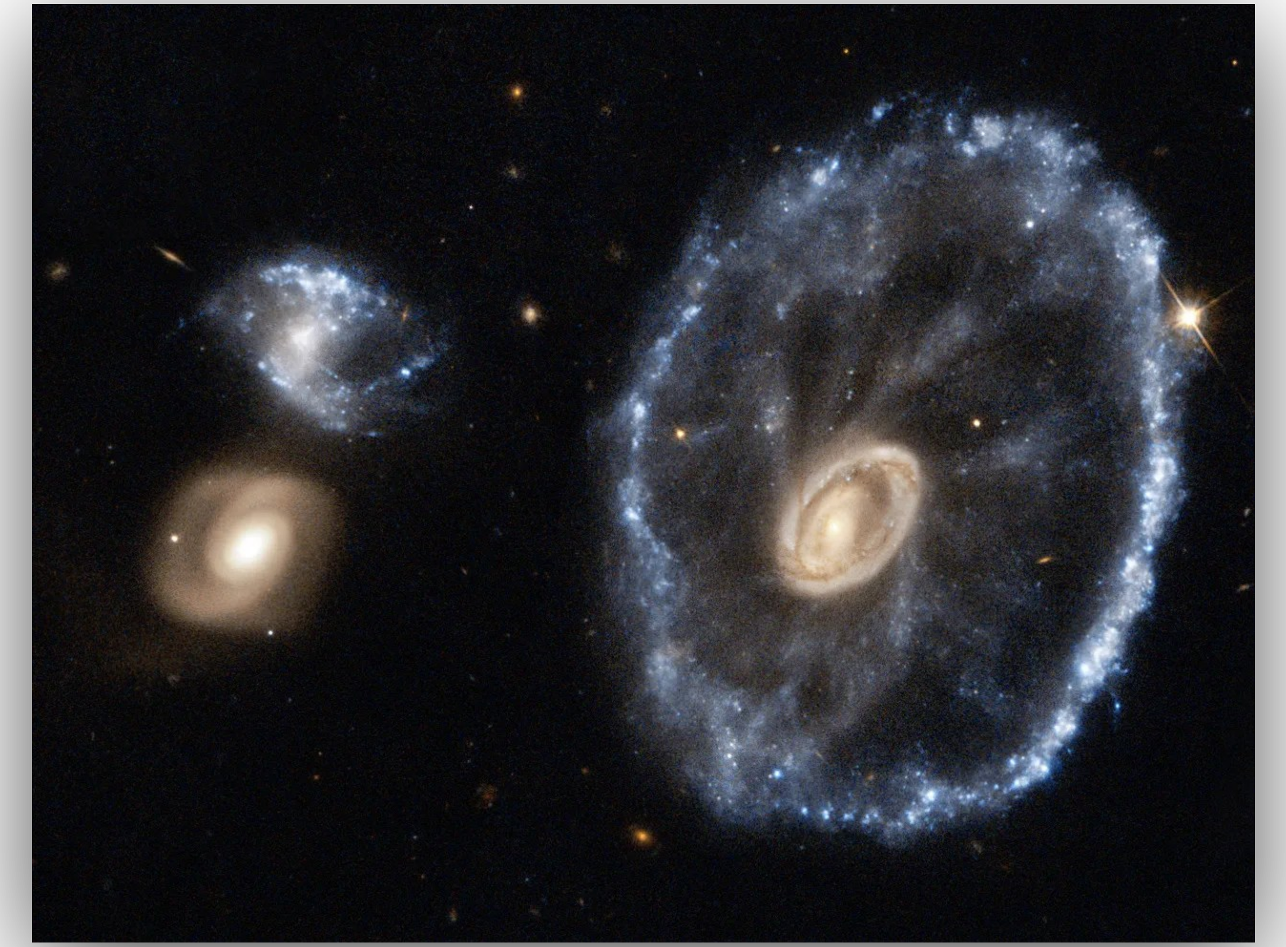
# Fundamentals of Galaxies

## What is a galaxy ?

- Gravitationally-bound system, comprising of ~ billions of stars, gas
- Building block of our Universe
- Comes with a variety of flavours...
    - Mass, size, morphology
    - Dynamical properties
    - Formation & evolution path



Cartwheel galaxy

Credit HST, NASA/ESA

La Silla Observatory, Chile

P.C : Dr. B. Rajpoot

Ladakh, India

Photo courtesy : Dorje Angchuk, IIA, Hanley Observatory

# Historical anecdote

- **Greek mythology**

**Hḗras gala —> Milk of Hera**

**(River of milk flowing from the breast of Hera,**

**the wife of Greek God Zeus)**

Artist : Jacopo Tintoretto.

- **The Romans saw it, too!**

*Via Lactea —> Milky Way (literally, the Road of milk)*

- **Hindu mythology**

*Akashganga —> The Ganges river of the sky*

**Bhagavata Purana**

# Galileo to the 'Rescue'...


A Fresco by Giuseppe Bertini

- **Built the first telescope in 1610**
- **Could resolve the 'celestial fluid' into a conglomeration of many faint stars**

Thus, the Milky Way was discovered to be primarily a stellar structure

(In retrospect, a disk-like structure would appear as A band of light from the disk plane)

# Milky Way - in the eyes of Kant

"General Natural History and

Theory of the Heavens"

(Mid-eighteenth century)

*Immanuel Kant*

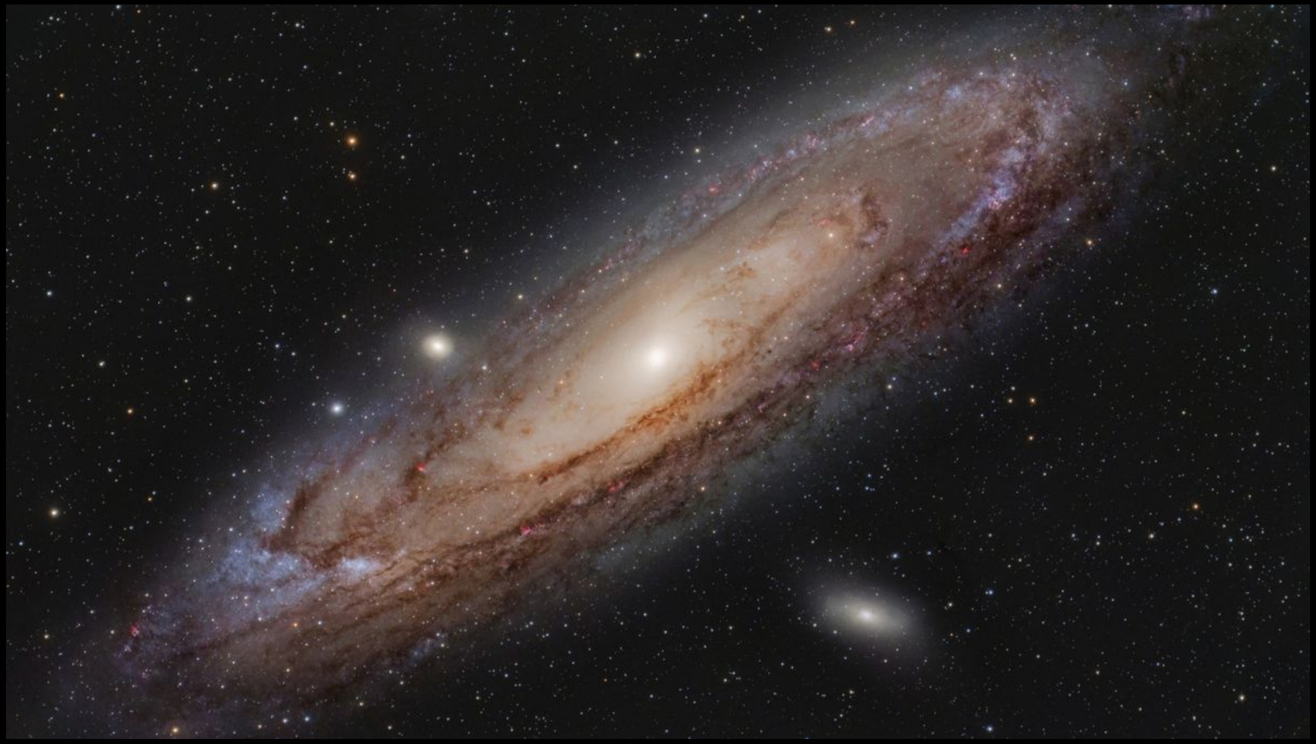
- **Planar structure of the Solar system arises naturally due to attractive force of gravity between the Sun and its planets**
- **He postulated a similar dynamical scenario for the Milky Way - except at a much larger scale**
- **Milky Way might not be the 'only' such stellar system…**
- **Existence of 'nebulae' —> might be completely 'isolated universe', similar in structure to the MW, but viewed from a large distance & at different viewing angle**

# Messier catalogue

- Systematic study of the nebulae
- Complied a catalogue of 109 bright nebulae in the northern sky

This is known as Messier catalogue

*Charles Messier*



*Andromeda galaxy*

*(Closest neighbour of the Milky Way)*

**Messier 31 or M 31**

**(31st entry in the Messier catalogue)**

# The Work of Lord Rosse

- Equipped with advanced telescope

  (72-inch diameter)

- Classified nebulae into two types
  - Elliptical nebulae
  - Spiral nebulae

*Sketch of M51*

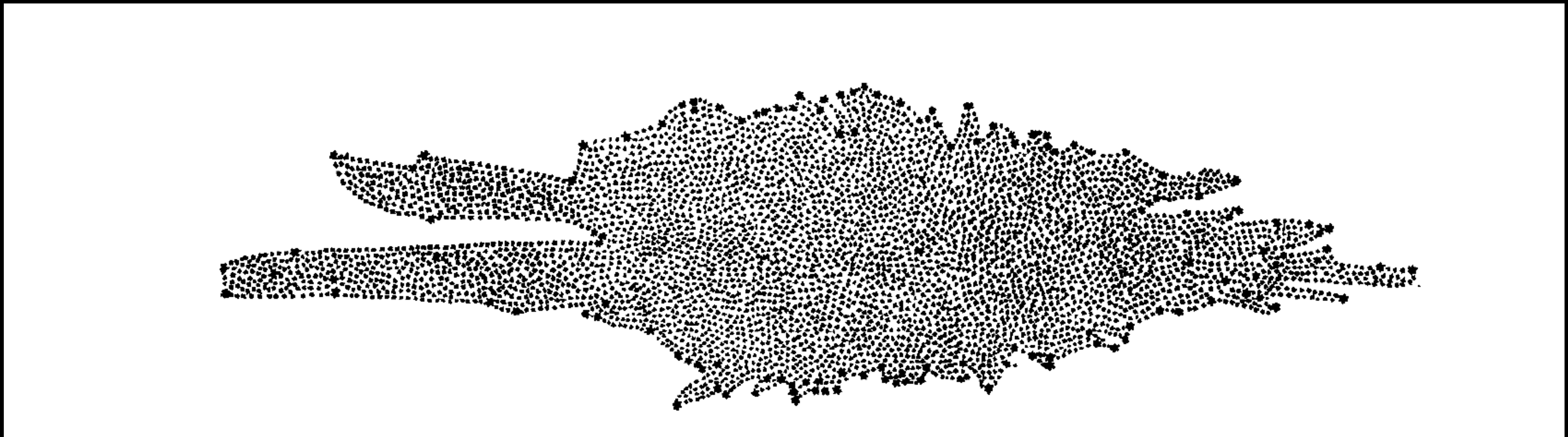
*(Whirlpool galaxy)*

The findings of Lord Rosse's work supported the theories of Kant

End of Nineteenth century -> applications of photographic plates -> beginning of the era of a more quantitative astronomy

# Photometric models of the Milky Way

- Herschel's view



- Technique : Star gauging (~ 683 regions)

- Basic assumptions :

1. All stars have almost same intrinsic brightness
2. They are distributed almost uniformly throughout the Milky Way
3. One could see through all the way to the edge of the MW

## Herschel's conclusion

1. The Sun lies close to the centre of the stellar distribution
2. The distribution is flattened - approx. 5 times more in the in-plane as compared to direction perp. to the plane

No absolute scale for the size of the MW proposed

## KAPTEYN'S UNIVERSE

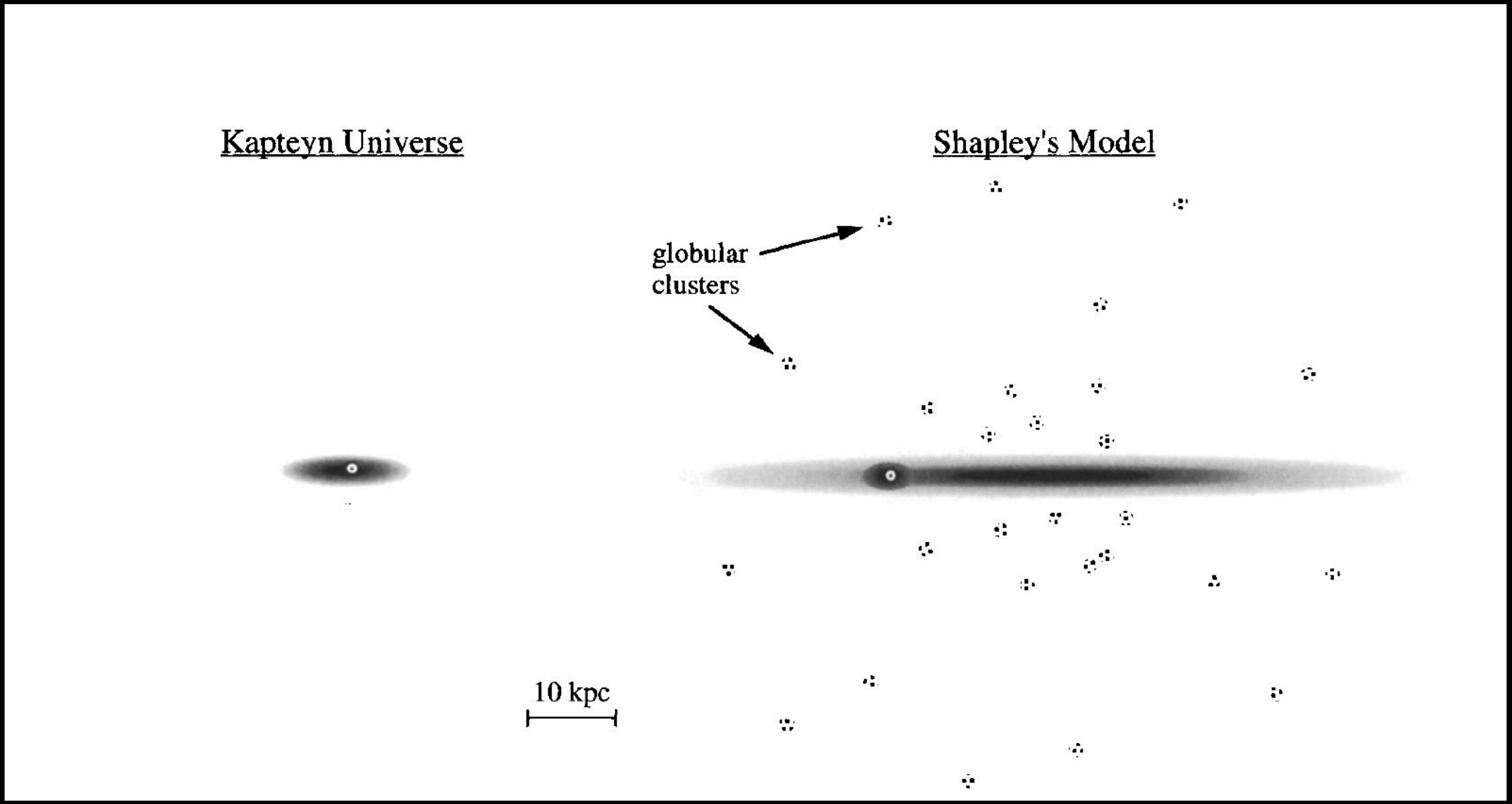
In agreement with Herschel's work

Density of the stars drops to half its maximum value at ~ 800 pc

Spiral nebulae are 'isolated Universe' - a separate entity with properties similar to the MW

Missing ingredient : absorption due to interstellar medium

# Shapley's Universe




- A radically different view than Kapteyn

- Technique : studying distribution of the globular clusters

## Shapley's findings

- distribution of the globular clusters is not uniform

  (Especially along the longitude)

## Argument of Shapley

- globular clusters must be a major structural component
- Must be distributed wrt to the centre of the whole system

The large asymmetry signifies that the Sun is *not* at the centre

## Shapley's conclusion

- The Sun is not at the centre of the MW (~ 15 kpc from the centre)
- The spiral nebulae are part of the Milky Way

# THE GREAT DEBATE (1920)


## The nature of the Spiral Nebulae & their extragalactic nature

- National academy of Science, Washington
- Participants : Harlow Shapley & Heber Curtis

### Harlow Shapley

- Mostly focused on his model for the Milky Way

Some passing comments about the nature of the spiral nebulae

### Heber Curtis

Presented arguments in great detail, for and against the 'Island Universe' hypothesis

# Hubble to the Rescue (1922)

- Measured the intrinsic luminosities of the Cepheid variable stars (from their period-luminosity relation) in the Andromeda nebula (M31)
- Comparing the apparent magnitude to the intrinsic one, measured the distance of M31
- Distance of M31 is ~ 300 kpc and hence not a part of the Milky Way

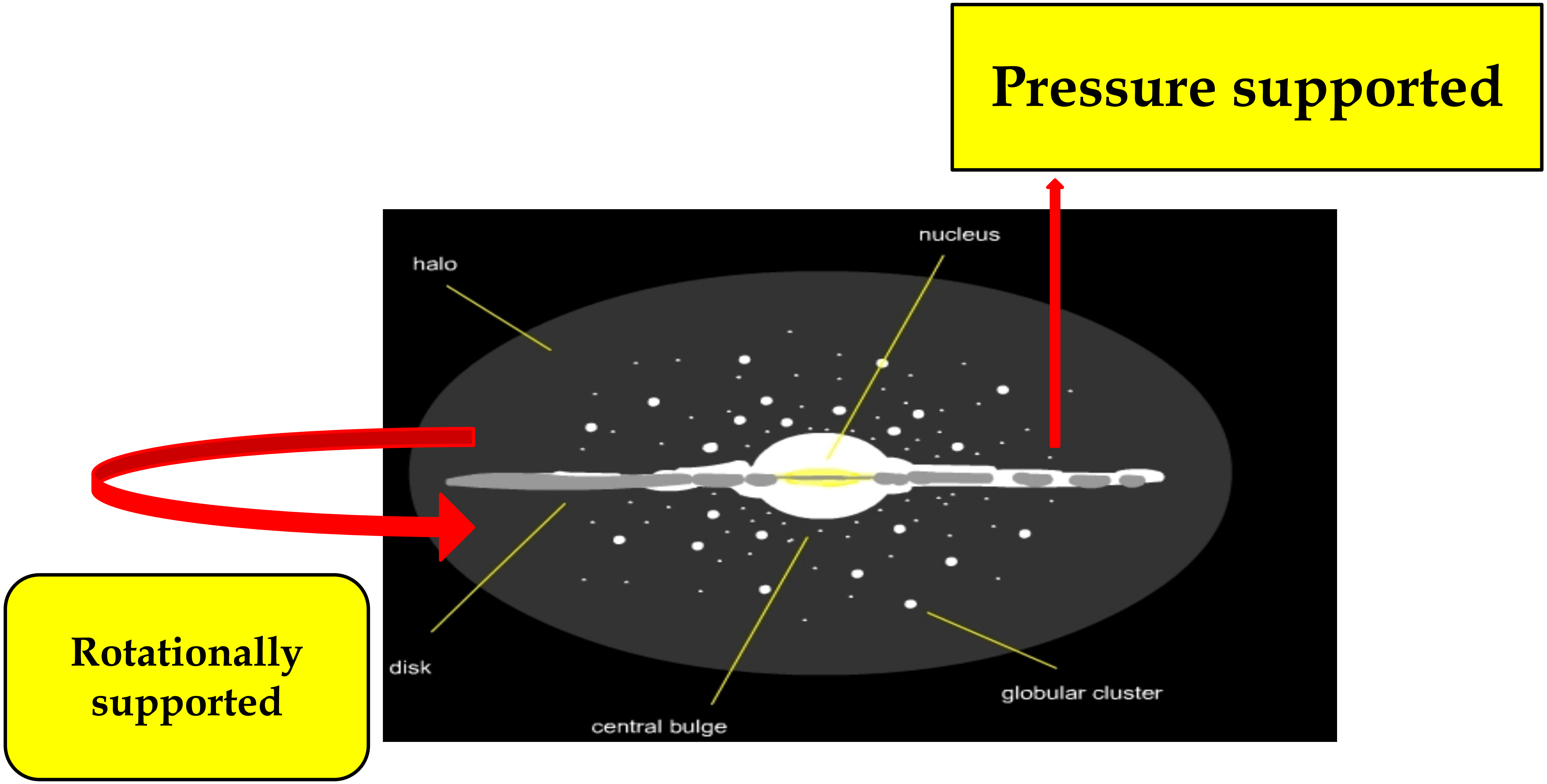
# Ellipticals vs Spirals

- Fairly regular, elliptical in shape,
- mostly featureless
- Does not show much ordered rotation (in general)
- Some of the massive galaxies are Indeed ellipticals

- Presence of disks (stars + gas)
- Complex structure (spirals, bars)
- Dominated by ordered rotation

Hubble Space Telescope

# Basic structure of a disk galaxy




**Disk galaxy = stellar disk + central bulge + gas disk + asymmetries (spiral arms, bars etc.)**

# M 100 (NGC 4321)

## Grand-design spiral structure

# M 101 (NGC 5457)

## Intermediate spiral structure

*Image Courtesy : Hubble Space Telescope*

# M 63 (NGC 5055)

## Flocculent spiral structure

**A swirling hotchpotch of pieces of spiral arms...**

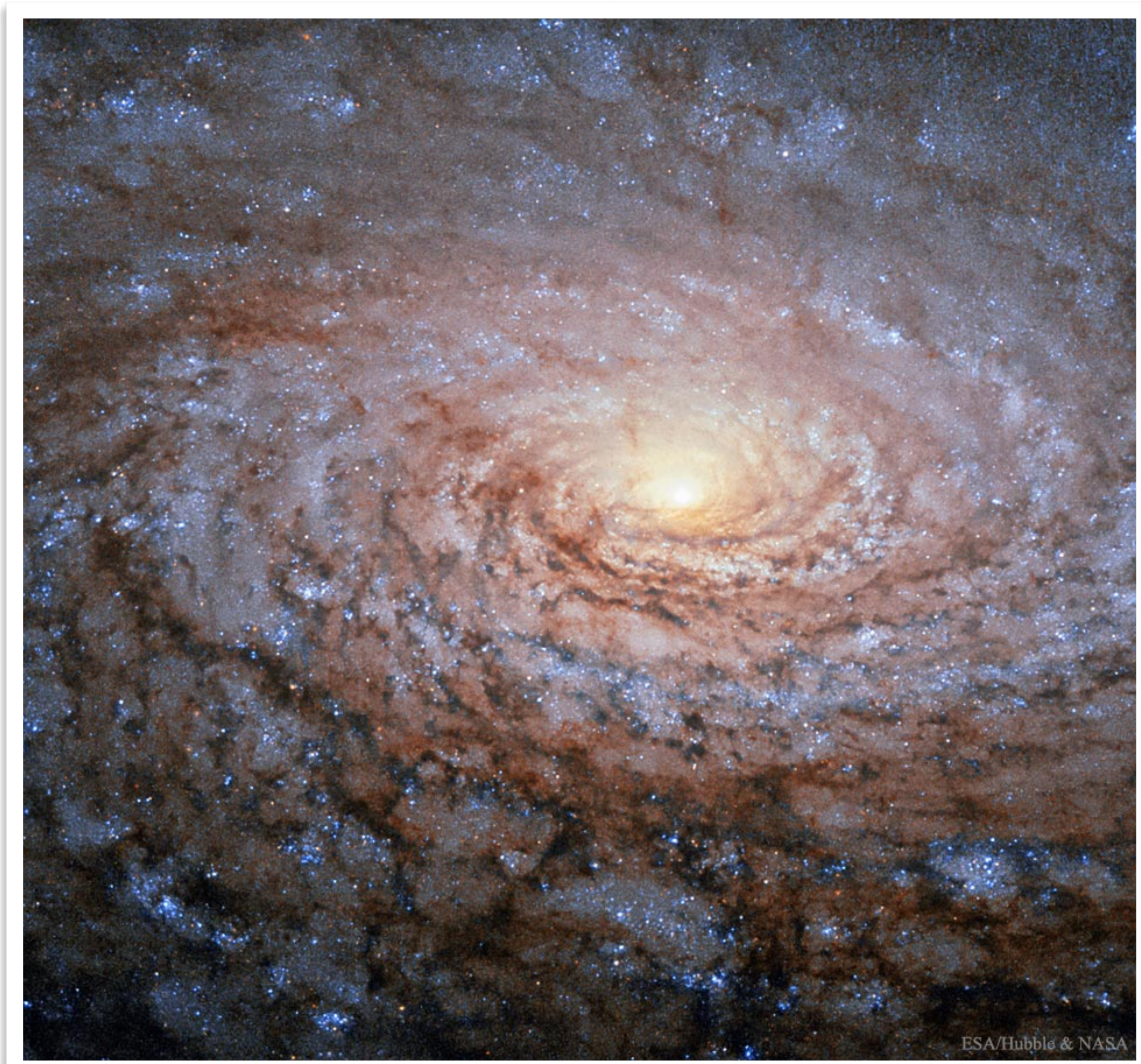



*Image Courtesy : Hubble Space Telescope*

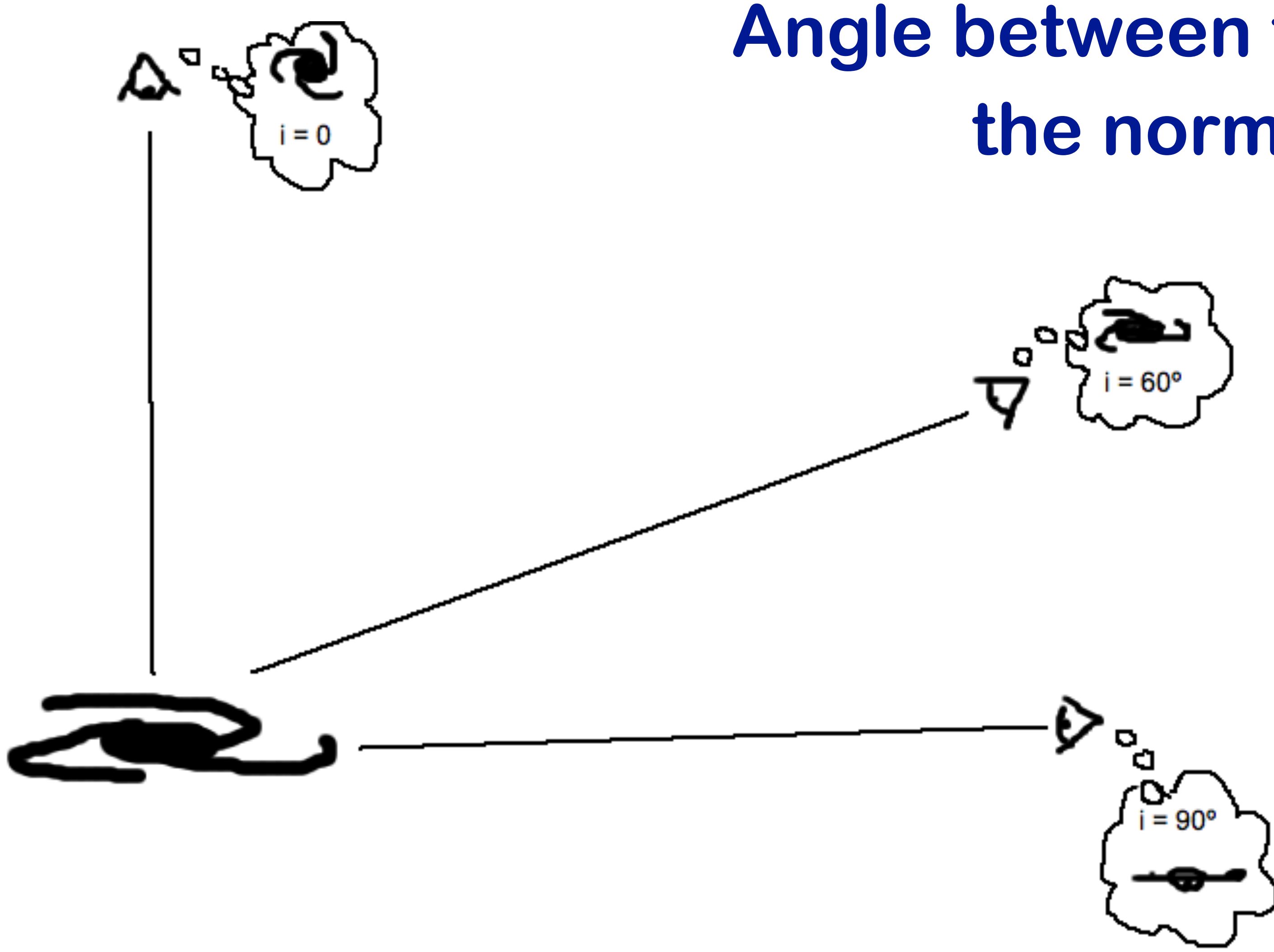
# NGC 1300

## Barred-spiral galaxy

The bar driving the spiral structure ?

# Angle of inclination

Angle between the line-of-sight (LOS) and the normal to the disk plane




Face-on —> more appropriate for morphological studies of spirals, bar (basically in-plane structures)

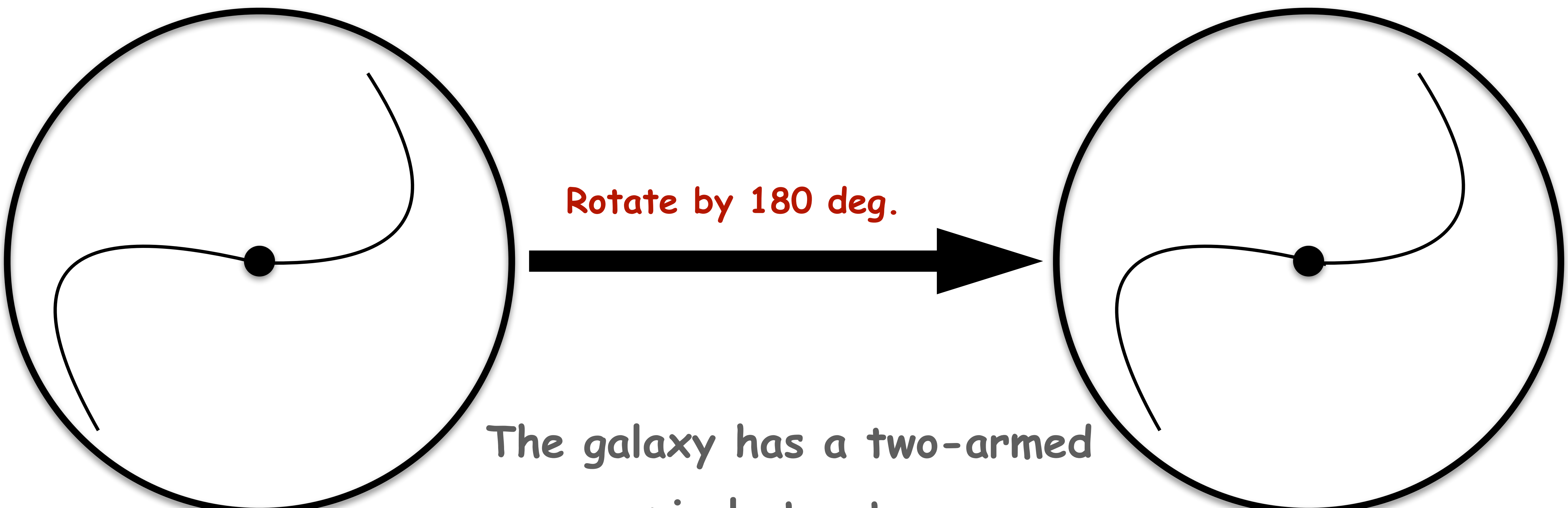
Edge-on —> more appropriate for morphological studies of structures in the vertical direction (e.g., boxy/peanut bulge)

# Number of spiral arms — m-fold symmetry

$$I(R,\phi) \rightarrow \text{Face}-\text{on surafce brightness}$$

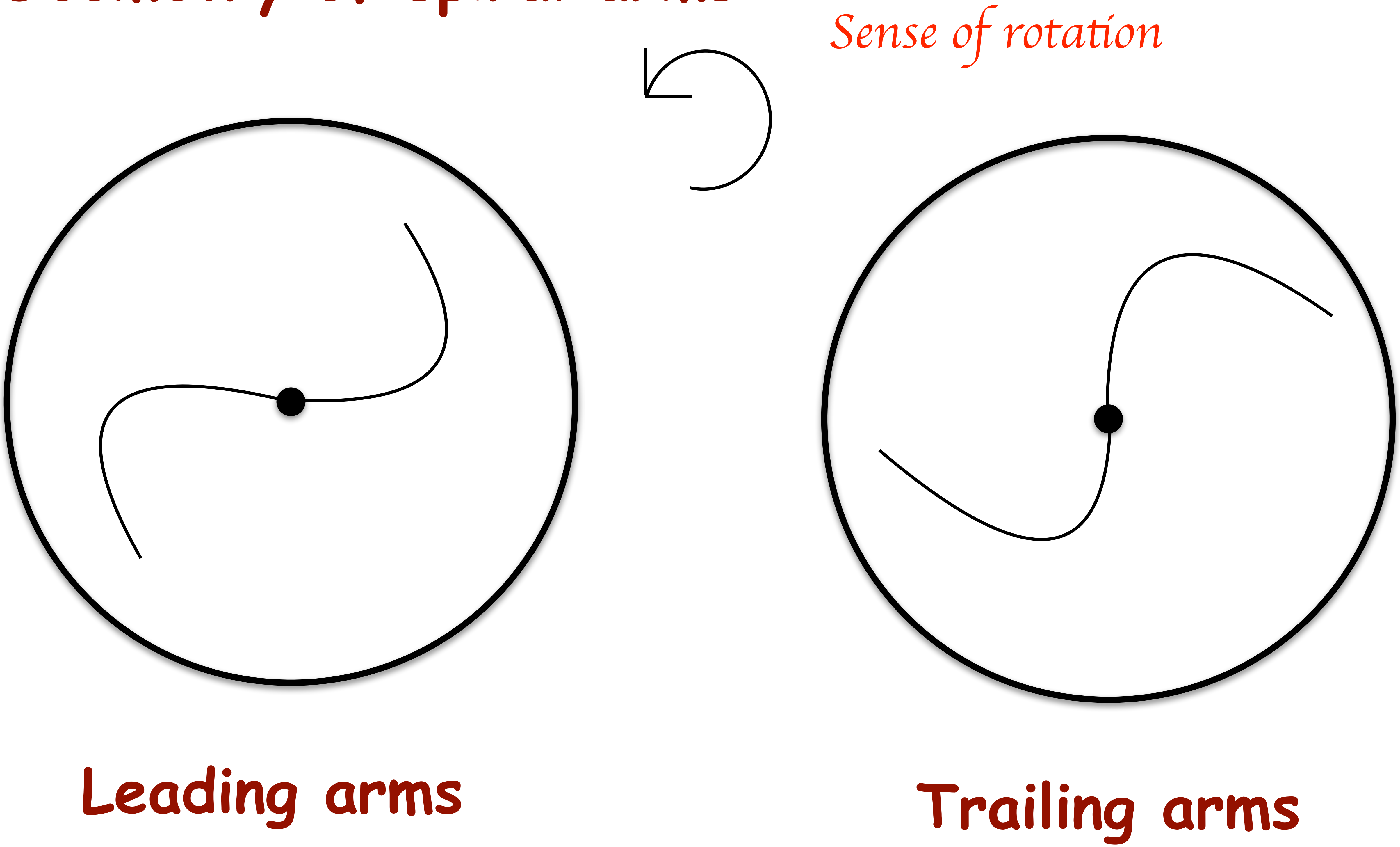
$$I(R,\phi + 2\pi/m) = I(R,\phi)$$ **m-fold symmetry**

**The galaxy is said to have m arms (m>0)**




The galaxy has a two-armed spiral structure

# Geometry of spiral arms

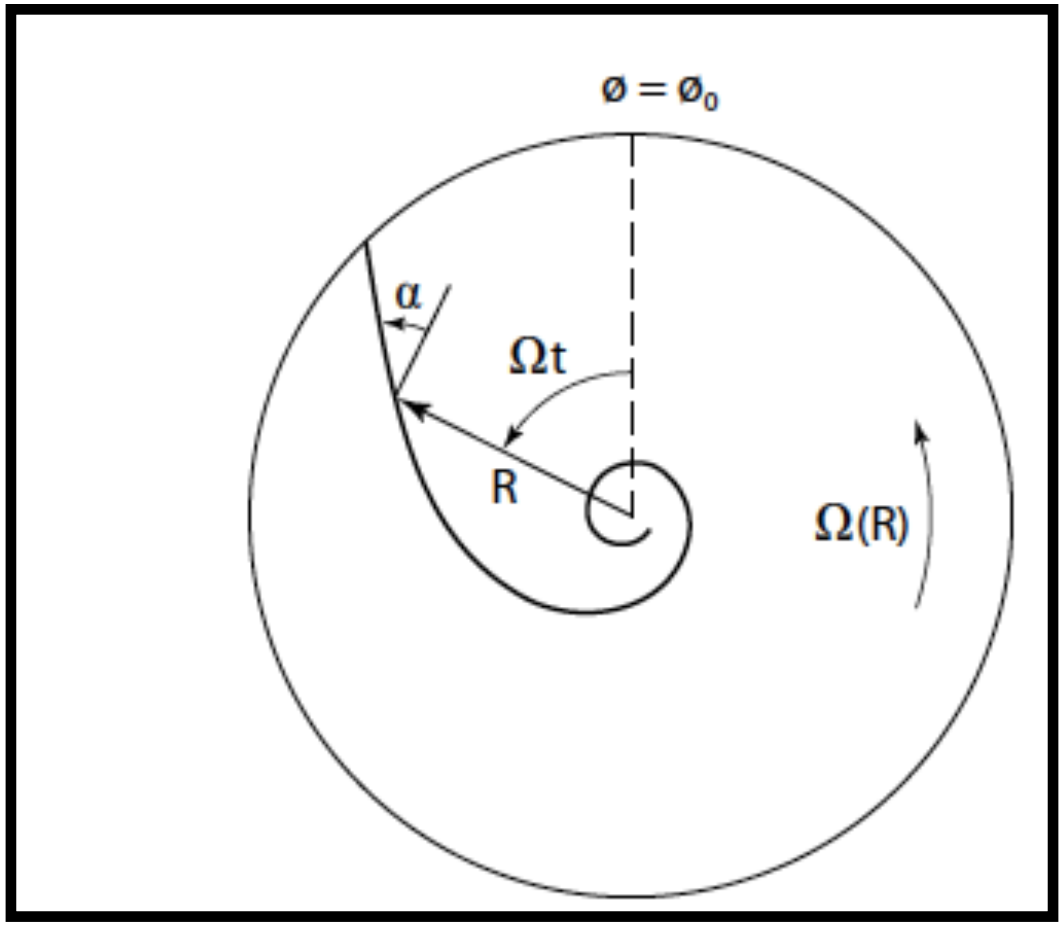



**However, detecting observationally is not straightforward!**

# Pitch Angle

**Angle between the tangent to the arm and the circle *R =constant***

$$\boxed{0 \leq \alpha \leq \pi/2}$$




**Expression for calculating pitch angle**

$$\cot \alpha = |R \frac{\partial \phi}{\partial R}|$$

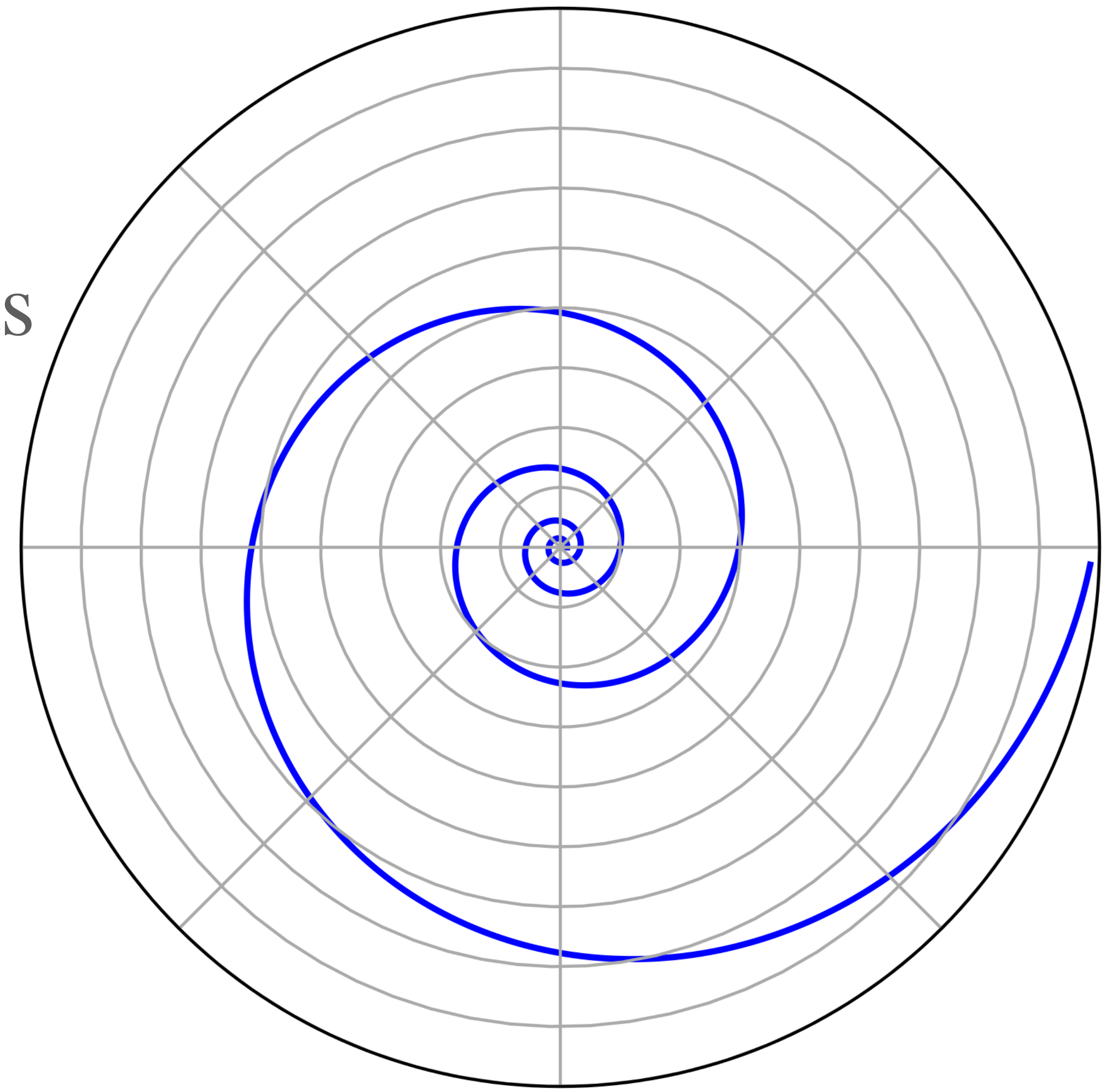
- **Pitch angle serves as a measure of openness of the spiral arms**
- **Lesser the value of pitch angle is, more tightly-wound will be the resulting spiral arm**

# Logarithmic Spiral : an example

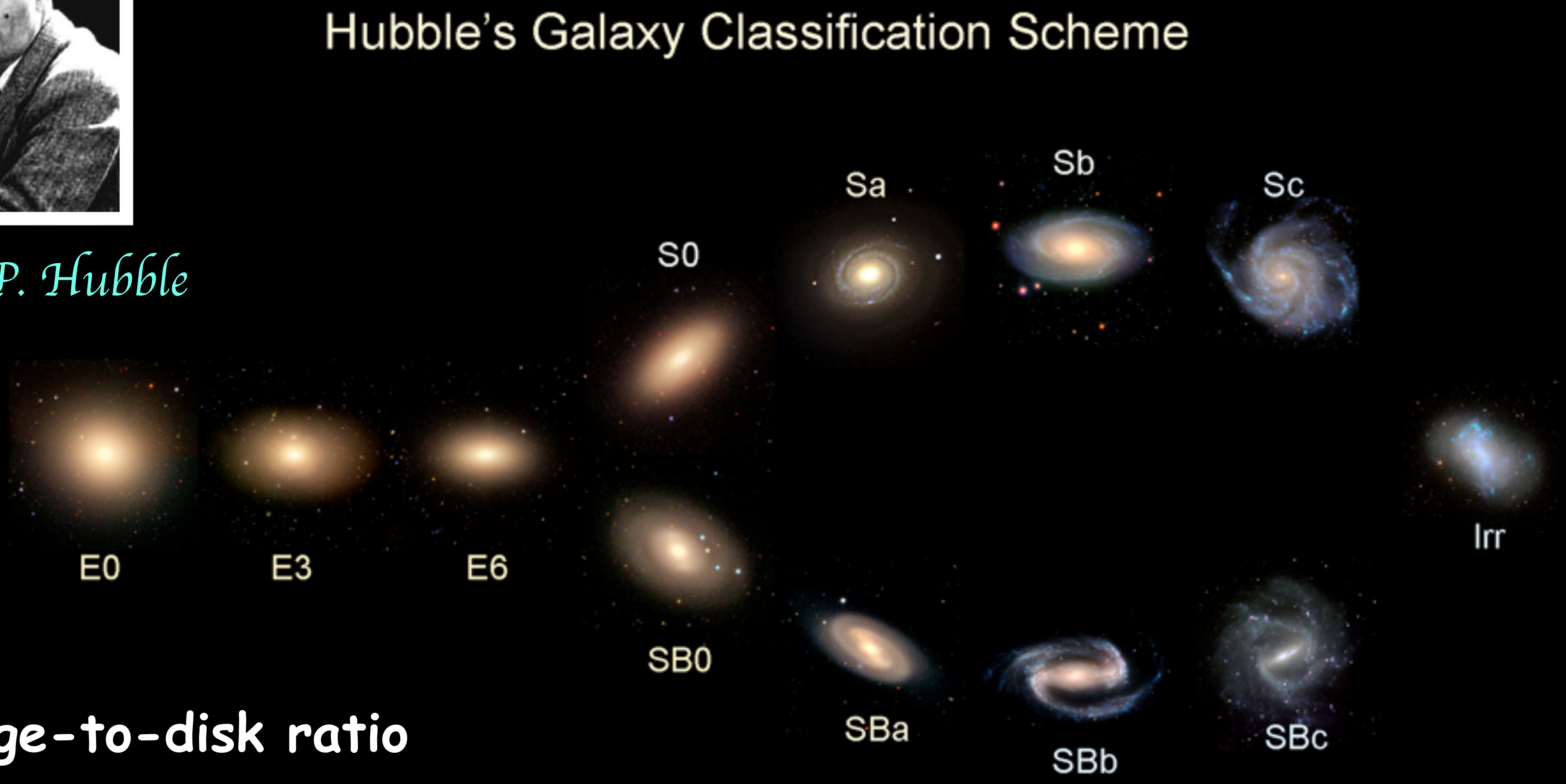
**In polar $(r, \varphi)$ coordinates,**

$$r = a \exp[k\varphi]$$

$a > 0$, $k$ are real constants



*Edwin P. Hubble*




- Bulge-to-disk ratio
- Openness of the spiral arms and degree of resolution of arms into stars
- Presence of bars

## Classification criteria

# A few trends

Hubble's Galaxy Classification Scheme

Don't have bar

$$n = 1 - b/a$$


Have bar

Lenticulars (S0)

- Gas fraction increases
- Bulge contribution decreases
- Spiral arms get more open and flocculent

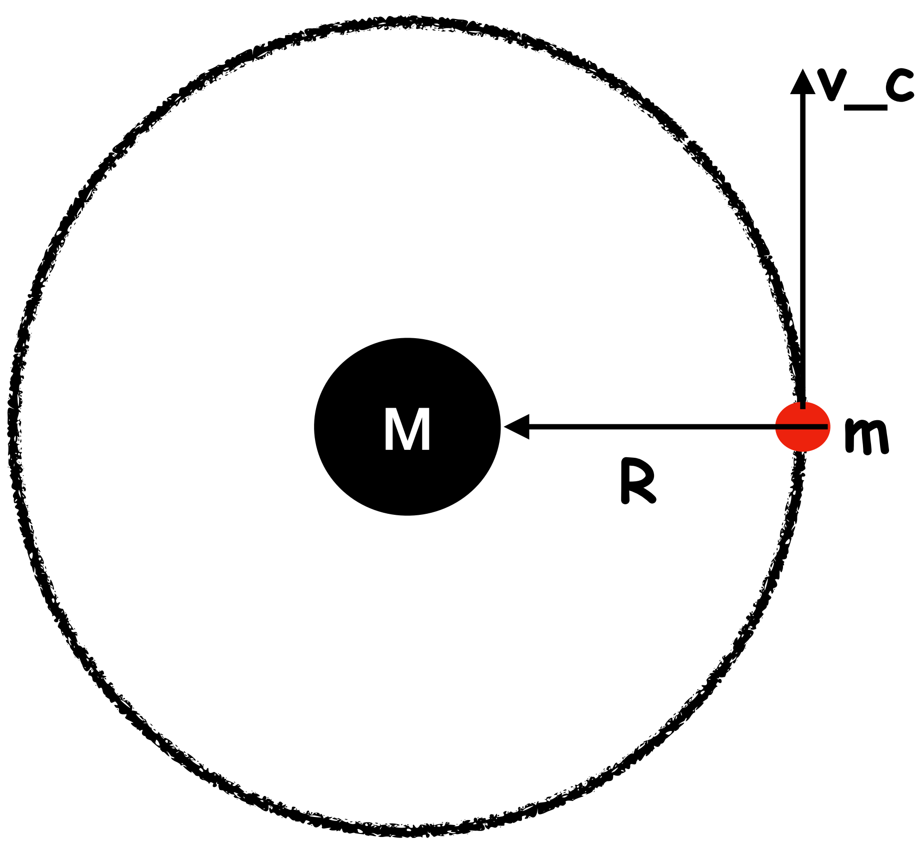
# Rotation curve & dynamical mass

**Rotation curve** ⟶ Circular velocity as a function of galactocentric radius

$$\frac{GMm}{R^2} = \frac{mv_c^2}{R}$$

$$\boxed{v_c^2 = \frac{GM}{R}}$$

$$\boxed{M = \frac{Rv_c^2}{G}}$$



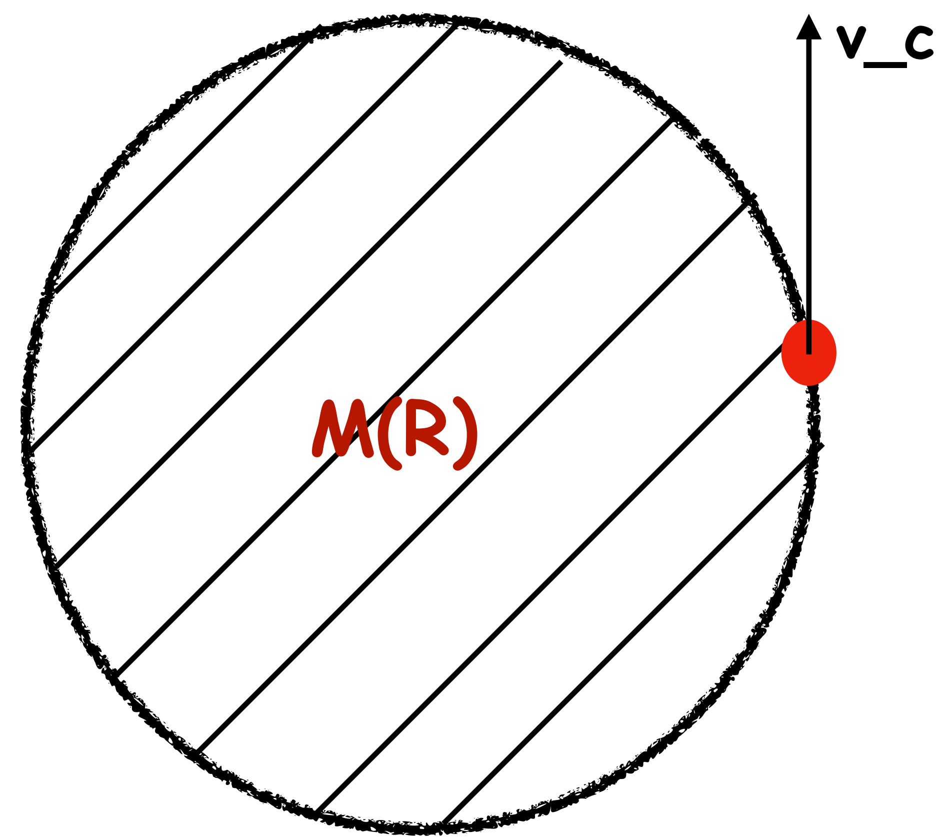

Estimate of the dynamical mass

# Case of a continuous mass distribution

$$\frac{GM(R)m}{R^2} = \frac{mv_c^2}{R}$$

$$\boxed{v_c^2 = \frac{GM(R)}{R}}$$

$$\boxed{M(R) = \frac{Rv_c^2}{G}}$$




Estimate of the dynamical mass within a shell of radius R

## Generalised case

$$\phi \rightarrow \rho$$

$$\boxed{\nabla^2 \Phi = 4\pi G\rho}$$

Density -potential pair

Poisson equation

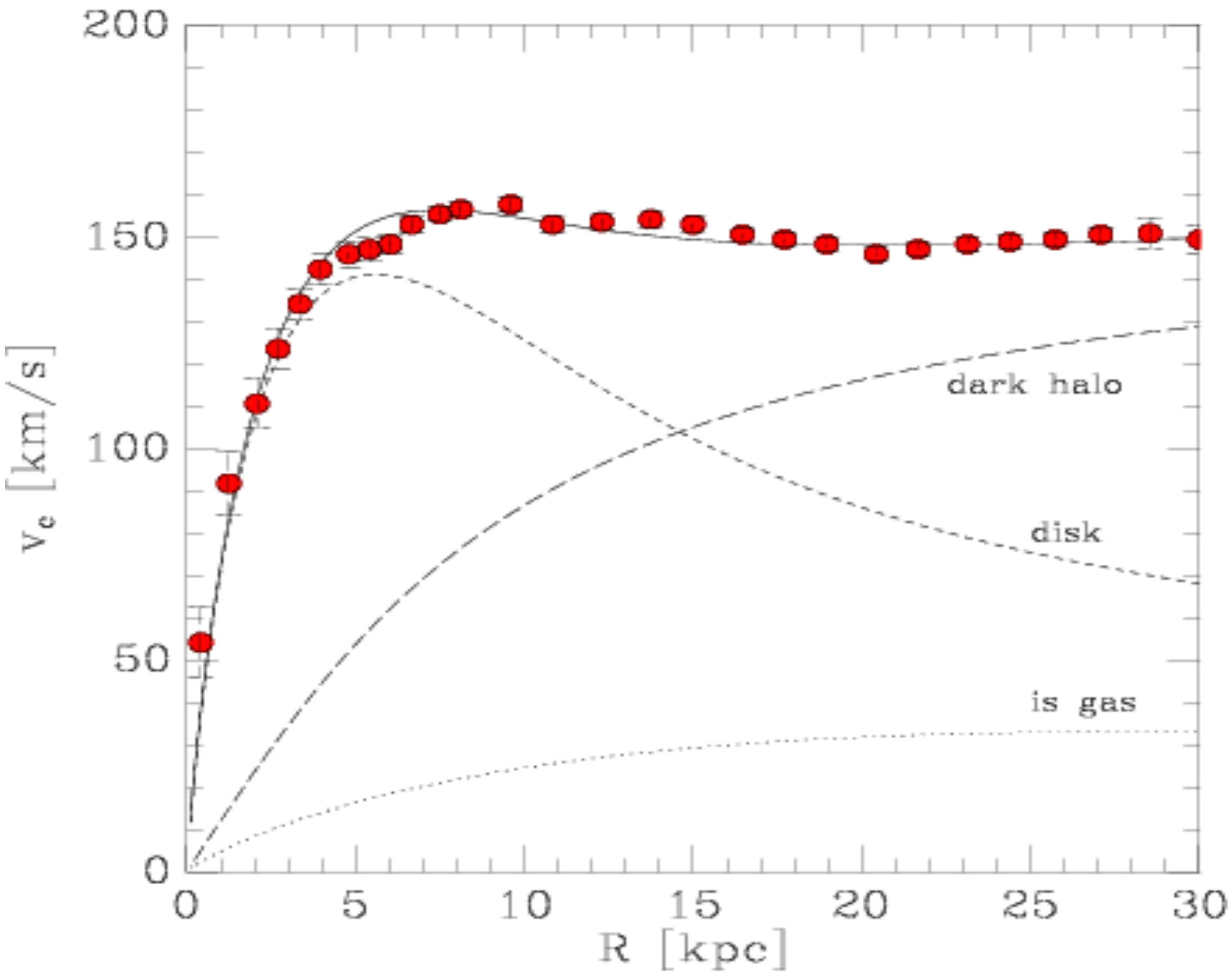
$$v_c^2(R) = R\frac{\partial \Phi}{\partial R}$$

The underlying mass distribution sets the circular motion

For a continuous density distribution, it's a property of location,
not an individual particle (star, mass blob) !

# Rotation curve of disk galaxies

For ellipticals, the rotational velocity is too small…




In the outer parts,

the rotation curve is

Mostly 'flat'!

**In the inner parts,**

$$\Omega(R) = \frac{v_c(R)}{R} = \text{constant} \qquad v_c^2 = \frac{GM(R)}{R}$$

$$\boxed{M(R) \propto R^3}$$

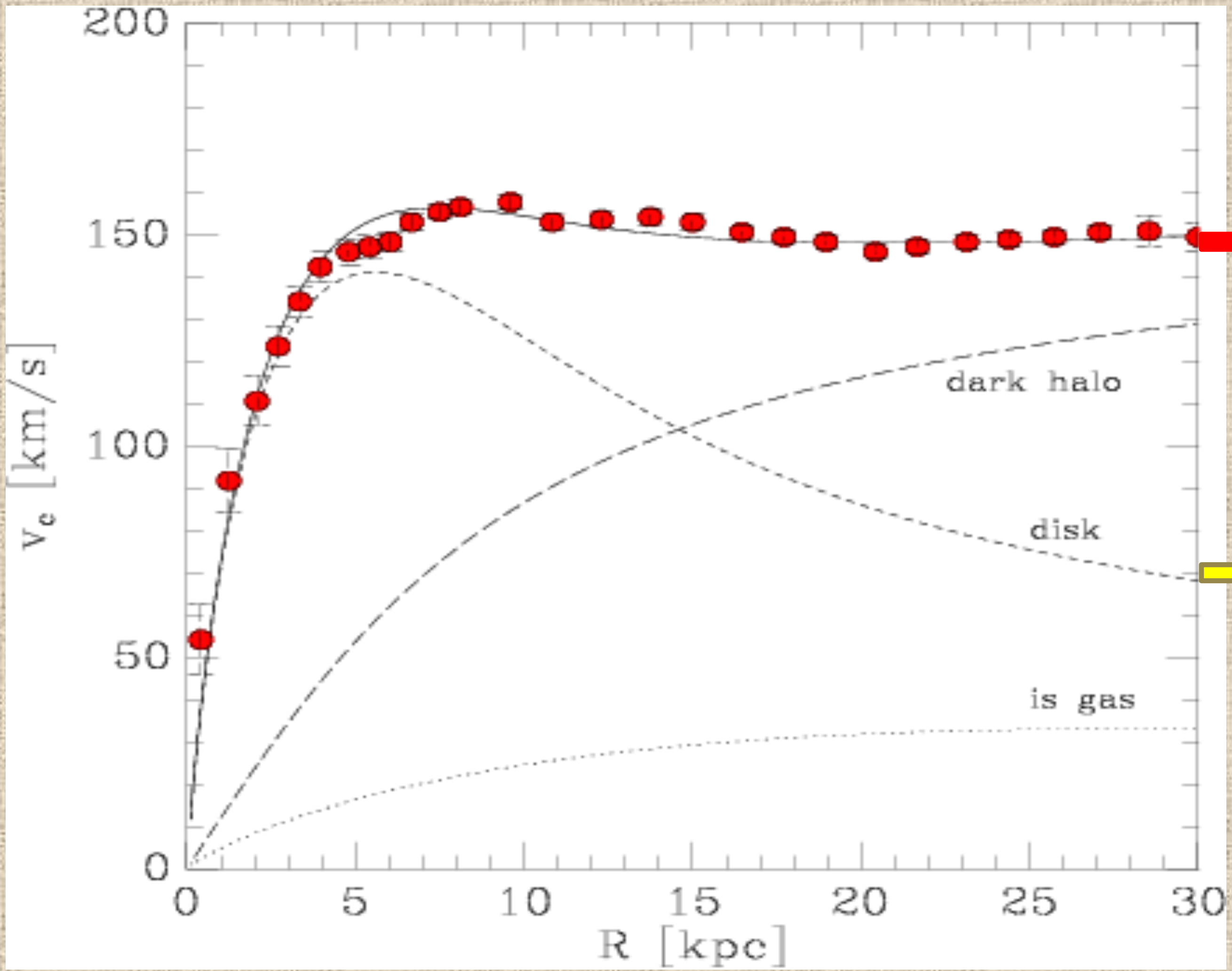
**In the outer parts,**

$$v_c(R) = \text{constant} \qquad v_c^2 = \frac{GM(R)}{R}$$

$$\boxed{M(R) \propto R}$$

**Mass continues to increase with R — counter-intuitive!**

# Mismatch between prediction & observation




Observed

Expected

Dark / Unseen matter Present !!!

Inner part matches well with baryonic contribution,

The outer part does not!

Vera Rubin

# Prediction of dark matter in galactic scale

Optical rotation curve used in the inner few kpcs

The mass discrepancy predicted was only ~ factor of 2-3

ARTICLES

## The Rotation of Spiral Galaxies

Vera C. Rubin[1]

+ See all authors and affiliations

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Article | Info & Metrics | eLetters | PDF

### Abstract

There is accumulating evidence that as much as 90 percent of the mass of the universe is nonluminous and is clumped, halo-like, around individual galaxies. The gravitational force of this dark matter is presumed to be responsible for the high rotational velocities of stars and gas in the disks of spiral galaxie. At present, the form of the dark matter is unknown. Possible candidates span a range in mass of $10^{70}$, from non-zero-mass neutrinos to massive black holes.

## Prediction of dark matter in galactic scale using HI rotation curve

Neutral Hydrogen (HI) extends much further away than the optical disk

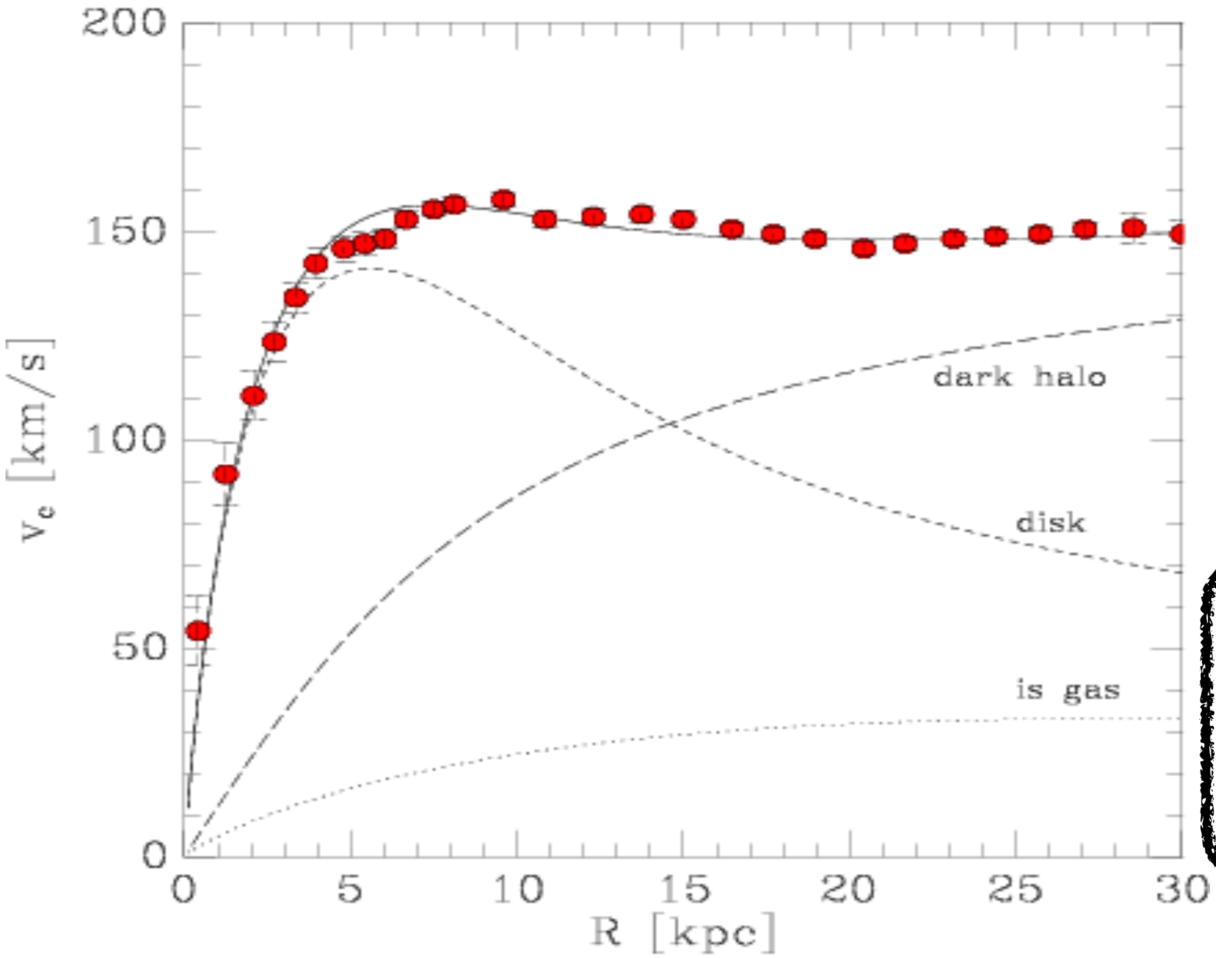
Facilitate measuring rotational velocity at largest distance

**Pioneering work of A. Bosma**
**(1978, PhD Thesis, University of Groningen)**

measured the rotation curve for 20 disk galaxies out to several disk scale-lengths

These observed flat rotation curves extended beyond the optical disk and these showed the presence of mass discrepancies, thus putting the proposition for existence of dark matter in disk galaxies on a firm basis

# Modelling Dark matter from Rotation curve of disk galaxies




$$v_{c,net}^2 = v_{c,bary}^2 + v_{c,DM}^2$$

$$v_{c,bary}^2 = v_{c,disk}^2 + v_{c,bulge}^2 + v_{c,gas}^2$$

$$\boxed{v_{c,DM}^2 = v_{c,net}^2 - v_{c,bary}^2}$$

For an assumed $\rho \rightarrow \phi$

$$\boxed{v_{c,\,DM}^2(R) = R\frac{\partial \Phi_{DM}}{\partial R}}$$

Least-square fitting will provide the best-fit parameters

# Dark matter halo density profile — 'Core-Cusp' problem

**Pseudo-Isothermal profile**

$$\rho(R,z) = \frac{\rho_0}{1 + R^2/R_c^2}$$

**Observationally favoured**

**A constant value at the centre - cored density distribution**

**NFW profile (Navarro-Frenk-White)**

$$\rho(r) = \rho_{crit}\frac{\delta_{char}}{(r/r_s)(1 + r/r_s)^2}$$

**Predictions from cosmological simulation**

**Singularity at the centre - cuspy density distribution**