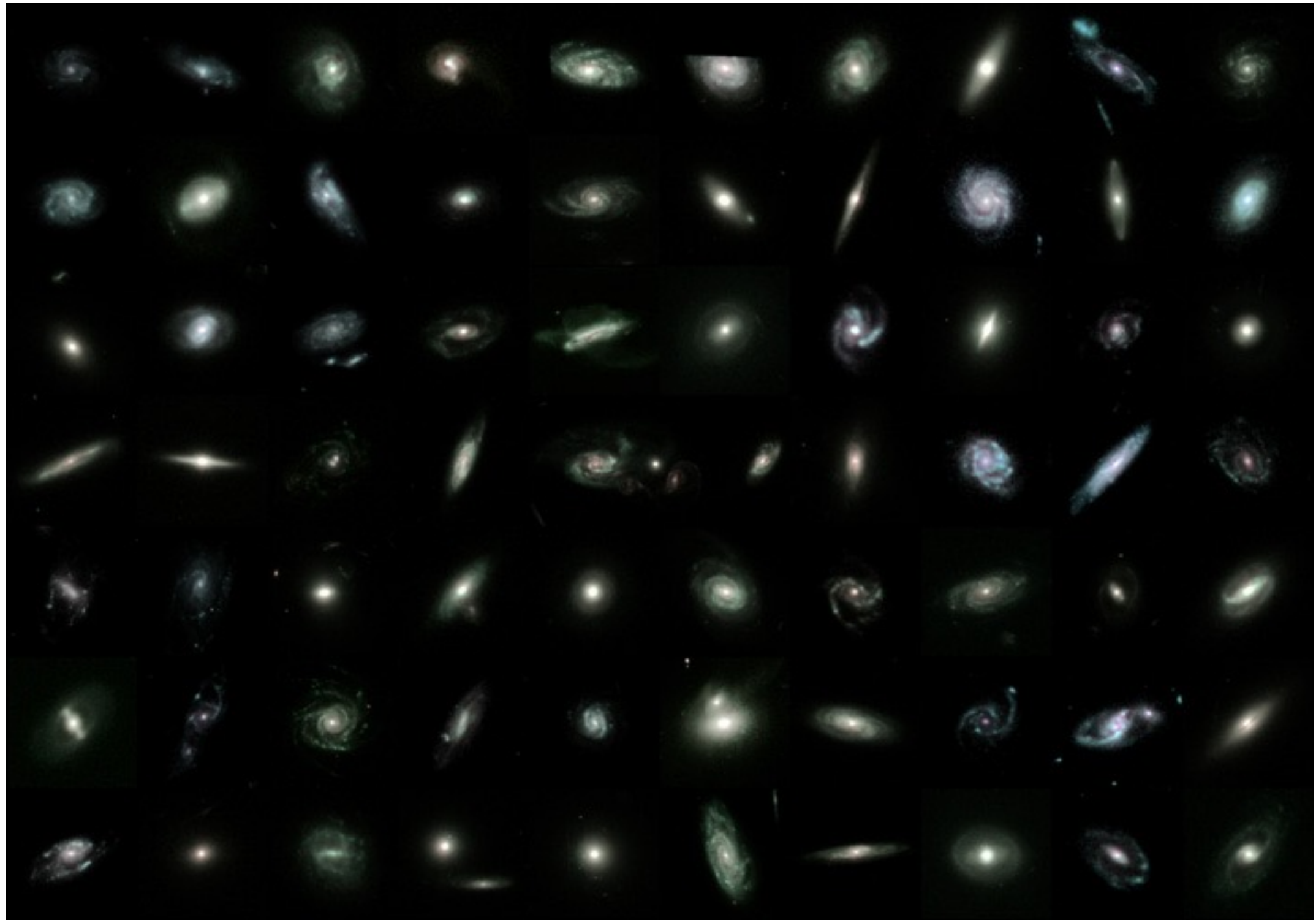


Galaxy Morphology

Karina Caputi

*Physics of Galaxies 2019-2020 Q4
Rijksuniversiteit Groningen*

The diversity of galaxy morphologies



What features can you recognise here?

Picture credit: NASA

Galaxy morphology depends on wavelength

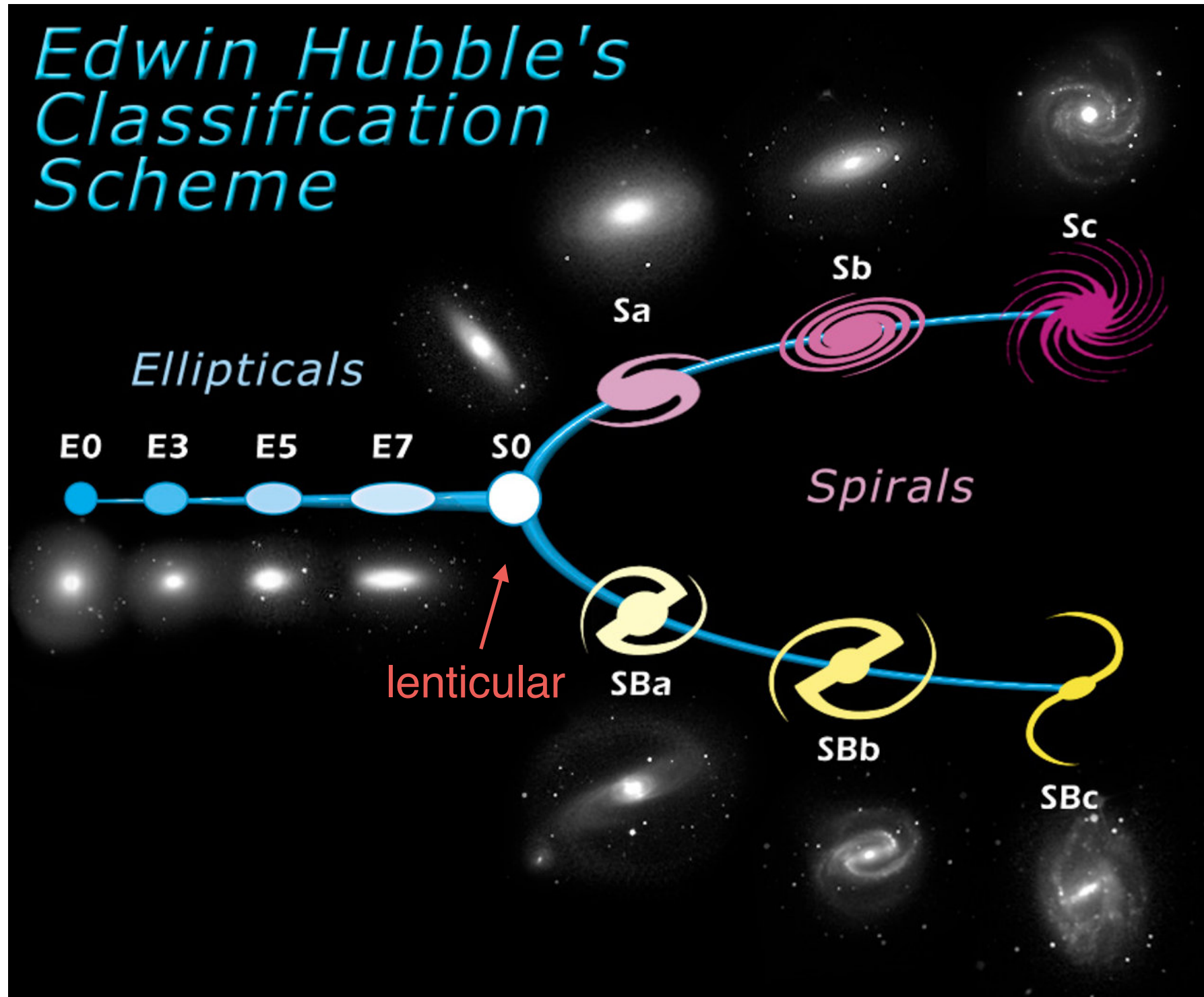
e.g. Andromeda



Picture credit: ESA

The Hubble Sequence

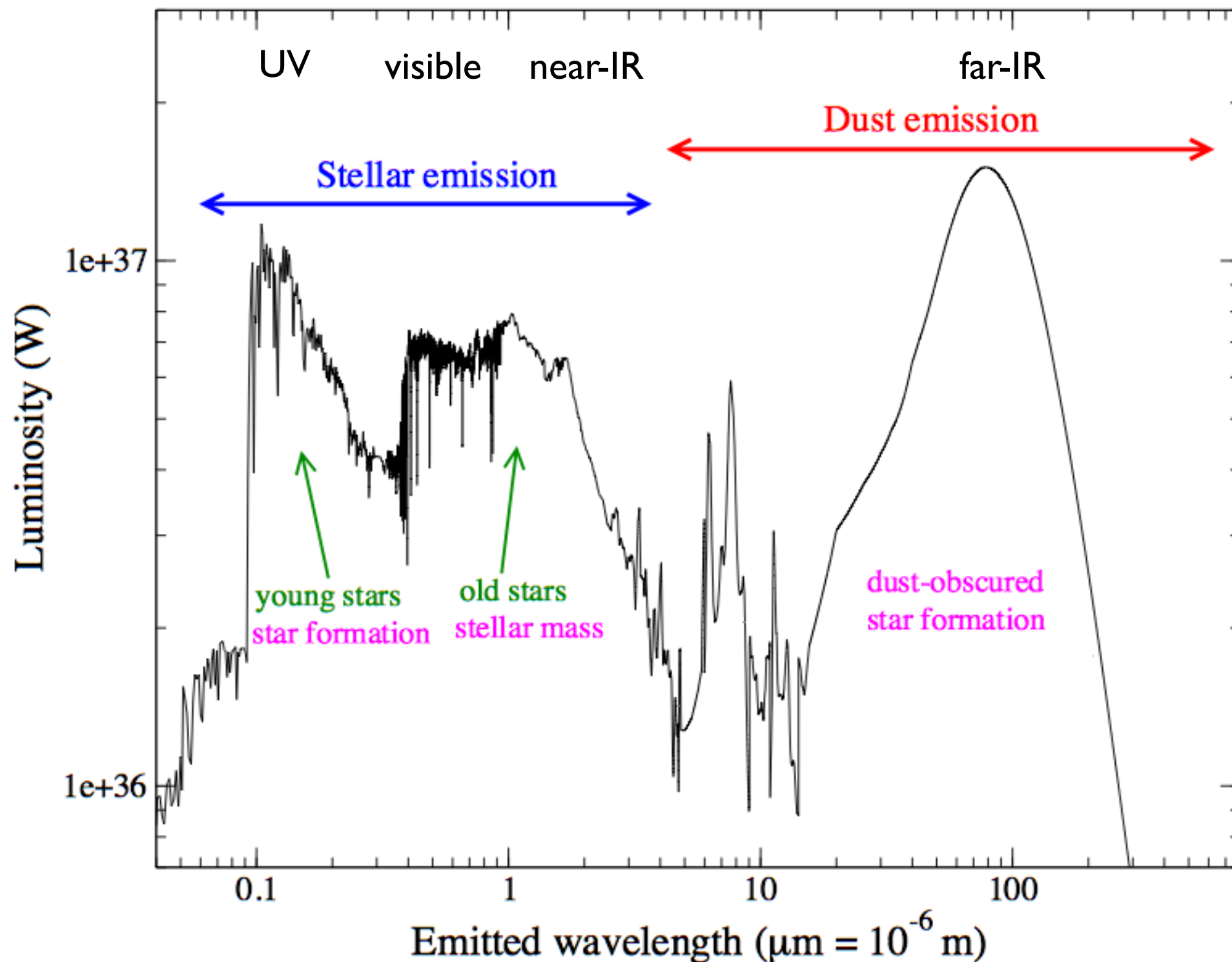
The Hubble Tuning Fork



The Hubble sequence holds up to $z \sim 1$

Qualitative classification

A Galaxy's Spectral Energy Distribution (SED)



The Sloan Digital Sky Survey (SDSS)

optical
images

The Sloan Digital Sky Survey

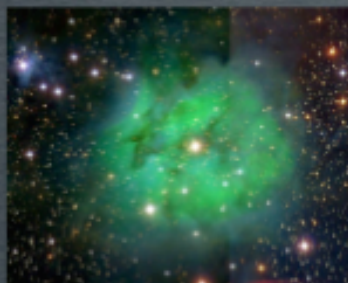


The most ambitious
survey of the sky ever
undertaken.

Imaging survey of 8600
square degrees.

Redshifts of more than
1,000,000 galaxies & QSOs.

Robotic 2.5m telescope - imaging & Spectroscopy



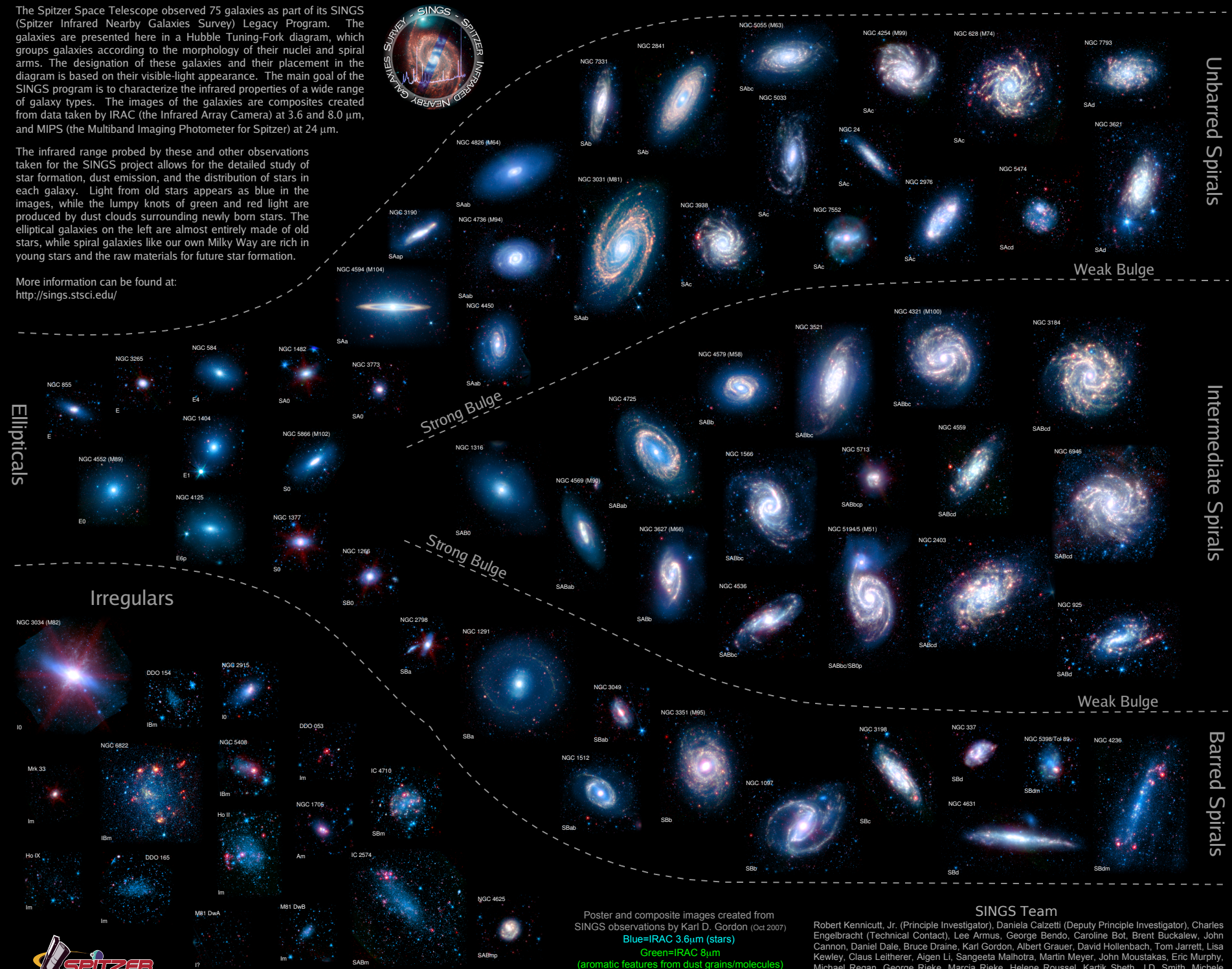
Spitzer provided images in mid-IR

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork

The Spitzer Space Telescope observed 75 galaxies as part of its SINGS (Spitzer Infrared Nearby Galaxies Survey) Legacy Program. The galaxies are presented here in a Hubble Tuning-Fork diagram, which groups galaxies according to the morphology of their nuclei and spiral arms. The designation of these galaxies and their placement in the diagram is based on their visible-light appearance. The main goal of the SINGS program is to characterize the infrared properties of a wide range of galaxy types. The images of the galaxies are composites created from data taken by IRAC (the Infrared Array Camera) at 3.6 and 8.0 μm , and MIPS (the Multiband Imaging Photometer for Spitzer) at 24 μm .

The infrared range probed by these and other observations taken for the SINGS project allows for the detailed study of star formation, dust emission, and the distribution of stars in each galaxy. Light from old stars appears as blue in the images, while the lumpy knots of green and red light are produced by dust clouds surrounding newly born stars. The elliptical galaxies on the left are almost entirely made of old stars, while spiral galaxies like our own Milky Way are rich in young stars and the raw materials for future star formation.

More information can be found at:
<http://sings.stsci.edu/>



Poster and composite images created from
SINGS observations by Karl D. Gordon (Oct 2007)

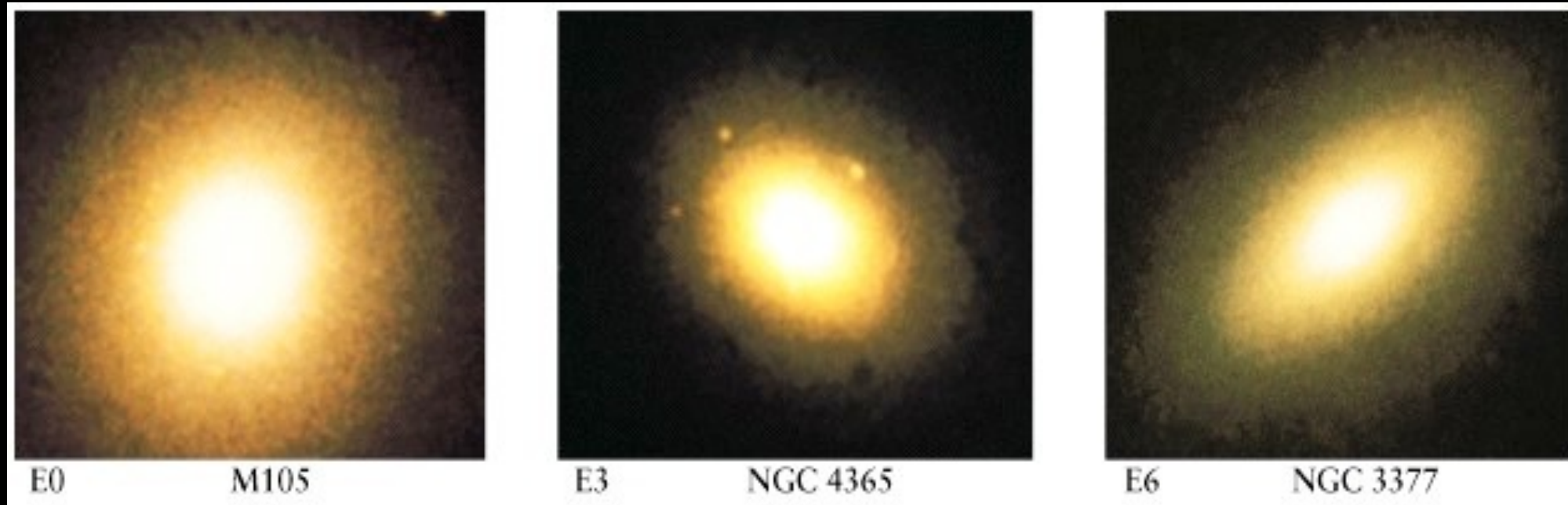
Blue=IRAC 3.6 μ m (stars)
Green=IRAC 8 μ m
(aromatic features from dust grains/molecules)
Red=MIPS 24 μ m (warm dust)

SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Alberto Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

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

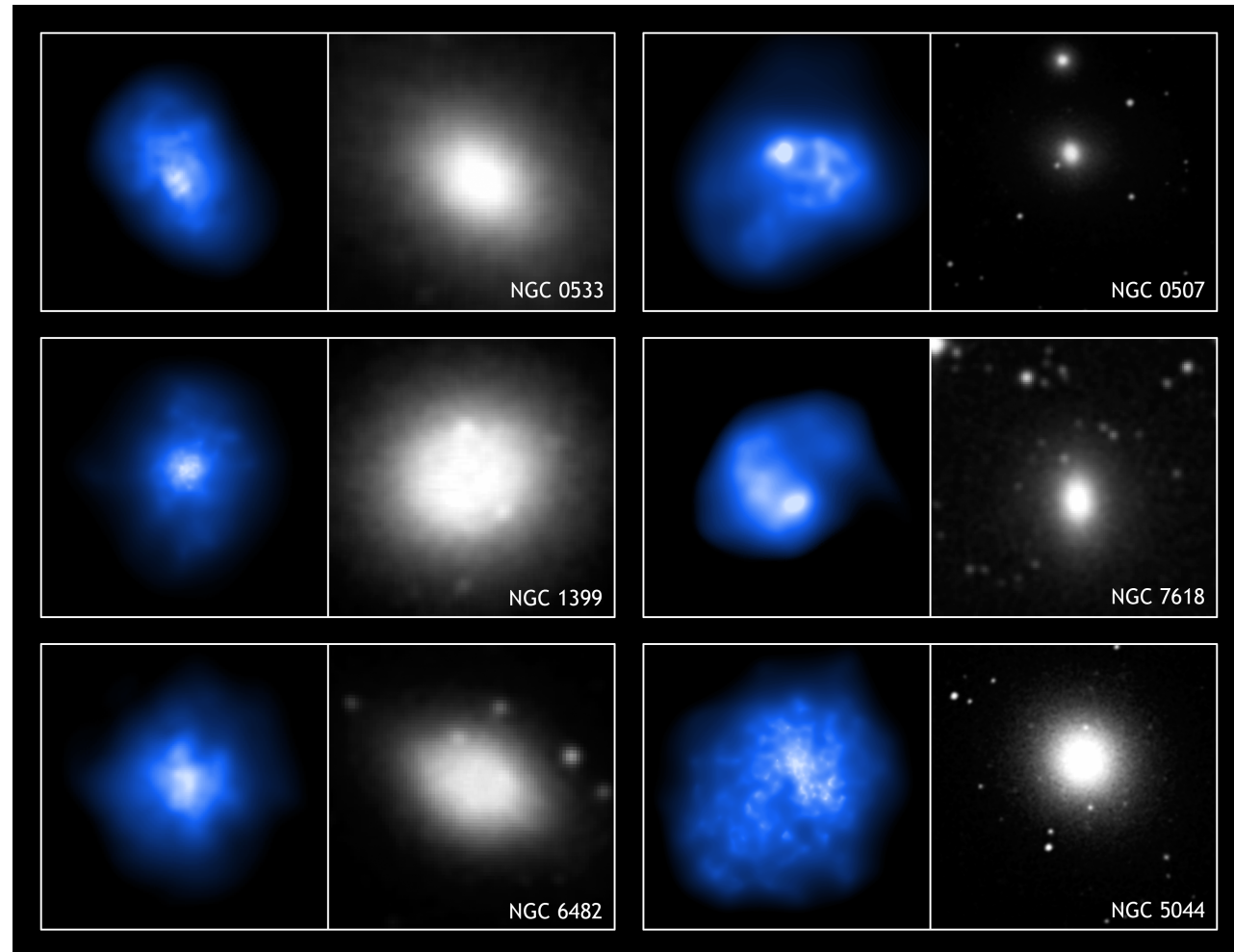
Shells in Cen A



...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.

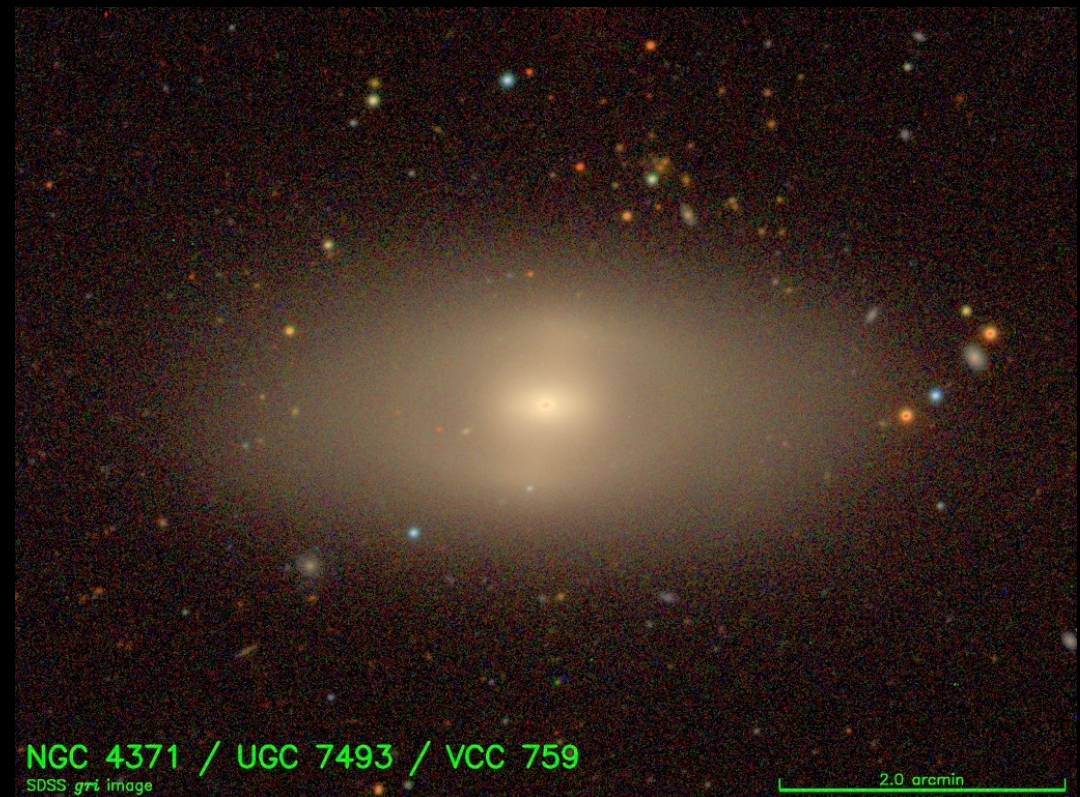
A correlation between the shape of the hot gas clouds and the power produced at radio wavelengths by high-energy electrons suggests this power source can be traced back to a super-massive black hole in the central regions.

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 $\rightarrow$ 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.

Basic points:

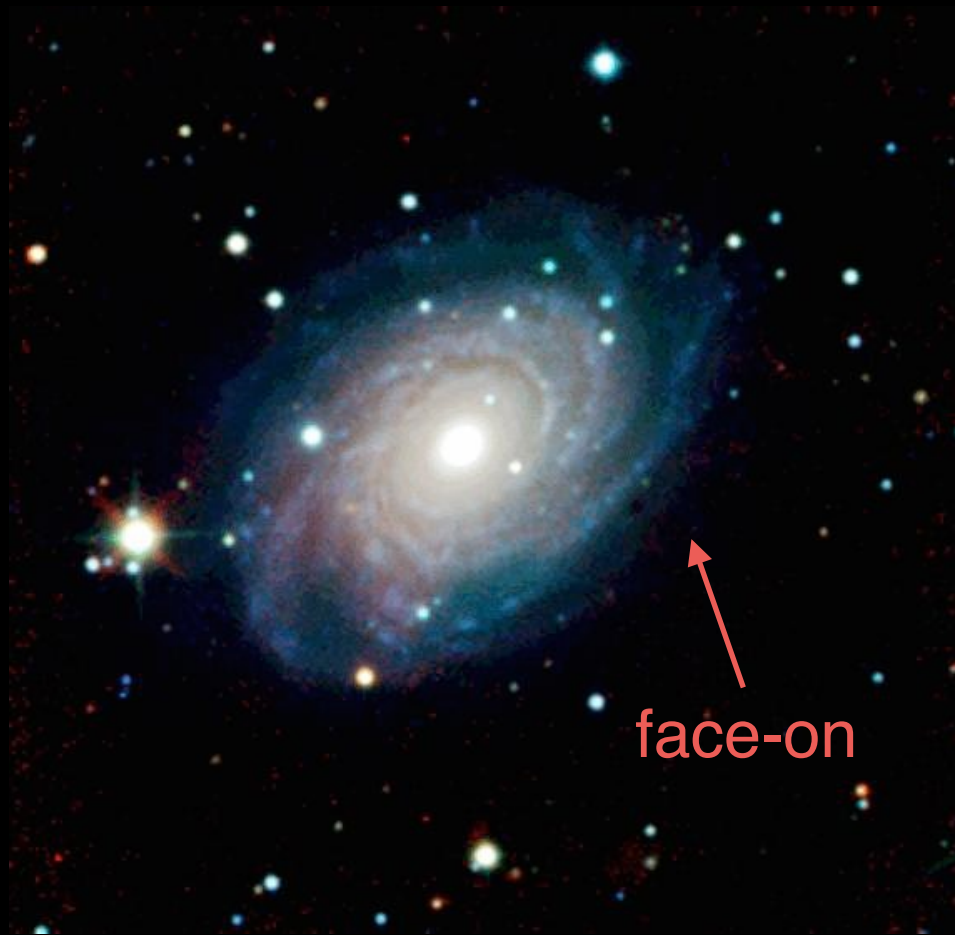
- disks are flat
- disks have spiral structure
- orbits are almost in a single plane
 - disks rotate
 - random motions are small
 - stars have a large range of ages

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



Spiral (Sa) Galaxies

Spiral (Sa) Galaxies:



face-on

NGC 3223: Sa-galaxy



edge-on

M 104 (Sombrero), Sa-galaxy

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

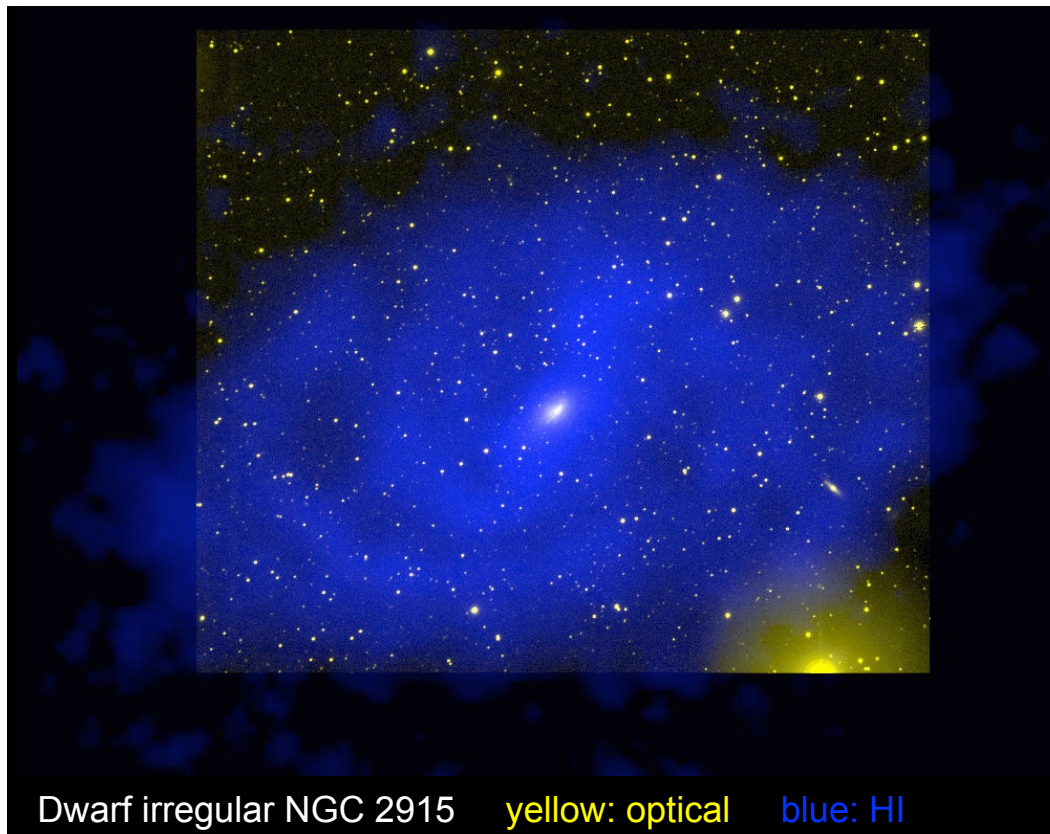
Dwarf Irregulars



I Zw 18 : BCD galaxy



Leo A: dIrr-galaxy

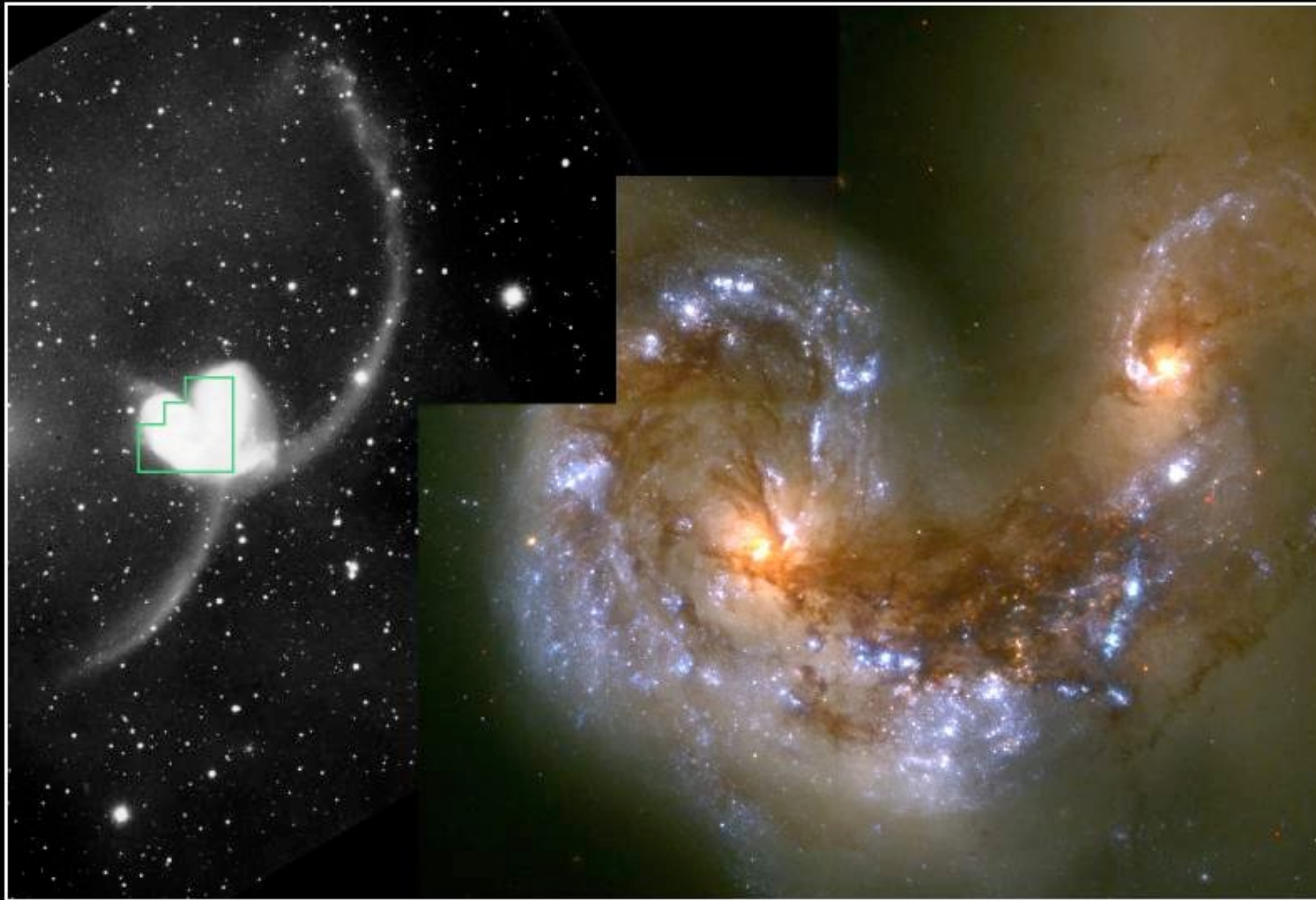


Dwarf irregular NGC 2915 yellow: optical blue: HI

Dwarf irregulars
usually have large
HI haloes

Galaxy Mergers

Collisions: Antennae

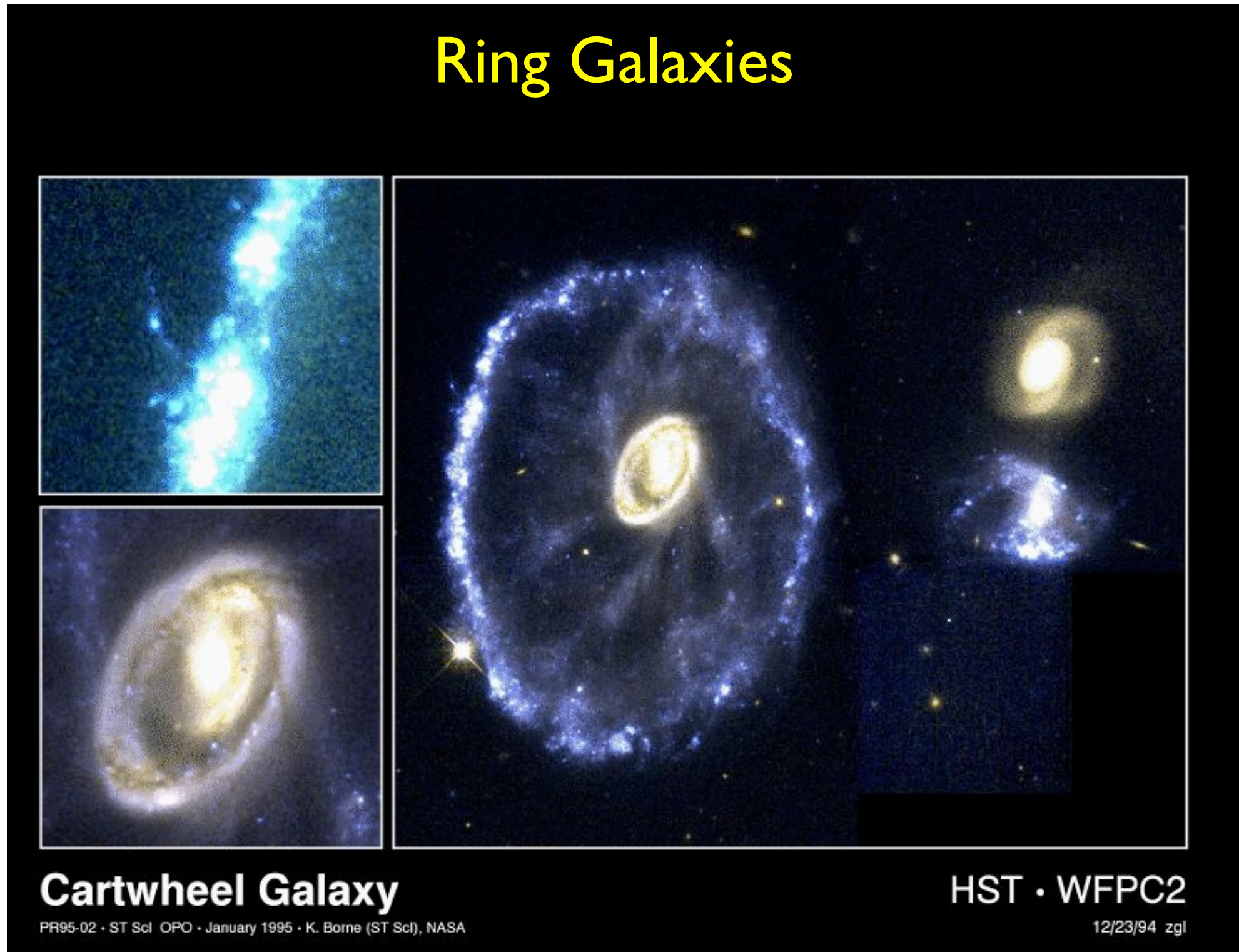


Colliding Galaxies NGC 4038 and NGC 4039

HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

Ring Galaxies



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

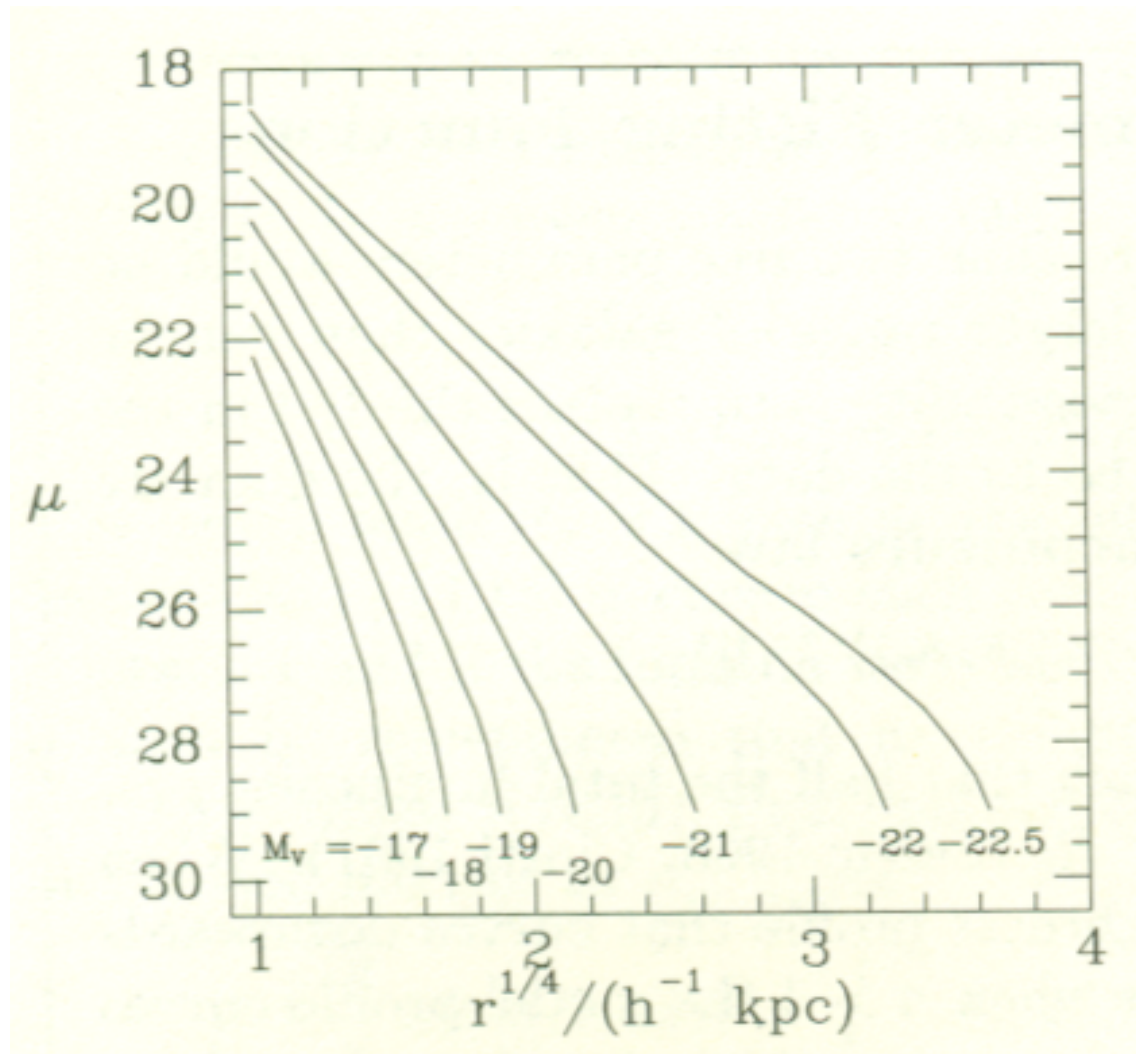
Galaxy Zoo Project

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

Quantitative Analysis

Light Profiles of Elliptical Galaxies

Characteristic surface brightness profiles for Es of different luminosities



from Binney & Merrifield, section 4.3

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

mag arcsec⁻²

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

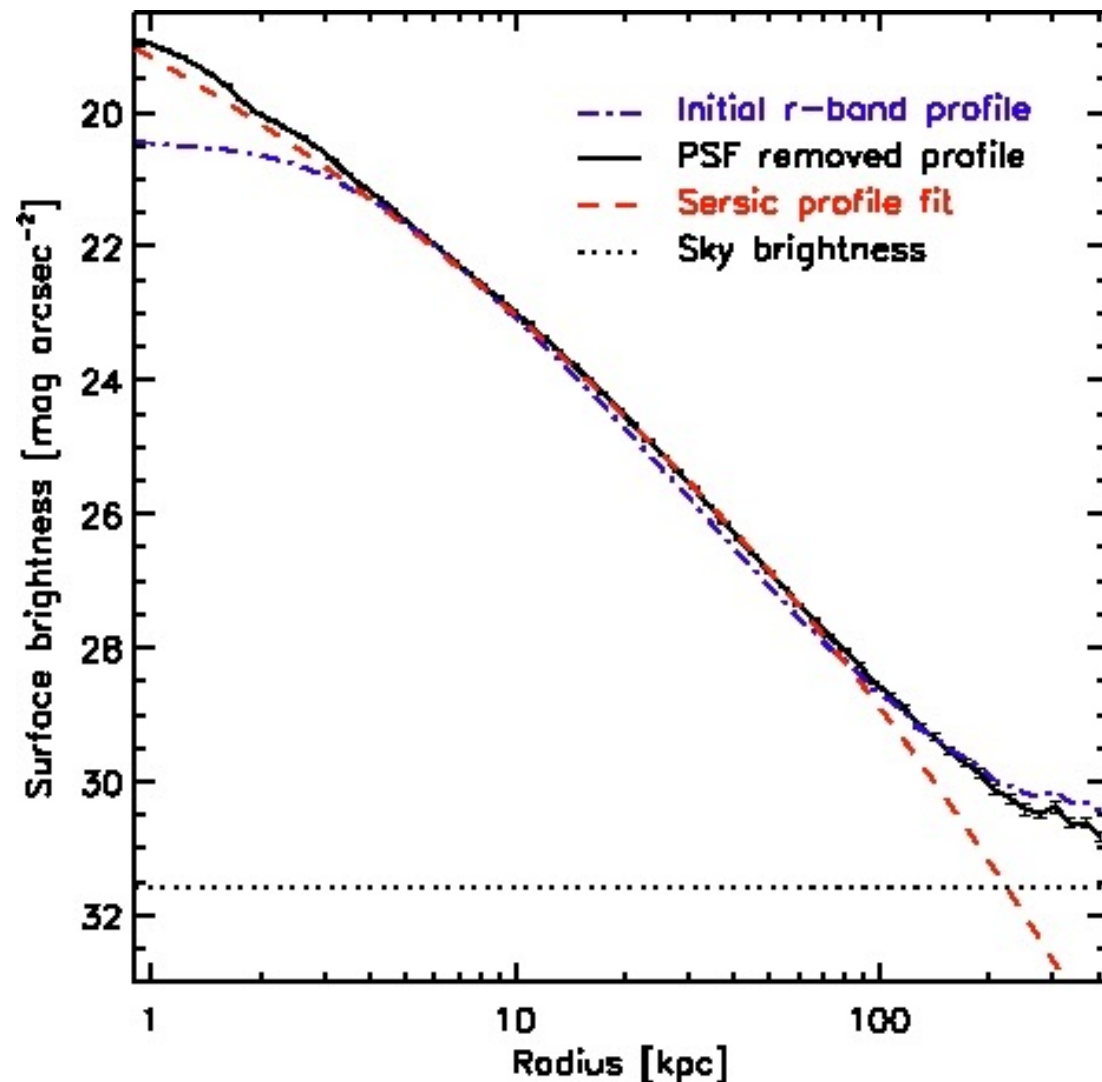
equivalent to:

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

de Vaucouleurs's law

The factor 7.67 is obtained after imposing that at $r=r_e$ the intensity ($I=I_e$) must be 1/2 of total. The total is obtained after integrating between $r=0$ and $r=\infty$.

General Light Profiles



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

3 free-parameter model

n = Sérsic index

$n = 1$ - exponential (pure disk)

$n = 4$ - de Vaucouleurs

Picture credit: P. Van Dokkum

General light profiles: $I(r) = I_0 \exp \left\{ -b_m \left[(r/r_c)^{1/m} - 1 \right] \right\}$

where $n = \text{Sérsic index}$

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

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

$$L = \int_0^{2\pi} \int_0^\infty I(r) r dr d\phi$$

this is an integrated flux
(not luminosity!)



2D - polar coord.
(r, θ).

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

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

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

$$\therefore L = 2\pi I_0 \alpha^2 m \int_0^\infty x^{2m-1} \exp(-x) dx$$

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 $\alpha = \frac{b_m}{r_c}$ scale change.

But remember

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

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

~~this eqn.~~

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

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

$\Downarrow$

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

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

For $m=1 \rightarrow m = \mu_0 - 5 \log_{10} \alpha - 2$

average mag
surface density

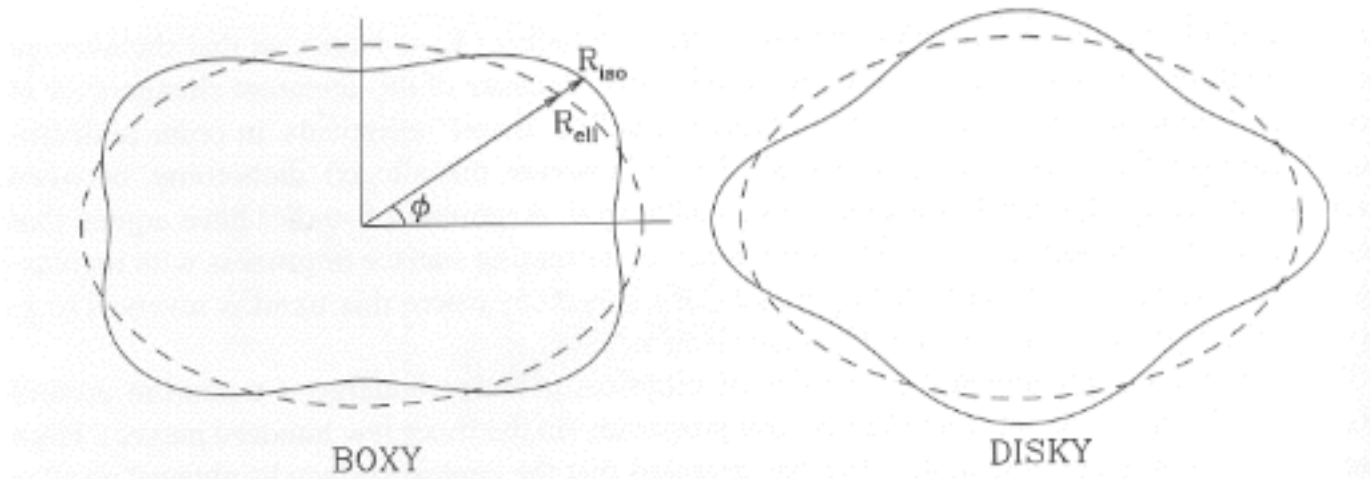
For $m=4 \rightarrow m = \mu_0 - 5 \log_{10} \alpha - 12.7$

Variations in Elliptical Light Profiles

$$x = a \cos t \quad y = b \sin t$$

Fourier decomposition

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



$$a_4 < 0$$

$$a_4 > 0$$

From Bender et al. (1998)

Variations in Elliptical Light Profiles II

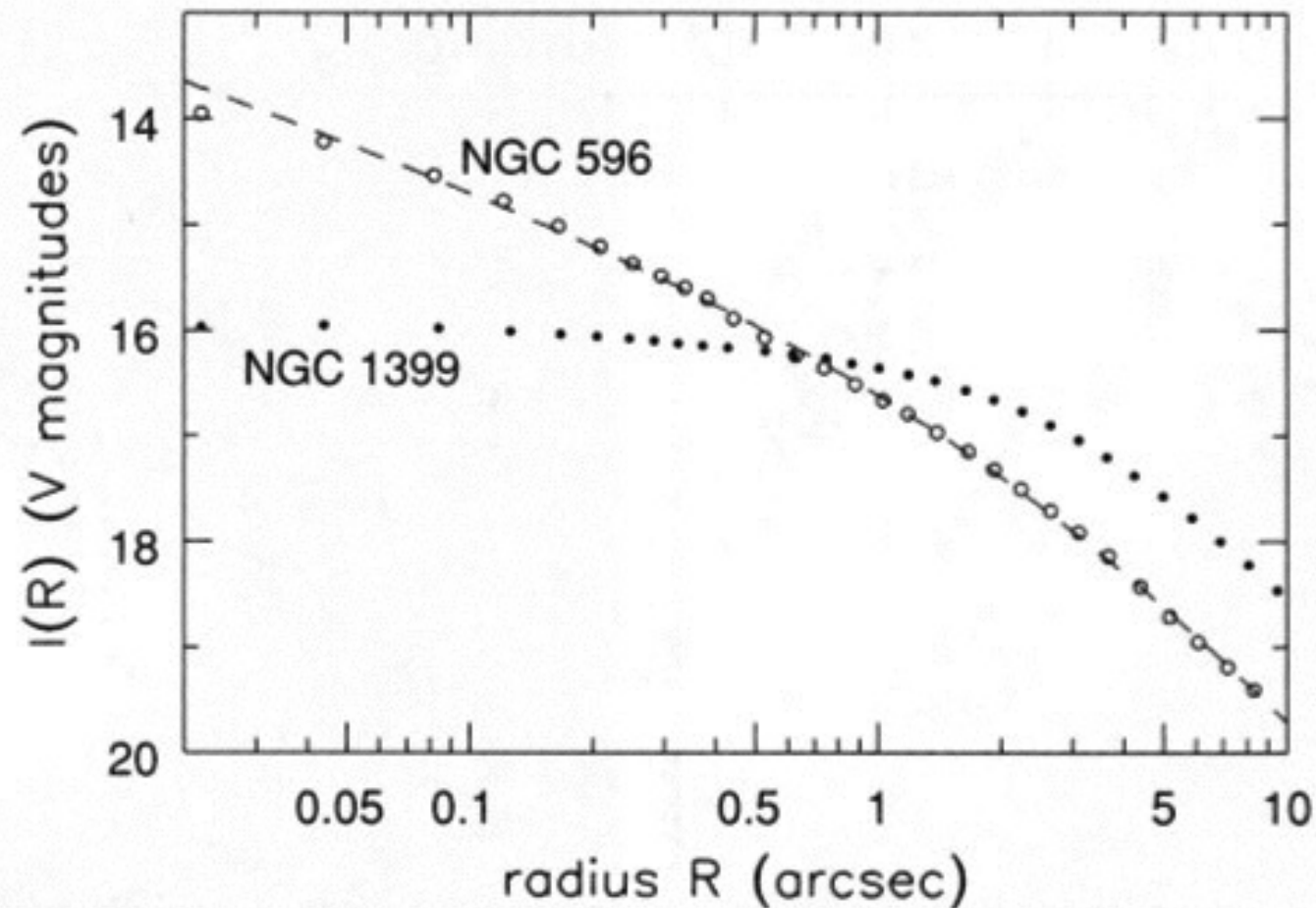


Fig. 6.7. Surface brightness $I_V(R)$ in the V band at the centers of two elliptical galaxies. The cD galaxy NGC 1399 ($M_V = -21.7$) has a *core* at $R \lesssim 1''$, where $I(R)$ is nearly constant. NGC 596 ($M_V = -20.9$) is half as luminous; the surface brightness continues to rise as a *cusp*. The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

Bulge and Disk Decomposition

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

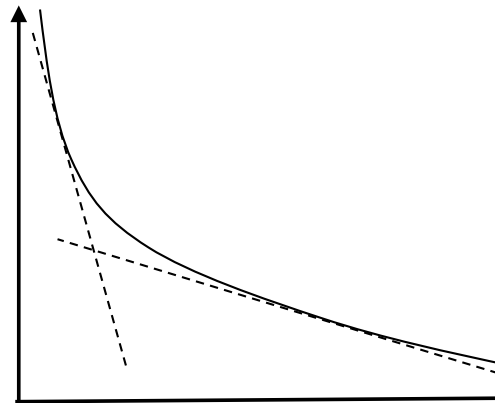
$$\Sigma(R) = \Sigma_0^{(d)} \exp(-R/R_d) + \Sigma_e^{(b)} \exp(-7.67 ([R/R_e]^{1/4} - 1))$$

- 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

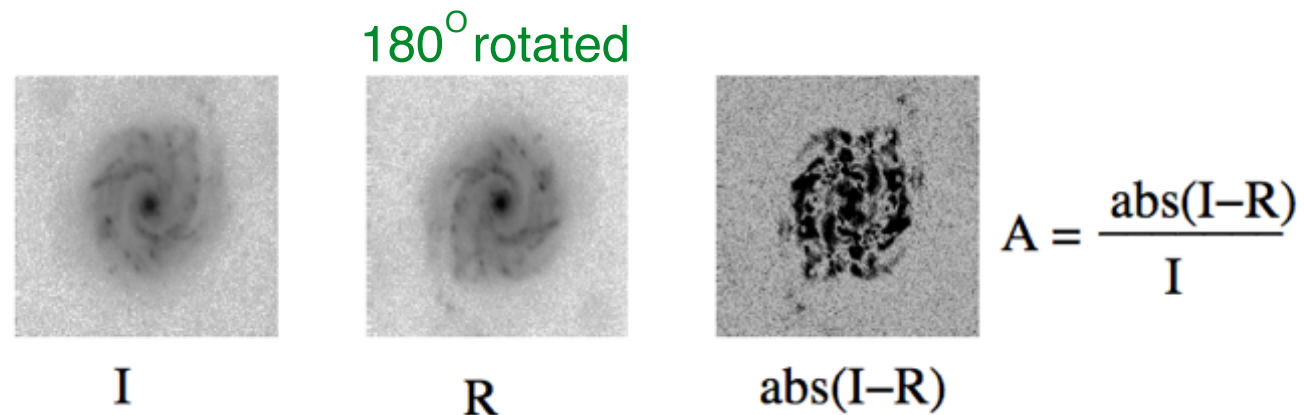
$$L = 2\pi \Sigma_0^{(d)} R_d^2 + 7.22\pi R_e^2 \Sigma_e^{(b)}$$



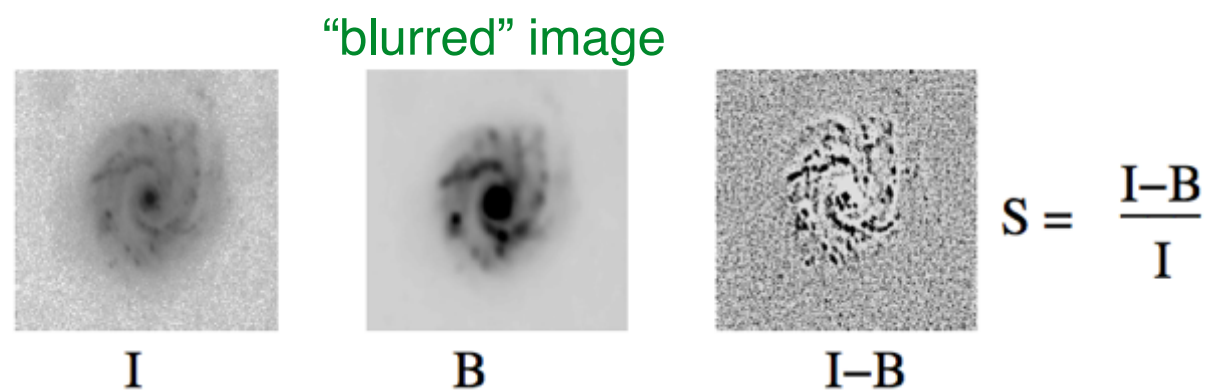
type	B/T
S0	0.65
Sa	0.55
Sb	0.3
Sc	0.15

The CAS classification

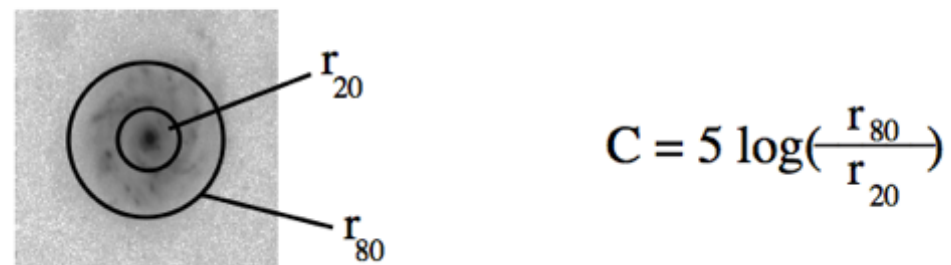
Non-parametric classification (does not assume any functional form)
Typically used for $z > 1$ galaxies



asymmetry



smoothness



concentration

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

$$\eta(r) = \frac{I(r)}{\underbrace{\langle I(<r) \rangle}_{\substack{\text{average} \\ \text{intensity} \\ \text{within radius } r}}} \quad \text{intensity in an annulus } (r-\delta r; r+\delta r)$$