Evolution of Galaxies:

Other galaxies, Abundance gradients, Mass-Metallicity

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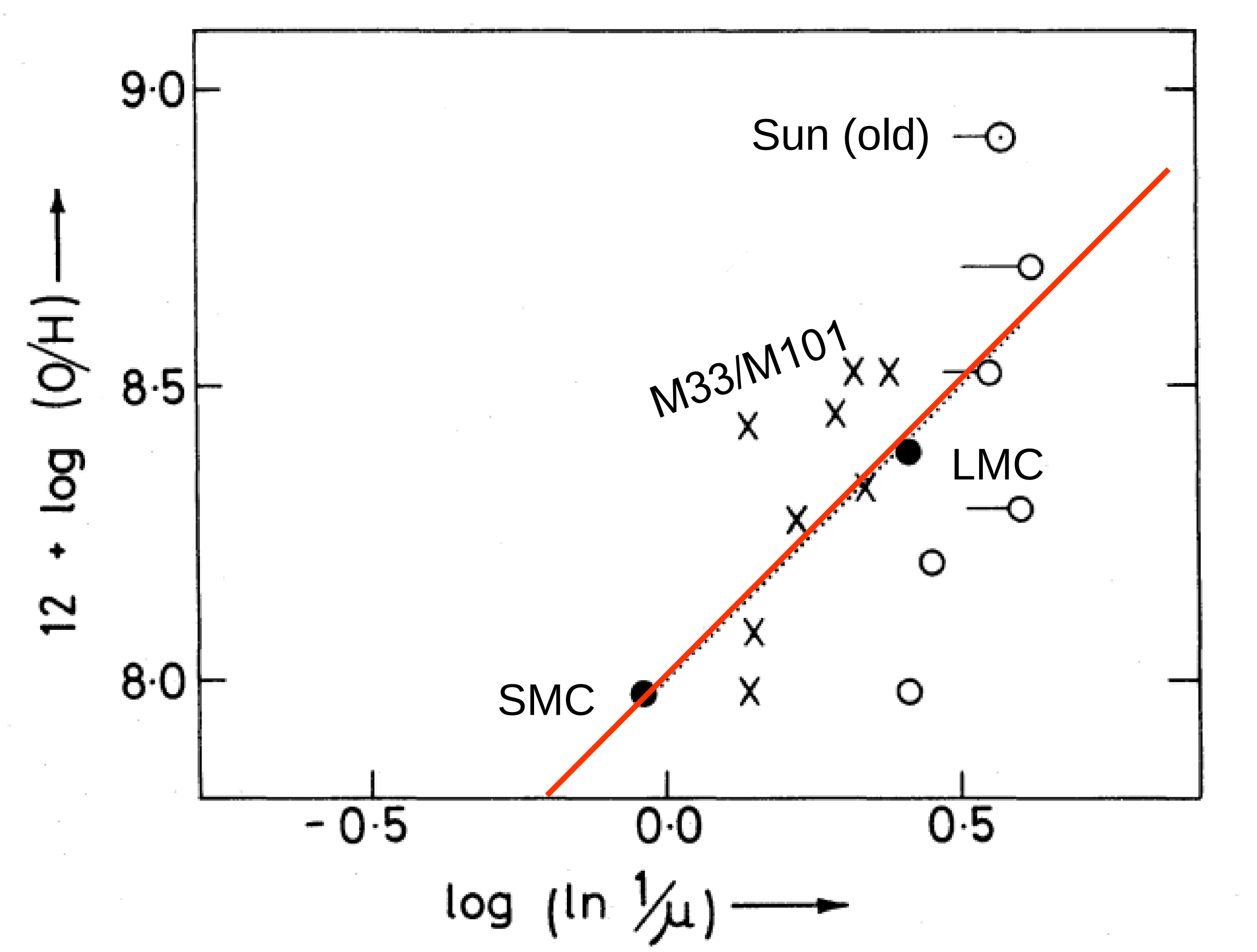
http://astro.u-strasbg.fr/~koppen/JKHome.html

Irregular galaxies

- Abundances: HII regions ➔ uniform composition
  good test-beds for chemical evolution,
  but single events (SN) can disrupt dwarf galaxy
- f_{gas}-Z relation:
  - low effective yield 0.2 Z_{sun} + large scatter
  - steep IMF? SN-driven galactic winds? Accretion?

Magellanic clouds have same yield

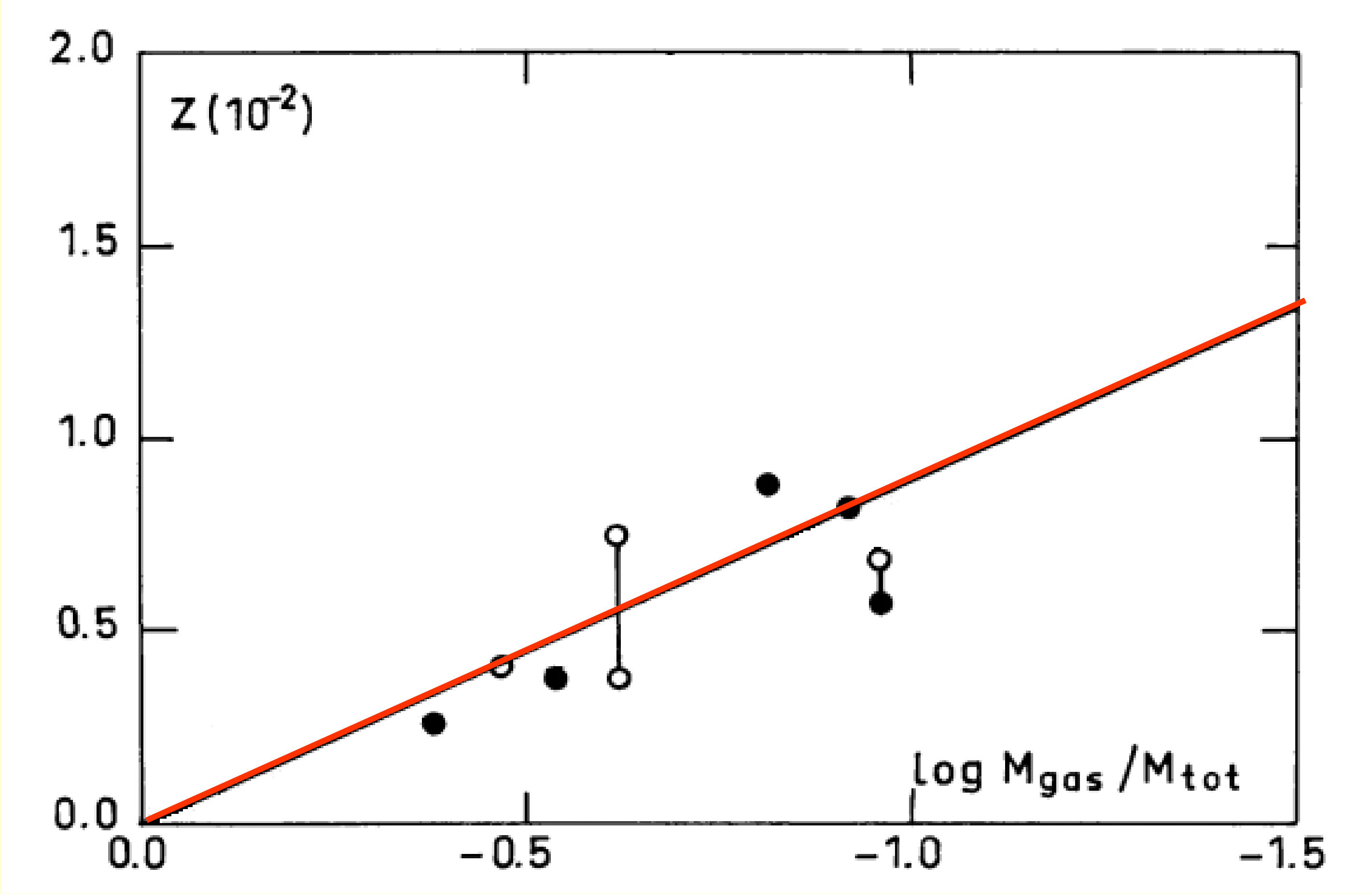


Pagel et al. 1978

y = 0.003

lower than MWG

This agrees with other Irrs, too

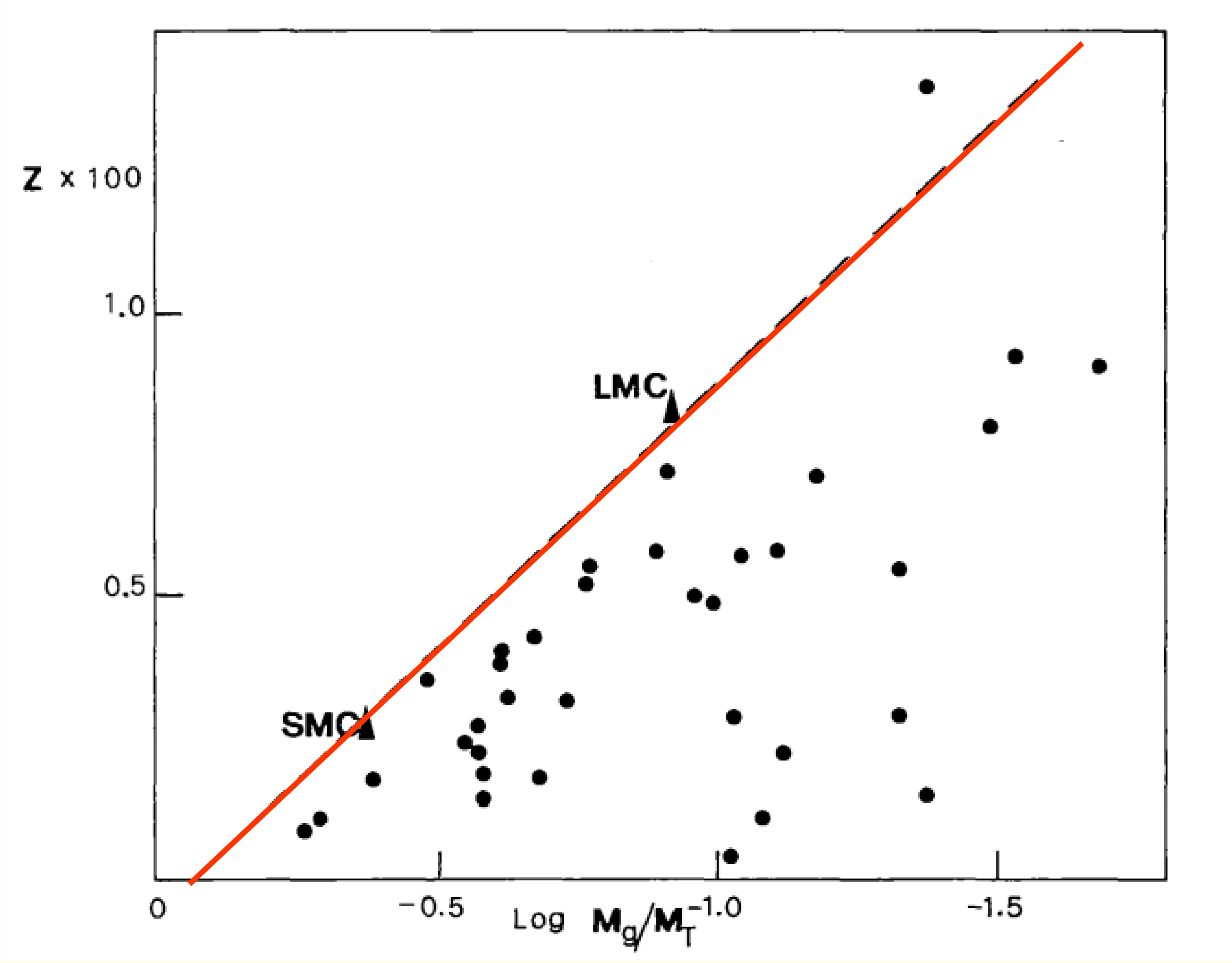


Lequeux et al. 1979

y = 0.003

lower than MWG

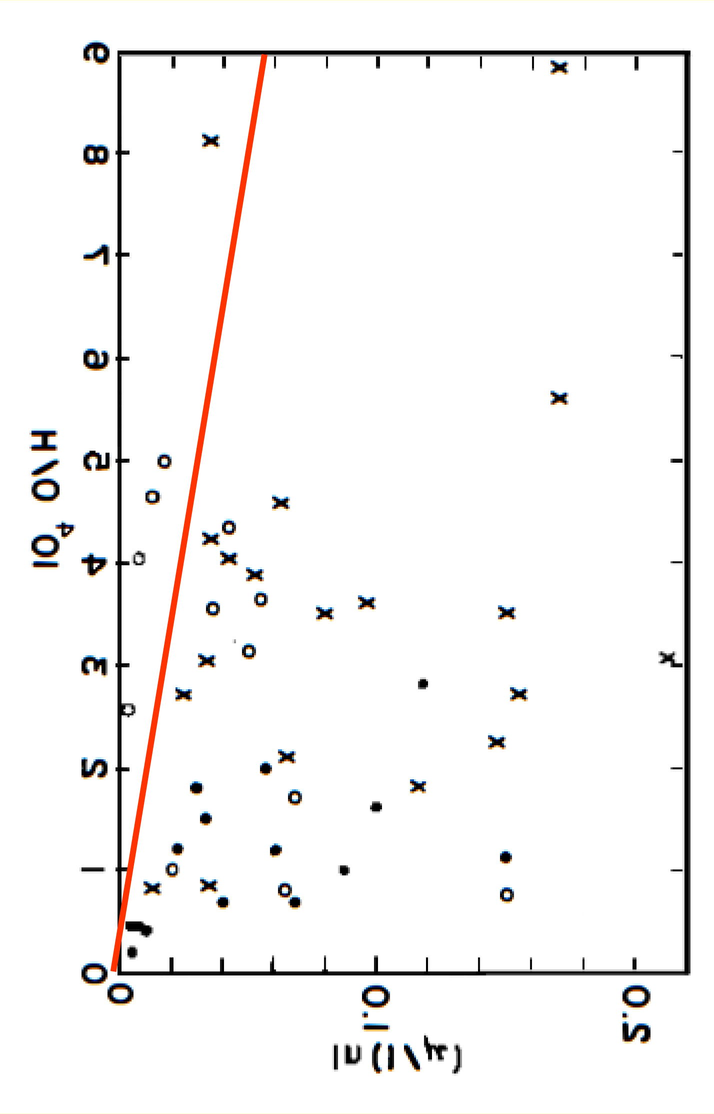
Are the MCs special?



Matteucci+Chiosi 1983

Other irregulars need lower yields, e.g. by Infall, galactic winds

Irregulars have large scatter



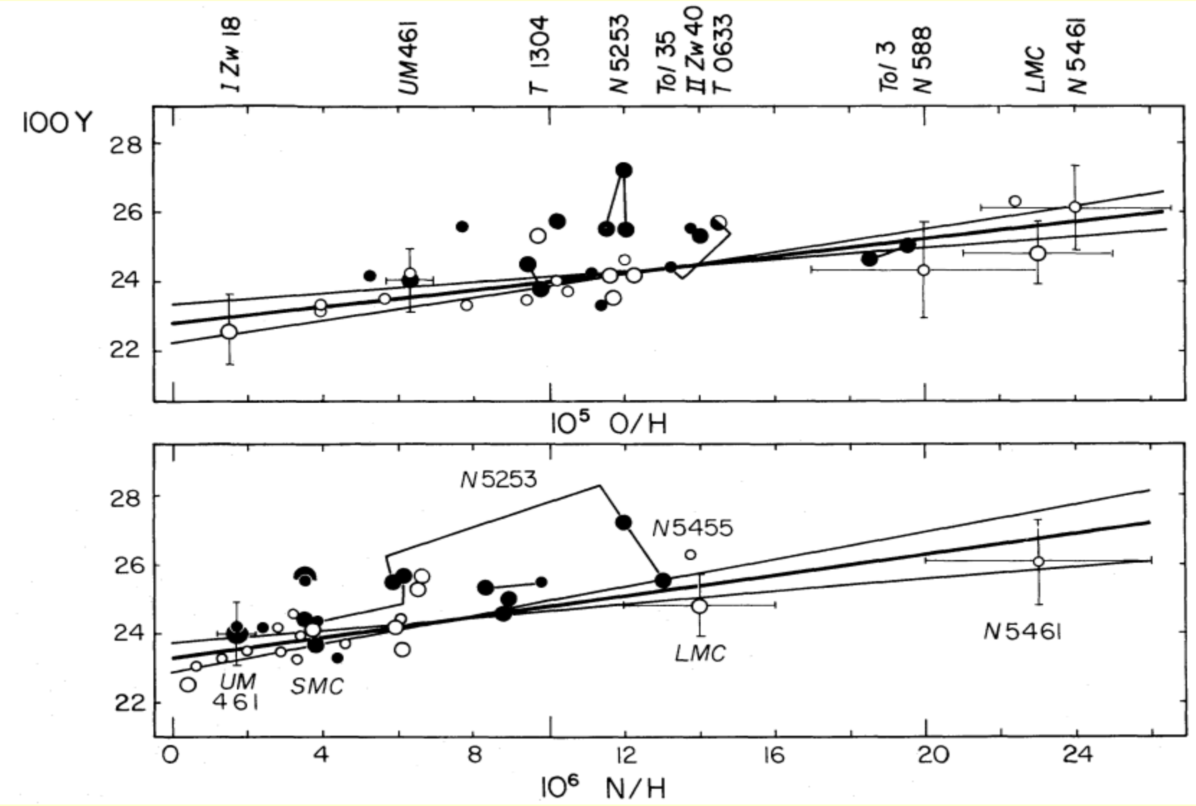
Gallagher+Hunter 1984

No systematic behaviour of different types of irregulars

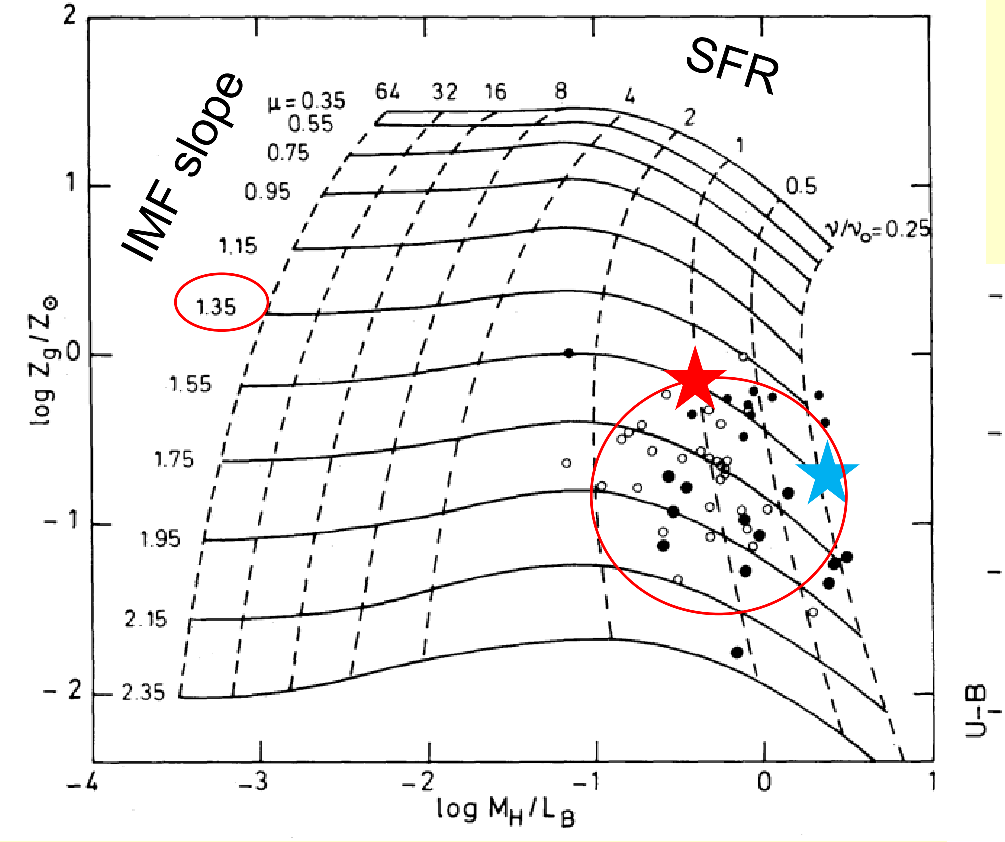
NB. Abundances are estimated from empirical relations (strong line methods), because weak [OIII] 4363 cannot be observed…

Irregular galaxies

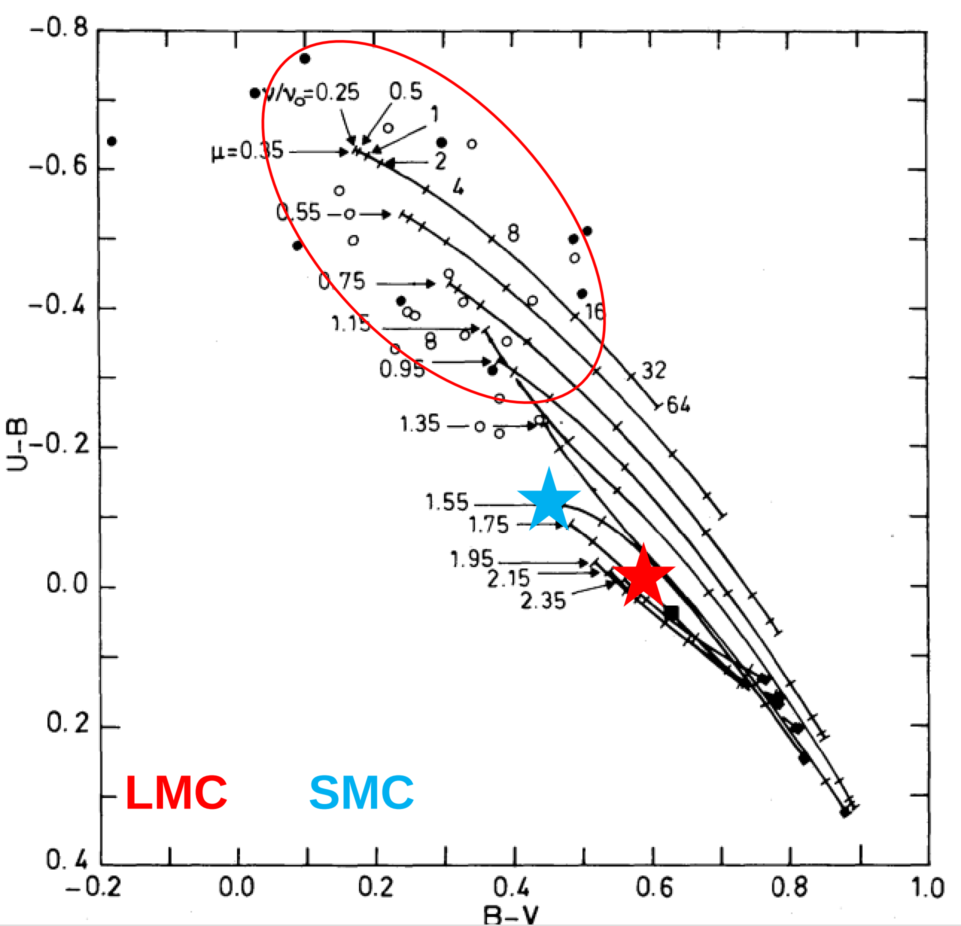
- Abundance ratios:
  - – $dY/dZ \approx 3..4 > y_{He}/y_Z \approx 2$ (stellar nucleo)
    - Maeder92: m>25Msun ➔ no SN but BH
    - Metal-enhanced SN-driven winds eject Z (from HMS) but not He (from IMS)
  - – C/O and N/O: see EoG_7



Chemistry vs. Photometry



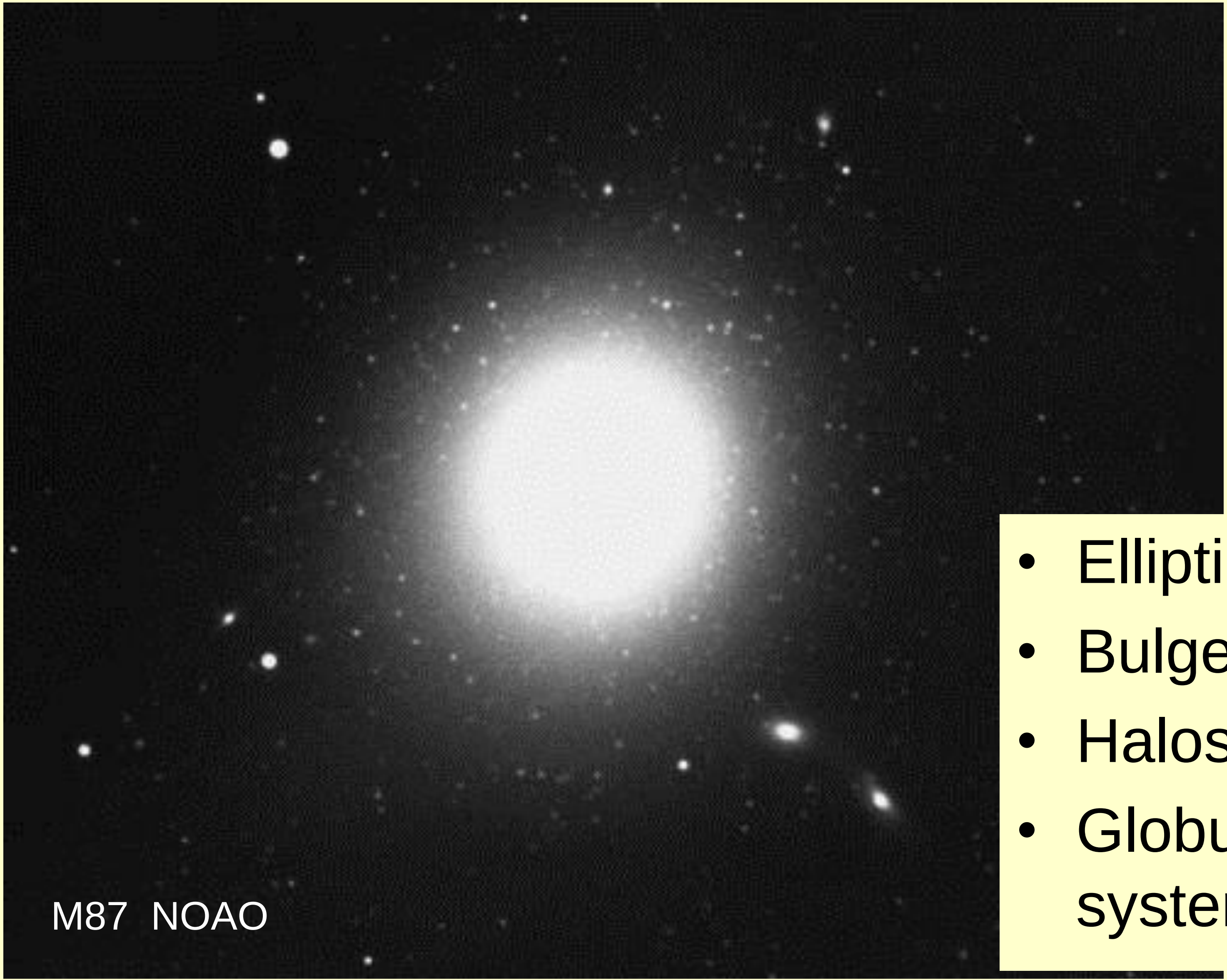
Irregular have bluer colours than expected from models with continuous star formation histories



blue colours have short memory:
influenced by recent SF ➔ starbursts

Arimoto + Tarrab 1990

Spheroidal systems


M87 NOAO

- Ellipticals and S0
- Bulges
- Halos
- Globular cluster systems

Ellipticals and Bulges

Data = integrated colours and spectra

= mixture of ages & metallicities

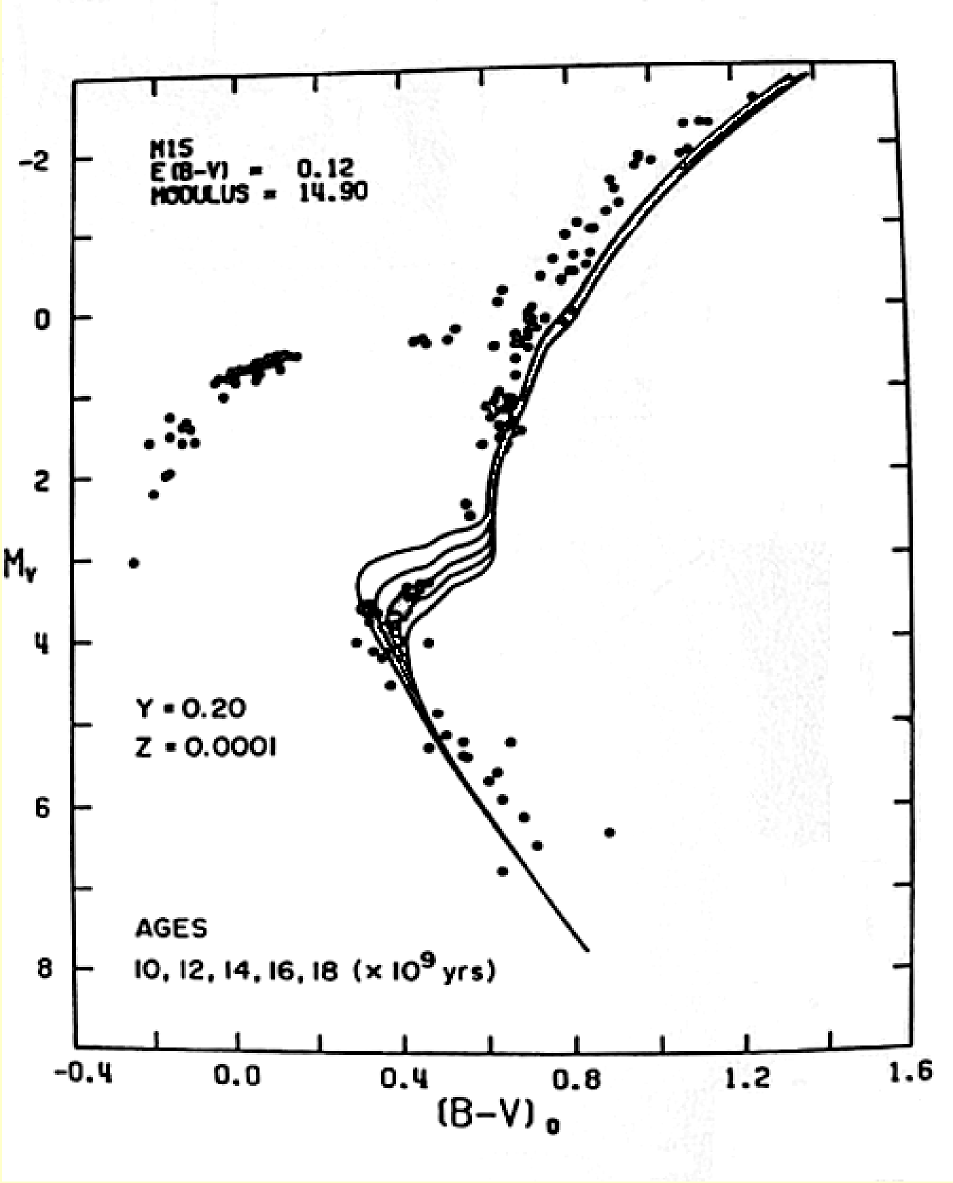
Requires modeling (A.Lançon …)

- Population synthesis: fit data by
  - SFH + AMR + IMF + isochrones + stellar spectra (theo/obs.)
  - SFH + AMR + library of observed spectra of MW+MC clusters (Z, age)
- Evolutionary population synthesis

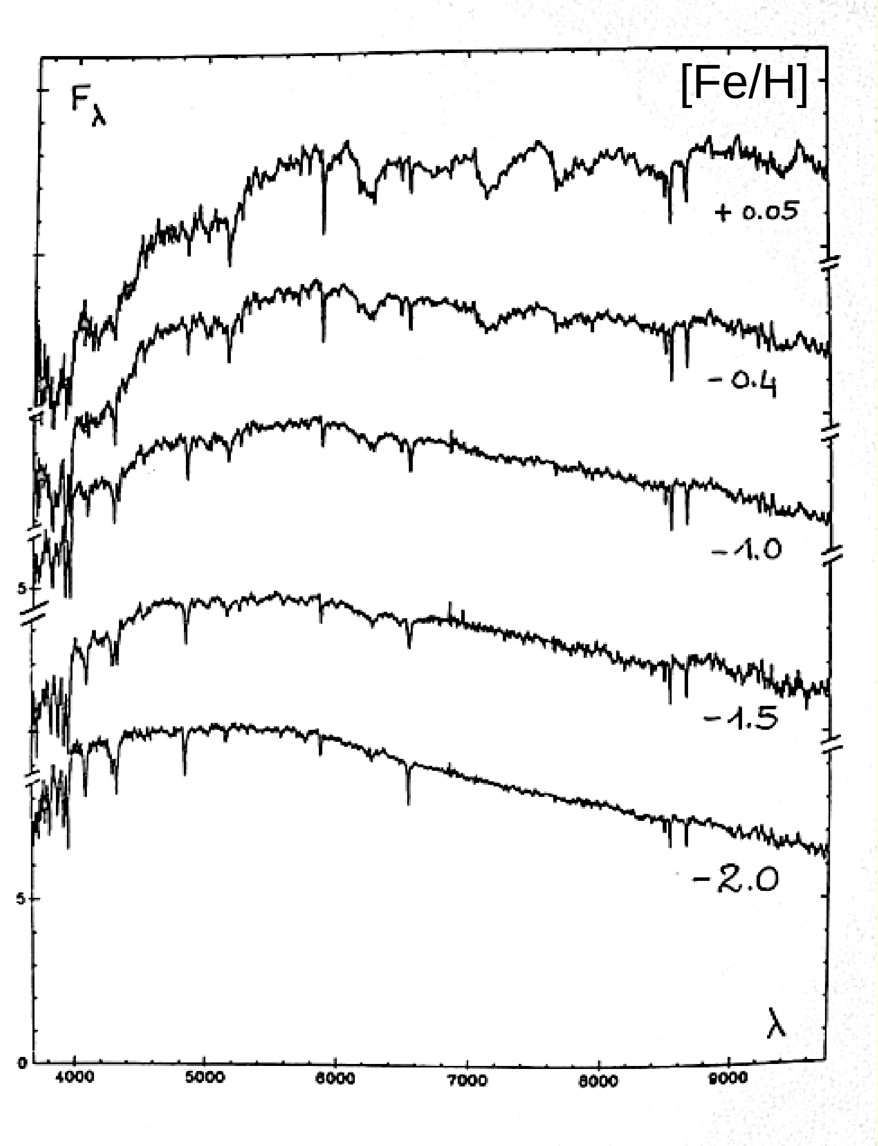
  SFR + infall etc + (AMR=chem.ev) + IMF + isochrones + stellar spectra
- Base = objects of single age & metallicity
  - Stellar clusters (obs.)
  - SingleStellarPopulation (theor.)

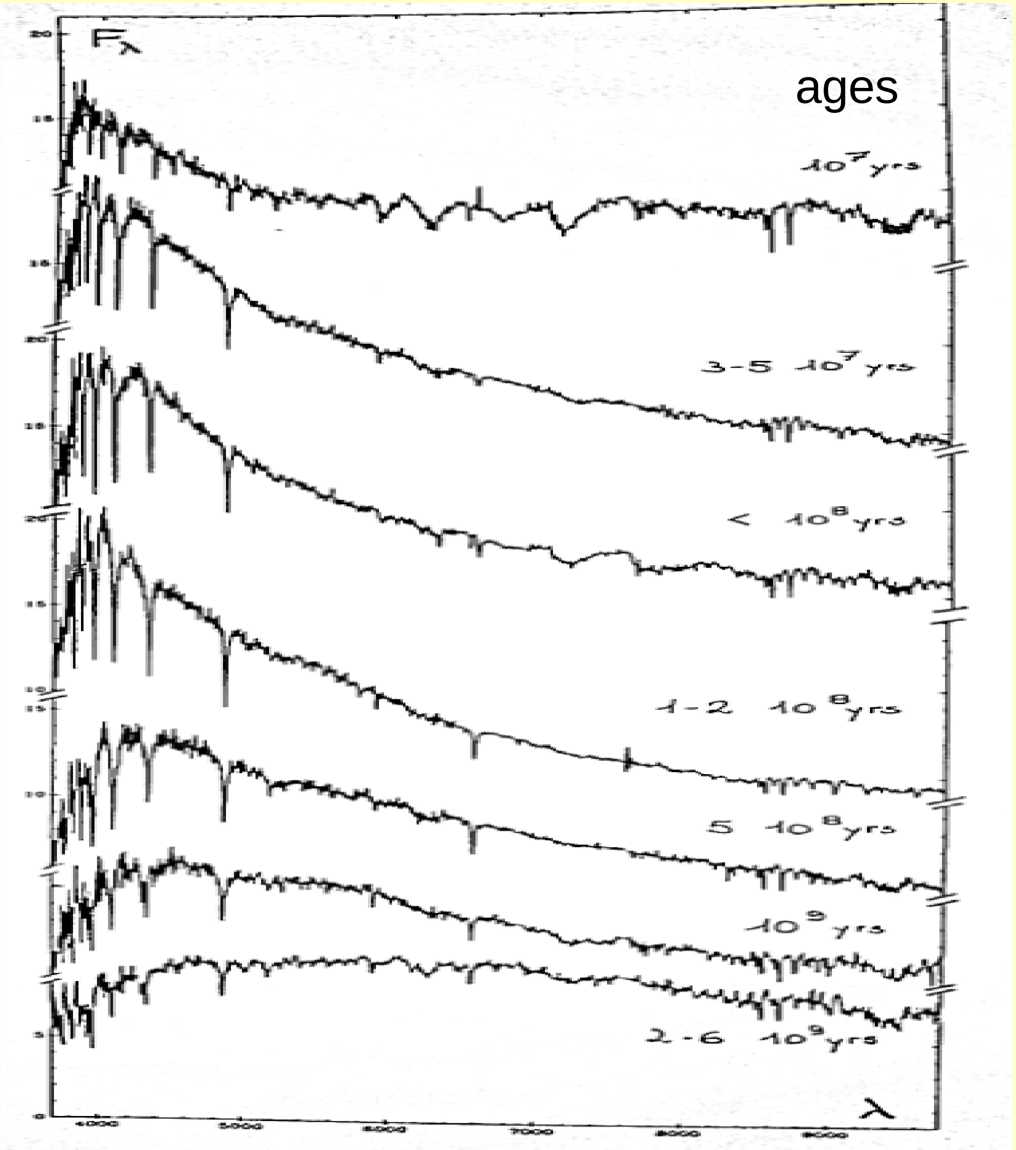
Degeneracy $Mg_2 \sim (Z^*age)^{0.41}$

Globular clusters are single-age populations

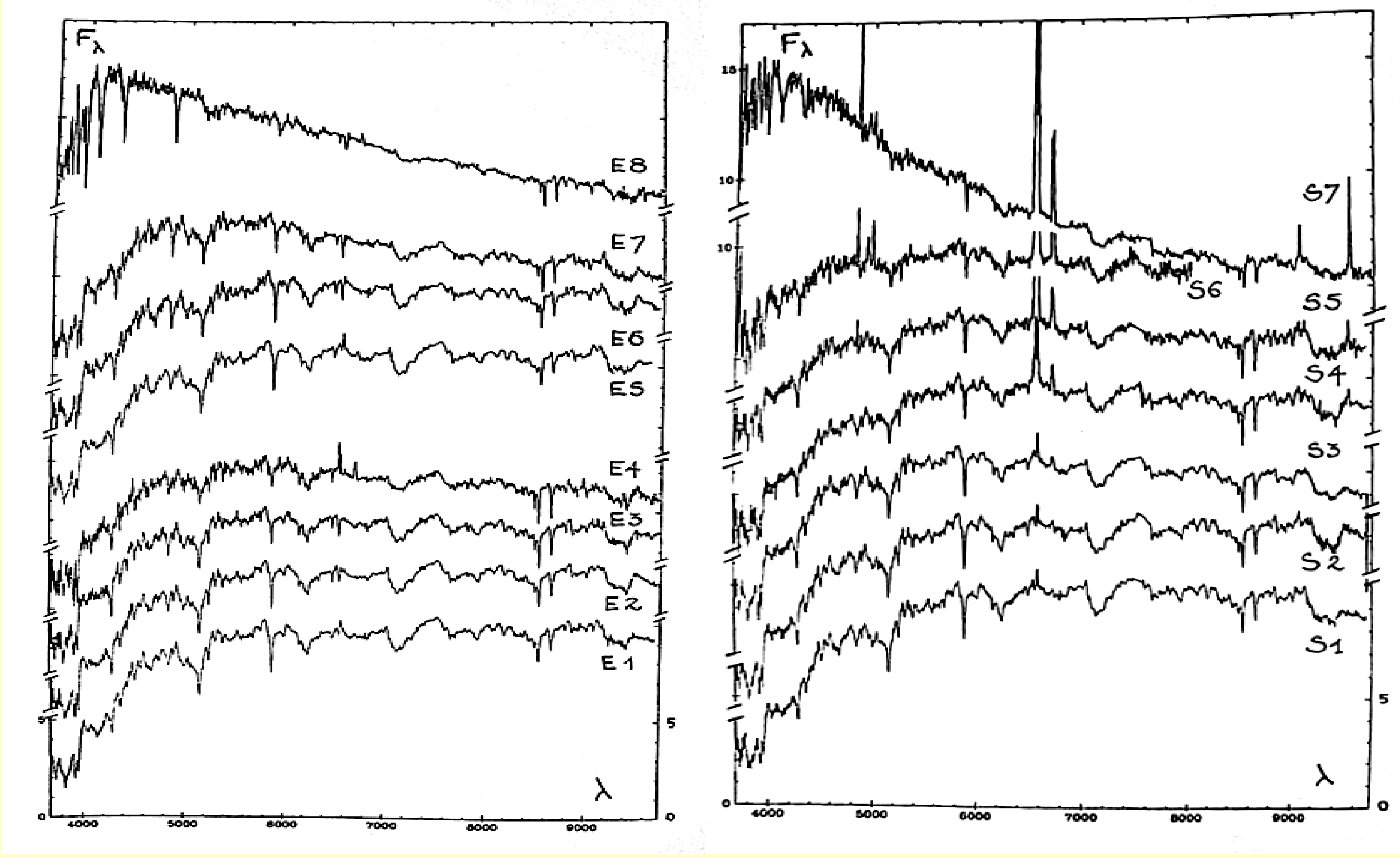


Cluster spectra (Bica 1986)



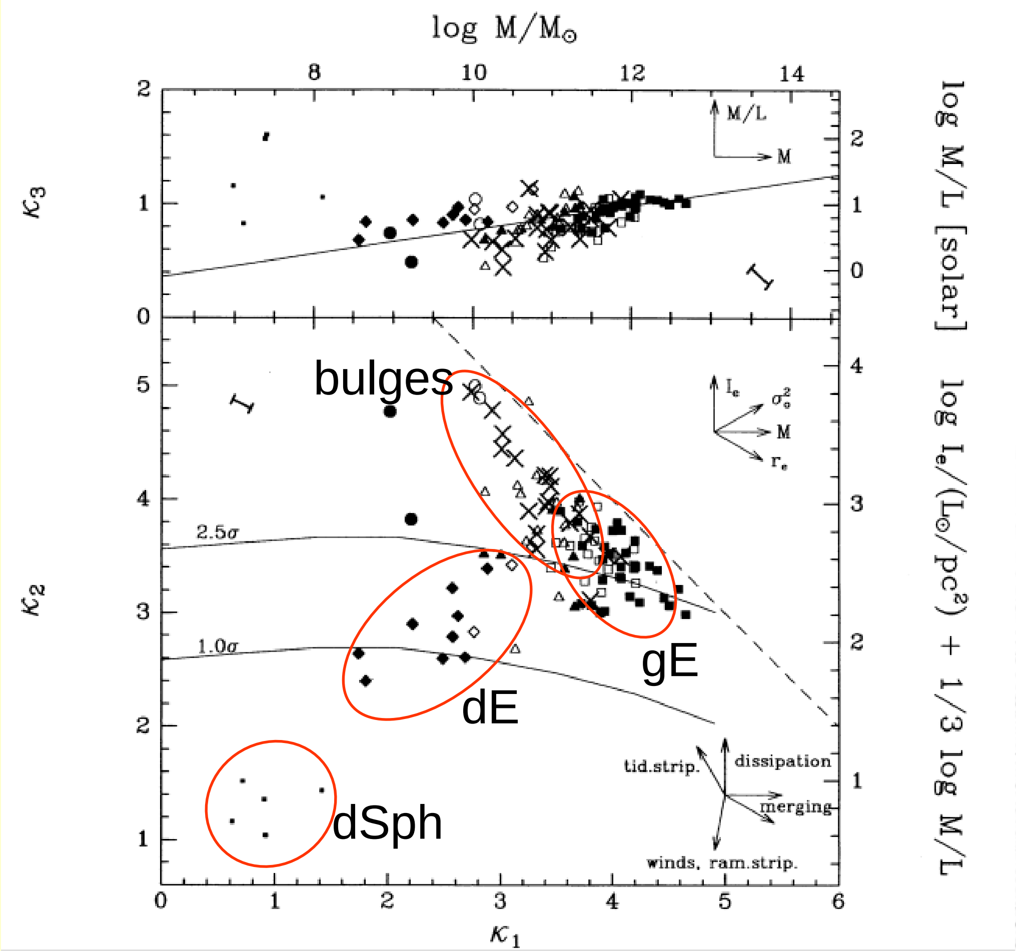


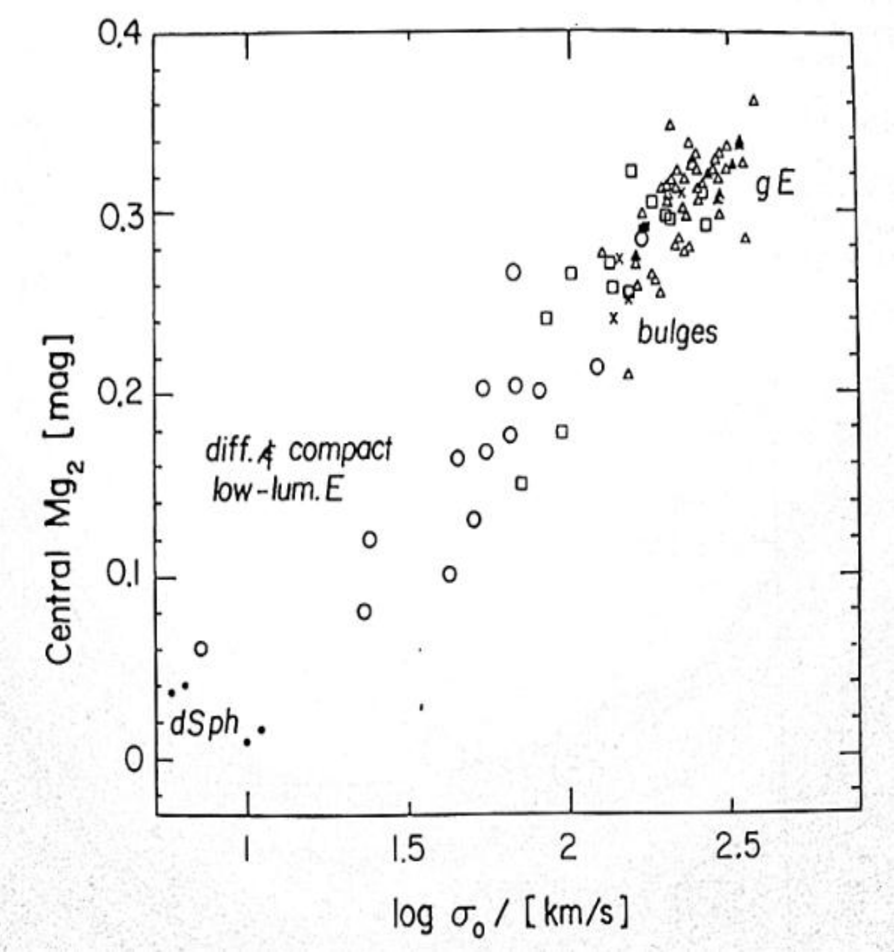
Spectra of E and S galaxies



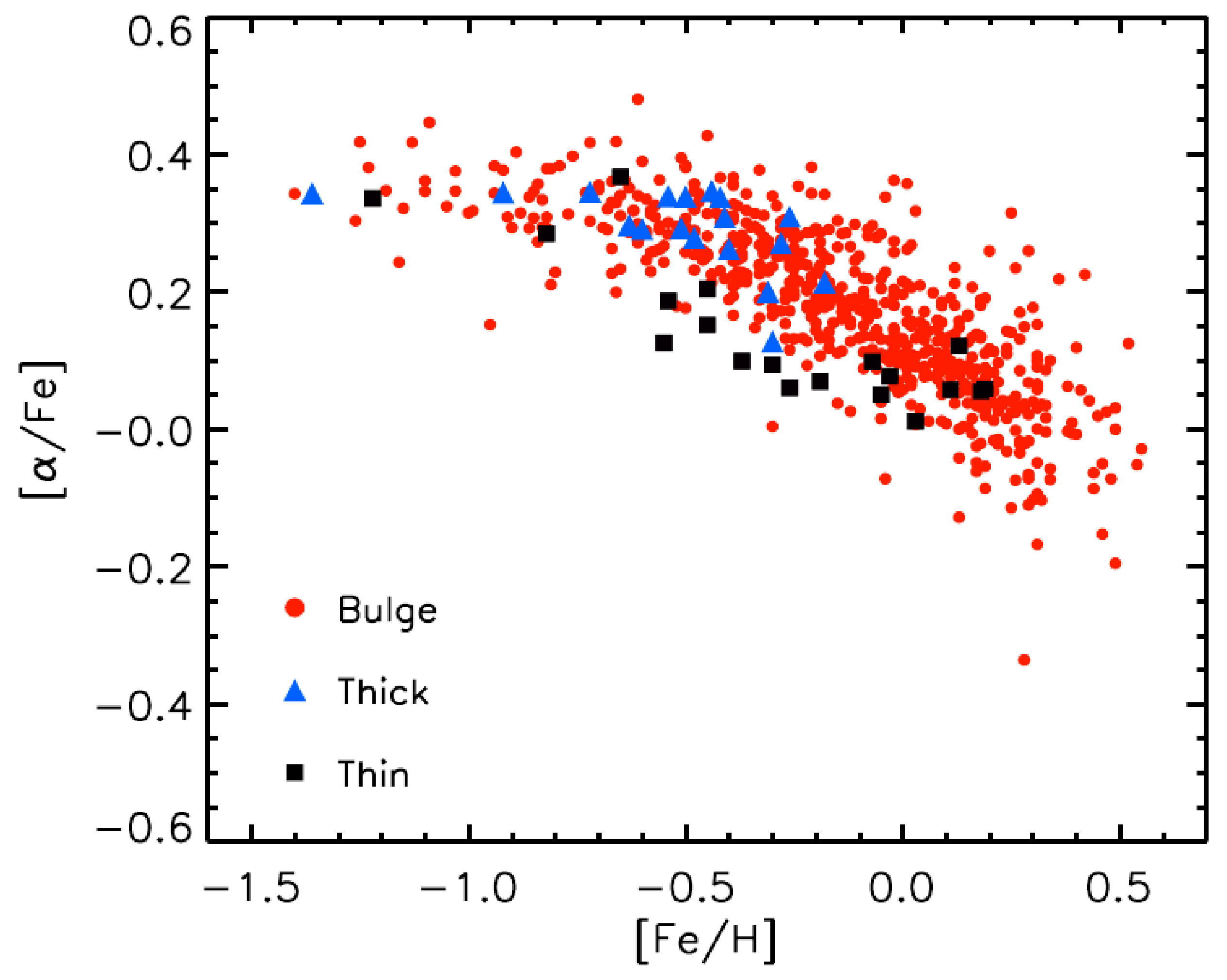
Fundamental Plane in (σ, Σ, R) space

Two sequences, but all follow the **same** mass-metallicity relation





Galactic Bulge



Spectro R=20000
ESO VLT
S/N = 40..90

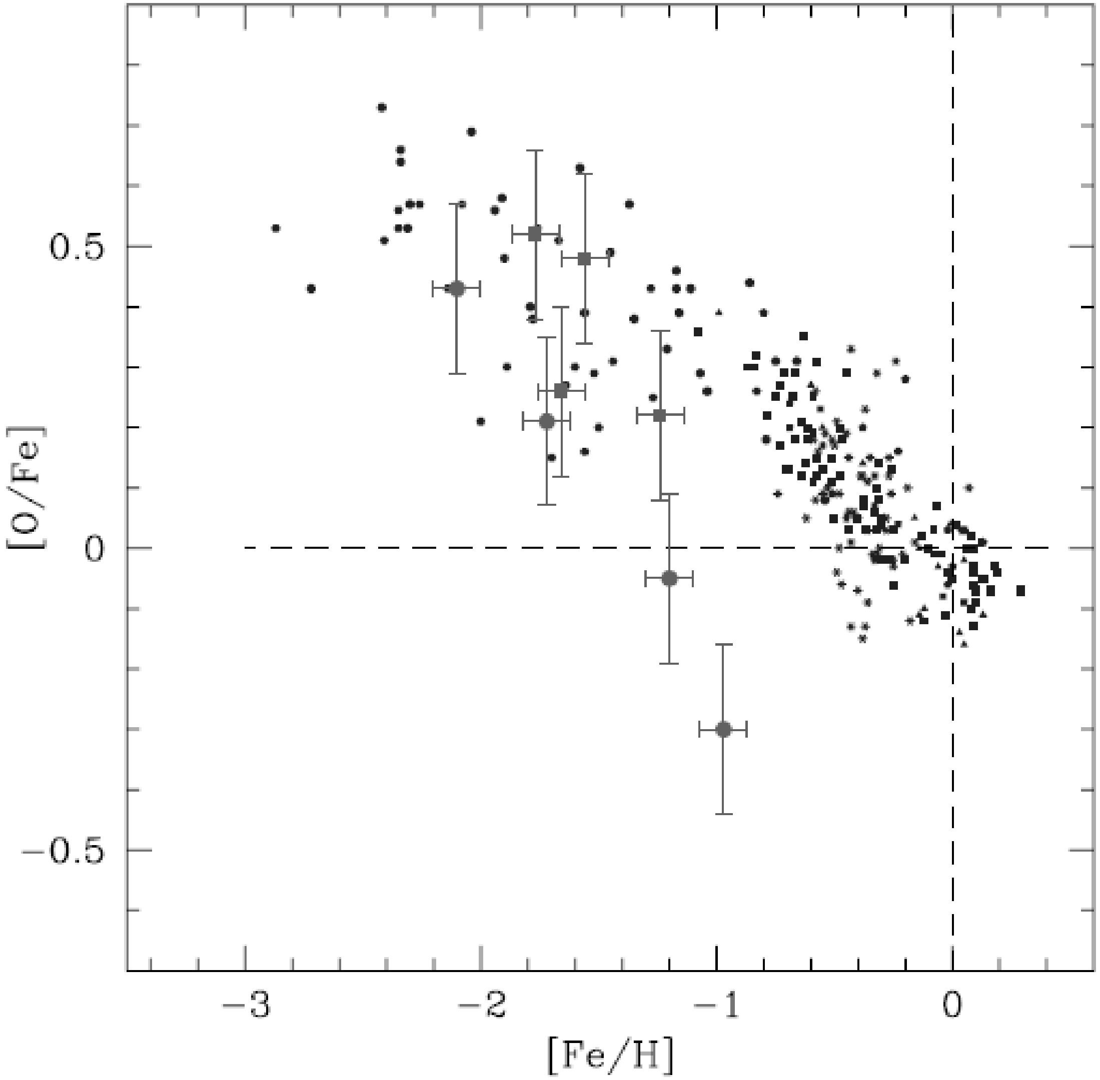
Similar [Fe/H] range as thin disk

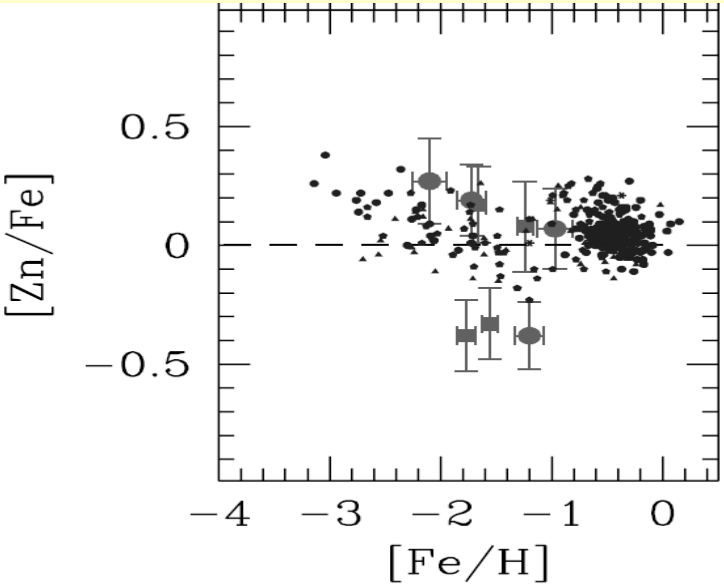
[α/Fe] is higher than in the disk

Thick disk:
[Fe/H] = -1.5 … -0.2
[α/Fe] like bulge

Gonzales 2011

Sculptor dSph galaxy



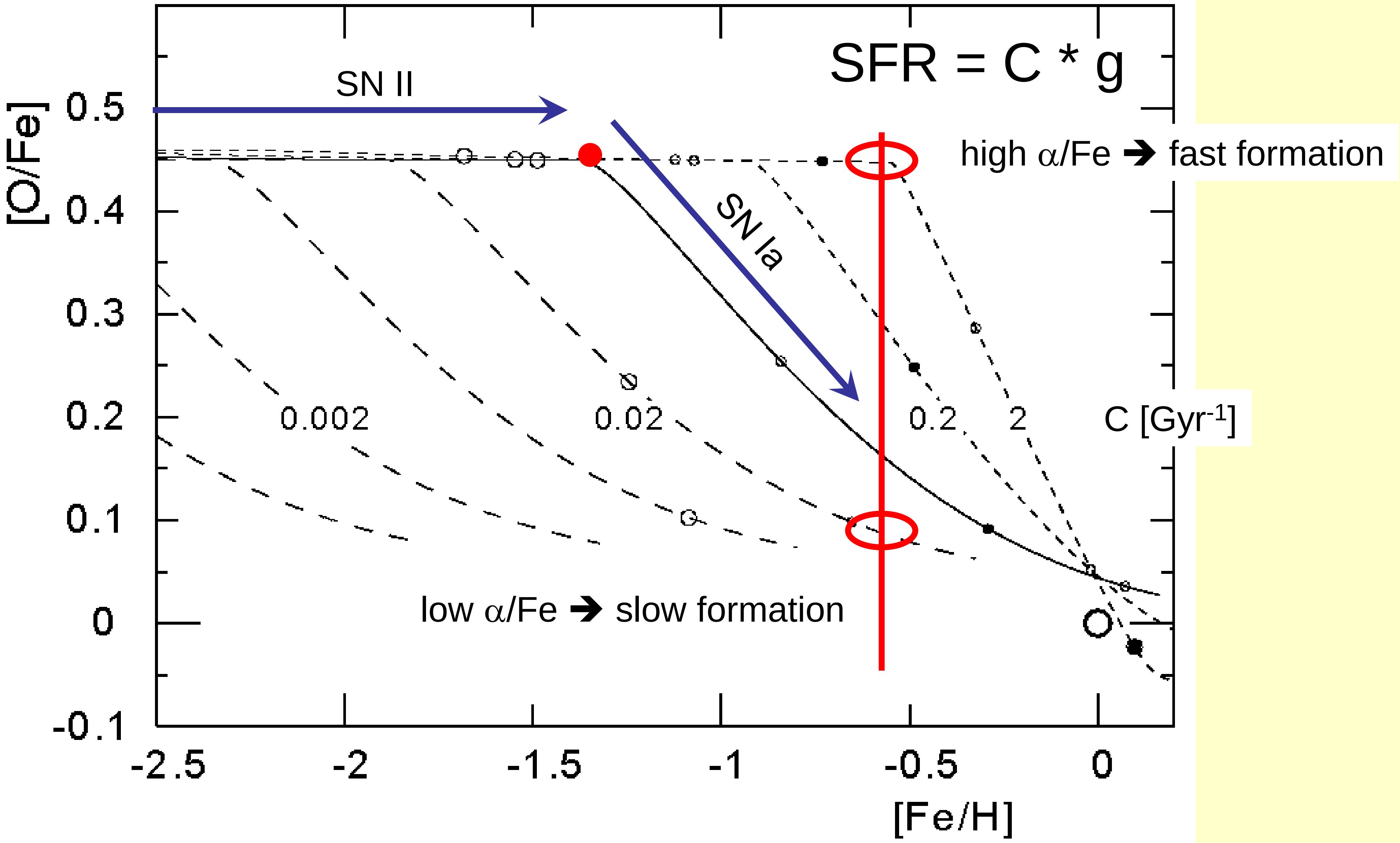


Giant stars compared to solar neighbourhood:

➔ lower {Fe/H]
➔ steeper O/Fe-Fe/H relation!

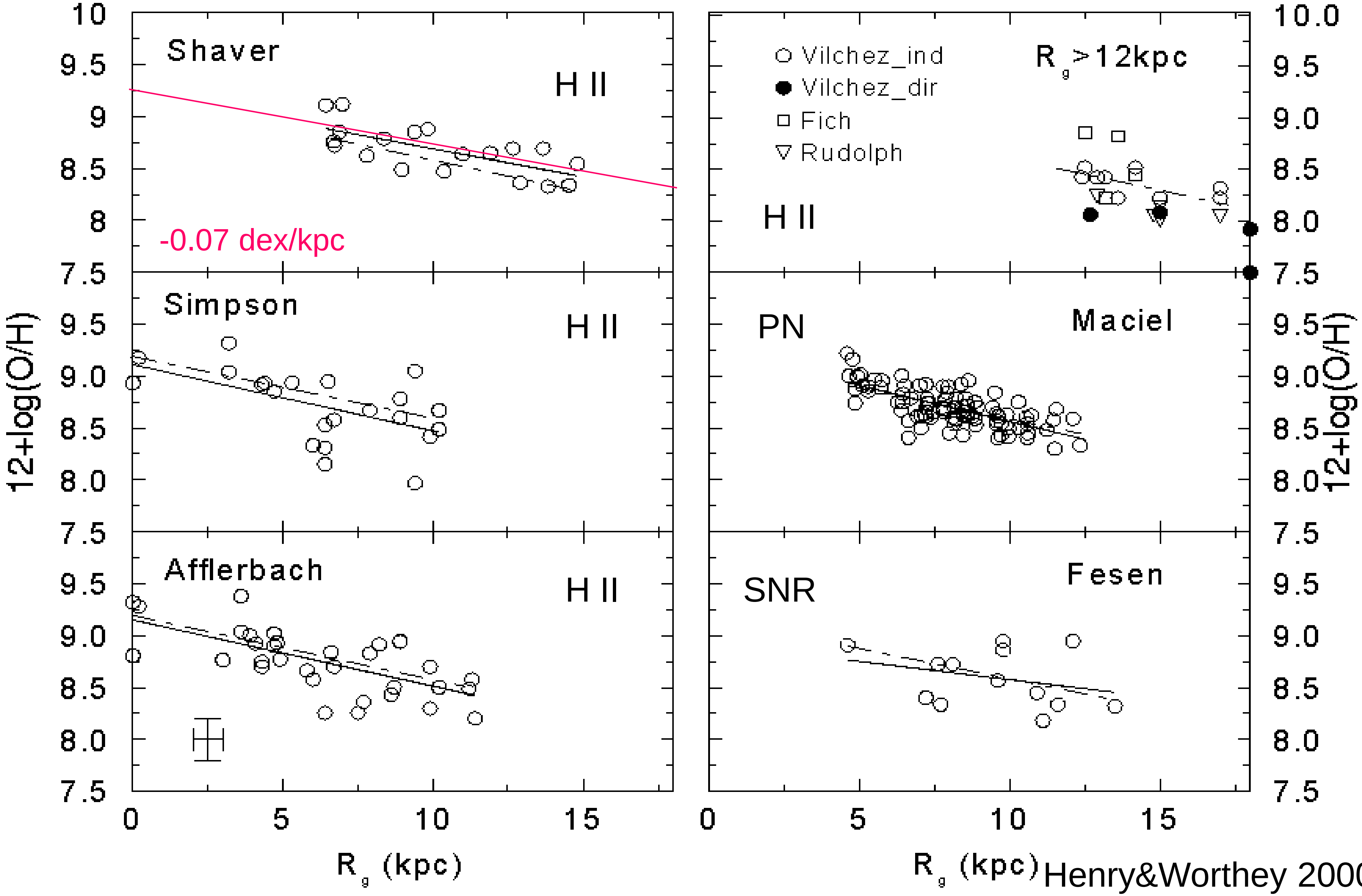
Geisler 2005

O/Fe (or α/Fe) ratio measures SFR time-scale (illustrative model)



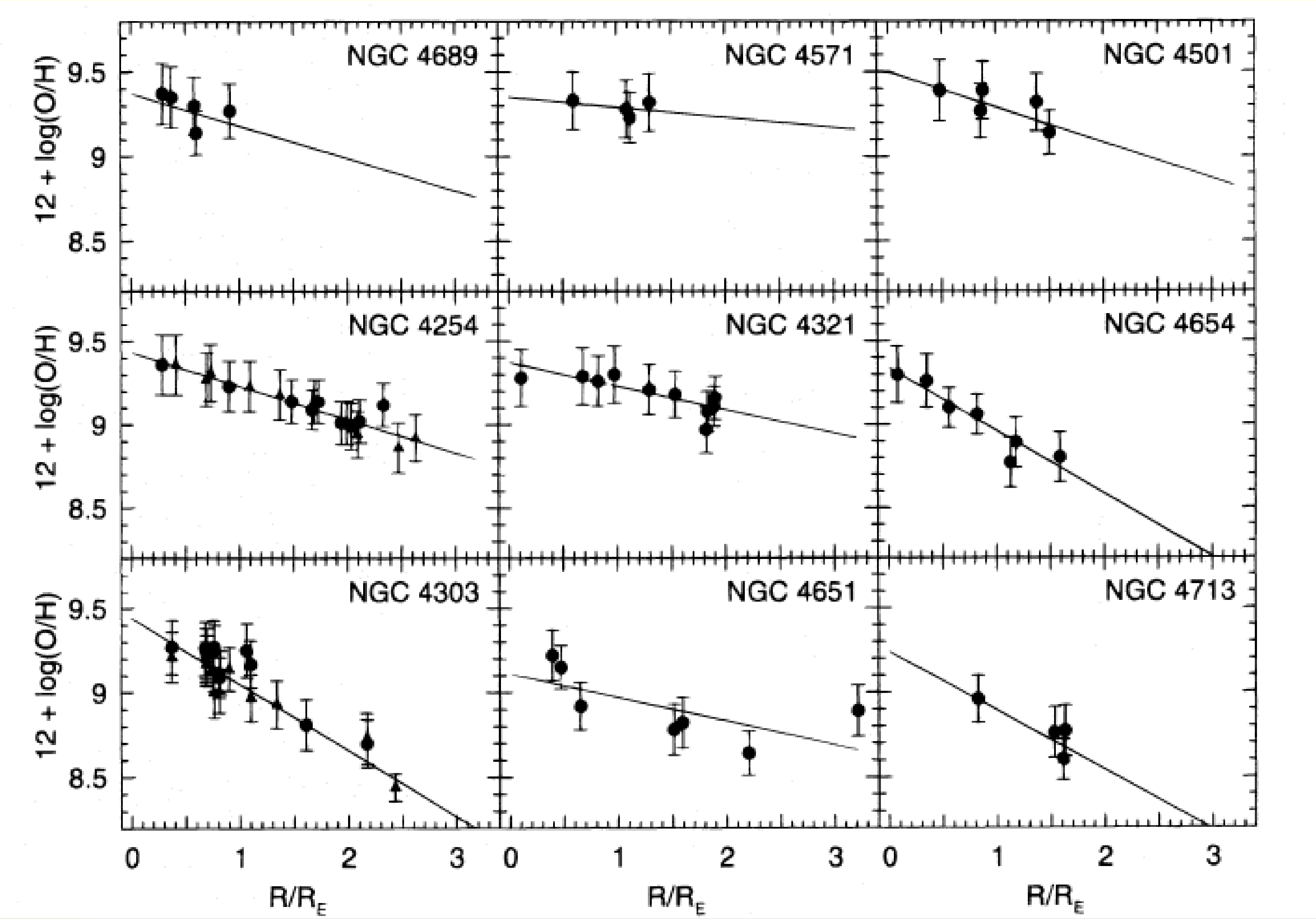
Radial abundance gradients in disk galaxies

e.g. the Milky Way



Henry&Worthey 2000

Virgo cluster spirals



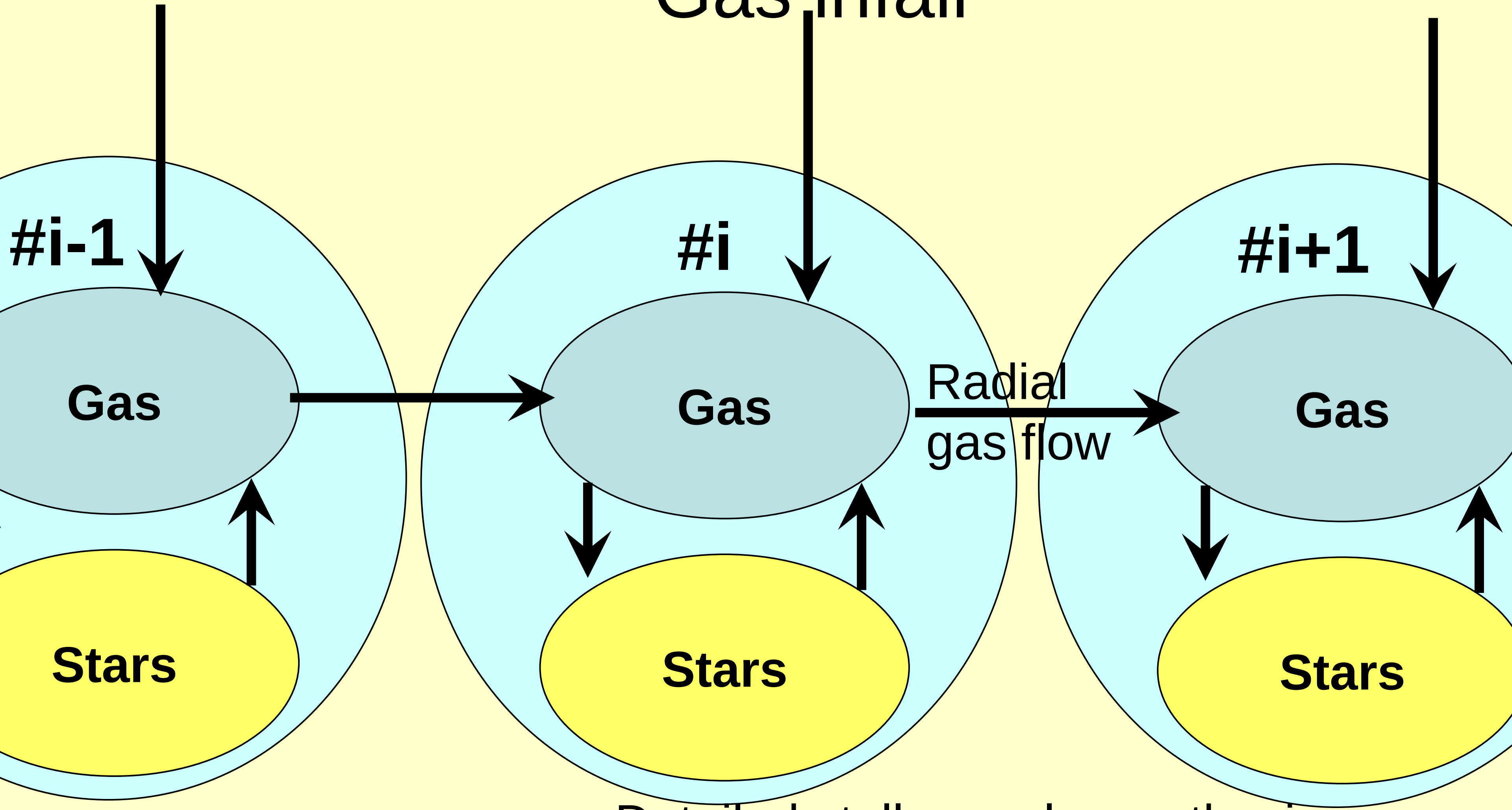
Skillman et al. 1989

Gradients: proposed explanations

- Gas fraction increases radially (i.e. state of evolution)
- Radial variation of SFR
- Radial variation of nucleosynthesis
- Radial variation of IMF
- Radially dependent infall ➔ ‘dilution’
- Radial gas flows (various origins)
- …

Make a model for the disk

Gas infall



#i-1

Gas

Stars

#i

Gas

Stars

Radial
gas flow

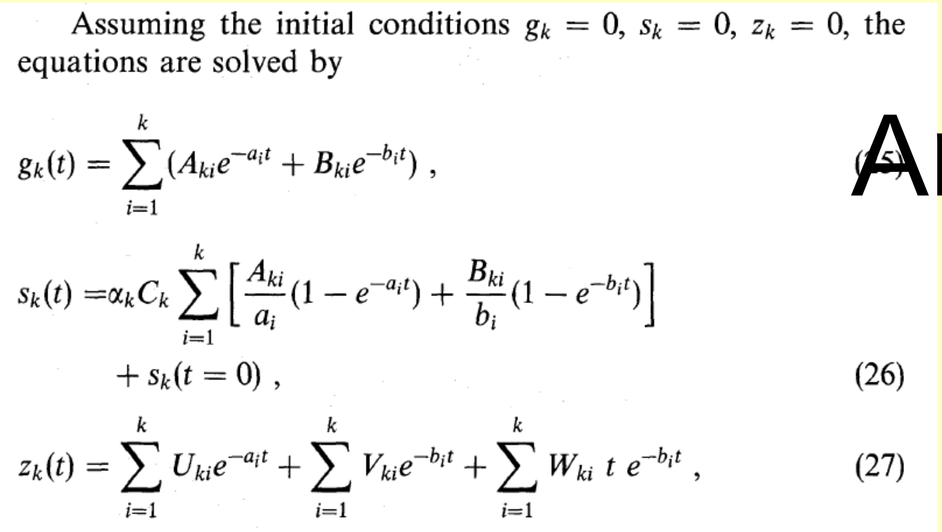
#i+1

Gas

Stars

Detailed stellar nucleosynthesis

Analytical solution

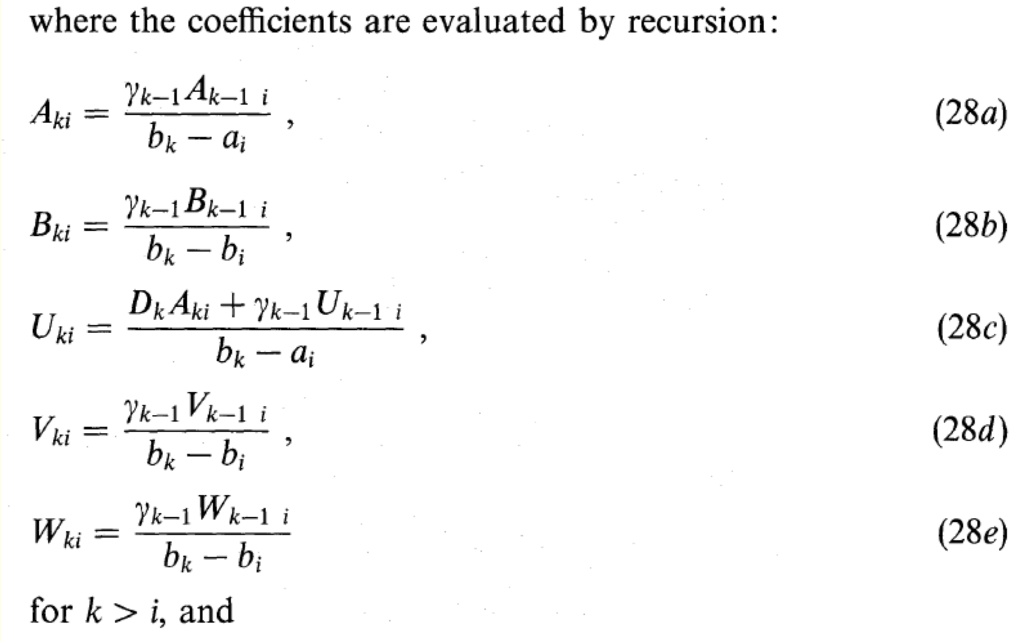


Assuming the initial conditions $g_k = 0$, $s_k = 0$, $z_k = 0$, the equations are solved by

$$g_k(t) = \sum_{i=1}^{k} (A_{ki} e^{-a_i t} + B_{ki} e^{-b_i t}) \,, \tag{25}$$

$$\begin{aligned} s_k(t) =& \alpha_k C_k \sum_{i=1}^{k} \left[\frac{A_{ki}}{a_i}(1 - e^{-a_i t}) + \frac{B_{ki}}{b_i}(1 - e^{-b_i t}) \right] \\ &+ s_k(t = 0) \,, \end{aligned} \tag{26}$$

$$z_k(t) = \sum_{i=1}^{k} U_{ki} e^{-a_i t} + \sum_{i=1}^{k} V_{ki} e^{-b_i t} + \sum_{i=1}^{k} W_{ki}\ t\ e^{-b_i t} \,, \tag{27}$$



where the coefficients are evaluated by recursion:

$$A_{ki} = \frac{\gamma_{k-1} A_{k-1\ i}}{b_k - a_i} \,, \tag{28a}$$

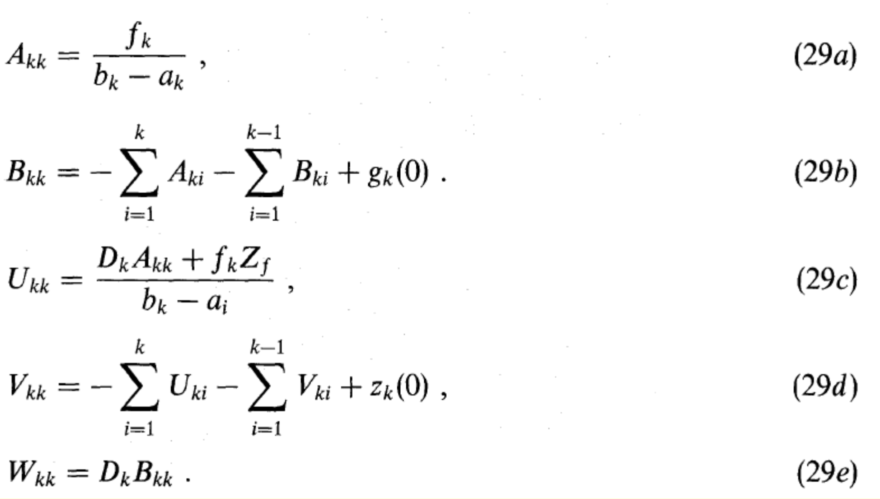
$$B_{ki} = \frac{\gamma_{k-1} B_{k-1\ i}}{b_k - b_i} \,, \tag{28b}$$

$$U_{ki} = \frac{D_k A_{ki} + \gamma_{k-1} U_{k-1\ i}}{b_k - a_i} \,, \tag{28c}$$

$$V_{ki} = \frac{\gamma_{k-1} V_{k-1\ i}}{b_k - b_i} \,, \tag{28d}$$

$$W_{ki} = \frac{\gamma_{k-1} W_{k-1\ i}}{b_k - b_i} \tag{28e}$$

for $k > i$, and



$$A_{kk} = \frac{f_k}{b_k - a_k} \,, \tag{29a}$$

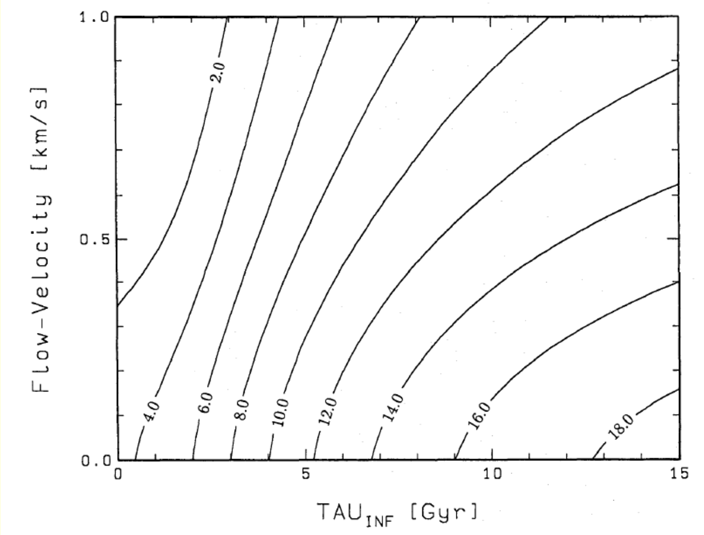
$$B_{kk} = -\sum_{i=1}^{k} A_{ki} - \sum_{i=1}^{k-1} B_{ki} + g_k(0) \,. \tag{29b}$$

$$U_{kk} = \frac{D_k A_{kk} + f_k Z_f}{b_k - a_i} \,, \tag{29c}$$

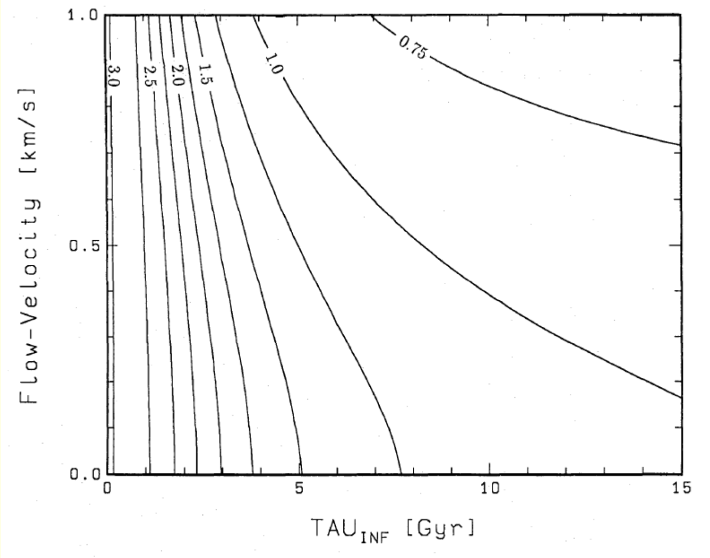
$$V_{kk} = -\sum_{i=1}^{k} U_{ki} - \sum_{i=1}^{k-1} V_{ki} + z_k(0) \,, \tag{29d}$$

$$W_{kk} = D_k B_{kk} \,. \tag{29e}$$

Easier maps

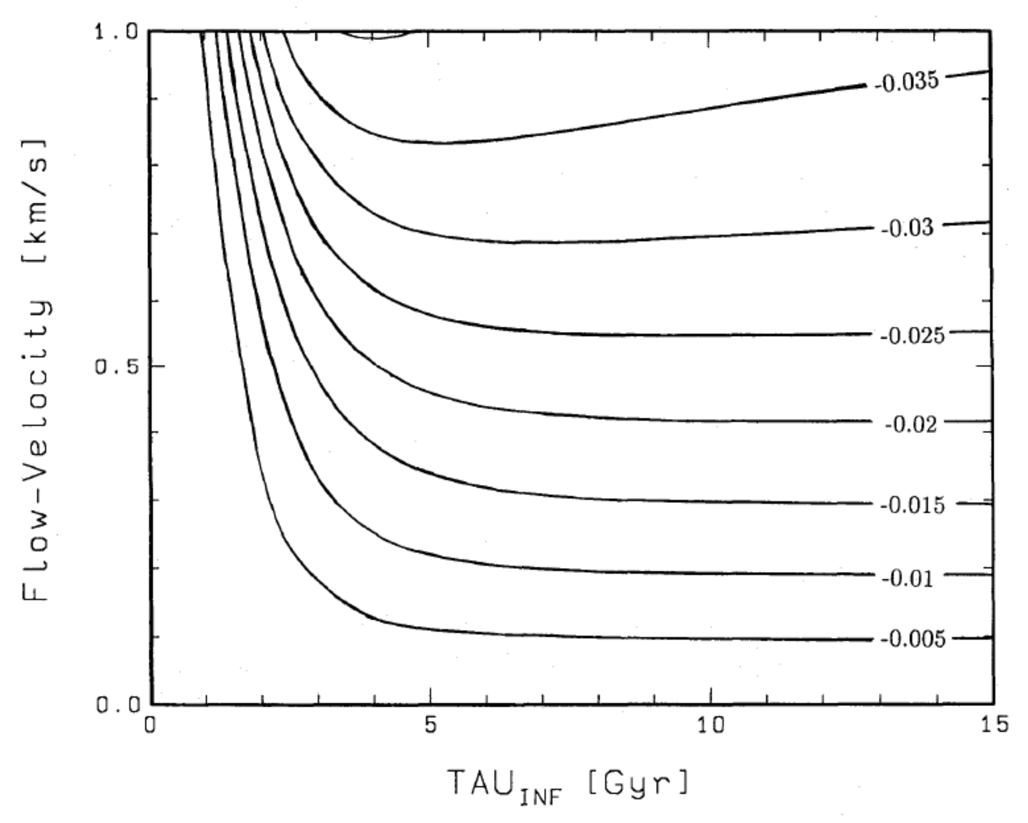


Gas surface density



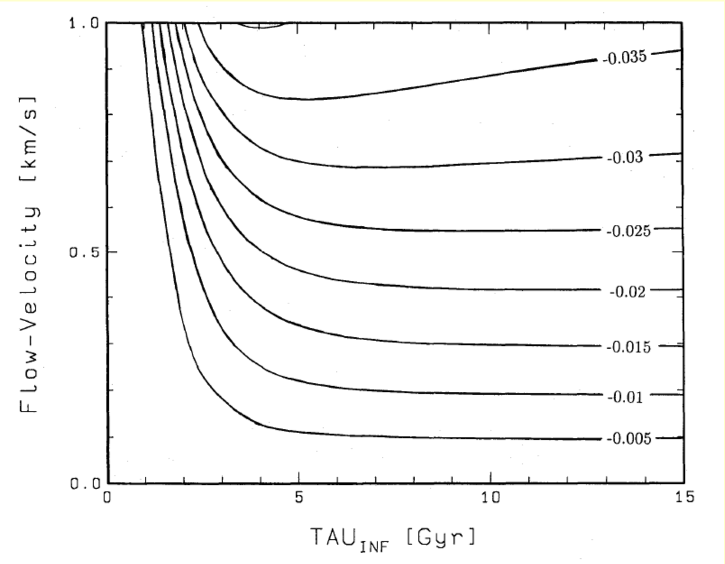
Gas metallicity

Abundance gradient

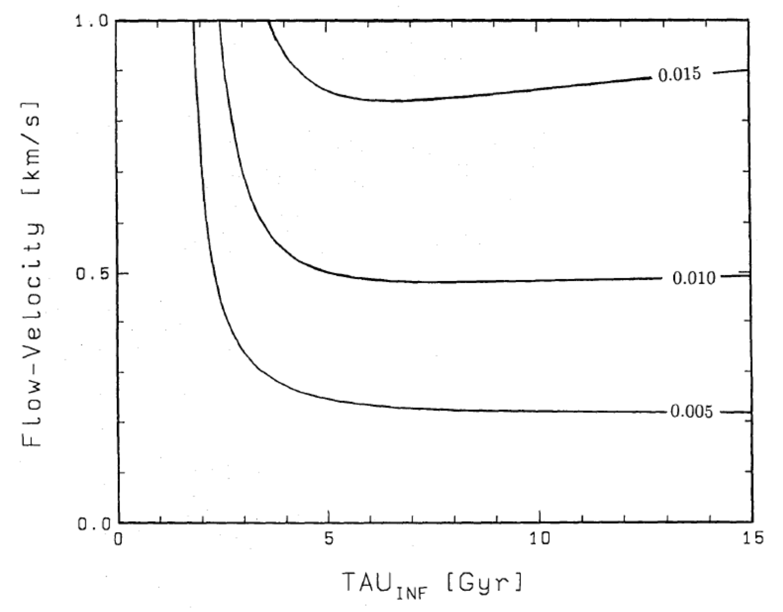


Götz & Köppen 1992

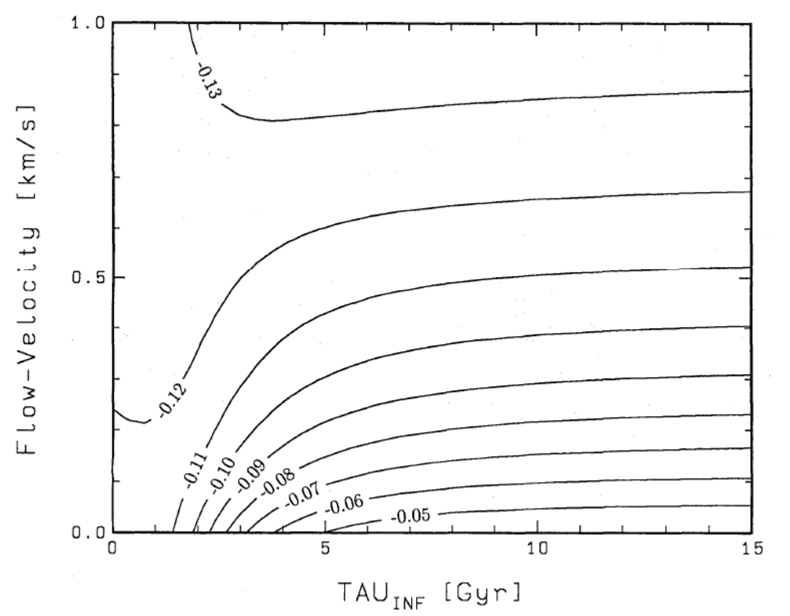
Gradient maps: boring



With gradient in radial velocity …



… and SFR gradient



Götz & Köppen 1992

Let’s look at the equation (IRA)

surface densities:

$$\frac{\partial g}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvg) = -\alpha(r)\Psi(r,t) + f(r,t)$$

accretion

$$\frac{\partial z}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(rvz) = -\,\alpha(r)Z(r,t)\Psi(r,t) + \alpha(r)y(r)\Psi(r,t) \;+ Z^{f}(r)f(r,t)$$

With $z = Zg$ one gets

$$\frac{\partial \ln Z}{\partial t} = \frac{1}{Zg}\frac{\partial z}{\partial t} - \frac{1}{g}\frac{\partial g}{\partial t} = \frac{\alpha y \Psi}{gZ} - (1 - \frac{Z^{f}}{Z})\frac{f}{g} - v\frac{\partial \ln Z}{\partial r}$$

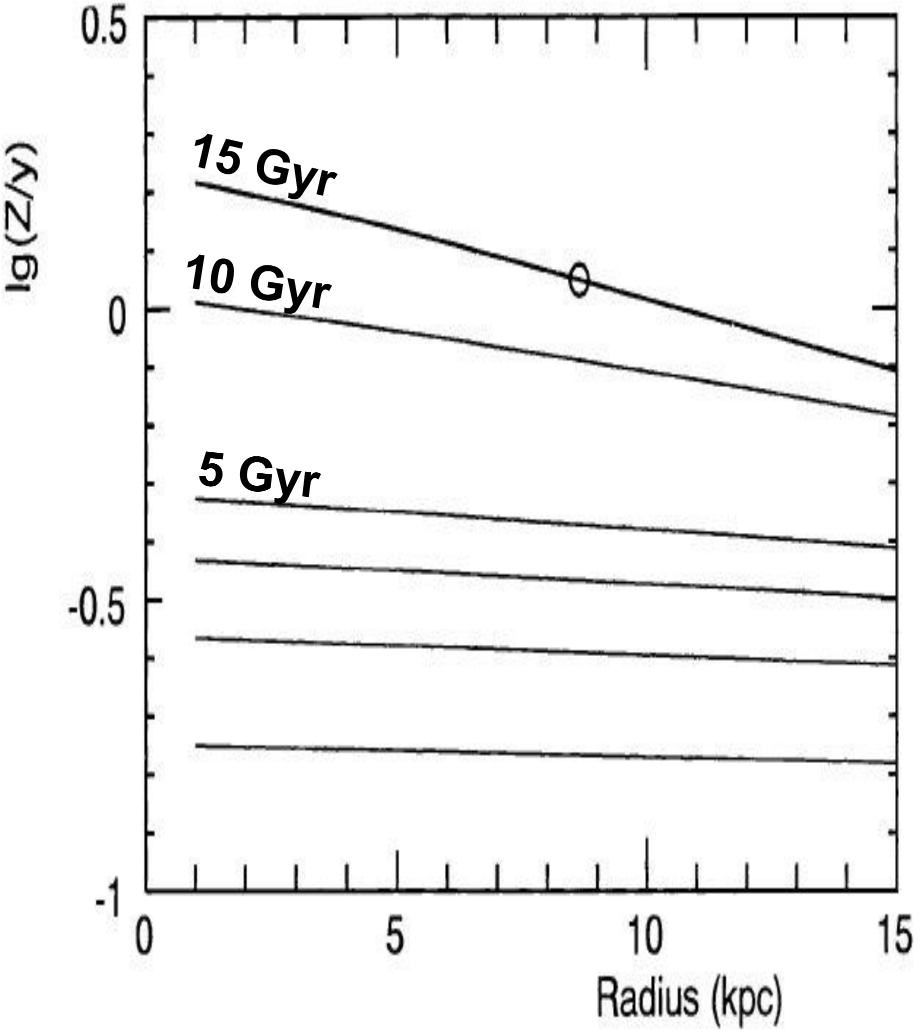
for continuously differentiable functions we have:

$$\frac{\partial}{\partial t}\left(\frac{\partial \ln Z}{\partial r}\right) = \frac{\partial}{\partial r}\left(\frac{\partial \ln Z}{\partial t}\right)$$

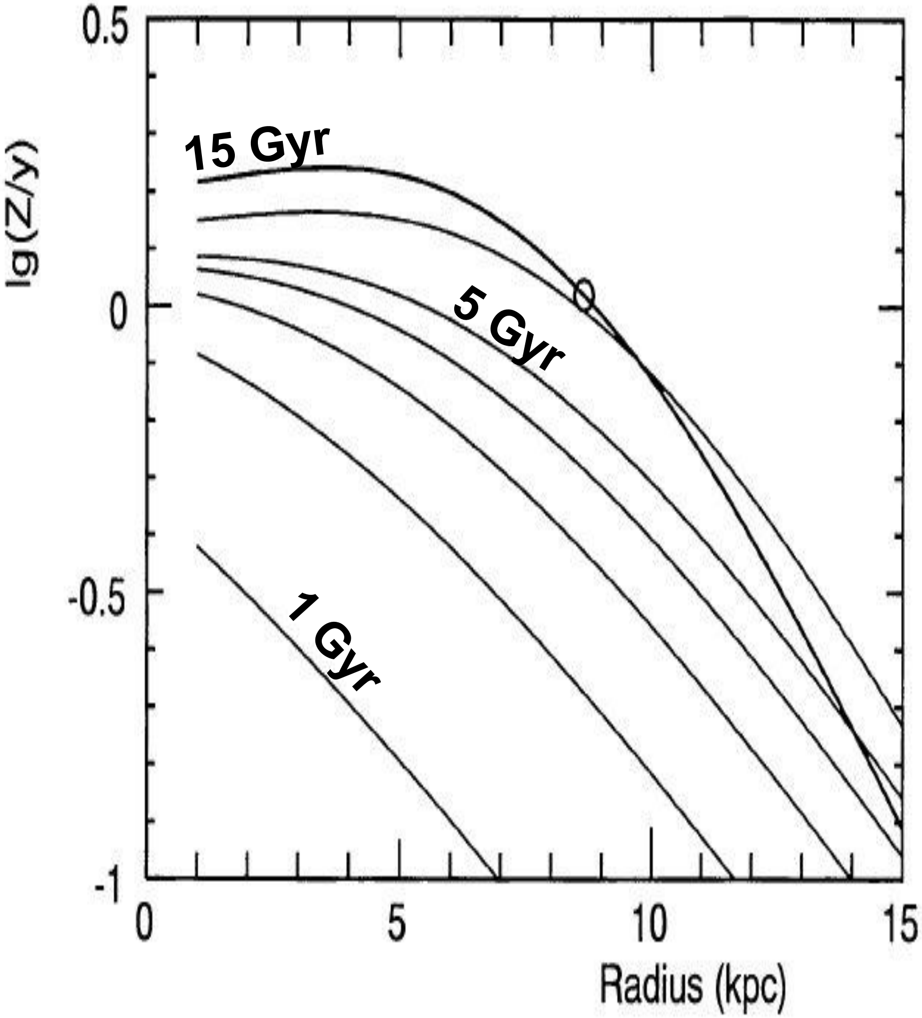
Time evolution of the gradient:	gradients grow by
$\frac{\partial}{\partial t}\left(\frac{\partial \ln Z}{\partial r}\right) = + \frac{\alpha y \Psi}{g Z} \frac{d \ln(\alpha y)}{d r}$	**yield,IMF gradient**
$+ \frac{\alpha y \Psi}{g Z} \frac{\partial \ln \enclose{circle}{(\Psi / g)}}{\partial r}$	**nonlinear SFR, SFR gradient**
$- \frac{f}{g} \frac{\partial \ln(f/g)}{\partial r}$	**accretion rate gradient**
$+ \frac{\partial}{\partial r}\left(\frac{Z^f f}{Z g}\right)$	**accretion metallicity gradient**
$- \frac{dv}{dr} \enclose{circle}{\frac{\partial \ln Z}{\partial r}} - v \enclose{circle}{\frac{\partial^2 \ln Z}{\partial r^2}}$	**radial outflows, if dZ/dr ≠ 0**
$\enclose{circle}{-} \frac{\alpha y \Psi}{g Z} \frac{\partial \ln Z}{\partial r}$	**gradients flatten themselves**

Götz & Köppen 1992

linear SFR:



quadratic SFR:



http://astro.u-strasbg.fr/~koppen/galdisk/Galdisk.html

Gradient evolution: summary

- Initial gradient by yield gradient, non-linear SFR, infall gradient:

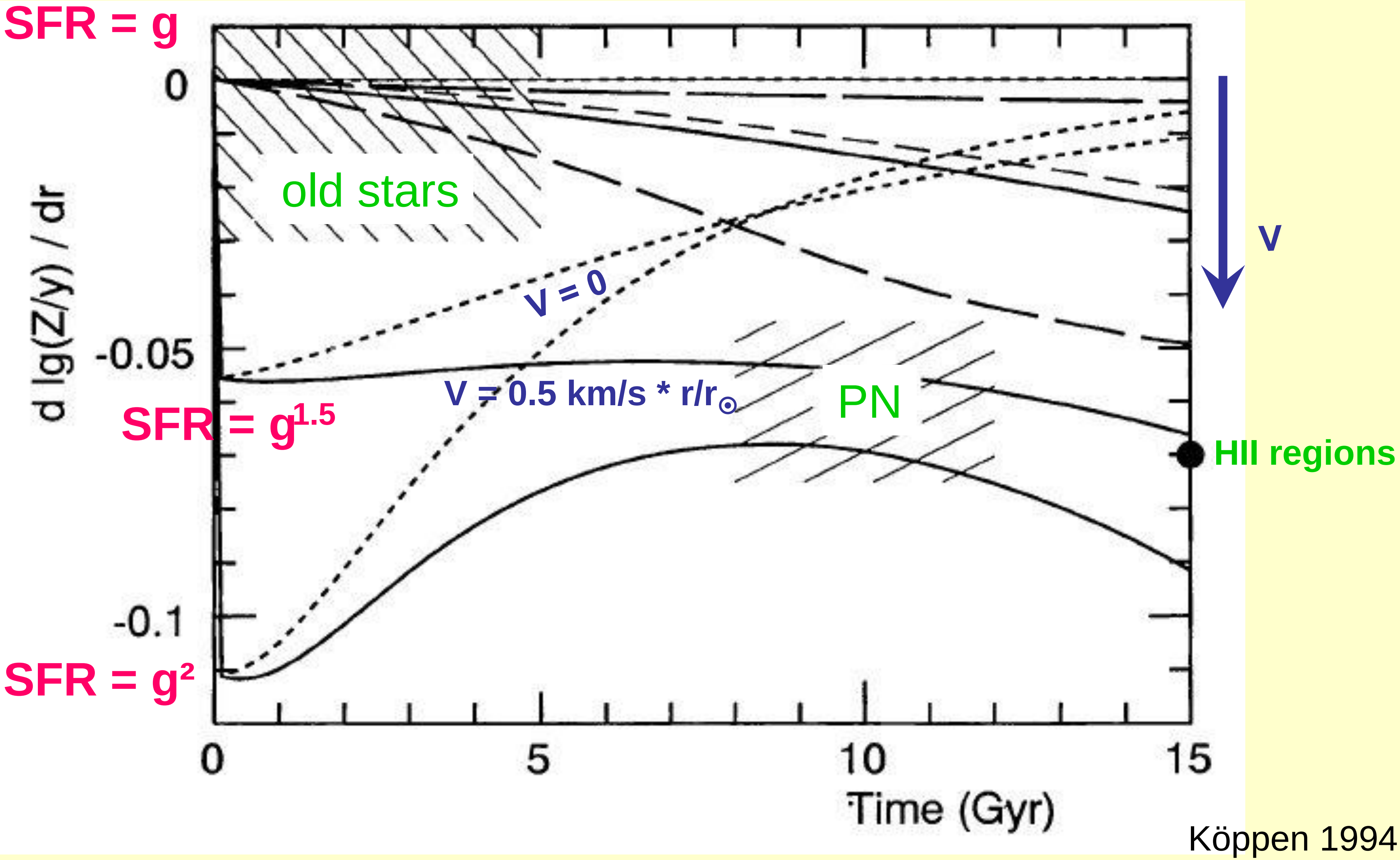
$$d \ln Z / dr = d \ln(\alpha\, y\, \Psi / g)/dr$$

$$\{\Psi = g^n \Rightarrow d \log Z/dr = -0.4343 * (n-1)/r_\odot\}$$

- Infall and radial flows can modify gradient in <u>any</u> direction

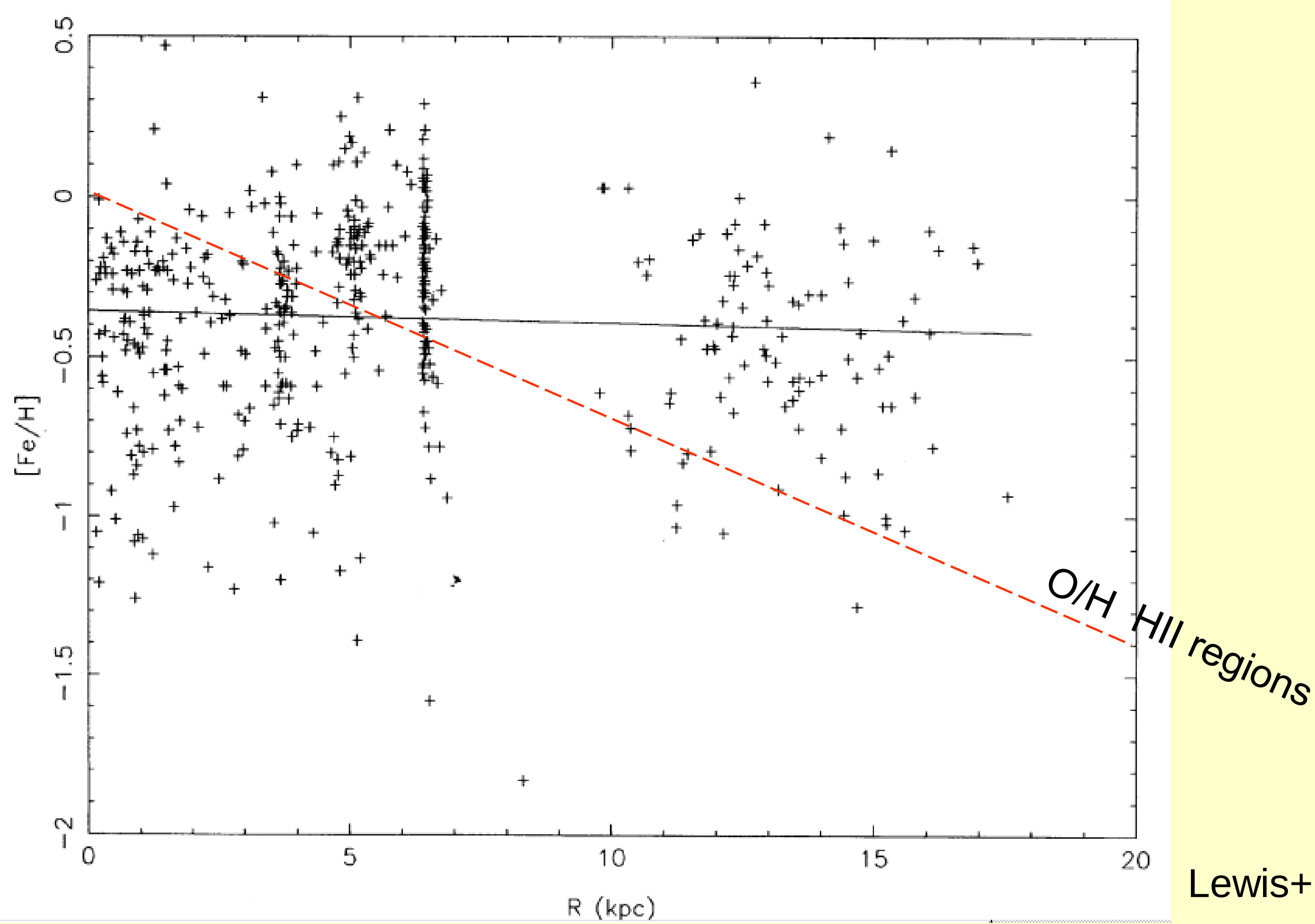
- Radial flows alone cannot make a gradient

Time evolution of gradients



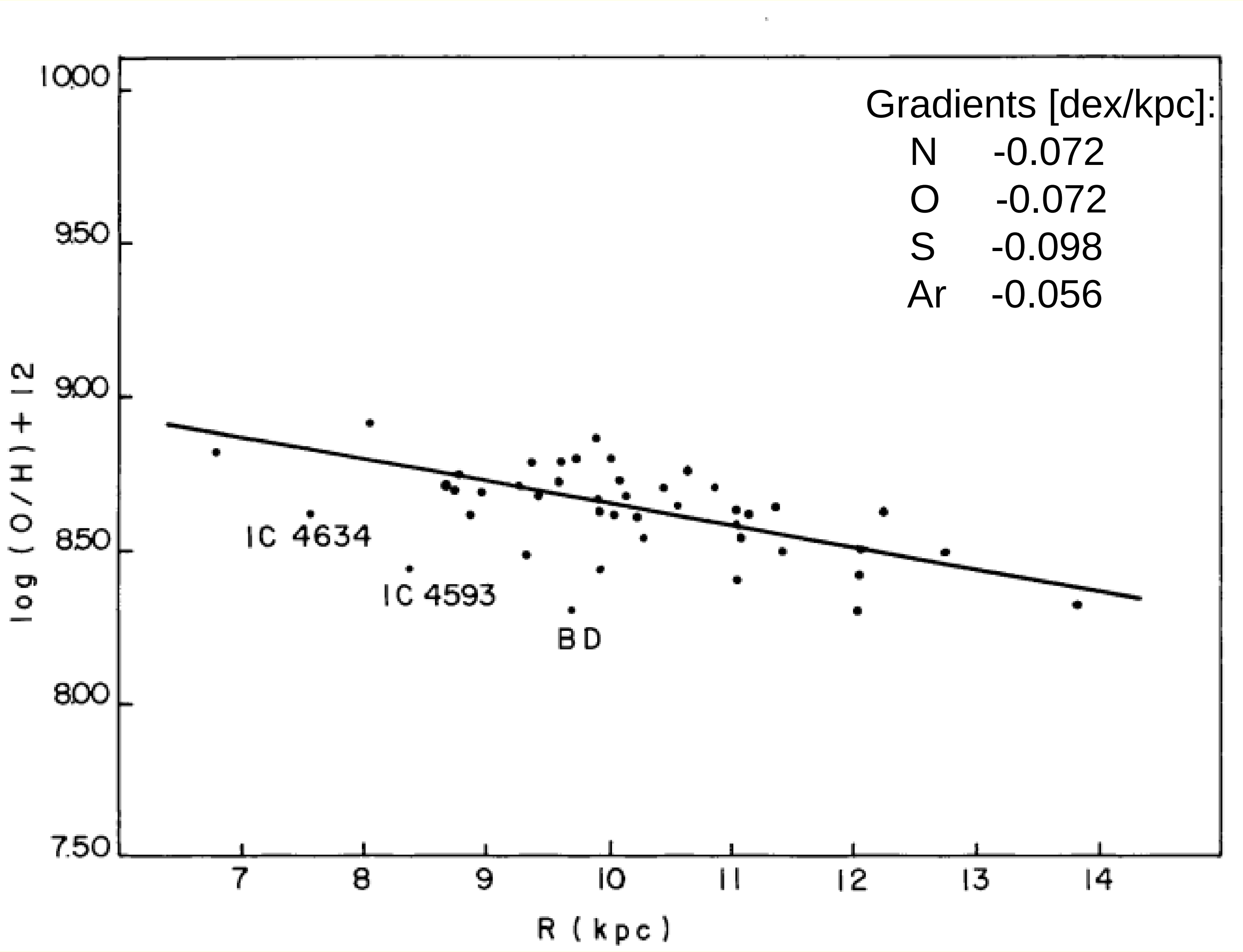
Köppen 1994

600 old K giants: ‘no sign.slope’



Lewis+Freeman 1989

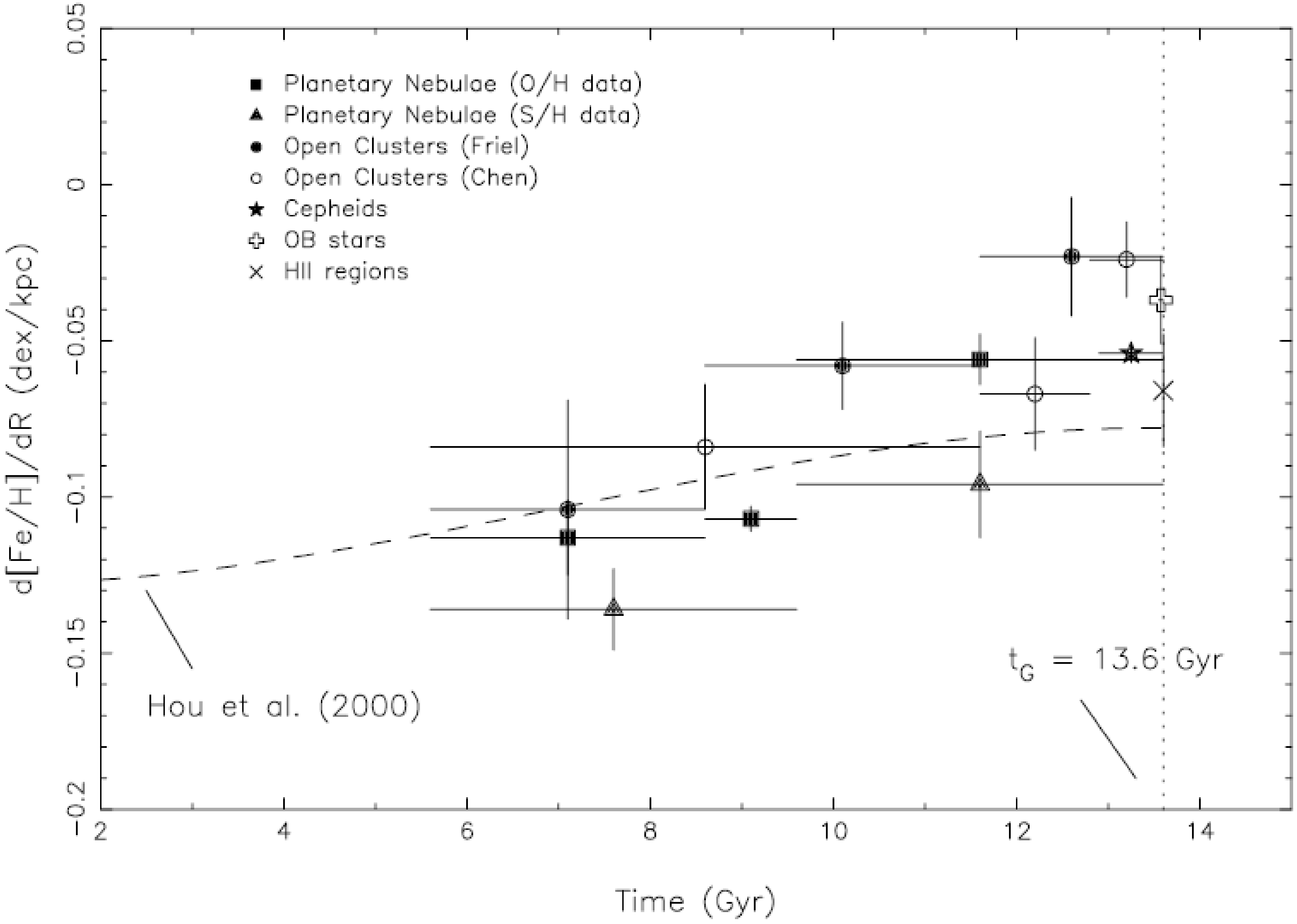
Disk Planetary Nebulae



Gradients [dex/kpc]:

N	-0.072
O	-0.072
S	-0.098
Ar	-0.056

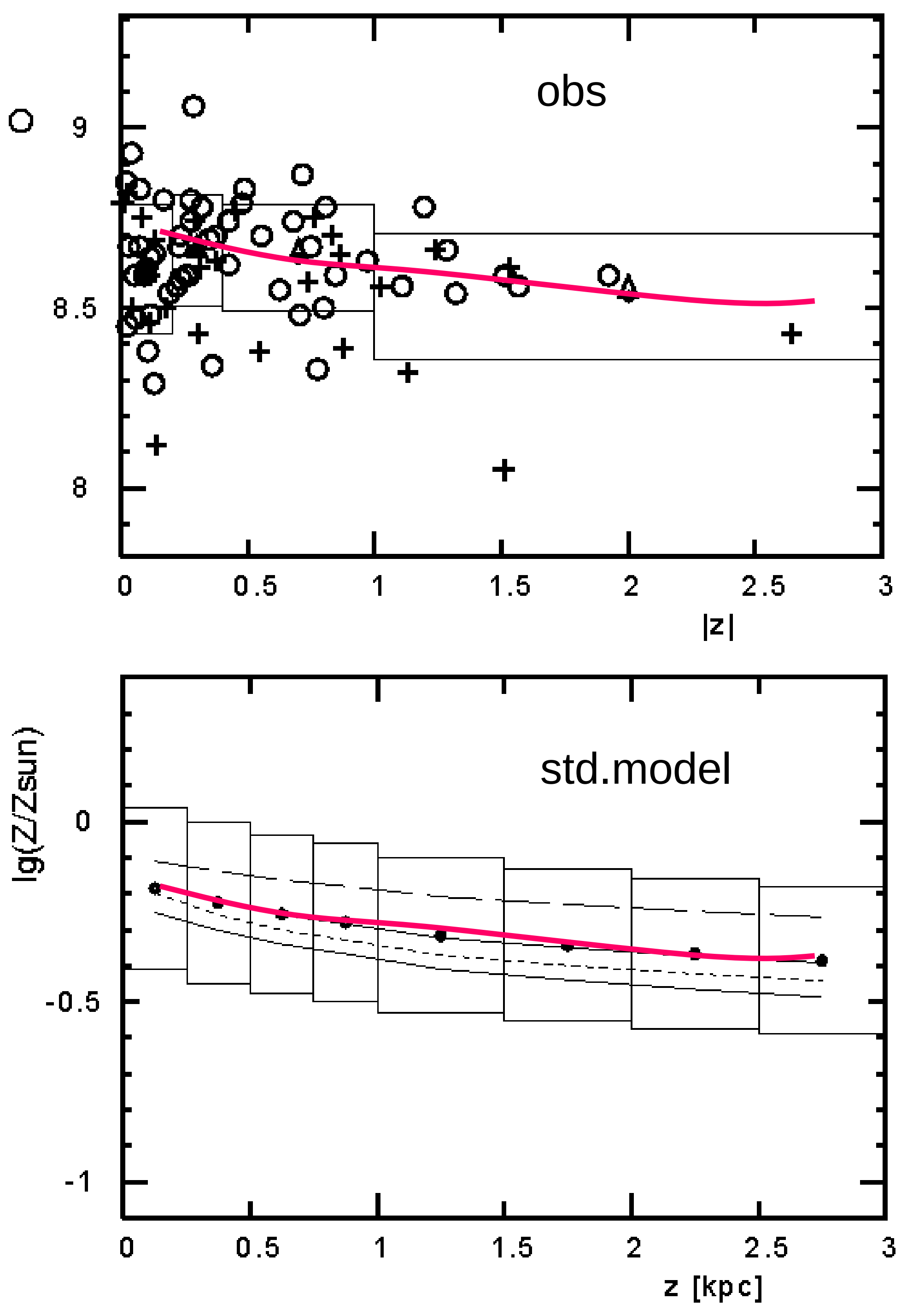
Faundez-Abans+Maciel 1986



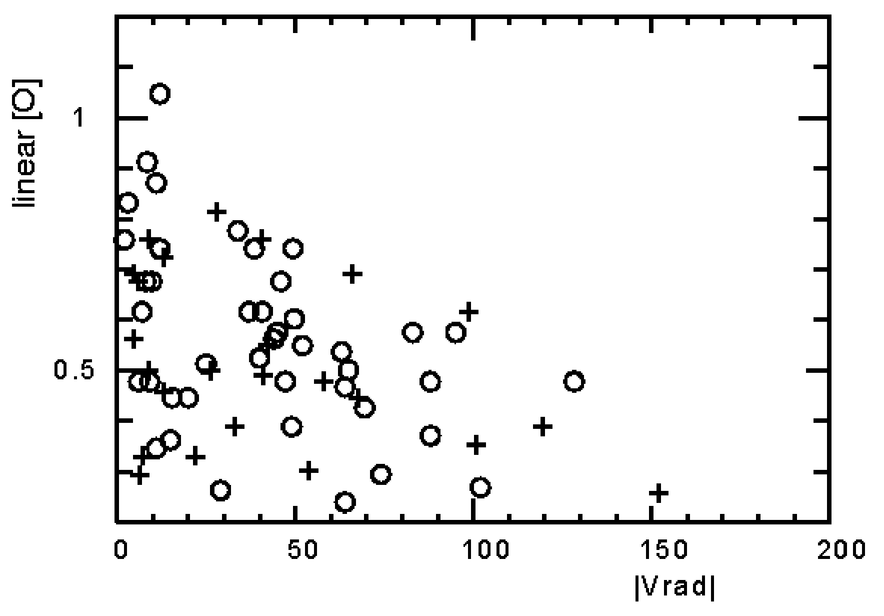
Maciel et al. 2005

Vertical ‘gradients’

- General idea: old stars have higher vertical velocity dispersions (kinematical heating?) and thus larger mean heights above plane
- Observations with PN show tendency for O/H to decrease with height above plane (Cuisinier et al. 1997) in agreement with expectations from ‘standard’ model of kinematical heating of the disk and radial diffusion of stars



… but also:



Cuisinier et al. 1997

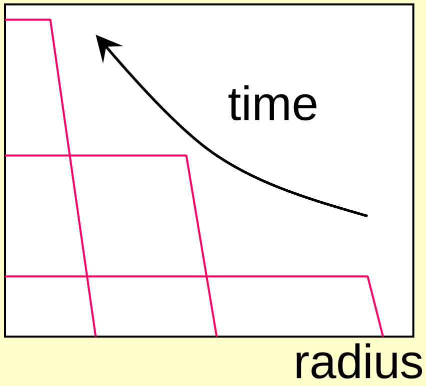
Gradients in spheroidal systems

Observed: Radial colour (=metallicity) gradients
    Detailed character varies widely

Interest: monolithic collapse (more later)

➔ Lynden-Bell’s concentration model

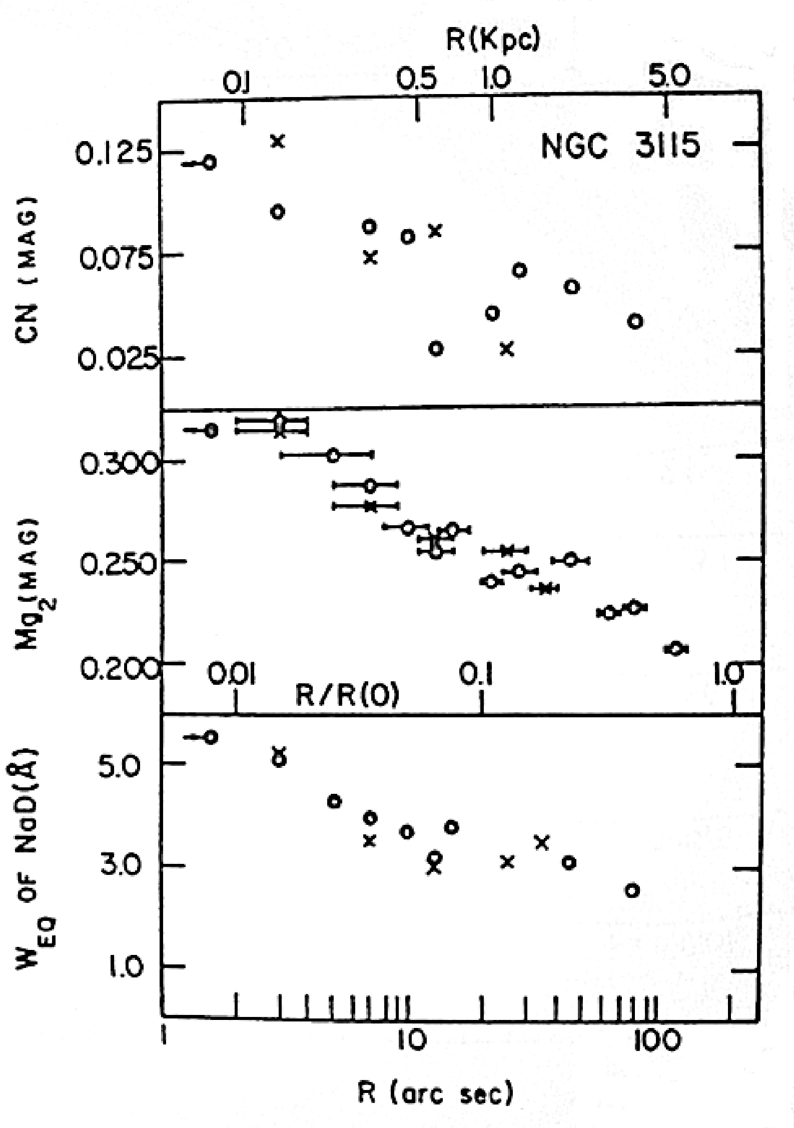
➔ does it work?

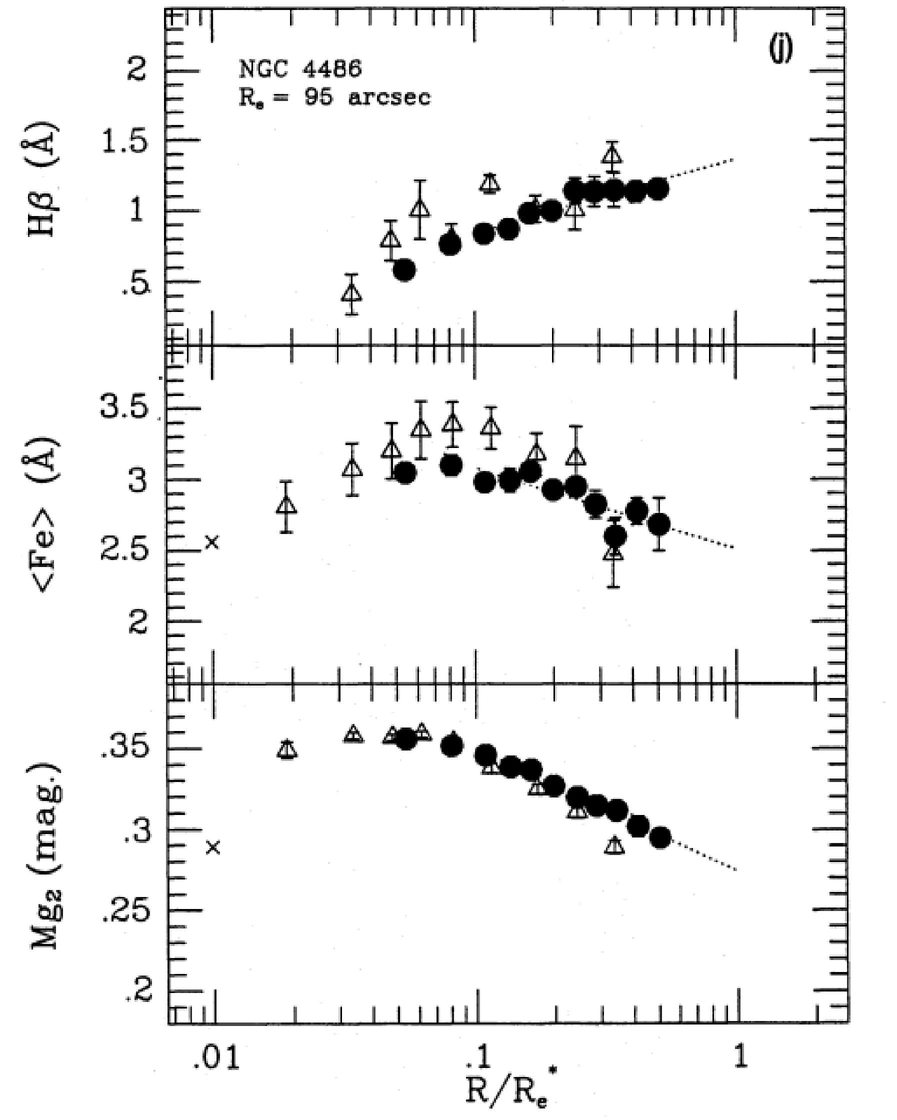


Difficulties

- deprojection
  - assume geometry
  - not possible for individual objects ➔ large data sets
- stars: mixture of ages

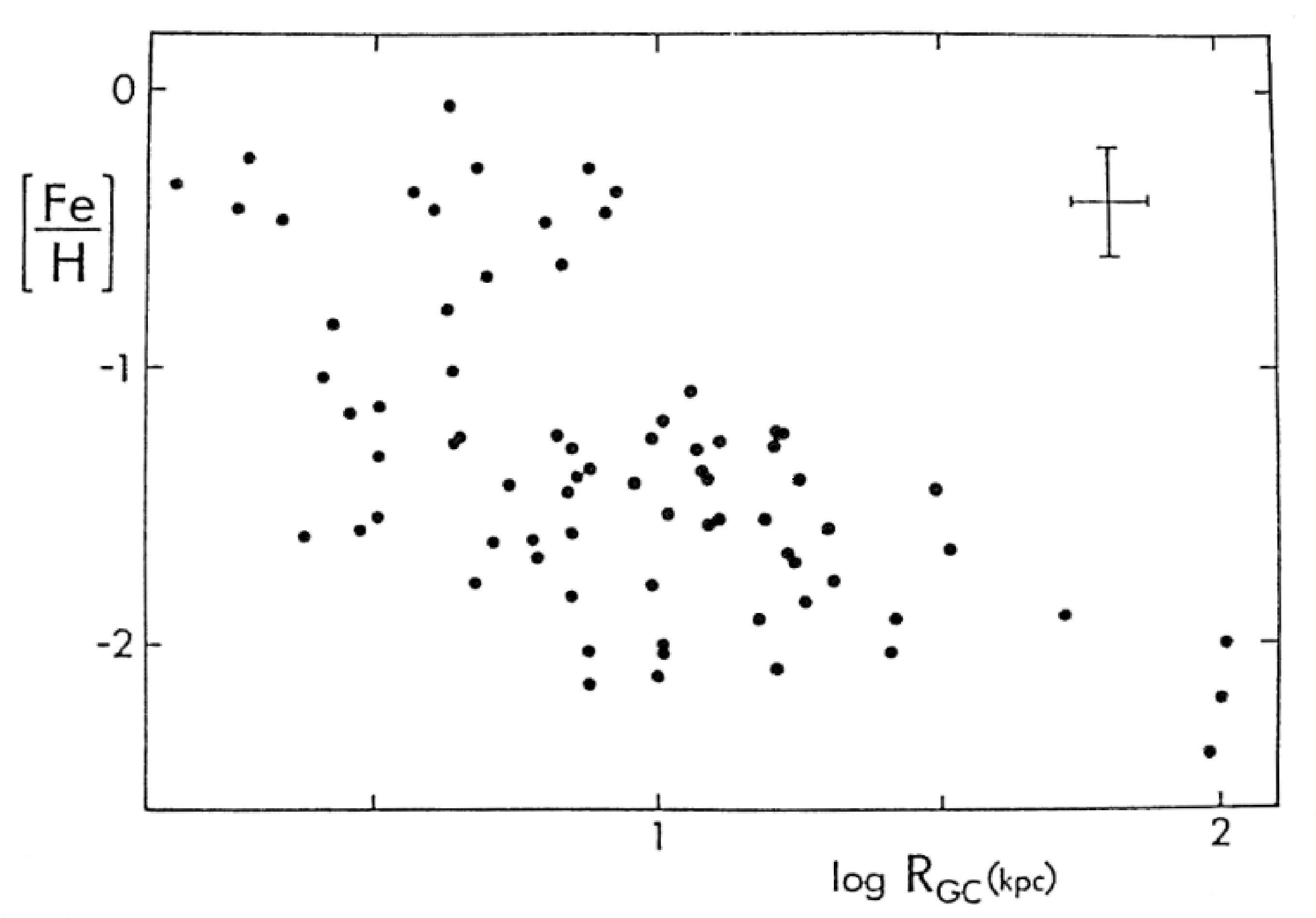
Gradients of photometric indices in Ellipticals



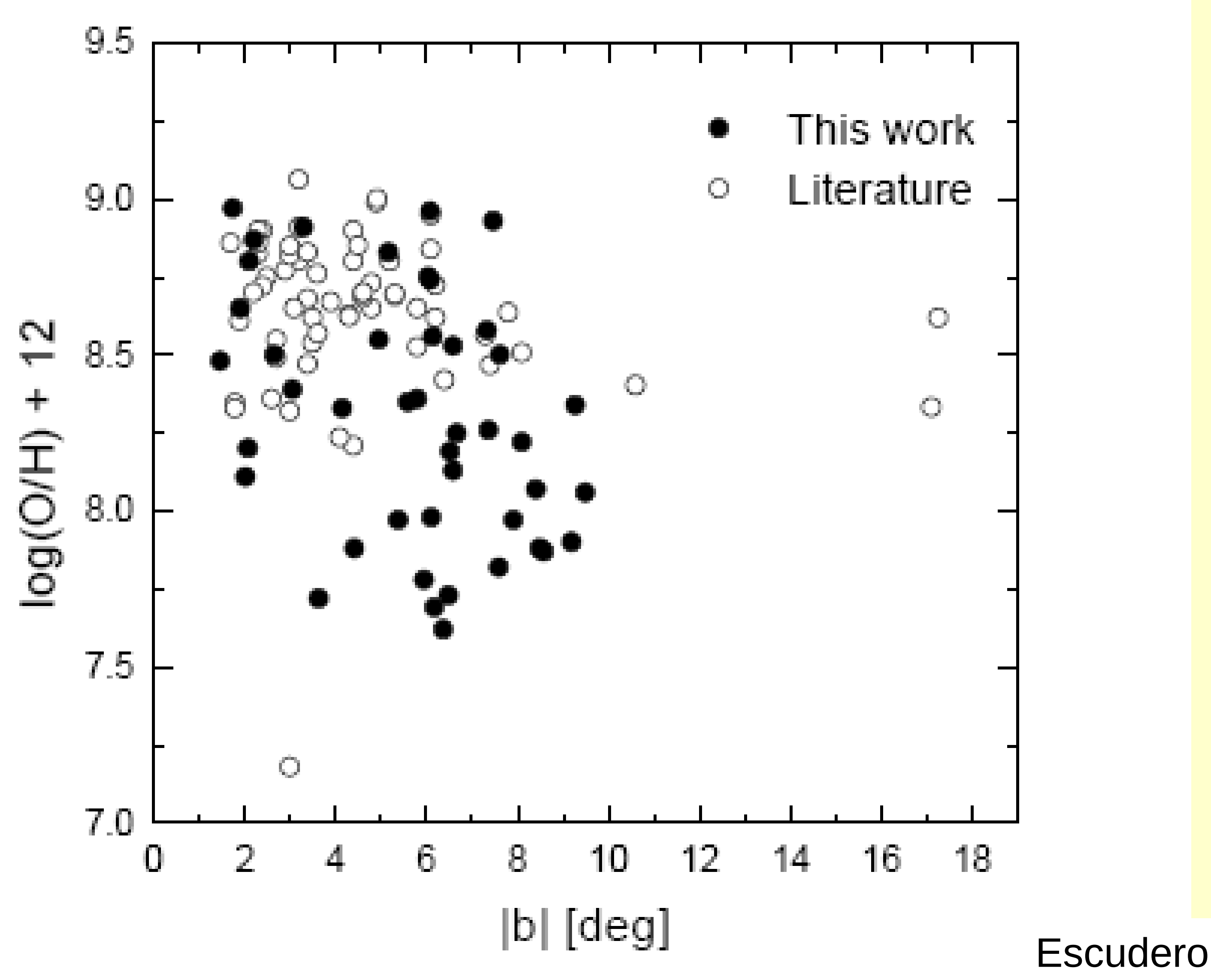


Davies 1993

Galactic Globular Cluster System



Galactic Bulge with PN

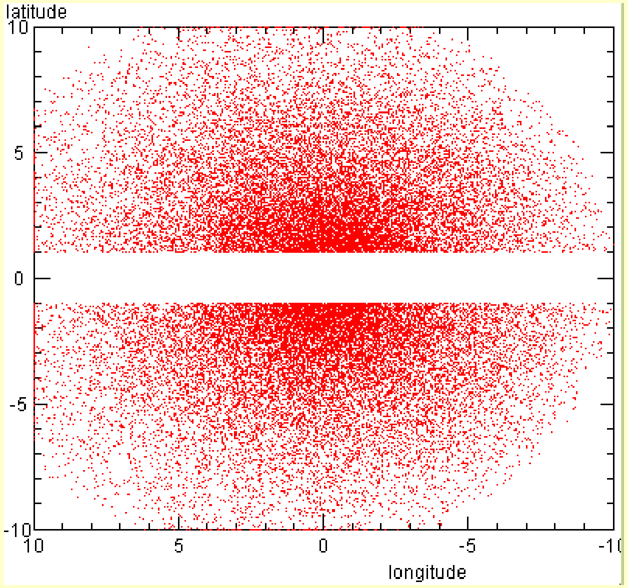


Gradient?

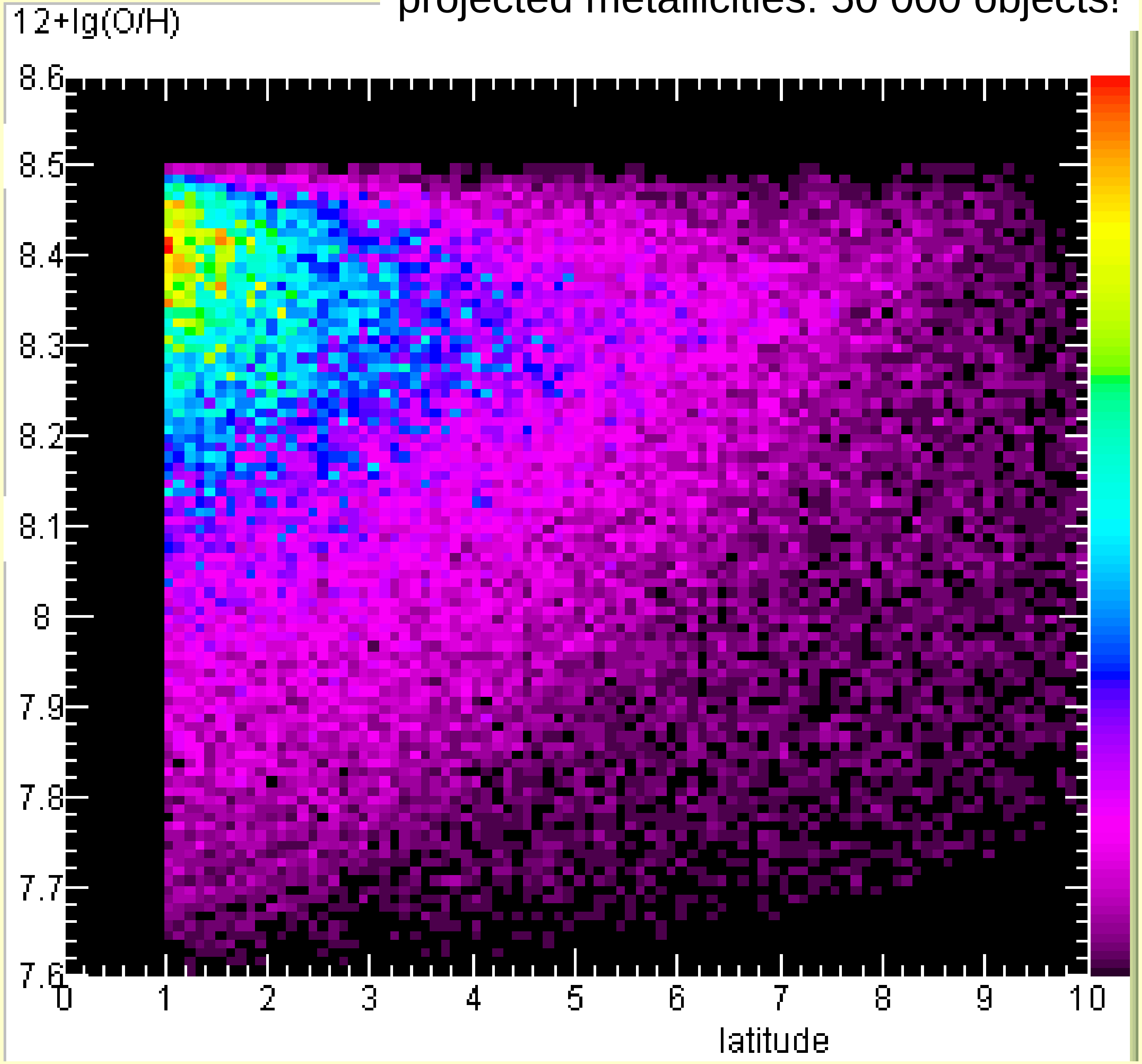
Escudero, Costa, Maciel 2004

… but it’s tough!

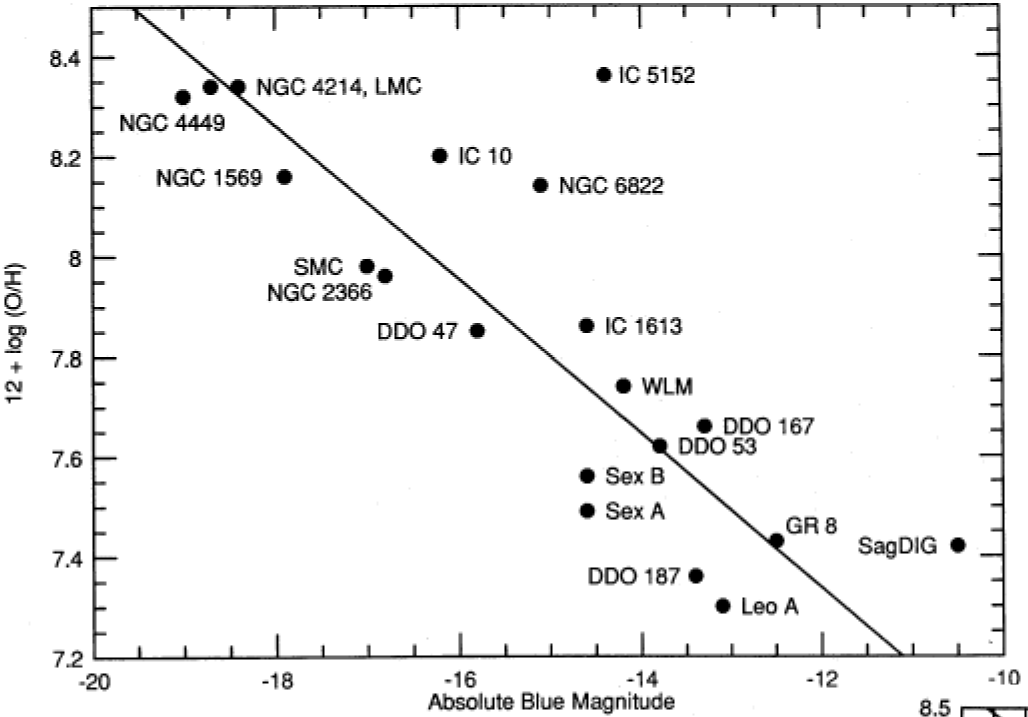
Simulation: assume
- spheroidal bulge
- radial abundance gradient



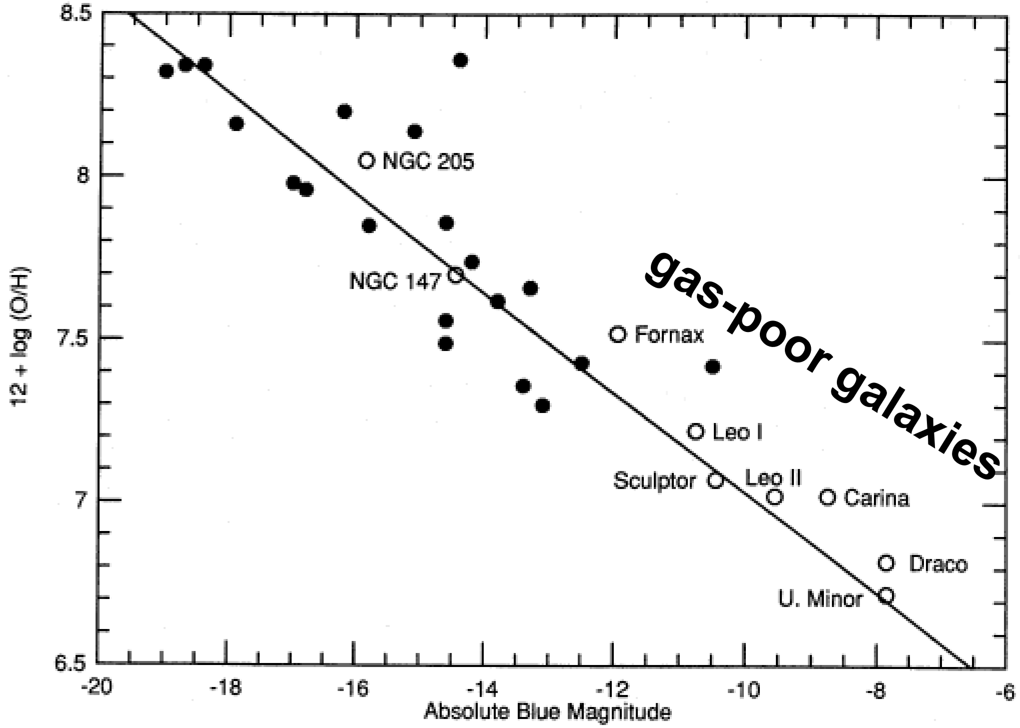
projected metallicities: 50 000 objects!



Mass-Metallicity Relation in galaxies



gas-rich galaxies

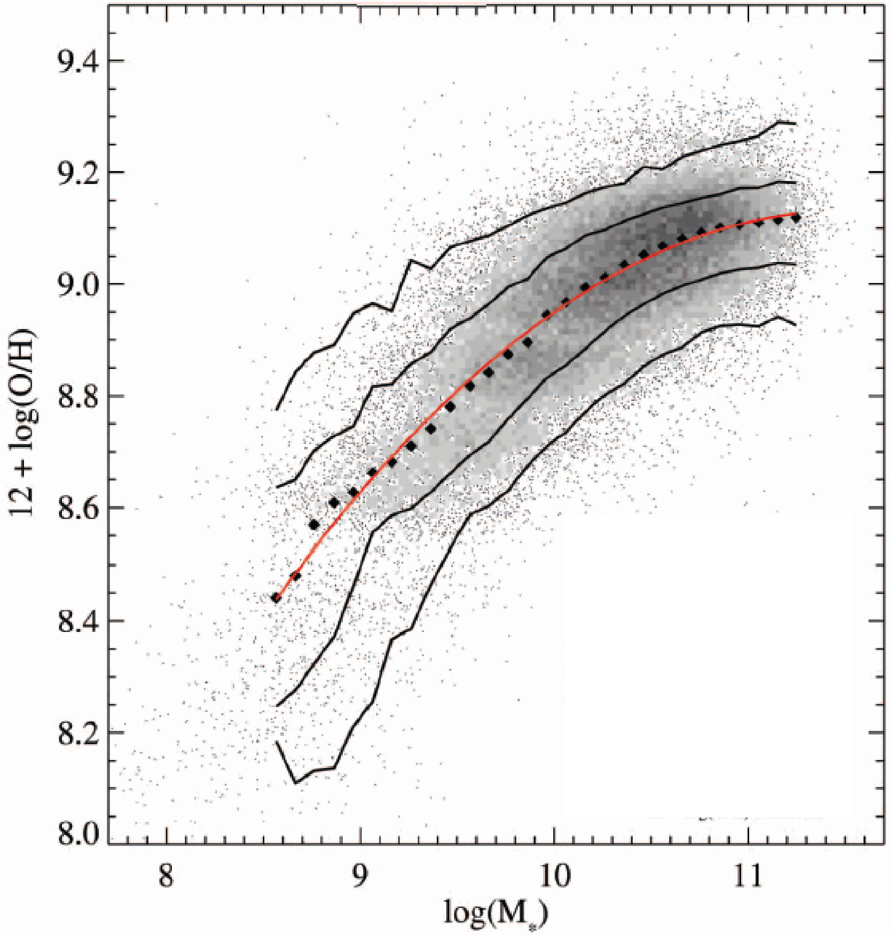


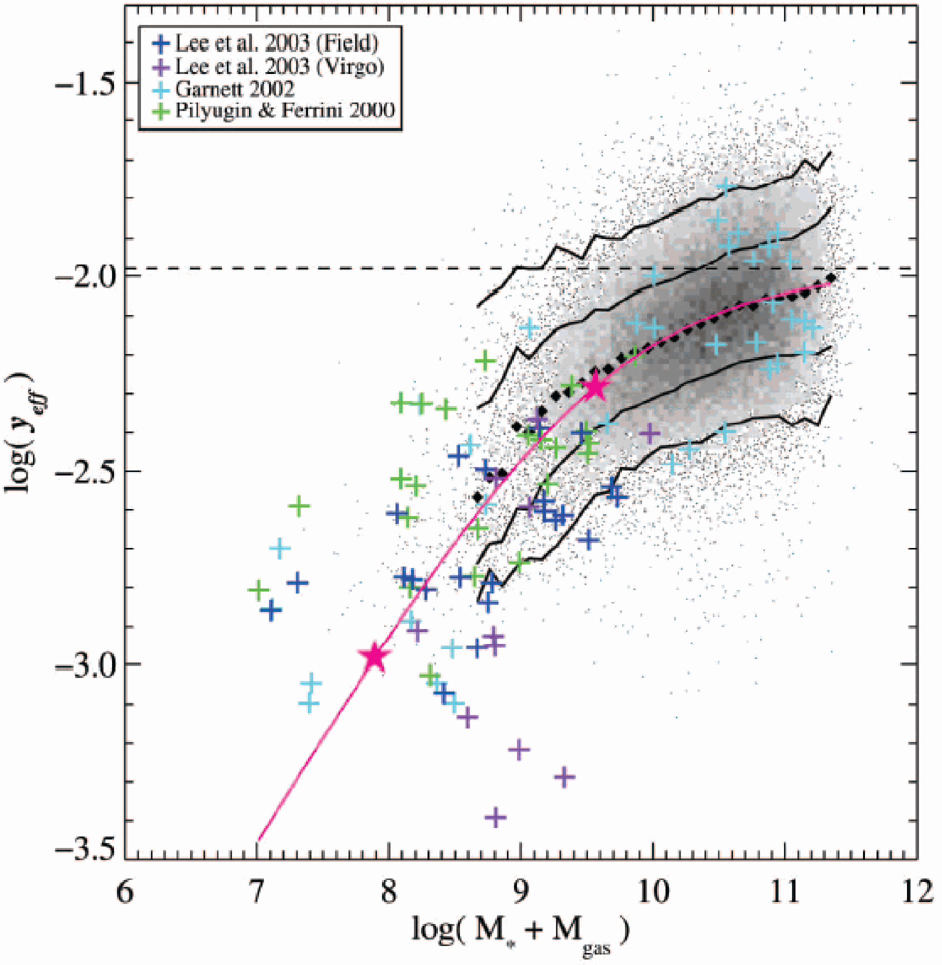
gas-poor galaxies

Skillman, Kennicutt, Hodge 1989

SDSS data

53 000 galaxies





Tremonti et al. 2004

Origins of Mass-Metallicity Relation

Less massive galaxies

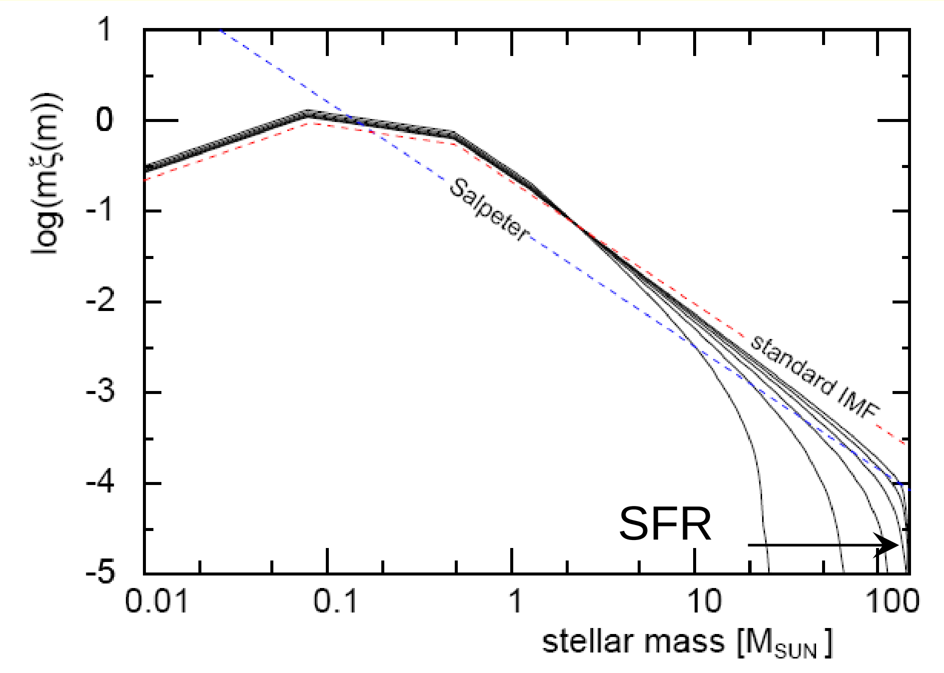
- are chemically less evolved (i.e. higher gas fractions)
  - have lower SFR
  - have shorter lifetime (or time of essential SF)
- have lower (effective) yields
  - cannot keep all their metals in gravitational well:

$$y_{\rm eff} = \frac{y_0}{1 + \left(M_0/M_{\rm baryon}\right)^{0.57}}$$

Tremonti et al. 2004

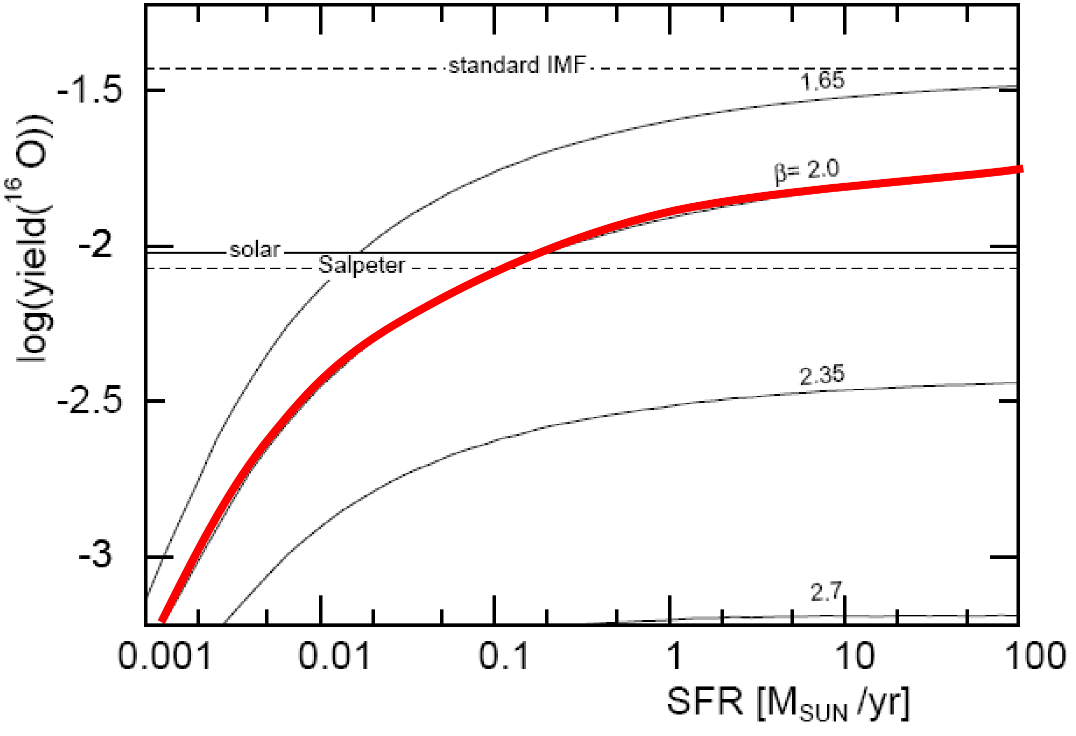
  - IMF has fewer massive stars in low-SFR environments

Variable IMF:



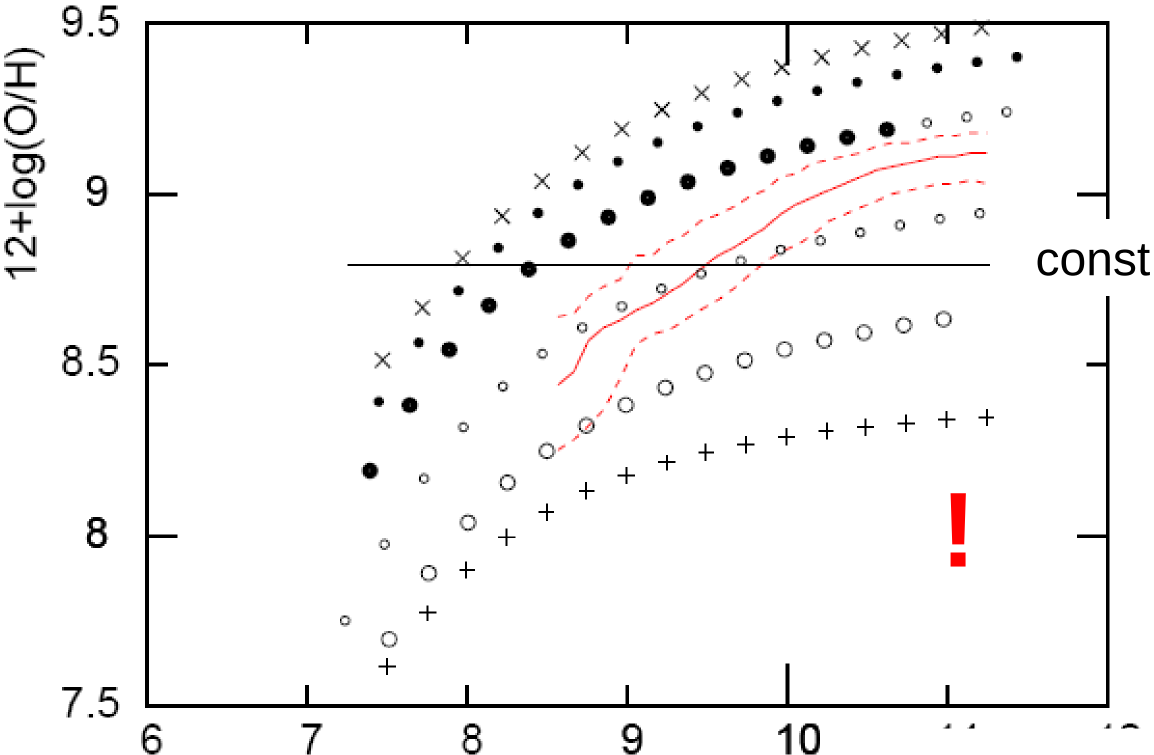
In a high-SFR environment,
the newly formed star cluster
contains a larger fraction
of massive stars

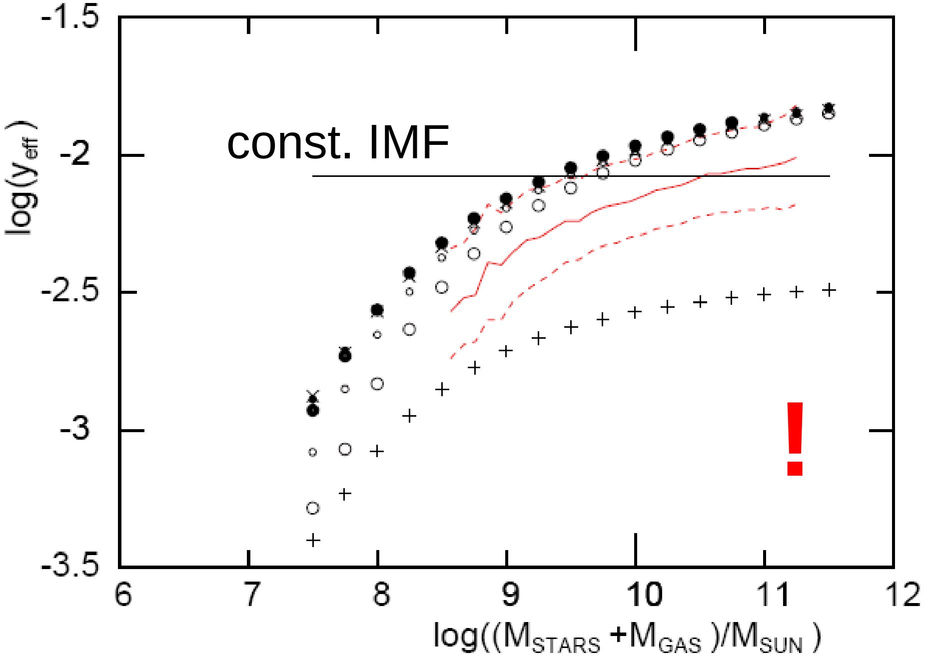
Weidner & Kroupa 2004ff



Köppen, Weidner, Kroupa 2007

Just a closed box model





Köppen, Weidner, Kroupa 2007