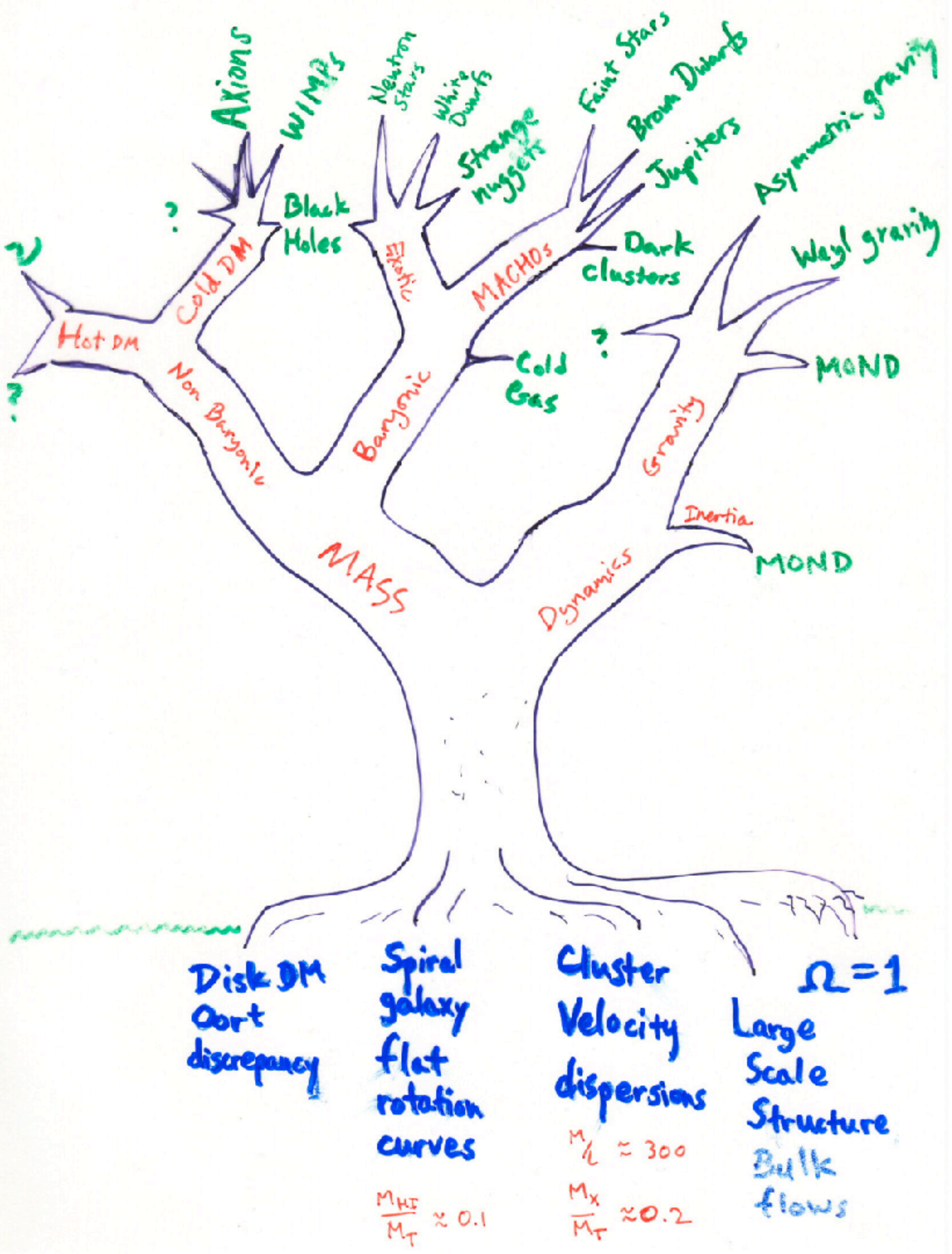
Dark Matter

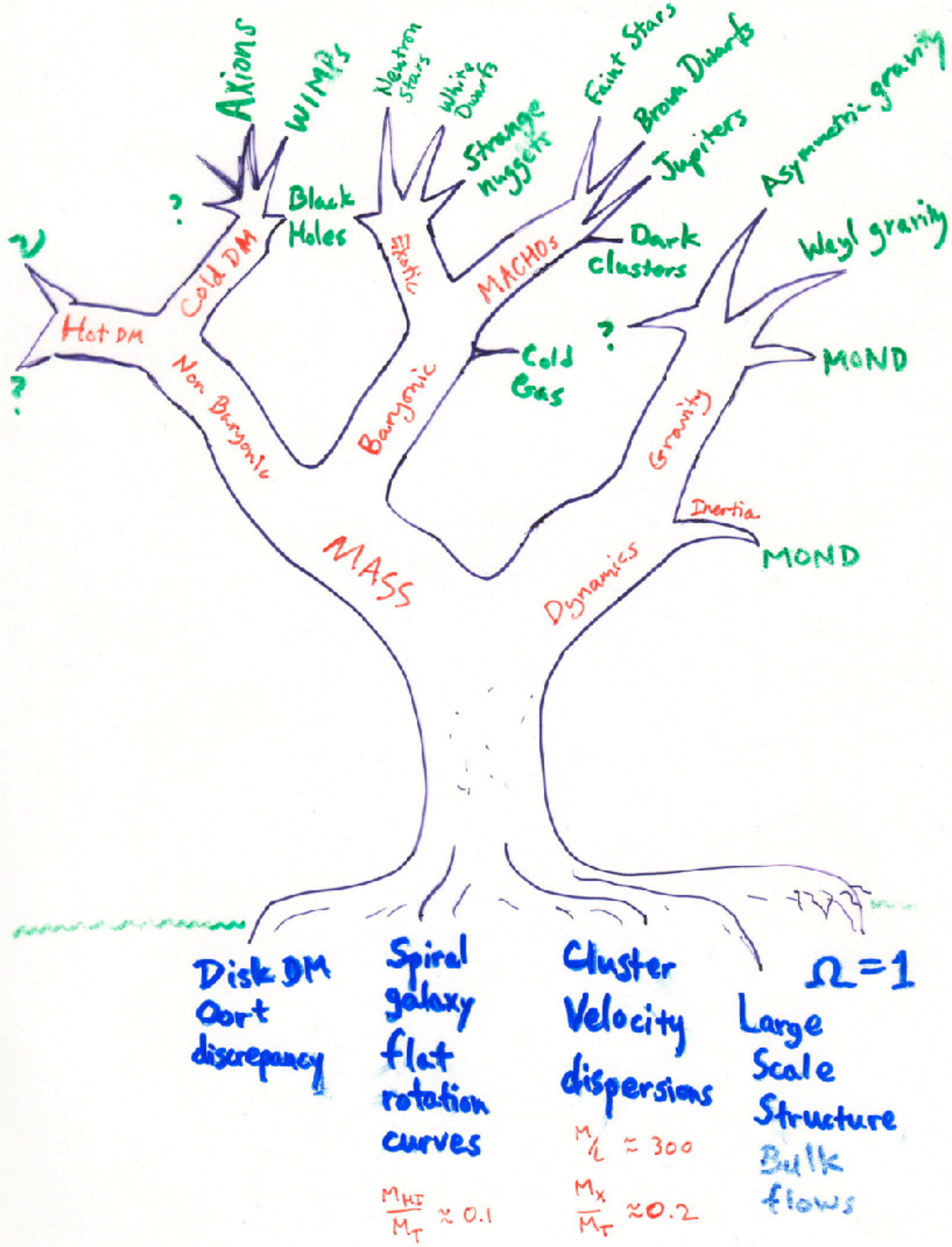
ASTR 333/433
Spring 2026
TR 11:30am–12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

Prof. Stacy McGaugh
Sears 558
368-1808
stacy.mcgaugh@case.edu



Case Western Reserve University
EST. 1826



Back to observations

Dark Matter has always been driven by data - specifically, astronomical observations of large structures like galaxies, clusters of galaxies, and the universe as a whole.

Zwicky's problem: clusters of galaxies

Coma cluster

See **Virial Theorem** in notes

Coma cluster velocity dispersion

Colless & Dunn 1996

N

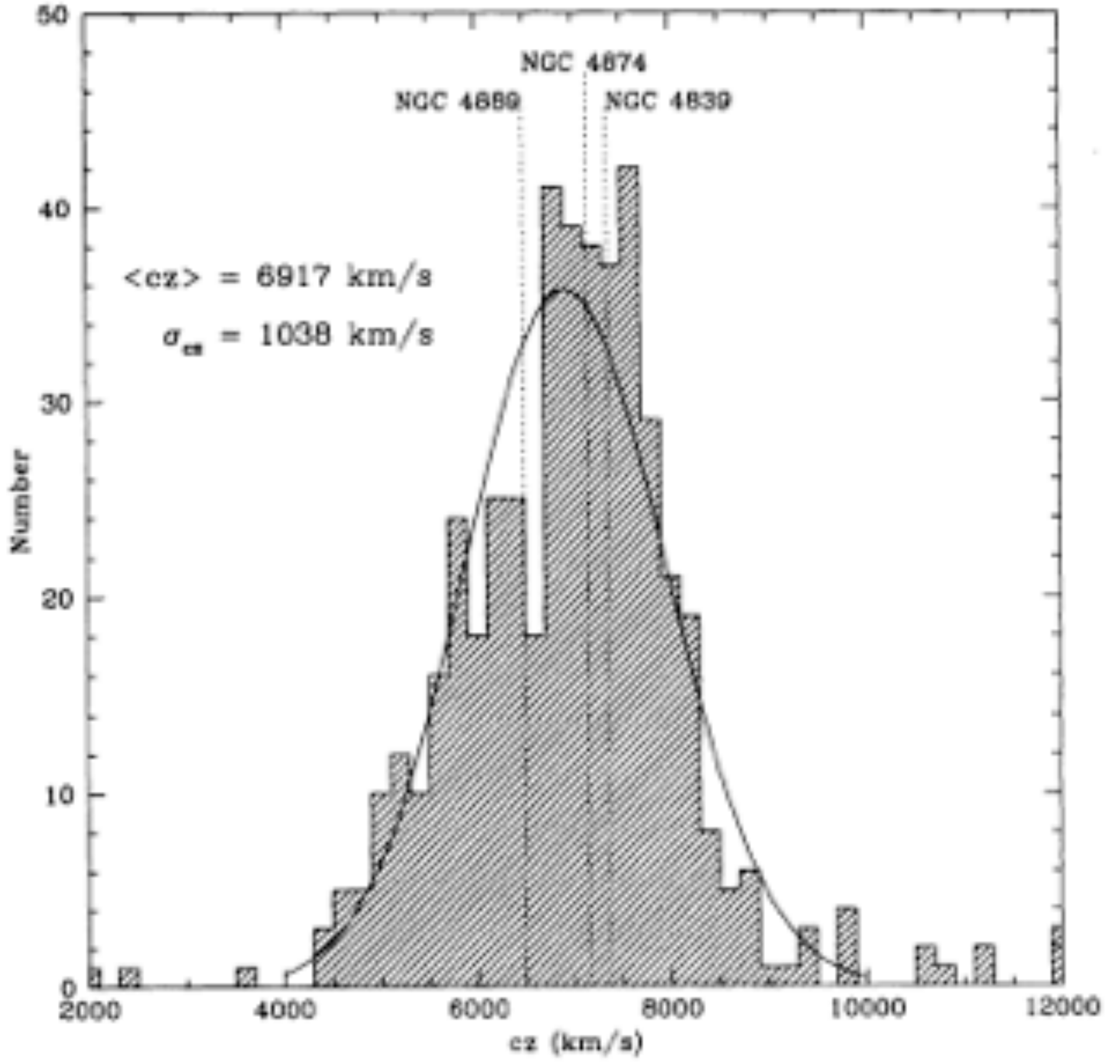


FIG. 5.—Distribution of radial velocities for galaxies in the Coma cluster. The curve is a Gaussian with mean 6917 km s^{-1} and standard deviation 1038 km s^{-1}. The velocities of the three dominant cluster galaxies are indicated.

Distribution of radial velocities for galaxies in Coma

Cluster observations are usually interpreted with the **Virial Theorem**.
This assumes the system is "virialized," which is to say, relaxed to an equilibrium configuration.

Galaxy clusters form late by the merger of smaller groups; it is not obvious that they have achieved this state.

See also the "Technical literature" course web page
https://astroweb.case.edu/ssm/ASTR333/revlit.html

the relative richness of the subclusters from this analysis.

An alternative visualization of the subclustering is provided by Figure 10, which shows the smoothed density of galaxies as a function of velocity and distance from the cluster center along the NE–SW diagonal [i.e., $(X + Y)/2^{1/2}$, with NE

projected galaxy distribution in the core of Coma centered on NGC 4874 and NGC 4889, it is no surprise to see that these two dominant galaxies are projected in the spatial dimension onto the primary and secondary peaks, respectively, in the core galaxy distribution. Contrary to naive expectation, however,

Coma (smoothed)

Clusters often exhibit substructure in phase space (lumps in both configuration and velocity). Kinda violates virial assumption. But the discrepancy is too large to be explained entirely by non-equilibrium effects.

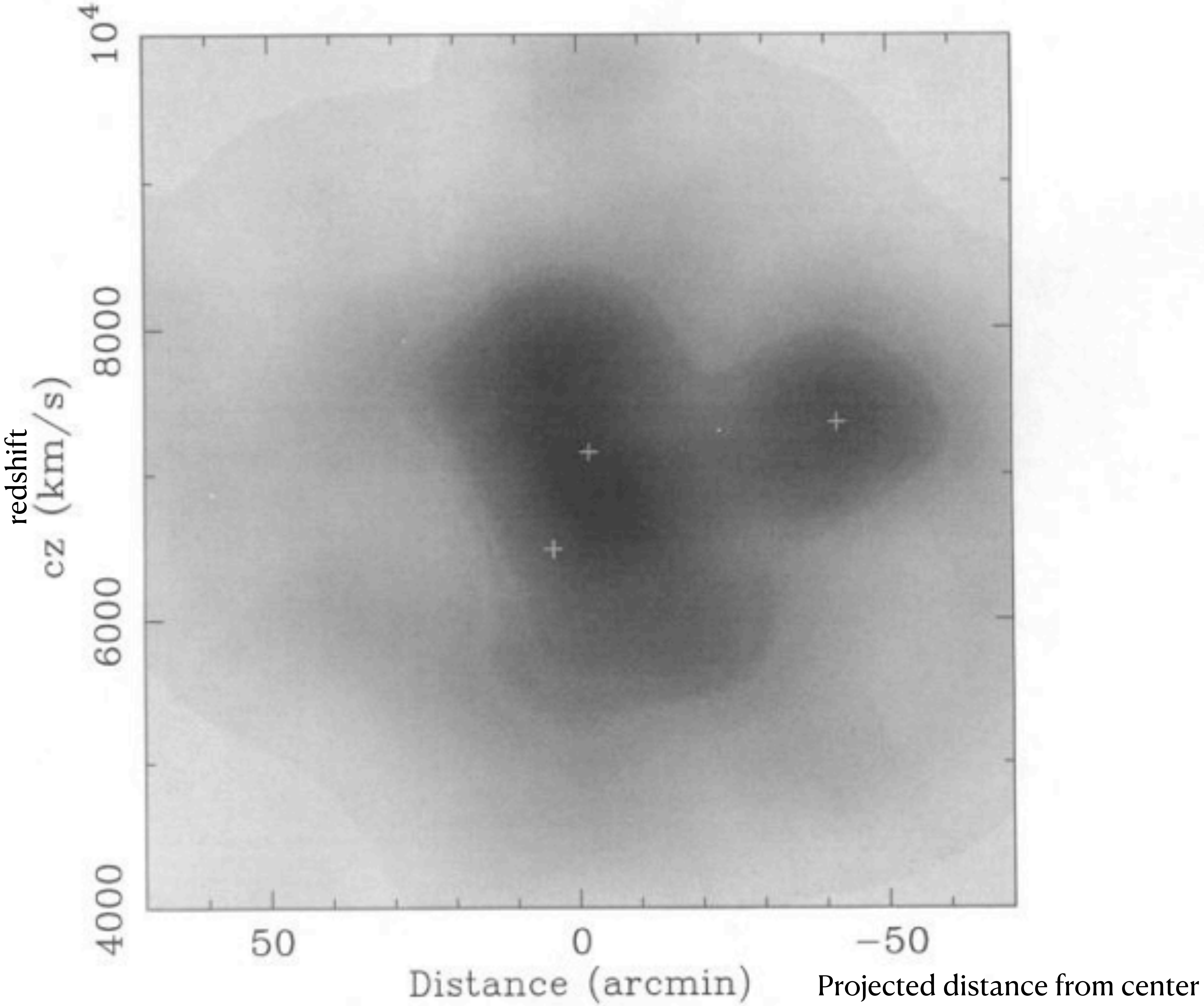


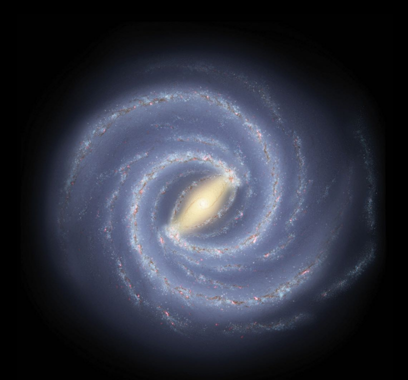
FIG. 10.—Galaxy density distribution projected onto the plane of radial velocity versus projected distance from the cluster center along the NE–SW diagonal (NE positive). The density is smoothed with a Gaussian of dispersion 8′ in the spatial dimension and 300 km s^{-1} in the velocity dimension. The positions of the three dominant galaxies are marked by crosses (*left to right*: NGC 4889, NGC 4874, NGC 4839). The gray scale is linear with density and runs from zero to the maximum.


Milky Way
(artisist's rendition)
informed by Spitzer data
You are here

Basic Picture:

Dark Matter Halo

Galaxies are embedded in extended, quasi-spherical halos of dark matter



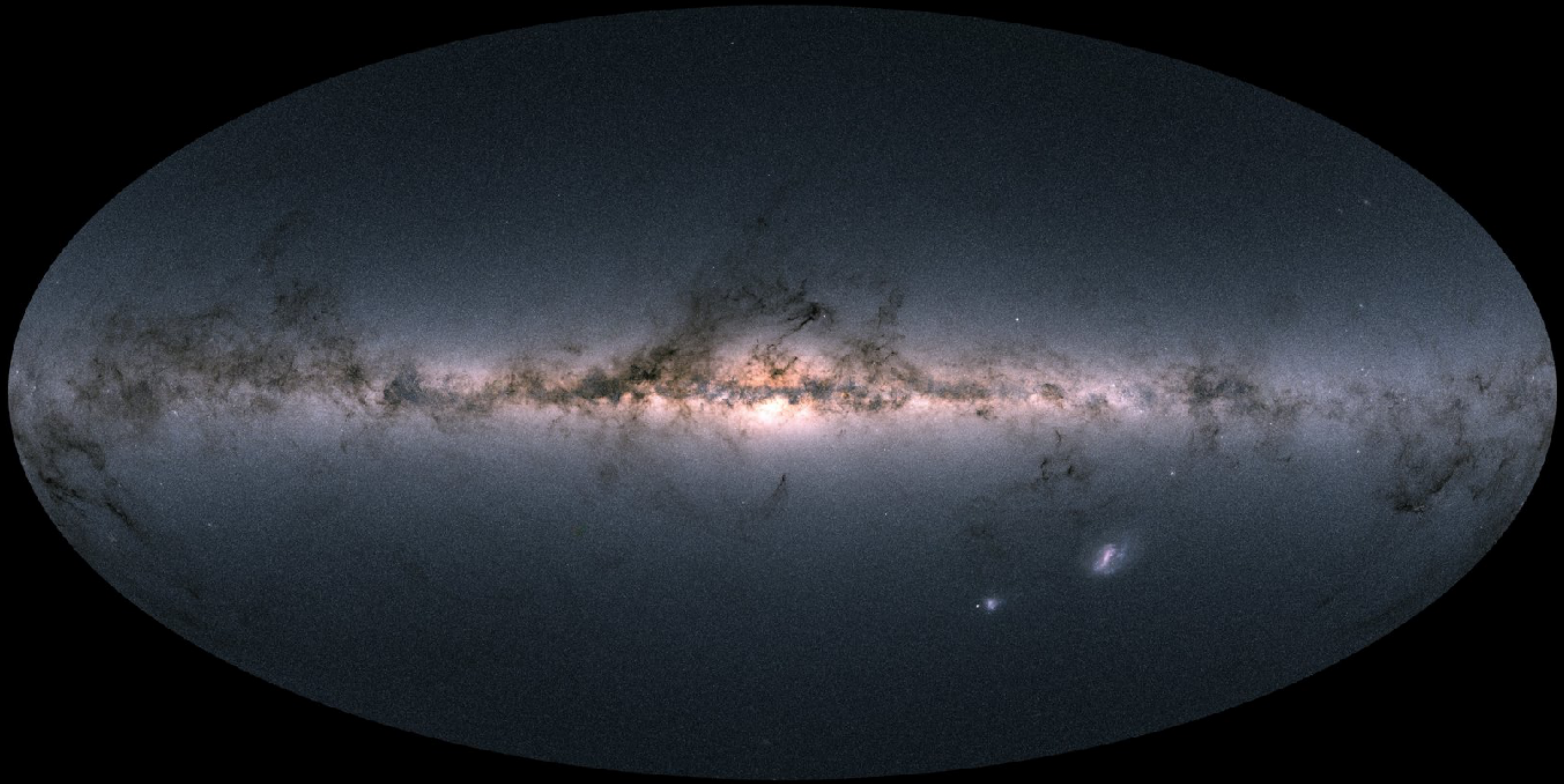
Luminous Galaxy
stars, gas, dust, etc.

There is no hard edge: there are some halo stars and warm/hot coronal gas mixed in with the dark matter

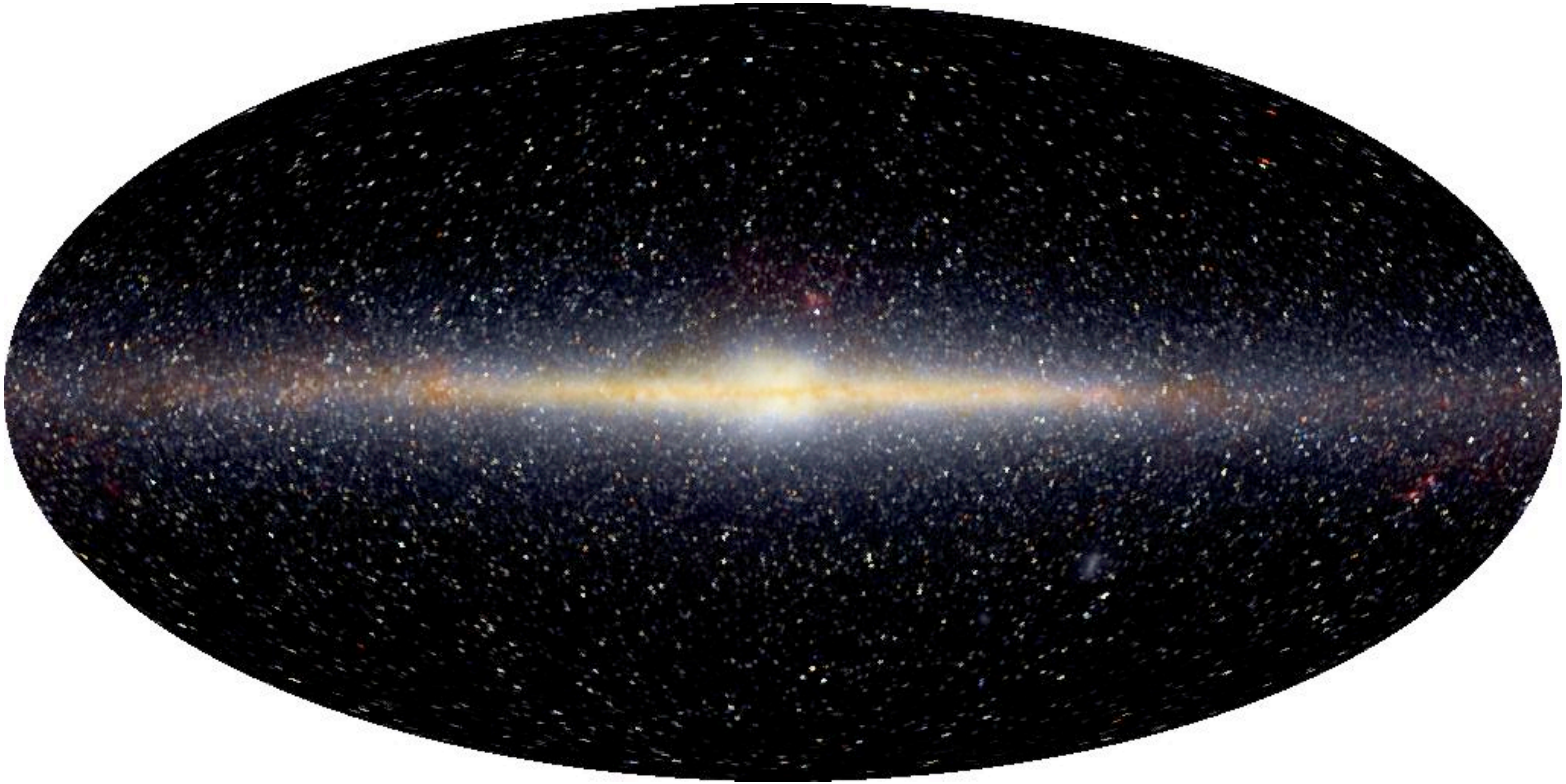
$R_{vir} \gg R_*$

The virial radius of the dark matter halo is much larger than the luminous galaxy

Milky Way in the optical (Gaia data)



Milky Way in the near-infrared (COBE data)



Baryonic Content of Galaxies

- **Stars**
  - Majority of baryonic mass in bright galaxies
- **Gas**
  - *Atomic gas* - H I
    - traced by 21 cm line Majority of baryonic mass in faint field galaxies
  - *Molecular gas* - H_2
    - traced by CO Mass usually a distant third to stars and atomic gas
  - *Ionized gas* - H II
    - traced by Hα Large volume but little mass where stars are; there might be a lot out to the virial radius.
- **Dust**
  - little mass, but it does get in the way.

Multi-wavelength Milky Way

relativistic electrons

atomic gas

ionized gas

molecular gas

warm dust

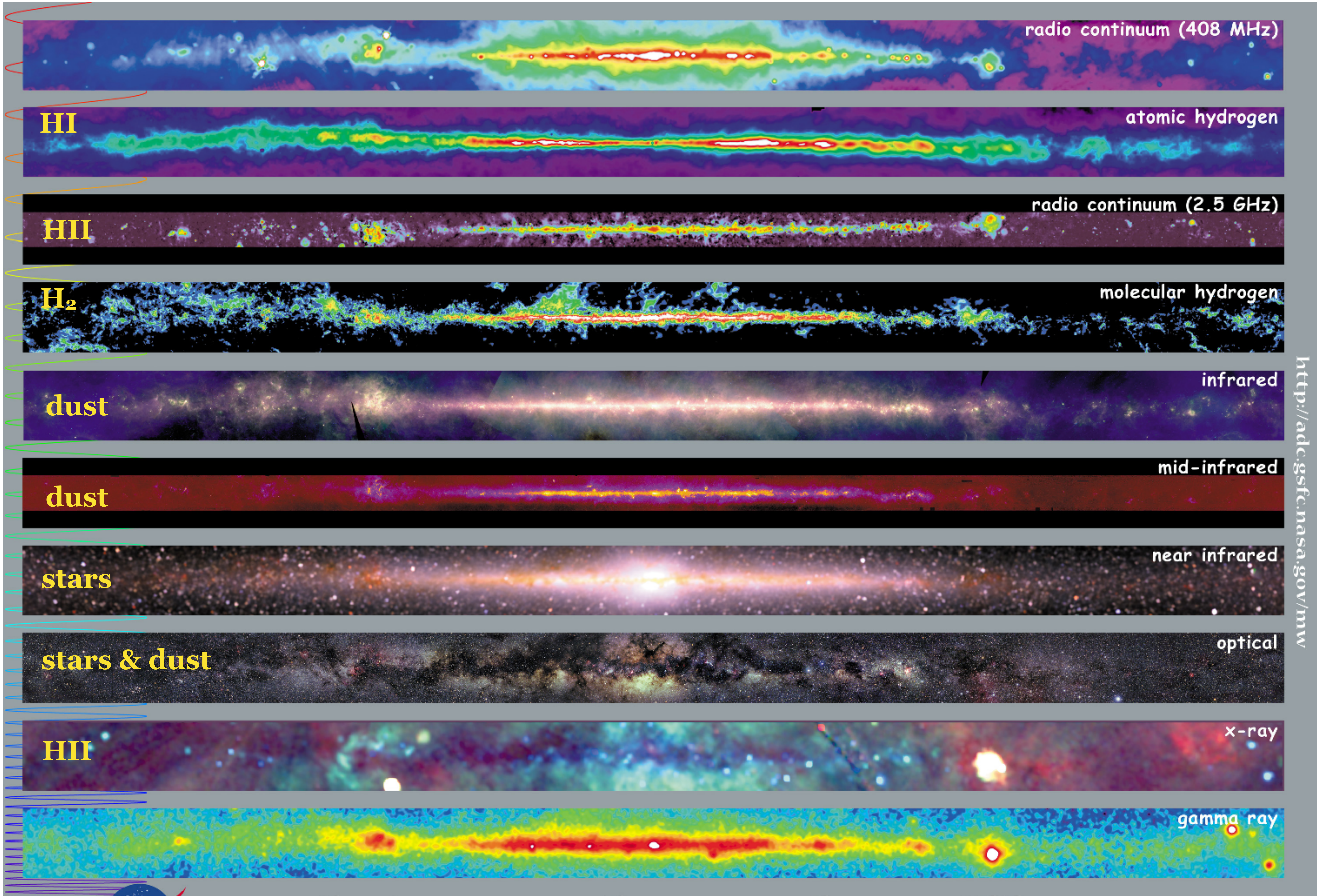
PAH dust

stars

stars & dust

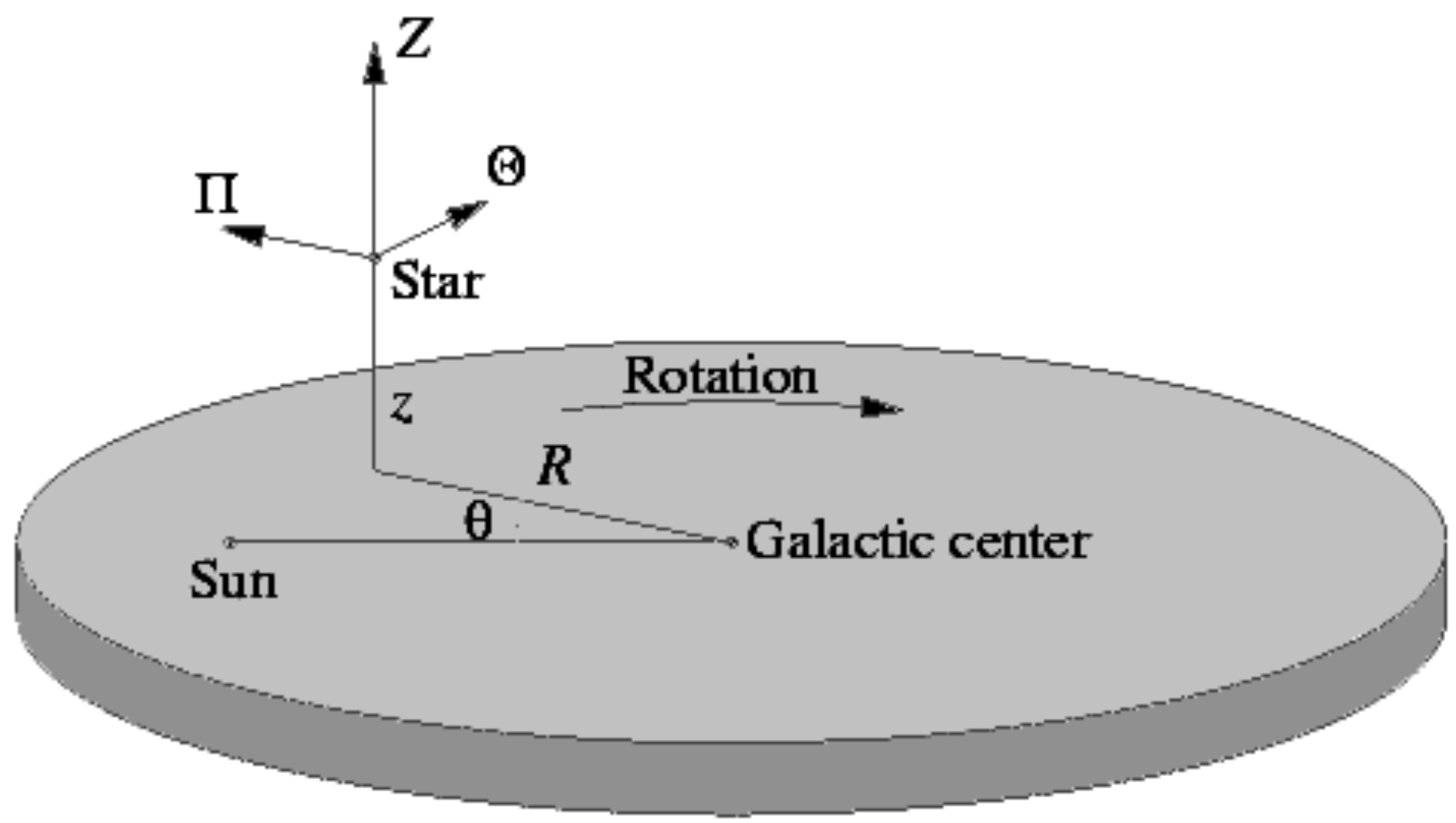
hot ionized gas

cosmic rays



Cylindrical coordinates

Let's define a coordinate system:



$$\text{Position} : (R, \theta, z) \quad \text{Velocity} : (\Pi, \Theta, Z)$$

- R = galactocentric distance
- theta = azimuthal coordinate
- z = height above/below the plane

- Pi = velocity in/out from center
- Theta = tangential velocity
- Z = velocity up and down

OR (X,Y,Z) centered on either the sun or the G.C.

Oort limit - imagine the disk as a plane parallel slab

First, think of balancing KE with PE for a small mass m orbiting a big mass M: $\frac{1}{2}mv^2 \sim \frac{GMm}{r}$

So we can solve for the big mass M: $v^2 \sim \frac{2GM}{r}$

Now, instead of a big mass M, think of a circular patch of radius r and surface density Sigma (in M_{sun}/pc^2). It has a total mass: $M \sim \Sigma_0 \pi r^2$

So plug that in and get $v^2 \sim 2\pi G \Sigma_0 r$

Or, now thinking about a group of stars: $\sigma_z^2 \sim 2\pi G \Sigma_0 z_0$

So if we measure velocity dispersions and scale heights for groups of stars, we can measure the mass density of the Galaxy's disk. This was first done in the early 1960s by Jan Oort and is called the Oort limit. A recent (and more sophisticated) analysis gives ~ 70 M_{sun}/pc^2.

Now let's just add up all the mass we see:

Stars	25 M_{sun}/pc^2
Stellar remnants (mostly WDs)	20 M_{sun}/pc^2
Gas (HI+H2)	5 M_{sun}/pc^2
Total	50 M_{sun}/pc^2

From **Sparke & Gallagher**

Are we happy with these sums?