Galaxy Structure plots revisited

Galaxies span a huge range in luminosity and surface brightness.

Absolute magnitude span of 20 mags ⇒ a factor of 10^8 in luminosity!

Tolstoy+ ARAA 09

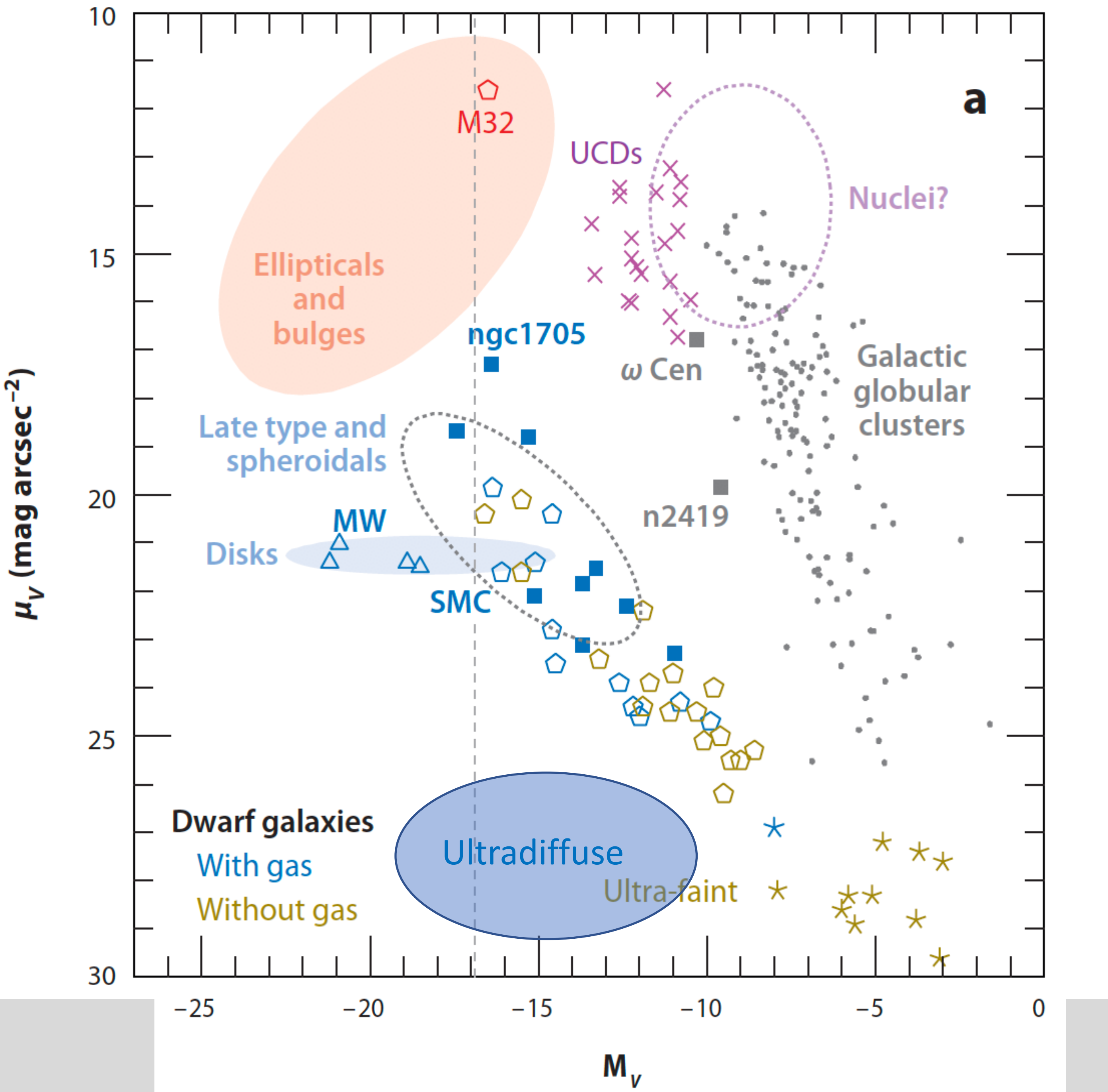


Figure 1

Here are plotted the relationships between structural properties for different types of galaxies (after Kormendy 1985, Binggeli 1994), including as dotted lines the classical limits of the dwarf galaxy class as defined by Tammann (1994). (*a*) The absolute magnitude, M_V, versus central surface brightness, μ_V, plane; (*b*) The M_V versus half light radius, $r_{1/2}$, plane. Marked with colored ellipses are the typical locations of elliptical galaxies and bulges (*light red*), spiral galaxy disks (*light blue*), galactic nuclei (*dashed purple*), and large early-(spheroidals) and late-type systems (*dashed gray*). Galactic globular clusters are plotted individually as small gray points. M31, the Milky Way (MW), M33 and LMC are shown as blue open triangles. Some of the blue compact dwarfs with well-studied color-magnitude diagrams are marked as blue solid squares. The peculiar globular clusters ω Cen and NGC 2419 are marked close to the globular cluster ellipse, M32 in the region of elliptical galaxies, and the SMC near the border of the dwarf class. The ultracompact dwarfs (UCDs) studied in the Virgo and Fornax clusters are marked with purple crosses. Local Group dwarf galaxies are plotted as open pentagons, blue for systems with gas, and yellow for systems without gas. The recently discovered ultrafaint dwarfs are given star symbols, and the same color code. For references see text.

Galaxy Structure plots revisited

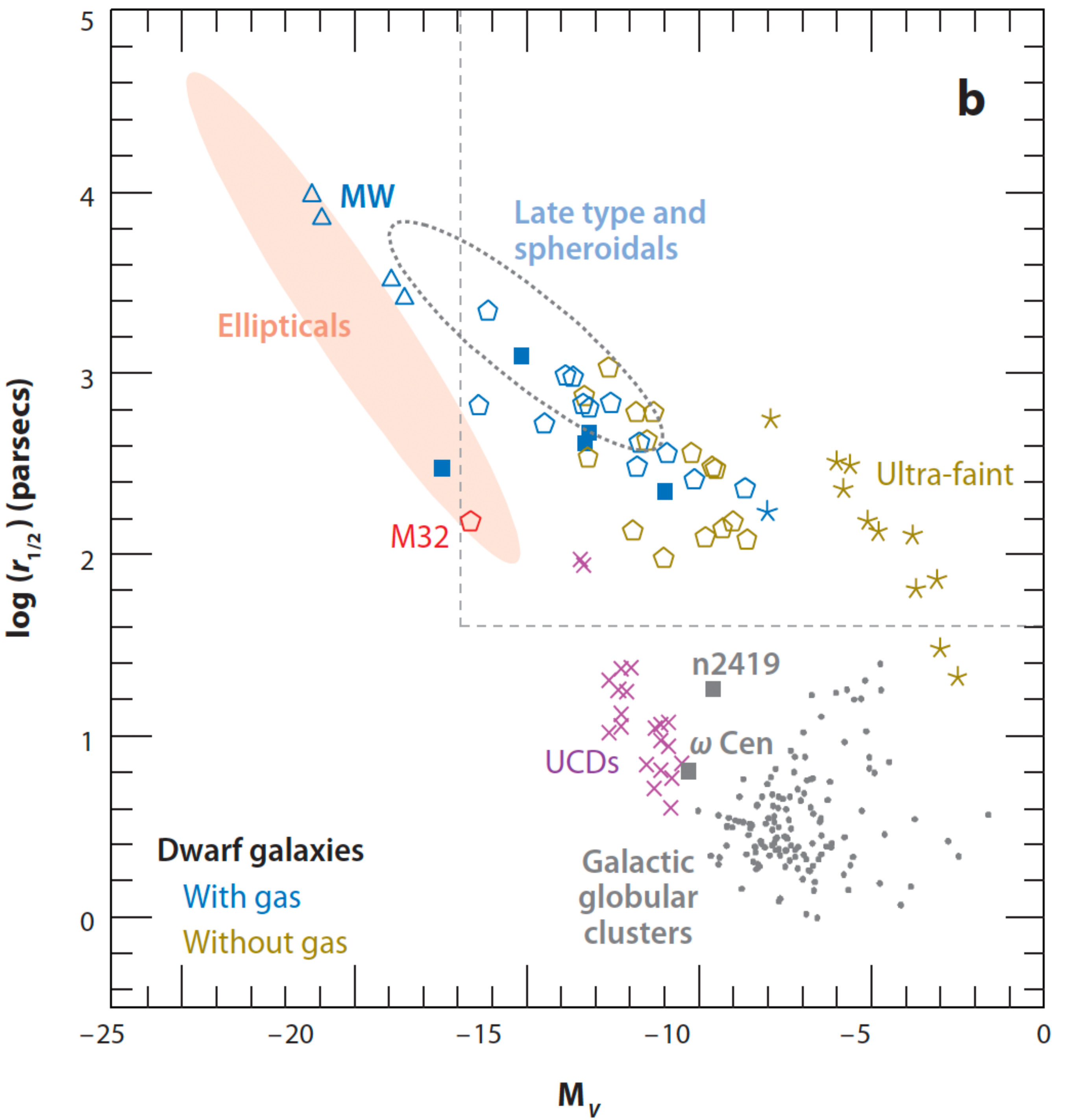
And a huge range in size, too!

Half-light radii range from 10 pc to > 10 kpc…

Tolstoy+ ARAA 09

Figure 1

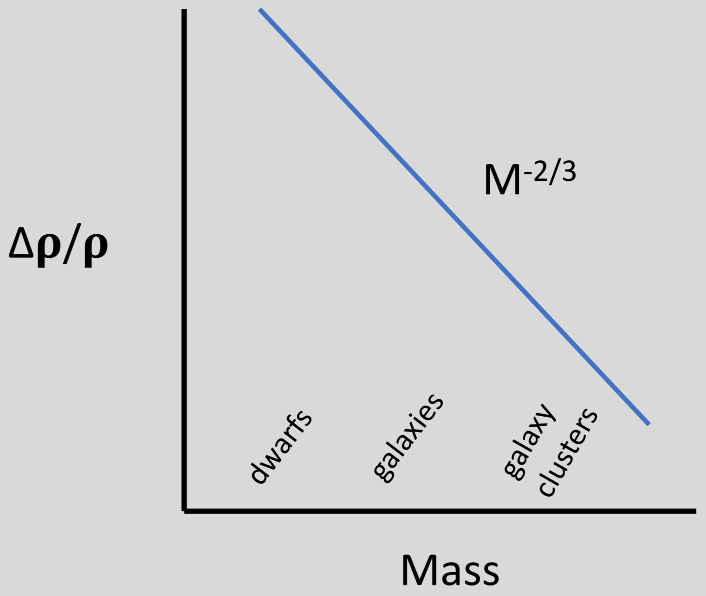
Here are plotted the relationships between structural properties for different types of galaxies (after Kormendy 1985, Binggeli 1994), including as dotted lines the classical limits of the dwarf galaxy class as defined by Tammann (1994). (*a*) The absolute magnitude, M_V, versus central surface brightness, μ_V, plane; (*b*) The M_V versus half light radius, $r_{1/2}$, plane. Marked with colored ellipses are the typical locations of elliptical galaxies and bulges (*light red*), spiral galaxy disks (*light blue*), galactic nuclei (*dashed purple*), and large early-(spheroidals) and late-type systems (*dashed gray*). Galactic globular clusters are plotted individually as small gray points. M31, the Milky Way (MW), M33 and LMC are shown as blue open triangles. Some of the blue compact dwarfs with well-studied color-magnitude diagrams are marked as blue solid squares. The peculiar globular clusters ω Cen and NGC 2419 are marked close to the globular cluster ellipse, M32 in the region of elliptical galaxies, and the SMC near the border of the dwarf class. The ultracompact dwarfs (UCDs) studied in the Virgo and Fornax clusters are marked with purple crosses. Local Group dwarf galaxies are plotted as open pentagons, blue for systems with gas, and yellow for systems without gas. The recently discovered ultrafaint dwarfs are given star symbols, and the same color code. For references see text.



Dwarf Galaxies: Formation

Remember the very early universe is filled with matter density fluctuations of different size scales and amplitudes. These fluctuations are strongest on small scales: dwarf galaxies.

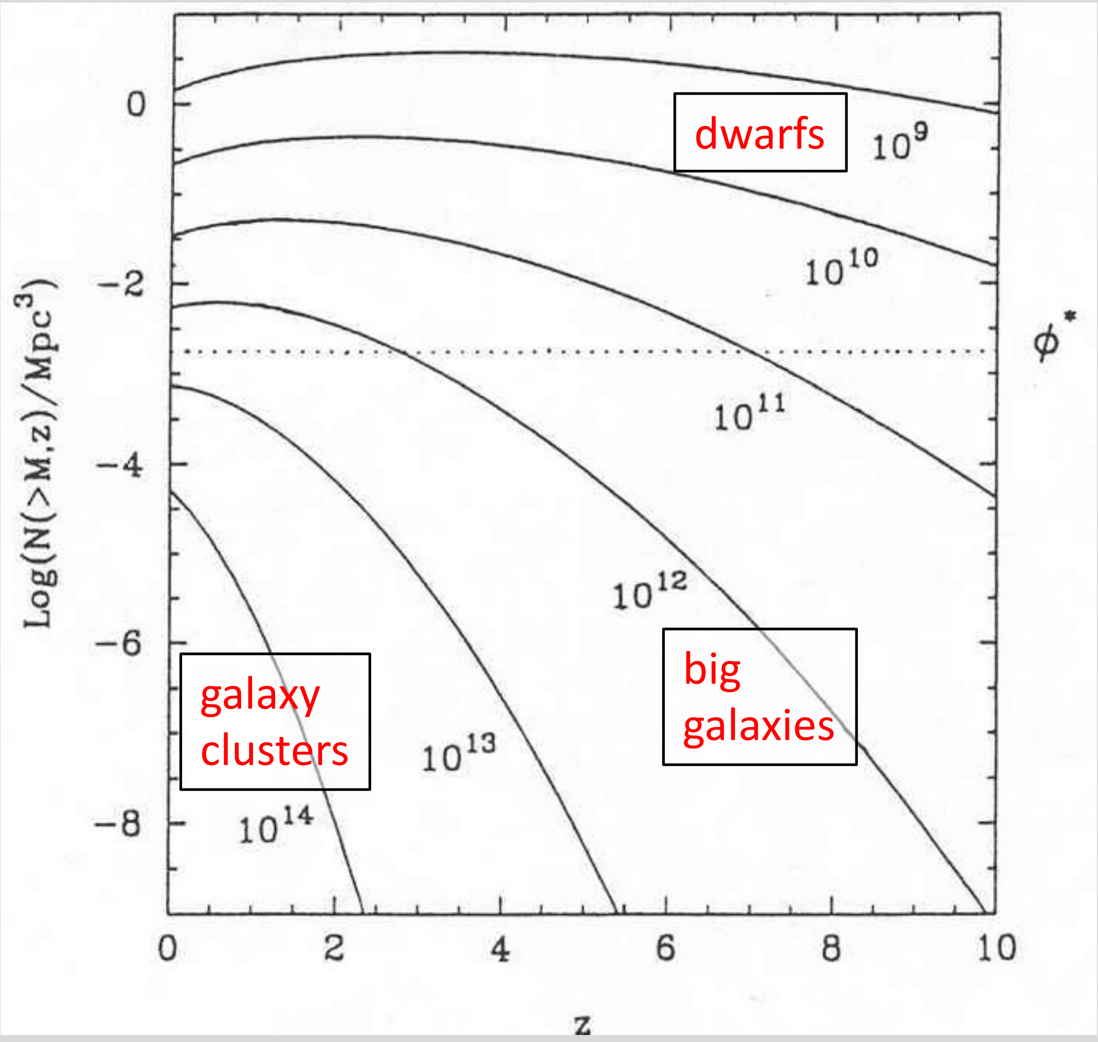
early universe density fluctuations



Then remember also basic gravitational collapse time: $t_c \approx \frac{1}{\sqrt{G\rho}}$.

So since low mass things are at higher density contrast, they collapse and form first. The start of hierarchical galaxy formation.

Number density of dark halos as a function of mass and redshift:



Note: "dwarfs start forming first" does NOT mean "all dwarfs formed early."

Dwarf Galaxies: Shallow Potential Wells

Dwarf galaxies are low mass and very diffuse. Consider the escape velocity:

$$v_{esc} \approx \sqrt{\frac{2GM}{R}} \approx 20 \left(\frac{M}{10^7\, M_\odot}\right)^{\frac{1}{2}} \left(\frac{300\ pc}{R}\right)^{\frac{1}{2}}\ km/s$$

compare this to:

- Milky Way: $v_{esc,MW} \approx 500 - 600\ km/s$
- supernovae wind speeds $v_{wind} \gtrsim 100 - 1000\ km/s$
- thermal velocity of hot gas:

$$\frac{1}{2} m_H v^2 = \frac{3}{2} kT \quad \Longrightarrow \quad v_{th} = \sqrt{\frac{3kT}{m_H}} \approx 150 \left(\frac{T}{10^6 K}\right)^{\frac{1}{2}} km/s$$

So as galaxies form and star formation starts, big galaxies can hold on to much of their gas and metals, enrich chemically, and sustain star formation.

At lower masses, dwarfs are increasingly unable to retain metals – they get blown out in starburst winds. ⇒ ***mass-metallicity relation***

At the lowest masses, they may not be able to hold their gas at all. “One and done” star formation(?).

Dwarf Galaxies: Tidal Limits

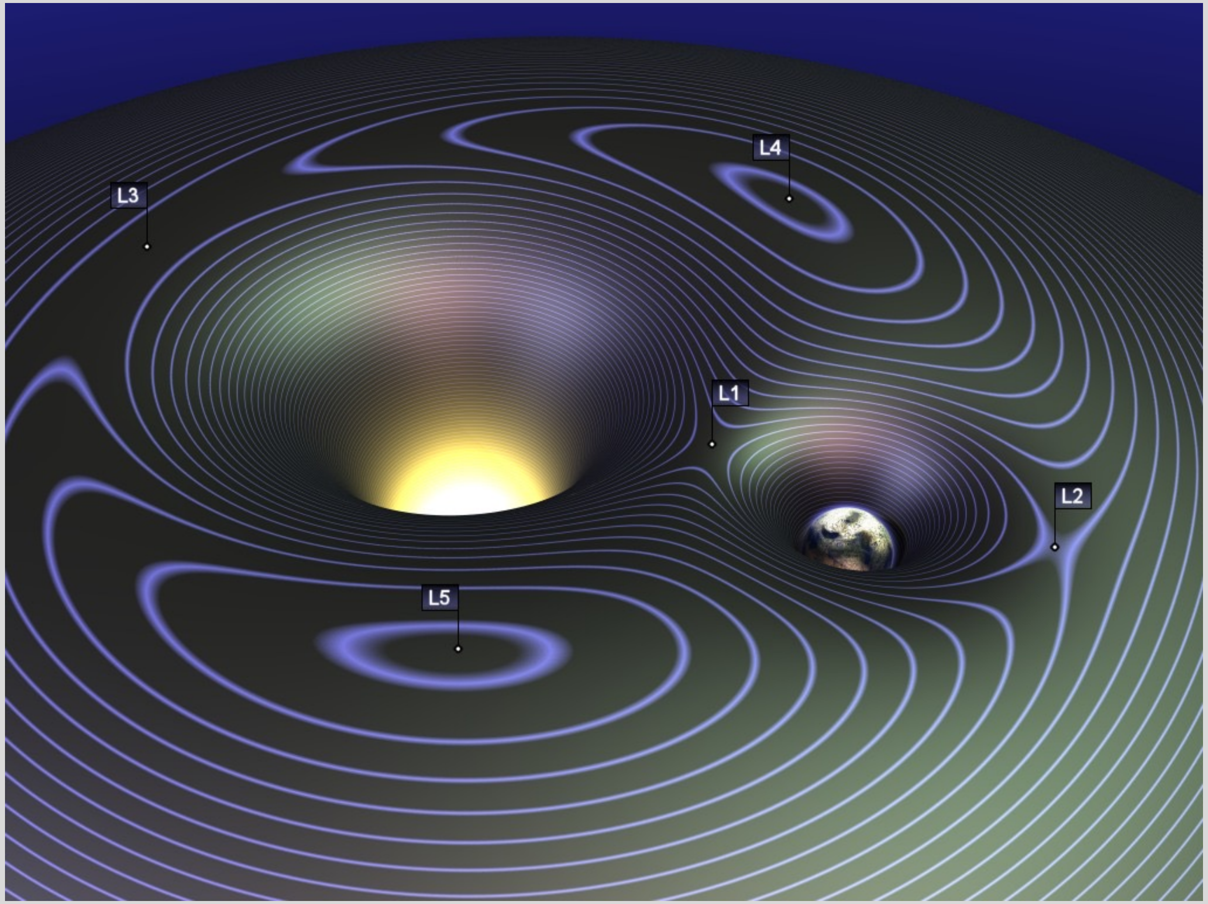
Lagrange L1/L2 points define the radius at which stars remain bound to the satellite. Beyond this, stars are tidally stripped. Also known as the "Jacobi radius" r_J:

$$r_J = D\left[\frac{m}{2M(<D)}\right]^{1/3}$$

where D is the satellite's distance from the center, and m and M(<D) are the satellite mass and galaxy mass interior to D, respectively.

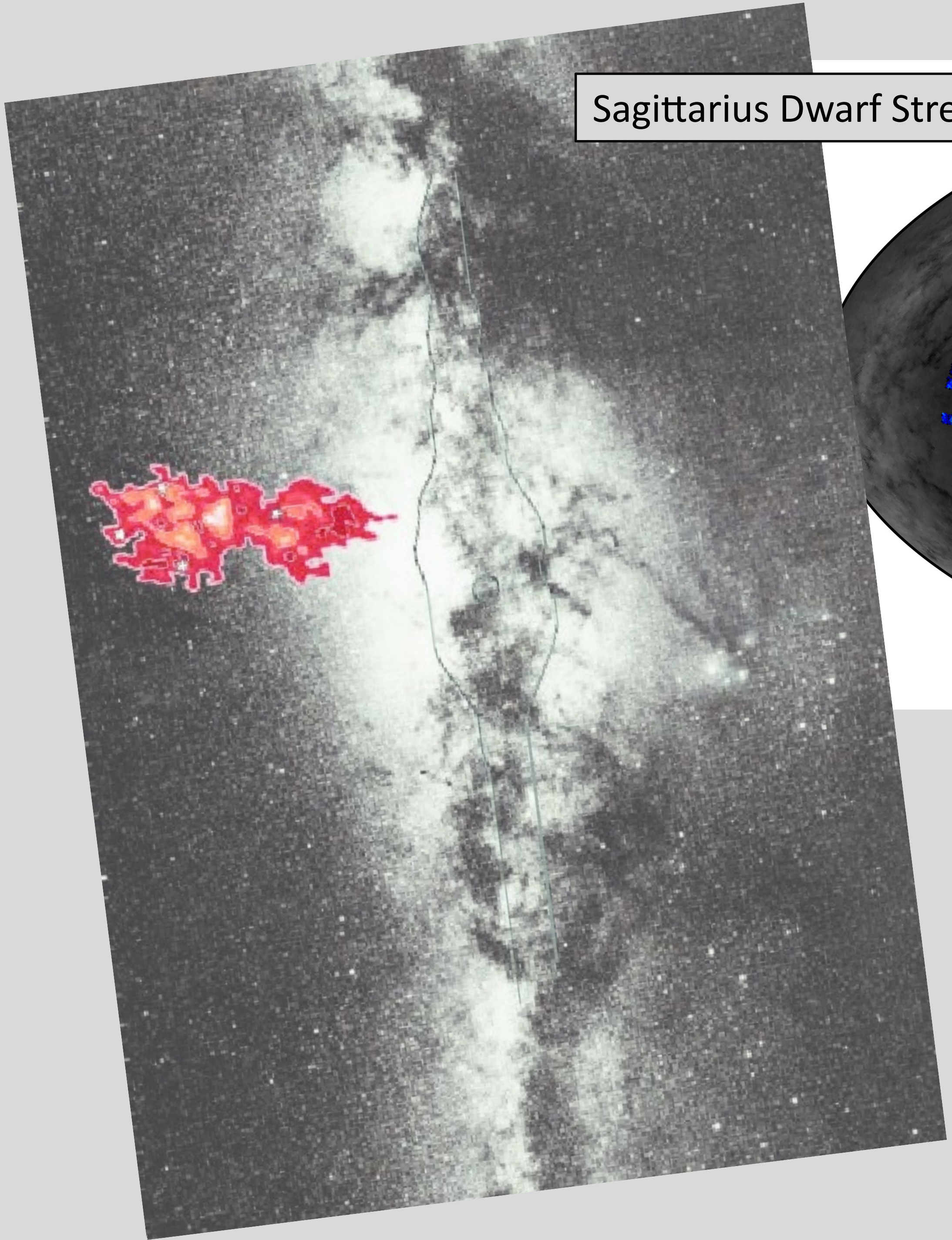
For the LMC, $D \approx 50$ kpc, $m \approx 10^{10}\ M_\odot \Rightarrow r_J \approx 10$ kpc.

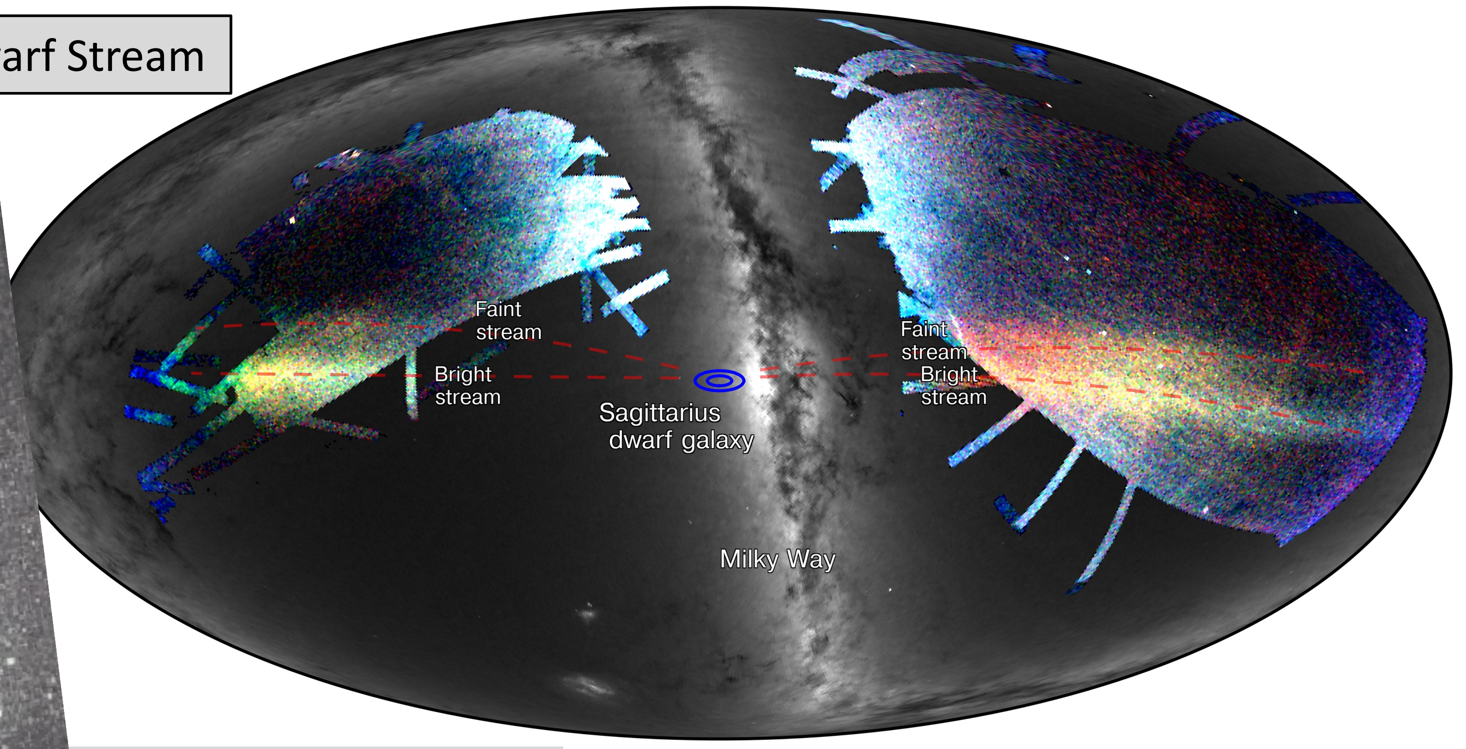
For lower mass satellites, $r_J \lesssim 2$ kpc.



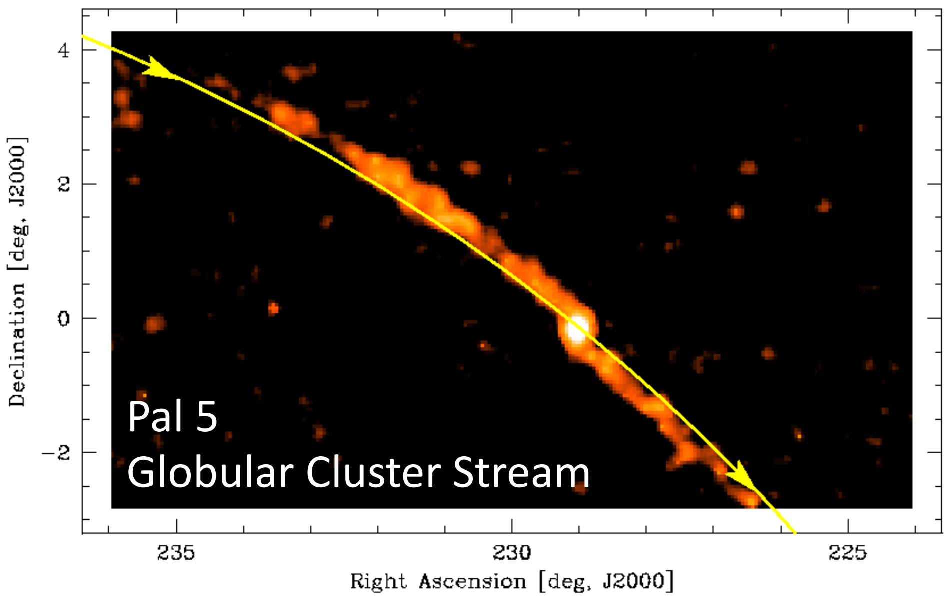
Effective potential for rotating two body system

Sagittarius Dwarf Stream

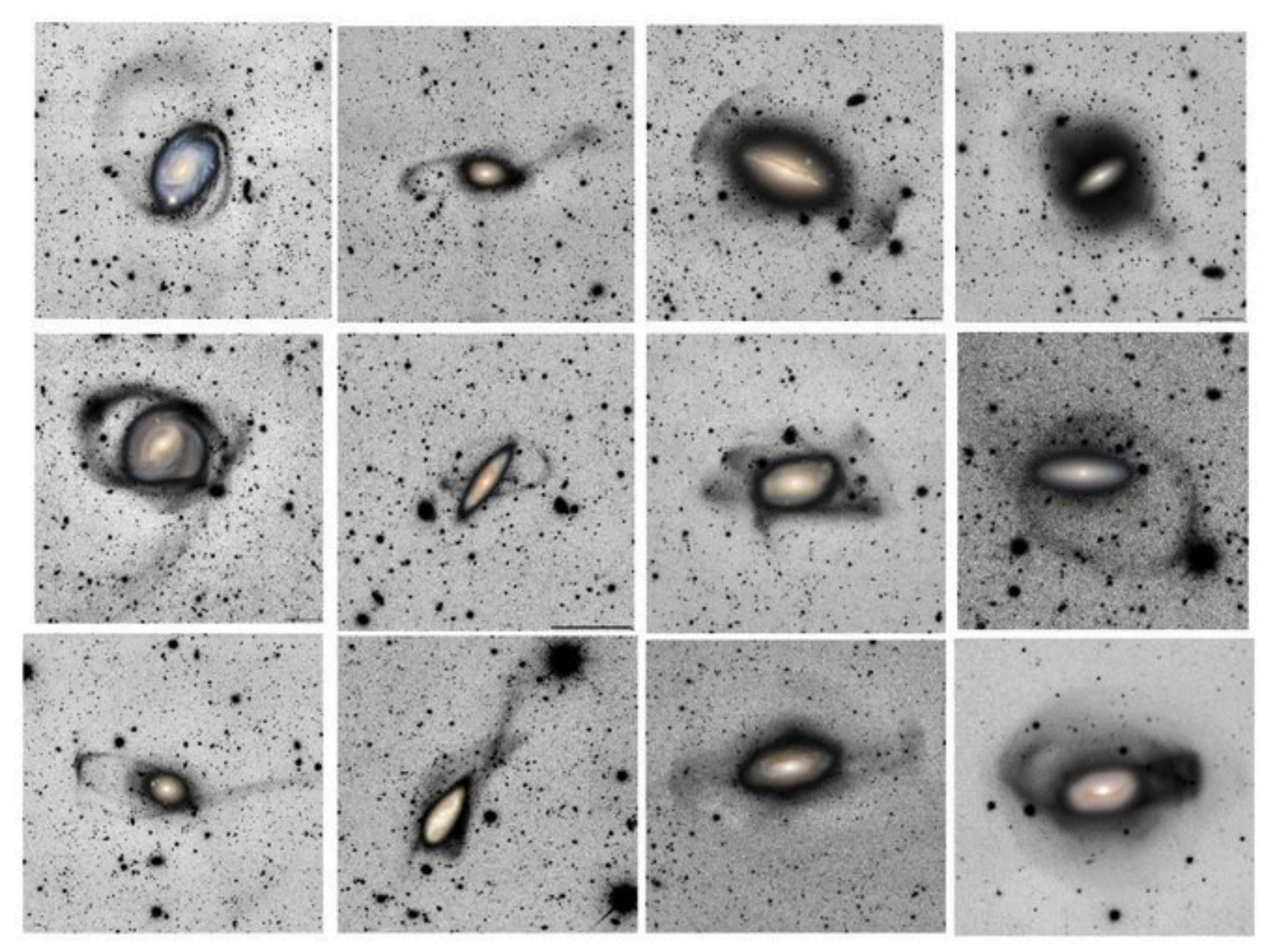




Happens to globular clusters, too!



Star Streams in Other Galaxies



courtesy
David Martinez-Delgado

Dwarf Galaxies: Ram Pressure Stripping

Ram-pressure stripping: as a gas-rich dwarf moves through a hot, low density gaseous halo, the halo gas exerts a pressure on the dwarf's gas:

$$P_r \approx \rho v^2$$

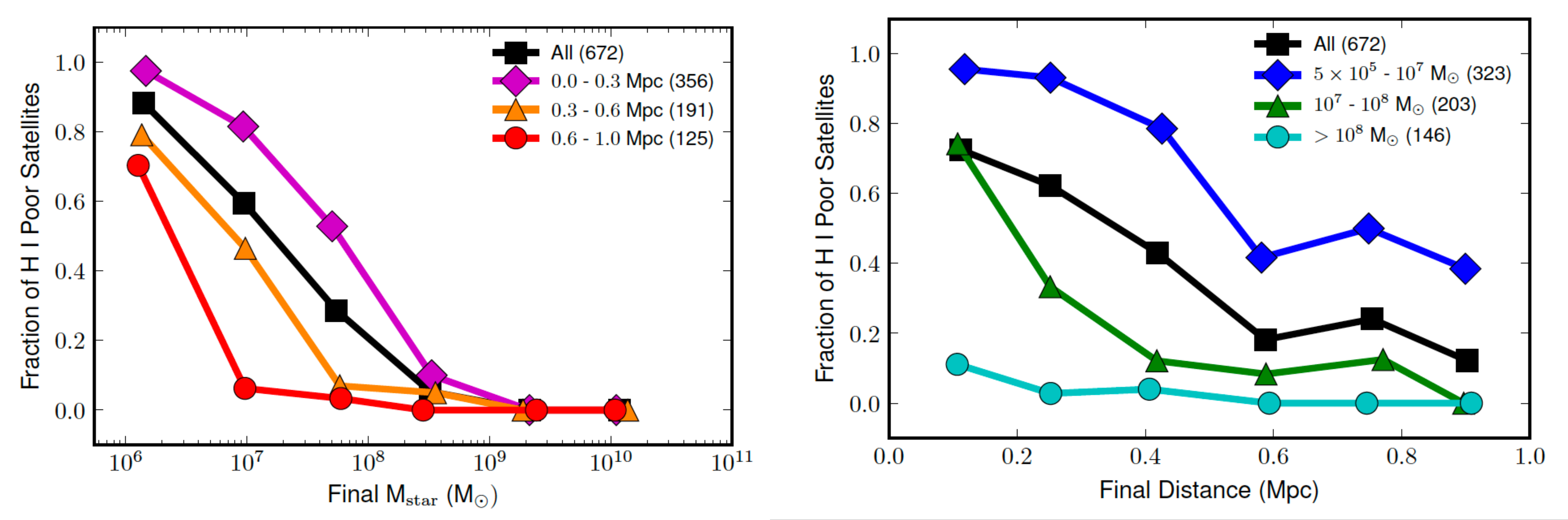
If this ram pressure exceeds the restoring gravitational force to the dwarf, the gas can be stripped out. (First applied to galaxies in clusters by Gunn & Gott 77.) Ram pressure stripping animation

X-ray halo of NGC 5746

Simulations ⇒ suggest stripping at work on Local Group dwarfs.

Most important at low mass and small MW distances

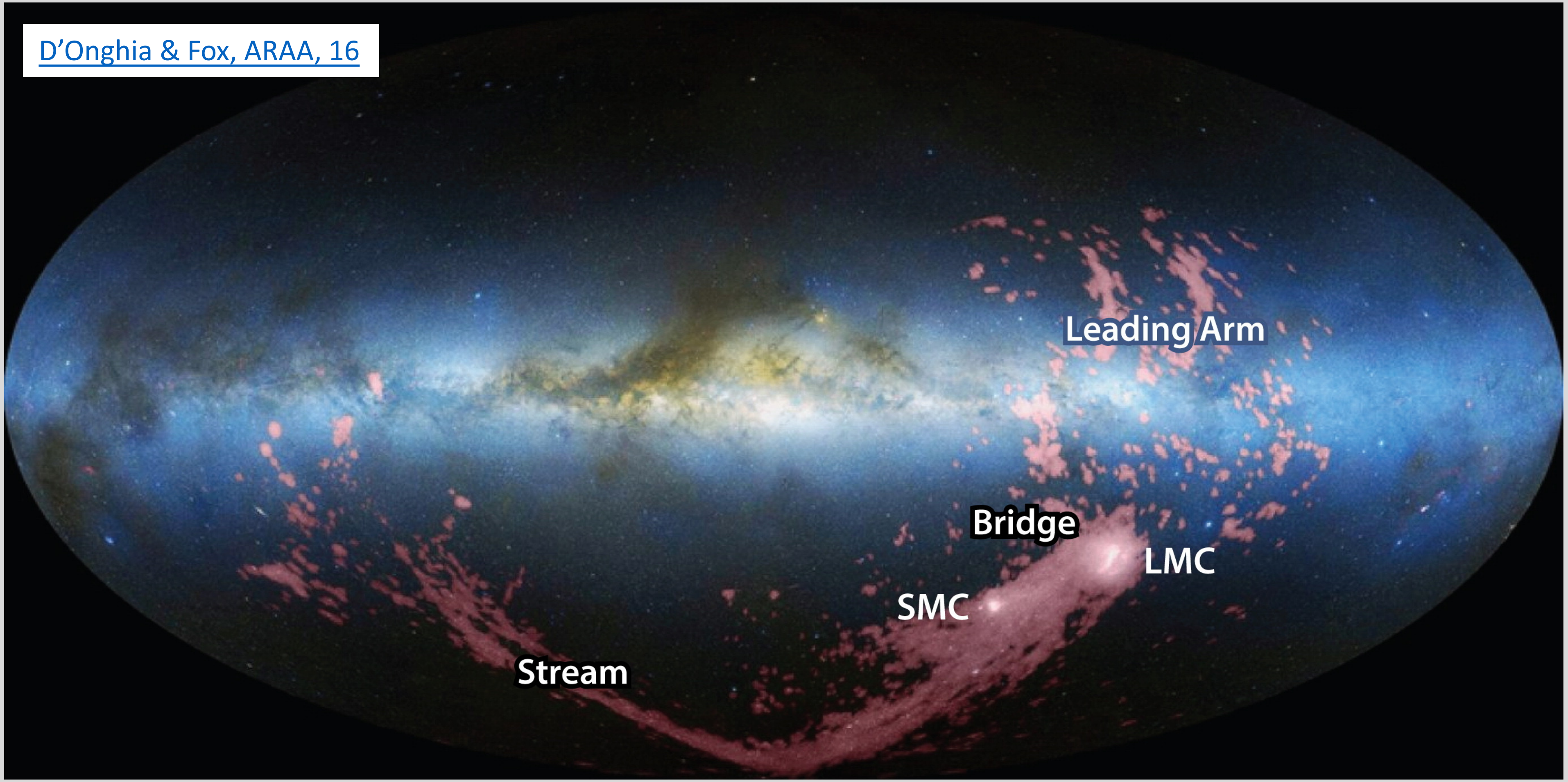
(Simpson+ 18)



The Magellenic Stream

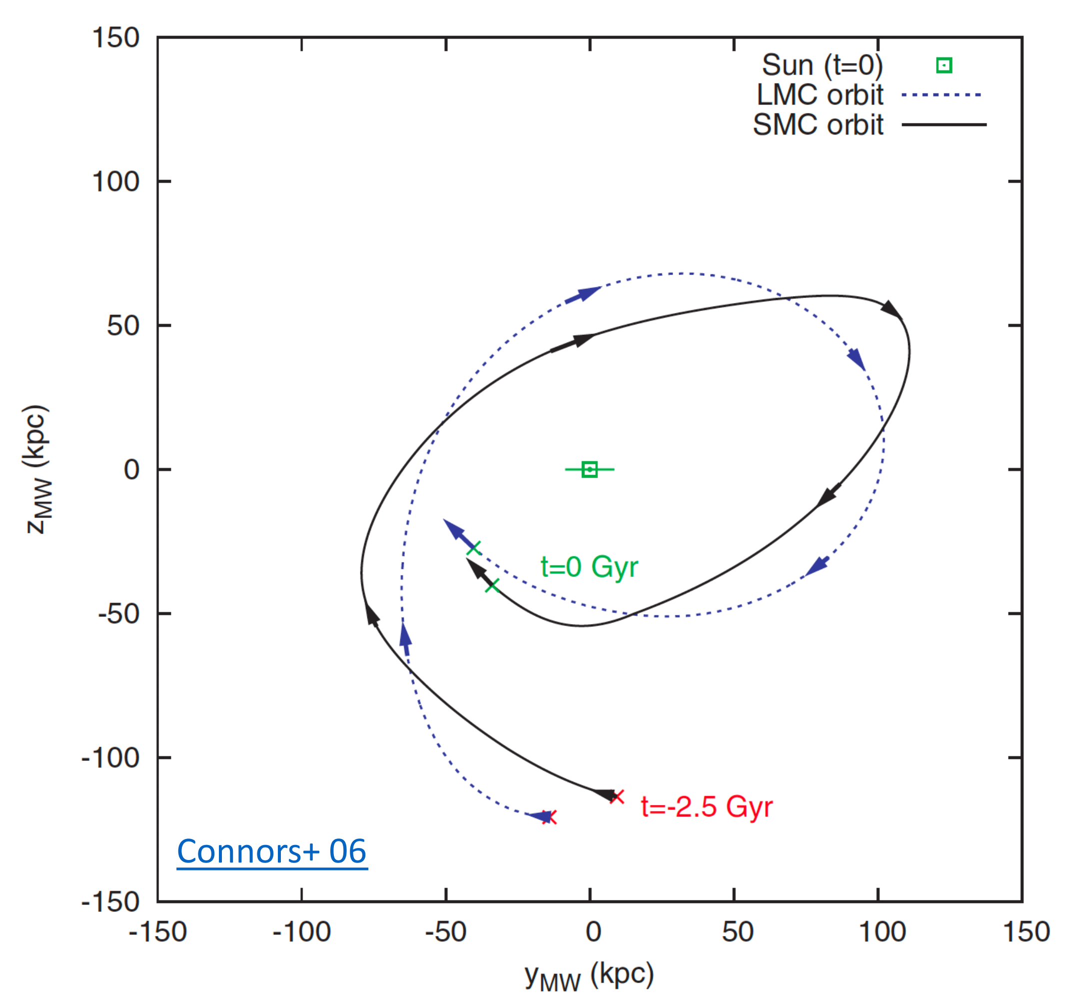
Long HI stream coming from the Magellenic Clouds, stretching across the sky.

Dynamical history uncertain. Various scenarios: tidal stripping, ram pressure stripping, or some combination of both.



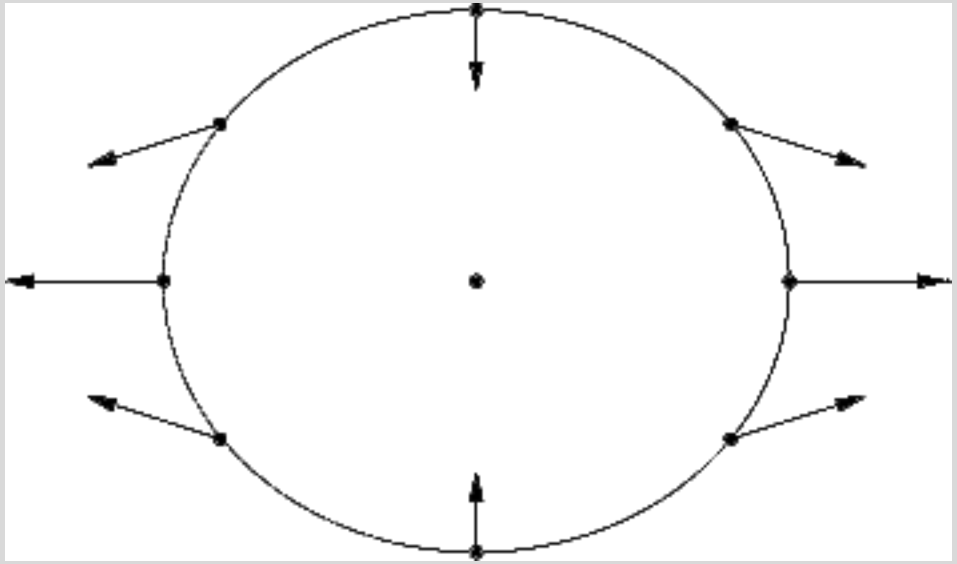
Orbital Effects

Satellite galaxies are thought to be on elongated orbits (due to low angular momentum infall), so $r_{peri} < (or \ll) r_{apo}$. For example, reverse-integration of the orbit of the LMC looks something like this:



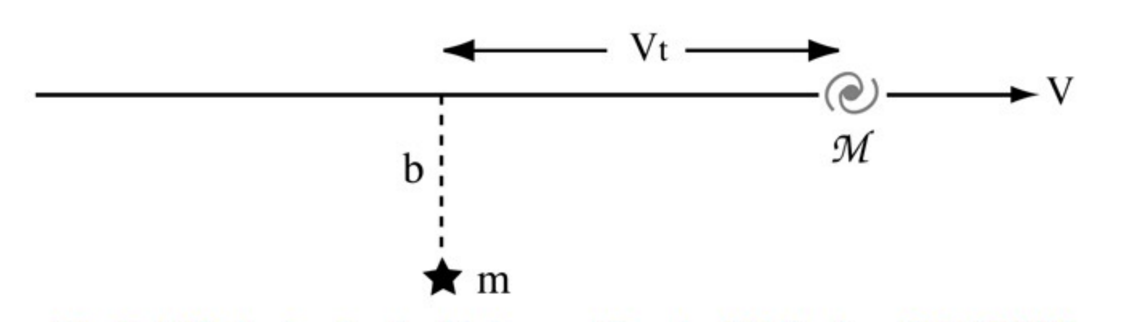
At Milky Way (MW) perigalacticon:

- *MW tidal forces are stronger*
  - $\Longrightarrow$ *more tidal stripping*
  - $\Longrightarrow$ *periodic compression (starburst?)*
- *MW hot halo gas is denser*
  - $\Longrightarrow$ more ram pressure stripping
- *Dwarf may pass through MW disk*
  - $\Longrightarrow$ even more ram pressure stripping
  - $\Longrightarrow$ disk "shocking": sudden gravitational compression and rebound of satellite by disk gravity



*Remember: gravitational tides stretch **and** compress*

Dwarf Galaxies: Dynamical Friction



Imagine a satellite galaxy of mass M passing by a star of mass m. The perpendicular force on the satellite is

$$\vec{F}_\perp = \frac{GmMb}{(b^2 + V^2t^2)^{3/2}} = M\frac{d\vec{V}_\perp}{dt}$$

which we can integrate over time to get a change in perpendicular velocity:

$$\Delta V_\perp = \frac{1}{M}\int_{-\infty}^{\infty} \vec{F}_\perp(t)dt = \frac{2Gm}{bV}$$

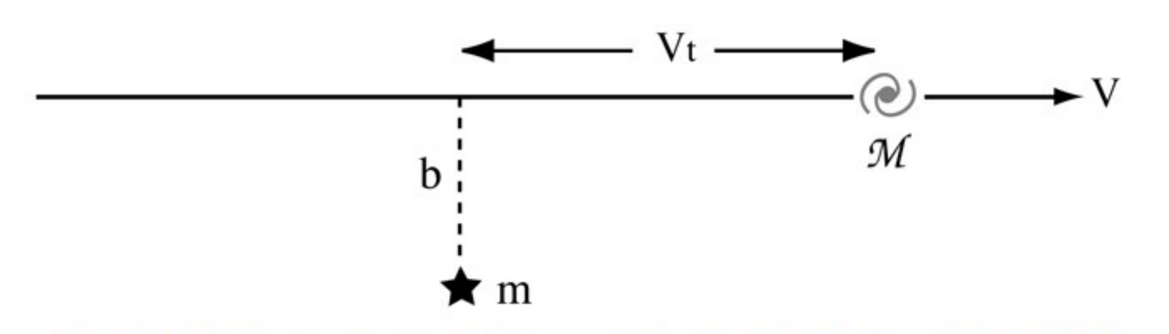
We must conserve momentum, so the star must also pick up a (much bigger!) $\Delta V_\perp$ from the satellite. This means the total change in perpendicular kinetic energy is:

$$\Delta KE_\perp = \underbrace{\frac{1}{2}M\left(\frac{2Gm}{bV}\right)^2}_{\text{change in galaxy's KE}} + \underbrace{\frac{1}{2}m\left(\frac{2GM}{bV}\right)^2}_{\text{change in star's KE}} = \frac{2G^2mM(m+M)}{b^2V^2}$$

This must come from the parallel kinetic energy of the system. If we balance kinetic energy before and after the encounter:

$$\underbrace{\frac{1}{2}MV^2}_{\text{original KE}} = \underbrace{\Delta KE_\perp}_{\text{total}\perp\text{ KE}} + \underbrace{\frac{1}{2}M(V+\Delta V_\parallel)^2}_{\text{galaxy's new}\parallel\text{ KE}} + \underbrace{\frac{1}{2}m\left(\frac{M}{m}\Delta V_\parallel\right)^2}_{\text{star's new}\parallel\text{ KE}}$$

Dwarf Galaxies: Dynamical Friction



so we had: $\frac{1}{2}MV^2 = \Delta KE_\perp + \frac{1}{2}M(V+\Delta V_\parallel)^2 + \frac{1}{2}m\left(\frac{M}{m}\Delta V_\parallel\right)^2$

expand/collect terms and divide by V^2 to get

$$\frac{\Delta KE_\perp}{V^2} + \frac{M\Delta V_\parallel}{V} + \frac{1}{2}\left(\frac{\Delta V_\parallel}{V}\right)^2 + \frac{1}{2}\frac{M^2}{m}\left(\frac{\Delta V_\parallel}{V}\right)^2 = 0$$

if $\Delta V_\parallel < V$, drop terms in $(\Delta V_\parallel/V)^2$ to find that each star m slows the dwarf galaxy by an amount

$$-\Delta V_\parallel \approx \frac{\Delta KE_\perp}{MV} = \frac{2G^2m\,(m+M)}{b^2V^3}$$

if the density of stars of mass m is n stars per cubic parsec, we can integrate over all these encounters to get

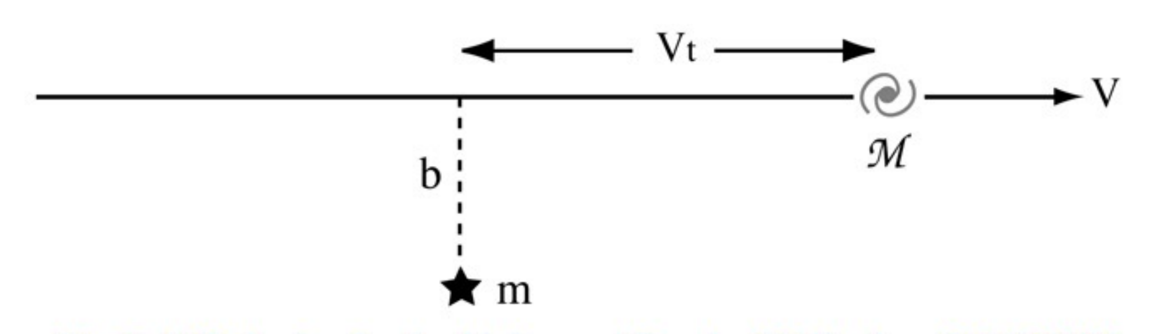
$$-\frac{dV}{dt} = \int_{b_{min}}^{b_{max}} nV \frac{2G^2m\,(m+M)}{b^2V^3} 2\pi b db = \frac{4\pi G^2(m+M)}{V^2} nm \ln\Lambda$$

rate of encounters
$\Delta V_\parallel$ per encounter
probability of encounter

"Coulomb logarithm":

$$\Lambda = \left(\frac{b_{max}}{b_{min}}\right)$$

Dwarf Galaxies: Dynamical Friction



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if $M \gg m$ and we re-write the density of stars as $\rho = nm$, we get:

$$-\frac{dV}{dt} = \frac{4\pi G^2 M\rho}{V^2} \ln \Lambda$$

The Coloumb logarithm: $\ln \Lambda = \ln\left(\frac{b_{max}}{b_{min}}\right)$

b_{max} is essentially the size of the large galaxy being orbited (i.e., the size of the system of stars of mass m).

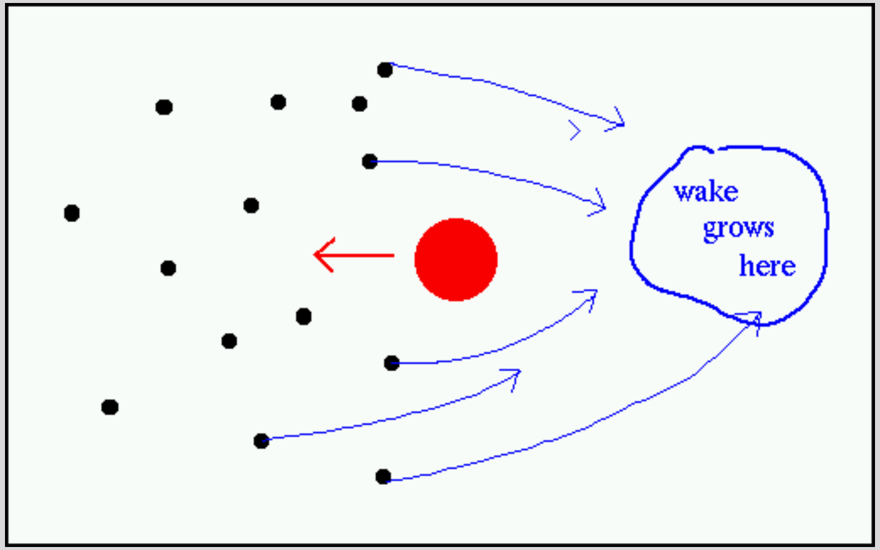
When we did it for star-star scattering, b_{min} was the close scattering radius for a star of mass m: $b_{min} \approx \frac{2Gm}{V^2} \approx 1\ AU$

But here it is larger, since we are dealing with a galaxy of mass M: $b_{min} \approx \frac{2GM}{V^2} \approx$ kiloparsec scales for MW satellites.

Dwarf Galaxies: Dynamical Friction

$$\frac{dV}{dt} = -\frac{4\pi G^2 M\rho}{V^2}\ln\Lambda$$

Also can consider it as a wake



Things to note:

- The net result is a drag term, the satellite is slowed down.
- Massive satellites affected more than low mass
- Denser regions do more slowing
- Fast encounters are less affected
- Does it have to be stars dragging on the satellite? What else could do the dragging?

Effects:

Circularization of satellite orbits: At peri on an elongated orbit, $V_{sat} > V_{circ}$. Friction is also strongest at peri. So over time, successive "braking" of the satellite changes the orbit form elongated to circular.

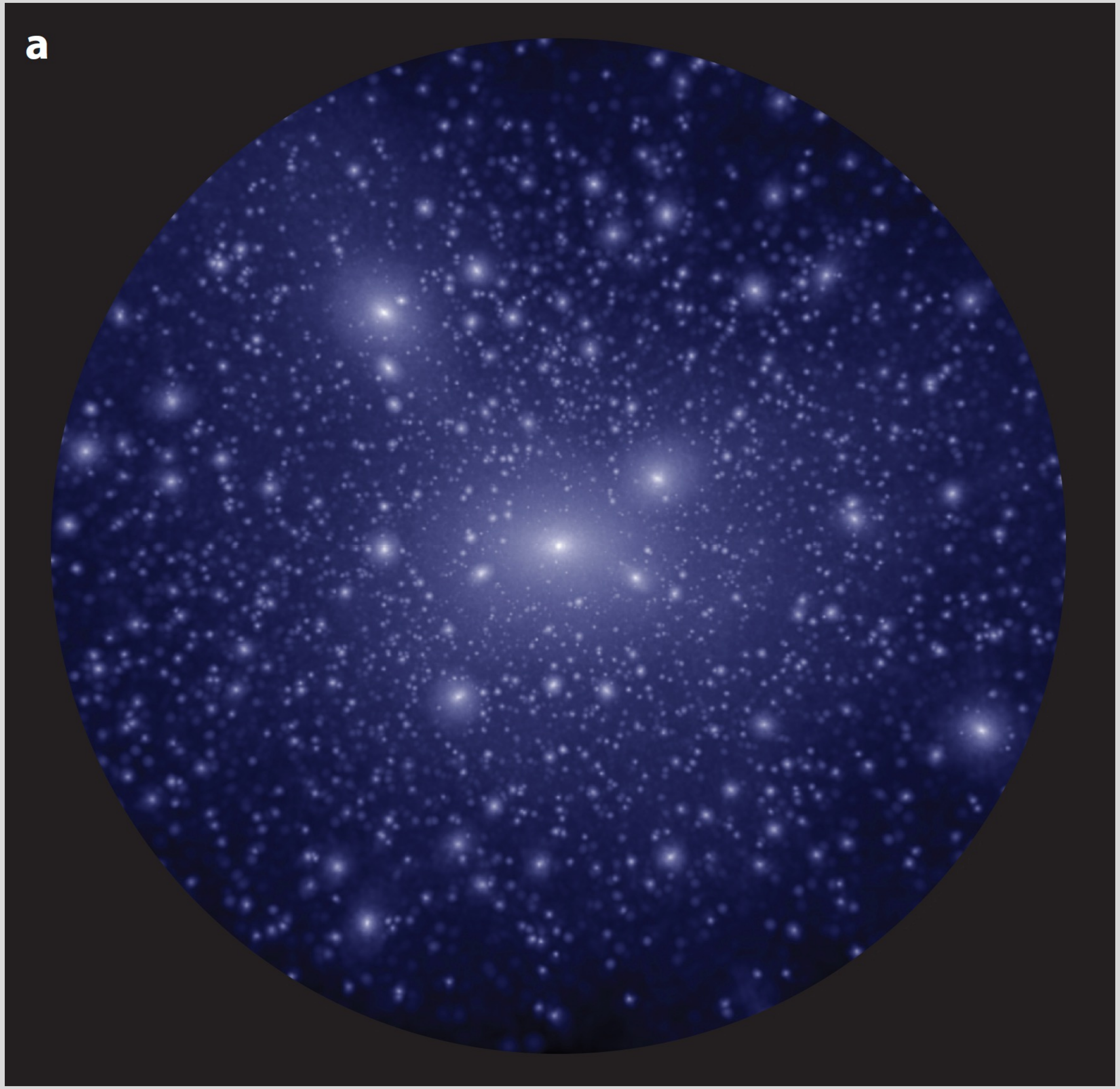
Satellite inspiral: Continual friction removes energy from satellite orbit, orbit decays and satellite spirals inward.

Merging: If satellite is dense enough to survive tidal stripping, it can merge to the center of the big galaxy.

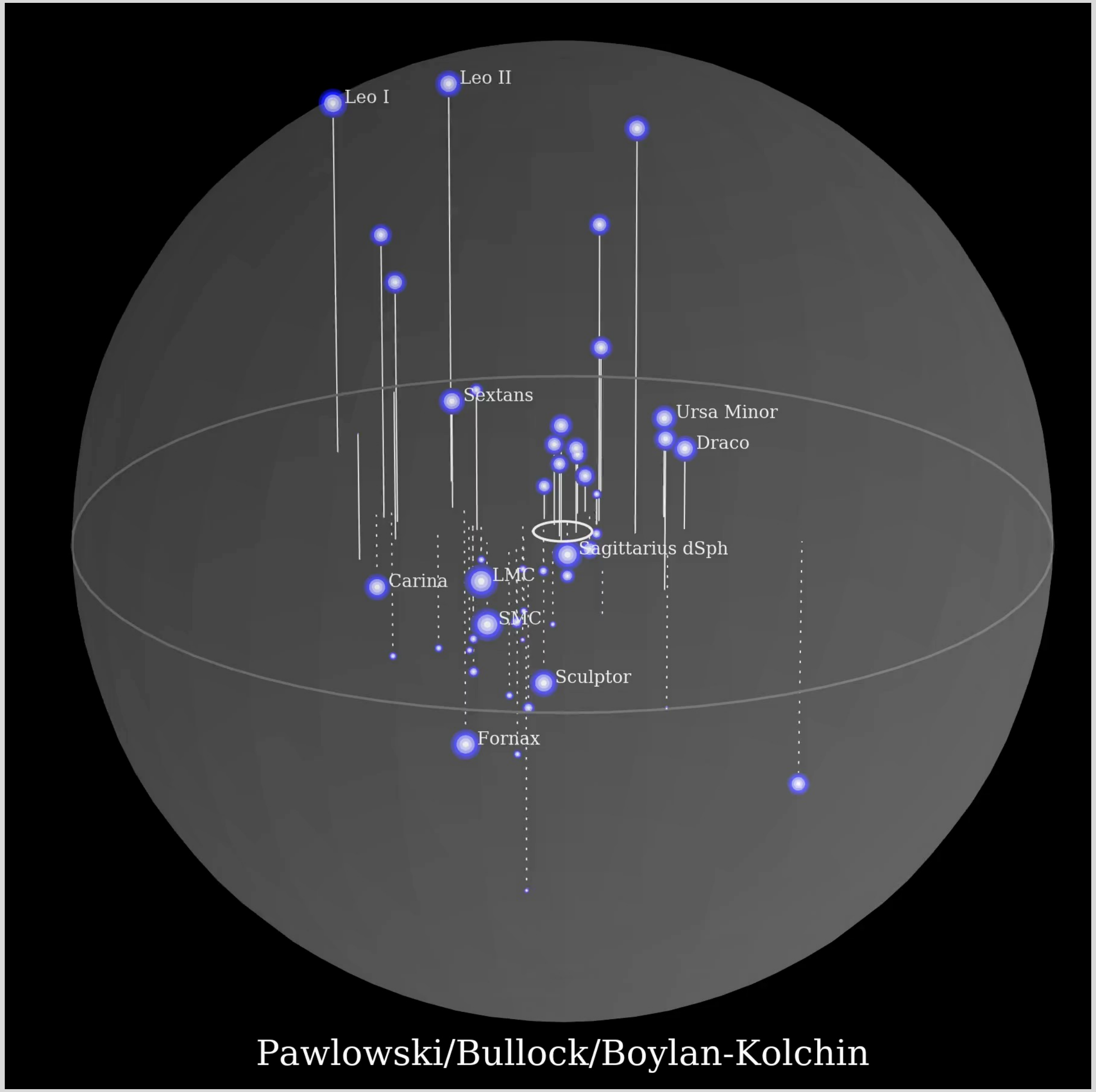
Missing Satellite Problem

Bullock & Boylan-Kolchin, ARAA, 2017

Dark Matter simulations of MW galaxies look like this:



But we see many fewer satellite galaxies:



Missing Satellite Problem

Bullock & Boylan-Kolchin, ARAA, 2017

Solving Missing Satellites: Need to say that galaxy formation becomes extremely inefficient at low dark halo mass. So lots of low mass halos exist, they just dont have galaxies in them.

Why would low mass dark matter halos fail to make/host galaxies?

Shallow potential wells: Any early star formation may result in energetic "feedback" (stellar winds, supernovae) that blow gas out of a low mass halo before many stars form.

"Proximity Effect": star formation from a *nearby* massive galaxy may do the same thing.

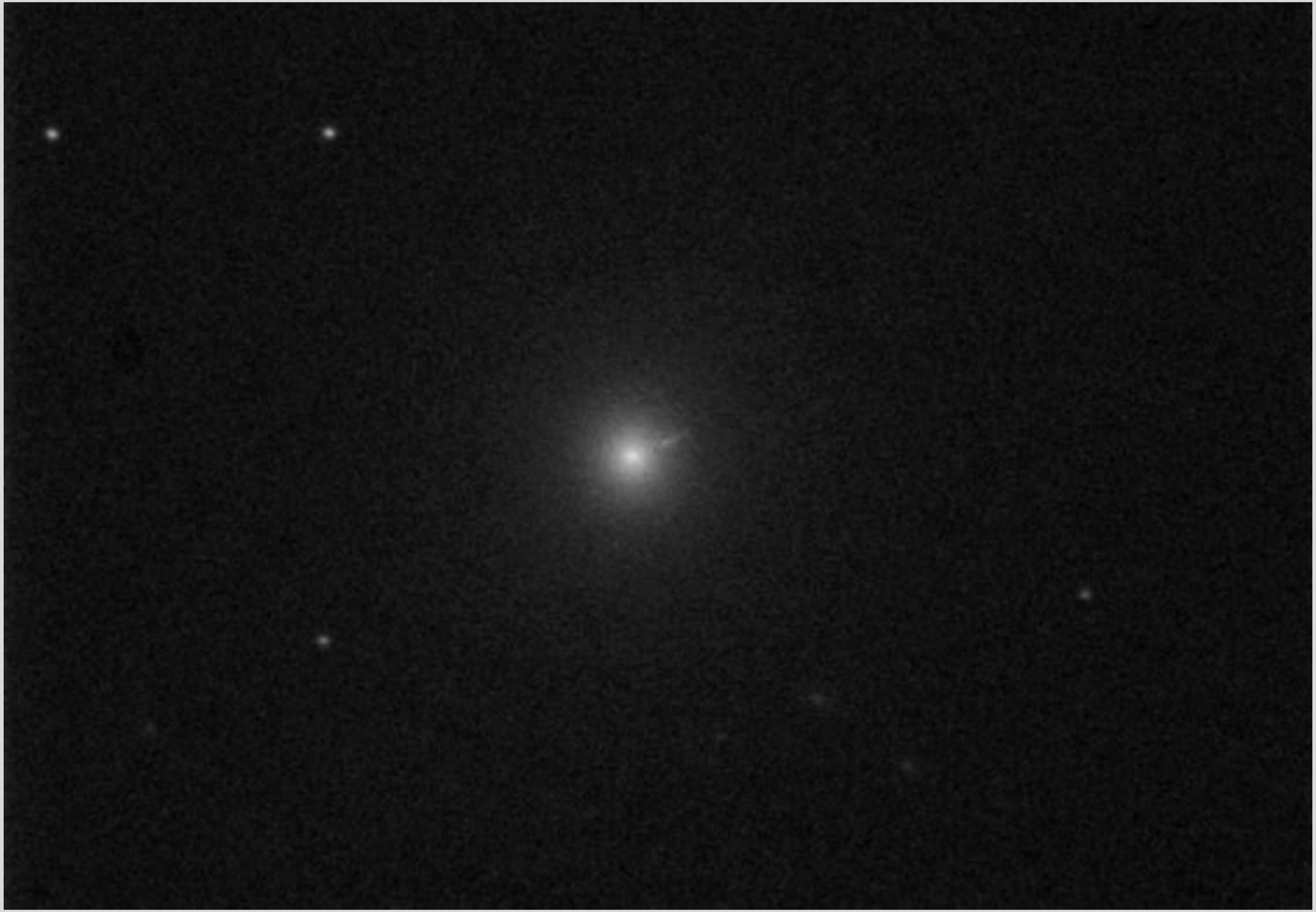
Reionization: At higher redshift, before stars can form, the gas has cooled from the Big Bang and can collapse into dark matter halos. Once star formation kicks in (around $z \approx 6-10$), the young stars ionize gas throughout the universe, heating it up so that it can't collapse into low mass halos

$$\frac{3}{2}kT_{gas} > \frac{GM_{halo}}{R}$$

gas thermal energy | potential well

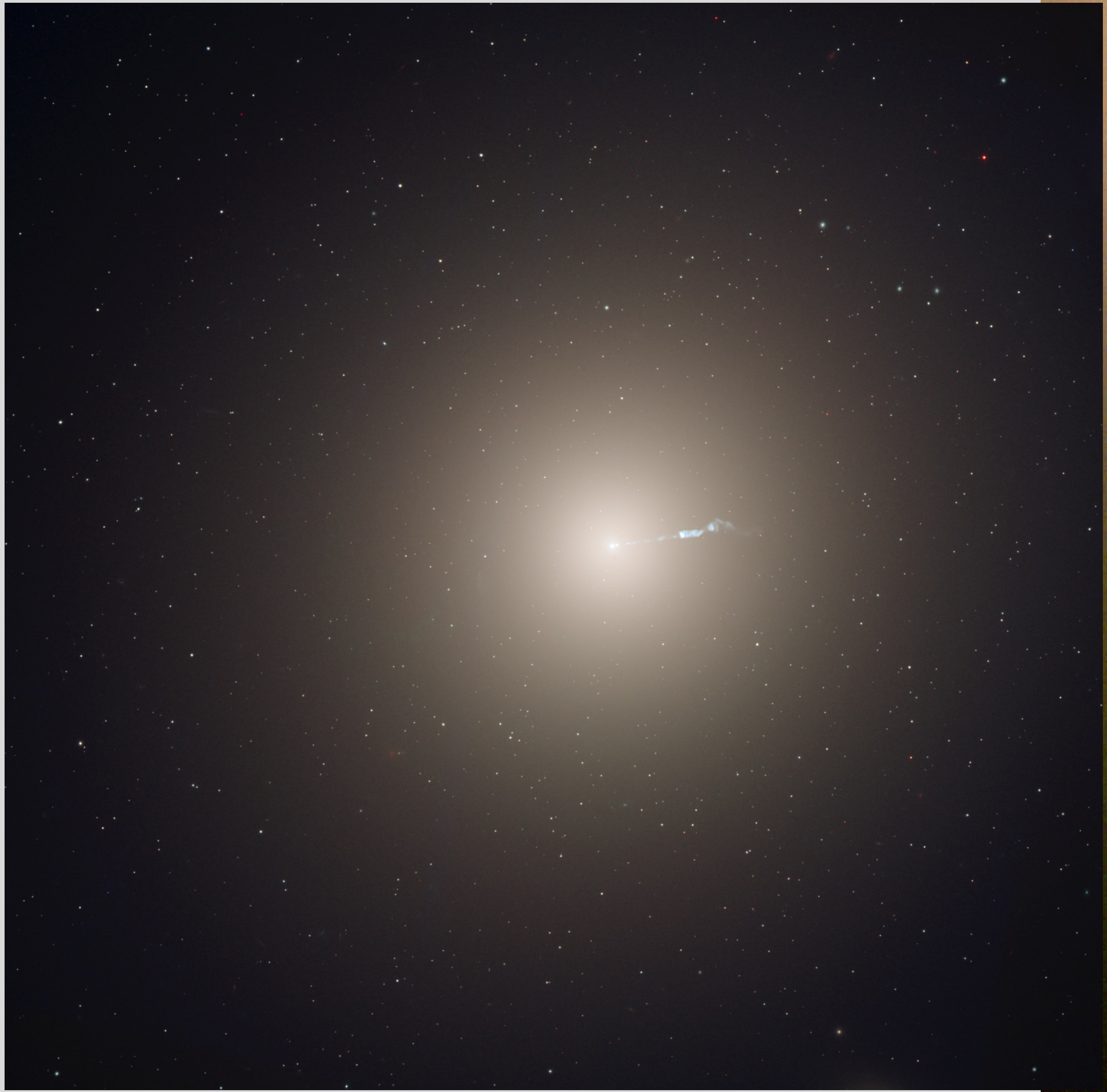
Active Galaxies (AGN)

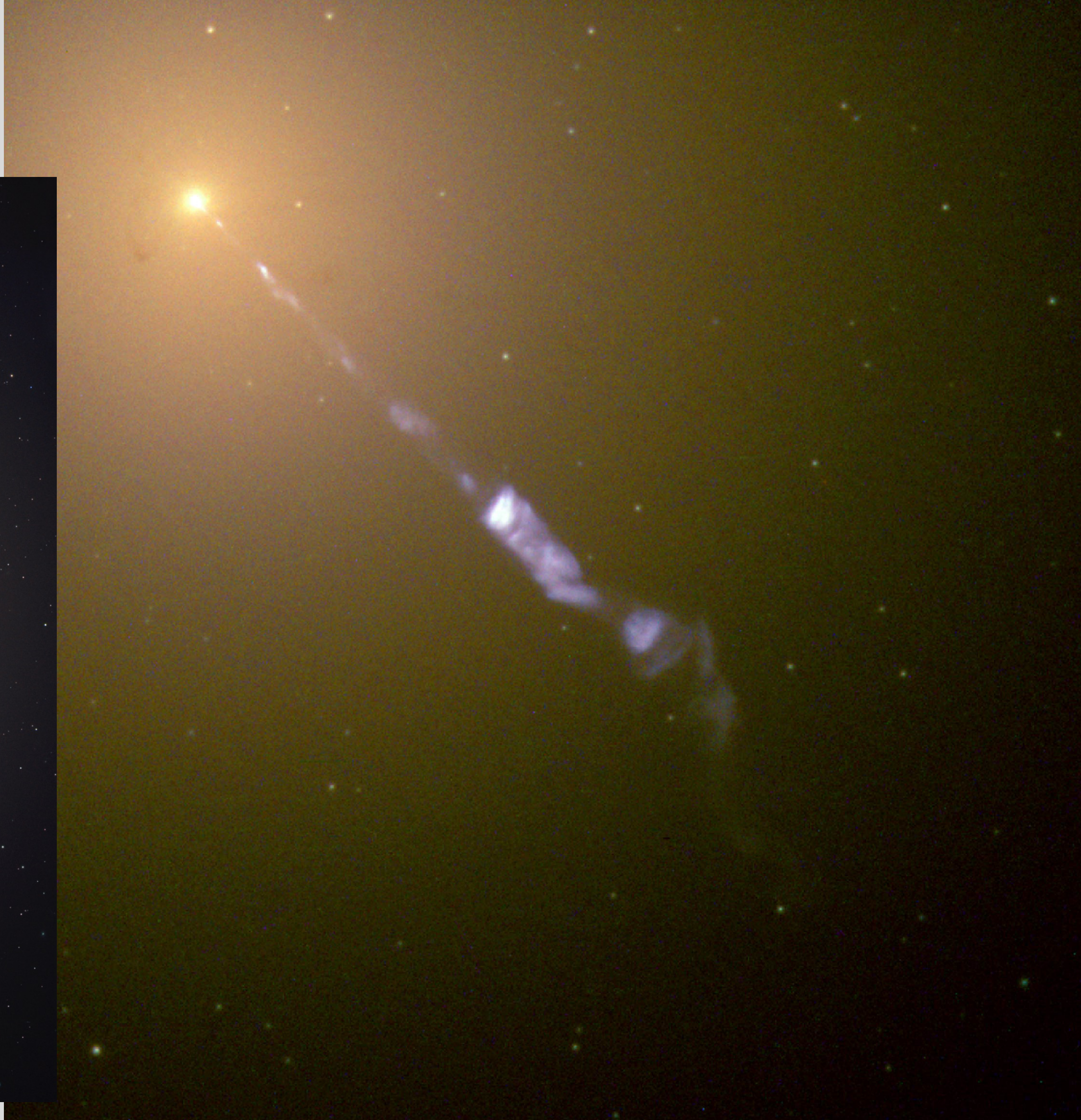
1917: Heber Curtis notices a “curious straight ray” emanating from the center of the Virgo elliptical galaxy M87



Active Galaxies (AGN)

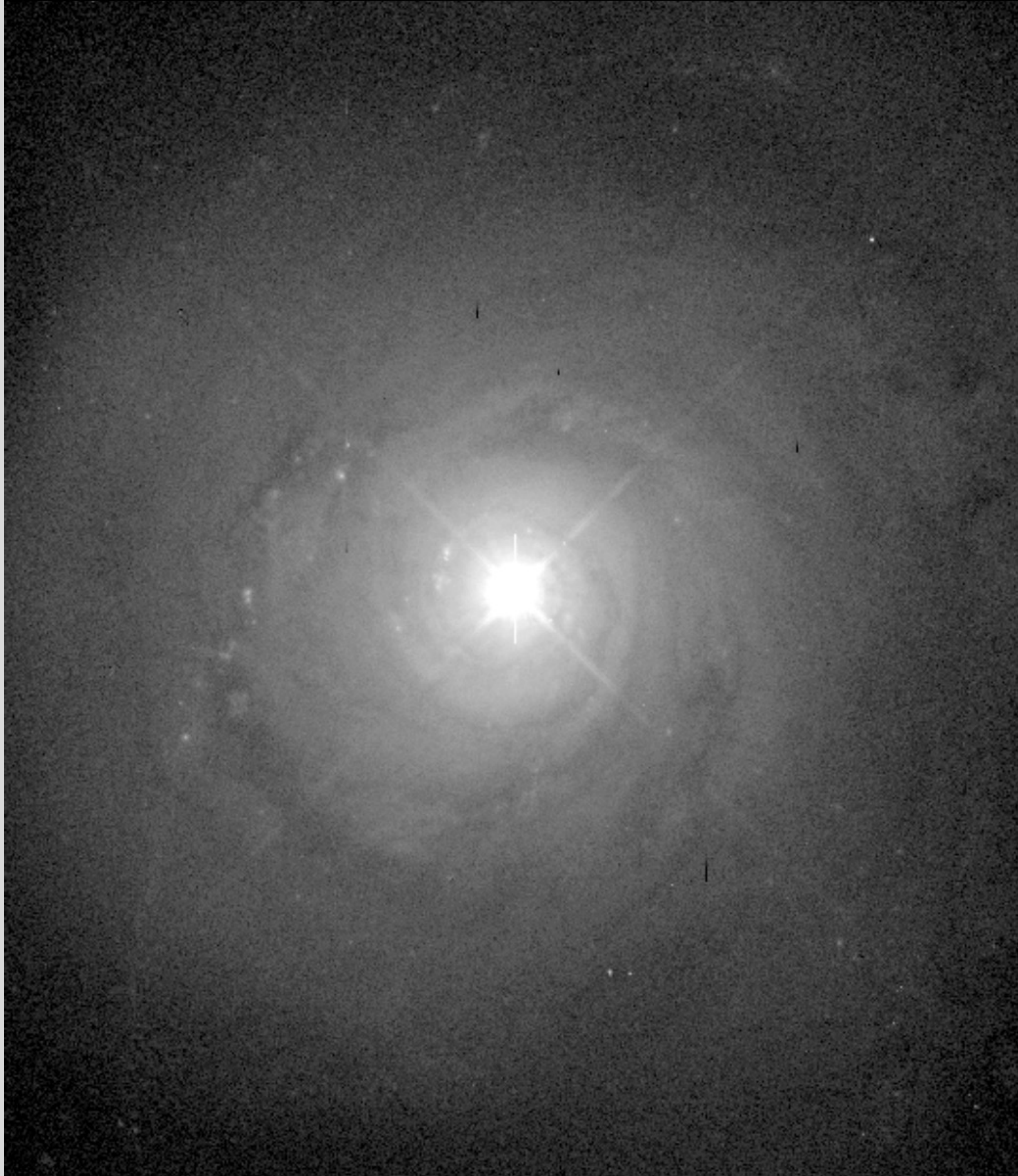
Modern views of M87





Seyfert Galaxies (1940s)

Spiral galaxies with very bright point-like nuclei.



Type 1 and Type 2 Seyfert Galaxies

Seyfert galaxy nuclei come in two types, characterized by their spectra.

Type 1 Seyferts:

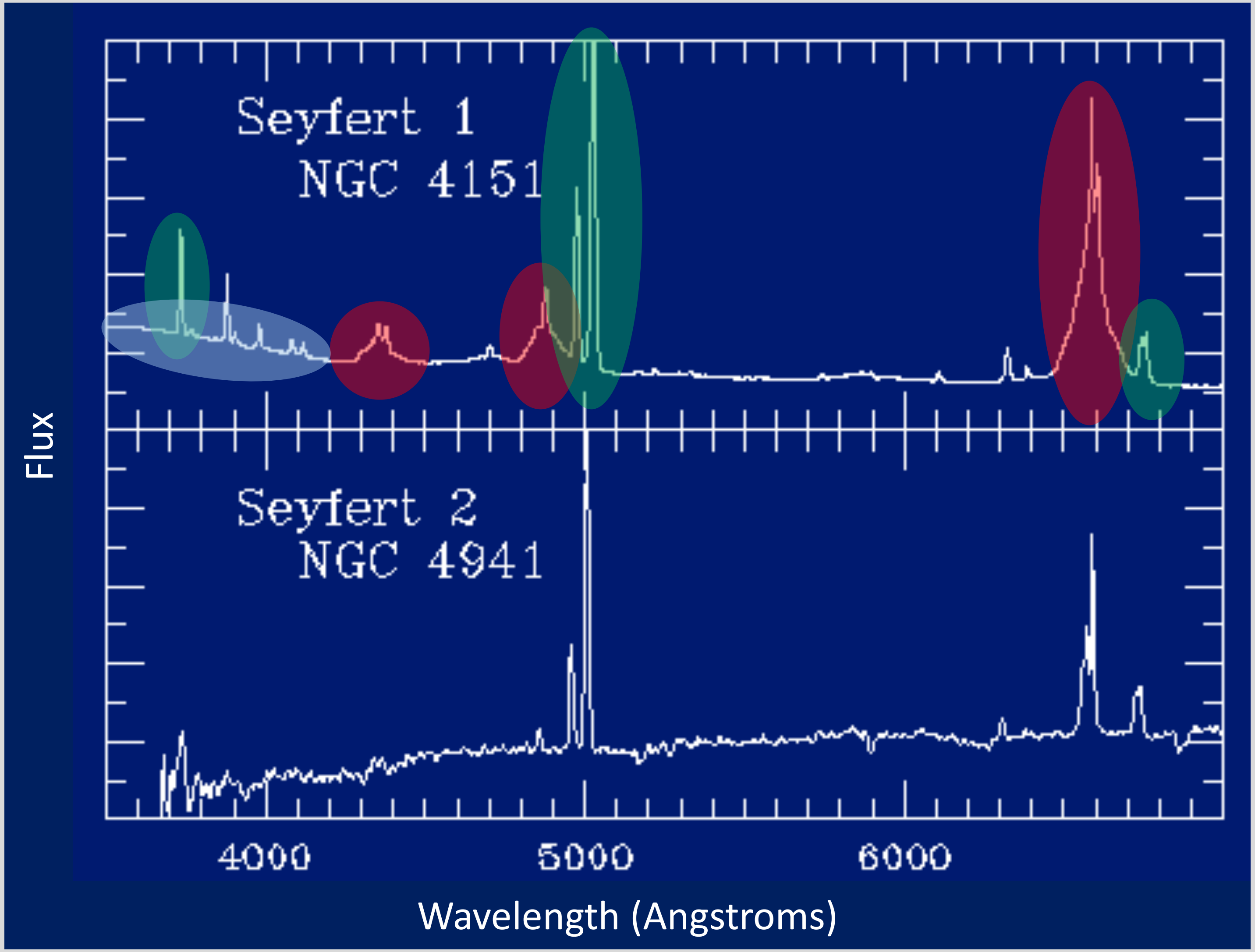
- Broad emission lines from ionized gas, with a Doppler width of 1000 – 5000 km/s.
- Narrow emission lines from ionized gas with Doppler widths ≈ 500 km/s.
- Spectral continuum that rises in the blue

Type 2 Seyferts:

- Lines are all narrow
- No broad lines
- Continuum flat or falling in the blue.

(Note: we now know that other kinds of AGN show similar Type 1 / Type 2 behavior as well…)

courtesy Bill Keel

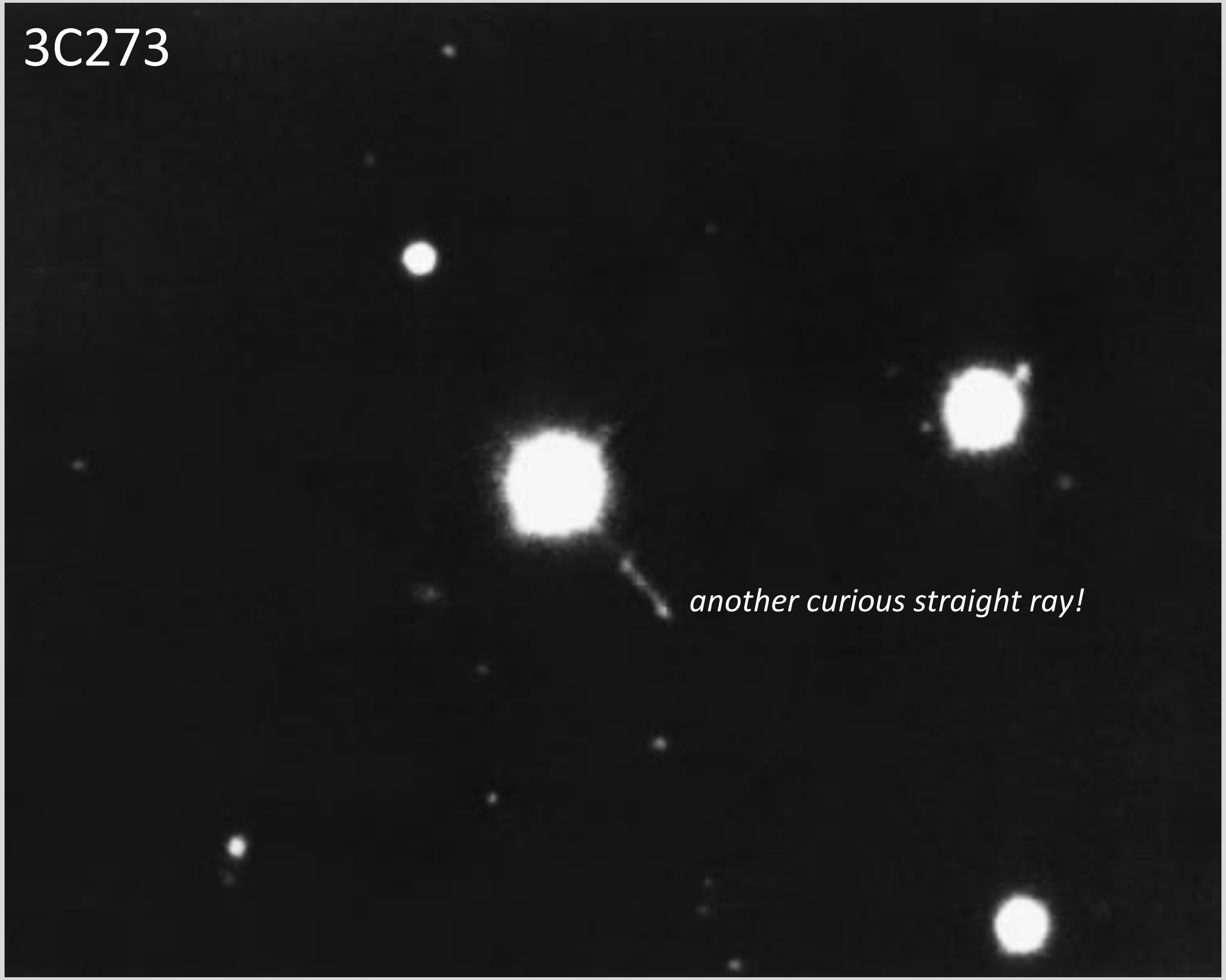


Quasars

Radio surveys in the 1950s identified bright radio sources often with no optical counterpart, or only a faint point source.

Quasar: “Quasi-stellar radio source”

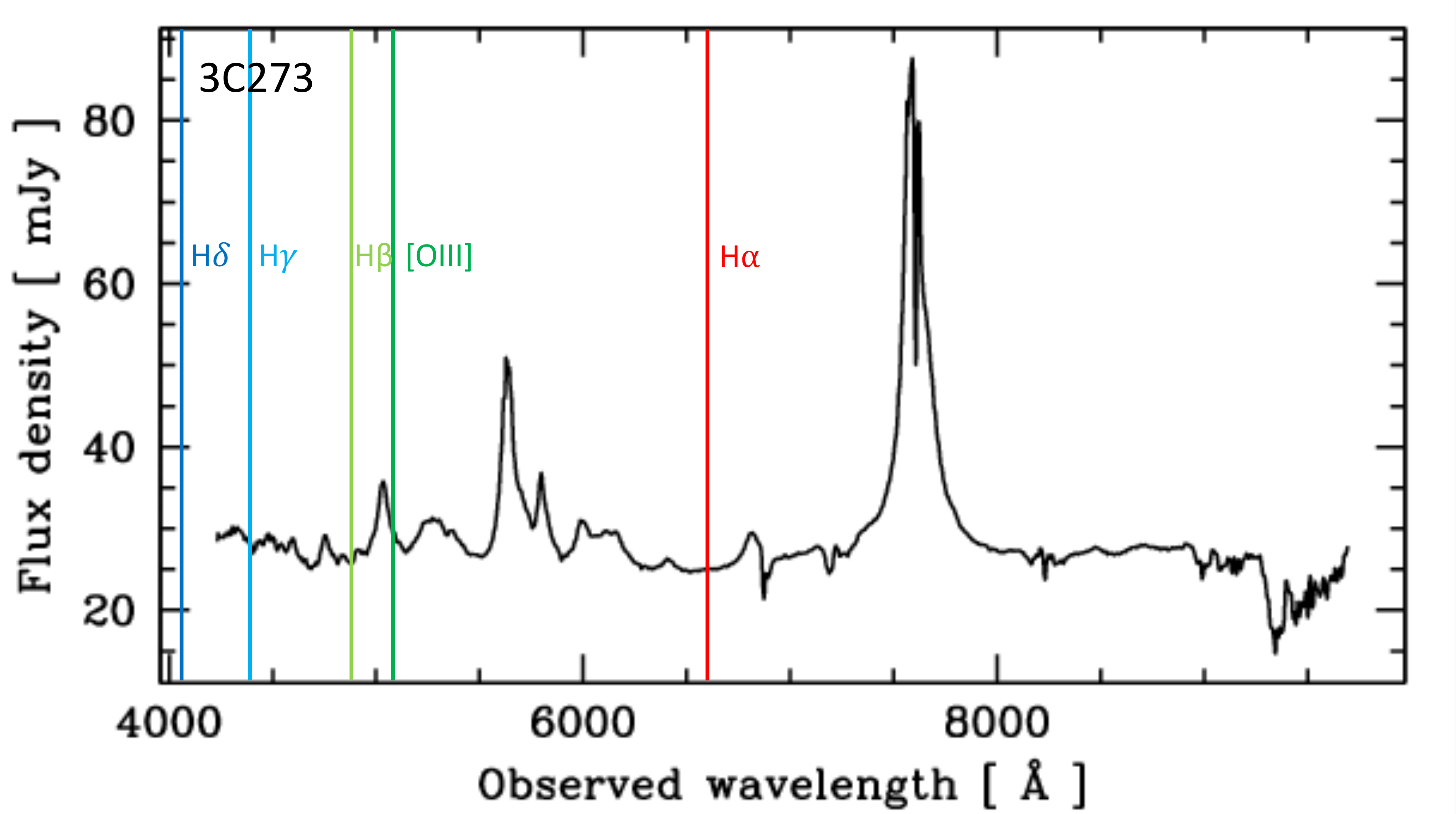
Star-like in appearance, but stars aren’t significant radio emitters.



(early optical image of 3C273)

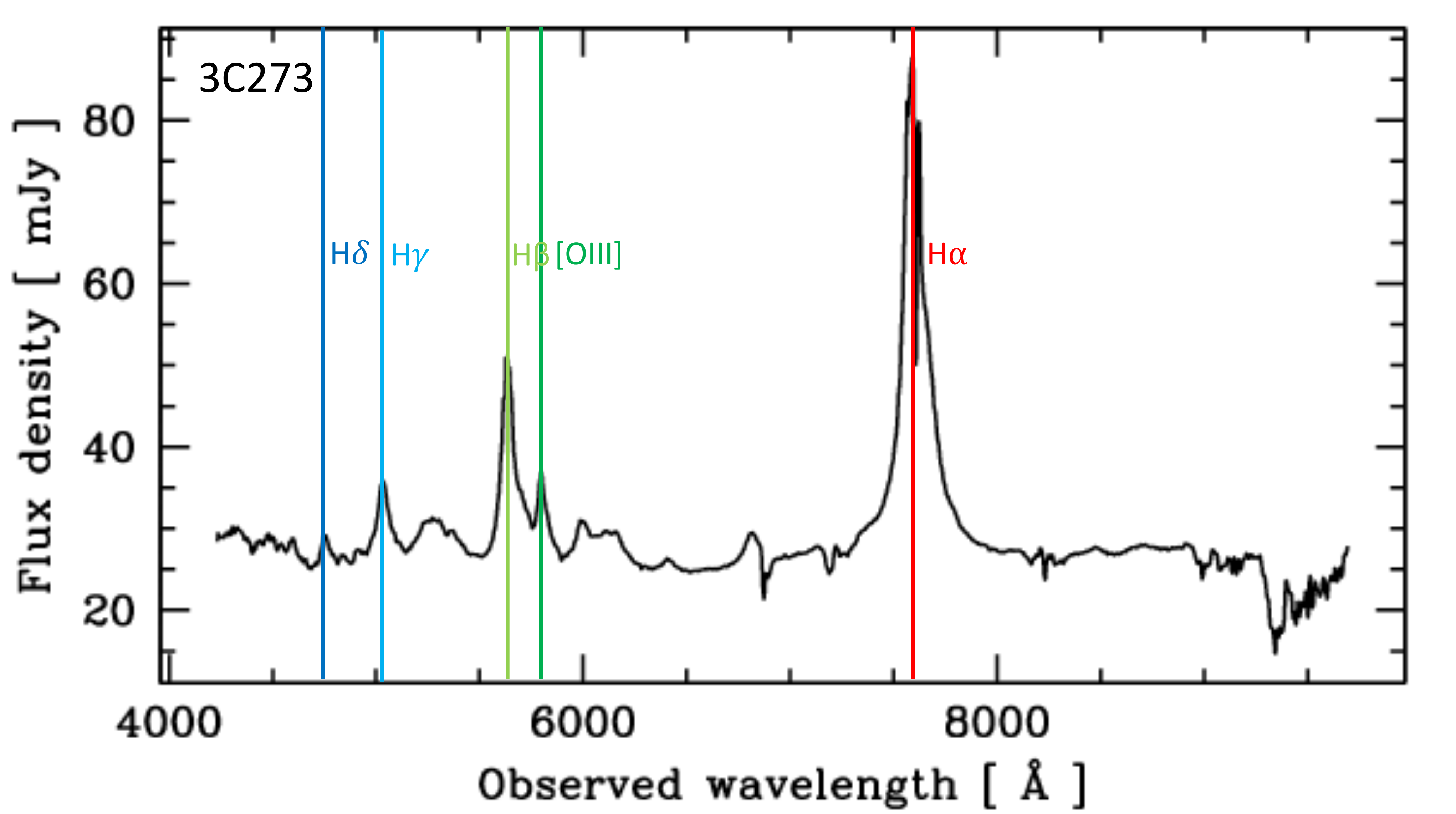
Quasars

Optical spectra showed unrecognizable emission lines...



Quasars

Optical spectra showed unrecognizable emission lines... until Martin Schmidt (1964) pointed out they could be redshifted.



Quasars

3C273: redshift $\frac{\Delta\lambda}{\lambda} = z = 0.158$ ⇒ luminosity distance of 750 Mpc!

This gives it a luminosity of $L \approx 10^{13} L_{\odot} \approx 500\times$ Milky Way's luminosity

At the time, no galaxy could be seen.

Today: With HST, we can detect the galaxy, which is a couple ***orders of magnitude fainter*** than the nucleus.

What fraction of galaxies host AGN? Today,

- 1 in a million host luminous quasars
- 5% host bright Seyfert-like nuclei
- 30% host low level nuclear activity
- at extremely low levels, the distinction between AGN and normal galaxies is minimal (consider the Milky Way)