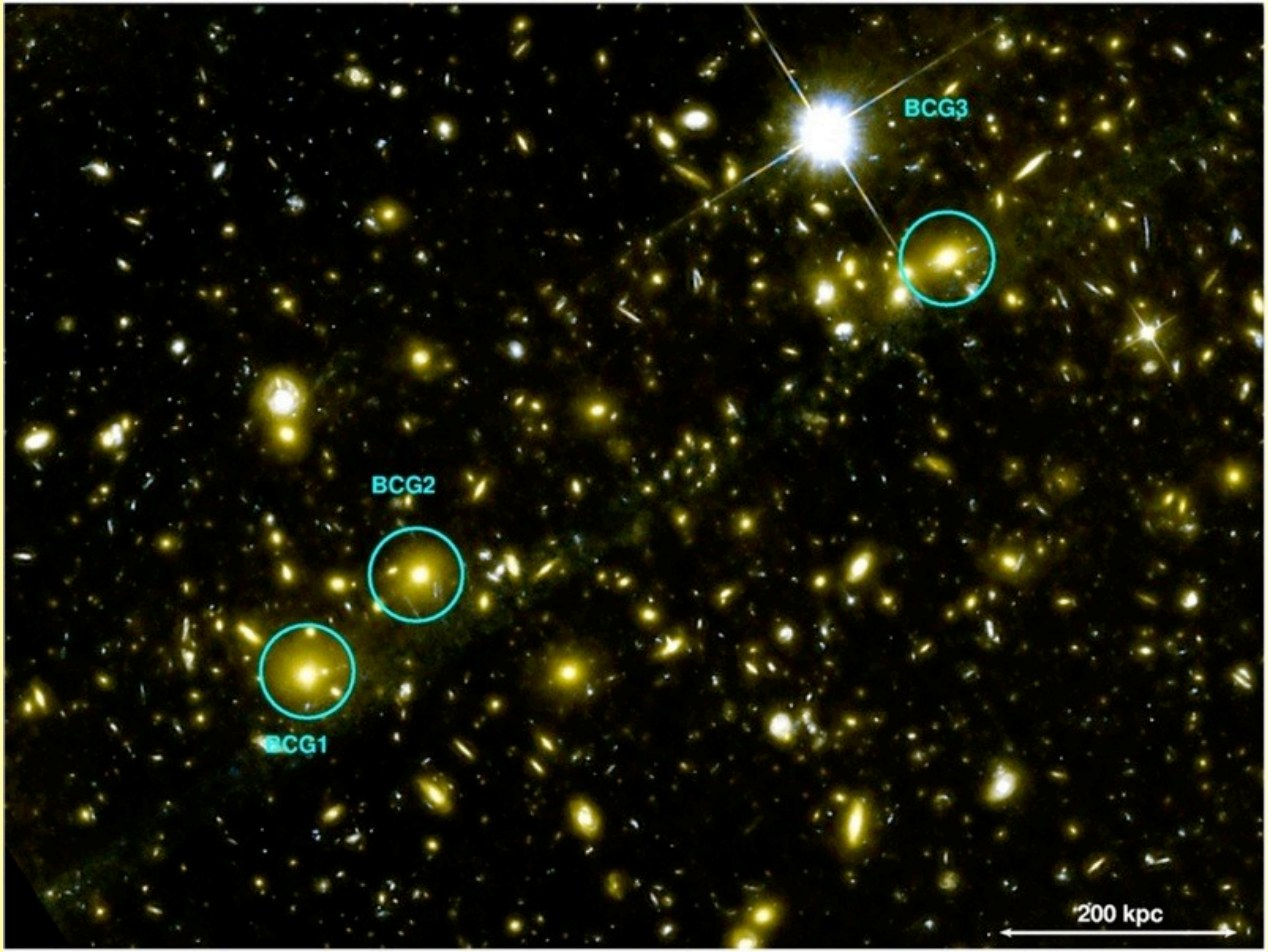
- The galaxies originally in the dark core could have been ejected through a multiple-body interaction
- Weakly self-interacting dark matter: requiring $3.8 \pm 1.1\ \mathrm{cm^2 g^{-1}}$ (Bullet cluster constraints $\sigma/m < 0.7\ \mathrm{cm^2 g^{-1}} = 1.3\mathrm{barn/GeV}$)

Finding more Bullet-like clusters

Finding more Bullet-like clusters

The Nature of Dark Matter
The “Baby” Bullet Cluster
MACSJ0025-1222

Baby Bullet* Cluster MACSJ0025-1222



* Neither baby (daddy!) nor bullet

- F450W WFPC2 5orbits
- F555W ACS 2orbits
- F814W ACS 2orbits

Galaxy Distribution

* Two cluster at the same redshift (0.586+-0.001) separated by 600 kpc (projected)

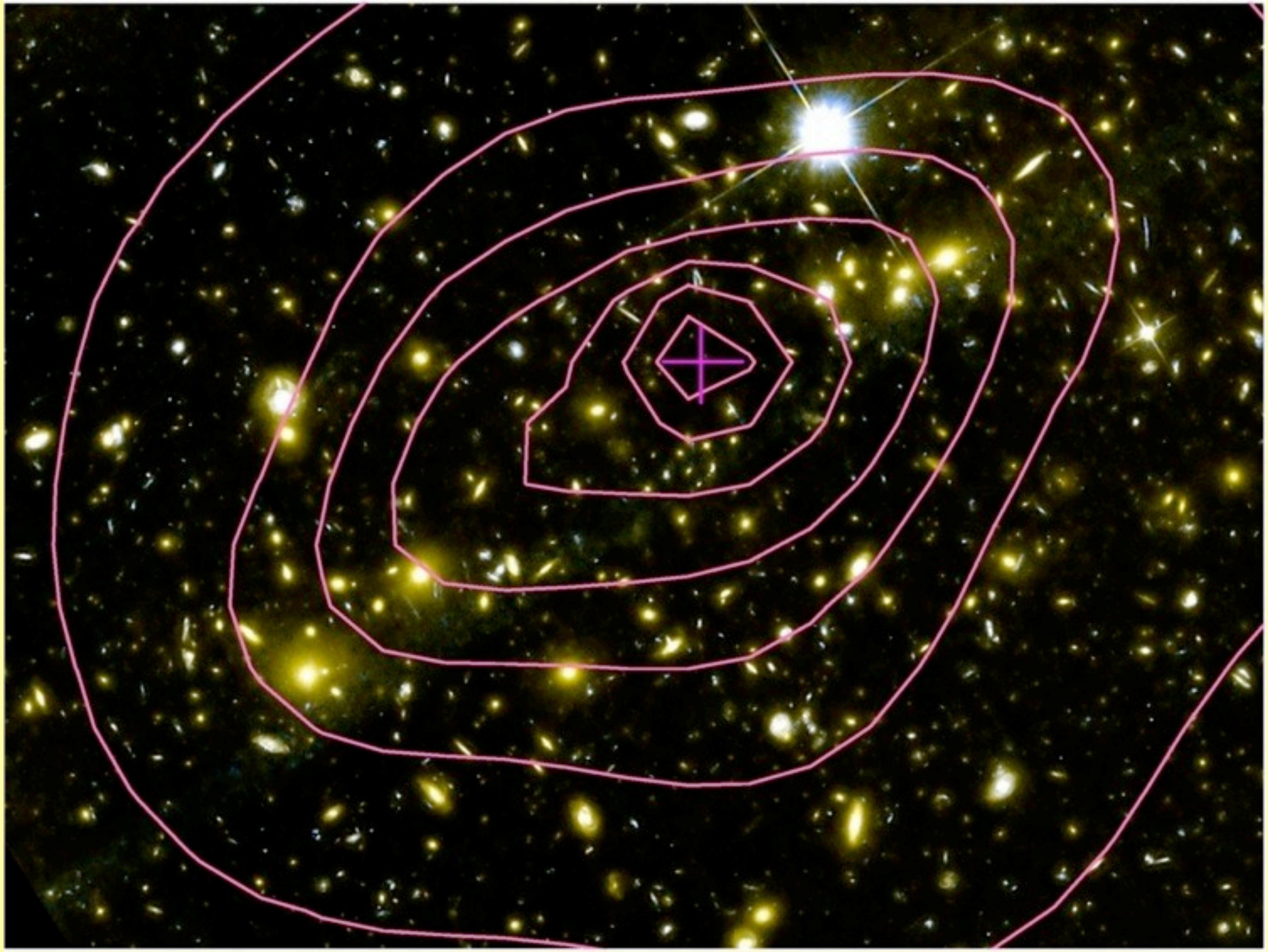
* Velocity separation of the BCG's radial direction
  $\Delta z = 0.0005 \pm 0.0004$ (100±80 km/s)

* Richness / stellar masses of an average massive cluster.

  SE(<300kpc): 2.7 10^{12} $M_\odot$ (3.6 10^{12} $L_\odot$)

  NW(<300kpc): 1.9 10^{12} $M_\odot$ (2.5 10^{12} $L_\odot$)

Gas Distribution



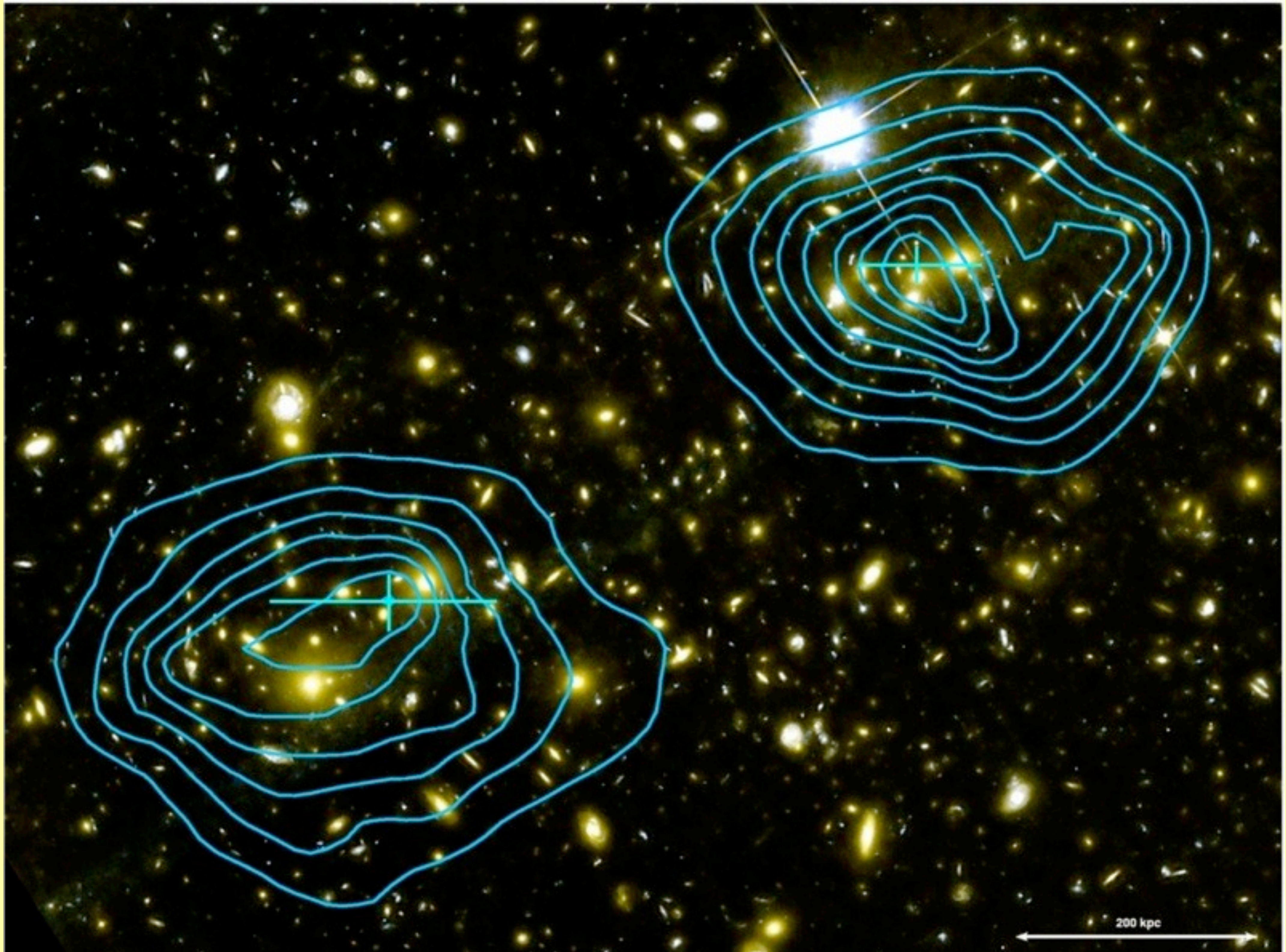
* 38ks Chandra (115ks more to come)
* Gas peak
* Too shallow to see a shock front

Why is Daddy Bullet not a "Bullet"

* The Bullet cluster is a merger of a cool core (low entropy gas) and a non-cool core cluster
* Daddy Bullet is a merger of two non-cool core clusters
* Dynamical information from the shock - still likely

Why is Daddy Bullet not a "Bullet"

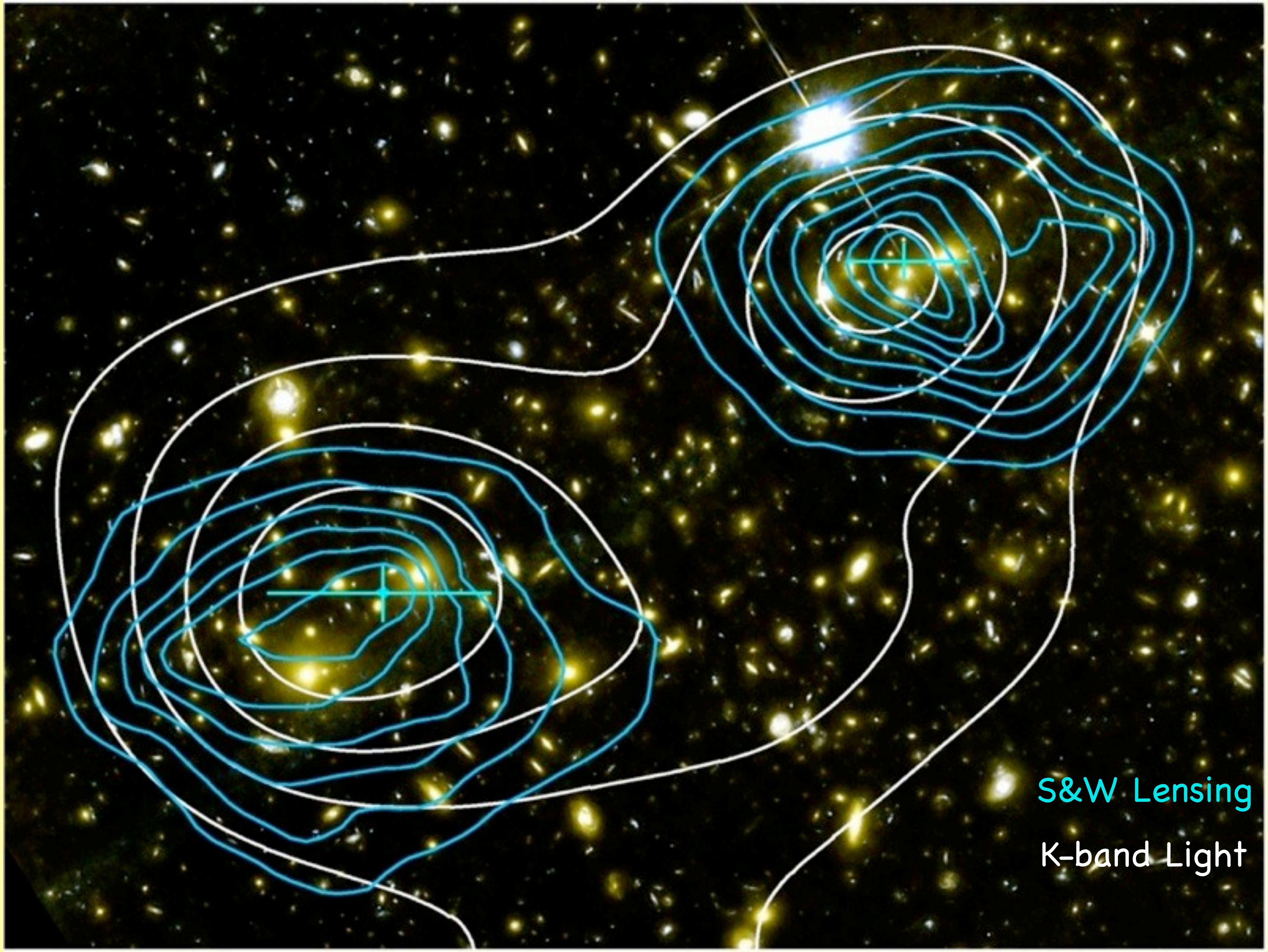
Total Mass Distribution



S&W Lensing

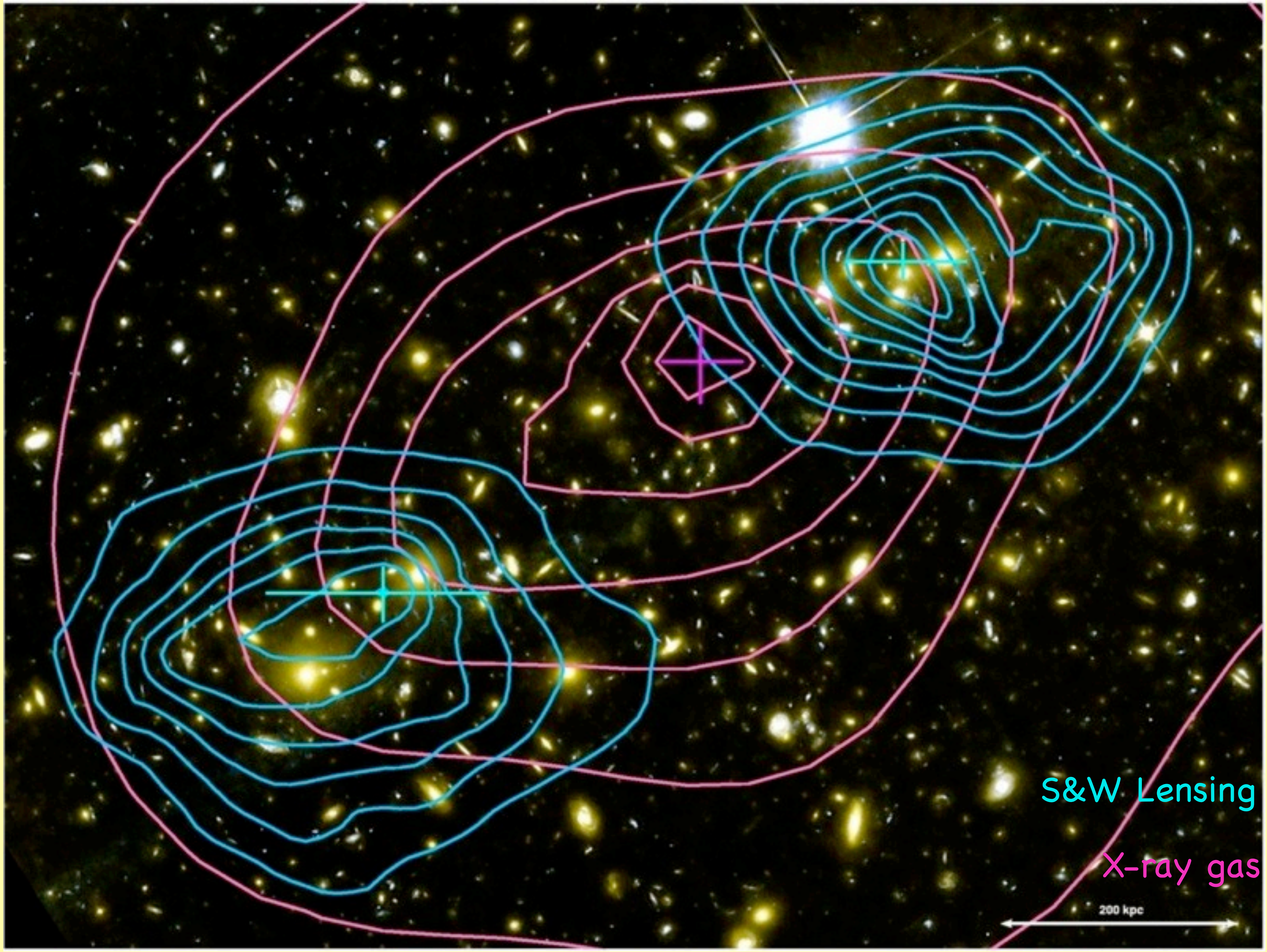
Bradač et al. 2008b

Mass vs. Light



Bradač et al. 2008b

Mass vs. Gas



Bradač et al. 2008b

Dissecting MACSJ0025-1222 Into Dark Matter and Baryons

* Significant offset of both sub-cluster peaks from the gas peak

$> 4\sigma$

Dark Matter Properties

* Combining the Chandra data with lensing mass maps -> place an upper bound on the dark matter self-interaction cross section $\sigma/m < 4\ \mathrm{cm^2 g^{-1}} = 8$ barn/GeV.

    -> Significant offset between subcluster X-ray gas core and dark matter peak

$$\tau = \Sigma \frac{\sigma}{m}$$

    -> ~~Survival of the subcluster~~ (need velocity info)

    -> ~~No loss of mass from subcluster~~

* The Bullet Cluster: $\sigma/m < 0.7\ \mathrm{cm^2 g^{-1}} = 1.3$barn/GeV (Randall et al.2008)

A Mommy Bullet or Daddy Trainwreck?

von der Linden et al.
in prep.

Decaying Dark Matter?

* Idea: Use gas-depleted dark matter concentrations in cluster mergers to look for X-ray signatures of radiatively decaying DM

* How: Combine S+W lensing measurements + X-ray flux measurements

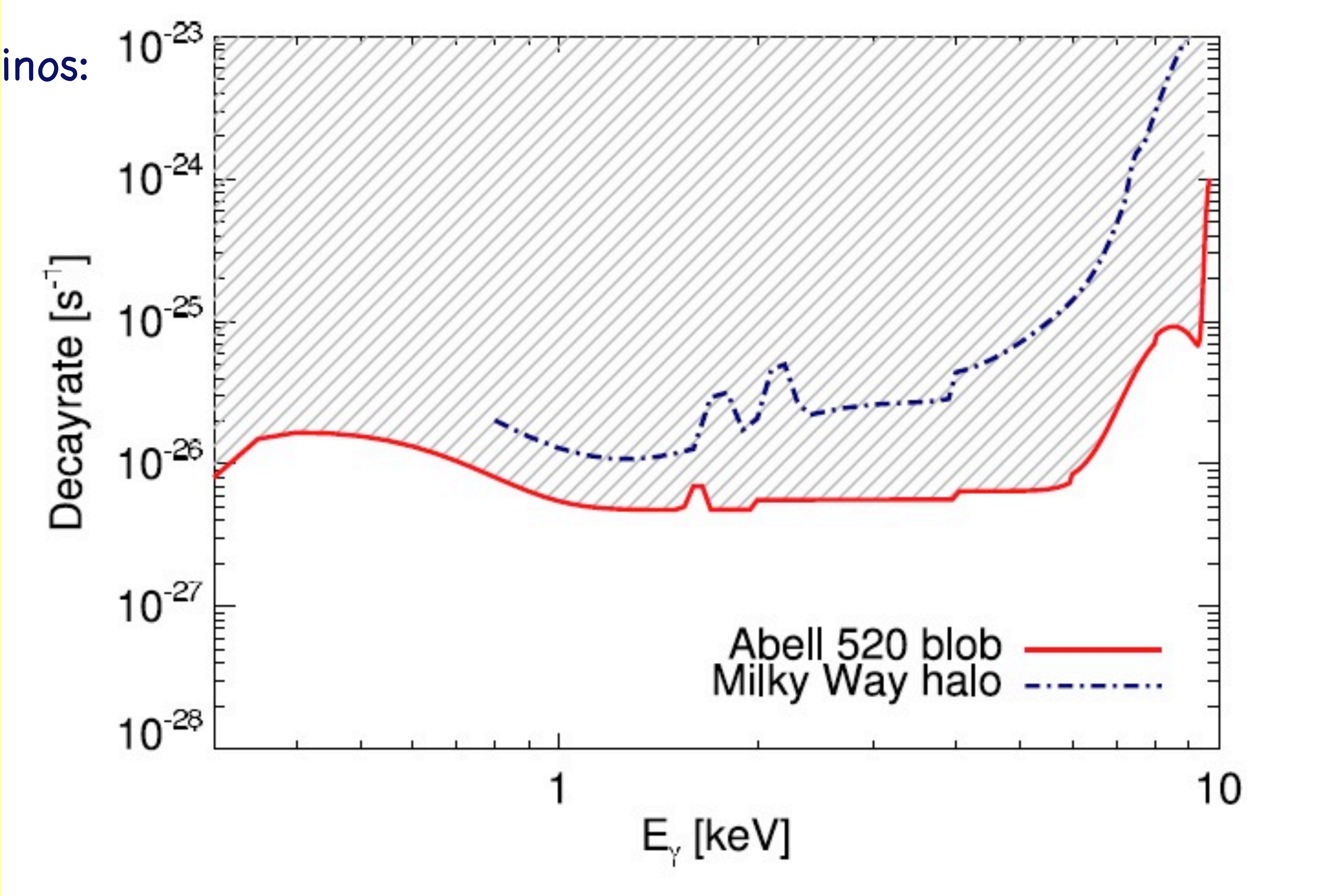
* Examples:

  -> Sterile neutrinos: Riemer-Sørensen et al. (2007), Boyarsky et al. (2007)

  -> Kaluza-Klein axions: Riemer-Sørensen et al. (2007)

Decaying Dark Matter?

Sterile neutrinos:



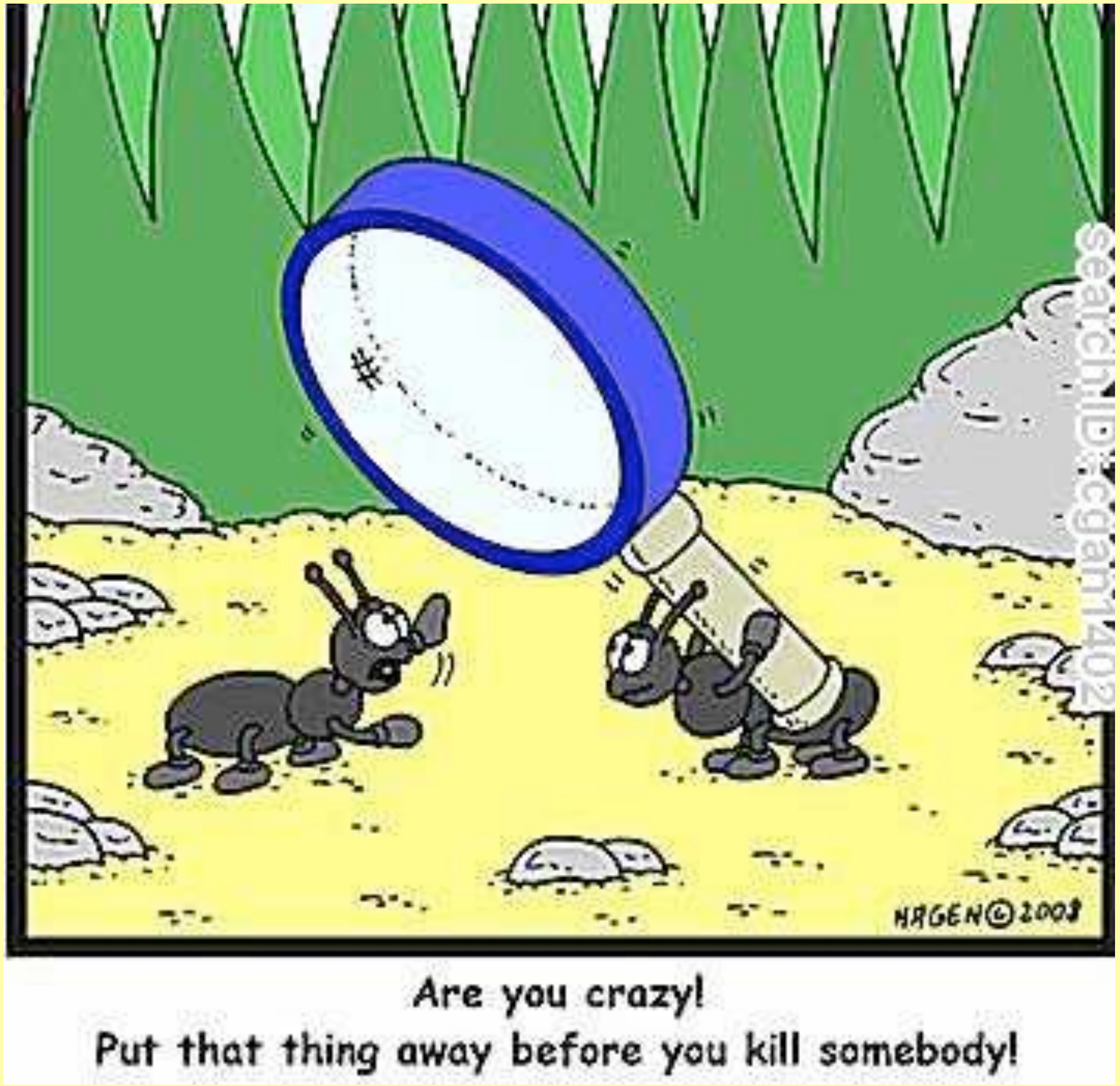
Kaluza-Klein axions - lower limit on luminosity, upper limit on $\tau \gtrsim 10^{26}$ s

And now for something completely different.....

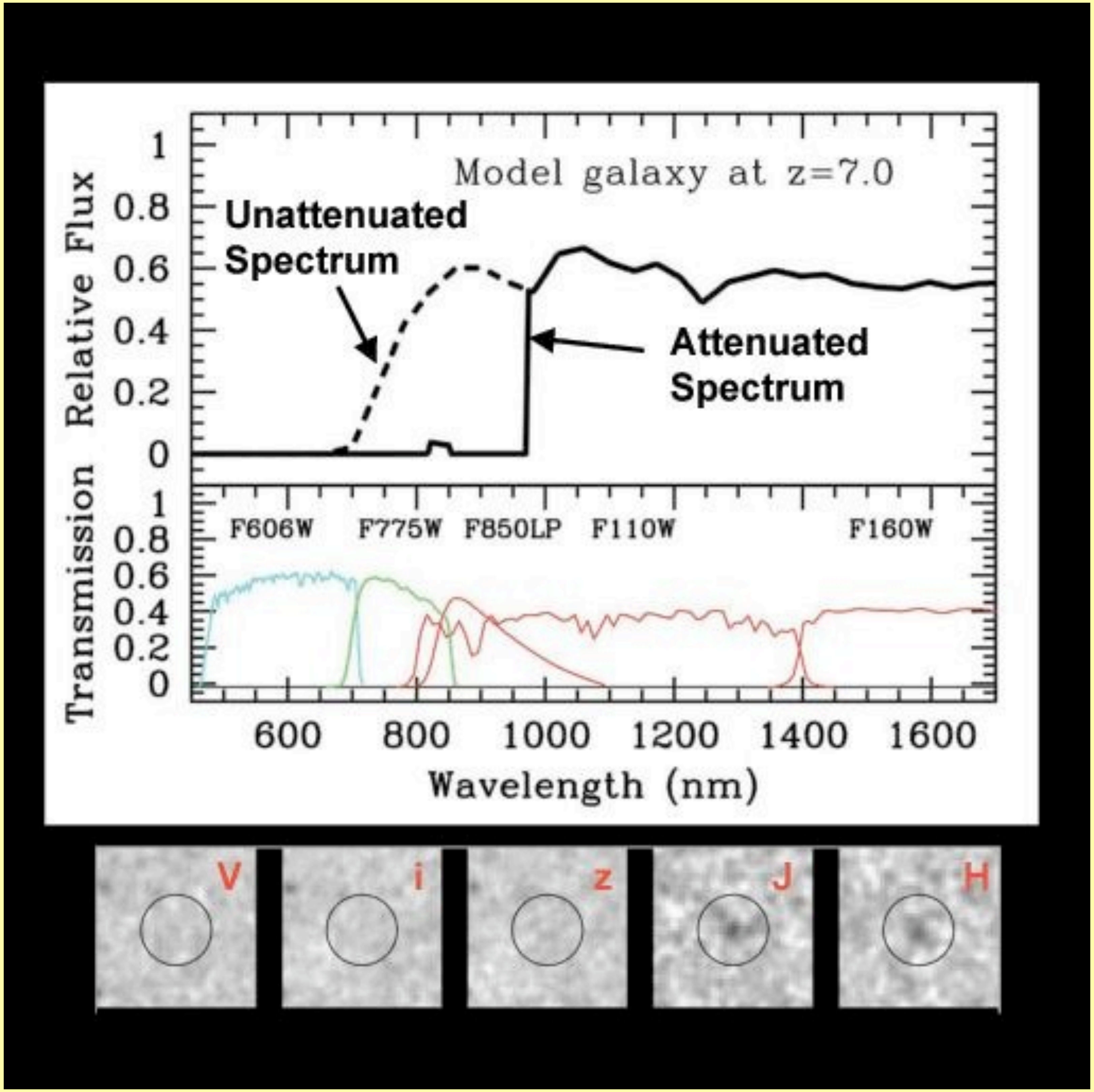
Reionization is important!

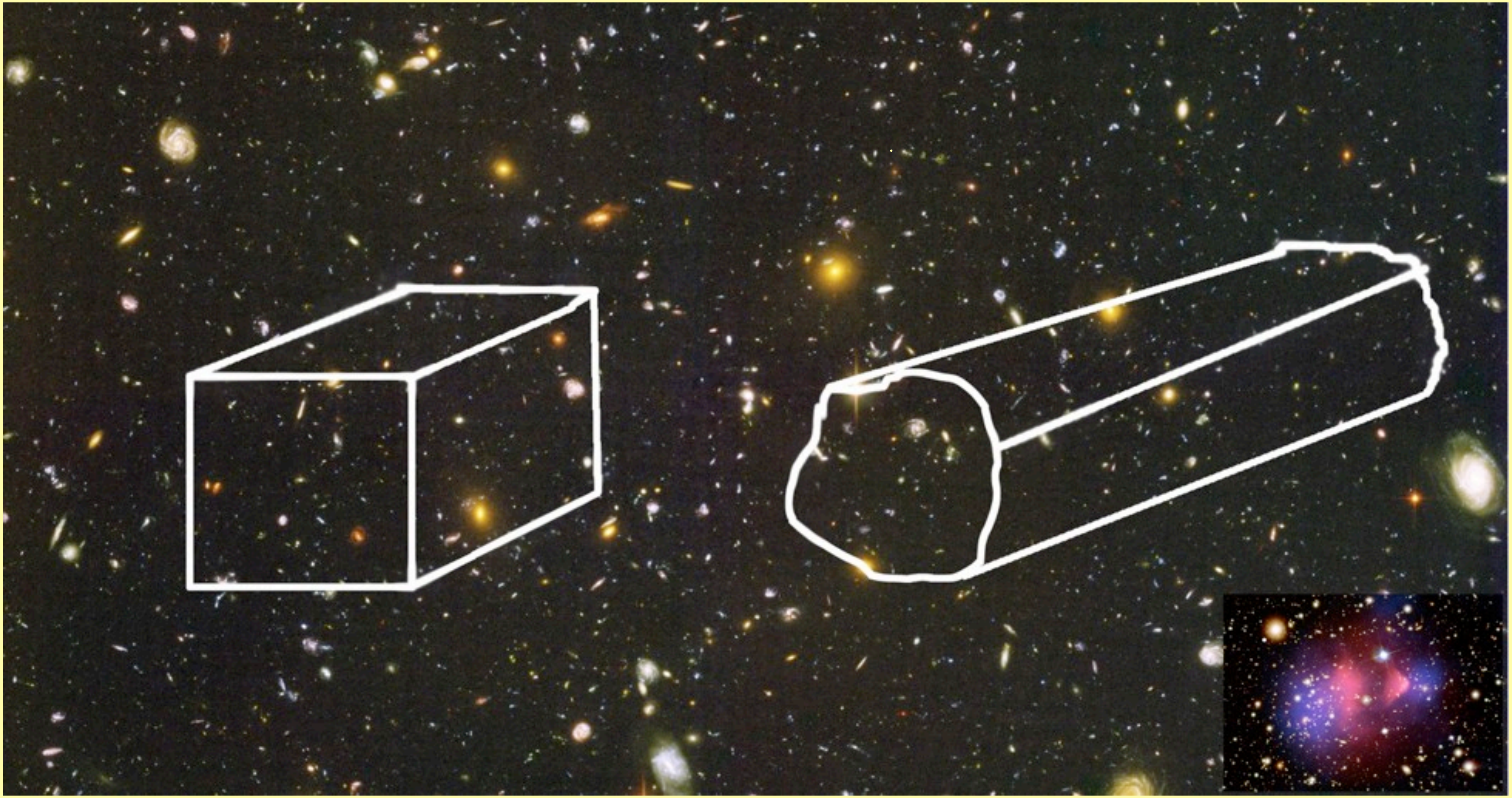
Using Cosmic Telescopes to Study First Galaxies

=



High-z Universe

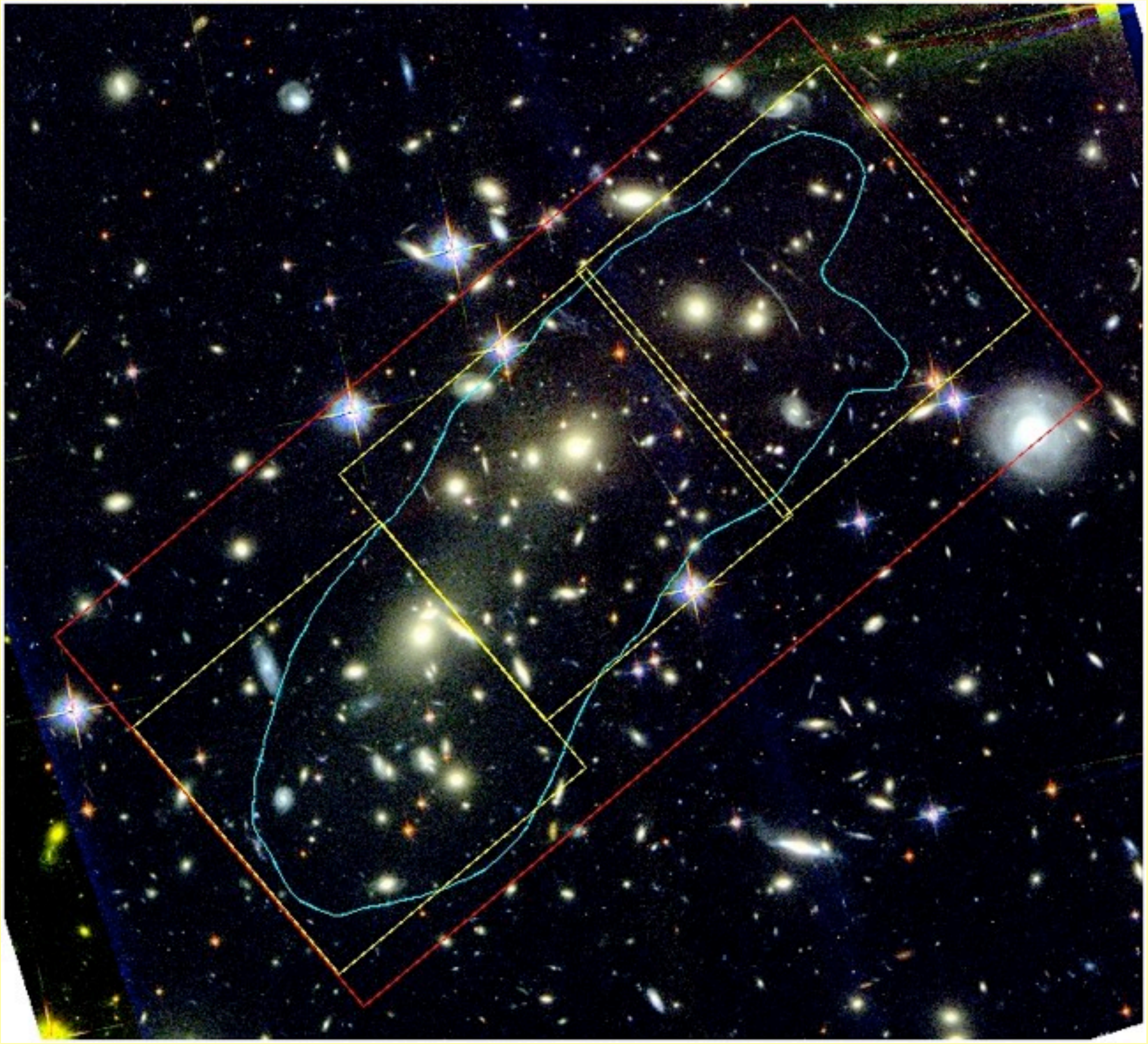




Observing z>7 Universe Through Gravitational Telescopes

* Lensing is fantastic!
* Large magnification factors, allows us to get larger number counts (provided the luminosity function is steep)
* Large areas with observed multiple images - much eased identification; no need for often prohibitive spectroscopy
* Magnification maps are known to sufficient accuracy to constrain the number counts (and for best cases also individual luminosities)
* With good mass (hence magnification) map -> errors under control
  Bradač et al. (2009)

High-z Universe through 1E0657-56



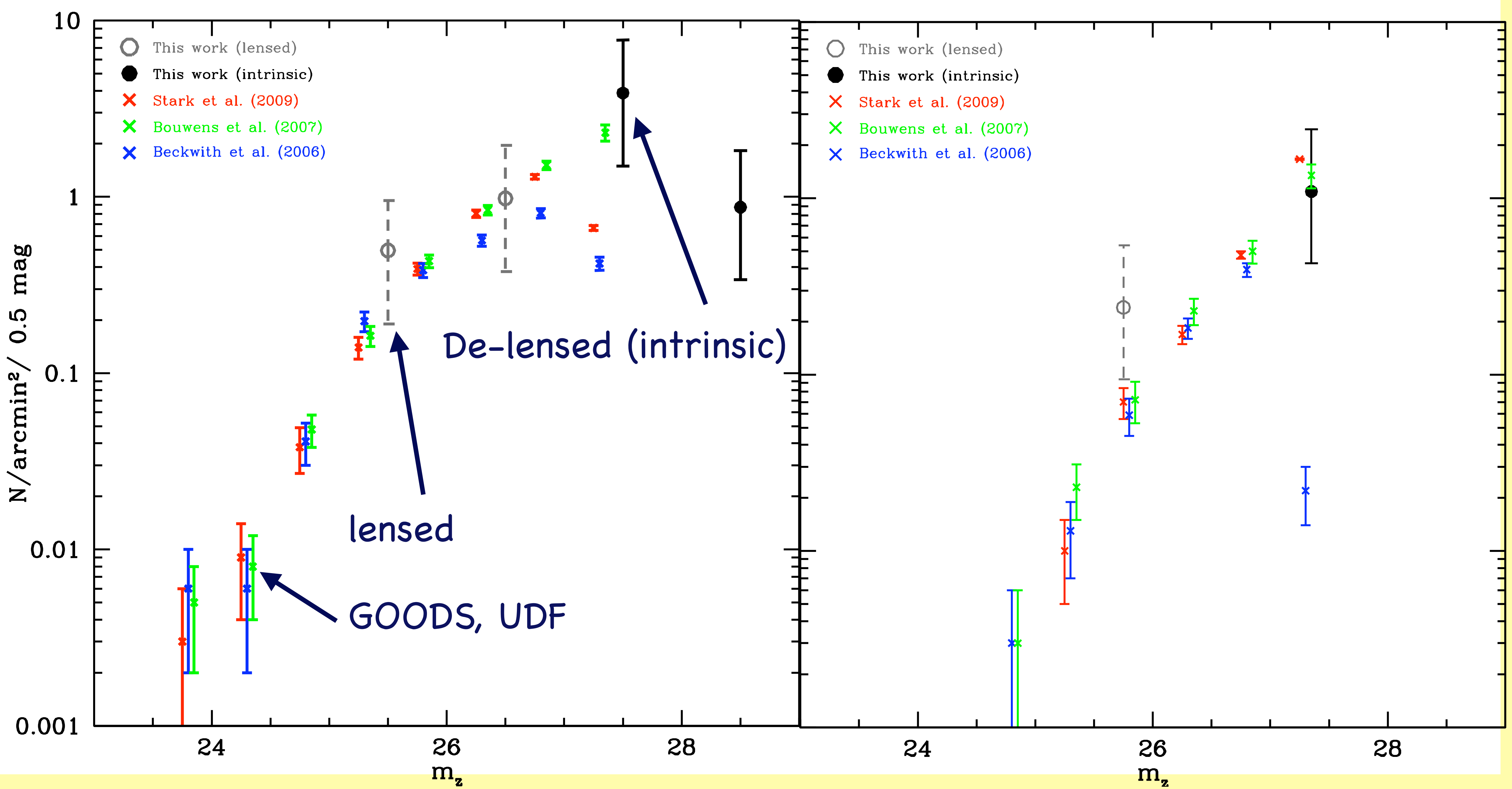
z>7 Universe through 1E0657-56

* Not quite yet
* Cycle 16 NICMOS -> Cycle 17 WFC3 YAY!!
* Deep ACS data: F606W (V , 2340s), F775W (i, 10150s), and F850LP (z, 12700s)
* Search for V and i-band dropouts -> z=5-6 population, compare with blank surveys

  -> GOODS (v1): V - 5000s, i - 5000s, z - 10660s (320 arcmin^2)

  -> HUDF: V - 135ks, i - 347ks, z - 347ks (10 arcmin^2)

It Works! Galaxies at z=5-6



Z ~ 5 (V-dropouts)

Z ~ 6 (i-dropouts)

Bradač et al. (2009)


DARK MATTER
Most of the universe can't even be bothered to interact with you.
S.Caroll