Ay 1 – Lecture 12

Our Galaxy, The Milky Way

Galactic Bulge, ESO

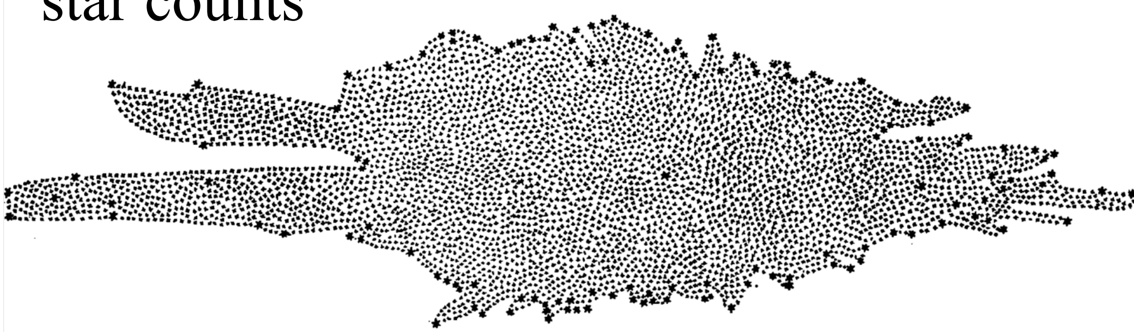
12.1 The Basic Properties and Components of the Galaxy

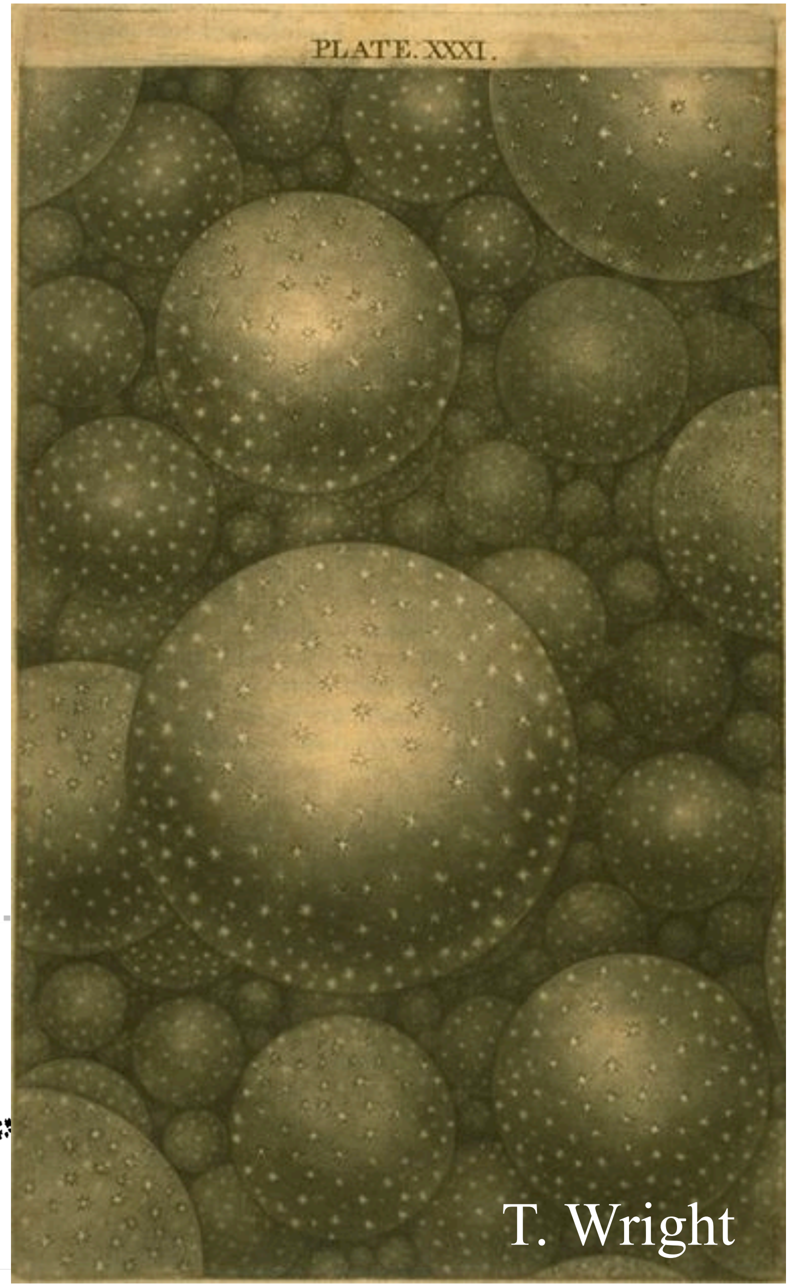
(R. Hurt, IPAC)

The Discovery of Galaxies

- At first, the Milky Way was thought to be *the universe*, not as one of many galaxies
- "Island universes": Thomas Wright, Immanuel Kant, William Herschel
- 19th/20th century: star counts and Galactic structure (Jakobus Kapteyn, Harlow Shapley)

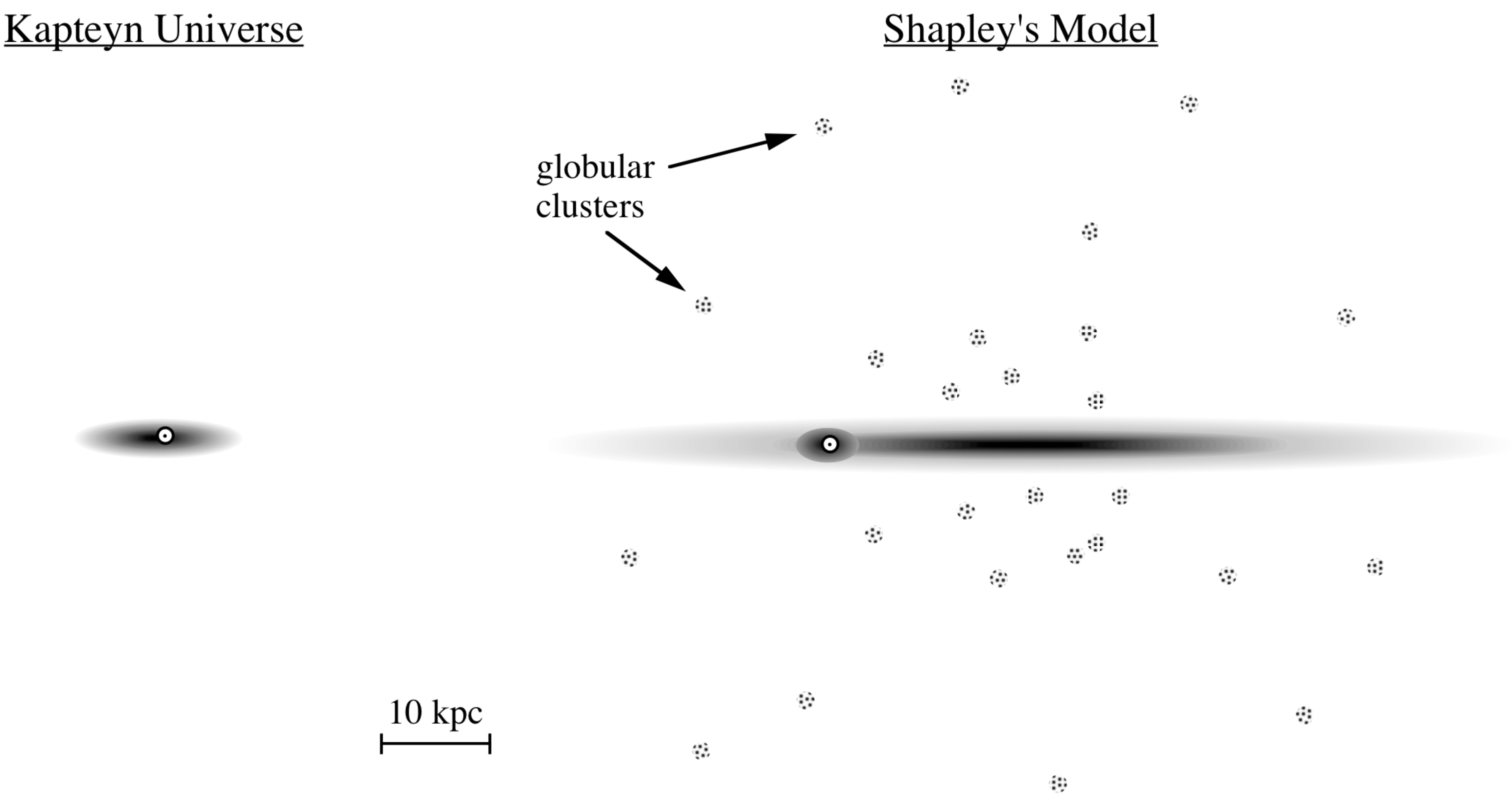
Herschel's sketch of the Galaxy, from his star counts





Expanding the Scale of the Galaxy

Discovery of the interstellar extinction circa ~ 1920's (Trumpler, Shapley) greatly expanded the scale of the Milky Way, and displaced the Sun from its center



The Shapley-Curtis Debate

on the nature of faint nebulae (= galaxies)

At the meeting of the National Academy of Sciences in Washington on 26 April 1920, Harlow Shapley of Mount Wilson and Heber D. Curtis of Lick Observatory gave talks under the title "The Scale of the Universe"

☚ Shapley argued that the nebulae are parts of our own Galaxy, the only one

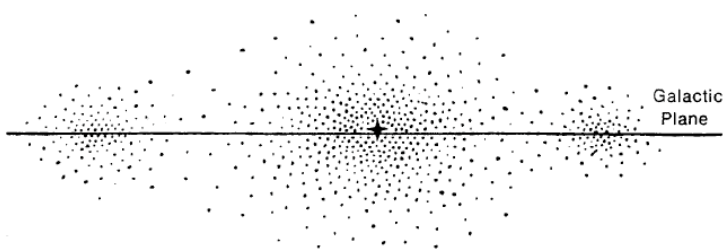
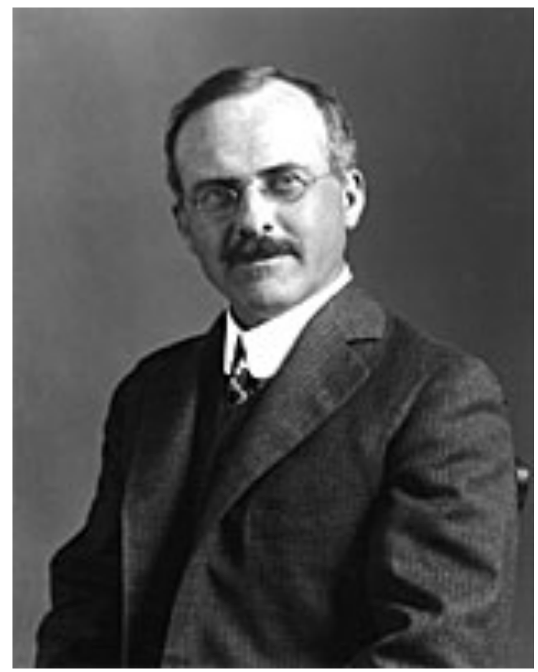


FIG. 3—Arthur Eddington's (1912) galaxy placed the Sun's position 60 LY above the center of the galactic plane.

Curtis ☛

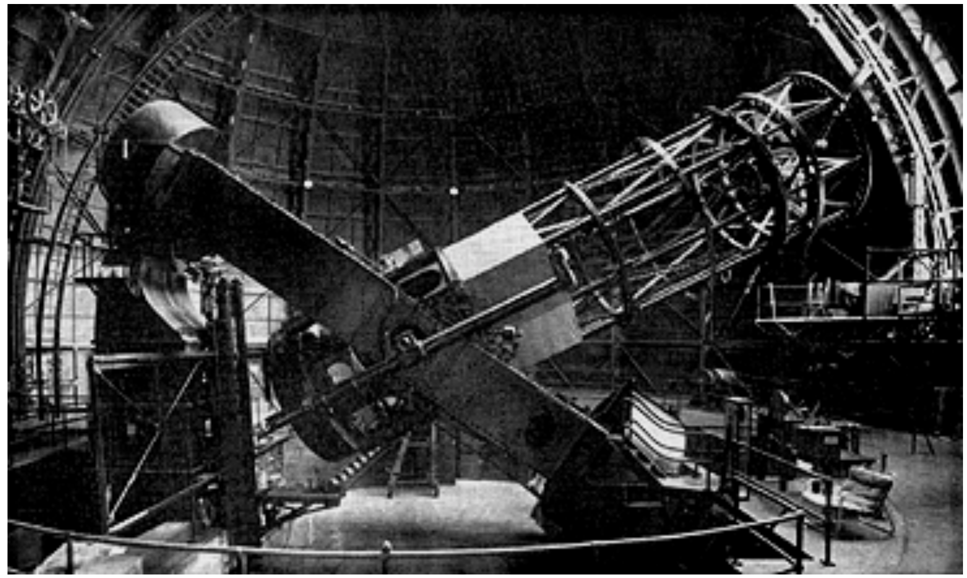
thought that these are other galaxies, just like ours



The Resolution: Nebulae are Extragalactic

- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe

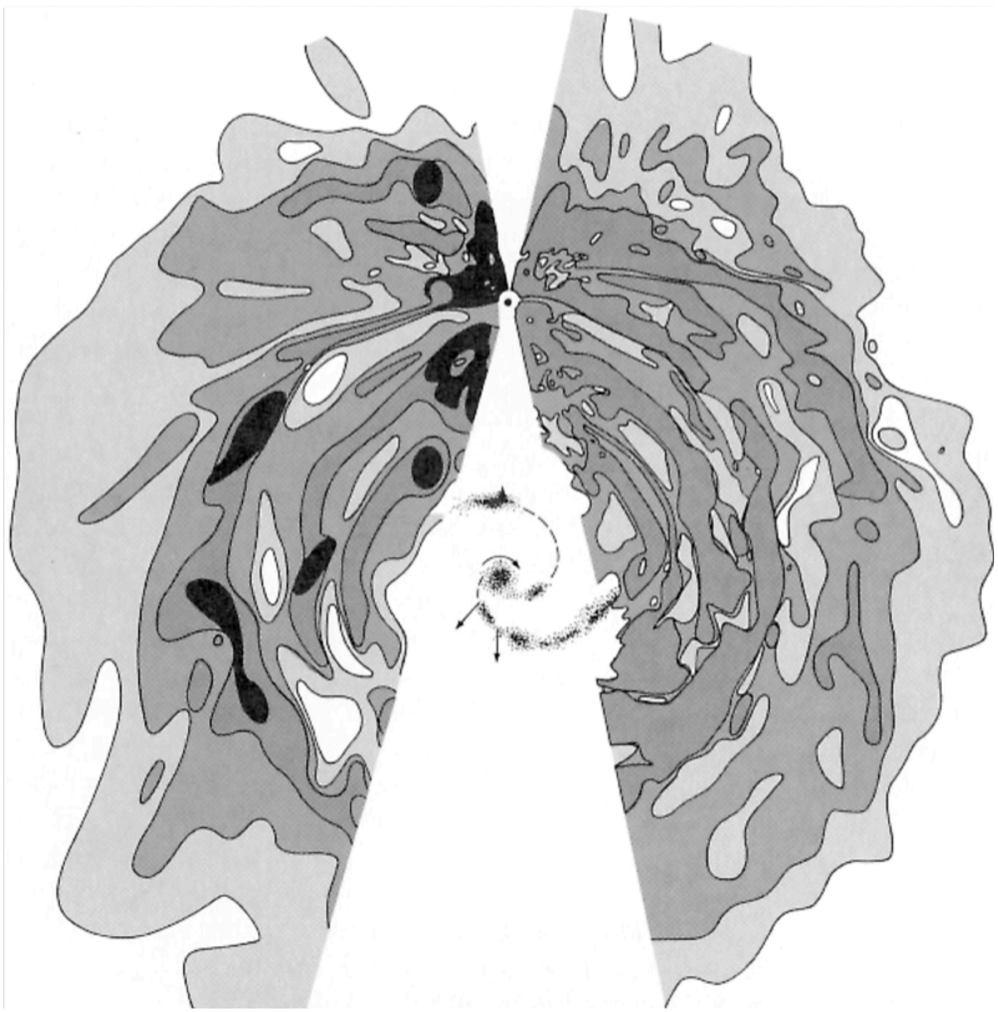
Edwin Hubble



The Mt. Wilson 100-inch

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 opened the 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.

A Modern View of the Galaxy

Actually, there is the thin disk, and the thick disk

Actually, there is the stellar halo, the gaseous corona, and the dark halo

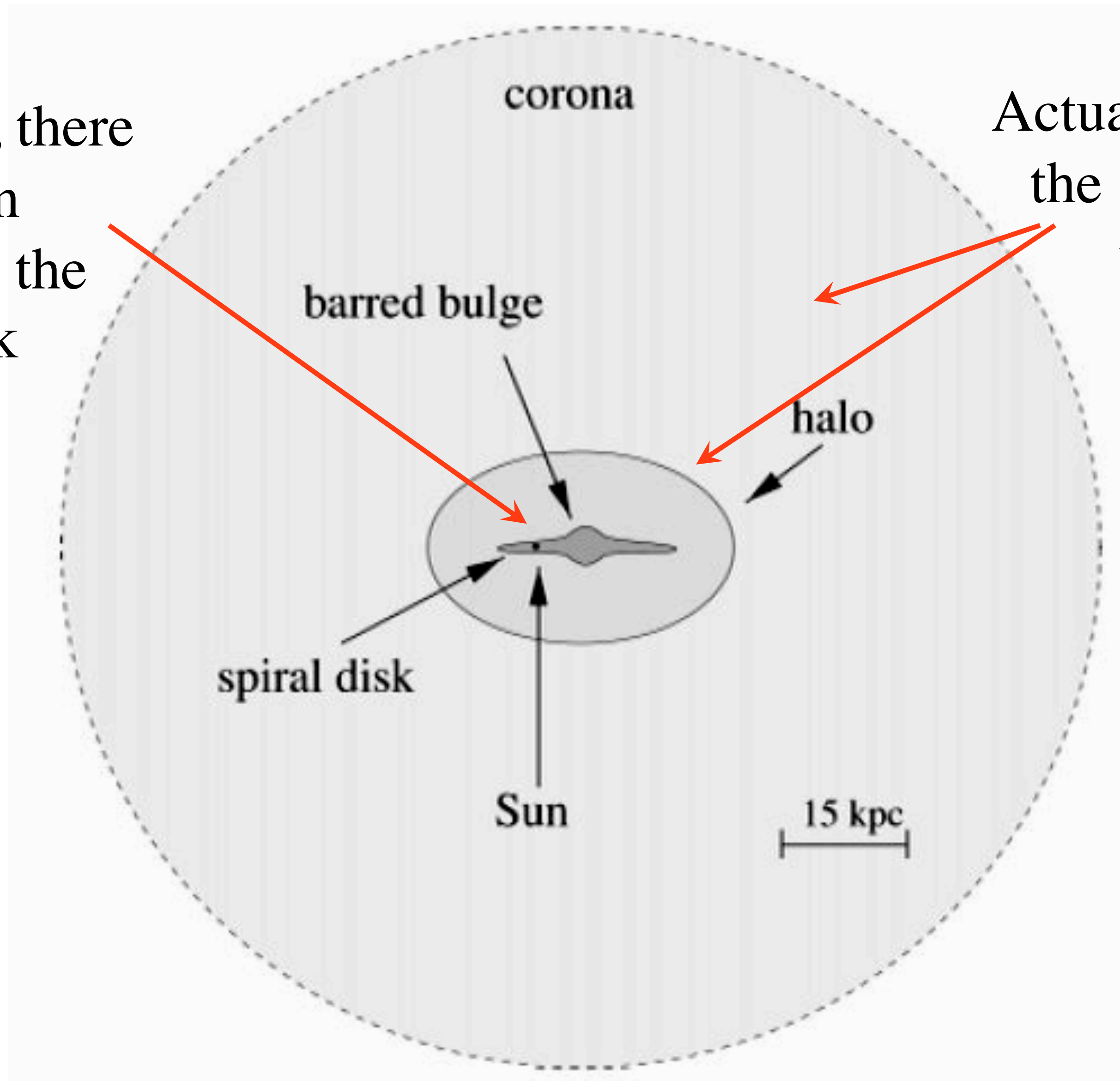
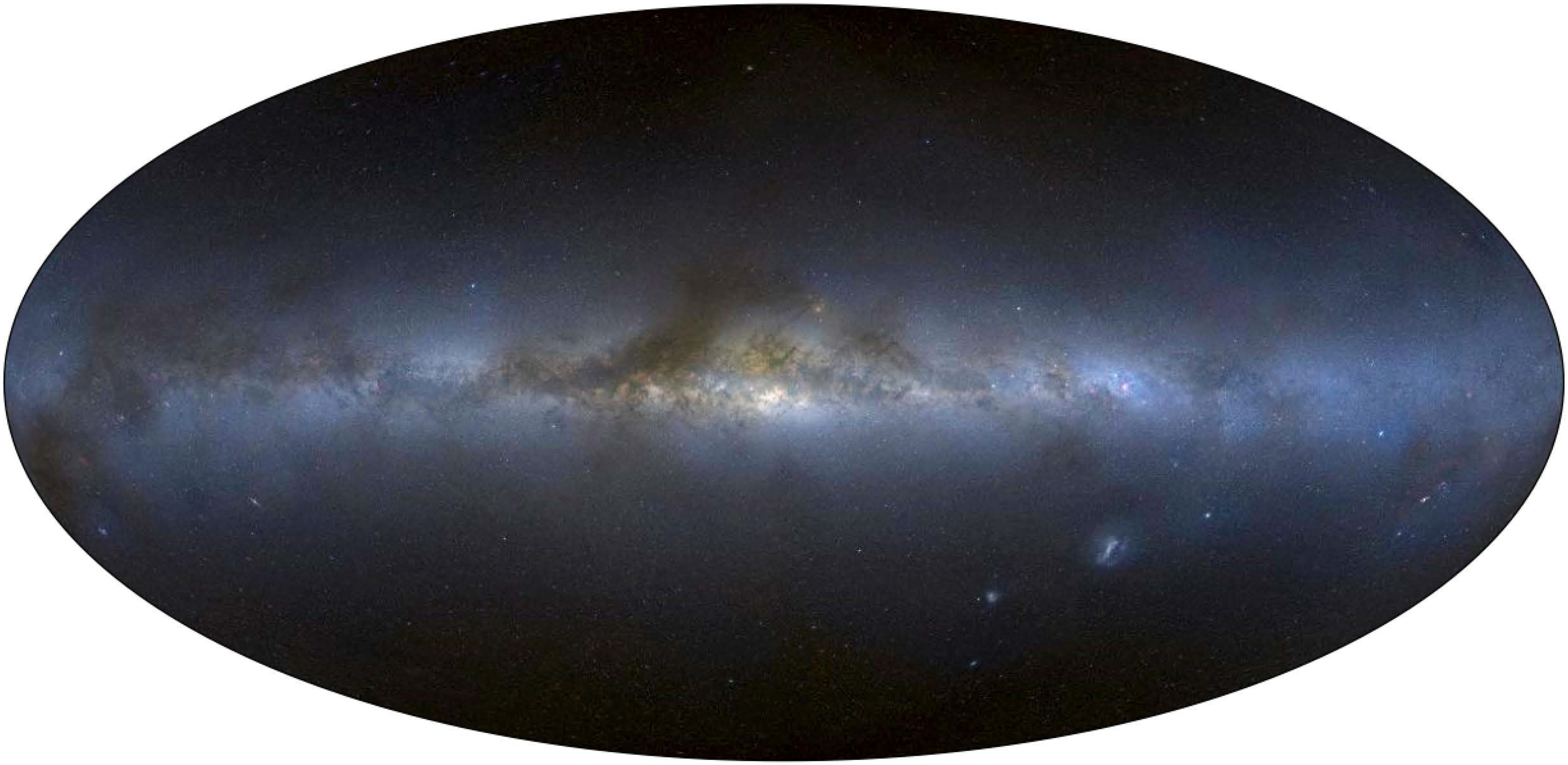


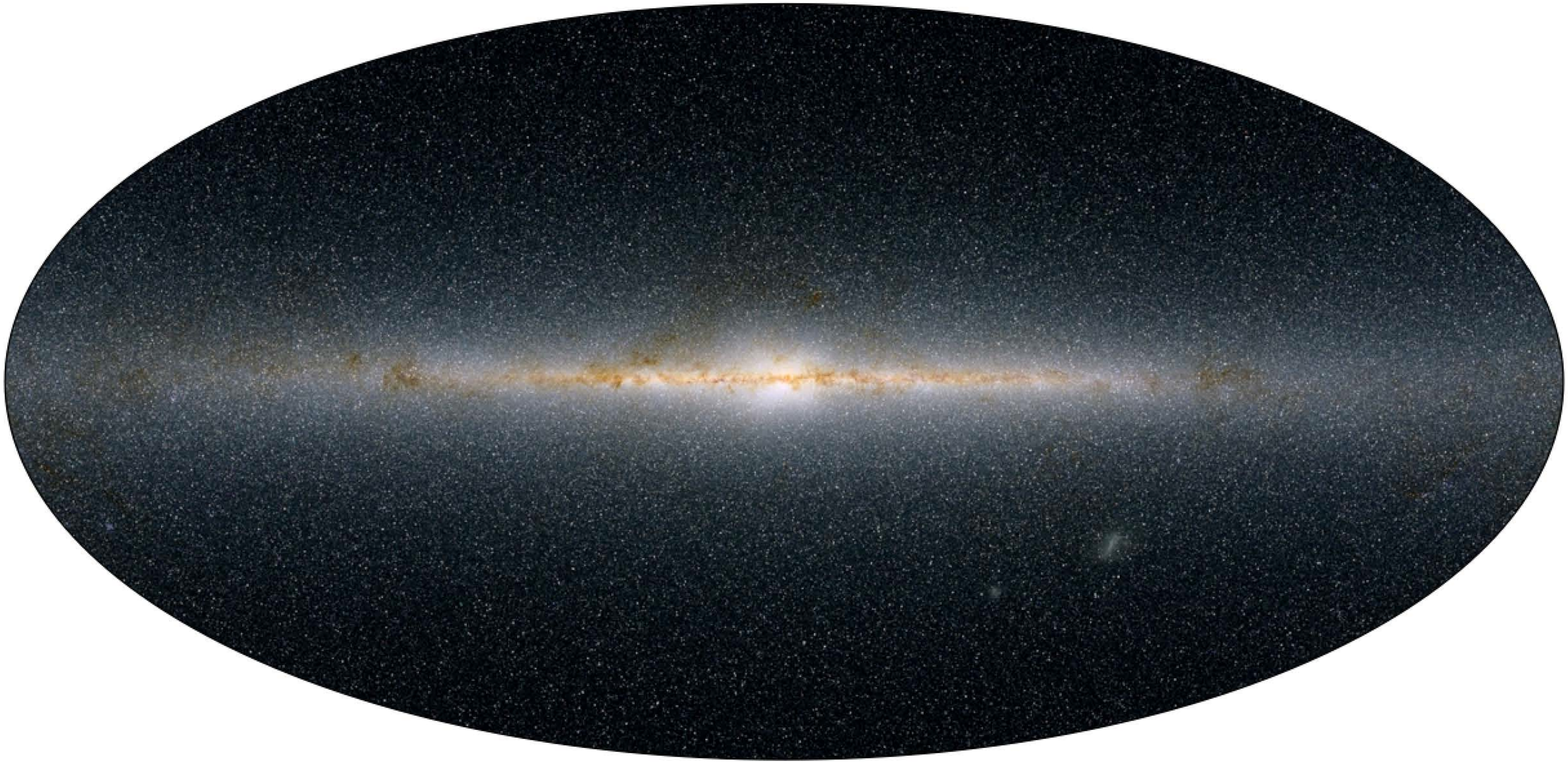
Figure 1. Main structural components of the Milky Way

Milky Way in the Visible Light

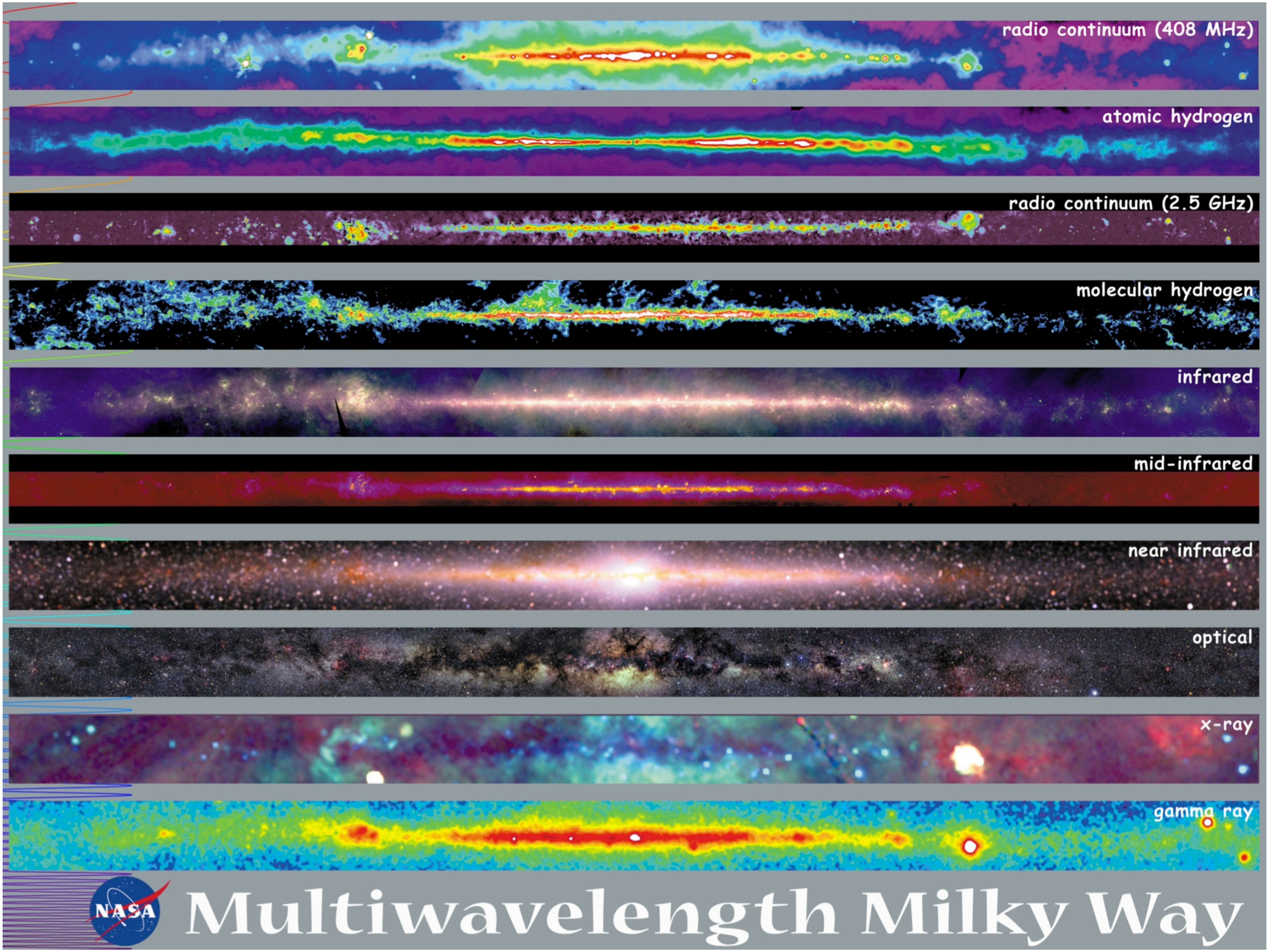


(A. Mellinger)

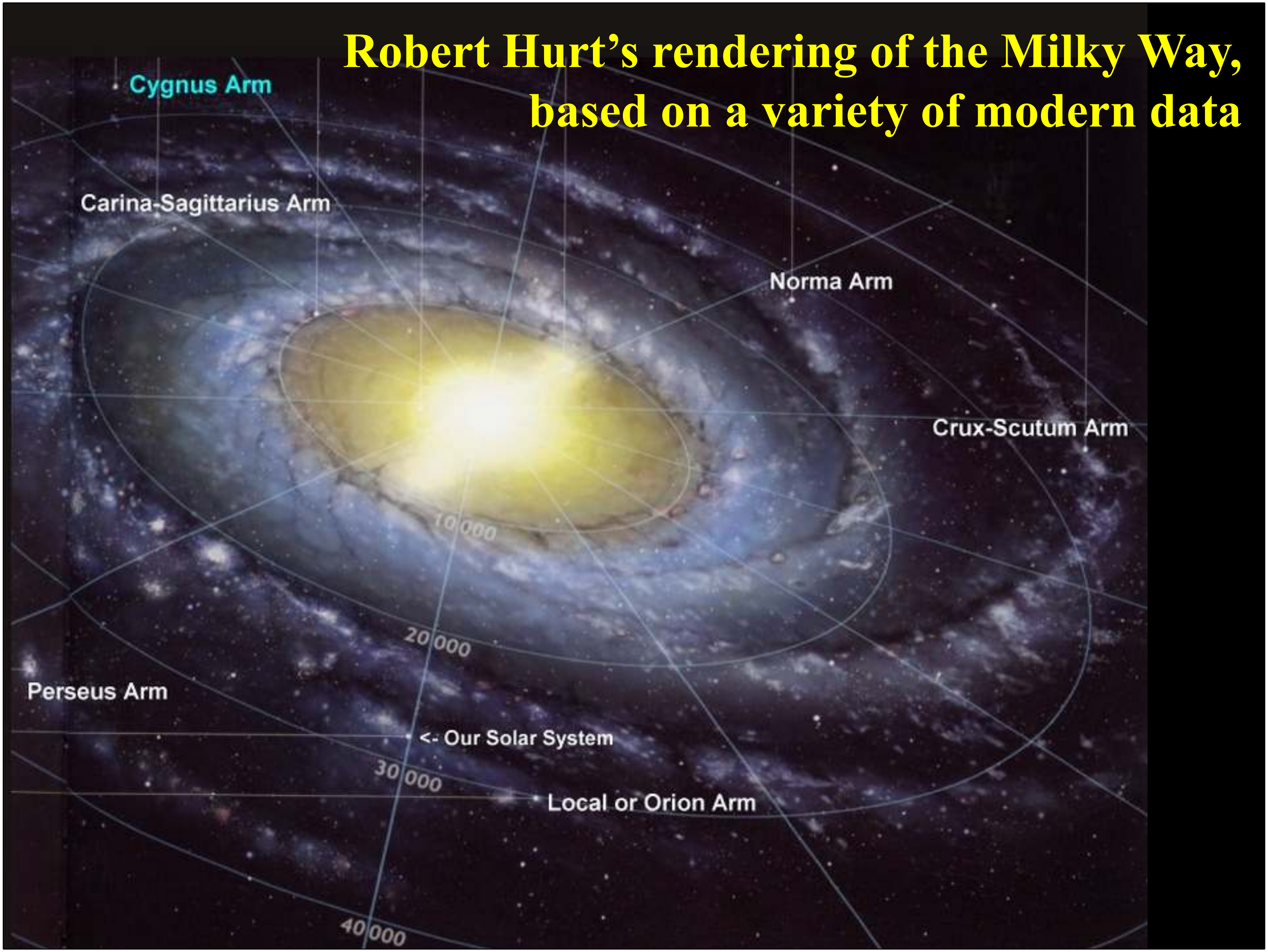
Milky Way in the Near Infrared



(2MASS)


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
NASA
Multiwavelength Milky Way

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



The Concept of Stellar Populations

- Originally discovered by Walter Baade, who came up with 2 populations:

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

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

  – Today, we distinguish between the old, metal-rich stars in the bulge, and old, metal-poor stars in the halo

  – Not clear whether the Pop. I is homogeneous: young thin disk, vs. intermediate-age 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

Major Components of the Galaxy

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

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

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

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

disk scale length $h_R \sim 3$ kpc

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

Most of the stars (95%) lie in a young, **thin disk,** with a vertical scale height ~ 300 pc. Rest form an older, **thick disk** with a vertical scale height ~ 1 kpc

A thin gas disk (mostly H I, also H II, dust)

Major Components of the Galaxy

- **The bulge**: central, mostly old spheroidal stellar component

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

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

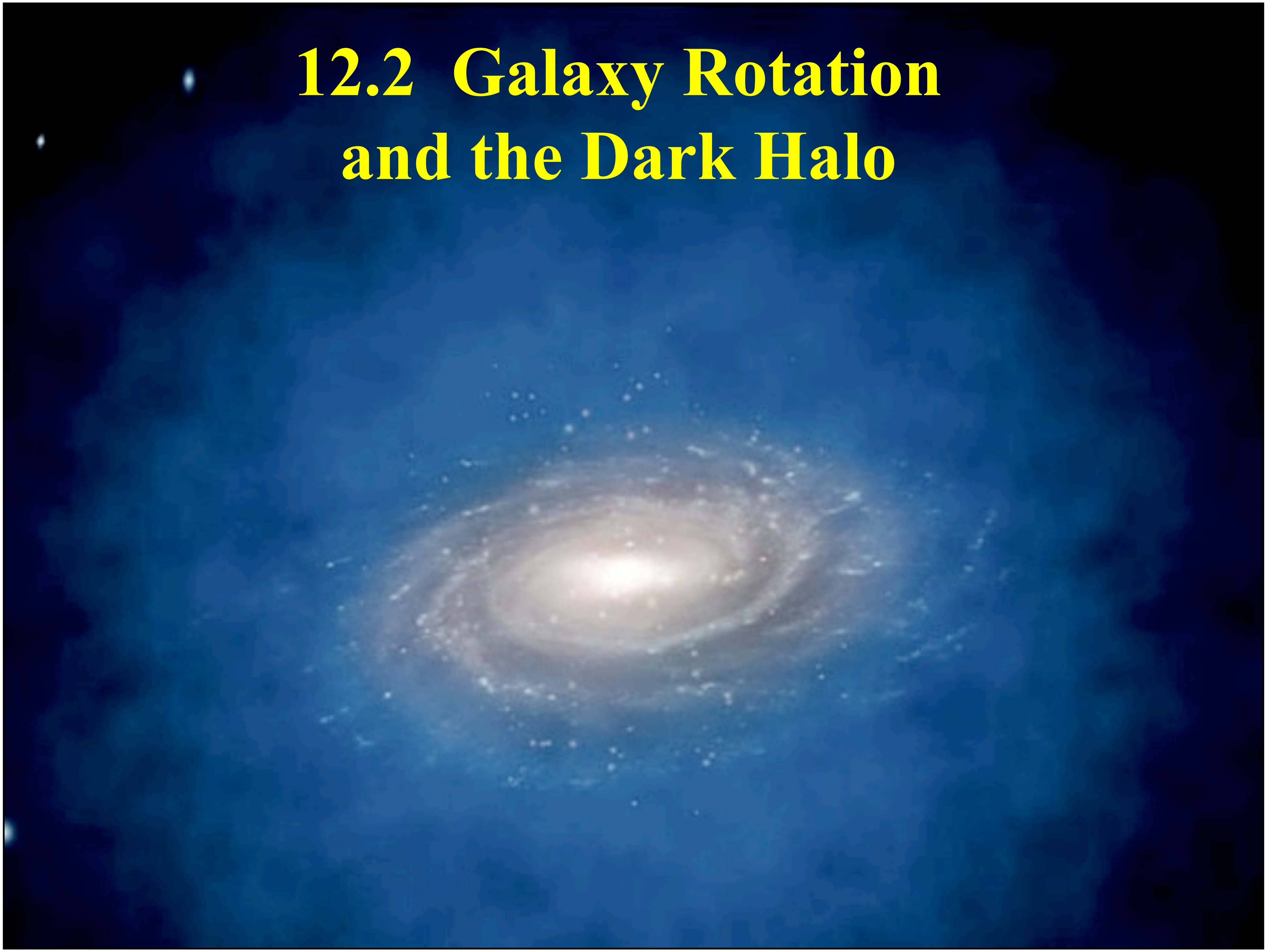
Galactic center is about 8 kpc from the Sun, the bulge is a few kpc in radius

- **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_{sun}
  - ★ Globular clusters. A few % of the total halo stellar content
  - ★ Gas with T ~ 10^5 - 10^6 K. Total mass unknown
  - ★ Dark matter. Physical nature unknown. About 90% of the total mass

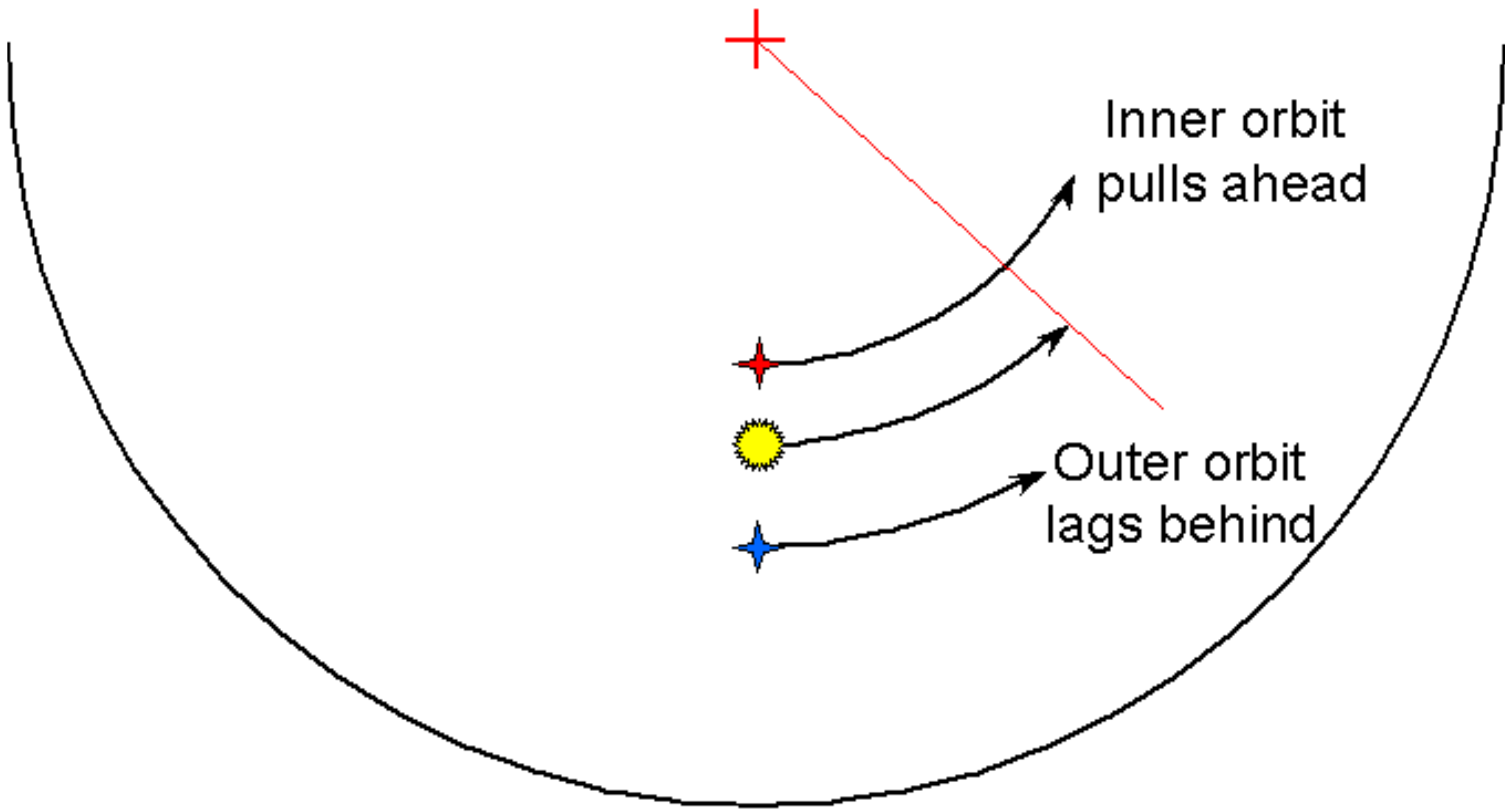
Where Do They Come From?

- **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

12.2 Galaxy Rotation and the Dark Halo



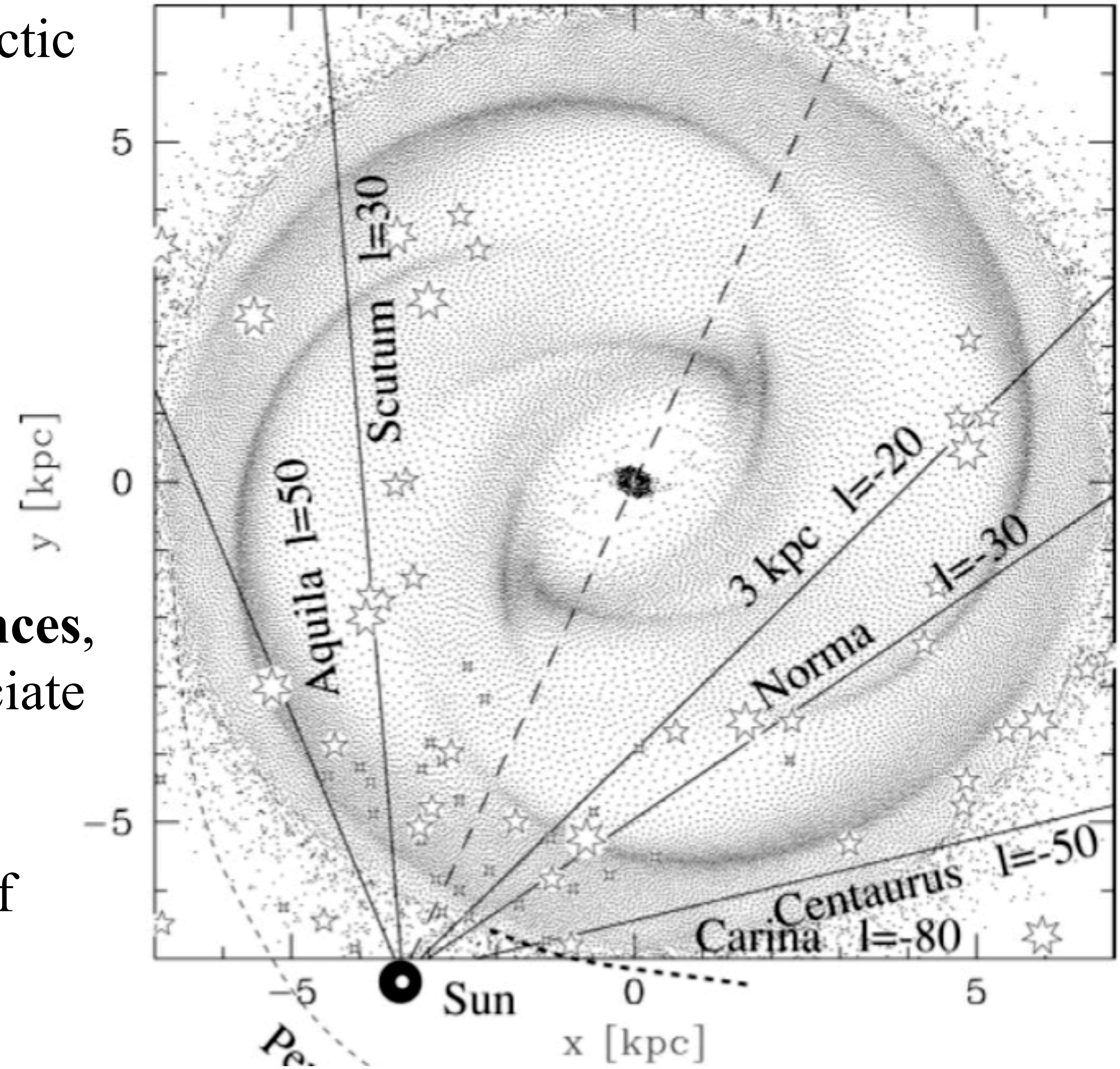
Galaxy Has a Differential Rotation: Angular Velocity Declines Outwards



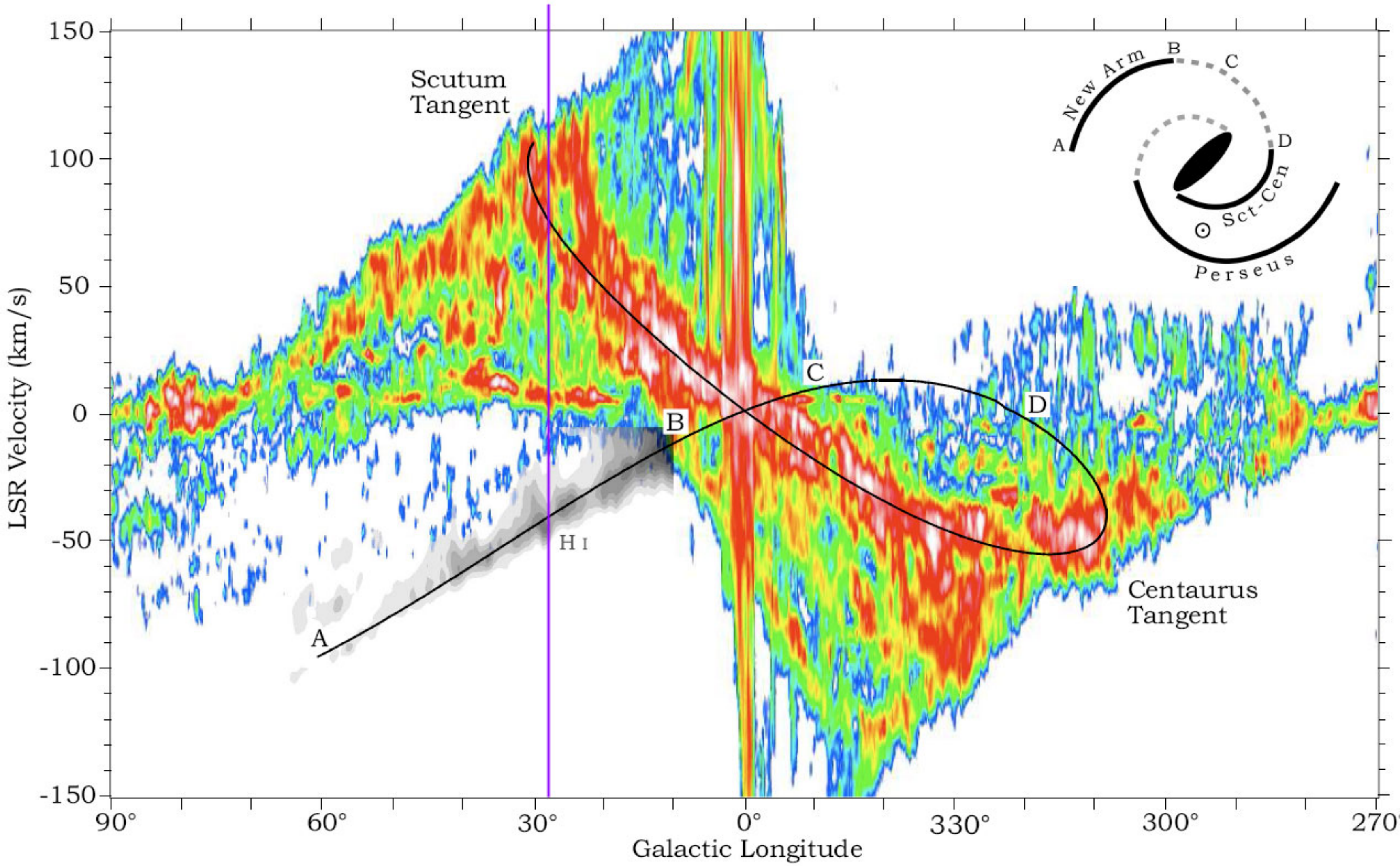
Locally, we can use stellar velocities, but to measure the ***global kinematics*** of the Galaxy, and thus map its rotation, we use the H I 21 cm line, as it penetrates through the dust

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 with the concentrations of the gas



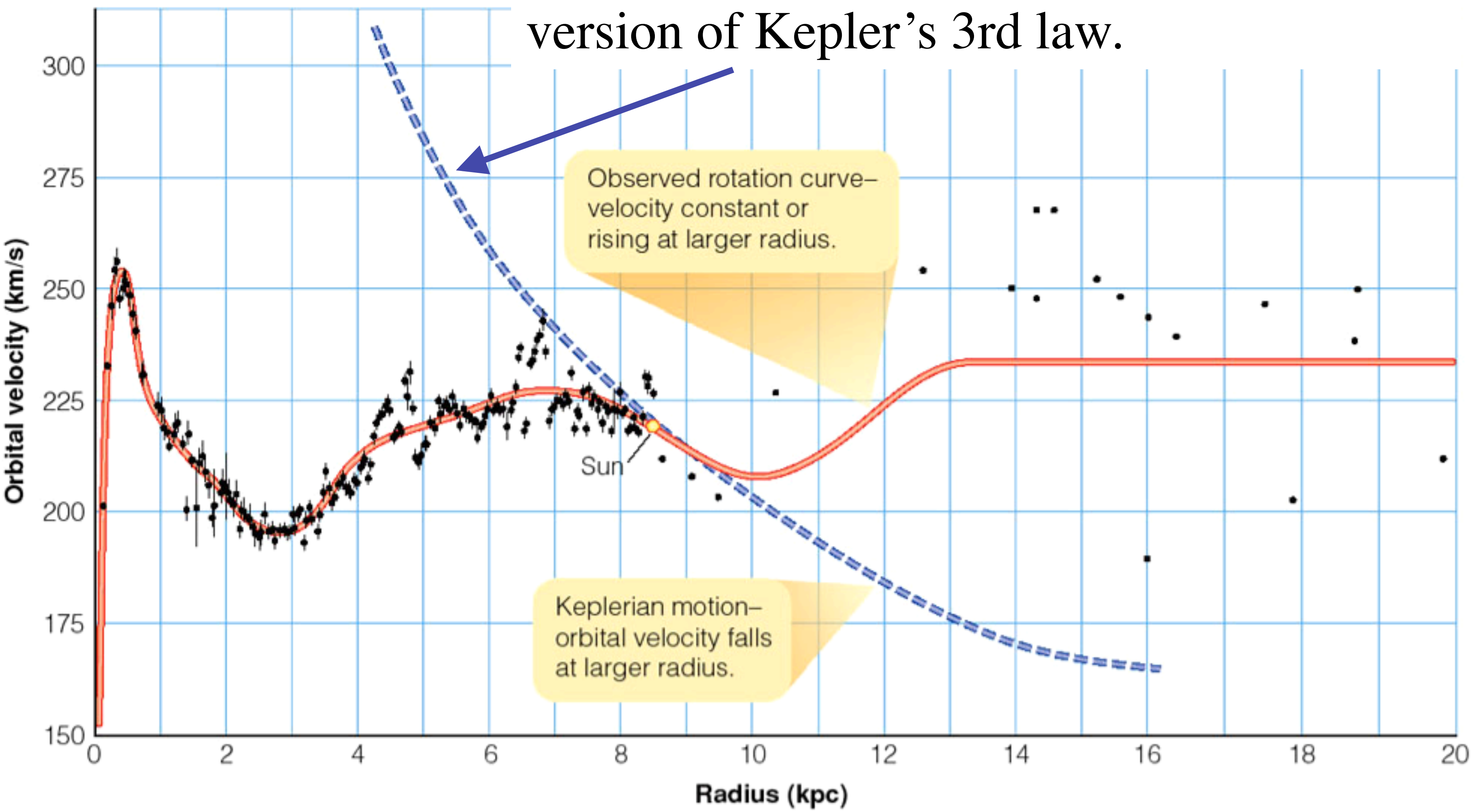
The Longitude-Velocity Diagrams



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

The Observed Rotation Curve of the Milky Way

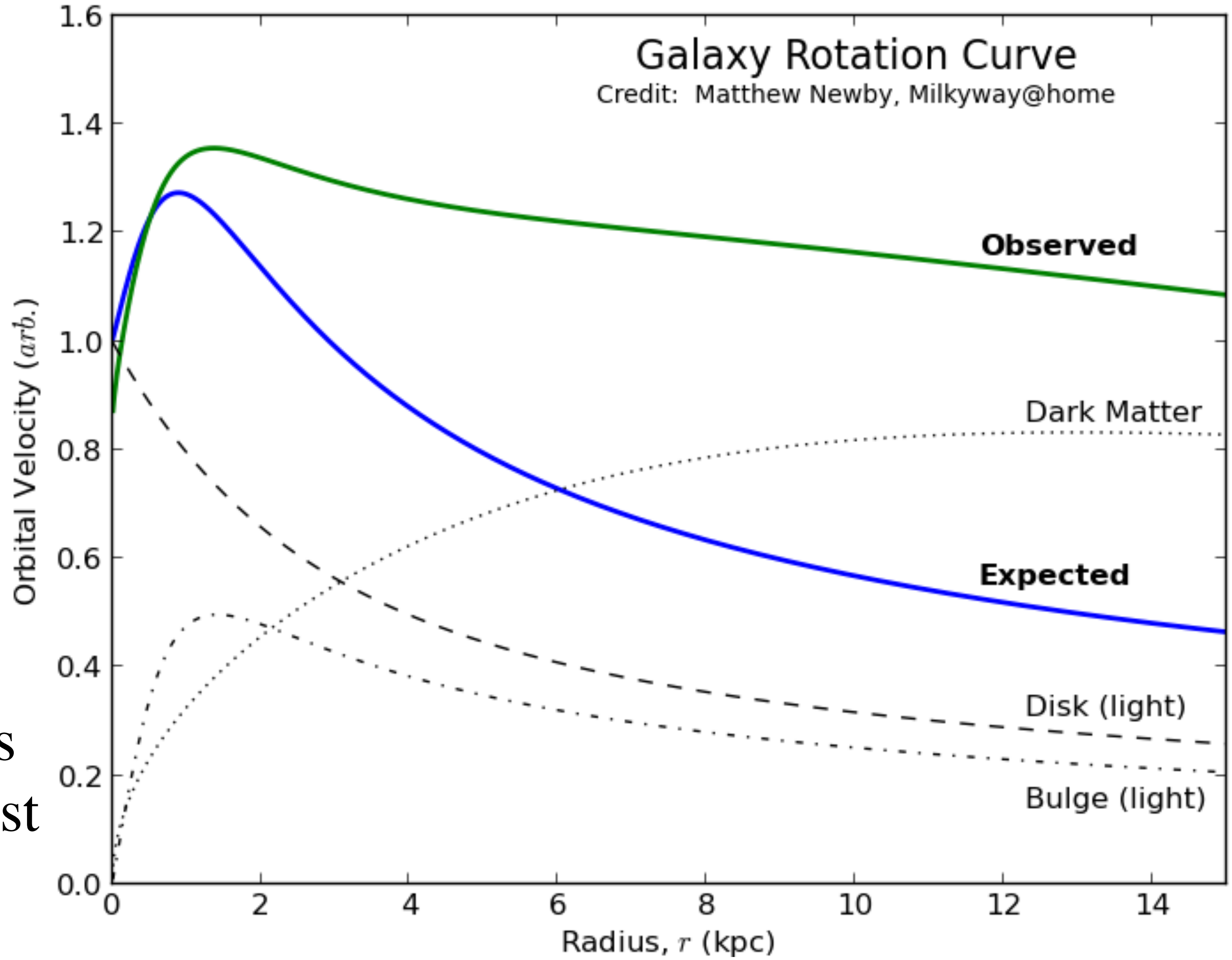
If all mass was concentrated in the center, rotation curve would follow a modified version of Kepler's 3rd law.



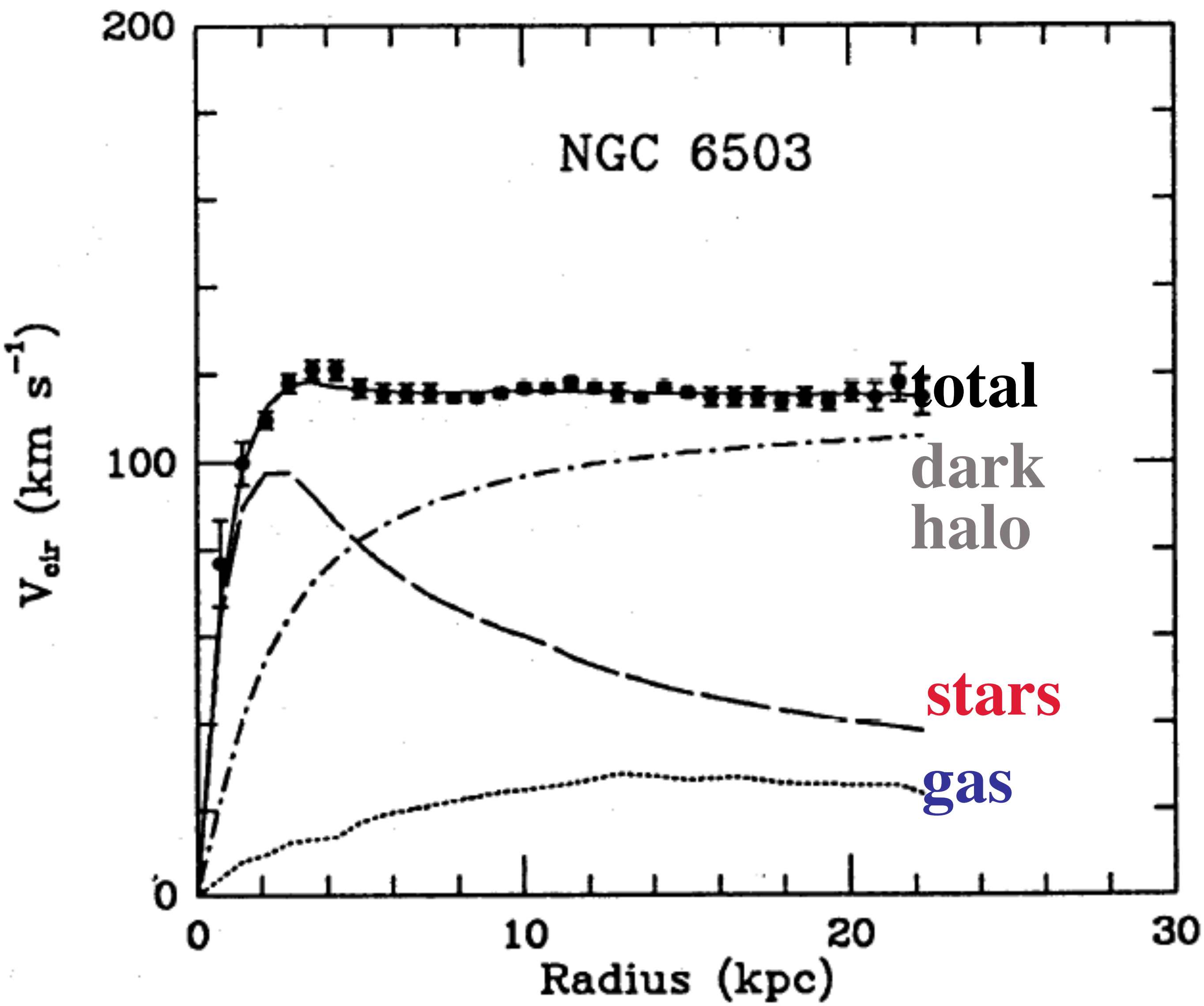
Rotation Curve and the Dark Halo

Gravity from the visible mass is insufficient to account for the observed rotation speeds

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



This is Commonly 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

Interpreting the Rotation Curve

Motions of the stars and gas in the disk of a spiral galaxy are approximately circular (V_R and V_Z << V_R).

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

$$\frac{V^2(r)}{r} = -F_r(r)$$

To calculate $F_r(r)$, must in principle sum up gravitational force from bulge, disk and halo. If the mass enclosed within radius *r* is *M(r)*, gravitational force is:

$$F_r = -\frac{GM(r)}{r^2}$$

Thus, from observed *V(r)*, we can infer *M(r)*

Mass Distribution and Rotation Curve

If the density $\rho = const.$, then: $M(r) = \frac{4}{3}\pi r^3 \rho$

Implied rotation curve rises linearly with radius; this is about right for central regions of spirals, but fails at the larger radii where $V(r) \sim const.$

$$V(r) = \sqrt{\frac{4\pi G\rho}{3}}\, r$$

Consider instead a power law density profile: $\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\alpha}$

with $\alpha < 3$, the rotation curve is:

$$V(r) = \sqrt{\frac{4\pi G\rho_0 r_0^{\alpha}}{3-\alpha}}\, r^{1-\alpha/2}$$

$V(r) = const.$ then implies $\rho(r) \sim r^{-2}$. This profile is called a *singular isothermal sphere*. Note that the enclosed mass increases linearly with radius, $M(r) \sim r$! (Where does it stop?)

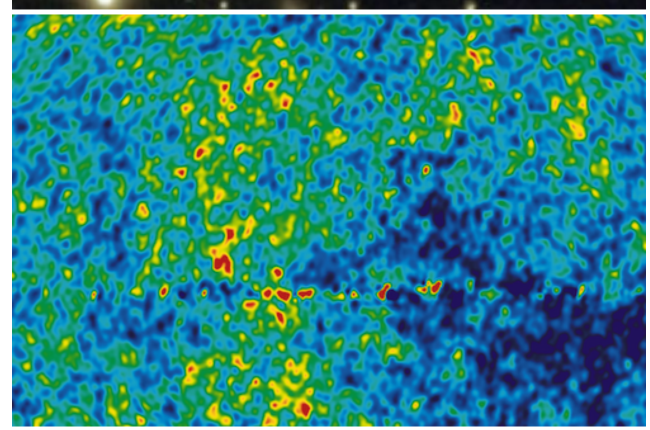
Other Evidence for the Dark Matter

X-ray gas in galaxy clusters: too hot to be explained by the gravity of the visible matter alone

Gravitational lensing: implies the existence of an unseen mass component

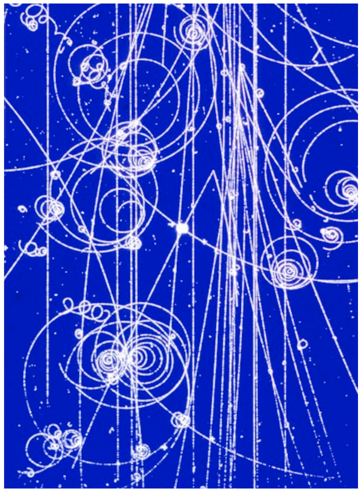
Cosmic Microwave Background fluctuations: also require a substantial non-baryonic dark matter component

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



… and they all agree!

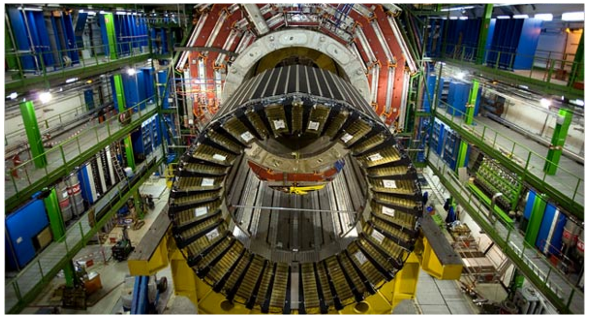
The Physical Nature of the DM



We know that ***some of it*** is regular matter, H and He atoms and ions, just hidden; and some is in massive cosmological neutrinos

But we also know that ***most of it*** is composed of some as yet unknown type of particles, or represents some new physics

The proposed possible constituents range from unknown ultra-light particles, to massive black holes and cosmic strings, but the favorite DM particles are WIMPs, or axions



These particles could be detected in laboratory experiments, or with accelerators like the LHC

12.3 The Origin of Spiral Arms

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, thus lifetime is << galactic rotation period

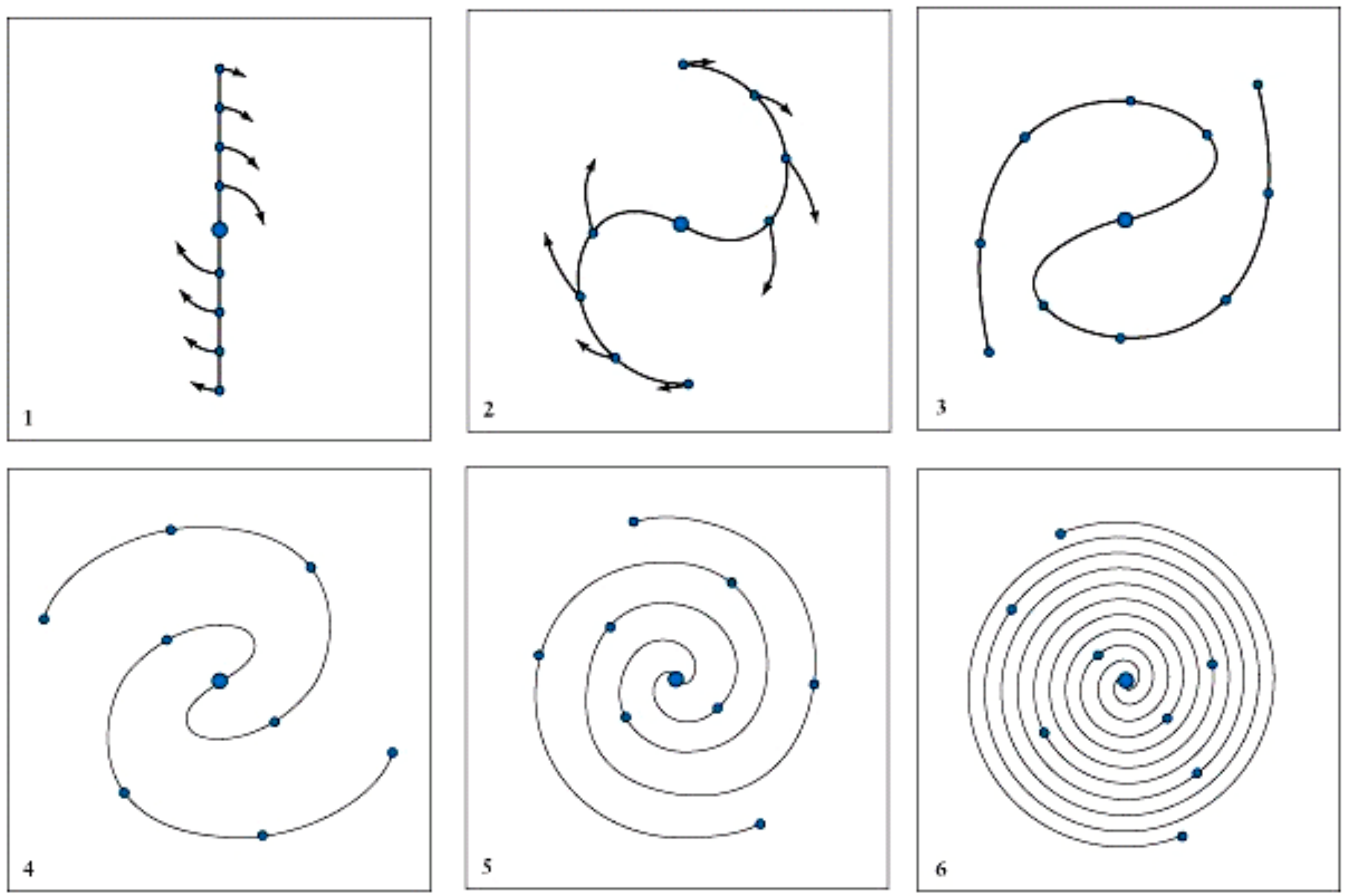
When the sense of the galactic rotation is known, the spiral arms almost always trail the rotation

The Winding Dilemma

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

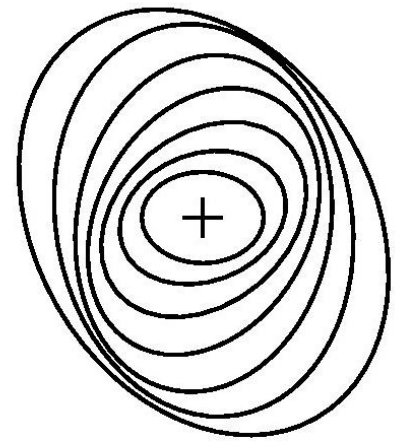
But this is <u>not</u> why galaxies have spiral arms!

Because spiral arms seem to be **persistent**

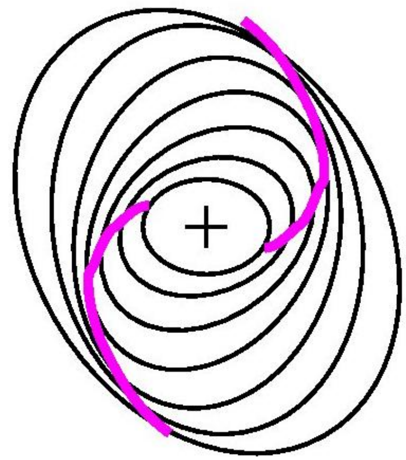


Spiral Density Waves

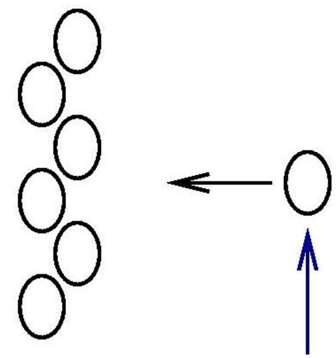
- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other



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

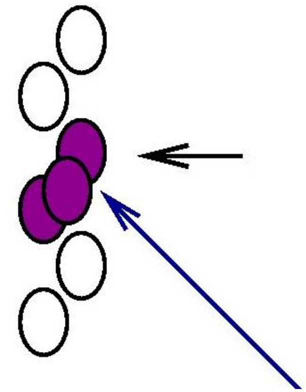


- Objects (such as a gas cloud) will be attracted to these regions and will drift towards them.

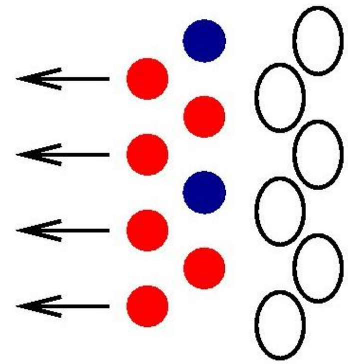


Spiral Density Waves and Star Formation

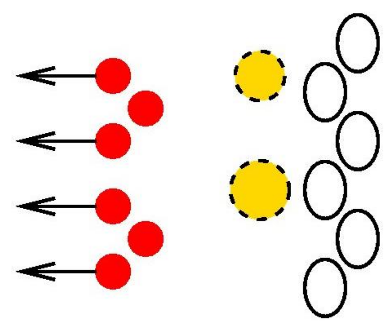
- When the gas cloud collides with other gas clouds, stars will be formed. This is where most of the star formation takes place



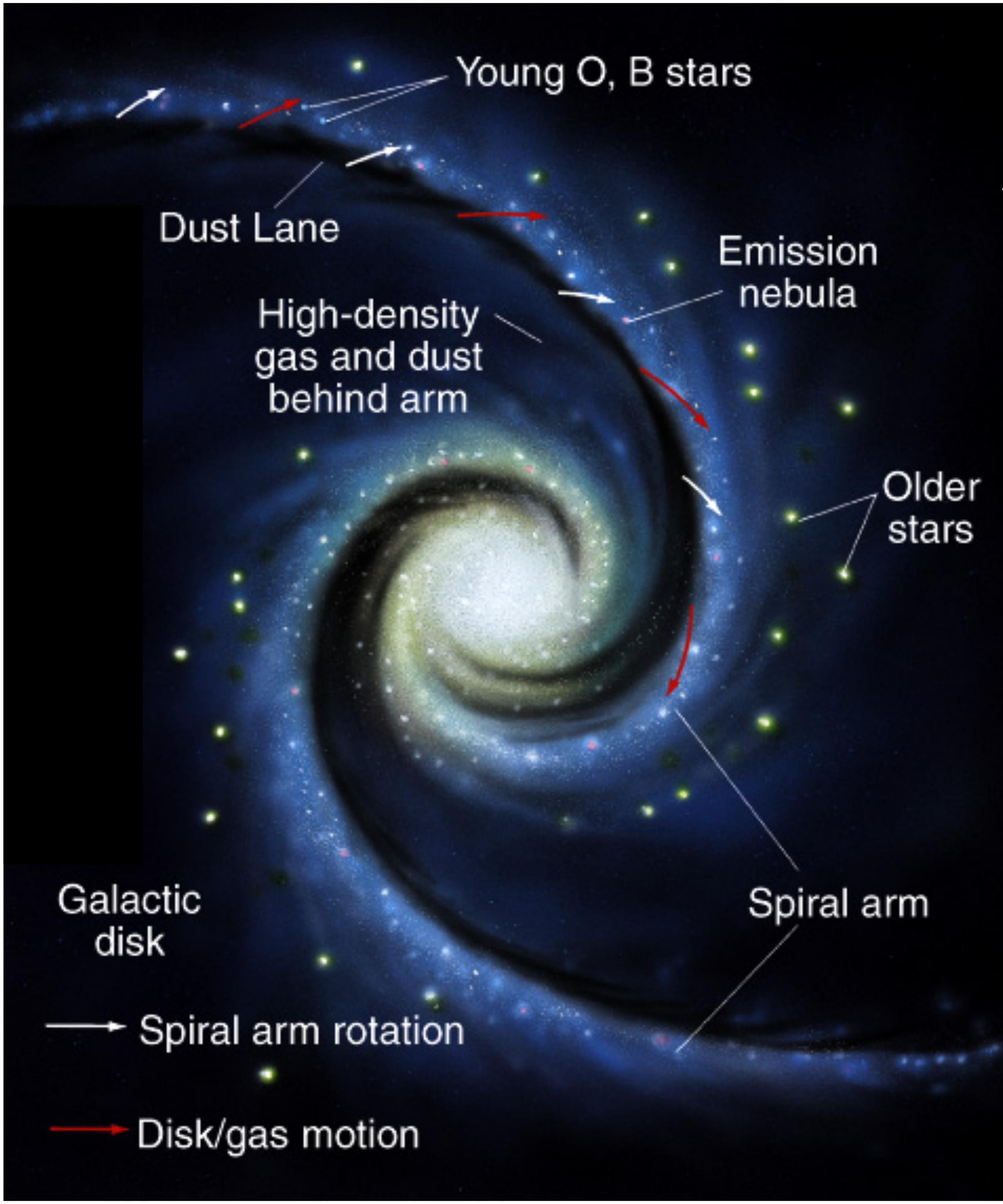
- Newly formed stars, including the luminous OB stars will continue to drift through the region



- 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



The Density Wave Theory



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***)

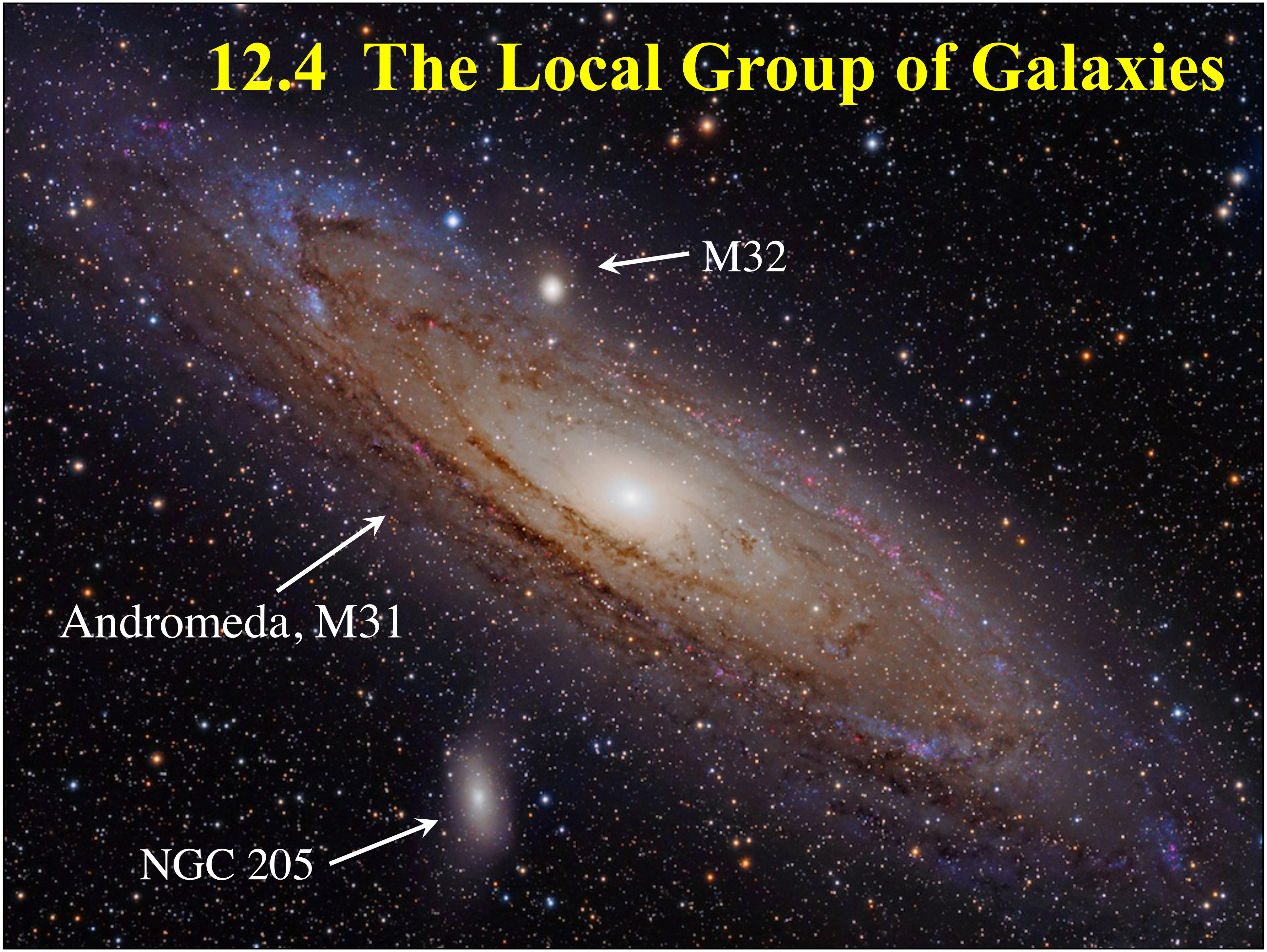

M81, a “Grand Design” Spiral


NGC 2841,
a "Flocculent" Spiral

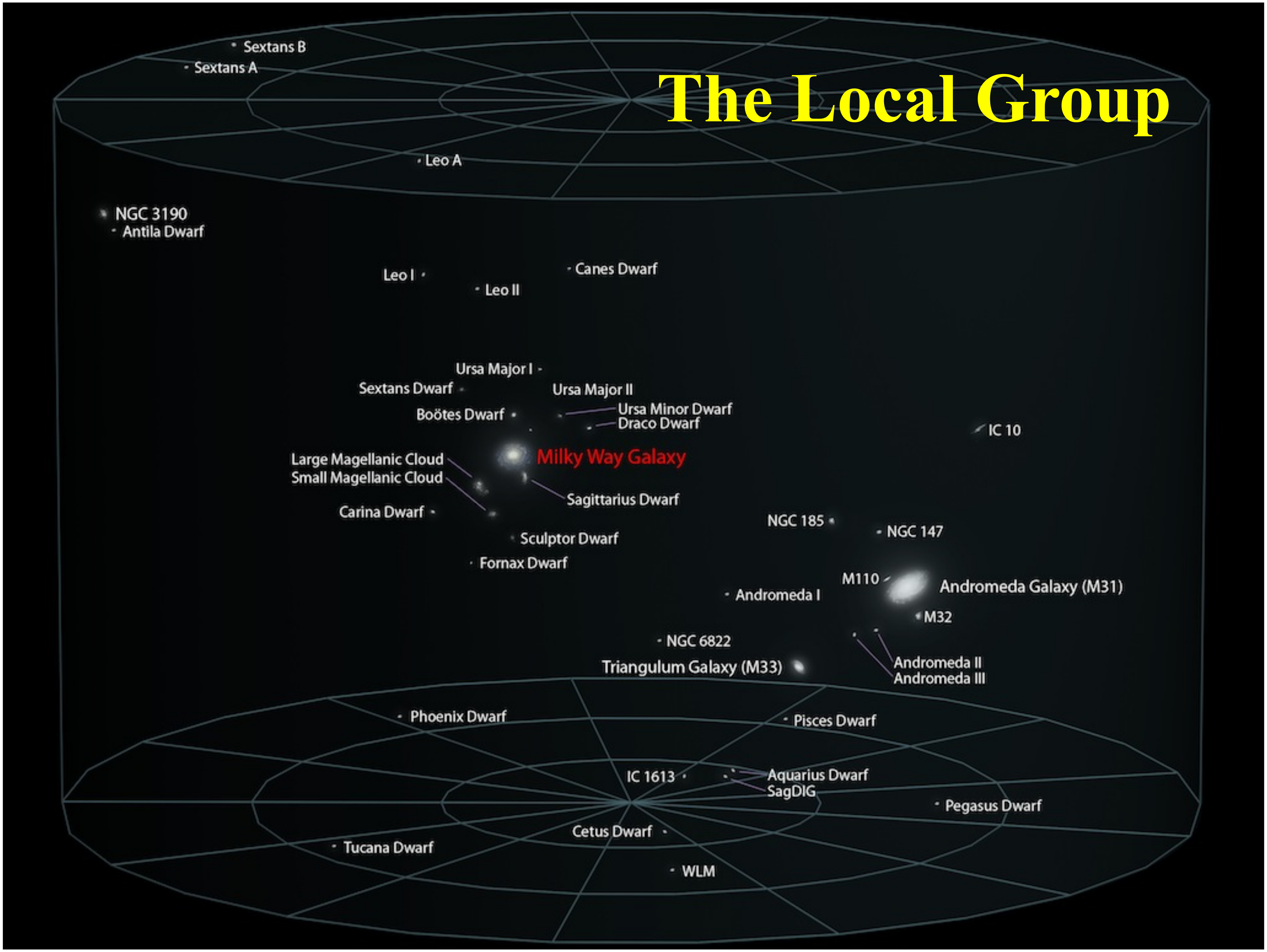
Galaxy Bars

- 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
- 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, if one is present

12.4 The Local Group of Galaxies



The Local Group



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, …
- About 1 Mpc in size (M31 is 700 kpc away)
- Not gravitationally bound (some parts are)
- Part of the Local Supercluster
- Most galaxies are found in groups

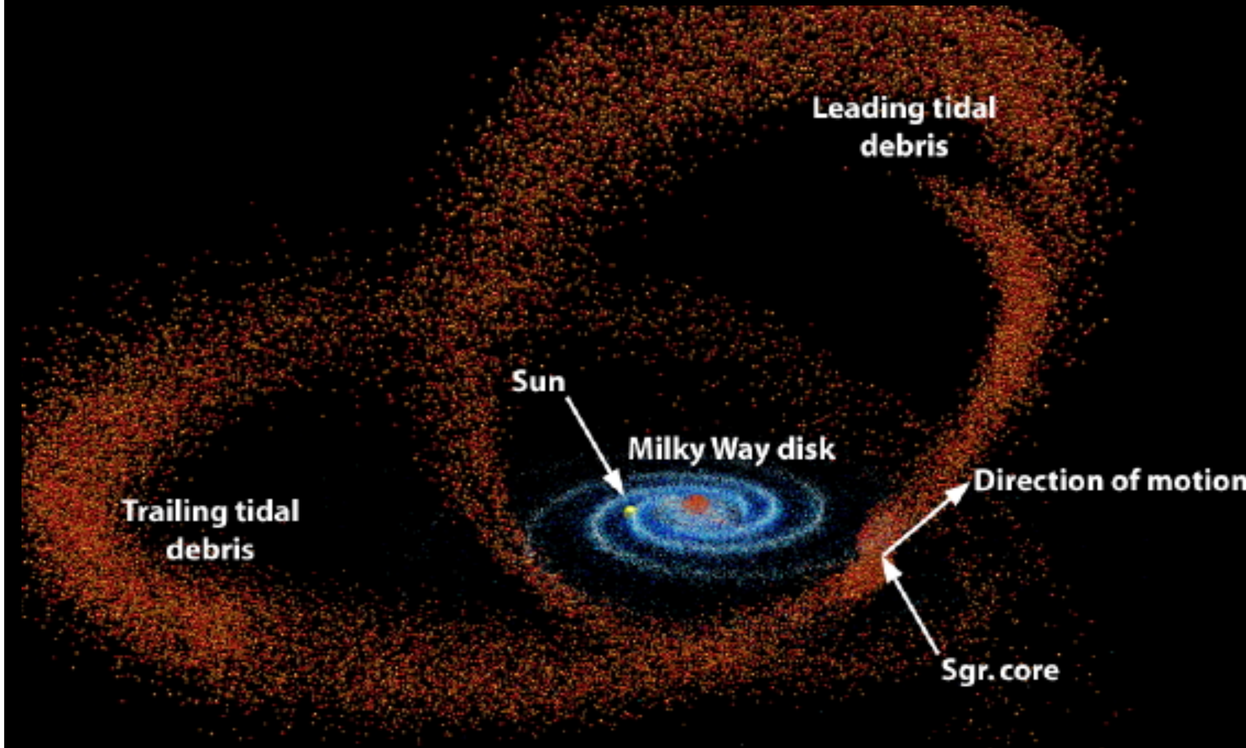
Some Local Group Members

Leo I dwarf spheroidal

M33

Large and Small Magellanic Clouds
(dwarf irregulars)

Tidal Tails and Shredding of Dwarf Galaxies



Dwarf galaxies are disrupted by their massive neighbors, leaving "tidal tails" of stars in the process

All halo stars probably come from disrupted/evaporated dwarf galaxies

An example is the Sagittarius dwarf >