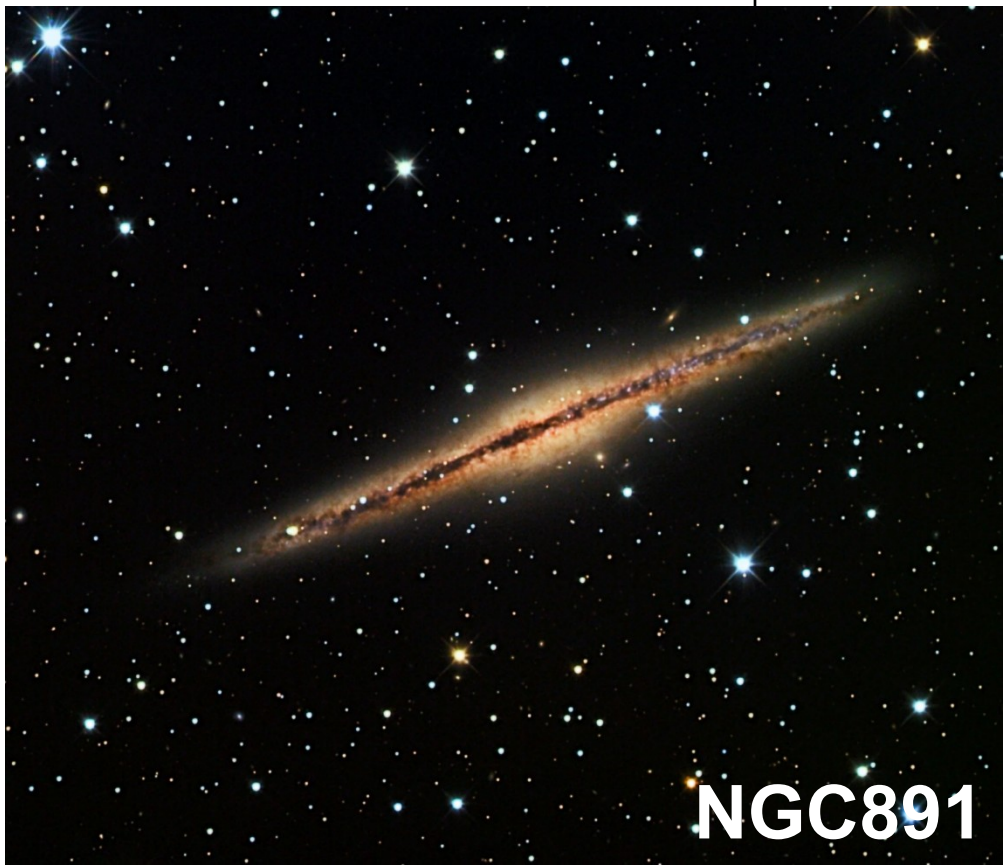
The Milky Way Is An Island

Stars in the Milky Way

- In the visible light we do not see very far because of dark interstellar clouds and the demon hiding in them (the demon story is for the next time…).
- The infrared band is the best to see most of the stars. In the IR we see the galactic disk and the bulge in the middle, which is called the ***bulge***.
- Thus, the Milky Way looks like a typical spiral galaxy.
- The Milky Way = the Galaxy.

Typical Spiral Galaxies



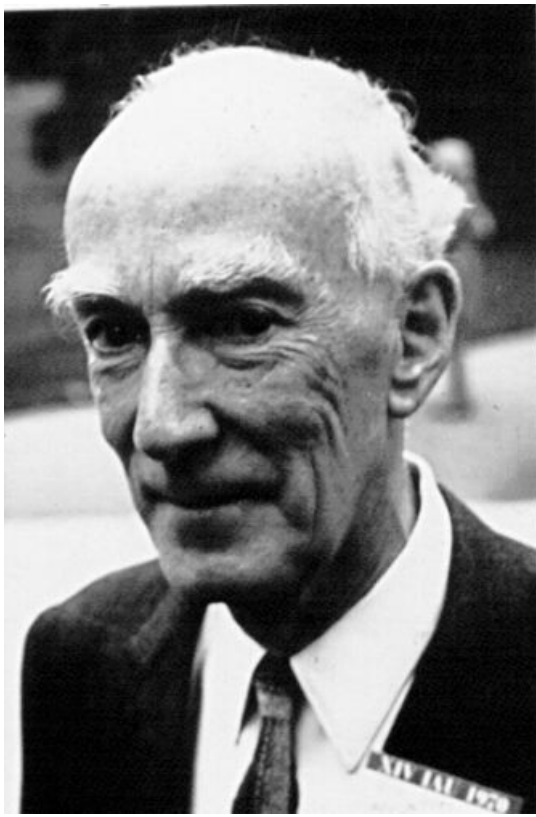
Stellar Halo

- In addition to the disk and the bulge, the Milky Way also has a stellar ***halo*** – a round-ish distribution of stars, including globular clusters.
- Halo does not have a sharp boundary, it gradually becomes more and more tenuous.
- A halo is very faint – in other galaxies it can only be seen in a highly overexposed photograph.

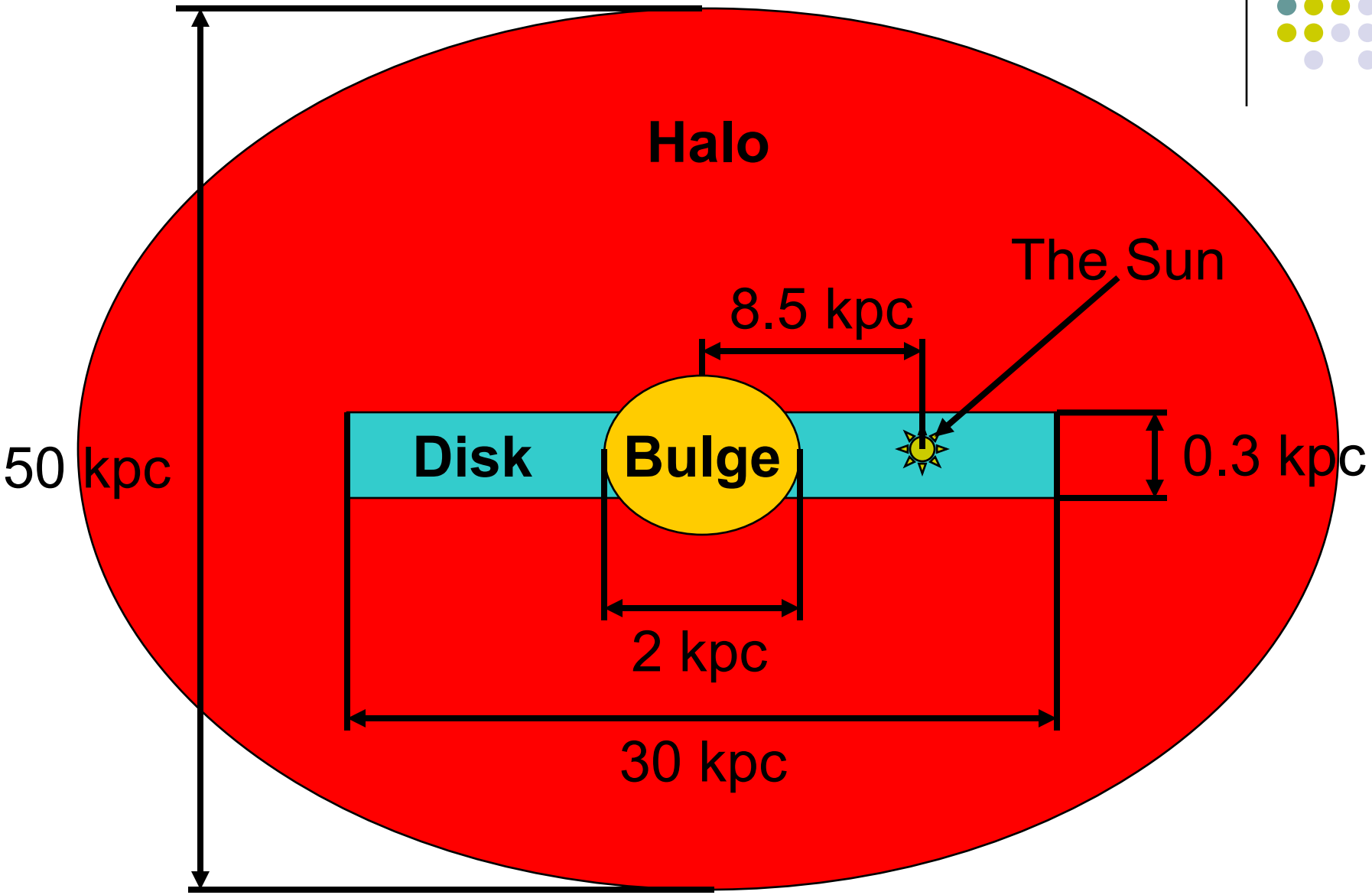

Sombrero galaxy

Jan Oort (1900 – 1992)

- Professor at Leiden Observatory (near Amsterdam, Netherlands).
- In 1924 he discovered the stellar halo by tracing the motions of stars.
- In 1927 he measured the rotation of the Milky Way, confirming the earlier theory by Lindblad.
- One of the founder of Radio Astronomy. Used Radio observations to map spiral arms in the disk (that's a story for another day).



Scales

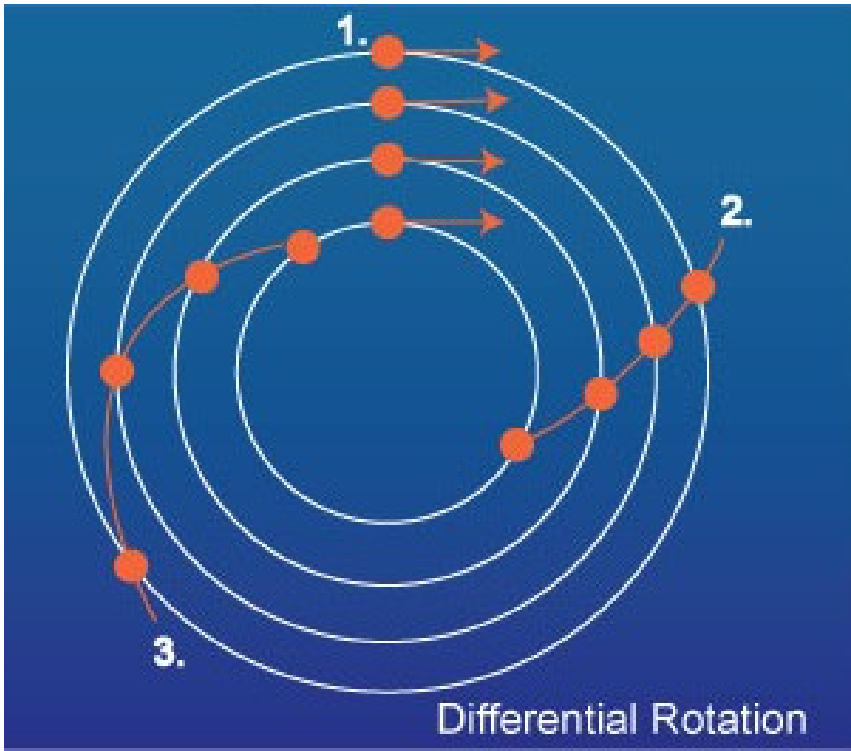


Disk

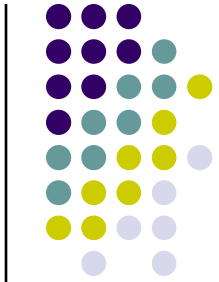
- Disk is the downtown of the Milky Way. All exciting things (good and bad) happen there.
- Bulge is a financial district – majestic and archaic (with a horrible beast hidden within - stay tuned).
- Halo is a suburb – safe and boring.
- The disk has its shape because
  - **A**: stars rotate around the galaxy.
  - **B**: few stars move up and down.
  - **C**: gravity compresses the galaxy into a disk.
  - **D**: halo presses down on the disk, squashing it.

Differential Rotation

- Stars rotate in the disk on nearly circular orbits.
- Just like planets around the Sun, stars at different radii have different periods – the disk does ***not*** rotate as a single, solid body.
- Differential rotation tends to stretch any pattern into a ***spiral***.
- The Sun takes about 240 Myr (million years) to make one circle.



Bulge

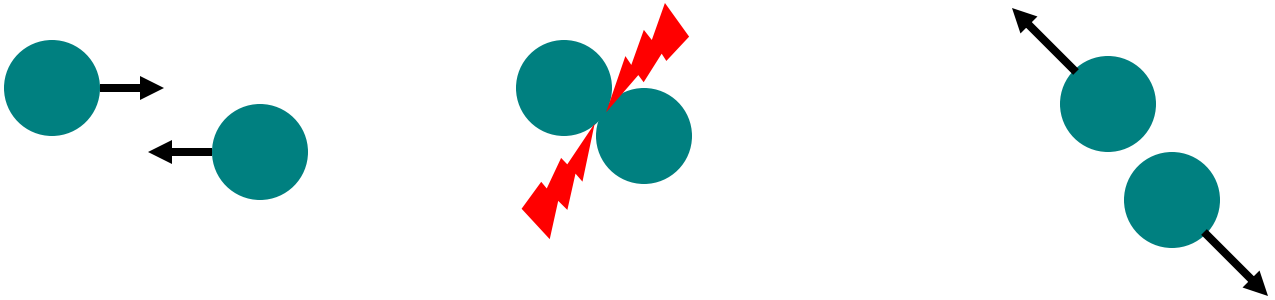


- Bulge is elliptical in shape – not a disk, not a sphere.
- It is very dense – 100 to 1,000 times denser that the solar neighborhood. There is no night in the bulge – you can read in starlight.
- The bulge is in the equilibrium, it doesn't collapse under its own gravity – there must be a force that balances gravity. What is it?
  - **A**: pressure
  - **B**: centrifugal force
  - **C**: levity

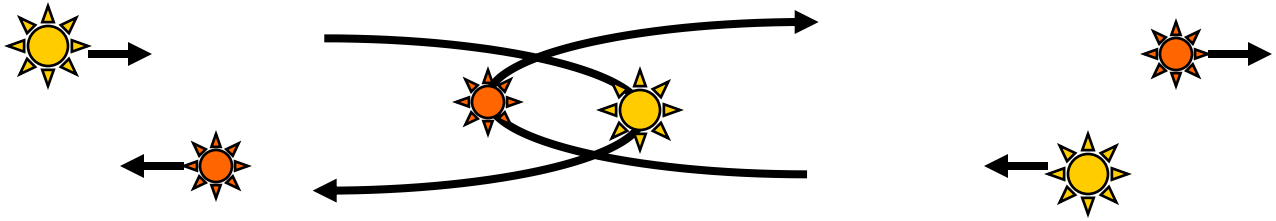
Gas of Stars

- Stars in large numbers behave as atoms in a gas – clouds of stars do have ***pressure***!

Atoms



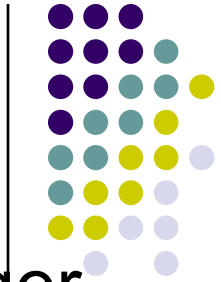
Stars



Walter Baade (1893 – 1960)

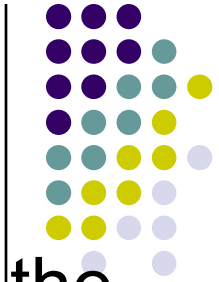
- A German astronomer; immigrated to the US in 1931.
- Discovered that Cepheids come in two distinct types.
- With Fritz Zwicky discovered that supernovae were different from (and much brighter than) novae – two different types of stellar explosions.
- Following the trend, in 1944 he also discovered that stars in the Milky Way belong to two distinct categories – he called them ***stellar populations***.

Stellar Populations



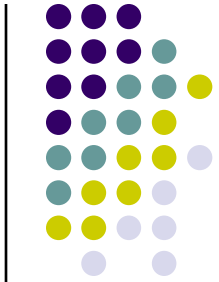
- Stars in the disk are, on average, much younger than bulge and halo stars.
  - Disk stars (***Population I***): a large range of ages, anywhere from 0 to 10 Gyr old. The Sun is a very typical Pop I star (4.6 Gyr).
  - Halo stars (***Population II***): very few are younger than 10 Gyr.
  - Bulge: a mixture of two populations, with Pop II stars dominating.
- Two stellar populations also differ by other properties, especially the abundance of ***heavy elements*** (elements heavier than helium).

Stellar Metallicity



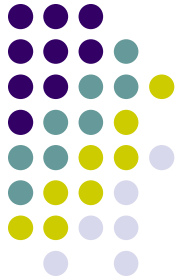
- Disk stars, like the Sun, all have more-or-less the same chemical abundance (1% oxygen, 0.5% carbon, 0.1% iron, etc).
- Pop II stars have a much smaller abundance of chemical elements (30% to 50% of the Sun).
- The relative abundance of different elements is the same, but their total amount changes:
  - 50% solar: 0.5% oxygen, 0.25% carbon, 0.05% iron
  - 30% solar: 0.3% oxygen, 0.15% carbon, 0.03% iron
- The total abundance of heavy elements is called ***metallicity*** (labeled Z). It is often measured in solar units: $Z_{\odot} = 1$.

Two Populations



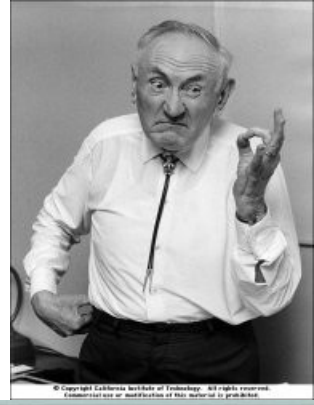
- Population I stars:
  - are located mostly in the disk, but some are in the bulge.
  - are younger than 10 Gyr.
  - move on nearly circular orbits.
  - have solar metallicity (Z=1).
- Population II stars:
  - are located mostly in the halo and bulge.
  - are older than 10 Gyr.
  - move on random, often skinny orbits.
  - have low metallicity (Z=0.3 – 0.5).

Stellar Populations and the Milky Way History



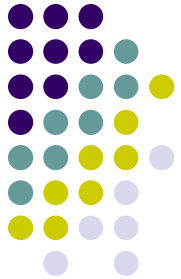
- The existence of stellar populations implies that the Milky Way galaxy did not form all at once.
- Which part of the Galaxy formed first?
  - **A**: Halo
  - **B**: Bulge
  - **C**: Disk

Fritz Zwicky (1898 – 1974)



- Swiss immigrant to the US.
- He was a Professor of Astronomy at Caltech, and a research director/consultant for Aerojet Engineering Corporation.
- Made large contributions in jet engine design.
- In 1933, while studying motions of galaxies in the Coma galaxy cluster, he concluded that all ***visible matter*** was not enough to explain the motions. He postulated the existence of the invisible ***dark matter***. He was ridiculed.

Measuring Masses



- In a rotating system, centrifugal force balances gravity:

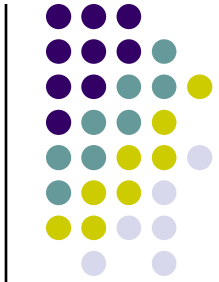
$$M\frac{V_{\rm rot}^2}{R} = \frac{GM^2}{R^2}$$

- In an elliptical system, the pressure of random motions of stars balances gravity:

$$M\frac{V_{\rm rand}^2}{R} = \frac{GM^2}{R^2}$$

- This is simply the third law of Kepler!

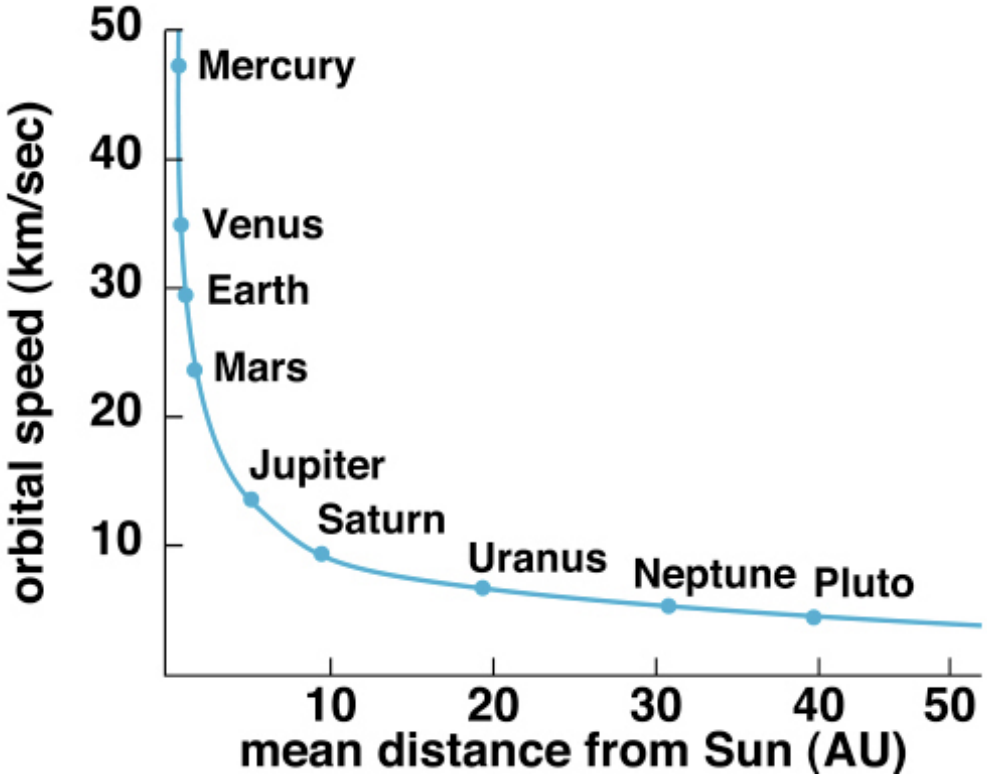
Thank You, Kepler!



- Cancel one M: $$\frac{V^2}{R} = \frac{GM}{R^2}$$
- Re-arrange: $$\frac{RV^2}{G} = M$$
- A miracle! We got the mass of something we cannot put on a scale or even reach!

Rotation Curve

- Rotation curve plots orbital velocities of rotating bodies versus their distance from the center.
- A rotation curve for the Solar system has a definite shape – ***Keplerian rotation curve***.

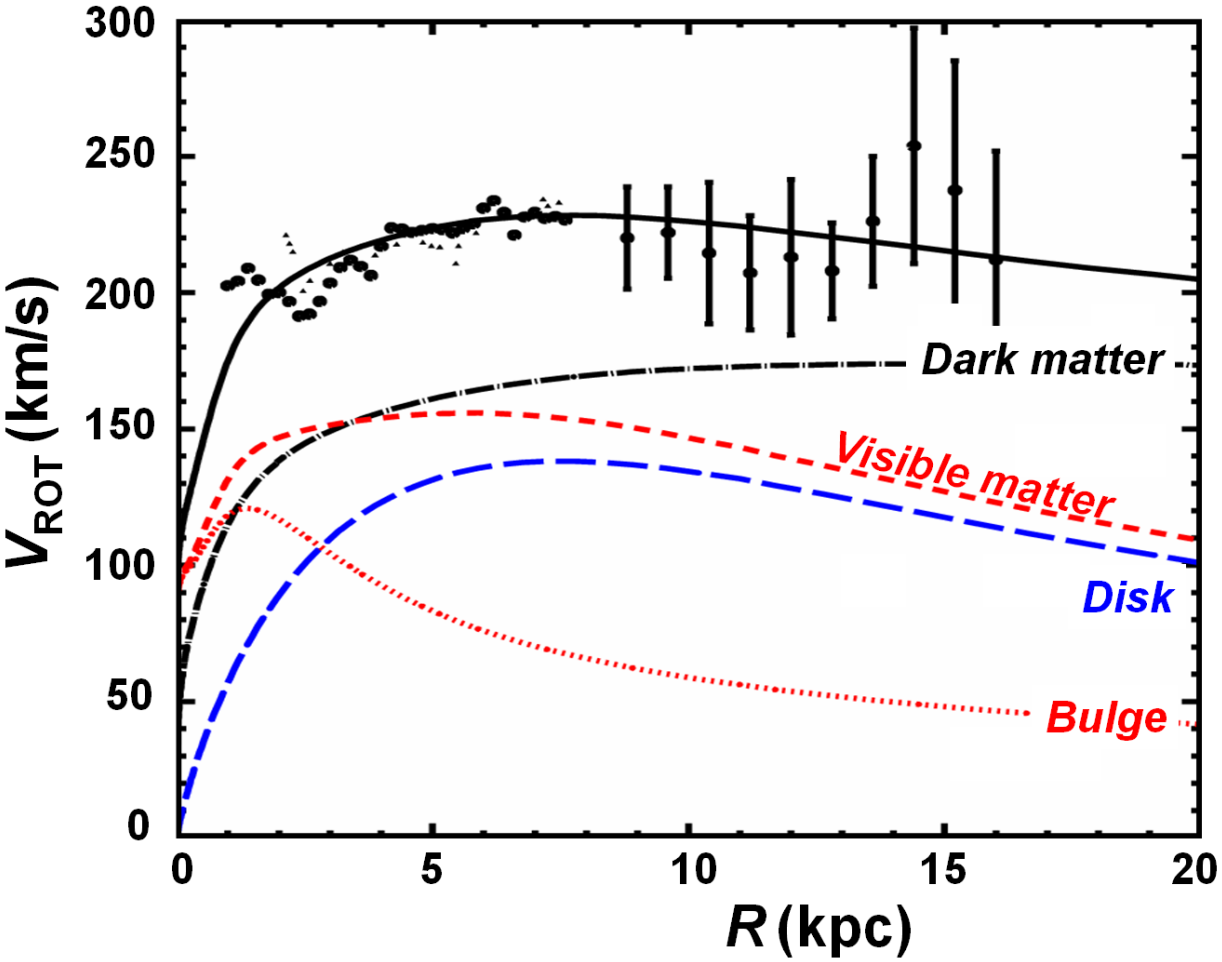


Rotation Curves in Spiral Galaxies

- In 1959, Louise Volders found that spiral galaxy M33 rotates faster than it should.
- In 1975, Vera Rubin presented her measurements of rotation of several spiral galaxies. Rotation curves were “flat”, very different from Keplerian.
- Using these observations, Jerry Ostriker & Jim Peebles estimated the masses of typical spiral galaxies. These masses were 10 times higher than the total mass of the disk, the bulge, and the stellar halo.

Galactic Rotation Curve

- In the Milky Way stars rotate way too fast for its mass – it must contain invisible ***dark matter***!

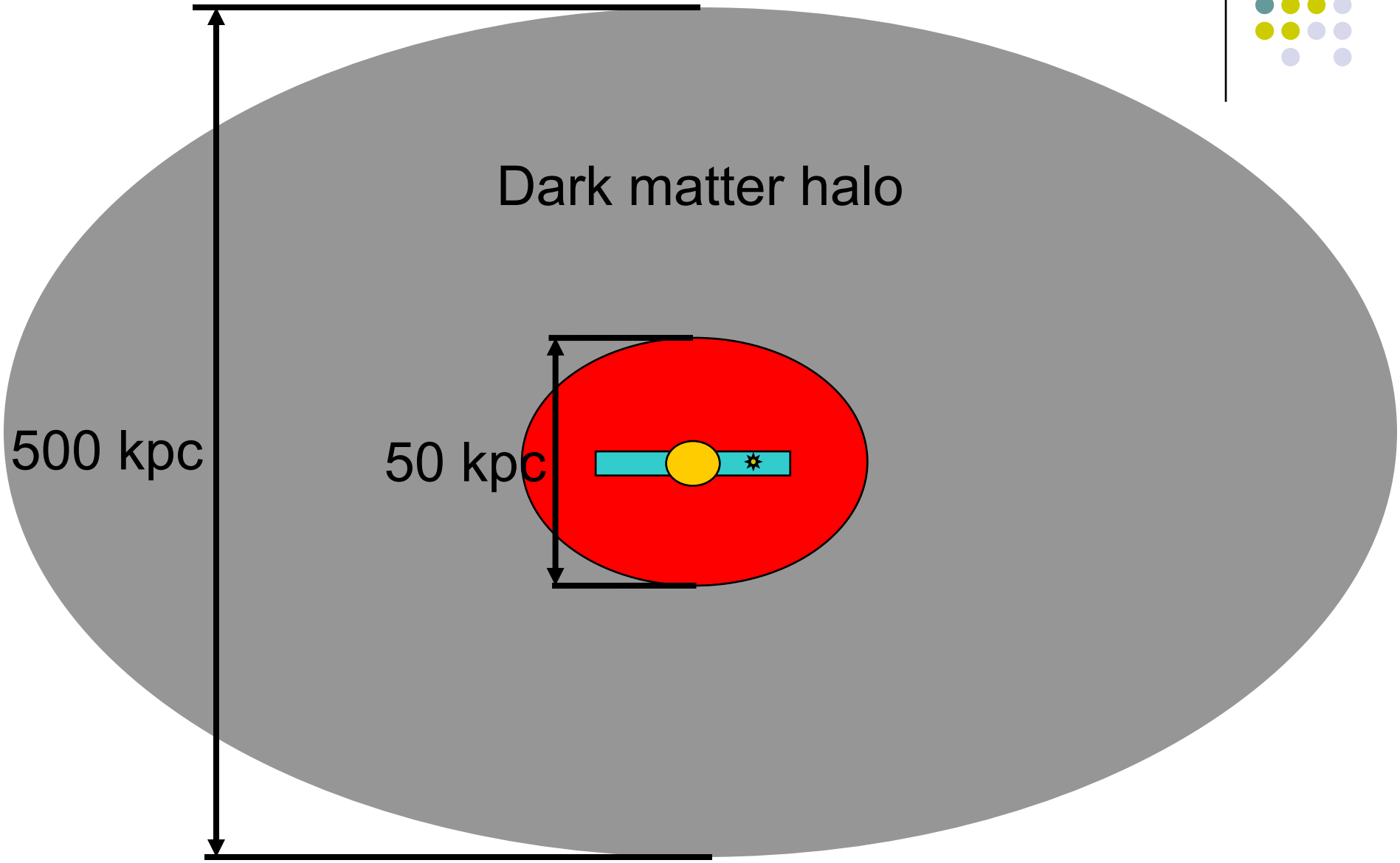


From the work of Anatoly Klypin, HongSheng Zhao, & Rachel Somerville.

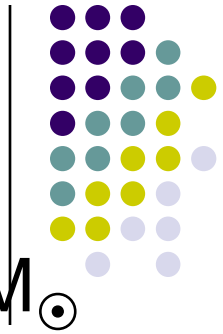
Dark Matter Halo

- The Galaxy is thought to have an extended (250 kpc) halo of dark matter.
- The halo is quasi-spherical, but its precise shape is not known.
- The nature of the dark matter is currently unknown – it is the main topic of modern cosmology. A multitude of astronomical observations and physics experiments are aimed at uncovering this mystery.
- We are not venturing into that domain…

Scales



Mass of the Milky Way



- Dark matter halo: $9 \times 10^{11}\ M_\odot$ = 900 billion $M_\odot$
- Stellar & gas disk: $5 \times 10^{10}\ M_\odot$ = 50 billion $M_\odot$
- Stellar bulge: $1 \times 10^{10}\ M_\odot$ = 10 billion $M_\odot$
- Gaseous halo: $3 \times 10^{9}\ M_\odot$ = 3 billion $M_\odot$
- Stellar halo: $1 \times 10^{9}\ M_\odot$ = 1 billion $M_\odot$

- Total: $1 \times 10^{12}\ M_\odot$ = 1 trillion $M_\odot$