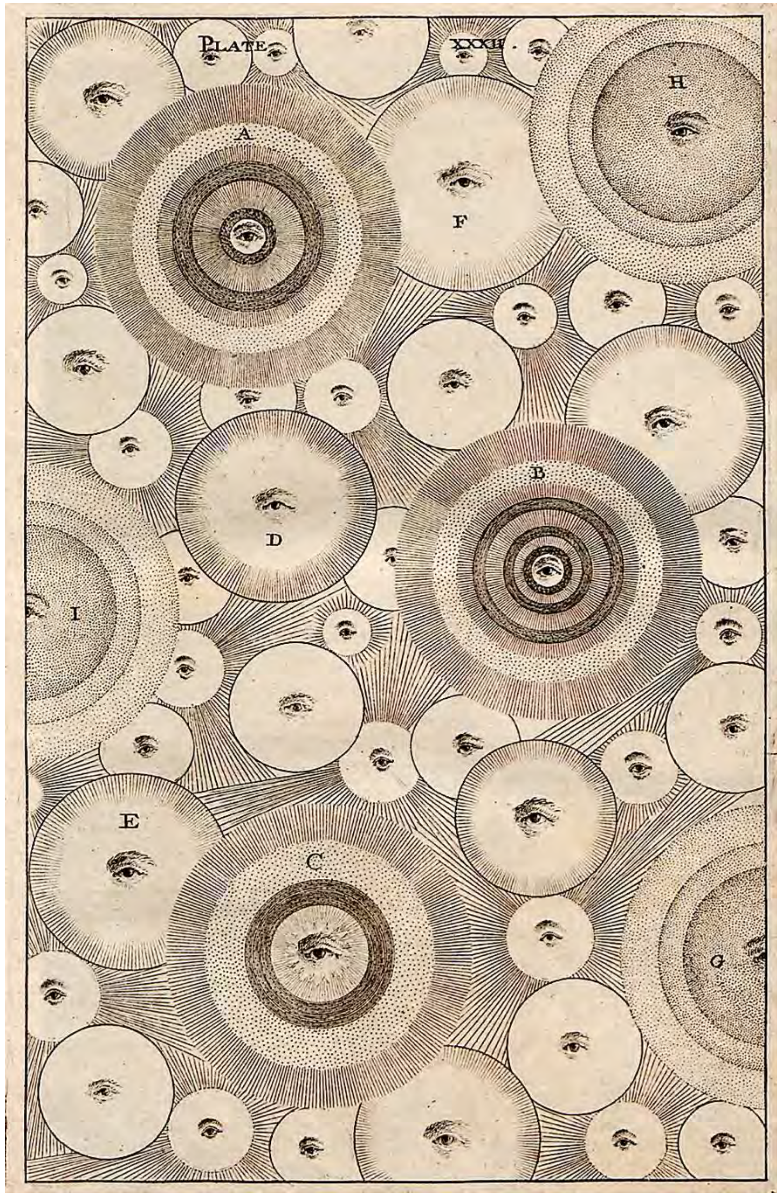
Ay 1 – Lecture 11

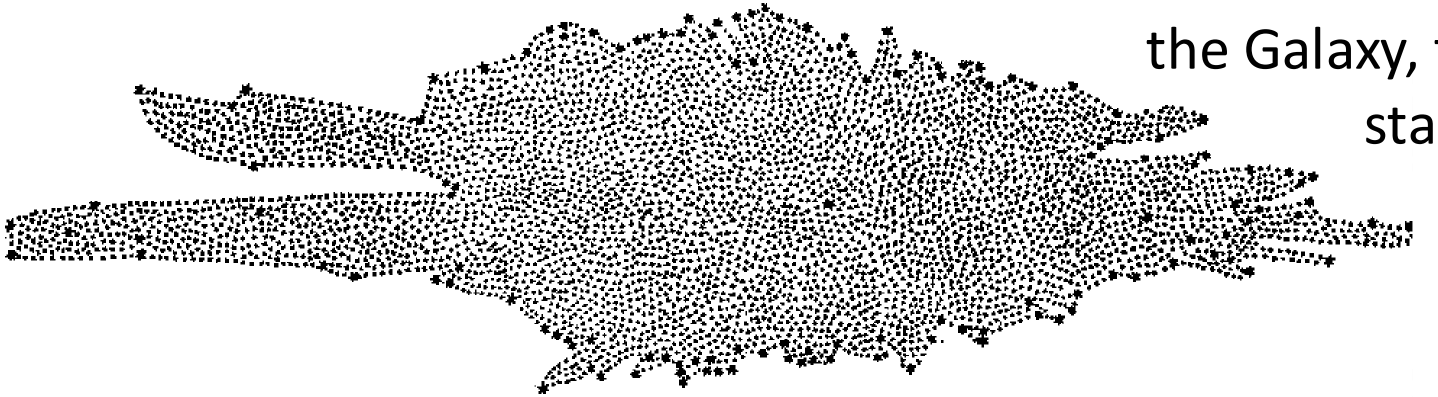
Our Galaxy,
The Milky Way

Nebulae and Their Nature

Fuzzy patches on the sky, not like stars. Nobody knew what they were.

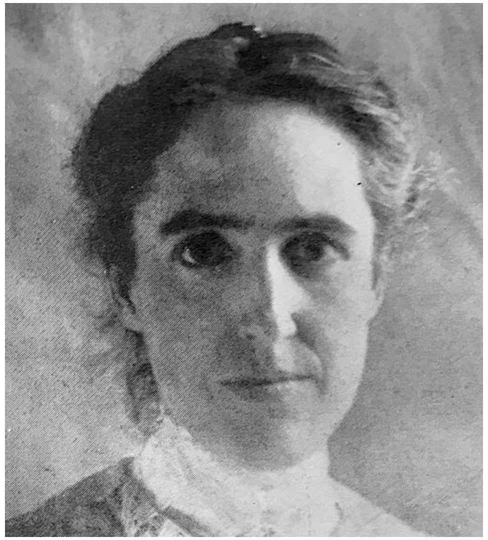


- After Galileo resolved into stars, the Milky Way was thought to be *the entire universe*, not as one of many galaxies
- In mid-18th century Thomas Wright, Immanuel Kant, and William Herschel speculated that the nebulae were “Island universes”, and the Milky way just one of them, with the Sun at its center

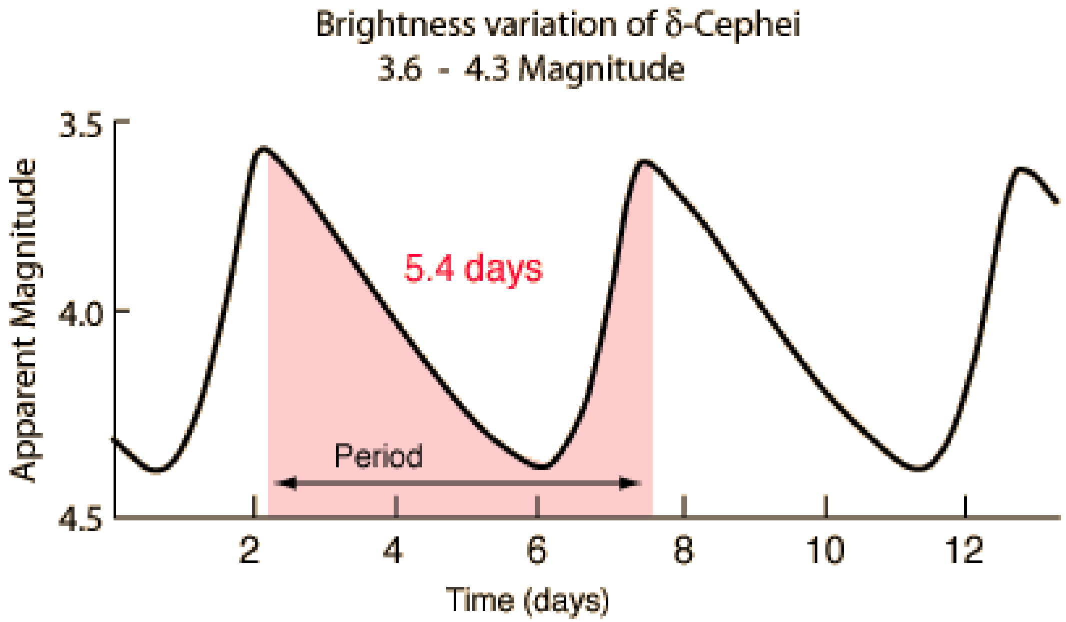


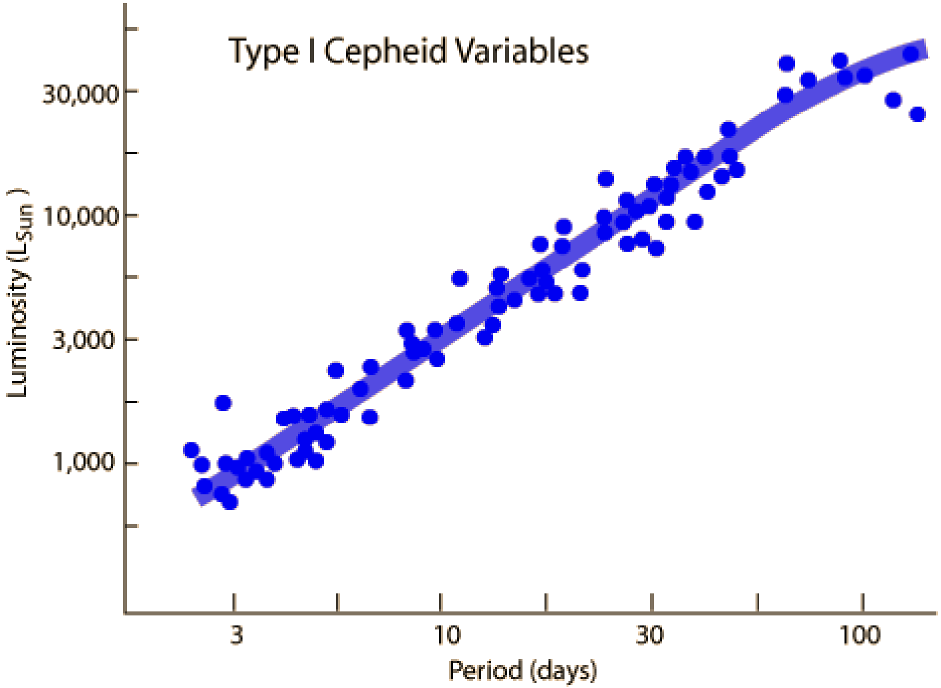
Herschel’s sketch of the Galaxy, from his star counts

Measuring Distances using Cepheids



In 1912, **Henrietta Leavitt** at Harvard was studying pulsating variable stars, **Cepheids**, in the Magelanic Clouds

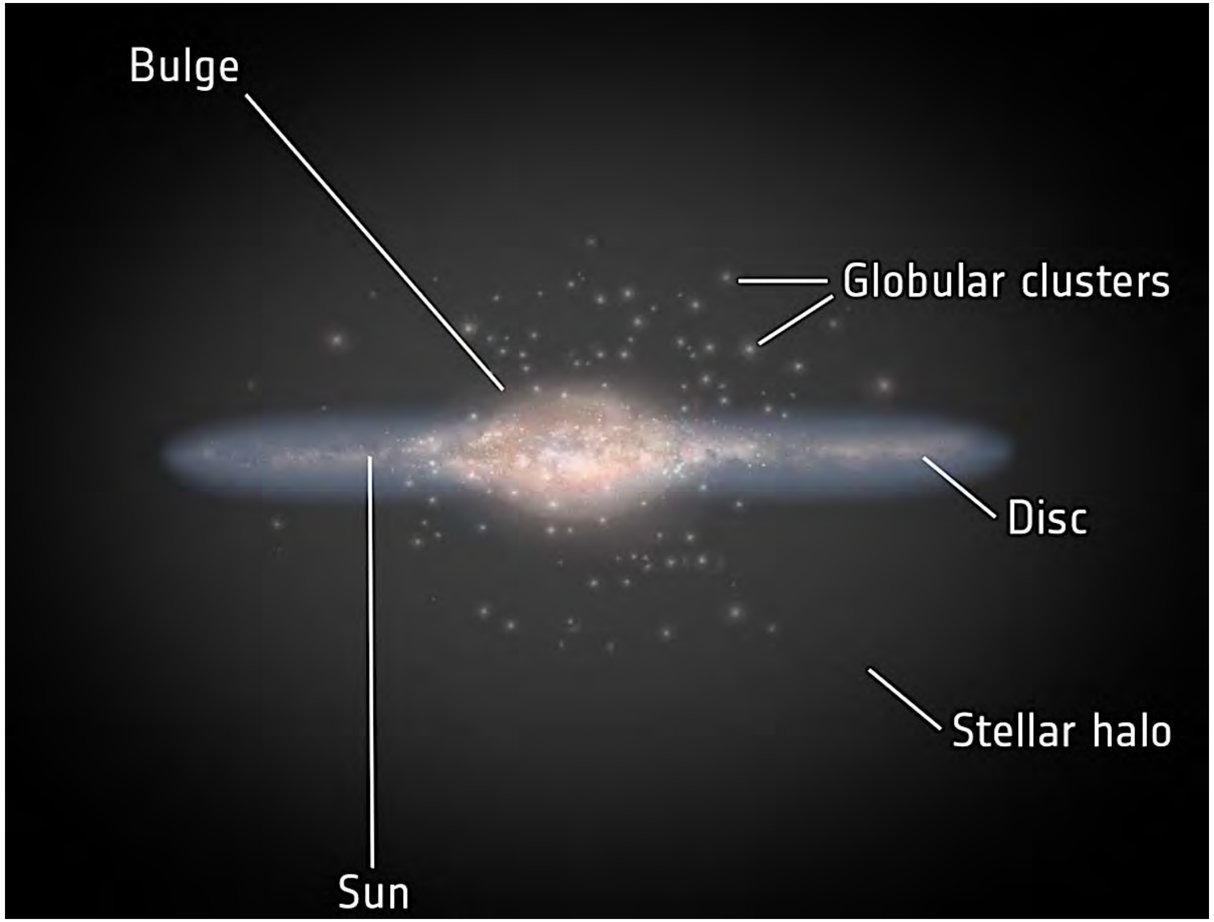




She discovered that the more luminous ones have longer periods. That made them good **distance indicators**. Periods do not depend on the distance. They can be used to deduce the absolute luminosity, and from that and the apparent brightness, the distance.

Shapley's Universe: the Size of the Milky Way

In 1918, **Harlow Shapley**, using the Mt. Wilson 60-inch telescope and Levitt's period-luminosity relation measured distances to globular star clusters

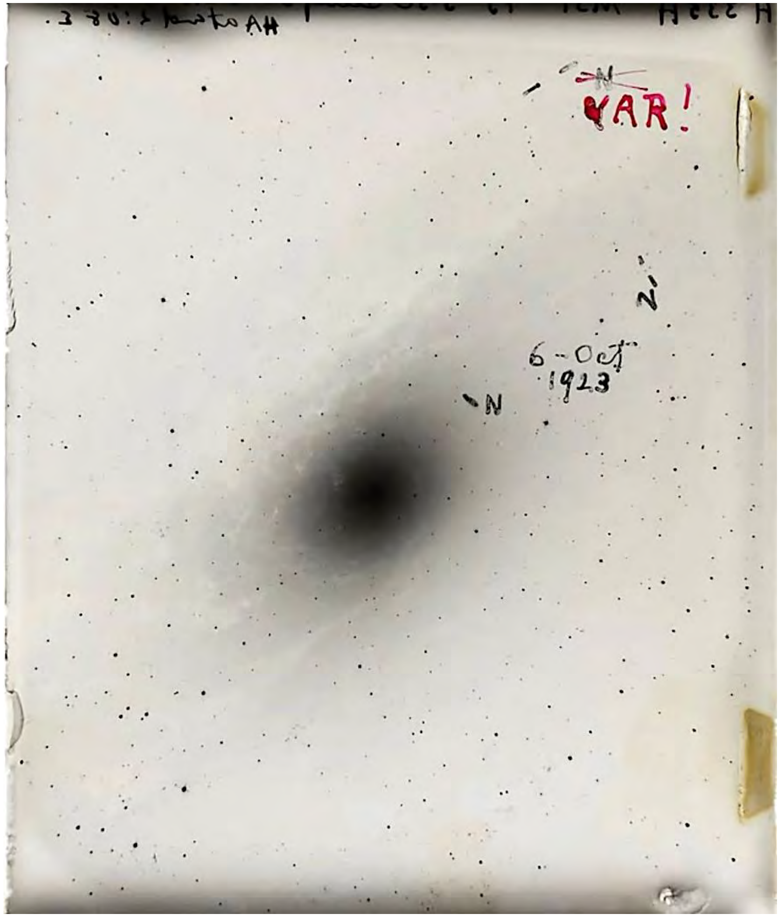


He found out that they are concentrated around a point about 30,000 light years from the Sun, which he correctly assumed was the center of the Milky Way galaxy

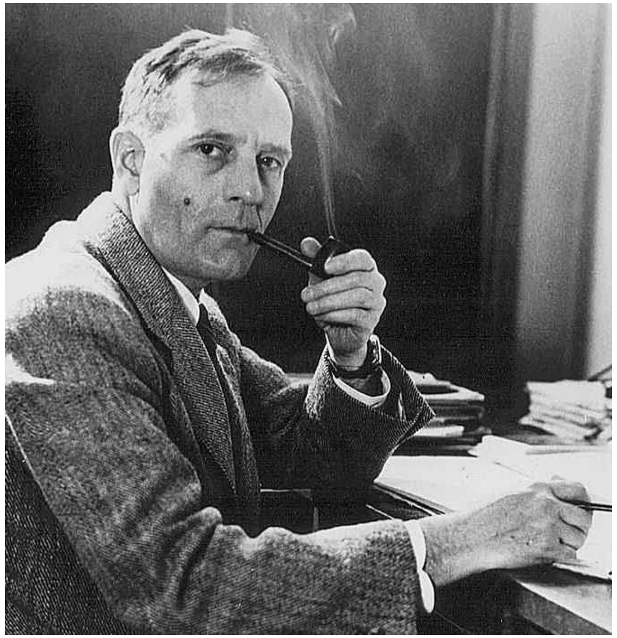
He estimated that the diameter of the Milky Way is about 100,000 light years, about 10 times larger than previously thought

But he also believed that the Milky Way is the *entire universe*

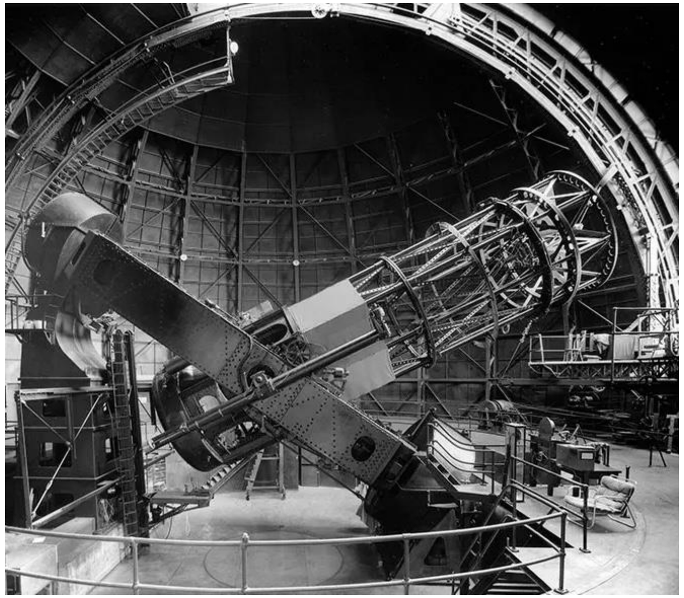
Hubble Determines the Nature of Galaxies



In 1923, Edwin Hubble at Mt. Wilson Observatory obtained a photographic plate of M31, on which he identified a Cepheid

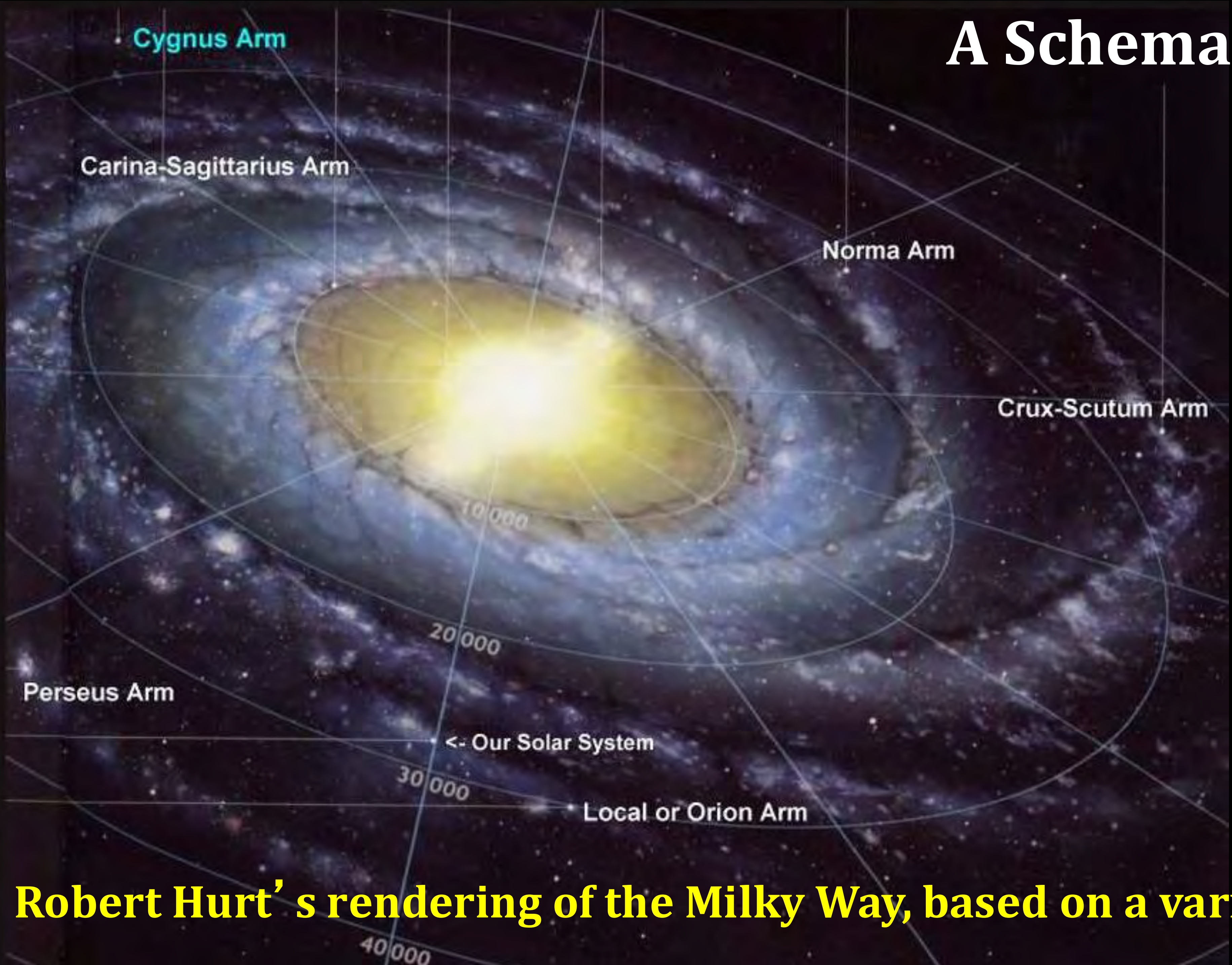


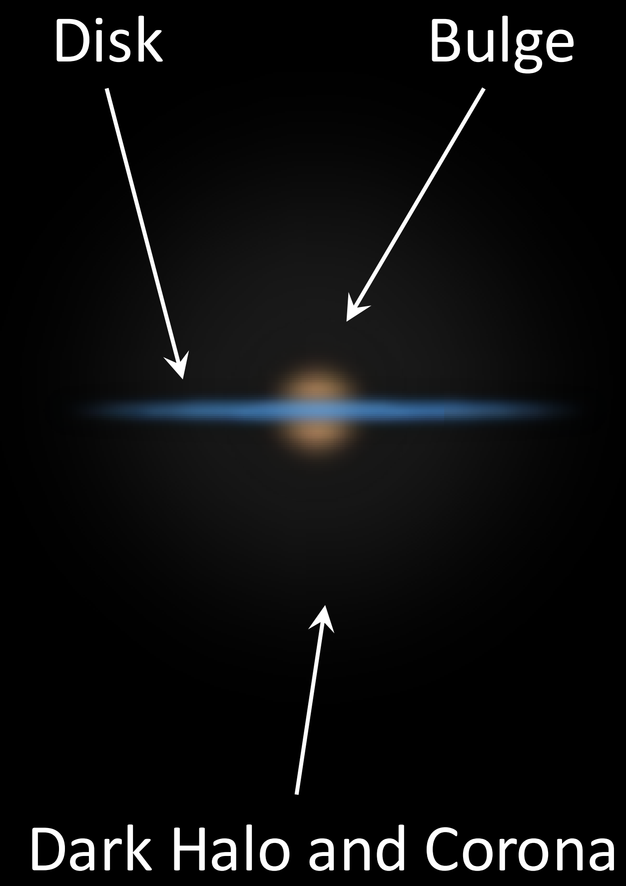
From measuring its period, he inferred the distance to M31 of 930,000 light years, and thus far outside the Milky Way



This resolved the debate: *galaxies are comparable to the Milky Way, which is only one of many, and the universe is much, much larger than it was believed*

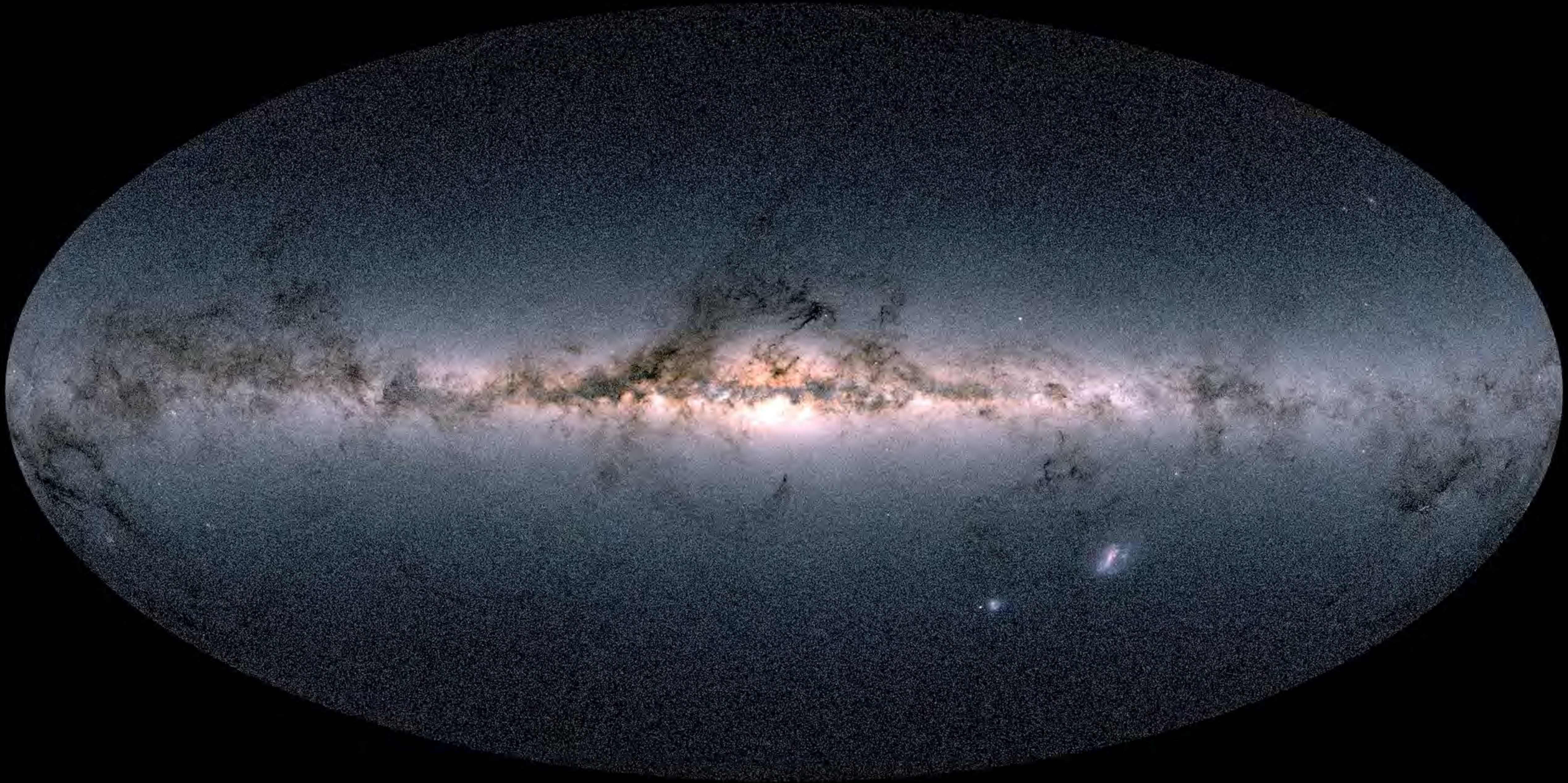
A Schematic View of the Milky Way



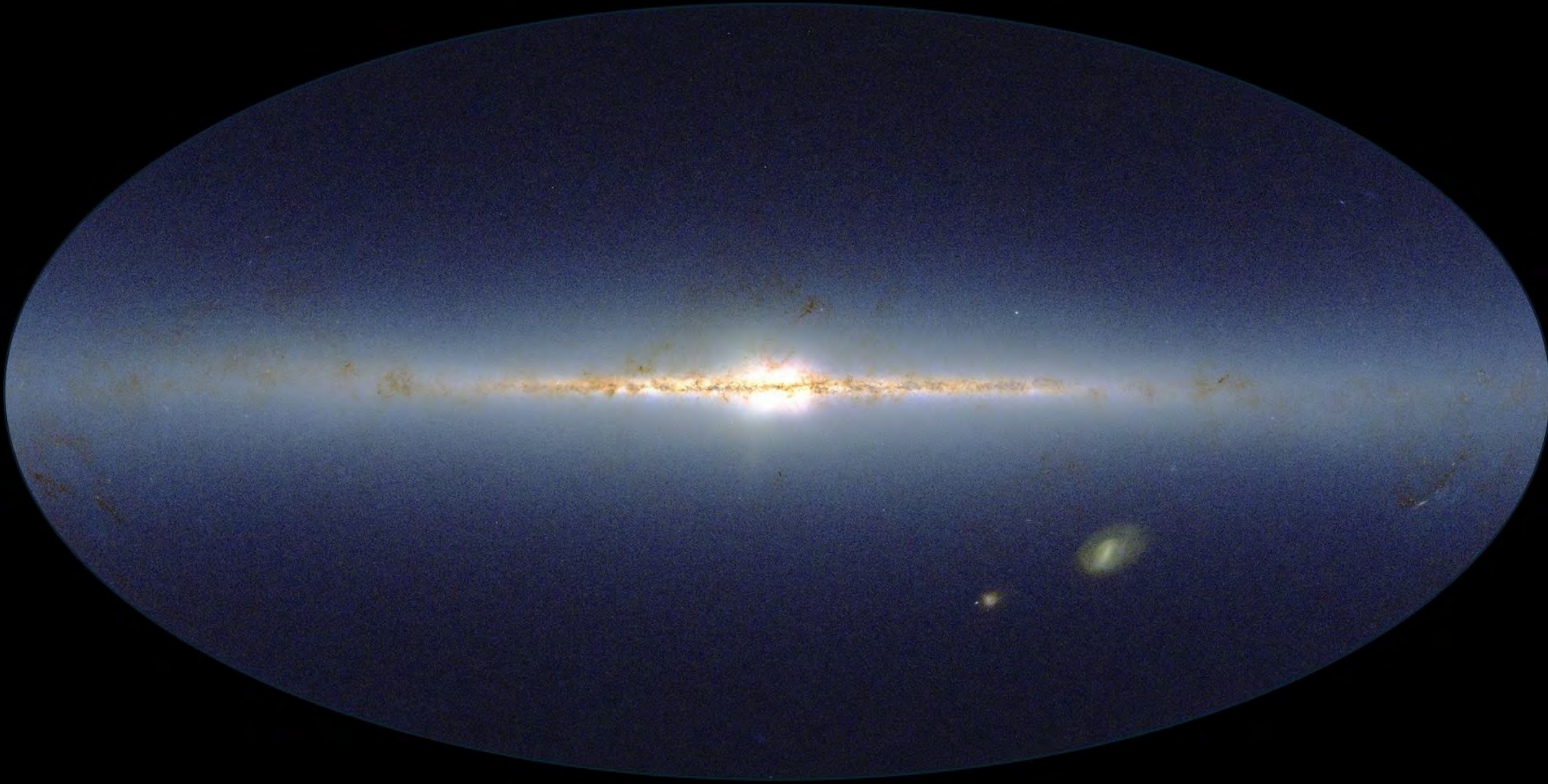


Robert Hurt's rendering of the Milky Way, based on a variety of modern data

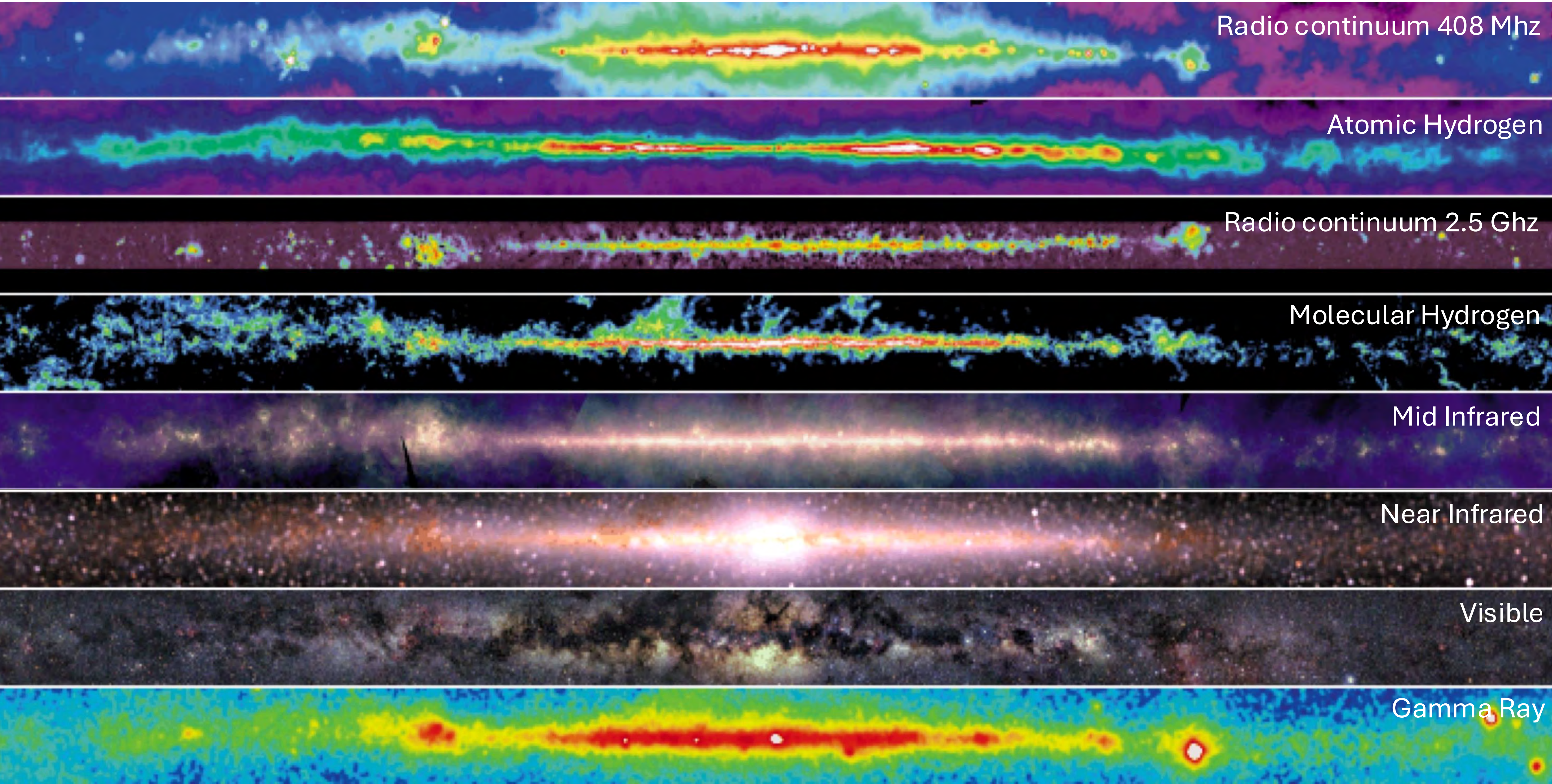
Gaia View of the Milky Way in the Visible Light



2MASS View of the Milky Way in the Near IR



Milky Way Plane: a Panchromatic View



Major Components of the Galaxy

The disk: thin, roughly circular disk of stars with a coherent rotation about the Galactic center

$$L_{disk} \approx 15-20 \times 10^{9} L_{sun}$$

$$M_{disk} \approx 6 \times 10^{10} M_{sun}$$

The **stellar disk** extends to at least 20 kpc from the Galactic center. Density of stars falls off ***exponentially***, both radially and vertically:

$$n(R) \propto e^{-R/h_R}$$

disk scale length: $h_R \sim 3 \text{ kpc}$

Most of the stars (95%) are in a young, **thin disk,** with a vertical scale height of ~ 300 pc. The rest form an older, **thick disk** with a vertical scale height of ~ 1 kpc. They share the same central Galactic plane

A **thin gas disk** (mostly H I, also H II, dust) is where all star formation happens

Major Components of the Galaxy

- **The bulge**: central, mostly old, but metal-rich spheroidal stellar component. Most kinetic energy is in random motions

  $$L_{bulge} \approx 5 \times 10^9 L_{sun}$$

  Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius

  $$M_{bulge} \approx 2 \times 10^{10} M_{sun}$$

- **The bar**, an ellipsoidal component superposed on the bulge

- **The halo**, containing:

  ★ *Stellar halo (field stars)*: low density, old, metal poor, random motions; total mass ~10^9 $M_{\odot}$

  ★ *Globular clusters*. A few % of the total halo stellar content

  ★ *Gas corona* with T ~ 10^5 - 10^6 K. Total mass unknown

  ★ *Dark matter halo*. Physical nature unknown. About 90% of the total mass

Where Do They Come From?

- **The thin disk**: stars formed out of the thin gas disk, it gets gradually puffed up (thicker) due to dynamical effects
- **The thick disk**: it could be a thin disk that was dynamically heated by minor mergers with other galaxies
- **The bulge**: the original, self-enriched stellar population that formed at the bottom of the galaxy's potential well
- **The bar**: formed from the disk material due to a dynamical instability, that funnels out the gas, and ceases the star formation
- **The stellar halo**: debris from the tidal disruptions of dwarf galaxies and globular clusters
- **The halo gas:** ejected by supernovae ("Galactic fountain")
- **The dark halo:** collapse of density fluctuations in the early universe, the original "container" for galaxy building

The Concept of Stellar Populations

- Originally discovered by Walter Baade, who came up with two populations in 1952:

  Pop. I: *young stars in the (thin) disk, open clusters*

  Pop. II: *old stars in the bulge, halo, and globular clusters*

  (Added later: ***Pop. III:*** *the first stars in the first galaxies, made from H and He only)*

  - Today, we distinguish between the old, metal-rich stars in the bulge, and old, metal-poor stars in the halo
  - Pop. I also has a range of ages and metallicities: young thin disk, vs. thick disk

- A good modern definition of stellar populations:

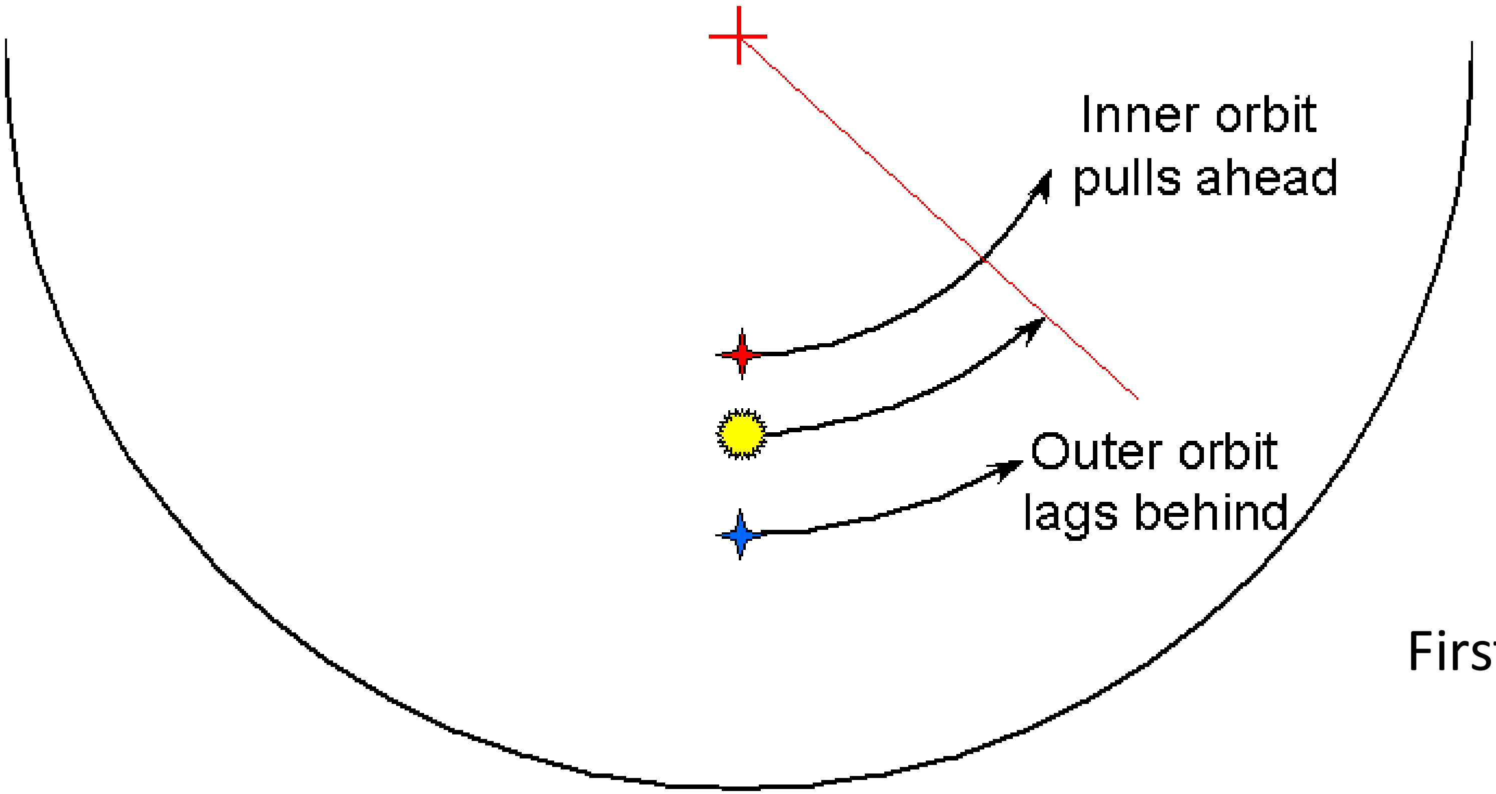
  Stellar sub-systems within the Galaxy*, distinguished by density distributions, kinematics, chemical abundances, and presumably formation histories. Could be co-spatial, sharing the same gravitational potential well*

Stellar Halo Is…

A. Younger than the Galactic disk
B. Composed of metal-poor stars
C. Composed of metal-rich stars
D. The same thing as the bulge
E. Has a mass $\sim 10^9\ M_\odot$
F. Rotating rapidly

Galaxy Has a Differential Rotation:

Constant Linear Velocity, Angular Velocity Declines Outwards



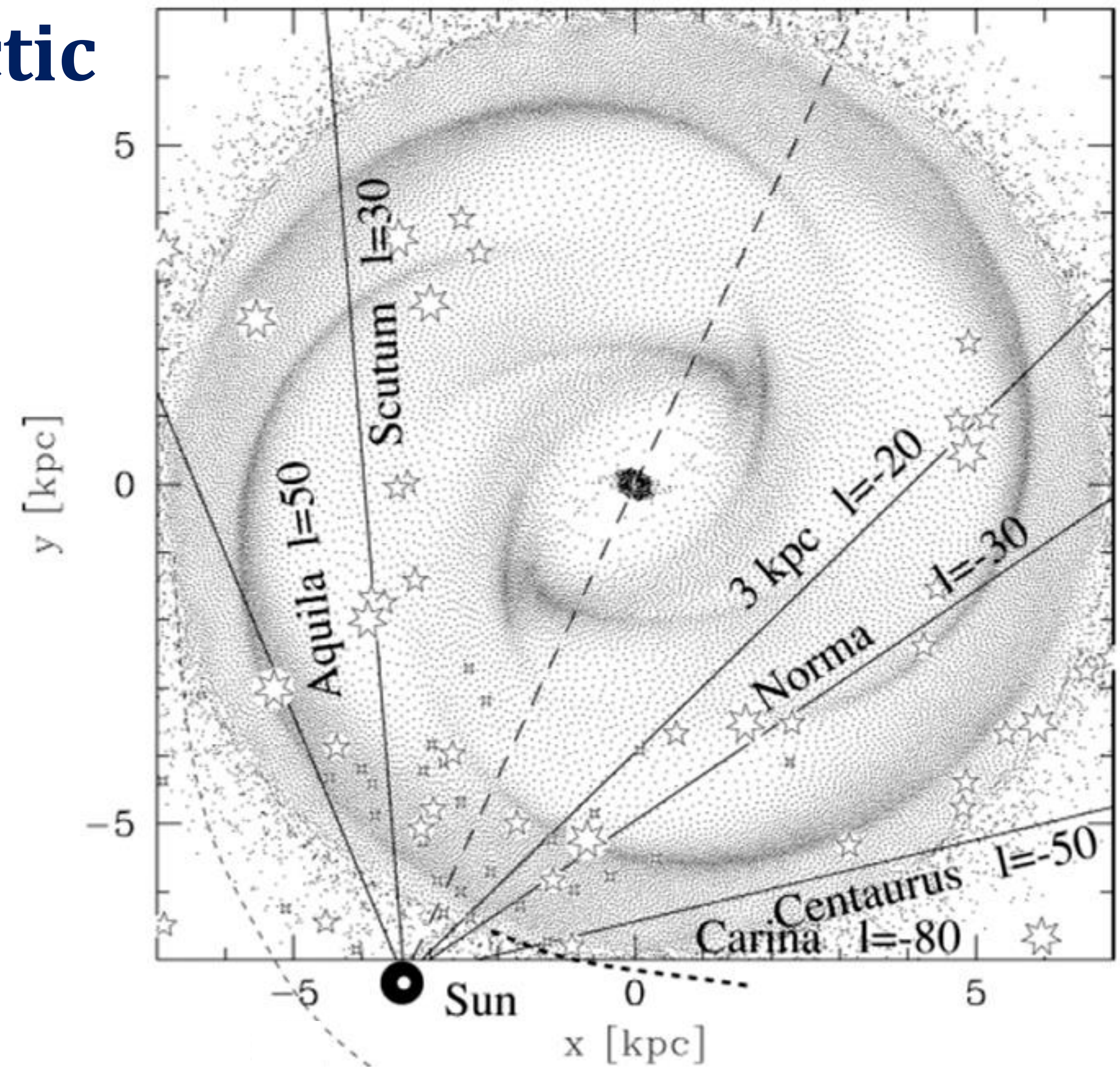
First quantified by Jan Oort (1900-1992), along with many other discoveries

Locally, we can use stellar velocities, but to measure the ***global kinematics*** of the Galaxy, and thus map its rotation, we use the H I 21 cm line, as it penetrates through the dust

Measuring the Galactic Rotation Using H I

Along every line of sight in the Galactic plane, we can measure the H I intensity as a function of the **radial velocity**

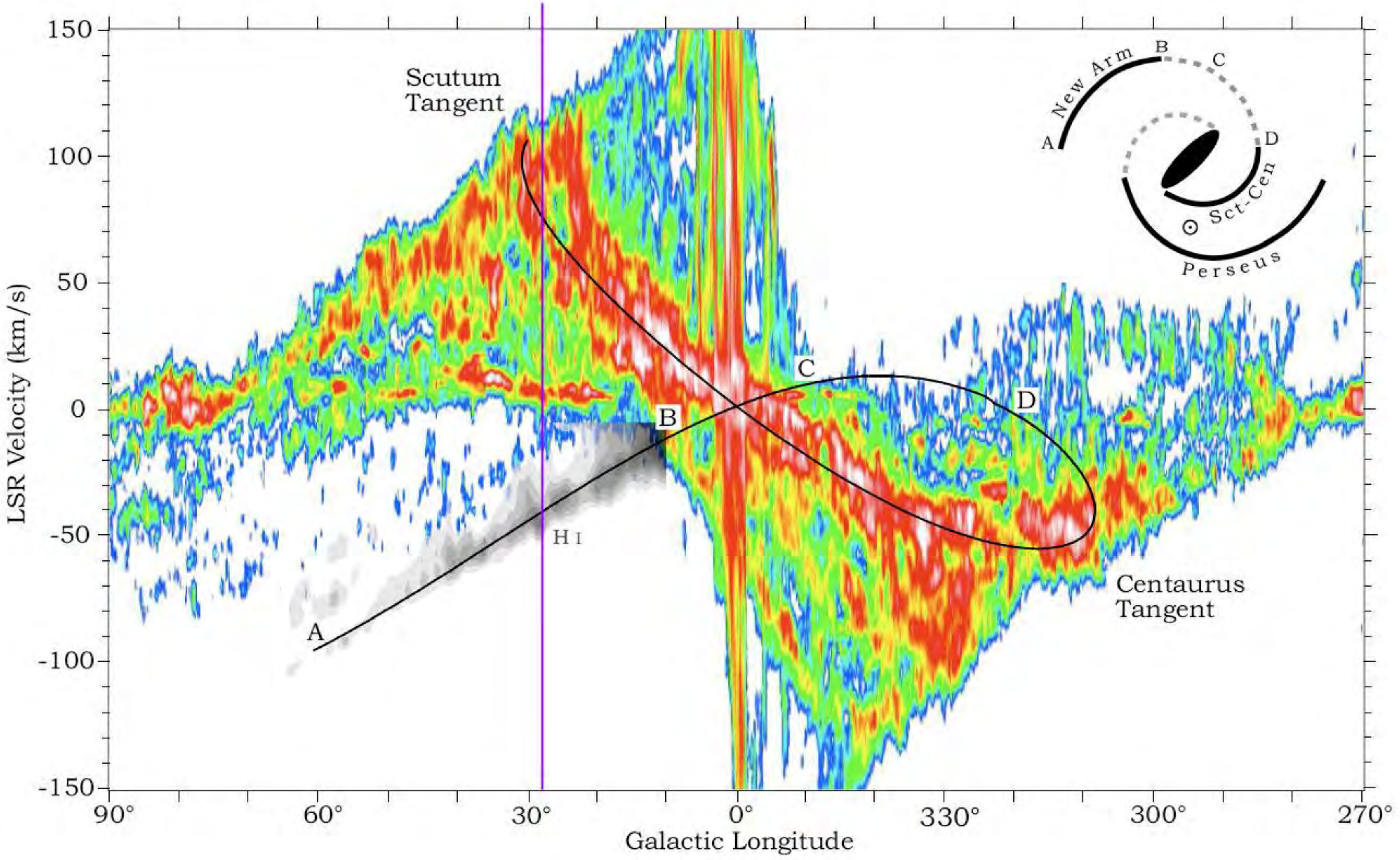
To get the **distances**, we have to associate objects like star clusters to which we can measure distances, that are associated with the concentrations of the gas



The Longitude-Velocity Diagrams

Along every line of sight we see the gas at different distances and with different velocities

They have to be disentangled using models of Galactic rotation



Velocities + distances can then be used to construct the models of the differential rotation, as well as the locations of the spiral arms

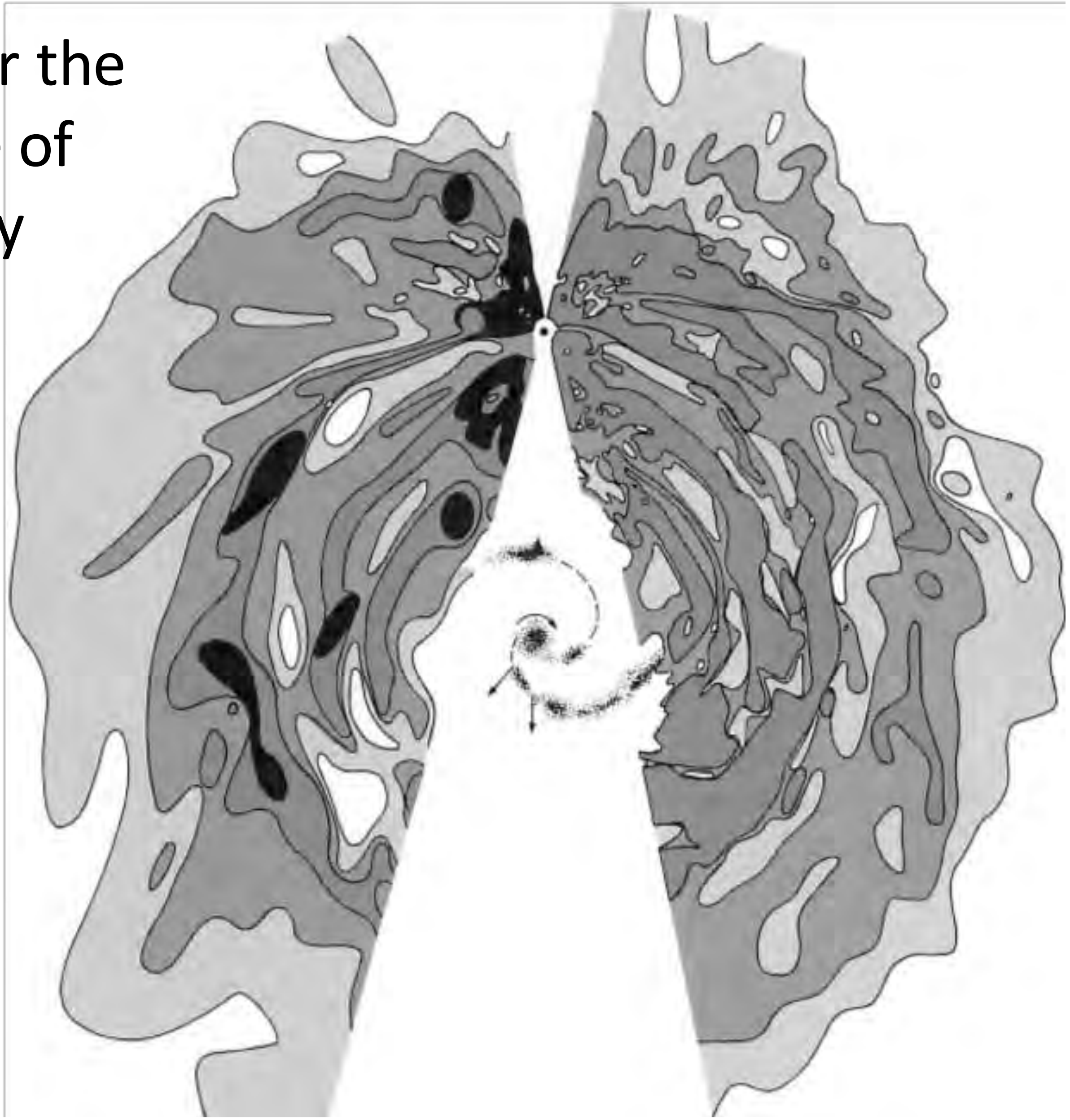
Mapping the Milky Way and Its Kinematics

The development of radio astronomy after the WW2, and the discovery of the 21 cm line of H I, enabled the mapping of the Milky Way independent of the optical extinction

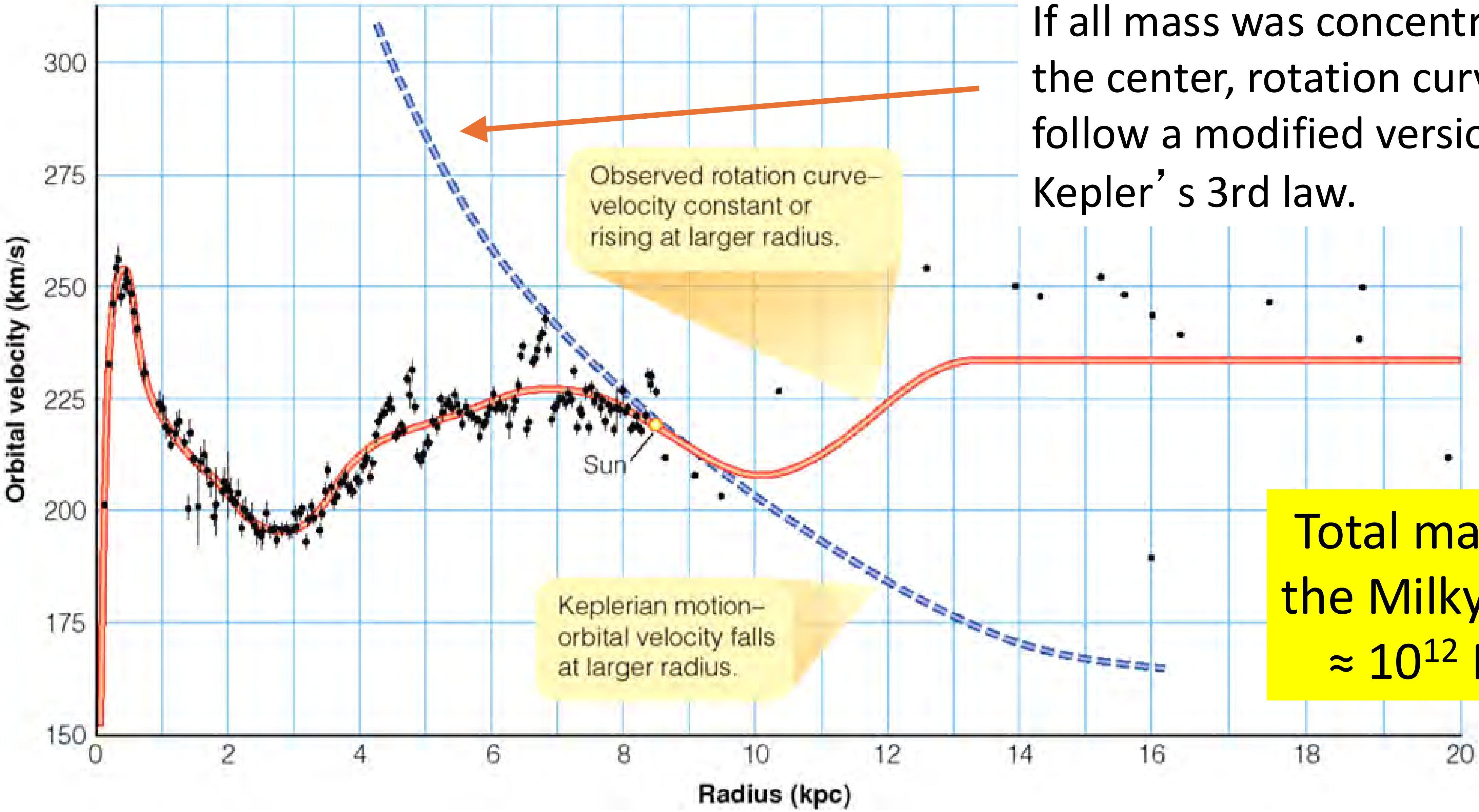
That also enabled the measurements of the global kinematics and rotation of the Milky Way (Jan Oort et al. 1958)

Until then, only the local kinematic of stars could be measured

The first H I map of the Galaxy →



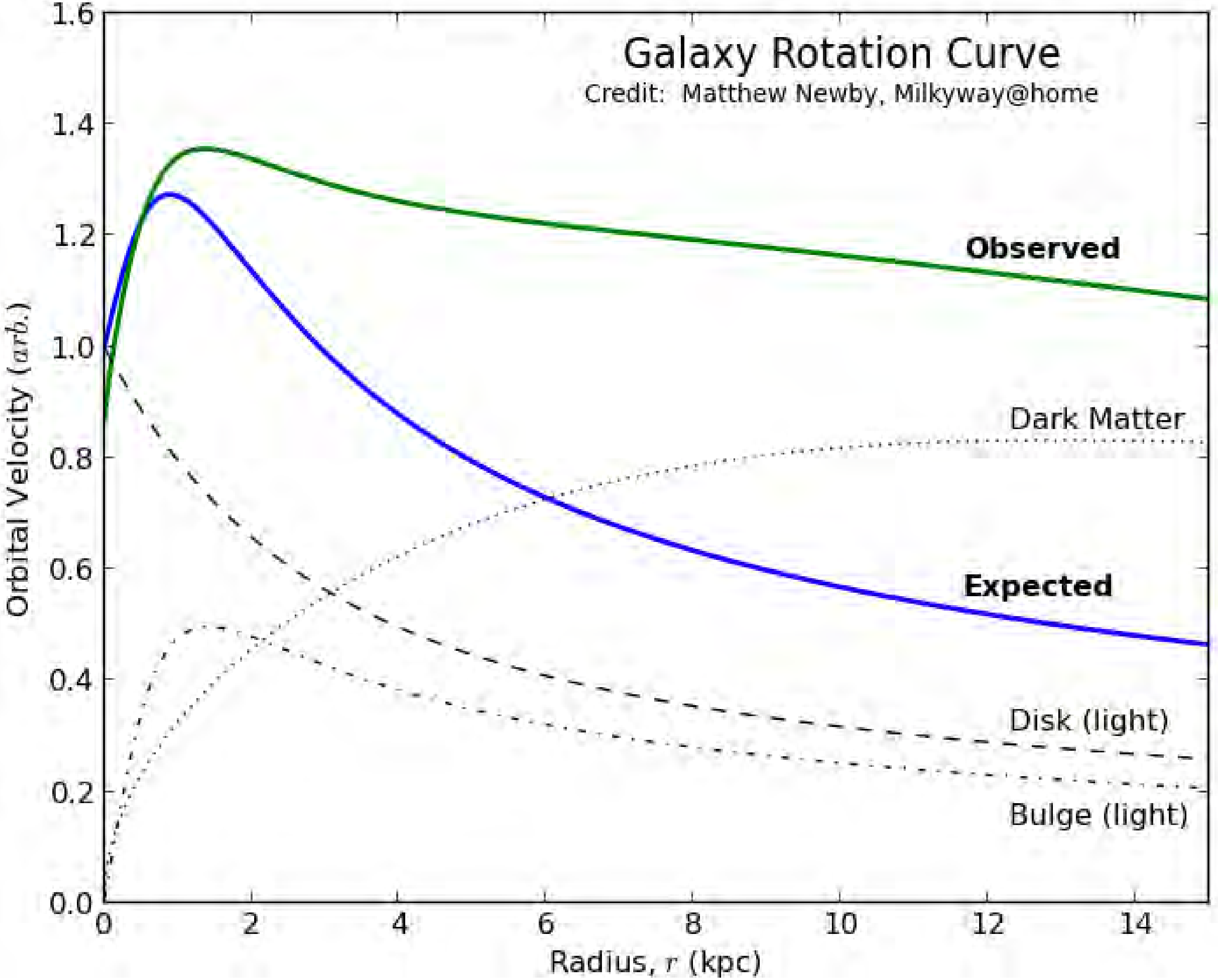
The Observed Rotation Curve of the Milky Way



If all mass was concentrated in the center, rotation curve would follow a modified version of Kepler's 3rd law.

Total mass of the Milky Way $\approx 10^{12}\ M_\odot$

Rotation Curve and the Dark Halo

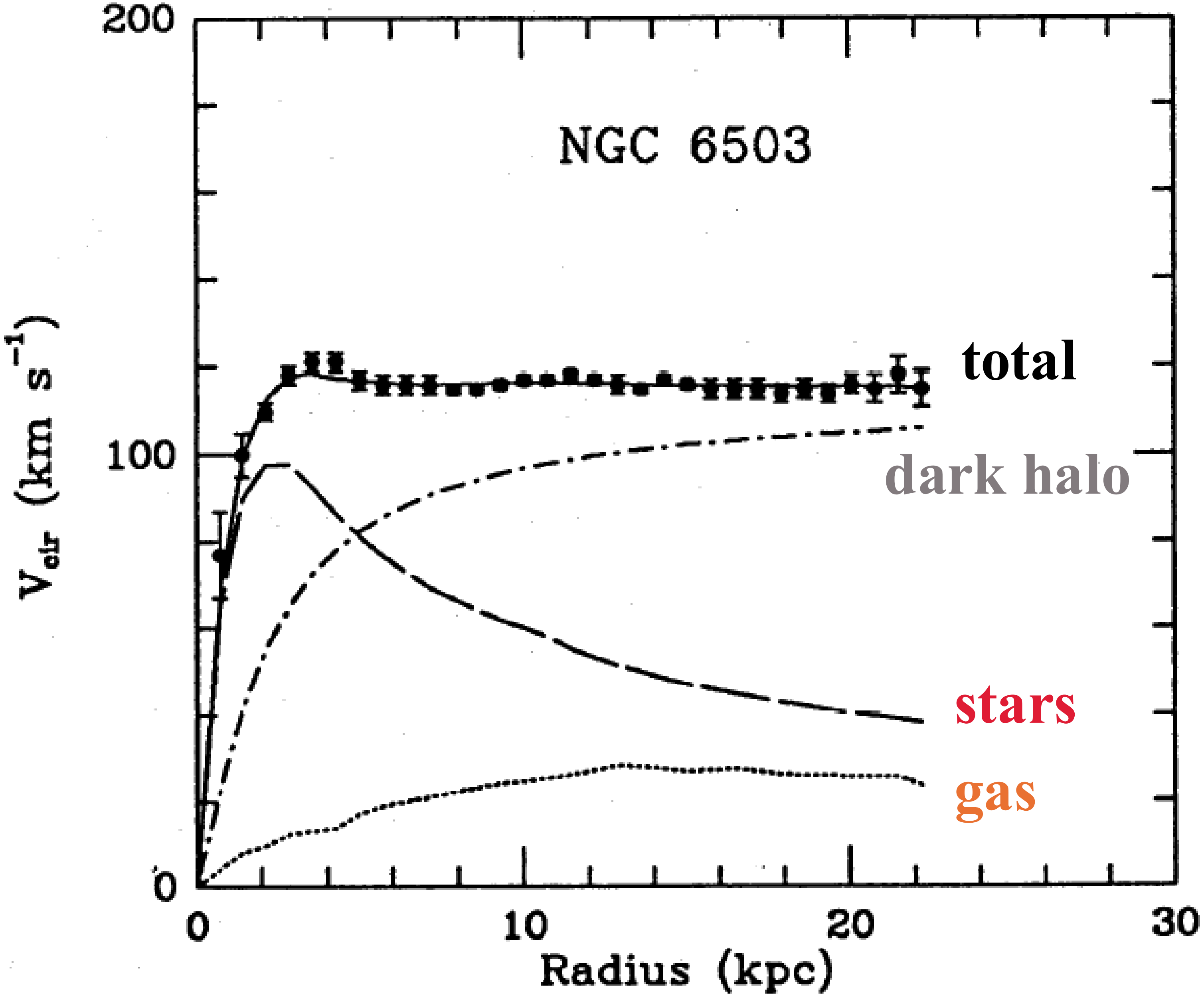


Rotation speed tells us how much mass there is within a given radius: *centrifugal force must balance the gravity*

But visible mass of gas and stars is *insufficient* to account for the observed rotation speeds

Therefore, an *additional mass component* must be present: **the dark halo**

This is Also Observed in Other Spiral Galaxies



Note:

Dark Matter dominates at large radii

It cannot be concentrated in the disk, as it would make the velocity dispersion of stars too high

Thus it must be have a more spheroidal distribution

Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular, the only component of velocity that matters is the tangential one, V_T, and other velocity components are much smaller (V_R and $V_Z << V_T$)

Define the circular velocity at radius r in the galaxy as $V(r)$. The centrifugal acceleration of the star moving in a circular orbit must be balanced by the gravitational force:

$$mV^2(r) / r = G\, m\, M(r) / r^2$$

Where $M(r)$ is the enclosed mass within r

$$V^2(r) = G\, M(r) / r$$

In the Keplerian case, all the mass is in the center, $M = const.$

Thus: $V(r) \sim r^{-1/2}$

But if the rotation curve is flat, $V(r) = const.$, $M(r) / r = const.$
so the enclosed mass increases linearly with the radius, $M(r) \sim r$

Mass Distribution and the Rotation Curve

If $M(r) \sim r$, then also $dM(r) \sim dr$ and $dM / dr = const.$

The enclosed mass increment is: $dM(r) = 4\,\pi\, r^2\, \rho(r)\, dr$

$$dM/dr = 4\,\pi\, r^2\, \rho(r) = const.$$

Thus: $\rho(r) \sim r^{-2}$

The **dark halo density profile**

This is called a ***singular isothermal sphere***. *Singular* since $\rho \longrightarrow \infty$ as $r \longrightarrow 0$ (obviously this does not happen in reality), and *isothermal* since $mV^2/2 = 3/2\, k_B T = const.$

If $M(r) \sim r$, then $M \longrightarrow \infty$ as $r \longrightarrow \infty$, and it must cut off at some point

Data and theory indicate that this happens by ~ 100 kpc

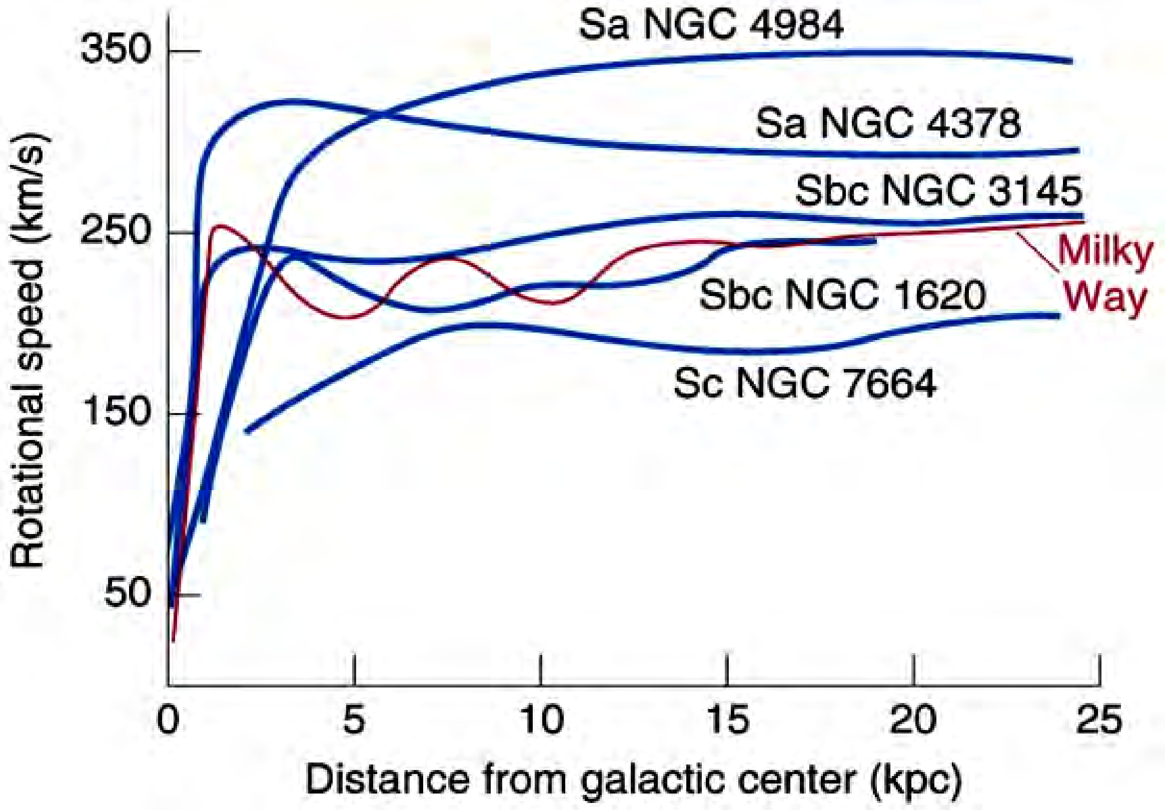
Flat Rotation Curves of Disk Galaxies:

A Key Piece of Evidence for the Existence of Dark Matter

Dark matter (DM) was discovered in 1937 by **Fritz Zwicky**, who noted that the velocities of galaxies in the Coma cluster implied the existence of an additional "dark" matter needed to bind the cluster

Fritz Zwicky

But it was the **rotation curves of disk galaxies** really convinced everyone in the 1970s, due to the work by **Vera Rubin**, Kenneth Ford, Ken Freeman, Mort Roberts, and others



There were also theoretical reasons (stability of spiral galaxies, large-scale structure)

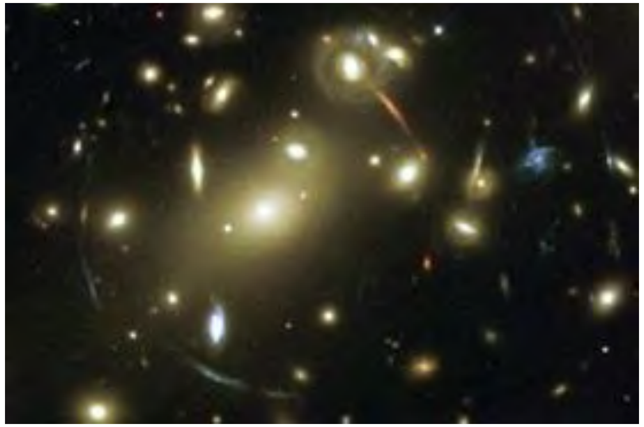
The nature of DM remains as an outstanding challenge

Vera Rubin

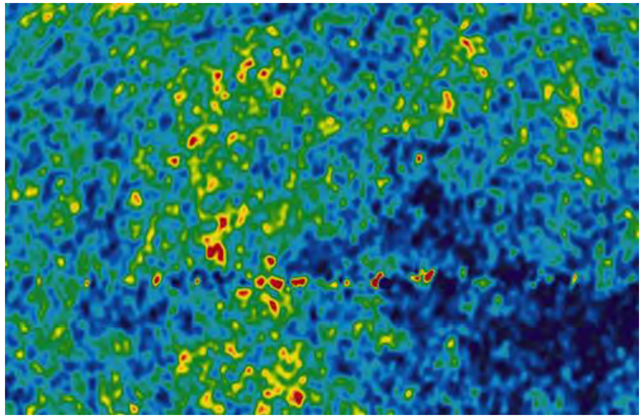
Other Evidence for the Dark Matter

X-ray gas in galaxy clusters: too hot to be explained by the gravity of the visible matter alone. Galaxy motions within clusters are also too fast to be accounted for by the visible mass alone

Gravitational lensing: implies the existence of an unseen mass component – and exactly the amount required by the kinematical measurements



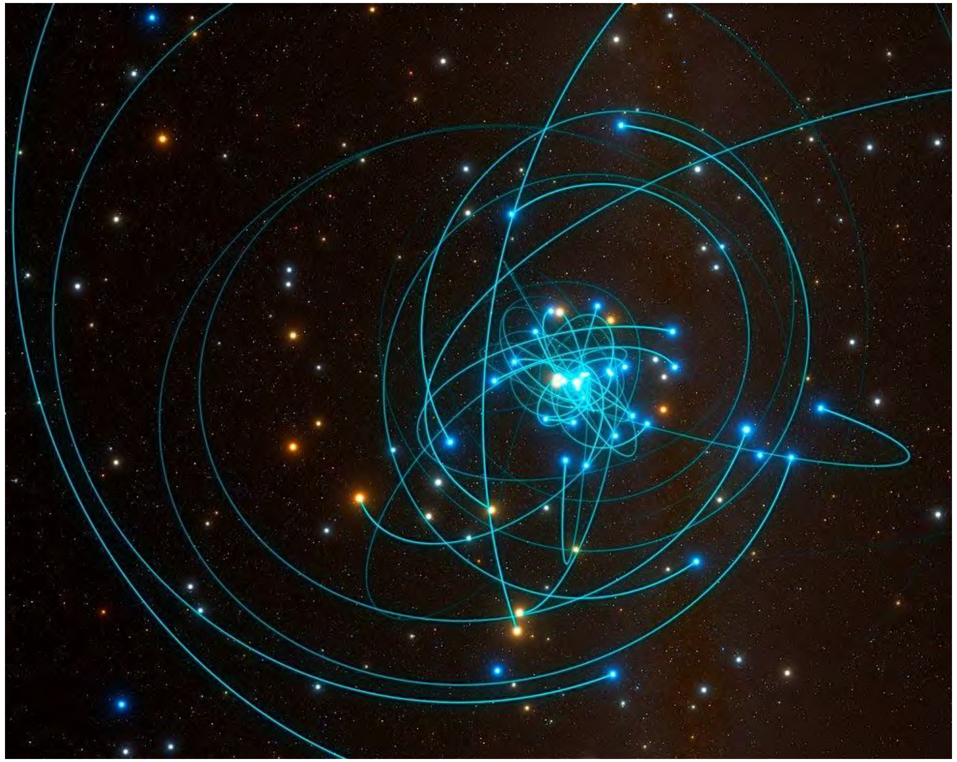
Cosmic Microwave Background fluctuations: also require a substantial non-baryonic dark matter component

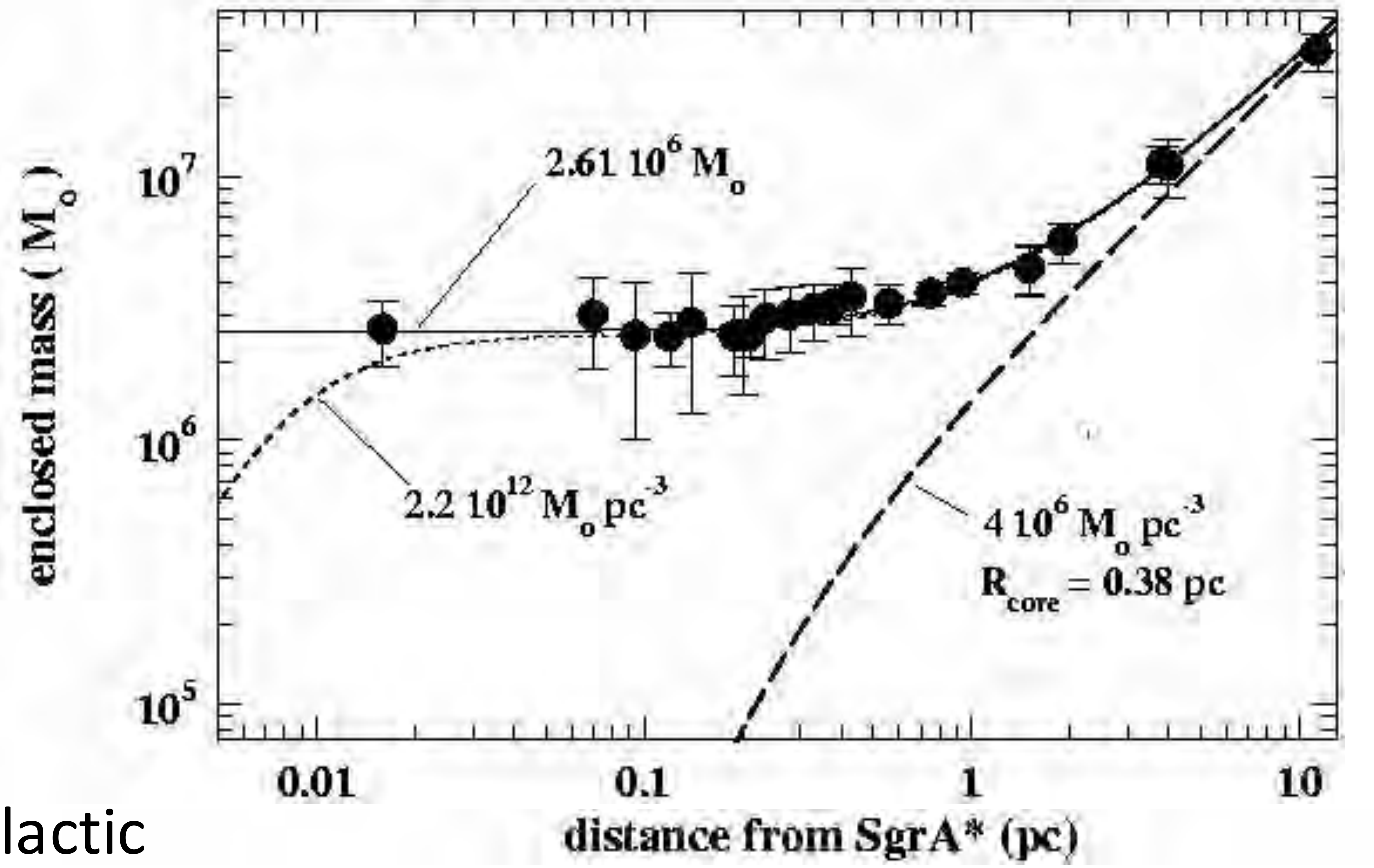


Large-scale structure formation and evolution also needs a substantial amount of dark matter

… and all of them agree

Dynamical Evidence for a Supermassive Black Hole at the Galactic Center





From the motions of stars near the Galactic center, acting as test particles probing the gravitational field. An improved measurement gives the mass of $M_\bullet = 4.1 \times 10^6 M_\odot$

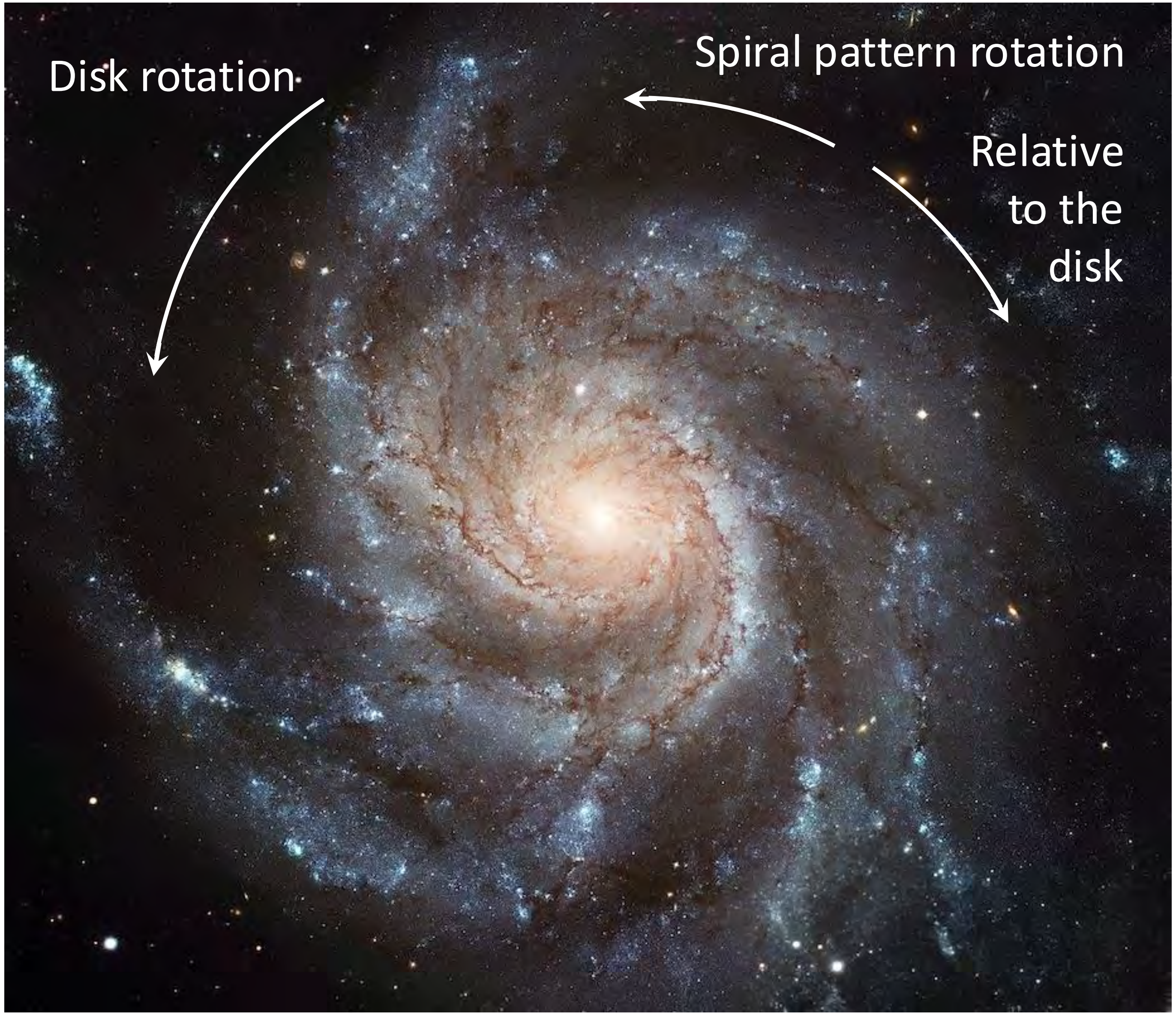
Nobel Prize in Physics 2020 to A. Ghez and R. Genzel

Spiral Arms

Defining feature of spiral galaxies - what causes them?

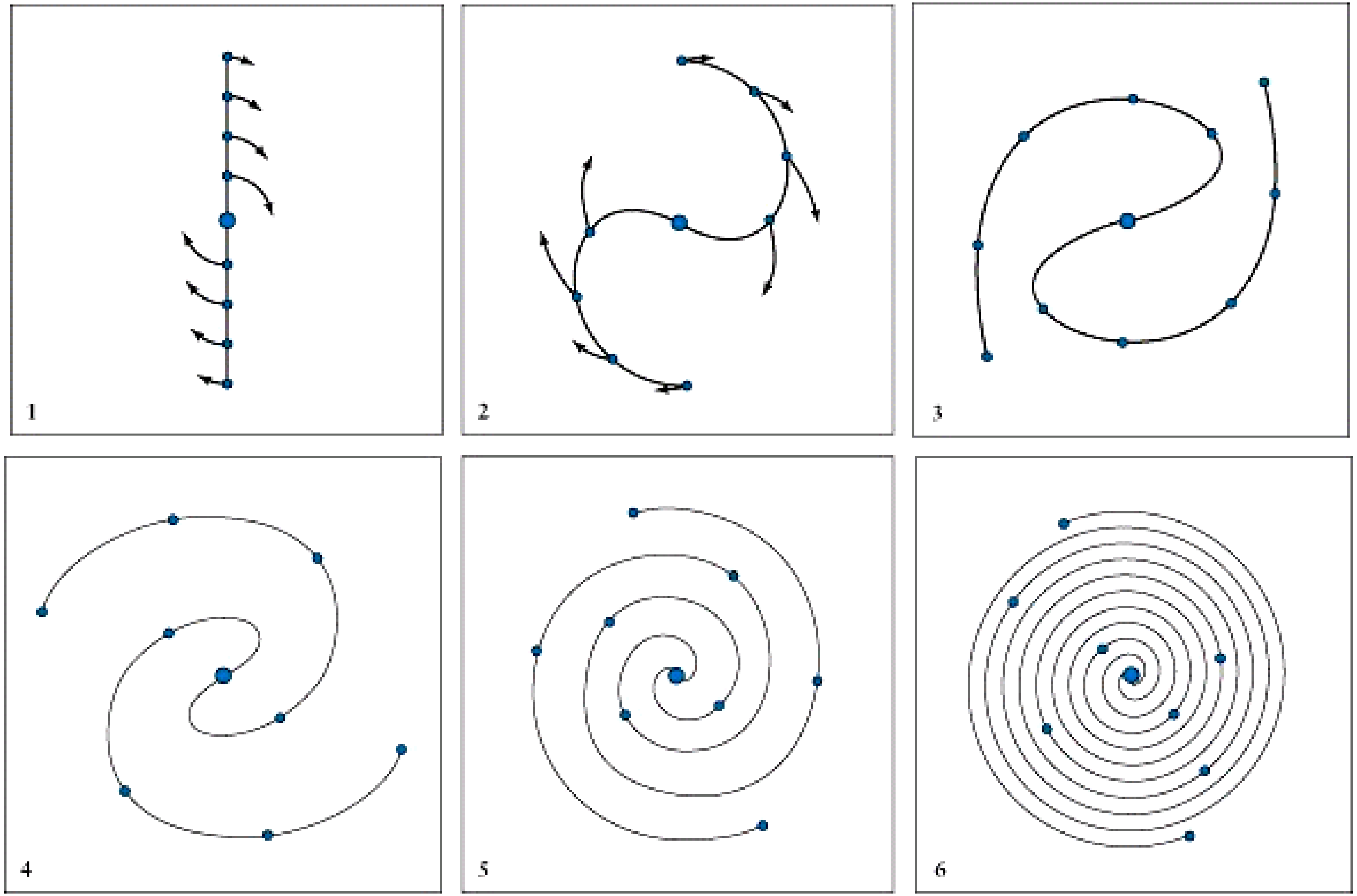
Observational clues:

- Seen in disks that contain gas, but not in gas poor S0 galaxy disks
- Defined mainly by blue light from hot massive stars, whose lifetime is << galactic rotation period
- When the sense of the galactic rotation is known, the spiral arms pattern rotates with half the angular speed of the disk



The Winding Dilemma

Differential rotation could turn an initial radial feature into an ever tighter spiral one:

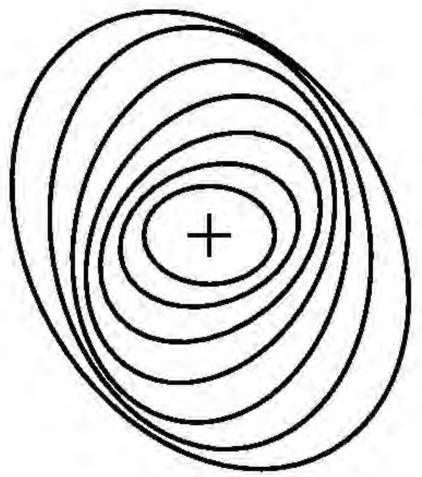


But this is <u>not</u> why galaxies have spiral arms!

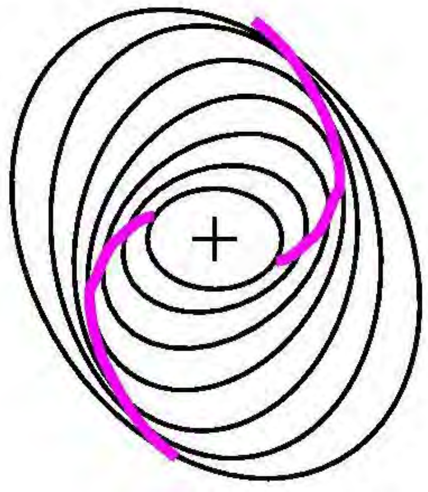
Because spiral arms seem to be **persistent**

Spiral Density Waves

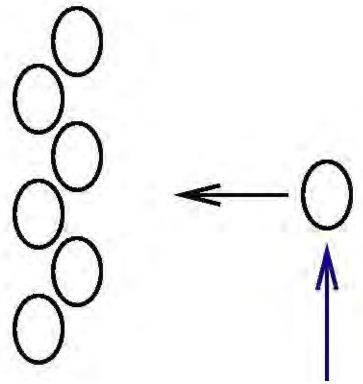
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other



- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

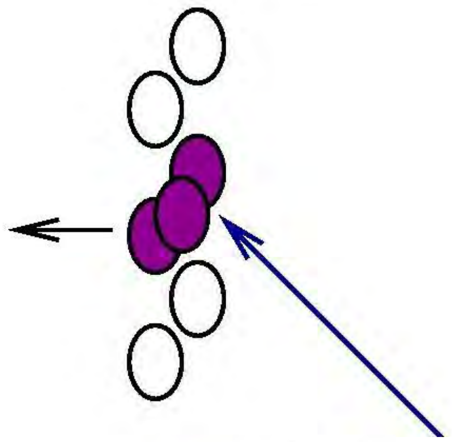


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them, and then get compressed as they encounter other clouds

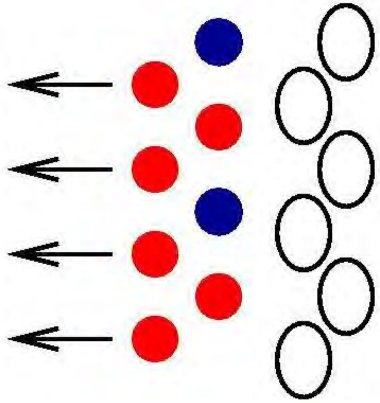


Spiral Density Waves and Star Formation

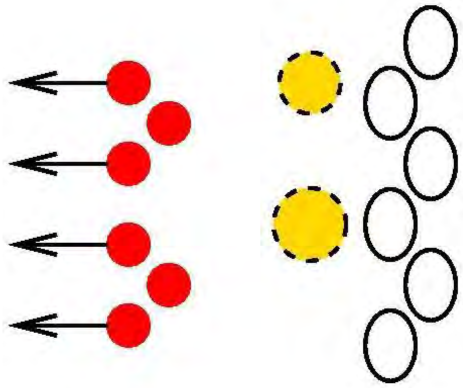
- When the gas cloud collides with other gas clouds, stars will be formed. This is where most of the star formation takes place



- Newly formed stars, including the luminous OB stars will continue to drift through the region



- The brightest and bluest, OB stars explode within a few million years, and thus don't go far from the spiral arm where they were born



Note the dust lanes that mark the denser, compressed regions of the ISM along the inner edges of the spiral arms

And the resulting star formation regions along the outer edges

Star Formation in Spiral Arms

- Spiral density wave creates spiral arms by the gravitational attraction of the stars and gas flowing through the arms
- Even if there was no star formation, there would be spiral arms - but star formation makes them more prominent
- This can explain the so-called ***"grand design" spirals***
- Star formation can ***self-propagate*** in a differentially rotating disk, e.g., as supernova shocks compress neighboring molecular clouds
- This may be responsible for the branches and spurs in the spiral arms, or disks without evident spiral density waves (the so-called ***flocculent spirals***)

Galaxy Bars

- They are due to a **dynamical instability** in differentially rotating galaxy disks
- Very common: occur in ~50% of all spirals (MW included)
- Isophotes not fit by ellipses; more **rectangular**, probably **flat** in disk plane
- Bars are **straight**, and stars **stay in the bar** rigid rotation of pattern
- Bars are **not** density waves: Stars **move along the bar** on closed orbits in frame rotating at a constant angular speed

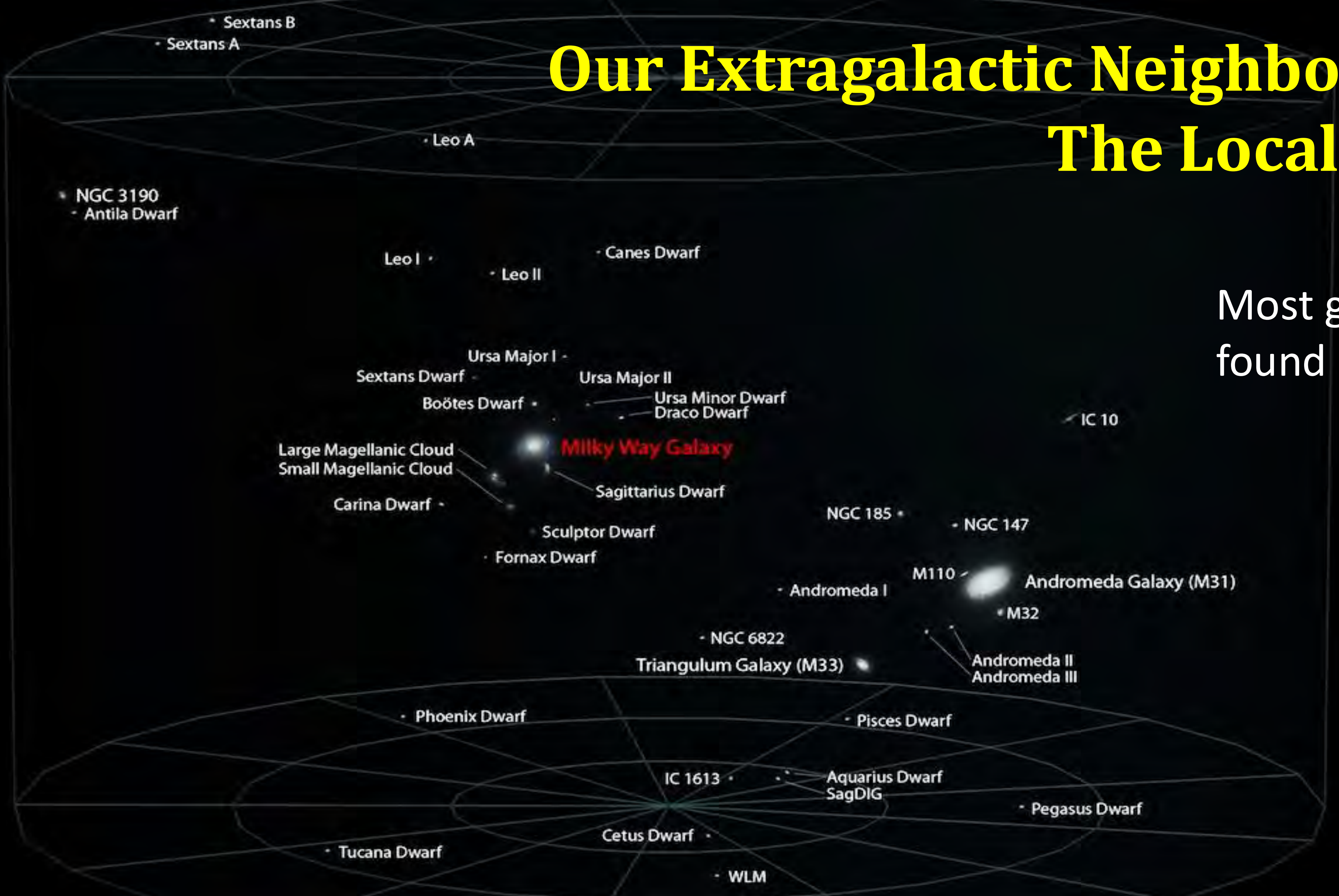
- But they can *drive a density wave in disk* and help maintain spiral structure, and also funnel gas to the center, where it could feed an active nucleus

Spiral Arms…

A. Wind up ever tighter
B. Last a long time
C. Are density waves
D. Do not depend on the differential rotation of the disk
E. Stimulate star formation
F. Are always composed of the young stars and star forming regions

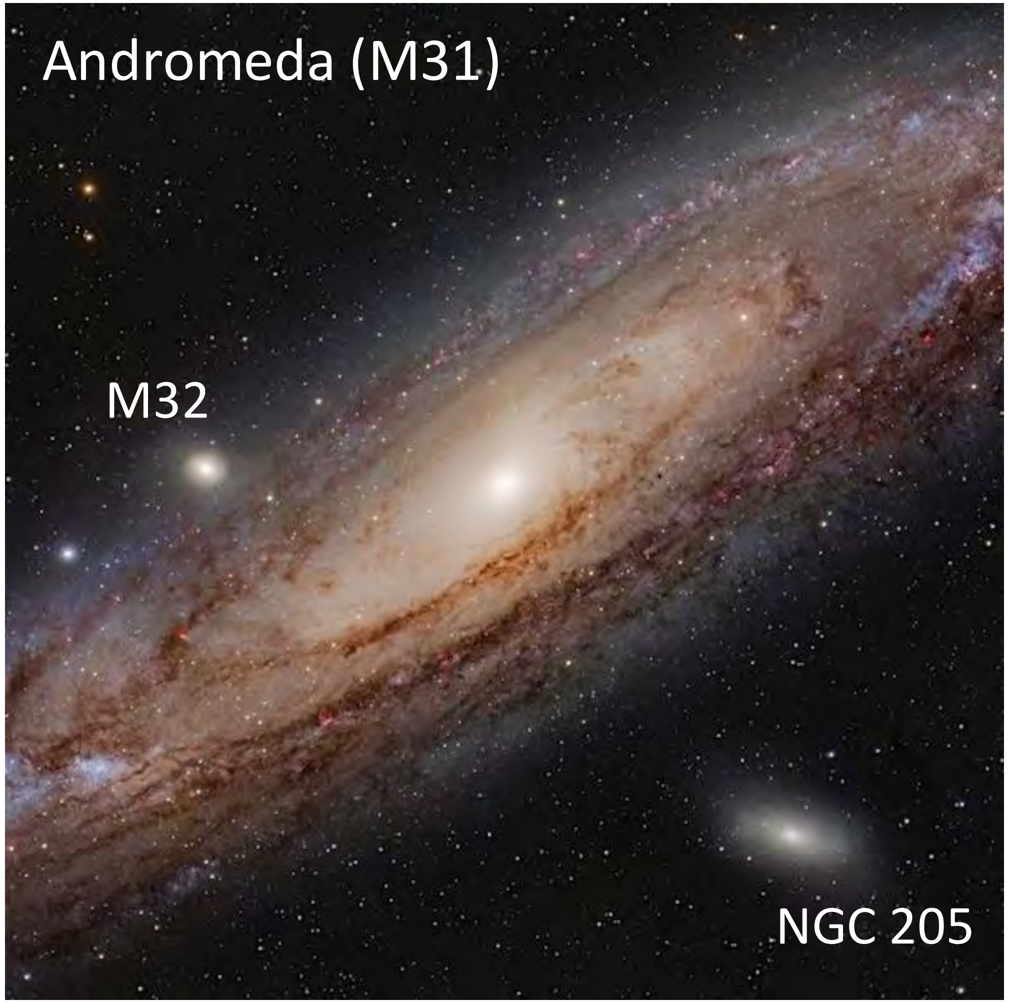
Our Extragalactic Neighborhood: The Local Group

Most galaxies are found in groups



The Local Group

- A collection of nearby galaxies, consisting of:
  - 2 large spirals (the Milky Way and Andromeda)
  - 1 small spiral (M33)
  - 1 small elliptical (M32)
  - A lot of dwarf galaxies of different kinds: Magellanic Clouds, other dwarf irregulars, dwarf spheroidals, … many are still being found
- About 1 Mpc in size (M31 is 700 kpc away)
- Not gravitationally bound (some parts are)
- Part of the Local Supercluster



Disk of M31 resolved into stars ⟶

Some Local Group Members

The Local Group

A. Consists of the Milky Way and its satellite galaxies
B. Consists of the Milky Way and Andromeda, and their satellite galaxies
C. Is 700 Mpc in size
D. Is gravitationally bound
E. Is a part of the Local Supercluster
F. Consists of astronomy groupies

Key Concepts in This Lecture

- **Milky Way** Galaxy is a fairly typical barred spiral, with the Solar system ~ 8 kpc from the center, with the orbital speed of 220 km/s. Its major components are:
  - **Thin stellar disk**, embedded in a **thicker stellar disk**, and with the **gas and active star formation** concentrated towards the disk plane
  - Elliptical-like central **bulge and a bar,** composed of **old, metal-rich stars**
  - Spheroidal, **metal-poor stellar halo**, also containing globular star clusters
  - **Hot gaseous corona** created by Supernova ejecta from the Galactic plane
  - **Dark matter halo**, with a **flat rotation curve**, and density distribution $\rho(r) \sim r^{-2}$ (singular isothermal sphere) that dominates the total mass
  - A supermassive (4 million $M_{\odot}$) black hole in the center
- **Spiral structure** represents **density waves** propagating in a differentially rotating disk. They can compress the molecular gas clouds, causing **star formation**

?