# Local Group See S&G ch 4 _{MBW fig 2.31}

- Our galactic neighborhood consists of one more 'giant' spiral (M31, Andromeda), a smaller spiral M33 and lots of (>35 galaxies), most of which are dwarf ellipticals and irregulars with low mass; **most are satellites of MW, M31 or M33**

- The gravitational interaction between these systems is complex but the local group is apparently bound.

- Major advantages
  – close and bright- all nearby enough that individual stars can be well measured as well as HI, H₂, IR, x-ray sources and even γ-rays

  – wider sample of universe than MW (e.g. range of metallicities, star formation rate etc etc) to be studied in detail
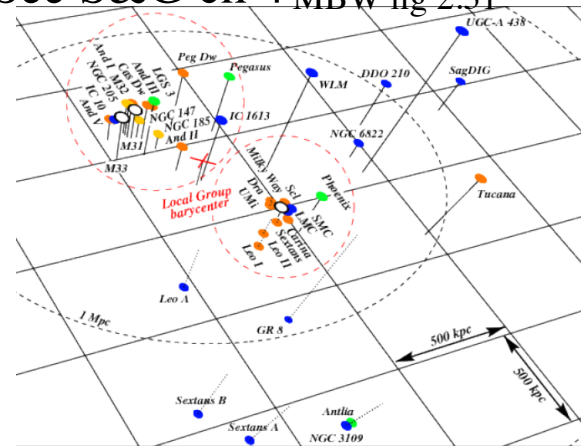
–allows study of dark matter on larger scales and first glimpse at galaxy formation

–calibration of Cepheid distance scale

ARA&A1999, V 9, pp 273-318 The local group of galaxies S. van den Bergh
Star formation histories in local group dwarf galaxies Skillman, Evan D.   1
New Astronomy Reviews, v. 49, iss. 7-9 p. 453-460.
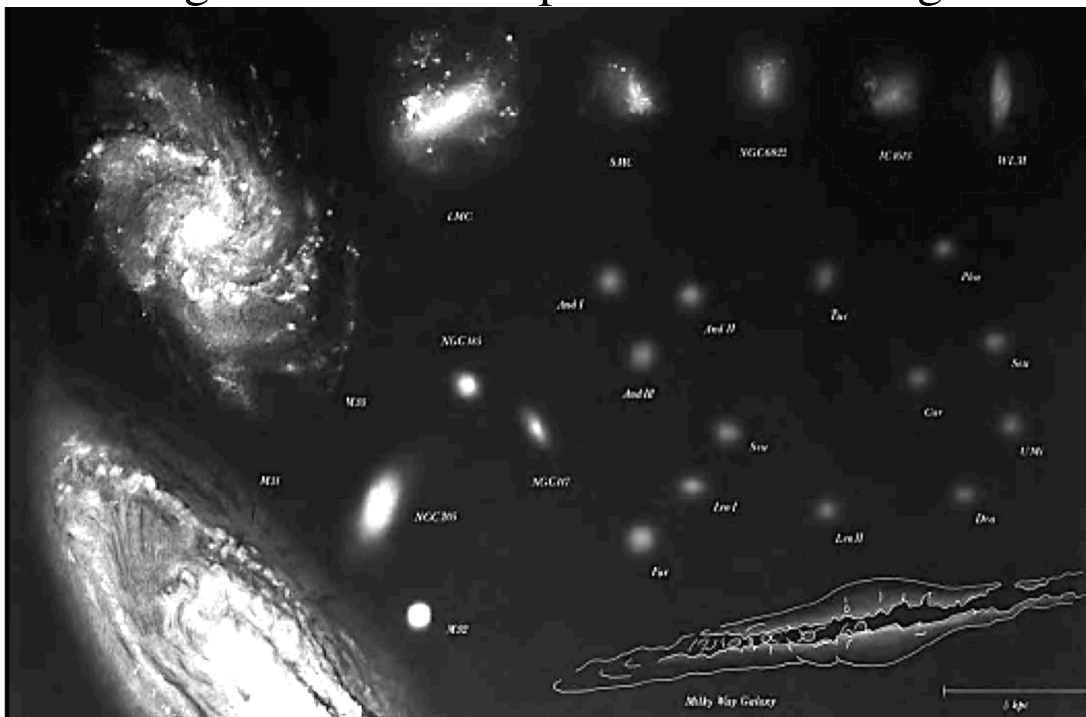
Image of Local Group to Scale S&G Fig 4.1

Fig. 4.1. Galaxies of the Local Group, shown to the same linear scale, and to the same level of surface brightness. The spiral   2
and irregular galaxies stand out clearly, while the dwarf spheroidals are barely visible – B. Binggeli.

Local Group Galaxies -Wide Range of Luminosity

- Local Group dwarfs galaxies trace out a narrow line in the surface brightness luminosity- plane

(Tolstoy et al 2009)

see table 4.1 in S&G
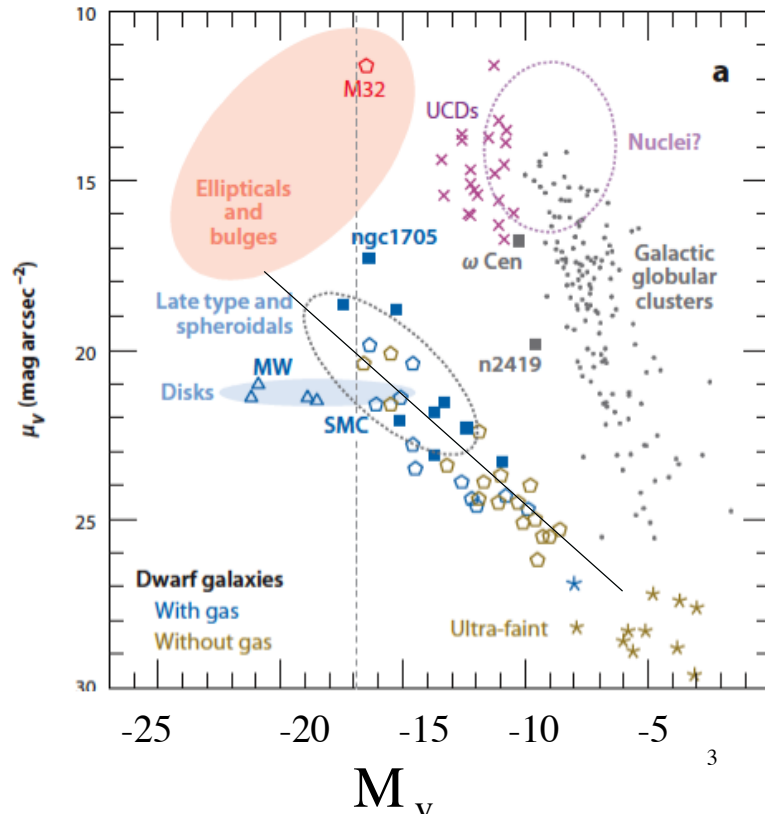
Comparison of Galaxies and Globulars

- Comparison of dwarf galaxies in the local group- plot of absolute magnitude vs size
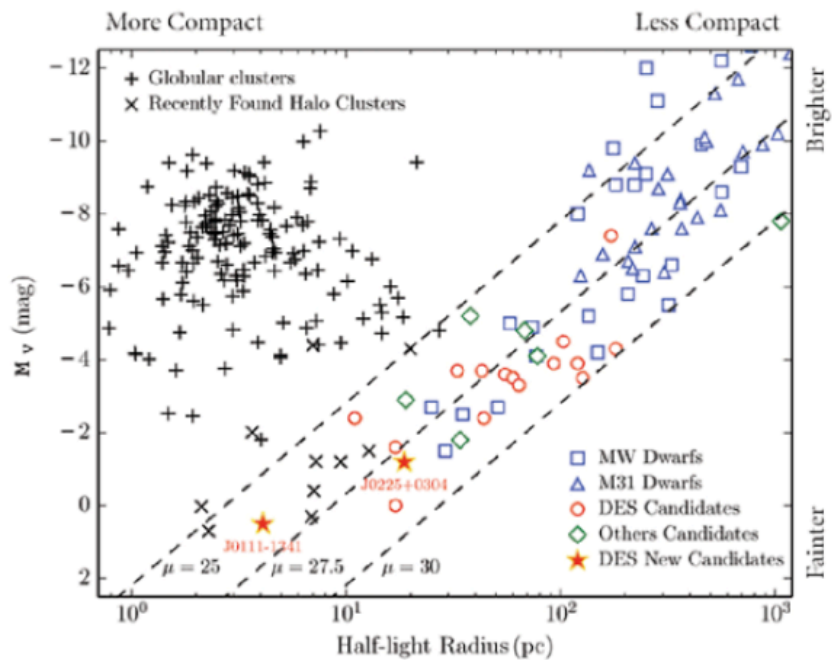 - + are globular clusters

Figure 2. Absolute magnitude versus half-light radius for globular clusters and dwarf

Wide Range of Luminosities/ Chemical Abundance

- MW/M31~$2 \times 10^{10} L_{v\odot}$
- LMC~$2 \times 10^9 L_{v\odot}$
- Formax dSph $1 \times 10^7 {}_v L_\odot$
- Carina dSph $3 \times 10^5 L_{v\odot}$

- Because of closeness and relative brightness of stars the Color Magnitude Diagram combined with Spectroscopy of resolved stars can produce 'accurate'
  - star formation histories
 - Chemical evolution
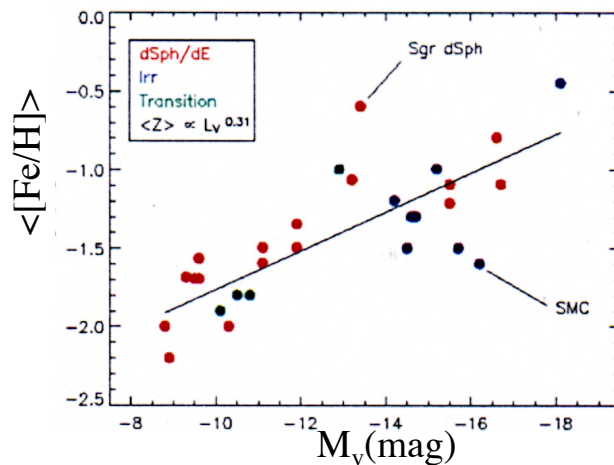
T. Smecker-Hane

Despite wide variety of 'local' environments (near/far from MW/M31) trends in chemical composition seem to depend primarily on galaxies properties
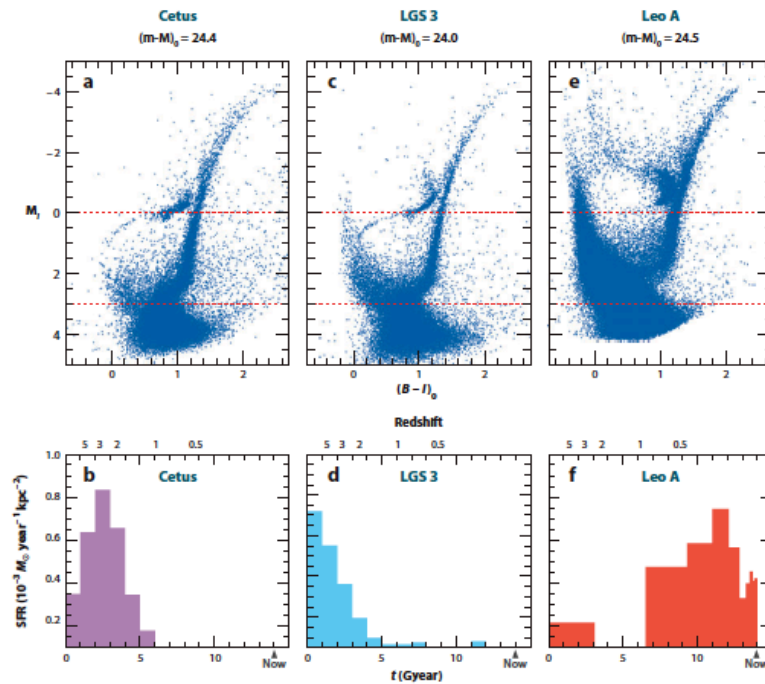
Star Formation Histories

- Analysis of CMDs shows presence of both old and (some) young stars in the dwarfs -complex SF history
- The galaxies <u>do not</u> show the same SF history- despite their physical proximity and being in a bound system
- Their relative chemical abundances show some differences with low metallicity stars in the MW.

Star Formation Histories Local Group Dwarfs
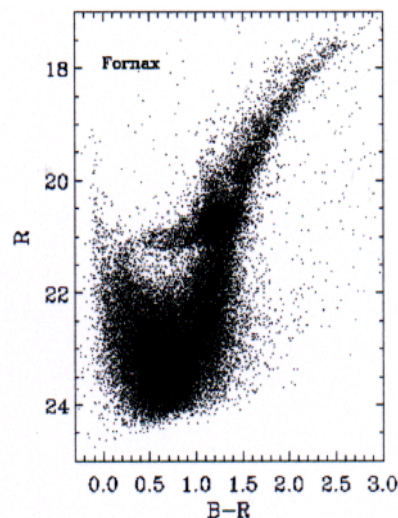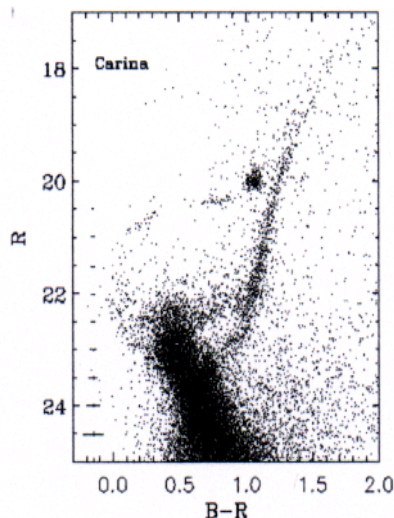
- With HST can observed color magnitude diagram for individual stars in local group galaxies
- Using the techniques discussed earlier can invert this to get the star formation history
- Note 2 extremes: very old systems Cetus, wide range of SF histories (Leo A)
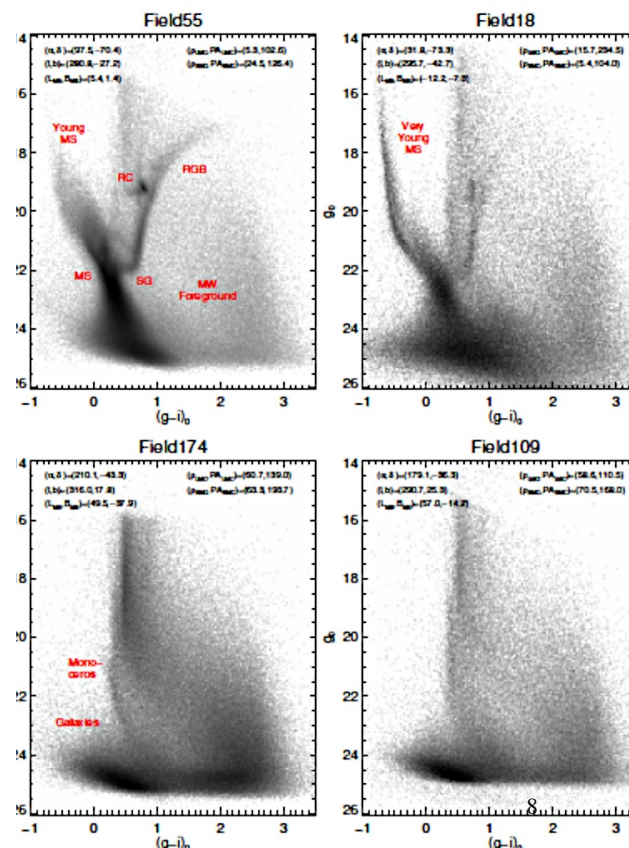- (Tolstoy, Hill, Tosi Annual Reviews 2009)
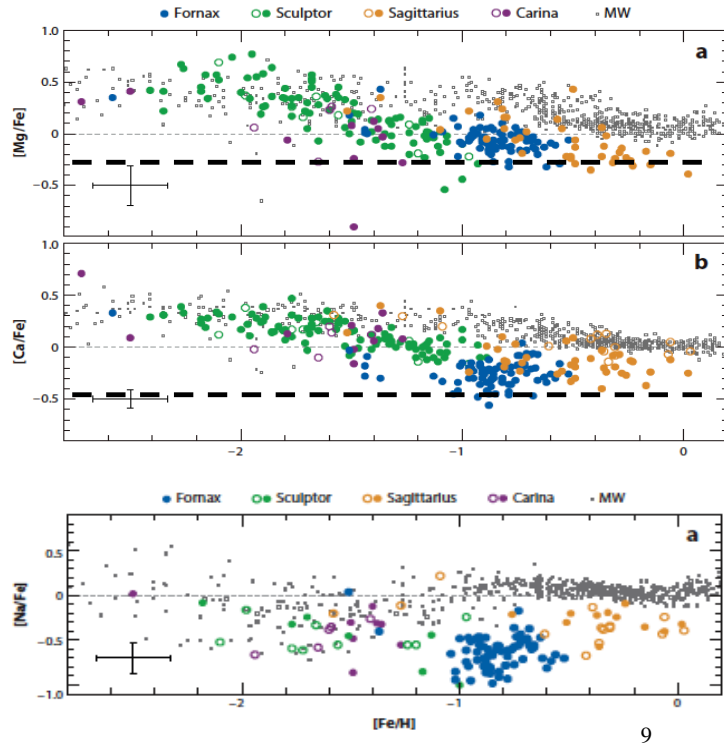
0   10   now   7

t (Gyr)

Different Places in the LMC

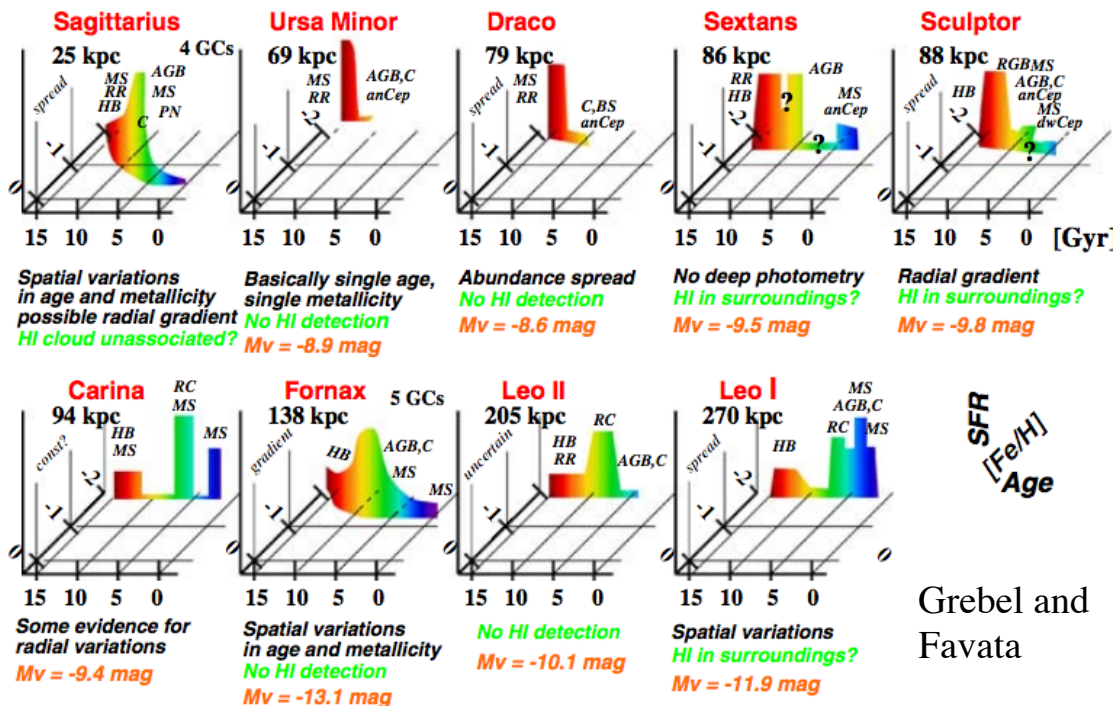- Different parts of a galaxy can have different star formation histories

8

- Overall metallicity of LG dwarfs is low but some patterns but different to stars in MW (black dots-Tolstoy et al 2009)-
- How to reconcile their low observed metallicity with the fairly high SFR of the most metal-poor systems many of which are actively star-forming
- best answer metal-rich gas outflows, e.g. **galactic winds**, triggered by supernova explosions in systems with shallow potential wells, efficiently remove the metal-enriched gas from the system.
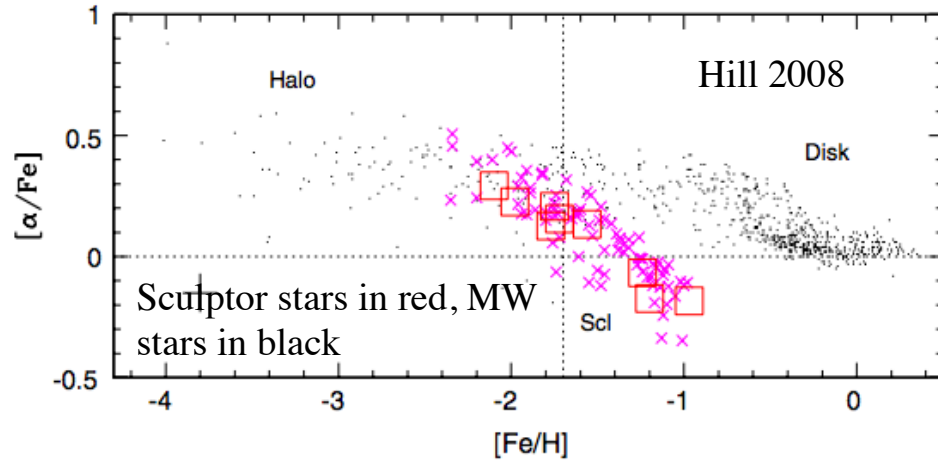- In Local Group can wind models be well constrained by chemical abundance observations.

Metallicities In LG Dwarfs Vs MW
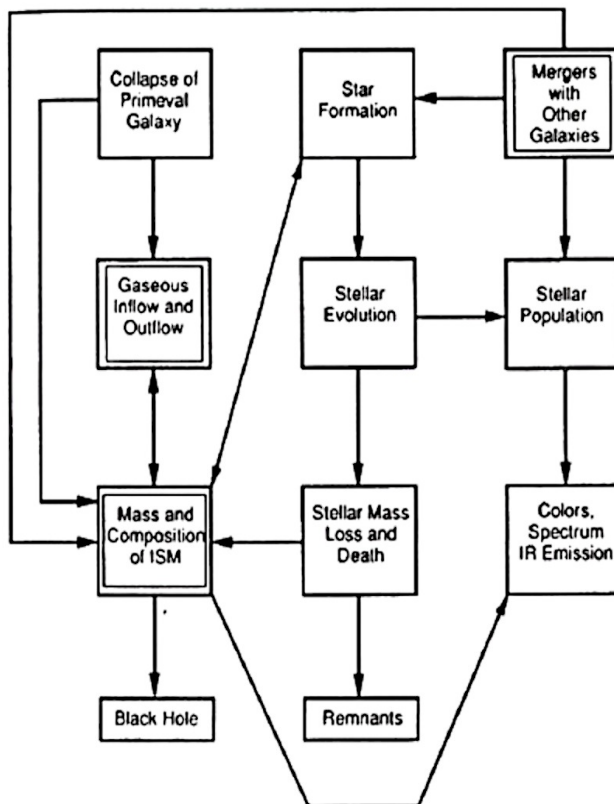

History of SFR In Local Group Dwarfs

Grebel and Favata

Abundances in Local Group Dwarfs

Halo

Hill 2008

Disk

Sculptor stars in red, MW
stars in black

Scl

[α/Fe]

[Fe/H]

- Clear difference in metal
  generation history

Collapse of Primeval Galaxy

Star Formation

Mergers with Other Galaxies

Gaseous Inflow and Outflow

Stellar Evolution

Stellar Population

Mass and Composition of ISM

Stellar Mass Loss and Death

Colors, Spectrum IR Emission

Black Hole

Remnants

**Key parameters
in chemical evolution:**

- Lifetimes of stars (as a function of mass)

- Mass distribution of stars at their birth

- Star formation rate

- Element production of stars

- Ejection mechanisms

- Mixing with interstellar gas

- Interaction with environment (gas inflow/outflow)

(diagram from Tinsley 1980,
Fund. of Cosmic Physics, Vol. 5)

Conservation Equations

- (7.1) $M = M_s + M_g$

$$\begin{cases} M = \text{total mass} \\ M_s = \text{mass in stars} \\ M_g = \text{mass in gas} \end{cases}$$

- (7.2) $\dfrac{dM}{dt} = f - e$

$$\begin{cases} f = \text{rate of infalling gas} \\ e = \text{rate of ejected gas} \end{cases}$$

(7.3) $\dfrac{dM_s}{dt} = \Psi - E$

$$\begin{cases} \Psi = \text{star formation rate} \\ E = \text{gas ejection rate of all stars} \end{cases}$$

(7.4) $\dfrac{dM_g}{dt} = -\Psi + E + f - e$

Maeder 1992
$f = e = 0$, $M_g(t = 0) = M$, $M_s(t = 0) = 0$ (closed-box-model):

Closed Box Approximation-Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388

- To get a feel for how chemical evolution and SF are related (S+G 4.13-4.17)- but a different approach (Veilleux 2010)

- at time t, mass ΔM_{total} of stars formed, after the massive stars die left with $\Delta M_{low\ mass}$ which live 'forever'

- massive stars inject into ISM a mass $p\Delta M_{total}$ of heavy elements (p depends on the IMF and the yield of SN- normalized to total mass of stars).
- Assumptions: galaxies gas is well mixed, no infall or outflow, high mass stars return metals to ISM faster than time to form new stars)

Closed Box Approximation-Tinsley 1980, Fund. Of Cosmic

Physics, 5, 287-388

$M_{total}=M_{gas}+M_{star}=$constant ($M_{baryons}$)

M_h mass of heavy elements in gas $=ZM_{gas}$

$dM'_{stars}=$total mass made into stars, $dM''_{stars}=$amount of mass instantaneously returned to ISM enriched with metals

$dM_{stars}=dM'_{stars}-dM''_{stars}-$ net matter turned into stars

y is the yield of heavy elements- $yM_h=$mass of heavy elements returned to ISM

Z= metallicity of gas

Closed Box- continued

- Net change in metal content of gas
- $dM_h = y\,dM_{star} - Z\,dM_{star} = (y - Z)\,dM_{star}$

- Change in Z since $dM_g = -dM_{star}$ and $Z = M_h/M_g$ then
- $dZ = dM_h/M_g - M_h\,dM_g/M^2_g = (y - Z)\,dM_{star}/M_g + (M_h/M_g)$
  $(dM_{star}/M_g) = y\,dM_{star}/M_g$

- $d\,Z/dt = -y(dM_g/dt)\,M_g$

- If we assume that the yield y is independent of time and metallicity (Z) then
- $Z(t) = Z(0) - y\,\ln M_g(t)/M_g(0) = Z(0) = y\ln \mu$

Closed Box- continued

- metallicity of gas grows with time logarithmically

mass of stars that have a metallicity less than Z(t) is

$M_{star}[< Z(t)] = M_{star}(t) = M_g(0) - M_g(t)$ or

$M_{star}[< Z(t)] = M_g(0)*[1 - \exp((Z(t) - Z(0))/y]$

when all the gas is gone, mass of stars with metallicity Z, Z+d Z is

$M_{star}[Z] \alpha \exp((Z(t) - Z(0))/y)\,d Z$- we use this to derive the yield from data

$Z(today) \sim Z(0 - y\ln[M_g(today)/M_g(0)]$; $Z(today) \sim 0.7\,Z_{sun}$

since intial mass of gas was sum of gas today and stars today

$M_g(0) = M_g(today) + M_s(today)$ with $M_g(today) \sim 40 M_\odot/pc^2$
$M_{stars}(today) \sim 10 M_\odot/pc^2$

get $y = 0.43\,Z_{sun}$ go to pg 180 in text to see sensitivity to average metallicity of stars

Closed Box- Problems

- Problem is that closed box connects todays gas and stars yet have systems like globulars with no gas and more or less uniform abundance.

- Also need to tweak yields and/or assumptions to get good fits to different systems like local group dwarfs.

- 'G dwarf' problem in MW (S+G pg 180-181) nearly half of all stars in the local disk <u>should have less than a quarter of the Sun's metal content.</u> BUT less than 25% have such low abundances

- Go to more complex models - leaky box (e.g inflow/outflow);
  - assume outflow of metal enriched material g(t) which is proportional to star formation rate **g(t)=cdM$_s$/dt**;
  - solution is $Z(t)= Z(0)-[(y/(1+c))*ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change relative abundances

S. Zhukovska et al.: Evolutic
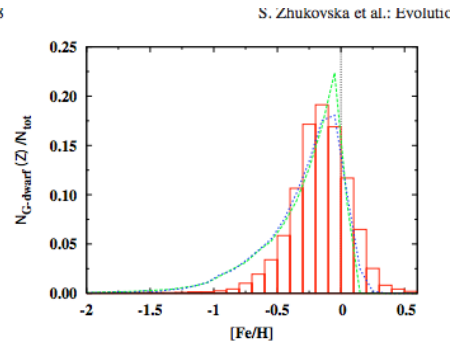
Green is closed box model
red is observations of local stars

19

Leaky-Box Model

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

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

- 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 $Z(t) = Z(0) -[y/(1+c)] * ln[M_g(t)/M_g(0)]$
  - 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, Eq (2) is still valid: the mass of heavy elements produced i

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

- However, Eq. (1) 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 $M_s \gg M_g$, 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 $M(<0.25)/M(<0.7) \sim 10\%$, in much better agreement with the observations of the solar neighborhood

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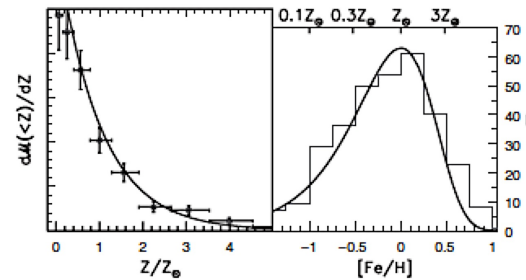
    Metallicity distribution of stars in Milky Way disk

    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

23

Leaky box

Outflow and/or accretion is needed to explain
- Metallicity distribution of stars in Milky Way disk
- Mass-metallicity relation of local star-forming galaxies

Local Star-Forming Galaxies

■ **Mass-metallicity relation** of galaxies favors leaky-box models:
→ $y_{eff} = [1/(1+c)] \, y$ → winds are more efficient at removing metals from shallower galaxy potential wells ($V_{rot} < 150$ km s^{-1})
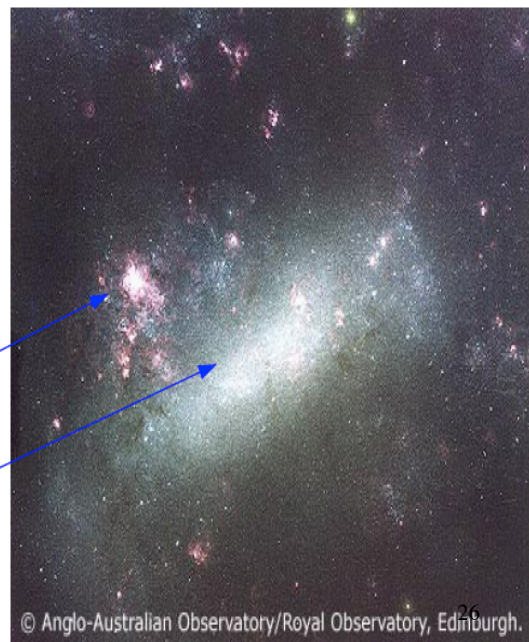
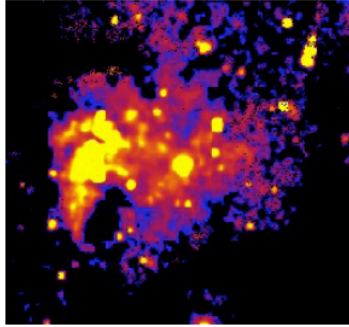*Reminder: $Z(t) = Z(O) - [y/(1+c)] * \ln[M_g(t)/M_g(O)]$ (here assume $Z(O) = 0$)*
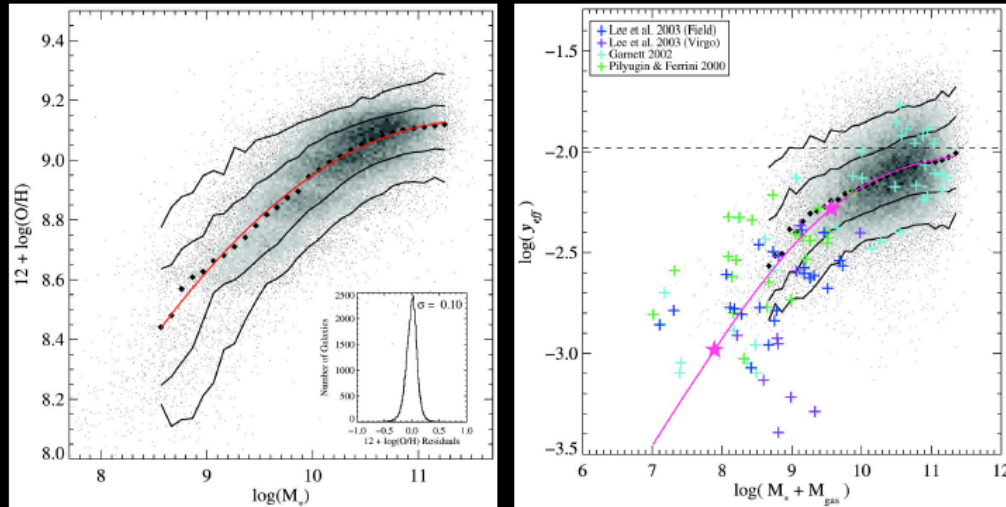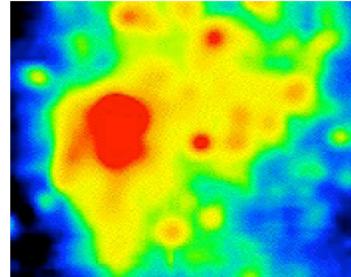

(e.g., Garnett+02; Tremonti+04; Kauffmann+03)

The LMC

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

© Anglo-Australian Observatory/Royal Observatory, Edinburgh.
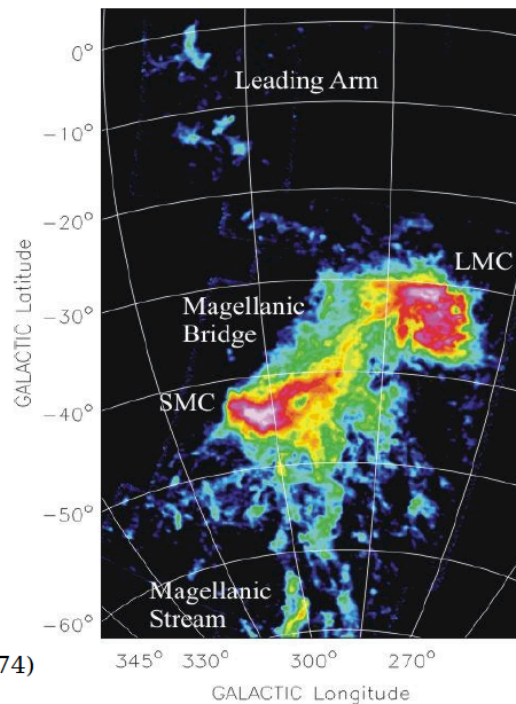
26

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 $M_{gas} \sim 0.6 \times 10^9$ M$_\odot$ (~10% of Milky Way)Supernova rate ~0.2 of Milky Way

  Position of LMC and SMC over time- in full up dynamical model; no merger with MW in 2 Gyrs
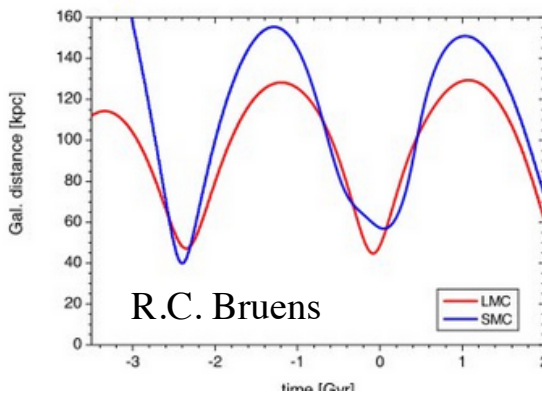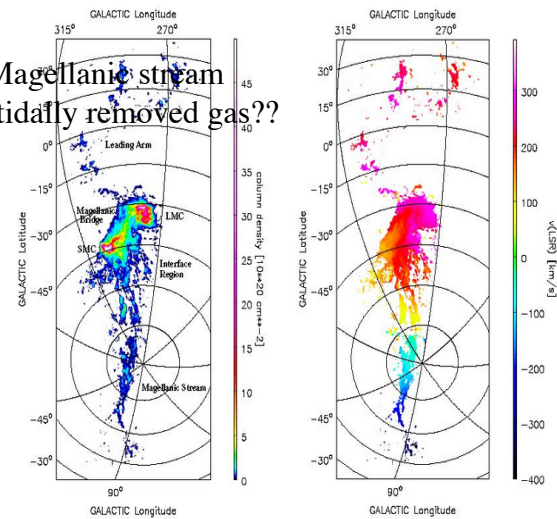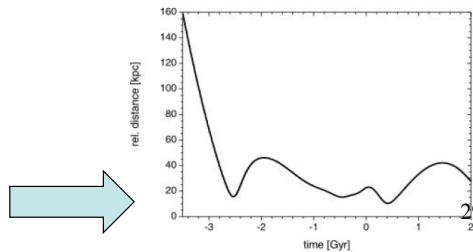
Magellanic stream -tidally removed gas??

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.

R.C. Bruens

29

Dynamical Friction

- Transfer of energy of the forward motion of the galaxies into internal energy (e.g. motion of test particles inside the galaxies)

- this drag force, is called dynamical friction, which transfers energy and momentum from the subject mass to the field particles.

- Intuitively, this can be understood from the fact that two-body encounters cause particles to exchange energies in such a way that the system evolves towards thermodynamic equilibrium.

- The set-up is an infalling galaxy of mass M_s moves into a large collisionless object whose constituents have mass m<< M_s

- 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: $m_1 <v_1^2> = m_2 <v_2^2>$

30

Dynamical Friction Derivation pg 285 S&G

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

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

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

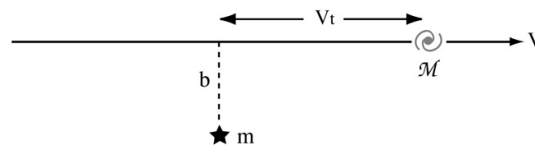notice that the smaller object acquires the most energy which can only come from the forward motion of galaxy M

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

31

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}
- independent of the mass of the particles but depends on their total density- e.g. massive satellite slowed more quickly than a small one

32

Analytic Estimate How Fast Will Local Group Merge?

- Dynamical friction (S+G 7.1.1.MBW sec 12.3, sec 8.1 MBW)-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 $= Mdv/dt \sim 4\pi G^2 M + m)nm/V^2$ (eq 7.8) for particles of equal mass m and number n-so time to 'lose' significant energy-timescale for dynamical friction- **slower galaxy moves, larger its deacceleration a more massive satellite is slowed more quickly**

- $t_{friction} \sim V/(dv/dt) \sim V^3/4\pi G^2 Mm\rho/\ln\Lambda$ (in previous lecture)

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

putting in typical values for LMC

$t_{friction} \sim 3Gyrs$
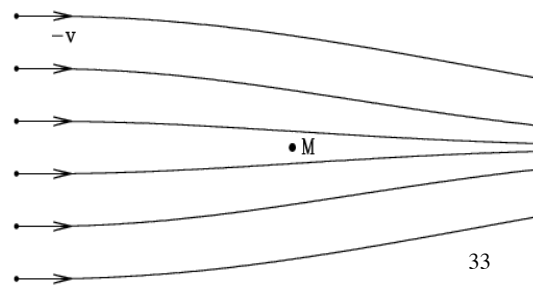
- Accurate estimates of the effects of dynamical friction and the timescale for an orbiting satellite to lose its energy and angular momentum to merge with a host are essential for many astrophysical problems.

- 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)

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.
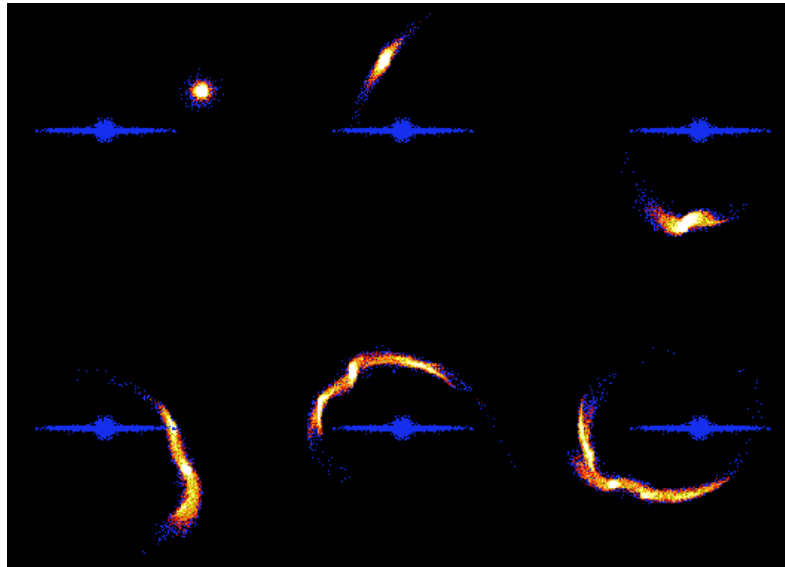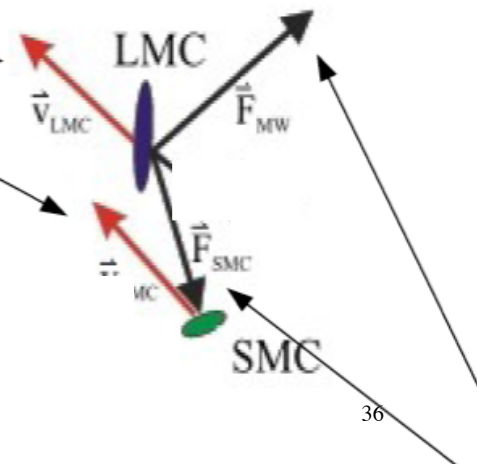
K. Johnston

Need distance to convert angular coord to physical units

Forces on the Magellanic Clouds

Space Velocity

Dynamical friction vectors depend on shape and size

LMC

$\vec{v}_{LMC}$ $\vec{F}_{MW}$

$\vec{F}_{SMC}$

MC

SMC

To get orbit to 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
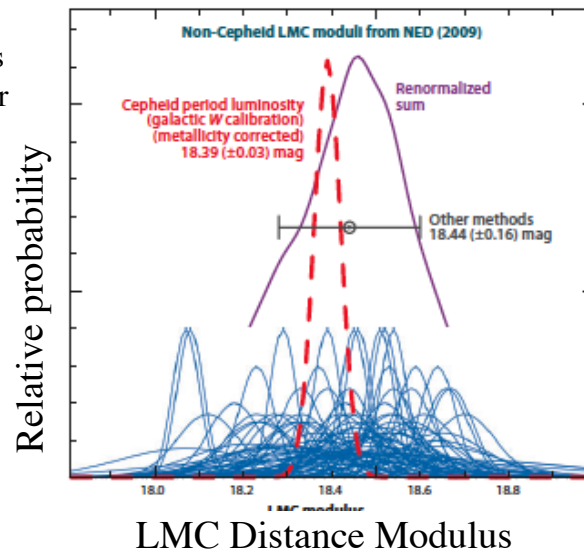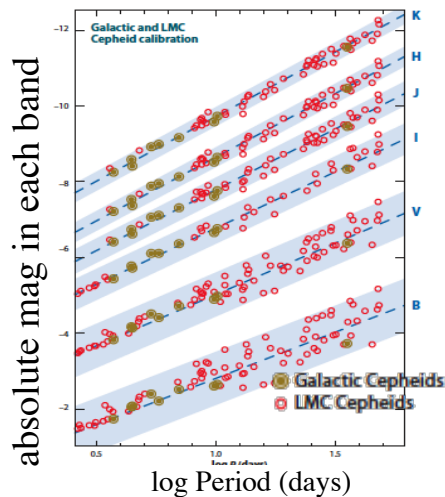
Distance to LMC

- 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)


LMC Distance Modulus

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


37

Rotation of the LMC New result from Gaia

- Each vector shows motion of stars over next 7.2Myr
- Big vector is overall motion of LMC (van den Marel and Sahlmann 2017)
- Proper motion is ~ 1mas/yr and velocities are in km/sec to connect the 2 need distance.
- Fit gives m-M=18.54 mag or D=

38
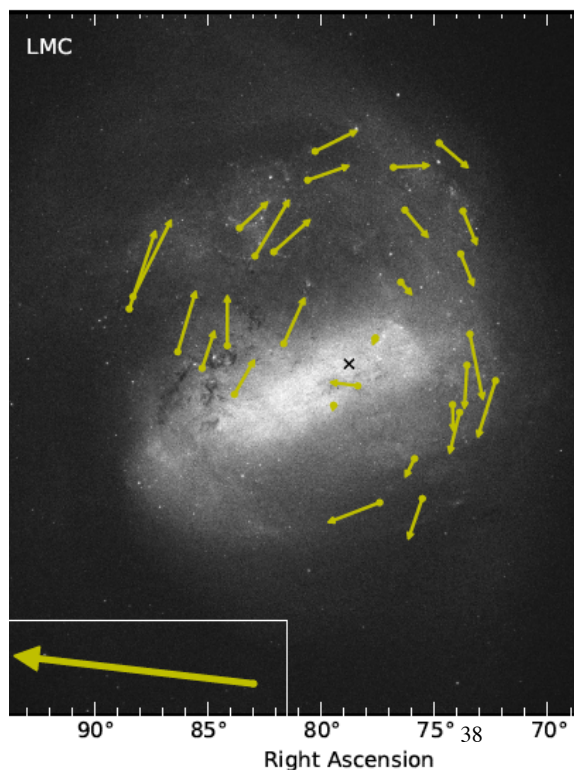
Cosmic Rays and γ-rays

- LMC, SMC and M31 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

Spitzer Image of LMC

γ-ray intensity scale
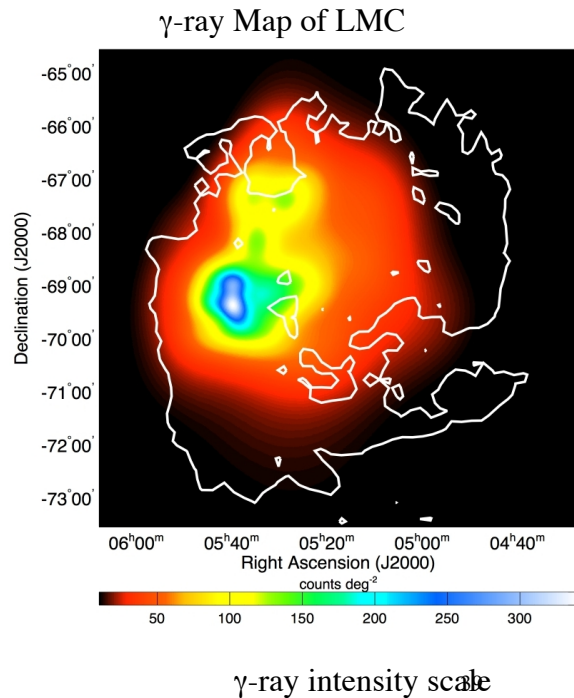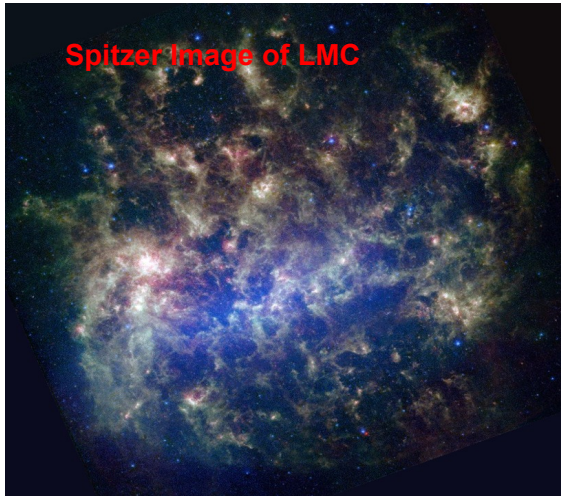
LMC Cosmic Rays and γ-rays

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
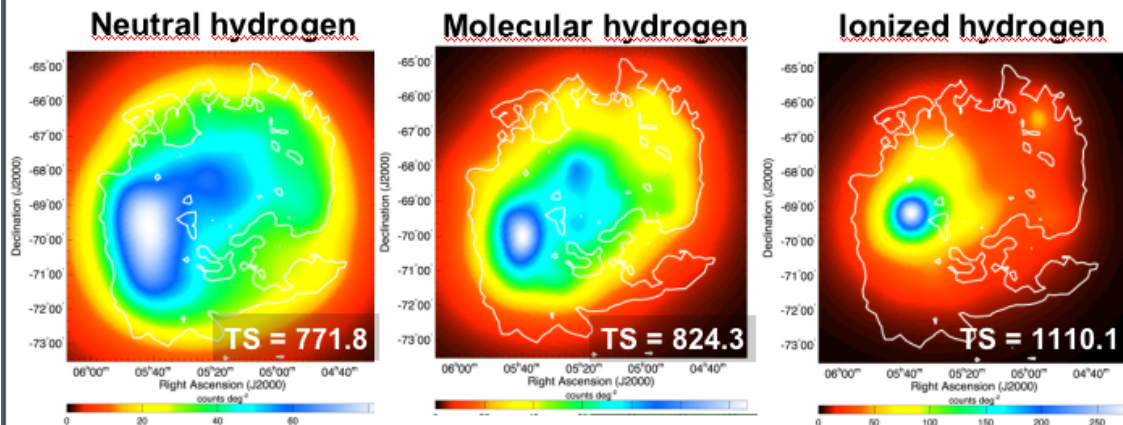

- **Neutral & molecular hydrogen templates poorly fit the data**
- **Ionized hydrogen template provides best fit**

Dermer 2011   40

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*

- local group best place 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

41
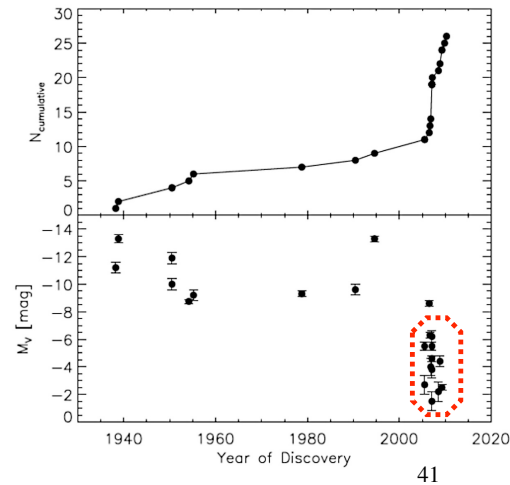
Number of Satellites around MW- Observed vs Theoretical

- 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*


42
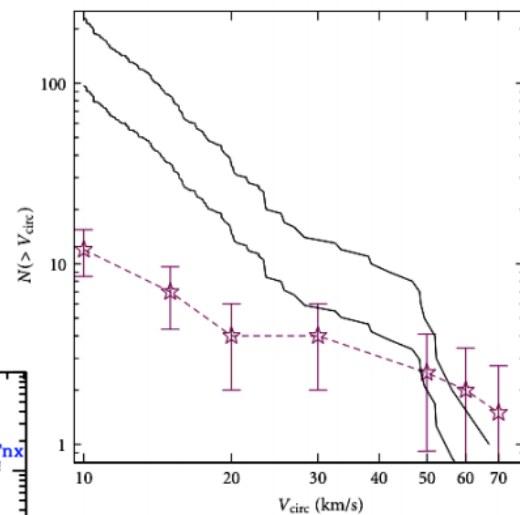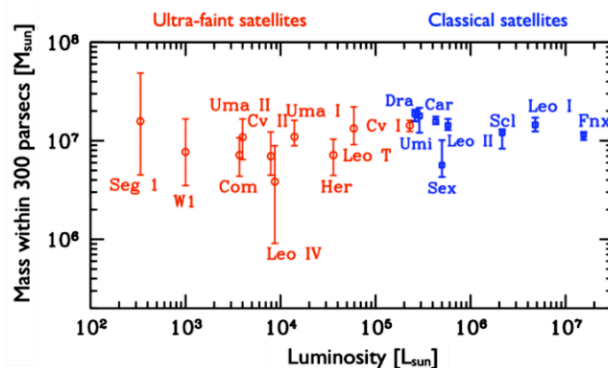
Where are the Satellites of MW?-Bullock 2010

- 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
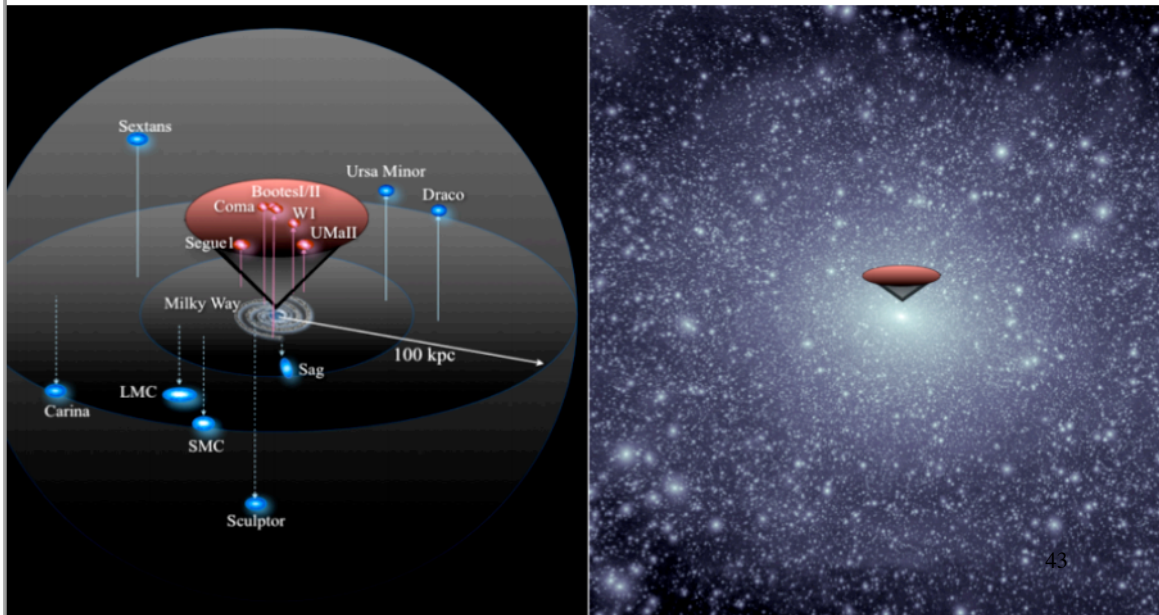

Dwarfs

- 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

M/L_V

M_v (mag)
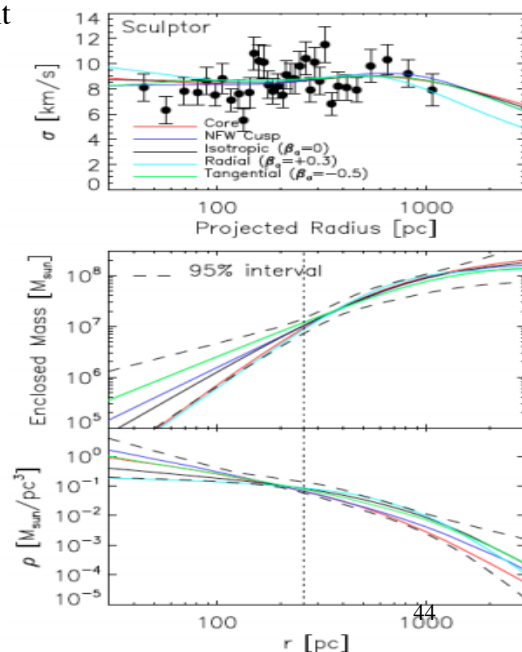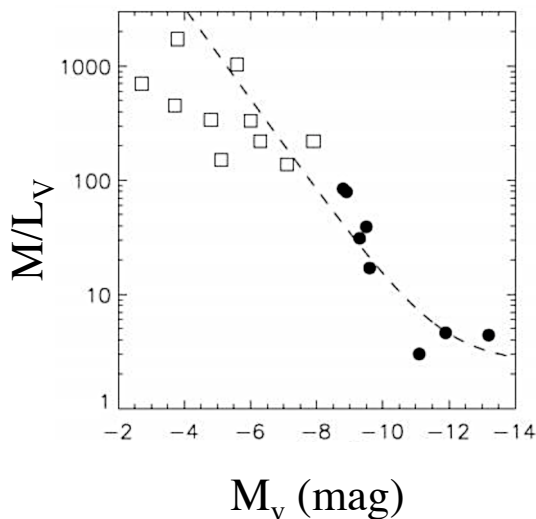
Dwarfs

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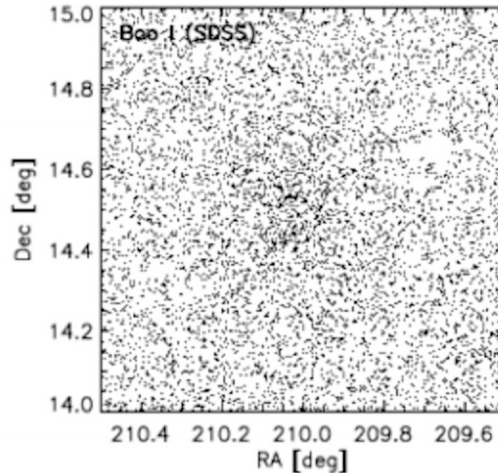
Local Group Summary

- 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

M31 and the MW

- the Milky Way and M31 have different properties
- M31 shows a lower star formation rate (SFR) than the Milky Way
- M31 appears to be a more typical spiral galaxy than the Milky Way (Hammer et al. 2007).
- M31 shows evidence for a formation and evolution history affected by merging and/or accretion events, including substructures in its halo- MW does not
- scale length of 6kpc is 3x that of the MW (2.3 kpc) but similar rotation curve.
- stellar mass $M_{star} \sim 10.3 \times 10^{10} M_\odot$ for M31; disk $7.2 \times 10^{10} M_\odot$ and bulge $3.1 \times 10^{10} M_\odot$
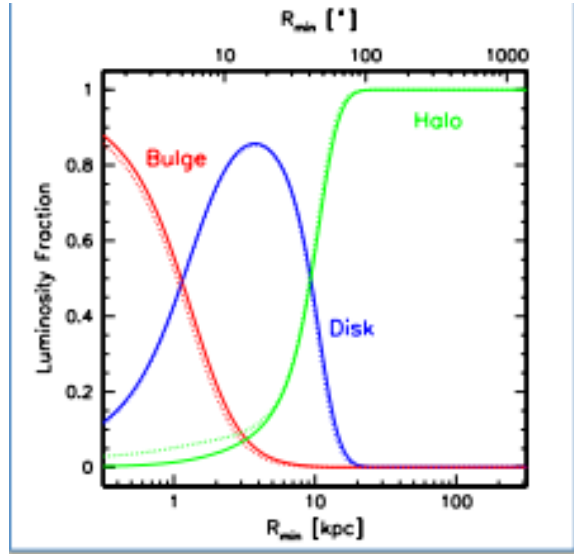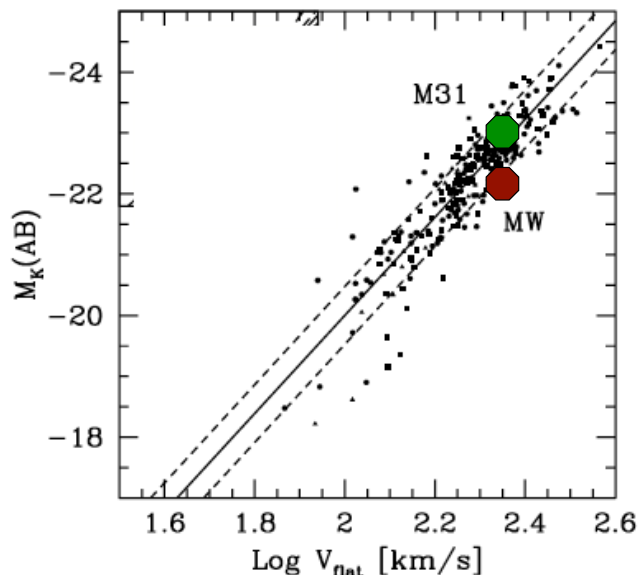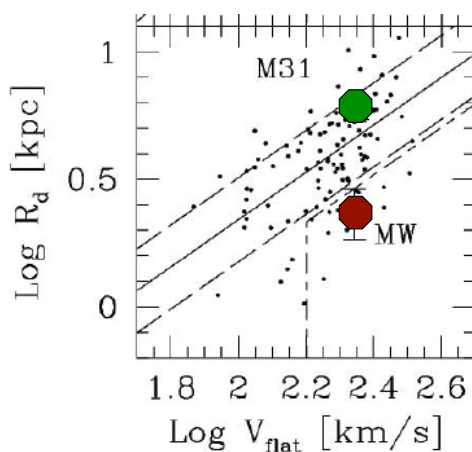

decomposition of M31
Courteau 2012

Tully Fisher Relation

- The relationship of luminosity to rotation speed for spirals-
- M31 and MW have similar v_{rot} but factor of 2 different luminosities and scale lengths - MW is more discrepant from large statistical samples


M31, compared to the Milky Way, has 2 x more stellar mass and 2.5 x more specific angular momentum
Hammer 2007

Comparison of Metallicity of Halo Stars in M31 and MW

- The vastly different chemical compositions of the halo of MW and M31 indicate different formation histories or processes EVEN in the Local Group

- Comparison of observed metallicities to theoretical yields from a closed box approx (S+G 4.13-4.16) indicates outflow of enriched material
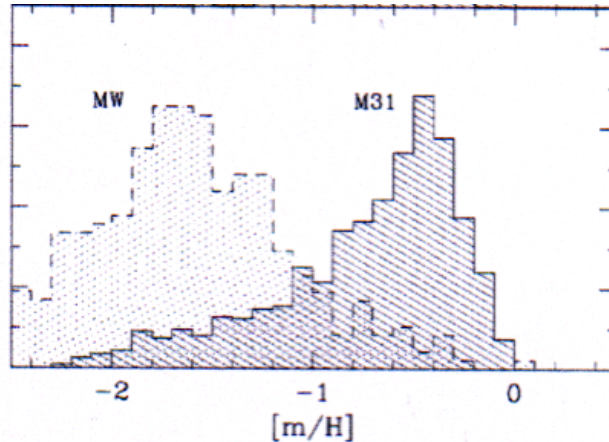
• Halo of M31 = Andromeda (Durrell et al. 2001)

• Halo of the Milky Way (Ryan & Norris 1991)

49

Mass Models For M31

- Several different potential forms give reasonable fits to velocity data; differ in 'total' mass by <50%- probable detection of drop in v_{circ} at large R.

- the merging history of a galaxy, together with its star formation history, and mass re-arrangement (such as gas flows or stellar radial migration) is written in its structure, stellar ages, kinematic and chemical-elemental abundance distribution functions.
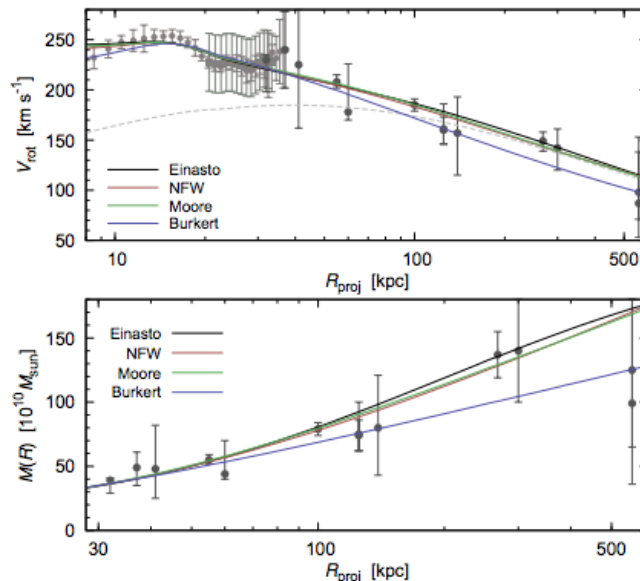
- .

**Fig. 6.** Outer rotation curve observations and models (*upper*

50

Comparison of Rotation Curve for MW, M31,M33

- Black is total curve blue is bulge (*notice no bulge in M33*), green is DM and red is disk

- observed maximum circular velocity for each galaxy: $V_c \approx 239$ kms at the solar radius for the MW, $V_c \approx 250$km/s for M31 $V_c \approx 120$ kms M33

- S+G says that M31 has a higher rotation velocity, latest data on MW has changed that ! Notice where DM becomes dominant- 22 kpc for M31, 18kpc for MW, 8kpc for M33
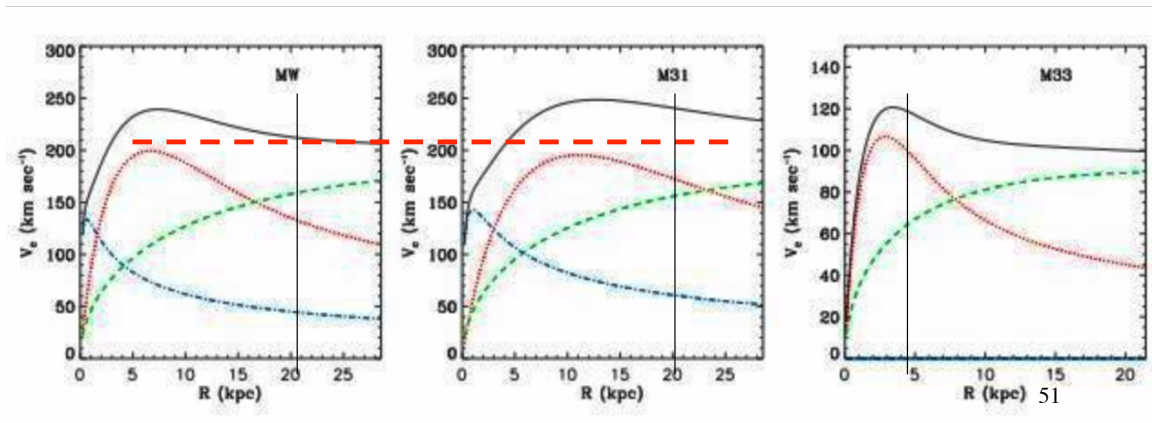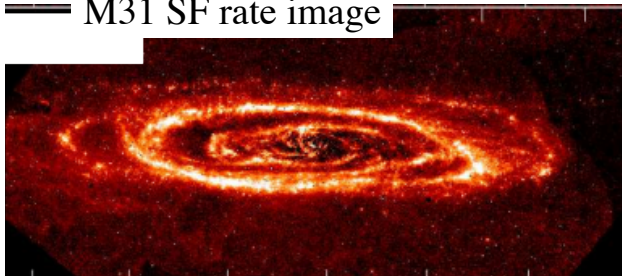

Star Formation in M31,M33

- the specific star formation rate in M31 is less than in the MW with a present rate of ~0.6M/yr.

- the SF is concentrated in a ring 10kpc out

- M33 on the other hand is vigorously forming stars 0.45M/yr all over
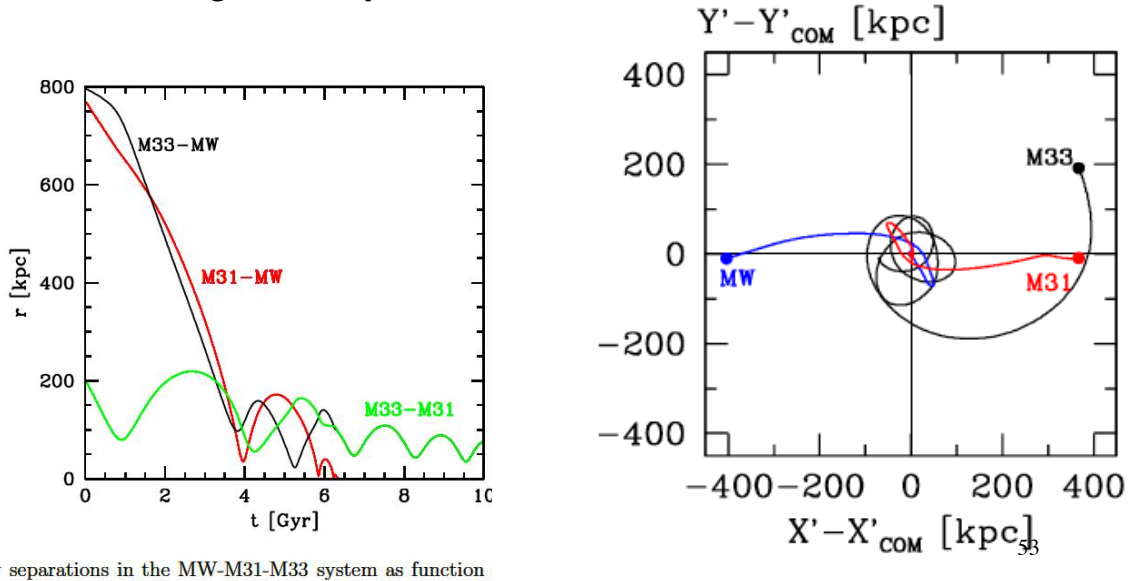

M33 SF rate vs radius
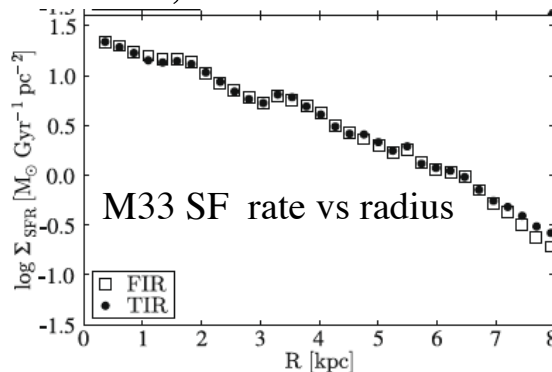
M33 UV and IR images

M31 SF rate image

The future of the local group (S+G 4.5)

- It seems clear that M31 has had a much more active merger history than the MW- so beware of close by objects
- given what we know about the mass of M31, M33 and MW they will all merge in ~6Gyrs (van den Maerl 2012)

separations in the MW-M31-M33 system as function

The future of the local group (S+G 4.5)

- Orbit of the LMC depends on mass of the MW and how it grows with time
- Kallivayalil give orbital periods of ~4Gyr
- The assumption that

the Magellanic Clouds constitute a long-lived binary pair implies that the Clouds are likely on their first infall about the MW.
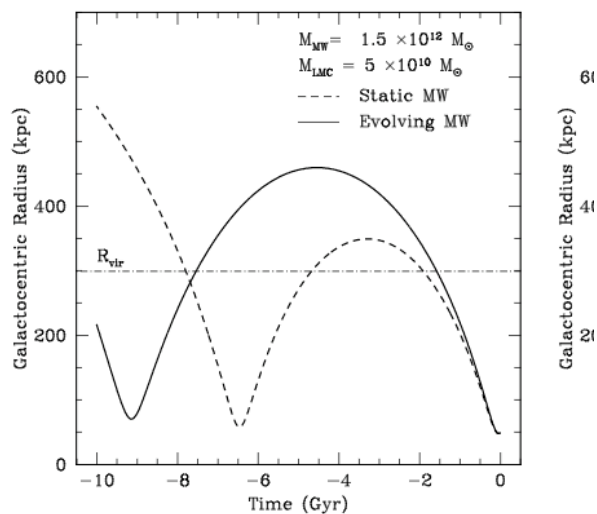

Figure 11. *Left:* the LMC Galactocentric radius as a function of time i

54

Timing Argument for Mass of MW and M31

- the two galaxies are now approaching each other. assume that (i) the two galaxies were formed close together, (ii) that their combined mass was sufficient to make them a bound unit, and (iii) that they have performed the larger part of at least one orbit with a period of no more than 15 Gyr.

- Simple radial orbit and simple Keplerian dynamics shows that the mass of the (M31–Milky Way) system is about 20 times larger than the masses of the stars of the two galaxies.

Local Group timing argument sec 4.5 S&G

- Use dynamics of M31 and the MW to estimate the total mass in the LG.
- the radial velocity of M31 with respect to the MW ~-120km/sec e.g. towards MW presumably because their mutual gravitational attraction has halted, and eventually reversed their initial velocities from the Hubble flow.
- neglect other galaxies in LC, and treat the two galaxies as an isolated system of two point masses.

- assume orbit is radial, then Newton's law gives $dr^2/dt^2 = GM_{total}/r^2$
- Period of orbit less than age of the universe:
  - Kepler's Law $P^2 = 4\pi a^3/GM$
- radial orbits (no net ang Mom) so $GM/2a = [GM/d] - E_k$; d=distance to center of mass and E_k is KE/unit mass

derive total $M > 1.8 \times 10^{12} M_\odot$

timing argument

- $M_{total}=3.66\times10^{12}\,M_{\odot}$ and mass MW ~1/3 of total
- $R_{halo}=GM_{MW}/V^2_c=G*10^{12}/(220km/s)^2=90kpc$
- If, the rotation speed drops at large R, then R_{halo} is even bigger
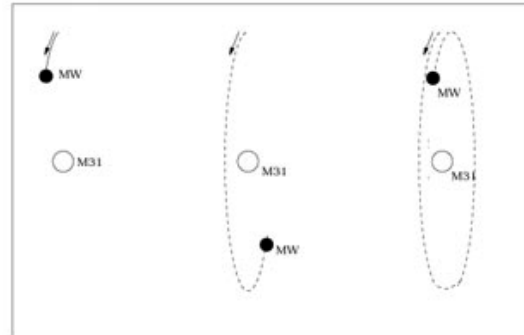
57

M33

- M33 is almost unique in having very tight constraints placed on the presence of a supermassive black hole in its nucleus.
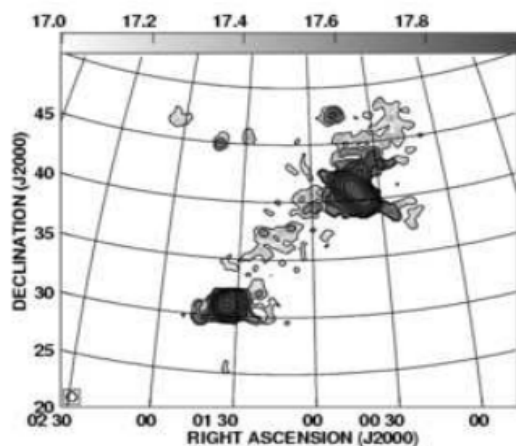
- It is probably tidally involved with M31-220kpc away

$M_{disk,stellar}\sim3.8\times10^9 M_{\odot}$
$M_{bulgek,stellar}\sim1\times10^8 M_{\odot}$
$M_{virial}\sim2.2\times10^{11} M_{\odot}$

Fig. 9. Integrated H I emission from the subset of detected features apparently associated with M31 and M33. The grey-scale

HI image of sky around M33 notice connecting stream to M31

58

Black Holes

- It is now believed that 'all' massive galaxies have super massive black holes in their nuclei whose mass scales with the bulge properties of the galaxies
- What about the smaller galaxies in the local group?
- Search for BHs 2 ways
  - dynamics
  - presence of an AGN (active galactic nucleus)
- <u>None</u> of the Local group galaxies host an AGN (today)
- Of the small galaxies <u>only</u> M32 shows *dynamical* evidence for a black hole (van der Maerl 2009) of M~2.5x10^6 M$_\odot$ for a galaxy of luminosity -16.83 compared to -21.8 for M31 (100x less luminous) **which has a similar mass BH**- M32 is spheroidal (all bulge)
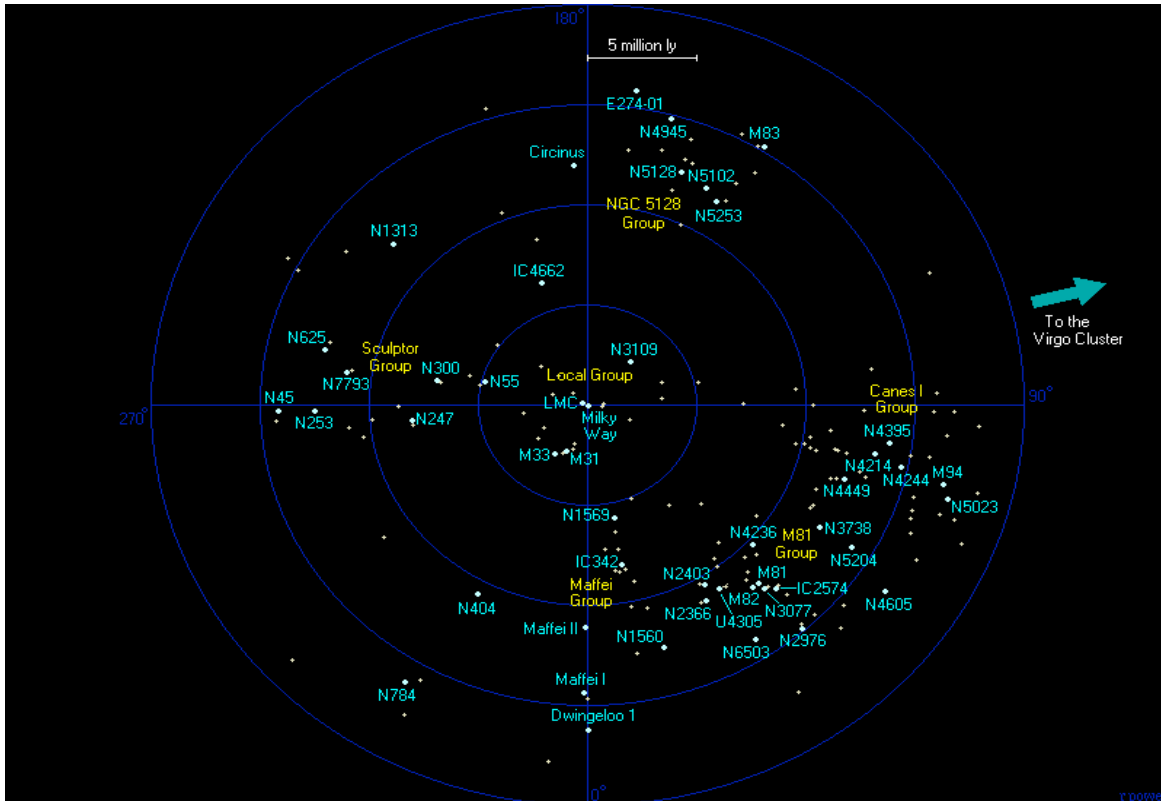
		M$_{BH}$(M$_\odot$)	M$_{bulge}$(M$_\odot$)	
M33	Scd	< 3 x 10^3	1.5 x 10^8	
NGC205	E	< 2.4x10^4	2.7 x 10^8	satellite of M31
M32	E	~2.5x10^6	~2.5x 10^8	satellite of M31

- Black hole mass vs bulge velocity dispersion σ
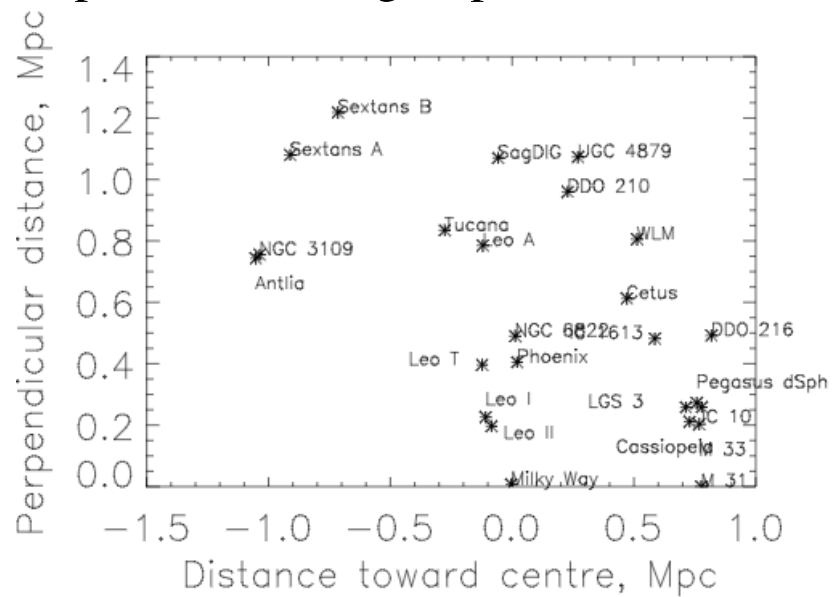- Local group galaxies ☐

Gultekin et al 2009
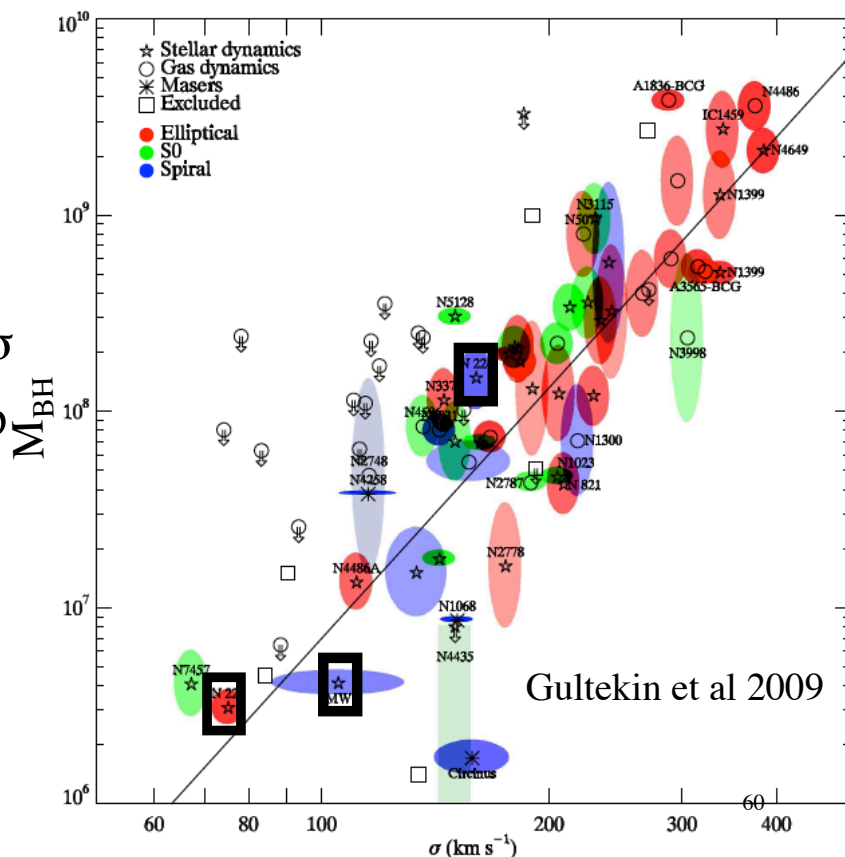
Beyond the Local Group

Map of the Local group

- the kinematics of the Local Group is not well-sampled by the visible galaxies.
- their sparseness and asymmetry managed to fool statistical techniques of moderate sophistication (Whiting 2014)

Local Volume of Space

As indicated by CDM simulations the universe is lumpy
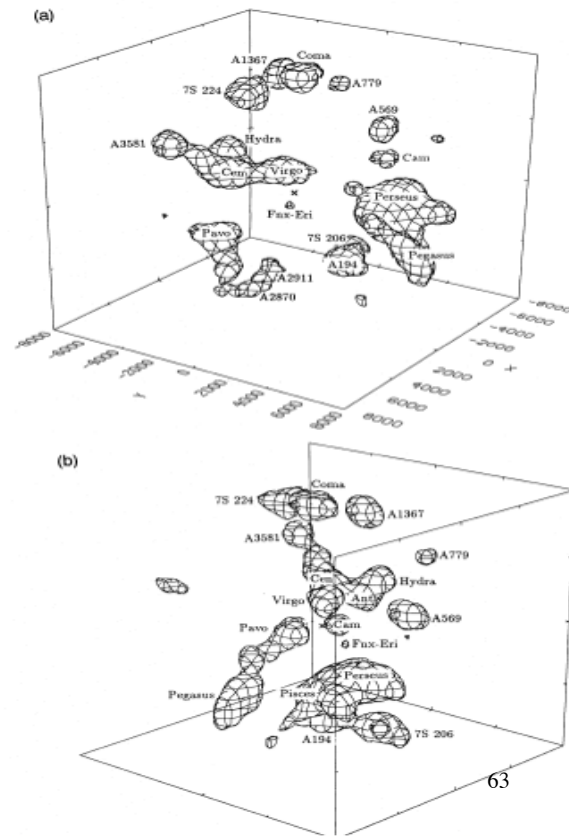
Here is a 'map' (Hudson 1994) of the nearby universe

Objects labled 'A' are rich clusters

other massive clusters are labeled Virgo Coma, Cen, Perseus
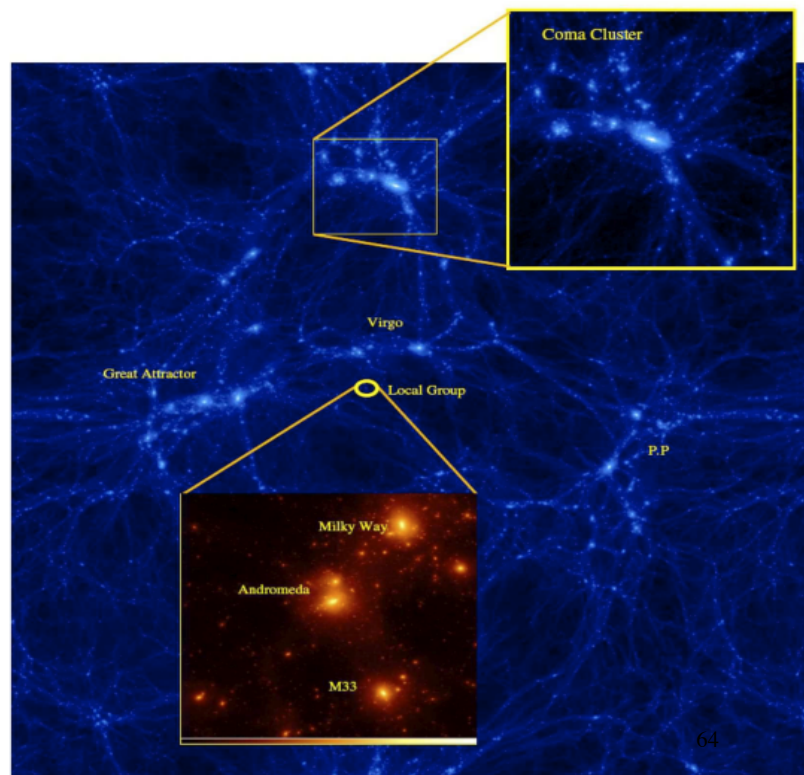
of galaxies from Abells catalog - axis are labeled in velocity units (km/sec)

Notice filamentary structure.

Constrained Realization

- In order for numerical galaxy formation models to 'work' properly need to sample a large volume of space.

- Constrained to have properties of Local group

Where is the Local Group

- This visualization shows our "Local Universe", as simulated in the constrained realization project.
- The Local Group is in the centre of the sphere. In the initial orientation of the sphere, the Great Attractor is on the left, and the Cetus Wall on the lower right.
- Credit: Volker Springel
- Simulation code: Gadget

Summary of Today's Lecture Local Group

- Introduction of Tully-Fisher scaling relation- how to compare galaxies- much more in discussion of spirals next week.
- Discussion of detailed properties of M31, M33 comparison to MW; differences in how they formed; MW very few 'major mergers' M31 more; not all galaxies **even those close to each other do not have the same history.**
- Dynamics of local group allow prediction that M31 and MW (and presumably the Magellanic clouds) will merge in ~6 gyr
- A supermassive black hole exists in the centers of 'all' *massive* galaxies- properties of BH are related to the bulge and not the disk of the galaxy
- Use 'timing argument' to estimate the mass of the local group (idea is that this is the first time MW and M31 are approaching each other and the orbit is radial) use 'simple' mechanics to get mass
- Local group is part of a larger set of structures- the 'cosmic web' galaxies do not exist in isolation