Introduction to Galaxies: The Milky Way

Chapter 19

Recap: lecture 20

- **What are the major ideas of General Relativity?**
  - The main idea is the **equivalence principle**, which states that the effects of gravity are exactly equivalent to effects of acceleration
  - We can combine “space” and “time” into a 4-dimensional space-time

- **What is Einstein’s view of gravity?**
  - Gravity arises from “curvature” of space-time
  - Mass causes space-time to curve, and the curvature determines the motion of objects
  - This view predicts deflection of light when it travels near massive objects, which we observe as **gravitational lensing**

- **What is a black hole?**
  - A **black hole** is a region where space-time is curved so much that time appears to completely stop
  - Nothing can escape; not even light
  - This happens when a large mass is packed into a small volume

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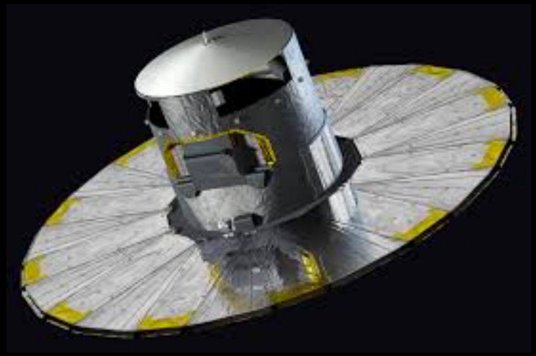
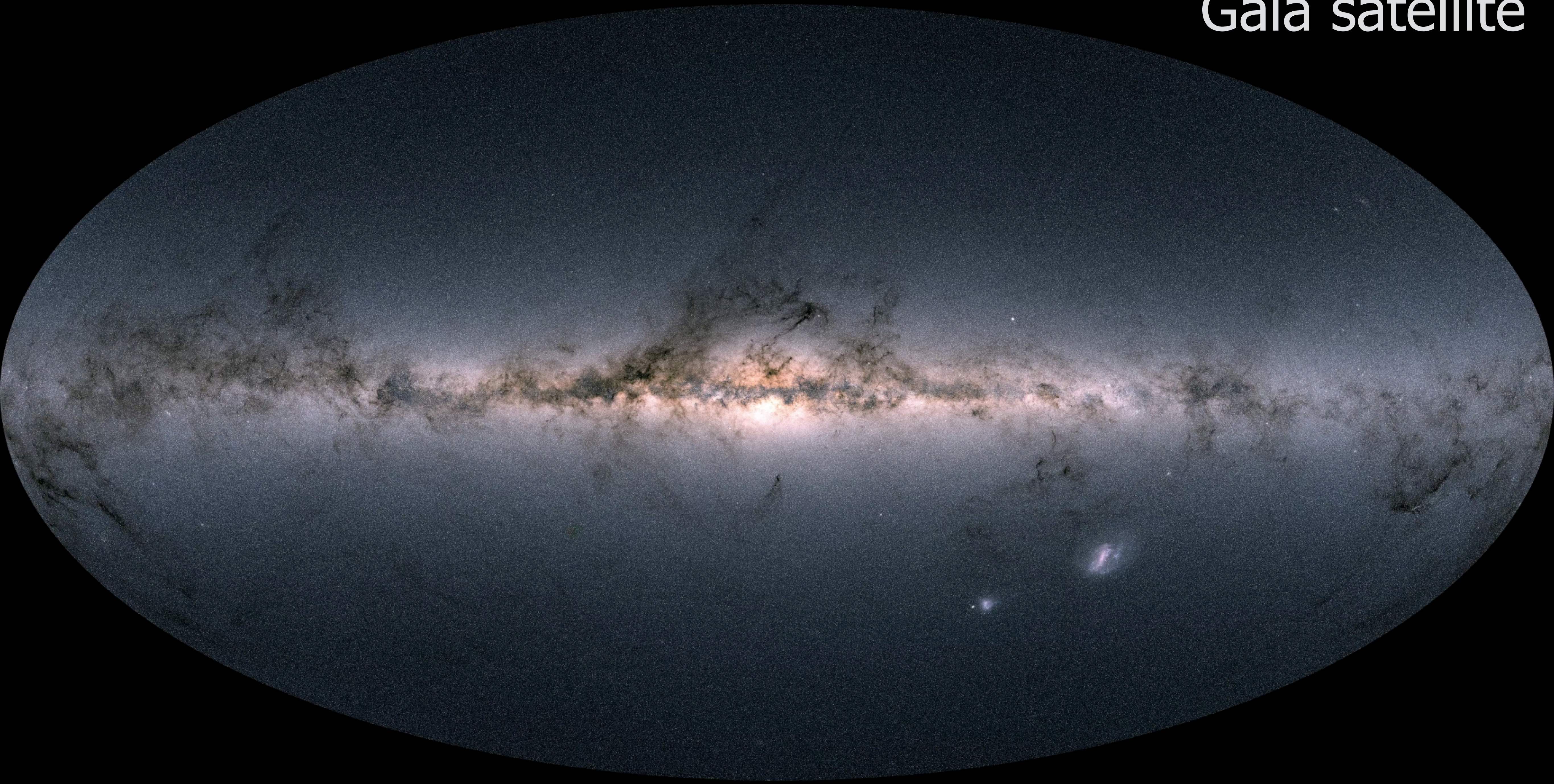
Chapter 19

Full-sky view of the Milky Way — in “real” time!



Gaia satellite



Last part of Ast 25: putting it all together!

- Gravity makes objects in space move
  - We can use motions to measure masses of objects
- The light from astronomical objects reveals their temperature and their elemental composition
  - We can figure out what an object is made of
- Stars: the main sequence size, luminosity, temperature (color), lifetime, and evolutionary endpoint of stars (white dwarfs, neutron stars, or black holes), all of which are governed almost entirely by their masses
  - We can measure the properties of populations of stars, and predict what they will do in the future
- Stars create new, heavier elements through nuclear fusion; some of these are ejected back into space by stellar winds and supernovae
  - This material is incorporated into the next generation of new stars
  - From the amount of heavy elements, we can learn about previous generations of now-dead stars

Implications for galaxies

Collections of stars (such as galaxies) are evolving, interconnected systems!

Stars are born

Stars die

New elements heavier than H and He ("metals") are created

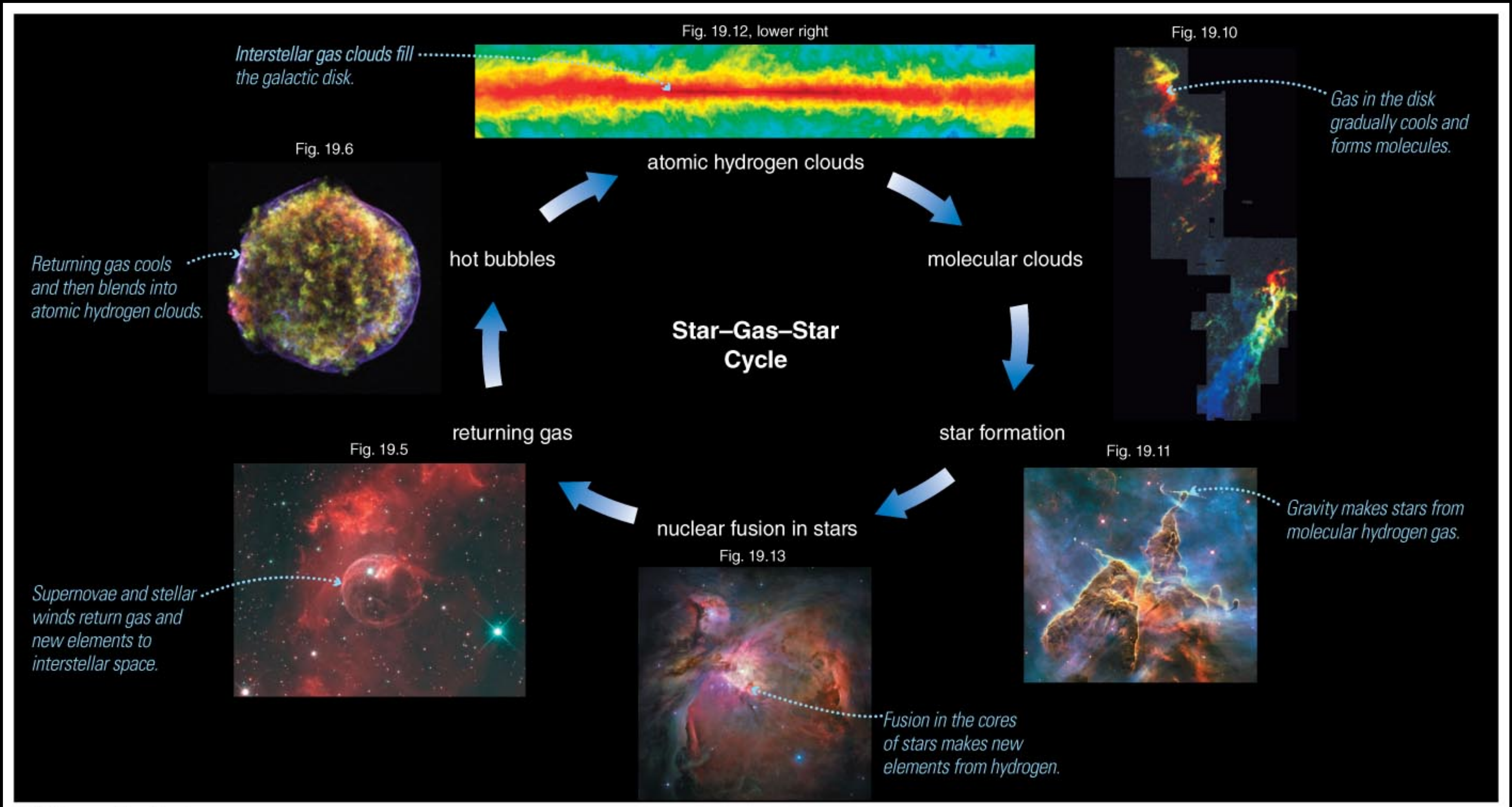
Supernovae, stellar winds, and planetary nebulae send gas outwards

Gravity pulls things together

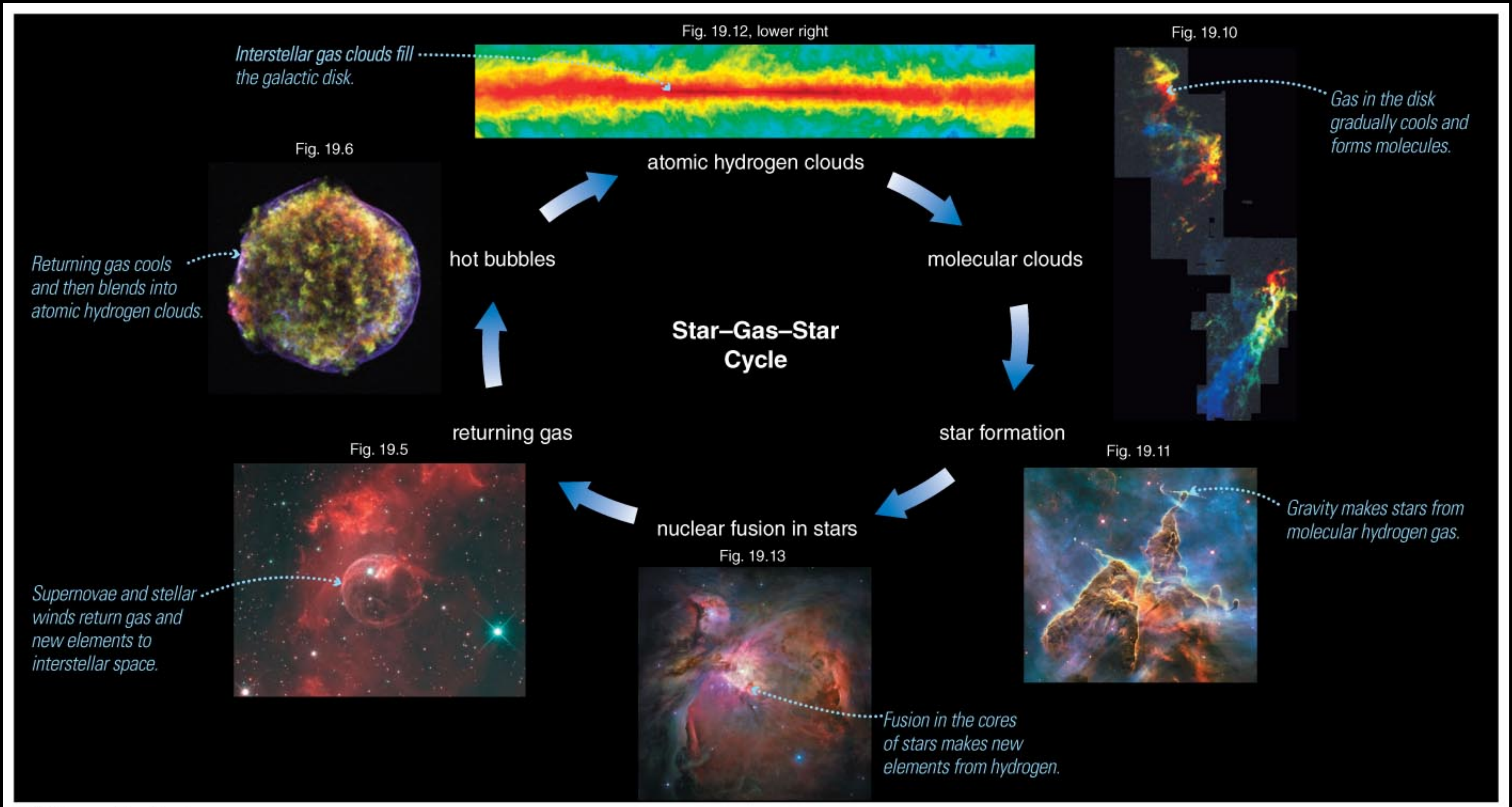
New stars are born

The size and shape of galaxies, the amount of stars and gas within them, and their elemental composition all change with time!

Gas recycled



Gas recycled



Star–gas–star cycle

Recycles gas from old stars into new star systems.

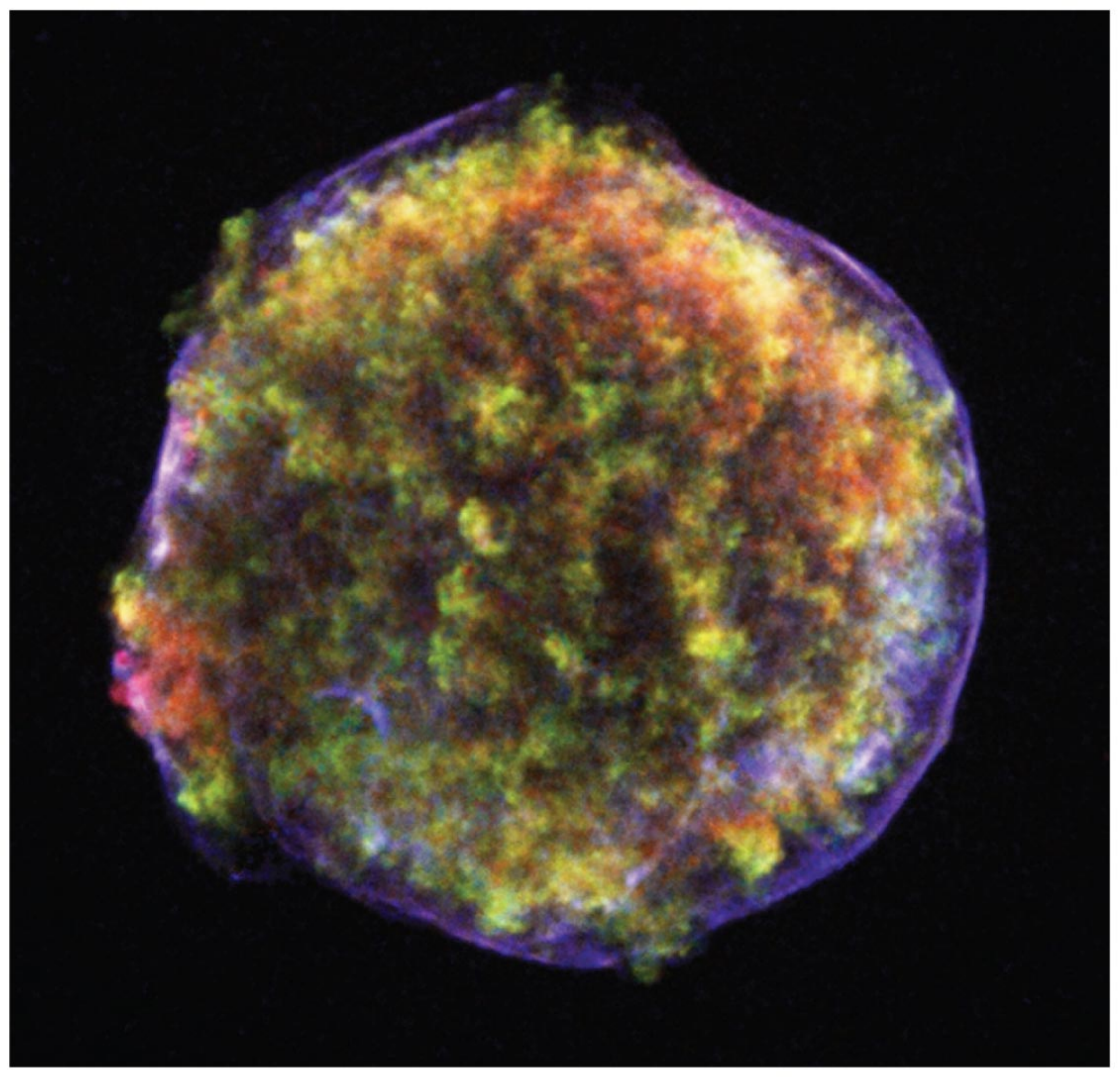
Gas recycled

High-mass stars have strong stellar winds that blow bubbles of hot gas.

Gas recycled

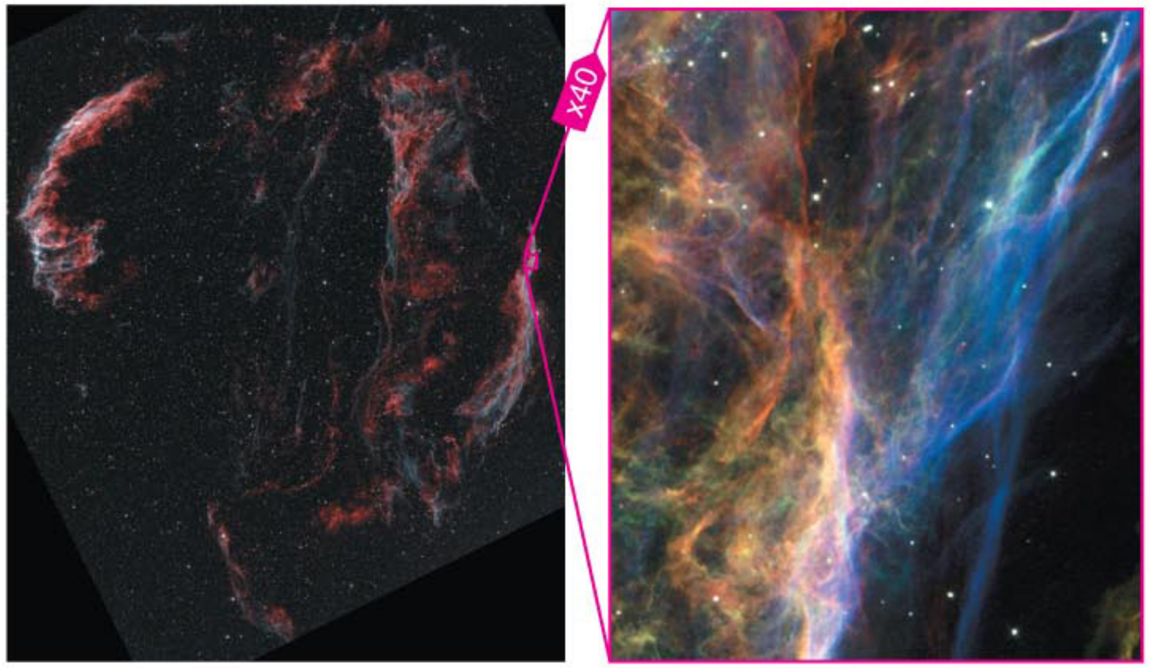
Lower mass stars return gas to interstellar space through stellar winds and planetary nebulae

Gas recycled



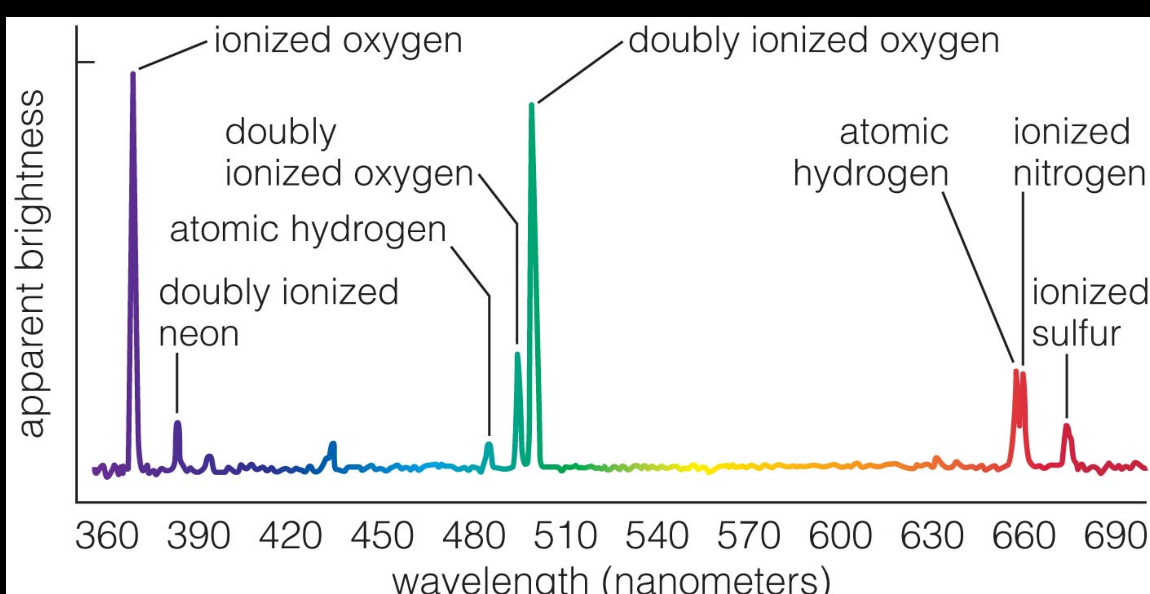
X rays from hot gas in supernova remnants reveal newly made heavy elements.

Gas recycled



a This visible-light image shows the entire supernova remnant, which is about 130 light-years across and spans an angular width in our sky six times that of the full Moon.

b This Hubble Space Telescope image shows fine filamentary structure in a small piece of the remnant. The colors come from emission lines of the atoms and ions indicated in part c.



c A visible-light spectrum of the Cygnus Loop shows the strong emission lines that account for the distinct colors in the Hubble Space Telescope image.

A supernova remnant cools and begins to emit visible light as it expands.

New elements made by a supernova mix into the interstellar medium.

Summary of Galactic Recycling

- Stars make new elements by fusion.
- Dying stars expel gas and new elements, producing hot bubbles (~106 K).
- Hot gas cools, 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 (and planets) in molecular clouds.

Definitions: what is a galaxy?

- A **galaxy** is a large collection of stars held together by gravity
  - (not a complete definition, but good enough for now)
  - It usually contains gas and other matter as well

- The Milky Way galaxy
  - from “galactos” = Greek for “milk”
  - “Milky Way” refers to the pattern seen in the night sky

Tools to study galaxies: same as the tools we use to study stars

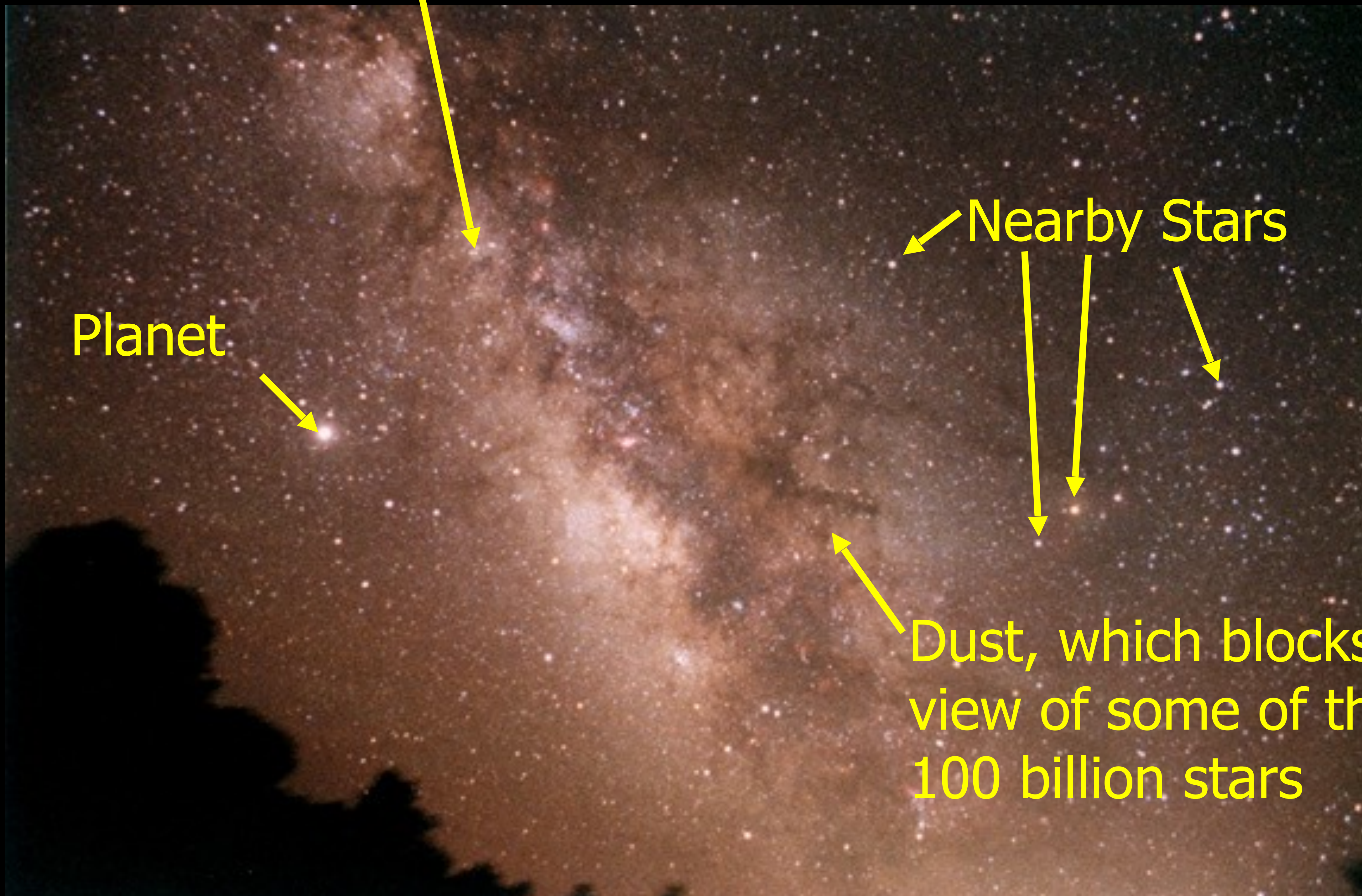
- Colors
- Spectra
- Distance + apparent brightness = luminosity
- Plus, structure (shape & size), a new tool for galaxies

We see galaxies as a collection of stars

- Held together by their own gravity
- Major ingredients of galaxies:
  - Stars
  - Gas
  - Dust
  - Mystery material

  } The Interstellar Medium (ISM)
- Relative amounts and distributions of these ingredients determine the galaxy type
- Let's start by looking at the Milky Way…

The Milky Way, made of 100 billion stars (10^{11}), one of which is the Sun

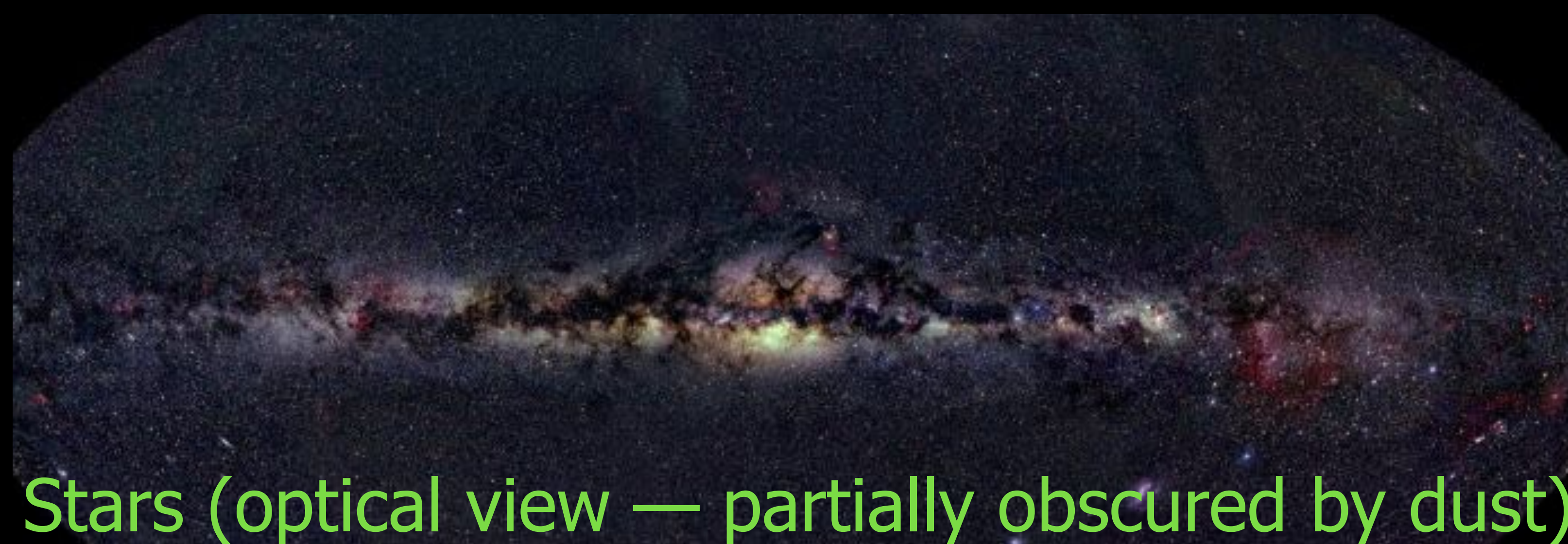


Questions of the day

- What does our galaxy actually look like?
- How do stars move (orbit) within our galaxy?

What does the Milky Way actually look like?

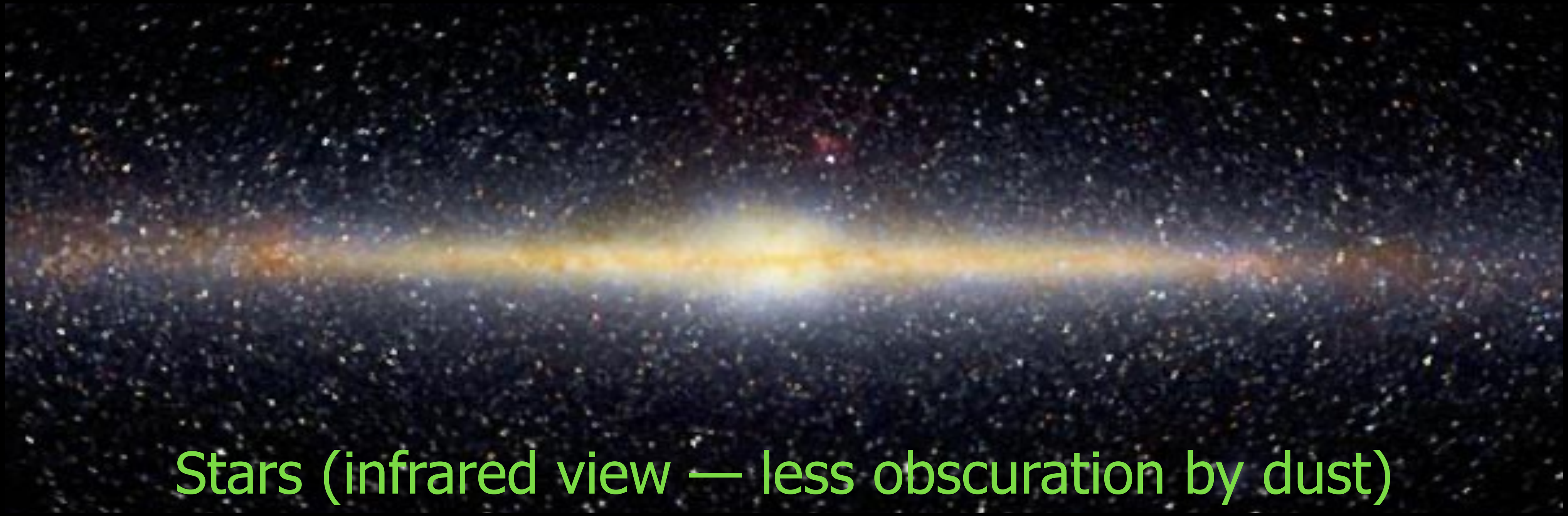
Stars (infrared view — less obscuration by dust)



Stars (optical view — partially obscured by dust)

Gas (hydrogen, which comprises most of the gas)

What does the Milky Way actually look like?



- We see a relatively narrow band of stars, with a thicker area in the middle
  - What could create this narrow line of stars?
- We cannot get a view from outside the Milky Way, but we can see other galaxies that may tell us about the Milky Way
  - What do some of these look like?

What does the Milky Way actually look like?

Other galaxies with similar size and number of stars

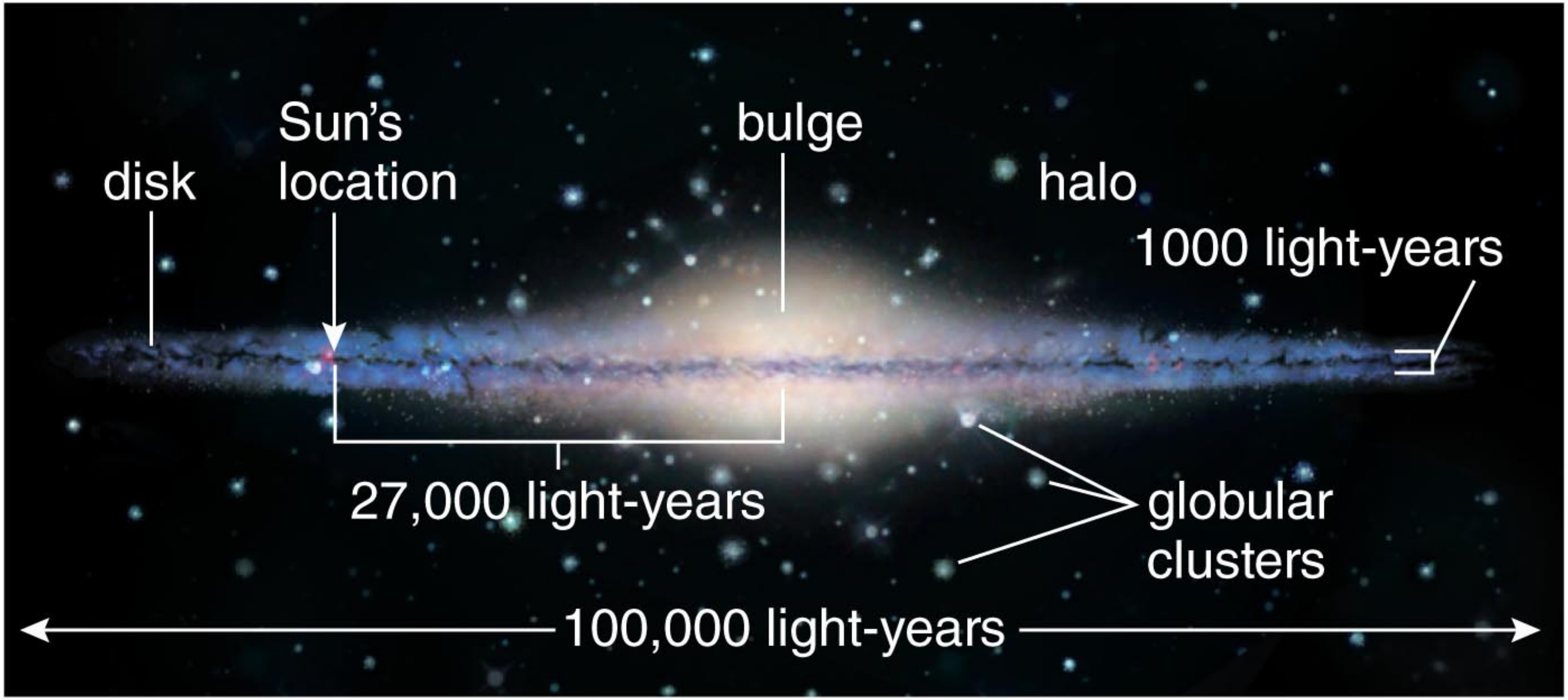
Side View

Top View

What does the Milky Way actually look like?

A nearby galaxy (Andromeda, or "M31" — NOT the Milky Way, but similar in size and number of stars)

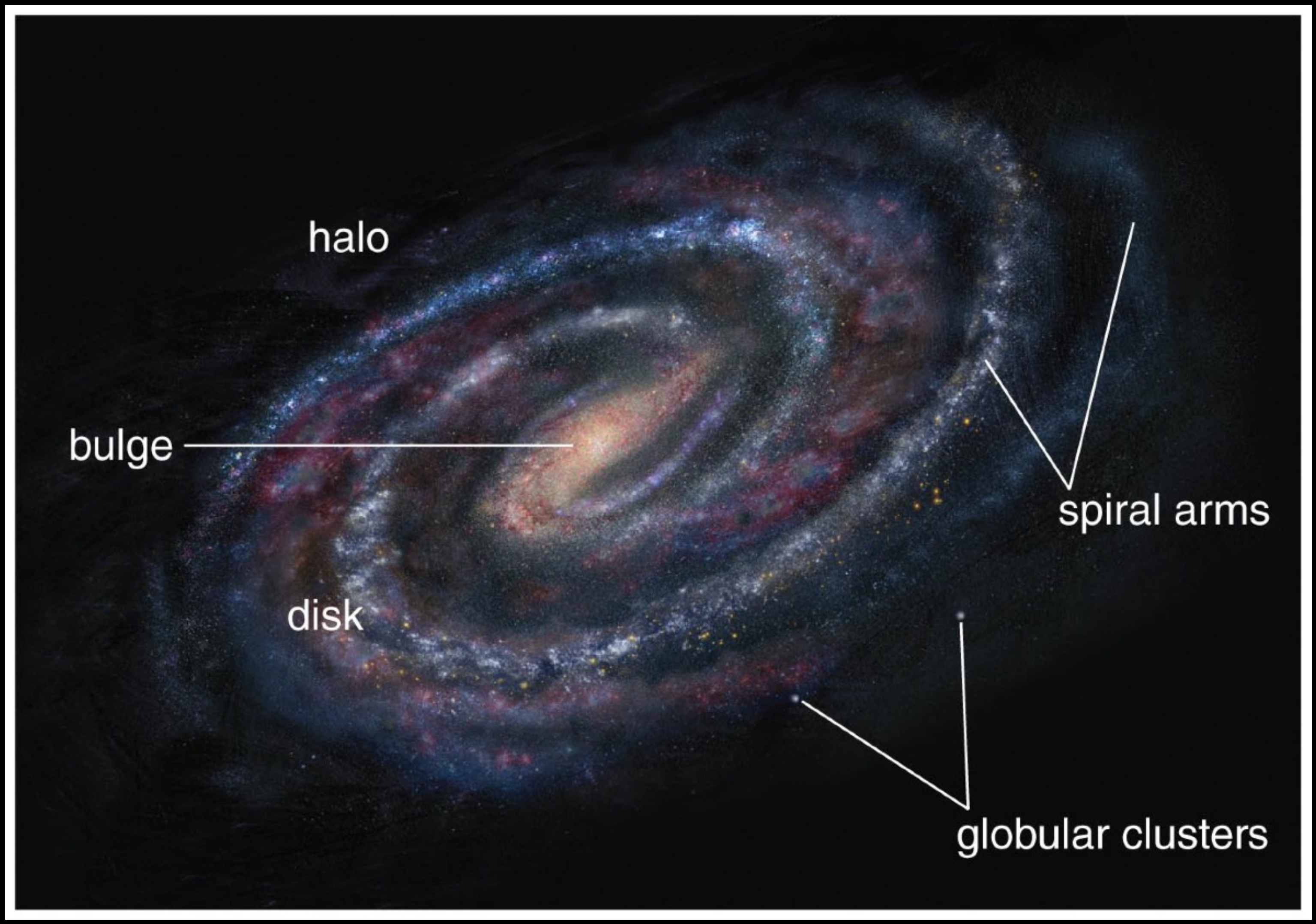
Schematic View of the Milky Way



b Edge-on schematic view of the Milky Way.

The "halo" here is a sparse, faint collection of old stars

Artist’s view of the Milky Way

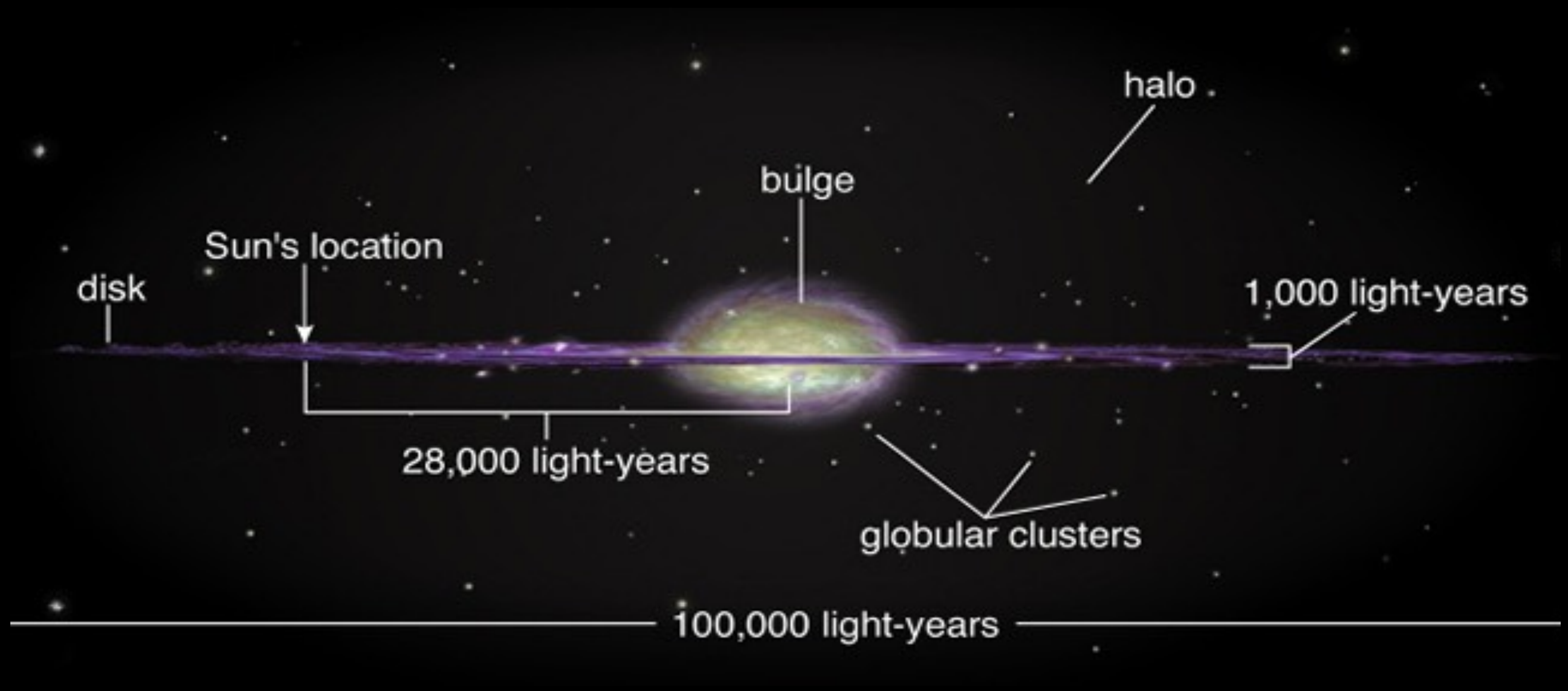


- Note the pattern of “spiral arms”
- The Milky Way is an example of a type of galaxy known as a “spiral galaxy” or “disk galaxy”

- Why are the spiral arms blue?
  - They contain hot, massive, blue stars

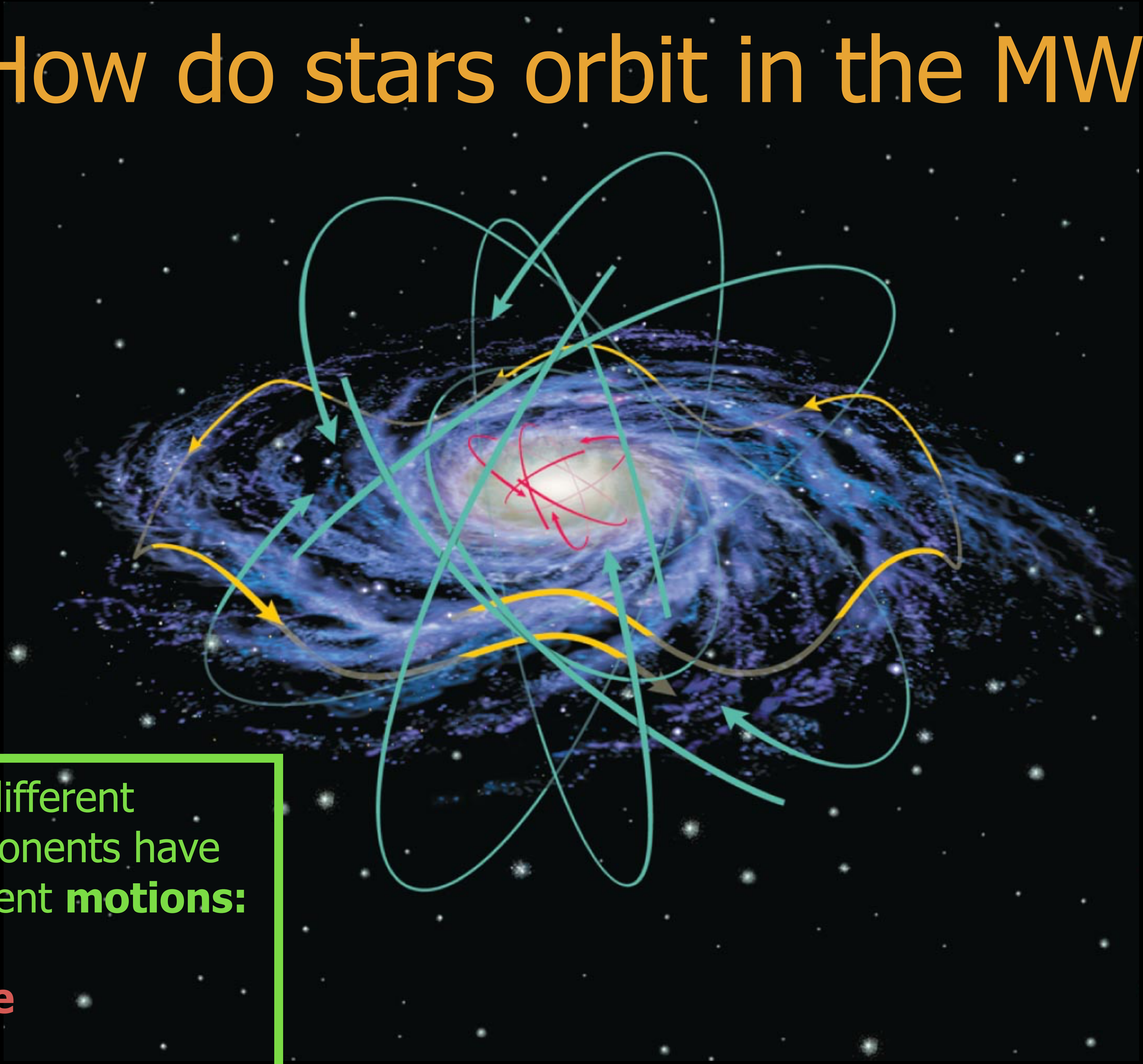
Stellar components of the MW

- Disk (flat, circular distribution)
  - All of the young stars are in the disk
  - The gas and dust also is in the disk
- Bulge (spheroidal distribution)
- Stellar halo (spheroidal distribution)
  - <u>Old</u> and faint stars in the halo (sparse distribution)



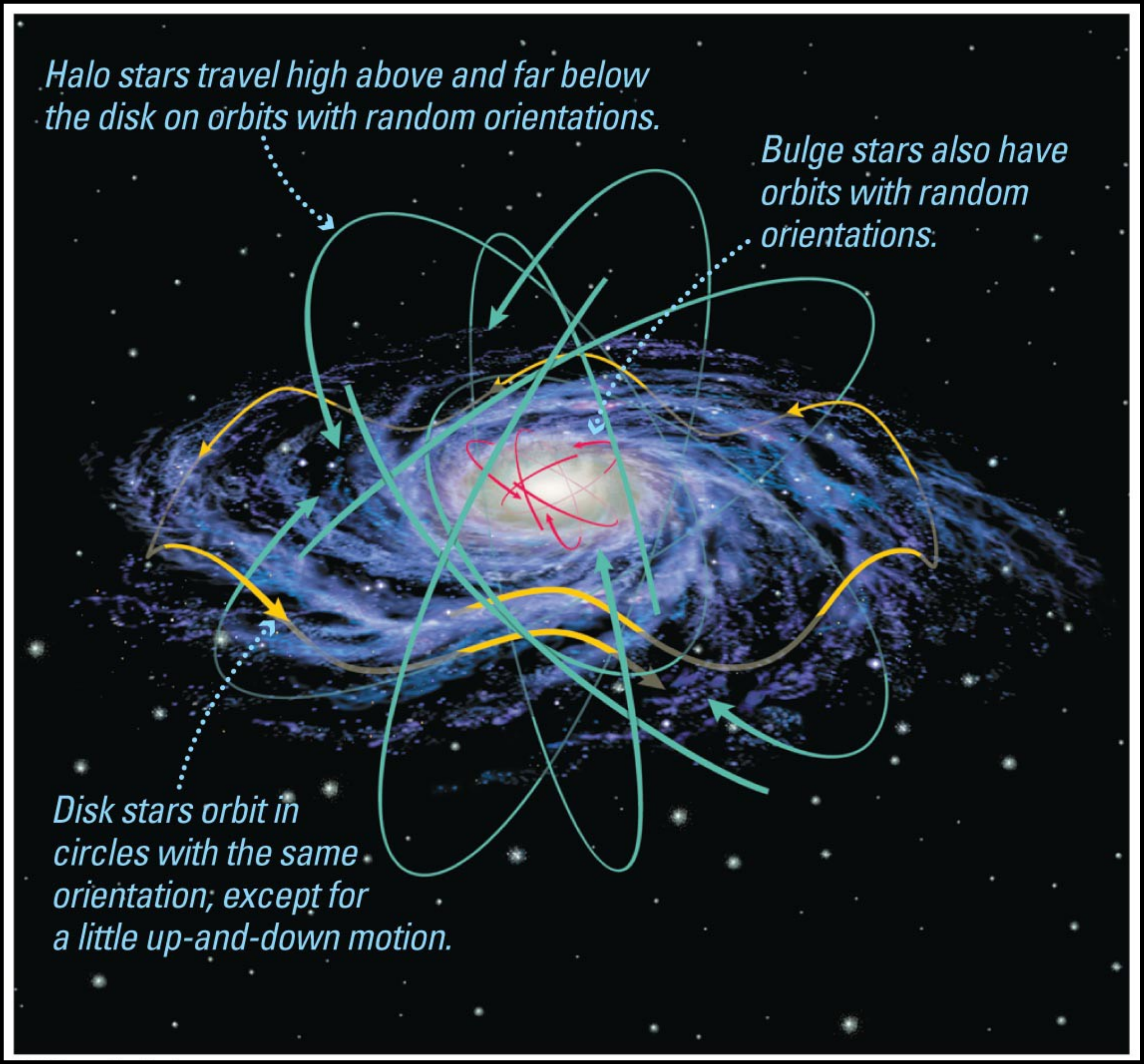
The different components have different colors, motions, ages, and chemical compositions → different origins!

How do stars orbit in the MW?



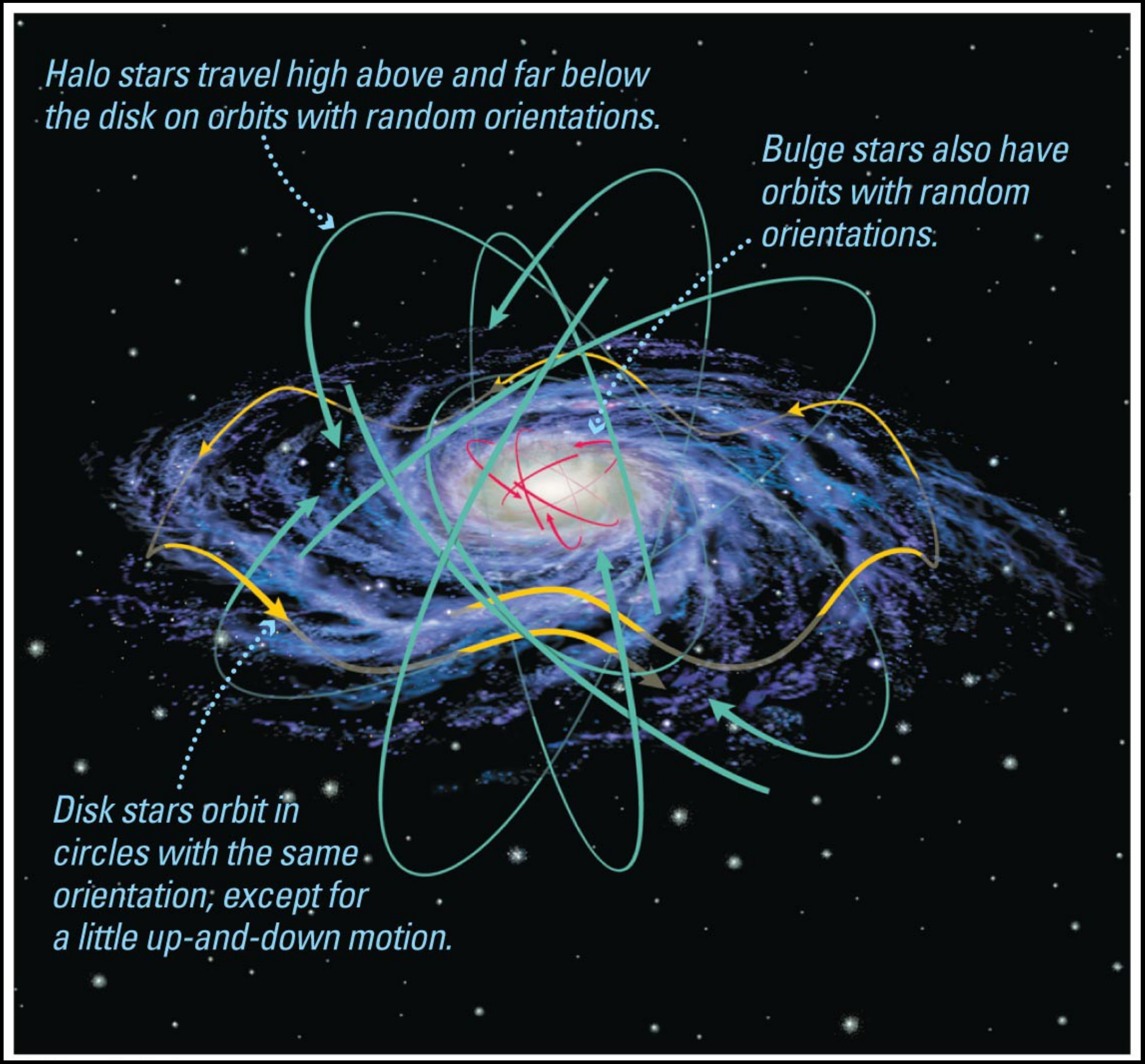
The different components have different **motions:**
halo
bulge
disk

How do stars orbit in the MW?



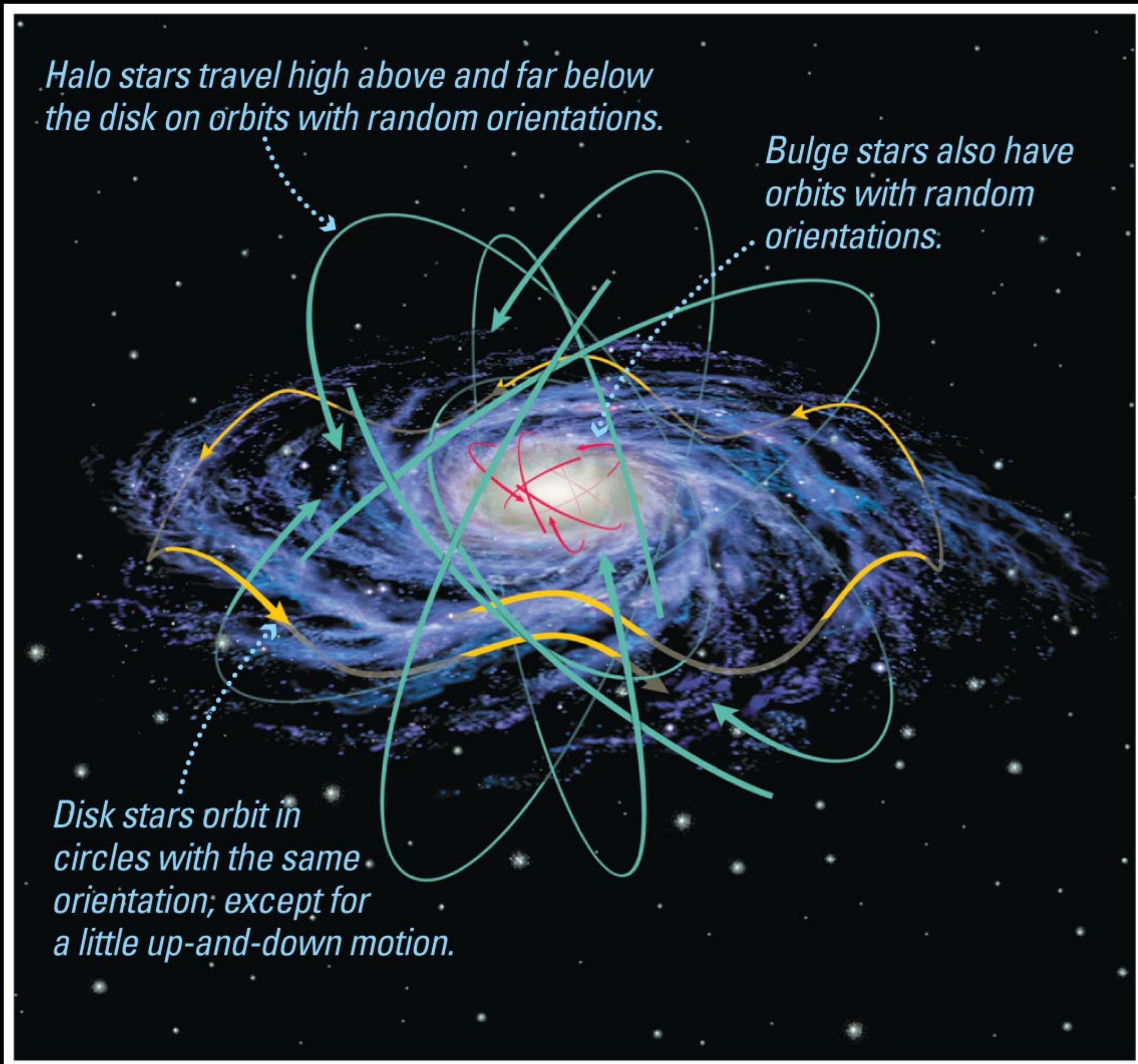
- **Halo stars**: random orientations, farther out from the bulge

How do stars orbit in the MW?



- **Halo stars**: random orientations, farther out from the bulge
- **Bulge stars**: random orientations

How do stars orbit in the MW?



- **Halo stars**: random orientations, farther out from the bulge
- **Bulge stars**: random orientations
- **Disk stars**: orbit in the same direction and same plane (with only a little up-down motion)

Recap: what have we learned?

- **What does the Milky Way look like?**
  - It has a **disk** of stars, gas, and dust. The young stars are found in spiral arms.
  - It has a spherical **bulge** of stars located at the center of the disk
  - The disk and bulge are surrounded by a more extended spherical **halo** of stars
- **How do stars orbit within our galaxy?**
  - Stars in the disk orbit within the plane of the disk, moving in the same direction
  - Stars in the bulge and halo move in random directions

How did our galaxy form?

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Halo Stars:

0.02–0.2% heavy elements (O, Fe, …), only old stars

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Disk Stars:

2% heavy elements, stars of all ages

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Halo Stars:
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Halo stars formed first, then stopped.

Disk Stars:
2% heavy elements, stars of all ages

How did our galaxy form?

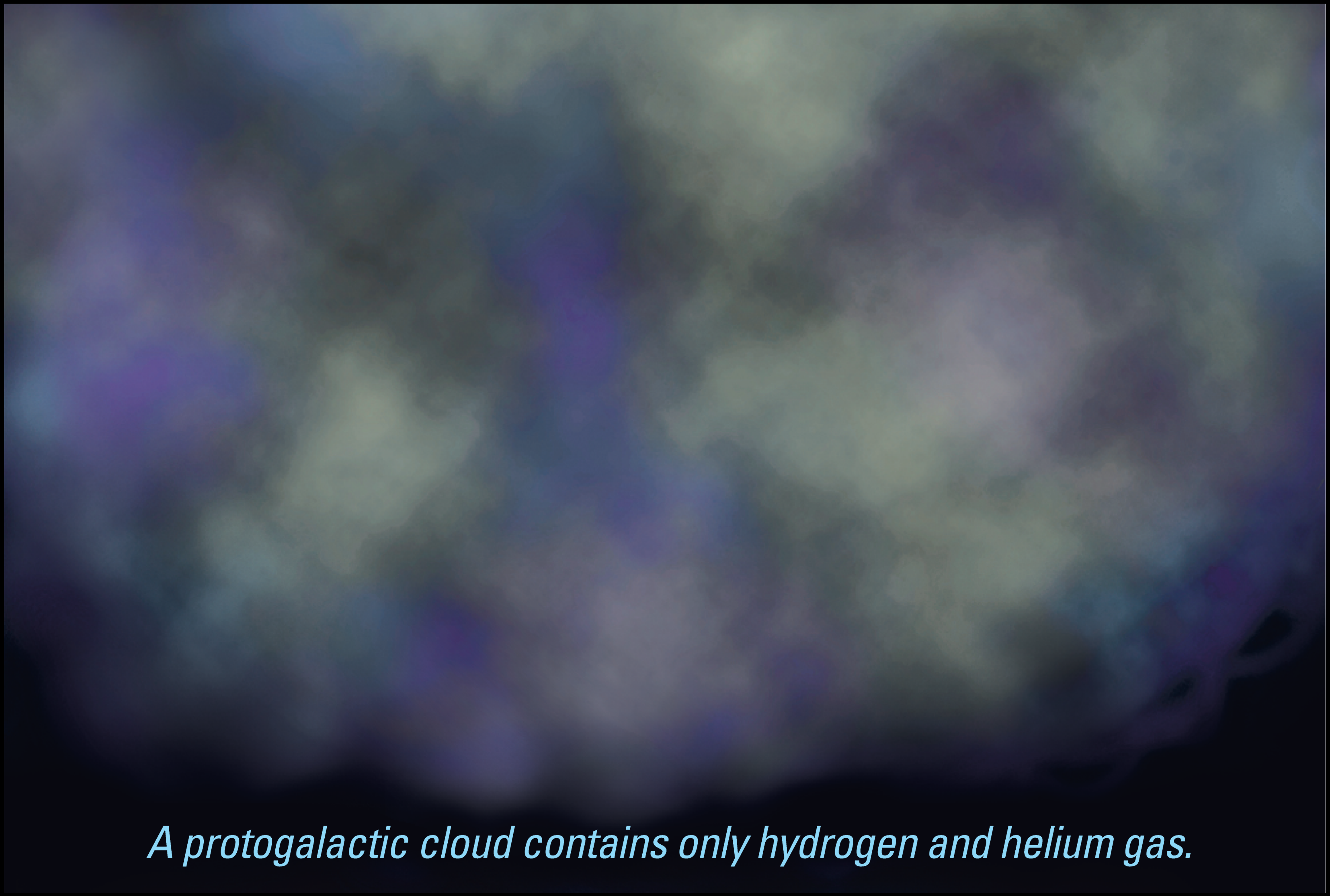
Halo Stars:
0.02–0.2% heavy elements (O, Fe, …), only old stars

Halo stars formed first, then stopped.

Disk stars formed later, kept forming.

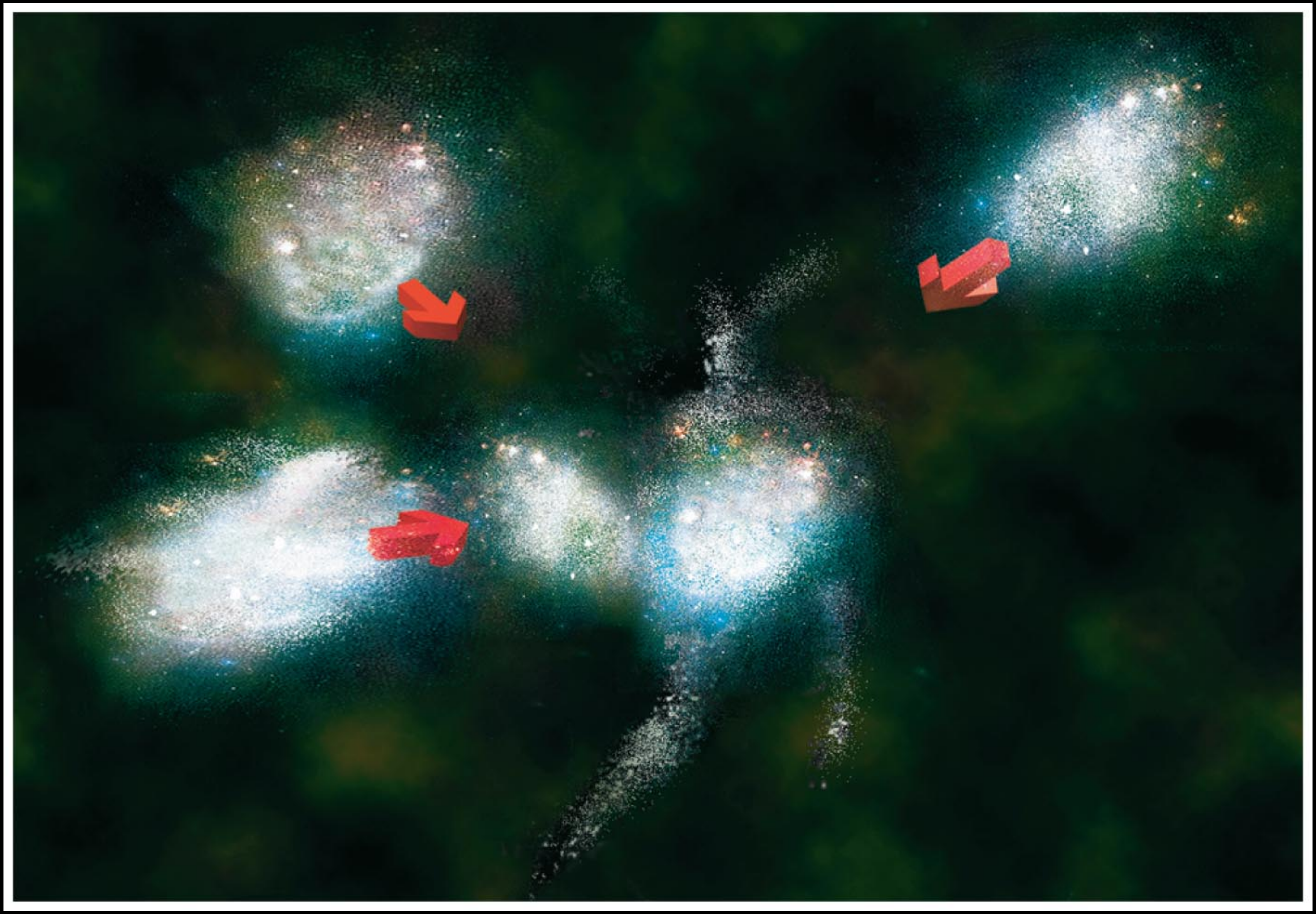
Disk Stars:
2% heavy elements, stars of all ages

How did our galaxy form?



Our galaxy formed from a cloud of intergalactic gas.

How did our galaxy form?



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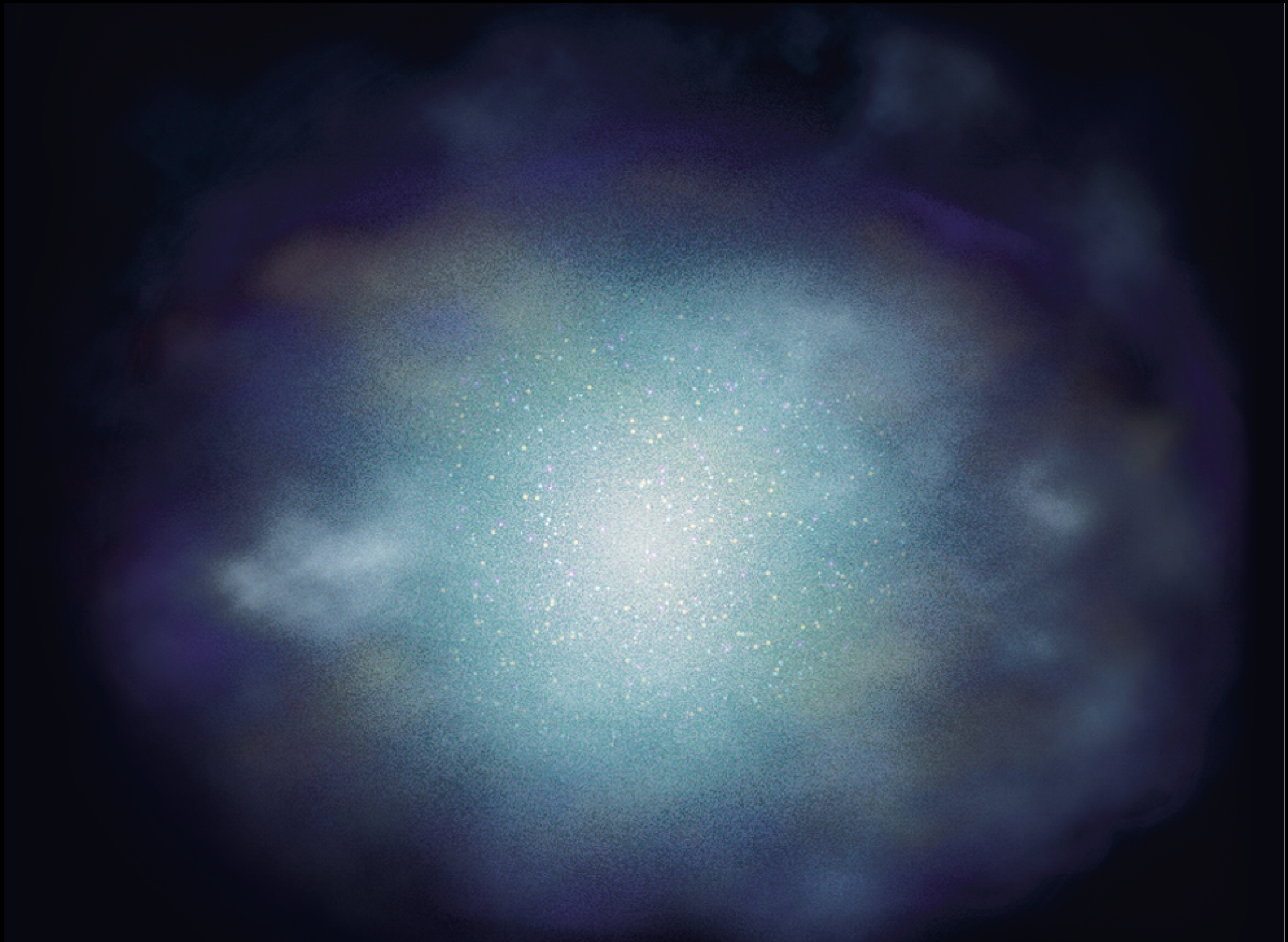
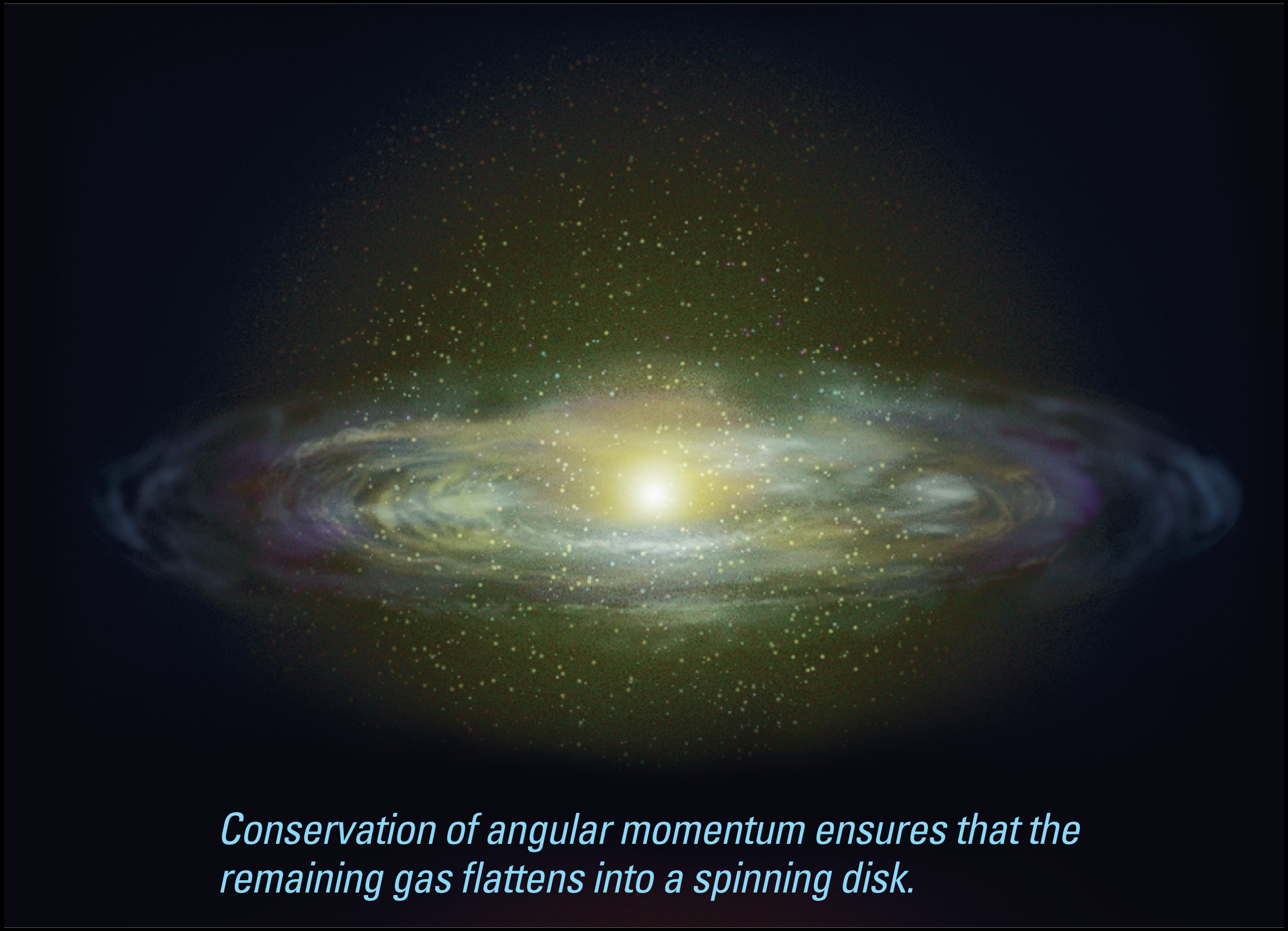


Halo stars begin to form as the protogalactic cloud collapses.

Halo stars formed first as gravity caused gas to contract.

How did our galaxy form?

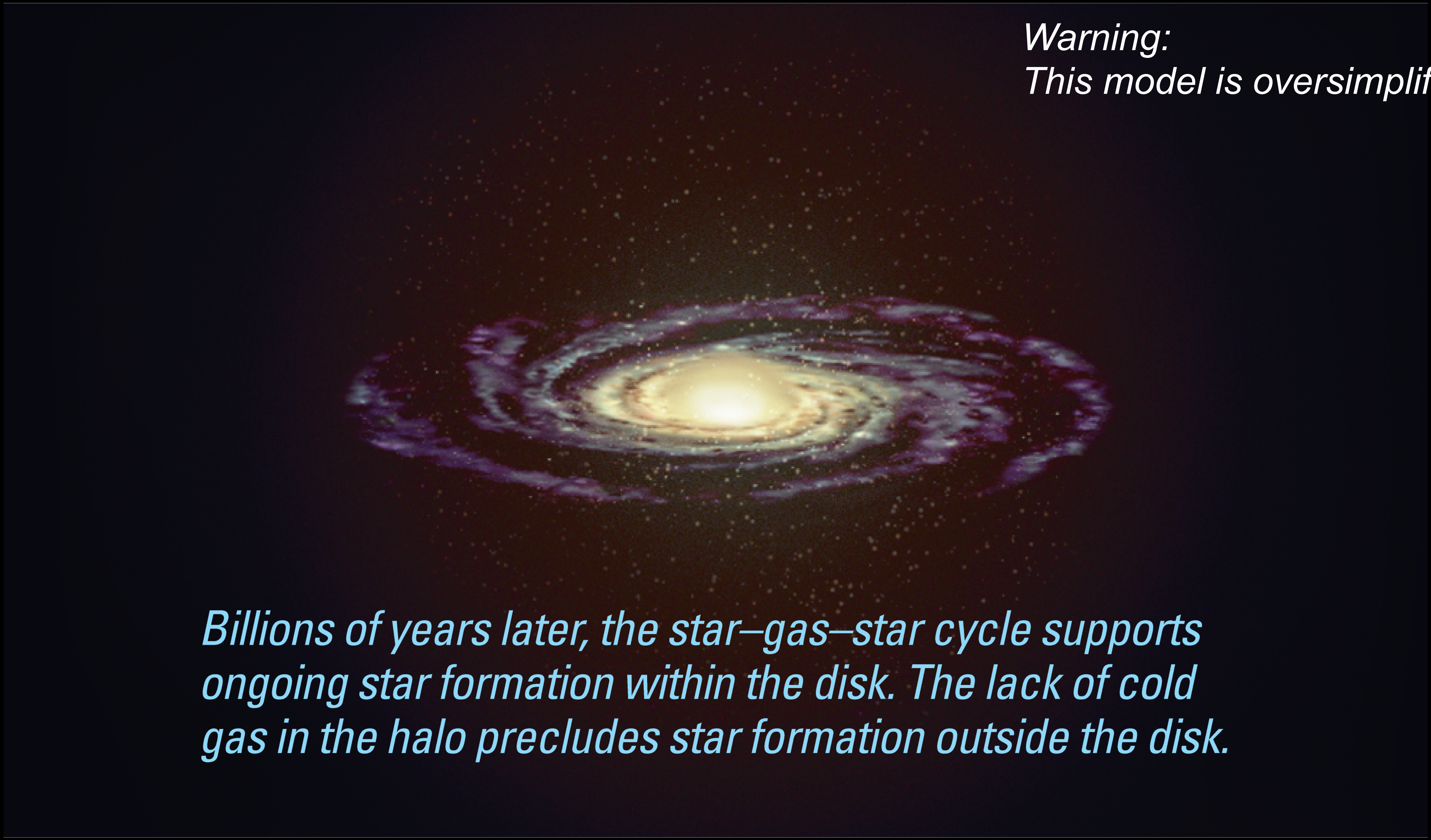


Remaining gas settled into a spinning disk.

How did our galaxy form?

Stars continuously form in disk as galaxy grows older.

How did our galaxy form?



Warning:
This model is oversimplified!

Stars continuously form in disk as galaxy grows older.

Simulation of a Milky Way-like galaxy

Simulation of a Milky Way-like galaxy

Dark Matter
(in the Milky Way and other galaxies)

Chapter 23