The Light Side of the Universe

Movie by B. Tully

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DARK SIDE OF THE UNIVERSE

Dark Matter and First Galaxies Light Up

Revealing the Invisible with 2 Cosmic Supercolliders the "Bullet Cluster" 1E0657-56 and MACSJ0025-1222

Maruša Bradač

Steve Allen, Douglas Clowe, Anthony Gonzalez, Nicholas Hall, Maxim Markevitch, Bill Forman, Christine Jones, Tim Schrabback, Dennis Zaritsky, Roger Blandford, Phil Marshall, Harald Ebeling, Tommaso Treu, Anja von der Linden, Douglas Applegate

Dark Matter and The Bullet Cluster

Dark Matter and The Baby Bullet Cluster

High-redshift Universe

The Light Side of the Universe

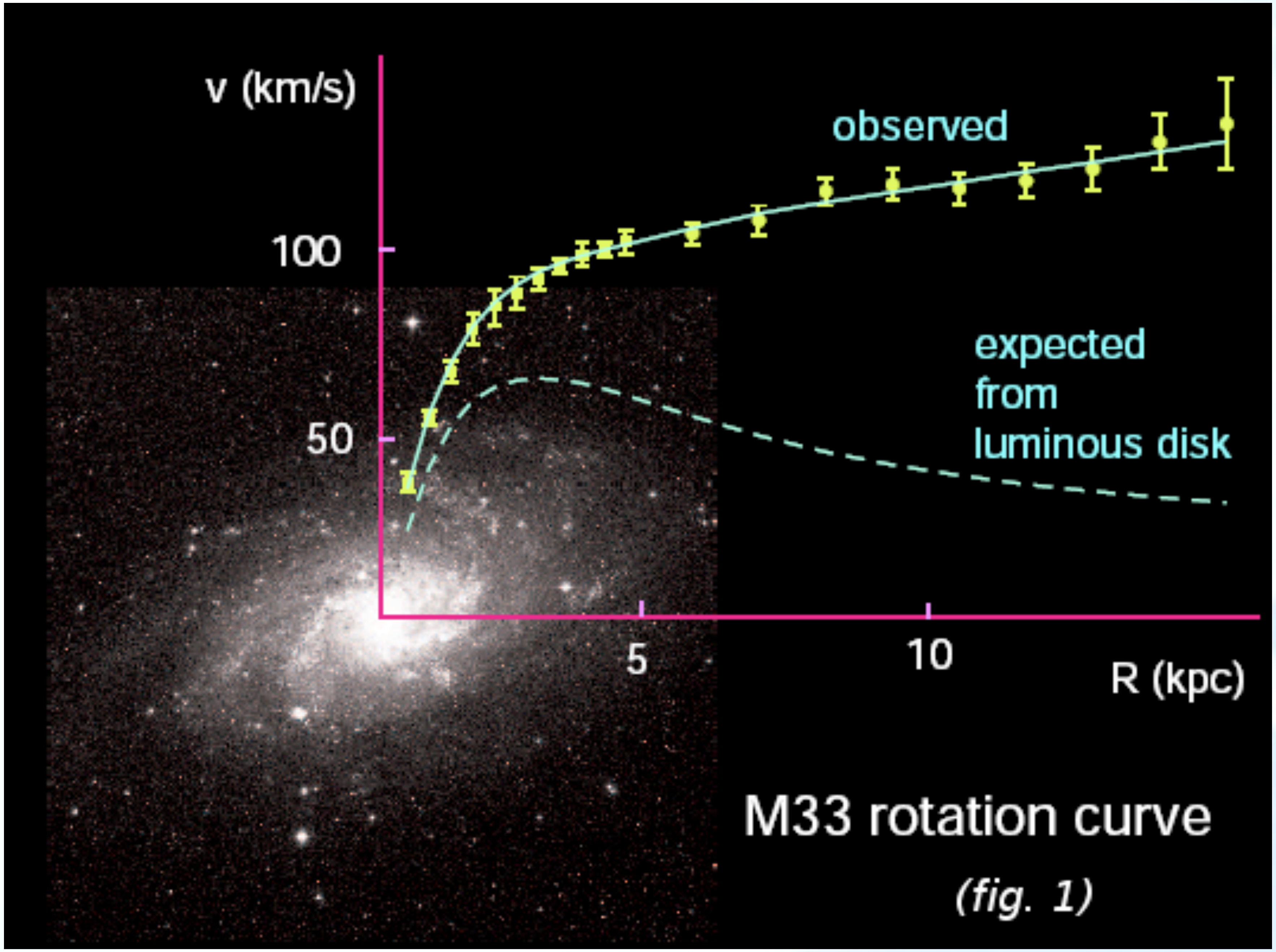
* Our solar system - 1 star
* The Milky Way contains about 4×10^{11}
* More than 10^{11} galaxies in the Universe

The Dark Side of the Universe

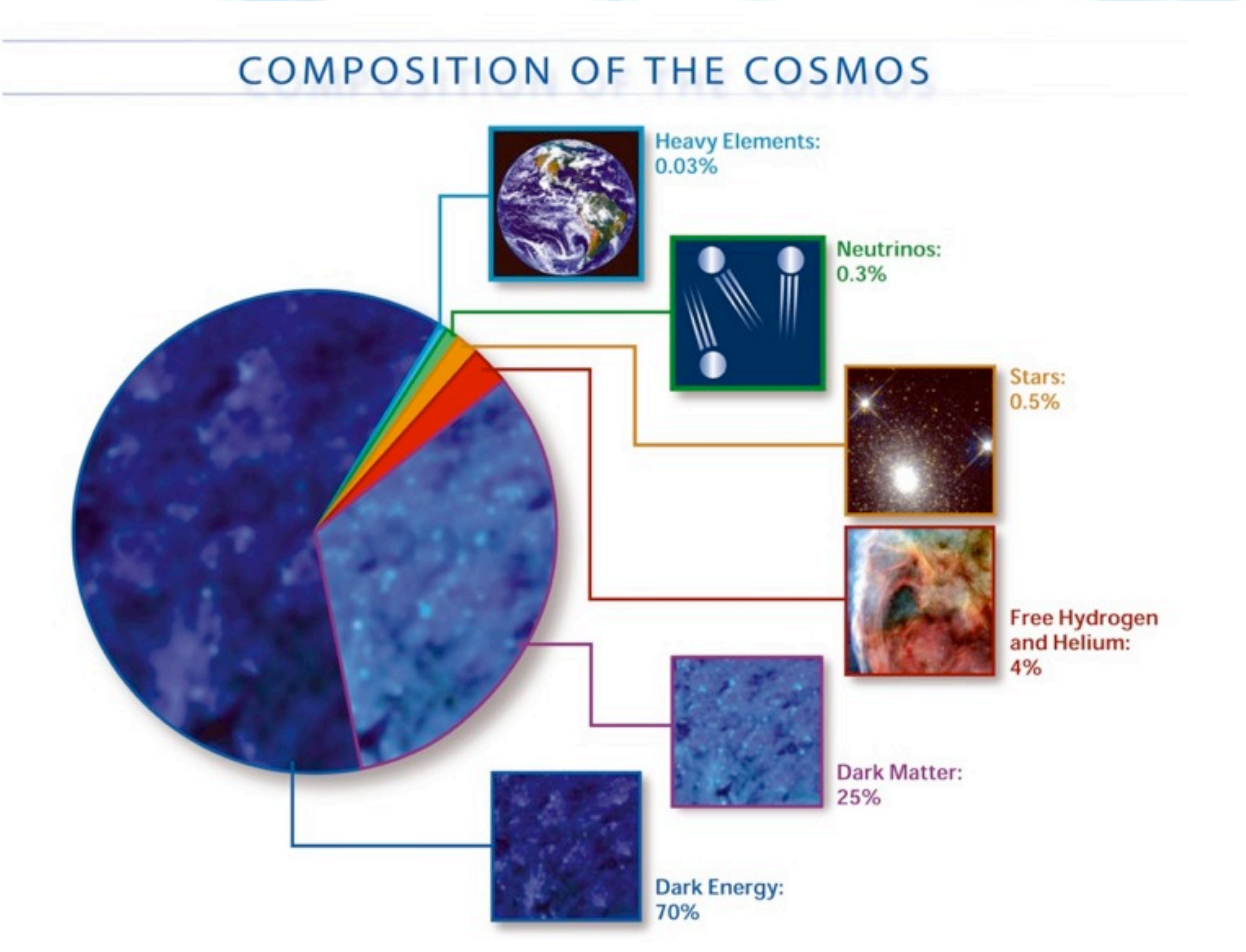
* Zwicky 1933: Galaxy velocities are too high if clusters are only made of galaxies (Virial Theorem)!

The Dark Side of the Universe

* 1970: Vera Rubin discovers galaxies rotate too fast...

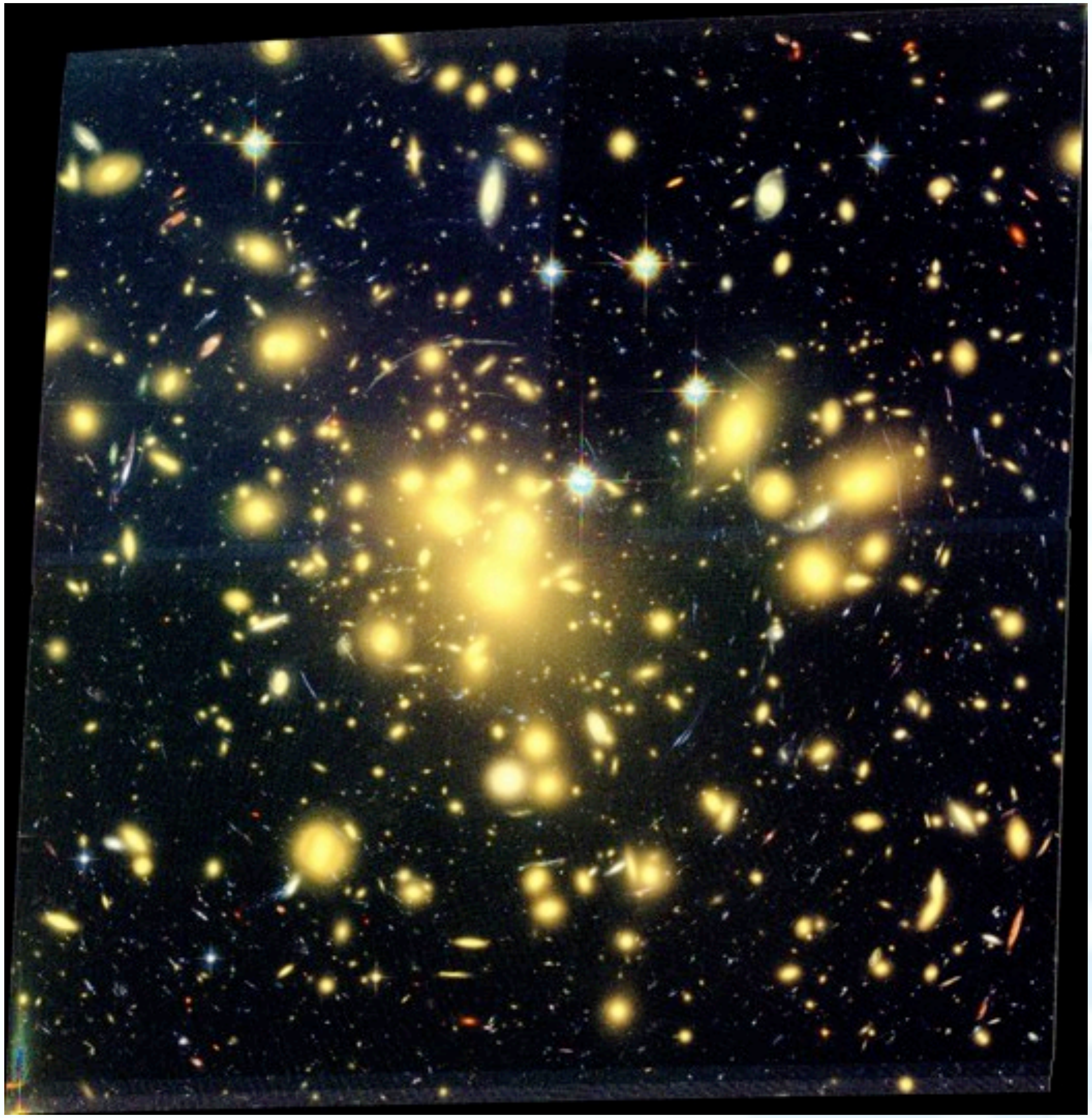


Another Brick In The Wall



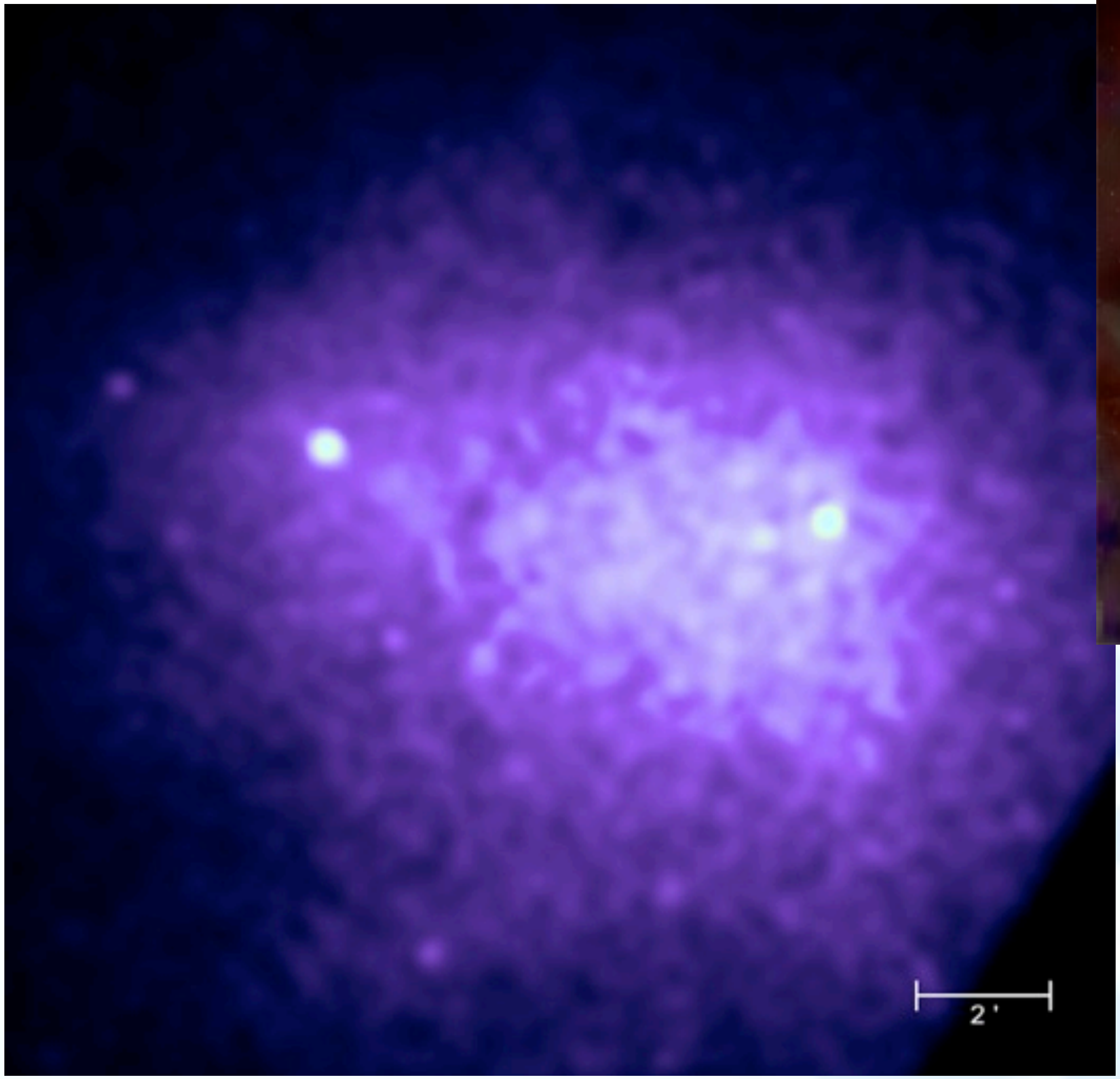
Clusters of Galaxies: Galaxies

* Hundreds of galaxies containing stars, and dust



Clusters of Galaxies: Hot Gas

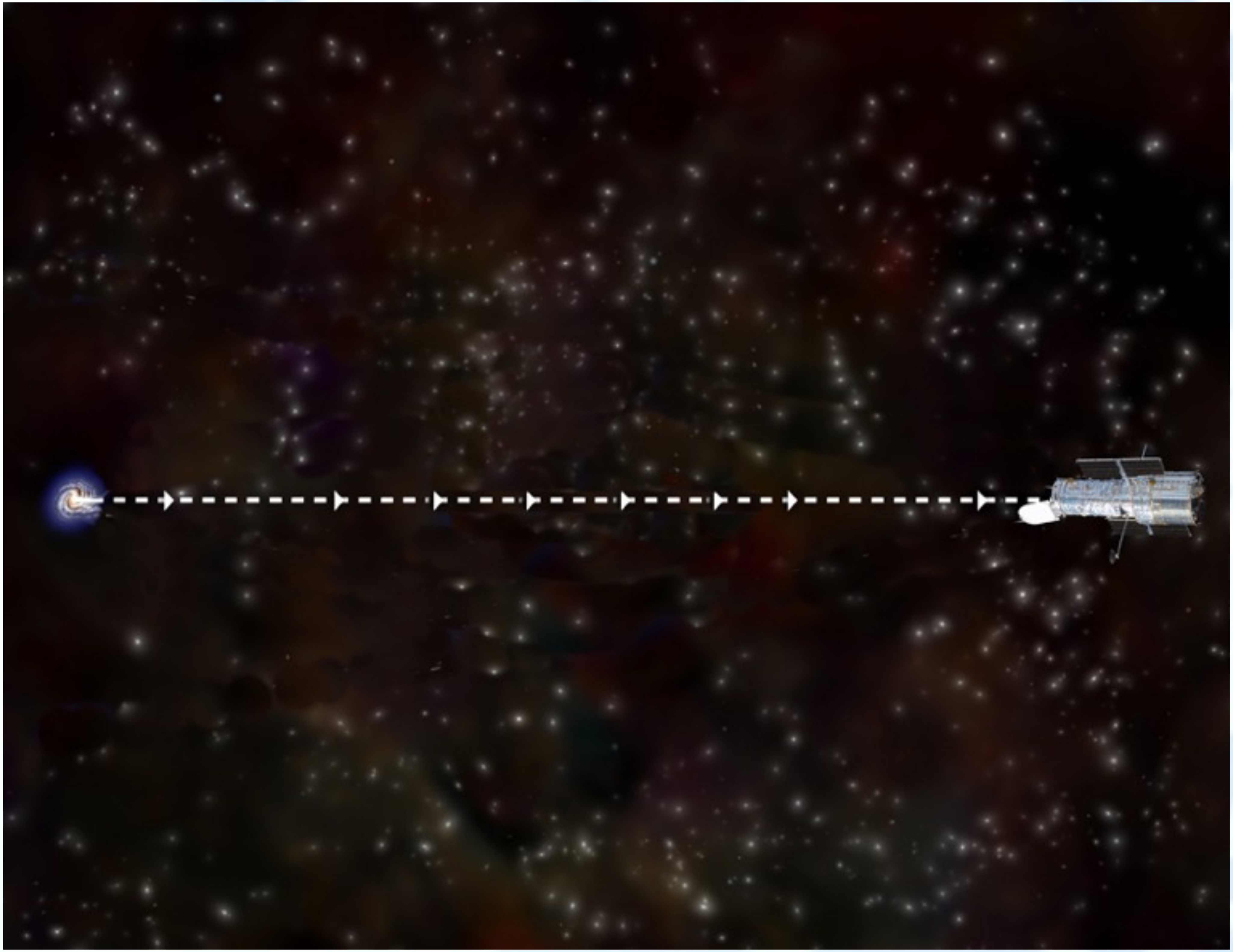
* Vast clouds of hot (30 - 100 million degrees Celsius) gas that is invisible to optical telescopes



The Dark Side of the Universe

* Galaxy velocities are too high if clusters are only made of galaxies, dust, and gas!

Gravitational Lensing



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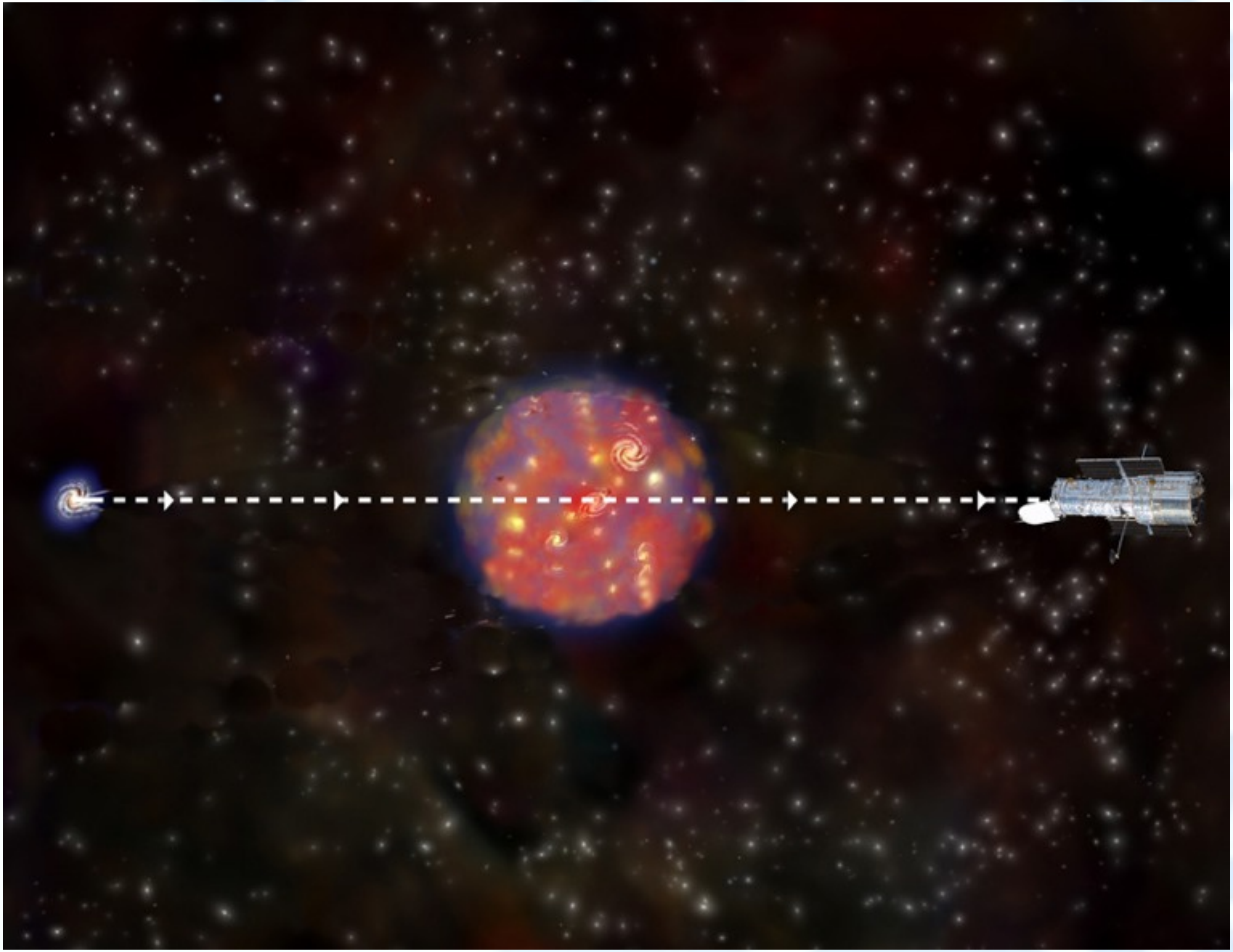
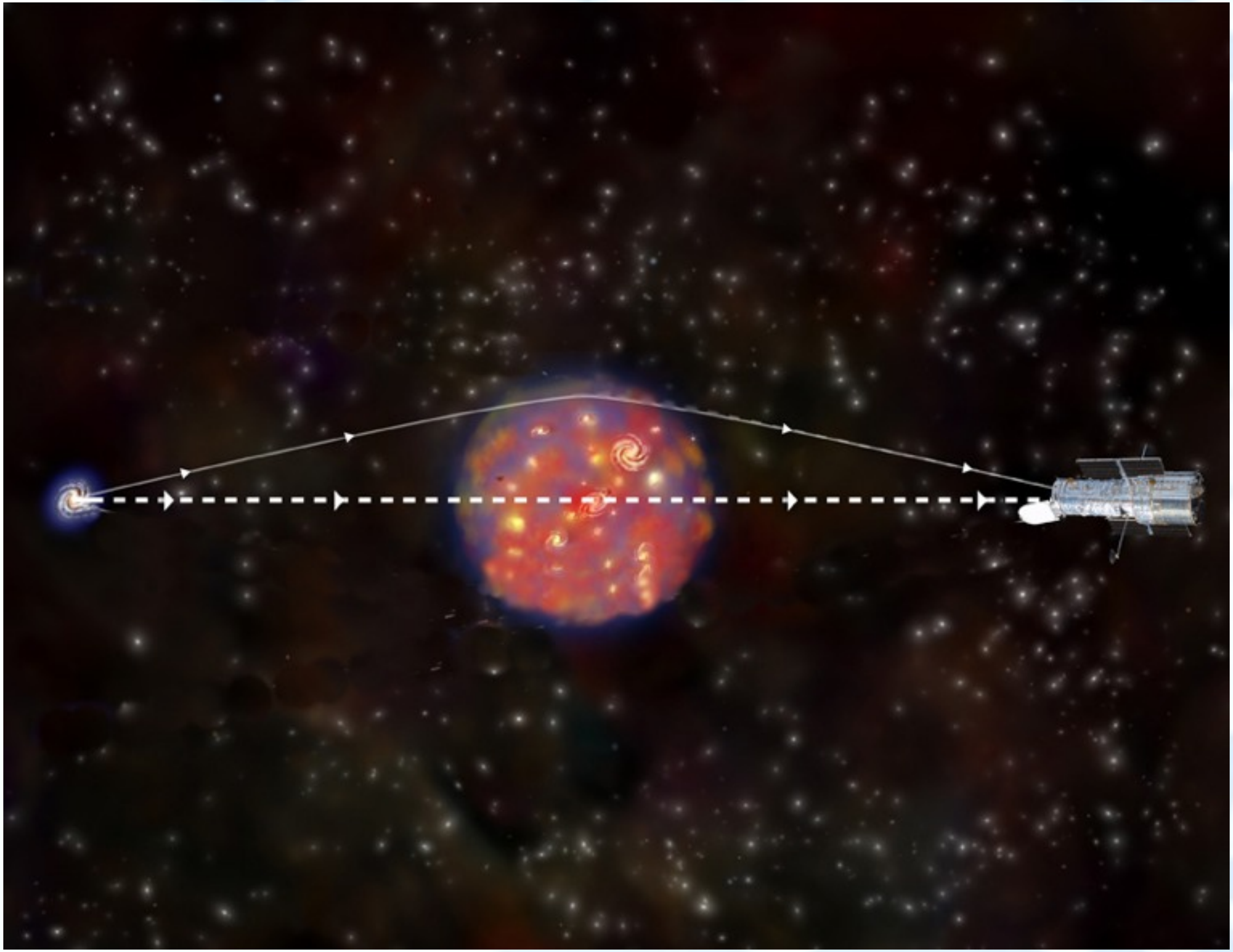
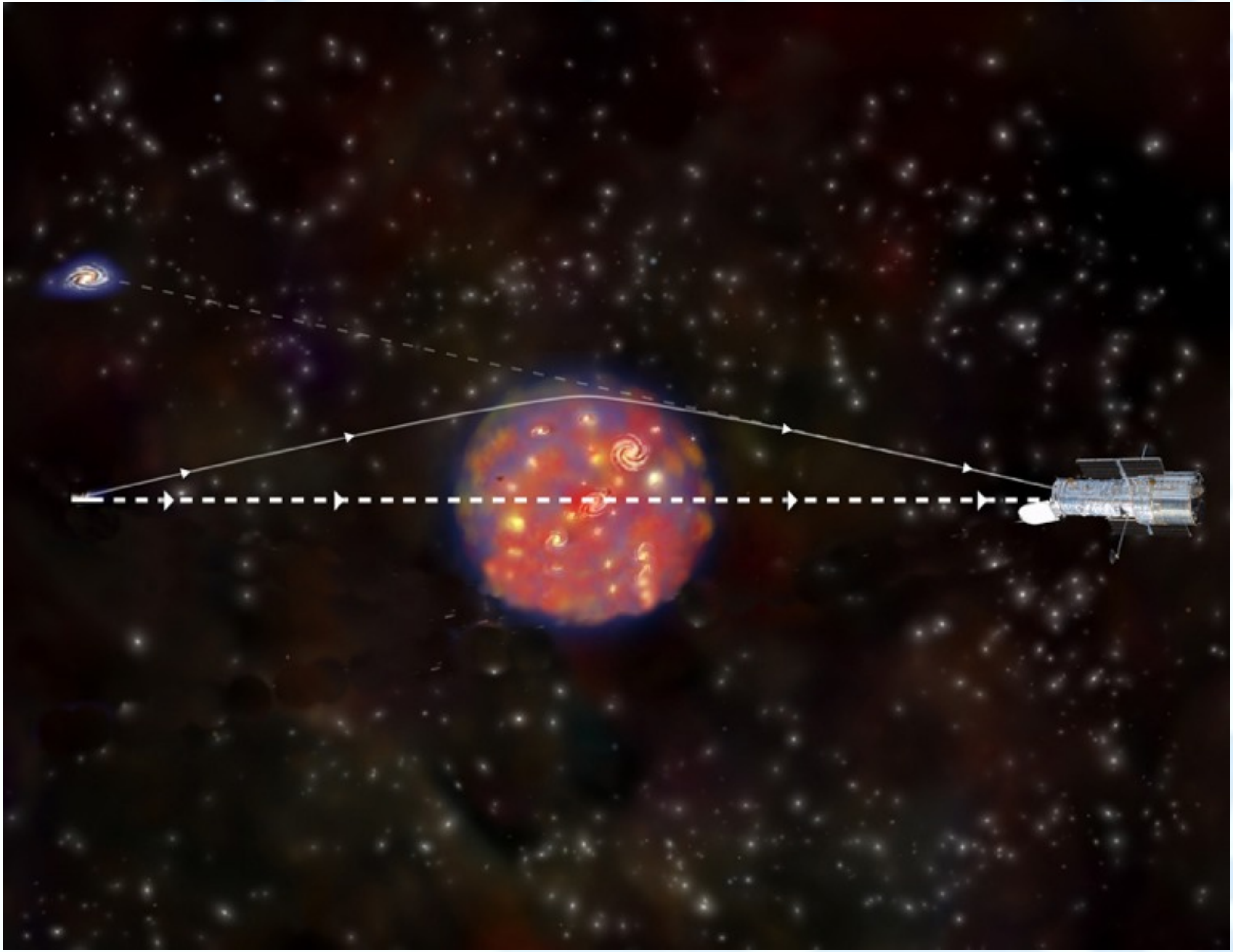


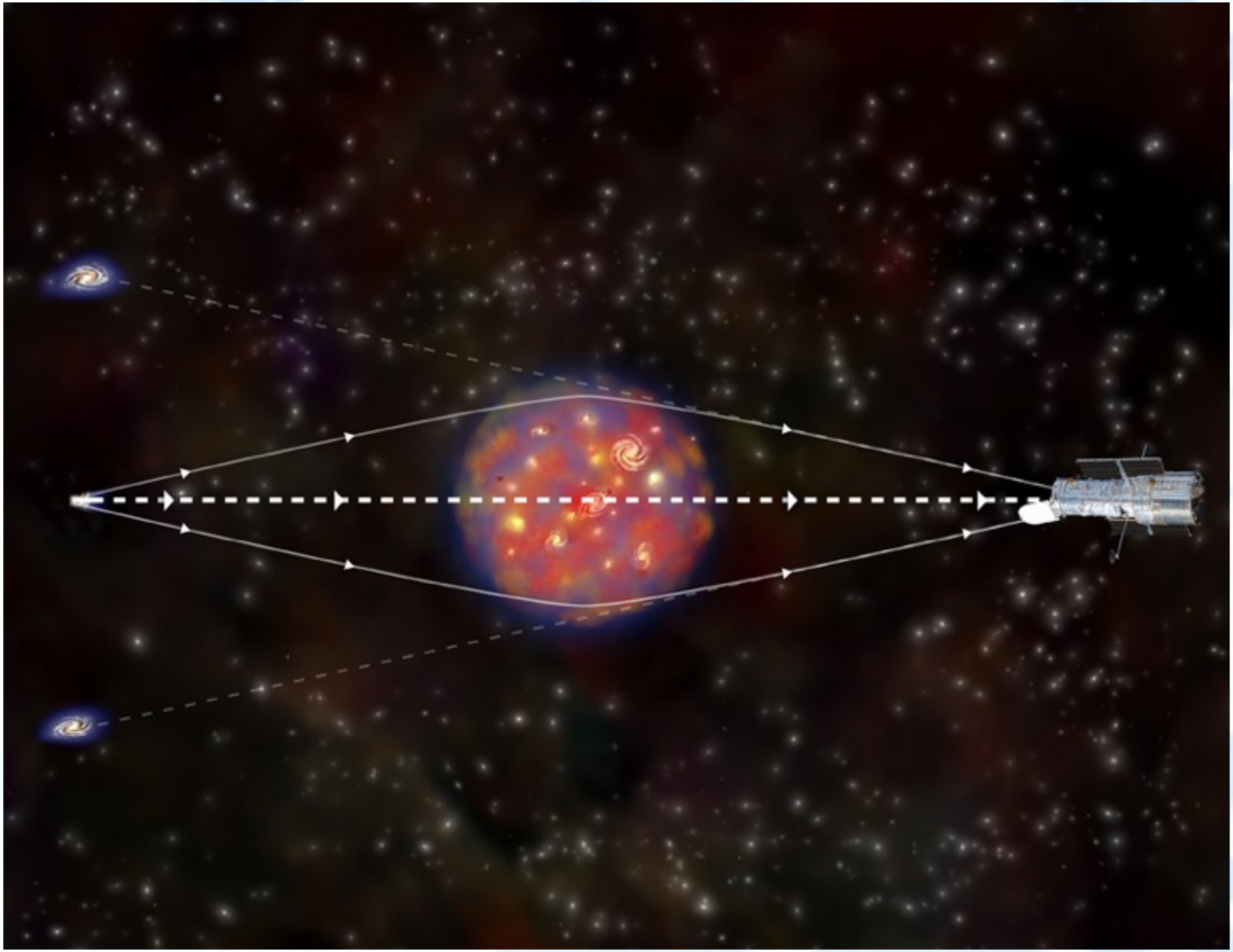
Gravitational Lensing



Gravitational Lensing

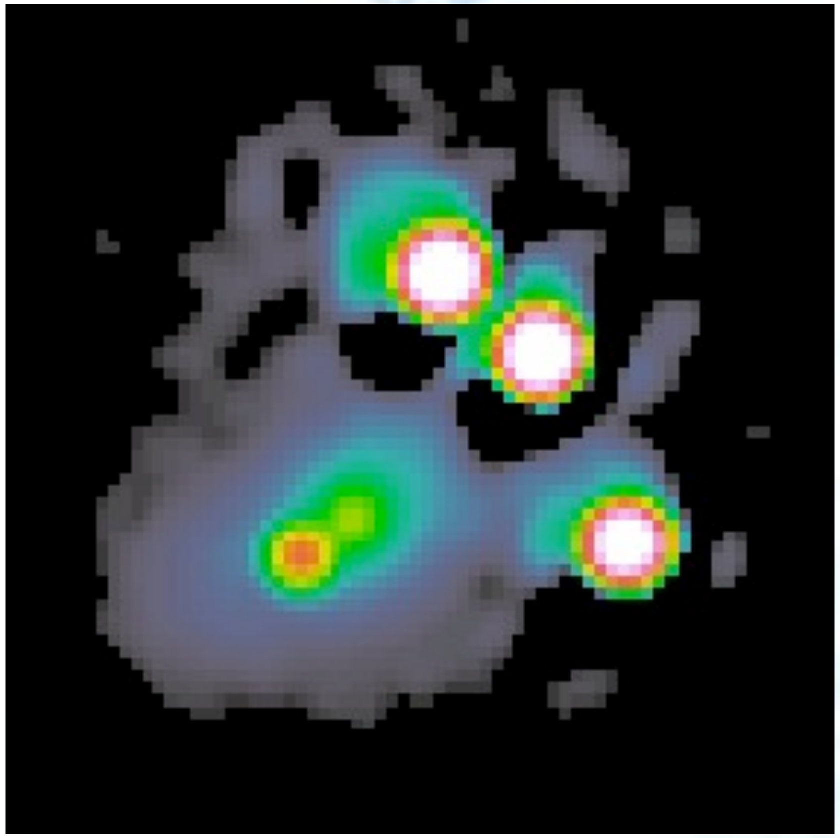


Gravitational Lensing



Gravitational Lensing in Action

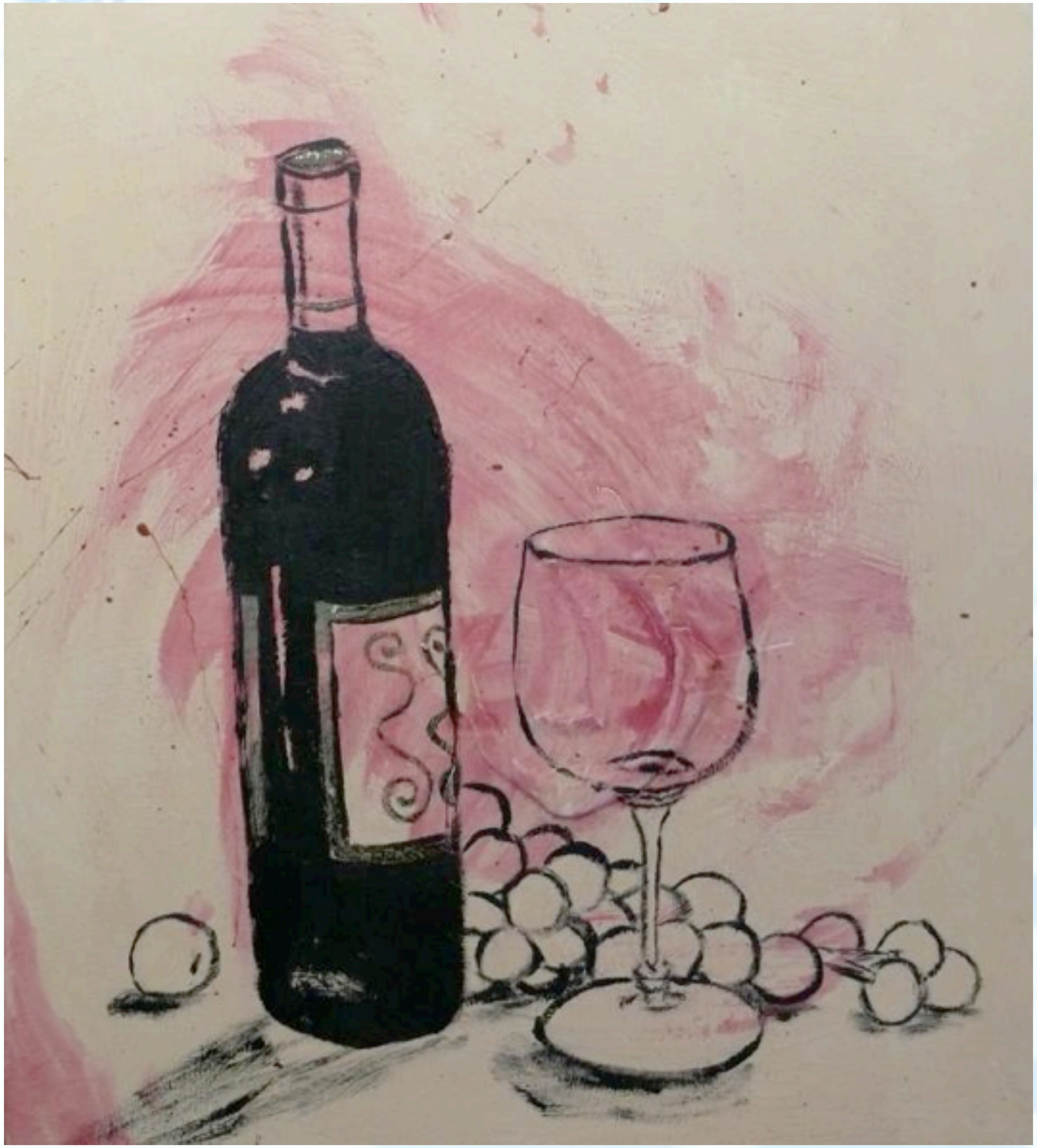
Galaxy



Clusters of Galaxies

Galaxy

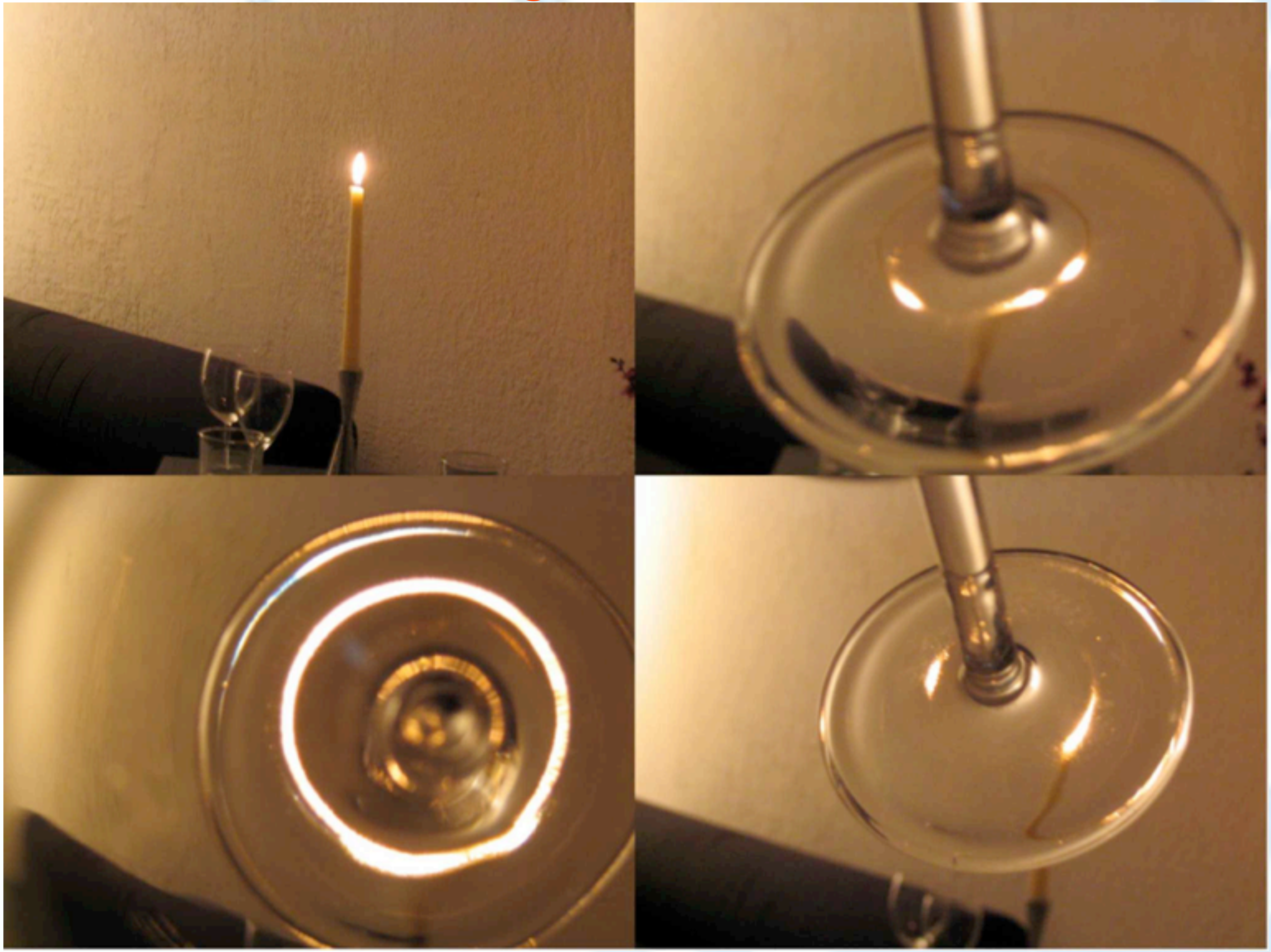
Gravitational Lensing DIY



Gravitational Lensing DIY

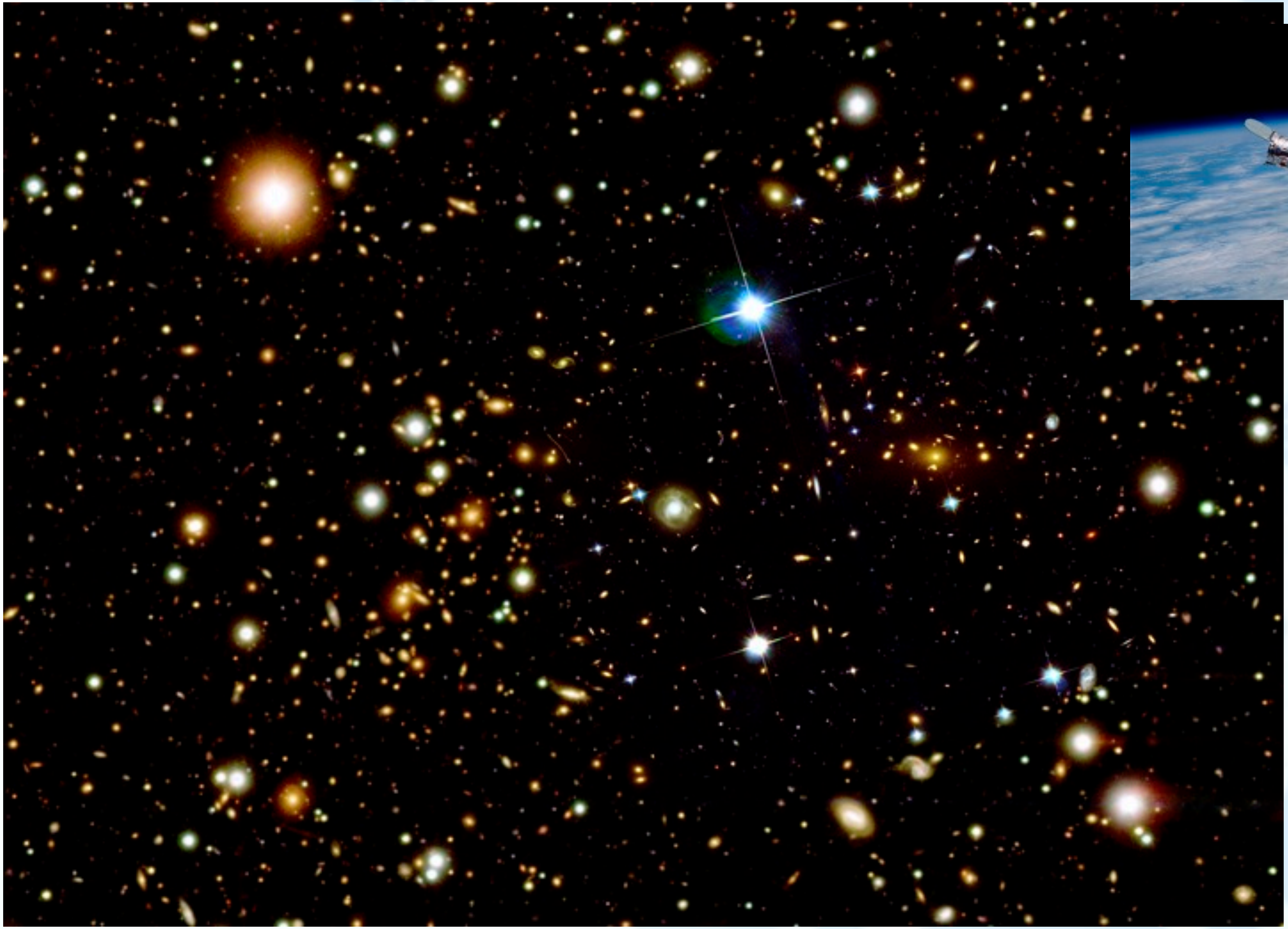
Gravitational Lensing DIY

Gravitational Lensing DIY

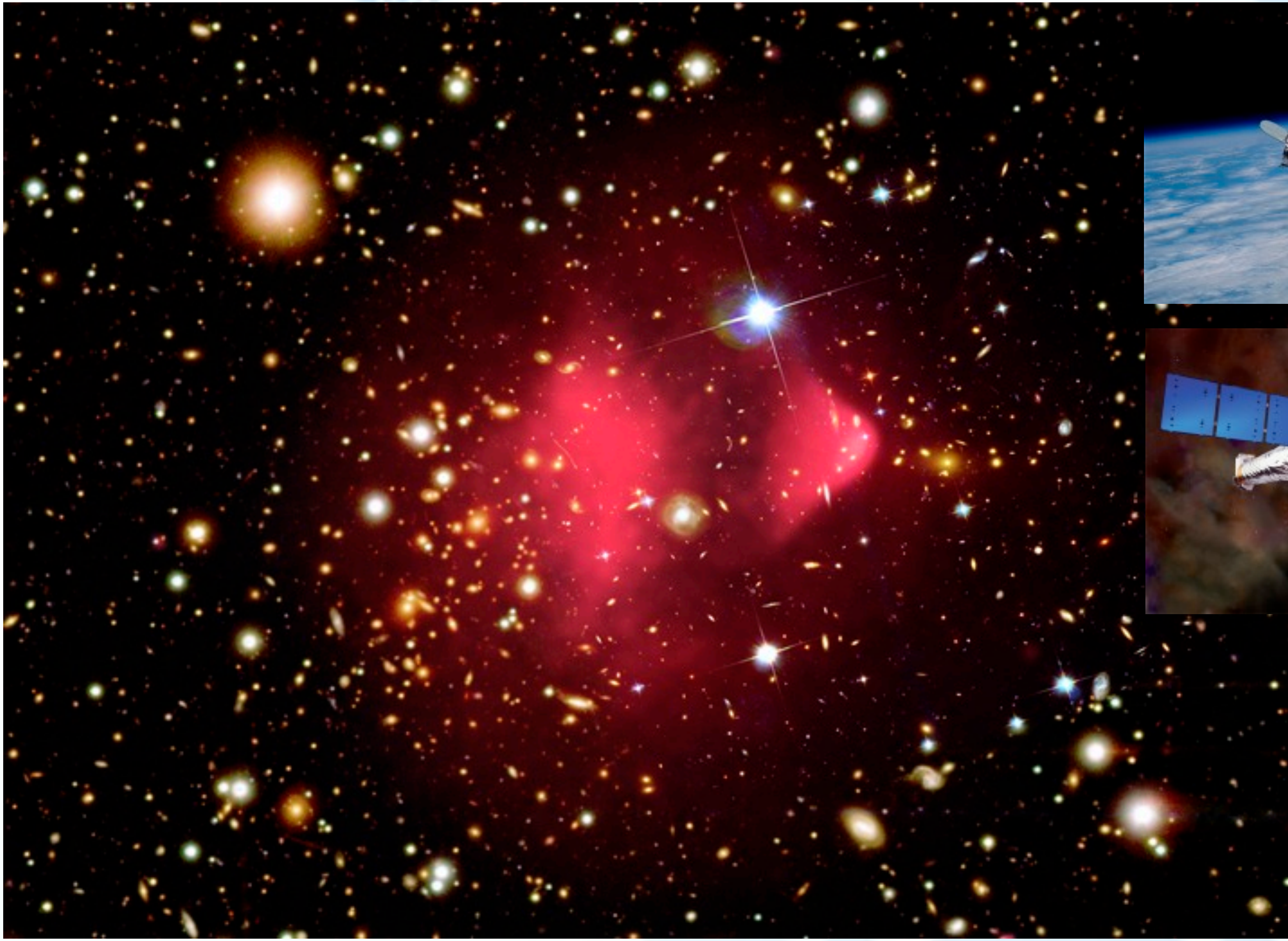


The Nature of Dark Matter
The Bullet Cluster
1E0657-56

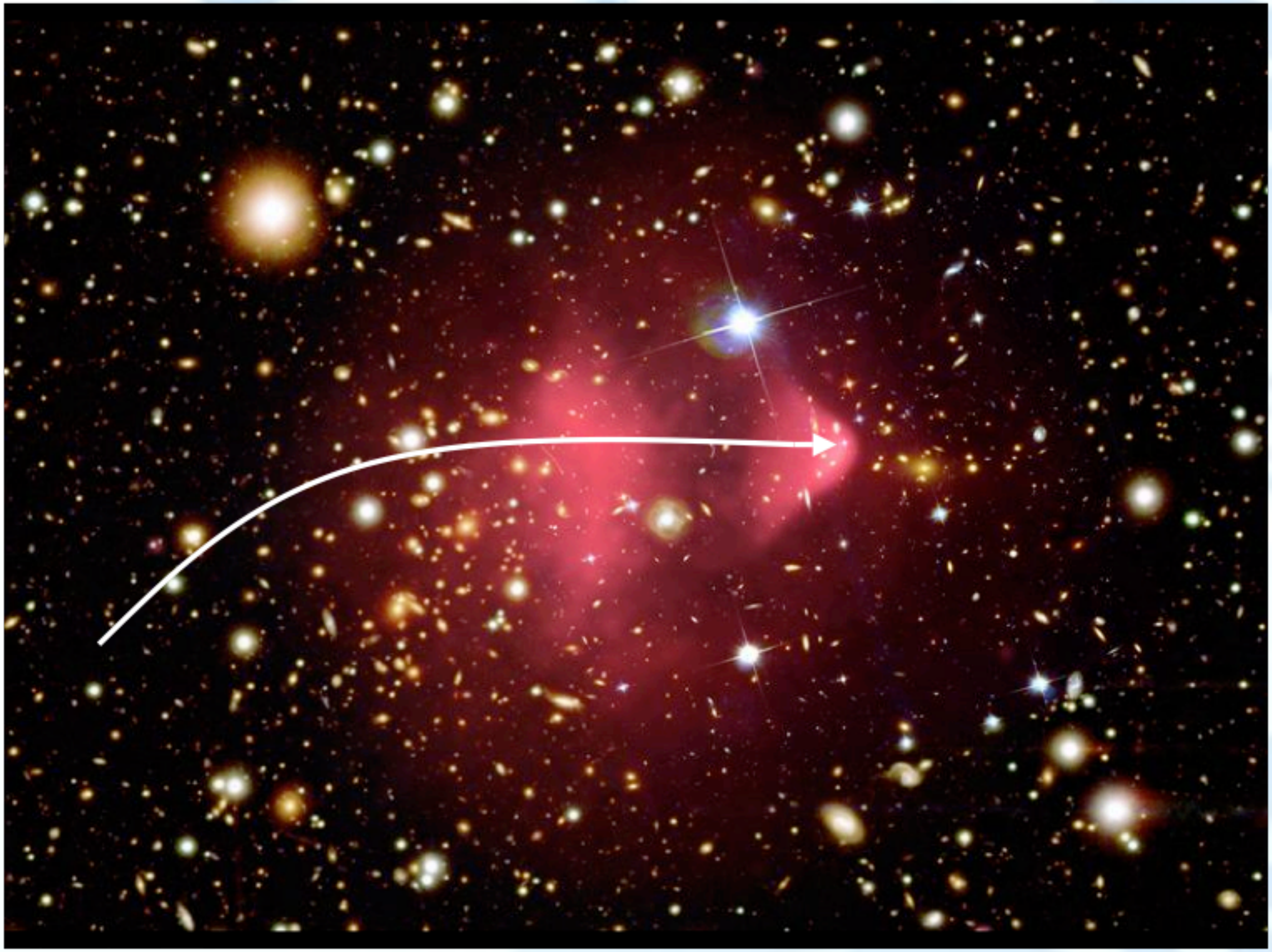
A Very Special Cluster of Galaxies - Bullet Cluster



A Very Special Cluster of Galaxies - Bullet Cluster



A Very Special Cluster of Galaxies - Bullet Cluster



Surfing and Snow-Plowing Through the Universe

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).

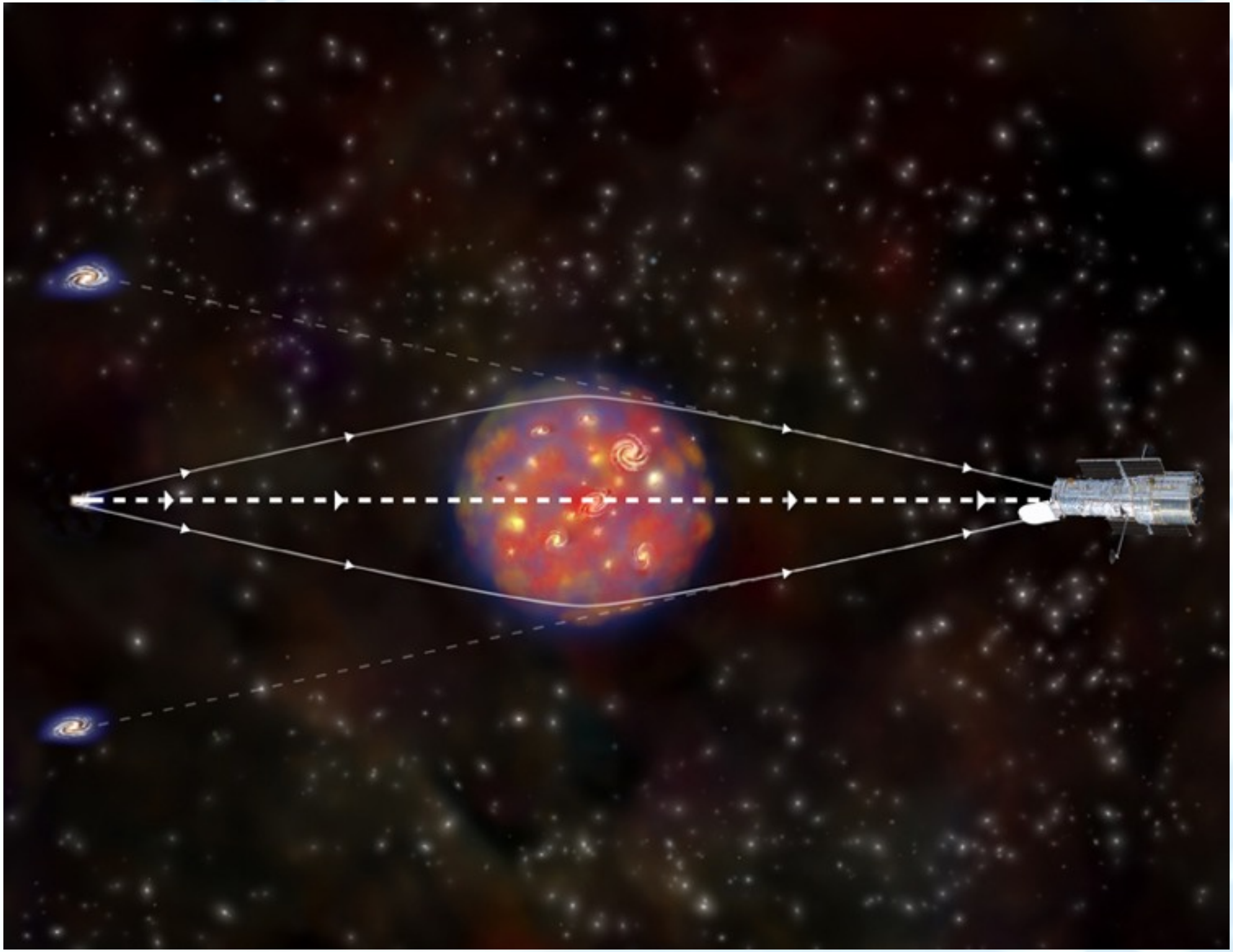
* Using the gas density jump at the shock we derived a shock Mach number of 3.2 ± 0.8, which corresponds to a shock velocity 4500 ± 1000 kms^{-1}

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

Clusters as Astroparticle Physics Laboratories

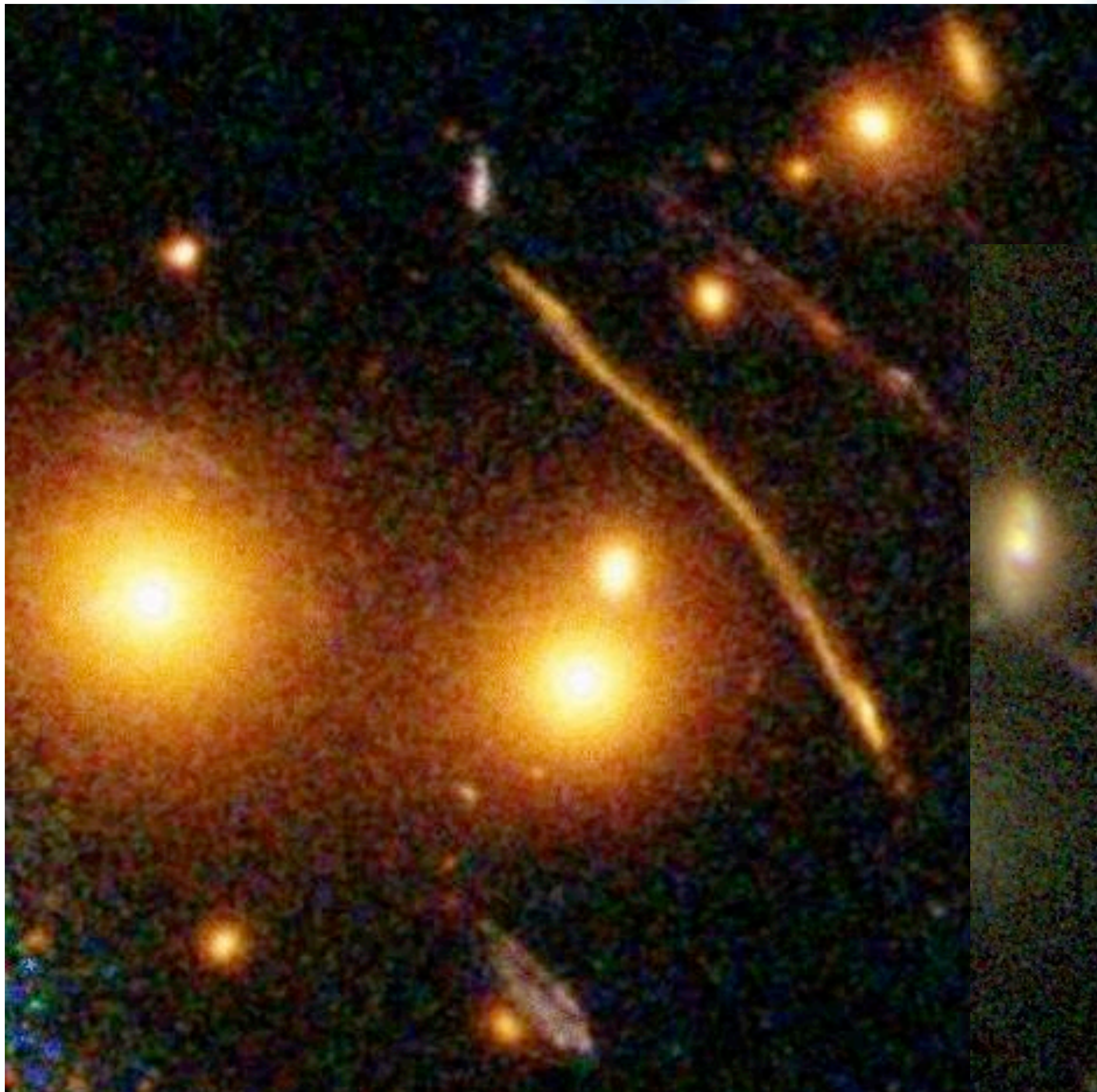
* Clusters of galaxies consist of approximately 13% of hot gas, 2% of stars and 85% of dark matter.
* The bullet cluster is no exception of this. But because of its unique geometry we are able to study the effects of each of these separately.
* Unique astroparticle physics laboratory - study dark matter distribution and its properties.

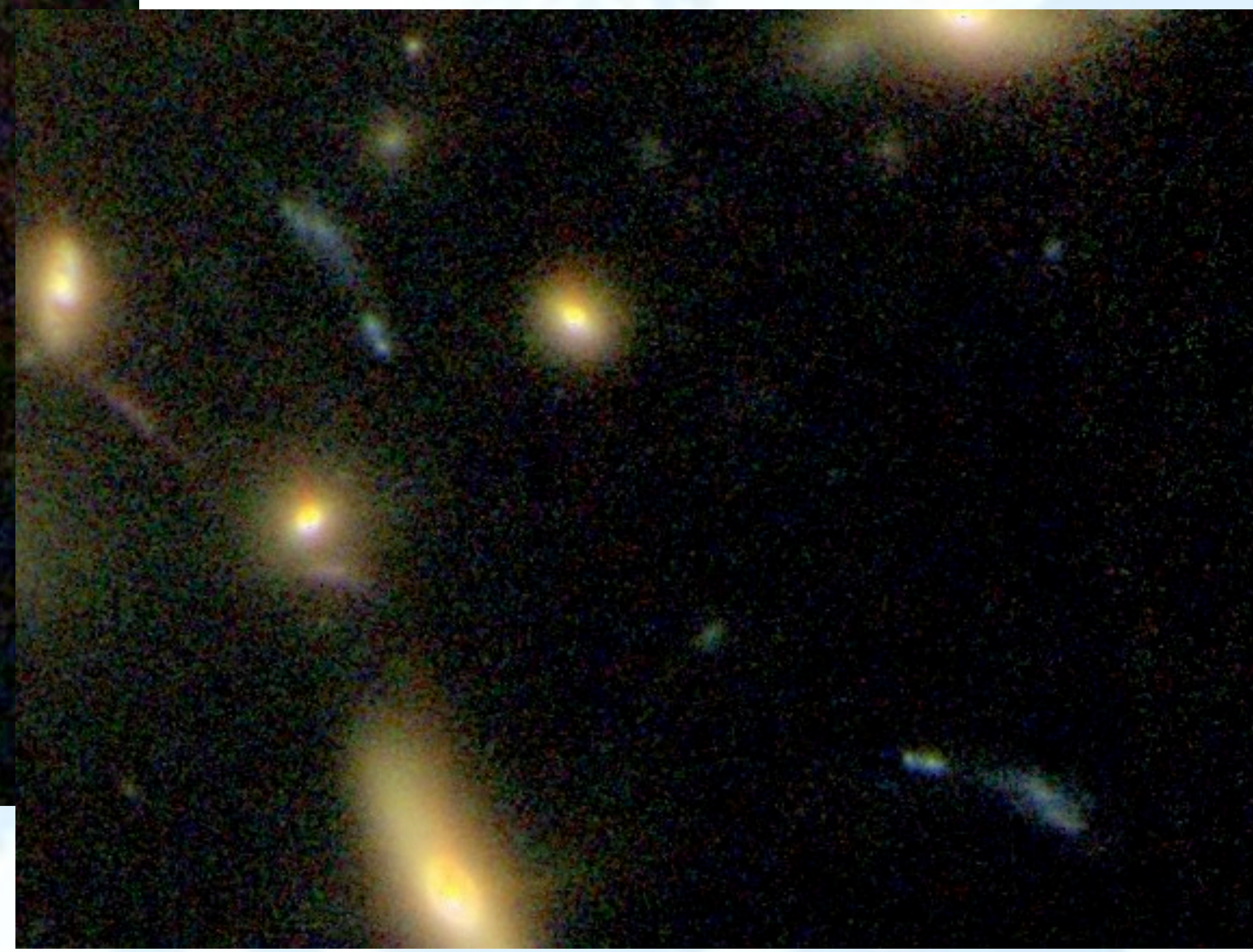
Gravitational Lensing



Strong Gravitational Lensing

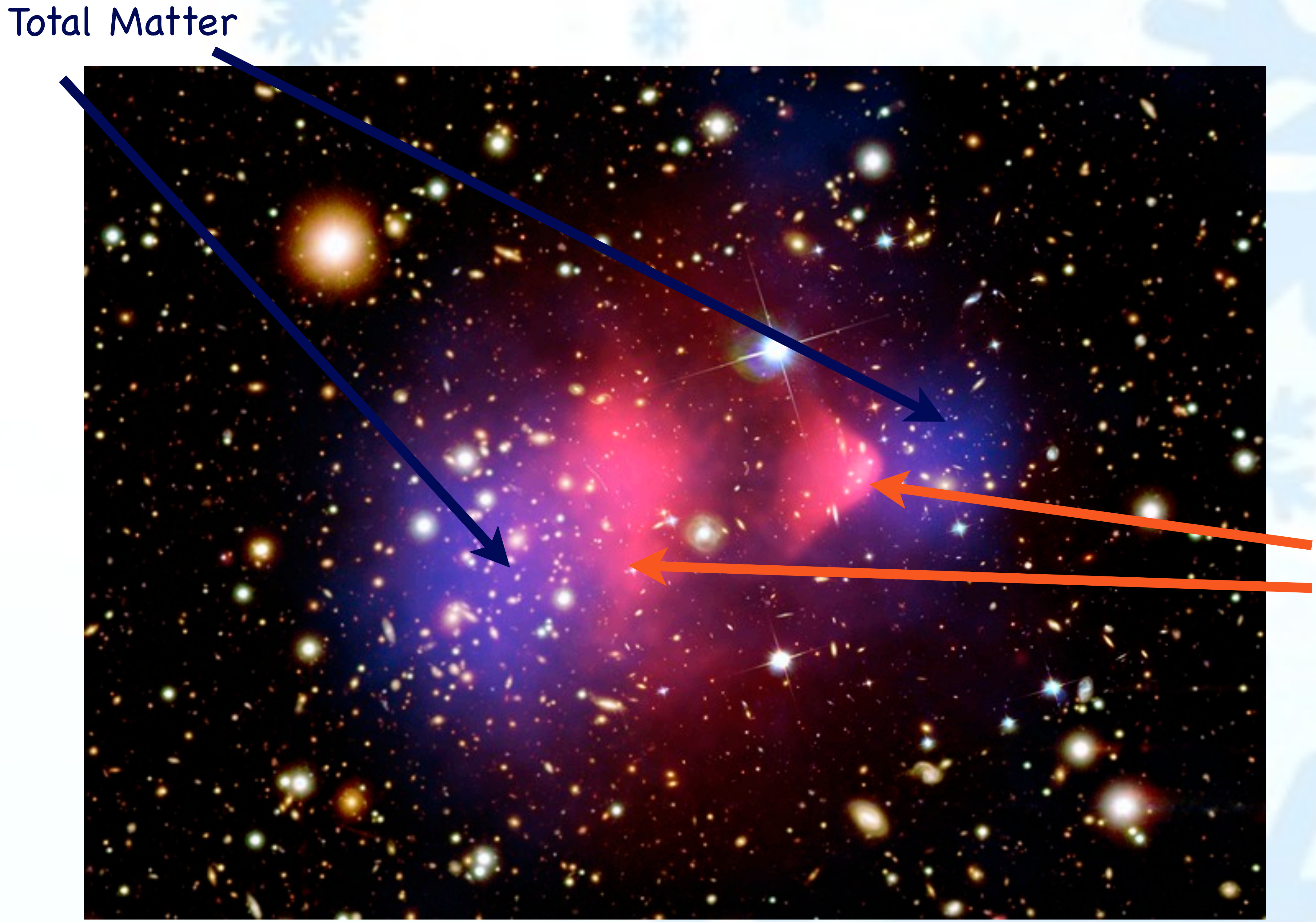
Strong Gravitational Lensing





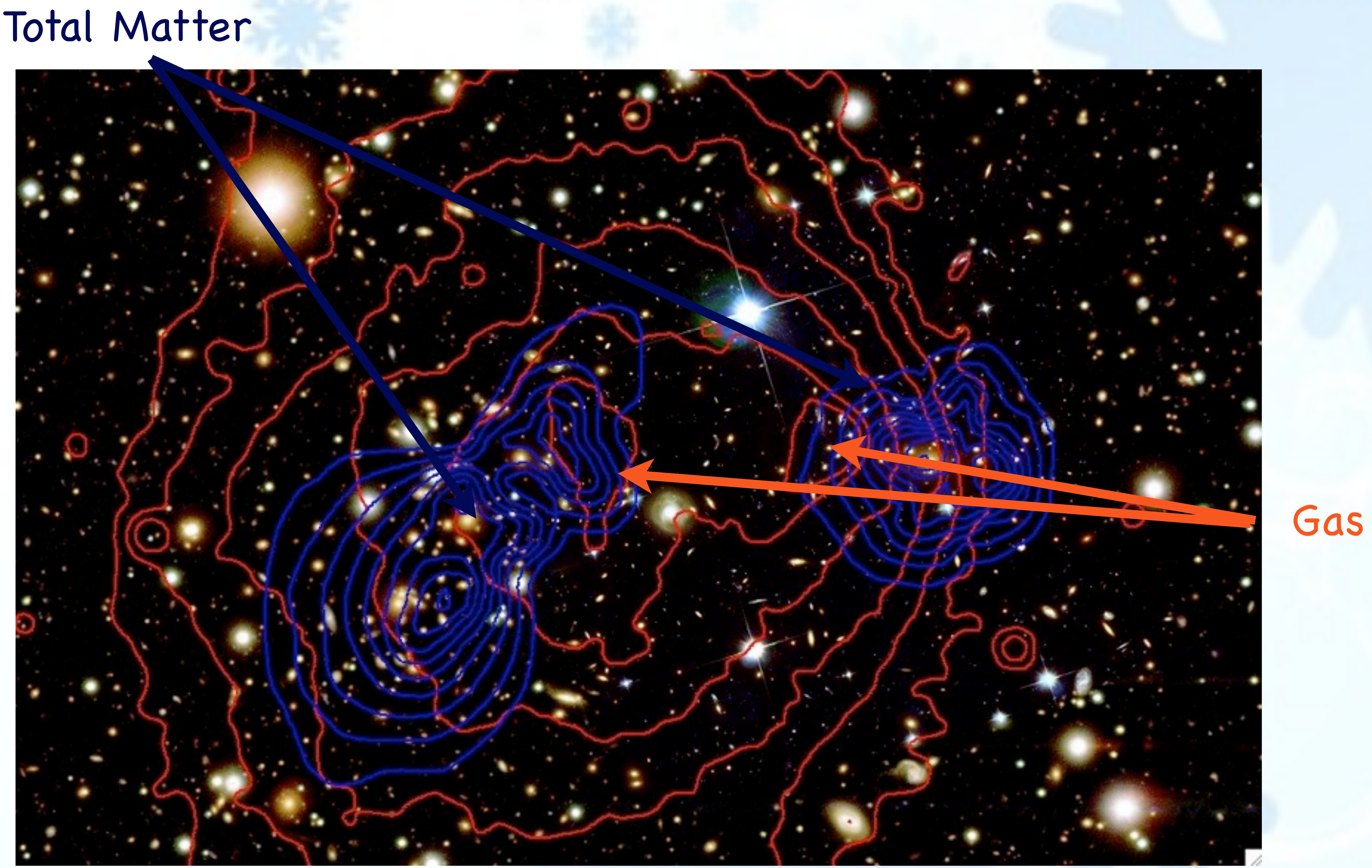
Weak Gravitational Lensing

Weak Gravitational Lensing



Clowe, MB et al. 2006

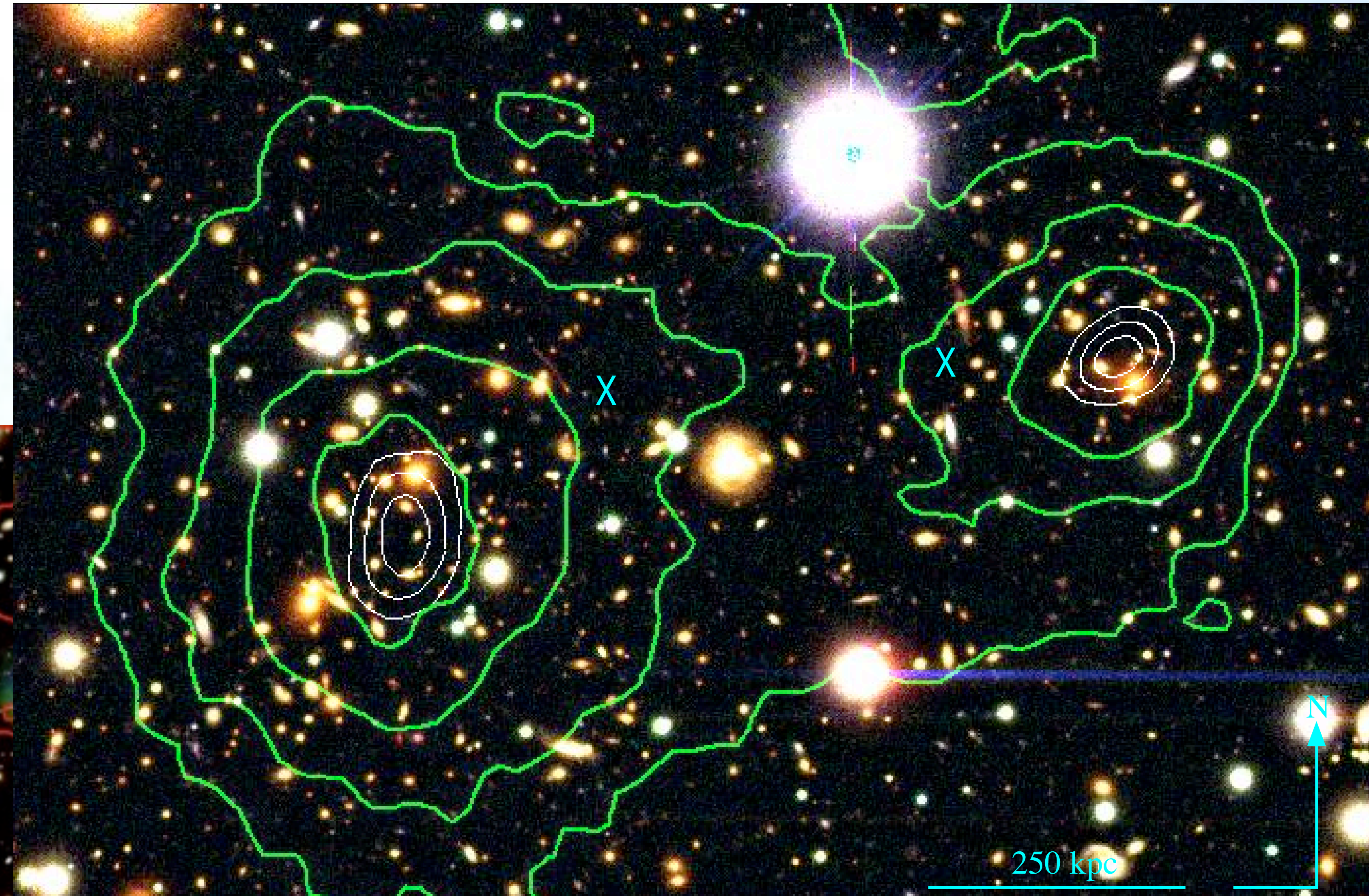
1E0657-56: Strong and Weak Lensing



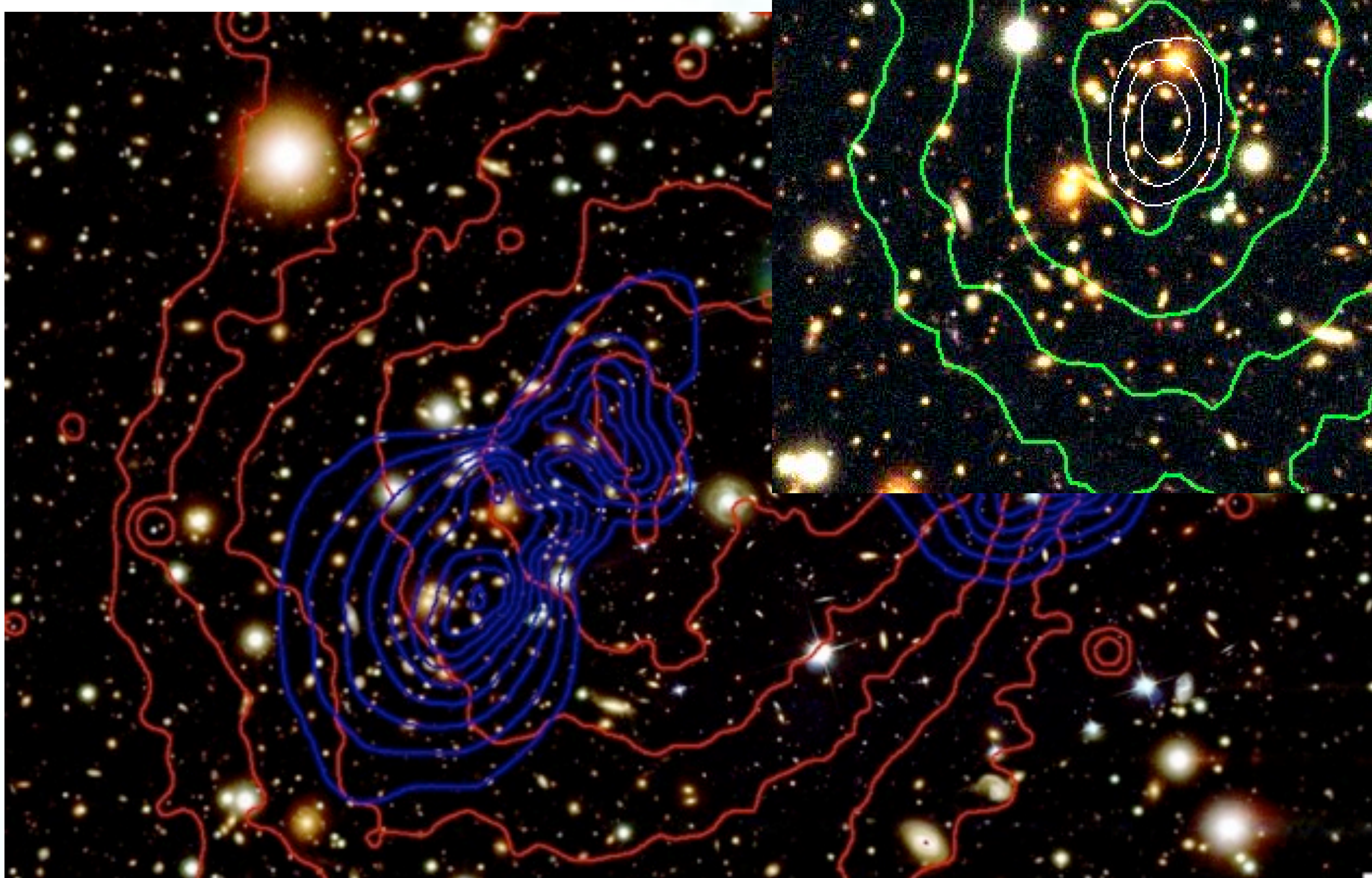
Bradač et al. 2006

1E0657-56: Strong and Weak Lensing

Only weak lensing



Strong and weak lensing

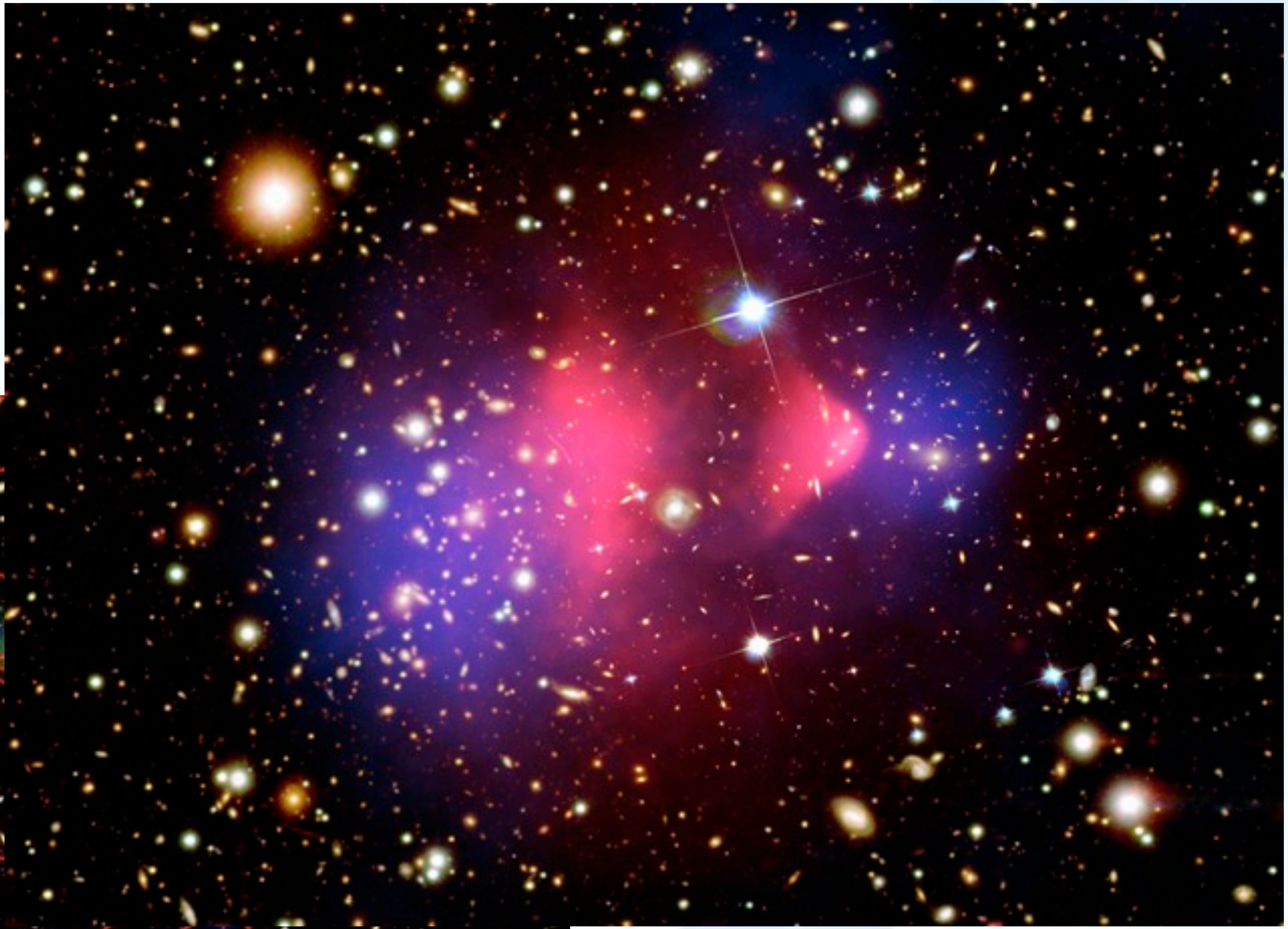


Clowe, MB et al. 2006

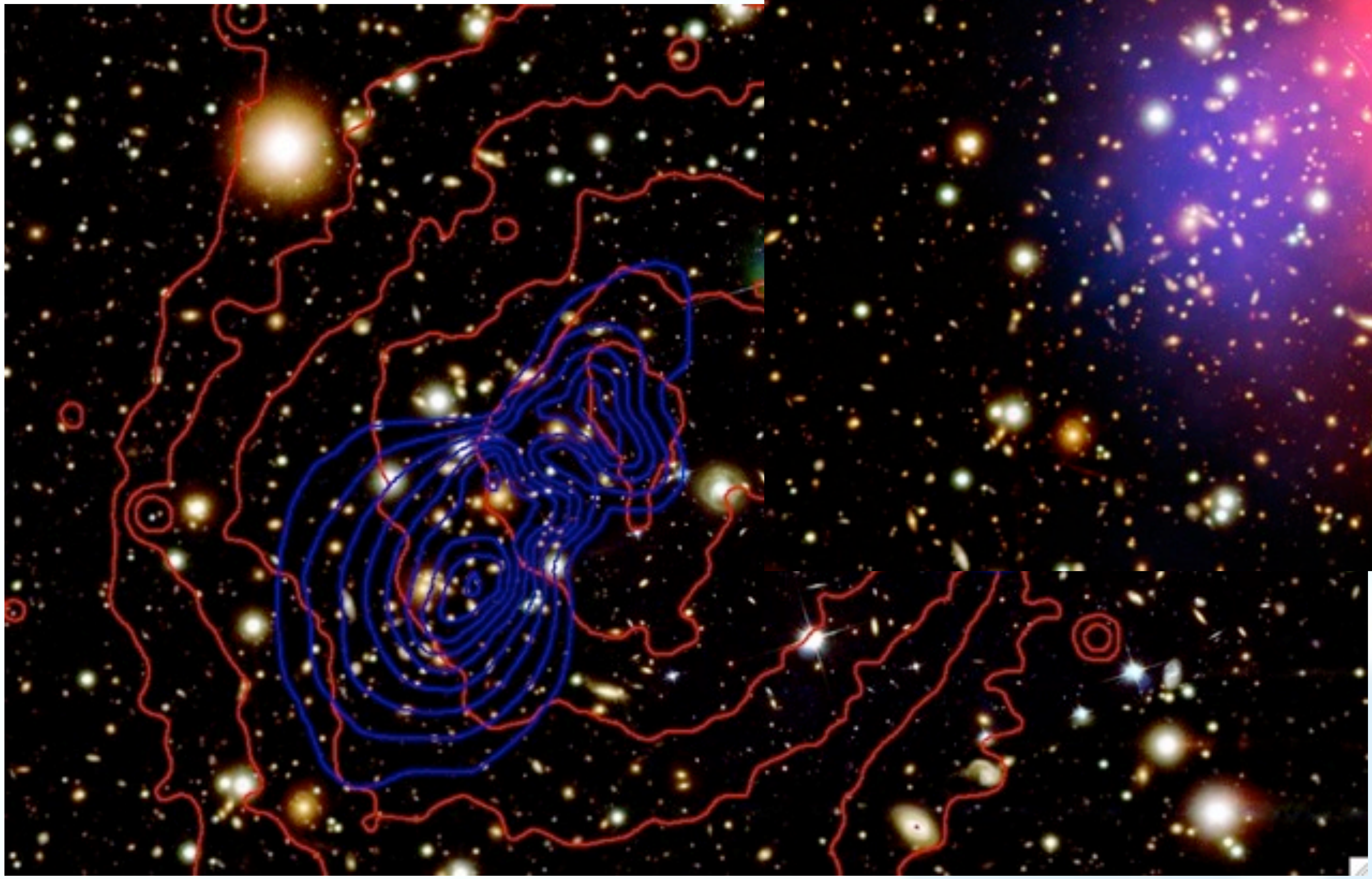
Bradač et al. 2006

1E0657-56: Strong and Weak Lensing

Only weak lensing

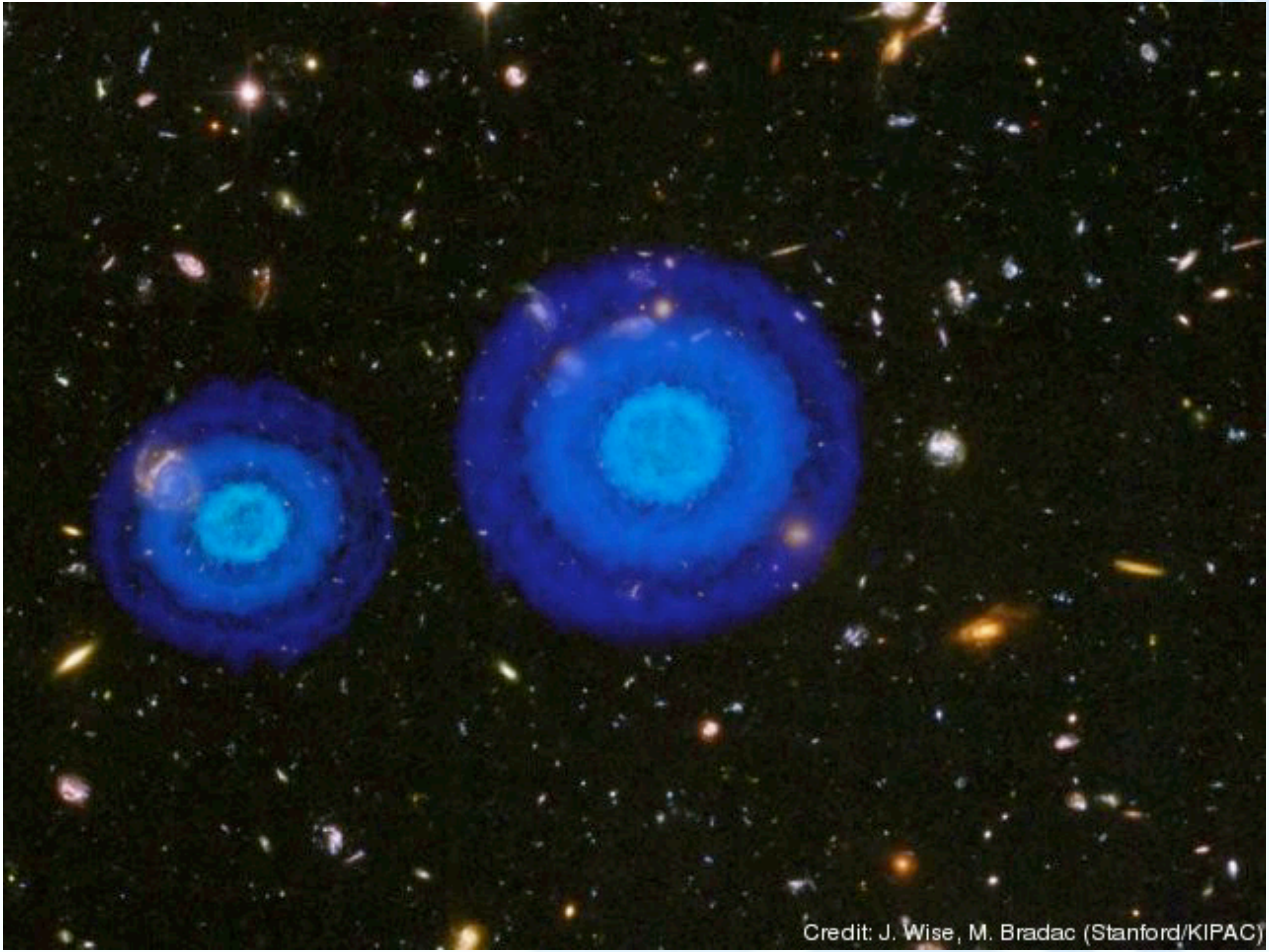


Strong and weak lensing



Clowe, MB et al. 2006

Bradač et al. 2006


Credit: J. Wise, M. Bradac (Stanford/KIPAC)

Dark Matter Properties

* Combining the Chandra data with lensing mass maps -> place an upper bound on the dark matter self-interaction cross section $\sigma/m < 1\ \mathrm{cm^2 g^{-1}} = 1.8\mathrm{barn/GeV}$ (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 $\sigma/m < 3\ \mathrm{cm^2 g^{-1}}$

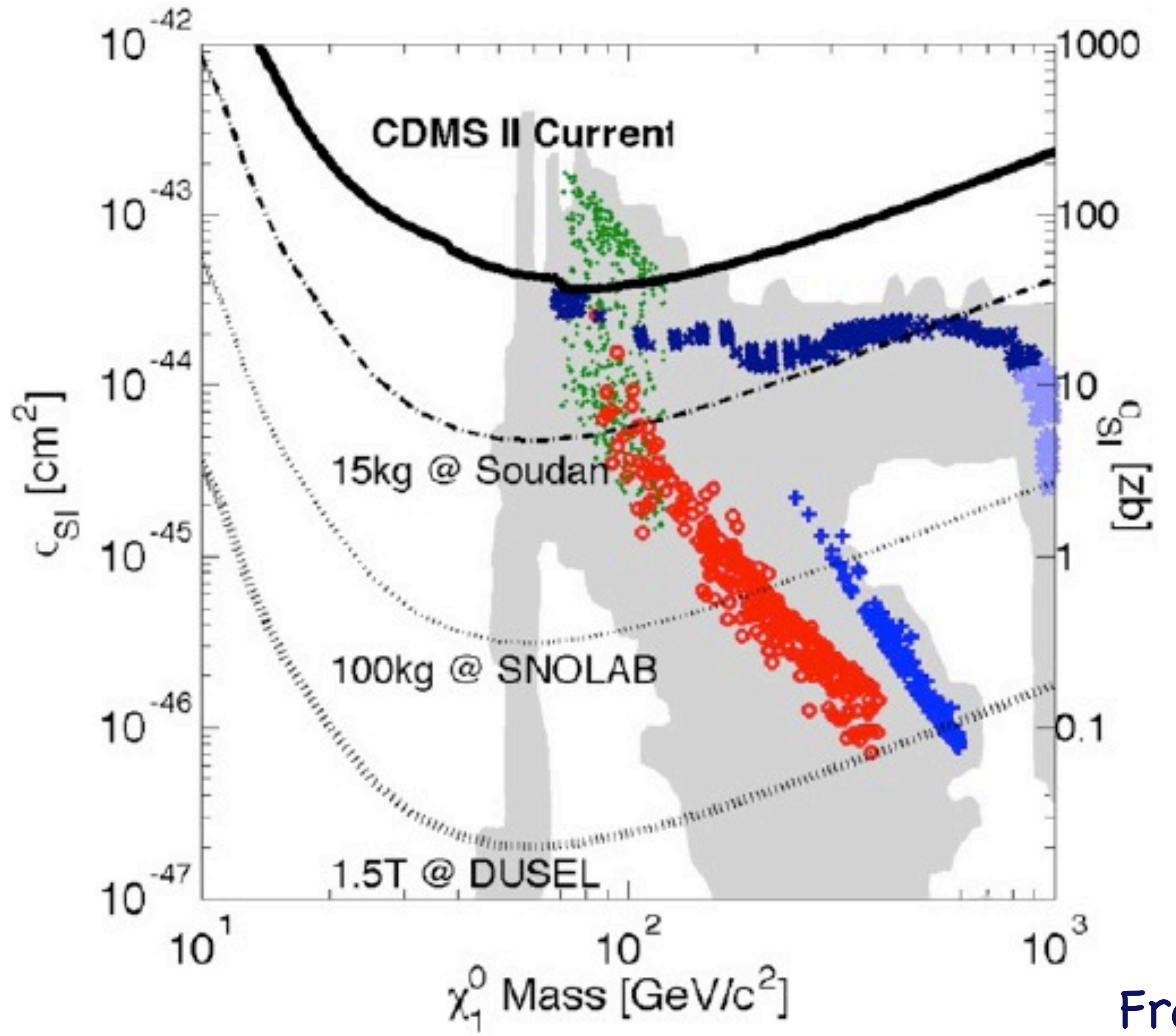
  -> No loss of mass from subcluster during interaction gives $\sigma/m < 0.8\ \mathrm{cm^2 g^{-1}}$

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

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

Search for Dark Matter

* Cryogenic Dark Matter Search
  -> every once in a while one of the DM particles should bump into an atom, knocking its nucleus out of place.
  -> Soudan/Minnesota



From J. Cooley & CDMS

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

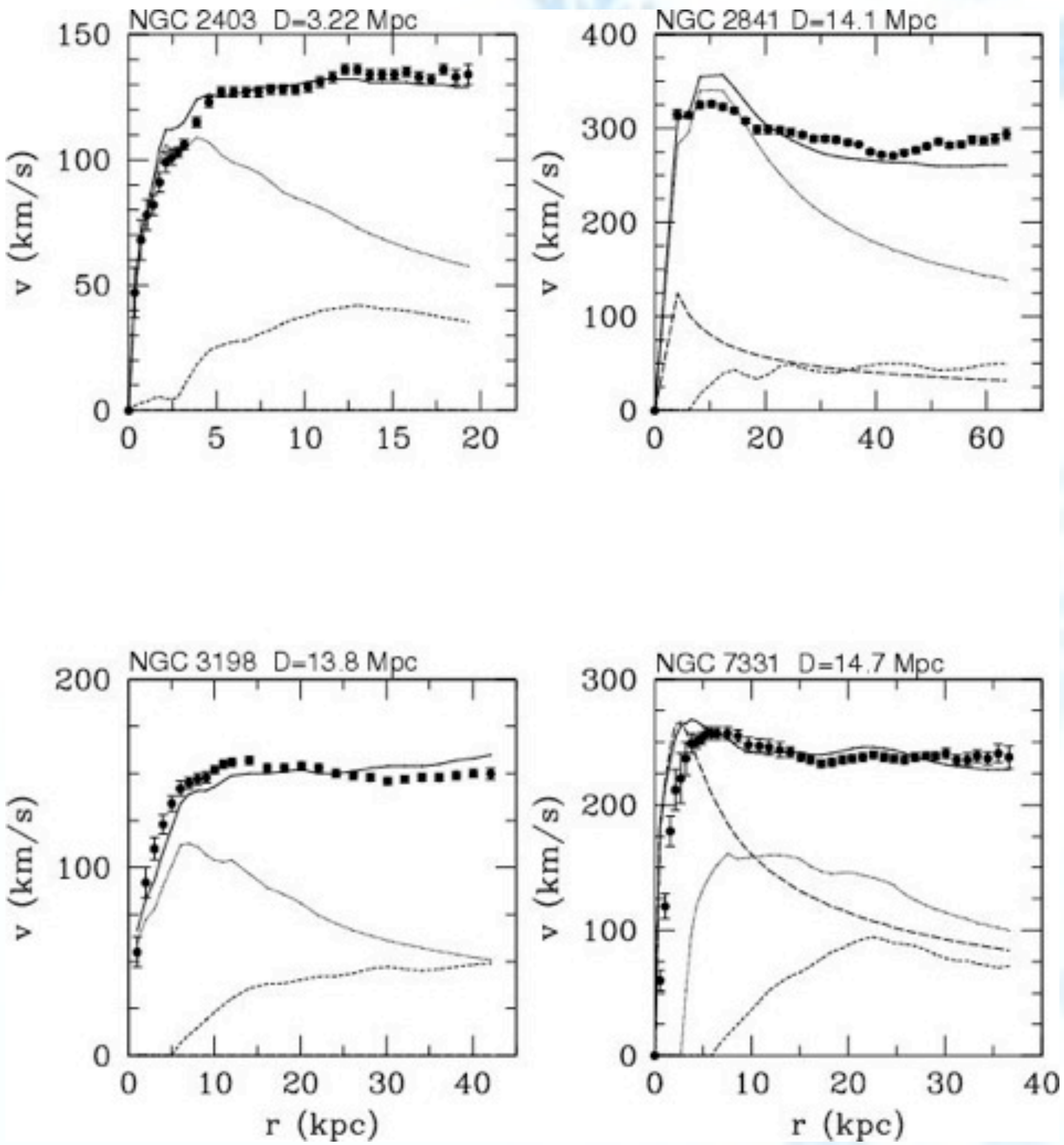
  ->Still require > 70% of the mass to be hot non-baryonic matter

  ->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.

Alternatives



$$a = \sqrt{\frac{GM}{R^2} a_0}$$

- Maybe there is no dark matter at all; maybe gravity is playing games on us.
- Modified Newtonian Dynamics - MOND
- The acceleration (modified at large distances)
- Can fit galaxy rotation curves well with either DM in Newtonian gravity or in Modified gravity without dark matter (Bottema et al. 2002).

Really Direct Evidence for Dark Matter?

* But MOND can't explain masses of clusters
* Adopting MOND gravity:

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

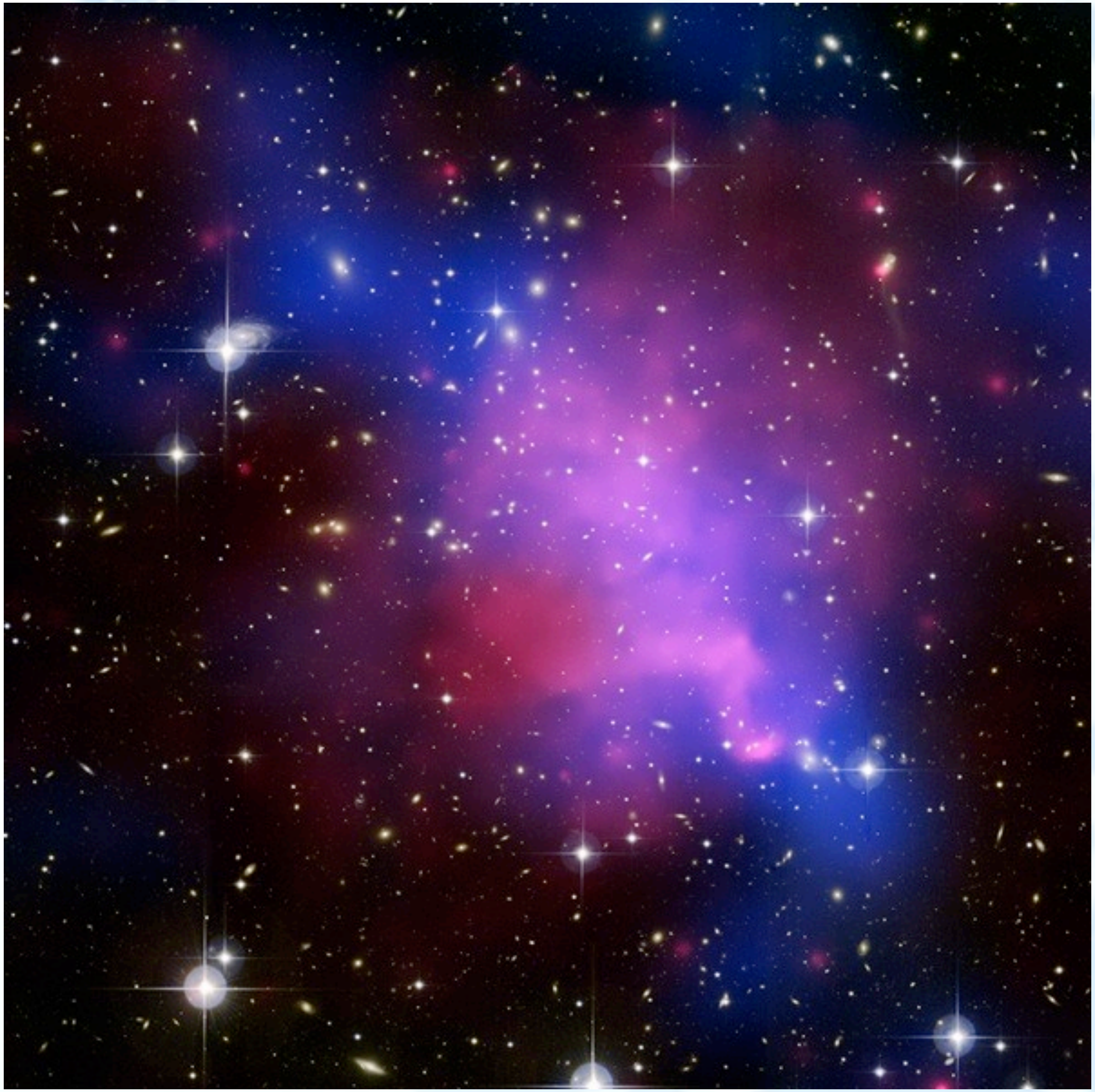
  ->Still require > 70% of the mass to be hot non-baryonic matter

  ->Incompatible with strong+weak lensing analysis.

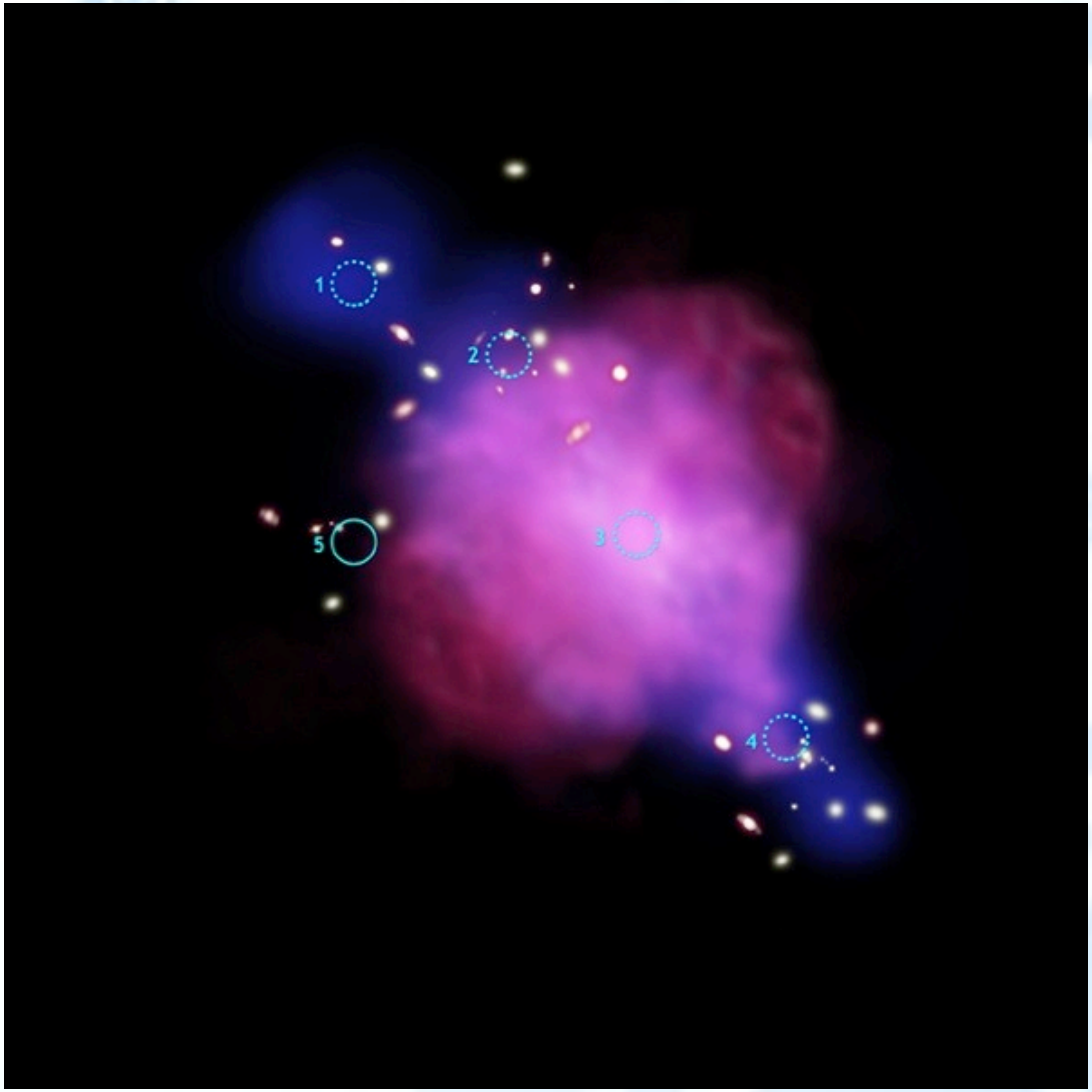
  ->Gas mass too low for the subcluster.
* Moffat (2006) - MOG to displace kappa peaks away from gas peaks - very unphysical profile.

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

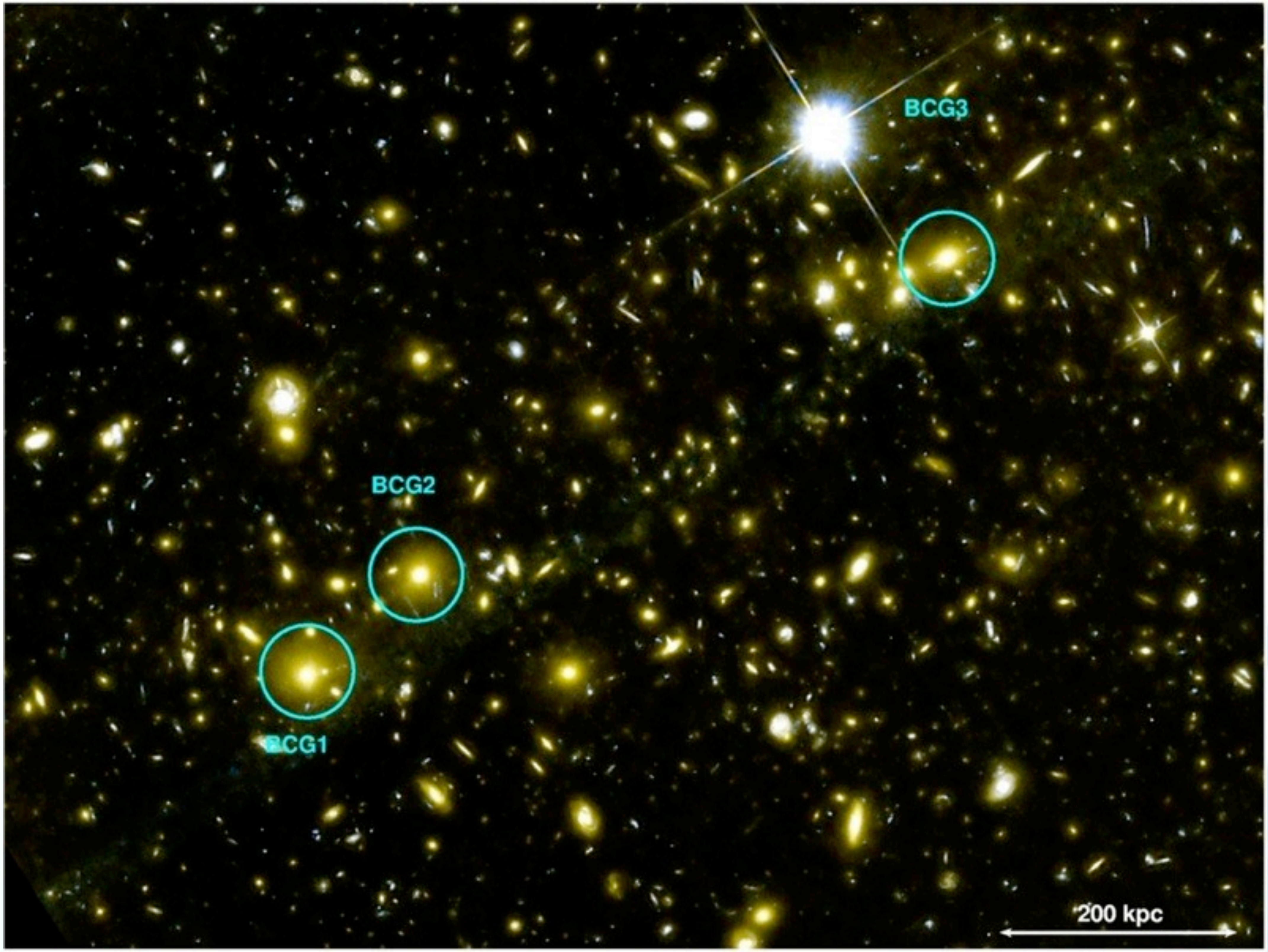
* Weakly self-interacting dark matter: requiring $3.8 \pm 1.1\ cm^2 g^{-1}$ (Bullet cluster constraints $\sigma/m < 0.7\ cm^2 g^{-1} = 1.3 barn/GeV$)

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 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)

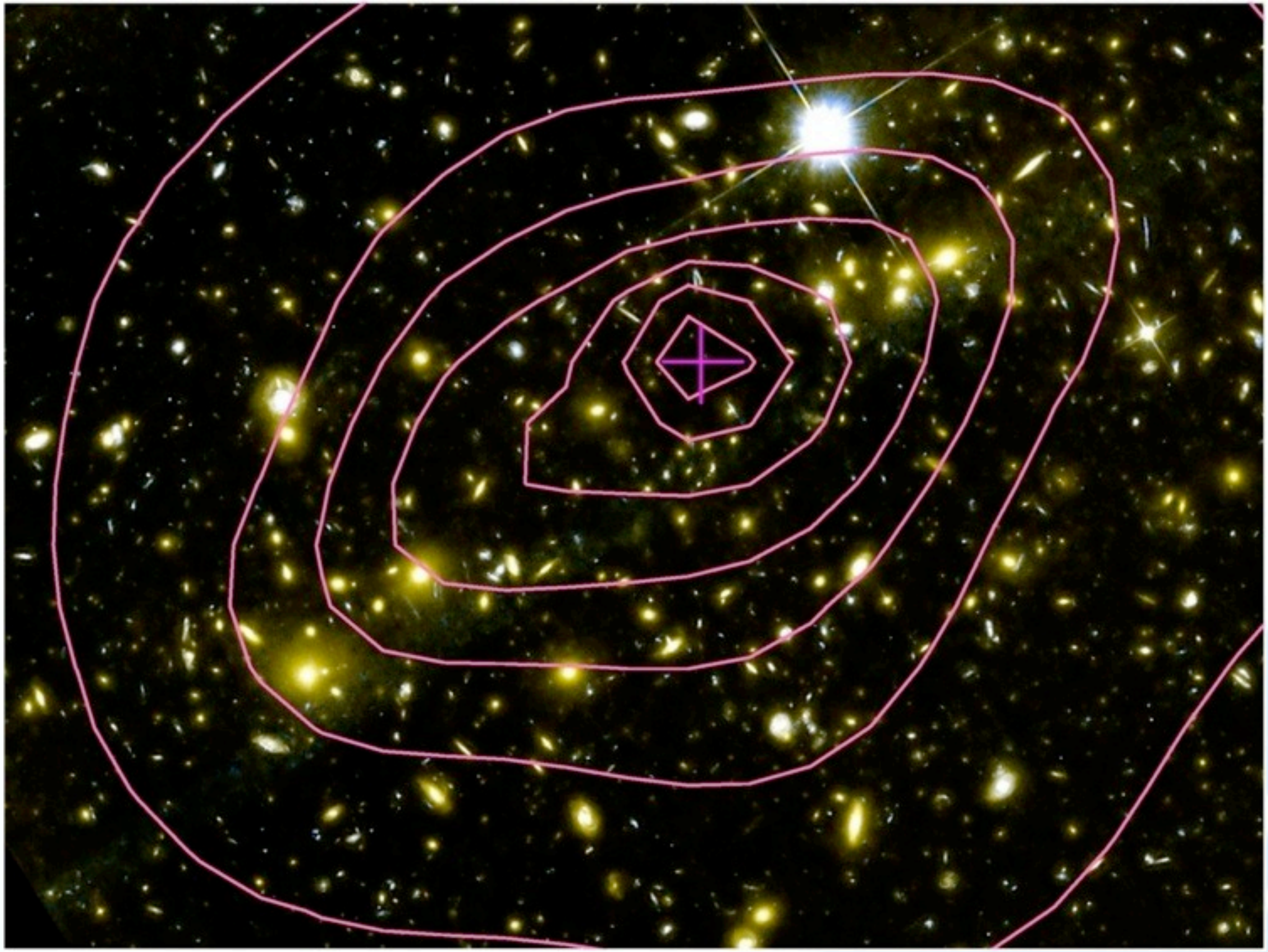
* Velocity separation of the BCG's radial direction
  $\Delta z = 0.0005 \pm 0.0004$ (100±80 km/s)

* 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

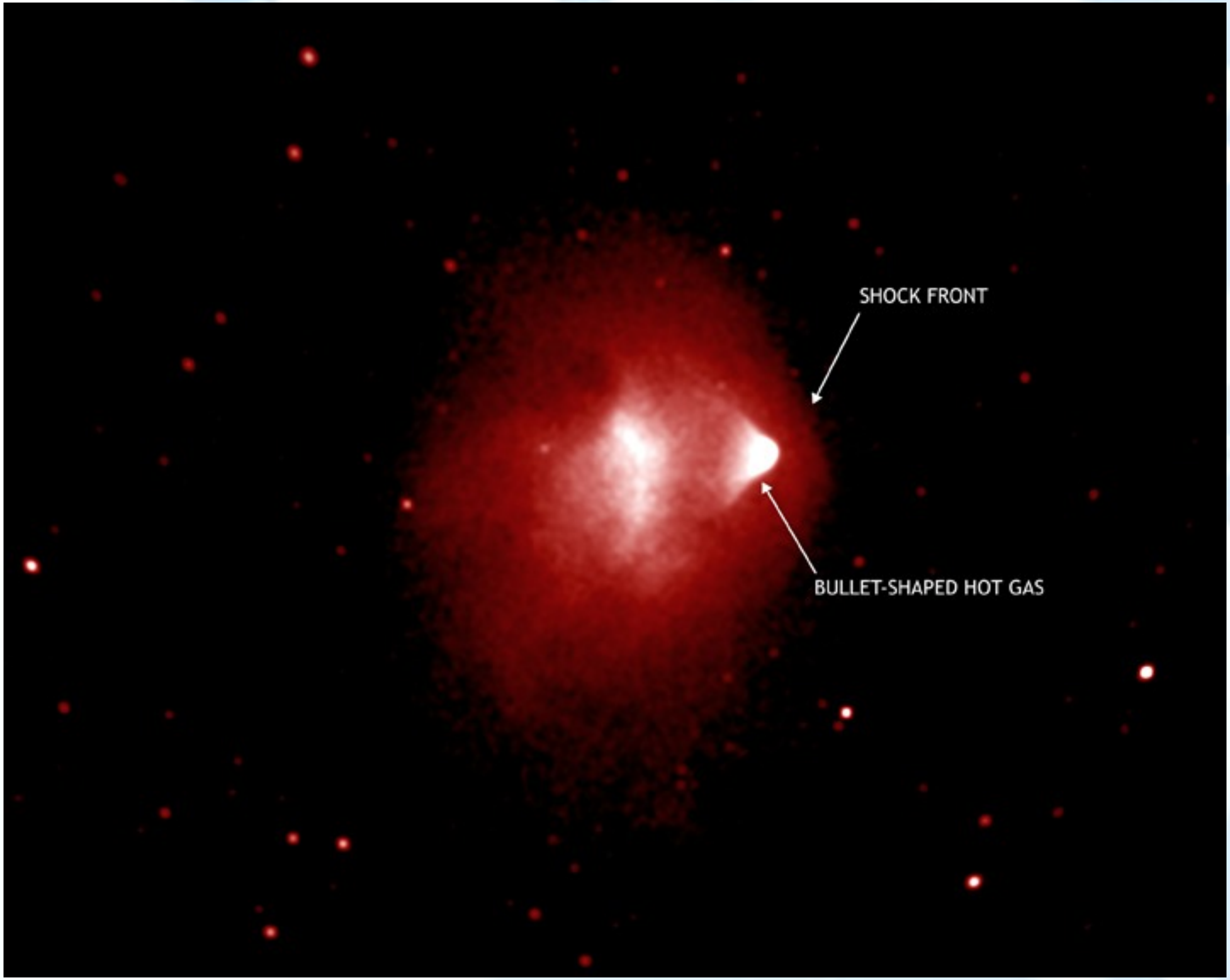


* 38ks Chandra (115ks more to come)
* Gas peak
* Too shallow to see a shock front

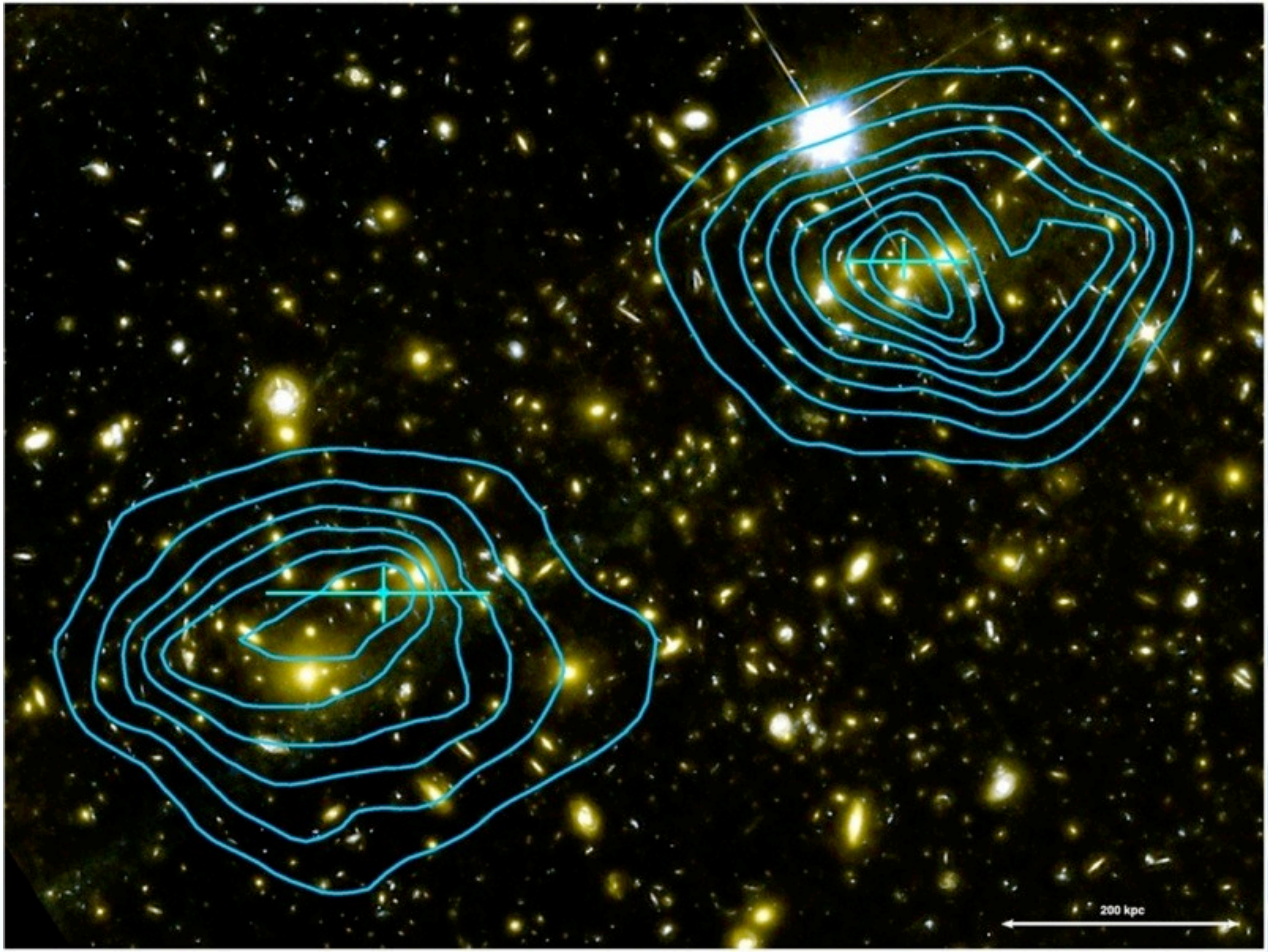
Why is Baby Bullet not a “Bullet”

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

Why is Baby Bullet not a "Bullet"



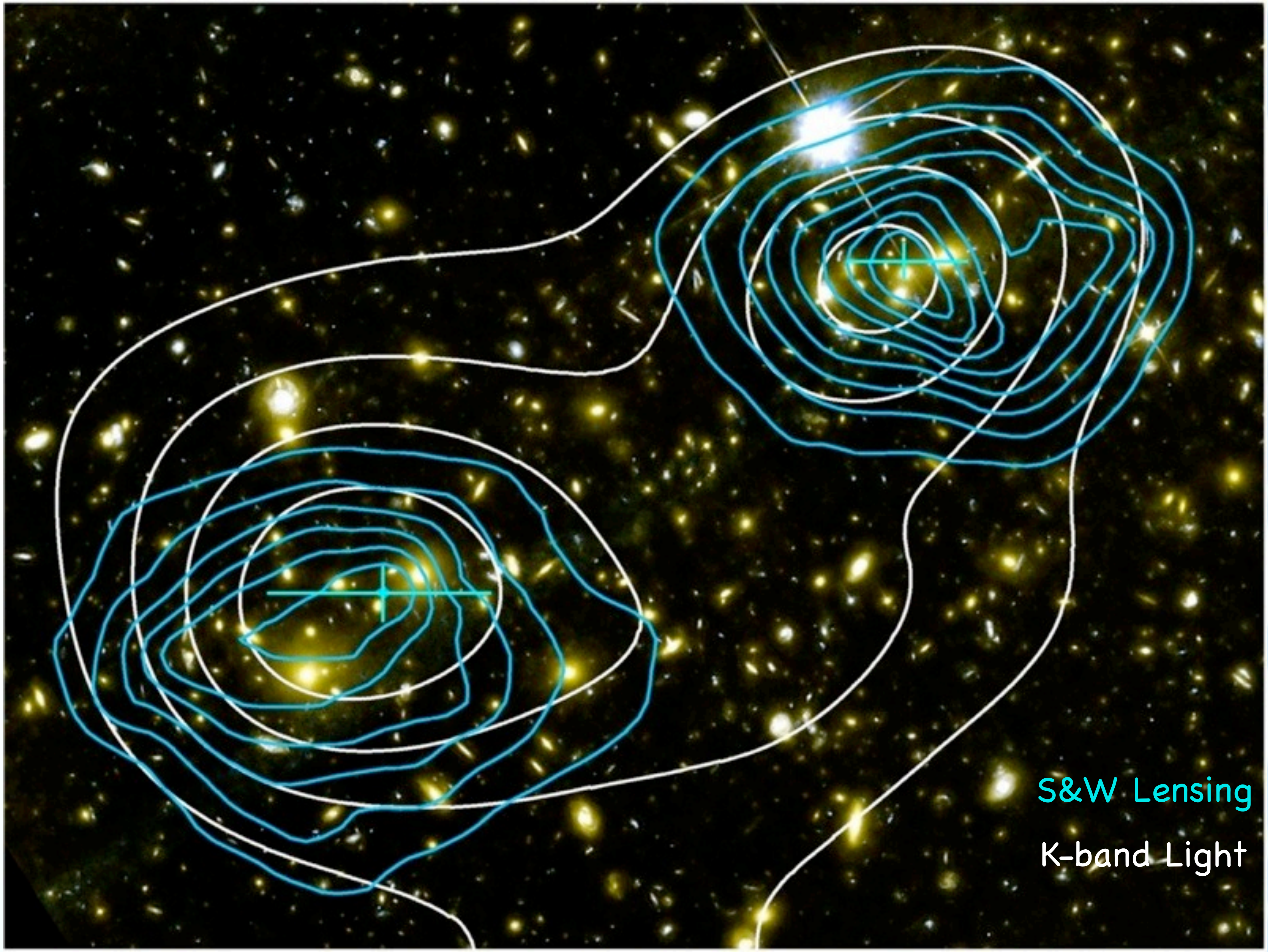
Total Mass Distribution



S&W Lensing

Bradač et al. 2008b

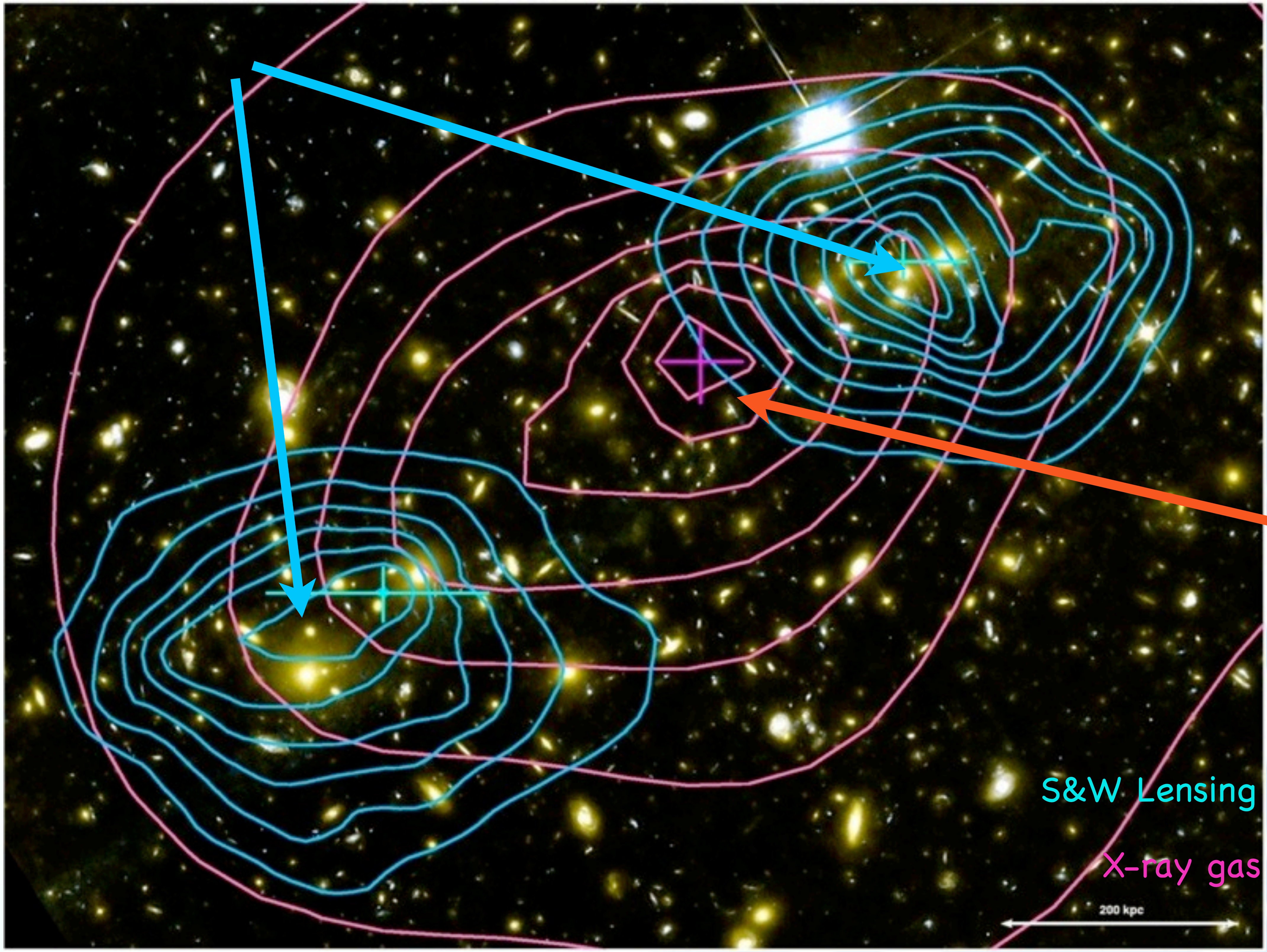
Mass vs. Light



Bradač et al. 2008b

Mass vs. Gas

Total Matter



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 $\sigma/m < 4\ cm^2 g^{-1}$ = 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)

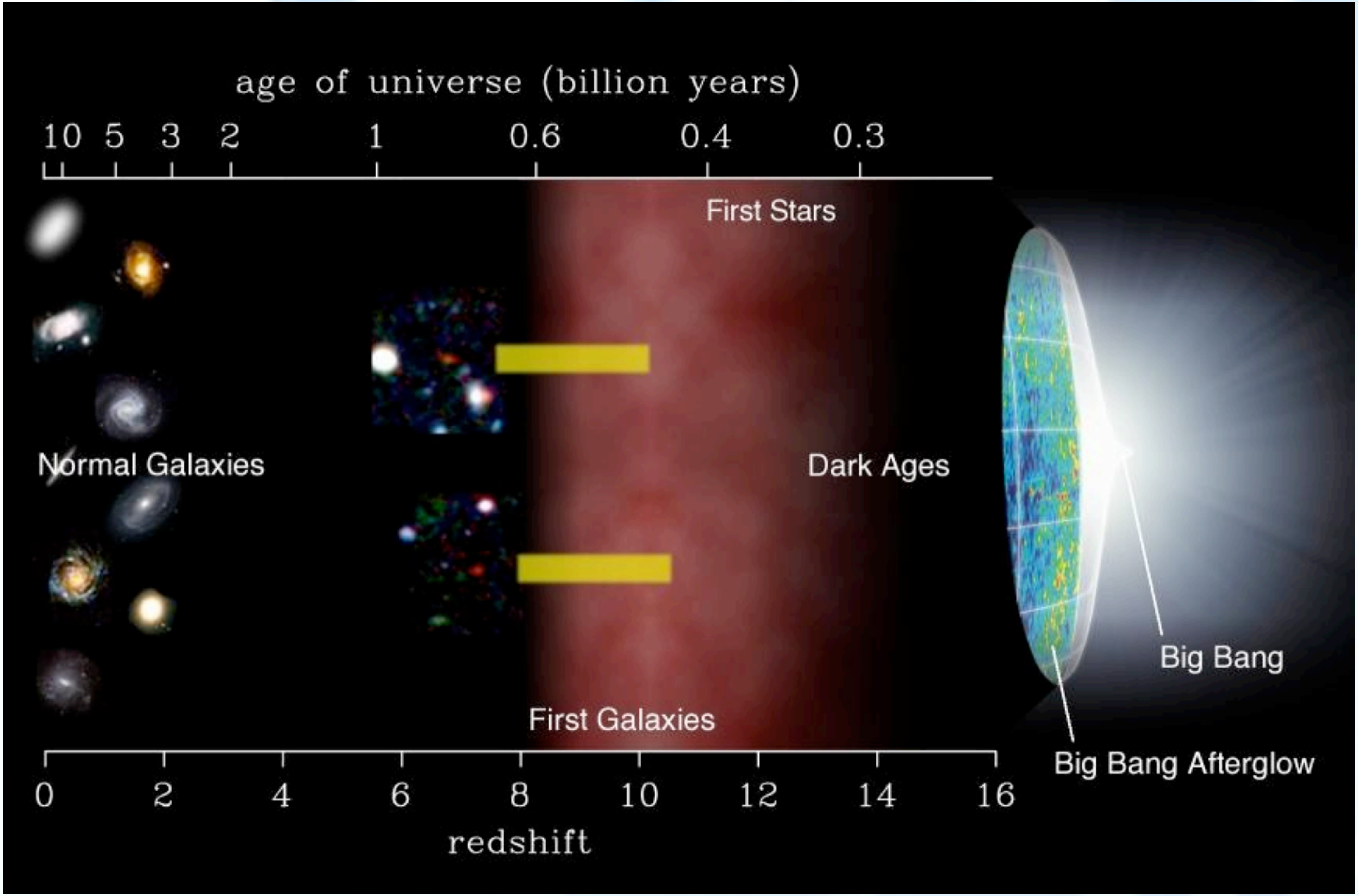
  -> ~~No loss of mass from subcluster~~

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

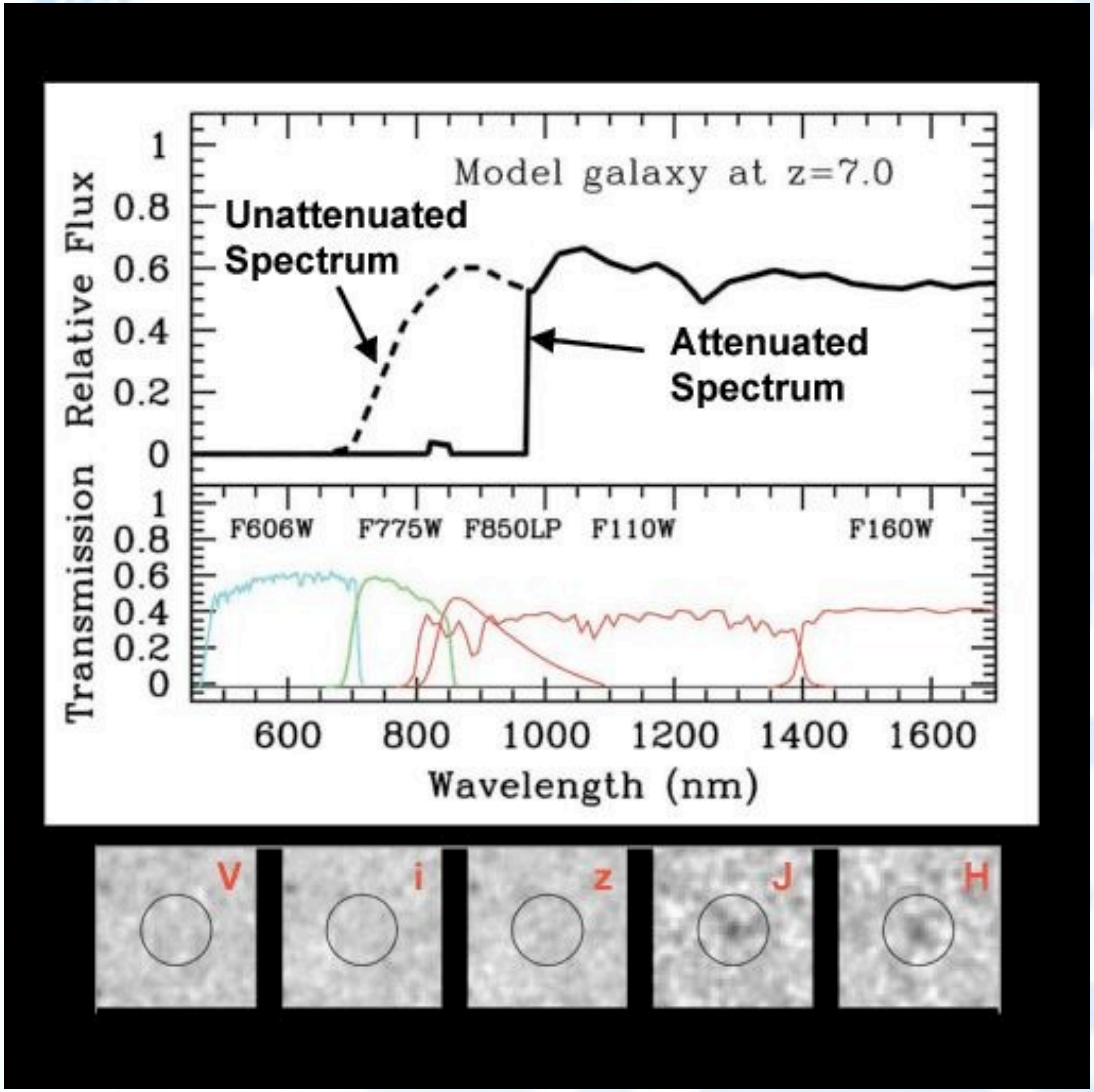
Sharpening Cosmic Telescopes to Study First Galaxies

=

High-z Universe

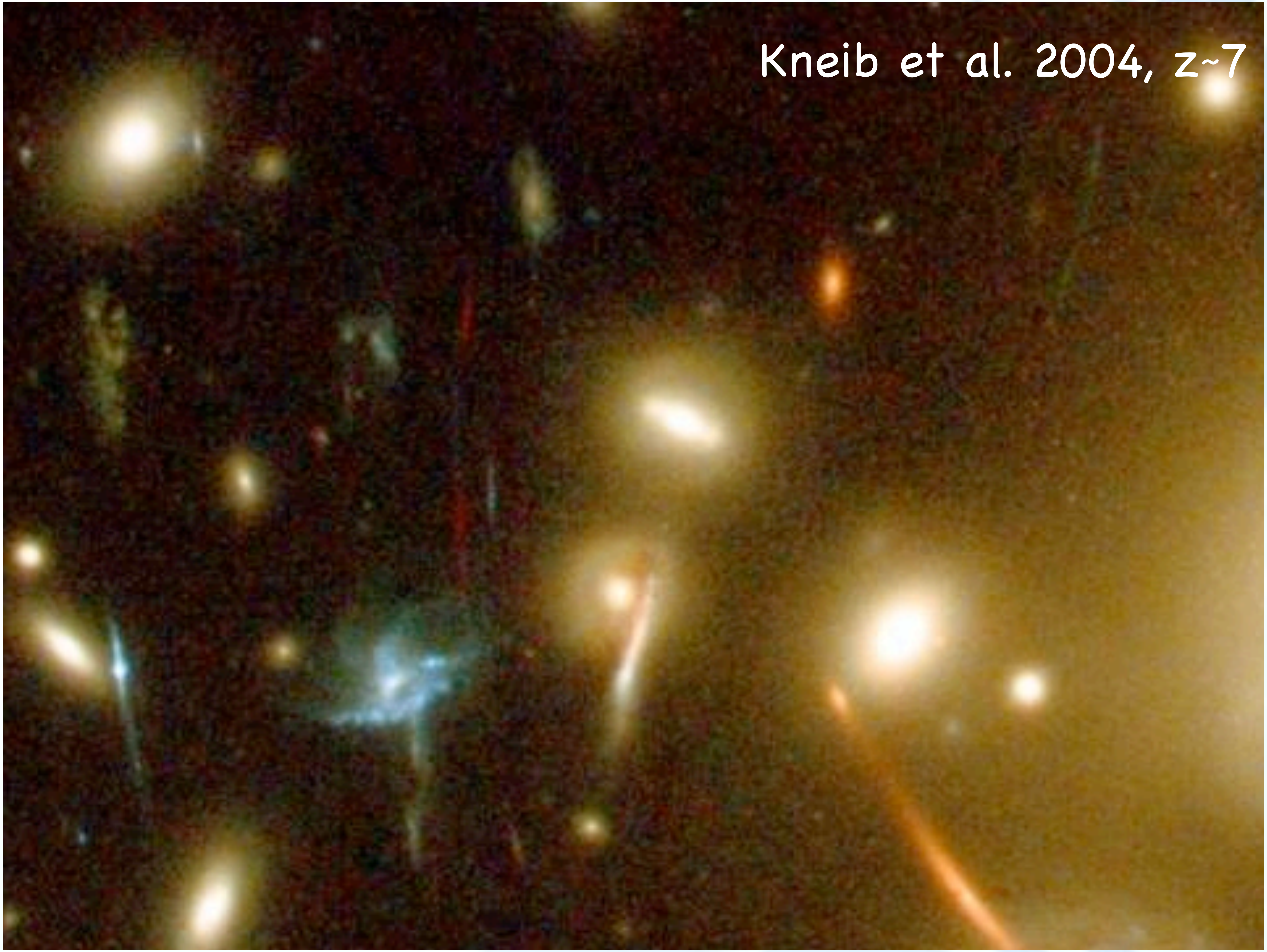


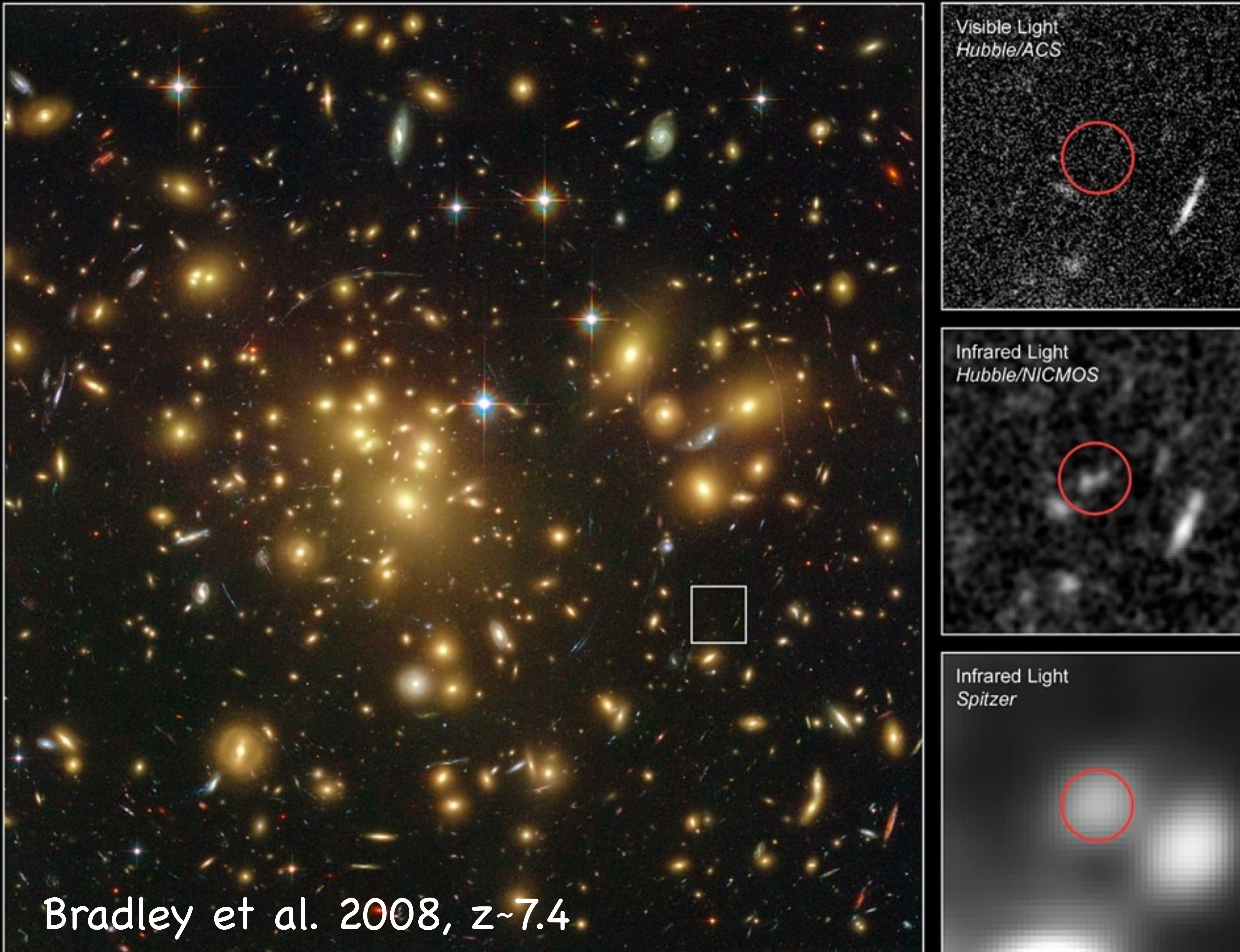
High-z Universe



Observing z>7 Universe Through Gravitational Telescopes

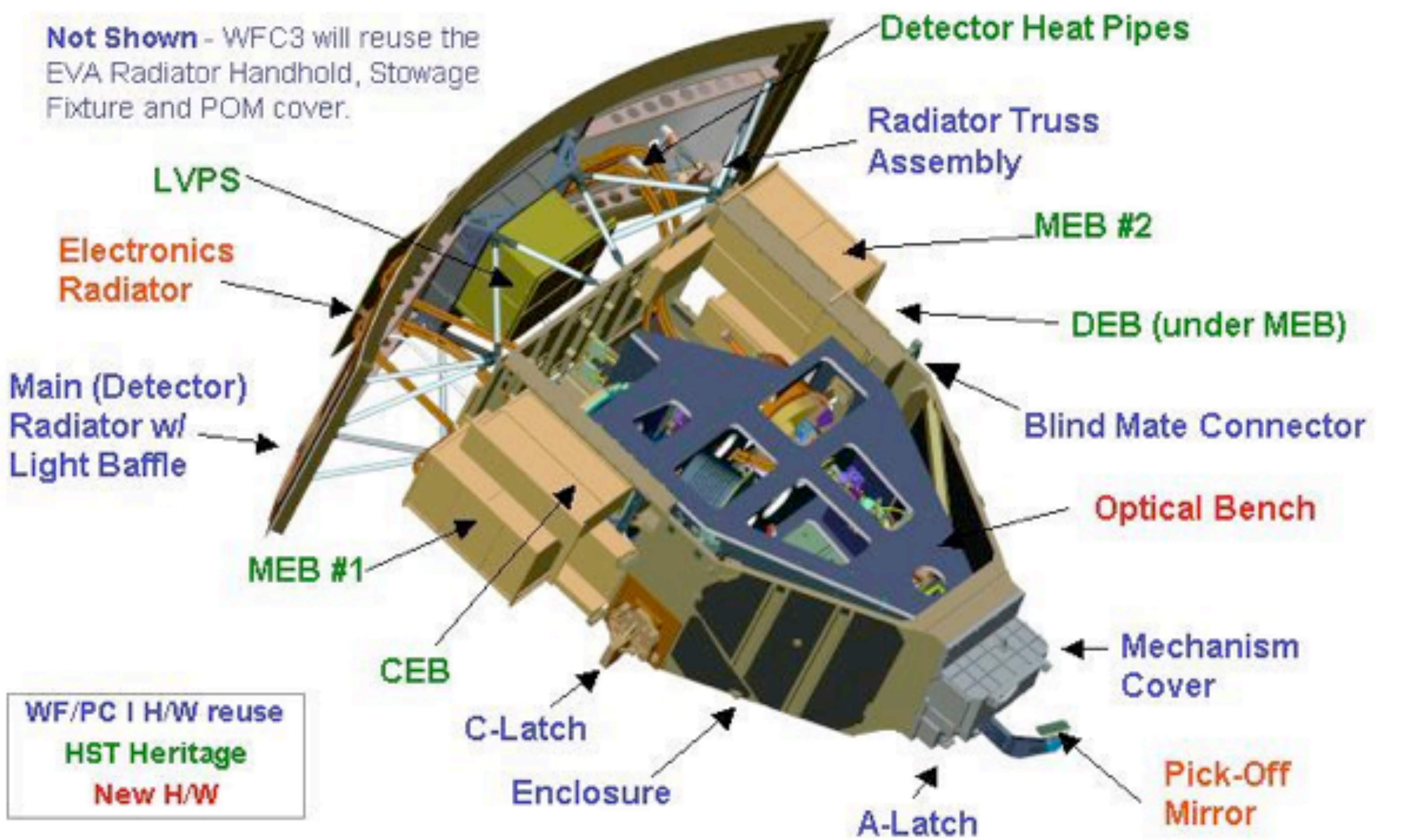
* Lensing is fantastic!
* Large magnification factors, allows us to get larger number counts (provided the luminosity function is steep)
* Large areas with observed multiple images - much eased identification; no need for often prohibitive spectroscopy
* Magnification maps are known to sufficient accuracy to constrain the number counts (and for best cases also individual luminosities)


Kneib et al. 2004, z~7

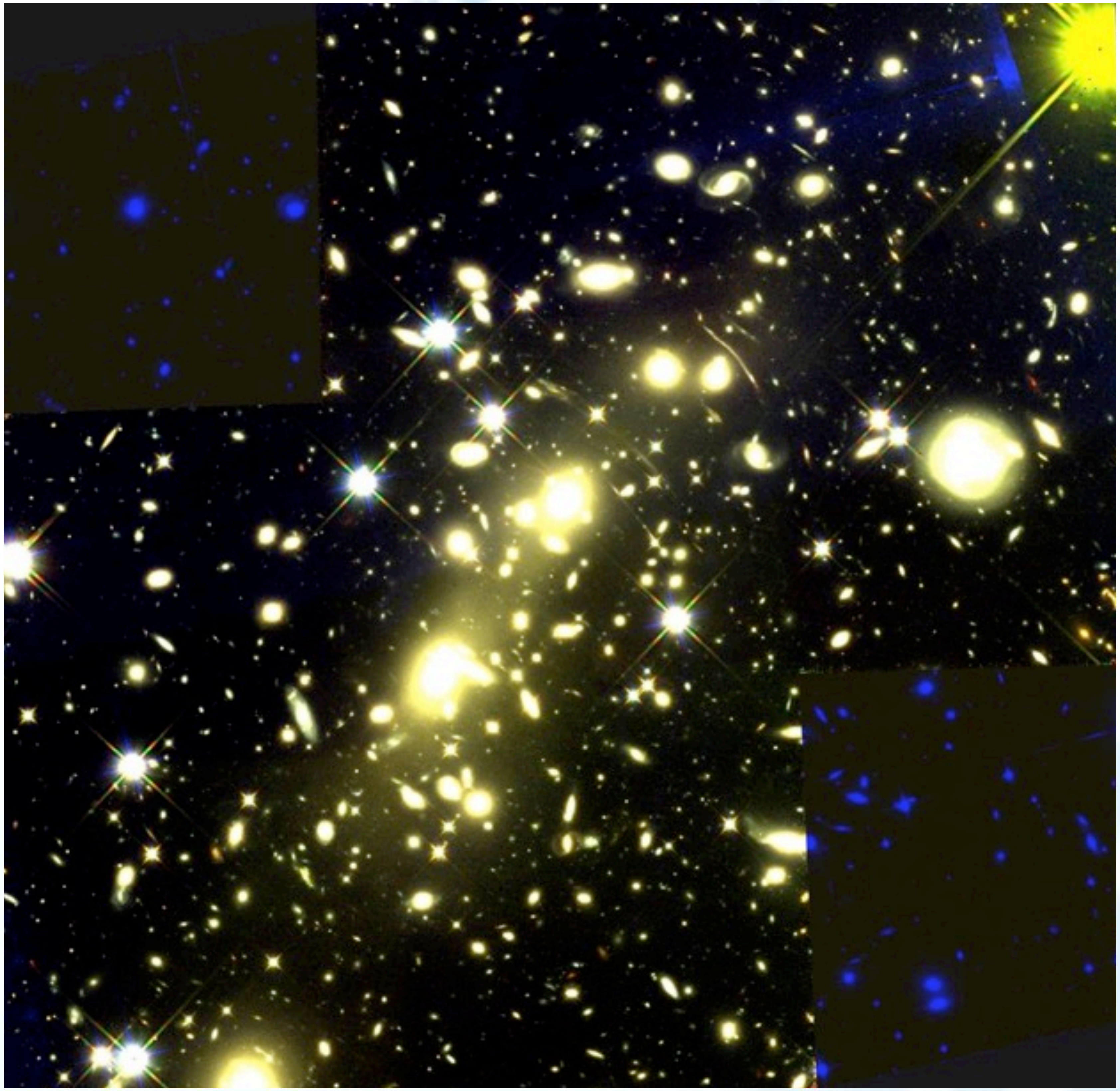

Visible Light
Hubble/ACS
Infrared Light
Hubble/NICMOS
Infrared Light
Spitzer
Bradley et al. 2008, z~7.4

New Camera WFPC3 on HST!

* Horray!

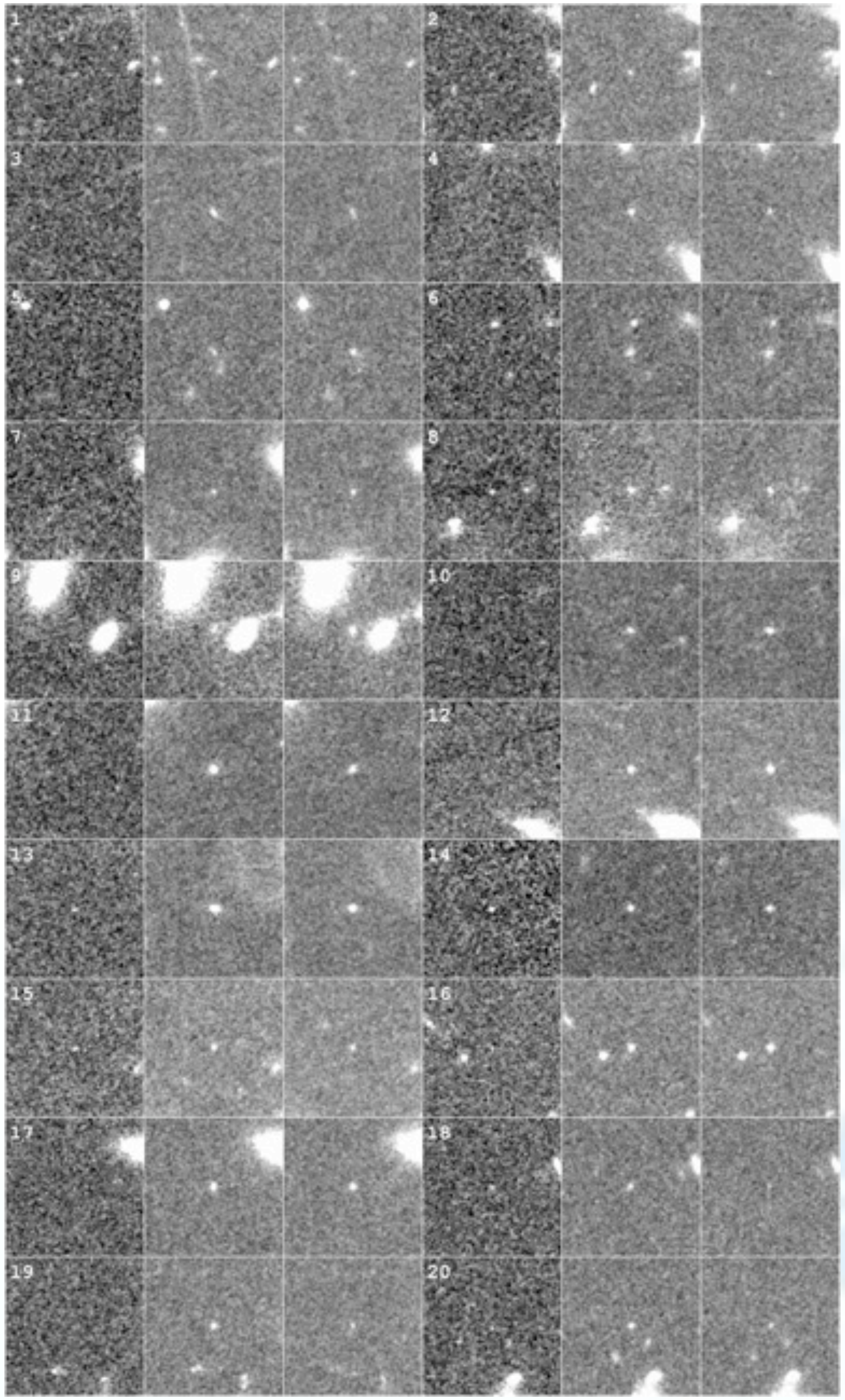


Baby Galaxies Behind the Bullet Cluster



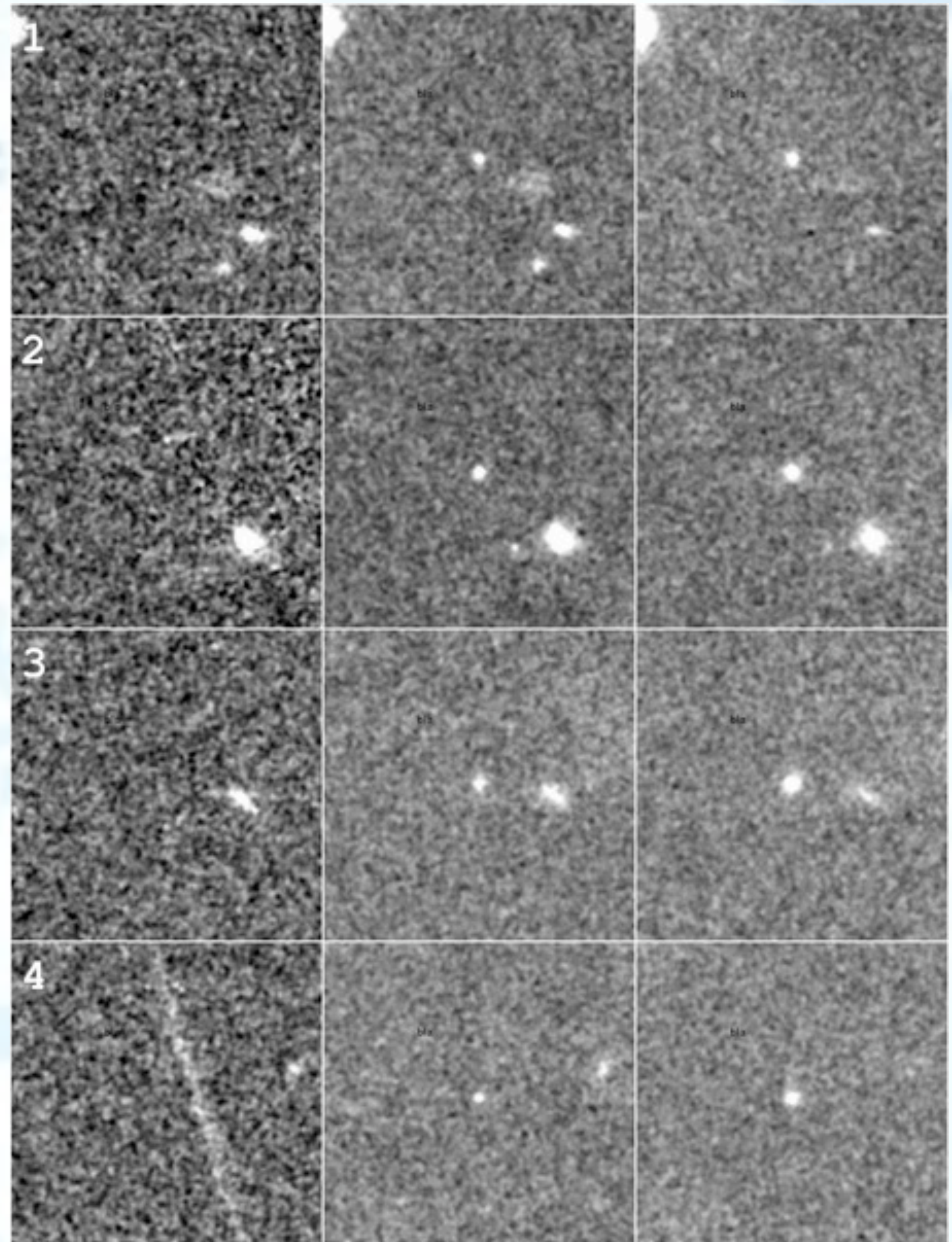
F850LP (ACS)
F110W (WFC3)
F160W (WFC3)

Hall, MB et al in prep.



Z ~ 5 (V-dropouts)

F606W F775W F850LP



Z ~ 6 (i-dropouts)

Conclusions

* Massive clusters are ideal tools to do cosmology

  -> Measure mass and mass distribution reliably (yes we can)

  -> We learn a lot about dark matter from both individual examples and large samples (yes we do)

  -> Bring first generation of galaxies within our reach (yes we will)


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

S.Caroll