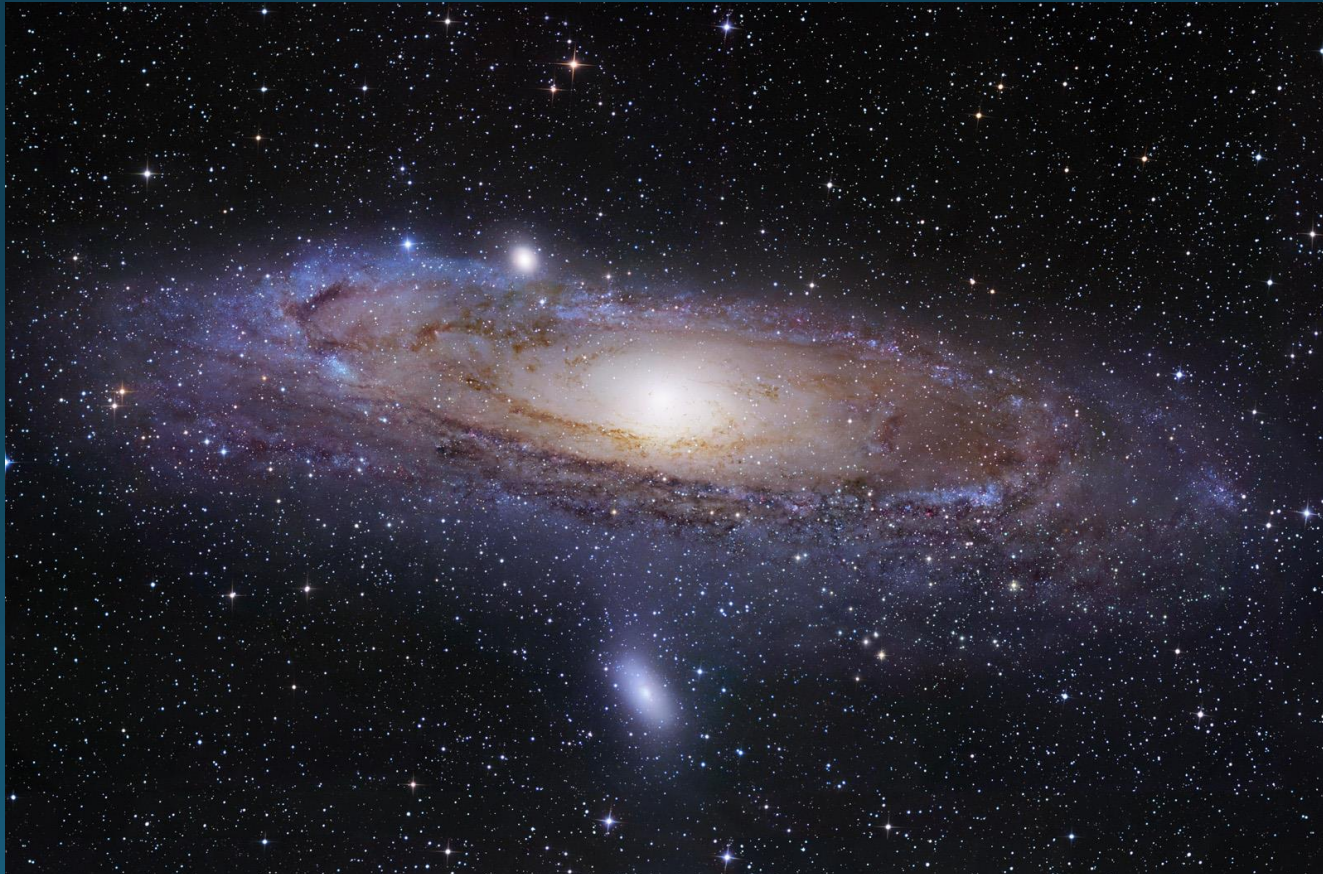


# Physics of Galaxies 2019

10 credits

## Lecture 4: Disks and ellipticals



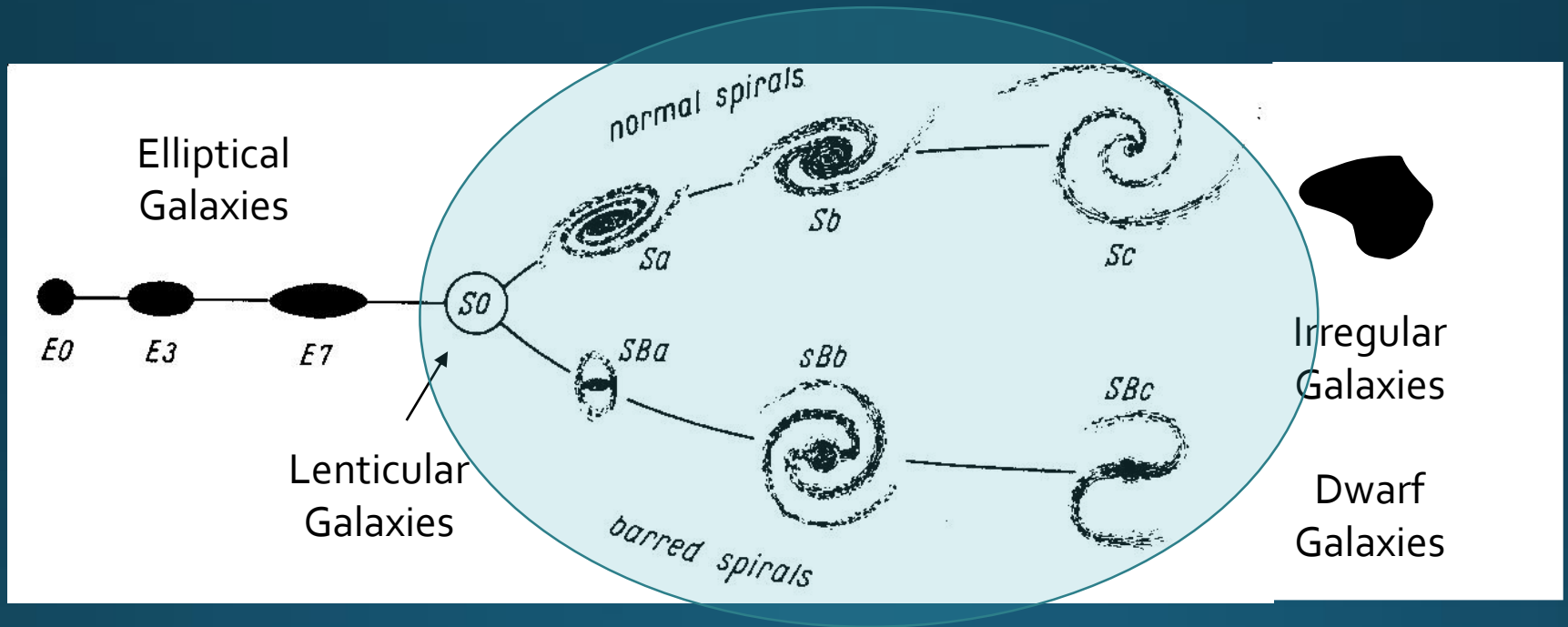
# Outline I

- Disk galaxies
  - Surface brightness profiles
  - Stars and gas
  - Rotation curves
  - The Tully-Fisher relation
  - Spirals and bars

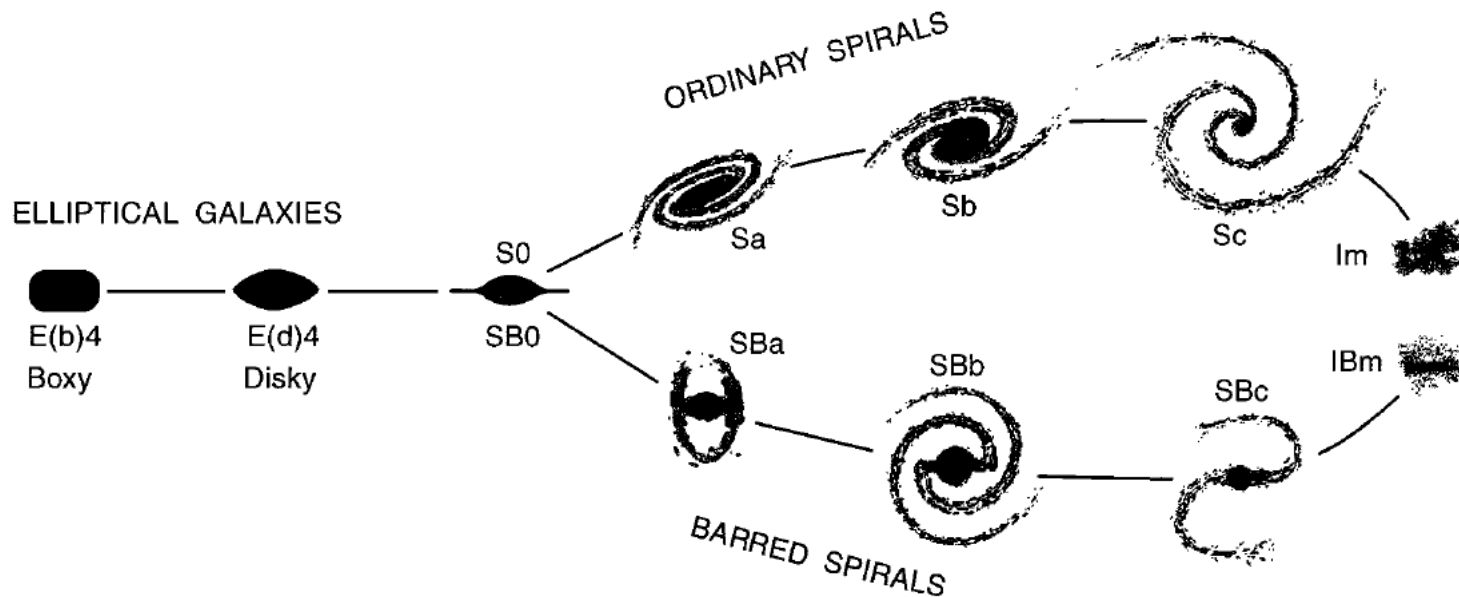
# Outline II

- Elliptical galaxies
  - Surface Brightness Profiles
  - Stars
  - cD-Galaxies
  - Triaxiality
  - Stellar Motions
  - The Faber-Jackson Relation
  - Masses

# Recall the Hubble Tuning Fork

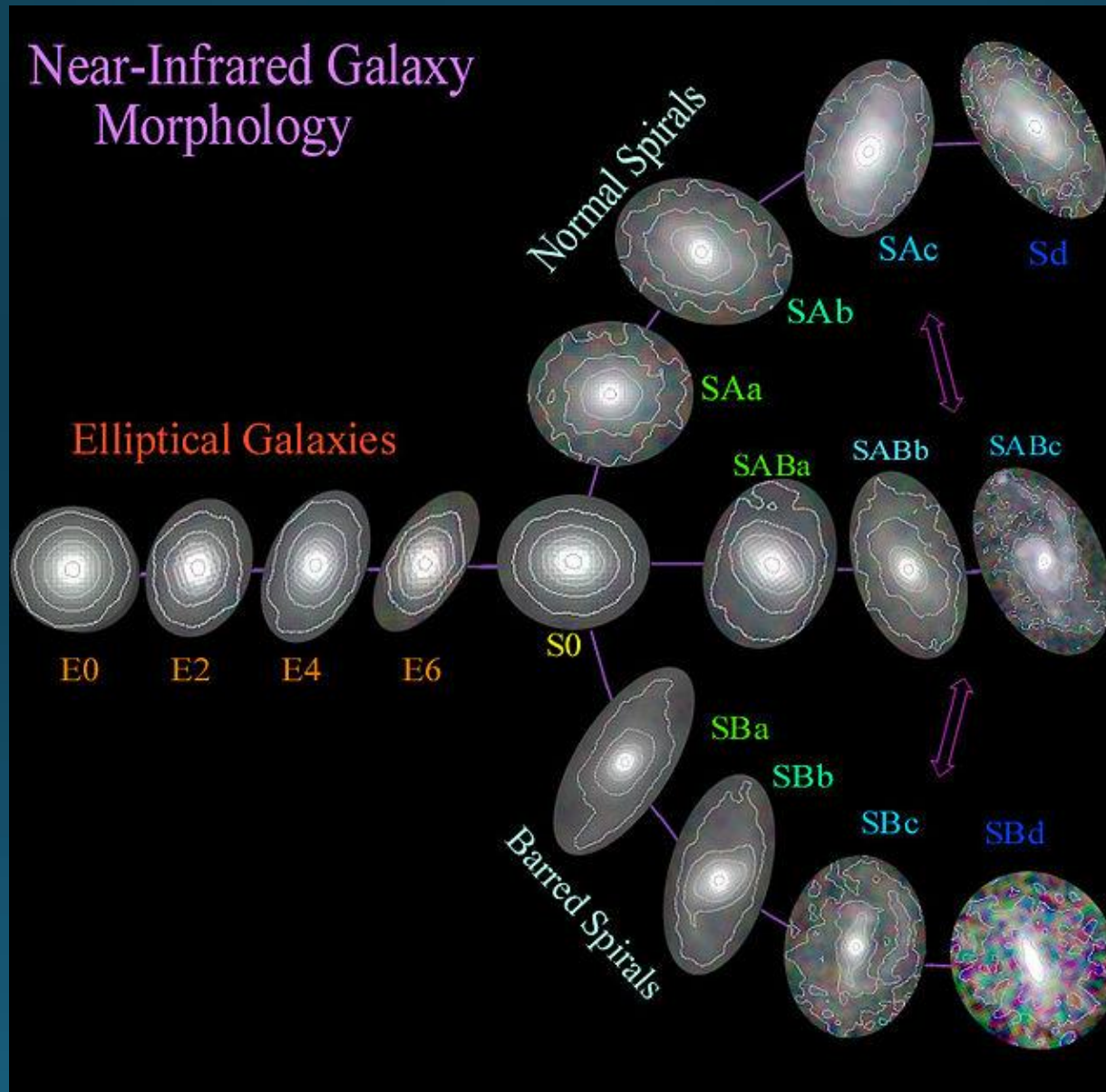


# Alternative version: More elliptical subclasses



Kormendy & Bender (1996)  
Featured in Schneider's book

# Alternative version: More spiral subclasses





# Disk galaxies

- Sequence:

S0-Sa-Sb-Sc-Sd-Sm

SB0-SBa-SBb-SBc-SBd-SBm

Early-type disks

Late-type disks

- Outside the original Hubble Tuning fork:

- Sd-galaxies: Bulgeless disks
- Sm-galaxies: Magellanic spirals (almost irregular, prototype LMC)

# Disk galaxies

	S0-Sa	Sd-Sm
Spiral arms:	Absent or tight	Open spiral
Bulges:	Big	Small
Color (B-V):	Red (0.7-0.9)	Blue (0.4-0.8)
Young stars:	Few	Many
HII-regions:	Few, faint	Many, bright
Surface brightness:	High	Low
Mass:	High	Low
Rotation:	Fast rising	Slow rising



Intermission: Which of these disks is the most "early-type"?



# Surface Brightness

$$\alpha \approx \frac{D}{d}$$

Size of object

Distance to object

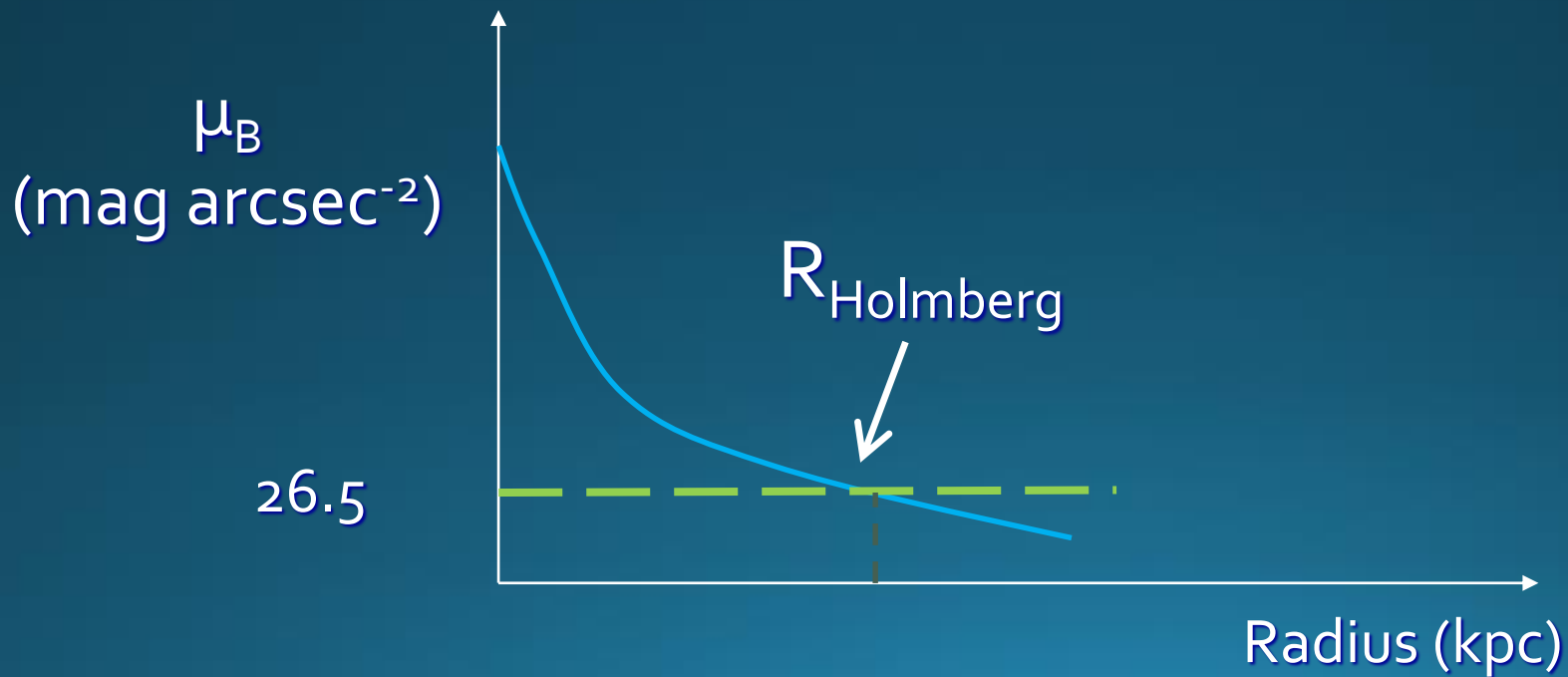
$$I(r) = \frac{F}{\alpha^2} = \frac{L / 4\pi d^2}{D^2 / d^2} = \frac{L}{4\pi D^2}$$

$$\mu(r) \propto -2.5 \log_{10} I(r)$$

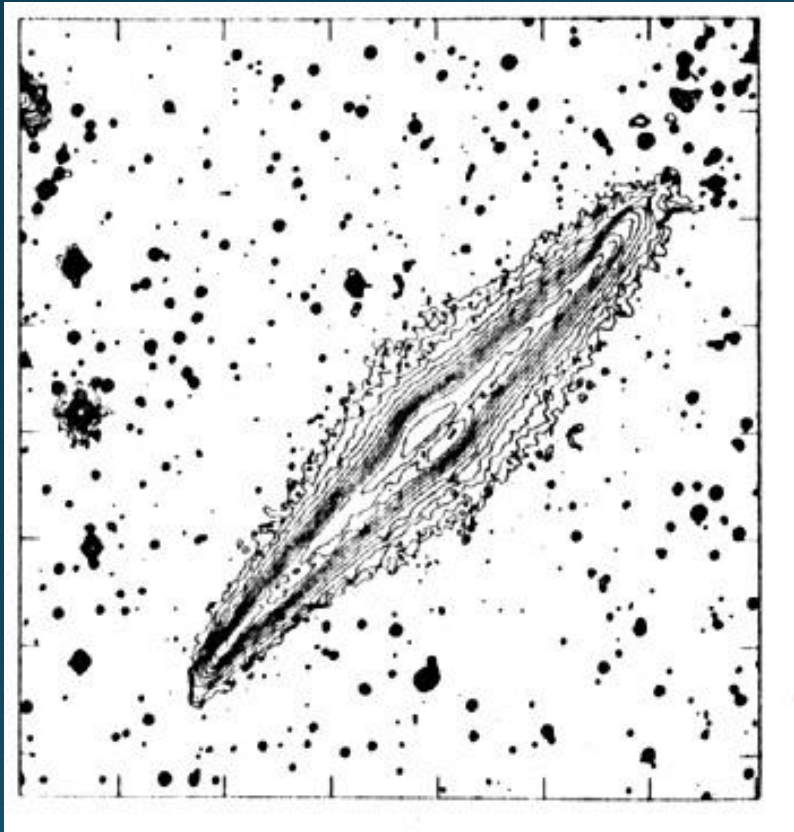
- $I(r)$  usually  $L_{\odot} \text{ kpc}^{-2}$ , but  $\mu(r)$  in mag arcsec<sup>-2</sup>
- Determines observability of extended objects (e.g. galaxies)
- $I(x)$  independent of distance(!) in local universe...
- ... but subject to factor  $(1+z)^{-4}$  of redshift dimming →  
One reason why high-redshift objects are extremely difficult to detect

# Surface Brightness

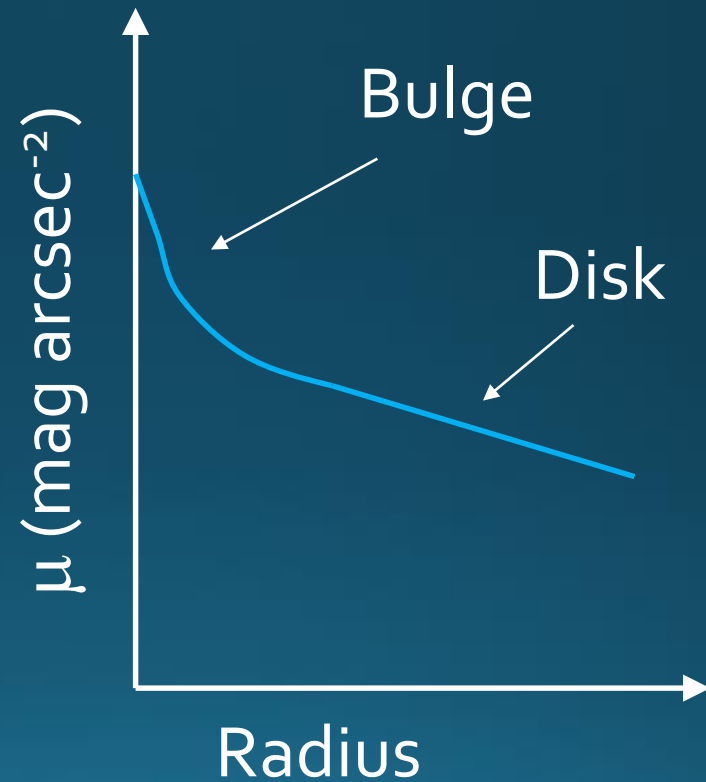
- Sizes of galaxies often given out to a specified isophote:
  - $R_{25}$ : Radius at 25 mag arcsec<sup>-2</sup> in B-band
  - Holmberg radius: Radius at 26.5 mag arcsec<sup>-2</sup> in B-band



# Surface Brightness Profiles I



Isophotes  
(constant surface brightness)



# Surface Brightness Profiles II

- Radial direction — Sérsic formula:

$$I(R) = I(0) \exp\left(- (R / h_R)^{1/n}\right)$$

$h_R$ : Scale length

$I(0)$ : Central surface brightness

$n=4 \rightarrow$  de Vaucoleur formula (for bulges & ellipticals)

$n=1 \rightarrow$  Exponential disk (for the disks of disk galaxies)

# Surface Brightness Profiles III

- Profiles of exponential disks (n=1):

$$I(R) = I(0) \exp(-R / h_R) \quad (L_{\odot} \text{ kpc}^{-2})$$

- Alternative formulation (3.14 in Schneider):

$$\mu(R) = \mu_0 + 1.09 \frac{R}{h_R} \quad (\text{mag arcsec}^{-2})$$

$\mu_0$ : central surface brightness

# Surface Brightness Profiles IV

- Alternative formulation of Sérsic formula (3.39 in Schneider)

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

$R_e$ : effective radius

(radius inside which half of the light is emitted)

$I_e$ : Surface brightness at  $R_e$

$b_n$ : coefficient given by  $b_n \approx 1.999n - 0.327$



# Stars and Spectra of Disk Galaxies

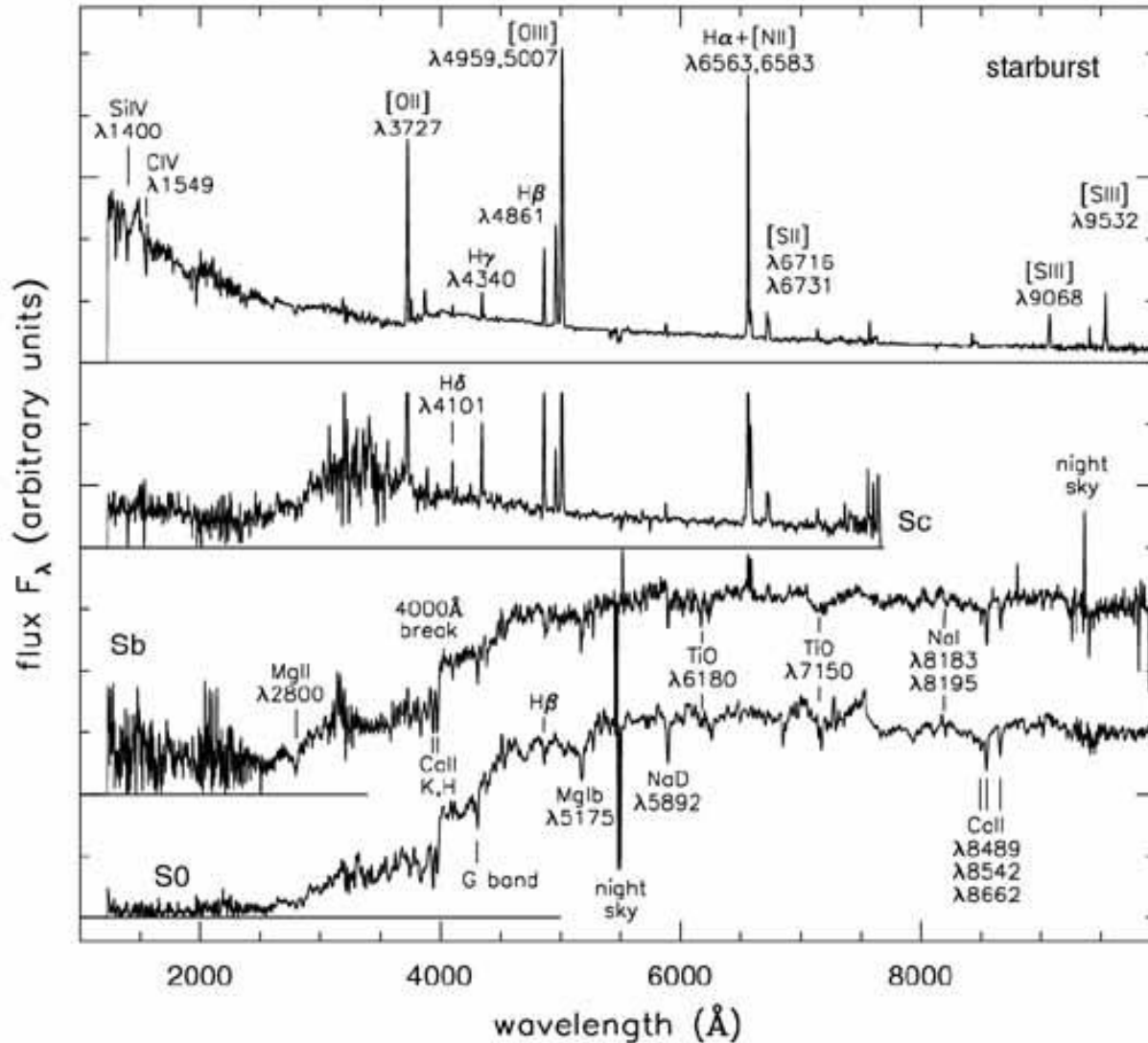
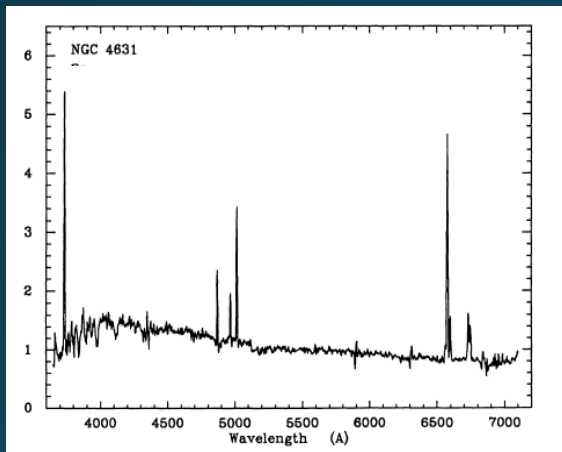


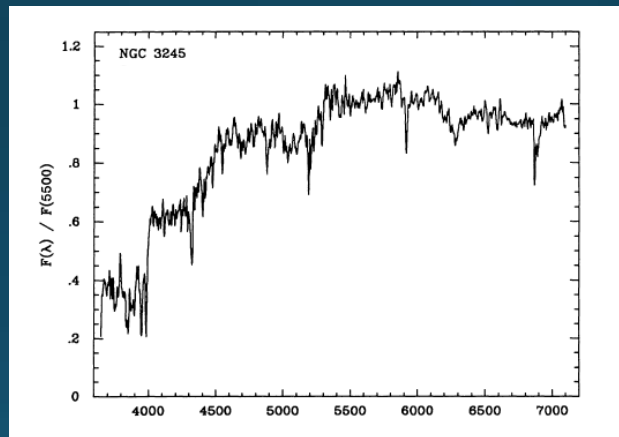
Fig 5.24 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- Sc: Young stars
- S0: Old stars

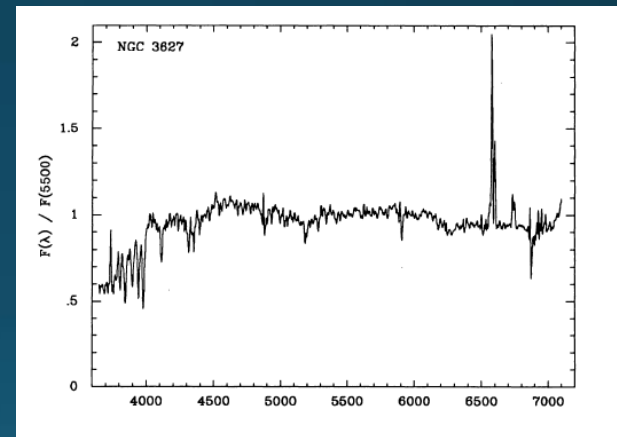
Intermission:  
Order these disk-galaxy spectra from  
early-type to late-type



A

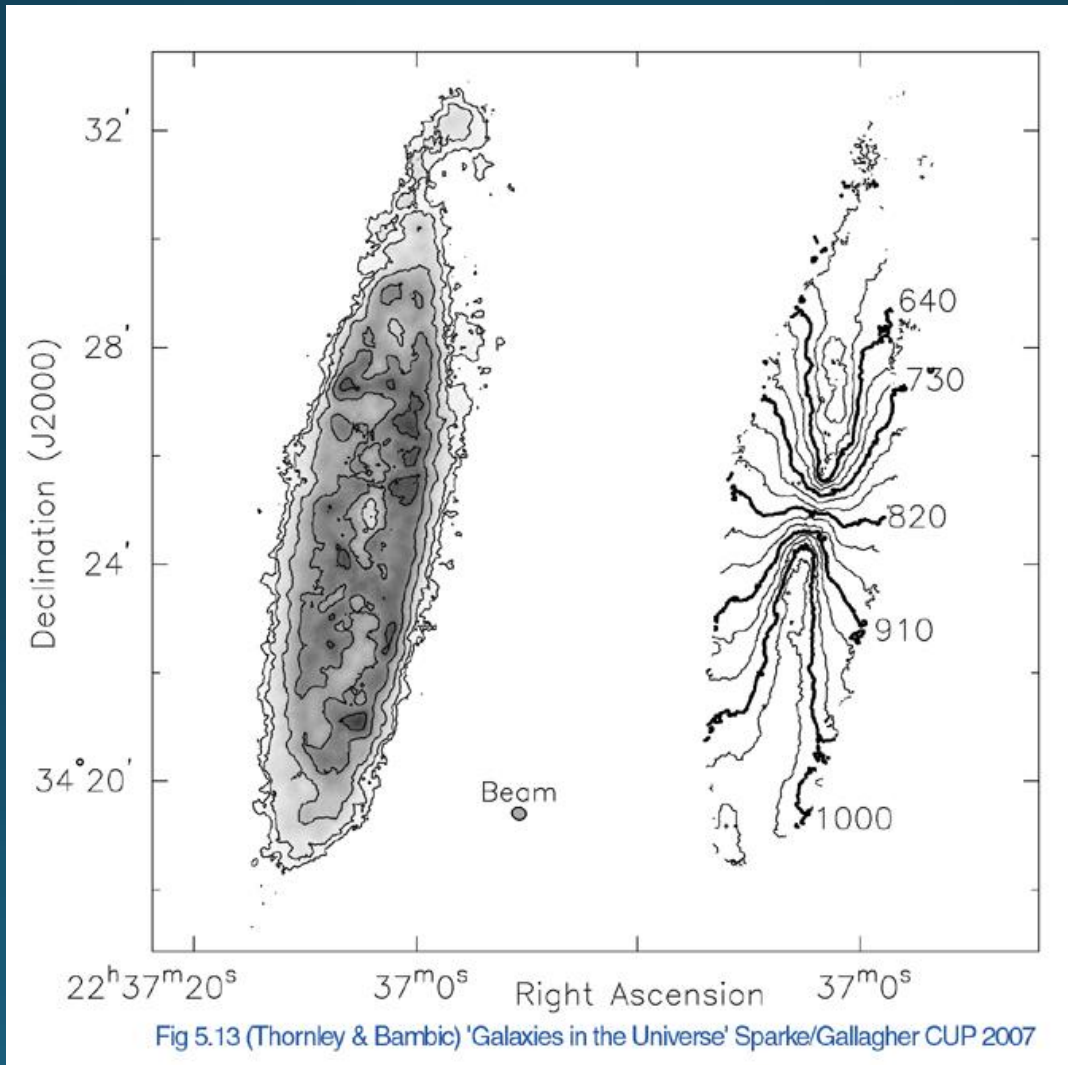


B



C

# Neutral hydrogen



# Neutral hydrogen


- Flux in 21 cm line → HI mass:

$$\frac{M(\text{HI})}{M_{\text{solar}}} = 2.356 \times 10^5 D^2 \int F_{\nu} dV_r$$

Distance  
In Mpc



Integration  
over line profile



# Molecular hydrogen

- $\text{H}_2$  most abundant molecule, but difficult to observe in emission
- 2.6 mm line of CO can be used as tracer:
  - $M(\text{H}_2)/F(\text{CO})=X$
  - However: the conversion factor  $X$  depends on metallicity; very uncertain in metal-poor galaxies

# Gaseous and stellar motions

In disks:

Average  
rotational  
velocity



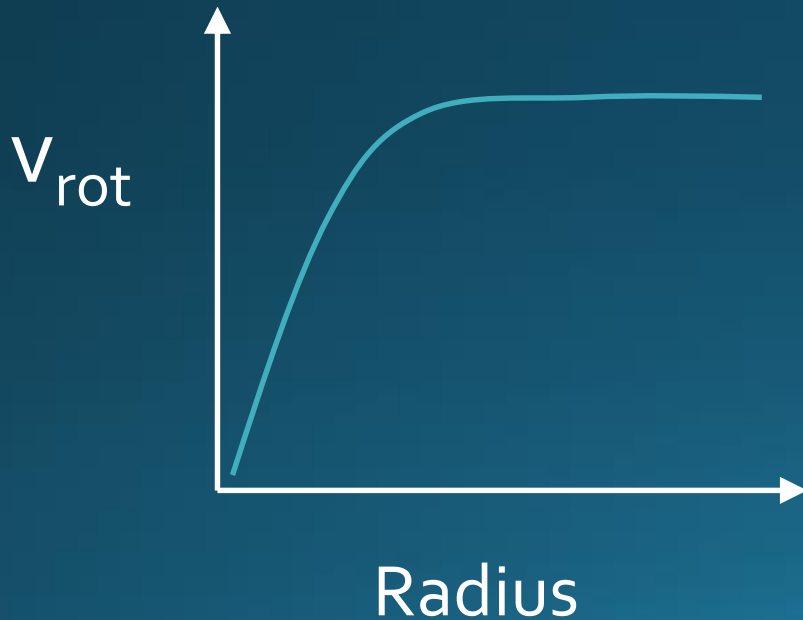
Typical  
velocity  
dispersion



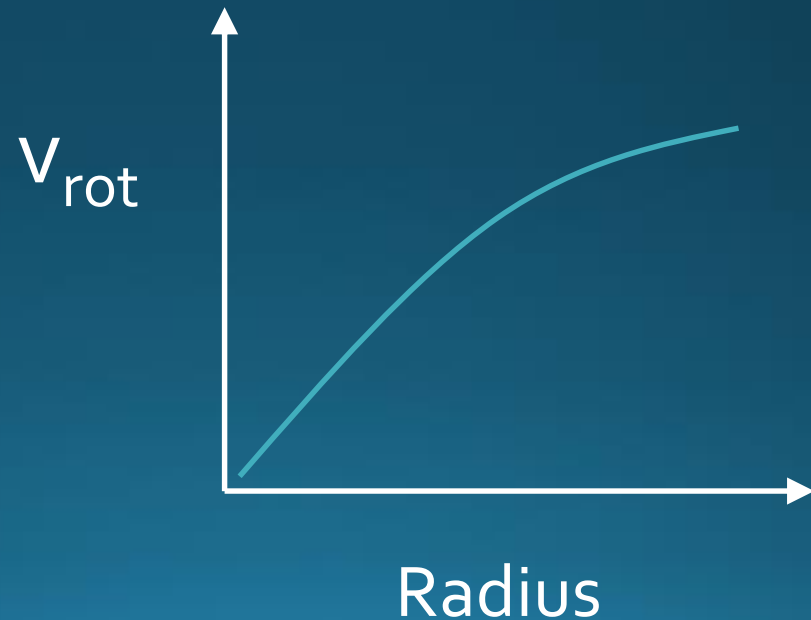
$$\frac{v_{\text{rot}}}{\sigma_v} \sim 10$$

# Rotation curves

Typical  
high surface  
brightness galaxy



Typical  
low surface  
brightness galaxy

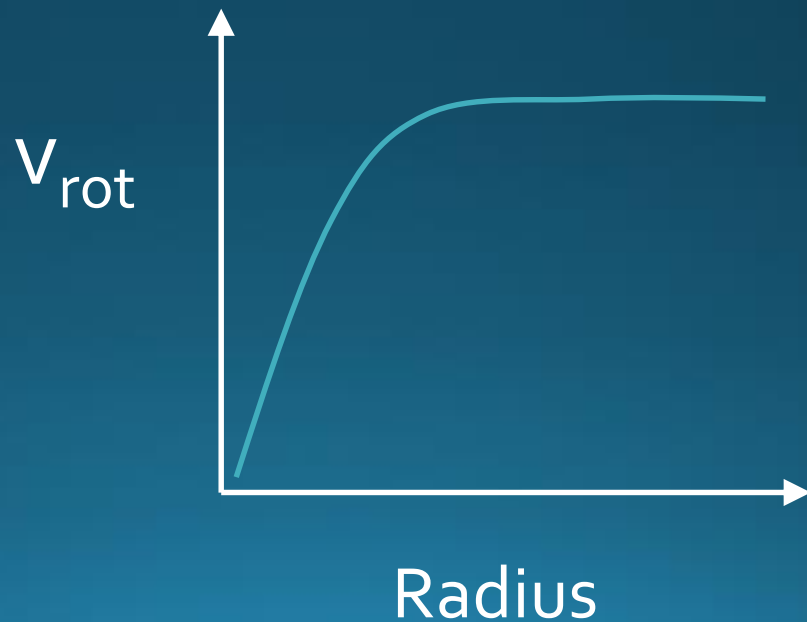




# Rotation curves



$$v_{\text{rot}} = \frac{v_{\text{obs}}}{\sin(i)}$$

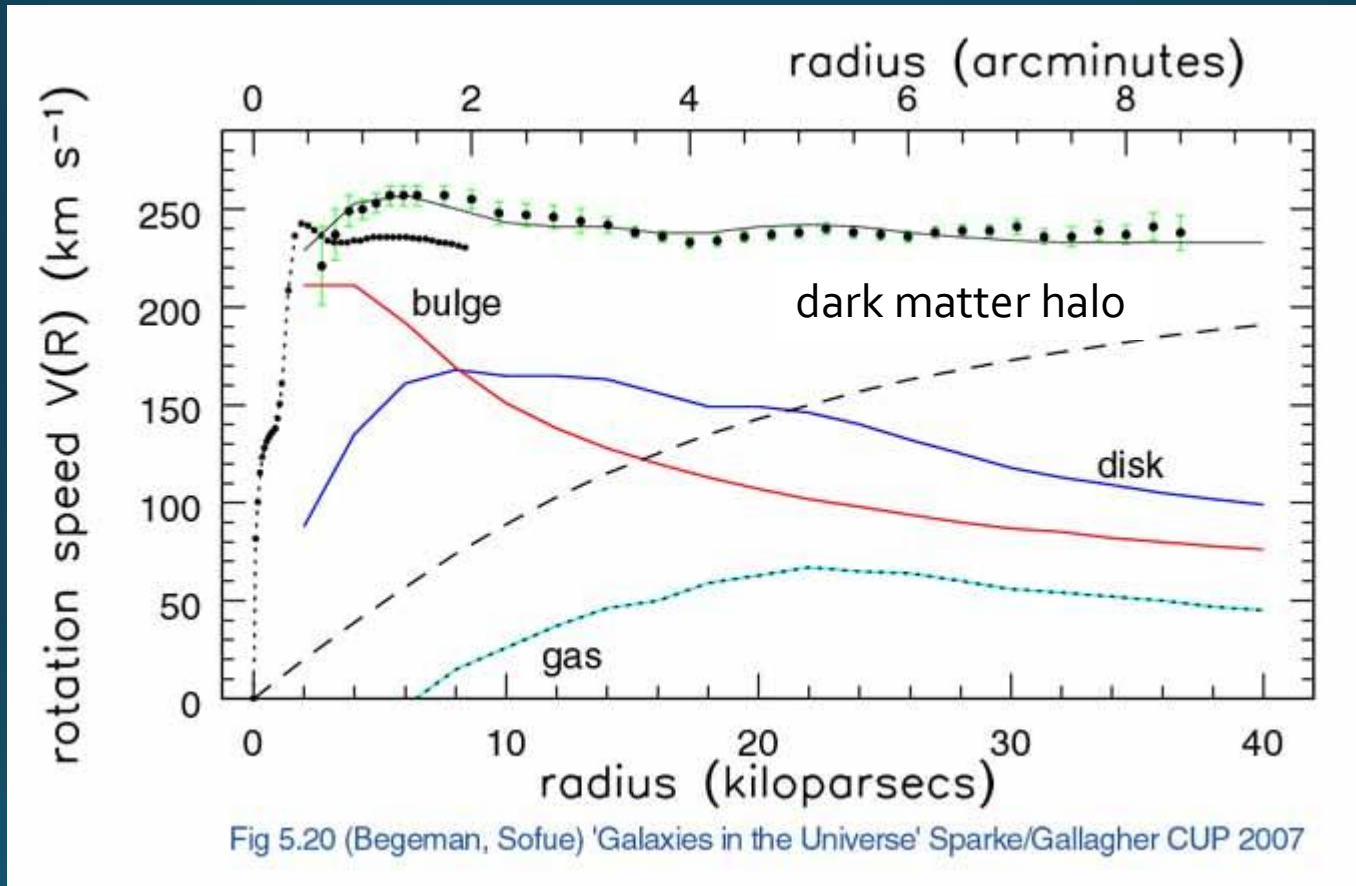


# Rotation curves

Recall from lecture 3:

$$M(< R) = \frac{v_{\text{rot}}^2 (R)^3}{G}$$

# Rotation curve decomposition



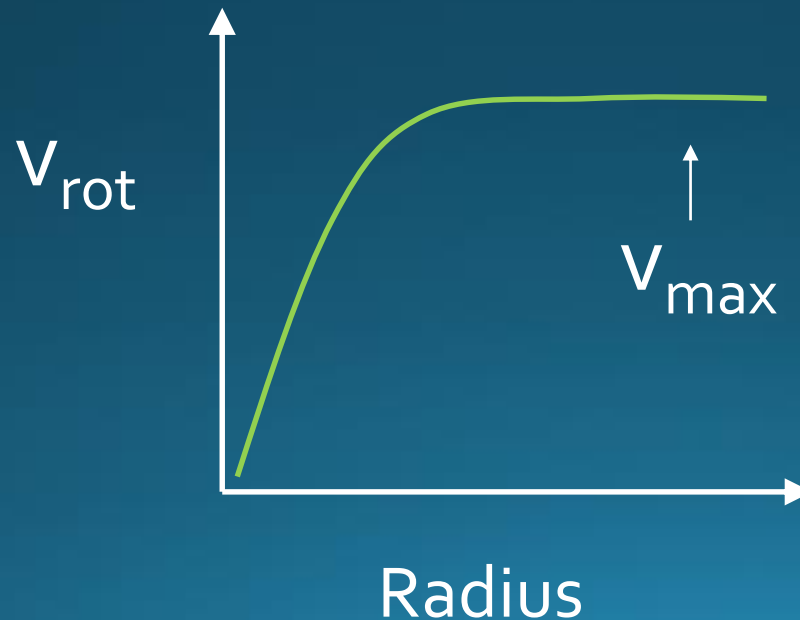
Typical global  $M/L \sim 10-100$

# The Tully-Fisher relation

$$L \propto V_{\max}^4$$

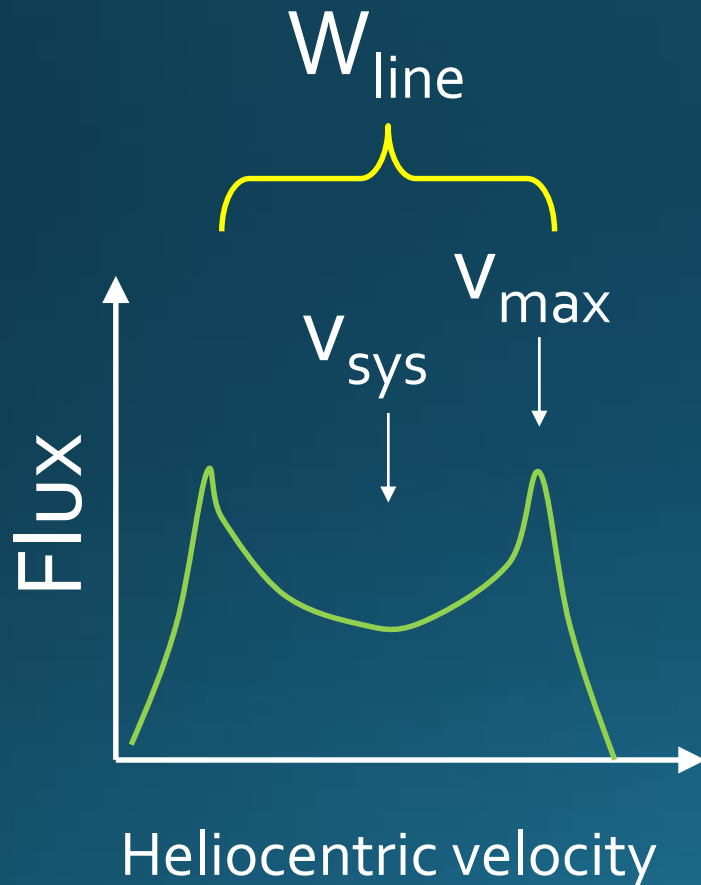
Example:

$$\frac{L_H}{3 \times 10^{10} L_{H\text{solar}}} = \left( \frac{v_{\max}}{196 \text{ km/s}} \right)^{3.8}$$



# The Tully-Fisher relation II

Don't need rotation curve — you can also use HI spectral line profile



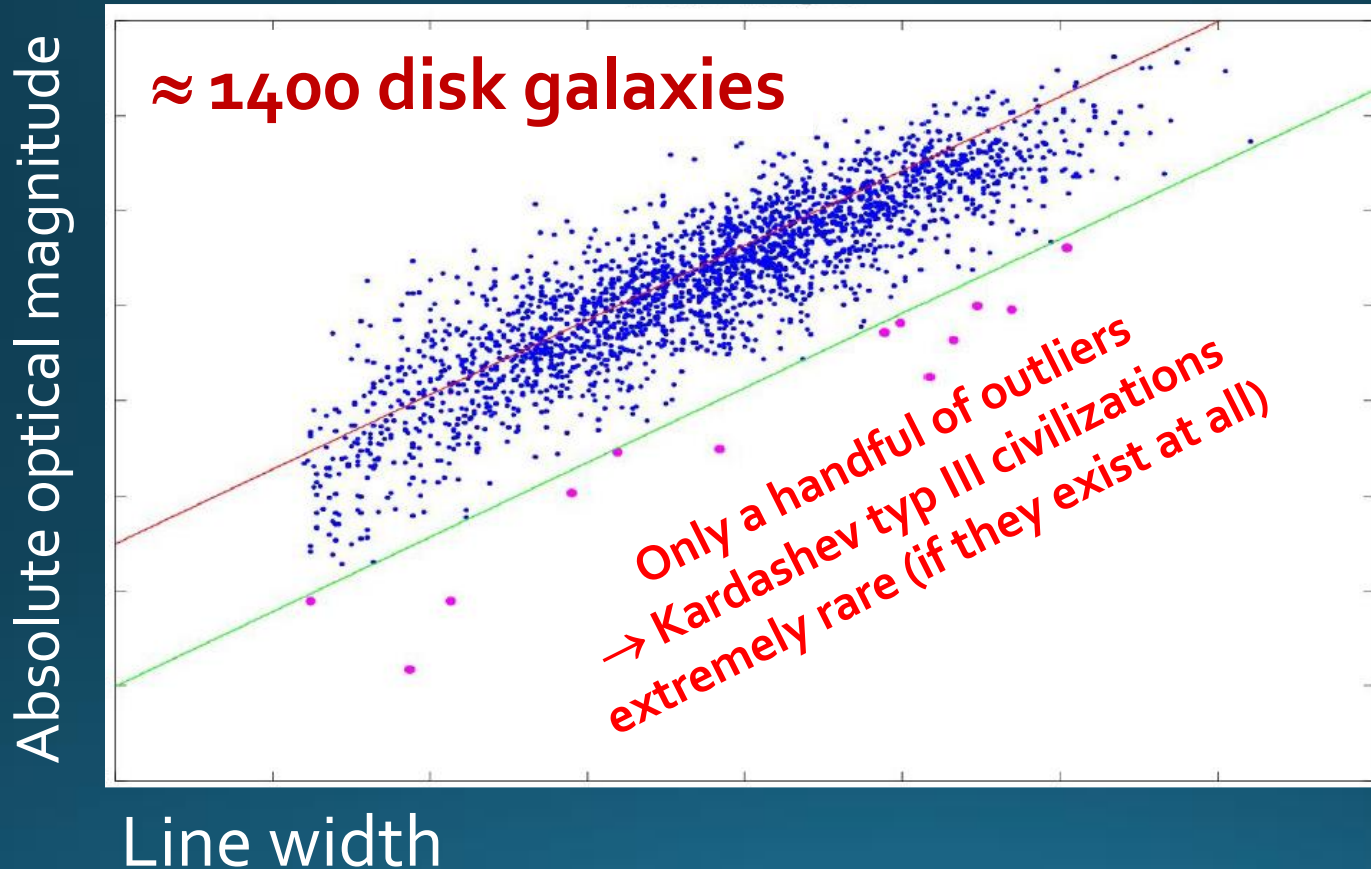
$$v_{\text{max}} \approx \frac{W_{\text{line}}}{2}$$

In one of the exercises, we use the following form of the TF relation:

$$M_H \approx -9.50(\log_{10} W - 2.50) - 21.67,$$

$W_{\text{line}}$

# Weird stuff: The Tully-Fisher relation as a tool to search for extraterrestrial intelligence



**Shameless self-promotion:** Zackrisson, E., Calissendorff, P., Asadi, S., Nyholm, A. 2015, *Astrophysical Journal*, 810, 23

# Spiral patterns I: A “Grand Design” Spiral



Spiral Galaxy NGC 2997 (VLT UT1 + FORS1)



# Spiral patterns II: A Flocculent Spiral

Spiral Galaxy NGC 4414



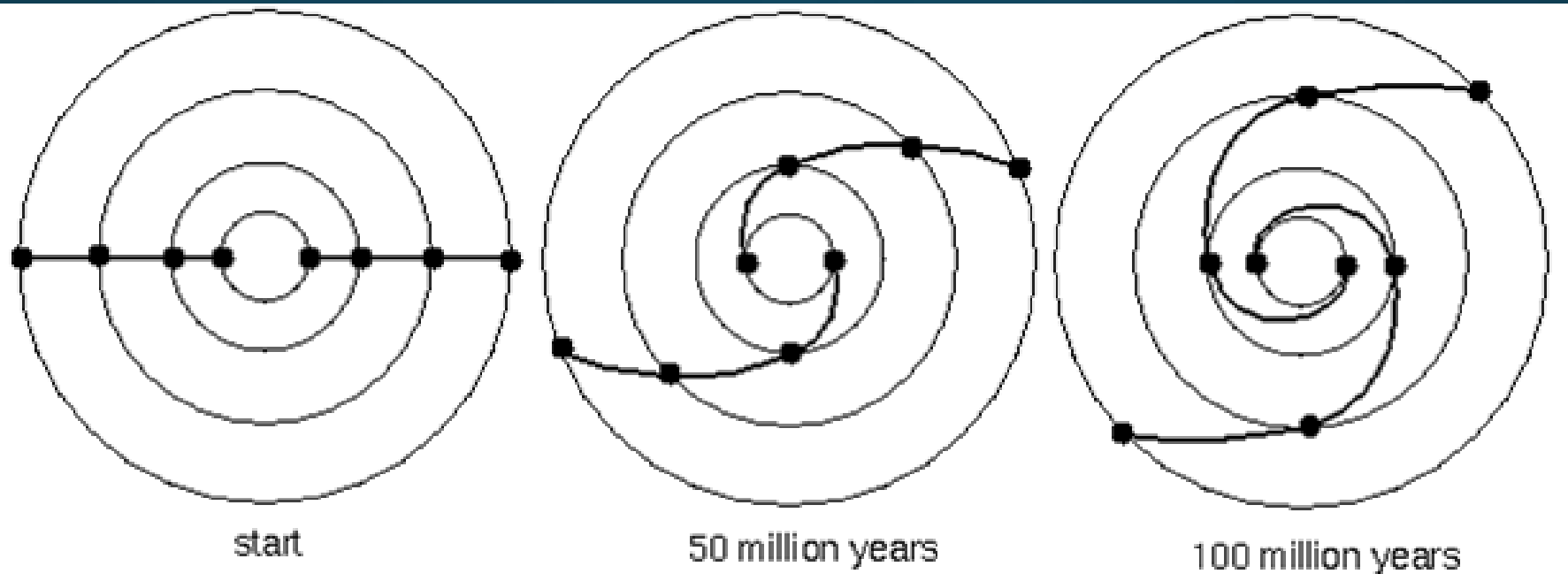
Hubble  
Heritage

PRC99-25 • Hubble Space Telescope WFPC2 • Hubble Heritage Team(AURA/STScI/NASA)

Intermission:  
What type of spiral is this?

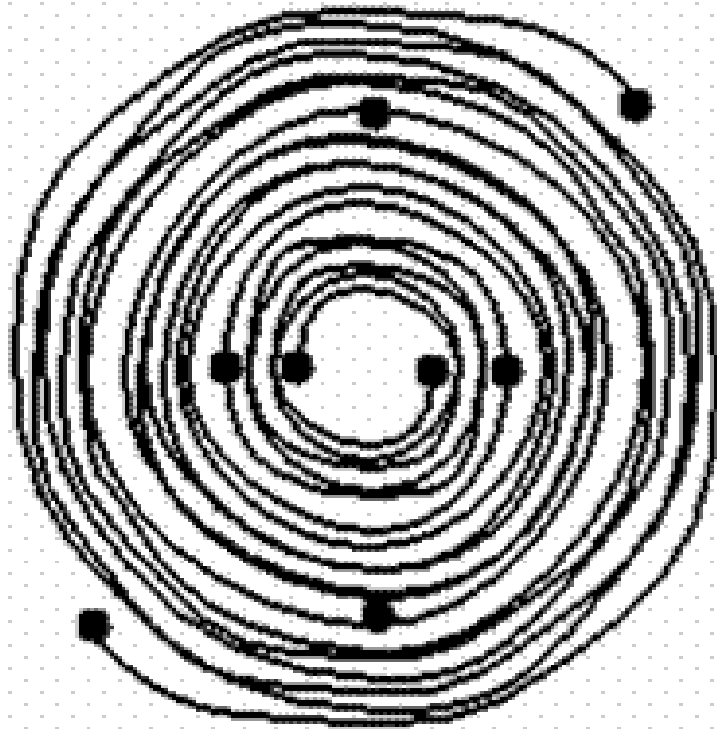


# Spiral patterns III: Differential rotation

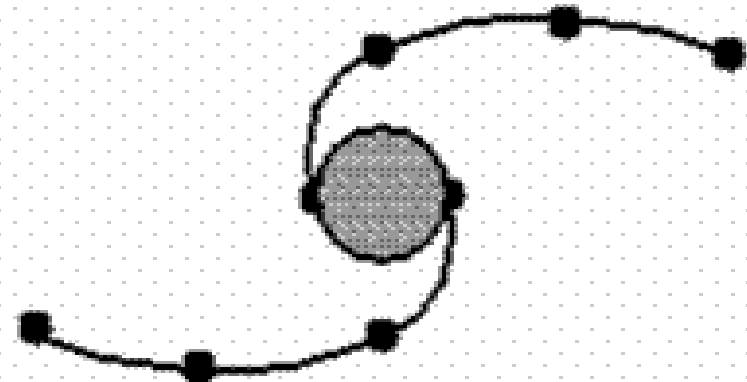


*Differential rotation:* stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

# Spiral patterns IV: The winding-up dilemma

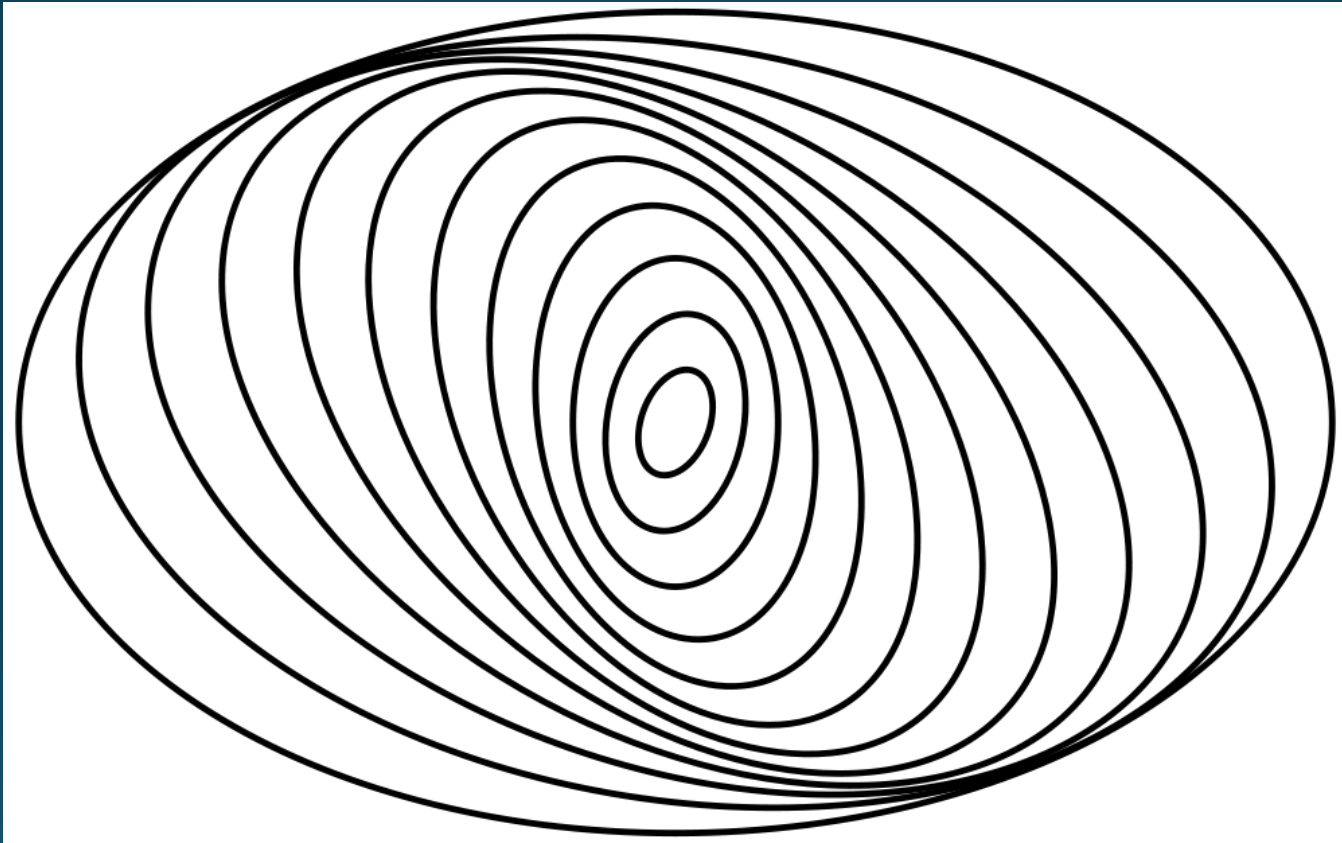


**Prediction:** 500 million years



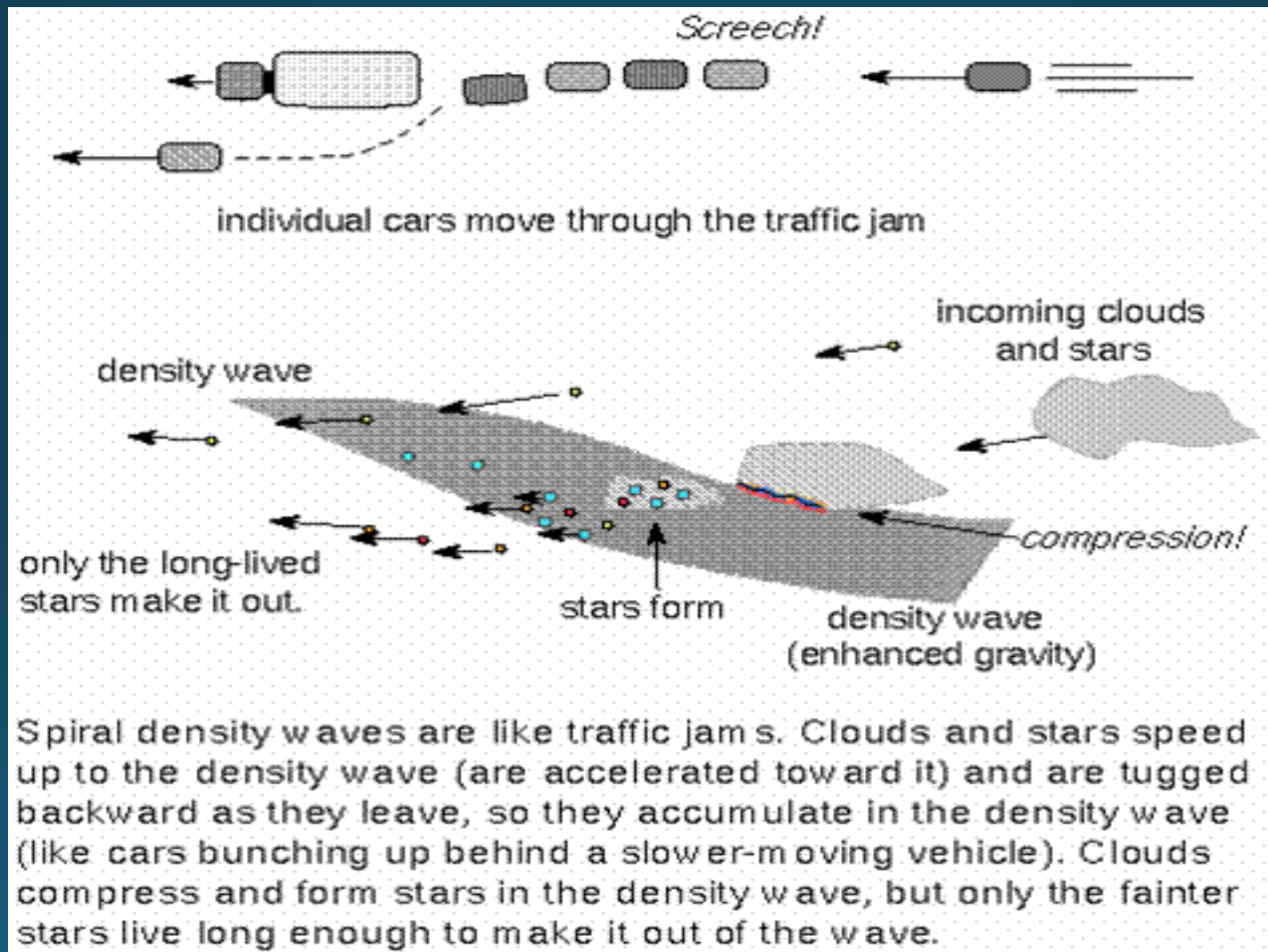
**Observation:** 15,000 million years

# Spiral patterns V: Density waves



Stars on elliptical orbits with different orientations → stars in spiral arms continuously replaced

# Spiral patterns VI: Density-wave theory



# Spiral patterns VII:

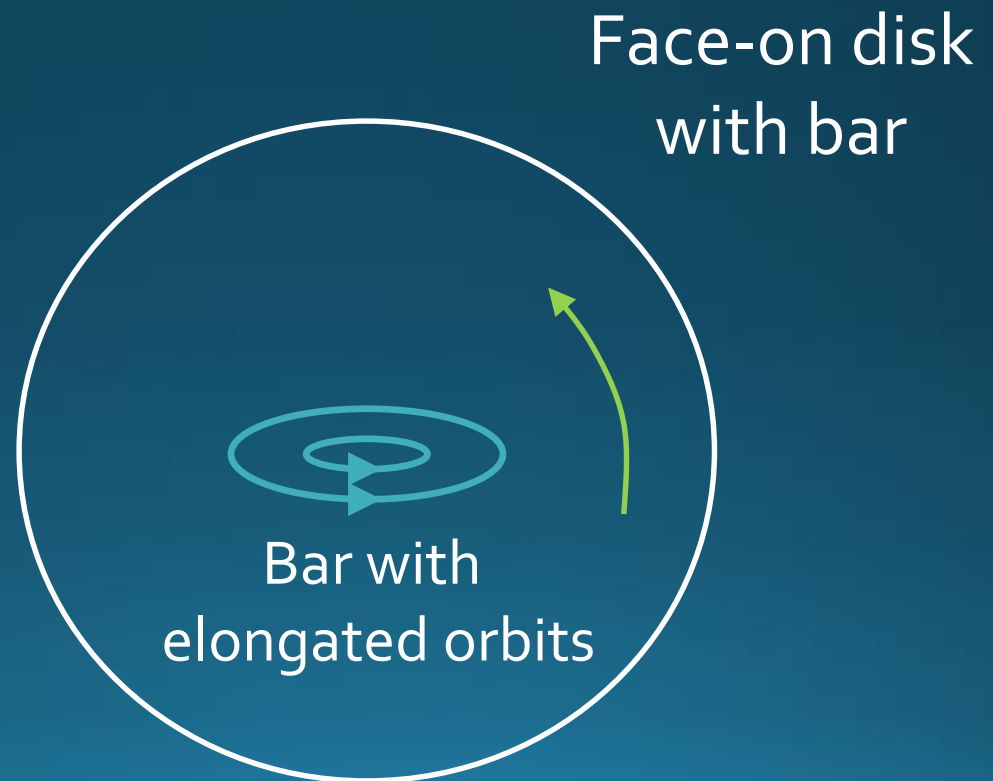
## Problems with density waves

- From where does the density wave get its energy?
  - From the rotation of the disk?
  - From a companion galaxy?
  - Internal forces from a central bar?
- Spiral patterns remain mysterious...



# Bars

- At least 50% of all disk galaxies have bars
- Bars are not density waves!
- Elongated orbits



# Bulges

- In bulges:

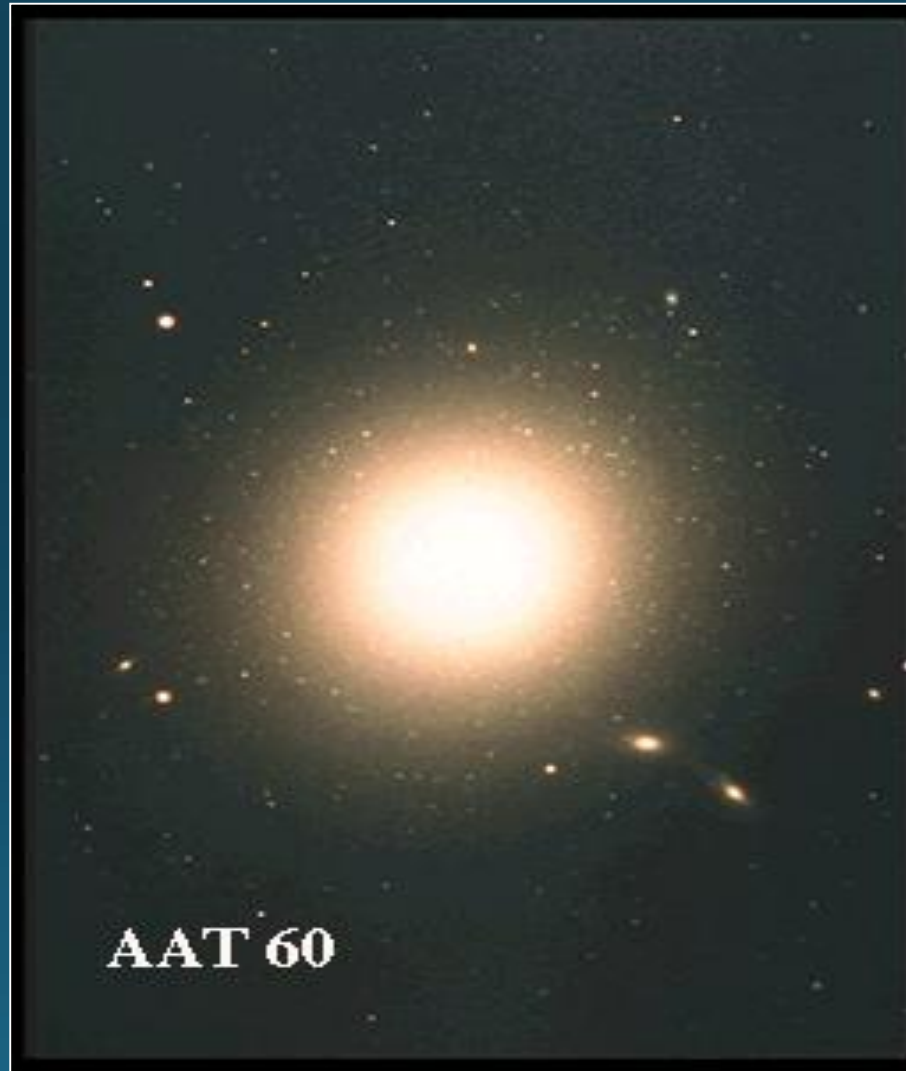
$$\frac{v_{\text{rot}}}{\sigma_v} \sim 1$$



# Intermission: The Galaxy Zoo Project

<https://www.galaxyzoo.org/>

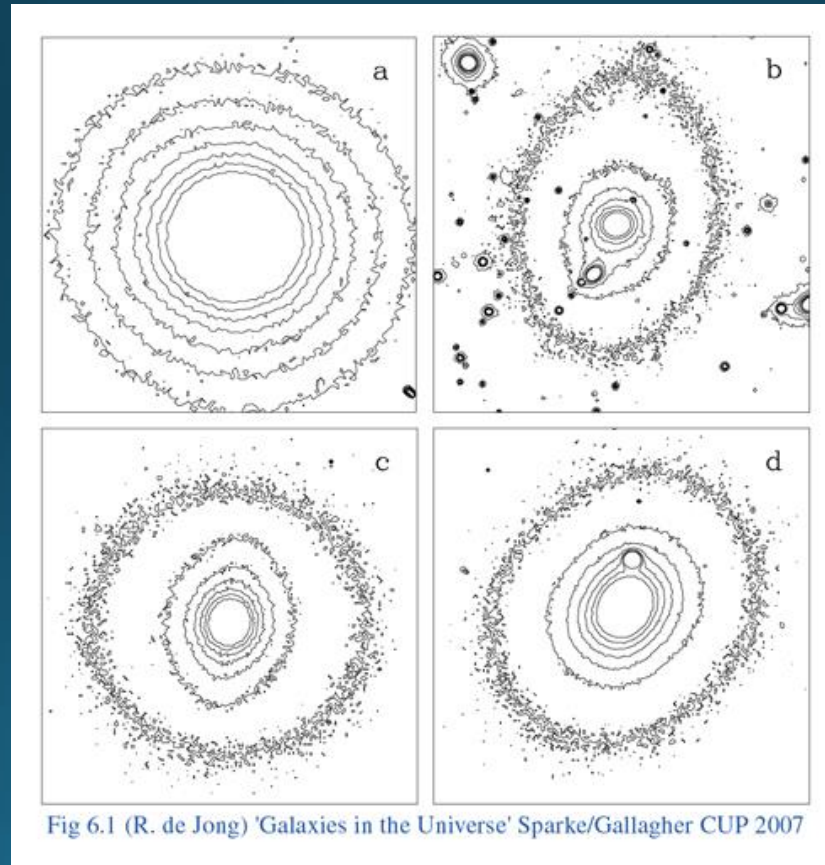
# Elliptical Galaxies



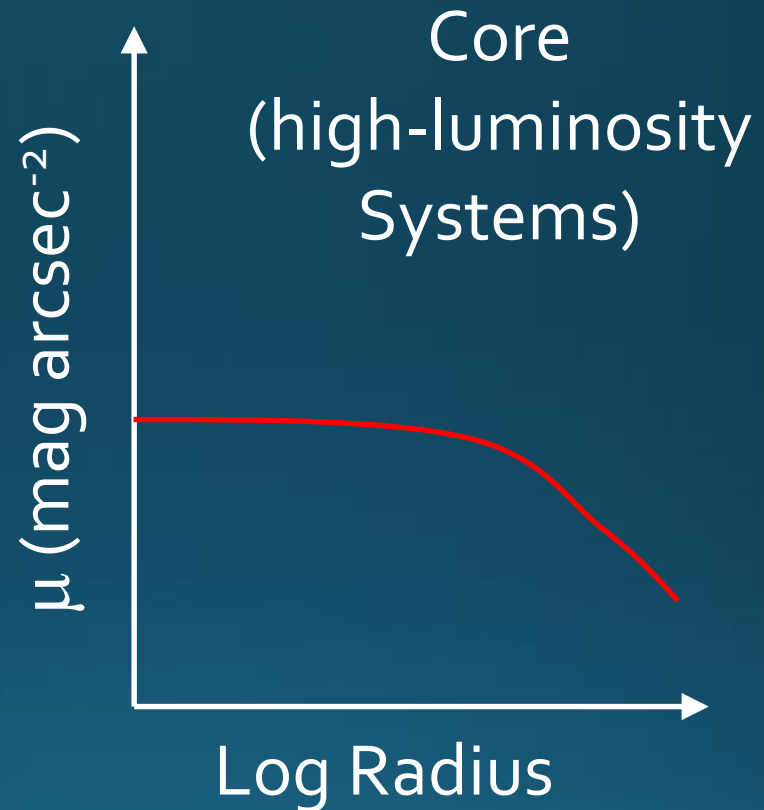
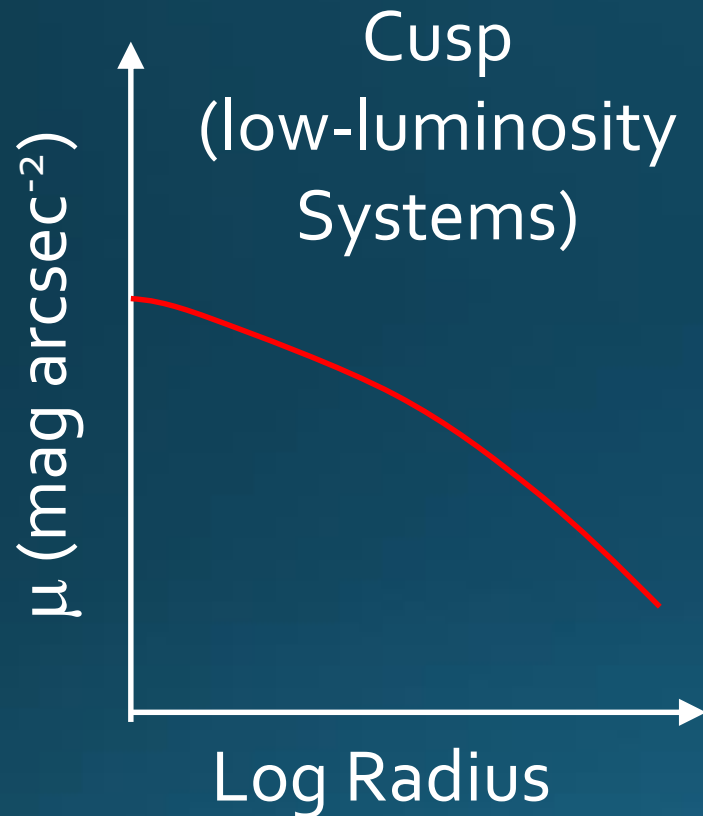
# Surface Brightness Profiles of Ellipticals I

$R^{1/4}$  or De Vaucouleurs law ( $n \approx 4$ )

$$I(R) = I(0) \exp\left(-\left(R / h_R\right)^{1/n}\right)$$



# Surface Brightness Profiles of Ellipticals II



**Late-breaking news:** The core is due to influence from the central supermassive black hole. The radius of the core correlates strongly with the black hole mass (Thomas et al. 2016, Nature)!

# Stars and Spectra of Ellipticals I

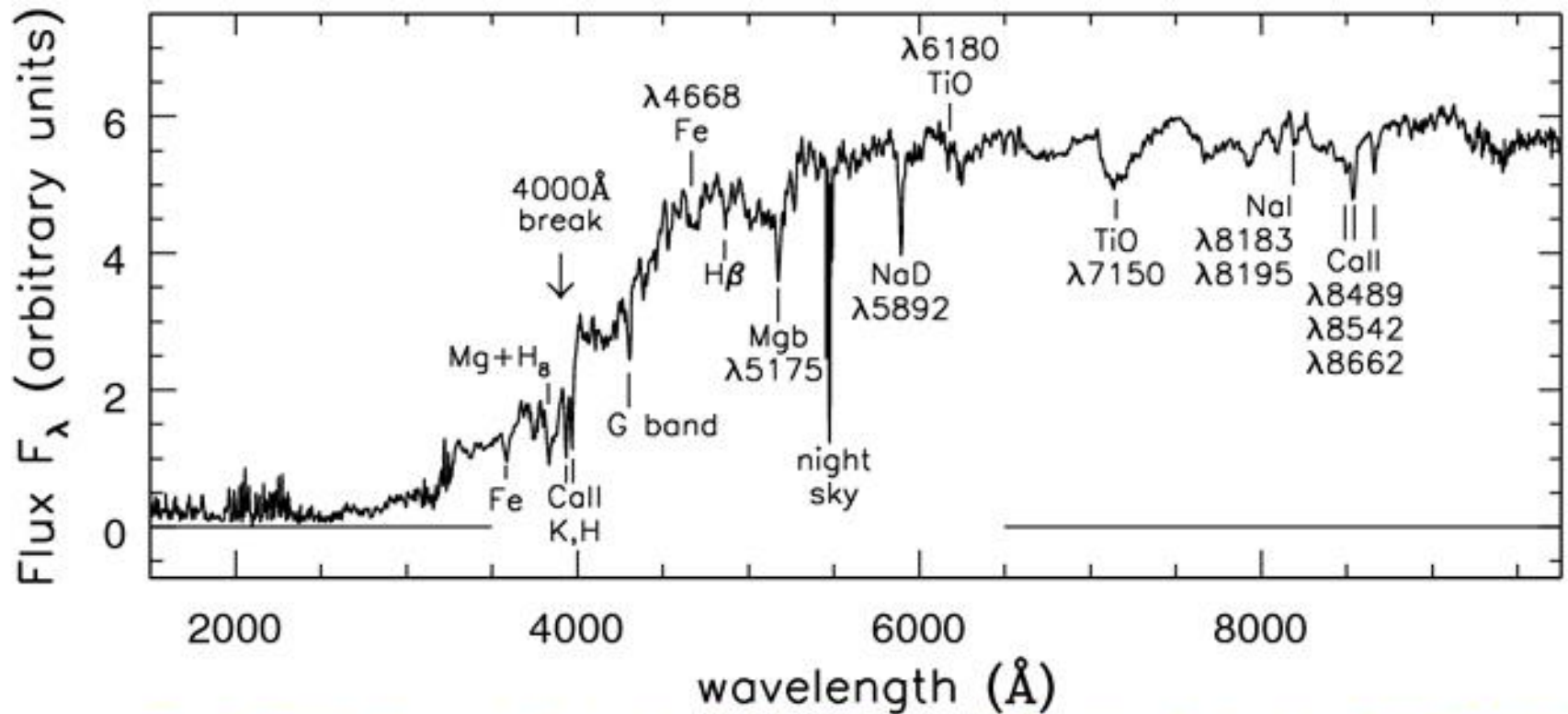
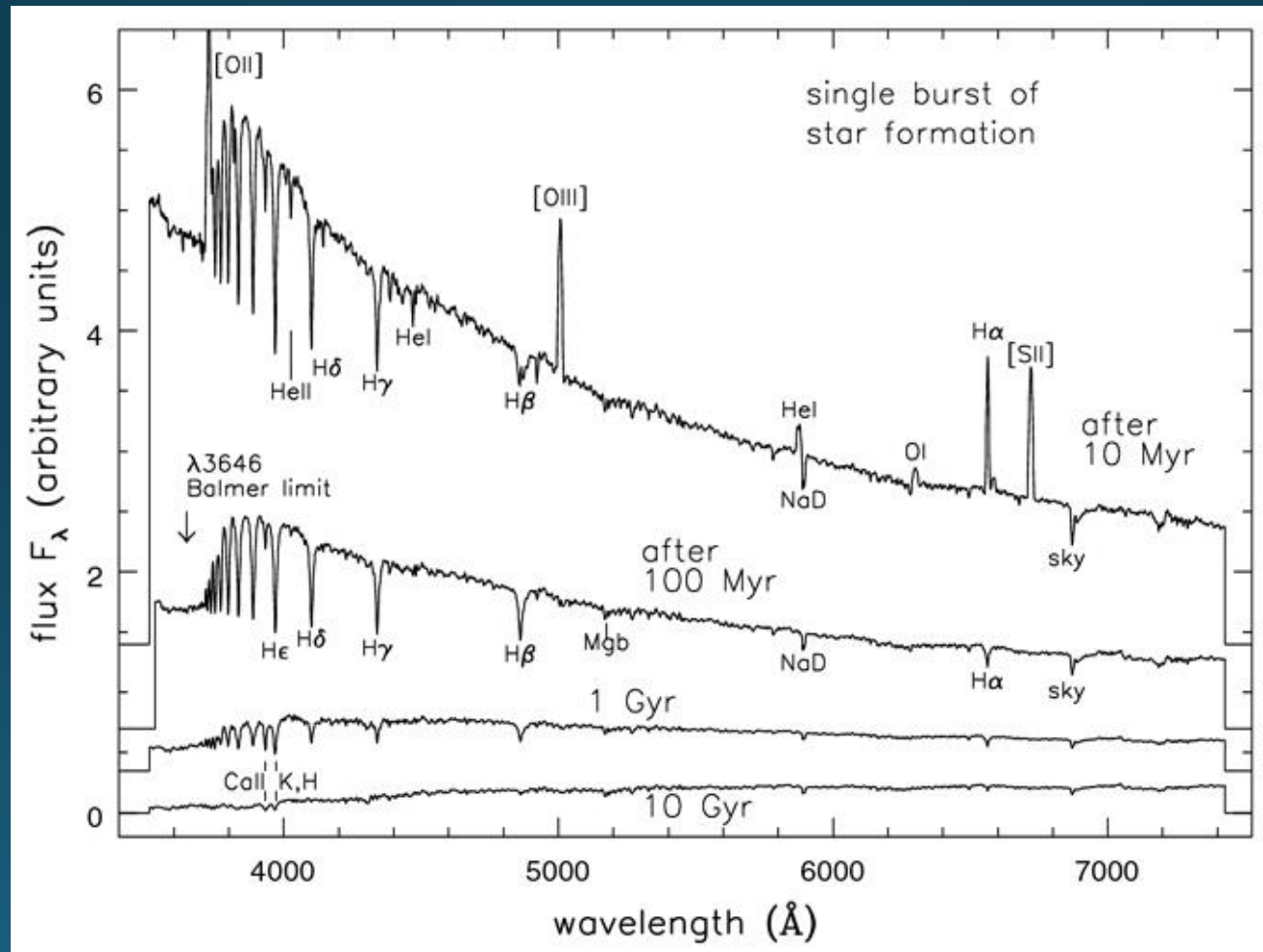


Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

# Stars and Spectra of Ellipticals II

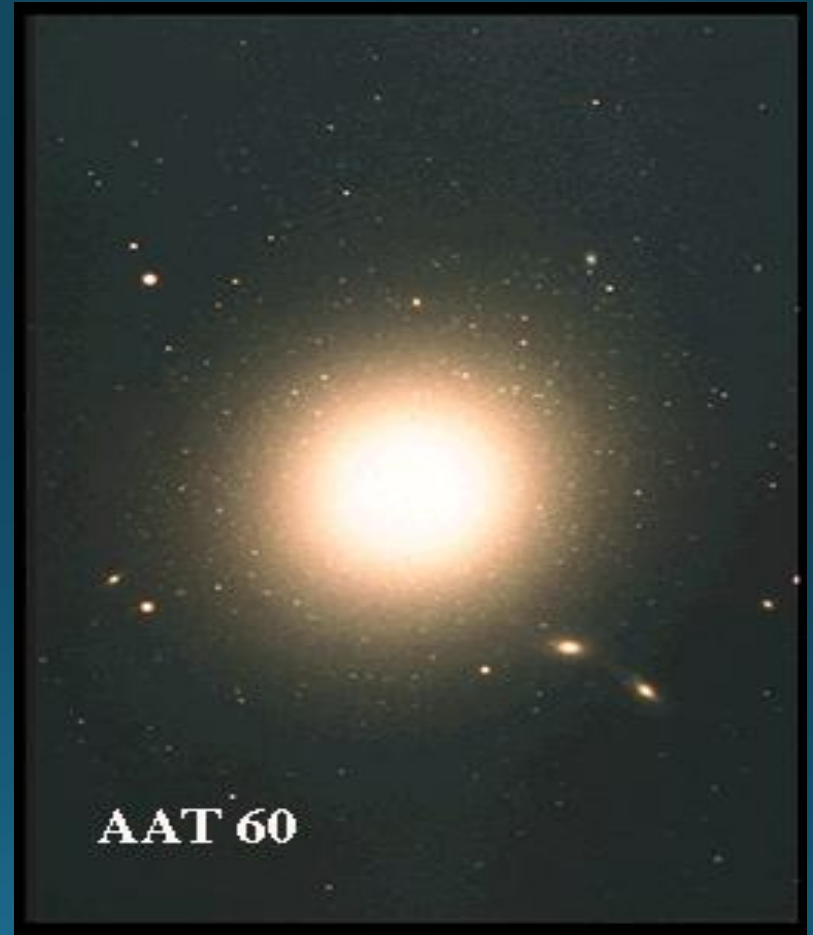
'E+A'-systems: Ellipticals with spectral signatures of recent star formation





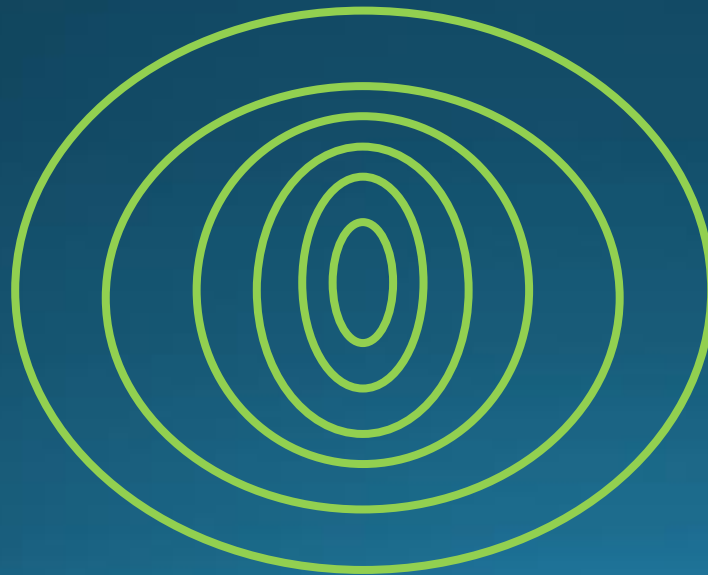
# cD-Galaxies

- The most luminous, non-active galaxies
- “Cannibal-galaxies”, found only in centres of galaxy groups and clusters
- Brighter than  $R^{1/4}$ -law prediction at large radii



# Triaxiality

- $X \neq Y \neq Z$
- Isophote twisting: a tell-tale sign of triaxiality



# Stellar Motions in Ellipticals

- Flattening of ellipticals not always due to rotation, but rather velocity anisotropy ( $\sigma_x \neq \sigma_y$ )

$$\frac{v_{\max}}{\sigma_v} \approx 0.01 - 1$$

# The Faber-Jackson Relation

$L \propto \sigma_0^4$ , e.g.

$$\frac{L_V}{2 \times 10^{10} L_{V\text{solar}}} = \left( \frac{\sigma_0}{200 \text{ km/s}} \right)^4$$

which is a projection of the “fundamental plane” of elliptical galaxies:

$$R_e \propto \sigma_0^{1.4} \langle I \rangle_e^{-0.85}$$

where  $R_e$  is the effective radius,  $\sigma_0$  is the central velocity dispersion and  $\langle I \rangle_e$  is the average surface brightness within  $R_e$

# Mass Determinations for Ellipticals

- More difficult than for disk galaxies
- A few methods:
  - For gas-rich Es: HI rotation curves
  - X-ray gas:  $M=f(\rho_{\text{gas}}, r, T)$
  - Virial theorem:  $M=f(\sigma, r)$  with
    - Stellar  $\sigma(r)$  from absorption lines
    - Stellar  $\sigma(r)$  and  $v_{\text{rot}}$  from planetary nebula emission lines