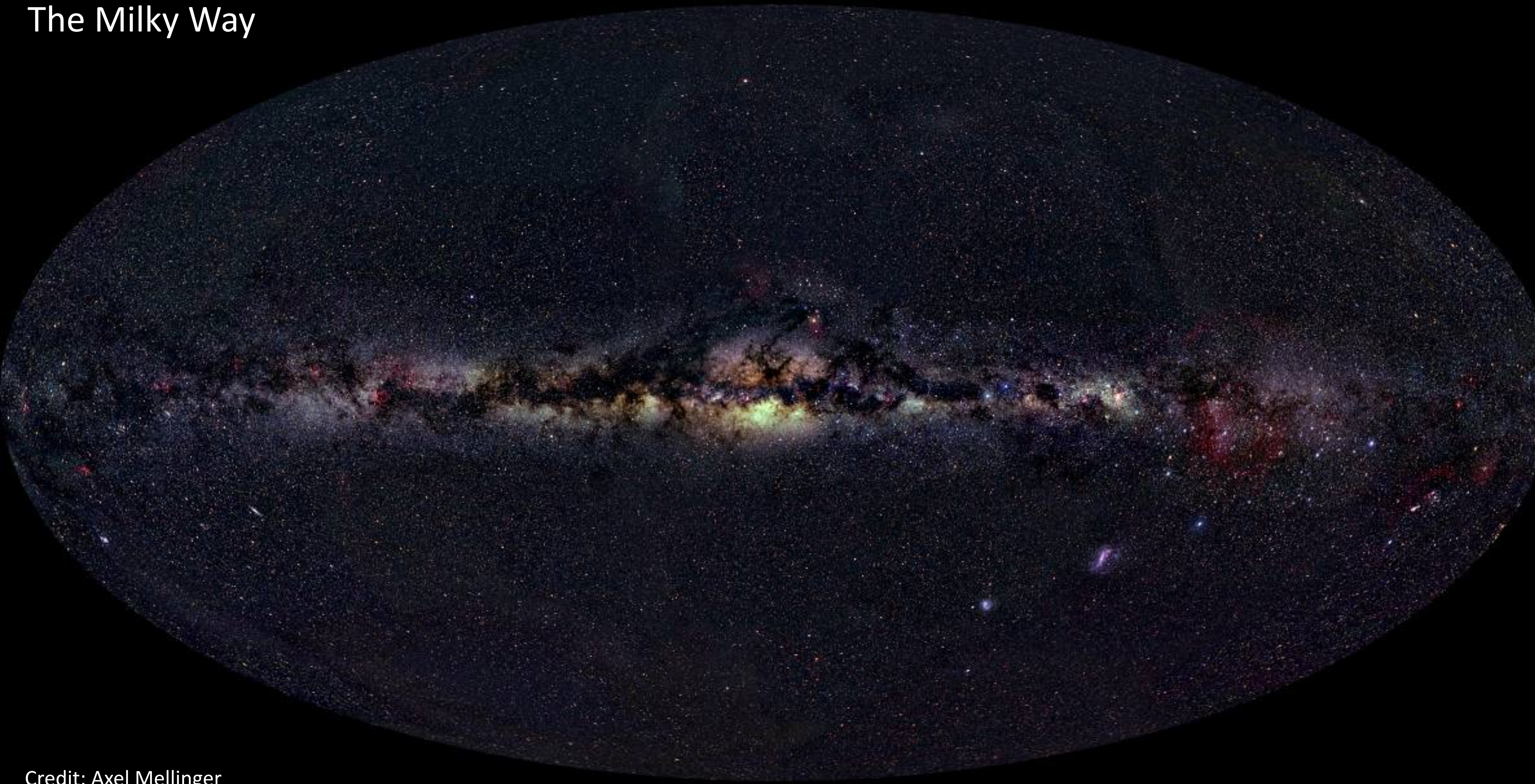
The Milky Way

Credit: NOIRlab

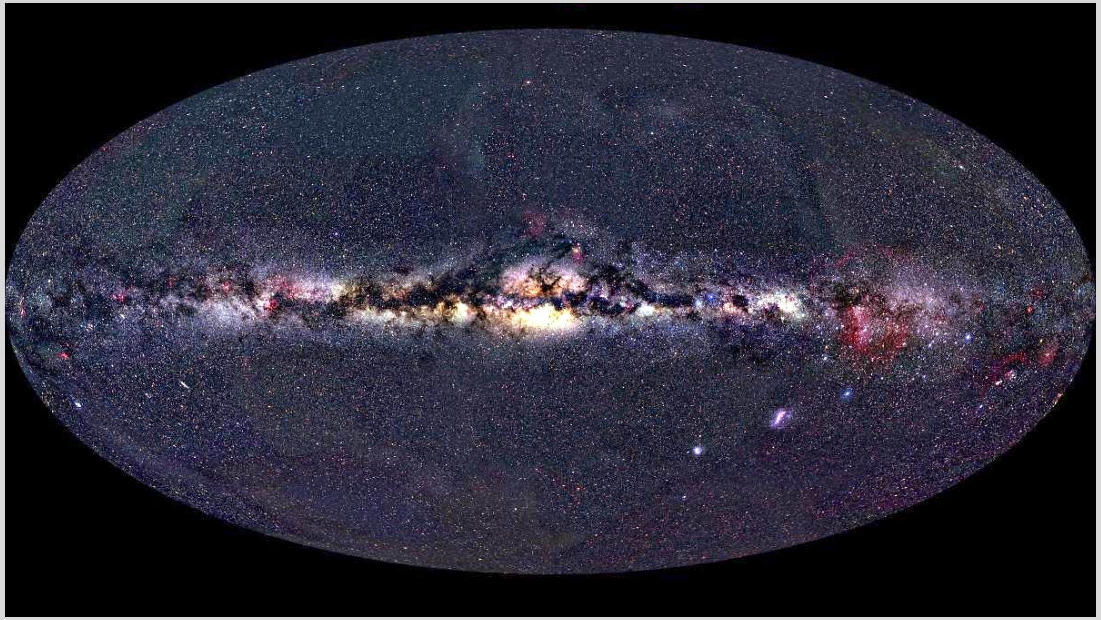
The Milky Way



Credit: Axel Mellinger
https://www.milkywaysky.com/

The Milky Way: Early studies

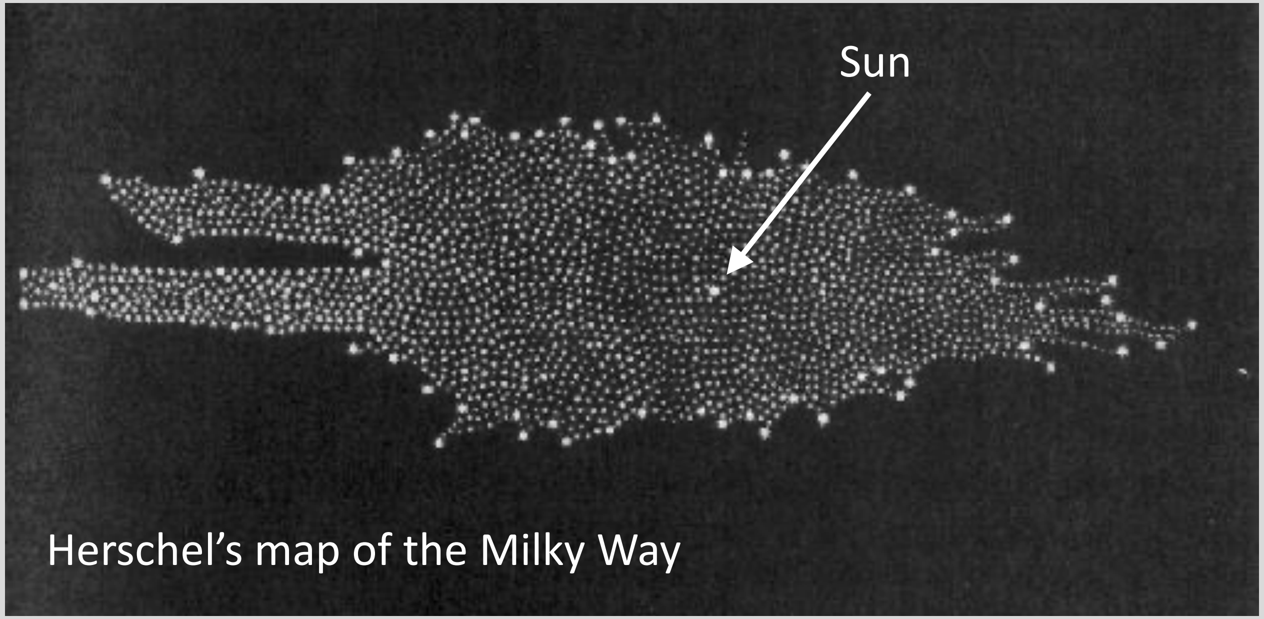
1755: Immanuel Kant proposes that the Galaxy is a disk of stars (including our Sun) and that there might be “island universes” of other galaxies like our own.



1785: Wiliam Herschel uses star count data to map the Milky Way. He assumes:

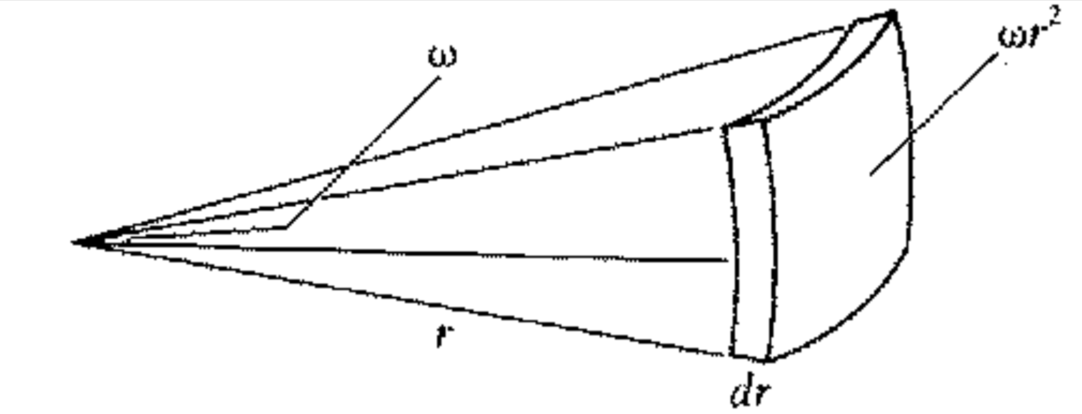
- all stars have the same brightness
- the galaxy has a uniform density
- we can see to the edge

Herschel's map of the Milky Way puts the Sun very near the center of the Galaxy.



Herschel’s map of the Milky Way

Studying Star Counts in the Galaxy



If we choose stars which are all the same absolute magnitude, we can use their apparent magnitude as a substitute for distance. So let's look at **star counts as a function of apparent magnitude**.

If the galaxy has a uniform density of stars (given by ρ), and we integrate over radius, we get the total number of stars **between us and $\boldsymbol{r}$**:

$$N(r) = \rho\omega \int_0^r r^2 dr = \frac{1}{3}\omega\rho r^3$$

Volume of a shell at distance r is given by $dV = \omega r^2 dr$

So the number of stars in the shell is given by $\rho\omega r^2 dr$

We can use the distance modulus equation to solve for r, given the apparent magnitude m:

$$m - M = 5\log r - 5 \dashrightarrow \; r = 10^{[0.2(m-M)+1]}$$

Plugging that into N(r), we get N(m) the number of stars **brighter than** some apparent magnitude m:

$$N(m) = 10^{(0.6m+C_1)} \;\text{ or }\; \log N(m) = 0.6m + C_1$$

So for every magnitude fainter that we look, we ought to see $10^{0.6} \approx 4\times$ as many stars. ***That's not what we see!***

But it gets worse! Lets look at how much light we'd get from all those stars.....

If an $m = 0$ star has a brightness given by f_0, then a star of magnitude m has a brightness $f(m) = f_0 10^{-0.4m}$.

The flux of light coming from stars of magnitude m is given by

$$dF(m) = f(m)\frac{dN(m)}{dm} = C_2 \times 10^{0.2m}$$

So the total flux of light coming from all stars ***brighter*** than an apparent magnitude m is given by:

$$F_{tot}(m) = \int_{-\infty}^{m} dF(m)dm = C_2 \int_{-\infty}^{m} 10^{0.2m} dm = C_3 10^{0.2m}$$

As we look fainter and fainter ($m \to \infty$), the amount of light diverges ($F_{tot} \to \infty$).

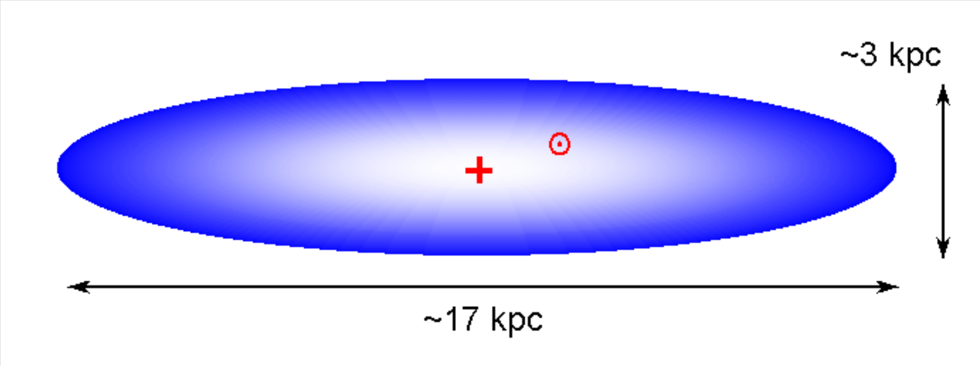
This result is known as **Olber's paradox: If the Galaxy was infinite in size and homogenous in density, the night sky should be infinitely bright!**

What's wrong with our assumptions?

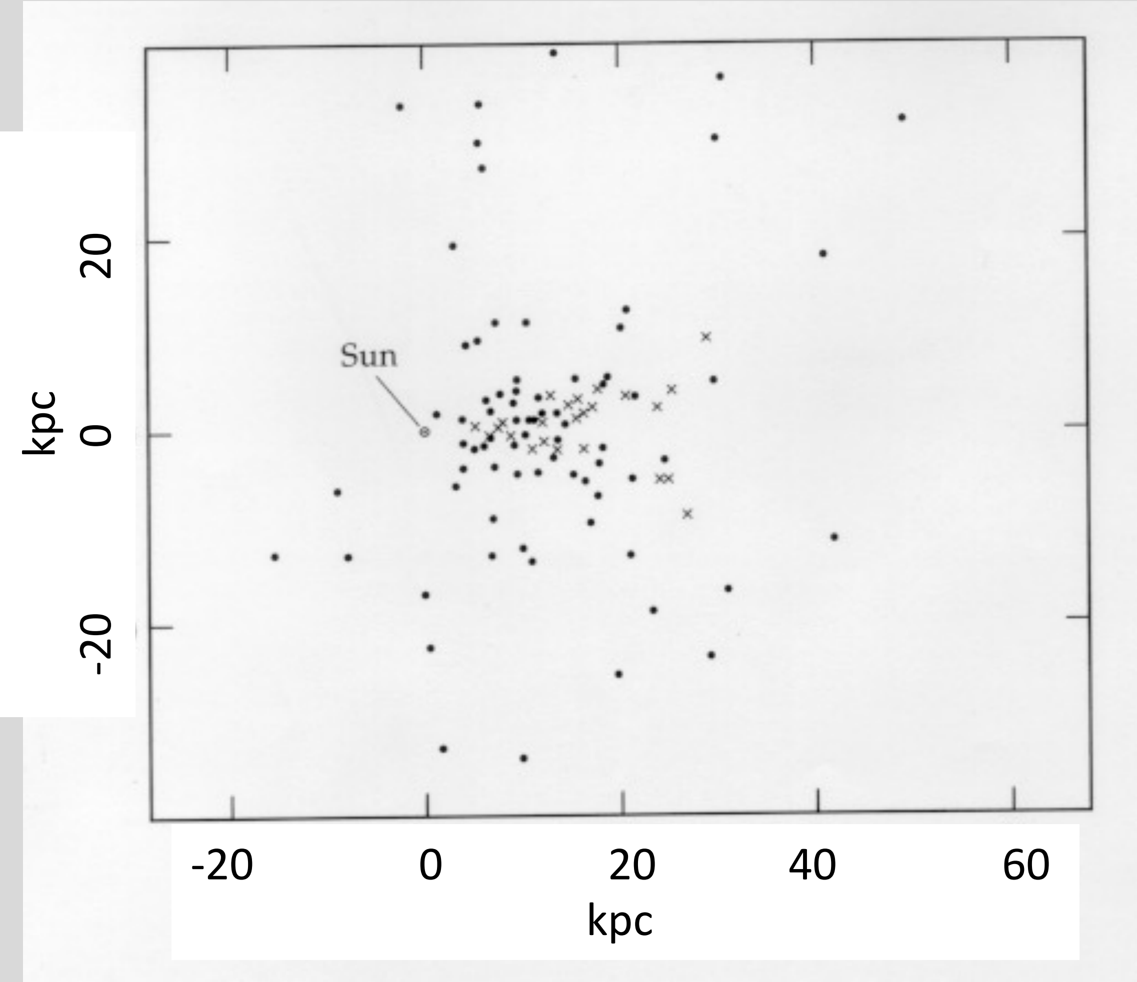
Turn the problem around: use the observed N(m) to work out $\rho(r)$, and figure out the density structure of the Galaxy.

The Size of the Milky Way (1920s perspective)

Jacobus Kapteyn: used star counts to measure the size of the Galaxy: ellipsoidal, 20 kpc across, Sun is a few kpc from center.



Harlow Shapley: uses variable stars to get distances to globular clusters, determines Galaxy is ~ 100 kpc across and the Sun is ~ 15 kpc from the center.

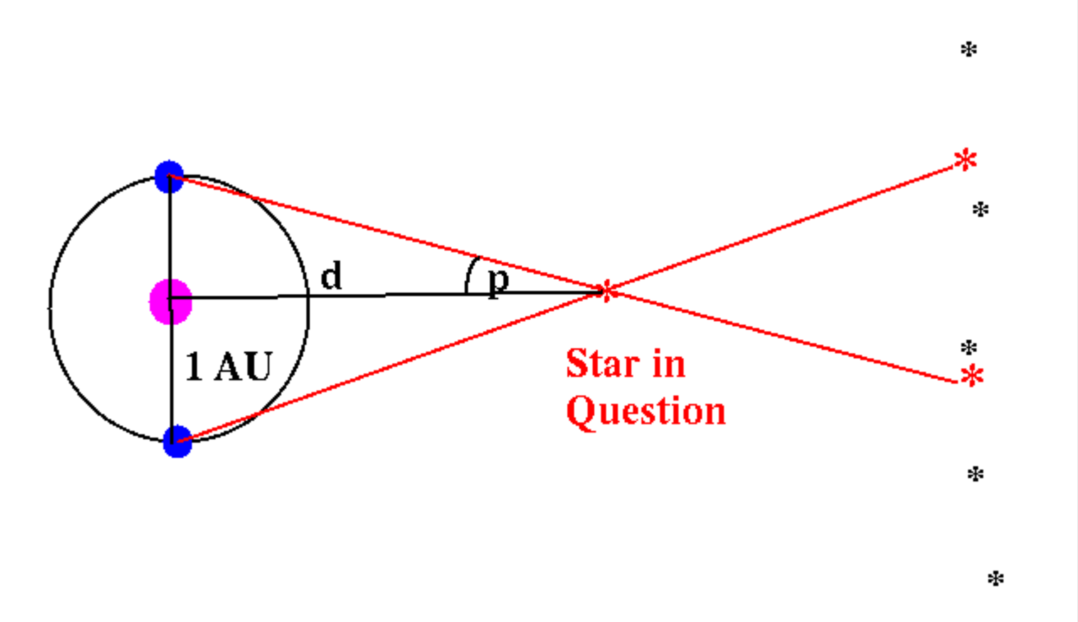


Both were wrong, because astronomers of the time didn't know about the effects of dust.

Dust blocks light from faint, distant stars, so Kapteyn couldnt see those distant stars and thought the Galaxy ran out of stars about 10 kpc away.

Shapley's variable stars were bright enough to see, but dust made them fainter, so Shapley thought they were further away. *(But Shapley was closer to the truth than Kapteyn!)*

Distances to stars: Parallax



As the Earth orbits the Sun, the position of nearby stars in the sky shifts relative to background objects.

The parallax angle is one-half of this angular shift, then the distance to the star is given by simple trigonometry:

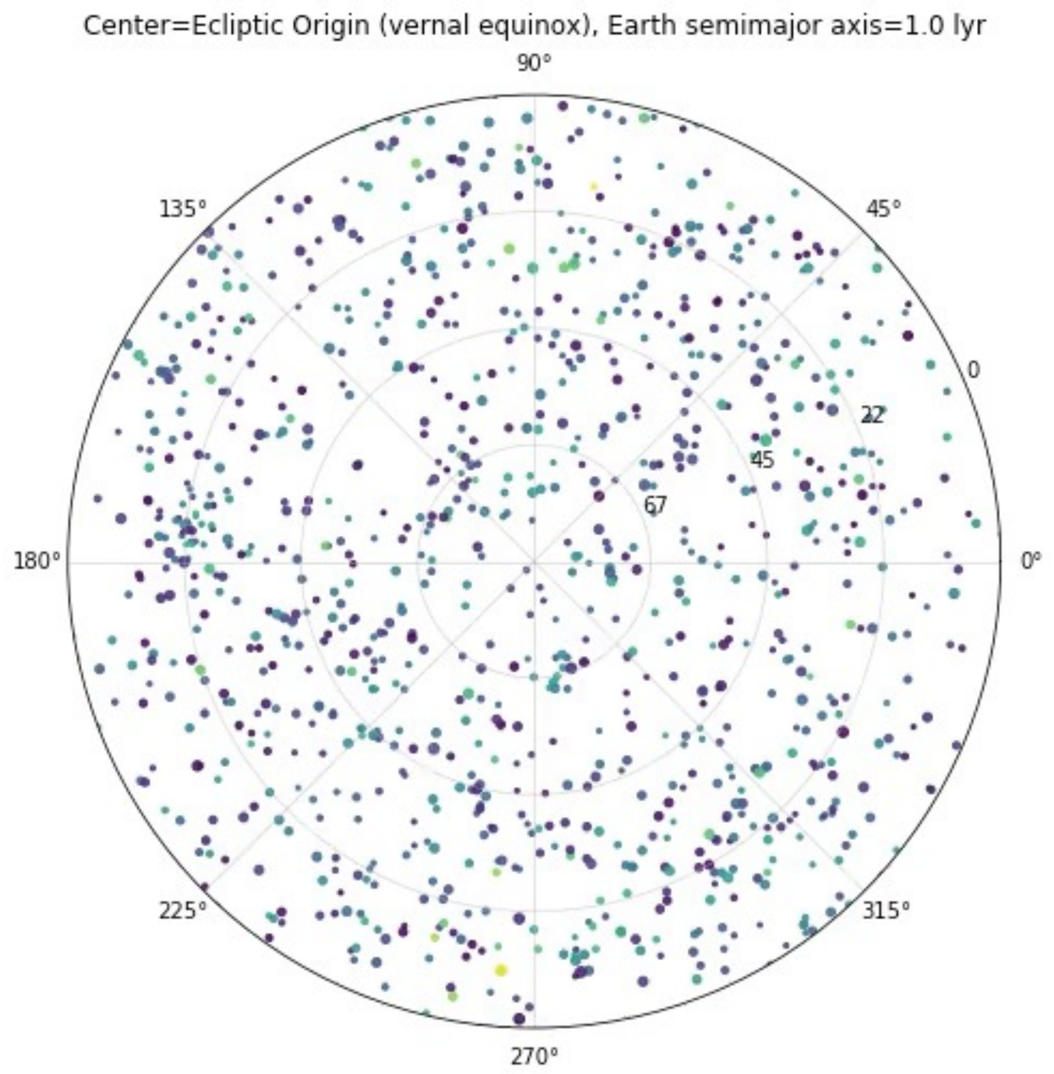
$$d = \frac{1\ AU}{\tan p}$$

In ASTR 221, we showed that if we measure p in arcsec ($''$) and define a parsec to be the distance where $p = 1''$, we get

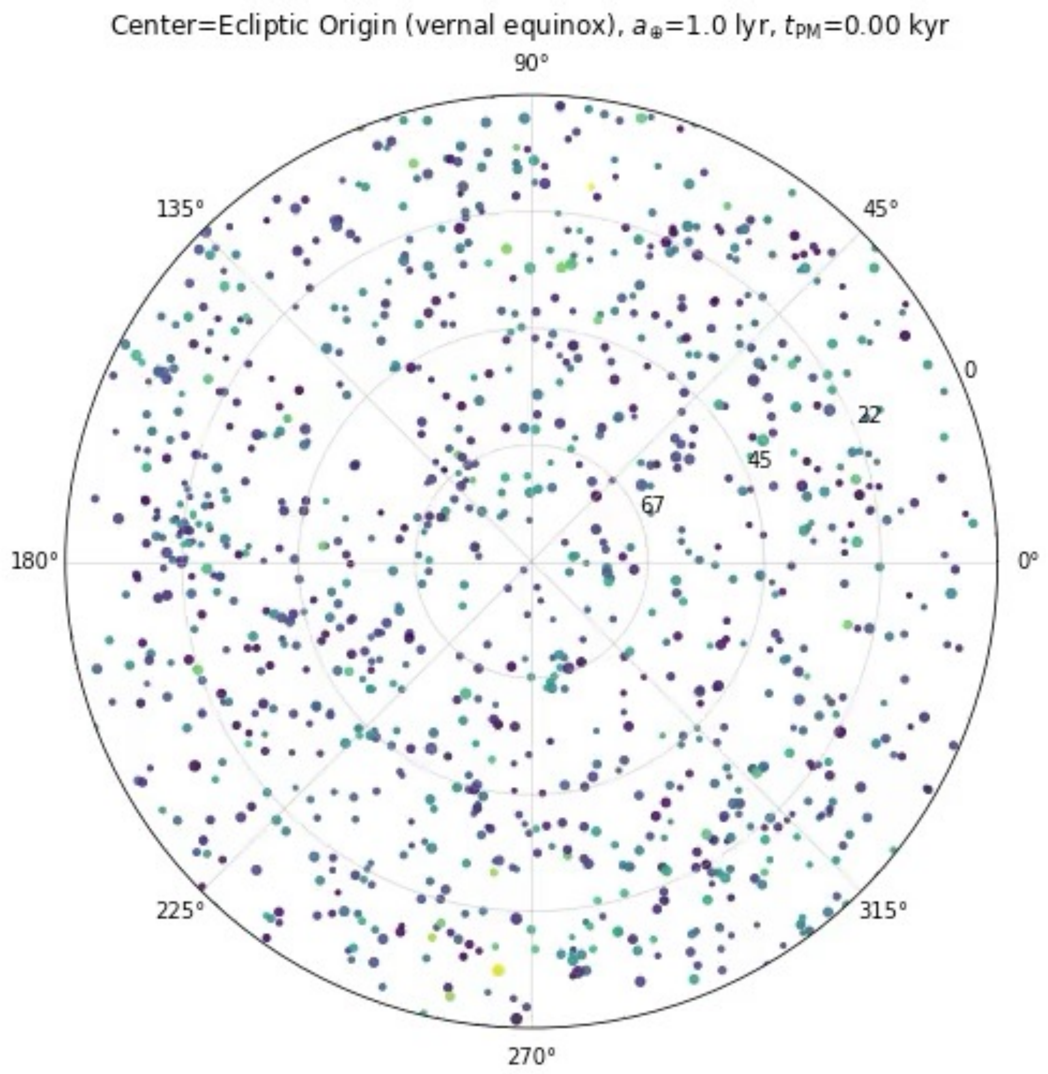
$$d[pc] = \frac{1}{p['']}$$

Animations *(courtesy Erik Tollerud and James Davenport)*

Parallax Only



Parallax + Proper Motion



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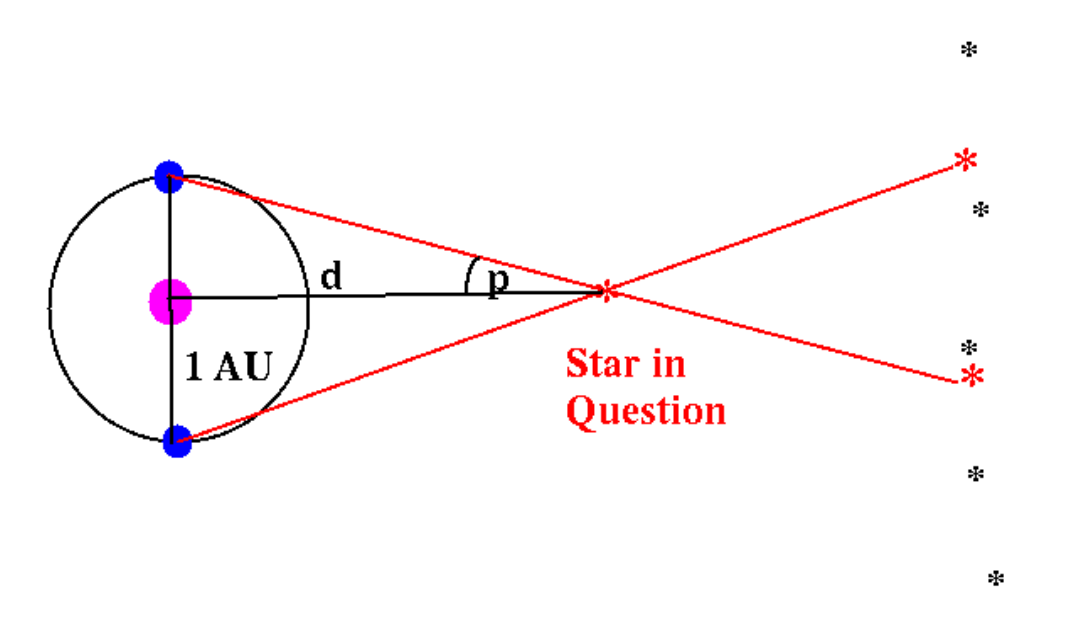

Satellite Parallax Missions

	Hipparcos
Dates	1989-1993
Limiting magnitude	~ 12
Parallax precision	milliarcsec
Distance	1 kpc
N(stars)	100,000


Gaia
12/19/2013 – 1/15/2025

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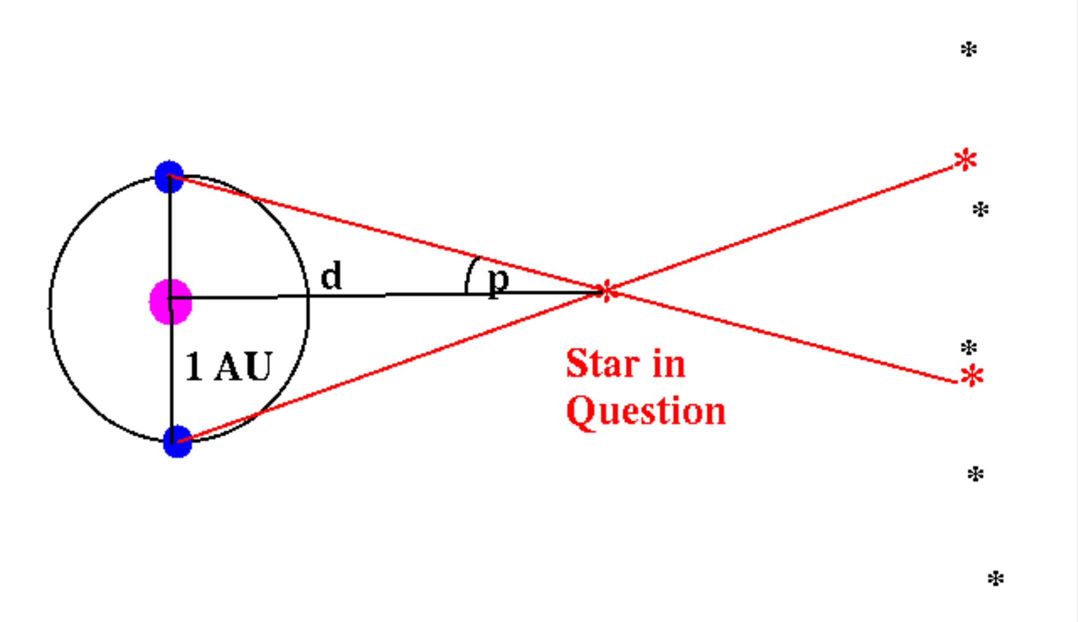

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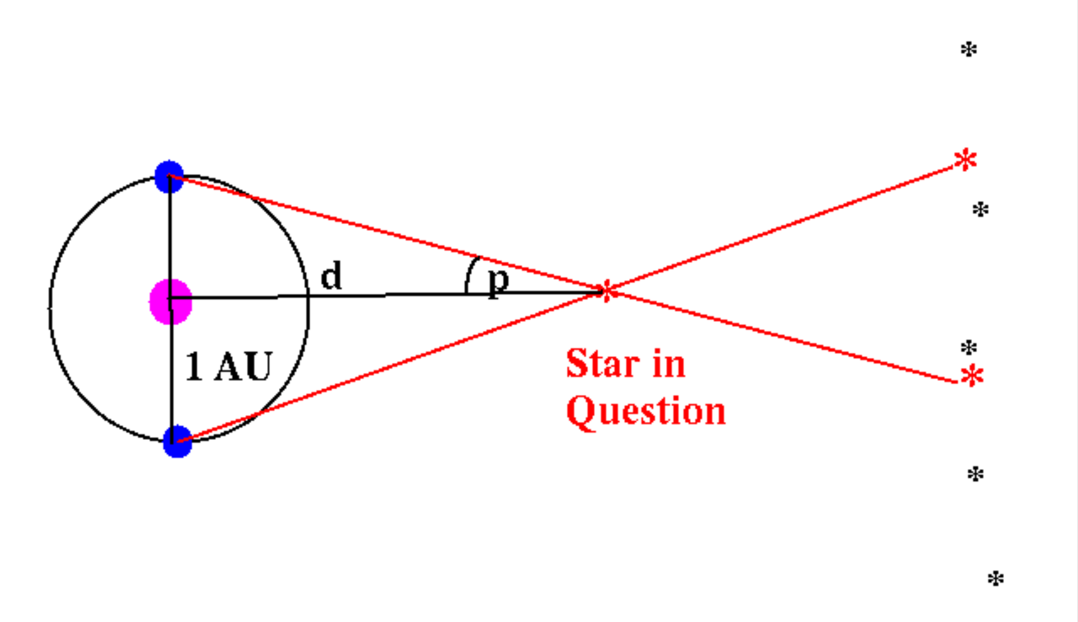


Satellite Parallax Missions

	Hipparcos	Gaia
Dates	1989-1993	2014-2025
Limiting magnitude	~ 12	~ 21
Parallax precision	milliarcsec	20-200 microarcsec
Distance	1 kpc	10-50 kpc
N(stars)	100,000	~ 1+ billion

Distances to Star Clusters: Main Sequence Fitting

Clusters are groups of stars all at the same age and distance. We can plot a color-magnitude diagram using apparent magnitude (m) and it will be shifted vertically from absolute-magnitude calibrated (M) "zero-age" main sequence (ZAMS) simply by the distance modulus:

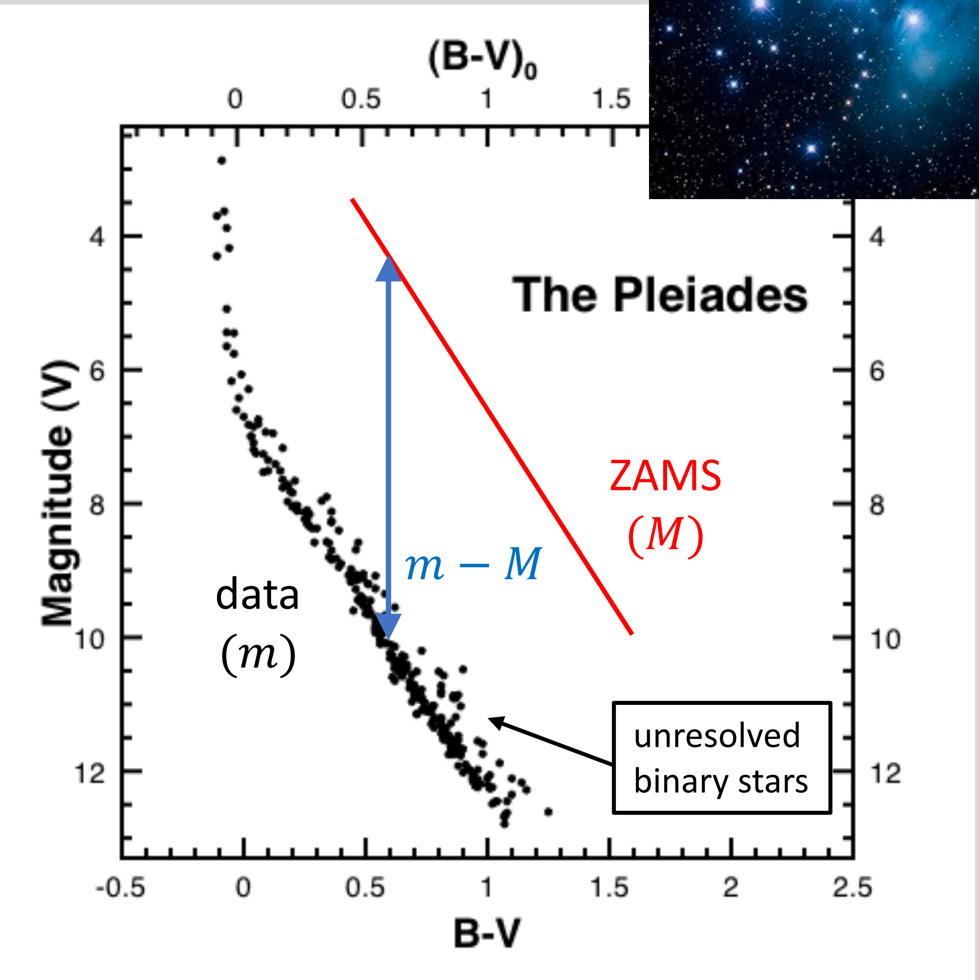
$$m - M = 5 \log d - 5$$

Two ways to do this, both conceptually the same:

1) Measure the apparent magnitude of cluster stars at a given color on the main sequence and compare to the absolute magnitude of main sequence stars at that color. The difference is the distance modulus.

2) Overplot an absolute magnitude main sequence, shifting it by different amounts until it lines up with the observed cluster main sequence. The shift that lines it up is the distance modulus.

Open star cluster (young stars)



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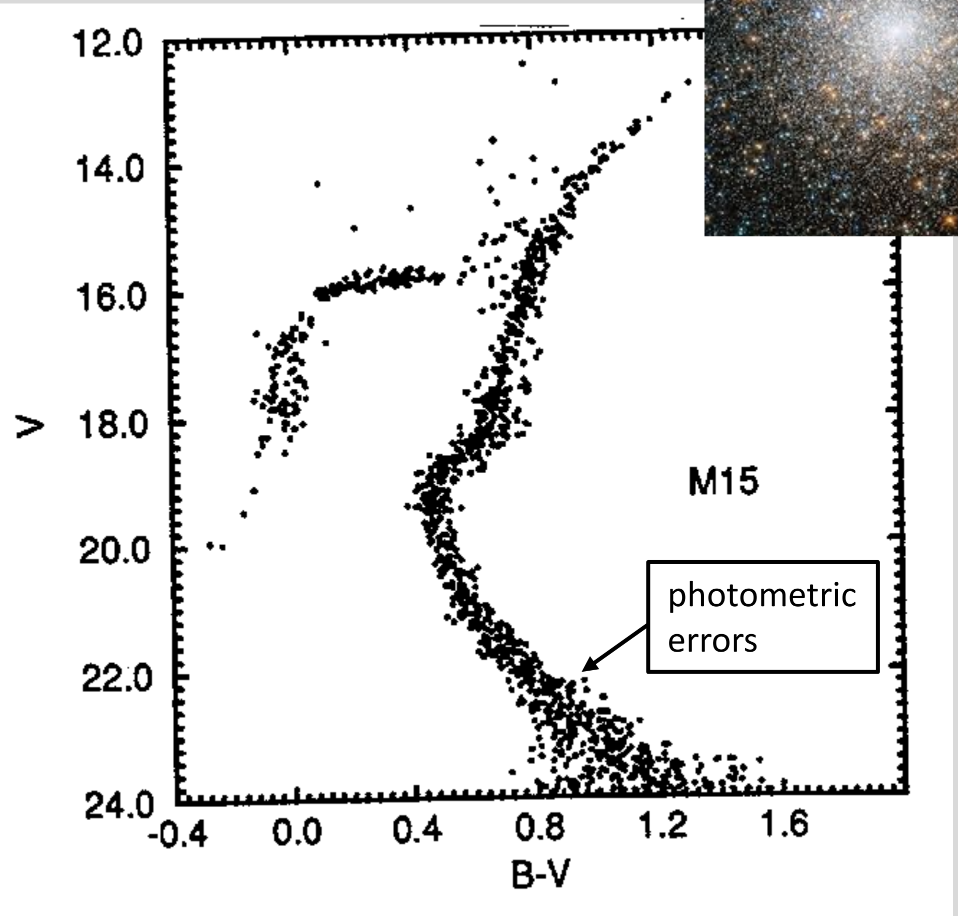
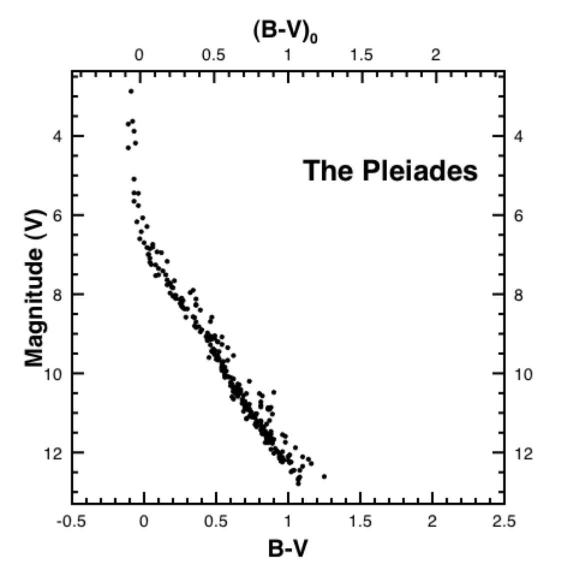
Works for globular clusters, too, just make sure you are looking at the main sequence!

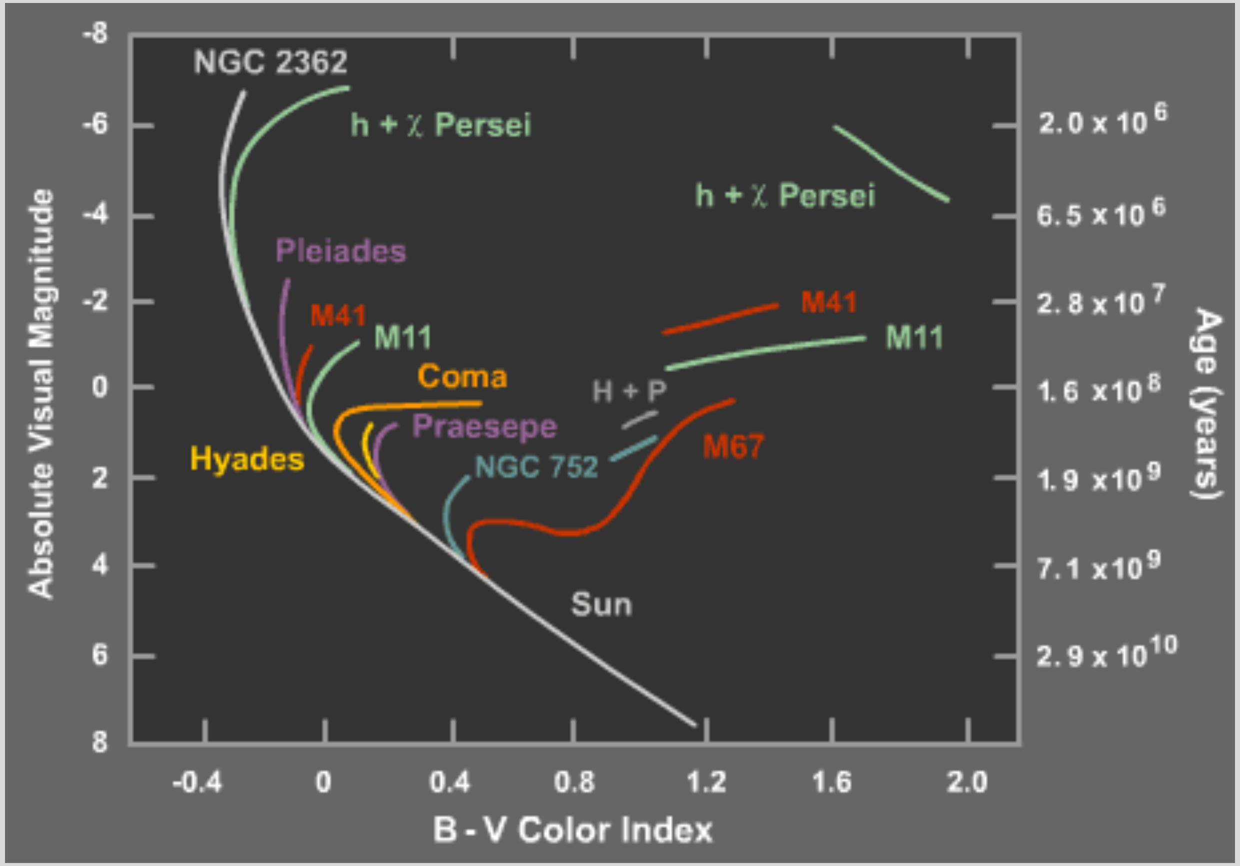
Globular star cluster (old stars)

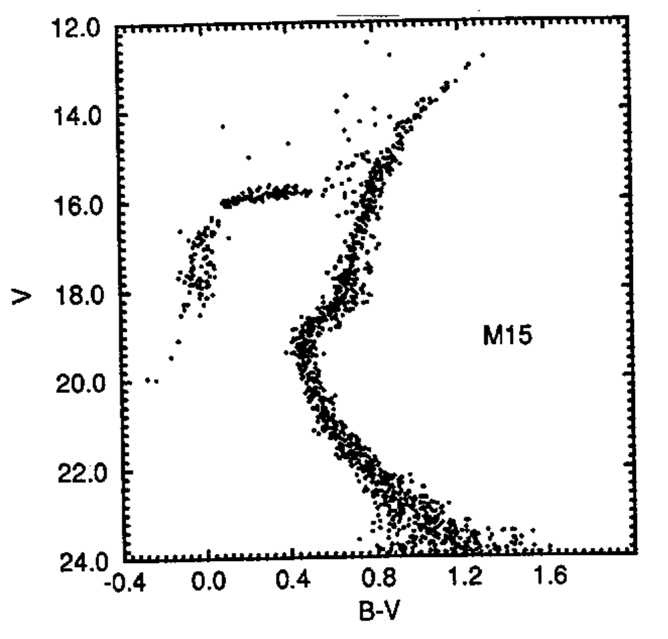


Color Magnitude Diagrams of Star Clusters: Deriving ages

As a star cluster ages, its high mass stars rapidly evolve off the main sequence. This “turnoff point” is a good indicator of the age of the star cluster.







Interstellar dust

Interstellar dust: Extinction

Remember our simple physical model for absorption (from ASTR 221). Think of a slab of dust particles with number density N, thickness L, and absorption cross-section σ. As light passes through this slab, it is attenuated in intensity by an amount $I = I_0 e^{-\tau}$ where $\tau = N\sigma L$.

We can convert this to true and extincted magnitudes like this:

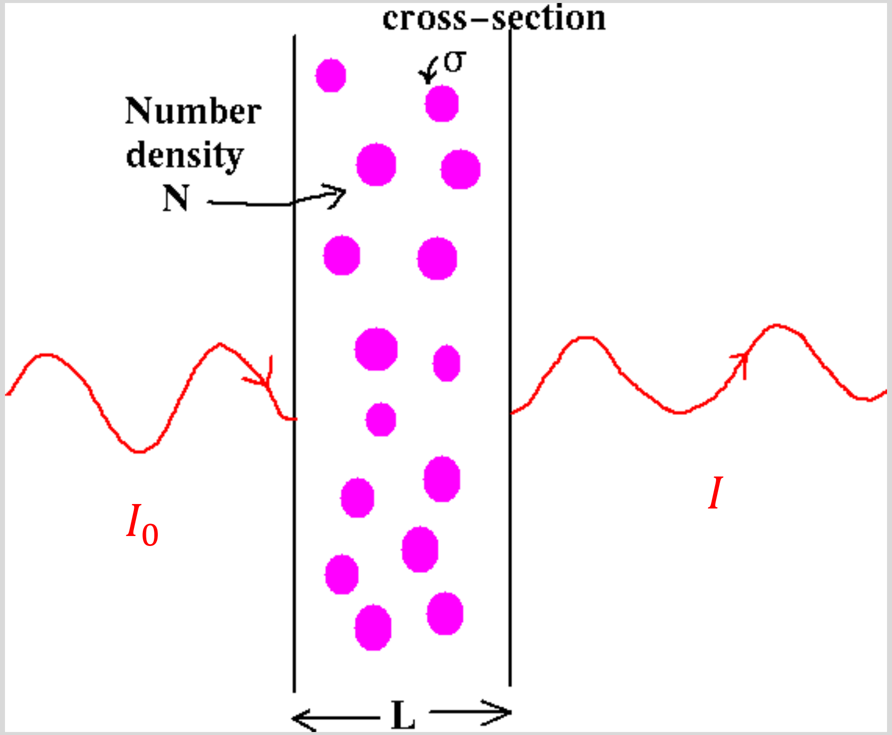
$$\begin{aligned} m - m_0 &= -2.5\log(I/I_0) \\ &= -2.5\log(e^{-\tau}) \\ &= -2.5(-\tau)\log e \\ &= 1.086\tau \end{aligned}$$

Let's define **extinction** (in magnitudes) as $A = 1.086\tau$, then we can correct the observed magnitude for the effects of dust like this:

$$m - m_0 = A$$

or

$$\underbrace{m_0}_{\text{true mag}} = \underbrace{m}_{\text{observed mag}} - \underbrace{A}_{\text{extinction}}$$



Questions:

1. Does it make sense that we ***subtract*** A to get the true magnitude?
2. If we didn't correct for extinction, what would this do to our inferred distance to a star?
3. How do we measure the extinction A?

Interstellar dust: Reddening

The extinction value (A) depends strongly on wavelength. The shorter the wavelength, the higher the extinction -- blue light is extincted more strongly than red light. Therefore, stars behind a lot of dust look redder than they really are. This is called **interstellar reddening**.

For example, the observed $B - V$ color is redder than the true color; we refer to the amount of reddening as $\mathrm{E}(B-V)$:

$$\mathrm{E}(B-V) = \underbrace{(B-V)}_{\text{observed color}} - \underbrace{(B-V)_0}_{\text{true color}}$$

Question: how could we measure $E(B-V)$*?*

Trumpler (1930): Noticed that stars in clusters at greater distances were systematically redder and fainter than expected.

It's reasonable to expect that the more extinction there is, the more reddening there is. So extinction and reddening are correlated:

$$A_\lambda = C_\lambda E(B-V)$$

Filter	Central Wavelength	C_λ
B	~ 4400 Å	4.1
V	~ 5500 Å	3.1
R	~ 6500 Å	2.7
K	~ 22000 Å	0.5

Interstellar dust: Scattering

Extinction is not just due to dust absorbing light. Dust also scatters light, and blue light is scattered much more than red light. This leads to “reflection nebulae” that show dust.

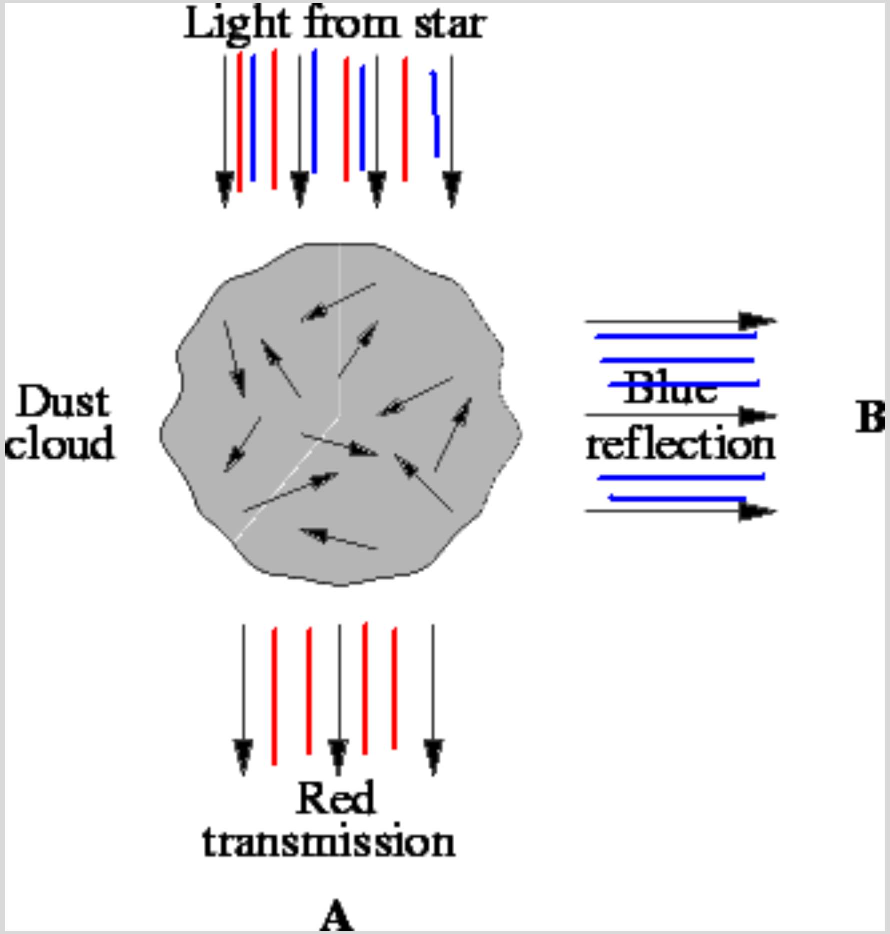


image credit: Miguel Claro

Interstellar dust: Emission

At mid- and far-infrared wavelengths, the dust glows: a combination of a thermal blackbody and emission lines.

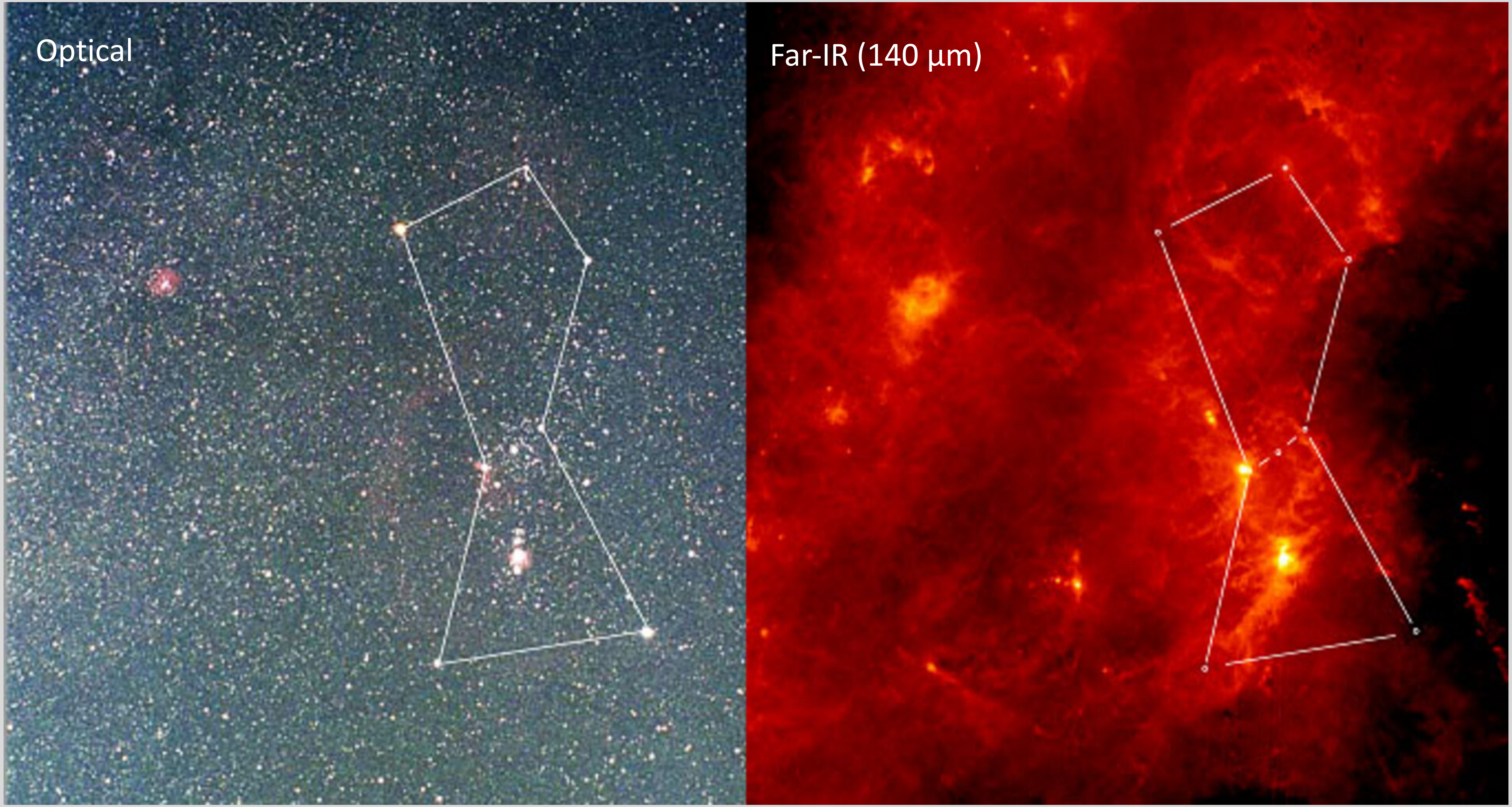
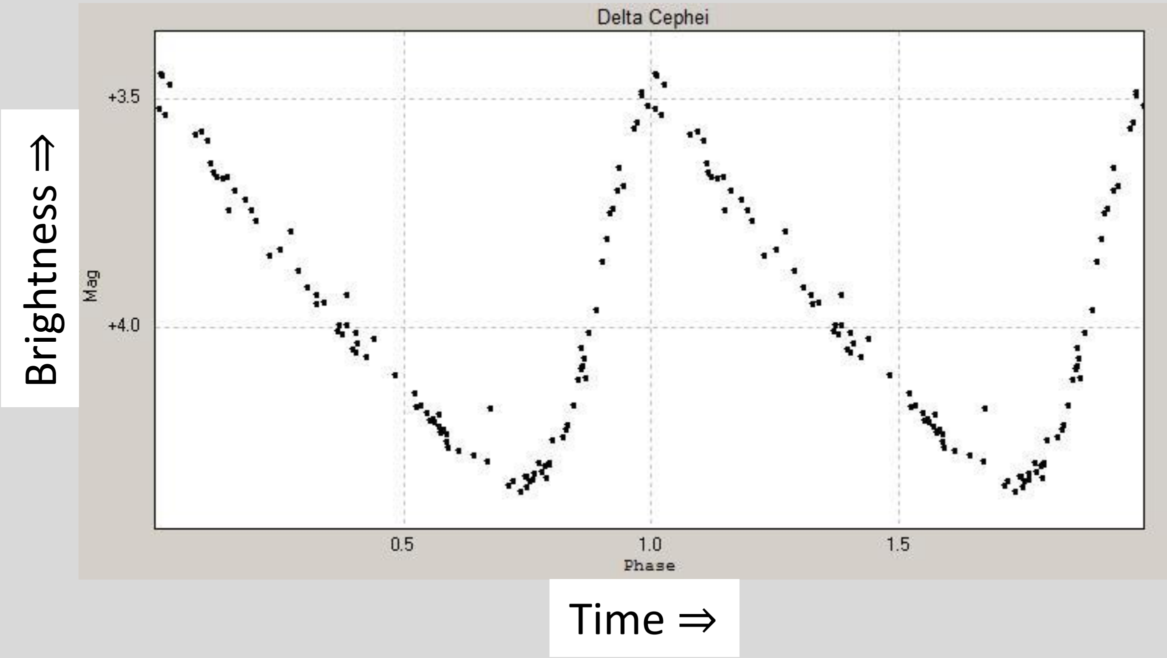


image credit: ESA

Cepheid variable stars

Cepheids are a class of variable stars named after the (naked-eye) star Delta Cephei which varies in brightness by ~ 1 mag over a 5.367 day period.



We can tell they are pulsating stars by examining their brightness, temperature, size, and radial velocity during the period. ⇒

Over the pulsation period, **Cepheids are brightest when they are smallest and hottest**. Does this make sense?

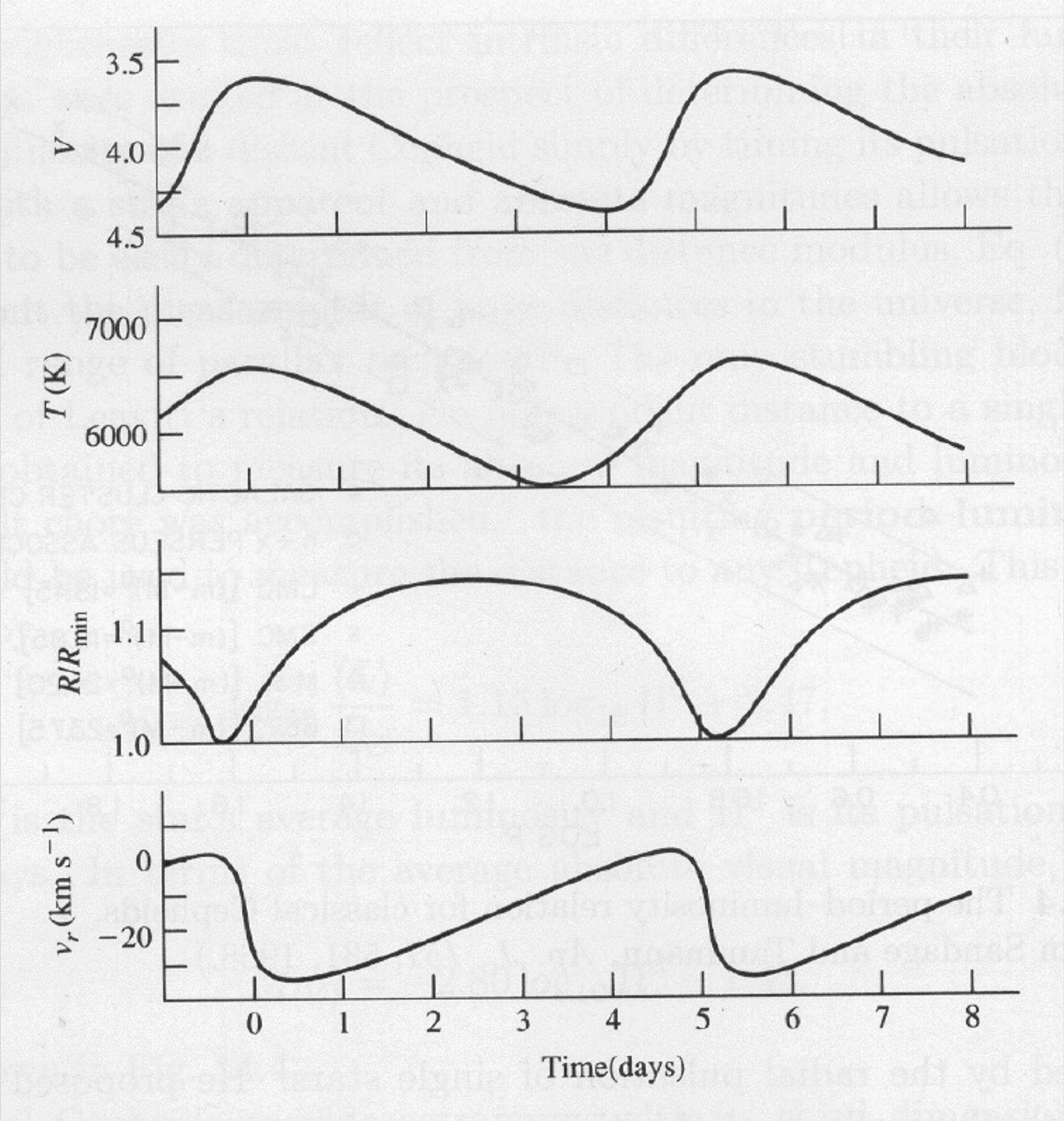


Figure 14.5 Observed pulsation properties of δ Cephei.

Cepheid variable stars

What are these things? Plot them on an H-R diagram, see where they are. Overplot stellar evolution tracks as well.

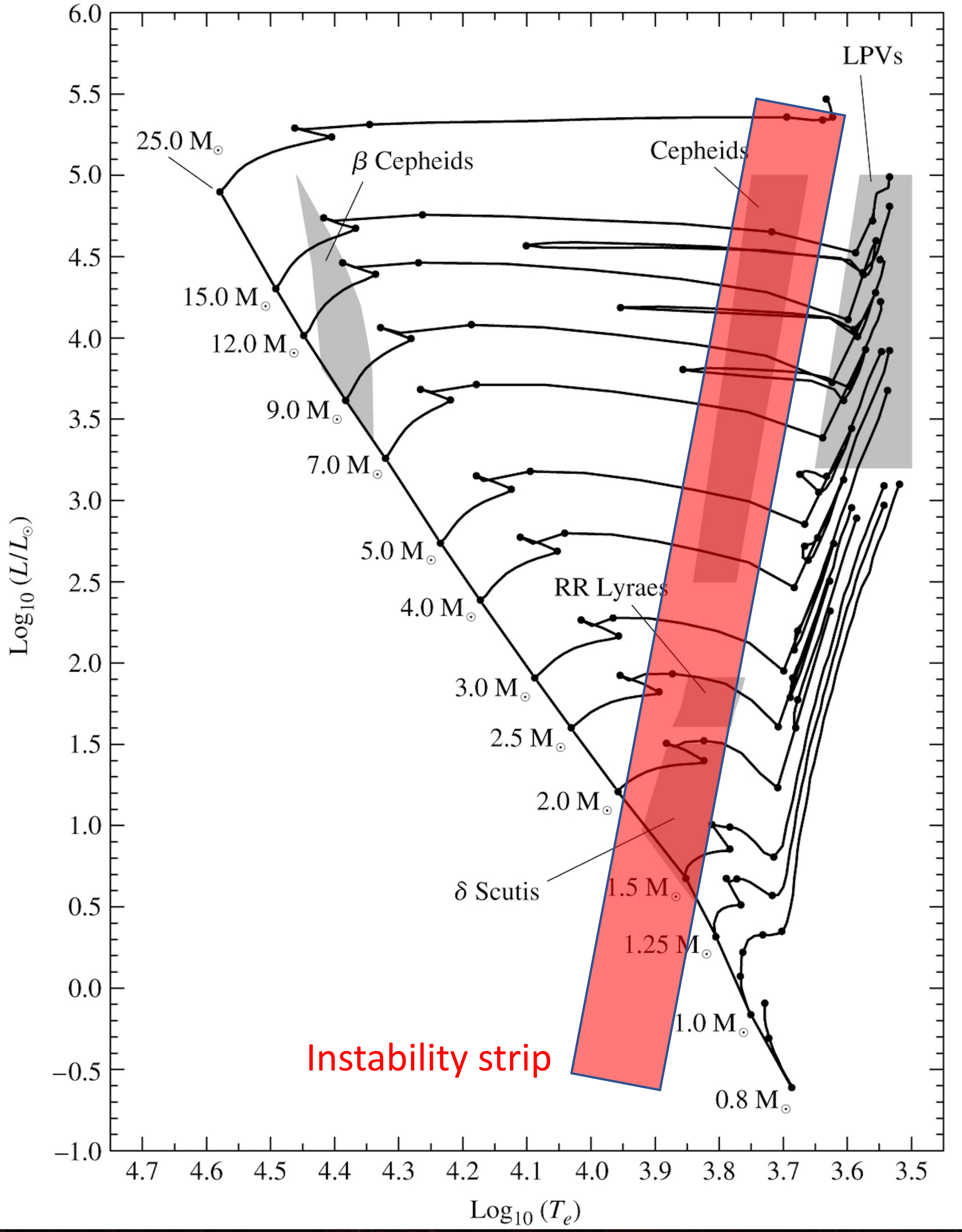
Cepheids are evolving high mass stars!

There are other types of pulsating stars, which define an "instability strip" on the H-R diagram:

- Cepheids
- W Virginis stars (metal-poor, underluminous Cepheids)
- RR Lyrae stars (evolved low mass stars)
- Delta Scuti stars (evolved F stars)
- ZZ Ceti stars (pulsating white dwarfs!)

When stars evolve into these regions of the H-R diagram, the physical conditions (temperature, pressure, opacity) inside the star start to drive pulsation.

(Pulsation physics explained...)



Cepheid as distance indicators

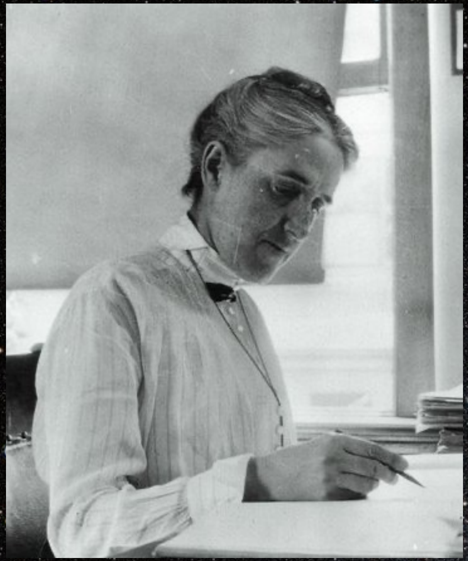
1912: Henrietta Leavitt studies Cepheids in the Small Magellanic Cloud, finds brighter ones have longer periods.

Since all these Cepheids lie at the same distance, this implied a fundamental relationship between luminosity and period.

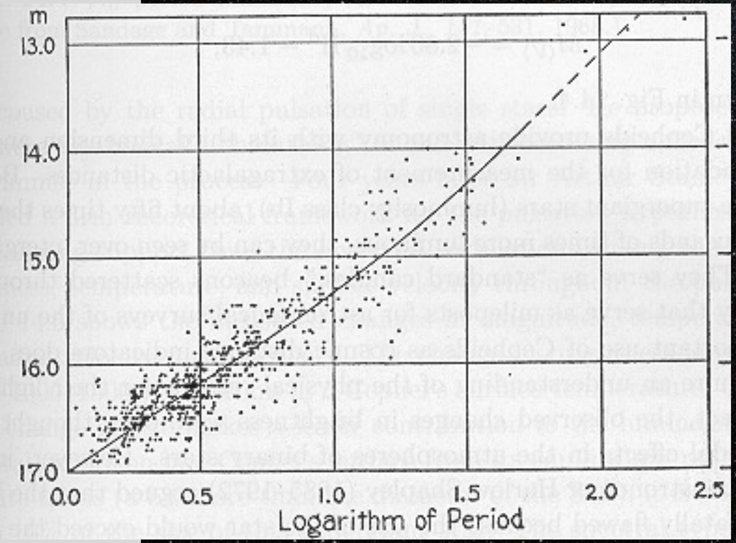
If we can calibrate "Leavitt's Law"(aka the period-luminosity relationship) using Cepheids with ***known*** distances, we can use it as a distance indicator:

- Measure period and app mag (m)
- Use period to derive abs mag (M)
- Derive distance from

$$m - M = 5 \log d - 5$$



Henrietta Leavitt (1868-1921)

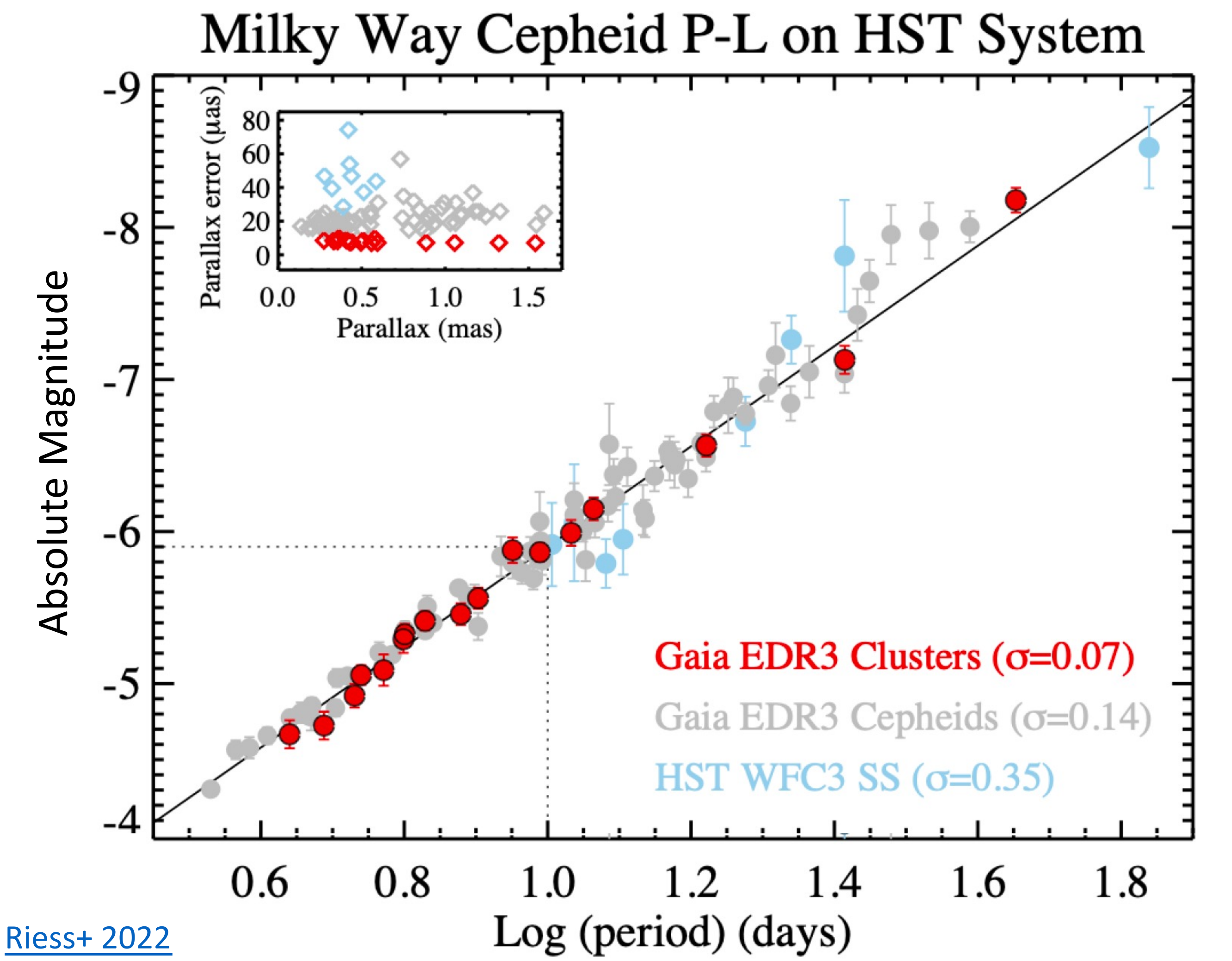


Small Magellanic Cloud

Cepheid as distance indicators

Since Cepheids are massive, evolved stars, they are very rare, and there aren't many nearby. For a long time we couldnt get parallaxes for them, so we used "secondary calibrators" to get their distances (main sequence fitting, for example).

But now, using a combination of Gaia data and Hubble data, we can get parallaxes to distant Cepheids and calibrate the relationship!



Riess+ 2022

Cepheid distances: pros and cons

Pros:

- Cepheids are bright (1000x the Sun) and can be seen even in other galaxies.
- Cepheids are driven by reasonably well-understood pulsation physics.

Cons:

- Cepheids are very rare.
- Their period also depends on their metallicity (so its a P-L-Z relationship)

Metallicity of Stars

We can define chemical composition, or **metallicity**, for stars using the **Iron to Hydrogen ratio**. For the Sun, this is given by

$$\log(Fe/H)_{\odot} \approx -4.33$$

or about 20,000 hydrogen (H) atoms for every Iron (Fe) atom.

We measure this value for other stars relative to the Sun, using a quantity called **[Fe/H]**:

$$[Fe/H] = \log\left[\frac{(Fe/H)_*}{(Fe/H)_{\odot}}\right] = \log(Fe/H)_* - \log(Fe/H)_{\odot}$$

Defined this way, the Sun has $[Fe/H]_{\odot} \equiv 0.0$

$[Fe/H] = +0.5$: metal-rich star, metallicity is 3x solar
$[Fe/H] = 0.0$: solar metallicity star
$[Fe/H] = -2.0$: metal-poor star, metallicity is 1/100 solar.

Stars can span a wide range of metallicity:

$$-4.5 < [Fe/H] < +1.0$$

From ASTR221:

elemental abundance of the Sun.

	Mass Fraction	Solar Value
Hydrogen	X	0.70
Helium	Y	0.28
Everything else (“metals”)	Z	0.02

Notes:

- “Bracket notation” can be used to define abundance of any element. Iron commonly used because it is easy to measure.
- Sometimes stellar modelers use [Z/H], which is measuring all metals combined.

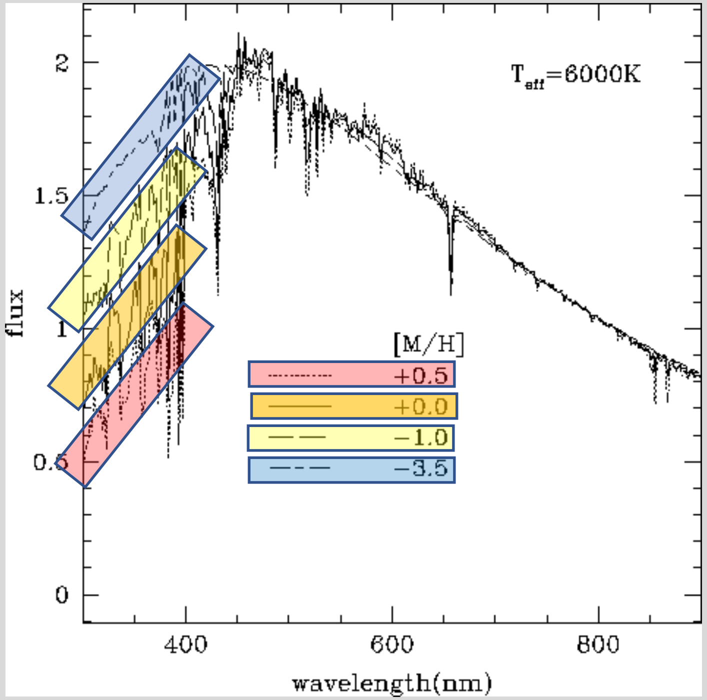
Metallicity of Stars

How does metallicity affect the ***observed*** properties of stars?

Simple rule of thumb: metal-poor makes stars bluer, metal-rich makes stars redder. Why?

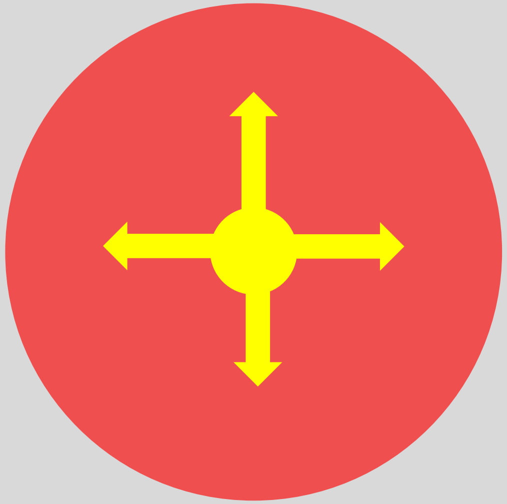
Line blanketing

Metals (particularly Iron) preferentially absorb light at bluer wavelength. More metals means more blue absorption, which makes stars redder.



Opacity

The metals absorb energy trying to get out from the interior of the star. This bottled up energy pushes out and makes red giants swell up even more. Larger red giants are cooler red giants (and thus redder).



Metallicity of Stars

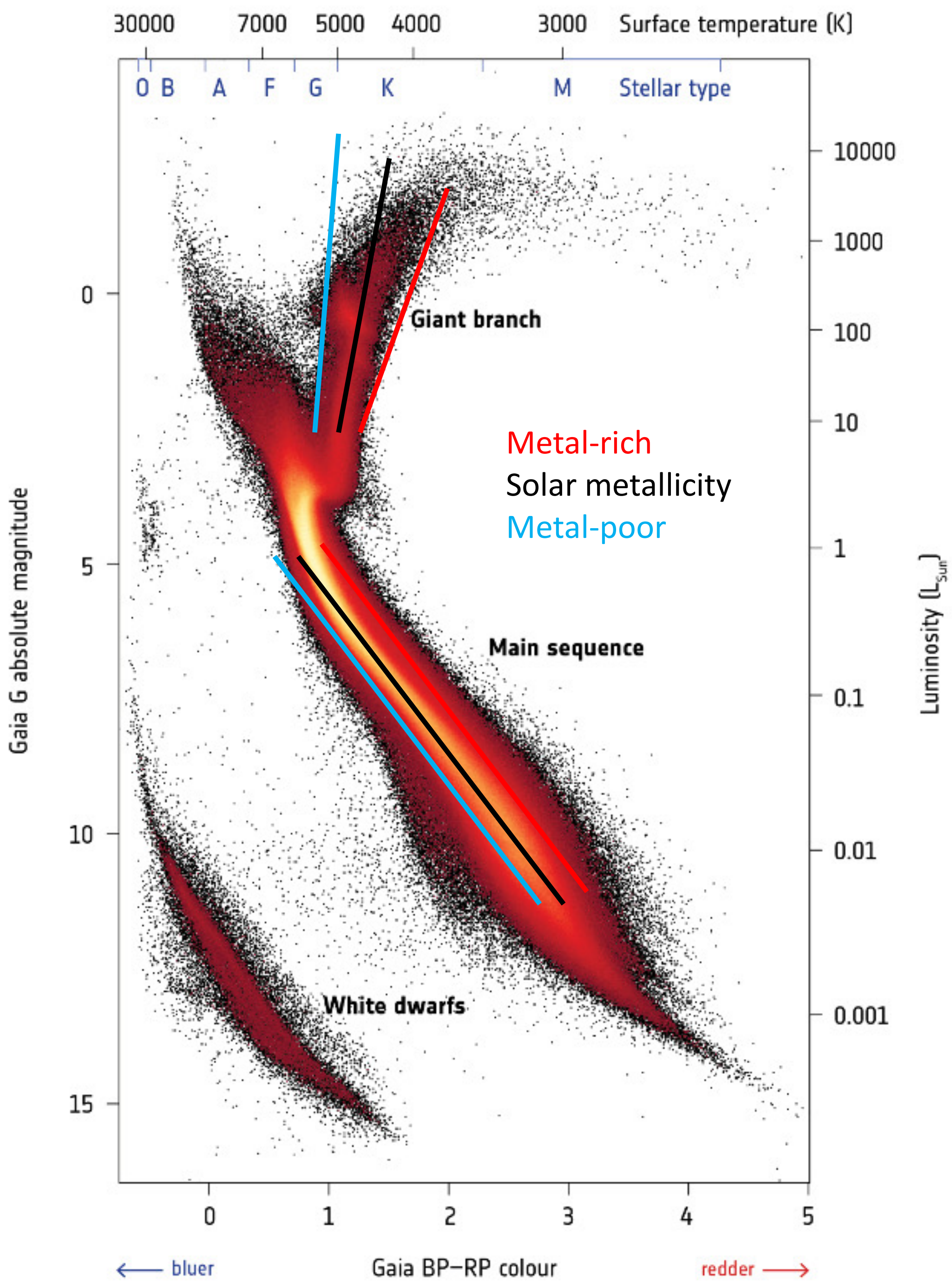
How does metallicity affect the ***color magnitude diagram***?

- RGB tracks get redder at high metallicity
- MS tracks get bluer at low metallicity, historically metal-poor MS stars were called "sub-dwarfs"

This means that lots of things can affect the colors of stars and star clusters:

- Age (older populations are redder on average)
- Metallicity (metal rich populations are redder on average)
- Dust (dusty populations are redder on average)

Distentangling all these effects is complicated, often requiring multiwavelength observations and spectroscopy.



Metallicity and Chemical Evolution in the Galaxy

Stars form from interstellar gas with a given metallicity (chemical composition), and this sets the metallicity of the star.

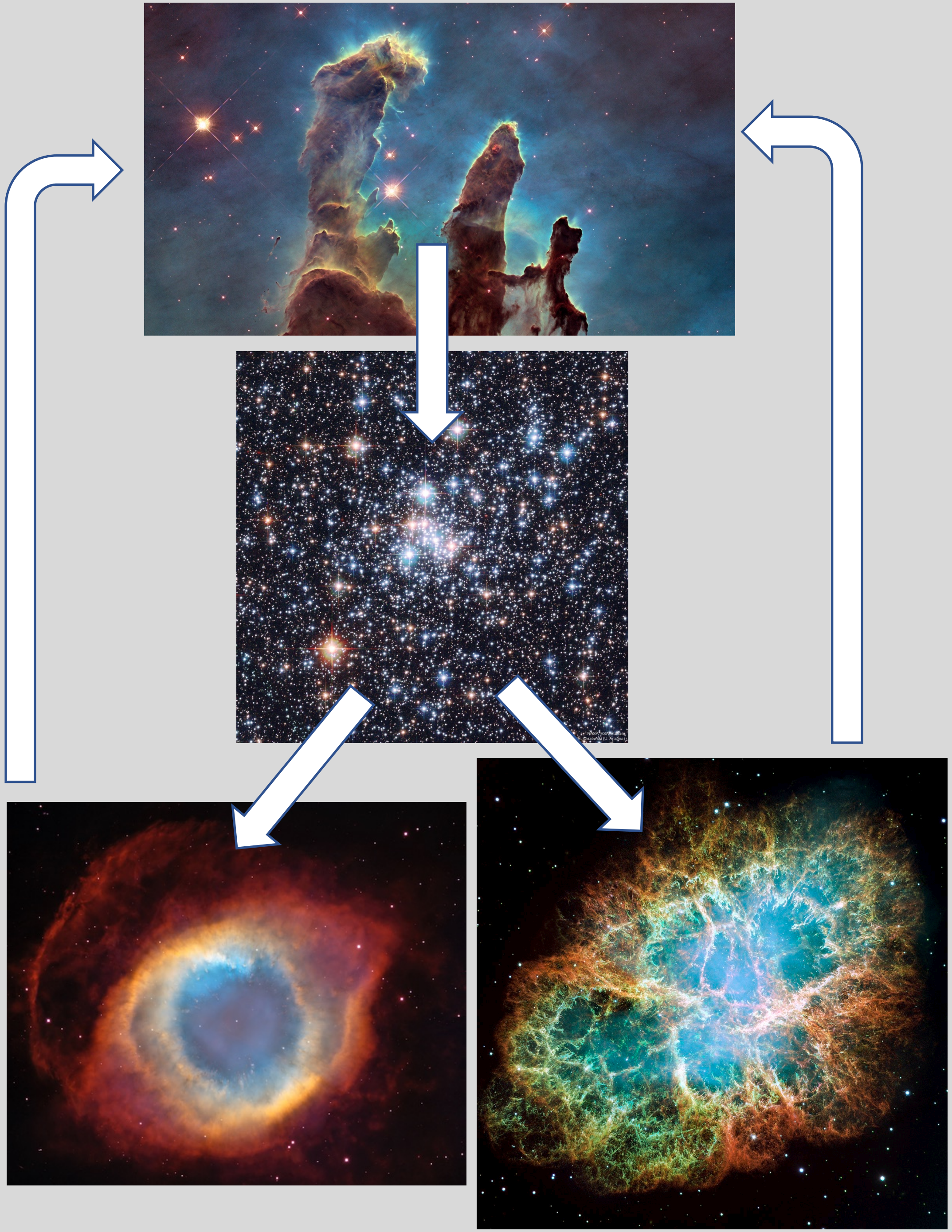
As the star undergoes nuclear fusion, it converts hydrogen into helium and heavier elements, but all this happens deep in the core of the star. The chemical abundances of the star’s outer layers is largely unaffected. **A star’s metallicity does not change with time.**

When the star dies it ejects its heavy elements into the surrounding gas, enriching the gas and raising the metallicity of the gas.

New stars form from this gas, and these **new stars have higher metallicity** than the previous generations.

Over time, as long as new stars are forming, **the metallicity of the overall population increases** even though individual stars are not changing metallicity.

Metallicity can build up rapidly if the star formation rates are high, or more gradually if star formation is limited. **But metallicity is not an absolute clock.** Old stars in our Galaxy have a wide range of metallicity.



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.

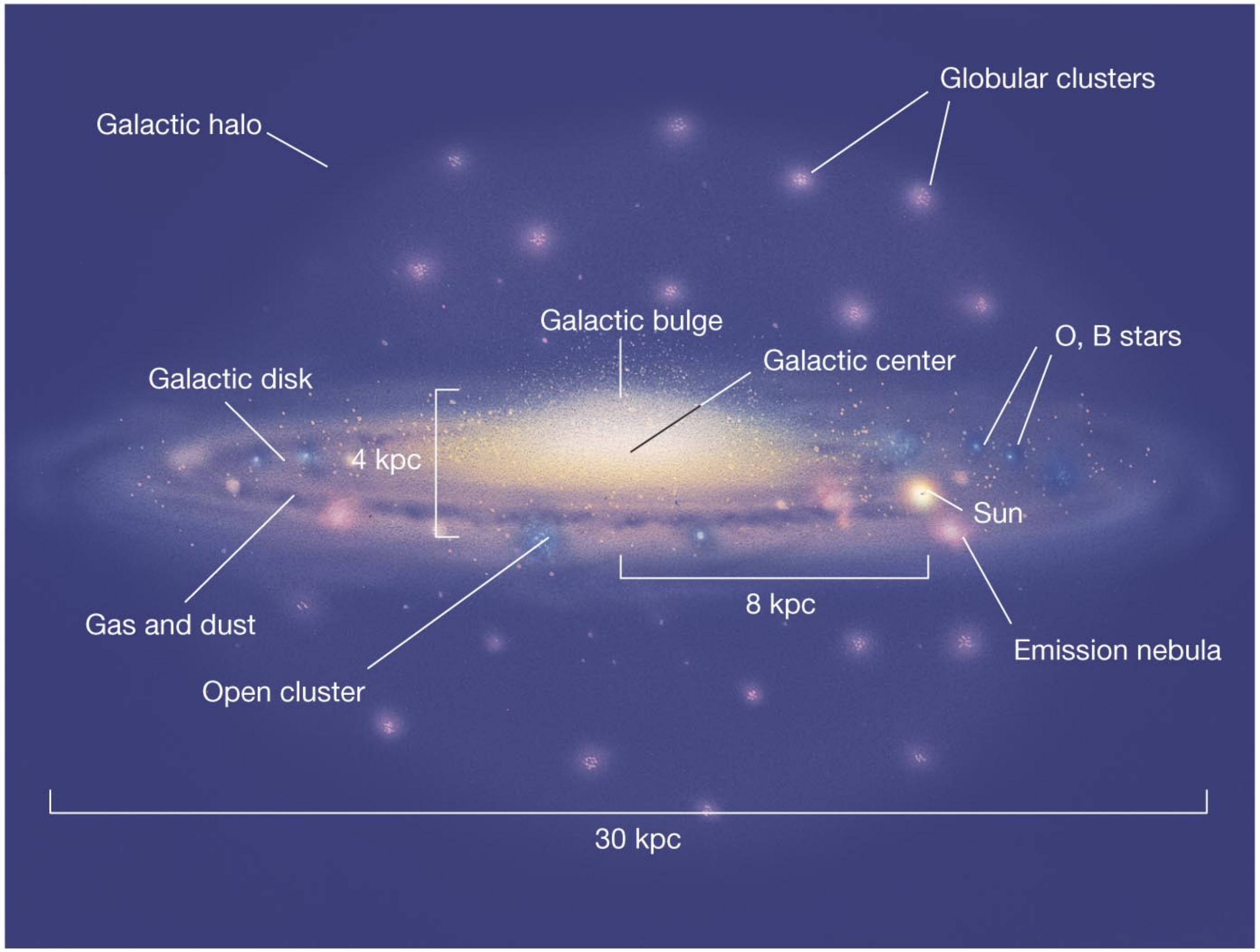
$$L_{B,disk} \approx 2 \times 10^{10}\ L_{\odot}$$

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.

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



Stellar Populations in the Milky Way

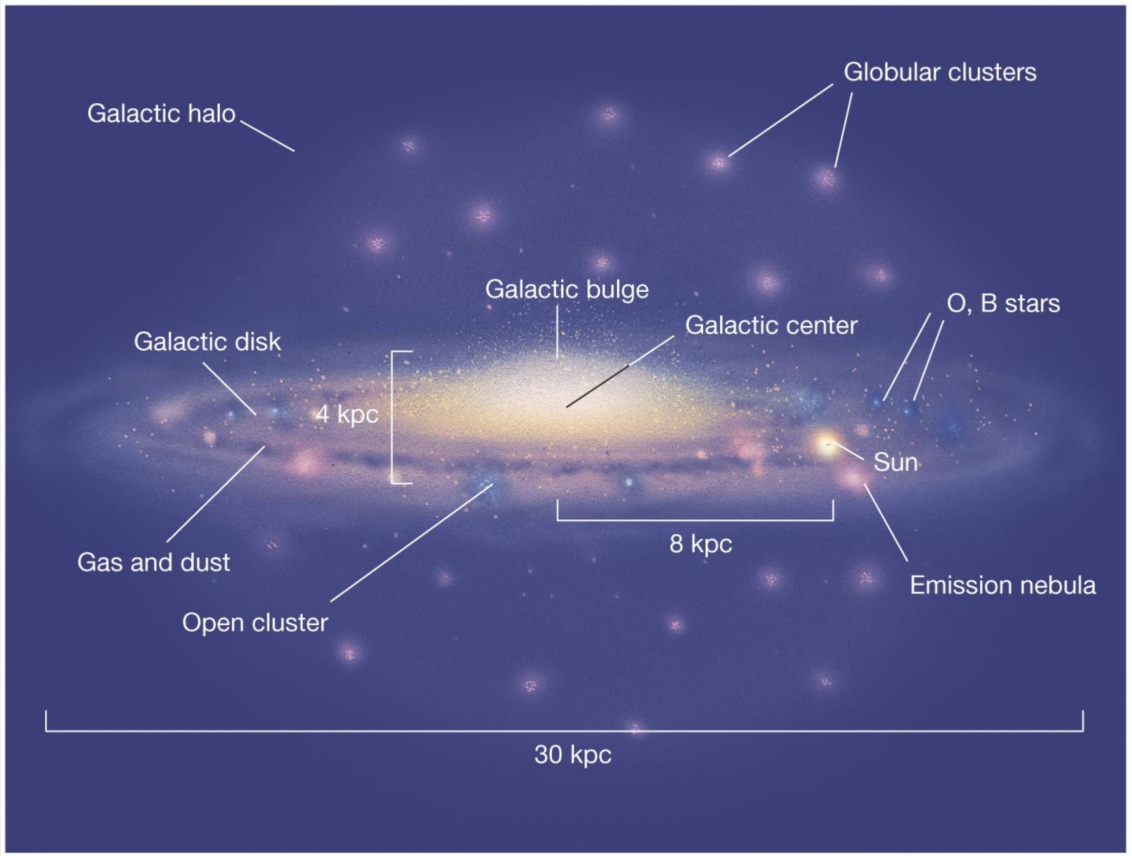
1940s: Walter Baade develops the idea of distinct stellar populations in the Milky Way.

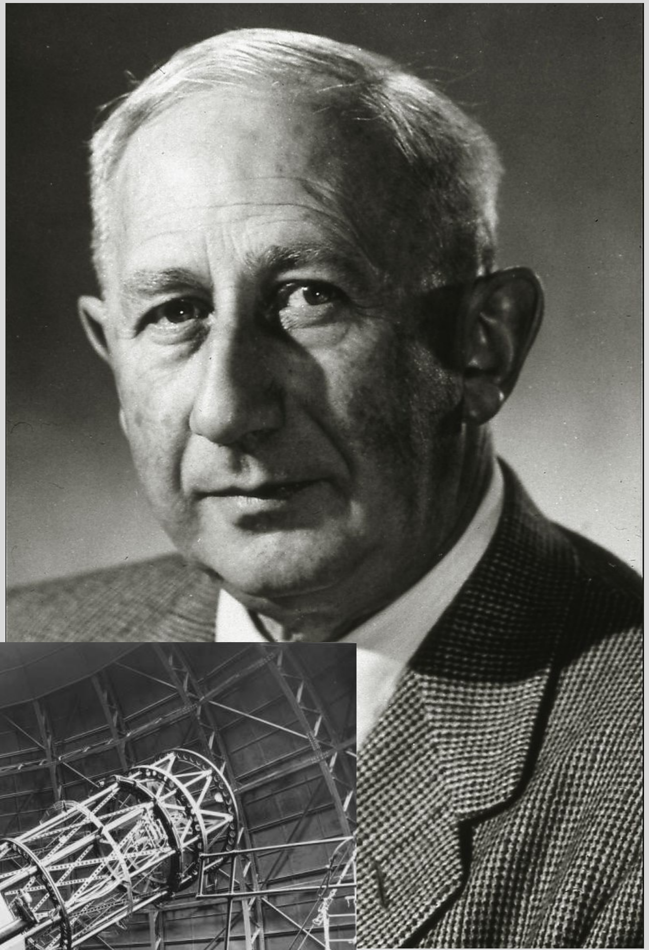
Population I

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

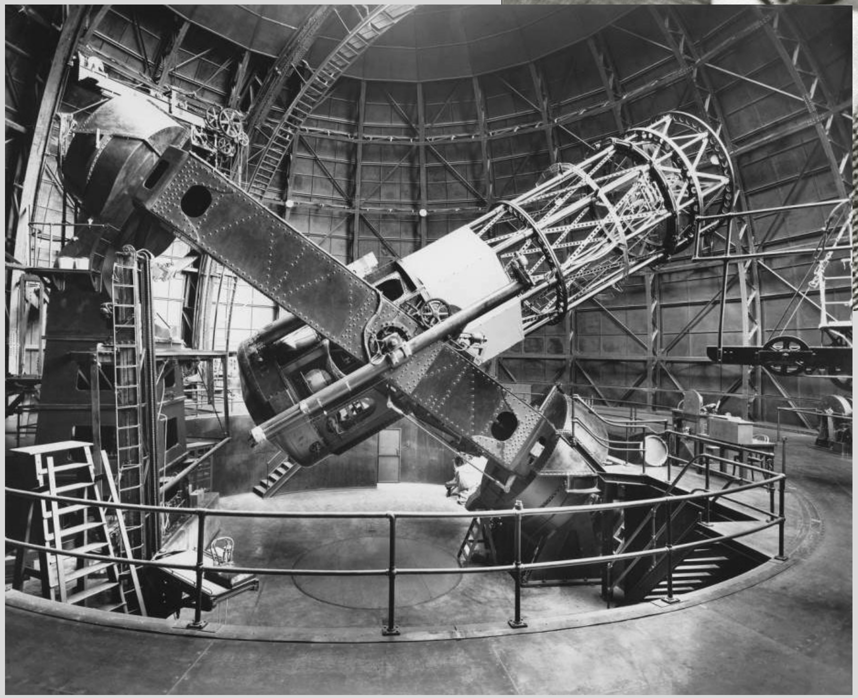
Population II

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





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.

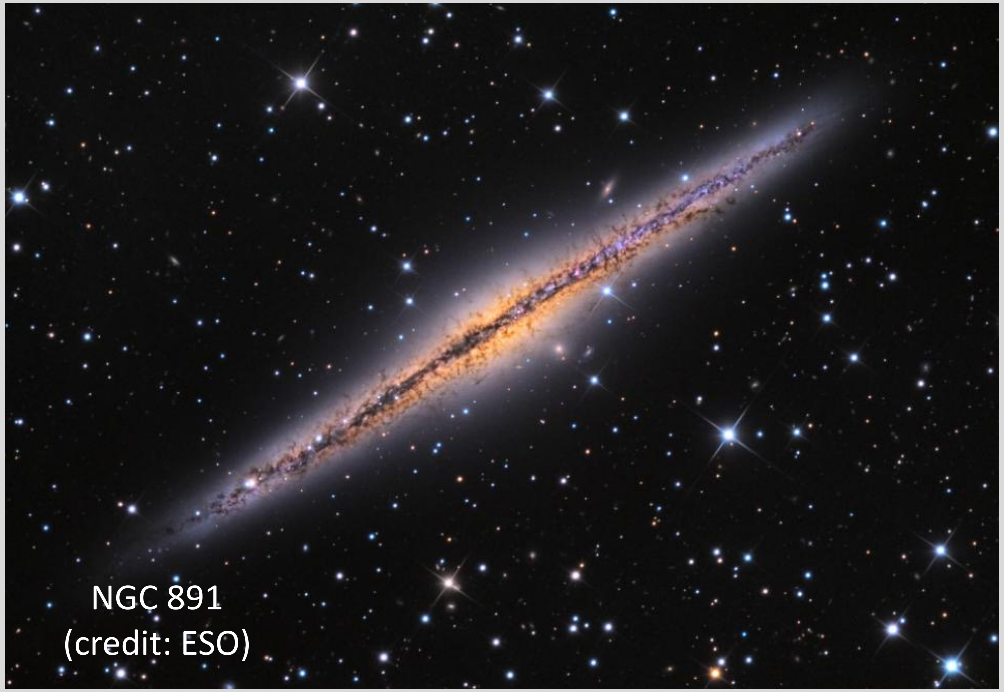
For the Milky Way, the scale length is $h \approx 3$ kpc, and the Sun lies at ≈ 8.2 kpc from the center.

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!


Andromeda Galaxy
(credit: David Dayag)


NGC 891
(credit: ESO)

The Disk of the Milky Way

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

M101
Robert Gendler

Multiwavelength Spiral Structure

Gas and young stars trace spiral structure most closely

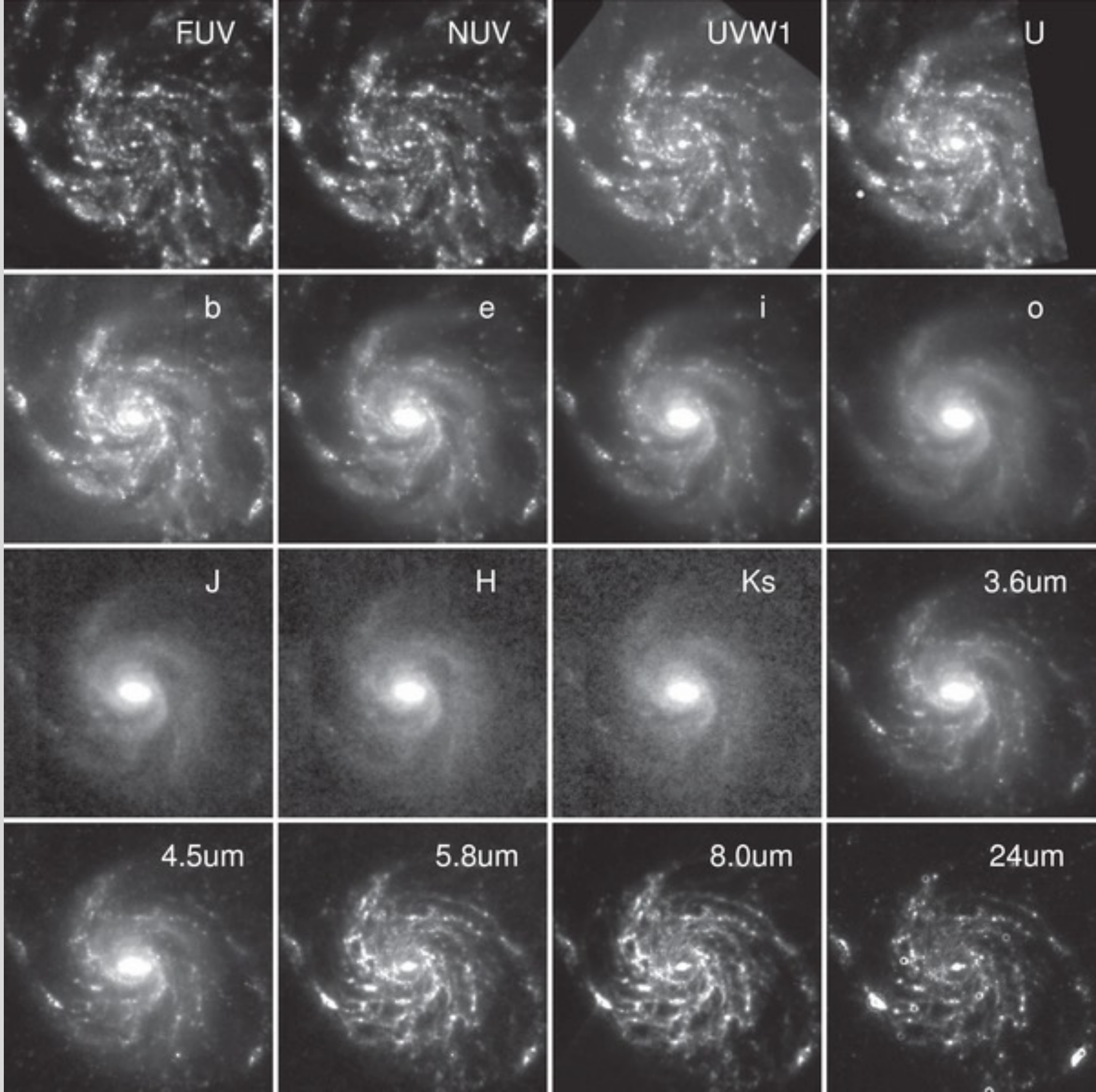
Older stars are more smoothly distributed throughout the disk, and also contribute most of the bulge light.

ultraviolet
young stars

optical
all stars

near IR
old stars

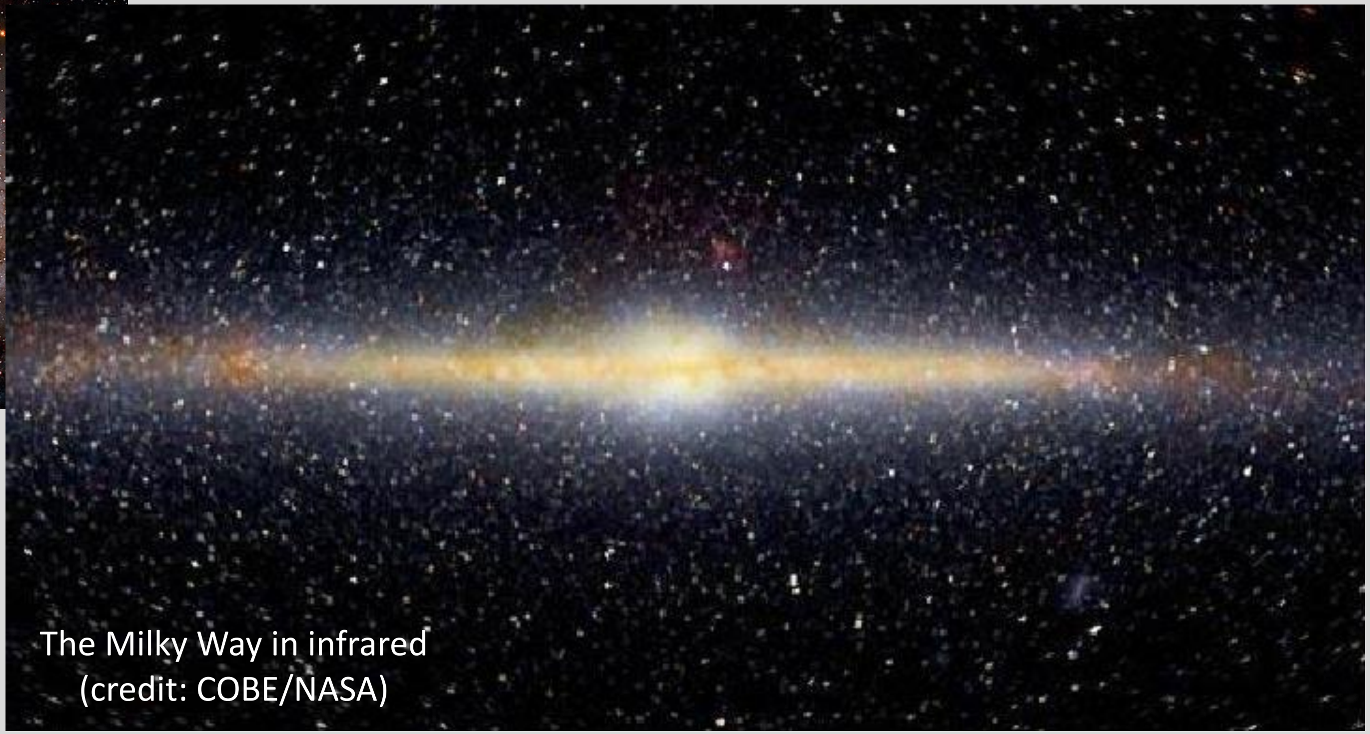
mid IR
warm dust



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

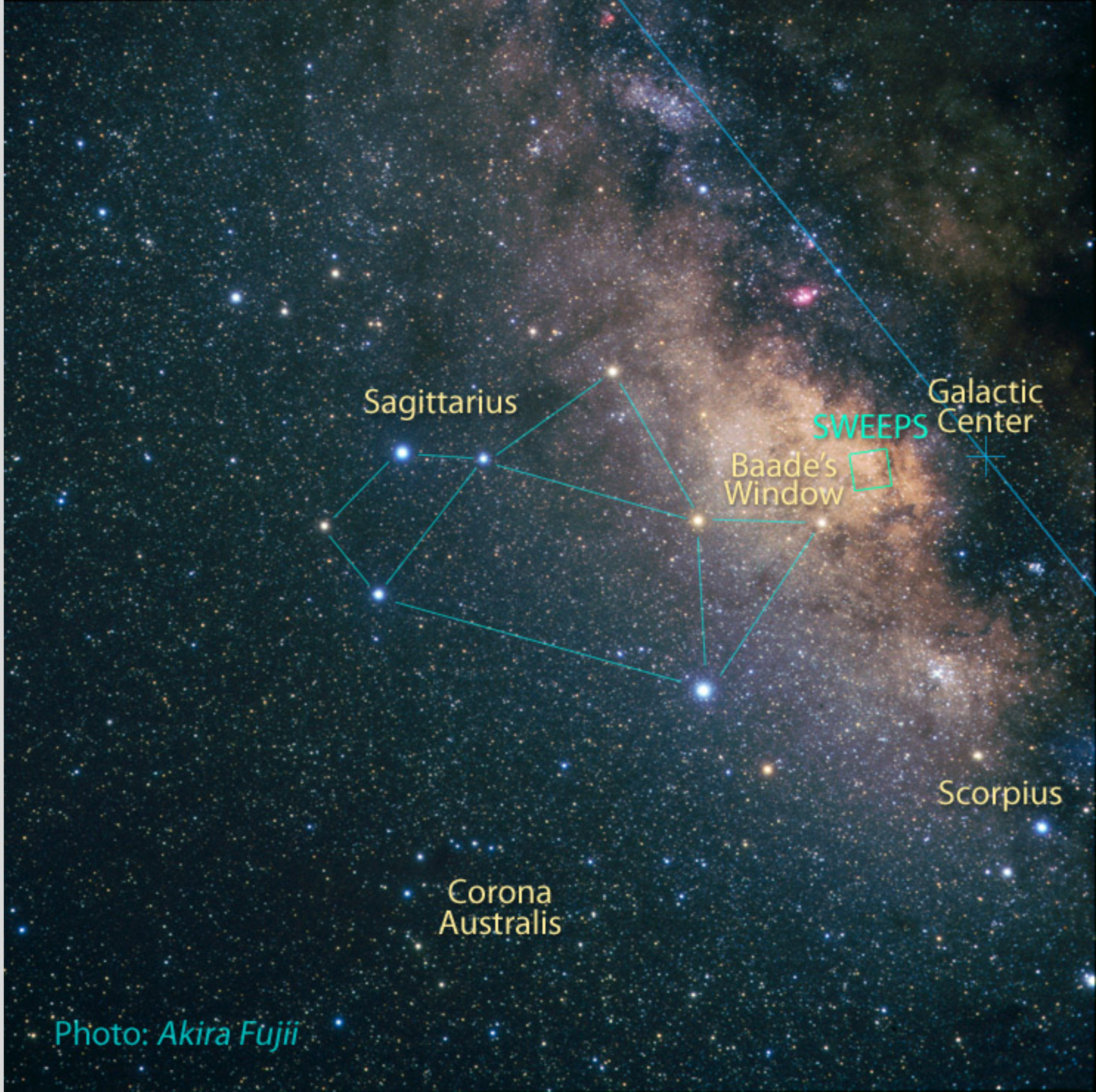
The bulge was historically very hard to study due to dust: optically there is as much as 28 magnitudes of extinction towards the Galactic center.

$\Delta m = 28 \;\rightarrow$ 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.

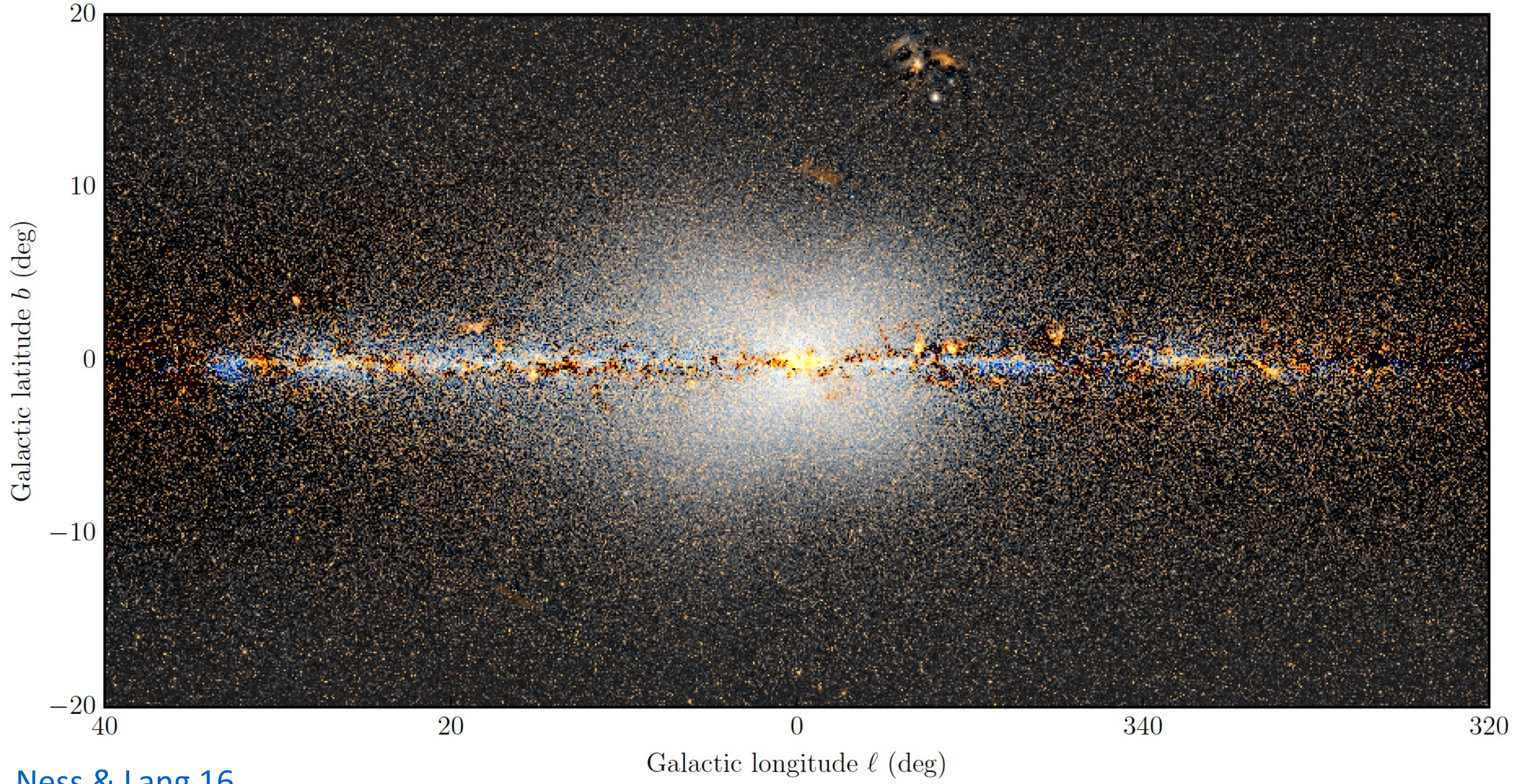
Bulge stars are generally old (ages > 9 Gyr) and have a wide range of metallicity (−1 < [Fe/H] < +0.5) with an average of [Fe/H]=−0.2.



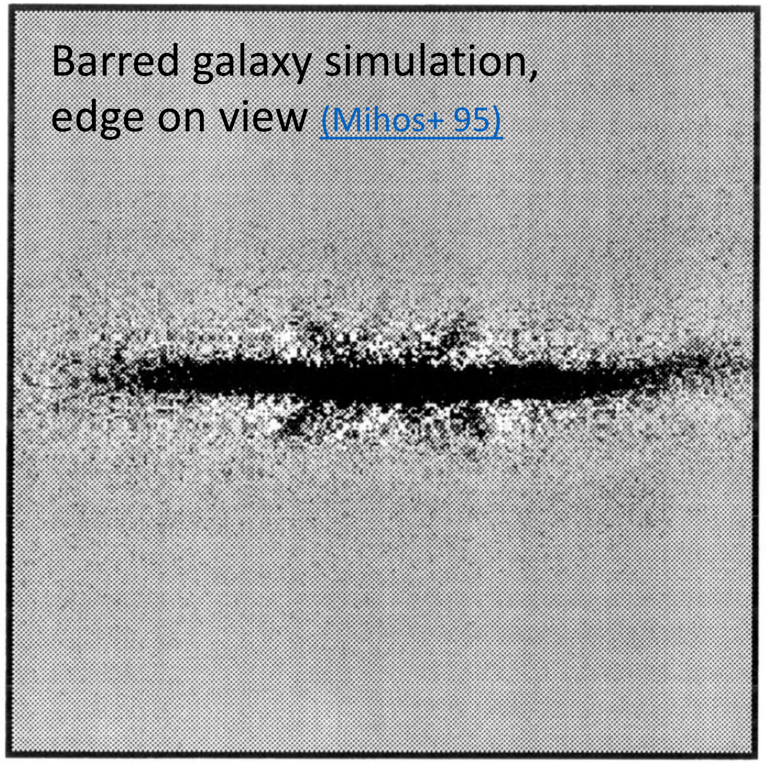
The Milky Way's bulge... maybe not a bulge?

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!

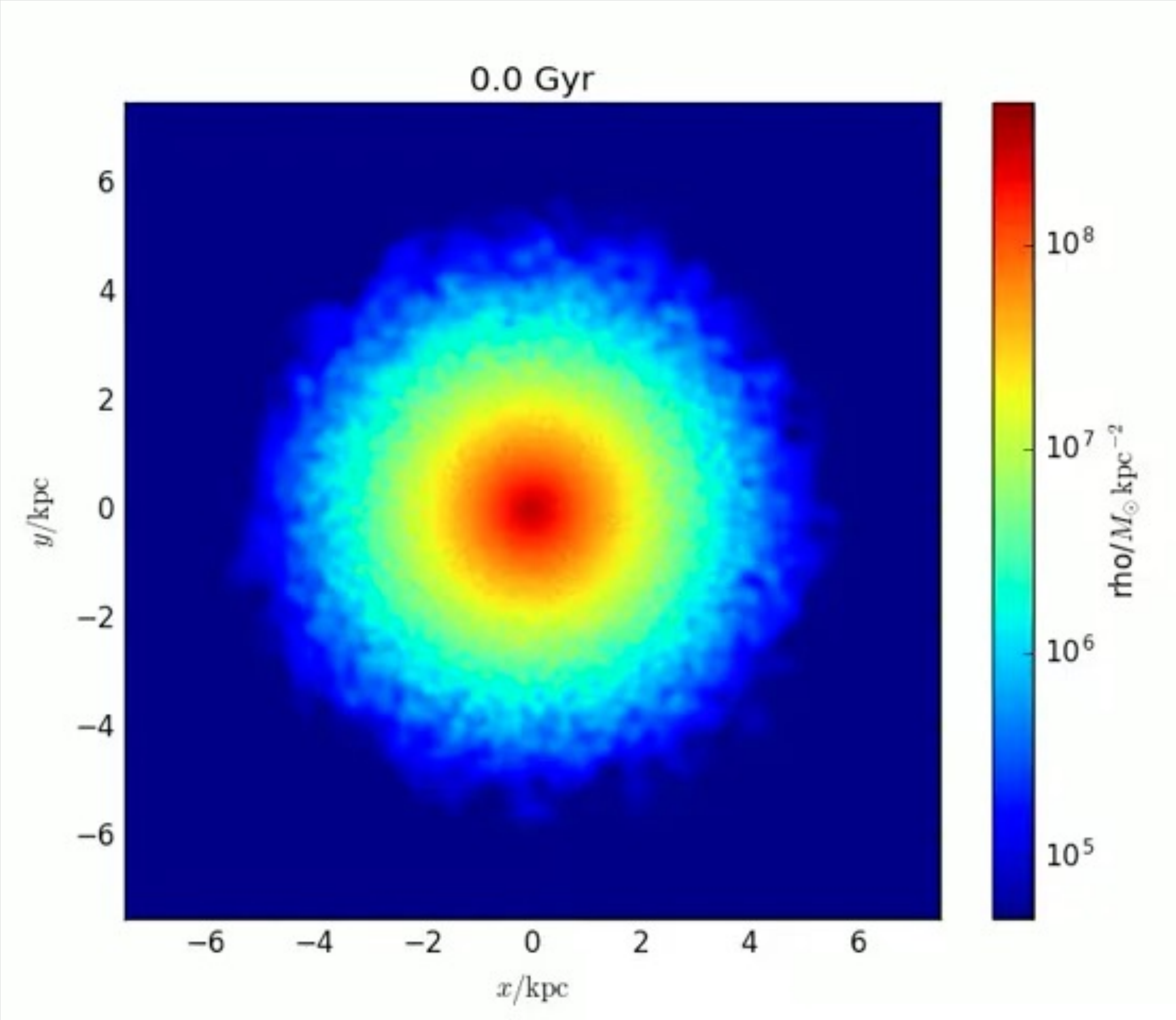
New interpretation is that the Milky Way has a bar in its center. 🍻🍸🍷

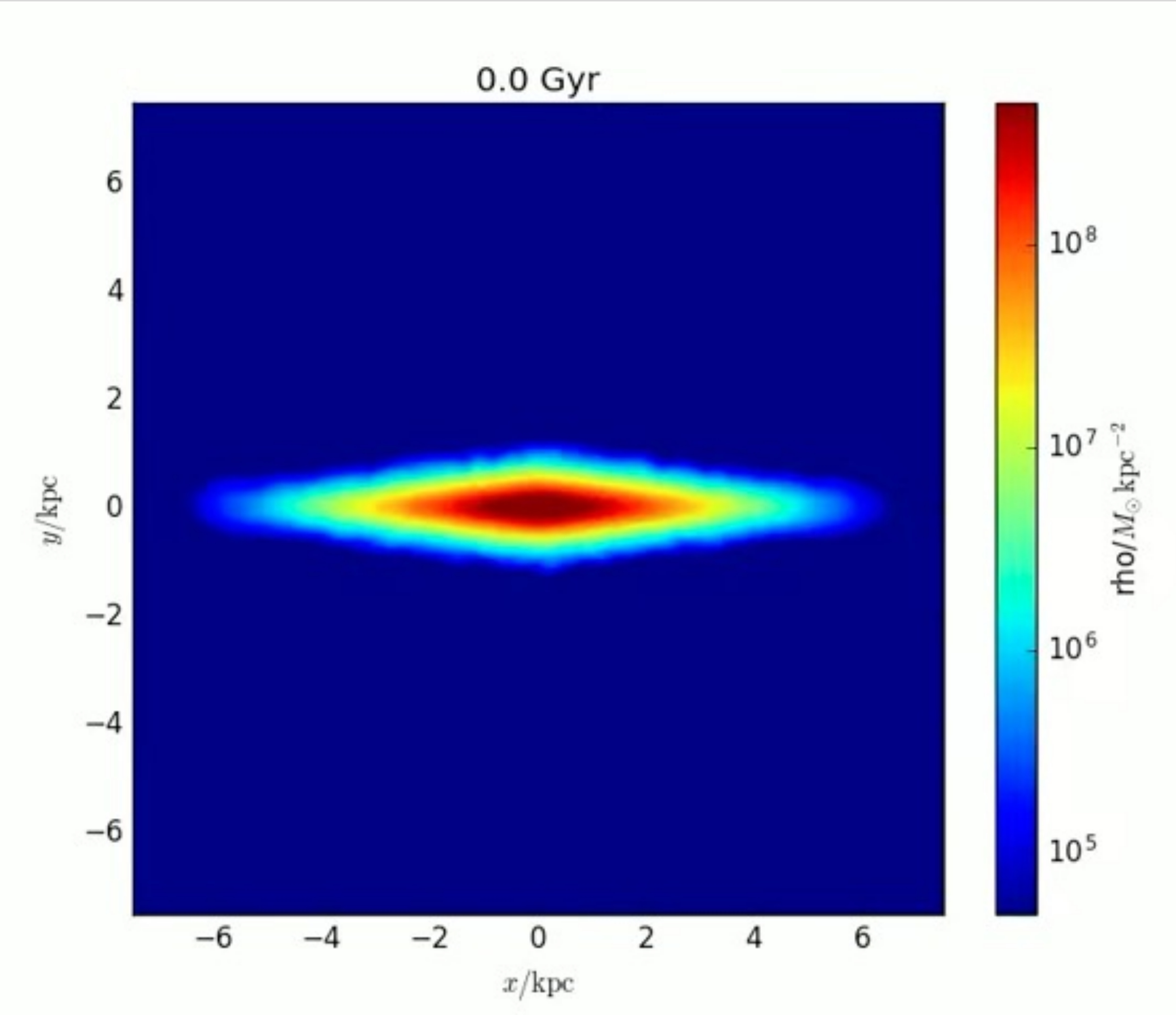


Ness & Lang 16

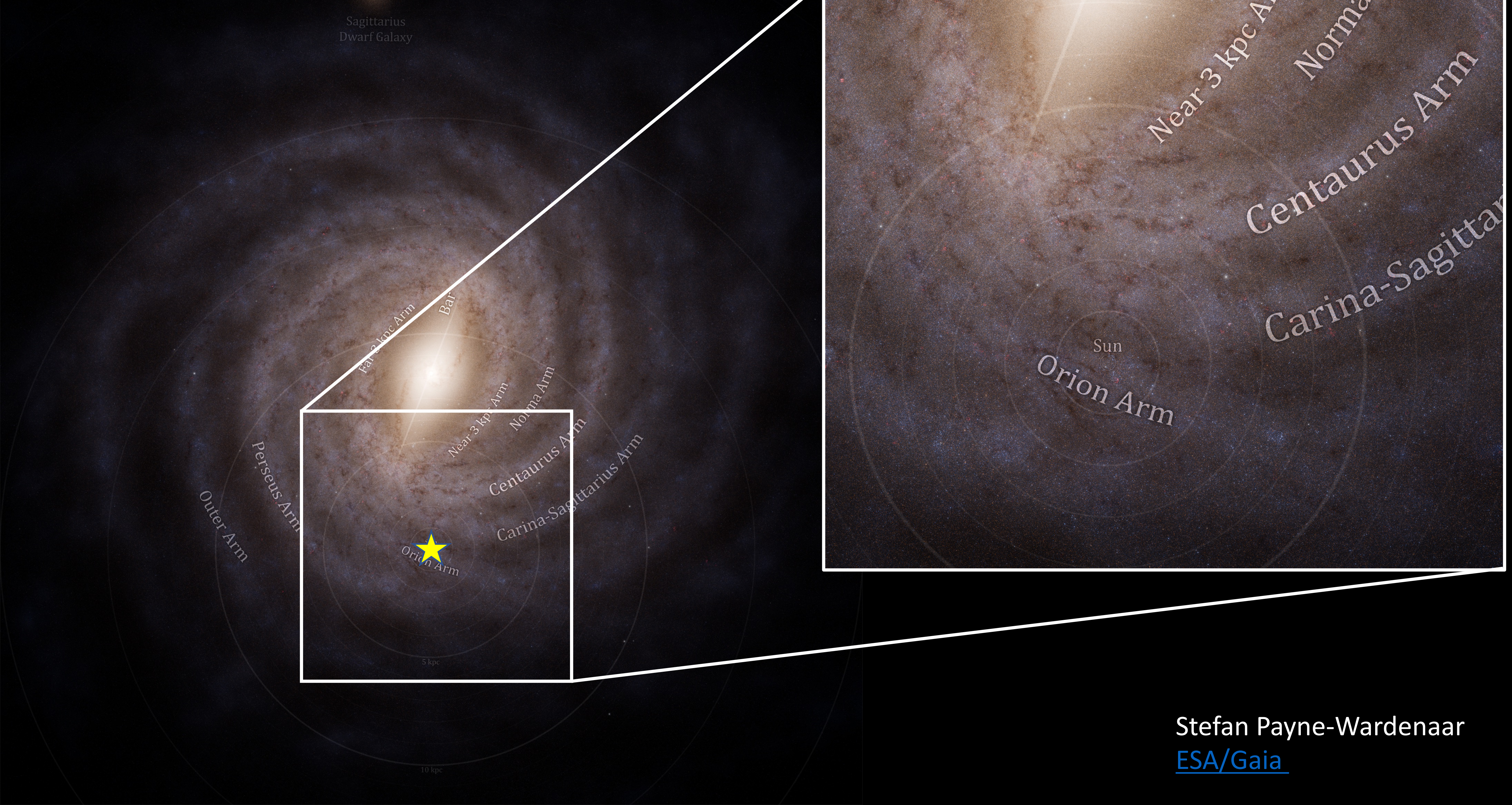


Bar Instability movies





The face-on Milky Way perspective



Stefan Payne-Wardenaar

ESA/Gaia

The edge-on Milky Way perspective

Stefan Payne-Wardenaar
ESA/Gaia

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.

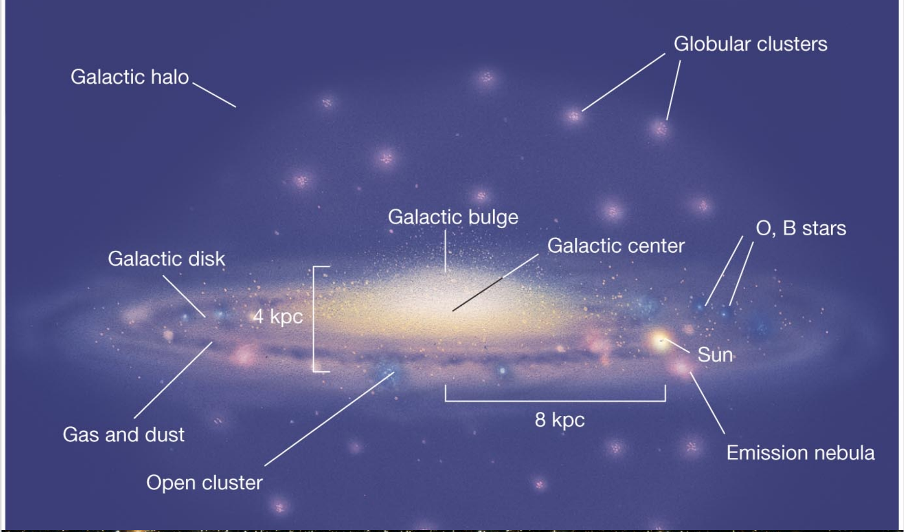
The total mass of the stellar halo is $\approx 10^9 \; \mathcal{M}_\odot$, of which only about 1% is in the globular clusters.

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

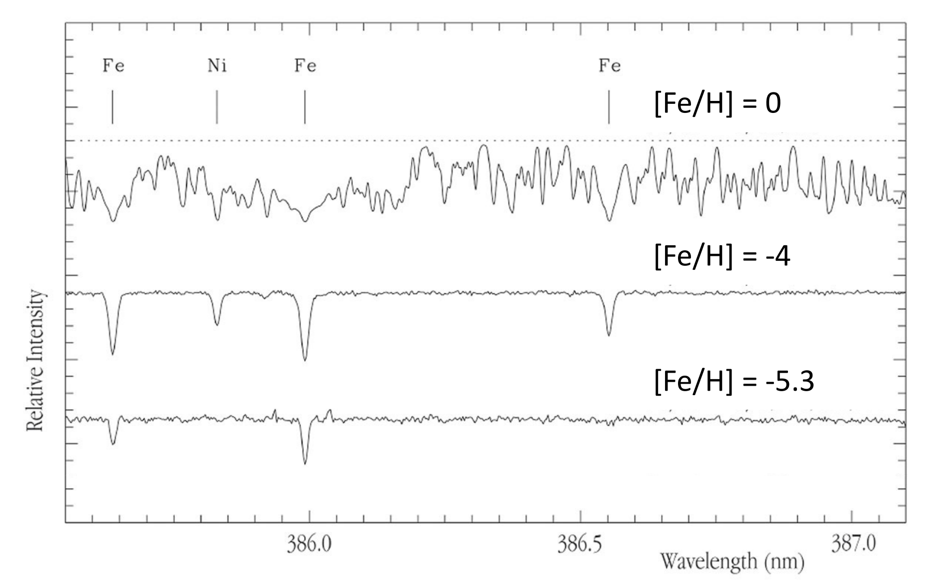
The Milky Way's halo consists of globular clusters and field stars, which have high random velocities and orbit far out of the Galactic disk.

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.

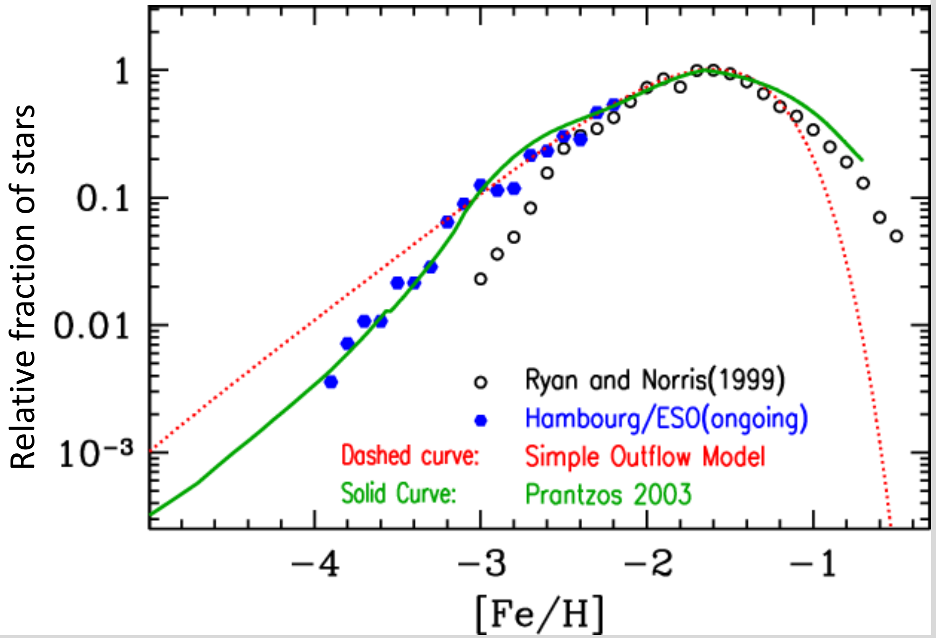
Density distribution falls very roughly as $\rho(r) = \rho_0 r^{-3.5}$ or so, but shows a lot of variation in different directions.

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



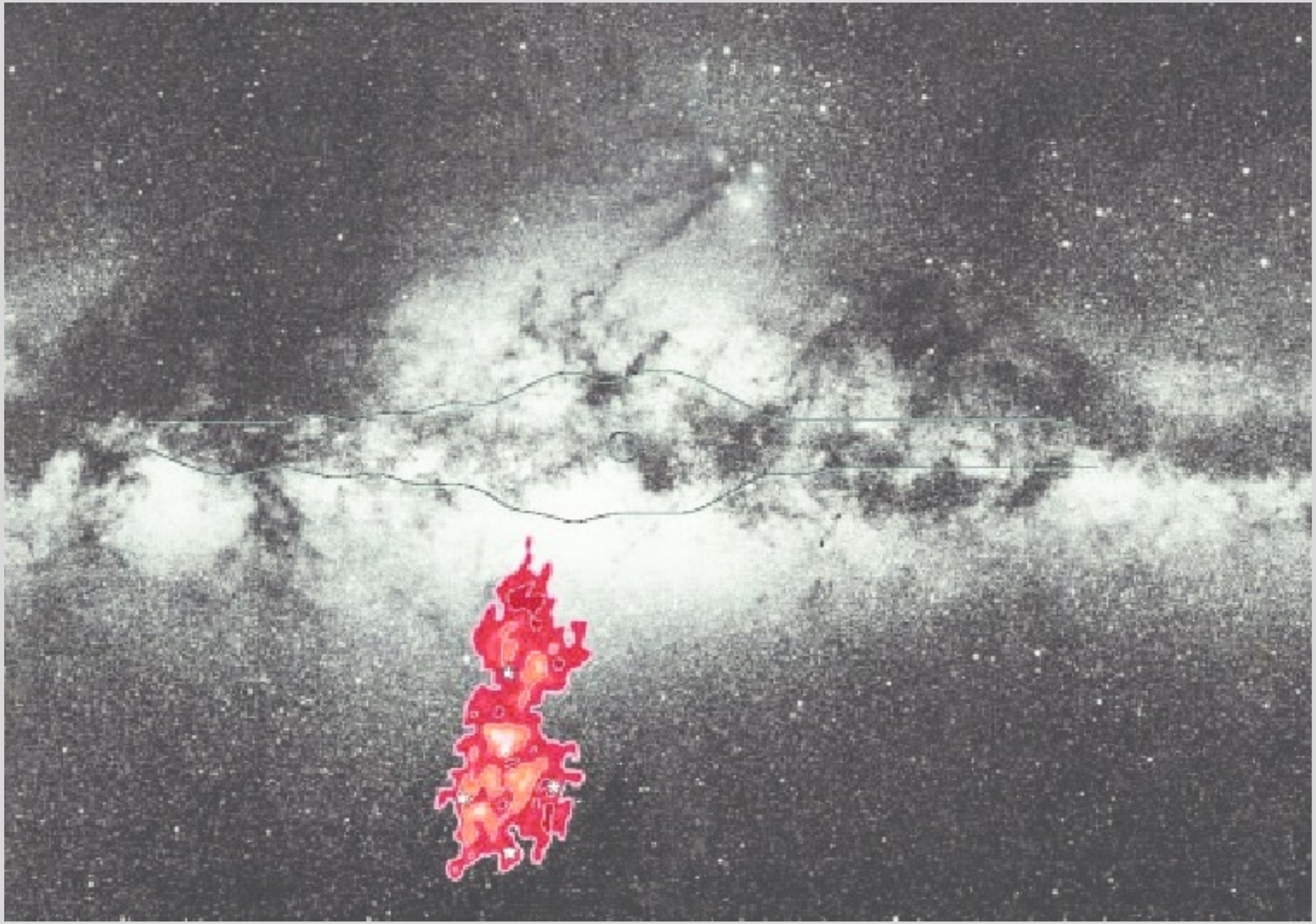
Spectra of Stars with Different Metal Content

Halo star metallicity distribution function (Prantzos 08)

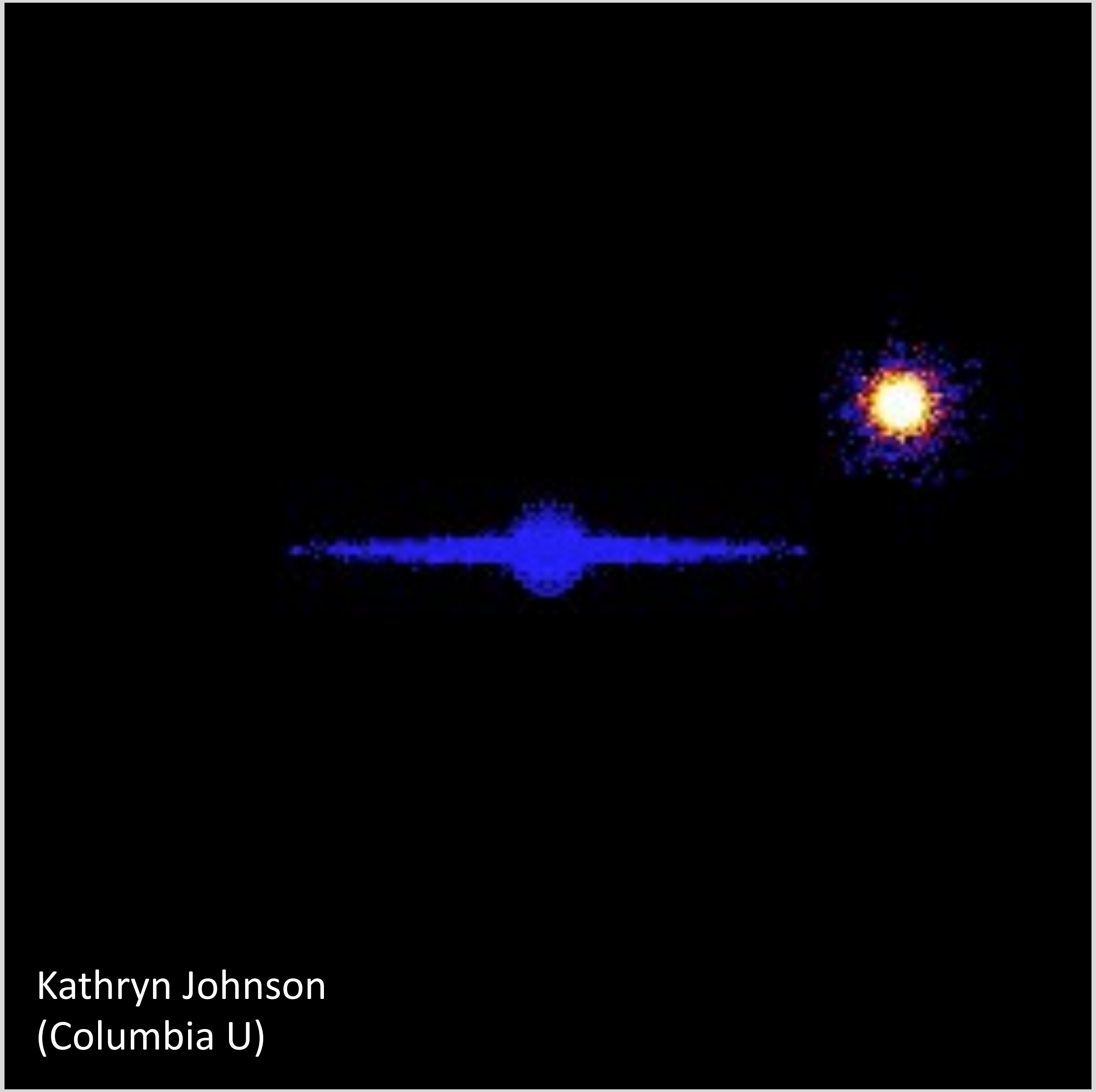


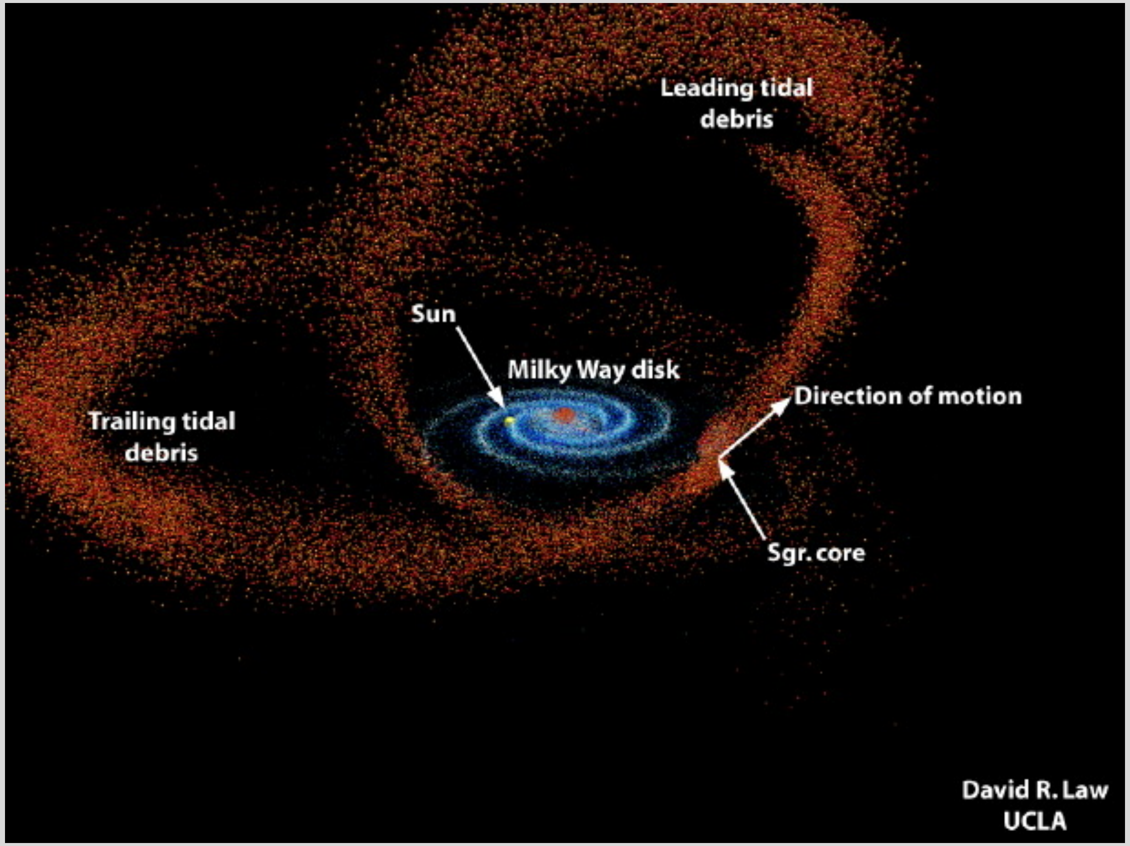
Star streams in the Stellar Halo

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.



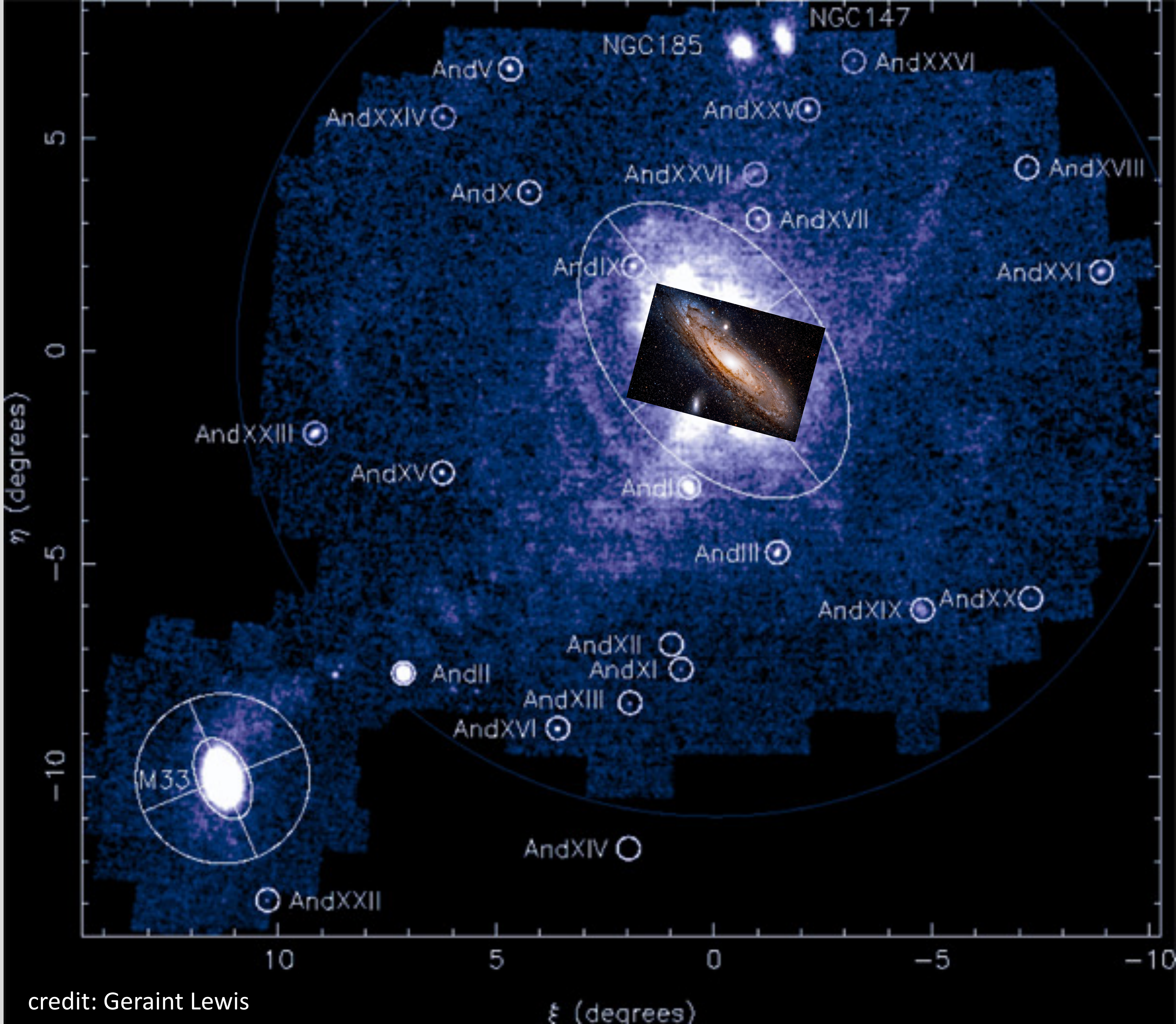
Star streams in the Stellar Halo





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

Star streams around Andromeda....



credit: Geraint Lewis

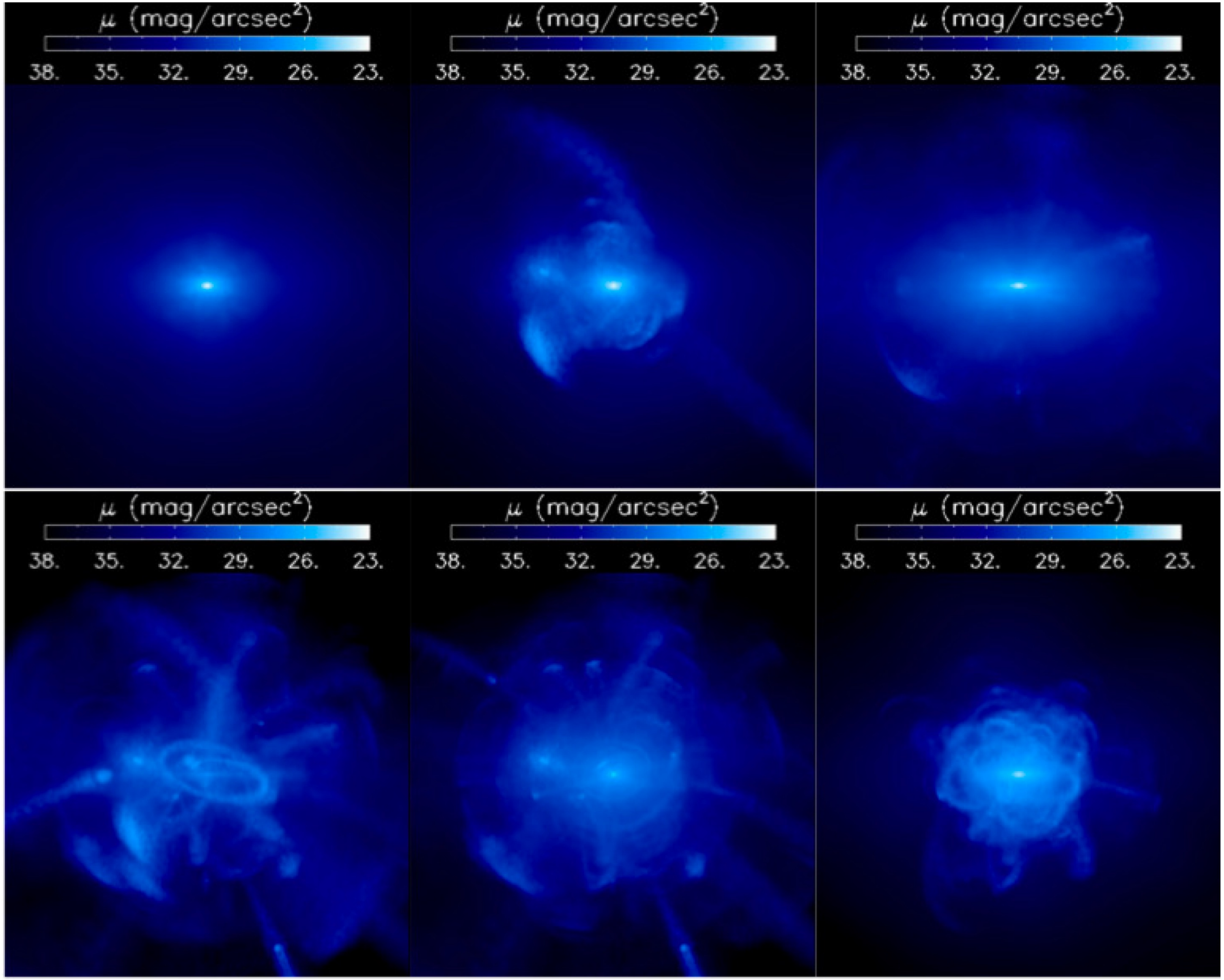
...and around NGC 5907

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

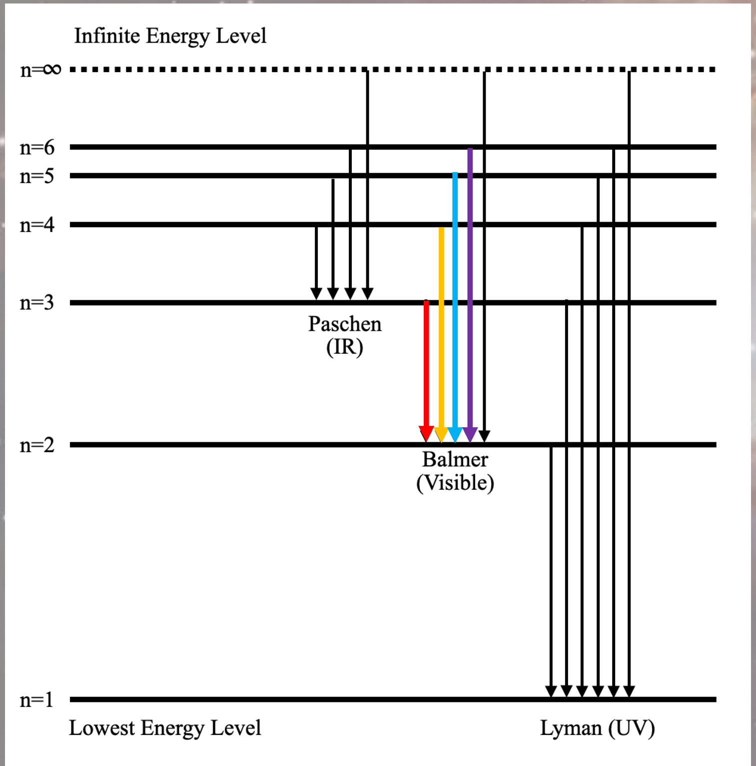
Ionized Gas in Star Forming Regions

Ionized Gas in Star Forming Regions (HII regions)

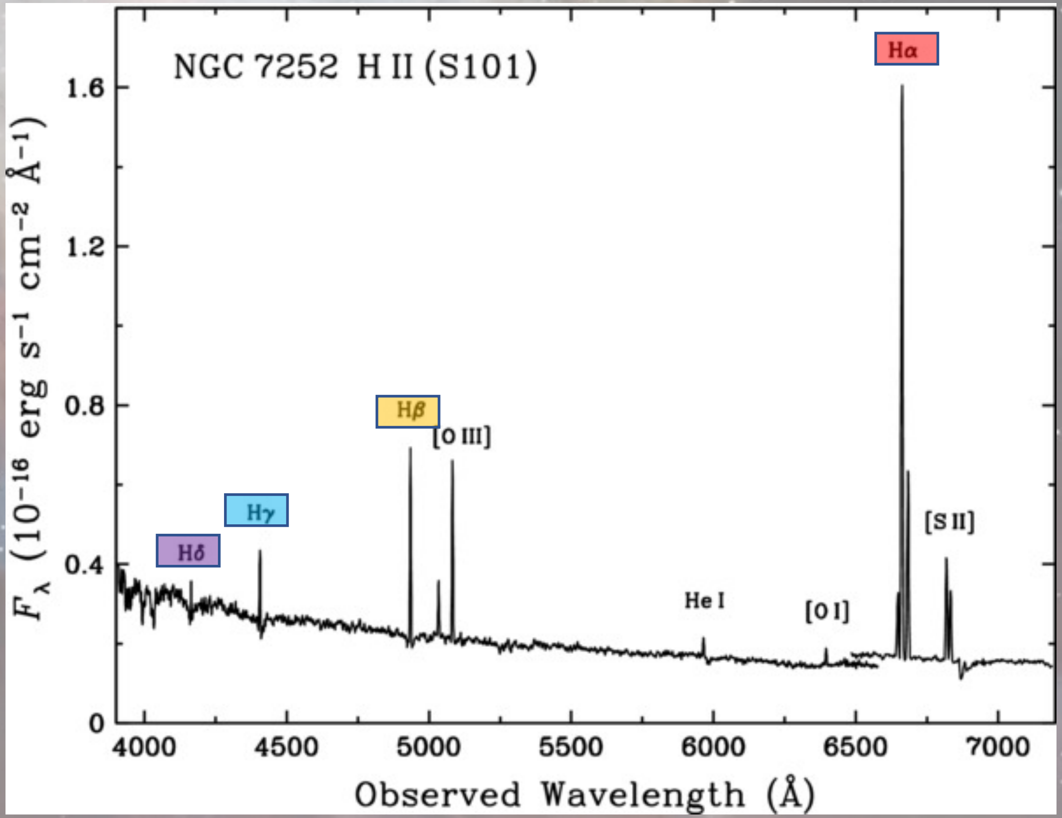
When stars form, the young stars heat up the surround gas and ionize it. When the electrons recombine with atoms, they cascade down in energy level and emit emission lines. Different elements emit different emission lines.

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

Hydrogen atom energy levels



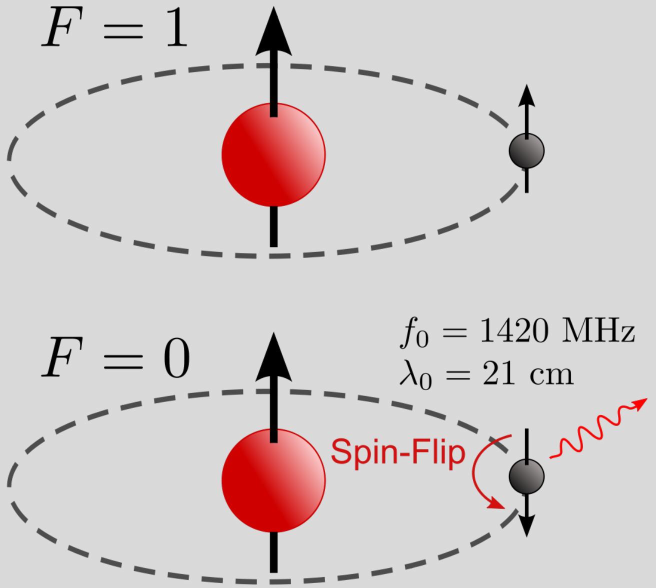
HII region spectrum




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}.

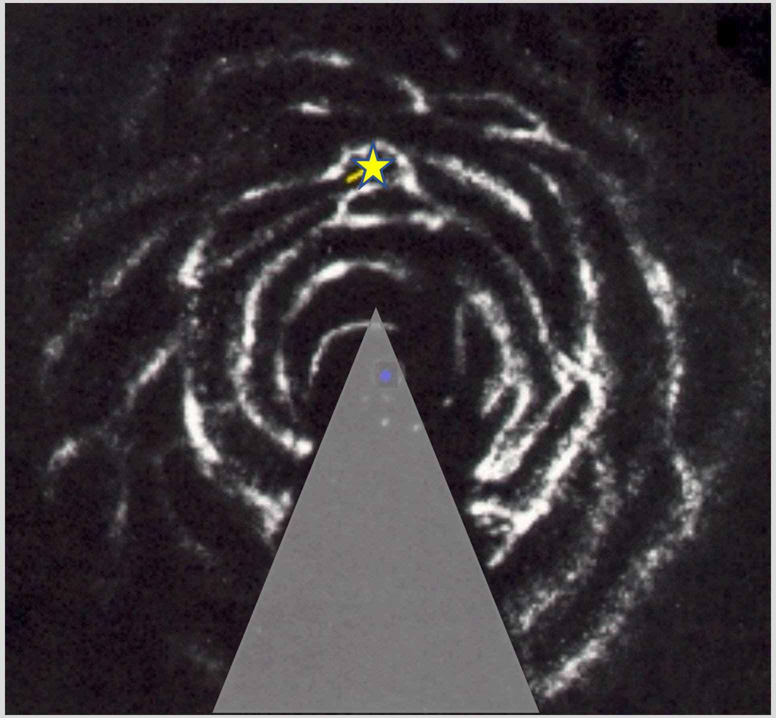


Hydrogen spin flip

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!

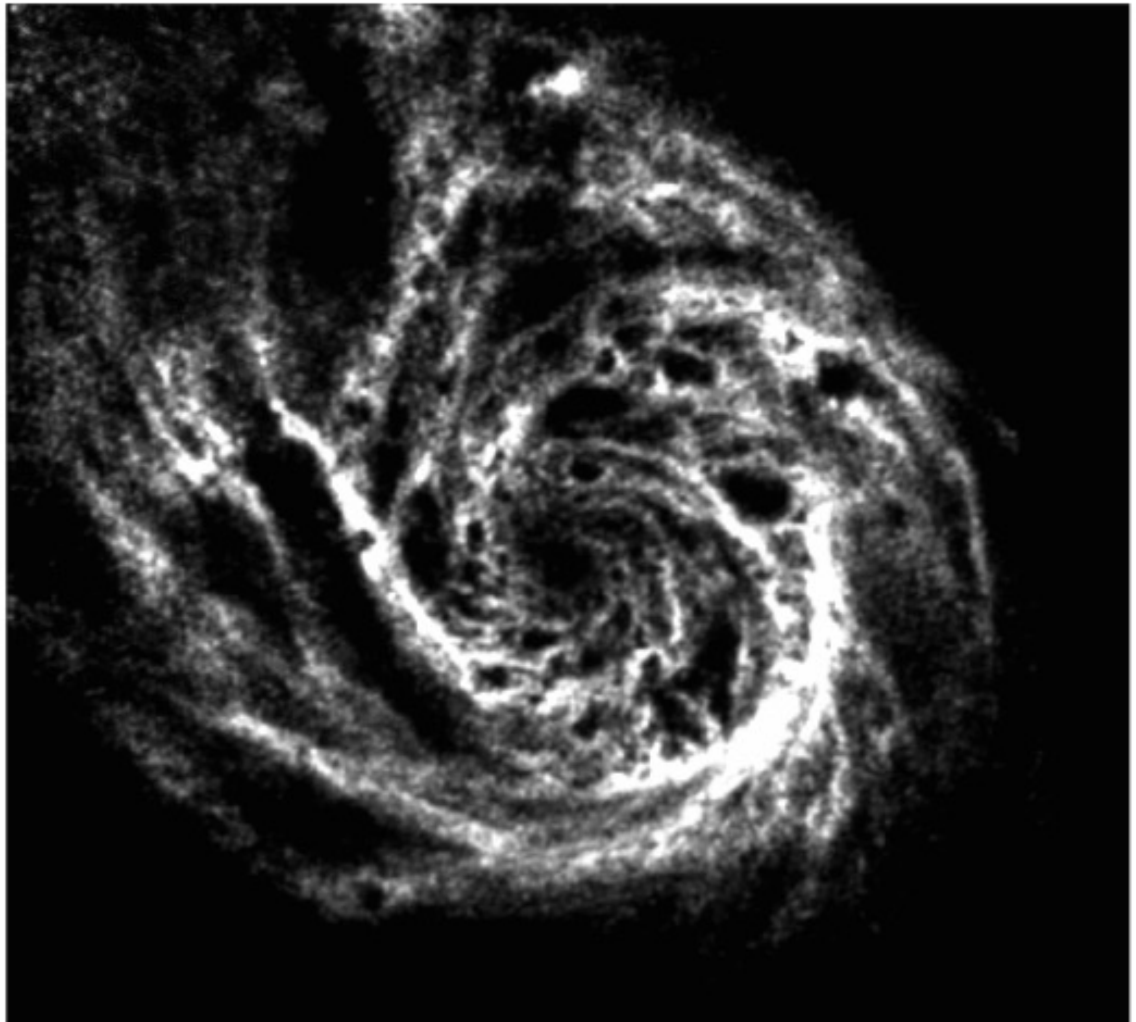
How often does this happen? Once every few million years. But there are so many hydrogen atoms in the gas that it is constantly radiating 21-cm photons!



21-cm map of the Milky Way

Atomic Hydrogen in M101

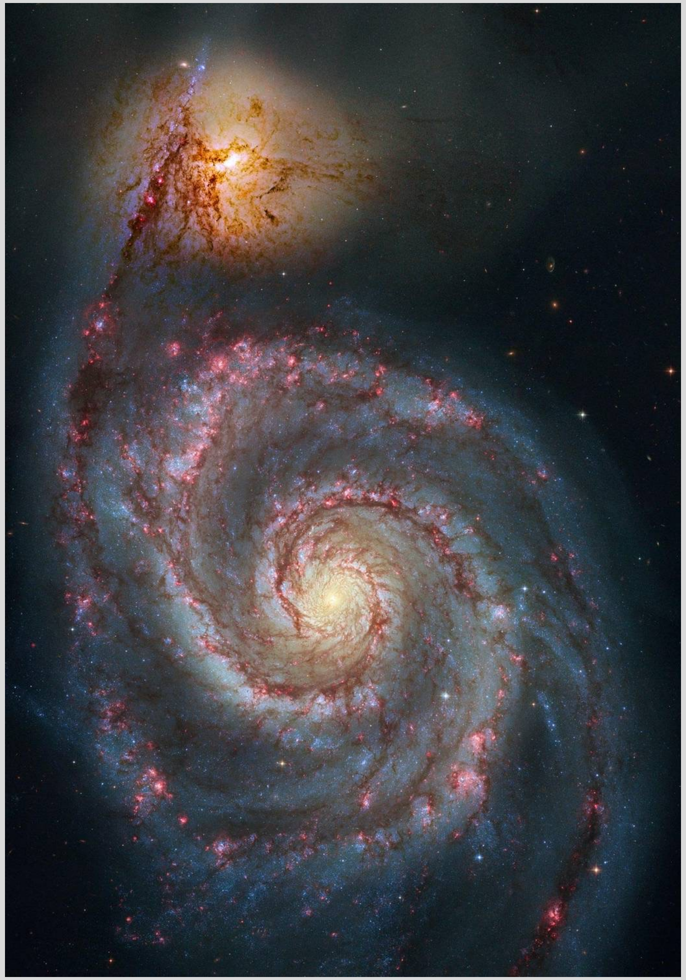
M101 optical star light

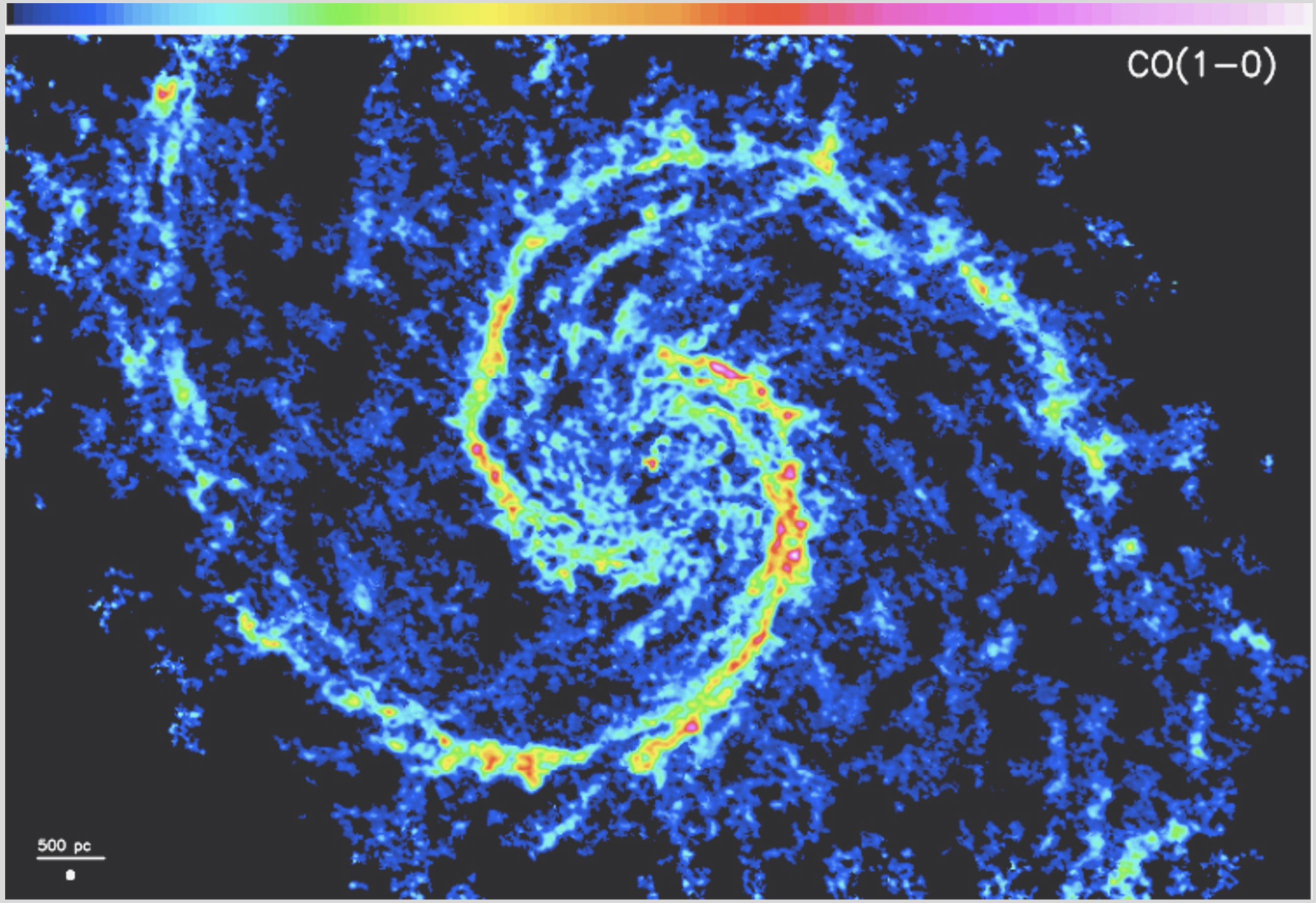


M101 21cm neutral hydrogen

Phases of the Interstellar Medium: Molecular Gas

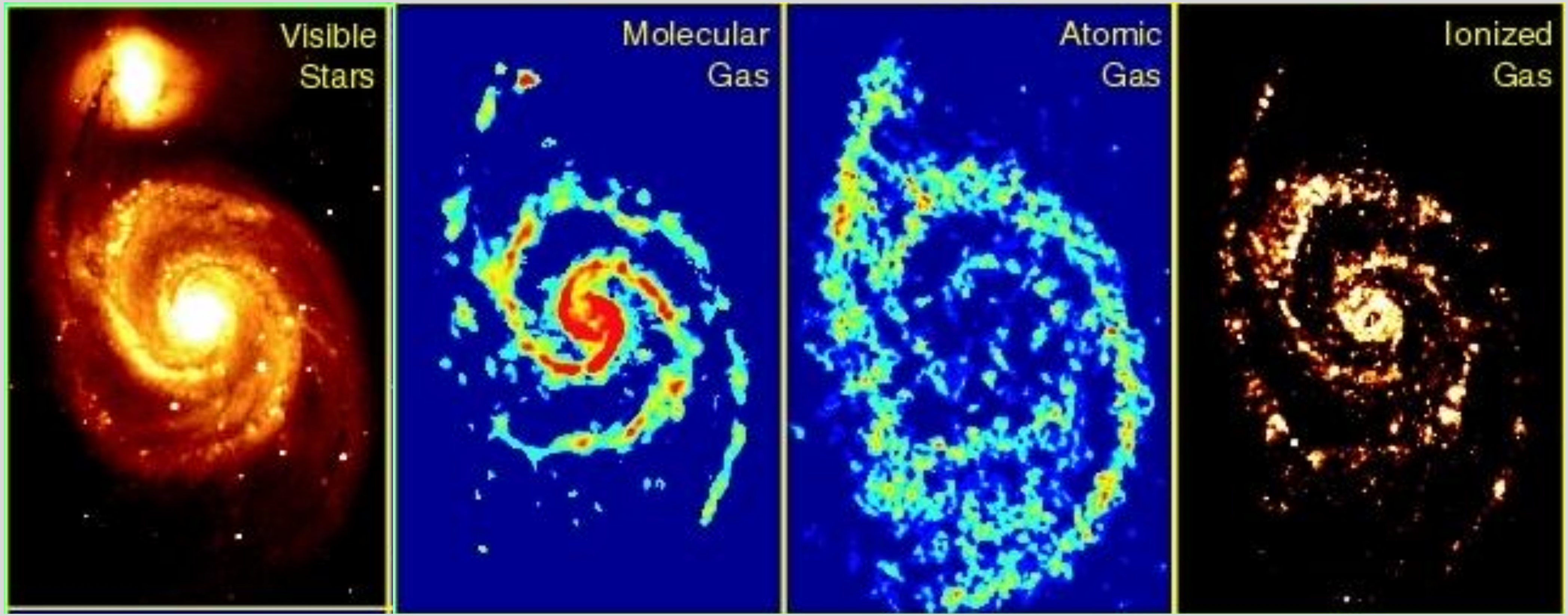
When the density of gas gets high enough, atoms can bond together to form molecules, most commonly molecular hydrogen (H_2). Molecular hydrogen does not emit optical or radio photons, and is very hard to trace. We use emission from other molecules, most notably carbon monoxide (CO), to trace the molecular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





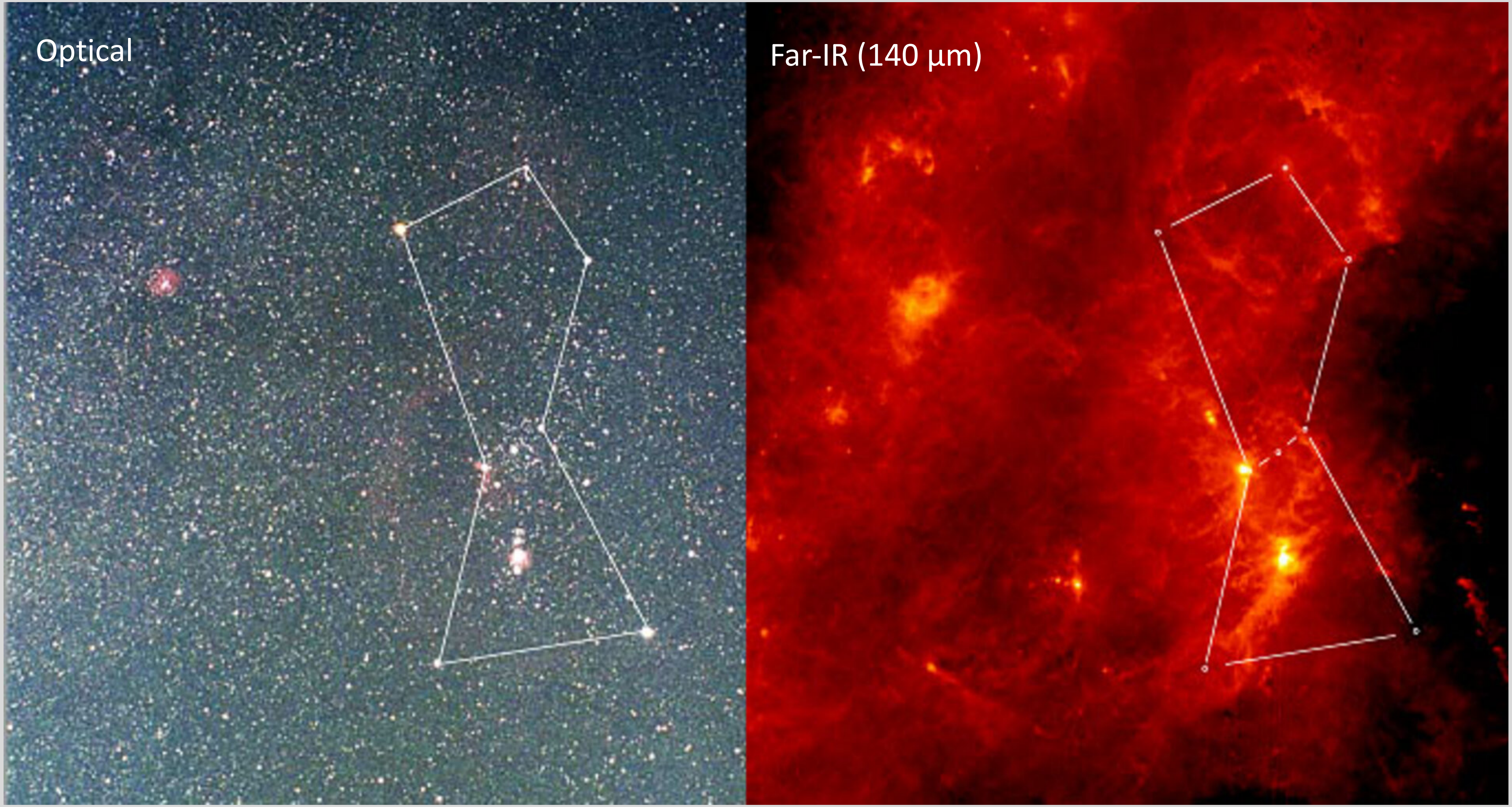
The Distribution of Gas in Spiral Galaxies like the Milky Way

- 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 (ionized gas).



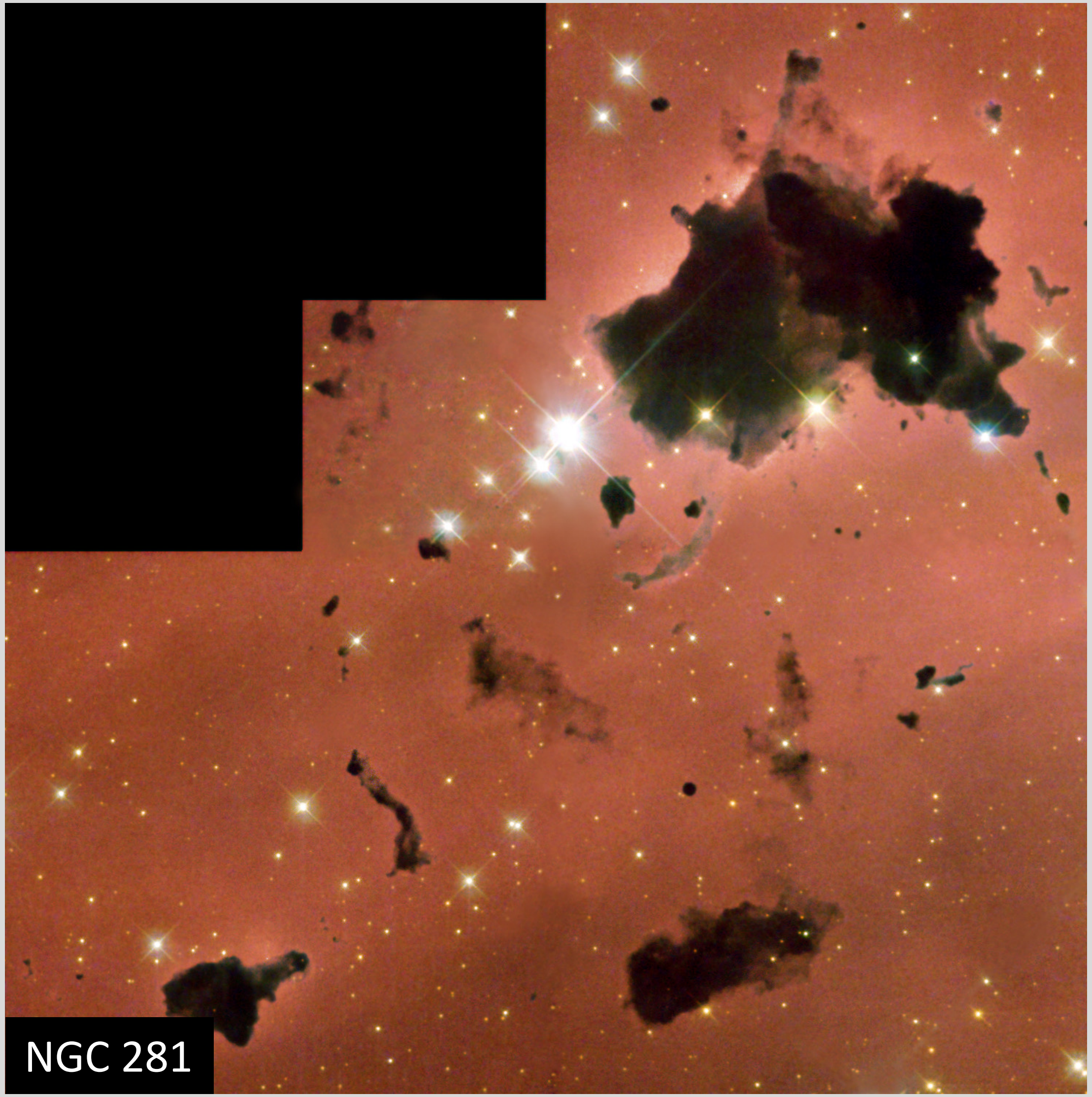
Dust in the interstellar medium

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

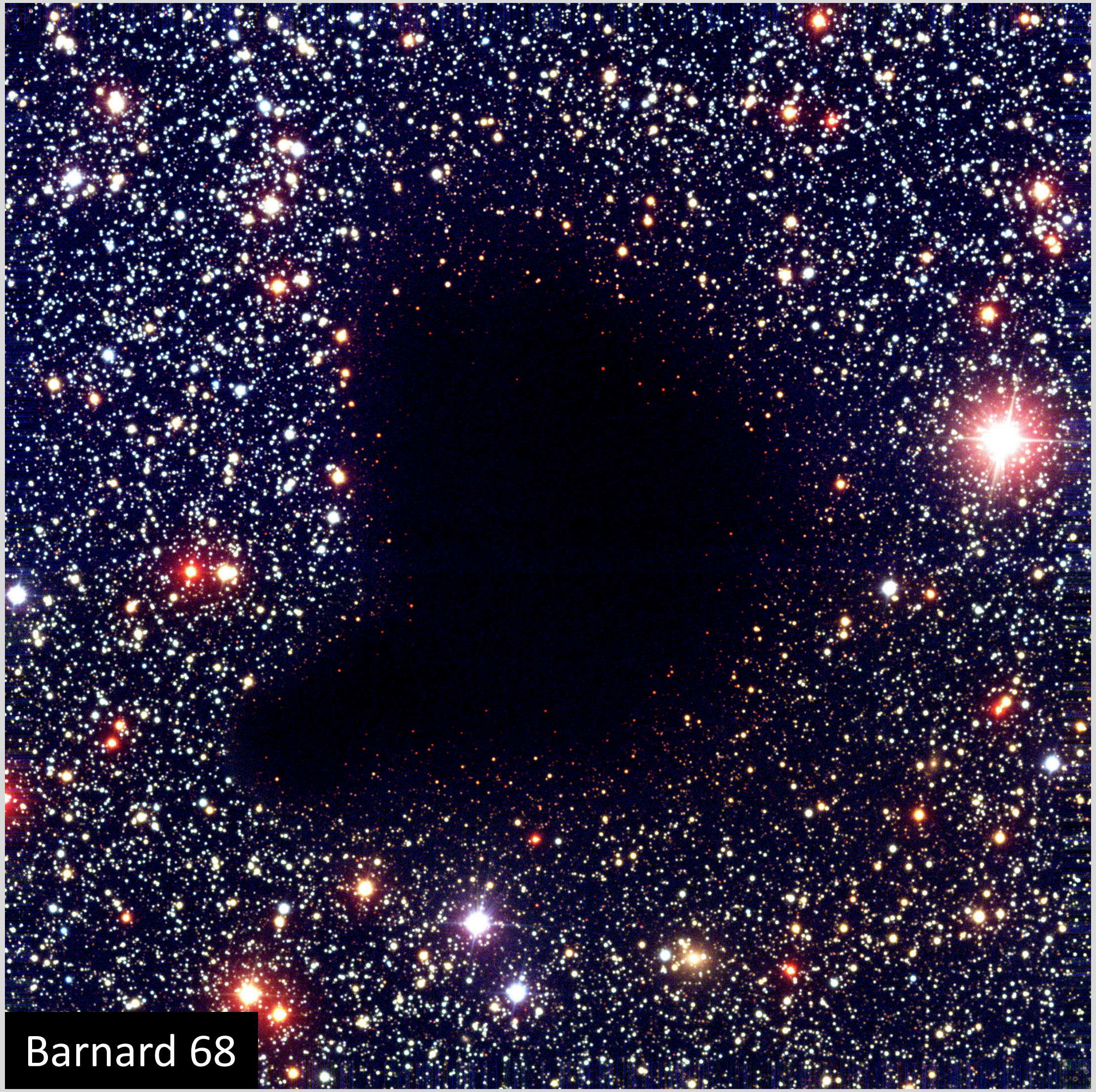


Dust in the interstellar medium

When the density of dust is very high, in optical imaging we see “Bok globules” silhouetted against the background.



NGC 281



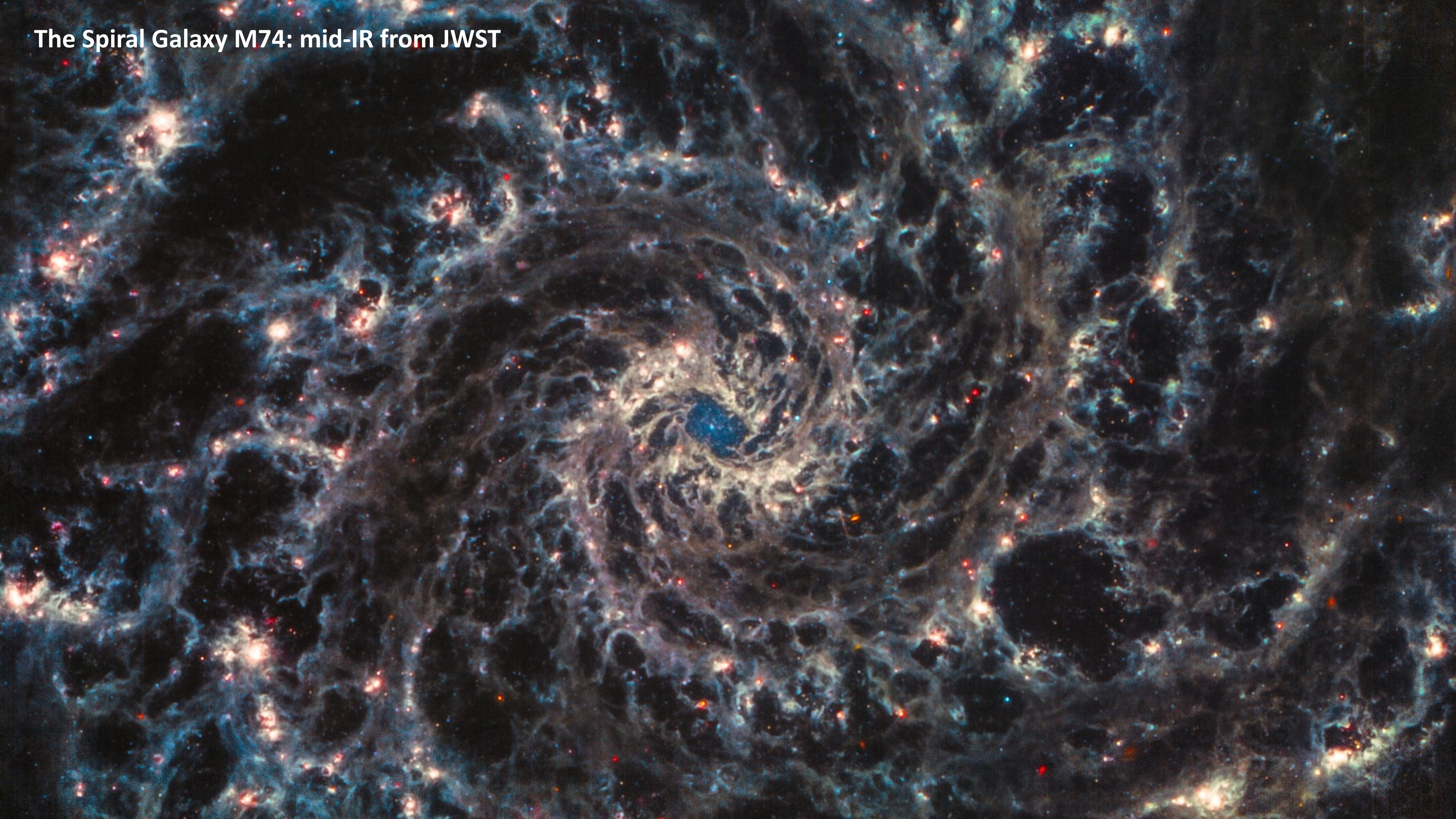
Barnard 68

Dust in the Eagle Nebula


Dust in the Eagle Nebula

Hubble / Optical

The Spiral Galaxy M74: mid-IR from JWST



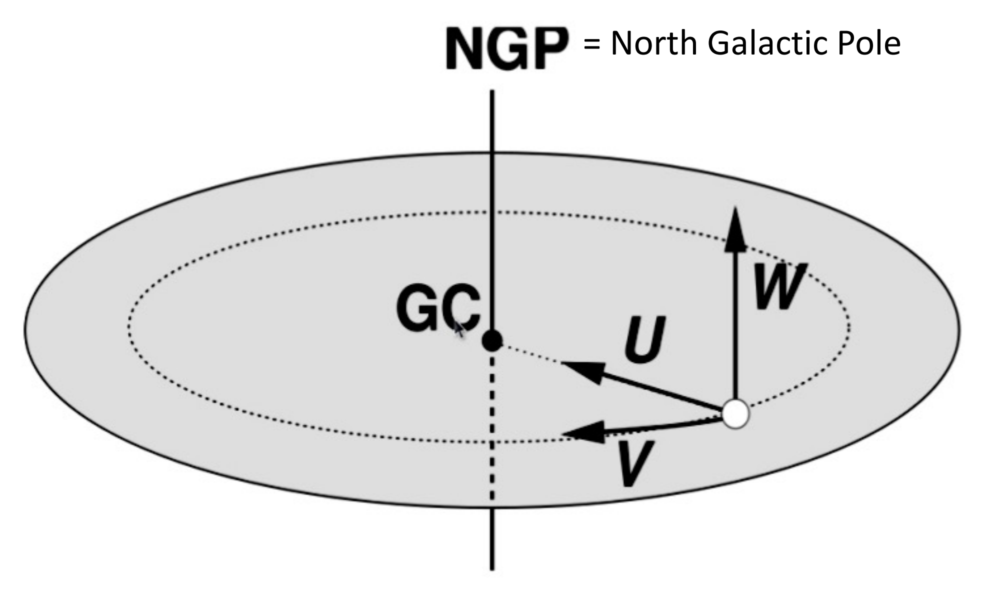
Solar Motion

How do we define the motion of the Sun? How do we even know the Sun is moving? Look at the velocities of nearby stars:

- Most stars have small velocities relative to the Sun: $\lesssim 30$ km/s.
- Metal-poor halo stars have a high relative velocity: $V_{rel} \approx 200 - 250$ km/s.

Define velocities relative the **Local Standard of Rest** (LSR), which is a point in space which is:

- located at the Sun's position (R=8.2 kpc from center);
- moving on a perfectly circular orbit around the Galaxy;
- staying exactly in the disk plane



Stars (including the Sun) will have a motion ***with respect to this LSR*** of (U, V, W) where

U	Towards/Away from GC	$+U$ is inward
V	Along the direction of rotation	$+V$ is forward
W	Up/Down out of disk plane	$+W$ is northward

So in these coordinates, a star moving on a perfectly circular orbit has $(U, V, W) = (0,0,0)$ km/s.

Solar Motion

How do we measure the Sun's motion relative to the Local Standard of Rest?

Imagine looking at the radial velocities (v_r) and proper motions (μ) of stars in all directions around us. Stars around us, on average, should be moving with the LSR (even though any individual star may not be!).

If the Sun was moving with the LSR, then the average velocities of stars in all directions around us should be zero. But if the Sun is moving in a particular direction, then stars in that direction should on average be moving towards us.

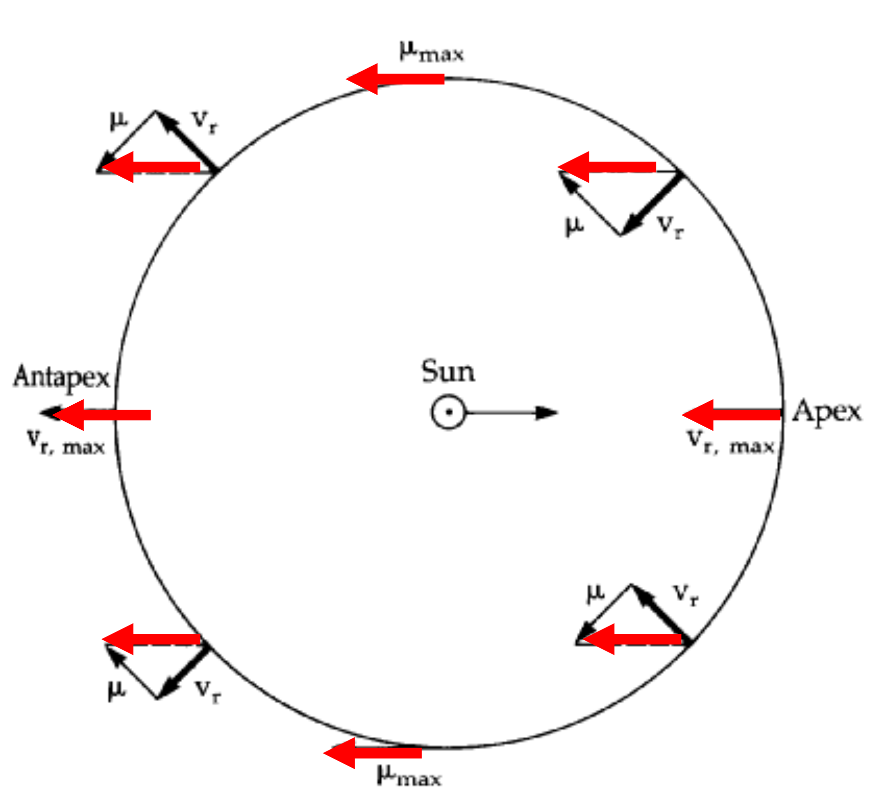
By measuring the average motions of stars in all directions, we derive the Sun's peculiar motion with respect to the LSR:

$(U_\odot, V_\odot, W_\odot) = (+11, +12, +7)$ km/s (Schoenrich+10)

So the Sun is moving:

- a bit towards the Galactic Center ($U_\odot = +11$ km/s)
- a bit faster than the LSR ($V_\odot = +12$ km/s)
- a bit northward out of the Galactic Plane ($W_\odot = +7$ km/s)

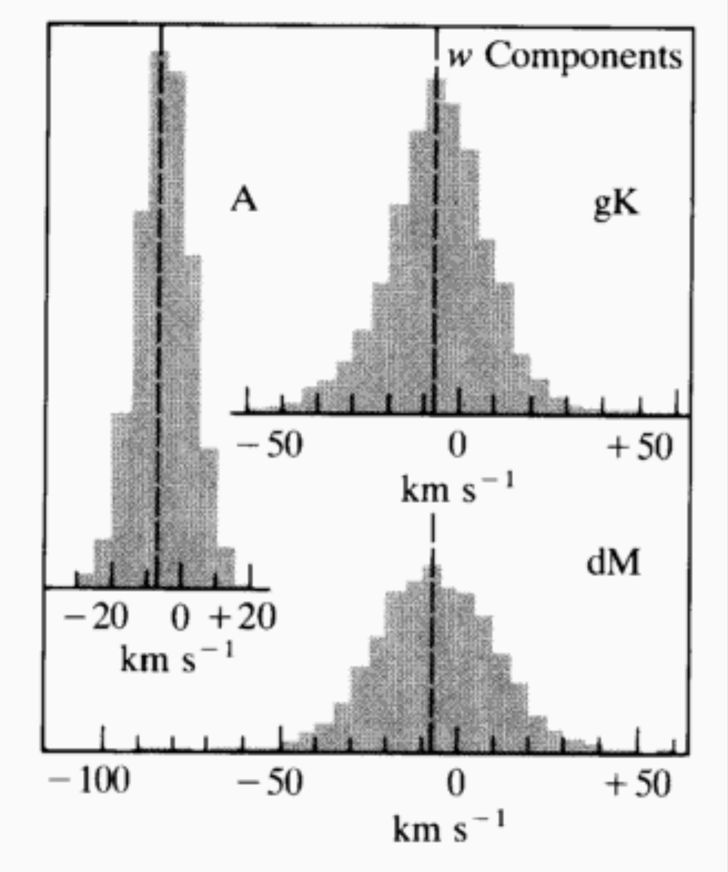
Remember: this is doesn't include the rotation speed ($V_{circ} \approx 230$ km/s).



The Velocities of stars

Look at a histogram of W (vertical) velocities of samples of stars with different spectral types:

- **A stars**: fairly massive main sequence stars
- **gK**: evolved red giant stars
- **dM**: low mass main sequence stars



Notice:

- The average velocity of each sample is ≈ -7 km/s. *Why?*
- The spread in velocities (the "velocity dispersion") is smaller for A stars than for gK and dM stars. *Why?*

Add in B stars and white dwarfs (WD), and compare velocity dispersion and scale height (thickness) of the different populations

Increasing Mean Age

Stars	Velocity Dispersion	Scale height
B	6 km/s	60 pc
A	9 km/s	120 pc
gK	17 km/s	270 pc
dM	18 km/s	350 pc
WDs	25 km/s	500 pc

Questions:

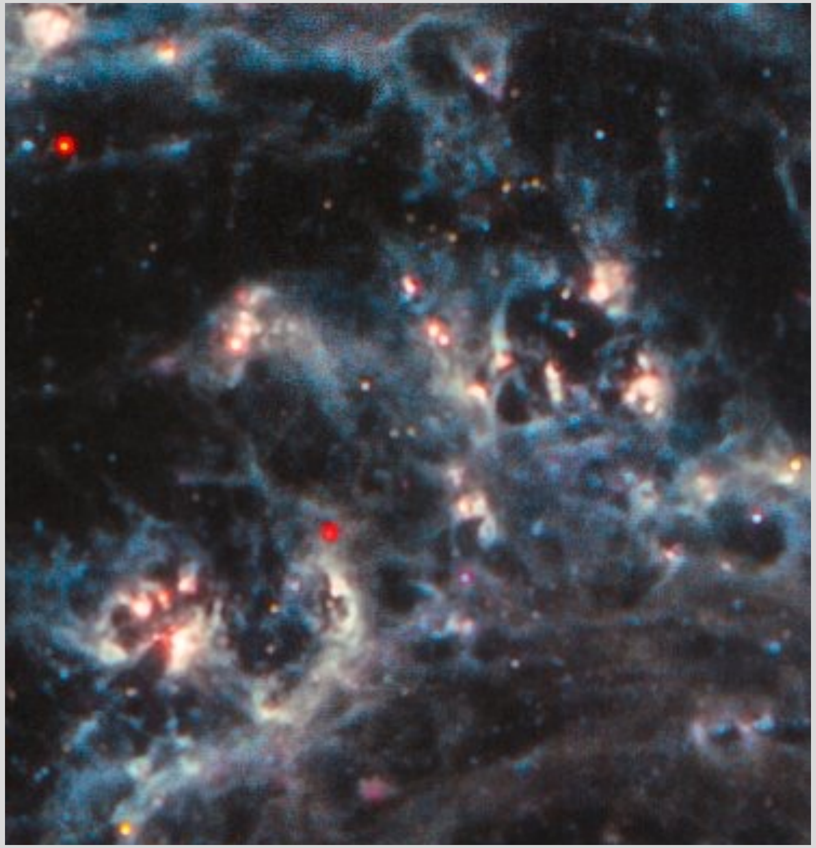
- Why does velocity dispersion increase with age?
- Why does velocity dispersion correlate with scale height?

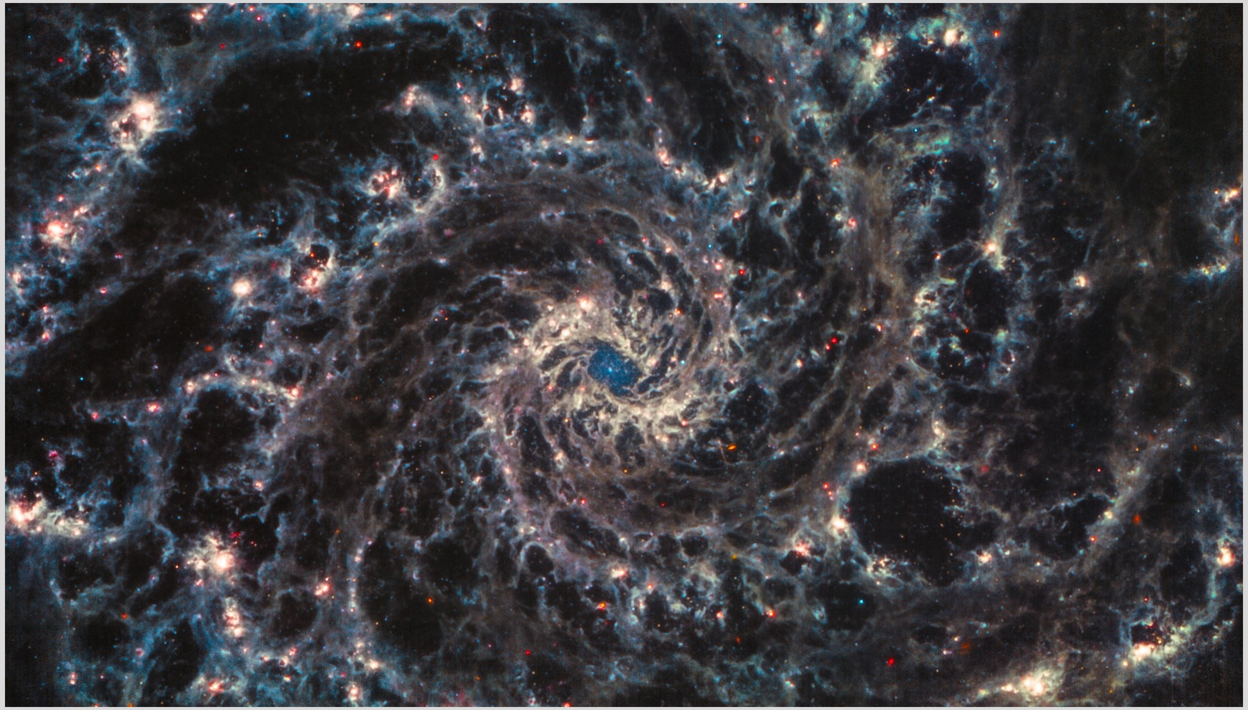
Disk Heating

The Galaxy's disk is not perfect smooth: there are lumps of material on large scales (spiral arms, the bar) and small scales (giant molecular clouds).

Stars are born from interstellar gas which moves on nearly circular orbits, and so newly formed stars also move on nearly circular orbits.

But over time, gravitational encounters with spiral arms and giant molecular clouds can scatter stars, increasing their random motions. As a group, their velocity dispersion increases with time. This process is called "disk heating."





Vertical velocity dispersion and the Oort Limit

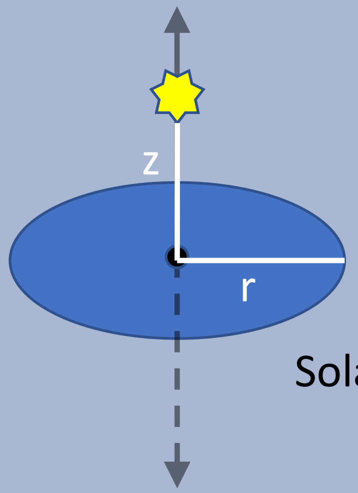
Why would velocity dispersion and scale height correlate? Because of gravitational balance.

Think of a star oscillating up and down in the disk, held by the gravitational force of some mass $\mathcal{M}$. We can balance kinetic and potential energy: $\frac{1}{2}m_* v_z^2 \cong \frac{G\mathcal{M}m_*}{z}$ or, more simply: $v_z^2 \cong \frac{2G\mathcal{M}}{z}$.

What is M? think of a patch of the disk with radius r and surface density Σ_0 (in $\mathcal{M}_\odot/\mathrm{pc}^2$). It will have a mass of $\mathcal{M} = \Sigma_0 \pi r^2$.

If $r \approx z$, we can put that in for $\mathcal{M}$ and get $v^2 \cong 2\pi G \Sigma_0 z$

Now consider of a group of stars. Replace individual values (v^2, z) with group values (σ_W^2, h_z) to get: $\sigma_W^2 \sim 2\pi G \Sigma_0 h_z$



Solar neighborhood

This is known as the **Oort Limit**, and can be used to estimate the total mass density of the Galactic disk in the solar neighborhood.

Current estimates come in around $\Sigma_0 \approx 70\ \mathcal{M}_\odot/\mathrm{pc}^2$ or so.

Compare

Inventory of Stars and Gas	
Stars	$\Sigma_{stars} \approx 37\ \mathcal{M}_\odot/\mathrm{pc}^2$
Gas (HI+H_2)	$\Sigma_{gas} \approx 13\ \mathcal{M}_\odot/\mathrm{pc}^2$
Total	$\Sigma_{tot} \approx 50\ \mathcal{M}_\odot/\mathrm{pc}^2$

Galactic disk

The Rotation of the Milky Way

The circular velocity of the disk at the Sun's distance from the Galactic center ($R_0 = 8.2$ kpc) is $V_c \approx 230$ km/s.

From this we can derive:

- The orbital period of the Sun:

$$T = \frac{2\pi R_0}{V_c} = \frac{2\pi(8200\ pc)}{230\ km/s} \approx 225 \text{ Myr.}$$

because 1 km/s ≈ 1 pc/Myr!

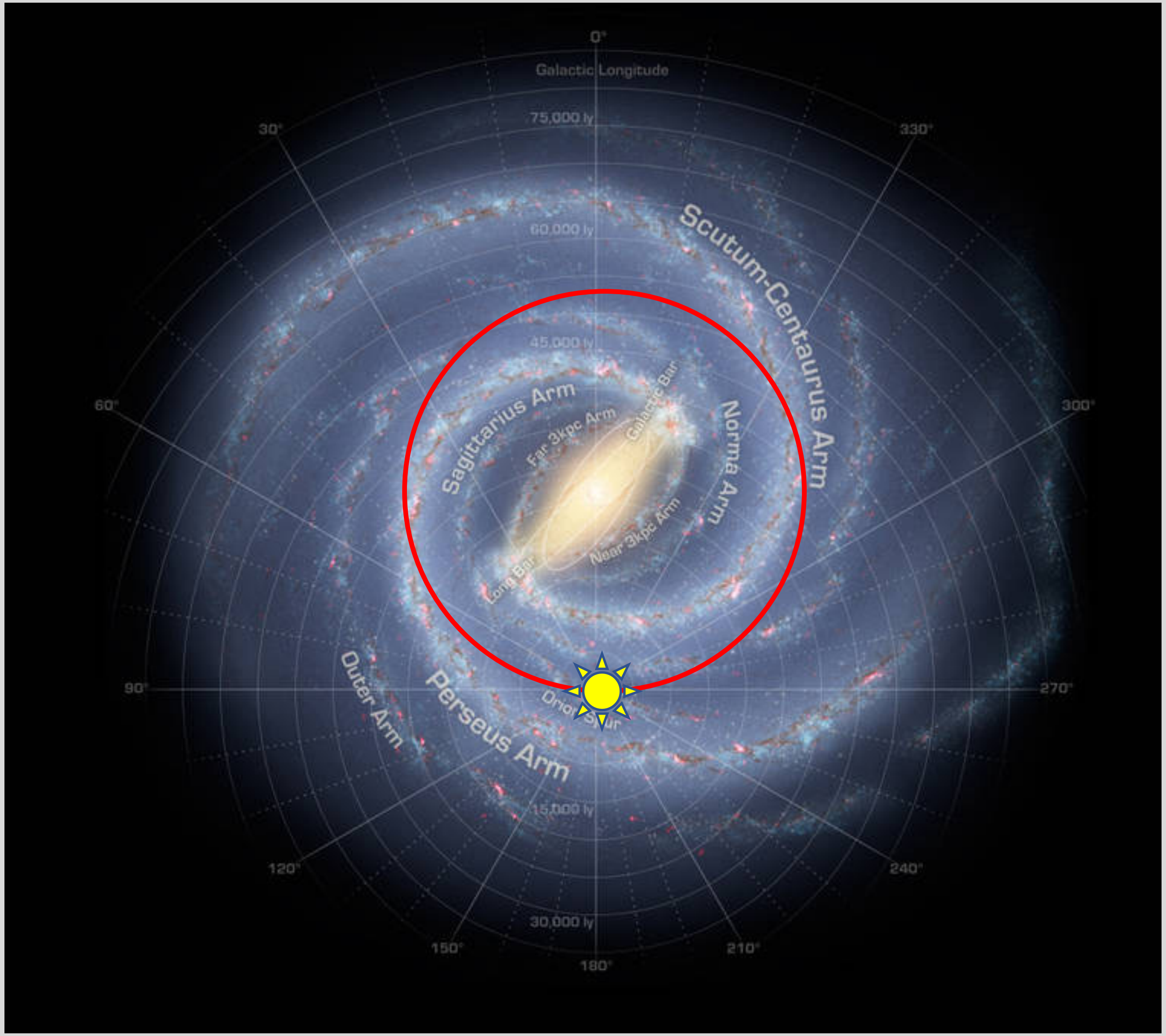
- The Galaxy's mass inside R_0:

$$\mathcal{M}(< R_0) = \frac{V_c^2 R_0}{G} = \frac{(230^2)(8200)}{4.3\times10^{-3}} \approx 10^{11}\ \mathcal{M}_\odot$$

using [pc,km/s,M$_\odot$] version of G!

But what about the rotation speed at other radii?

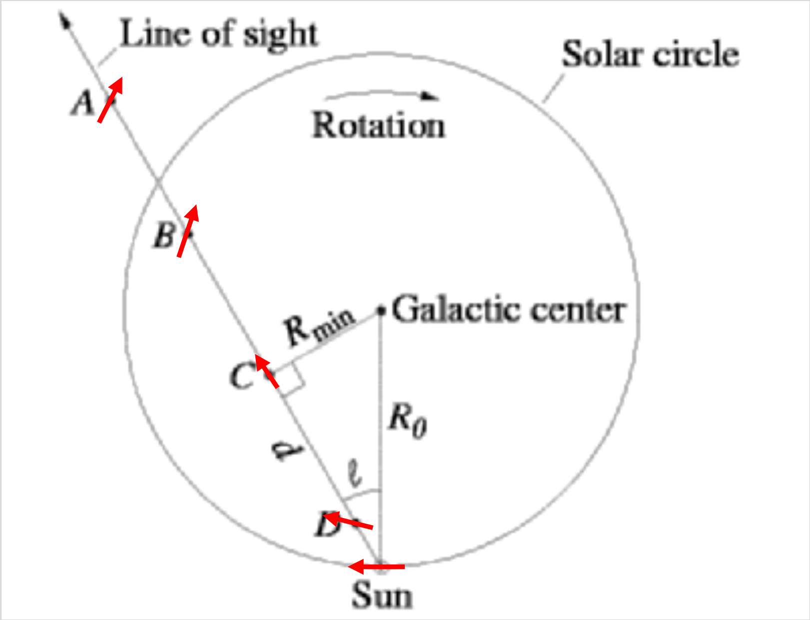
- *What does the rotation curve $V_c(R)$ look like?*
- *What would we **expect** it to look like?*

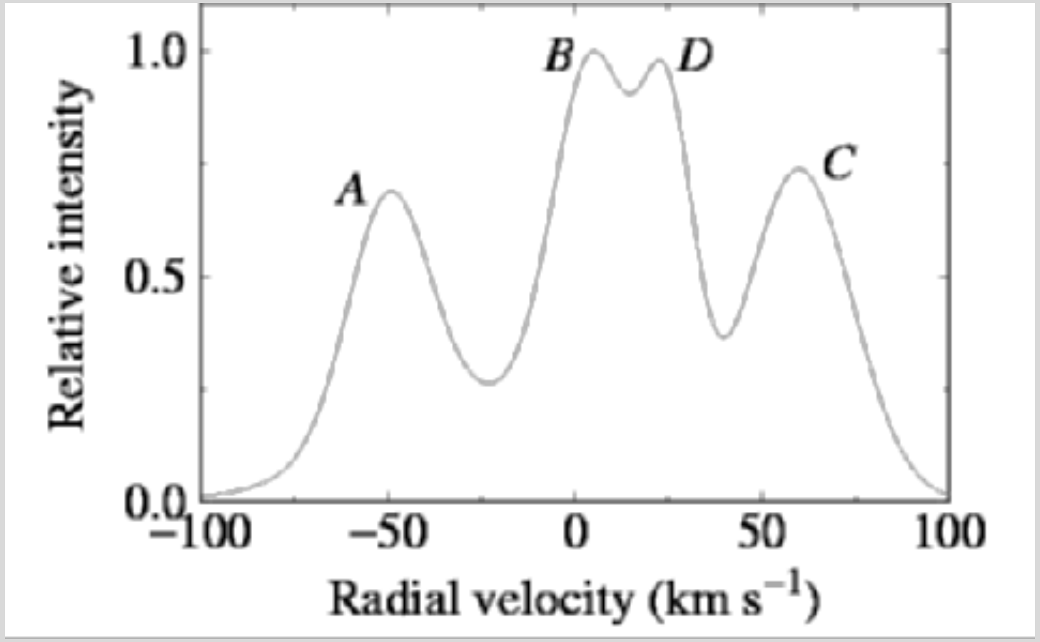


Measuring the Milky Way Rotation Curve

Want to map velocities of objects in the disk moving on ***circular*** orbits. What kinds of objects are these? *gas clouds!*

21-cm HI emission: no extinction at radio wavelengths. Map the HI velocities as a function of Galactic longitude, look for maximum velocity. Imagine gas clouds strung out along some line of sight, and the velocities you measure:





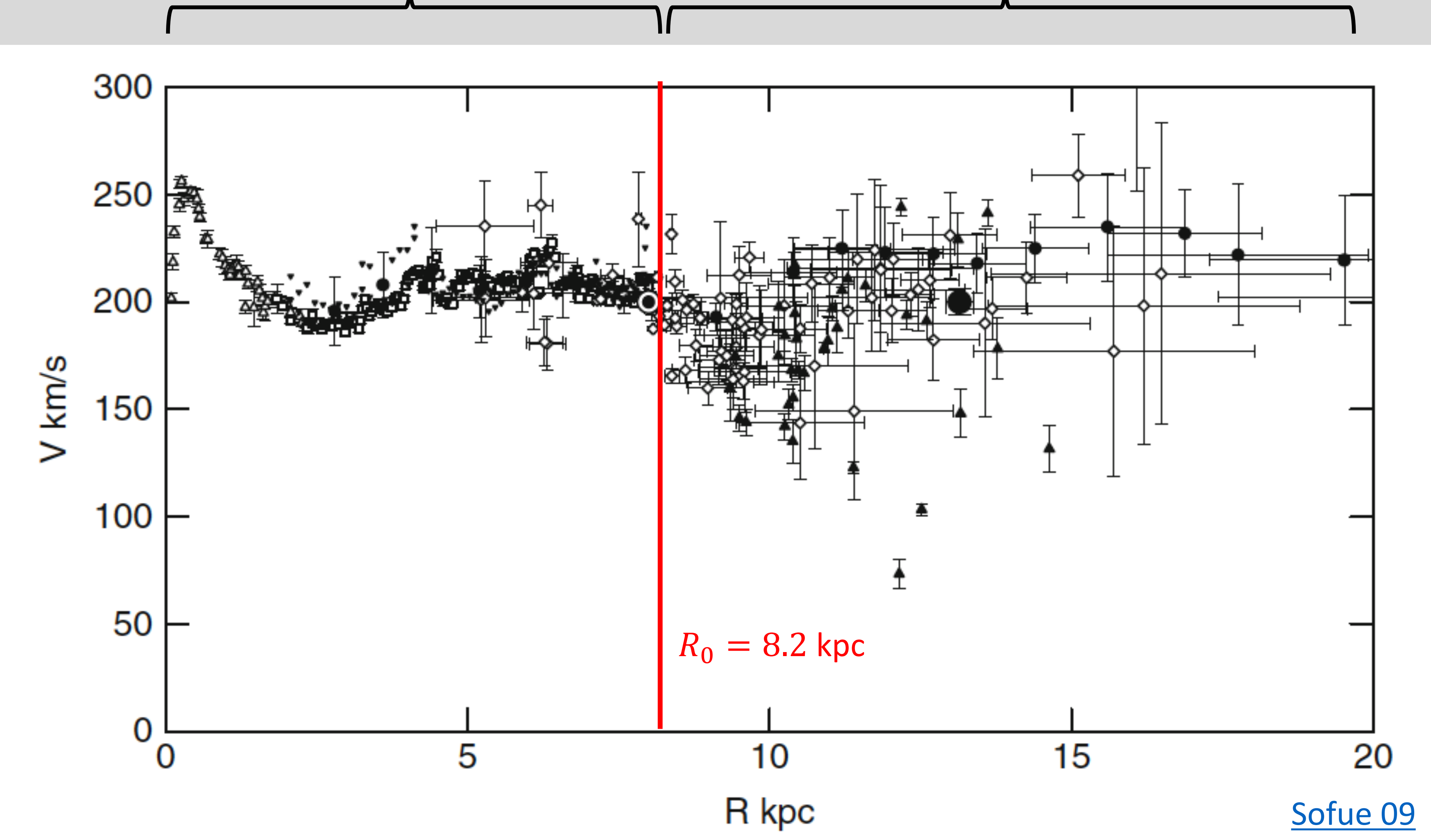
After taking out the Sun's motion, the line of sight velocity of cloud C should be the circular speed at $R_{min} = R_0 \sin \ell$.

Works well inside the solar circle: R < R_0. Beyond that, there is no tangent point and actual distances are needed. Use other tracers of young stars: Cepheids, HII regions, etc.

Milky Way Rotation Curve

Inside R_0 the tangent point method works well.

Outside R_0 we need distances to objects, which increases uncertainties.



Sofue 09

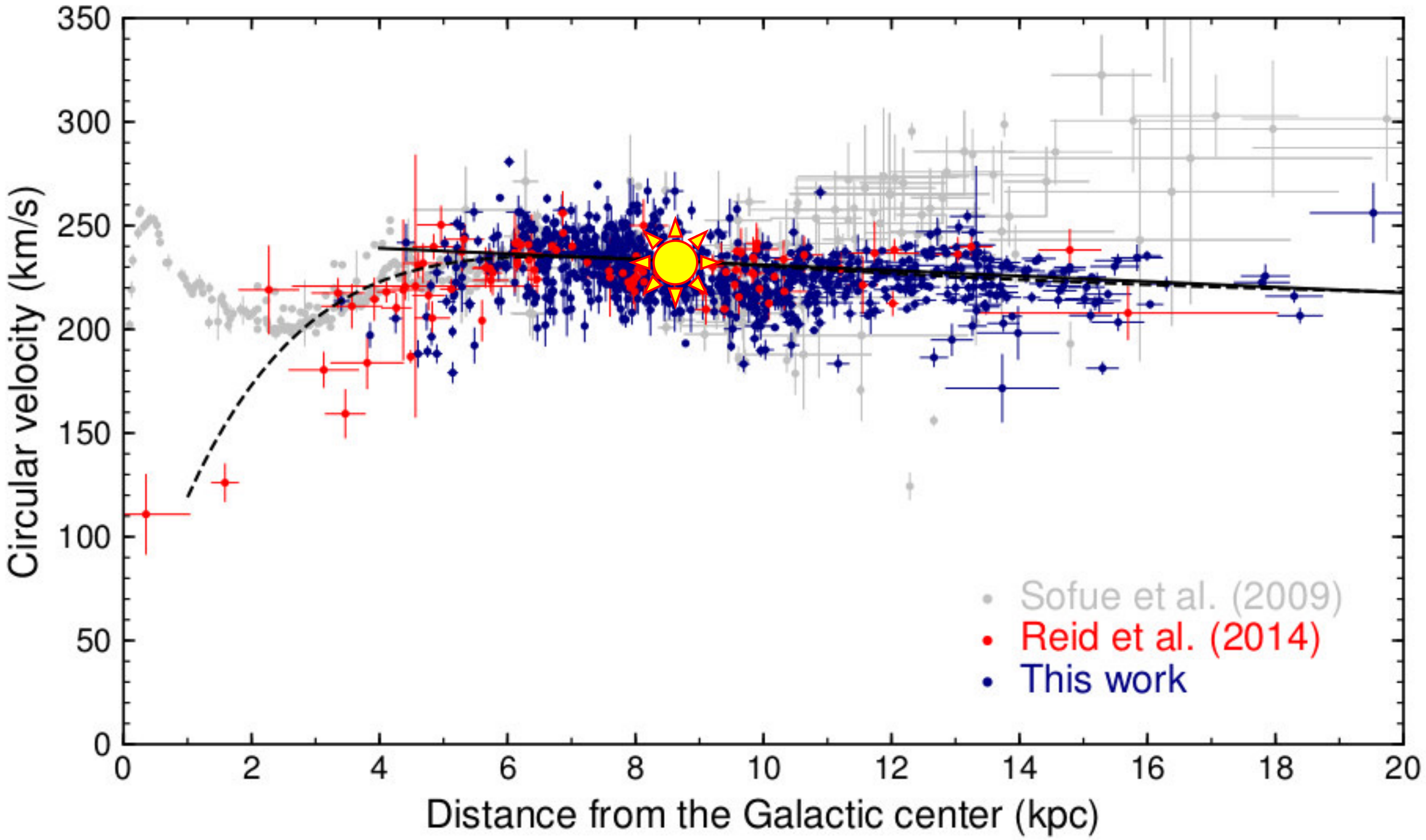
Milky Way Rotation Curve

Better distances mean better estimates!

Updated using Gaia Cepheid data:

$V_c(R_0) = 234$ km/s

Mroz+ 19



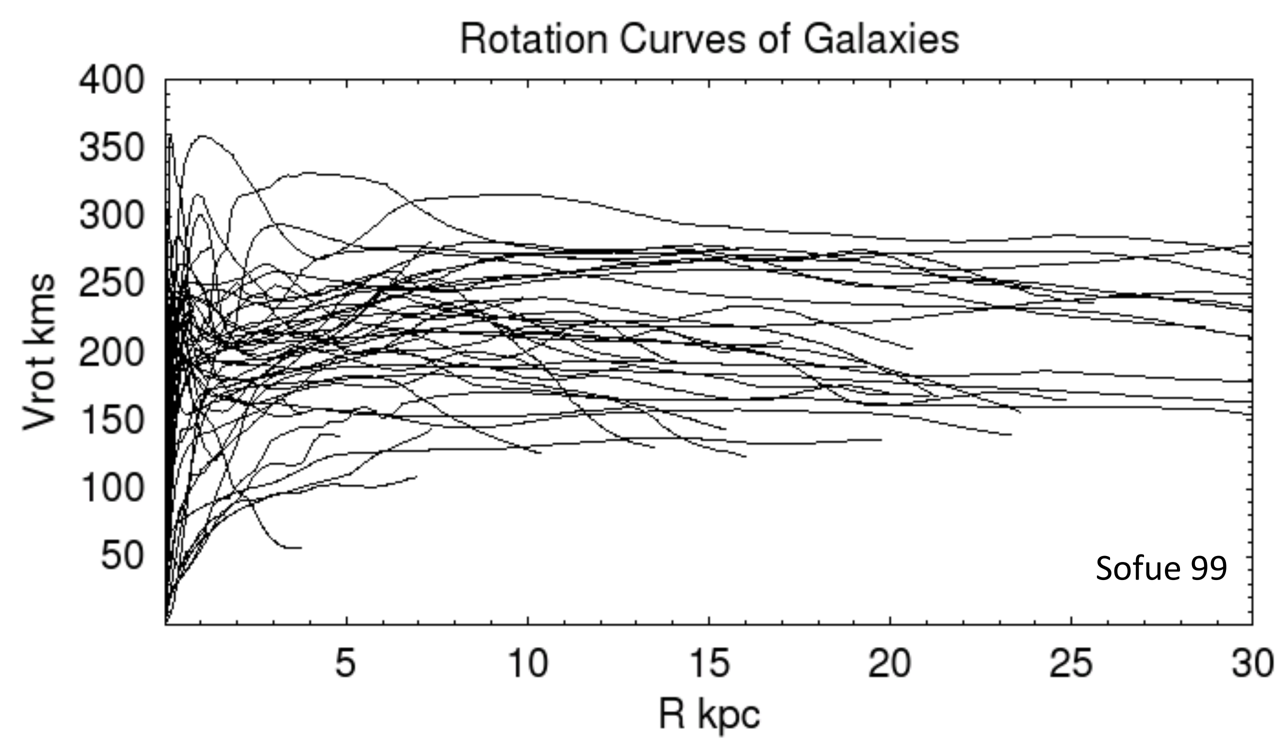
Flat Rotation Curves

The rotation curve of the Milky Way (*and nearly all other spiral galaxies!*) is essentially **flat:** $V_c(R) \approx$ constant.

What does this mean? Think about dynamical mass:

$$V_c{}^2(R) = \frac{G\mathcal{M}(< R)}{R} \quad \longrightarrow \quad \mathcal{M}(< R) = \frac{RV_c{}^2(R)}{G}$$

If $V_c(R) =$ constant, then $\mathcal{M}$ grows as R: there is more and more mass at larger and larger distances from the center! This is most definitely ***not*** how the stars are distributed!



Evidence for a lot of mass as far out as 100 kpc or more!

$$\left.\begin{array}{l}\text{Total dynamical mass} \approx 10^{12}\ \mathcal{M}_\odot \\ \text{Total star + gas mass} \approx 10^{11}\ \mathcal{M}_\odot\end{array}\right\}$$ *So roughly 90% of the mass in galaxies like the Milky Way is unseen "dark matter."*

The Dark Matter Halo

Doesn’t emit light (at any wavelength)
Doesn’t absorb light (at any wavelength)

The only way to detect (so far) it is through gravitational motions.

What could it be?

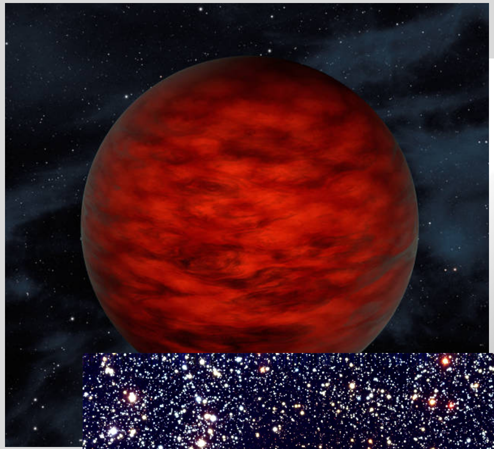
- low mass stars (brown dwarfs)?
- dark interstellar gas clouds?
- free floating space donkeys?

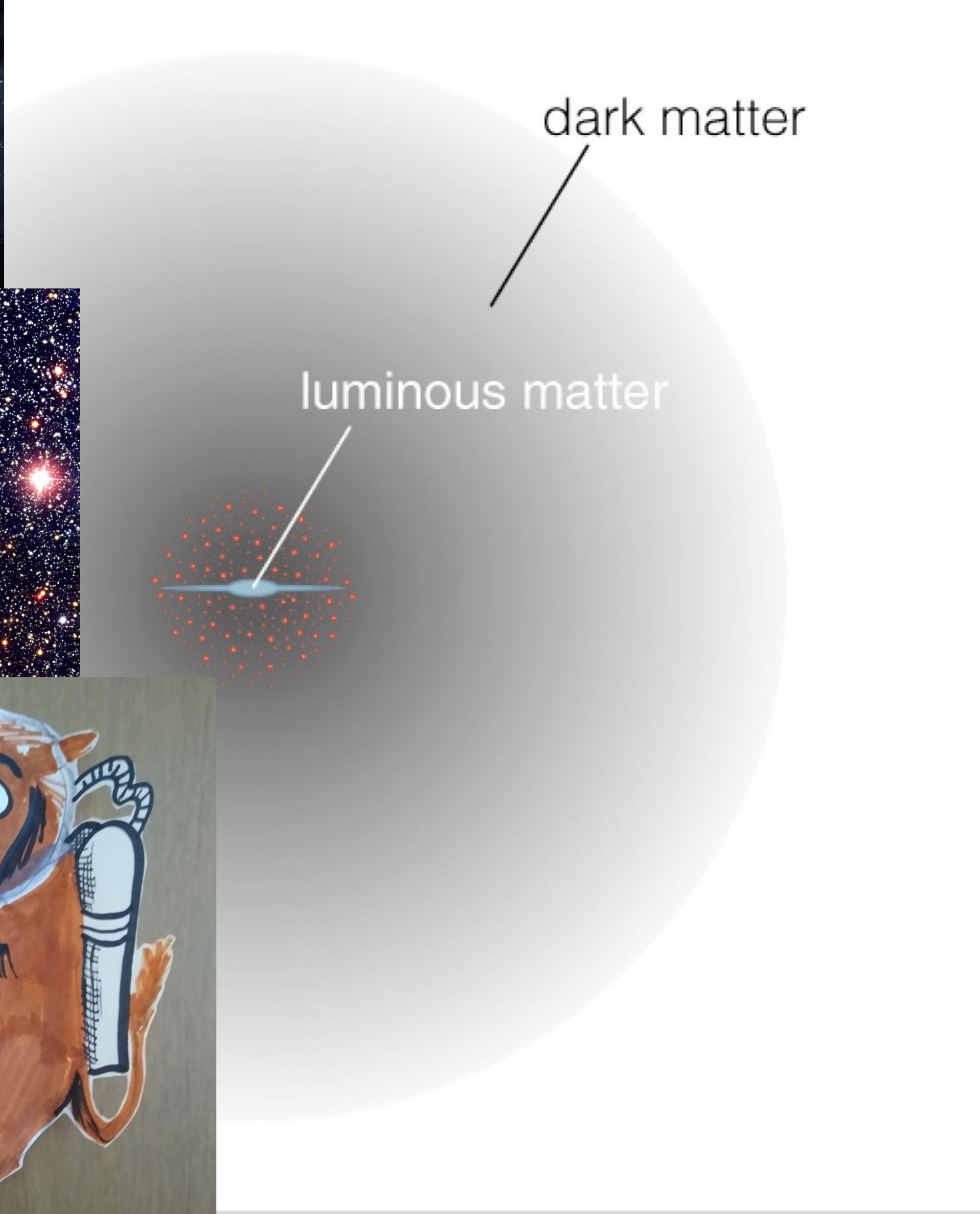
No! Anything made of normal matter (a.k.a. “baryonic matter”) is ruled out by cosmological considerations.

Two classes of solutions:

- **Particle physics:** hypothetical new class of particles, never observed or detected.

- **Gravity:** The law of gravity changes in ways we dont understand, so motion does not imply large unseen mass.





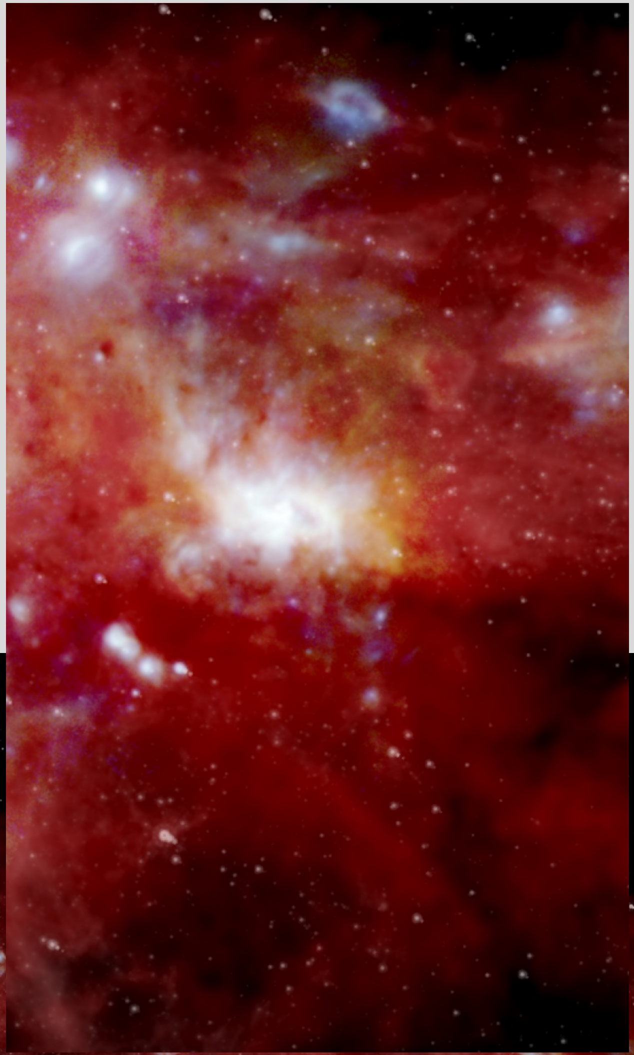
Studying the Galactic Center

Can’t be done in visible light: 28 magnitudes of dust obscuration

Infrared light

- much less obscured
- old red giants are bright in the near-infrared
- dust emits in the mid infrared

In the inner few parsecs, the density of stars rises as $\sim r^{-2}$: very dense, lots of old stars AND massive young stars (recent star formation), very high energy density.



Radio emission

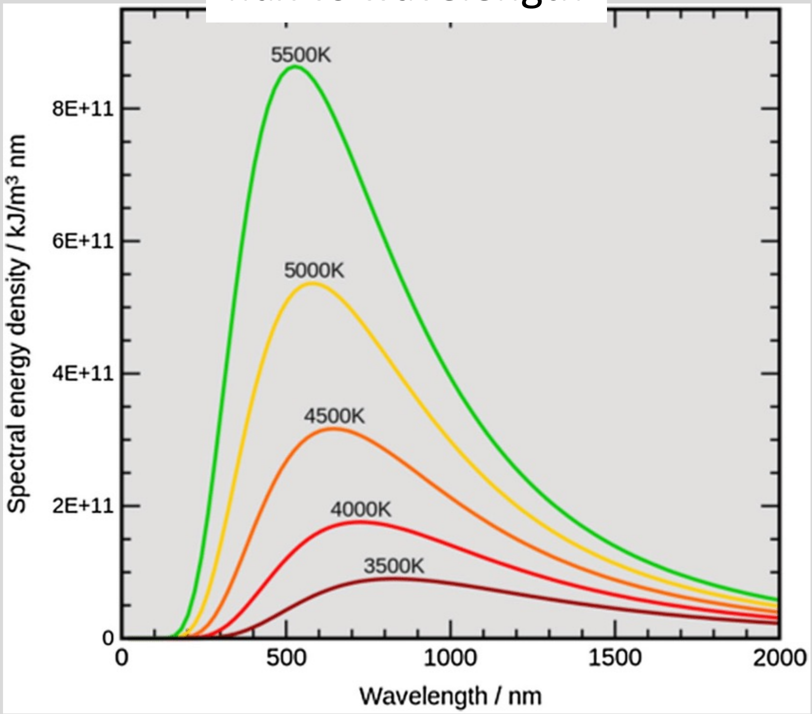
Remember Kirchoff’s laws from optical spectra:

“bound-bound emission”

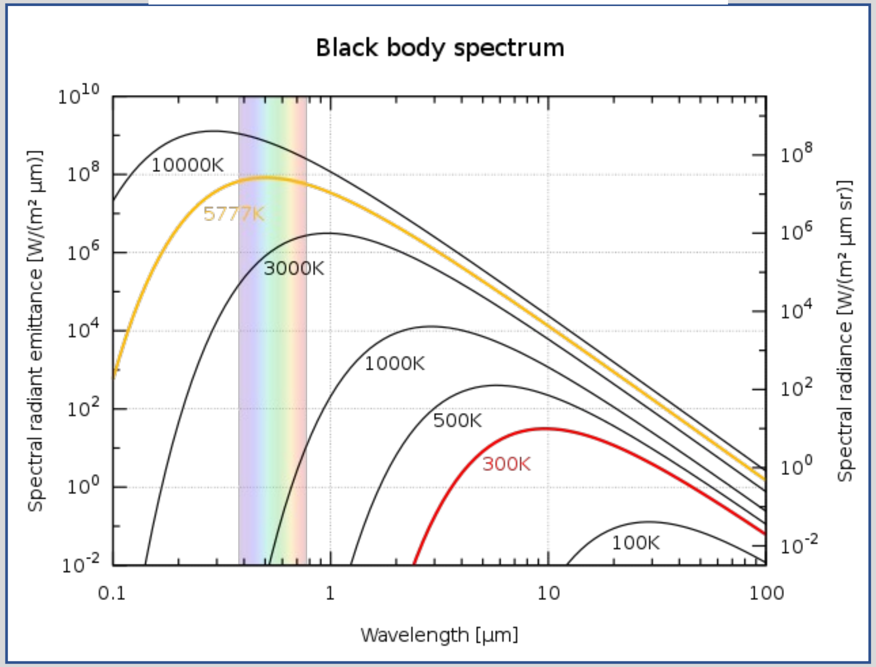
- Hot dense gas or solid emits **continuous spectrum**: black body
- Low density gas shows an **emission line spectrum** when electrons jump down in energy level
- Low density gas in front of a continuum source shows an **absorption line spectrum** when electrons absorb light and jump up in energy level

Blackbody spectra plotted different ways. At long wavelengths (Rayleigh-Jeans tail), the spectrum is a power law: $F \propto \nu^2$

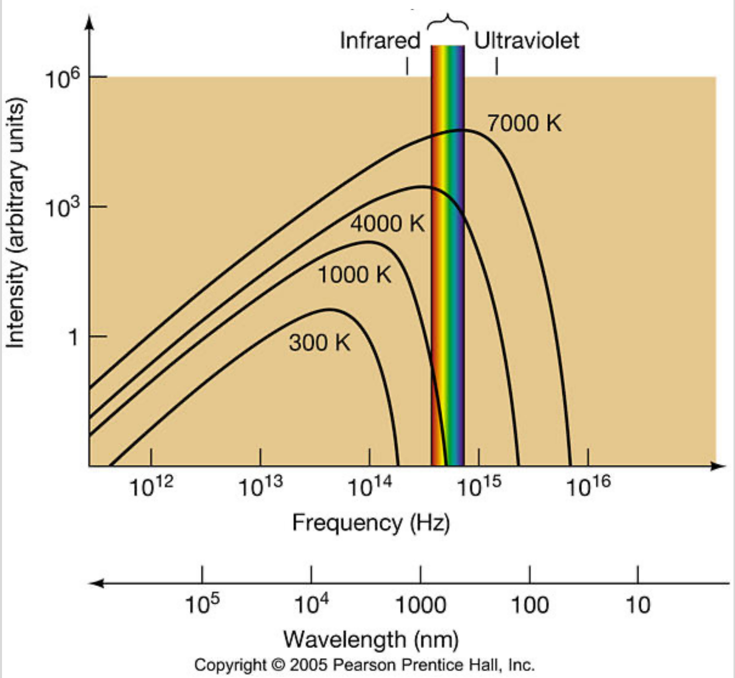
flux vs wavelength



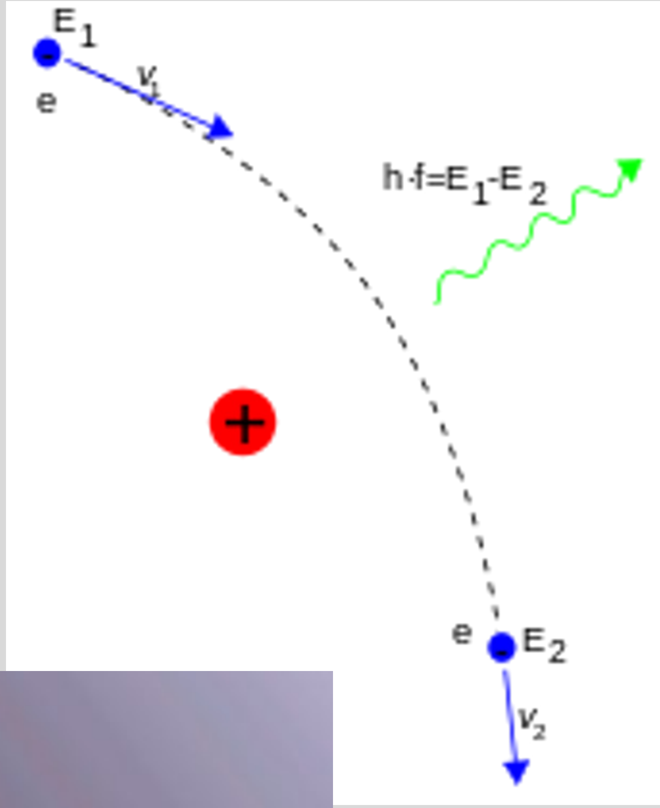
log(flux) vs log(wavelength)



log(flux) vs log(frequency)



(Other) Radio emission processes



Free-free ("Bremsstrahlung") emission:

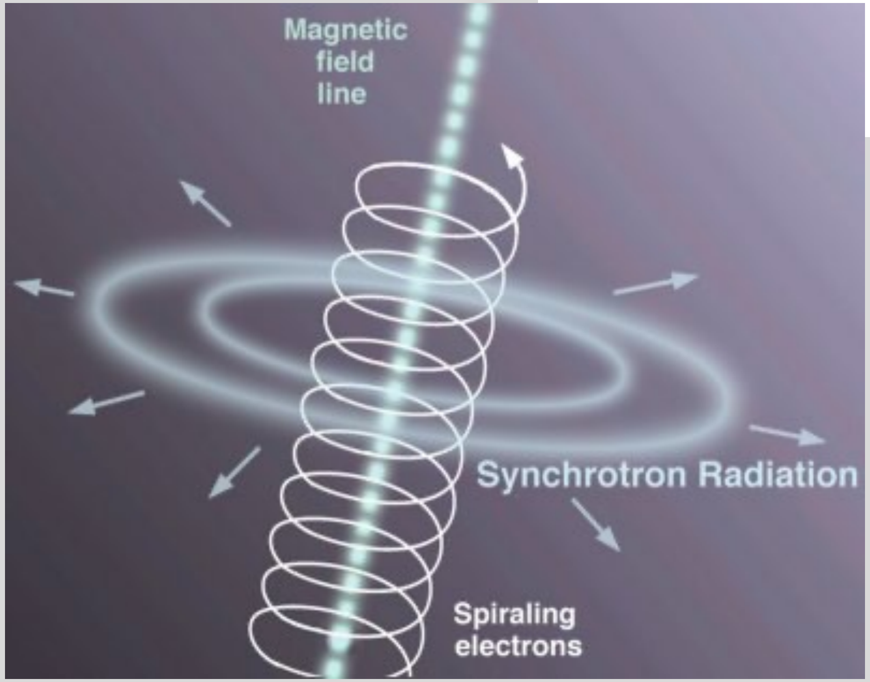
Charged particles in ionized gas interact with one another electrostatically, which accelerates them. Accelerated charged particles emit energy (photons). Most important is electrons interacting with ions.

At low frequencies (radio), the emitting gas is opaque and emits like a blackbody, with a power law spectrum: $F \propto \nu^2$

Synchrotron Emission

Relativistic electrons are accelerated by magnetic fields, spiral along magnetic field lines, and emit synchroton radiation.

Also gives a power law spectrum, but with a spectral index that depends on frequency and particle energy.



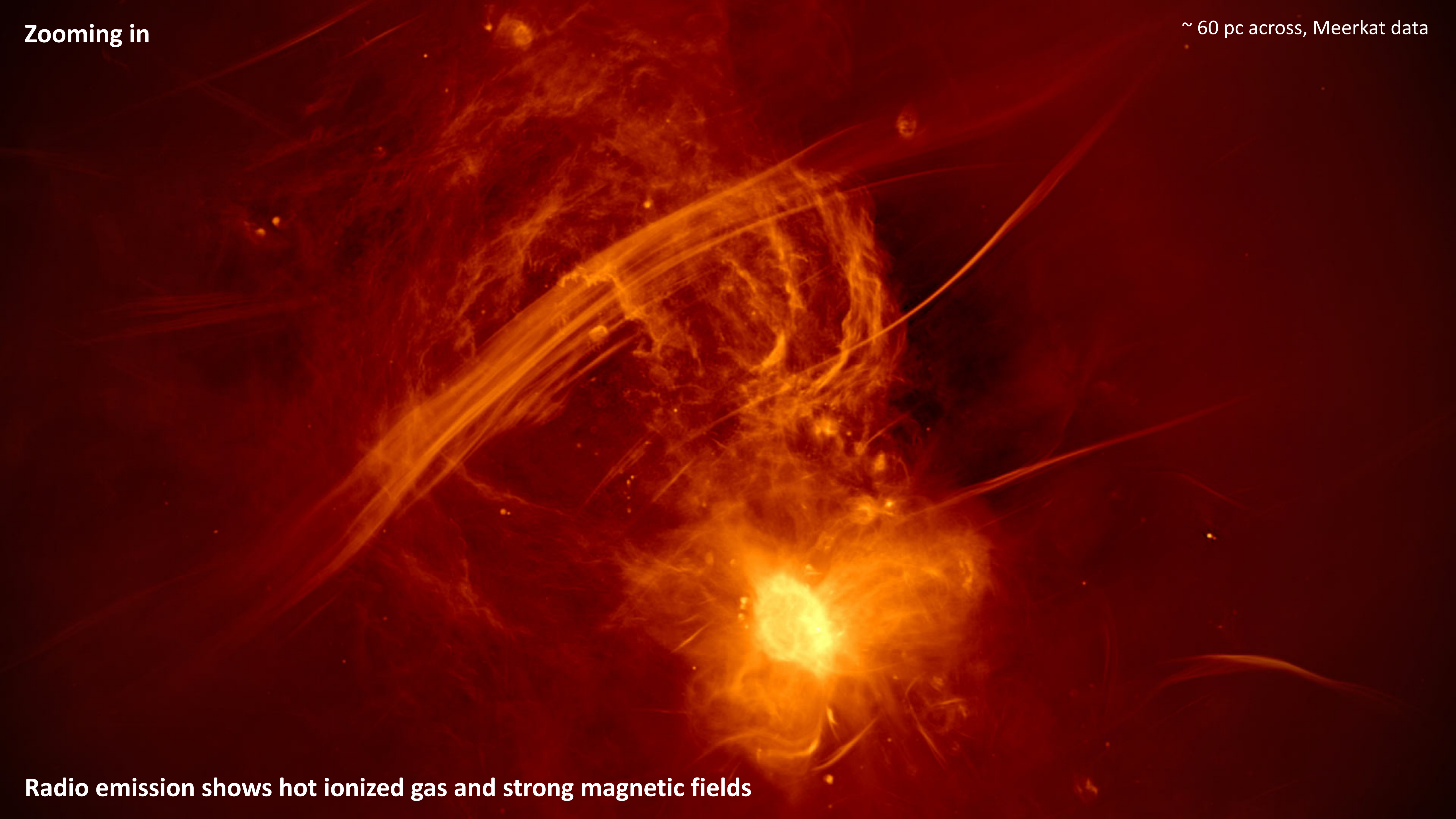
details and figure courtesy Scott Ransom

The Galactic Center in Radio Emission

~ few hundred pc across, Meerkat data

- unobscured, not stellar emission
- synchrotron emission: charged particles spiraling in magnetic fields
- free-free emission: charged particles interacting with each other

Zooming in



Radio emission shows hot ionized gas and strong magnetic fields

At the center

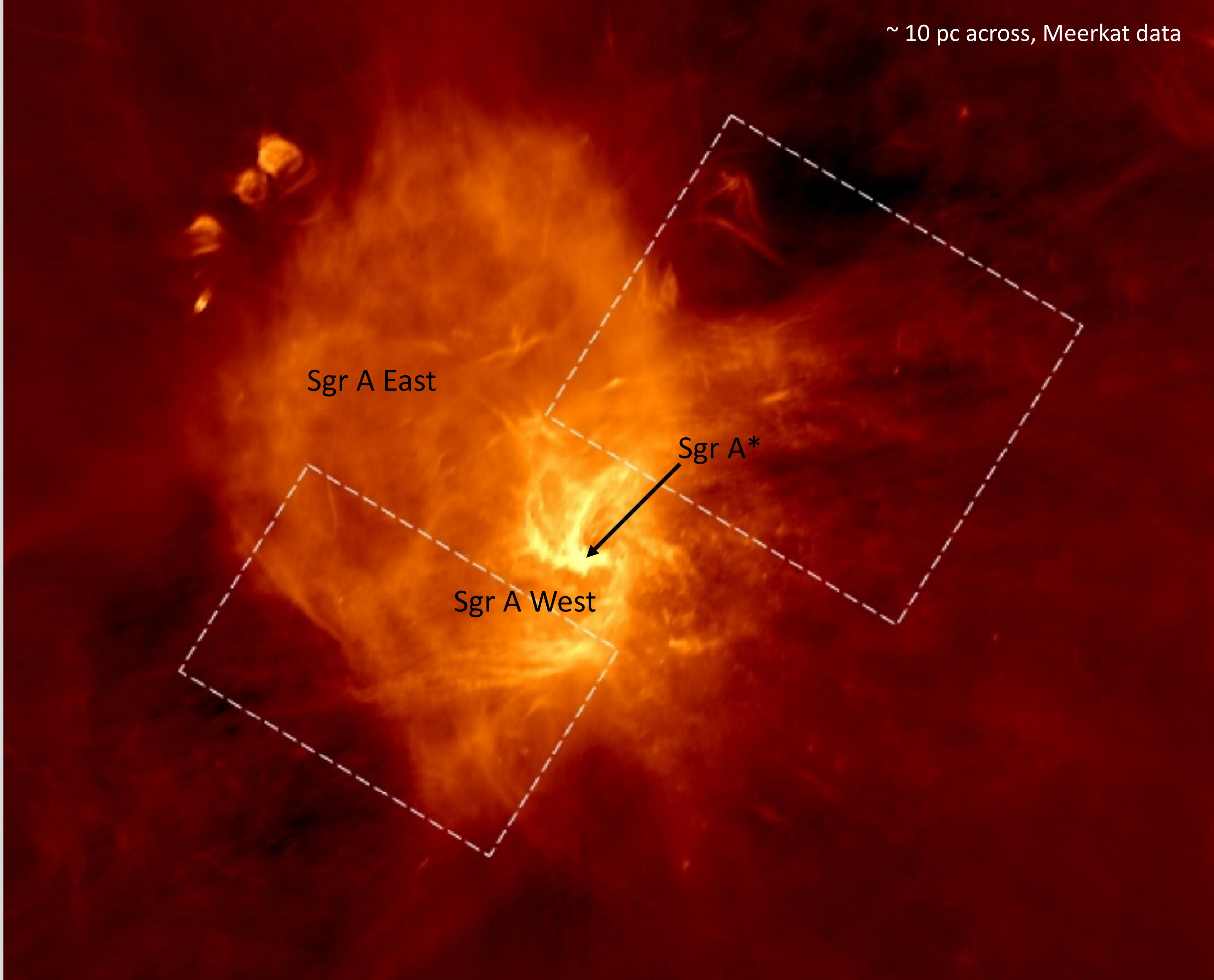
Sgr = Sagittarius

Sgr A East: hot gas, possible supernovae remnant

Sgr A West: ionized gas, spiral shaped.

Sgr A*: bright, very compact radio source at the center.

What's going on??



The central object: Sgr A*

Sgr A* is also an **X-ray source**, with luminosity $L_X \approx 10^5\ L_\odot$.

The X-ray luminosity varies on timescales of a few months. This puts a limit on its size, due to **causality**.

Variability is caused by some disturbance in the object, and the fastest any disturbance can travel is the speed of light. So causality says that the size must be less than:

$$R < c\Delta t$$

So the size of the central object must be less than a few light-months, which corresponds to < 0.1 pc.

At **radio wavelengths** Sgr A* is also unresolved down to a few milliarcseconds, meaning it must be smaller than 20 AU.

So that's $10^5\ L_\odot$ worth of energy packed into a size comparable to the size of our solar system!

The central object: Stellar kinematics

Look at the velocity dispersion of stars in the inner few parsecs.

What would we expect to see? Balance kinetic energy of motion (σ_v^2) with gravitational potential:

$$\sigma_v^2 \propto \frac{G\mathcal{M}(r)}{r}$$

The mass should just be volume times density, so:

$$\sigma_v^2 \propto \frac{G}{r}\frac{4\pi r^3}{3}\rho(r)$$

We said earlier that the density of stars rises towards the center: $\rho(r) \propto r^{-2}$, so

$$\sigma_v^2 \propto \frac{G}{r}\frac{4\pi r^3}{3}r^{-2}$$

The r terms all cancel, so **the velocity dispersion should be constant with r** – it should not change as we near the galactic center.

What we actually see!

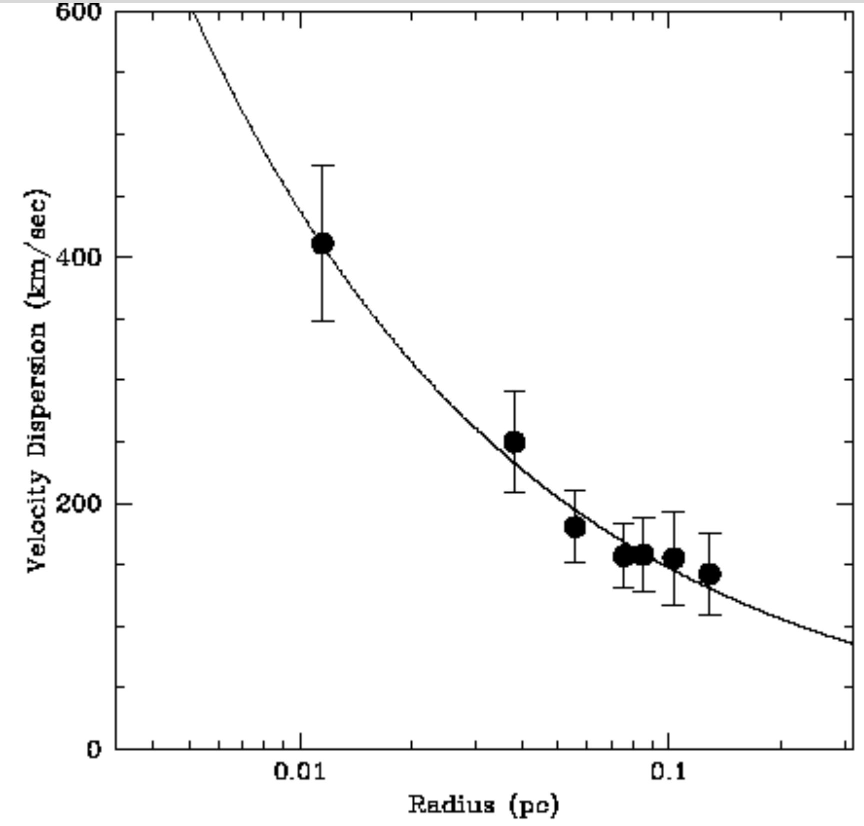


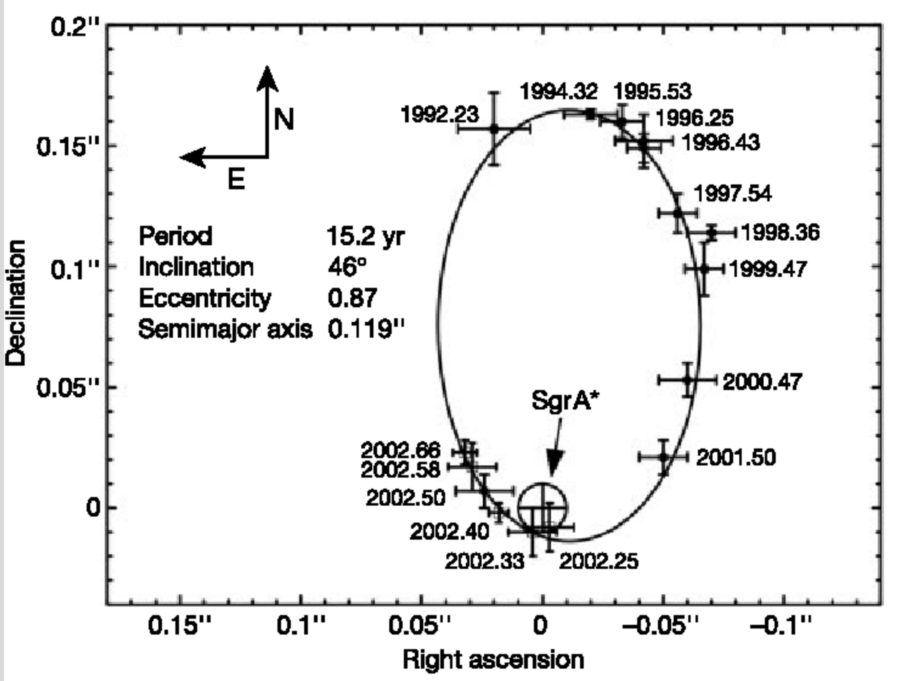
FIG. 5.—Projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies the gravitational field is dominated by mass within 0.1 pc.

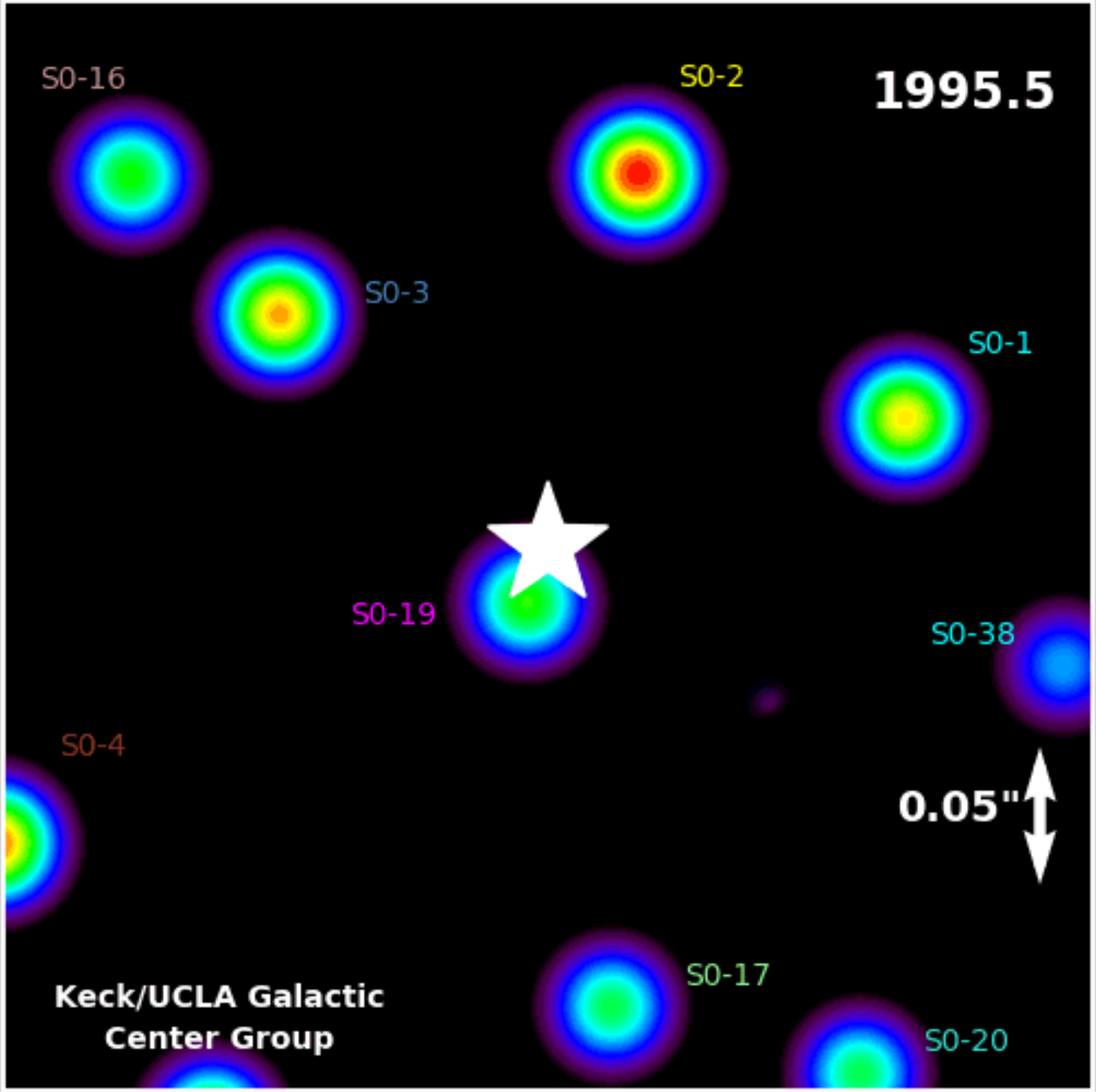
The kinematics are dominated by a massive object at the center no larger than 0.1 parsecs in size.

The central object: Stellar orbits

Using infrared data, we can follow the motion of individual stars passing within a hundred AU of Sgr A*. The orbits are Keplerian!

Use the orbits to derive a mass for Sgr A* of $\approx 4{\times}10^6\, \mathcal{M}_\odot$



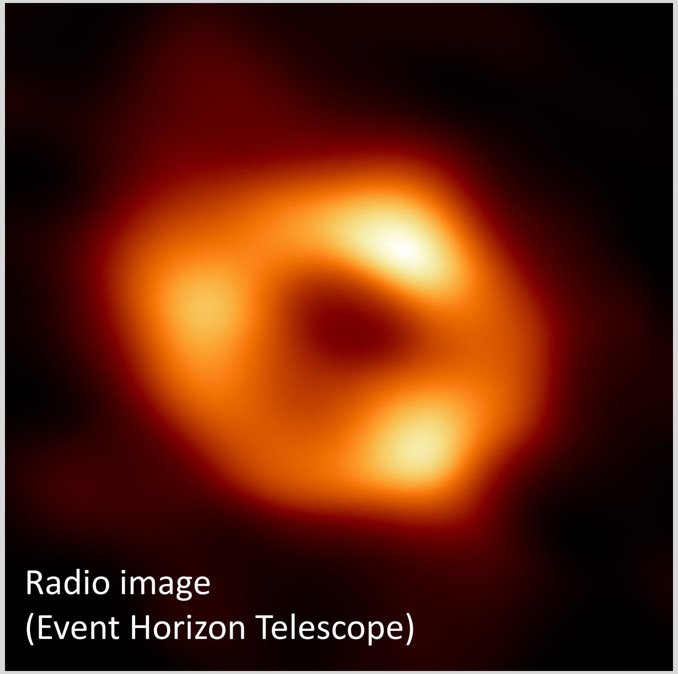


The Milky Way's supermassive black hole

At the heart of Sgr A* is a $\approx 4\times10^{6}\,\mathcal{M}_{\odot}$ supermassive black hole.

Surrounding the black hole is an accretion disk of infalling hot gas which emits the X-rays.

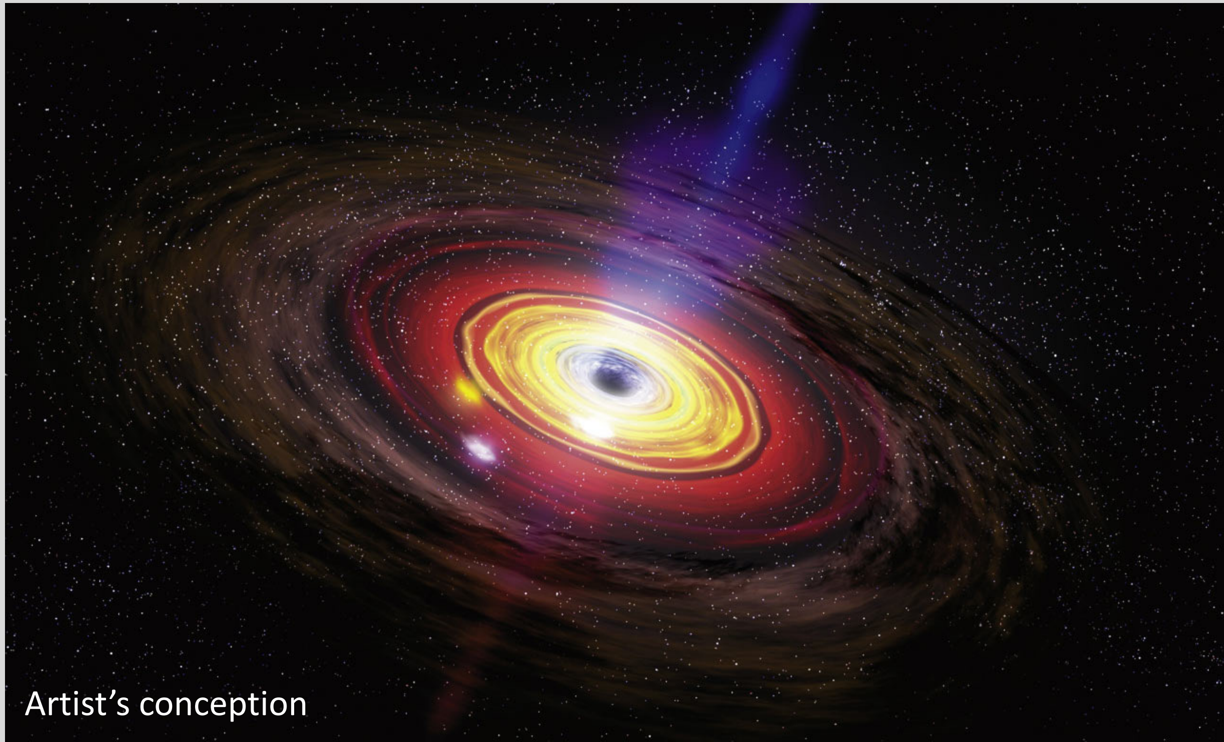
The energy ionizes the surrounding gas, creating the radio emission.



Radio image
(Event Horizon Telescope)

Outstanding Questions:

- *How did it form? How did it grow?*
- *How has it affected the galactic center?*
- *It's fairly quiet now, but what happens when it feeds?*
- *Is there one of these at the center of every galaxy?*



Artist's conception

The Milky Way's Environment: Satellite Galaxies

The Milky Way is orbited by a host of small satellite galaxies at a distances of 10-100 kpc.

Brightest two are the **Large and Small Magellanic Clouds**, two gas-rich irregular dwarf galaxies.

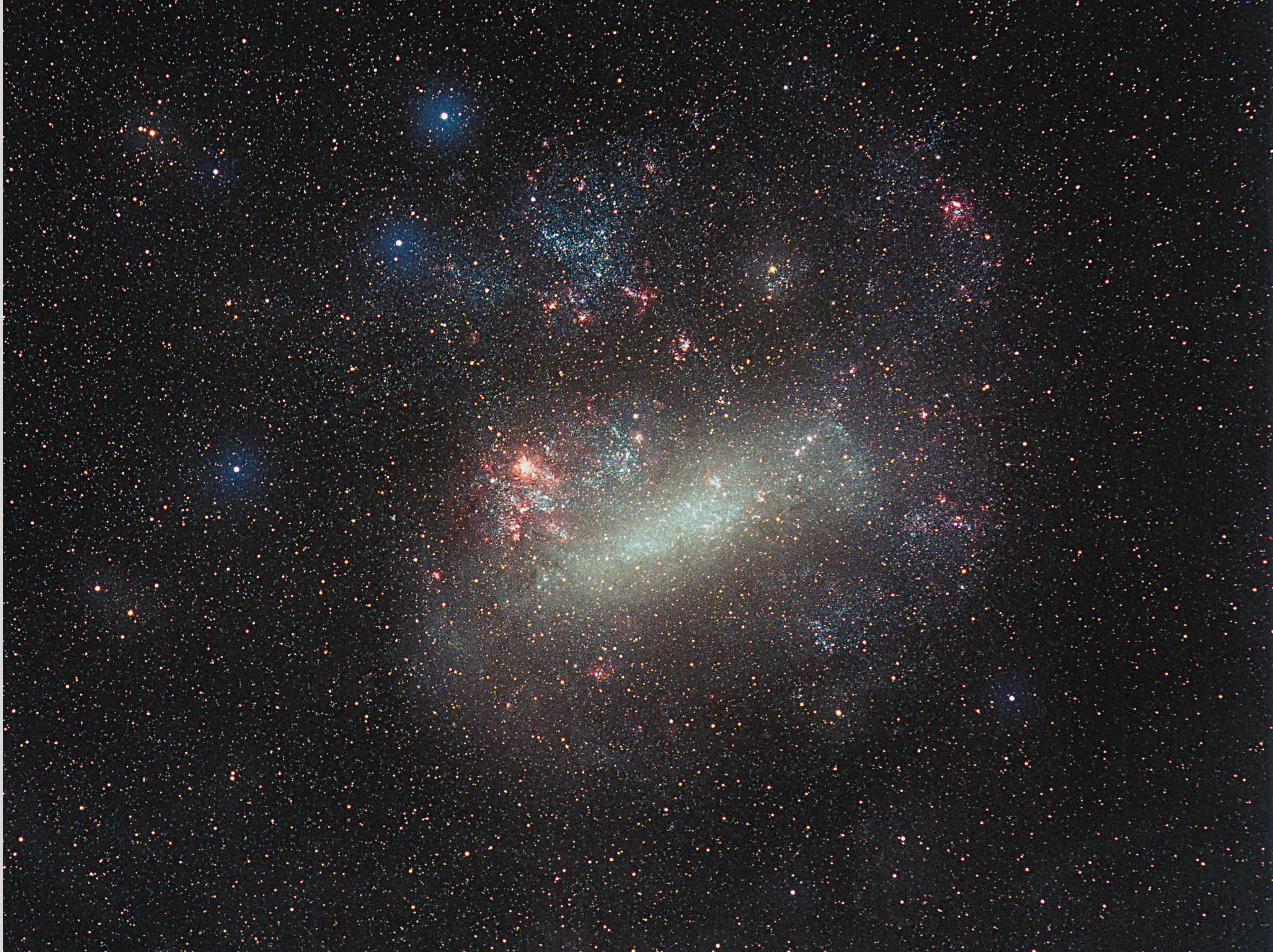
LMC and SMC are visible as naked eye objects in the southern hemisphere.

Large Magellanic Cloud (LMC)

distance ≈ 50 kpc

diameter ≈ 15 kpc

mass $\approx 2 - 3 \times 10^{10}\ \mathcal{M}_{\odot}$
(few % of MW mass)



Small Magellanic Cloud (SMC)

distance ≈ 60 kpc

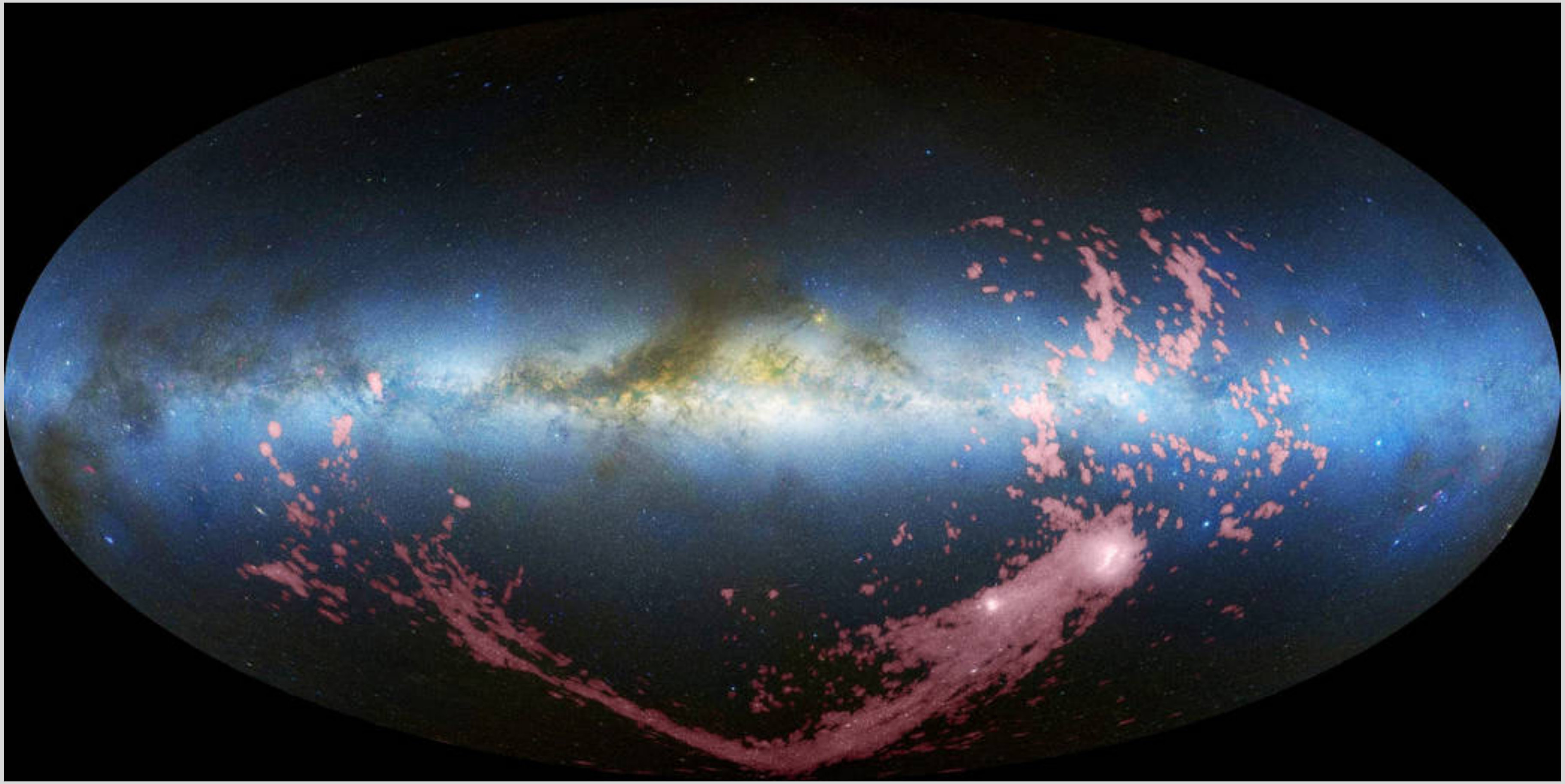
diameter ≈ 5 kpc

mass $\approx 3 - 5 \times 10^9\ \mathcal{M}_\odot$
(< 1% of MW mass)

The Magellanic Clouds

The Clouds orbit each other as they orbit the Milky Way. The combined interaction has pulled a long stream of neutral hydrogen (HI) gas out of the galaxies and spread it across the sky: **The Magellanic Stream**. (HI overlaid in pink, below)

Dynamics of the system suggest the clouds orbit the MW with semimajor axis a ≈ 125 kpc and T ≈ few billion years, *but these numbers are very uncertain.*



Dwarf Spheroidal Galaxies (dSph)

low mass: $10^6 - 10^8\ \mathcal{M}_\odot$

small ($\leq$ kpc)

low density

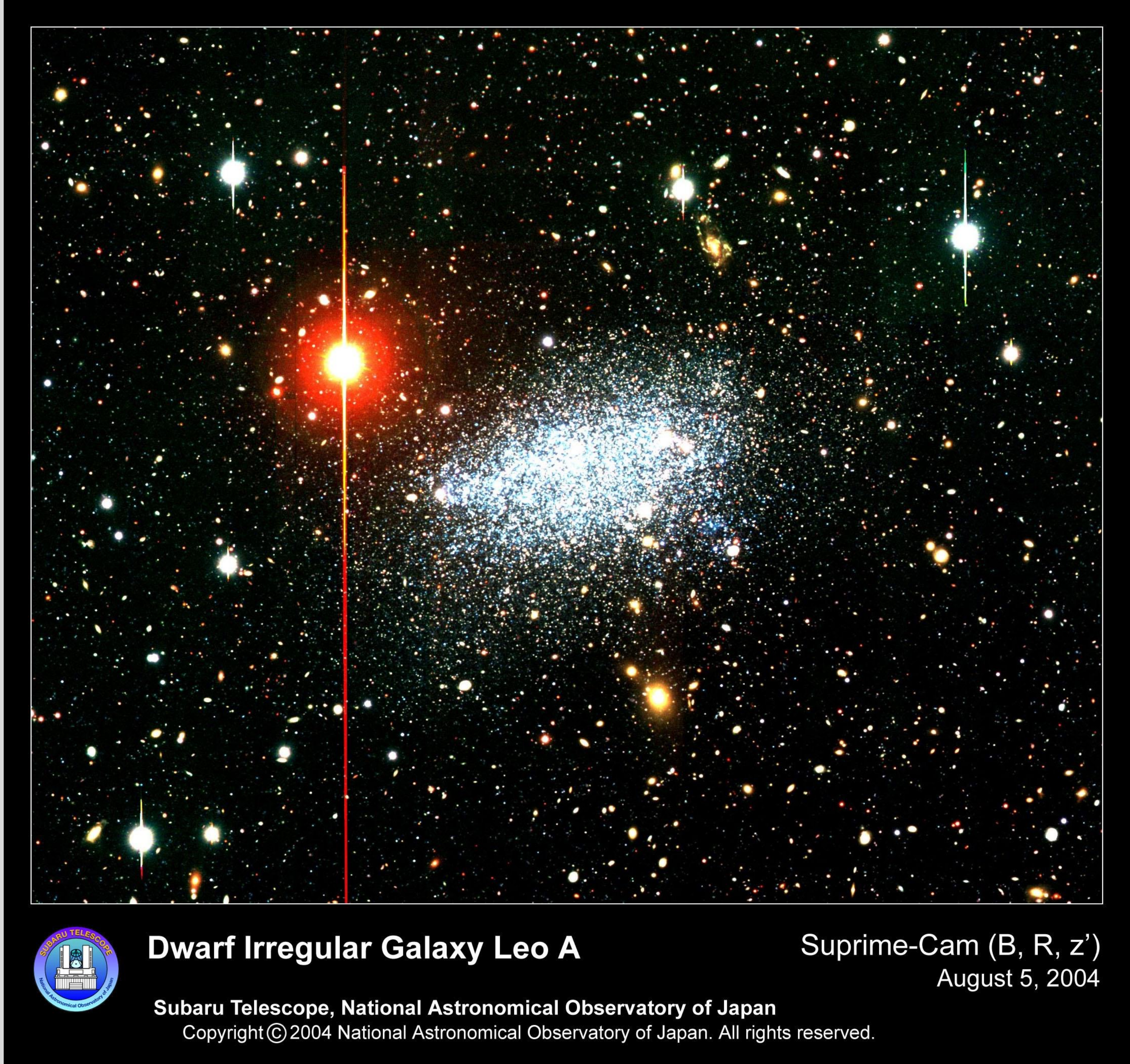
gas poor, no ongoing star formation

Leo I dSph

Dwarf Irregular Galaxies (dIrr)

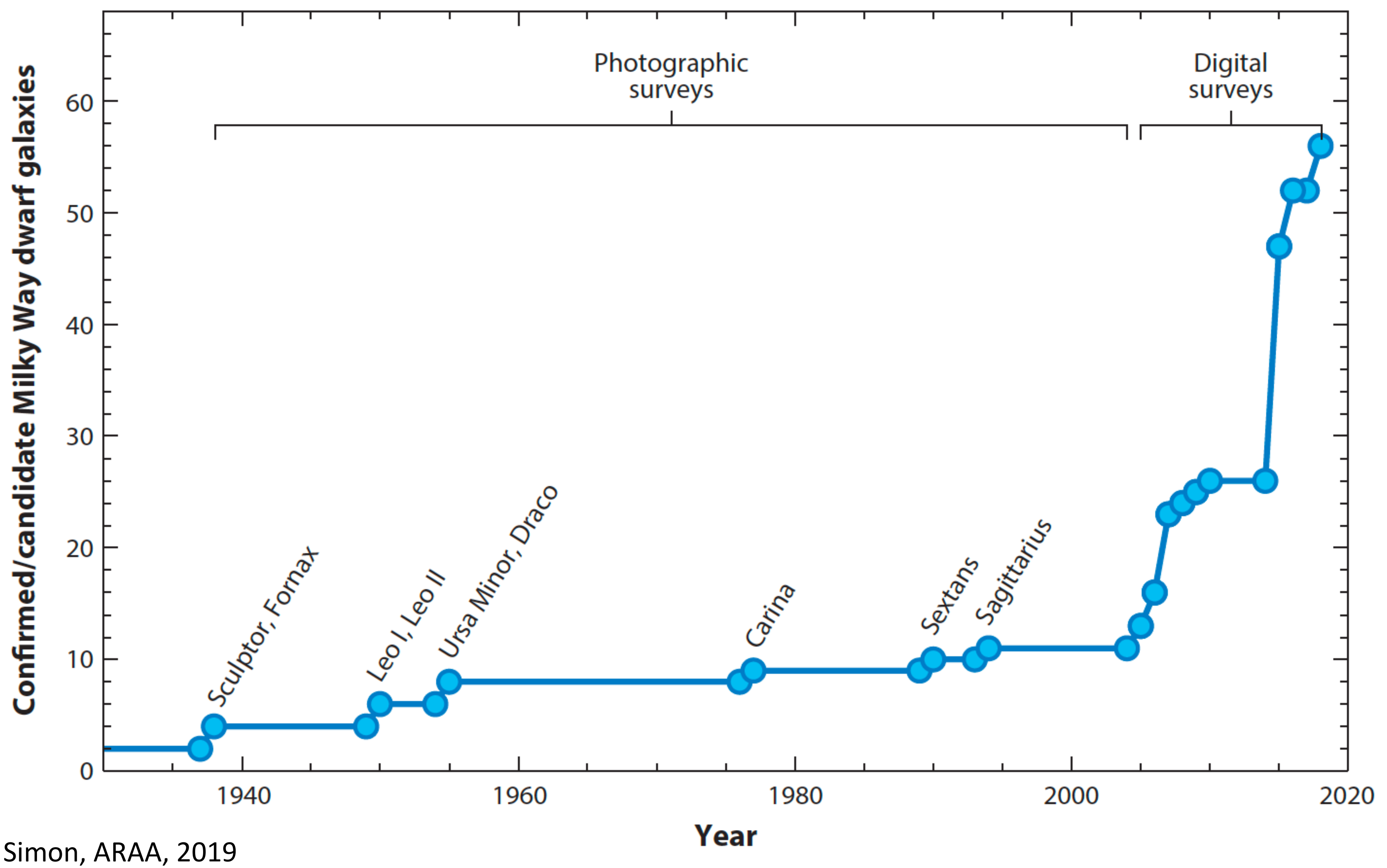
Similarly low in mass and size to dSph galaxies, but brighter, and gas-rich with active star formation.

The brightest ones are the LMC and SMC, but there are more faint ones.



Ultrafaint Dwarfs

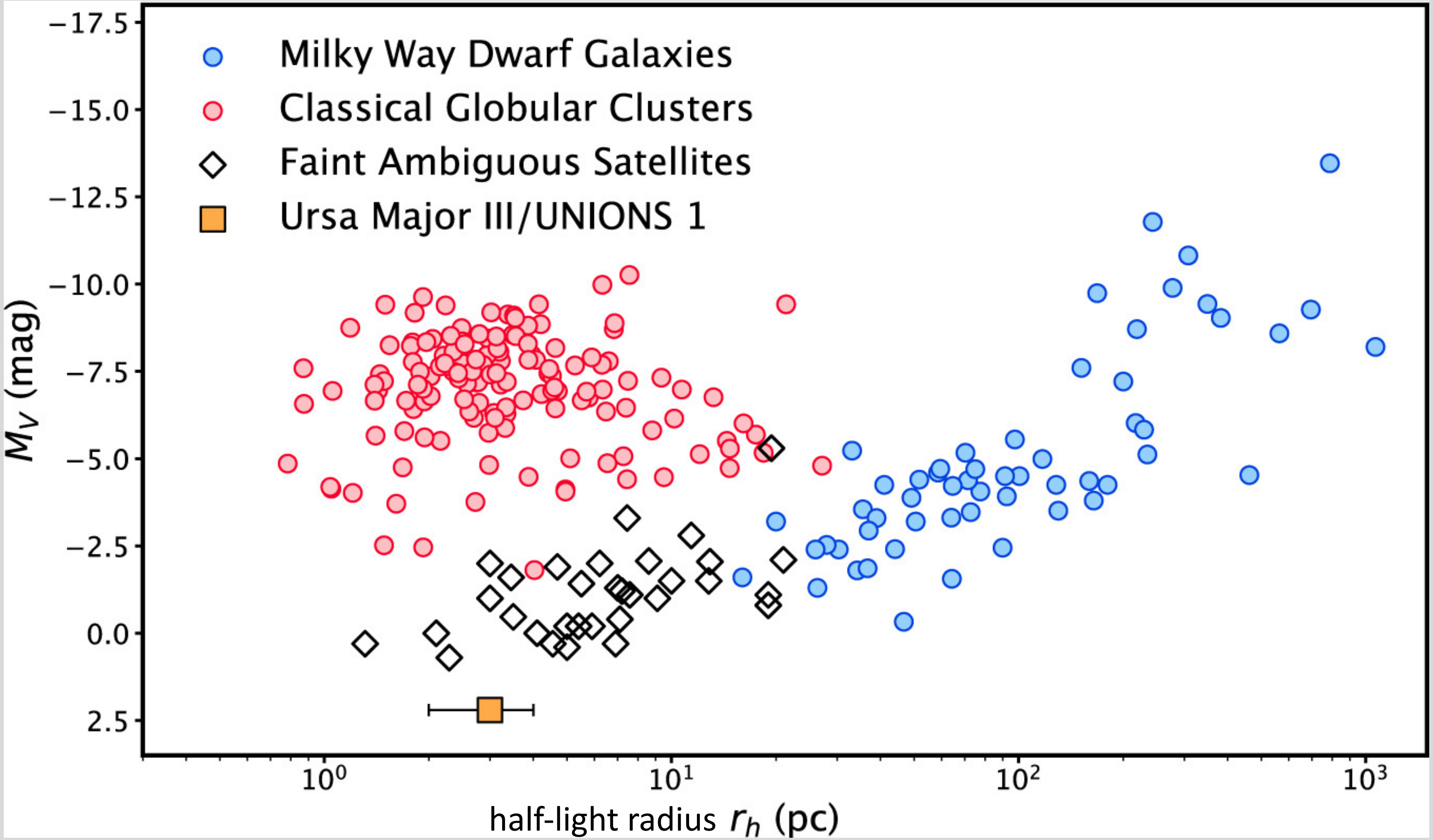
New deep imaging surveys are finding lots and lots of dwarf galaxies orbiting in the Milky Way's halo:



Simon, ARAA, 2019

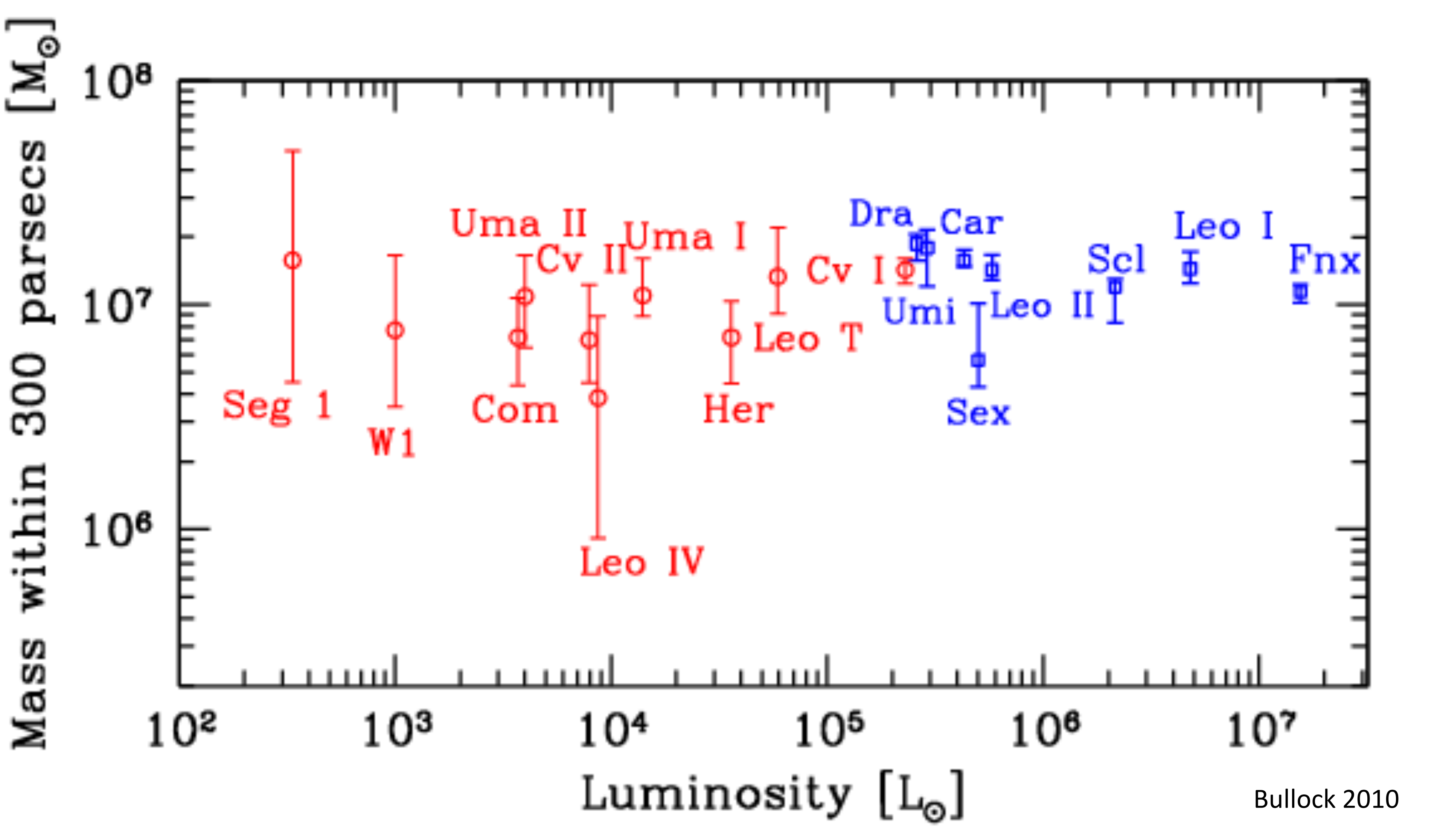
Ultrafaint Dwarfs

New deep imaging surveys are finding lots and lots of dwarf galaxies orbiting in the Milky Way's halo:



Ultrafaint Dwarfs

These new galaxies are extremely low in luminosity ("ultrafaint"), but still show evidence for dark matter halos.



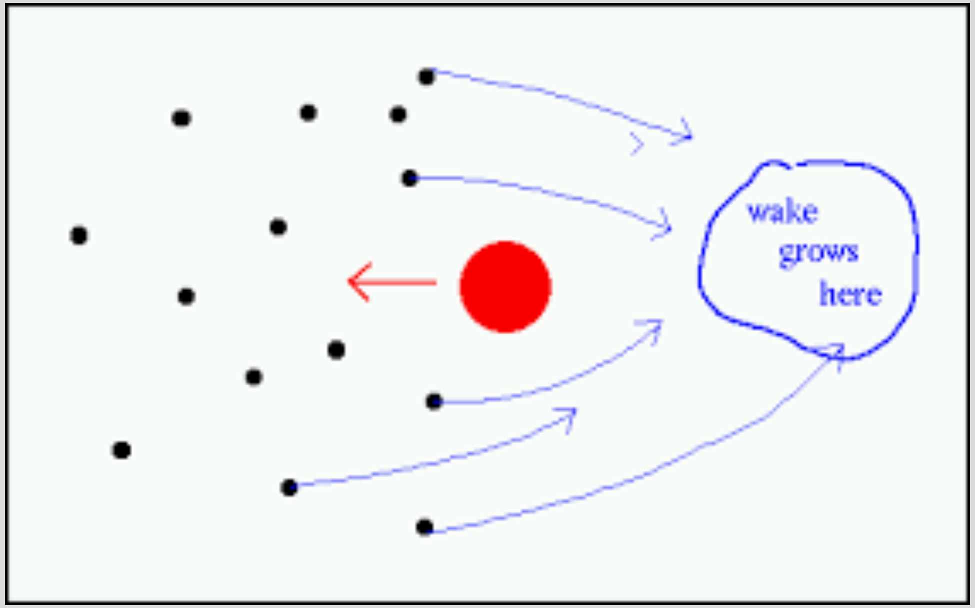
Bullock 2010

Dwarf Galaxies: Dynamical Friction

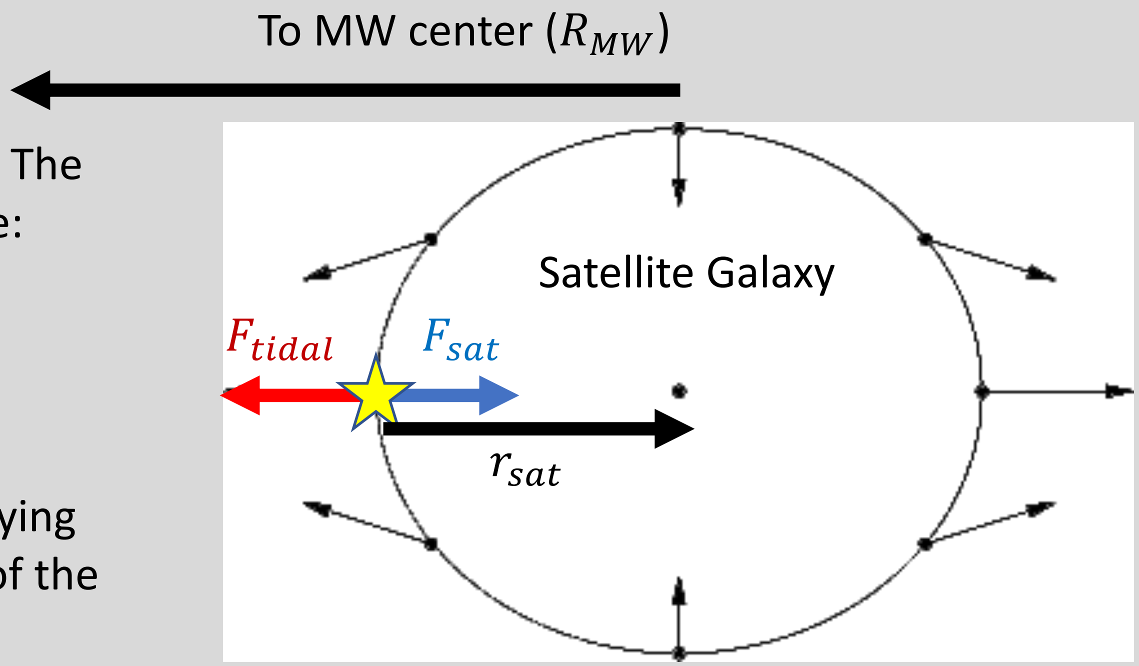
Imagine a massive object moving through a sea of low mass particles. As it moves through, it gravitational pull deflects the low mass particles into an overdense “wake” behind it.

This wake has mass and pulls backwards on the object, slowing its motion: **dynamical friction**.

This causes satellite galaxy orbits to decay with time, and the satellite slowly spirals inwards. The effect is stronger for massive satellites, and for satellites close to the Milky Way.



Dwarf Galaxies: Tidal Stripping



Imagine a satellite galaxy orbiting the Milky Way at a distance R_{MW}. The satellite's stars feel a gravitational force binding them to the satellite:

$$F_{sat} = \frac{G\mathcal{M}_{sat}}{r_{sat}^2}$$

But they also feel the gravitational tidal force from the Milky Way trying to pull them away from the satellite. The tidal force is the gradient of the Milky Way's gravitational force across the body of the satellite.

$$F_{tidal} = \left(\frac{\partial F_{MW}}{\partial R_{MW}}\right) \times r_{sat} = \frac{\partial}{\partial R_{MW}}\left[\frac{G\mathcal{M}_{MW}}{R_{MW}^2}\right] \times r_{sat}$$

$$= \frac{2G\mathcal{M}_{MW}}{R_{MW}^3} r_{sat}$$

Where $F_{tidal} > F_{sat}$, stars will be stripped from the satellite and lost. This happens at a critical ***tidal radius*** for the satellite given by:

$$r_{sat} > R_{MW}\left(\frac{\mathcal{M}_{sat}}{2\mathcal{M}_{MW}}\right)^{1/3}$$

This is *essentially* a density argument. Cube both sides to get

$$r_{sat}^3 > R_{MW}^3\left(\frac{\mathcal{M}_{sat}}{2\mathcal{M}_{MW}}\right)$$

do some algebra to get

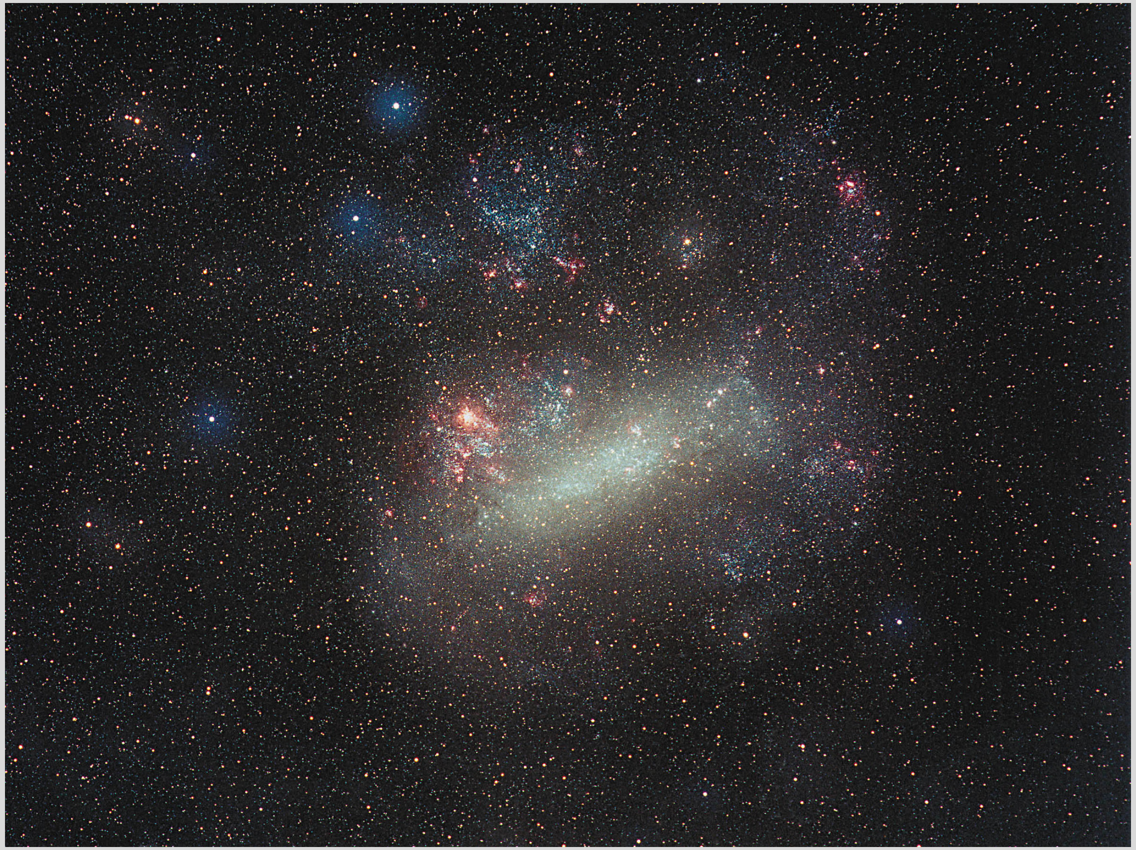
$$\frac{\mathcal{M}_{MW}}{R_{MW}^3} > \frac{1}{2}\frac{\mathcal{M}_{sat}}{r_{sat}^3}$$

which is essentially

$$\rho_{MW} > \frac{\rho_{sat}}{2}$$

Dwarf Galaxies: Tidal Stripping

Stars outside this tidal radius will be stripped from the satellite.



For a big satellite galaxy like the Large Magellanic Cloud, $r_{tidal} \approx 10$ kpc.

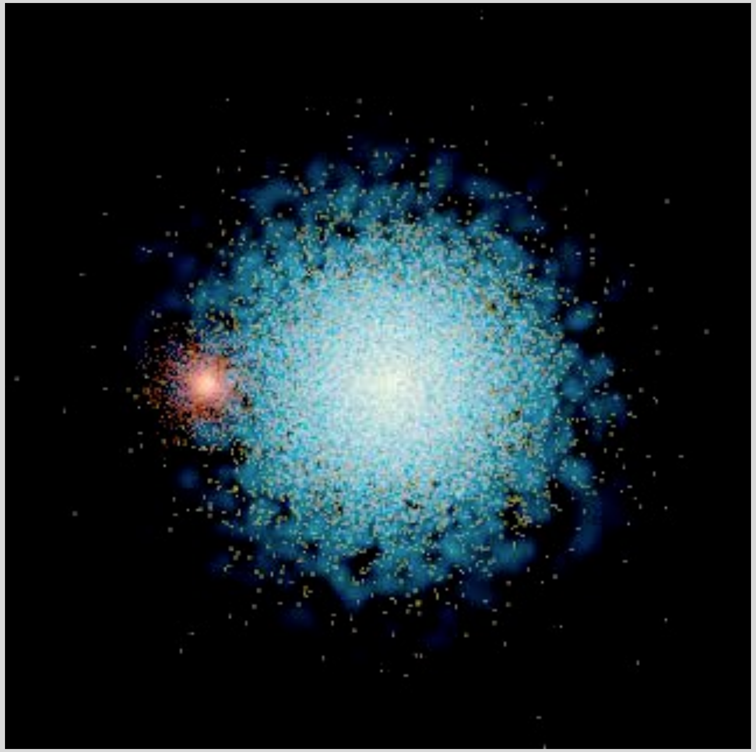
For smaller satellites like the Leo I dwarf spheroidal galaxy, $r_{tidal} \approx 2$ kpc.

As stars are stripped, satellite loses mass. Satellite also moves inwards due to dynamical friction. Stripping gets stronger....

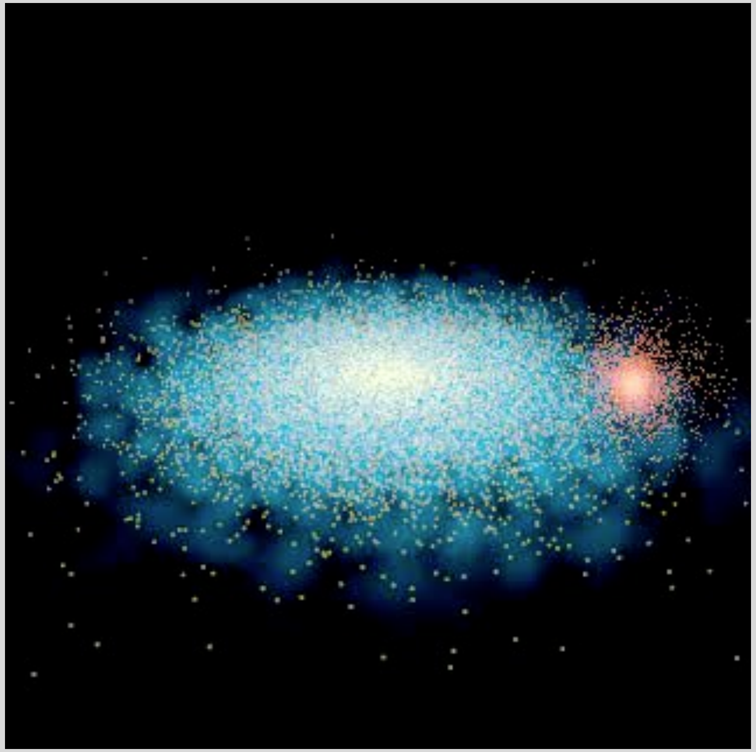
Dwarf Galaxies: Orbits, infall, and destruction

Putting it all together, its a race between dynamical friction and tidal stripping:

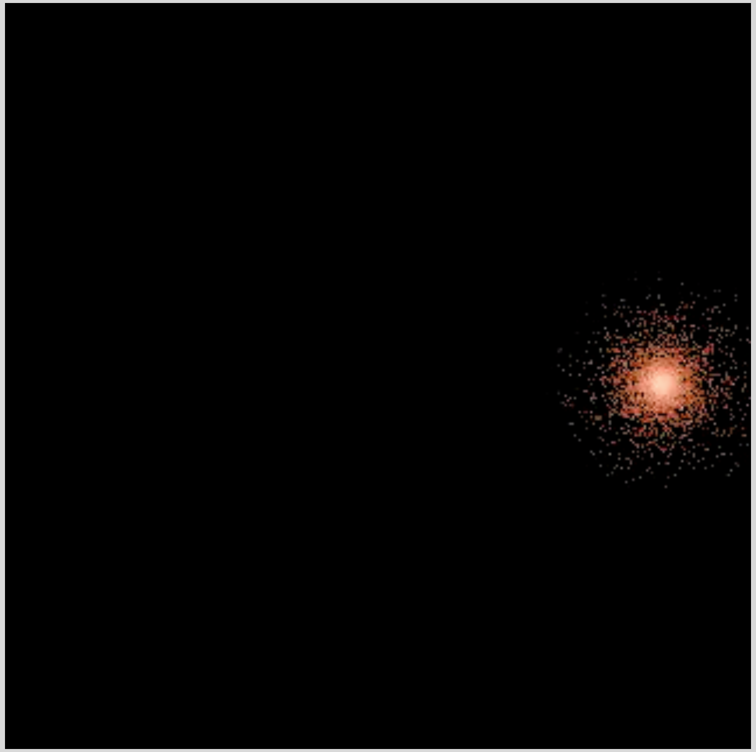
Overhead view



Inclined View



Satellite only



- Massive and dense satellites can survive being completely stripped and will sink to the center.
- Low mass, low density satellites have long sinking times and will be tidally disrupted in the halo.

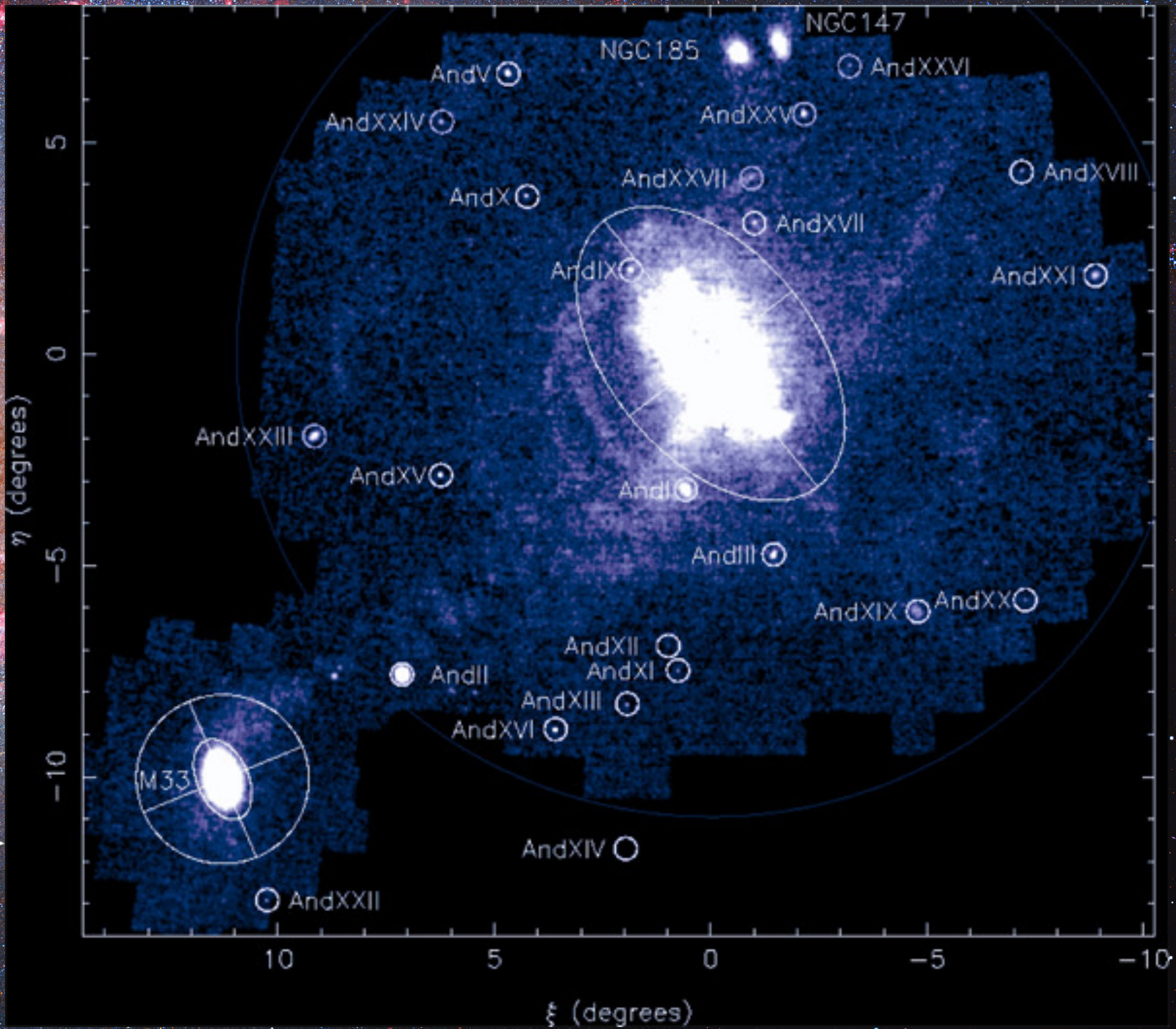
The Neighbors: Andromeda (M31)

comparable in size and mass to MW, maybe a bit bigger.

distance: 750 kpc
radial velocity: -200 km/s

The Neighbors: Triangulum (M33)

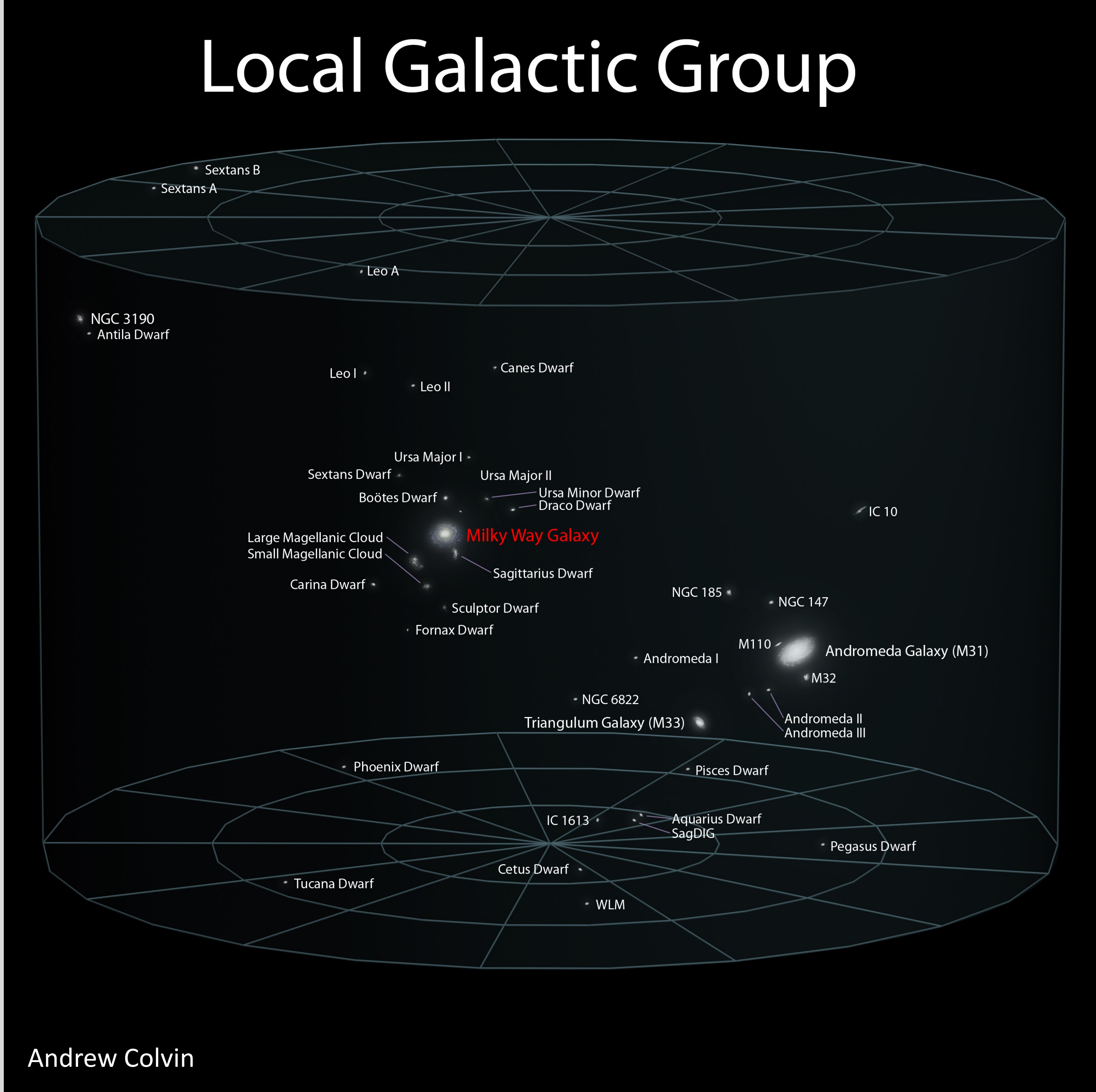
much smaller than MW/Andromeda
distance: 900 kpc
interacting with Andromeda

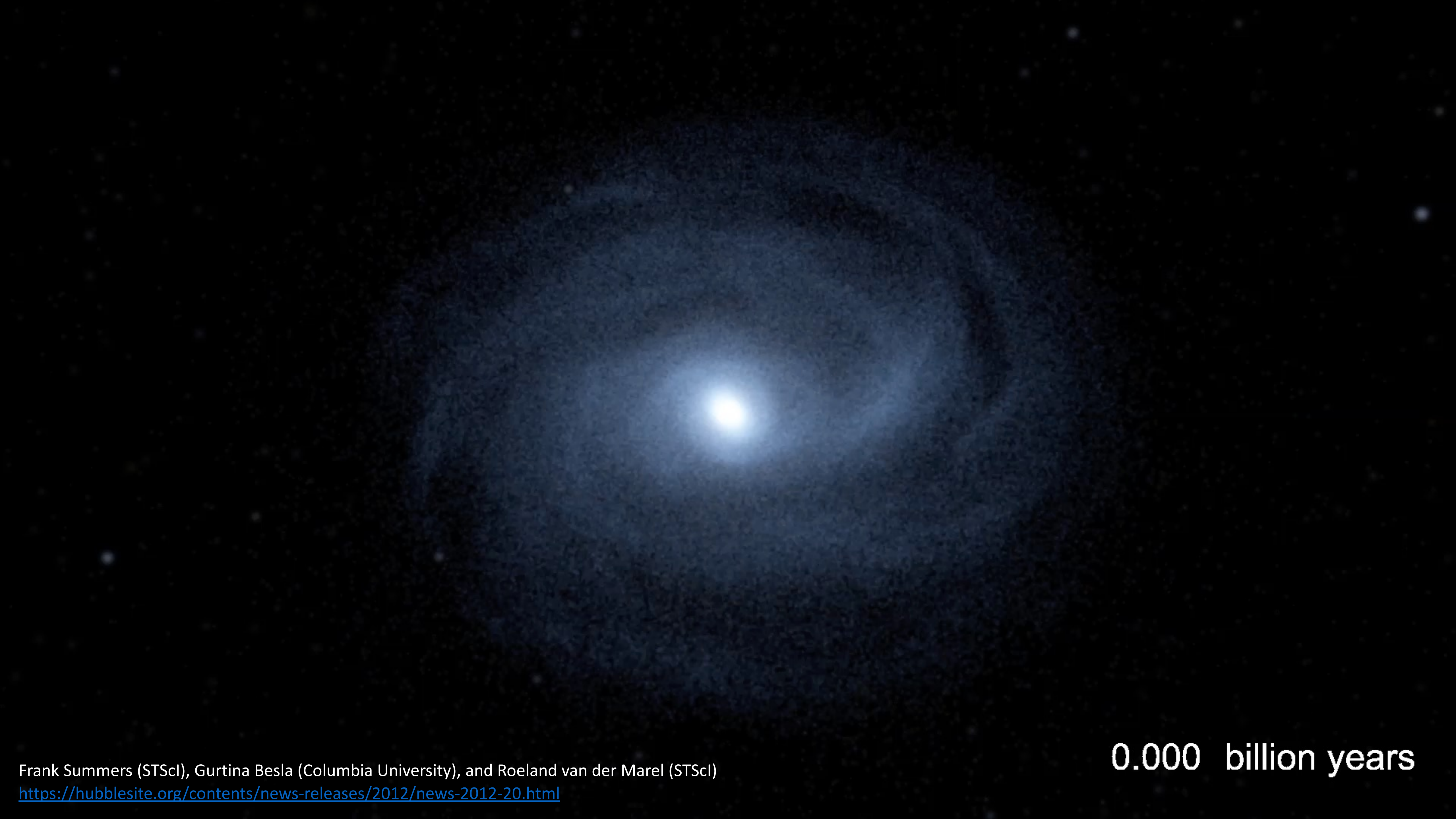


The Local Group

The Milky Way, Andromeda, and M33, plus their their satellite galaxies and a few rogue dwarfs all form the Local Group of galaxies.

Roughly 1 Mpc across.





Frank Summers (STScI), Gurtina Besla (Columbia University), and Roeland van der Marel (STScI)
https://hubblesite.org/contents/news-releases/2012/news-2012-20.html


The Future
Andromeda
Today


+ 2 billion years


+3.75 billion years


+3.85 billion years


+3.95 billion years


+4 billion years


+5 billion years


+7 billion years