Dwarf Galaxies

Remember the luminosity function of galaxies: rising at faint magnitudes.

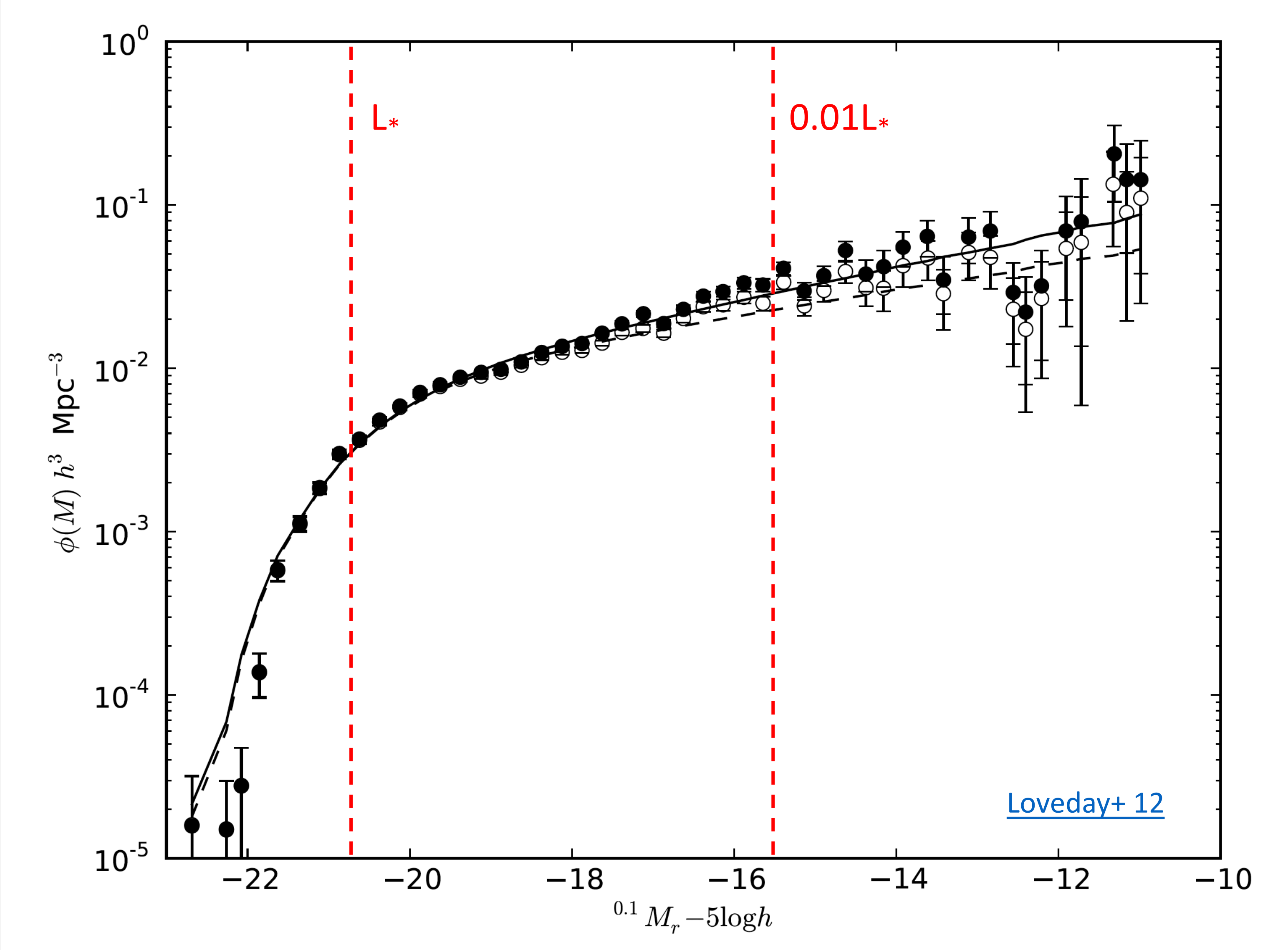
By number, low luminosity dwarfs far outnumber bright galaxies. (But luminous galaxies contain most of the stars.)

Schechter Function:

$$\Phi(L)dL = \Phi_* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*} dL$$

The faint end slope (α) of the LF is:

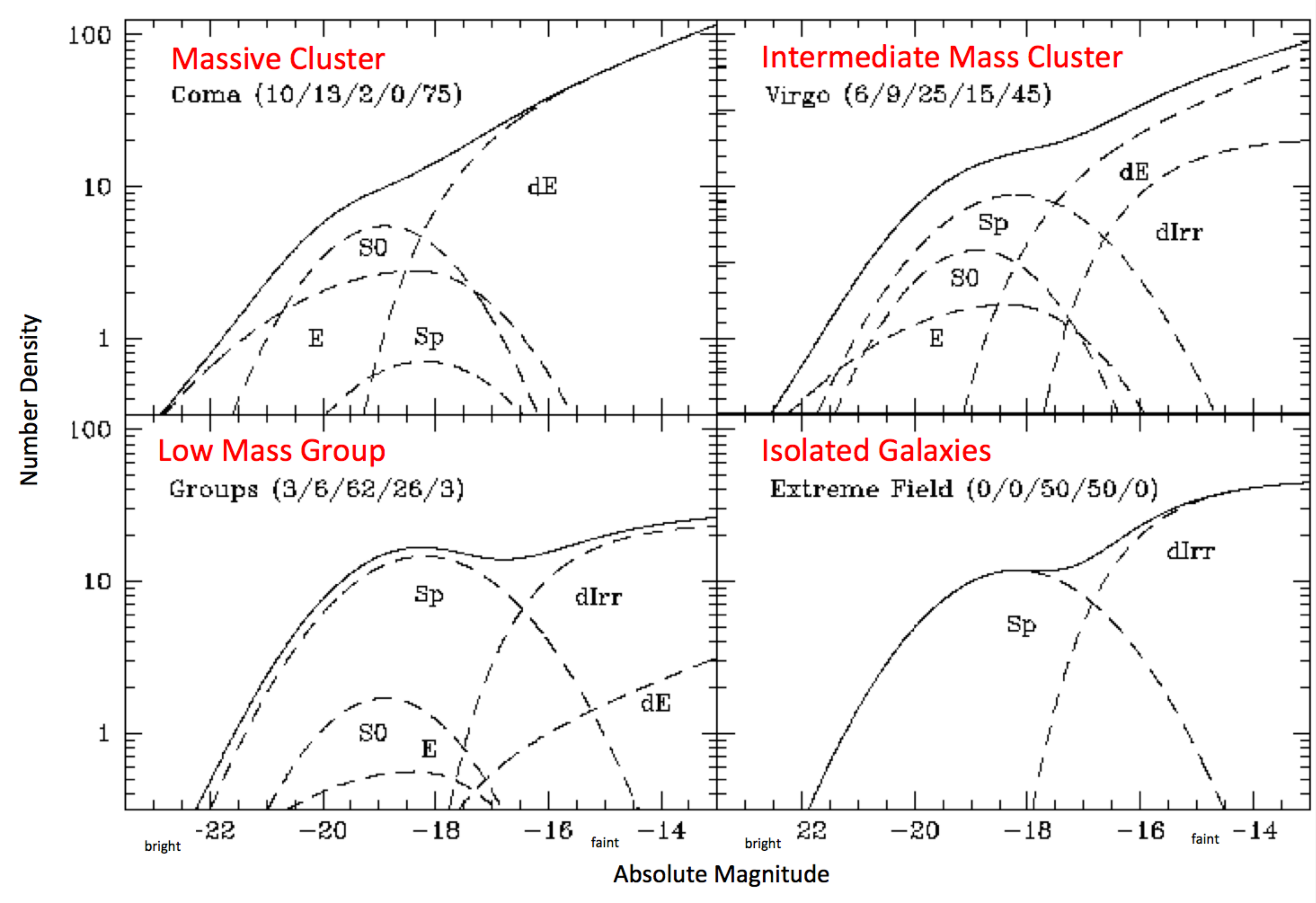
- environmentally dependent
- color dependent
- hard to measure



Galaxies: Luminosities

…and a very strong dependence on galaxy type and environment

These are schematic LFs, not real



Classical Dwarfs: Local Group Galaxies

"Dwarfs" have usually been defined by luminosity: M_V fainter than −17 or so ($L_V \lesssim 5{\times}10^8\ L_\odot$ or a few % of MW).

At fixed surface brightness, this generally also means small objects (since $L \sim R^2\Sigma$).

But as we detect more and more extremely low surface brightness galaxies, they can have low total luminosities even though they are quite big.

So definitionally, "dwarf" is a bit of a fuzzy term.

courtesy Sparke & Gallagher

Table 4.1 Galaxies of the Local Group within 1 Mpc of the Sun: the Milky Way and its satellites are listed in **boldface**; M31 and its companions are listed in *italics*

Galaxy	*Type*	d (kpc)	L_V ($10^7 L_\odot$)	$V_r(\odot)$ (km s^{-1})	l (*deg*)	b (*deg*)	$\mathcal{M}$(HI) ($10^6 \mathcal{M}_\odot$)
M31 (NGC 224)	Sb	770	2700	−299	121	−22	5700
Milky Way	Sbc	8	1500	−10	0	0	4000
M33 (NGC 598)	Sc	850	550	−183	134	−31	1500
Large MC	SBm	49	170	274	280	−33	700
NGC 205	dE	850	40	−241	121	−21	0.4
Small MC	Irr	58	34	148	303	−44	650
M32 (NGC 221)	E2	750	30	−203	121	−22	none
NGC 6822	Irr	490	30	−56	25	−18	c
IC 10	Irr	820	20	−344	119	−3	150
NGC 147	dE	760	12	−193	120	−14	none
NGC 185	dE	600	10	−202	121	−15	0.1
IC 1613 (DDO 8)	dIrr	715	10	−231	130	−61	60
Pegasus (DDO 216)	dIrr	760	8	−183	95	−44	3
WLM (DDO 221)	dIrr	970	4	−120	76	−74	80
Leo A (DDO 69)	dIrr	690	2	20	197	52	20
Fornax	dSph	120	1.4	53	237	−66	none
Sagittarius	dSph	25	1	170	6	−14	none
And I	dSph	770	0.5	−370	122	−25	none
Leo I (DDO 74)	dSph	270	0.5	285	226	49	none
And VII/Cas dSph	dSph	760	0.5	−307	110	−10	—
And II	dSph	590	0.3	−188	129	−29	—
And VI/Peg dSph	dSph	830	0.3	−341	106	−36	—
Aquarius (DDO 210)	dIrr	950	0.2	−137	34	−31	3
Sculptor	dSph	72	0.14	107	288	−83	$\lesssim$0.1c
Sagittarius DIG	dIrr	800	0.1	−78	21	−16	4
And III	dSph	770	0.1	−352	119	−26	<0.1
Phoenix	dIrr/dSph	420	0.08	56	272	−69	0.2
Cetus	dSph	775	0.08	—	101	−73	—
LGS3 (Pisces)	dIrr/dSph	810	0.06	−281	127	−41	0.2
Leo II (DDO 93)	dSph	207	0.06	76	220	67	none
Tucana	dSph	870	0.05	—	323	−47	none
Sextans	dSph	83	0.04	225	244	42	none
Carina	dSph	100	0.03	223	260	−22	none
And V	dSph	810	0.03	−387	126	−15	—
Ursa Minor	dSph	64	0.02	−247	105	45	none
Draco (DDO 216)	dSph	72	0.02	−293	86	35	none

Note: d is measured from the Sun; $V_r(\odot)$ is the radial velocity with respect to the Sun.
c: HI is confused with Galactic emission (NGC 6822) or gas of the Magellanic Stream (Sculptor).

Classical Dwarfs: Local Group Galaxies

Magellenic Clouds: star-forming dwarf irregulars (dIrrs).

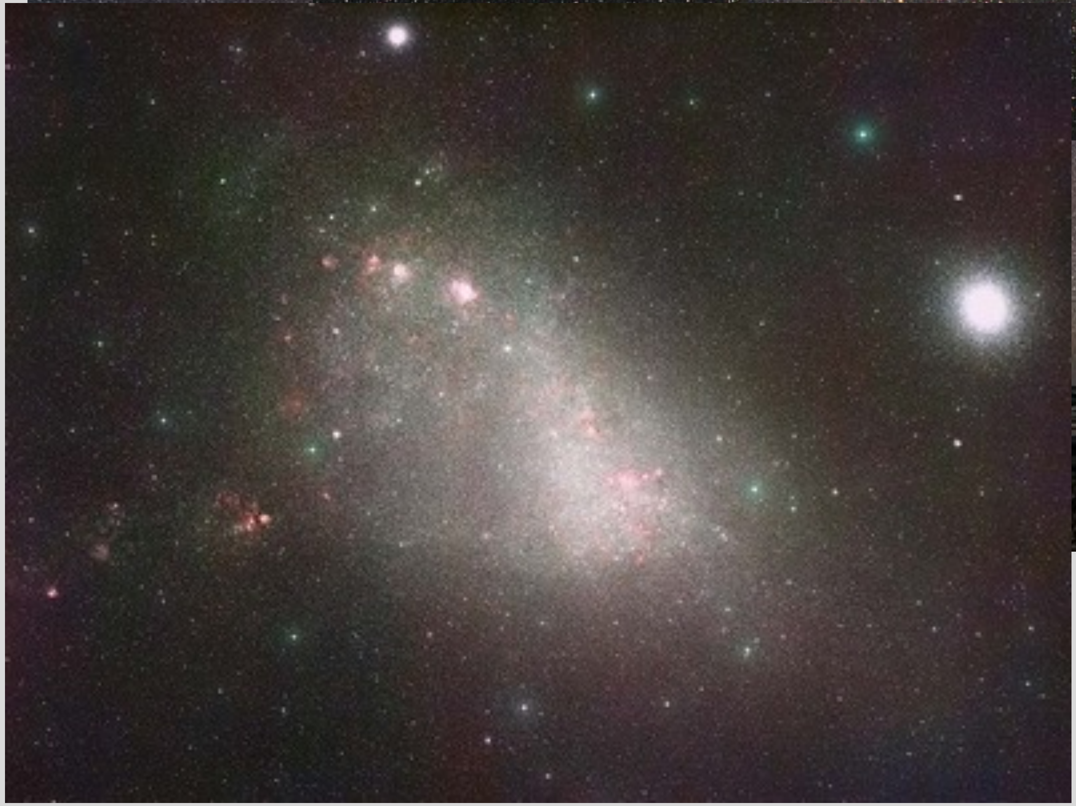
Brightest of MW companion galaxies.

Large Magellenic Cloud (LMC)

- $D \approx 50$ kpc
- Size ≈ few kpc
- Luminosity $\approx 2\text{x}10^9\ M_\odot$ (10% of MW)
- Mass $\approx 2\text{x}10^{10}\ M_\odot$

Small Magellenic Cloud (SMC)

- $D \approx 60$ kpc
- Size $\lesssim 1$ kpc
- Luminosity $\approx 3.5\text{x}10^8\ M_\odot$ (2% of MW)
- Mass $\approx 2\text{x}10^9\ M_\odot$



Classical Dwarfs: Local Group Galaxies

Irregulars (Irr) / Dwarf Irregulars (dIrr):

Star forming, gas-rich. $M_{HI}/M_{tot} \gtrsim 10\%$

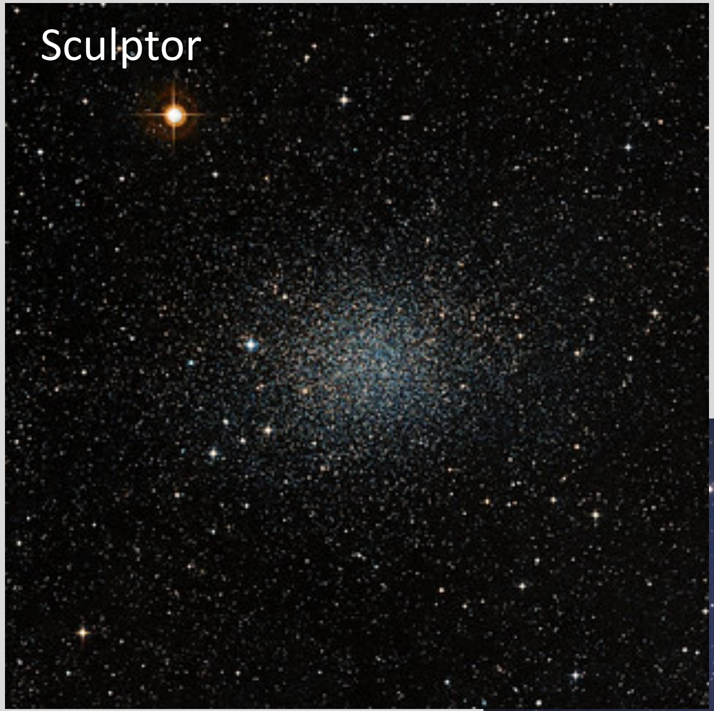
Rotating, but low circular velocity (low mass).

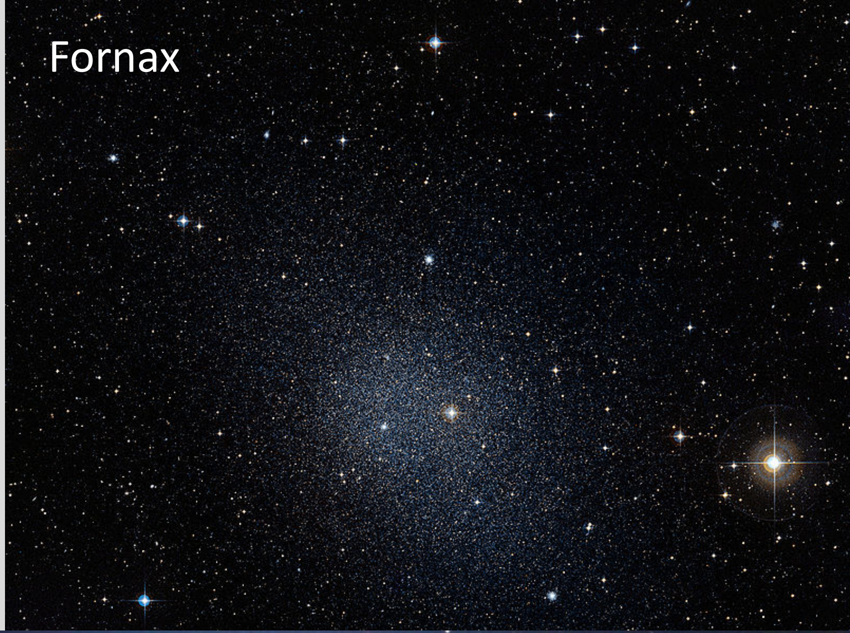
Classical Dwarfs: Local Group Galaxies

Dwarf Spheroidals (dSph)

Gas poor, low/no rotation, no ongoing star formation.

Very low surface brightness.



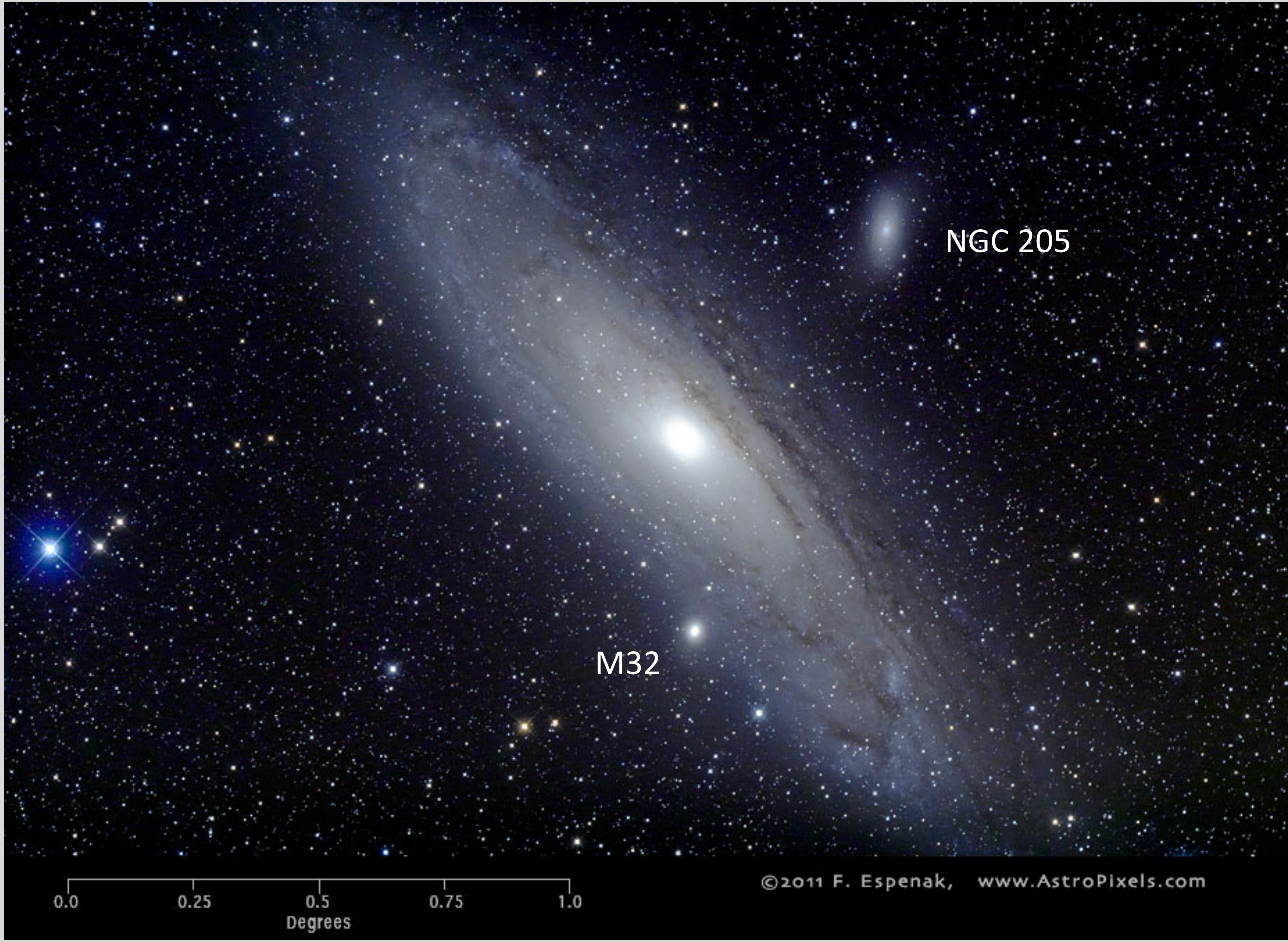


Classical Dwarfs: Local Group Galaxies

Dwarf Ellipticals (dE)

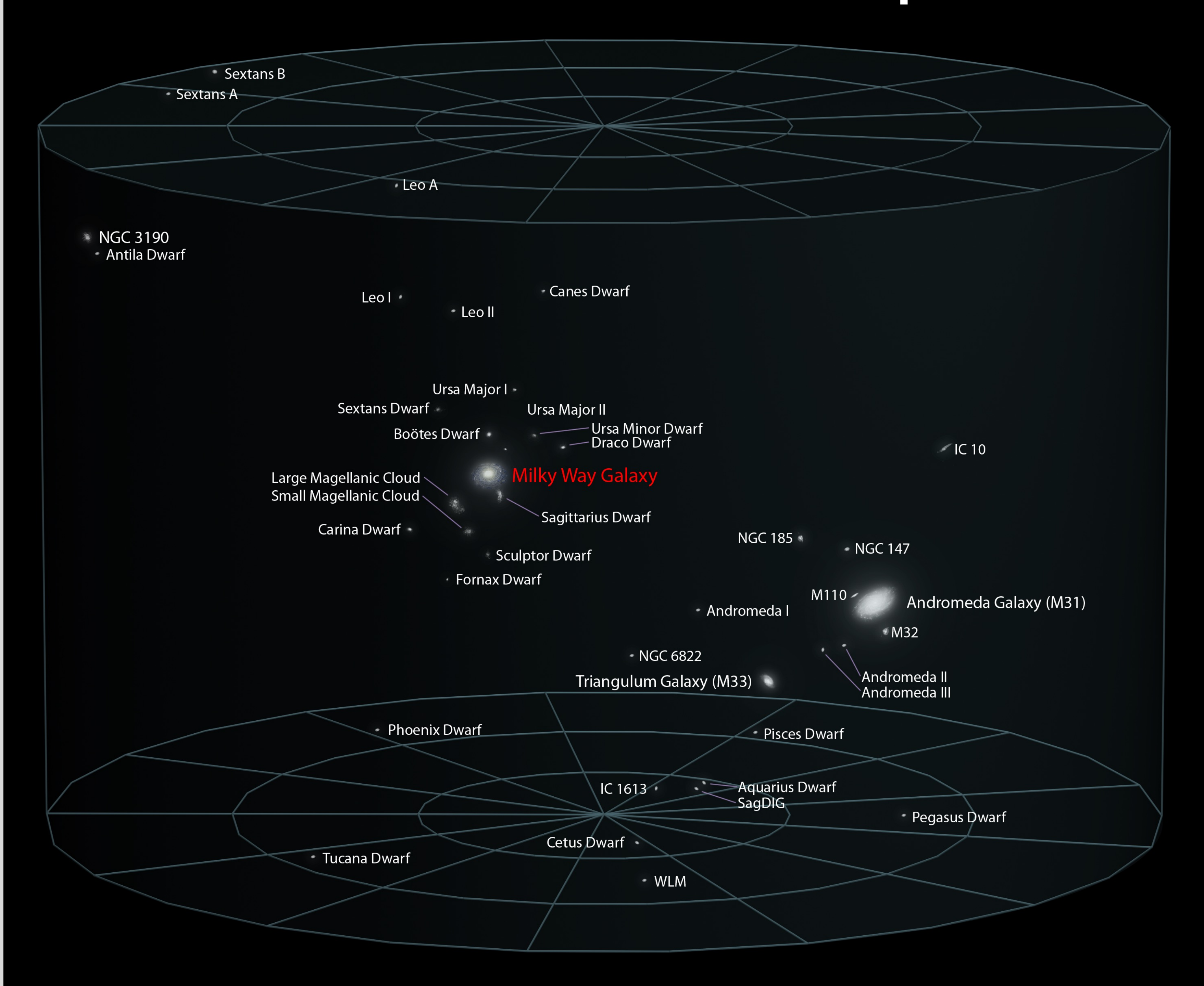
More luminous and higher in surface brightness than dSph.

But beware of nomenclature: some people call dSph galaxies dE's



Classical Dwarfs: Spatial Distributions

Cluster around bright galaxies (MW, And) but also found throughout the Local Group.



Classical Dwarfs: Spatial Distributions

Star-forming Irr/dIrr tend to live further away from bright galaxies.

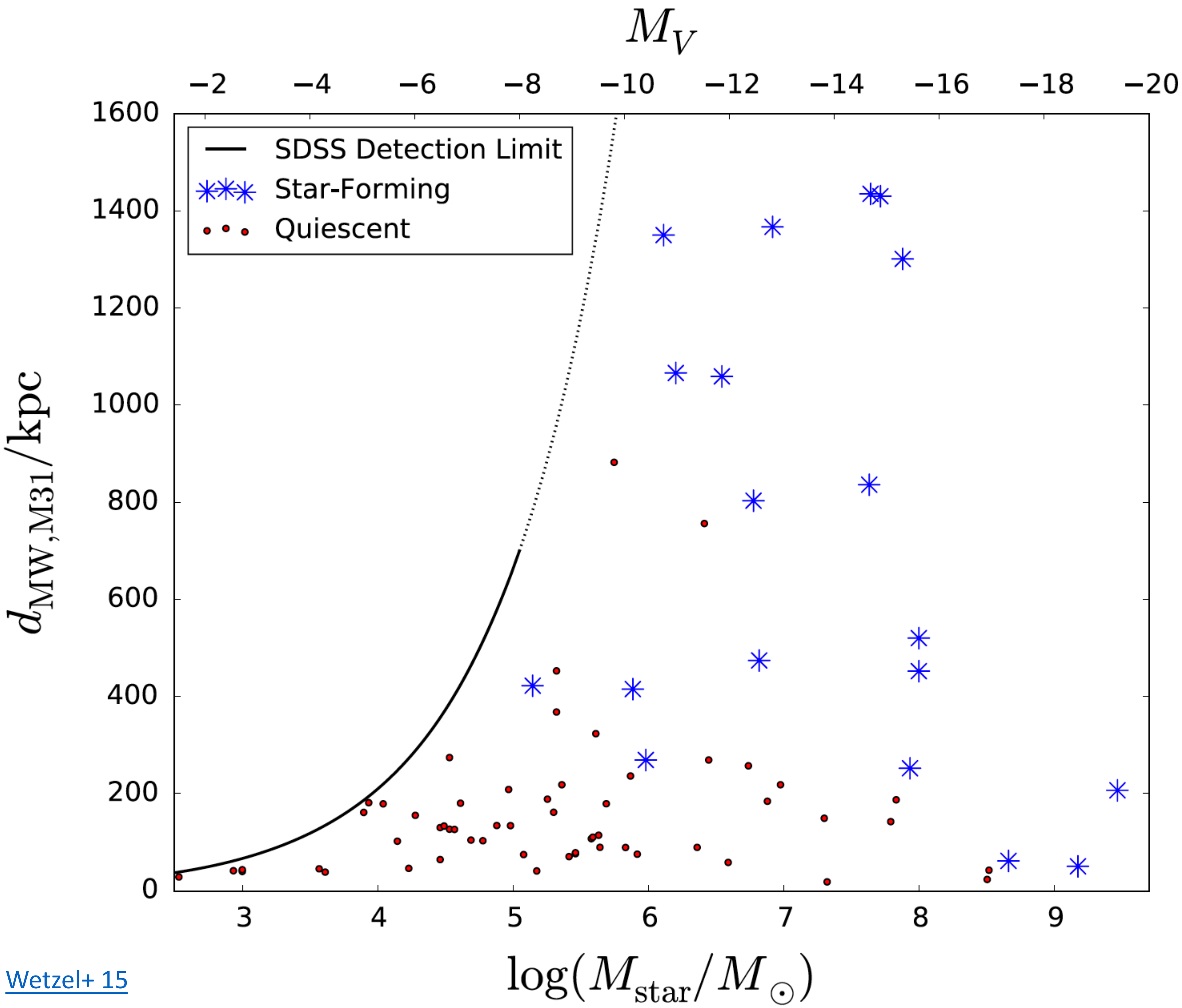
Quiescent dSph galaxies found closer to bright galaxies.

“quiescent” defined as gas-poor:

$M_{gas}/M_{star} < 0.1$

Distance from MW or M31

Possible signature of ram pressure stripping of gas from dwarf galaxies by a hot halo of gas around the Millky Way?



Wetzel+ 15

Classical Dwarfs: Structural Properties

Dwarf galaxies are structurally distinct from luminous galaxies.

Dwarfs are generally much lower in surface brightness.

dSph's follow exponential profiles, not $r^{1/4}$ *(Sersic n=4)* profiles, but they are **not** rotating disks.

Fainter dwarfs are generally lower in surface brightness (unlike what regular E's do....)

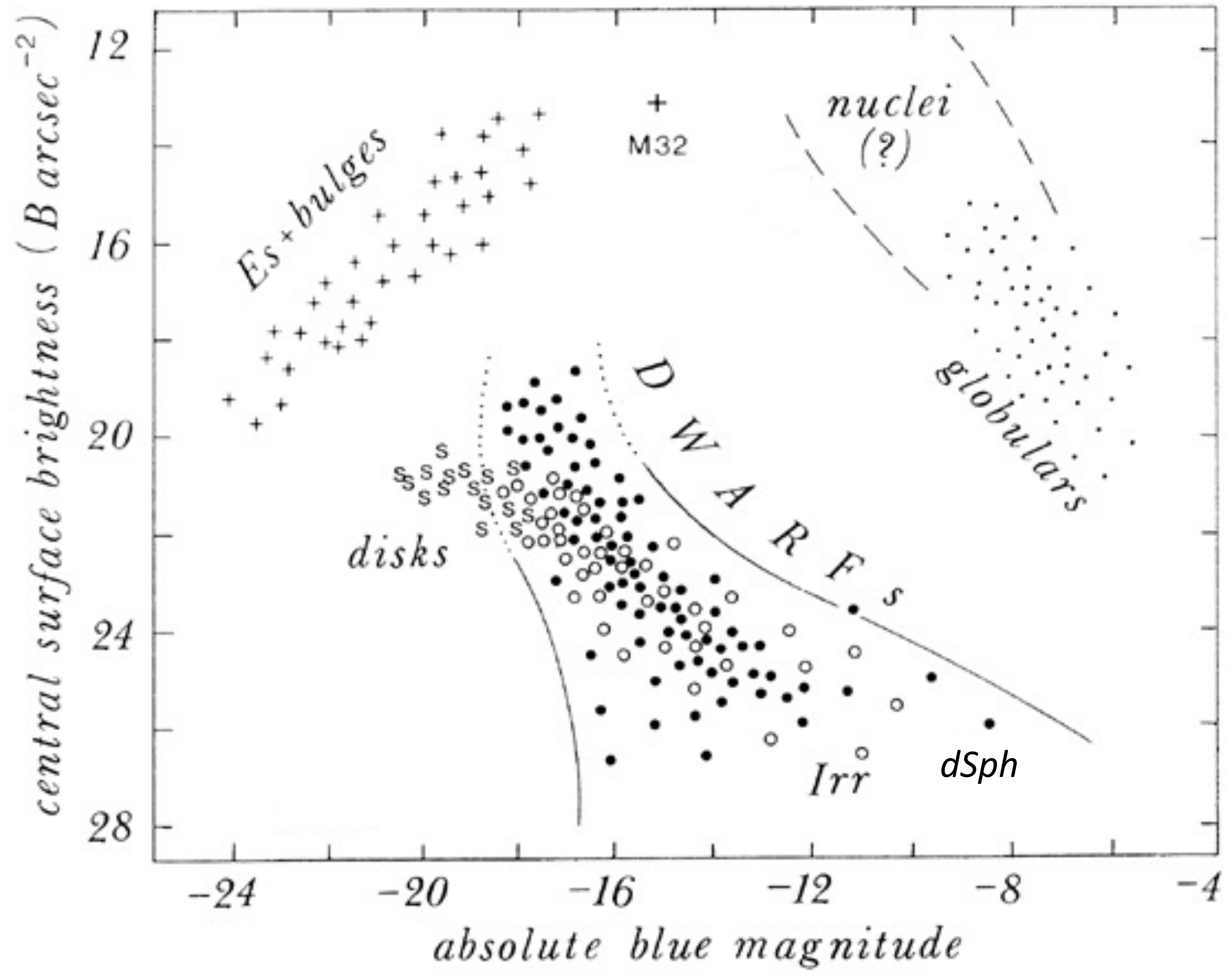
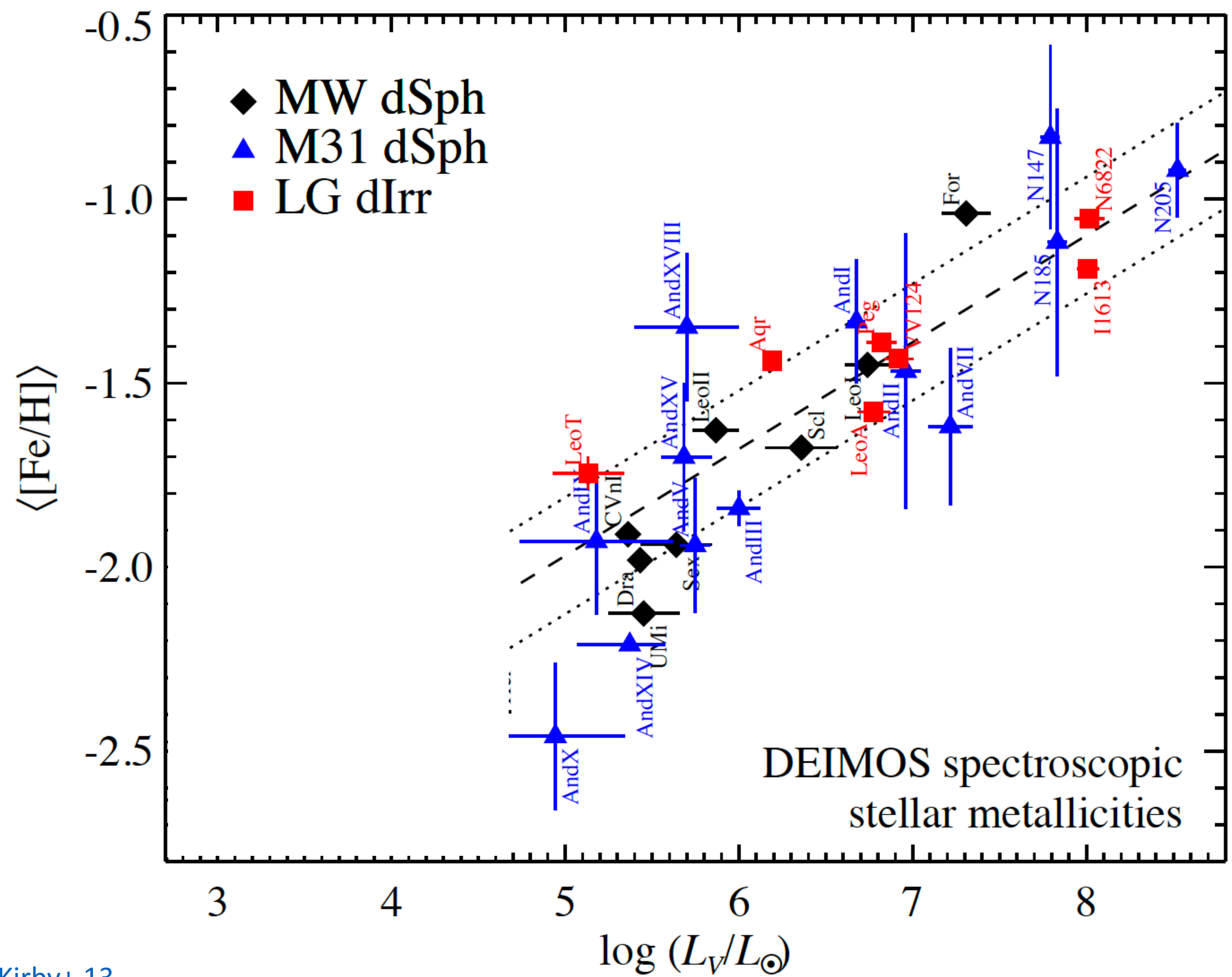


Fig 4.18 (B. Binggeli) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Classical Dwarfs: Stellar Populations

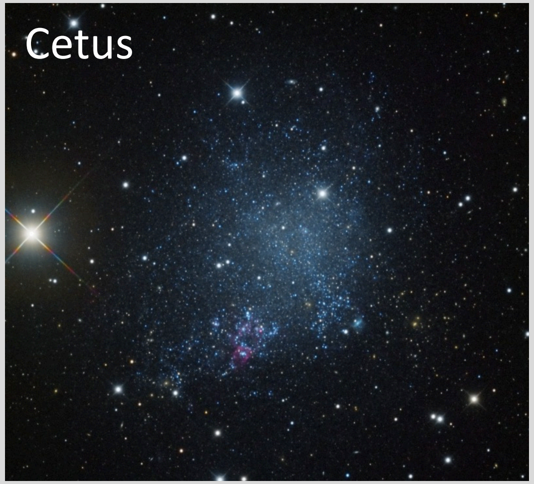
Continue the mass-metallicity (or luminosity-metallicity) relationship to even lower levels.



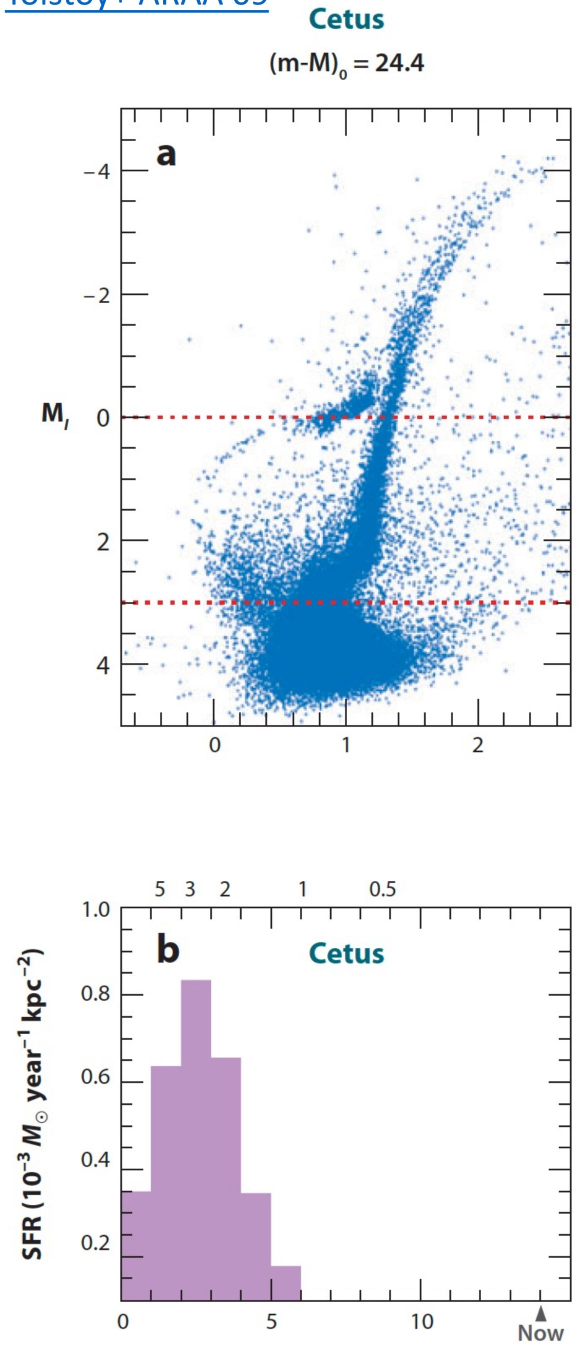
Kirby+ 13

Classical Dwarfs: Stellar Populations

Star formation histories show a wide variation.

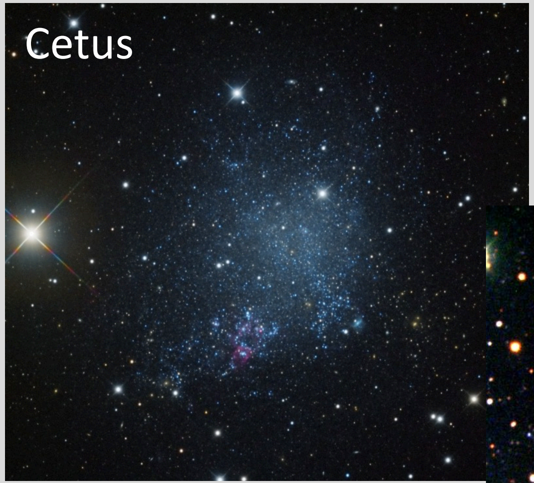


Tolstoy+ ARAA 09

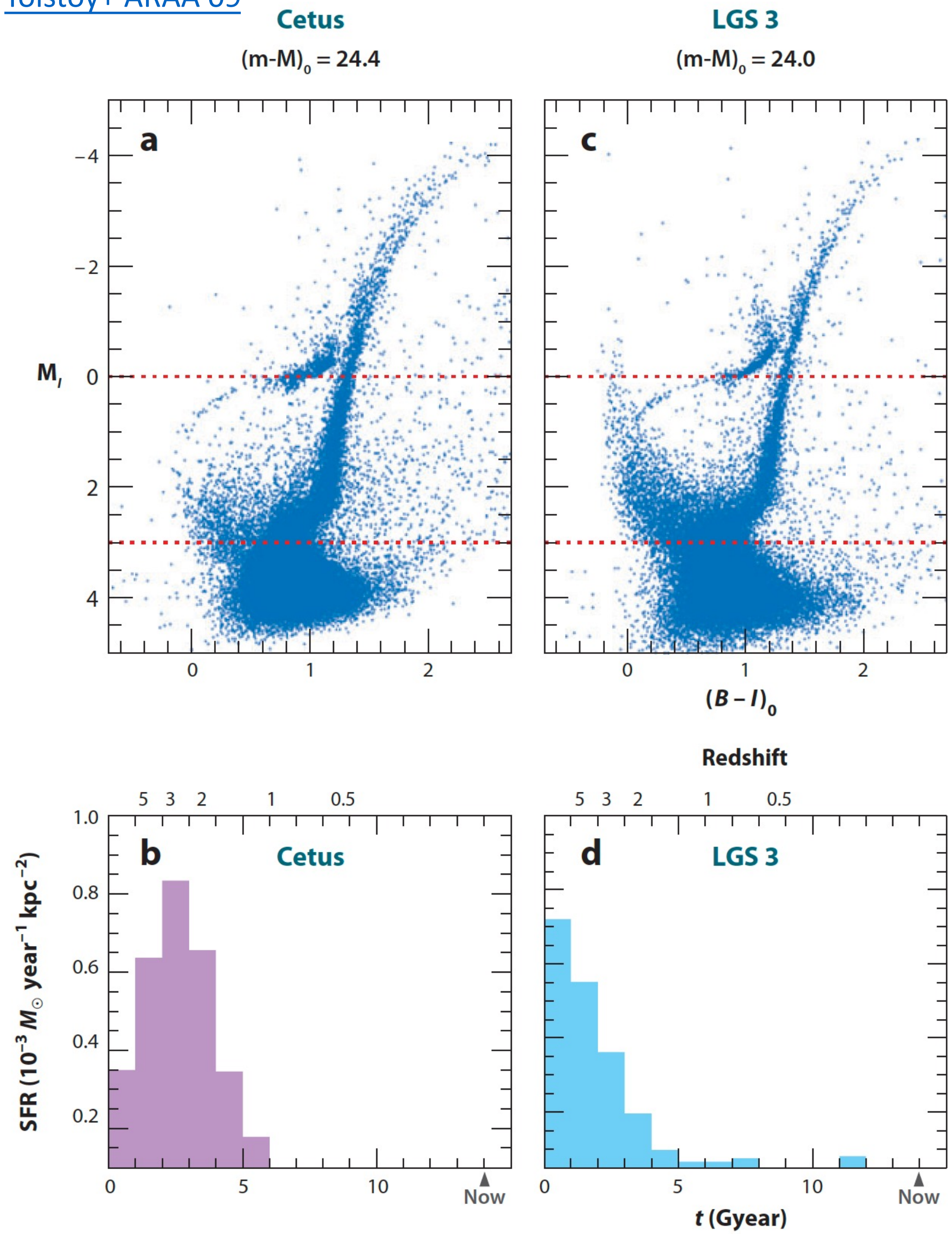


Classical Dwarfs: Stellar Populations

Star formation histories show a wide variation.

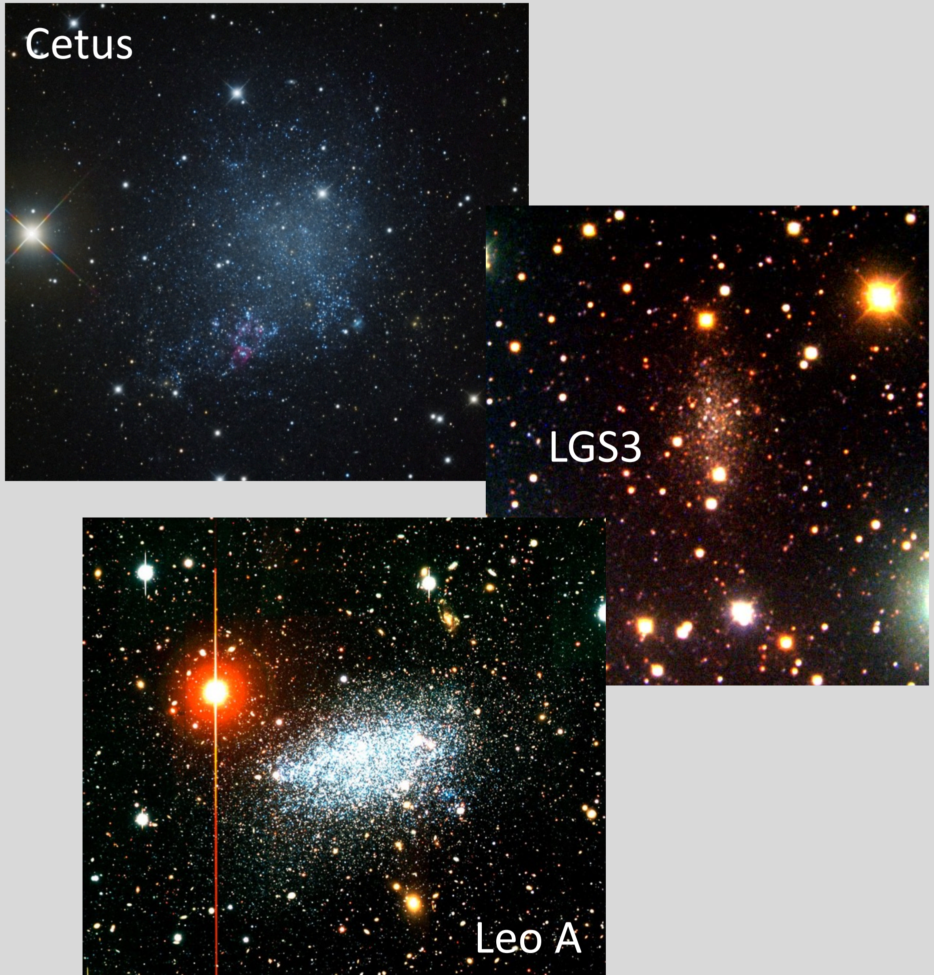


[Tolstoy+ ARAA 09]

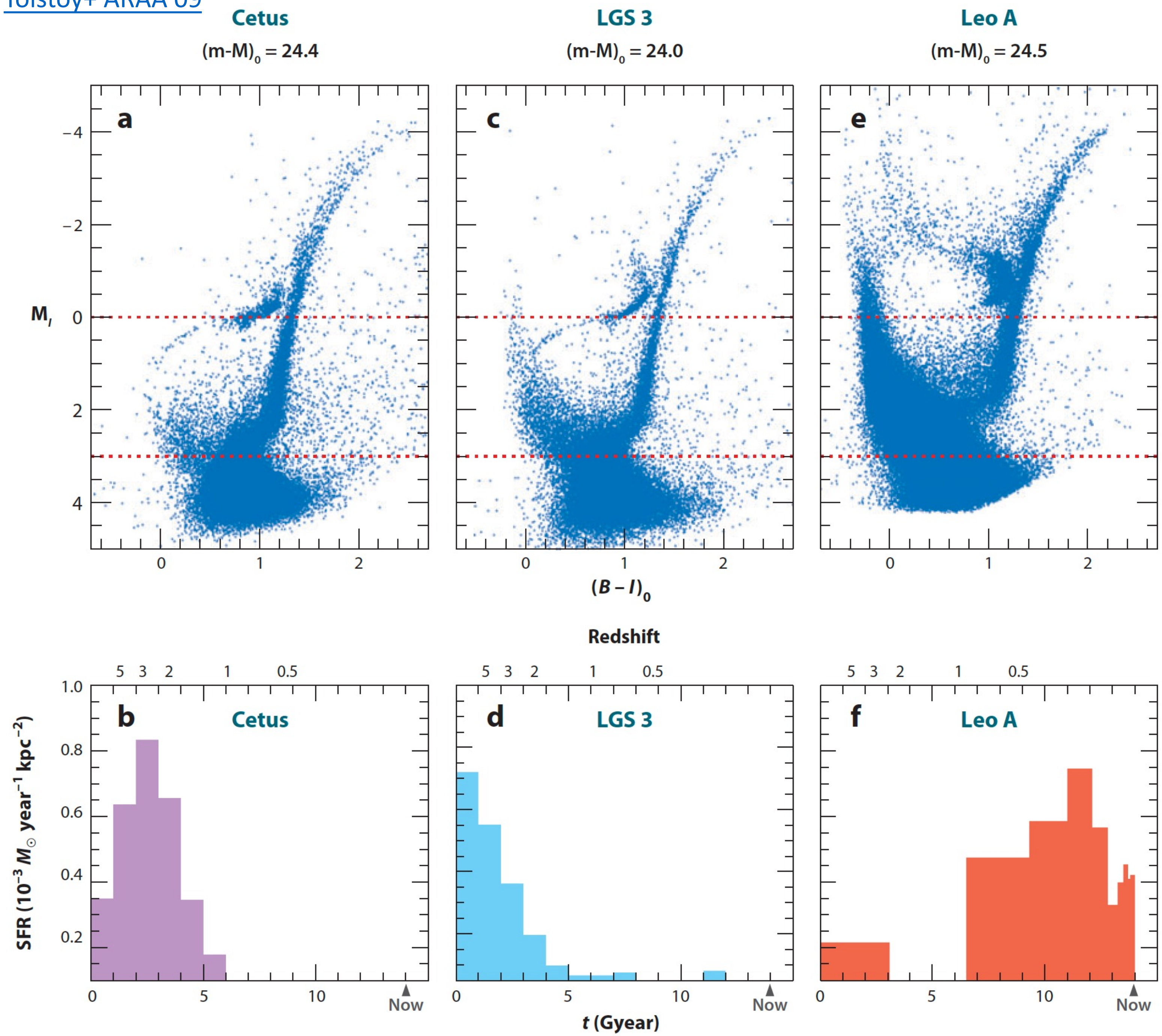


Classical Dwarfs: Stellar Populations

Star formation histories show a wide variation.



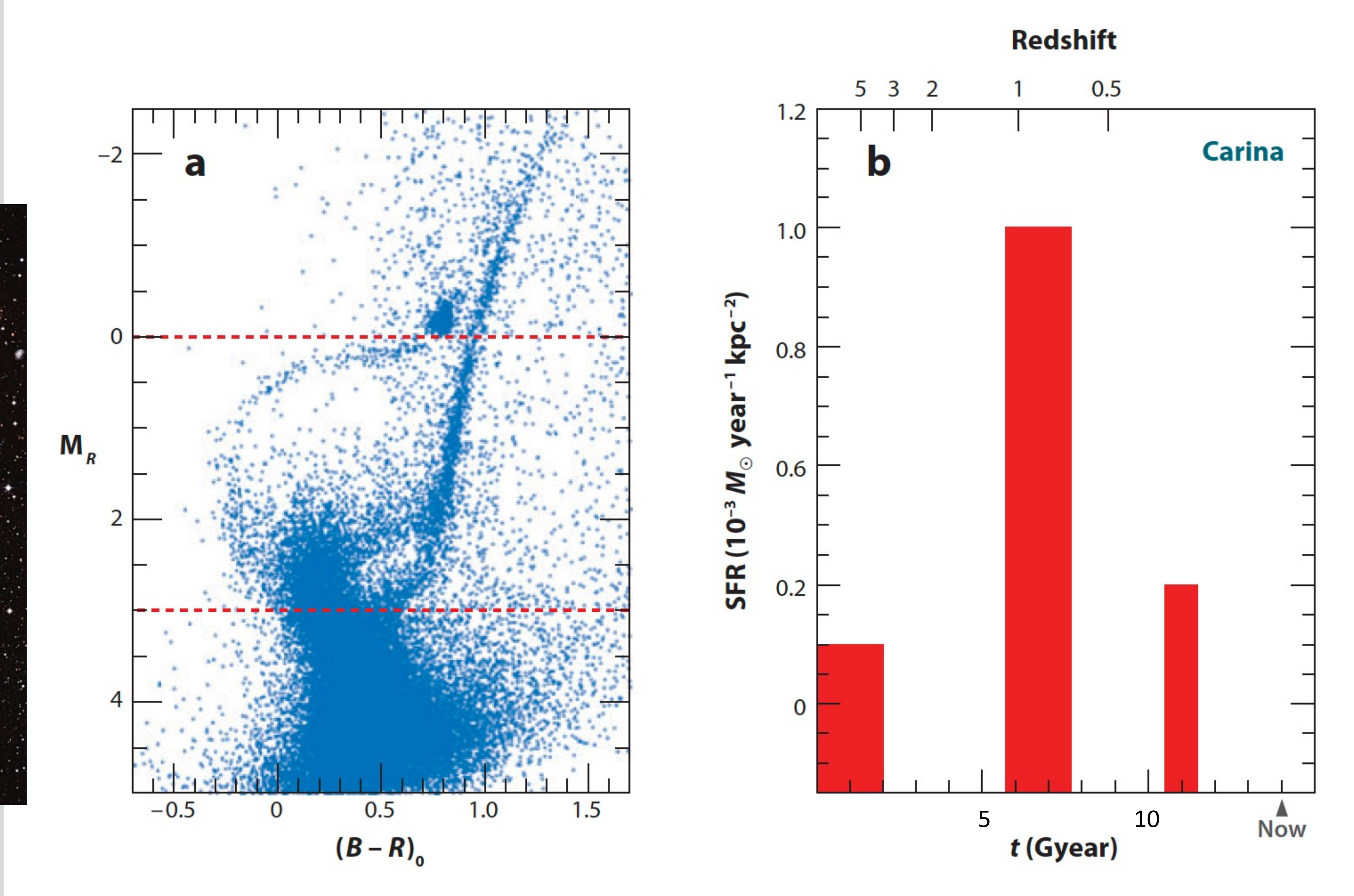
[Tolstoy+ ARAA 09]



Classical Dwarfs: Stellar Populations

Tolstoy+ ARAA 09

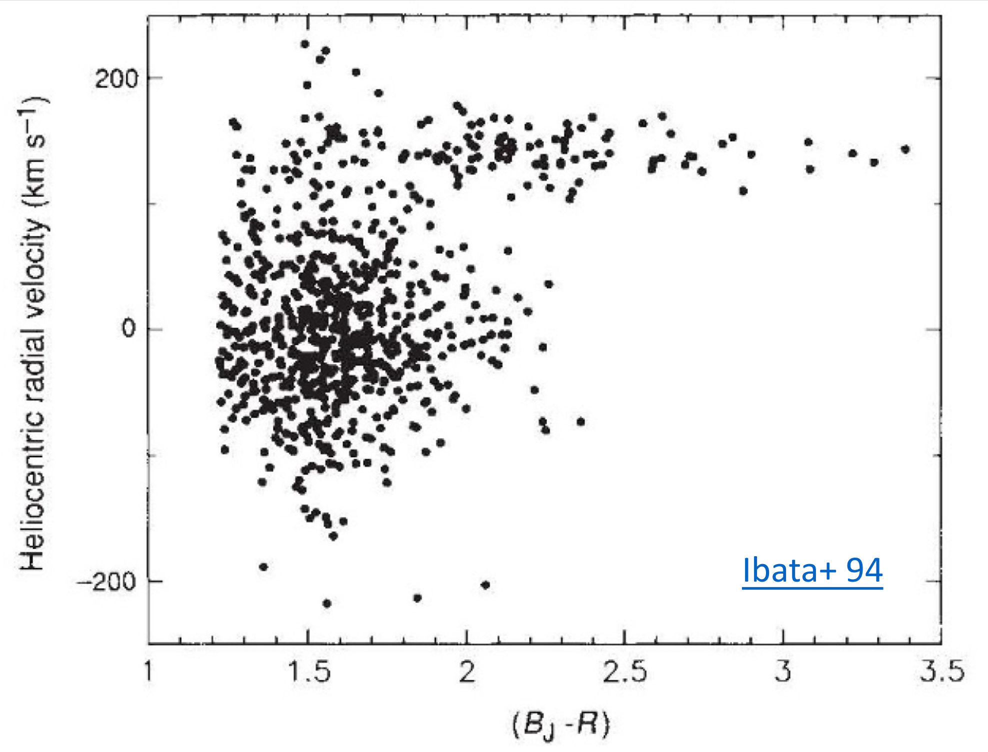
and look at Carina!

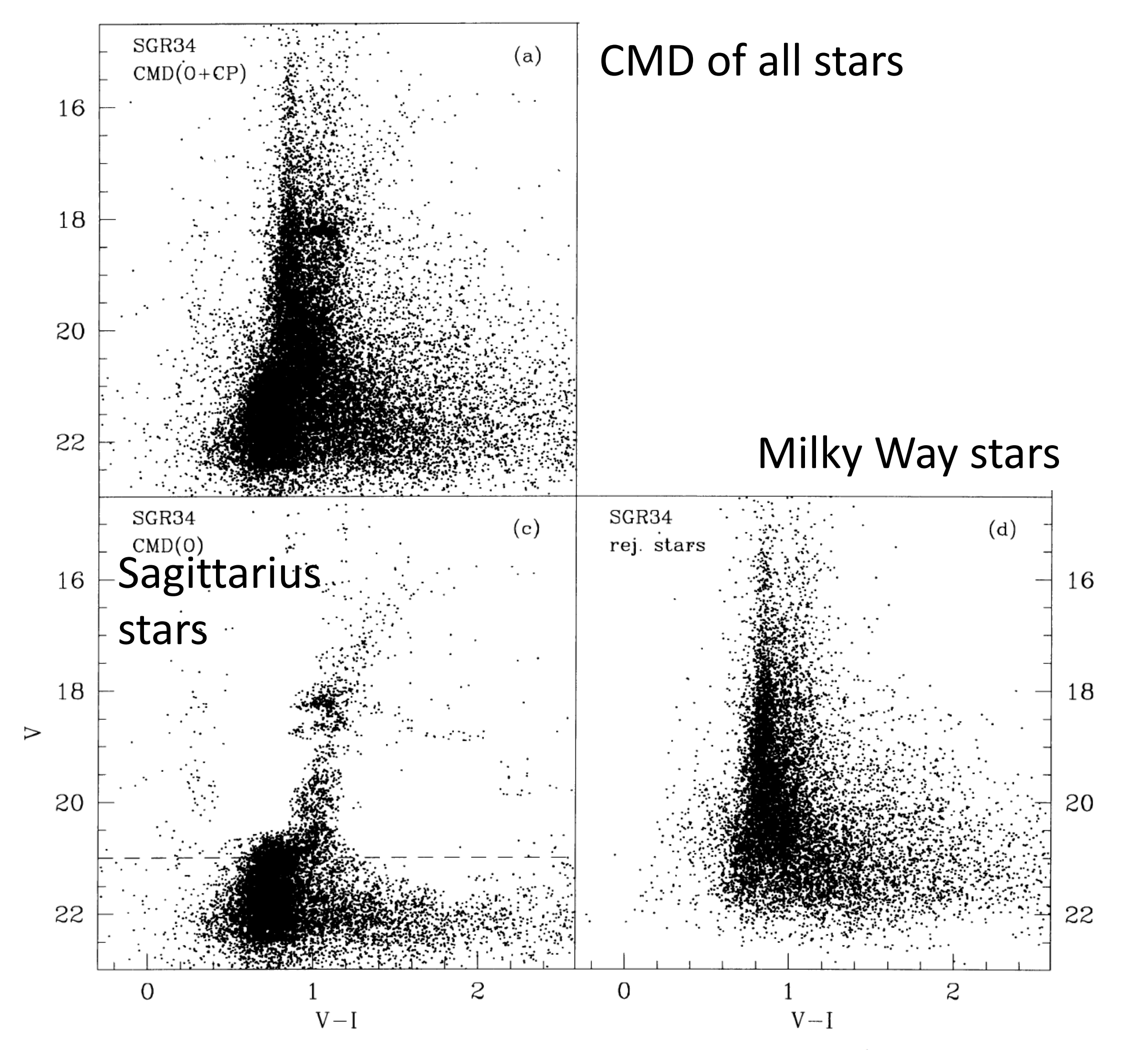


Multiple, discrete bursts of star formation....

The New Dwarfs: The discovery of Sagittarius

1994: Surveying stars in the MW bulge, Ibata+ 94 discover new satellite galaxy via kinematic sub-structure in properties of stars. Called the Sagittarius Dwarf. D ≈ 20 kpc, other side of MW.





Bellazzini+ 99

The New Dwarfs: The discovery of Sagittarius

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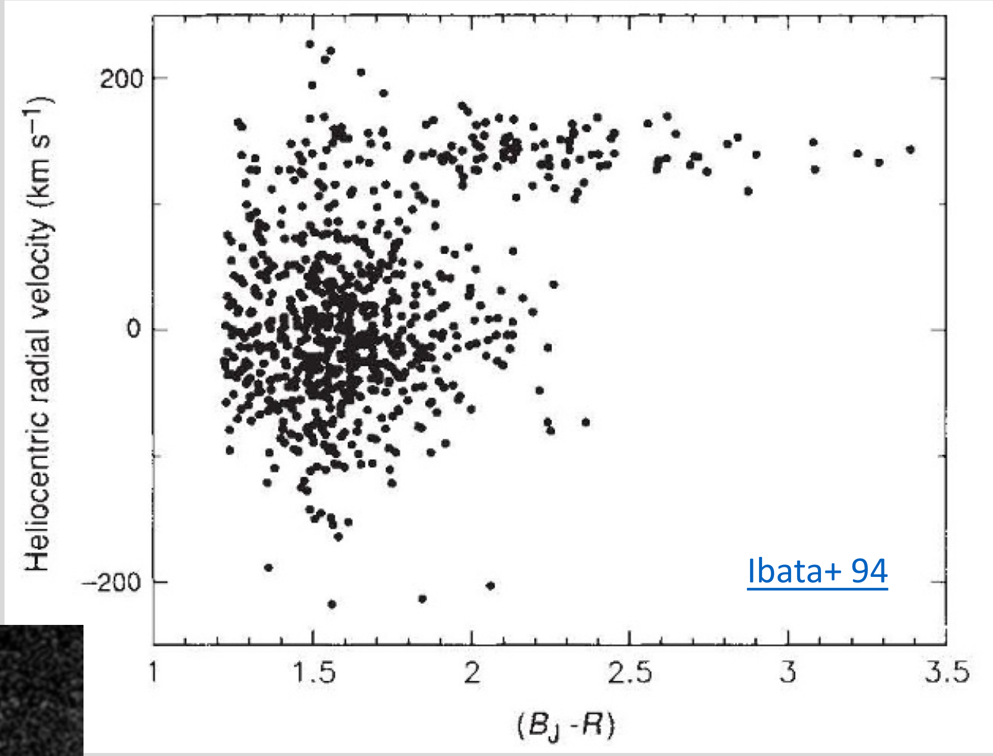
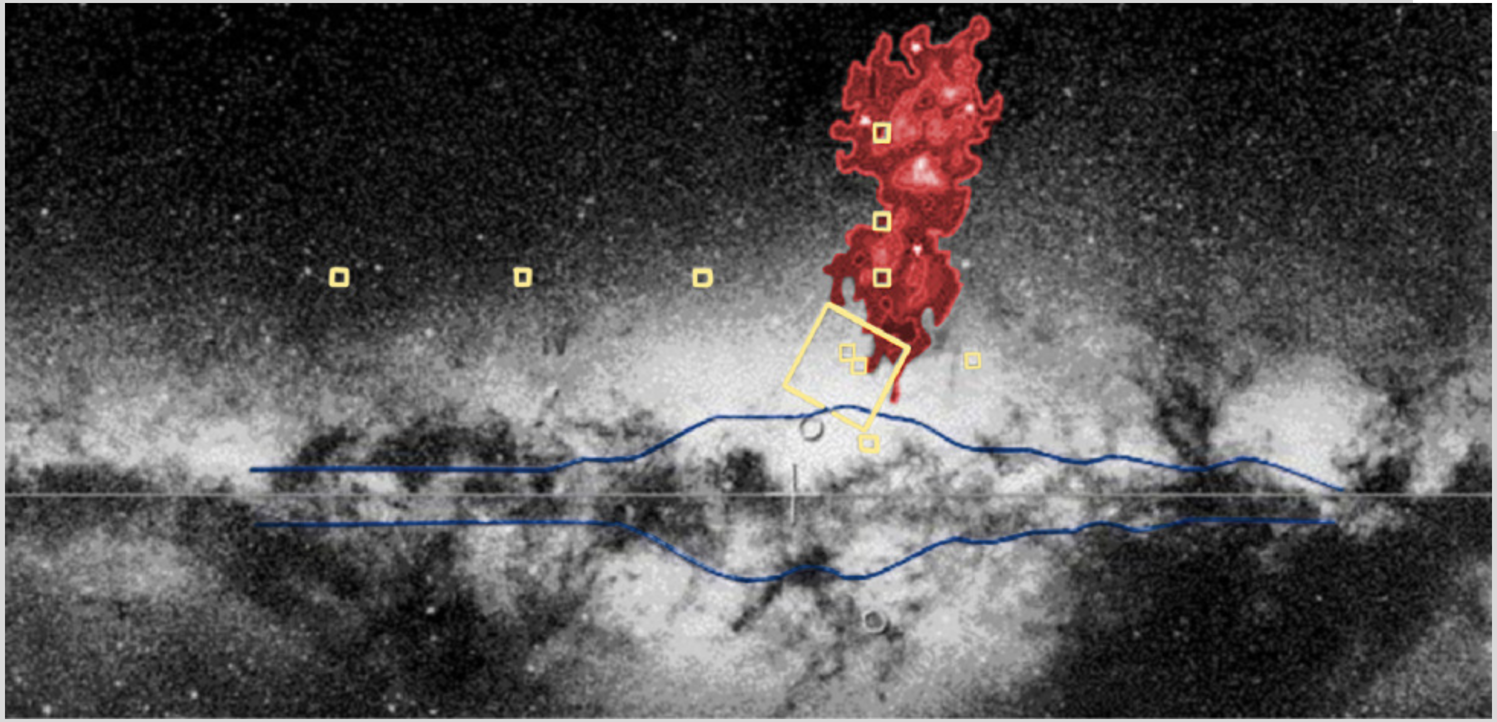


Knowing that something is there, you can look for overdensity in star counts at a given set of photometric properties (i.e. horizontal branch stars at a given distance). Trace out its shape.

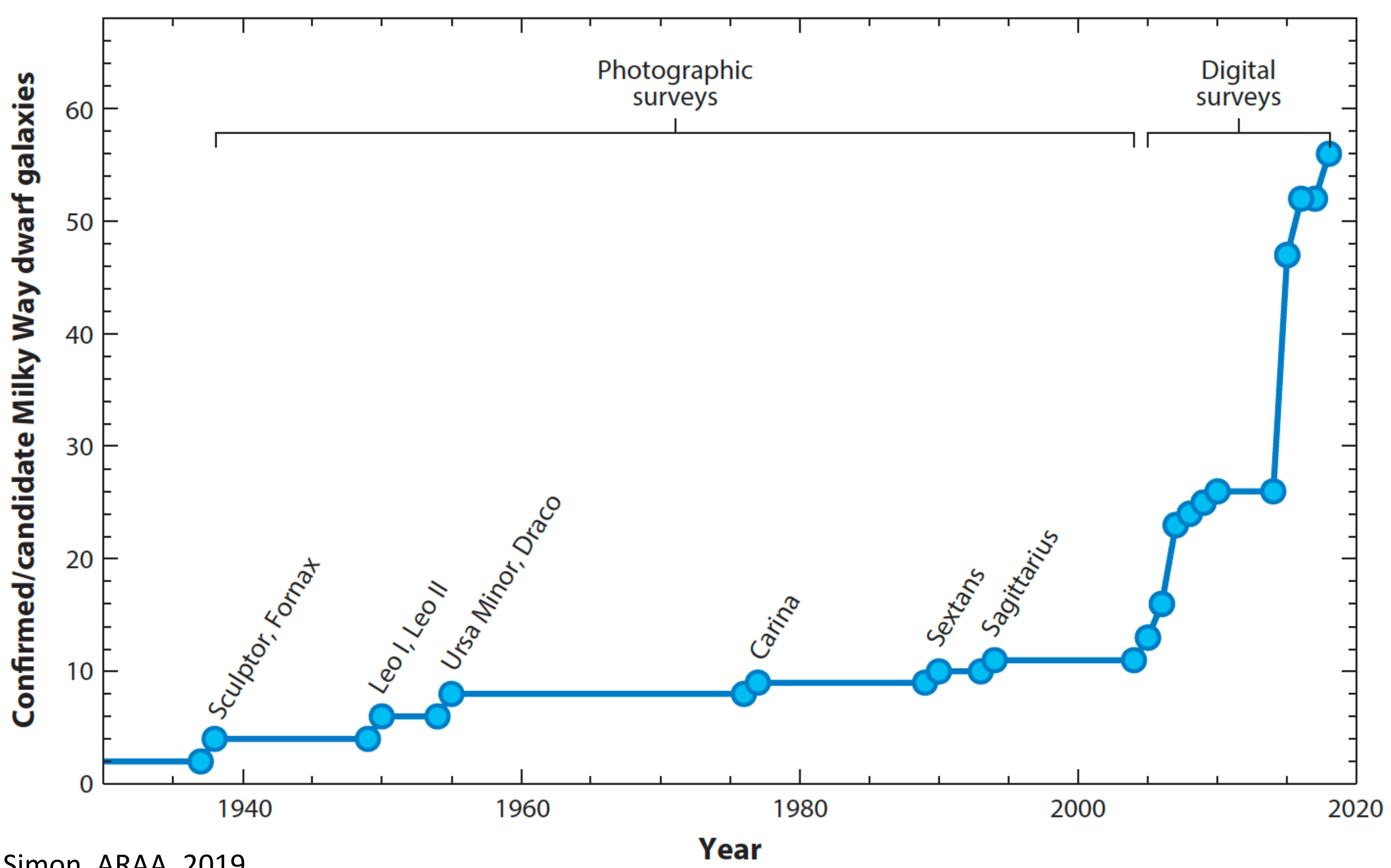


Elongated perpendicular to galactic plane, thought to be tidally disrupting on a polar orbit.

Sagittarius stars have since been traced across the sky – tidal streamers in the halo.

The New Dwarfs

Modern surveys are finding new (and very faint) Local Group dwarfs at a furious pace.



Simon, ARAA, 2019

The New Dwarfs

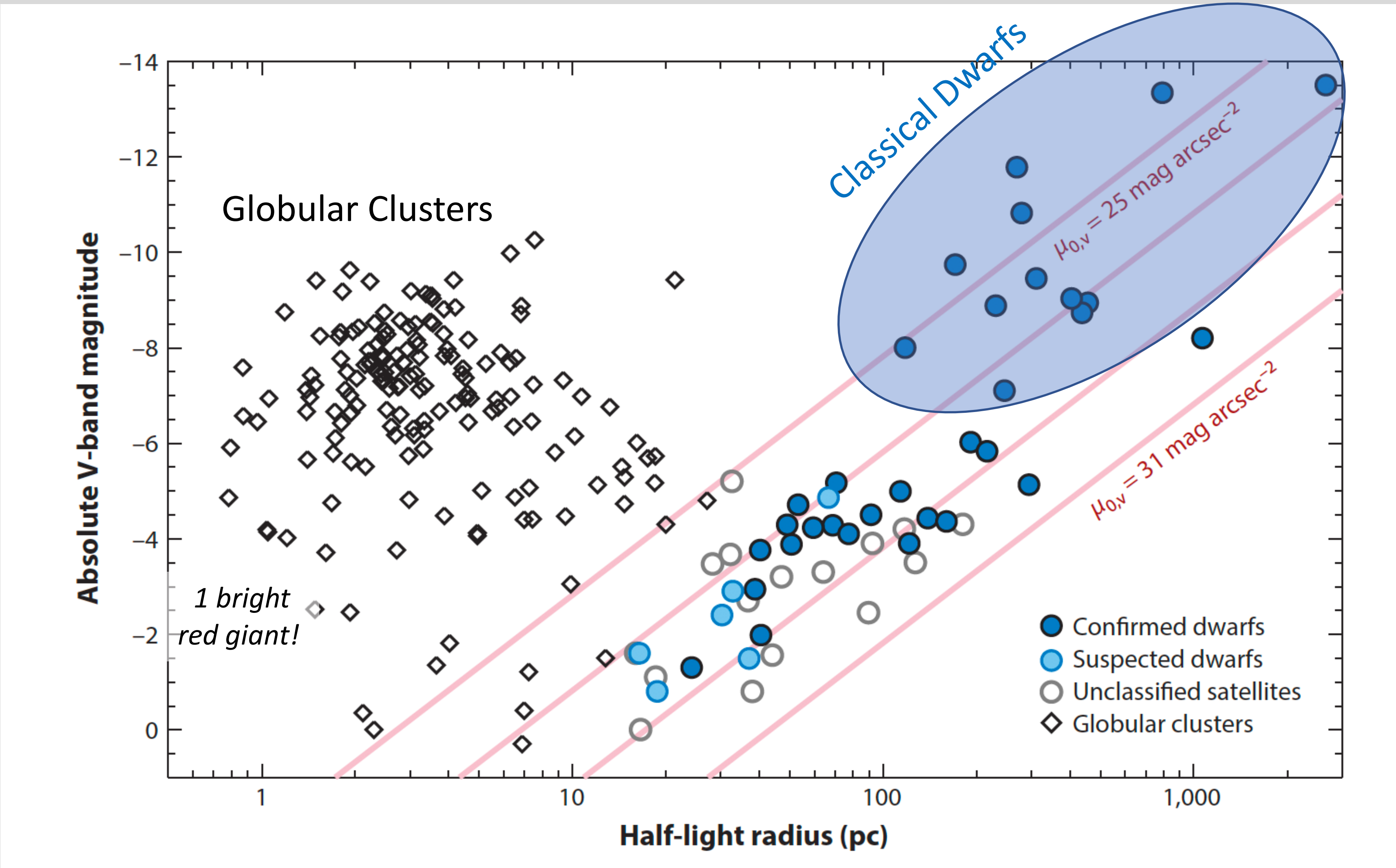
Simon, ARAA, 2019

Newly discovered dwarfs are very low in luminosity and surface brightness.

Luminosities often less than those of globular clusters!

Questions:

- what makes something a galaxy versus a star cluster?
- how well-defined is the luminosity of these extreme dwarfs?



The New Dwarfs

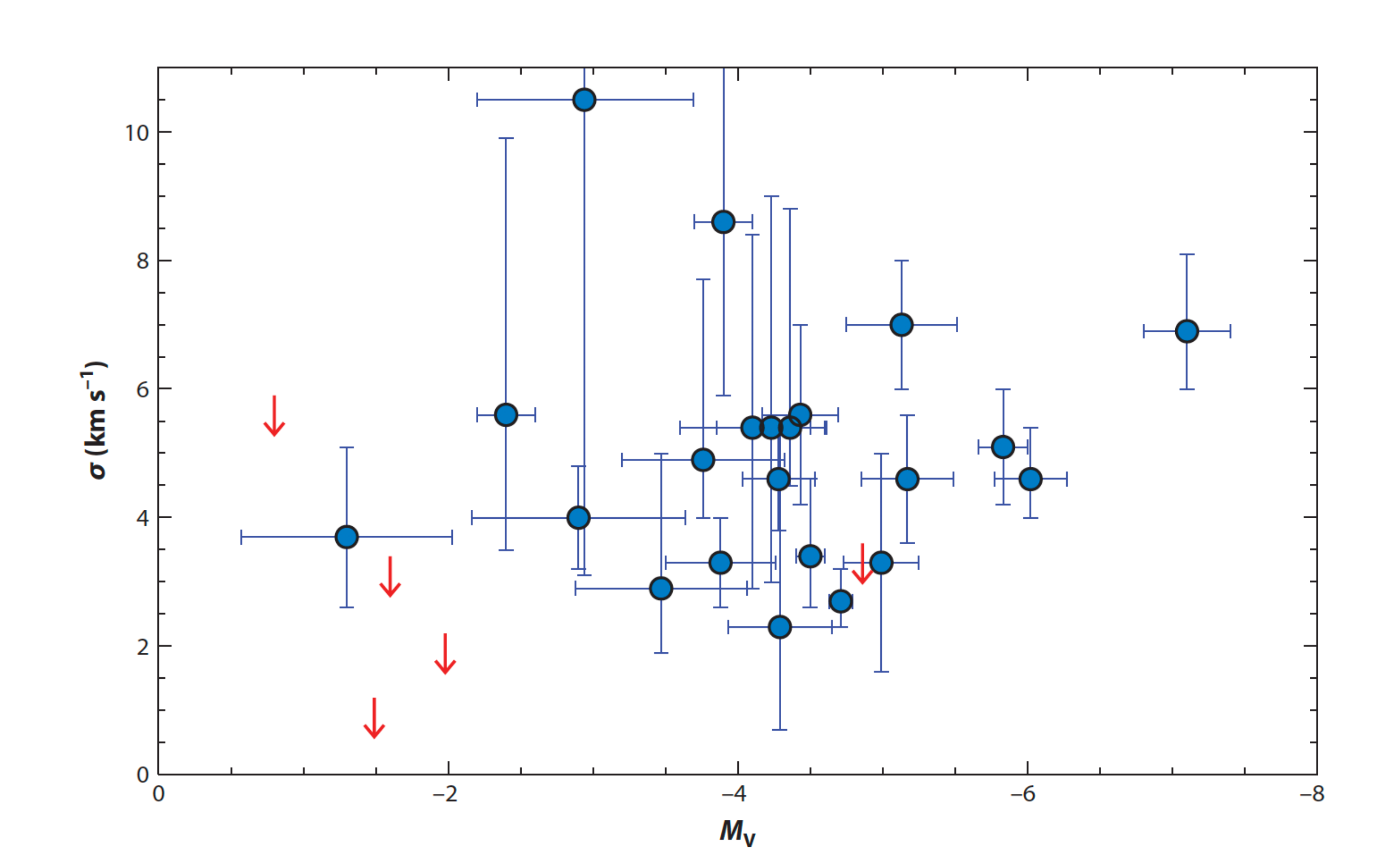
Simon, ARAA, 2019

Measure velocities of individual stars, calculate the velocity dispersion based on those stars.

(Why is this hard?)

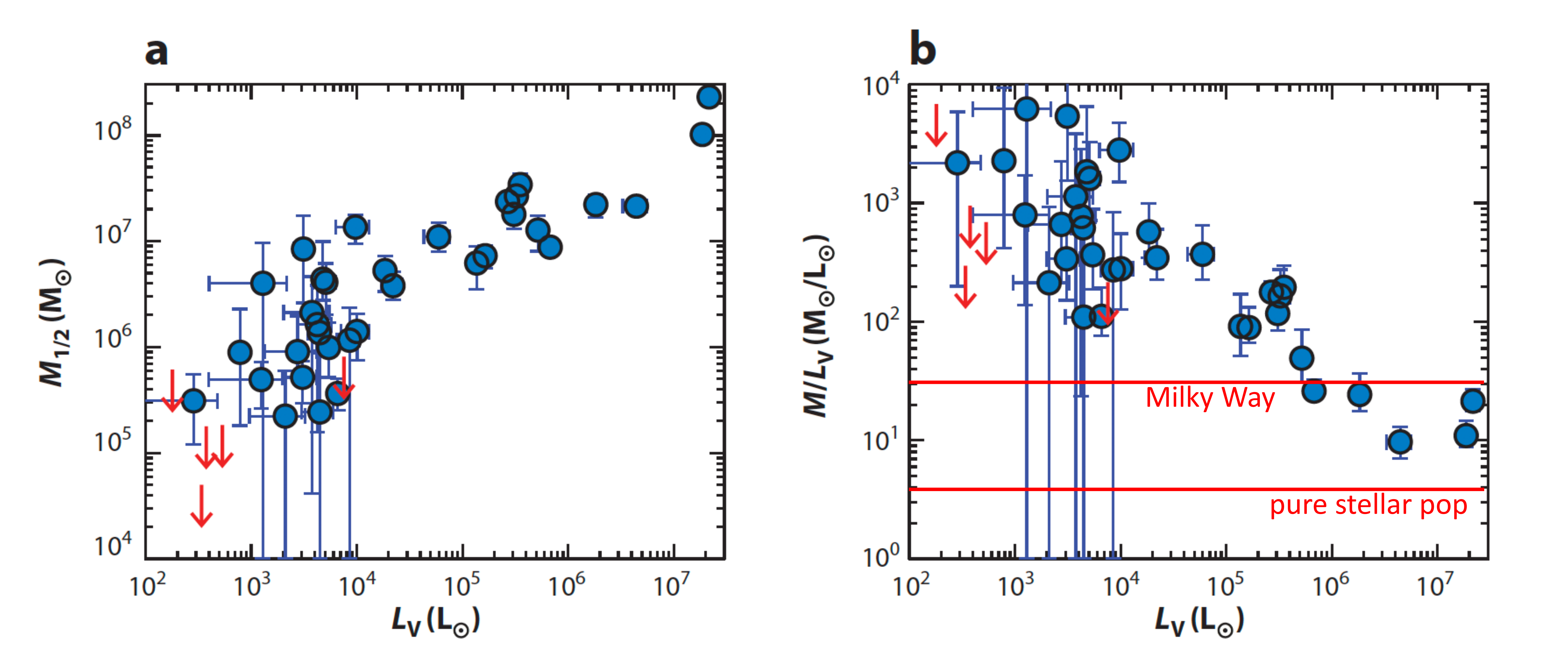
Can then estimate the mass within the half-mass radius from (Wolf+ 10)

$$M_{1/2} = 930 \left(\frac{\sigma}{km/s}\right)^2 \left(\frac{R_{1/2}}{pc}\right) M_\odot$$



The New Dwarfs

Simon, ARAA, 2019



These “ultra-faint dwarfs” have extraordinarily high mass-to-light ratios: ***dark matter dominated.***

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]

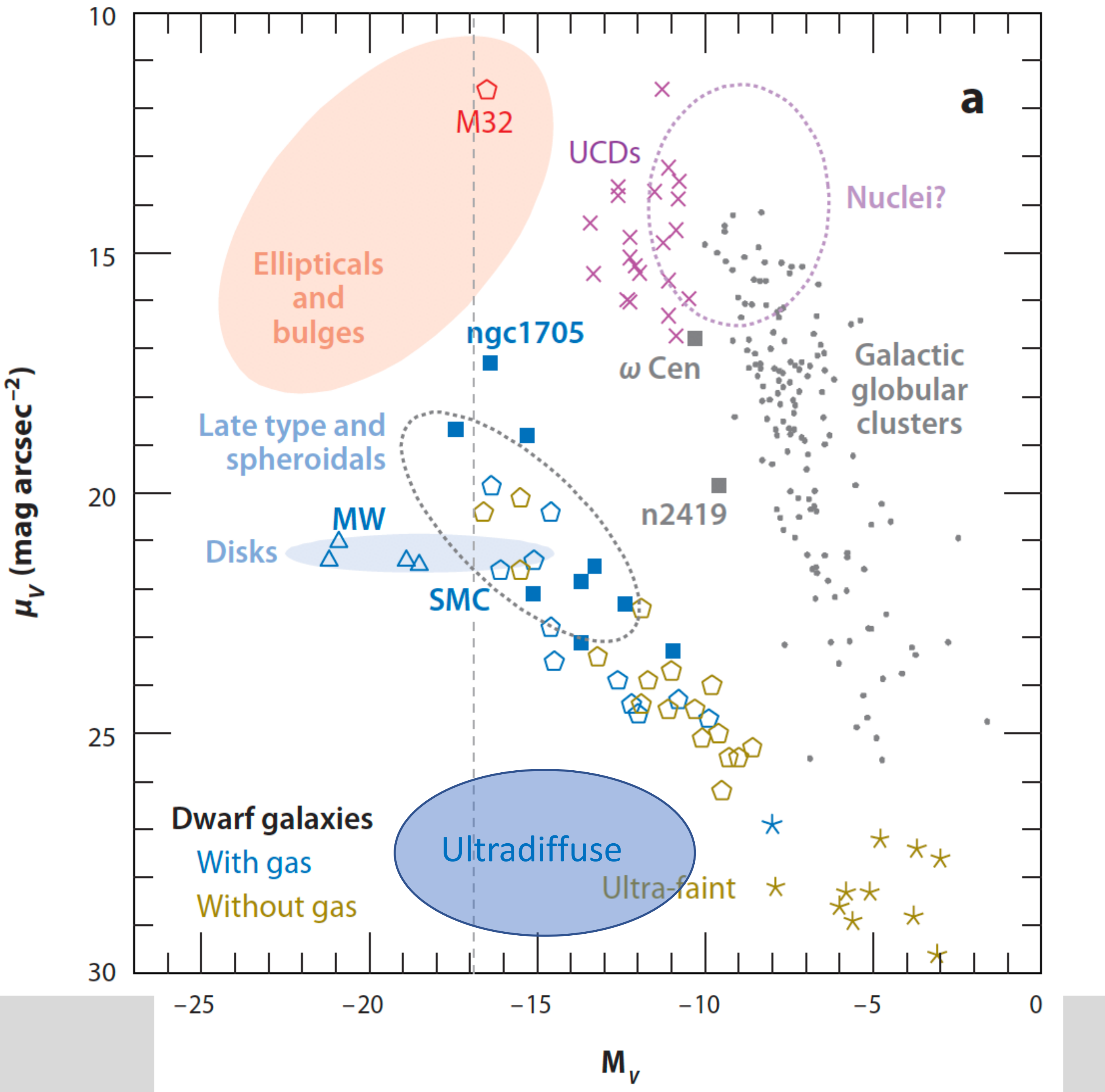


Figure 1

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

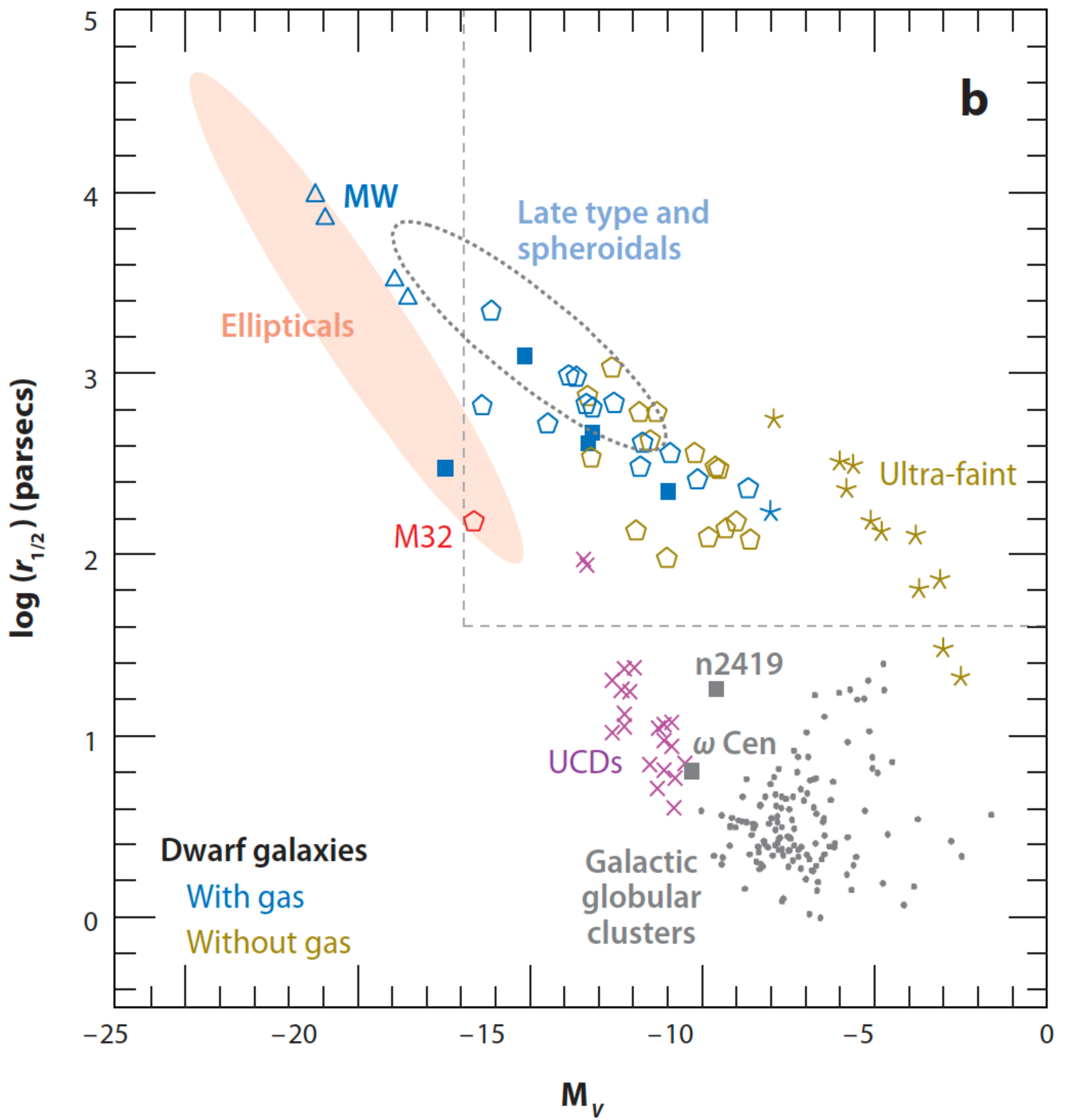
And a huge range in size, too!

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

Tolstoy+ ARAA 09

Figure 1

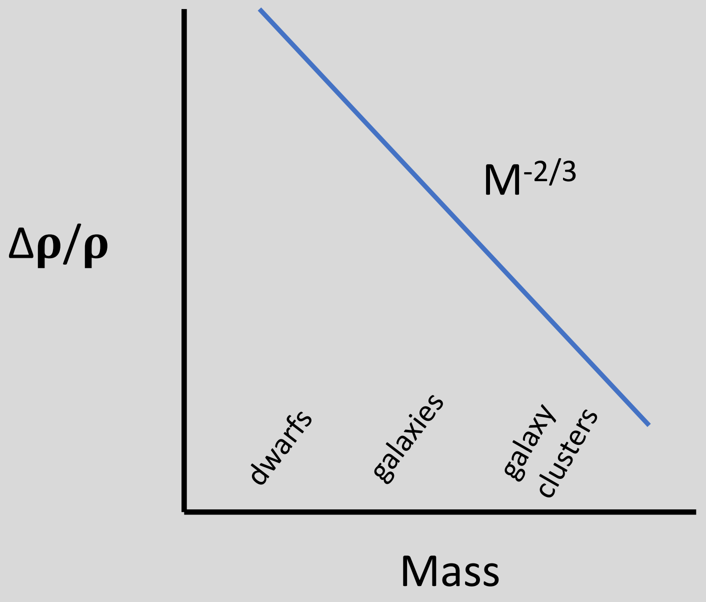
Here are plotted the relationships between structural properties for different types of galaxies (after Kormendy 1985, Binggeli 1994), including as dotted lines the classical limits of the dwarf galaxy class as defined by Tammann (1994). (*a*) The absolute magnitude, M_V, versus central surface brightness, 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.

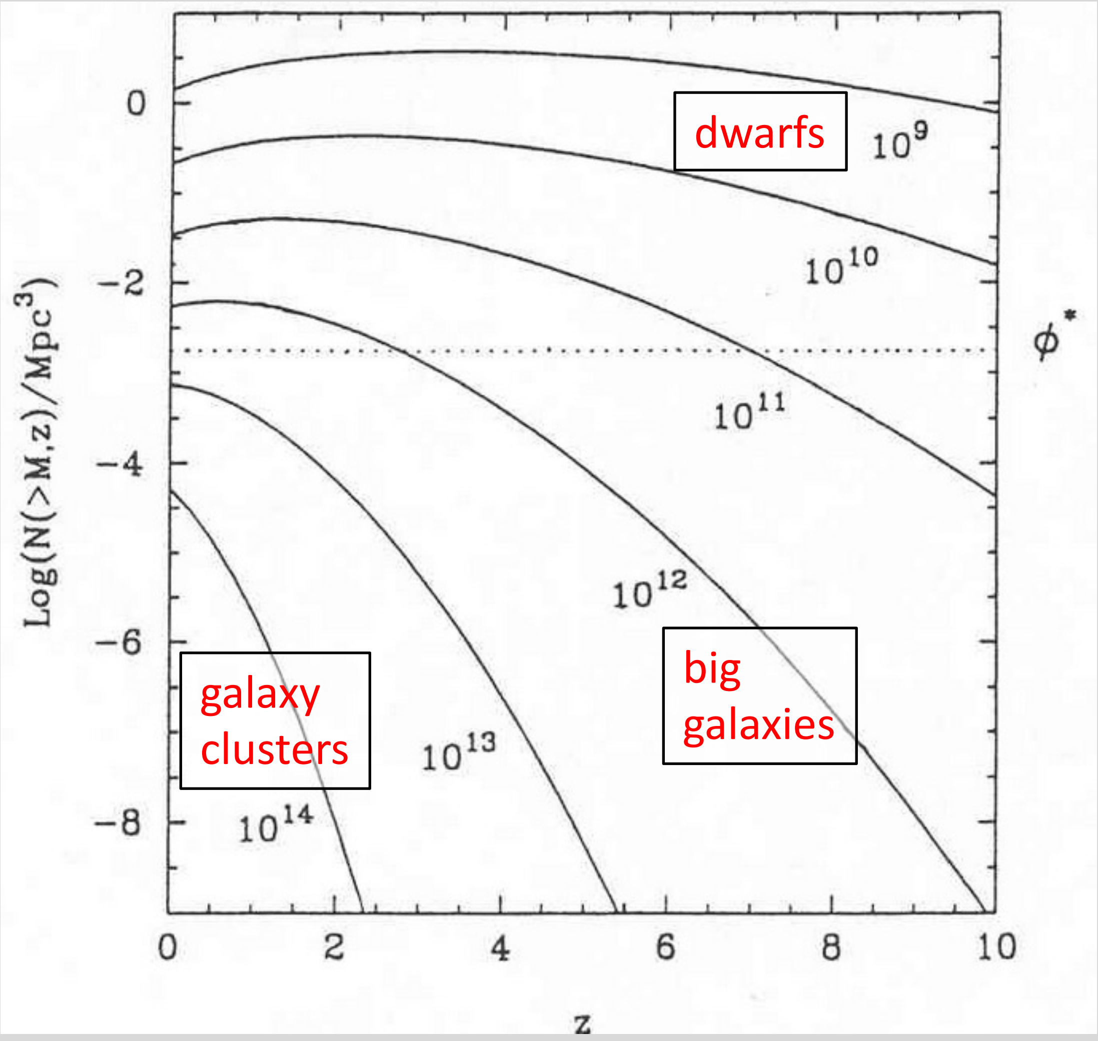
early universe density fluctuations



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

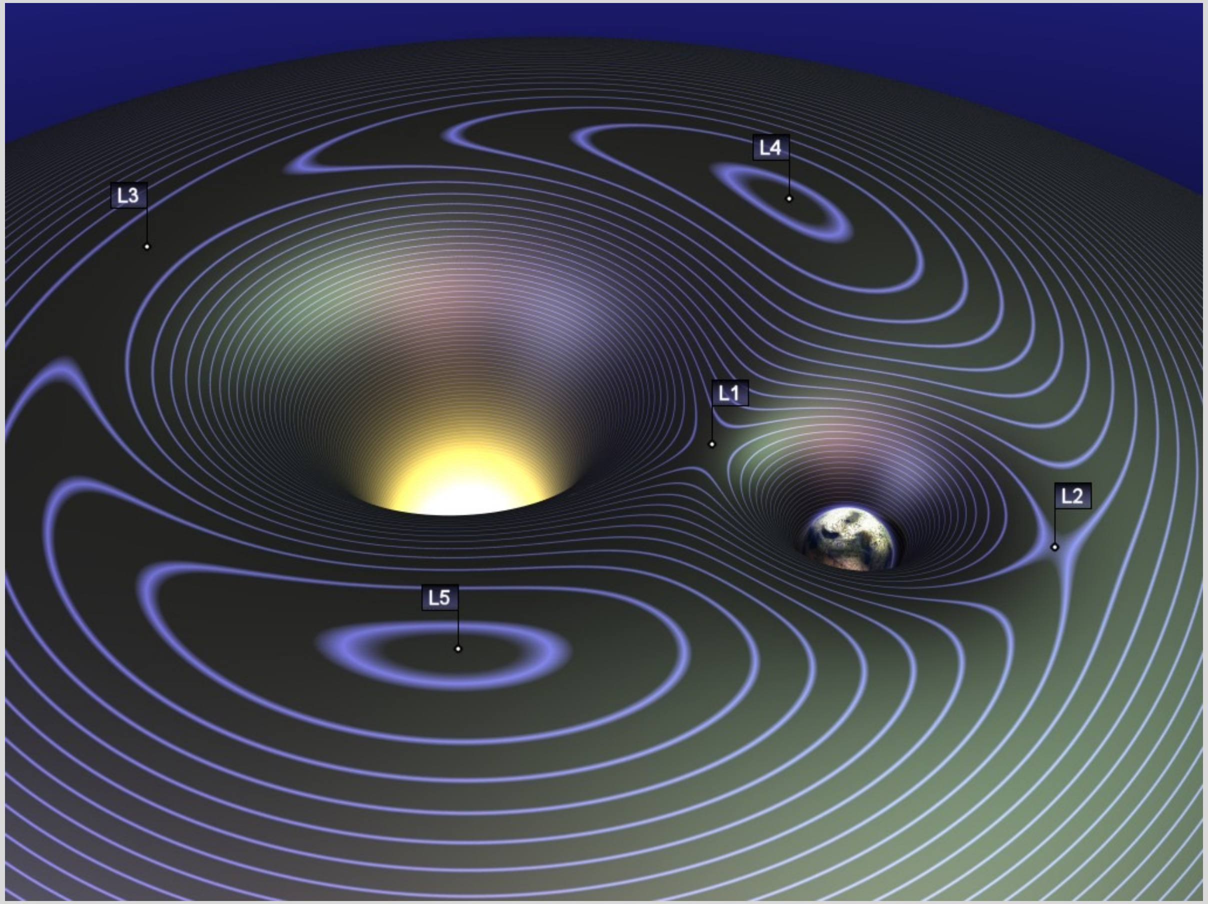
Lagrange L1/L2 points define the radius at which stars remain bound to the satellite. Beyond this, stars are tidally stripped. Also known as the "Jacobi radius" r_J:

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

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.

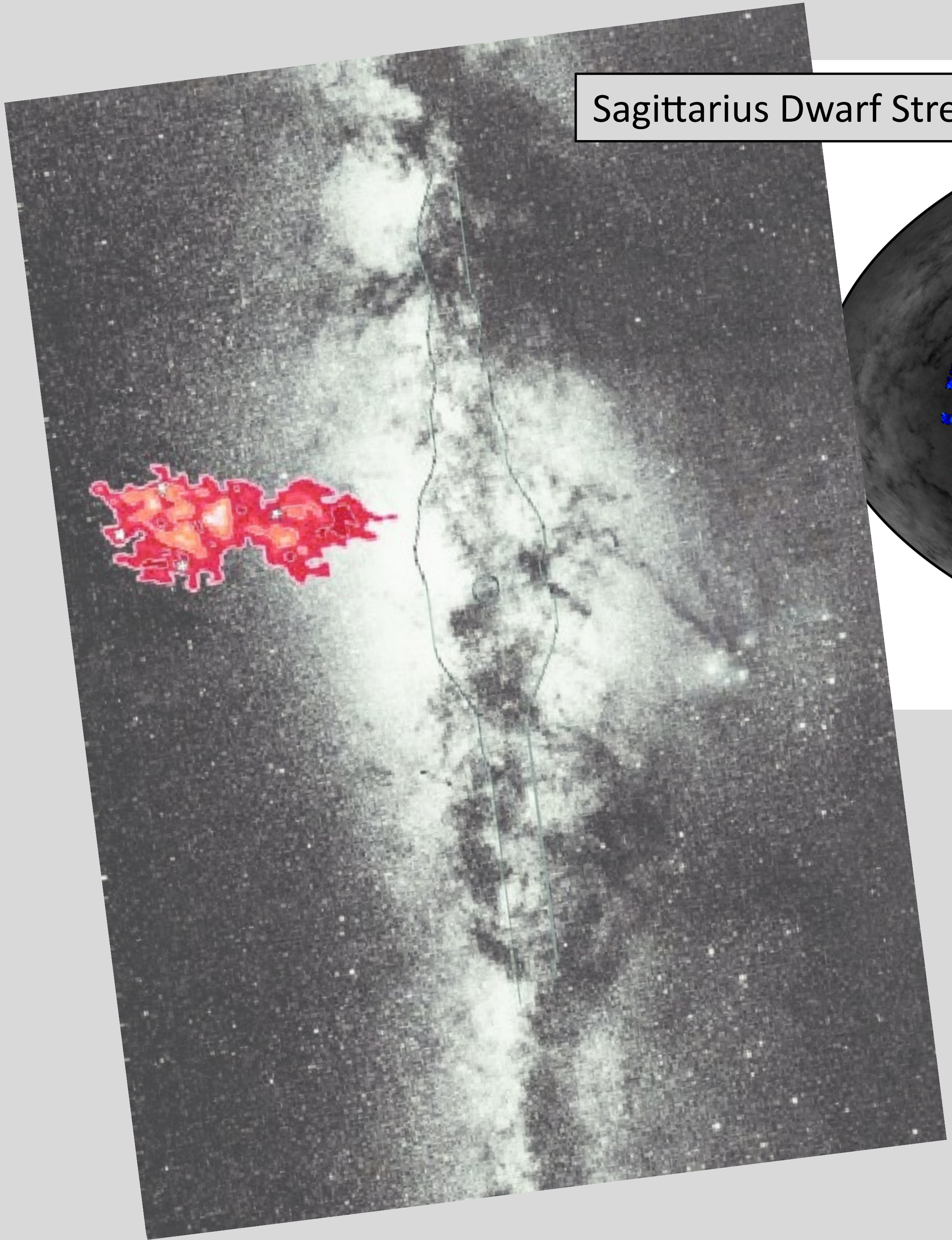
For the LMC, $D \approx 50$ kpc, $m \approx 10^{10}\ M_\odot \Rightarrow r_J \approx 10$ kpc.

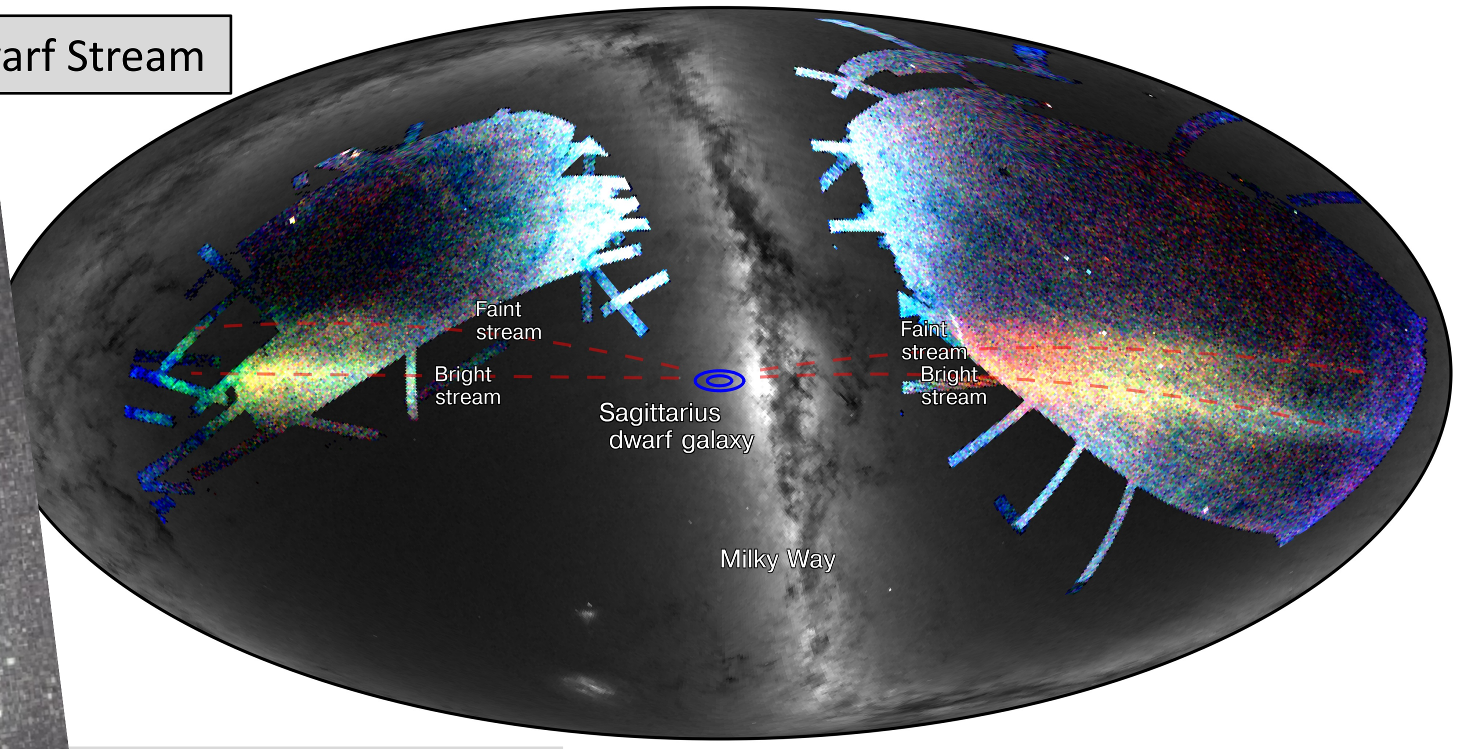
For lower mass satellites, $r_J \lesssim 2$ kpc.



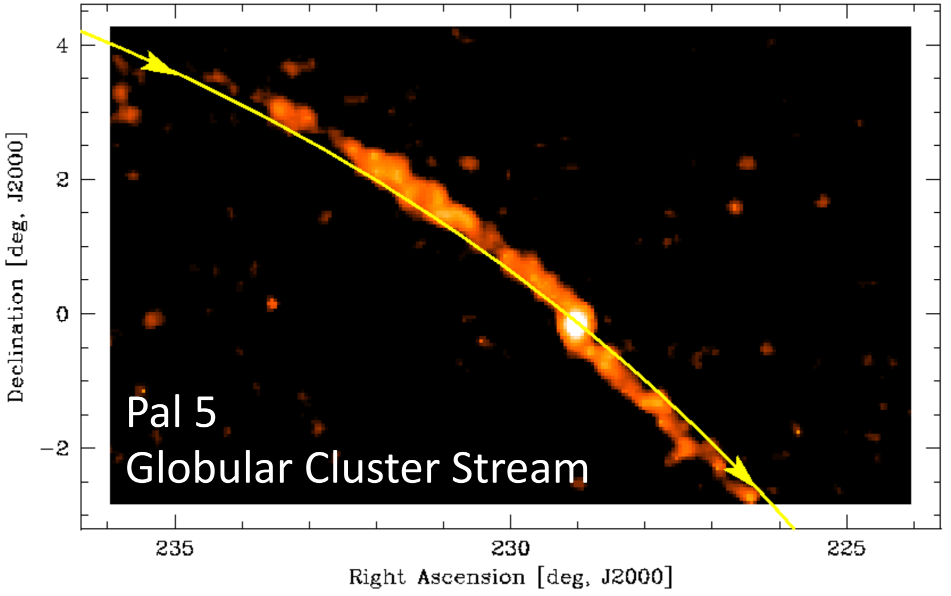
Effective potential for rotating two body system

Sagittarius Dwarf Stream

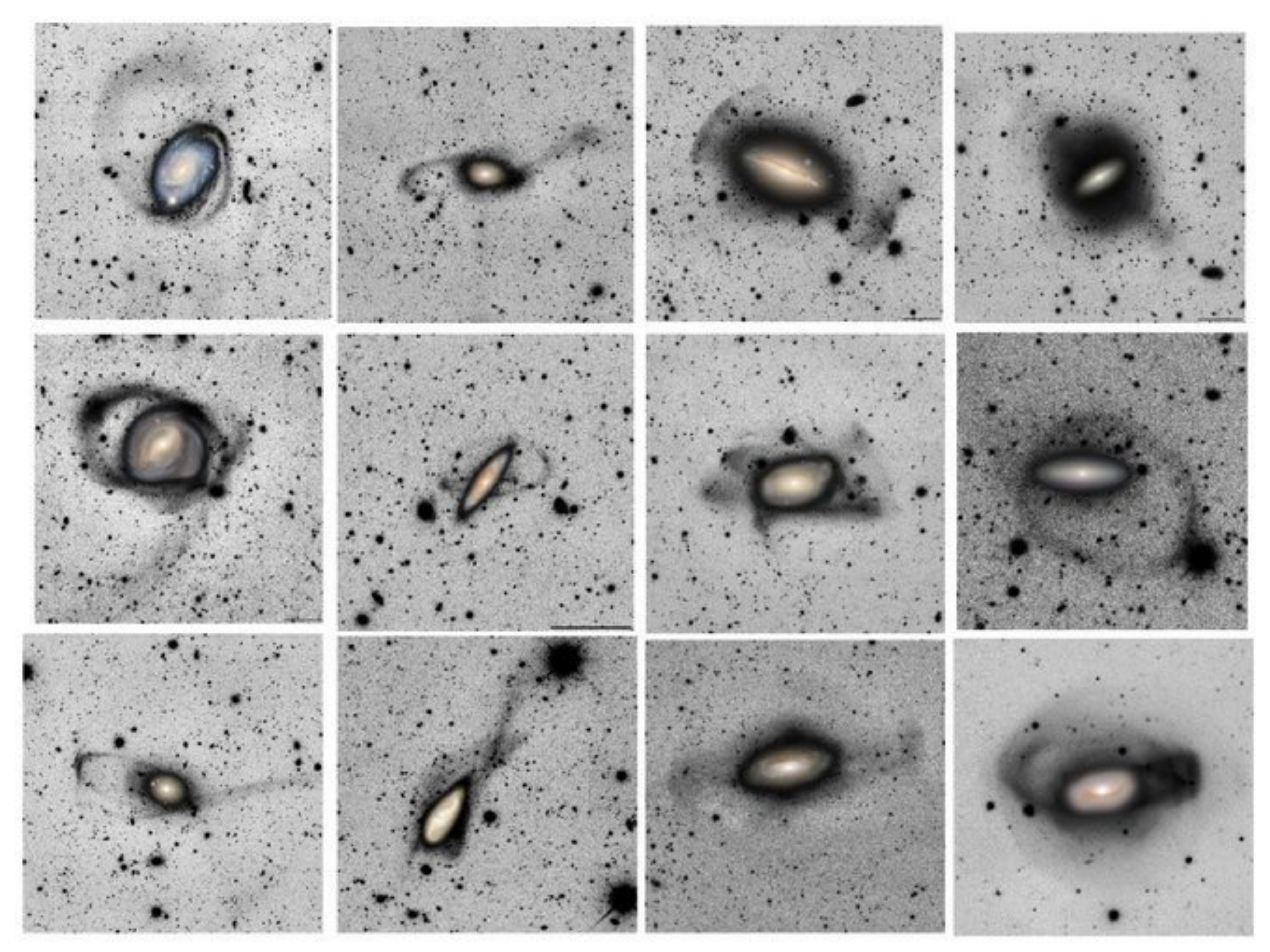




Happens to globular clusters, too!



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:

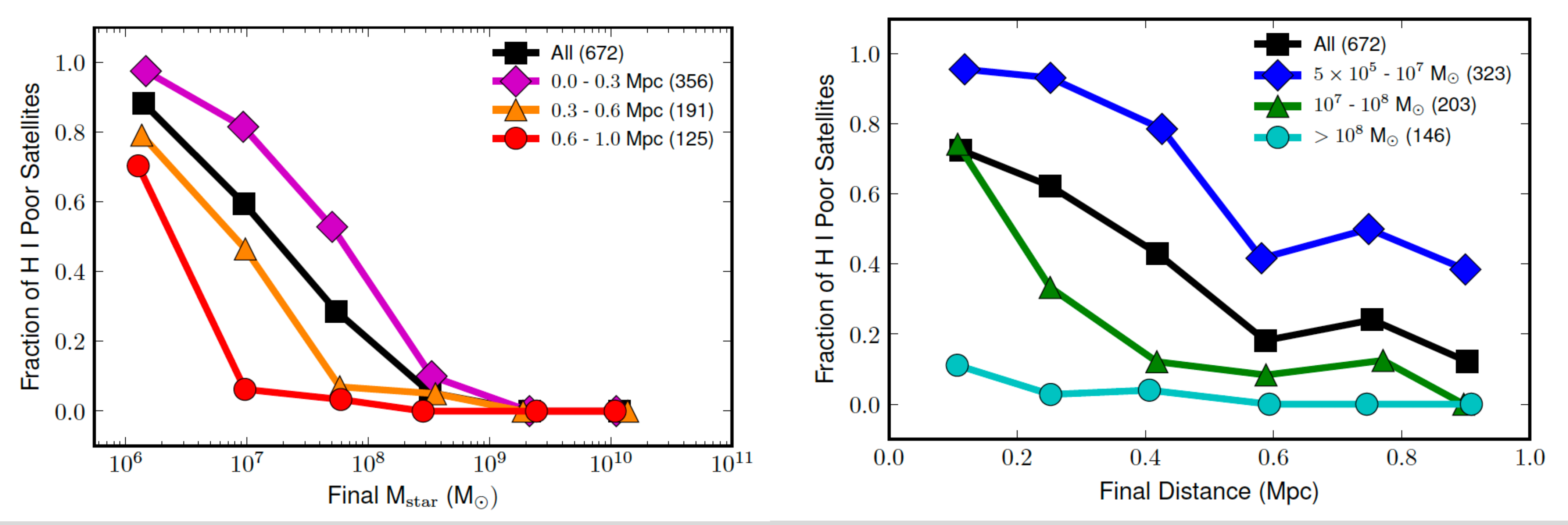
$$P_r \approx \rho v^2$$

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

Simulations ⇒ suggest stripping at work on Local Group dwarfs.

Most important at low mass and small MW distances

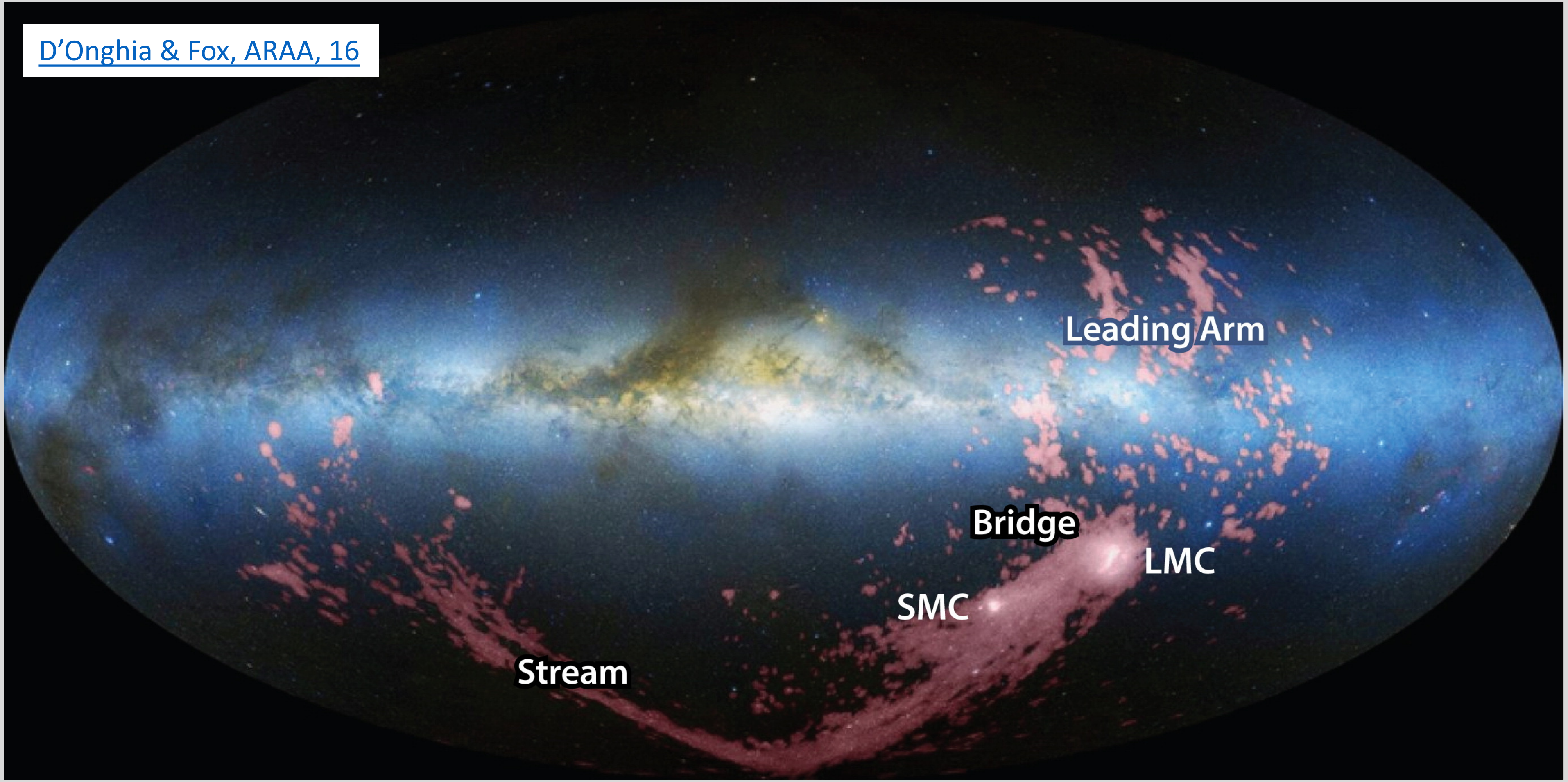
(Simpson+ 18)



The Magellenic Stream

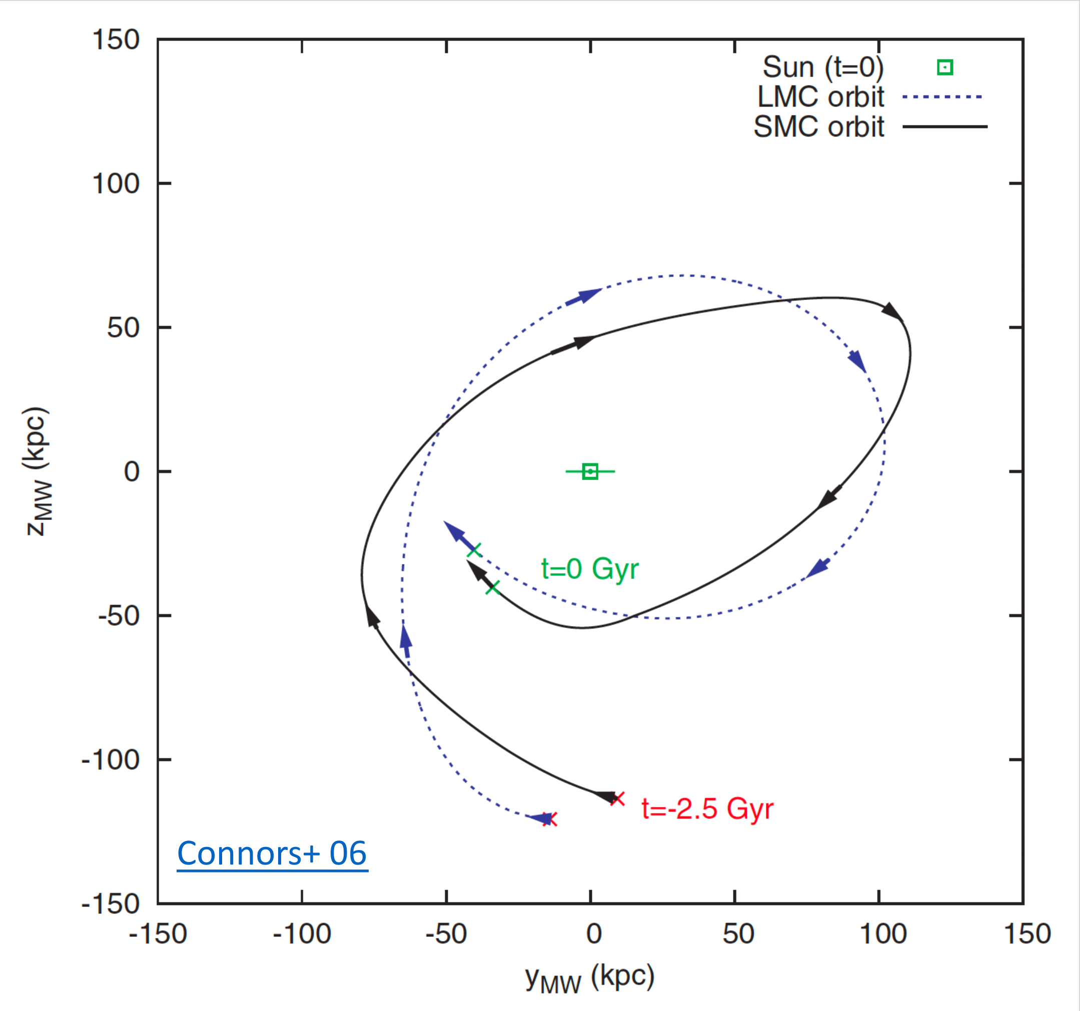
Long HI stream coming from the Magellenic Clouds, stretching across the sky.

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



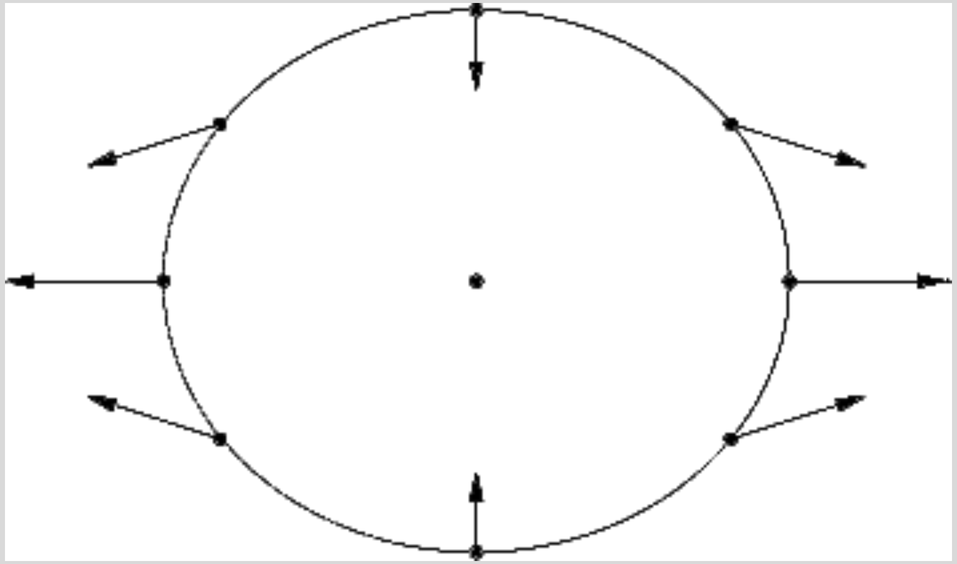
Orbital Effects

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:



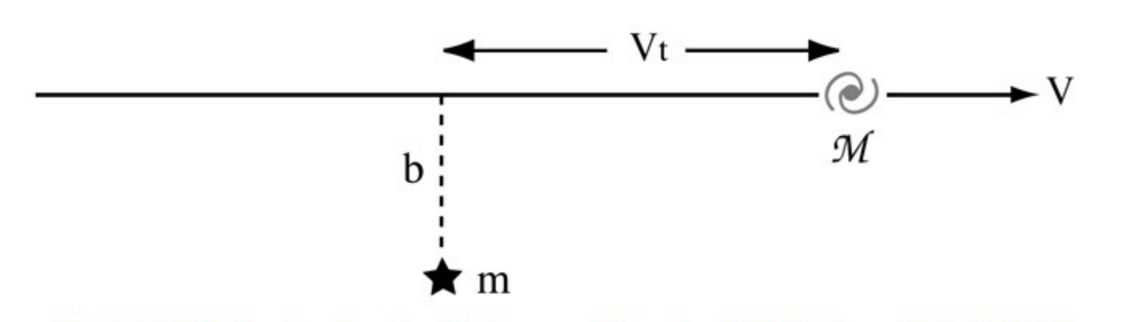
At Milky Way (MW) perigalacticon:

- *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:

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

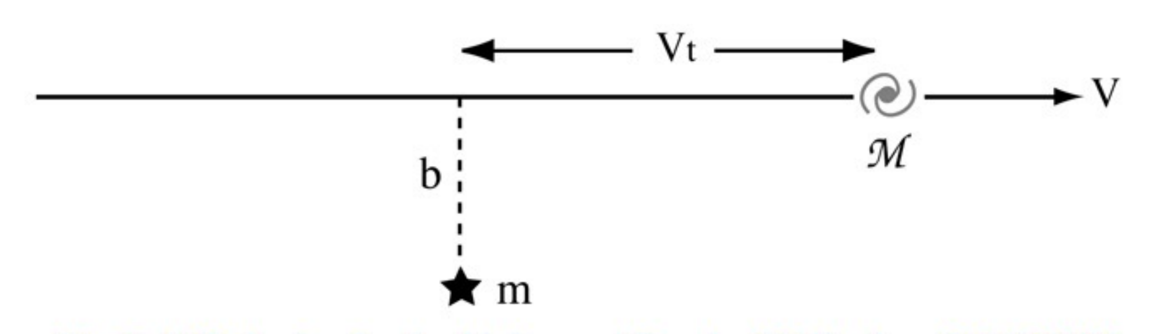
We must conserve momentum, so the star must also pick up a (much bigger!) $\Delta V_\perp$ from the satellite. This means the total change in perpendicular kinetic energy is:

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

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

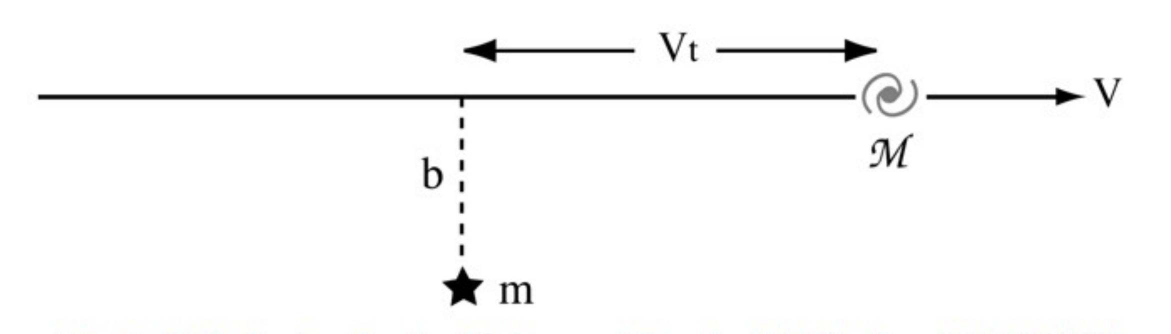
$$-\frac{dV}{dt} = \int_{b_{min}}^{b_{max}} nV\,\frac{2G^2m\,(m+M)}{b^2V^3}\,2\pi b\,db = \frac{4\pi G^2(m+M)}{V^2}\,nm\ln\Lambda$$

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



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

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

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

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

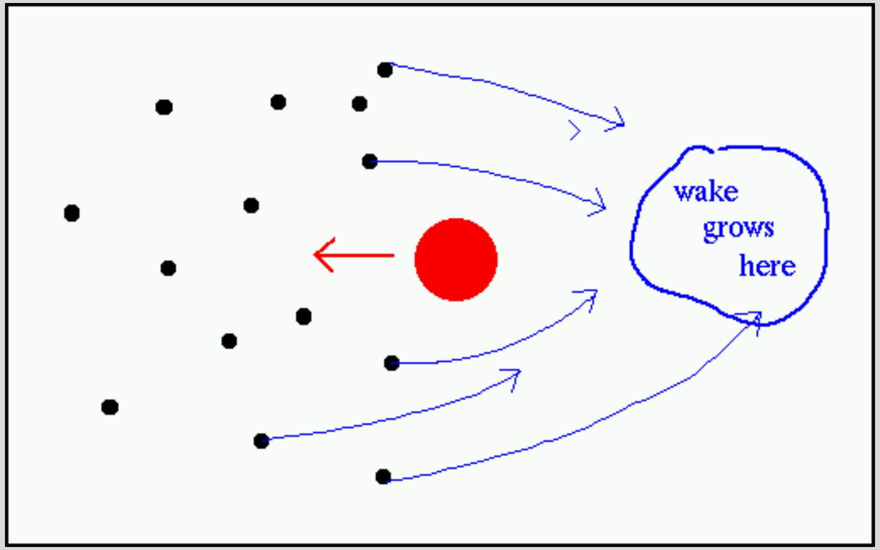
When we did it for star-star scattering, b_{min} was the close scattering radius for a star of mass m: $b_{min} \approx \frac{2Gm}{V^2} \approx 1\ AU$

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.

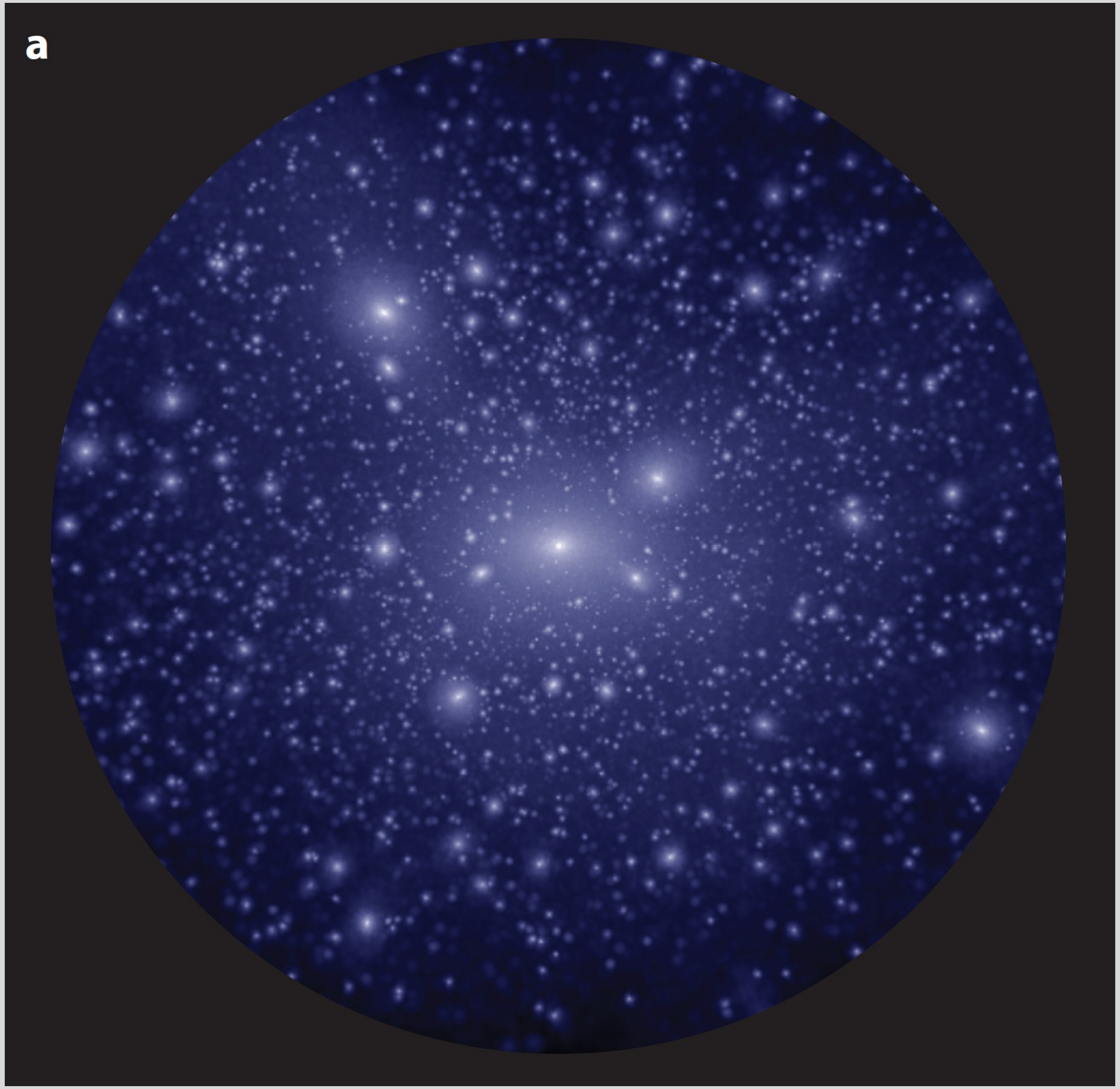
Satellite inspiral: Continual friction removes energy from satellite orbit, orbit decays and satellite spirals inward.

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

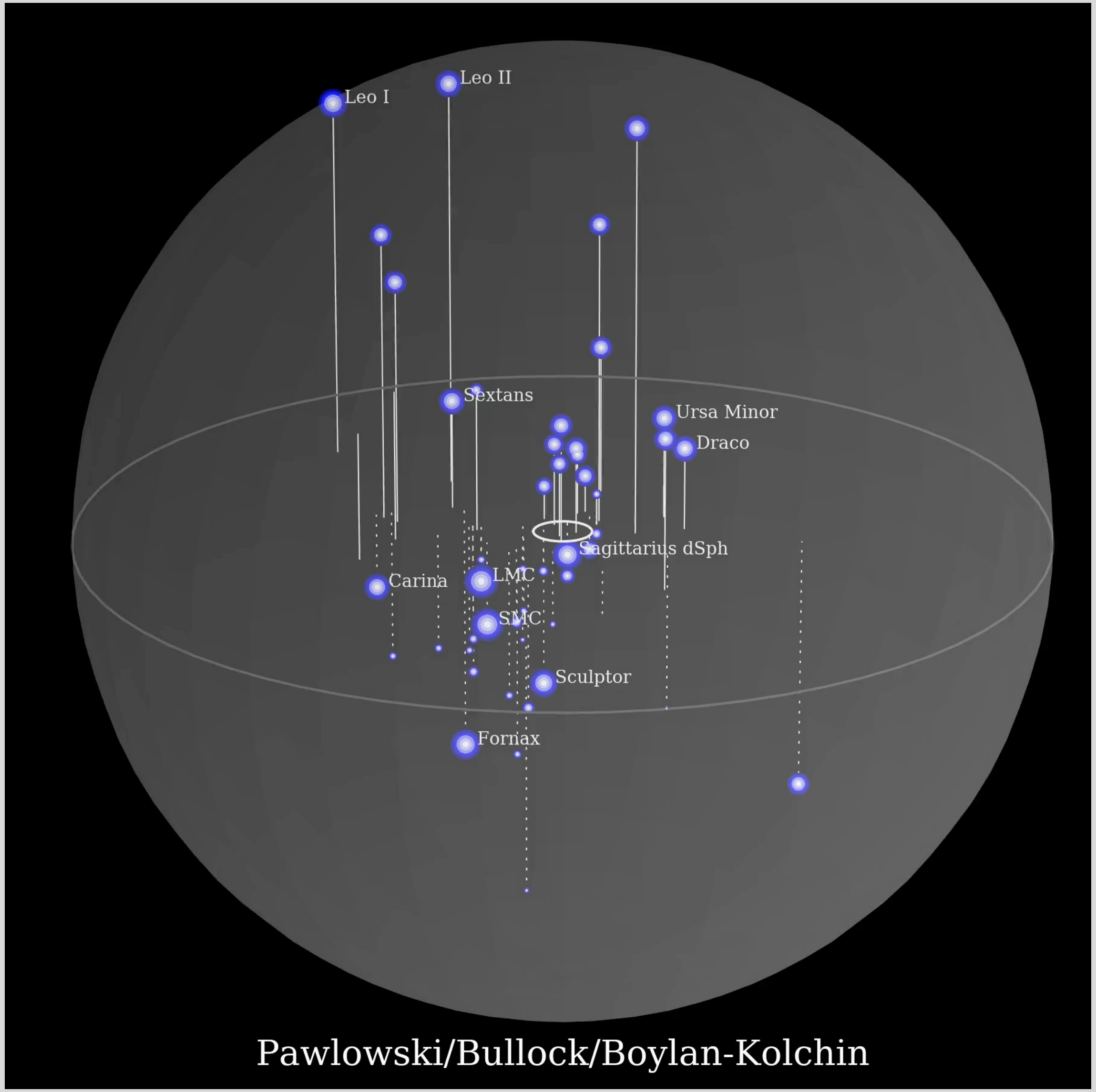
Missing Satellite Problem

[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

$$\frac{3}{2} k T_{gas} > \frac{G M_{halo}}{R}$$

gas thermal energy   potential well