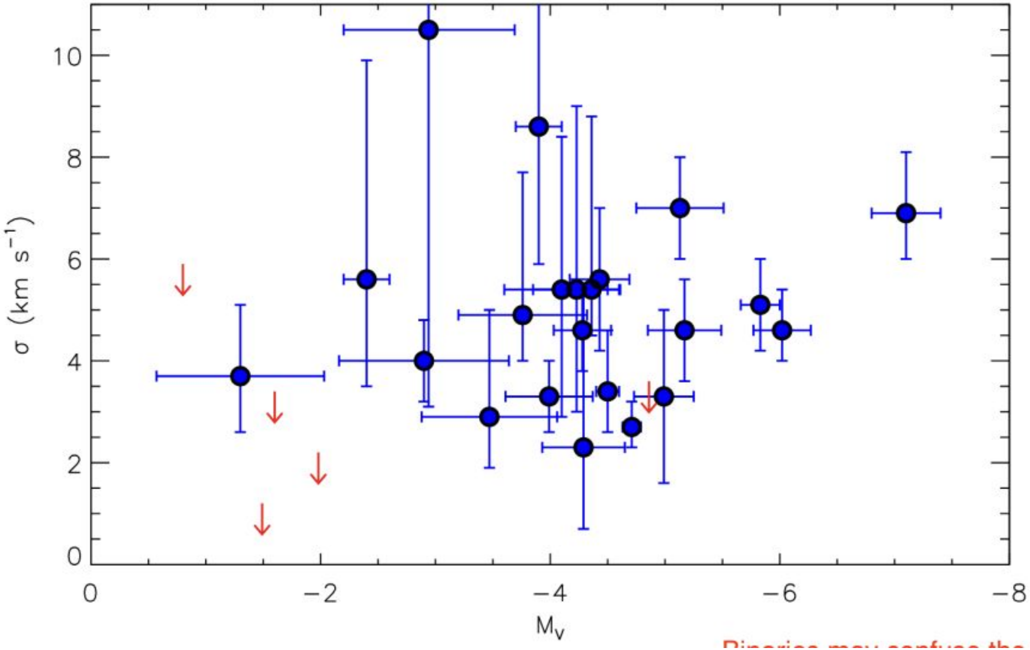
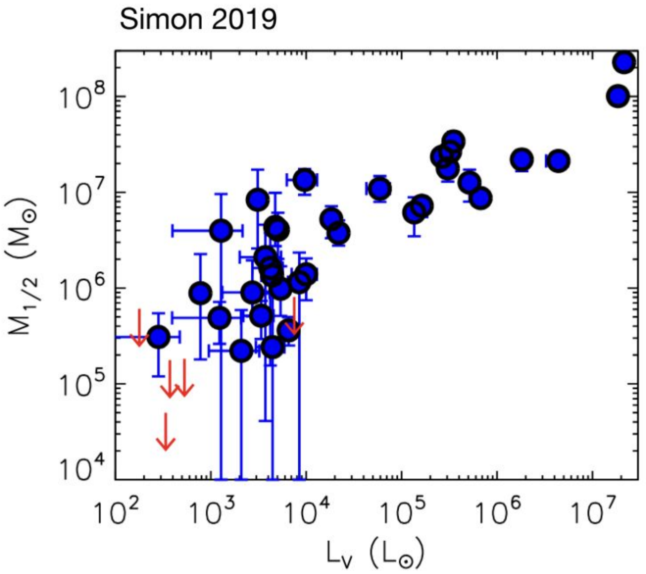
Galaxies Lec 3

The Local Group, Intro to Galaxy Formation

Dwarf Galaxies: Kinematics and Mass modeling





Mass measurements by measuring velo dispersion and absolute magnitudes. Then we can use the jeans equations to derive the half light mass.

We want to use the jeans equations to get a mass profile. The Virial Problem: A simple virial estimate can't distinguish between a high-mass galaxy with circular orbits and a low-mass galaxy with radial orbits. To break this degeneracy we need the jeans equation.

- at $r \ll R_{1/2}$, σ_{los} mostly sensitive to radial motion, need to know β to get M(r).

- at $r \gg R_{1/2}$, σ_{los} mostly sensitive to tangential motion, need to know β to get M(r).

- at $r \sim R_{1/2}$, sweet spot where β matters least.

At the half light radius, it doesnt really matter if the velocity is tangential or radial when we measure the V_los. And because this is broken we can obtain a measurement of the dynamical mass.

We apply Jeans-based modeling to almost every "dispersion-supported" system (systems where objects move in random directions rather than a flat disk).

$$\frac{d}{dr}\left(n_\star \sigma_{rr}^2\right) + 2\beta \frac{n_\star \sigma_{rr}^2}{r} = -n_\star \frac{d\Phi}{dr}.$$

where β is the velocity anisotropy parameter

$$\beta(r) \equiv 1 - \frac{\sigma_{\theta\theta}^2 + \sigma_{\phi\phi}^2}{2\sigma_{rr}^2} = 1 - \frac{\sigma_t^2}{\sigma_{rr}^2}.$$

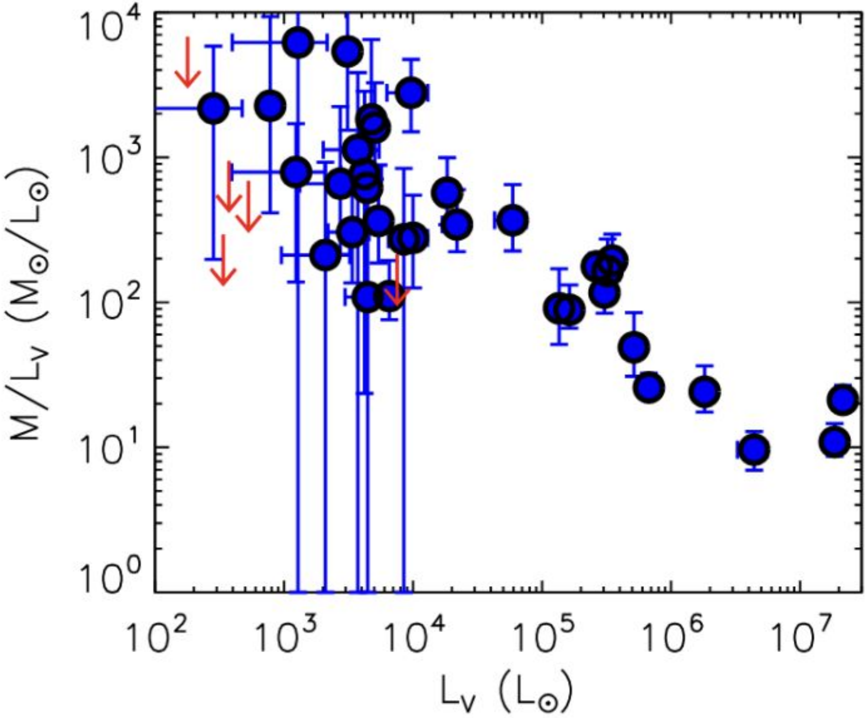
This degeneracy is broken by the anisotropy parameter. Which gives a dynamical mass measurement.

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

This allows dynamical masses to be computed, constraining mass within $r_{1/2}$ — not a total dark matter mass!

→this correction can be >10x for dwarf spheroidals.

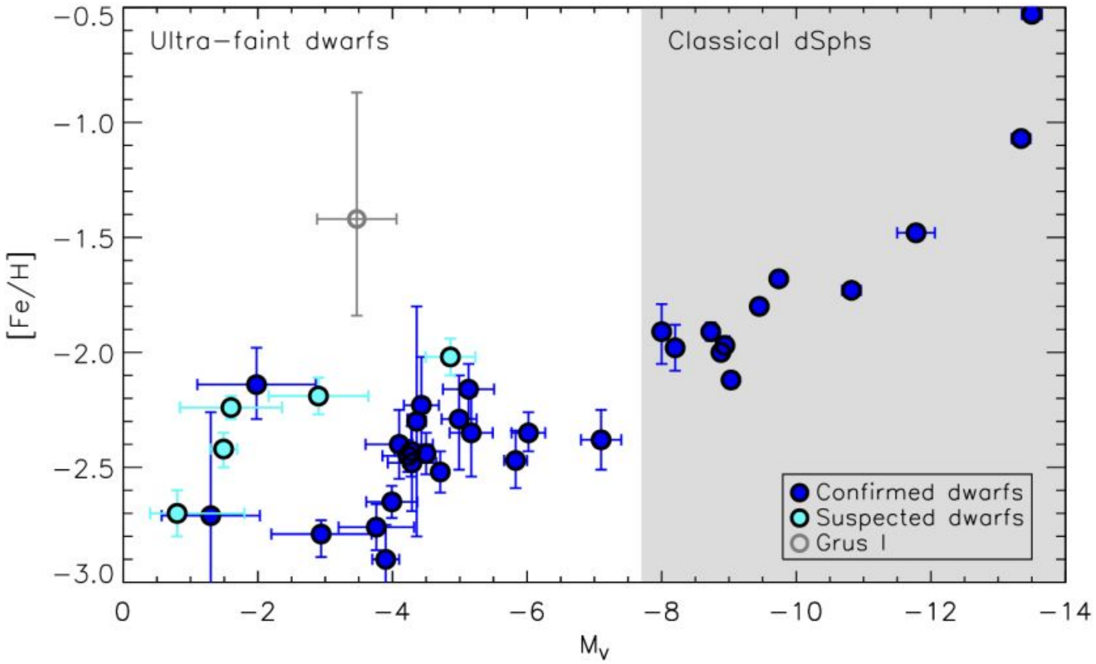
Simon 2019



We can get the mass to light ratio and see that it must be heavy mass dominated. With little light meaning it is likely to be dark matter dominated.

Dwarf Galaxies: Chemical Evolution

Simon 2019



When we look at the metallicities we see that there is a dependence between the luminosity and metallicities. The faint ones are metal poor.

Closed box model:

Assumptions:

system of stars+gas, no mass flow in/out of system.

- matter initially gaseous and free of heavy elements.
- as time increases, stars form and return metals to ISM.
- turbulent motions keep gas well-stirred and homogenous.
- ISM gradually locked in stars (+stellar remnants), remaining gas becomes polluted.

Metallicity $Z = M_h / M_g$

$$\delta M_h = p\,\delta M_s - Z\,\delta M_s = (p - Z)\,\delta M_s$$

p: yield of stars (units of metallicity)

$p\delta M_s$: mass of heavy elements produced from SFR

$Z\delta M_s$: metals taken away from ISM to form stars

Apply product rule/quotient rule:

- As stars form, the metallicity changes

Recall $Z=M_h/M_g$

$$\delta Z = \delta\left(\frac{M_h}{M_g}\right) = \frac{\delta M_h}{M_g} - \frac{M_h}{M_g^2}\delta M_g$$

- So we can write the following

$$\delta Z = \frac{1}{M_g}\left(\delta M_h - Z\,\delta M_g\right)$$

- And plugging in our earlier equation for δM_h, we have

$$\delta Z = \frac{1}{M_g}\left[(Z-p)\,\delta M_g - Z\,\delta M_g\right]$$

where we set $\delta M_s = -\delta M_g$

- We can now cancel terms and solve for an equation for the metallicity evolution of the stellar population

$$\delta Z = -\,p\frac{\delta M_g}{M_g} \longrightarrow Z(t) = -p \ln\left[\frac{M_g(t)}{M_g(0)}\right] = p \ln\left[\frac{M_g(0)}{M_g(t)}\right]$$

$M_g(t)+M_s(t)/M_g(t)$ = 1/gas fraction

This may help explain why dwarf irregulars (with higher gas fractions than MW) have lower metallicities.

Does not help explain why the dwarf spheroidals have **low** metallicities! Dwarf spheroidals have no gas, so if they formed their metals as a closed box, we should expect much **larger** metallicities.

Leaky box model.

In Class Exercise — The Leaky Box Model

- Here we consider whether a leaky box model can better explain the dwarf galaxy metallicities.

- We allow a fraction of metals to escape via outflows, as might be expected given the weaker gravitational potential of dwarf galaxies. The outflow rate scales as a factor η times the star formation rate.

$$\delta M_{out} = \eta \, \delta M_s$$

η = mass loading factor

- Following the methodology for the closed box model, **derive an equation for Z(t) in the leaky boxy model.**

- Hint 1:

$$\underbrace{\delta M_g}_{\text{gas taken from ISM}} = - \underbrace{\delta M_s}_{\text{some forms stars}} - \underbrace{\delta M_{out}}_{\text{some removed as outflows}} = -\delta M_s (1+\eta)$$

- **Next step:** write an equation for δMh in terms of δMs (adding term for metals removed from system!), then write+solve an equation for δZ

Solution to the leaky Box model

Str dyg.   Strs form.   outflow

$$dm_h = p\,dm_s - z\,dm_s - z\,dm_{out}$$

$$= p\,dm_s - z\,dm_s - z\,(N)\,dm_s$$

$$dm_h = p\,dm_s - z(1-N)\,dm_s$$

$$\boxed{dm_h = (p - z(1+N))\,dm_s}$$

$$z = \frac{m_h}{m_g} \Rightarrow \boxed{m_h = z\,m_g} \qquad dm_s = \frac{dm_g}{1+N}$$

$$dm_h = dz\,m_g + z\,dm_g$$

$$\left(\frac{p - z(1+N)}{(1+N)}\right)dm_g = dz\,m_g + z\,dm_g$$

$$\left(\frac{(p - z(1+N)) - z(1+N)}{(1+N)}\right)dm_g = dz\,m_g$$

$$\left(\frac{p}{1+N}\right)dm_g = dz\,m_g$$

$$\boxed{\frac{p}{1+N}\ln(m_g) = z}$$

Dwarf Galaxies: Star Formation and populations

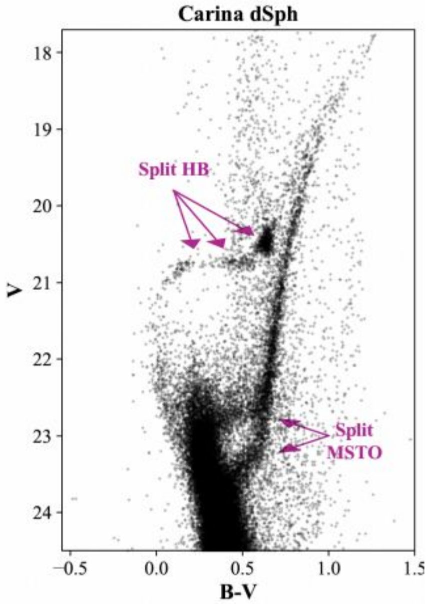
Theory:

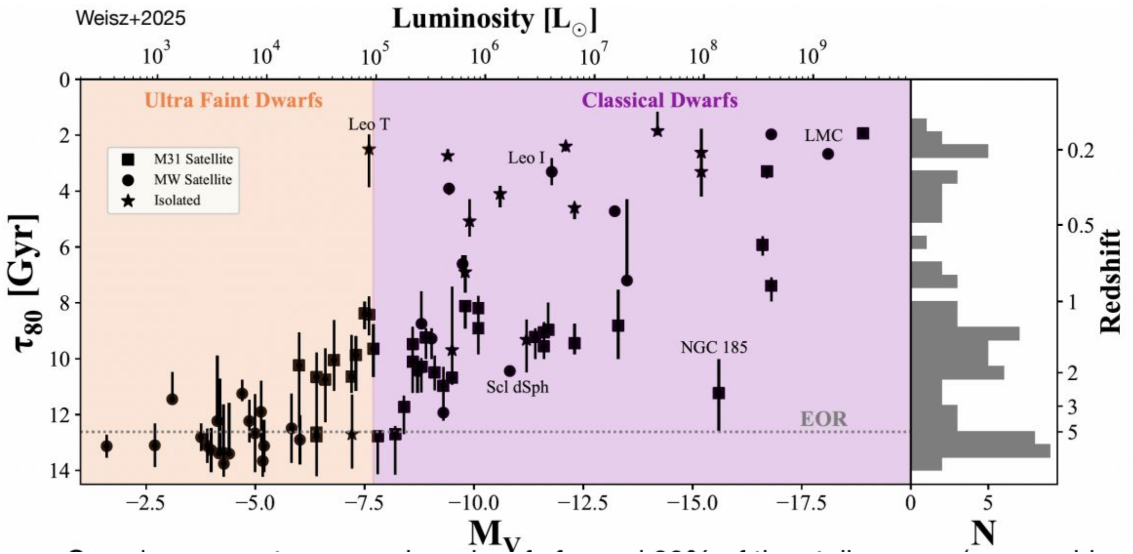
Reionization heats gas, raising thermal pressure of intergalactic medium. This says that gas accretion halted for halos < 10^9 M_solar. This means that all the dwarfs should stop gaining gas.

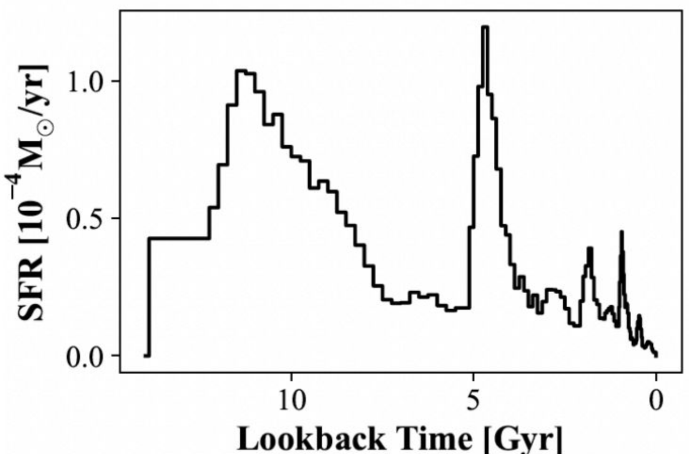
Photoevaporation: After reionization, all galaxies are surrounded by photoionized gas that is 10^4 K. This evaporate existing gas supply for low mass halos because sound speed is now greater than the escape speed. For halos ~ 10^7M_solar which kills star formation

Observations:

Resolved stars: CMD reveal split branches.
Indicating different stellar populations and could pinpoint that stars could have formed not all at once??
We can get formation history from population synthesis codes







Observations:

Ultra-faint dwarfs: many did not quench until after reionization!

- Classical dwarfs: some continue forming stars until relatively recently!

Something else has to quench them after reionization!

SNe -> likely not enough energy

Ram Pressure Stripping: => likely the cause for quenching - environmental impacts.

Dwarf Galaxies: Evolution and formation

Tidal disruption?

Jacobi radius, derived the distance where the differential forces pulling the star away centrifugal force + gravit vs its own self gravity…

$$r_t = \left(\frac{m_{\rm dwarf}}{3M_{\rm MW}} \right)^{1/3} d,$$

In Class Exercise — Two Parts

1. Can supernovae unbind (and quench) ultra-faint dwarf galaxies?

   Assume $M^{*}=10^{4}\ M_{\odot}$, $M_{tot}=10^{9}\ M_{\odot}$ (assumed to be prior to any tidal disruption / mass loss)

   We can assume $M_{gas} \sim 10^{6}\ M_{\odot}$, although larger values are possible (up to baryon fraction * total mass).

   Assume a size scale for the UFD of R~0.5 kpc

   Typical supernova energy ~10^{51} erg and you may assume that fraction of the IMF that goes supernova is $\eta=0.01$

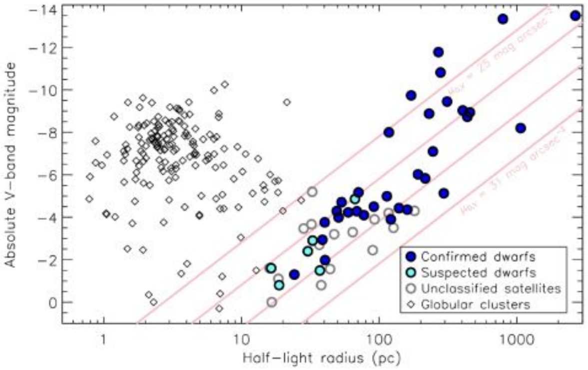
   Not all supernova energy couples to ISM! Assume an efficiency factor $\varepsilon \sim 0.1$ (optimistic, could be 0.01).

   Steps: (1) compute energy supernovae provide to ISM, (2) compute binding energy of gas to galaxy.

2. Will dwarf satellites be tidally destroyed by Milky Way?

   Consider $M_{dwarf} \sim 10^{9}\ M_{\odot}$ with pericenter distance of 30 kpc. Then consider a case where a dwarf with $M_{dwarf} \sim 10^{8}\ M_{\odot}$ comes within 5 kpc of the disk.

   - Assume flat rotation curve with v=200 km/s.
   - For UFDs, half light radii are 20-100 pc.
   - For classical dwarfs, half light radii are 100-1000 pc.



Solution

① SNe bindy.

Edge 10^{51} ergs $\quad M_{gas} \sim 10^6 M_\odot \quad M_{tot} = 10^9 M_\odot \quad M_{ne} = 10 M_\odot$

$R \simeq 0.5$ kpc.

Fraction $N = 0.01$

Tidyhld thngh free.

$$\text{SNe} \sim 10^{51} \cdot (0.01) \cdot 10^4 \cdot \underset{0.1}{\varepsilon} = 10^{52} \text{ ergs}$$

$$\text{Gravity} \quad \frac{G m_1 m_2}{r} = \frac{G\, 10^6 \cdot 10^9}{0.5 \text{ kpc}} = \frac{G \cdot 10^{15}}{0.5} = 10^{53} \text{ ergs}$$

② dwarf galaxies

$M_{dwarf} = 10^9 \quad r = 30$ kpc.

$M_{gal} = 10^{12}$

$$r = \left(\frac{10^9}{3 \cdot 10^{12}}\right)^{1/3} d. \qquad \text{radius of MW}$$

$$= \left(10^{-3}\right)^{\frac{1}{3}} = 0.1\, d$$

$= 3$ kpc?

radius is larger

Than Typical size

$r_t > r_{dwarf} \Rightarrow$ Safe

Dwarf Galaxies: Dark matter probes

Missing Satellites problem

CDM predicts large population of sub-halos in MW Halo. However we don’t see them?

Dwarf galaxy discoveries in 2000s changed this! We carefully measured the bias in observation/selection function and saw that it is consistent, we just didnt seem them lol.

Cusp Core Problem

Simulations predict dark matter halos have a **cuspy** inner halo density profile

Observations indicated **dwarf** irregular galaxies have **cored** inner halo density profiles

Baryonic effects can change the inner profile. Sims say supernovae feedback leads to rapid changes in gravitational potential — heats dark matter particles?

Could be resolved if nature of dark matter is different?

Too big to fail problem

Simulations predict lots of massive subhalos but we dont see them

Perhaps varying feedback has accreted them all?
Dynamical interactions through tidal disruption removes these subhalos through mass loss?

TD ripped apart these large halos!