An introduction to

Milky Way Formation

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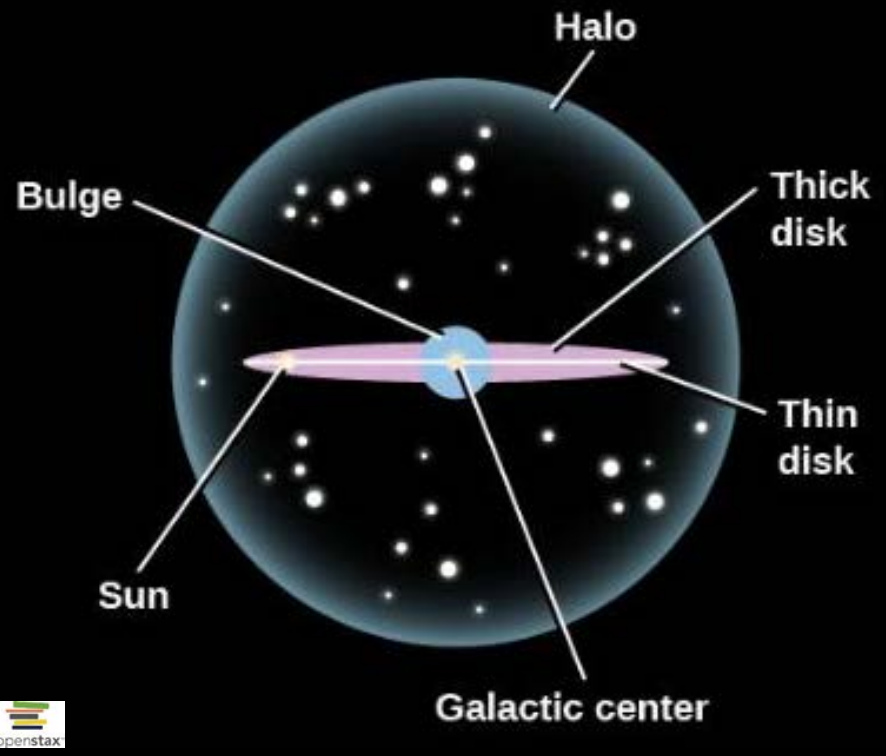
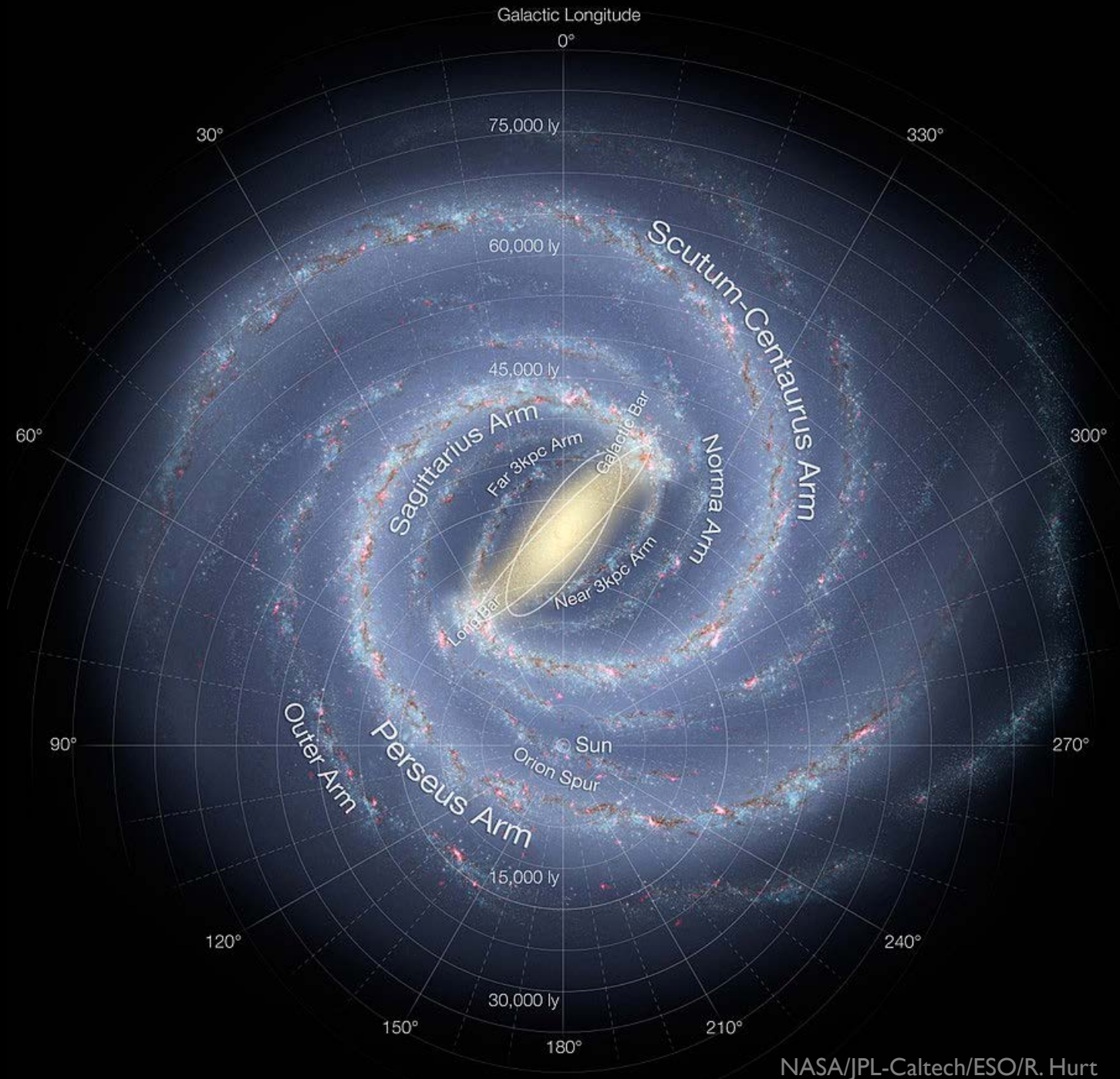
How did the Milky Way wind up looking like this?

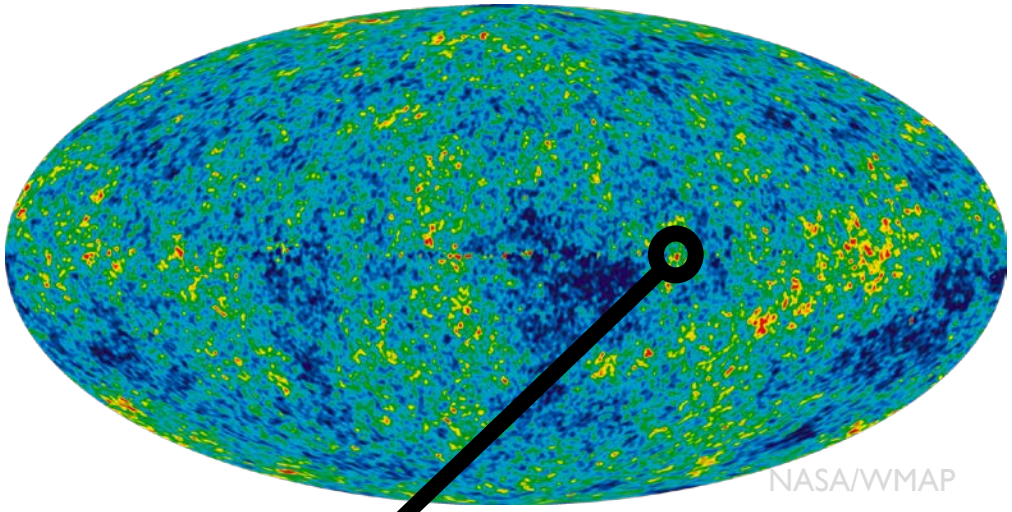


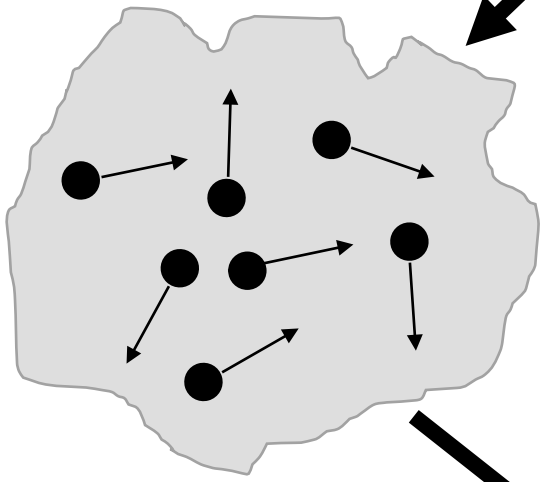


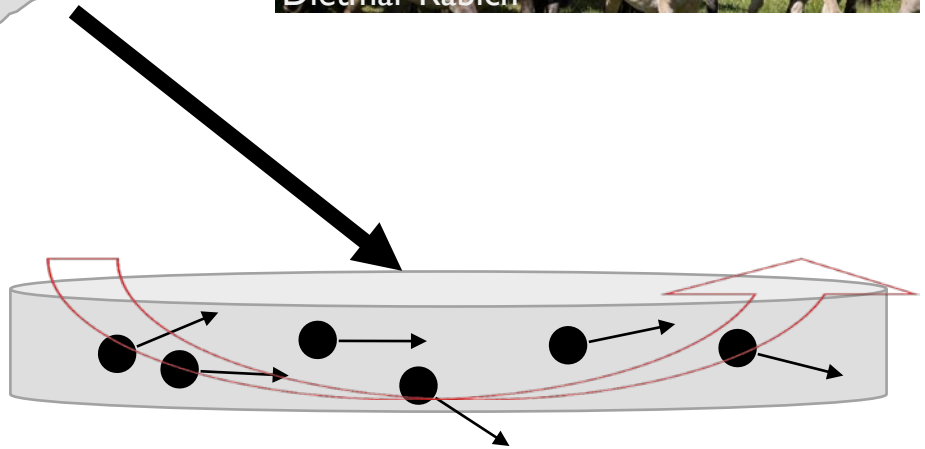
NASA/JPL-Caltech/ESO/R. Hurt

Disk formation

- Fluctuations in the early universe resulted in slightly higher-density regions, where the local gravity results in a gas cloud collapsing
- Particles in the cloud will have random motion, where the average motion is likely not zero.
  i.e. there will be some net rotation
- As gas particles collide, fewer and gentler collisions will happen to particles moving in the direction of rotation
- Thus, after a long time, the collapsing clump will form a disk
- Why isn't the dark matter concentrated in a disk too?
  It doesn't interact via electromagnetic interactions that are responsible for essentially all of the normal matter collisions





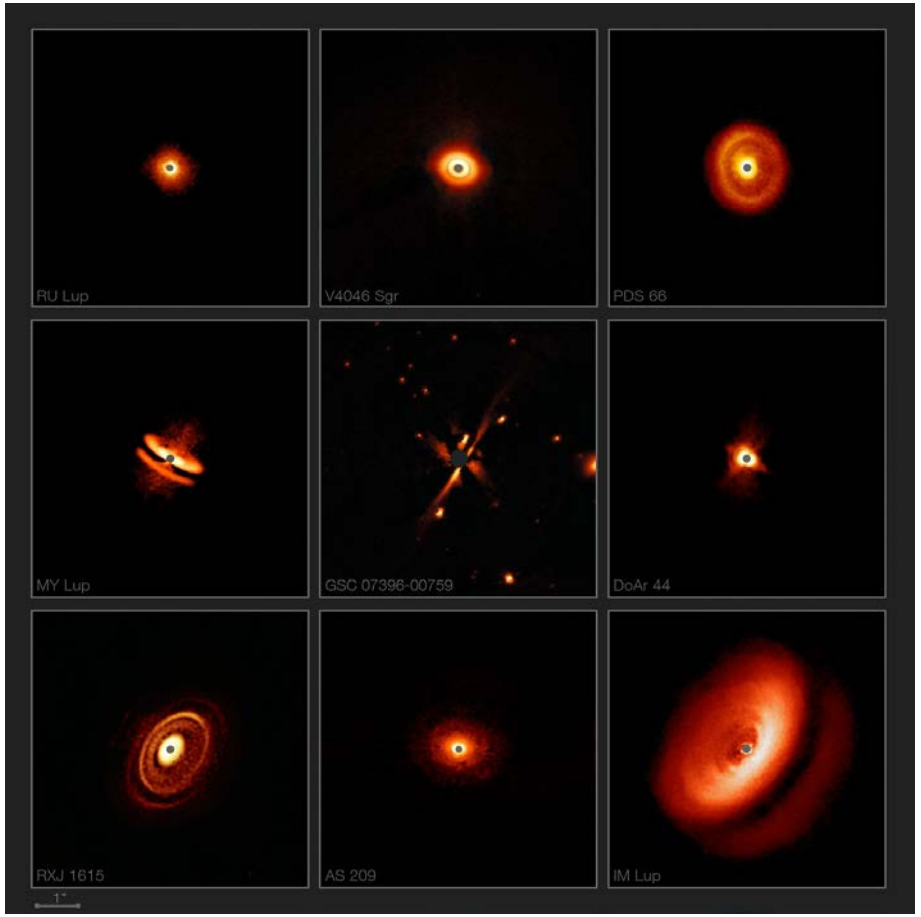


Disk formation

- Note that we see the same type of disk formation in young stellar systems, which is ultimately what leads to stellar systems with orbiting planets
- There can still be spherical-ish blobs of stars (e.g. globular clusters)
  - Stars collide infrequently compared to molecules in a cloud of gas
  - So there aren't enough collisions to force a disk-like shape

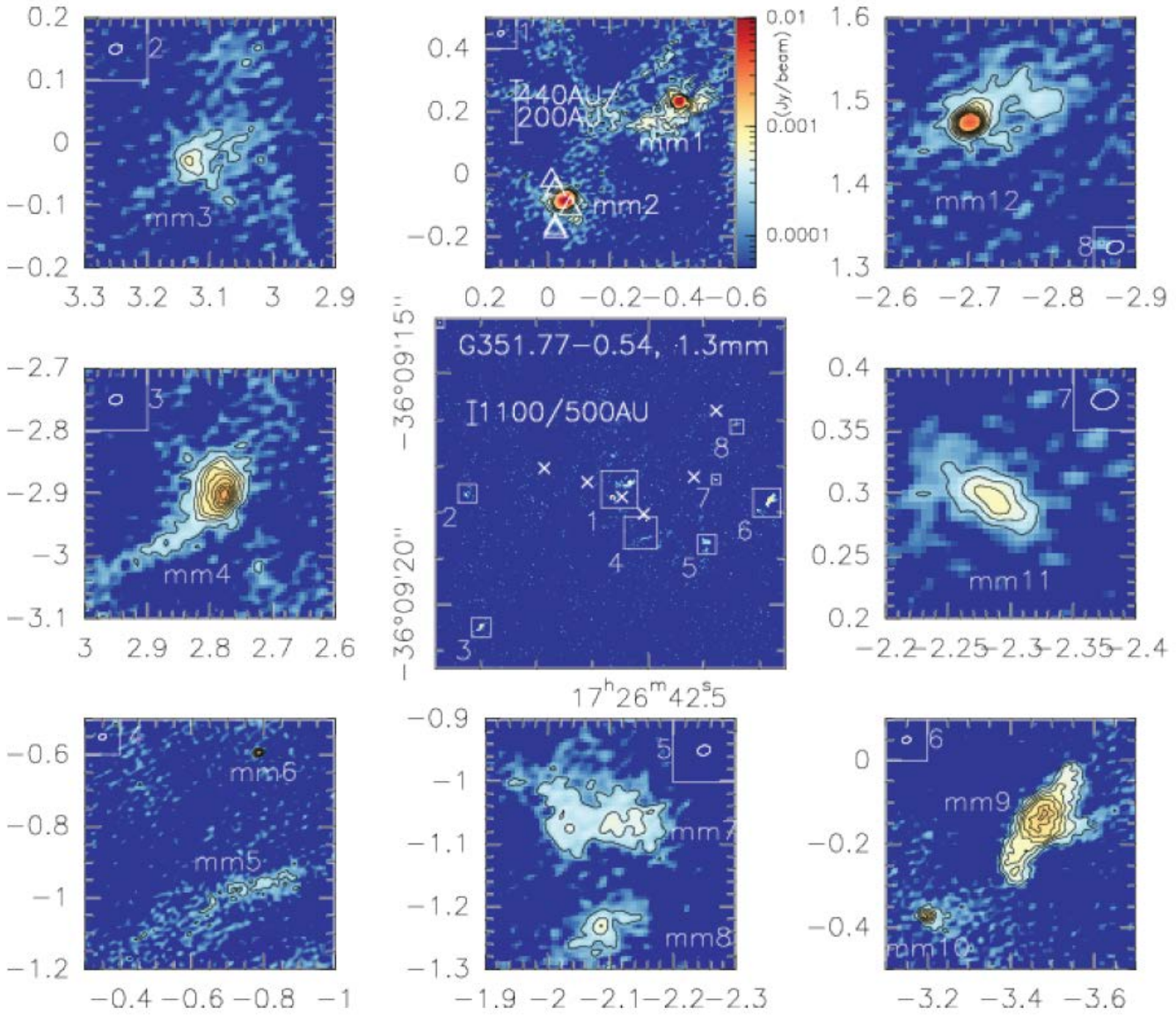
NASA/STScI/AURA

ESO/H.Avenhaus et al./E. Sissa et al./DARTT-S/SHINE



Star and star cluster formation

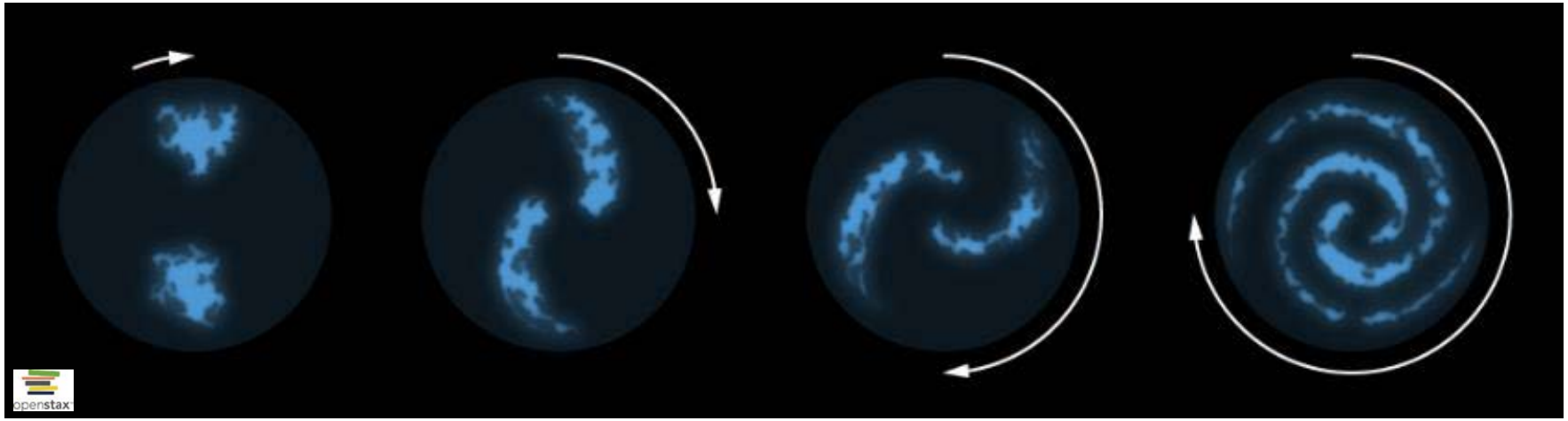
- Just as overdense regions of gas clump to form galaxies, overdense regions within the proto-Galaxy (and mature Galaxy) clump to form stars
- Stars are often formed in groups, since collapsing gas-clouds fragment and because radiation from stars helps create more overdense regions
- Tightly spaced groupings of stars in the Galactic halo are known as globular clusters



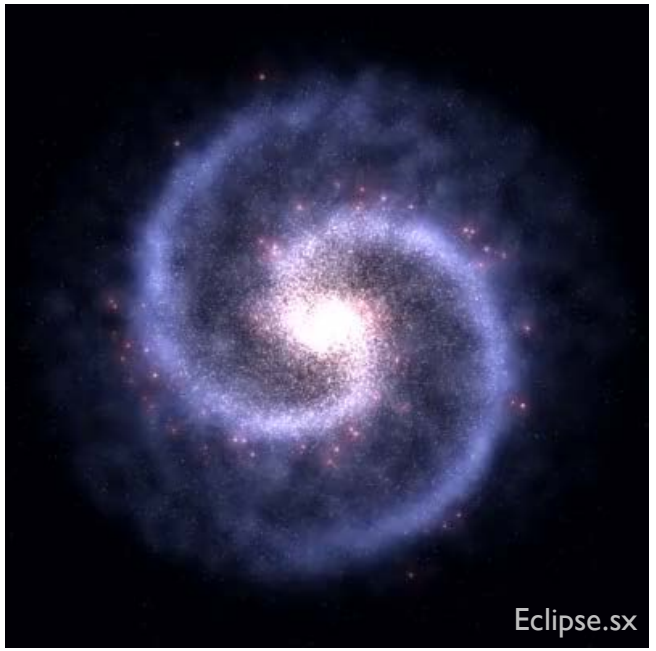
H. Beuther et al. A&A 2019 / ALMA

Spiral structure formation

- Objects orbiting a central point are acted on by gravity and feel a centrifugal force
- Equating the two forces results in Kepler's 3rd law: objects that are further out orbit slower
- This differential rotation would produce spirals
- …but also destroy them
- "Winds" from star formation and stellar explosions could perpetuate the arm structure



- Alternatively, "density wave theory" says there are regions with higher density that stars pass in & out of
- The galaxy rotates, but the spiral structure does not



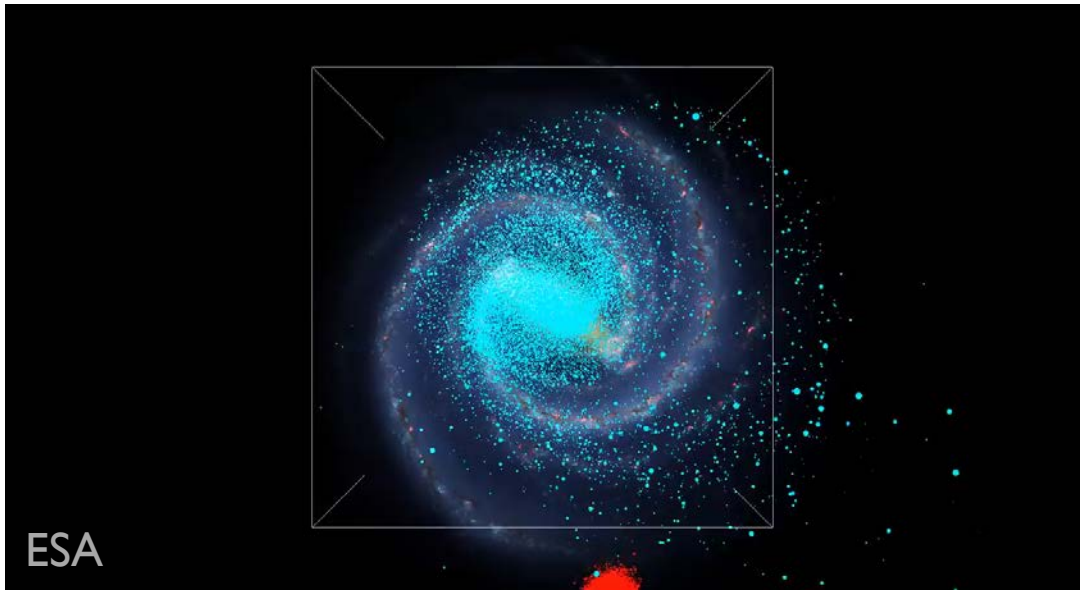
Bulge formation

- The Galactic center would naturally be the place with the highest concentration of matter upon formation of the Milky Way
- So, there's going to be a lot of stuff there

Except collisions are as (or more) important

- We just covered the "monolithic collapse" model, in which a large cloud of gas breaks up to form small stuff
- A competing idea is one of multiple mergers, where lots of small clouds of matter (including dark matter) were formed in the early universe and these combined to make the Galaxy
- The general processes and end result are similar to the monolithic collapse model
- Unique chemical signatures of groupings of stars show that several mergers have happened in the Milky Way in the past
- This also explains the puffy thick disk and the presence of the Galactic halo

This simulation is a reproduction of something like what is believed to have happened in the Milky Way ~10Gyr ago



https://www.youtube.com/watch?v=9fTGPkp-CJg

The fate of the Milky Way

- Andromeda is approaching at ~100 km/s and will collide with the Milky Way in ~4 Gyr
- Assuming Earth isn't flung to a different location, here is what the view would be:

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NASA; ESA; Z. Levay, R. van der Marel, STScI; T. Hallas, and A. Mellinger)