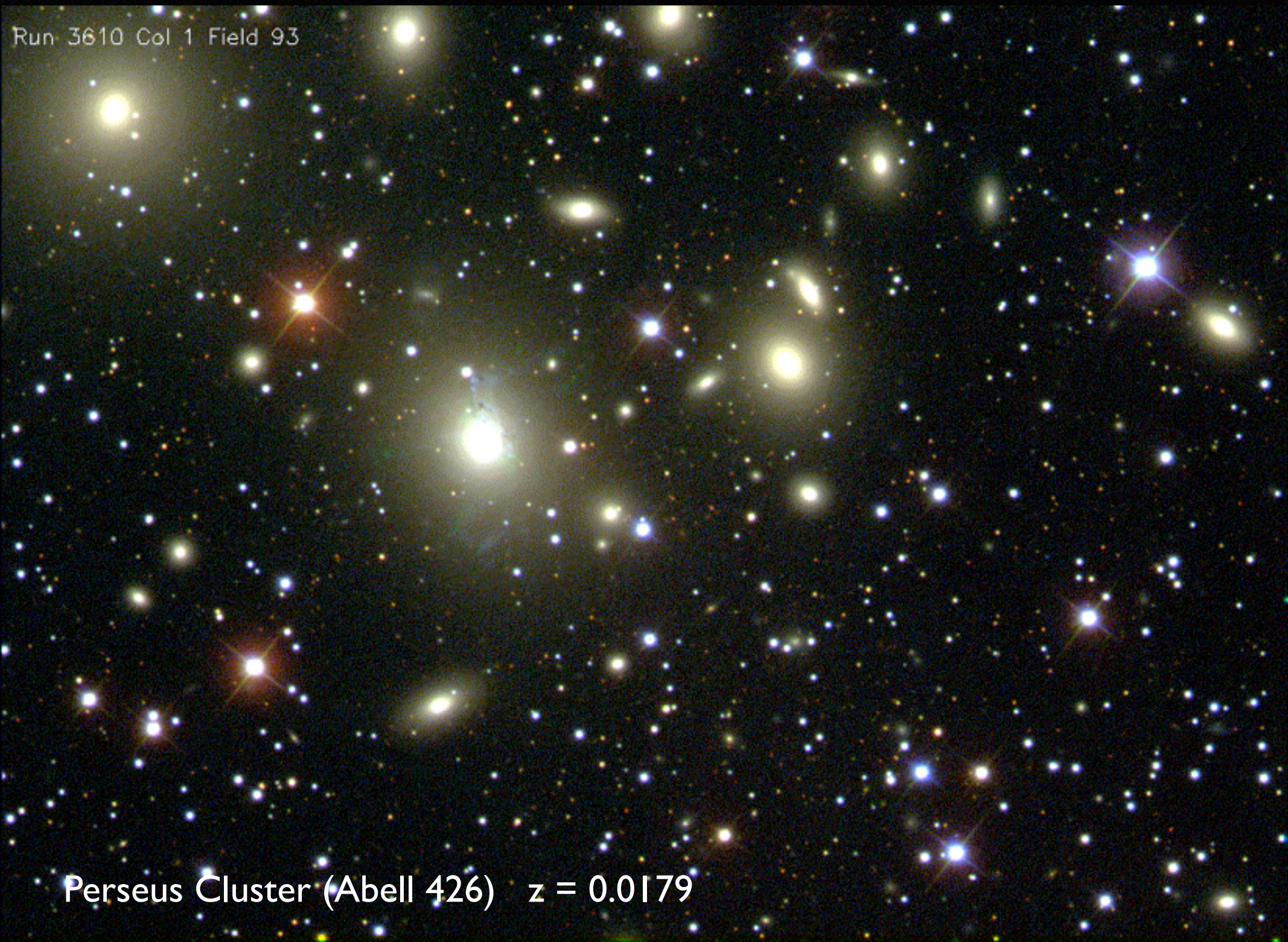


Run 3610 Col 1 Field 93



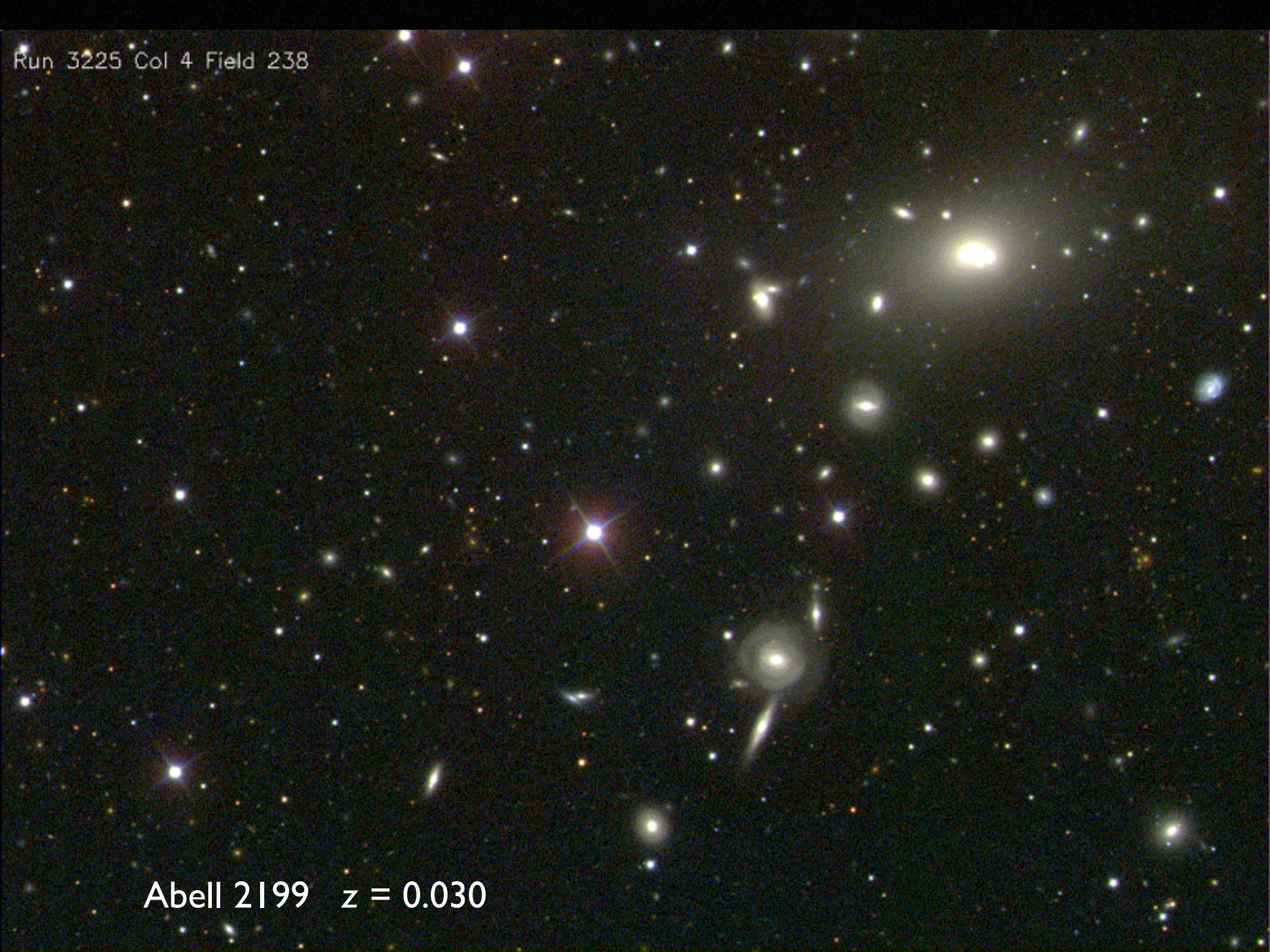
Perseus Cluster (Abell 426) $z = 0.0179$

Run 5115 Col 5 Field 150



Coma cluster (Abell 1656) NGC 4874 $z = 0.023$

Run 3225 Col 4 Field 238



Abell 2199 $z = 0.030$


Run 4649 Col 4 Field 376



Hercules cluster (Abell 2151) $z = 0.0366$

Run 4014 Col 2 Field 165

Corona Borealis cluster (Abell 2065) $z = 0.0726$



Run 1140 Col 6 Field 300

Abell 1689 $z = 0.183$



III. THE VIRIAL THEOREM APPLIED TO CLUSTERS OF NEBULAE

If the total masses of clusters of nebulae were known, the average masses of cluster nebulae could immediately be determined from counts of nebulae in these clusters, provided internebular material is of the same density inside and outside of clusters.

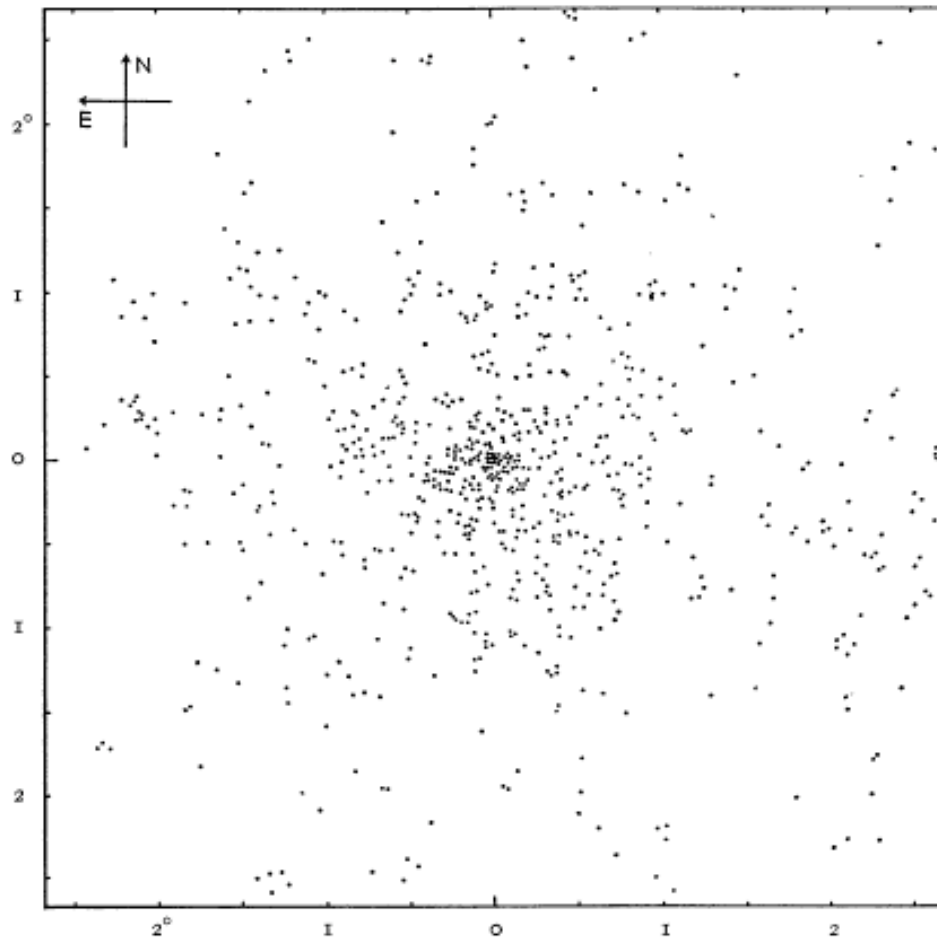


FIG. 3.—The Coma cluster of nebulae

As a first approximation, it is probably legitimate to assume that clusters of nebulae such as the Coma cluster (see Fig. 3) are mechanically stationary systems. With this assumption, the virial theorem of classical mechanics gives the total mass of a cluster in terms of the average square of the velocities of the individual nebulae which constitute this cluster.⁵ But even if we drop the assumption that clus-

clusters are gravitating systems in equilibrium - galaxies move on orbits that depend on the total amount of matter

the mass of the cluster can be determined by measuring the cluster size and the velocities of the galaxies

Moon: distance = 60.3 R_E , period = 655 hours

geostationary satellite: = 6.62 R_E , period = 24 hours

Shuttle orbit: distance = 1.05 R_E , period = 1.5 hours

Kepler's 3rd Law says that $R^3 / P^2 = \text{constant}$

$$60.3^3 / 655^2 = 0.51$$

$$6.62^3 / 24^2 = 0.50$$

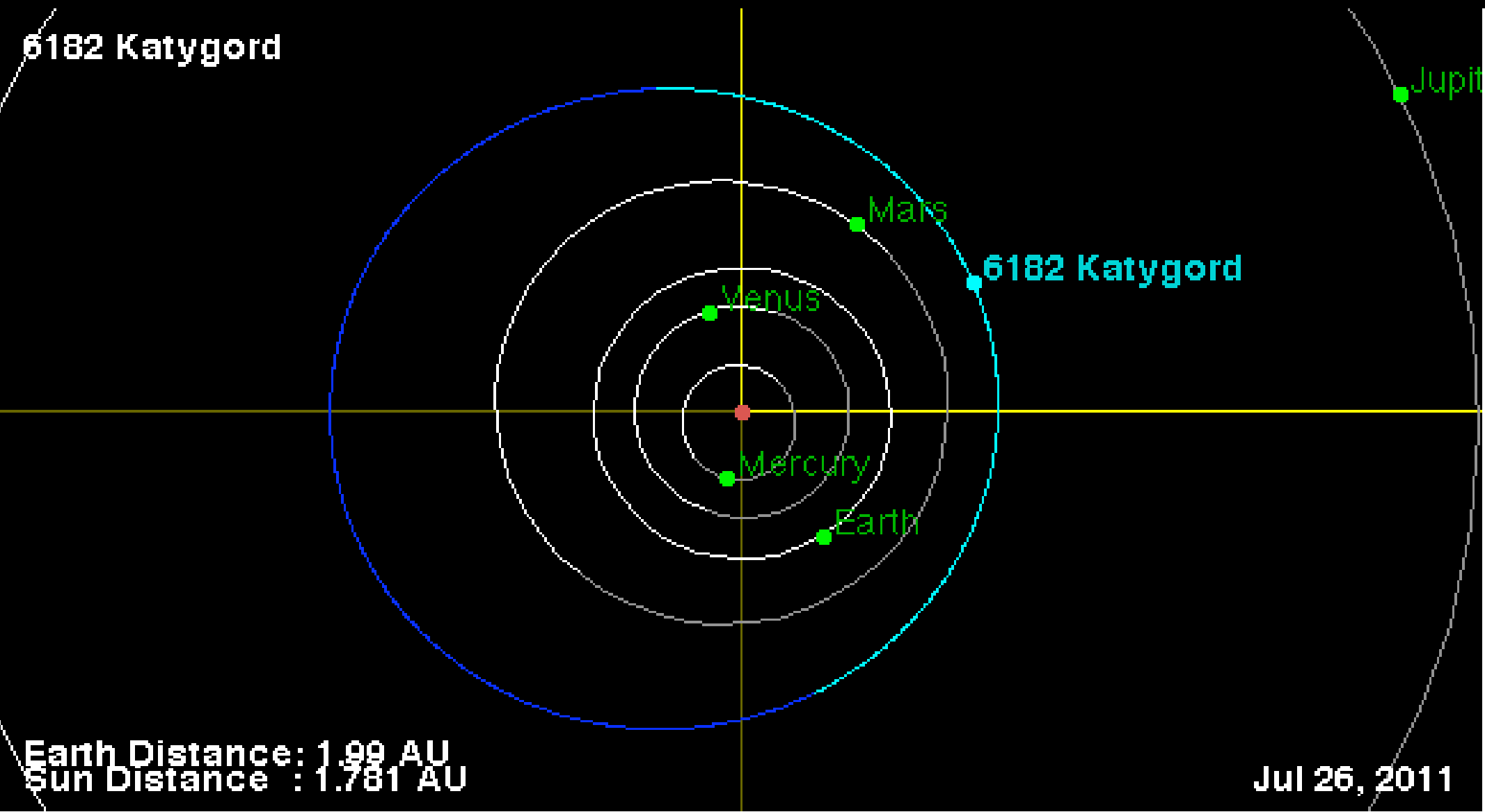
$$1.05^3 / 1.5^2 = 0.51$$

Jupiter and its four largest satellites



light takes 6.3 seconds to travel from Jupiter to Callisto

light takes 500 seconds (8.3 minutes)
to travel from Sun to Earth



globular cluster Messier 3: 200 light-years in diameter



M 87, member of Virgo cluster of galaxies:
60,000 light-years in diameter



A deep-field photograph of the Coma cluster of galaxies. The image shows a vast field of galaxies, including many bright, yellowish-white galaxies and several smaller, fainter galaxies. A prominent, bright star with a pinkish-red hue and a four-pointed diffraction pattern is located in the upper right quadrant. The background is a dark, deep blue-black color, filled with numerous small, distant stars and galaxies.

Coma cluster of galaxies: two largest galaxies separated by 1 million light-years

planet distance from Sun (AU) period of orbit (yr)

a

P

Mercury 0.387

0.241

Venus 0.723

0.615

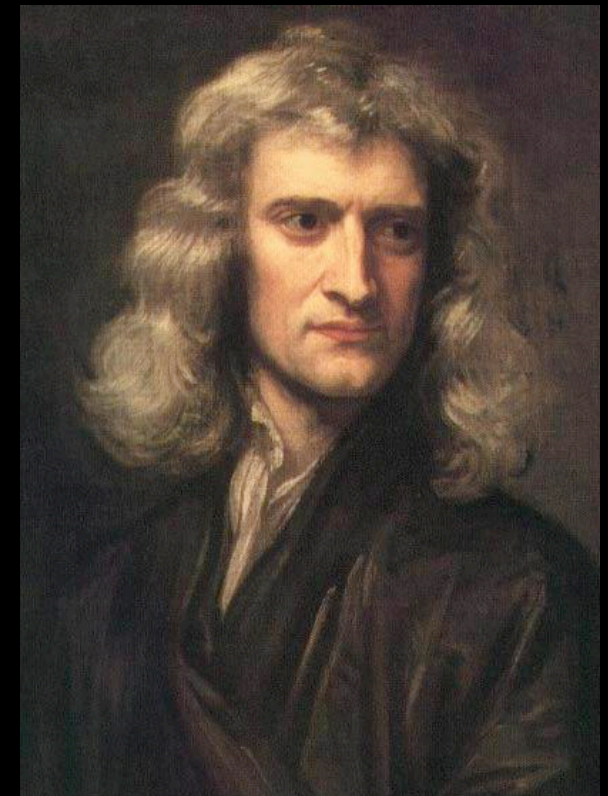
Earth 1.000

1.000

$$a^3 / P^2 = 1.000 = \text{mass of the Sun}$$



“Kepler’s Third Law”



finding the mass of a cluster of galaxies

Kepler's 3rd Law: $M = a^3 / P^2$

a (*semi-major axis*) is measured in Astronomical Units (AU)

P (*period of the orbit*) is measured in years

M (*mass of the cluster*) is measured in solar masses

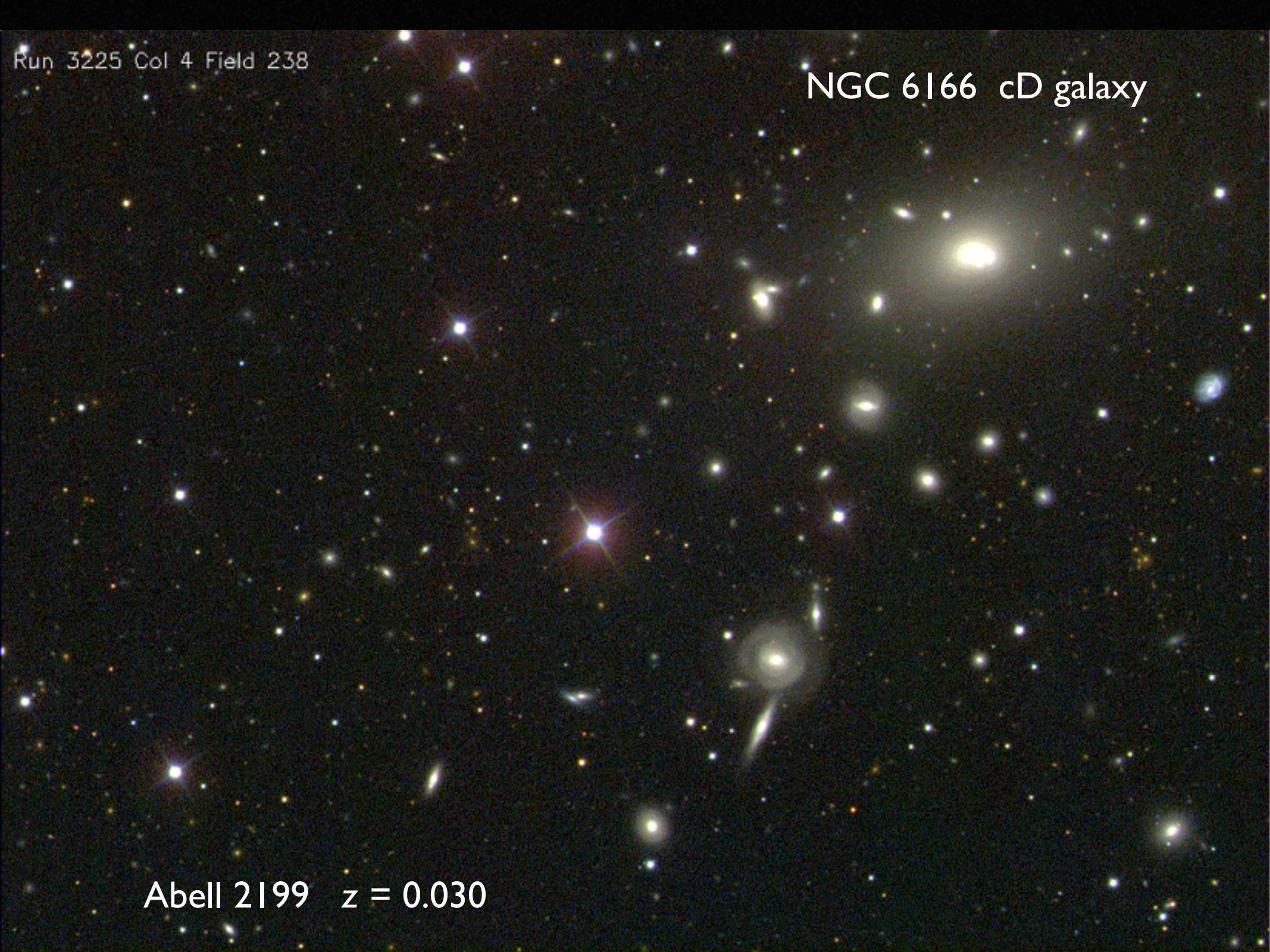
we can't measure P for galaxies in clusters (too long!), but we can measure a *velocity*.

velocity = distance / time = circumference / P = $2\pi a / P$

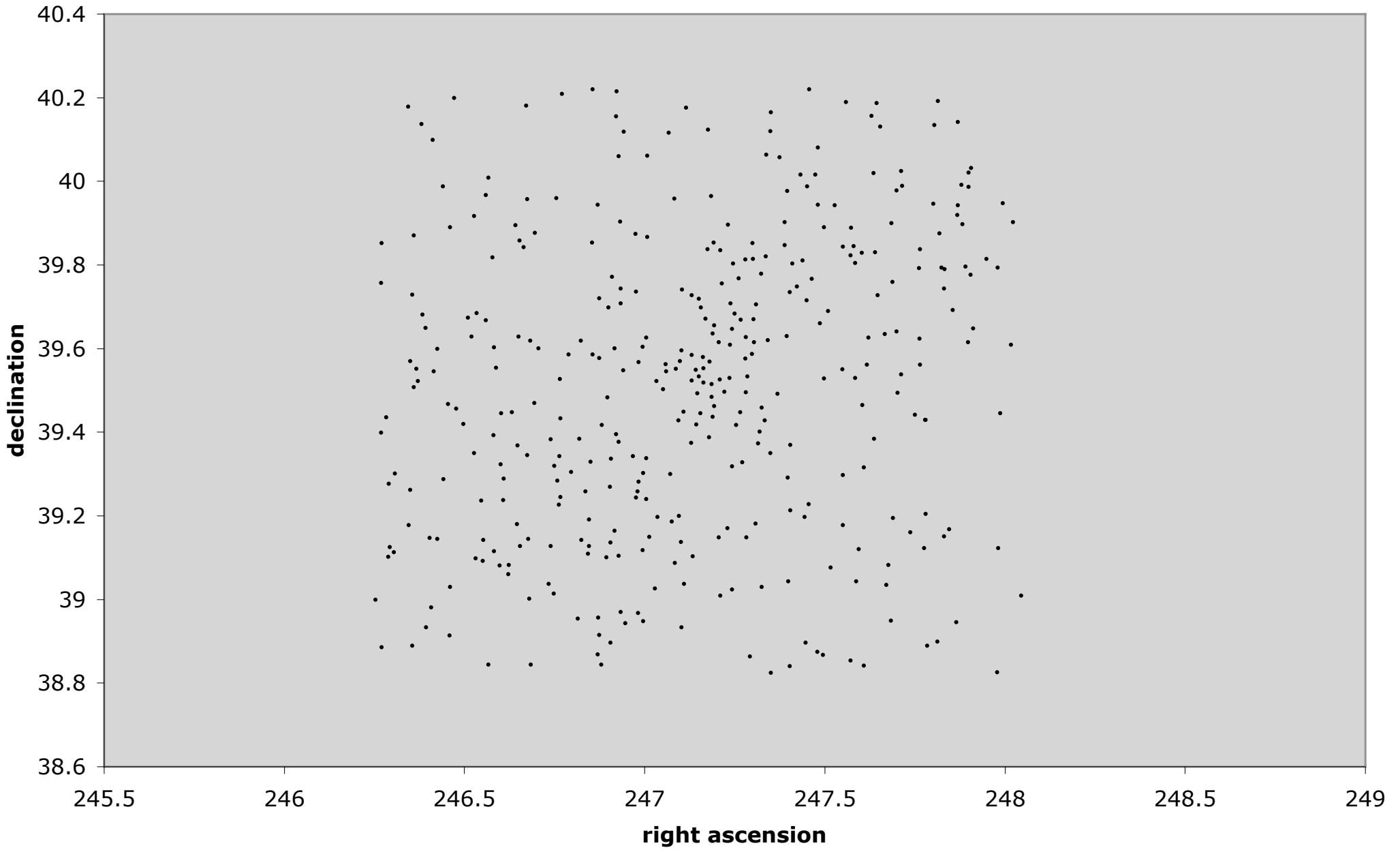
Run 3225 Col 4 Field 238

NGC 6166 cD galaxy

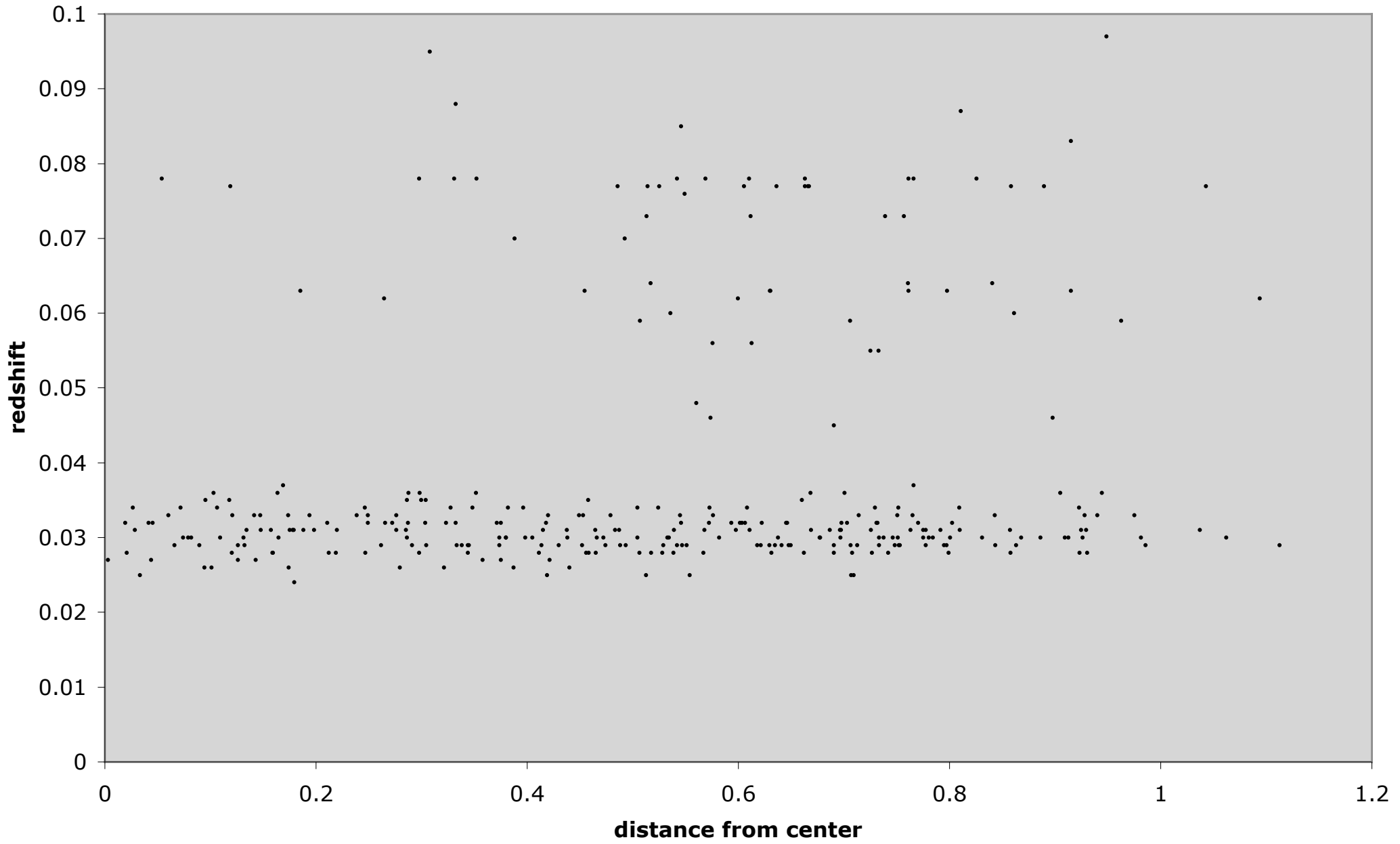
Abell 2199 $z = 0.030$



Abell 2199



Abell 2199



members of Abell 2199 have a *mean redshift* of $z = 0.03$

distance = $c z / H_0 = 125 \text{ Mpc}$

the root-mean-square scatter around this mean is 0.0025

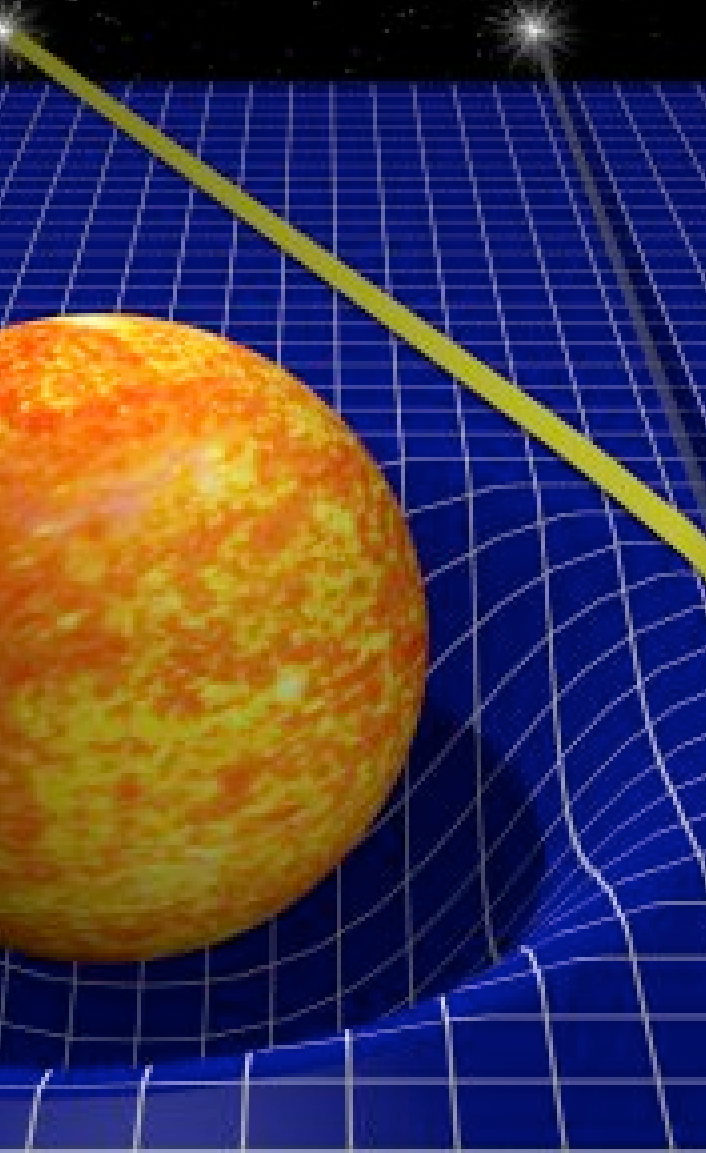
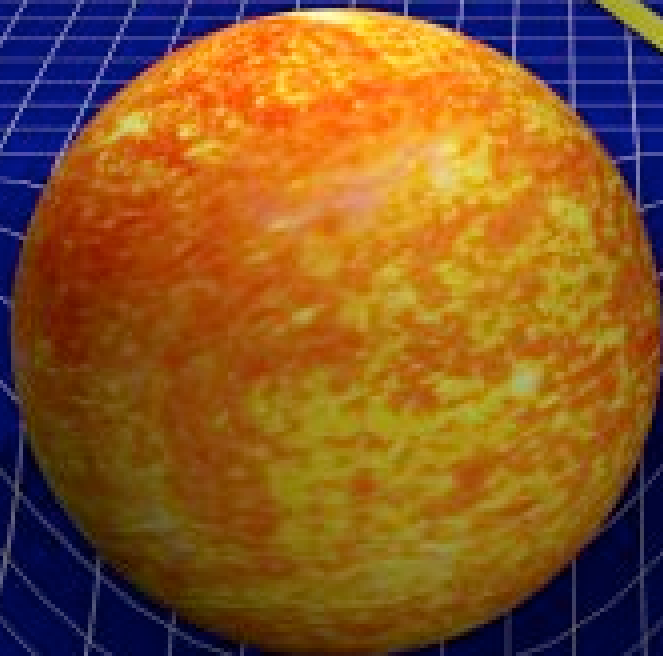
velocity dispersion = $c \times 0.0025 = 750 \text{ km/sec}$

velocities

low orbit around Earth	7.4 km/sec
Earth escape velocity	11 km/sec
Mercury	48 km/sec
Earth	30 km/sec
Saturn	9.6 km/sec
Sun around center of MW	220 km/sec
light	300,000 km/sec

Real

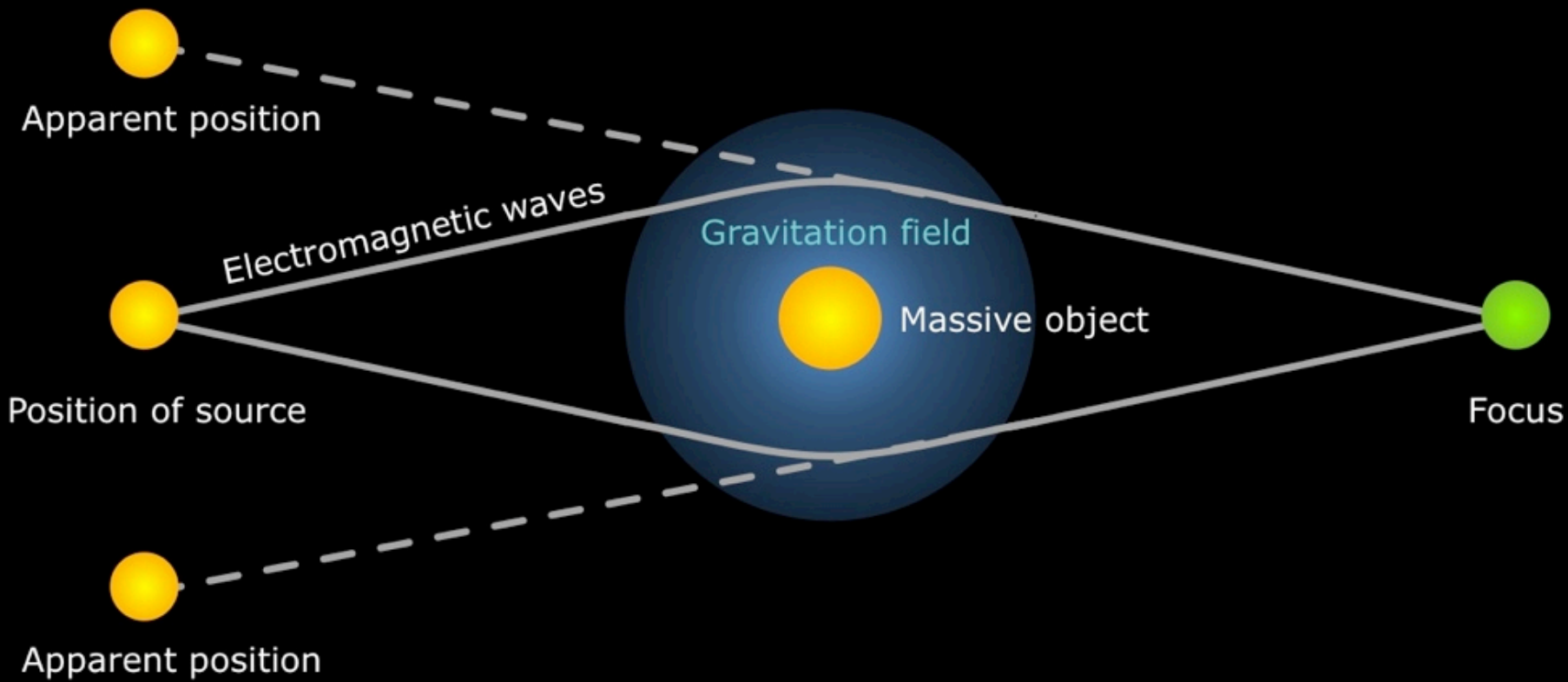
Observed



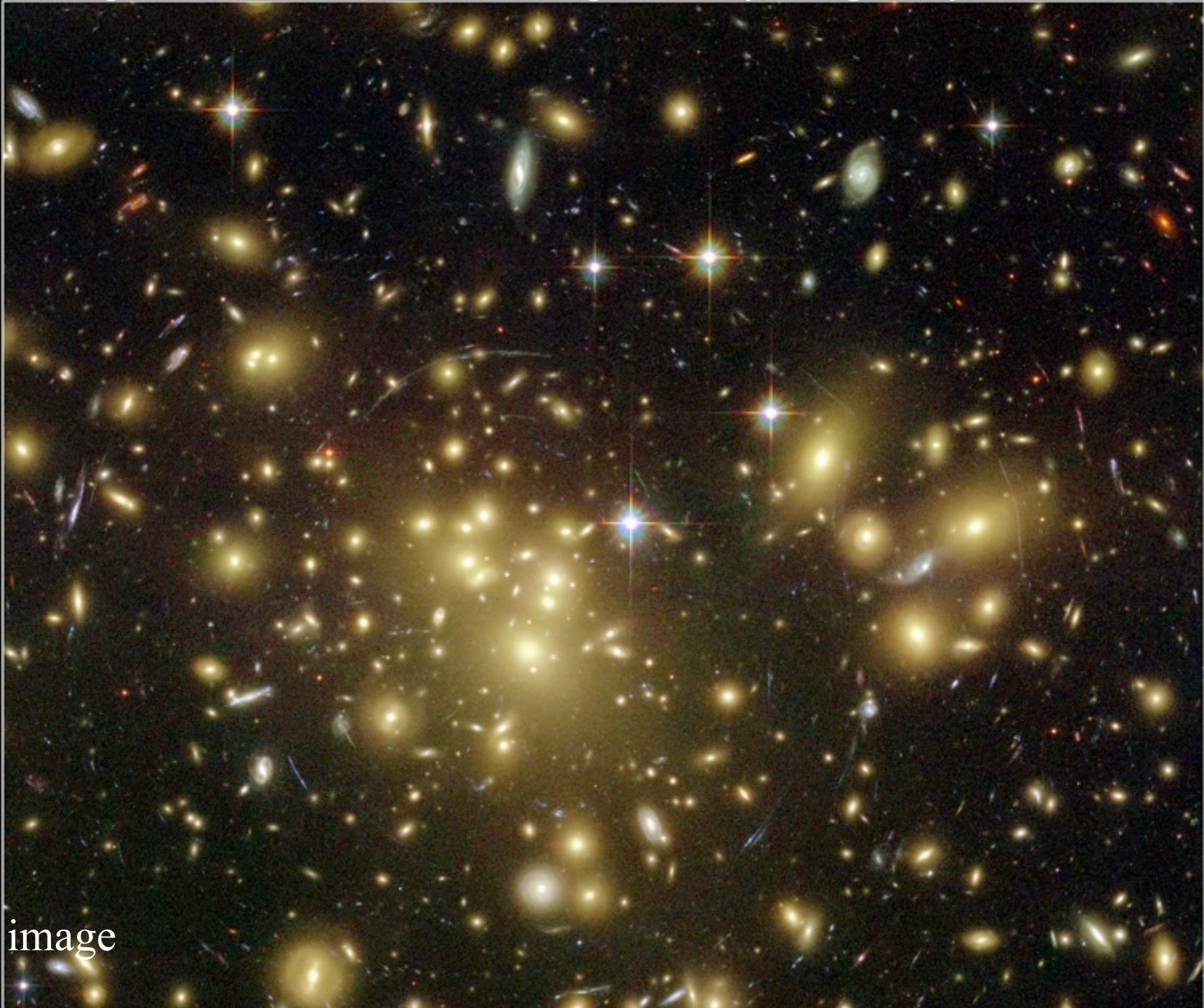
A, B, C, D are quadruple images
of the *same* quasar. The
gravitational lens is the central
massive galaxy and cluster.

30"






Rich cluster of galaxies (yellow). The small blue arcs are much more distant galaxies that have been magnified by the gravity of the cluster.



HST image

A field of stars with a prominent yellow star in the center, illustrating gravitational lensing. The background is dark with many small, distant stars. A few stars are significantly brighter and larger than the others, indicating they are closer or more massive. The central yellow star is the most prominent, with a bright, circular glow around it. Other stars are scattered throughout the field, some appearing as small points of light and others as larger, more diffuse shapes. The overall scene is a rich field of stars, likely a star cluster or a galaxy core, with the central star acting as a gravitational lens for the background stars.

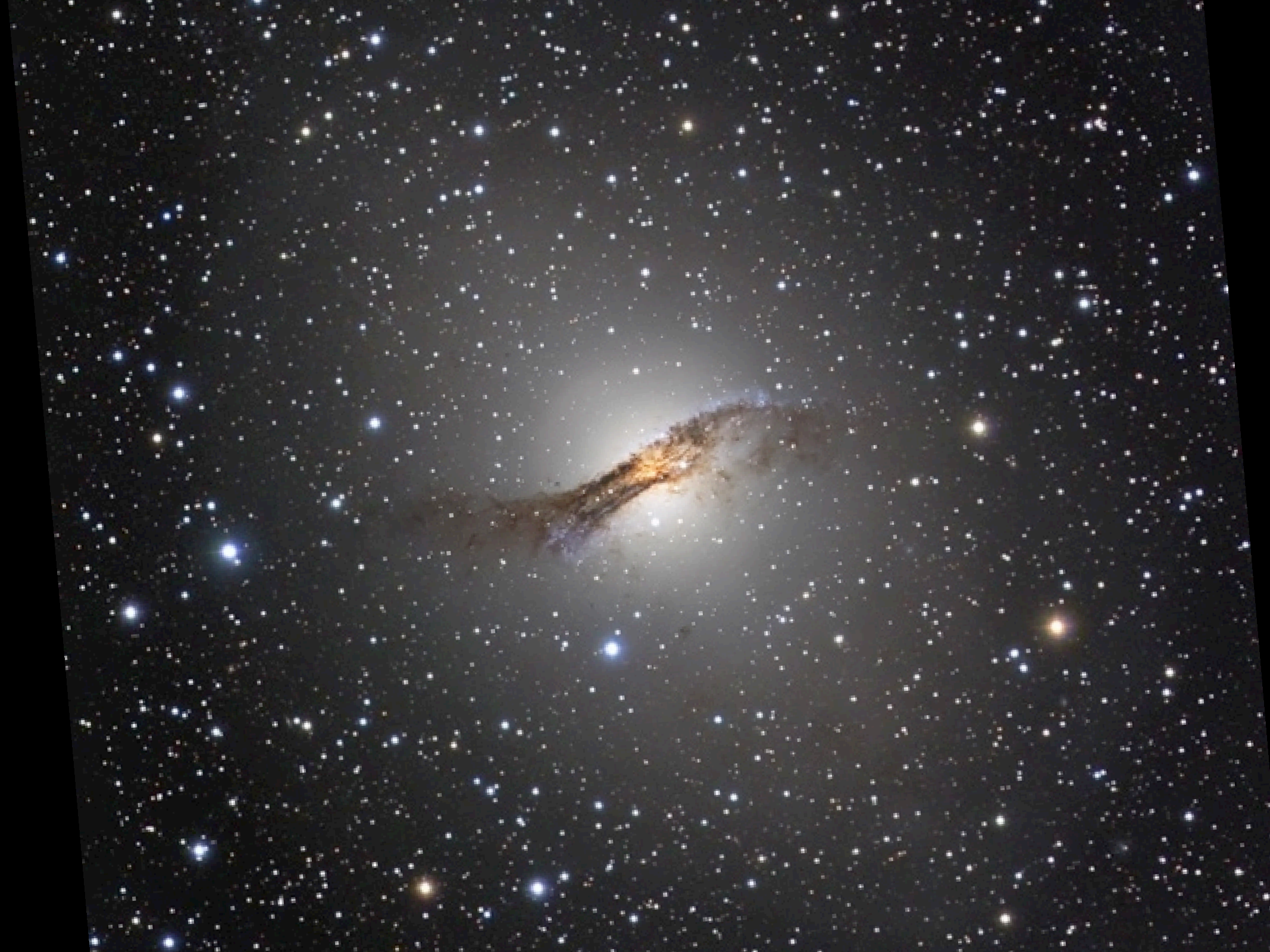
The more mass, the more magnification:
we can use these “gravitational lenses” to
determine the total mass of the cluster.















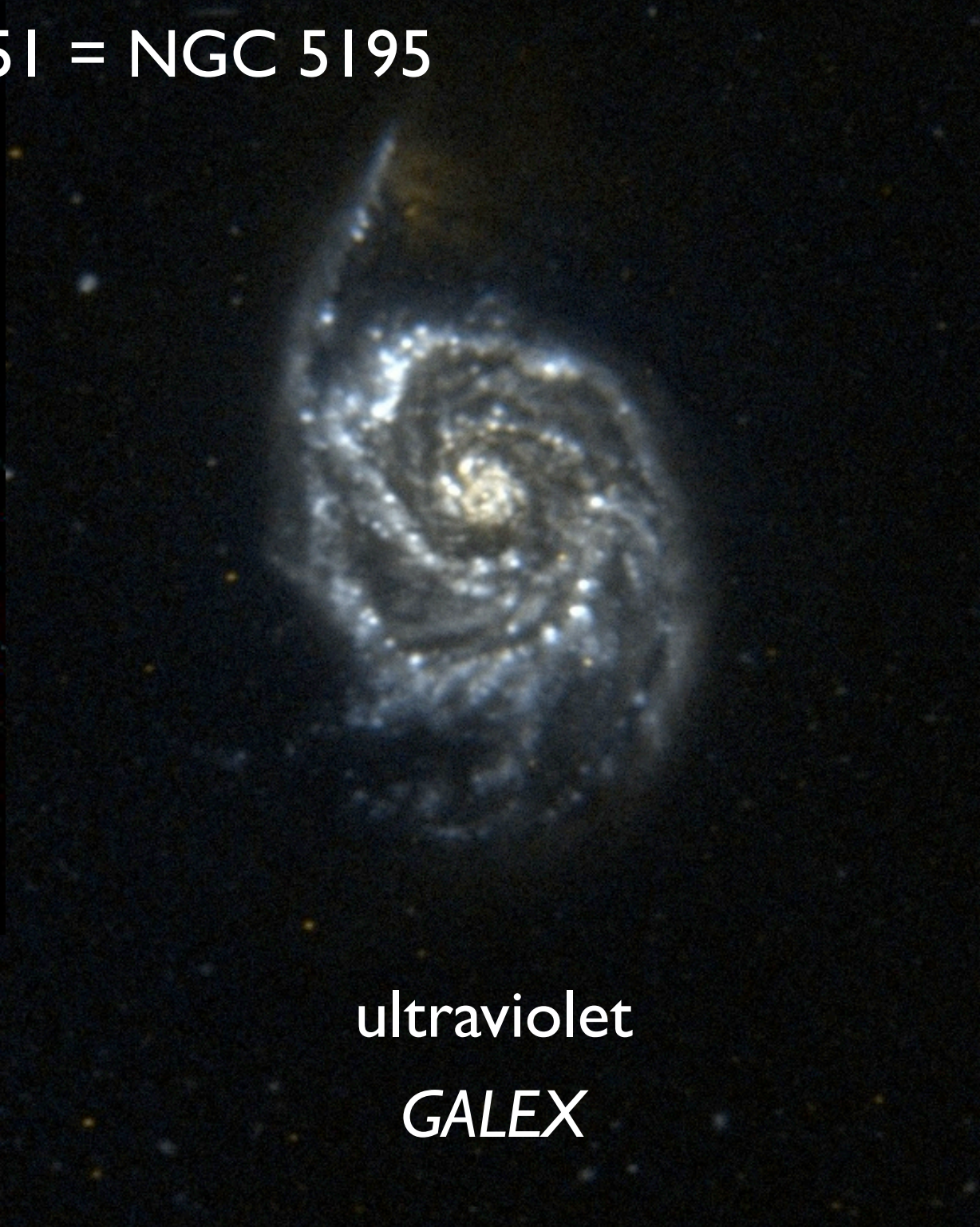


Messier 51 = NGC 5195



infrared

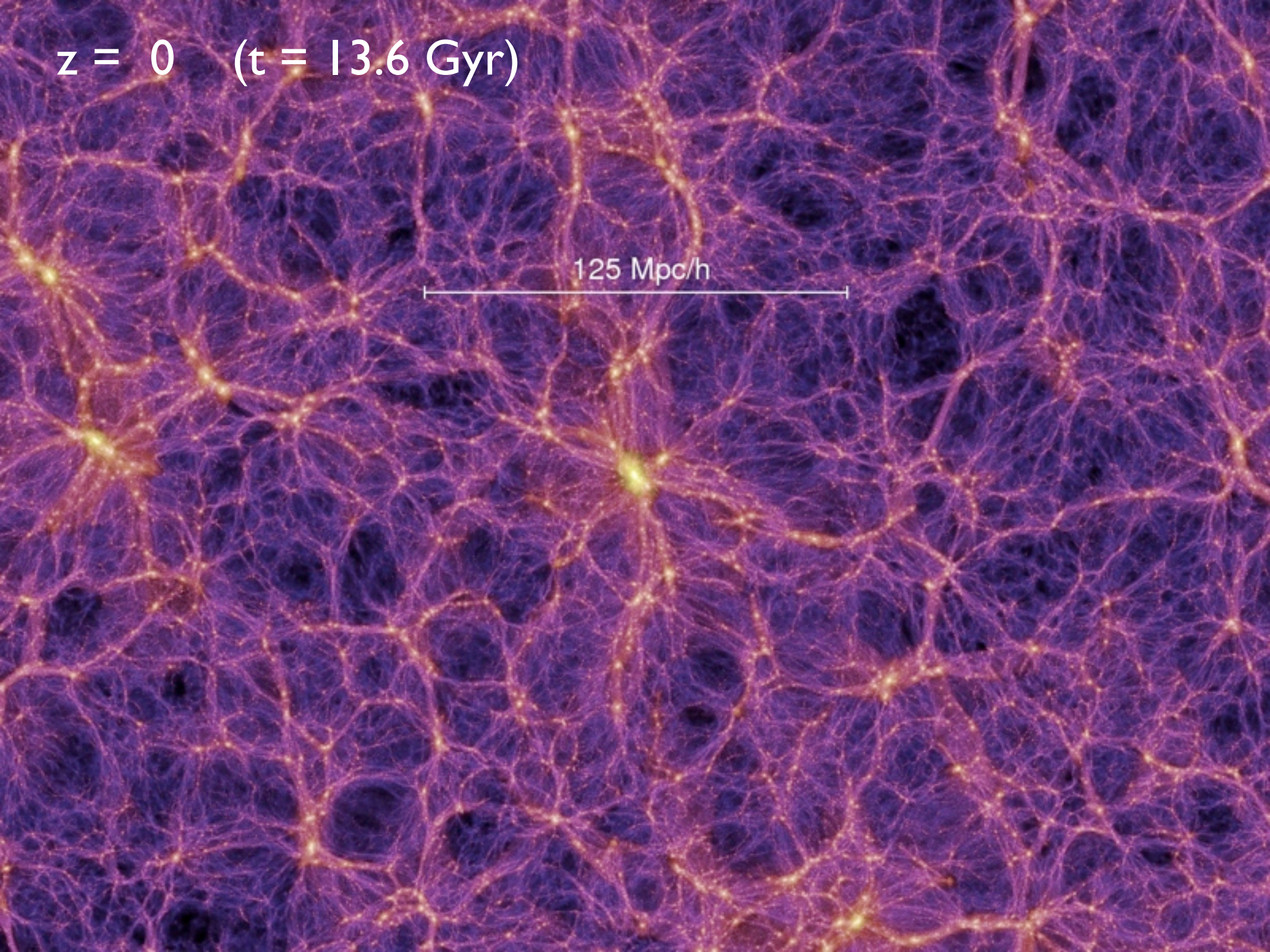
Spitzer Space Telescope



ultraviolet

GALEX

$z = 0$ ($t = 13.6$ Gyr)



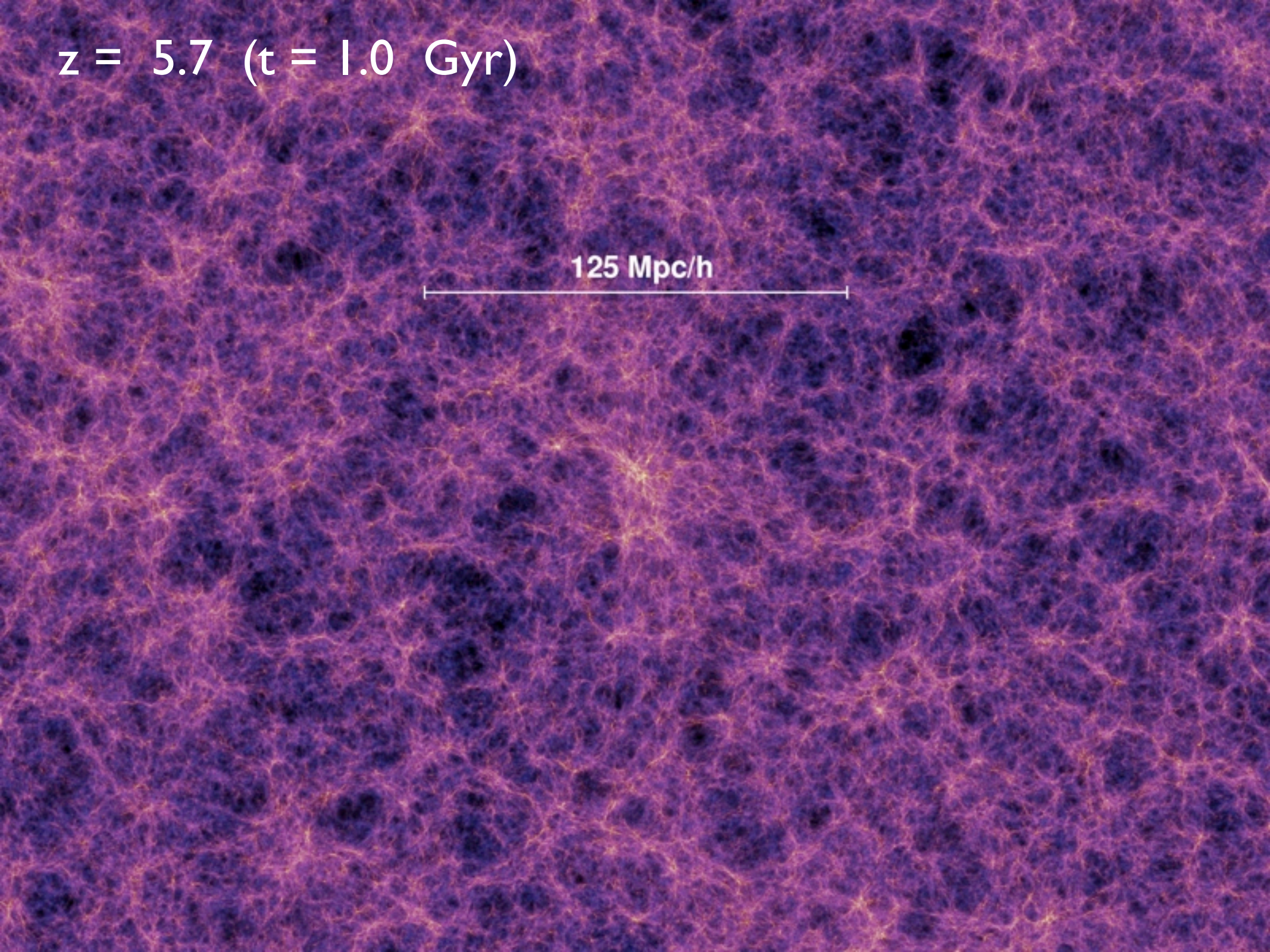
$z = 1.4$ ($t = 4.7$ Gyr)

125 Mpc/h

A visualization of the cosmic web at redshift z=1.4, showing a complex network of filaments and nodes. The filaments are colored in shades of purple and blue, while the nodes are highlighted in yellow and orange. A horizontal scale bar is located in the upper-middle part of the image, with the text "125 Mpc/h" above it. The background is dark blue, representing the voids between the filaments.

$z = 5.7$ ($t = 1.0$ Gyr)

125 Mpc/h

A visualization of the cosmic web at redshift z=5.7, showing a dense network of filaments and nodes. The filaments are colored in shades of purple and blue, with brighter yellow and orange spots indicating regions of higher density or star formation. A horizontal scale bar is located in the upper-middle part of the image, consisting of a white line with vertical end caps, labeled "125 Mpc/h".

$z = 18.3$ ($t = 0.21$ Gyr)

125 Mpc/h





Cryogenic Dark Matter Search

