Leaky-Box Model

Veilleux

- *If there is an outflow of processed material, g(t), the conservation of mas*
  becomes

$$dM_g/dt + dM_s/dt + g(t) = 0$$

see MBW 10.4.3

- *And the rate of change in the metal content of the gas mass becomes*

$$dM_h/dt = y\, dM_s/dt - Z\, dM_s/dt - Zg$$

- *Example: Assume that the rate at which the gas flows out of the box is proportional to the star formation rate:*
  - $g(t) = c\, dM_s/dt$ (c is a constant; c = 0.01 - 5)
  - As before $dZ/dt = y * (dM_s/dt) / M_g(t)$
  - Where $dM_s/dt = -[1/(1+c)]\, dM_g/dt$
  - So $dZ/dt = -[y/(1+c)] * [1/M_g] * dM_g/dt$
  - Integrating this equation, we get $Z(t) = Z(0) - [y/(1+c)] * \ln[M_g(t)/M_g($
  - The only effect of an outflow is to reduce the yield to an effective yield = y/(1

Accreting-Box Model

- *Example: Accretion of pristine (metal-free) gas to the box*
- *Since the gas accreted is pristine, the mass of heavy elements produced in a SF episode is*

$$dM_h/dt = (y - Z)\, dM_s/dt$$

- *However, for the conservation of mass in the box becomes:*

$$dM_g/dt = -\, dM_s/dt + f(t)$$

- *Consider the simple case in which the mass in gas in the box is constant. This implies then*

$$dZ/dt = 1/M_g * [(y - Z)\, dM_s/dt - Z\, dM_g/dt] = 1/M_g * [(y - Z)\, dM_s/dt]$$

Accreting-Box Model

- *Integrating and assuming that* $Z(0) = 0$

  $Z = y\,[1 - e^{-M_s/M_g}]$

- *Therefore when* $M_s >> M_g$, *the metallicity* $Z \sim y$
- *The mass in stars that are more metal-poor than* Z *is*

  $M_s(< Z) = -M_g \ln(1 - Z/y)$

- *In this case, for* $M_g \sim 10\ M_{sun} / pc^2$ *and* $M_s \sim 40\ M_{sun}/pc^2$, *and for* $Z = 0.7\ Z_{sun}$, *then* $y \sim 0.71\ Z_{sun}$. *Thus the fraction of stars more metal-poor than* $0.25\ Z_{sun}$ *is* $M(<0.25) / M(<0.7) \sim 10\%$,

MBW pg 488-491

- But simple closed-box model works well for bulge of Milky Way
- Outflow and/or accretion is needed to explain

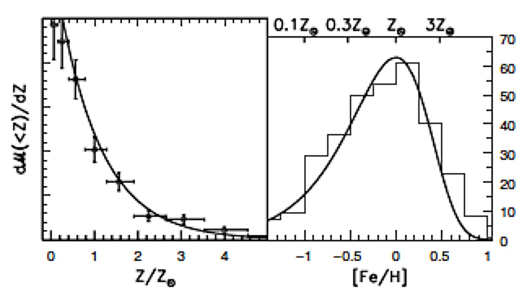
  Metallicity distribution of stars in Milky Way disk

  Mass-metallicity relation of local star-forming galaxies

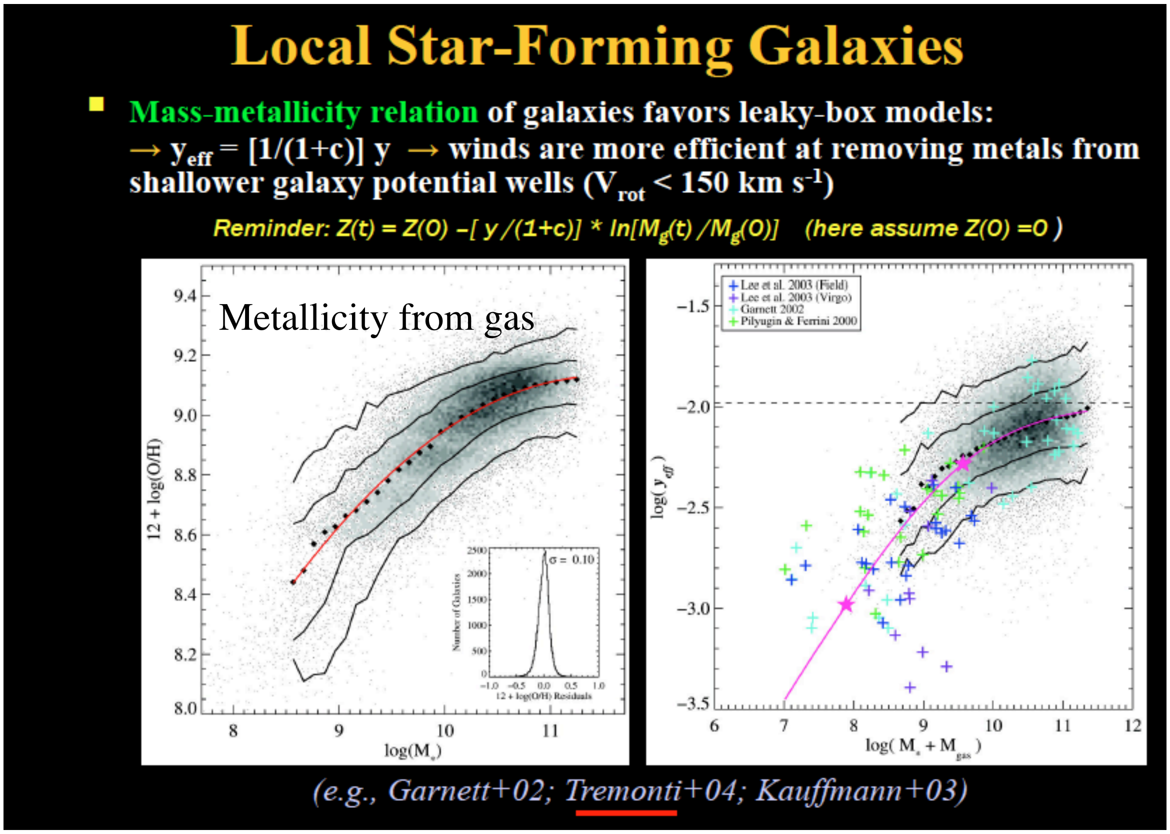
  Metallicity-radius relation in disk galaxies

  Merger-induced starburst galaxies

  Mass-metallicity relation in distant star-forming galaxies



Galactic **bulge** metallicity distributions of stars S&G fig 4.16- solid line is closed box model



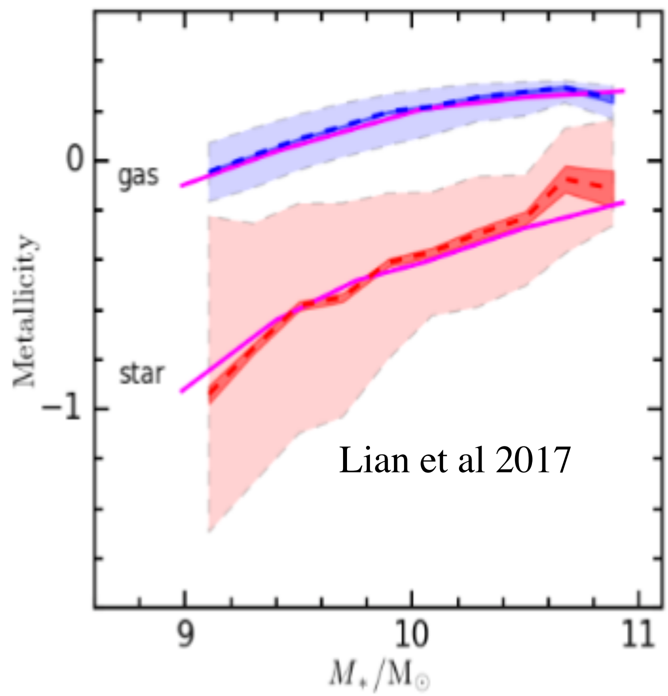
Veilleux

New Results !

- see arXiv:1710.11135The mass-metallicity relations for gas and stars in star-forming galaxies: strong outflow vs variable IMF , Lian et al
- **Find that the dependence on metallicity vs stellar mass is different for the gas vs stars**

- Lots of figures showing effects of outflow, inflow and varying IMF
- Conclude "among all the parameters, only two scenarios fit the observations,
  - a strong metal outflow or
  - a steep IMF slope at early times

- The mass-weighted stellar metallicities of star-forming galaxies are much lower than their gas metallicities. With the difference increasing at low mass
- Since gas metallicity represents the current metal abundance of a galaxy while stellar
- metallicity carries information about metal enrichment at early epochs, this result implies significant metallicity evolution at early times at low metallicity

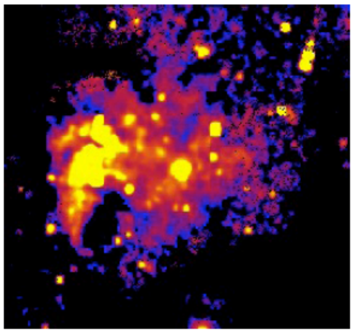


Either enhanced metal outflows or steeper IMF slopes at early times, are required to match the observed difference

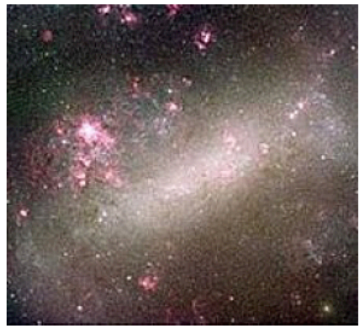
The LMC

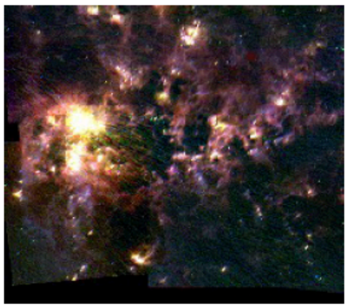
- Distance 50kpc
- Dwarf Irregular
  - Type Sm
- Tarantula Nebula
  - active star forming region
- Barred galaxy
- $L \approx 1.7 \times 10^9 L_\odot$

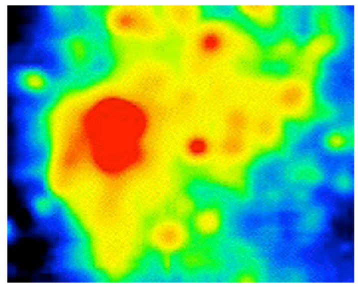
Xray: ROSAT



AAO optical 3 color





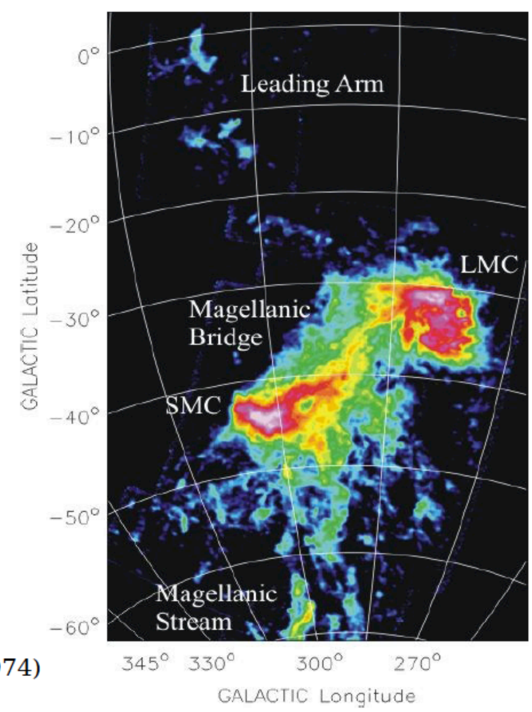


IRAS (Jason Surace) Radio (RAIUB/MPIFR Bonn

Each image is about 4°.5 on a side (9x moon's diameter)

- Clues to the MC's dynamics
  - Common HI envelope
  - Stream of gas "following" the MC's

Magellanic Bridge (Hindman 1961)
Magellanic Stream (Mathewson et al. 1974)
Leading Arm (Putman et al. 1998)



(RAIUB/MPIFR Bonn) Brüns et al 2004 A&A

Magellanic Clouds

- Satellites of the MW: potentially dynamics of SMC and LMC and the Magellanic stream can allow detailed measurement of mass of the MW.
- LMC D~50kpc M_{gas} ~ $0.6 \times 10^9 M_{\odot}$ (~10% of Milky Way)Supernova rate ~0.2 of Milky Way

Magellanic stream
-tidally removed gas??

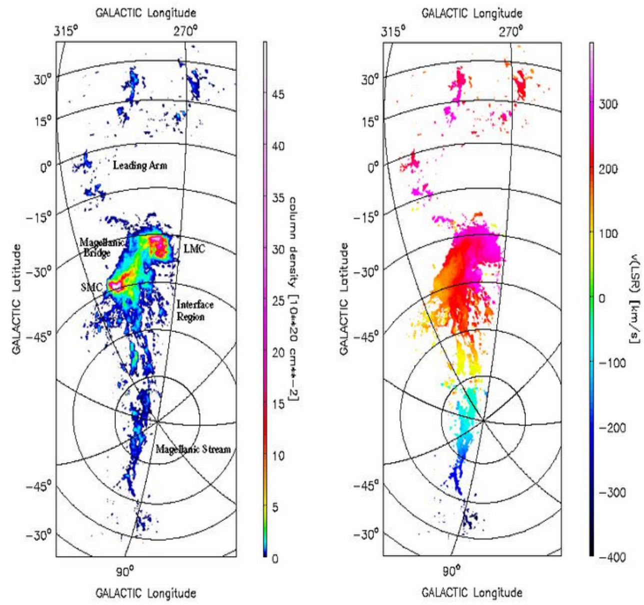


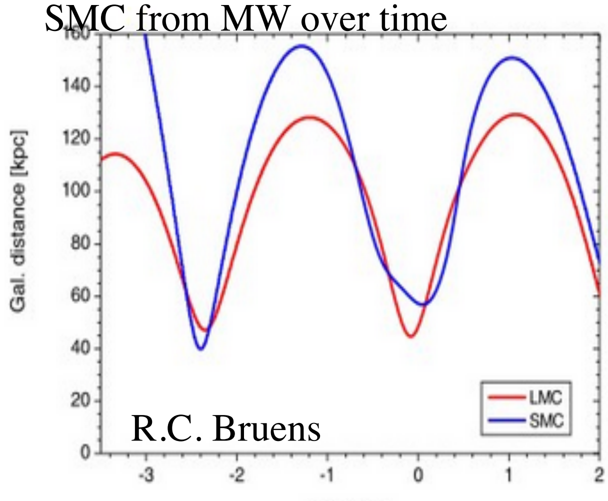
Figure 2: Single-dish observations of HI gas (Brüns et al. 2004).
Left: HI column density map of the entire Magellanic System. ***Right:*** Mean velocity v(LSR), map of the entire Magellanic System.

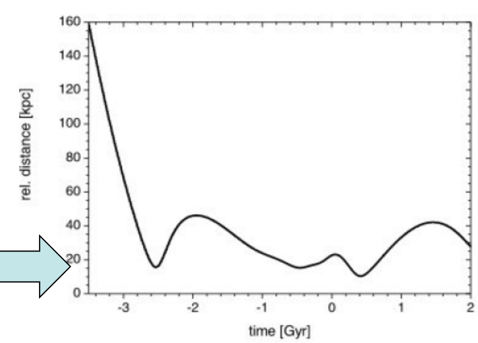
Density if gas velocity of gas

Magellanic Clouds

Position of LMC and SMC over time- in full up dynamical model;
no merger with MW in 2 Gyrs

Distance of LMC and SMC from MW over time





Separation of LMC and SMC over time

Dynamical Friction MBW pg 553

- When an object of mass M_S (hereafter the subject mass) moves through a large collisionless system whose constituent particles (stars) have mass $m << M_S$, it experiences a drag force, called dynamical friction
- This transfers energy and momentum from the subject mass to the field particles.
- Fundamentally this can be related to the fact that two-body encounters cause particles to exchange energies in such a way that the system evolves towards thermodynamic equilibrium.
- Thus, in a system with multiple populations, each with a different particle mass m_i, two-body encounters drive the system towards equipartition, in which the mean kinetic energy per particle is locally the same for each population
- Alternative explanation: moving subject mass perturbs the distribution of field particles causing a trailing enhancement (or 'wake') and the gravitational force of this wake on the subject mass M_S then slows it down.

Why Important??

- Accurate estimates of the effects of dynamical friction and the timescale for an orbiting satellite to lose its energy and angular momentum to merge with a host are essential for many astrophysical problems.

- the growth of galaxies depends on their dynamical evolution within larger dark matter halos.

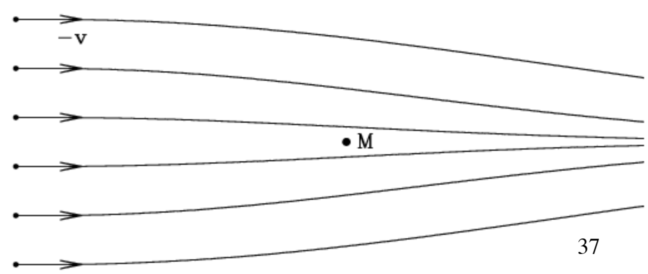
- dynamical friction provides a critical link between dark matter halo mergers and the galaxy mergers that determine, e.g., stellar masses, supermassive black hole masses, galaxy colors, and galaxy morphologies. (Boylan-Kolchin et al 2007)

Analytic Estimate How Fast Will Local Group Merge?

- Dynamical friction (S+G 7.1.1, MBW sec 12.3)-occurs when an object has a relative velocity wrt to a "stationary set of masses". The moving stars are deflected slightly, producing a higher density 'downstream'- producing a net drag on the moving particles
- Net force =Mdv/dt~ C $G^2M^2\rho/V^2$ for particles of equal mass -so time to 'lose' significant energy-timescale for dynamical friction-slower galaxy moves larger its deacceleration
- $t_{friction} \sim V/(dv/dt) \sim V^3/4\pi G^2 M m \rho \ln\Lambda$

M~10^{10} M;m=1M; $\rho \sim 3\times10^{-4}$ M/pc^3 Galactic density at distance of LMC (problem 7.6)

putting in typical values **$t_{friction}$~3Gyrs**



Dynamical Friction Derivation pg 285 S&G

- As M moves past it gets a change in velocity in the perdicular direction

$\delta V = 2Gm/bV$ (in the limit that b >>$2G(M+m)/V^2$

momentum is conserved so change in kinetic energy in the perpendicular direction is

$\delta(KE)=(M/2)(2Gm/bV)^2+(m/2)(2GM/bV)^2=$

$2G^2mM(M+m)/b^2V^2$ (eq 7.5 S&G)

$\delta V \sim [2G^2m(M+m)/b^2V^3]$

and $dV/dt \sim 4\pi G^{2[}(M+m)/V^2]$

notice that the smaller object acquires the most energy which can only come from the forward motion of galaxy M

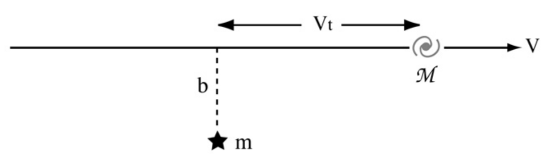


Fig 7.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Dynamical Friction

- However Chandrasekar's derivation had to make certain assumptions which turn out not be be completely valid.
- Recently Boylan-Kolchin et al (2007) showed that the timescales were too short by factors of 1.7-3.5 depending on the ratio of the masses.

Dynamical Friction-cont

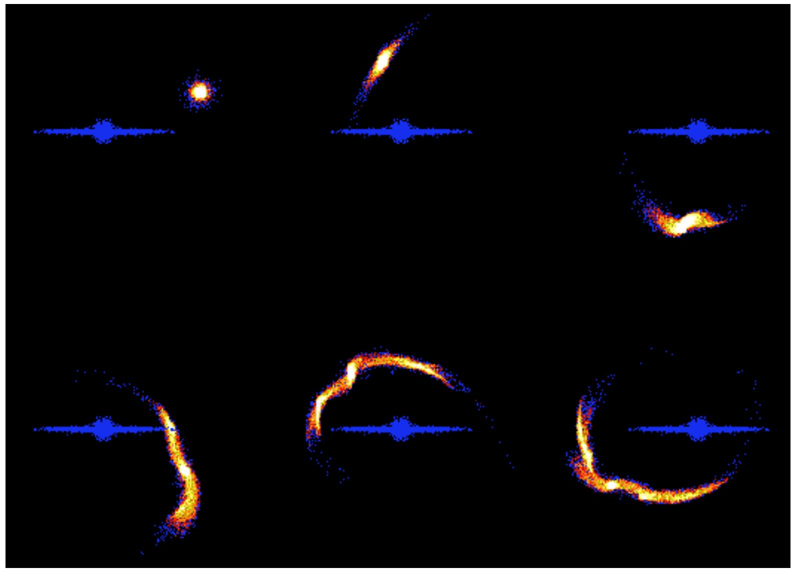
- basically this process allows the exchange of energy between a smaller 'incoming' mass and the larger host galaxy
- The smaller object acquires more energy
- -removes energy from the directed motion small particles (e.g. stars) and transfers it to random motion (heat) - incoming galaxy 'bloats' and it loses stars.
- It is not identical to hydrodynamic drag in the low velocity limit the force is ~velocity, while in the high limit is goes as v^{-2}
- It is also independent of the mass of the particles but depends on their total density- e.g. massive satellite slowed more quickly than a small one

LMC Merger??

- Depends sensitively on LMC orbit and model of MW potential-

At the Clouds' present-day position, a large fraction of their observed line of sight and proper motion speeds are due to the Sun's motion around the Galactic center!

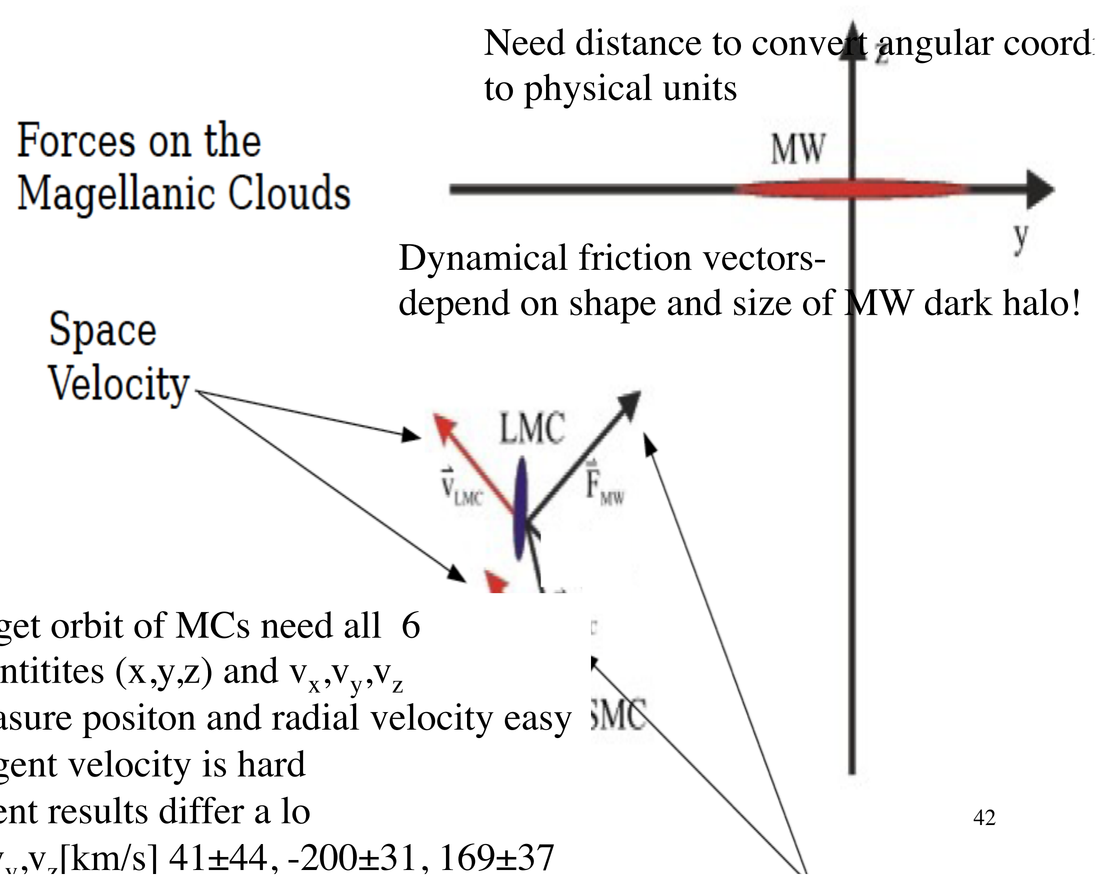
- The origin of the Magellanic Clouds is still an enigma as they are the only blue, gas-rich irregulars in the local group.



K. Johnston

Need distance to convert angular coord to physical units

Dynamical friction vectors- depend on shape and size of MW dark halo!



To get orbit of MCs need all 6 quantitites (x,y,z) and v_x,v_y,v_z

measure positon and radial velocity easy

tangent velocity is hard

recent results differ a lo

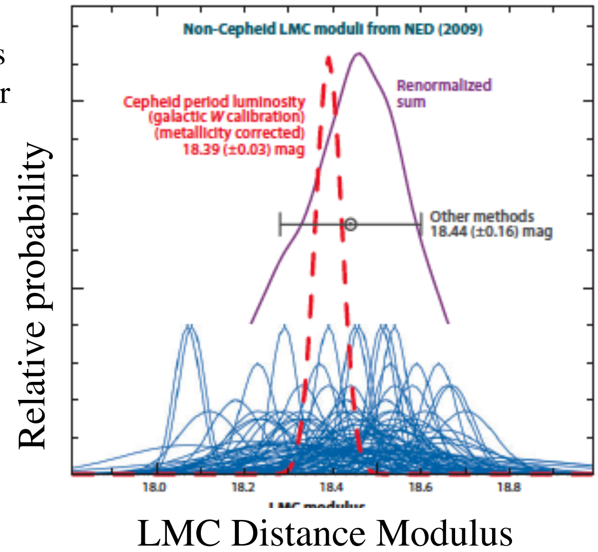
v_x,v_y,v_z[km/s] 41±44, -200±31, 169±37

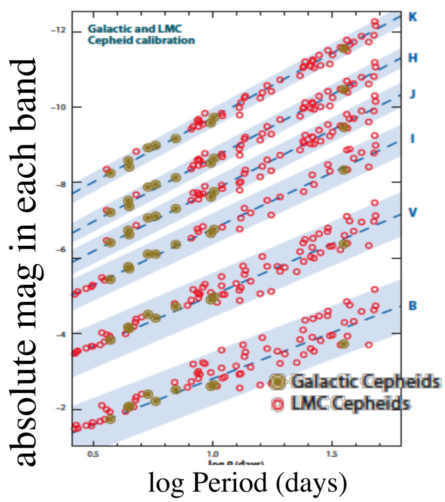
Distance to LMC

- LMC is unique in that many Cepheids can be detected in a galaxy with rather different metallicity with no effect of crowding

distance modulus, μ,(log d=1+μ/5) pc

LMC μ= 18.48 ± 0.04 mag; (49.65 Kpc)

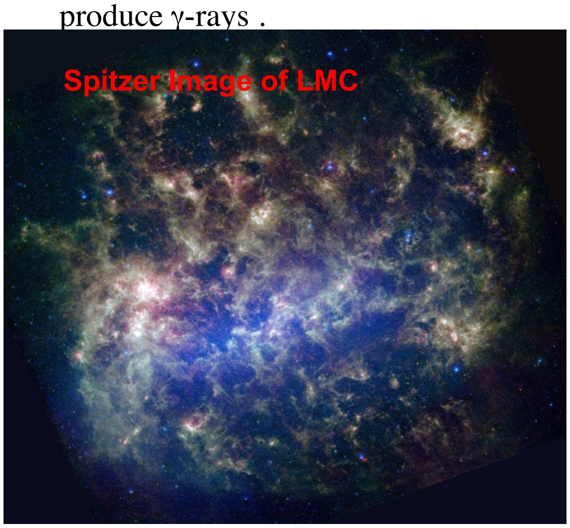




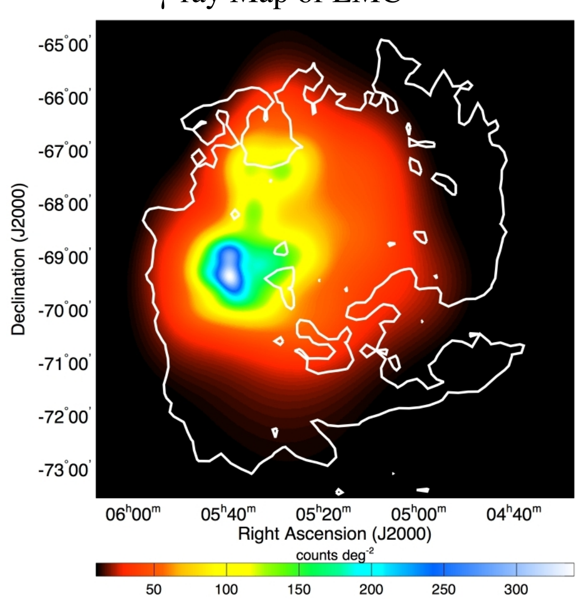
This sets the distance scale for comparison with Cepheids in nearby galaxies (Freedman+Madore 2010)

Cosmic Rays and γ-rays

- LMC and SMC are only galaxies, other than MW, for which γ-ray images exist.
- Look for correlations with sites of CR acceleration and/or for dense gas which the CRs interact with to produce γ-rays .



γ-ray Map of LMC

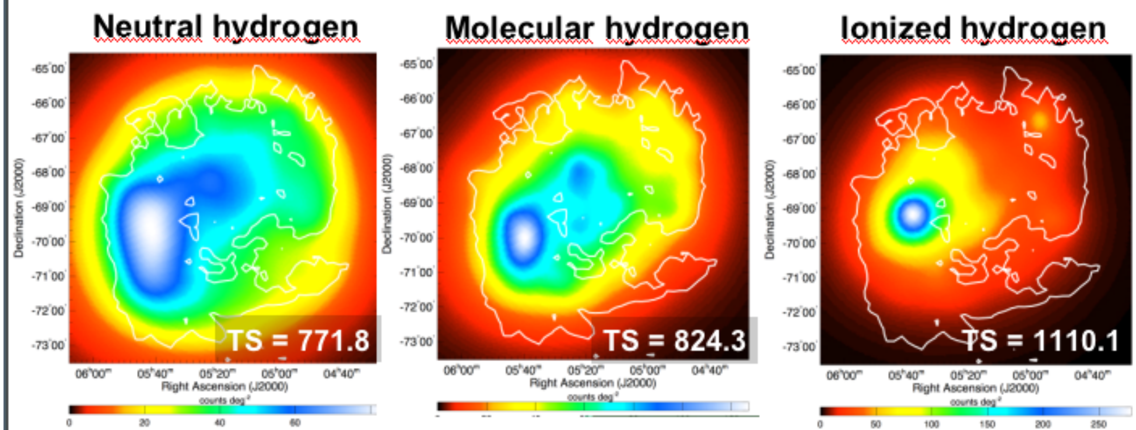


γ-ray intensity scale

LMC Cosmic Rays and γ-rays

γ-ray emission correlates with massive star forming regions and not with the gas distribution (simulated images if the γ-ray emission was distributed like the source)

- Compactness of emission regions suggests little CR diffusion
- 30 Doradus star forming region is a bright source of gamma rays and very likely a cosmic-ray accelerator



- **Neutral & molecular hydrogen templates poorly fit the data**
- **Ionized hydrogen template provides best fit**

Dermer 2011

γ-ray emission poorly correlated with dense gas (!)

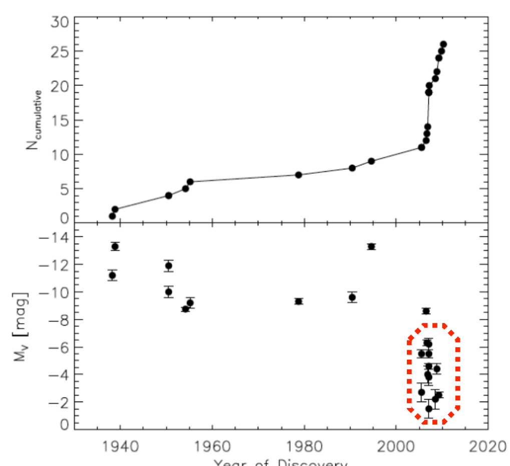
Dwarf Galaxies

- As we will discuss later one of the main problems with the present cold dark matter (CDM) paradigm for galaxy formation is the *relative absence of small, low mass galaxies*
- It is only in the local group that such systems can be discovered and studied
- they are the most dark matter dominated of all objects- and the smallest and least luminous galaxies known.
- very faint and very low surface brightness, very hard to find (Walker 2012).
- Many people believe that some dwarf spheroidals are 'relics' of the early universe

TABLE 1

Galactic Dwarf Spheroidal Galaxies with Large M/L

Name	L ($10^5 L_\odot$)	d (kpc)	r_k (pc)	M/L ($M_\odot/L_\odot$)
Carina...	2.4 ± 1.0	85 ± 5	581 ± 86	59 ± 47
Draco...	1.8 ± 0.8	72 ± 3	498 ± 47	245 ± 155
Ursa Minor...	2.0 ± 0.9	64 ± 5	628 ± 74	95 ± 43
Sextans...	4.1 ± 1.9	83 ± 9	3102 ± 1028	107 ± 72

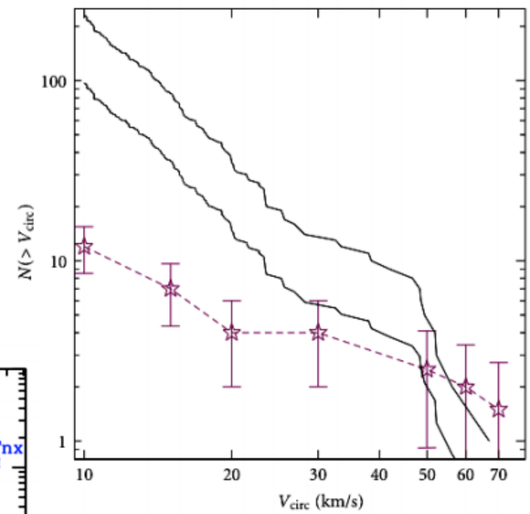


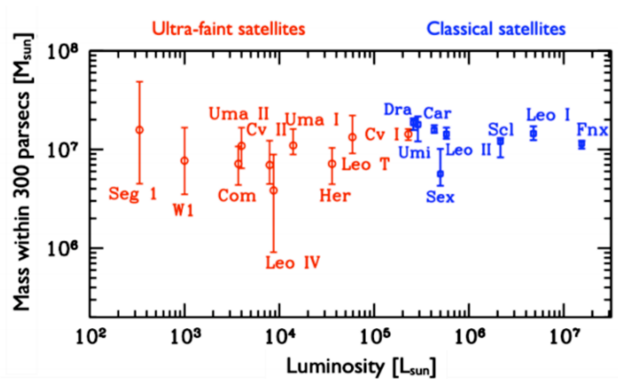
Number of Satellites around MW- Observed vs Theoretical

- Number of satellites vs their circular velocity: theory - between black lines

  red points observed objects (Klypin 2010)- order of magnitude discrepancy at low masses?

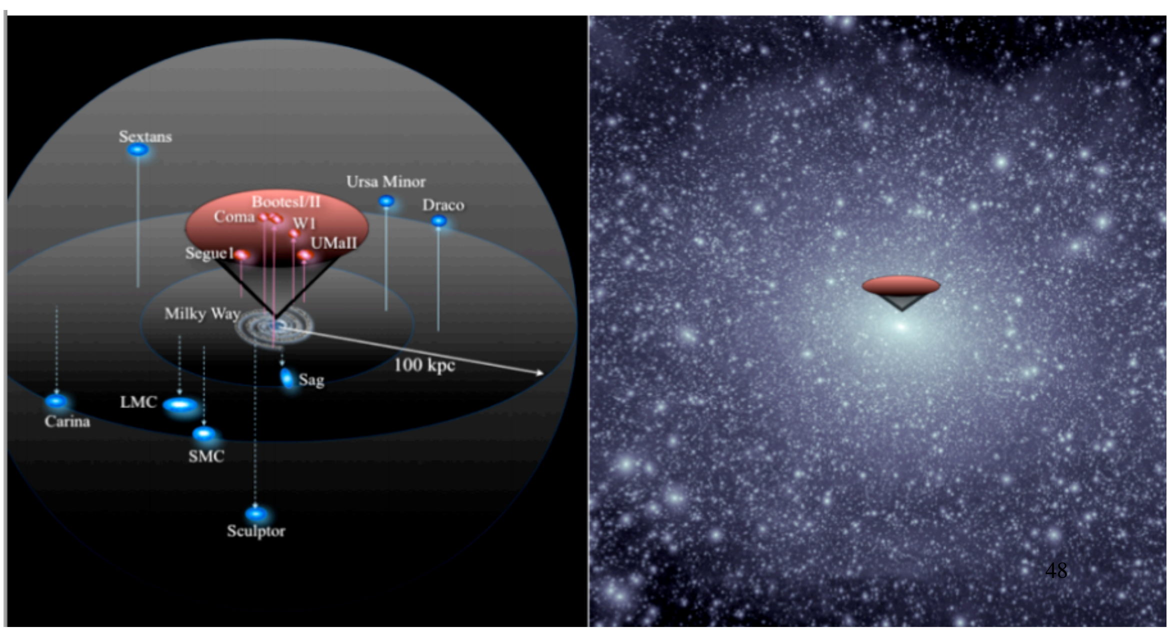
- Odd property that satellites all have *same mass, but 10^5 range in luminosity*





Where are the Satellites of MW-Bullock 2010

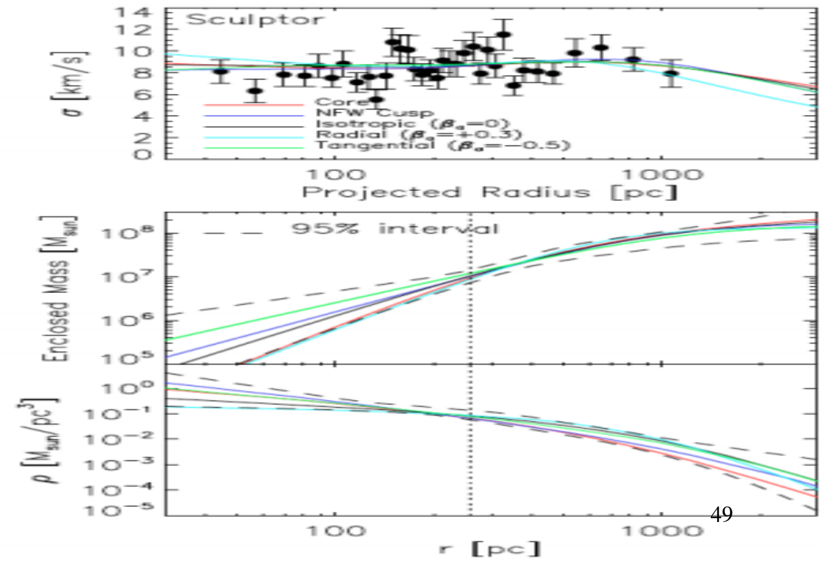
- Know satellites of MW within 100kpc-left
- Right- CDM simulation of LG/ MW halo- cones show where sample of dwarfs is complete-SDSS data, only in the north



Dwarfs

- Have VERY low internal velocity dispersion~10km/sec, r_{scale}~50-1000pc
- IF mass follows light- very dark matter dominated- but precise mass is not well determined even with ~3000 stars individually measured (!)
- - using Jeans method: all solutions (different

shapes of the potential or orbital distributions) are ok

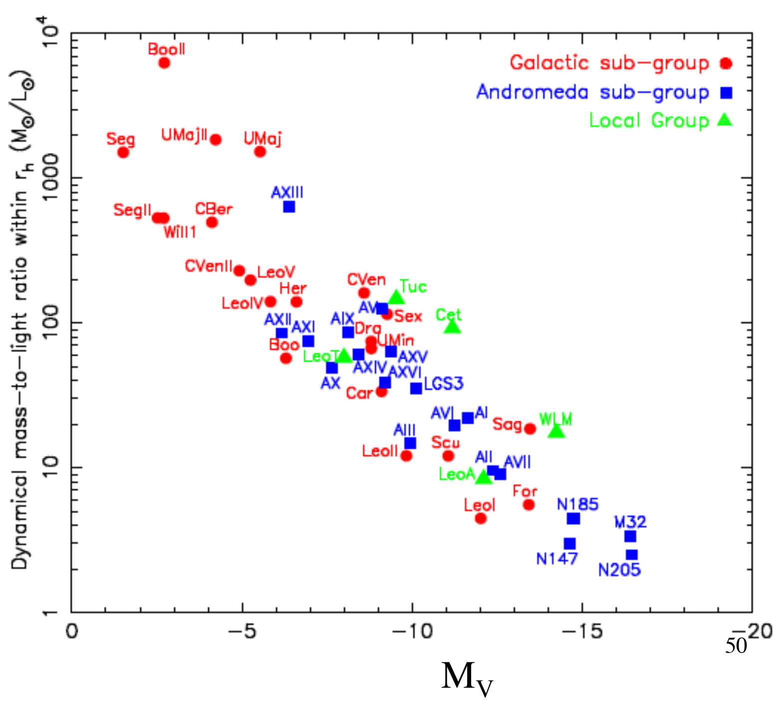


Dwarfs Have Very High Mass to Light Ratios

- The lower the absolute luminosity of local group dwarfs the higher the mass to light ratio (McConnachie 2012)

Since we know a lot about the stars this is not due to a strange stellar population

Indicates extreme dark matter dominance



Dwarfs

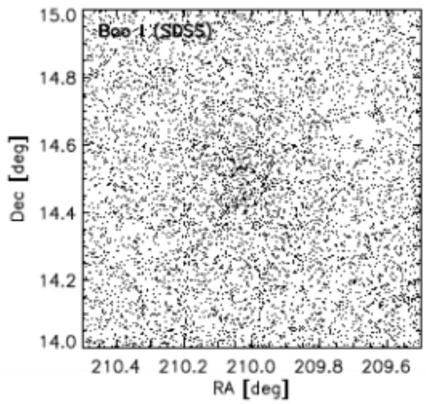
- They are detected as overdensities of intrinsically bright red giant stars

which detectable as point sources with m_V<21 mag out to distances of ~0.5 Mpc- (modern large telescopes can reach 4 mags fainter; - since red giants have a 'unique' luminosity can use them as distance selector)

- the 'ultrafaint' satellites discovered with SDSS data are not apparent to the eye, even in deep images- *detected by correlating spatial overdensities with overdensities in* color-magnitude space
- the low surface densities of dSphs imply internal relaxation timescales of >10^3 Hubble times

27 are known in M31

Image of Boo I



Local Group Summary

- What is important
  - local group enables detailed studies of objects which might be representative of the rest of the universe (e.g CMDs of individual stars to get SF history, spectra of stars to get metallicity, origin of cosmic rays etc)
    - wide variety of objects -2 giant spirals, lots of dwarfs
  - chemical composition of other galaxies in local group (focused on dwarfs and satellites of the MW) similar in gross terms, different in detail; indications of non-gravitational effects (winds); went thru 'closed box' and 'leaky box' approximations, allowed analytic estimate of chemical abundance distribution and its evolution.
  - dynamics of satellites of MW (Magellanic clouds) clues to their formation, history and amount of dark matter
    - dwarfs are the most dark matter dominated galaxies we know of- closeness allows detailed analysis.
    - dwarf galaxy 'problem' are there enough low mass dwarfs around MW??- leads to discussion later in class about galaxy formation and Cold dark matter models