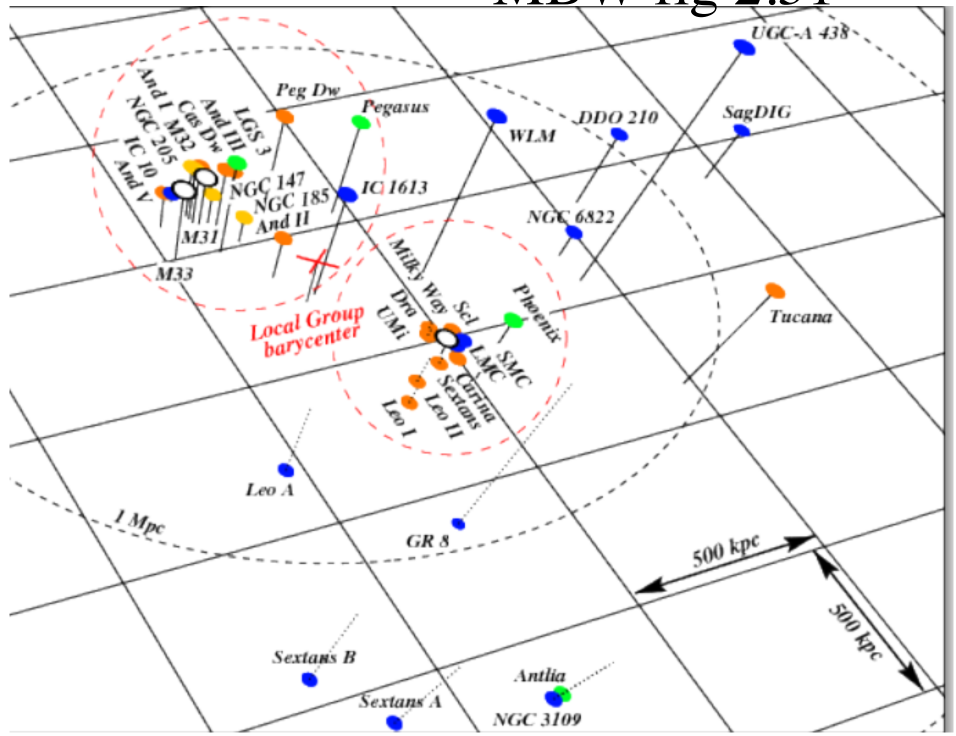
Local Group See S&G ch 4 MBW fig 2.31



- Our galactic neighborhood
  - '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.
New Astronomy Reviews, v. 49, iss. 7-9 p. 453-460.

e, Oct 29

THE KEY TO GREAT teaching IS SETTING CLEAR EXPECTATIONS AND PERIODICALLY REVISING THEM AS CONDITIONS CHANGE.
Dilbert.com DilbertCartoonist@gmail.com
IF YOU PLAN TO REVISE EXPECTA– TIONS, THAT TELLS ME YOU KNOW THEM TO BE FAULTY NOW.
10-29-13 ©2013 Scott Adams, Inc.
MAYBE.
STOP INSPIRING ME SO MUCH.

Dwarf Galaxies

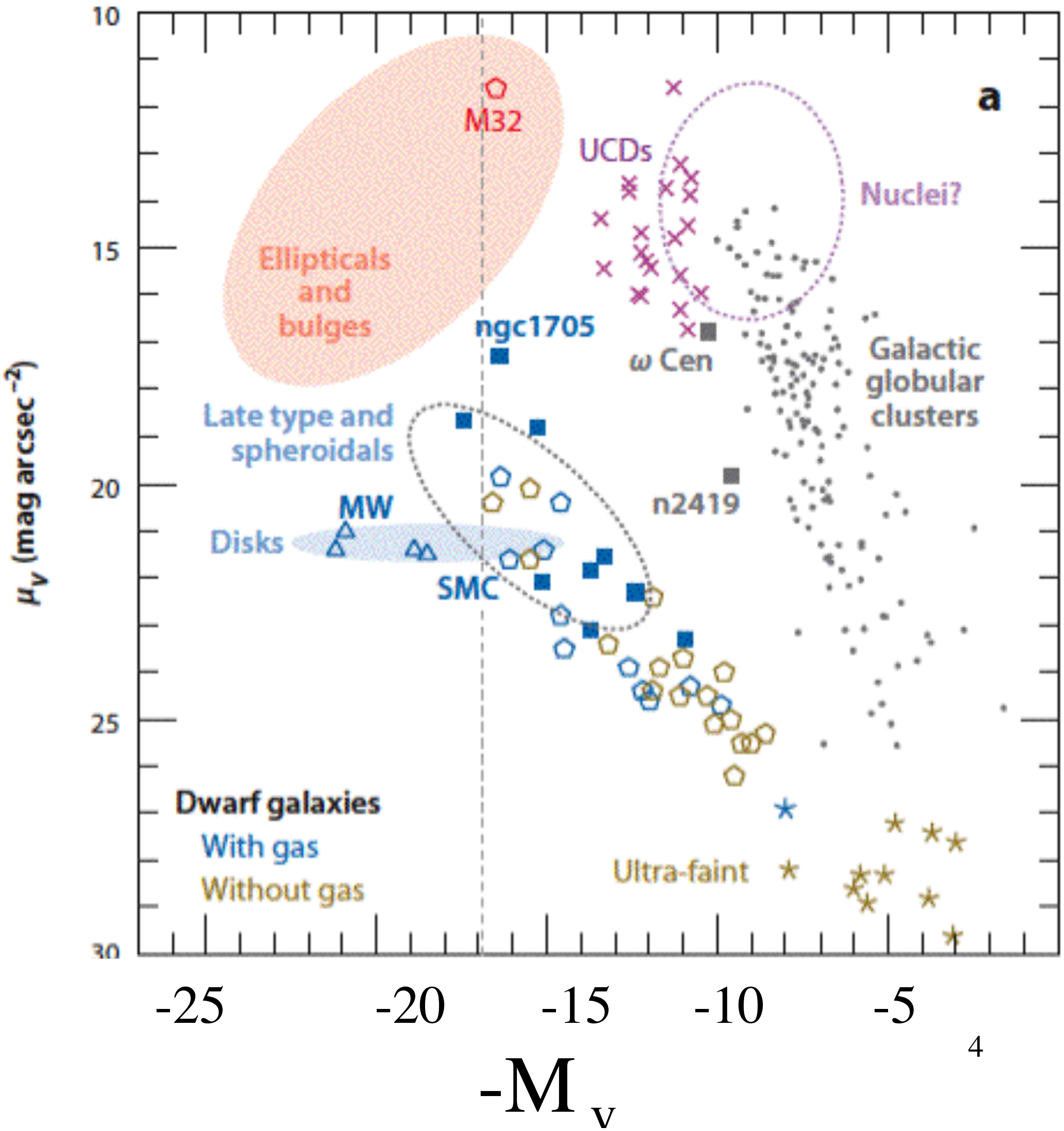
- Dwarf galaxies are commonly used as probes of a *simple* “single cell” star-forming environment.
- They cover a range of mass and metallicity and may be representative of how galaxies in the early universe may have looked.
- Spectroscopic studies using large ground-based telescopes have allowed the determination of abundances and kinematics for significant samples of red giant branch (RGB) stars and more massive O, B and A stars in several local group galaxies
- as with larger systems, the global properties of dwarf galaxies correlate well with luminosity, half-light radius and surface brightness.
- Dwarf galaxies thus allow us to study specific aspects of galaxy formation and evolution on a small scale.

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-ASP Conference Series, Vol. 445 The Local Group: Inventory and History)

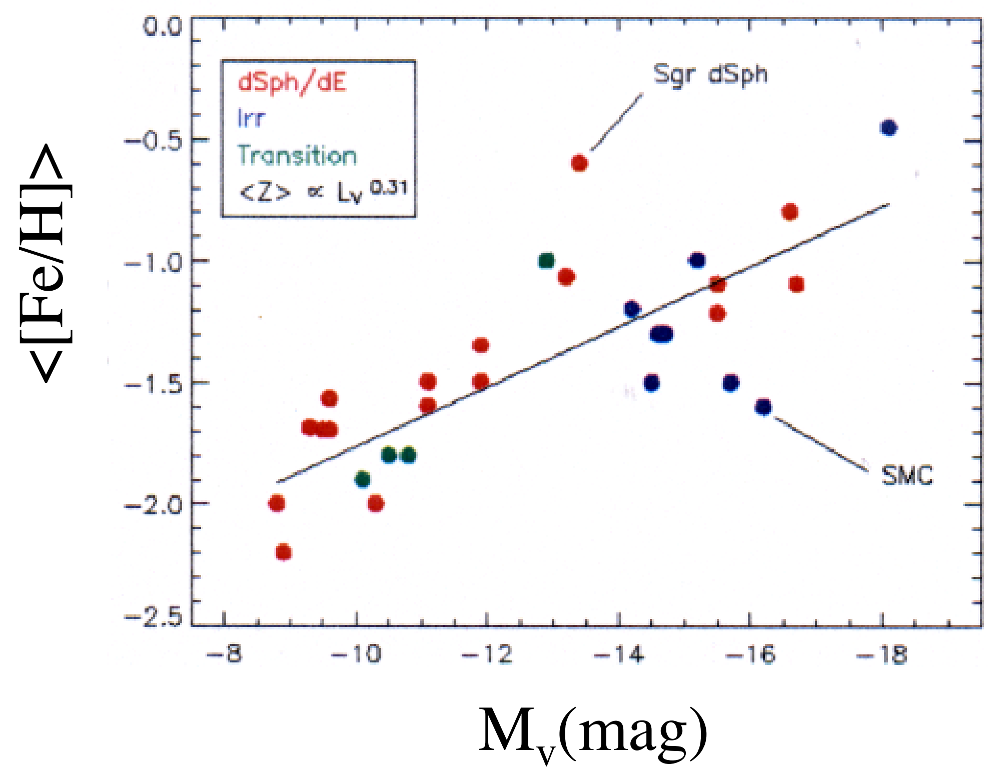
- This is one cut through the fundamental plane: notice separation of different types of stellar systems



Wide Range of Luminosities

- MW/M31~$2x10^{10}L_{v\odot}$
- LMC~$2x10^{9}L_{v\odot}$
- Formax dSph $1x10^{7}L_{v\odot}$
- Carina dSph $3x10^{5}L_{v\odot}$

- 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



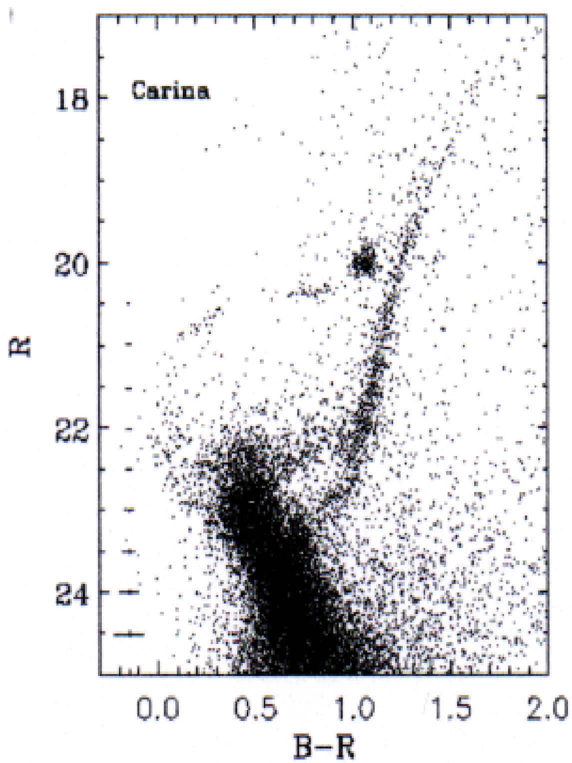
T. Smecker-Hane

Despite wide variety of 'local' environments (near/far from MW/M31) trends in chemical composition depend primarily on galaxies properties- the correlation between mass and metallicity continues to higher masses

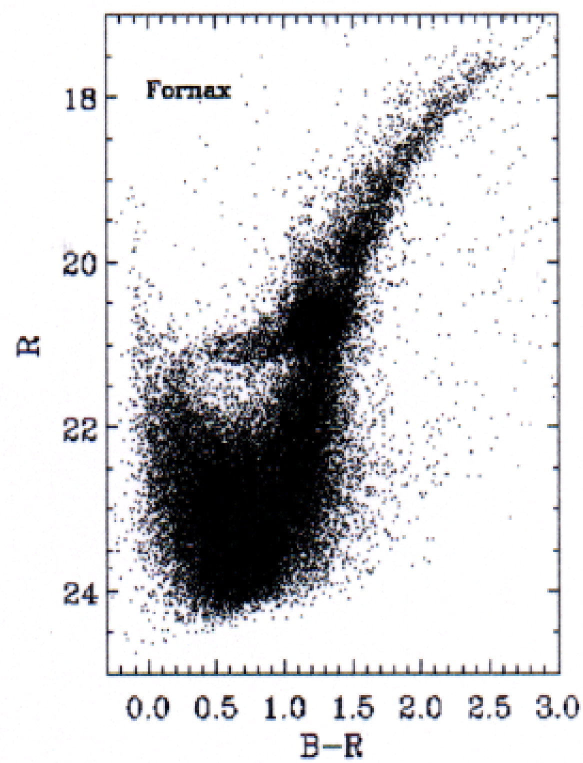
Star Formation Histories

- Analysis of CMDs shows presence of both old and (some) young stars in the dwarfs -complex SF history
- The galaxies do not 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.

Carina galaxy

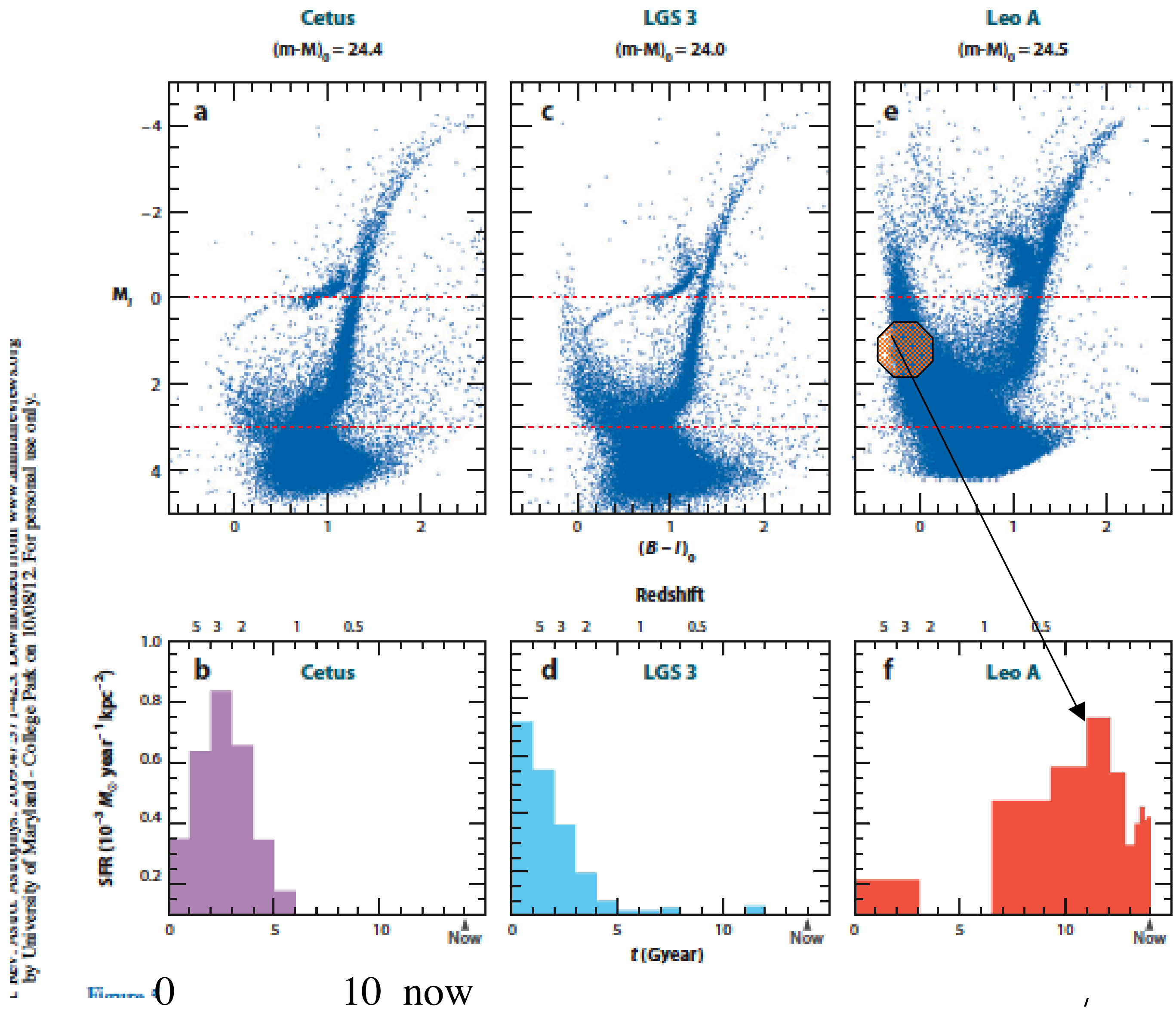


Fornax dwarf



Star Formation Histories Local Group Dwarfs

- With HST can observe 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

t (Gyr)

Star Formation History of MW -
Fraternali arxiv :1310.2956

How can star formation be sustained? 3

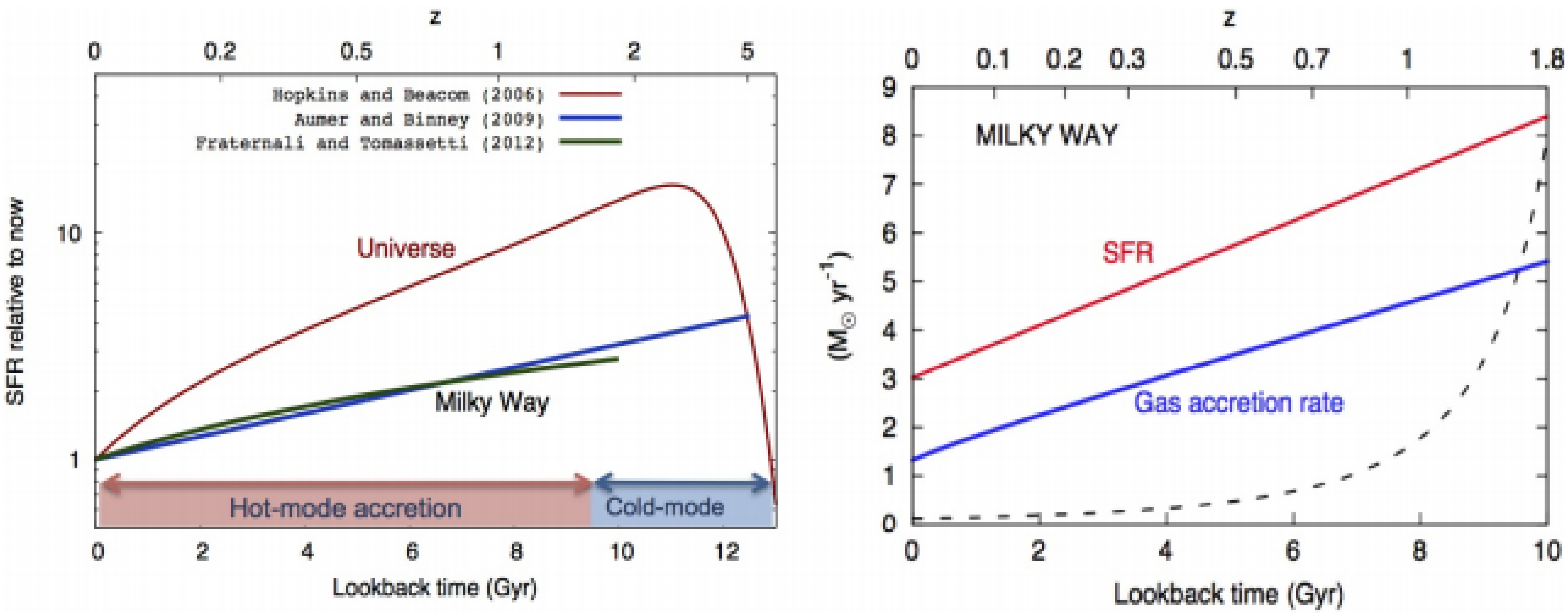
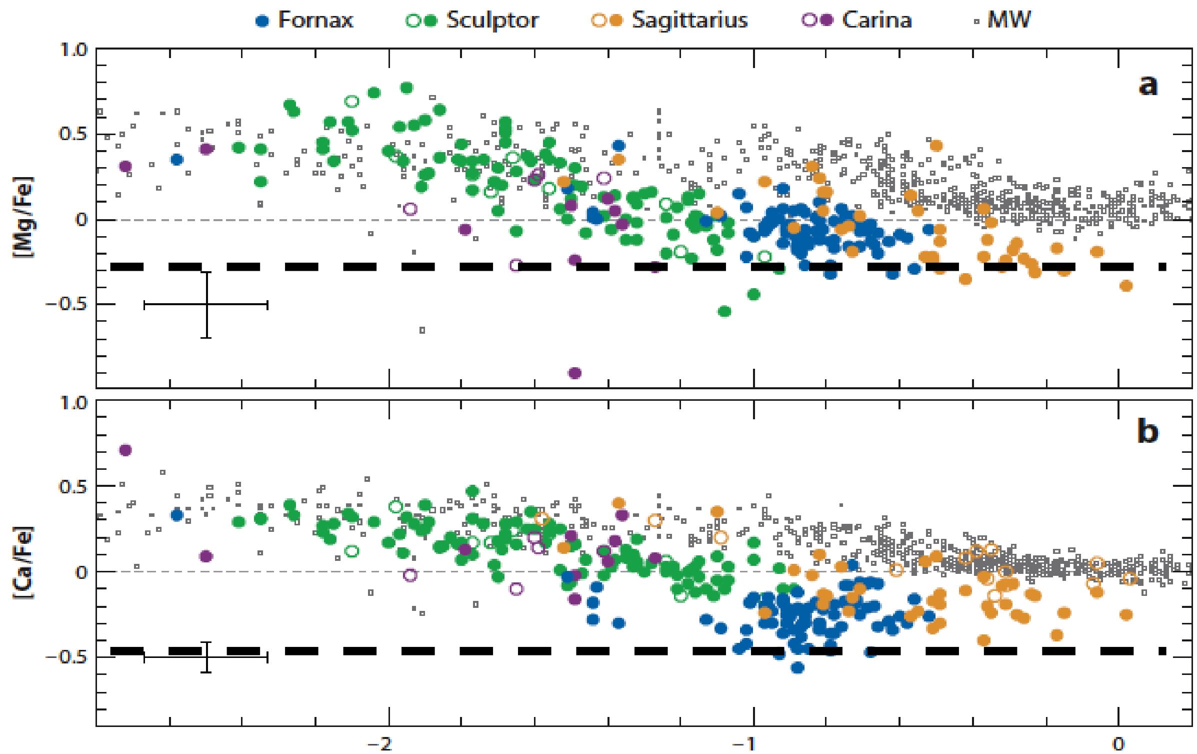
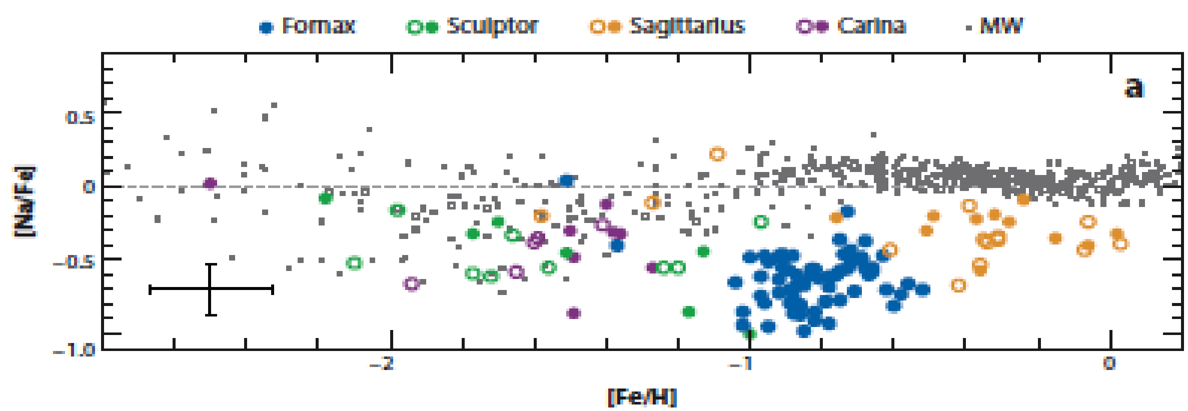


Figure 1. *Left:* comparison between two determinations of the SFH of the Milky Way (Aumer & Binney 2009; Fraternali & Tomassetti 2012) and the average star formation rate density of the Universe (Hopkins & Beacom 2006). The three distributions are normalized at the current time. *Right*: reconstruction of the SFH of the Milky Way's disc and the gas accretion rate required by the Kennicutt-Schmidt law (see Fraternali & Tomassetti 2012); the dashed line shows the evolution of a closed-box galaxy starting with the same initial amount of gas.

Metallicities In LG Dwarfs Vs MW

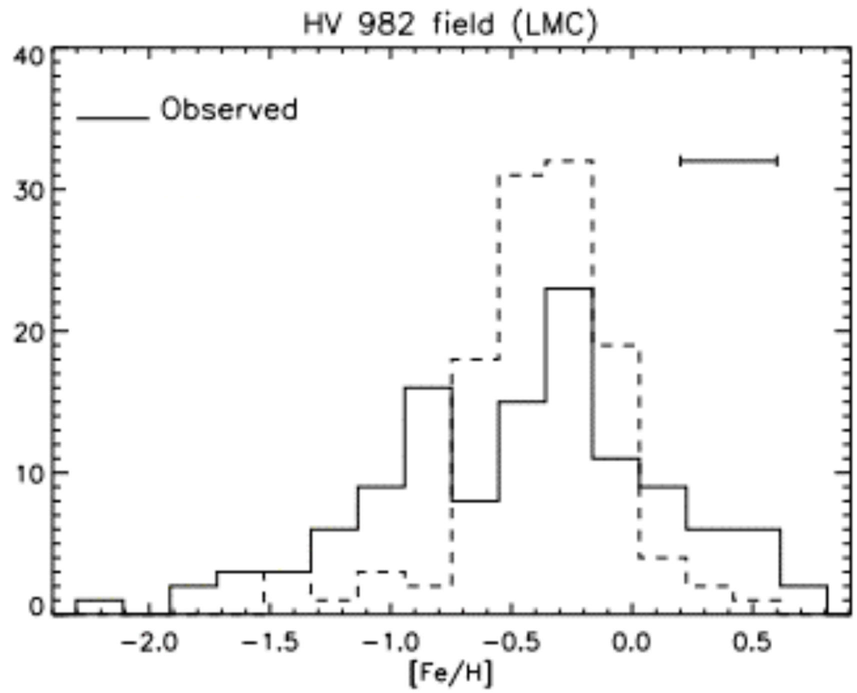
- Overall metallicity of LG dwarfs is low but some patterns similar, others different to stars in MW (black dots- Tolstoy et al 2009)- different SN??
- How to reconcile low observed metallicity with the fairly high SFR - many of which are actively star-forming
- best answer metal-rich gas outflows, e.g.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

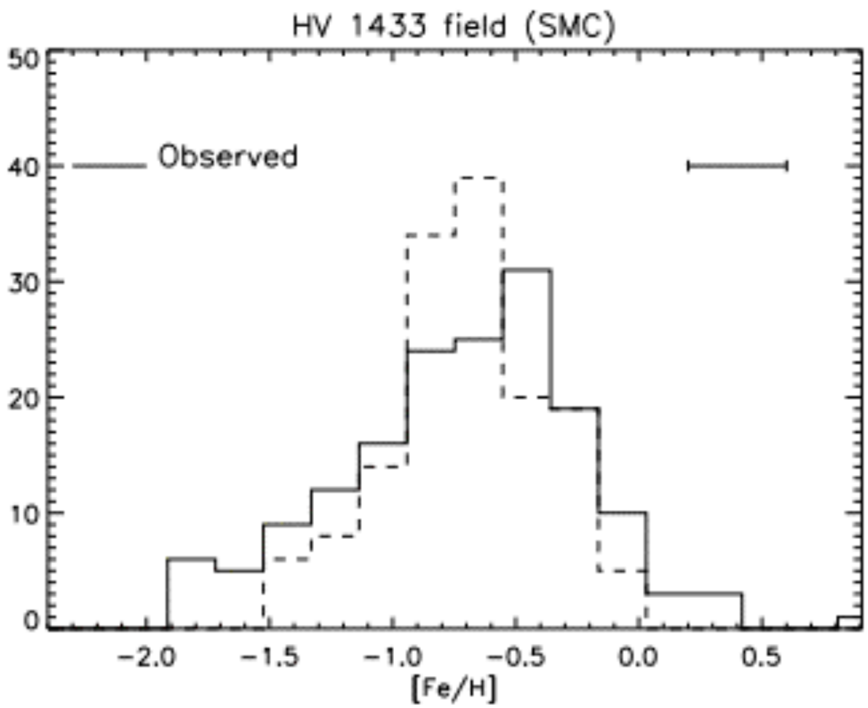




Chemical Evolution

- The one zone no infall or outgo model while analytic (S&Geq 4.13-4.16) does not really represent what has happened
- LMC and SMC are more 'metal poor' than the MW or M31; [Fe/H]~-0.35 and -0.6 respectively - but with considerable variation from place to

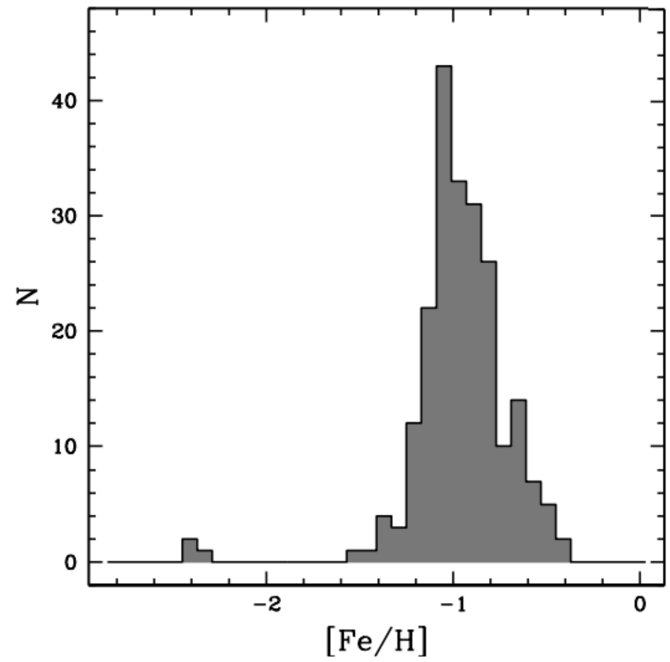


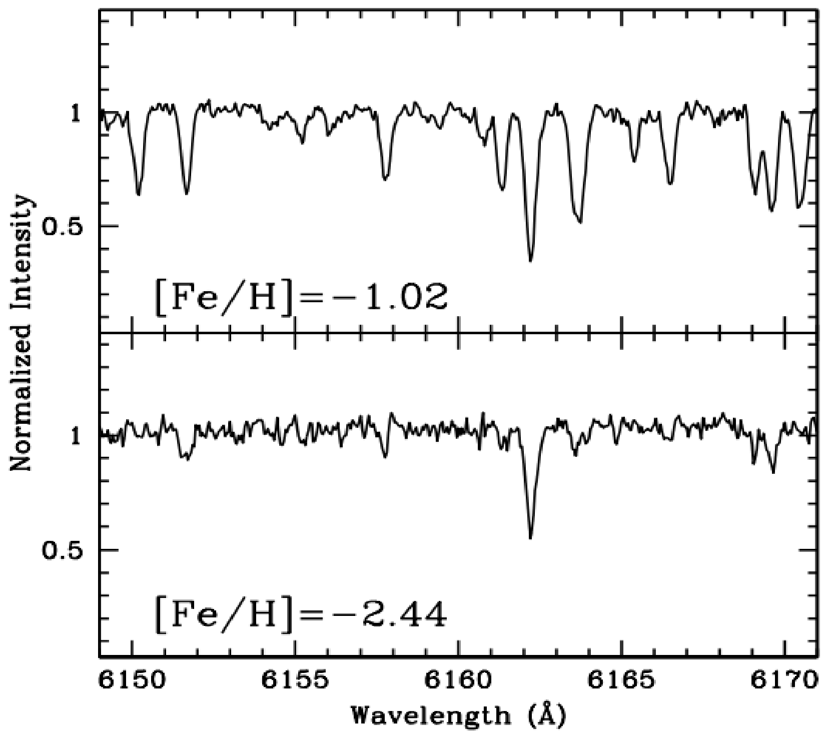


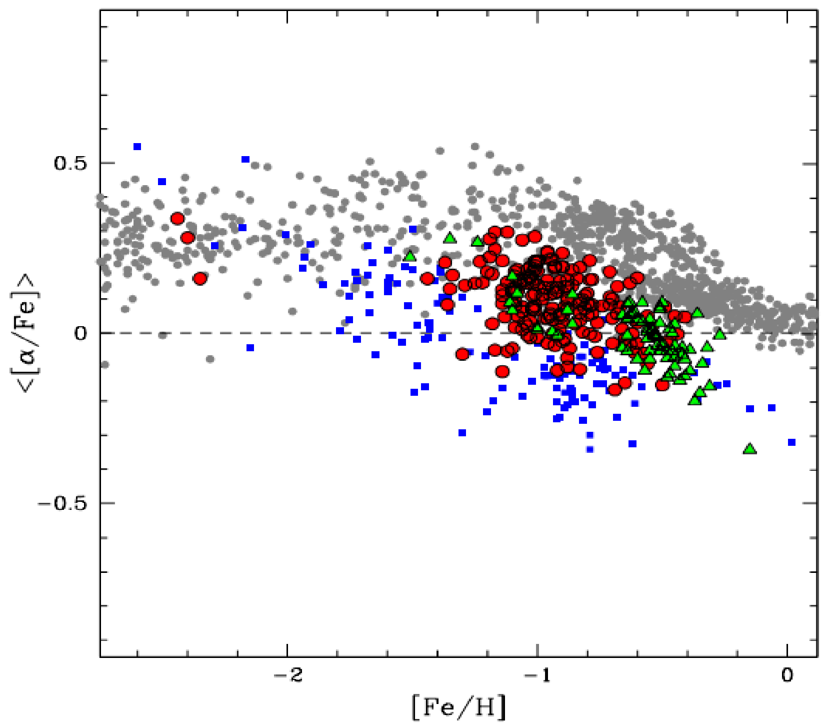
In general line of trend for less massive galaxies to be more metal poor (but large scatter)

SMC Metallicity

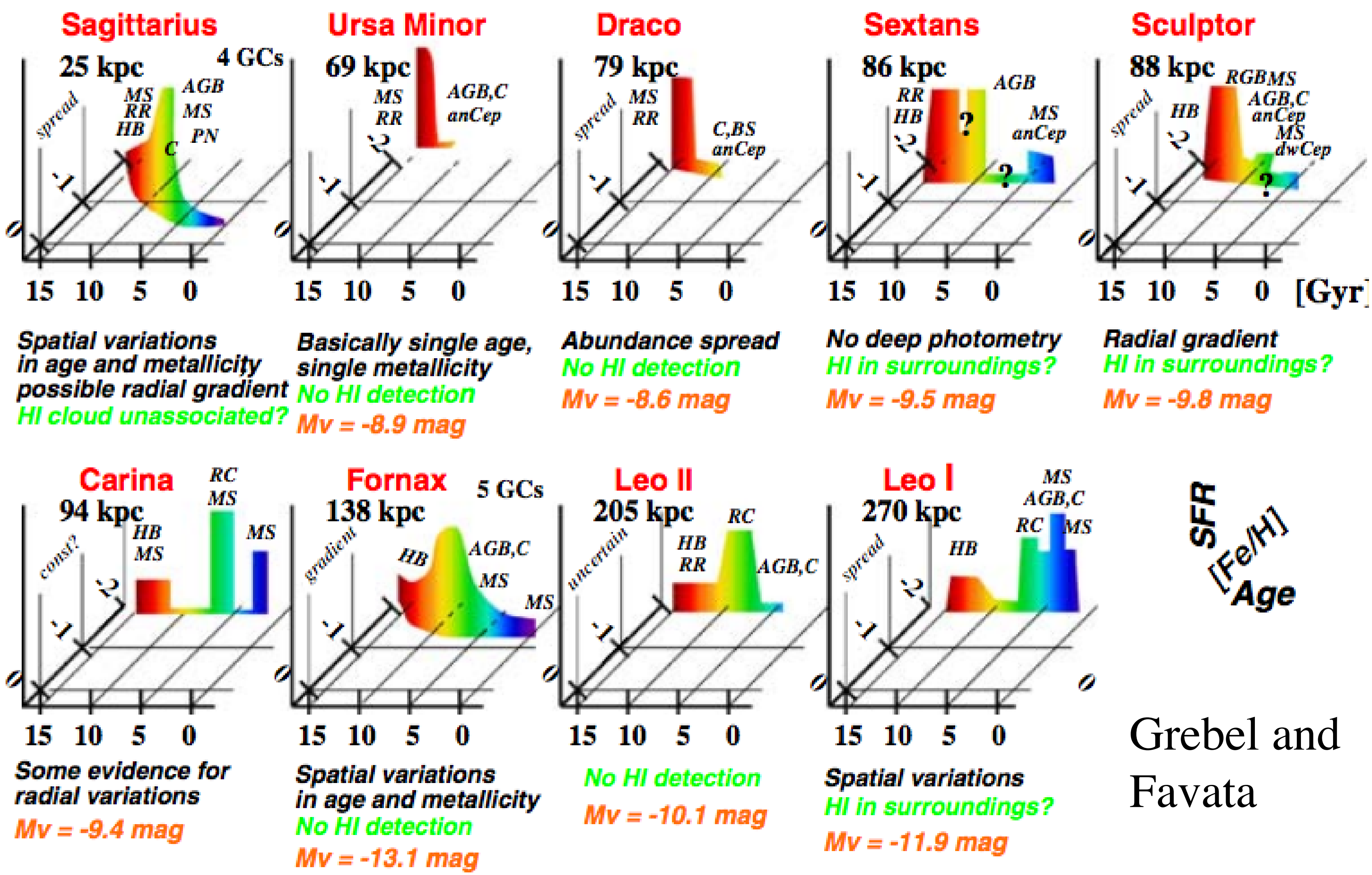
- Resolved stars in the SMC (Mucciarelli et al arxiv 1310.6888)
- SMC has a a complex star formation history
- Even though overall metallicity is sub-solar [α/Fe] is solar
- e SMC giant stars in red, LMC green, MW grey, other Local group dwarfs blue





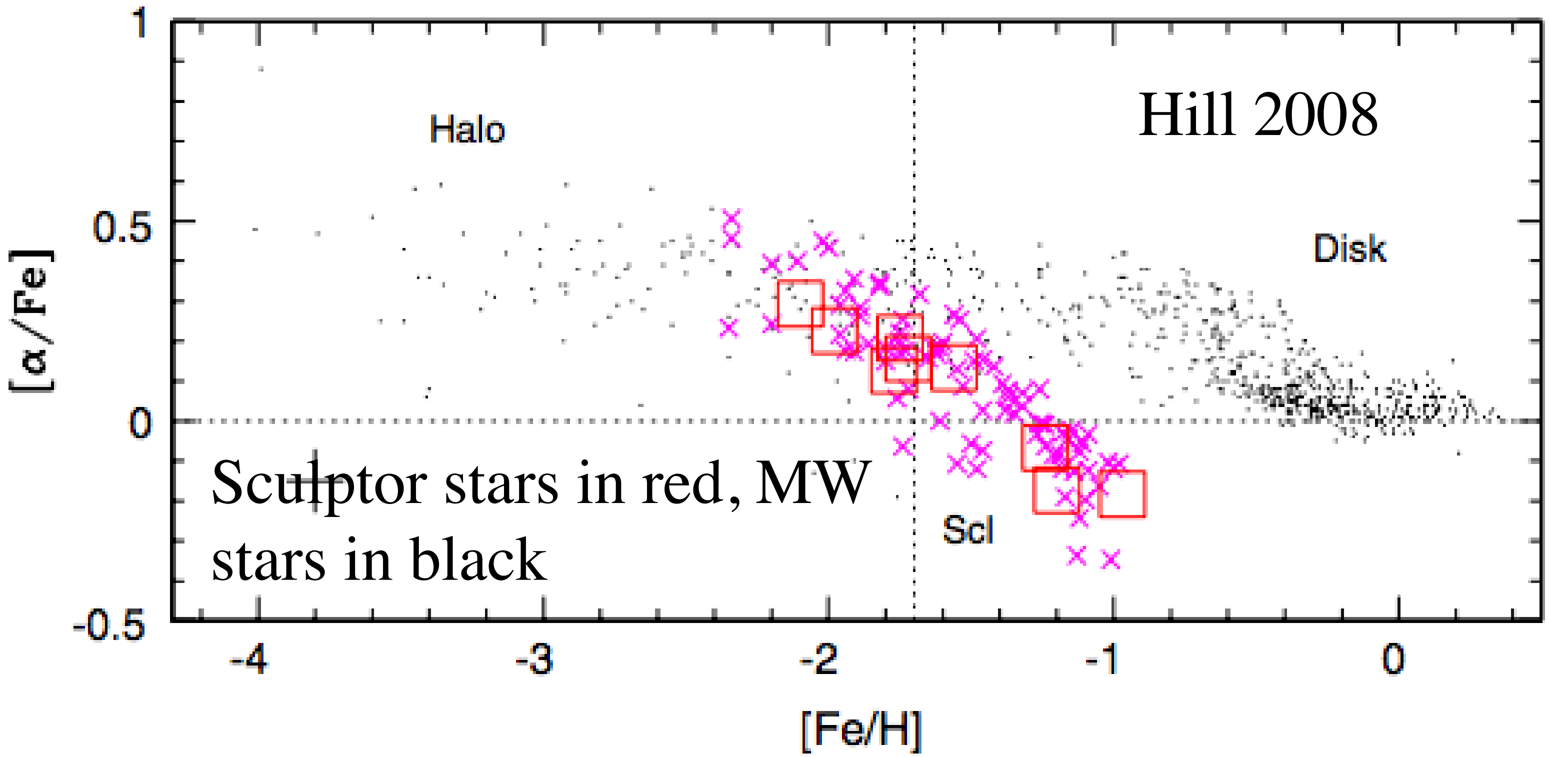


History of SFR In Local Group Dwarfs



Grebel and Favata

Abundances in Local Group Dwarfs

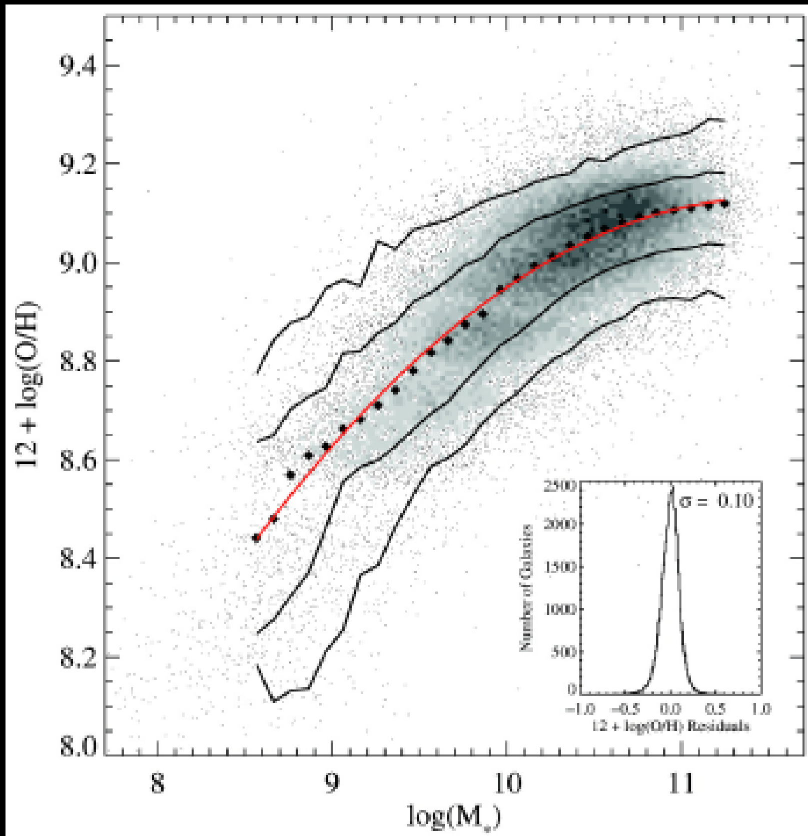


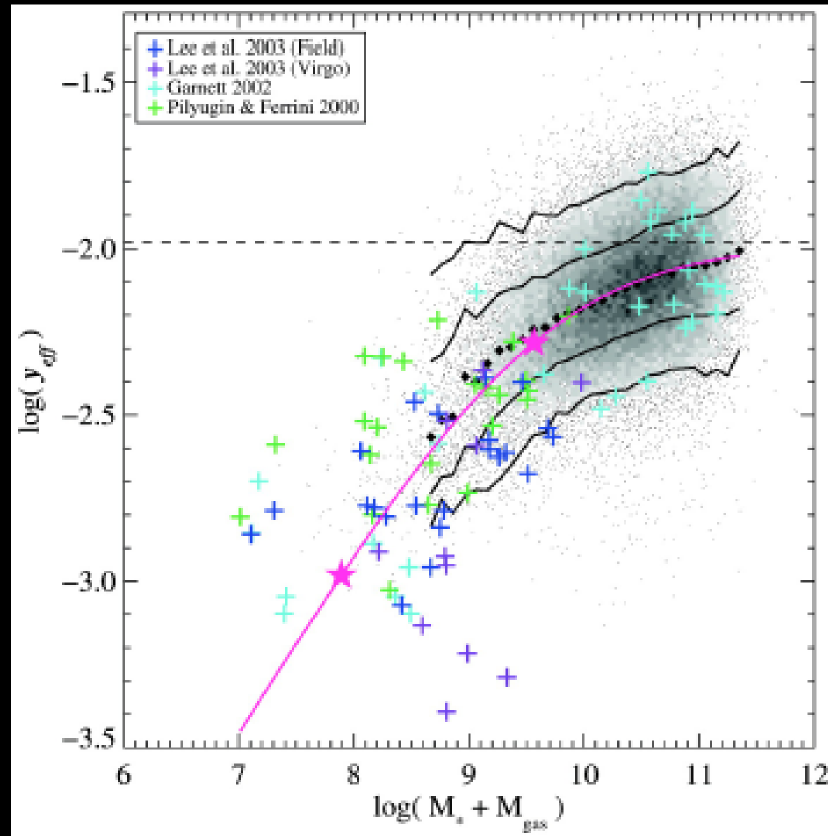
- Clear difference in metal generation history- will discuss in more detail in next lecture on chemical evolution

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: $Z(t) = Z(0) - [\,y/(1+c)] * \ln[M_g(t)/M_g(0)]$ (here assume $Z(0) = 0$)



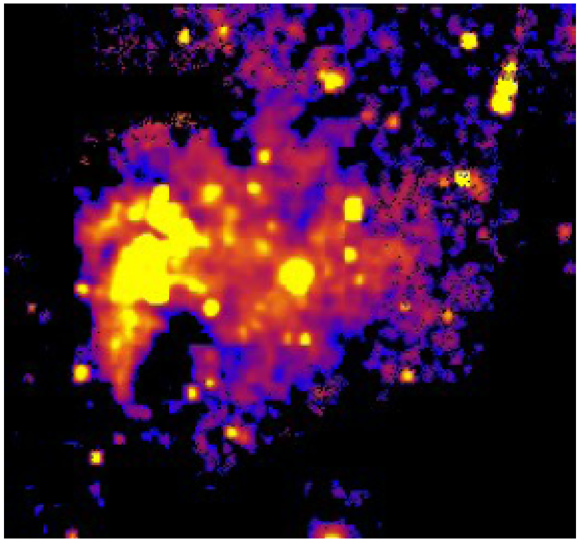


(e.g., Garnett+02; Tremonti+04; Kauffmann+03)

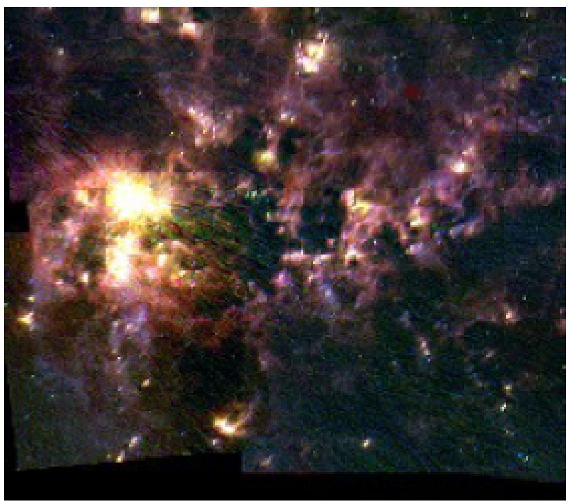
The LMC

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

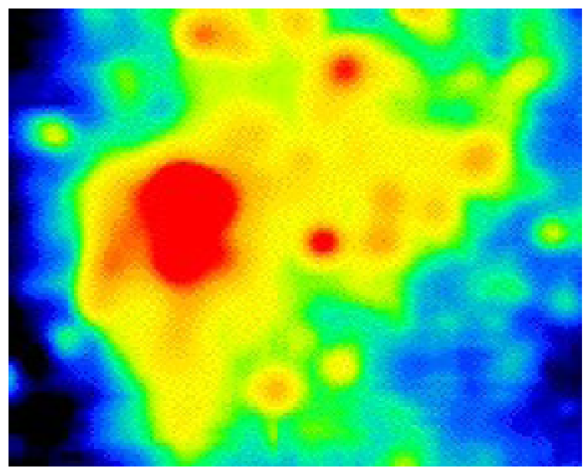
Xray: ROSAT



AAO optical 3 color



IRAS (Jason Surace)

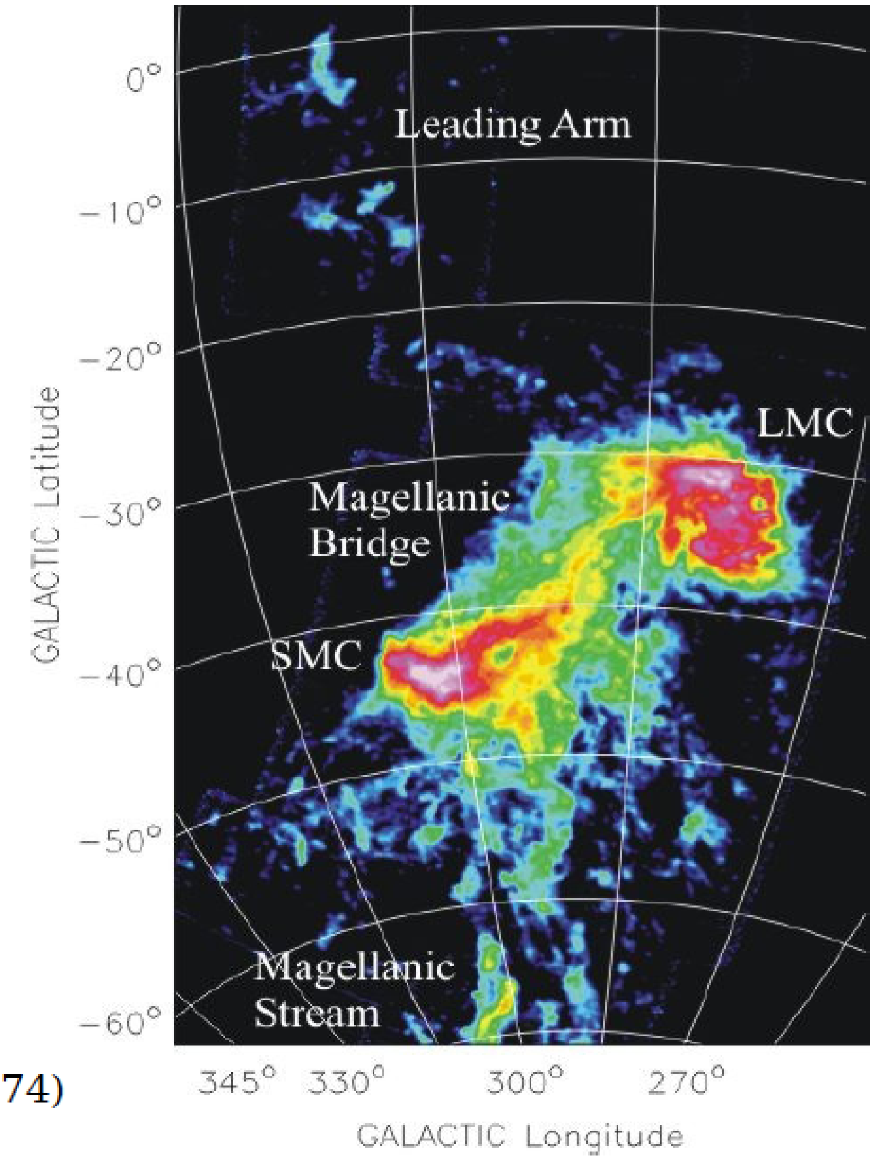


Radio (RAIUB/MPIFR Bonn

Each image is about 4°.5 on a side

- 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 $M_{gas} \sim 0.6\times10^{9}\ M_{\odot}$ (~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??

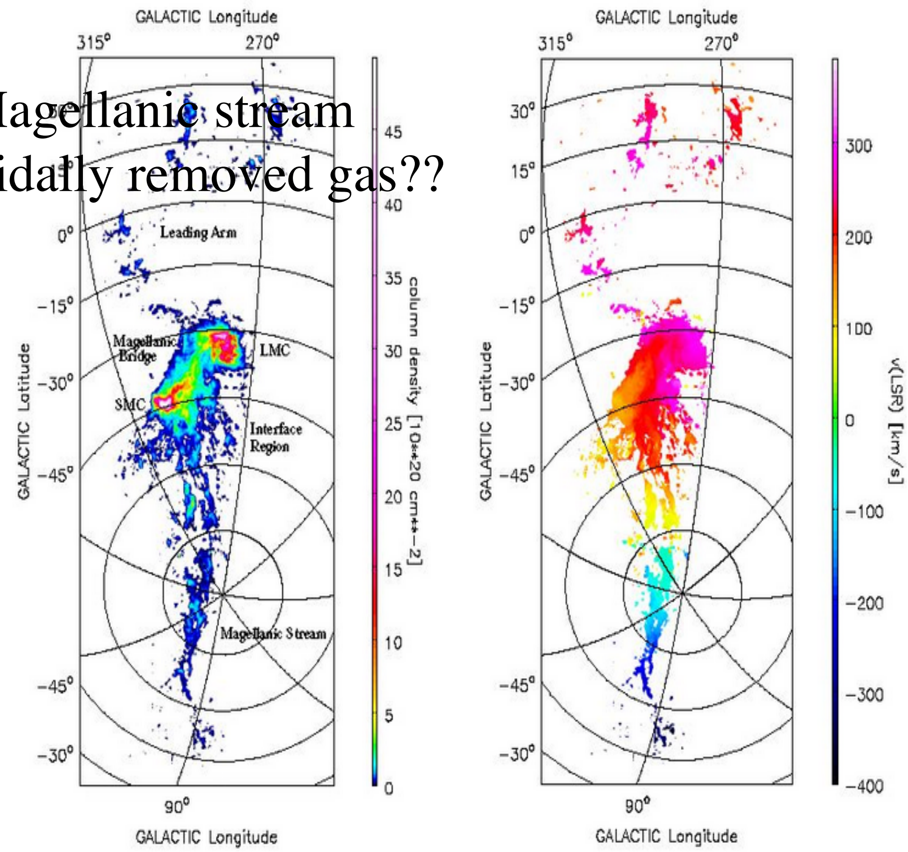
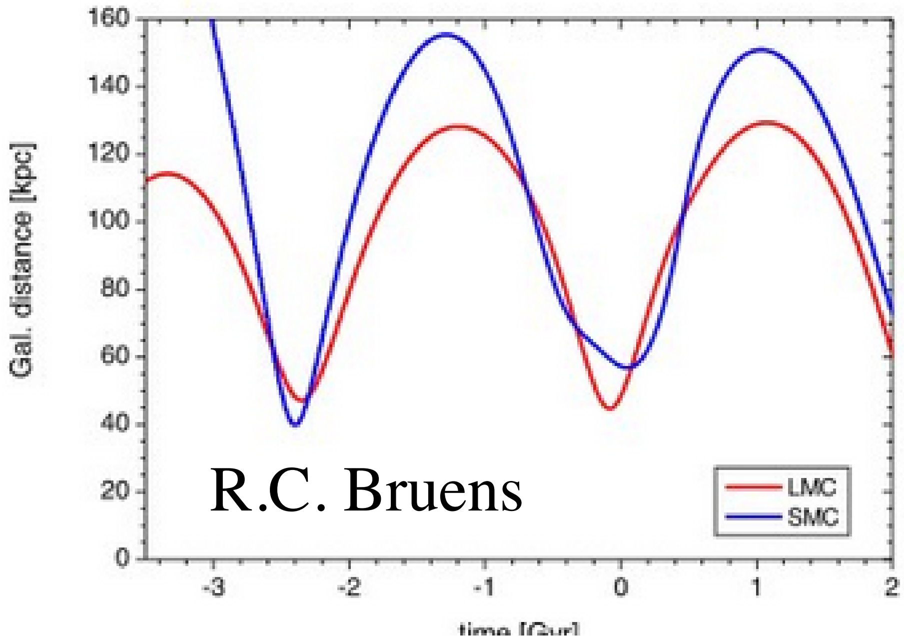
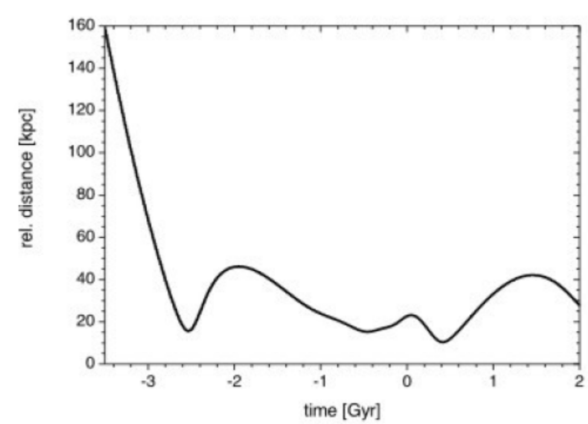


Figure 2: Single-dish observations of HI gas (Brüns et al. 2004).
Left: HI column density map of the entire Magellanic System. ***Right:*** Mean velocity v(LSR), map of the entire Magellanic System.



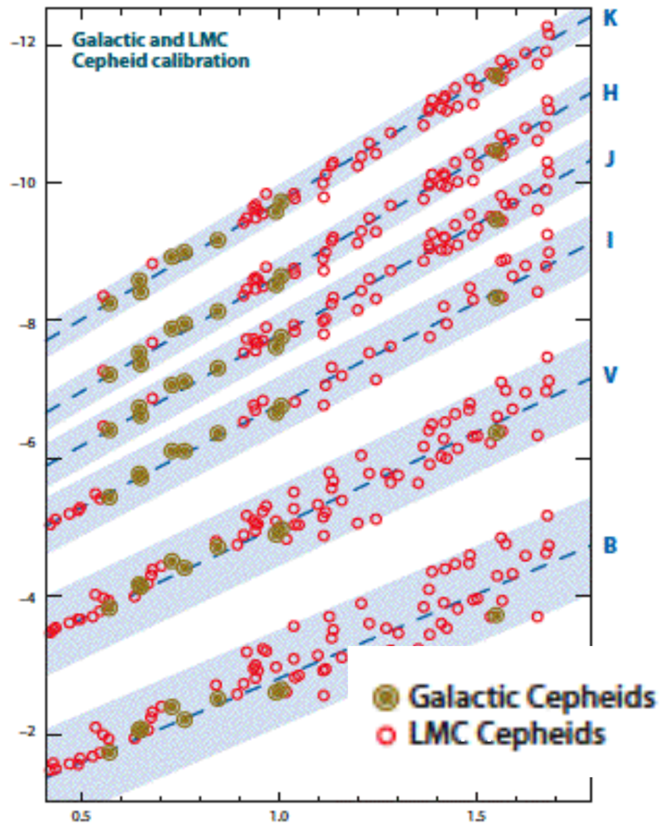
R.C. Bruens



Distance to LMC

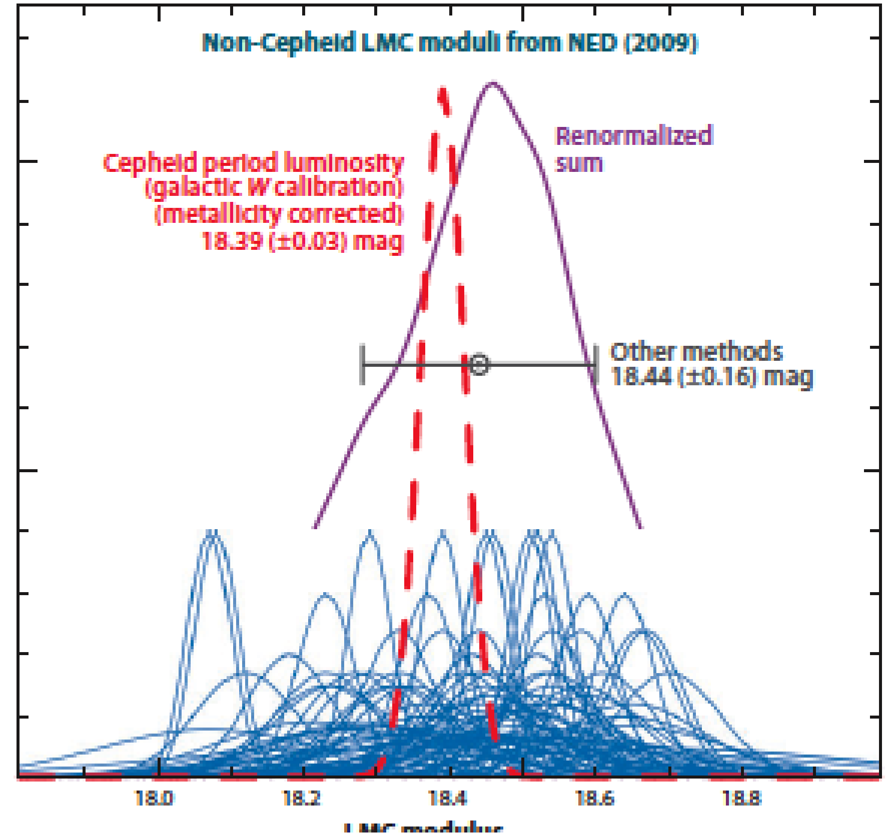
- LMC is unique in that many Cepheids can be detected in a galaxy with rather different metallicity with no effect of crowding

LMC distance modulus, μ, of 18.48 ± 0.04 mag; log d=1+μ/5 (49.65 Kpc)



absolute mag in each band

log Period (days)



Relative probability

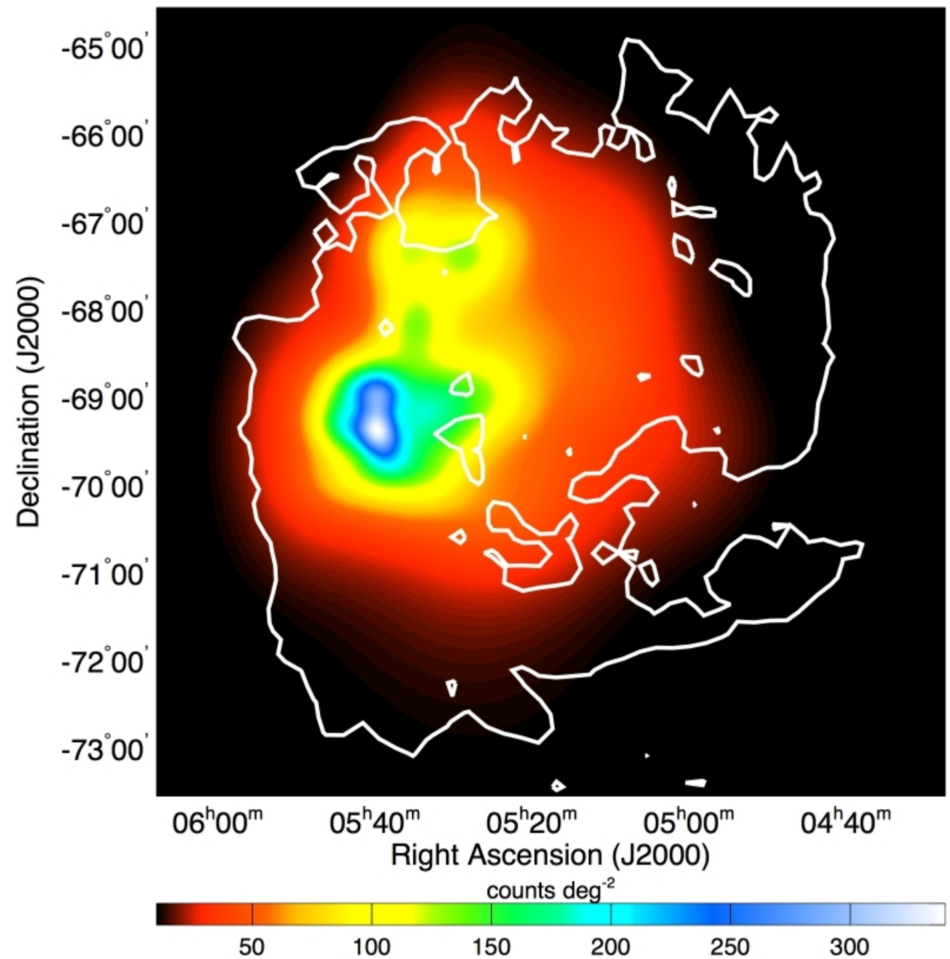
LMC Distance Modulus

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

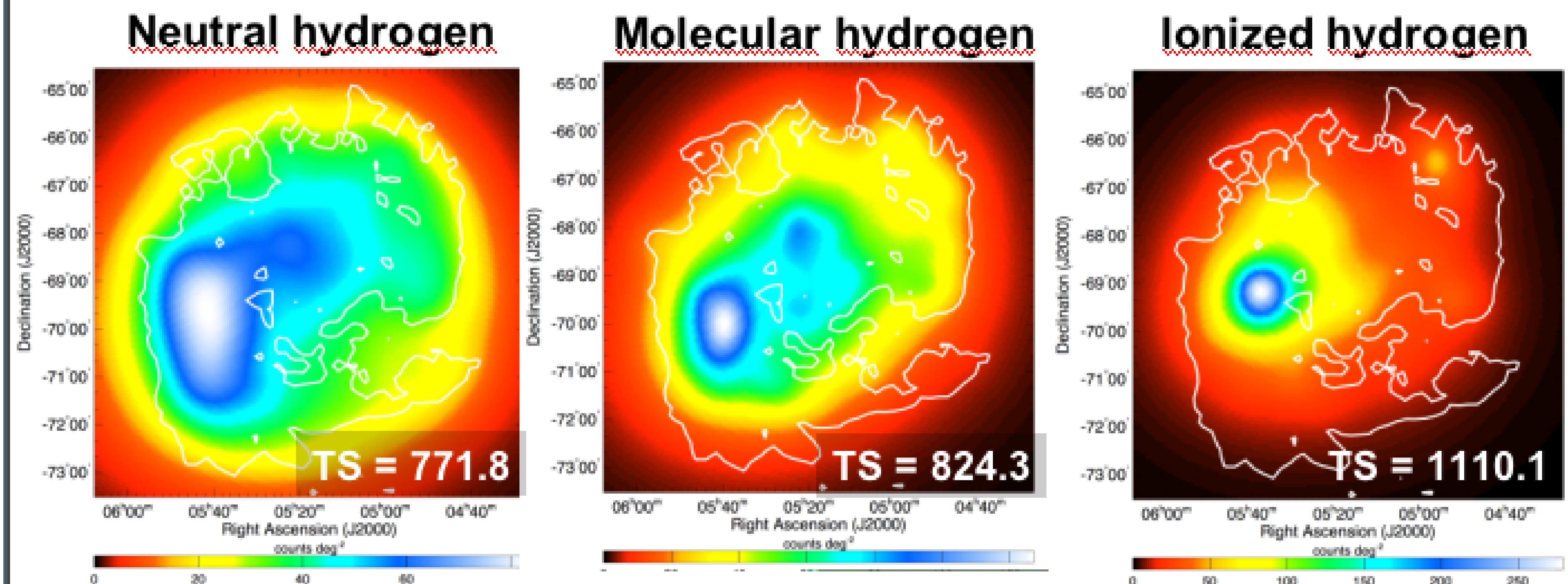


γ-ray intensity scale

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 (!)

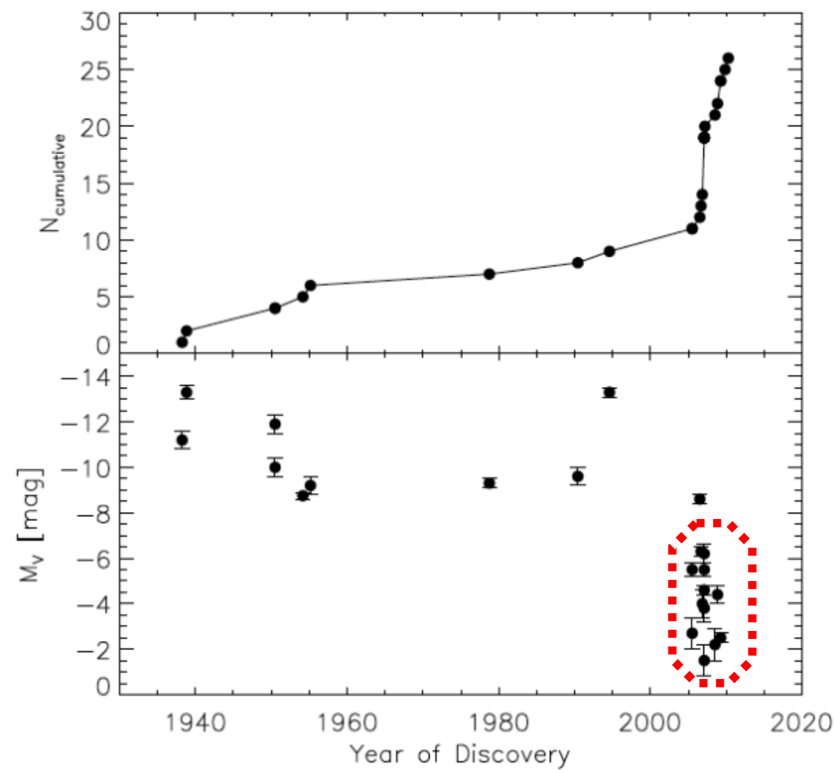
Dwarf Galaxies

- 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 (well actually see arXiv:1310.1079 The Dwarfs Beyond: The Stellar-to-Halo Mass Relation for a New Sample of Intermediate Redshift Low Mass Galaxies Sarah H. Miller et al)
- 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



Dwarfs

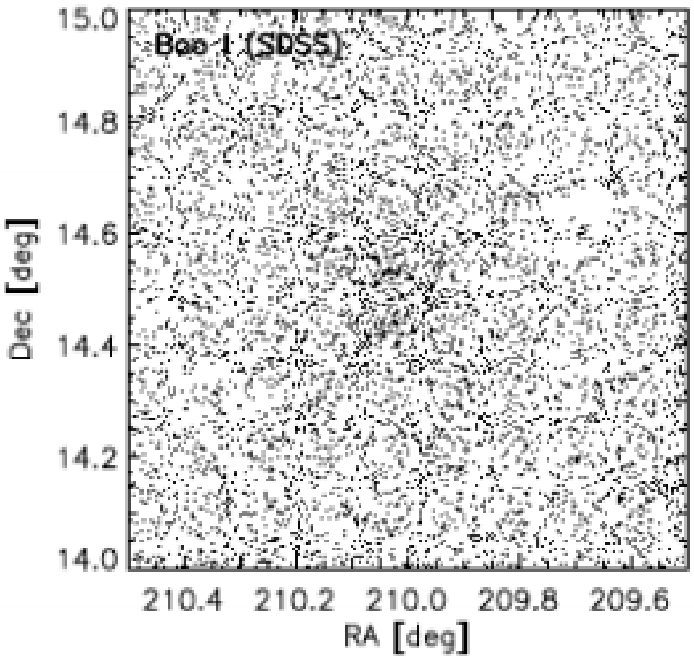
- They are detected as overdensities of intrinsically bright red giant stars

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

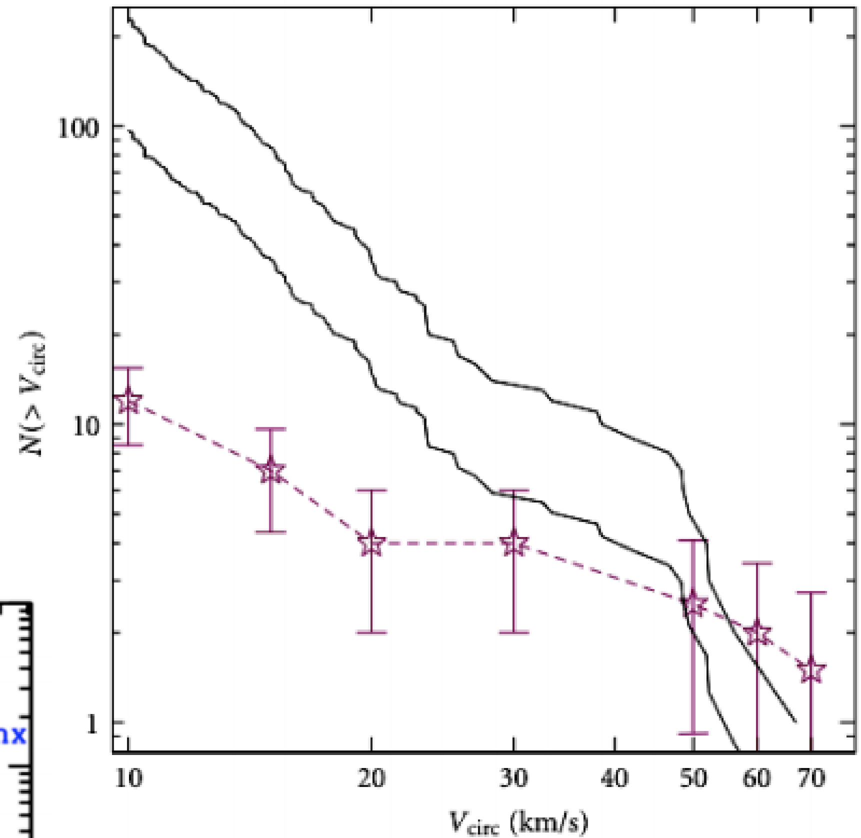
27 are known in M31

Image of Boo I

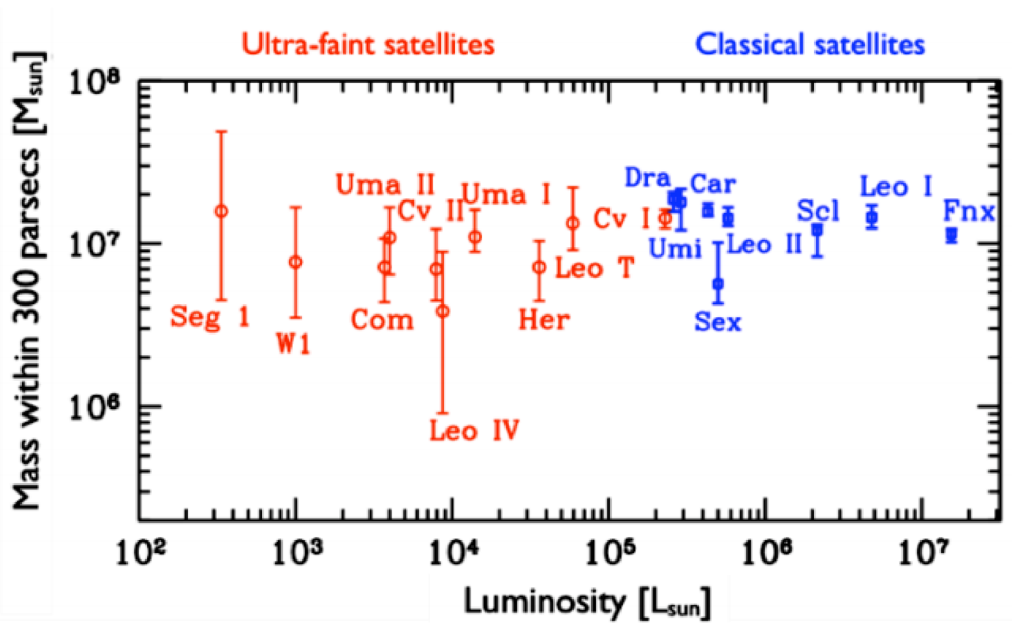


Number of Satellites around MW- Observed vs Theoretical

- Number of satellites vs their circular velocity: theory - between black lines
  red points observed objects (Klypin 2010)- order of magnitude discrepancy at low masses?

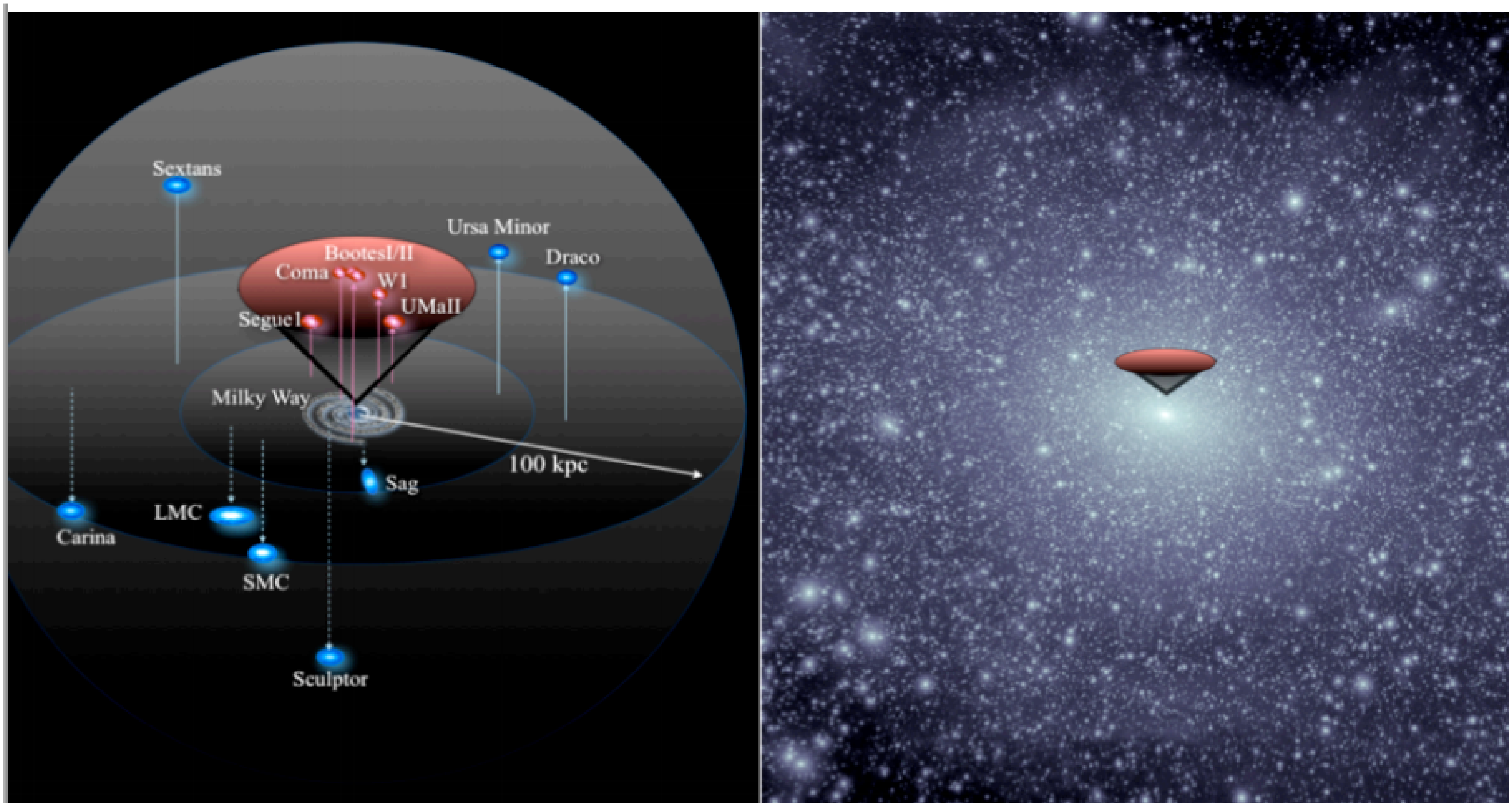


- Odd property that satellites all have *same mass, but* 10^5 *range in luminosity*



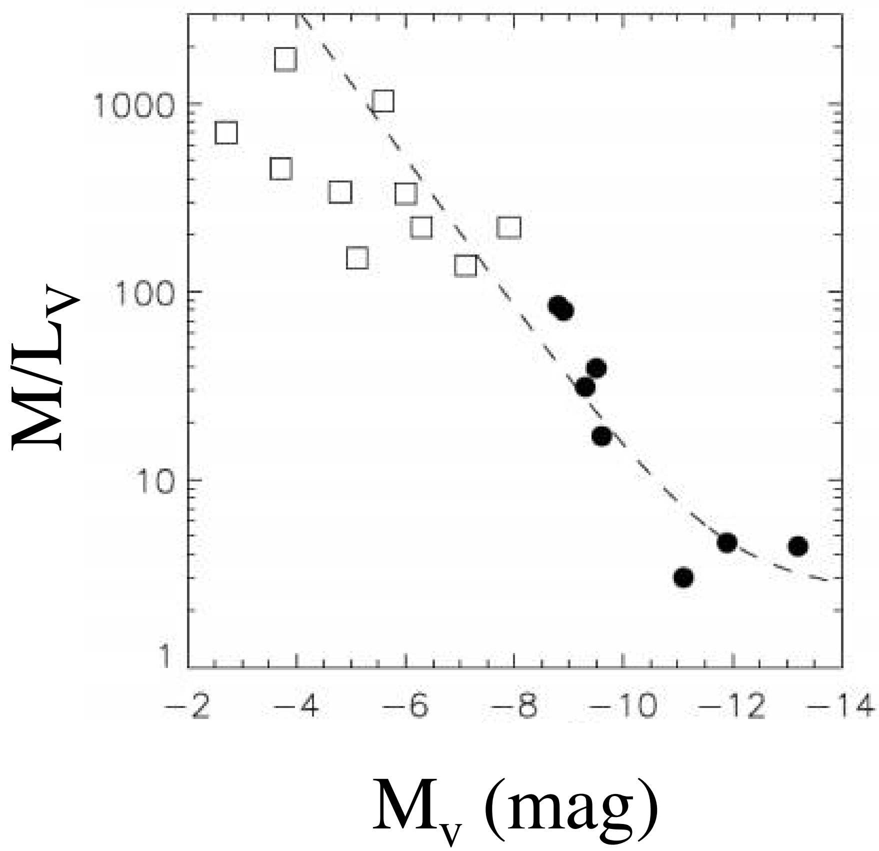
Where are the Satellites of MW-Bullock 2010

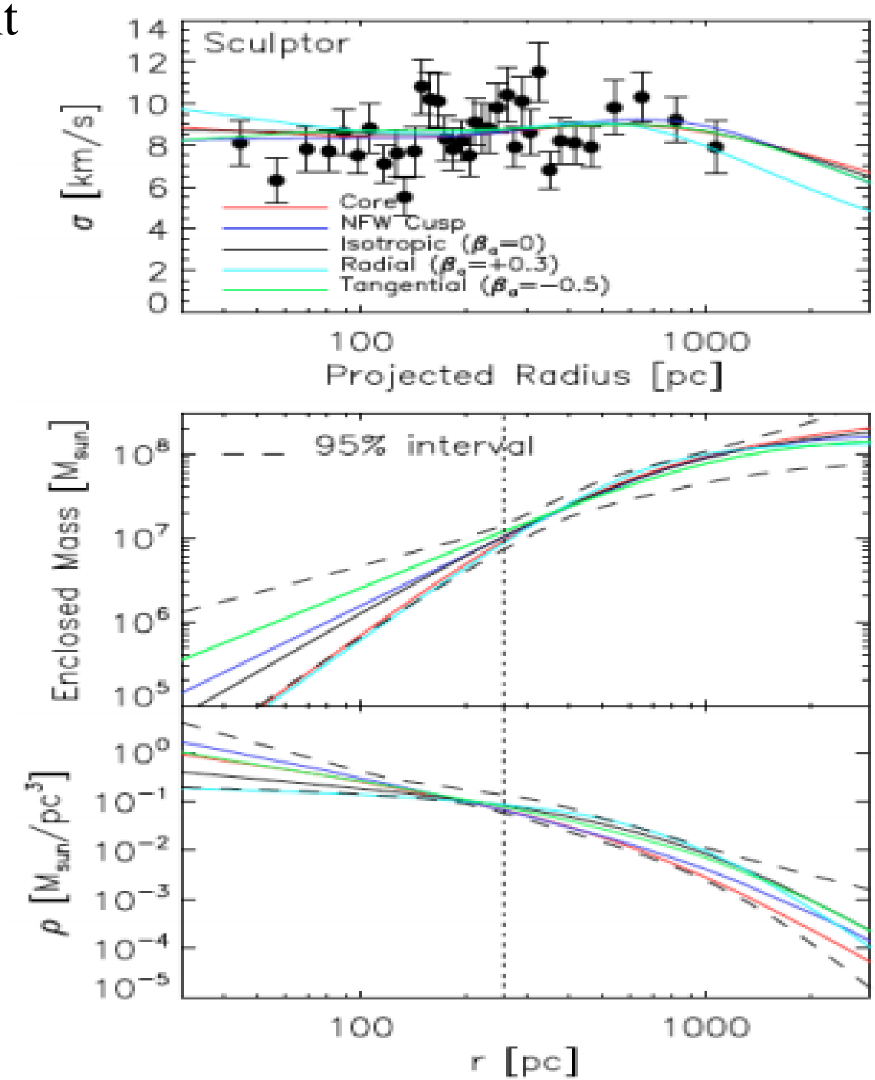
- Know satellites of MW within 100kpc-left
- Right- CDM simulation of LG/ MW halo- cones show where sample of dwarfs is complete-SDSS data, only in the north



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



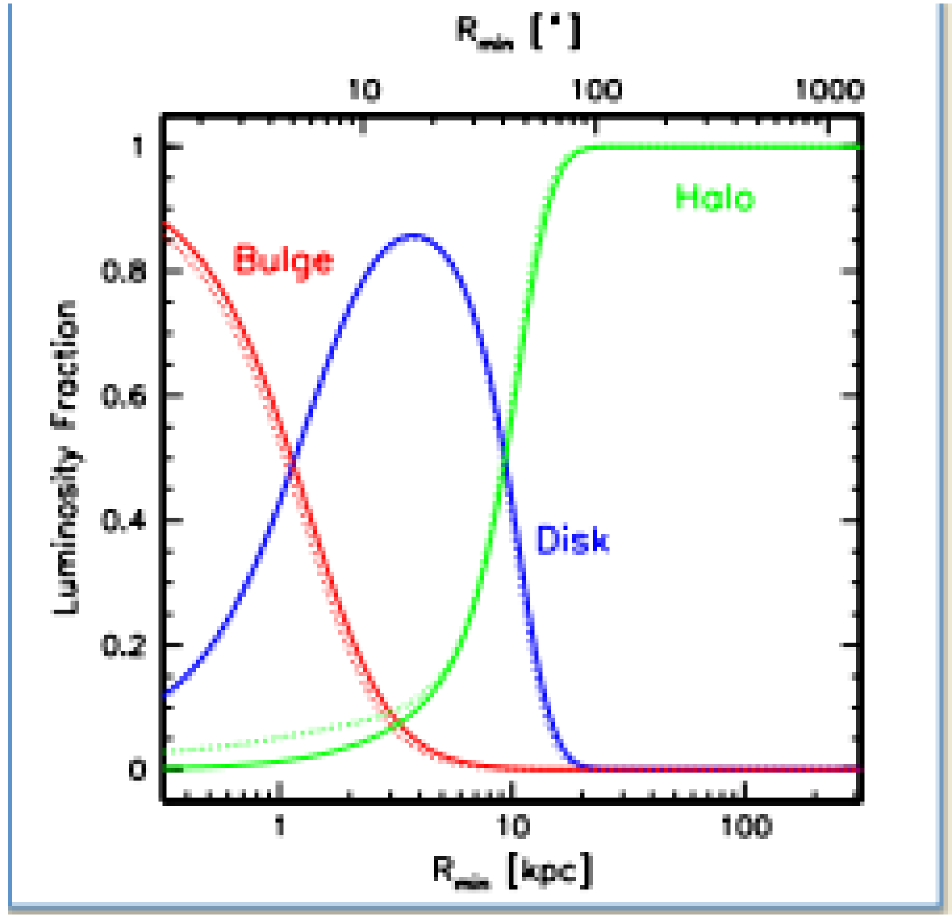


Local Group Summary

- 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);
  - 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??- lead to discussion later in class about galaxy formation and Cold dark matter models

M31 and the MW

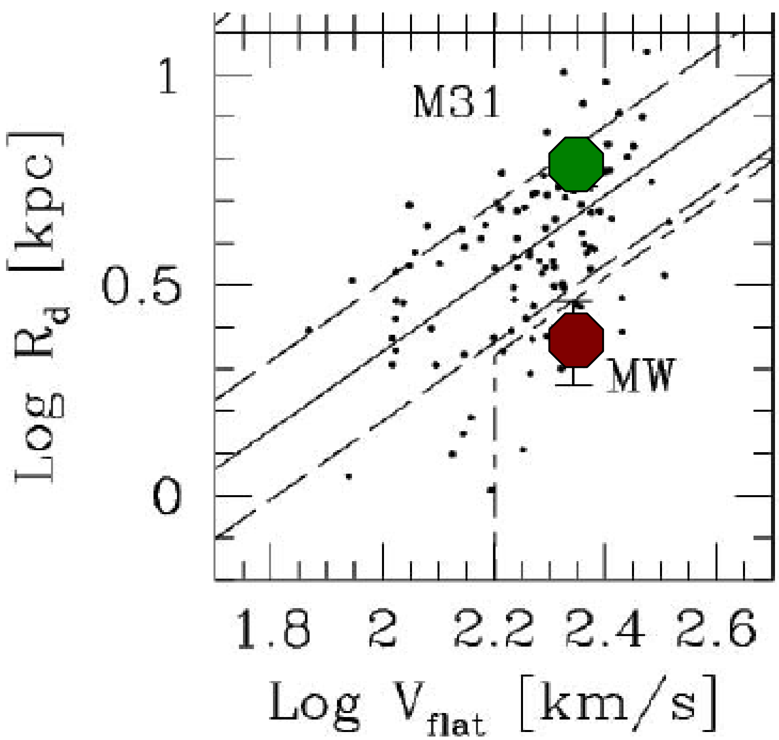
- the Milky Way and M31 have different properties
- M31 shows a lower star formation rate (SFR) than the Milky Way
- M31 appears to be a more typical spiral galaxy than the Milky Way (Hammer et al. 2007).
- M31 shows evidence for a formation and evolution history affected by merging and/or accretion 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} ~10.3 x $10^{10} M_\odot$ for M31; disk 7.2x $10^{10} M_\odot$ and bulge 3.1x 10^{10} $M_\odot$

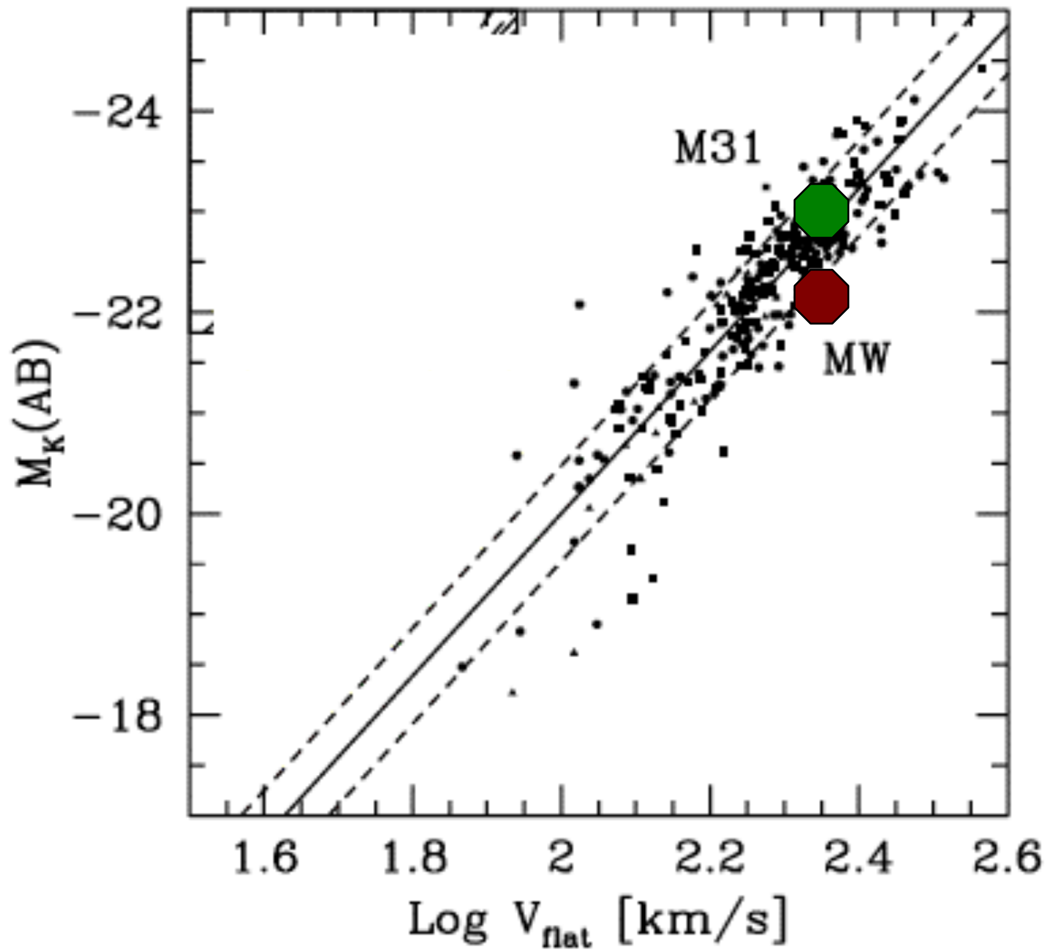


Mass decomposition of M31
Courteau 2012

Tully Fisher Relation

- The relationship of luminosity to rotation speed for spirals- also relation of scale length to rotation velocity
- M31 and MW have similar v_{rot} but factor of 2 different luminosities+scale lengths - MW is more discrepant

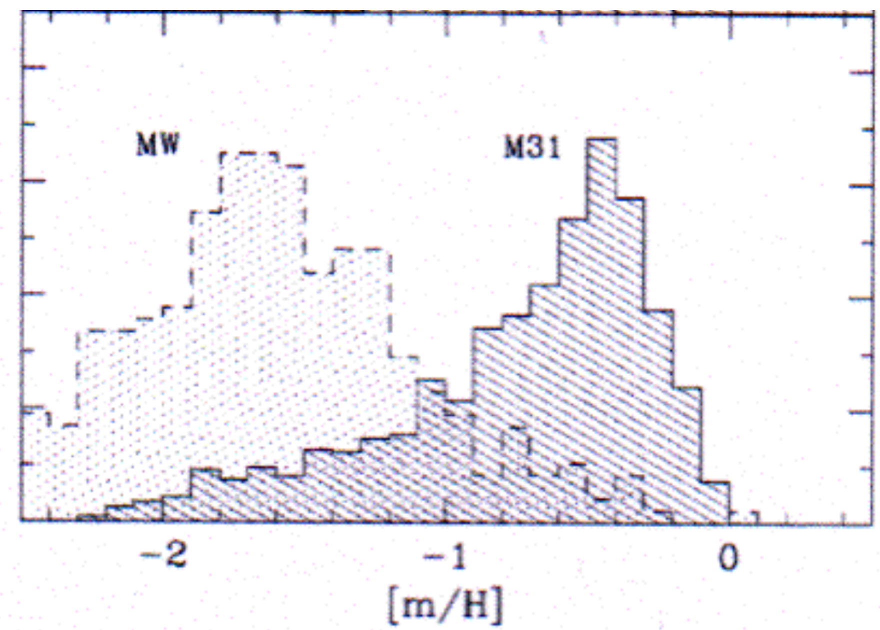




M31, compared to the Milky Way, has 2 x more stellar mass and 2.5 x more specific angular momentum Hammer 2007

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 with galaxies of similar mass.
- Chemical composition of stars in the dwarfs differs subtly from stars in globular clusters or MW halo.
- Comparison of observed metallicities to theoretical yields to those of a closed box approx indicates outflow of enriched material (or according to S+G inflow of material enriched to 0.15 solar)



- Halo of M31 = Andromeda (Durrell et al. 2001)
- Halo of the Milky Way (Ryan & Norris 1991)

Mass Models For M31

- Several different potential forms give reasonable fits to velocity data; differ in 'total' mass by <50%

- 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.

- .

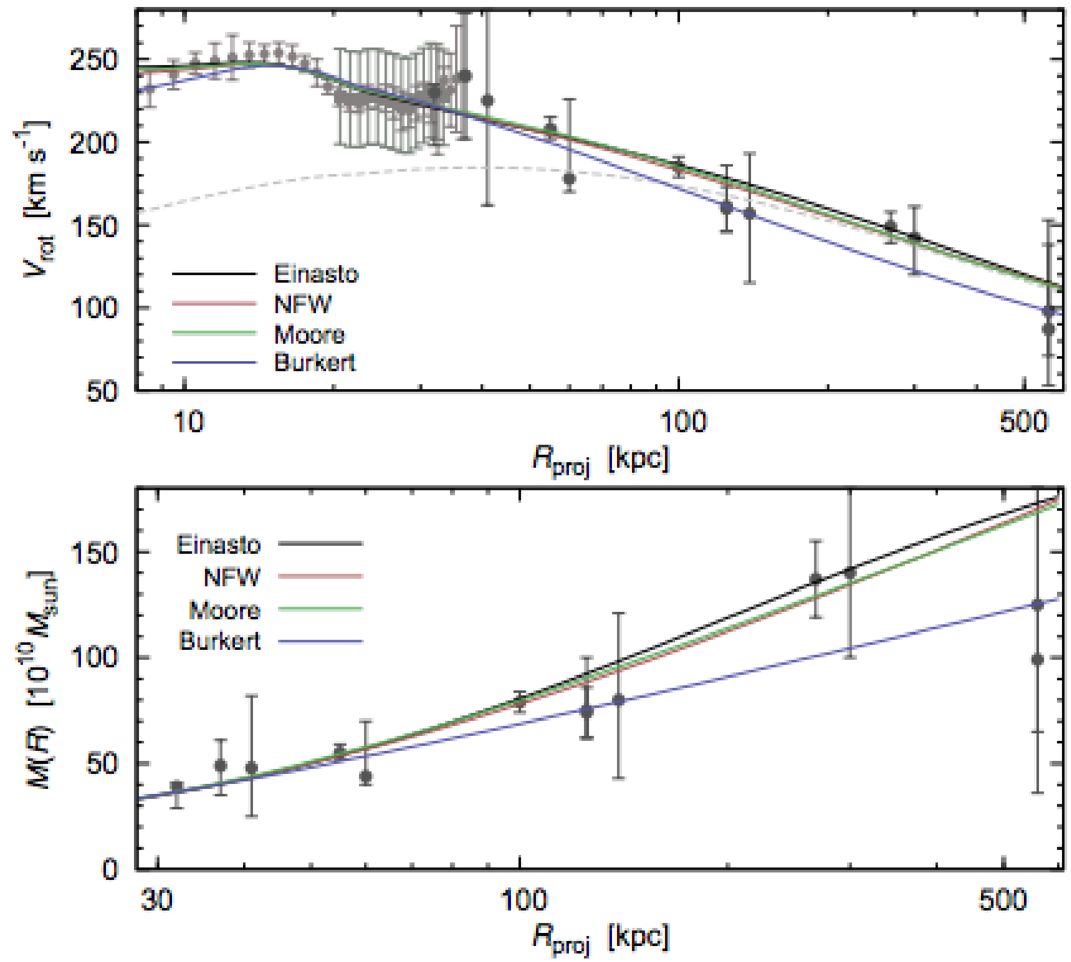


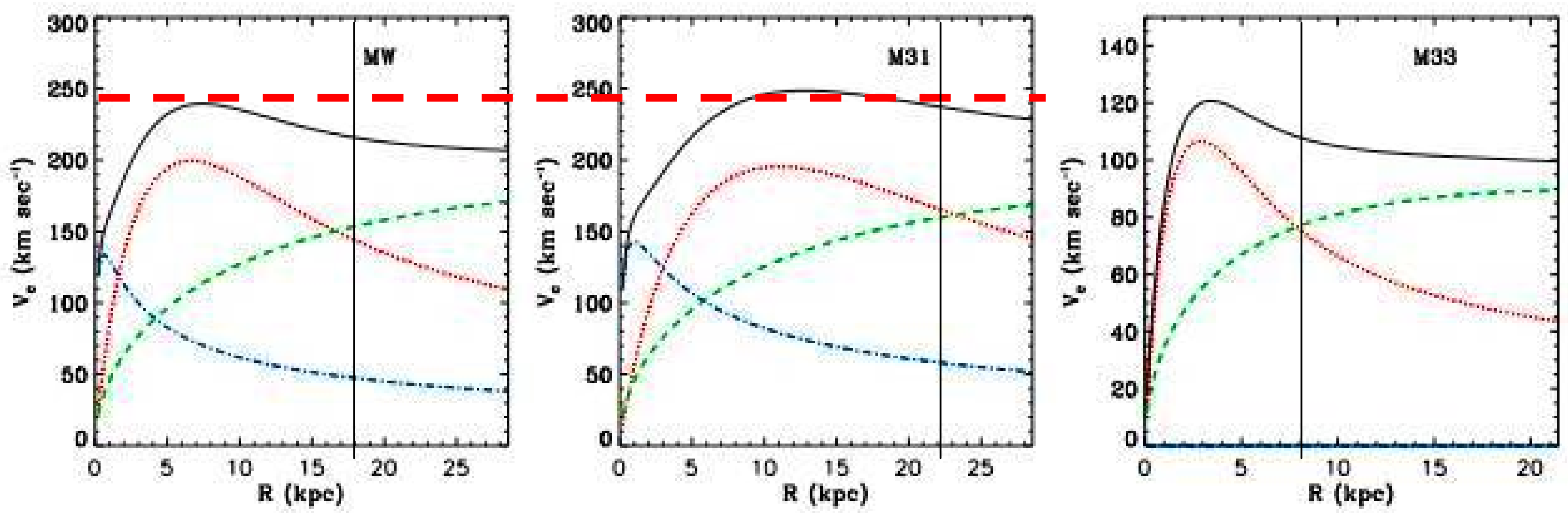
Fig. 6. Outer rotation curve observations and models (*upper*

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 (data from van der Maerl 2012)
- observed maximum circular velocity for each galaxy: $V_c \approx 239$ kms at

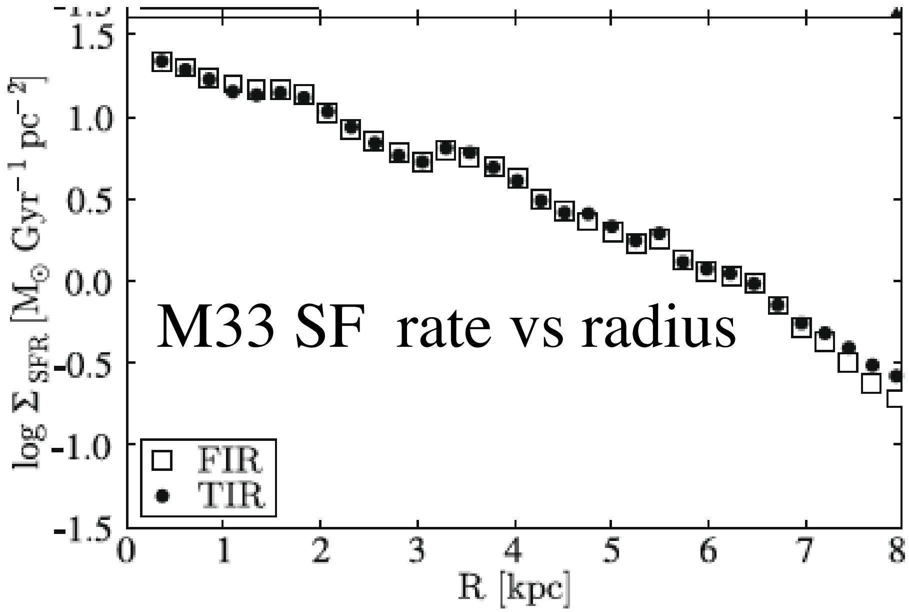
the solar radius for the MW, $V_c \approx 250$km/s for M31 $V_c \approx 120$ kms M33

- 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*
- Virial mass of M33=$2.2\text{x}10^{11} M_\odot$

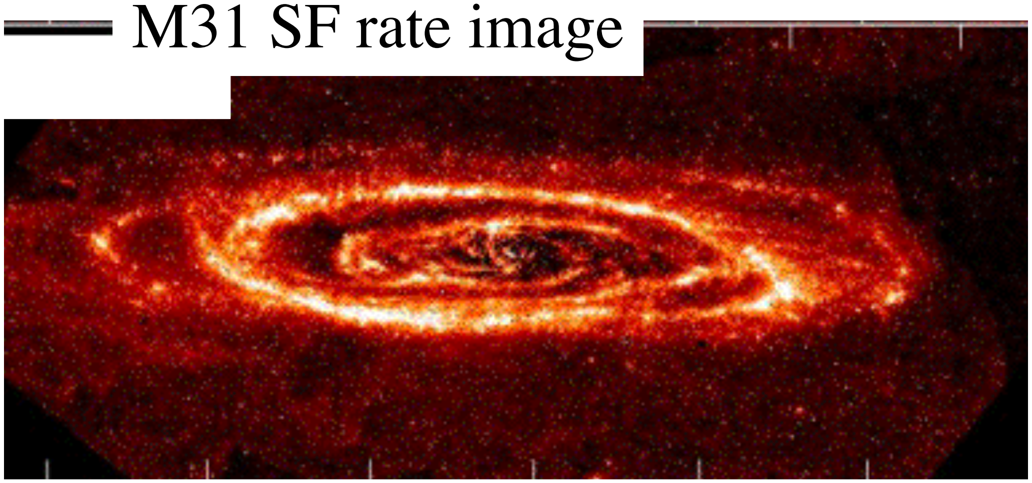


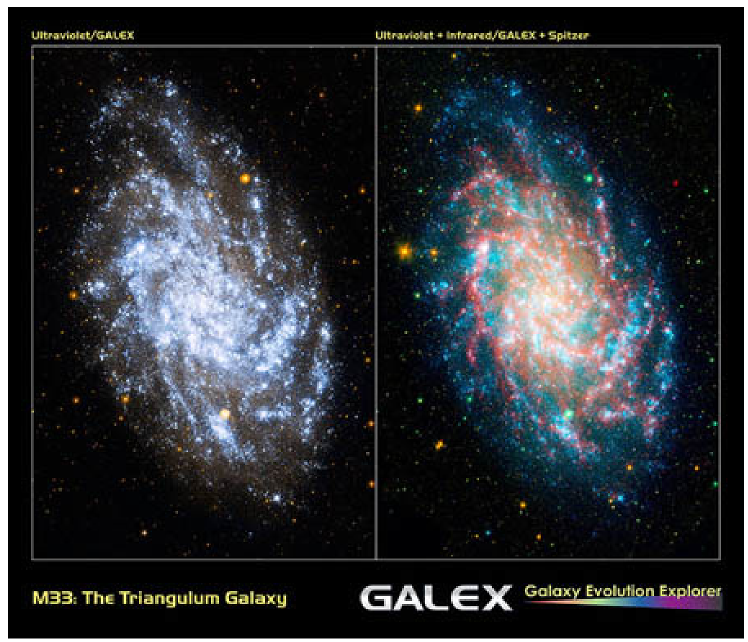
Star Formation in M31,M33

- 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 (why??)



M33 UV and IR images





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

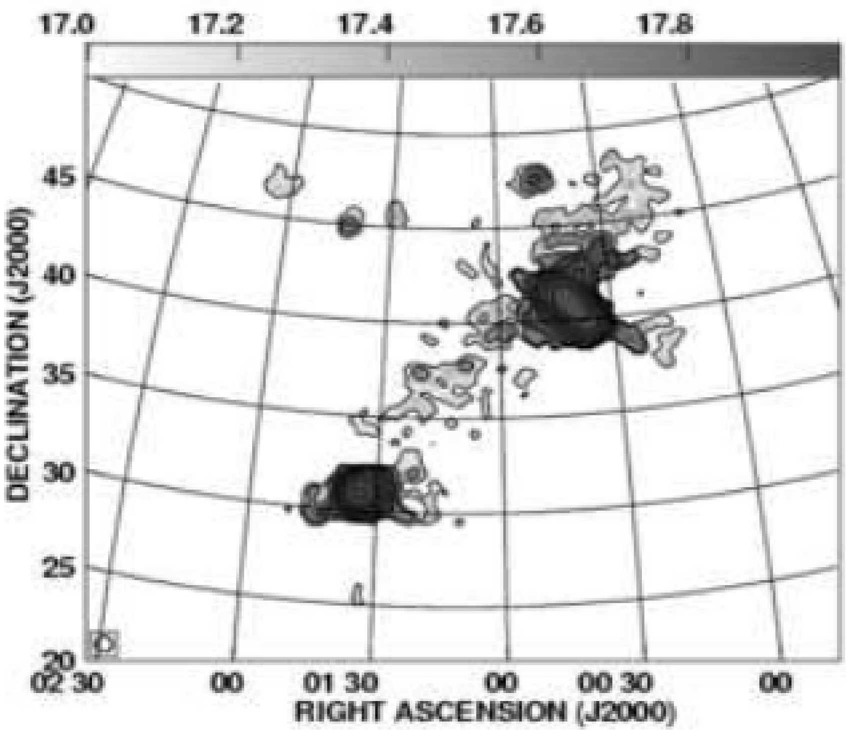


Fig. 9. Integrated H I emission from the subset of detected features apparently associated with M31 and M33. The grey-scale

$M_{disk,stellar}$~$3.8x10^9 M_\odot$
$M_{bulgek,stellar}$~$1x10^8 M_\odot$
M_{virial}~$2.2x10^{11} M_\odot$

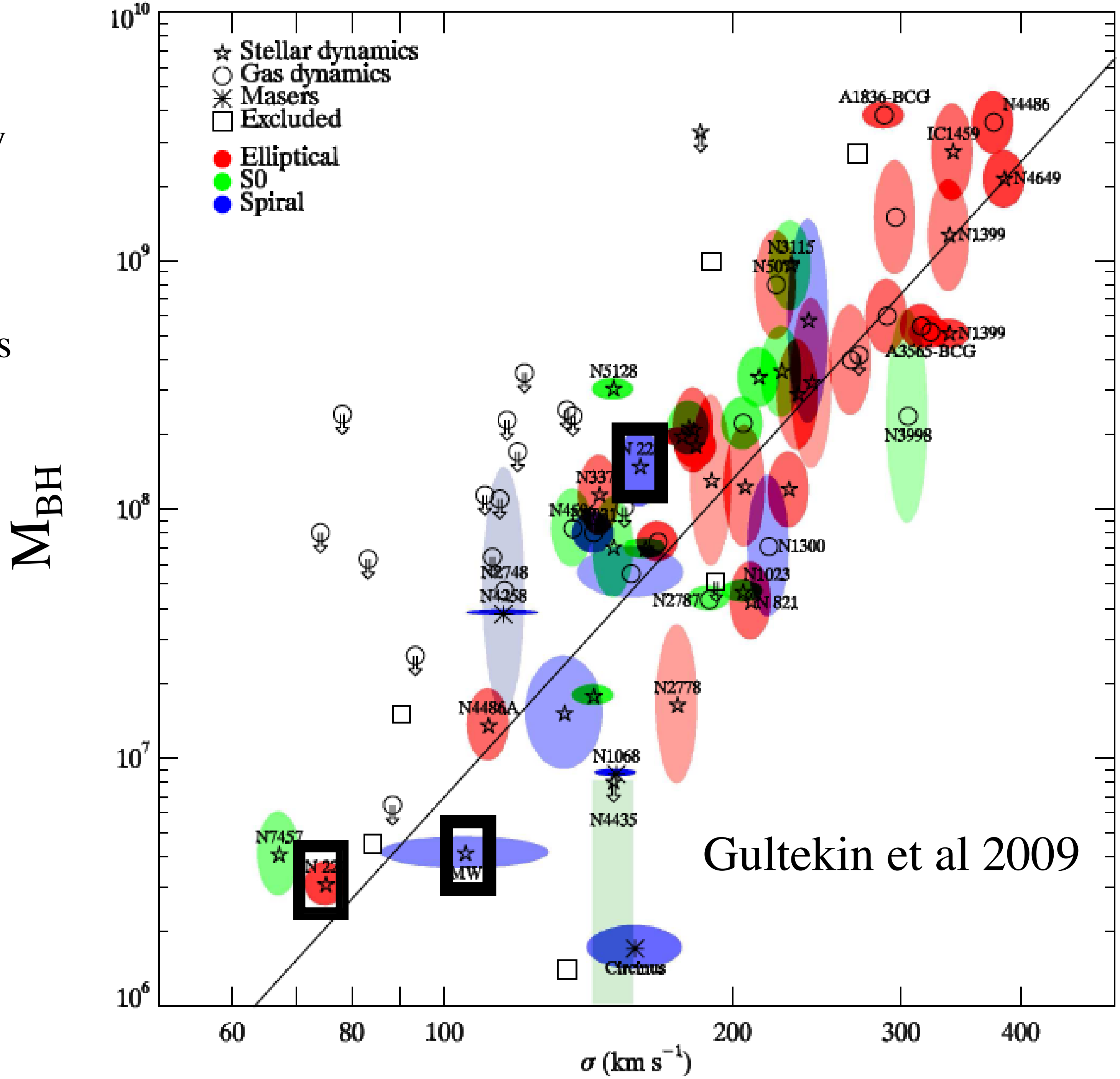
HI emission from M33 and M31

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)
- None of the Local group galaxies host an AGN (today)
- Of the small galaxies only M32 shows dynamical evidence for a black hole (van der Maerl 2009) of $M \sim 2.5 \times 10^6 M_\odot$ 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	$< 3 \times 10^3$	1.5×10^8
NGC205	E	$< 2.4 \times 10^4$	2.7×10^8
M32	E	$\sim 2.5 \times 10^6$	$\sim 2.5 \times 10^8$

- Black hole mass vs bulge velocity dispersion
- Mass of central supermassive Black hole scales with the galaxy
- Local group galaxies

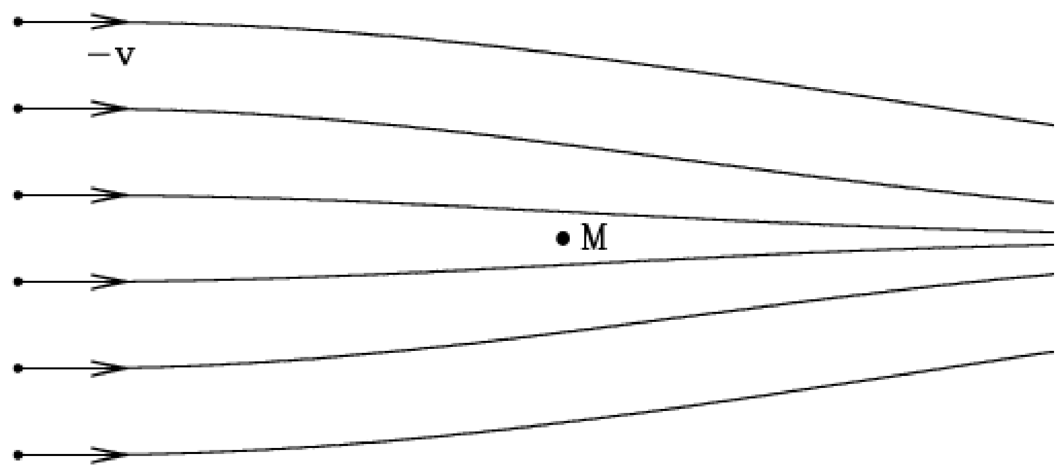


Analytic Estimate How Fast Will Local Group Merge?

- Dynamical friction (S+G 7.1.1.MBW sec 12.3, sec 8.1 MBW) : occurs when an object has a relative velocity wrt 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
- $t_{friction}$~V/(dv/dt)~$R^2V/GM\log\Lambda$; $\Lambda=R^2V/G(M+m)$

$M\sim10^{10}\ M_\odot$;$m=1M_\odot$; $\rho\sim3\times10^{-4}\ M_\odot/pc^3$ Galactic density at distance of LMC

putting in typical values **$t_{friction}$~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 important.
  - the growth of galaxies depends on their dynamical evolution within larger dark matter halos.
- Dynamical friction/tidal stripping 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)

Dynamical Friction Derivation

- 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

$dKE=(M/2)(2Gm/bV)^2+(m/2)(2G M/bV)^2=$

$2G^2mM(M+m)/b^2V^2$

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

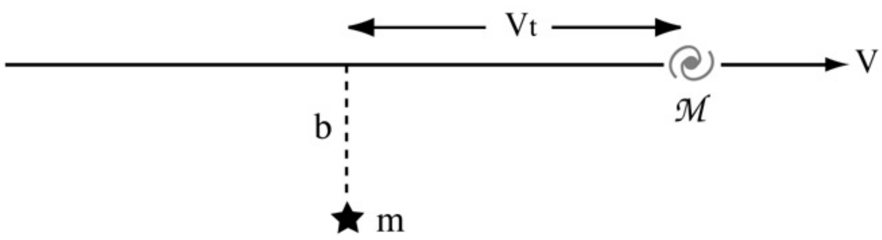


Fig 7.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

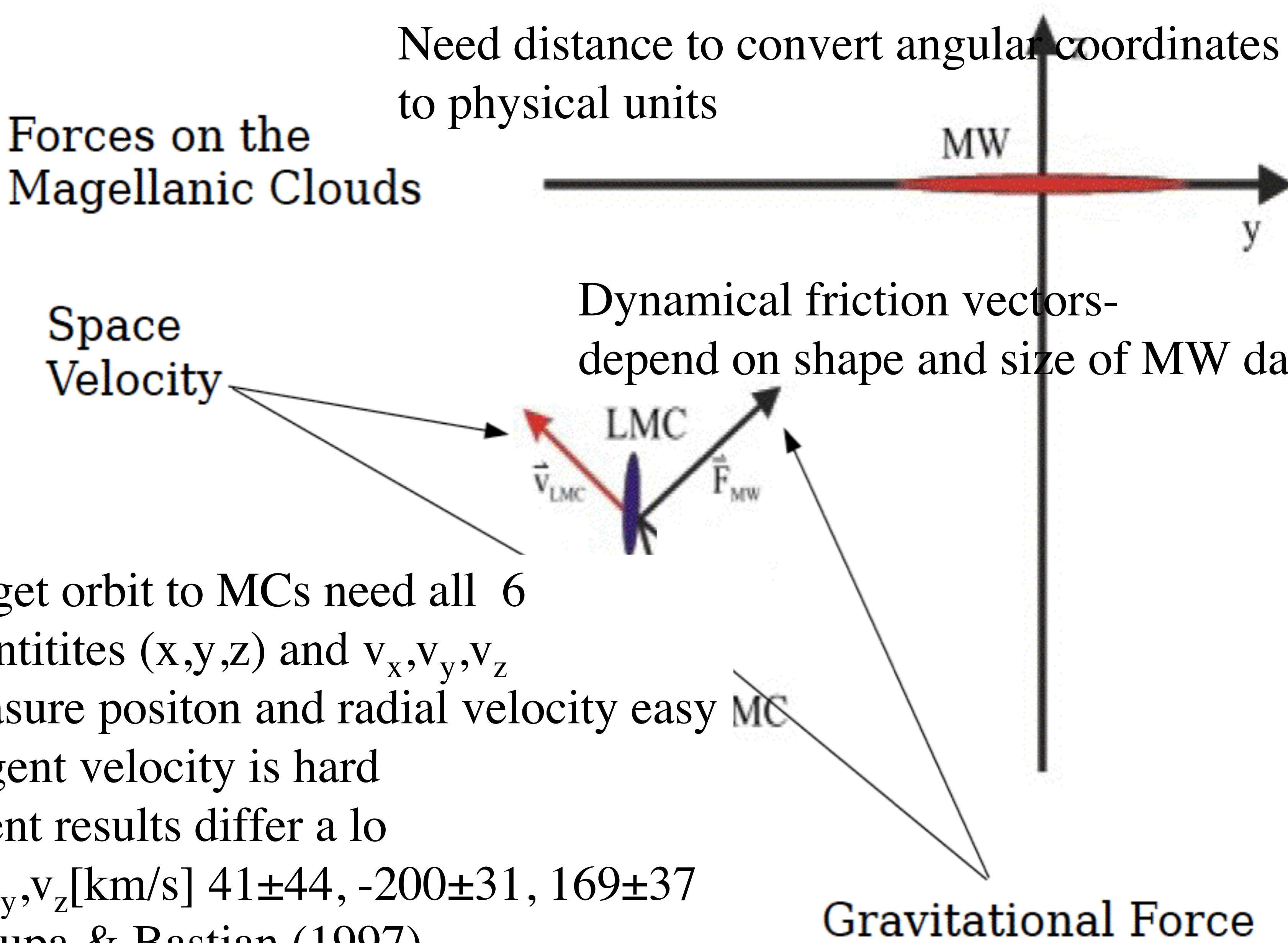
Dynamical Friction-cont

- MWB pg 554: follow derivation due to Chandrasekhar : conservation of momentum; momentum lost by by interacting body is equal to that gained by the field particles.
- Simpler but not as correct derivation in S&G sec 7.1.1
- the derivation is complex, but 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 on their total density- e.g. massive satellite slowed more quickly than a small one

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.

Need distance to convert angular coordinates to physical units



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

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

recent results differ a lo

v_x, v_y, v_z[km/s] 41±44, -200±31, 169±37 Kroupa & Bastian (1997)

v_x, v_y, v_z[km/s] -56±39, -219±23, 186±35 van der Marel et al. (2002)

Local Group timing argument

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

derive total $M>1.8\times10^{12}M_\odot$

Local Group timing argument

M_{total} is the sum of the 2 masses Initially, take r=0 at t=0

- solution of the form $r=R_{max}/2(1\text{-}\cos\theta)$ and $t=(R^3{}_{max}/8M_{total}G_{total})^{1/2}(\theta\text{-}\sin\theta)$
- The distance increases from 0 (for$\theta=0$) to some maximum value R_{max} (for$\theta=\pi$), and then decreases again. The relative velocity is

  $v=dr/dt=(dr/d\theta)/(d\theta/dt) =(2GM_{total}/R_{max})^{1/2}(\sin\theta/(1-\cos\theta))$

- The last three equations can be combined to eliminate R_{max}, and M_{tota} , to give

  $vt/r=\sin\theta*(\theta-\sin\theta)/(1-\cos\theta)^{1/2}$

v can be measured from Doppler shifts, and r from Cepheid variables. For t take the age of the Universe, 13.8Gyrs.

Local Group timing argument

solve the previous equation (numerically) to find θ=4.32radians, assuming M31 is on its first approach to the MW

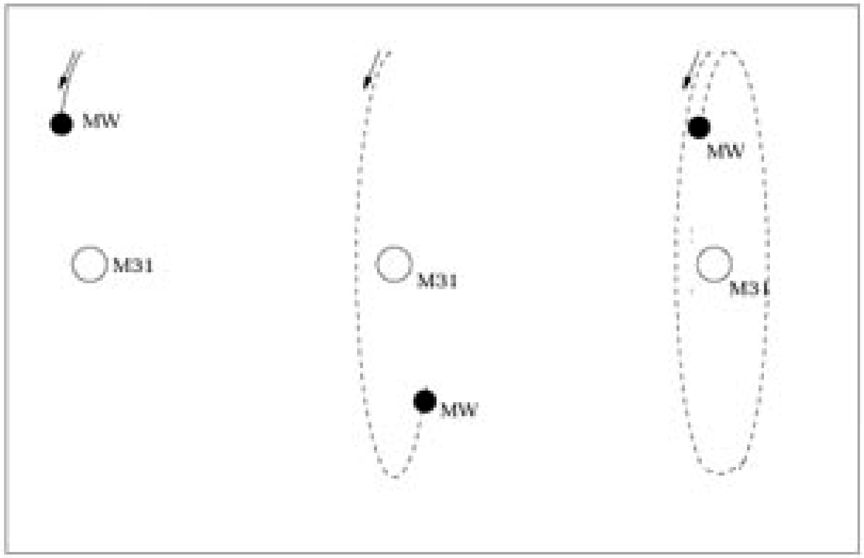
- M_{total}=3.66x10^{12} $M_{\odot}$and mass MW ~1/3 of total
- the estimate of M_{total} is increased if the orbit is not radial, or M31 and the MW have already had one (or more) pericenter passages since the Big Bang.

- So the very large mass inferred from the LG dynamics strongly corroborates the evidence from rotation curves and Oort's constants, that most of the mass in the MW (and presumably also in M31) is dark.

- estimate the extent of such a putative dark halo. If V^2_c is circular velocity out to R_{halo}, then 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.
- Hence the extent of the dark matter halo around the MW and M31 is very large. the size of the stellar disk is of order 20kpc or so, and 780kpc is the distance to M31 . So the dark matter haloes of the MW and M31 may almost overlap

timing argument

- M_{total}=3.66x10^{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



- general solution for orbits in Newtonian mechanics http://ned.ipac.caltech.edu/level5/March01/Battaner/node16.html
- $r=\alpha(1-\varepsilon\cos\eta)$

$\Omega t=\eta-\varepsilon\sin\eta$; ε is the eccentricity ;Ω α are constants; r= mutual distance

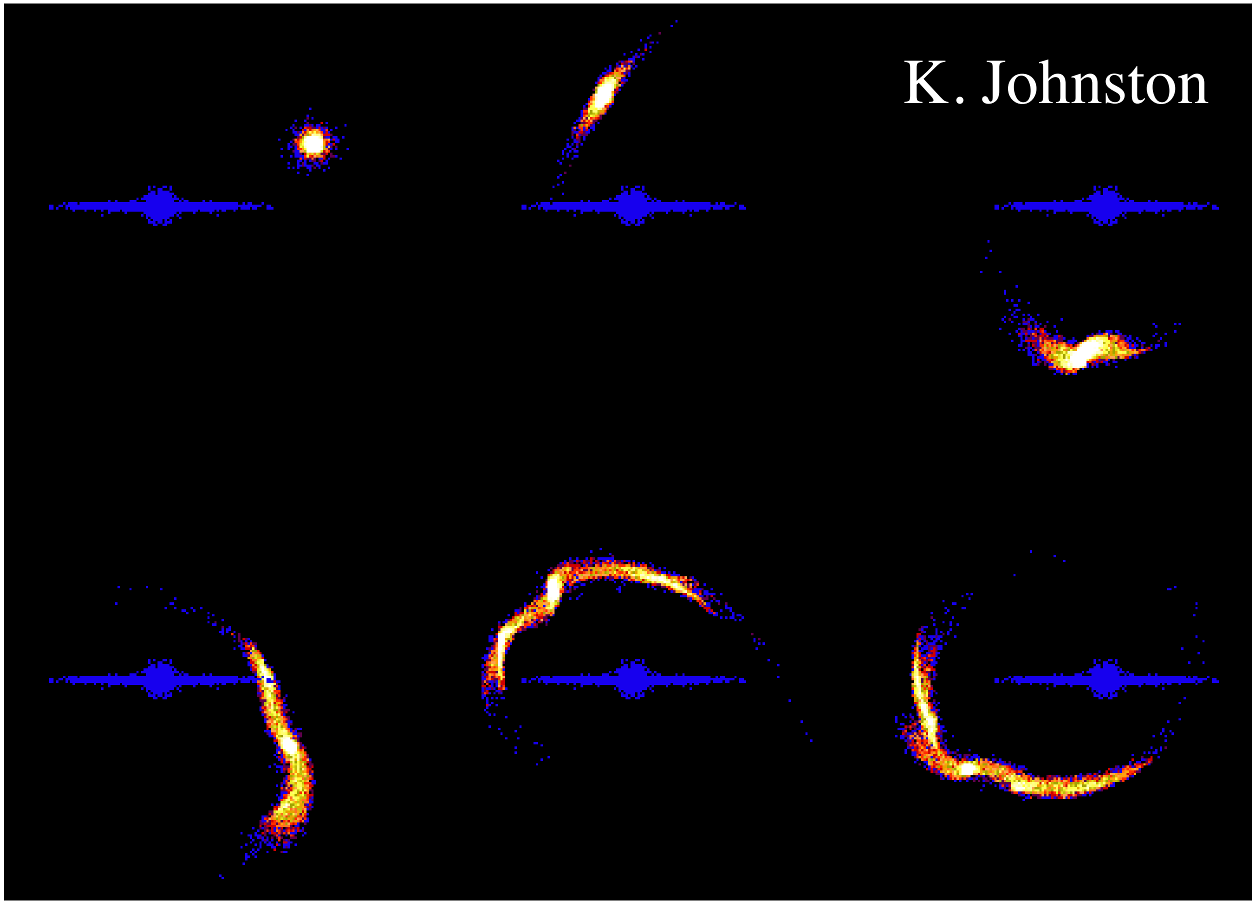
- $GM=\Omega^2a^3$
- consider ε=1 radial orbit
- $dr/dt=\alpha(\sin\eta)d\eta/dt$
- $d\Omega/dt=1(-\cos\eta)d\eta/dt$

LMC Merger??

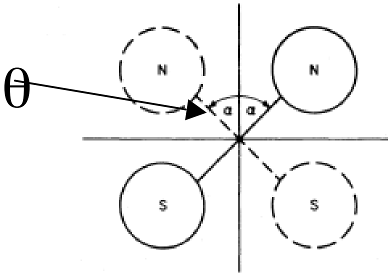
- Depends sensitively on LMC orbit and model of MW potential-

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.

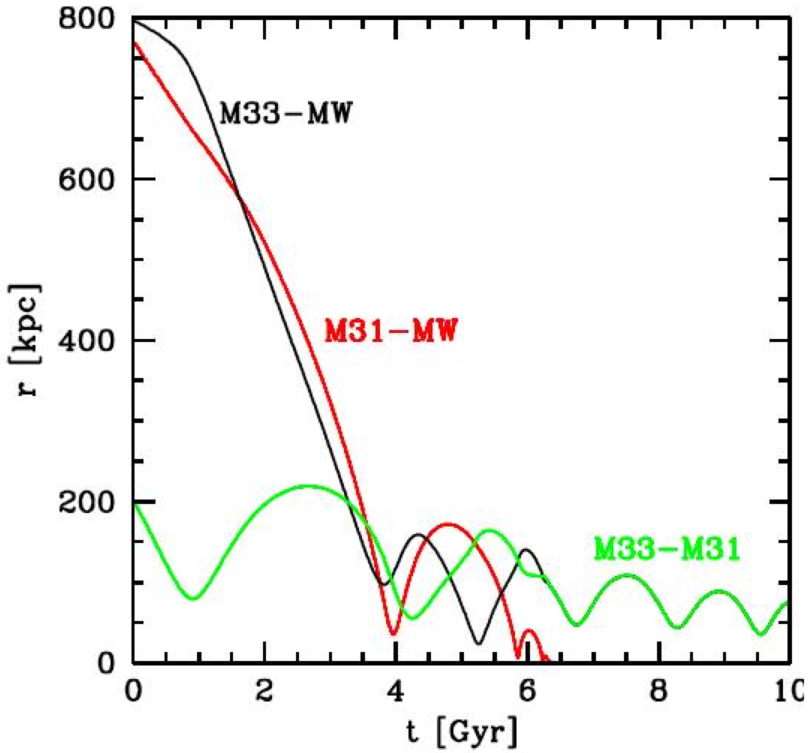


Criteria for 2 galaxies to be bound to each other $V_r R_p < 2GM\sin^2\theta\cos\theta$; V_r radial velocity offset, R_p is the projected radial separation, θ is the angular separation

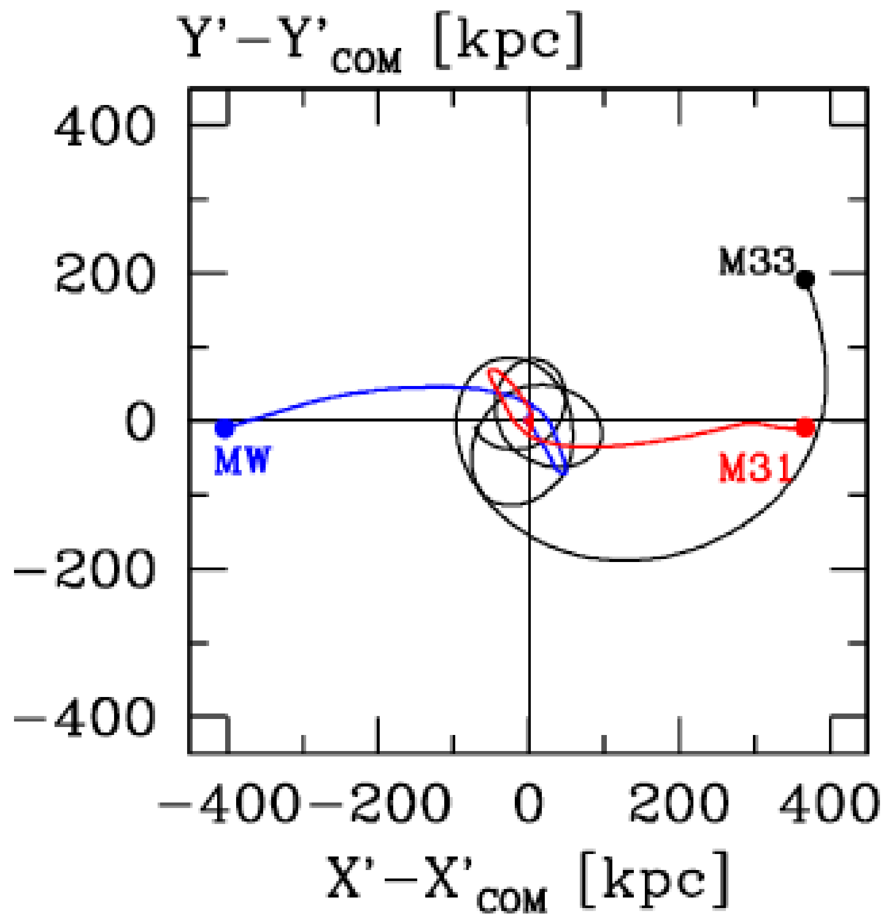


The future of the local group (S+G 4.5)

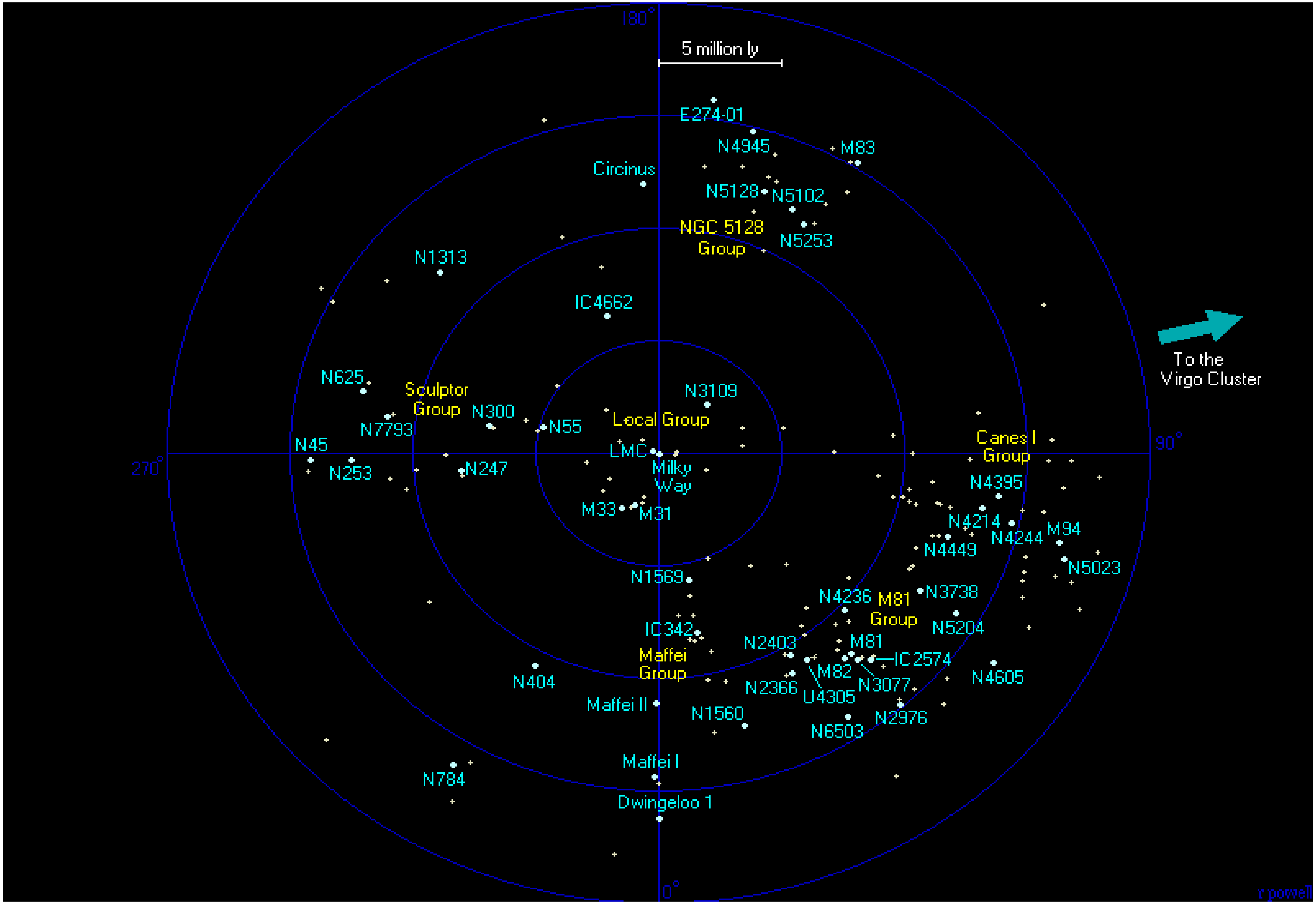
- It seems clear that M31 has had a much more active merger history than the MW- so beware of close by objects
- given what we know about the mass of M M33 and MW they will all merge in~6Gy (van den Maerl 2012)



ʏ separations in the MW-M31-M33 system as function



Beyond the Local Group



Local Volume of Space

As indicated by CDM simulations the universe is lumpy

Here is a 'map' (Hudson 1994) of the nearby universe

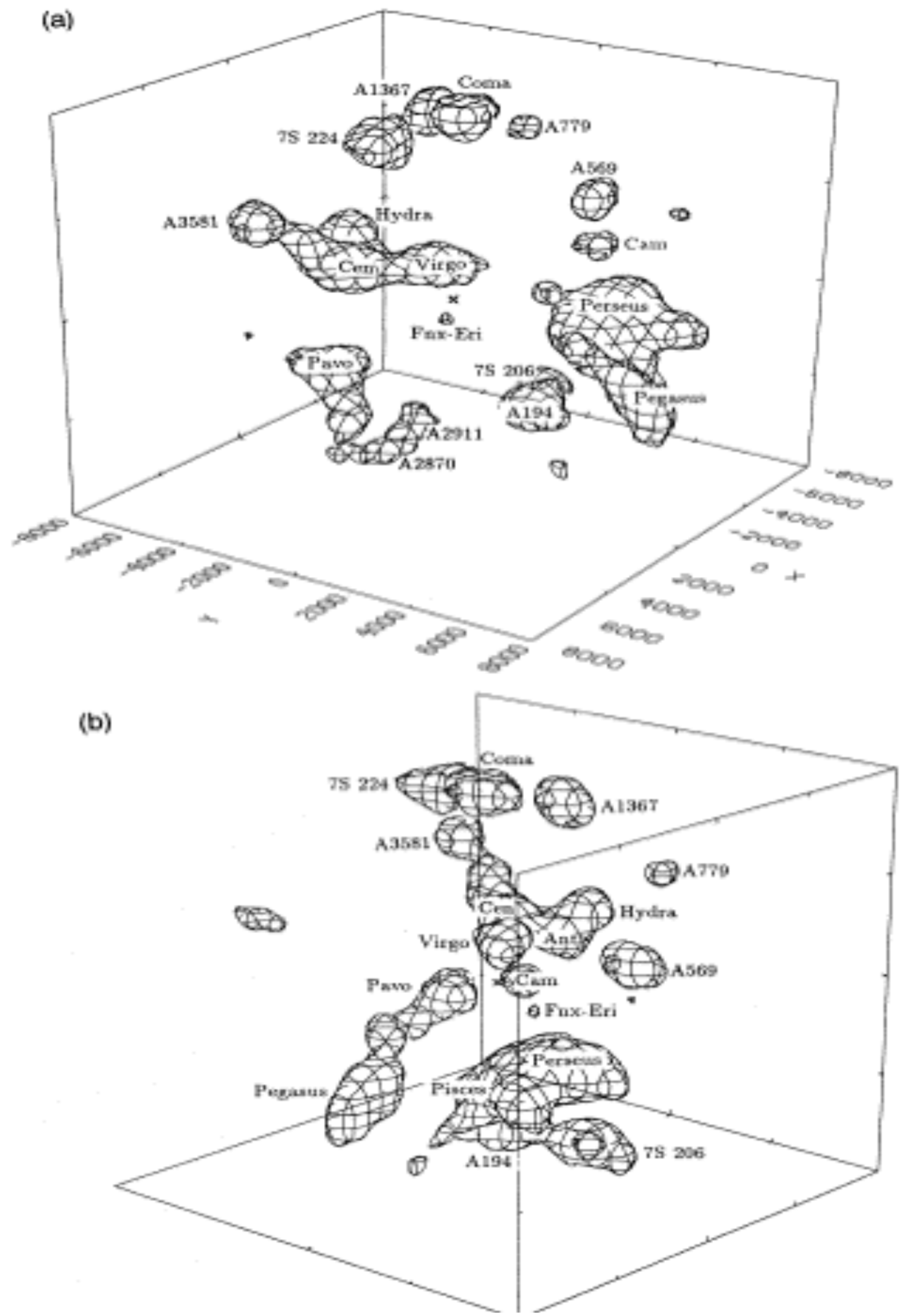
Objects labled 'A' are rich clusters

other massive clusters are labeled Virgo Coma, Cen, Perseus

of galaxies from Abells catalog - axis are labeled in velocity units (km/sec)

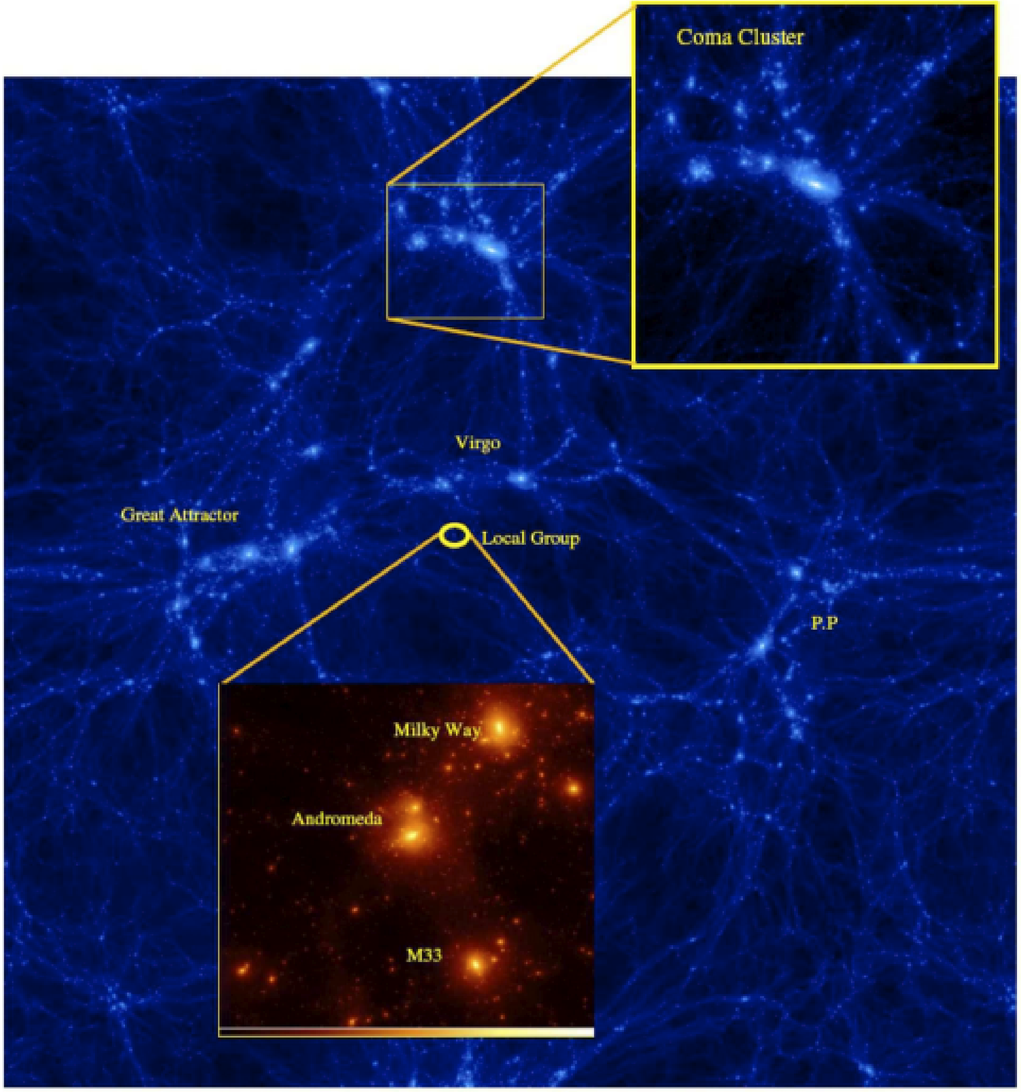
Notice filamentary structure.

Next step in distance is the Virgo Cluster- detailed studies of galaxy in Virgo are now within reach of large telescopes (see arXiv:1310.7575 The Dynamical Properties of Virgo Cluster Disk Galaxies Ouellette et al)



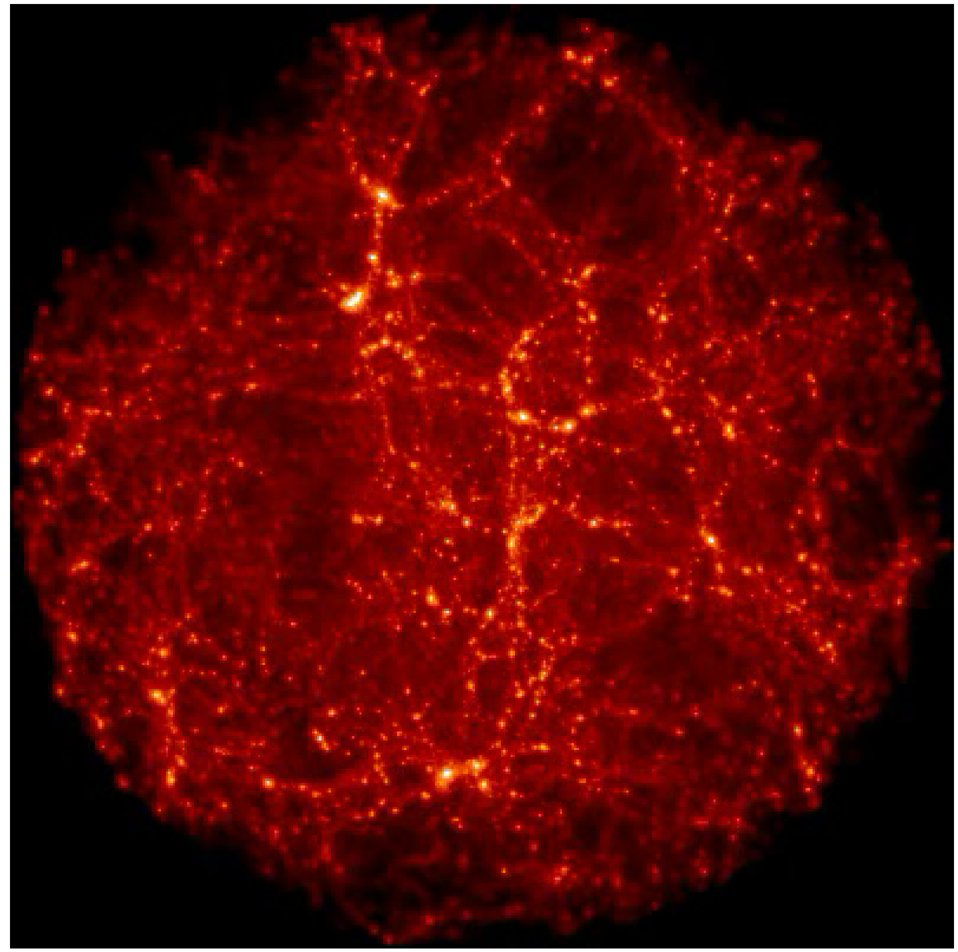
Constrained Realization

- 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 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

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 q 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)

$M_{total}=M_{gas}+M_{star}$=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

define y as the yield of heavy elements- yM_{star}=mass of heavy elements returned to ISM

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
- d Z=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) =ydM_{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)=yln μ metallicity of gas grows with time as log

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] α exp((Z(t)- Z(0))/y) d Z is we use this to derive the yield from data

Z(today)~ Z(0-yln[M_g(today)/M_g(0)]; Z(today)~0.7 Z_{sun}

since intial mass of gas was sun of gas today and stars today $M_g(0)=M_g$(today)+M_s(today) with M_g(today)~40$M_\odot/pc^2$ M_{stars}(today)~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.
- Also 'G dwarf' problem in MW (S+G pg 11) and different relative abundances (e.g C,N,O,Fe) amongst stars

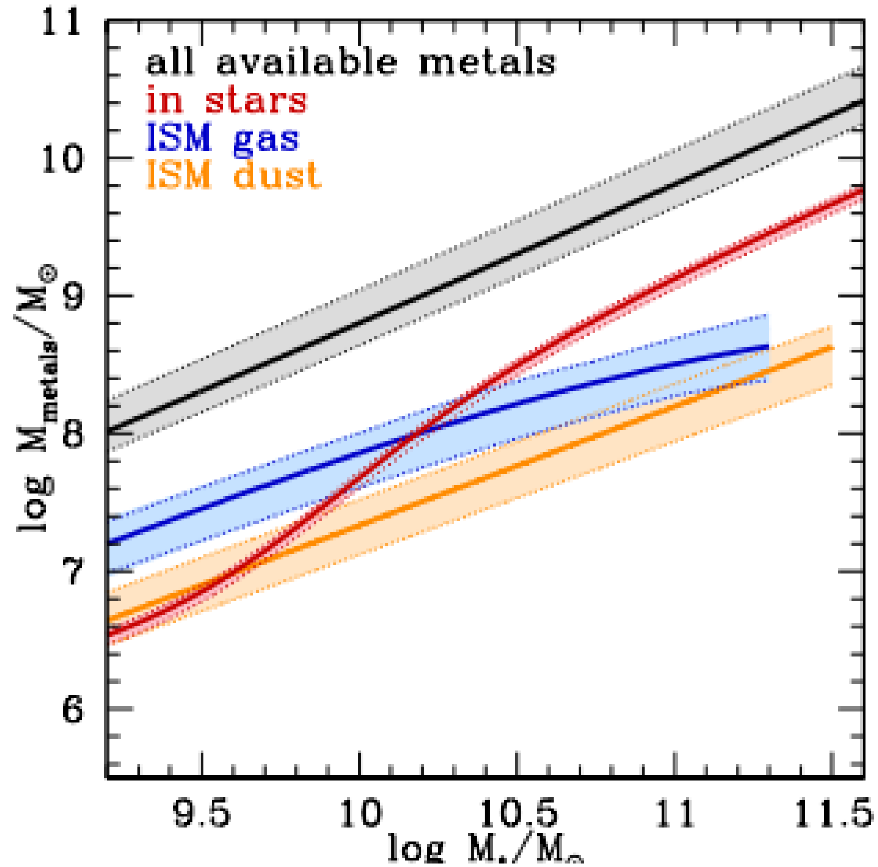
- Go to more complex models - leaky box (e.g outflow); if assume outflow of metal enriched material g(t); if assume this is proportional to star formation rate $g(t)=cdM_s/dt$; result is $Z(t)= Z(0)-[(y/(1+c))*\ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change relative abundances

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
- Metallicity-radius relation in disk galaxies
- Metals in the IGM in clusters and groups

- see arXiv:1310.2253 A Budget and Accounting of Metals at z~0: Results from the COS-Halos Survey Molly S. Peeples, et al



Leaky-Box Model

- If there is an outflow of processed material, $g(t)$, the conservation of mas 1) becomes

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

- And the rate of change in the metal content of the gas mass (Eq. 2) now 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 = $y/(1$

Veilleux

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 in a SF episode is

  $dM_h/dt = (y - Z)\, dM_s / dt$
- 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 $M_s >> M_g$, 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*