Lecture 11:

Ages and Metalicities from Observations

A Quick Review

Ages from main-sequence turn-off stars

Main sequence lifetime:

lifetime = fuel / burning rate

$$\tau_{MS} = 7\times10^{9}\left[\frac{M}{M_{\odot}}\right]\left[\frac{L}{L_{\odot}}\right]^{-1}\ \text{yr}$$

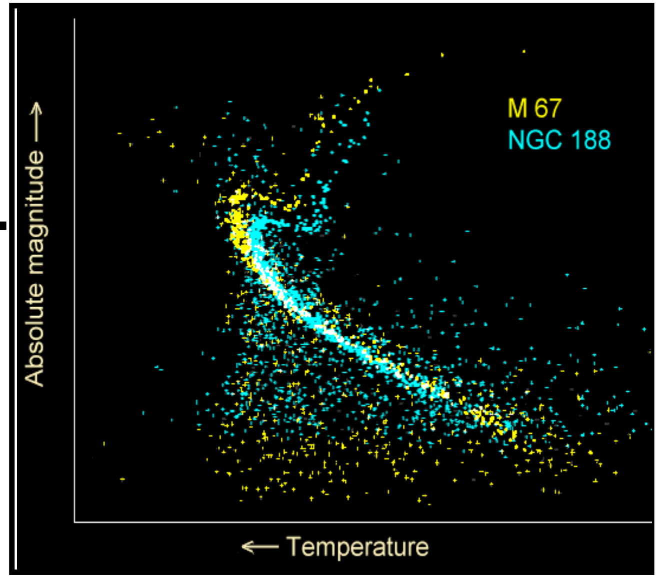
$$\tau_{MS} = 7\times10^{9}\left[\frac{L}{L_{\odot}}\right]^{-\frac{3}{4}}\ \text{yr}$$

(since $L \propto M^4 \rightarrow M \propto L^{1/4}$)

HR diagram

M_V

M_V(TO)



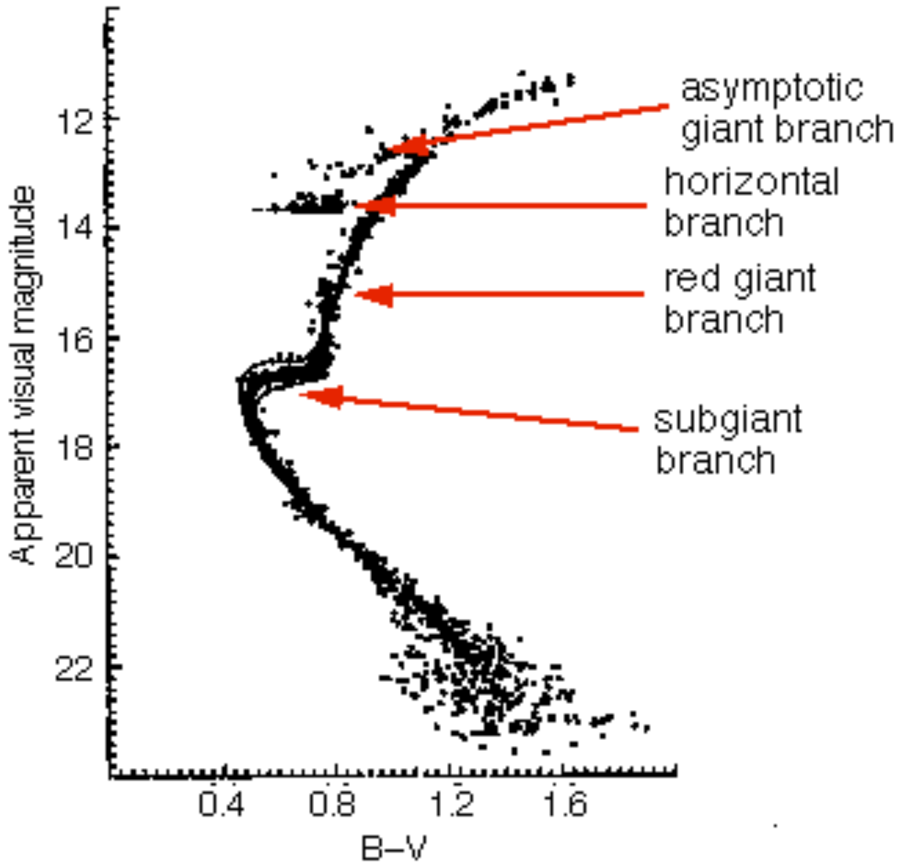
B-V

Luminosity at the top of the main sequence (turn-off stars) gives the age *t*.

Ages from main-sequence turn-off stars

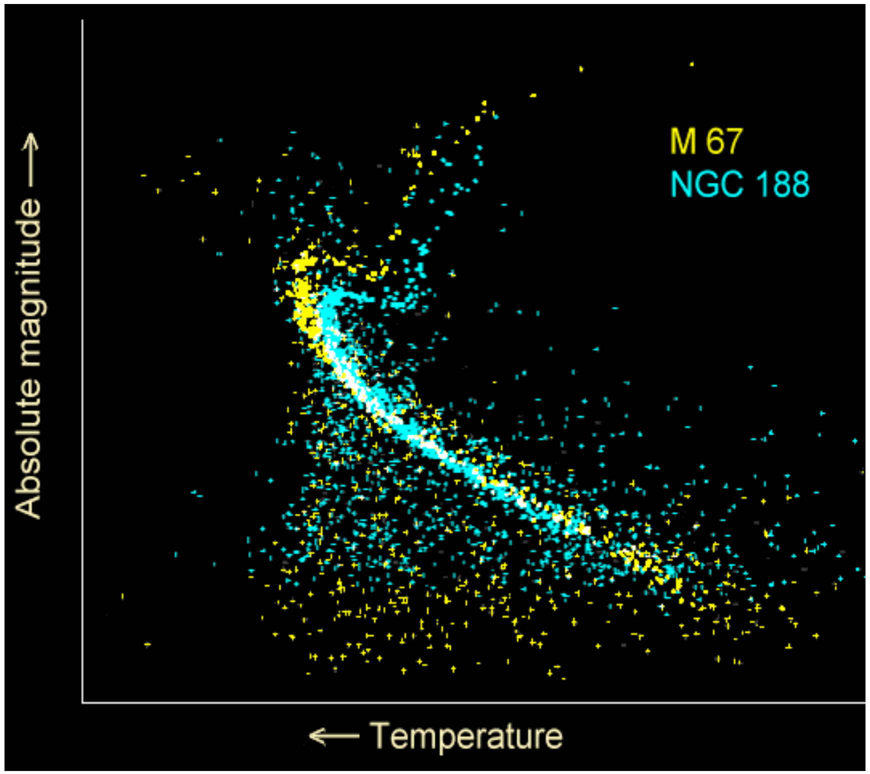
$$M_V(TO) = 2.70 \log (t / \mathrm{Gyr}) + 0.30 [Fe/H] + 1.41$$

Globular Cluster in Halo



47 Tuc: 12.5 Gyr

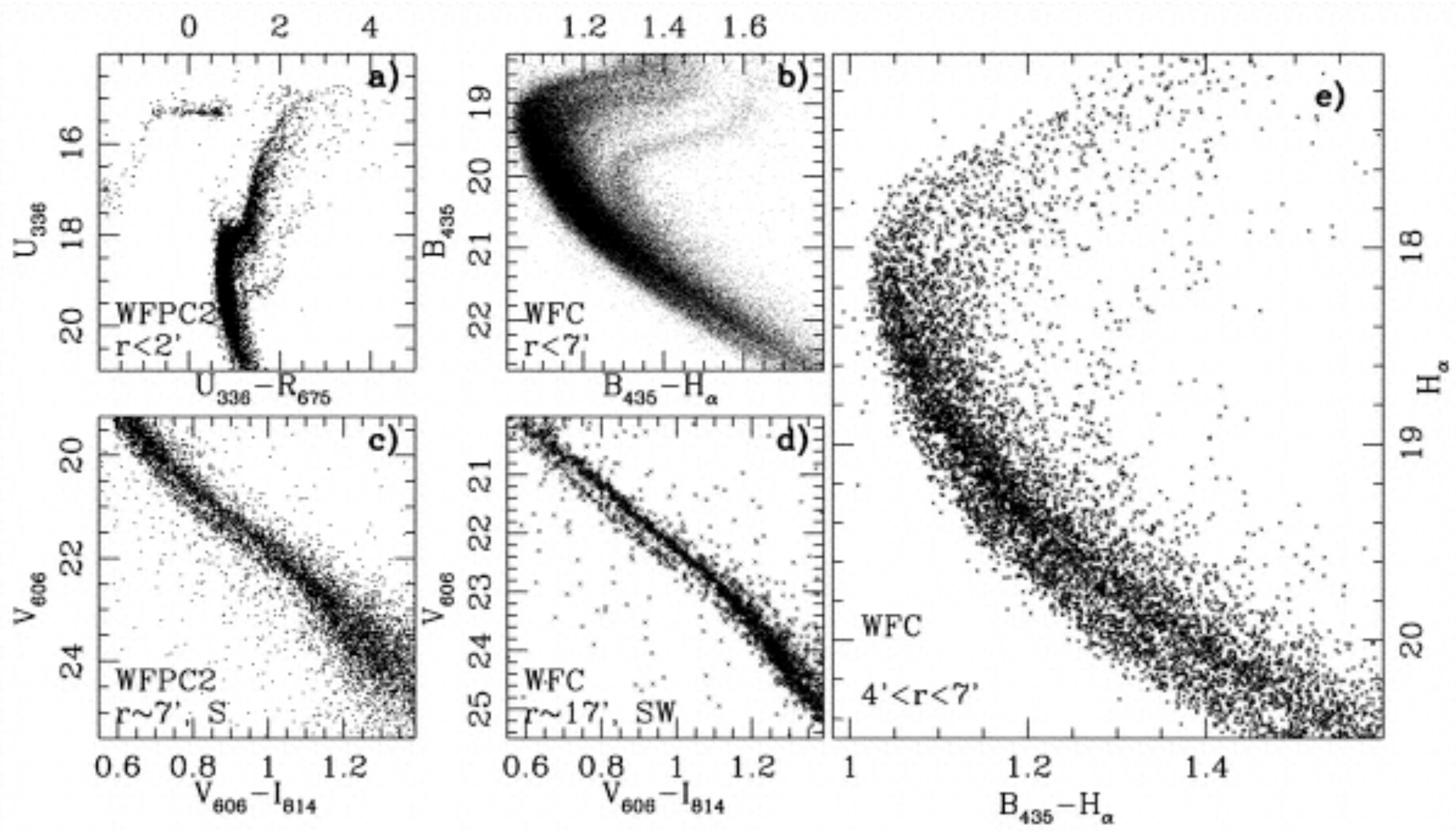
Open Clusters in Disk



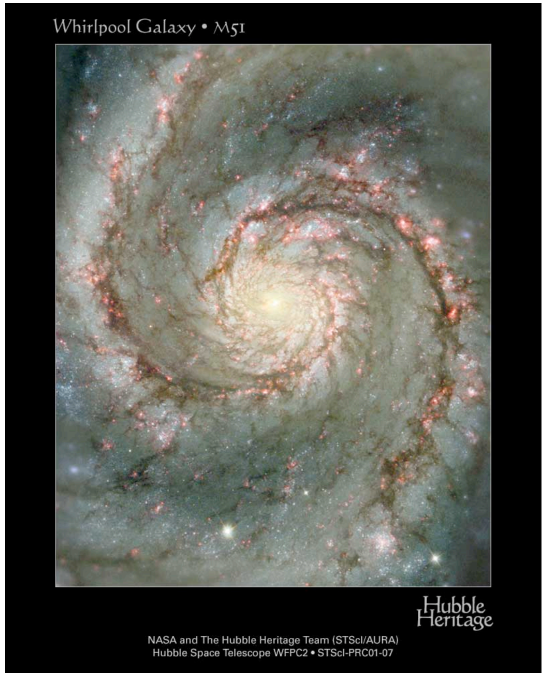
M67: 4 Gyr

NGC188: 6 Gyr

Multiple Ages of stars in Omega Cen



Star Formation Rates



- Star-formation can be measured in many ways:
  - FUV flux
  - Optical colours e.g., (g-r)
  - Hα, [OII], [OIII]
  - FIR flux
- See review by Kennicutt (1998), ARA&A
- Here we look at one: The Hα recombination line.
- FUV rad from recent star-form ionises cloud which recombined and cascades
- Only stars with $M>10M_o$ with lifetimes <20Myr produce FUV

$$SFR(M_{\otimes} yr^{-1}) = 7.9 \times 10^{-42} L(H\alpha)(ergs^{-1}) = 1.08 \times 10^{-53} Q(H^o)(s^{-1})$$

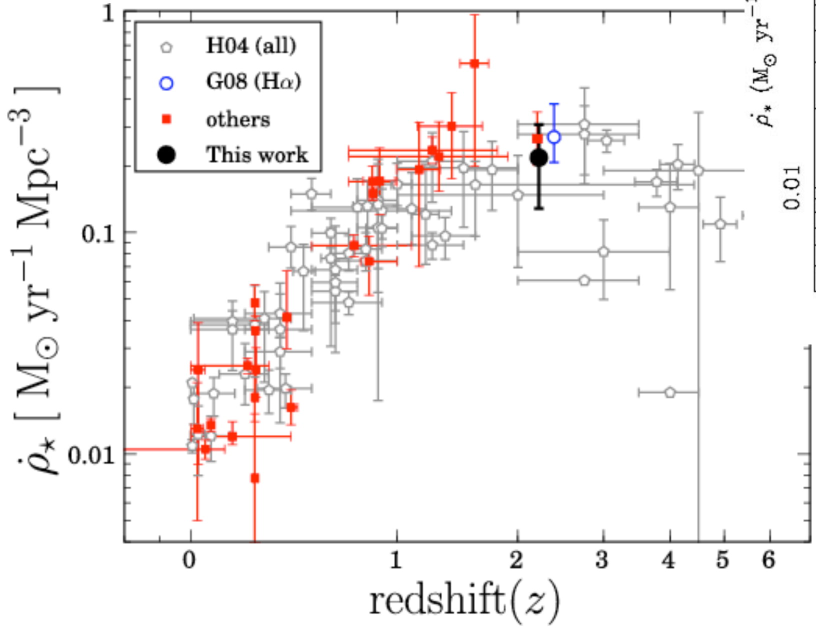
$Q(H^o)$ is the ionising photon luminosity

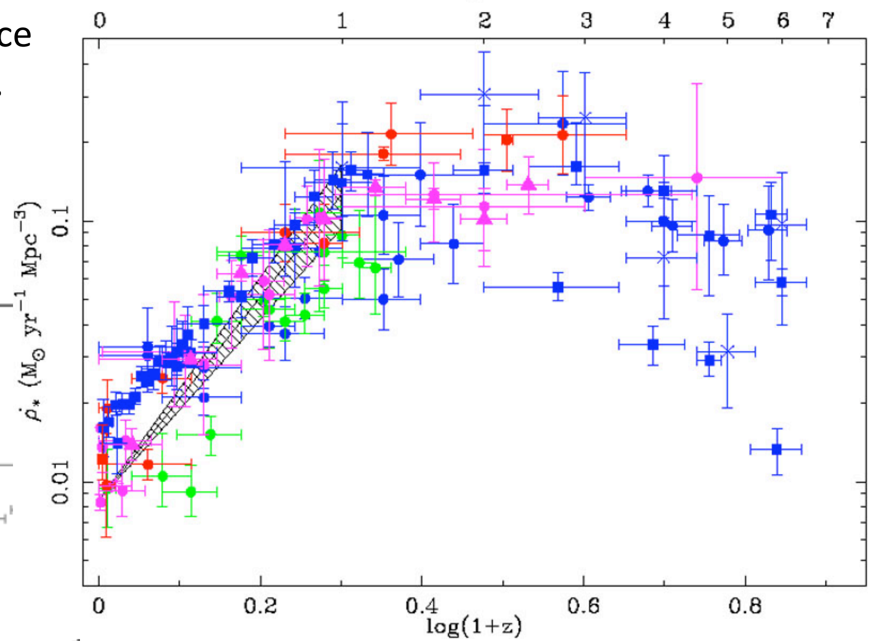
constants are derived from evol. synthesis models (e.g., Kennicutt 1982)

Cosmic Star Formation History

Star-formation has declined 10-fold since a redshift of 1 (~half age of Universe).

Most stellar mass formed early

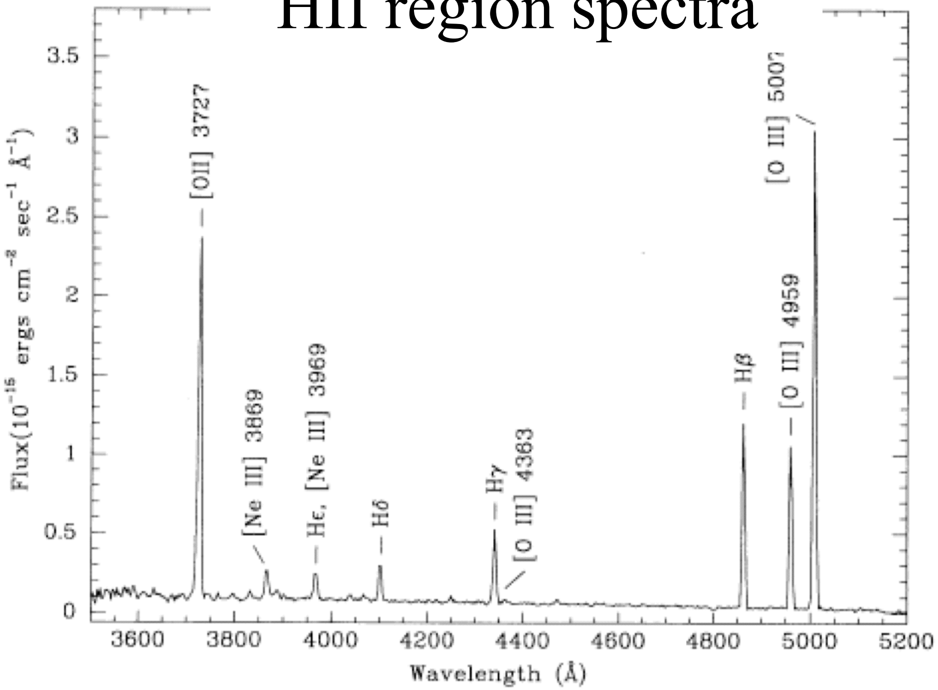




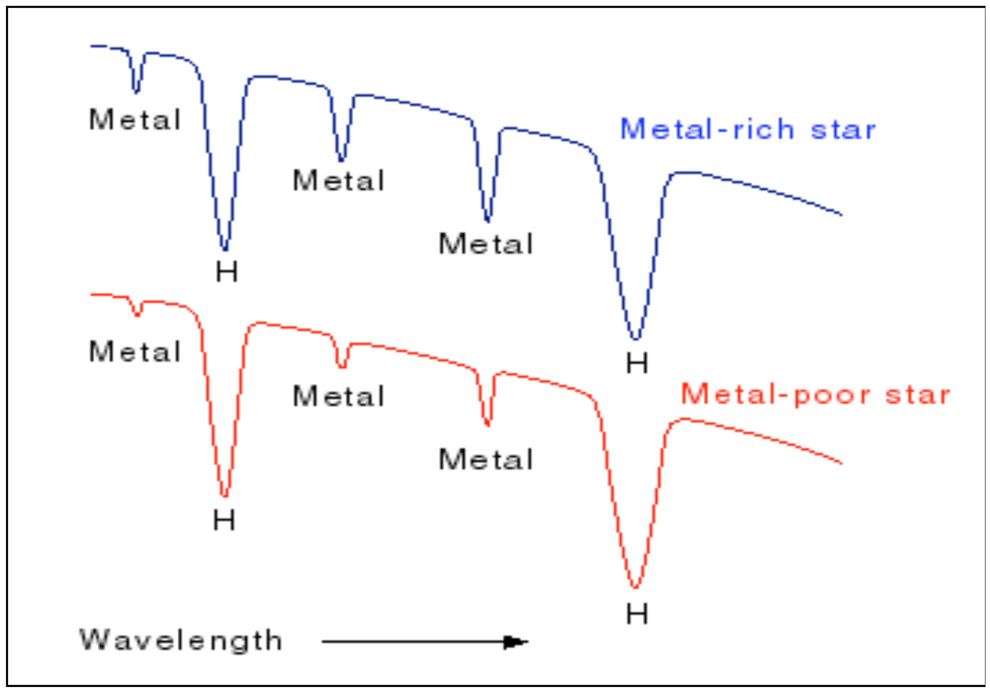
Abundance Measurements

- Star spectra: absorption lines
- Gas spectra: emission lines
- Galaxy spectra: both
- Metal-rich/poor stars: stronger/weaker metal lines relative to H.

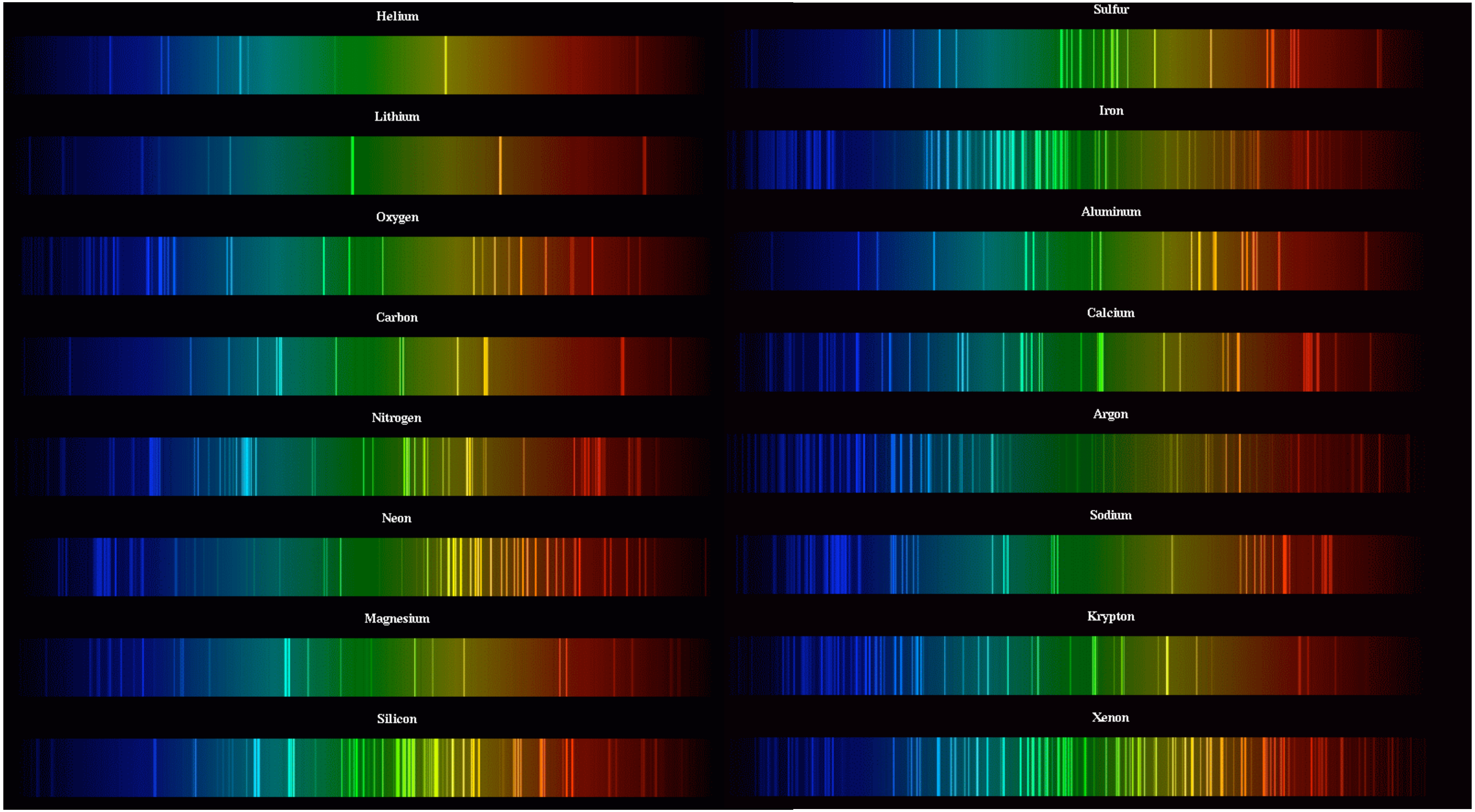
HII region spectra



Stellar spectra



- Lab measurements: Unique signature (pattern of wavelengths and strengths of lines) for each element.

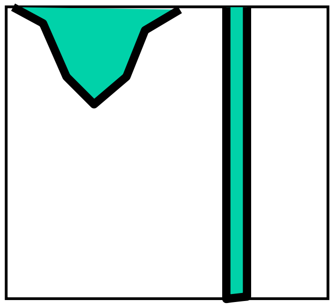


High-Resolution Spectra

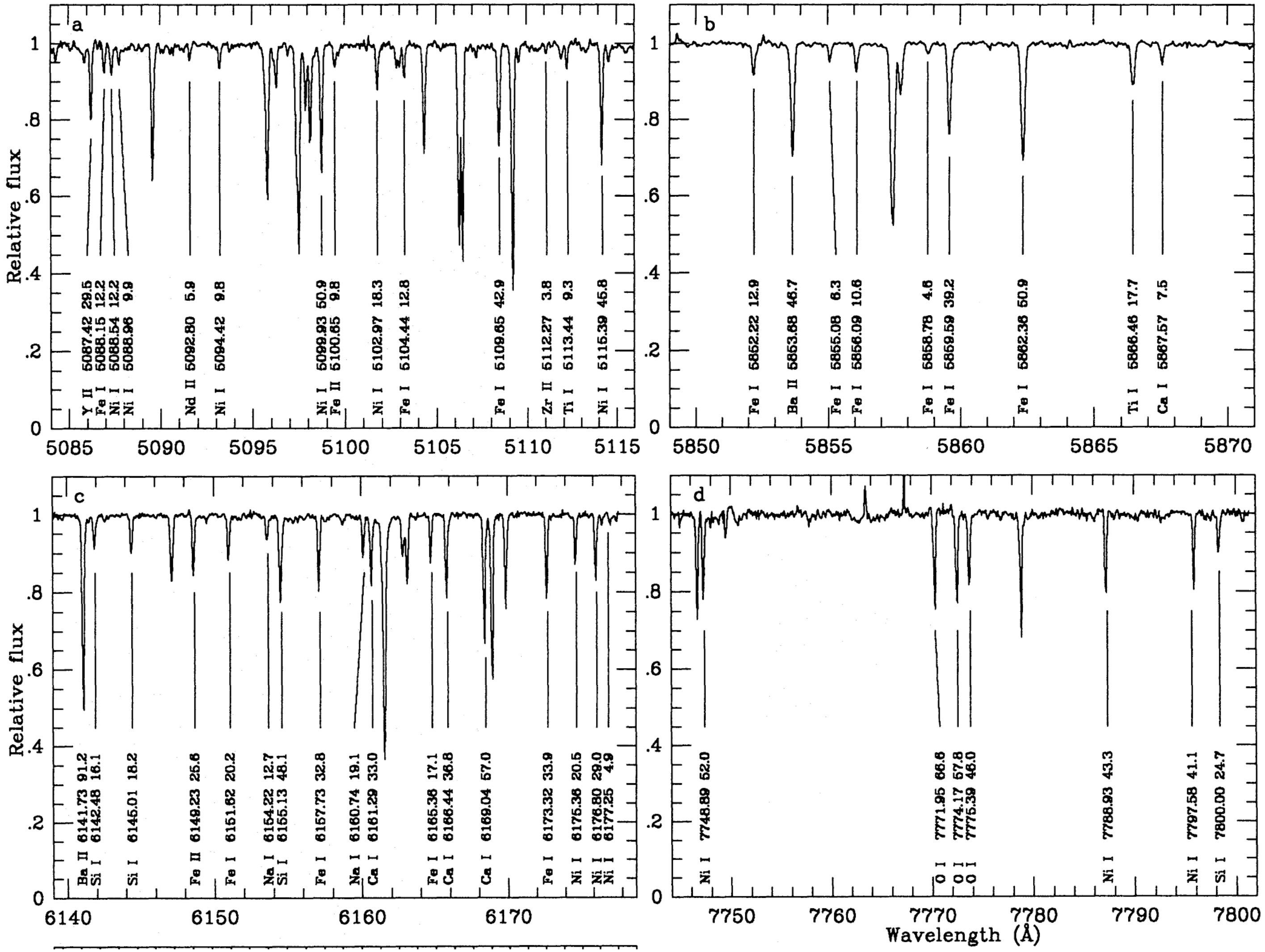
Measure line strengths (equivalent widths) for individual elements.

Equivalent Width

measures the **strength** (not the width) of a line.



EW is width of a 100% deep line with same area.



Abundance Measurements

Spectra	$\Rightarrow$	Line strengths (equivalent widths)
		+
Astrophysics	$\Rightarrow$	Stellar atmosphere models
		+
Physics	$\Rightarrow$	Laboratory calibrations

$$\Downarrow$$

Abundances: $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right]$, etc.

(Temperature, surface gravity, and metal abundances in the stellar atmosphere models are adjusted until they fit the observed equivalent widths of lines in the observed spectrum. Full details of this are part of other courses)

Bracket Notation

Bracket notation for Fe abundance of a star relative to the Sun:

$$\left[\frac{Fe}{H}\right] \equiv \log_{10}\left(\frac{n(Fe)}{n(H)}\right)_{*} - \log_{10}\left(\frac{n(Fe)}{n(H)}\right)_{\odot}$$

atoms of Fe

atoms of H

$$= \log_{10}\left(\frac{\left(n(Fe)/n(H)\right)_{*}}{\left(n(Fe)/n(H)\right)_{\odot}}\right)$$

And similarly for other metals, e.g. relative to Fe:

$$\left[\frac{O}{Fe}\right], \left[\frac{C}{Fe}\right], \ldots$$

Star with solar Fe abundance: $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] = 0.0$

Twice solar abundance: $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] = \log_{10}(2) = +0.3$

Half solar abundance: $\left[\frac{\mathrm{Fe}}{\mathrm{H}}\right] = \log_{10}(1/2) = -0.3$

Metallicity vs Abundance

Metalicity (by mass):

$$Z = \frac{\sum_{metals} A_i\, n_i}{n(\mathrm{H}) + 4\, n(\mathrm{He}) + \sum_{metals} A_i\, n_i}$$

$$X = \frac{n(\mathrm{H})}{n(\mathrm{H}) + 4\, n(\mathrm{He}) + \sum_{metals} A_i\, n_i}$$

To infer Z from a single line:

$$\frac{Z}{X} = f\, \frac{n(\mathrm{Mg})}{n(\mathrm{H})} \qquad f \equiv \frac{\sum_{metals} A_i\, n_i}{n(Mg)}$$

Abundance (by number):

$$\left[\frac{\mathrm{Mg}}{\mathrm{H}}\right] \equiv \log_{10}\left(\frac{n(\mathrm{Mg})}{n(\mathrm{H})}\right)_* - \log_{10}\left(\frac{n(\mathrm{Mg})}{n(\mathrm{H})}\right)_\odot$$

$$= \log_{10}\left(\frac{Z}{f\ X}\right)_* - \log_{10}\left(\frac{Z}{f\ X}\right)_\odot$$

$$= \log_{10}\left(\frac{Z_*}{Z_\odot}\, \frac{f_\odot}{f_*}\, \frac{X_\odot}{X_*}\right)$$

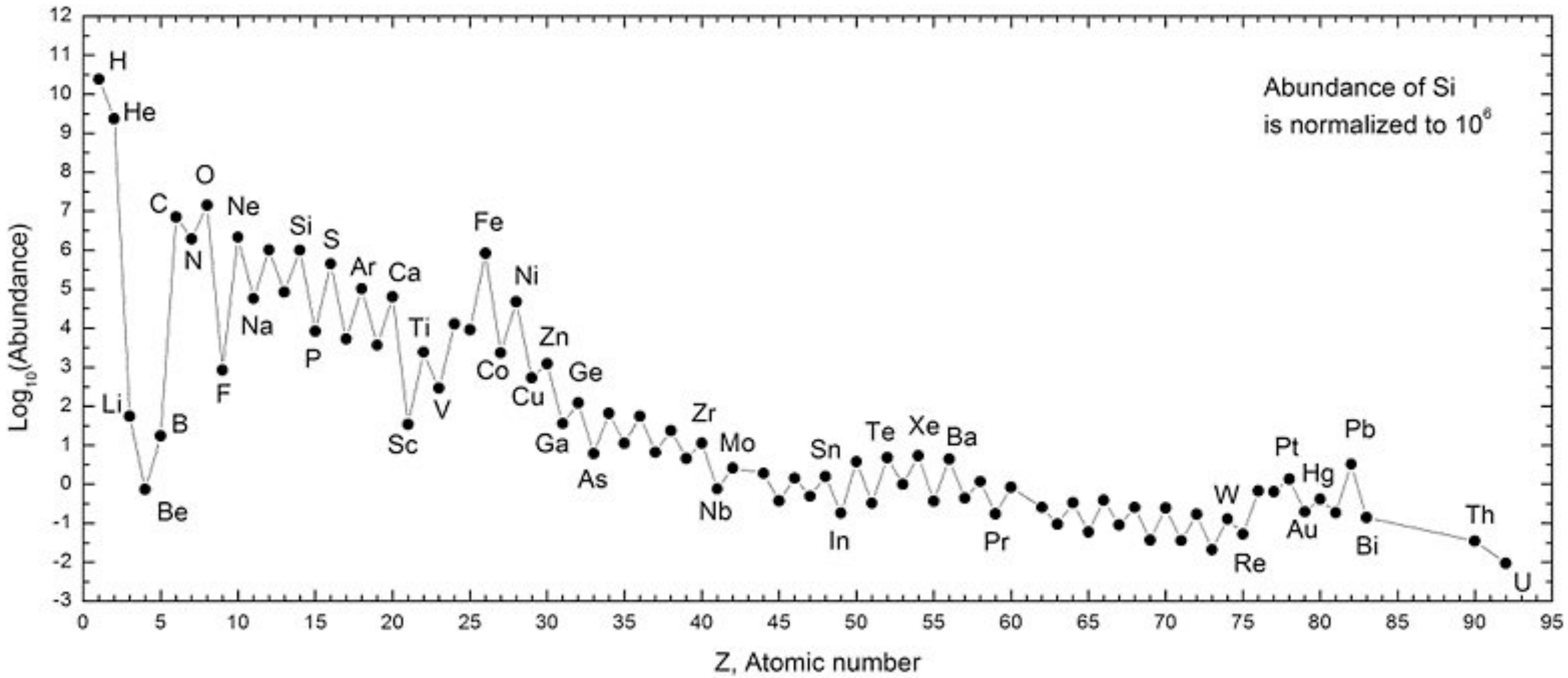
$$\boxed{\frac{Z_*}{Z_\odot} = \frac{X_*\, f_*}{X_\odot f_\odot} 10^{[\ \mathrm{Mg}\ /\ \mathrm{H}\ ]} \approx 10^{[\ \mathrm{Mg}\ /\ \mathrm{H}\ ]}}$$

Primordial: $X_{\mathrm{p}} = 0.75,\quad Y_{\mathrm{p}} = 0.25,\quad Z_{\mathrm{p}} = 0.00$

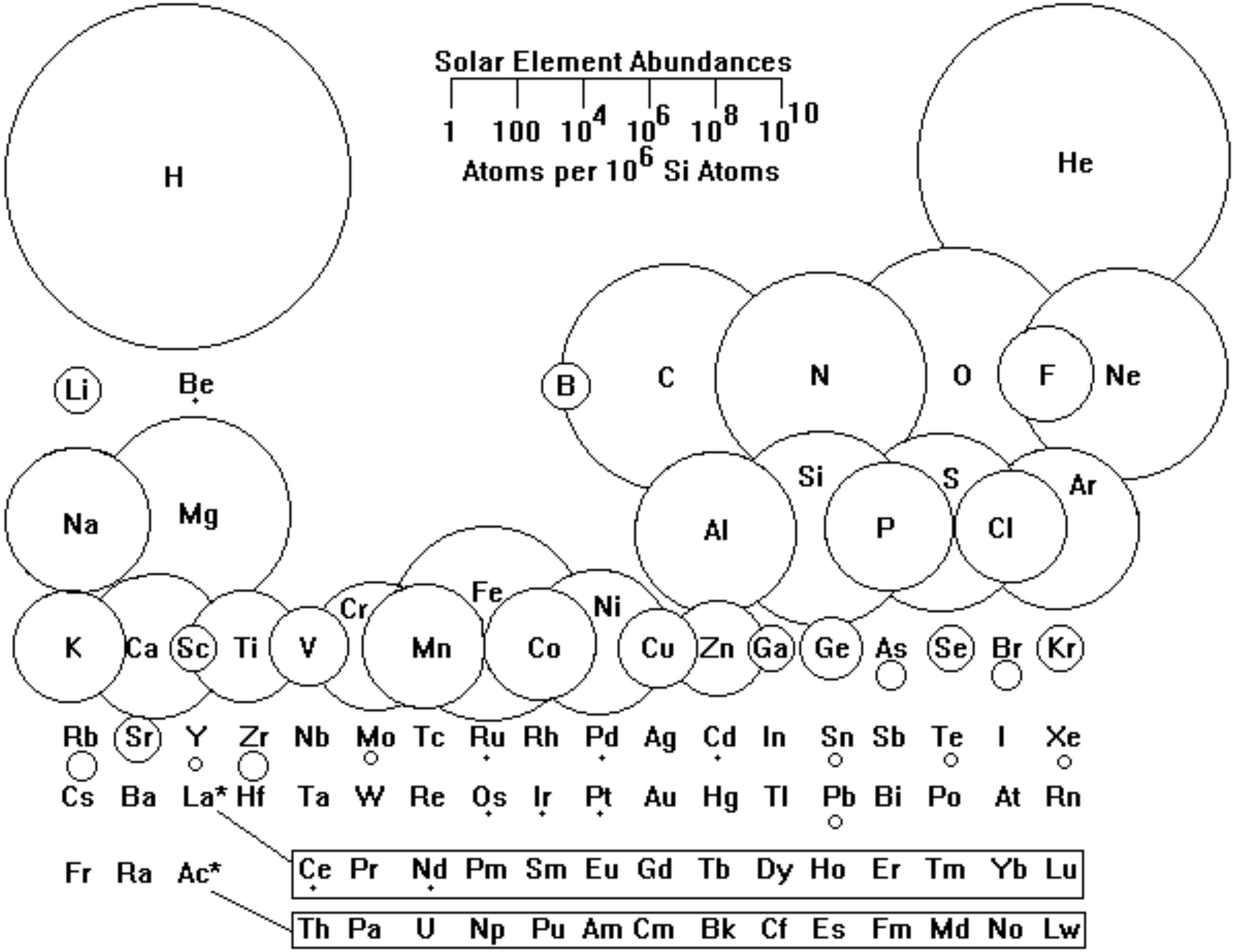
Solar: $X_\odot = 0.70,\quad Y_\odot = 0.28,\quad Z_\odot = 0.02$

Solar Abundances

Abundance of elements in the solar system, y-axis logarithmic



Solar Abundances



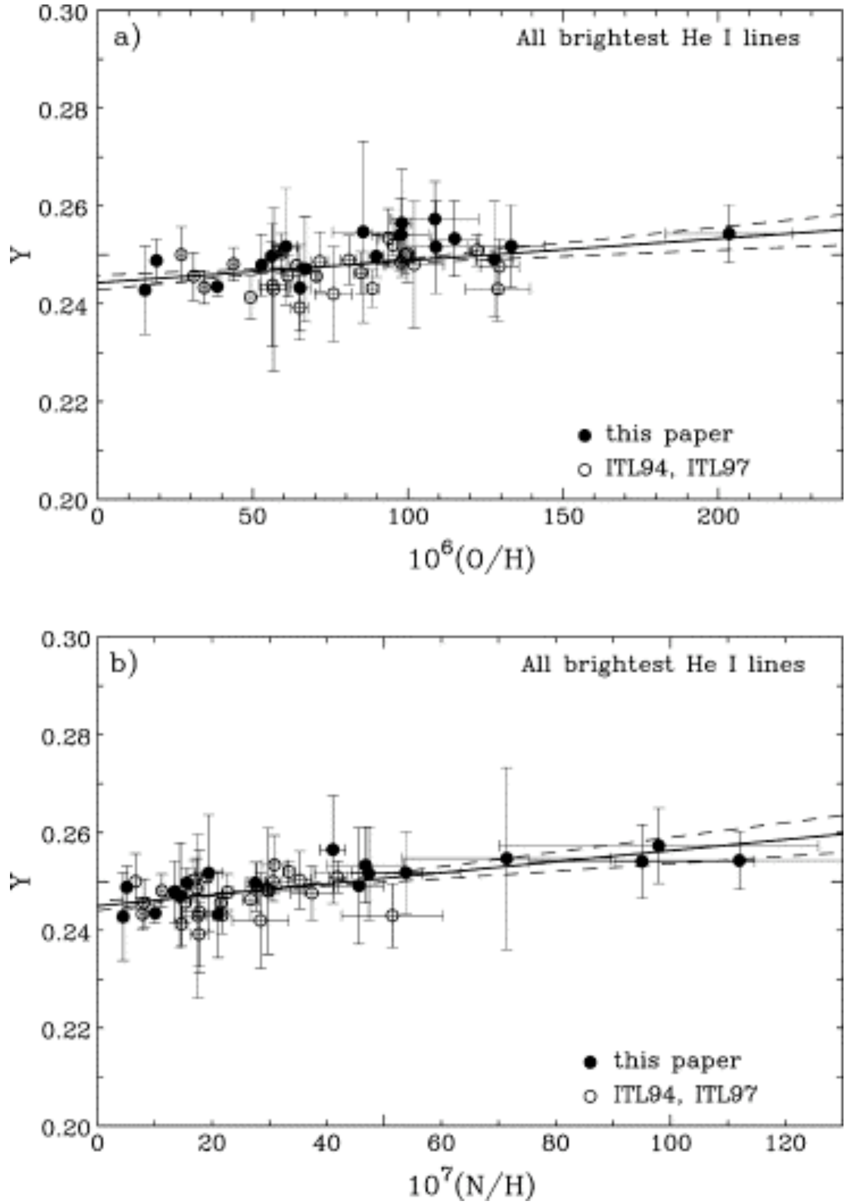
Primordial He/H measurement

• Emission lines from H II regions in low-metalicity galaxies.

• Measure abundance ratios: He/H, O/H, N/H, …

• Stellar nucleosynthesis increases He along with metal abundances.

• Find Y_p by extrapolating to zero metal abundance.



[X_i/Fe] vs [Fe/H]

Most metals enrich at approx same rate as Fe (e.g. to a factor of 2-3 over a factor of 30 enrichment).

Some elements (Mg,O,Si,Ca,Ti,Al) formed early, reaching 2-3 x Fe abundance in metal-poor stars

Lowest metal abundance seen in stars: [Fe/H] ~ -4

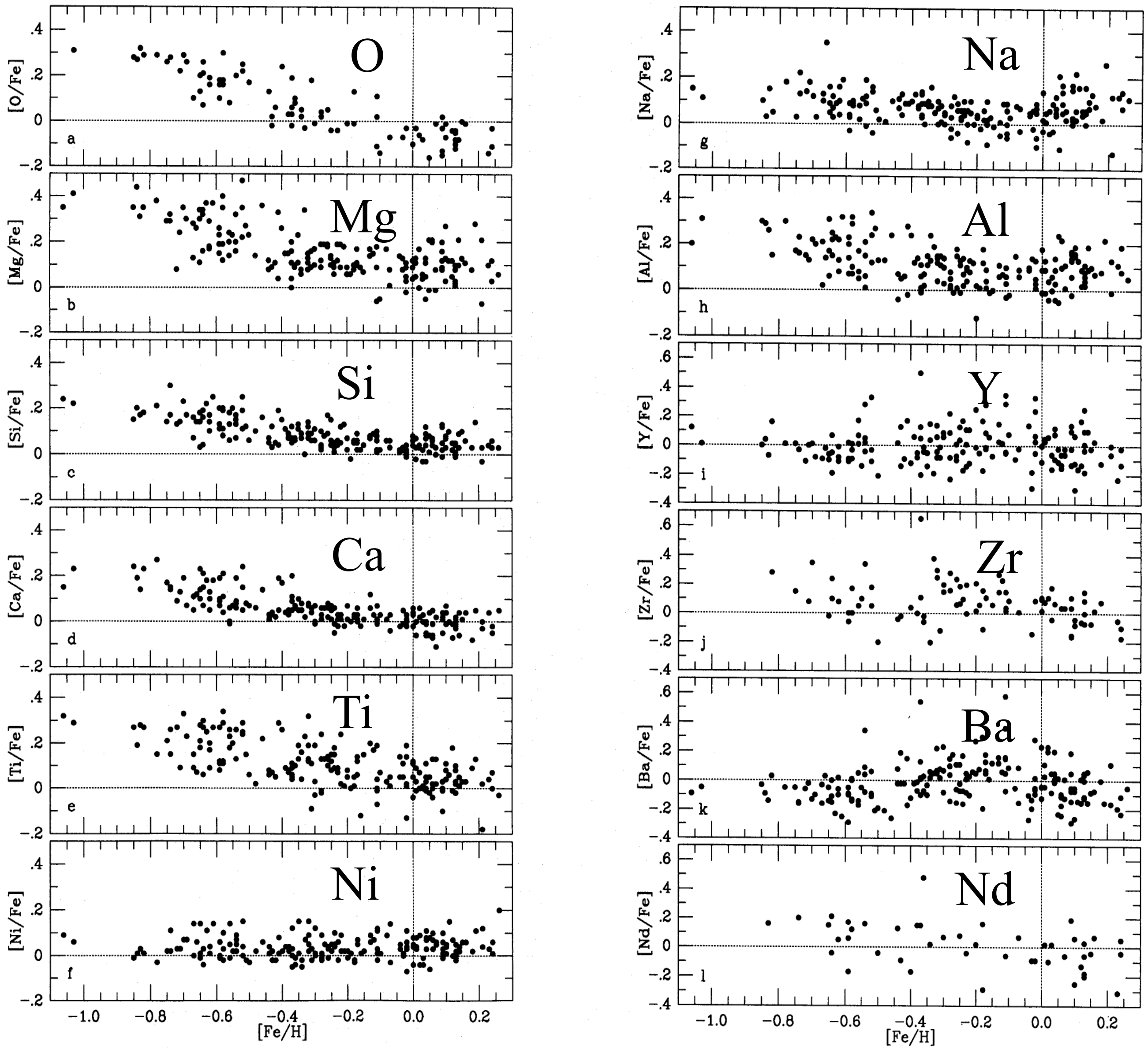


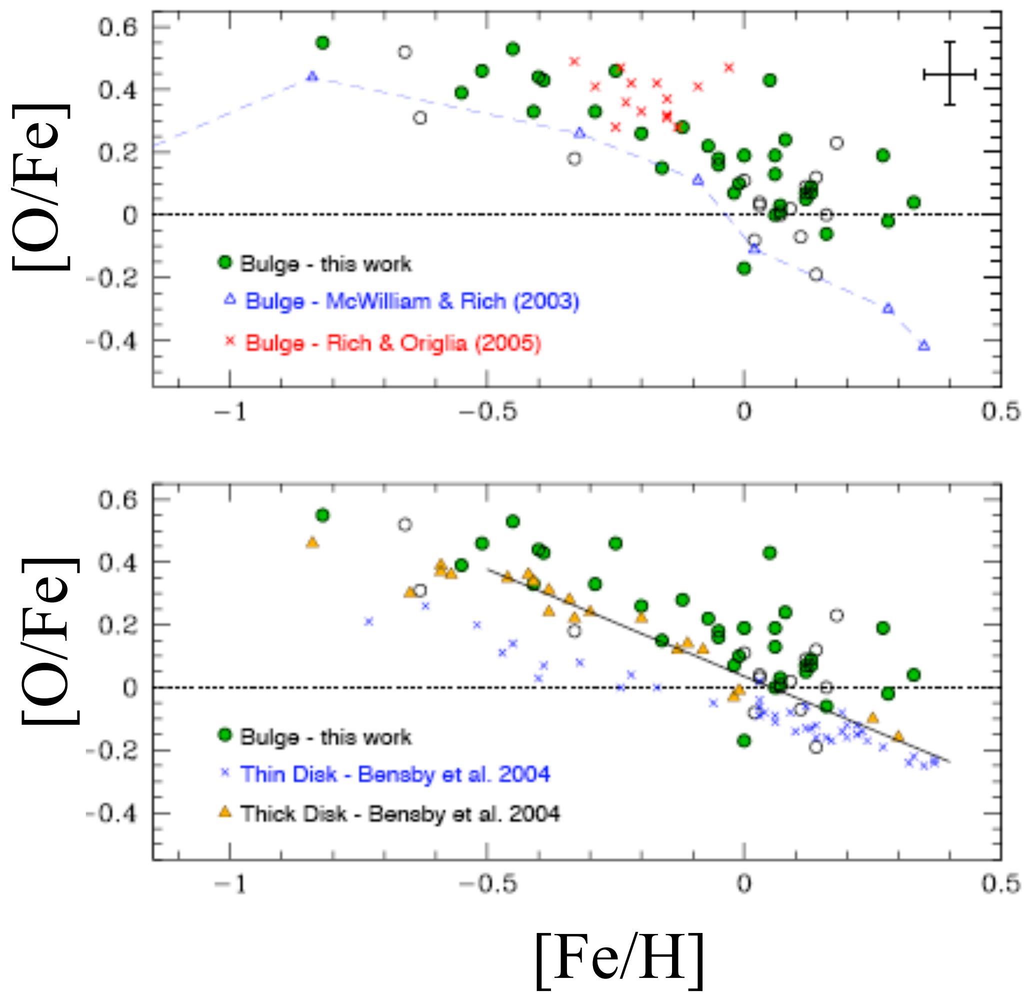
Fig. 15a-l. Abundances relative to iron vs the iron abundance. The solar position is at the origin in all the panels. In **a** the scaled ox abundances from Sect. 3.2.2 are used. Note that the vertical scale is expanded in panels **i, j, k** and **l**

Enhancement of α− Elements

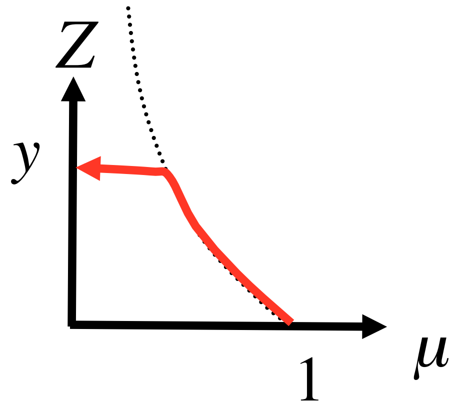
α-elements = multiples of He, more stable, **produced by Type II Supernovae** (high-mass stars, $M > 8M_{\odot}$)

Stars with high α elements must have formed early, e.g. before a **less α-enhanced mix added to ISM by Type Ia SNe** (WD collapse due to accretion from binary companion).

Most MW bulge stars are α-enhanced => Bulge must have formed early.



Some Key Observational Results



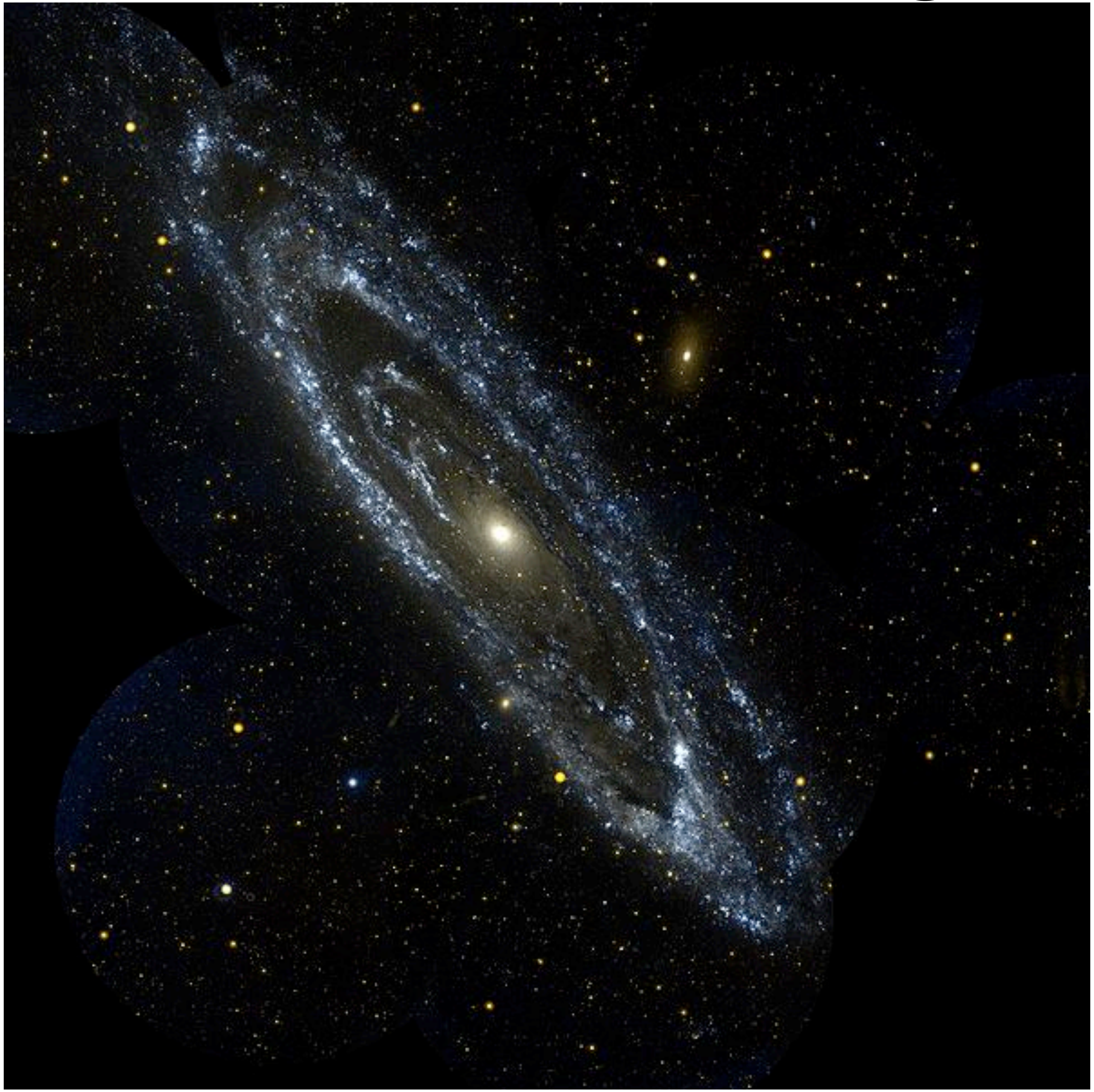
- **Gas consumption**: $Z = -y \log(\mu) \quad \text{for} \quad Z < y$
  More gas used --> higher metallicity.
- **Radius: more metals near galaxy centre**

  Near centre of galaxy: Shorter orbit period--> More passes thru spiral shocks --> More star generations --> μ lower --> Z higher. (Also, more infall of IGM on outskirts.)
- **Galaxy Mass : Low-mass galaxies have lower metallicity.**
  - Dwarf irregulars: form late (young galaxies), have low Z because μ is still high.
  - Dwarf ellipticals: SN ejecta expel gas from the galaxy, making μ low without increasing Z.

M31: Andromeda in Ultraviolet Light

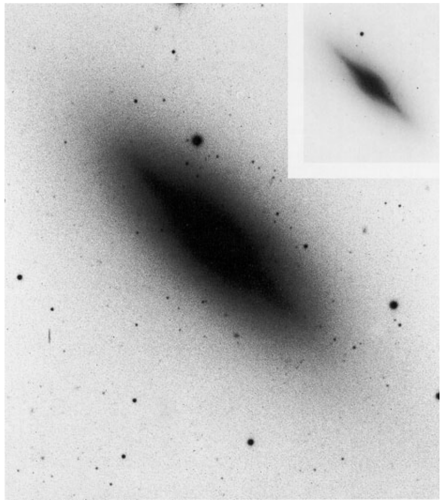
UV light traces hot young stars, current star formation.

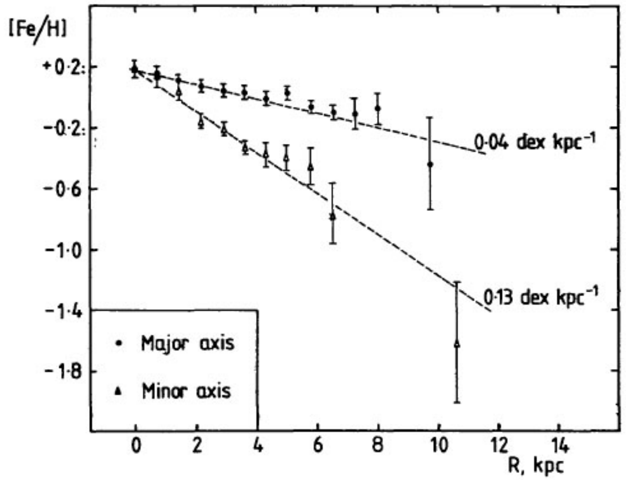
Gas depleted, hence no current star formation in the inner disk.



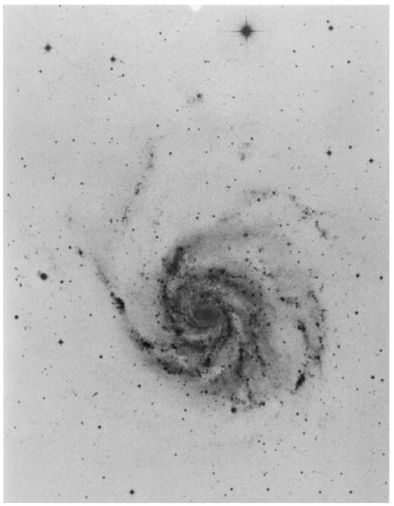
More metals near Galaxy Centres

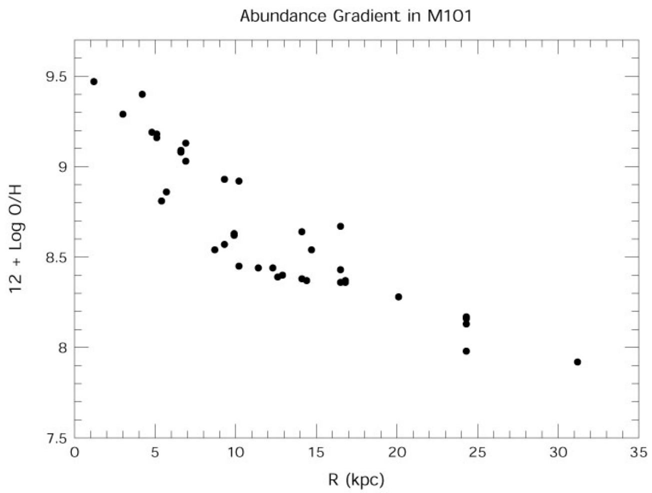
Ellipticals
(NGC 3115)





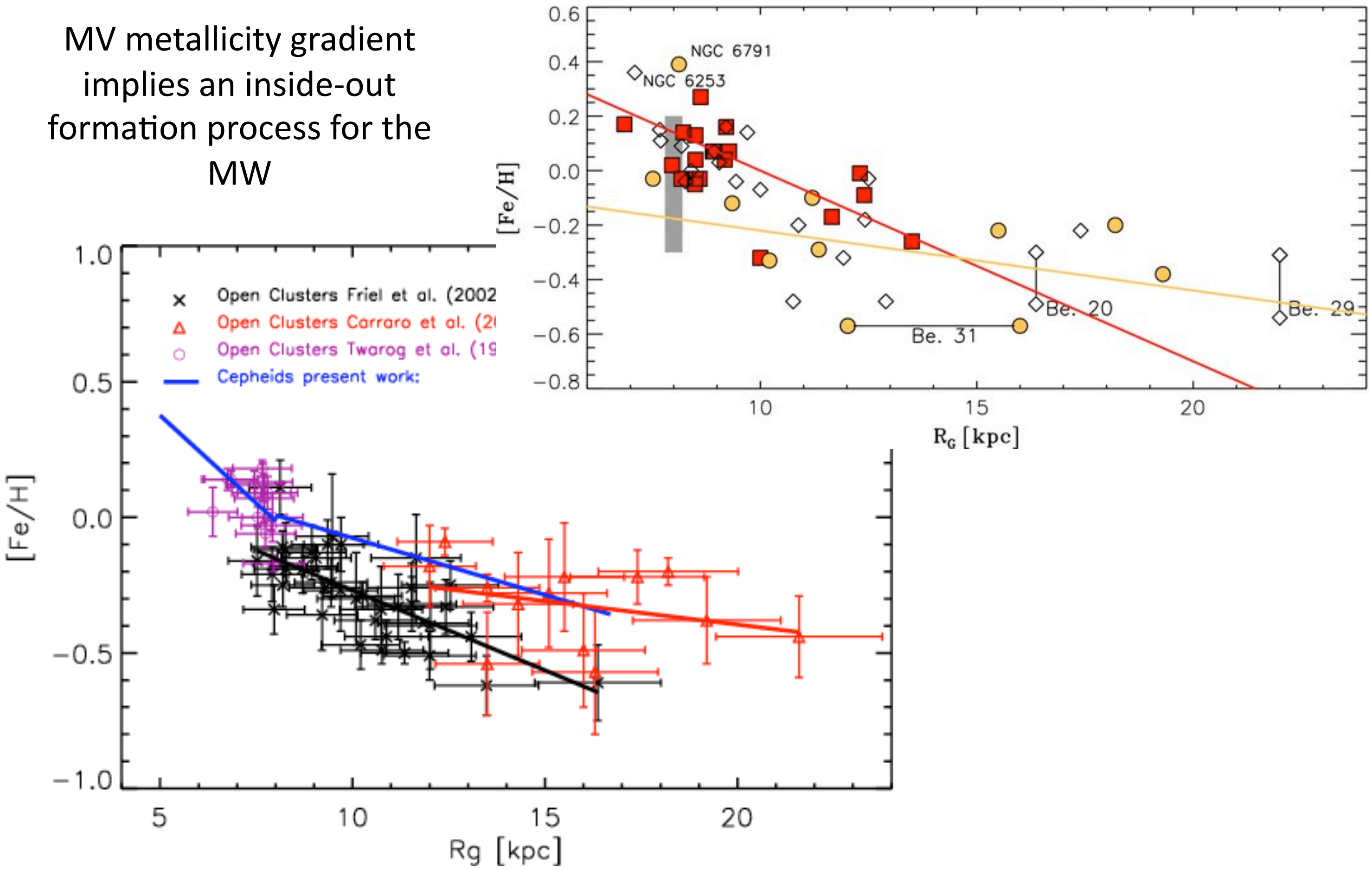
Spirals
(M100)





Metallicity gradient in MW

MV metallicity gradient implies an inside-out formation process for the MW

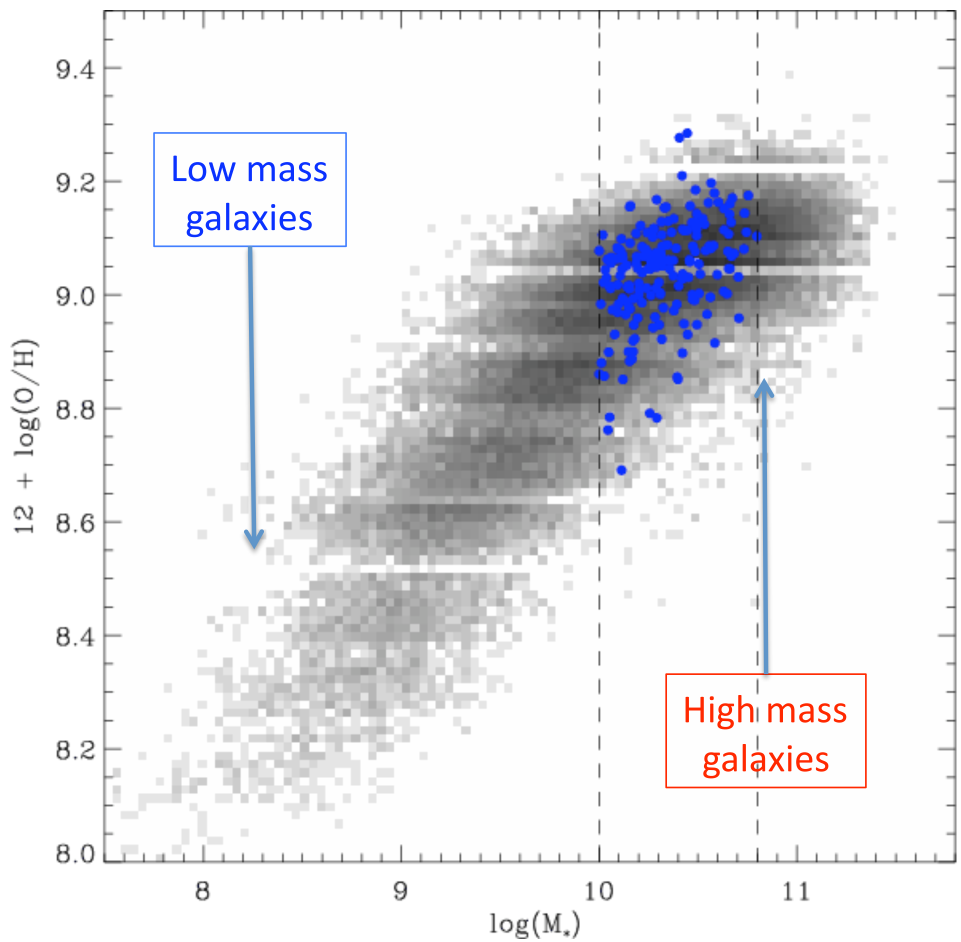


Mass-Metalicity relation

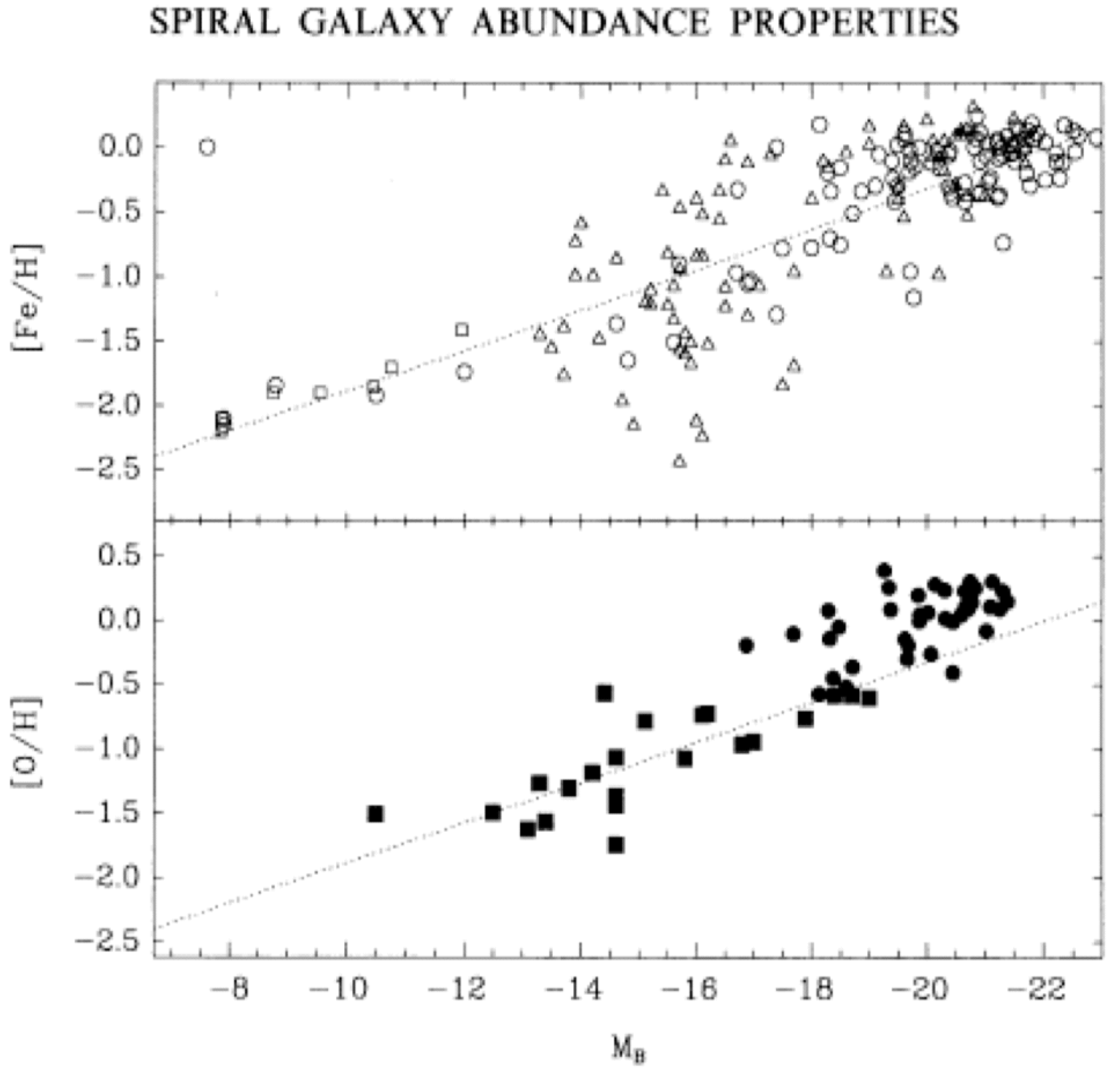
Why are low-mass galaxies are metal poor?

Some are young (not much gas used yet, so ISM not yet enriched).

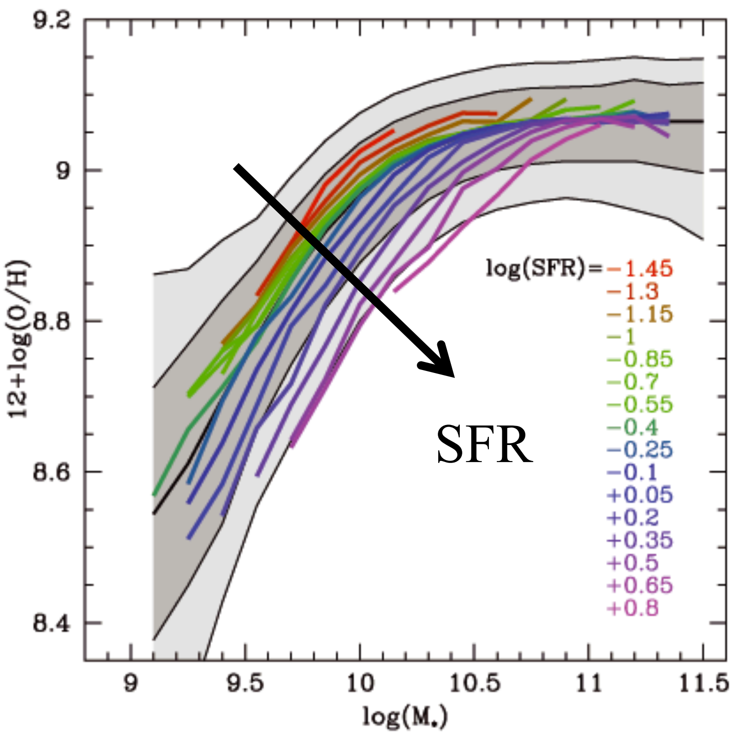
Supernovae eject the enriched gas from small galaxies.

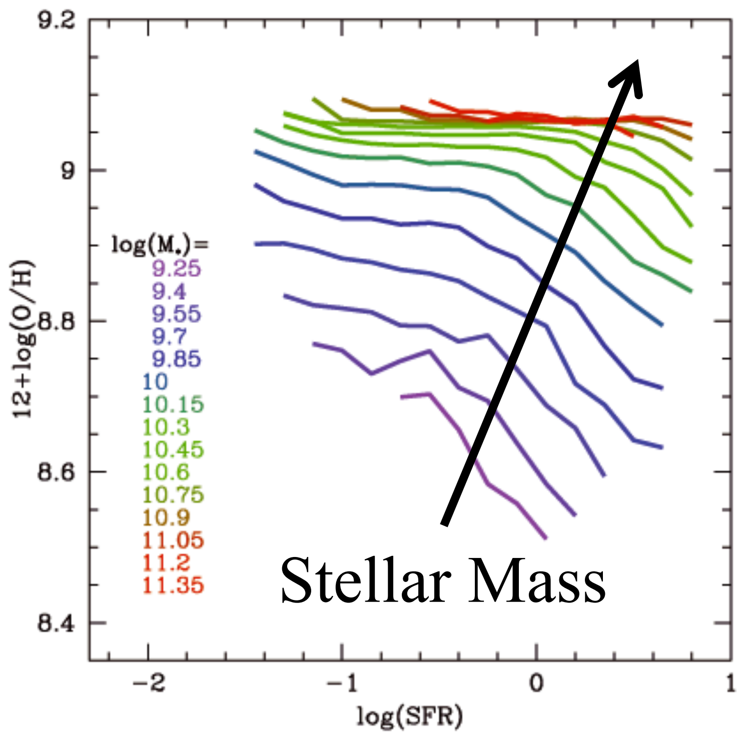


Less Metals in Small Galaxies

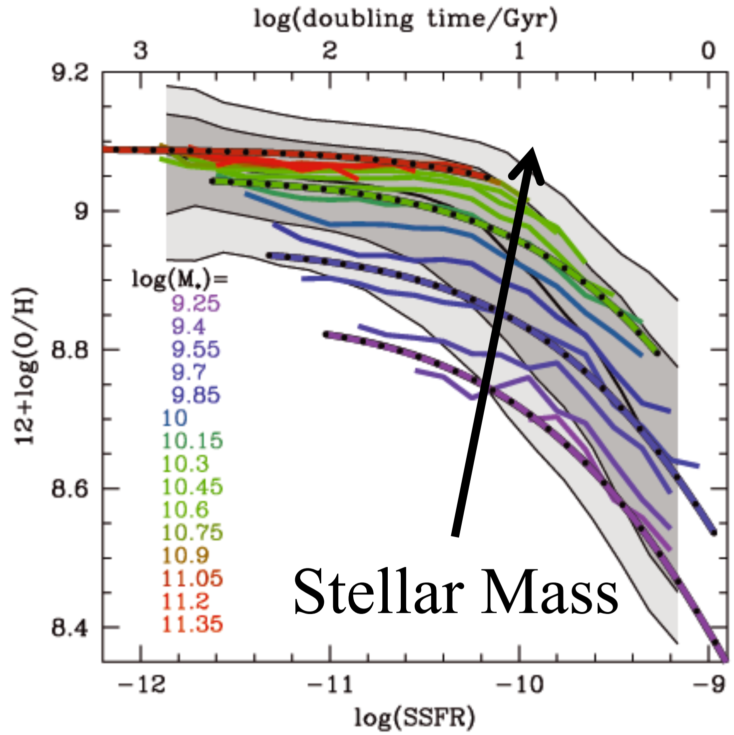


faint ----> bright





- Two fundamental parameters seem to determine observed metallicity: **mass** and **SFR**.
- This forms a **fundamental metallicity relation** (FMR).
- Despite extremely complex underlying physics, the relation seems to hold out to z = 2.5 and in a huge range of galaxies / environments.

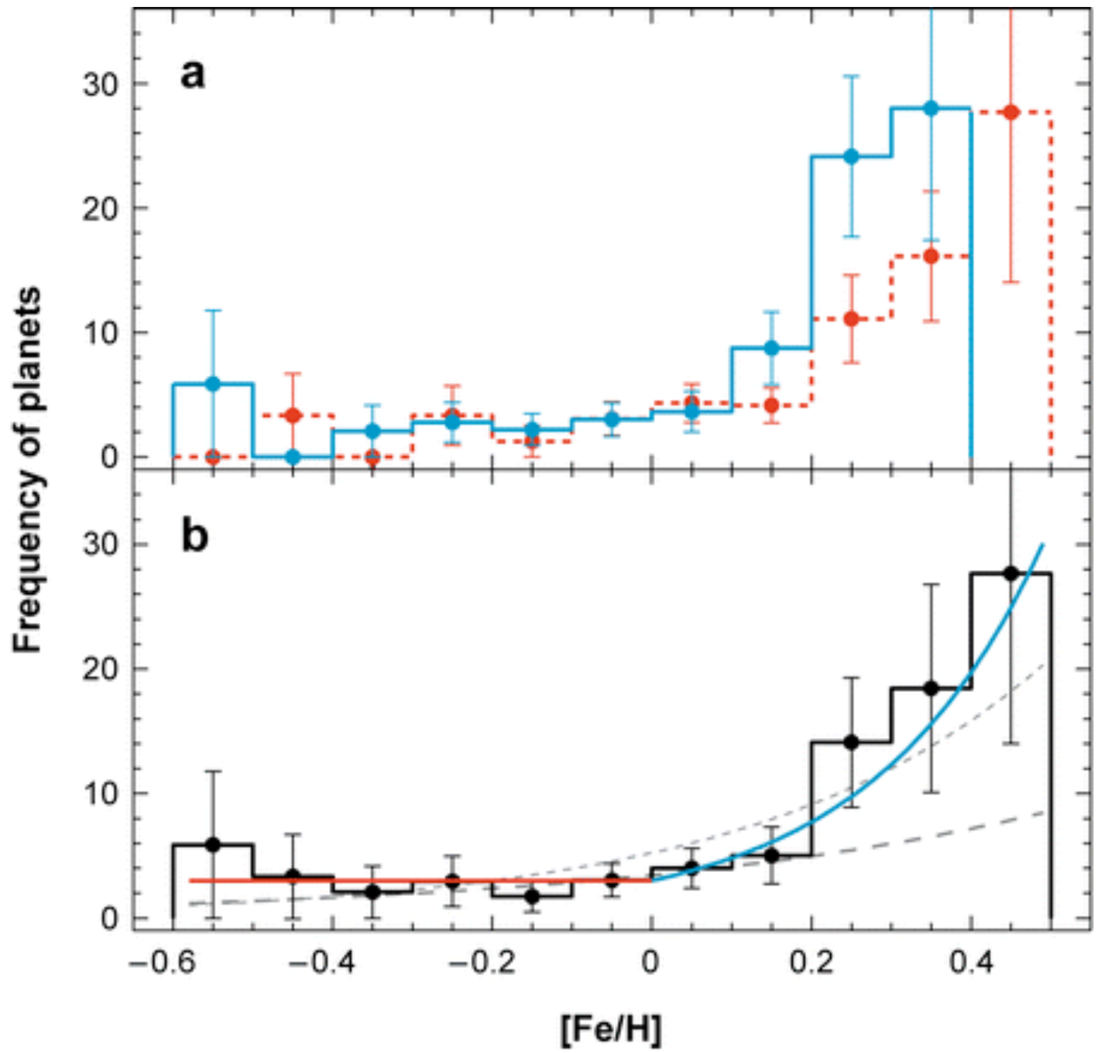


More Metals => More Planets

Doppler wobble surveys find Jupiters orbiting 5% of stars with solar metalicity.

This rises to 25% for stars with 3x solar abundance [Fe/H]=+0.5

Fischer & Valenti 2005



Udry S, Santos NC. 2007.
Annu. Rev. Astron. Astrophys. 45:397–439

A Quick Review

- ***Main events in the evolution of the Universe***:
  - The Big Bang (inflation of a bubble of false vacuum)
  - Symmetry breaking → matter/anti-matter ratio
  - Quark + antiquark annihilation → photon/baryon ratio
  - The quark soup → heavy quark decay
  - Quark-Hadron phase transition and neutron decay → *n/p* ratio
  - Big Bang nucleosynthesis → primordial abundances

    $X_p = 0.75 \quad Y_p = 0.25 \quad Z_p = 0.0$
  - Matter-Radiation equality $R \sim t^{1/2} \rightarrow R \sim t^{2/3}$
  - Recombination/decoupling → the Cosmic Microwave Background
  - CMB ripples ($\Delta T/T \sim 10^{-5}$ at $z=1100$) seed galaxy formation
  - Galaxy formation and chemical evolution of galaxies

- ***<u>Main events in the chemical evolution of galaxies</u>***:
  - Galaxy formation → Jeans Mass ($\sim 10^6 M_\odot$)
    - Ellipticals
    - Spirals
    - Irregulars

    } → { Initial mass and angular momentum, plus mergers. Star formation history $S(t)$, gas fraction $\mu(t)$
  - Star formation → α = efficiency of star formation
    - The IMF (e.g., Salpeter IMF power-law with slope -7/3)
    - First stars (Population III) from gas with no metals (none seen)
  - Stellar nucleosynthesis → metals up to Fe
  - Supernovae (e.g. SN 1987A) → metals beyond Fe
    - p, s, and r processes
    - white dwarfs ($M < 8\ M_\odot$) or black holes, neutron stars ($M > 8\ M_\odot$).
  - Galaxy enrichment models: (e.g. $Z = - y \ln(\mu)$, yield y)
    - Metal abundances rise → $X = 0.70$ $Y = 0.28$ $Z = 0.02$ (solar abundances)
  - Gas with metals → Stars with Planets → Life!