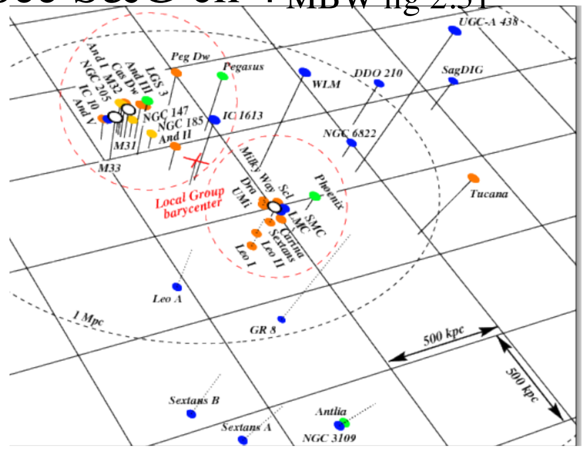
Local Group See S&G ch 4 MBW fig 2.31



- 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.

Image of Local Group to Scale S&G Fig 4.1

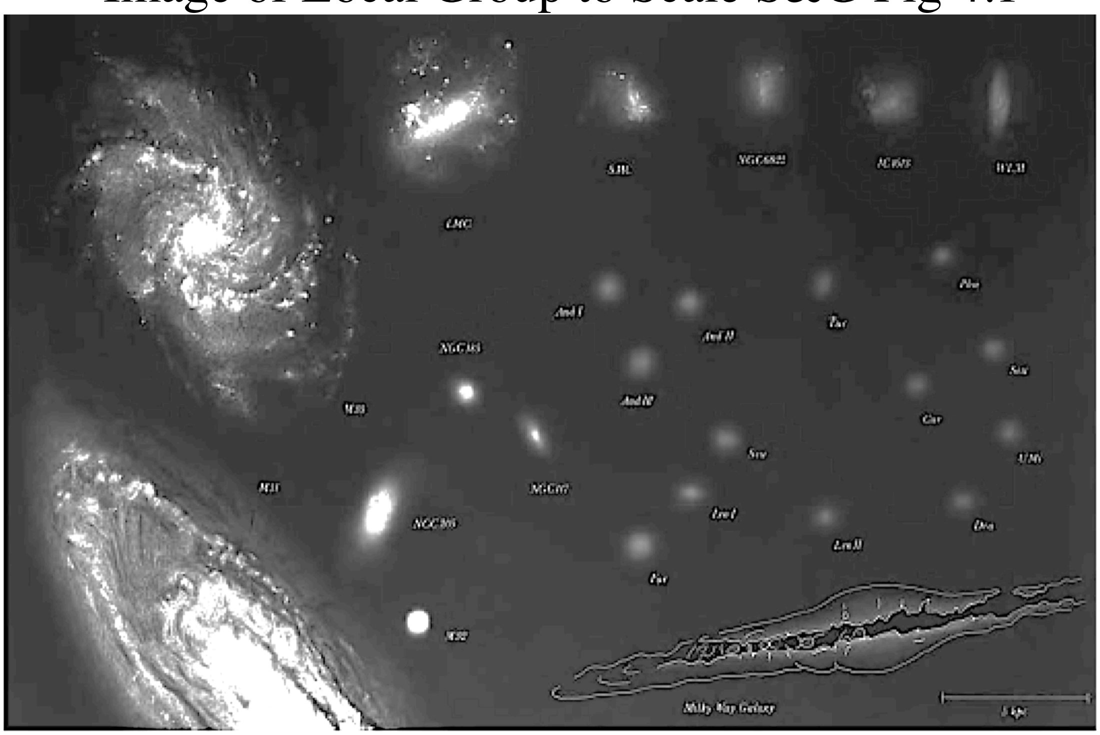
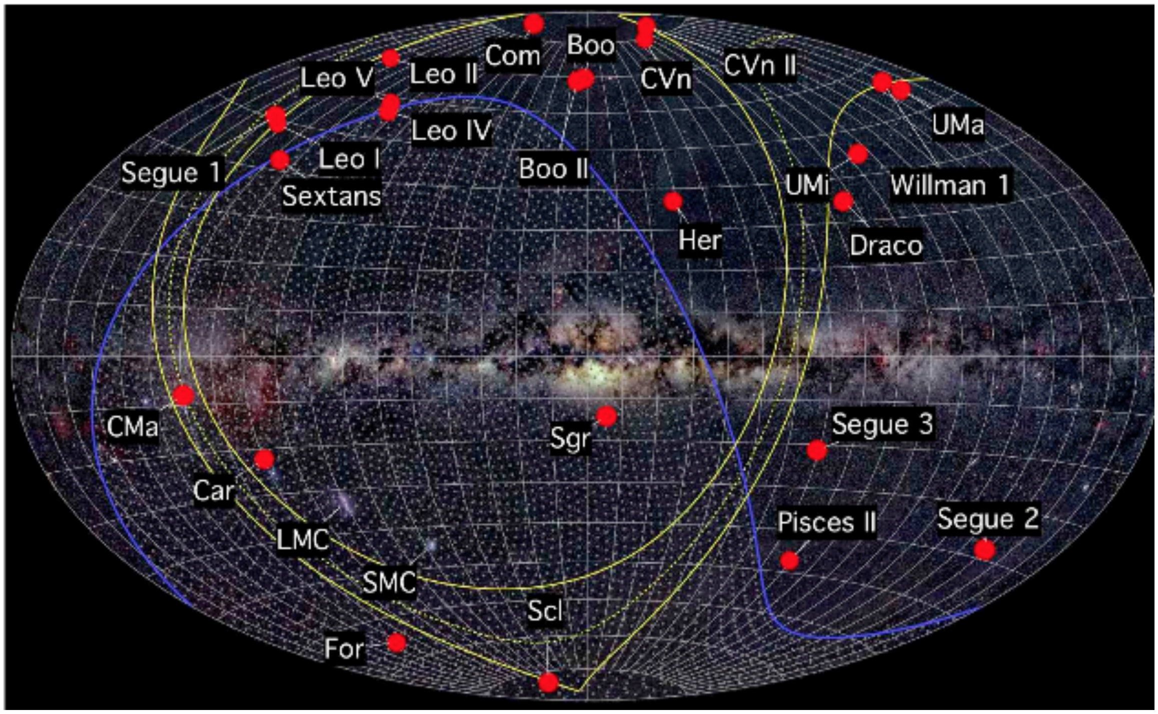


Fig. 4.1. Galaxies of the Local Group, shown to the same linear scale, and to the same level of surface brightness. The spiral and irregular galaxies stand out clearly, while the dwarf spheroidals are barely visible – B. Binggeli.

MW Companions Dwarfs –

A. Frebel

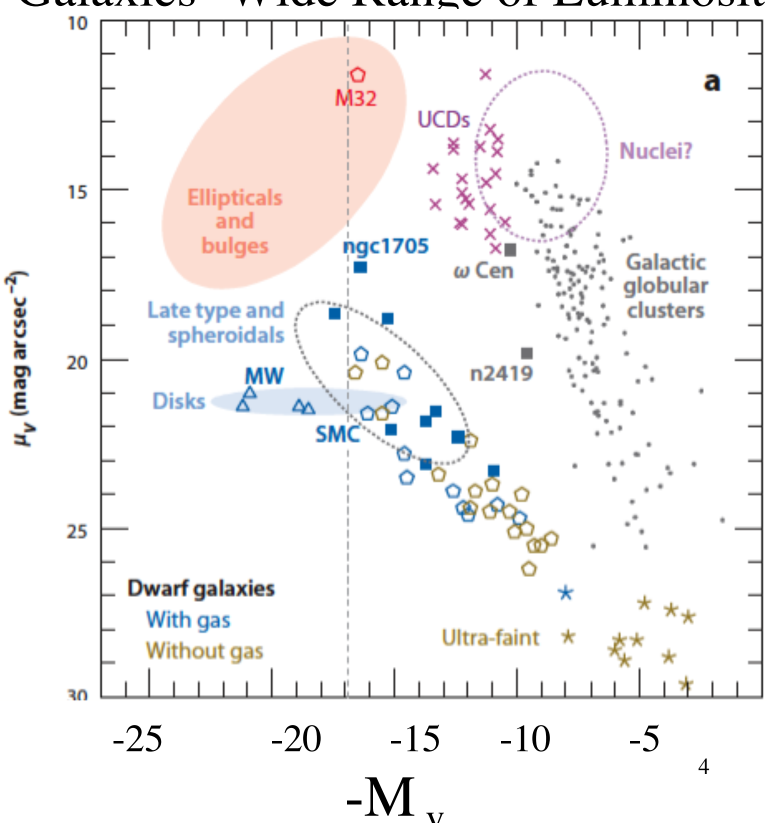


Local Group Galaxies -Wide Range of Luminosity

- 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



Why Study the Local Group

- Only place, outside of MW where properties of individual stars can be well measured.
- Detailed measurements of dwarf galaxies are possible
  - dwarfs have received a lot of attention lately because of
    - apparent very high fraction of dark matter
  - 'existence' as possible relics of the early universe (so-called near field cosmology – JSI meeting in 2013
  - Book The Origin of the Galaxy and Local Group
  - Volume 37 of the series Saas-Fee Advanced Course pp 1-144

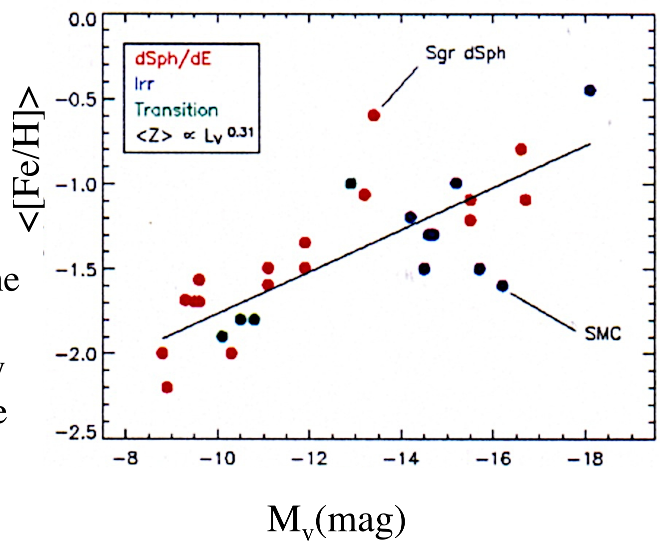
concept of near field cosmology

- there are ancient signatures in the MW and nearby galaxies providing evidence of the formation processes that led to the Galaxy and the Local Group (Freeman & Bland-Hawthorn 2002).
- ancient stars in the old thin disk, the thick disk, the stellar halo, the inner bulge, and in nearby dwarf galaxies.
- About half of all stars in the Galaxy today formed before redshift $z<1$.
- Dwarf galaxies are possibly the best probes of the first stars within the framework of near-field cosmology

Wide Range of Luminosities

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

- 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

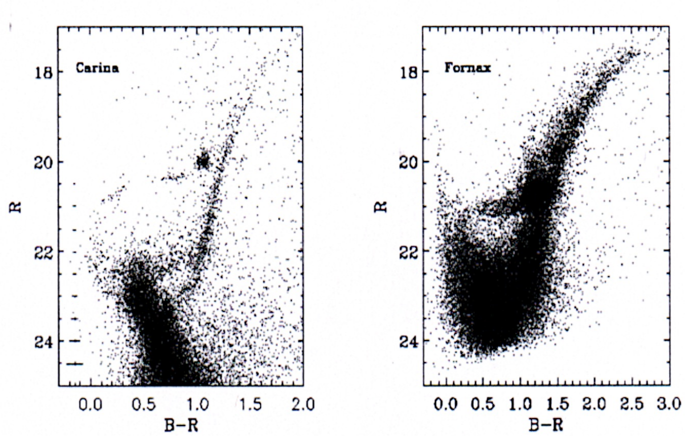


T. Smecker-Hane

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

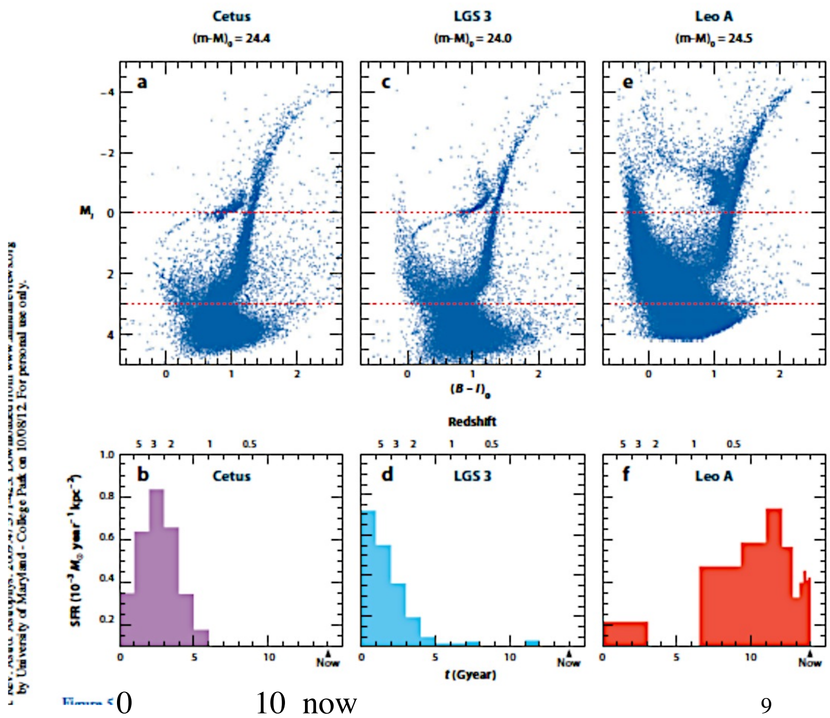
Star Formation Histories

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



Star Formation Histories Local Group Dwarfs

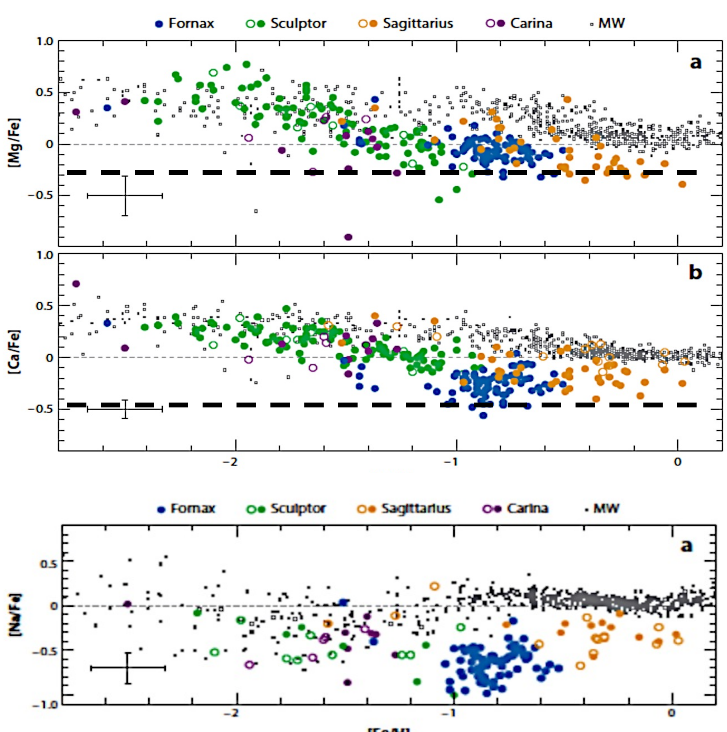
- With HST can observe color magnitude diagram for individual stars in local group galaxies
- Using the techniques discussed earlier can invert this to get the star formation history
- Note 2 extremes: very old systems Cetus, wide range of SF histories (Leo A)
- (Tolstoy, Hill, Tosi Annual Reviews 2009)



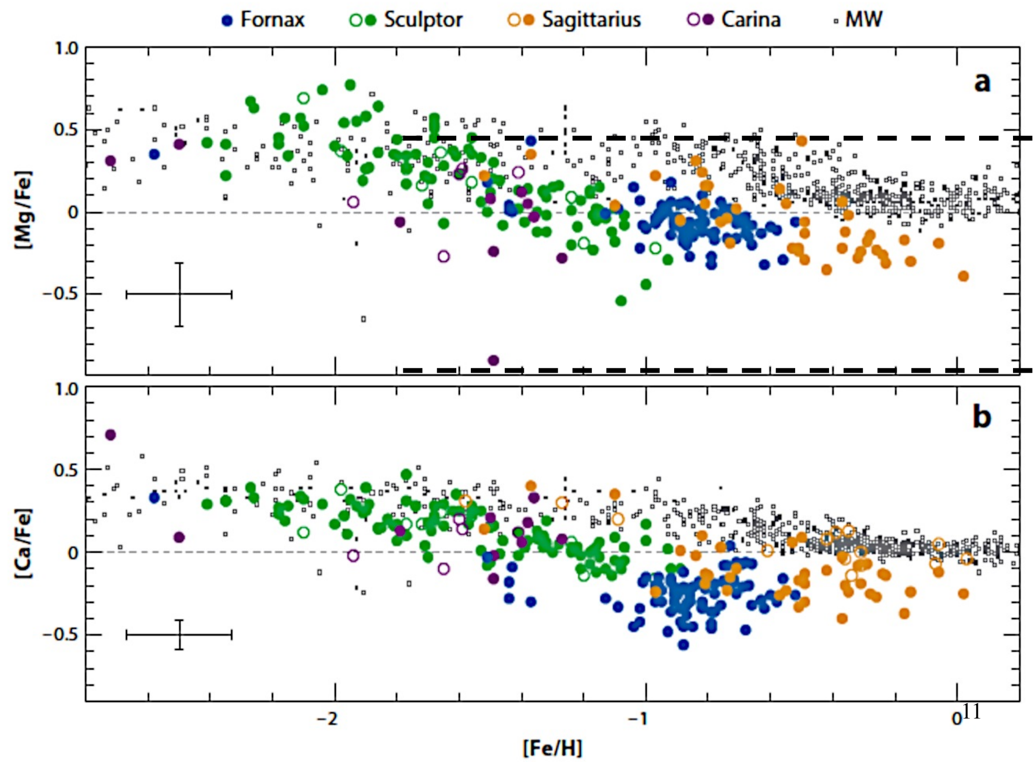
t (Gyr)

- Overall metallicity of LG dwarfs is low but some patterns some similar others 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 LG can wind models be well constrained by chemical abundance observations.

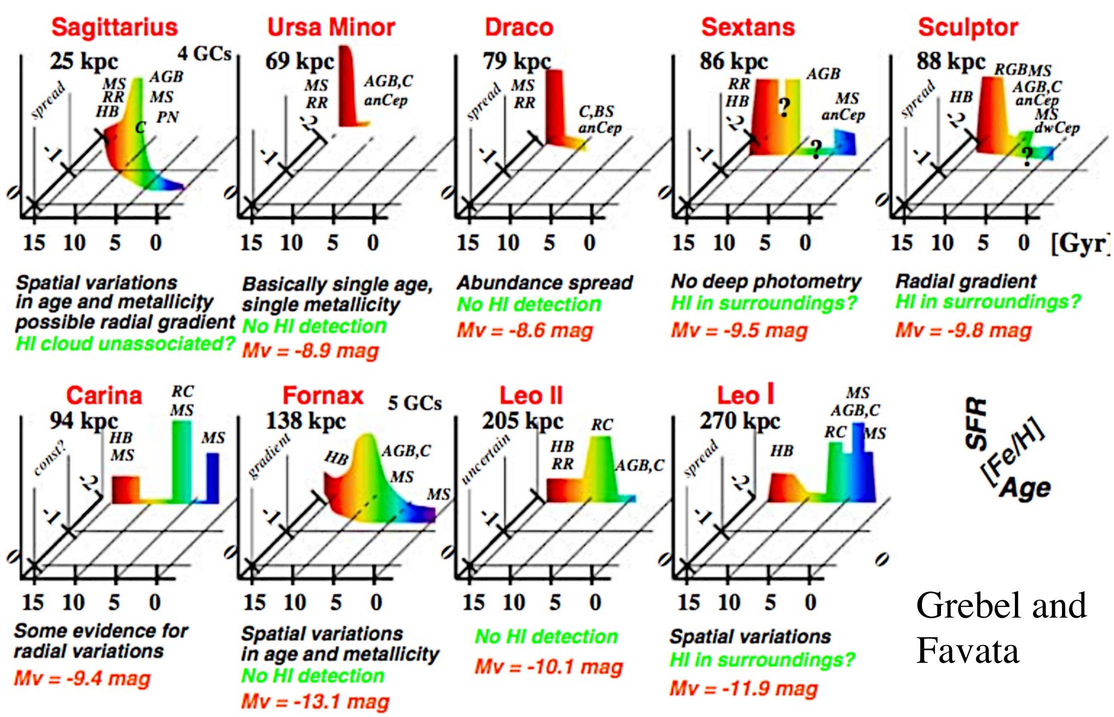
Metallicities In LG Dwarfs Vs MW



Metallicities In LG Dwarfs Vs MW



History of SFR In Local Group Dwarfs

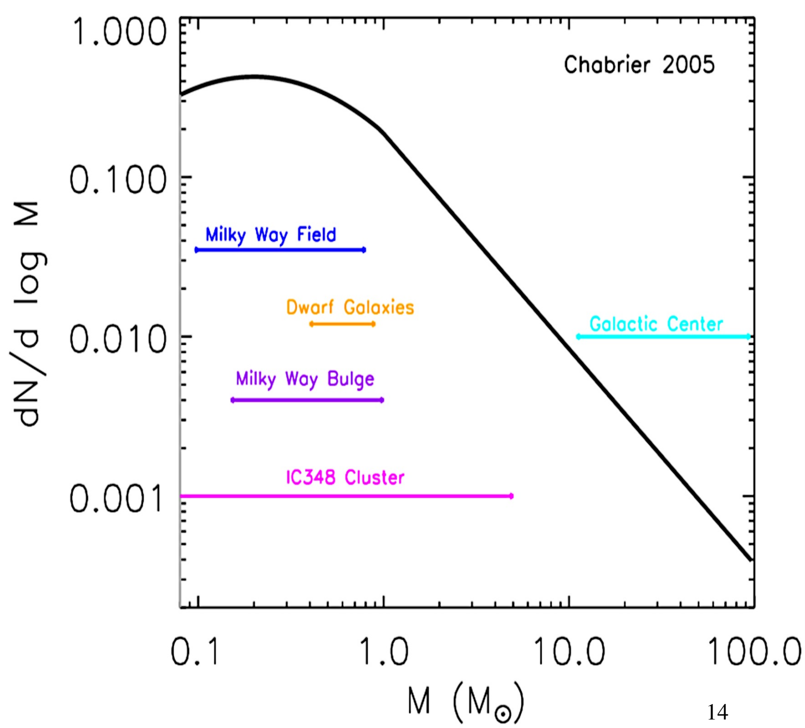


Grebel and Favata

Where Can IMF be Measured

- 1510.06027

An Observational Perspective of the IMF: Progress and Challenges. S. R. Offne



IMF in Local Group

arXiv: 1510.06027 An Observational Perspective of the IMF: Progress and Challenges. S. R. Offner

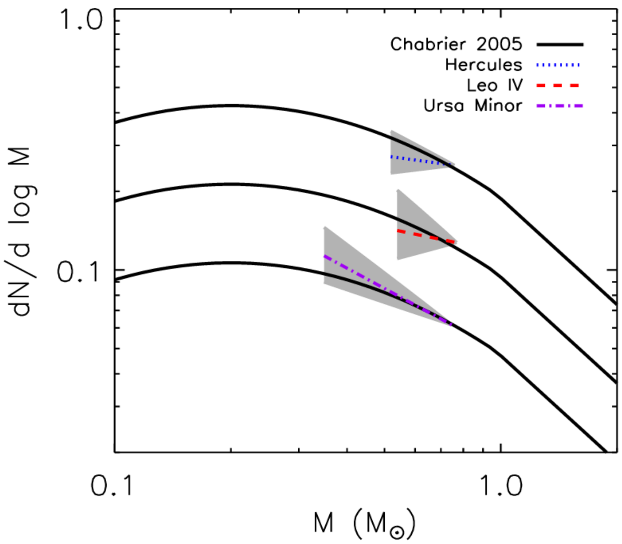
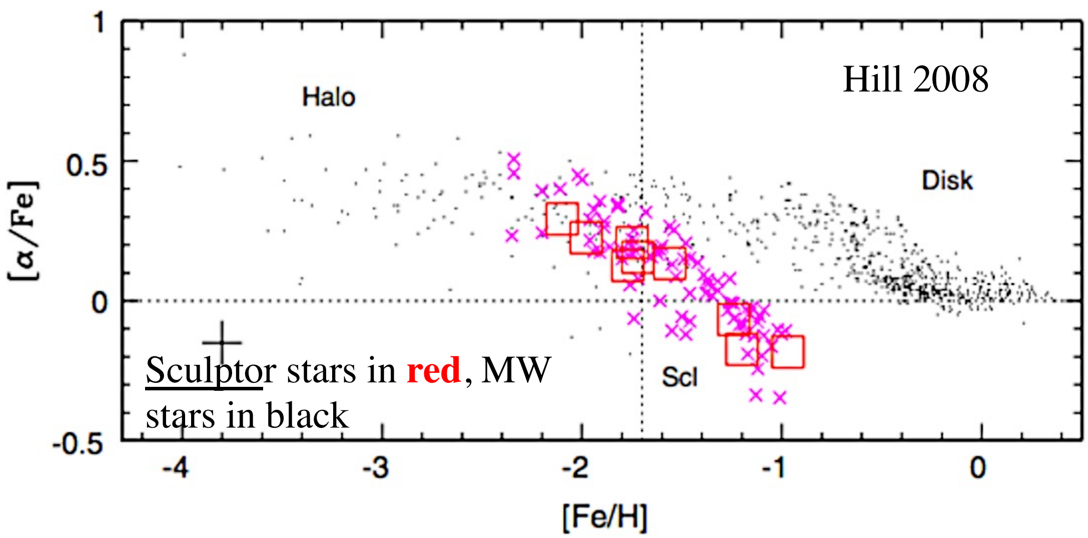


Figure 3. The IMF slopes obtained for three local dwarf galaxies using resolved population studies (Geha et al. 2013, Wyse et al. 2002): $\alpha = -0.2^{+0.4}_{-0.5}$ (Hercules), $\alpha = -0.3 \pm 0.8$ (Leo IV), and $\alpha = -0.8$ (Ursa Minor). The dwarfs have visual magnitudes M_v = -6.2, -5.5 and -9.2, respectively. The 1σ uncertainty in the slope is indicated by the grey shaded area, where 15% uncertainly is adopted for the latter case based on the LF error. The lines are offset for clarity.

Abundances in Local Group Dwarfs



Sculptor stars in **red**, MW stars in black

- Clear difference in metal generation history

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 sec 4.13-4.17)- but a different approach (Veilleux 2010) **Please read MWB 10.4.2**

- 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)

The Simple Model for the chemical evolution

- .The basic assumptions of the Simple Model are:
- - the system is one-zone and closed, no inflows or outflows
- - the initial gas is primordial (no metals),
- - IRA holds (instaneous recycling approximation0
- - the IMF, is assumed to be constant in time,
- - the gas is well mixed at any time (instantaneous mixing approximation,IMA).

The Simple Model fails in describing the evolution of the Milky Way

- (G-dwarf metallicity distribution, elements produced on long timescales and abundance ratios) and the reason is that at least two of the above assumptions are manifestly wrong, if one intends to model the evolution of the abundance of elements produced on long timescales, such as Fe.

- In particular, the assumptions of the closed box and the IRA are likely to be wrong.

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

define y as the yield of heavy elements- yM_h=mass of heavy elements returned to ISM

(ignore lifetimes of the stars)

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
- $Z(t)= Z(0)-y \ln M_g(t)/M_g(0)= Z(0)=y\ln \mu$ 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

Closed Box- continued

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

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 $M_g(today)\sim 40M_\odot/pc^2$
$M_{stars}(today)\sim 10M_\odot/pc^2$

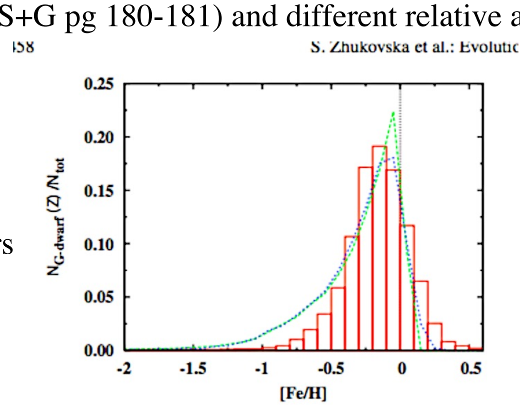
get $y=0.43 Z_{sun}$ go to pg 180 in S&G to see sensitivity to average metallicity of stars

- Note that the above solutions are obtained under the assumption that the yield yZ is independent of Z.

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 180-181) and different relative abundances (e.g C,N,O,Fe) amongst stars

Green is closed box model
red is observations of local stars

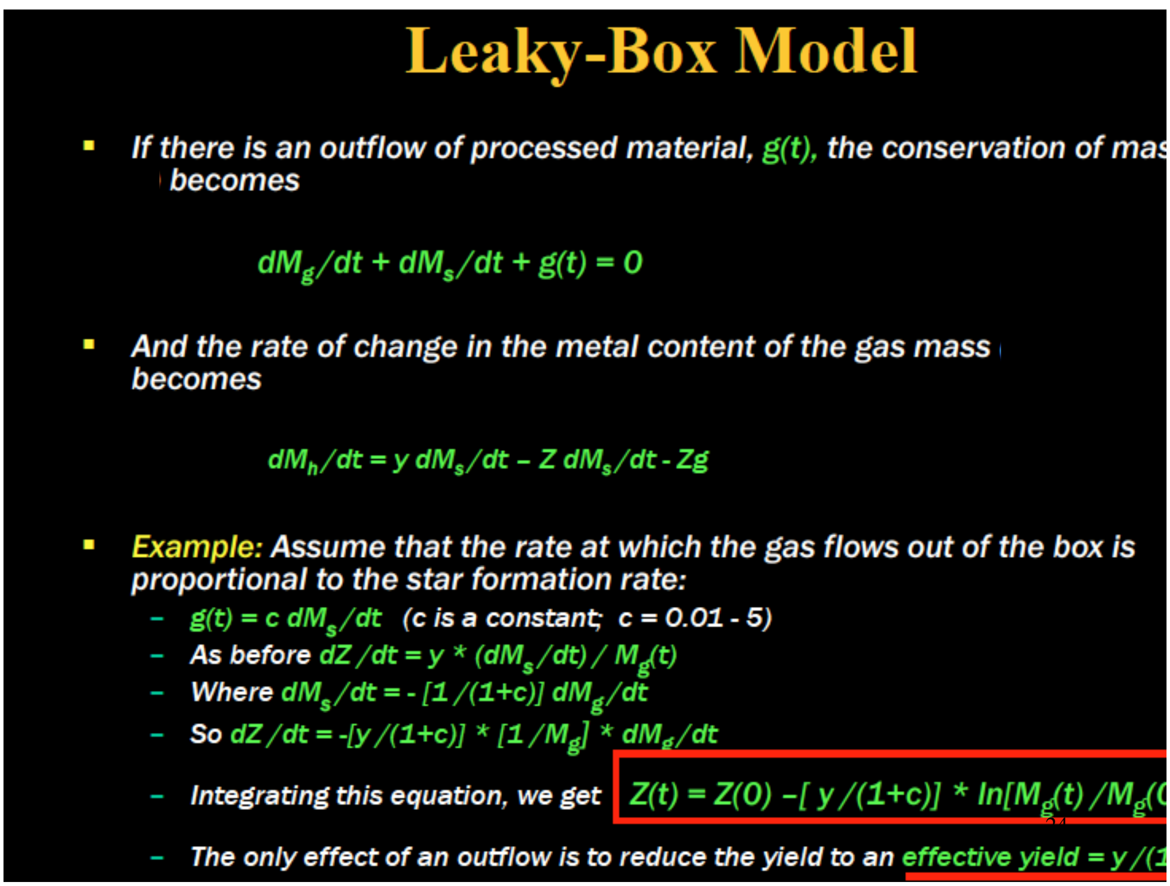


- Go to more complex models - leaky box (e.g inflow/outflow);
  - if we assume outflow of metal enriched material g(t); and assume this is proportional to star formation rate $g(t)=c\,dM_s/dt$;
  - result is $Z(t)= Z(0)-[(y/(1+c))*\ln[M_g(t)/M_g(0)]$- reduces effective yield but does not change relative 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
- Booking of star formation rate, metal generation and total metals in stars and gas



Accreting-Box Model

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

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

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

25

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

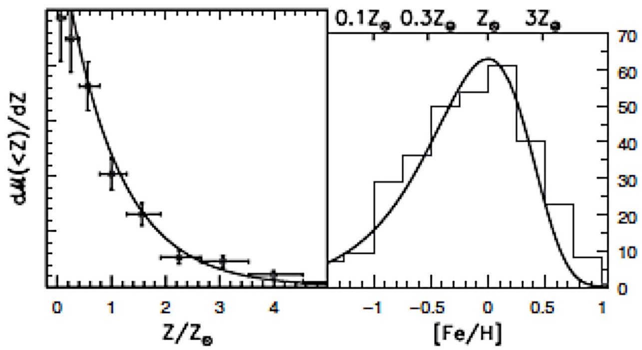
  $M_s(< Z) = - M_g \ln(1 - Z/y)$
- In this case, for $M_g \sim 10\ M_{sun} / pc^2$ and $M_s \sim 40\ M_{sun}/pc^2$, and for $Z = 0.7\ Z_{sun}$, then $y \sim 0.71\ Z_{sun}$. Thus the fraction of stars more metal-poor than $0.25\ Z_{sun}$ is $M(<0.25)/M(<0.7) \sim 10\%$, in much better agreement with the observations of the solar neighborhood

26

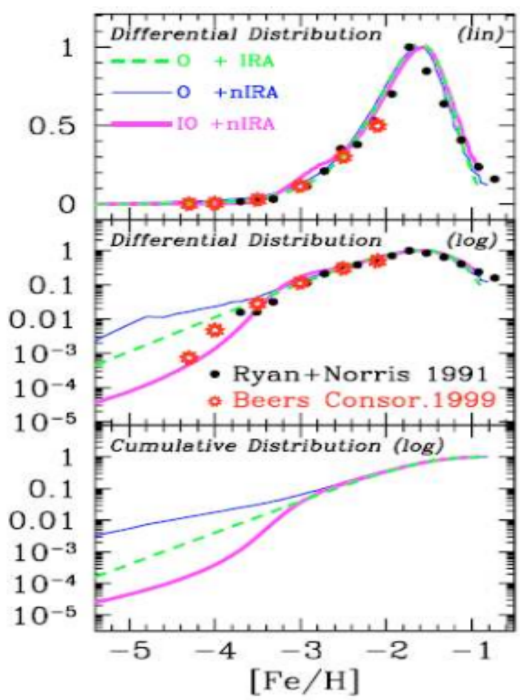
the presence of an outflow decreases the effective yield, in the sense that the true yield of a system is lower than the effective yield.

Simple closed-box model works well for bulge of Milky Way

- But 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
- cf. Matteucci & Chiosi (1983) solutions for models with outflow and infall



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



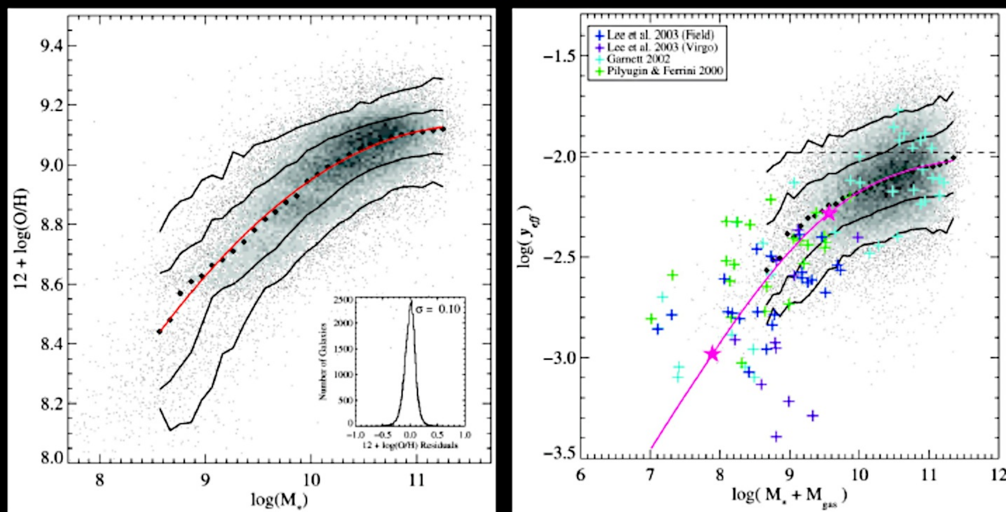
Inflow/Outflow Models
(Matteucci 2013)

ig. 2.11 Metallicity distribution for the halo stars. Upper panel: observed and predicted ıetallicity distributions. The models are: pure outflow with IRA (dashed curve), pure ıtflow without IRA (thin solid curve) and early infall +outflow without IRA (thick solid ırve). The distribution is on a linear scale. Middle panel: the same as above but the istribution is on a logarithmic scale. Lower panel: predicted cumulative distributions.

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})

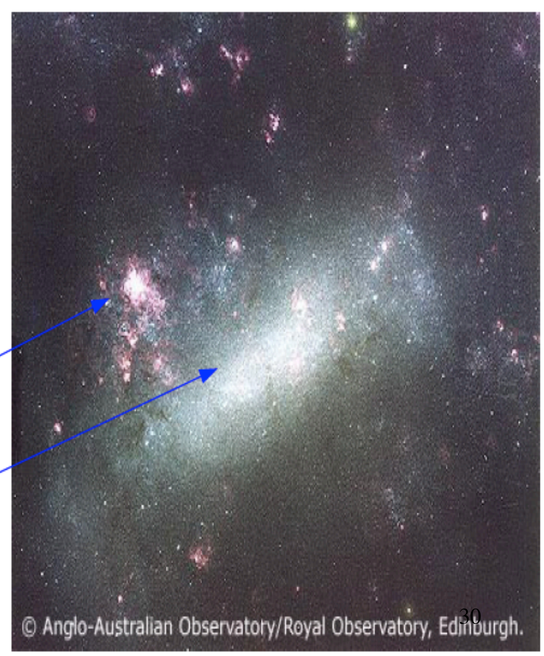
Reminder: $Z(t) = Z(0) - [\, y/(1+c)] * \ln[M_g(t)/M_g(0)]$ (here assume $Z(0) = 0$)



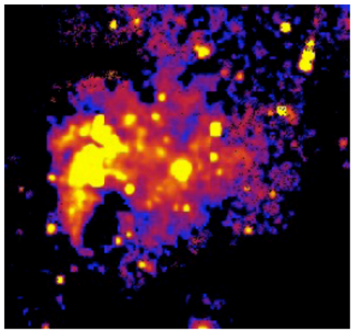
(e.g., Garnett+02; Tremonti+04; Kauffmann+03)

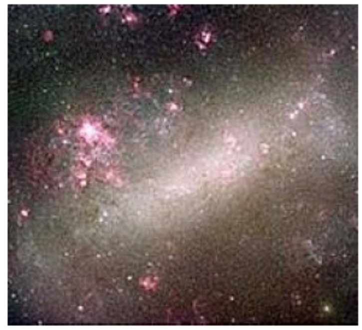
The LMC

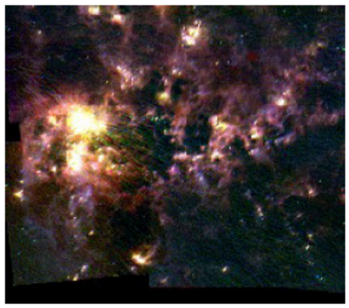
- Distance 50kpc
- Dwarf Irregular
  - Type Sm
- Tarantula Nebula
  - active star forming region
- Barred galaxy
- $L \approx 1.7 \times 10^9\, L_\odot$

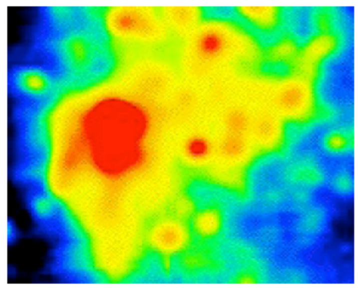


Xray: ROSAT   AAO optical 3 color









IRAS (Jason Surace) Radio (RAIUB/MPIFR Bonn

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