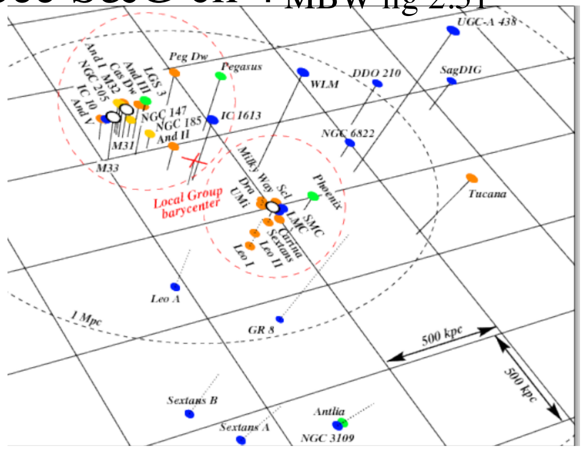
# Local Group See S&G ch 4 MBW fig 2.31




- 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, $H_2$, 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

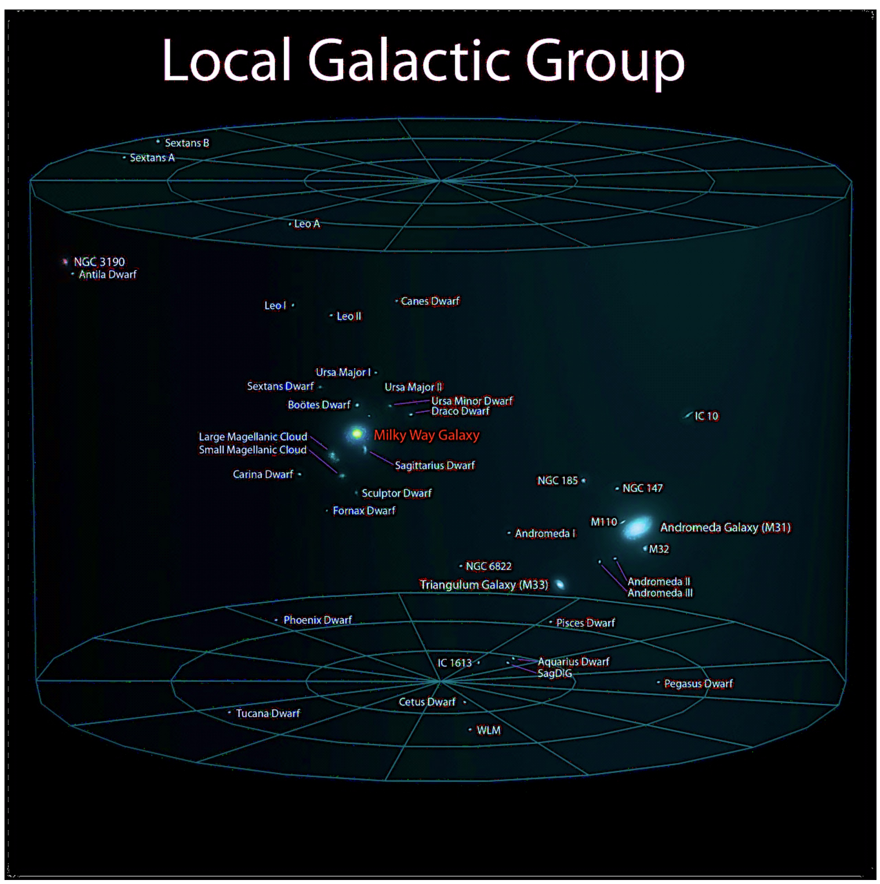
–calibration of Cepheid distance scale

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.



https://sciencesprings.wordpress.com/tag/milky-way/

Local Group. Andrew Z. Colvin 3 March 2011



# Image of Local Group to Scale S&G Fig 4.1

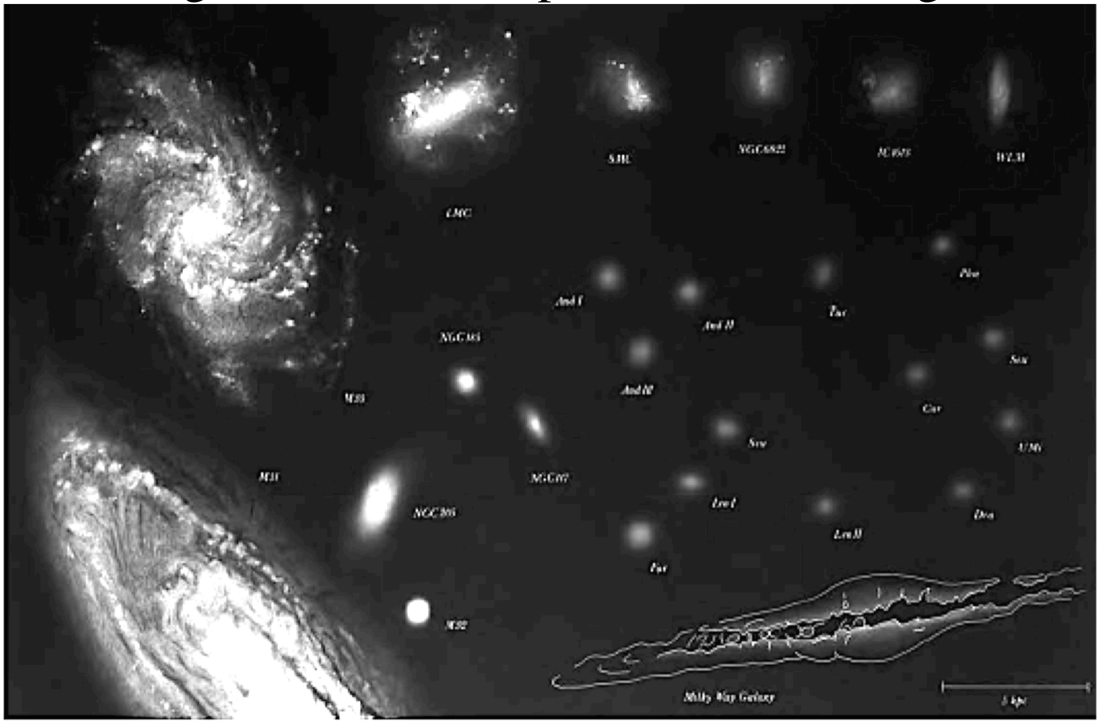



**Fig. 4.1.** Galaxies of the Local Group, shown to the same linear scale, and to the same level of surface brightness. The spiral and irregular galaxies stand out clearly, while the dwarf spheroidals are barely visible – B. Binggeli.

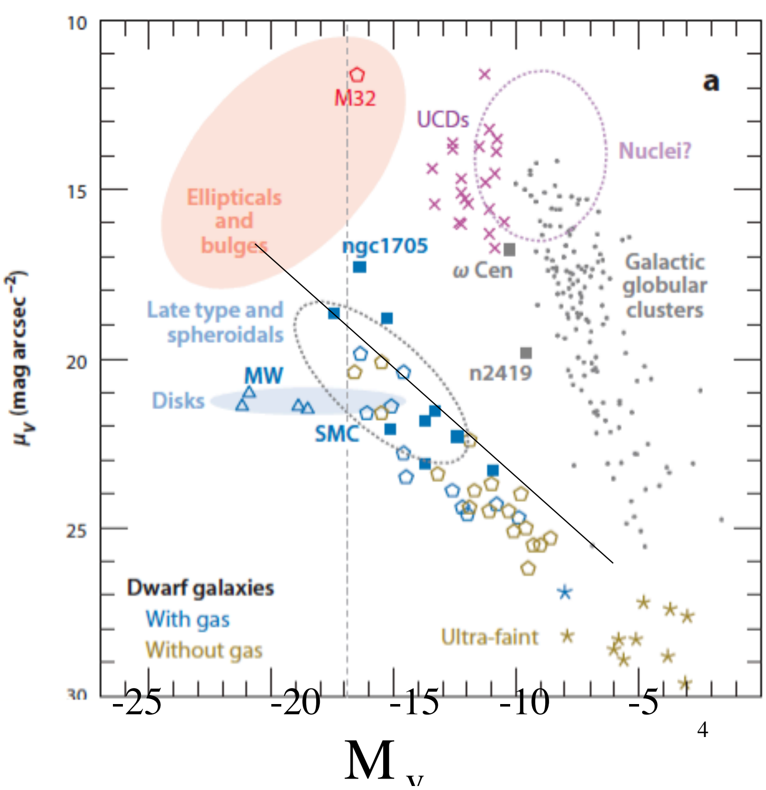


# Local Group Galaxies -Wide Range of Luminosity

- 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

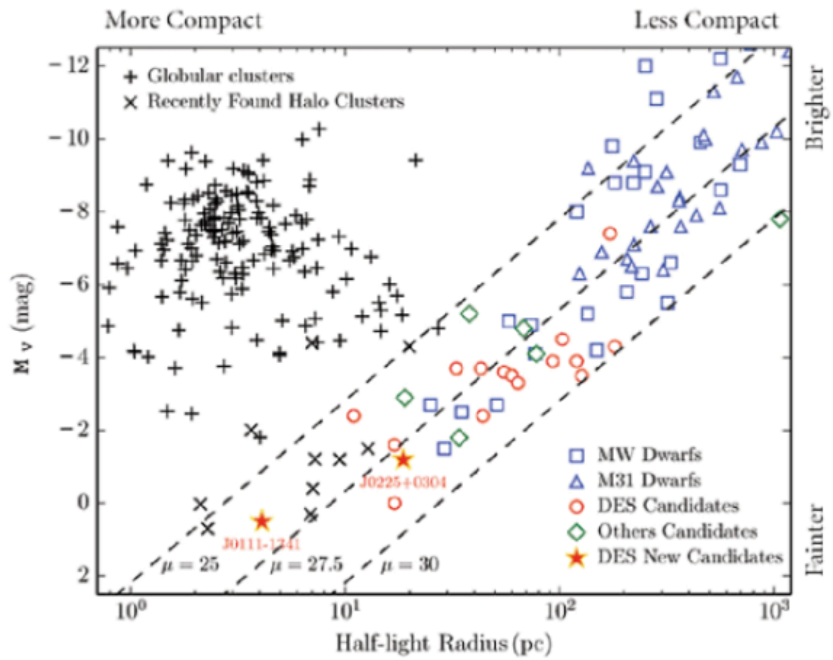


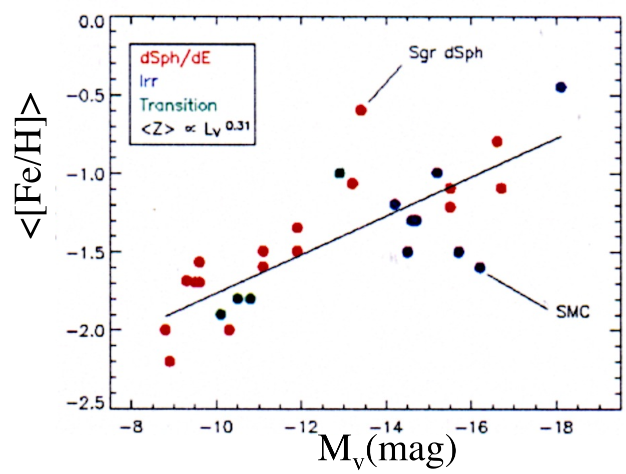

*Figure 2. Absolute magnitude versus half-light radius for globular clusters and dwarf*



# Wide Range of Luminosities/ Chemical Abundance

- MW/M31~$2\times10^{10}L_{v\odot}$
- LMC~$2\times10^{9}L_{v\odot}$
- Formax dSph $1\times10^{7}{}_{v}L_{\odot}$
- Carina dSph $3\times10^{5}L_{v\odot}$

- 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

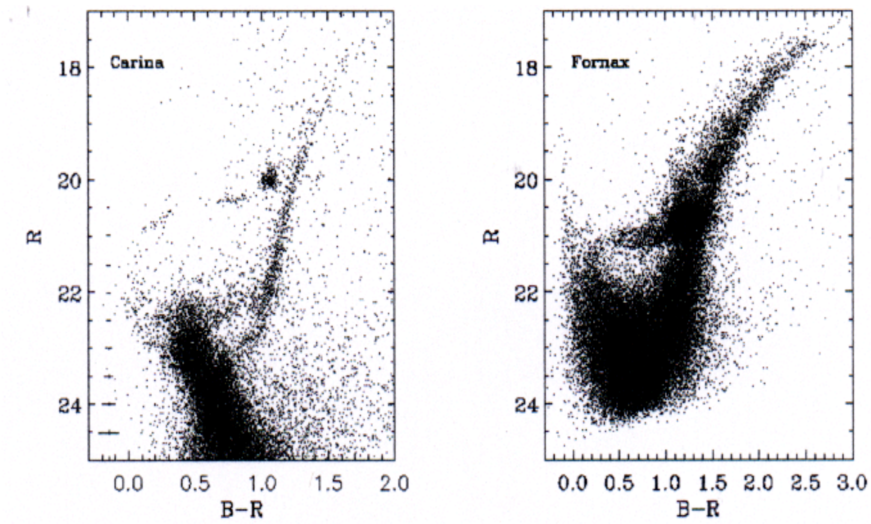



T. Smecker-Hane

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

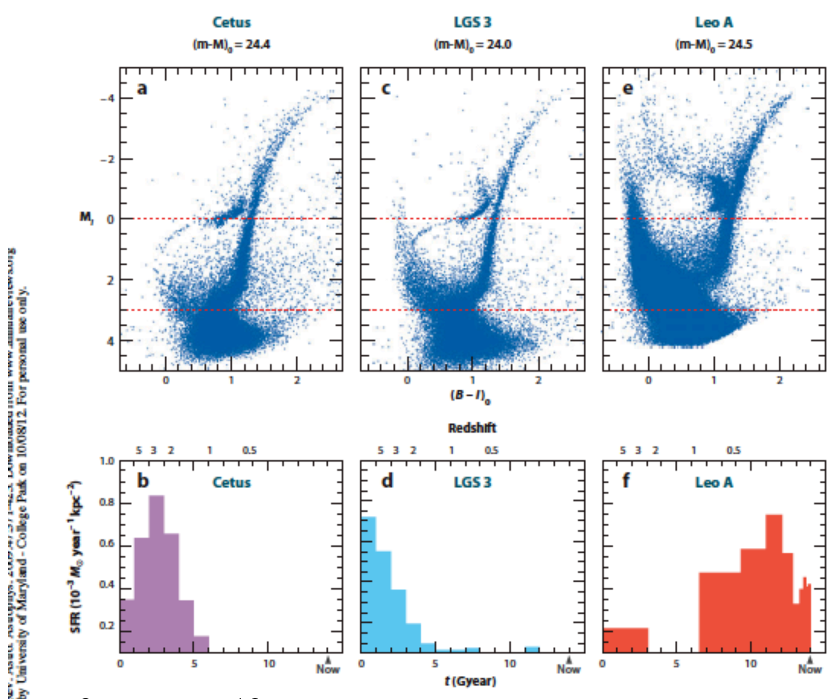
- Analysis of CMDs shows presence of both old and (some) young stars in the dwarfs -complex SF history
- The galaxies <u>do not</u> show the same SF history- despite their physical proximity and being in a bound system
- Their relative chemical abundances show some differences with low metallicity stars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






# Star Formation Histories Local Group Dwarfs

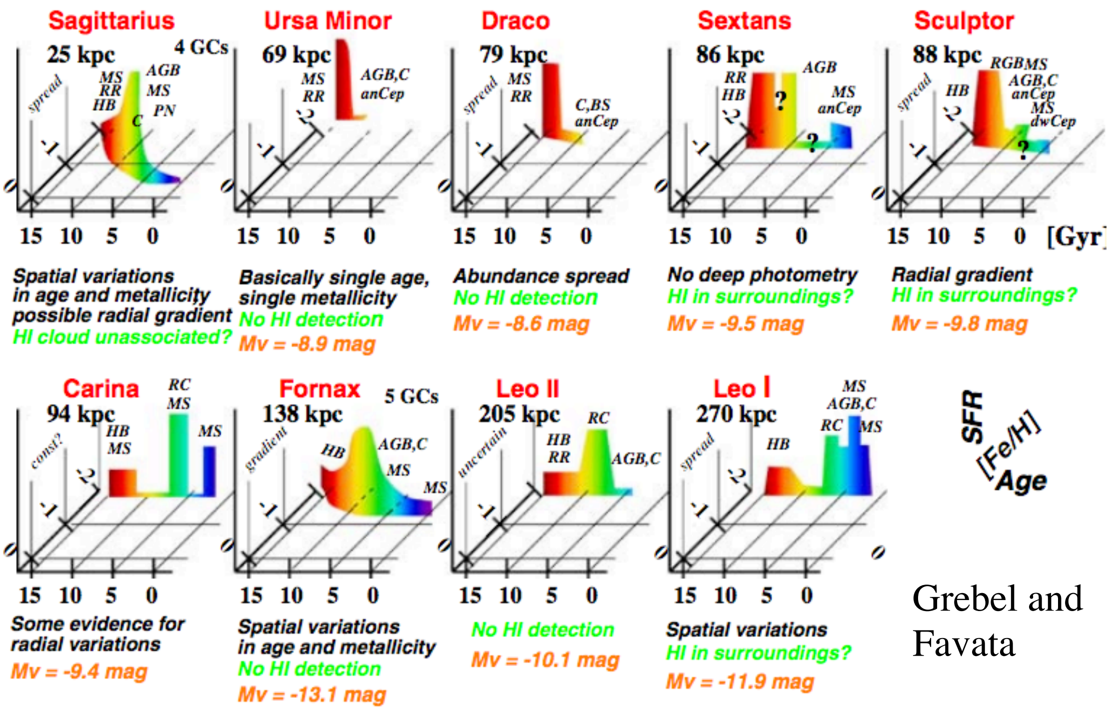
- With HST can observed color magnitude diagram for individual stars in local group galaxies
- Using the techniques discussed earlier can invert this to get the star formation history
- Note 2 extremes: very old systems Cetus, wide range of SF histories (Leo A)
- (Tolstoy, Hill, Tosi Annual Reviews 2009)




0 10 now

t (Gyr)

# History of SFR In Local Group Dwarfs

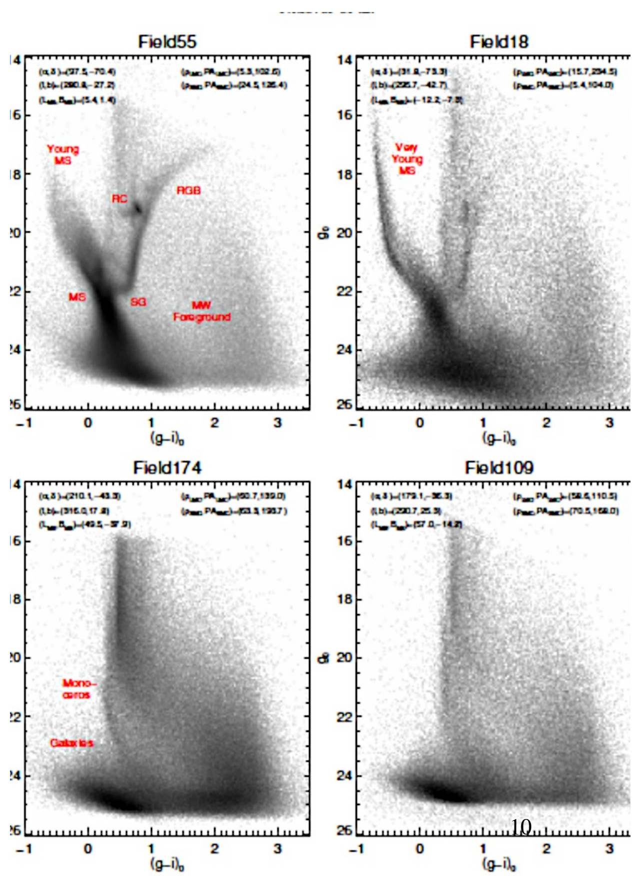



Grebel and Favata

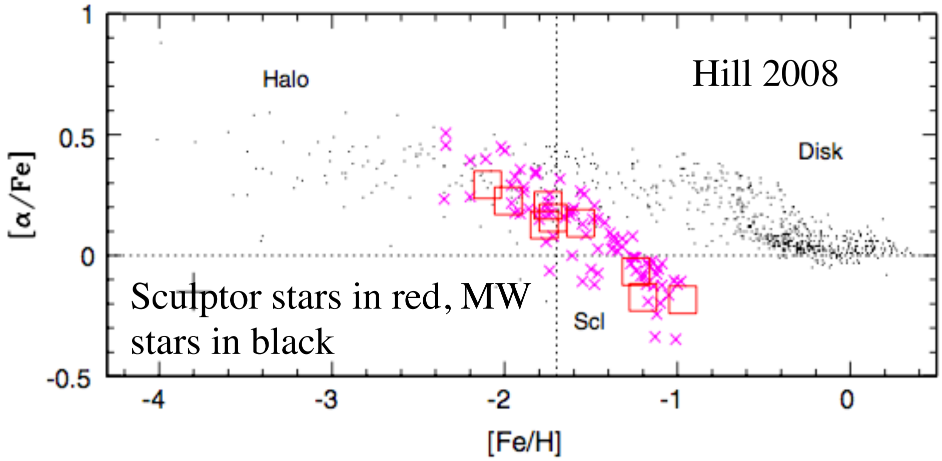


# Different Places in the LMC

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



# Abundances in Local Group Dwarfs

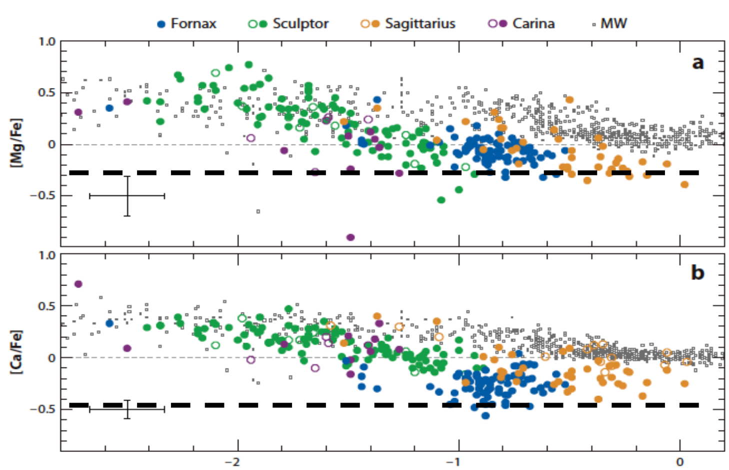



- Clear difference in metal generation compared to MW
  - Fe from type I SN
  - "α" from type II
    - "α" elements is O,Ne,Mg,Ar,Si,S,

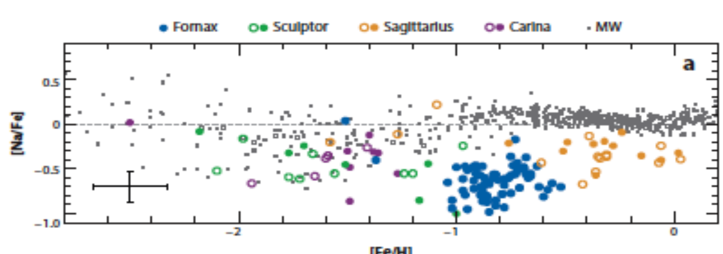


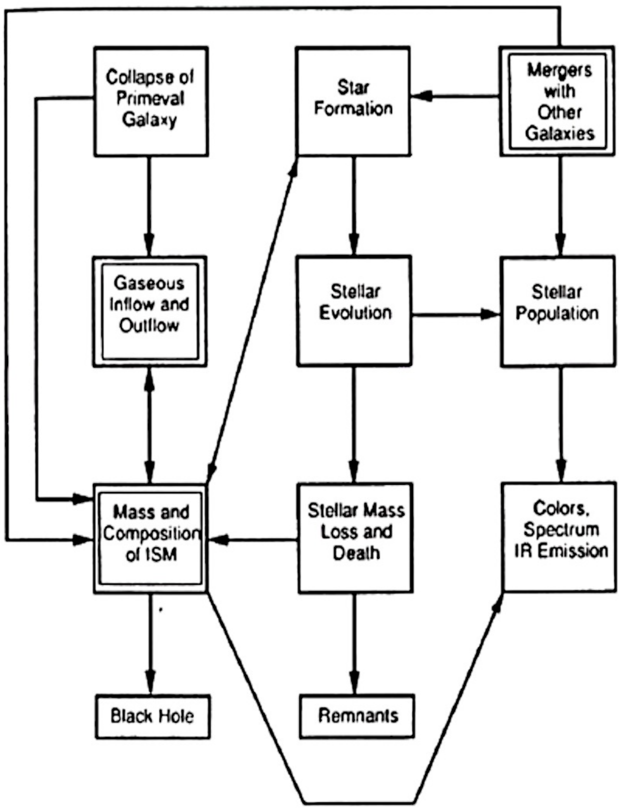
# Metallicities In LG Dwarfs Vs MW

- Overall metallicity of LG dwarfs is low :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 wind models be well constrained by chemical abundance observations (later in lecture).








**Key parameters in chemical evolution:**

- Lifetimes of stars (as a functior 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

- $$(7.1) \quad M = M_s + M_g \qquad \begin{cases} M = \text{total mass} \\ M_s = \text{mass in stars} \\ M_g = \text{mass in gas} \end{cases}$$

- $$(7.2) \quad \frac{dM}{dt} = f - e \qquad \boxed{\begin{cases} f = \text{rate of infalling gas} \\ e = \text{rate of ejected gas} \end{cases}}$$

$$(7.3) \quad \frac{dM_s}{dt} = \Psi - E \qquad \begin{cases} \Psi = \text{star formation rate} \\ E = \text{gas ejection rate of all stars} \end{cases}$$

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

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 **Read S&G 4.3**

- To get a feel for how chemical evolution and SF are related (S+G eqs 4.13-4.17)-
- at time t, mass $\Delta M_{total}$ 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)



# Formation of Elements ala S&G

- $M_g(t)$ the mass of gas in the galaxy at time t
- $M_*(t)$ the mass in low-mass stars and the white dwarfs, neutron stars and black the matter in these objects remains locked within them throughout the galaxy's lifetime)
- $M_h(t)$ is the total mass of elements heavier than helium in the gas;
- The metal abundance in the gas is then $Z(t) = M_h(t)/Mg(t)$.

When the massive stars end their lives, they leave behind a mass $\Delta M_*(t)$ of low-mass stars and remnants, and return gas to the interstellar medium which includes a mass $\mathbf{p}\Delta M_*(t)$ of heavy elements.

The yield is **p**

So
The mass $M_h(t)$ of heavy elements in the interstellar gas changes as the metals produced by massive stars are returned to the gas phase

- while a mass $Z\,\Delta M_*(t)$ of these elements is locked into low-mass stars and remnants.
- Taking all these terms
- We have
- $\Delta M_h(t) = p\Delta M_*(t) - Z\Delta M_*(t) = (p - Z)\Delta M_*(t)$

As the stars evolve the metallicity of the gas increases by

$\Delta Z=(M_h(t)/M(t)_g)=p\Delta M_*(t)-Z([\Delta M_*(t)+\Delta M_g(t)]/M_g(t)$ eq 4.14

Closed box approximation- no gas enters or leaves the system sosum of mass remains constant e.g. $\Delta M_*(t)+\Delta M_g(t)= 0$ (e.g. sum of changes in gas and stellar mass balance)

Integrate eq. 4.14 to get

$Z(t)=Z(t=0)+p\ln[M_g(t=0)/M_g(t)]$



- Metallicity grows with time as stars form and gas is used up

- The mass of stars formed before time t is $M_g(0)-M_g(t)$
- These stars have a metallicity $<Z(t)$ and so
- $M_*(<Z))=M_g(0)[(1-\exp[Z-Z(0)/p)]$ eq 4.16

- The mass $M_*(<Z)$ of slowly evolving stars that have abundances below the given level Z depends only on the quantity of gas remaining in the galaxy when its metal abundance has reached that value.
- Once all the gas is gone, this model predicts that the mass of stars with metallicity between Z and Z + Z should be
- $[dM_*(<Z)/dZ]\,\Delta Z \propto \exp\{- [Z(t) - Z(0)]/p\}\Delta Z.$

# Closed Box- continued

- Net change in metal content of gas
- $dM_h$=p $dM_{star}$ - Z $dM_{star}$=(p- Z) $dM_{star}$
- Change in Z since $dM_g$= -$dM_{star}$ and $Z=M_h/M_g$ then
- $dZ=dM_h/M_g - M_h\, dM_g/M^2_g = (p- Z)\, dM_{star}/M_g + (M_h/M_g)(dM_{star}/M_g) = p dM_{star}/M_g$
- $d Z/dt=-p(dM_g/dt) M_g$
- If we assume that the yield y is independent of time and metallicity (Z) then
- $\mathbf{Z(t)= Z(0)-p \ln M_g(t)/M_g(0)}$ metallicity of gas grows with time logarithmically 4.15



# 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

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

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

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

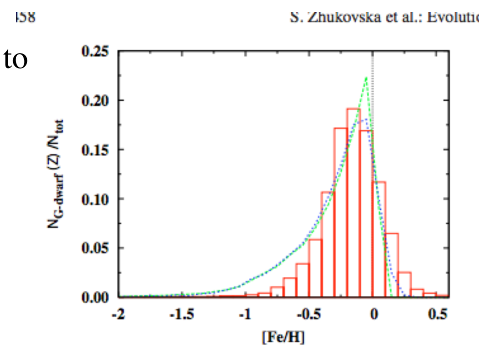
$Z(today) \sim Z(0-p\ln[M_g(today)/M_g(0)]$; $Z(today) \sim 0.7\, Z_{sun}$

since initial mass of gas was sum of gas today and stars today $M_g(0)=M_g(today)+M_s(today)$ with for MW $M_g(today) \sim 10 M_\odot/pc^2$ $M_{stars}(today) \sim 40 M_\odot/pc^2$

get $p=0.43\, Z_{sun}$ 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 **$g(t)=c dM_s/dt$**;
  - solution is $Z(t)= Z(0)-[(p/(1+c))*\ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change relative abundances




Green is closed box model
red is observations of local stars



# Leaky-Box Model

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

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

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

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

in this and the following the yield is y

- *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 $\boxed{Z(t) = Z(0) -[ y/(1+c)] * \ln[M_g(t)/M_g}$
  - The only effect of an outflow is to reduce the yield to an effective yield = y /

## 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

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

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

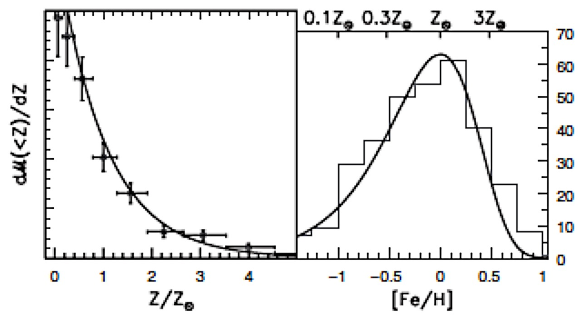
    Metallicity distribution of stars in Milky Way disk

    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



# 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

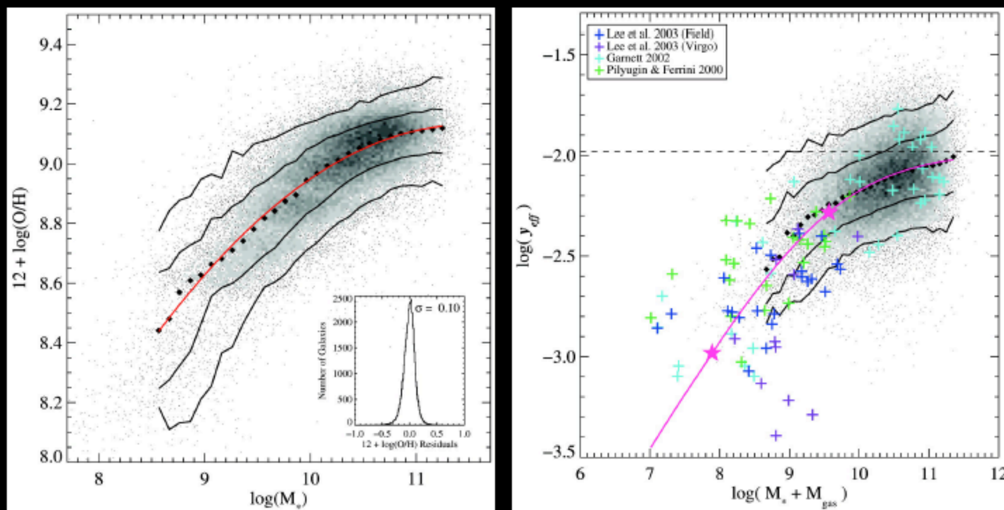
- In a growing universe (remember galaxy masses increase with time) expect gas inflow

- Gas outflow could be caused by the effects of star formation (supernova) and active galaxies injecting huge amounts of energy

# Local Star-Forming Galaxies

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

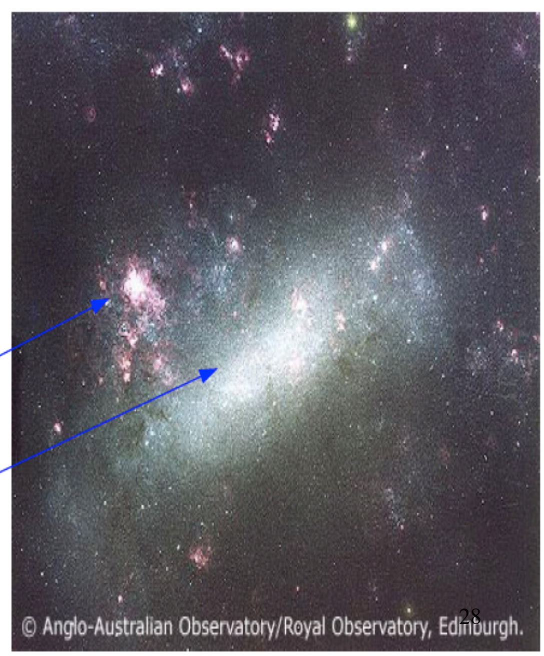
*Reminder: $Z(t) = Z(0) - [\, y/(1+c)] * \ln[M_g(t)/M_g(0)]$ (here assume $Z(0) = 0$)*



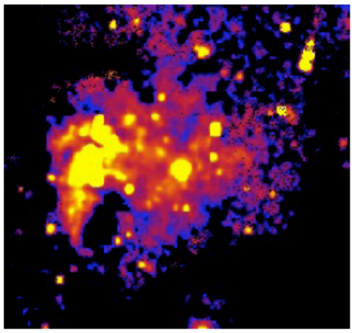

*(e.g., Garnett+02; Tremonti+04; Kauffmann+03)*

# The LMC

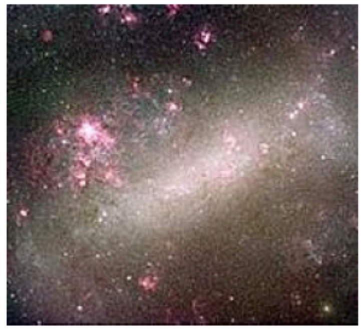
- Distance 50kpc
- Dwarf Irregular
  - Type Sm
- Tarantula Nebula
  - active star forming region
- Barred galaxy
- $L \approx 1.7 \times 10^9\ L_\odot$

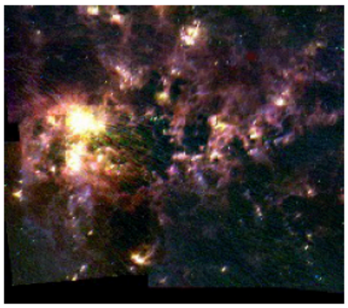


Xray: ROSAT

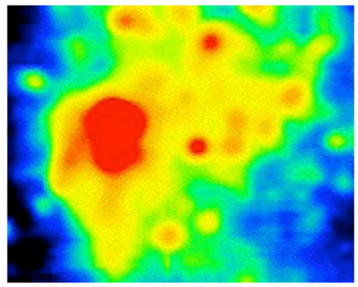


AAO optical 3 color





IRAS (Jason Surace)



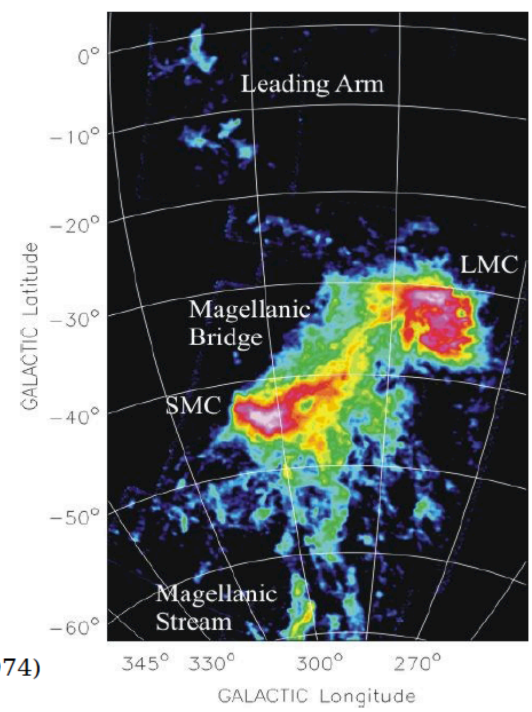
Radio (RAIUB/MPIFR Bonn

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



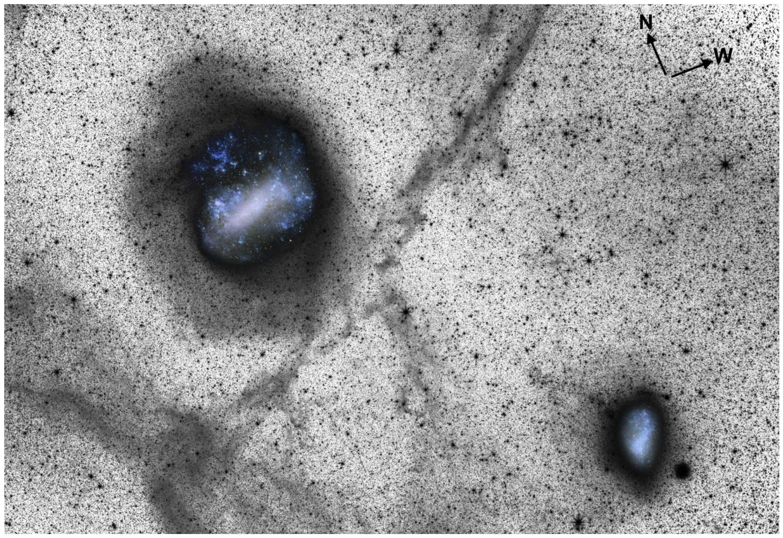
- Clues to the MC's dynamics
  - Common HI envelope
  - Stream of gas “following” the MC's

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

Optical Image of LMC and SMC

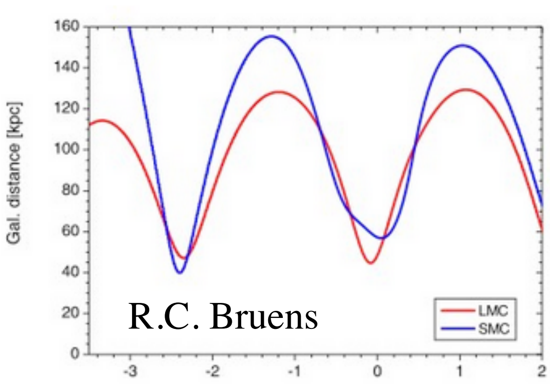





# Magellanic Clouds

- 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??

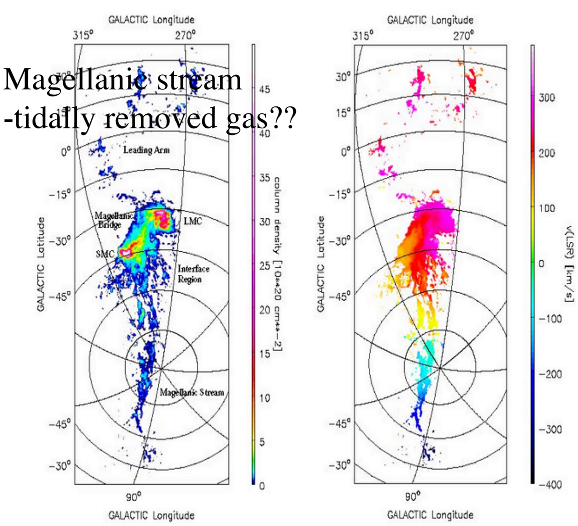
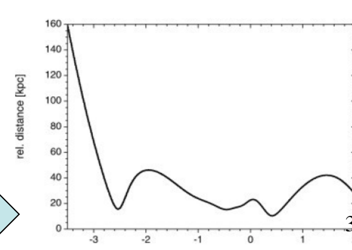



**Figure 2:** Single-dish observations of HI gas (Brüns et al. 2004).
***Left:*** HI column density map of the entire Magellanic System. ***Right:*** Mean velocity v(LSR), map of the entire Magellanic System.



# 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 $m \ll M_s$

- 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: $m_1\langle v_1^2\rangle = m_2\langle v_2^2\rangle$



# 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

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

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

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

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

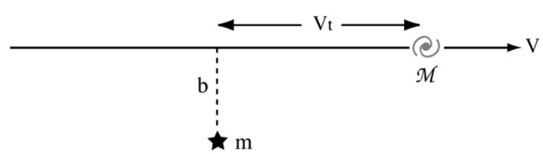



Fig 7.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

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

# 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



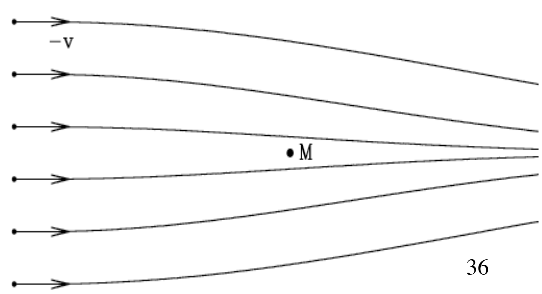
# Analytic Estimate How Fast Will Local Group Merge?

- Dynamical friction (S+G 7.1.1 )-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 $=Mdv/dt \sim 4\pi\ G^2M+m)nm/V^2$ (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**
- $t_{friction} \sim V/(dv/dt) \sim V^3/4\pi G^2 M m \rho / \ln\Lambda$ (in previous lecture)

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

putting in typical values for LMC

**$t_{friction} \sim 3$Gyrs**



- 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)

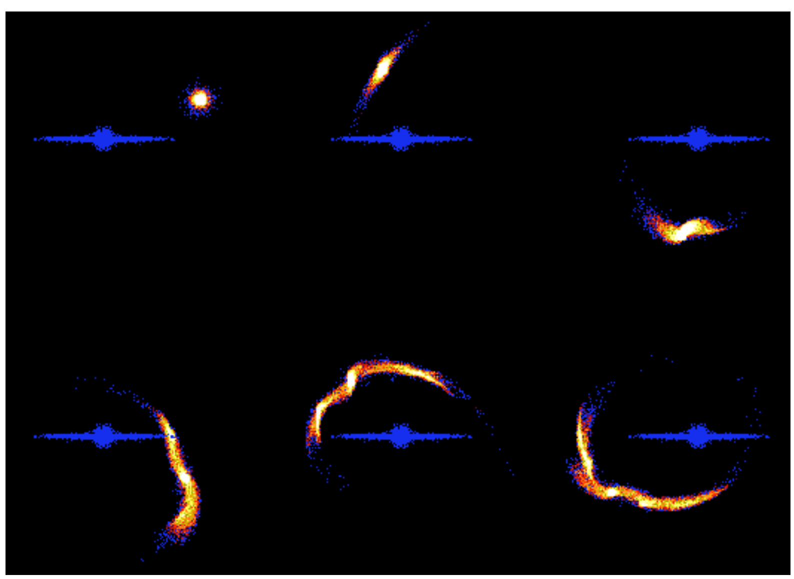


# LMC Merger??

- 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.



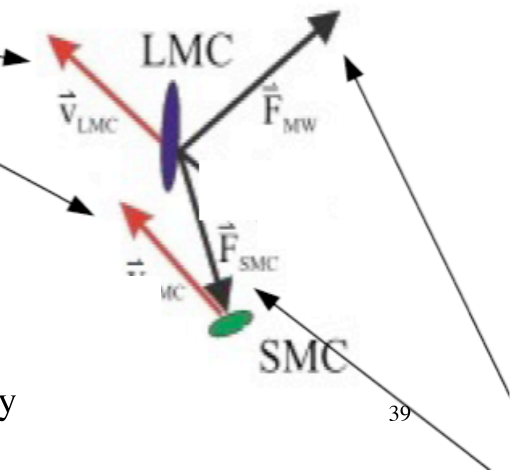
K. Johnston

Need distance to convert angular coord
to physical units

# Forces on the Magellanic Clouds

Space Velocity

Dynamical friction vectors
depend on shape and size




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

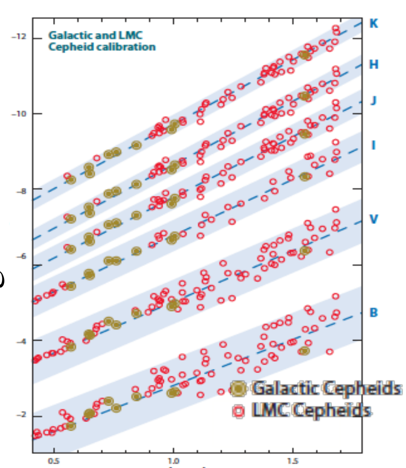


# Distance to LMC

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

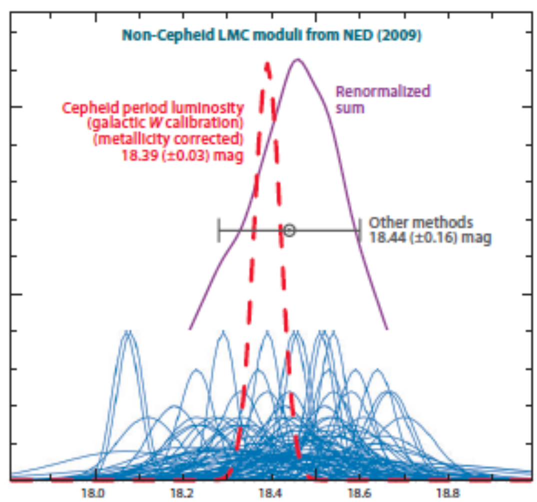
distance modulus, $\mu$,($\log d=1+\mu/5$) pc
LMC $\mu$= 18.48 ± 0.04 mag; (49.65 Kpc)

absolute mag in each band




log Period (days)

Relative probability

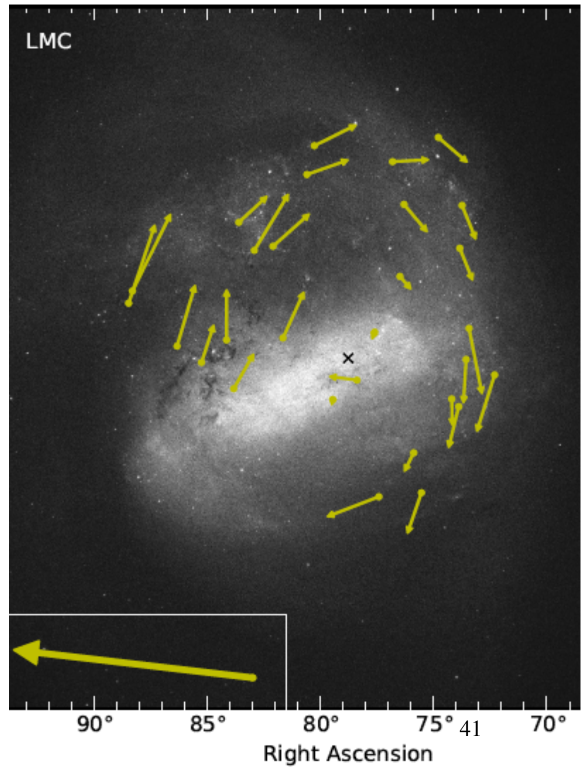



LMC Distance Modulus

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

# Rotation of the LMC New result from Gaia

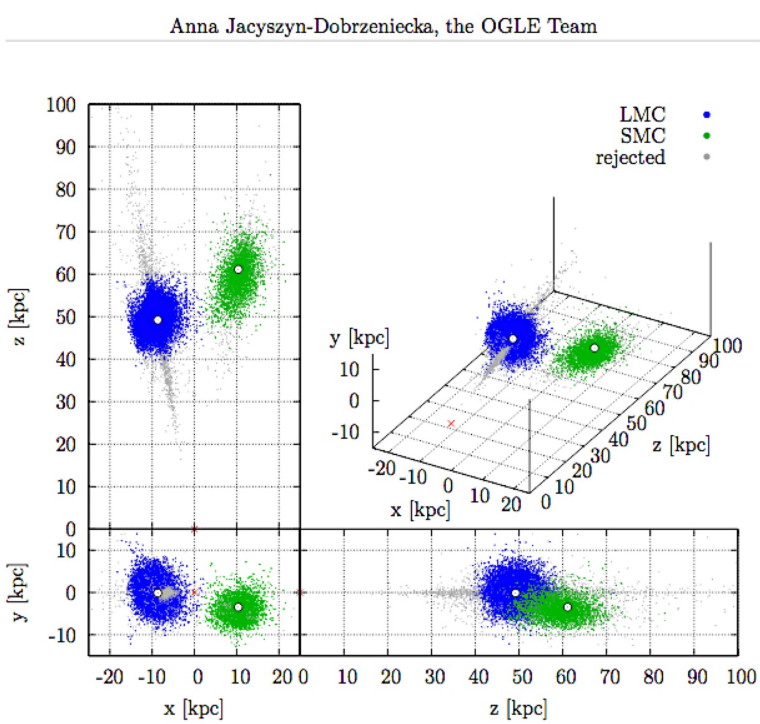
- Each vector shows motion of stars over next 7.2Myr
- Big vector is overall motion of LMC (van den Marel and Sahlmann 2017)
- Proper motion is ~ 1mas/yr and velocities are in km/sec to connect the 2 need distance.
- Fit gives m-M=18.54 mag or D= 51 kpc





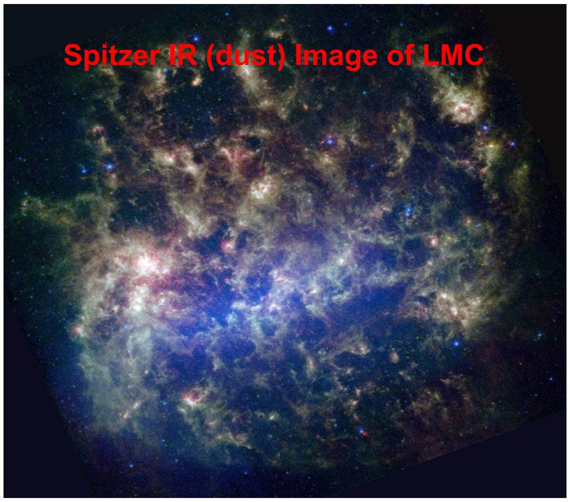

# 3D Map of LMC/SMC

- Data so precise get 3D 'map' of LMC/SMC

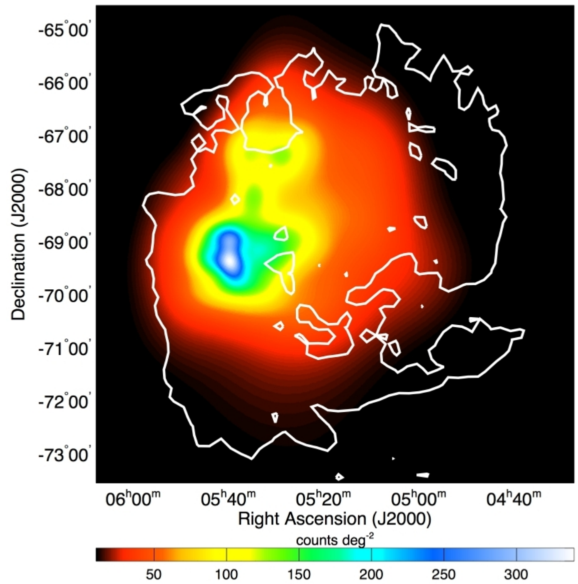


# Cosmic Rays and γ-rays

- 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




γ-ray intensity scale

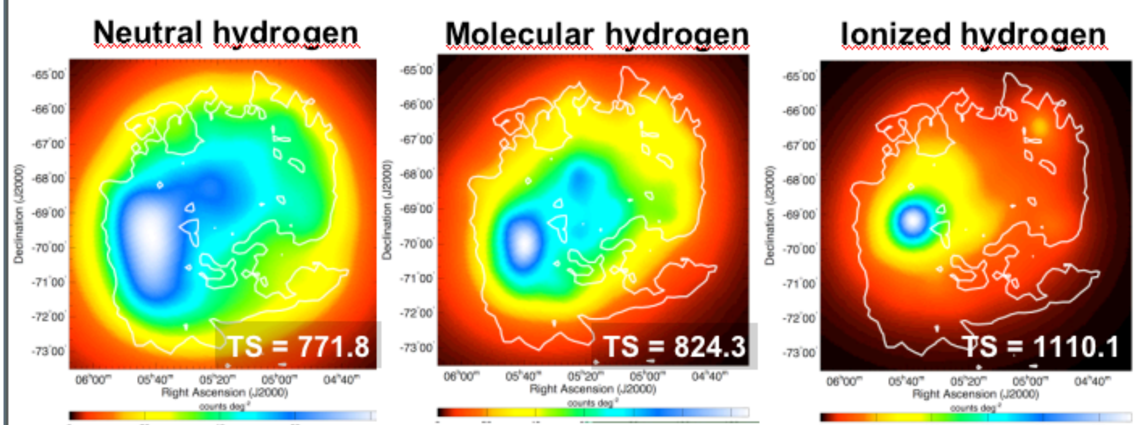


# LMC Cosmic Rays and γ-rays

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**

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

Dermer 2011