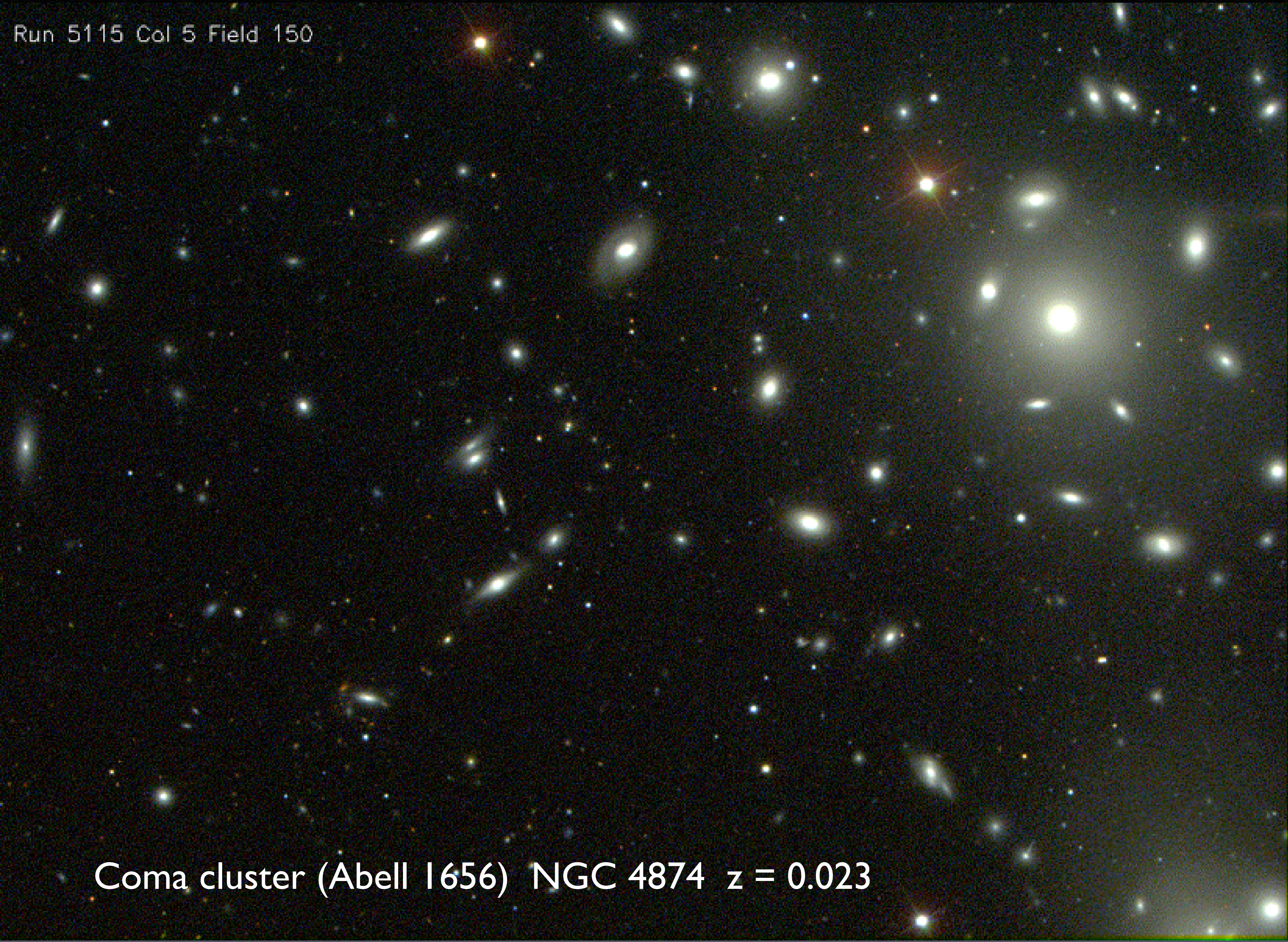
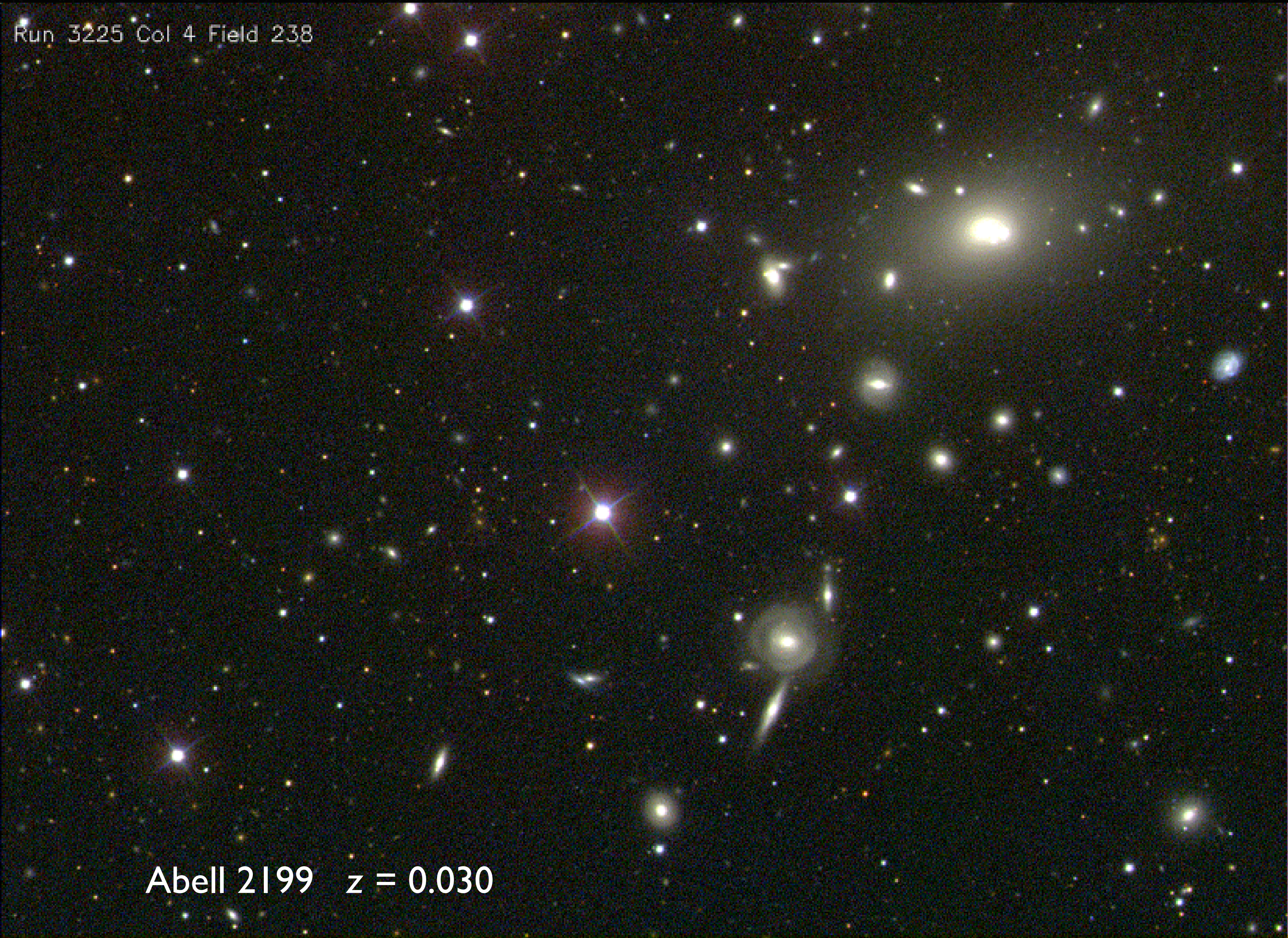
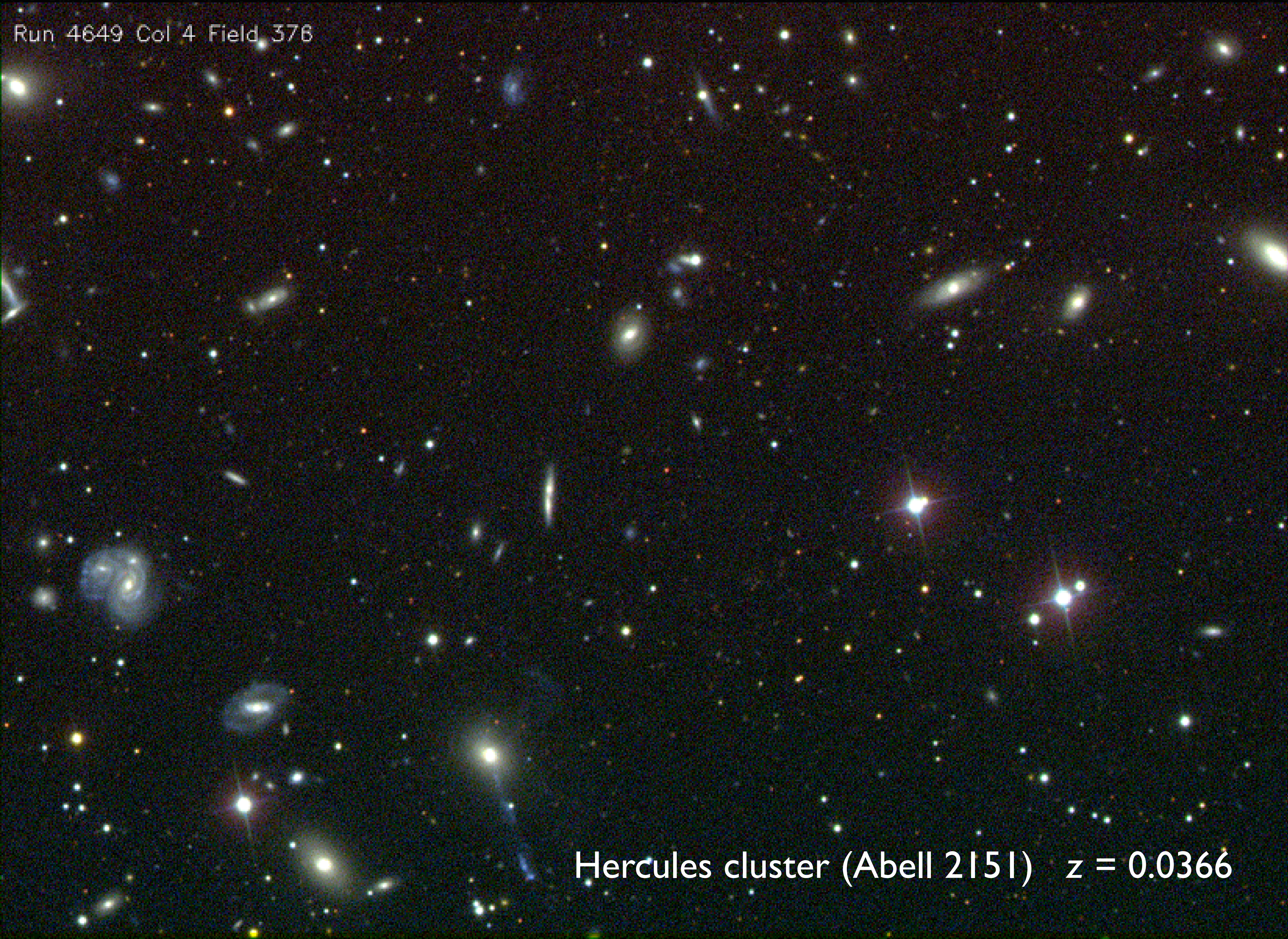
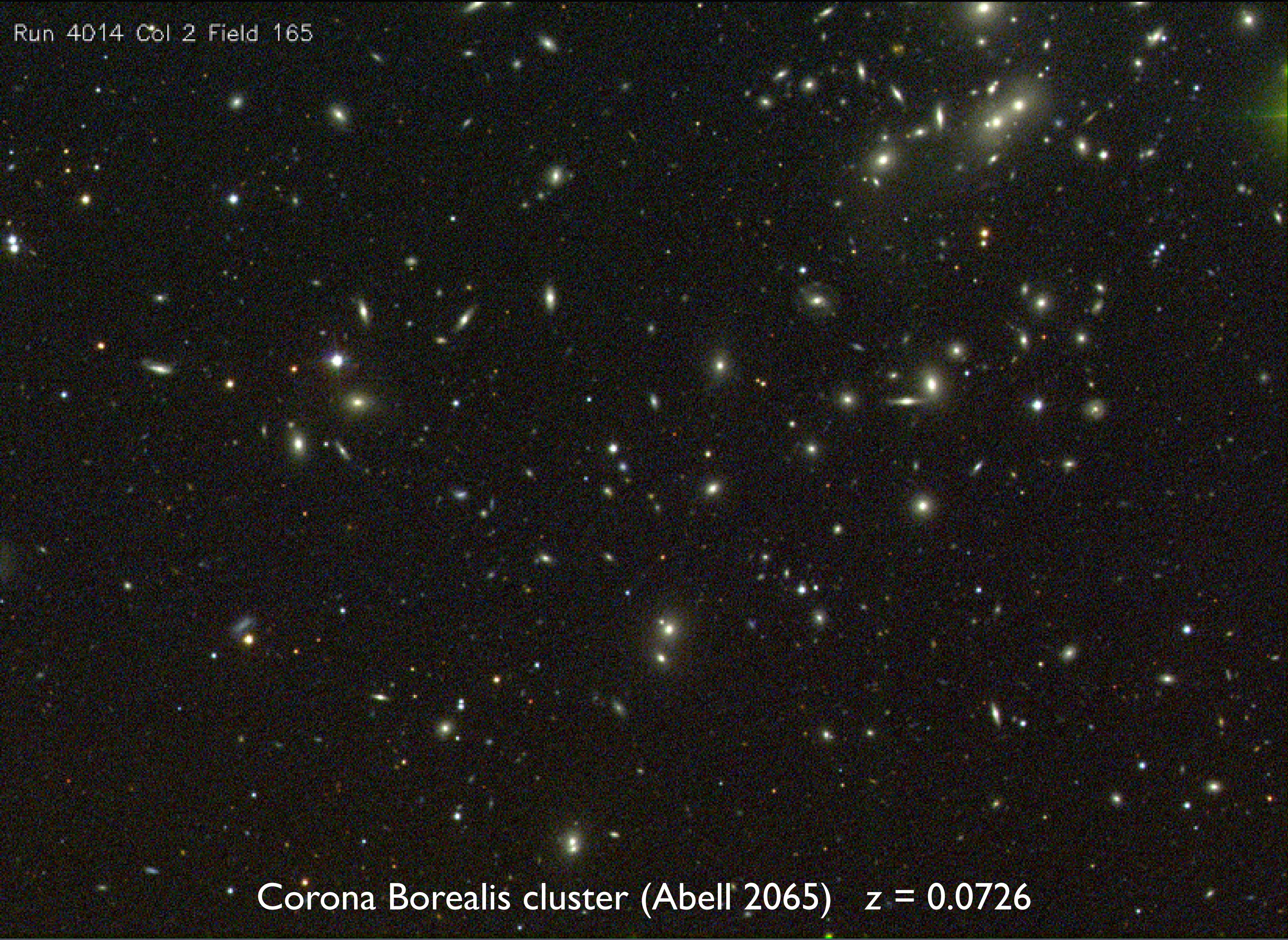

Run 3610 Col 1 Field 93
Perseus Cluster (Abell 426) z = 0.0179


Run 5115 Col 5 Field 150
Coma cluster (Abell 1656) NGC 4874 z = 0.023



Abell 2199 $z = 0.030$


Run 4649 Col 4 Field 376
Hercules cluster (Abell 2151) z = 0.0366



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.

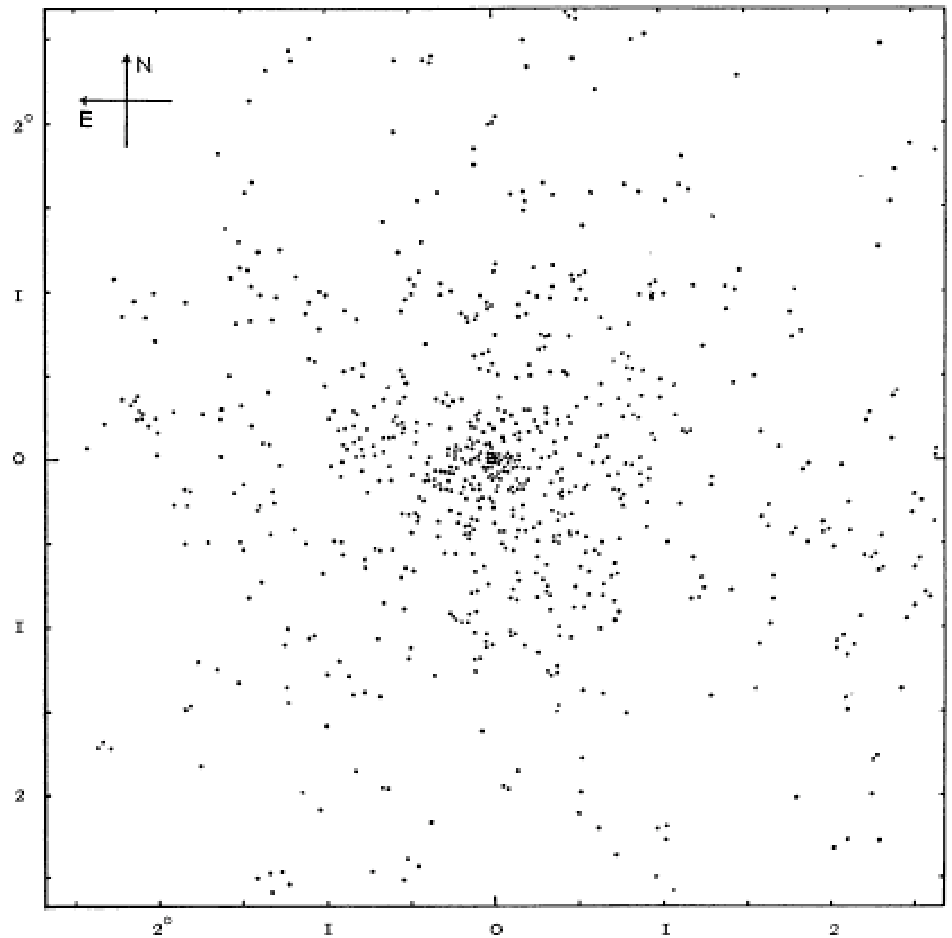


FIG. 3.—The Coma cluster of nebulae

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

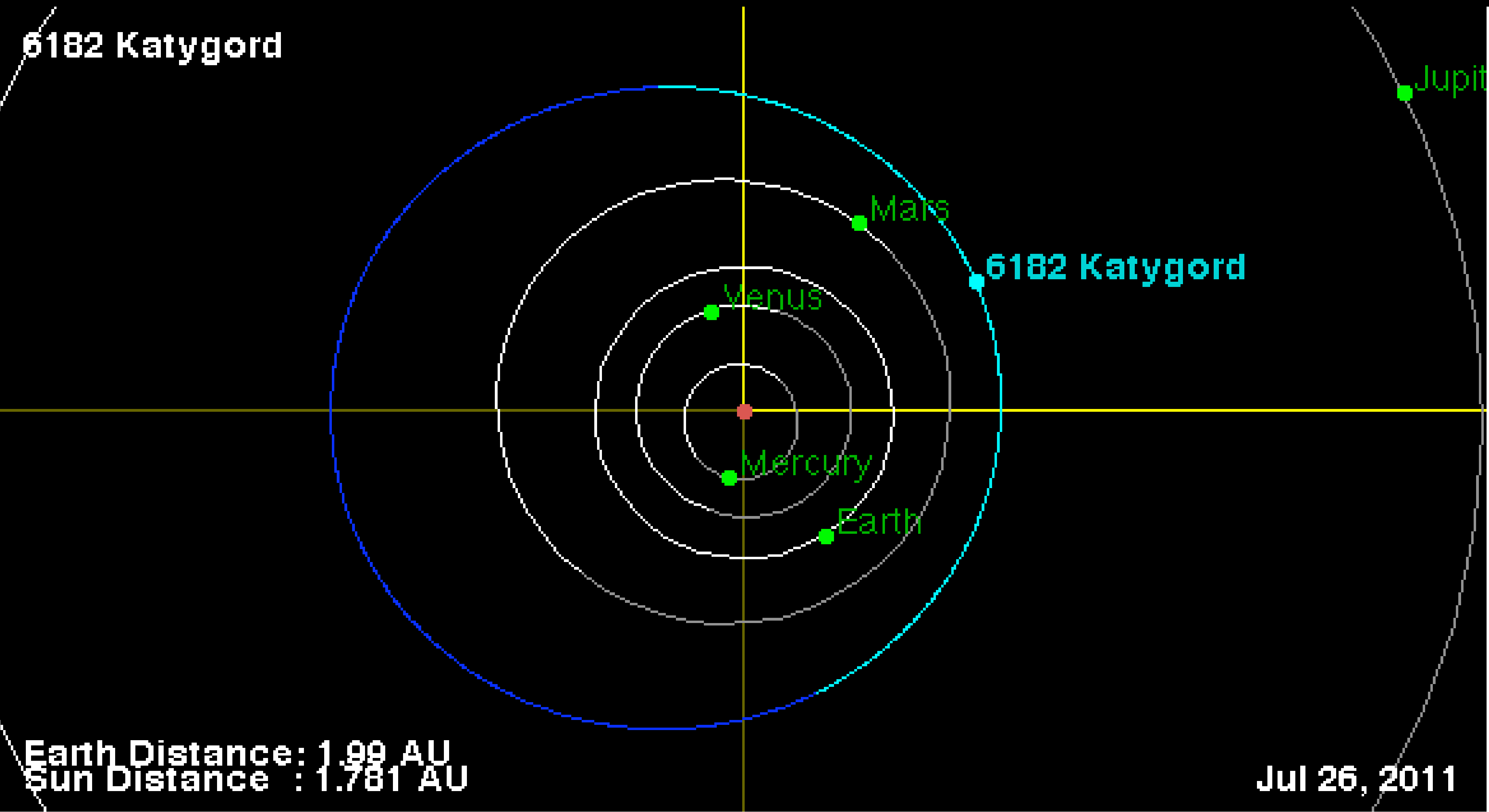
Kepler's 3rd Law says that R^3 / P^2 = constant

$60.3^3 / 655^2 = 0.51$
$6.62^3 / 24^2 = 0.50$
$1.05^3 / 1.5^2 = 0.51$

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

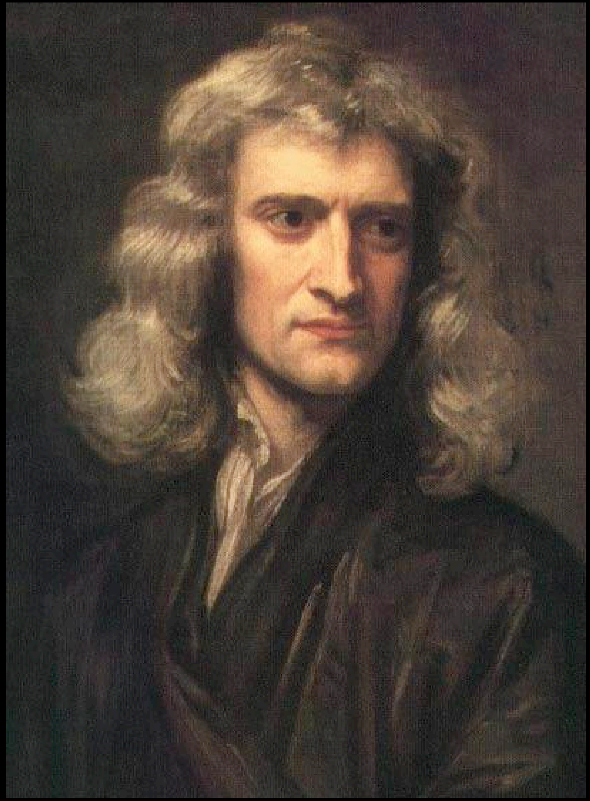


globular cluster Messier 3: 200 light-years in diameter

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

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



$a^3 / P^2 = 1.000 =$ mass of the Sun

"Kepler's Third Law"

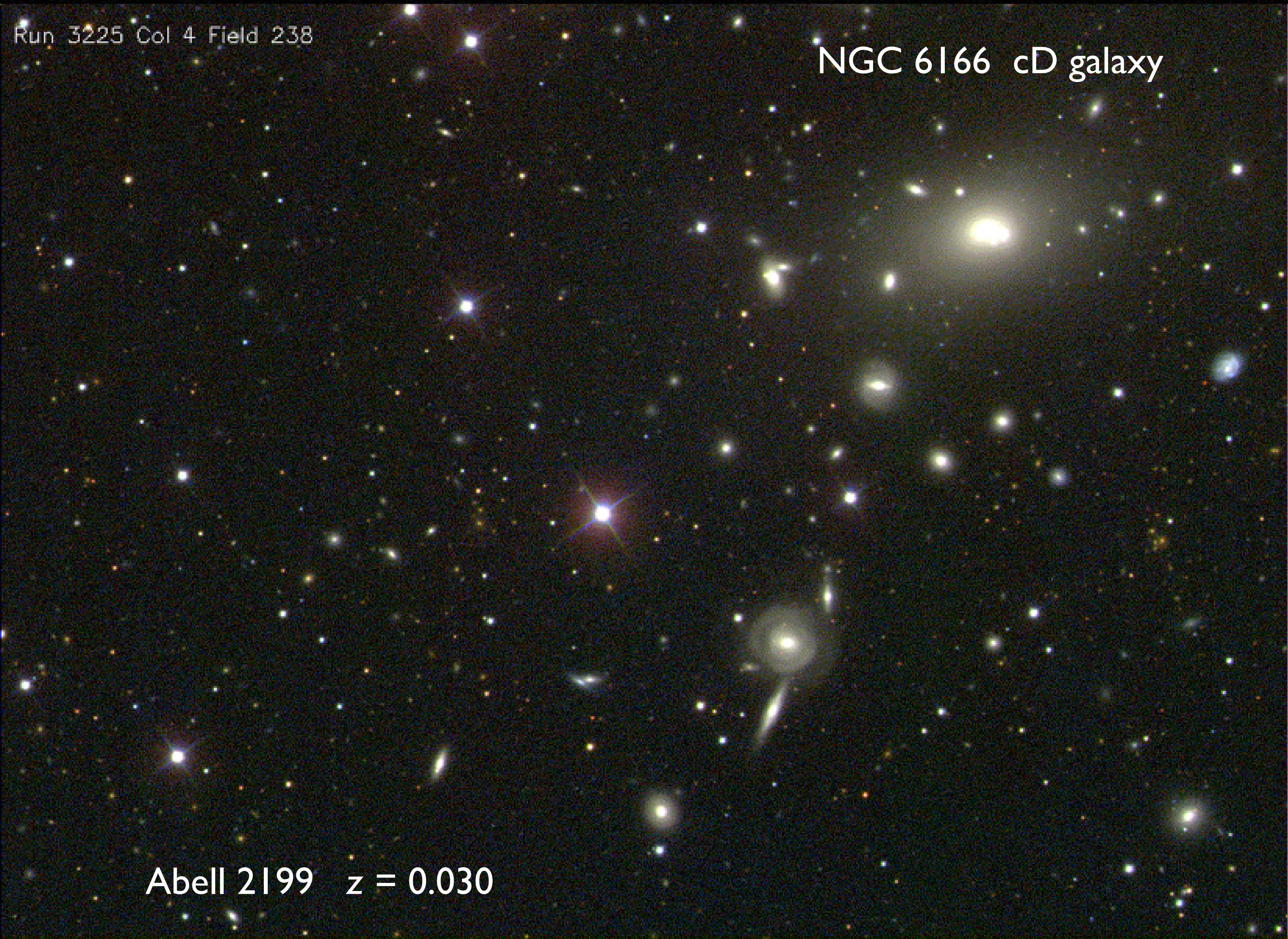
finding the mass of a cluster of galaxies

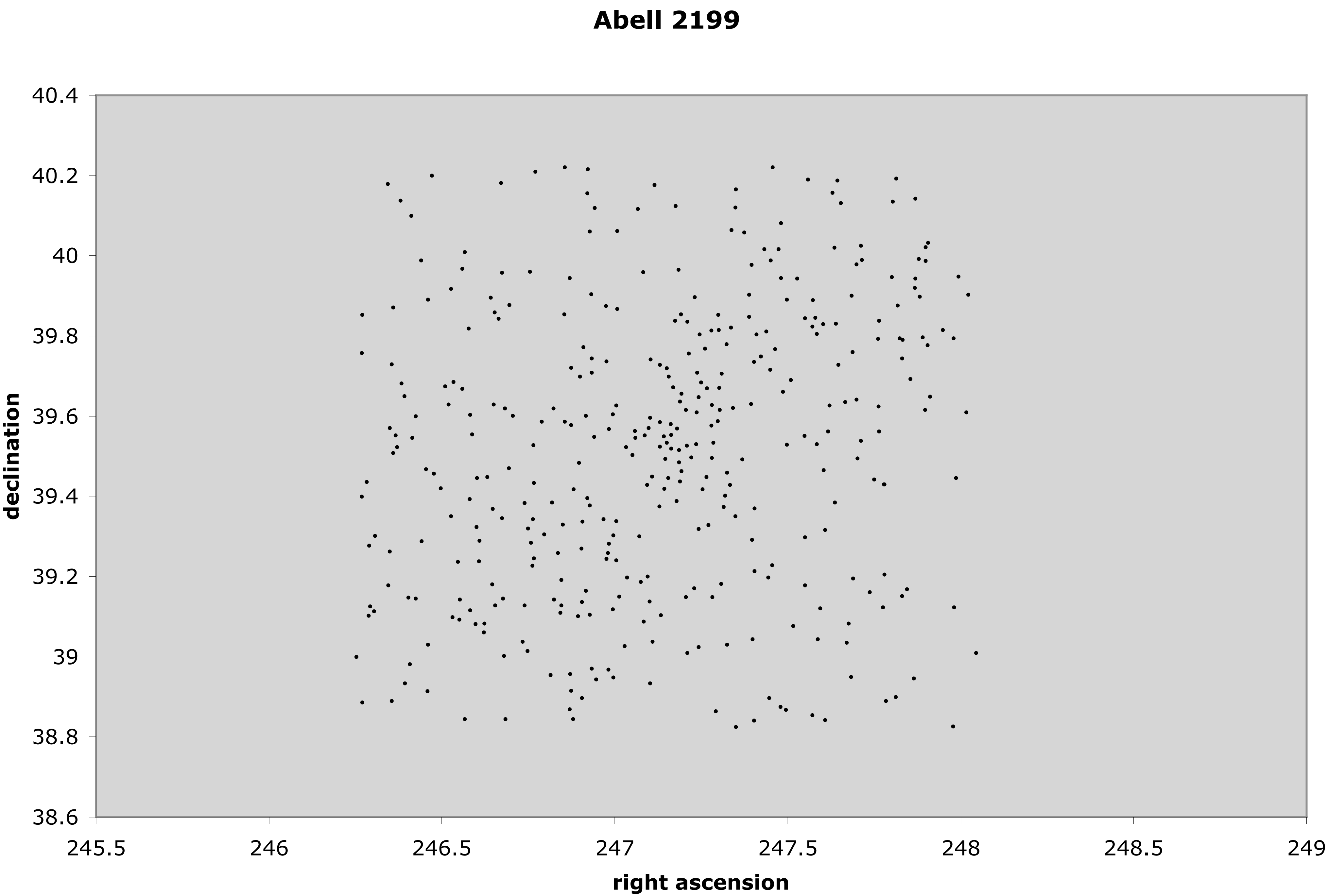
Kepler's 3rd Law: $M = a^3 / P^2$

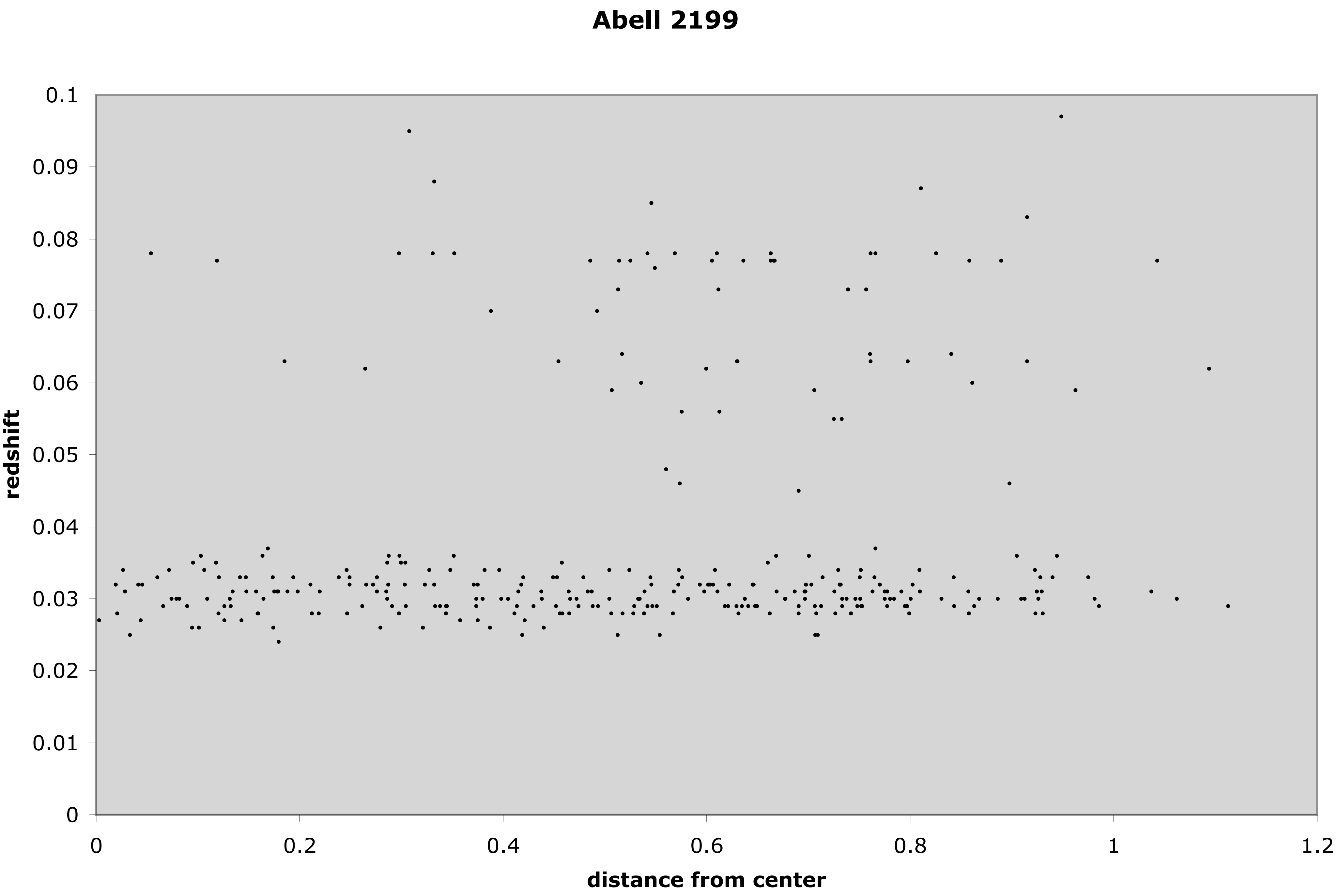
a (*semi-major axis*) is measured in Astronomical Units (AU)
P (*period of the orbit*) is measured in years
M (*mass of the cluster*) is measured in solar masses

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
declination
40.4
40.2
40
39.8
39.6
39.4
39.2
39
38.8
38.6
245.5
246
246.5
247
247.5
248
248.5
249
right ascension


Abell 2199
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
redshift
0
0.2
0.4
0.6
0.8
1
1.2
distance from center

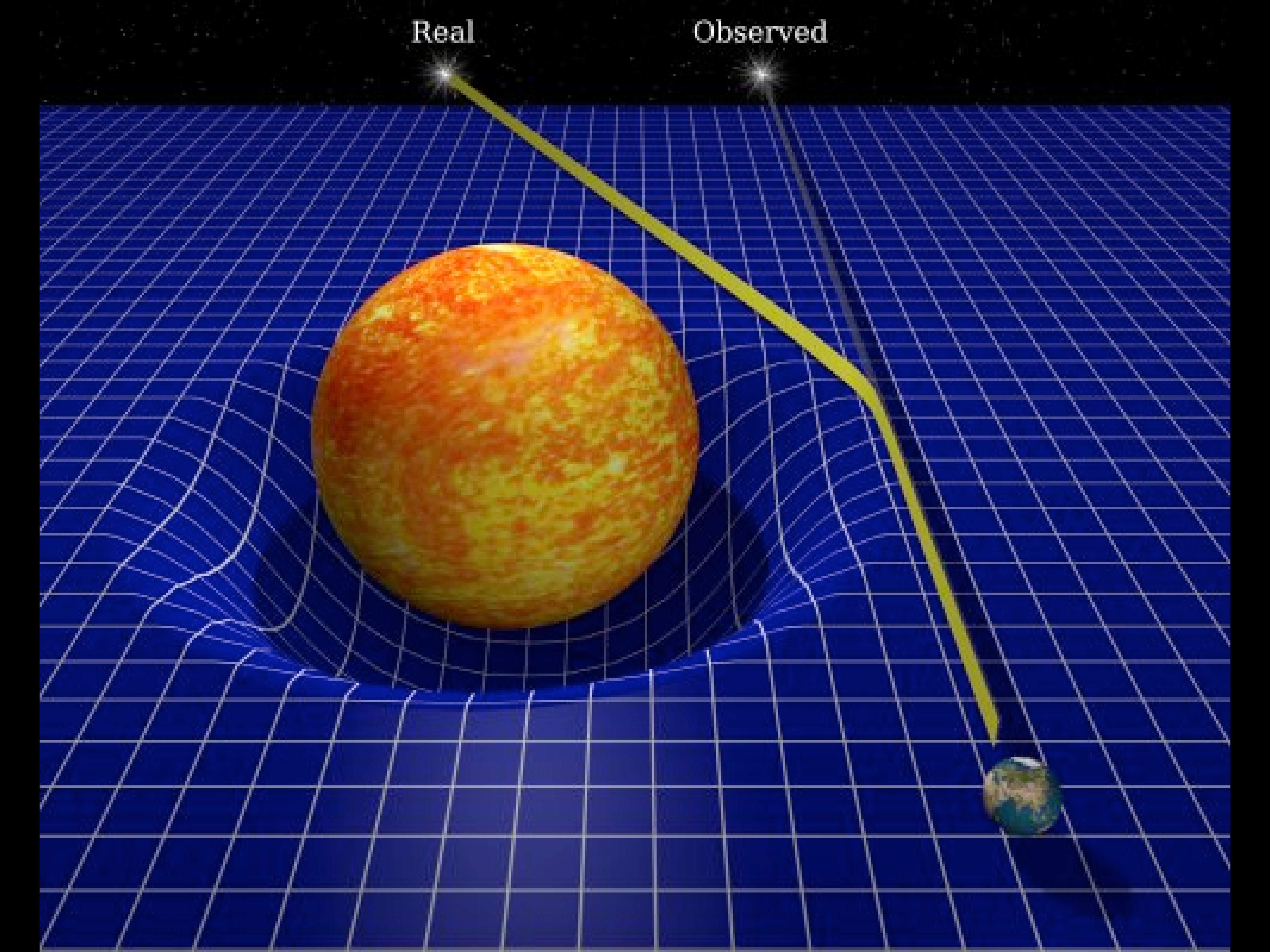
members of Abell 2199 have a *mean redshift* of $z = 0.03$

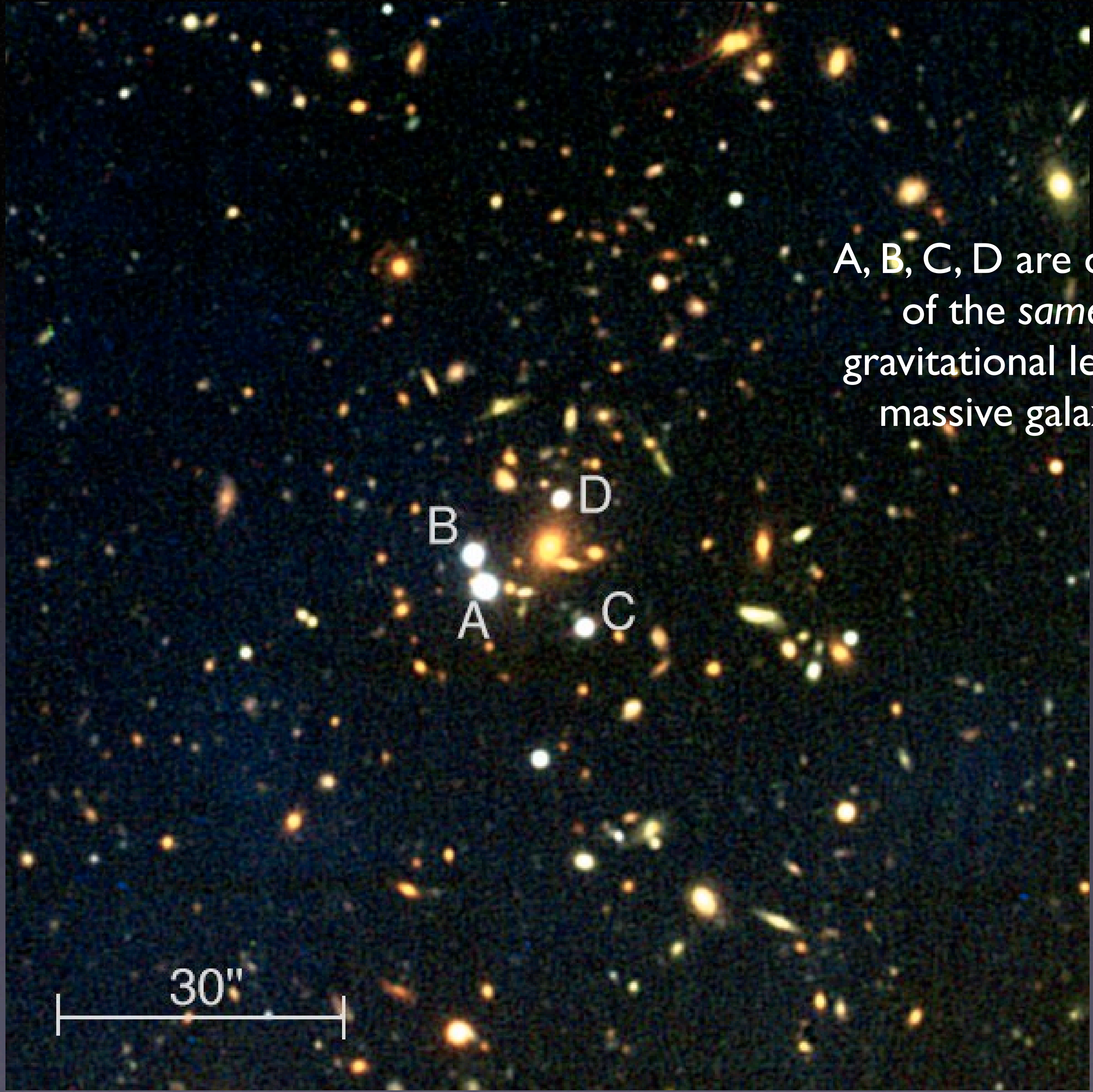
distance $= c\, z / H_0 = 125$ Mpc

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

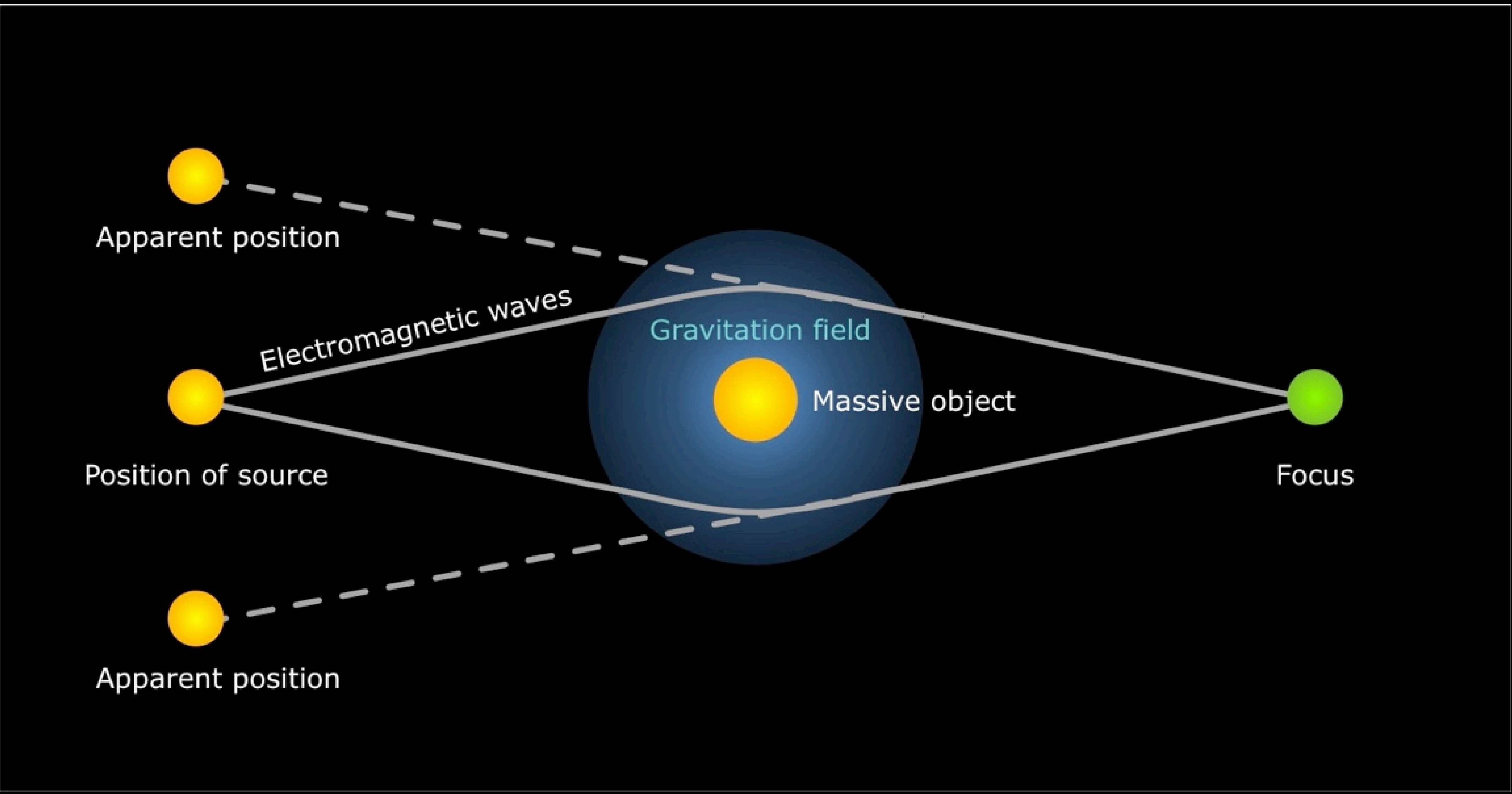
velocity dispersion $= c \times 0.0025 = 750$ km/sec velocities

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

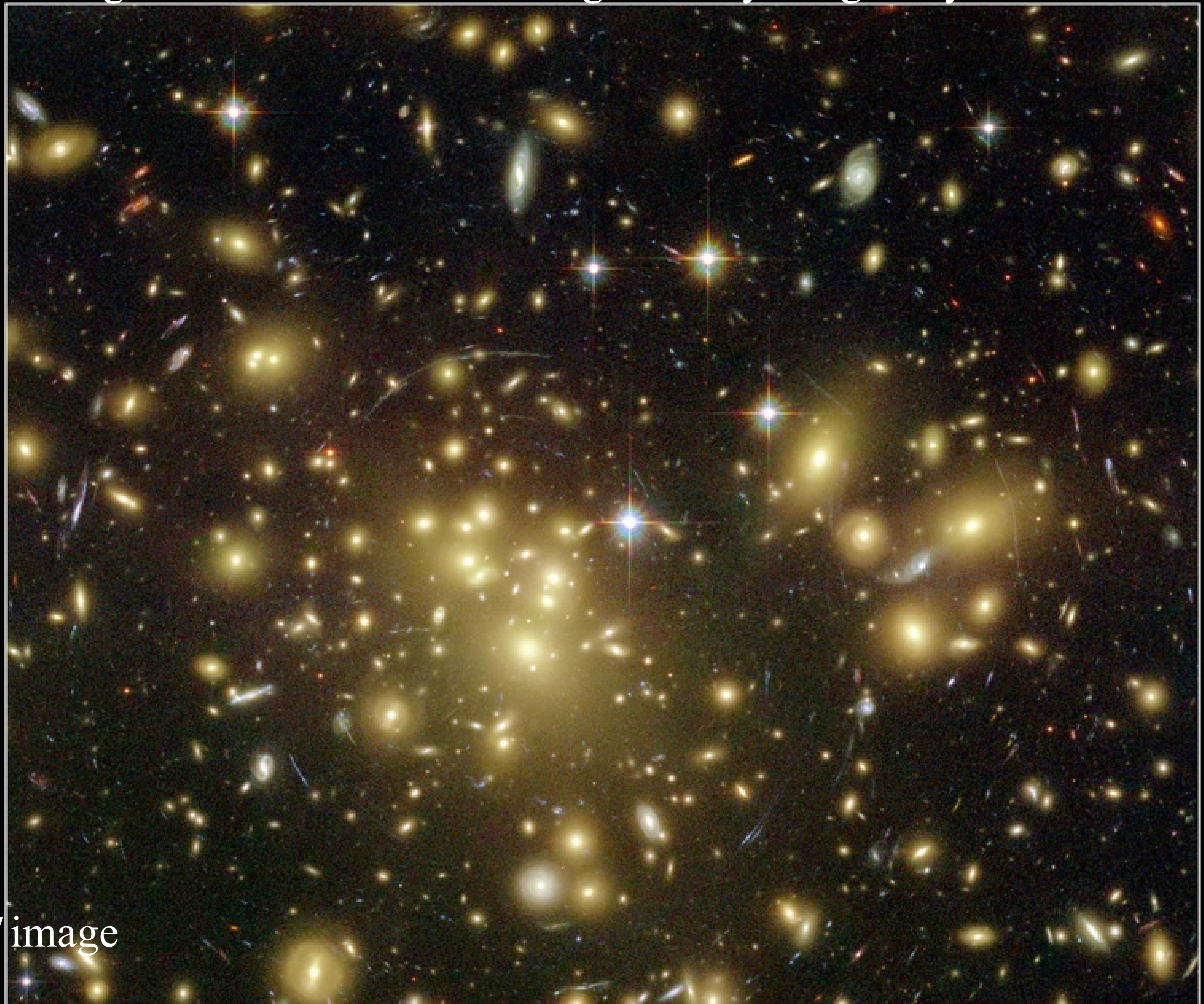

Real
Observed



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


Apparent position
Electromagnetic waves
Gravitation field
Massive object
Position of source
Focus
Apparent position

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


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

Messier 51 = NGC 5195

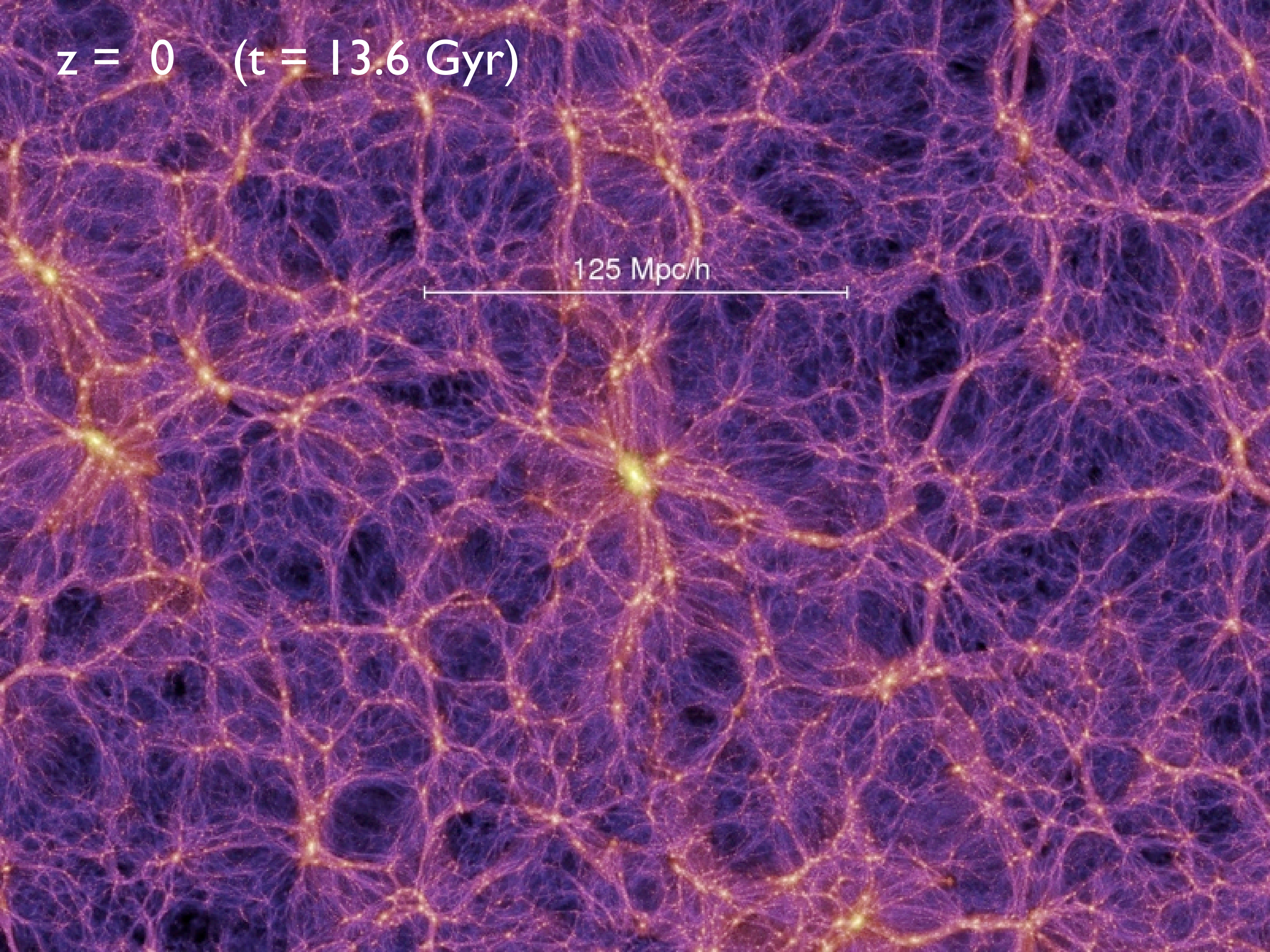
infrared

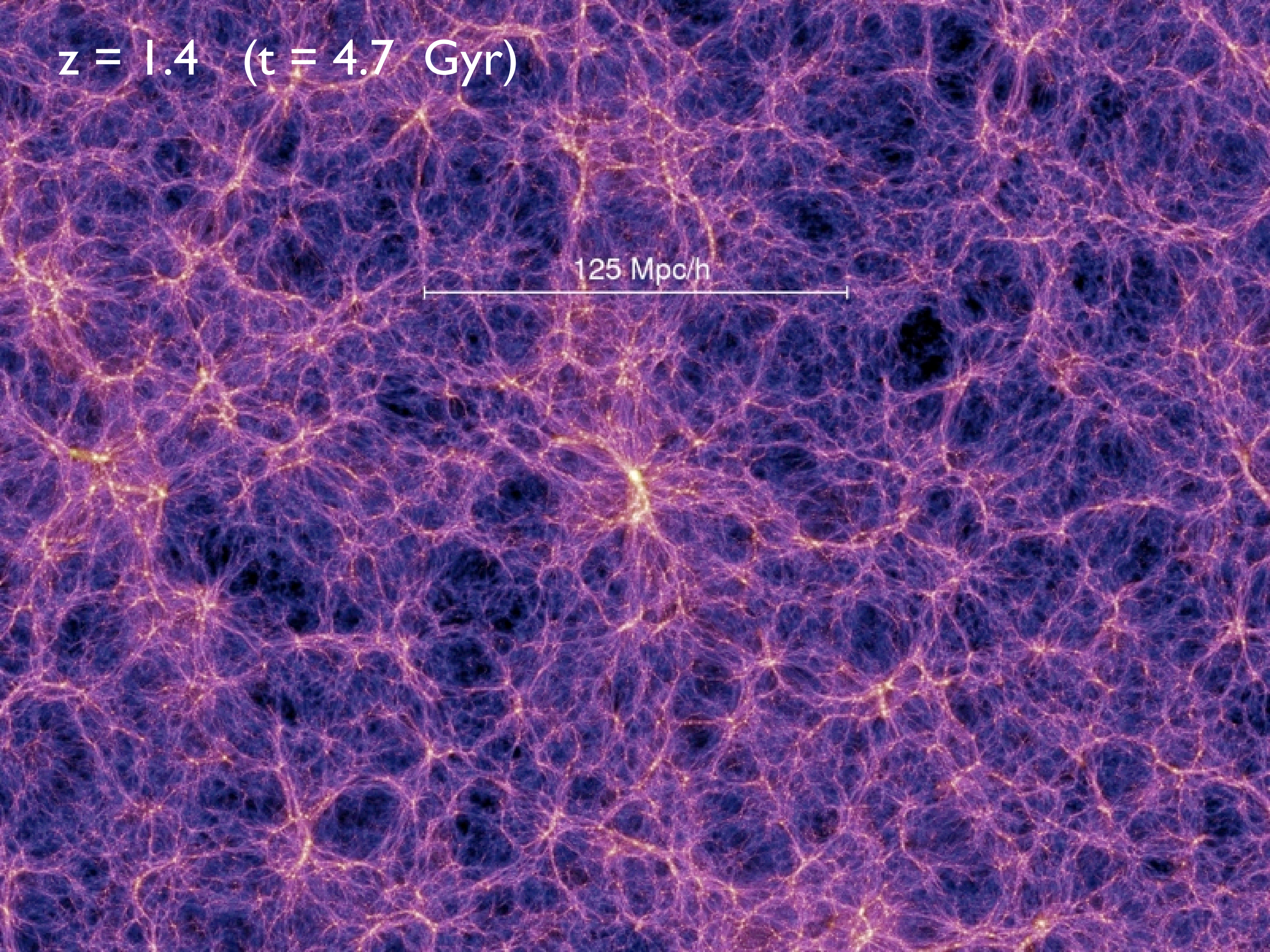
Spitzer Space Telescope

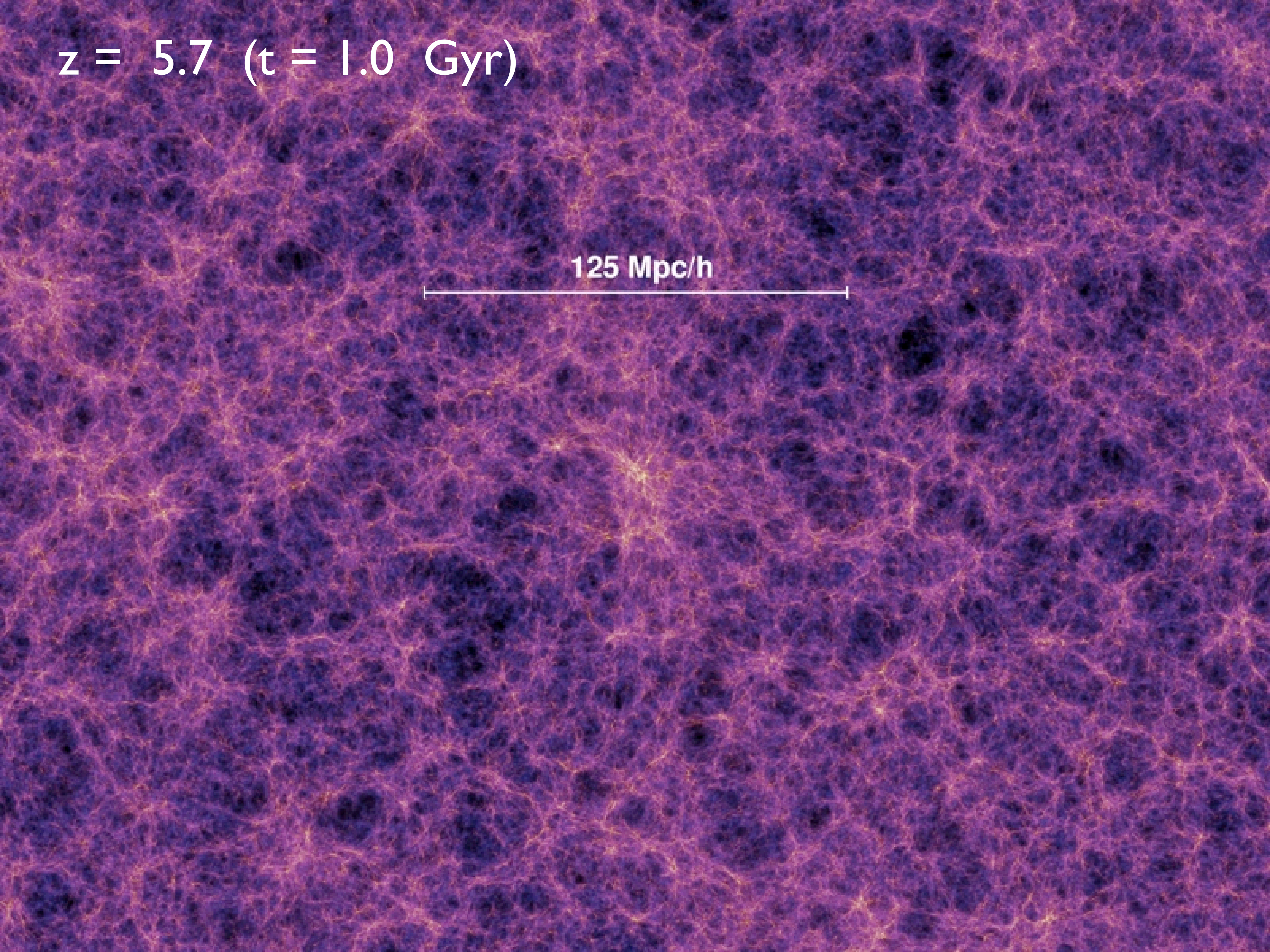
ultraviolet

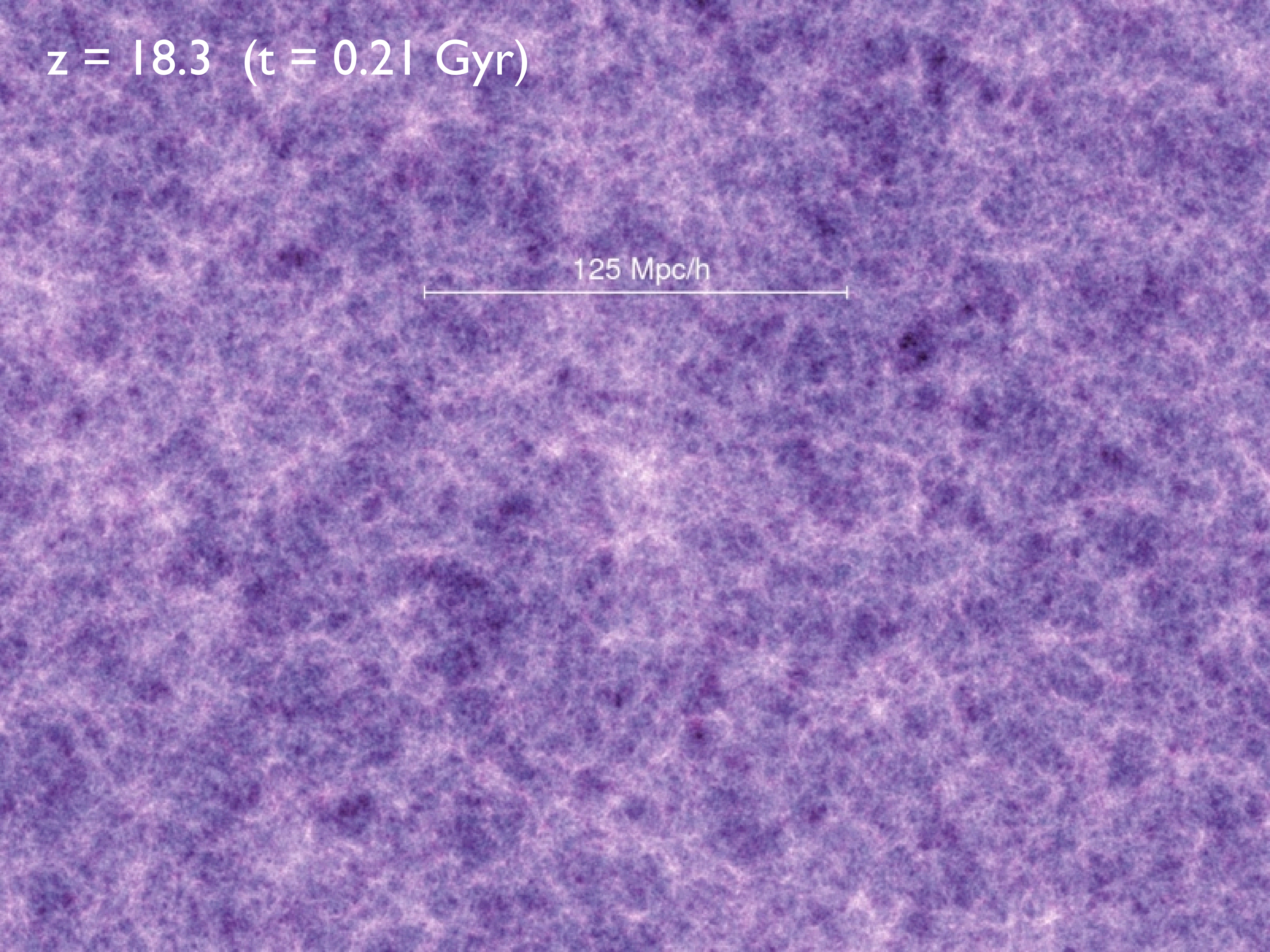
GALEX

z = 0 (t = 13.6 Gyr)




z = 1.4 (t = 4.7 Gyr)
125 Mpc/h


z = 5.7 (t = 1.0 Gyr)
125 Mpc/h


z = 18.3 (t = 0.21 Gyr)
125 Mpc/h

Cryogenic Dark Matter Search