Galaxy Morphology

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Physics of Galaxies 2019-2020 Q4
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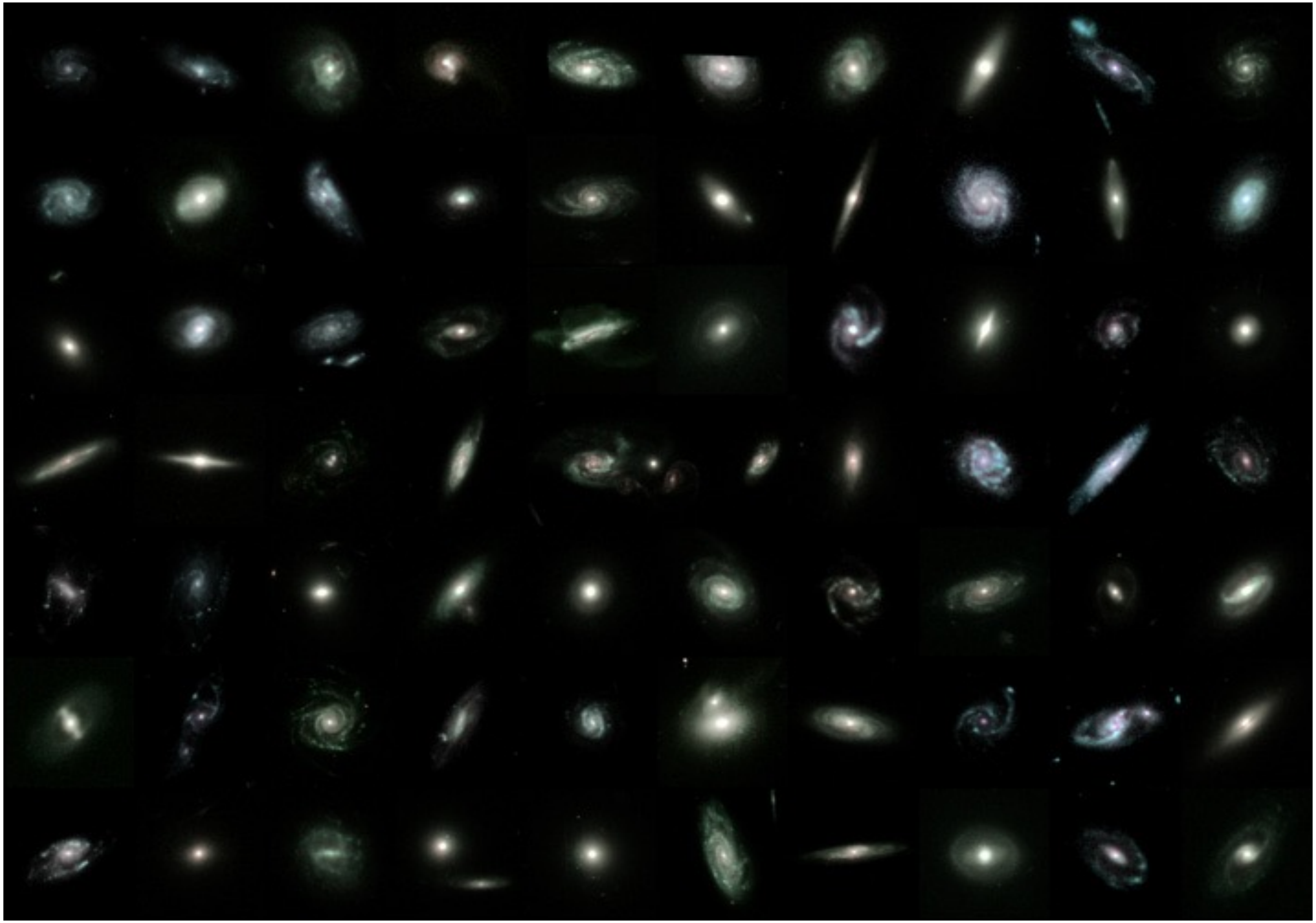
The diversity of galaxy morphologies

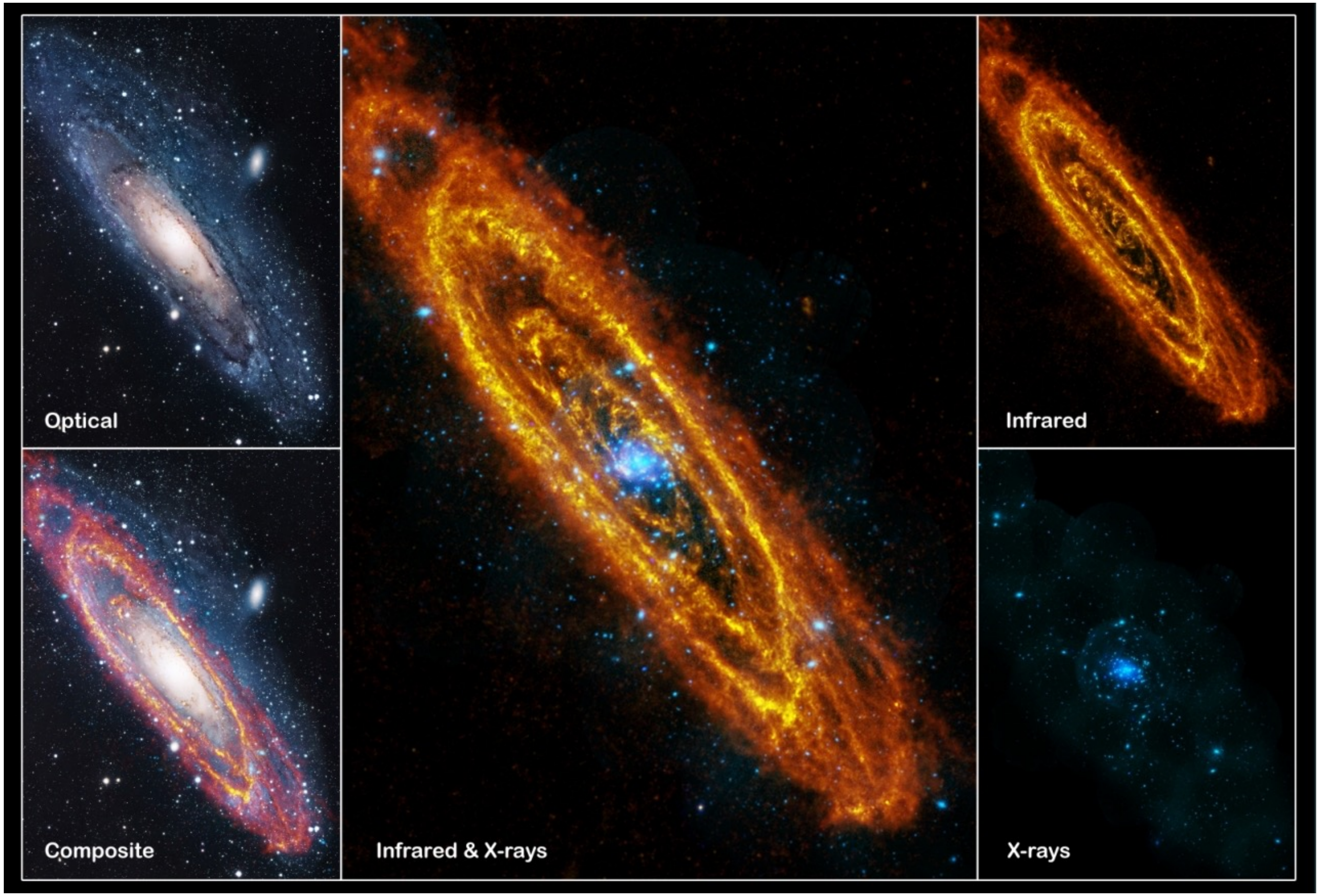


What features can you recognise here?

Picture credit: NASA

Galaxy morphology depends on wavelength

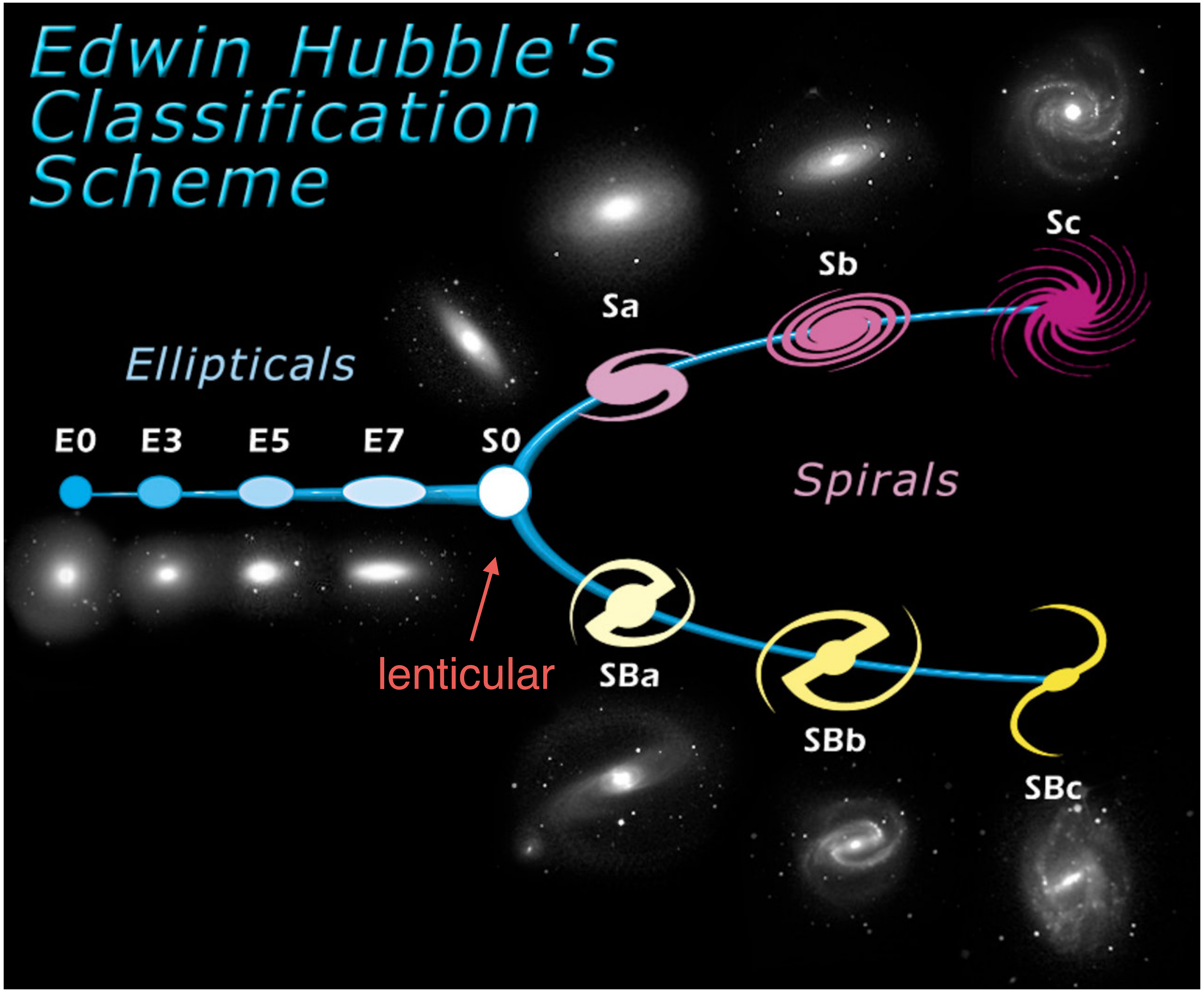
e.g. Andromeda



Picture credit: ESA

The Hubble Sequence

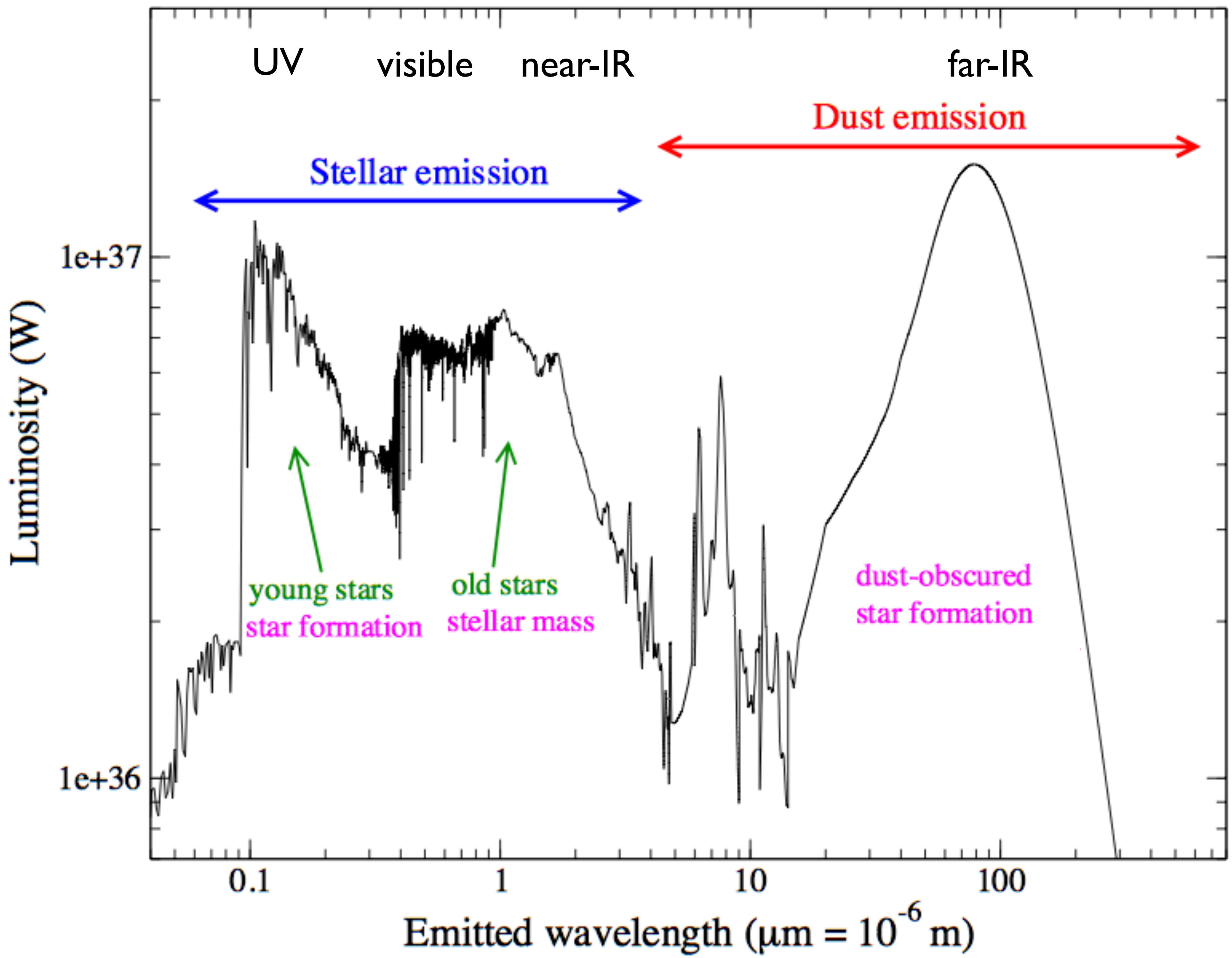
The Hubble Tuning Fork



The Hubble sequence holds up to z~1

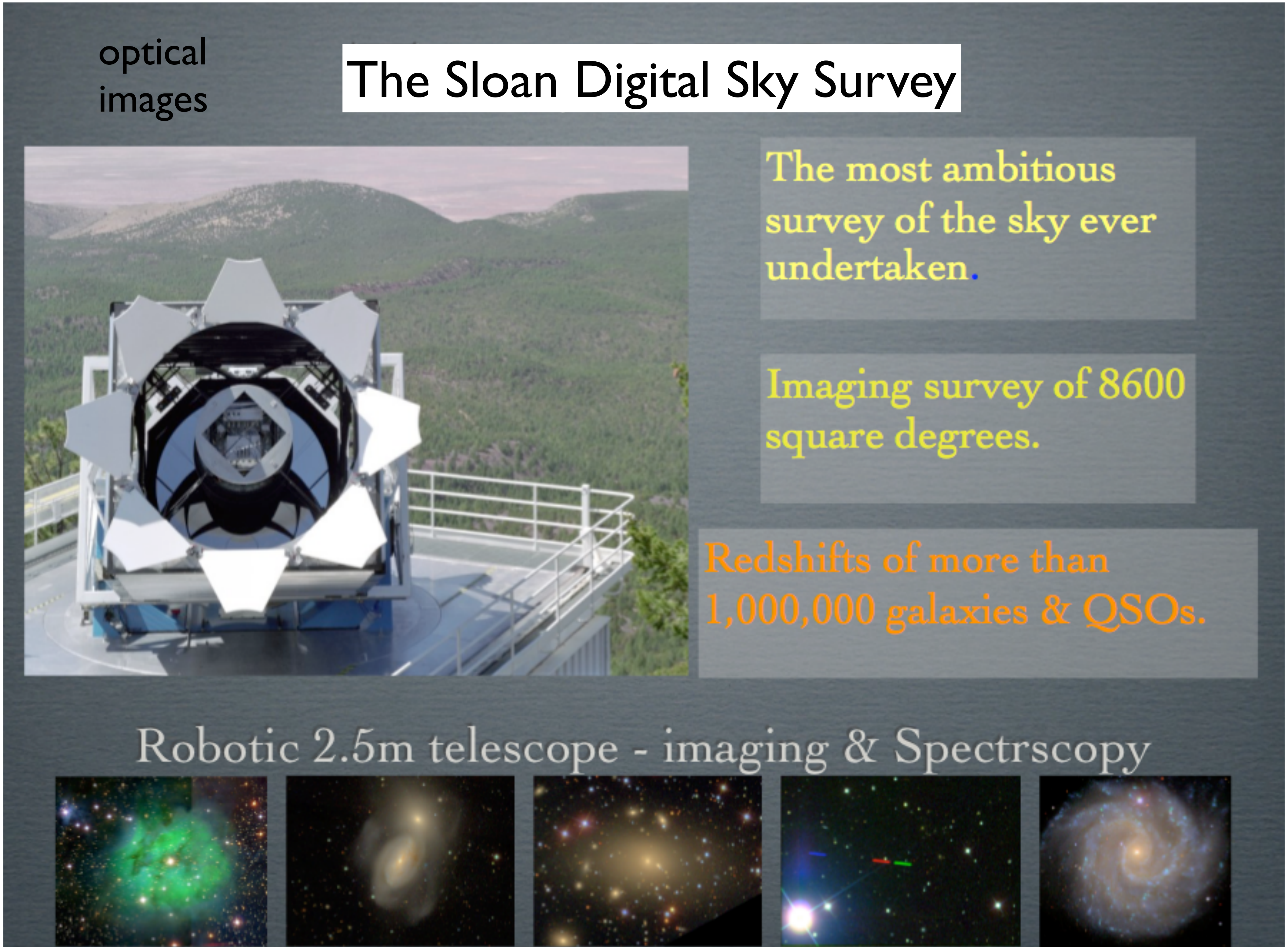
<u>Qualitative</u> classification

A Galaxy's Spectral Energy Distribution (SED)

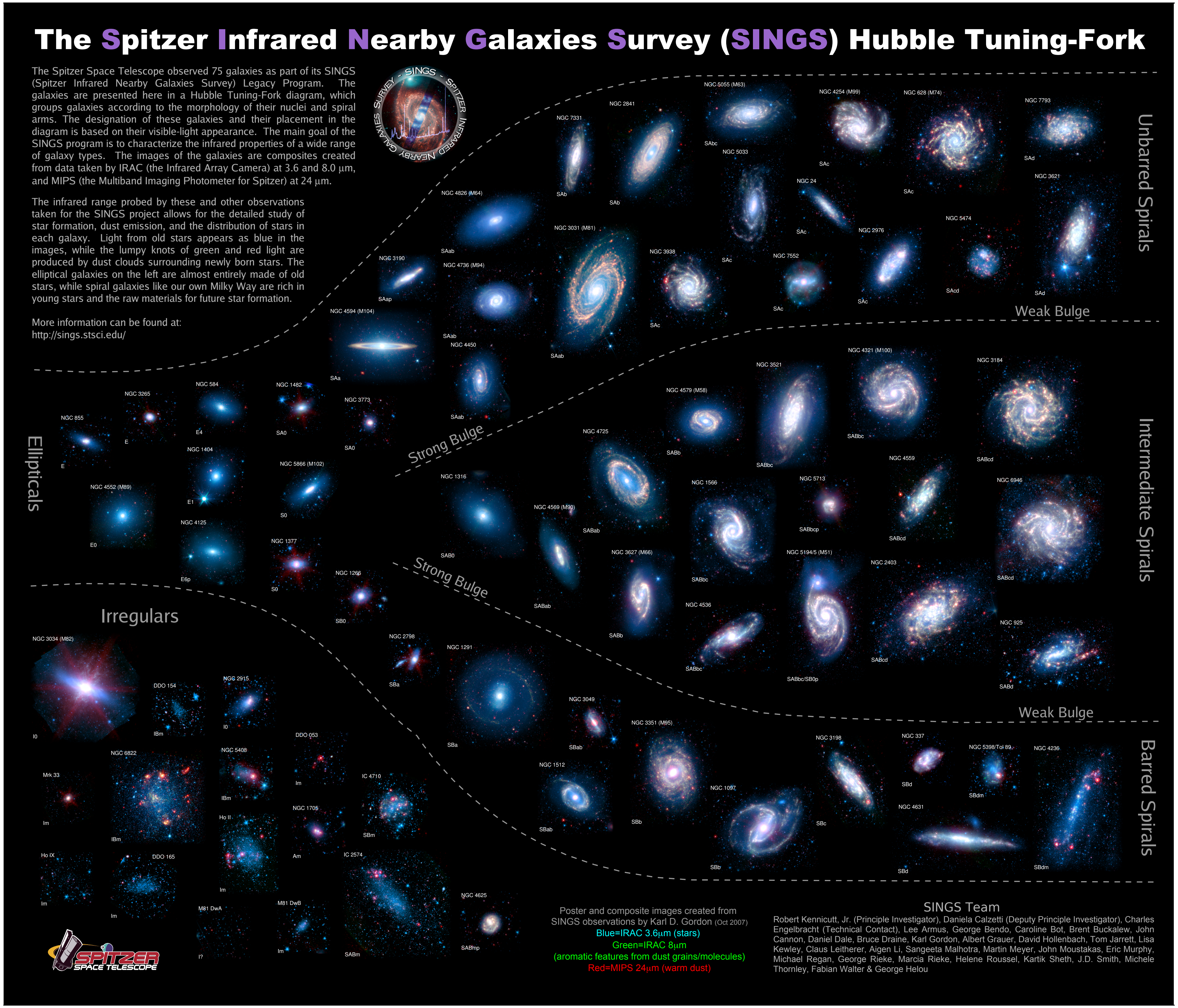


Picture credit: K. Caputi

The Sloan Digital Sky Survey (SDSS)

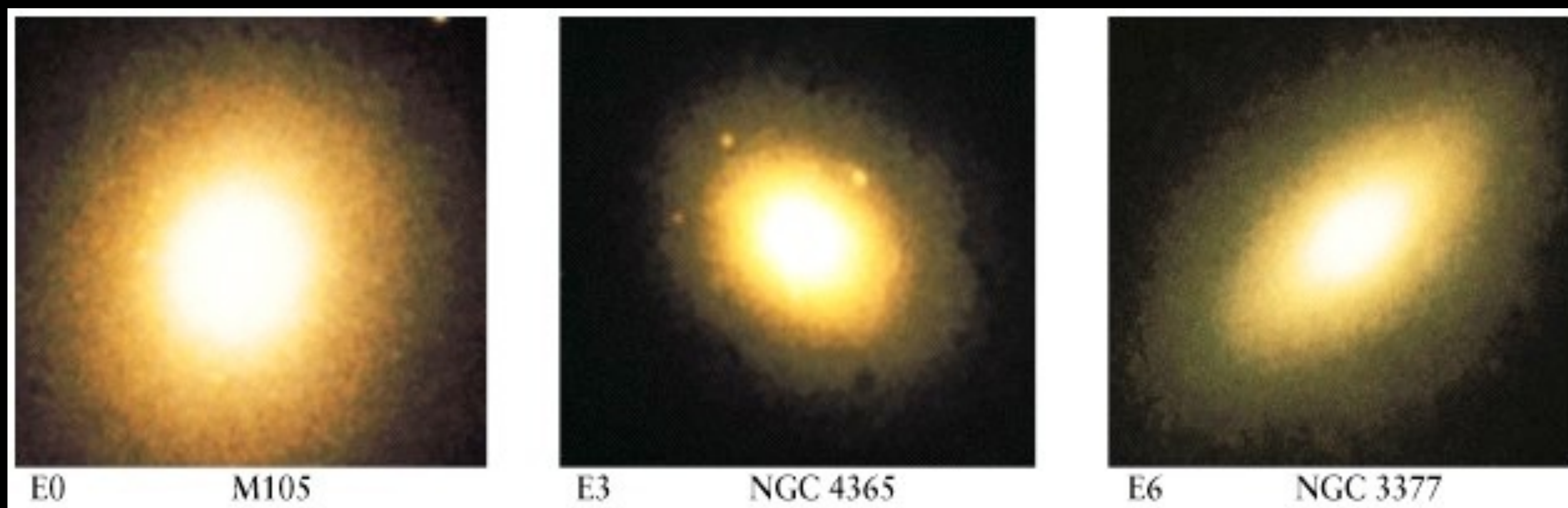


Spitzer provided images in mid-IR



Elliptical Galaxies

Elliptical Galaxies



Elliptical Galaxies: are almost featureless ellipses. They are predominantly made up of old stars. They are typically a few times more massive than the Milky Way, but there is a wide range: from a few percent to more than 10 times the mass of the Milky Way. They also vary in apparent elongation, from round to 2:1 flattened. This is mostly because of inclination.

*Ellipticals are mostly **red** because they have predominantly **old** stellar populations*

Ellipticals are not so boring…

Are Ellipticals really so smooth?

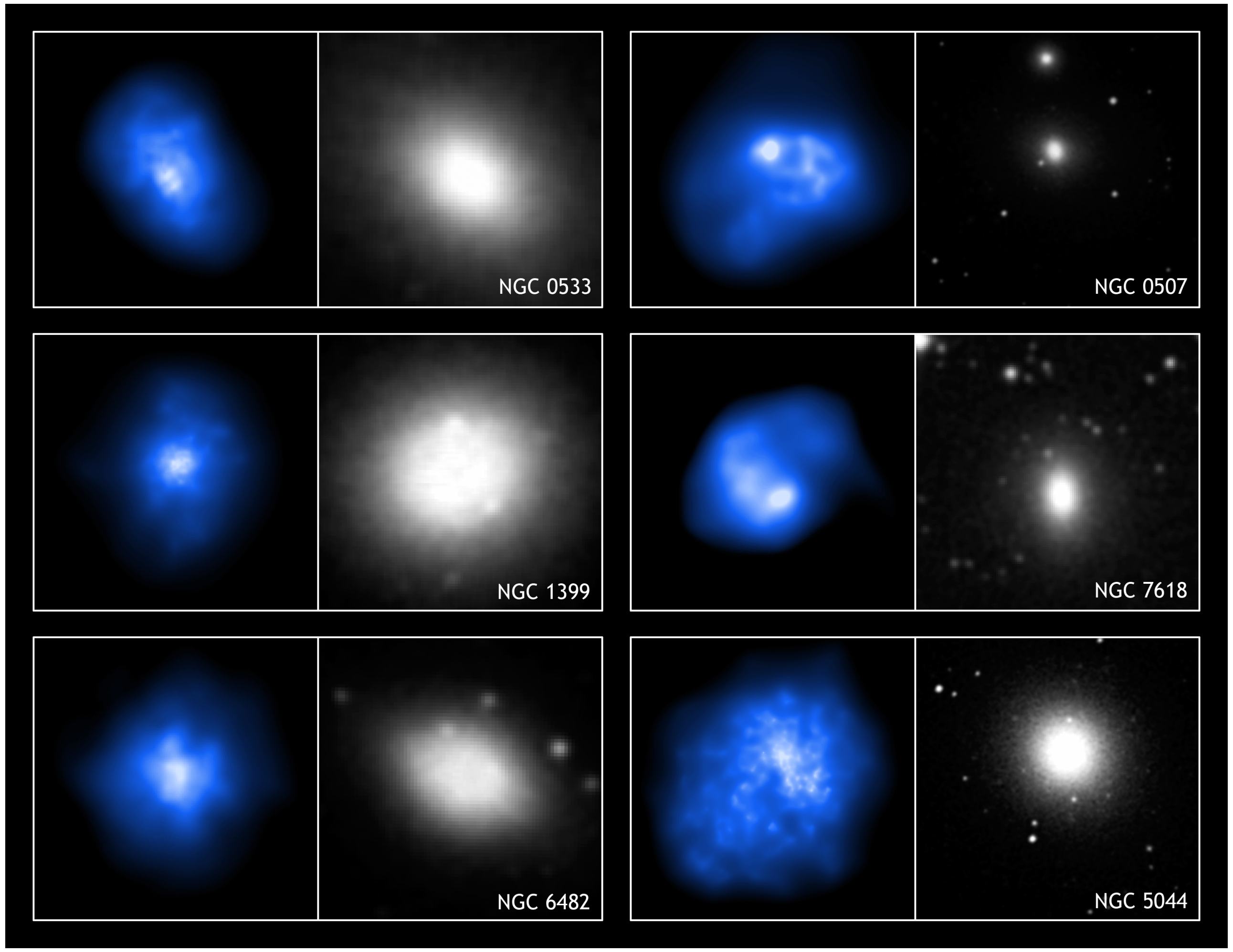
Shells - seen at faint levels around most E's
- Origin could be merger remnants or captured satellites
- prominent shells goes with evidence for some young stars in the galaxy

Shells in Cen A

…and dust

Dust - visible dust clouds seen in many nearby E's (maybe 50% of E's have some - but not much – dust)

Some ellipticals have active black holes



Chandra: images of elliptical galaxies

HST: giant elliptical galaxy NGC 1316.

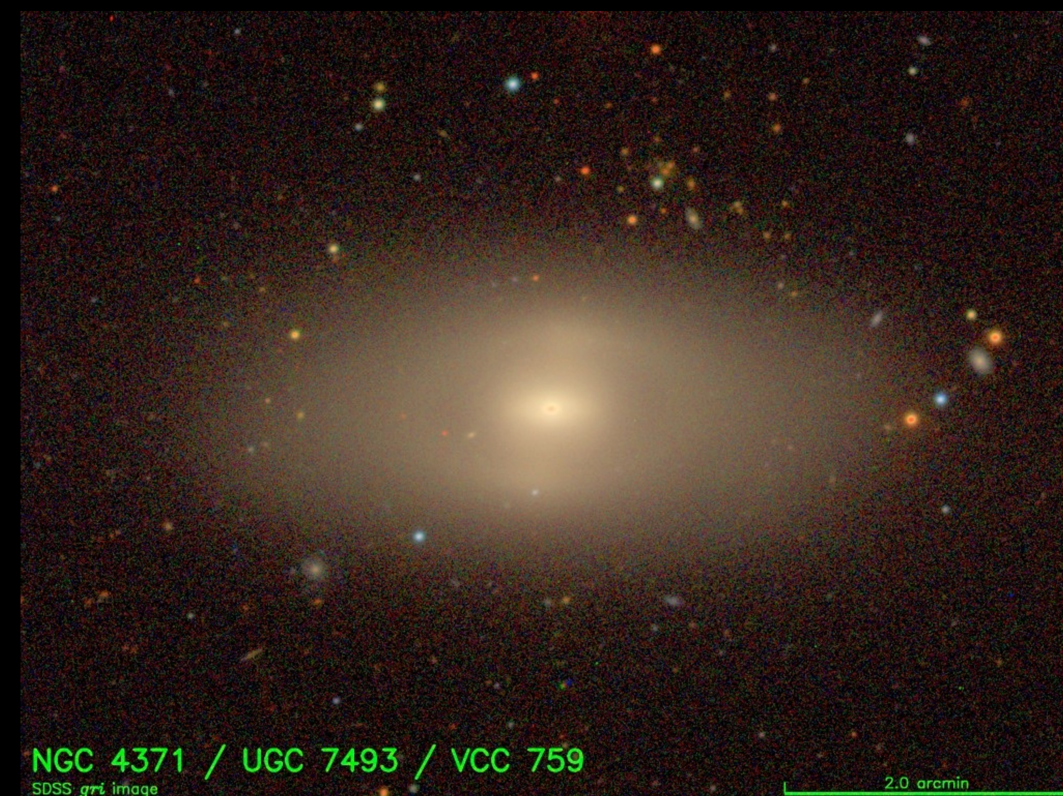
The shapes of the massive clouds of hot gas that produce X-ray light differ from the stellar distribution that produces the optical light. A powerful source of energy must be pushing the hot gas around and stirring it up.

A correlation between the shape of the hot gas clouds and the power produced at radio wavelengths by high-energy electrons suggests this power source can be traced back to a super-massive black hole in the central regions.

Lenticular Galaxies

Lenticular (S0) Galaxies

NGC 3115: S0-galaxy



NGC 4371: SB0-galaxy

Spiral Galaxies

Spiral Galaxies

Spiral galaxies contain a disk of stars and gas arranged in a spiral pattern. Sa and Sb galaxies also contain a central bulge that is like a small elliptical. The bulge is old ("Population II"). Usually the disk is made partly of young stars ("Population I"). There are two sub-types: barred and ordinary spirals.

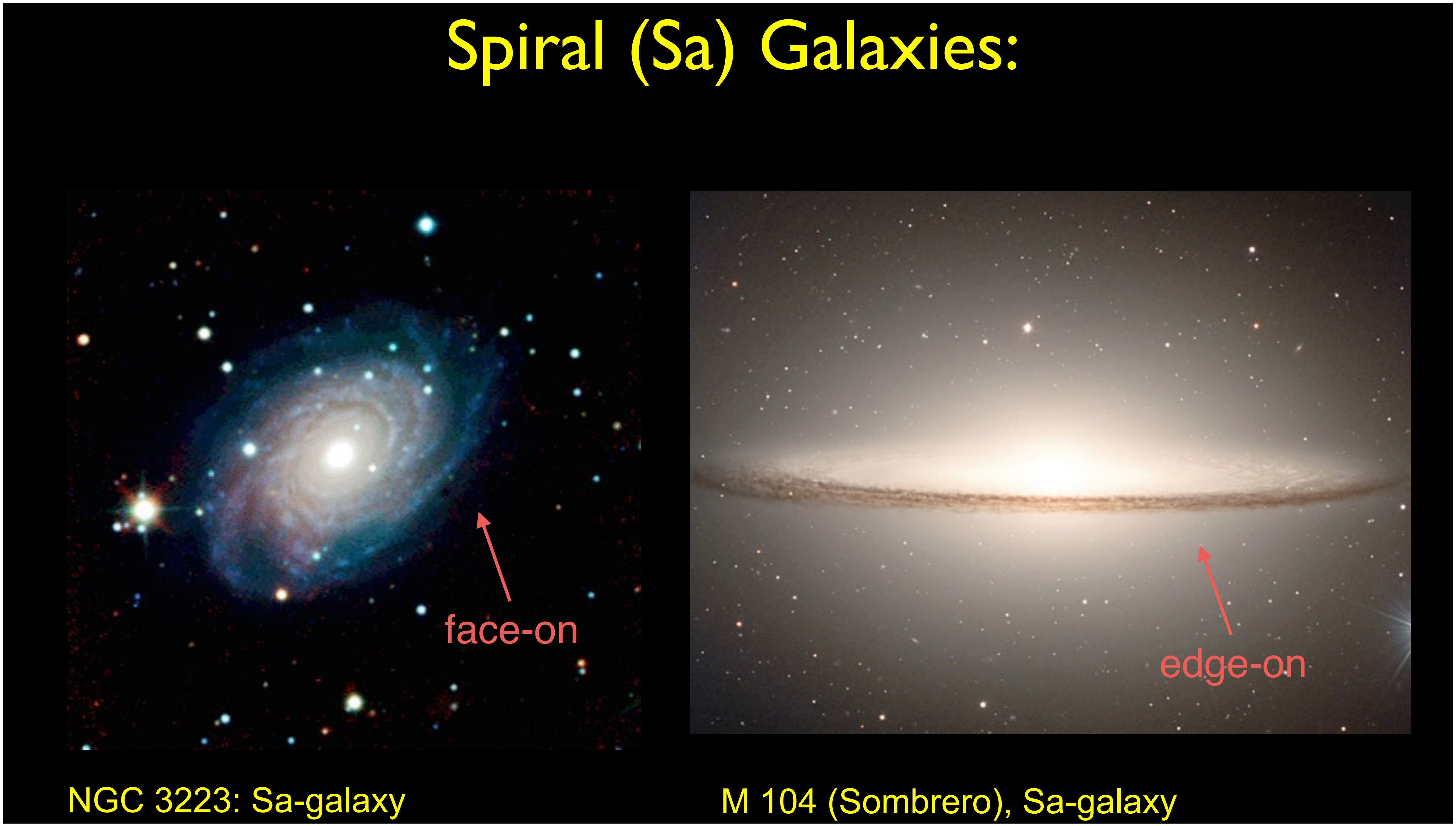
Along the sequence Sa → Sc,
- the contribution of the bulge decreases,
- the fractional amount of gas increases,
- the contribution of young stars increases
- the disk looks more patchy, and
- the spiral arms become more open.

Our Milky Way is a typical spiral, intermediate between Sb and Sc. It has a weak bar.

Basic points:
- disks are flat
- disks have spiral structure
- orbits are almost in a single plane
  - disks rotate
  - random motions are small
  - stars have a large range of ages

Kormendy

Spiral (Sa) Galaxies



Spiral (Sb) Galaxies

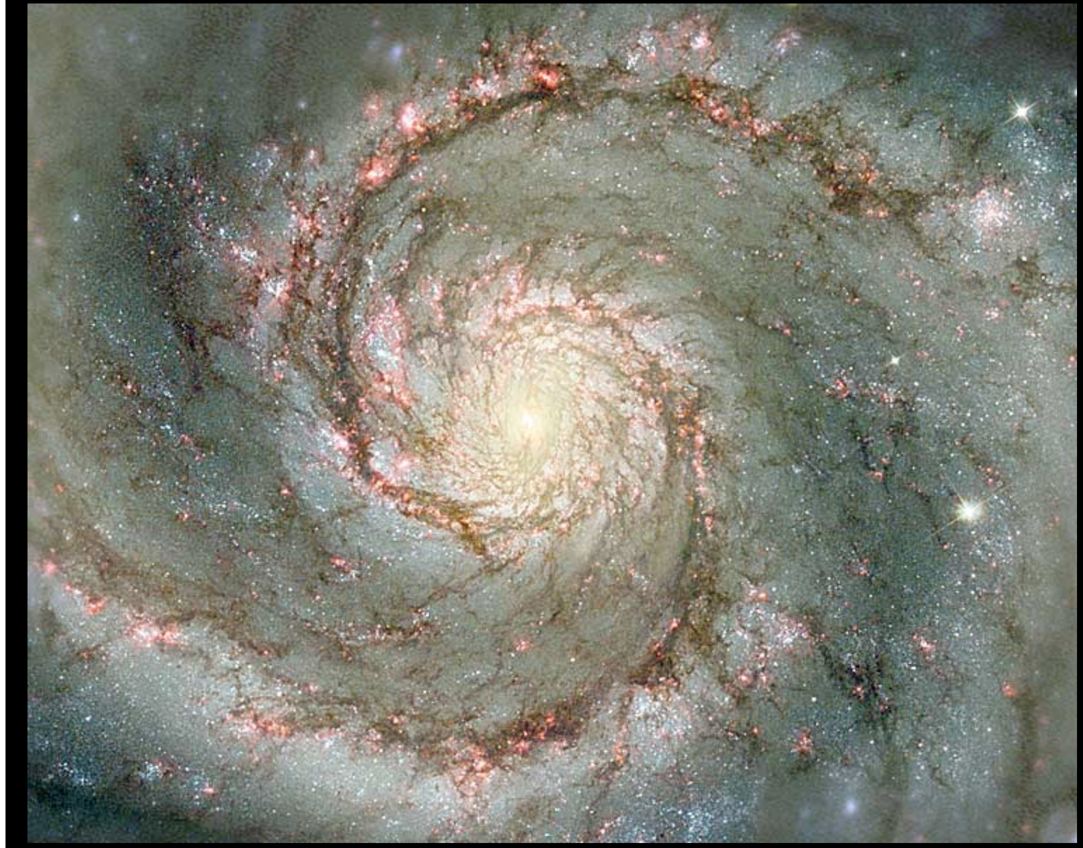
Spiral (Sb) Galaxies:

M 31 (Andromeda): Sb-galaxy

M 81: Sb-galaxy

Spiral (Sc) Galaxies

Spiral (Sc) Galaxies:



M 51: Sc-galaxy

M 101: Sc-galaxy

Barred Spiral (SBc) Galaxies

Barred-Spiral (SBc) Galaxies:

NGC 1365: SBc-galaxy

NGC 613: SBc-galaxy

Irregular Galaxies

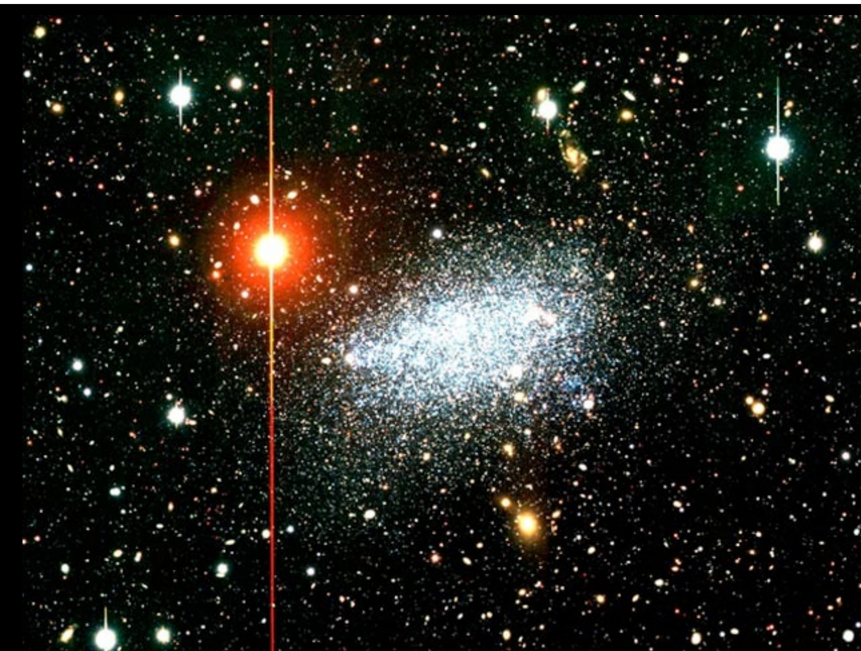
Irregular (Irr) Galaxies:

LMC: Irr-galaxy

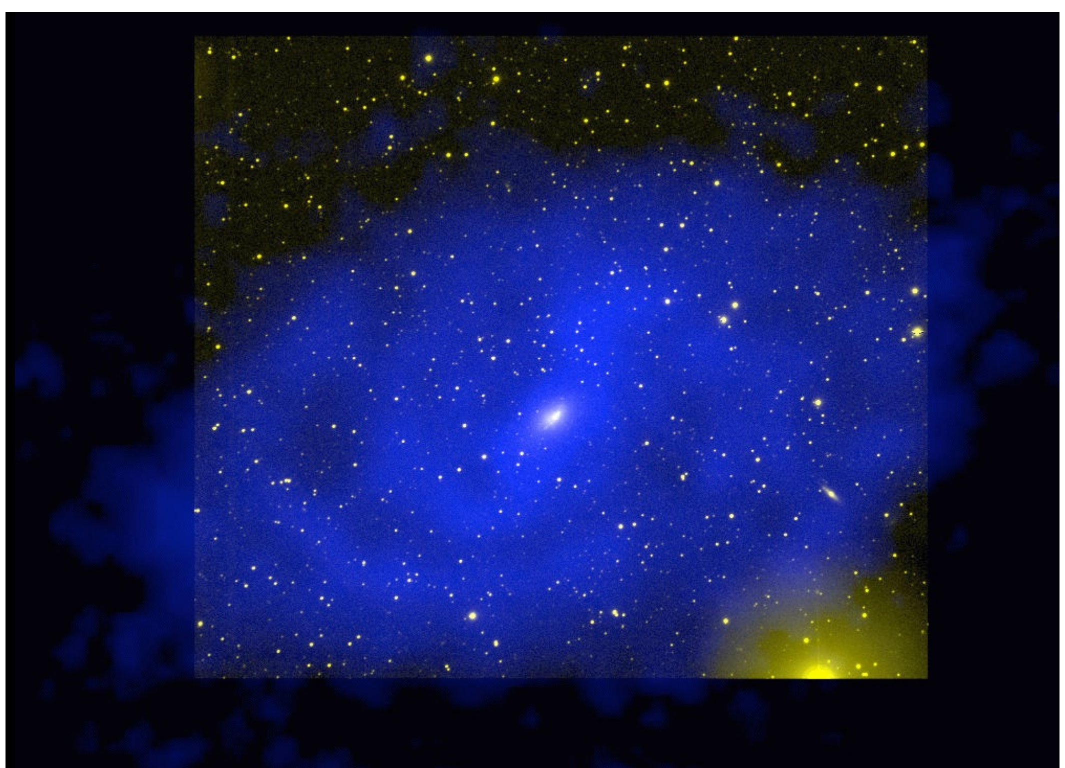
SMC: Irr-galaxy

Dwarf Irregulars

I Zw 18 : BCD galaxy



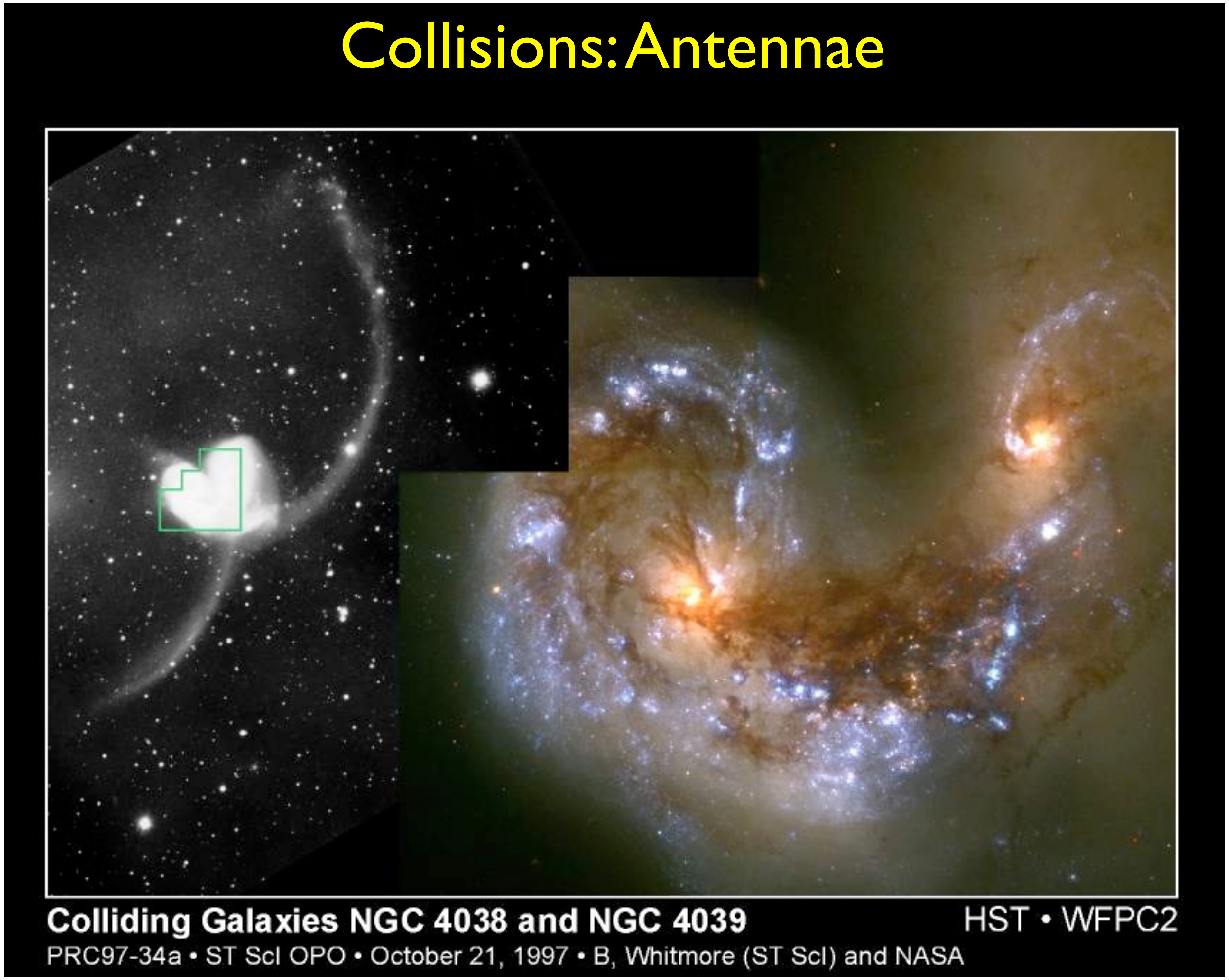
Leo A: dIrr-galaxy



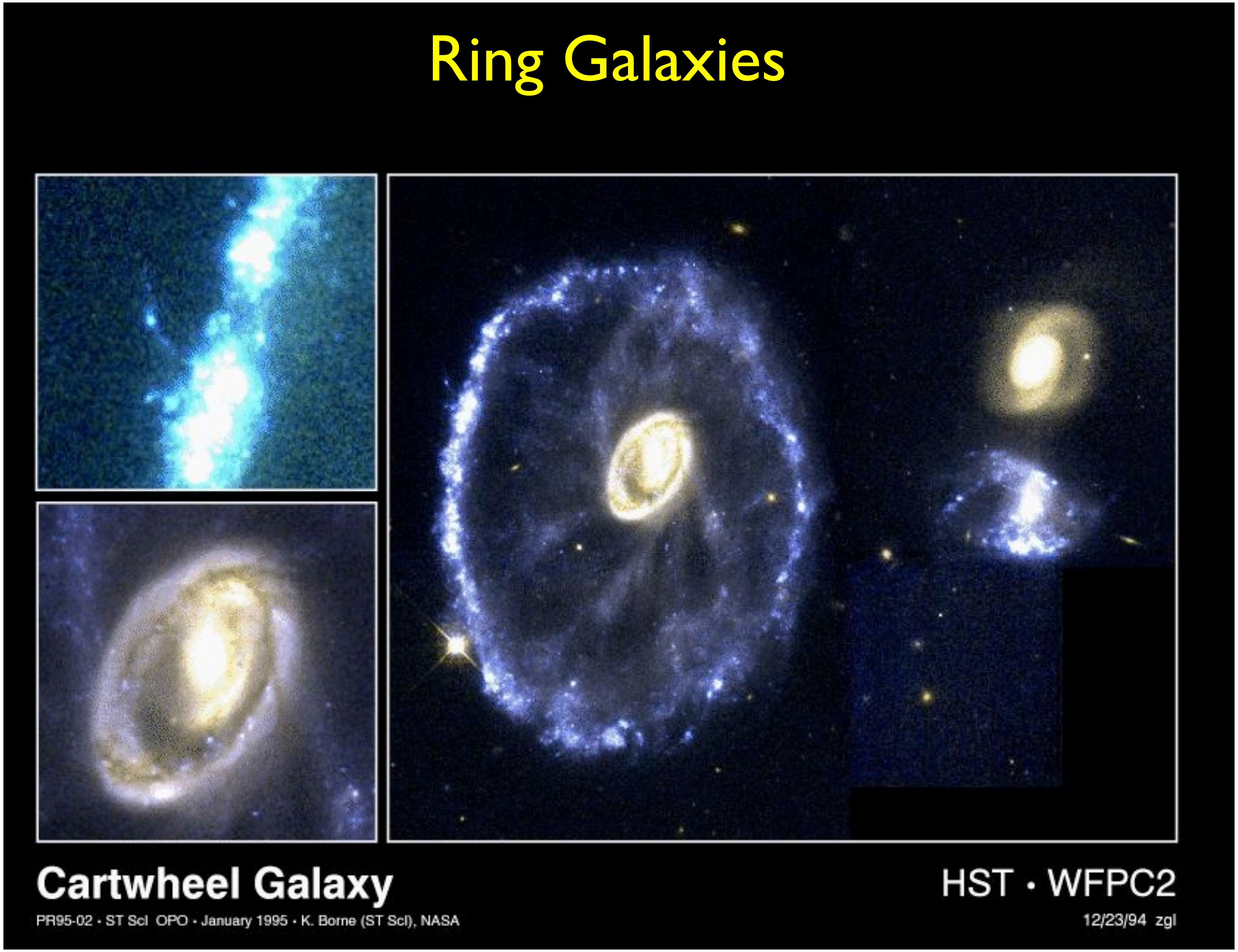
Dwarf irregular NGC 2915 yellow: optical blue: HI

Dwarf irregulars usually have large HI haloes

Galaxy Mergers



Ring Galaxies



Likely the consequence of a nearly head-on collision with a smaller galaxy

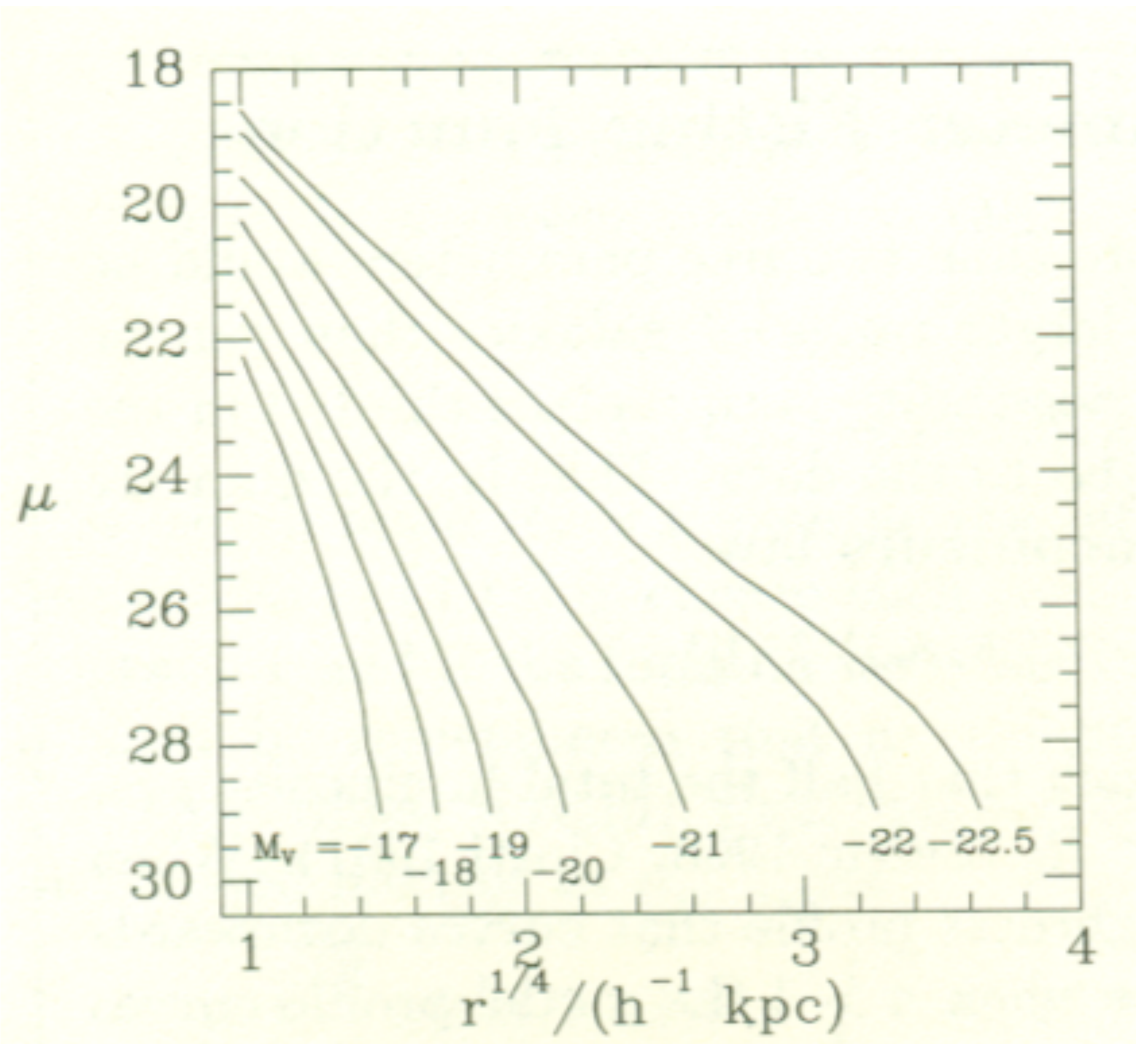
Galaxy Zoo Project

See http://zoo1.galaxyzoo.org/Project.aspx

Quantitative Analysis

Light Profiles of Elliptical Galaxies

Characteristic surface brightness profiles for Es of different luminosities



$$\mu(r) = \mu_e + 8.3268\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$$

mag arcsec^{-2}

Effective radius, r_e, is the projected radius within which one-half of the galaxies light is emitted.

equivalent to:

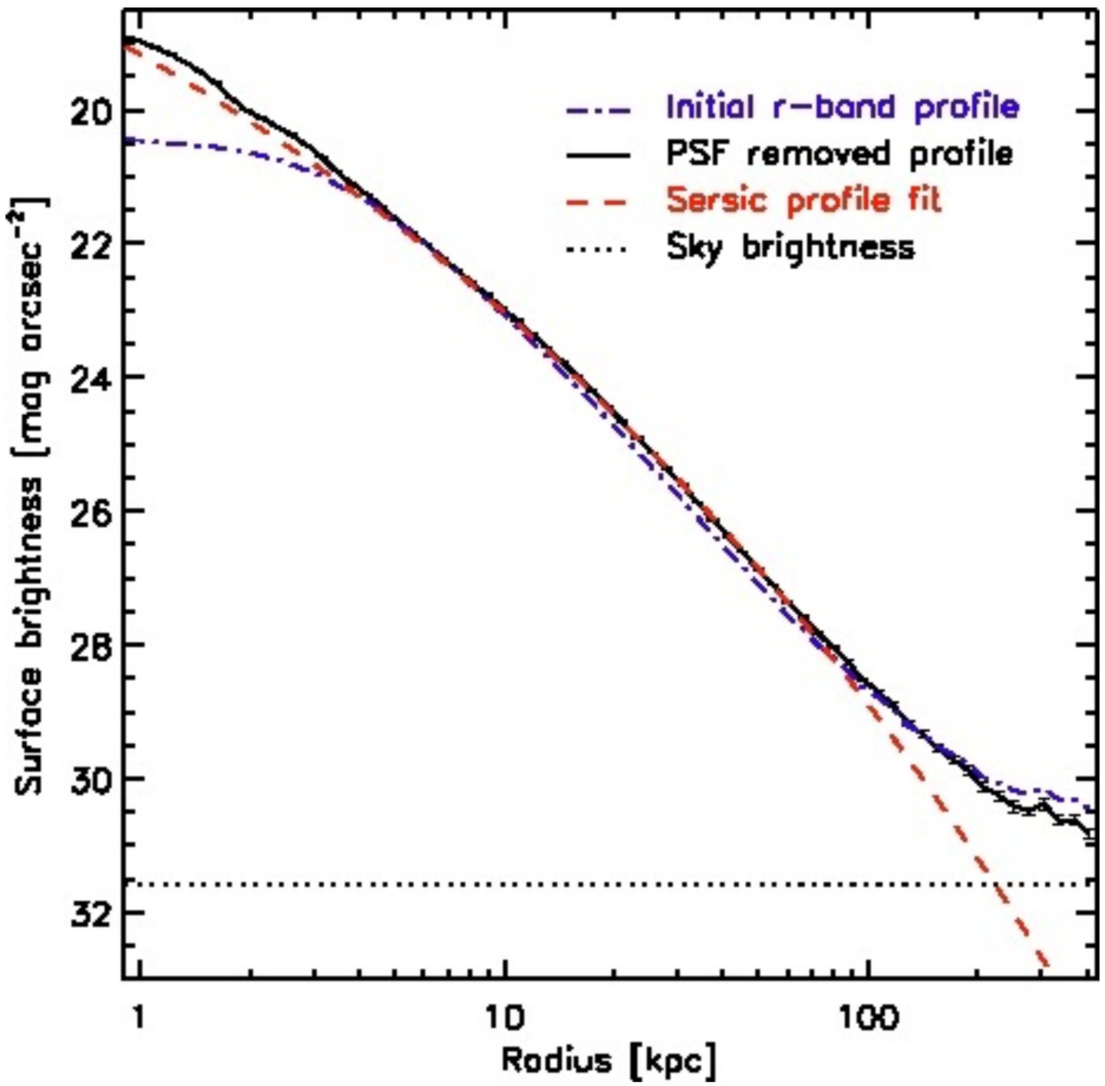
$$I(r) = I_e\, exp\left\{-7.67\,[(r/r_e)^{1/4} - 1]\right\}$$

de Vaucouleurs's law

from Binney & Merrifield, section 4.3

The factor 7.67 is obtained after imposing that at r=re the intensity (I=Ie) must be 1/2 of total. The total is obtained after integrating between r=0 and r=oo.

General Light Profiles



$$I(r) = I_e \, exp \left\{ -b_n \left[(r/r_e)^{1/n} - 1 \right] \right\}$$

3 free-parameter model

n = Sérsic index

n = 1 - exponential (pure disk)

n = 4 - de Vaucouleurs

Picture credit: P. Van Dokkum

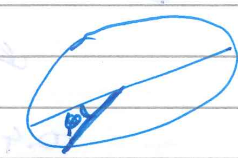
General light profiles: $I(r) = I_e \exp\left\{-b_m\left[(r/r_e)^{1/m} - 1\right]\right\}$

where $n =$ Sérsic index

$\begin{cases} n = 1 \rightarrow \text{disk} \\ n = 4 \rightarrow \text{de Vaucouleurs.} \end{cases}$

How to get the integrated light of a galaxy from the light profile:

$$\underset{\text{this is }\underline{\text{an integrated flux}}\text{ (not luminosity!)}}{L} = \int_0^{2\pi}\int_0^{\infty} I(r)\, r\, dr\, d\phi$$



2D – polar coord. (r, θ).

If we assume axial symmetry: $L = 2\pi \underset{\text{aver. intensity}}{I_0} \int_0^{\infty} r \exp\left(-(r/\alpha)^{1/m}\right) dr$ (✱)

If we substitute $x = (r/\alpha)^{1/m}$

$\Downarrow$

$r = x^m \alpha \Rightarrow dr = m x^{m-1} \alpha$

Remember that polar to cartesian conversion is:

$\begin{cases} x = r\cos\varphi \\ y = r\sin\varphi \end{cases}$

$\therefore \quad L = 2\pi I_0 \alpha^2 m \underbrace{\int_0^{\infty} x^{2m-1} \exp(-x)\, dx}_{\text{Euler's integral}}$

Solut. is $\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t} dt = (z-1)!$

So $L = 2\pi I_0 \alpha^2 m\, \Gamma(2m)$

For m integer: $L = \pi I_0 \alpha^2\, 2m\, (m-1)! = \pi I_0 \alpha^2 (2m)!$

(✱) Note that $\alpha = \underset{\text{scale change}}{b_m}/r_e$

But remember

$m = -2.5 \log_{10}(f/f_0)$

$f \propto 10^{-0.4\, m}$

So similarly to the previous equation, we can write in mag:

$10^{-0.4 m} = (2m)!\, \pi\, 10^{-0.4\mu}\, \alpha^2$

$\Downarrow$

$-0.4\, m = -0.4\, \mu + \log_{10}\left[(2m)!\, \pi\, \alpha^2\right]$

$$\boxed{m = \mu - 5\log\alpha - 2.5\log_{10}\left[(2m)!\, \pi\right]}$$

For $m = 1 \longrightarrow m = \underset{\text{average mag surface density}}{\mu_0} - 5\log_{10}\alpha - 2$

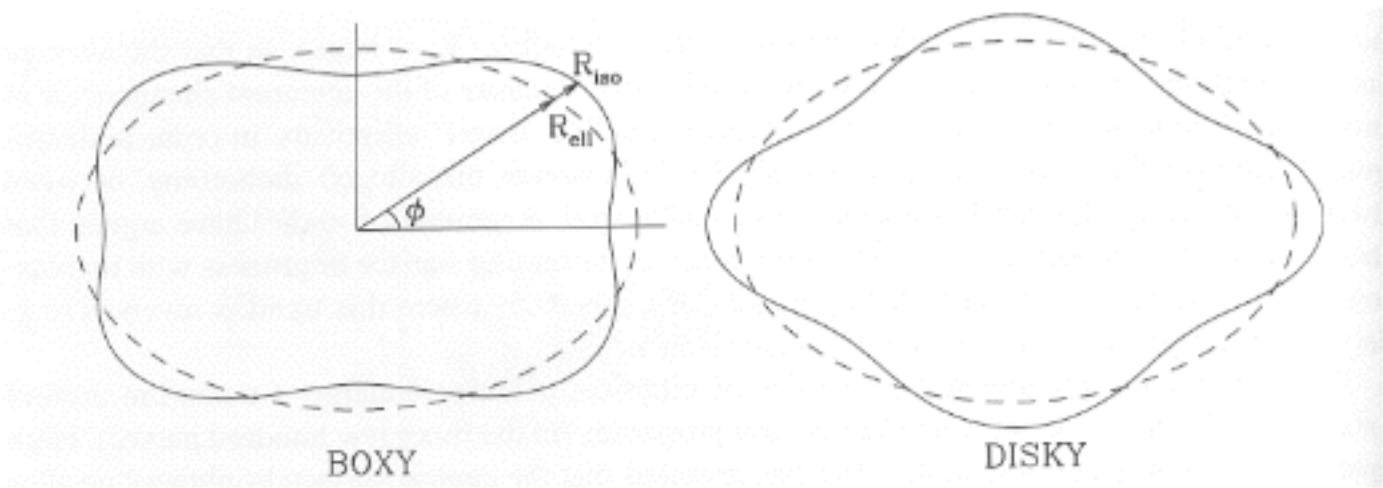
For $m = 4 \longrightarrow m = \mu_0 - 5\log_{10}\alpha - 12.7$

Variations in Elliptical Light Profiles

$$x = a\ cost \qquad y = b \sin t$$

Fourier decomposition

$$\Delta r(t) \approx \sum_k a_k \cos(kt) + b_k \sin(kt)$$



$a_4 < 0$ $\qquad$ $a_4 > 0$

From Bender et al. (1998)

Variations in Elliptical Light Profiles II

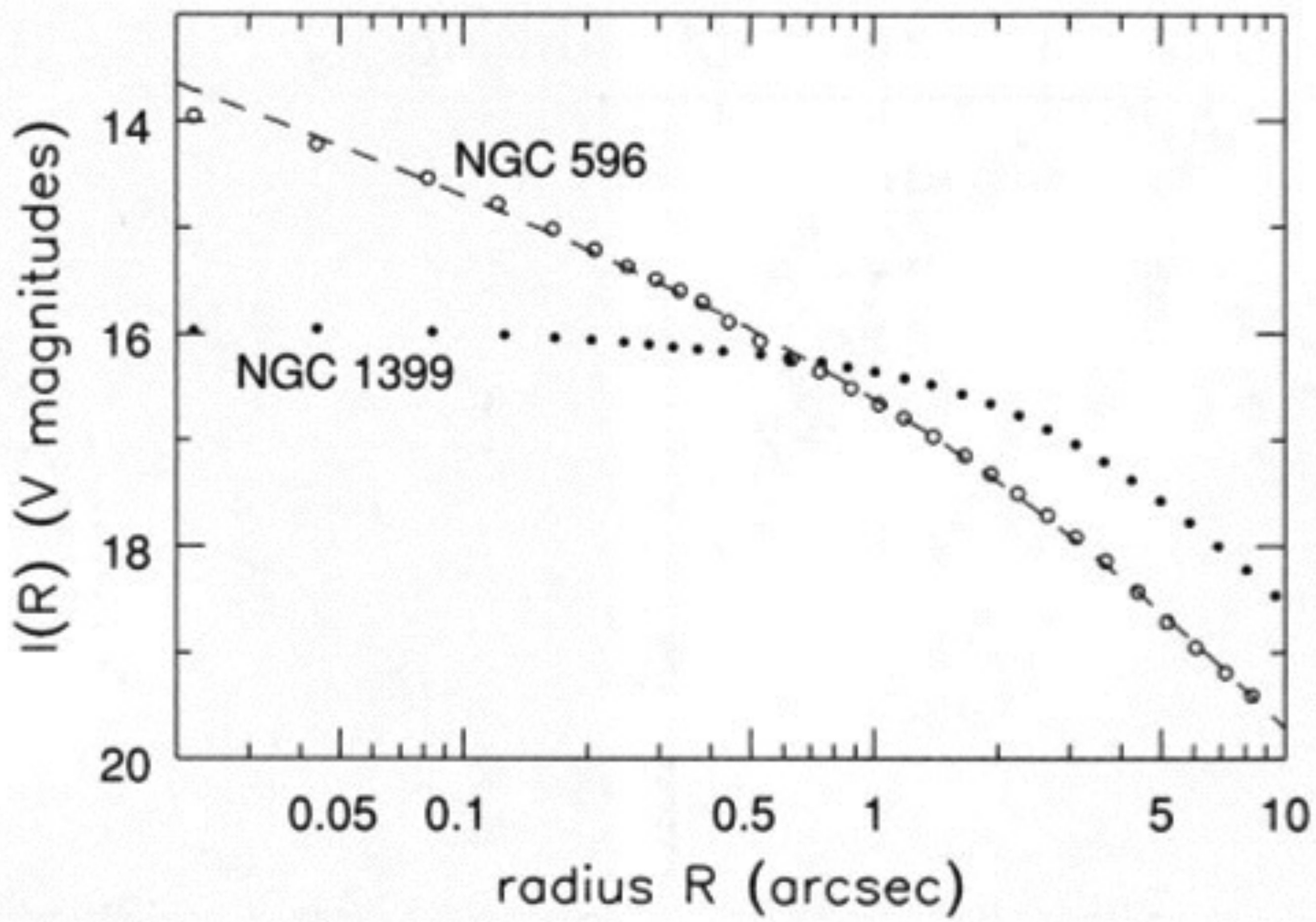


Fig. 6.7. Surface brightness $I_V(R)$ in the V band at the centers of two elliptical galaxies. The cD galaxy NGC 1399 ($M_V = -21.7$) has a *core* at $R \lesssim 1''$, where $I(R)$ is nearly constant. NGC 596 ($M_V = -20.9$) is half as luminous; the surface brightness continues to rise as a *cusp*. The dashed line shows $I(R) \propto R^{-0.55}$ – T. Lauer.

From A. Fontana's lecture

Bulge and Disk Decomposition

- including the bulge, we can describe the profile as the sum of a spiral and an elliptical power law:

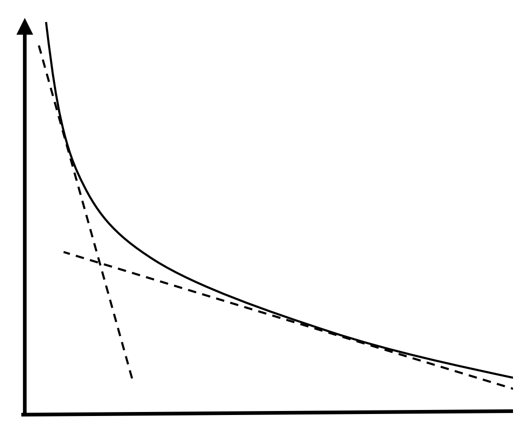
$$\Sigma(R) = \Sigma_0^{(d)} \exp(-R/R_d) + \Sigma_e^{(b)} \exp(-7.67\ ([R/R_e]^{1/4} - 1))$$

- but if the bulge is rather flat (pseudo-bulge) we can just use a second n=1 exponential with a smaller radius:

$$\Sigma(R) = \Sigma_0^{(d)} \exp(-R/R_d) + \Sigma_0^{(b)} \exp(-R/R_b)$$

- for the disk-plus bulge version, we get the total luminosity

$$L = 2\pi\ \Sigma_0^{(d)} R_d^2 + 7.22\pi\ R_e^2\ \Sigma_e^{(b)}$$



type	B/T
S0	0.65
Sa	0.55
Sb	0.3
Sc	0.15

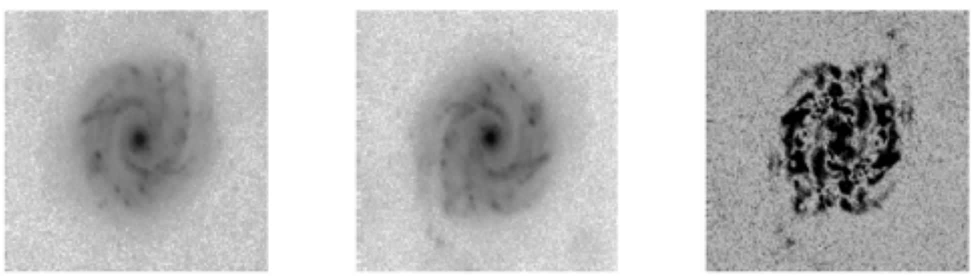
Credit: S. Driver

The CAS classification

Non-parametric classification (does not assume any functional form)

Typically used for z>1 galaxies

180^{O} rotated



I   R   abs(I–R)

$$A = \frac{\mathrm{abs(I-R)}}{\mathrm{I}}$$

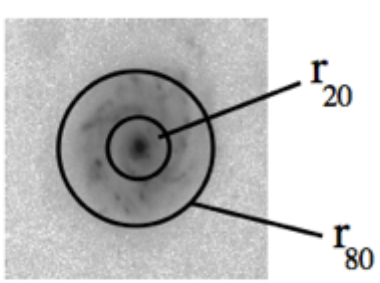
asymmetry

"blurred" image

I   B   I–B

$$S = \frac{\mathrm{I-B}}{\mathrm{I}}$$

smoothness



$$C = 5\log\left(\frac{r_{80}}{r_{20}}\right)$$

concentration

Conselice+(2000); Bershady+(2000); Conselice (2003)

The CAS classification (cont.)

CAS classification:

Smoothness $\rightarrow$ blurred image obtained by multiplying orig. image by

$$0.3 \times r \ (\eta = 0.2)$$

where r is the Petrosian radius for $\eta = 0.2$, which is defined by

$$\eta(r) = \frac{I(r)}{\underbrace{\langle I(<r) \rangle}_{\text{average intensity within radius } r}}$$

intensity in an annulus $(r-\delta r;\ r+\delta r)$