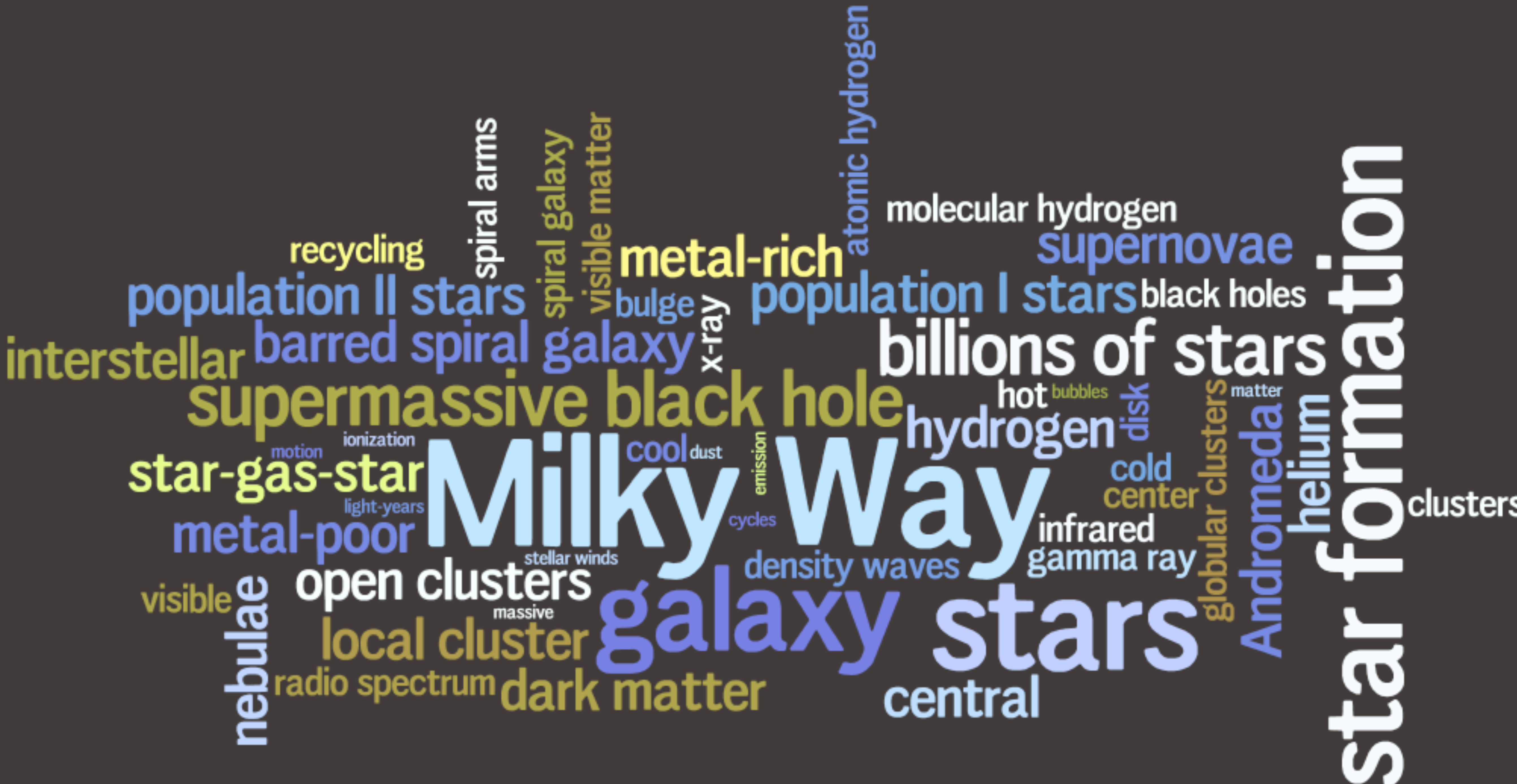
# Our Galaxy

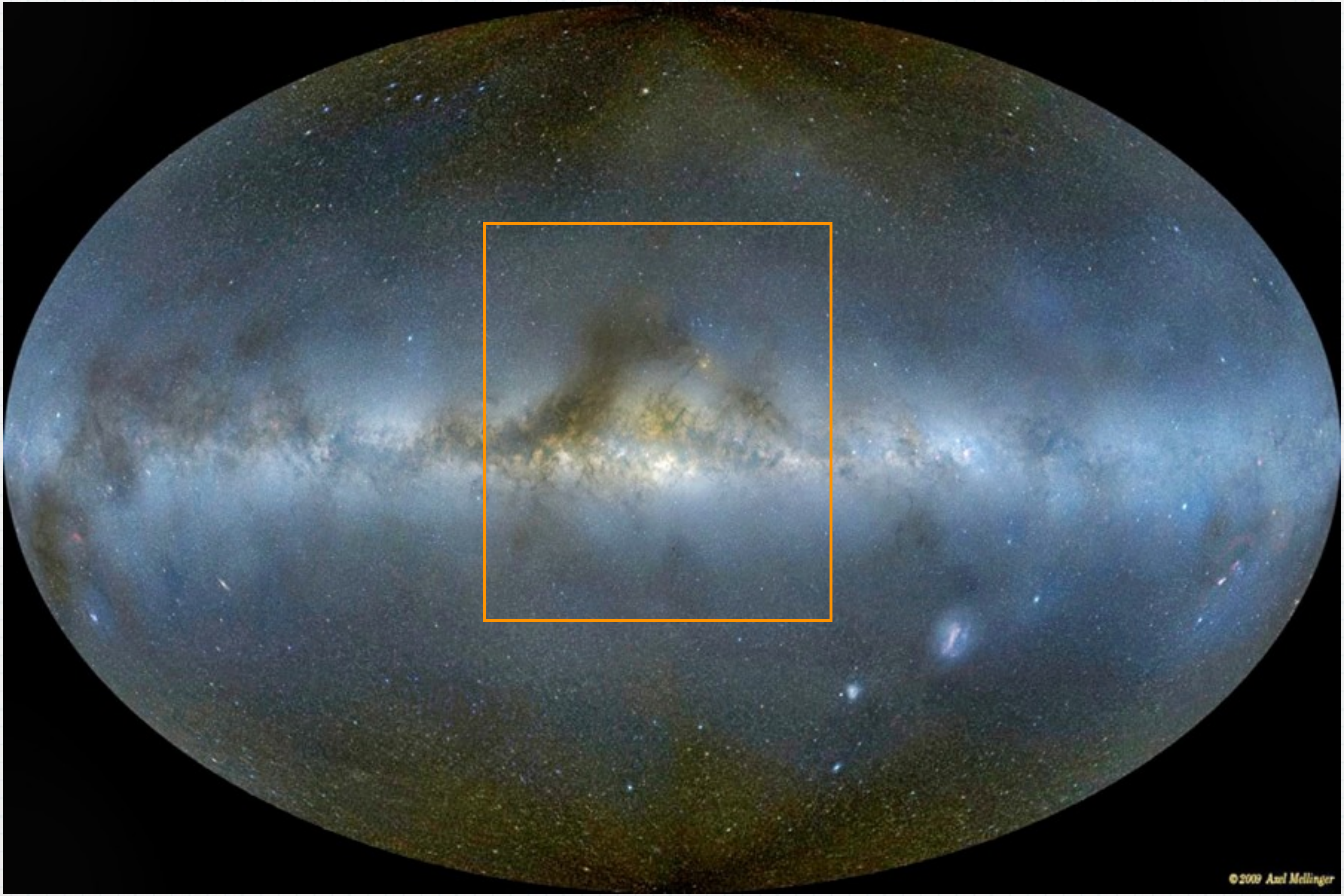
## Chapter: 14


Milky Way
galaxy
stars
star formation
supermassive black hole
billions of stars
population II stars
population I stars
barred spiral galaxy
interstellar
metal-rich
metal-poor
star-gas-star
open clusters
local cluster
dark matter
radio spectrum
nebulae
visible
hydrogen
molecular hydrogen
atomic hydrogen
supernovae
black holes
recycling
spiral arms
spiral galaxy
visible matter
bulge
x-ray
hot
bubbles
matter
disk
globular clusters
Andromeda
helium
clusters
cold
center
infrared
gamma ray
density waves
central
cool
dust
emission
cycles
motion
ionization
light-years
stellar winds
massive

# The Milky Way Revealed

* A galaxy is the ecosystem which permits stars to form
* And when the stars die, the stellar material blowing away is contained within the galaxy to permit its recycling

# The Milky Way galaxy appears in our sky as a faint band of light




Credit & Copyright: Axel Mellinger

Credit & Copyright: Axel Mellinger

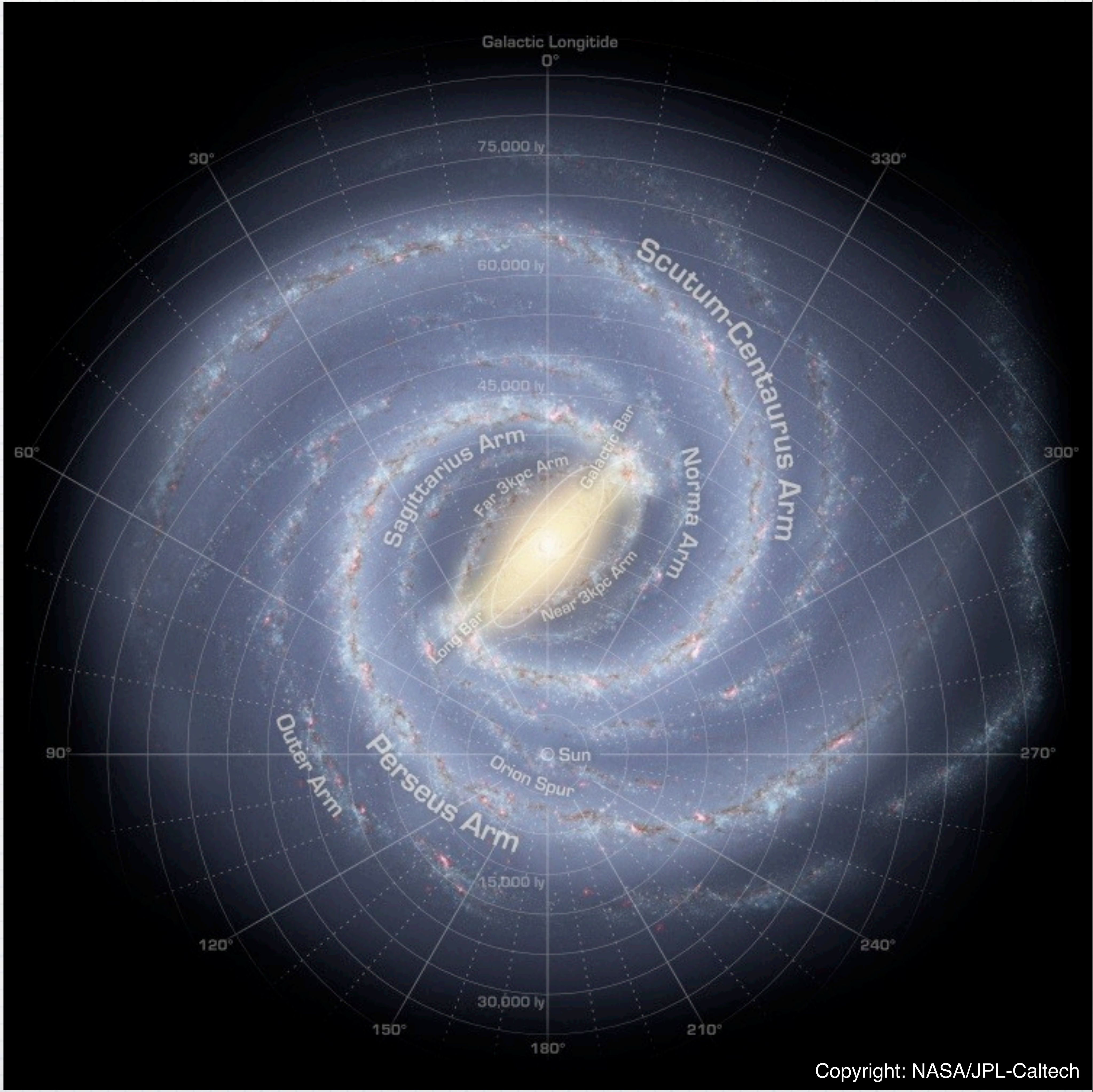
Dusty gas clouds obscure our view because they absorb visible light

This is the interstellar medium that makes new star systems

# What does our galaxy look like?

* We live in a **barred-spiral** type galaxy
* The **spiral arms** form a fairly flat **disk** surrounding a bright central **bulge**
* An **ellipsoidal halo** surrounds the entire disk
* In the halo, there exist about **200 globular clusters**

# A drawing of the Milky Way looking down from above

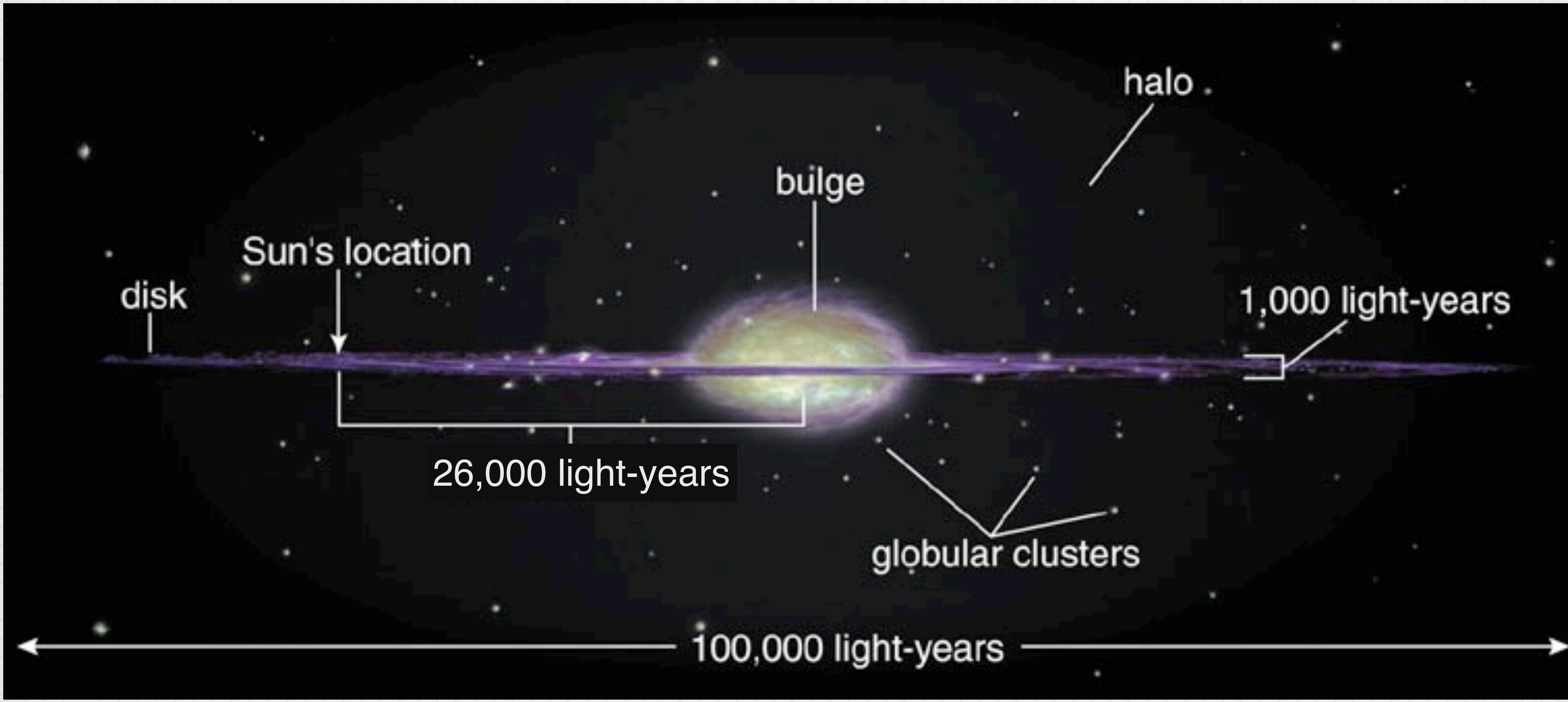


# What does our galaxy look like?...

* The galaxy is orbited closely by smaller satellite galaxies (such as the Magellanic clouds) called dwarf galaxies
* Most of the bright stars reside in the disk
* The most prominent stars found in the halo are found in the 200+/- globular clusters

# We see our galaxy edge-on

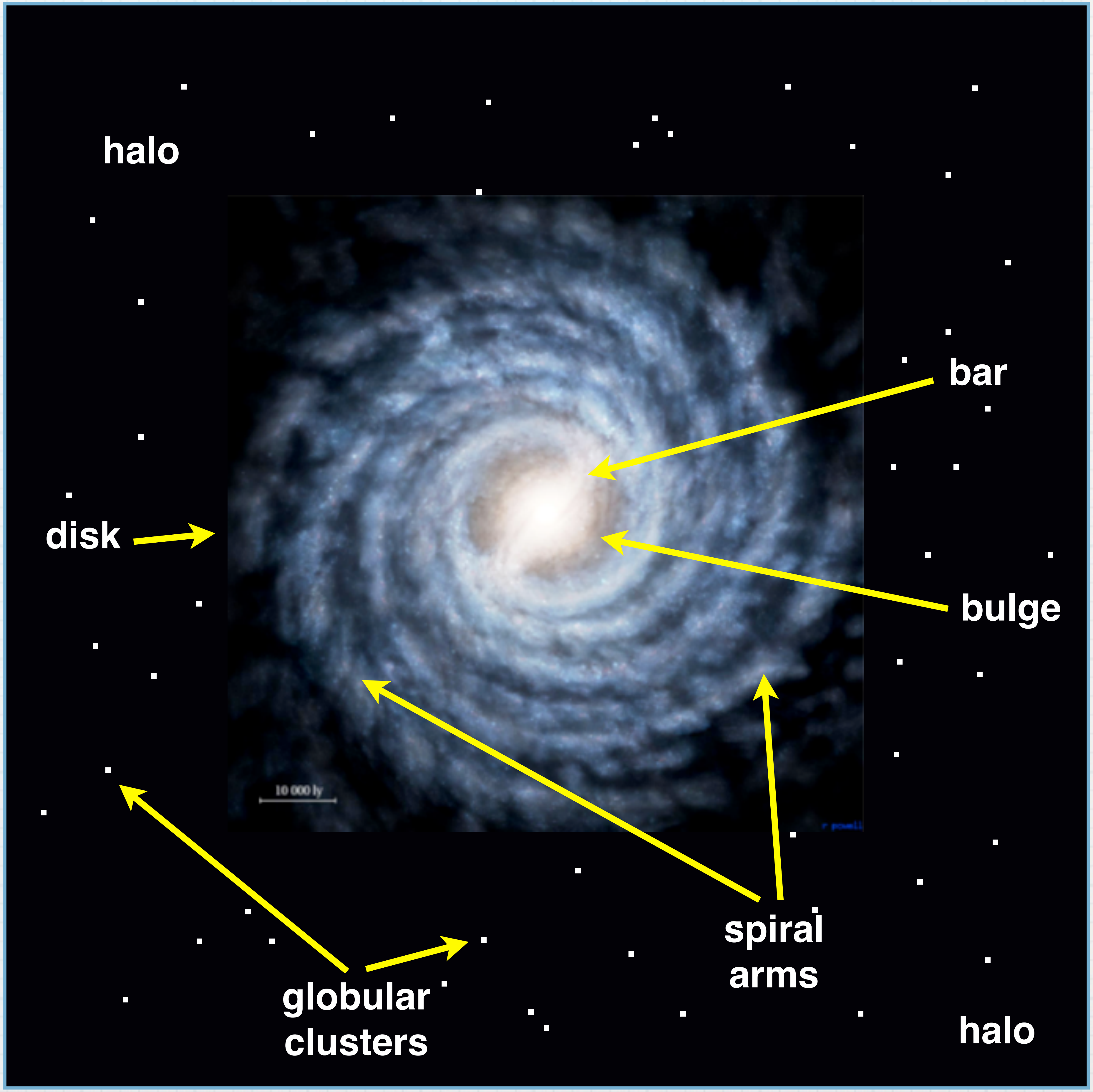
## Primary features: disk, bulge, halo, globular clusters



# What does our galaxy look like?...

* The galaxy's diameter is about 100,000 light-years
* The disk is about 1,000 light-years thick
* The entire galaxy holds between 200 billion and 400 billion stars
* Its mass is about 600 billion solar masses
* Its oldest known star is 13.2 billion year-old

# The galaxy as seen top-down



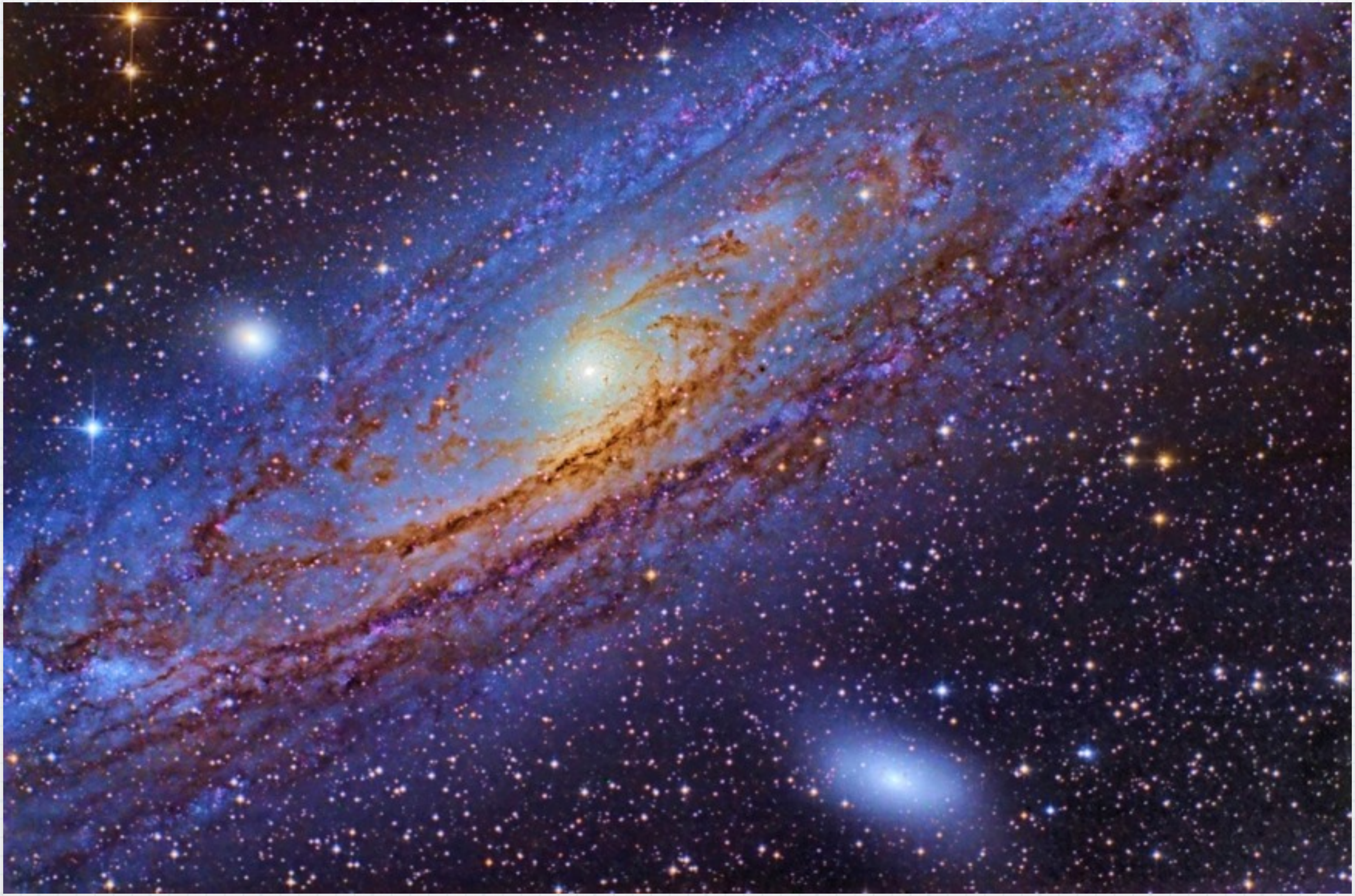

The bar is a sign of the maturity of a spiral galaxy

# A Lone Island?

* The Milky Way is part of the Local Group of galaxies
* This group comprises over 35 galaxies
* The two most massive members of the group are the Milky Way and the Andromeda Galaxy
* So far, it is estimated that there are about 500 billions galaxies in the visible Universe

# The Andromeda Galaxy, our sister neighbor

## Can you spot two of its satellite galaxies?



# Globular Clusters

* A globular cluster is a spherical collection of stars that orbits a galactic core as a satellite
* Globular clusters are very tightly bound by gravity, which gives them their spherical shapes and relatively high stellar densities toward their centers
* They are found in the galactic halo

# Globular Clusters...

* Their stars are very old and contain few heavy elements (metal-poor)
* A globular cluster may contain between 10,000 to 1 million stars
* Their diameters range from 50 to 200 light-years
* Globular clusters formed before our galaxy matured into its current shape

# Messier 3, about 500,000 stars

# Messier 72, a smaller globular cluster (± 100,000 stars)

# The halo and the extension of the spiral arms can be seen with very long exposures

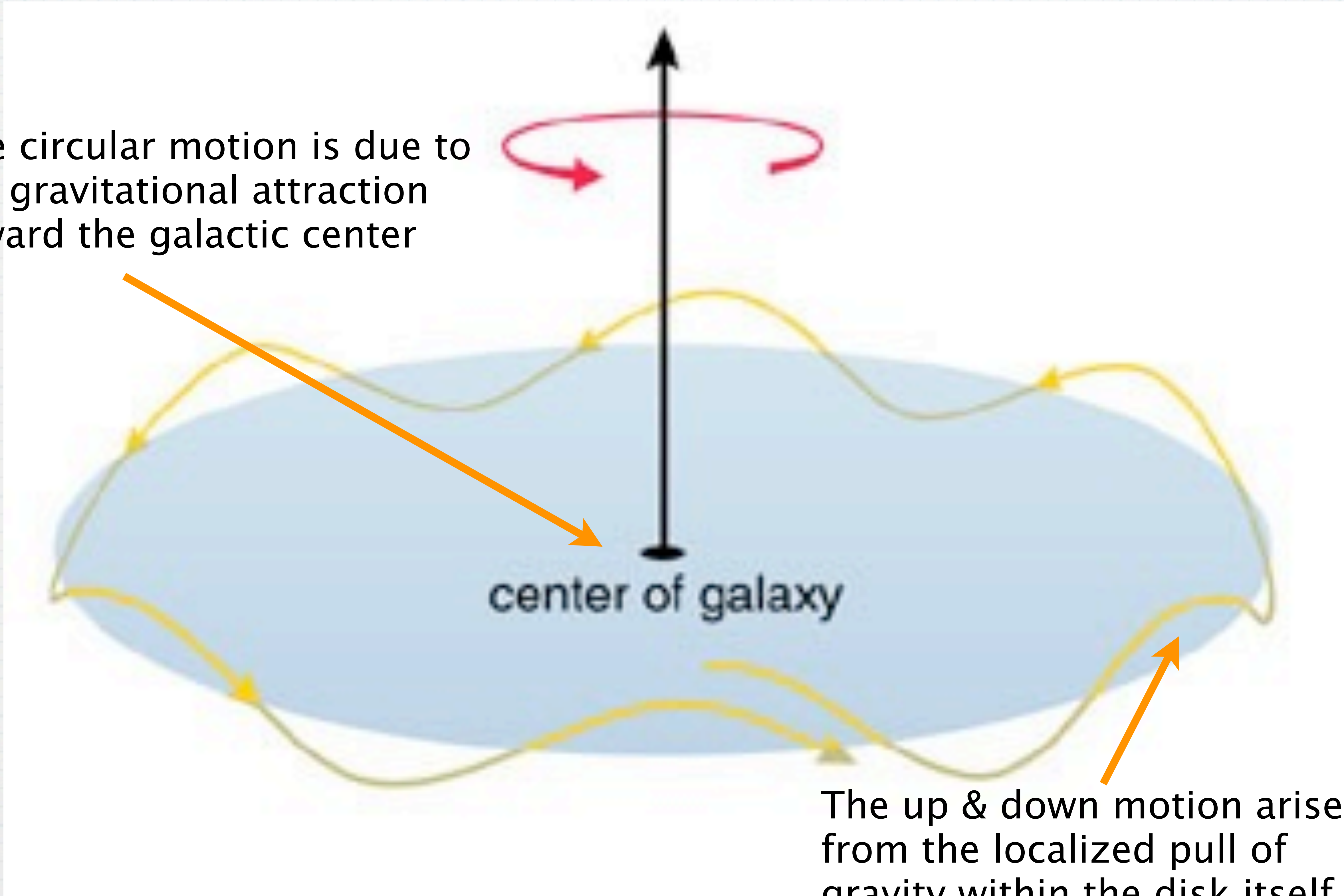
Credit & Copyright: Tony Hallas

Sunflower galaxy, Messier 63

# How do stars orbit in our galaxy?

* Our galaxy looks like a giant pinwheel but it does not spin as a whole
* Rather, each star follows a unique orbital path around the galactic center
* There are two basic orbital patterns
    * stars in the disk, and
    * stars in the halo and the bulge

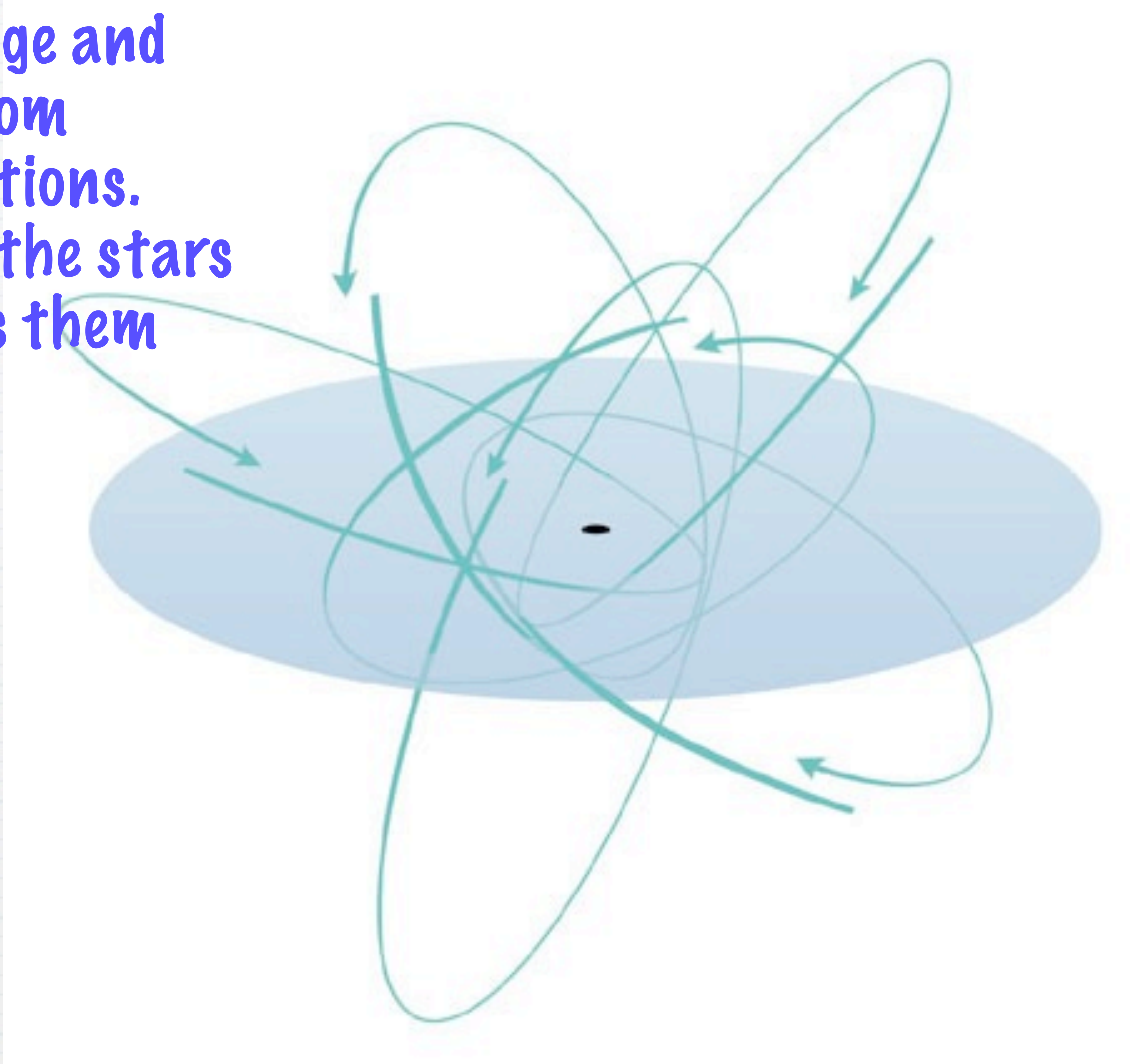
# Stars in the disk orbit in the same direction with a little up-and-down motion

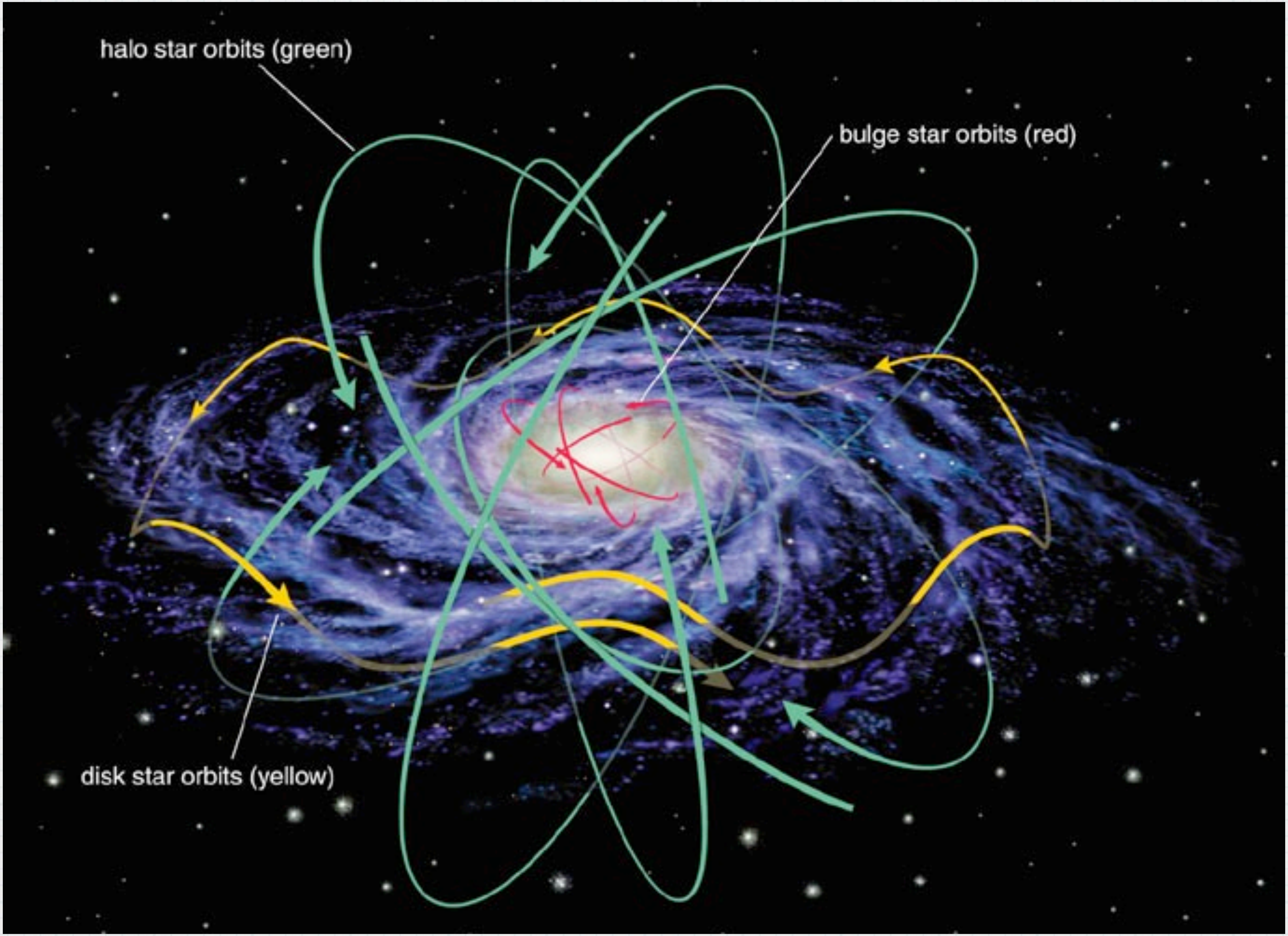



The circular motion is due to the gravitational attraction toward the galactic center

The up & down motion arises from the localized pull of gravity within the disk itself

Stars in the bulge and halo have random orbital orientations. The gravity of the stars in the disk pulls them




halo star orbits (green)
bulge star orbits (red)
disk star orbits (yellow)

# Question

* Why do orbits of disk stars bob up and down?

A. They're stuck to interstellar medium

B. Gravity of disk stars pulls them toward disk

C. Halo stars knock them back into disk

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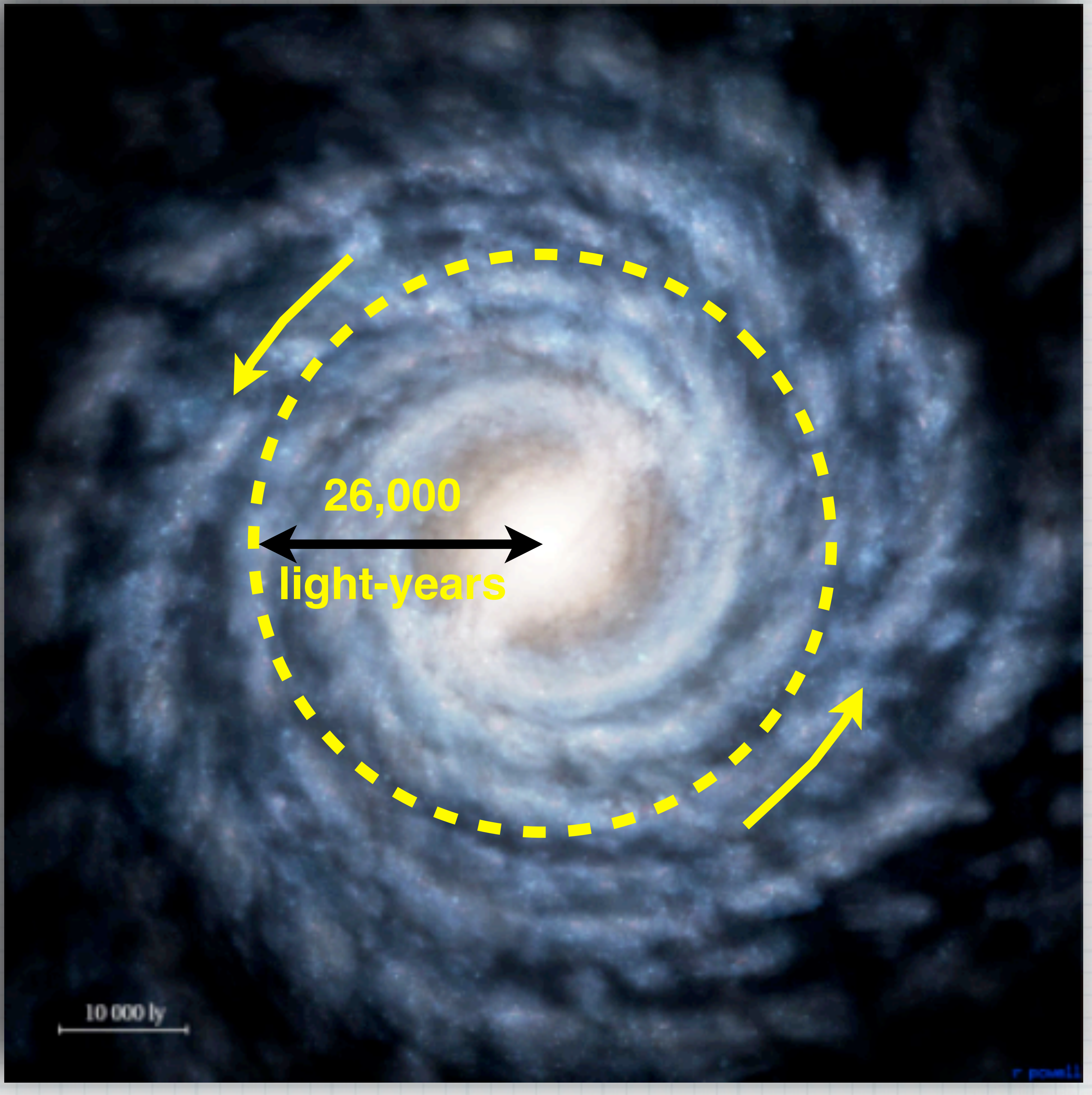
# Stellar Orbits and the Mass of the Galaxy

* The Sun is located 26,000 light-years from the galactic center
* It makes one full circle in 230 million years (255 km/s or 915,000 km/hr)
* We can use these numbers to find out how much galactic mass is **within** that orbit

Sun's orbital motion (radius and velocity) tells us mass within Sun's orbit:

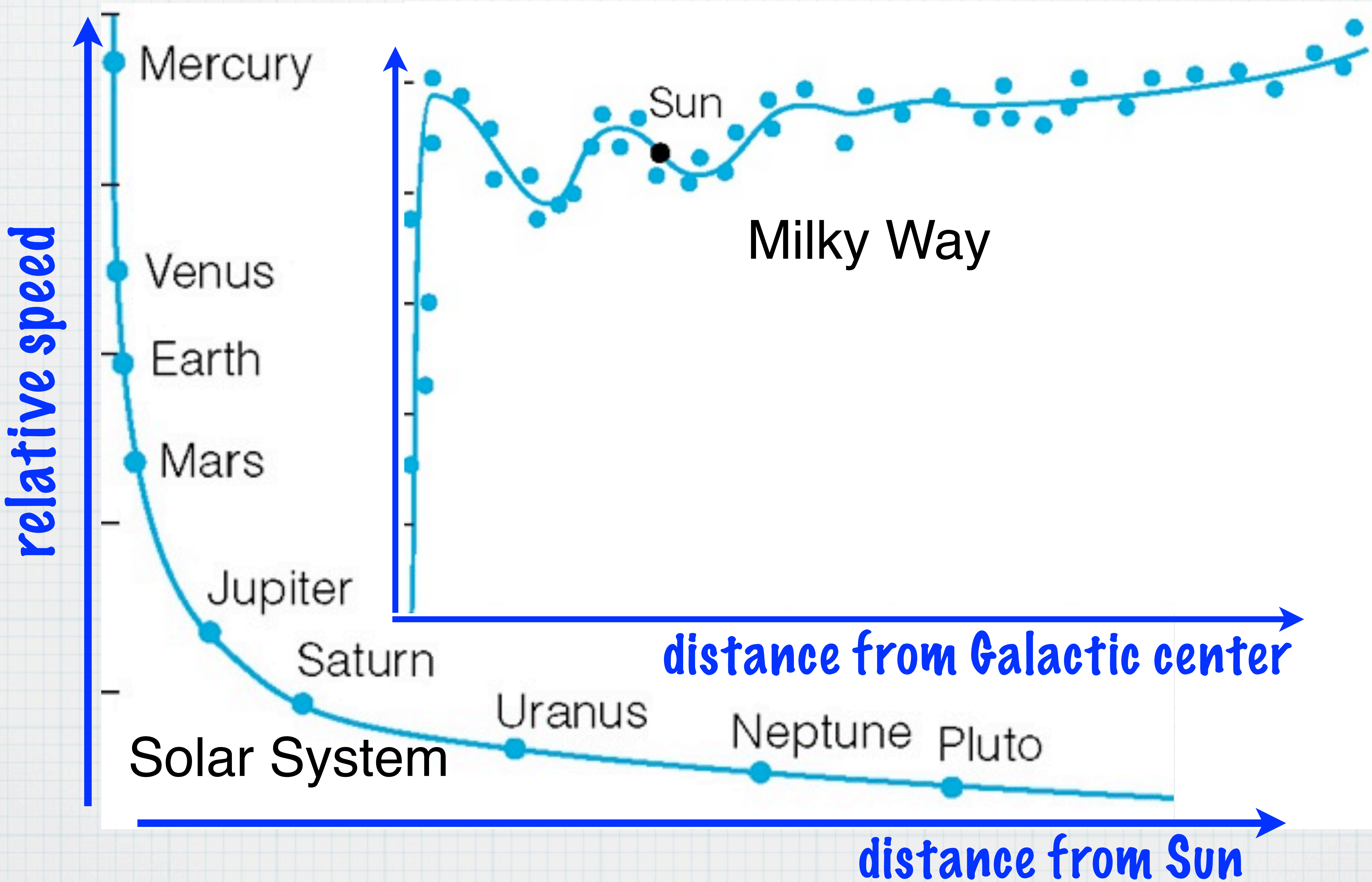
$1.0 \times 10^{11}$ $M_{Sun}$ or 100 billion $M_{Sun}$



# Stars Orbits ≠ Planets Orbits

* Doing the same analysis with more distant stars show that they, too, orbit the galactic center **with a similar velocity**
* This is a different pattern than that of planets orbiting a central star: the closer one orbits faster, the more distant ones orbit slower

# Orbital Speed Differences

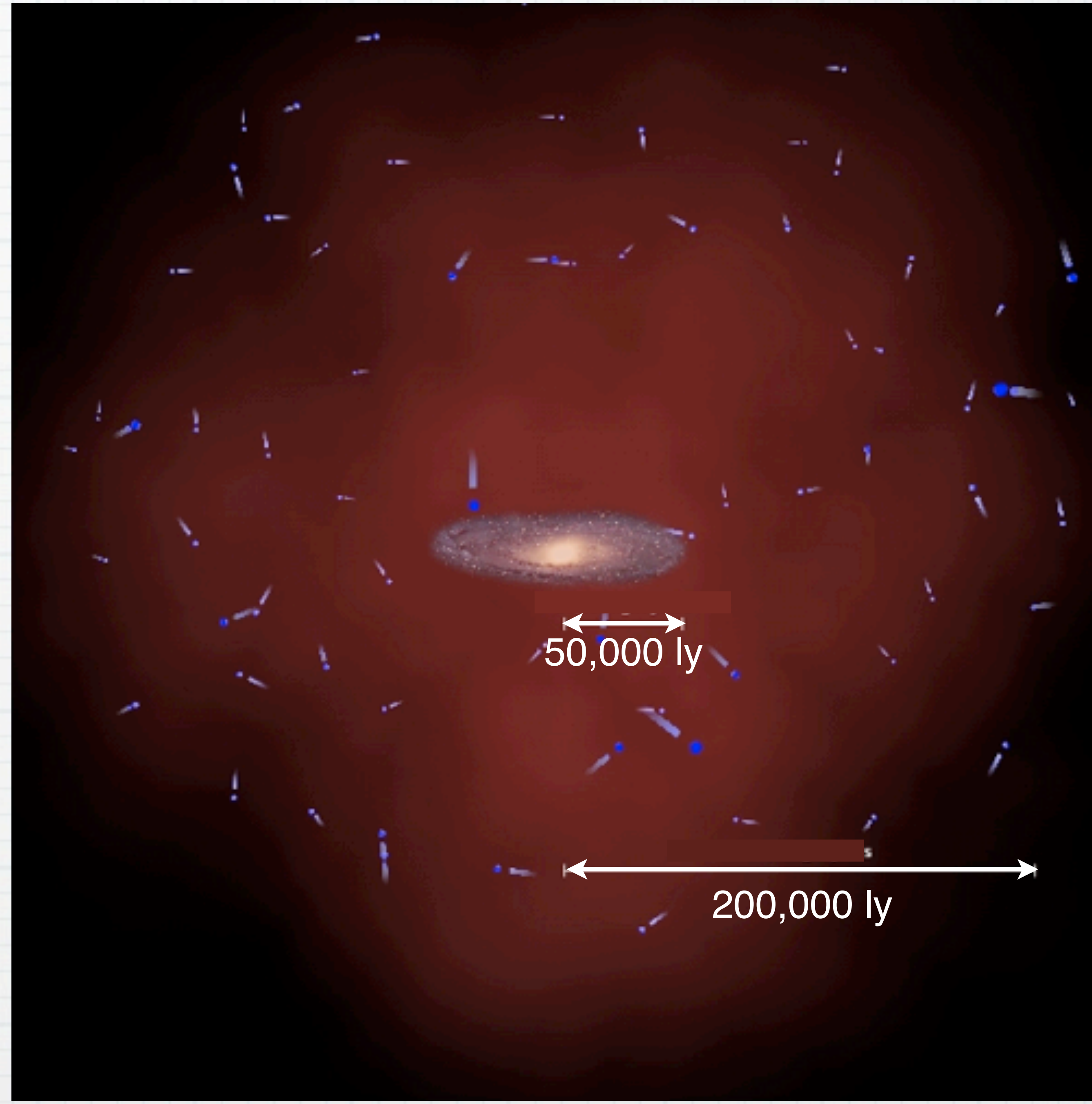


# Visible Mass is not enough... Introducing... Dark Matter

* This tell us that most of the galaxy's mass resides far from the center and is distributed throughout the halo
* But pictures tell us that most of the visible mass is in the center
* So most of the galactic mass is not shining light and is called dark matter

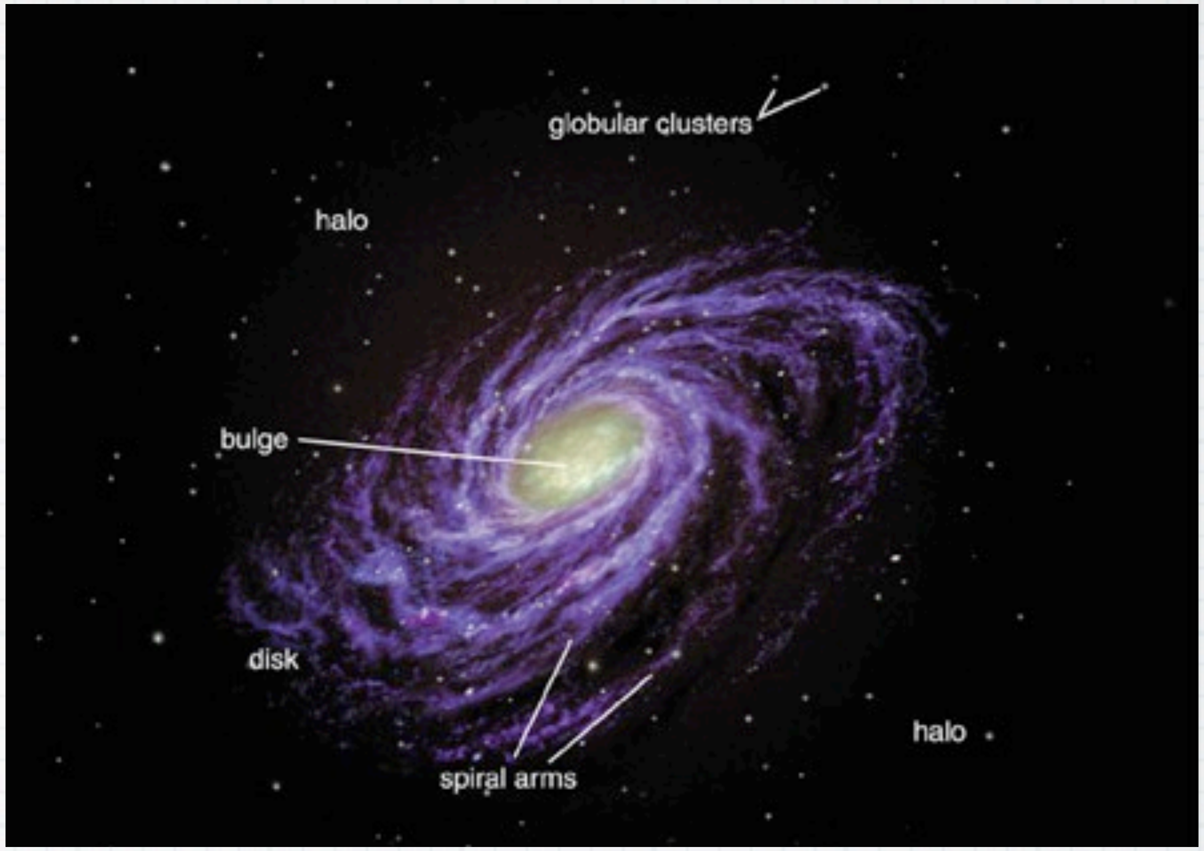
# What is Dark Matter?

* We do not know for sure
* Normal matter (fermionic) absorbs and emits photons
* Dark matter does not



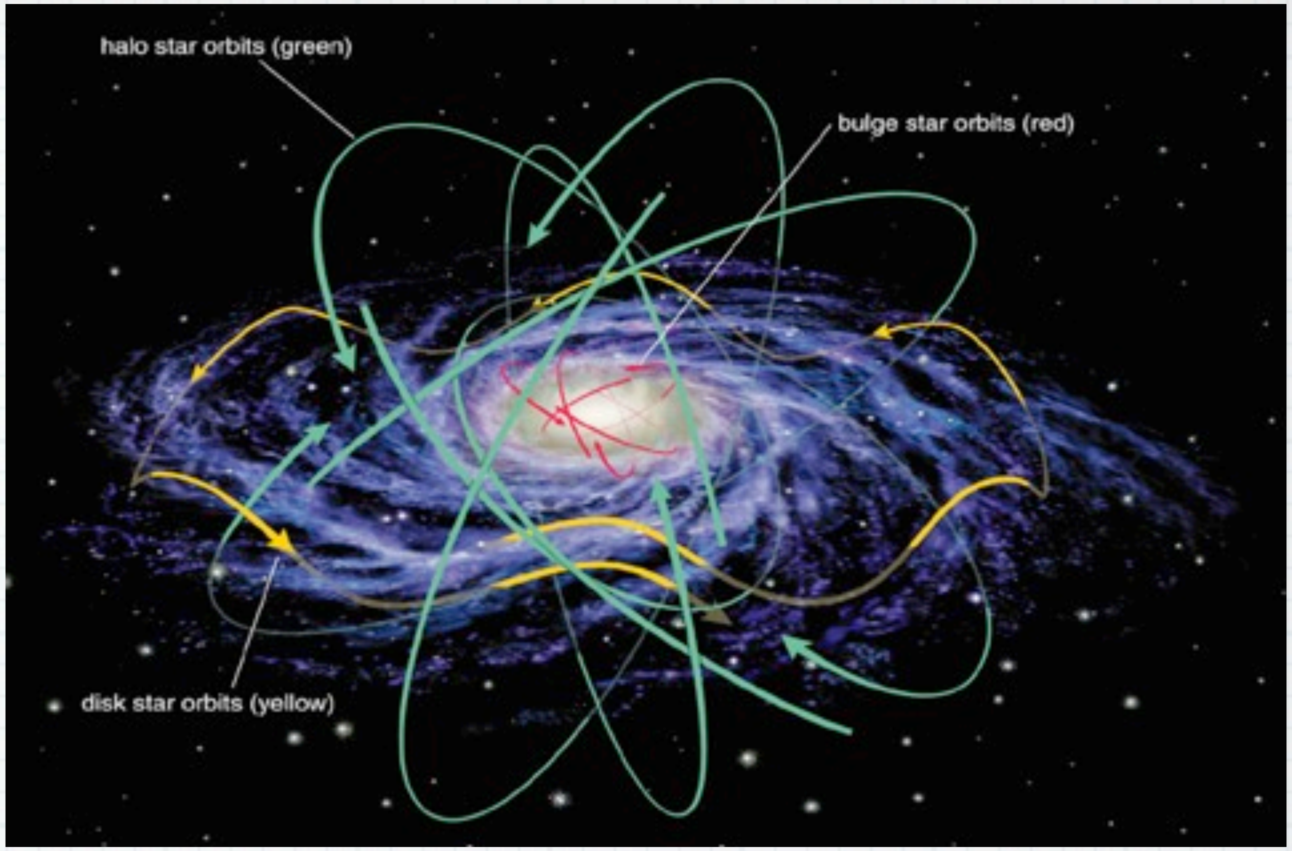

* Dark matter seems to be made of particles which are not sensitive to the electromagnetic force

# Snapshot



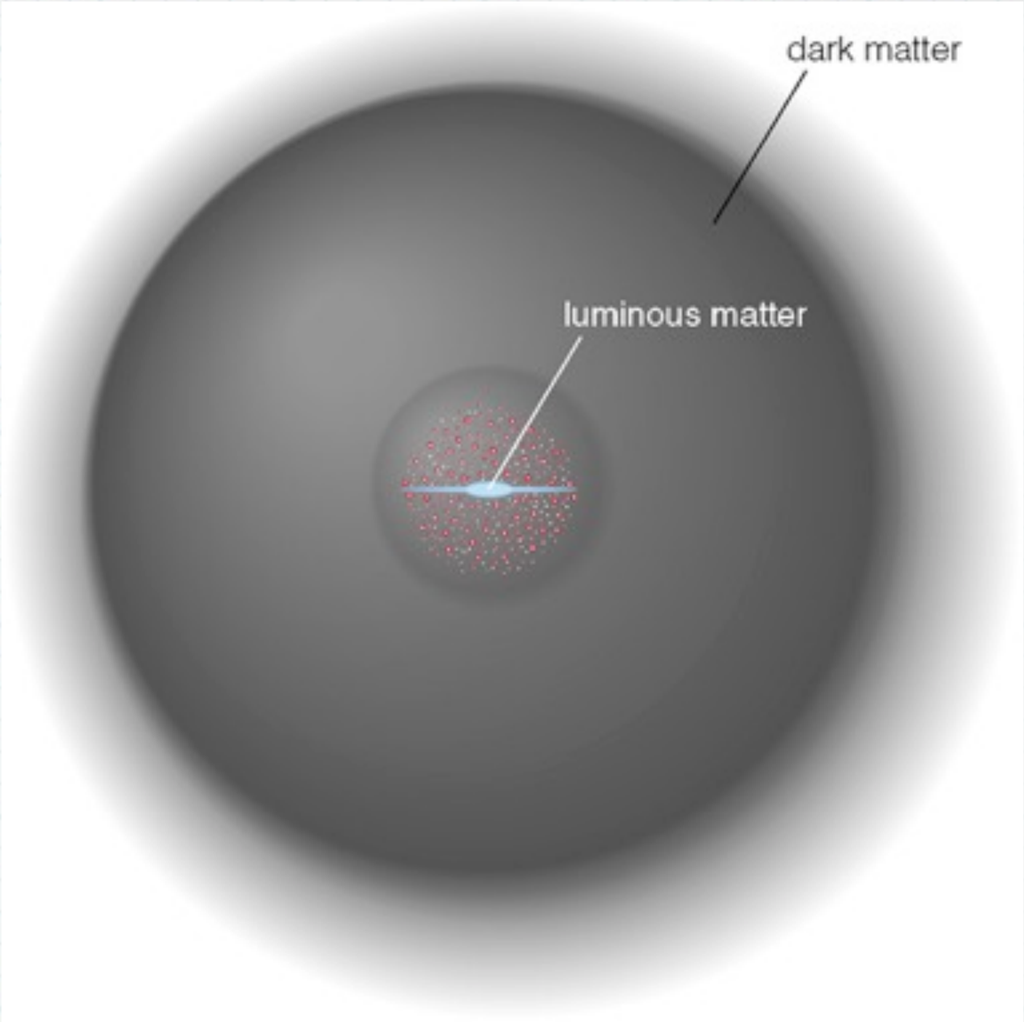

* What does our galaxy look like?
* The Milky Way Galaxy consists of a thin disk about 100,000 light-years in diameter with a central bulge and a spherical region called the halo that surrounds the entire disk. The disk contains the gas and dust of the interstellar medium, while the halo contains very little gas

# Snapshot




* How do stars orbit in our galaxy?
* Stars in the disk all orbit the galactic center in about the same plane and in the same direction. Halo and bulge stars also orbit the center of the galaxy, but their orbits are randomly inclined to the disk of the galaxy

# Snapshot




* Where is the galactic mass?
* Analysis show that the mass we see is not enough to explain the rotational behaviors of the stars in the disk. Most of the mass is "missing", or not visible. We call it dark matter. Dark matter does not absorb nor emit photons

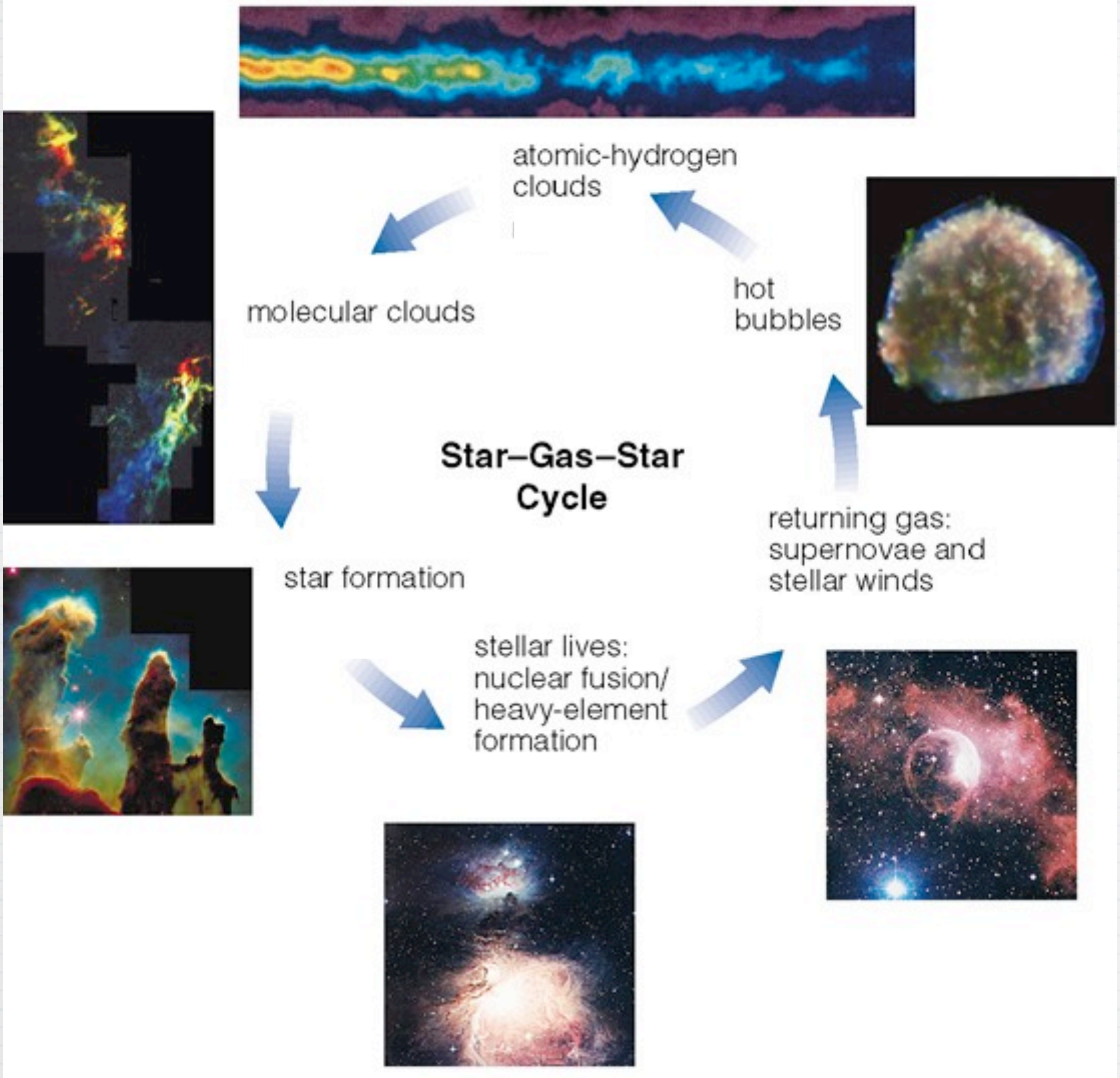
# Galactic Recycling

* Generations of stars continually recycle galactic matter via fusion
* Heavier and heavier elements are gradually made through each star generation
* The dust in the disk slows down the material ejected by supernovae permitting the **star-gas-star cycle**

# How does our galaxy recycle gas into stars?

* The recycling process happens in stages

1. stars are born in molecular clouds
2. they shine and make heavier elements
3. they die and blow contents back in interstellar space, contents which cool down to make molecular clouds

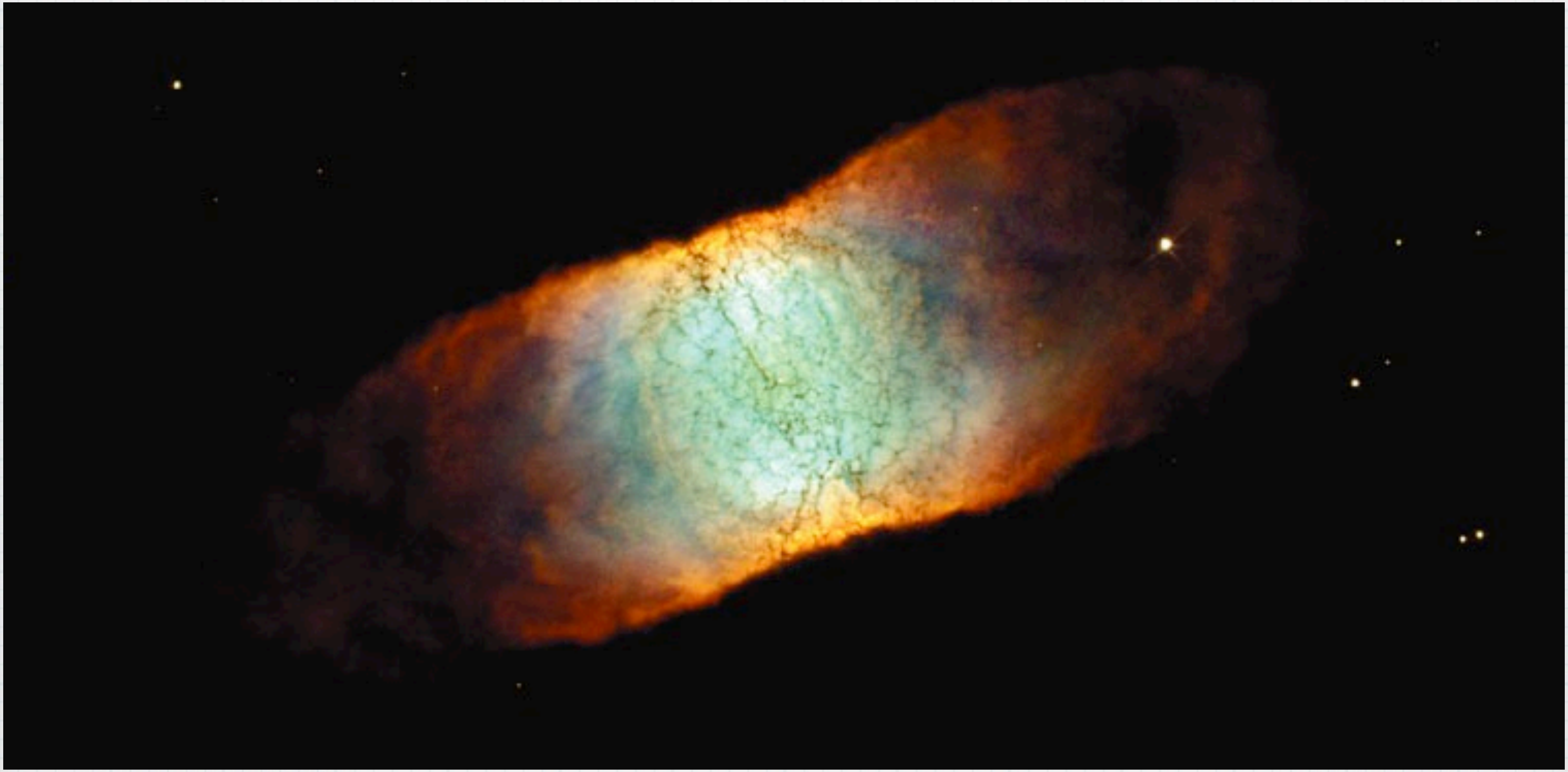



# Star-Gas-Star cycle

## Recycles gas from old stars into new star systems

# Gas from dying stars

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

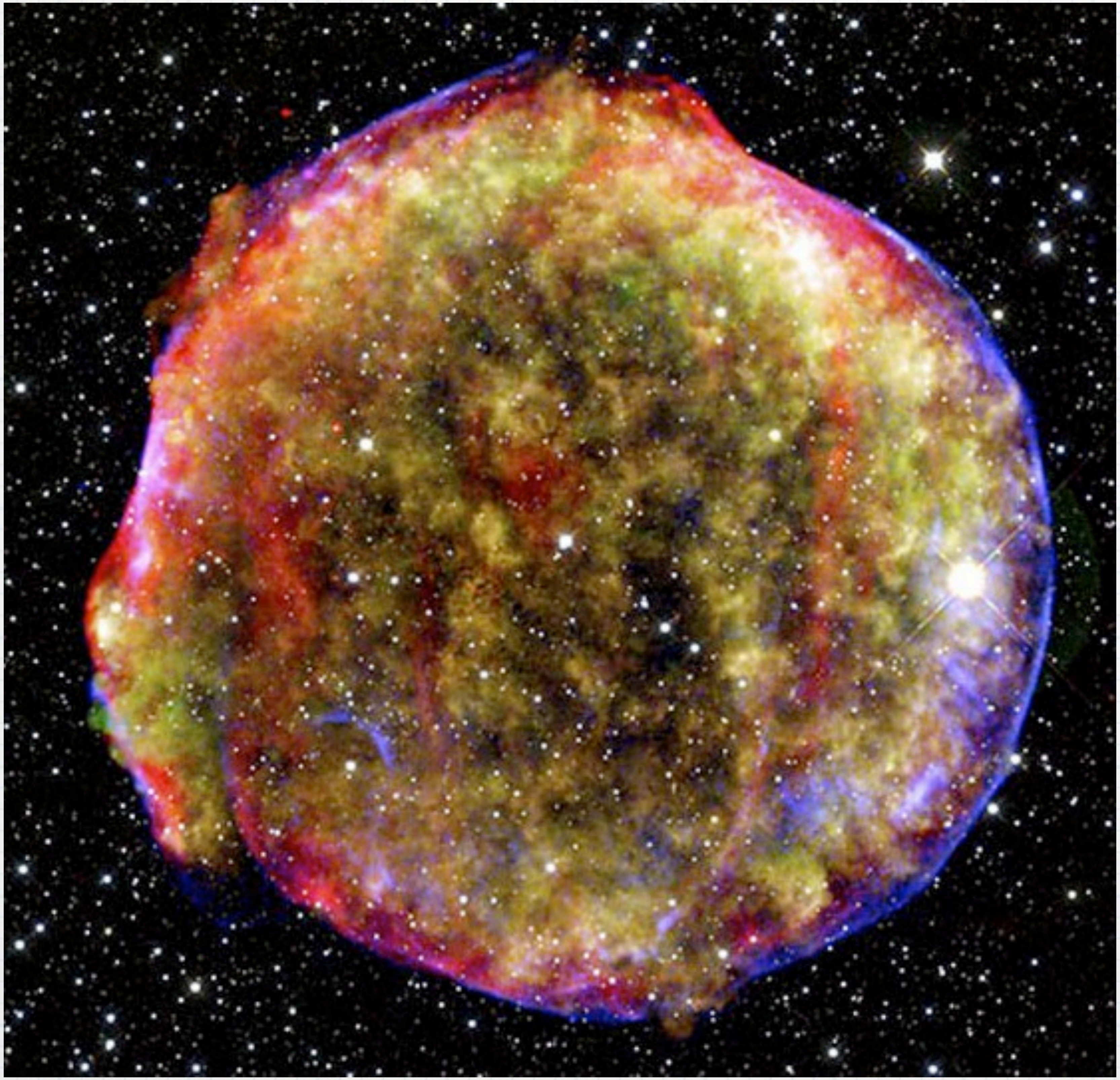


# Gas from dying stars...

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

The bubbles are detectable mostly via radio telescopes

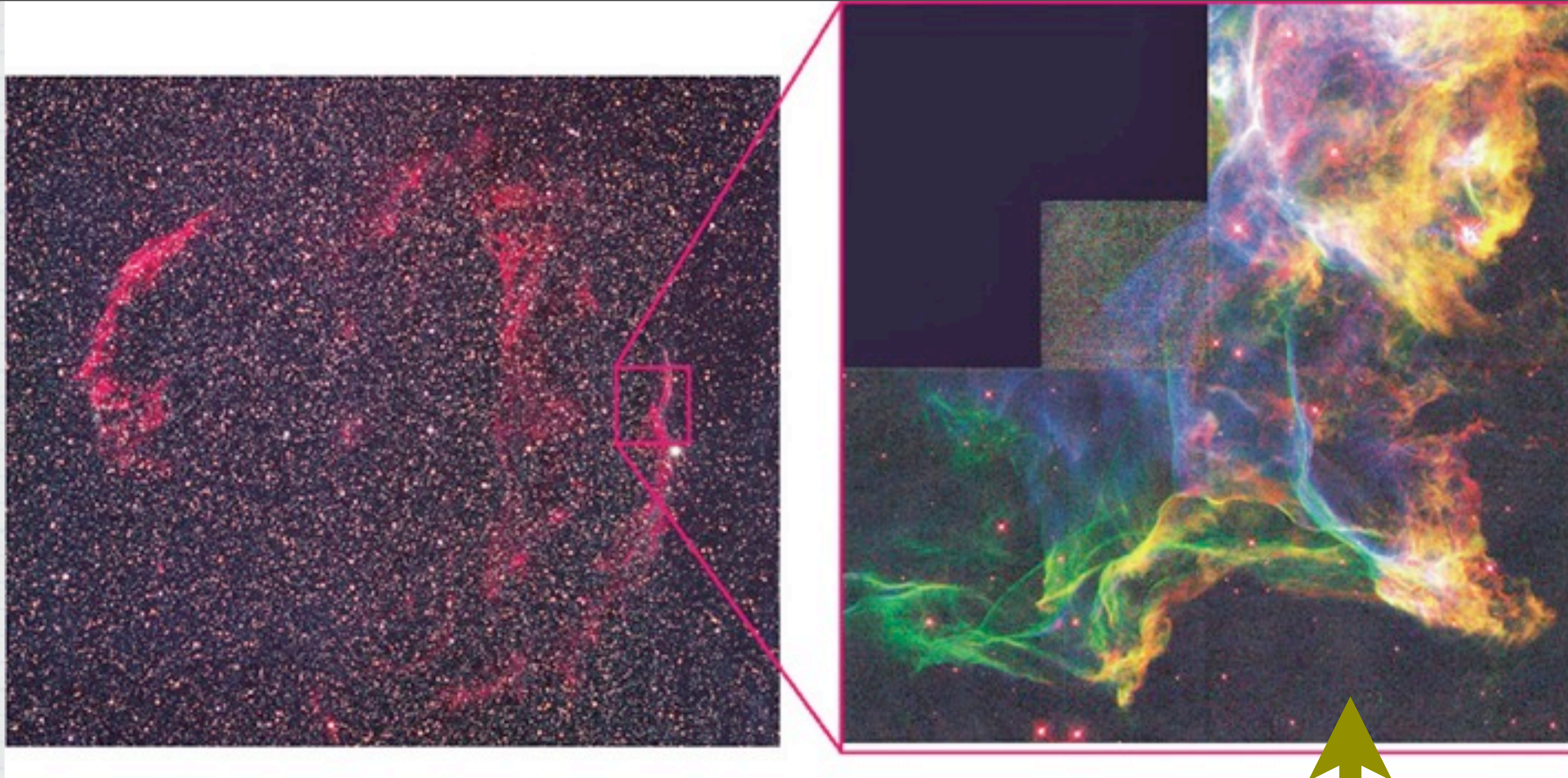
# Supernovae (high-mass stars) make heavy elements



Credit:X-ray: NASA/CXC/SAO; Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O. Krause et al.

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

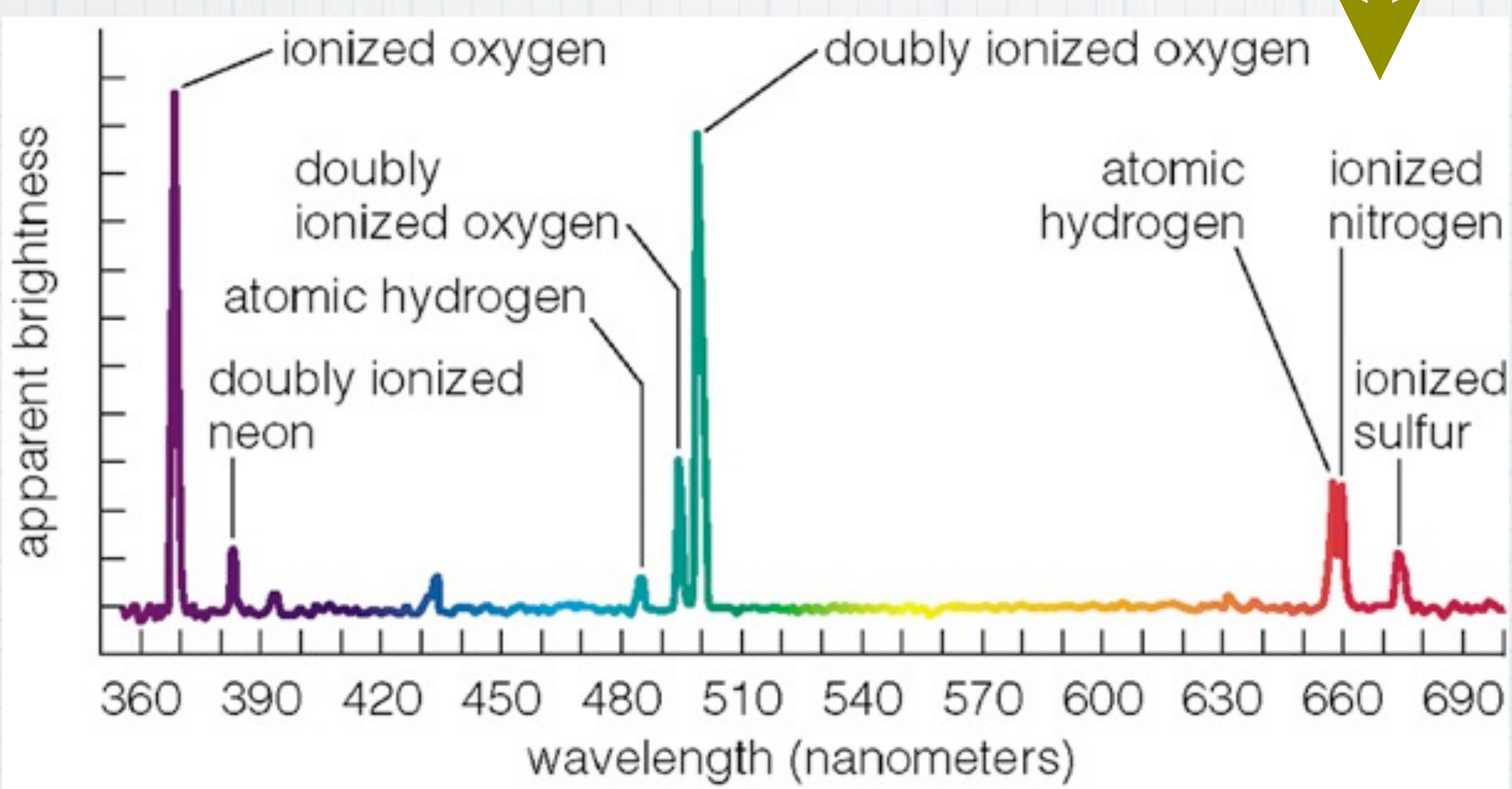
Supernova observed by Tycho Brahe in 1572

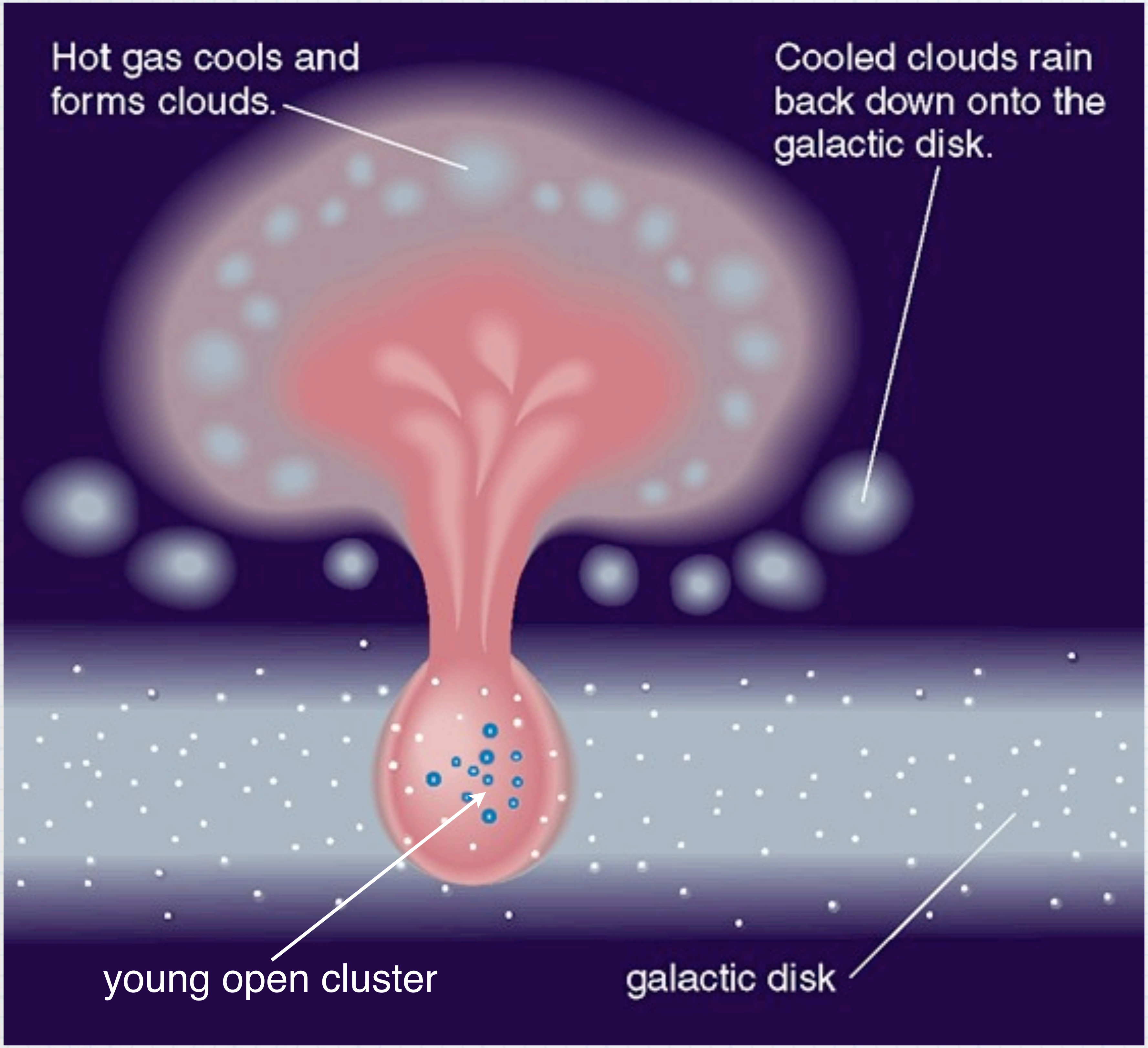


color match

Supernova remnant emit light due to radioactive decay (and some thermal radiation too)

New elements made by supernova mix into interstellar medium






Regions where multiple supernovae have occurred create huge hot bubbles that can blow out of disk

Gas clouds cooling in the halo can “rain” back down on disk being pulled by its gravity

The galaxy’s mass prevents most of the hot gas clouds from escaping but leakage is detectable, especially with active galaxies where it can be significant

# Cooling & Cloud Formation

* Atomic hydrogen gas forms as hot gas cools, allowing electrons to join with protons. This is the most common form of the gas found in the Milky Way
* Molecular clouds form next, after gas cools enough to allow to atoms to combine into molecules (70% H, 28% He, 2% heavier)
* Dust grains are tiny, solid flecks of carbon and silicon minerals (found in the winds of red giant stars)

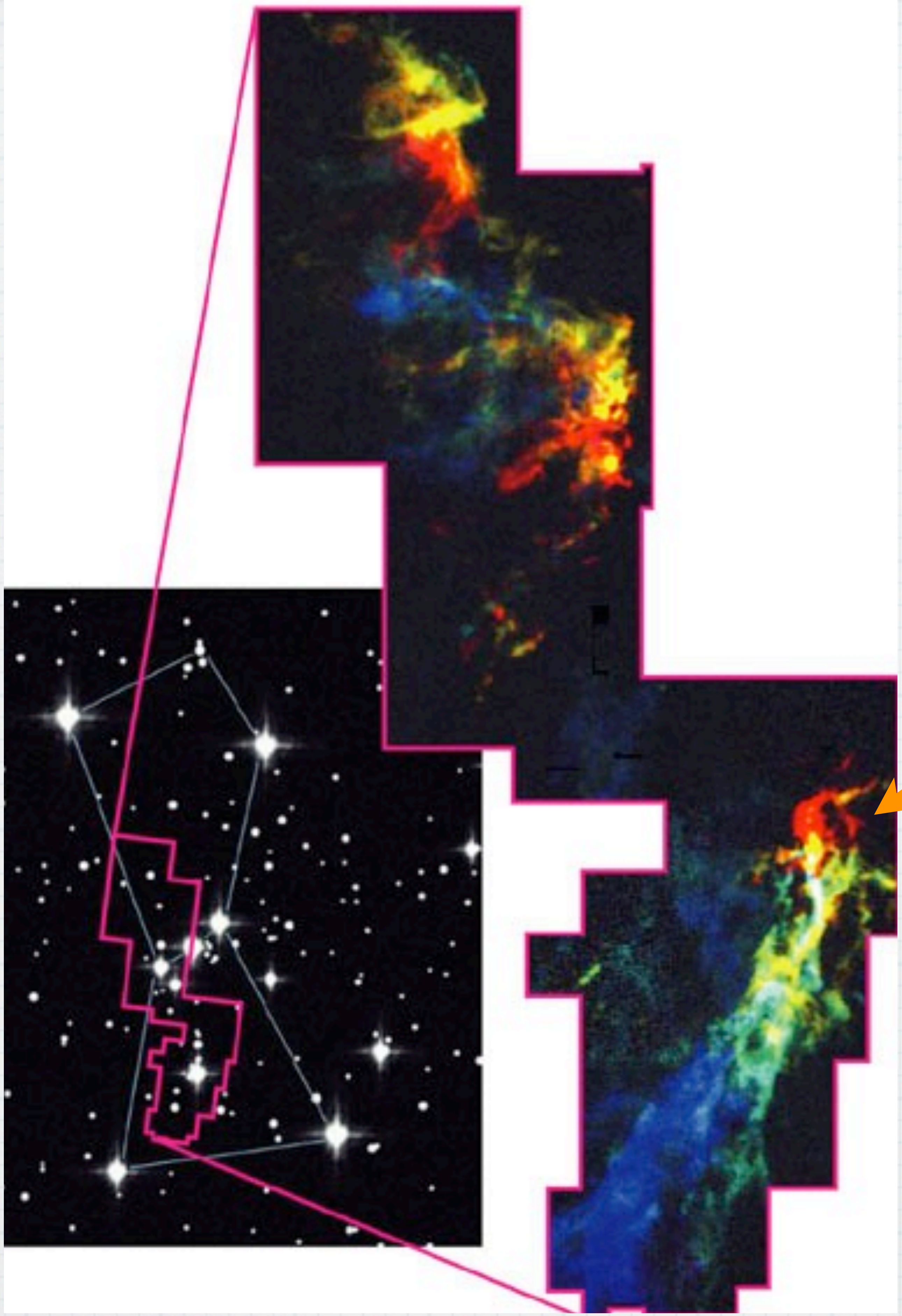
# Molecular Gas Clouds

* Molecular clouds are the coldest and densest clouds in interstellar space
* They contain up to 1 million solar masses
* Total molecular gas cloud mass in Milky Way is about 5 billion solar masses

# Molecular Gas Clouds...

* The clouds' temperature are at a few degree above absolute zero
* Too cold for $H_2$ to emit photons
* CO (carbon monoxide molecule) emits strong radio signals at the 10-30 K temperature range
* 120 other molecules have been identified as well via radio signals

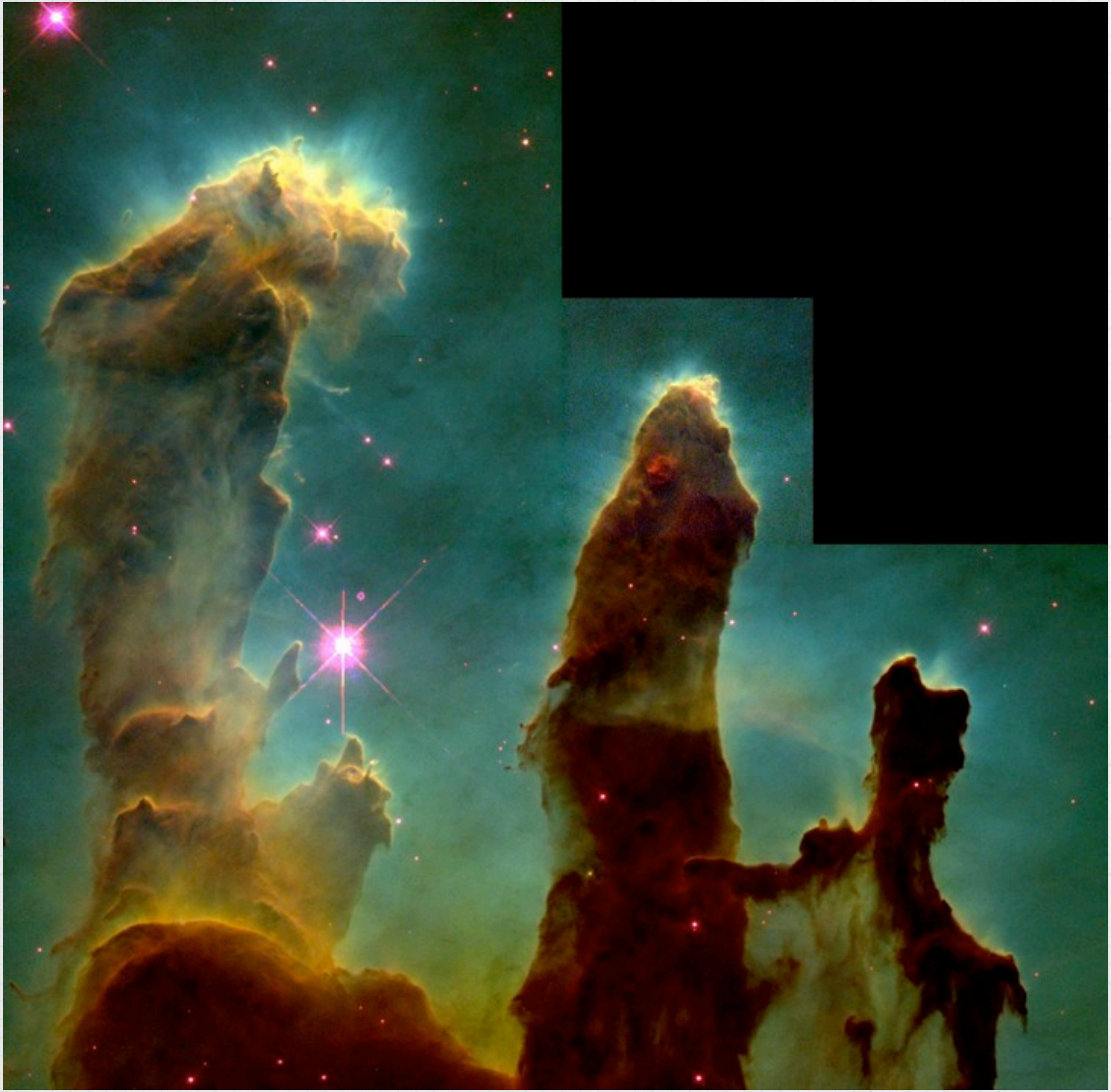
# Molecular clouds in Orion



Composition:

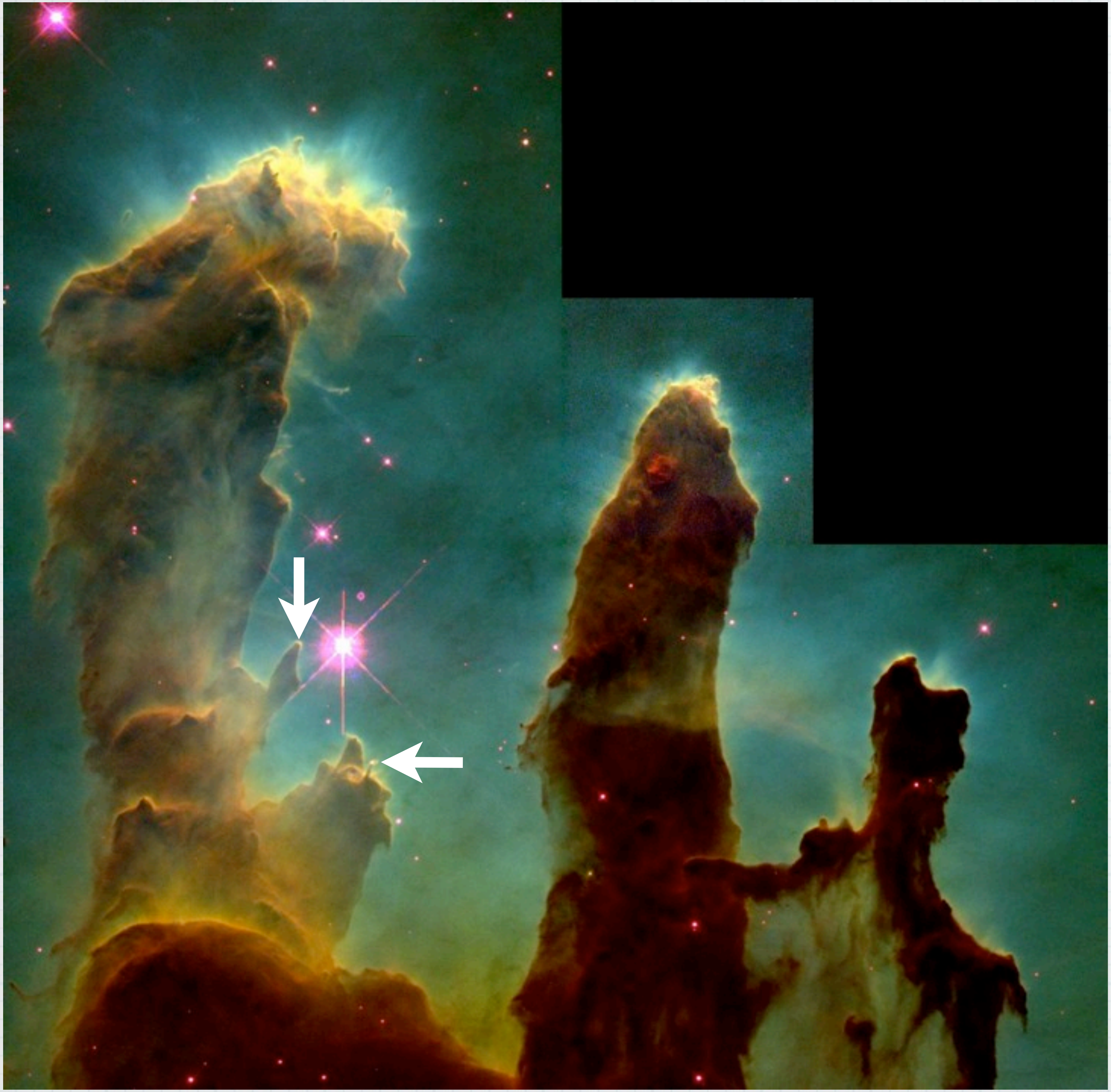
- About 70% $H_2$
- About 28% He
- About 1% CO
- Many other molecules

Doppler shifts of emission lines from carbon monoxide molecules (CO) Colors indicate gas motion: blue moves toward us and red moves away from us



# M16, Eagle Nebula

Gravity forms stars out of the gas in molecular clouds, completing the star-gas-star cycle



Radiation from newly formed stars is eroding these star-forming clouds, preventing many from forming

# Galactic Recycling Summary

Gas Cools

- Stars make new elements by fusion
- Dying stars expel gas and new elements, producing hot bubbles (≈$10^6$ 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, called **open clusters**

# Open Clusters

* **A molecular cloud will give birth to about 100 to several thousand stars,** loosely bound to each others by gravity
* In a region between 10 to 100 light-years in diameter
* **The stars will be young and will contain heavy elements (metal-rich)**
* (Anything heavier than helium is called "a metal" in Astronomy)

# The Pleiades (M44), an open cluster

# The Wild Duck cluster (M 11) - an open cluster

# Open Clusters...

* There are over 1,000 known open clusters in our galaxy, but the true total may be up to ten times higher than that
* Open clusters are invariably found in the spiral arms where gas densities are highest and so most star formation occurs

# NGC7331

Can you spot some open clusters...

# Stars Formation Forever?

* Despite the matter recycling, with each new generation of stars, matter gets "locked" in the low-mass stars
* Interstellar gas is slowly running out
* 50 billion years from now, star formation will cease in the Milky Way

# Question

* Where will the gas be in 1 trillion years?

A. Blown out of galaxy

B. Still recycling just like now

C. Locked into white dwarfs and low-mass stars

# Question

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A. Blown out of galaxy

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# Gas Distribution in the Milky Way

* Different regions are in different stages of the star-gas-star cycle
* We can visualize this by observing the galaxy at different wavelengths

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).

g Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

# We observe star-gas-star cycle operating in Milky Way's disk using many different wavelengths of light

galactic bulge is clearly evident at the center

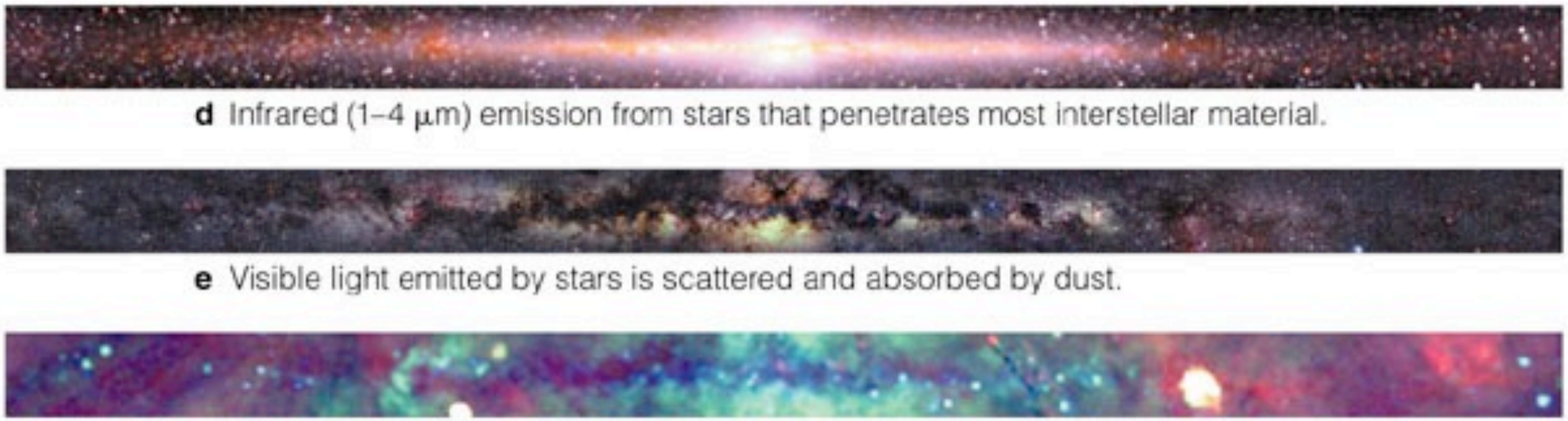
Infrared

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

Infrared light reveals stars whose visible light is blocked by gas clouds



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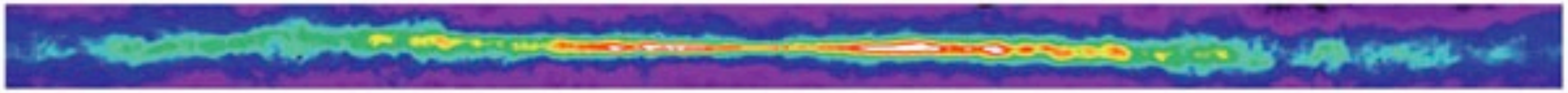
# X-rays

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



a 21-cm radio emission from atomic hydrogen gas.

Radio (21cm)

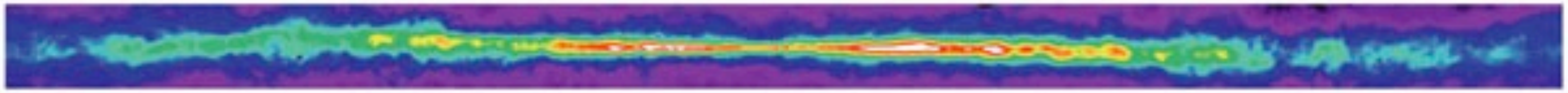
This gas fills much of the galactic disk

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).

## 21-cm radio waves emitted by atomic hydrogen show where gas has cooled and settled into disk



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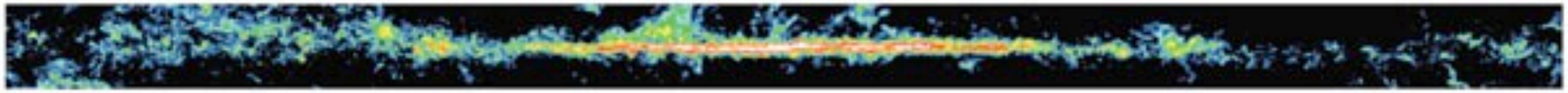


**b** Radio emission from carbon monoxide reveals molecular clouds.

## Radio (CO)

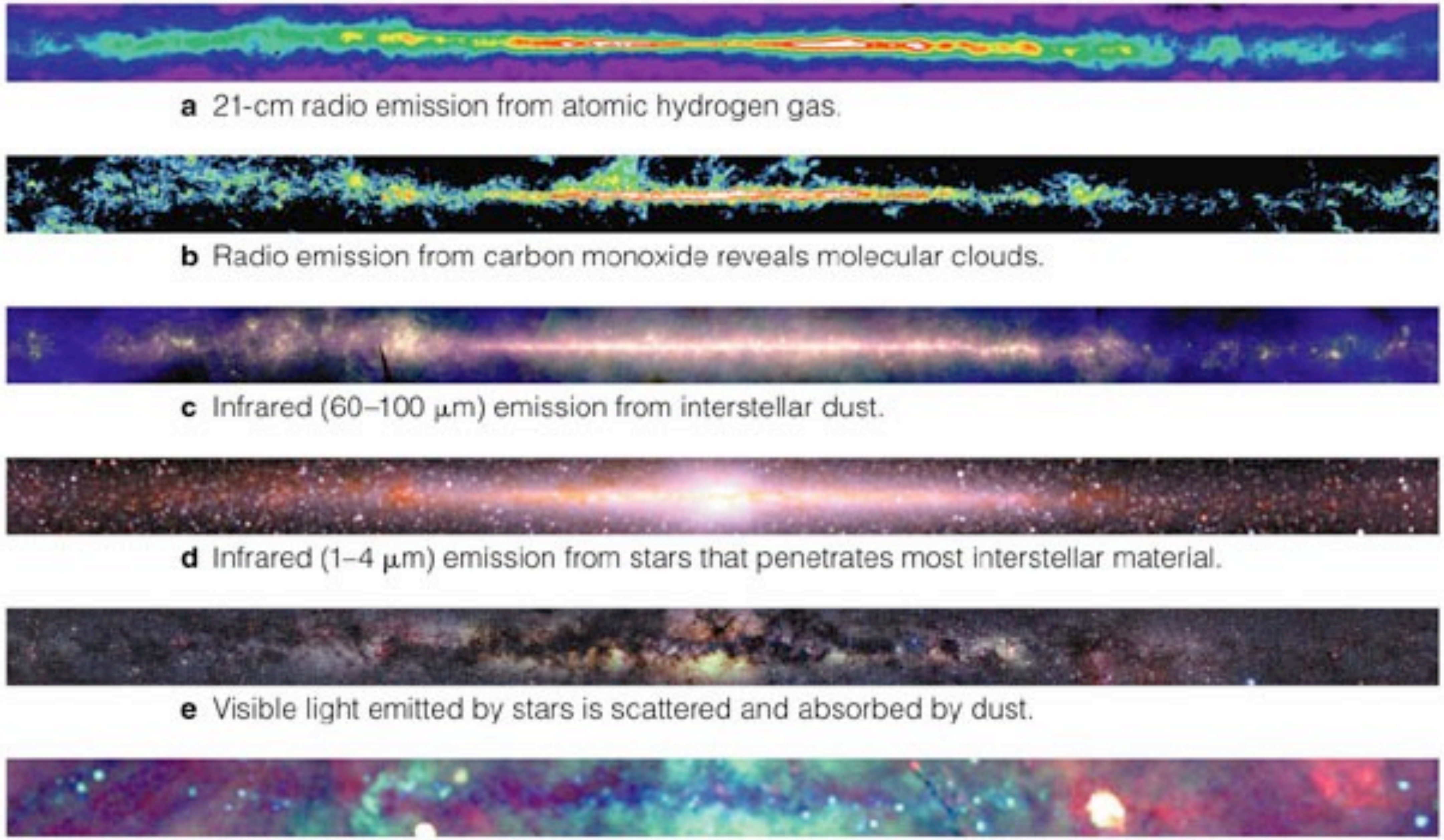
**d** Infrared (1–4 μm) emission from stars that penetrates most interstellar material.

**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).

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

These clouds are concentrated in a narrow layer in the mid-plane of the disk



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IR (dust)

Long-wavelength infrared emission shows where young stars are heating dust grains They are the same regions where the molecular gas clouds are at (b)

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

**g** Gamma-ray emission from collisions of cosmic rays with atomic nuclei in interstellar clouds.

# Gamma rays show where cosmic rays from supernovae collide with atomic nuclei in gas clouds

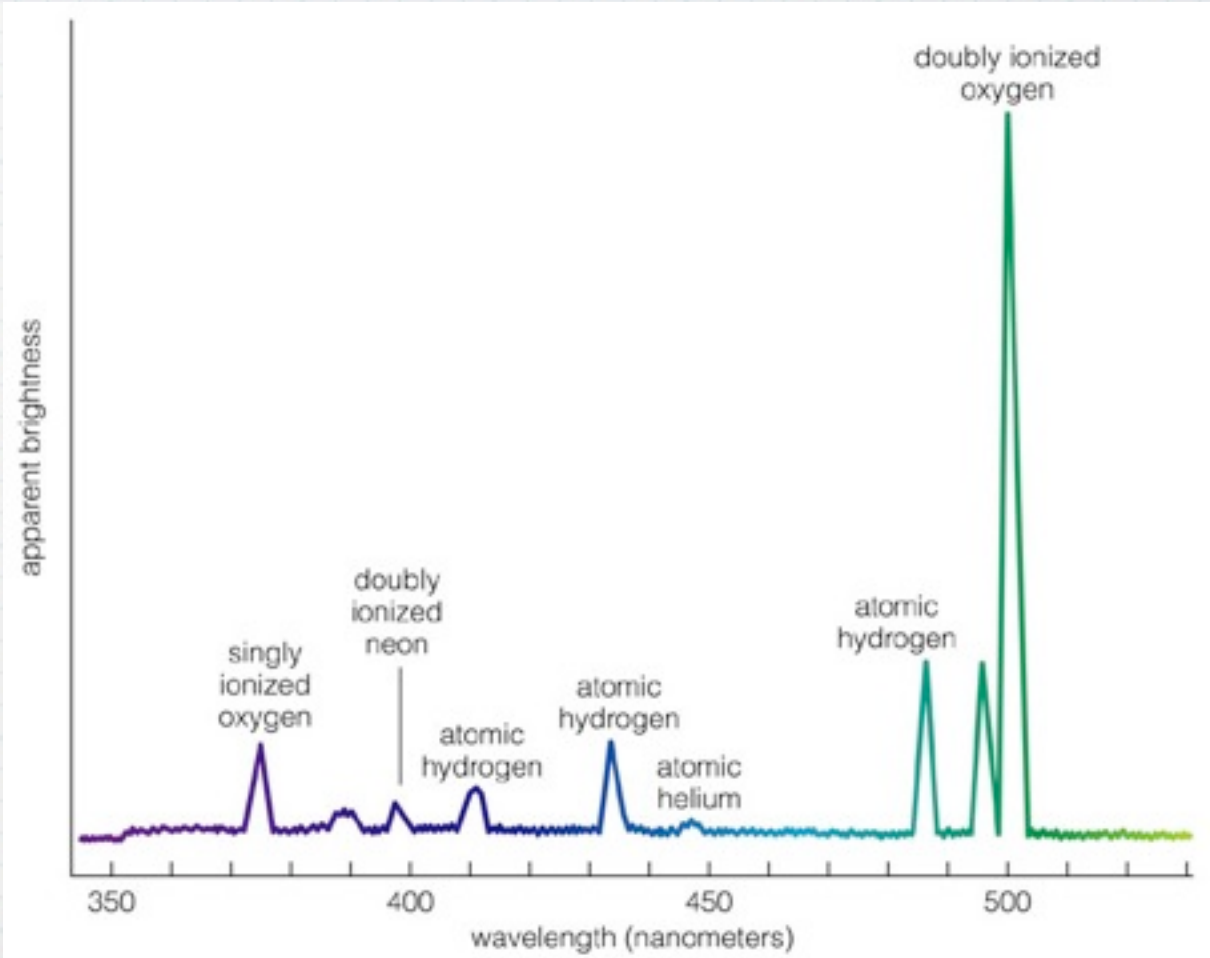
# Where do stars tend to form in our galaxy?

* Some regions seem to give birth to more stars than others
* Molecular gas rich regions spawn new stars easily
* **Spiral arms** are home to molecular clouds and numerous clusters of young, hot blue stars, called **open clusters**

# Orion nebula

Credit & Copyright: Tony Hallas

Ionization (emission) nebulae are found around short-lived high-mass stars, signifying active star formation

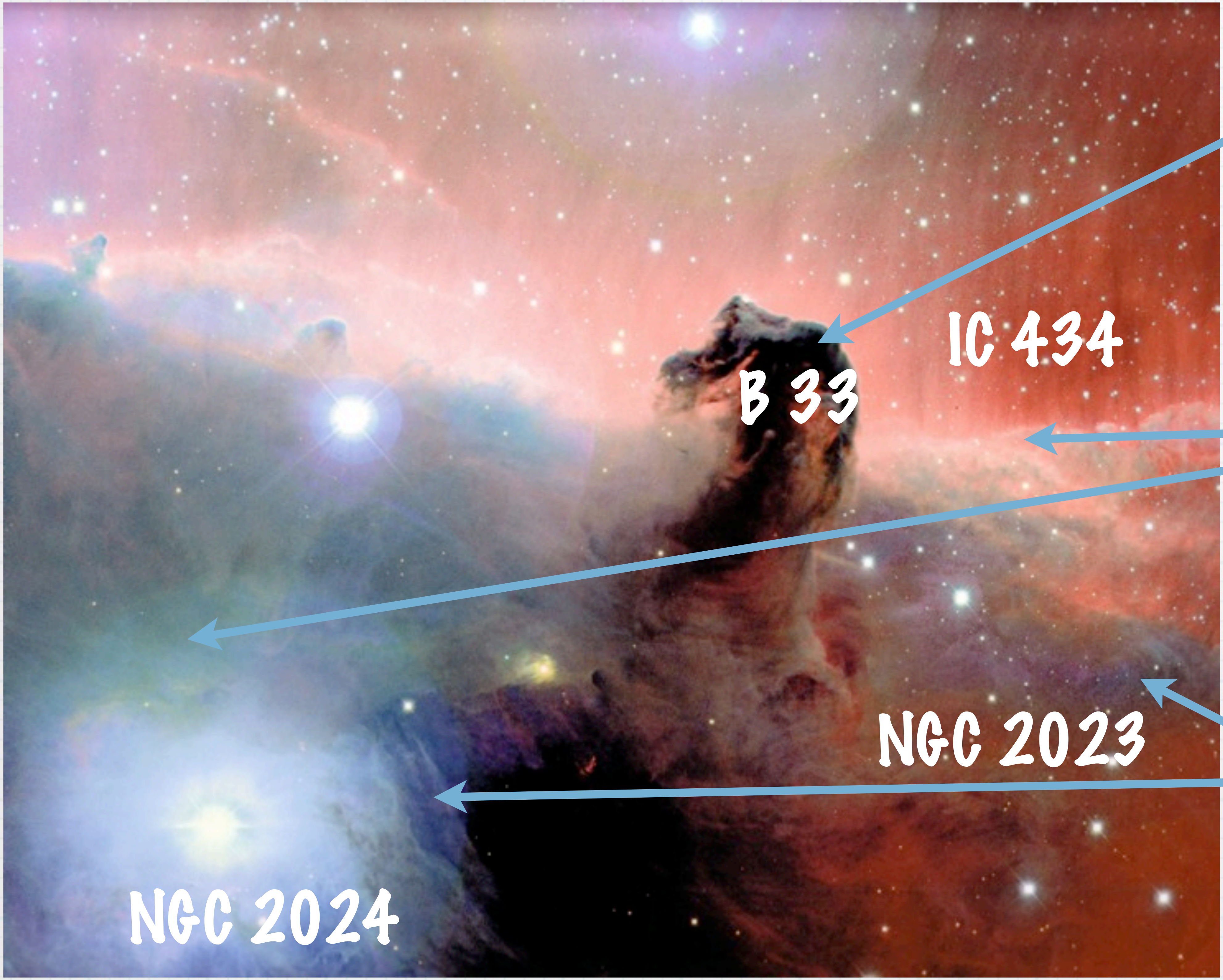


Dust grains in reflection nebulae scatter the light from stars

Reflection nebulae hence appear bluer than the stars supplying the light

# What kinds of nebulae do you see?

# What kinds of nebulae do you see?



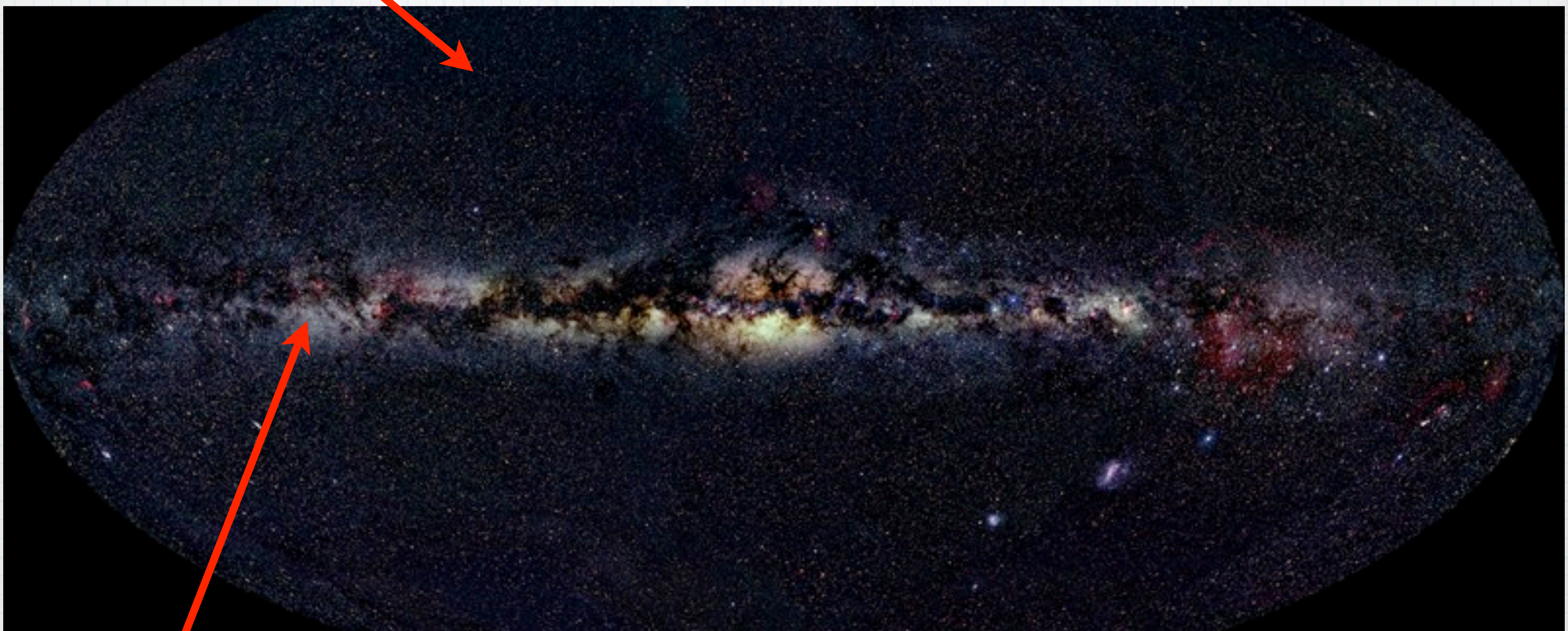

dark nebula

emission nebula

reflection nebula

Halo: No ionization nebulae, no blue stars

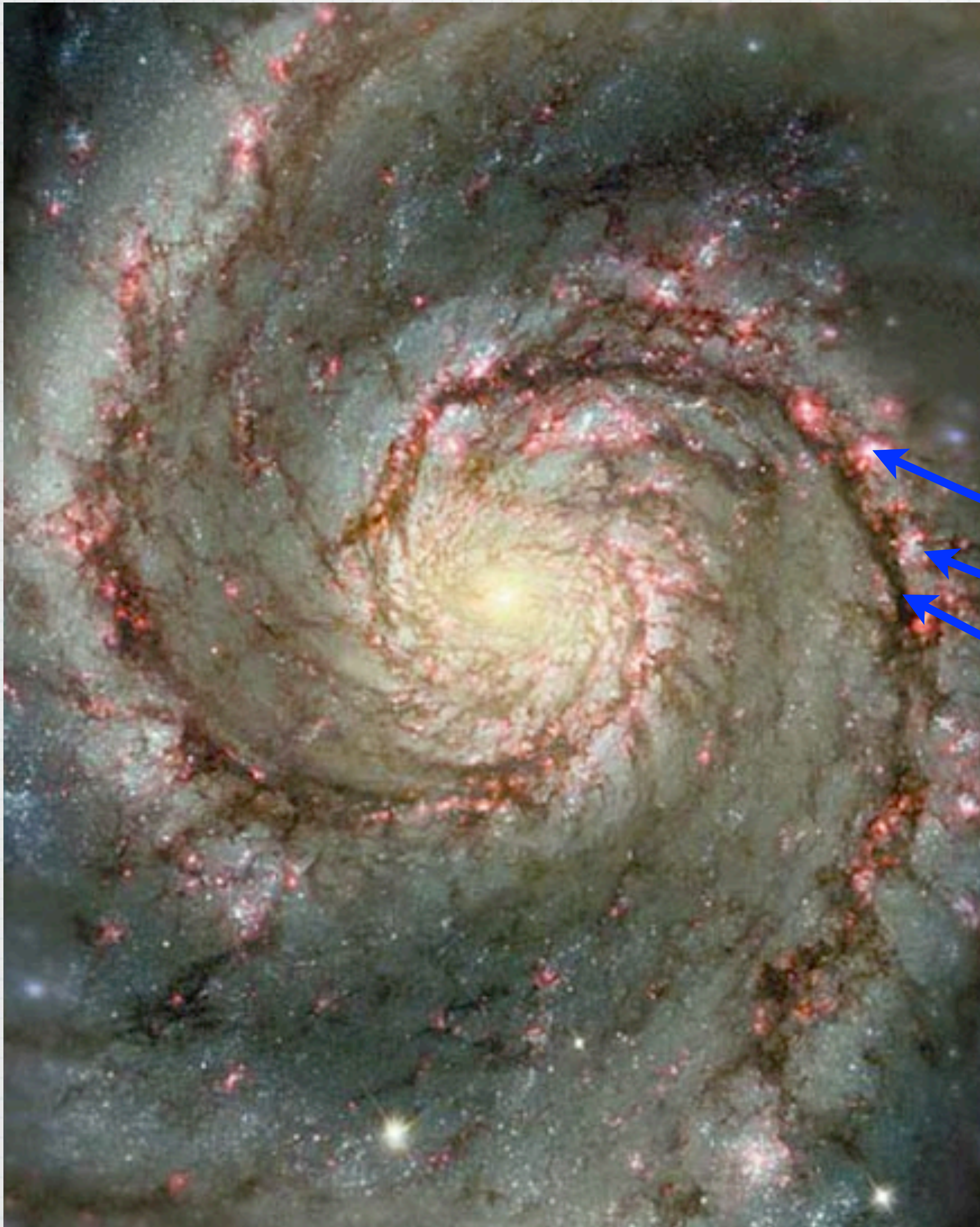
$\Rightarrow$ no star formation



Disk: Ionization nebulae, blue stars $\Rightarrow$ star formation

Much of star formation in disk happens in spiral arms

Whirlpool Galaxy



Much of star formation in disk happens in spiral arms

Ionization Nebulae
Blue Stars
Gas Clouds

Whirlpool Galaxy

Spiral arms do not rotate differentially. If they did they would wind up into tight coils

Spiral arms are waves of star formation

formed by a process called density waves, which is an area of active research

# Spiral arms are waves of star formation

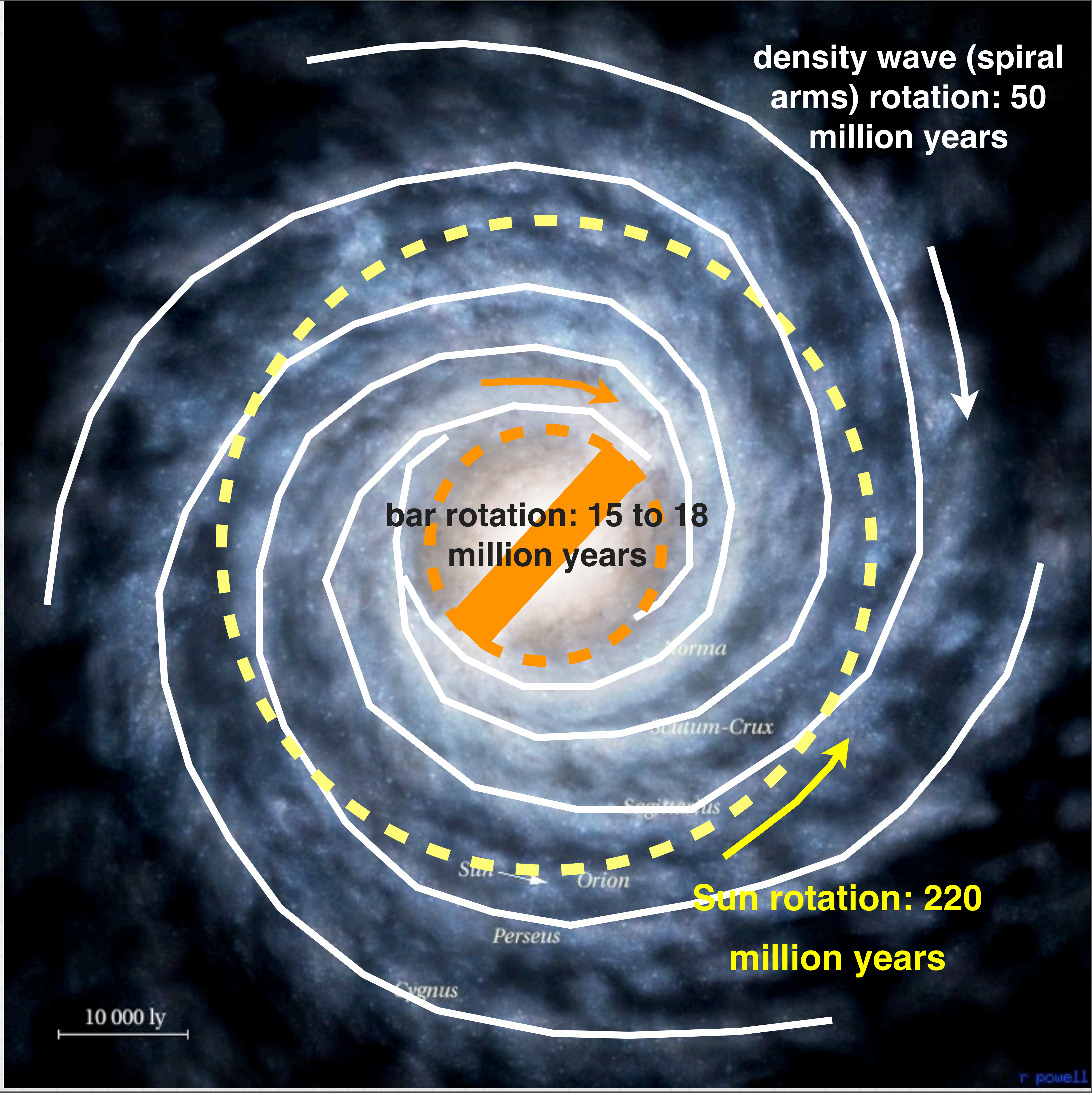
1. Gas clouds get squeezed as they move into spiral arms

2. Squeezing of clouds helps triggers star formation

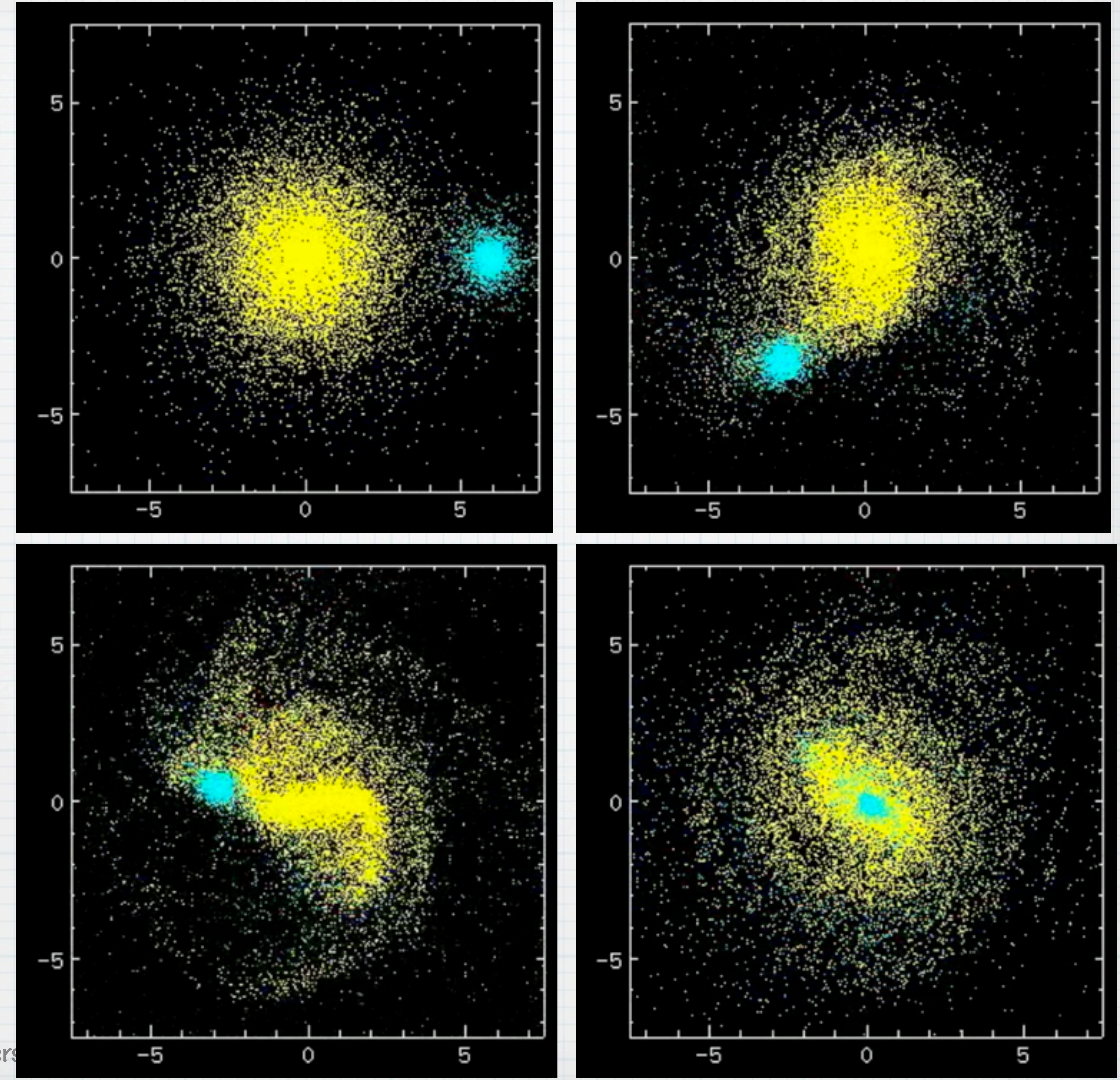
3. Young stars emerge out of the spiral arms

# Rotation patterns of the Milky Way

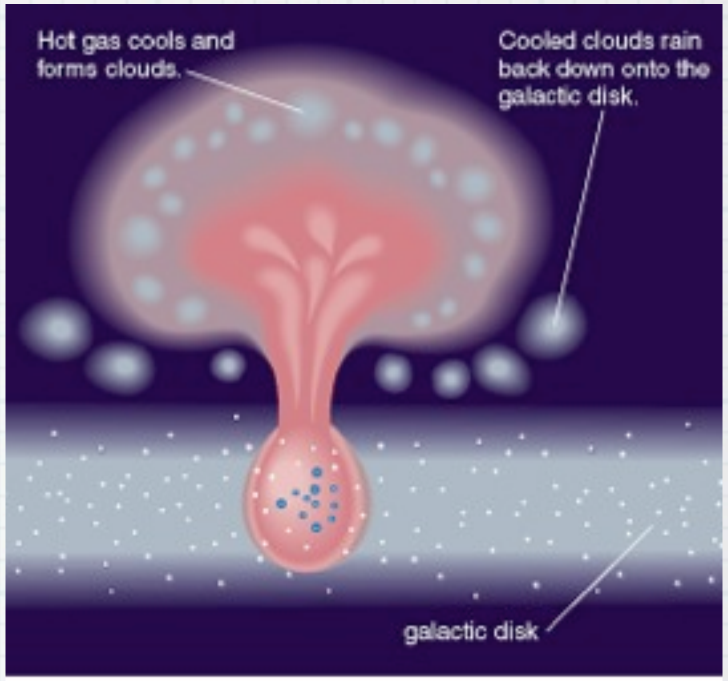
3 independent rotations:
1 - bar
2 - arms
3 - stars



Computer modeling shows that a spiral galaxy is formed as a result of the merger/collision of smaller spiral galaxies

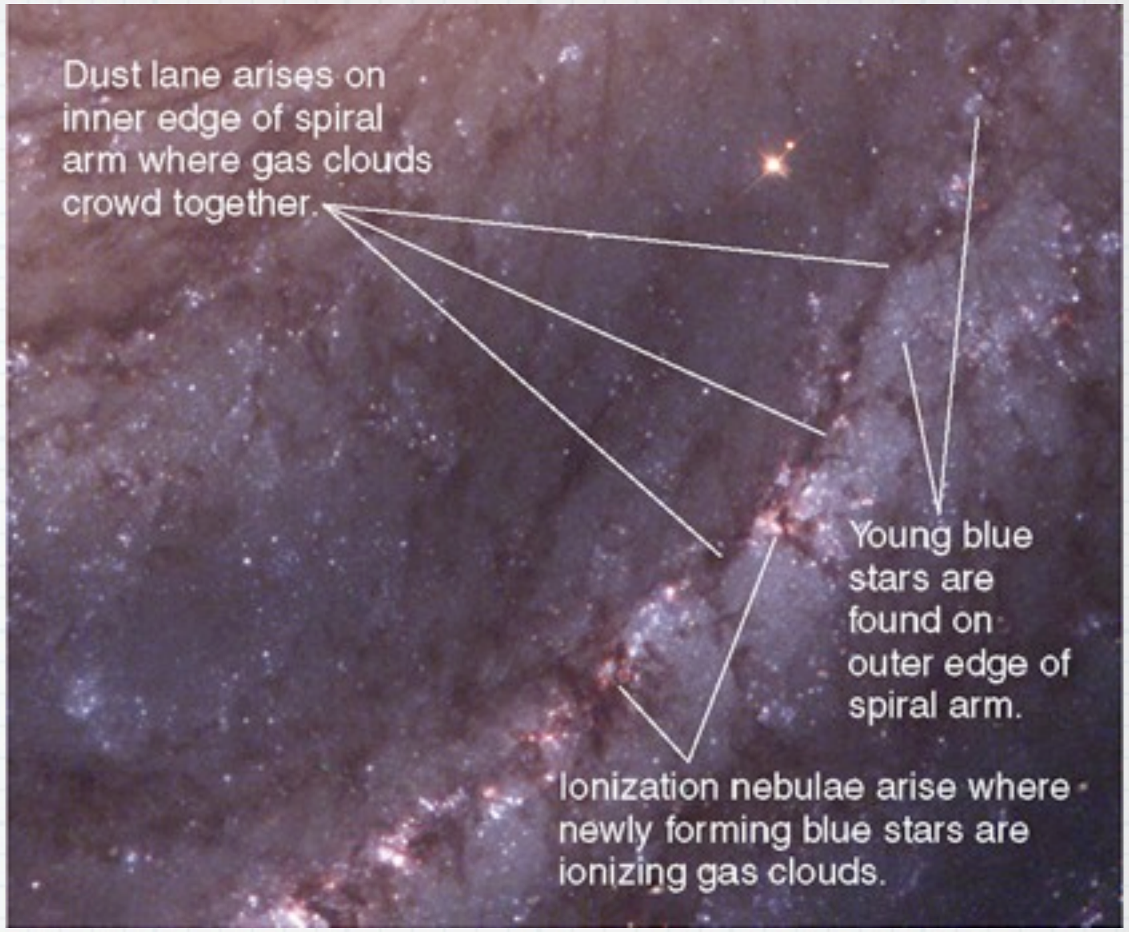


# Snapshot




* How does our galaxy recycle gas into stars?
* Stars are born from the gravitational collapse of gas clumps in molecular clouds. Near the ends of their lives, stars more massive than our Sun create elements heavier than hydrogen and helium and expel them into space via supernovae and stellar winds. The supernovae and winds create hot bubbles in the interstellar medium, but the gas within these bubbles gradually slows and cools as they expand. Eventually, this gas cools enough to collect into clouds of atomic hydrogen. Further cooling allows atoms of hydrogen and other elements to collect into molecules, producing molecular clouds. These molecular clouds then form stars, completing the star-gas-star cycle

# Snapshot




* Where do stars tend to form in our galaxy?
* Active star-forming regions, marked by the presence of hot, massive stars and ionization nebulae, are found preferentially in spiral arms. The spiral arms represent regions where a spiral density wave has caused gas clouds to crash into each other, thereby compressing them and making star formation more likely.

# The History of the Milky Way

* The great orbital differences between stars in the disk and stars in the halo and bulge indicates that they have different origins
* These different origins provide important clues as to how the galaxy formed

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

* No young stars are found in the halo
* They also contain **fewer heavy elements** than disk stars
* They are called **"metal-poor"**

# Population Classification

* **Population I stars**, also named **disk population** contain:
  * stars of all ages
  * 2% composed of heavy elements
  * also called "metal-rich"

# Population Classification...

* Population II stars, also named spheroidal population:
  * always old (so low original mass)
  * found in halo and bulge
  * have between 0.2% (bulge) to 0.02% (halo) of heavy elements
  * they are metal-poor

# Population Classification...

* Population III stars, also named metal-free stars are hypothetical stars:
* they formed within 300 millions years after the Big Bang
* they could have been as big as a 1000 solar masses

# Population Classification...

* Population III stars all ended in supernovae and started to seed their environment with heavier elements
* and then led the creation of early proto-galaxies

# Halo and Bulge

* The halo does not contain cold and dense molecular clouds (no new star formation). The little gas found there is usually quite hot
* The bulge contains lots of dust and some gas. The gas is too hot. Its stars are old too (> 9 billion years)
* This does not mean there are no blue stars in those regions: they exist due to star collisions

# How did our galaxy form?

1. Like a star forming cloud, a giant protogalactic cloud contracted
2. Stars in the halo formed first (population II)
3. The remaining gas then flattened in a spinning disk, bulge stars started and stopped (population II as well)
4. Stars formed in disk next (population I)

**Halo Stars** (metal-poor) **Bulge Stars**

0.02% heavy elements (O, Fe, ...) 0.2%

only old stars


**Disk Stars (metal-rich)**

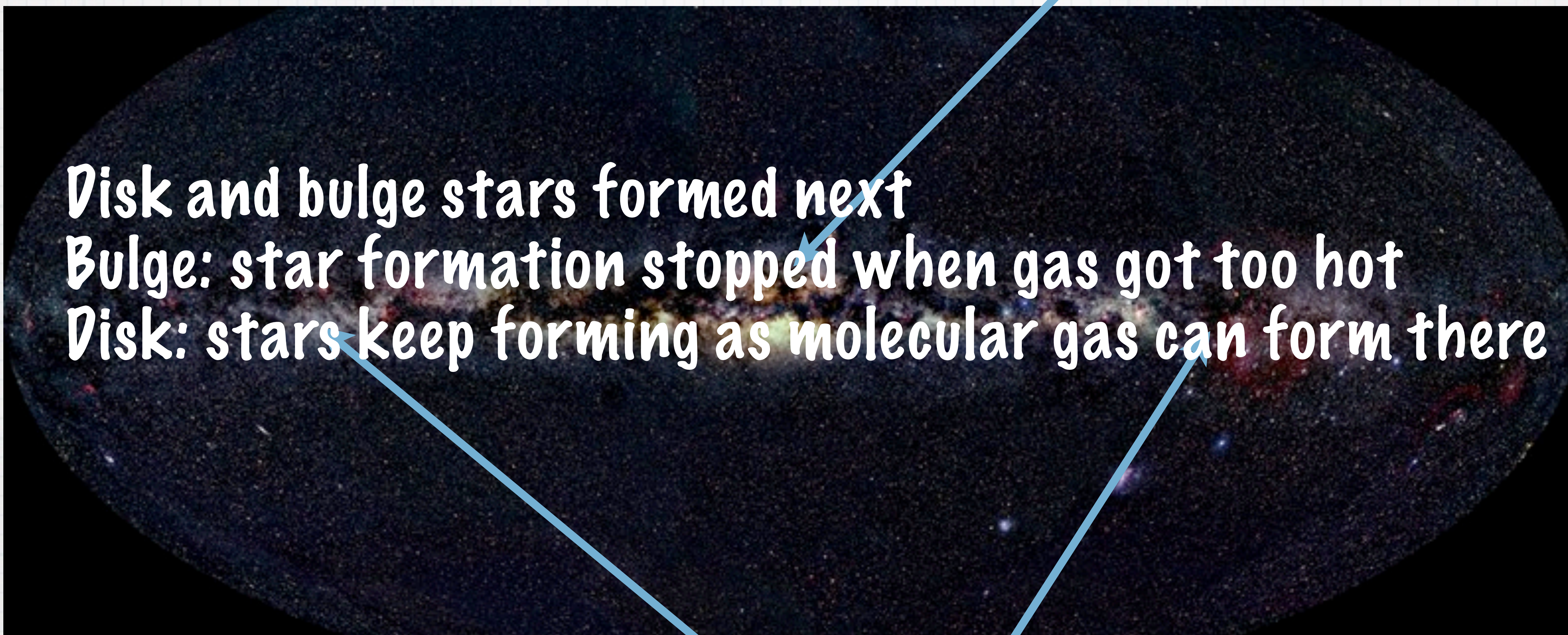
2% heavy elements

stars of all ages

Halo Stars (metal-poor) Bulge Stars

0.02% heavy elements (O, Fe, ...) 0.2%

only old stars



Disk and bulge stars formed next

Bulge: star formation stopped when gas got too hot

Disk: stars keep forming as molecular gas can form there

Disk Stars (metal-rich)

2% heavy elements

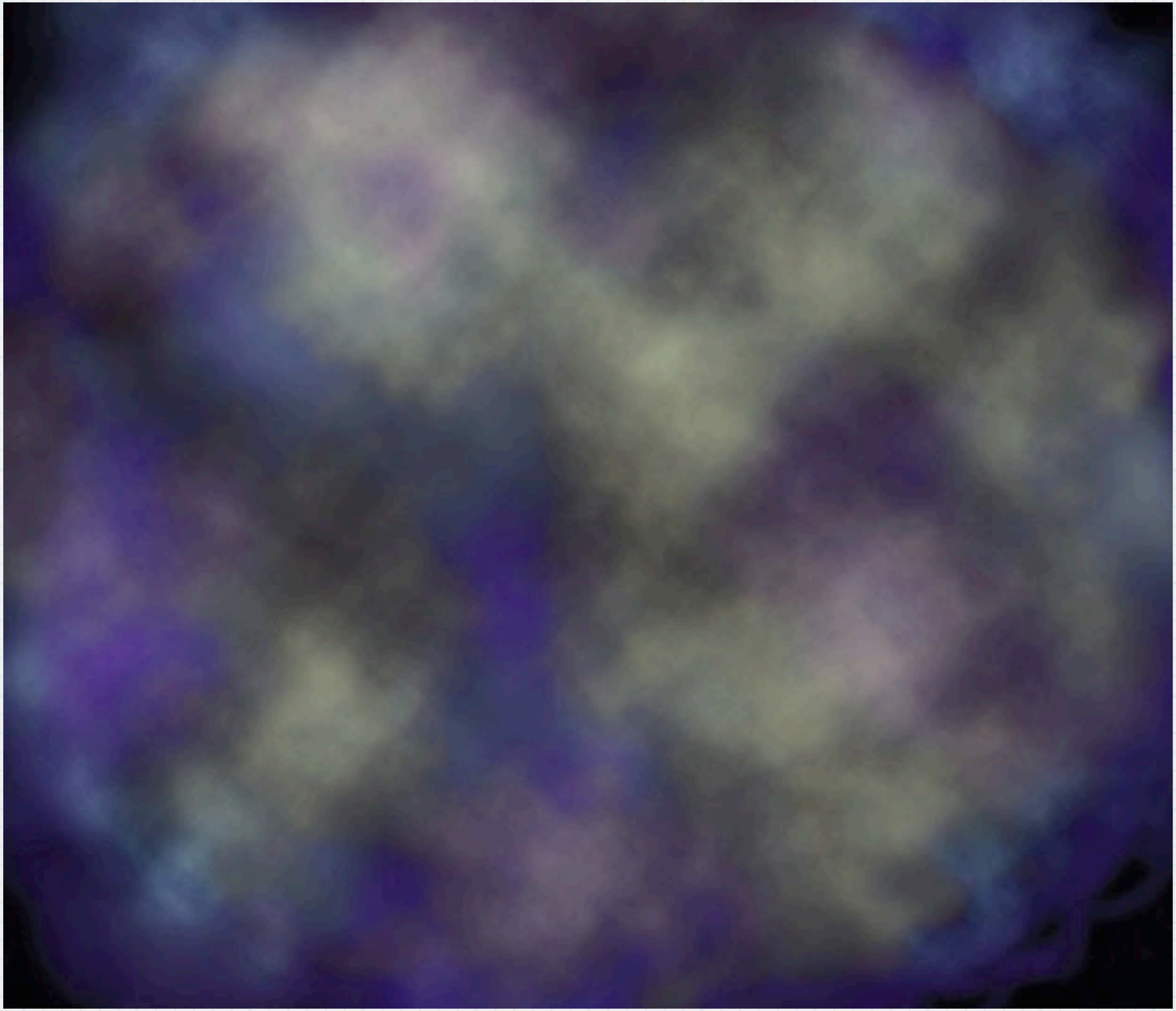
stars of all ages

Halo Stars
0.02%

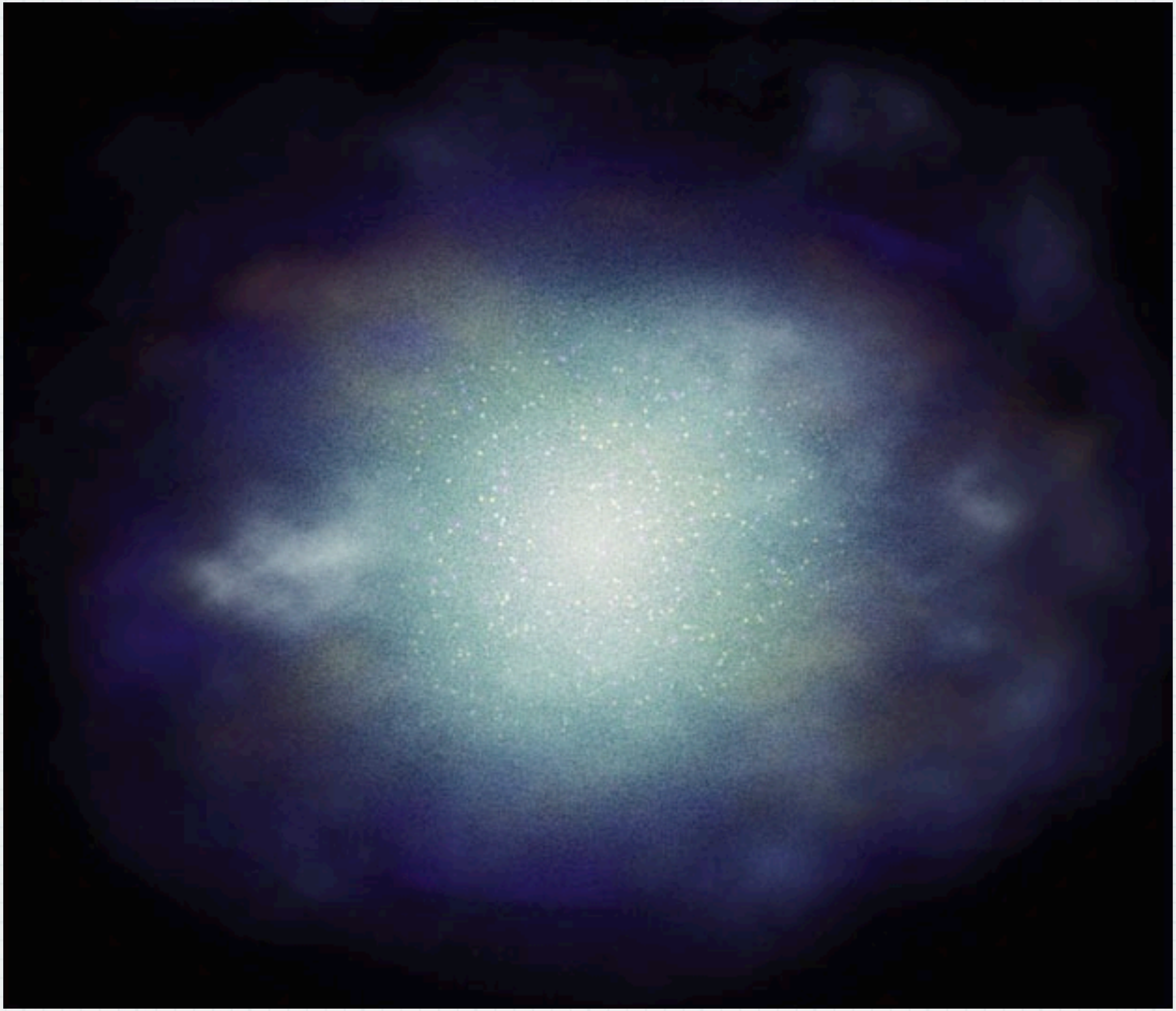
(metal-poor)
heavy elements (O, Fe, ...)
only old stars

Bulge Stars
0.2%

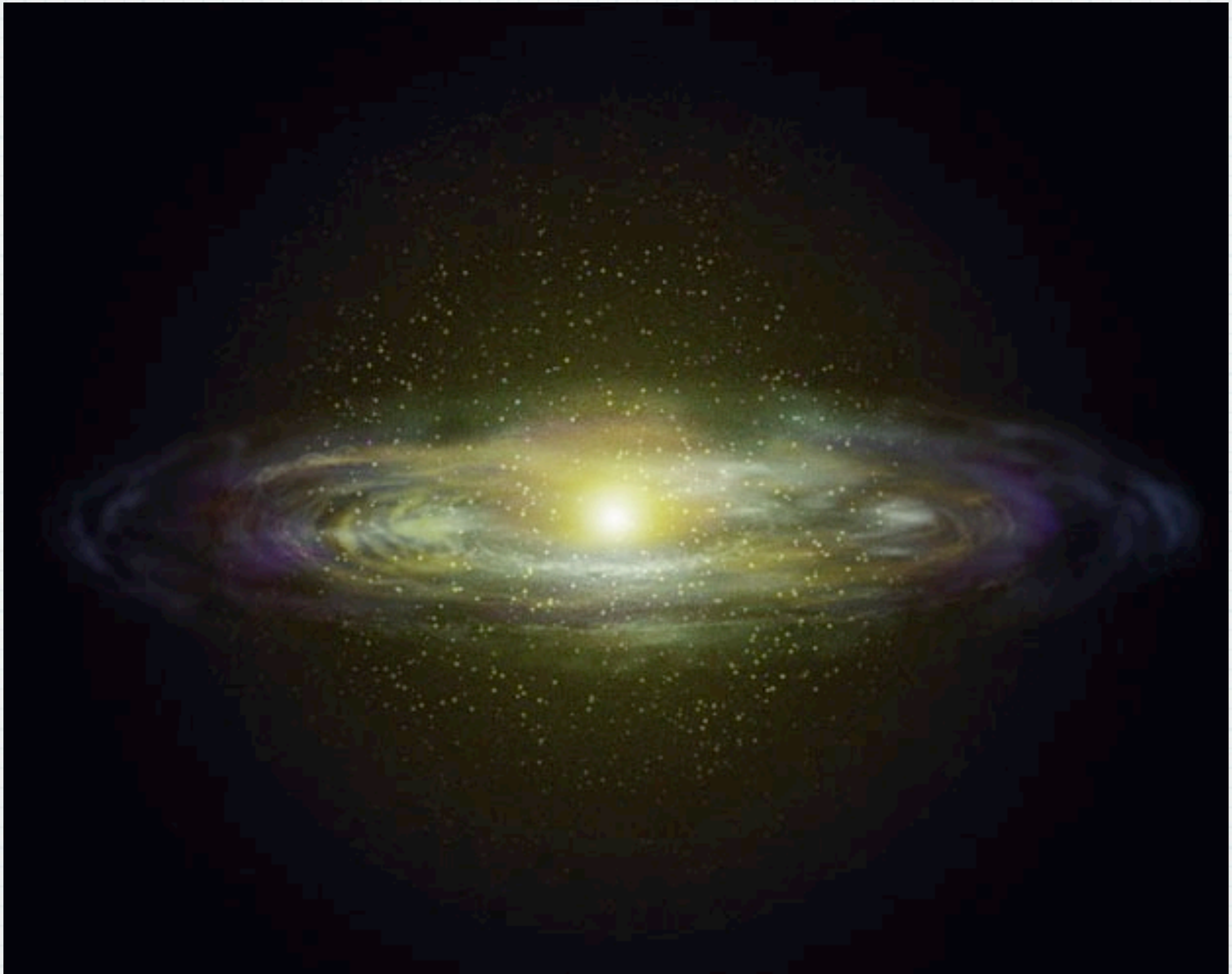

Disk Stars (metal-rich)
2% heavy elements
stars of all ages



Our galaxy probably formed from a giant gas cloud



Halo stars formed first as gravity caused cloud to contract



Remaining gas took billions of years to settle into an orderly spinning disk, with the most massive getting there first


Stars continuously form in disk as galaxy grows older and absorbs dwarf galaxies


Warning:  This model is oversimplified

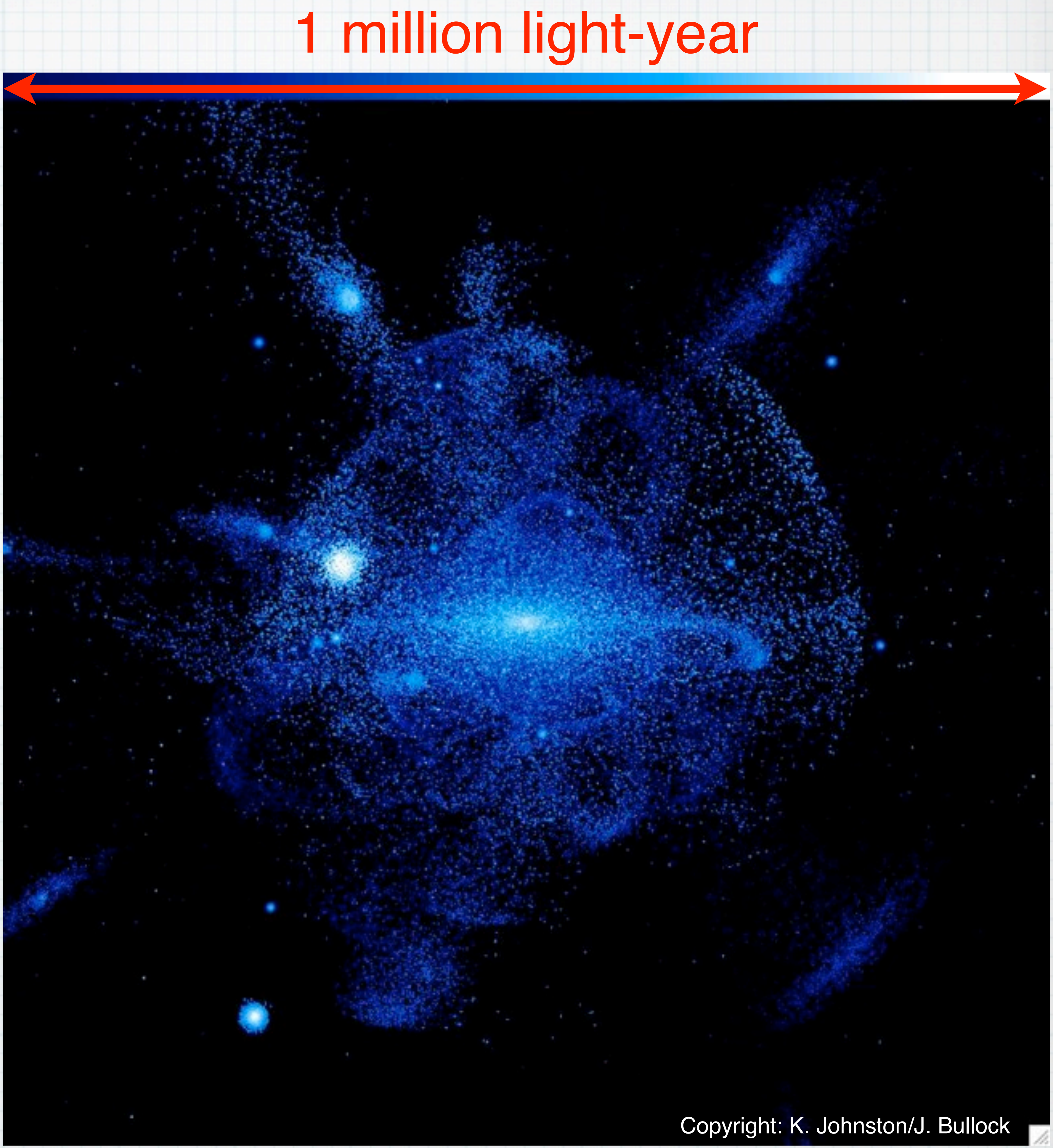
# Merging Protogalactic Clouds?

- Careful analysis of heavy elements (metals) proportions seem to indicate that **the Milky Way formed from absorbing many (small & dwarf) spiral galaxies**
- Two such clouds are crashing through the Milky Way now
  - such as the Sagittarius and Canis Major dwarf galaxies

# The Complex Halo

* The halo of stars that envelops the Milky Way is like a river delta crisscrossed by stellar streams large and small
* These streams were originally satellites or dwarf galaxies which collided with the Milky Way and got absorbed

A theoretical model of a galaxy like the Milky Way, showing trails of stars torn from disrupted satellite galaxies that have merged with the central galaxy



# Snapshot

* What clues to our galaxy's history do halo stars hold?
* The halo generally contains only old, low-mass stars with a much smaller proportion of heavy elements than stars in the disk. Thus, halo stars must have formed early in the galaxy's history, before the gas settled into a disk

# Snapshot

* How did our galaxy form?
* The galaxy probably began as a huge blob of gas called a protogalactic cloud. Gravity caused the cloud to shrink in size, and conservation of angular momentum caused the gas to form the spinning disk of our galaxy. Stars in the halo formed before the gas finished collapsing into the disk. The galaxy then grew by absorbing dwarf galaxies

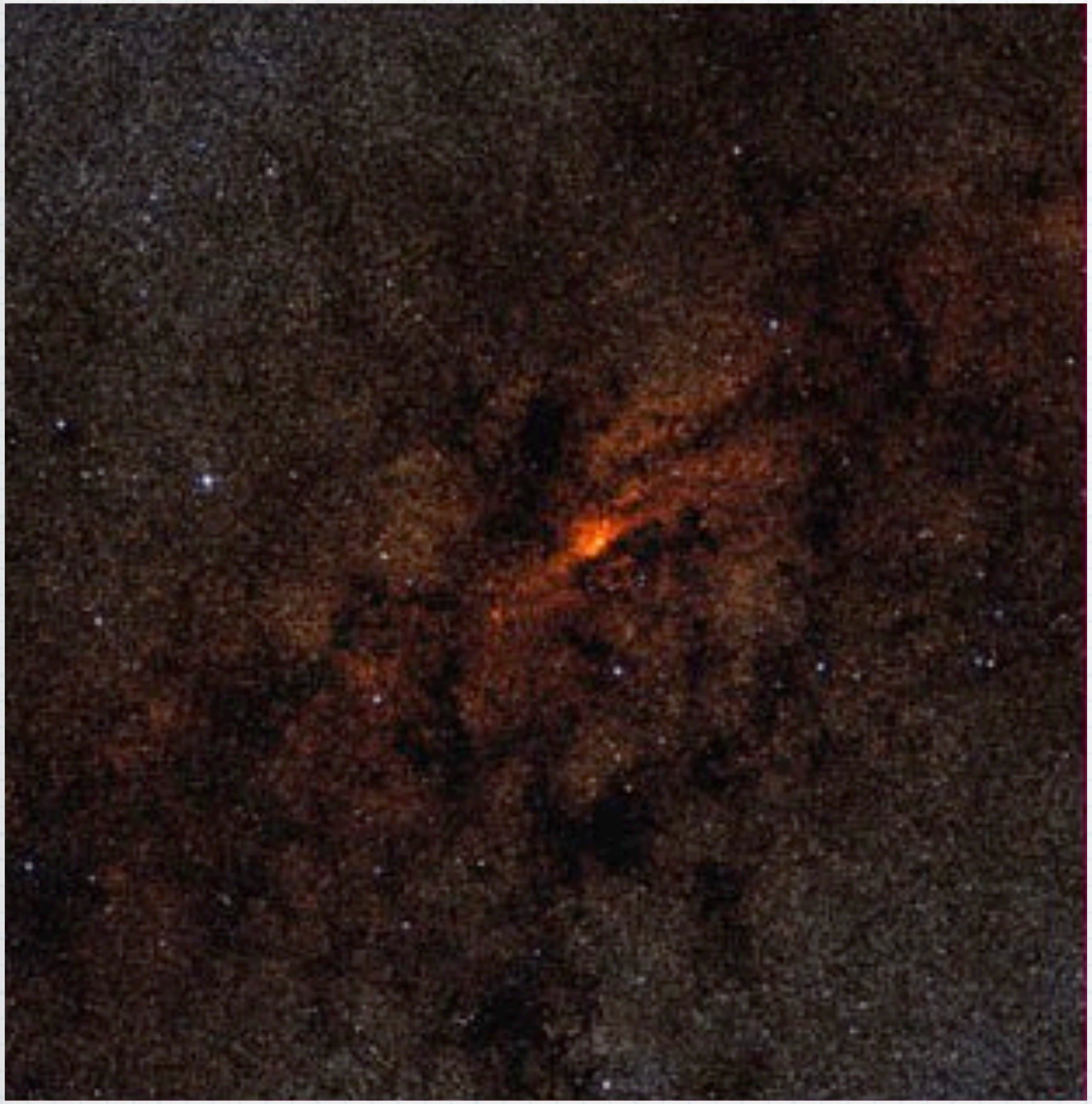
# The Mysterious Galactic Center

* A lot of dust blocks our view of the galactic center
* Without it, it would be quite a night sight
* A four million $M_{Sun}$ black hole is most likely there (Radius = 10 $R_{Sun}$)

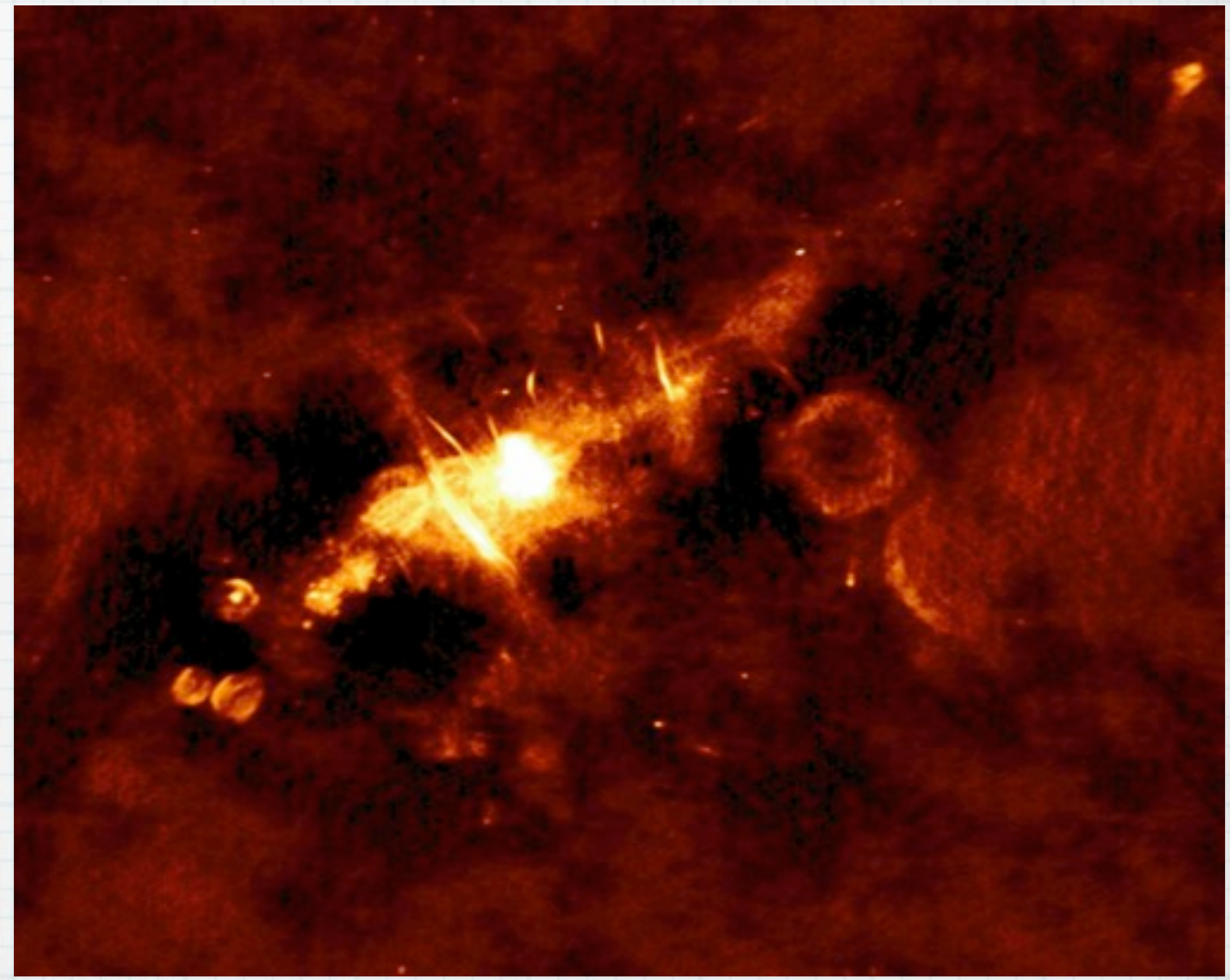
# What lies in the center of our galaxy?

* Fortunately, we can image the galactic center using radio, infrared and X-ray telescopes and "see" through the dust

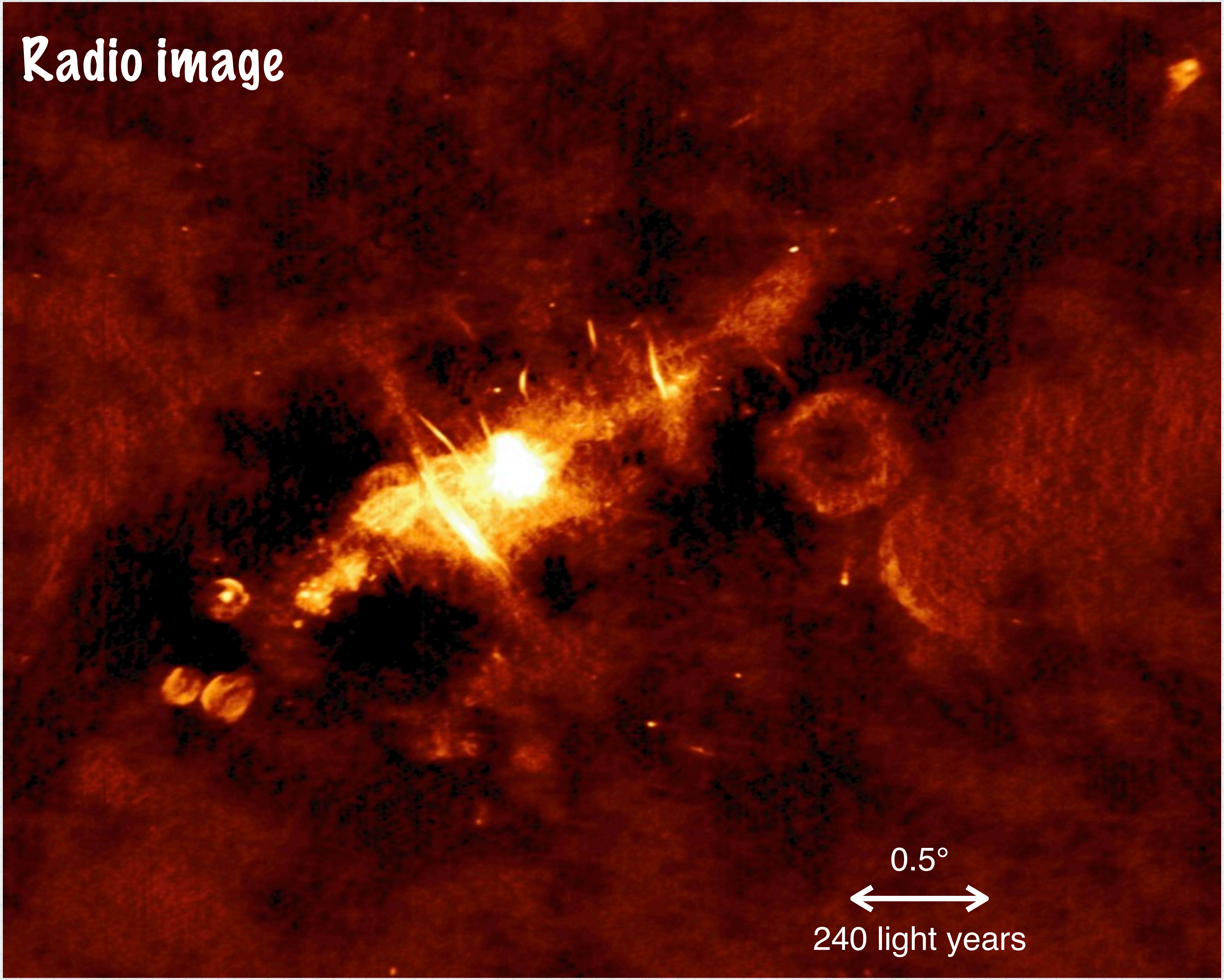
# Galactic center in infrared light

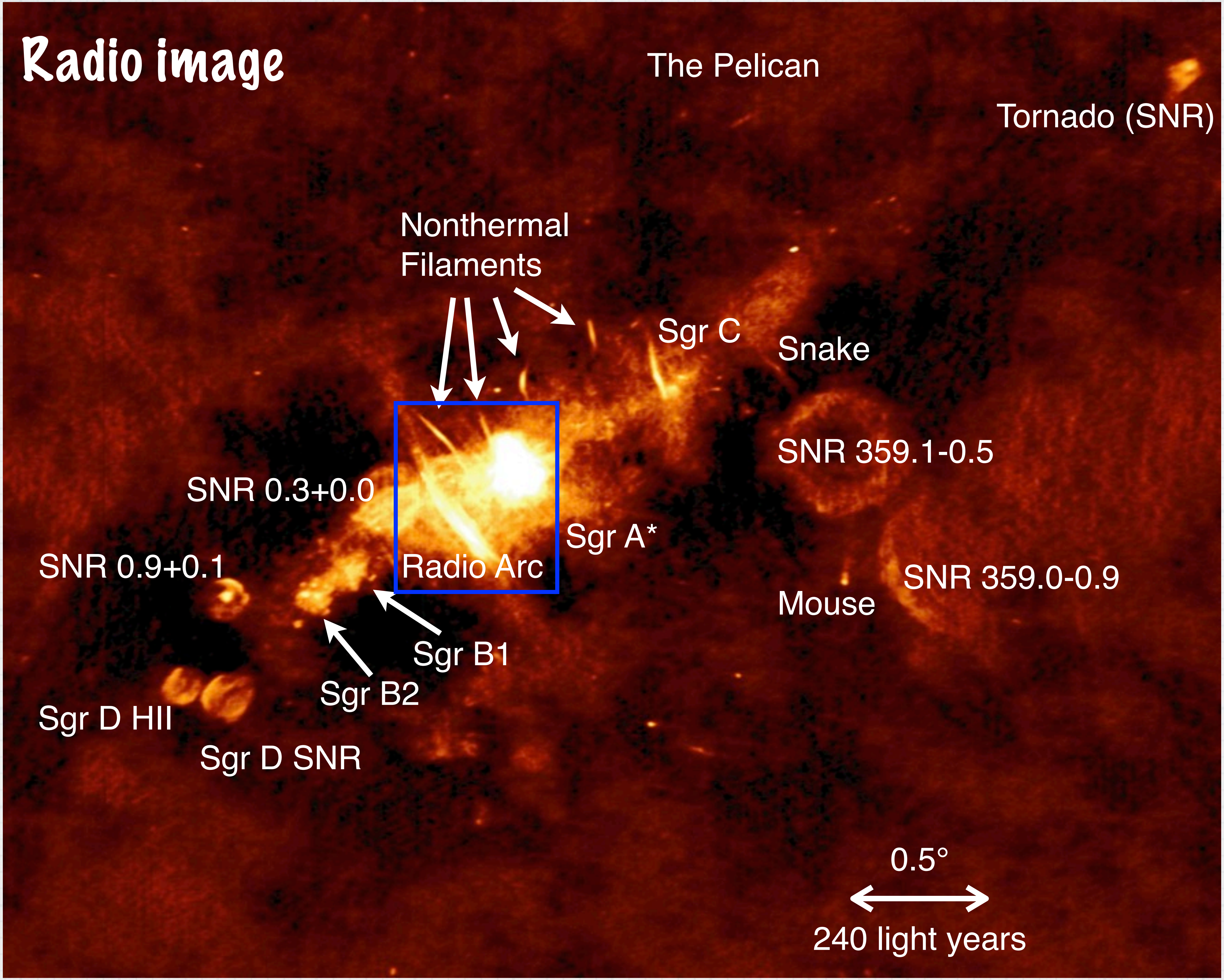


in radio light

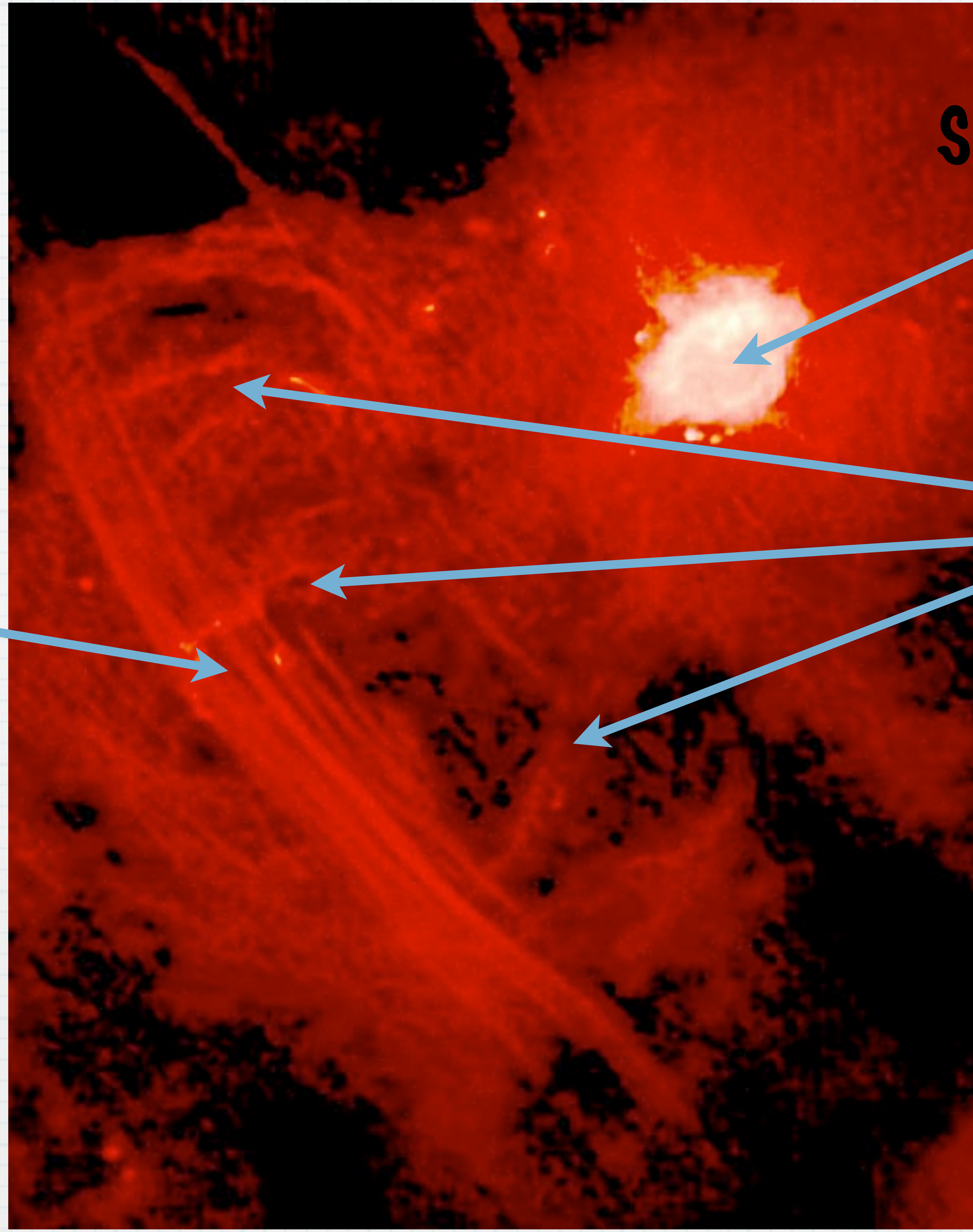


Scale is similar in both pictures


Radio image
0.5°
240 light years

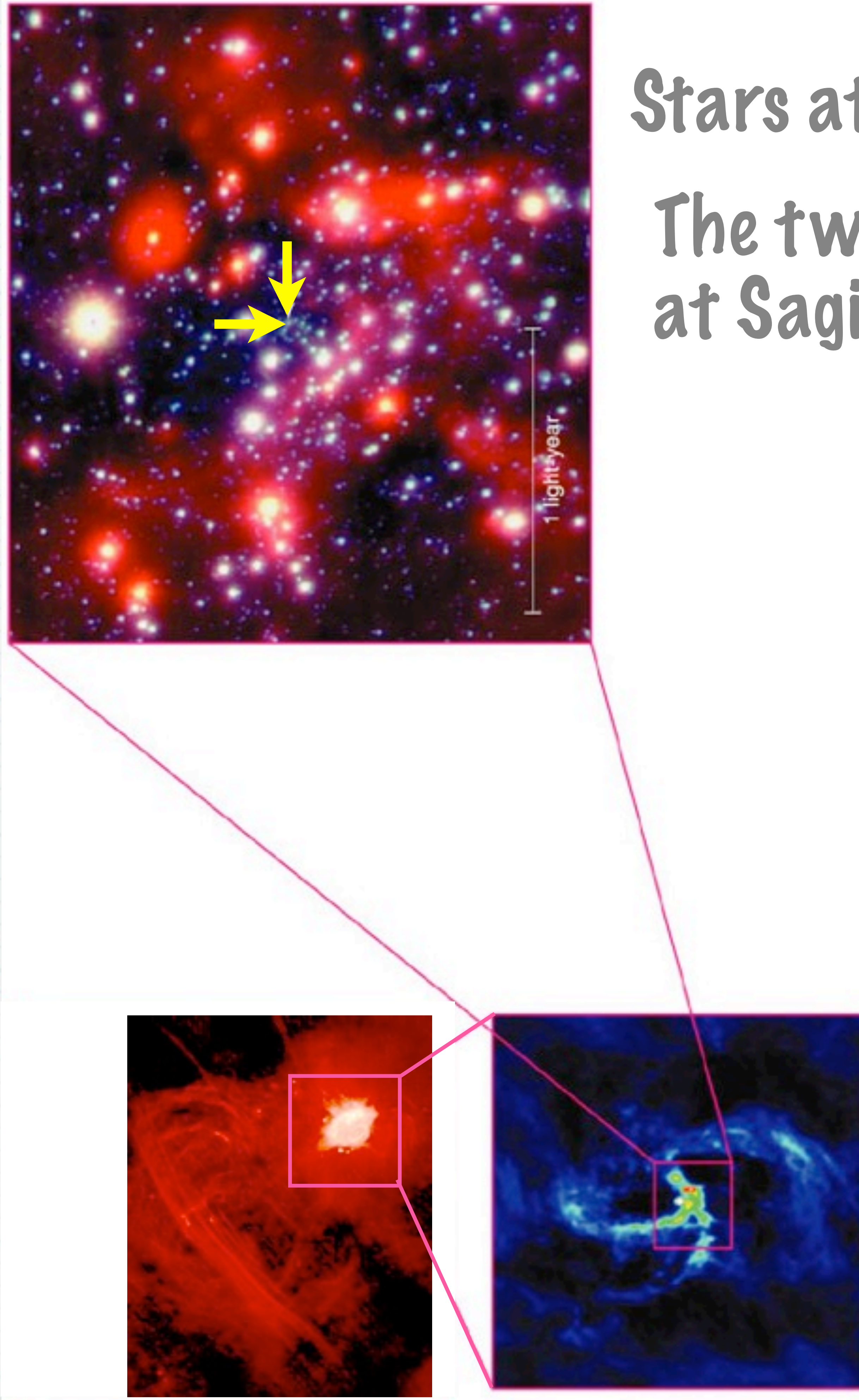

Radio image
The Pelican
Tornado (SNR)
Nonthermal Filaments
Sgr C
Snake
SNR 359.1-0.5
SNR 0.3+0.0
Sgr A*
Radio Arc
SNR 0.9+0.1
SNR 359.0-0.9
Mouse
Sgr B1
Sgr B2
Sgr D HII
Sgr D SNR
0.5°
240 light years

# Radio image


Sagittarius A*
the Arches
(magnetic field lines)
Galactic Center Radio Arc

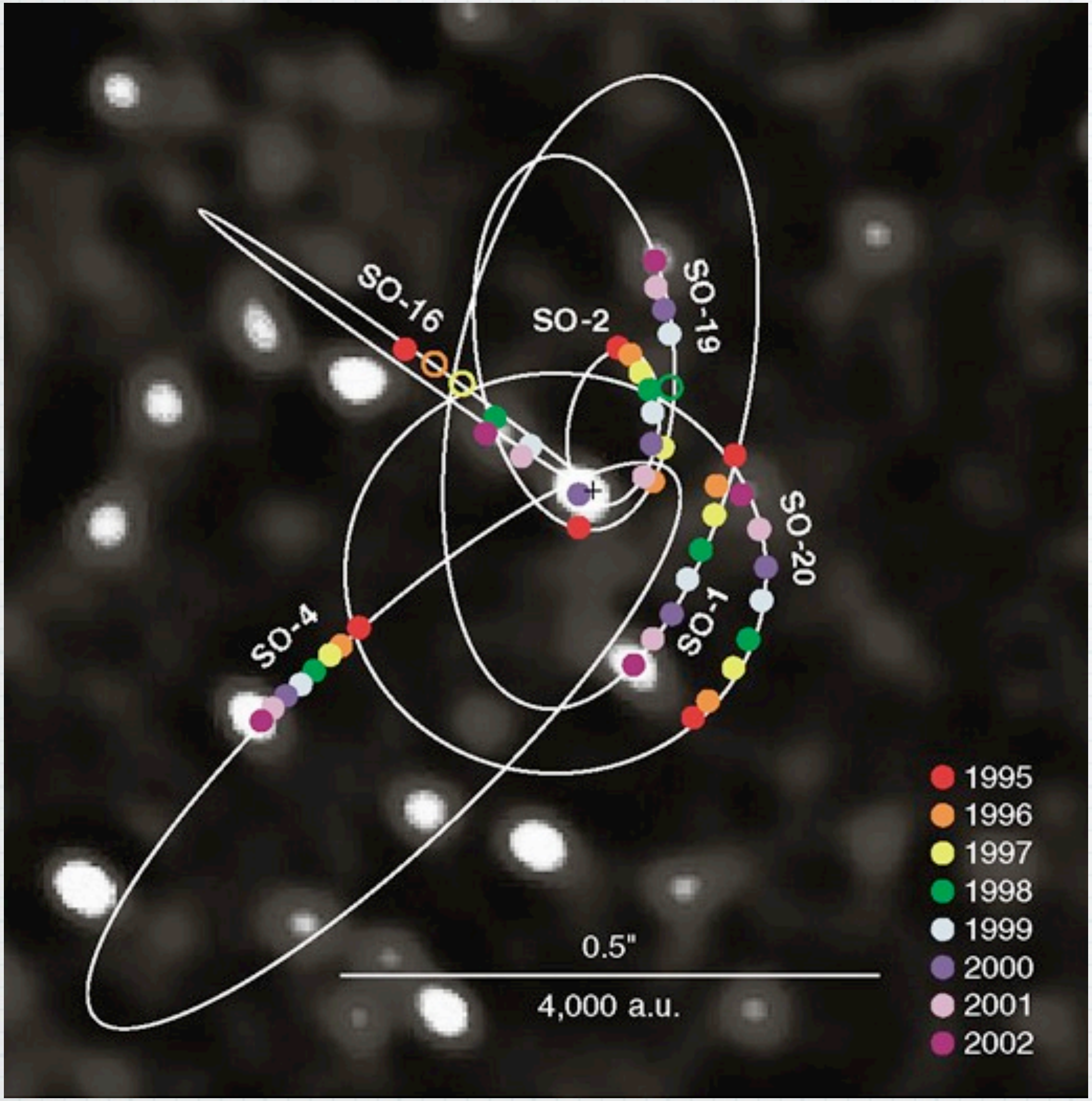
Stars at galactic center

The two arrows point at Sagittarius A*



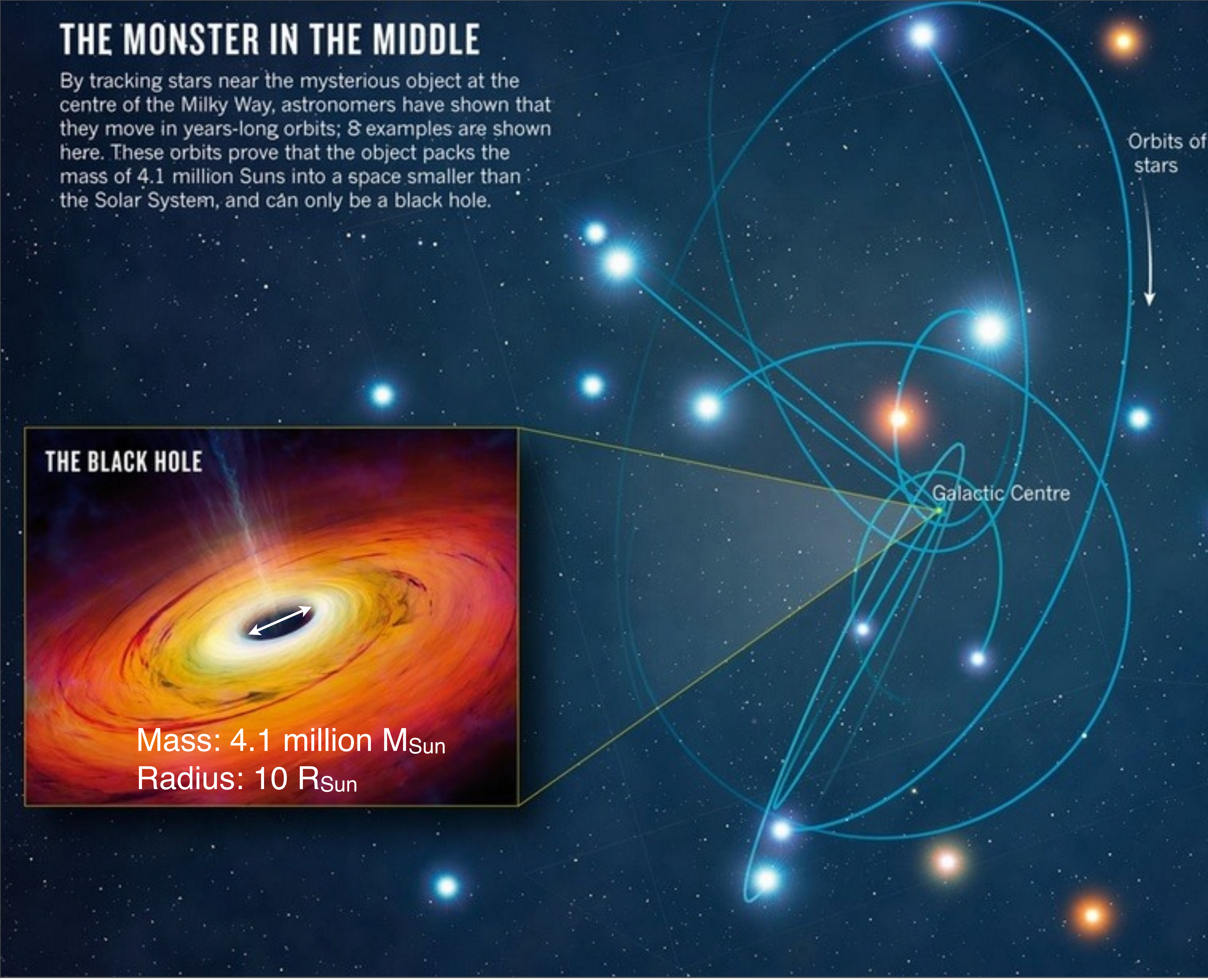

magnetic field lines

swirling gas in galactic center




Galactic center stars appear to be orbiting something massive but invisible ... a black hole?

Orbits of stars indicate a mass of about 4.1 ± 0.2 million $M_{Sun}$. Such a black hole would have a radius of 10 $R_{Sun}$

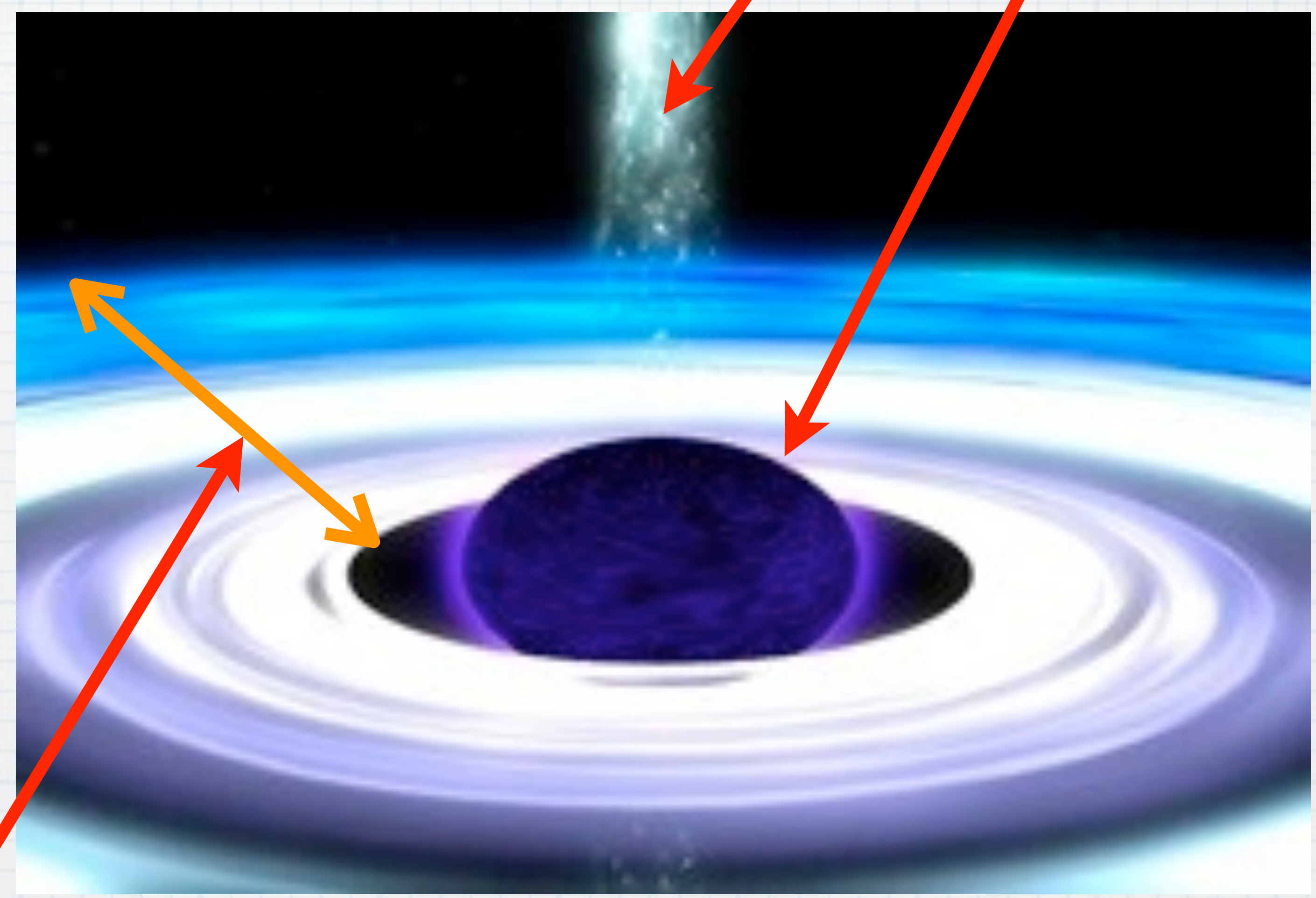

THE MONSTER IN THE MIDDLE
By tracking stars near the mysterious object at the centre of the Milky Way, astronomers have shown that they move in years-long orbits; 8 examples are shown here. These orbits prove that the object packs the mass of 4.1 million Suns into a space smaller than the Solar System, and can only be a black hole.
Orbits of stars
Galactic Centre
THE BLACK HOLE
Mass: 4.1 million $M_{Sun}$
Radius: 10 $R_{Sun}$

# Black Hole Confirmed?

* Due to recent technological advances, astronomers have detected structure at a tiny angular scale of 37 micro-arcseconds which is the Milky Way's central black hole region
* This is the equivalent of a baseball seen on the surface of the Moon: 240,000 miles away

# Black Hole Confirmed?...

A structure with a 37 micro-arcsecond angular scale, which corresponds to a size of about 30 million miles (**or about one-third the Earth-Sun distance**) at the galactic center can be clearly discerned in a 2008 study




Note: this is a drawing!

# Soon to be seen?

* Astronomers have discovered a gas could approaching Sagittarius A*
* The team thinks the cloud will reach the event horizon—a black hole's point of no return—some time in 2013, creating a bright radiation flare that will shed new light on the black hole's feeding behavior - Stay tuned

# A simulation shows how a gas cloud approaching our galaxy's supermassive black hole may break apart.

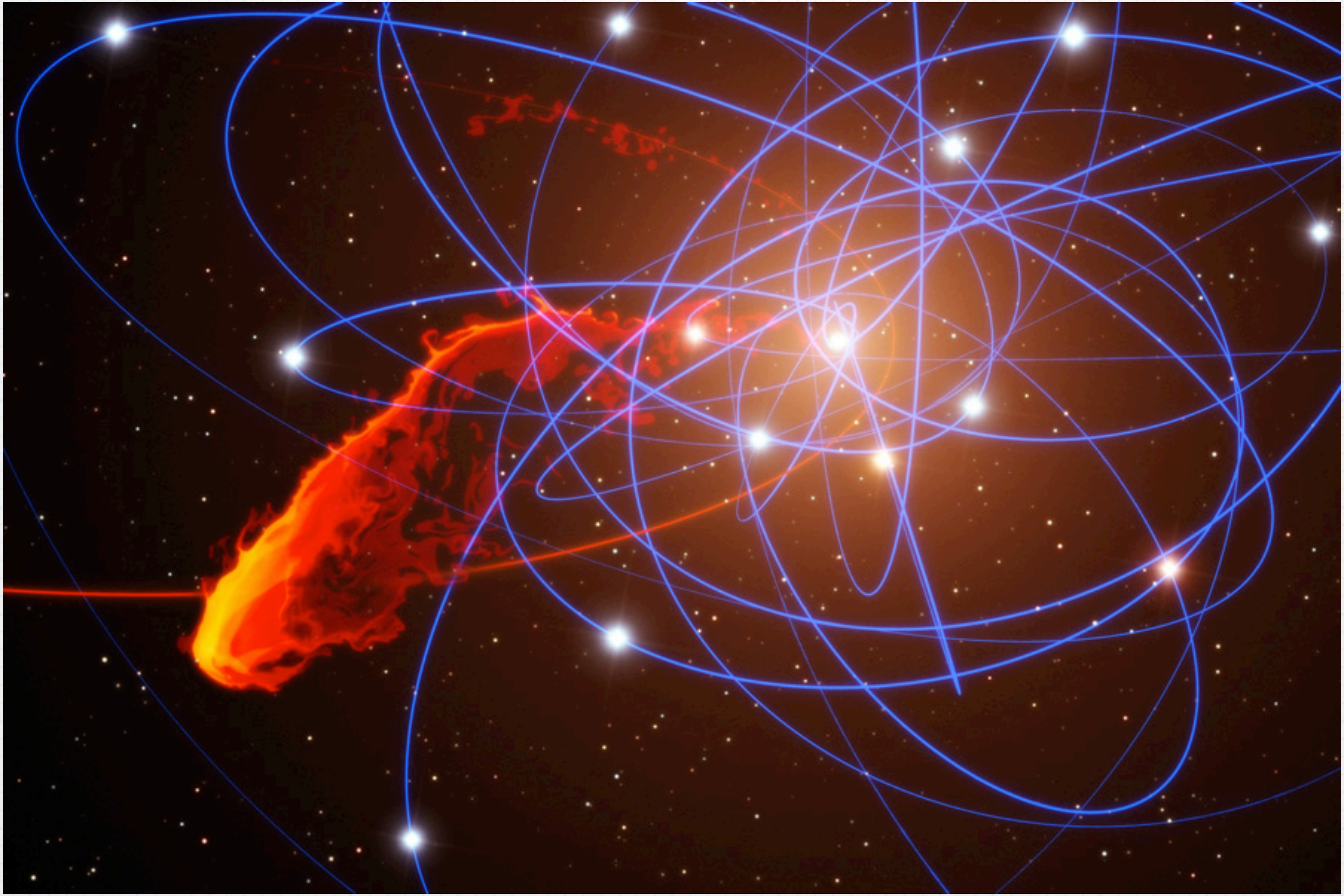


*Illustration courtesy Marc Schartmann, MPE/ESO*

# In the meantime, we can now see flares of X-ray energies emanating from the Sagittarius A* black hole

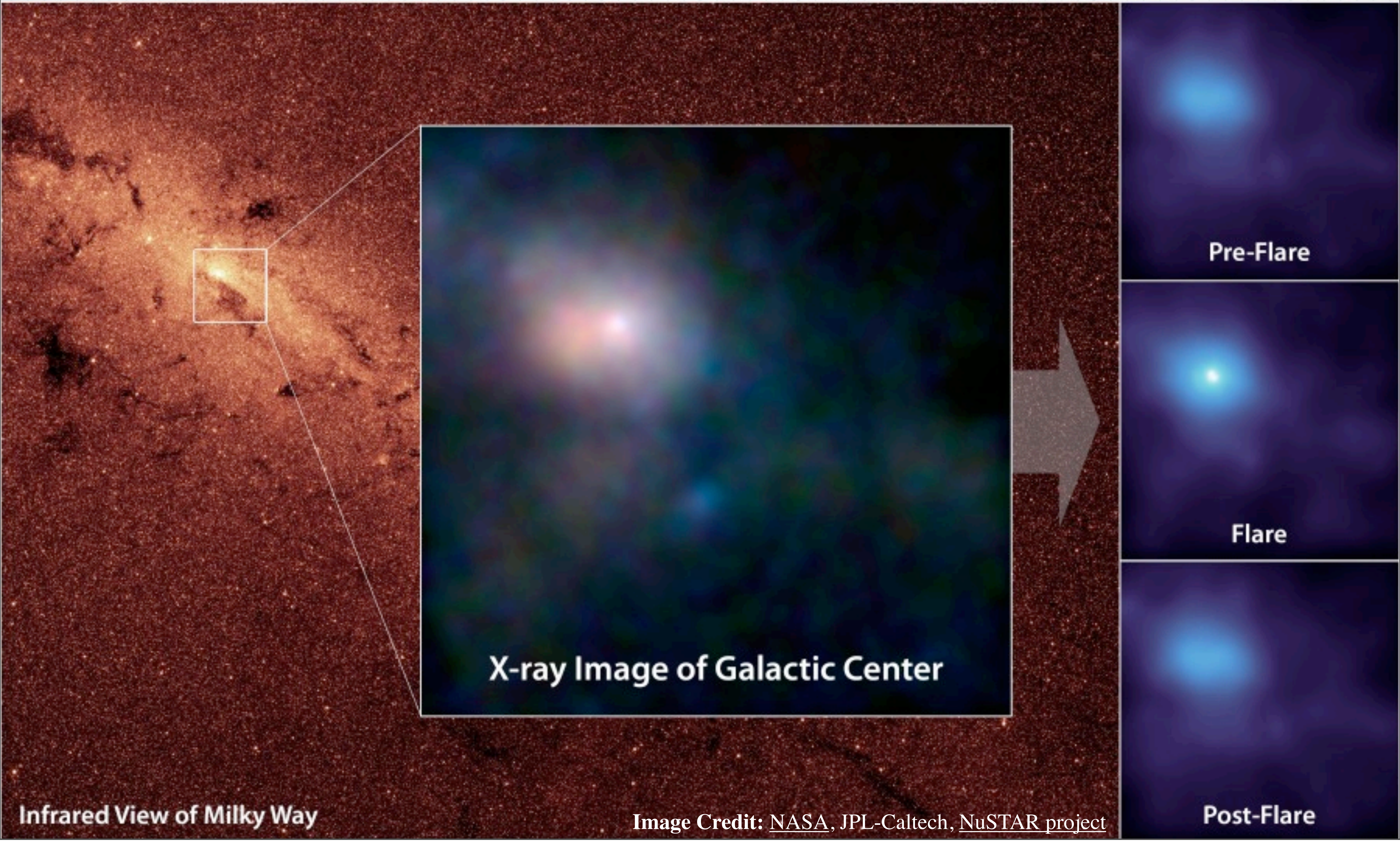
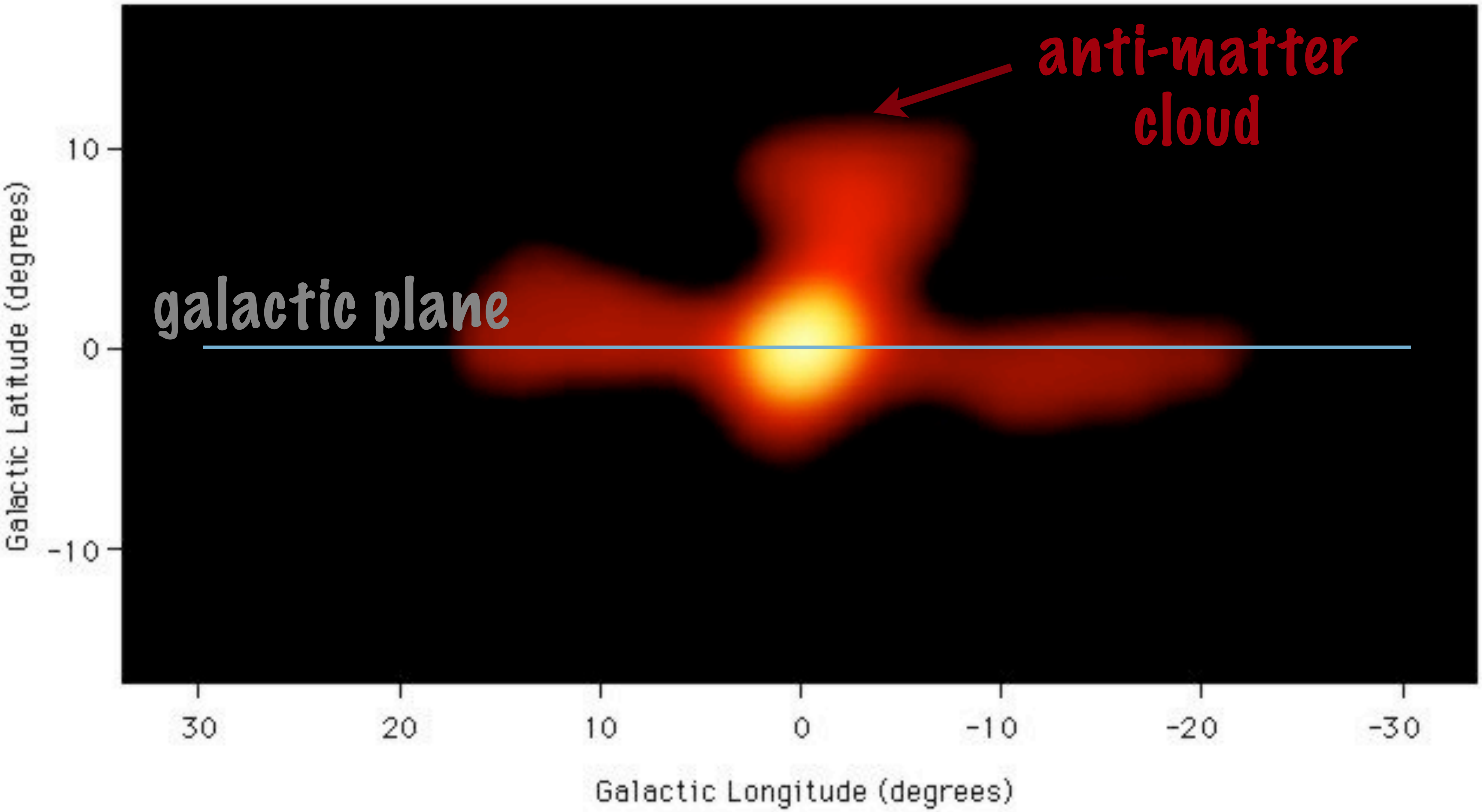



**Image Credit:** NASA, JPL-Caltech, NuSTAR project

# More Mysteries Left...

* A new space telescope looking at gamma rays spotted a cloud of **positrons (anti-electrons!)**
* Why are they there? What created them? Binary neutron stars, supernovae or the massive black hole or ...?

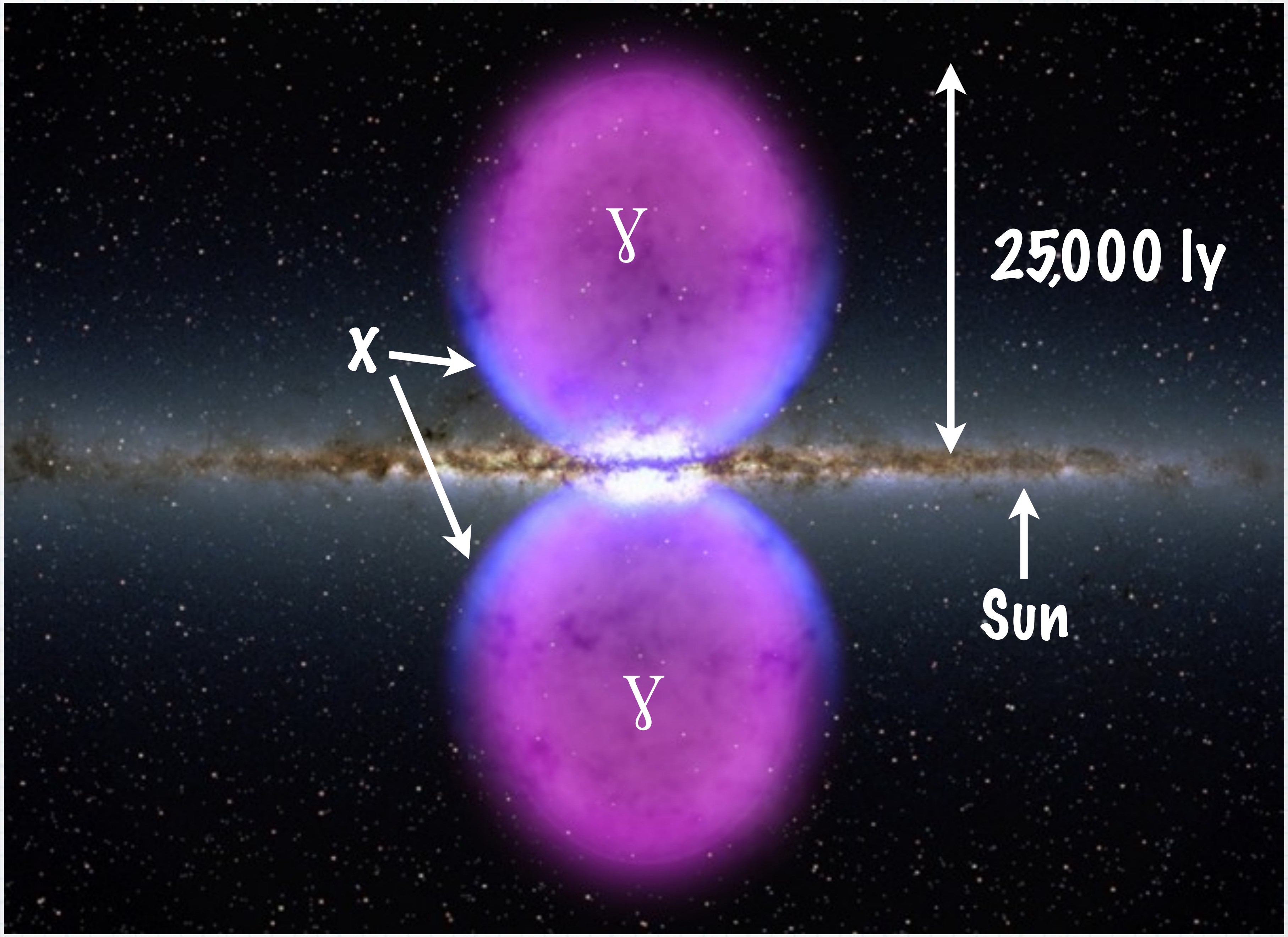



Caption: Map of the distribution of positrons towards the center of the Milky Way Galaxy, including the newly discovered antimatter "cloud". The brightest feature corresponds to the nucleus of the Galaxy. The horizontal structure lies along the plane of the Galaxy. The antimatter "cloud" is located above the Galactic center.

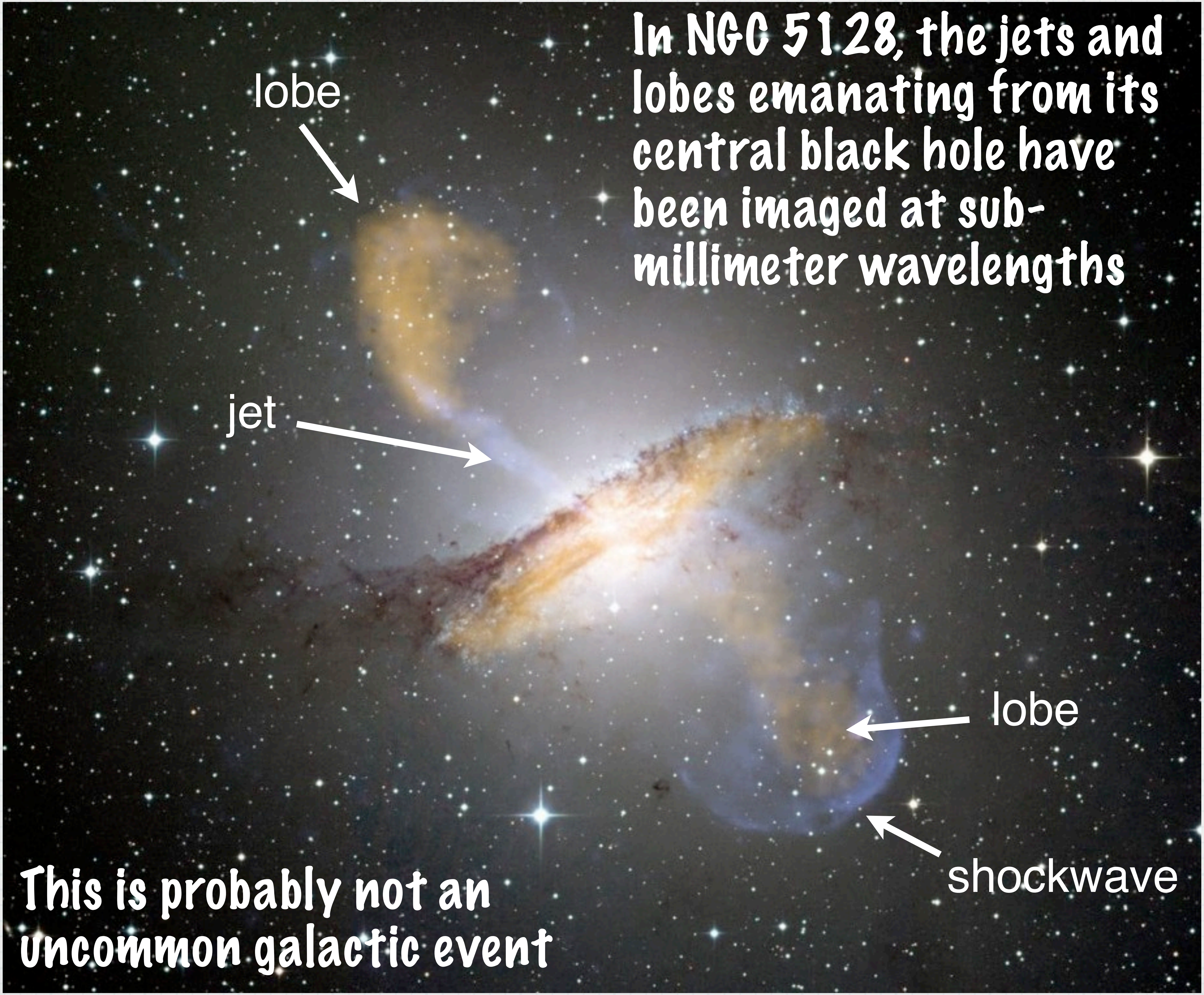
Courtesy of D. D. Dixon (University of California, Riverside) and W. R. Purcell (Northwestern University)

# Giant bubbles of gamma rays have been observed coming from center of our galaxy

The two bubbles could have been inflated by a past eruption from the supermassive black hole at the center of the Milky Way

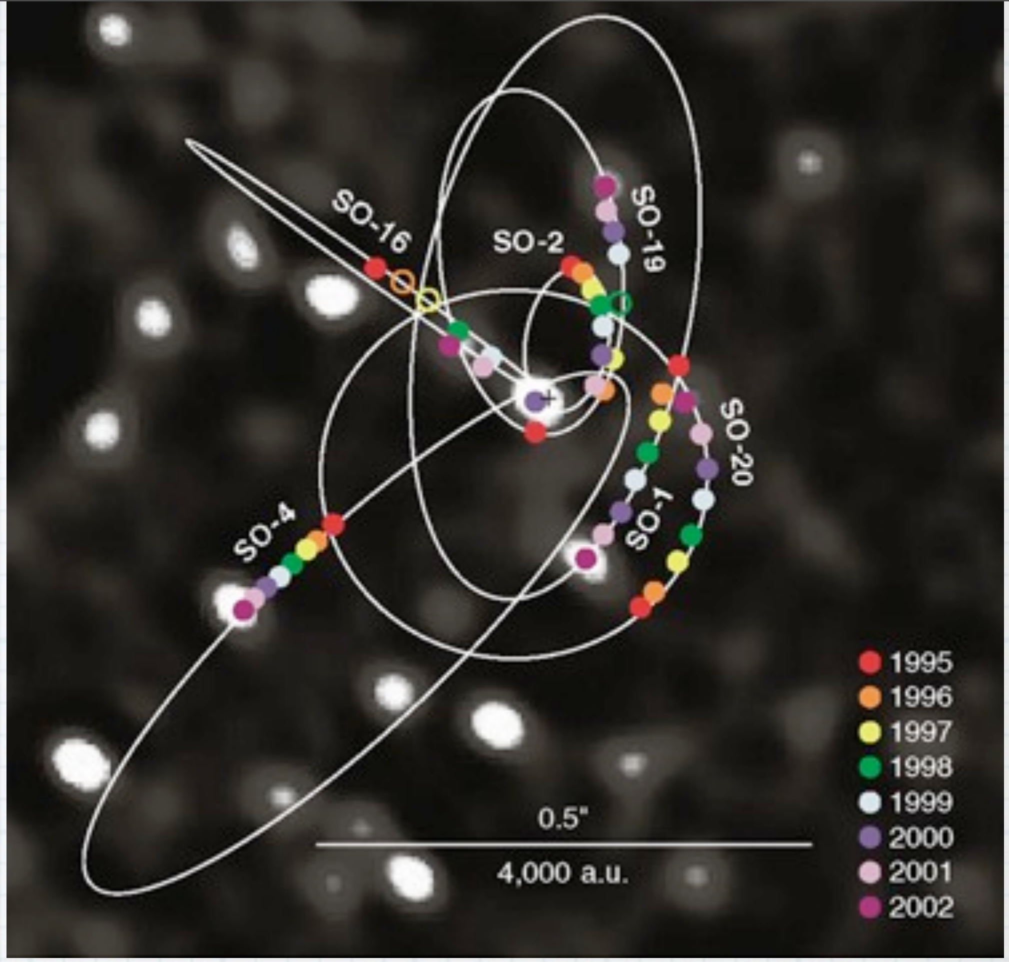



The structures are very distinct, with defined edges, and have as much energy in them as 100,000 supernova



In NGC 5128, the jets and lobes emanating from its central black hole have been imaged at sub-millimeter wavelengths
lobe
jet
lobe
shockwave
This is probably not an uncommon galactic event

# Snapshot




* What lies in the center of our galaxy?
* Motions of stars near the center of our galaxy suggest that **it contains a black hole about 4 million times as massive as the Sun**. The black hole appears to be powering a bright source of radio emission known as Sgr A*.

# Reference Material

- http://youtu.be/voq3Wfr5cho
- http://www.youtube.com/watch?v=qhaQ_f_5Z5k
- http://www.youtube.com/watch?v=KCADH3x56eE
- http://www.youtube.com/watch?v=0mRhVVCWm3I
- http://www.youtube.com/watch?annotation_id=annotation_487963&feature=iv&src_vid=cW7BvabYnn8&v=xp-8HysWkxw
- http://www.nasa.gov/mission_pages/GLAST/news/new-structure.html