Astronomy 110: SURVEY OF ASTRONOMY

12. The Milky Way Galaxy

1. Structure of the Milky Way
2. Generations of Stars
3. Origin and Center

The Milky Way Galaxy is a vast pinwheel of stars and gas turning within an enormous cloud of invisible matter. Many generations of stars have formed and died within its disk, enriching our galaxy's stock of heavy elements. Before the disk formed, the future Milky Way probably existed as several distinct galaxies which fell together and merged.

1. STRUCTURE OF THE MILKY WAY

a. Layout and Populations

b. Galactic Rotation

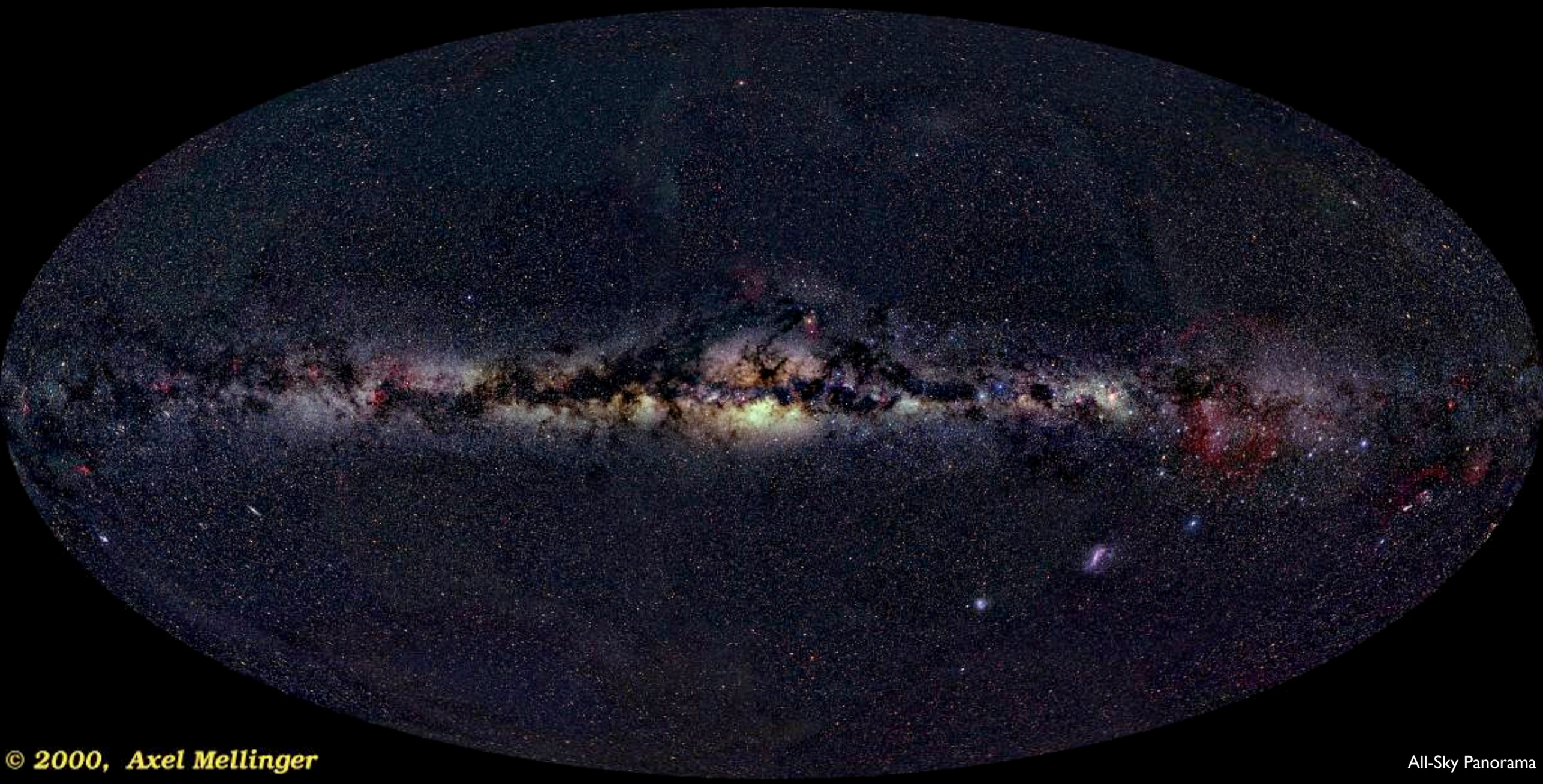
c. Visible and Dark Mass

Layout and Populations

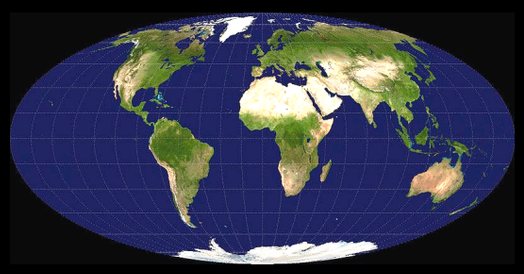
Moonlight, Mars, and Milky Way

The Milky Way From Mauna Kea

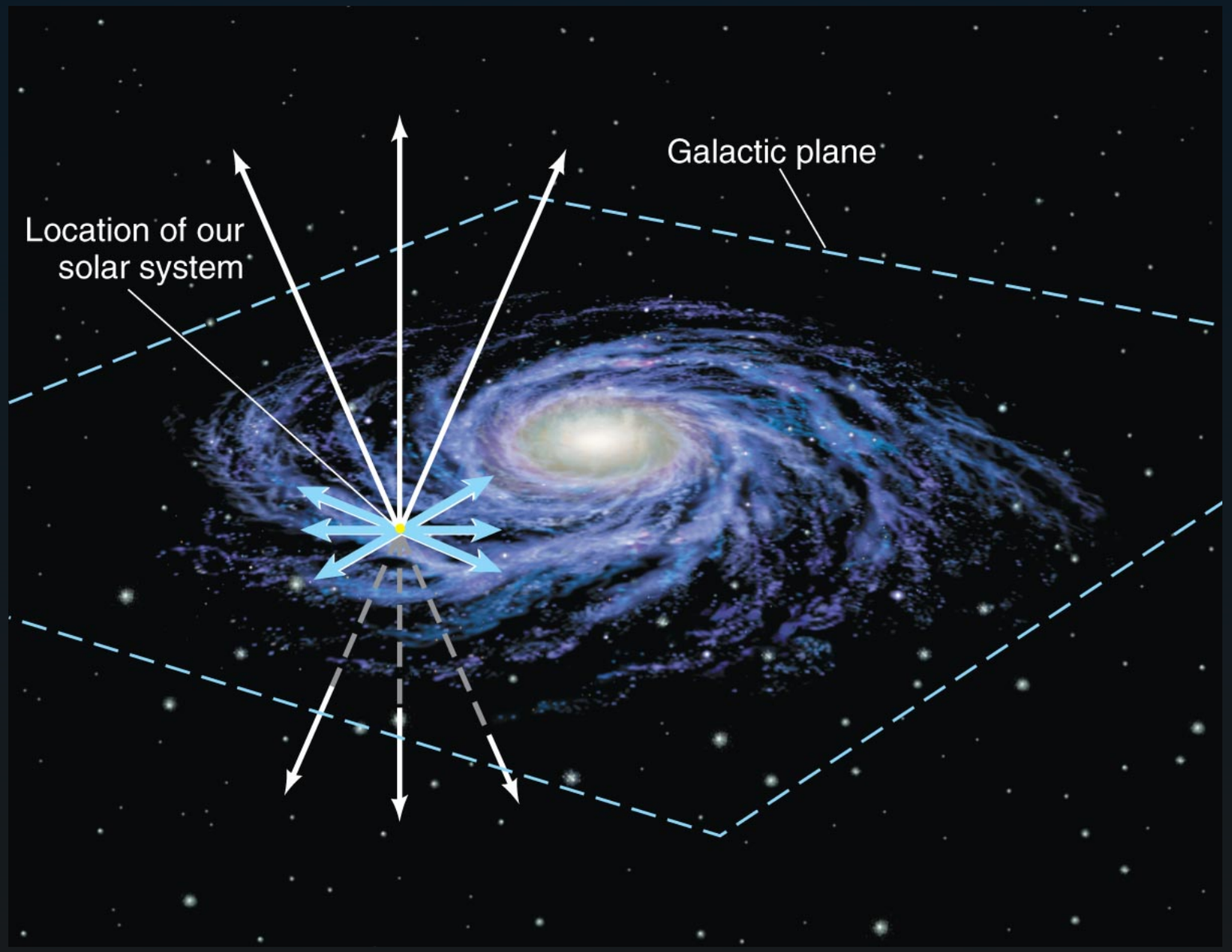
The Milky Way: All-Sky View



All-Sky Panorama

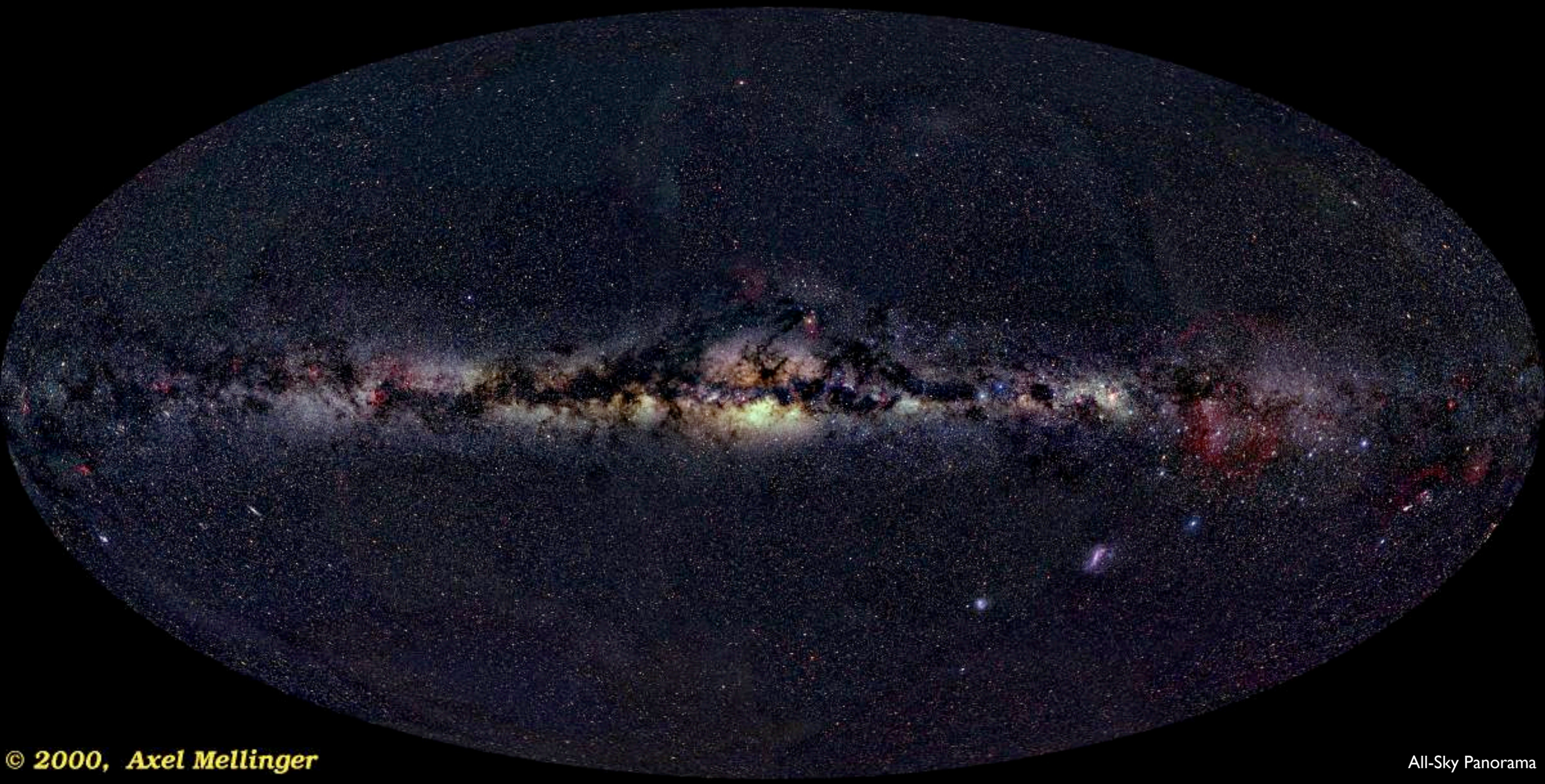


Our View in Perspective



We see the Milky Way as a band across the sky because we're looking at a vast disk of stars from *inside*.

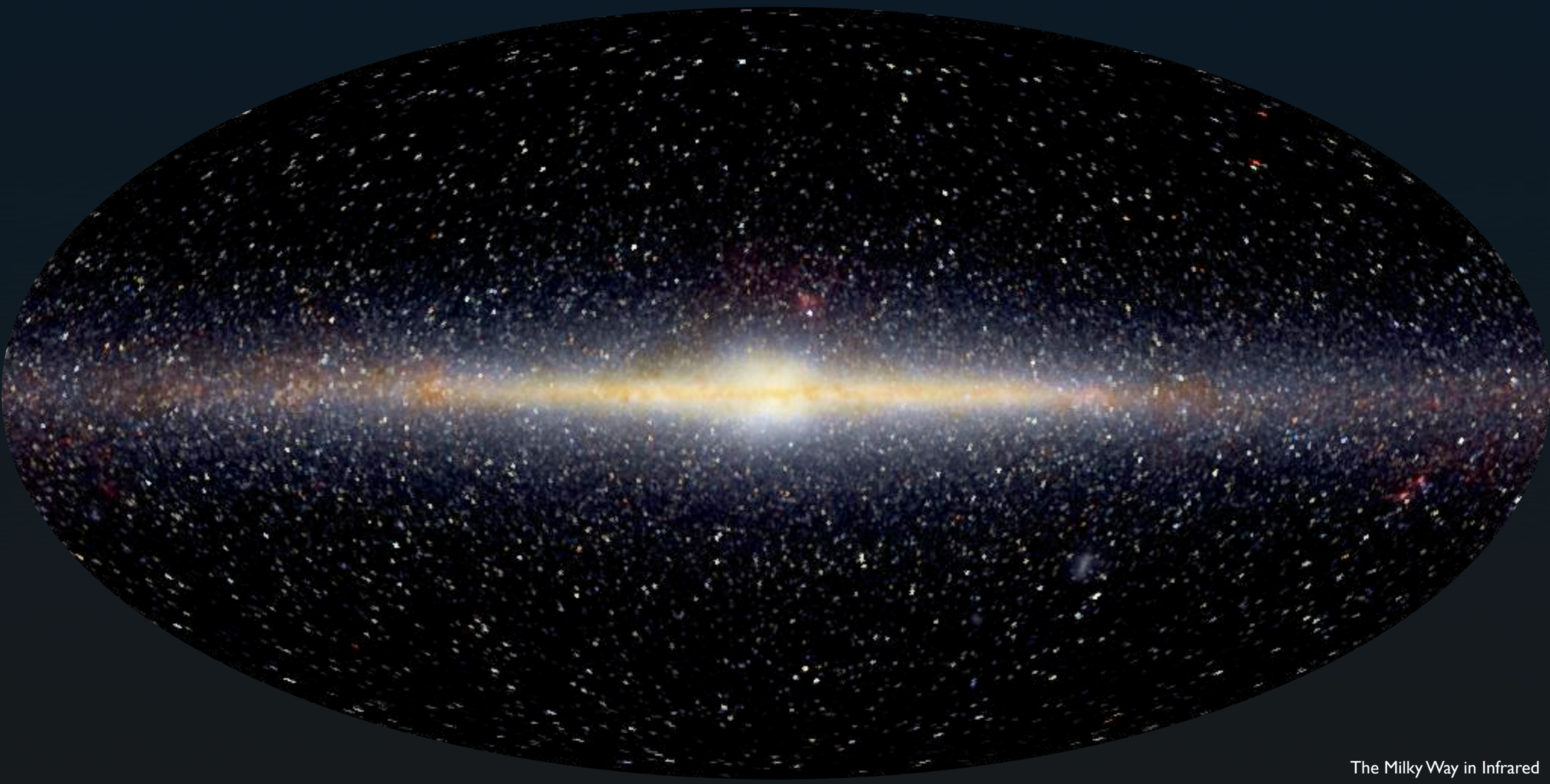
All-Sky View: Visible Light



All-Sky Panorama

We can't really see *where* we are because interstellar dust hides most of the Milky Way from out view.

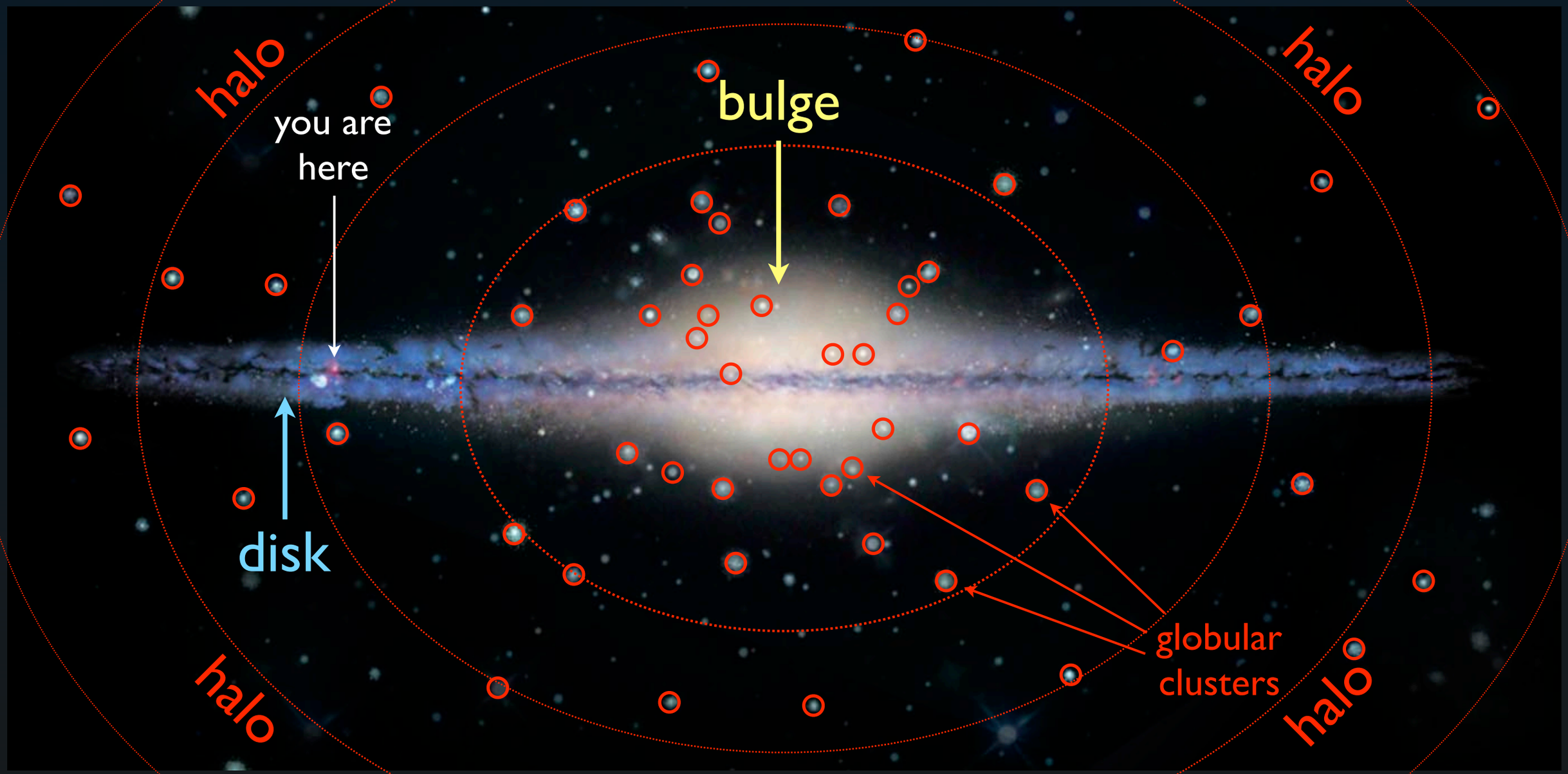
All-Sky View: Infrared Light



The Milky Way in Infrared

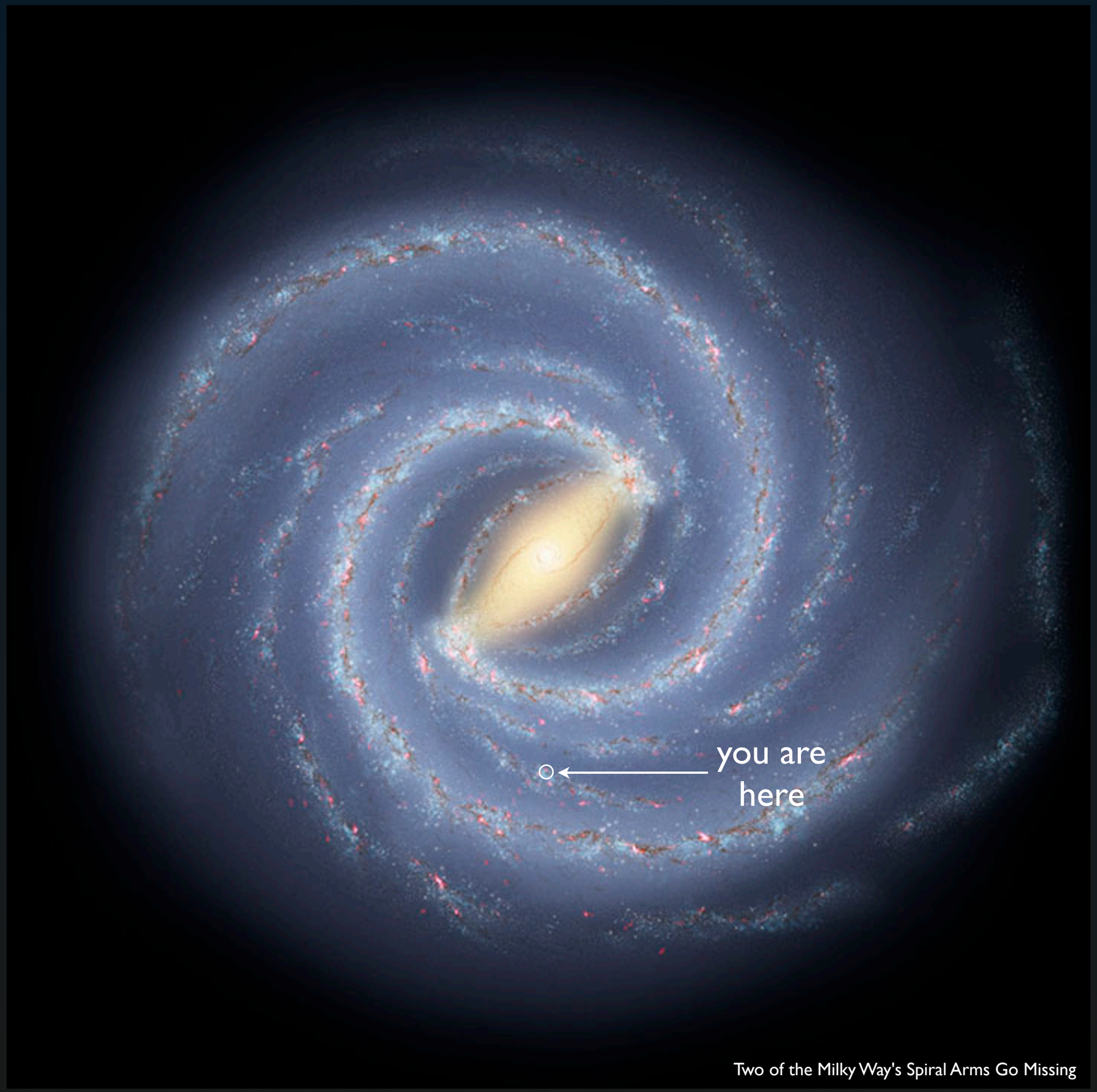
Infrared light is not absorbed by dust, affording us a view of the entire Milky Way.

From Outside: Edge-On View

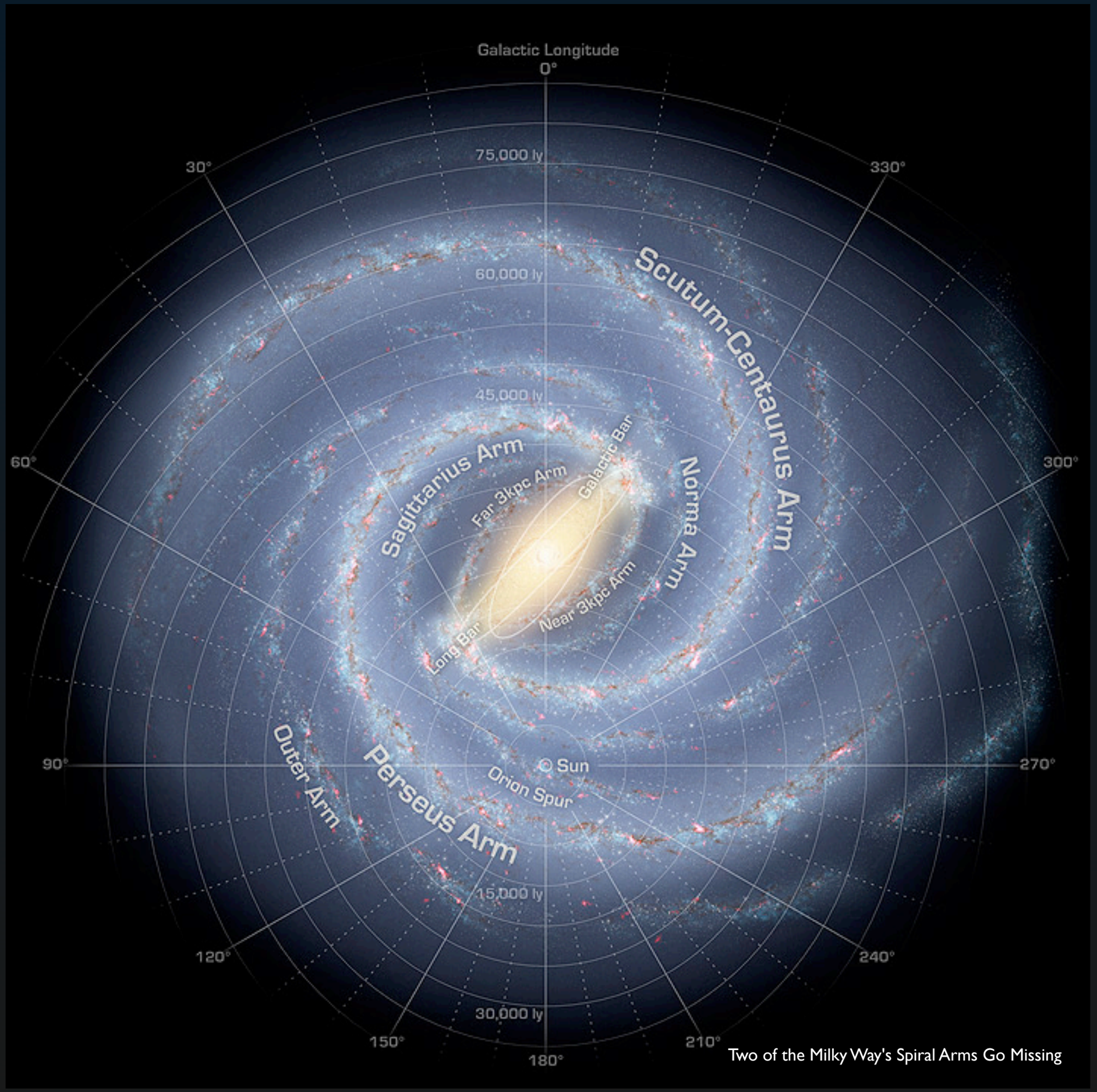


Globular clusters swarm around the galactic center.

The MW has three main parts: bulge, disk, & halo.



Two of the Milky Way's Spiral Arms Go Missing



Two of the Milky Way's Spiral Arms Go Missing

Open clusters

Globular clusters

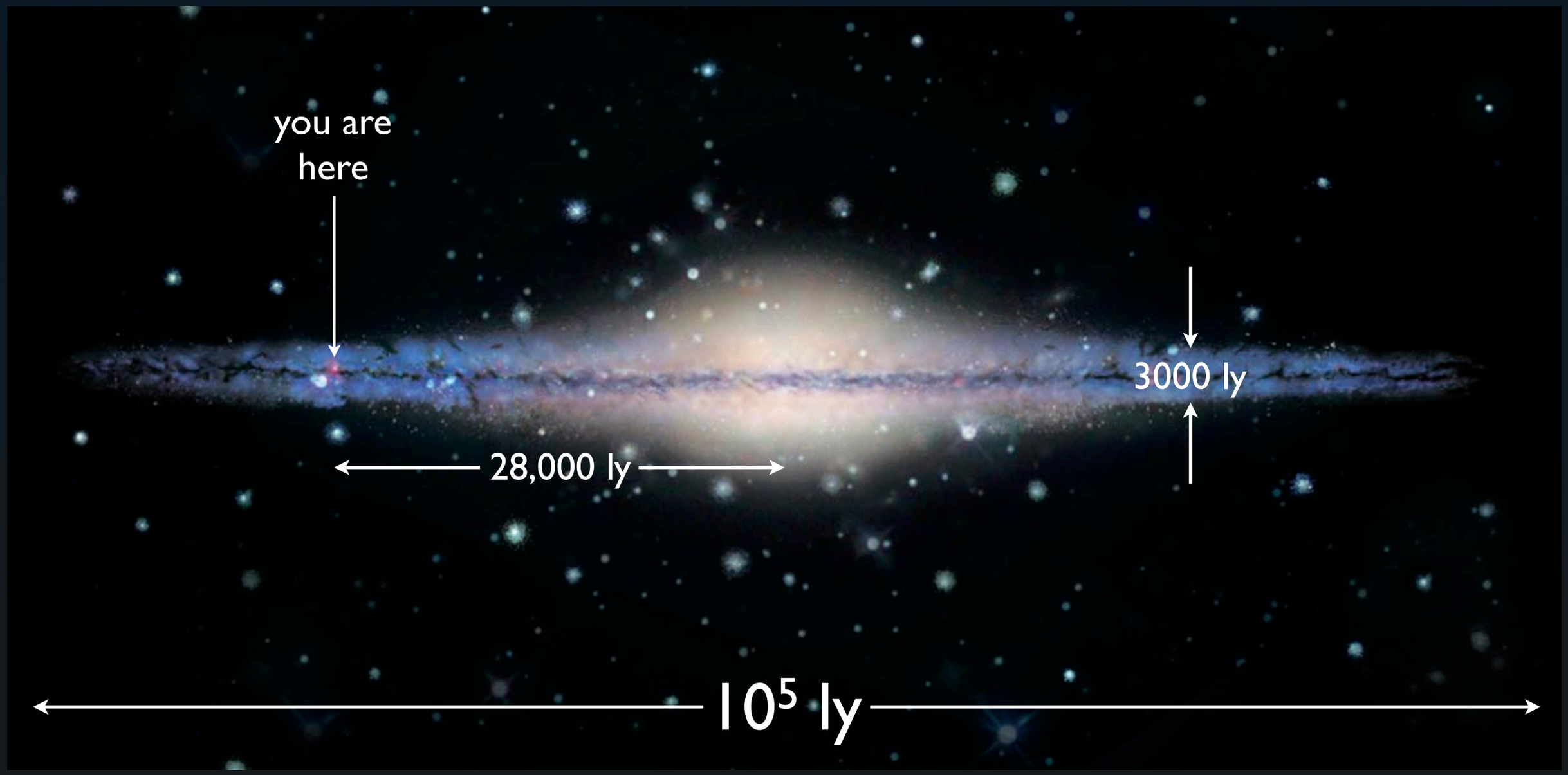
Population I

Population II

Populations of the Milky Way

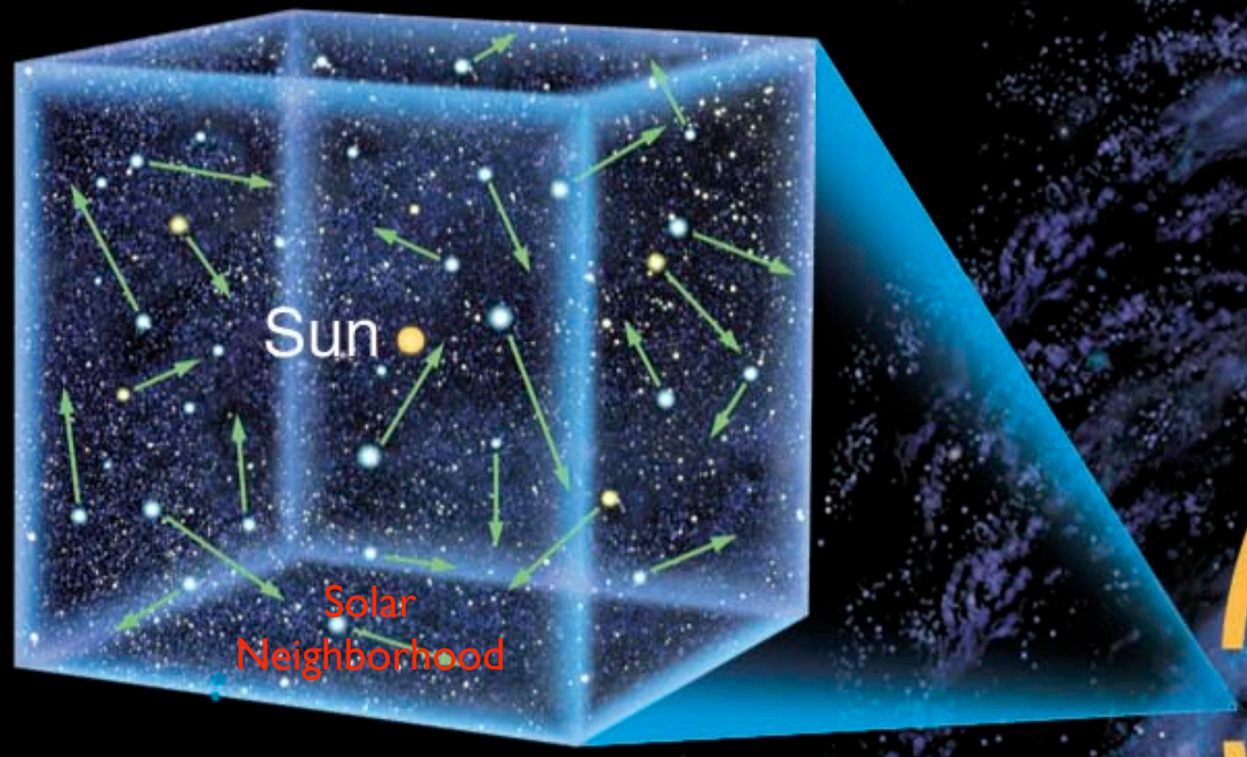
Population	I	II
Location	Disk	Bulge, Halo
Age (Gyr)	0 — 10	10 — 12
Metals	Solar	Sub-Solar
Orbits		

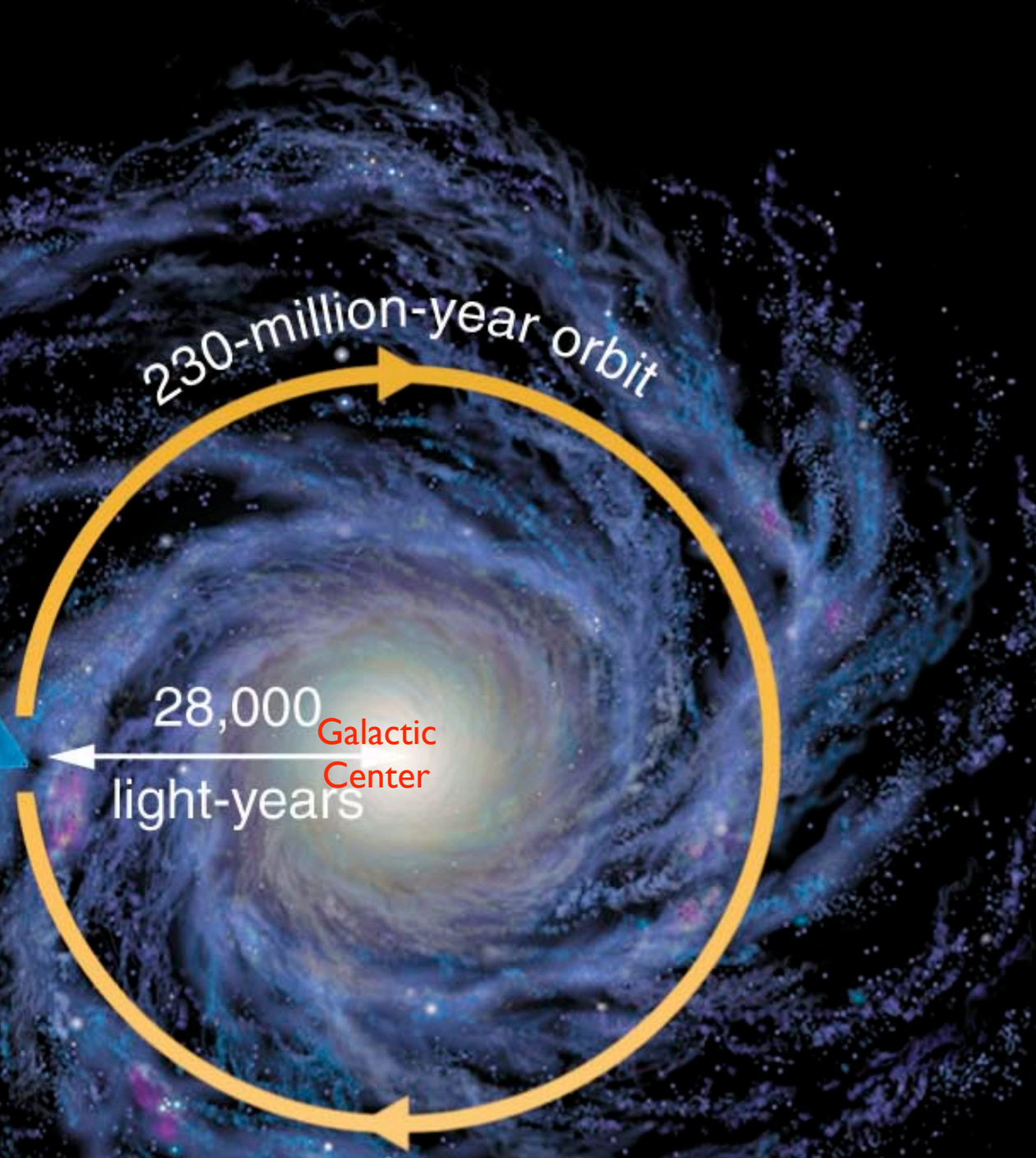
The Scale of the Milky Way



"Our galaxy itself contains 100,000,000,000 stars / It's 100,000 light years side to side / It bulges at the middle / 16,000 light years thick / But out by us it's just 3,000 light years wide / We're 30,000 light years from galactic central point... / We go 'round . . ." — *The Galaxy Song* (Monty Python)

Galacitc Rotation





Most stars near the Sun have random velocities of a few tens of km/sec.

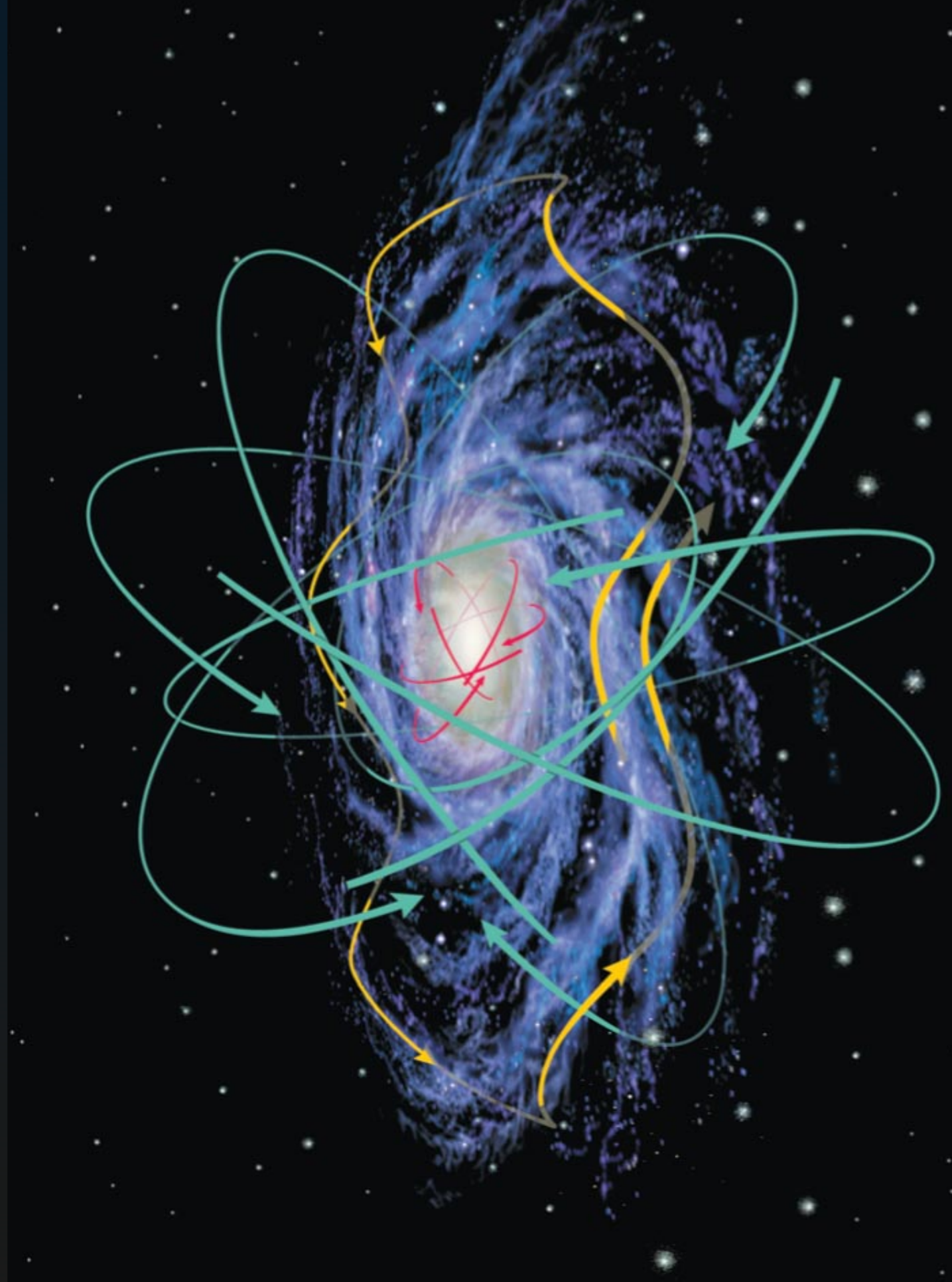
These stars orbit the galactic center at ~230 km/sec.

Stellar Orbits

Disk stars (yellow) all move in the *same direction* on roughly circular orbits.

Stars in the bulge (red) and halo (green) move in fairly *random orbits*.

Note: compare with orbits in solar system!



Populations of the Milky Way

Population	I	II
Location	Disk	Bulge, Halo
Age (Gyr)	0 — 10	10 — 12
Metals	Solar	Sub-Solar
Orbits	Circular	Random

This helps us understand the MW's history . . .

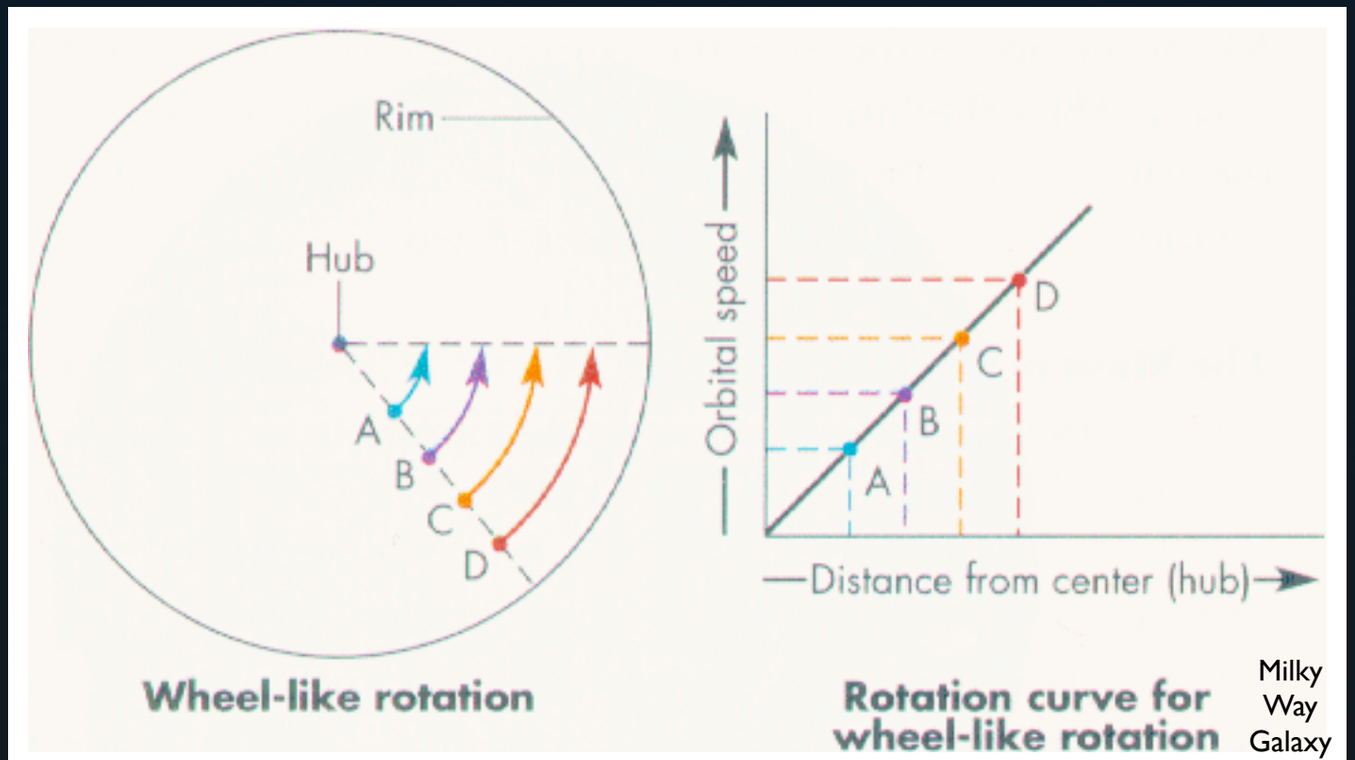
Disk Galaxy Simulation

Photo-Dynamic Galaxy Model

Rotation Curves

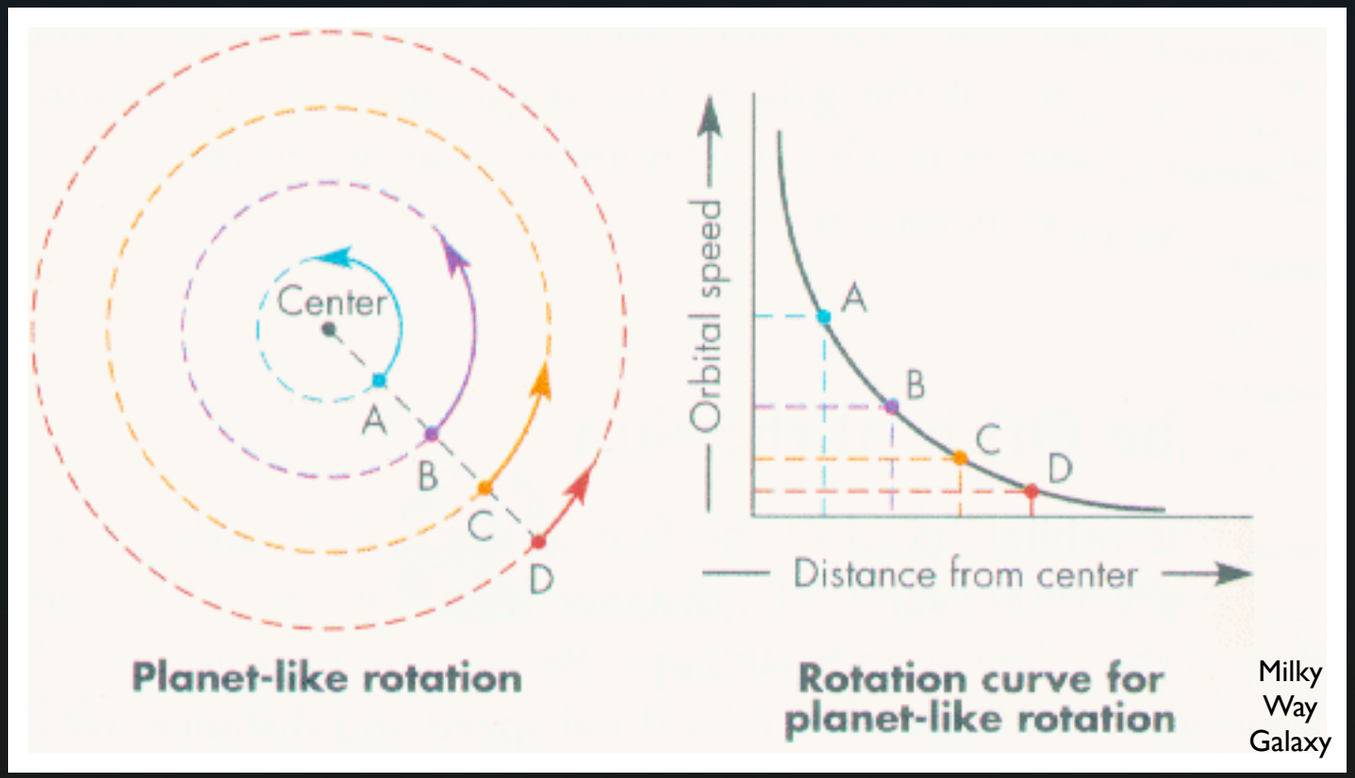
A wheel turns with speed proportional to distance from center:

$$v \propto r$$



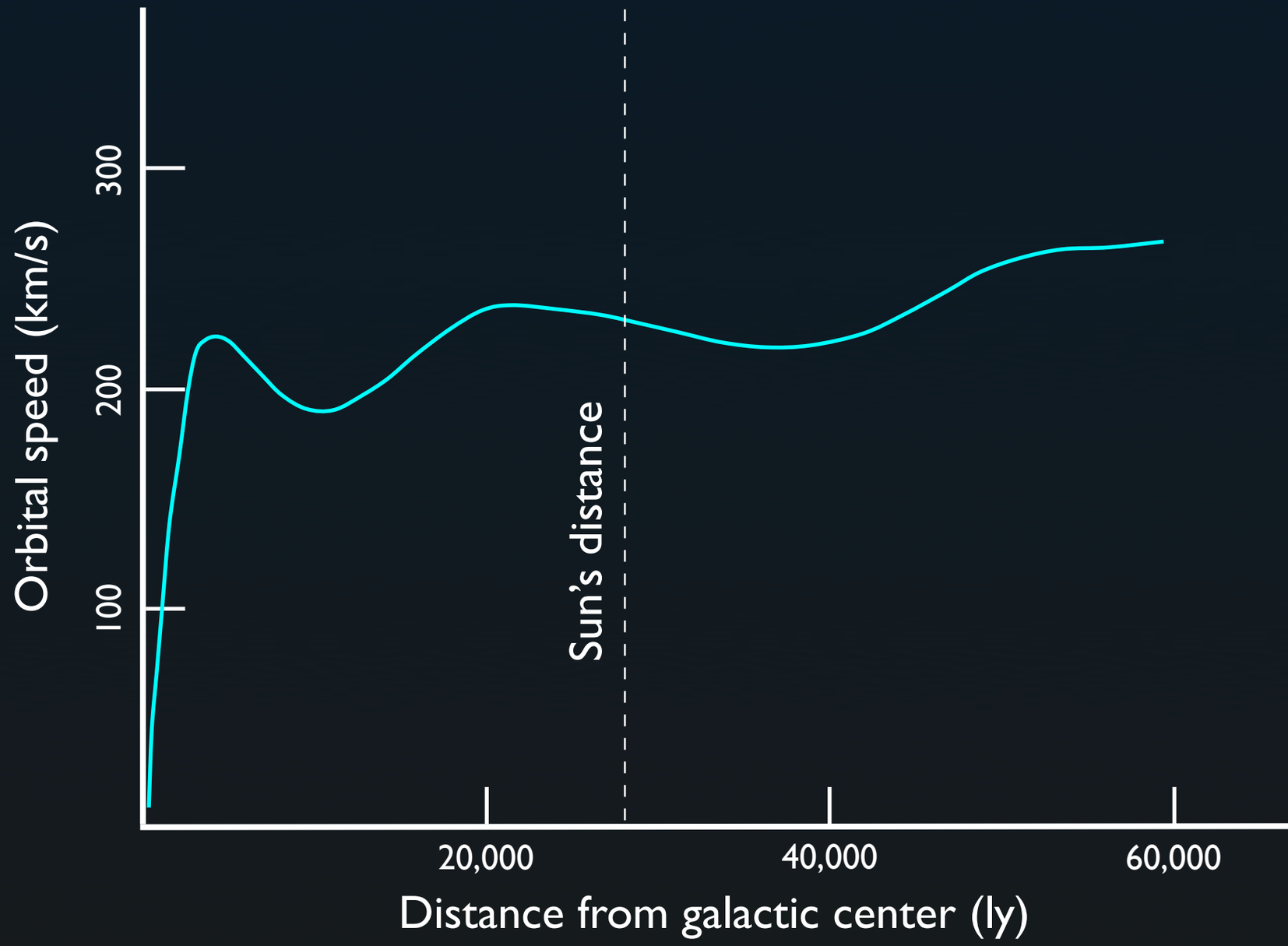
In a planetary system, planets further out orbit more slowly:

$$v \propto \frac{1}{\sqrt{r}}$$



Rotation Curve of the Milky Way

The Milky Way's rotation curve follows *neither* wheel-like nor planetary laws!



After rising steeply near the center, it stays roughly flat out to the last point we can measure . . .

Visible and Dark Mass

The period P and radius a of an orbit allow us to work out the total mass M:

$$M = \frac{a^3}{P^2}$$

(If P is in years and a in AU, get M in $M_\odot$.)

In general, given the radius r and speed v of a circular orbit, the total mass within r is:

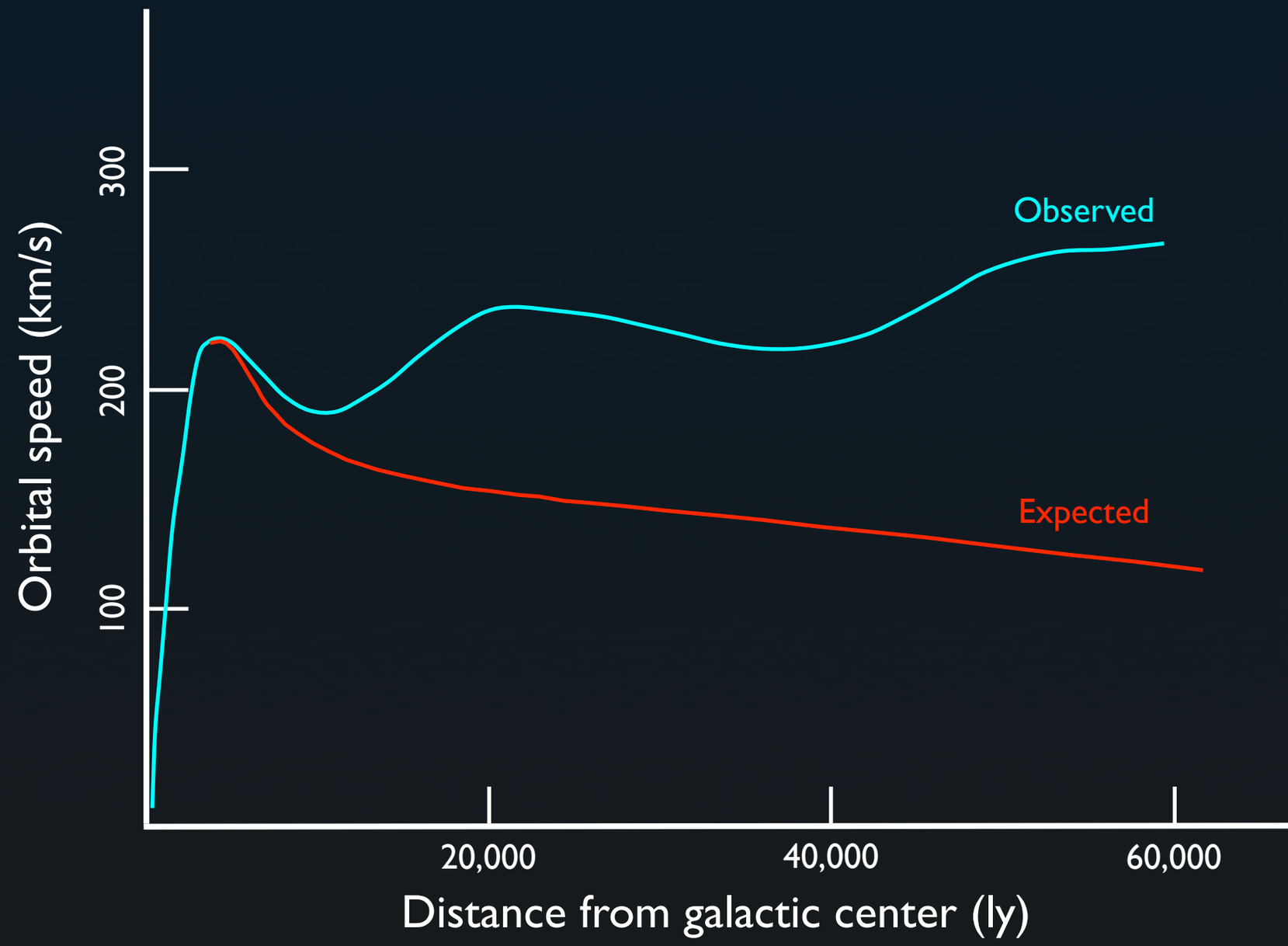
$$M \simeq \frac{r\,v^2}{G}$$

(This is *exact* if the mass is *spherical*.)

The mass within the Sun's orbit is about $10^{11}\ M_\odot$ — *twice the total mass in stars and gas* within this radius!

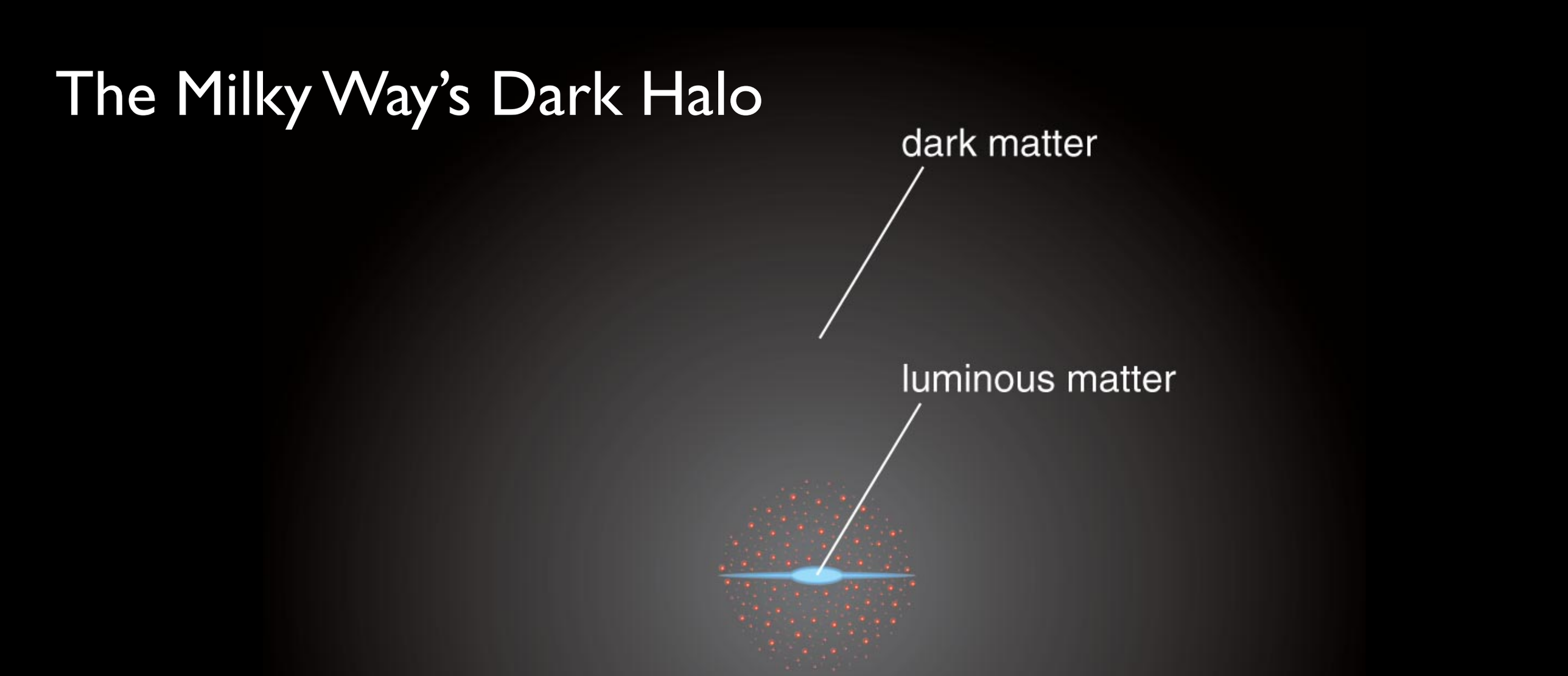
Dark Matter in the Milky Way

If visible stars and gas were all, the Milky Way's rotation curve should decline.



Most of our galaxy's mass is invisible! Since it emits no light, it's called **dark matter**.

The Milky Way's Dark Halo



The Milky Way's *total* mass is at least $5 \times 10^{11}\ M_\odot$. More than 80% of this mass is *dark*.

What Is All This Stuff?

We Dunno!

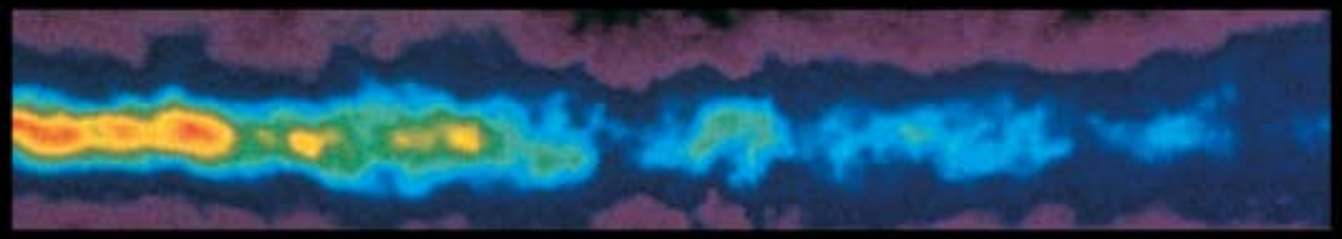
2. GENERATIONS OF STARS

a. Recycling Gas and Stars

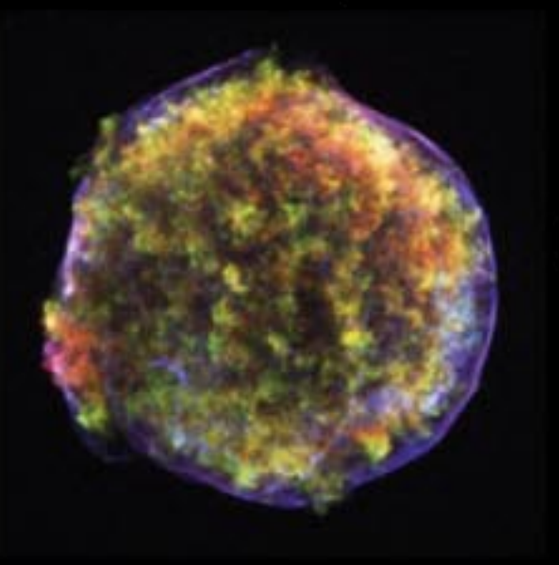
b. The Interstellar Medium

c. Where the Stars Form

Recycling Gas & Stars

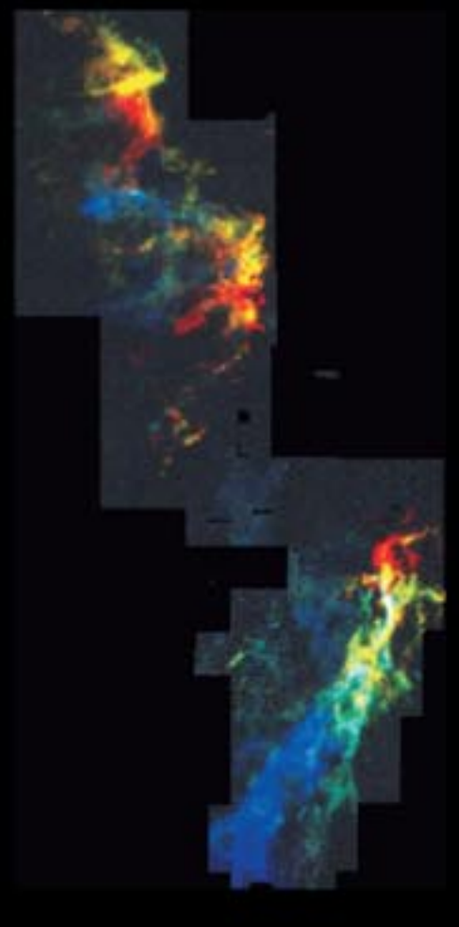


atomic hydrogen clouds



hot bubbles

molecular clouds



Star–Gas–Star Cycle

returning gas

nuclear fusion in stars

star formation

Aging low-mass stars eject their outer layers.

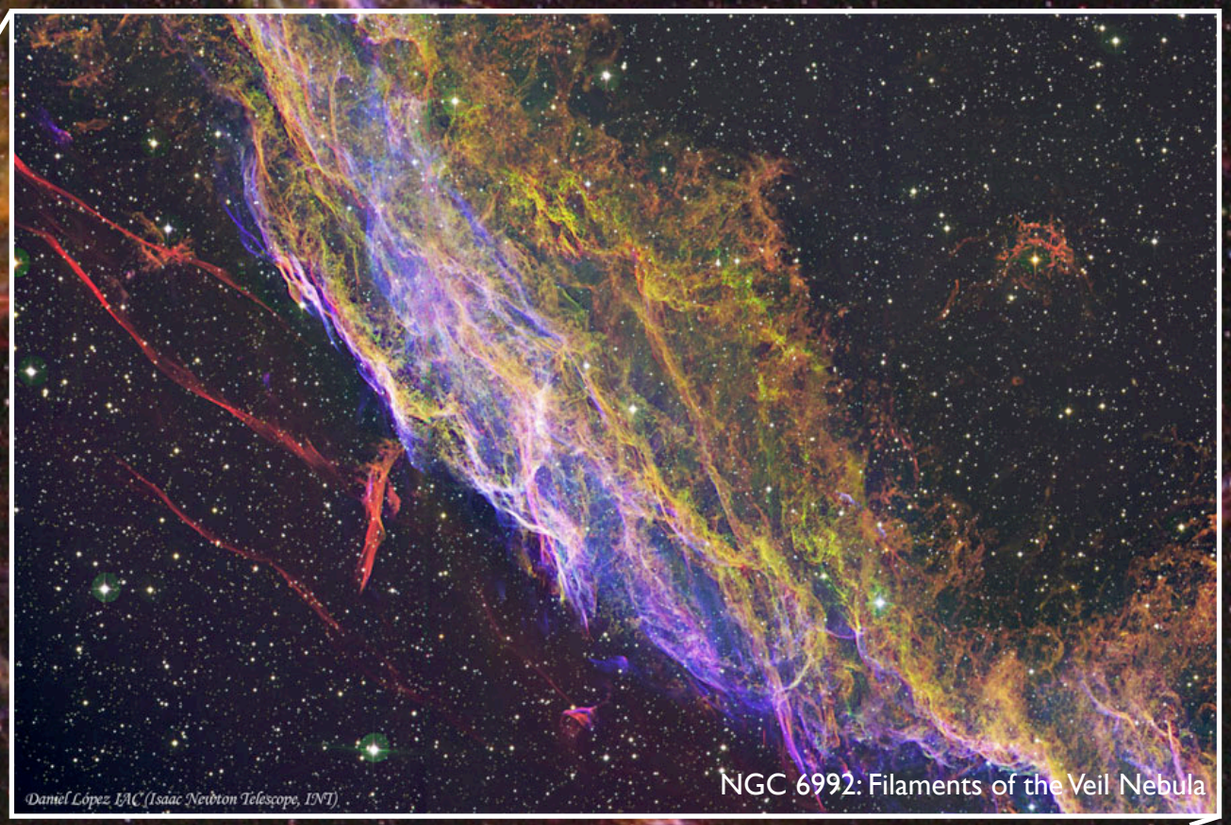
M57: The Ring Nebula

Winds from high-mass stars blow bubbles of hot gas.

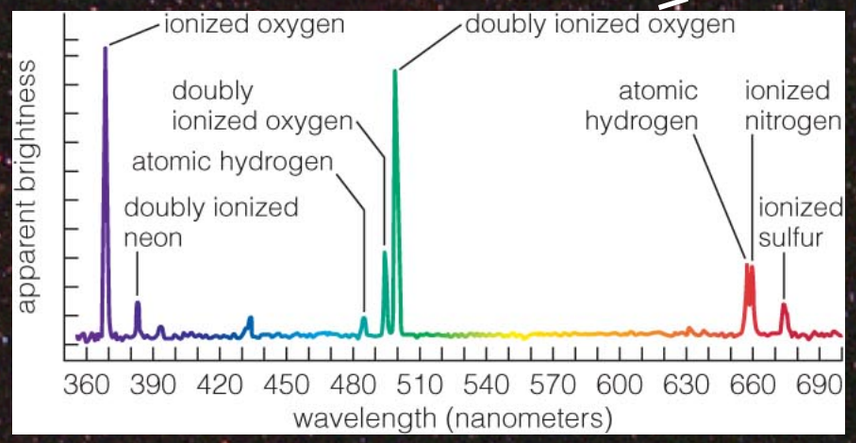
Thor's Emerald Helmet

Supernova blast waves expand into interstellar space.

SN 1006 Supernova Remnant



NGC 6992: Filaments of the Veil Nebula



Elements made in stars are mixed back into the gas.

The Veil Nebula Unveiled

Bubbles blown by high-mass stars burst out of the disk.

The W4 Chimney

The gas cools and falls back into the galaxy.

Burst of Star Formation Drives Bubble in Galaxy's Core

$p^+ + e^- \rightarrow H$

$H + H \rightarrow H_2$

Cooling gas forms clouds of atomic and then molecular H.

Dark Markings of the Sky

Stars form in molecular clouds, and the cycle repeats.

The Pillars of Eagle Castle

Galactic Recycling Summary

- Stars fuse hydrogen, making heavier elements.

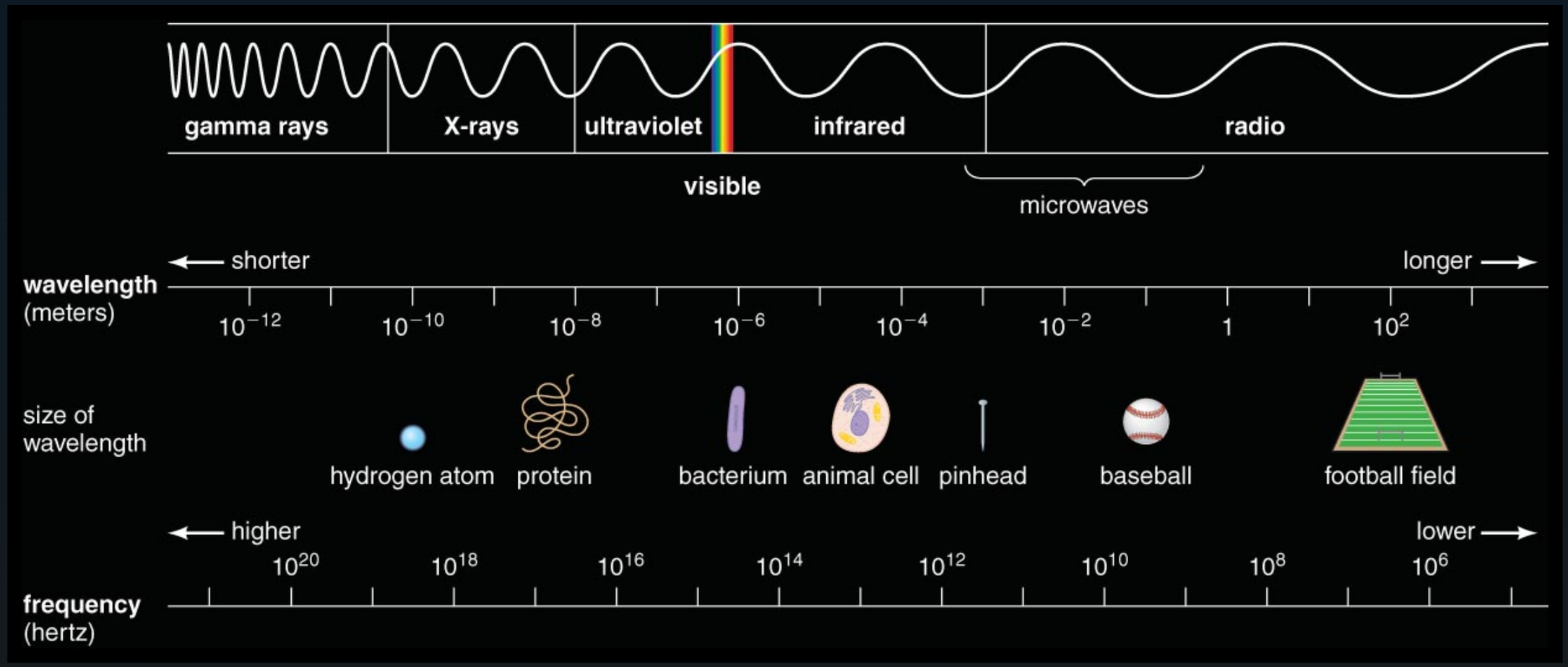
- Dying stars expel hot ($T \sim 10^6$ K) bubbles of gas.

- As gas cools ($T \sim 10^4$ K), hydrogen atoms recombine.

- Further cooling ($T \sim 30$ K) allows molecules to form.

- Gravity forms new stars in molecular clouds..

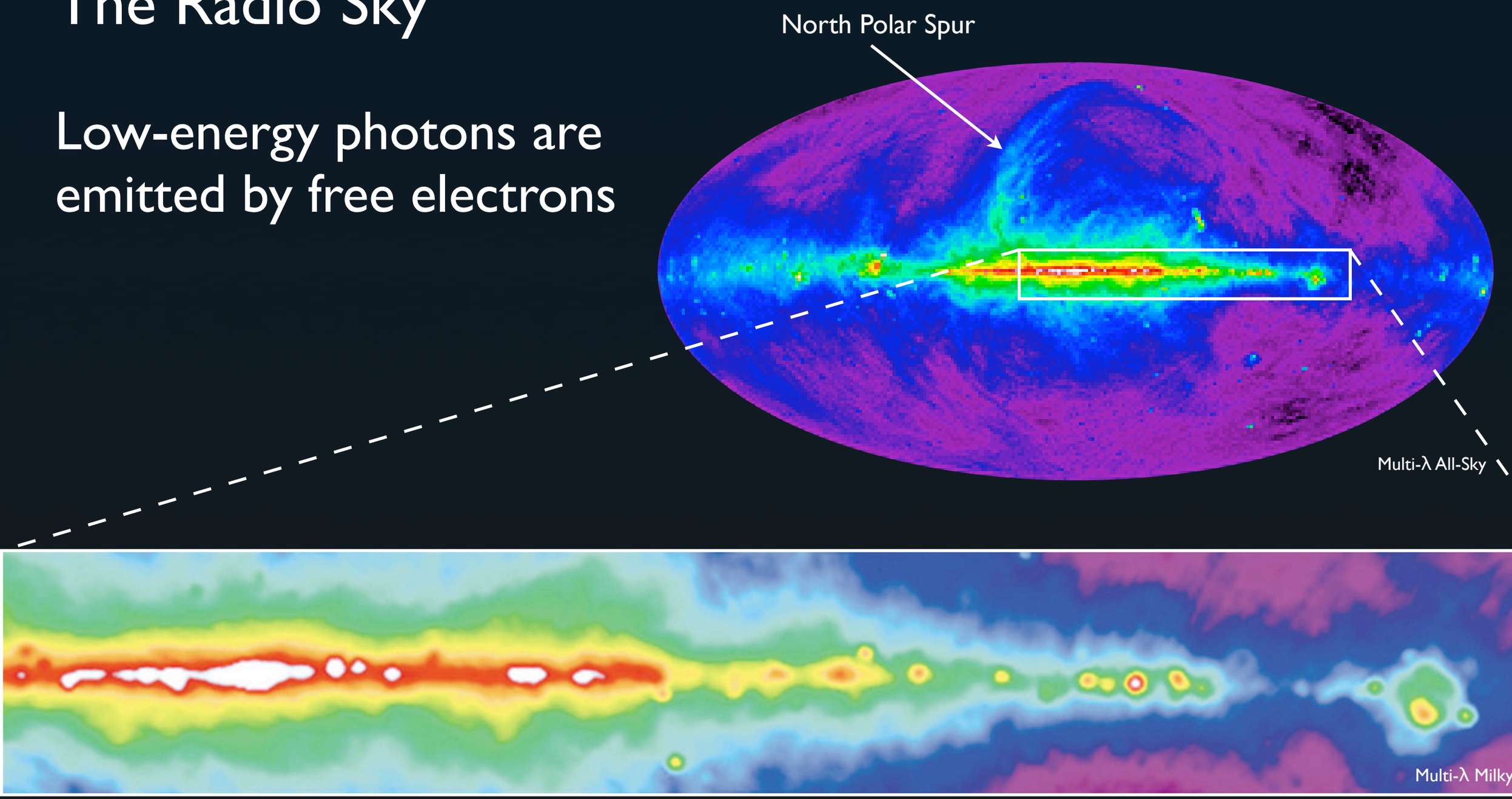
The Interstellar Medium: A Multi-Wavelength View



Observations at different wavelengths show different phases (ie, forms) of the **interstellar medium**.

The Radio Sky

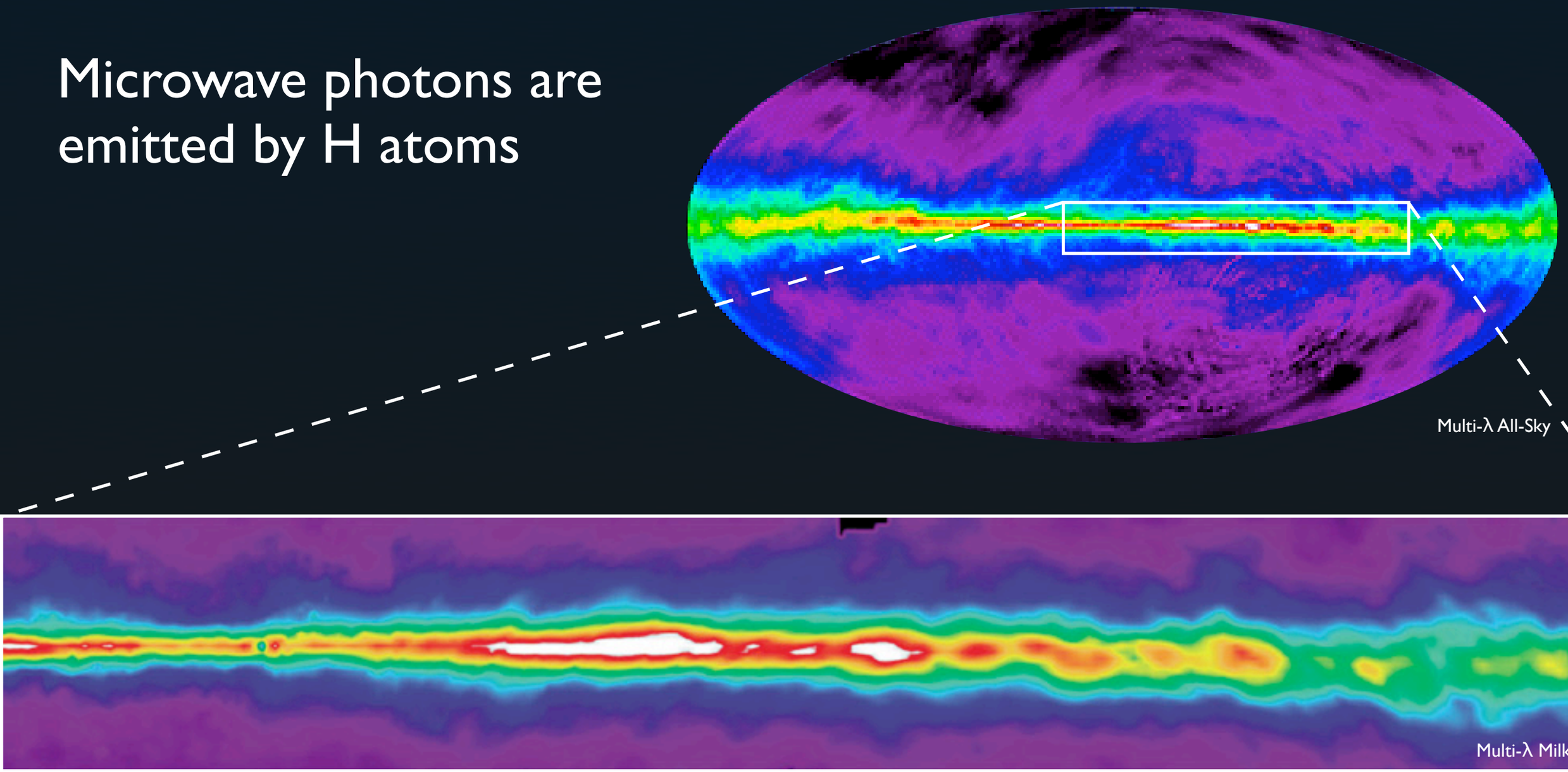
Low-energy photons are emitted by free electrons



Shows hot, ionized interstellar gas and magnetic fields; ‘North Polar Spur’ is an old, nearby supernova remnant.

The 21-cm Sky

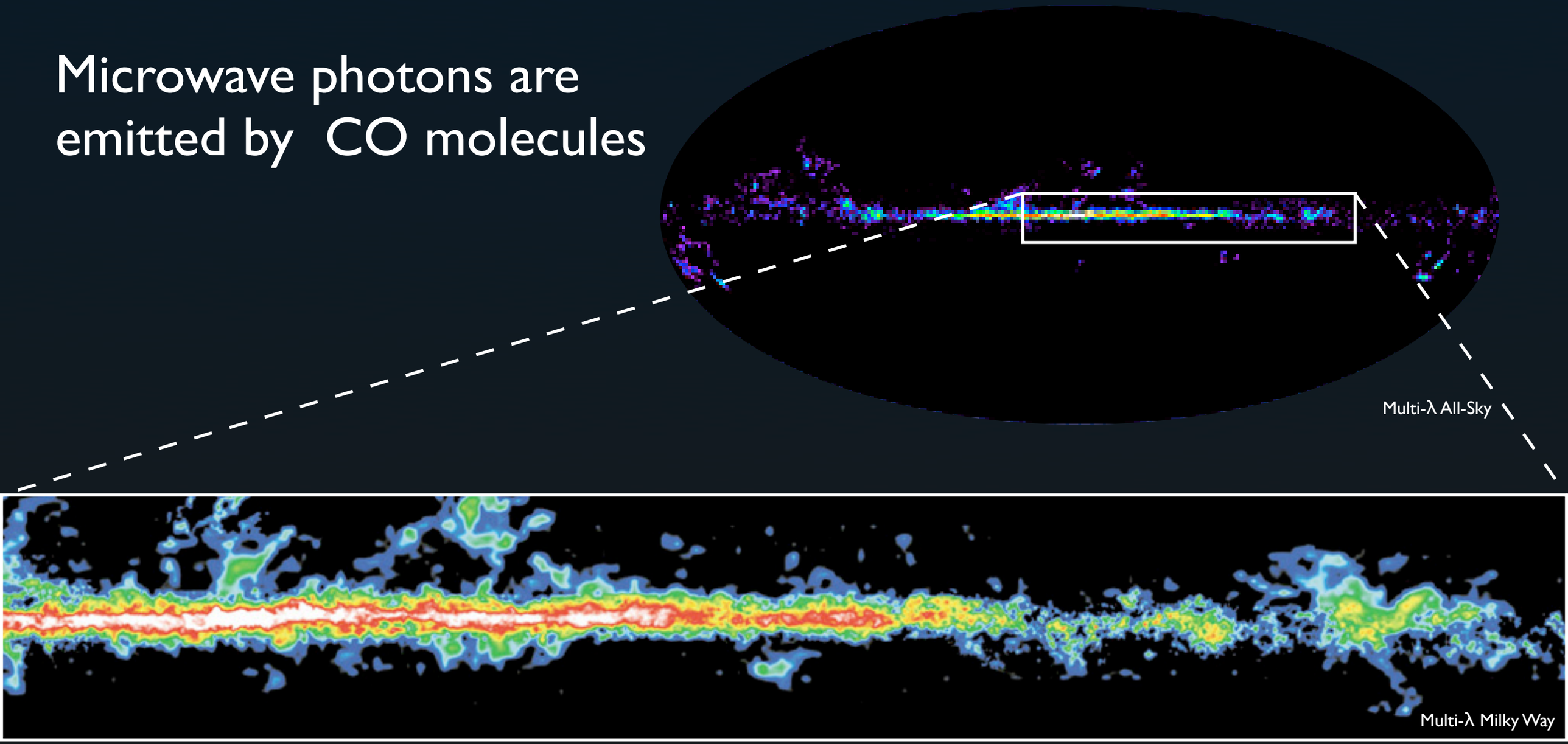
Microwave photons are emitted by H atoms



Shows warm, neutral interstellar gas clouds up to hundreds of light-years across.

The 2.6-cm Sky

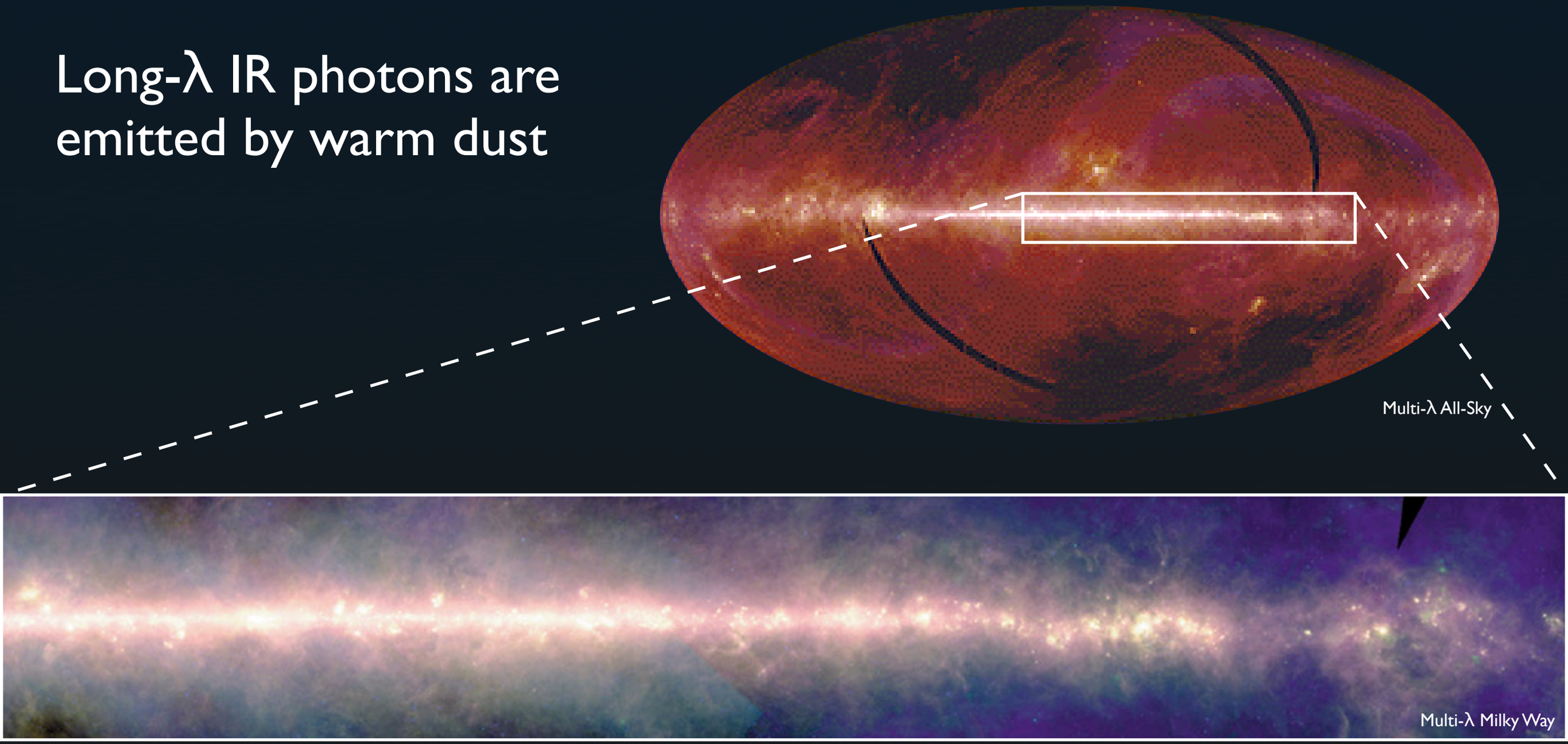
Microwave photons are emitted by CO molecules



Traces cold, dense H_2 clouds concentrated in disk of MW; often associated with star formation.

The Far-IR Sky

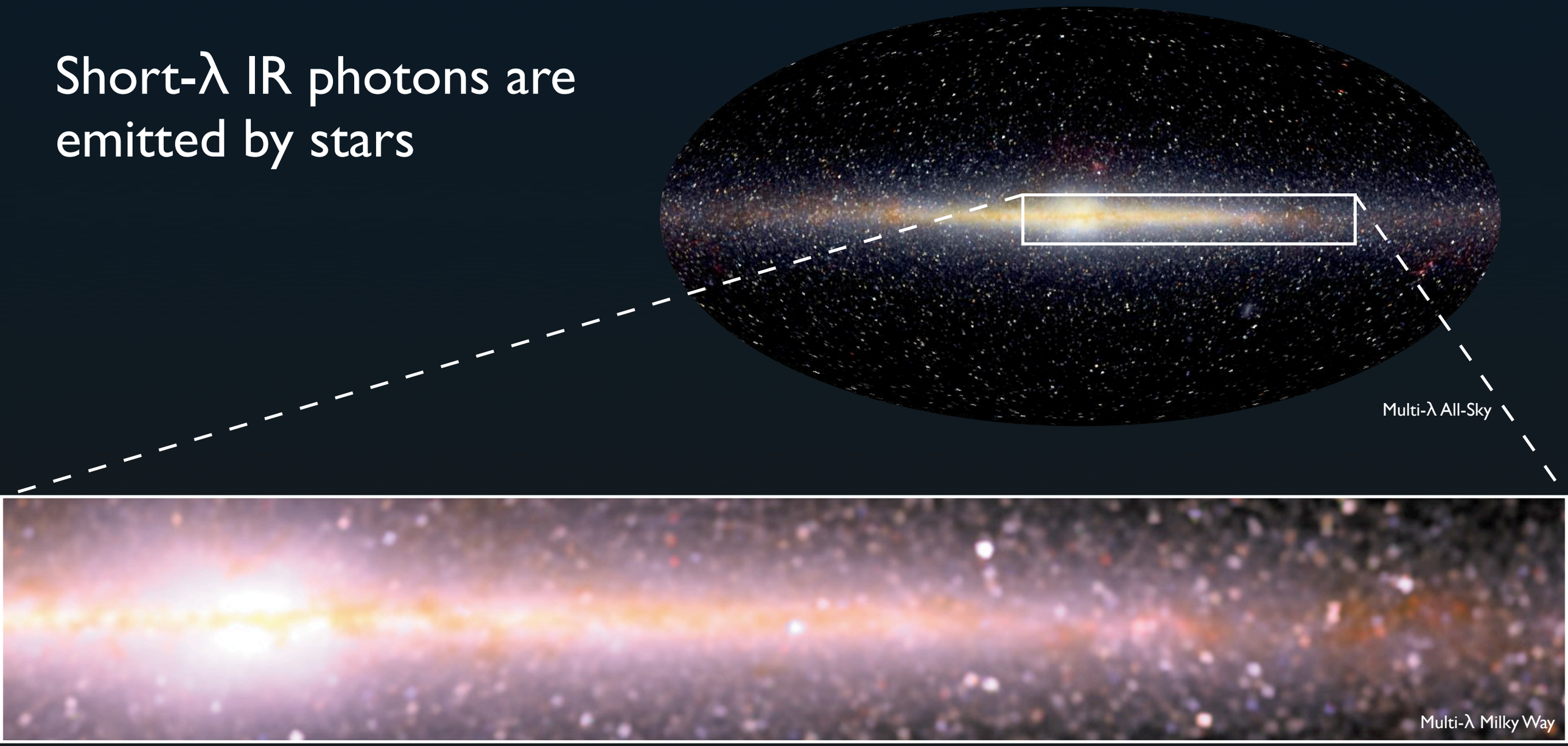
Long-λ IR photons are emitted by warm dust



Shows star-forming regions buried in molecular clouds, and diffuse dust far from MW's disk (red).

The Near-IR Sky

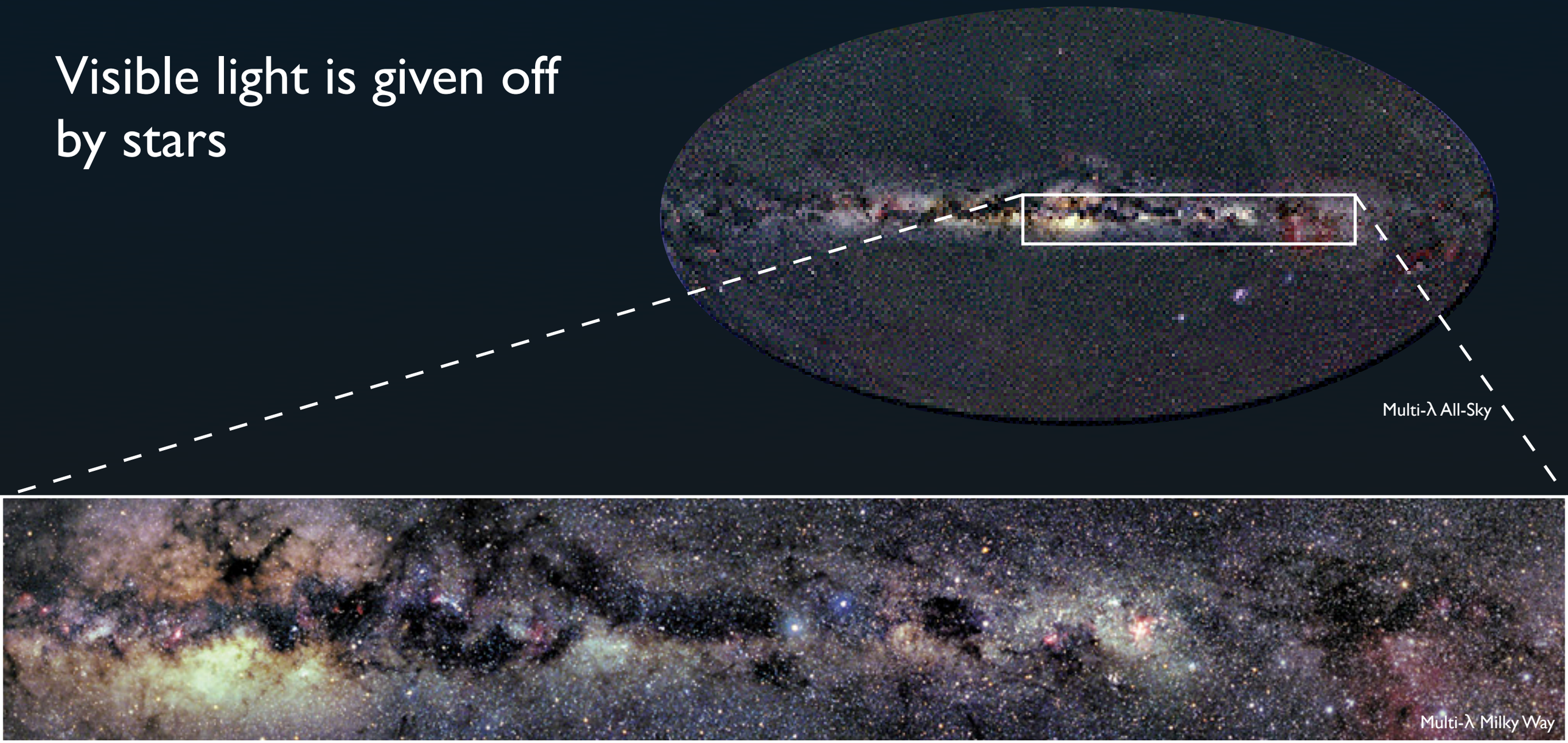
Short-λ IR photons are emitted by stars



Reveals cool main sequence and giant stars in MW's disk and bulge; some dust absorption at shortest λs.

The Visible Sky

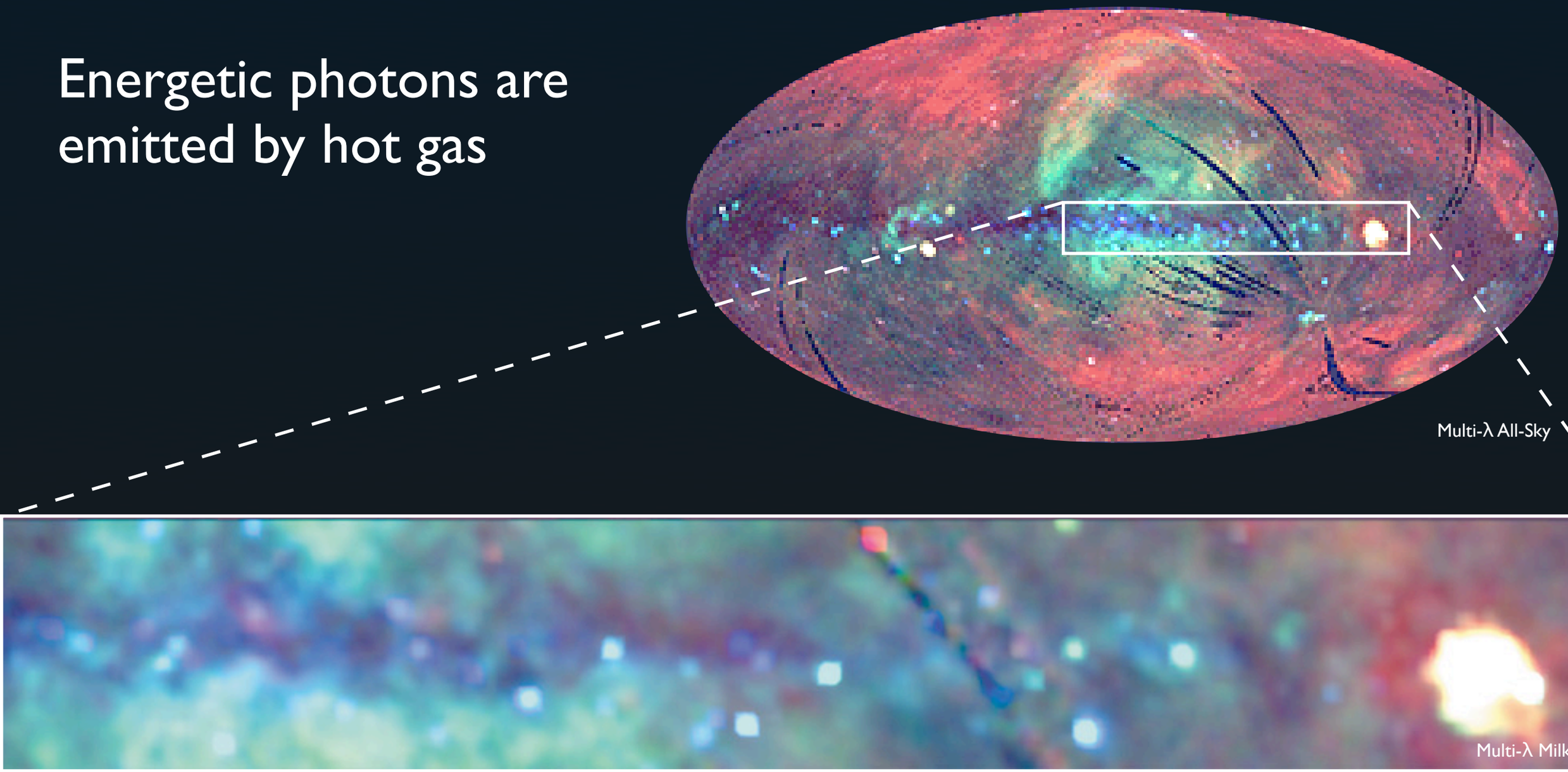
Visible light is given off by stars



Bright areas are star-fields and emission nebulae; dark blobs are clouds of dust and gas.

The X-Ray Sky

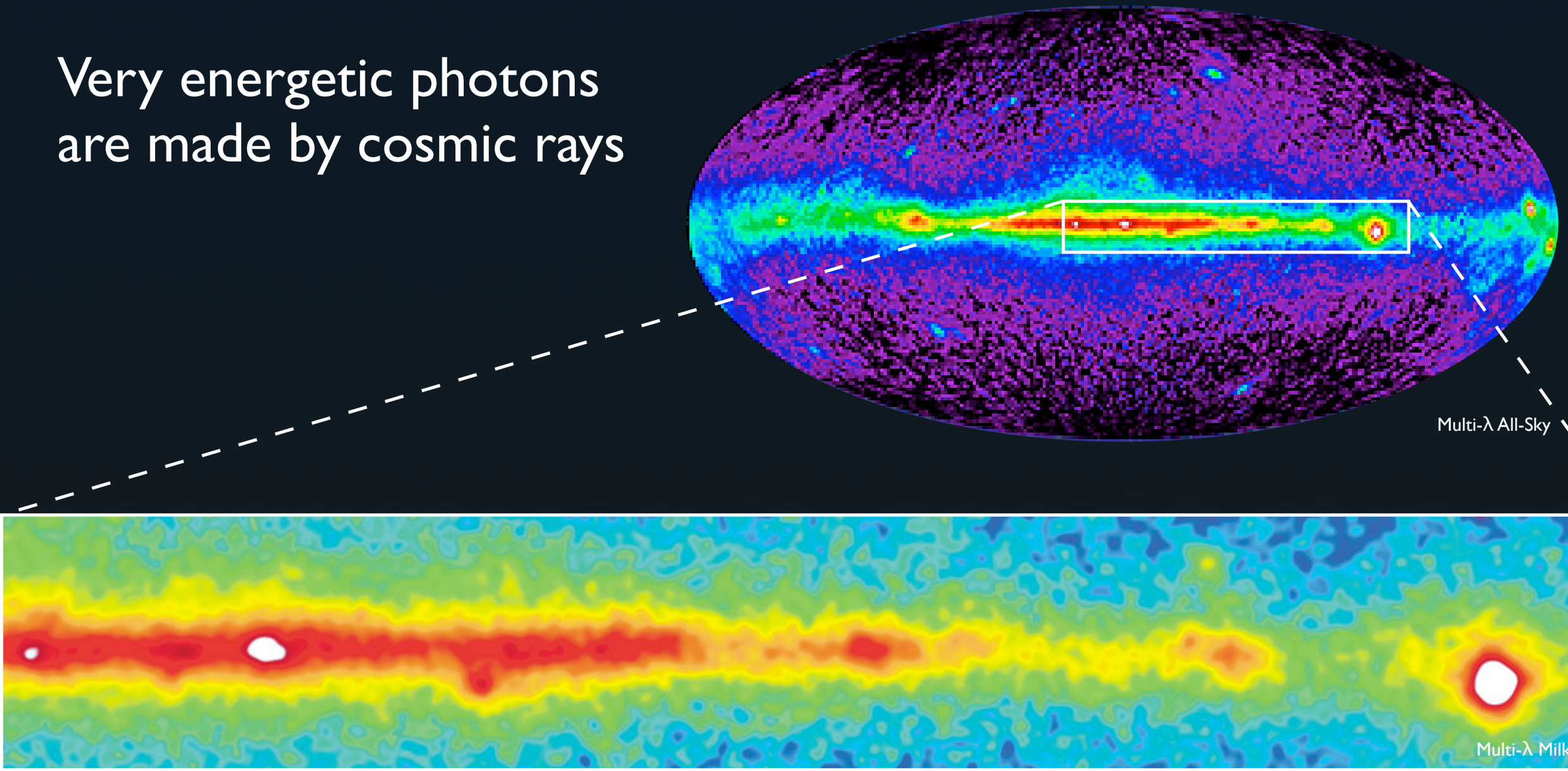
Energetic photons are emitted by hot gas



Traces hot gas bubbles bursting out of the disk; point sources are X-ray binaries.

The Gamma-Ray Sky

Very energetic photons
are made by cosmic rays



Traces high gas densities and supernova remnants —
and also other galaxies with central activity.

Radio

21 cm

cooling

2.6 cm

Far-IR

stars form

Near-IR

Visible

stars die

X-ray

Gamma ray

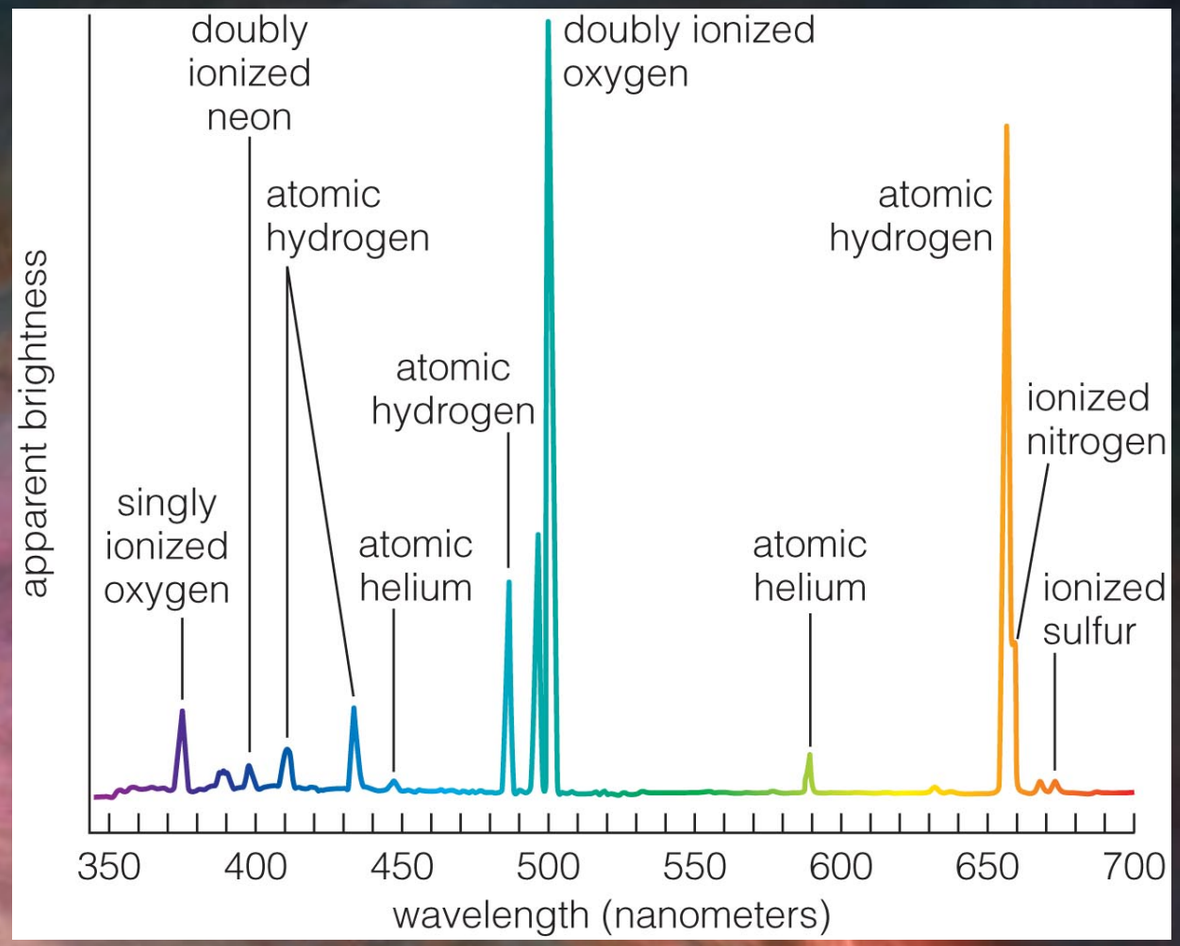
Phases of the Interstellar Medium: Summary

Cold dense gas ($T \approx 30$ K or less, $n \approx 300$ atoms/cm^3 or more). Most gas is in the form of molecules.

Warm gas ($T \approx 8000$ K, $n \approx 1$ atom/cm^3). Most of the gas is in the form of single atoms.

Hot gas ($T \approx 10^5$ K or more, $n \approx 0.001$ atom/cm^3 or less). Atoms are ionized (e^- and nuclei are separated).

Where the Stars Form



Young, hot stars ionize the surrounding gas; glowing **emission nebulae** are signposts of star formation.

Light from somewhat cooler stars is scattered by dust, producing blue **reflection nebulae**.

Galactic Star Formation

All-Sky Panorama

Halo, bulge: blue stars and emission nebulae *absent*

⇒ no star formation

Disk: blue stars and emission nebulae *present*

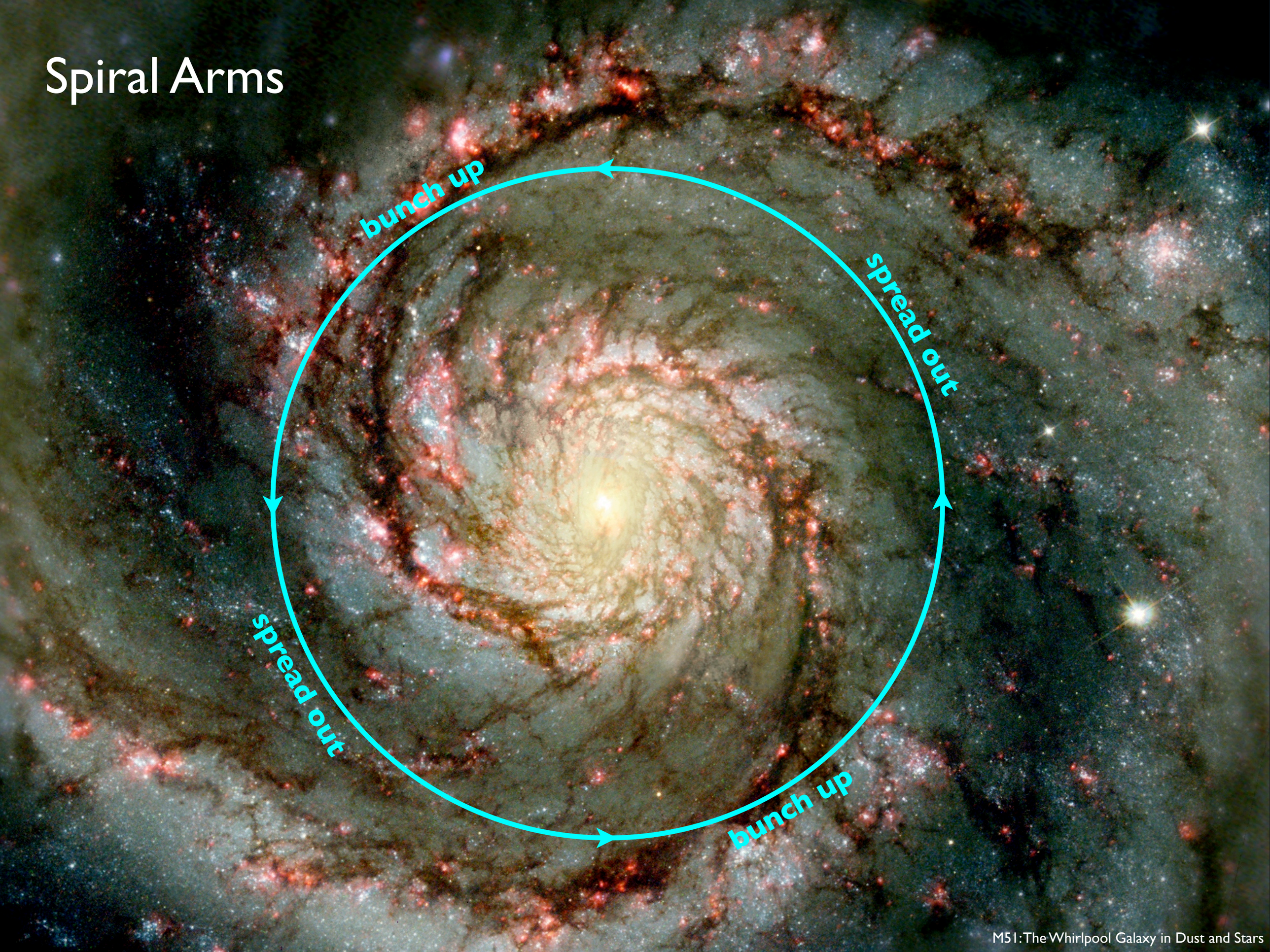
⇒ star formation!

Spiral Arms

Spiral arms are **density waves**; they rotate more slowly than the underlying stars and gas.

M51: The Whirlpool Galaxy in Dust and Stars

Spiral Arms



M51: The Whirlpool Galaxy in Dust and Stars

Spiral Arms

Blue stars

Molecular clouds

Emission nebulae

In the disk, spiral arms are sites of rapid star formation due to compression of gas clouds as they bunch up.

M51: The Whirlpool Galaxy in Dust and Stars

Disk Galaxy Simulation

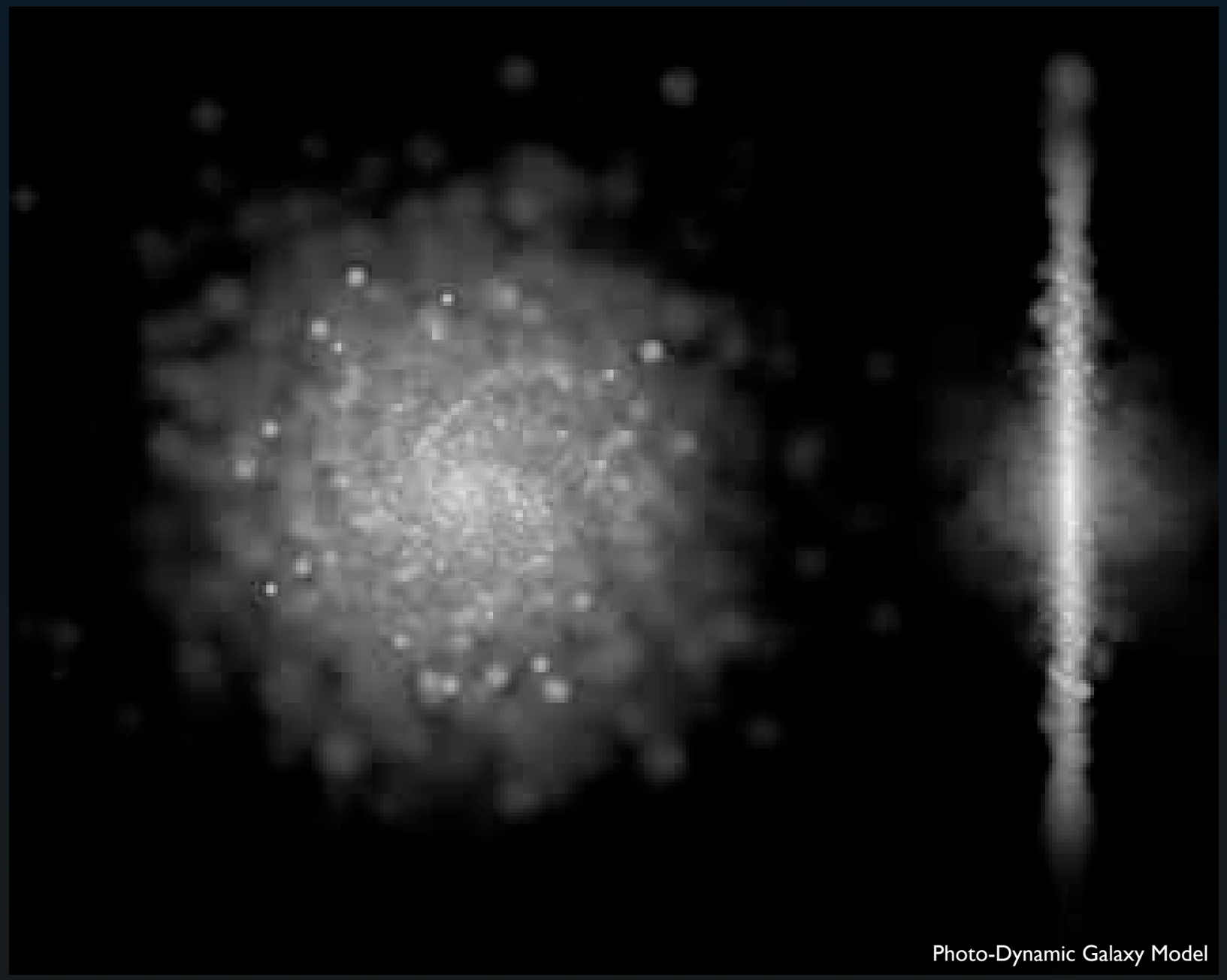


Photo-Dynamic Galaxy Model

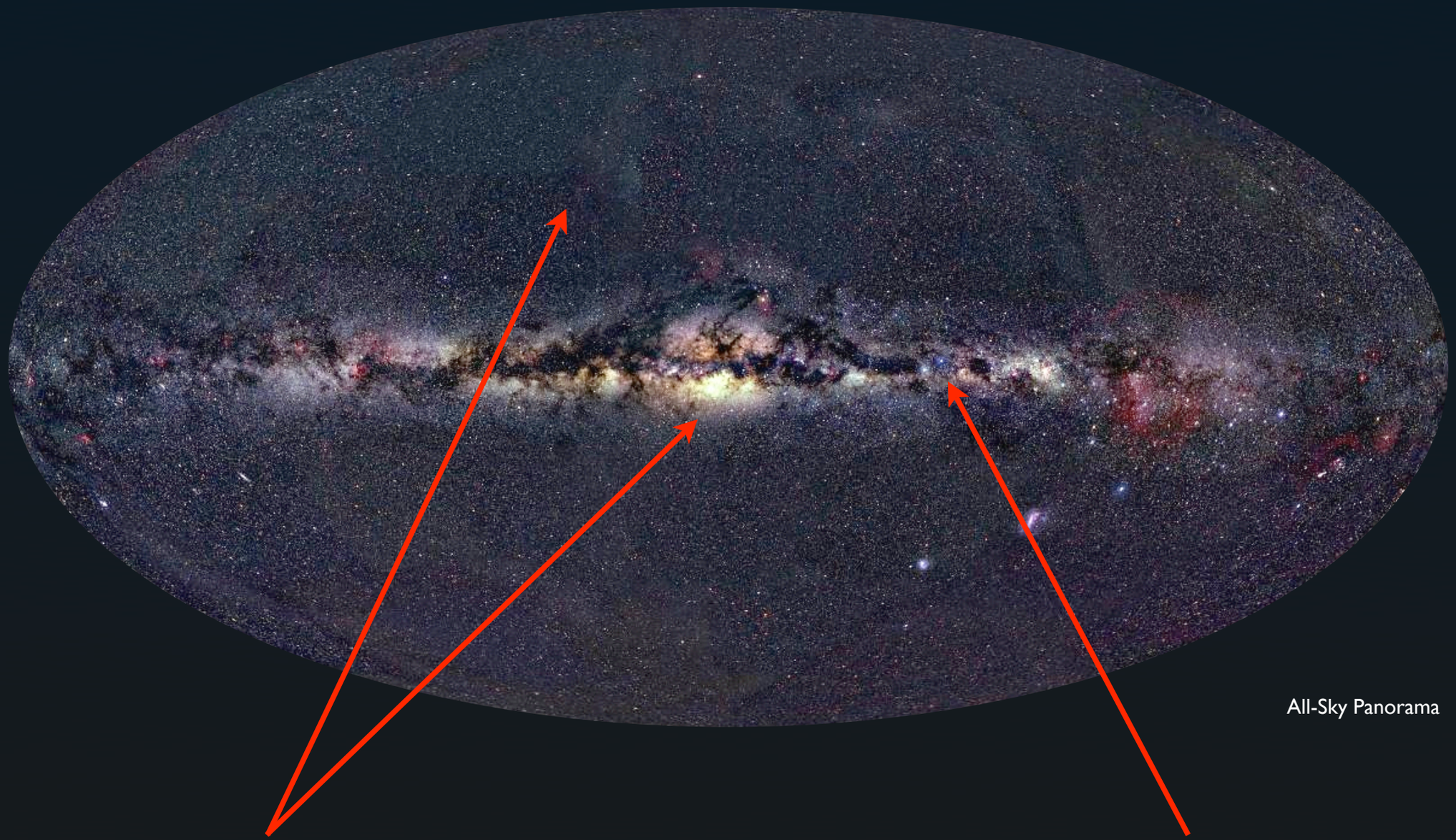
3. ORIGIN AND CENTER

a. The Collapse Scenario

b. Hierarchical Galaxy Formation

c. The Milky Way's Center

Stellar Populations

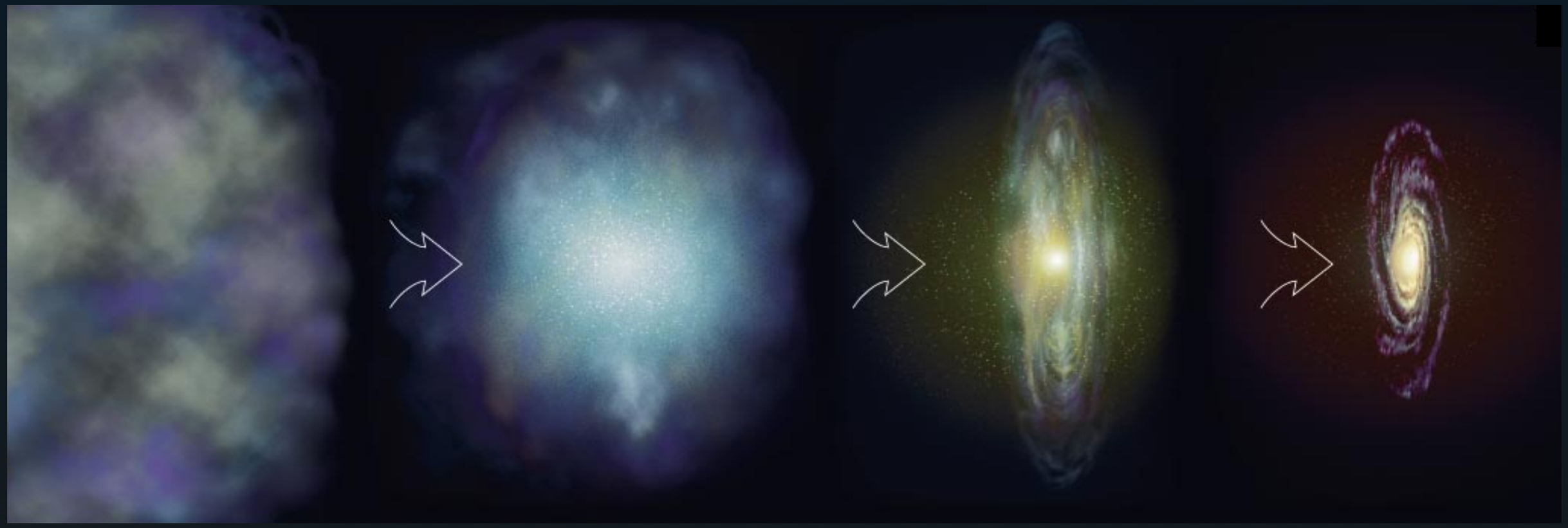


All-Sky Panorama

Halo, bulge: Population II
10 — 12 Gyr old; very low ‘metal’ content

Disk: Population I
0 — 10 Gyr old; near-Solar ‘metal’ content

The Collapse Scenario



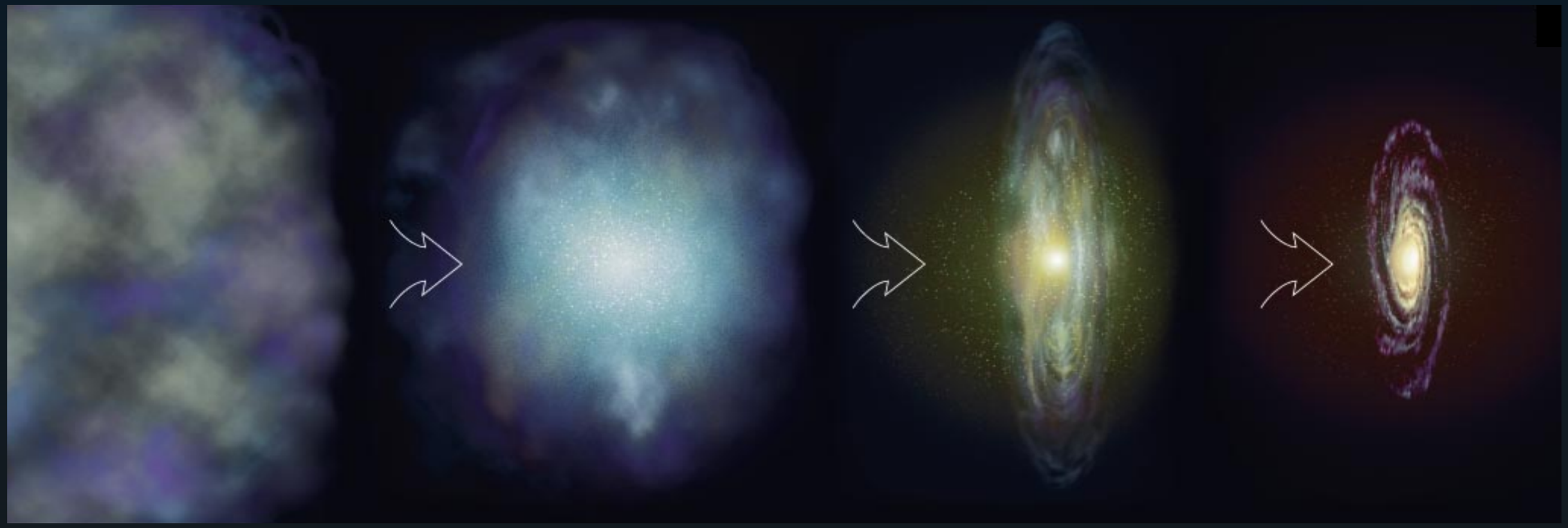
A giant gas cloud cools and collapses . . .

begins forming stars . . .

settles into a thin disk . . .

and continues forming stars.

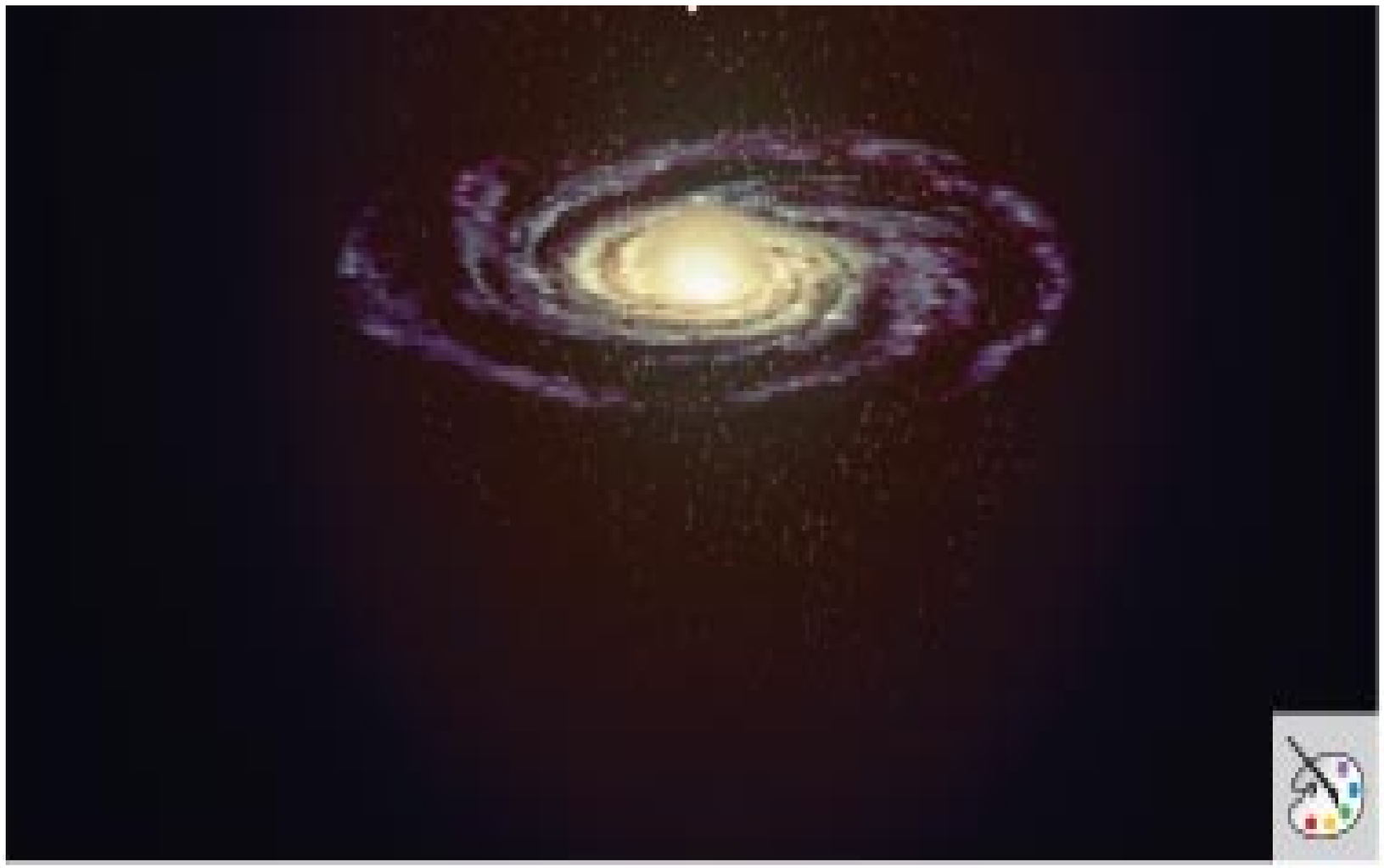
Origin of Stellar Populations



Stars formed early in the collapse have random, plunging orbits and low metal content ⇒ **Population II** (halo)

Stars formed later in the collapse are centrally concentrated and have intermediate metal content ⇒ **Population II** (bulge)

Stars formed after the gas settles into a disk have circular orbits and high metal content ⇒ **Population I** (disk)



Warning: This model is oversimplified.

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

Problems With the Collapse Scenario

1. Outer halo should be older and have less metals.

   — globular clusters show no clear trend with distance

2. Collapse to 1% of initial size needed to spin up disk.

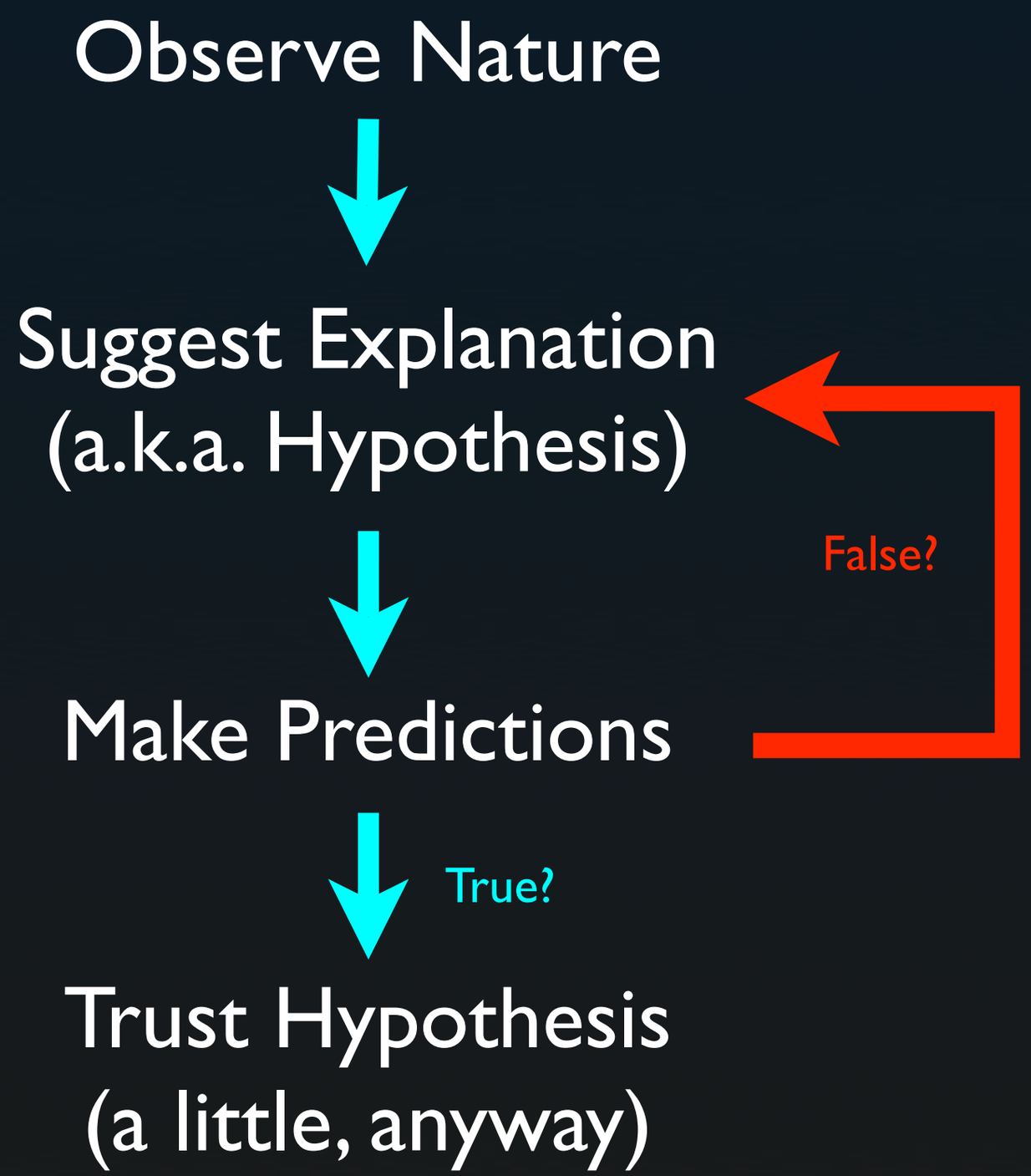
   — time required is comparable to age of universe

3. Expect metals to build up gradually in disk.

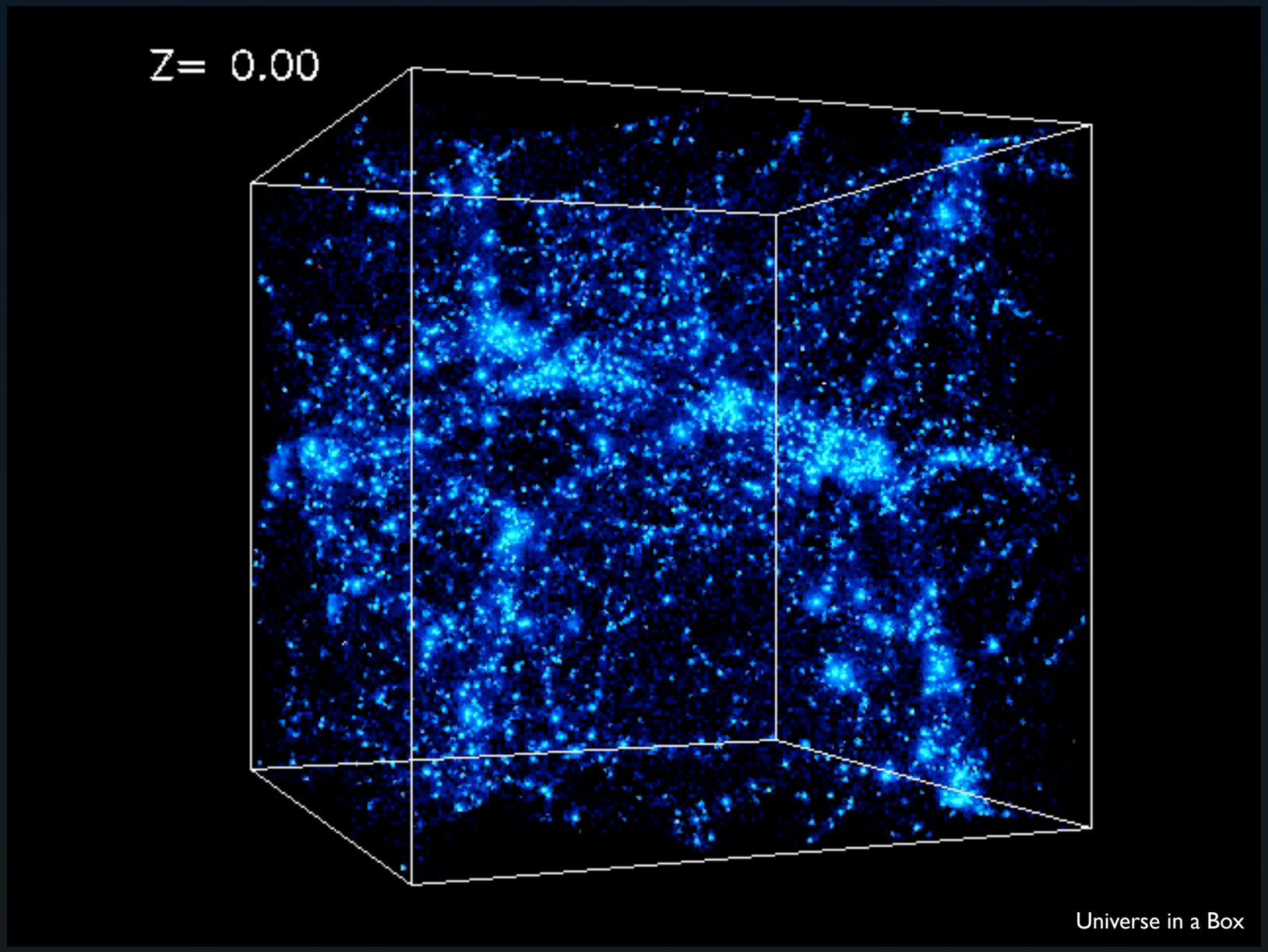
   — oldest disk stars nearly as metal-rich as the Sun

Does not address role or structure of dark halo!

Scientific Method

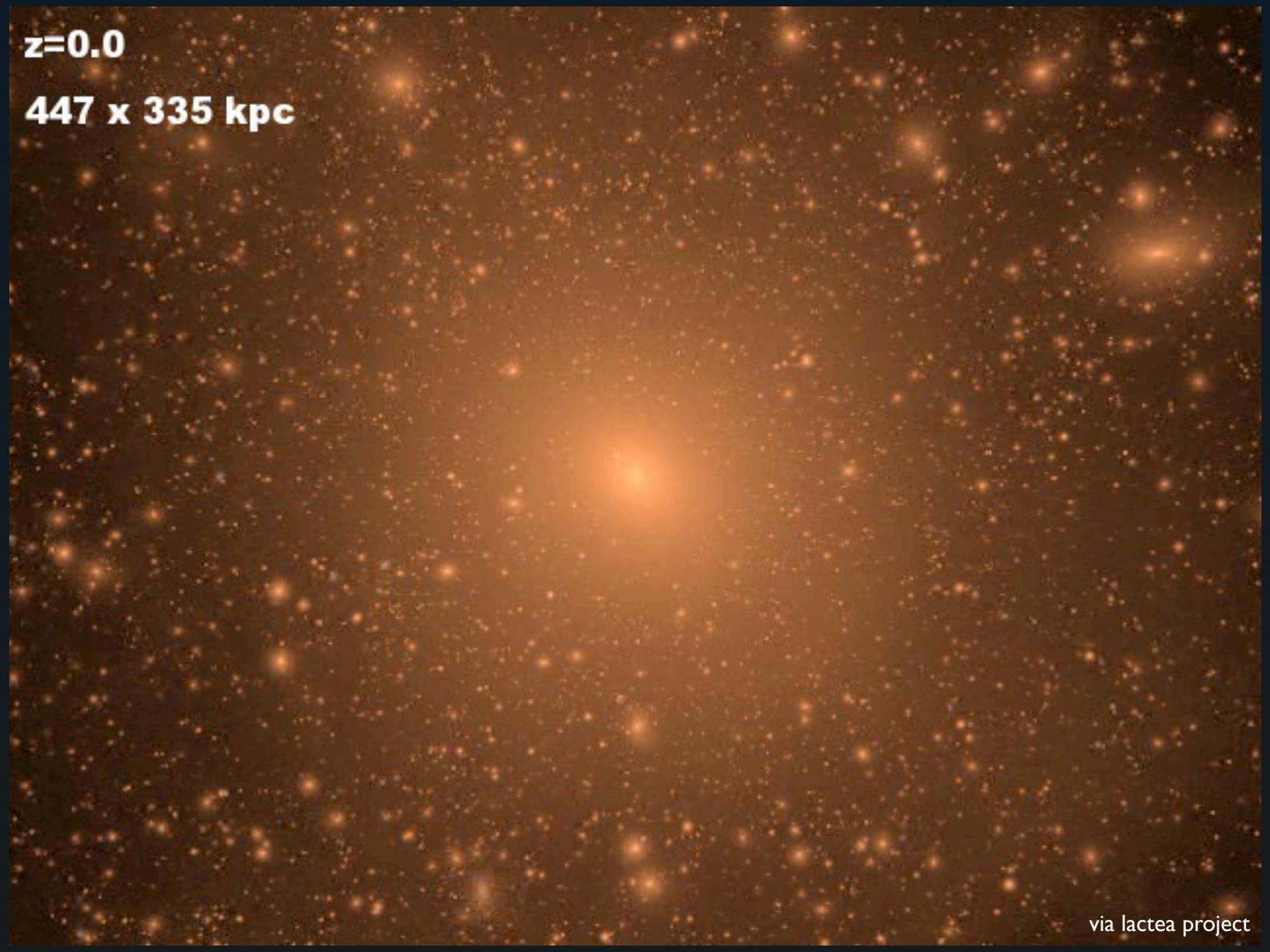


Hierarchical Galaxy Formation

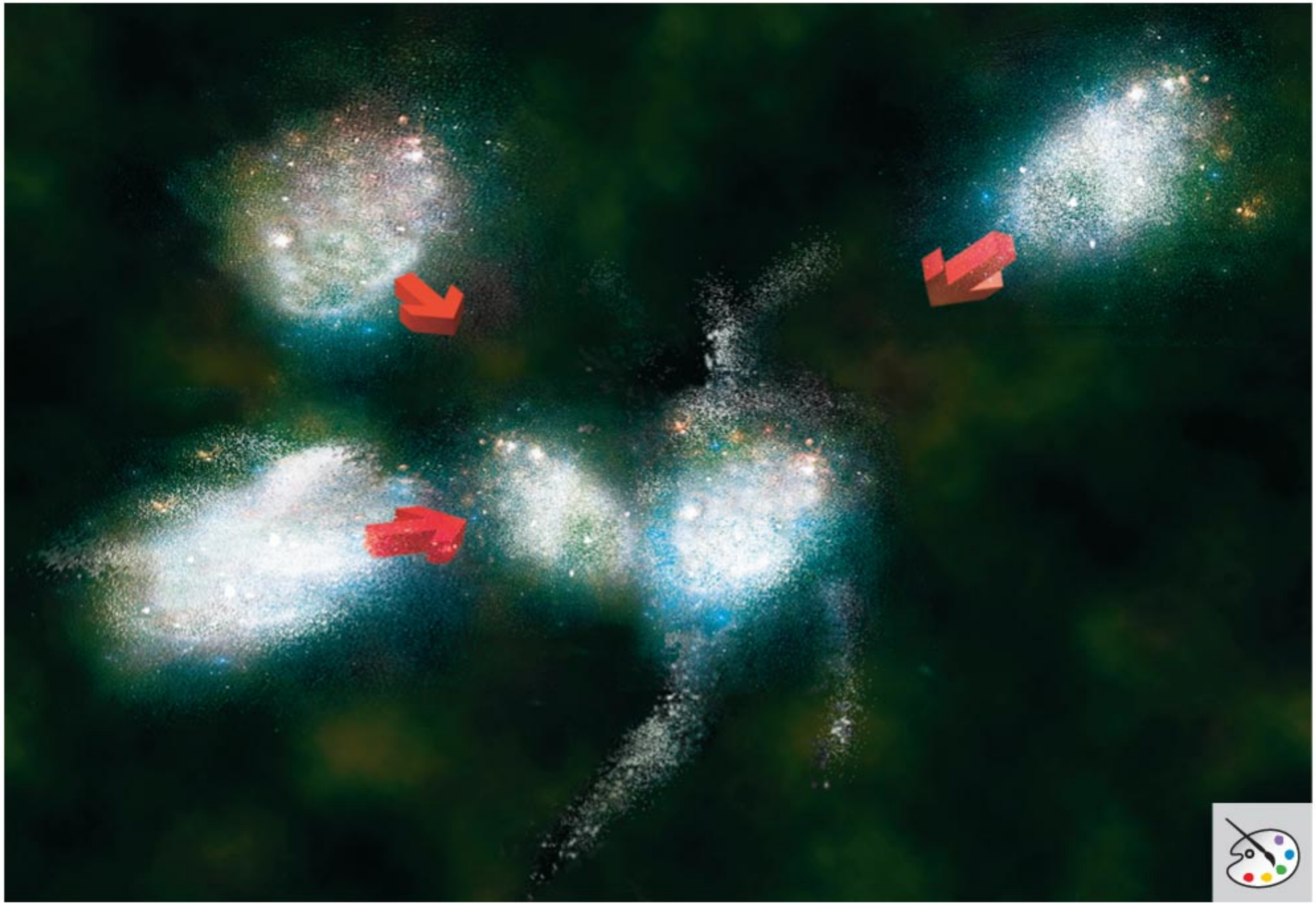


Clumps of dark matter fall together and merge, building up larger and larger objects over time.

Formation of Milky Way's Dark Halo

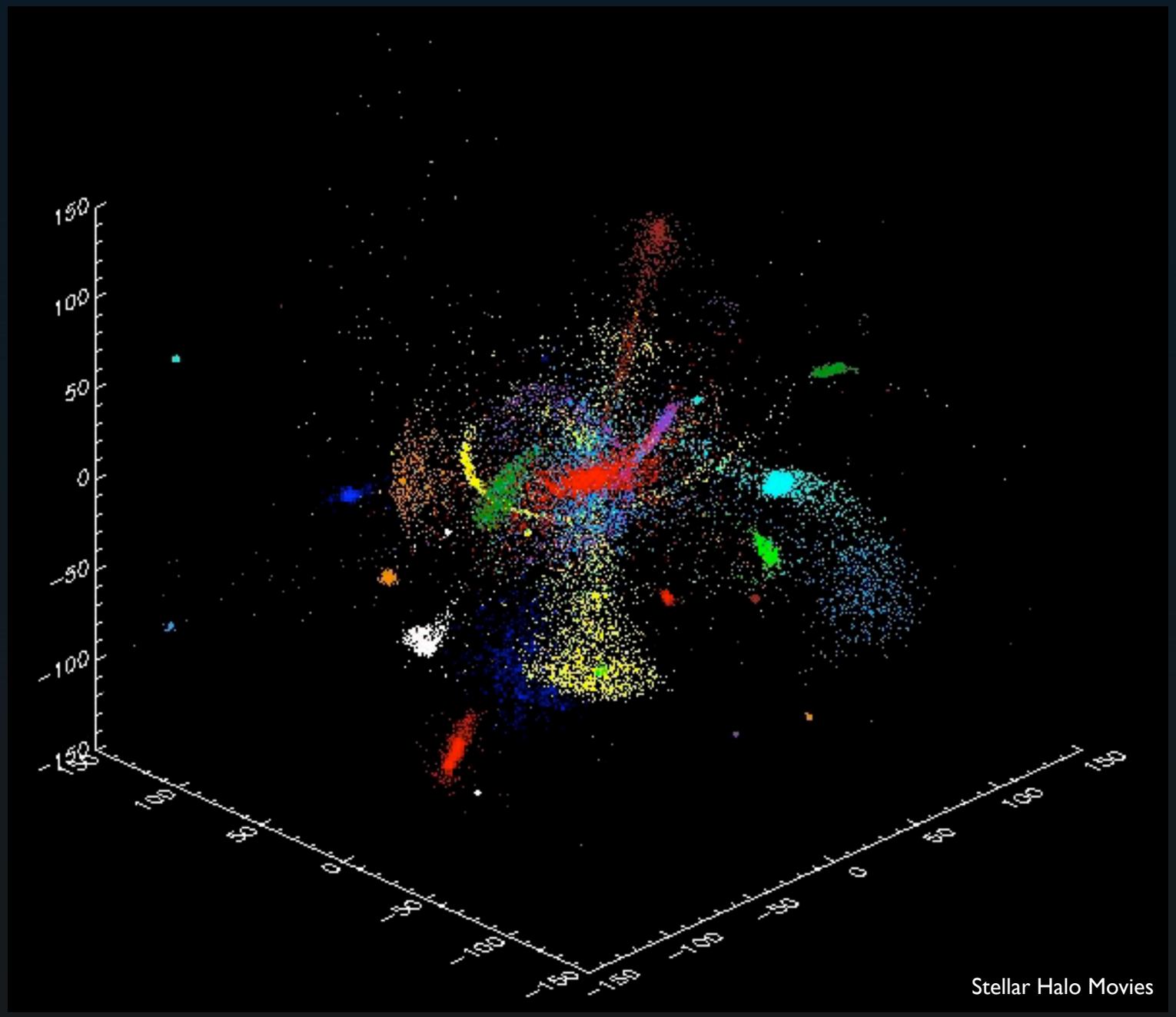


Builds up by repeated mergers of smaller dark halos.



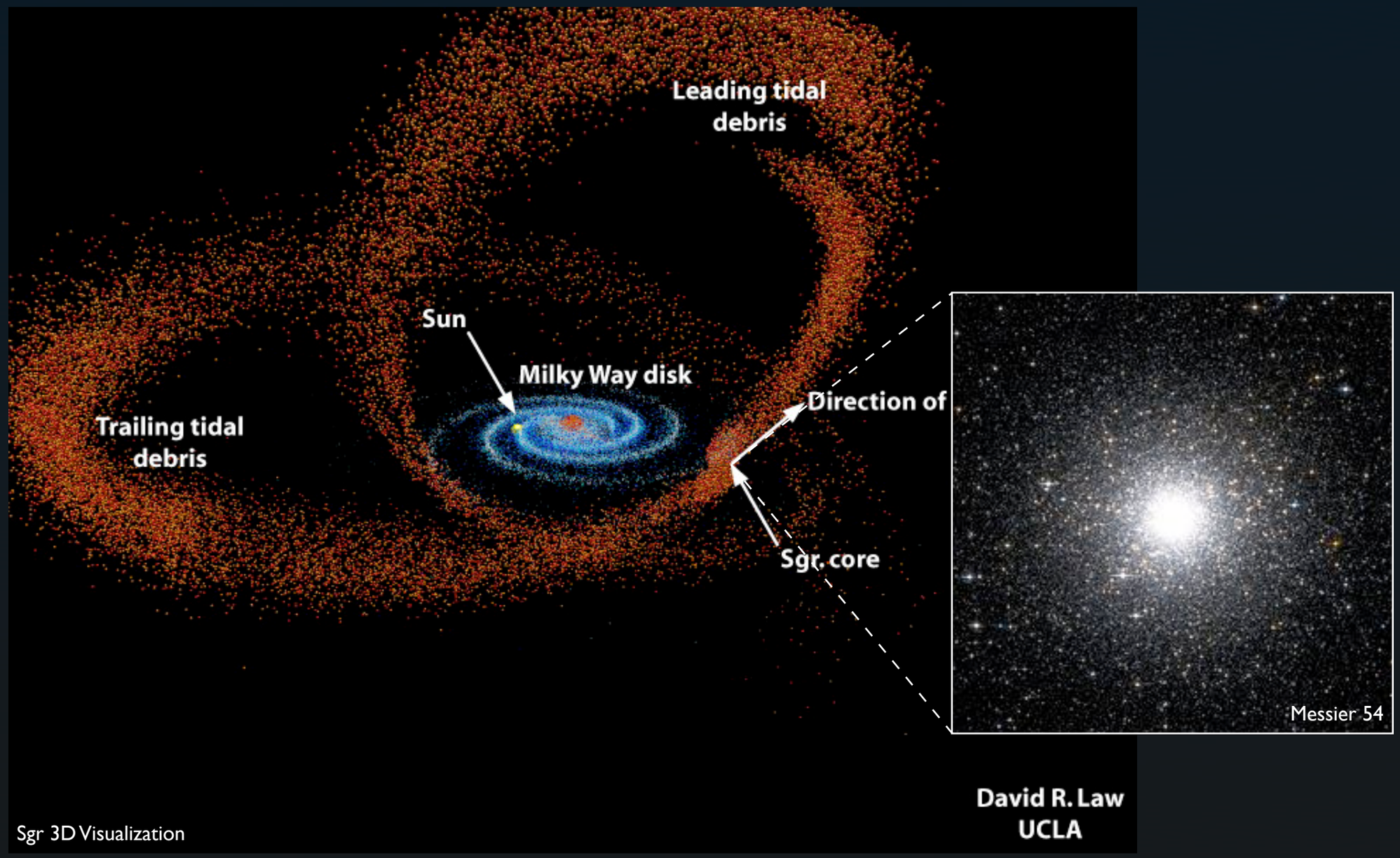
Detailed studies: Halo stars formed in clumps that later merged.

Stellar Halo Formation



Halo stars form in dwarf galaxies which are later torn apart by Milky Way's gravitational field.

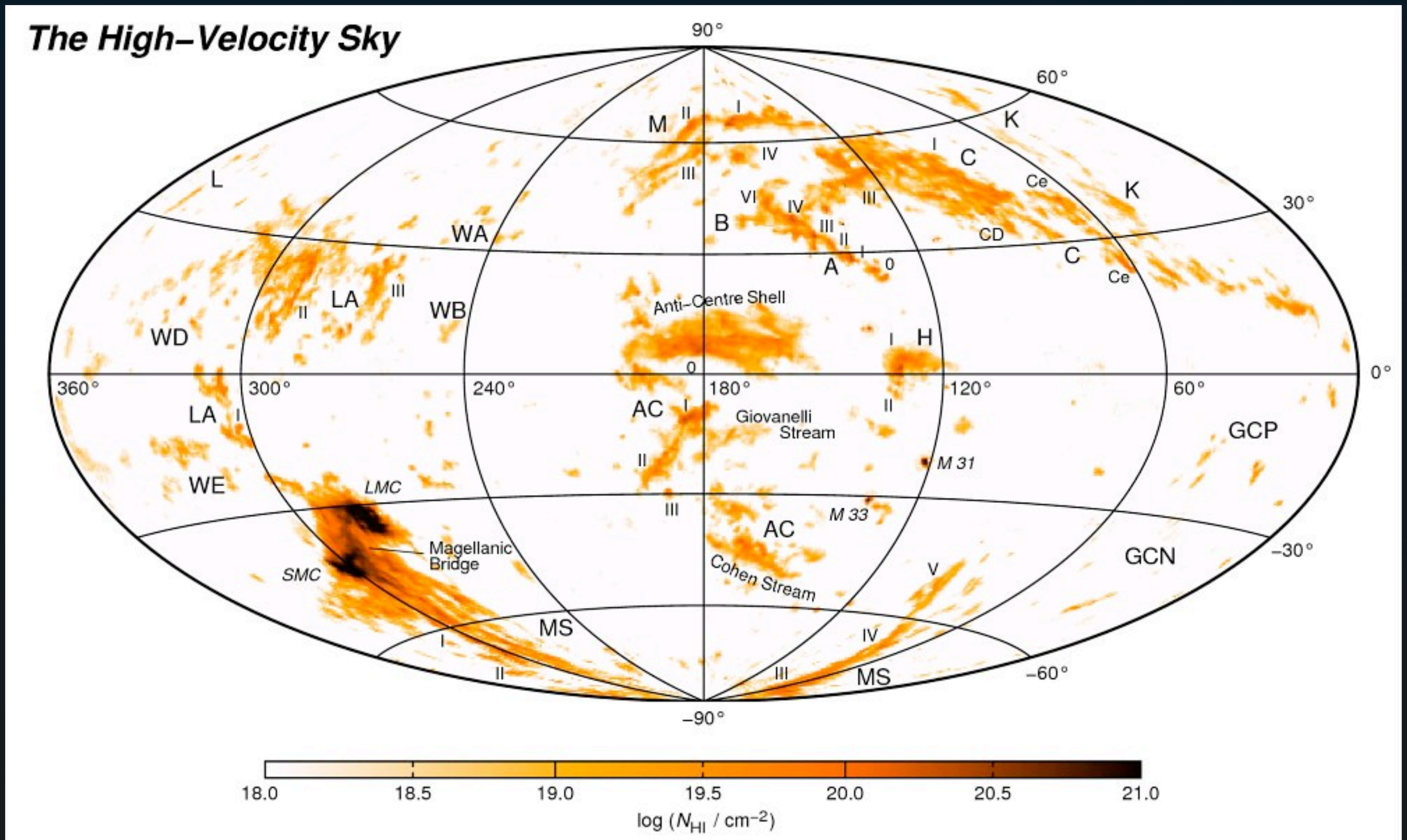
Disruption of the Sagittarius Dwarf Galaxy



Mergers are *still* adding long streams of stars to the Milky Way's stellar halo!

Disk Formation

Galactic disks form by infall of gas; they're disrupted by violent galaxy mergers.



An all-sky map of high-velocity clouds

Infalling gas is detected by 21-cm radio observations.

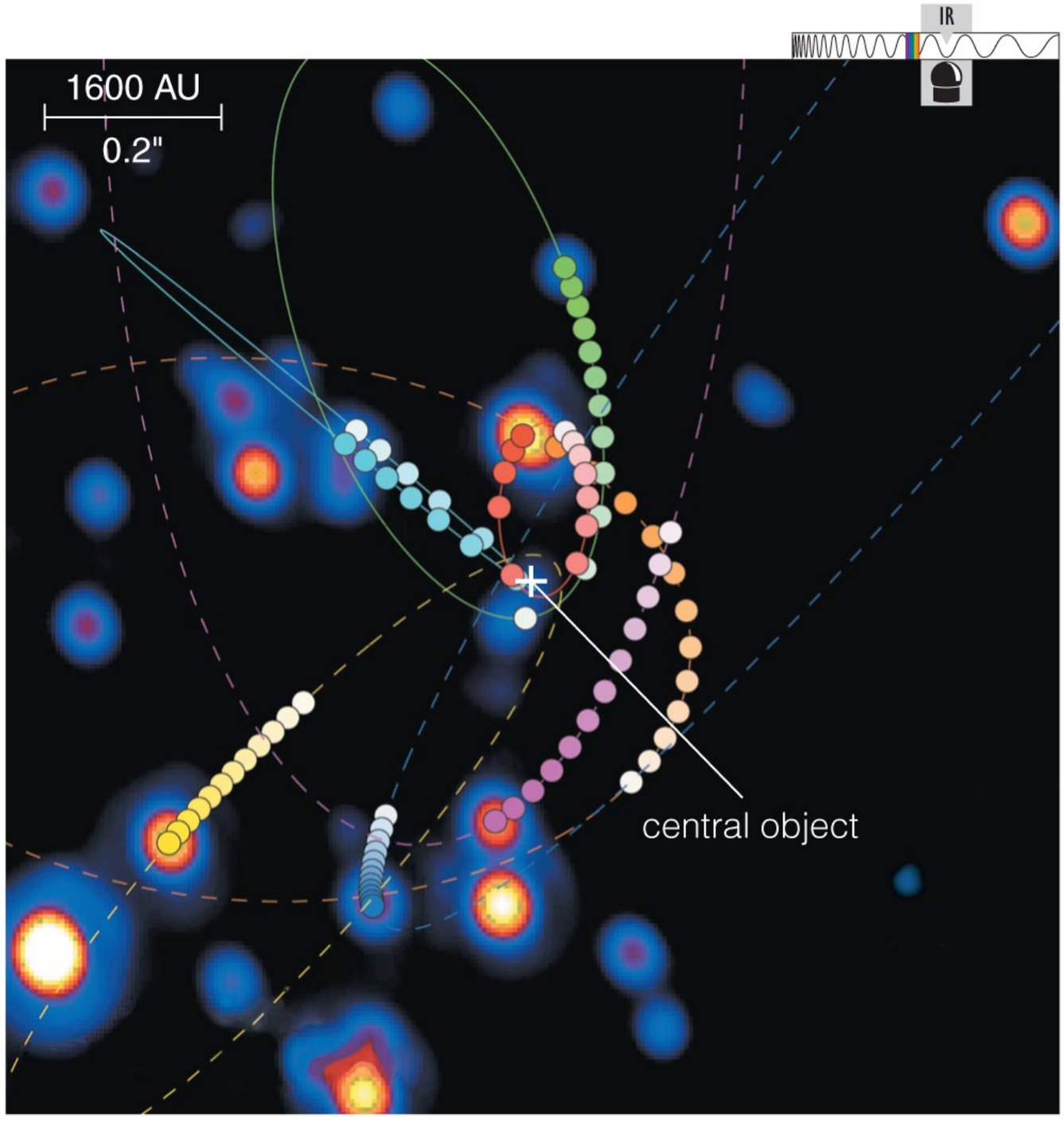
Hierarchical Galaxy Formation: Successes

Accretion of multiple dwarf galaxies explains 'mixed-up' properties of Milky Way's stellar halo.

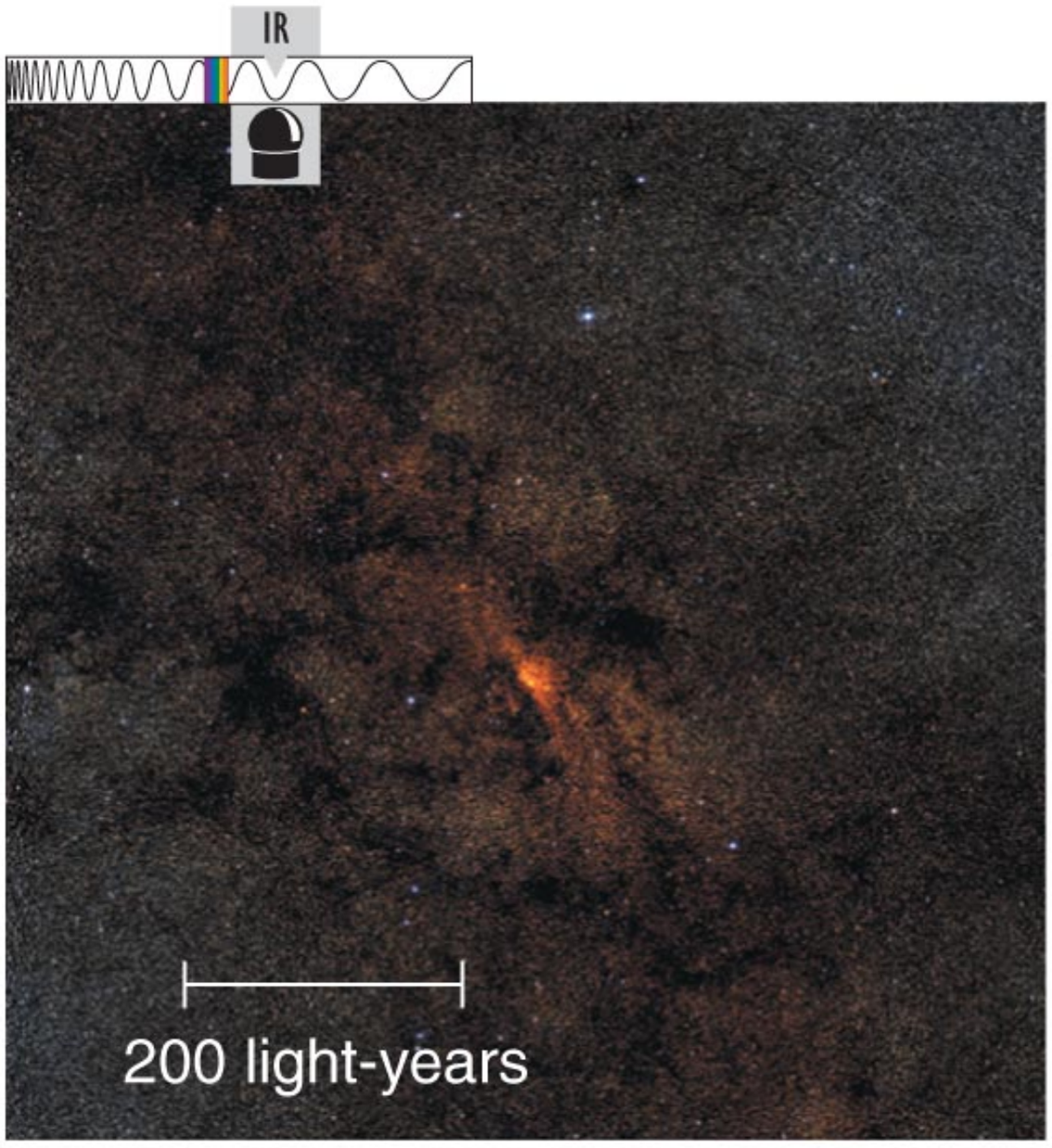
Disks form at centers of dark halos; problems with extreme and very slow collapse are resolved.

Continuous infall of gas allows disk to build up near-solar metal abundance early.

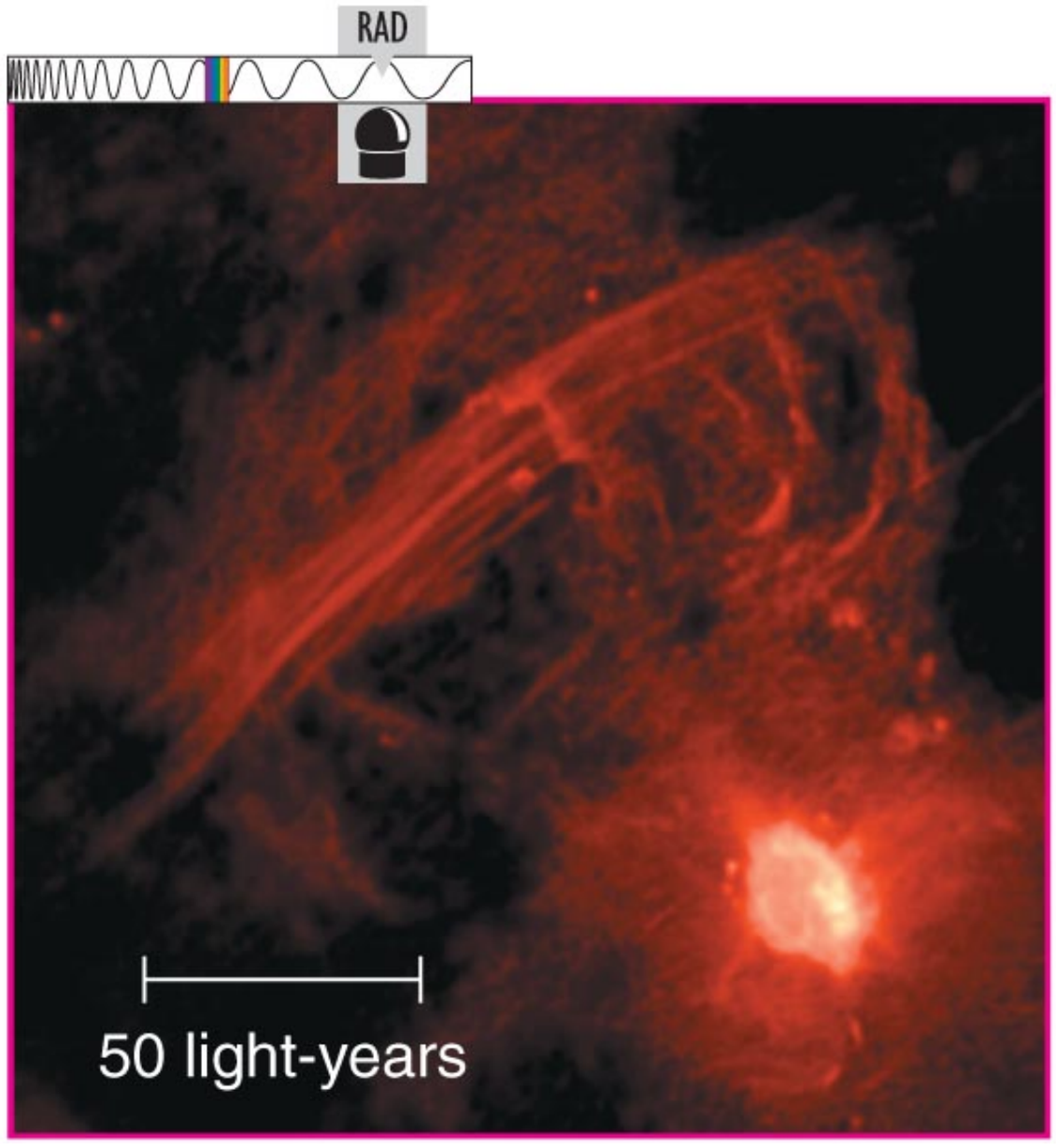
What lies in the center of our galaxy?



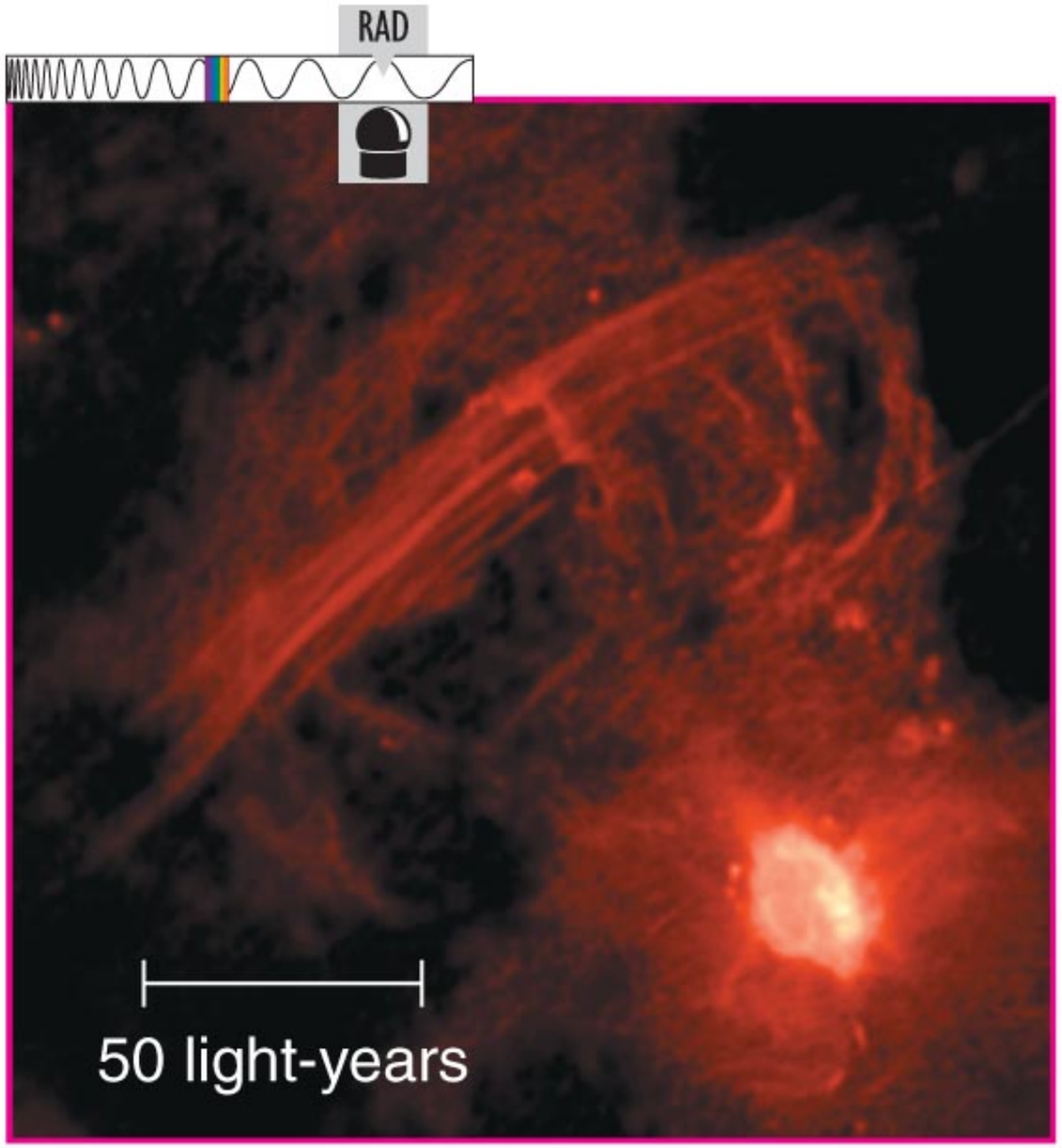
Infrared light from center



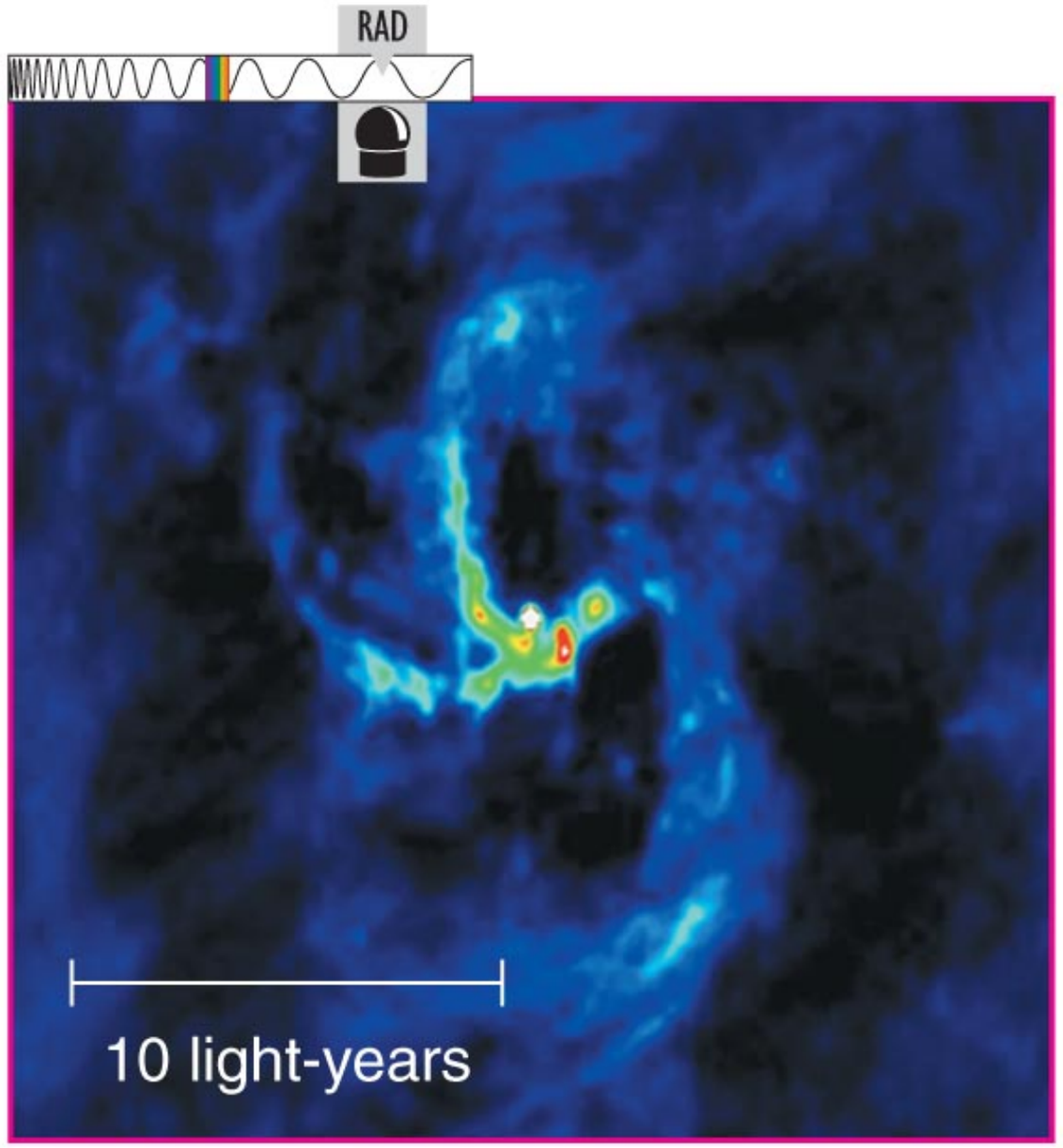
Radio emission from center



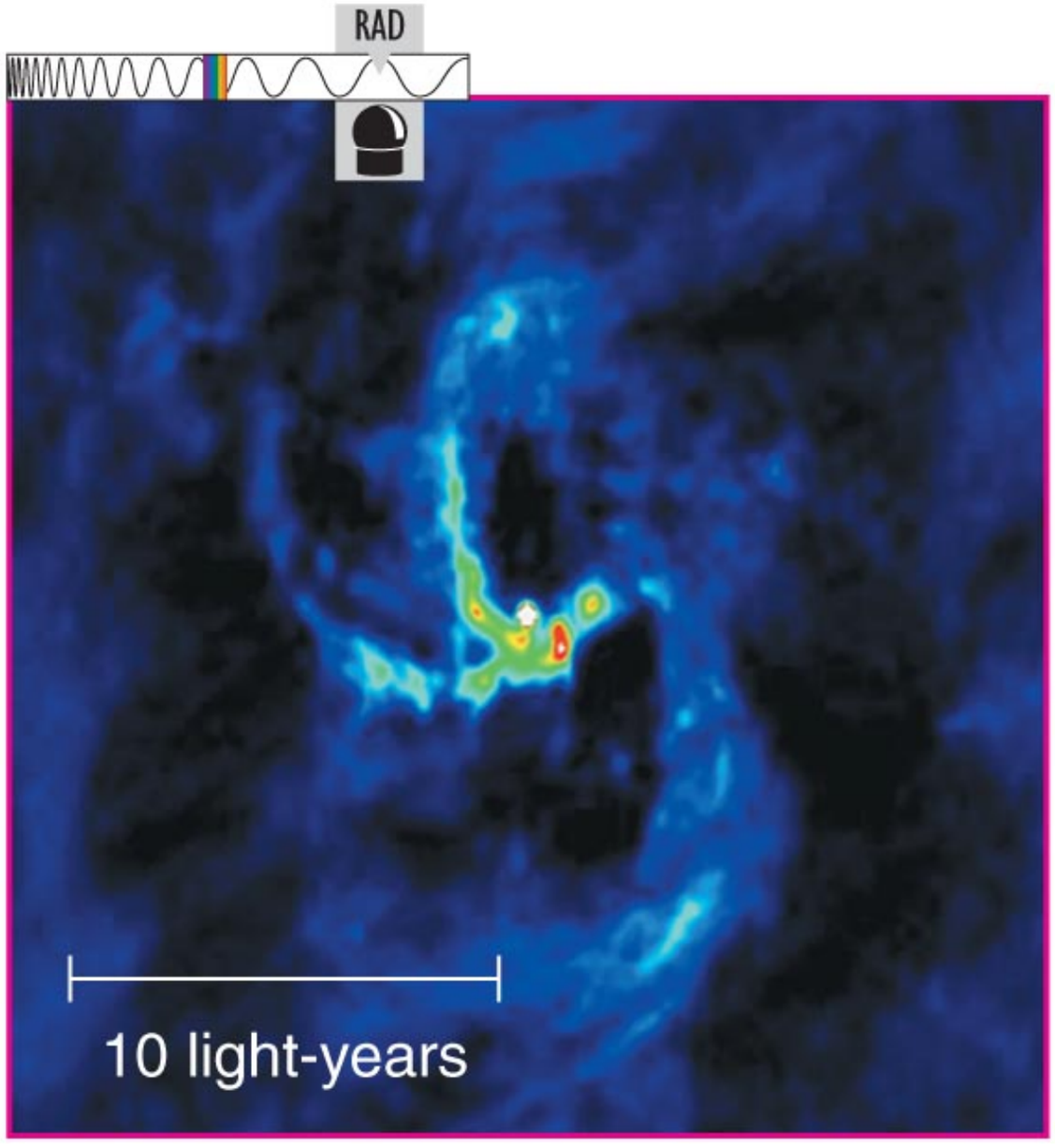
Radio emission from center



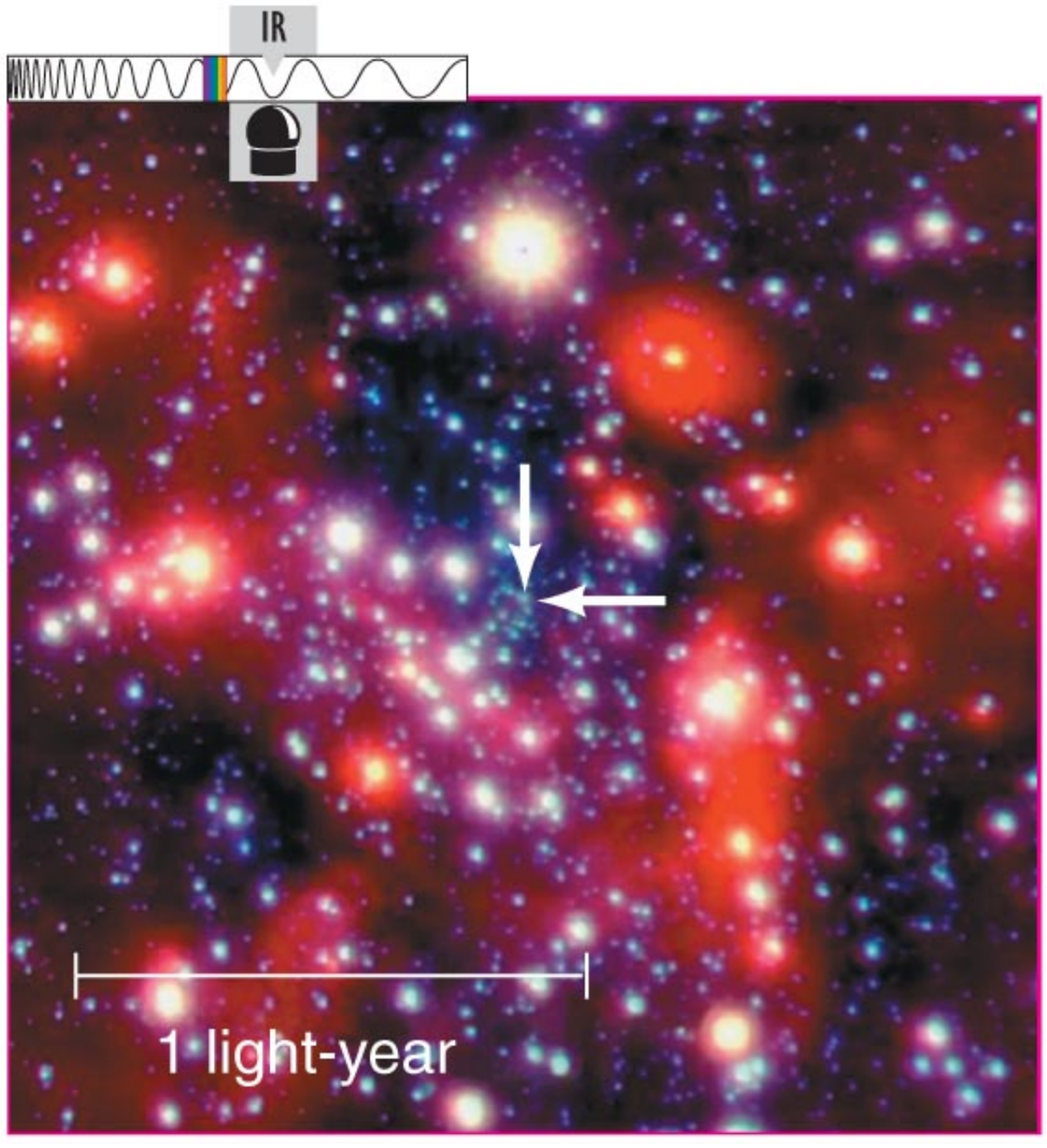
Swirling gas near center

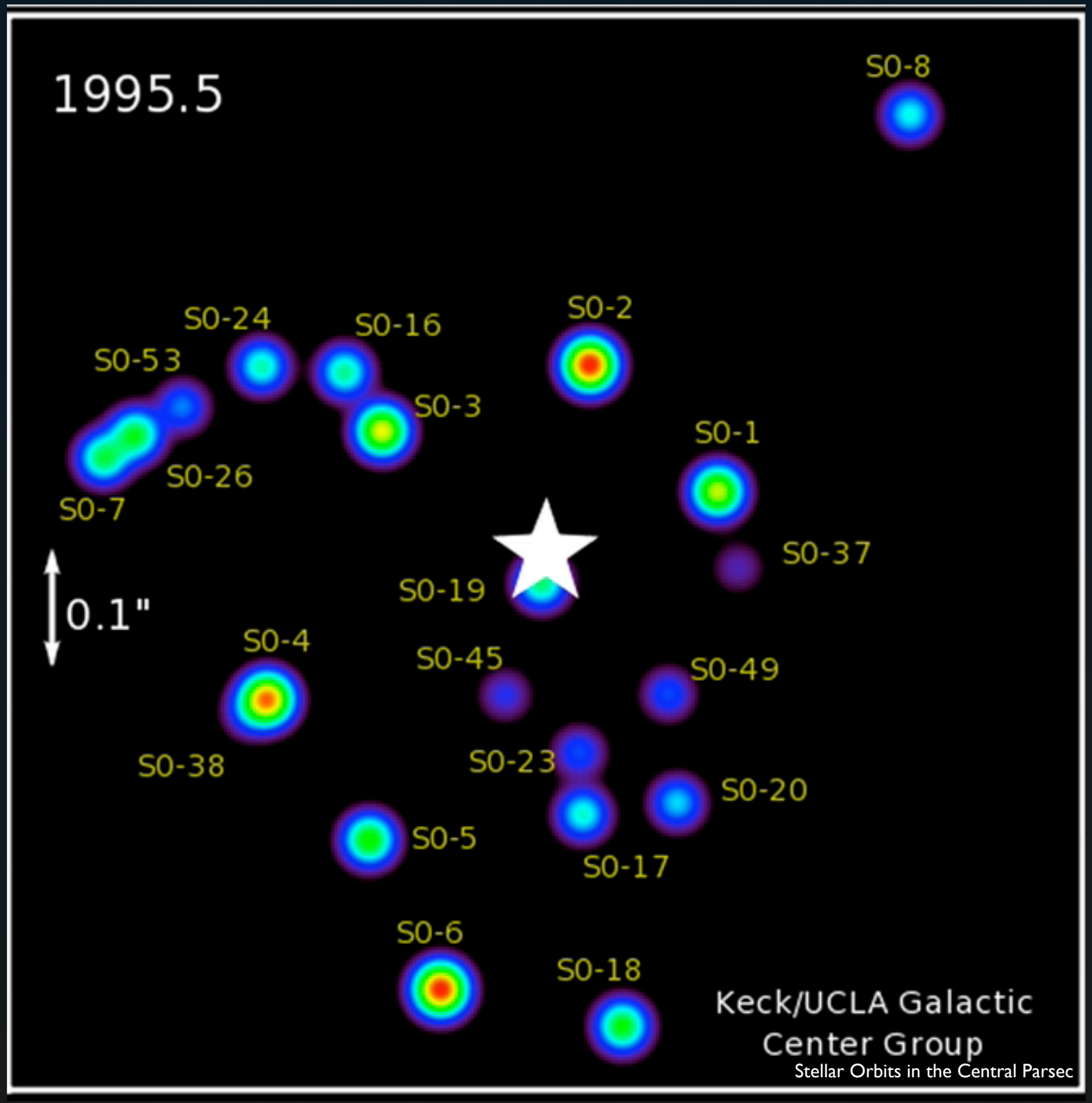


Swirling gas near center

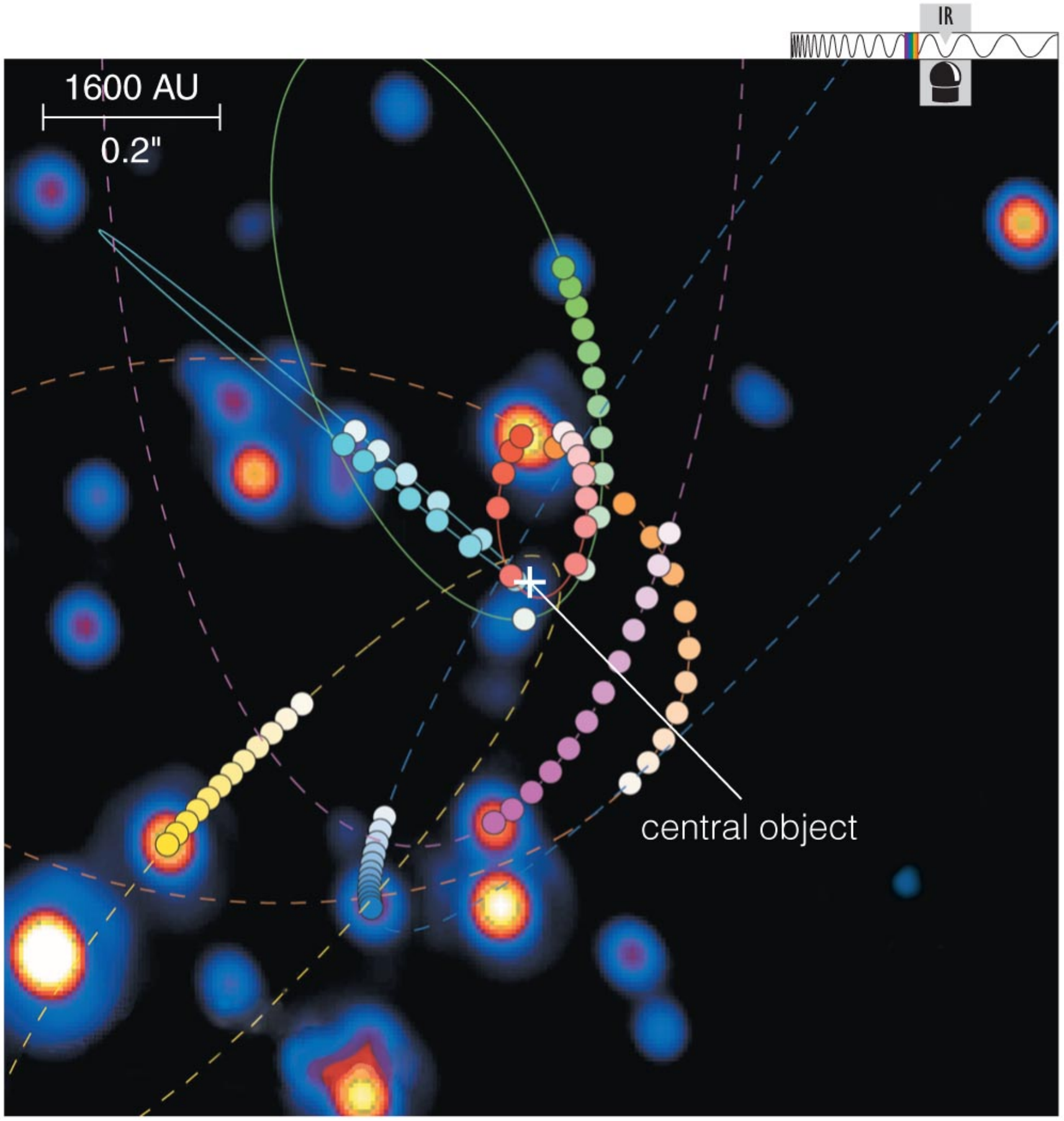


Orbiting stars near center



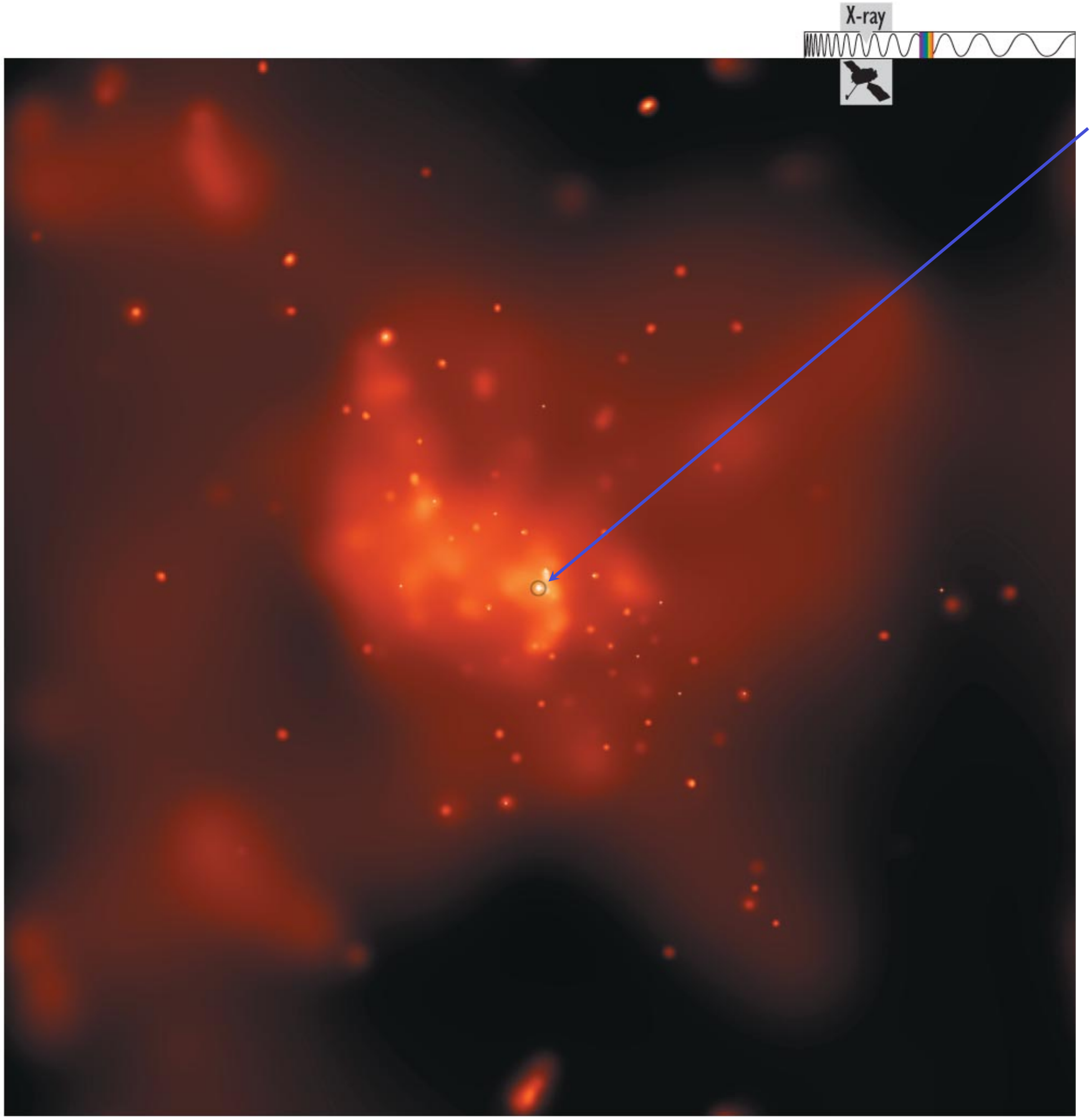


Stellar Orbits in the Central Parsec



Stars appear to be orbiting something massive but invisible …
a black hole?

Orbits of stars indicate a mass of about 4 million M_{sun}.



X-ray flares from galactic center suggest that tidal forces of suspected black hole occasionally tear apart chunks of matter about to fall in.