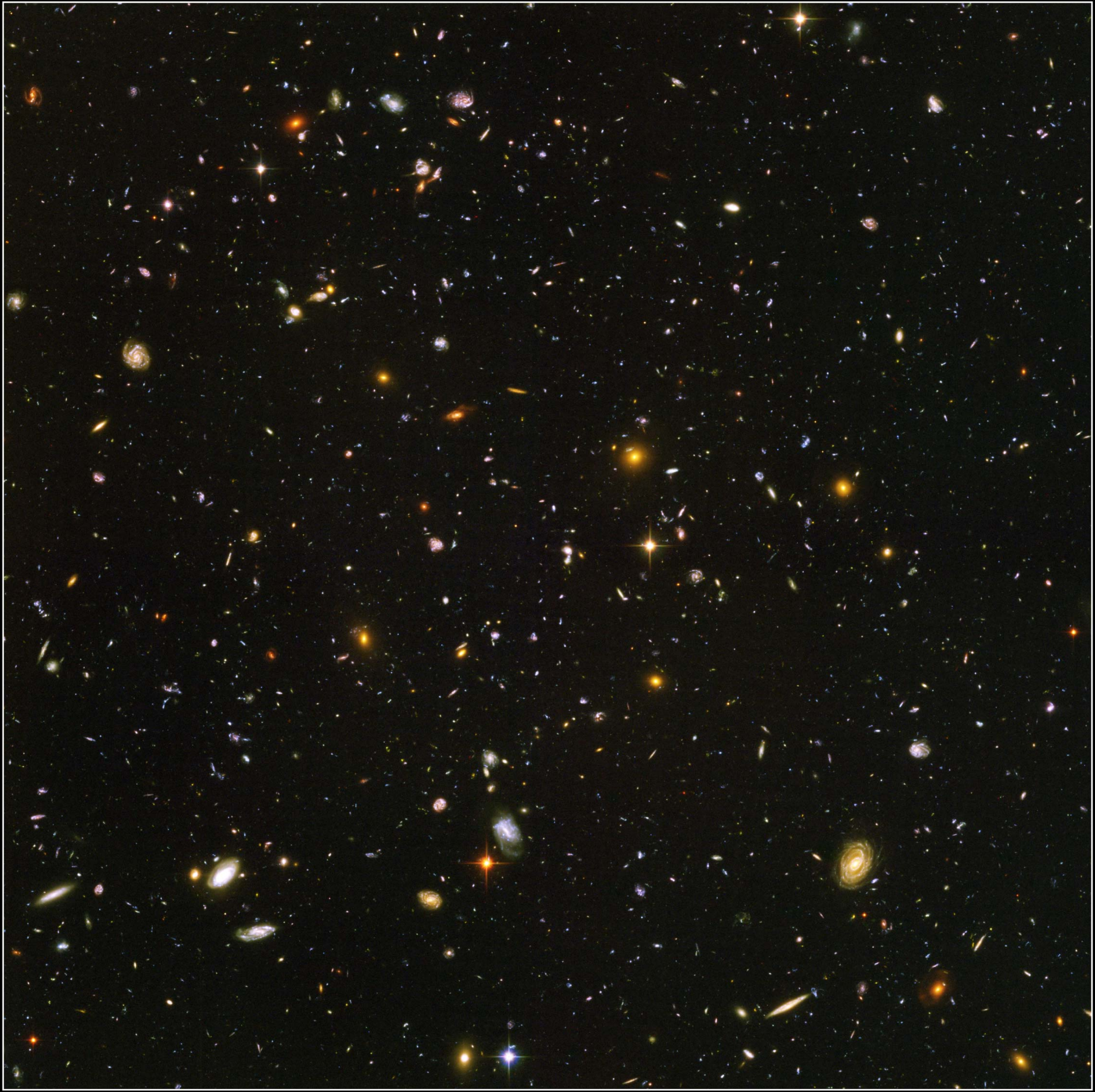


Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

11 days exposure time

10,000 galaxies

3 arcminutes size
(0.1 x diameter of moon)

Estimated number of galaxies in observable universe: ~200 billion

Galaxies with disks

Sombrero Galaxy • M104

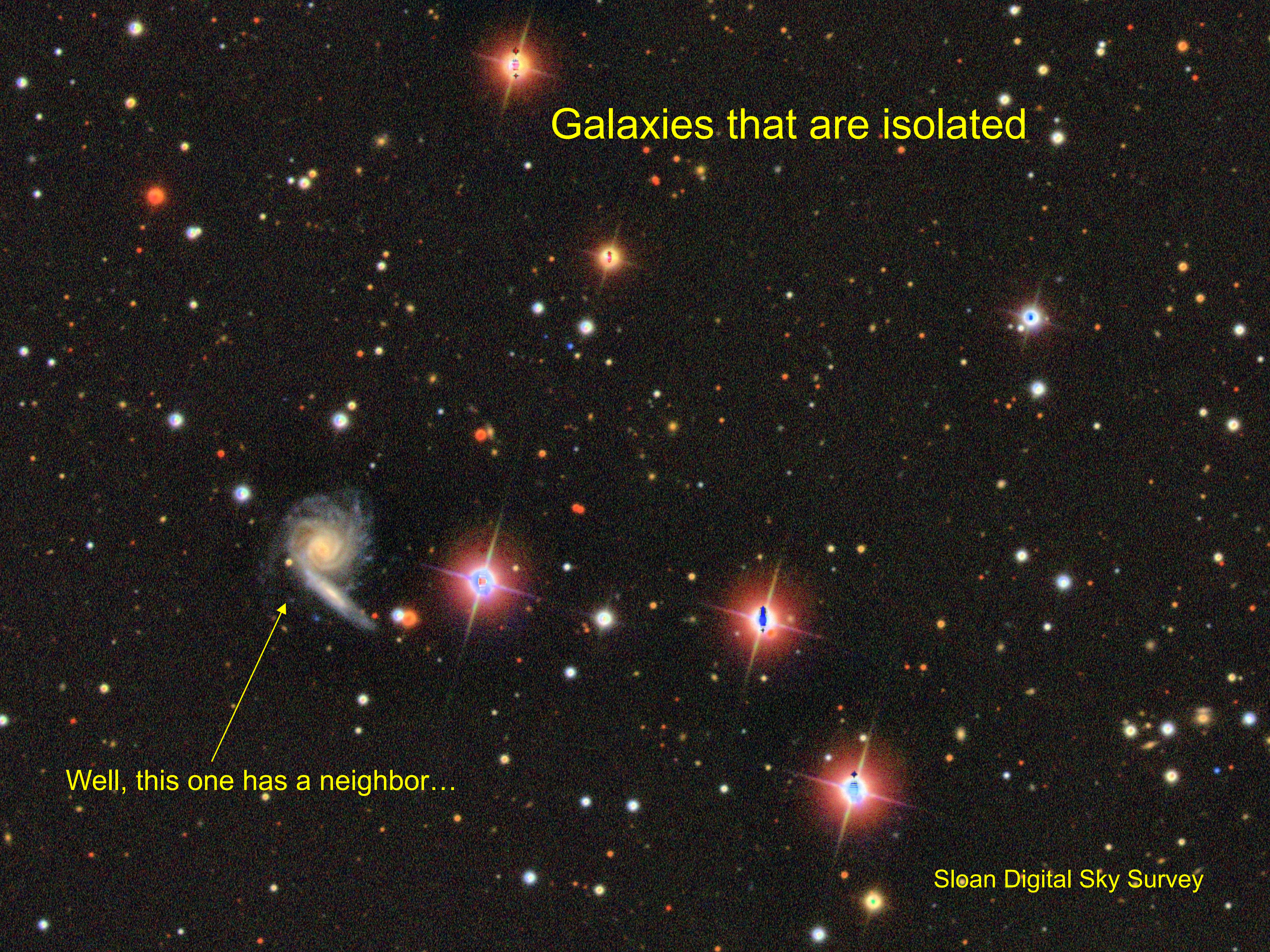
Hubble Heritage

NASA and The Hubble Heritage Team (AURA/STScI) • Hubble Space Telescope ACS • STScI-PRC03-28

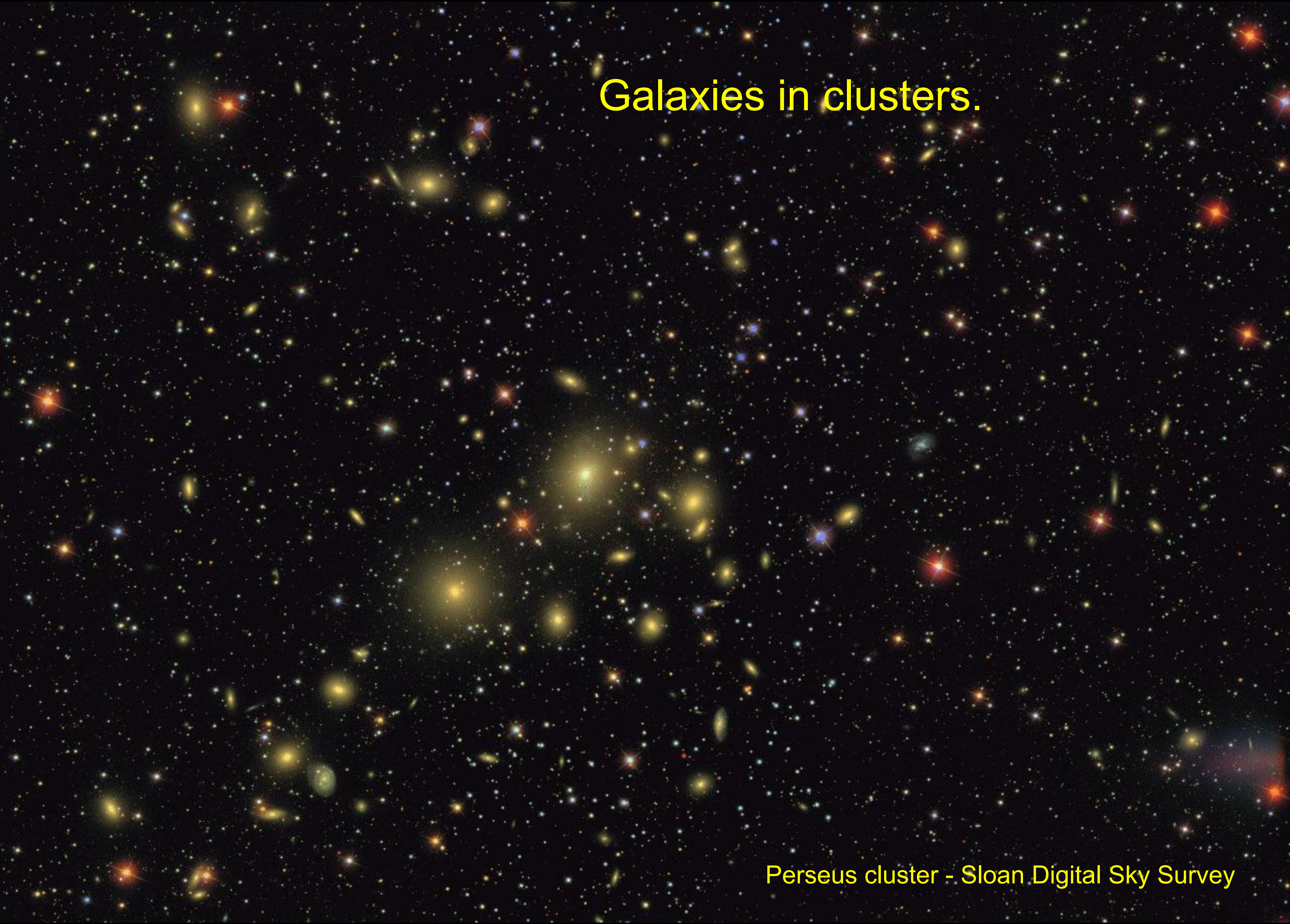
Clumpy spiral shapes

Smooth elliptical galaxies.

M87 © Anglo-Australian Observatory
Photo by David Malin


Galaxies that are isolated
Well, this one has a neighbor…
Sloan Digital Sky Survey

Galaxies in clusters.

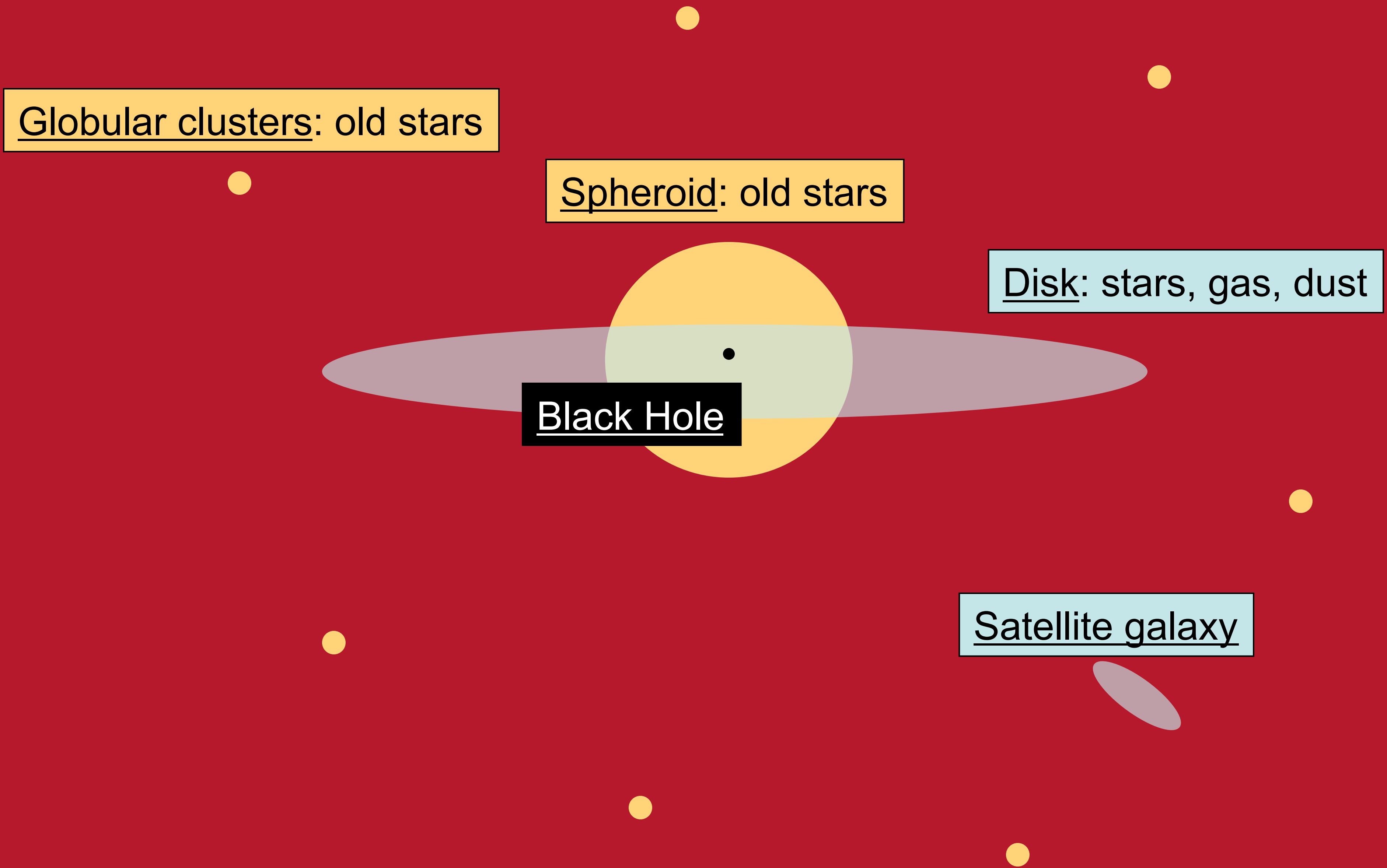


Perseus cluster - Sloan Digital Sky Survey

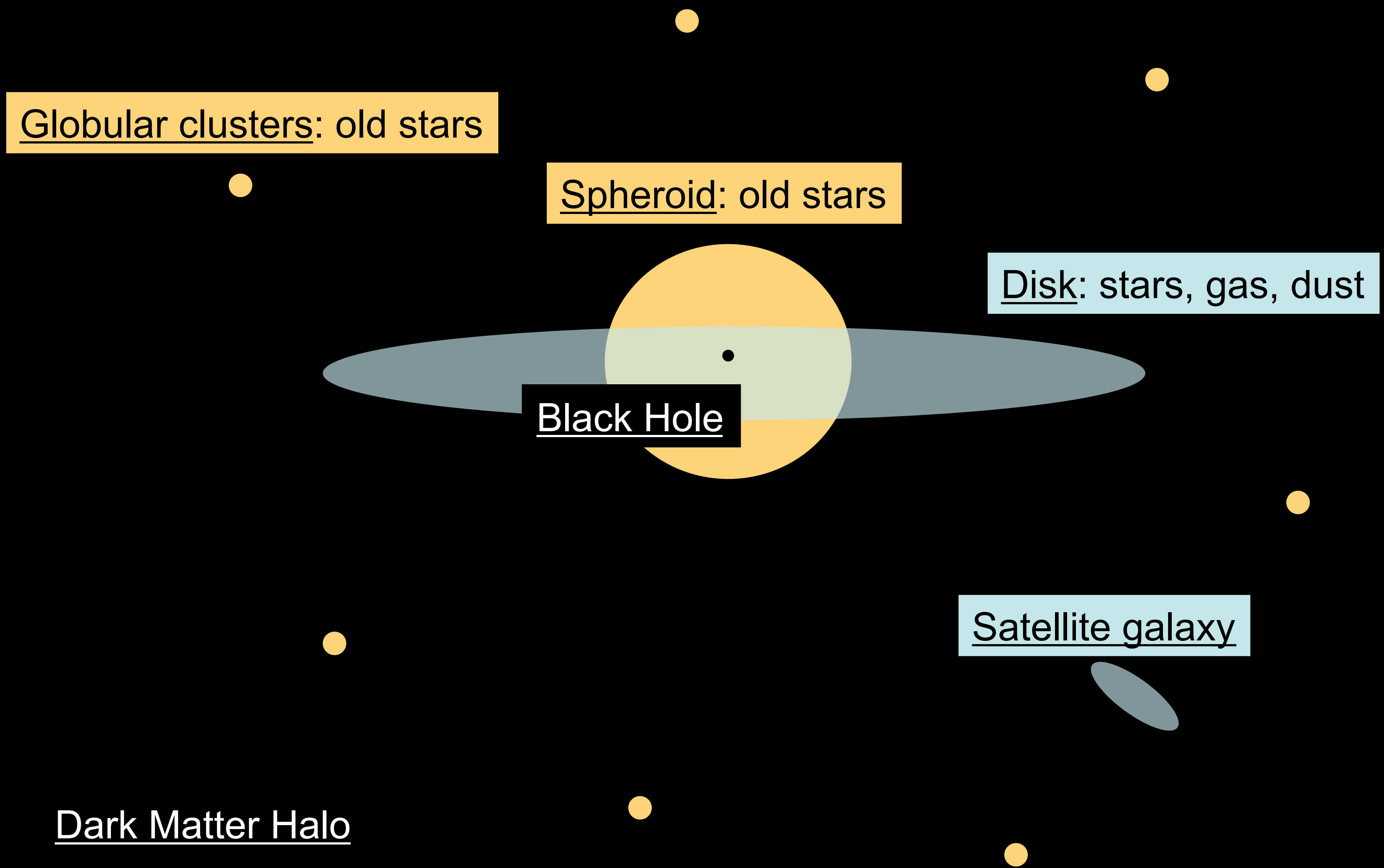
Galaxies that are weird.

Antennae galaxies – OSU Bright galaxy survey

Anatomy of a galaxy



Anatomy of a galaxy



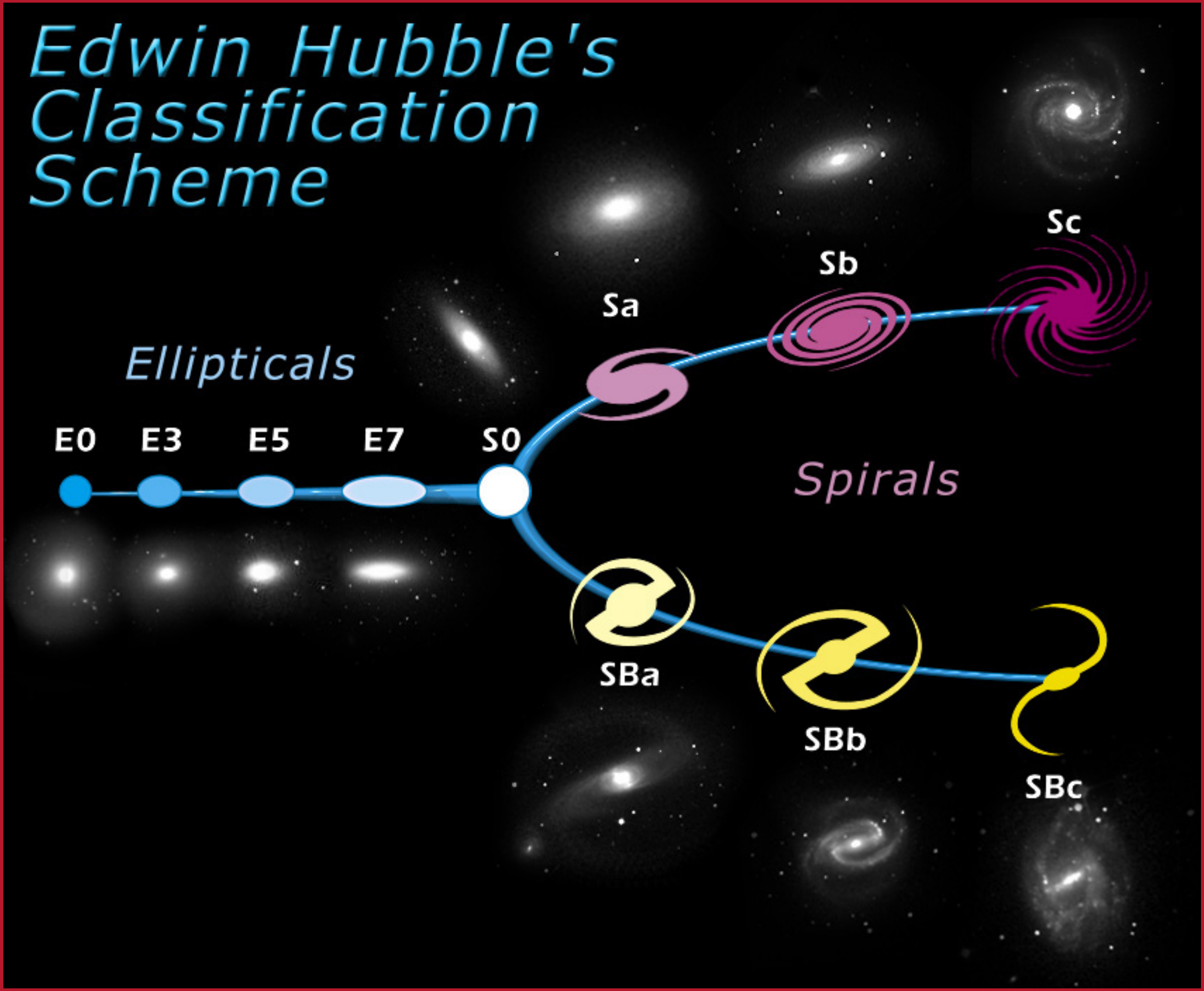
Very generally, there are two types of galaxies that we see:

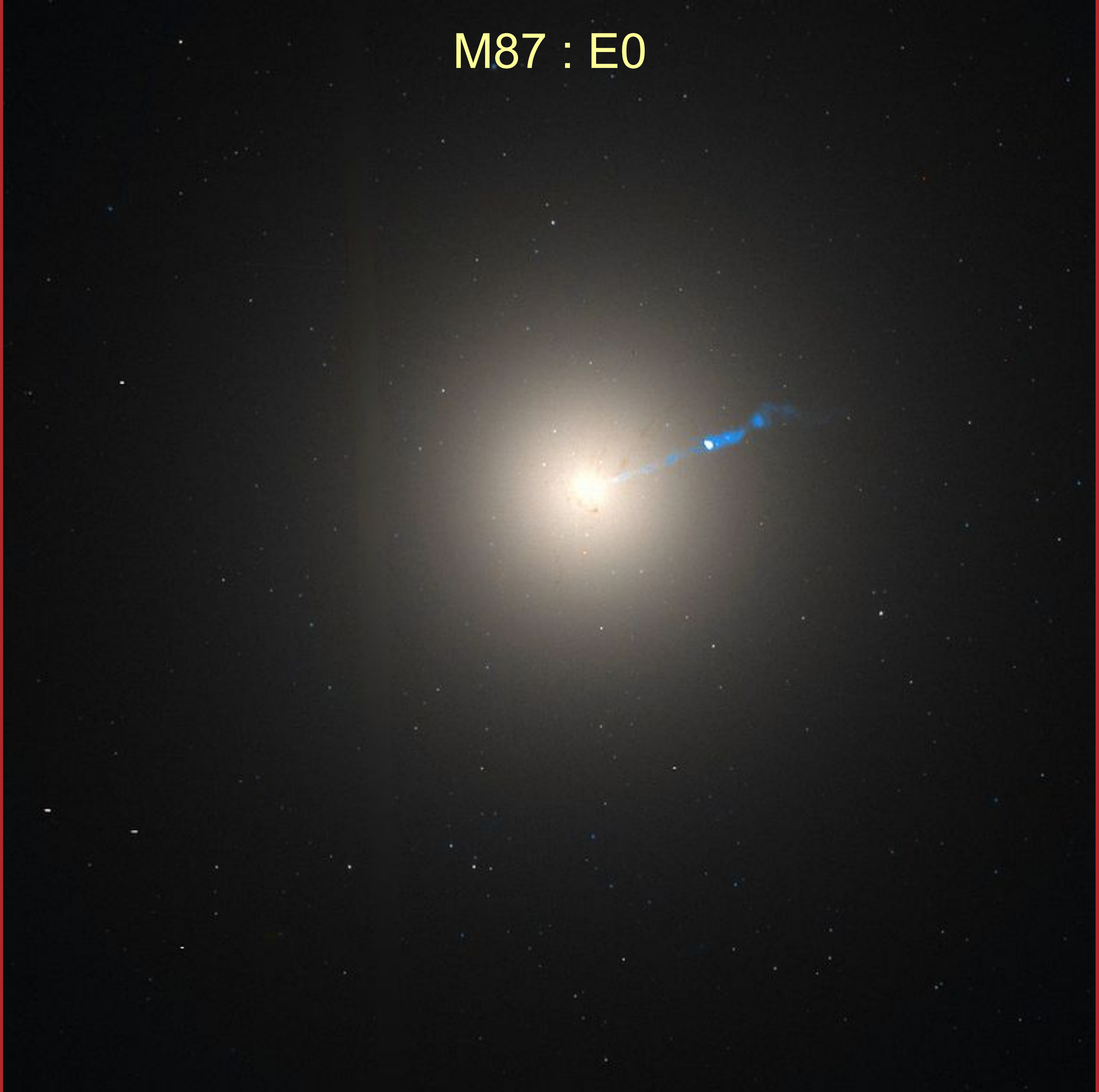
Spiral/disk galaxies:

- have a disk-like structure
- are blue-ish in color
- tend to be isolated

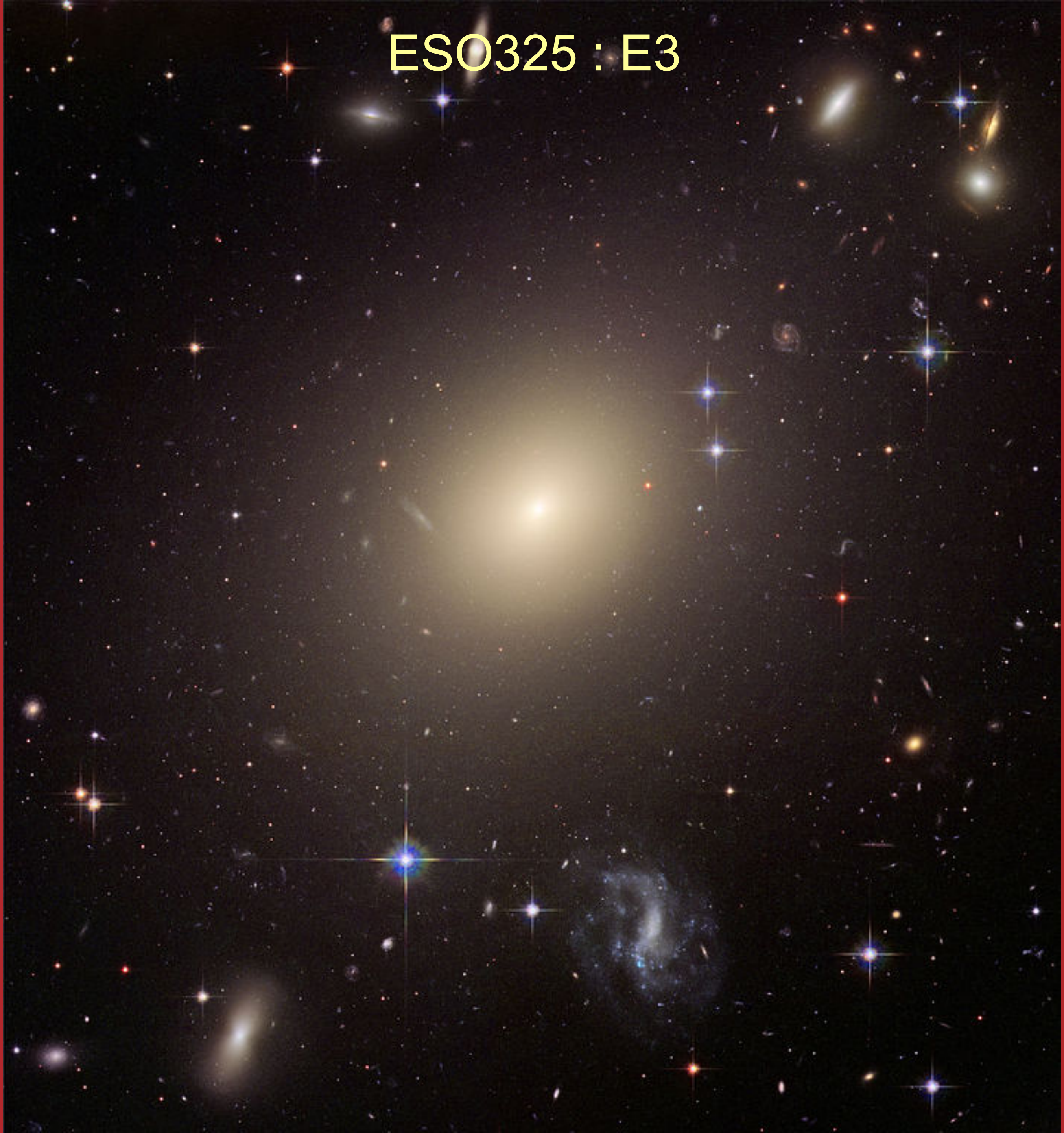
Elliptical galaxies:

- have no disk
- are red-ish in color
- tend to be located in clusters


Edwin Hubble's
Classification
Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

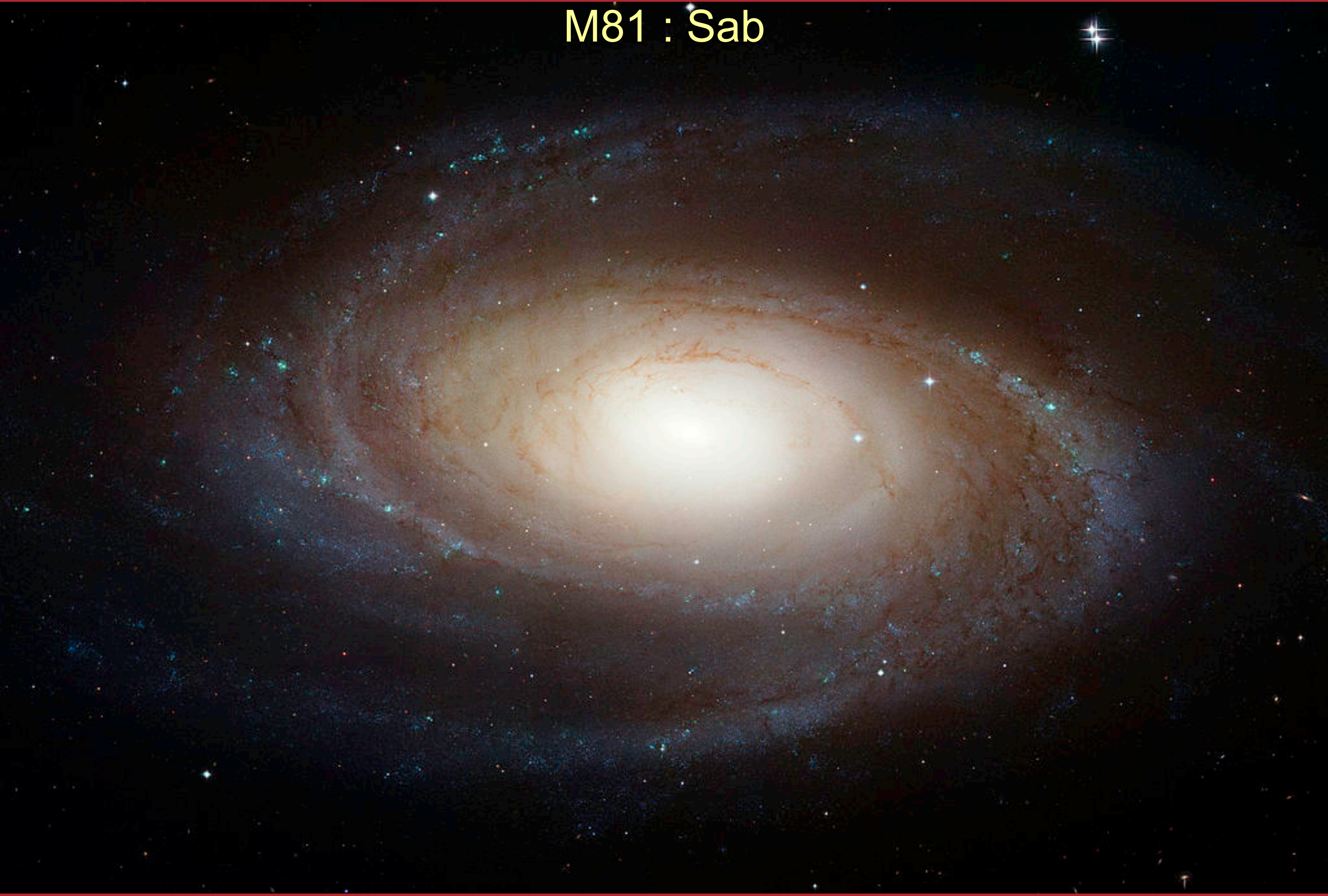

M87 : E0

ESO325 : E3



NGC5866 : S0

M81 : Sab



M101 : Scd

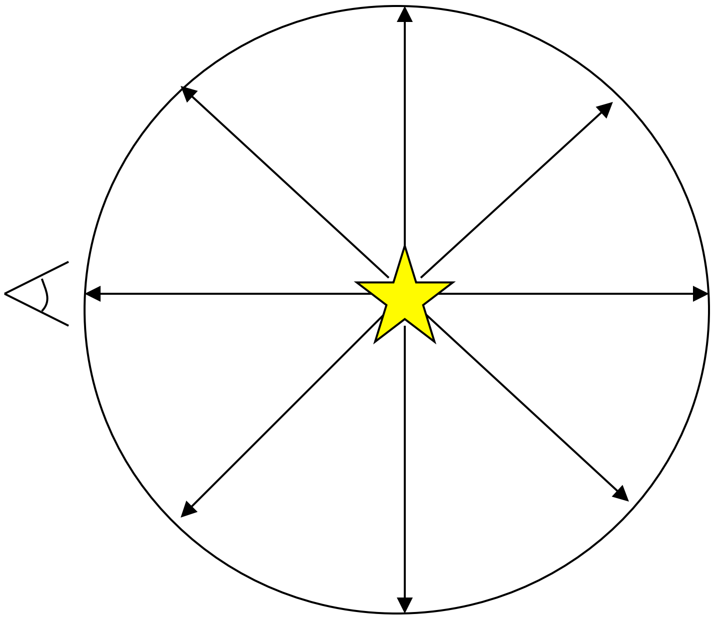
NGC1300 : SBbc

Luminosity and flux

Luminosity	L : energy/time (erg/s)
Flux	f : luminosity/area (erg/s/cm^2)

Inverse square law:

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



Surface brightness

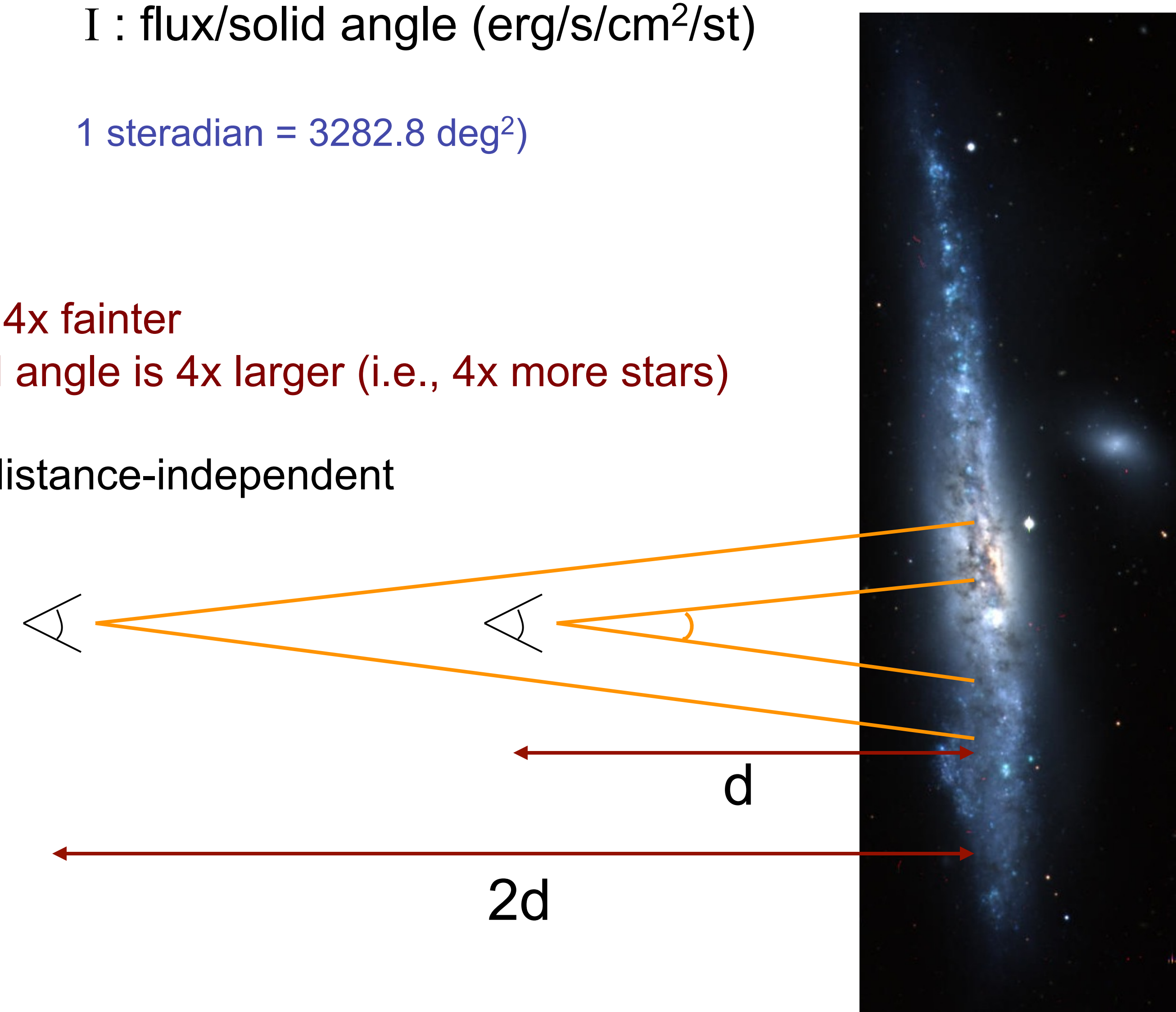
Surface brightness   I : flux/solid angle (erg/s/cm^2/st)

(4π steradians on the sky   1 steradian = 3282.8 deg^2)

At twice the distance:

- flux from each star is 4x fainter
- area covered by solid angle is 4x larger (i.e., 4x more stars)

Surface brightness is distance-independent



Apparent magnitude

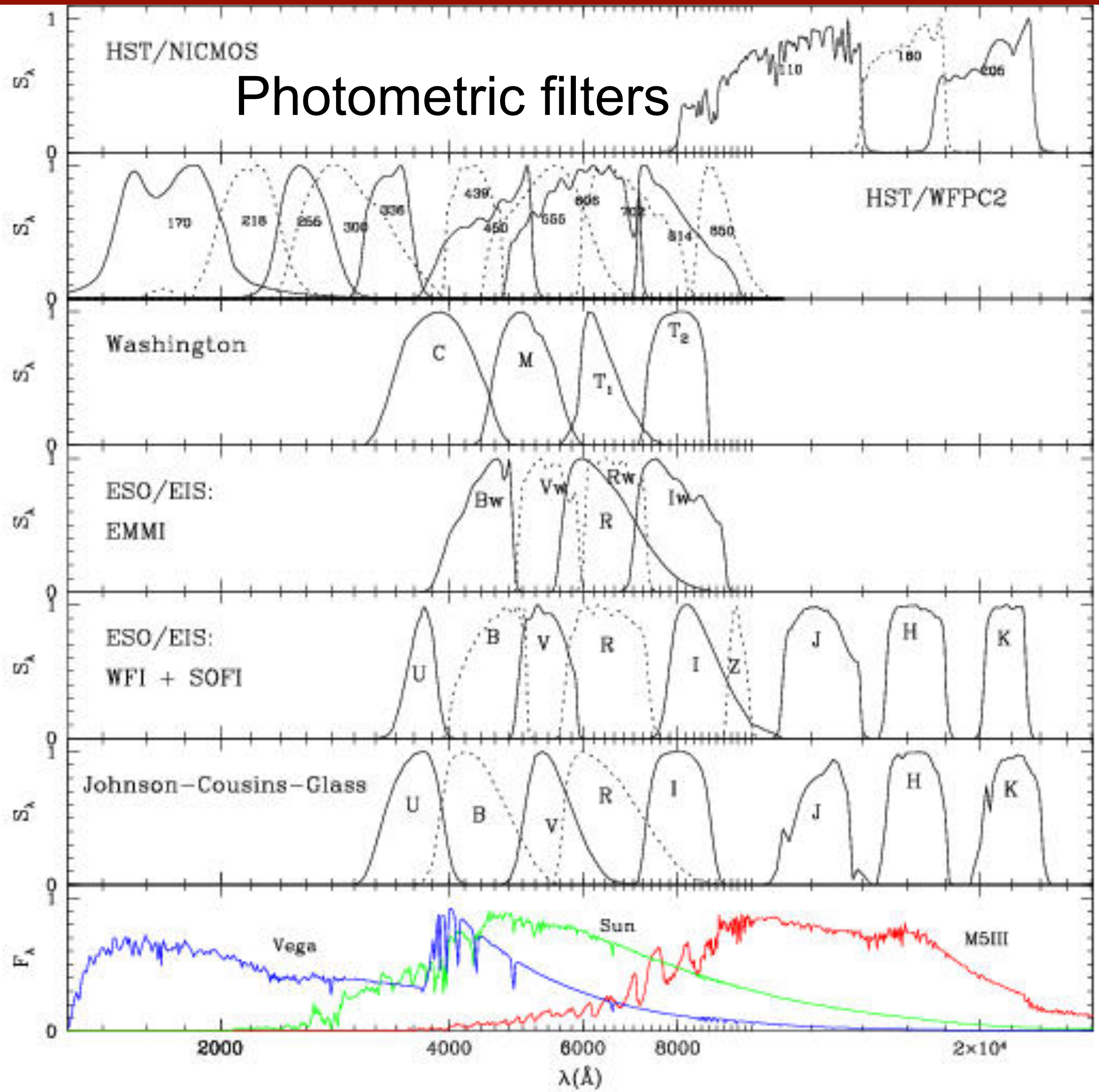
$$m = -2.5 \log f + const$$

A star that is 5 magnitudes brighter (smaller m) has 100x the flux.

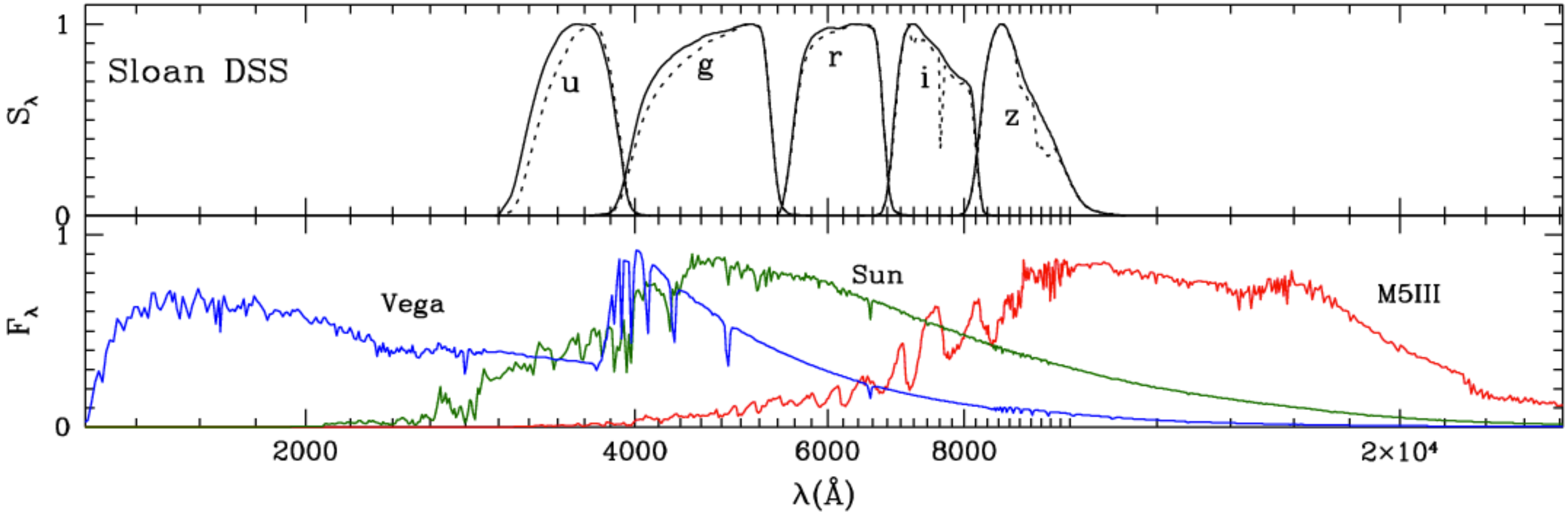
$$m_1 - m_2 = -2.5 \log\left(f_1 / f_2\right)$$

$$\frac{f_1}{f_2} = 10^{\left(m_2 - m_1\right)/2.5}$$

Basic Astronomical Measurements



Sloan Digital Sky Survey (SDSS) filters



Absolute magnitude

M = apparent magnitude the star would have if it were 10pc away.

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

$$f_{10} = \frac{L}{4\pi (10\,pc)^2}$$

$$m - M = 5\log\left(\frac{d}{10\,pc}\right)$$

distance modulus

For example, the distance modulus for M31 is about 24.5

Color

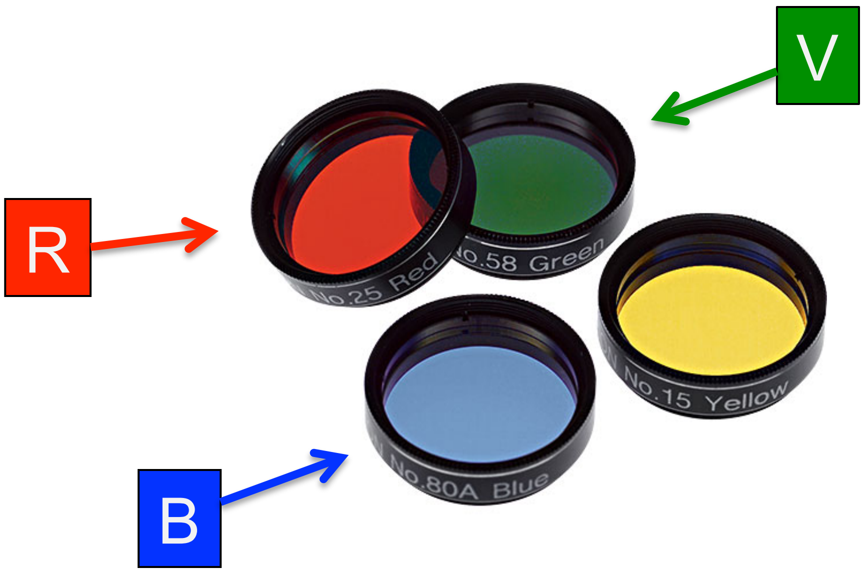
Color = crude, low resolution, estimate of spectral shape

$$B - V = m_B - m_V = M_B - M_V = -2.5\log\left(\frac{f_B}{f_V}\right)$$

- distance independent
- indicator of surface temperature
- by definition, B-V=0 for Vega (T~9500K)

Color

- Measure a star's brightness through two different filters

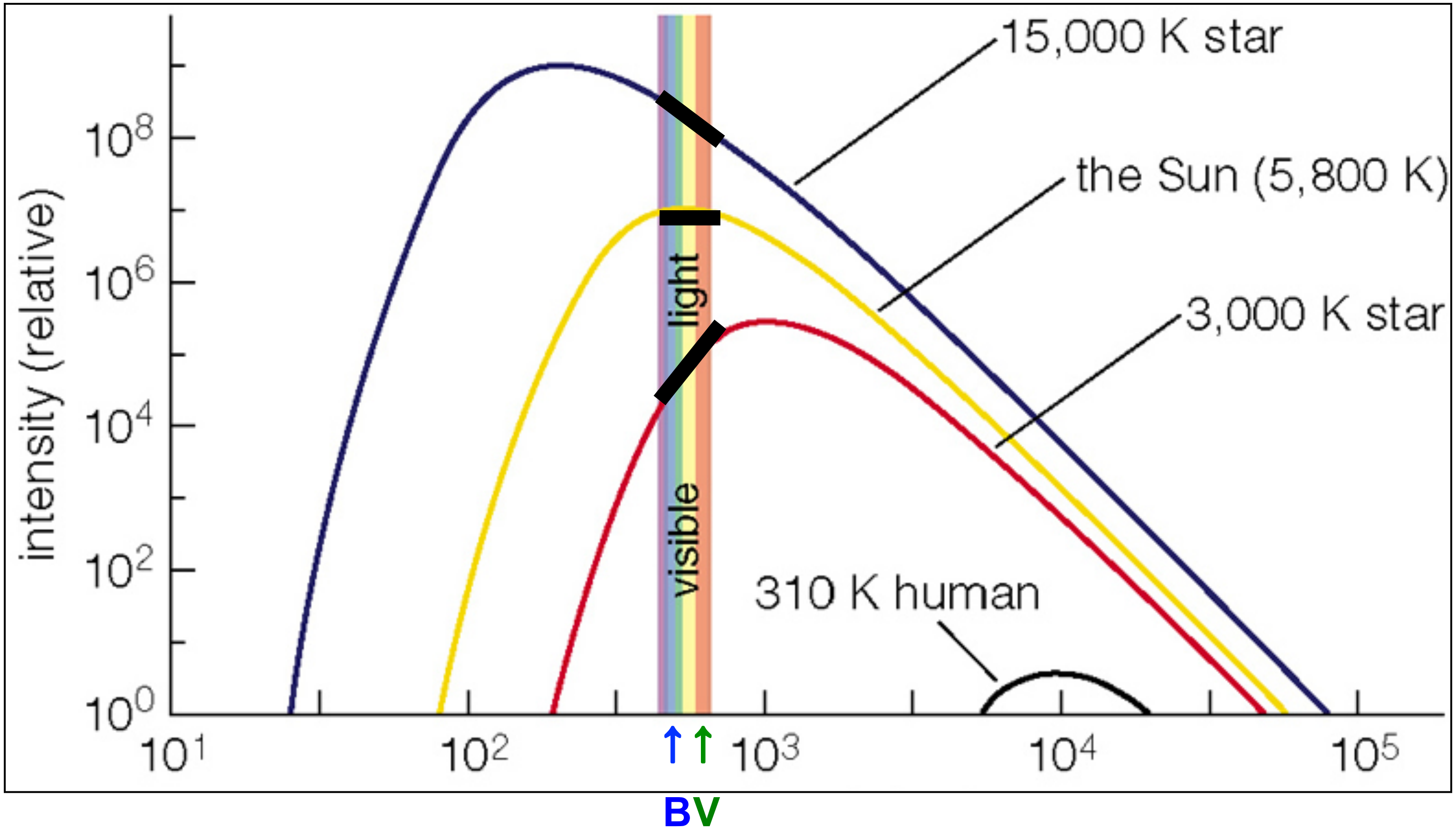


- Take the ratio of brightness: (redder filter)/(bluer filter)

  if ratio is large → red star
  if ratio is small → blue star

e.g., **V**/**B**

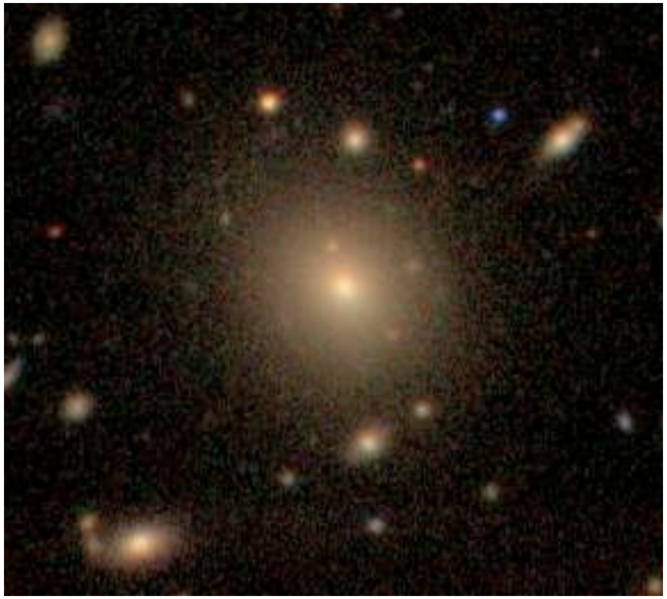
Color



The color of a star measured like this tells us its temperature!

Stellar Populations

- The light from a galaxy is mostly emitted by stars
- The spectro-photometric properties of a galaxy (brightness, color, spectrum, etc.) are therefore just a sum of the properties of all its stars.



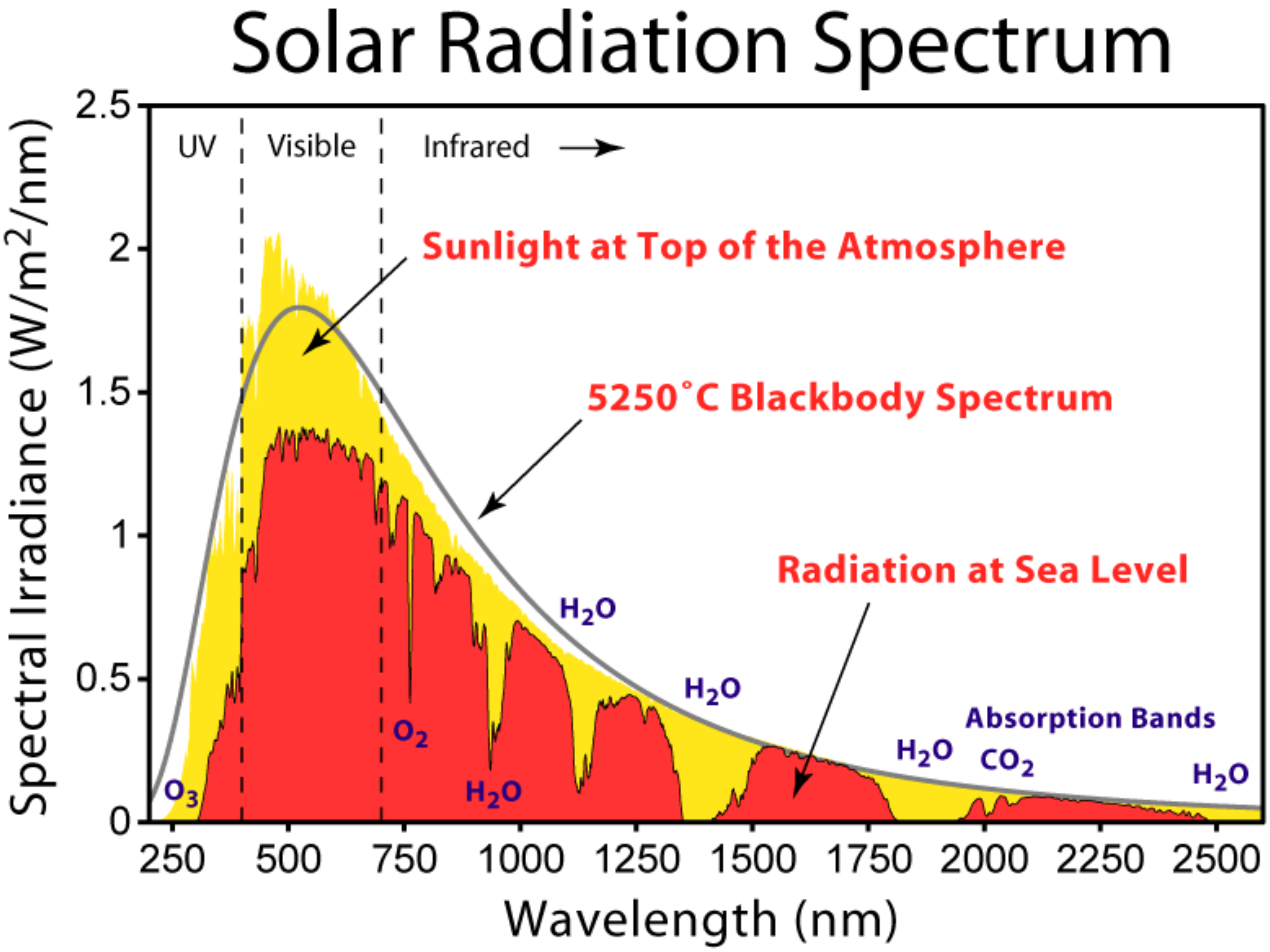
Stellar spectra

The solar spectrum can be approximated as

- a blackbody

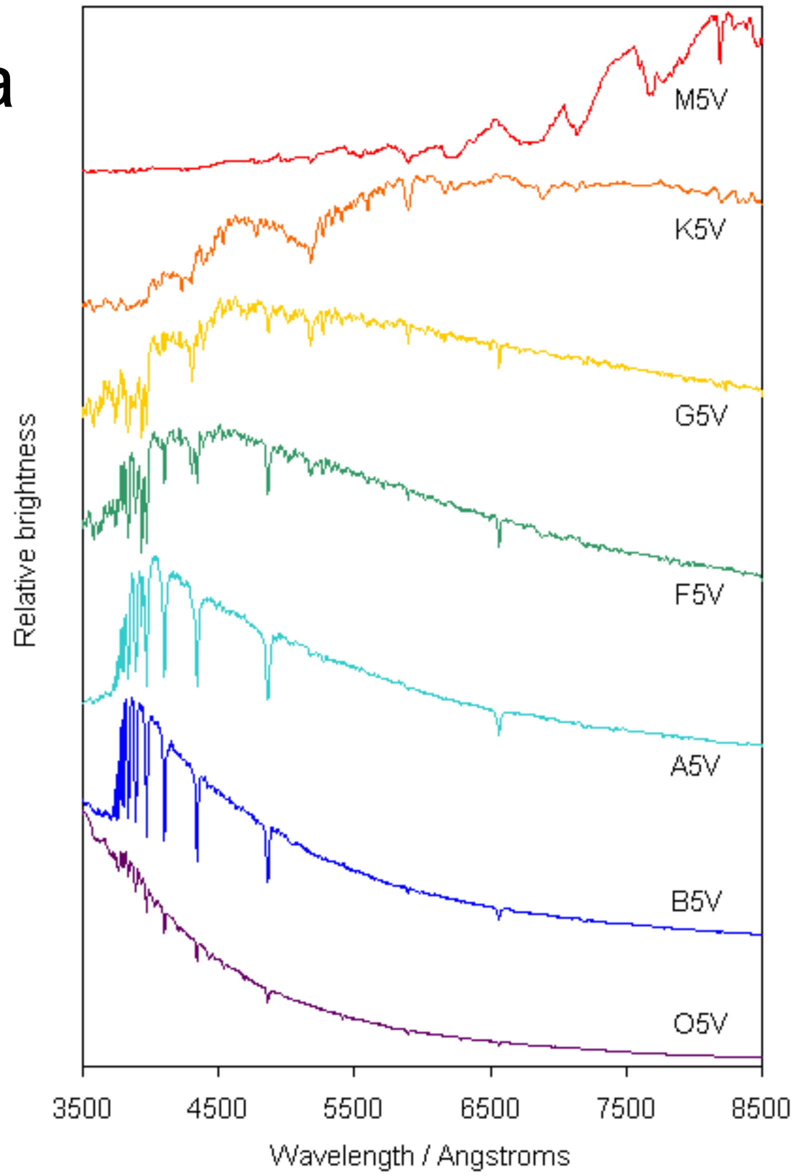
+

- absorption lines (looking at hotter layers through cooler outer layers)


Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250˚C Blackbody Spectrum
Radiation at Sea Level
H₂O
H₂O
O₂
H₂O
O₃
H₂O
Absorption Bands
CO₂
H₂O
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

Stellar Populations

Stellar Spectra



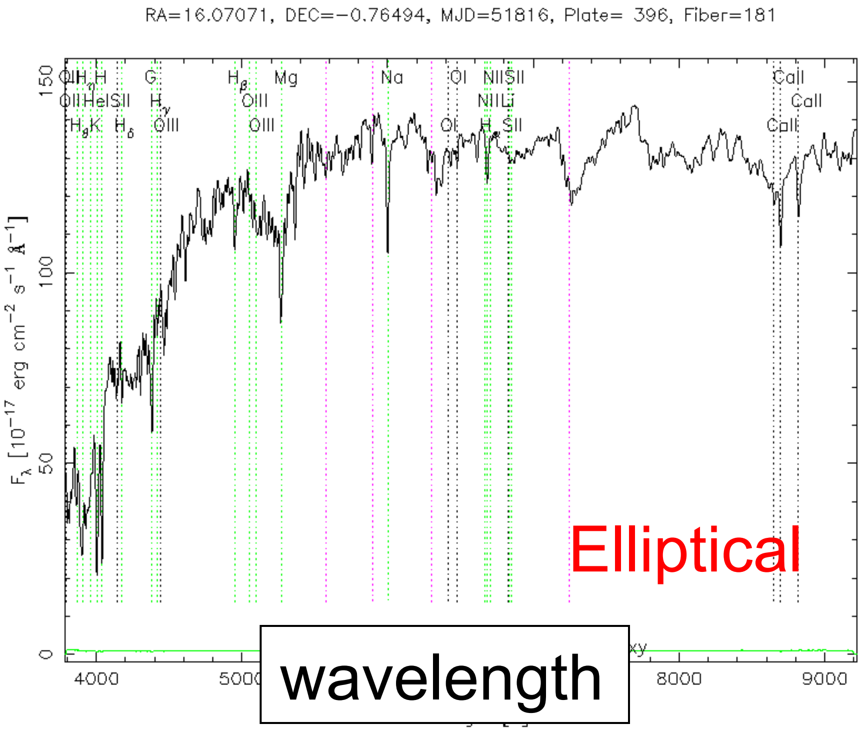
cool

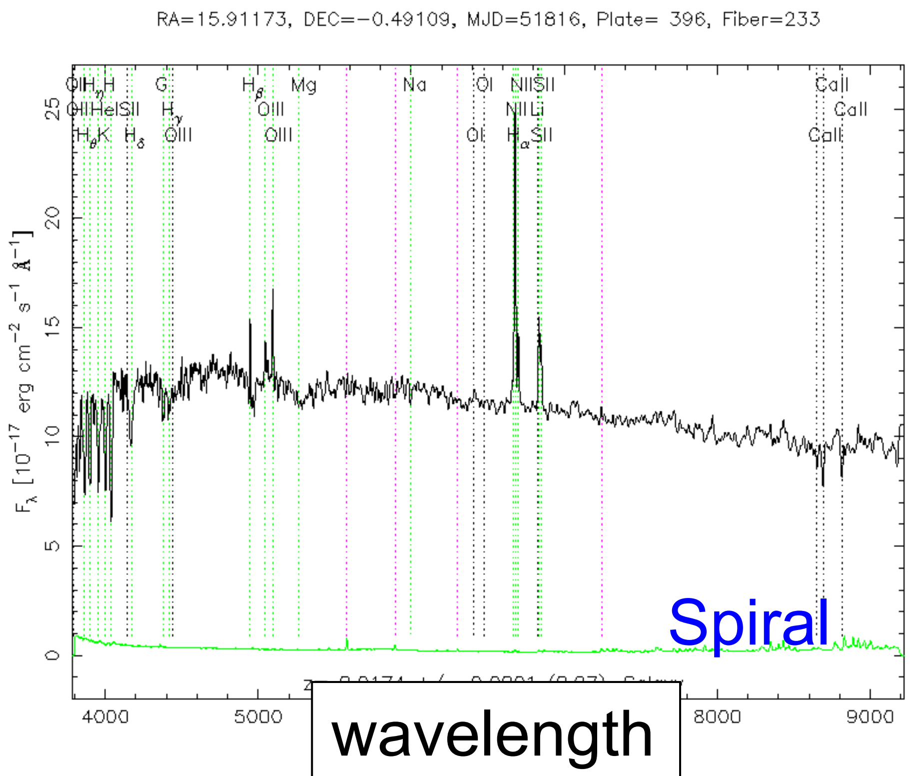
hot

Stellar Populations

Galaxy Spectra

Which one is an Elliptical and which is a Spiral?





Stellar Populations

B stars:

M ~ 6 M_{sun}

L ~ 1000 L_{sun}

t ~ 0.1 Gyr

A stars:

M ~ 2 M_{sun}

L ~ 10 L_{sun}

t ~ 1 Gyr

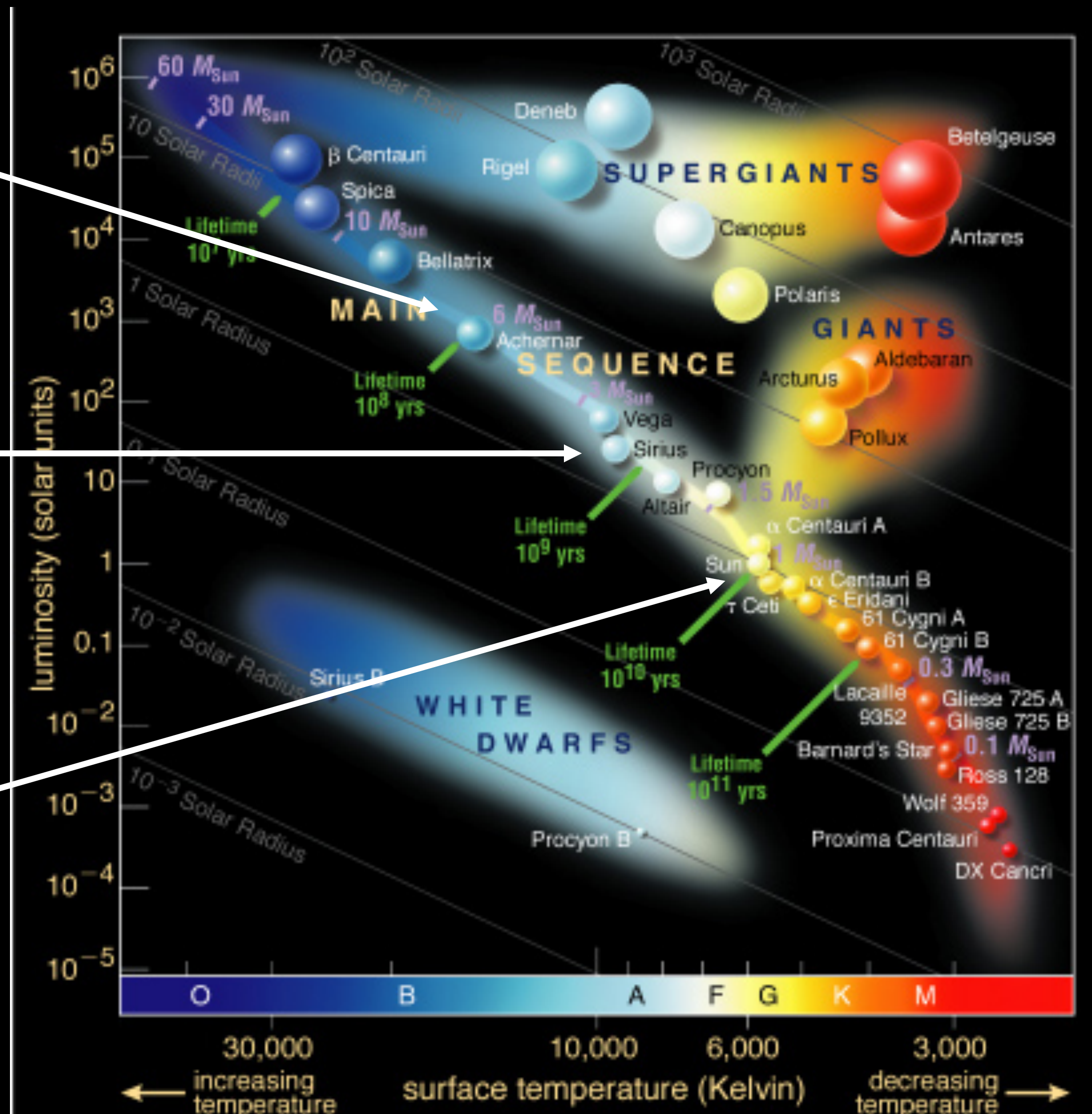
G stars:

M ~ 1 M_{sun}

L ~ L_{sun}

t ~ 10 Gyr

Hertzsprung - Russell Diagram



Stellar Populations

- Luminosity-mass relation

$$L \approx L_{\odot} \left(\frac{M}{M_{\odot}} \right)^{3.5}$$

- Lifetime on the Main Sequence

$$t \approx \frac{f \varepsilon M c^2}{L}$$

$\varepsilon = 0.07\%$ 4H ➔ He

$f \sim 0.1$ Fraction of total mass in core

$$t \approx 10\mathrm{Gyr} \left(\frac{M}{M_{\odot}} \right)^{-2.5}$$

$10\mathrm{Gyr}$	$1M_{\odot}$
$1\mathrm{Gyr}$	$2.5M_{\odot}$
$0.1\mathrm{Gyr}$	$6.3M_{\odot}$

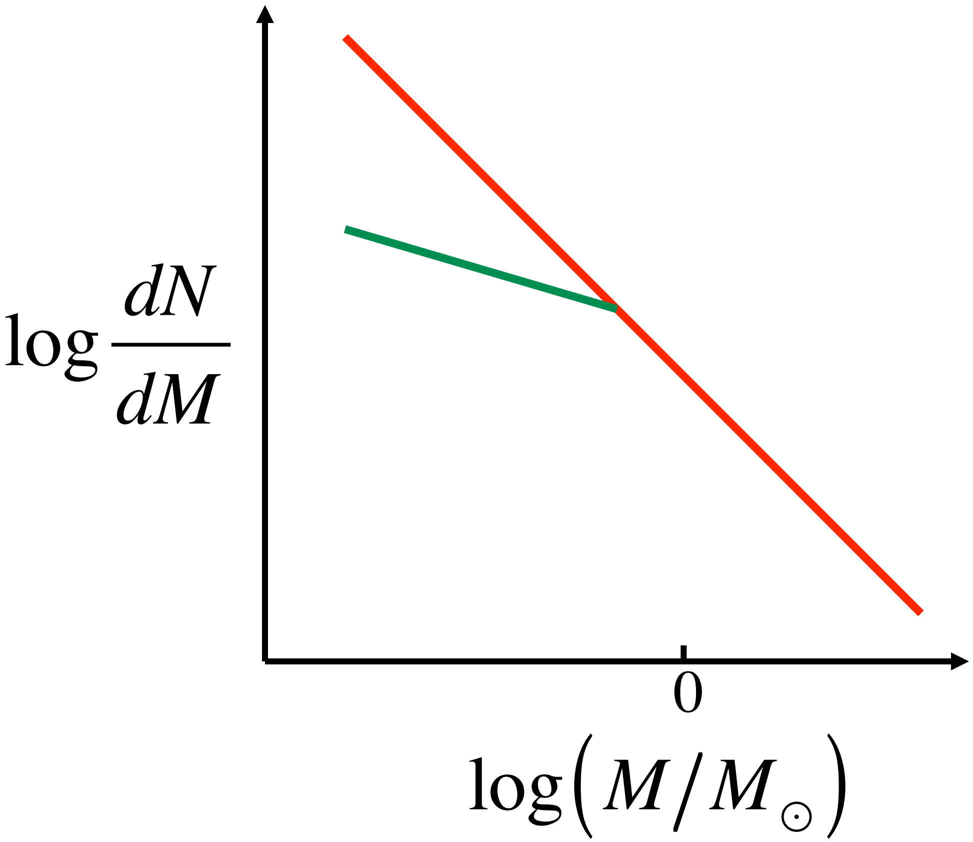
Stellar Populations

- Initial mass function

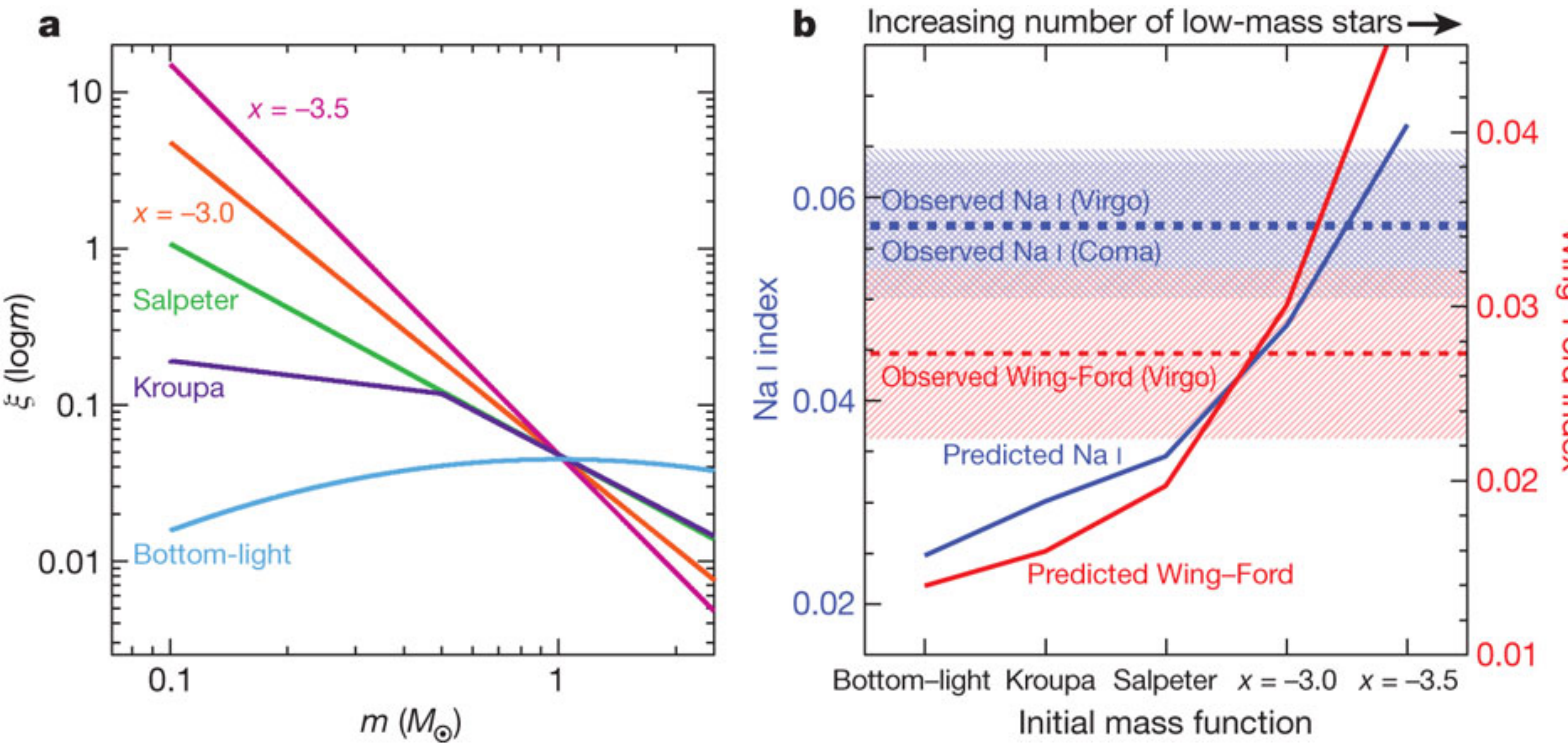
$$\frac{dN}{dM} = \text{const} \times M^{-\alpha}$$

Salpeter: α=2.35

Scalo , Kroupa: flattens below $1M_{sun}$



Stellar Populations



Van Dokkum & Conroy (2010)

Stellar Populations

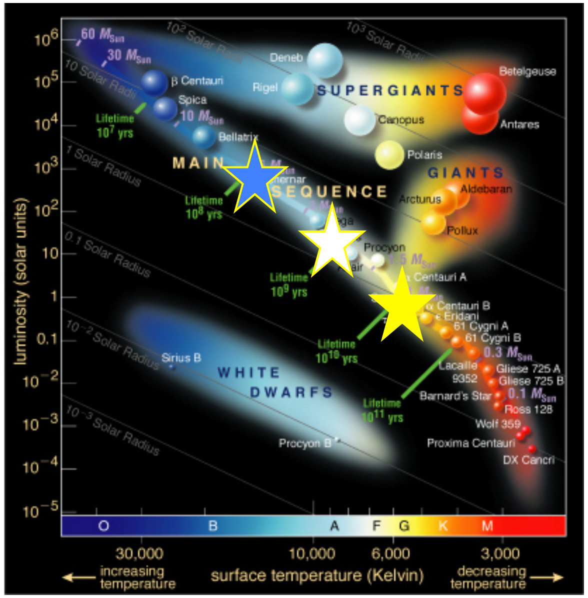
- Fraction of **number** of stars of different masses

$$N_{\mathrm{tot}}\left(M : M_1 \rightarrow M_2\right) = \int_{M_1}^{M_2} \frac{dN}{dM} dM$$

$$= \mathrm{const} \times \int_{M_1}^{M_2} M^{-2.35}\, dM$$

$$= \mathrm{const} \times \left(M_2^{-1.35} - M_1^{-1.35}\right)$$

Number of stars that live <0.1Gyr:	0.27%
Number of stars that live <1Gyr:	0.95%
Number of stars that live <10Gyr:	3.30%



Stellar Populations

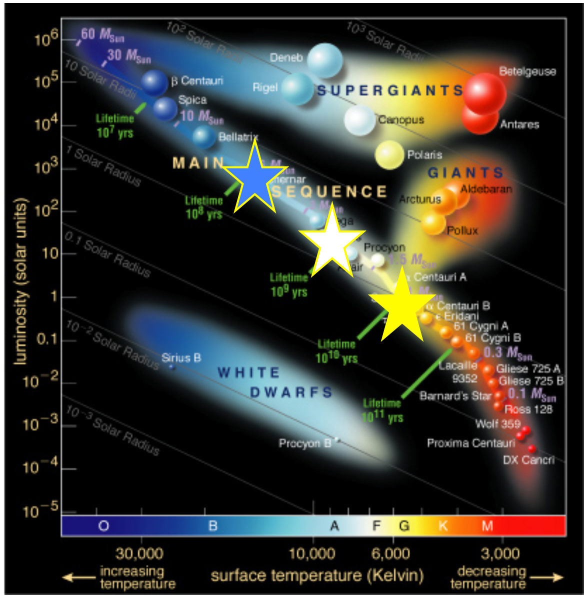
- Fraction of **light** from stars of different masses

$$L_{\rm tot}\left(M:M_1 \to M_2\right) = \int_{M_1}^{M_2} L(M)\frac{dN}{dM}dM$$

$$= \text{const} \times \int_{M_1}^{M_2} M^{3.5} M^{-2.35}\, dM$$

$$= \text{const} \times \int_{M_1}^{M_2} M^{1.15}\, dM = \text{const} \times \left(M_2^{2.15} - M_1^{2.15}\right)$$

Luminosity of stars that live <0.1Gyr:	99.74%
Luminosity of stars that live <1Gyr:	99.96%
Luminosity of stars that live <10Gyr:	99.99%



Stellar Populations

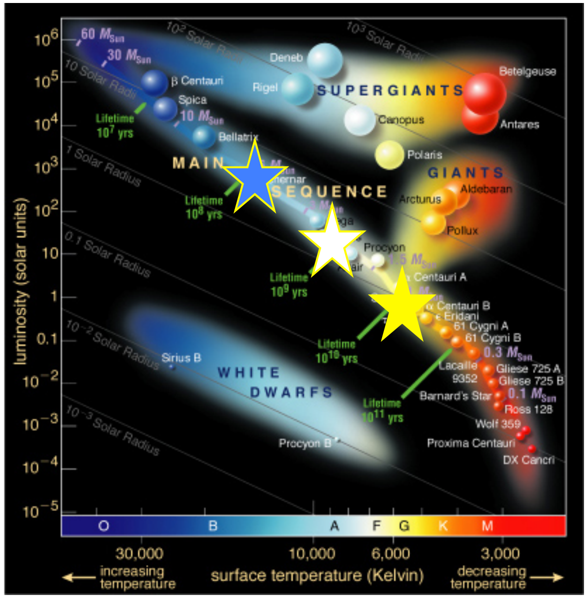
- Fraction of **mass** from stars of different masses

$$M_{\text{tot}}\left(M : M_1 \rightarrow M_2\right) = \int_{M_1}^{M_2} M \frac{dN}{dM} dM$$

$$= \text{const} \times \int_{M_1}^{M_2} M \cdot M^{-2.35} \, dM$$

$$= \text{const} \times \int_{M_1}^{M_2} M^{-1.35} \, dM = \text{const} \times \left(M_2^{-0.35} - M_1^{-0.35}\right)$$

Mass of stars that live <0.1Gyr:	14.66%
Mass of stars that live <1Gyr:	23.69%
Mass of stars that live <10Gyr:	36.04%



Stellar Populations: Evolution

At $t = t_0$, a new stellar population is formed

Stellar Populations: Evolution

100 Myr later

At $t = t_1$, star formation shuts off

100 Myr later

Stellar Populations: Evolution

100 Myr later

Stellar Populations: Evolution

1 Gyr later

Stellar Populations: Evolution

Once star formation turns off in a galaxy:

- Its luminosity decreases with time
- Its color gets redder with time
- Its spectrum looks more like that of low mass stars

This is called "Passive Evolution", i.e., involves no new star formation.

Stellar Populations: Evolution

Galaxy luminosity also depends on the total mass of the galaxy (i.e., total number of stars)

Color, however, does not

Galaxy color is thus an age indicator
Red galaxies are old
Blue galaxies are young

Color changes fast at first, and not much past 1Gyr
It is thus not a very *good* age indicator.

It is a much better star formation history indicator:
Red galaxies haven't formed new stars in the past Gyr
Blue galaxies are still forming stars