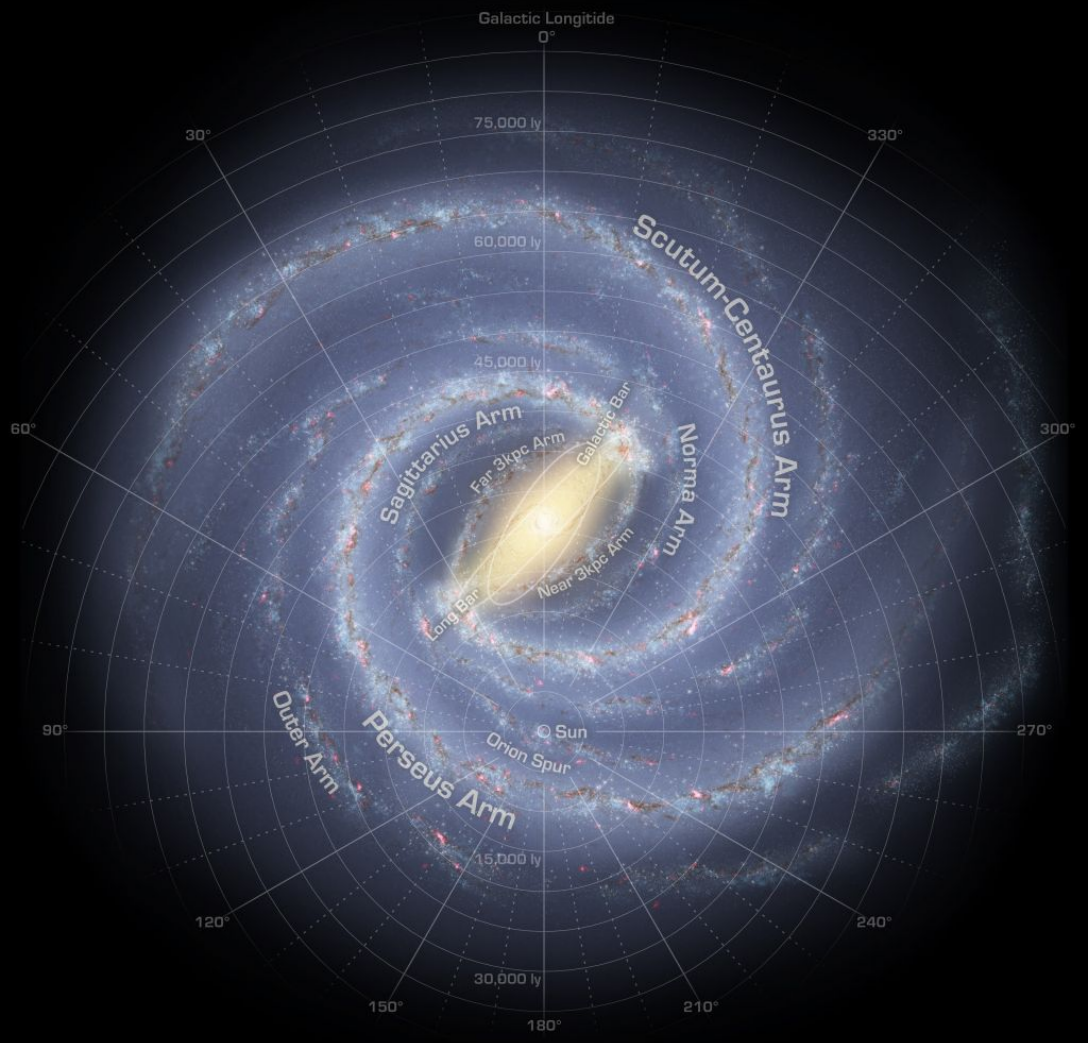
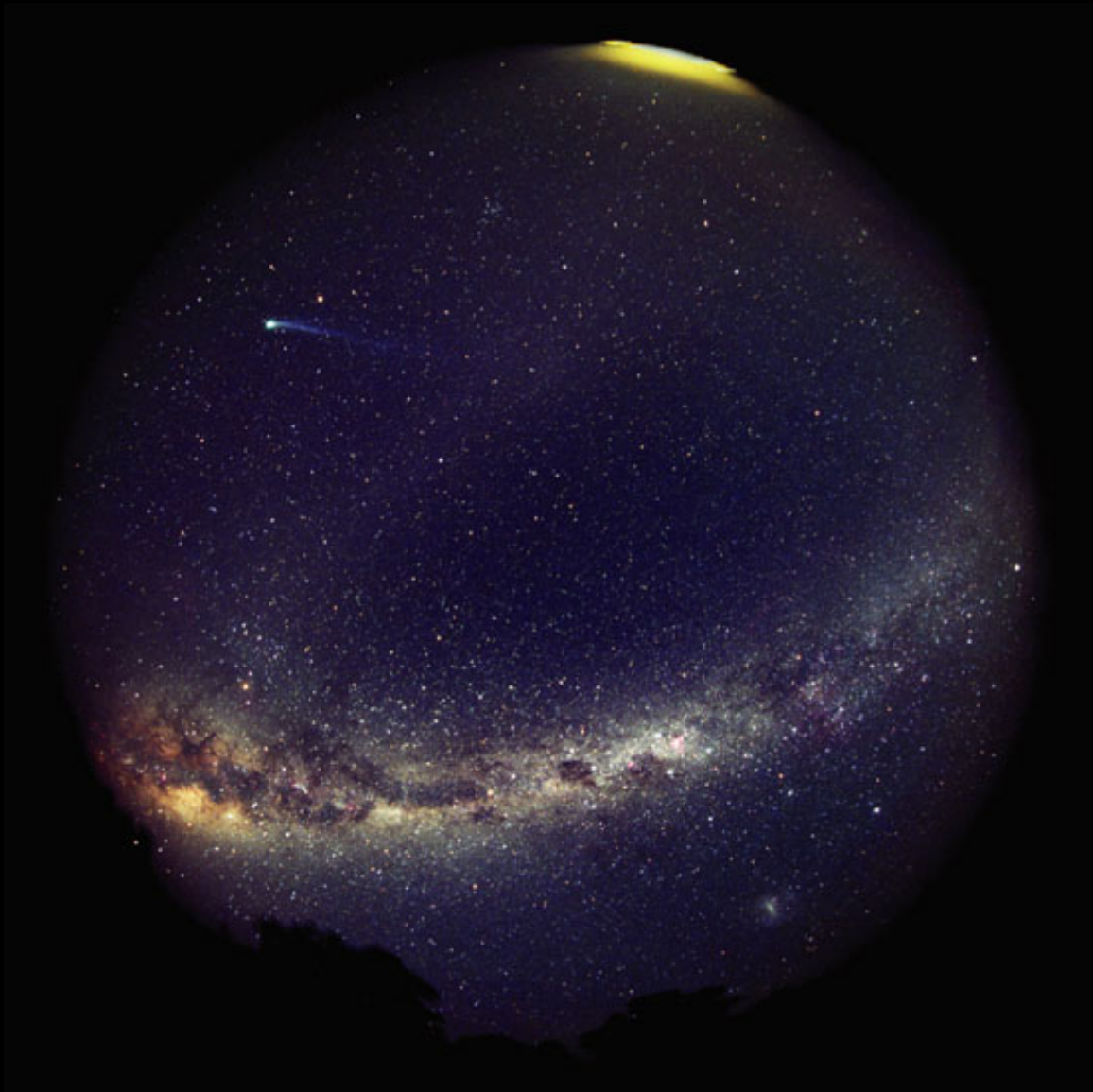
Lecture 21:
Our Galaxy, the Milky Way



What does the Milky Way look like?

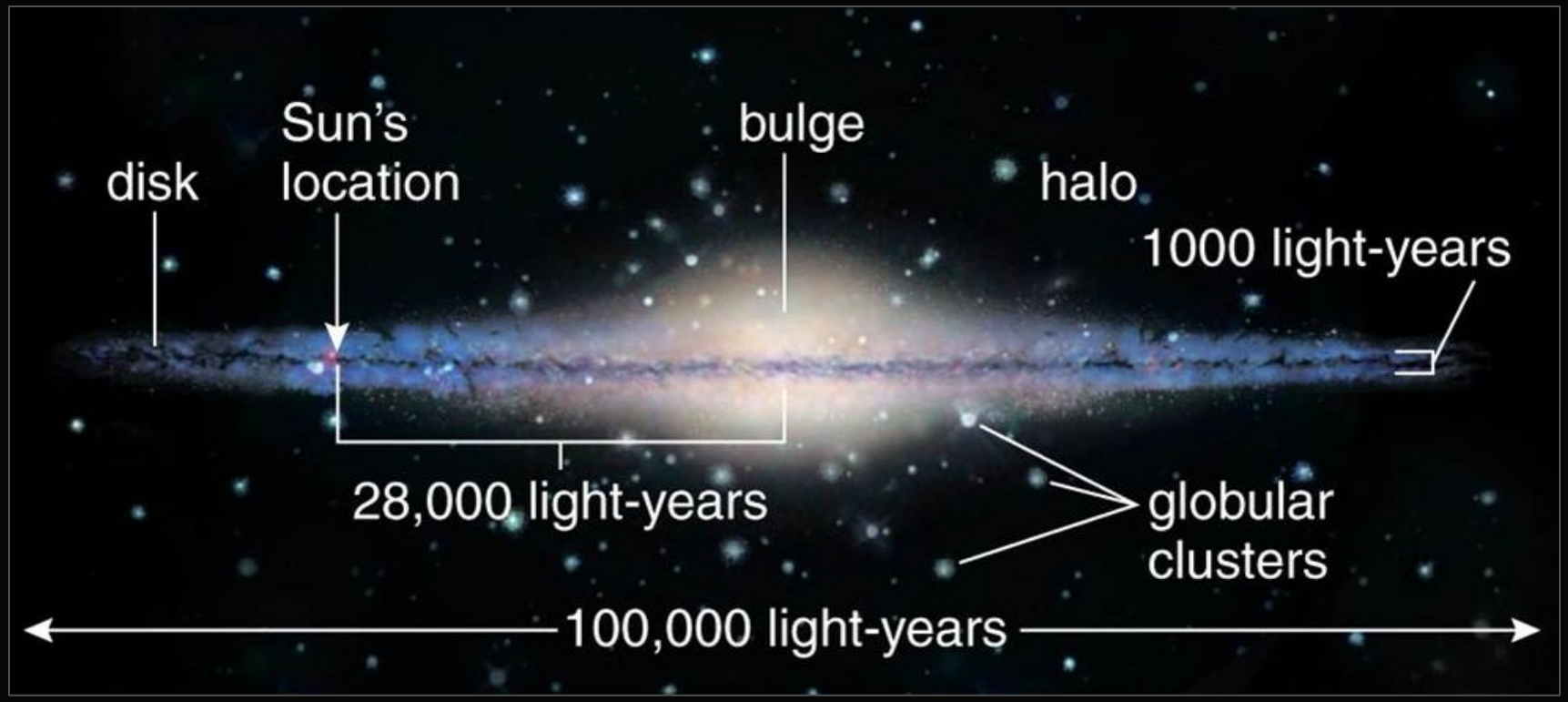
- This ***all-sky view*** shows the Milky Way's band of light
- Dusty gas clouds obscure our view - they absorb visible light.
- This ***interstellar medium*** makes new star systems.



Our galaxy – the Milky Way

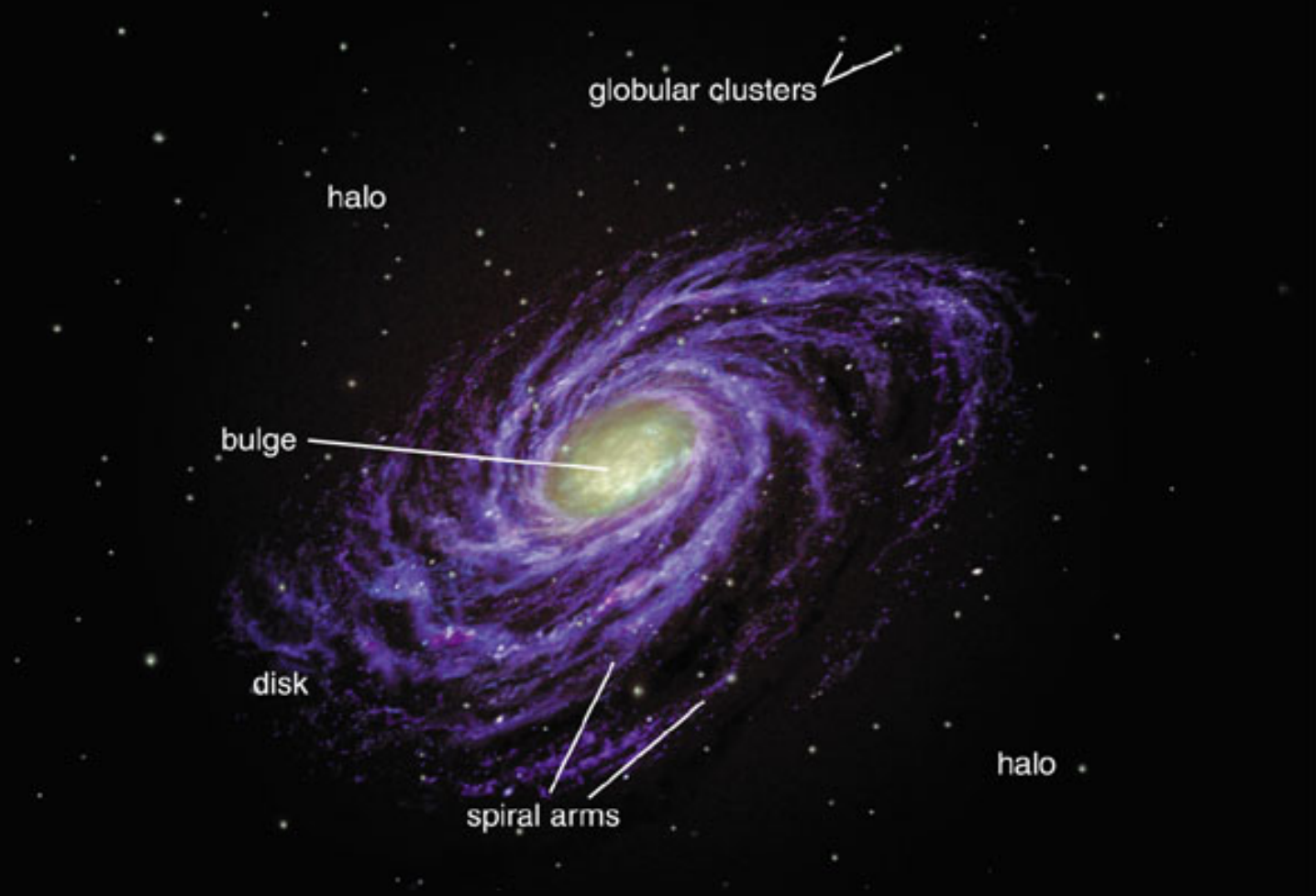
- All-sky map of Milky Way seen from inside
- Composed of *billions* of stars, much gas, dust

Our galaxy – the Milky Way



- We see our galaxy edge-on.
- Primary features: disk, bulge, halo, globular clusters

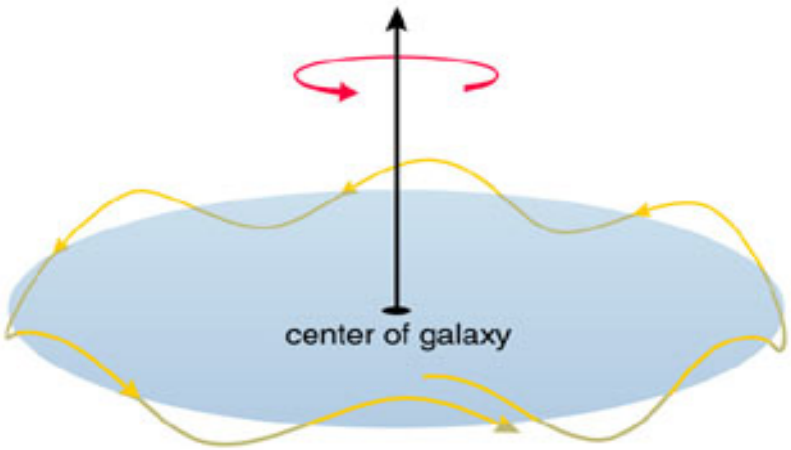
Our galaxy – the Milky Way

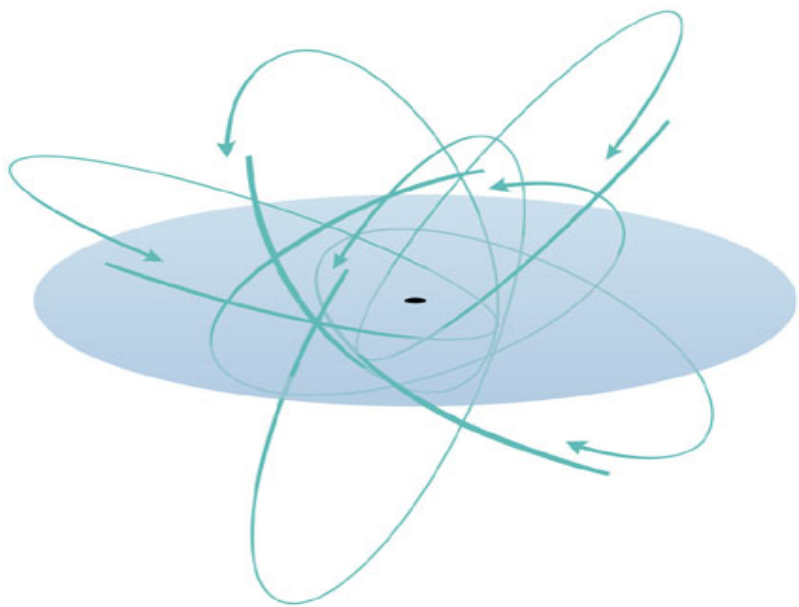


If we could view the Milky Way from above, we would see its spiral arms.

PLAY Structure of the Milky Way Galaxy

How do stars orbit in our galaxy?

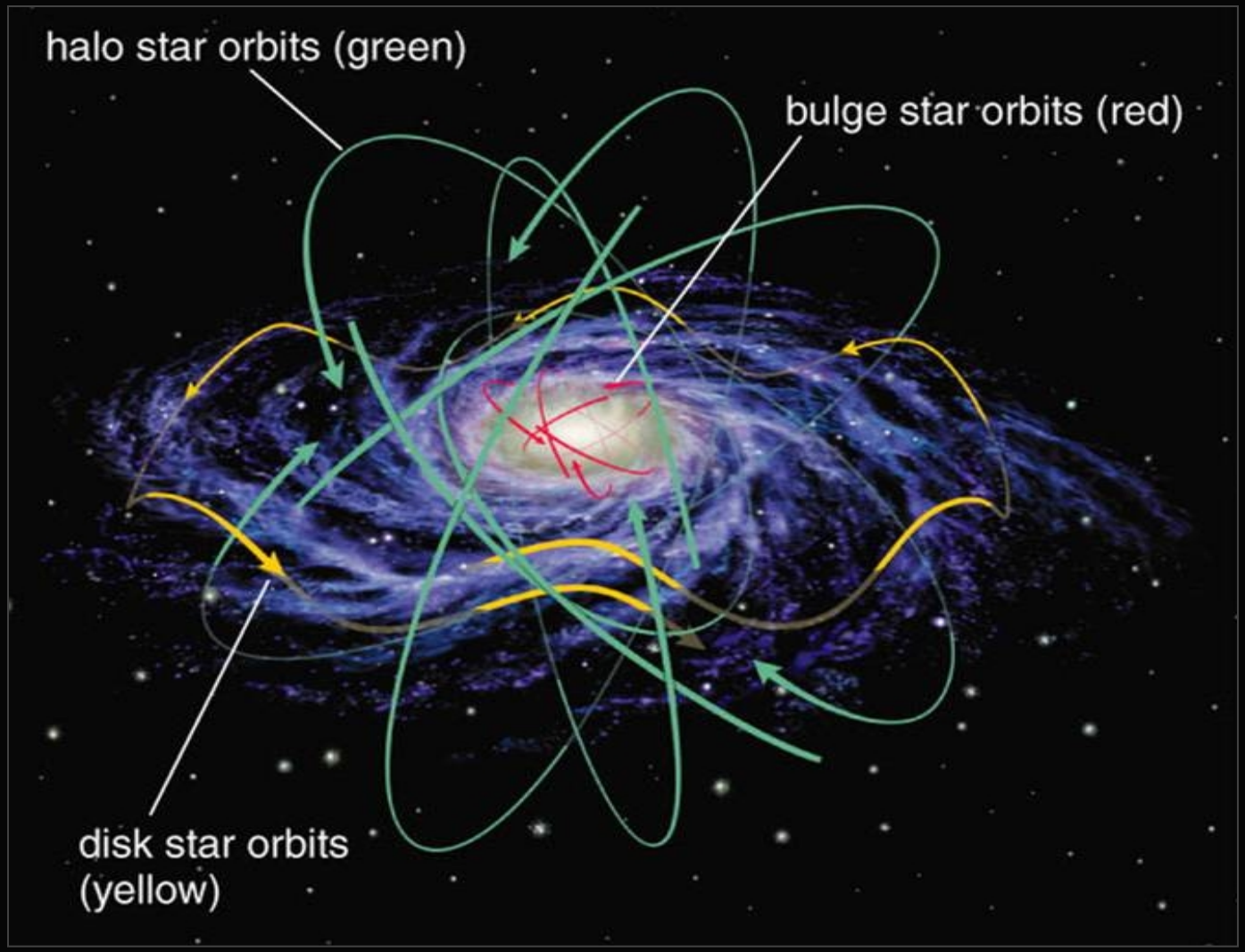




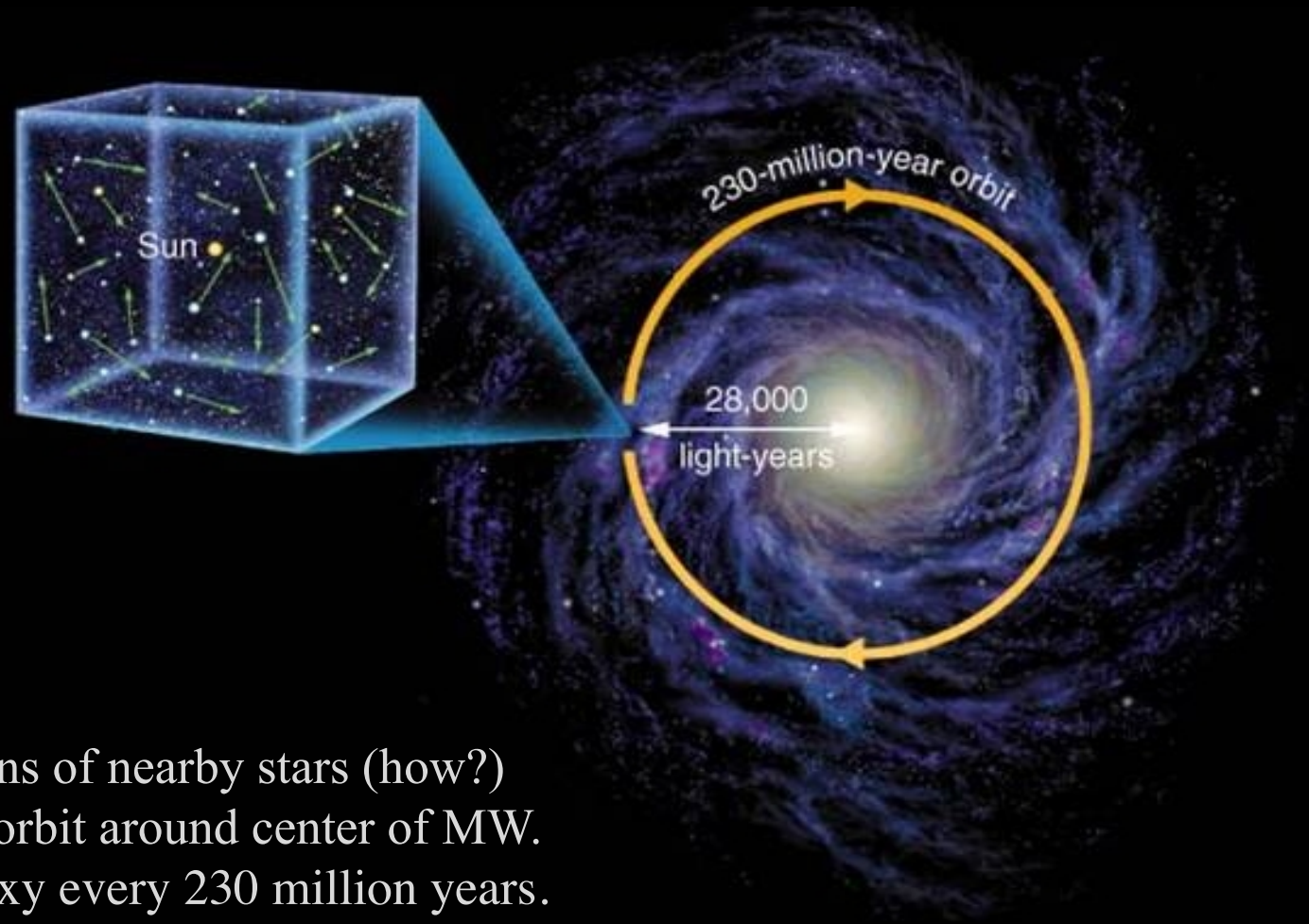
- Stars in the **disk** orbit in the same direction with a small up-and-down motion, roughly circular orbits

- Orbits of stars in the **bulge** and **halo** have random orientations, elliptical orbits

Stellar orbits



The Sun's orbit



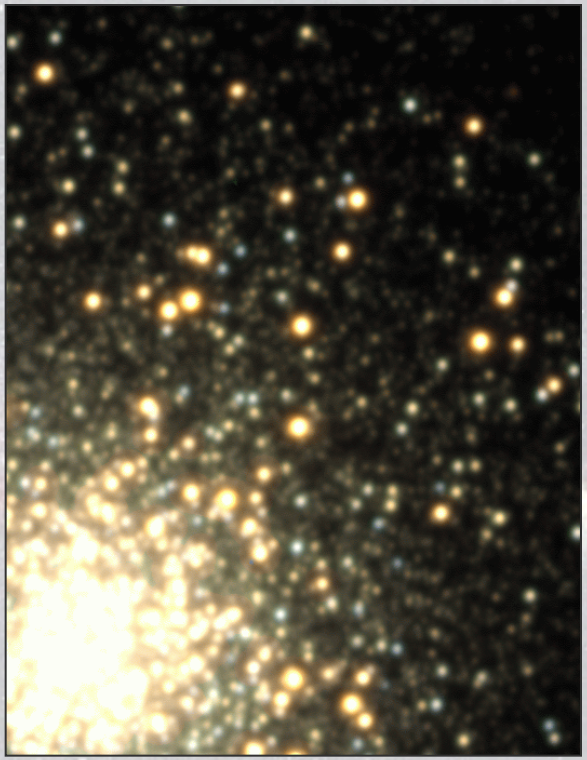
- We measure motions of nearby stars (how?) to determine Sun's orbit around center of MW.
- Sun orbits the galaxy every 230 million years.
- Sun's orbital motion (radius and velocity) tells us mass within Sun's orbit.

Orbital Velocity Law

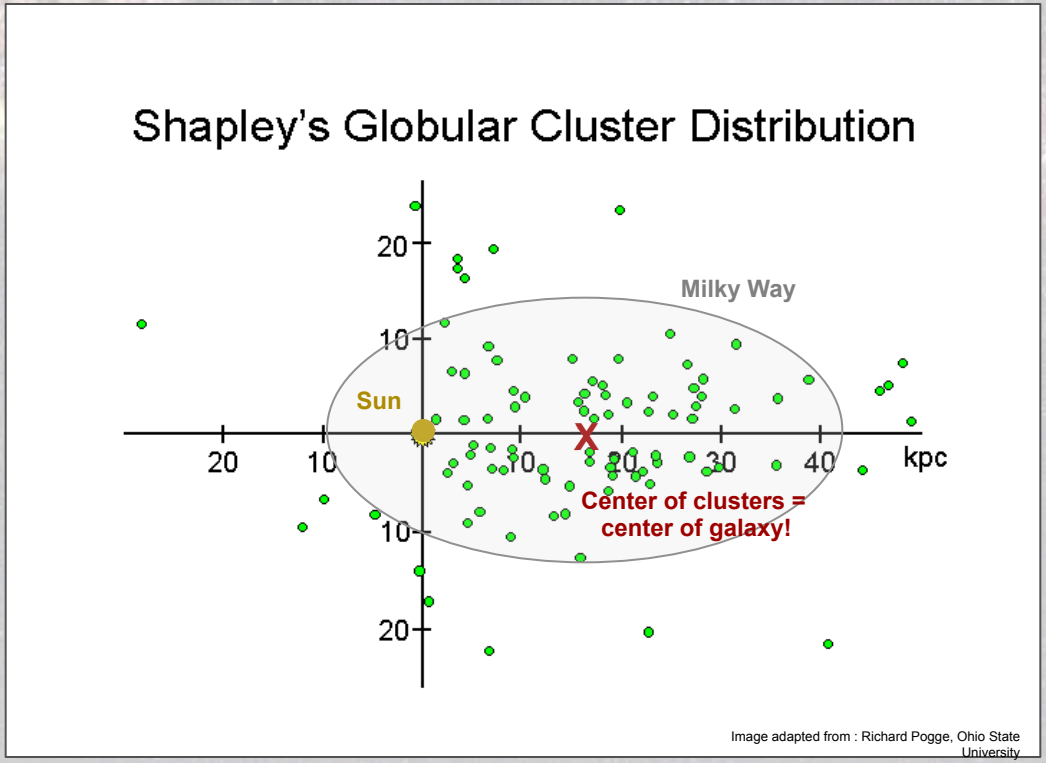
$$M_r = \frac{r \times v^2}{G}$$

- Orbital speed (v) and radius (r) of an object on a circular orbit around the galaxy tell us mass (M_r) within that orbit.
- For Sun's v = 220 km/sec, r = 28,000 ly:
- **Milky Way mass = 1.0×10^{11} M_{Sun}!**

How do we know our place in the Milky Way?



- In the 1920s, **Harlow Shapely** noticed *most **globular clusters** lie in one-half of the sky - we were not in their center*.
- **Shapely** used the periods and brightnesses of variable stars in **globular clusters** to <u>determine their distances</u>.
- Plotting their distances, he showed *their gravitational center was located thousands of light-years away.*



- Shapely found **<u>the center of the globular clusters was the center of the galaxy</u>**
- *<u>We was positioned about two-thirds of the way out from the Milky Way's center.</u>*.

What have we learned?

Begin 3 minute review

What have we learned?

What does our galaxy look like?

Our galaxy consists of a disk of stars and gas, a bulge of stars at center of disk, surrounded by a large spherical halo.

How do stars orbit in our galaxy?

Stars in the disk orbit in the same direction with a little up-and-down motion.

Orbits of halo and bulge stars have random inclinations

How do we know our place in the Milky Way?

Harlow Shapely mapped the distribution of globular clusters orbiting the center of the Milky Way and found we were not at their center.

Fig. 14.11a

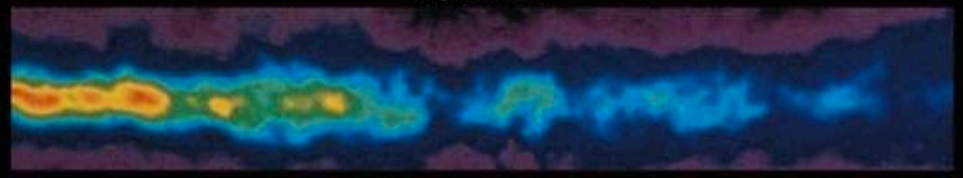


Fig. 14.09

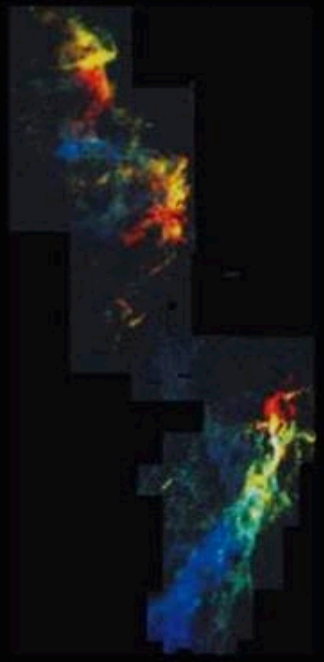
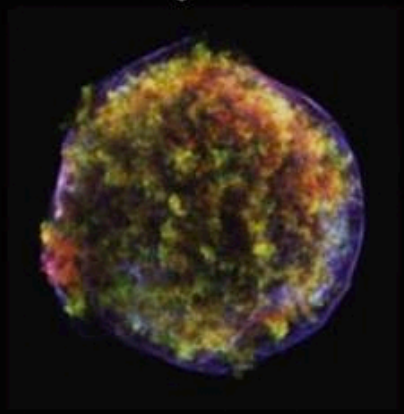


Fig. 14.6



atomic-hydrogen clouds

hot bubbles

molecular clouds

Star–gas–star cycle:

Gas from old stars is recycled into new star systems

returning gas

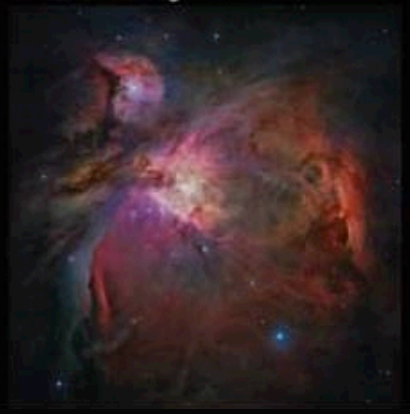
star formation

Fig. 14.5

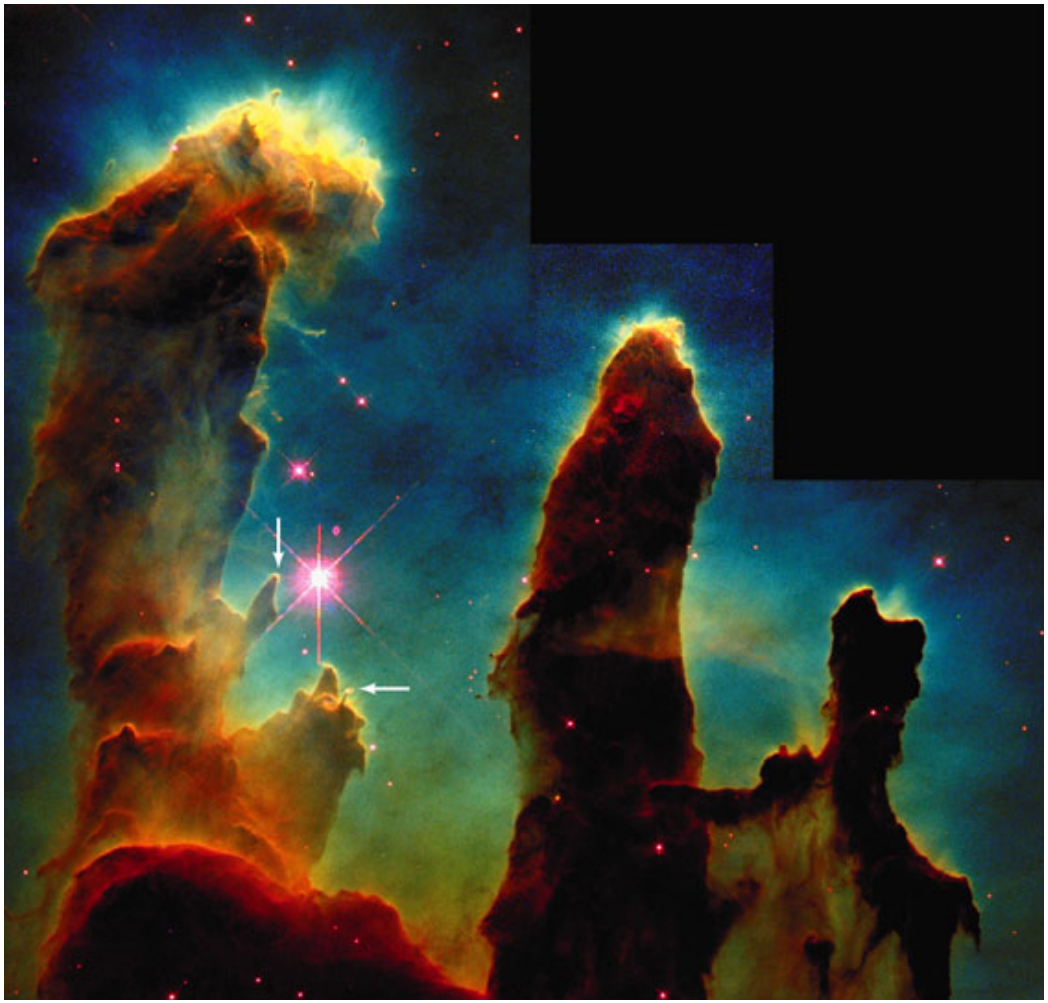
Fig. 14.10

nuclear fusion in stars

Fig. 14.12



Stellar recycling



- *Atomic* hydrogen clouds cool and form clouds of *molecular* hydrogen
- Temperature and density are right for gravity to form stars out of the gas
- Radiation from new stars is eroding these star-forming clouds.

Stellar recycling

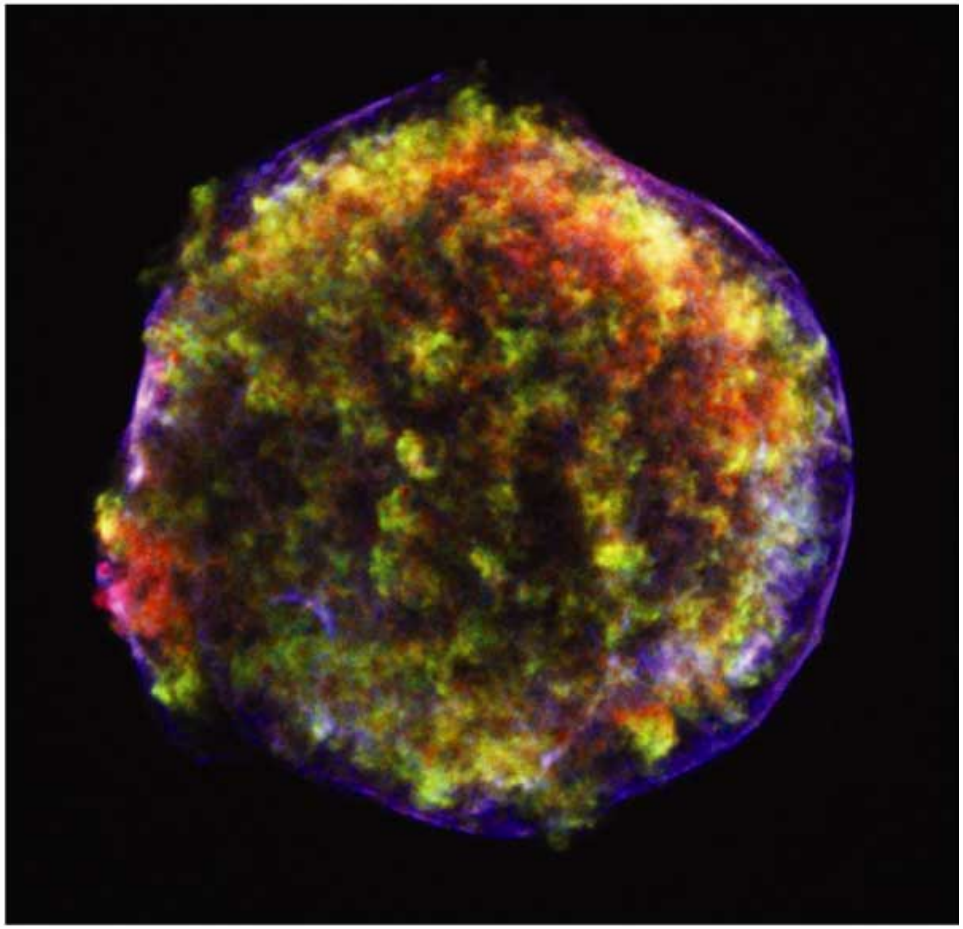
Stars fuse hydrogen to helium (and heavier elements) throughout their lifetimes

Stellar recycling

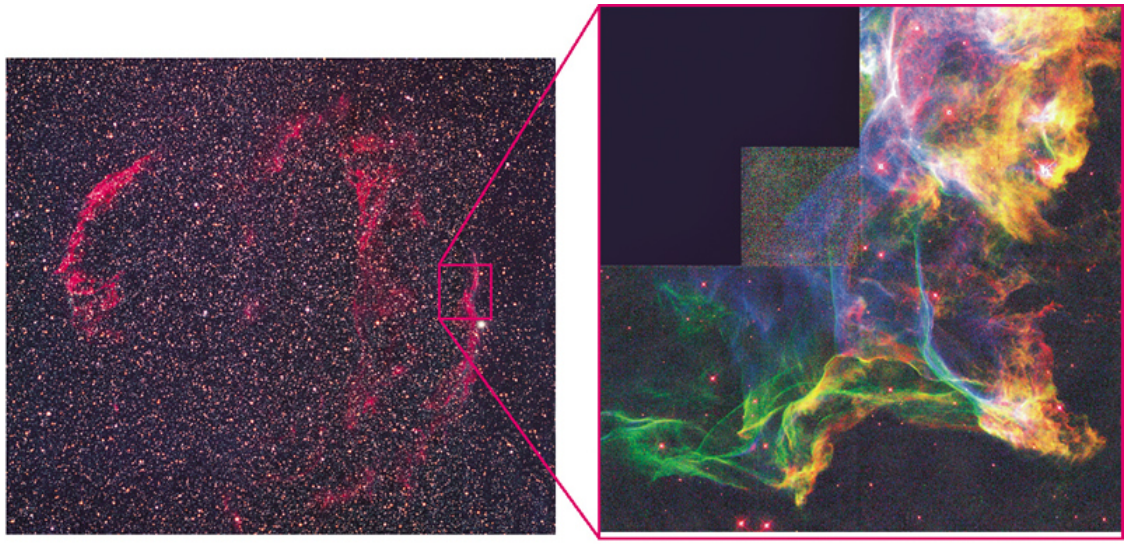
Low-mass stars return gas to interstellar space through modest stellar winds and planetary nebulae.

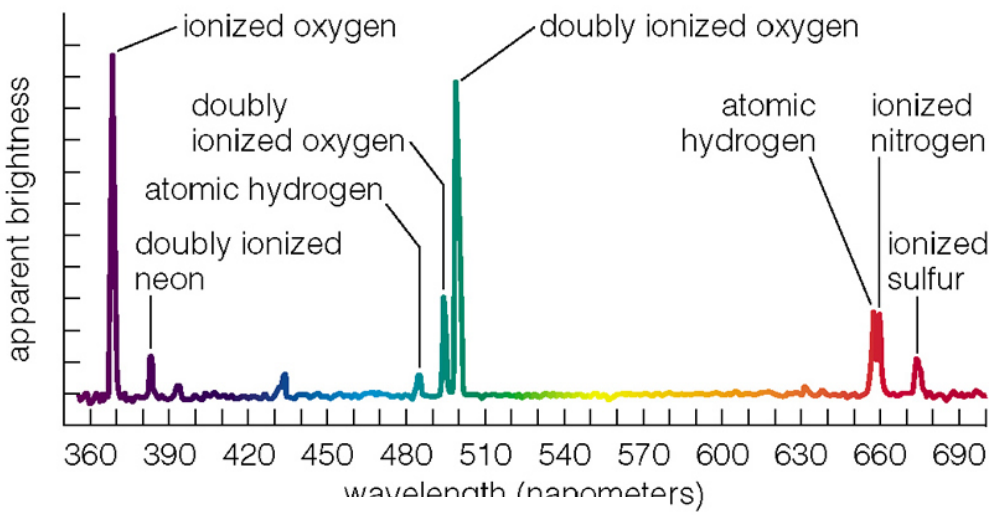
Stellar recycling

- High-mass stars also return much matter to ISM thru supernovae
- X-rays from hot gas in supernova remnants reveal newly made heavy elements.



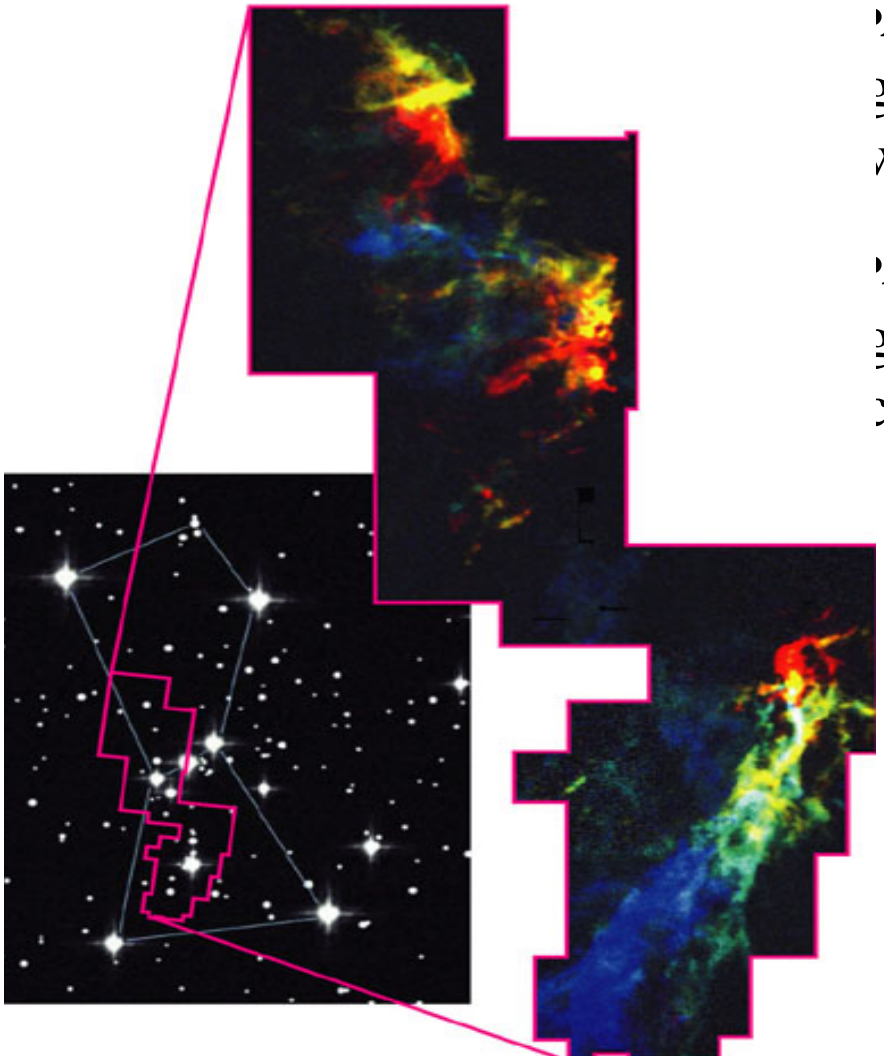
Stellar recycling





- A supernova remnant cools and begins to emit visible light as it expands.
- New elements made by supernova mix into interstellar medium.
- We see these in the spectra!

Stellar recycling



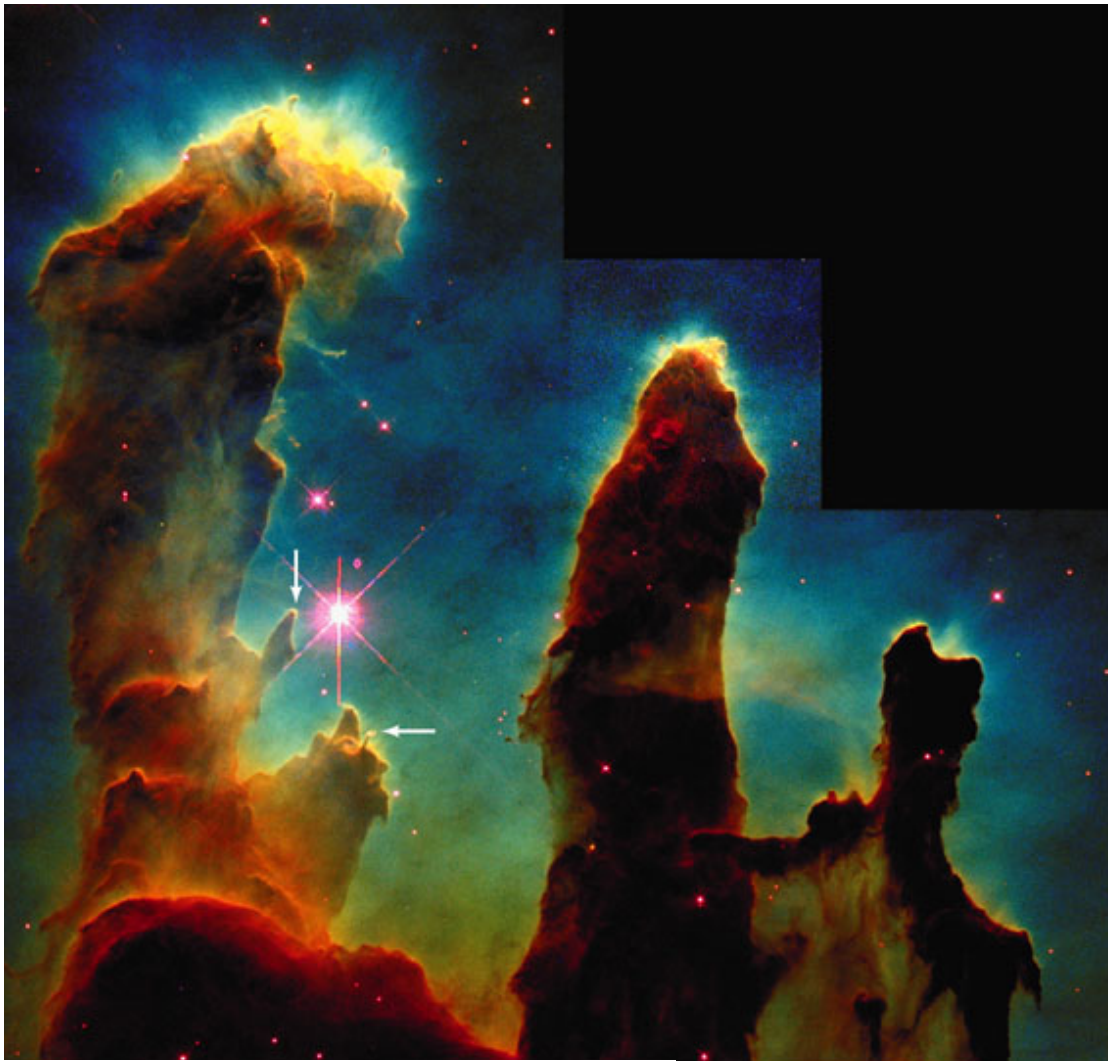
- ***Atomic hydrogen gas*** forms as hot gas cools, allowing electrons to join with protons.
- ***Molecular clouds*** form next, after gas cools enough to allow atoms to combine into molecules.

Molecular clouds in Orion

Composition:

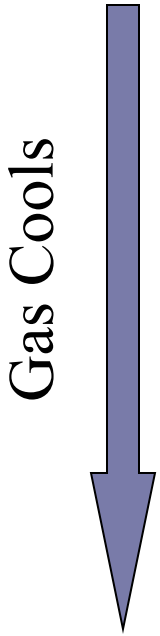
- Mostly H_2
- About 28% He
- About 1% CO
- Many other molecules

Stellar recycling

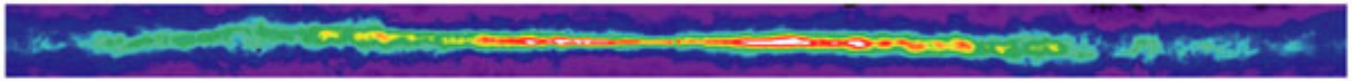


- Finally, gravity forms stars out of the gas in molecular clouds, *completing the star–gas–star cycle*.

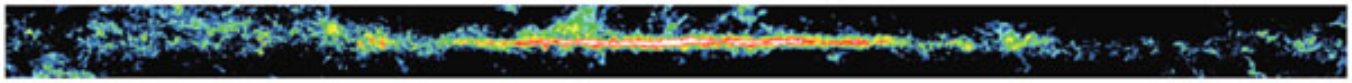
Summary of Galactic Recycling



- Gravity forms new stars in molecular clouds.
- Stars make new elements by fusion.
- Dying stars expel hot gas (and heavy elements) via stellar winds, planetary nebulae, and supernovae
- Hot (~10^6 K) bubbles of gas expand and cool, allowing atomic hydrogen clouds to form (~100–10,000 K).
- Further cooling permits molecules to form, making molecular clouds (~30 K).
- Gravity forms new stars in molecular clouds.



a 21-cm radio emission from atomic hydrogen gas.



b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared (60–100 μm) emission from interstellar dust.

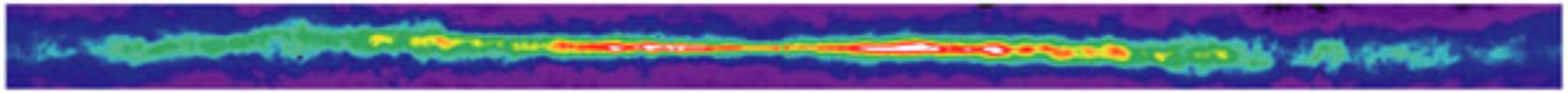
d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

We observe the star–gas–star cycle operating in Milky Way's disk using different wavelengths of light.

Stellar recycling

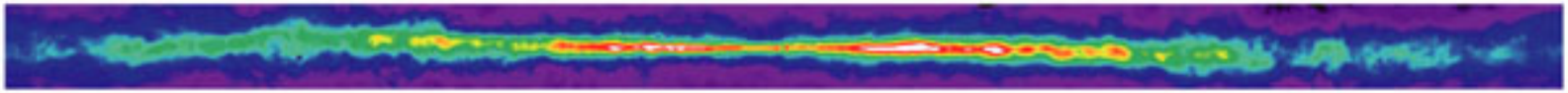


a 21-cm radio emission from atomic hydrogen gas.

Radio (21cm)

21-cm radio waves emitted by hydrogen show where hydrogen gas has settled into disk.

Stellar recycling



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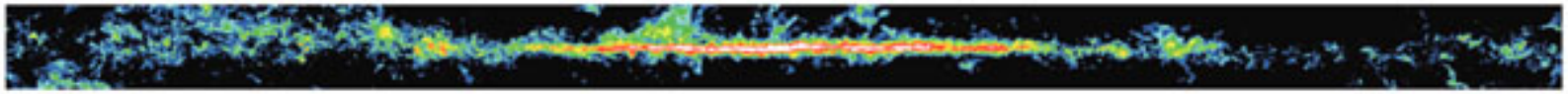
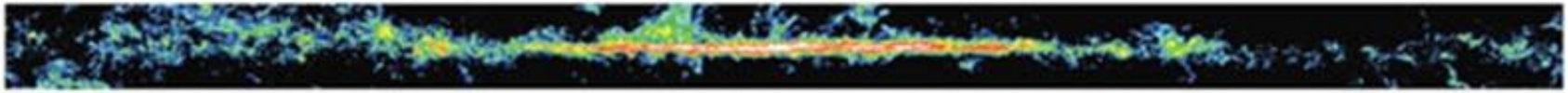


b Radio emission from carbon monoxide reveals molecular clouds.

Radio (CO)

Radio waves from carbon monoxide (CO) show locations of *molecular* hydrogen clouds.

Stellar recycling



b Radio emission from carbon monoxide reveals molecular clouds.

c Infrared (60–100 μm) emission from interstellar dust.

IR (dust)

Long-wavelength infrared emission shows where young stars are heating dust.

Stellar recycling

c Infrared (60–100 μm) emission from interstellar dust.

d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

Infrared

Shorter wavelength infrared light reveals stars whose visible light is blocked by gas clouds.

Stellar recycling

d Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

e Visible light emitted by stars is scattered and absorbed by dust.

Visible

Visible light reveals main-sequence stars burning hydrogen in their cores

Stellar recycling

e Visible light emitted by stars is scattered and absorbed by dust.

f X-ray emission from hot gas bubbles (diffuse blobs) and X-ray binaries (pointlike sources).

X-rays

X-rays are observed from hot gas expelled by stars above and below the Milky Way's disk.

Where do stars form in our galaxy?

Star formation

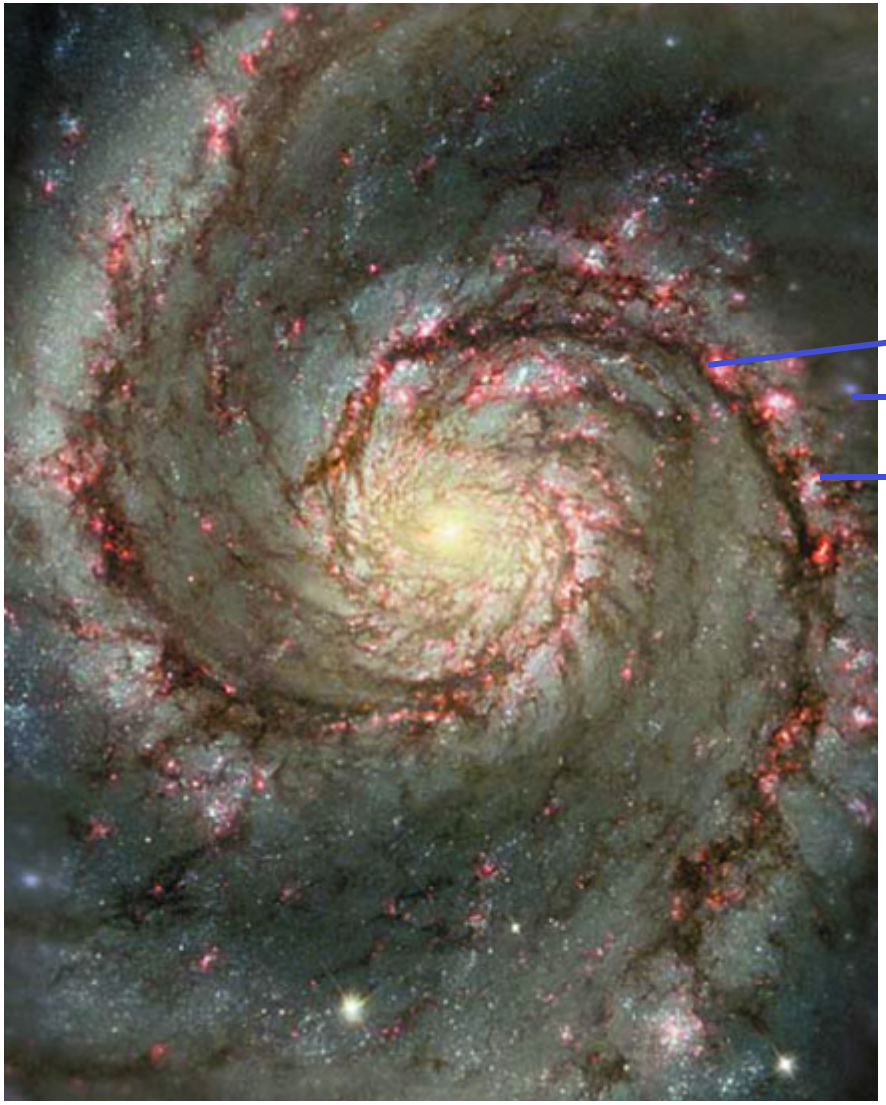
- Hot massive stars indicate sites of star formation – ***why?***
- ***Emission nebulae*** are found around high-mass stars, signifying active star formation.
- Gas ionized by UV from hot stars, re-emits light as electrons recombine
- The red glow of hydrogen indicates an emission nebula

Star formation

Halo: No emission nebulae, no blue stars $\Rightarrow$ no star formation

Disk: Many emission nebulae, blue stars $\Rightarrow$ star formation

Star formation



Most star formation in disk happens in **spiral arms**

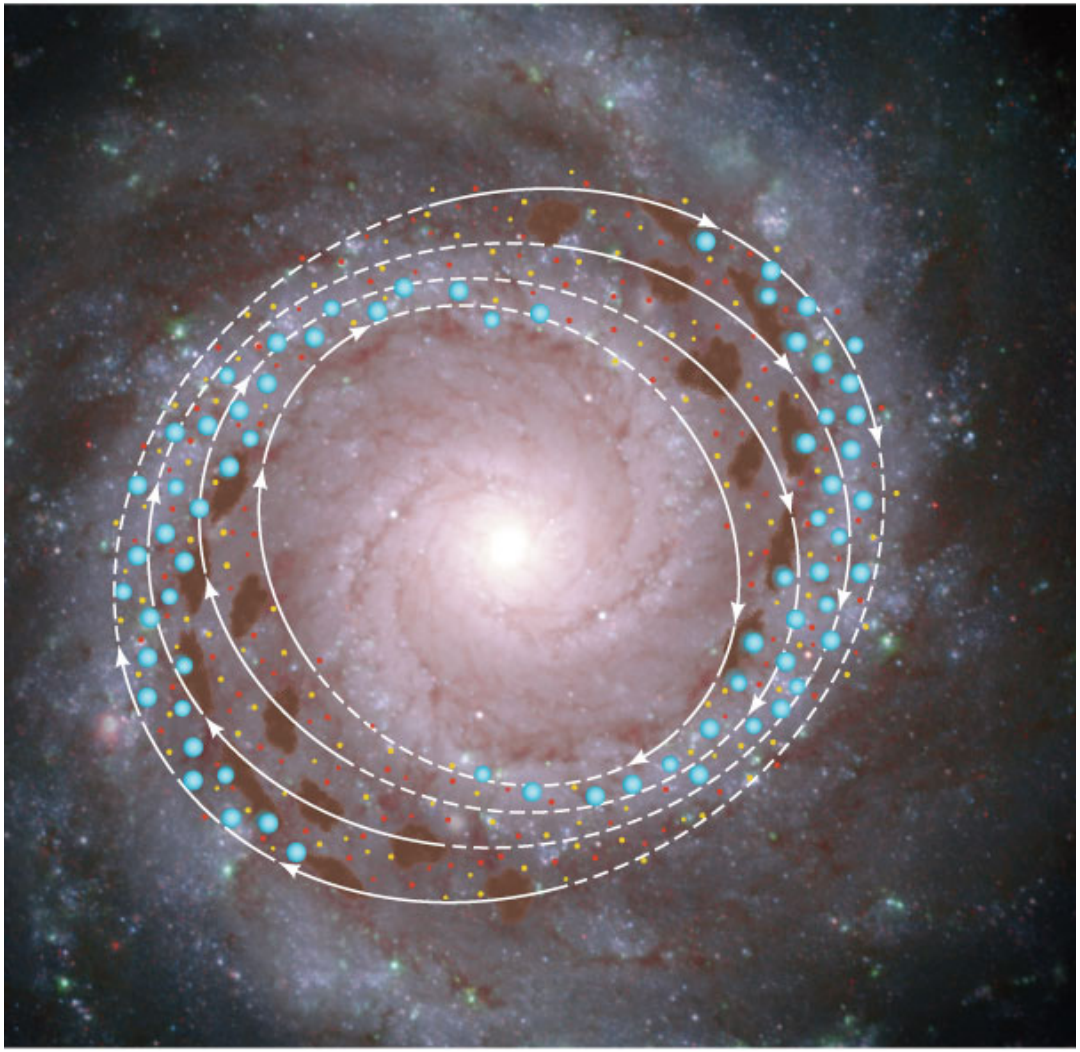
Emission nebulae
Clusters of blue stars
Gas clouds

Inner areas rotate faster than outer so spiral arms are not solid but **density waves** of star formation.

Star formation

Spiral arms are density waves of star formation:

1. Star density is higher due to elliptical orbits
2. Gas clouds get squeezed as they move into spiral arms.
3. The squeezing of clouds triggers star formation.
4. Young, bright stars are concentrated in spiral arms.



What have we learned?

Begin 3 minute review

What have we learned?

How is gas recycled in our galaxy?

Gas from dying stars mixes new elements into the interstellar medium which slowly cools, making molecular clouds where new stars form.

Those stars will eventually return much of their matter to interstellar space.

Where do stars tend to form in our galaxy?

Active star-forming regions contain molecular clouds, hot stars, and **emission nebulae**.

Much of the star formation in our galaxy happens in the spiral arms.

What clues to our galaxy's history do halo stars hold?

Stellar populations

Halo Stars (Population II): <0.2% heavy elements, only old stars

Halo stars formed first, then stopped (no gas)

Disk stars formed later, and kept forming.

Disk Stars (Population I): 2% heavy elements, young and old stars

How did our galaxy form?

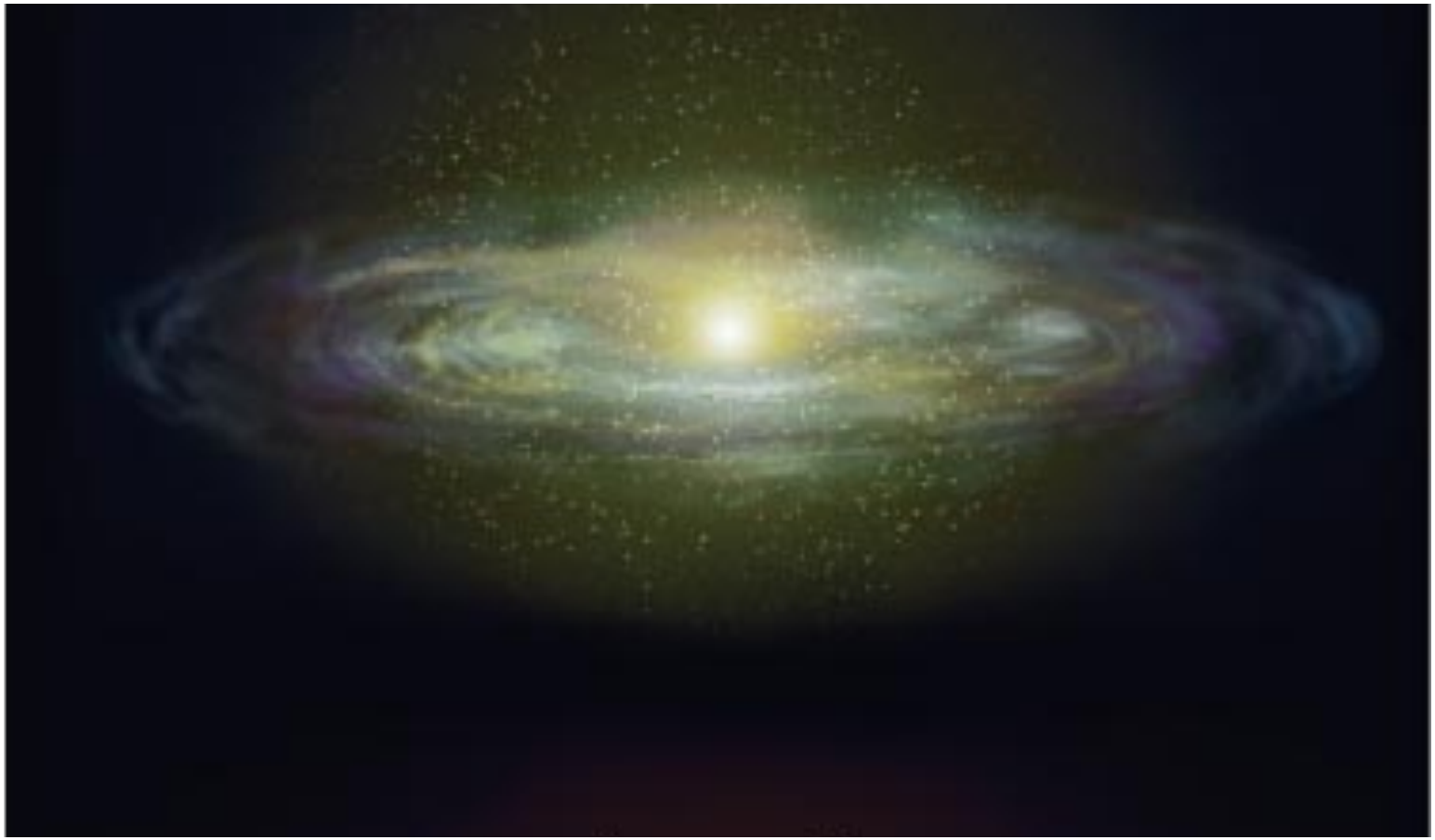
How did our galaxy form?

Our galaxy probably formed from an enormous gas cloud.

How did our galaxy form?

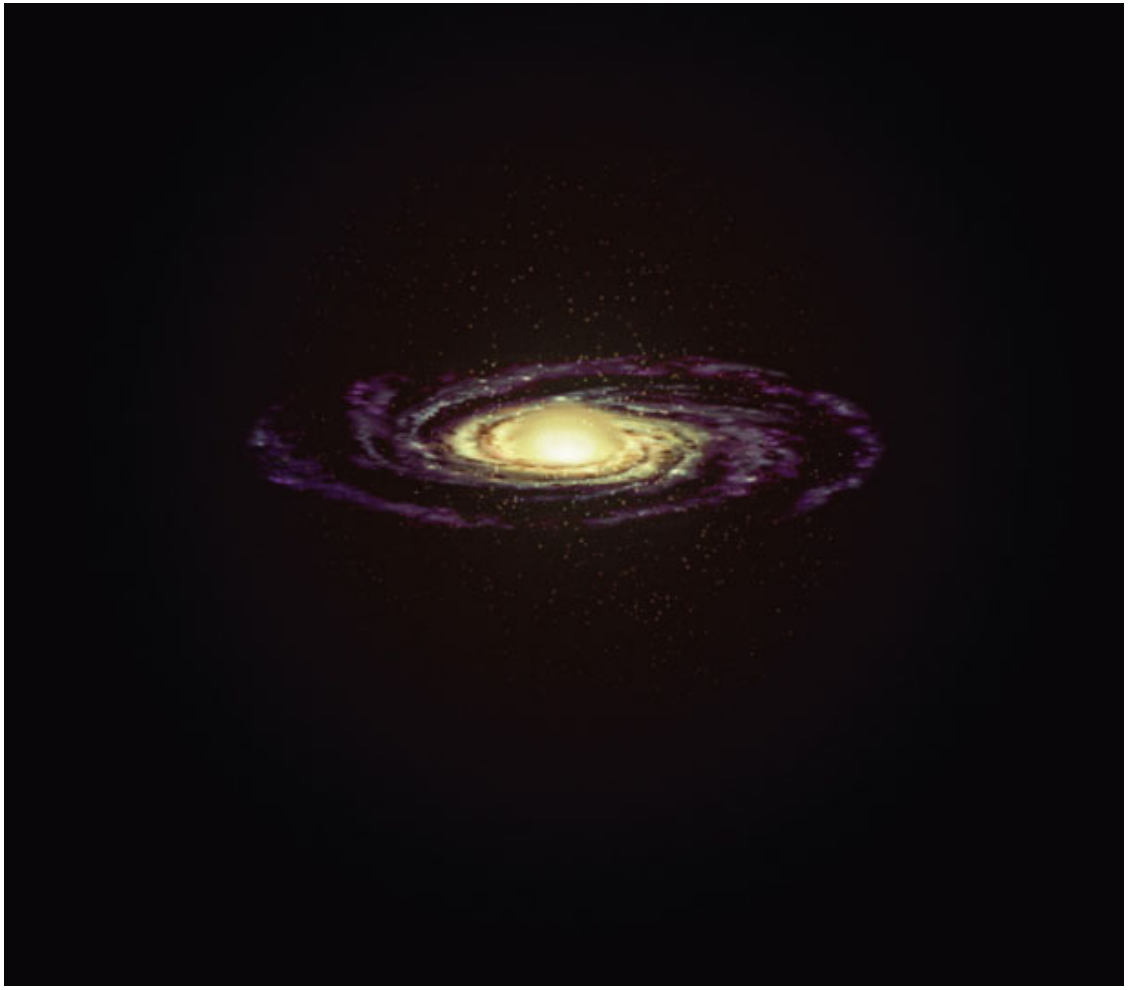
Halo stars with random orbits and no heavy elements formed first as gravity caused the cloud to contract.

How did our galaxy form?



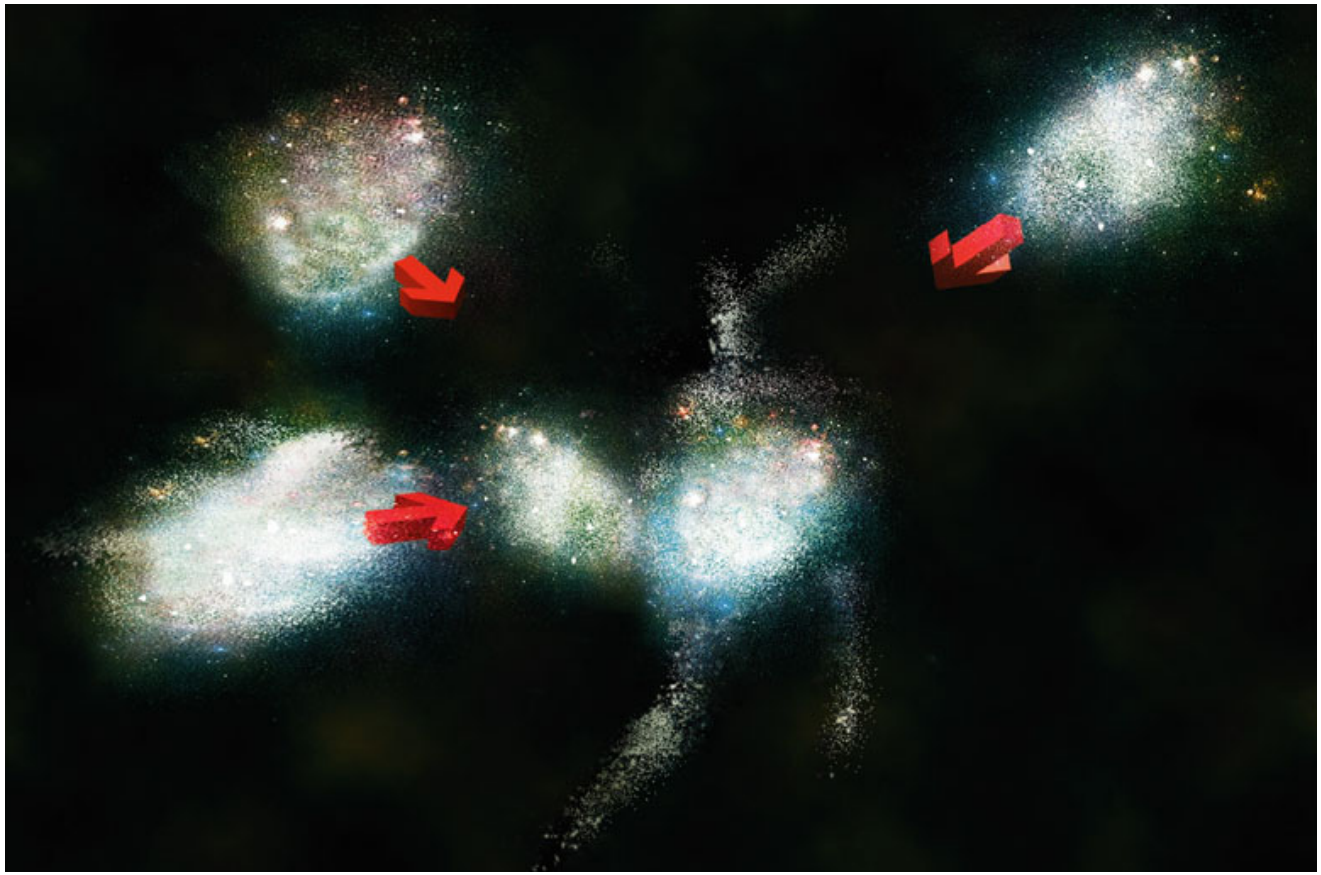
The remaining gas settled into a spinning disk, later formed stars with more heavy elements in circular orbits

How did our galaxy form?



Stars continuously form in the disk as the galaxy grows older.

How did our galaxy form?



Detailed studies: Halo stars formed in clumps that later merged.

Think/Pair/Share

How can the Milky Way galaxy have stars of all ages when it formed billions of years ago?

A. We are, uh, not really sure how this happened
B. New stars are acquired from other galaxies when the Milky Way absorbs them
C. New stars formed from new, unused interstellar material in the bulge over the life of the galaxy
D. Stellar recycling uses material from old stars to form new stars in the spiral arms

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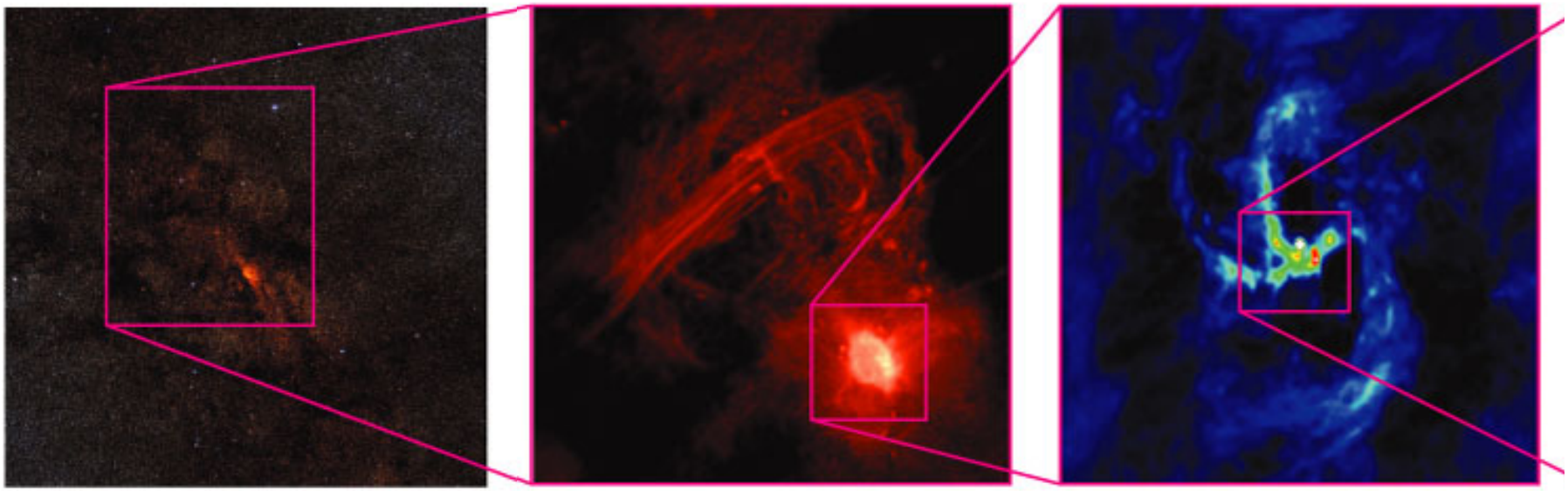
What lies in the center of our galaxy?

Infrared light from center

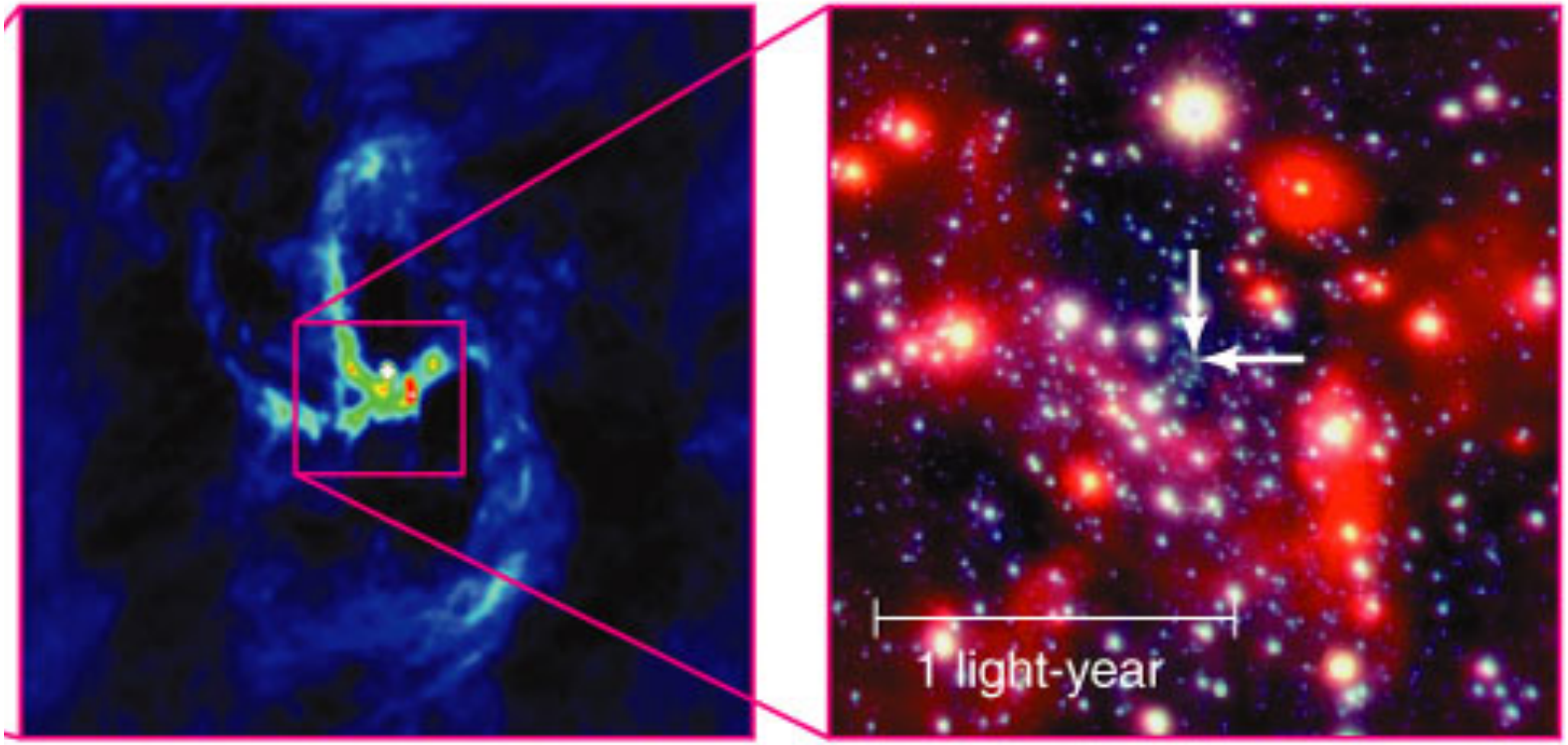
Swirling gas near center



Radio emission from center

The center of our galaxy

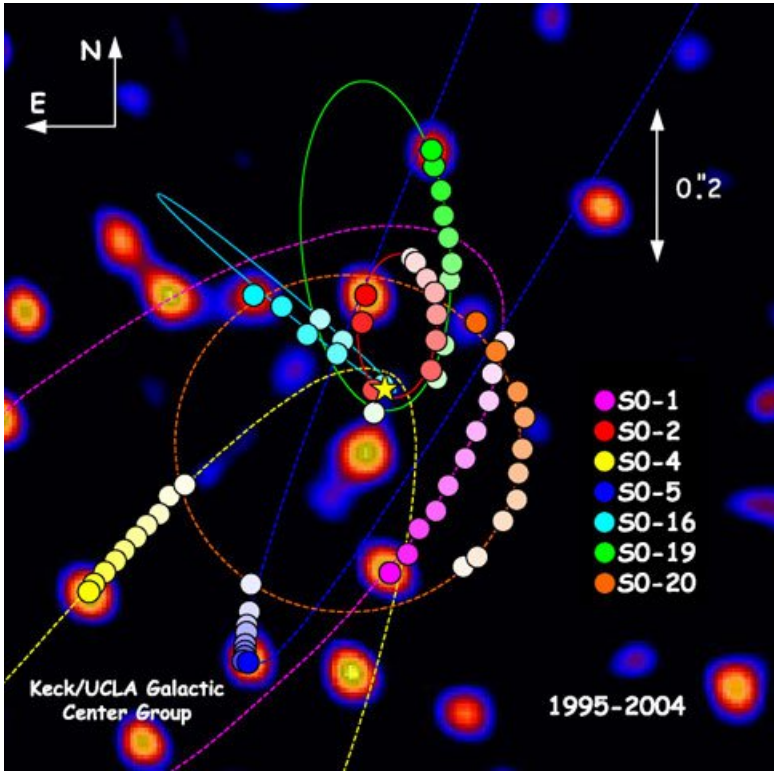
Swirling gas near center Orbiting stars near center



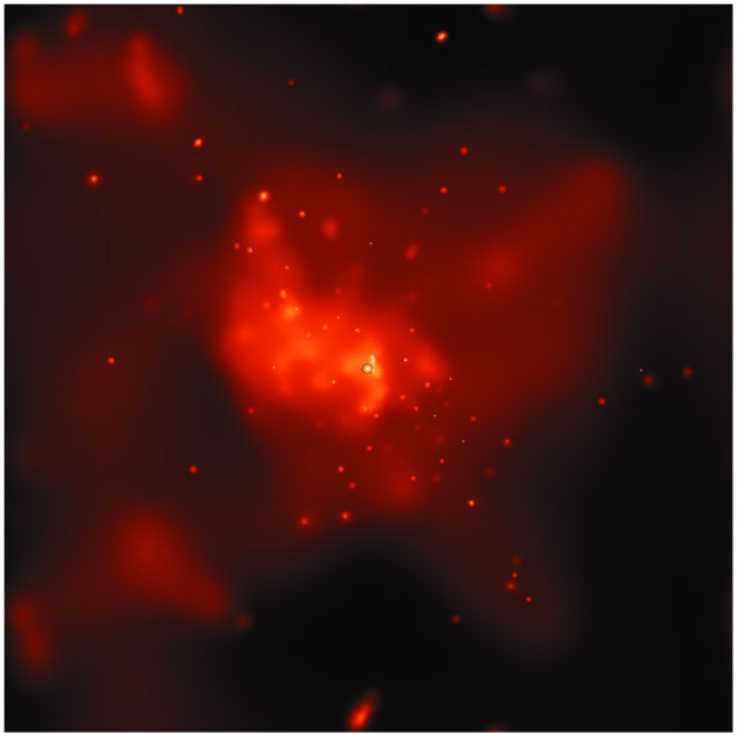
The center of our galaxy

- Stars are orbiting something very massive but invisible … ***a supermassive black hole!***

- Orbits of stars indicate a mass of 4 million M_{sun}!



The center of our galaxy



X-ray flares from galactic center show its black hole occasionally tear apart chunks of matter which fall in.

What have we learned?

Begin 3 minute review

What have we learned?

What clues to our galaxy's history do halo stars hold?

Halo stars are all old, with a smaller proportion of heavy elements than disk stars, indicating that the halo formed first.

How did our galaxy form?

Our galaxy formed from a huge cloud of gas, with the halo stars forming first and the disk stars forming later, after the gas settled into a spinning disk.

What lies in the center of our galaxy?

Orbits of stars near the center of our galaxy indicate a black hole with 4 million times the mass of the Sun.

Our Modern Milky Way