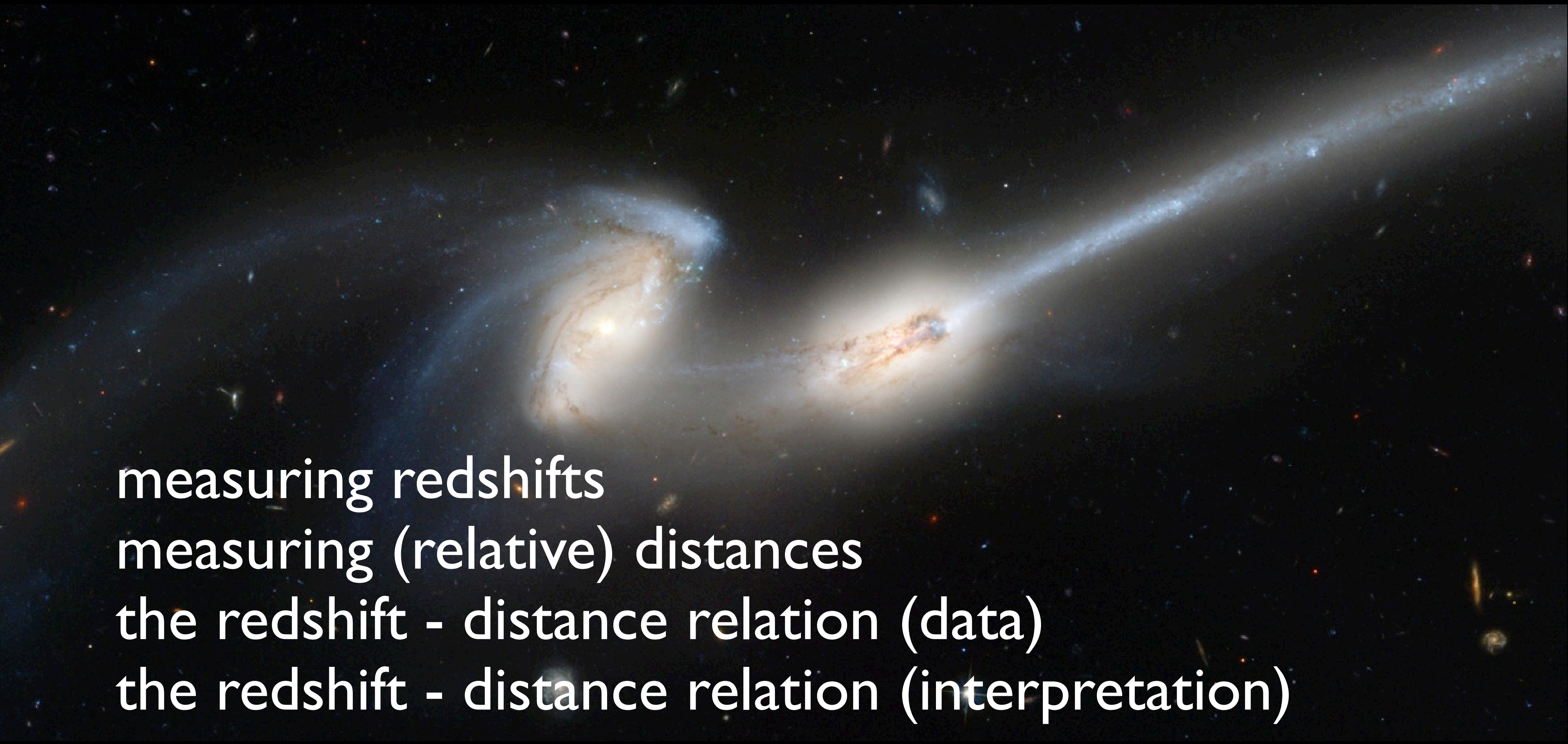
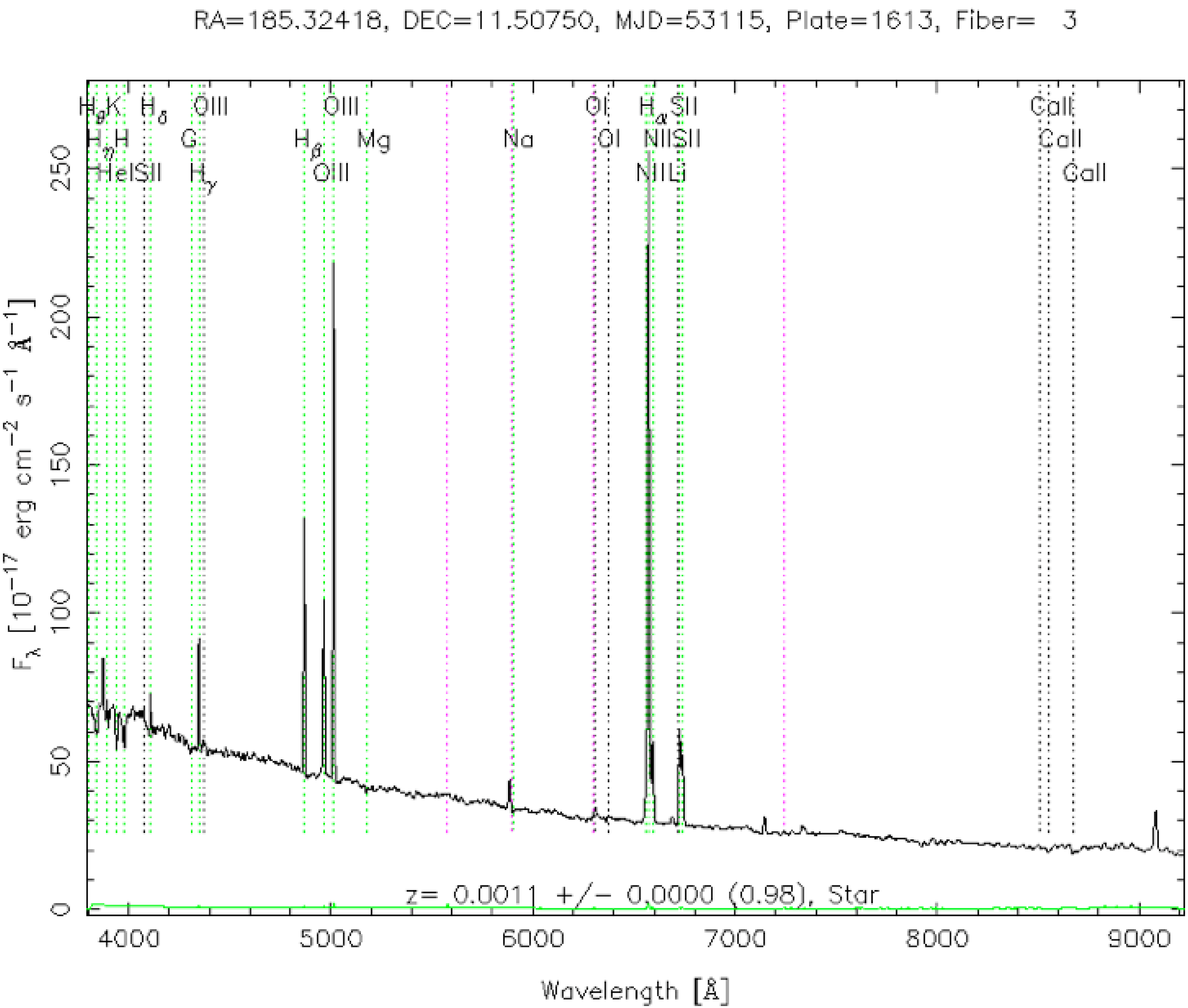
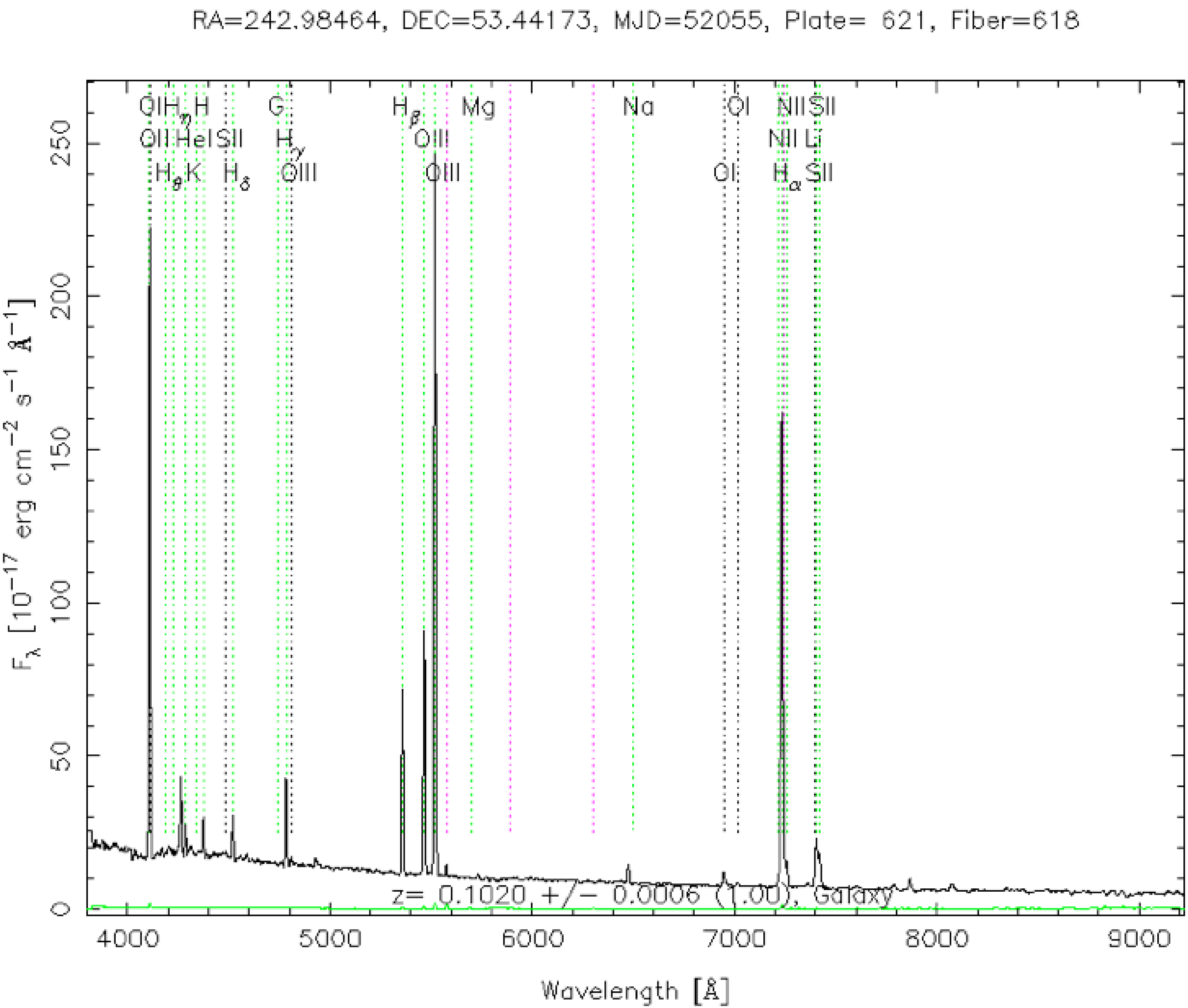
expansion of the Universe

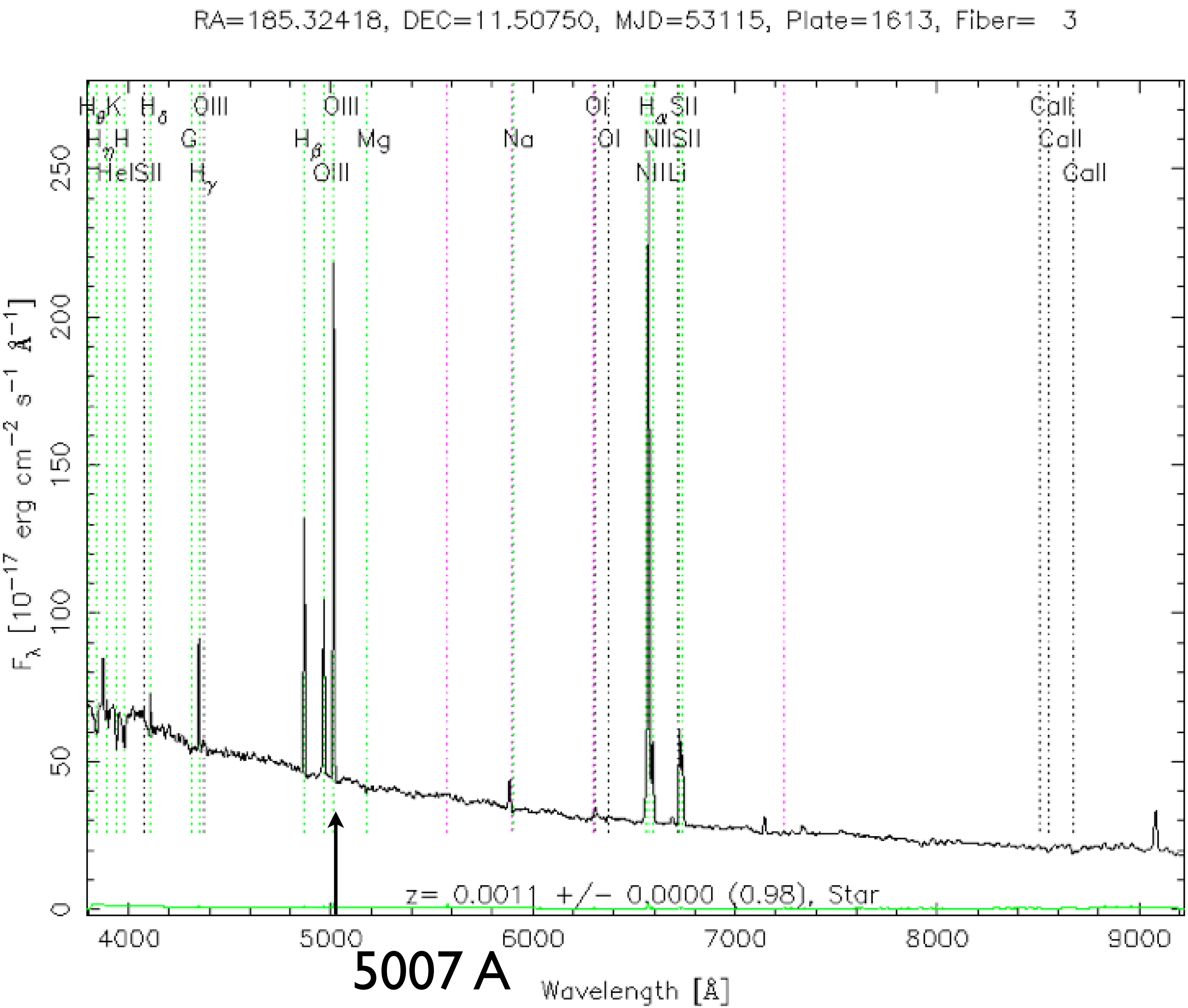


measuring redshifts
measuring (relative) distances
the redshift - distance relation (data)
the redshift - distance relation (interpretation)

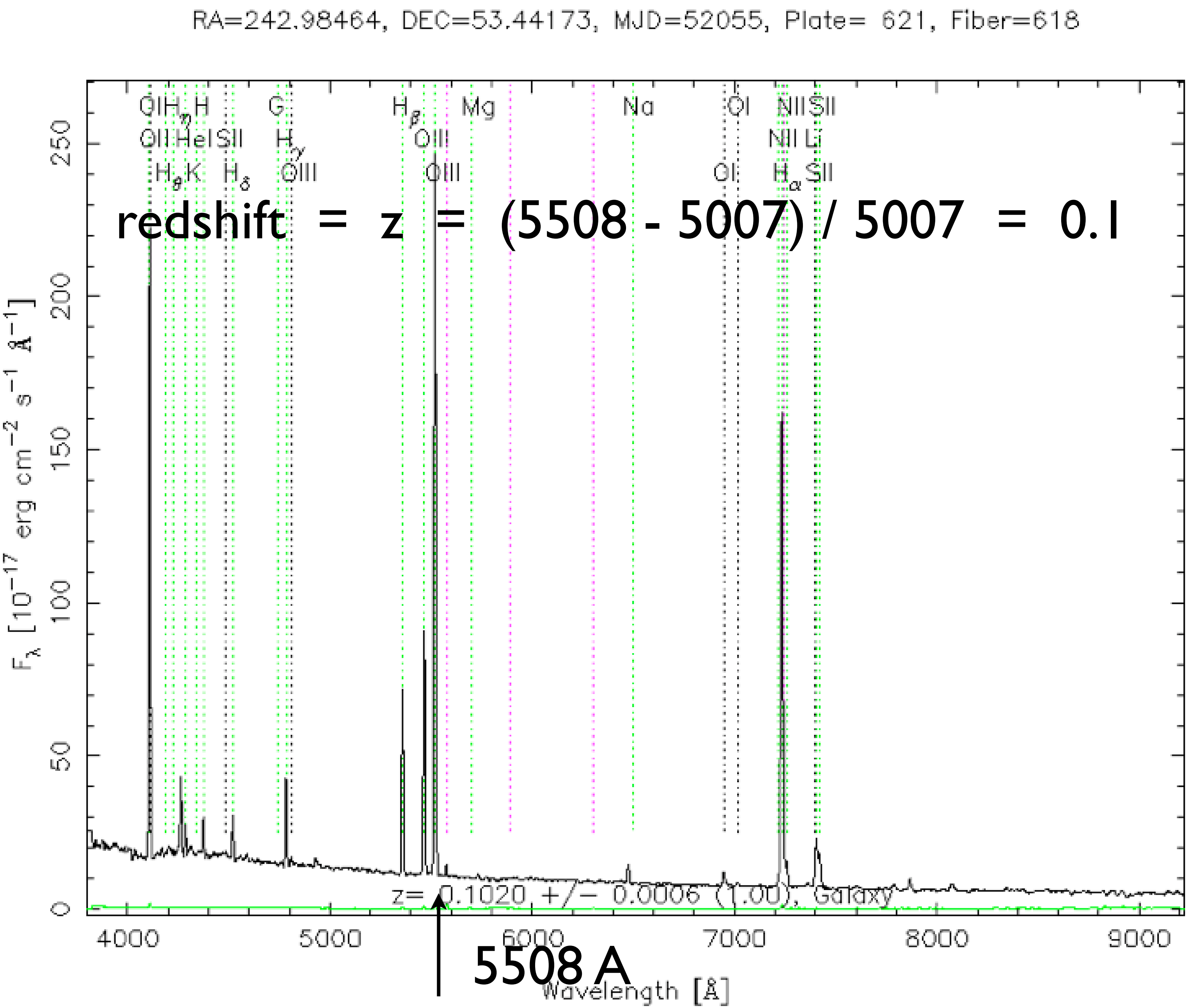


RA=185.32418, DEC=11.50750, MJD=53115, Plate=1613, Fiber= 3
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
z= 0.0011 +/- 0.0000 (0.98), Star
H$_\theta$ K H$_\delta$ OIII OIII OI H$_\alpha$ SII CaII
H$_\eta$ H G H$_\beta$ Mg Na OI NII SII CaII
HeI SII H$_\gamma$ OIII NII Li CaII
0 50 100 150 200 250
4000 5000 6000 7000 8000 9000


RA=242.98464, DEC=53.44173, MJD=52055, Plate= 621, Fiber=618
OII H_η H
OII HeI SII
H_θ K
H_δ
G
H_γ
OIII
H_β
OIII
OIII
Mg
Na
OI
OI
NII SII
NII Li
H_α SII
z= 0.1020 +/- 0.0006 (1.00), Galaxy
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
0
50
100
150
200
250
4000
5000
6000
7000
8000
9000



RA=185.32418, DEC=11.50750, MJD=53115, Plate=1613, Fiber= 3
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
z= 0.0011 +/- 0.0000 (0.98), Star
OIII
Hβ
Hα
NII
SII
Na
OI
Mg
CaII
5007 A



RA=242.98464, DEC=53.44173, MJD=52055, Plate= 621, Fiber=618
redshift = z = (5508 - 5007) / 5007 = 0.1
OII Hη H
OII HeI SII
Hθ K Hδ
G
Hγ
OIII
Hβ
OIII
OIII
Mg
Na
OI
OI
NII SII
NII Li
Hα SII
z= 0.1020 +/- 0.0006 (1.00), Galaxy
5508 A
Wavelength [Å]
Fλ [10^-17 erg cm^-2 s^-1 Å^-1]
0
50
100
150
200
250
4000
5000
6000
7000
8000
9000

λ is the observed wavelength of the spectral line

λ_0 is the wavelength if the source is not moving

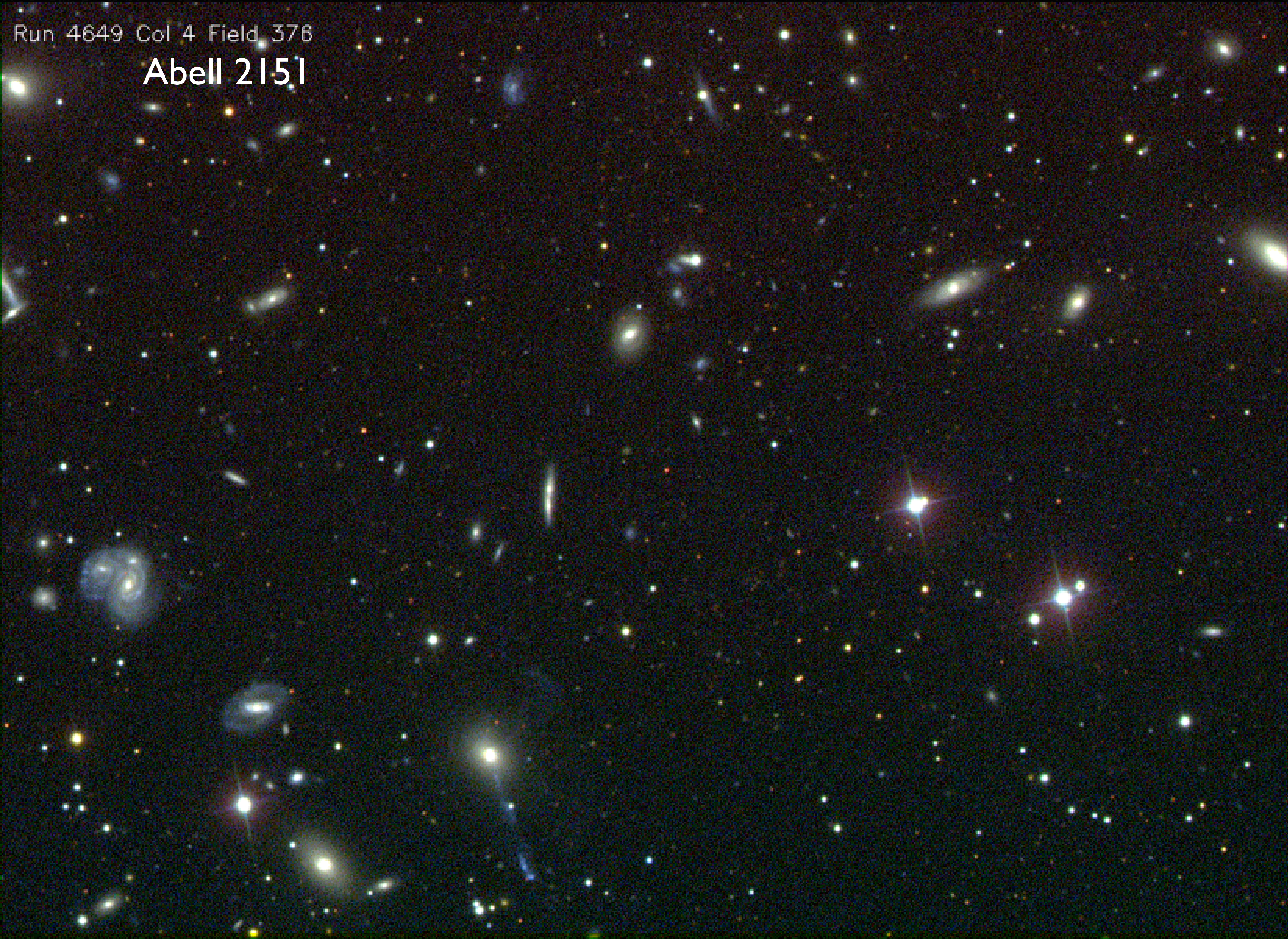
$$(\lambda - \lambda_0) / \lambda_0 \equiv z$$

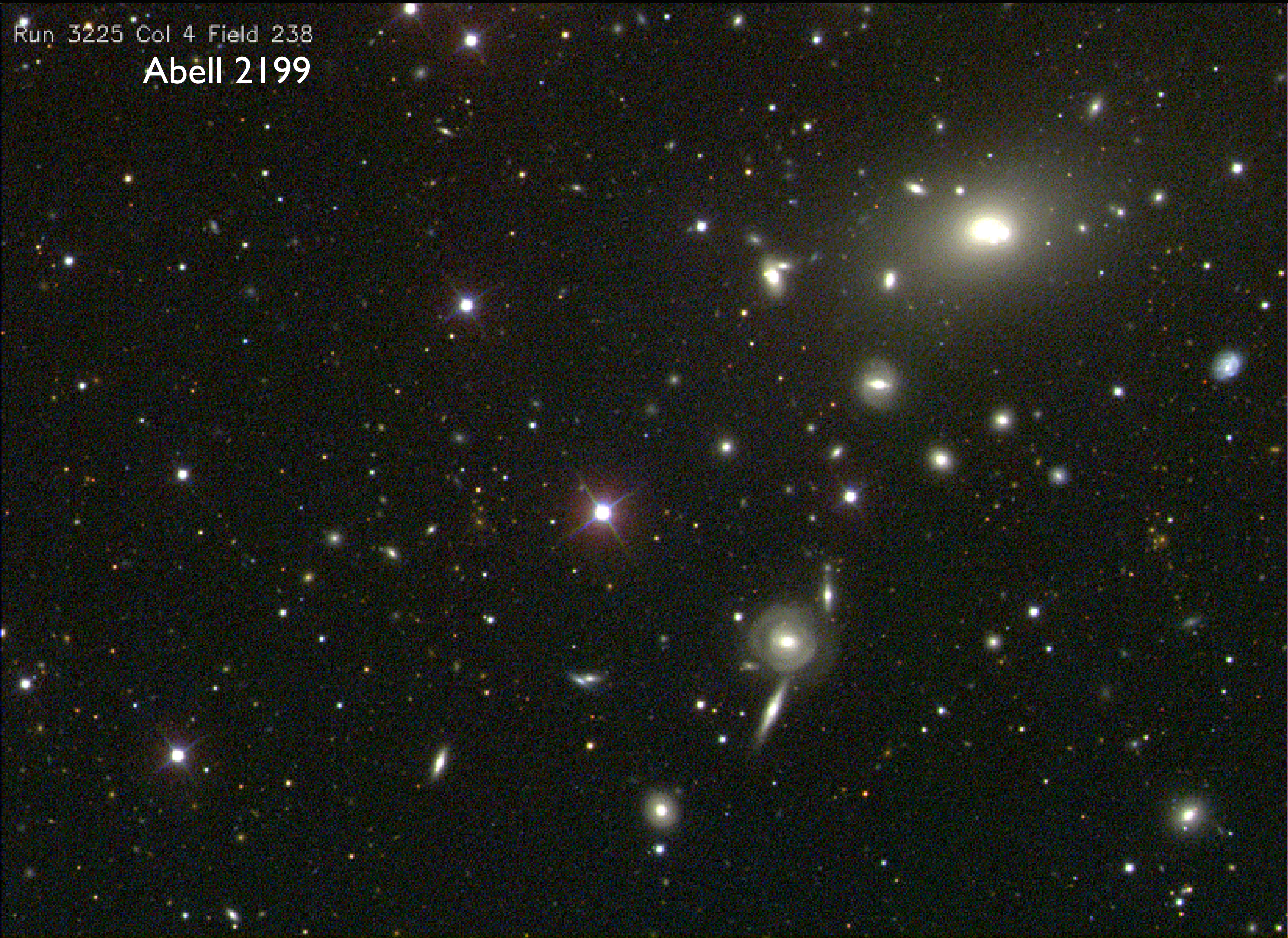
$+ \Rightarrow$ motion away (receding, or *redshift*)

$- \Rightarrow$ motion towards (approaching, or *blueshift*)

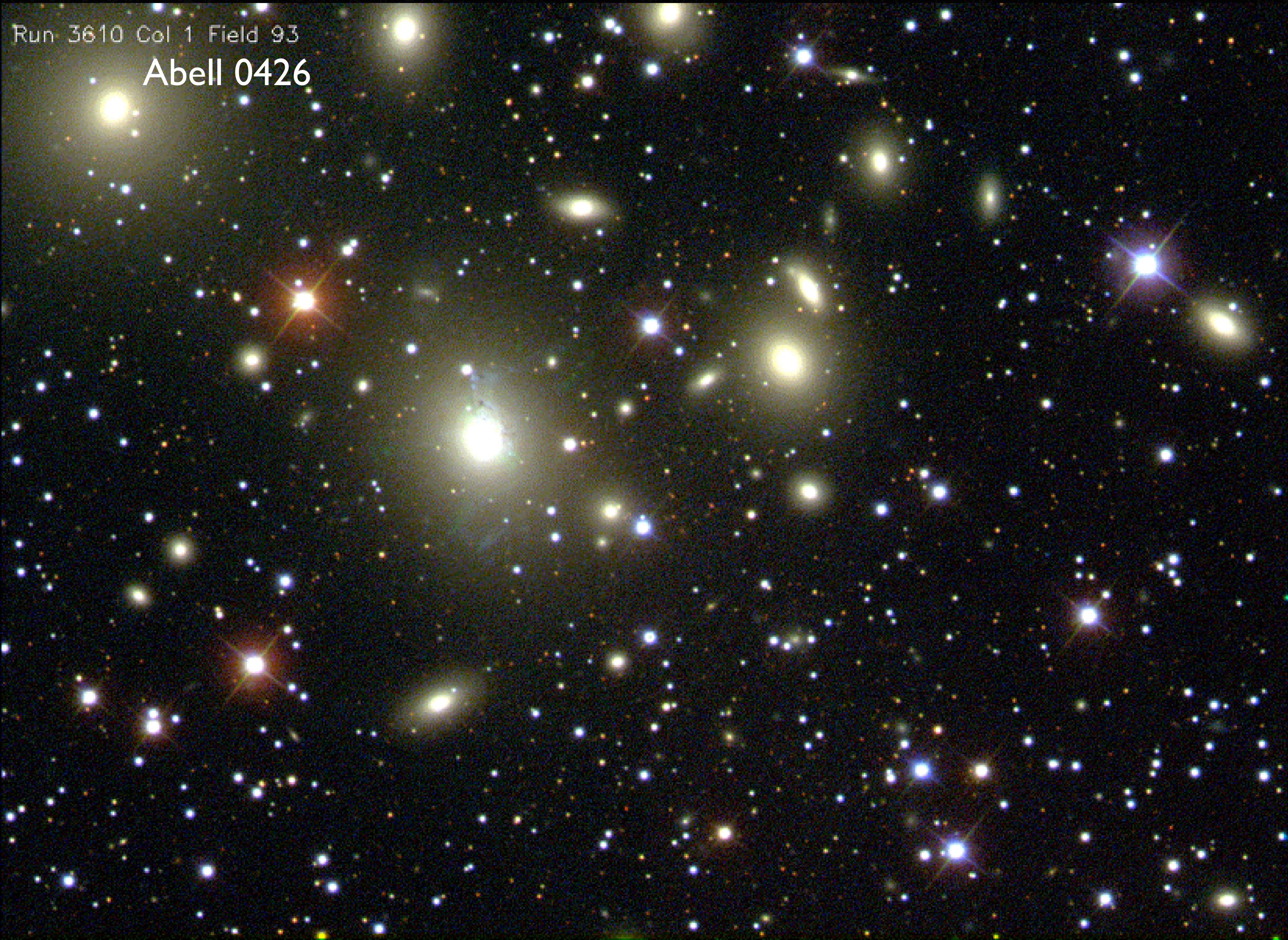
if $z \ll 1$, then $z \approx v / c$

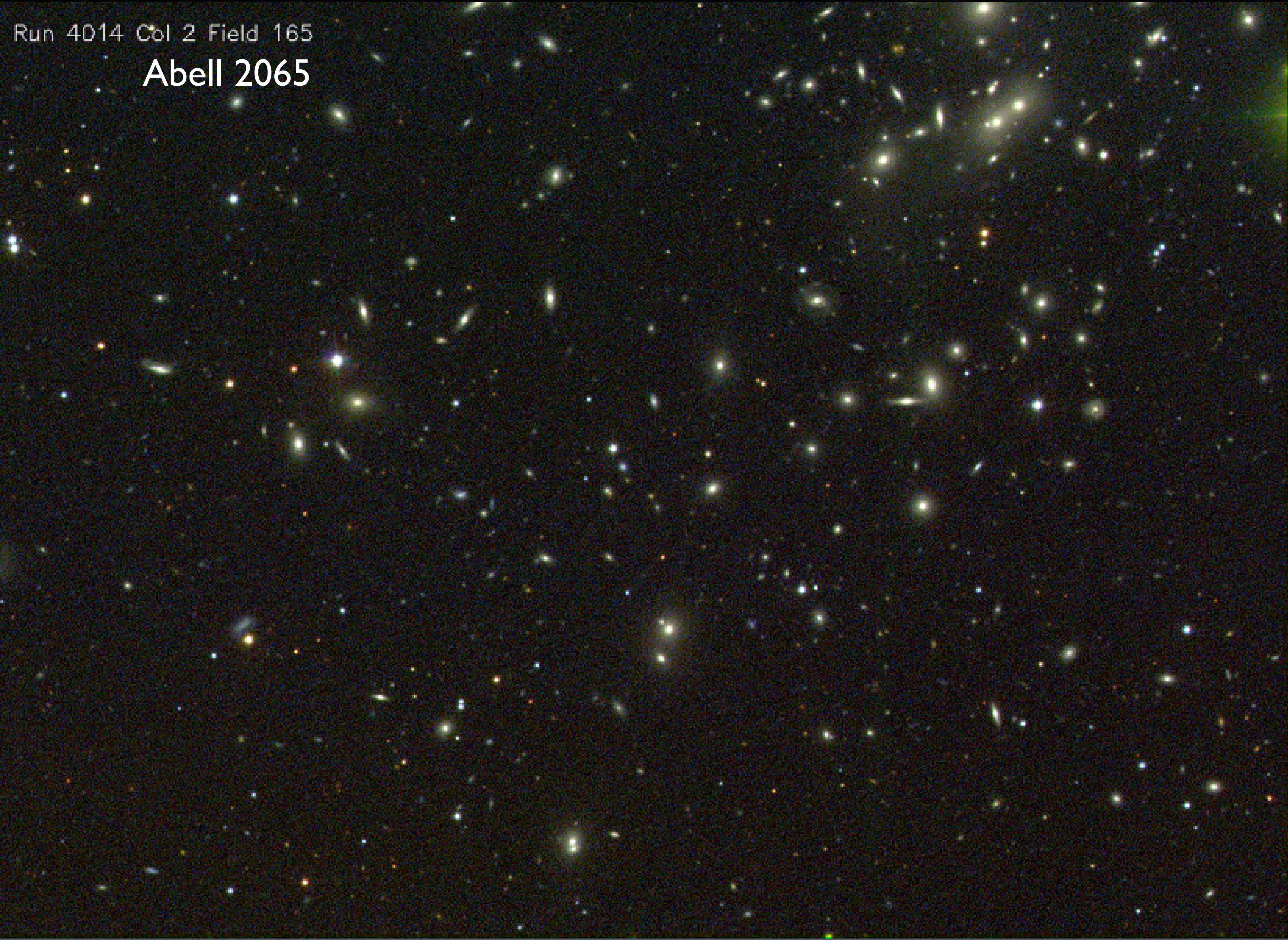
$v = c \times z$ is called the *radial velocity*

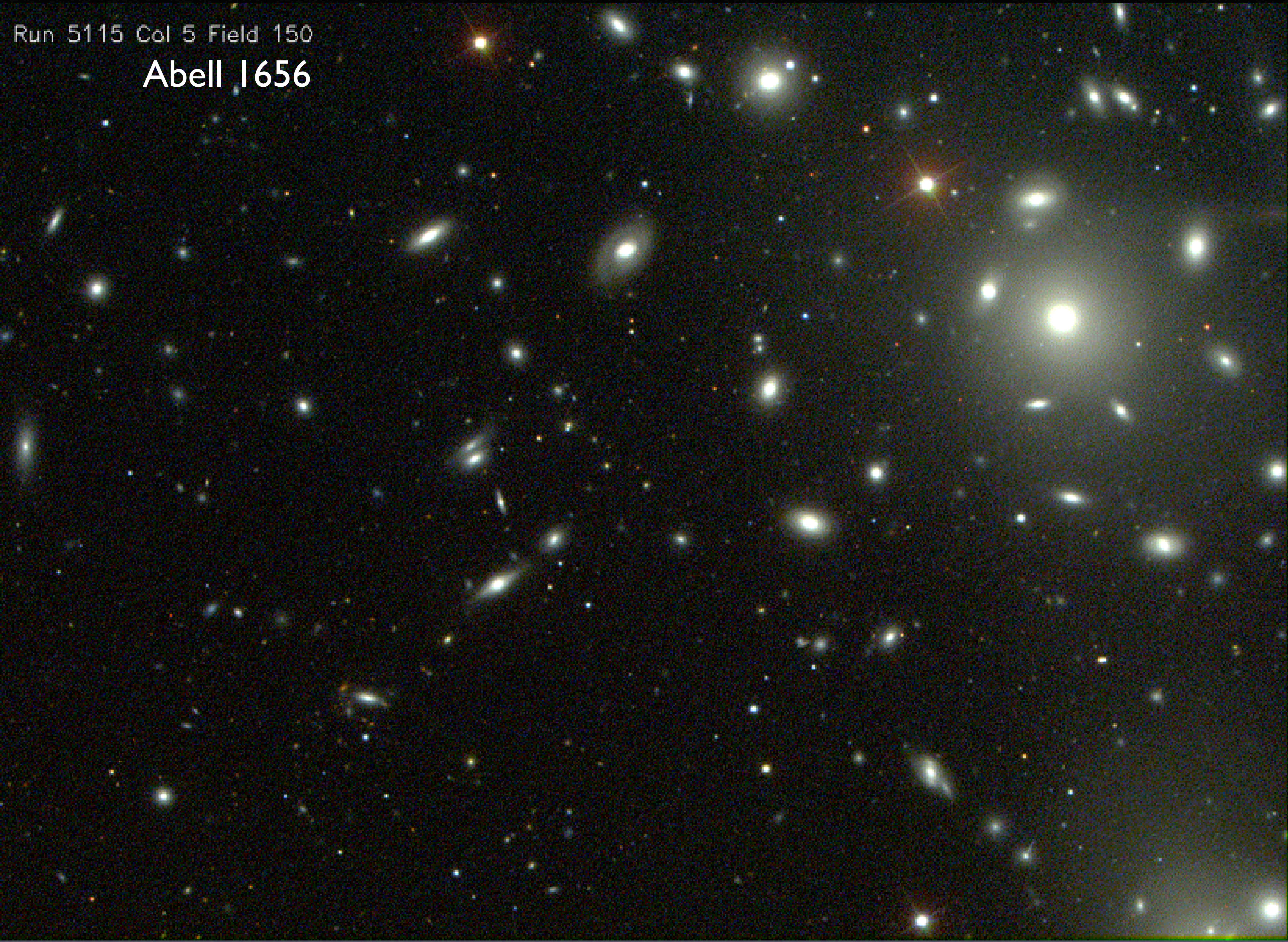

Run 4649 Col 4 Field 376
Abell 2151


Run 3225 Col 4 Field 238
Abell 2199


Run 1140 Col 6 Field 300
Abell 1689


Run 3610 Col 1 Field 93
Abell 0426


Run 4014 Col 2 Field 165
Abell 2065


Run 5115 Col 5 Field 150
Abell 1656


1910
CHAMPIONS
Champions of the West.

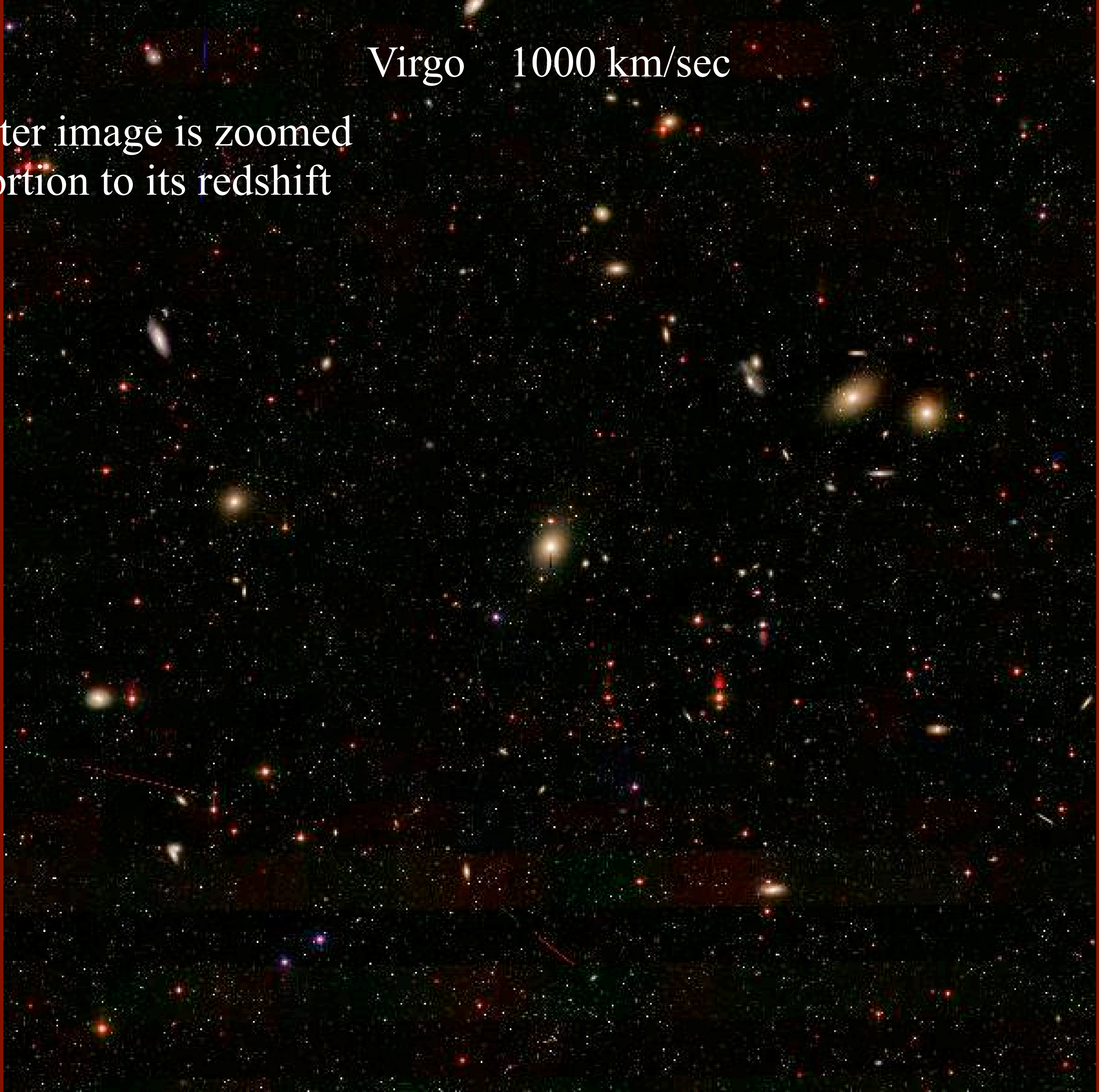
Yerkes Observatory staff, ca. 1917

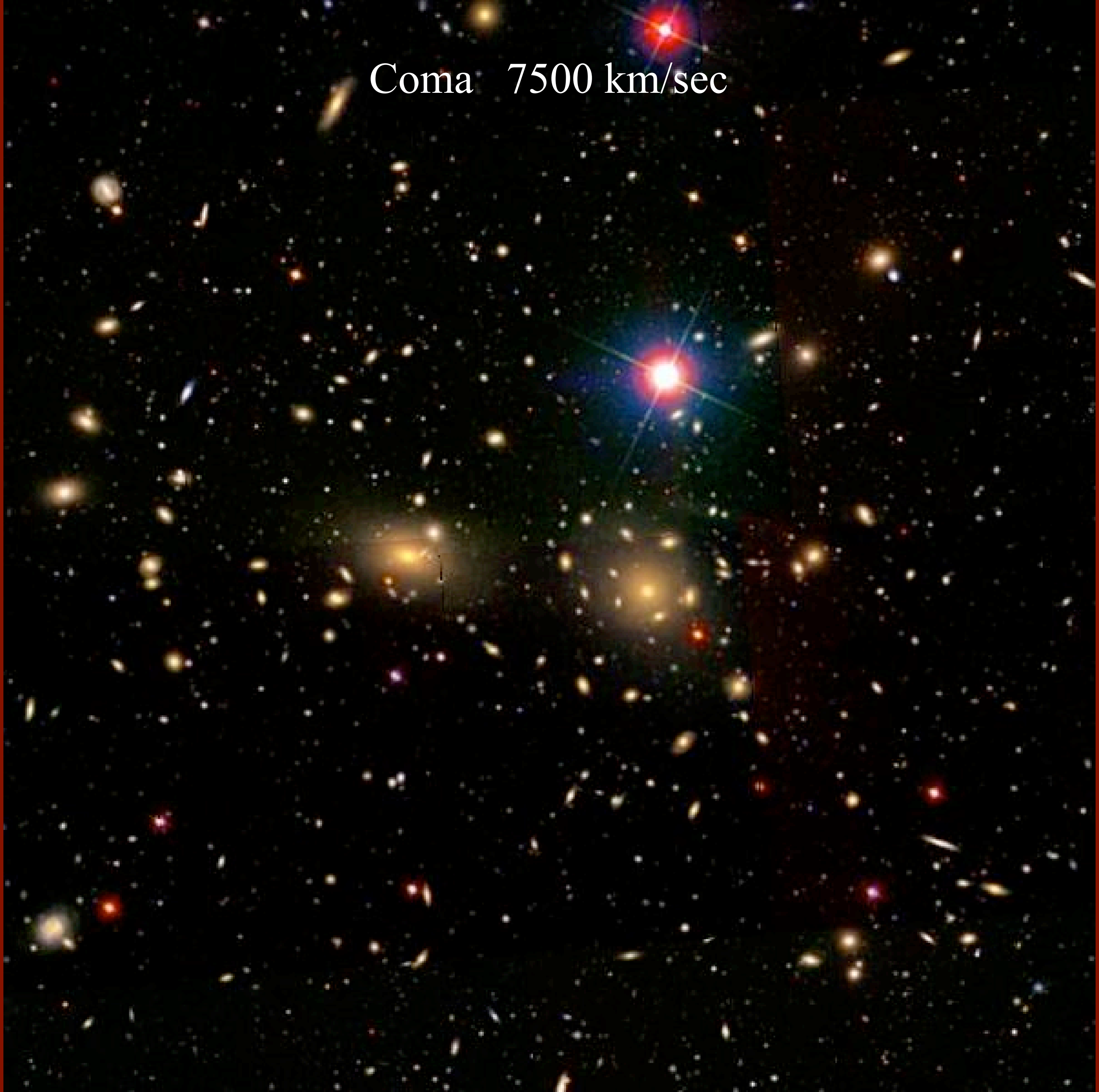
observing with 48-inch Schmidt survey telescope at Palomar, ca. 1950

Milton Humason,
Mt. Wilson Observatory

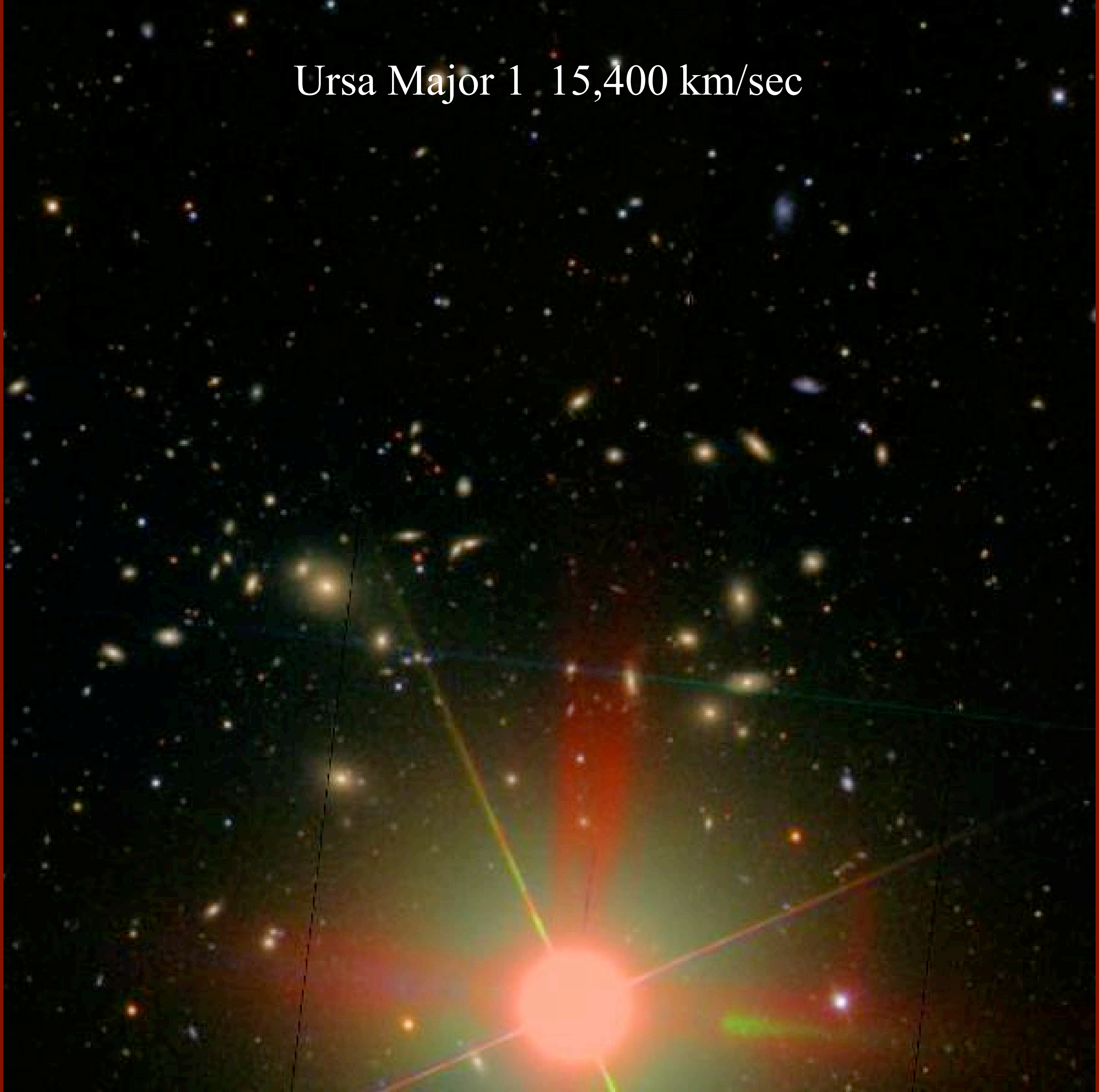
Hubble's main contribution was devising ways to measure distances to galaxies. The redshift data were obtained by these gentlemen.

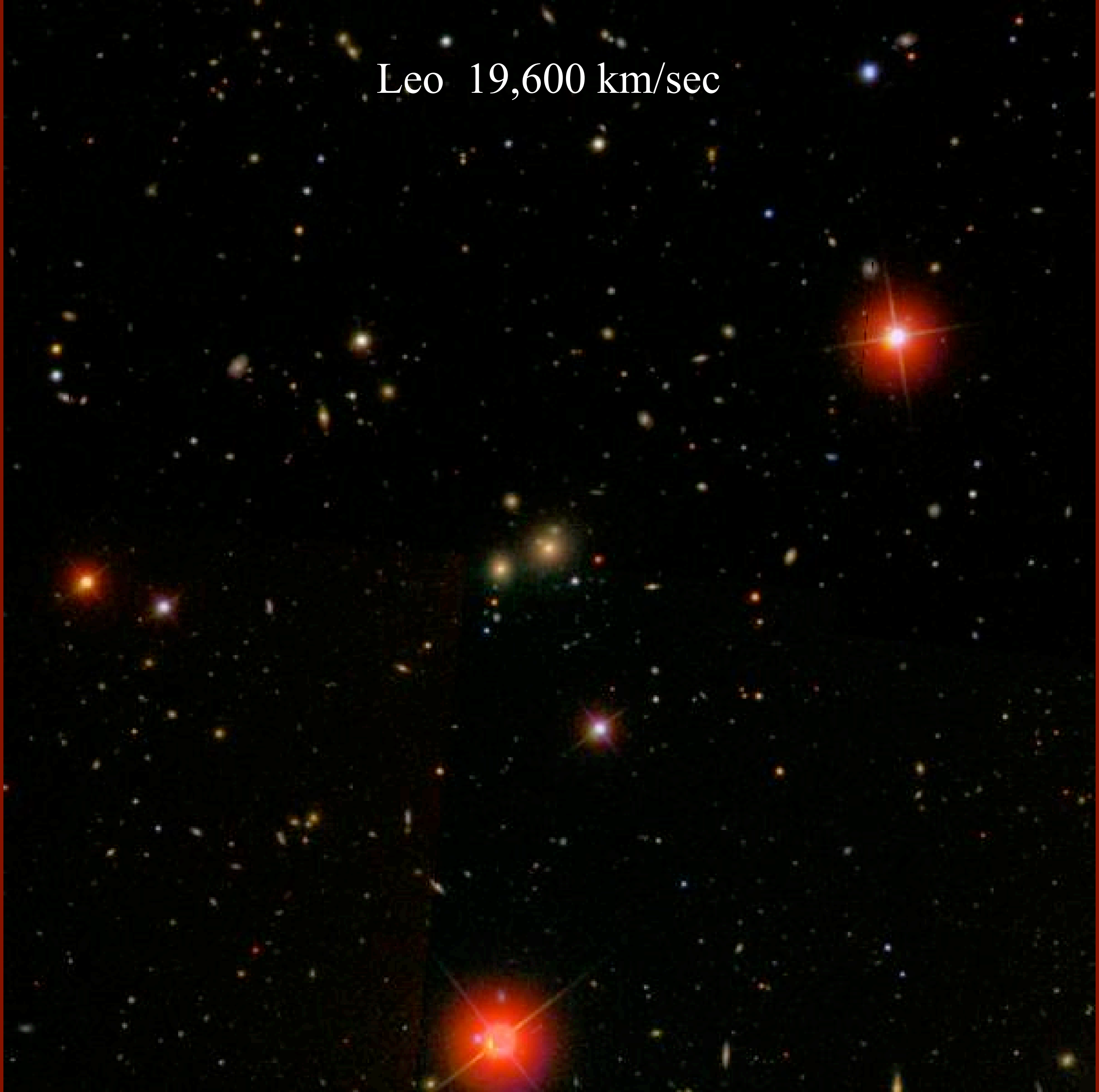
Vesto Slipher,
Lowell Observatory


Virgo 1000 km/sec
each cluster image is zoomed
in proportion to its redshift

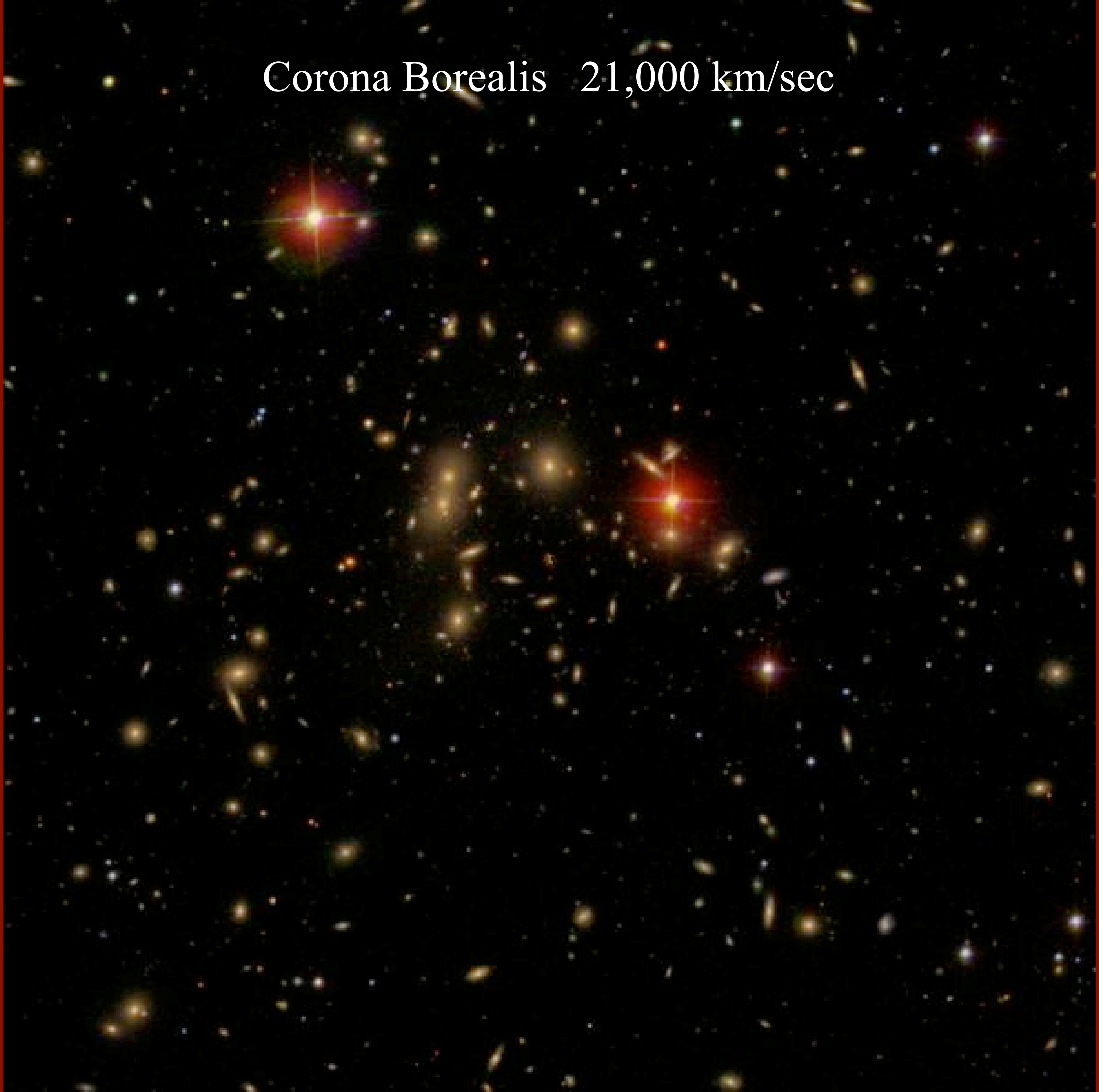

Coma   7500 km/sec

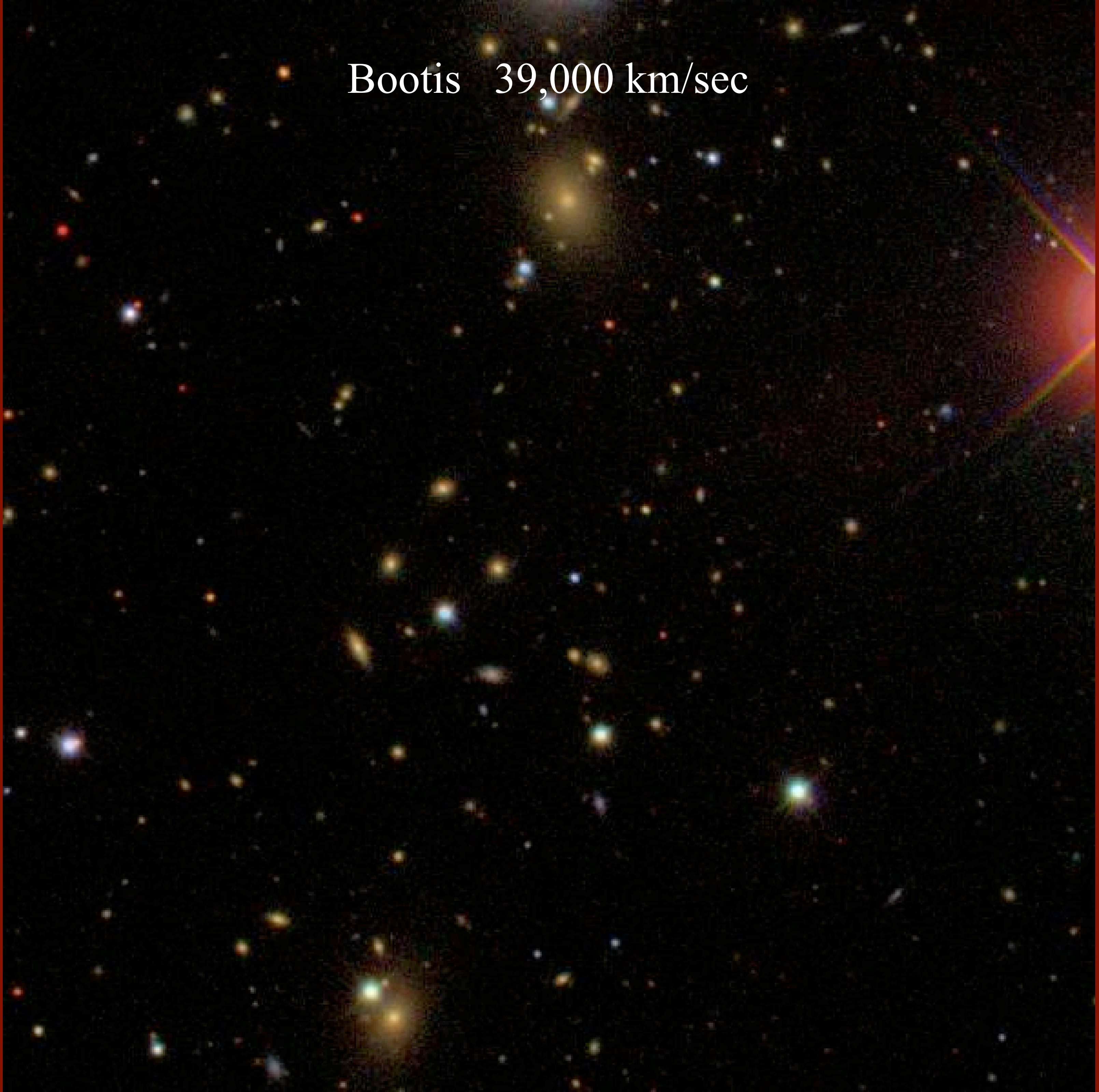
Ursa Major 1 15,400 km/sec



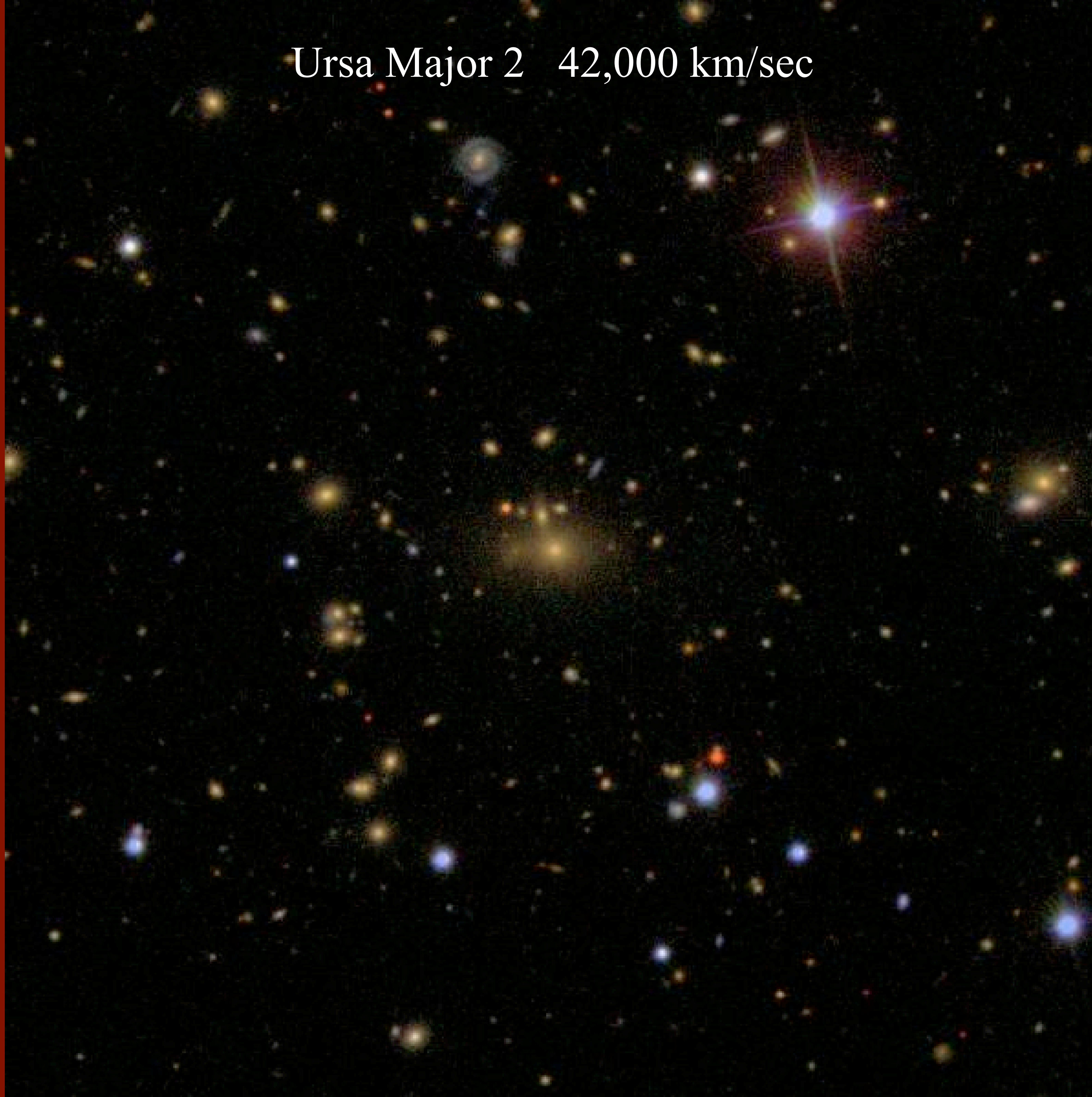

Leo 19,600 km/sec

Corona Borealis   21,000 km/sec




Bootis 39,000 km/sec

Ursa Major 2   42,000 km/sec



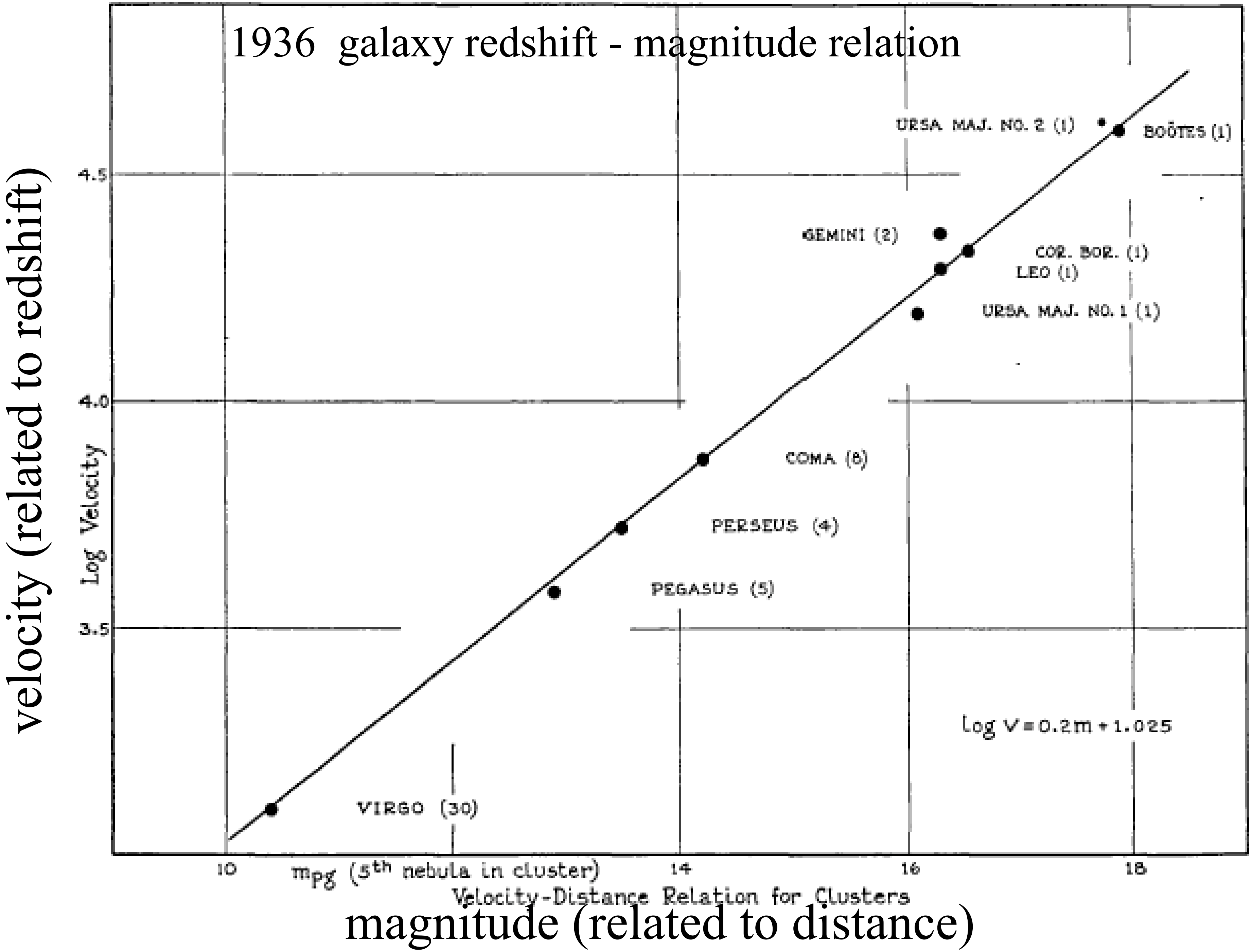
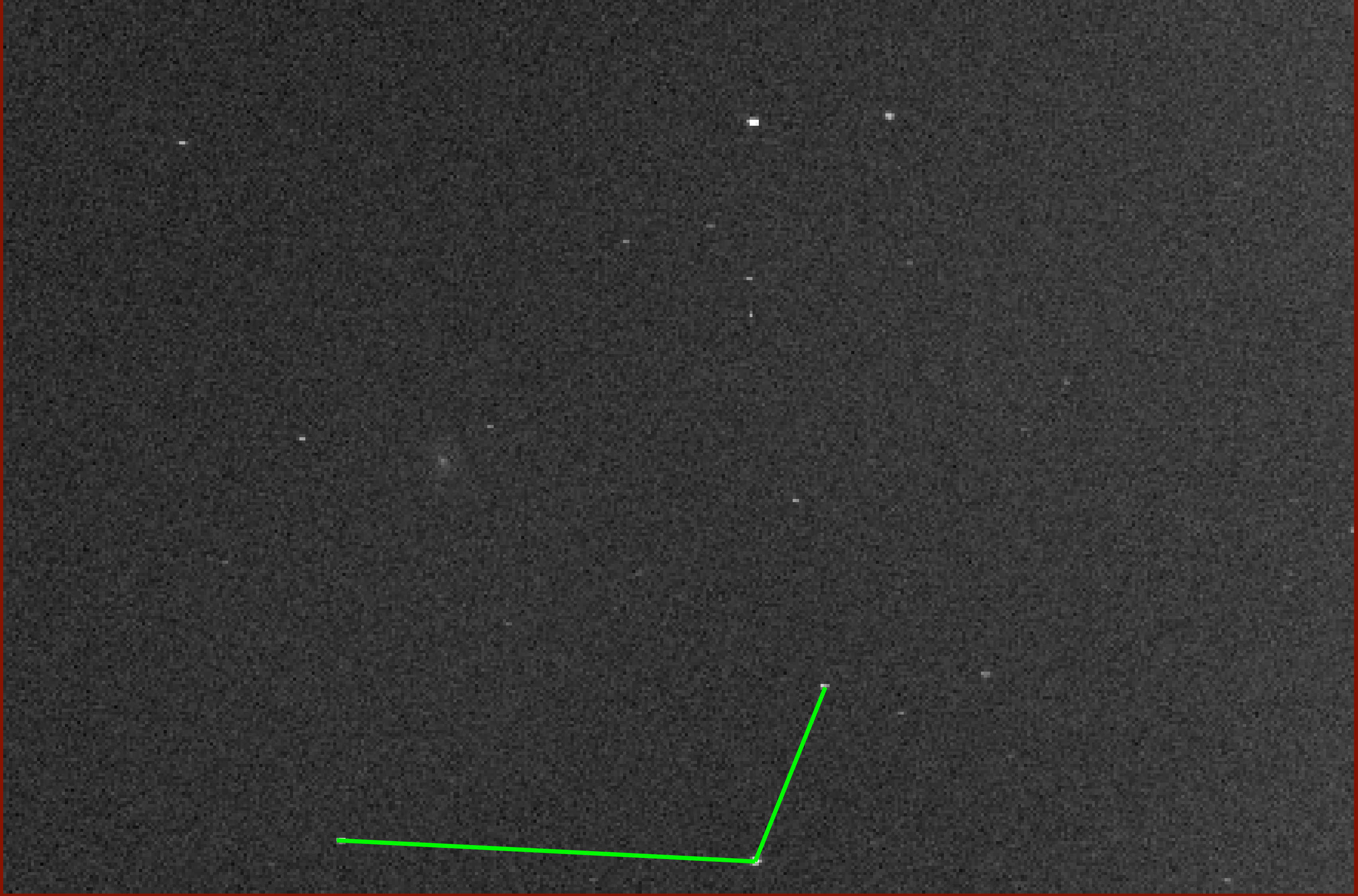


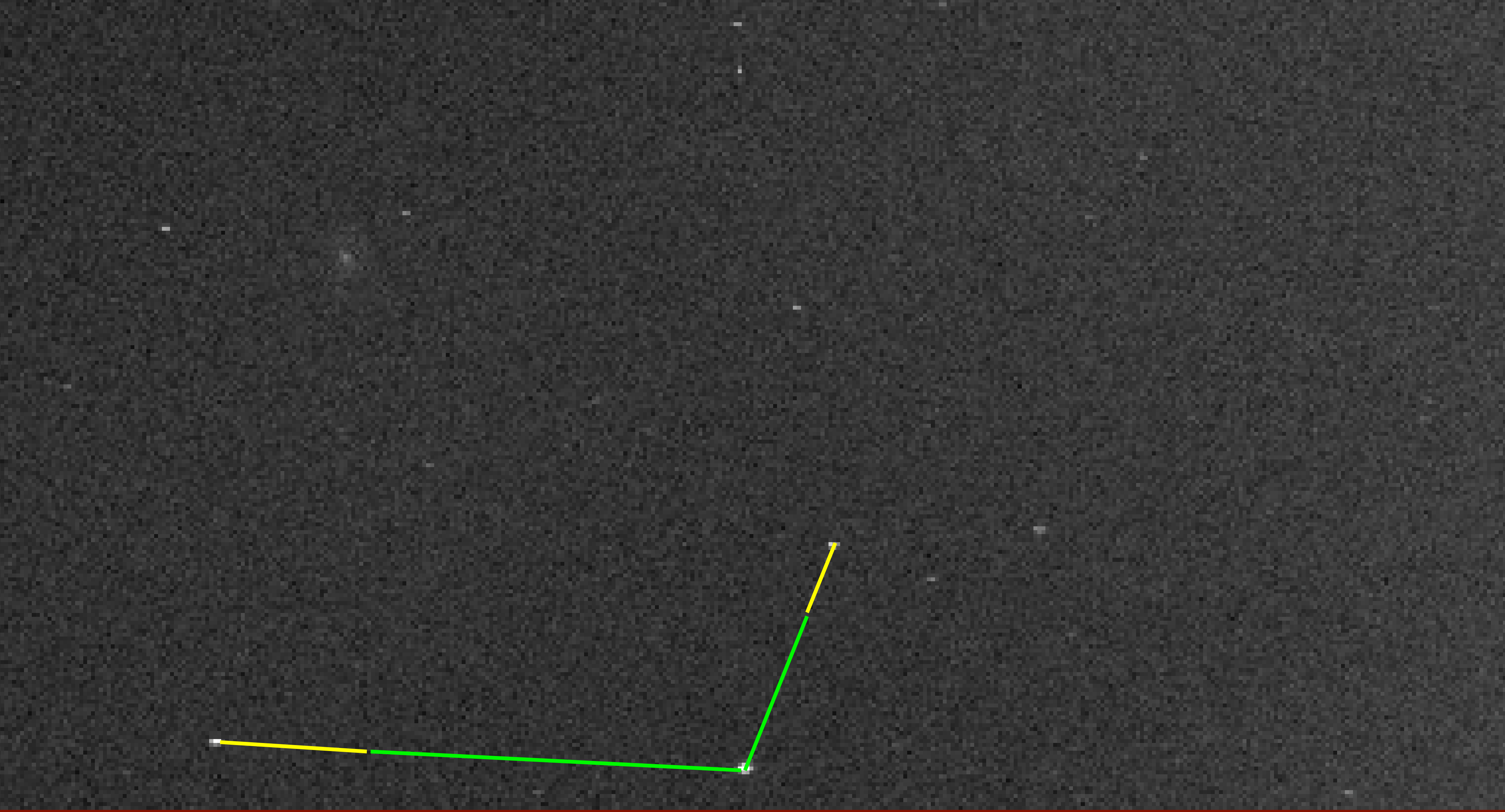
FIG. 2.—Figures in parentheses following the names of the clusters indicate the number of nebulae observed in each cluster.

distribution of things at some particular time

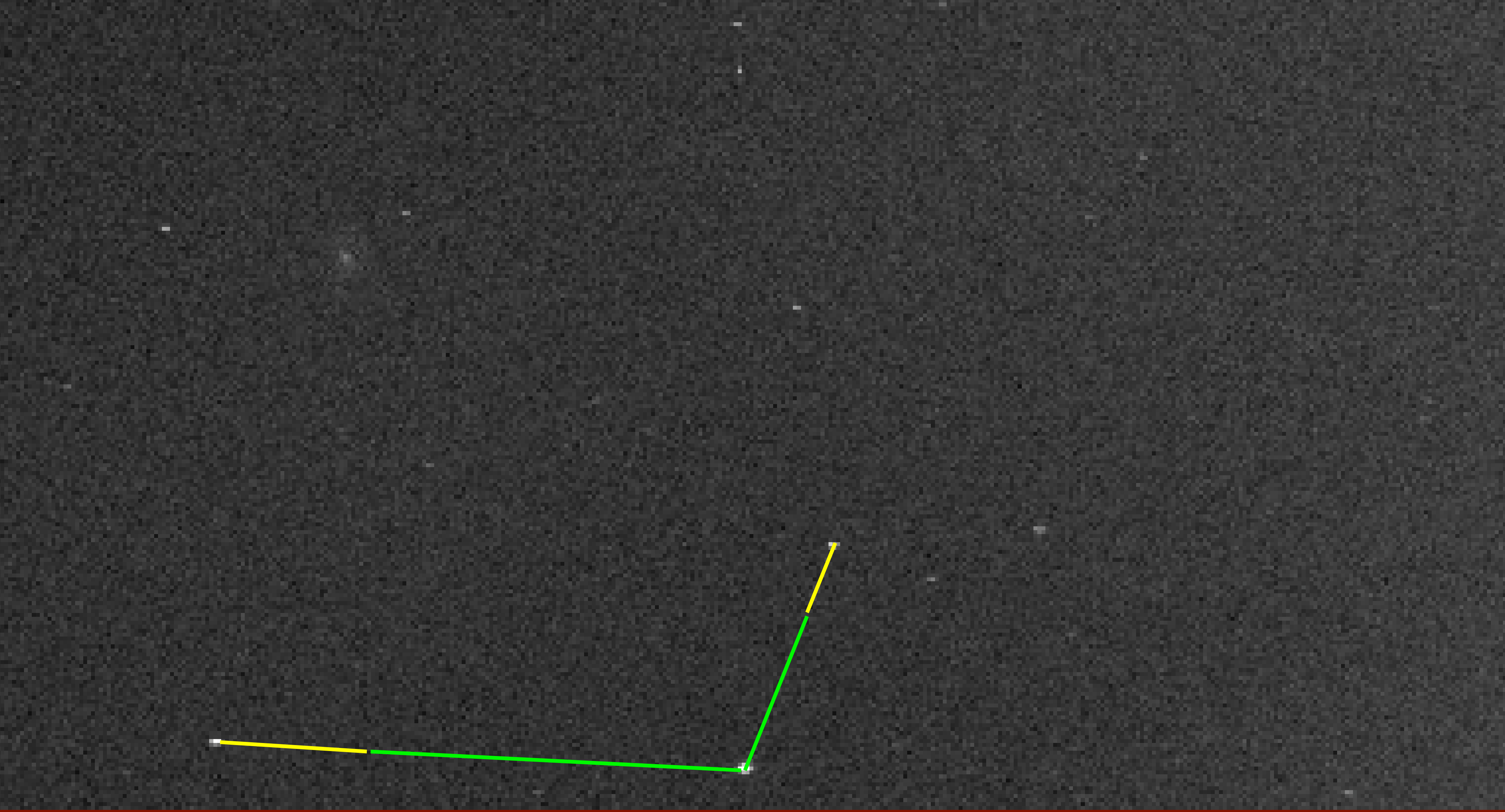
distribution of things at some later time:
all dimensions expanded by the same factor



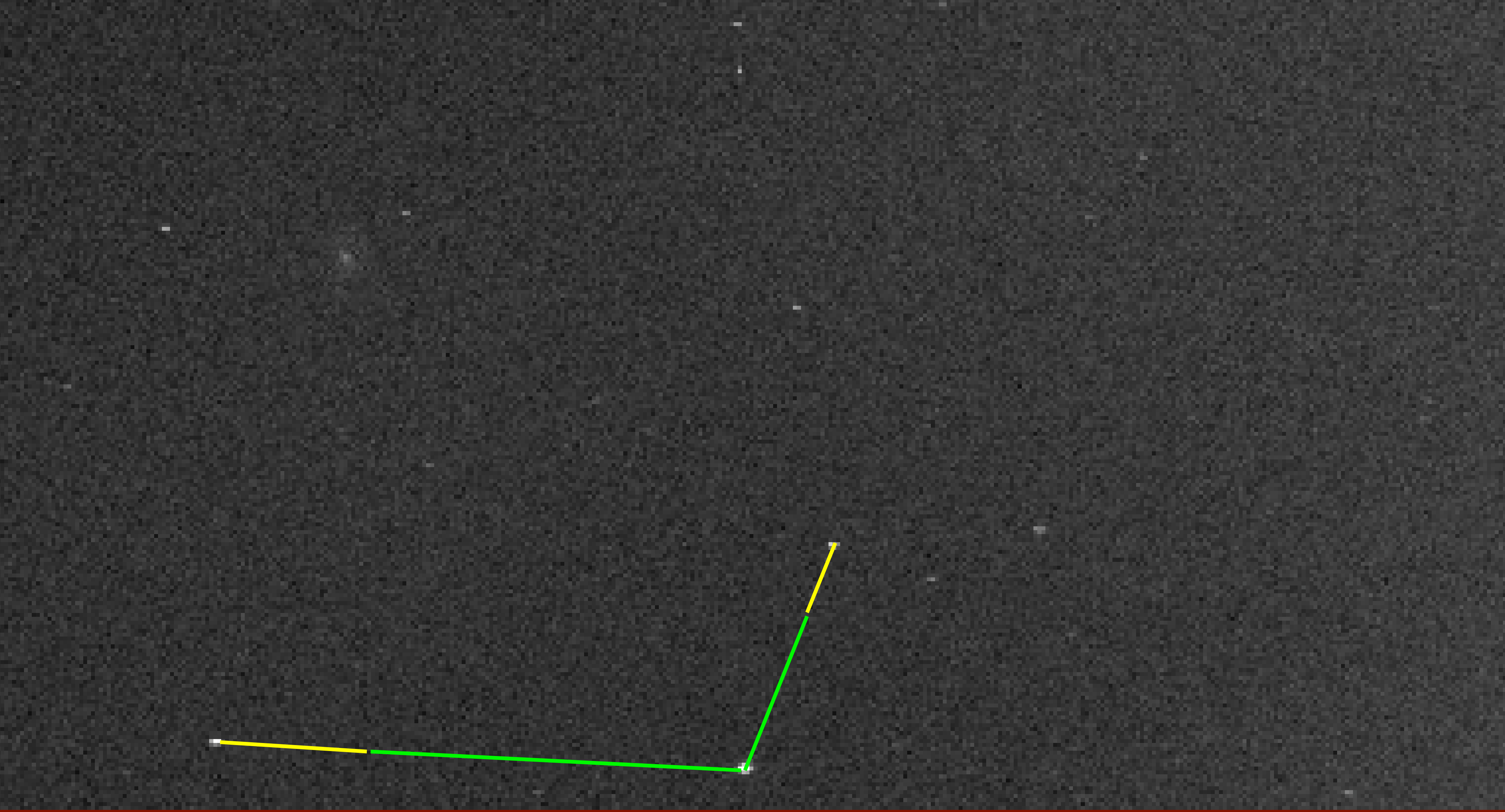
two separations marked at initial time



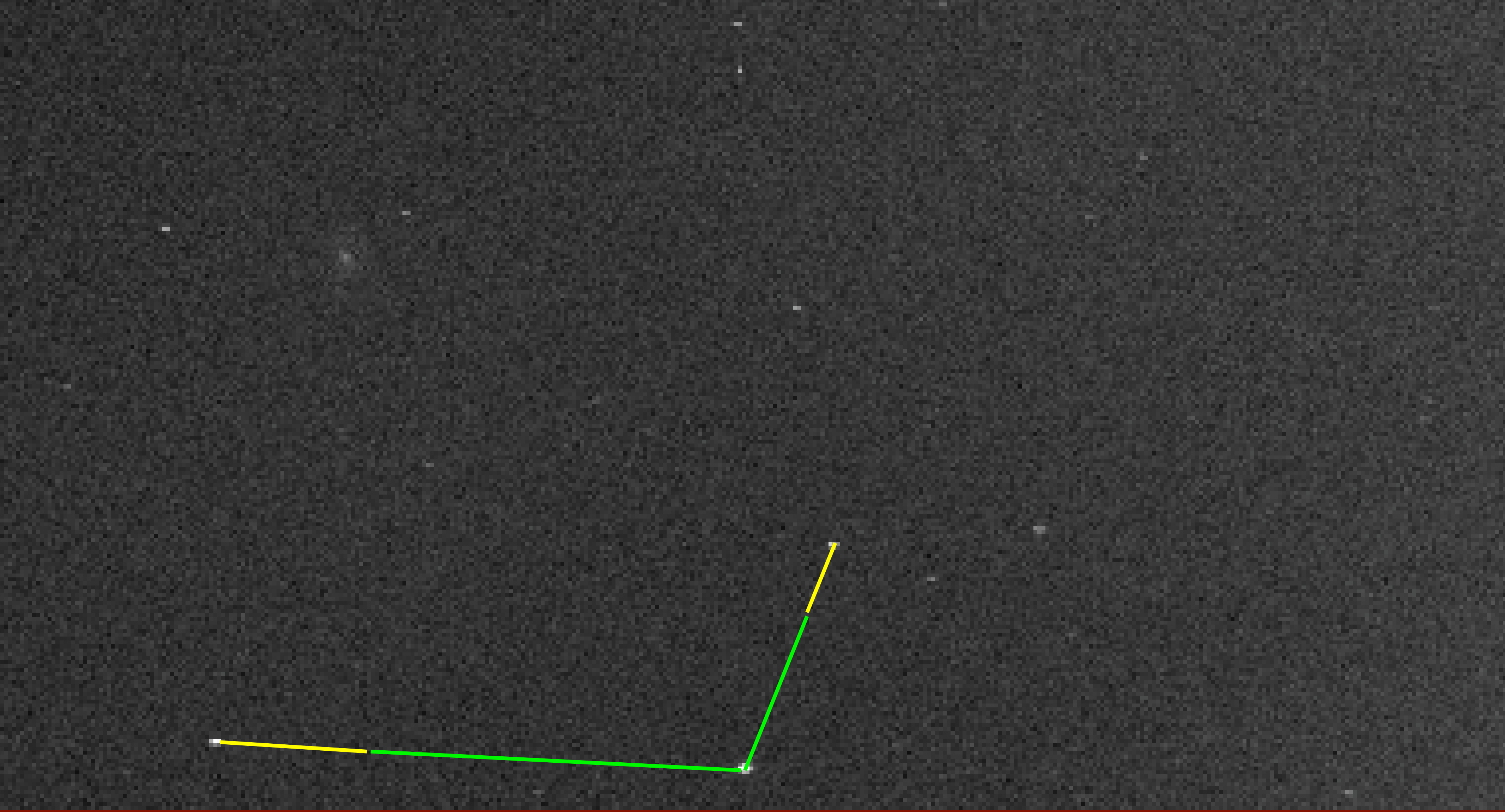
green segments: separations at initial time
yellow segments: incremental distances at later time



distances have increased in proportion to the original separations



apparent *velocities of recession*
are also in proportion to the distances



“apparent velocities of recession are in proportion to the distances” means:

$$v = \text{constant} \times \text{distance}$$

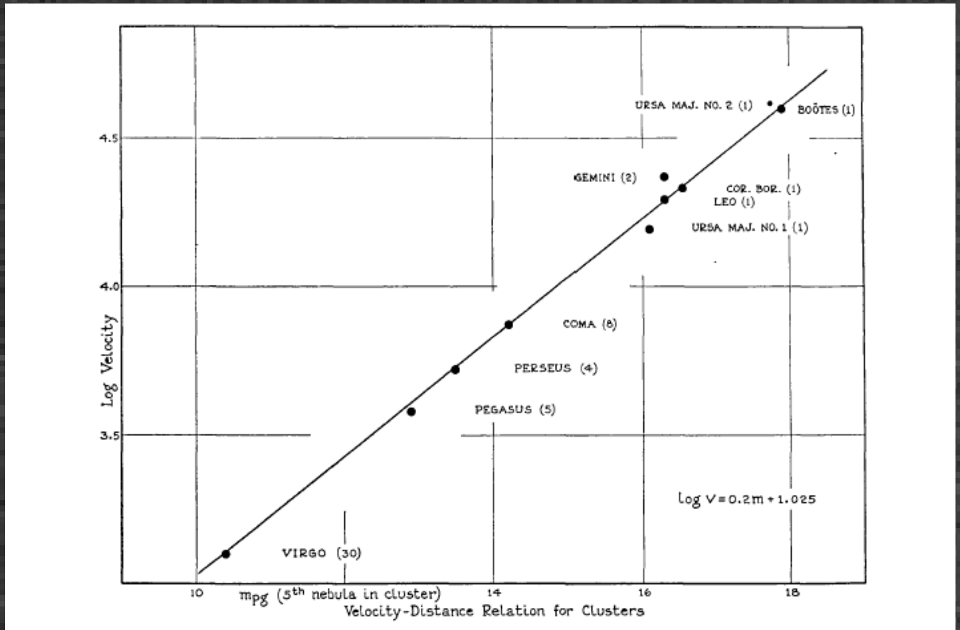


FIG. 2.—Figures in parentheses following the names of the clusters indicate the number of nebulae observed in each cluster.

this is just what Hubble observed:

$$v = H_0 \times \text{distance}$$

all dimensions expand with time *uniformly*

sides of triangles maintain their proportions

angles of triangles remain the same $\Rightarrow$ no distortion

chosen origin can be anywhere

all observers see all other galaxies receding from them with velocity proportional to distance

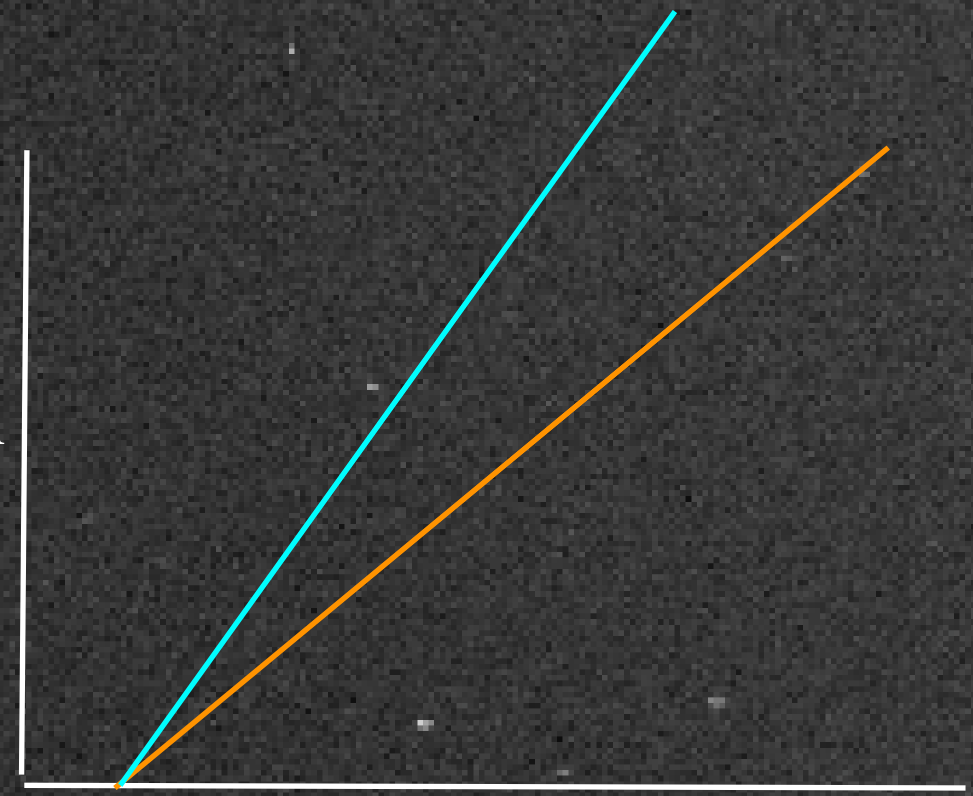
this also works in 3D

distances between galaxies are increasing

in the past, galaxies were closer together

this happened uniformly, everywhere

↑
separation between
any two galaxies



time →

time = distance / velocity

if the rate of expansion has been constant, then

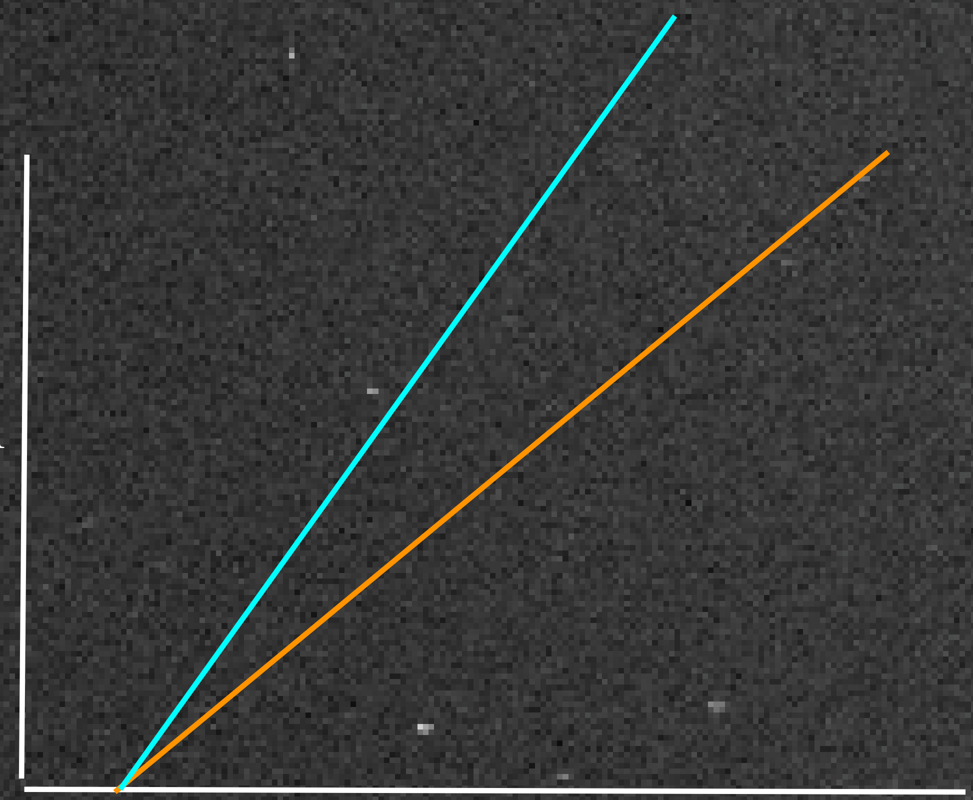
the beginning was $1/H_0$ years ago

for $H_0 = 71$ km sec^{-1} Mpc^{-1}

$1/H_0 = 13.7$ billion years

↑

separation between
any two galaxies



time →

λ is the observed wavelength of the spectral line
λ_0 is the wavelength if the source is not moving

$(\lambda - \lambda_0) / \lambda_0 = z$, or $(1 + z) = \lambda / \lambda_0$

How to interpret the redshift z:

The number $(1 + z)$ is the factor by which all (large) dimensions in the Universe have expanded since the epoch corresponding to z.

(Large = large enough not to be bound by gravity. The Solar System is not expanding.)

Features of the Big Bang picture:

since the expansion is uniform, all observers see the same thing: all the galaxies around them are receding with velocity proportional to distance

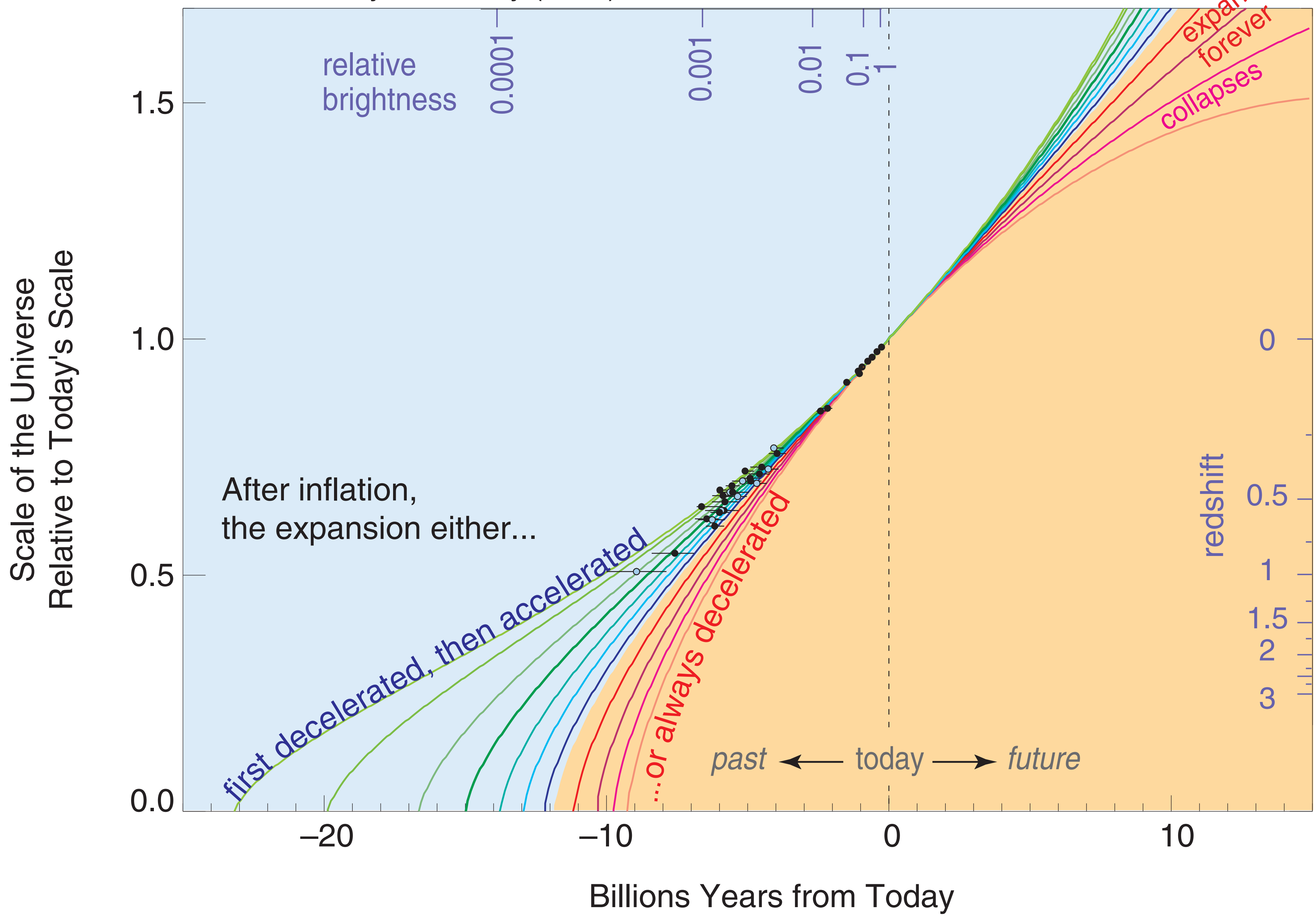
the number of galaxies is the same in different directions in the sky (*isotropy*)

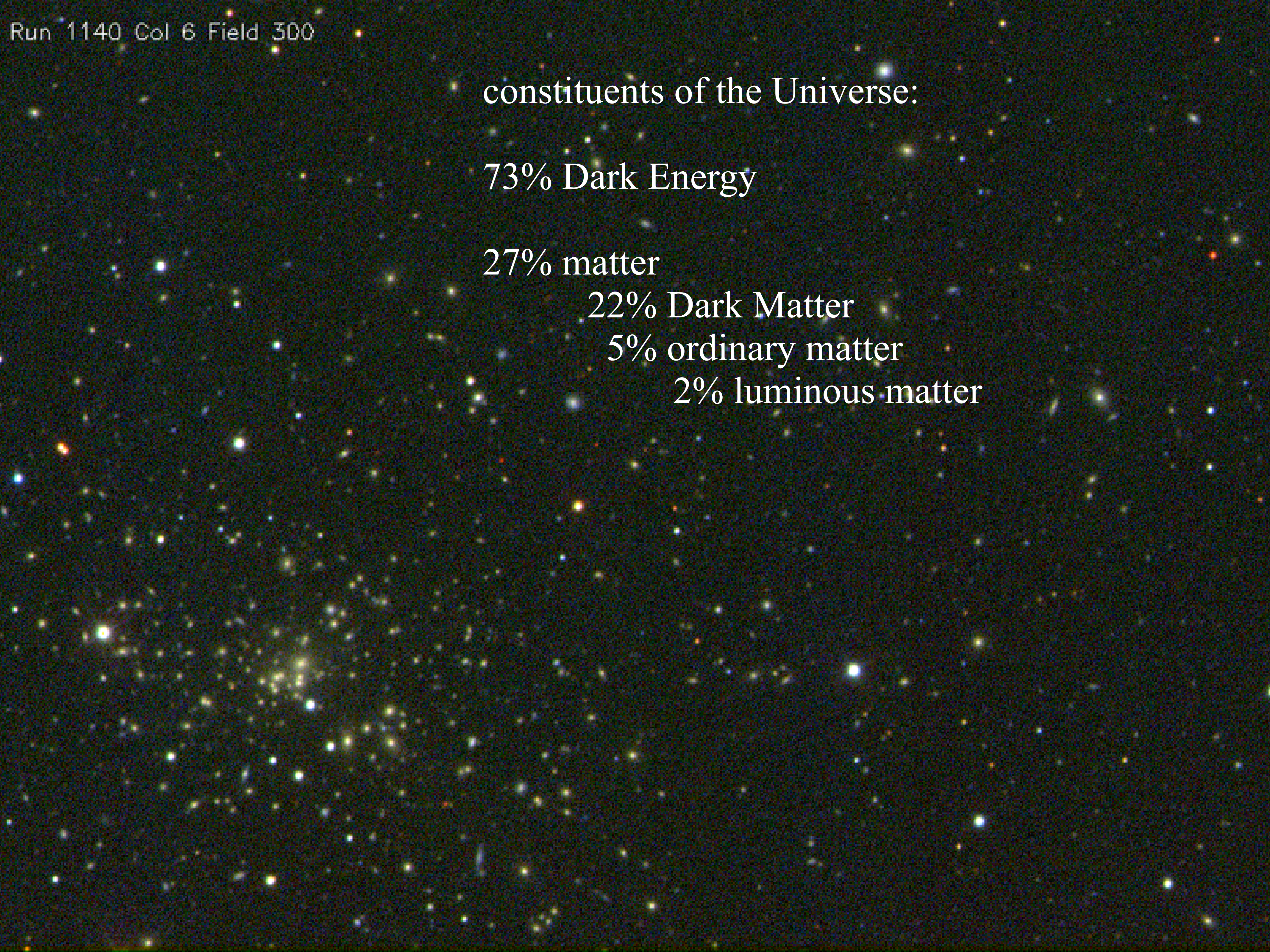
going back in time, the density increases everywhere uniformly

complication: in addition to the uniform expansion, galaxies have velocities related to their motions due to gravitational attraction

Expansion History of the Universe

Perlmutter, Physics Today (2003)




Run 1140 Col 6 Field 300
constituents of the Universe:
73% Dark Energy
27% matter
22% Dark Matter
5% ordinary matter
2% luminous matter