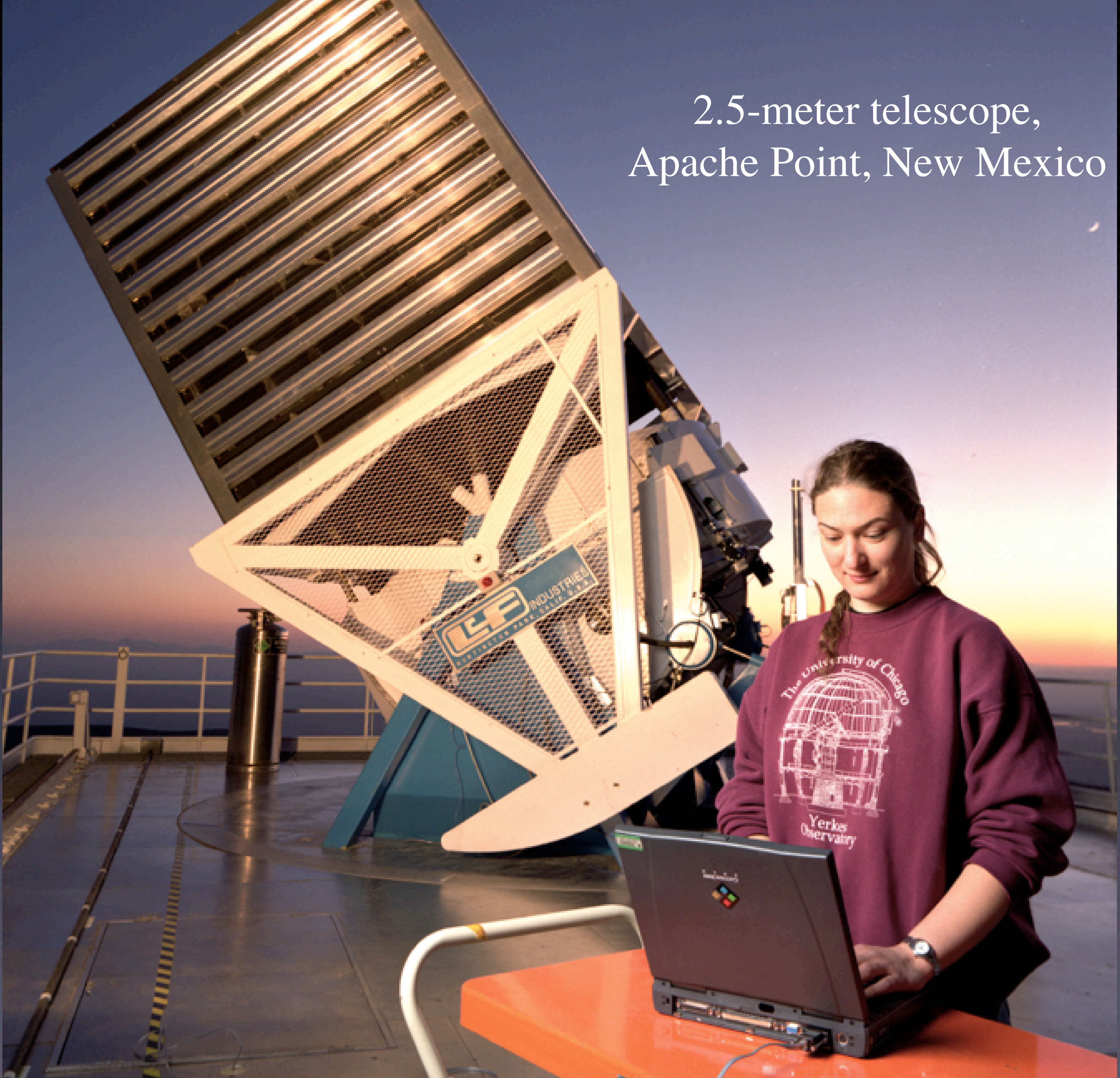
Measuring the Masses of Galaxies in the Sloan Digital Sky Survey

Rich Kron
ARCS Institute, 14 June 2005, Yerkes Observatory

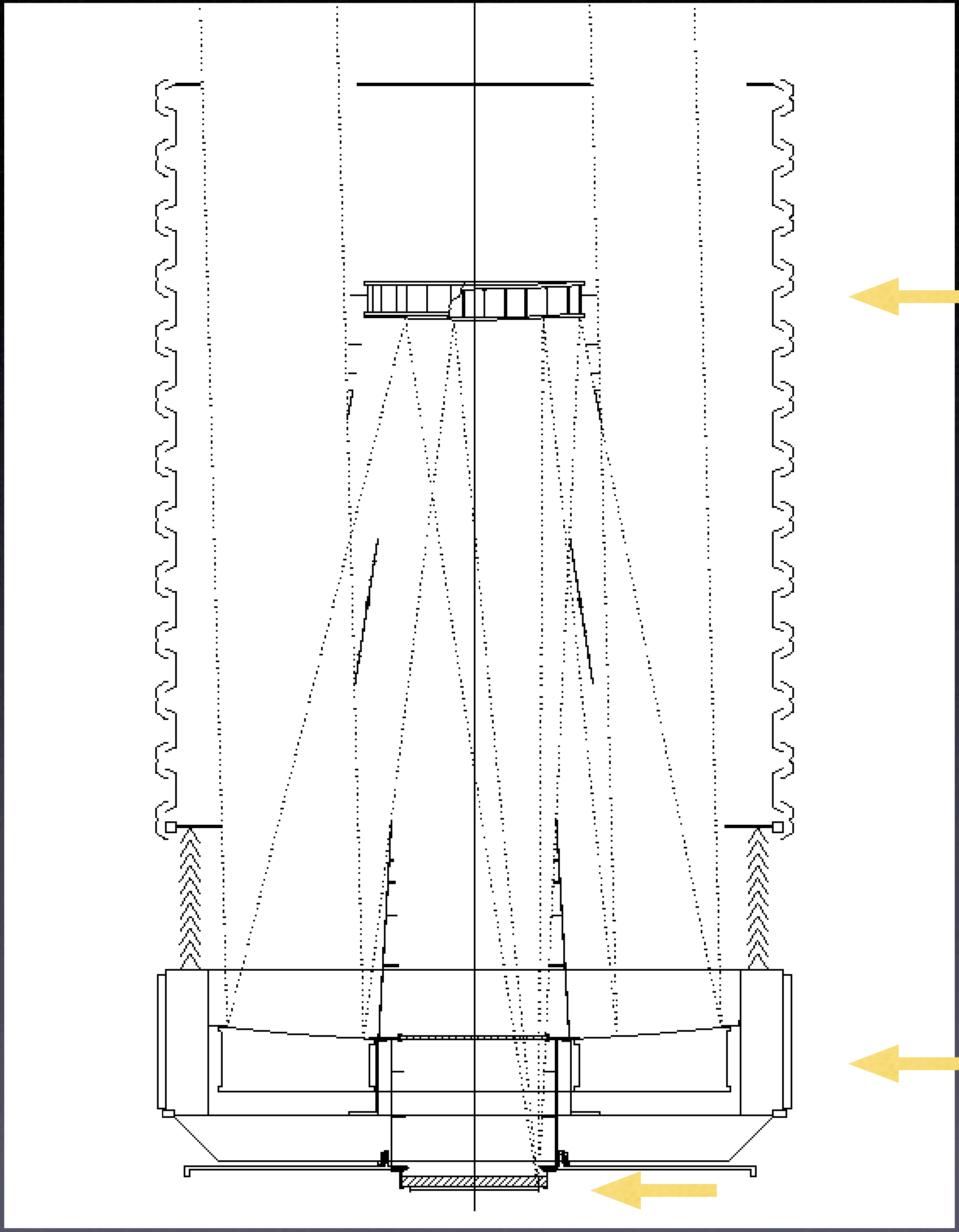
images & spectra of NGC 2798/2799

physical size, orbital velocity, mass, and luminosity

how to get data



2.5-meter telescope,
Apache Point, New Mexico



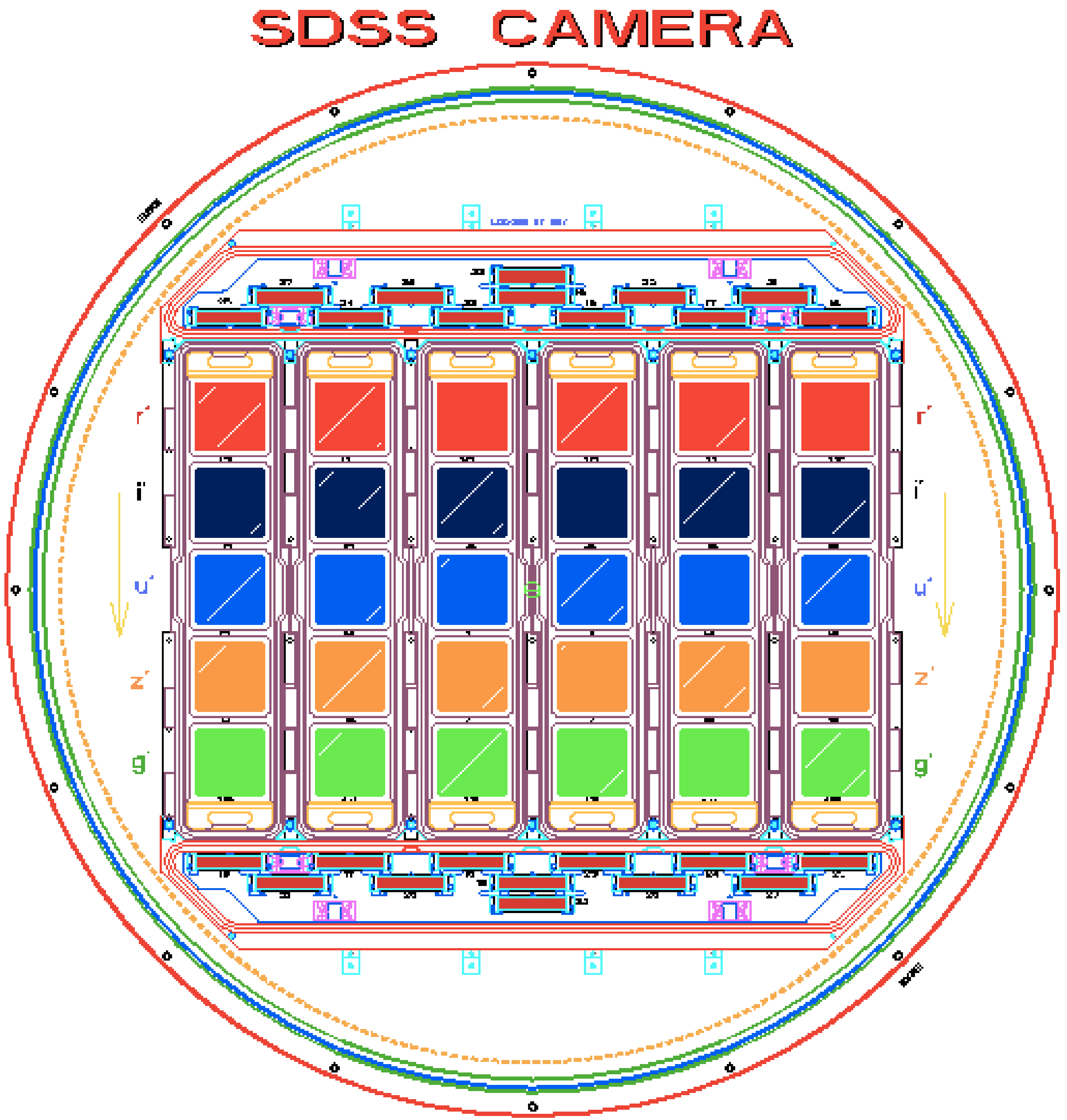
secondary mirror

focal ratio = f/5

field-of-view = 3 degrees

2.5-m primary mirror

camera or plate at focus

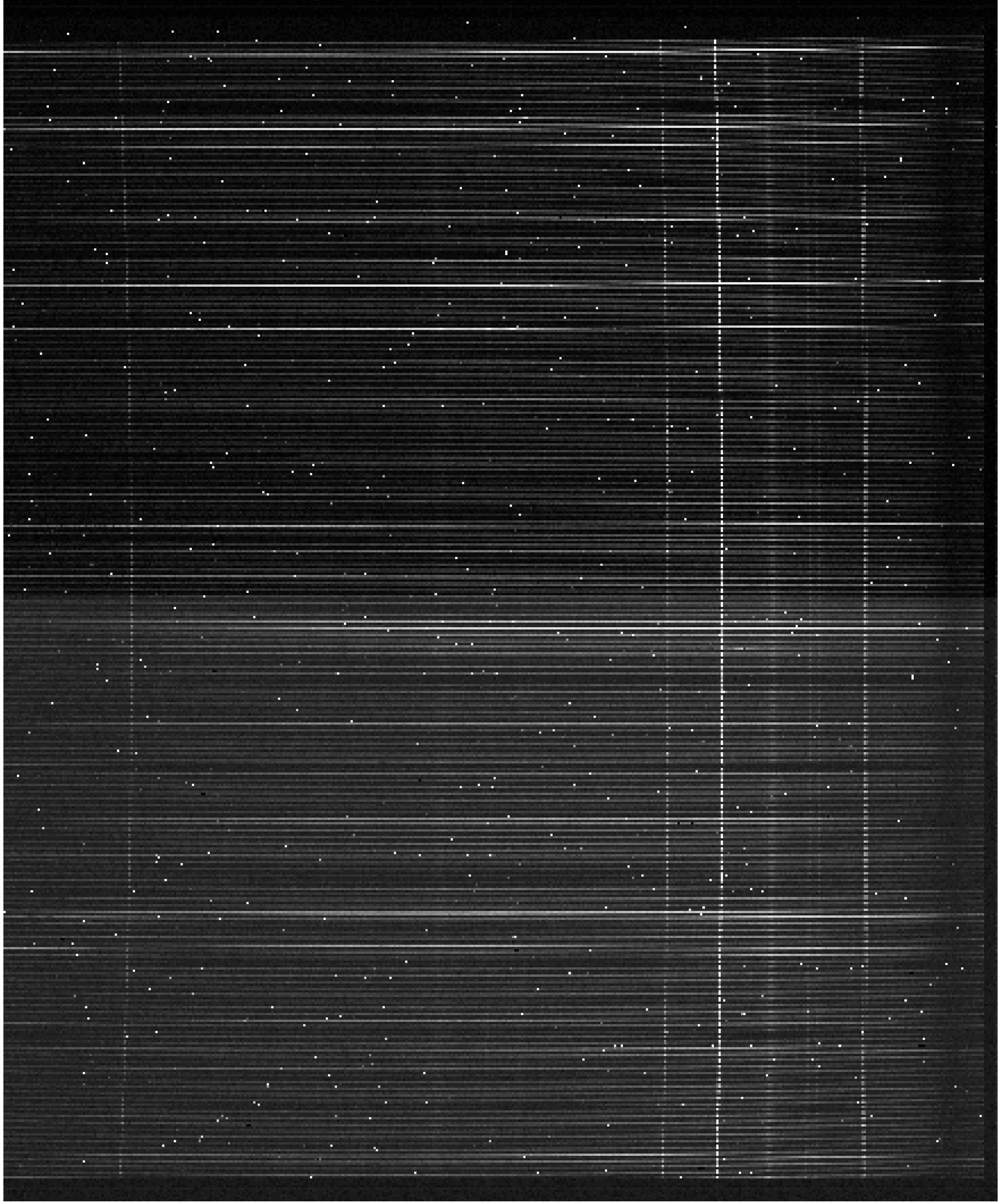


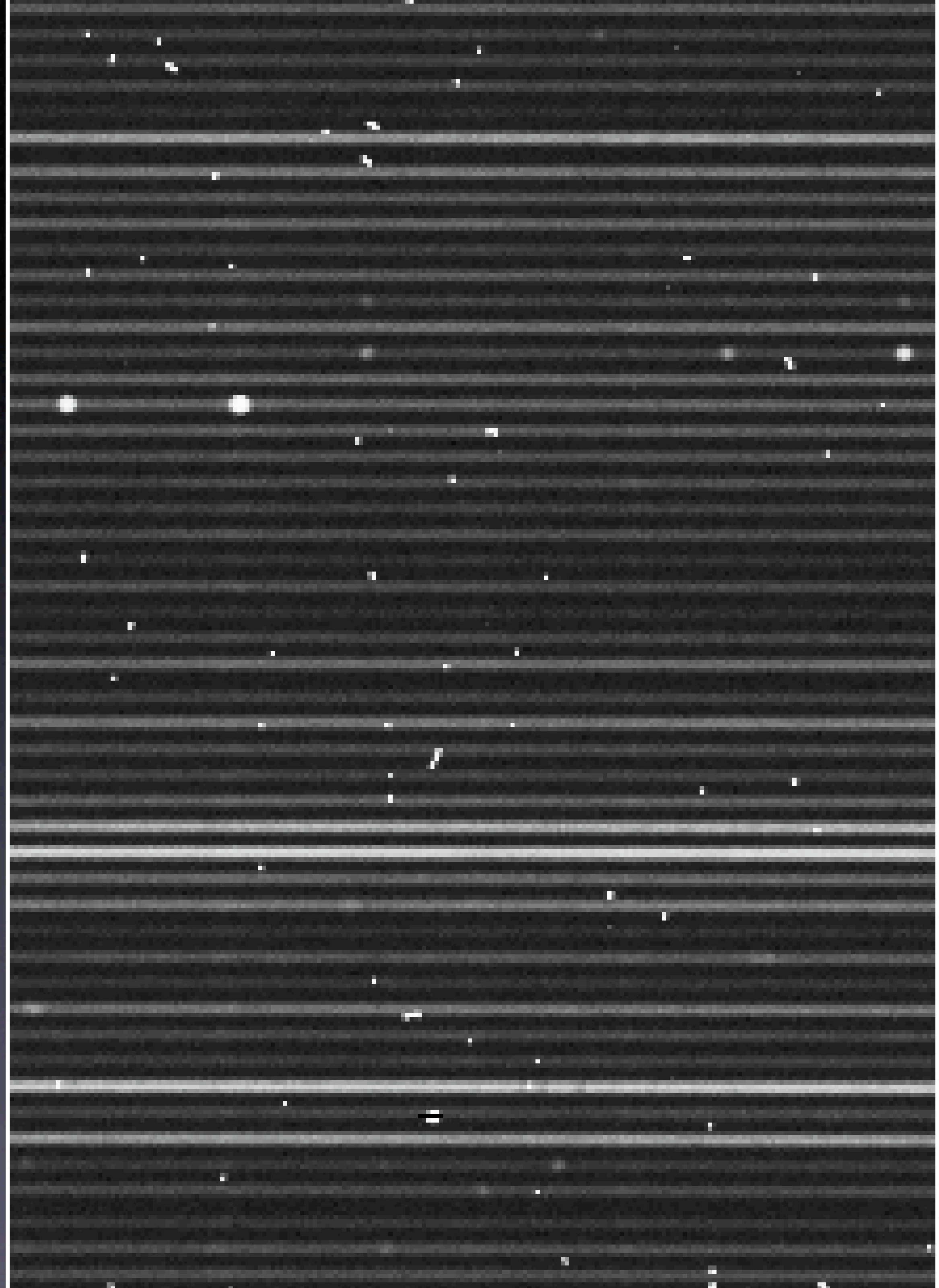
five rows =
five filters

six columns =
6 scan lines

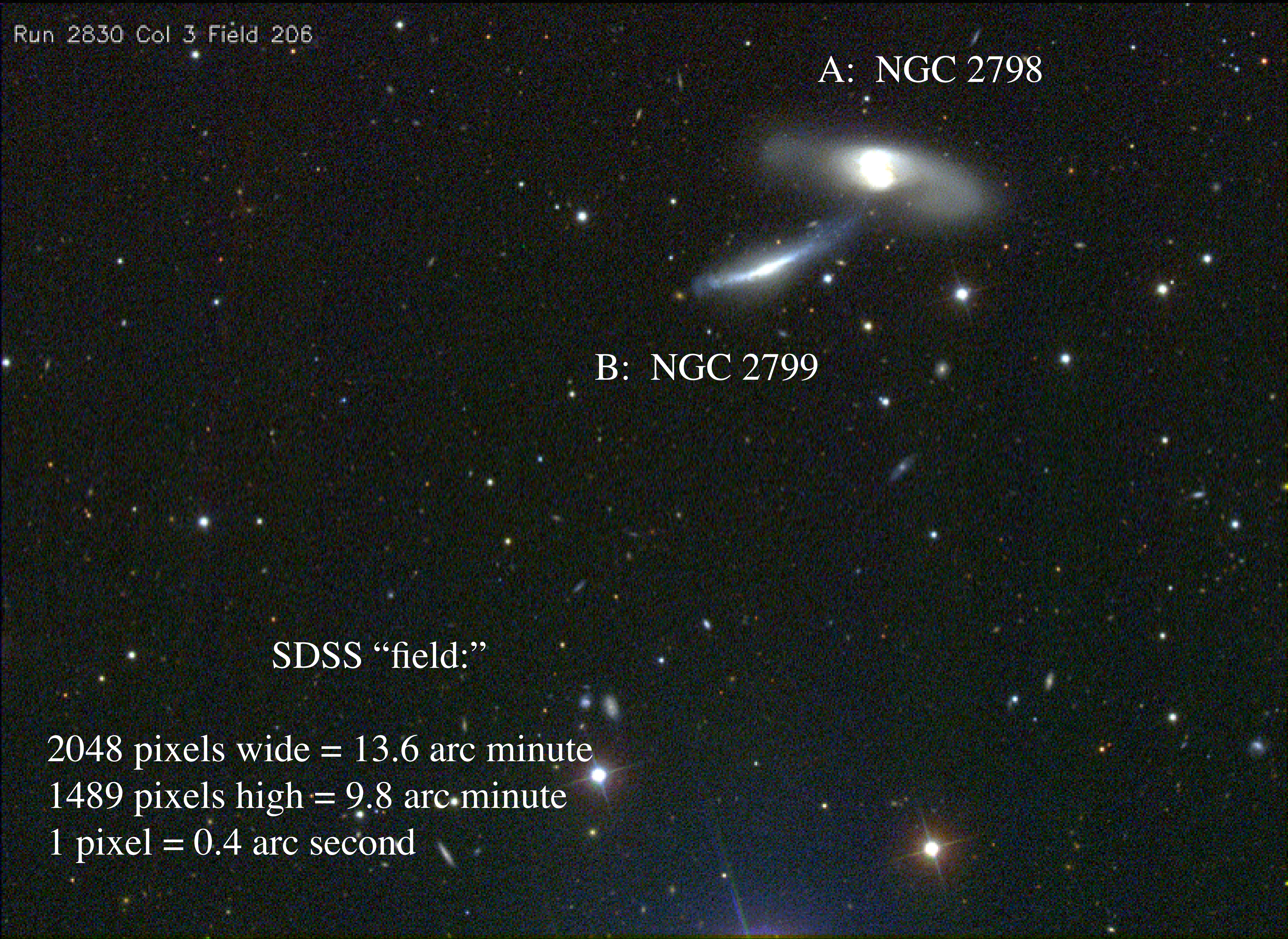
plugging 640 optical fibers into a drilled aluminum plate

telescope pointing sideways to left; spectrographs are the green boxes





nighttime operations in
observing room at
Apache Point Observatory


Run 2830 Col 3 Field 206
A: NGC 2798
B: NGC 2799
SDSS "field:"
2048 pixels wide = 13.6 arc minute
1489 pixels high = 9.8 arc minute
1 pixel = 0.4 arc second

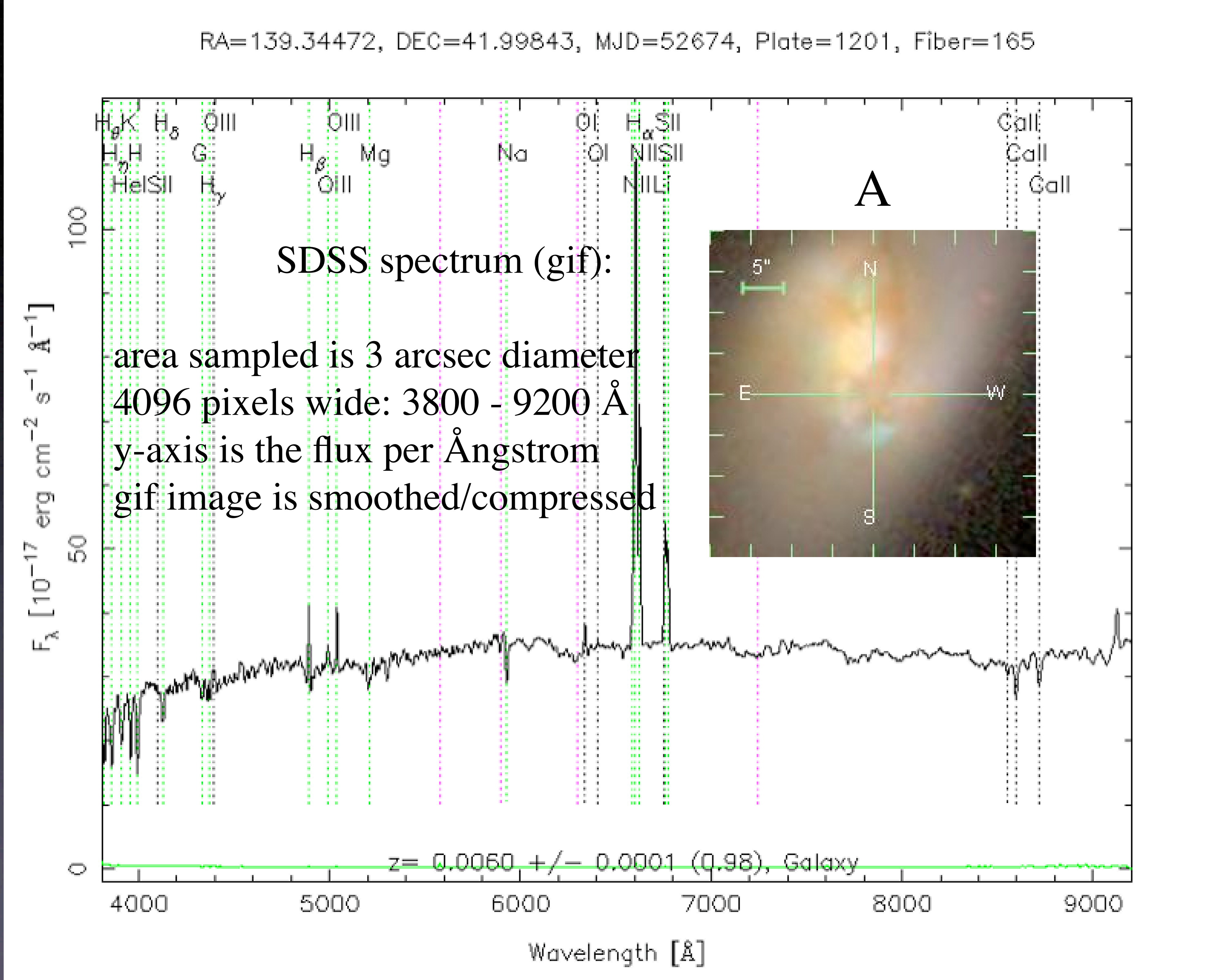
what can we learn about the galaxies?

physical size	R
orbital velocity	v
mass	M
luminosity	L
index of *dark matter*	M / L

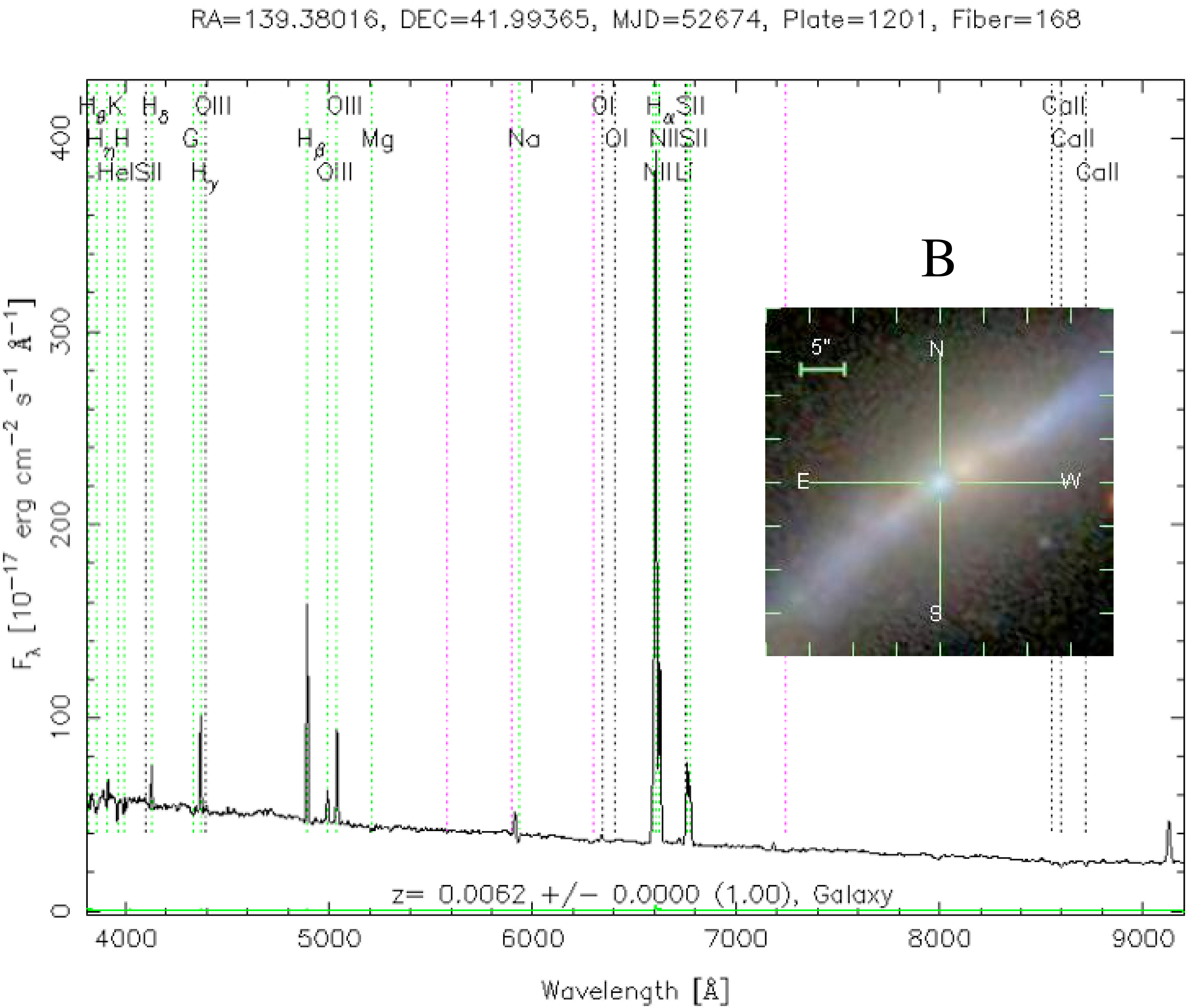
the first step is to determine the distance to the galaxies

we need *spectra* for the galaxies, from which we derive *redshifts*

spectrum ⇒ redshift ⇒ distance ⇒ physical size ⇒ *etc*.



RA=139.34472, DEC=41.99843, MJD=52674, Plate=1201, Fiber=165
SDSS spectrum (gif):
area sampled is 3 arcsec diameter
4096 pixels wide: 3800 - 9200 Å
y-axis is the flux per Ångstrom
gif image is smoothed/compressed
A
5"
N
E
W
S
Hθ K
Hη H
HeI SII
Hδ
G
Hγ
OIII
Hβ
OIII
OIII
Mg
Na
OI
OI
Hα SII
NII SII
NII Li
CaII
CaII
CaII
z= 0.0060 +/- 0.0001 (0.98), Galaxy
Fλ [10^-17 erg cm^-2 s^-1 Å^-1]
0
50
100
4000
5000
6000
7000
8000
9000
Wavelength [Å]


RA=139.38016, DEC=41.99365, MJD=52674, Plate=1201, Fiber=168
B
5"
N
E
W
S
z= 0.0062 +/- 0.0000 (1.00), Galaxy
Wavelength [Å]
4000
5000
6000
7000
8000
9000
0
100
200
300
400
OIII
Mg
Na
OI
SII
NII
CaII
G
HeI
Li

The redshift z is an observed property of a galaxy (or quasar).

It tells us the relative size of the Universe now with respect to the size of the Universe when light left the galaxy (or quasar).

$$(1 + z) = \text{(size now)} / \text{(size then)}$$

the redshift is measured from the observed positions of atomic lines in the spectra of galaxies and quasars

for example, the red line of hydrogen (Hα) has a wavelength of 6.563×10^{-5} cm, 6563 Ångstroms, 656.3 nm

suppose it were observed at 6603 Ångstroms

$$(1 + z) = 6603 / 6563 = 1.0061$$

all other lines will yield the *same* redshift

$$\text{distance} \approx z \times \text{age of Universe} \quad (z << 1)$$

$$\text{distance} \cong [z / (1+z)] \times \text{age of Universe}$$

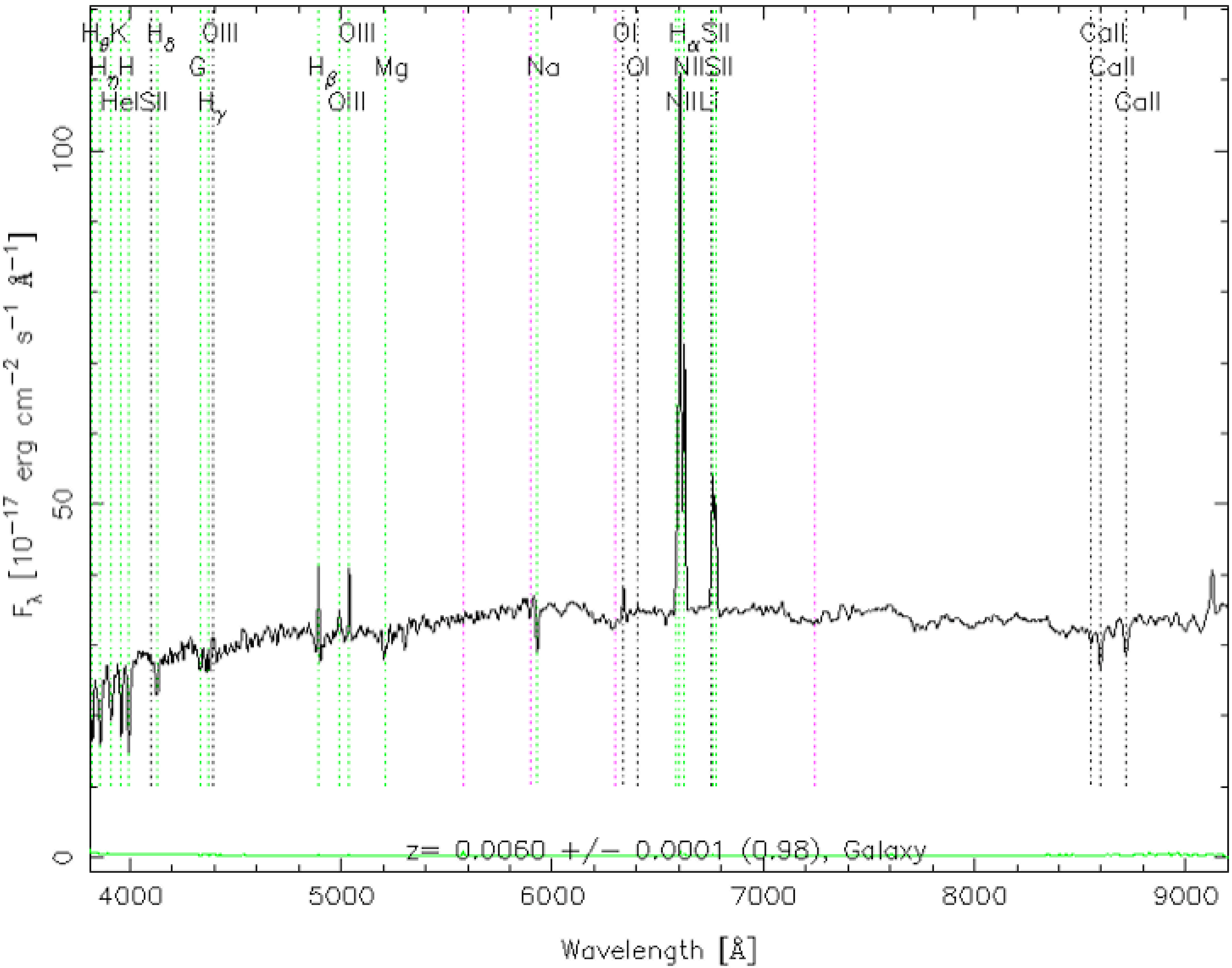
e.g., for $z = 0.0061$,

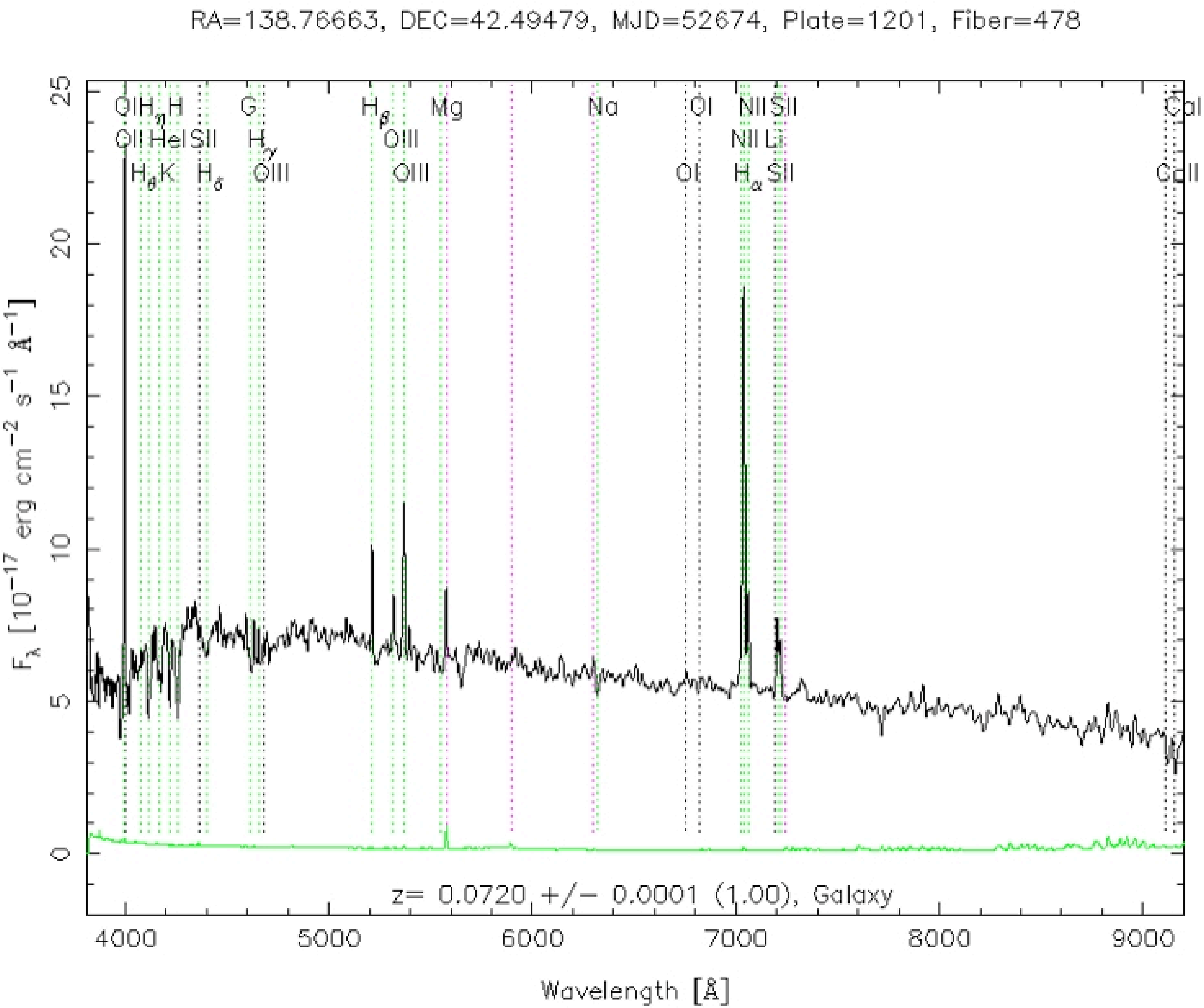
$$d = 0.00606 \times 13.5 \text{ billion} = 82 \text{ million light-years}$$

caveat:

redshift must represent expansion of Universe, not orbital motion

RA=139.34472, DEC=41.99843, MJD=52674, Plate=1201, Fiber=165





RA=138.76663, DEC=42.49479, MJD=52674, Plate=1201, Fiber=478
OI Hη H
OII HeI SII
Hθ K Hδ
G
Hγ
OIII
Hβ
OIII
OIII
Mg
Na
OI
OI
NII SII
NII Li
Hα SII
CaII
CaII
z= 0.0720 +/- 0.0001 (1.00), Galaxy
Fλ [10^-17 erg cm^-2 s^-1 Å^-1]
Wavelength [Å]
0
5
10
15
20
25
4000
5000
6000
7000
8000
9000

distances as light-travel times:

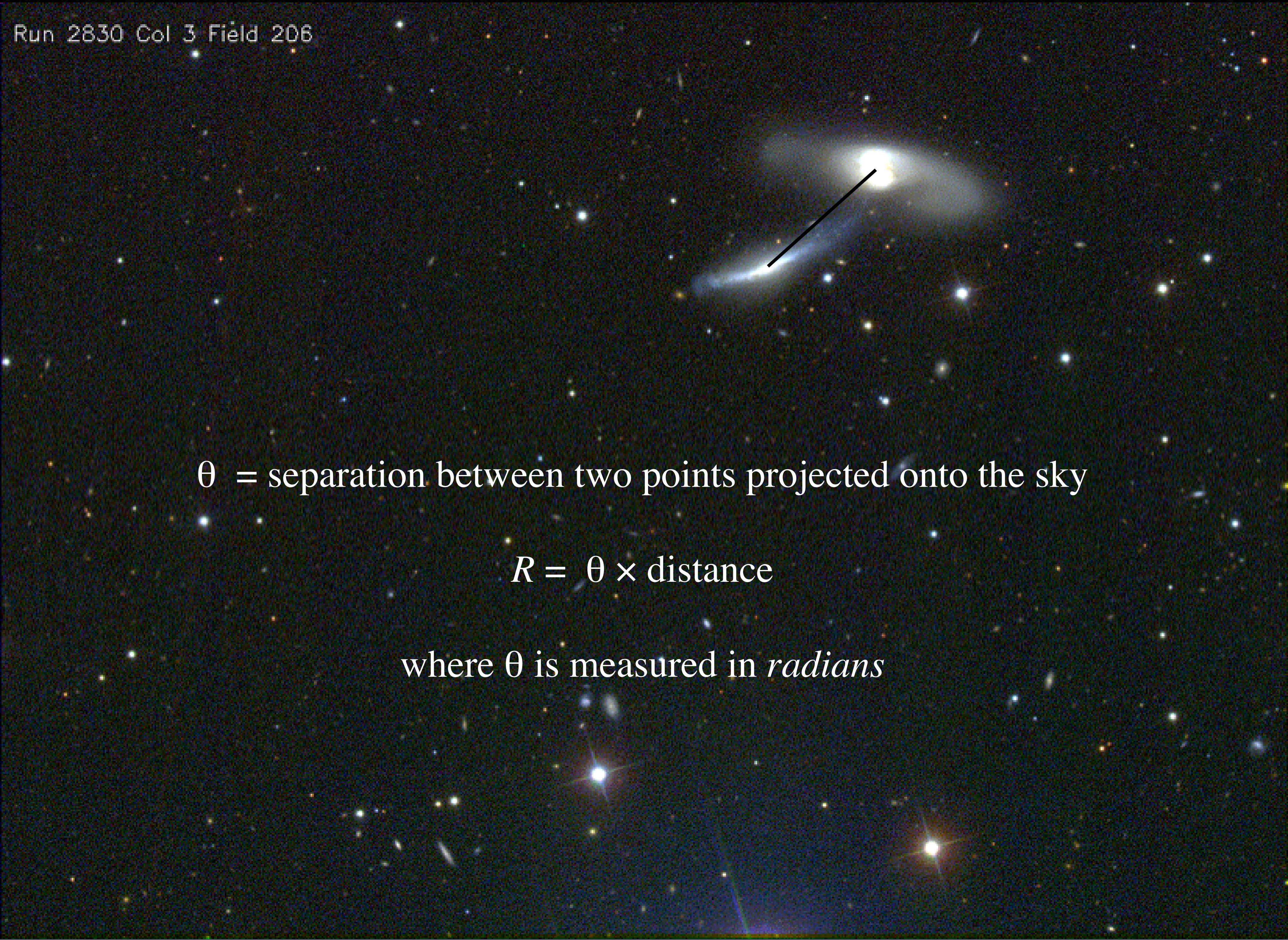
circumference of Earth	0.133 sec
distance to Moon	1.28 sec
circumference of Sun	15 sec
Sun	500 sec
Pluto	5.5 hours
diameter of Ring Nebula	20 months
α Centauri	4.3 years
center of Milky Way	27,000 years
Andromeda galaxy	2 million years
Virgo cluster	50 million years
galaxies A, B	82 million years
quasar Q	8.2 billion years
cosmic horizon	13.5 billion years

Cretacious	65 - 145 million years ago
Jurasic	145 - 210 million years ago
Triassic	210 - 245 million years ago

245 million years ago $z = 0.018$

1 billion years ago $z = 0.074$

all of these distances are well within the reach of the SDSS spectra



θ = separation between two points projected onto the sky

$R = \theta \times \text{distance}$

where θ is measured in *radians*

length of bar on print-out = 32 mm
width of print-out = 259 mm = 13.1 arc minutes

$\Rightarrow$ bar subtends 1.62 arc minutes or
$\theta = 0.000471$ radian

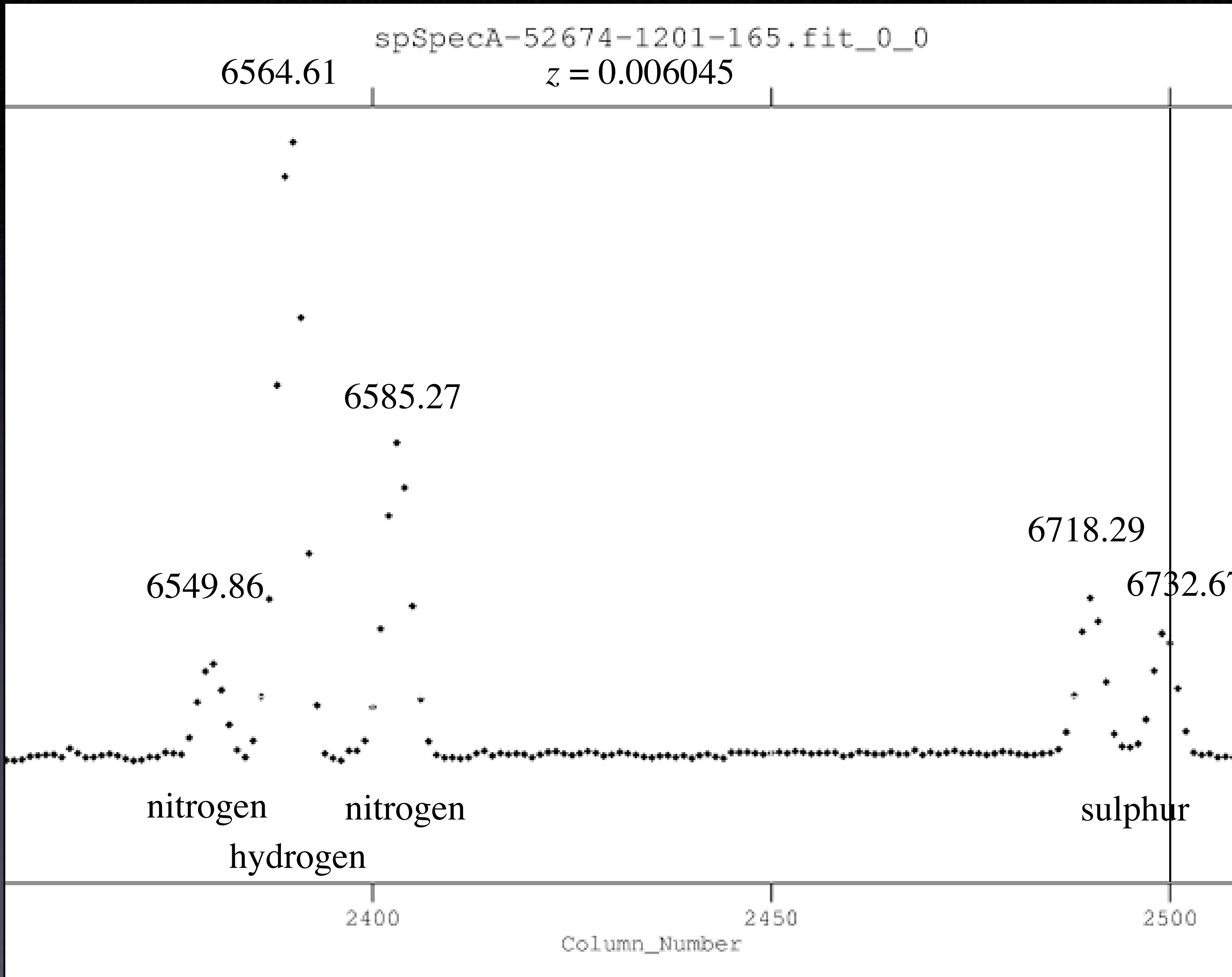
$R = \theta \times \text{distance}$
$R = 0.000471 \times 82$ million light-years
$R = 38{,}600$ light-years

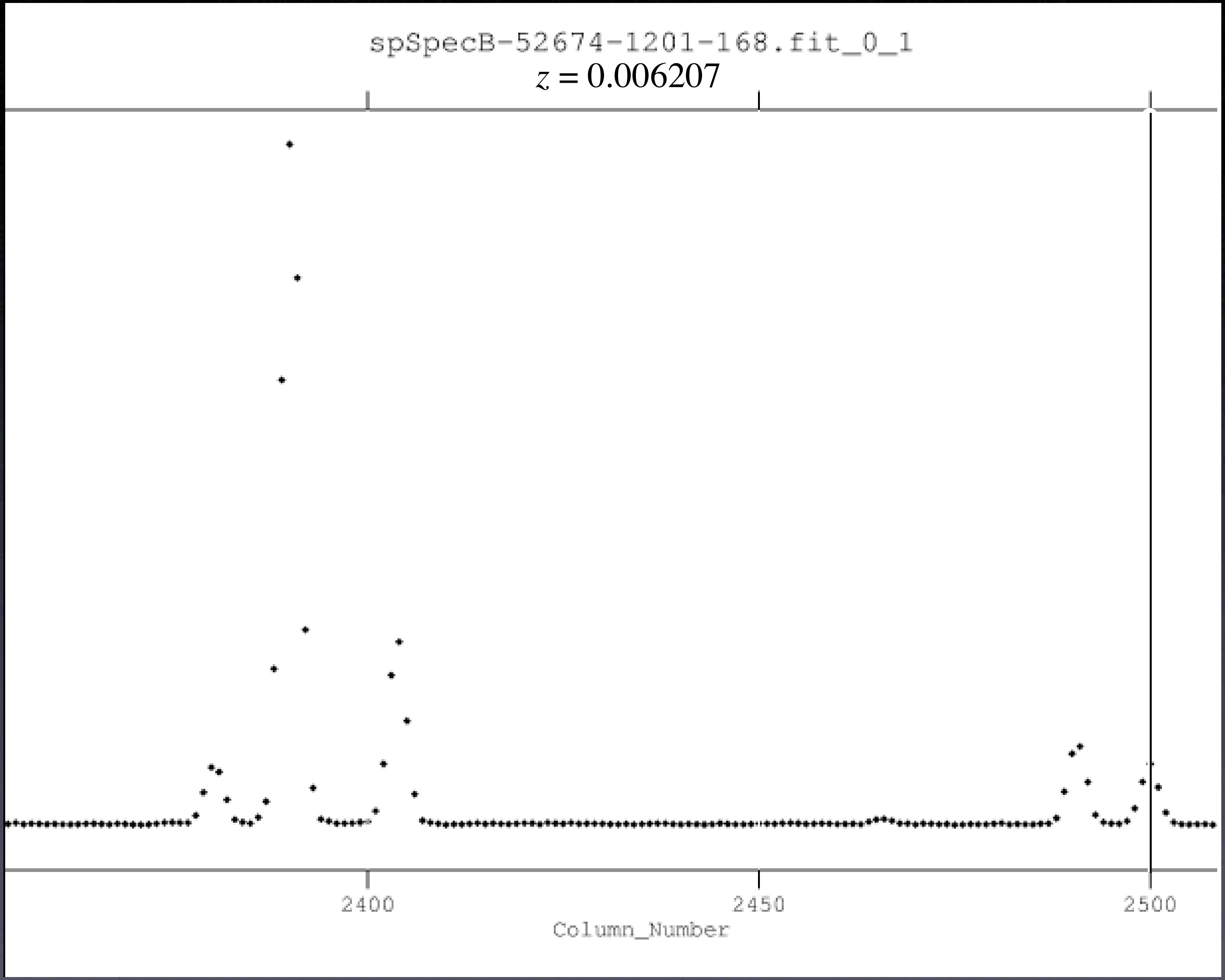
R is an *underestimate* of the true value because of projection orbital velocity $\Leftrightarrow$ Doppler shift

Δz = difference in redshift between two orbiting bodies

$$\Delta v \cong \Delta z \times c$$

(c is the speed of light)


spSpecA-52674-1201-165.fit_0_0
6564.61
z = 0.006045
6585.27
6718.29
6549.86
6732.67
nitrogen
nitrogen
hydrogen
sulphur
2400
2450
2500
Column_Number


spSpecB-52674-1201-168.fit_0_1
z = 0.006207
2400
2450
2500
Column_Number

$$z_A = 0.006045$$
$$z_B = 0.006207$$

$$\Delta z = -0.000162$$
$$c = 300{,}000 \text{ km/sec}$$

$$\Delta v \cong \Delta z \times c = 49 \text{ km/sec}$$

v is also an *underestimate* of the true value because of projection

velocities (all in *km/sec*)

low-Earth orbit	7.4
low-Sun orbit	435
Mercury	48
Earth	30
Saturn	10

Sun (w.r.t. nearby stars)	~ 30
Sun (around center of Milky Way)	220

sound	0.3
light	300,000

knowing the orbital velocity of the Earth around the Sun (v), and also the distance between the Earth and the Sun (R), we can measure the mass of the Sun (M)

$$M = (\Delta v)^2 R / G$$

(G is Newton's gravitational constant)

exactly the same technique can be used to measure the mass of a galaxy

Summary so far:

$z = 0.0061$

$d = 13.5 \times [z / (1+z)] = $ 82 million light-years

$\theta = 0.000471$ radian

$R = \theta \times d = $ 38,600 light-years

$\Delta z = -0.000162$

$\Delta v = \Delta z \times c = $ 49 km/sec

$M = (\Delta v)^2 R / G$

finding $M = M_A + M_B$ in units of the mass of the Sun, M_{sun}

$$M = (\Delta v)^2 R \,/\, G$$

$$M_{gal}/M_{sun} = (v_{gal}/v_{sun})^2 \times (R_{gal}/d_{sun})$$

$$M_{gal} > (49/30)^2 \times (38{,}600 \text{ years})/(500 \text{ sec})\ M_{sun}$$

$$M_{gal} > 6.5 \text{ billion Suns}$$

L = luminosity, f = flux or apparent brightness

$$L = f \times 4\pi \times d^2$$

$$L_{gal}/L_{sun} = (f_{gal}/f_{sun}) \times (d_{gal}/d_{sun})^2$$

$$f_{gal}/f_{sun} = 10^{-0.4(m_{gal} + 26.7)}$$

m_{gal} = 12.6 = "modelmag_r"

$(d_{gal}/d_{sun})^2$ = (82 million years/500 sec)^2

L_{gal} = 5 billion Suns

Comparison of Milky Way and NGC 2798

	Milky Way	NGC 2798
R	27,000 l-y	25,000 l-y
M	130 billion	> 6.5 billion Suns
L	14 billion	5 billion Suns

Do these galaxies contain *dark matter*? that depends on how we interpret the luminosity L. L depends on the kinds of stars present in the galaxy.

massive stars are exceptionally luminous (but are often shrouded by interstellar dust)

massive stars are hot $\Rightarrow$ blue

low-mass stars are low-luminosity and cool $\Rightarrow$ red

star	M	L
α Vir = Spica	12	2000
Sun	1	1
61 Cyg B	0.56	0.04

massive stars are short-lived; hence, if they are present, they must be young

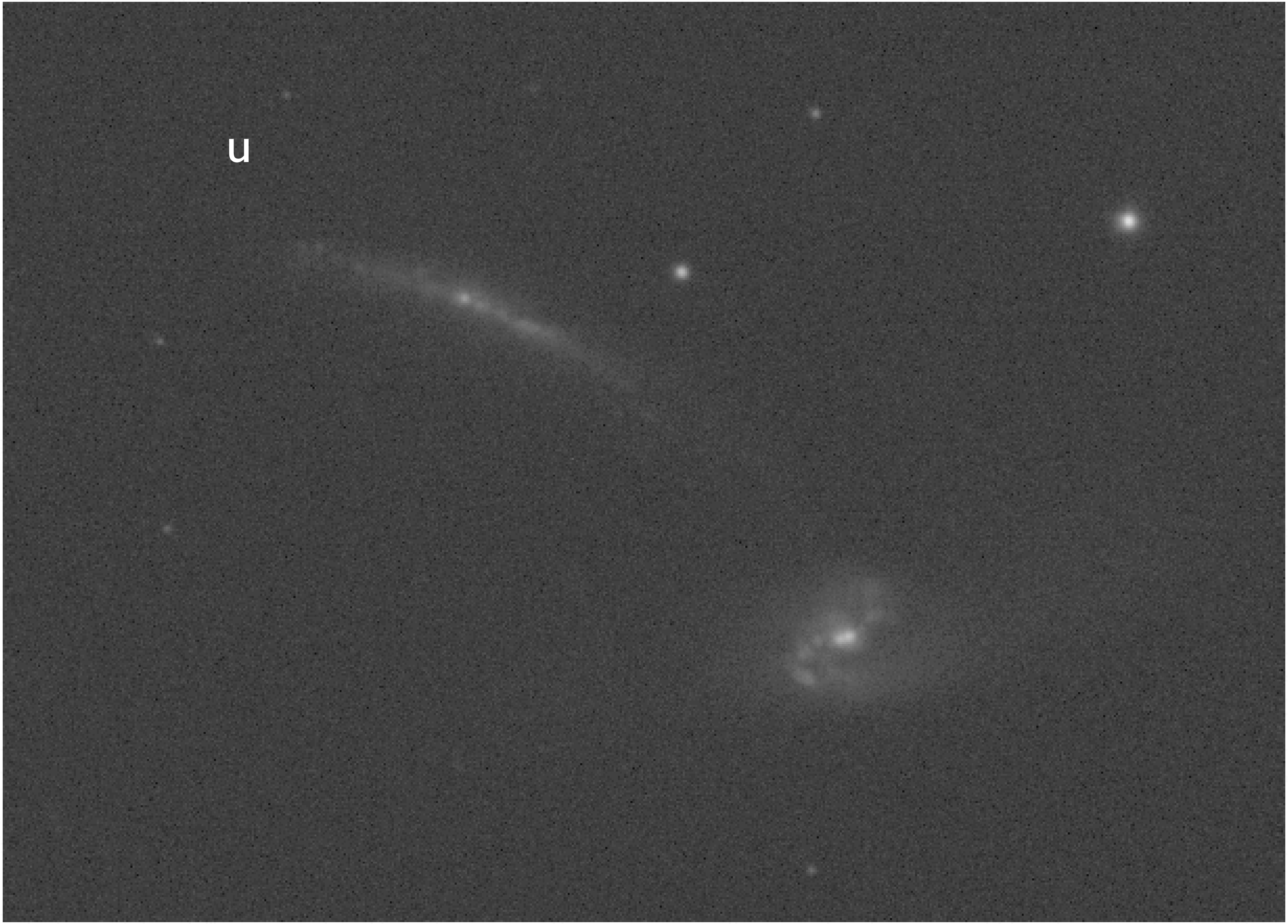
low-mass stars live a long time; they may be young or old

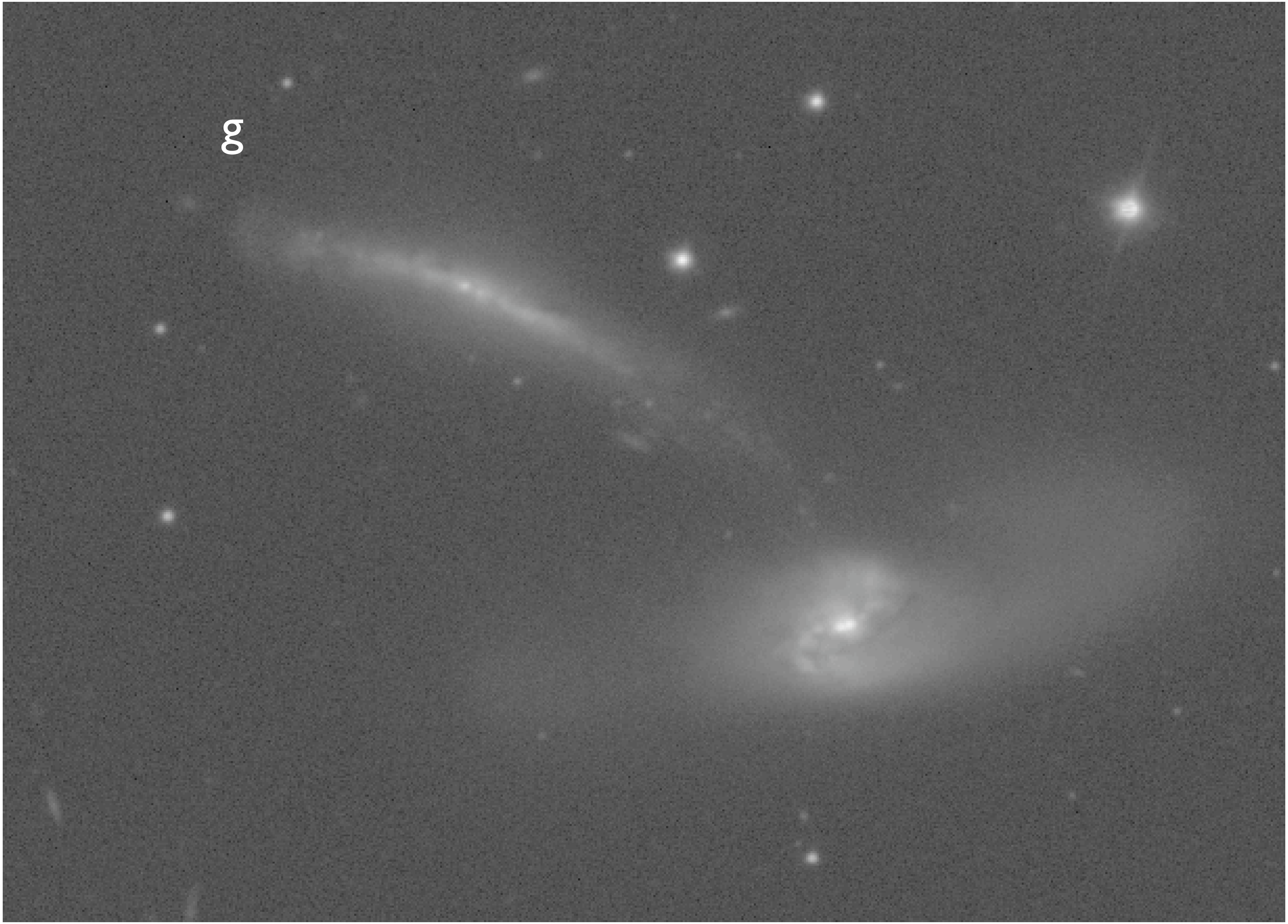
Summary for color:

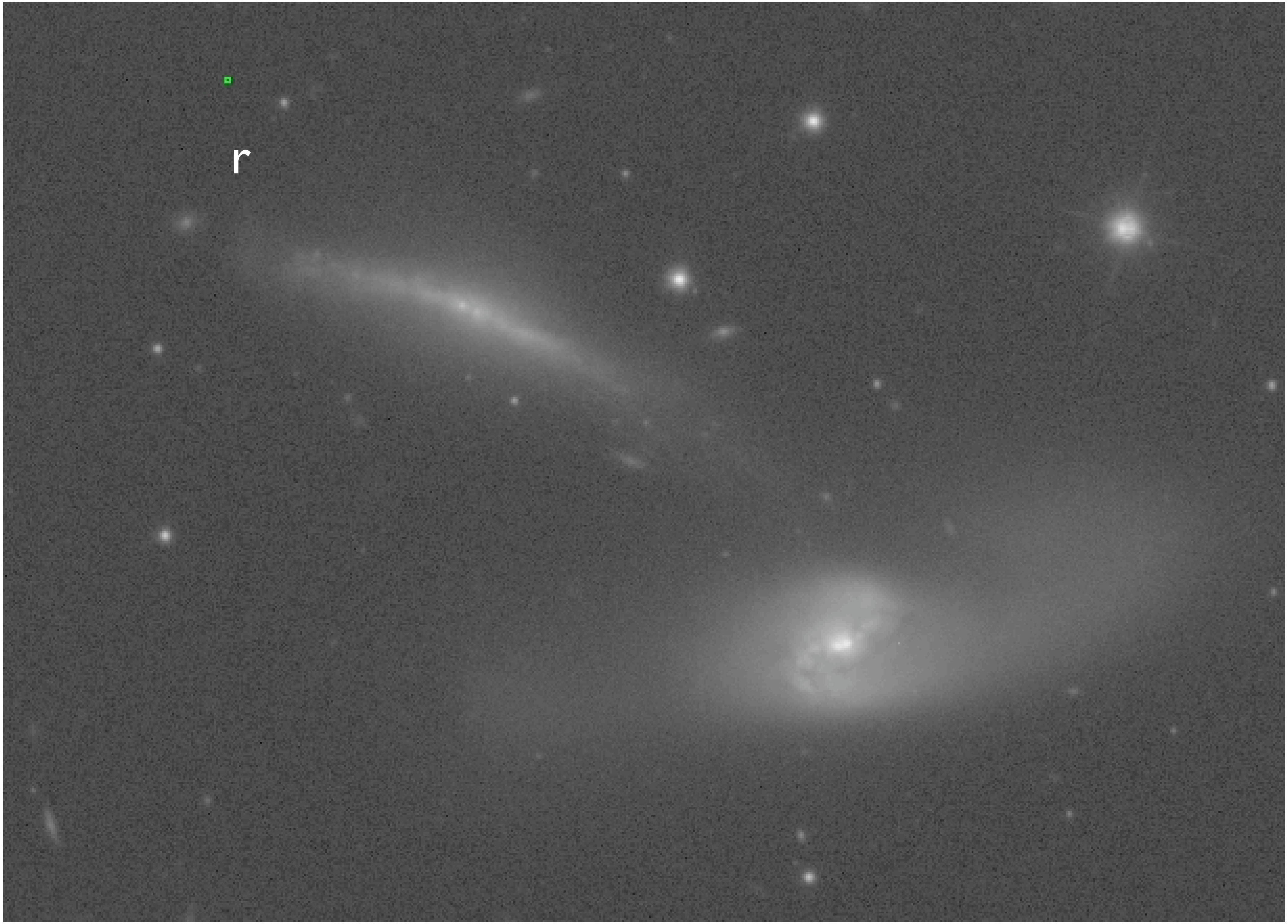
The *color* of a galaxy tells us about the kinds of stars present, their ages, and the amount of reddening by interstellar dust.

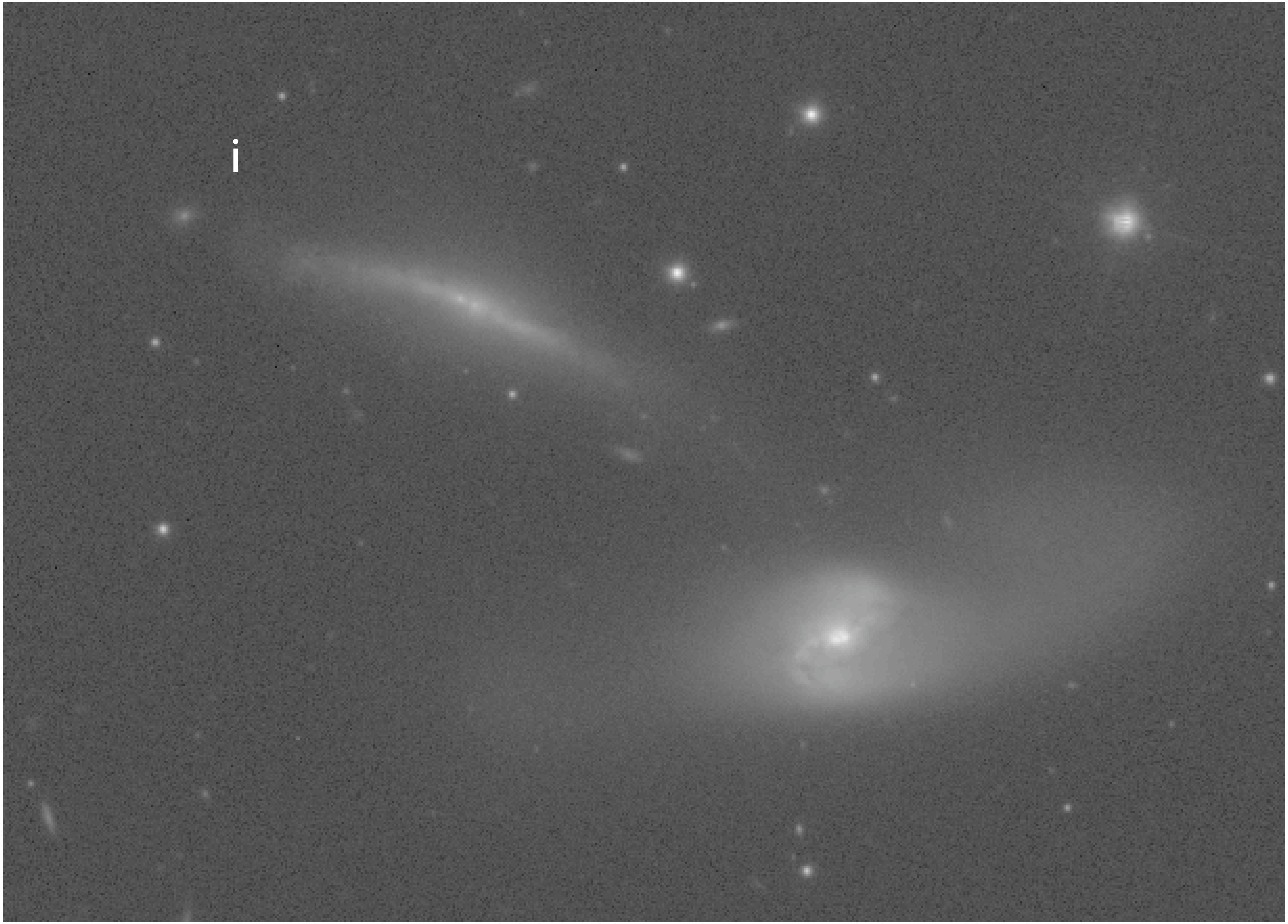
Astronomers quantify color by obtaining images through distinct filters, e.g. *u*, *g*, *r*, *i*, *z* for the SDSS.

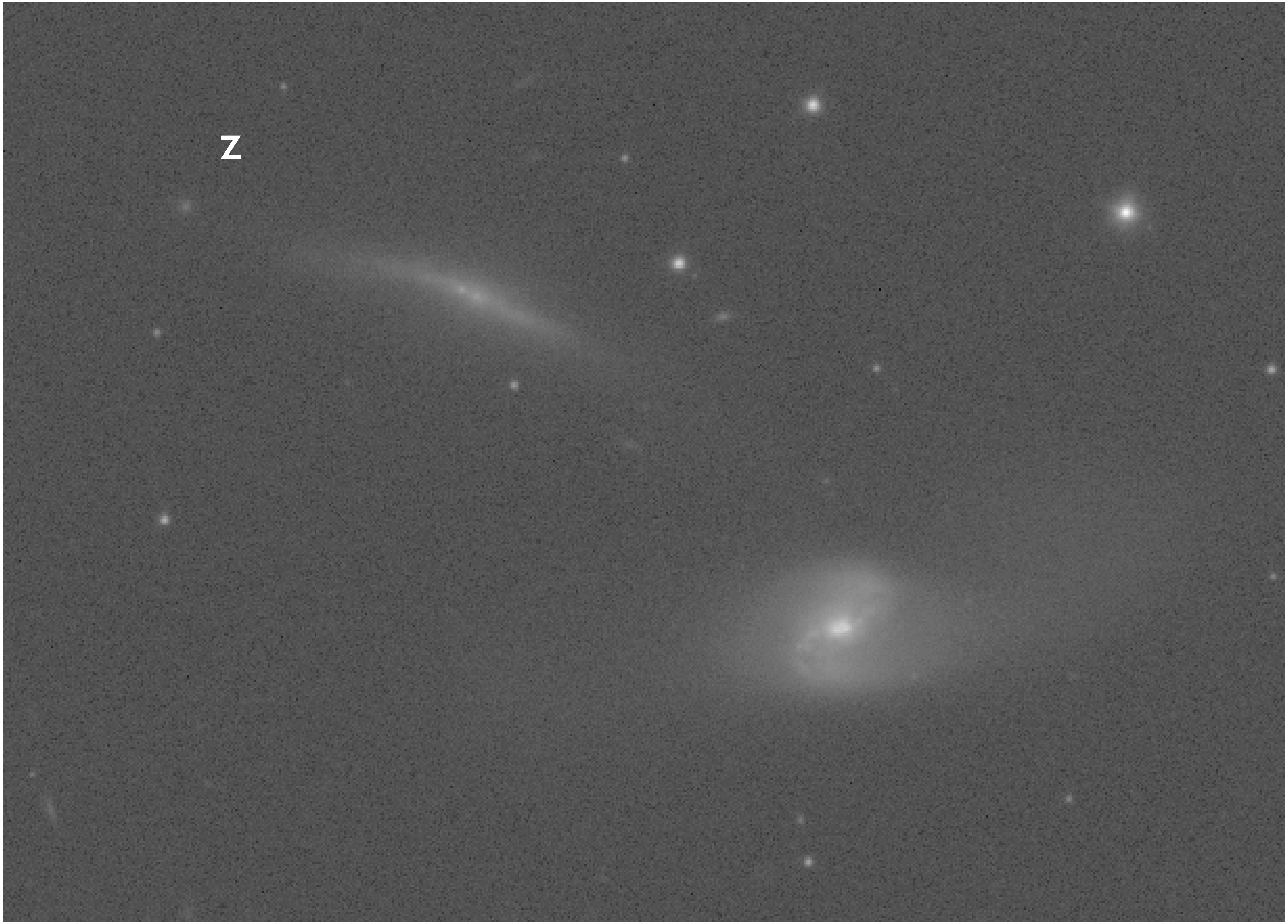
Numerical values are denoted *u-g*, *g-r*, *r-i*, *i-z*. The smaller the value, the bluer the color.

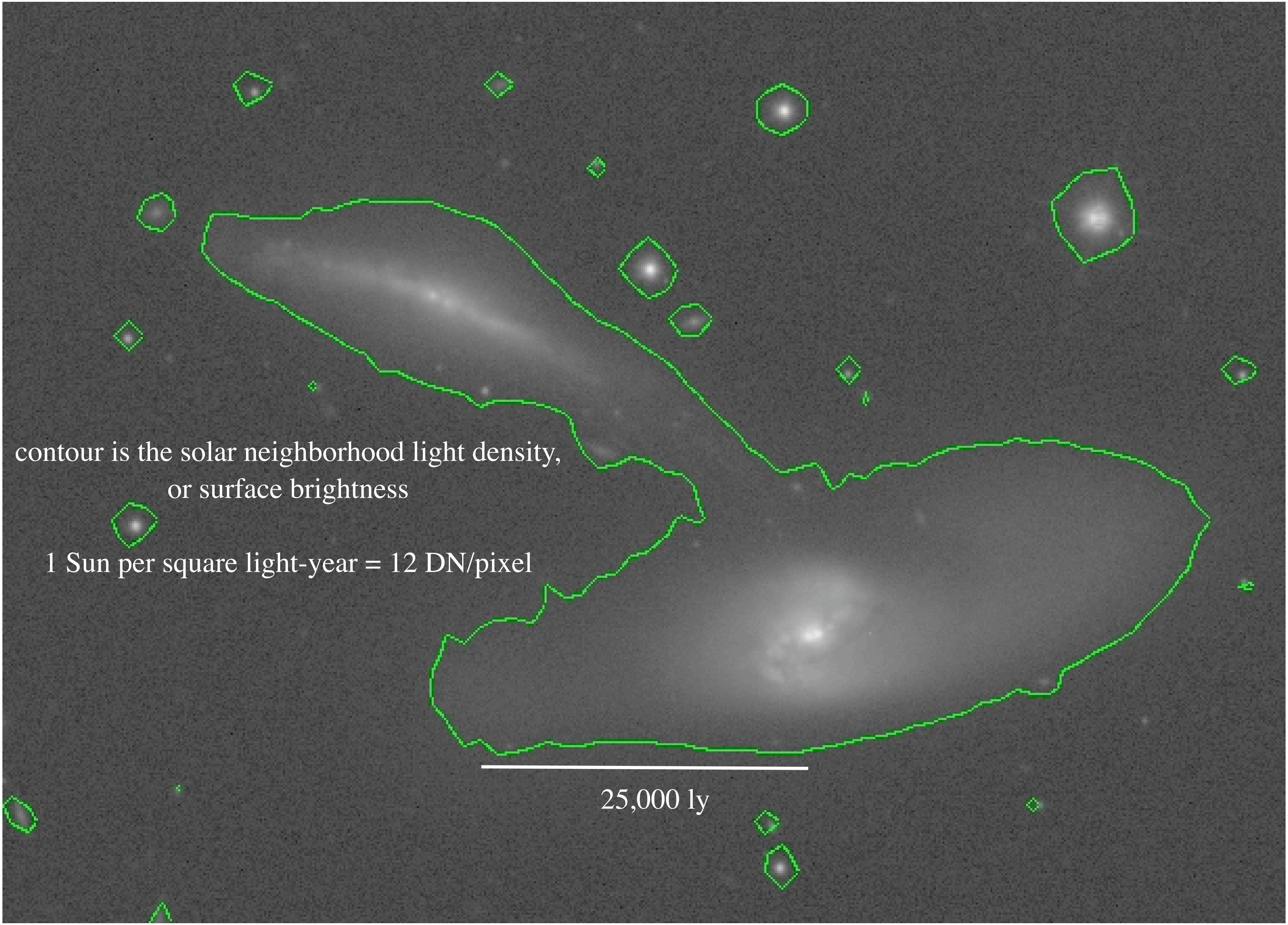

u

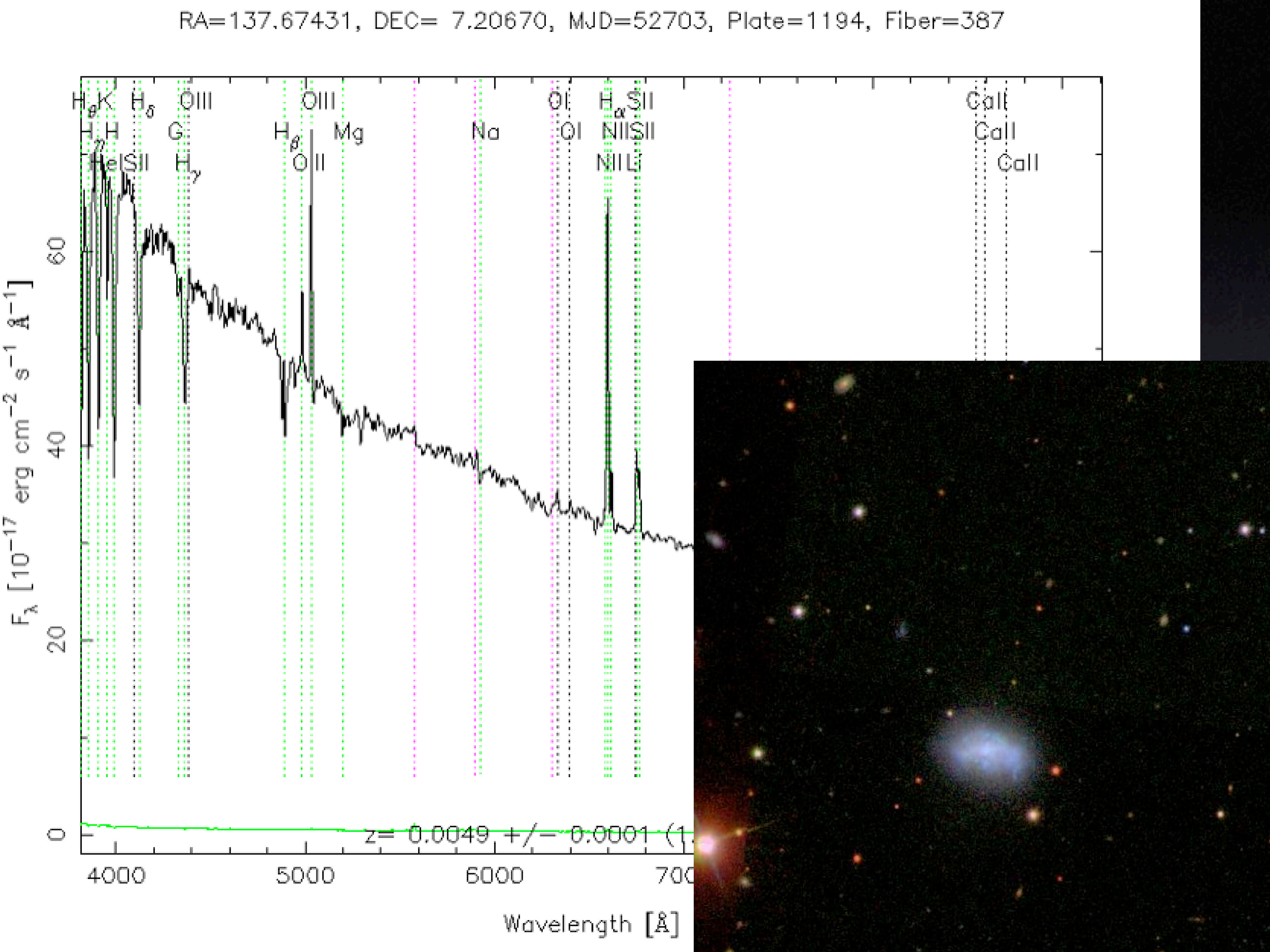

g

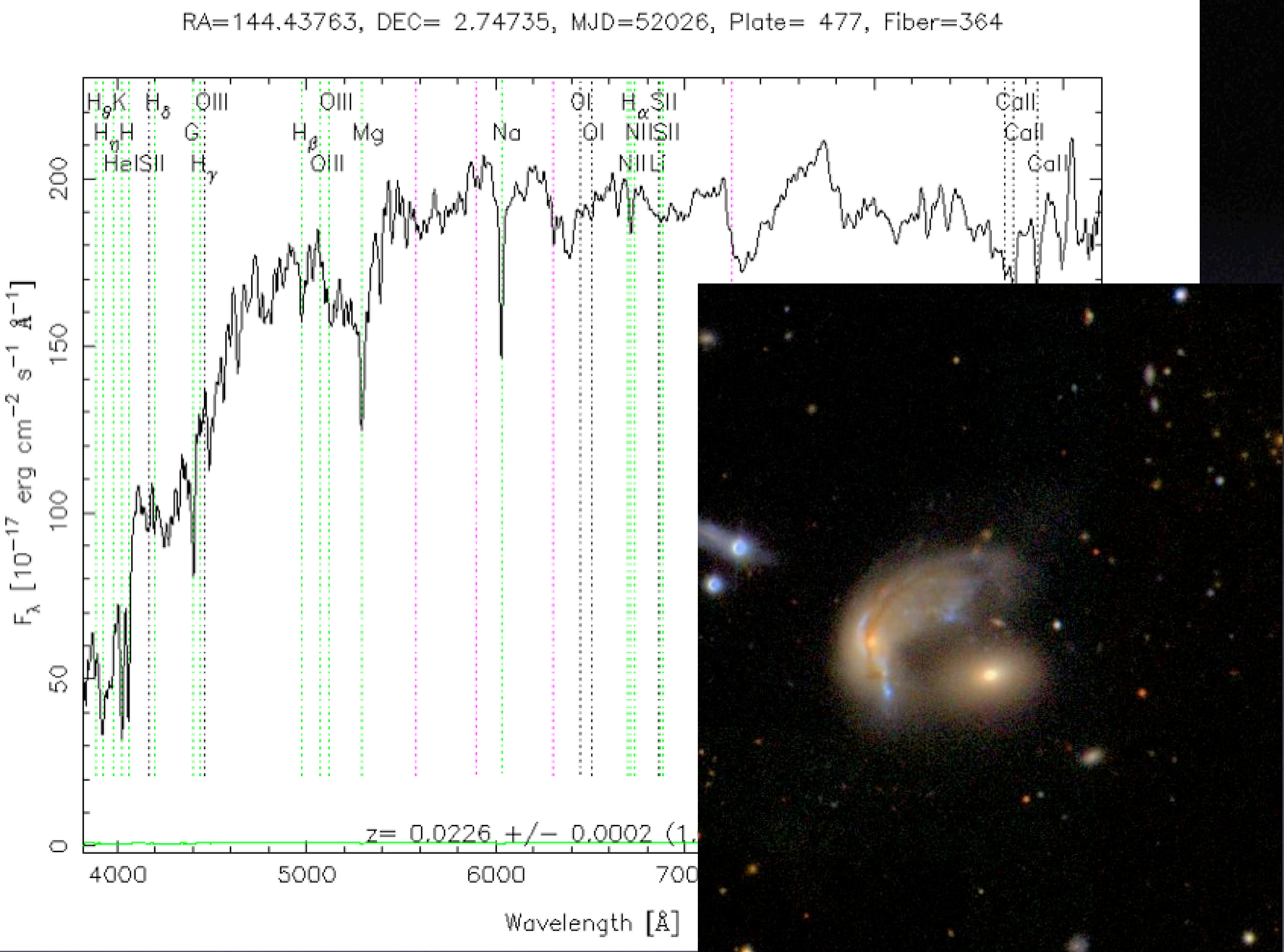

r

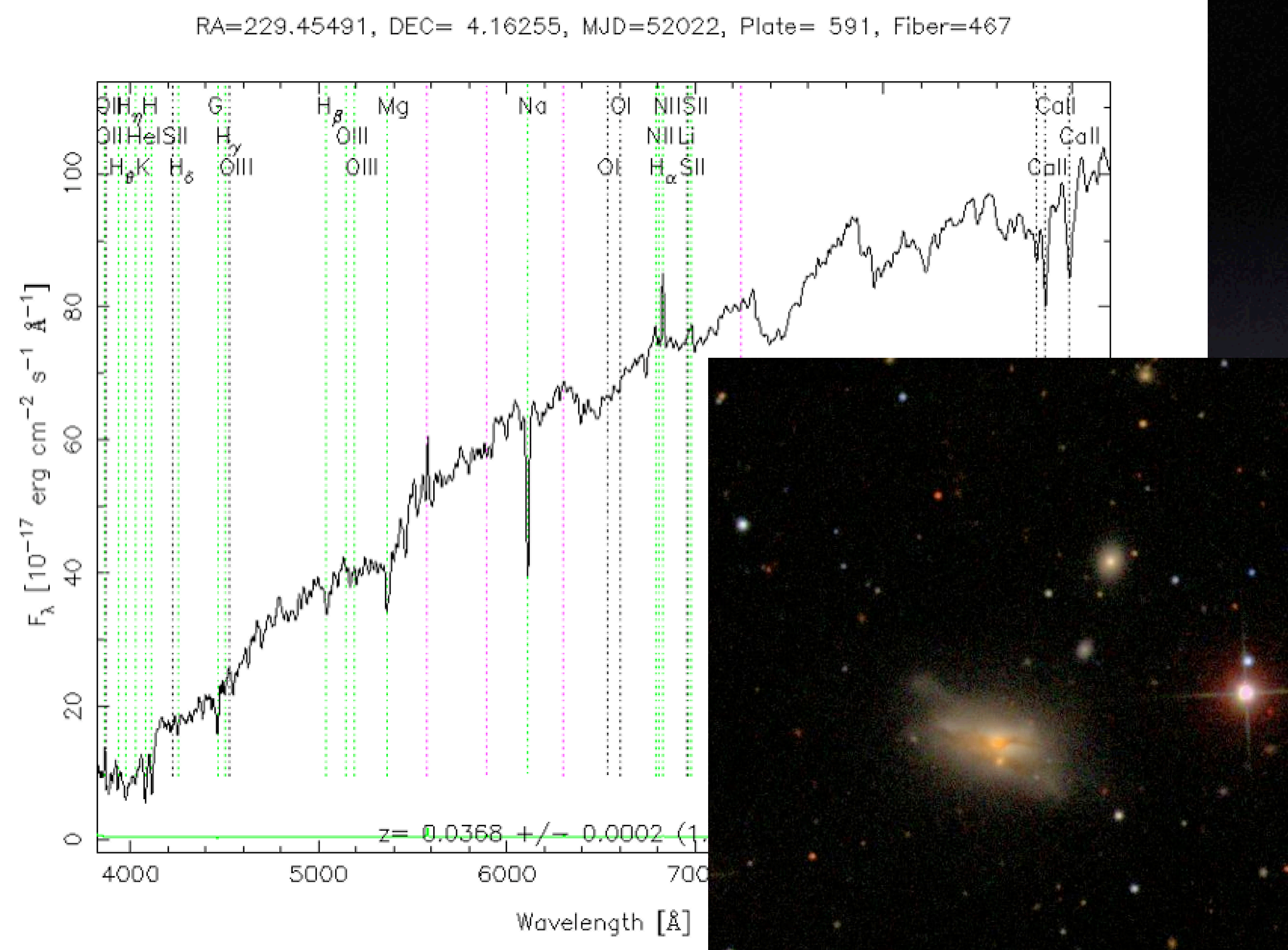

i


Z


contour is the solar neighborhood light density,
or surface brightness
1 Sun per square light-year = 12 DN/pixel
25,000 ly


RA=137.67431, DEC= 7.20670, MJD=52703, Plate=1194, Fiber=387
Hθ K Hδ OIII OIII OI HαSII CaII
Hη H G Hβ Mg Na OI NIISII CaII
HeISII Hγ OII NIILi CaII
60
40
20
0
4000
5000
6000
700
Wavelength [Å]
Fλ [10⁻¹⁷ erg cm⁻² s⁻¹ Å⁻¹]
z= 0.0049 +/- 0.0001 (1.


RA=144.43763, DEC= 2.74735, MJD=52026, Plate= 477, Fiber=364
H_δ
OIII
OIII
G
H_β
Mg
Na
OI
OI
H_α SII
NII SII
NII
CaII
CaII
CaII
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
0
50
100
150
200
4000
5000
6000
z= 0.0226 +/- 0.0002
Wavelength [Å]


RA=229.45491, DEC= 4.16255, MJD=52022, Plate= 591, Fiber=467
OII Hη H G Hβ Mg Na OI NIISII CaII
OII HeI SII Hγ OIII NII Li CaII
Hθ K Hδ OIII OIII OI Hα SII CaII
z= 0.0368 +/- 0.0002
F_λ [10^{-17} erg cm^{-2} s^{-1} Å^{-1}]
Wavelength [Å]
0
20
40
60
80
100
4000
5000
6000
700

Lacking knowledge of the angle of projection, and absent a detailed spectral analysis, NGC 2798 + NGC 2799 might or might not contain significant amounts of dark matter.

A good way to demonstrate the existence of dark matter is to study rich *clusters of galaxies*, where projection effects average out statistically.

Getting Redshifts

http://cas.sdss.org/DR3/en/

if you want to browse through spectra:

- tools
  - get images
    - plates

if you know the ra, dec of a galaxy:

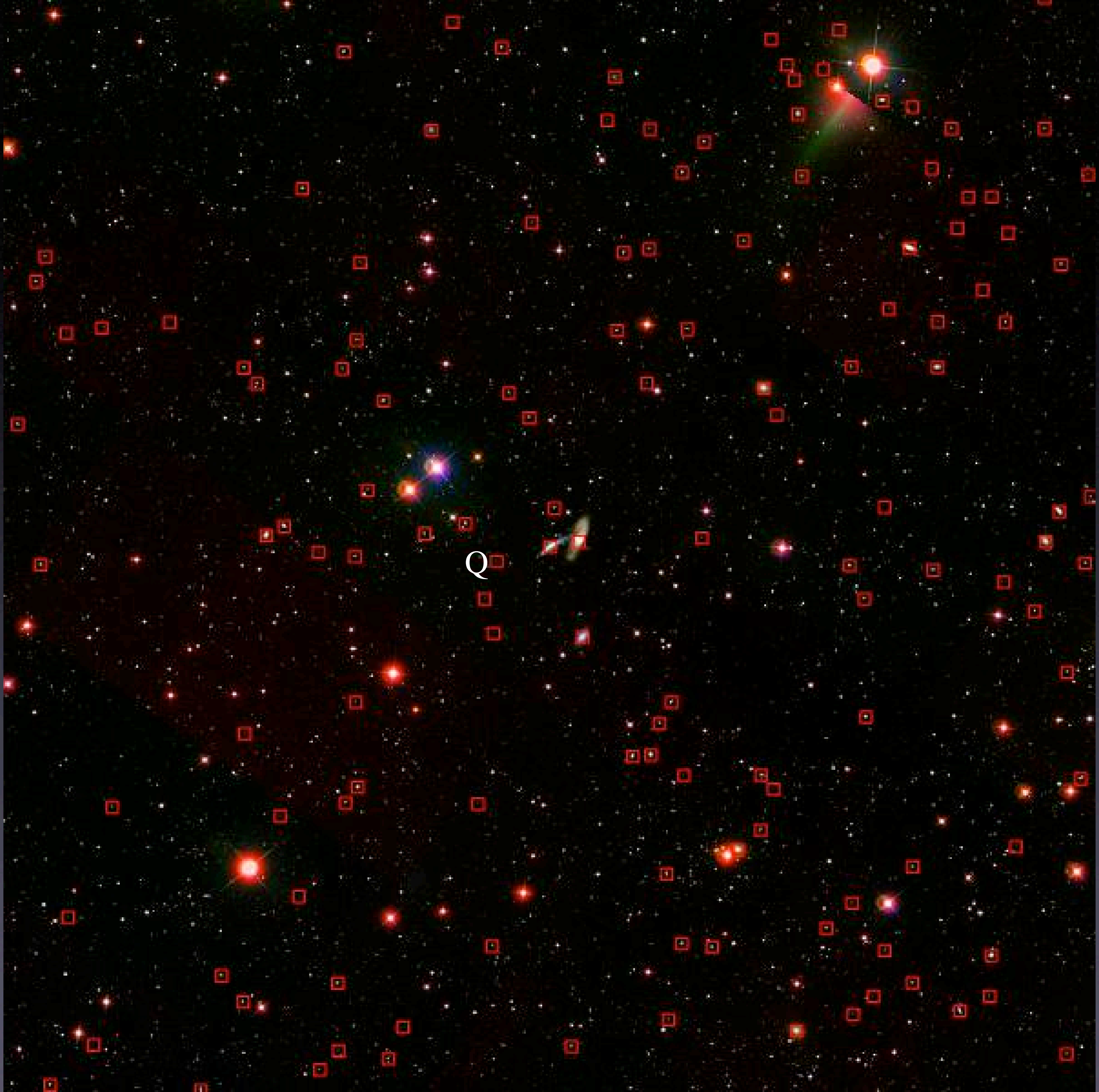
- tools
  - visuals tools
    - explore
      - search by Ra,dec

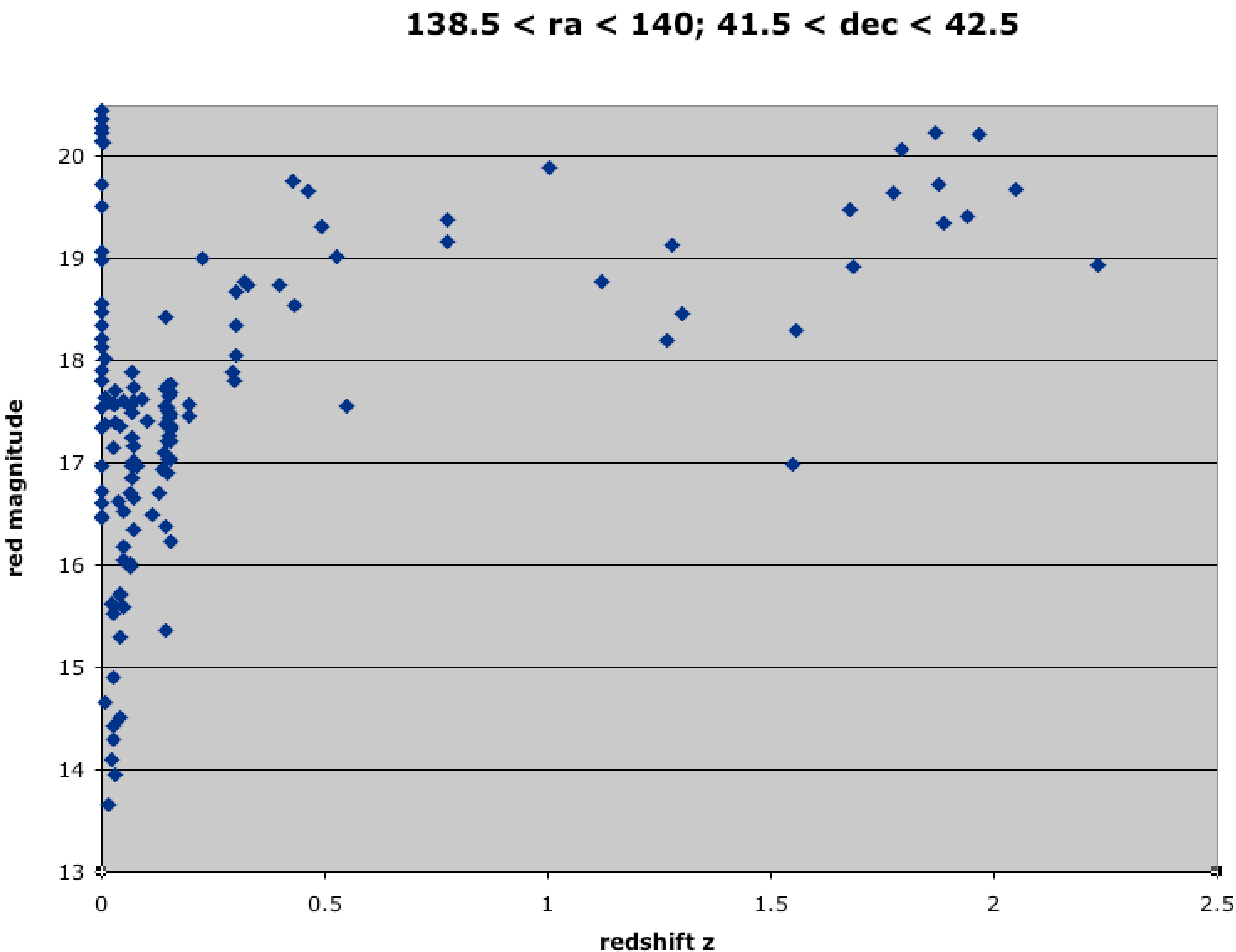
if you want to find things by their position on the sky:

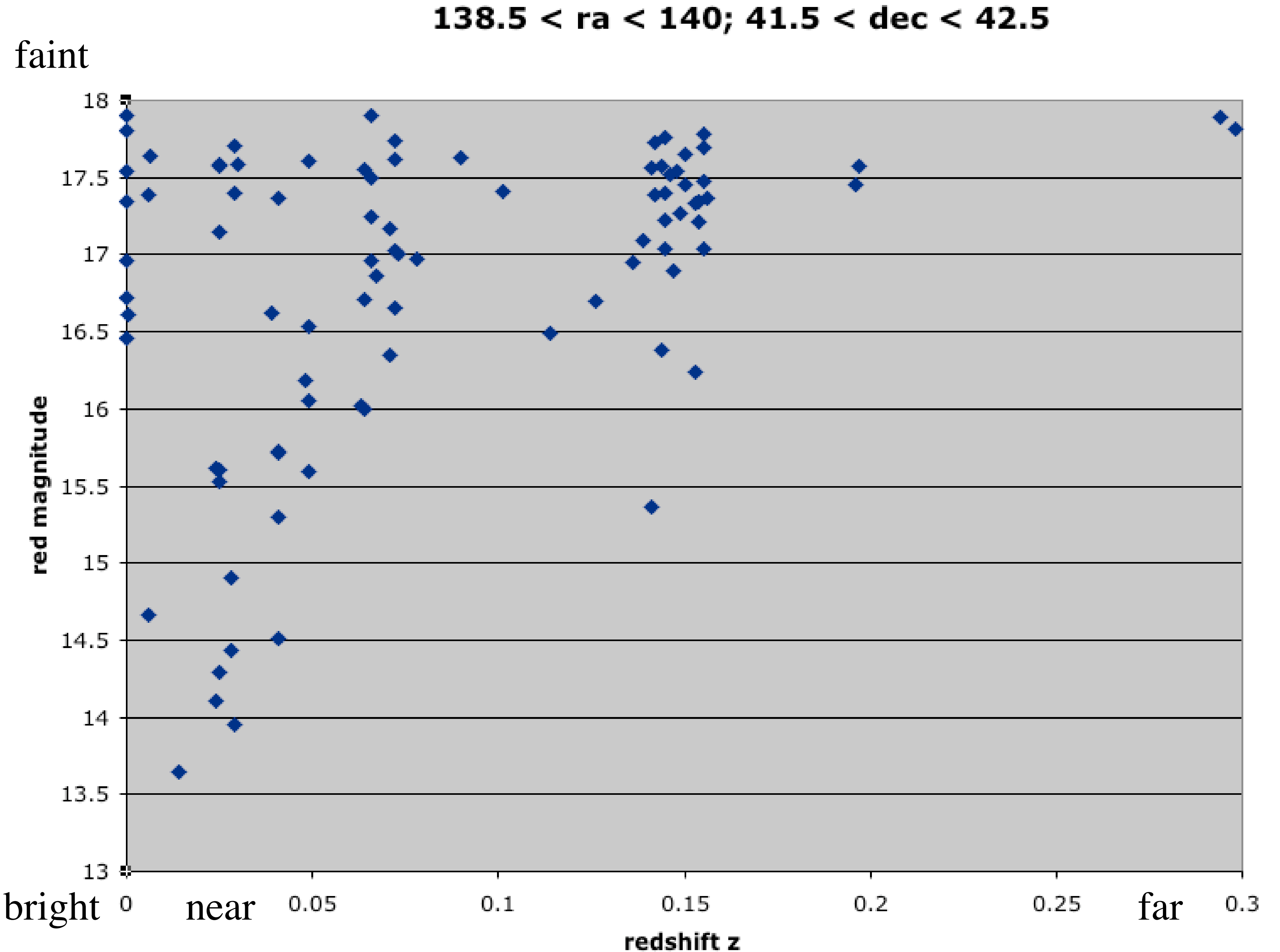
SQL Search

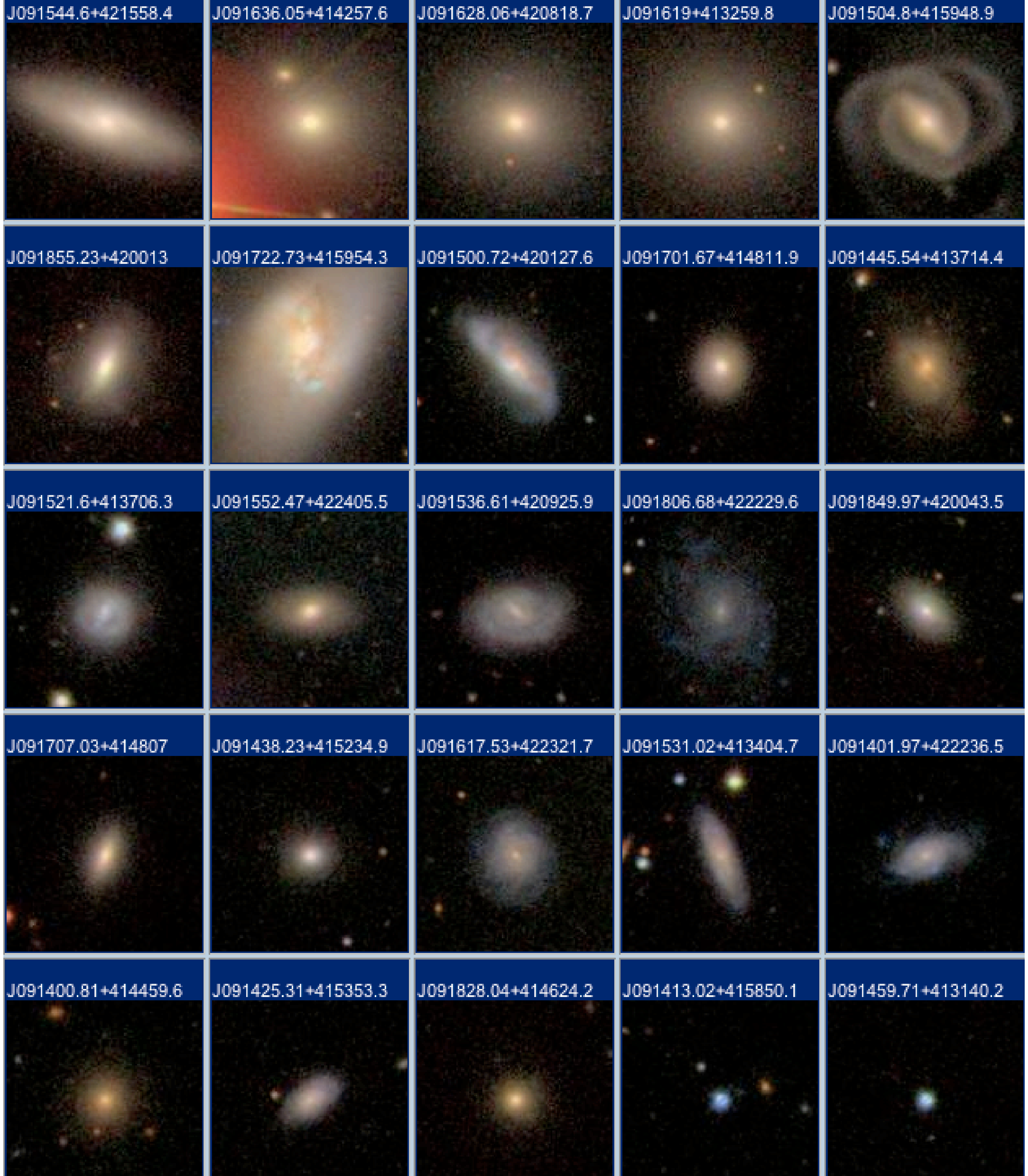
```
SELECT
ra, dec, z, modelmag_r

FROM
specphoto

WHERE
ra > 138.5 and ra < 140 and
dec > 41.5 and dec < 42.5
```

```
ra,dec,z,modelmag_r
138.50723,41.975331,5.805E-3,17.39
138.52559,41.909246,1.792,20.067
138.55104,41.855375,0.064,17.556
138.5039,41.890746,0.145,17.402
138.68143,41.560208,0.142,17.724
138.62703,41.607575,-1.913E-4,19.735
138.65475,41.570314,1.003,19.887
138.50339,41.749904,0.153,16.239
138.63331,41.654661,0.139,17.096
139.75682,41.576596,0.15,17.449
139.97149,41.653039,0.774,19.389
139.91793,41.754364,0.299,18.351
```


Q


138.5 < ra < 140; 41.5 < dec < 42.5
red magnitude
redshift z
13
14
15
16
17
18
19
20
0
0.5
1
1.5
2
2.5


138.5 < ra < 140; 41.5 < dec < 42.5
faint
bright
near
far
red magnitude
redshift z
18
17.5
17
16.5
16
15.5
15
14.5
14
13.5
13
0
0.05
0.1
0.15
0.2
0.25
0.3


J091544.6+421558.4
J091636.05+414257.6
J091628.06+420818.7
J091619+413259.8
J091504.8+415948.9
J091855.23+420013
J091722.73+415954.3
J091500.72+420127.6
J091701.67+414811.9
J091445.54+413714.4
J091521.6+413706.3
J091552.47+422405.5
J091536.61+420925.9
J091806.68+422229.6
J091849.97+420043.5
J091707.03+414807
J091438.23+415234.9
J091617.53+422321.7
J091531.02+413404.7
J091401.97+422236.5
J091400.81+414459.6
J091425.31+415353.3
J091828.04+414624.2
J091413.02+415850.1
J091459.71+413140.2

SDSS J091731.22+415936.8

"Explore" tool on SkyServer

DR4

Explore Home

Search by
ObjId
Ra,dec
5-part SDSS
Plate-MJD-Fiber
SpecObjId

Summary

PhotoObj
Field
Frame
PhotoZ
Neighbors
Finding chart
Navigate
FITS

SpecObj
SpecLine
SpecLineIndex
XCredShift
ELredShift
Spectrum
Plate
FITS

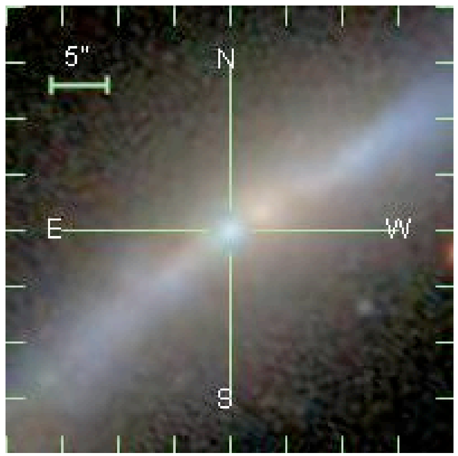
NED search
SIMBAD search
ADS search

Notes
Save in Notes
Show Notes

Print

GALAXY ra=139.38012, dec=41.99358, ObjId = 588013382730121230

mode	PRIMARY
status	TARGET PRIMARY OK_STRIPE OK_SCANLINE PSEGMENT RESOLVED OK_RUN GOOD SET
flags	STATIONARY BAD_MOVING_FIT BINNED1 DEBLENDED_AS_PSF INTERP CHILD
PrimTarget	TARGET_QSO_CAP
SecTarget	



run	rerun	camcol	field	obj	rowc	colc
2830	41	3	206	14	424.3	1212.2

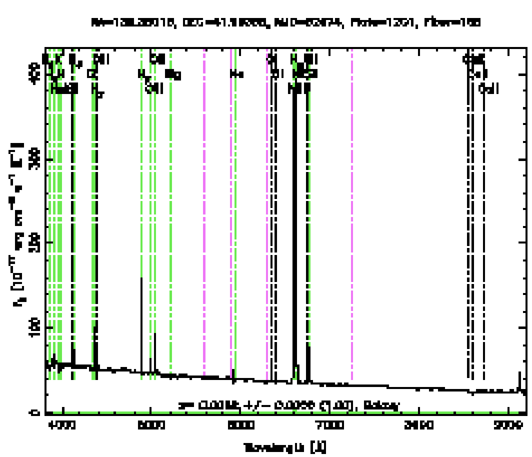
u	g	r	i	z
18.13	17.95	18.02	18.03	17.80

fiberMag_r	petroMag_r	devMag_r	expMag_r	psfMag_r	modelMag_r
17.02	18.06	18.01	18.02	18.19	18.02

extinction_r	petroRad_r	parentId	nChild
0.05	1.158	588013382730121227	0

SpecObjId = 338277680841490432

plate	mjd	fiberId	z	zErr	zConf	specClass	ra	dec	fiberMag_r	objId
1201	52674	168	0.006	0.00001	0.998	GALAXY	139.38016	41.99365	16.86	588013382730121230



zStatus	EMLINE_XCORR
zWarning	NOT_GAL
PrimTarget	TARGET_GALAXY TARGET_GALAXY_RED
SecTarget	
eClass	0.401
emZ	0.006
emConf	0.998
xcZ	0.006
xcConf	0.942

The SDSS project would like to make the SkyServer as useful to teachers and students as possible.

Please inform us of any ideas, suggestions, etc. We welcome a continuing dialog and direct involvement by teachers and students in developing projects and tools.

Summary

redshift is derived from a spectrum

distance is derived from the redshift

physical properties like R, M, L can be determined once the distance is known

astronomers attempt to understand the nature of galaxies (how they formed, how they evolve, what is in them), constrained by the values of these properties