Spiral & Elliptical Galaxies II

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Structure & Dynamics
Spirals

Spiral structure in disk galaxies

There are three main types of spiral arms

10%

"Grand Design", two well defined spiral arms

60%

Multiple-arm spiral arms

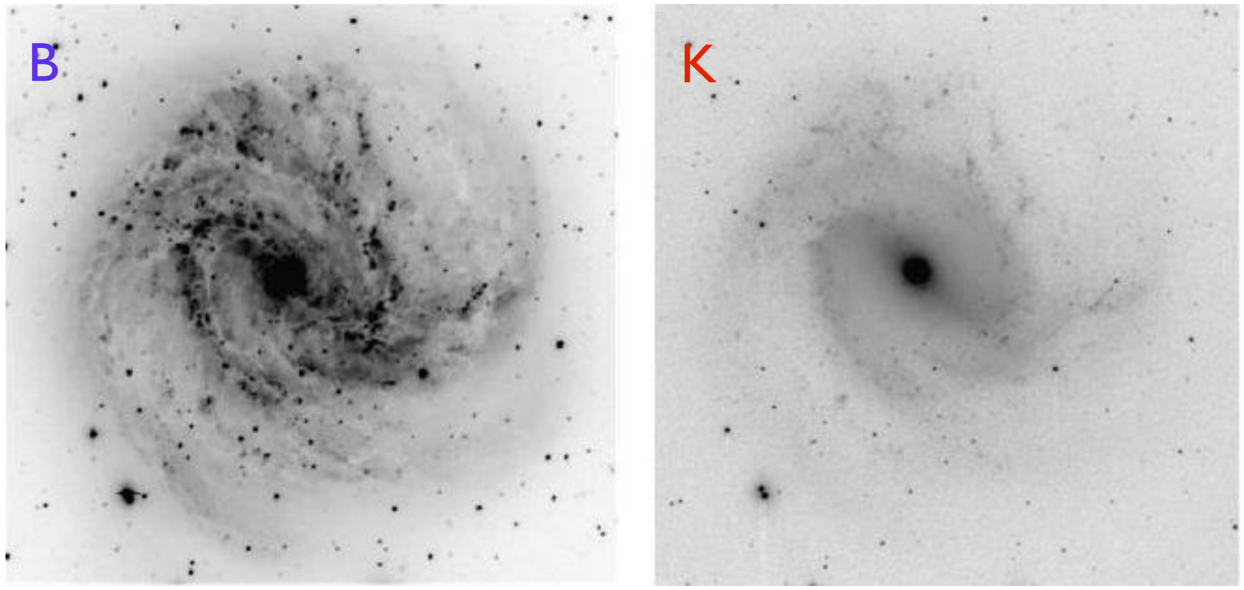
30%

Flocculent spirals - no well defined arms "ratty" structure

Spiral structure in disk galaxies (cont.)

Spiral structure seen in all bands, but is much smoother and less pronounced in redder bands

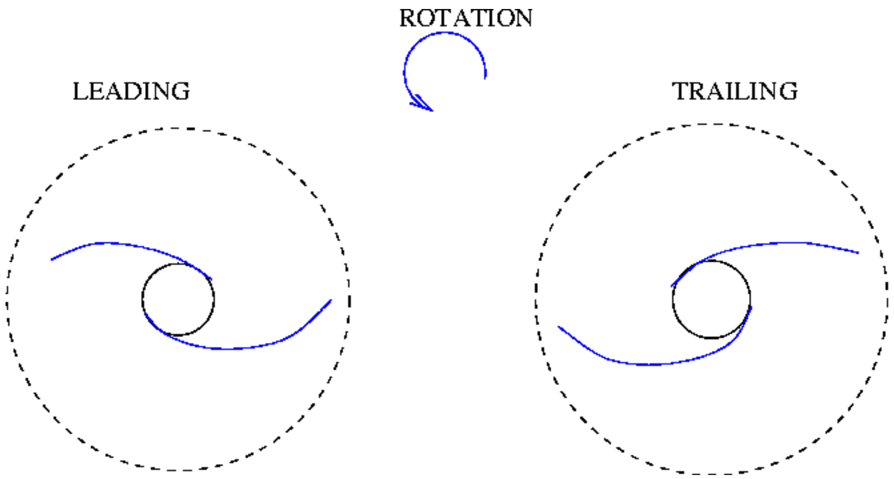
M83



The shapes of spiral galaxies are typically invariant under rotation about their centers

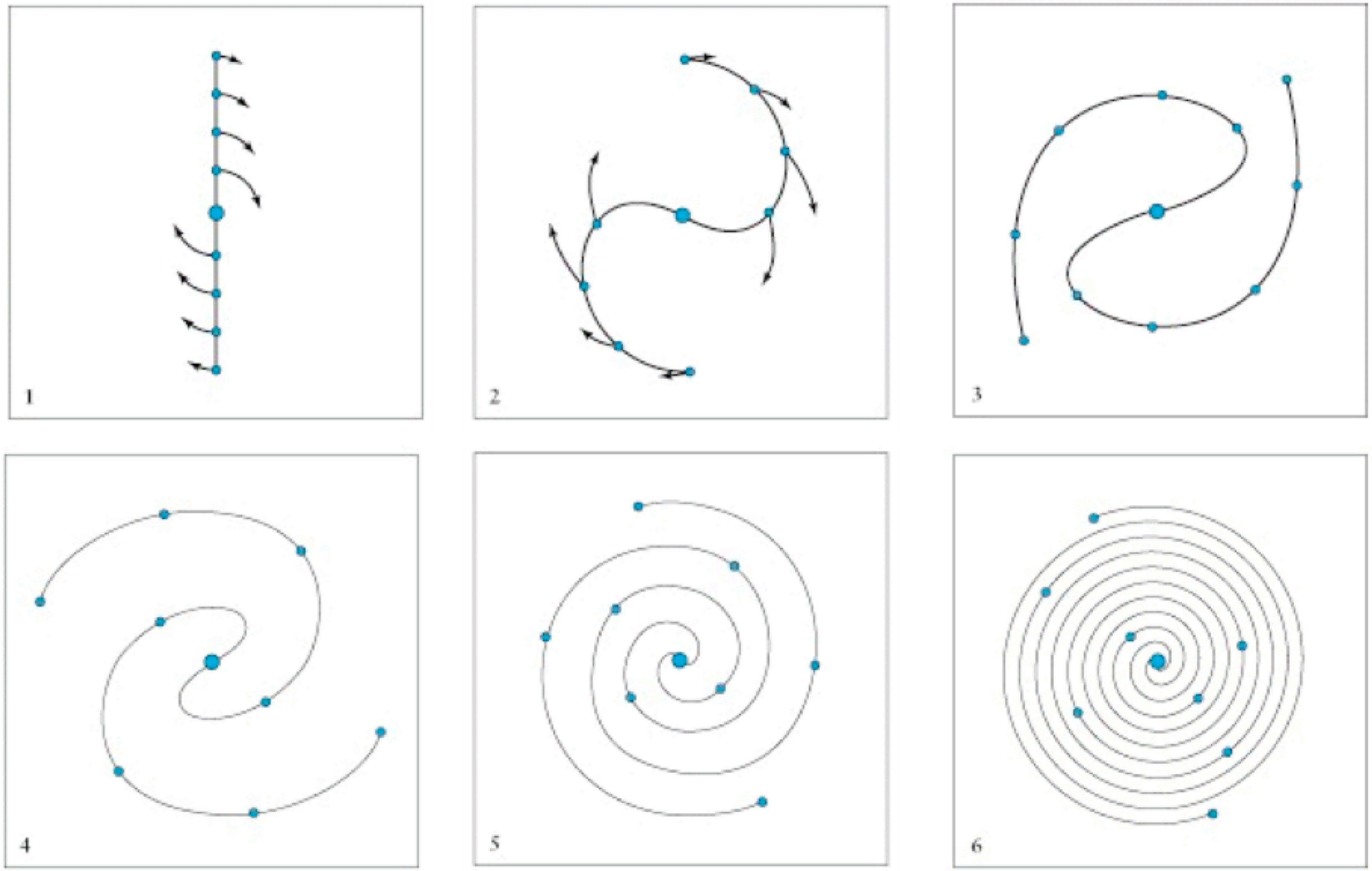
A galaxy that looks identical after a rotation of 2π/m has m-fold symmetry and has m spiral arms

Spirals are further classified by whether the arms are leading or trailing the rotation direction



most spiral arms are trailing

The expected spiral pattern…

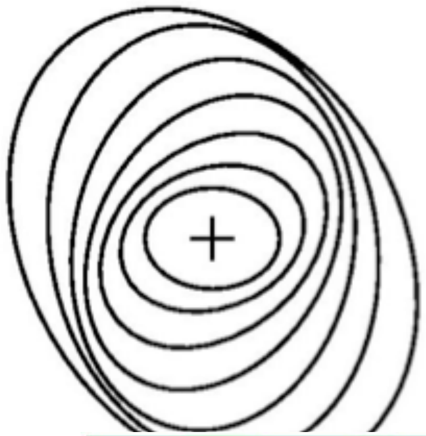


…but this does not happen…

Density waves

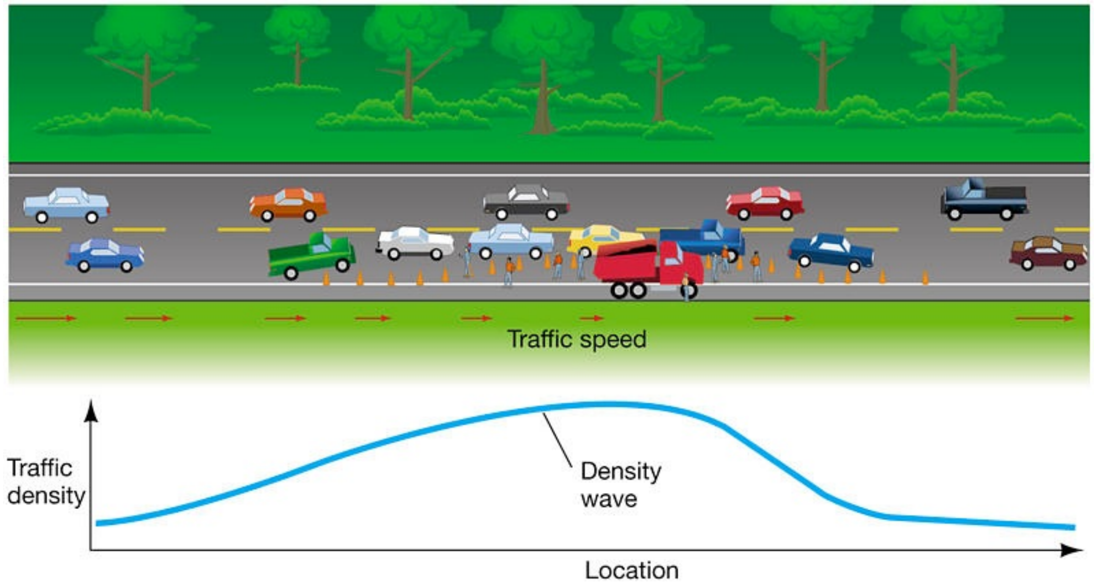
It seems likely that spiral arms are created by a density perturbation that moves along at a speed different from the objects around it. The density wave resists the spiral's tendency to wind up and causes a rigidly rotating spiral pattern. Like slow moving traffic on the highway.

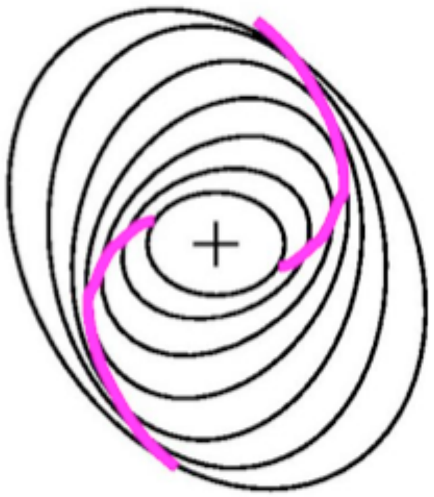
Pattern Speed - fixed angular speed of density wave rotating through galaxy.



There is an initial "seed" perturbation in the spiral disc. These come from either initial asymmetries in the disk and/or halo (galaxy formation processes), or induced via galaxy encounters.

Thus there are regions of slightly higher density than their surroundings. The higher density accelerates matter into the wave.



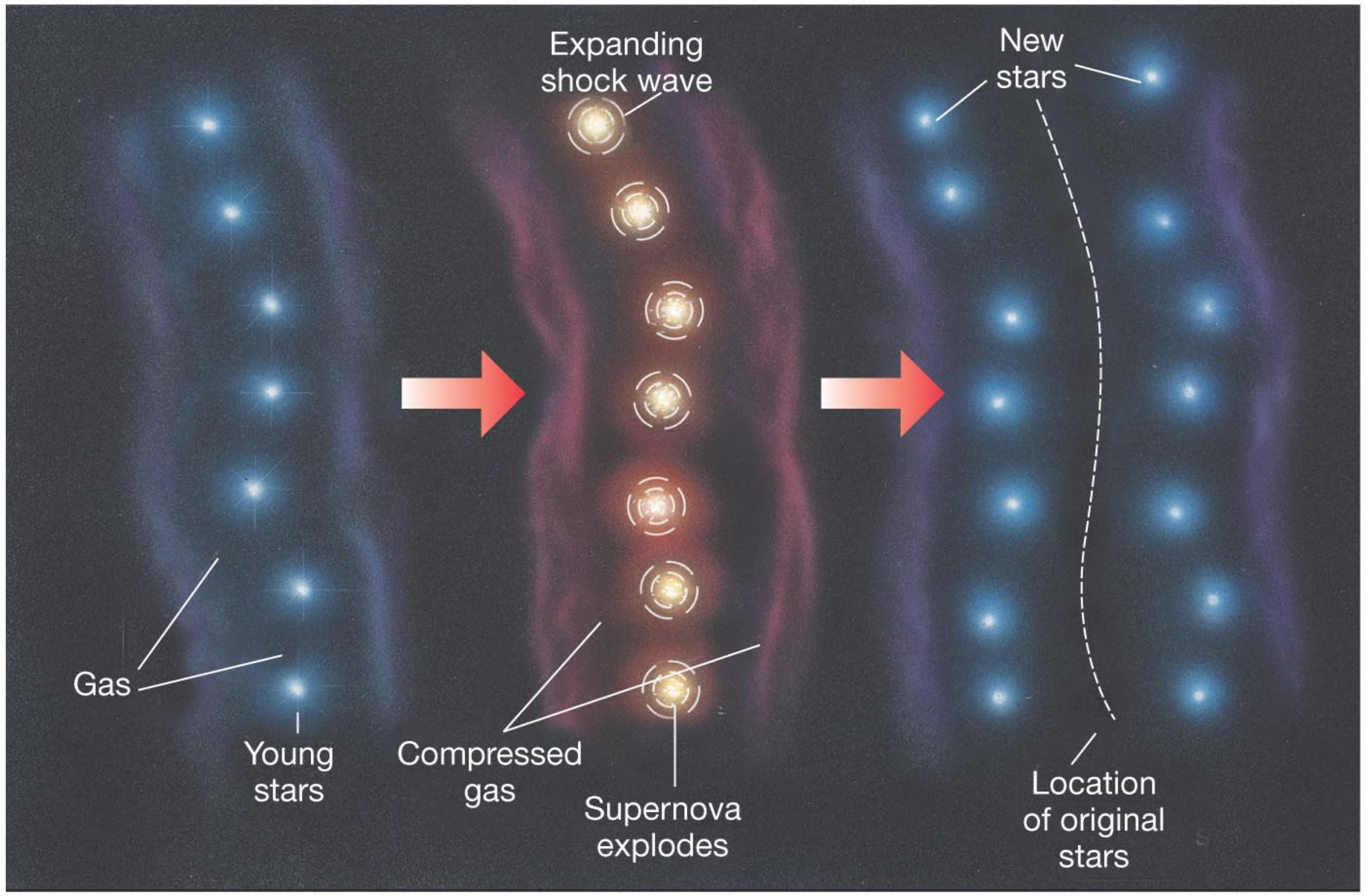


Spiral arm pattern is amplified by resonances between the epicyclic frequencies of the stars (deviations from circular orbits) and the angular frequency of the spiral pattern

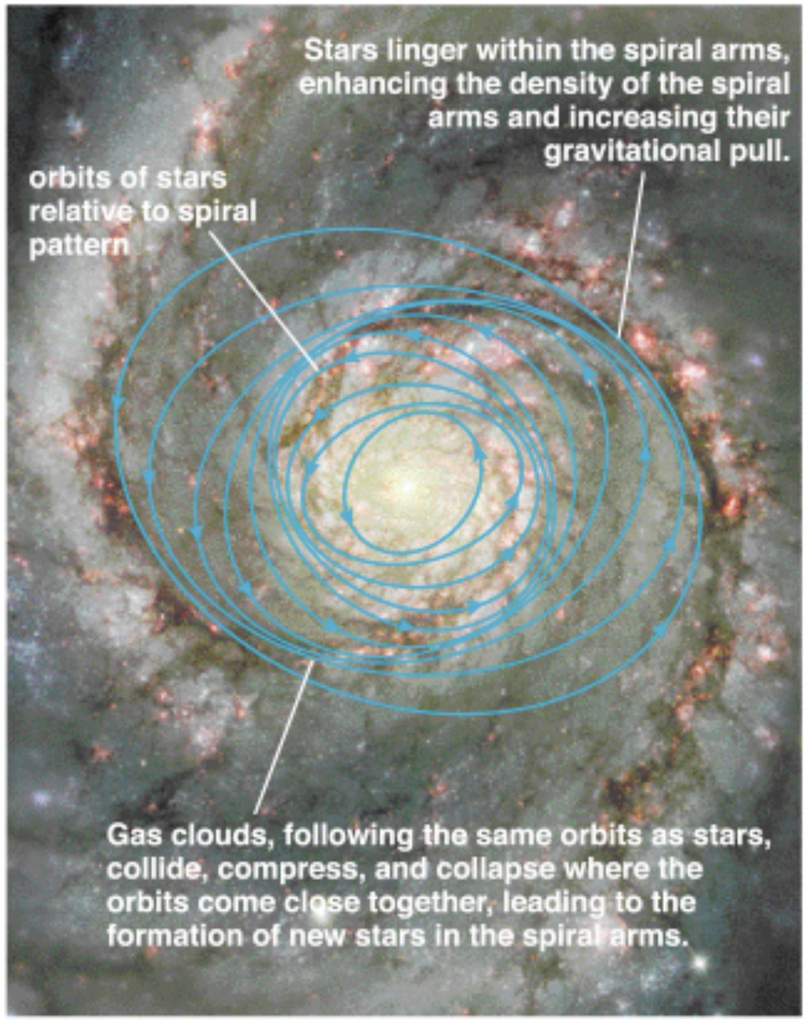
Self-propagating star formation

density wave theory can't explain flocculant spirals, but these can be explained by self-propagating star-formation.

star formation produces supernovae, which shock the gas, and triggers more star formation, and then differential rotation stretches out the regions of star formation into trailing fragmentary arms with no global symmetry.



(a)



Structure & Dynamics
Ellipticals

The centres of elliptical galaxies

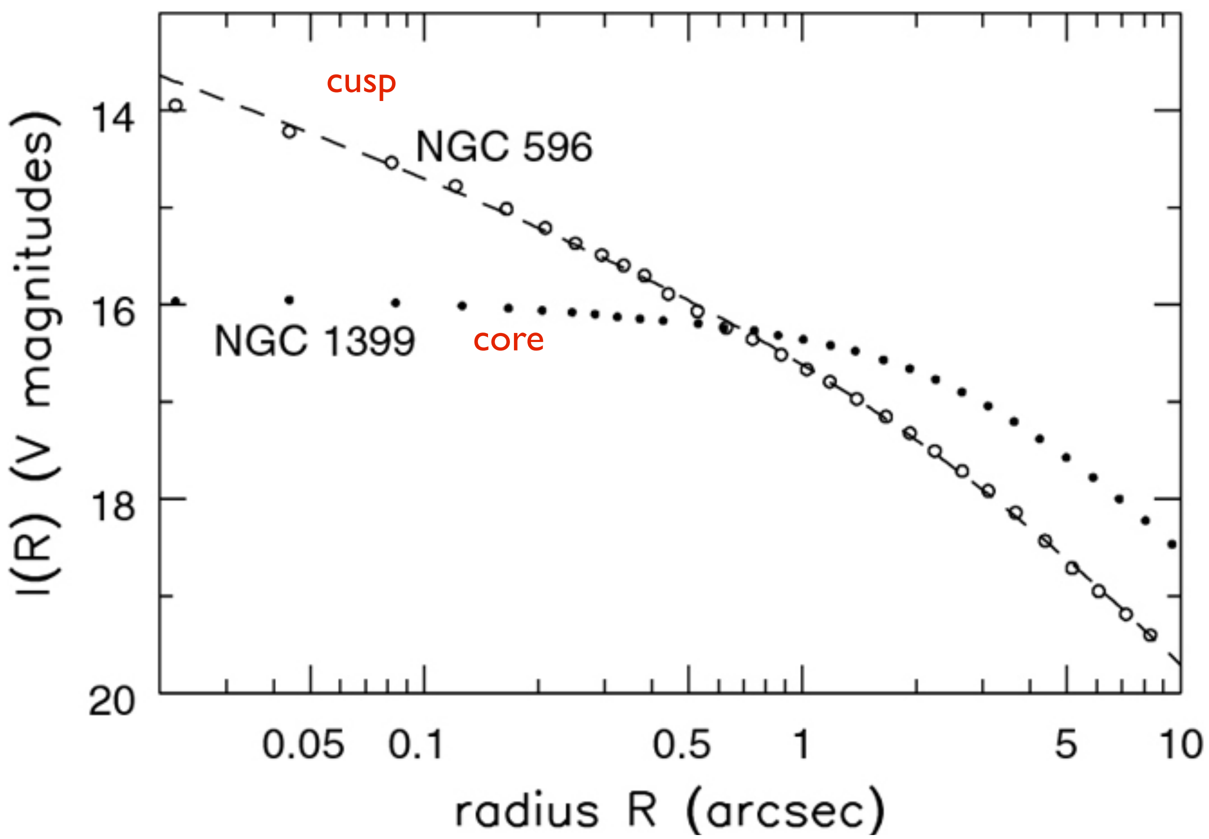
Observations from space suffer no seeing because there is no atmosphere!

Don't think that space observations have a δ-function PSF, though — the optics themselves impose a PSF...

Ellipticals have either a

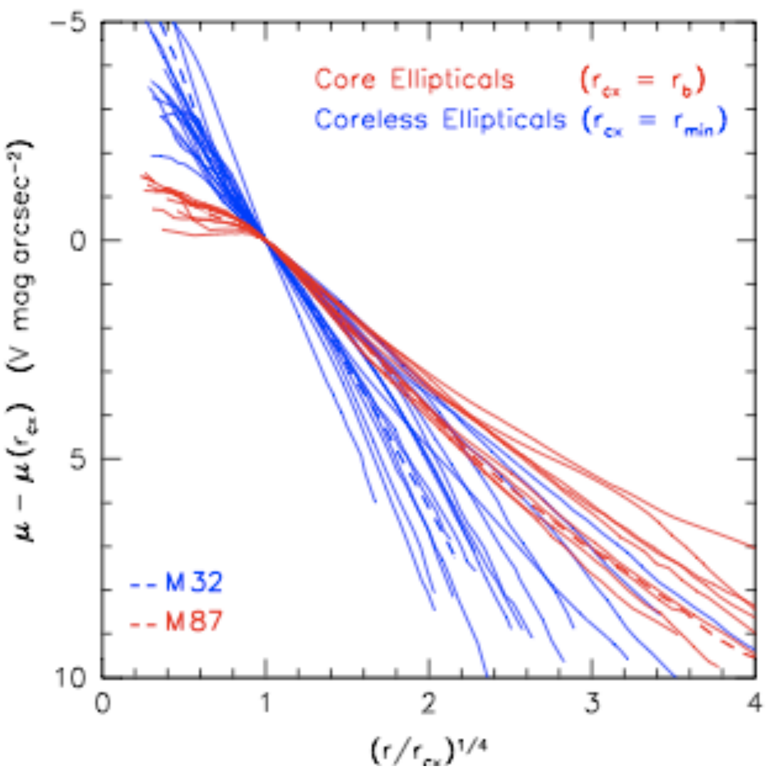
core: giant ellipticals

cusp: intermediate ellipticals (note that there is still a break radius)



The centres of elliptical galaxies (cont.)

- $R^{1/4}$ and Sersic fits tend to fail in the inner regions of Elliptical
- Regions of special interest because they host supermassive black holes
- Need HST since largest E's lie far away and seeing effects degrade profile centers



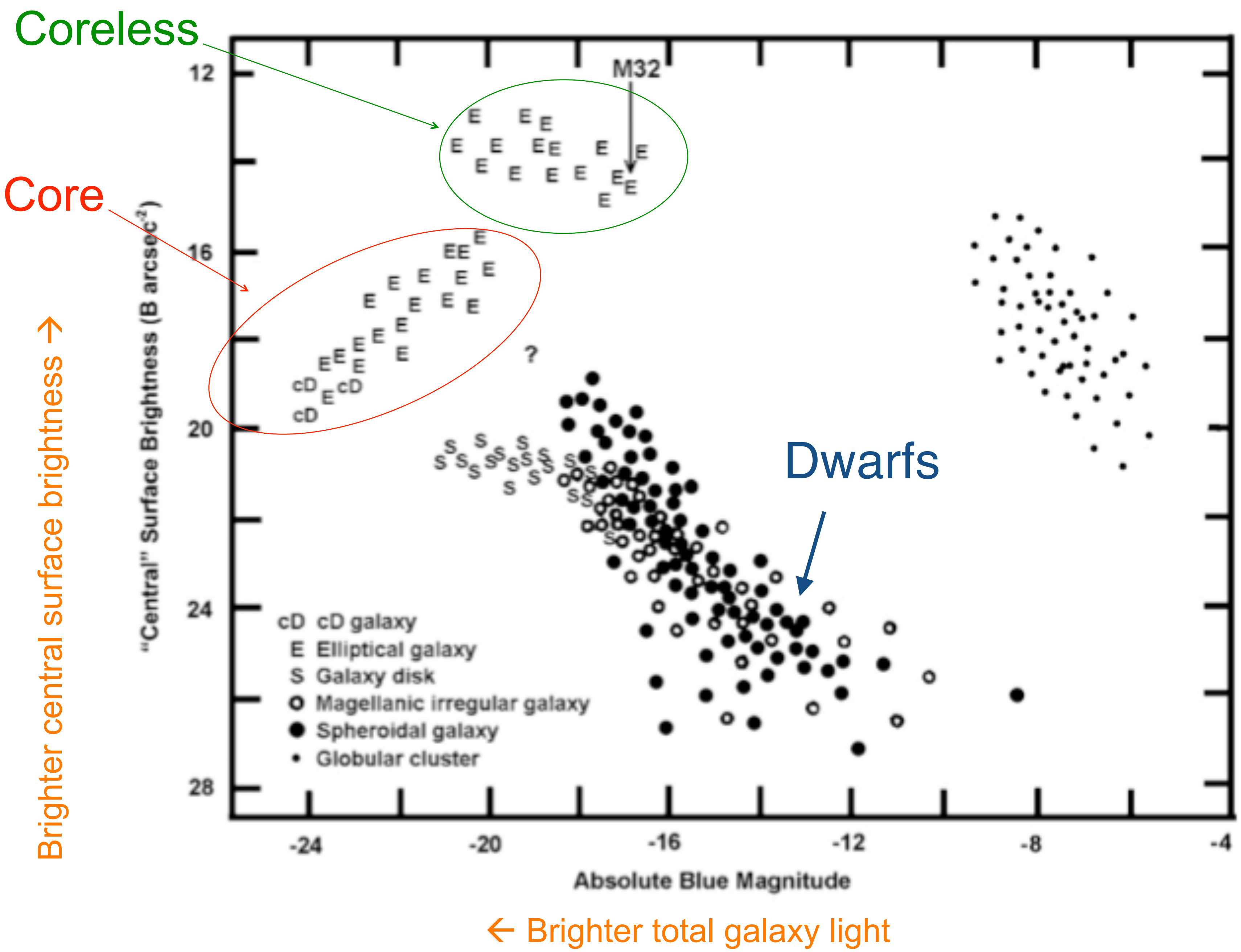
- More luminous E's (M_v<-21.7) tend to have **cores**, where the SB profile flattens towards center

- Midsize E's (-21.5<M_v<-15.5 with $L<2\times10^{10}L_{\odot}$) are typically **core-less** systems where the SB profile steeply rises to centre

- Cores could be the result of mergers so central nucleus is more diffuse – caused by binary BHs scouring out centers in "dry mergers" (no gas)

- Core-less also reveal "extra light" which may be result of nuclear starburst resulting from "wet mergers" (with gas)

Three classes of elliptical galaxies

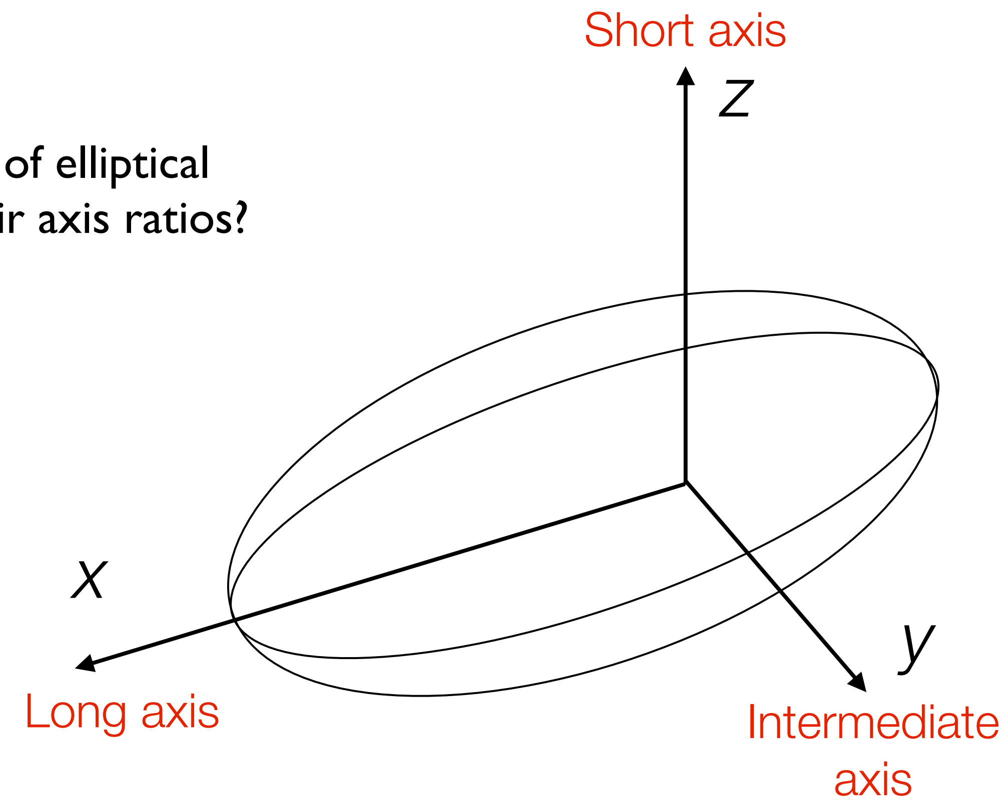


Shapes of Elliptical Galaxies

What, can we learn about the intrinsic shapes of elliptical galaxies from the observed distribution of their axis ratios?

In the most general case, the luminosity density $\rho(x)$ can be expressed as $\rho(m^2)$, where

$$m^2 = \frac{x^2}{\alpha^2} + \frac{y^2}{\gamma^2} + \frac{z^2}{\beta^2}$$



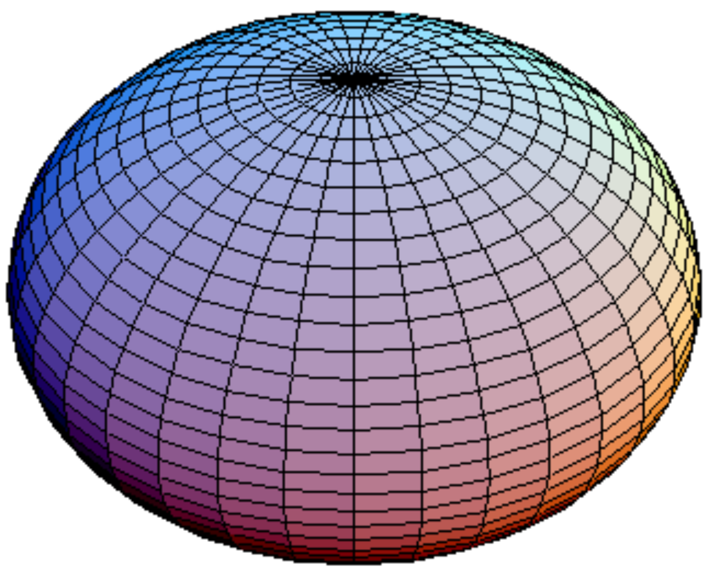
The contours of constant density are ellipsoids with m^2=constant

$\alpha \neq \beta \neq \gamma$: triaxial (three unequal axes; no axis of symmetry)

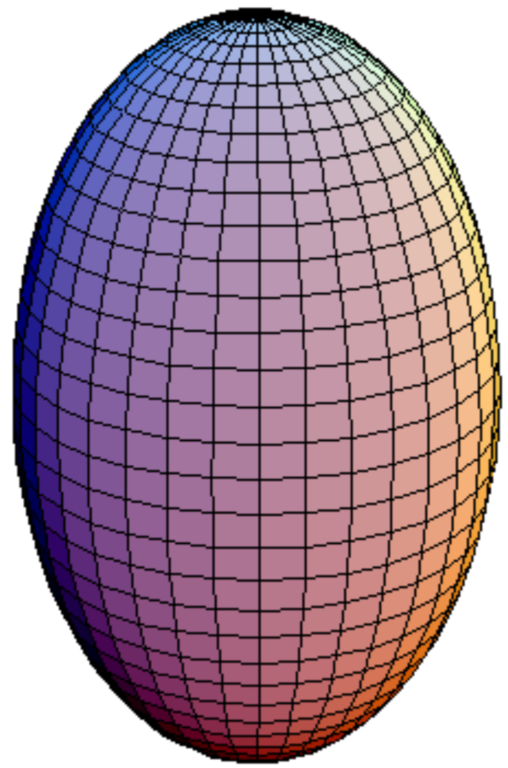
$\alpha = \gamma < \beta$: prolate (cigar-shaped)

$\alpha = \gamma > \beta$: oblate (pancake-shaped)

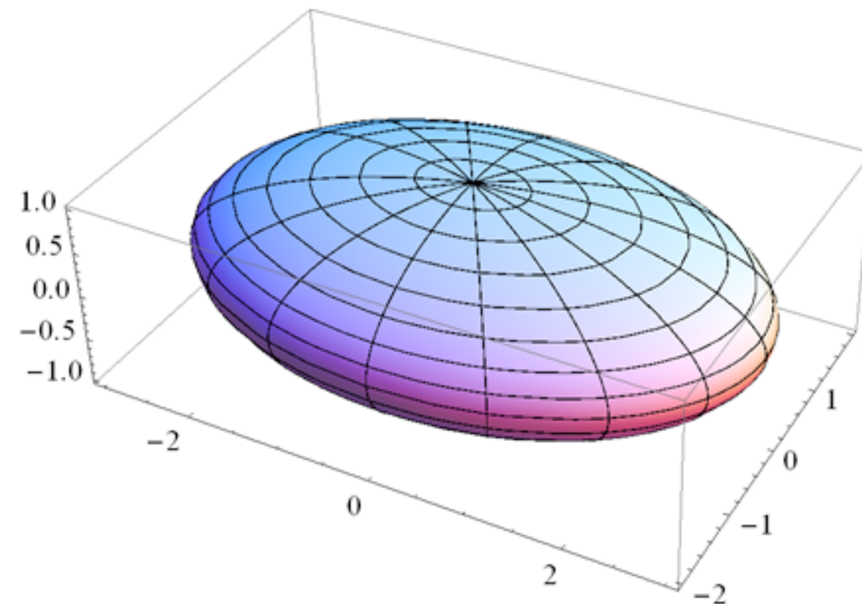
Family of Ellipsoids



Oblate



Prolate



Triaxial

Deviation from elliptical isophotes

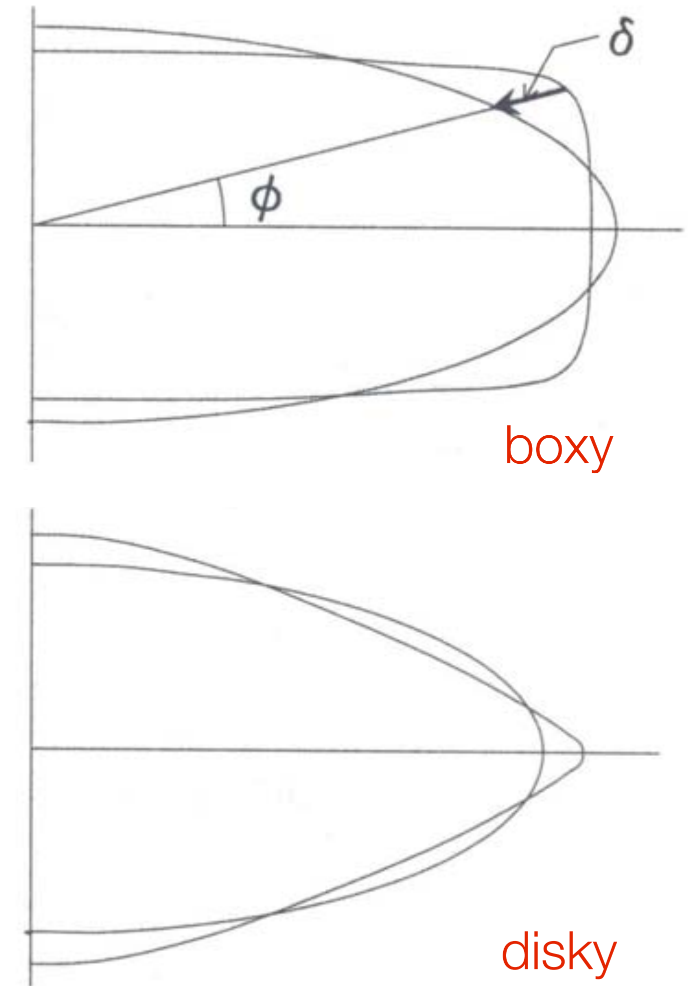
The diskiness/boxiness of an isophote is measured by the difference between the real isophote and the best-fit ellipse:

$$\delta(\phi) = \langle\delta\rangle + \sum_n (a_n \cos n\phi + b_n \sin n\phi)$$

If the isophotes have 4-fold symmetry (typical), then terms with n<4 and all b_n should be small, and a_4 gives the shape:

$a_4<0$: boxy

$a_4>0$: disky



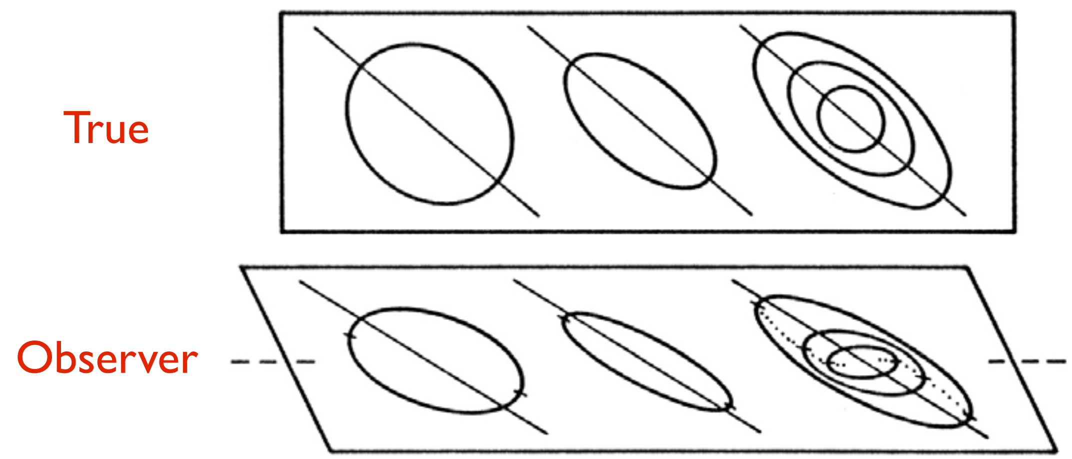
Boxy/disky & isophotal twisting

If the intrinsic shape of a galaxy is triaxial — that is, all three principal axes have different lengths — then the orientations of the projected ellipses depend on the inclination of the galaxy to the line of sight and the galaxy's true axis ratios

Because the ellipticity changes with radius, even if the major axis of all the ellipses have the same true orientation, they will appear as if they were rotated in the projected image

<u>This is isophote twisting</u>

Isophote twisting is generally taken to imply triaxiality, but it is impossible to distinguish a real twist from true triaxiality from images alone...



Boxy vs. Disky

In general,

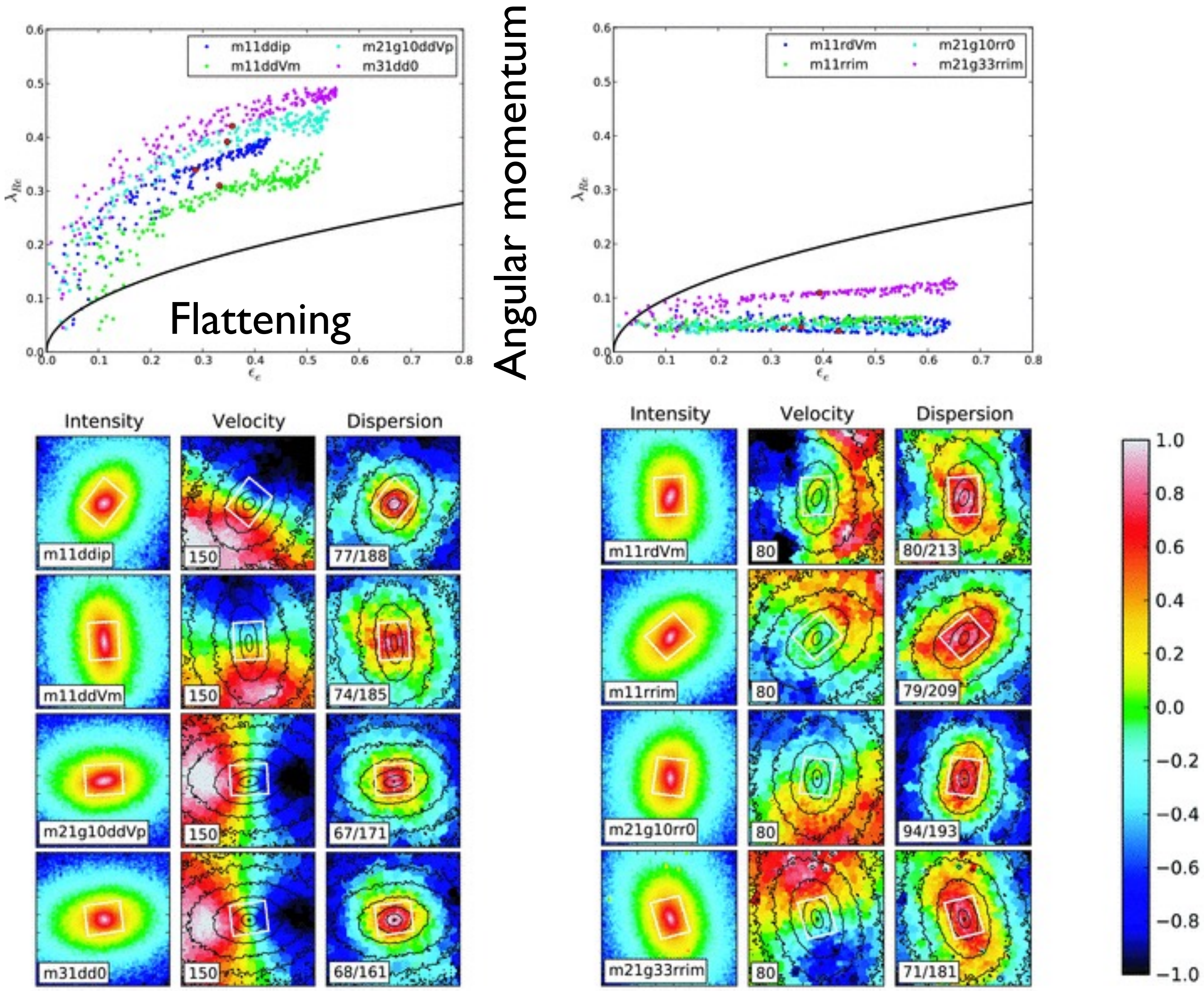
<u>Boxy galaxies</u> are

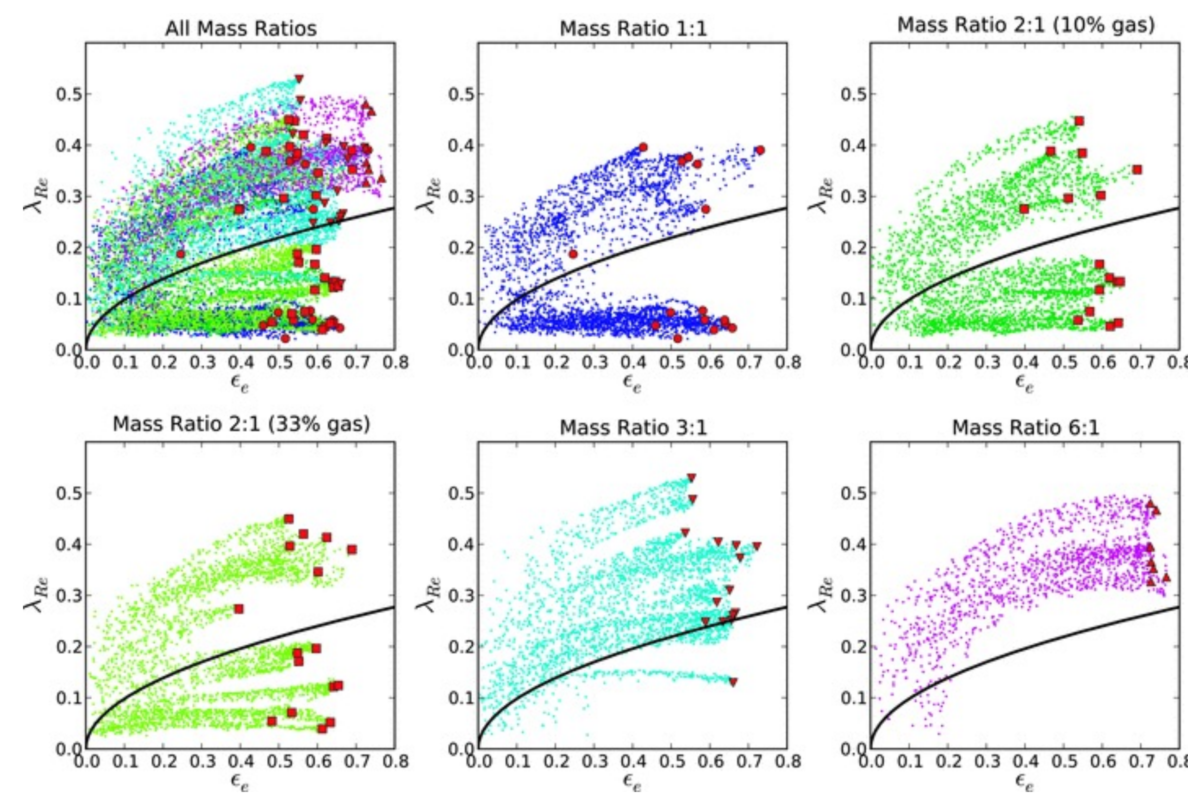
- more luminous
- more likely to show isophote twists
- probably triaxial

<u>Disky galaxies</u> are

- intermediate ellipticals
- often oblate
- faster rotators

Slow and fast rotators





slow and fast rotators are the consequence of different types of galaxy mergers

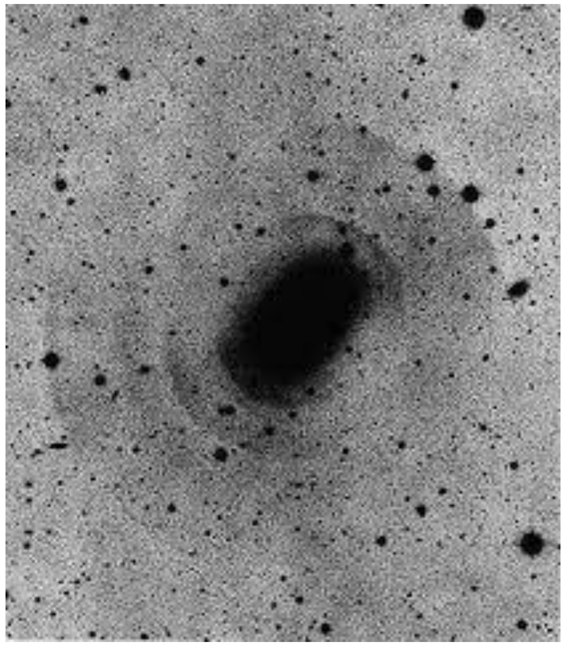
Bois et al. (2011)

See also Cappellari et al. (2011)

Fine structure in ellipticals

~10-20% of ellipticals show distinct "edges" in their surface brightness profiles, known as shells

Probably the result of the accretion (or merger) of a small galaxy that was originally on a nearly radial orbit



NGC 3923

Image: AAO

density waves produced by gravitational interaction produce "ripples" in the galaxy

in some cases there are kinematically decoupled cores, suggesting the existence of a complex formation history for the galaxy

NGC 474
NGC 470

Image: J.-C. Cuillandre (CFHT)

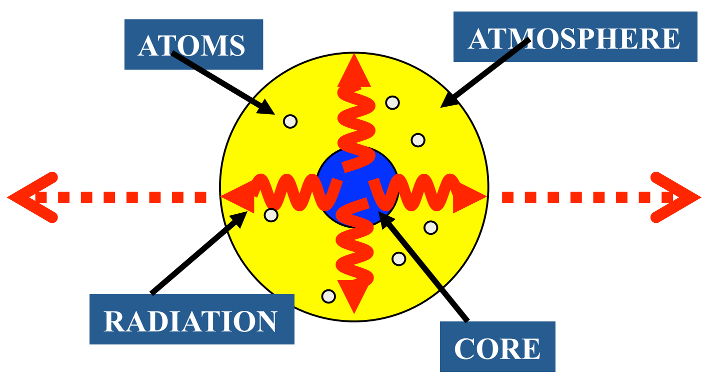
Spectral Properties

Absorption and emission lines in galaxy spectra

Absorption Lines

- Mainly caused by Atoms/Molecules in a star's atmosphere that absorb specific wavelengths

stellar lines

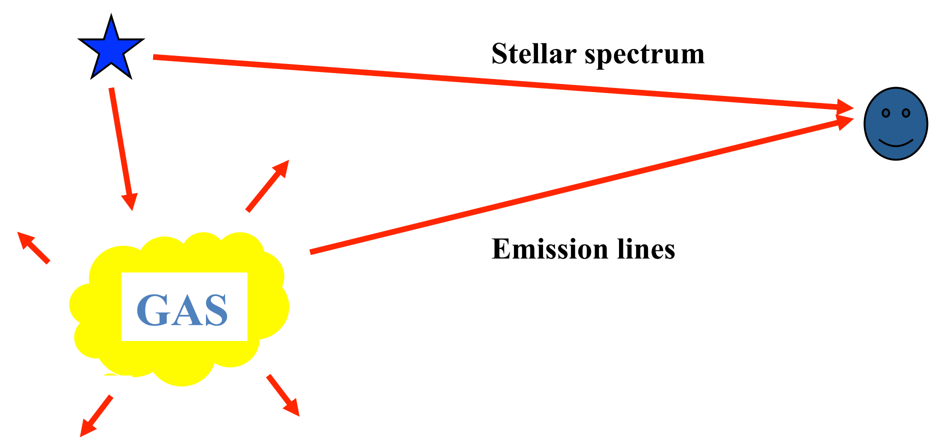


- Can also be due to COLD gas in the interstellar medium which can EXTRACT energy from the passing radiation

interstellar lines

Emission Lines

- Caused by gas being ionized and heated and then re-radiating at specific allowed wavelengths



- Stars form from gas so are often embedded
- Young stars ionise gas which releases radiation at a specific wavelength as it recombines

Credit: Simon Driver

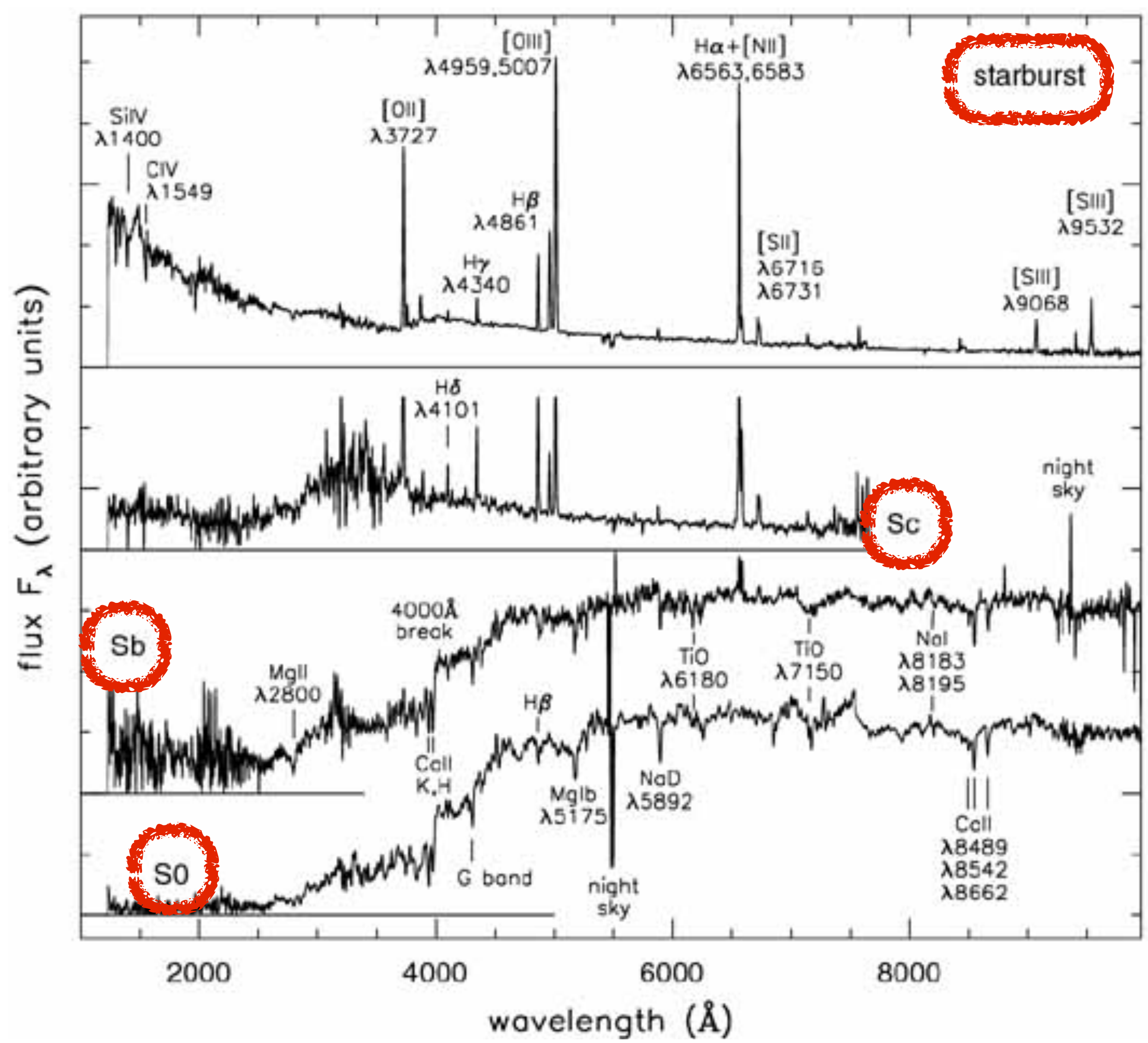
Spectra of star forming galaxies (incl. spirals)

the spectra of spiral galaxies (like those of all star-forming galaxies) are characterised by the presence of emission lines

Disc galaxies looks as you might expect given their colours:

early-type spirals have older stars and few if any emission lines from star-formation regions

late-type spirals have younger stars and emission lines from star-formation regions



Spectra of elliptical galaxies

the spectra of elliptical galaxies only has absorption lines

due to negligible level of on-going star formation

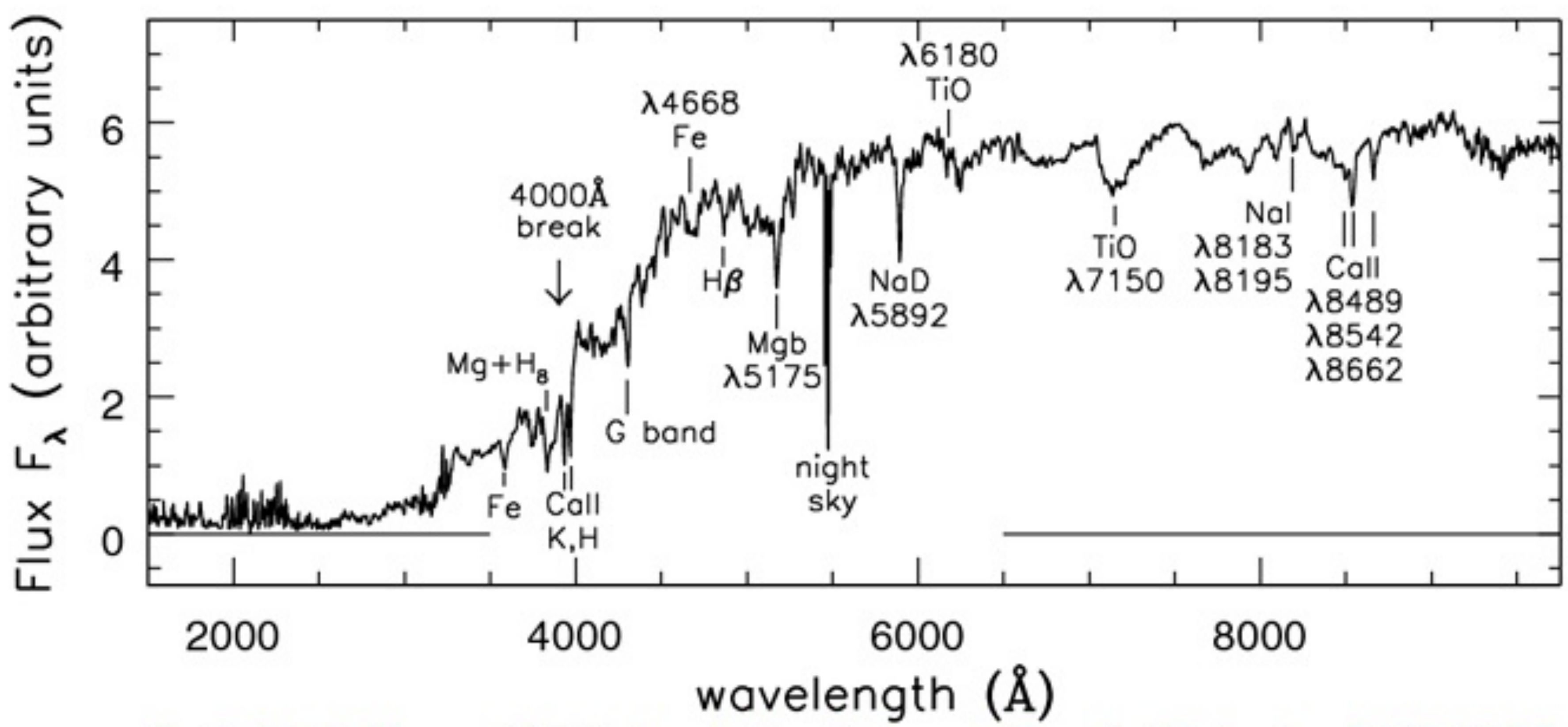
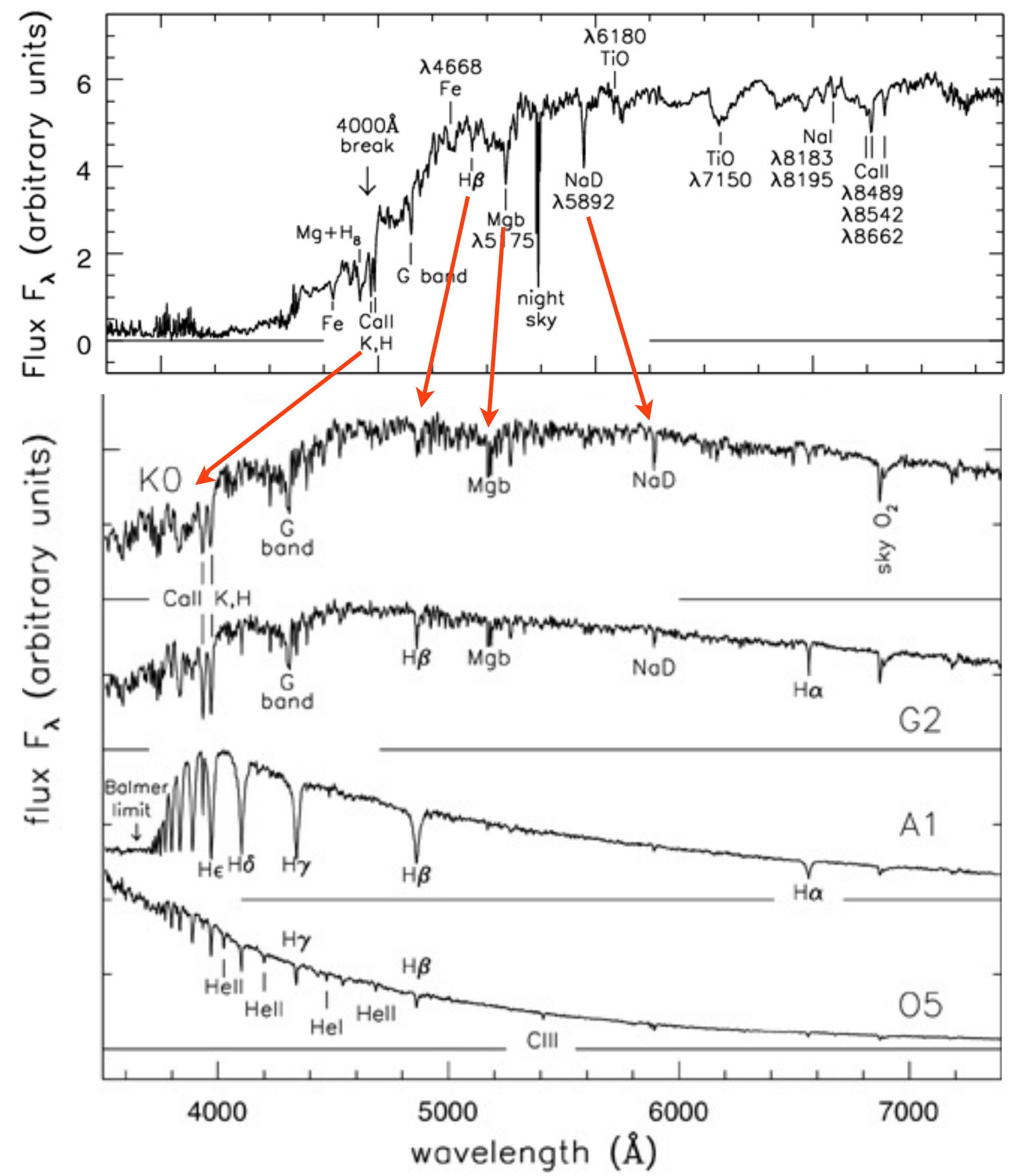


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Stellar components making elliptical spectra

The spectra of elliptical galaxies look, to first order, like G or K stars (with a few features of M stars)

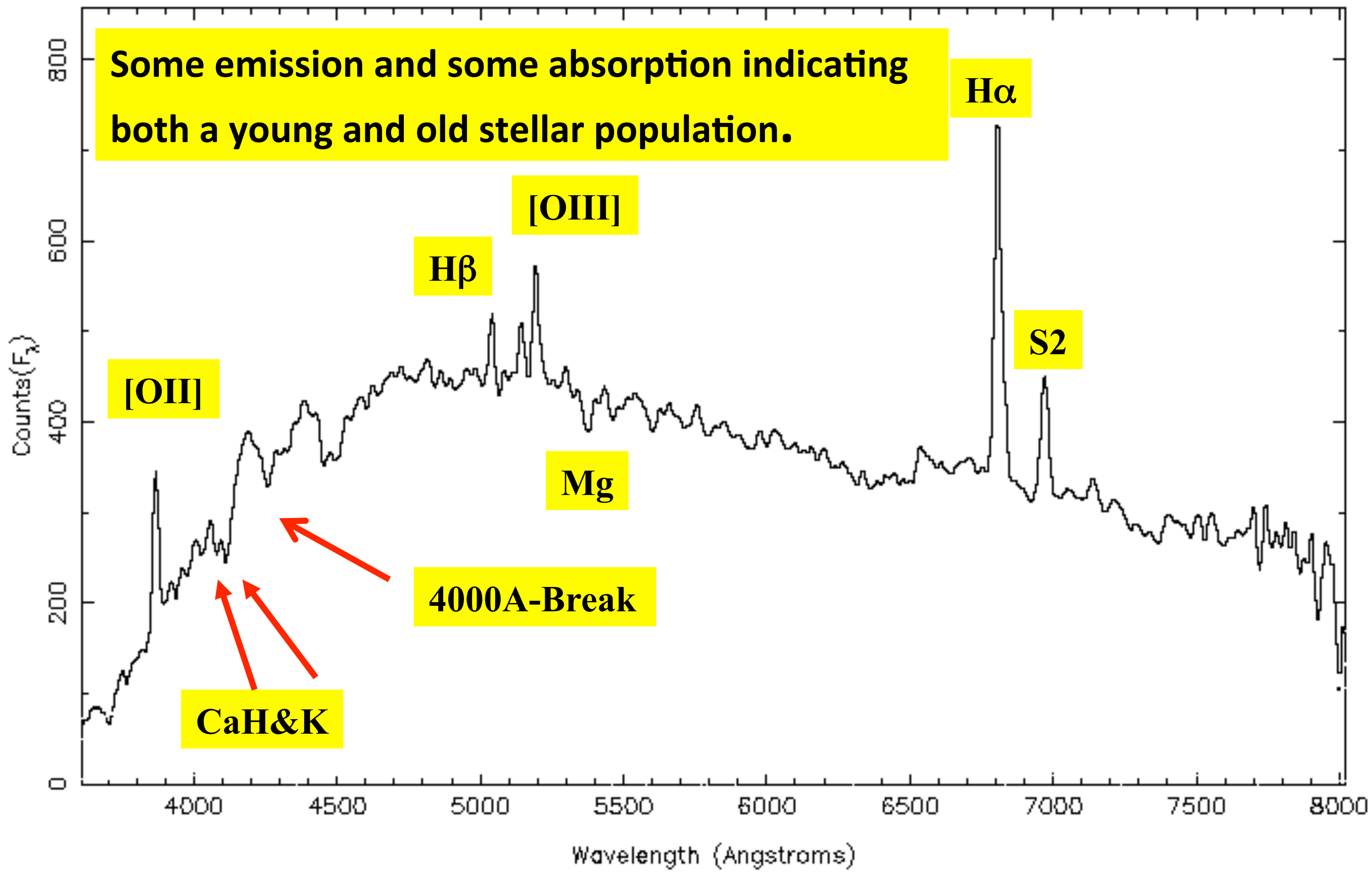
This implies that they must be, on average, older than a few Gyr in order not to have light from hot stars



Intermediate spectral types

some galaxies with underlying old stellar populations may still have fresh star-forming regions (molecular gas must be present)

mix of spectral features: red continuum + emission lines



Important to remember

- Absorption Lines
  - Need metals in stellar atmospheres or cold gas in the interstellar medium
- Implies
  - Old stellar population = old galaxy
- From
  - Ellipticals
  - Spiral Bulges

- Emission Lines
  - Need very hot gas and O and B type stars
- Implies
  - Newly formed stars = star-forming/young galaxy
- From
  - Spiral Disks
  - Irregulars

Main spectral lines

- Absorption
  - Ca(H) = 3933.7A
  - Ca(K) = 3968.5A
  - G-band = 4304.4A
  - Mg = 5175.3A
  - Na = 5894.0 A
- Emission
  - [OII] = 3727.3A
  - Hδ = 4102.8A
  - Hγ = 4340.0A
  - Hβ = 4861.3A
  - [OIII] = 4959.0A
  - [OIII] = 5006.8A
  - Hα = 6562.8A
  - S_2 = 6716.0A

can be in absorption too (Hδ, Hγ, Hβ, Hα)

Black Holes in the centre of Elliptical Galaxies

Evidence of black holes at elliptical centres

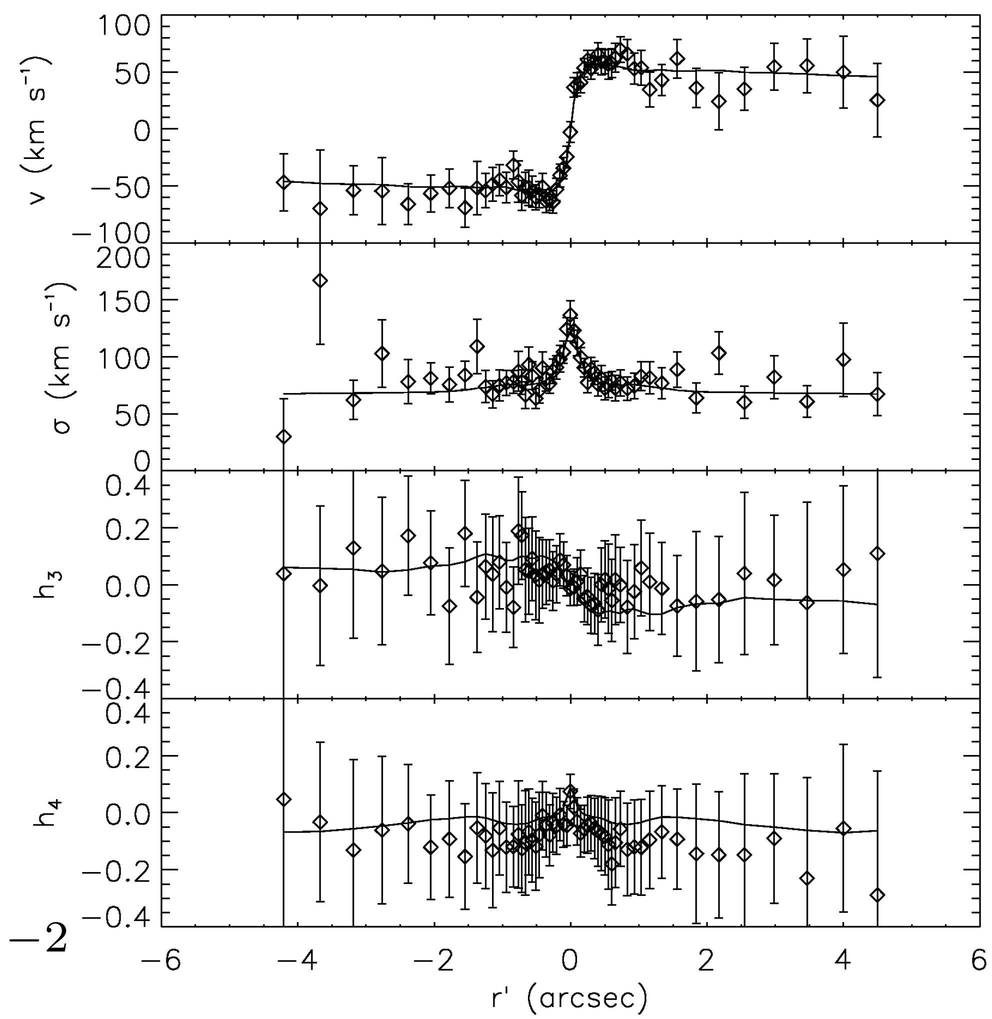
If a super-massive black hole (SMBH) lives at the centre of a galaxy, we should be able to detect this by looking at the speeds of stars that pass near to the black hole

So we need to find stars that have speeds of

$$V^2(r) \approx \frac{G\mathcal{M}_{\rm BH}}{r} \gtrsim \sigma_c^2$$

This means we need to look within a radius

$$r_{\rm BH} \approx 45\,{\rm pc}\left(\frac{\mathcal{M}_{\rm BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_c}{100\,{\rm km\,s^{-1}}}\right)^{-2}$$



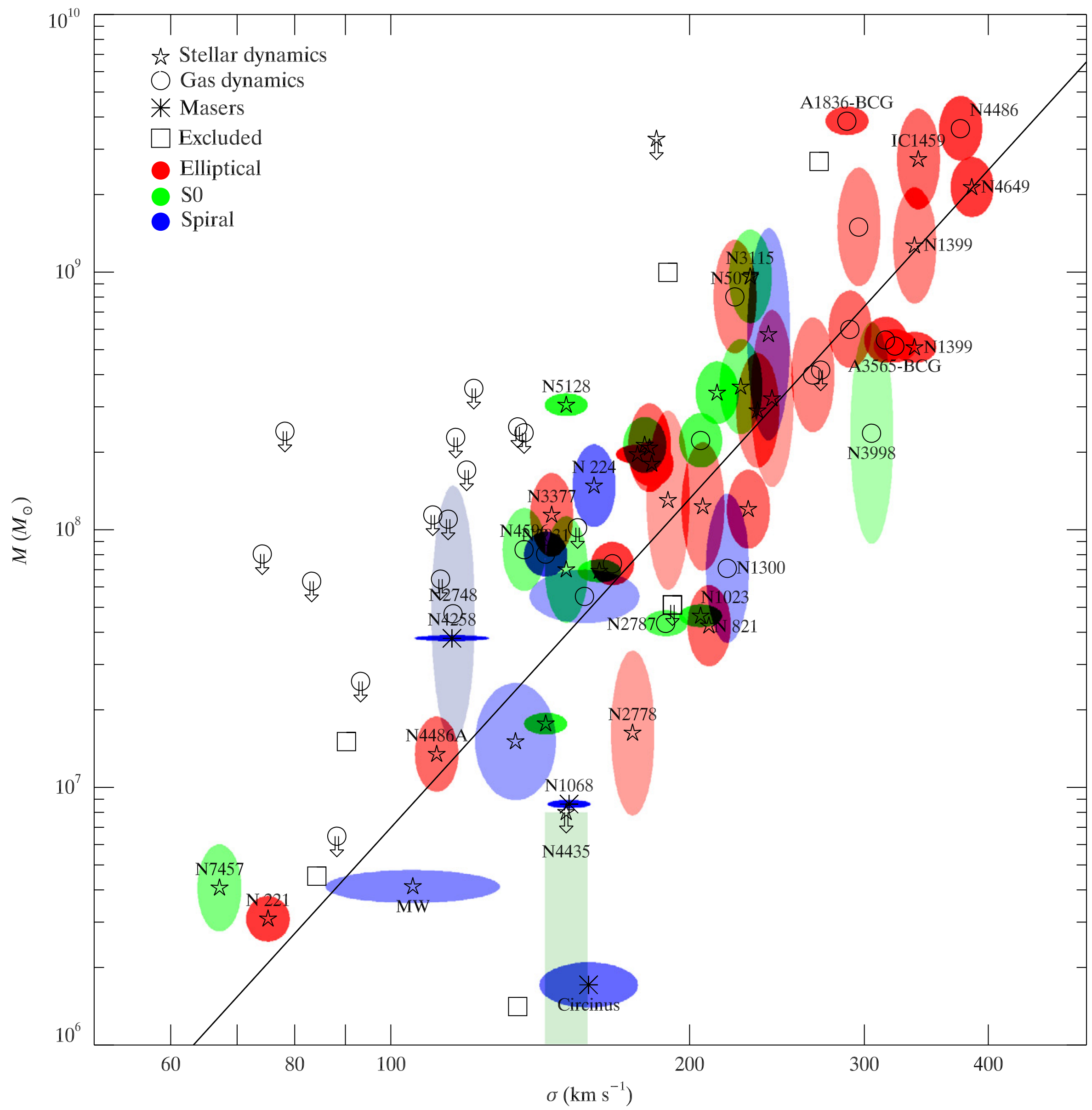
Verolme et al. 2002

In M32, $2\times10^6\ M_\odot$ are required inside the central parsec!

The black-hole mass/bulge-velocity relation

It is likely that every elliptical galaxy — even every spheroidal system, including bulges — has a super massive black hole (SMBH)

Moreover, there is a reasonable correlation between the mass of the SMBH and the velocity dispersion of the spheroid:



$$\log(\mathcal{M}_{\rm BH}/M_\odot) = 4.24\log(\sigma/200\,{\rm km\,s^{-1}}) + 8.12$$

The black-hole mass/bulge-mass relation

Because $M_{\rm bulge} \sim \sigma^2 r$

this implies a M_{BH}–M_{bulge} relation

$$\frac{M_{\rm BH}}{M_{\rm bulge}} = 2.2^{+1.6}_{-0.9} \times 10^{-3}$$

In other words, the black hole at the center of a galaxy is ≈0.2% of the mass of its bulge!