GALACTIC DYNAMICS
AND
INTERSTELLAR MATTER

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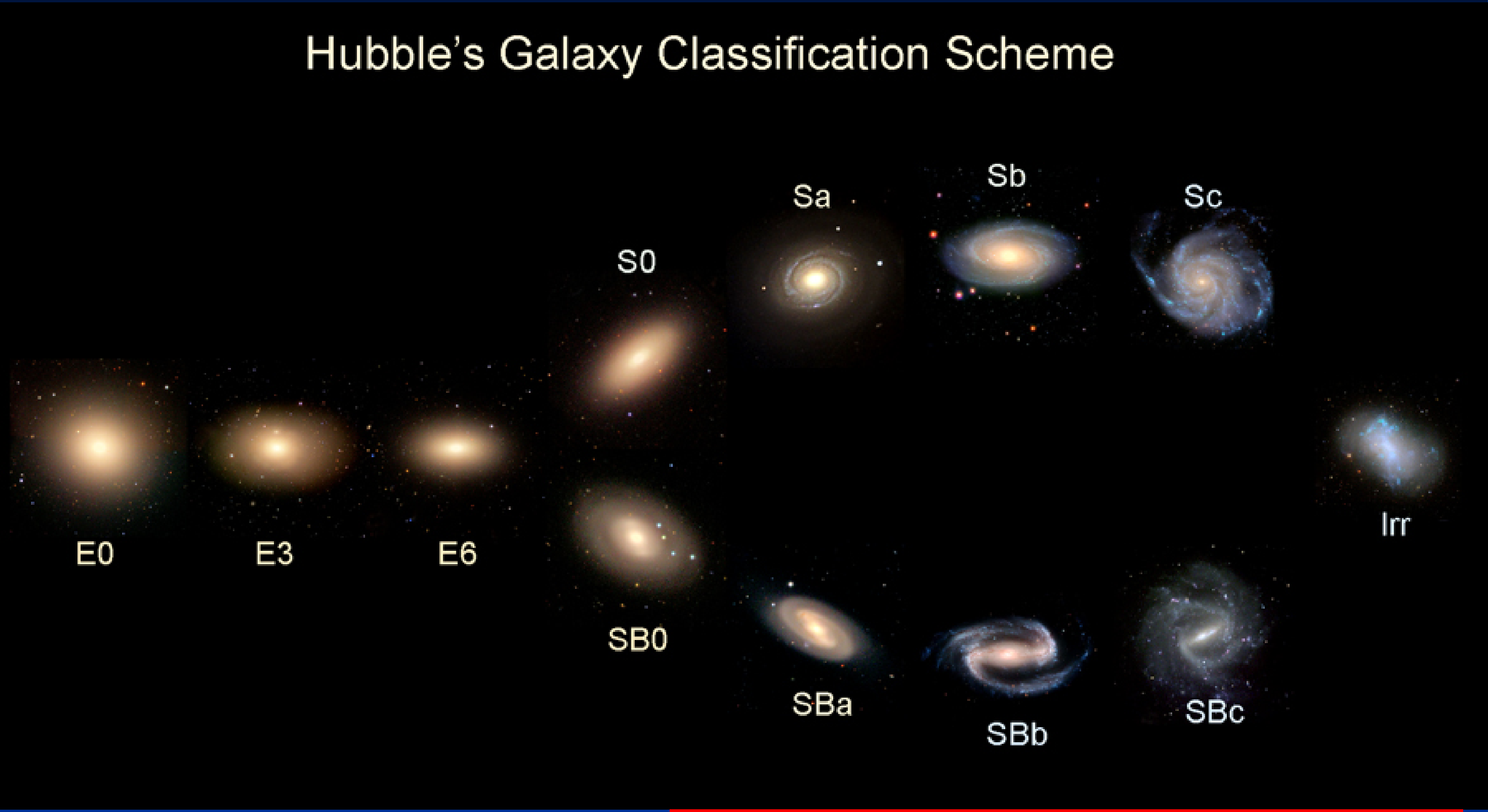
The goal:



Explain this!

…and few other things

OVERVIEW

* Milky Way galaxy

* “spiral nebulae” versus other galaxies

* Galaxy luminosity function

* Dark matter

* Large scale structure and cosmology

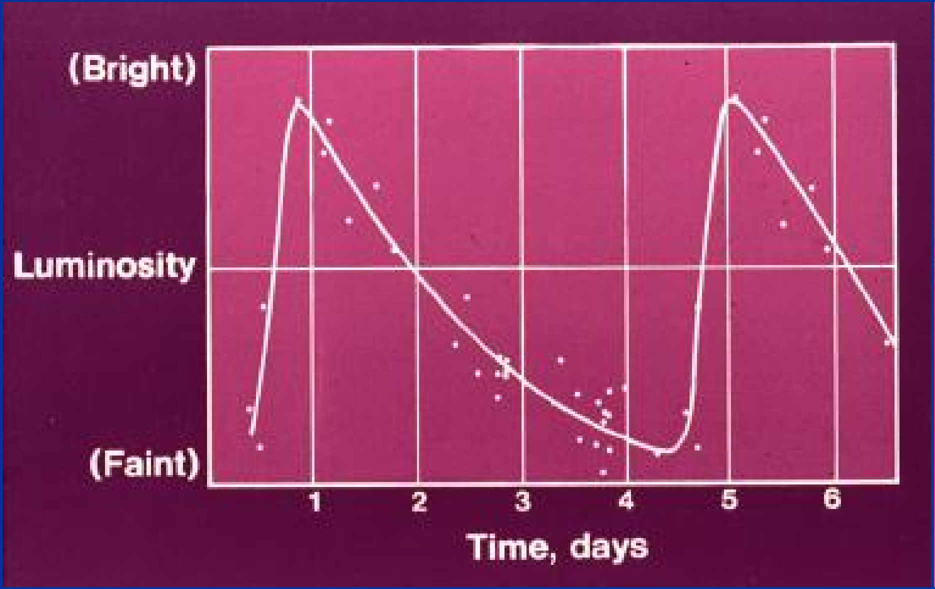
The distance ladder in the MW and beyond

STEP 1: use parallax

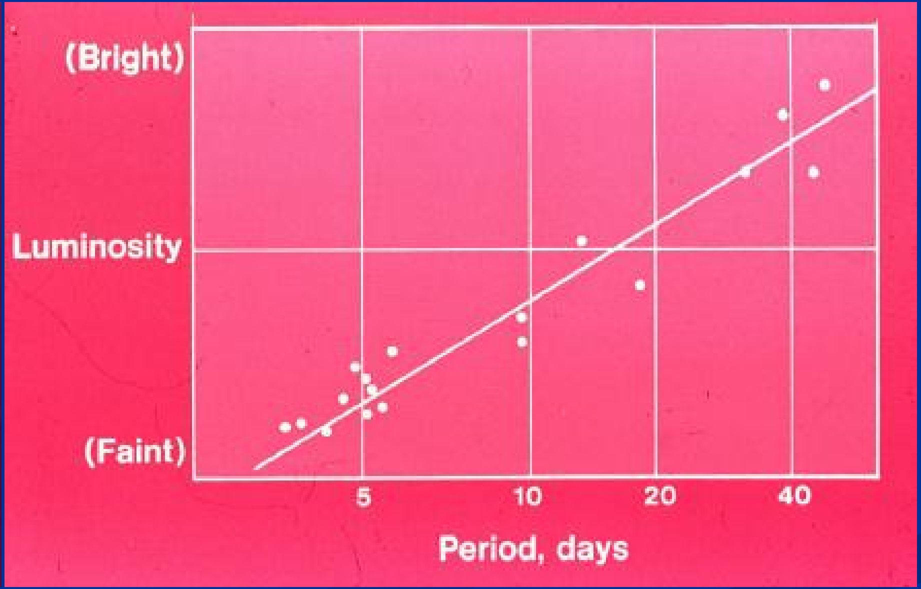
STEP 2: use HR diagram and start with the spectral class of a star

STEP 3: use Cepheid variables in the following way:

Cepheids as variable stars



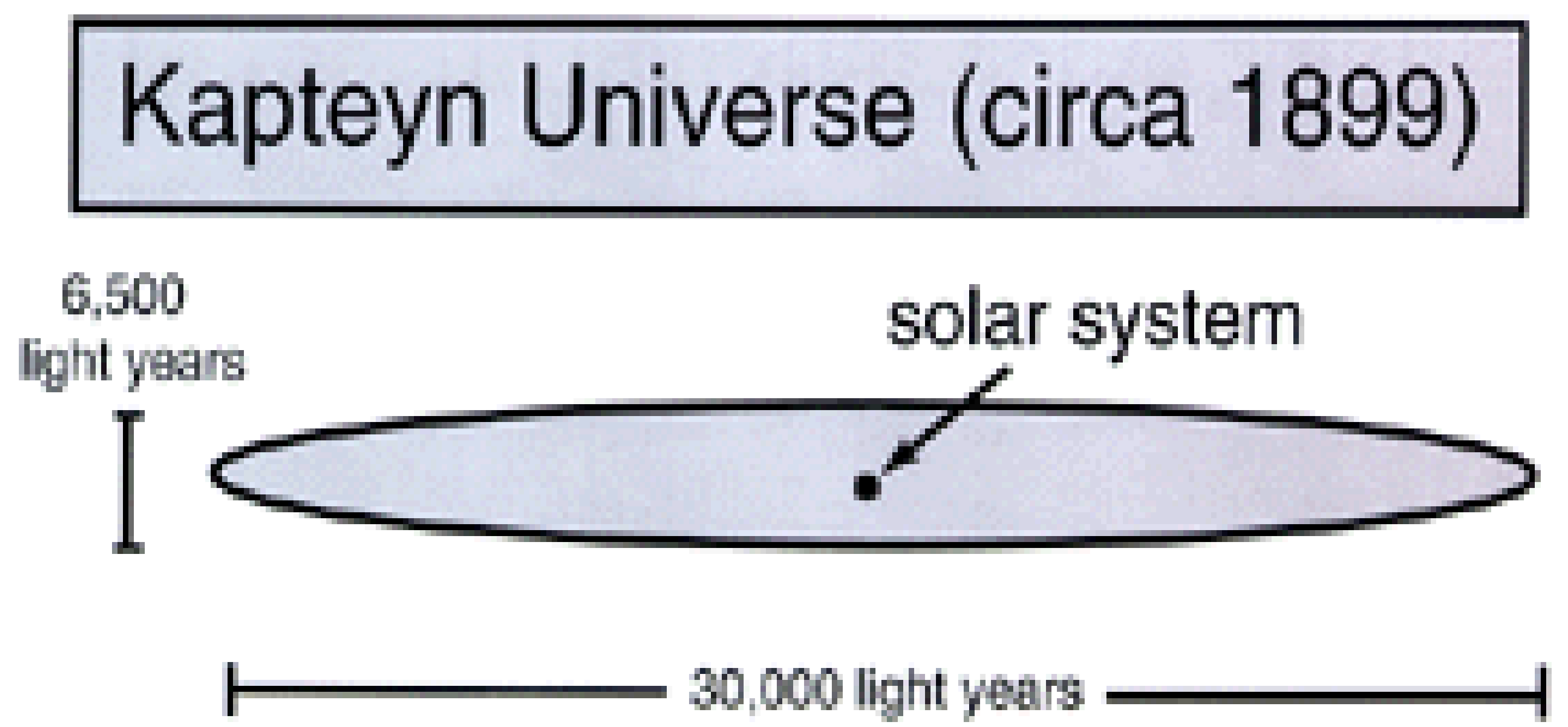
The period-luminosity relation



Cepheids are very luminous and only one star is needed …

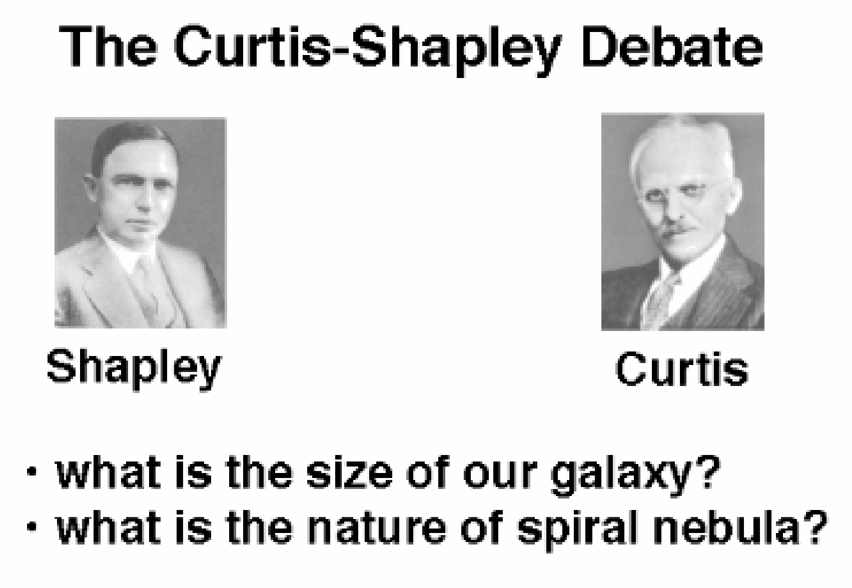
STEP 4: use supernovae Ia as “standard candles”

- What is the shape of the Milky Way (MW) galaxy?



Neglecting the dust obscuration: the MW appears too small!

The great nebula debate between Shapley and Curtis in 1920



The Curtis-Shapley Debate

Shapley

Curtis

- what is the size of our galaxy?
- what is the nature of spiral nebula?

Lord Rosse (1800-1867)

M51

M101

The leviathan
72” refractor
of Lord Rosse

Shapley: Spiral nebulae are nearby objects IN the MW

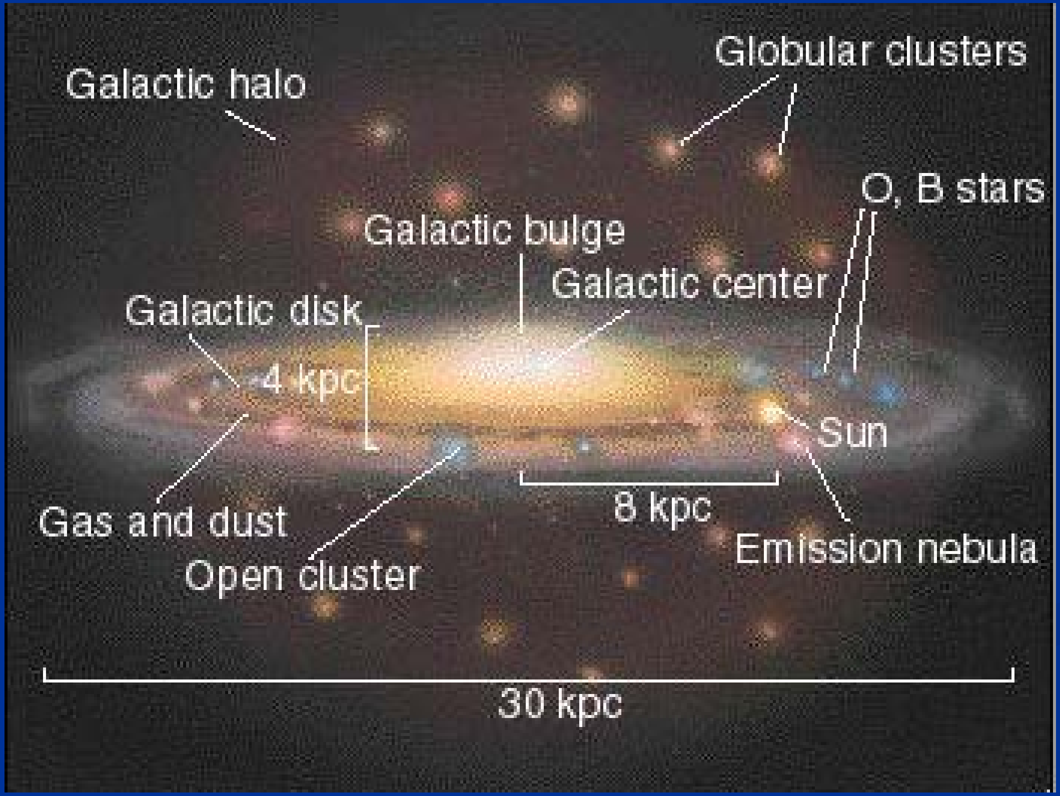
Curtis: Spiral nebulae are distant star systems OUTSIDE the MW

THE WINNER: **Shapley**
CORRECT: **Curtis**

1923-24: Hubble finds Cepheids in Andromeda Nebula and determines its distance

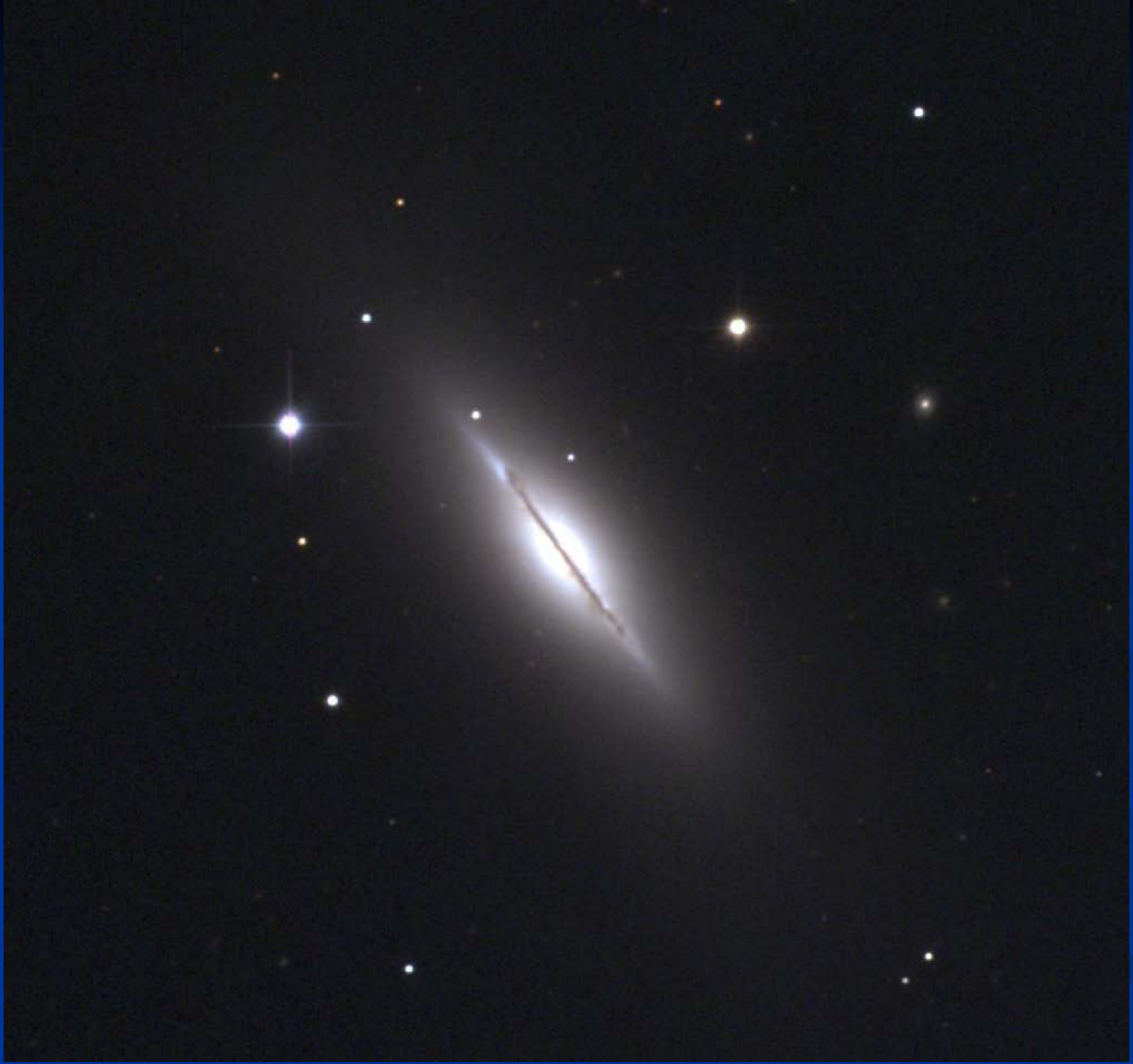
❖Contemporary view of the MW

COBE satellite IR image



All the components of the MW

M31 --- the giant disk galaxy in constellation Andromeda at 1 Mpc



M102 --- the Spindle galaxy --- edge-on disk galaxy at 12.5 Mpc

➢The Universe of galaxies

The broadest way to classify galaxies in three general types:

Disk galaxies (as the MW) --- most of the light comes from a thin rotationally-supported stellar disk

Elliptical galaxies --- ovally-shaped and nearly featureless. Rotation is not as important

M87 --- giant elliptical galaxy in Virgo at 19 Mpc

NGC 5128 (Centaurus A) --- giant elliptical cannibalizing a disk galaxy at 4.8 Mpc.
Has a supermassive black hole of $\mathbf{10^9\ M_\odot}$ in its center

The Universe of galaxies

The broadest way to classify galaxies in three general types:

Disk galaxies (as the MW) --- most of the light comes from a thin rotationally-supported stellar disk

Elliptical galaxies --- ovally-shaped and nearly featureless. Rotation is not as important

Irregular galaxies --- “renegades” which cannot be put in disks or ellipticals. Rotational symmetry is absent

The same ellipticals scaled to the same distance

Two stars of large mass ratio would occupy extremes of the HR diagram and have completely different (from each other) internal structure

↓

Unlike stars, galaxies of very different sizes can be built on nearly the same overall pattern


M87


M32

Important: gravitational dynamics is *scale-free!*

➢Luminosity distribution

What is the relative distribution of galaxies with absolute luminosity **L**?

NOTE: **Absolute L: the actual power output of an object**
Apparent L: the observed power of an object (from Earth)

Schechter function:

$$\varphi(L)\,dL = n_* \left(\frac{L}{L_*}\right)^{\alpha} \exp\left(-\frac{L}{L_*}\right) \frac{dL}{L_*}$$

Where $\varphi(L)\,dL$ -- number of galaxies per unit volume with luminosities between **L and L+dL**

n_* -- constant parameter (number density of galaxies)

L_* -- constant parameter (luminosity of a typical bright galaxy)

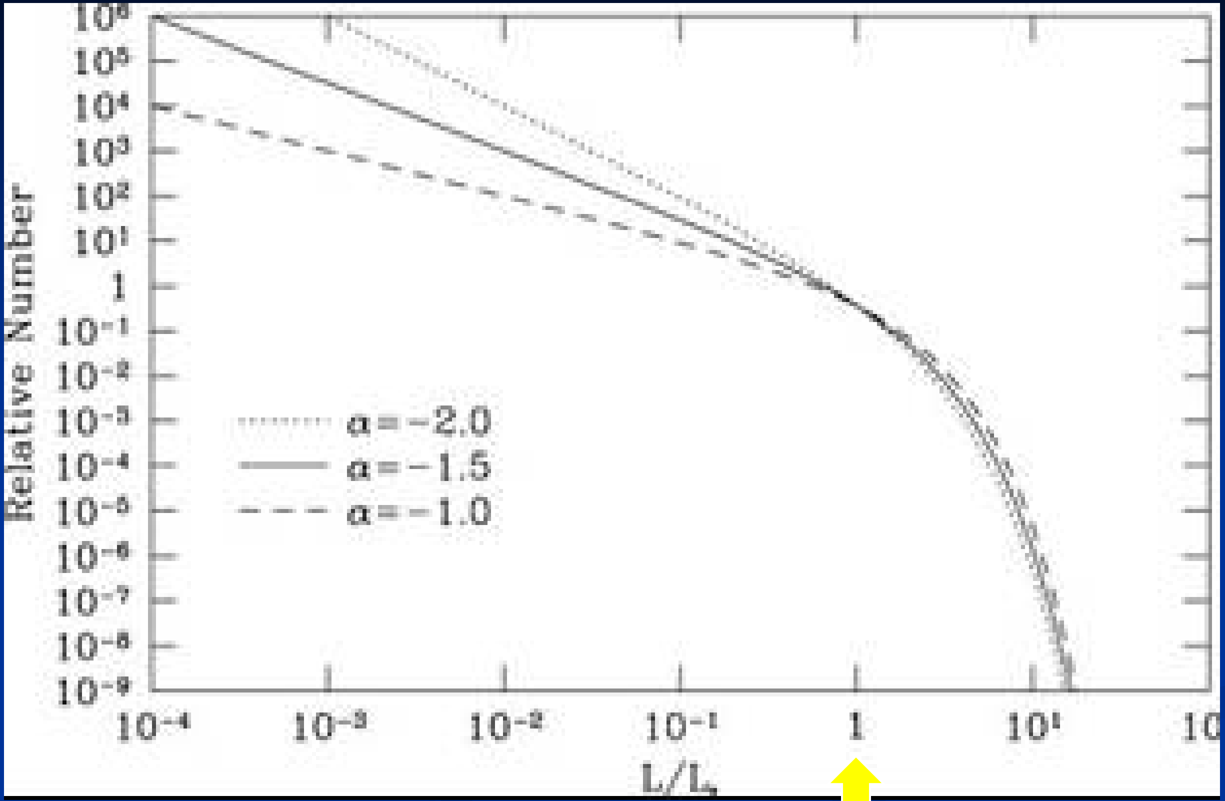
$\alpha \cong -1.25$ -- fainter galaxies are more common!

Schechter function: a power law for $L \ll L_*$ cuts off rapidly for $L \gg L_*$

Schechter luminosity function

NOTE: when **L→0**

$$\int_{L}^{\infty} \varphi(L)\,dL \to \infty$$



The total number of galaxies per unit volume diverges!

$L/L_* = 1$

L needs to be cut off at lower end

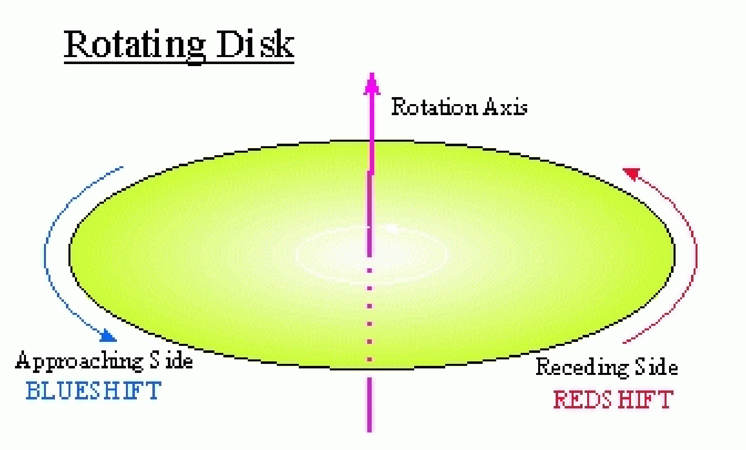
However, the total luminosity per unit volume:

$$\int_{L}^{\infty} L\,\varphi(L)\,dL$$ is finite

Most of the total luminosity is coming from galaxies with **$L > 0.1\,L_*$**

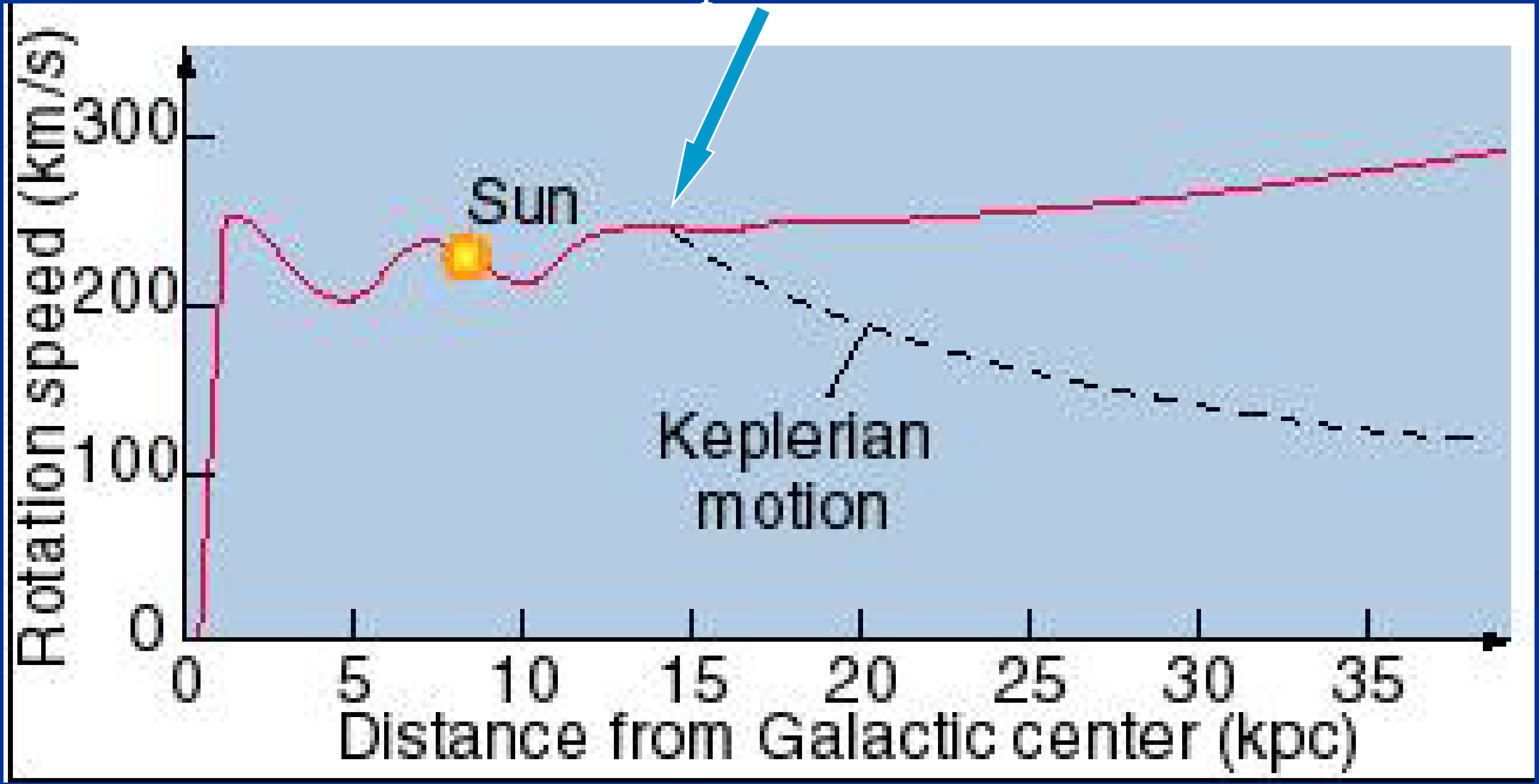
So what is the working definition of a galaxy?

A galaxy is a self-gravitating system of stars, interstellar gas/dust and dark matter

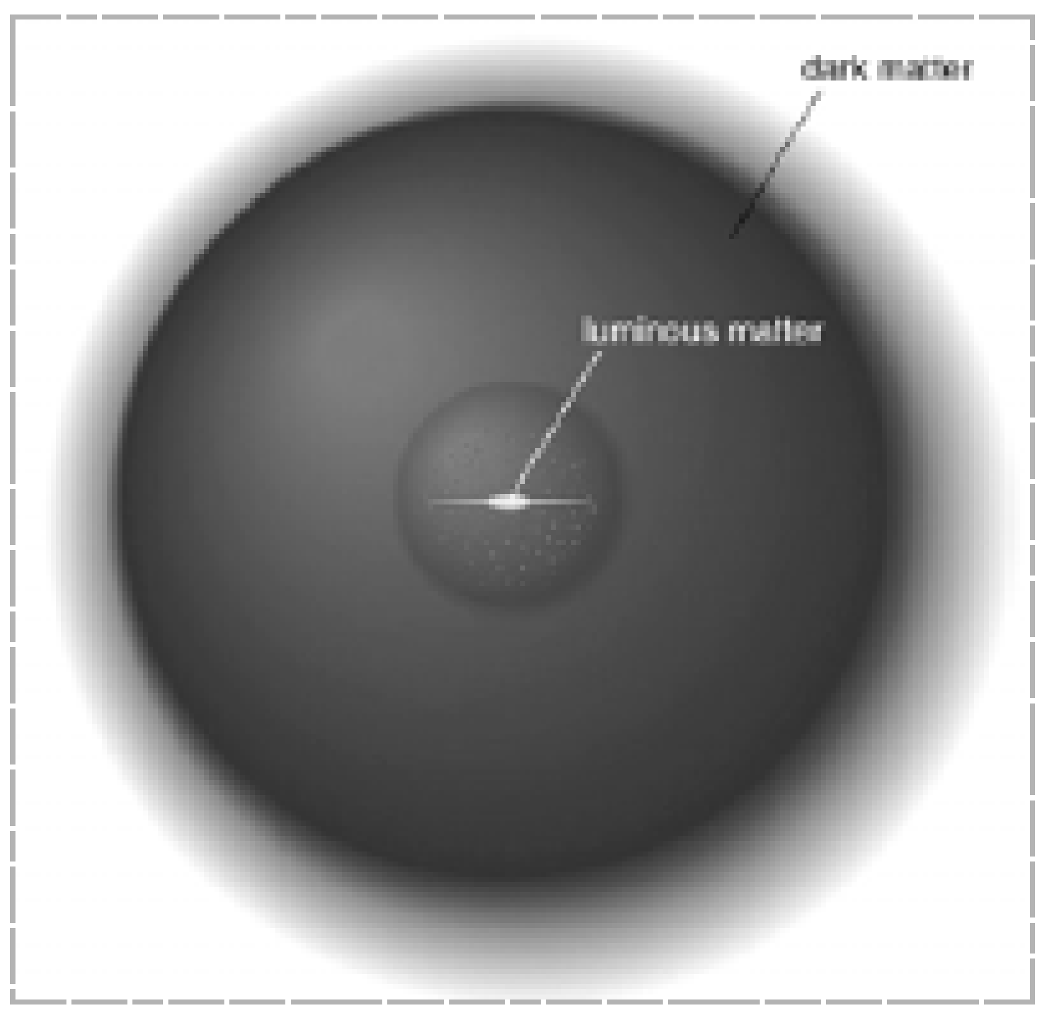


Why dark matter?

end of optical disk in the MW



a typical galaxy:

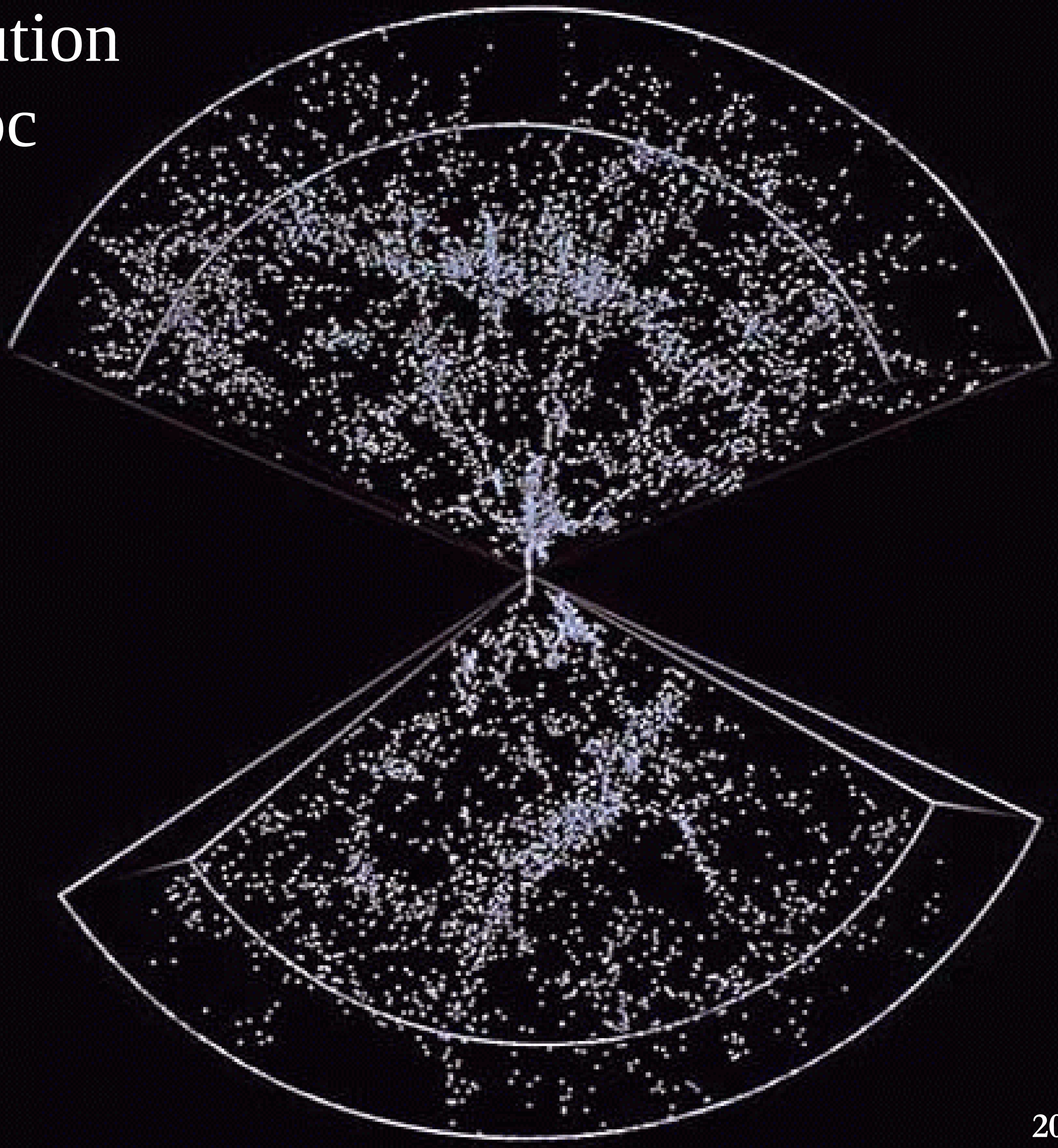


HOW MUCH DARK MATTER?

Visible matter makes up only a tiny fraction of galaxies. The remainder is in a halo of dark matter, roughly 10 times as big and 10 times as massive

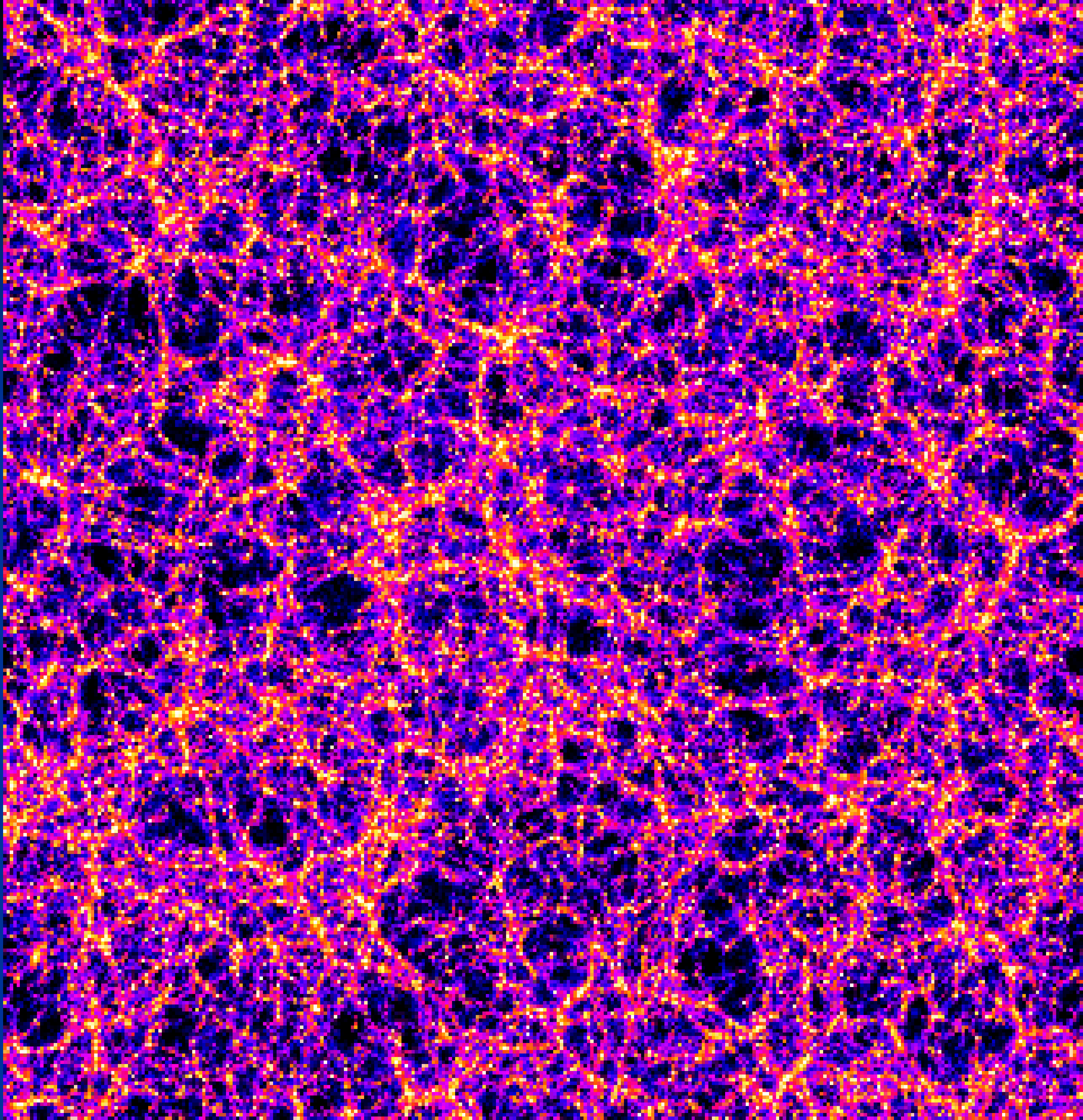
dark matter is about 84% of the total **matter** in the Universe ! !

- Galaxy distribution within 100 Mpc from the MW



The large-scale structure of the Universe

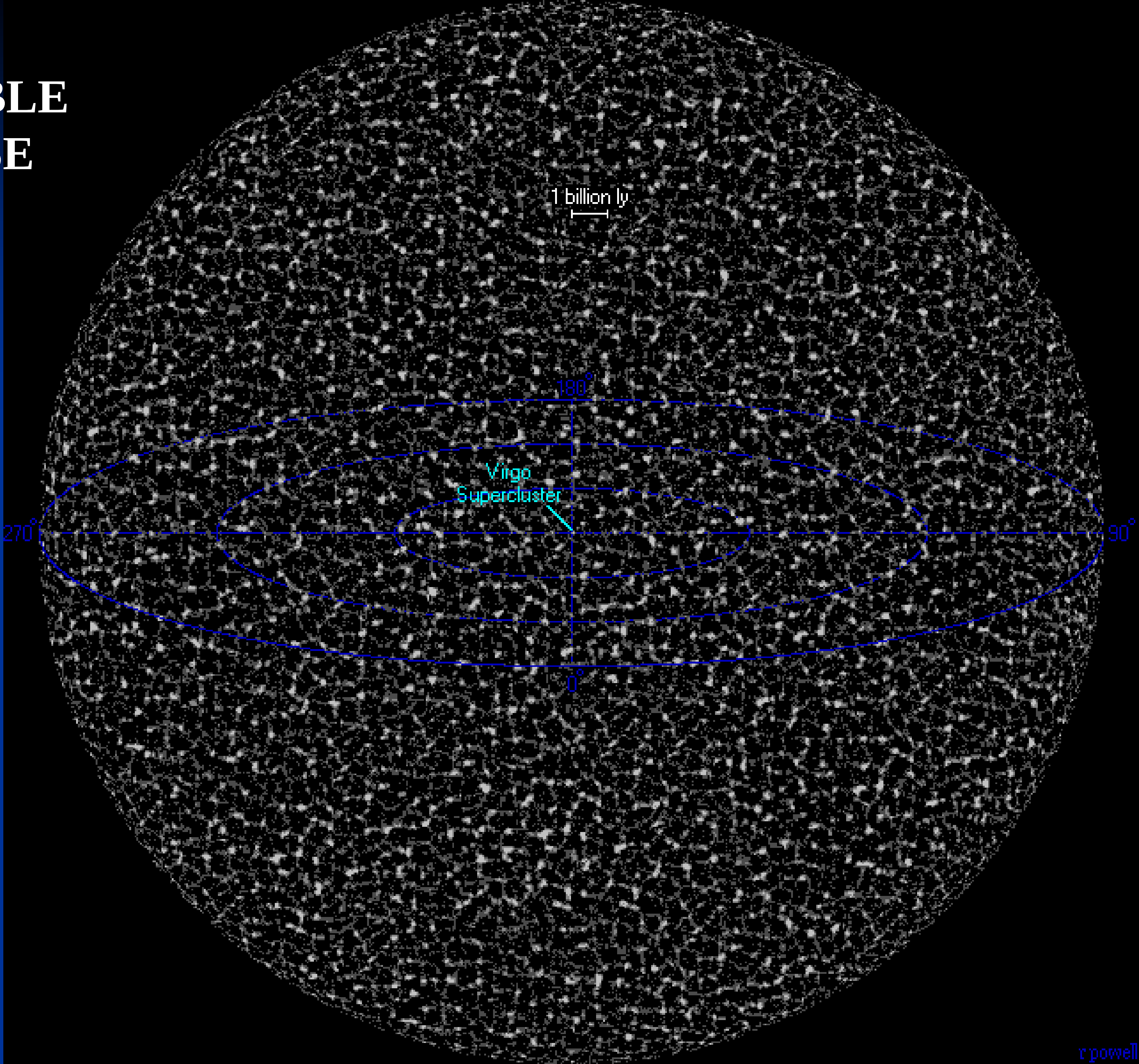
DARK MATTER **ONLY**



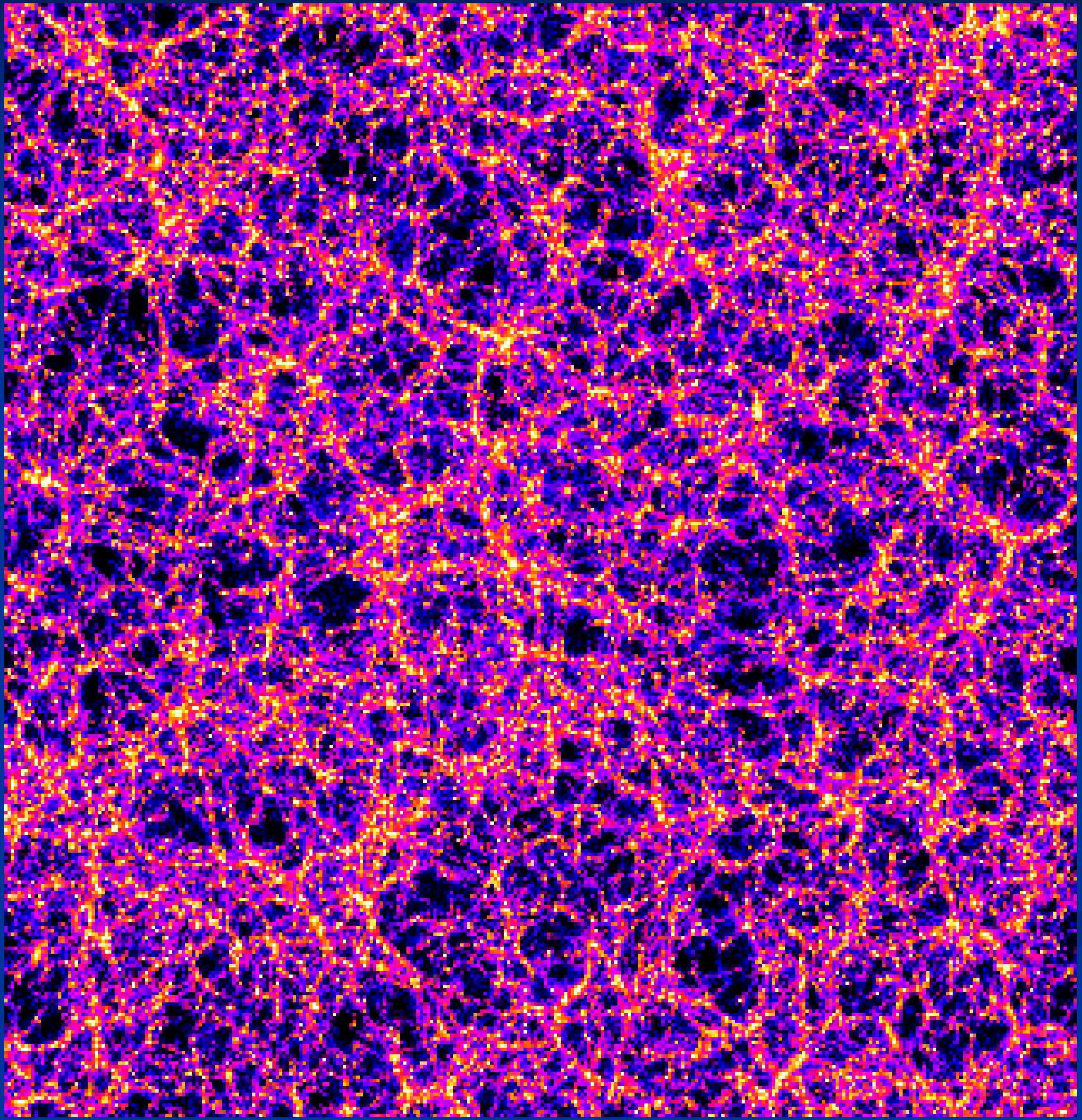
superclusters and voids

filaments and shells

THE VISIBLE UNIVERSE



MILLENIUM NUMERICAL SIMULATION: LARGE-SCALE STRUCTURE OF THE UNIVERSE



COSMOLOGY: THE HUBBLE LAW

The universe is defined as *everything*: all the *matter*, all *energy*, all *space*

➡ By definition, there is only one universe, and there can be *nothing outs*ide the universe

- What we can see of the universe is typical. That is, on the *large scale* the universe is:

ISOTROPIC: the same in every direction

HOMOGENEOUS: the same in every location

- The recession velocities of distant galaxies are proportional to their distances (d), that is

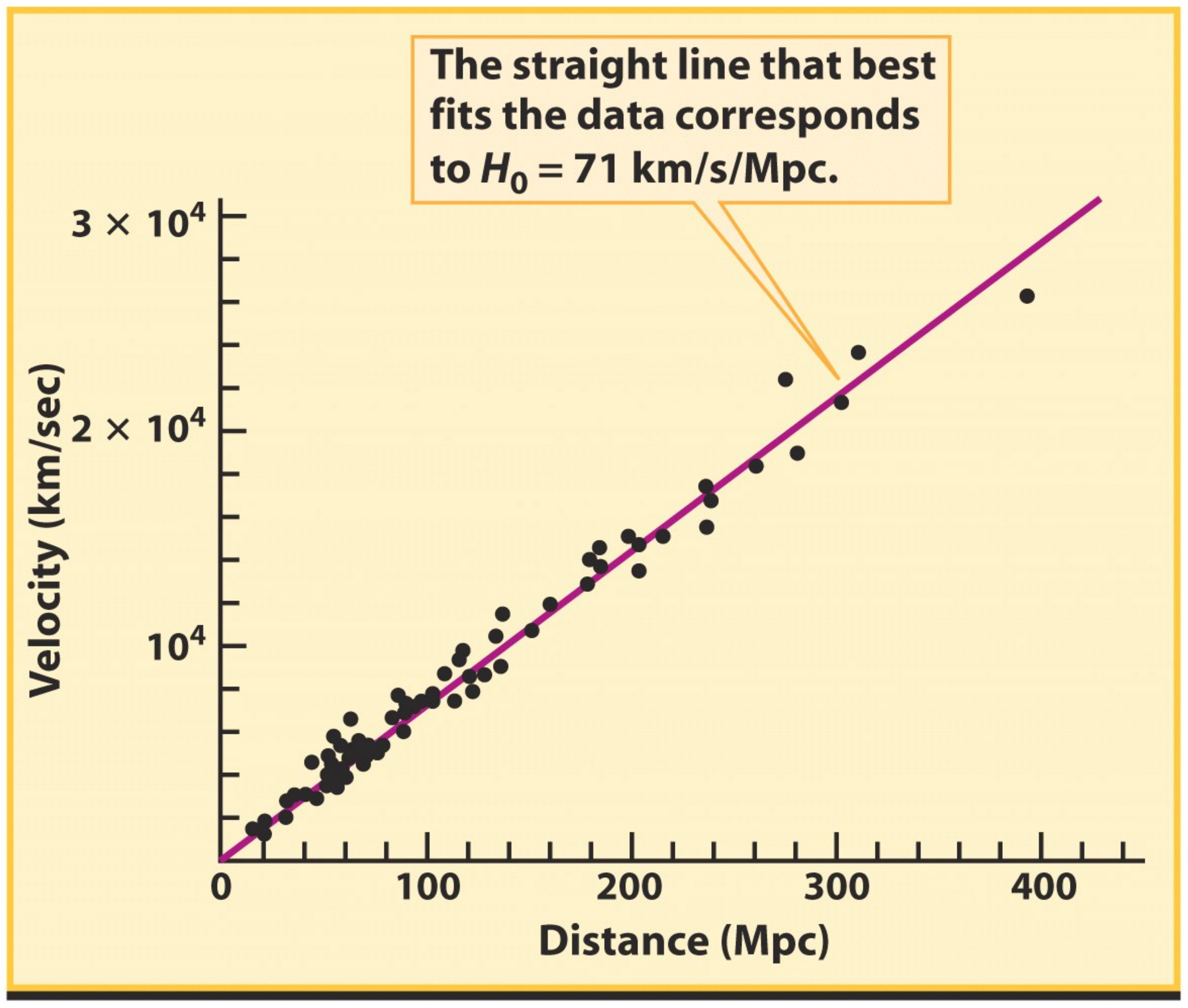
$$\boxed{\mathbf{v = H_o\, d}}$$

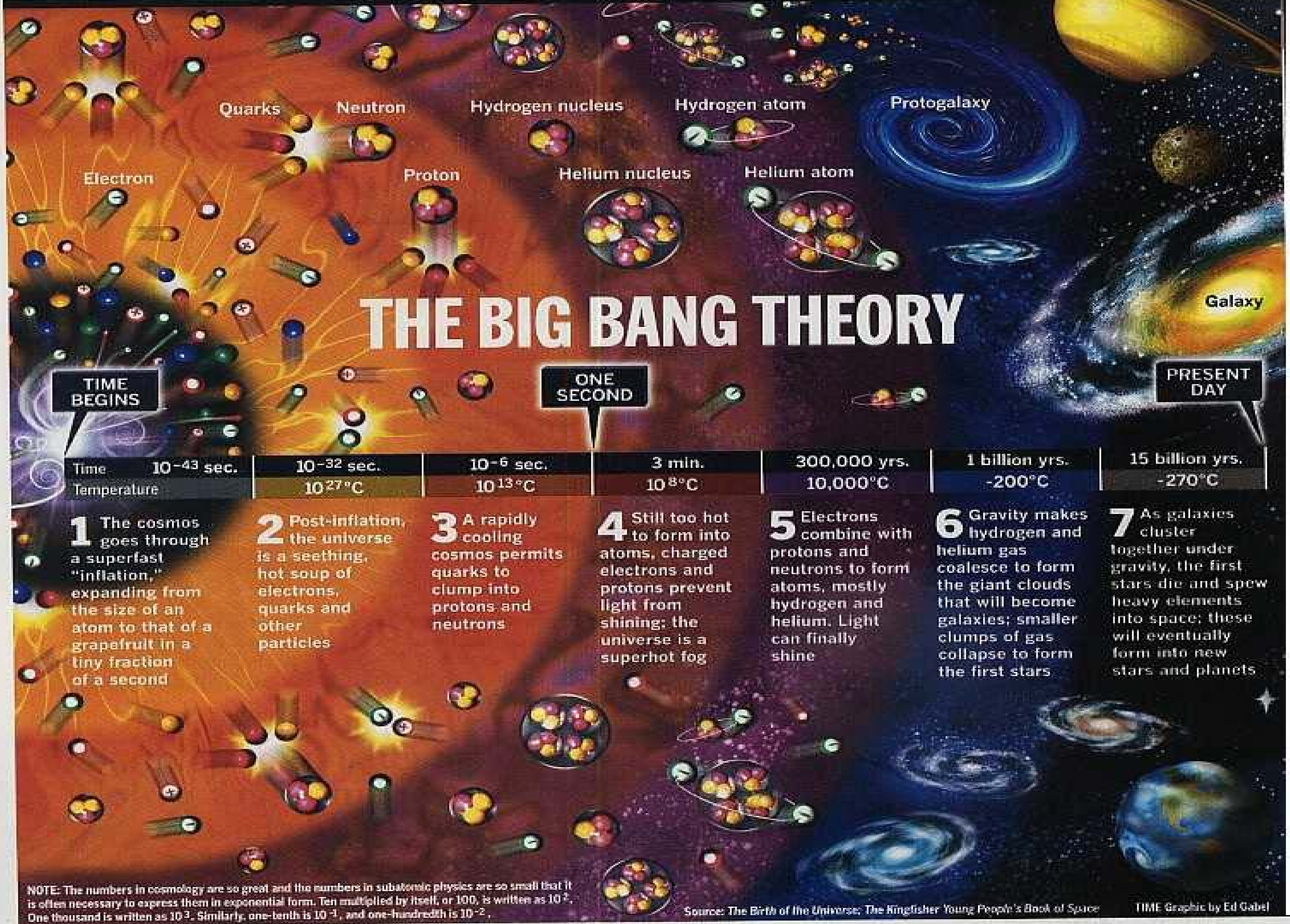
The constant of proportion (**H_o**) is called the Hubble constant

$$\boxed{\mathbf{H_o = 67.8 \pm 0.77 \text{ km/sec per Mpc}}}$$

(From the Planck mission
March 21, 2013)

THE HUBBLE LAW: $v = H_0 d$


The straight line that best fits the data corresponds to $H_0 = 71$ km/s/Mpc.



THE BIG BANG THEORY

Time	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature		10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

NOTE: The numbers in cosmology are so great and the numbers in subatomic physics are so small that it is often necessary to express them in exponential form. Ten multiplied by itself, or 100, is written as 10^{2}. One thousand is written as 10^{3}. Similarly, one-tenth is 10^{-1}, and one-hundredth is 10^{-2}.

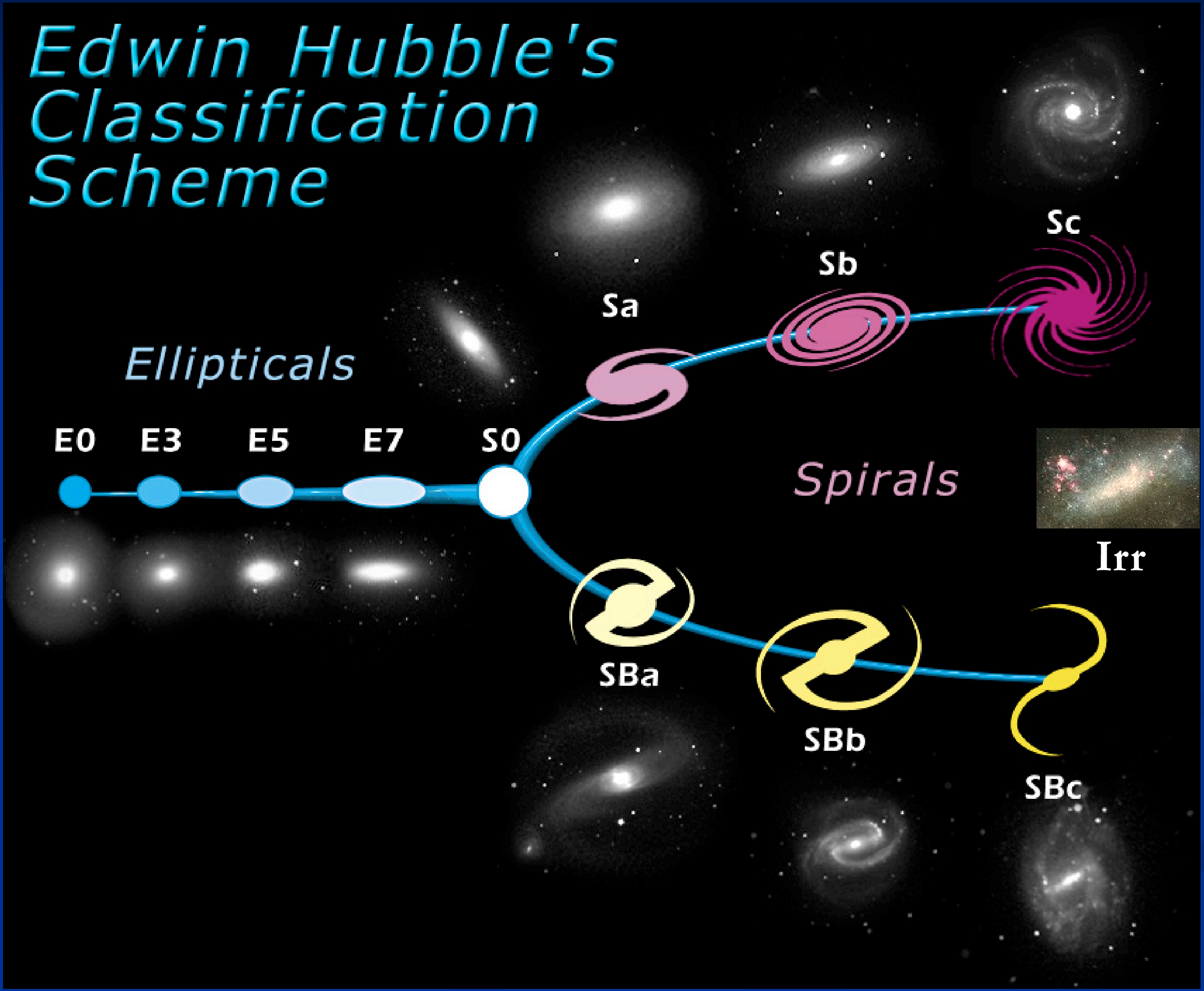
Source: *The Birth of the Universe; The Kingfisher Young People's Book of Space*

TIME Graphic by Ed Gabel

GALACTIC MORPHOLOGY AND CLASSIFICATION

*Classification systems
*Morphological distributions
*Magnitudes
*Quantitative morphology
*Basic components: elliptical and disk galaxies
*Disk kinematics
*Disk mass and dark matter
*Spirals and bars

➢Galaxy classification systems



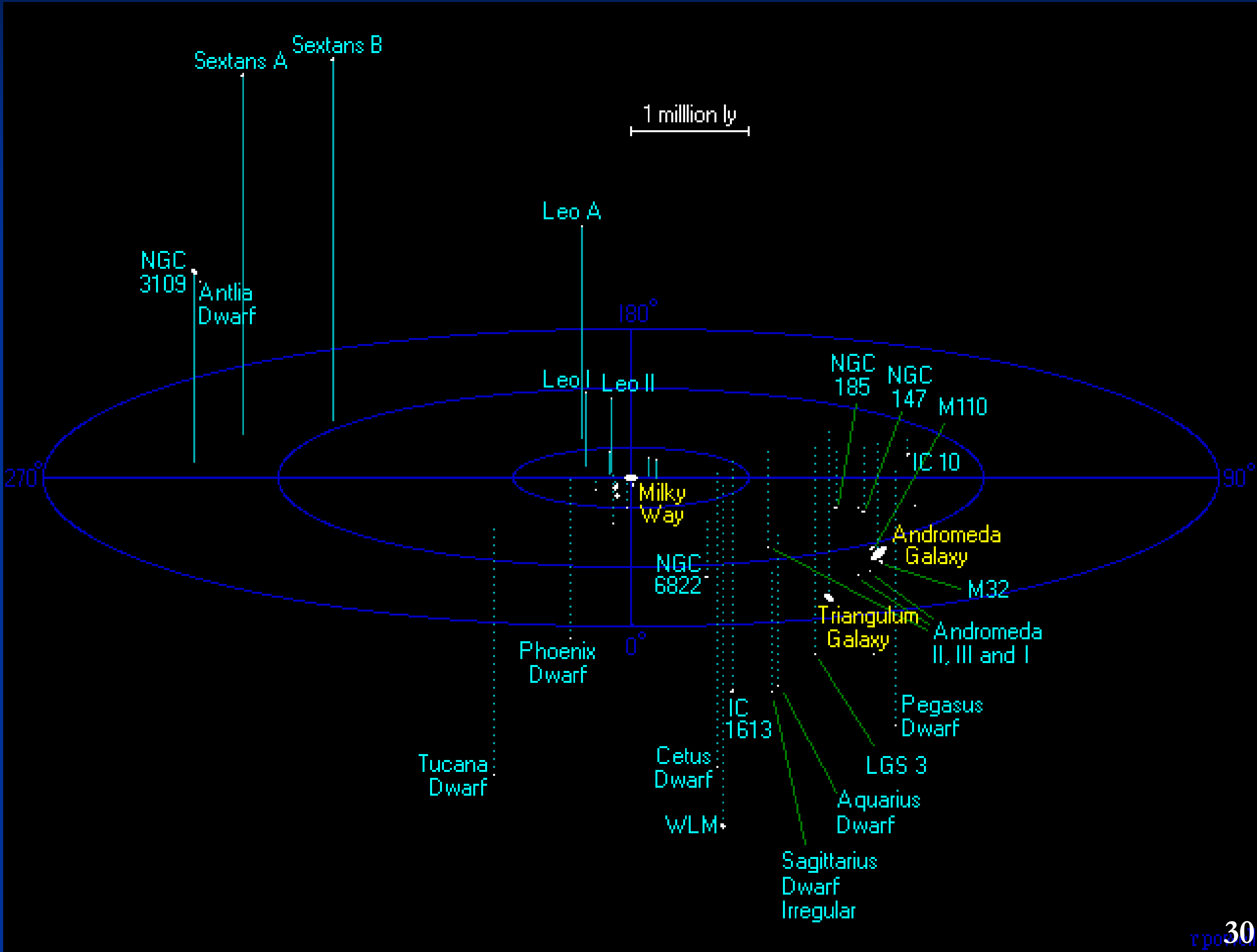
unbarred branch

barred branch

➢Morphological distributions

What are fractions of different galaxy types?

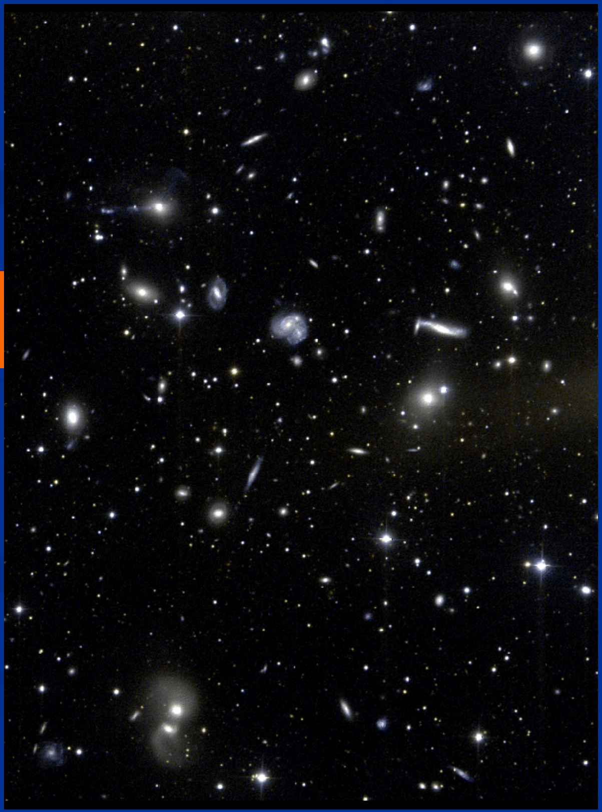
The Local Group of galaxies



- The Local Group: ~ 35-40 members:
  Only 3 are spirals (**M31**, the **MW**, **M33**)
  Others: irregulars and dwarf ellipticals

- Field samples: outside the rich clusters are strongly biased towards late-type (**Sc**) spirals. A typical field sample consists of 80% **S**, 10% **S0**, 10% **E** galaxies

- Rich clusters: bright galaxies early-type systems
  Morphological mix varies smoothly with galaxy density:



Hercules: rich cluster of galaxies

intermediate densitites: 40% **S**, 40% **S0**, 20% **E**
high densities: 10% **S**, 50% **S0**, 40% **E**

- Magnitudes:

apparent ‘**m**’, absolute ‘**M**’

Since Hipparcos (II AD):

brightest star in the sky --- 1st (apparent)magnitude
dimmest star --- 6th (apparent) magnitude

Still brighter stars: 0, then negative magnitudes
Still dimmer stars: 7 and larger magnitudes

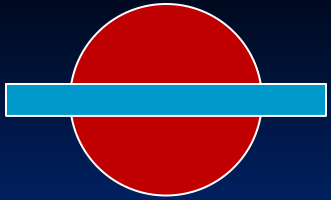
Difference by 1 (one) magnitude means brighter (dimmer) by 2.5

$$\mathbf{m_1 - m_2 = -2.5 \log_{10} (f_1/f_2)}$$

where $\mathbf{f_1}$ and $\mathbf{f_2}$ are measured (Earth) fluxes of two stars
$\mathbf{m_1}$ and $\mathbf{m_2}$ --- apparent magnitudes of the stars

NOTE: absolute magnitudes are defined the same way, except that they represent absolute fluxes (like absolute luminosities) and are denoted by $\mathbf{M_1}$ and $\mathbf{M_2}$

Quantitative morphology



Nearby galaxies: photometry
→superpositions of spheroid + disk components with standard light distribution (luminosity) profiles

Much more difficult at higher z:
the images are so small (few 100 pixels)

- Spheroid profiles: **E** galaxies, bulges of **S** galaxies

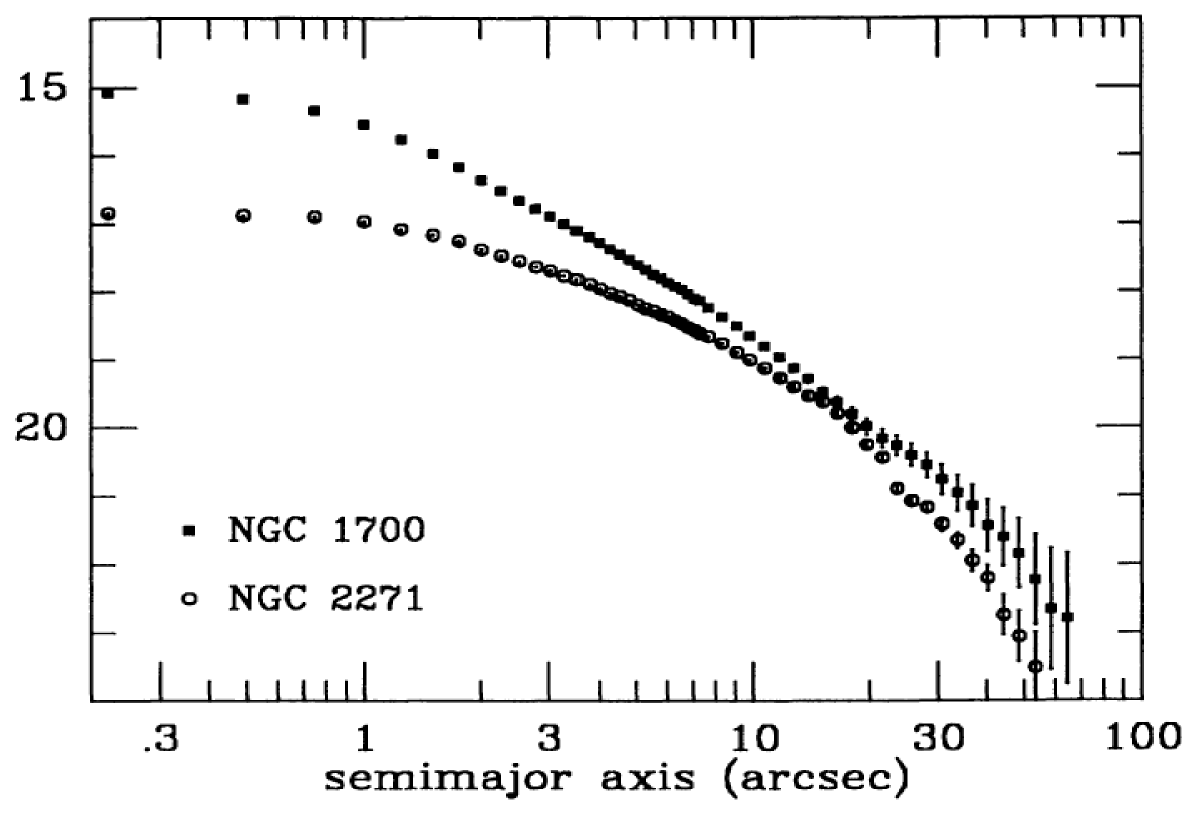
de Vaucouleurs law: $\boxed{I(R) = I_0 \exp(-kR^{1/4})}$

where **I(R)** – radial intensity profile (erg cm^{-2} s^{-1} or mag arcsec^{-2})
I_0 -- central intensity
k -- constant

Remember:
intensity is independent of distance! (except of cosmological z)

de Vaucouleurs $\mathbf{R}^{1/4}$ law:

$$\mathbf{I(R) \propto \exp(-R^{1/4})}$$



Because the measured I_0 depends on the seeing, it is often convenient to use the equivalent form

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

where $\mathbf{I_e}$ -- the surface brightness of the isophote containing 50% of the total light

$\mathbf{R_e}$ -- effective radius of this isophote

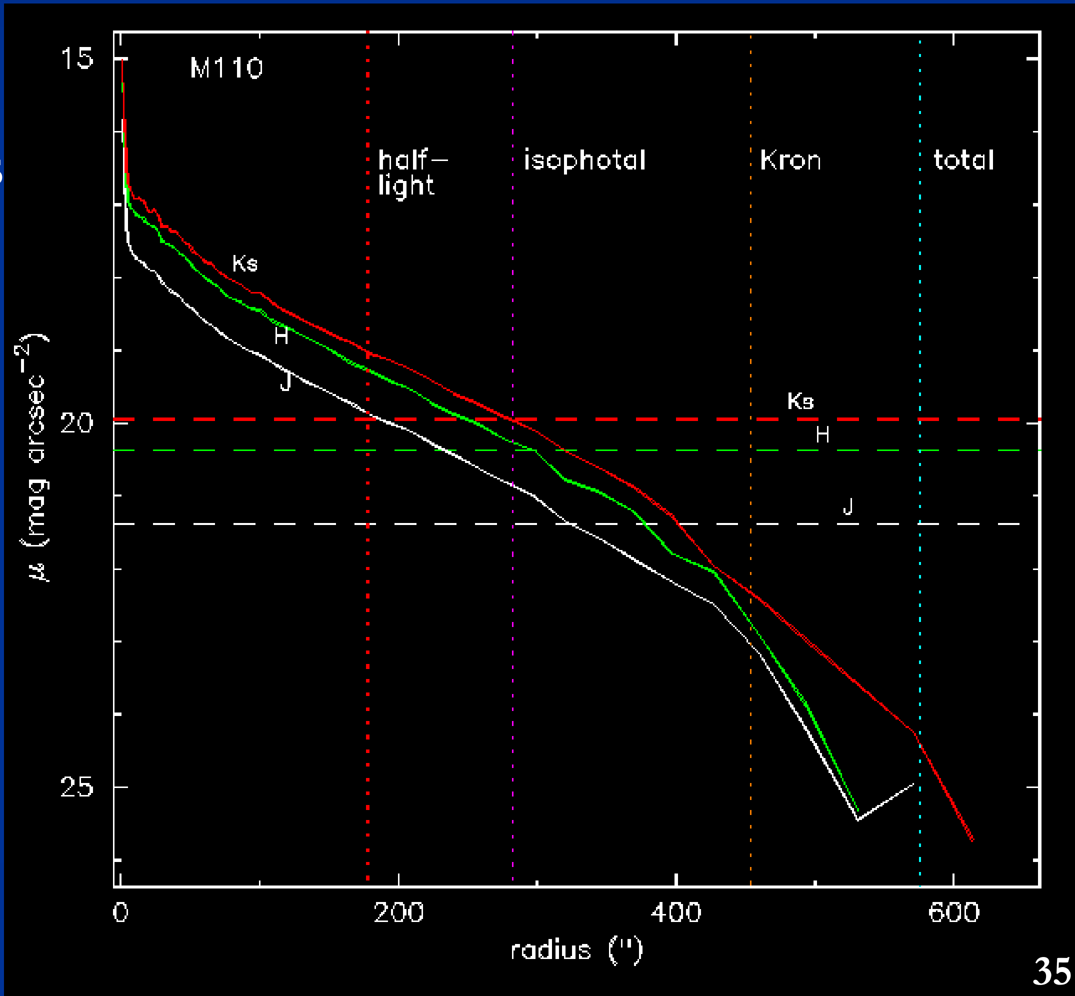
❖Disk profiles

Disks of **S** and **S0** galaxies can be fit to an exponential law:

$$I(R) = I_0 \exp(-R/h)$$

where **I_0** -- the (extrapolated) central surface brightness

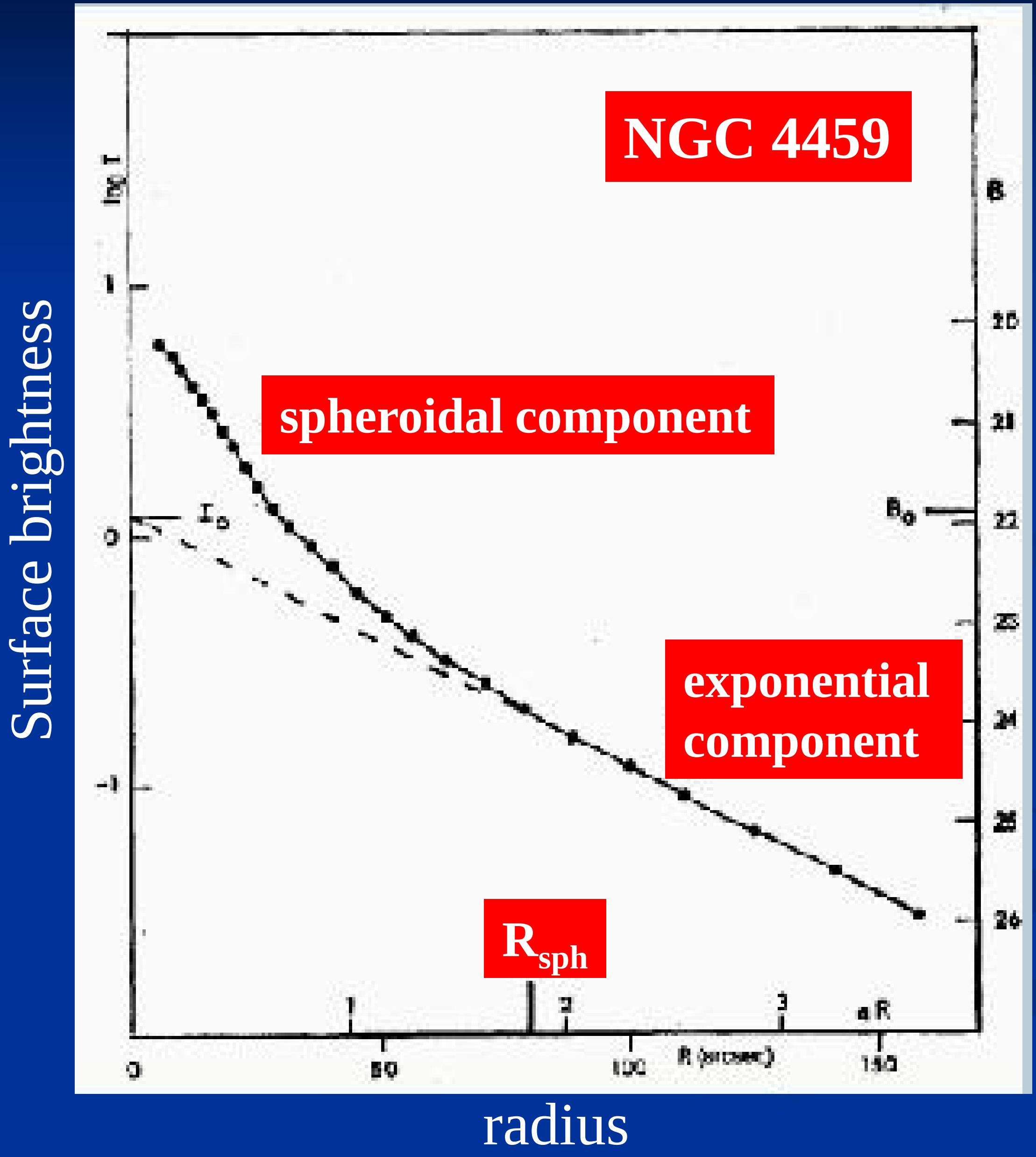
h -- the radial scale length



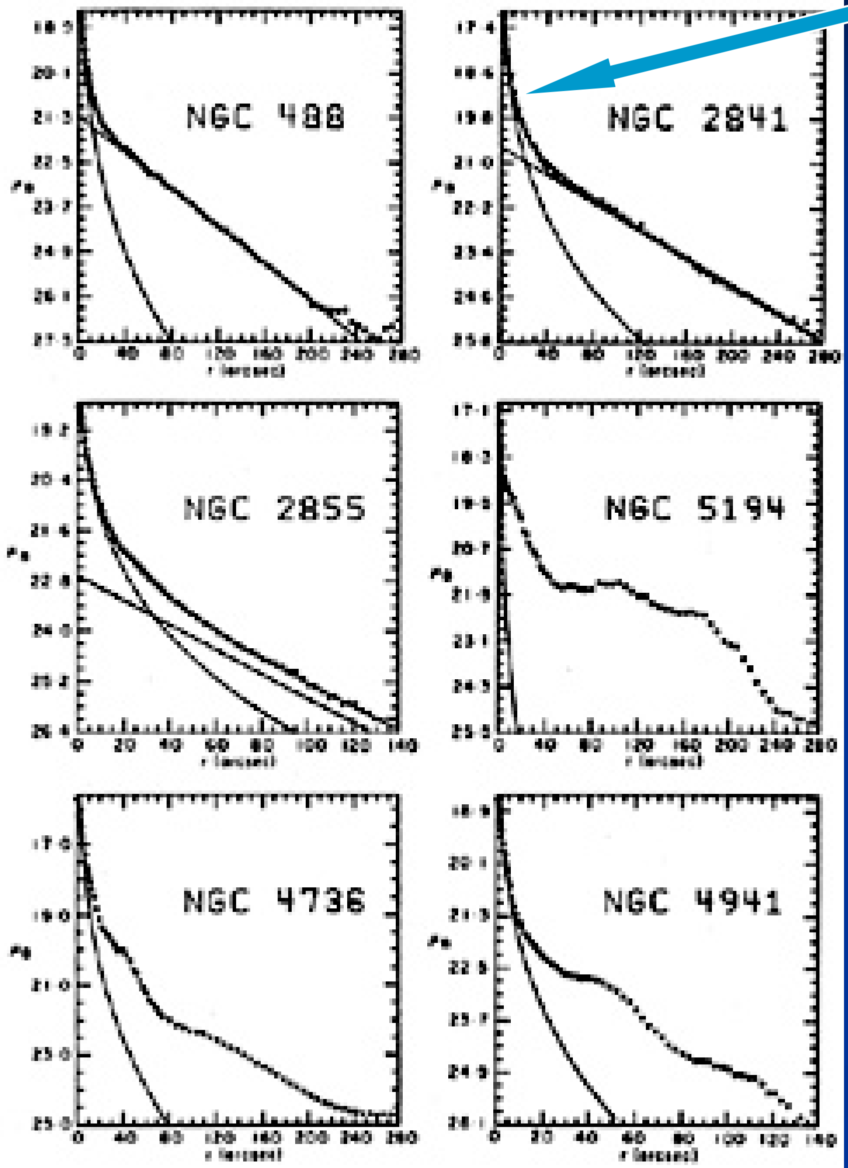
At small radii many disks deviate from this law!

At large **R**: cutoffs (end of self-gravitating gas disk?)

- Decomposition of **S** galaxy into disk + bulge



Exponential fits are good in some galaxies but a very poor approximation in others…



surface brightness

blue magnitudes

r (arcseconds)

Where the profile can be decomposed into **$r^{1/4}$** and exponential laws, both fits are shown

NGC 488 and 2841 have exponential disks (see Sersic profiles)

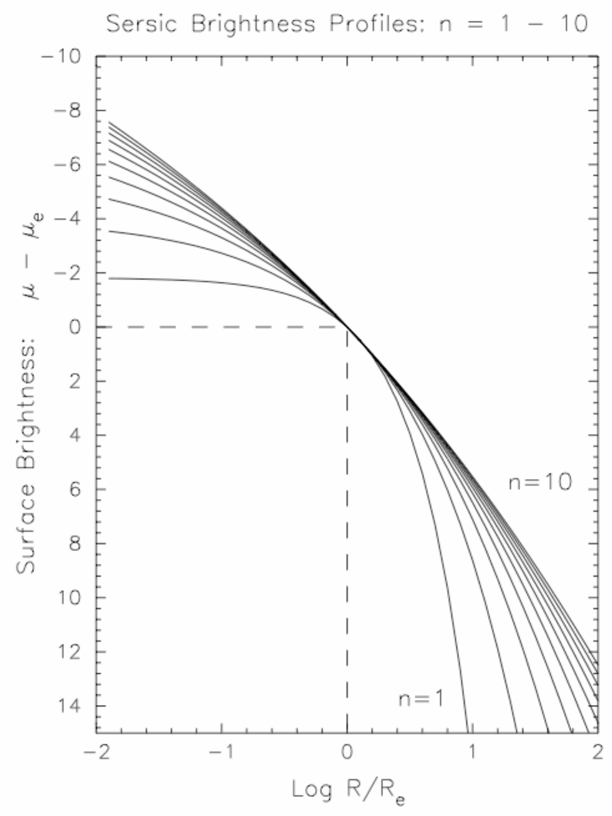
NGC 2855: inconclusive (bulge too big?)

NGC 5194, 4736 and 4941
→ non-exponential disks

Sersic $\mathbf{R}^{1/n}$ profiles

Canonical profiles of spheroids and disks can be represented by a single formula:

$$\mathbf{I(R) = I_0 \exp[-(R/R_0)^{1/n}]}$$



where $\mathbf{I_0}$ as before

$\mathbf{R_0}$ --- radial scale length

n --- shape parameter

When: **n** = 1 -- exponential profile

n = 4 – deVaucouleurs profile

Practically, $\mathbf{I(R) = I(R_e) \exp\{-b[(R/R_e)^{1/n} - 1]\}}$ is used

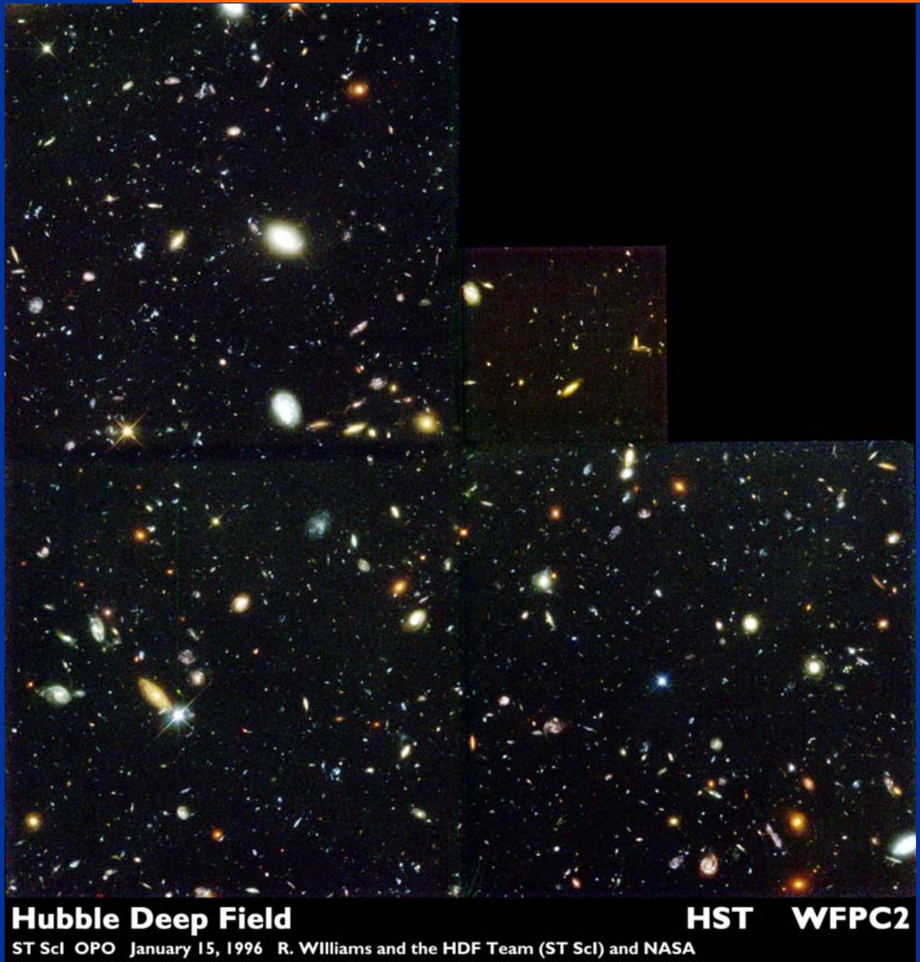
b – is chosen so that a circle of radius $\mathbf{R_e}$ (effective radius) includes half the light of the image (for **n** > 1, **b**=1.999**n**-0.327)

➢Distant galaxies

Cosmological effects: surface brightness falls off as $(1+z)^4$

We see originally bluer light emitted at the rest frames at redshift z

Can we classify higher redshift galaxies using our methods?



At **z** > 0.5 many more asymmetric galaxies… why?

Galaxy interactions or internal evolution?

ELLIPTICAL GALAXIES

*The very central profiles
*Shapes
*Kinematics
*Interstellar gas
*Shell structures
*Parameter correlations

The very central profiles

At (low) arc second angular resolution → the center is flat

Modified Hubble law:

$$\mathbf{I(R)} = \frac{\mathbf{I_0}}{1+(\mathbf{R/R_c})^2}$$

where $\mathbf{I_0}$ – the central brightness
$\mathbf{R_c}$ – core radius

But similar fit is given by de Vaucouleurs profile

$$\mathbf{I(R) = I_0 \exp(-kR^{1/4})}$$

with **I(R)** slowly rising as **R**→0 !

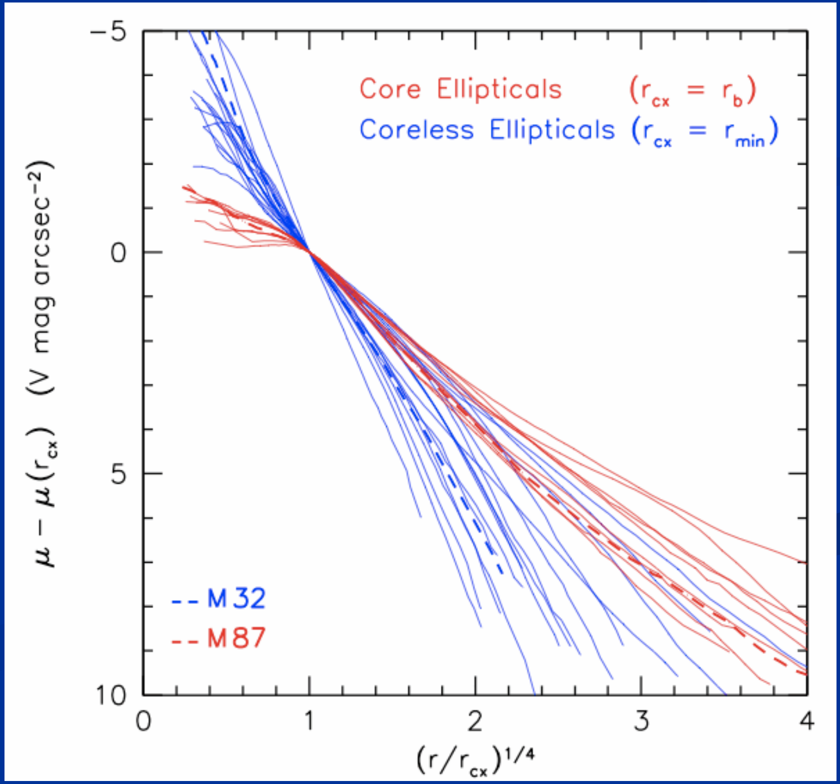
Hubble Space Telescope (HST) photometry:

flat cores of ellipticals are myth!

Two types observed:

Steep rise to resolution limit of 0.1”

Steep rise to a break and then slower rise



Giant ellipticals (cD galaxies) in cluster centers

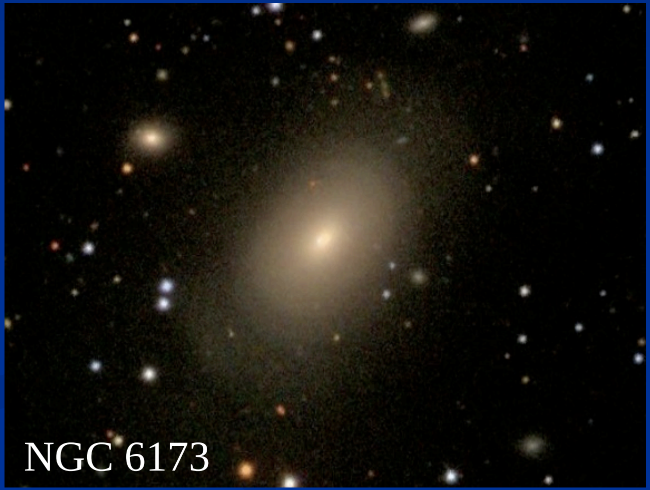
cD galaxies: giant ellipticals in centers of some galaxy clusters

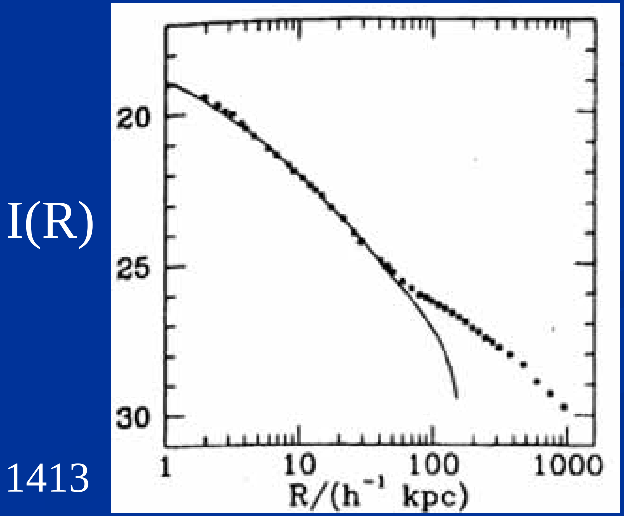
→ well fit by $R^{1/4}$ law

→ outside $R \sim 20R_e$ → $I(R)$ may exceed $R^{1/4}$ or Sersic laws


NGC 4874


NGC 3551


NGC 6173



Abell 1413

➢Kinematics of ellipticals

Expectations (prior to 1975): Es should be rotationally flattened

Results: Luminous **E**s: not rotationally flattened
are flattened by velocity anisotropy

Low luminosity **E**s and bulges of **S**s: are rotationally flattened
have two components
(rotating/non-rotating)

disky isophotes

boxy isophotes

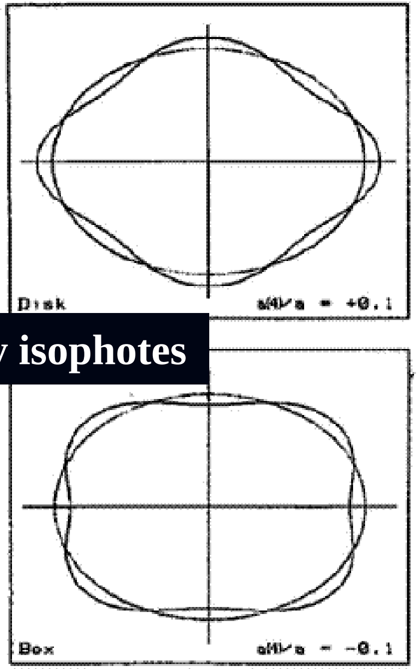


FIGURE 5. — Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.

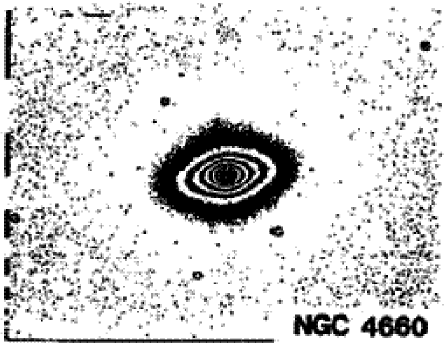


FIGURE 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

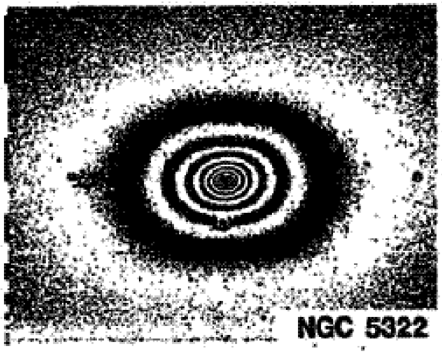
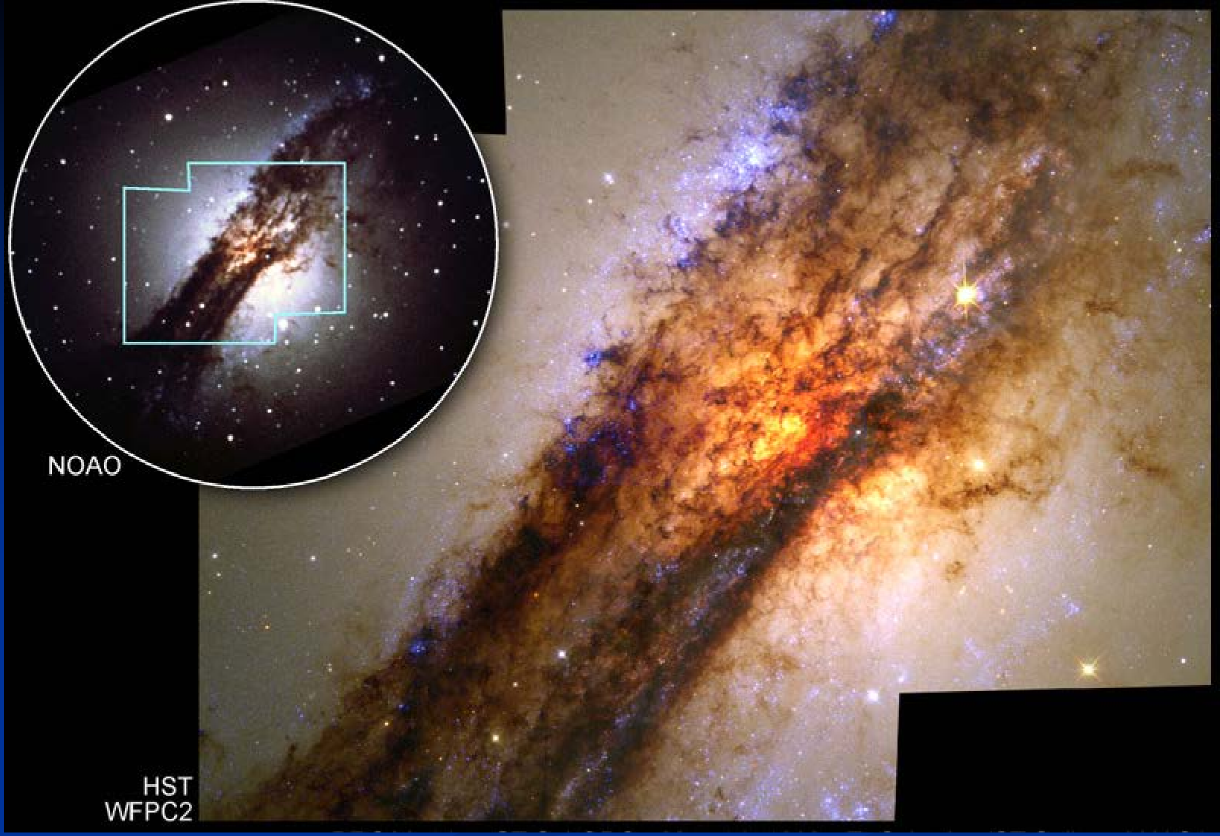


FIGURE 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).

disky **E**s rotate
boxy **E**s do not rotate

Interstellar gas in Ellipticals

- Dust and cold gas



Extreme example

Many **E**s show dust lanes produced by a cold (molecular) gas

- Hot gas

X-ray observations: $\boxed{\mathbf{10^9 - 10^{10}\ M_\odot}}$ of hot gas at 10^7 K

So ellipticals are not gas poor galaxies!

Shells and other fine structures

About 10% -- 20% of **E**s have sharp edged “ripples”

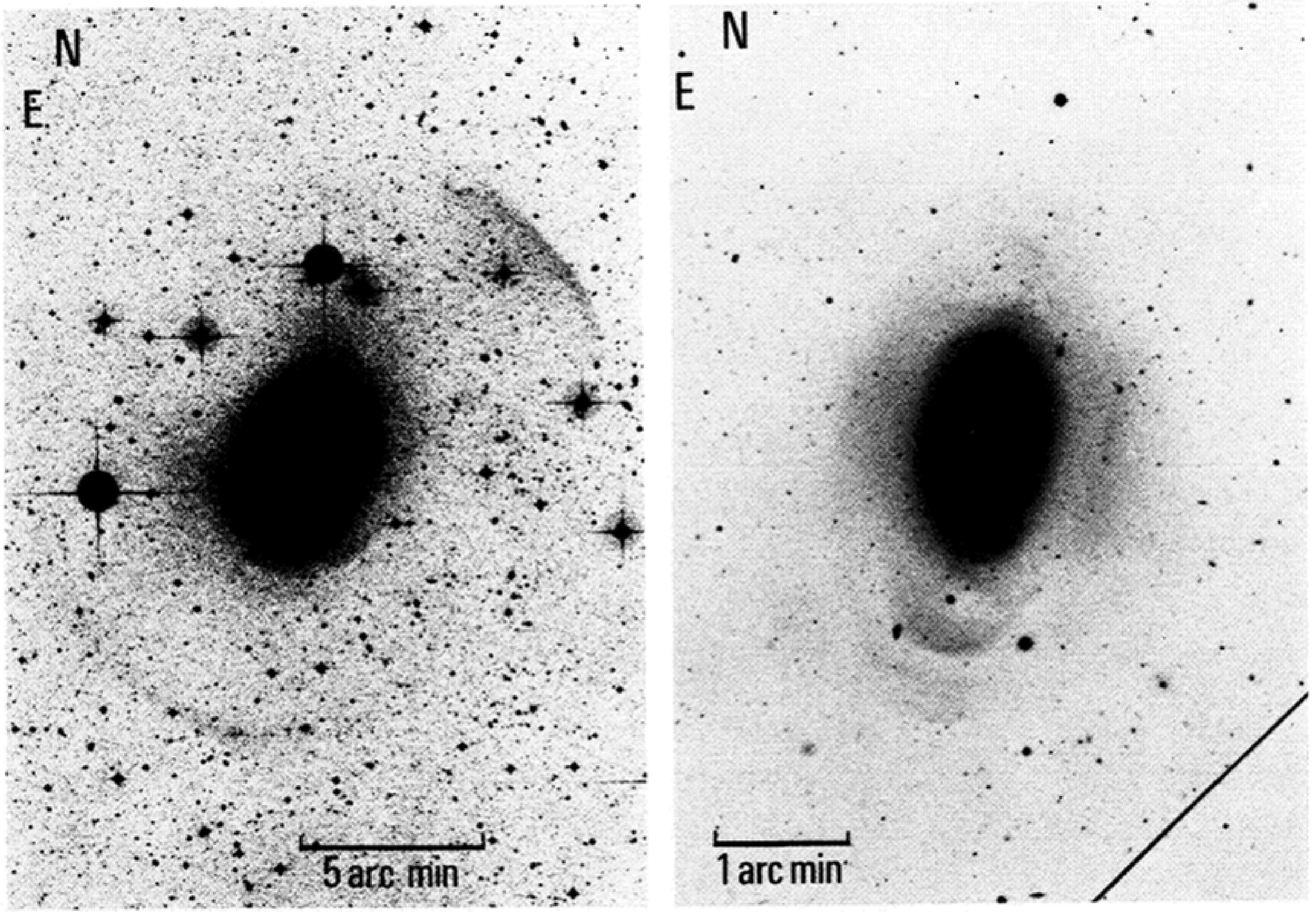


Fig. 1.—The shells around NGC 1344. The external shells (*left*) are revealed by photographic amplification and subsequent superimposition of three deep IIIa-J plates taken on the 1.2 m UK Schmidt telescope. The internal shells (*right*) are seen by applying an unsharp masking technique to a deep IIIa-J plate taken on the AAT.

Malin and Carter (*see* page 538)

Antenna-type features in Ellipticals:

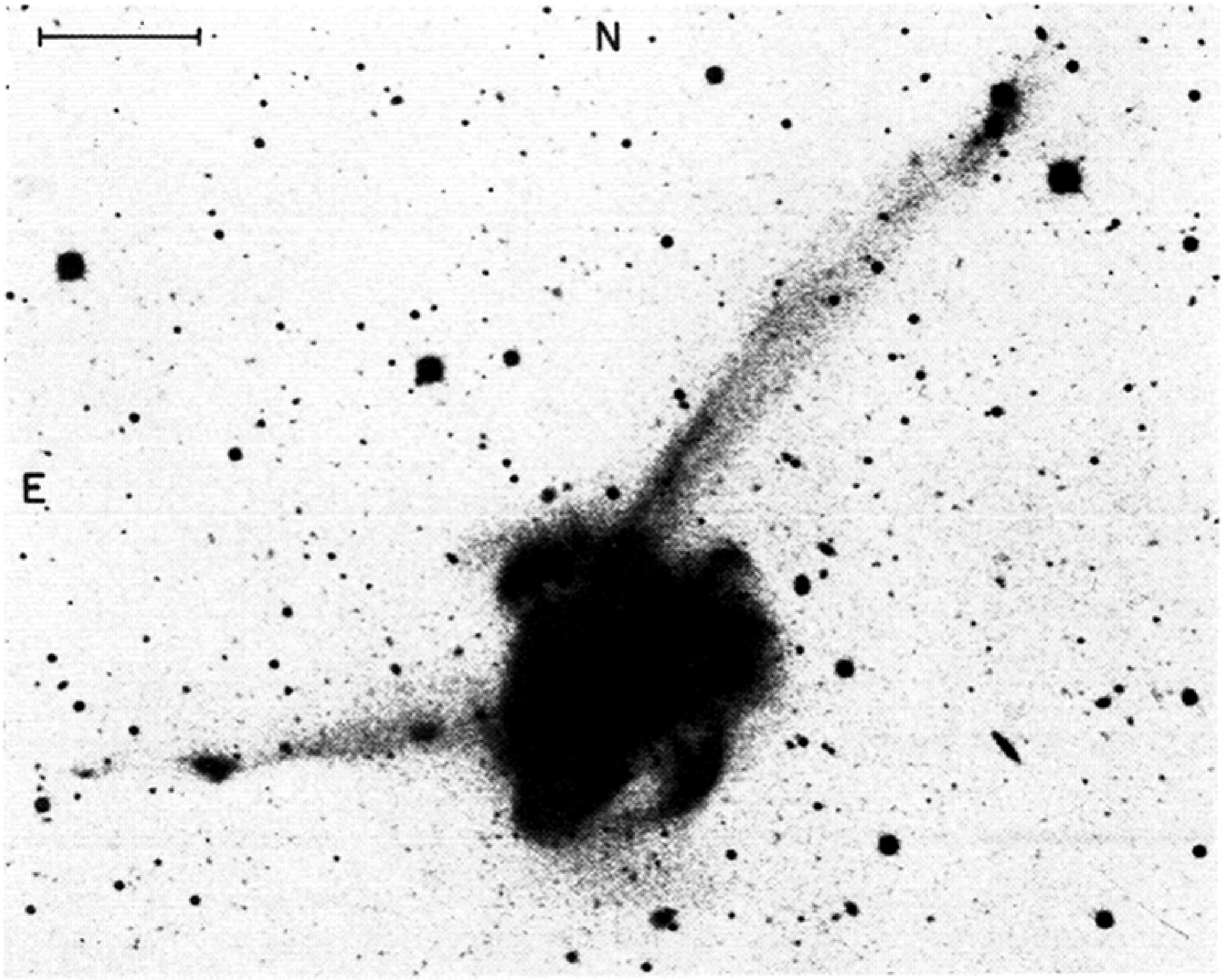


Fig. 1.—Blue photograph of NGC 7252, reproduced from a CTIO 4 m prime-focus plate (P-2403, baked IIIa-J + GG385, 85 min exposure, $0\farcs9$ seeing). The body of the galaxy has been dodged to better show the loops. The scale bar is 1′ (28 kpc).

Schweizer (*see* page 455)

These shells and antennae indicate recent accretion of gas-rich galaxies

Parameter correlations

- Luminosities of Es correlate highly with their velocity dispersions

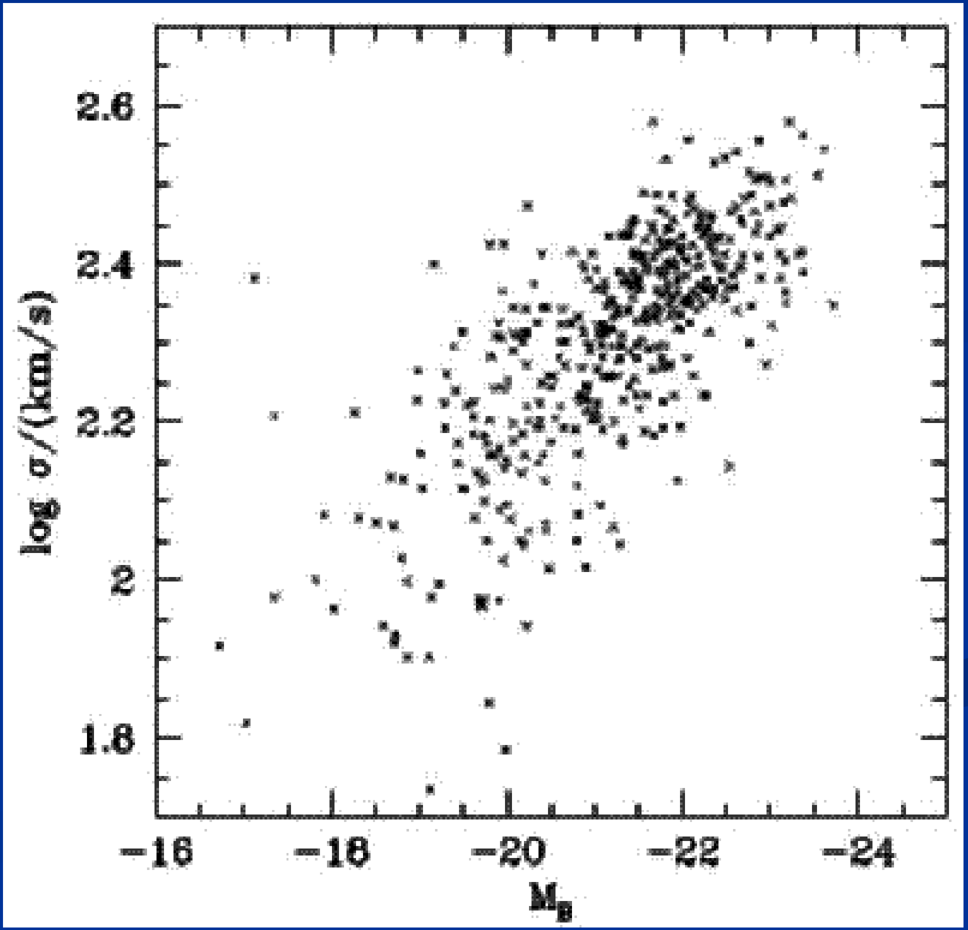
Faber-Jackson relation $\mathbf{L} \propto \boldsymbol{\sigma}^{n}$

where

L is the galaxy luminosity

σ- the central line-of-sight velocity dispersion

n~4 (scatter 3<n<5)



The scatter in $\mathbf{M_B}$ is real: 0.6 and greater than measurements errors!

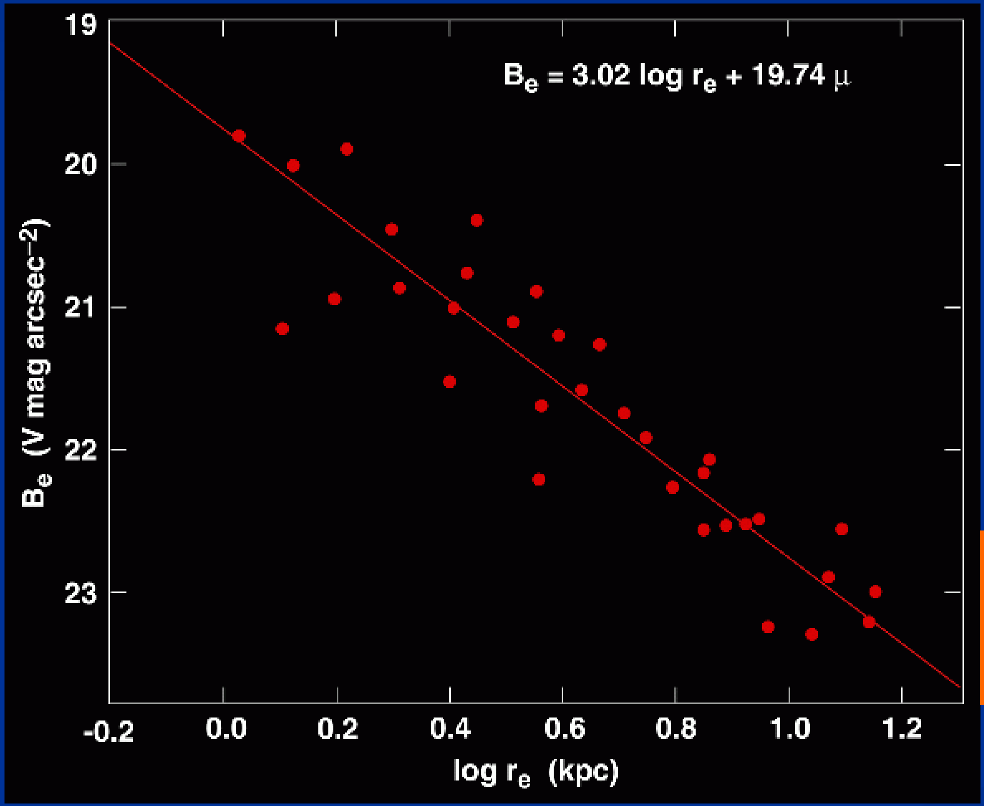
- Effective (half-light) radius, **R$_e$**, correlates with surface brightness at that radius, **I$_e$**:

$$\mathbf{R_e \propto I_e^{-0.83}}$$

but

$$\mathbf{L_e = 0.5\,L_{tot} = \pi\, I_e\, R_e^2}$$

$$\left.\begin{array}{l} \\ \end{array}\right\} \quad \mathbf{L_{tot} \propto I_e^{-2/3}}$$



Hence, luminous Es have lower average surface brightness

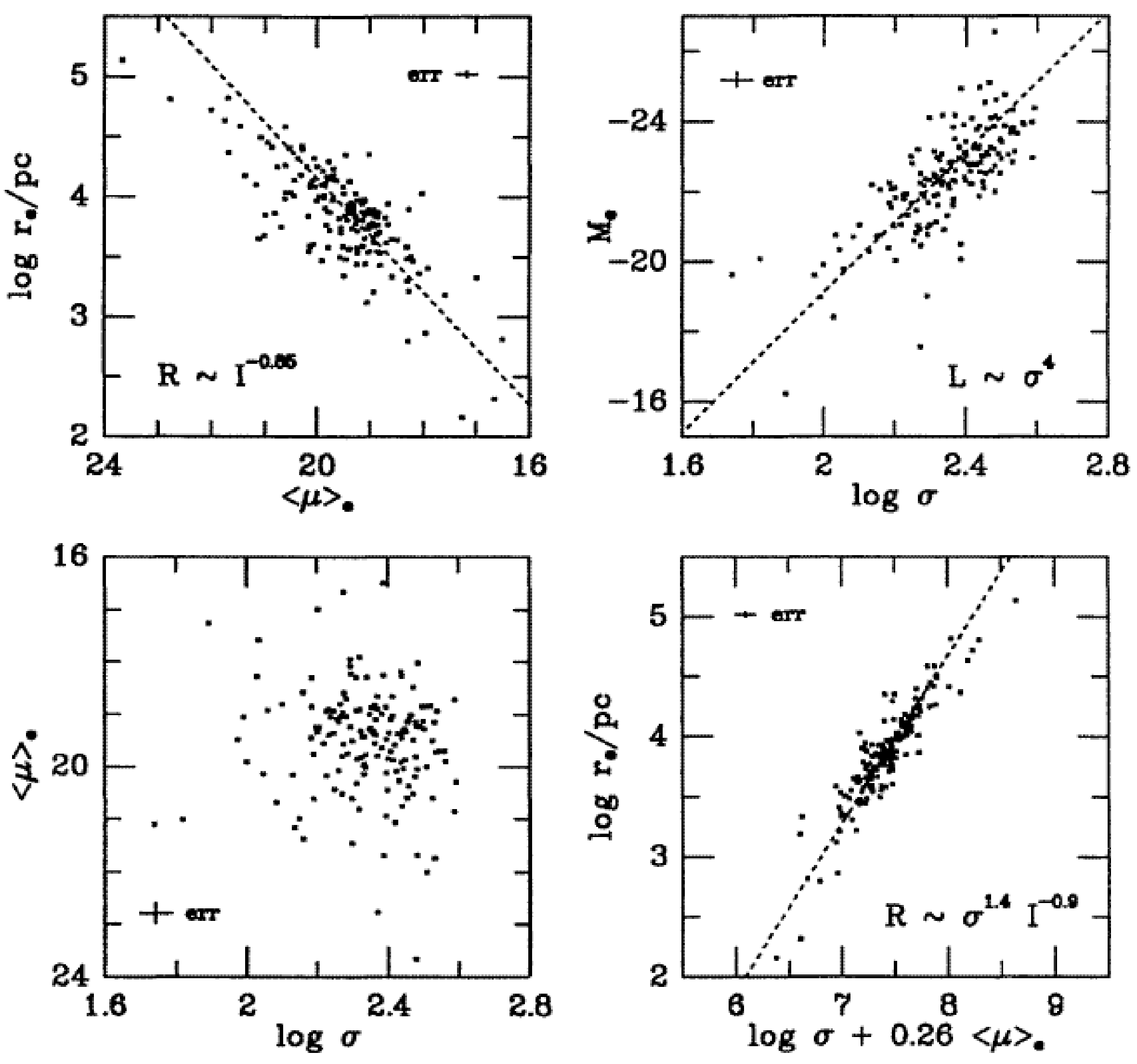
In other words: larger and more luminous galaxies are fluffier with lower densities

❖The 3-parameter fundamental plane for ellipticals

2-parameter correlations

Because of considerable real scatter in 2-parameter correlations we look for a tighter correlation among three parameters (not unique!):

- a tilted plane of points in 3-D volume, which:
- projects onto 2-D planes as the (looser) correlations seen on the right



Projections of the fundamental parameter plane of elliptical galaxies.

Eq. of fundamental plane, with ***R*** in kpc, ***I*** in mag arcsec^{-2}, **σ** in km s^{-1} :

$$\log R_e = 0.36 I_e + 1.4 \log \sigma + \text{const}$$

DISK GALAXIES

*basic components

*3-D shapes

*disk kinematics

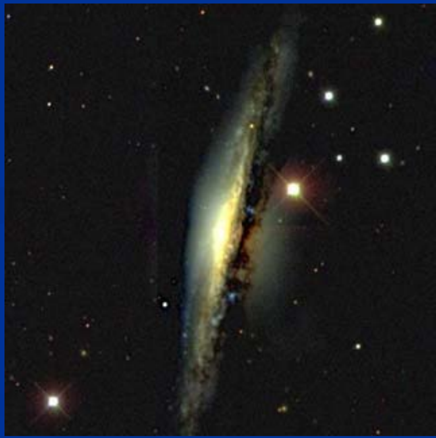
*disk mass and dark matter halos

*spirals and bars

➢Basic components

- disk: metal rich stars and ISM,
  nearly circular stellar orbits
  (about 5% random motion),
  spiral patterns

- bulge: classical --- metal-poor to super-rich stars,
  high stellar densities, $v_{rot} \sim \sigma$



+bulge: disky (pseudobulge)
--- metal-rich, $v_{rot} > \sigma$

- bar: flat distribution of stars,
  associated dust lanes and
  star formation,
  associated rings
  and spiral pattern

➢Basic components

nucleus: central (<10 pc) region of very high density (about $10^6\ M_{\odot} pc^{-3}$),
dense ISM and/or starburst and/or stellar cluster,
massive black hole

stellar halos: very low surfave brightness, few % of total light,
metal poor stars, globular clusters,
low-density hot gas,
little/no-rortaion

dark halo: dominates mass and gravitational potential outside 10 kpc,
mildly flattened (?) and/or triaxial (?), nature unknown

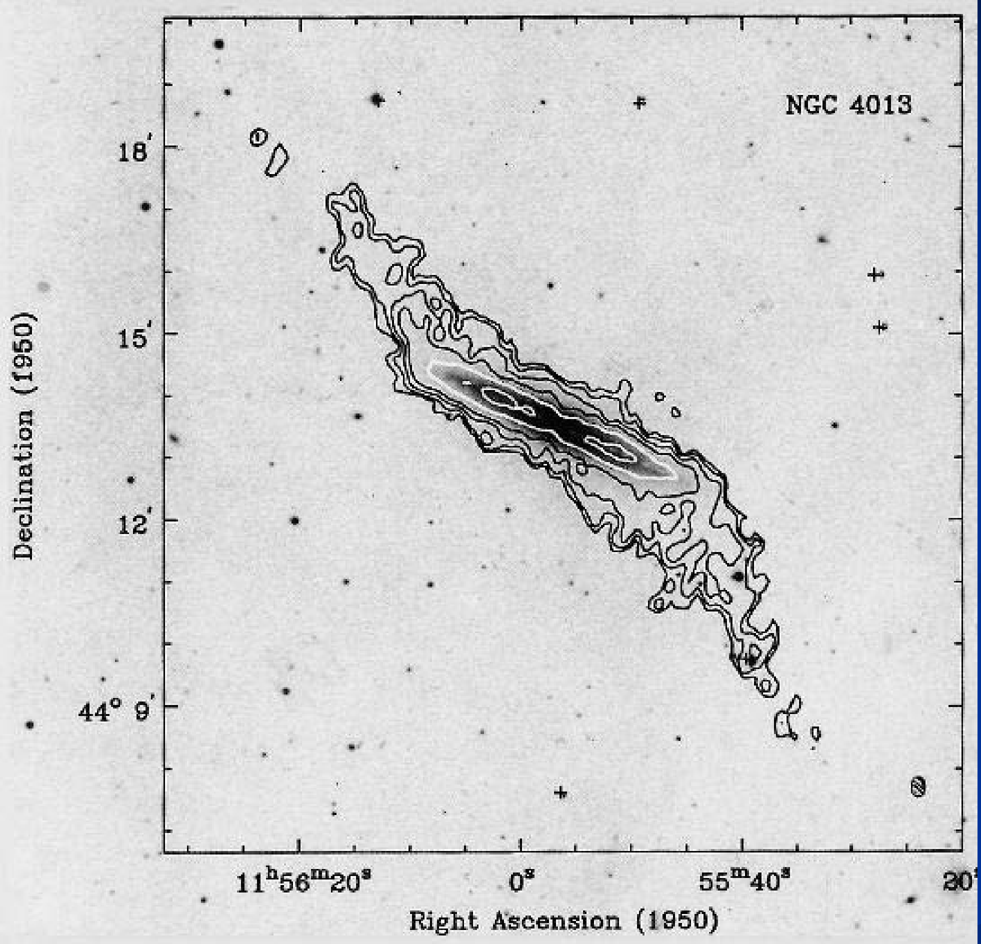
Warped disks

Starlight : typically flat
(if undisturbed!)

However, **HI** (atomic **H**)
is often warped

Symmetry: 180^{o} (integral sign)

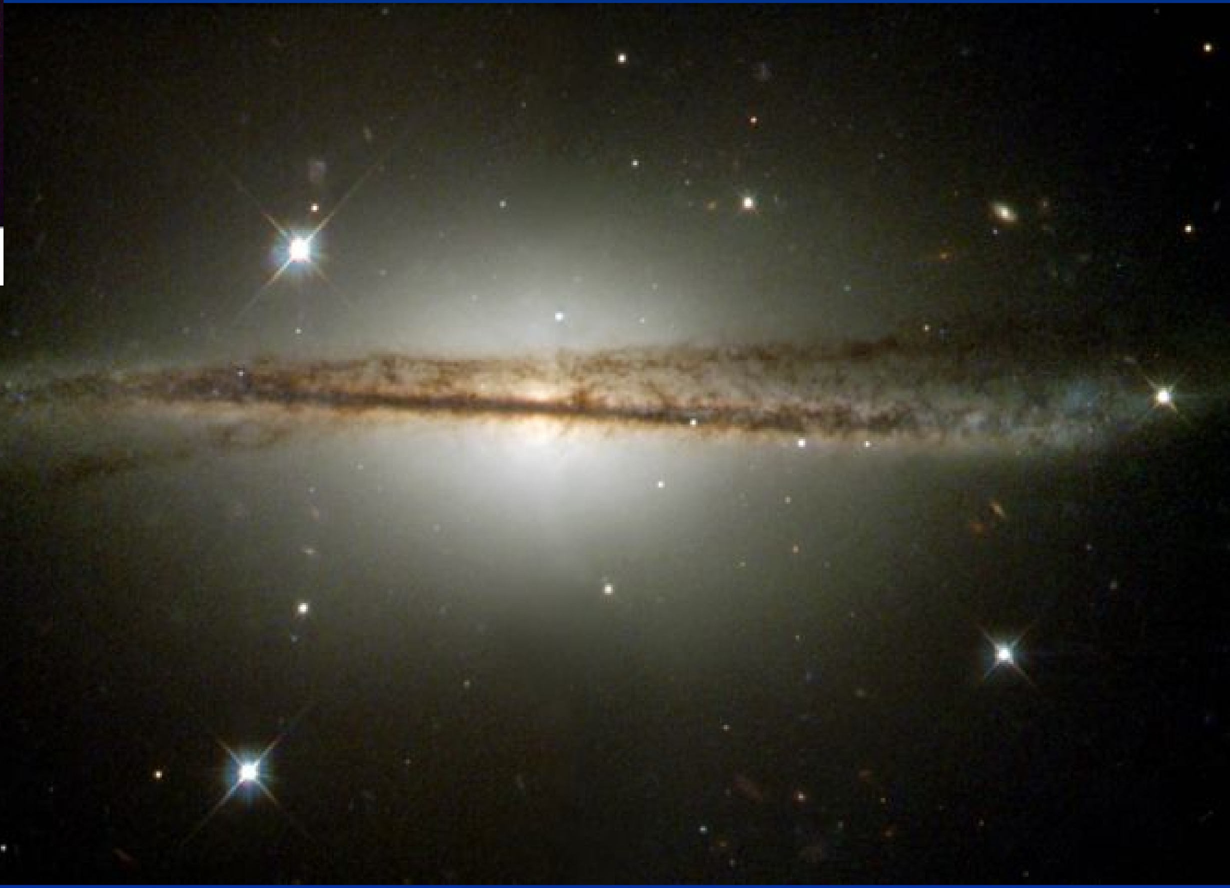
75% of warped galaxies have no significant companion



Galaxy with Warped Dust Lane
(VLT ANTU + FORS1)

ESO PR Photo 21c/99 (30 April 1999)

© European Southern Observatory



Explanation: misalignment between halo and disk axes?

❖Bulges

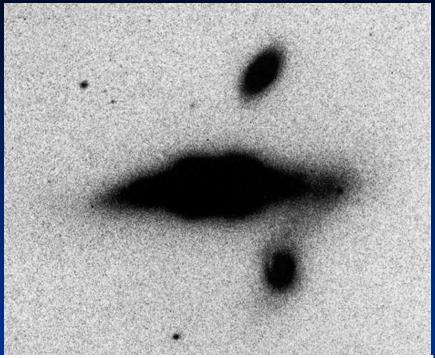
Probably similar to low-luminosity ellipticals

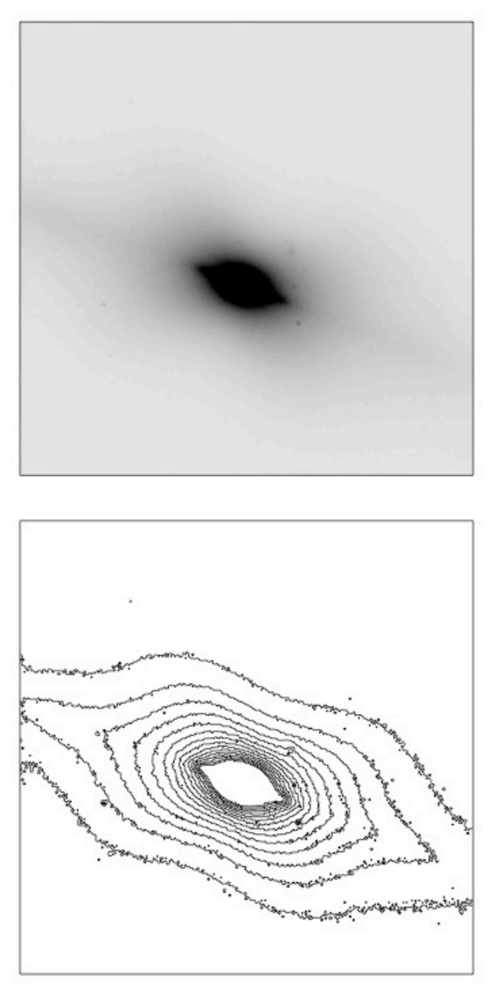
$0 < \varepsilon < 0.7$

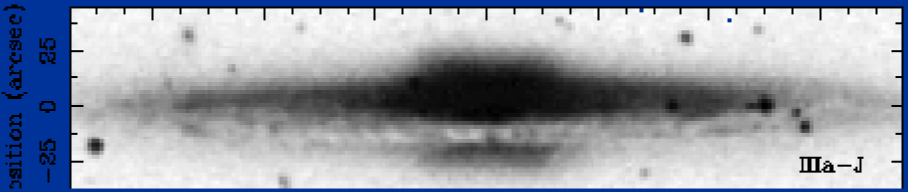
Classical bulges: oblate spheroids flattened by rotation

- 25% have very boxy isophotes
- Some are "peanut"—shaped → bar instabilities

NGC 128







NGC 5746

To be discussed later: association with stellar bars!

Stellar bars

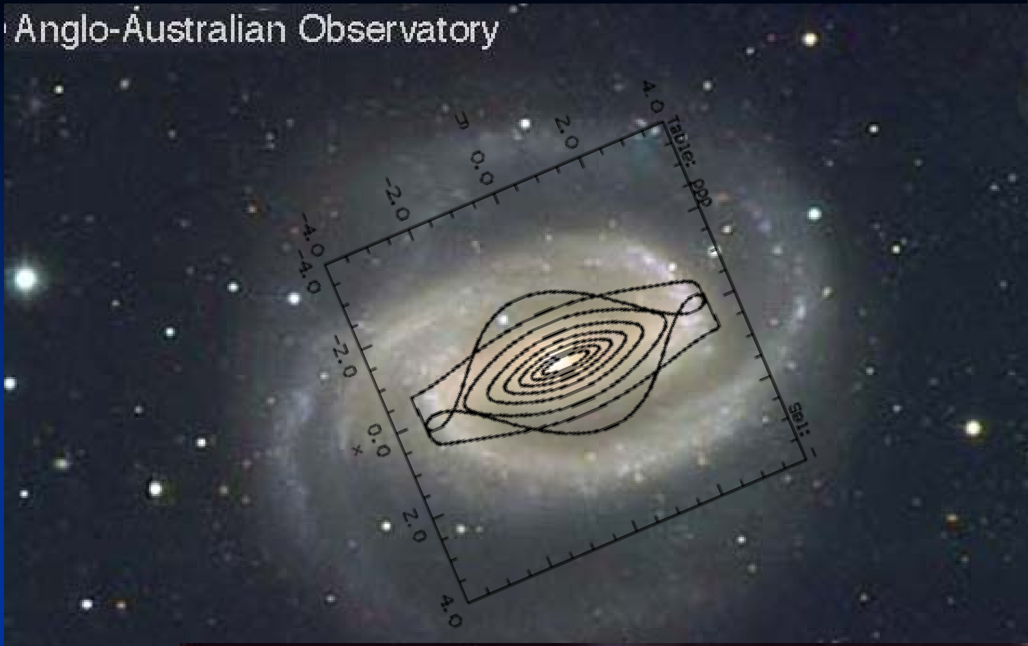
Axial ratios: a/b ~ 2.5 – 5
a/c ~ 10

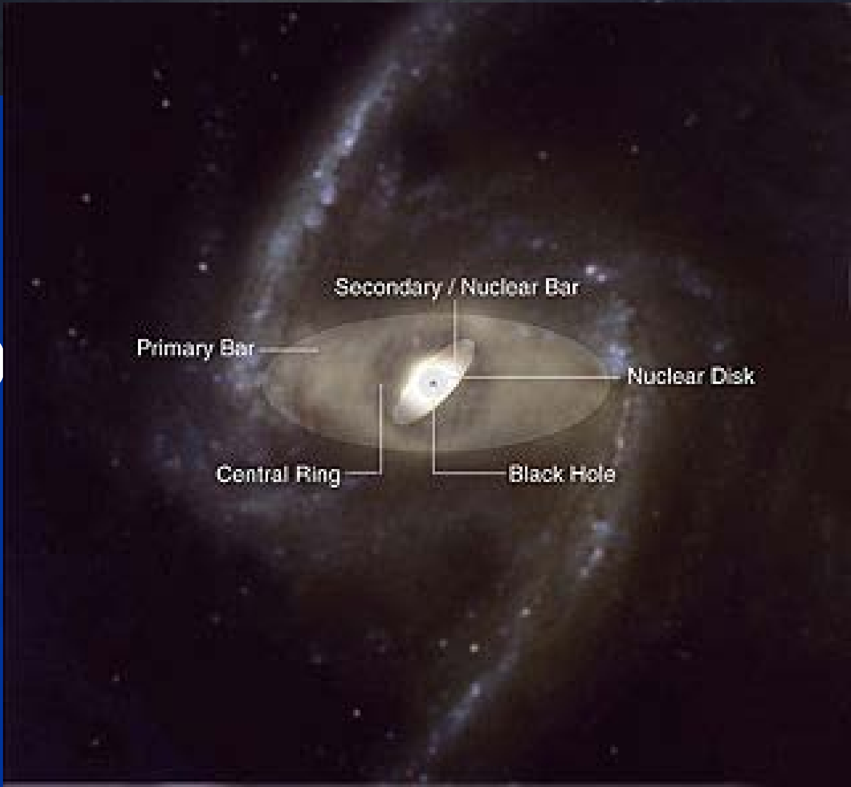
Bars are flat and cannot be seen in edge-on galaxies!

Stellar bars can be detected from isophote twists

More than one bar (of a different size) can be detected:

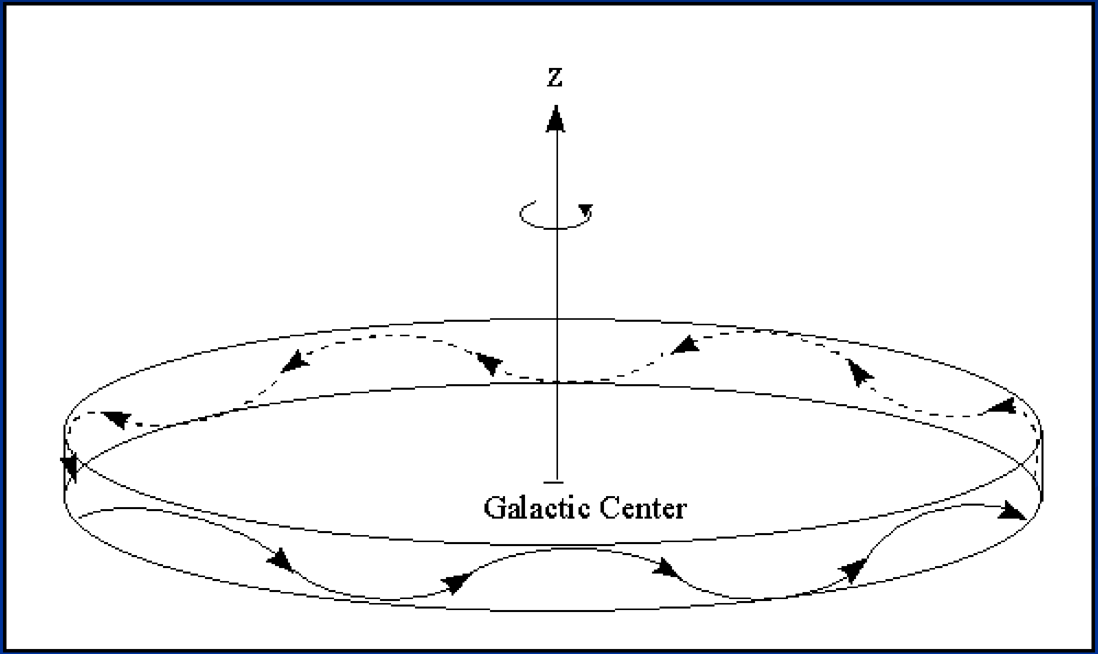
bars within bars or nested bars



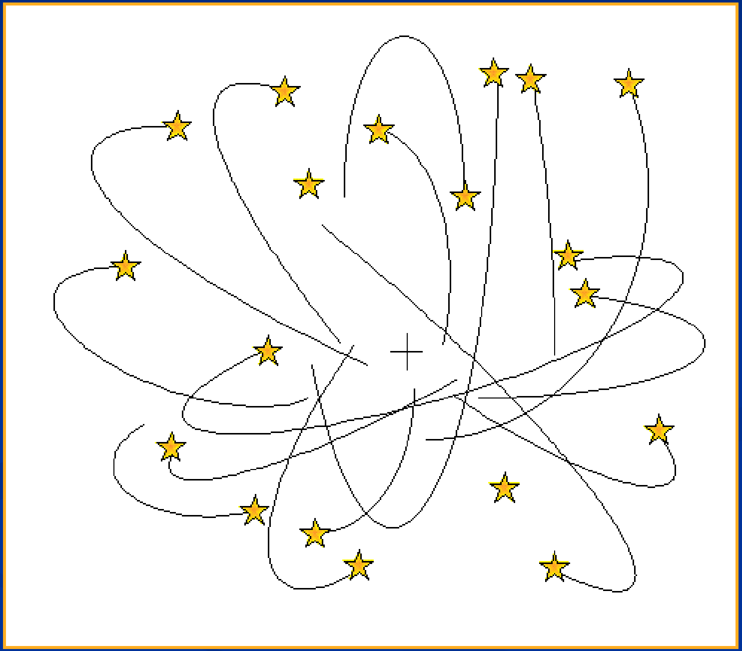


➢Disk rotation

How do stars move in the disk and in the spheroidal component:



in the disk

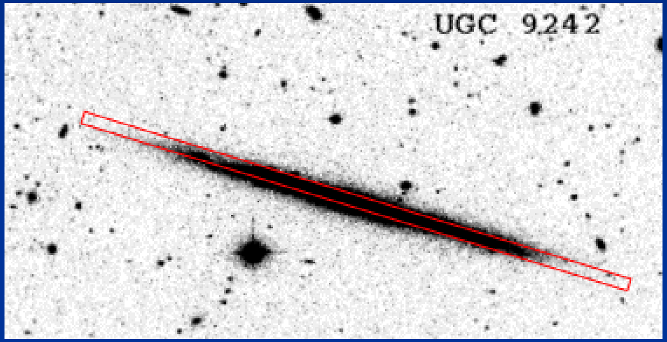


in the spheroid

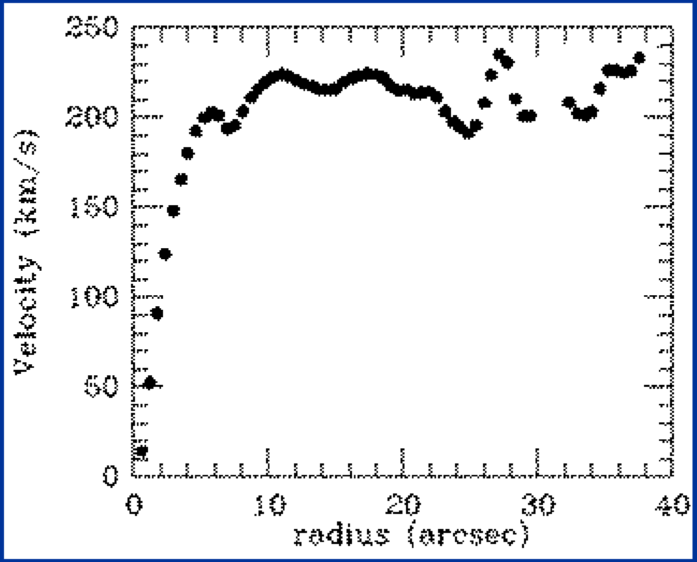
Disk velocity field

Generally: self-gravitating systems are supported by rotation and dispersion

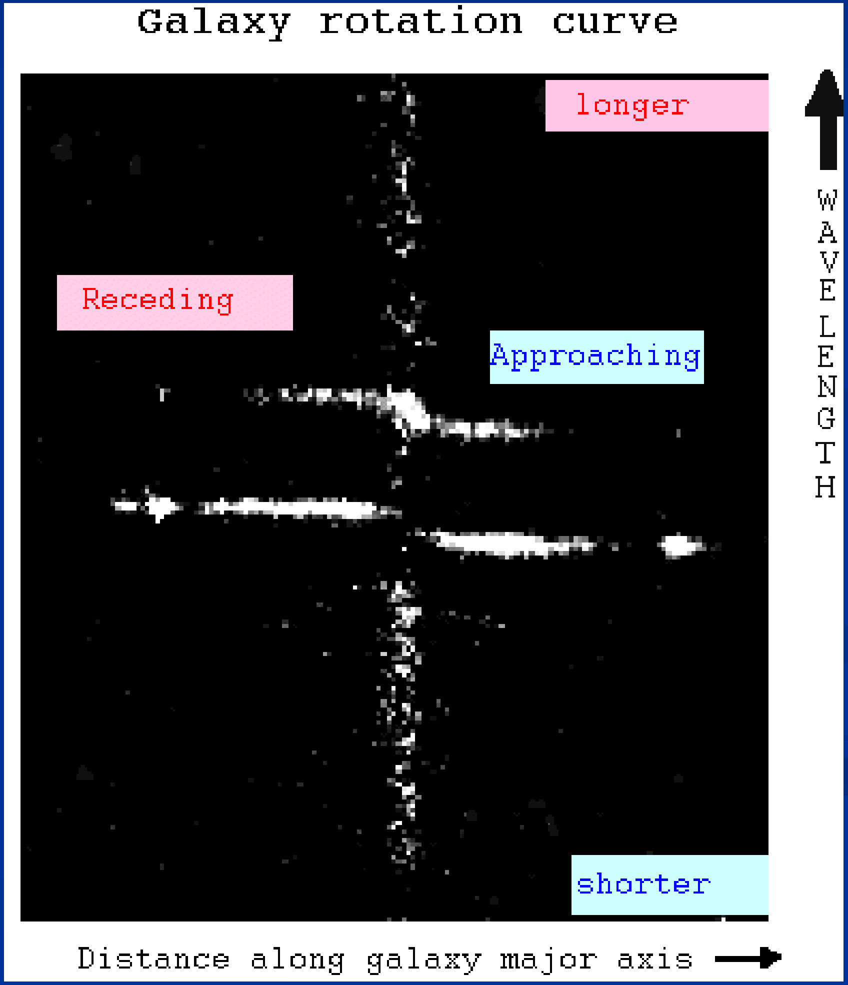
Disks: are cold (low dispersion!) so $v_{rot} \sim v_c$, where v_c is ideal circular velocity



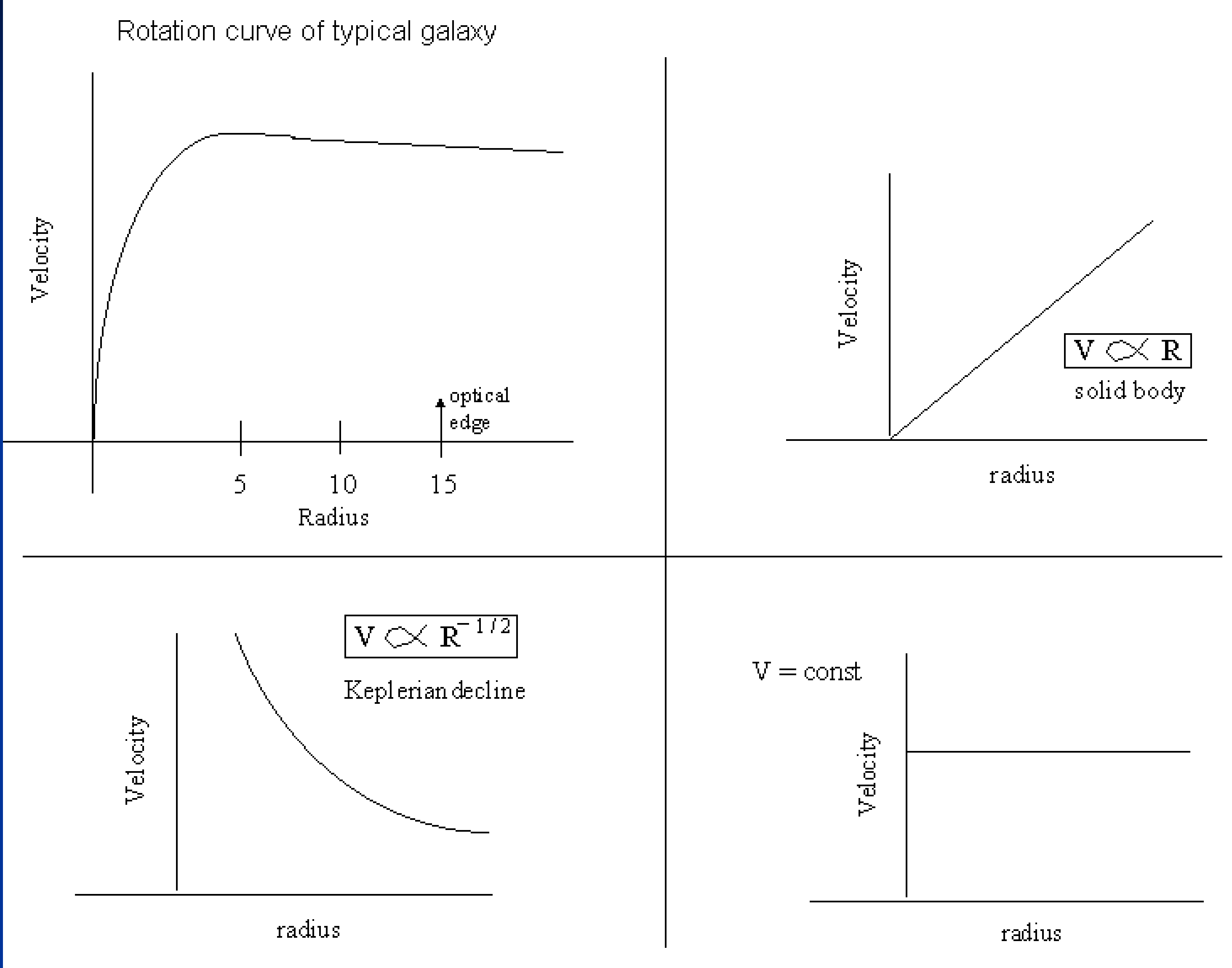
Slit orientation in edge-on galaxy



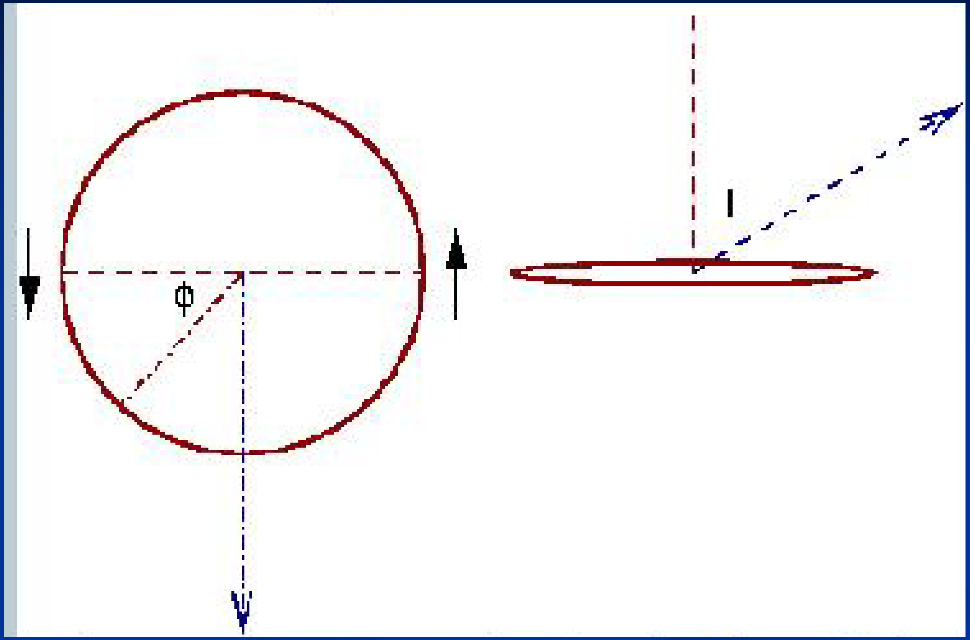
Resulting rotation curve



Examples of possible rotation curves



So far these have been deprojected rotation curves …



Generally, rotation axis makes an angle i to our line of sight

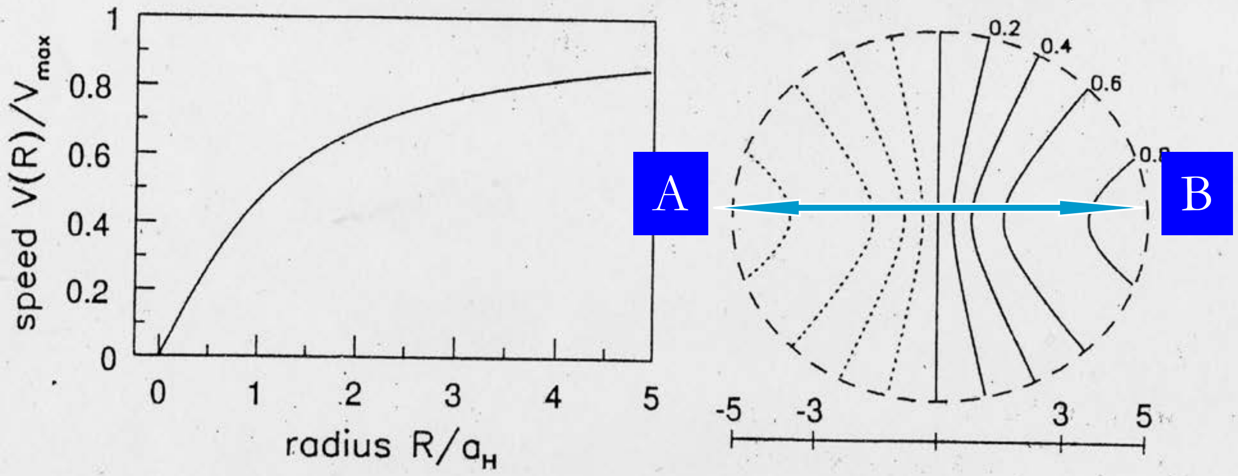
If we measure the apparent **v(r)** in the disk, then line of sight (radial) velocity is:

$$\mathbf{v}_{\mathbf{rad}}(\mathbf{r}, i) = \mathbf{v}_{\mathbf{sys}} + \mathbf{v}(\mathbf{r}) \, \mathbf{sin}\, i \, \mathbf{cos}\, \varphi$$

where $\mathbf{v}_{\mathbf{sys}}$ is the systemic velocity of the galaxy

If we measure $\mathbf{v}_{\mathbf{rad}}$ across the galaxy, and can infer the inclination *i*, we can obtain the full rotation curve **v(r)**

❖2-D velocity field: spider diagram → contors of projected velocity (LOS)



Left, rotation curve $V(R)$ in the 'dark halo' in units
$= V_{\max}$. Right, 'spider diagram' of V_r for a disk observed 30° from face-on;
urs are marked in units of $V_H \sin 30°$, negative velocities shown dotted.

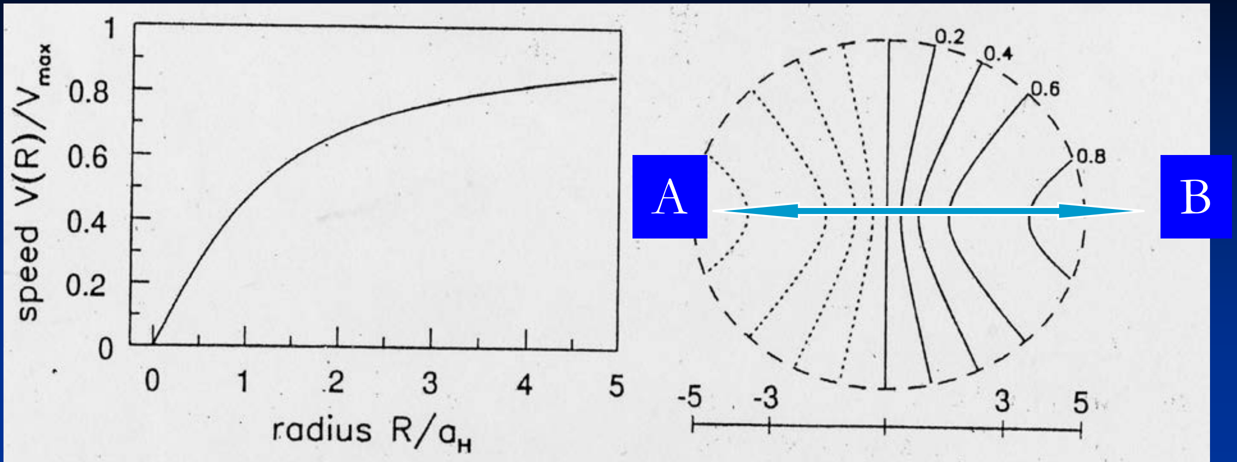
- Contours of $\mathbf{v}_{\mathbf{rad}}$ = const connect points with the same value of **v(r) cosϕ**

- The line AB: kinematic major axis --- where velocities deviate most
- In the central regions **v(r) ~ r**, the contours are parallel to the minor axis
- At larger radii, **v(r)** ~ const, the contours run radially away from the center
- If **v(r)** starts to fall, the extreme contours close on themselves

The above figure used:

halo
$$\begin{cases} 4\pi G \rho_H(r) = \dfrac{V_H^2}{r^2 + a_H^2} \\ V(r) = V_H \sqrt{1 - \left(\dfrac{a_H}{r}\right) \arctan(r/a_H)} \end{cases}$$

2-D velocity field: spider diagram



Left, rotation curve $V(R)$ in the 'dark halo' in units $= V_{max}$. Right, 'spider diagram' of V_r for a disk observed 30° from face-on; urs are marked in units of $V_H \sin 30°$, negative velocities shown dotted.

So:
modeling using concentric circular rings

i – galaxy inclination

r – radius vector in the plane of the disk

$\hat{\mathbf{n}}(r)$ -- unit vector normal to the ring of radius r

$\Omega(r)$ – angular velocity of the ring

$v = \Omega(r)\ \mathbf{n} \times \mathbf{r}$ -- velocity of material at r

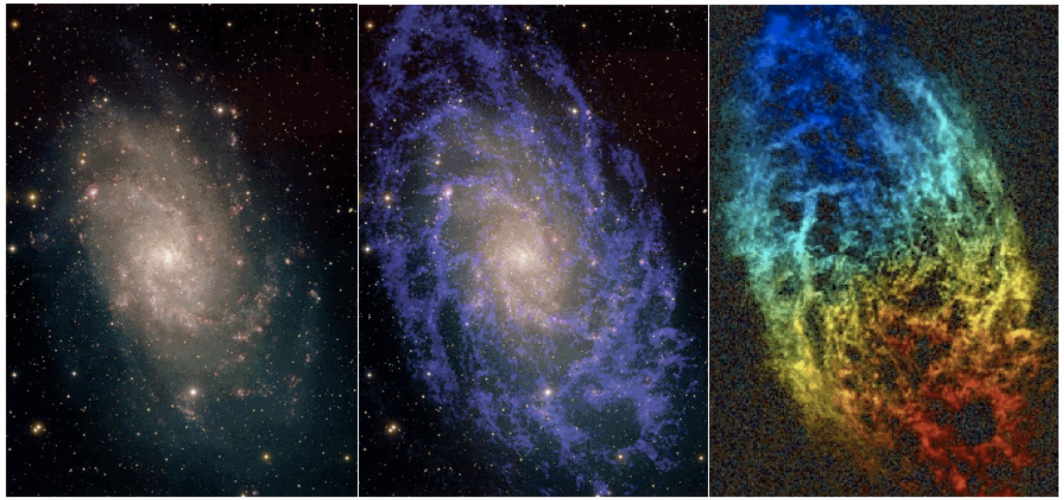
R – unit vector from the observer to the galaxy

$v_{los} \equiv \mathbf{R} \cdot \mathbf{v} = \Omega(r)\ \mathbf{r} \cdot (\mathbf{R} \times \mathbf{n})$ -- line-of-sight velocity

simplify: $v_{los} = \Omega(r) \sin i\ \mathbf{r} \cdot \mathbf{k}$ where $\mathbf{k} \equiv \mathbf{R} \times \mathbf{n} / \sin i$

k – unit vector ⊥ **R** and **n**

Spider diagram superposed on face-on disk galaxy **NGC 5123**

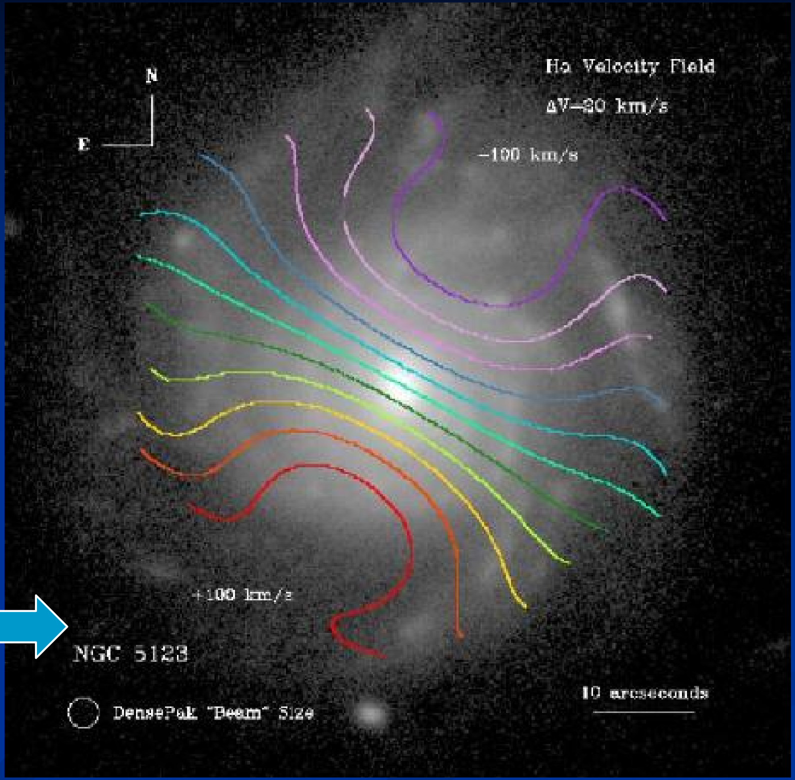


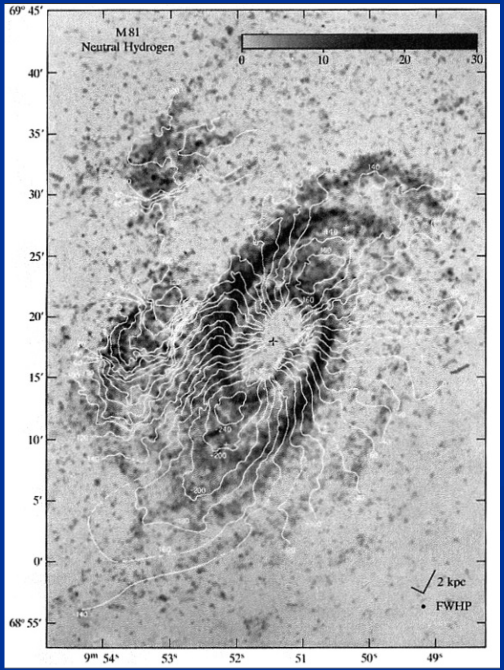
stars

stars + hydrogen

hydrogen velocity

M33





Spiral arms perturbations

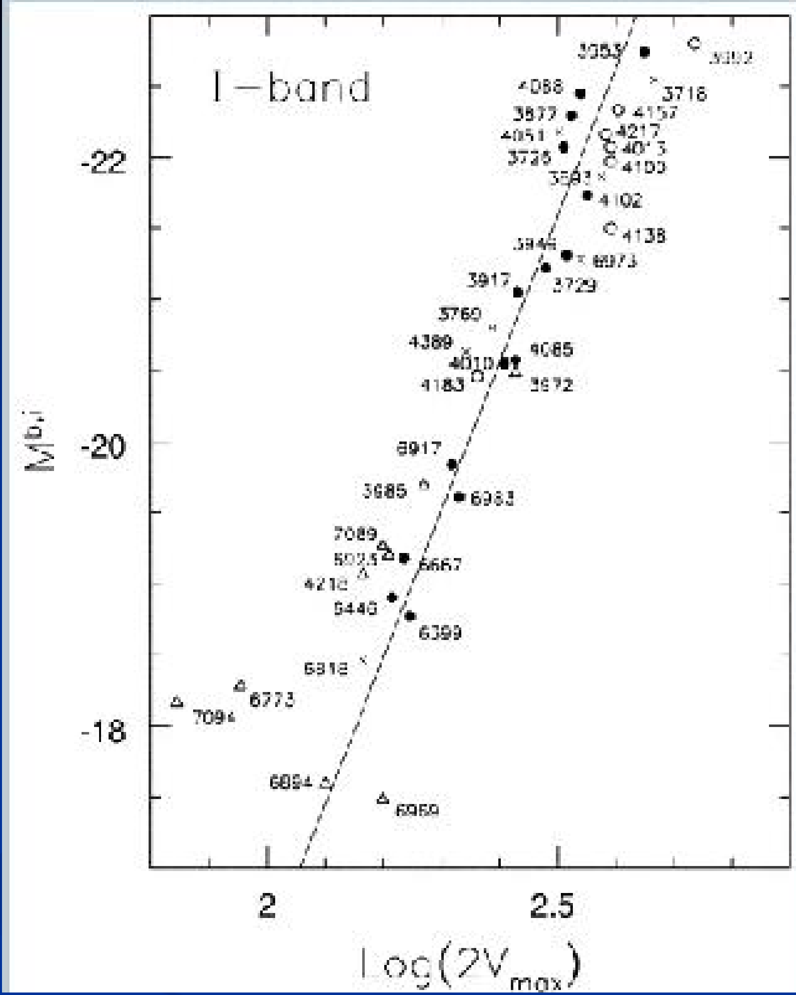
❖Tully-Fisher relation

Maximum circular velocity
v_{max} versus luminosity L

They appear to be closely correlated

The smallest scatter is in R or NIR

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



Important application -- extragalactic distance indicator:

- measure v_{max} for example from radio observations of **HI**
- infer **L** in a given band from the TF relation, and convert to absolute magnitudes
- measure apparent magnitude and use the distance **m-M** modulus

Disk mass and dark matter halos

The rotational velocity → important measure of
mass distribution

- Deriving **M(r)** from **v_c(r)**

Generally,

$$M(<r) = \beta \frac{RV_c^2(r)}{G}$$

where $0.7 < \boldsymbol{\beta} < 1.2$ is geometry factor

($\boldsymbol{\beta} = 1.0$ for sphere; ~0.7 for flattened)

For exponential disk with scale length $\mathbf{r}_d$:

$$V_c^2(r) \simeq 0.767 \frac{GM}{R_d} \frac{0.44(R/R_d)^{1.3}}{1+0.235(R/R_d)^{2.3}} \qquad R < 4R_d$$

Rotation curve of the thin exponential disk:

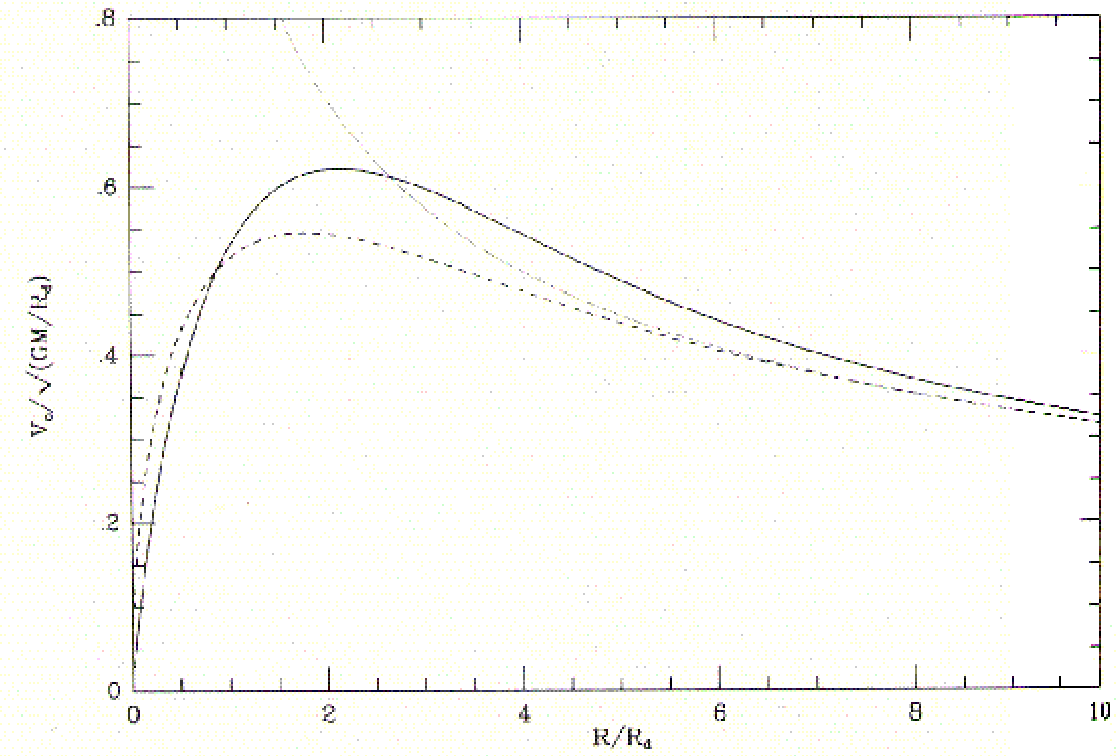


Figure 2-17. The circular-speed curves of: an exponential disk (full curve); a point with the same total mass (dotted curve); the spherical body for which $M(r)$ is given by equation (2-170) (dashed curve).

peak: $\mathbf{v}_{\mathbf{max}}$ at $\mathbf{r}_{\mathbf{max}}\sim 2.2\mathbf{r}_{\mathbf{d}}$

for $\mathbf{r}>3\mathbf{r}_{\mathbf{max}}$, $\mathbf{v}_{\mathbf{c}}\mathbf{(r)}\sim\mathbf{r}^{\mathbf{-1/2}}$ (Keplerian)

- From optical observations:

1960s: using stellar emission line (**Hα**) → assumed Keplerian fall-off…

1970-80s: ~flat out to 2-3r_d

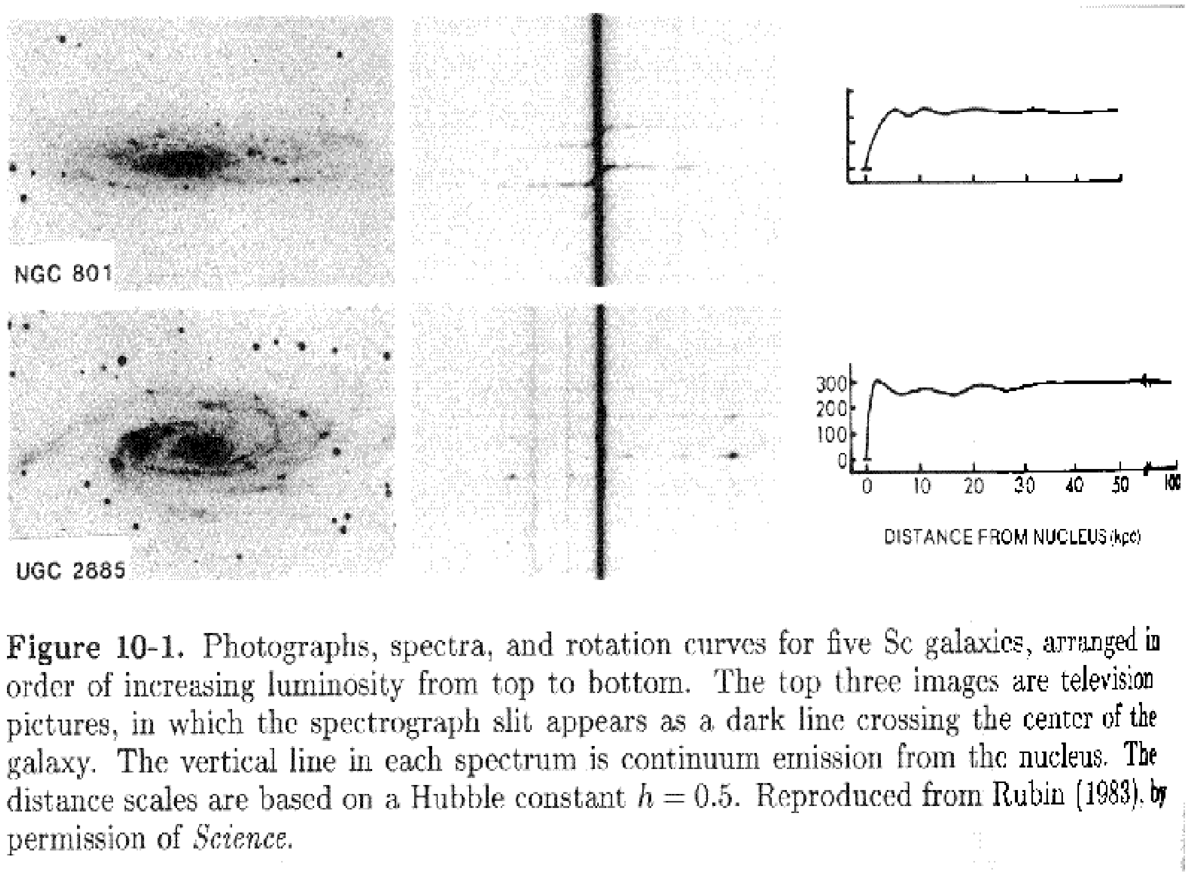
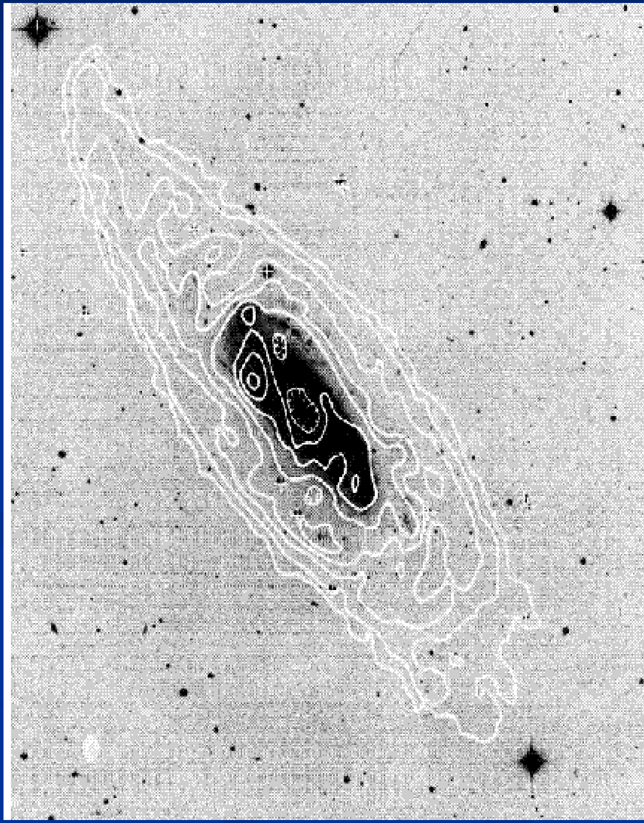


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.

optical band



radio observations (>5r_d)

Rotation *flat* out to 50-100 kpc

dark matter needed!!

What is needed:

- Typically: bulge + disk account for the inner rotation curve with reasonable $\mathbf{M/L_B} \sim 3$—5 (**M** stands for mass)
- Dark matter halo is needed giving total $\mathbf{M/L_B} \sim 30$!

In general: 5 times more **DARK MATTER** than mass in stars + gas

↓

This is still a lower limit as $\mathbf{v_c(r)}$~const means $\mathbf{M(r)}$~$\mathbf{r}$

❖Dark matter halo structure: disk-halo conspiracy

Obviously, since $\mathbf{v_c(r)}$~const at large radii: $\boldsymbol{\rho}\mathbf{(r)} \sim \mathbf{r}^{-2}$

Difficult to constrain the inner parts: usually disk + bulge are made to fit the inner $\mathbf{v_c(r)}$ ➔ this is called the "maximum" disk fit

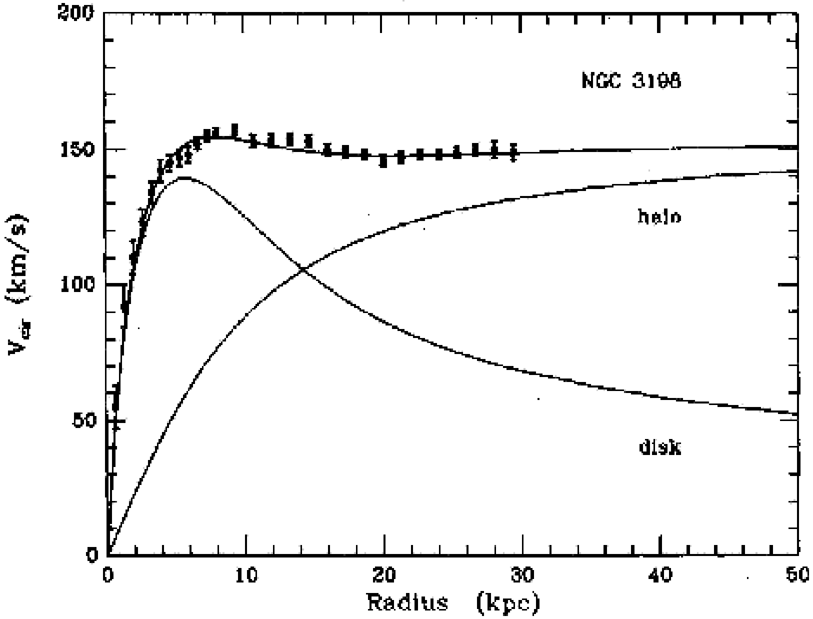


FIG. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal to that of the light distribution (60", corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0) = 0.0040\ M_\odot\ \mathrm{pc}^{-3}$.

see: van Albada et al. (1985) *ApJ*, **295**, 305

$$\Phi = \Phi_{halo} + \Phi_{disc} \Rightarrow v_{circ}^2 = v_{c,halo}^2 + v_{c,disc}^2 \left(v_{circ}^2 = r\frac{\partial \Phi}{\partial r} \right)$$

$100 question:

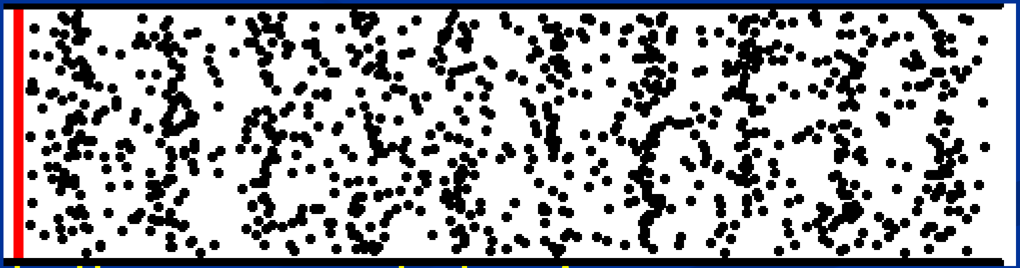
Why is it that the disk part of the rotation curve is so similar to halo part?

➢Spiral and bar structures

M51

- Spiral classes
  - grand design: two strong arms
  - flocculent: more chaotic
  - multiple arms: strong inner arms
- Arm prominence
  - spiral arms are bluer than the underlying (red) disk
  - spirals are younger than the disk
  - the old disk in grand design spirals has spiral pattern
  - the old disk in flocculents is *uniform*

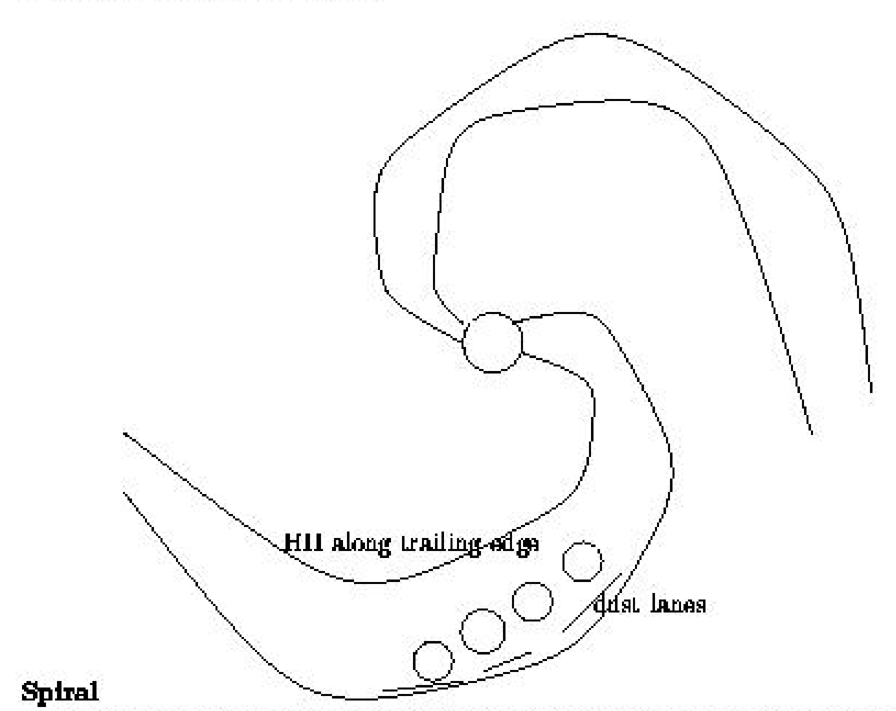
Interpretation:



grand design spiral is a globally-generated density wave
flocculent spirals are not global density waves,
but local perturbations

❖Leading or trailing spiral arms?

How to decide? Need to know which side of the disk is nearest



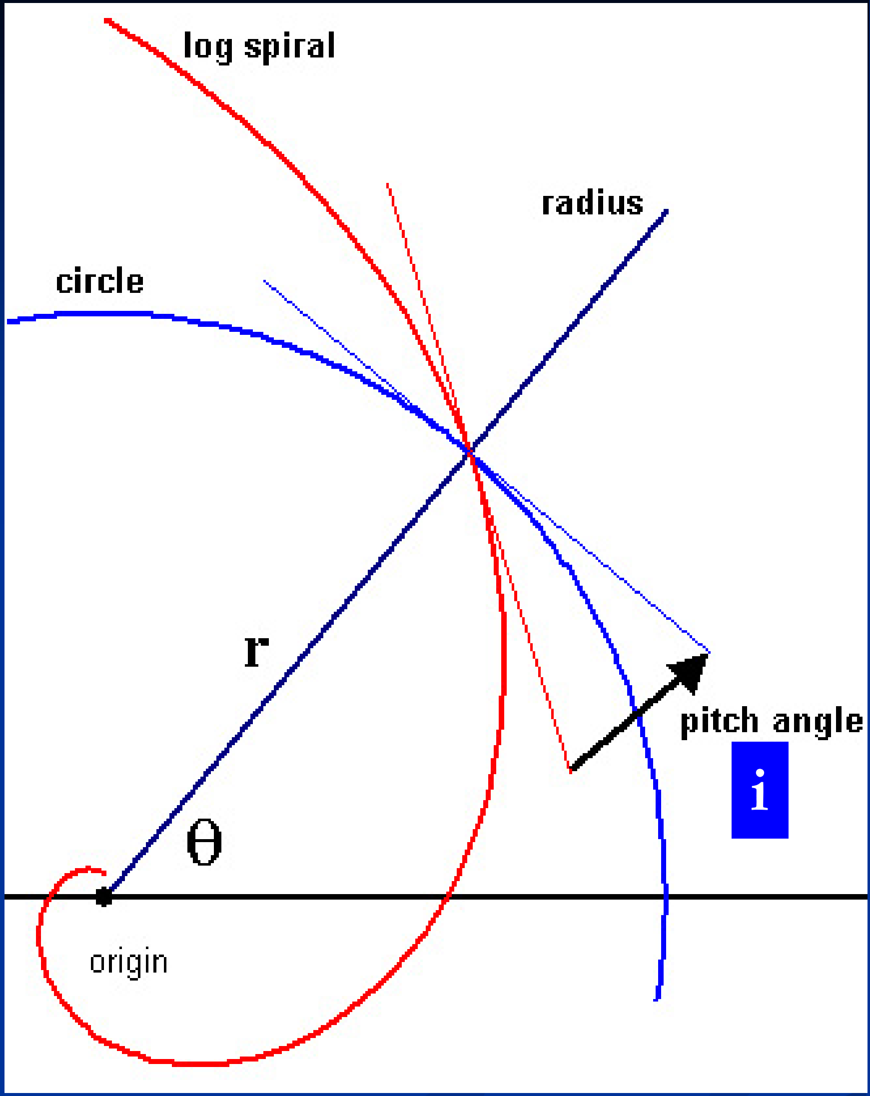
Using dust obscuration and positions of dust lanes, star forming Regions and young stars → arms are almost always *trailing*

Pitch angle

Defined as the angle *i* between the tangents to the spiral arm and circle

$$\tan i = \frac{1}{r}\frac{dr}{d\vartheta}$$

Most spirals have **i** ~ const throughout the disk

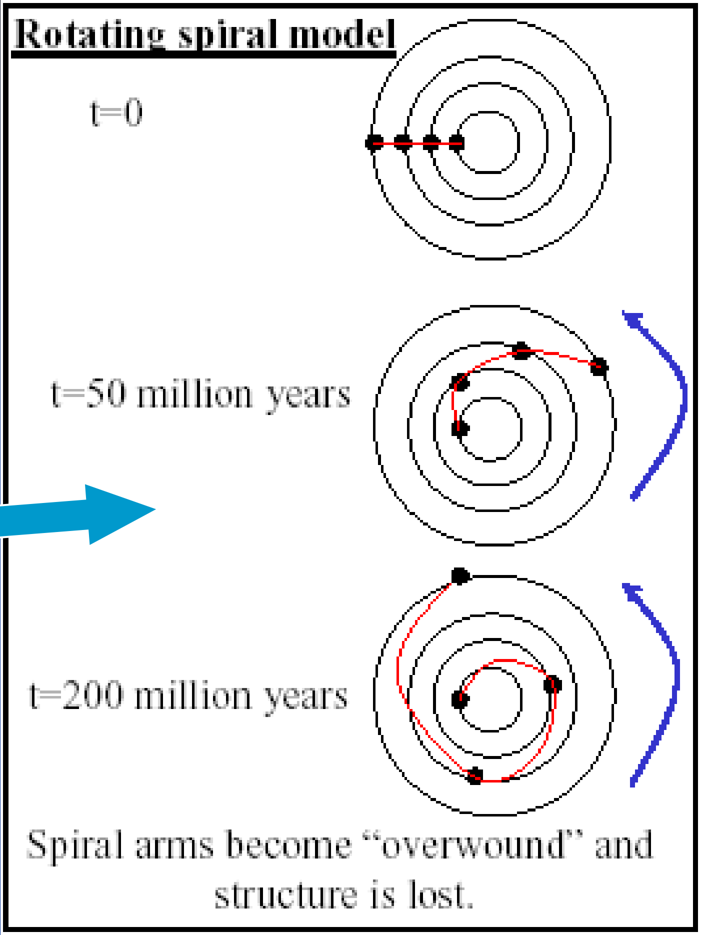


pitch angle of a logarithmic spiral
$\mathbf{r = a\, e^{b\theta}}$ in polar coordinates

❖The winding problem

The disk is rotating differentially except in the innermost parts

The spirals must wind up with time



Spiral arms become "overwound" and structure is lost.

Observations:

Sa galaxies: i~5^{o}

Sc galaxies: i~10^{o}—30^{o}

In reality: spiral arms are not material features, they are patterns, through which stars and gas flow

- Bars

Barred galaxies are common: in excess of 70% of all disks

Bars are straight → rigid rotation of pattern
with angular velocity $\Omega_b(\mathbf{r})$= const

Bars are not density waves: stars are trapped in the bars

Bars form (somehow!) and can be destroyed (somehow!)

$1,000 question:

Why do they exist at all?