# The Milky Way's: Disk, Bulge, and Halo

Luminous components of the Galaxy:

**The disk**: a rotating disk of stars and gas. Home of the Sun, young star clusters, on-going star formation. Range of metallicity, but mostly solar or a bit less.

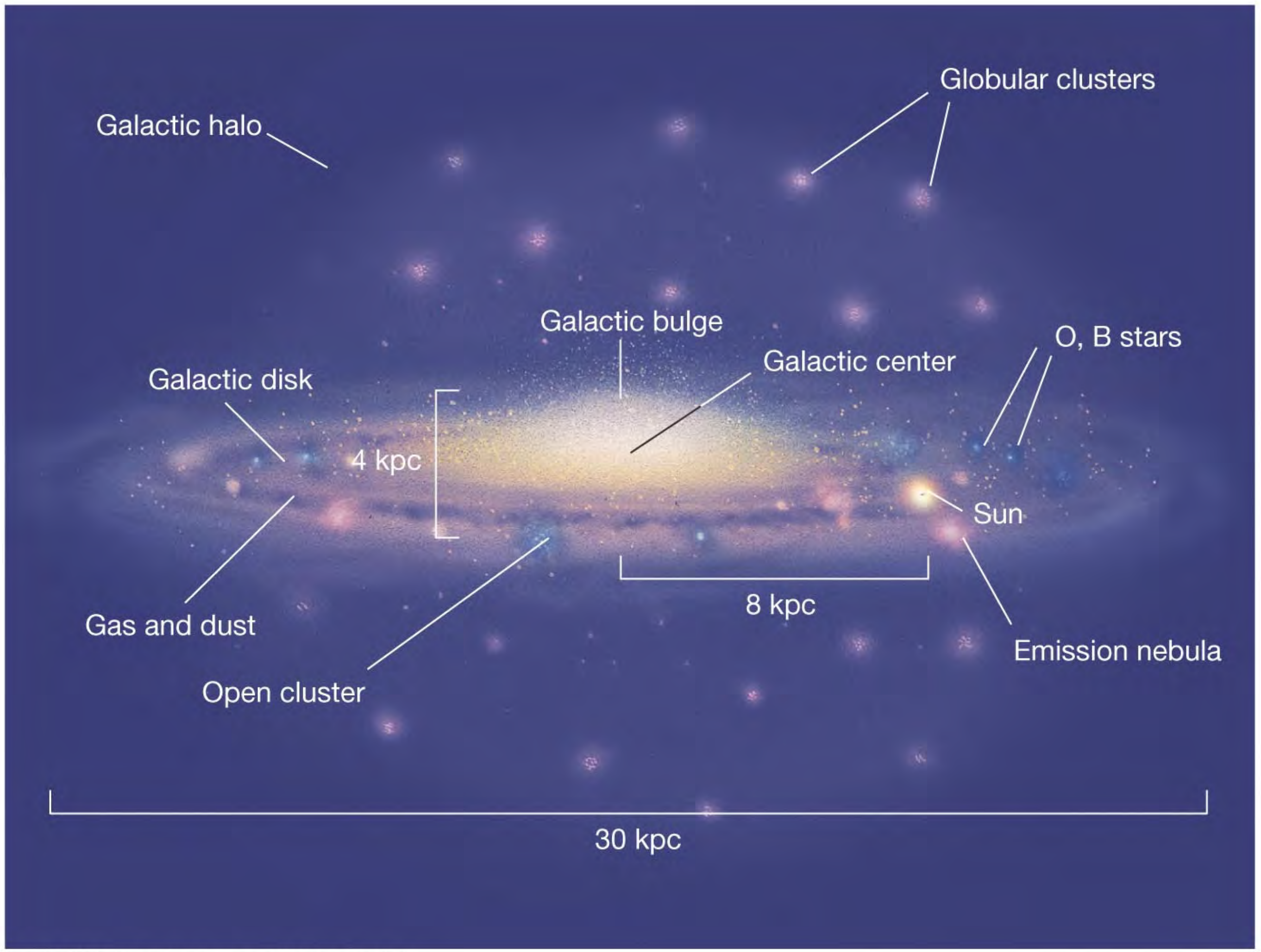
$$L_{B,disk} \approx 2 \times 10^{10} \, L_{\odot}$$

**The bulge**: inner part of the galaxy, generally older, wide range of metallicity (including metal-rich). Slower net rotation, some globular clusters.

$$L_{B,bulge} \approx 2 \times 10^{9} \, L_{\odot}$$

**The stellar halo**: Very extended, very little rotation, older, metal-poor stars and globular clusters.

$$L_{B,halo} \approx 1 - 2 \times 10^{9} \, L_{\odot}$$

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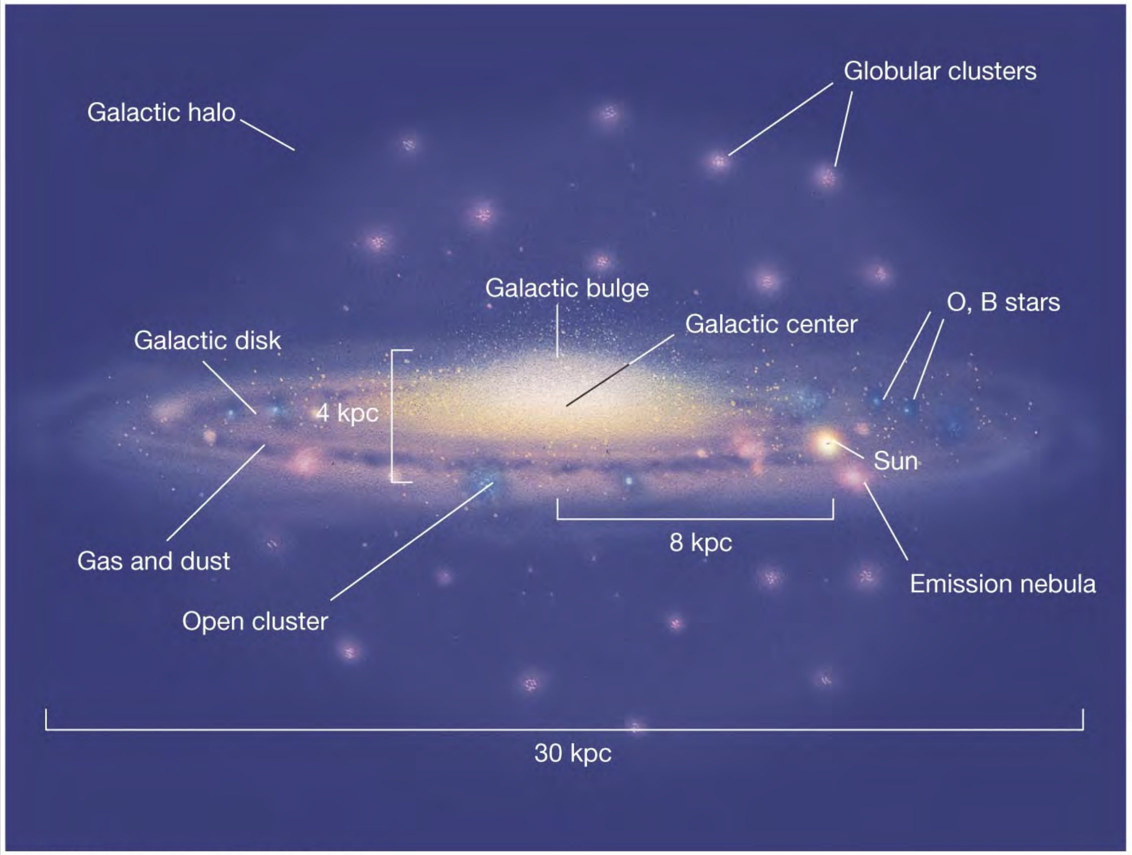
## Stellar Populations in the Milky Way

1940s: Walter Baade develops the idea of distinct stellar populations in the Milky Way.

### Population I
- higher metallicity stars: [Fe/H] > -1.0
- stars in the disk (including the Sun!)
- open clusters

### Population II
- low metallicity stars: [Fe/H] < -1.0
- stars in the Milky Way's halo
- globular clusters

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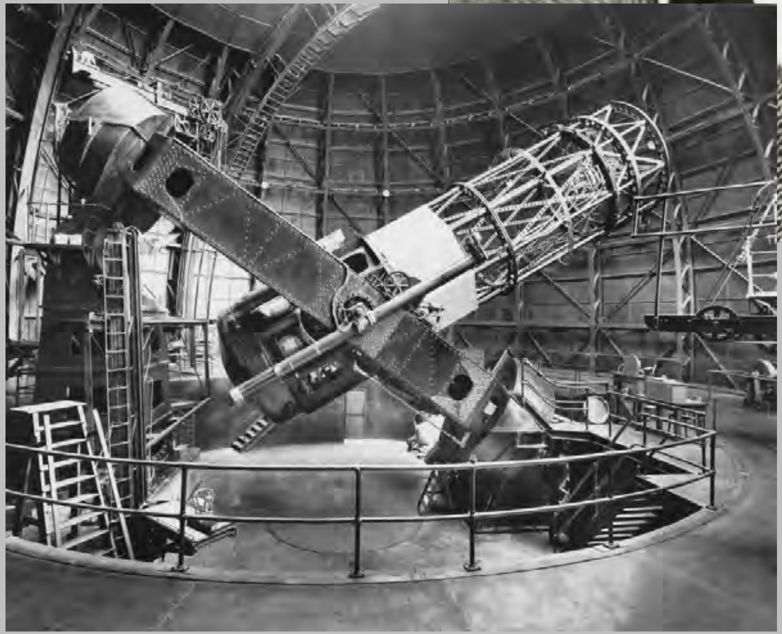
Walter Baade (1893-1960)



100-inch telescope at Mt Wilson

## The Disk of the Milky Way

Rotating disk of stars and gas. The density of stars drops roughly exponentially as you move out in radius, or up/down out of the disk plane:

$$\rho(R,z) = \rho_0 e^{-|z|/z_0} e^{-R/h}$$

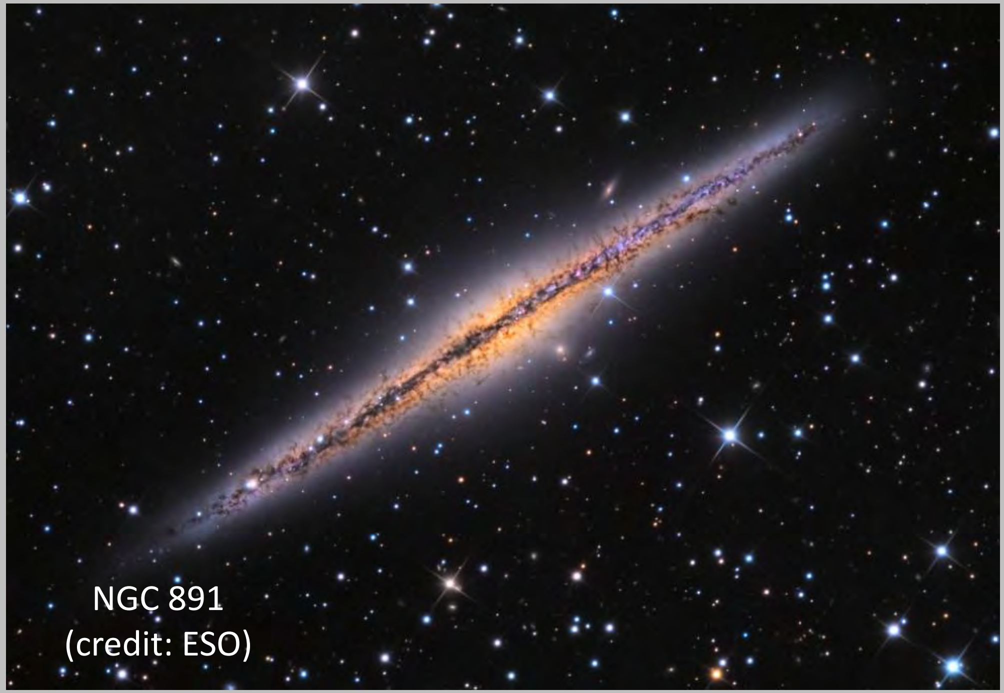
where $z_0$ and $h$ are the exponential scale height and scale length, respectively. At one scale length, the density of stars has dropped by a factor of $1/e \approx 0.37$ from the central value.

For the Milky Way, $h \approx 3$ kpc, and the Sun lies at $\approx 8.2$ kpc from the center.

The disk is mostly thin, but consists of several distinct populations:

- The young thin disk of gas and young stars ($z_0 \approx 50$ pc)
- The old thin disk of older stars like the Sun ($z_0 \approx 300$ pc)
- The thick disk of old metal-poor stars ($z_0 \approx 1 - 1.5$ kpc)

Most stars are in the thin disk, but the thick disk has a lot of information about the history of the Galaxy!

## The Disk of the Milky Way

The Milky Way disk has spiral arms, like the nearby spiral galaxy M101. (😍😍😍!)

# Multiwavelength Spiral Structure

Gas and young stars trace spiral structure most closely

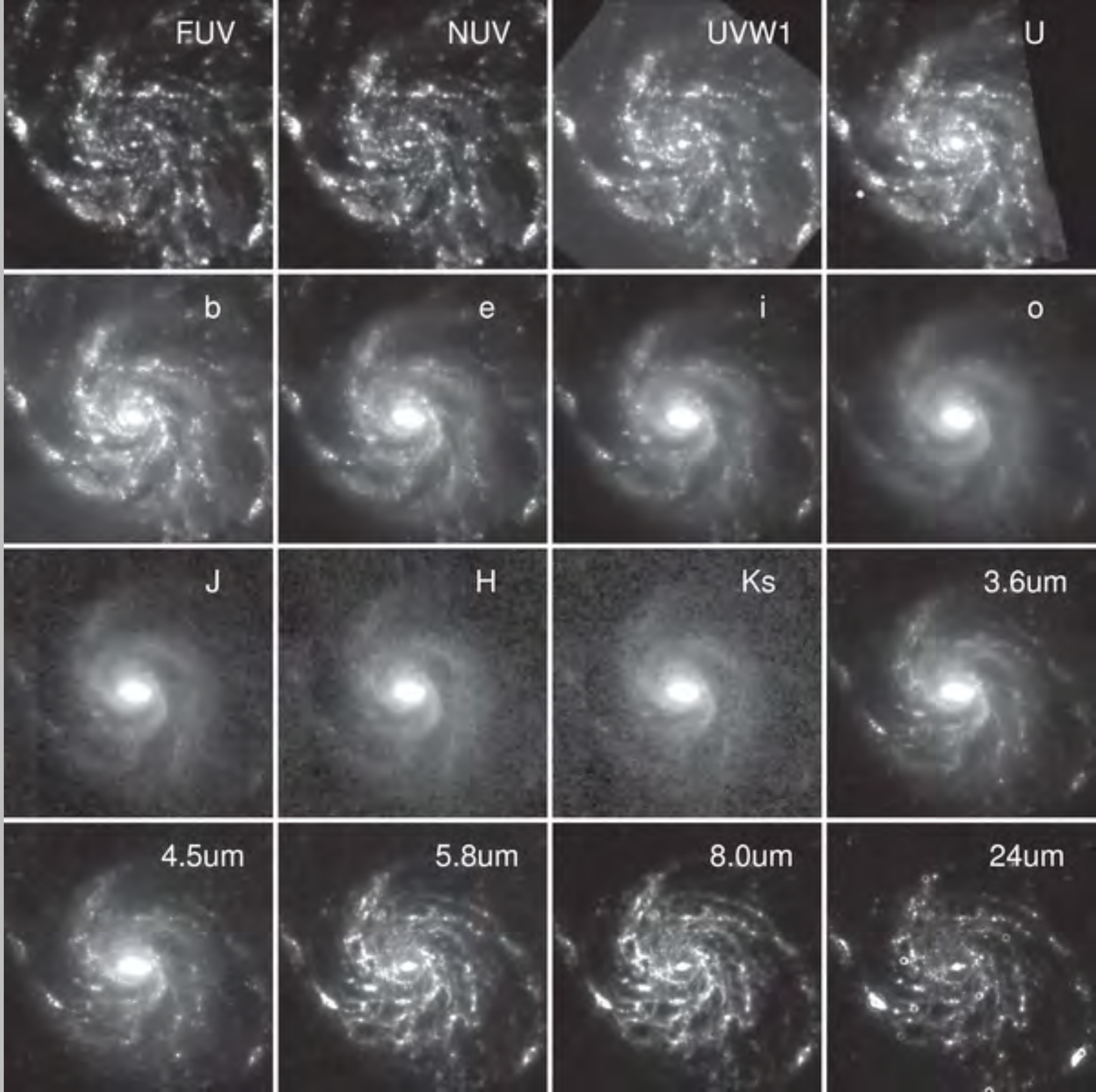
Older stars are more smoothly distributed throughout the disk, and also contribute most of the bulge light.

**ultraviolet**
young stars

**optical**
all stars

**near IR**
old stars

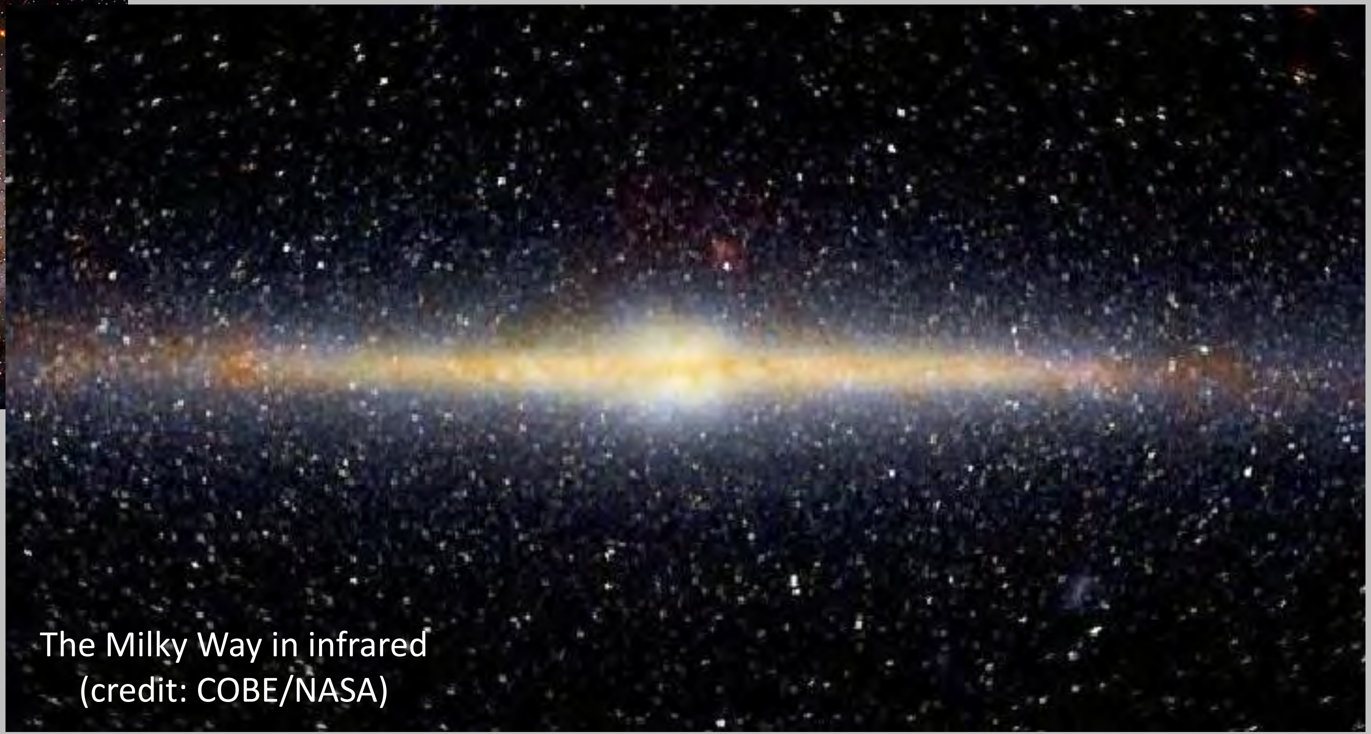
**mid IR**
warm dust



**The Milky Way’s bulge**

The vertical distribution of stars “thickens” as you go in towards the center, the signature of the Galaxy’s central bulge.

Andromeda Galaxy
(credit: David Dayag)



The Milky Way in infrared
(credit: COBE/NASA)

**The Milky Way's bulge**

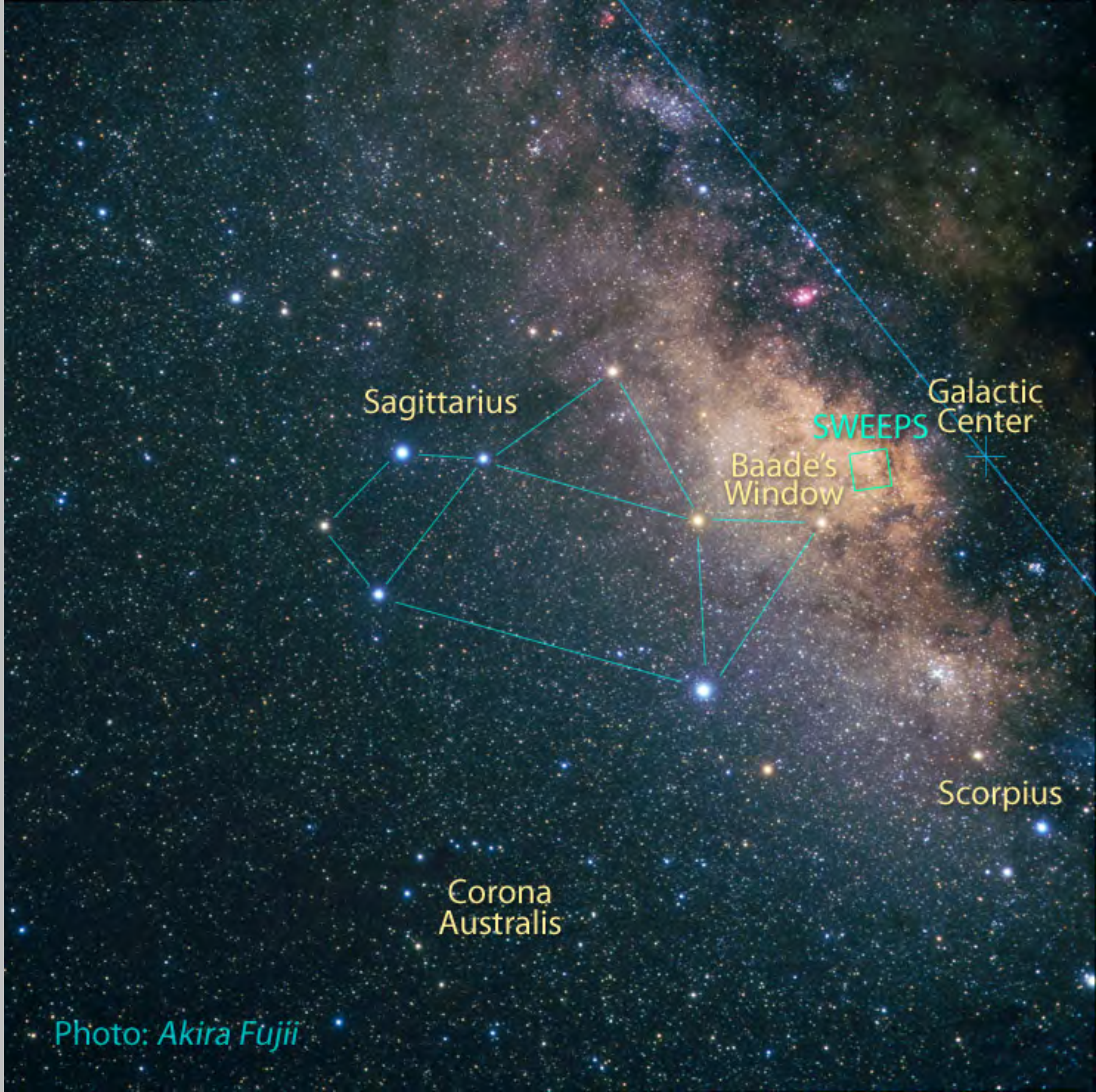
The bulge was historically very hard to study due to dust: optically there is as much as 28 magnitudes of extinction towards the Galactic center.

$\Delta m = 28 \rightarrow$ a factor of $10^{-0.4(28)} = 10^{-12}$!

But the dust is patchy and there are "holes" where we can peek through, like Baade's Window.

And today, we can use infrared telescopes to see through the dust.

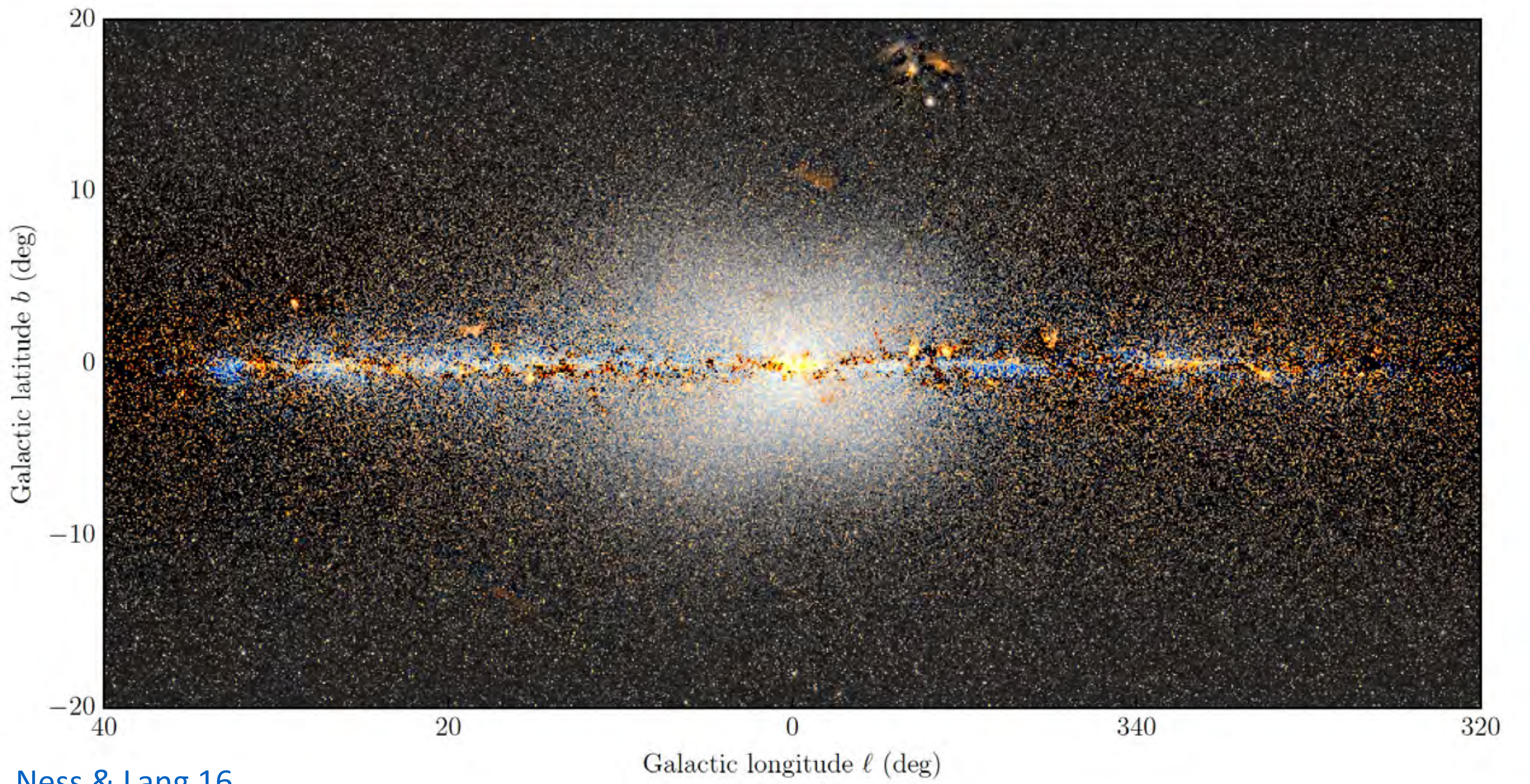
Bulge stars are generally old (ages > 9 Gyr) and have a wide range of metallicity (−1 < [Fe/H] < +0.5) with an average of [Fe/H]=−0.2.



**The Milky Way's bulge... maybe not a bulge?**

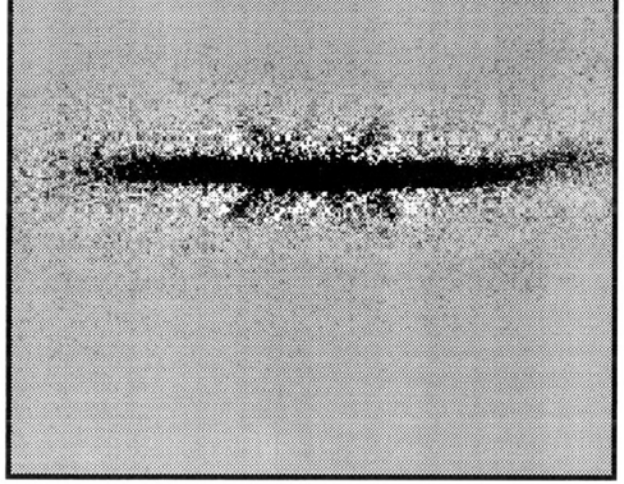
The original view was that the Milky Way's bulge is a flattened spheroid, like what we see in Andromeda. But newer infrared data show that bulge is thicker on one side of the galaxy than the other – this can't happen if the bulge is axisymmetric!

New interpretation is that the Milky Way has a bar in its center. 🍻🍸🍷




Ness & Lang 16

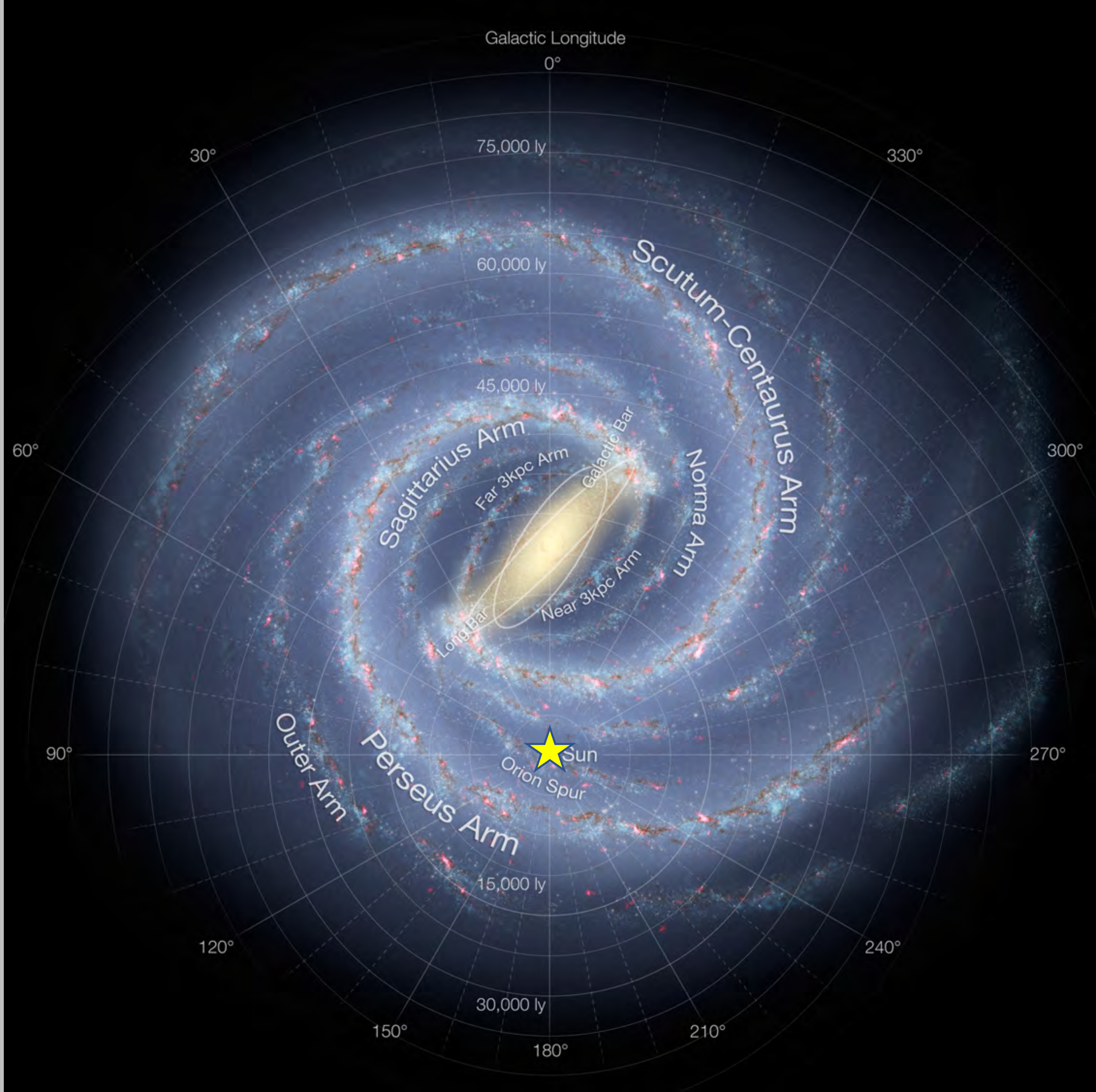
Barred galaxy simulation edge on view (Mihos+ 95)



Animations of bar instabilities:

- Face on view
- Edge on view

# The face-on Milky Way perspective



## The Stellar Halo

The Milky Way's halo consists of globular clusters and field stars, which have high random velocities and orbit far out of the Galactic disk.

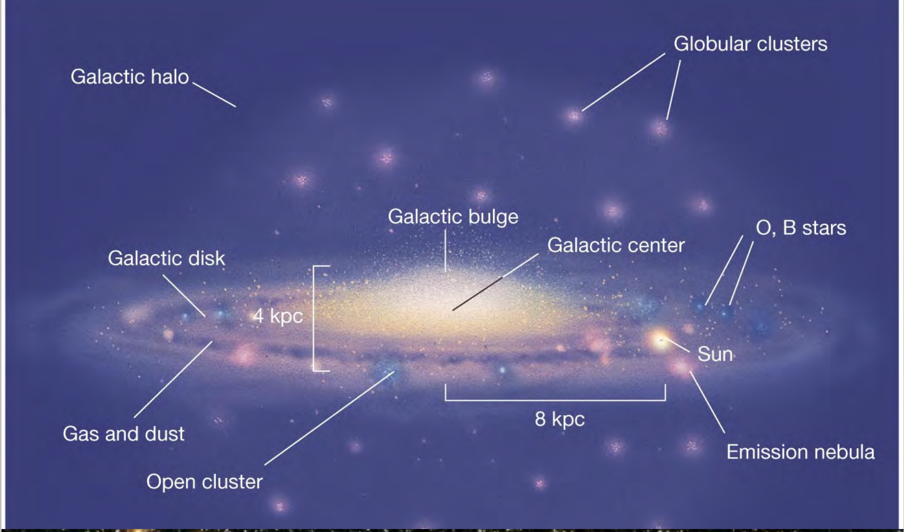
The total mass of the stellar halo is $\approx 10^9\ M_\odot$, of which only about 1% is in the globular clusters.

**Kinematics**:

- Disk: "**kinematically cold**" – disk stars orbit around the Galaxy in a highly ordered rotational fashion.
- Halo: "**kinematically hot**" – globular clusters and halo stars orbit randomly, with no net rotation.

**Globular clusters:** two populations

| | Halo GCs | "Disk" GCs |
|---|---|---|
| Metallicity | [Fe/H] < –0.8 | [Fe/H] > –0.8 |
| Age | Very old, 10 – 12 Gyr | Somewhat younger |
| Spatial Distribution | Very extended, spherical-ish | Concentrated near center, flattened |
| Kinematics | Random orbits | Somewhat more rotation |




NGC 362
ESA/NASA/Hubble

# The Stellar Halo

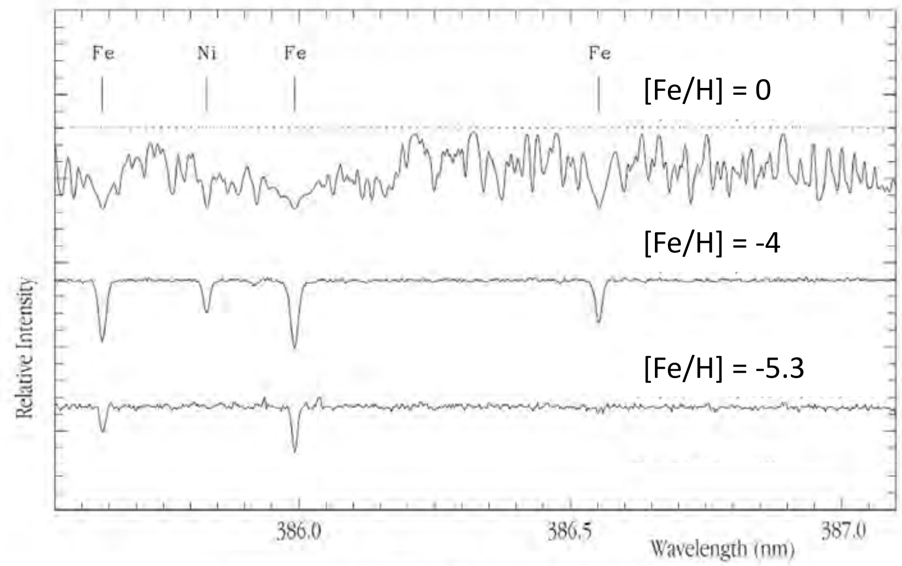
The Milky Way's halo consists of globular clusters and field stars, which have high random velocities and orbit far out of the Galactic disk.

**Field stars:** Hard to study because they are so rare: only ~ 1 in a 1000 nearby stars is a halo star. Find them by looking for high velocity stars.

Field stars are metal poor with a tail to extremely low metallicity. These stars must be tracing the earliest epochs of star formation in the universe.

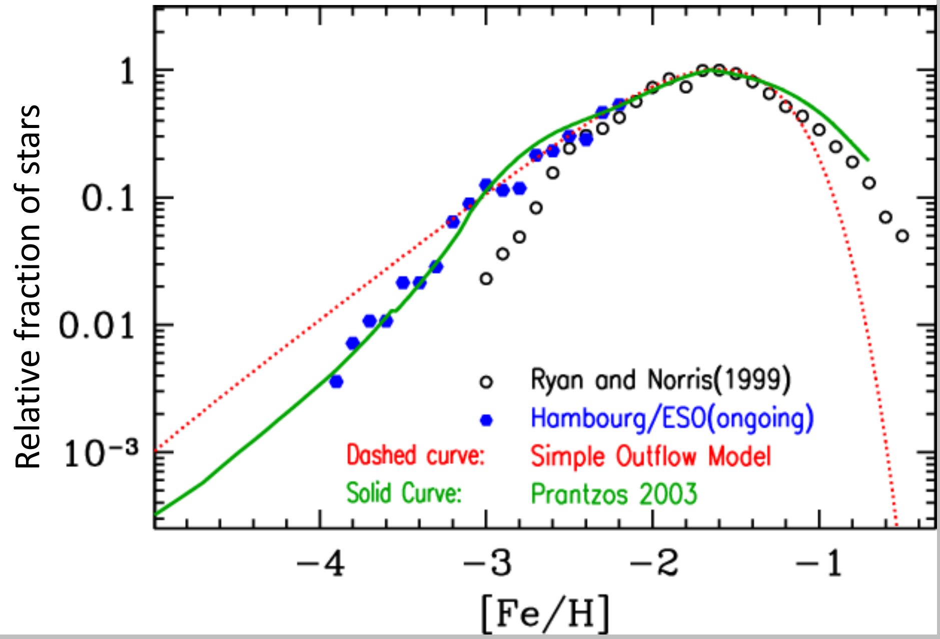
Density distribution falls very roughly as $\rho(r) = \rho_0 r^{-3.5}$ or so, but shows a lot of variation in different directions.

*And therein lies a tale... or a tail.*



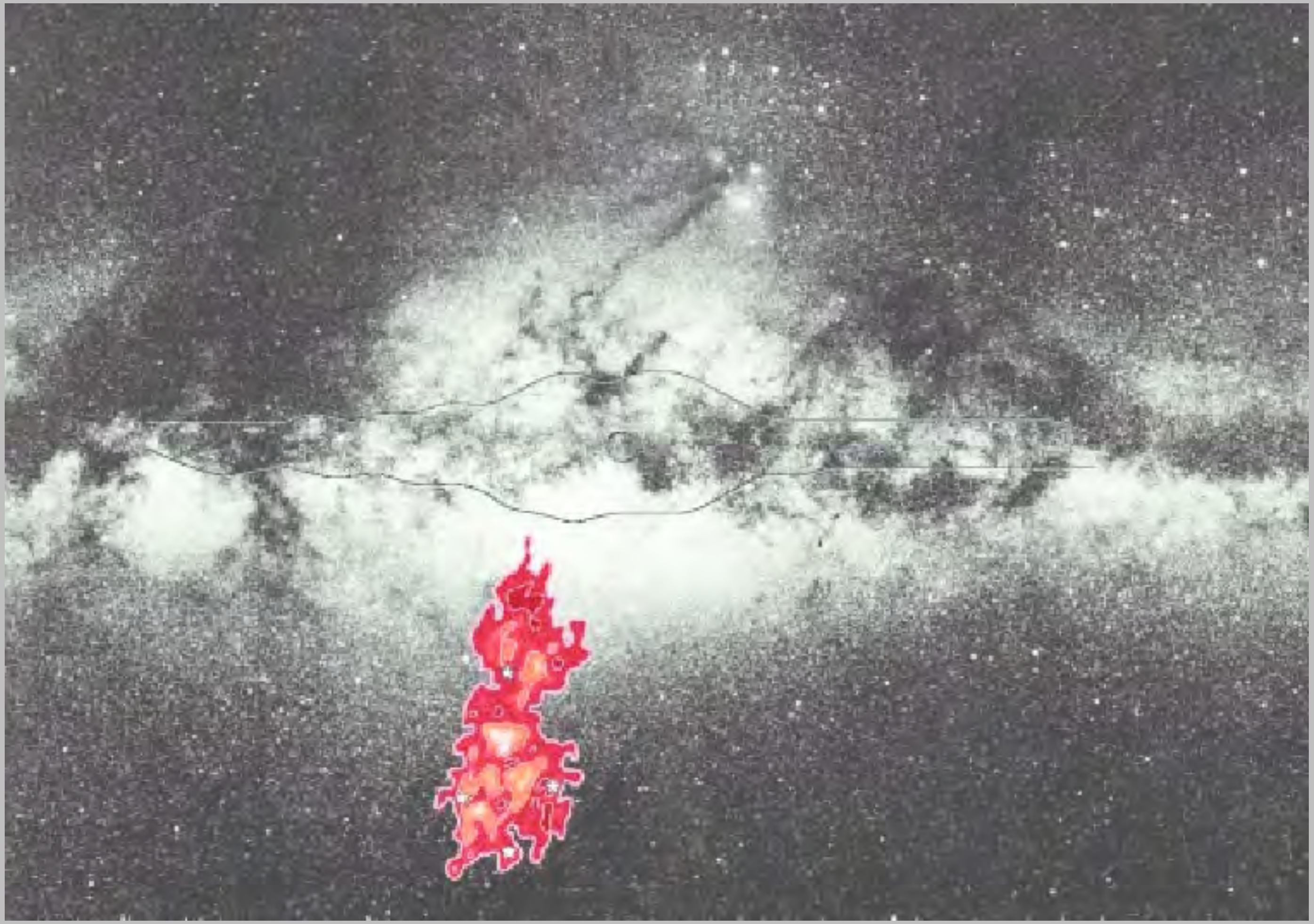
Spectra of Stars with Different Metal Content

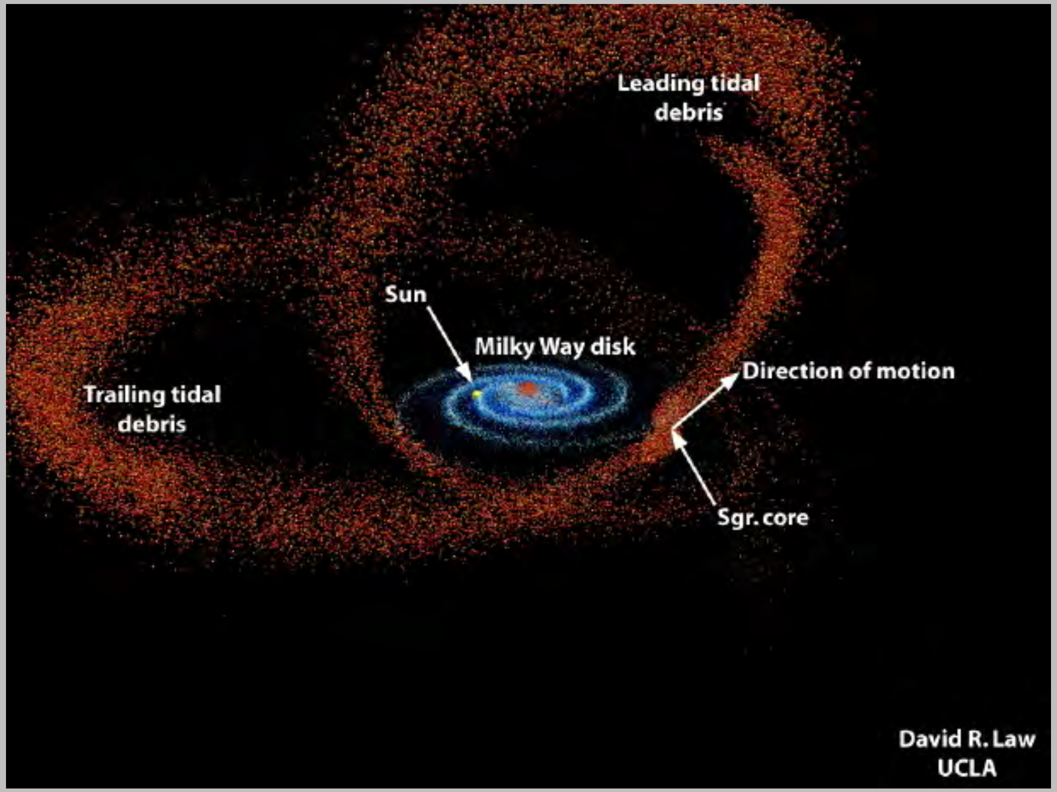
Halo star metallicity distribution function (Prantzos 08)



**Star streams in the Stellar Halo**

1994: Discovery of the Sagittarius dwarf galaxy, on the far side of the Milky Way, and being torn apart by the Milky Way's gravitational tidal field.

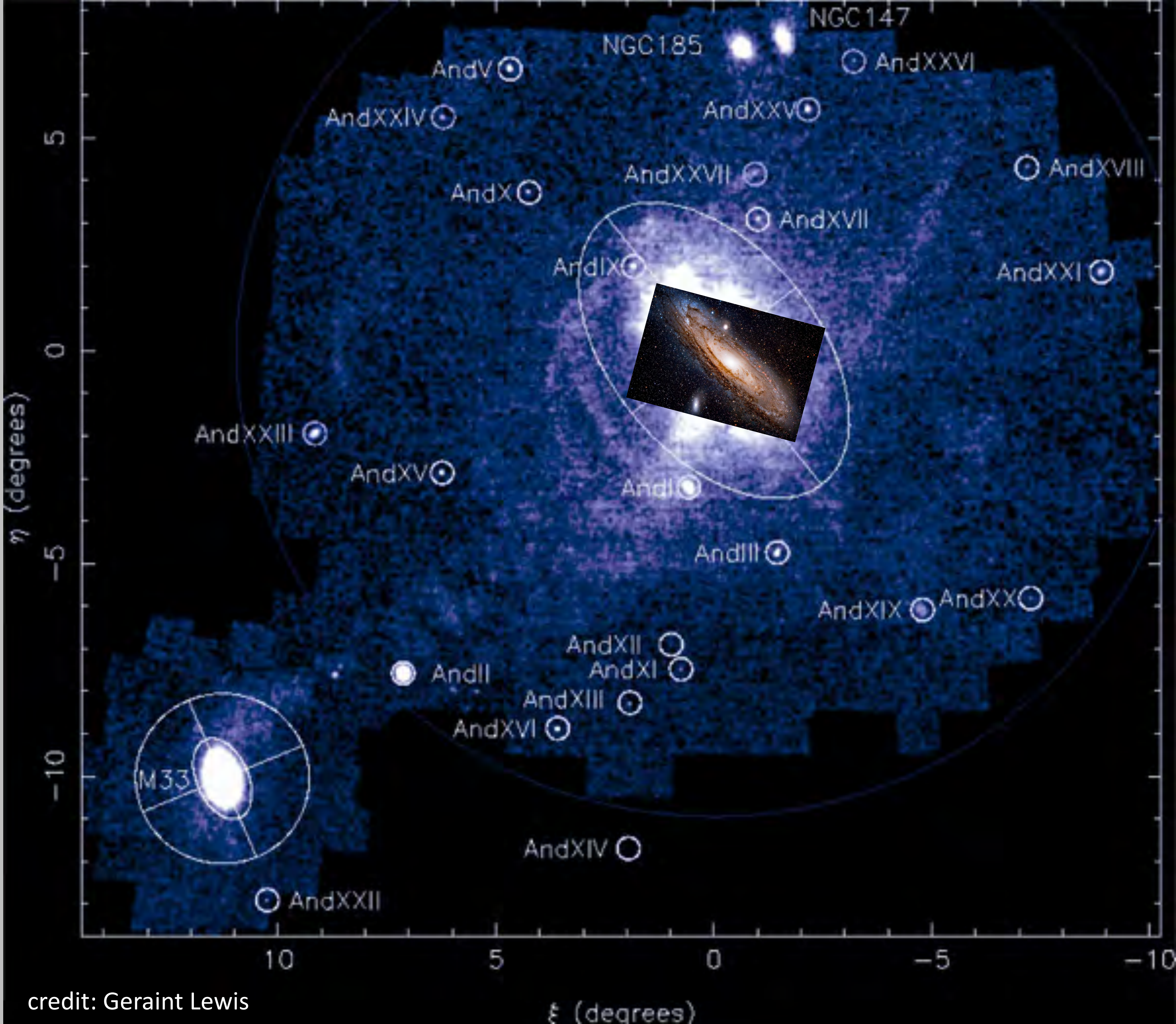





Subsequent observations have shown that streams from the Sagittarius dwarf wrap completely around the Galaxy.

Computer simulations show how this happens.
(credit: Kathryn Johnston, ColumbiaU)

**Star streams around Andromeda....**



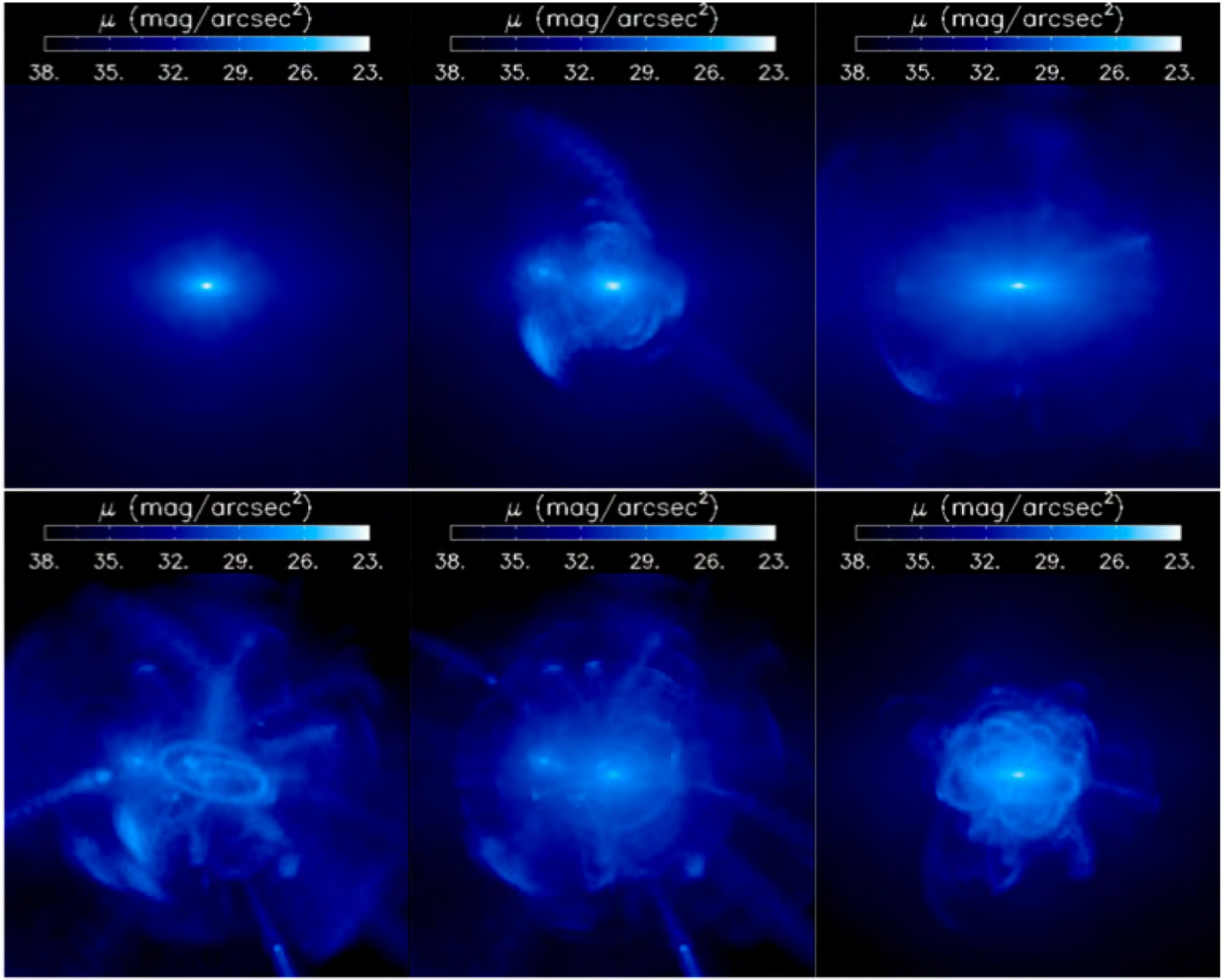

credit: Geraint Lewis

...and around NGC 5907

**Simulated Galaxy Halos**
Johnston 16

Satellite infall is an ongoing process, and **many** satellites have fallen in to the Milky Way over its lifetime. The Milky Way's halo is full of streams from these events.

**Unknown**: *how much of the Galaxy's halo was formed through accretion, and how much was formed in place ("in-situ")?*



# The Interstellar Medium: Gas and Dust in the Milky Way


Phases of the Interstellar Medium:

- Ionized gas
- Atomic gas
- Molecular gas
- Dust

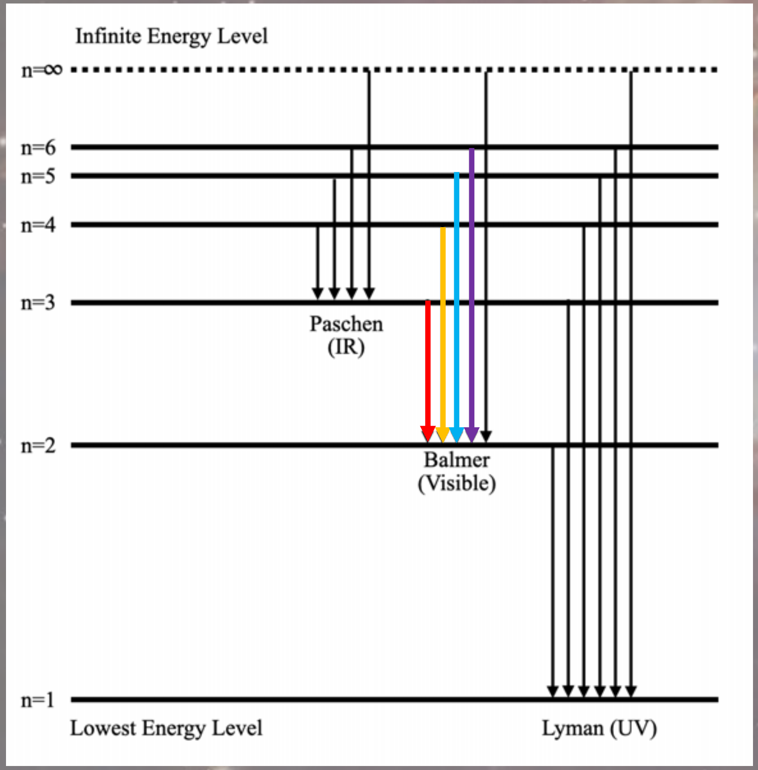
Ionized Gas in Star Forming Regions

**Ionized Gas in Star Forming Regions** (HII regions)

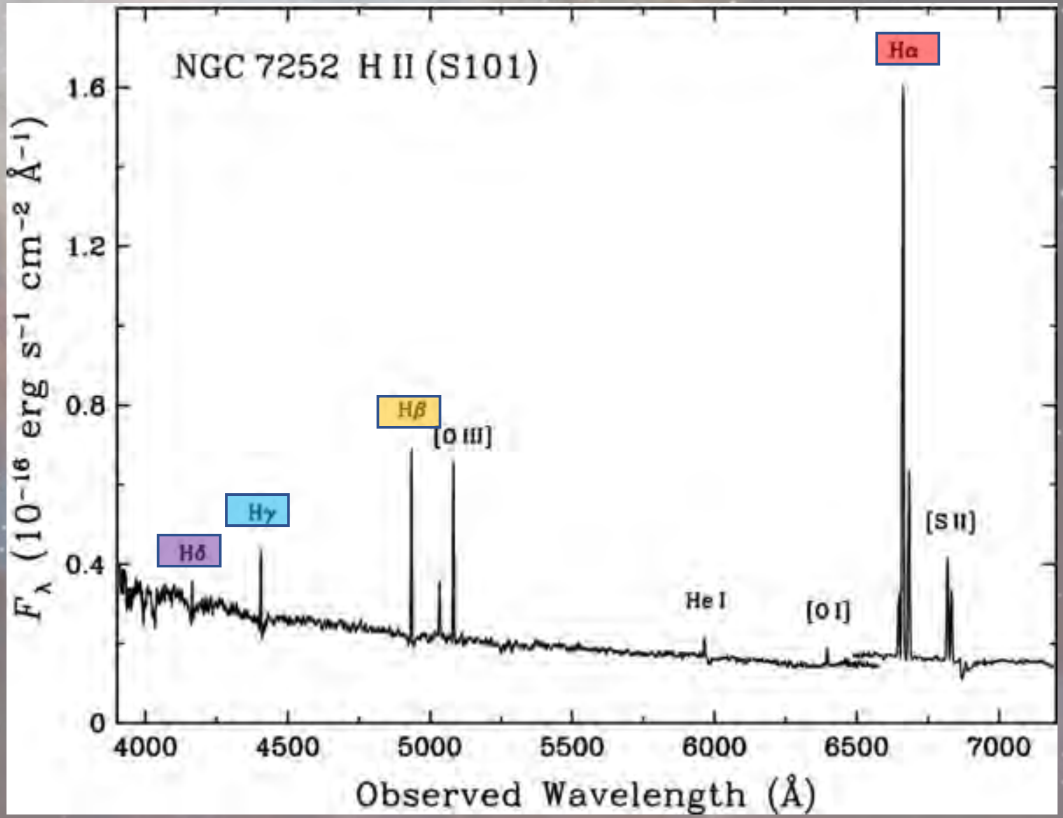
When stars form, the young stars heat up the surround gas and ionize it. When the electrons recombine with atoms, they cascade down in energy level and emit emission lines. Different elements emit different emission lines.

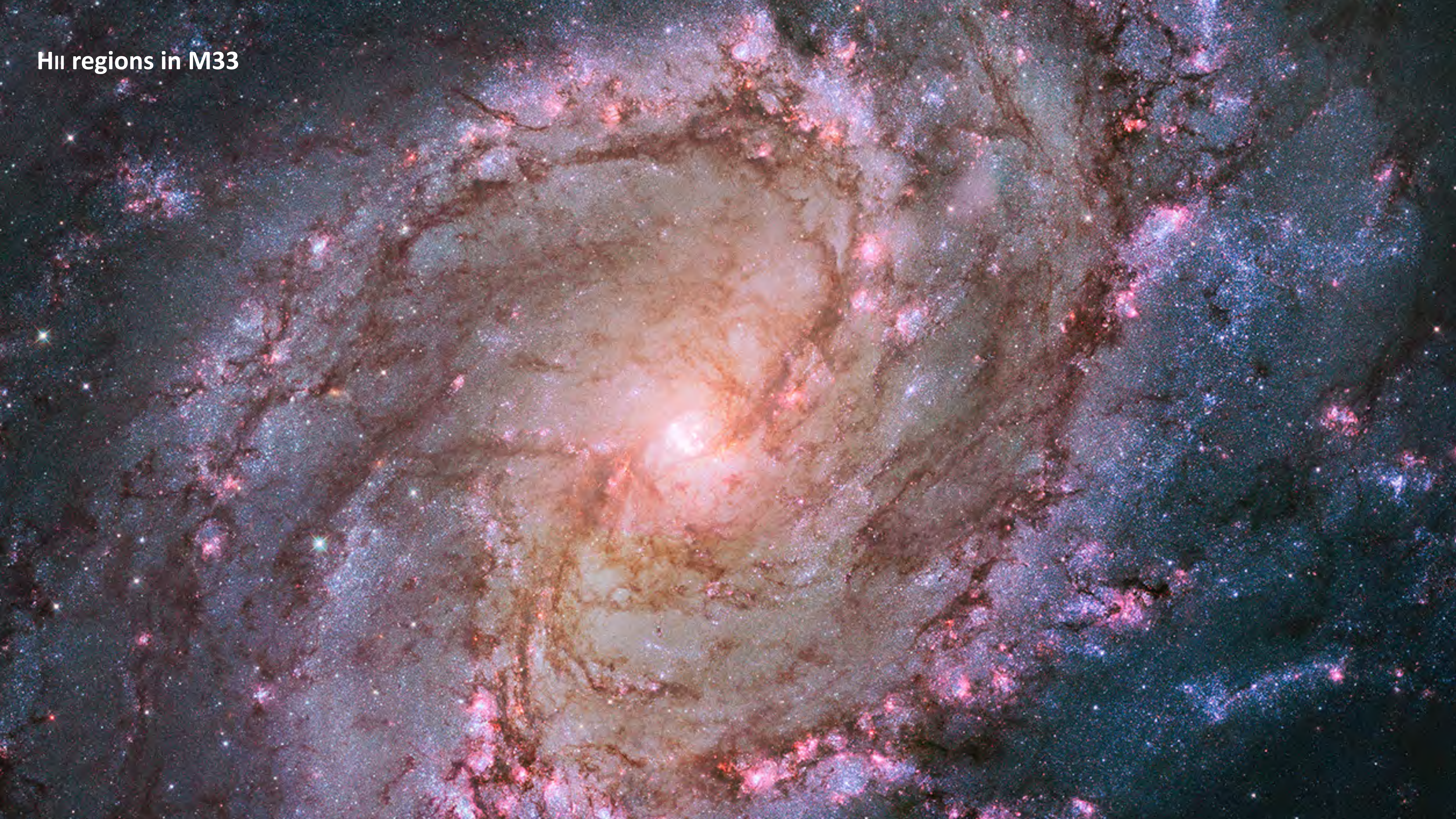
These lines tell us about temperature (~ 10,000 K), density (few hundred atoms $cm^{-3}$), and composition.

Hydrogen atom energy levels



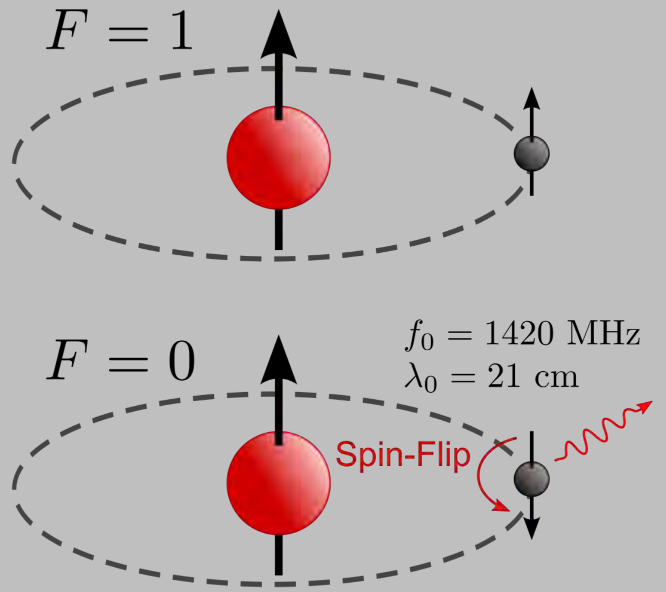

HII region spectrum




HII regions in M33

## Phases of the Interstellar Medium: Atomic Gas

Much of the gas in galaxies is in the form of atomic gas, dominated by **atomic hydrogen** or **HI** ("H-one"). It exists throughout the Galaxy, at temperatures of ~ 100 – 1000 K or so, and at densities of ~ 1000 atoms cm$^{-3}$.

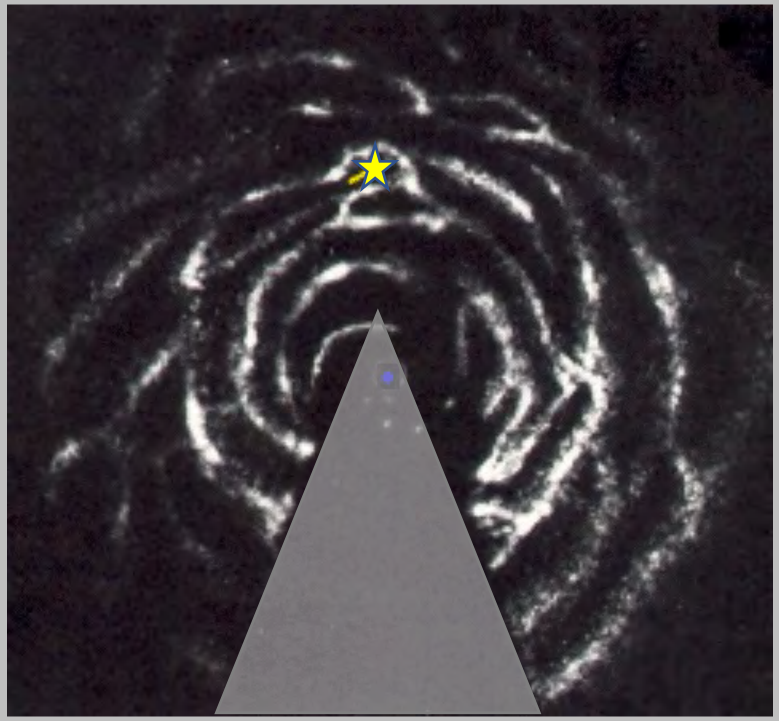



Hydrogen spin flip

At these low temperatures, the electron always lives in the ground state, so no optical emission lines.

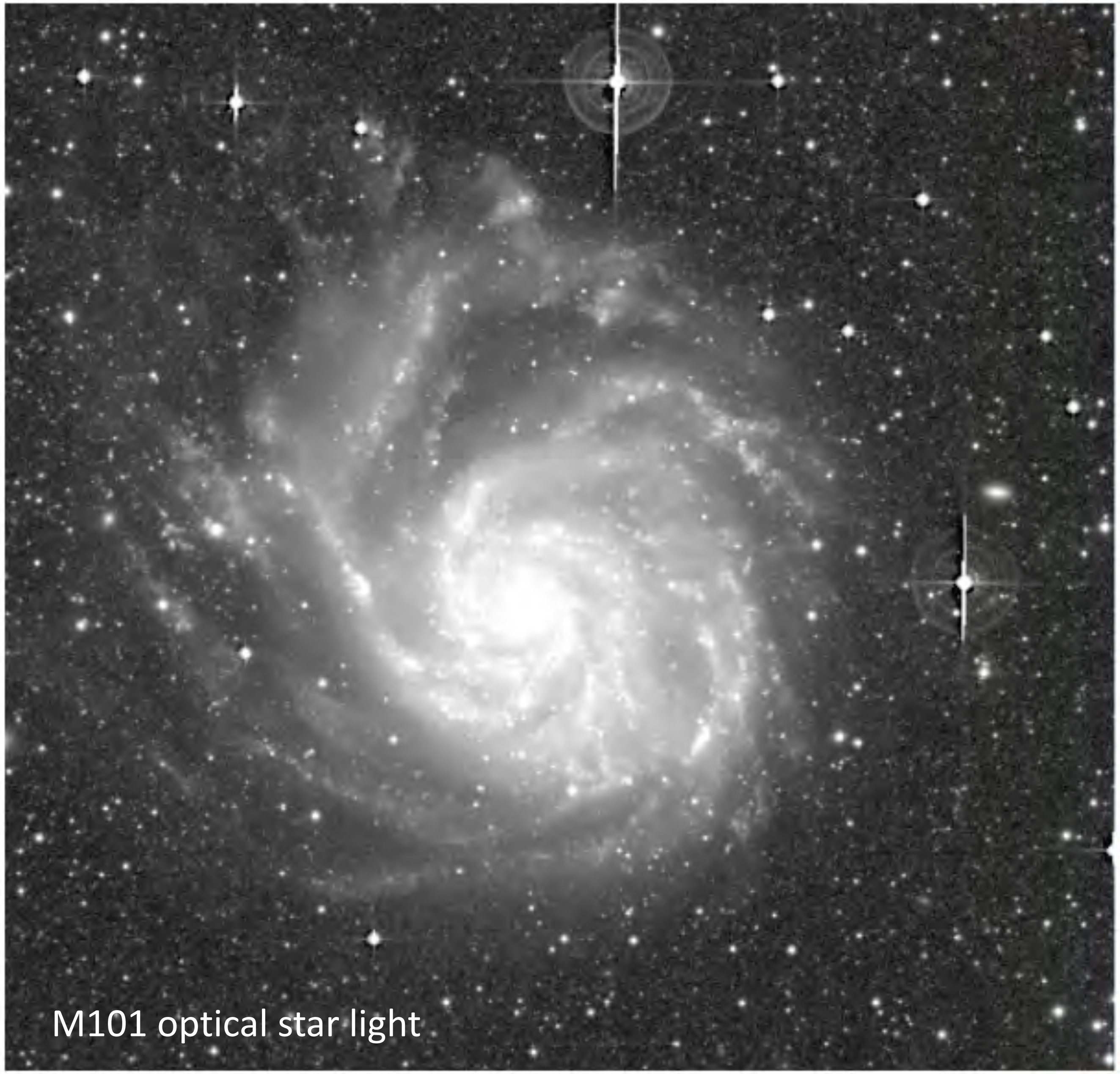
Instead on rare occasions, the electron can undergo a "spin flip" and drop to a slightly lower energy state, emitting a photon at $\lambda = 21$ cm. Radio!

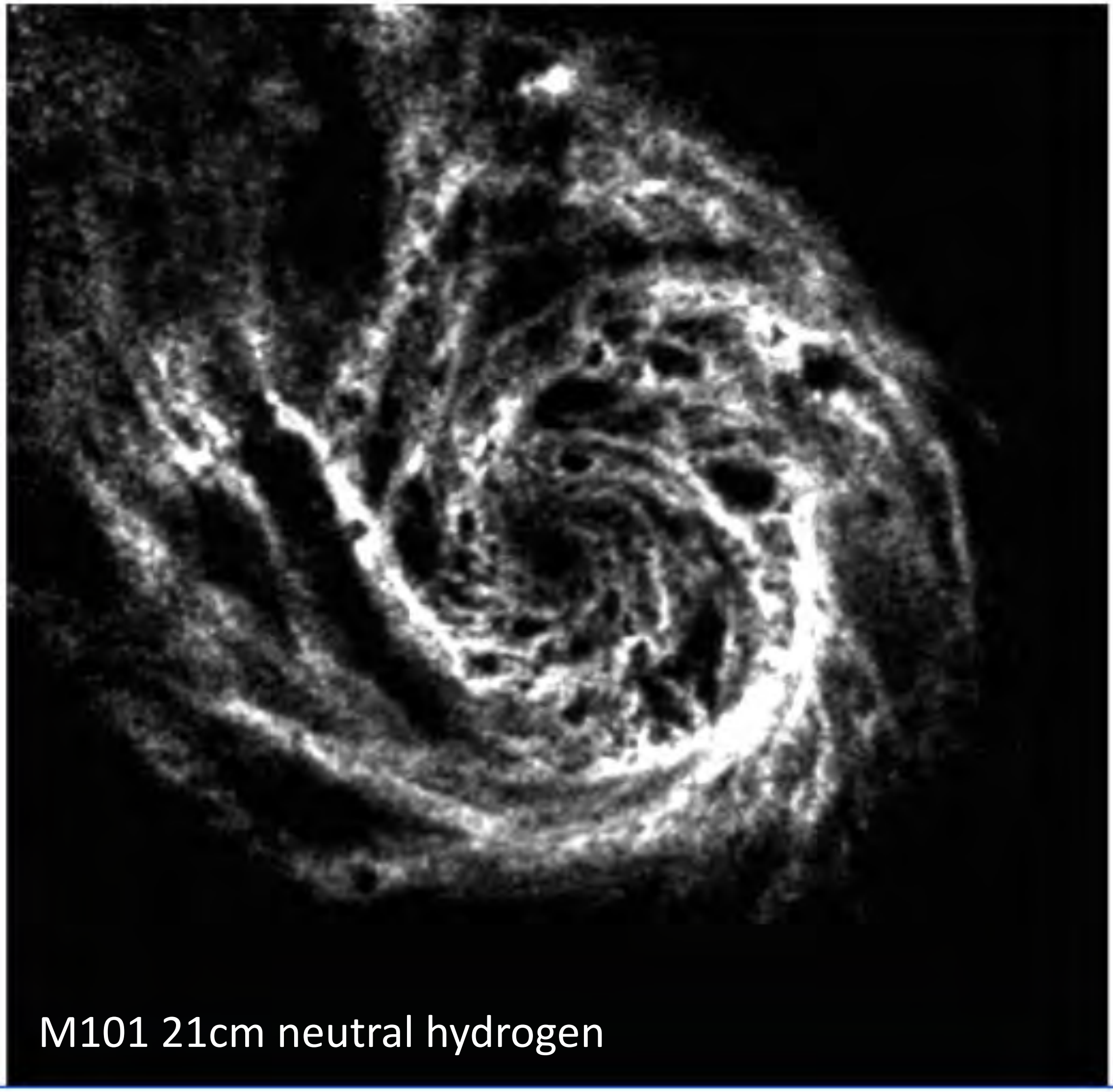
How often does this happen? Once every few million years. But there are so many hydrogen atoms in the gas that it is constantly radiating 21-cm photons!



21-cm map of the Milky Way

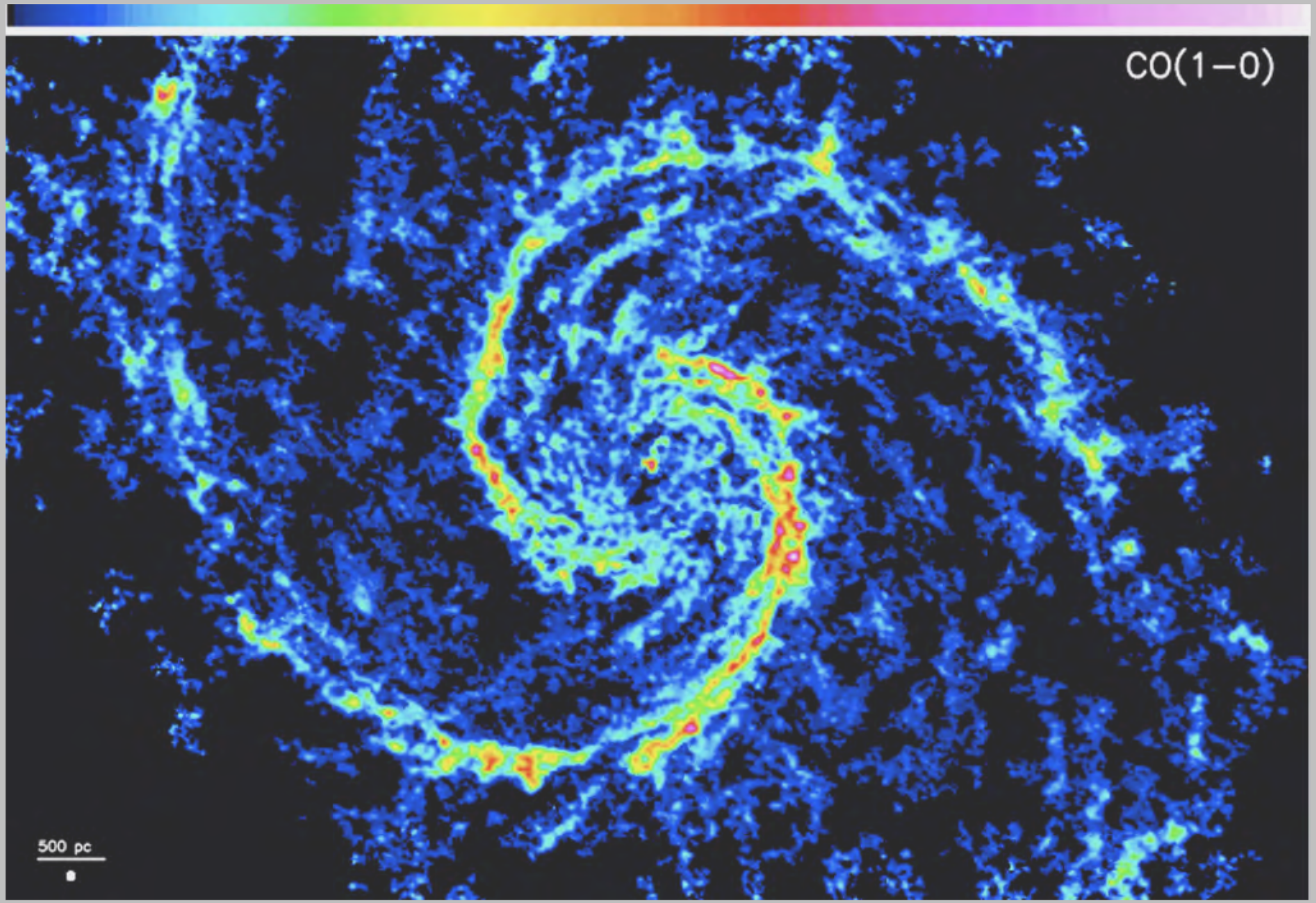
# Atomic Hydrogen in M101



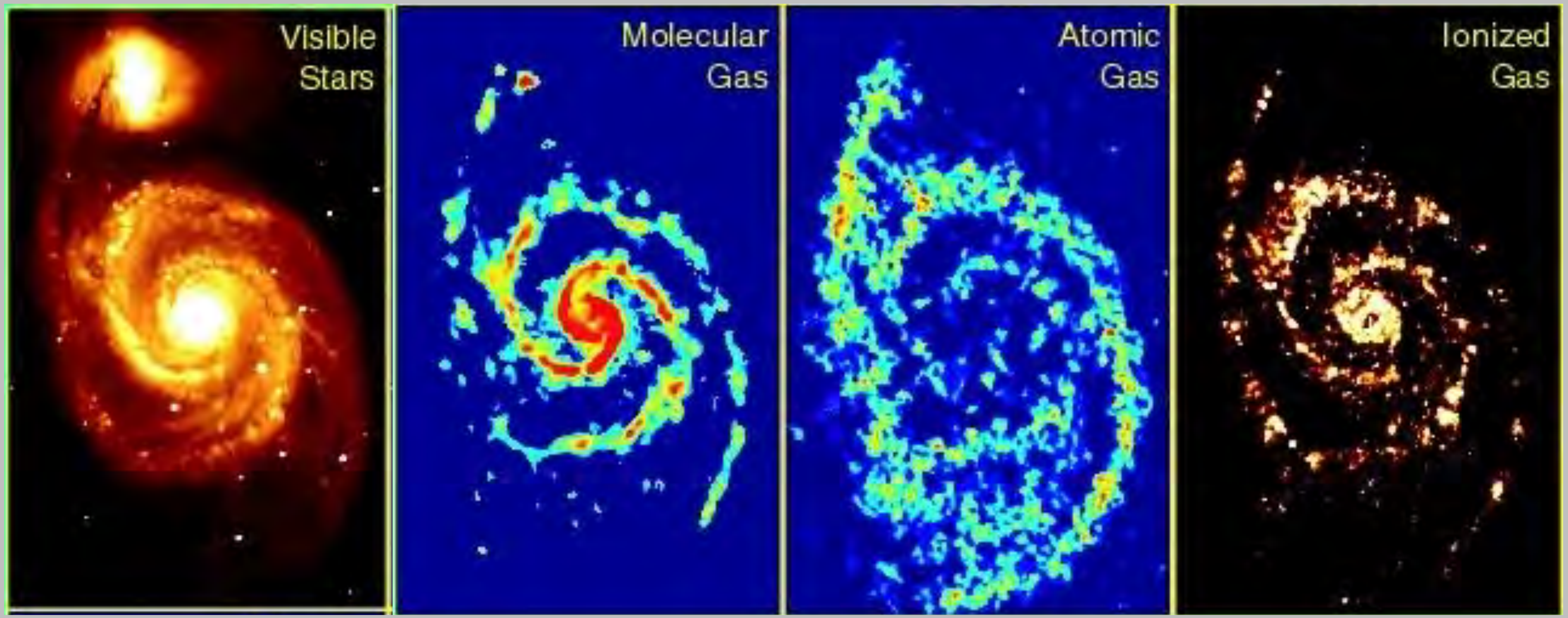
**Phases of the Interstellar Medium: Molecular Gas**

When the density of gas gets high enough, atoms can bond together to form molecules, most commonly molecular hydrogen ($H_2$). Molecular hydrogen does not emit optical or radio photons, and is very hard to trace. We use emission from other molecules, most notably carbon monoxide (CO), to trace the molecular gas. CO emits strongly at $\lambda = 2.2$ mm: microwaves!



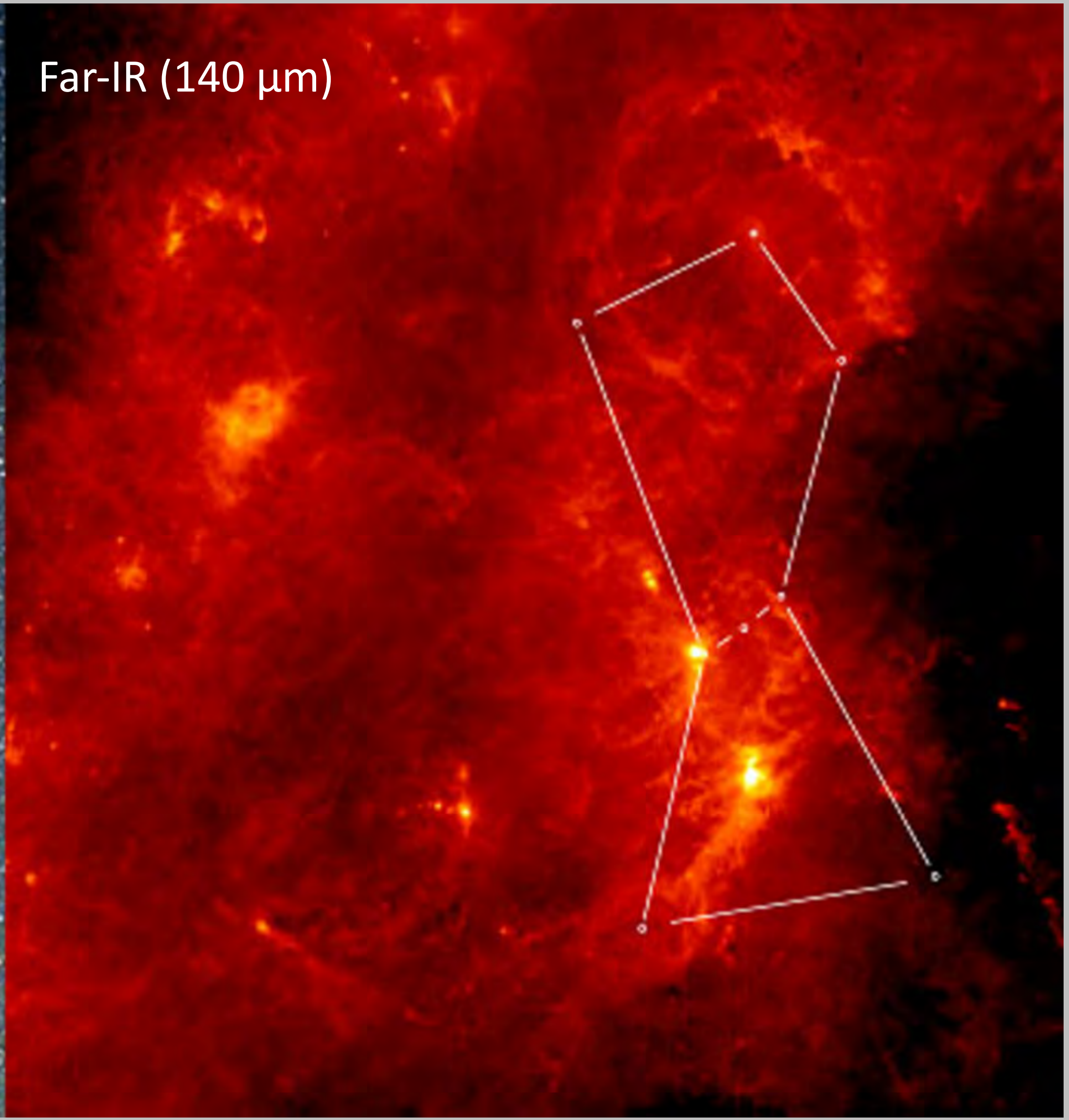
**The Distribution of Gas in Spiral Galaxies like the Milky Way**

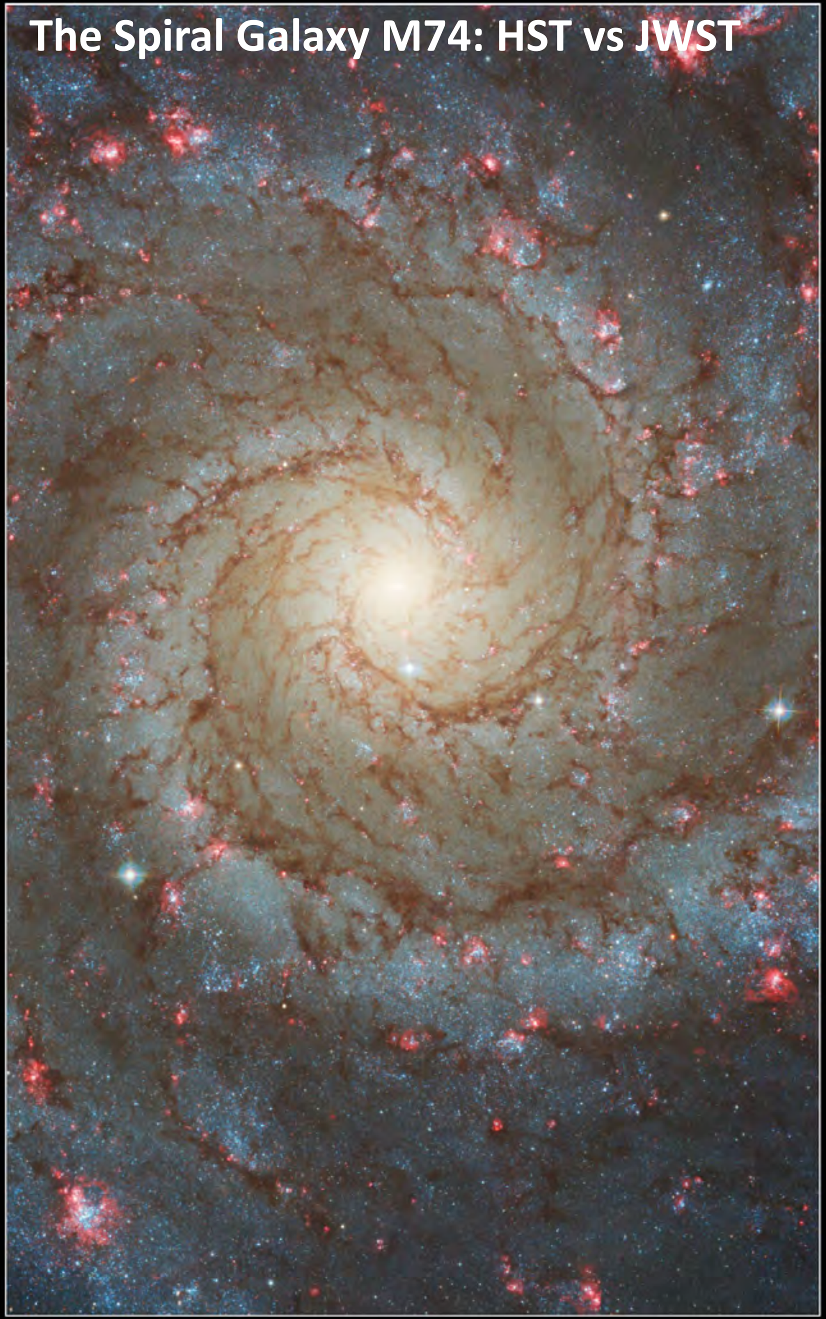
- Comparable amounts of molecular and atomic gas
- Total gas is about 10% of the mass in stars
- Molecular gas more centrally concentrated, atomic gas more extended
- Gas follows spiral arms, particularly molecular gas and HII regions.



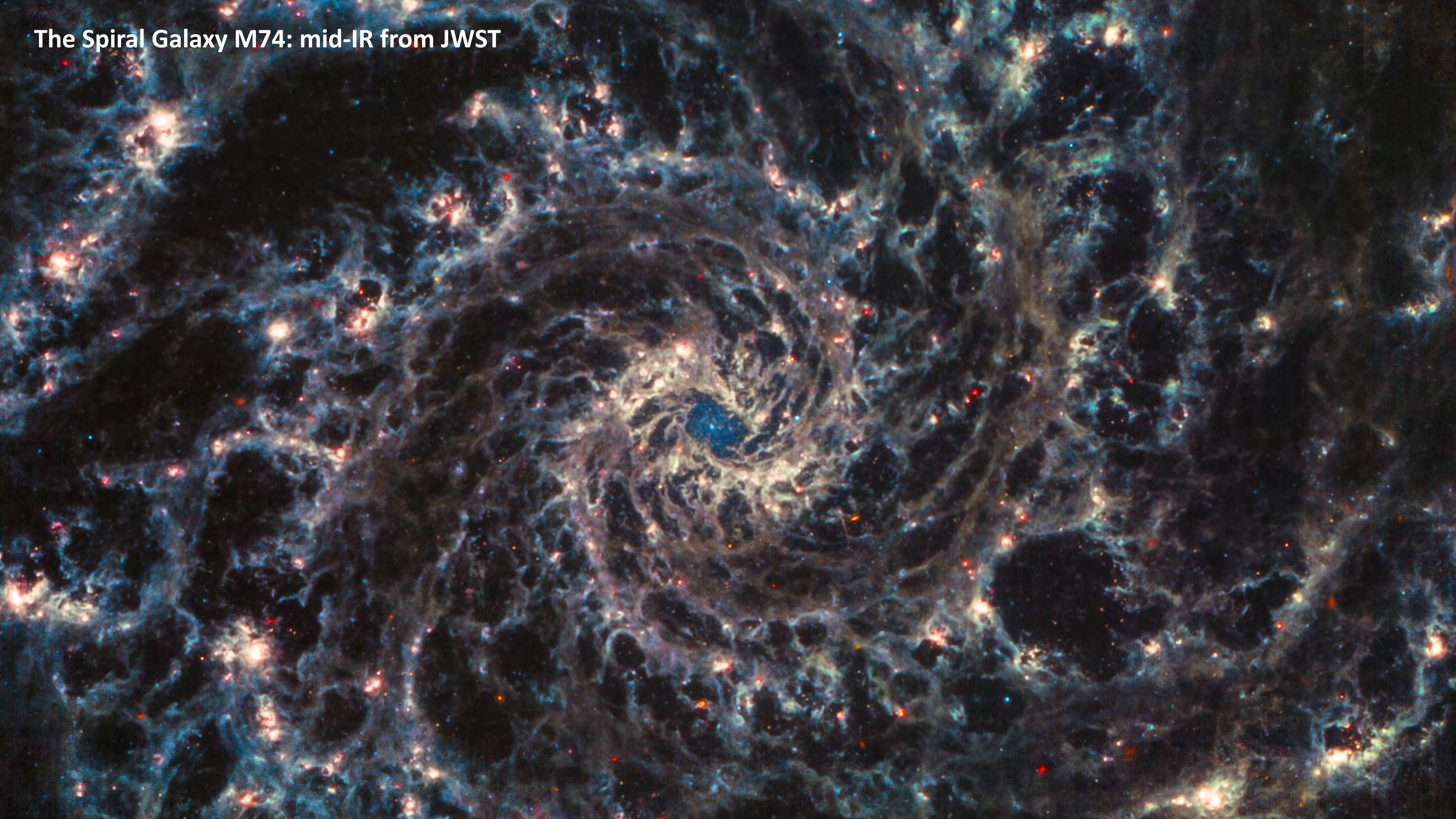
## Dust in the interstellar medium

Diffuse dust permeates the ISM, reddening and extincting light from stars. It also glows in the mid- and far-IR.




Hubble / Optical


The Spiral Galaxy M74: mid-IR from JWST