Galactic and Extragalatic Astronomy
AA 472/672
Spring Semester

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- **Oldest galaxies in universe**
  - most of their stars formed early in universe;
  - the galaxy may have grown or changed since early universe

- **Appear simple but are complex**

A typical elliptical galaxy

Characteristics of elliptical galaxies

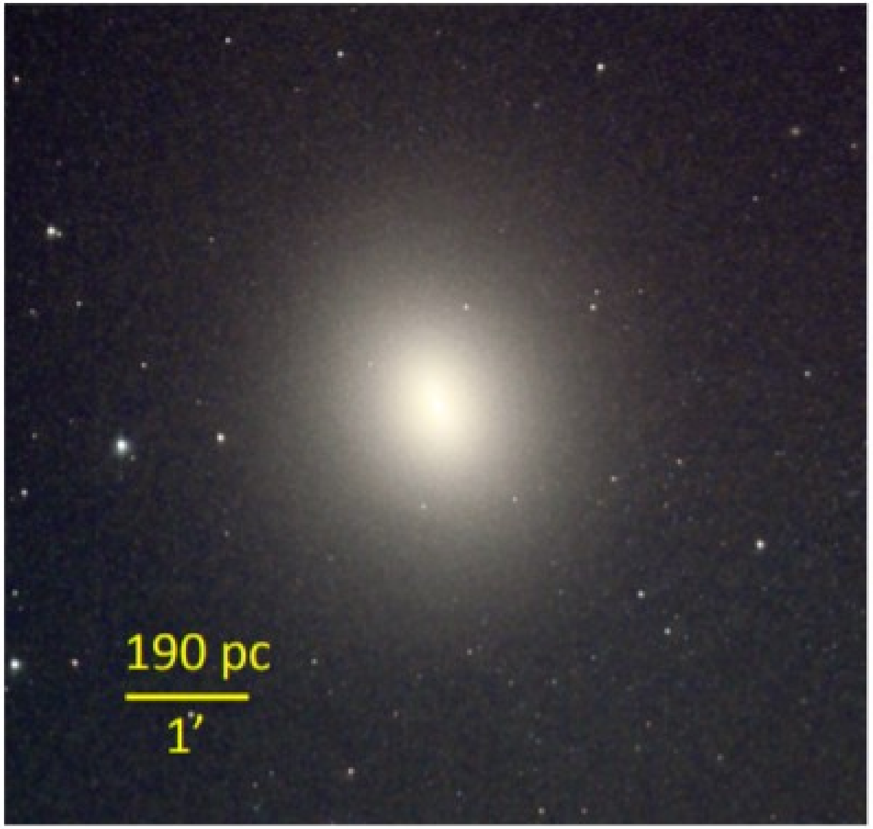
- Little or no star formation

- Little or no dust or cold gas

- Little or no substructure within galaxy

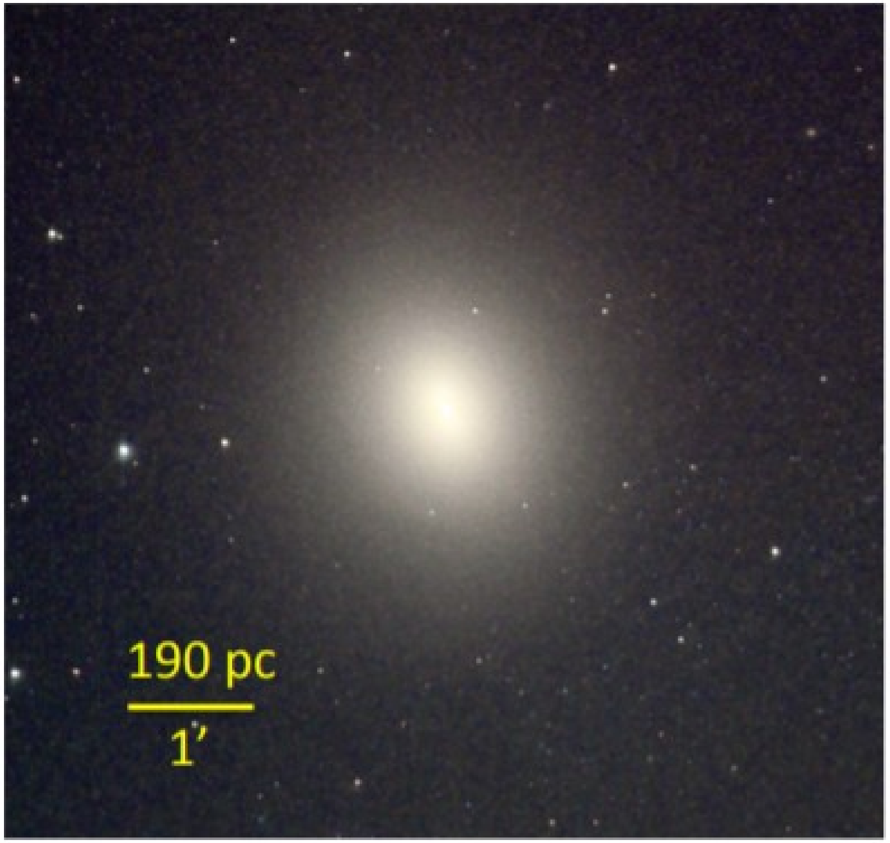
- Isophote shapes nearly ellip/cal

Real story is much more complex ….



Elliptical M32

Dwarf “elliptical” NGC 205



Elliptical M32

Compact, high central stellar density of stars

Little or no gas & star formation

Dwarf "elliptical" NGC 205

Not compact, low central surface density of stars

Little or no gas & star formation

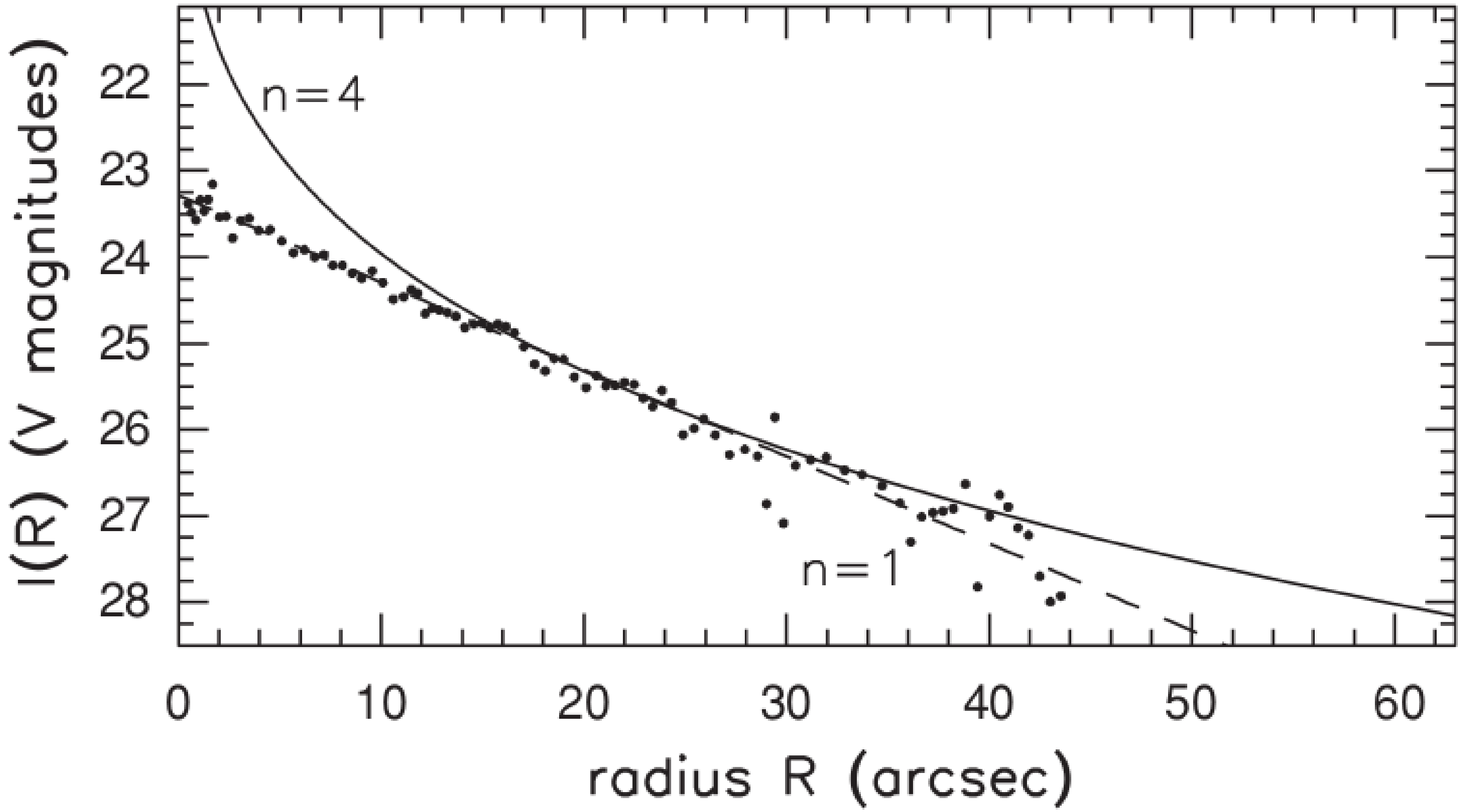
Brightness profile

$$I(R) = I_e \exp\left(-7.669\left[(R/R_e)^{1/4} - 1\right]\right)$$

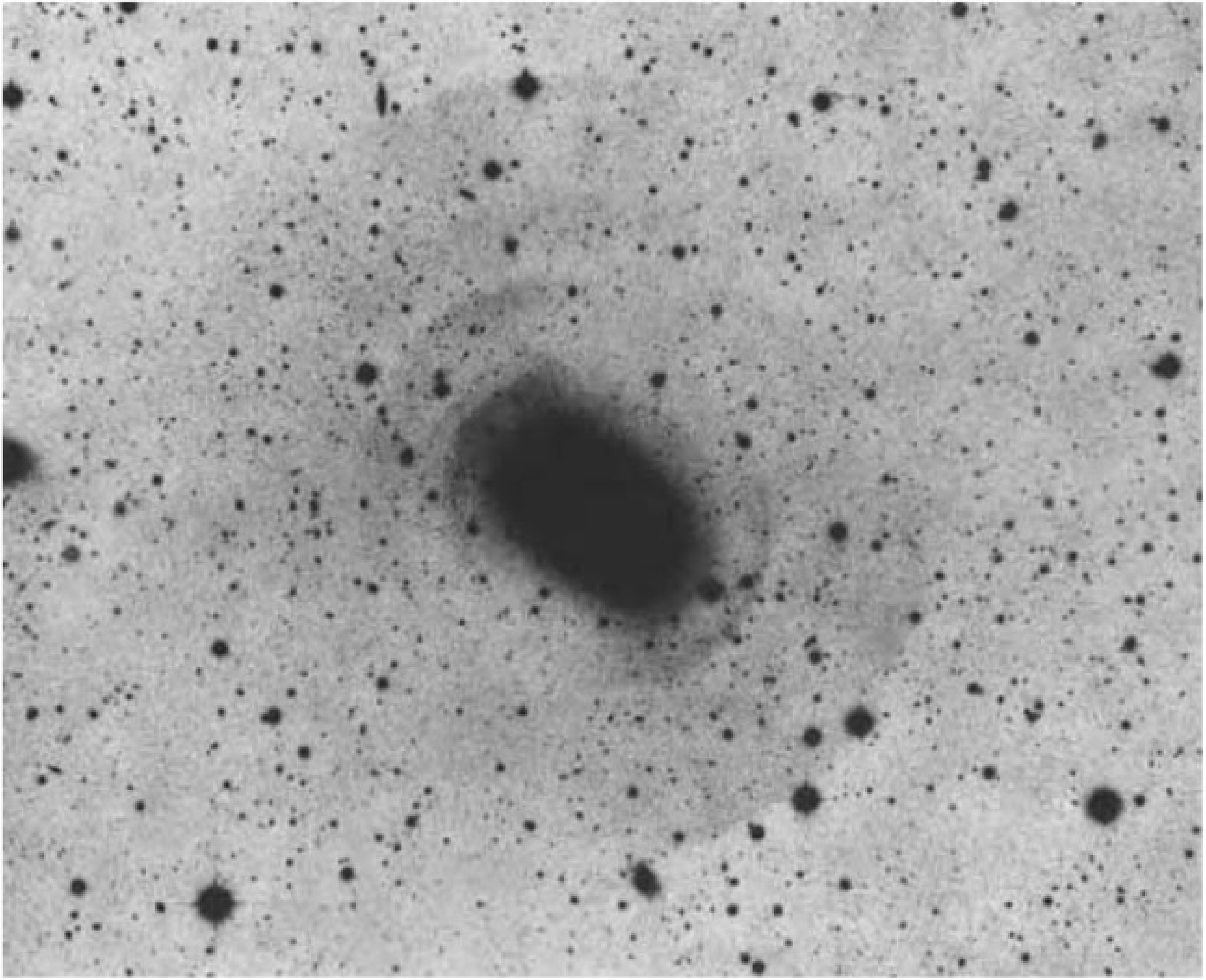
$I(R)$ → surface brightness

R_e → effective radius defined such that half of the luminosity is emitted from within R_e

de Vaucouleurs Profile



galaxy VCC753 in the Virgo cluster



NGC 3923

Arclike structures → signatures of merger or tidal stripping

Exponential disk: $I(r) = I(0) \exp(-r/r_d)$

deVaucouleurs $r^{1/4}$ bulge law: $I(r) = I(r_{eff}) \exp\{-7.67[(r/r_{eff})^{1/4}-1]\}$

Sersic law: $I(r) = I(r_{eff}) \exp\{-b_n[(r/r_{eff})^{1/n}-1]\}$

n = Sersic index

b_n chosen to make r_{eff} the effective radius (encloses ½ the light)

$b_n = 1.999n - 0.327$ for $n>1$

$n = 1\text{-}4$ typically

If $n=1$ exponential (all disk) disks of spirals, S0s, dwarf Es

If $n=4$ deVaucouleurs r/4 law (all bulge) giant E's, globular clusters

$1<n<4$ bulges of spirals and S0s (higher n for large L bulges)

If $n<2$ for entire spiral or S0: small bulge-disk ratio

If $n>2$ for entire spiral or S0: large bulge-disk ratio

Advantage of Sersic law: can describe entire profile shape with just 1 number n

Problem 6.1 Show that the $R^{1/4}$ formula yields a total luminosity

$$L = \int_0^\infty 2\pi R I(R)\,\mathrm{d}R = 8!\frac{e^{7.67}}{(7.67)^8}\pi R_\mathrm{e}^2 I(R_\mathrm{e}) \approx 7.22\pi R_\mathrm{e}^2 I(R_\mathrm{e}). \qquad (6.2)$$

(Remember that $\int_0^\infty e^{-t} t^7\,\mathrm{d}t = \Gamma(8) = 7!$) Use a table of incomplete Γ functions to show that half of this light comes from within radius R_e.

Properties characterizing E’s

- Little or no star formation
- Litte or no dust or cold gas
- Little or no substructure within galaxy
- Isophote shapes nearly elliptical

If you use just these properties, you include both “real ellipticals” as well as dwarf galaxies that are not true ellipticals

Properties characterizing E’s

- Little or no star formation
- Litte or no dust or cold gas
- Little or no substructure within galaxy
- Isophote shapes nearly elliptical
- Radial light distribution: $n \cong 4$

The Faber–Jackson relation and the fundamental plane

Vrot → rotational velocity
sigma_v → velocity dispersion

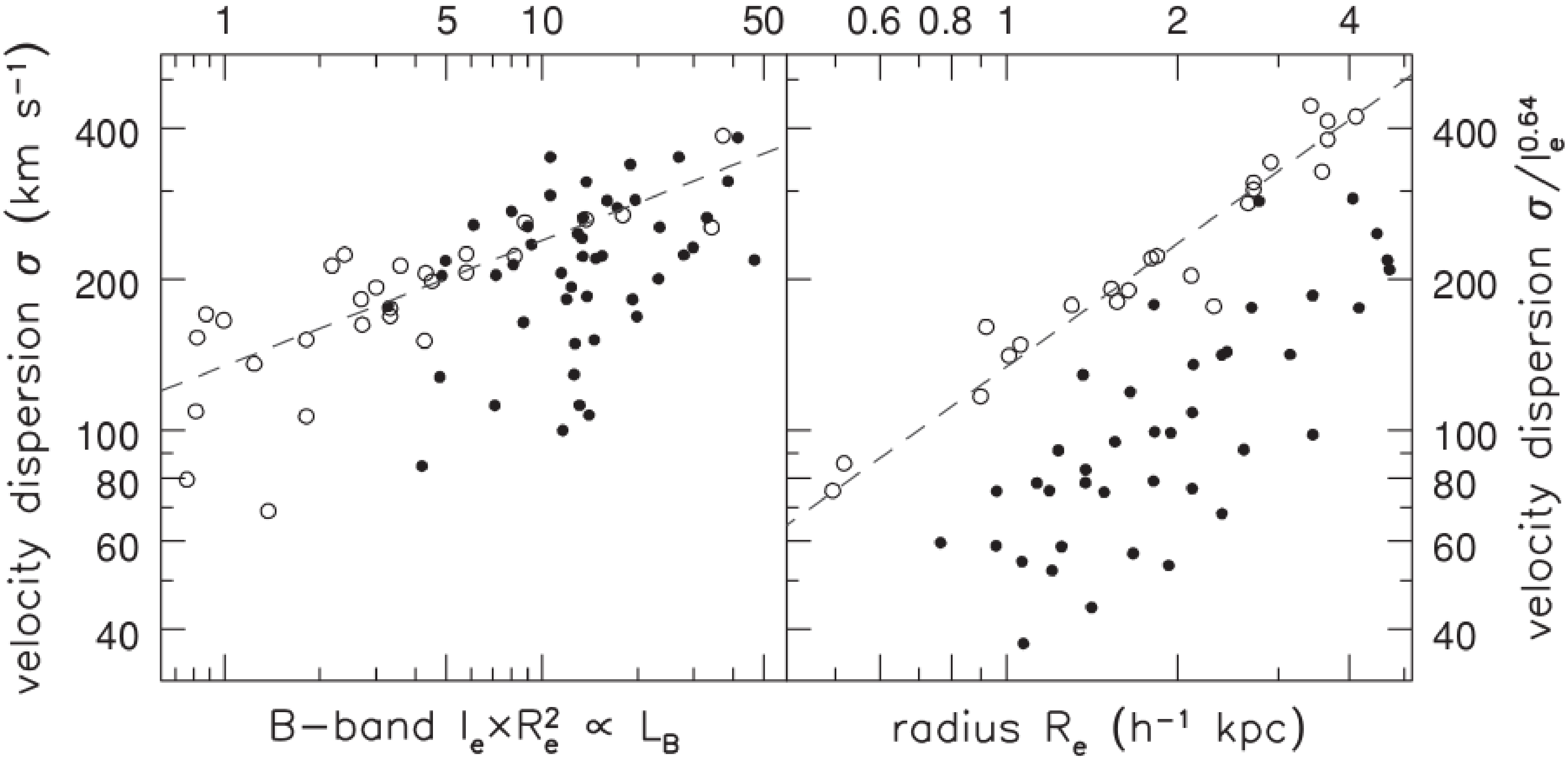
$$\frac{L_V}{2 \times 10^{10} L_\odot} \approx \left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}} \right)^4 .$$

Stars move faster in more luminous galaxies

At the centers of bright ellipticals, the dispersion can reach 500 km s^{-1} , while σ ∼ 50 km s^{-1} in the least luminous objects

Velocity measurement using 21 cm line

Line widths give estimates of velocity dispersion


1
5
10
50
0.6
0.8
1
2
4
400
200
100
80
60
40
velocity dispersion σ (km s^{-1})
B−band $I_e \times R_e^2 \propto L_B$
radius R_e (h^{-1} kpc)
velocity dispersion $\sigma / I_e^{0.64}$

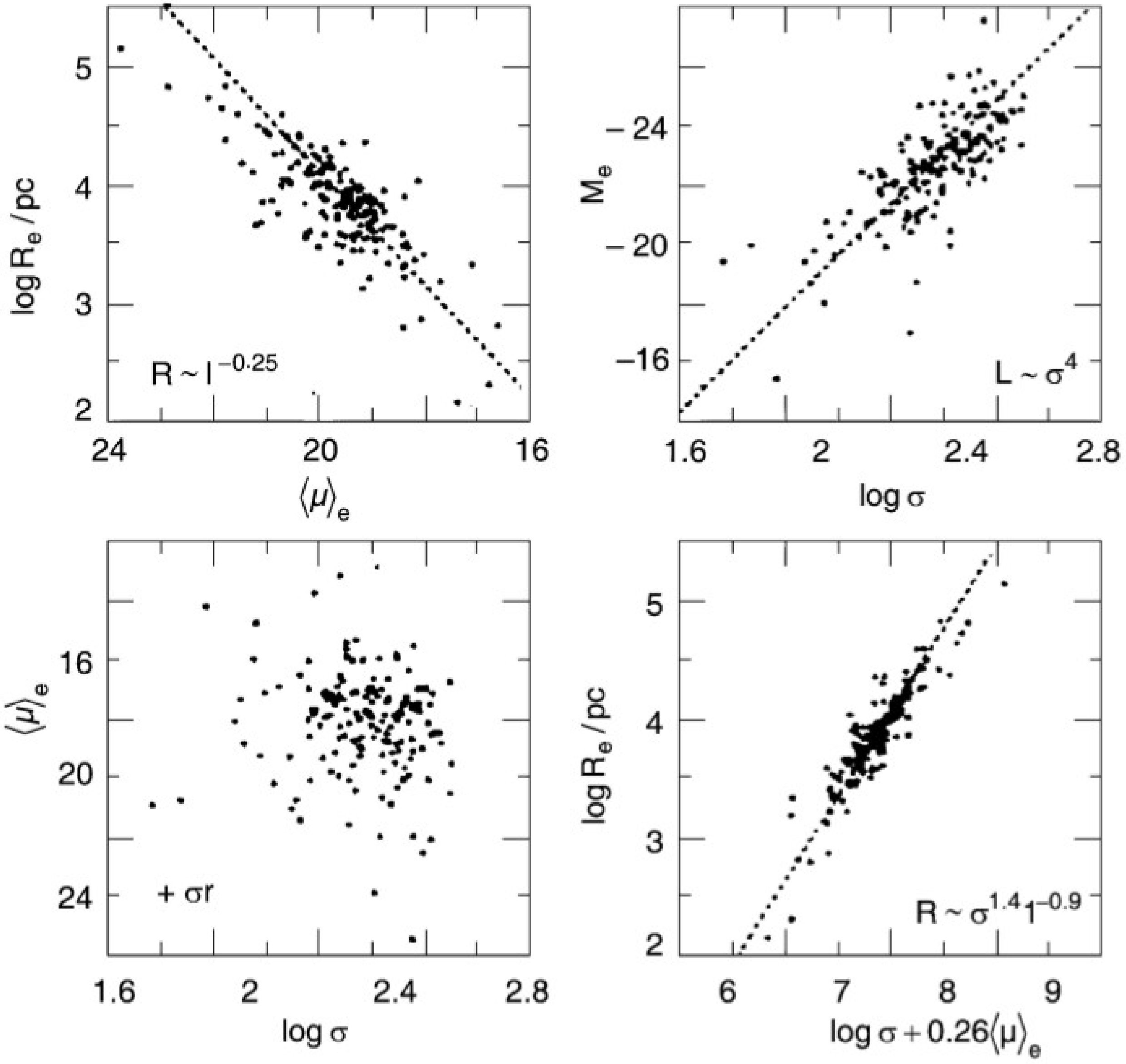
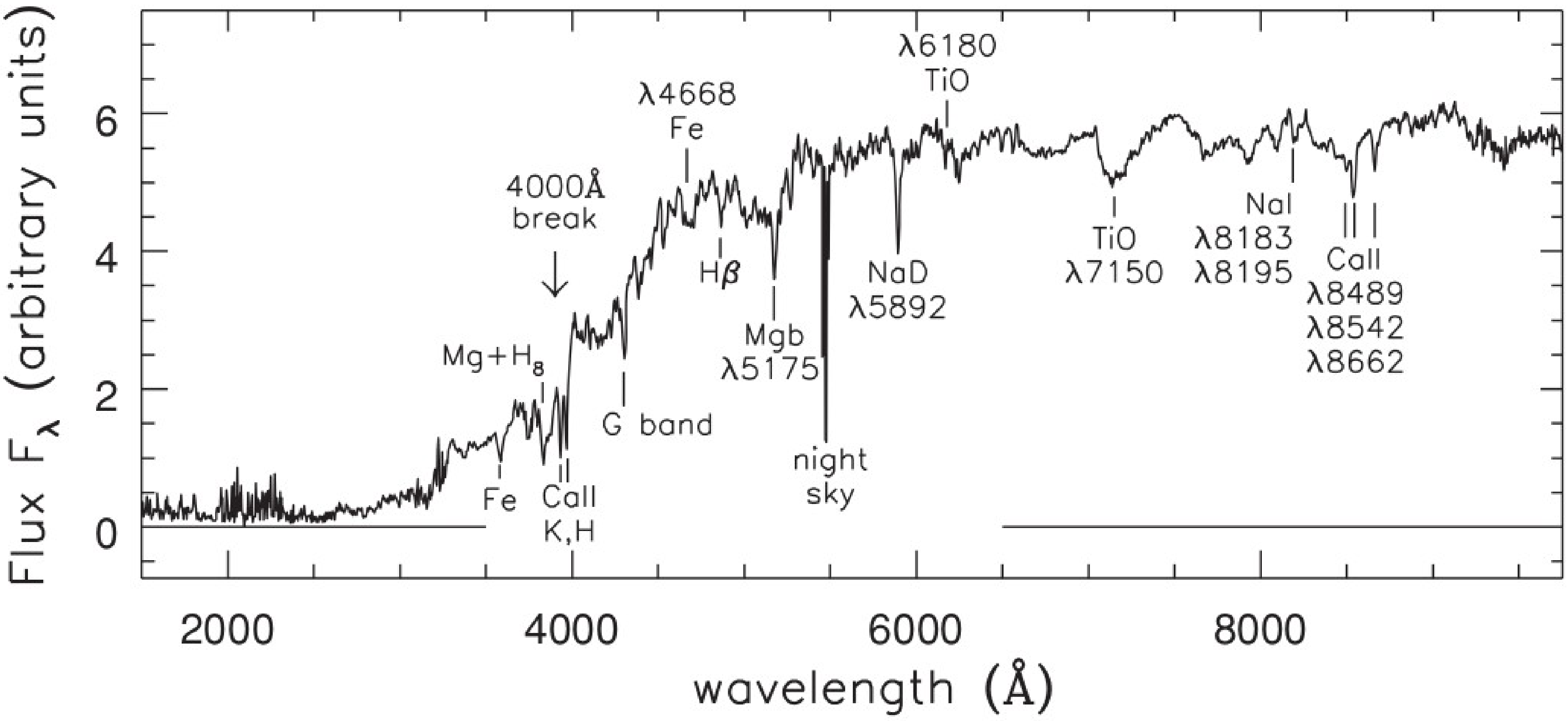


Fig. 3.23. Projections of the fundamental plane onto different two-parameter planes. Upper left: the relation between radius and mean surface brightness within the effective radius. Upper right: Faber–Jackson relation. Lower left: the relation between mean surface brightness and velocity dispersion shows the fundamental plane viewed from above. Lower right: the fundamental plane viewed from the side – the linear relation between radius and a combination of surface brightness and velocity dispersion



Spectrum of a typical elliptical galaxy

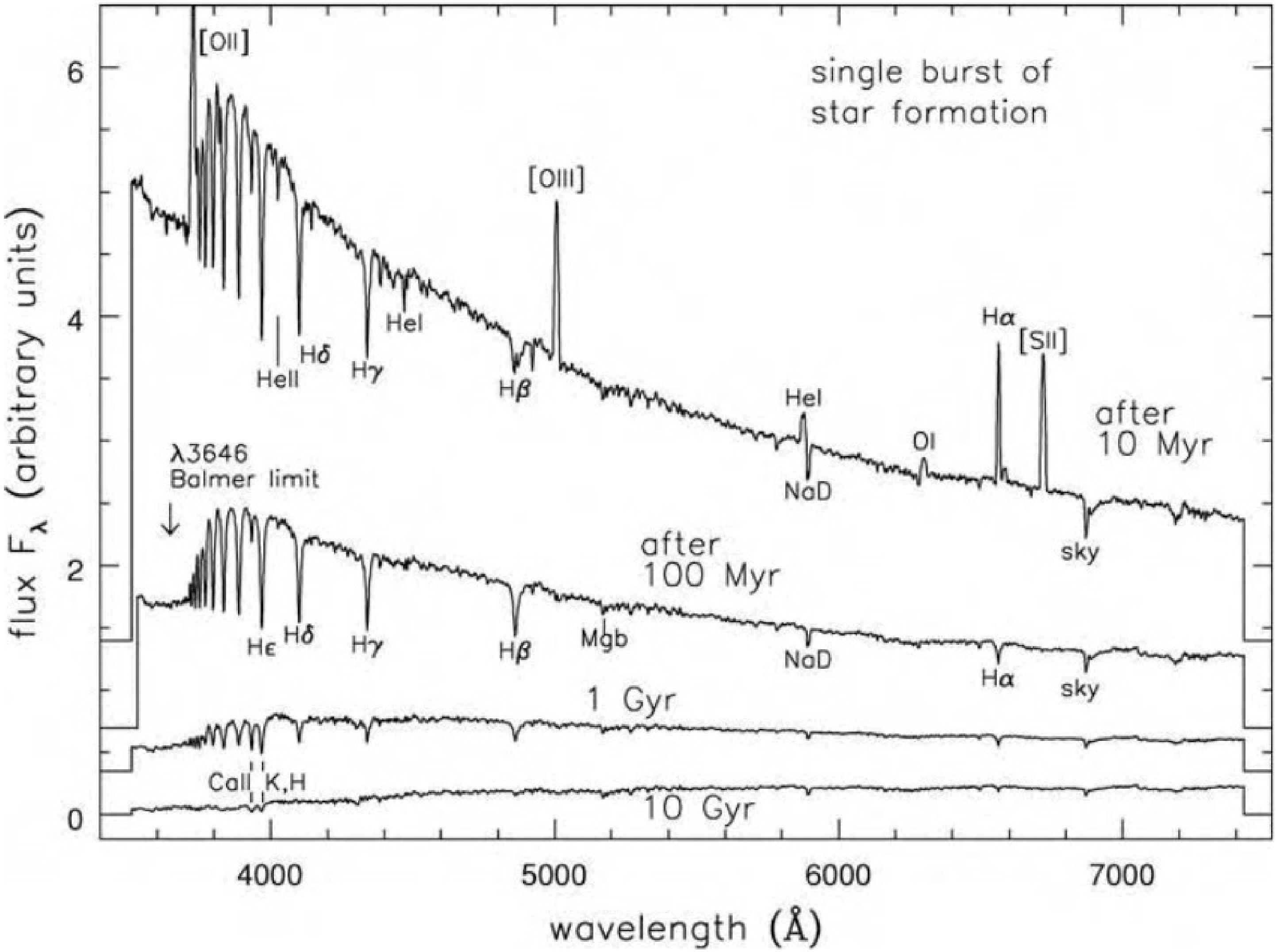
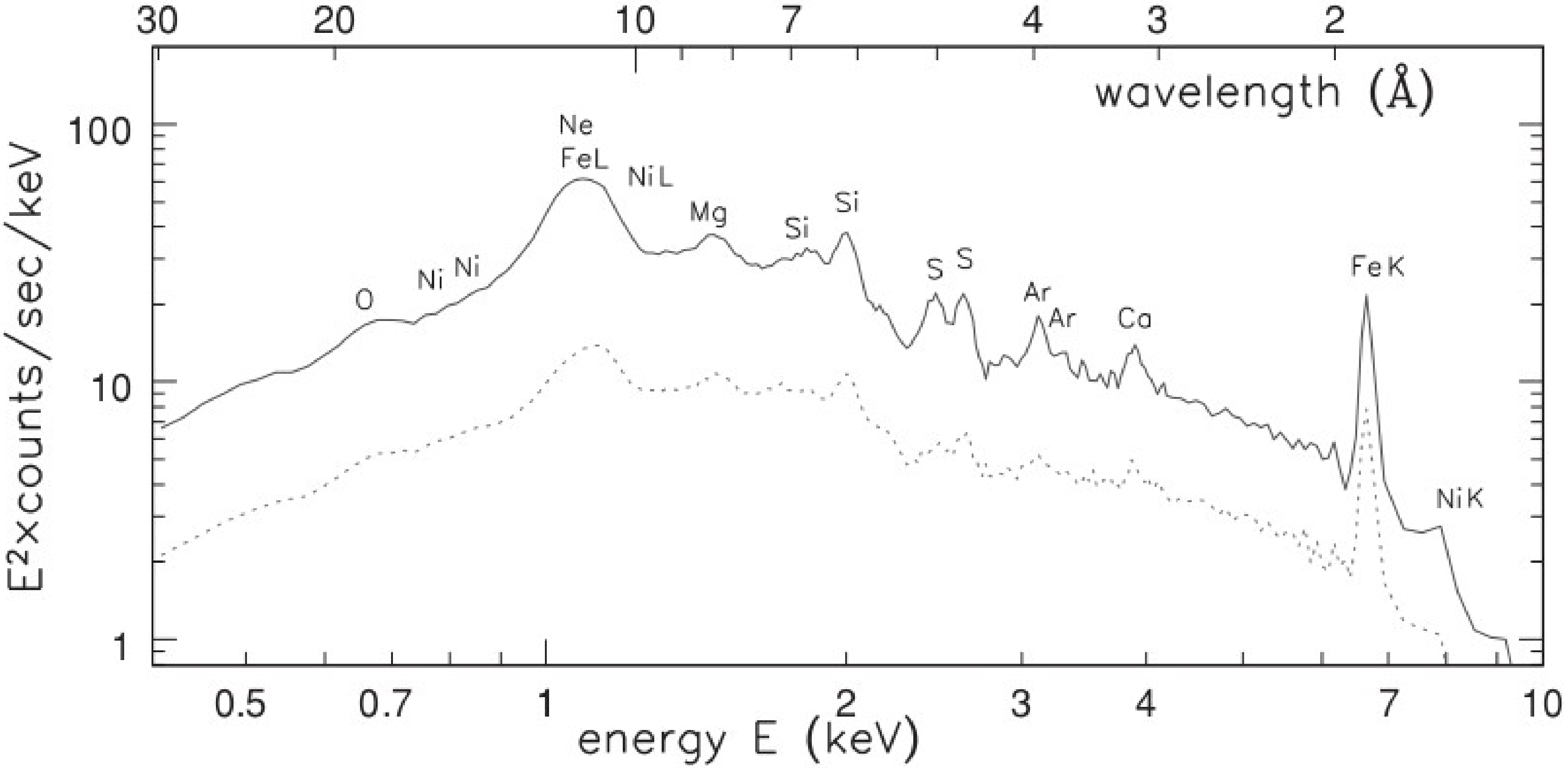


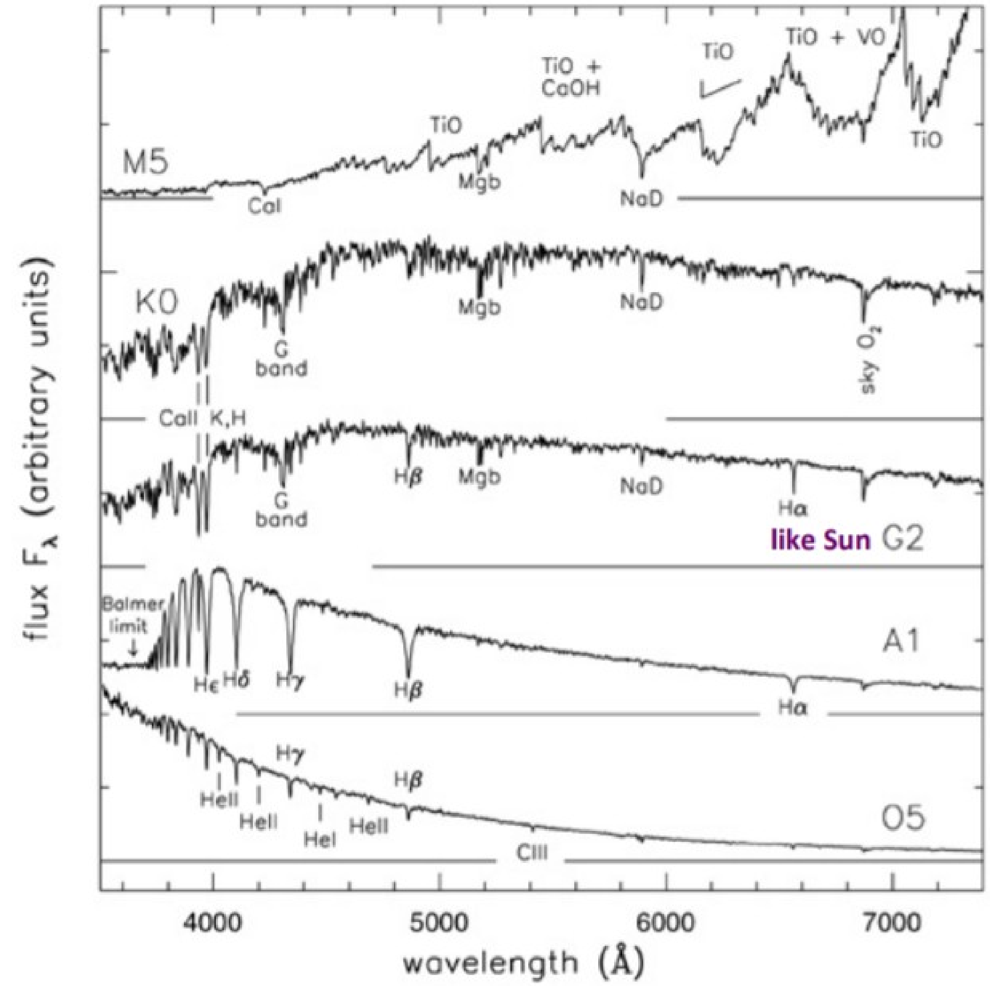
Fig. 6.18. Spectra for a 'galaxy' that makes its stars in a 10^8 yr burst, all plotted to the same vertical scale. Emission lines of ionized gas are strong 10 Myr after the burst ends; after 100 Myr, the galaxy has faded and reddened, and deep hydrogen lines of A stars are prominent. Beyond 1 Gyr, the light dims and becomes slightly redder, but changes are much slower – B. Poggianti.


30
20
10
7
4
3
2
wavelength (Å)
100
10
1
E²xcounts/sec/keV
Ne
FeL
NiL
Mg
Si
Si
O
Ni
Ni
S
S
Ar
Ar
Ca
FeK
NiK
0.5
0.7
1
2
3
4
7
10
energy E (keV)

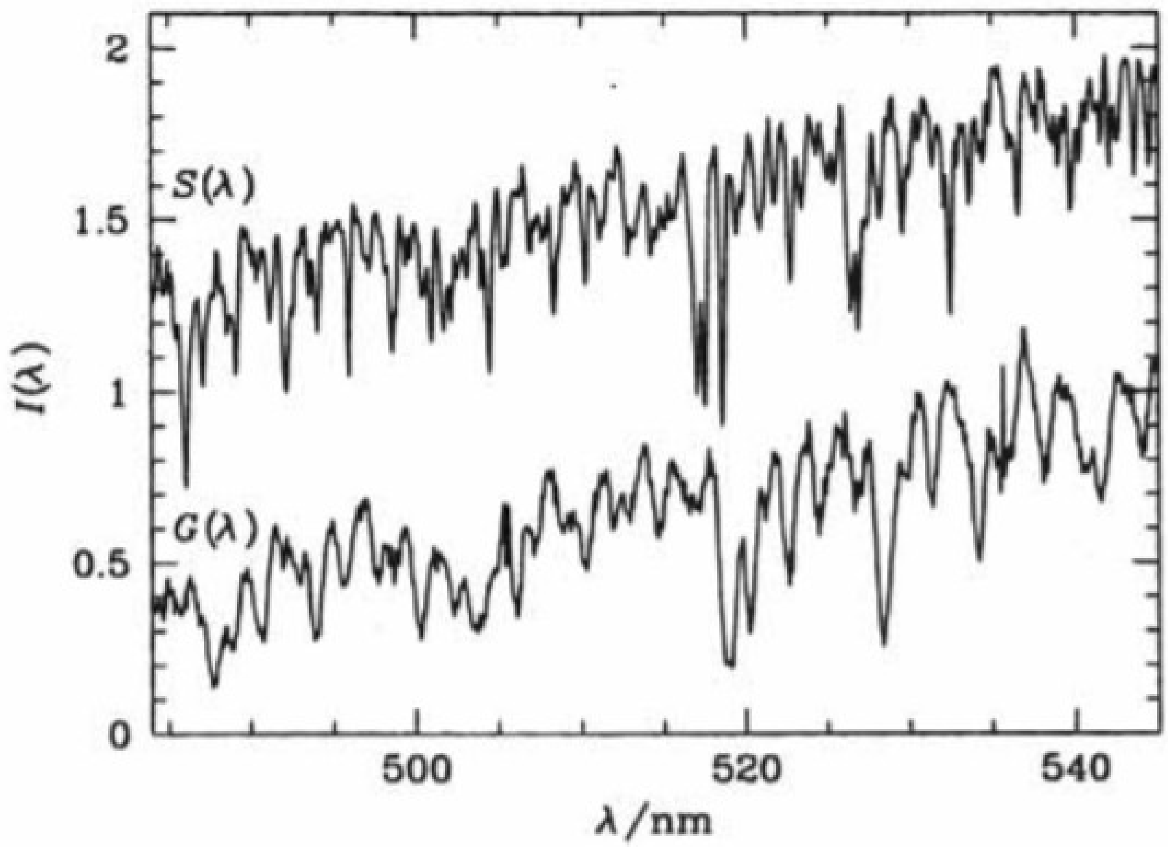
H

Hot gas
M 87

Spectra of main-sequence stars



Compare the spectra of K giant star & S0 galaxy



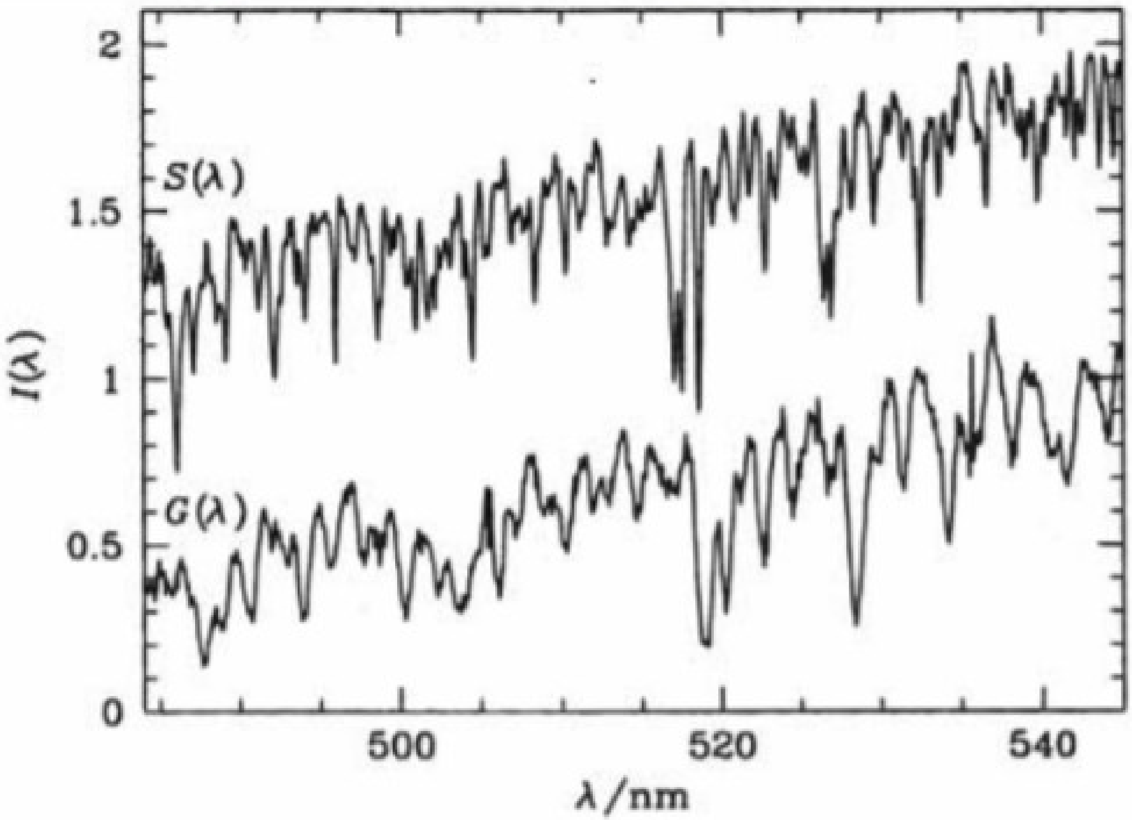
star (K giant)

S0 galaxy

Figure 11.1 Spectra of a K0 giant star (S) and the center of the lenticular galaxy NGC 2549 (G). These data cover a small part of the optical spectrum around the strong Mg b absorption feature at 518 nm.

Q: How are these spectra different?

Compare the spectra of K giant star & S0 galaxy



star (K giant)

S0 galaxy

Figure 11.1 Spectra of a K0 giant star (S) and the center of the lenticular galaxy NGC 2549 (G). These data cover a small part of the optical spectrum around the strong Mg b absorption feature at 518 nm.

2 differences:

1.galaxy spectrum is redshifted wrt MW star (expansion of universe)

2.lines broader in galaxy due to velocity smearing

Introduction to kinematics for Ellipticals

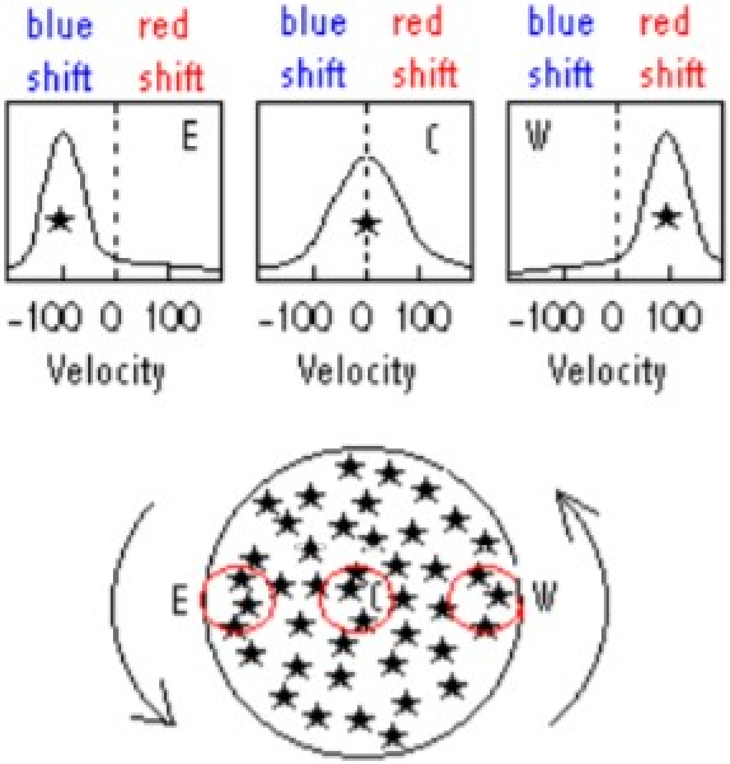
Ordered motions:

v: mean velocity $v = v_{rot} + v_{noncirc}$ *measured by peak or mean of line*

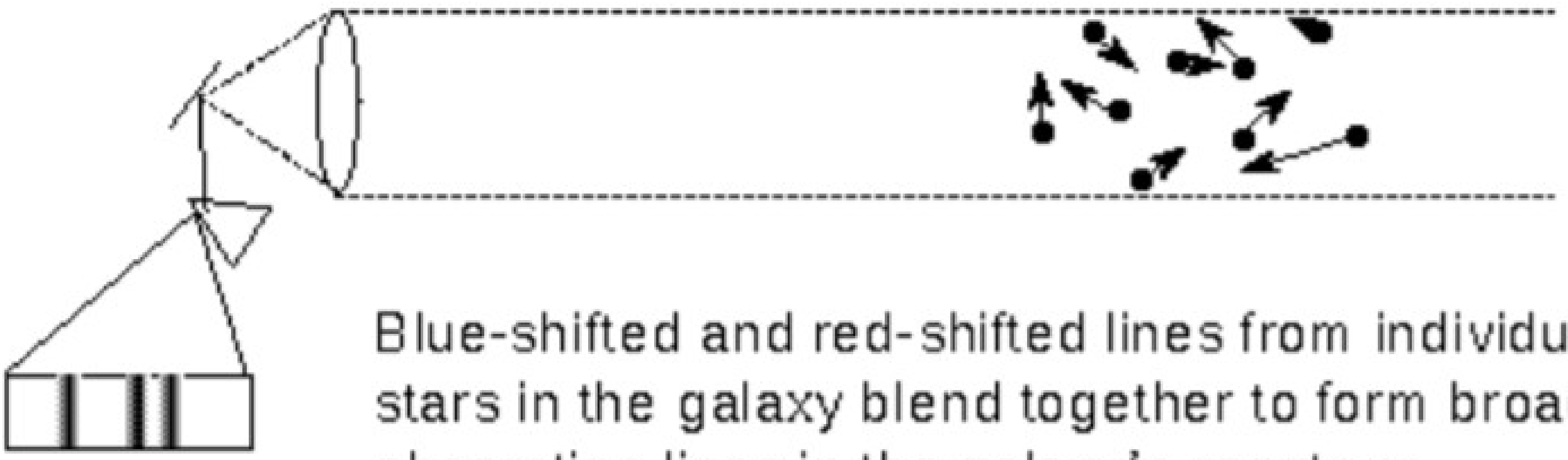
Disordered motions:

σ: velocity dispersion, *measured by linewidth*

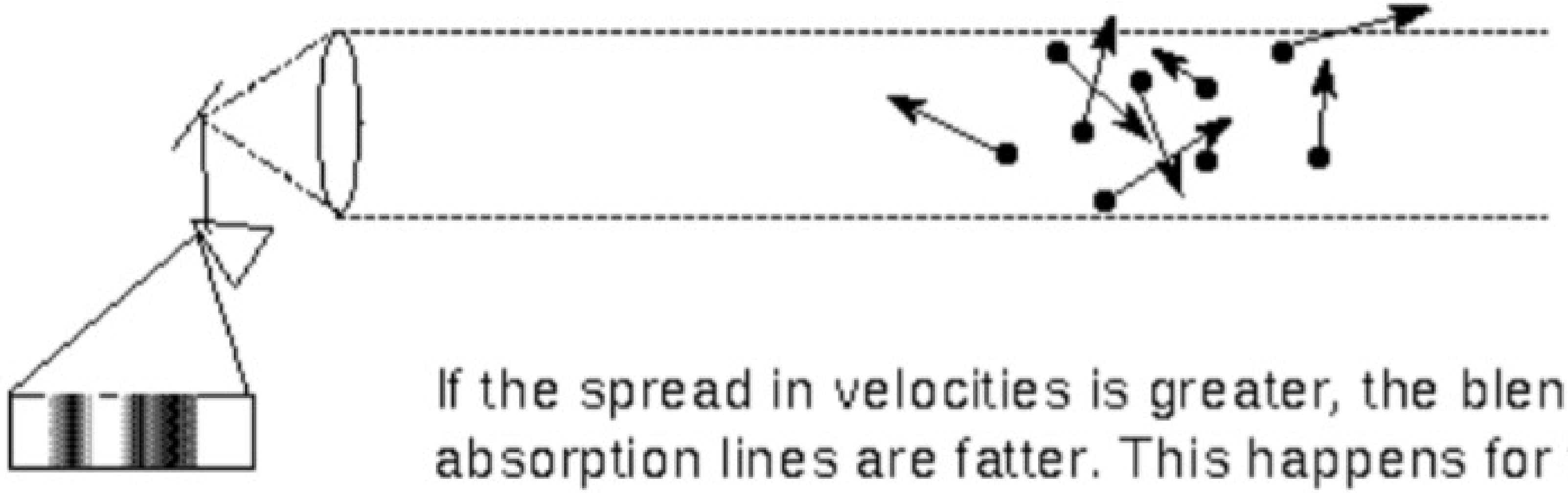
The ratio v/σ is used to compare the relative importance of ordered and random motions


blue shift
red shift
E
-100 0 100
Velocity
blue shift
red shift
C
-100 0 100
Velocity
blue shift
red shift
W
-100 0 100
Velocity
E
C
W

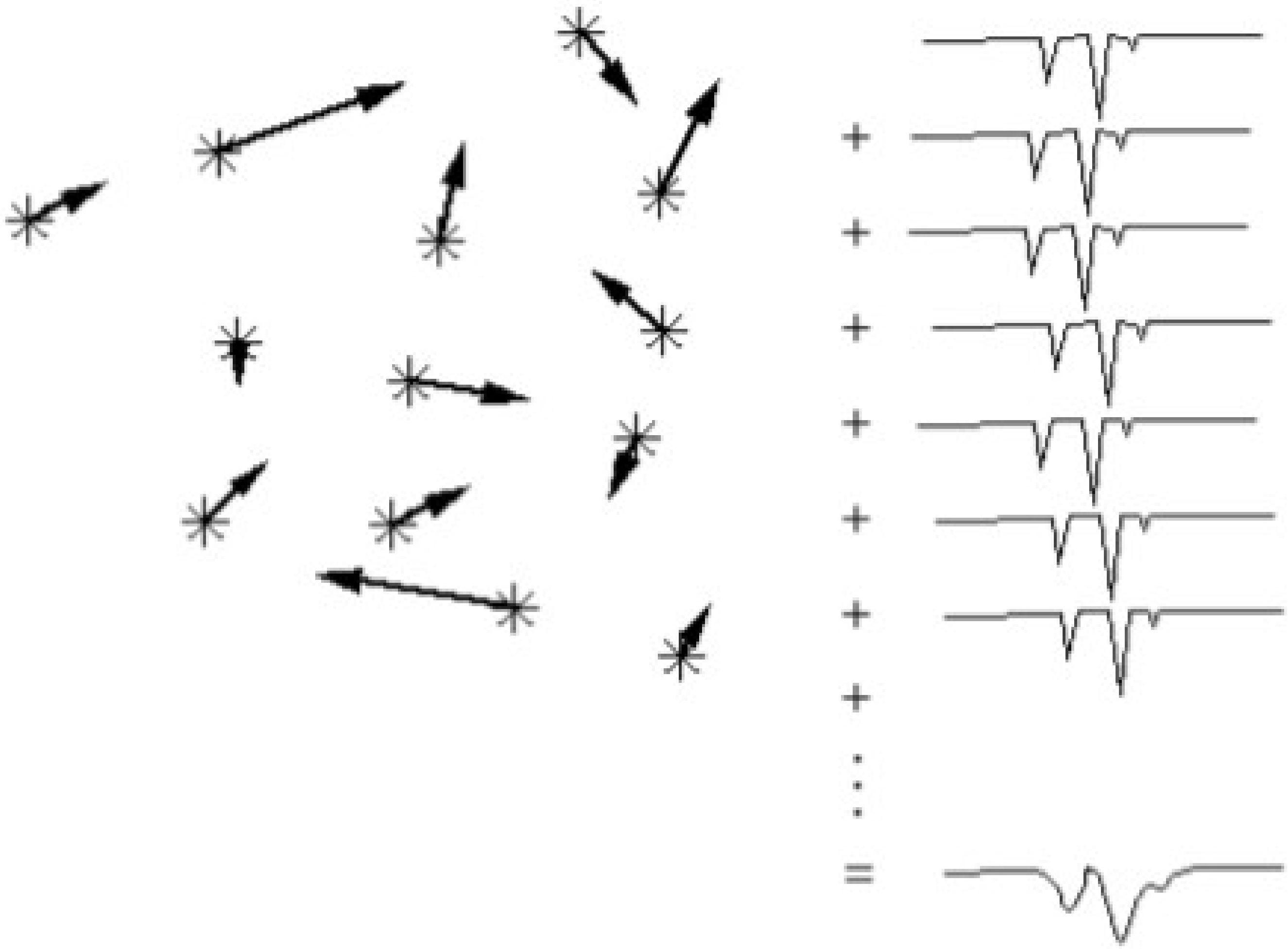

WIYN



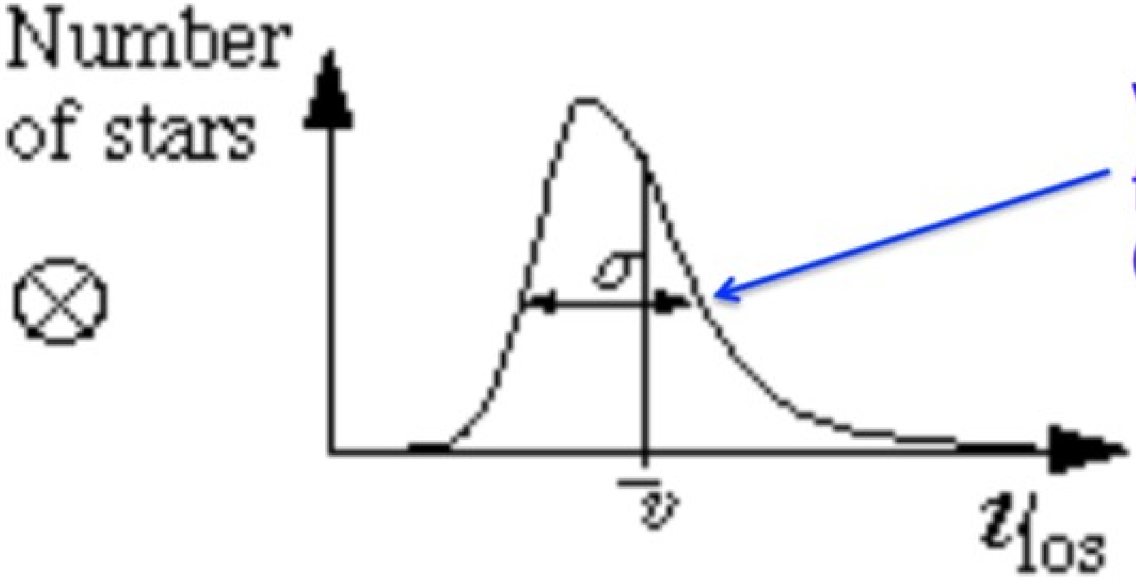
Blue-shifted and red-shifted lines from individual stars in the galaxy blend together to form broadened absorption lines in the galaxy's spectrum.



If the spread in velocities is greater, the blended absorption lines are fatter. This happens for the more massive and luminous galaxies.



LOSVD



Velocity dispersion σ -- fit LOSVD with gaussian
(even if distribution is not gaussian!)

LOS velocities of stars

$$R_{\rm e} \propto \sigma^{1.2} I_{\rm e}^{-0.8}. \tag{6.19}$$

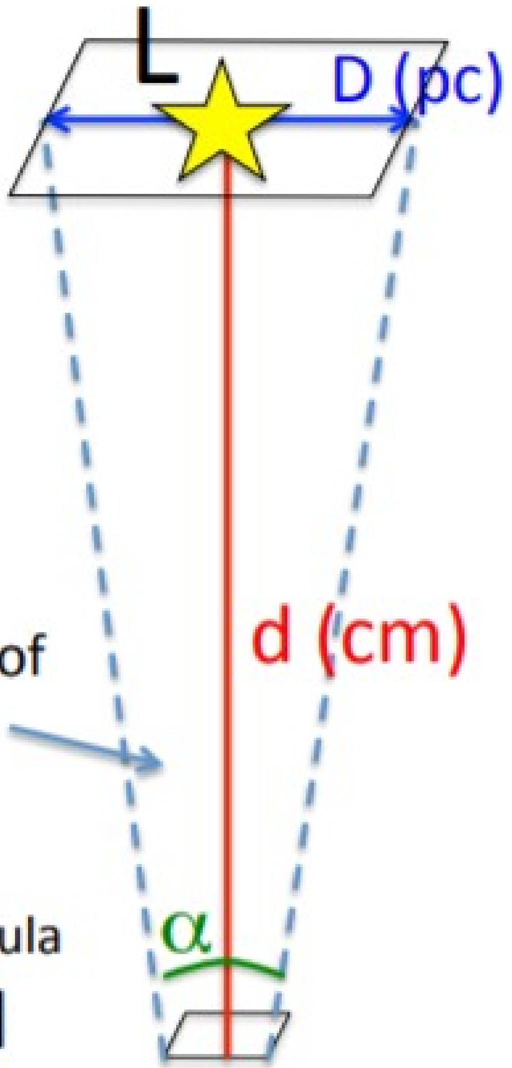
Problem 6.7 Assuming that the velocity dispersion σ and the ratio $\mathcal{M}/L$ are roughly constant throughout the galaxy, and that no dark matter is present, show that the kinetic energy $\mathcal{KE} = 3\mathcal{M}\sigma_{\rm r}^2/2$. Approximating it crudely as a uniform sphere of radius $R_{\rm e}$, we have $\mathcal{PE} = -3G\mathcal{M}^2/(5R_{\rm e})$ from Problem 3.12. Use Equation 3.44, the virial theorem, to show that the mass $\mathcal{M} \approx 5\sigma^2 R_{\rm e}/G$. If all elliptical galaxies could be described by Equation 6.1 with the same value of n, explain why we would then have $\mathcal{M} \propto \sigma^2 R_{\rm e}$ and the luminosity $L \propto I_{\rm e} R_{\rm e}^2$, so that $\mathcal{M}/L \propto \sigma^2/(I_{\rm e} R_{\rm e})$.

(a) Show that, if all ellipticals had the same ratio $\mathcal{M}/L$ and surface brightess $I(R_{\rm e})$, they would follow the Faber–Jackson relation.

(b) Show that Equation 6.19 implies that $I_{\rm e} \propto \sigma^{1.5} R_{\rm e}^{-1.25}$, and hence that $\mathcal{M}/L \propto \sigma^{0.5} R_{\rm e}^{0.25}$ or $\mathcal{M}^{0.25}$: the mass-to-light ratio is larger in big galaxies.

Surface brightness & flux: unresolved sources

unresolved (point) source



beam = angle of sensitivity for detector

small angle formula

$\alpha_{rad} = D/d$

solid angle of square patch

$\Omega = \alpha^2$

detector pixel

If source smaller than beam, detect total flux of source

$$f_{det} = \int_{\Omega_{beam}} I \, d\Omega = \bar{I} \, \Omega_{source} \quad \text{if } \Omega_s \ll \Omega_b$$

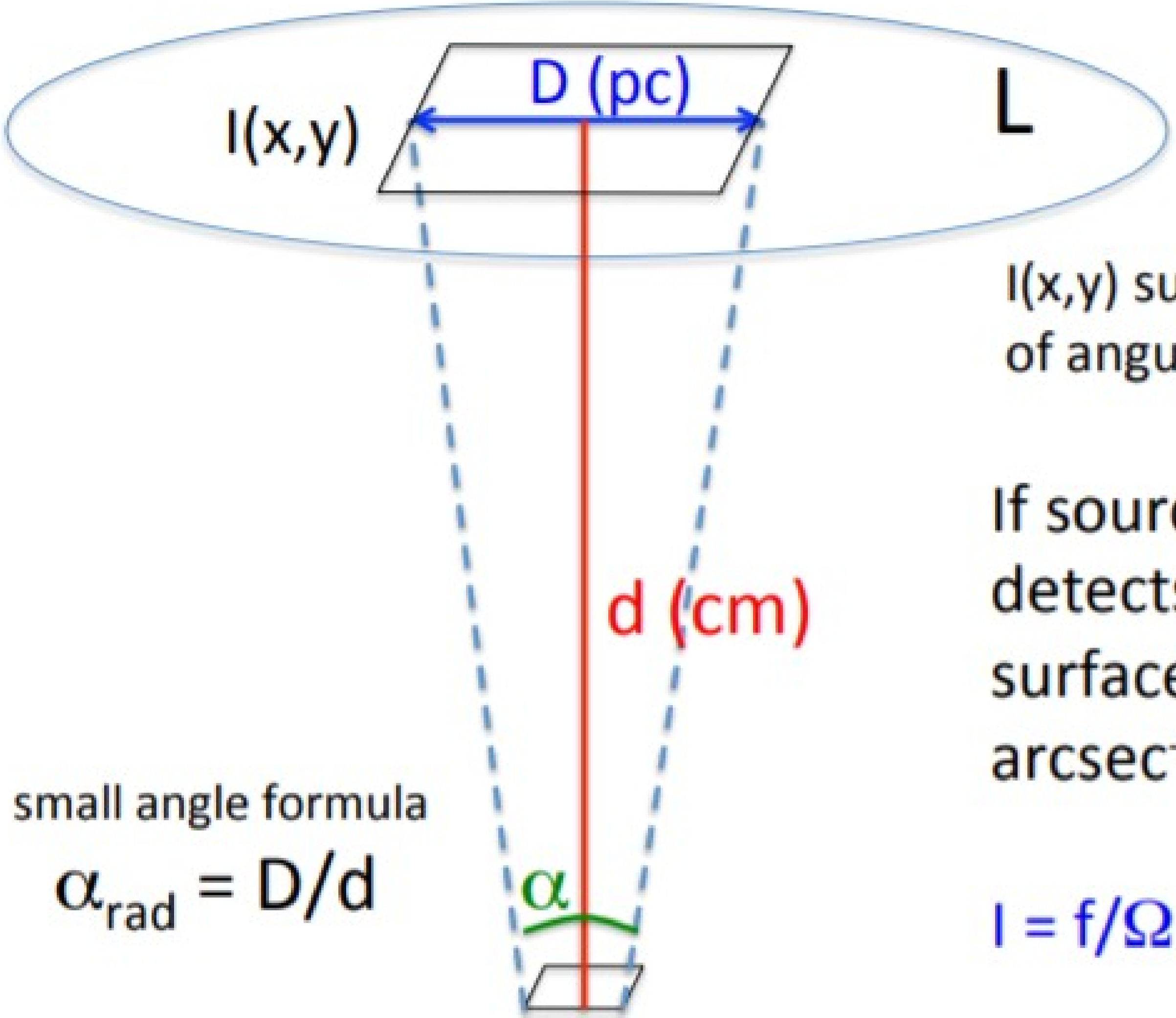
since $I(r) = 0$ for $r > r_s$

$$= f_{tot} = \frac{L}{4\pi d^2}$$

detects all of source flux

Surface brightness & flux: resolved sources

extended source



I(x,y) surface brightness I as a function of of angular coordinates x,y)

If source is resolved, a detector detects the flux per solid angle = surface brightness in erg s^{-1} cm^{-2} $arcsec^{-2}$ (or sr^{-1})

$I = f/\Omega = f/\alpha^2$

small angle formula

$\alpha_{rad} = D/d$

solid angle of square patch

$\Omega = \alpha^2$

detector pixel

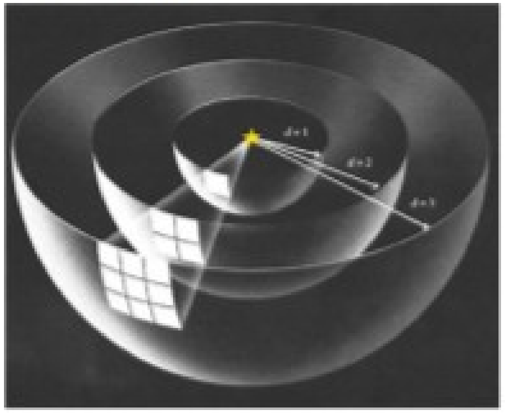
detects **only part** of source flux

Surface brightness is independent of distance!

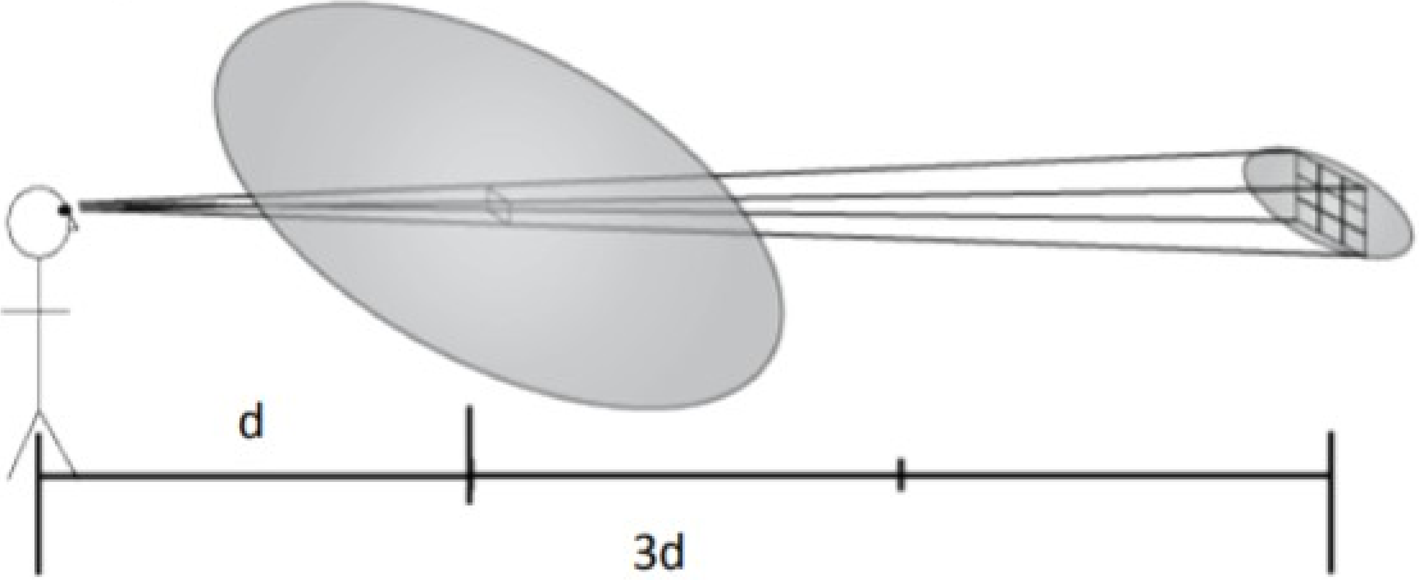
surface brightness = brightness or flux per solid angle

- Less light from each square meter of more distant source

(Inverse square law – B *decreases* by $1/d^2$)



- But more square meters (surface area) of source within same solid angle of observer for more distant source (surface area *increases* by d^2)



Surface brightness is distance independent

- If source is unresolved, a detector detects the flux in erg s^{-1} cm^{-2}
- If source is resolved, a detector detects the flux per solid angle = surface brightness in erg s^{-1} cm^{-2} $arcsec^{-2}$ (or sr^{-1})

$I = f/\Omega = f/\alpha^2$

Recall: angular size of source $\alpha = D/d$

angular area of source (square patch) $\Omega = \alpha^2 = (D/d)^2$

$f = L/4\pi d^2$ d = distance

$I = f/\Omega = (L/4\pi d^2) / (D/d)^2 = L/4\pi D^2$ where D=size of patch on source

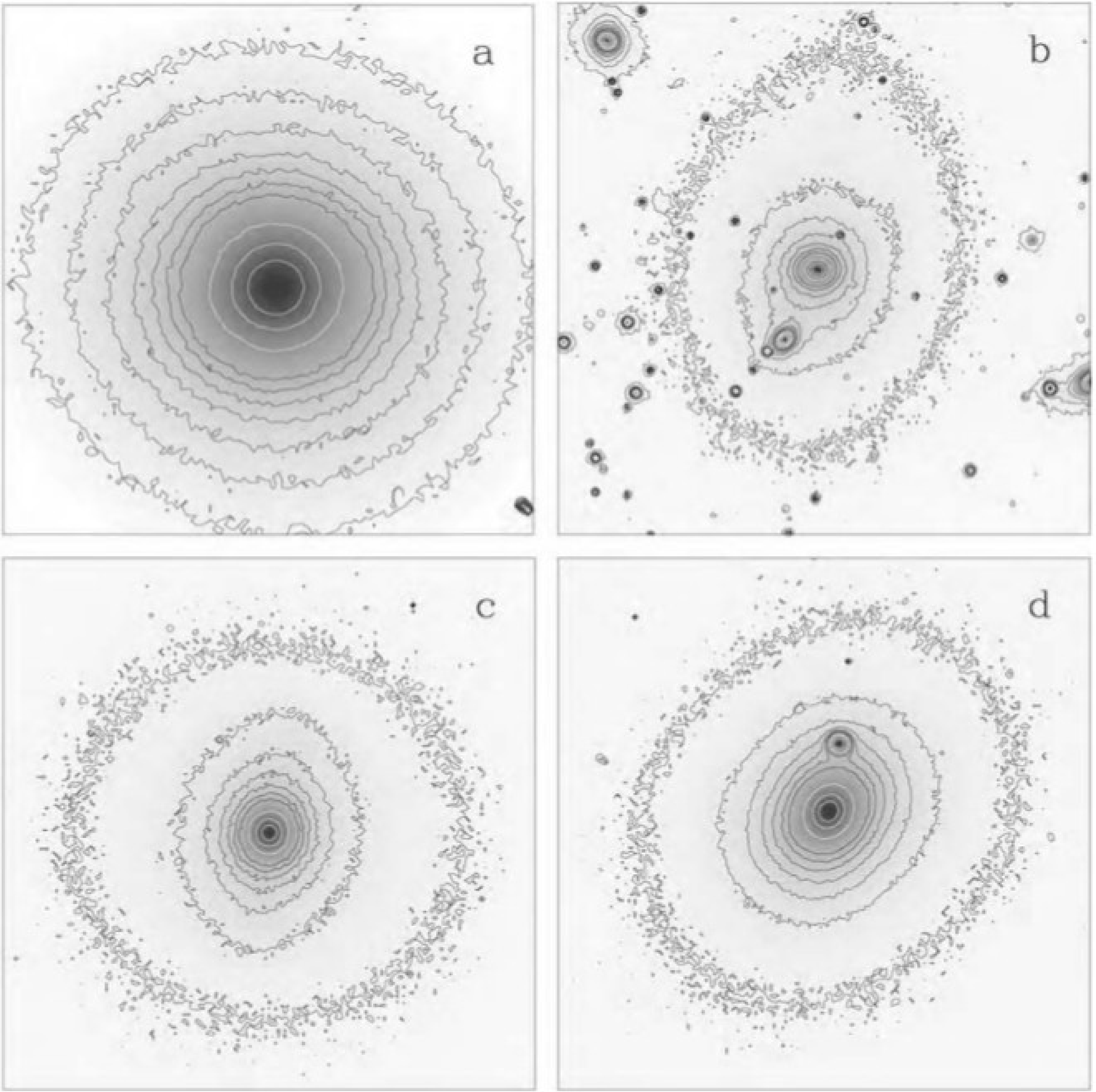
So units of I are L_{sun} pc^{-2} or erg s^{-1} cm^{-2} $arcsec^{-2}$

- Area on source (D^2 in pc^2) depends on distance (d in cm) and angular area ($\Omega = \alpha^2$ in $arcsec^2$); so that's why units of cm^{-2} $arcsec^{-2}$ are equivalent to pc^{-2} in SB
- Luminosity and area of patch in source both increase as d^2 so ratio doesn't depend on d!

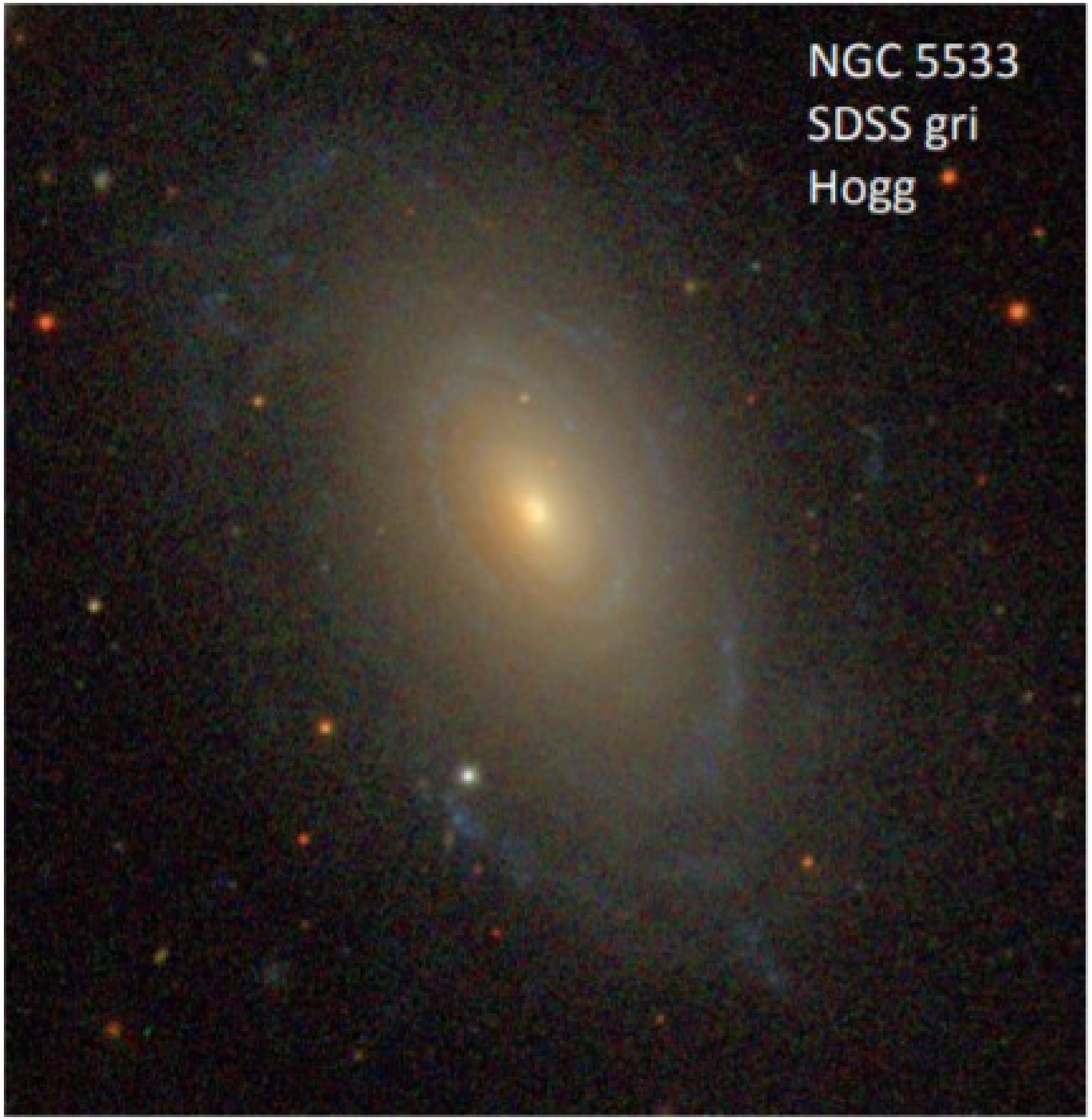
Surface brightness in magnitudes arcsec^{-2}

$$\underset{\substack{\nwarrow\\ \text{SB in}\\ \text{mag arcsec}^{-2}}}{\mu} = -2.5 \log \underset{\substack{\nearrow\\ \text{SB in}\\ \text{erg s}^{-1}\text{ cm}^{-2}\text{ arcsec}^{-2}}}{I} + C$$

- magnitudes arcsec^{-2} are strange units since magnitudes are not linear: if a point in a galaxy has a SB of 21 magnitudes arcsec^{-2} this means an area of 1 square arcsecond around this point emits as much light as a star of apparent magnitude 21.

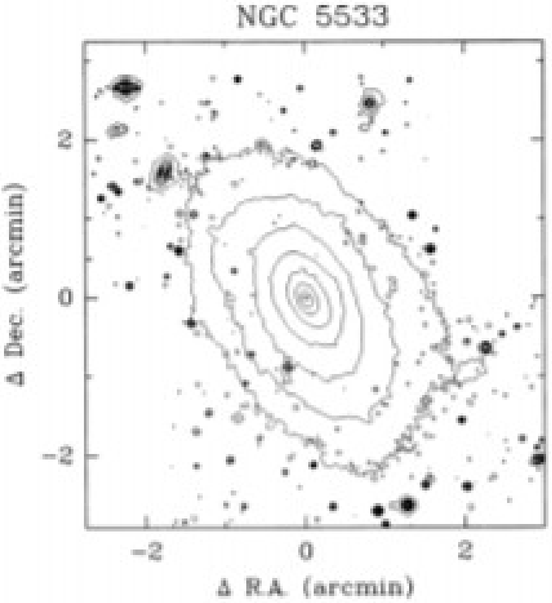

a
b
c
d

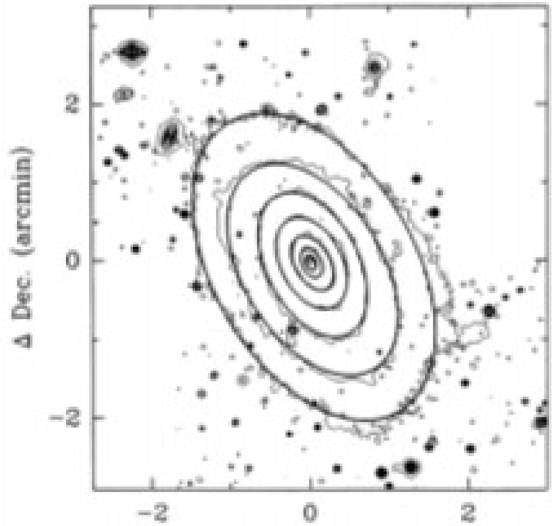
Color optical image of spiral galaxy



Separate images taken in 3 bands: g, r, i
3 images combined to make color image

Isophotes – contours of equal surface brightness





Fit ellipses to isophotes

Problem 6.13 The redshift of NGC 5266 is $cz \approx 3000\,\mathrm{km\,s^{-1}}$; if $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, show that its distance $d \approx 40\,\mathrm{Mpc}$. Use Equation 3.20 to show that the mass $\mathcal{M}(<4') \approx 7 \times 10^{11}\mathcal{M}_\odot$. The total apparent magnitude $B_\mathrm{T}^0 = 12.02$; show that $L_B \approx 4 \times 10^{10}L_\odot$ – this is a big galaxy – so that the mass-to-light ratio $\mathcal{M}/L_B \approx 18$.