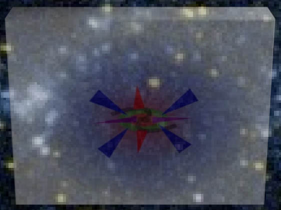
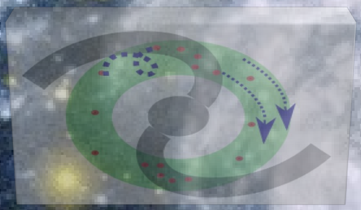
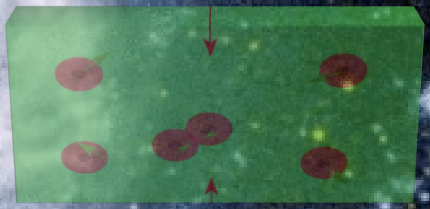
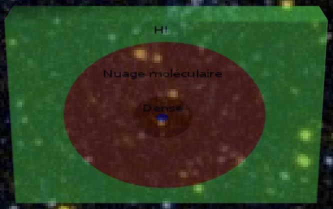
Physics of galaxies: some basis

I: Galactic (Chemical) Evolution; introduction, examples, abundance measurements, definitions, IMF, SFR, returned fraction.

II: Star Formation Laws; threshold, resolution effects, star formation laws, state of the art of observations, gas measurements.

III: Outskirts of galaxies: truncations, anti-truncations, XUV disks, HI,...

GALACTIC CHEMICAL EVOLUTION

a) Introduction

b) Measuring Abundances

c) Formalism of Galactic
Chemical Evolution

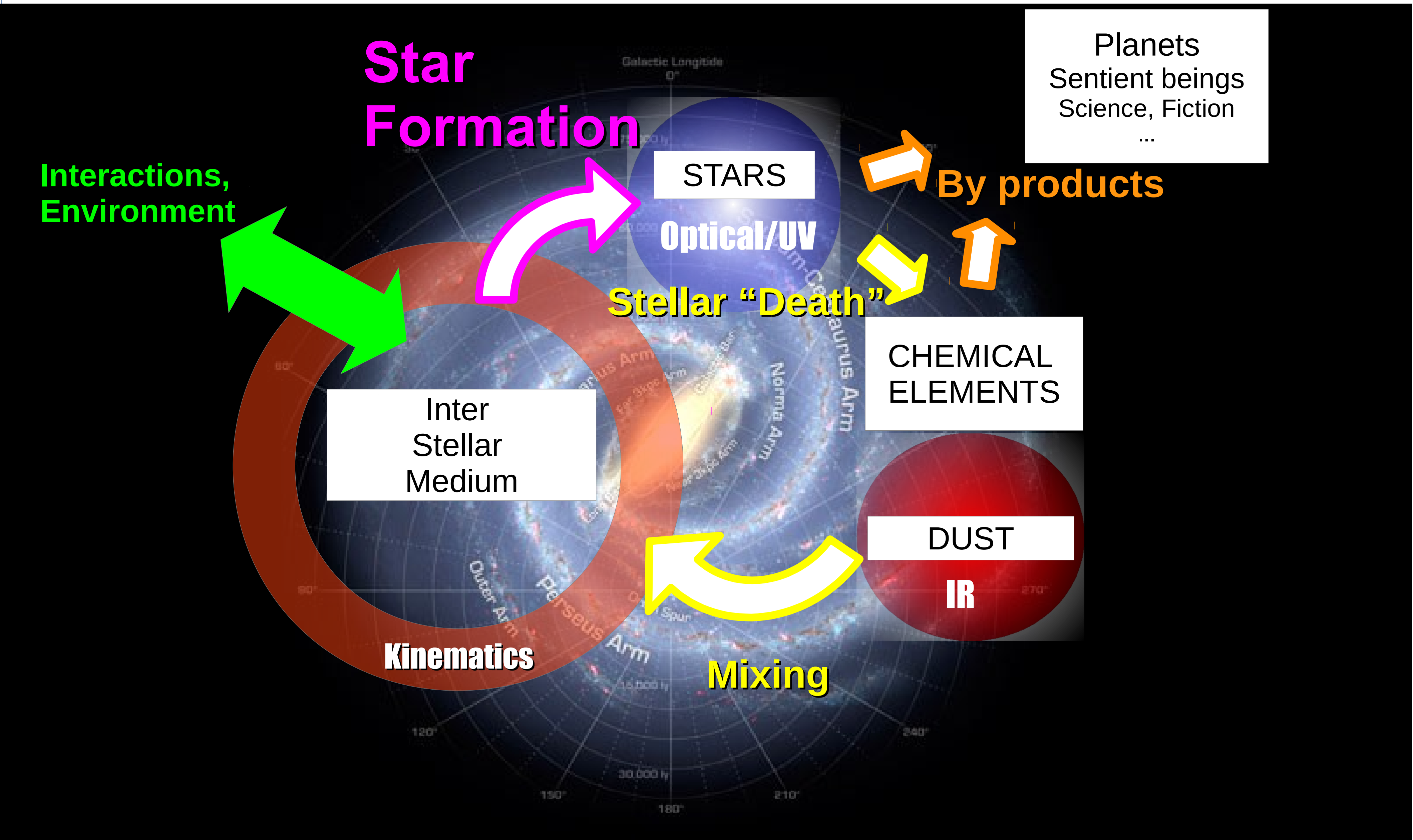
d) The "stellar" ingredients :
Yields, IMF, Lifetimes

e) The "galactic" ingredients

GALACTIC CHEMICAL EVOLUTION

a) Introduction

The cycle of transformation within galaxies



An abundance of notations

- **X = mass fraction**
  - X_i for element i
  - X for Hydrogen
  - Y for Helium
  - Z for all "metals"
  - X+Y+Z=1

    (Solar -Asplund et al. 2009)
  - X=0.7154,

    Y=0.2703,

    Z=0.0142 ~~0.02~~

- **N = Number**
  - N_i for element i

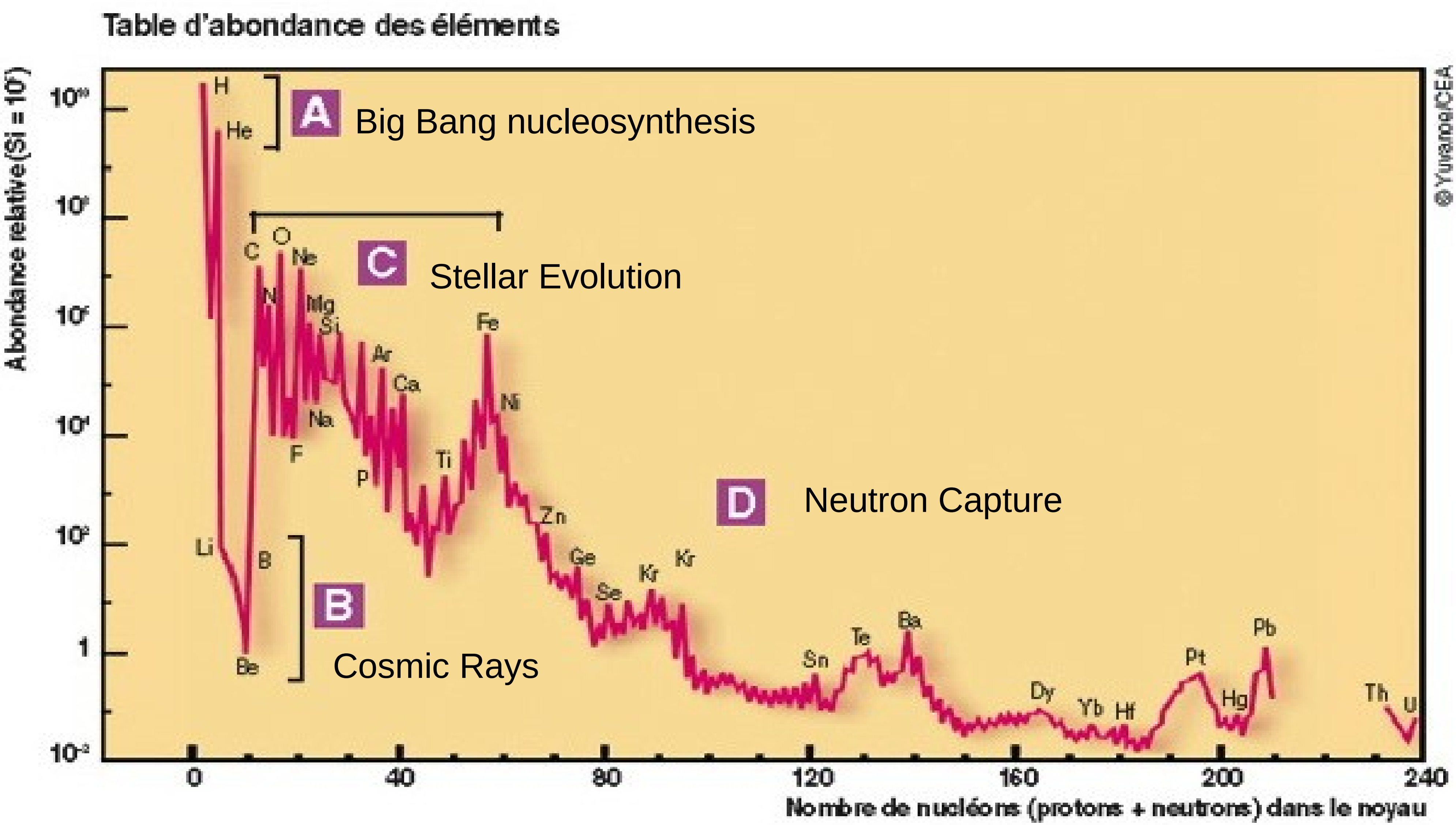
    Usually wrt a reference:

    e.g. N_O/N_H in 12+log(O/H)
- **"Relative to solar":**
  - Z / Zsun
  - $[X_i/X_j]=\log(X_i/X_j)-\log(X_i/X_j)_{sun}$
  - e.g. In the stars of the Milky Way,

    [O/Fe] is found between 0 and 1

    [Fe/H] between -5 and 0

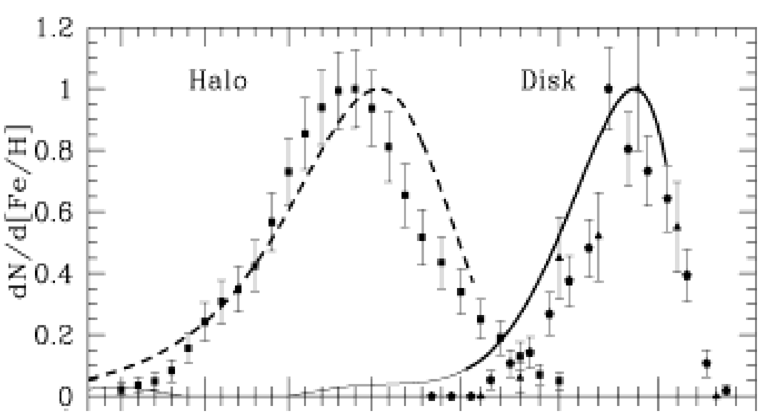
Pattern of abundance in the universe:



In the **Milky Way**:

Many constraints, especially: abundances in stars

Goswami & Prantzos 2000



202 A. Goswami & N. Prantzos: Evolution of intermediate mass elements in the Milky Way

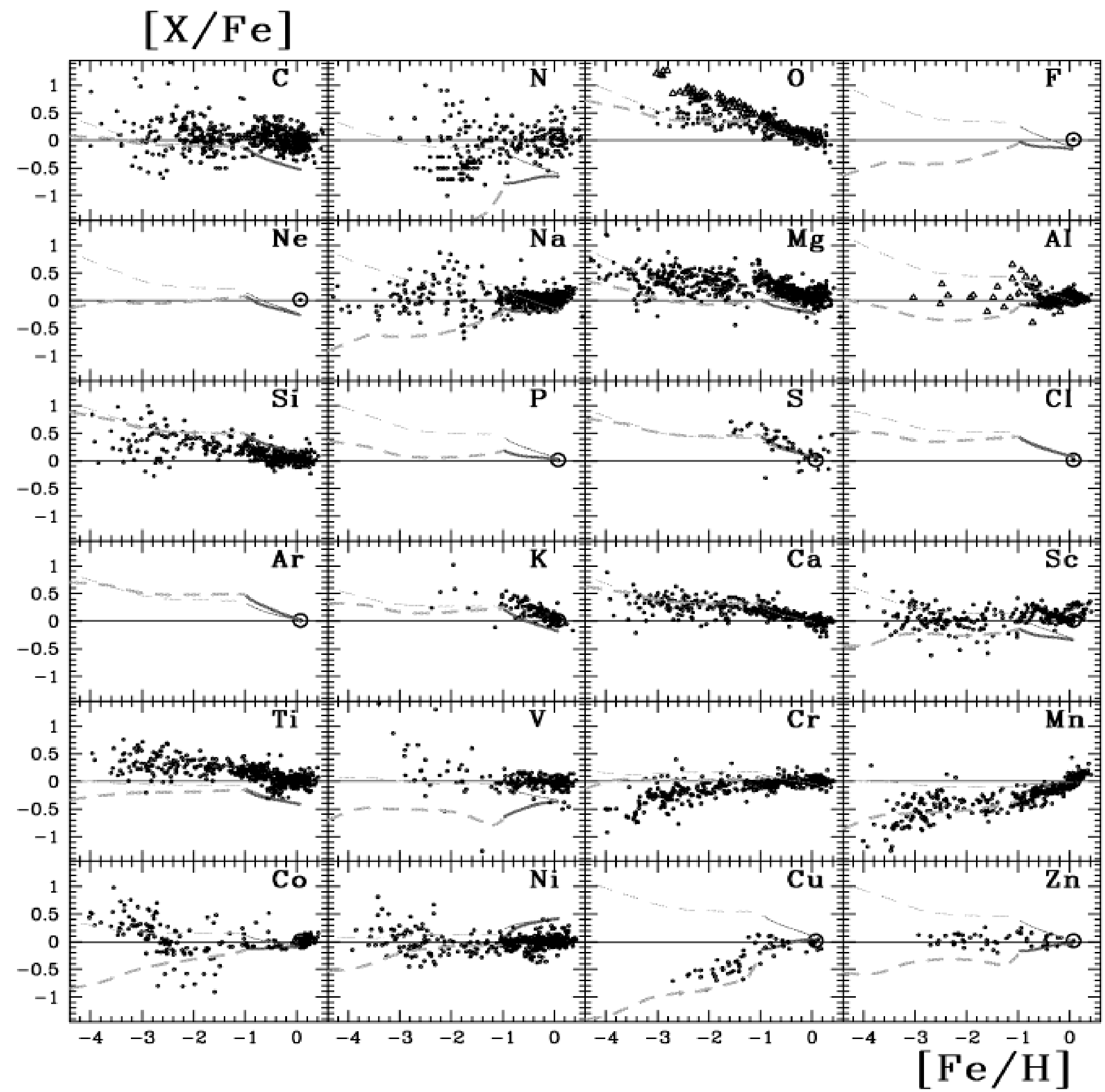
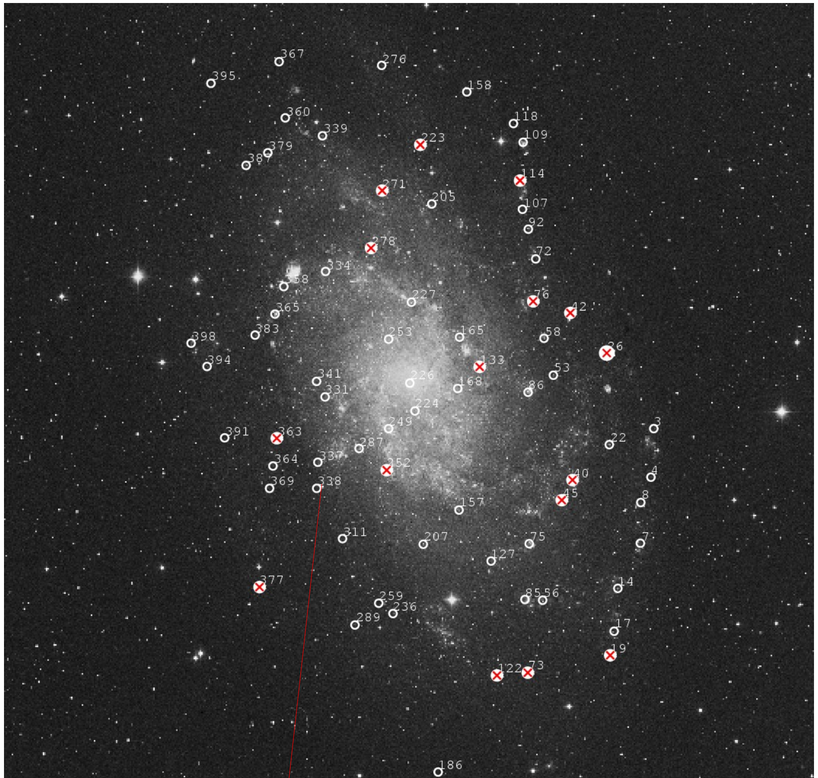


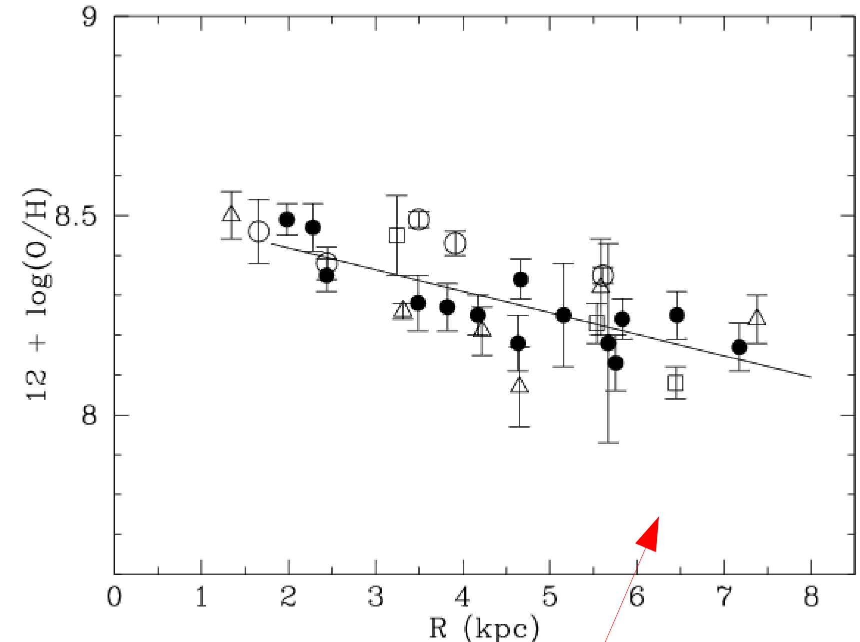
Fig. 7. Abundance ratios [X/Fe] of stars in the halo and the local disk, as a function of [Fe/H]. Theoretical results are obtained with models that treat properly the halo (*dashed curve* assuming *outflow*) and the disk (*solid curve* assuming *slow infall*). Two sets of massive star yields are used, both from WW1995: at constant (=solar) metallicity (*thin curves*, Case A, only for illustration purposes) and at variable metallicity (*thick curves*, the reference Case B). Yields of the W7 and W70 models of Iwamoto et al. (1999) for SNIa are used in both cases (properly interpolated as a function of metallicity); intermediate mass stars are not considered. It should be noted that WW1995 yields of Fe have been divided by 2, in order to obtain the observed α/Fe ratio in halo stars. Model trends below [Fe/H]=-3 are due to the finite lifetime of stars ([Fe/H]=-4 is attained at 10 Myr, corresponding to the lifetime of stars with mass $> 20 M_{\odot}$, while [Fe/H]=-3 is attained at 20 Myr, corresponding to the lifetime of $\sim 10 M_{\odot}$ stars). In view of the yield uncertainties of individual stars (Sect. 2) and of the uncertainties in the timescales at those early times of the halo evolution, those trends *should not be considered as significant*. The observed data points in the figure are taken from sources listed in Table 1. Observed abundance ratios of [O/Fe] from Israelian et al. (1998) and Boesgaard et al. (1999) are shown by *open triangles*; they suggest a trend quite different from all other alpha-elements. The *open triangles* in the [Al/Fe] panel correspond to observed data with NLTE corrections (from Baumüller & Gehren 1997)

Abundance gradients

M33



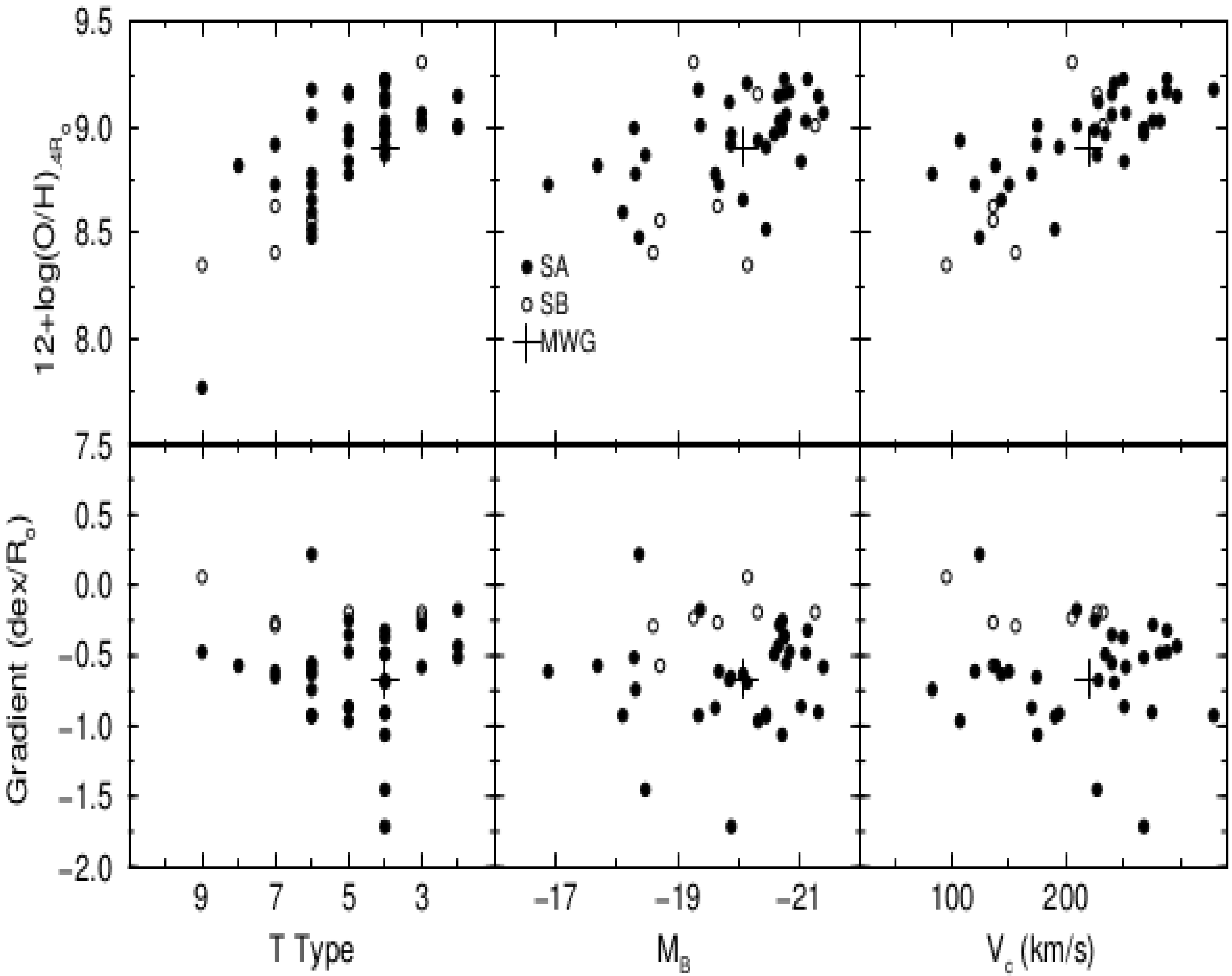
Magrini et al. 2007, A&A 470, 865-874



HII regions spectroscopy : **line emission** measurements: tracers of metallicity in the gas

Same thing can be done in many nearby galaxies
(see NED LEVEL5 NASA database for collection of abundance gradients)

Abundance gradients in the local universe



A typical metallicity (at a relative radius) varies with type, magnitude, rotational velocity or mass.

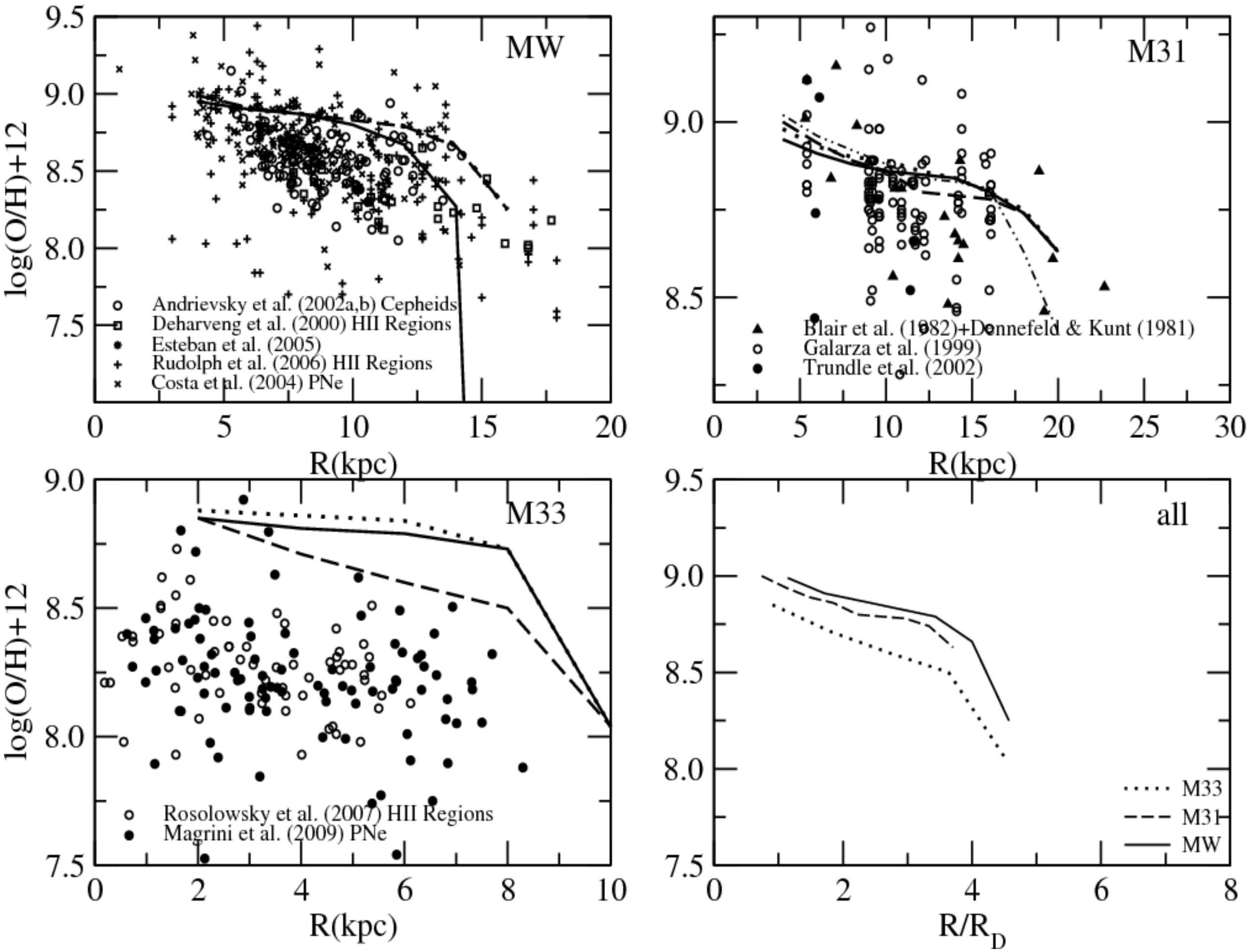
Gradients tend to have similar values when expressed in dex/scalelengh !

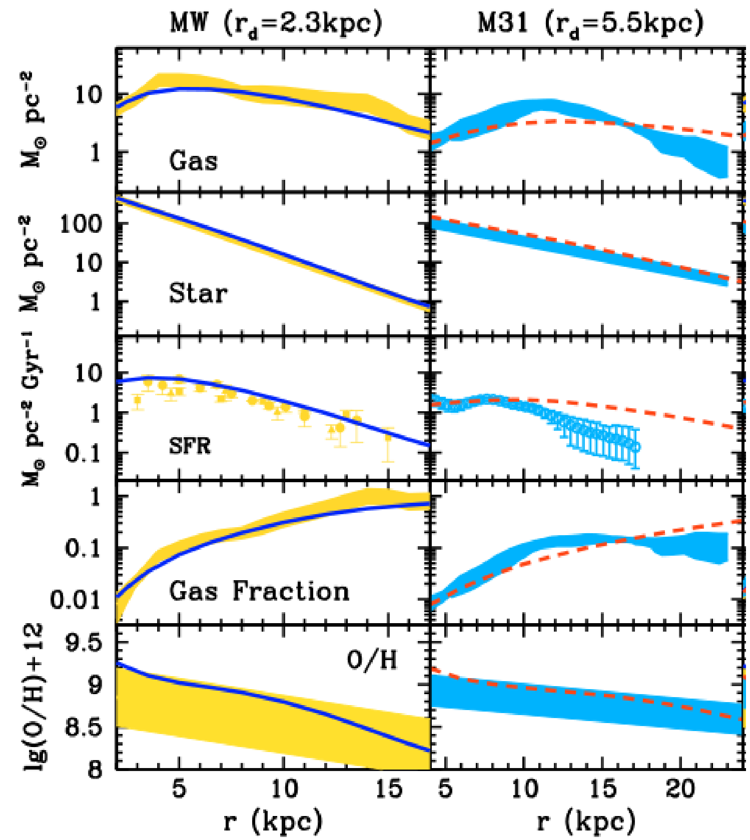
Henry & Worthey 1999

Chemical Evolution in MW, M31, M33

Constraints on the disks evolution : profiles
(abundances, stellar mass, gas mass, SFR ...)

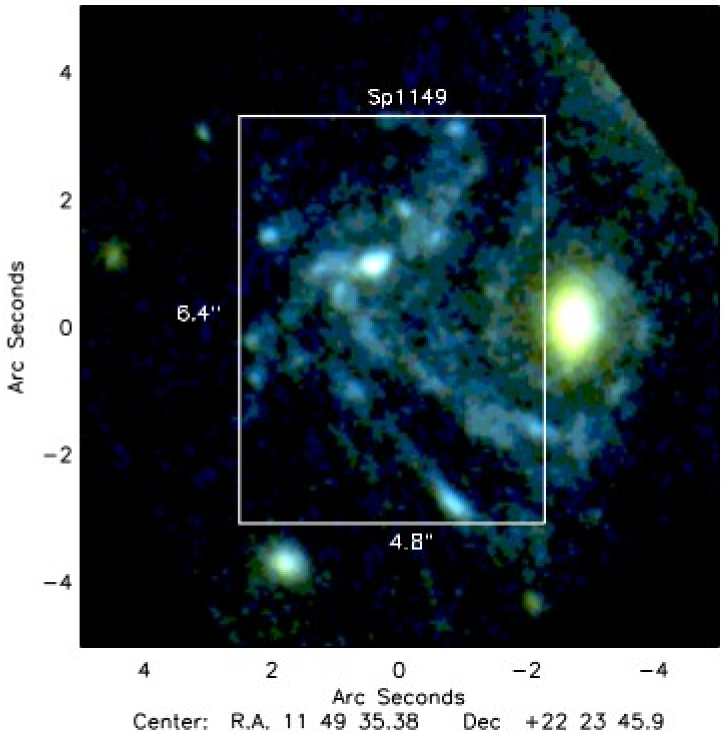
Marcon-Uchida, Matteucci & Costa 2010



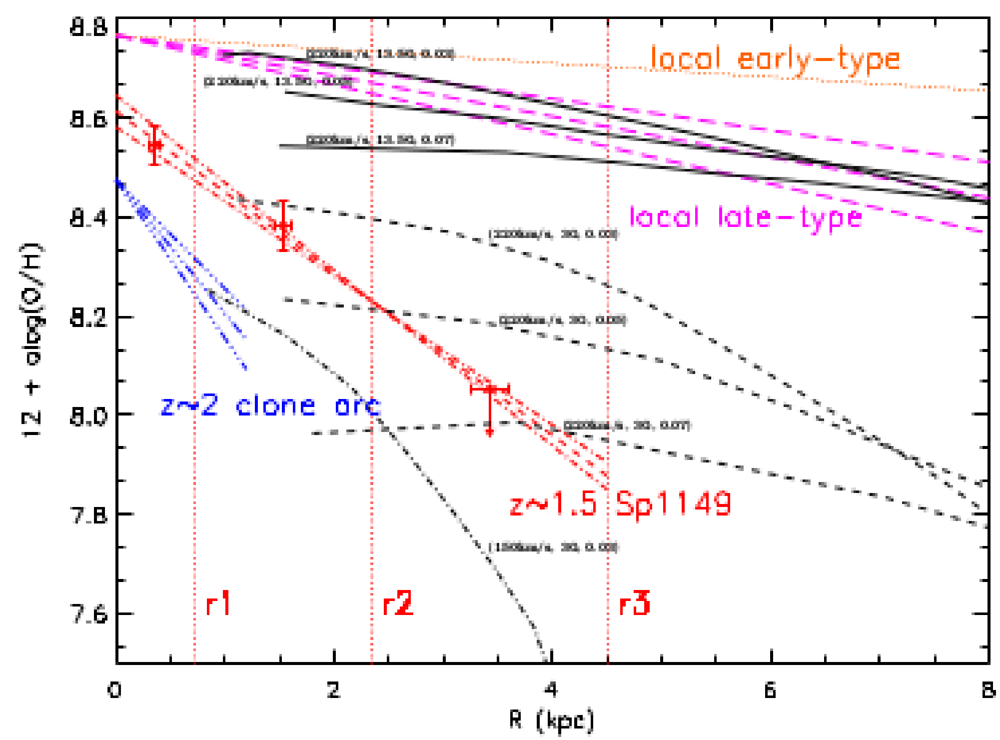


Yin et al. (2013)

Abundance gradients in distant galaxies



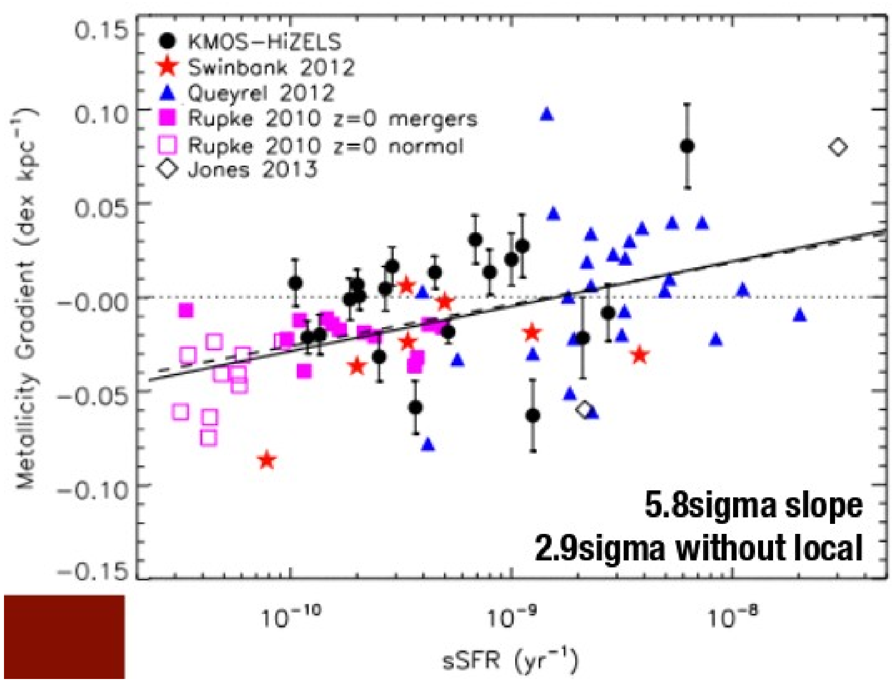
METALLICITY

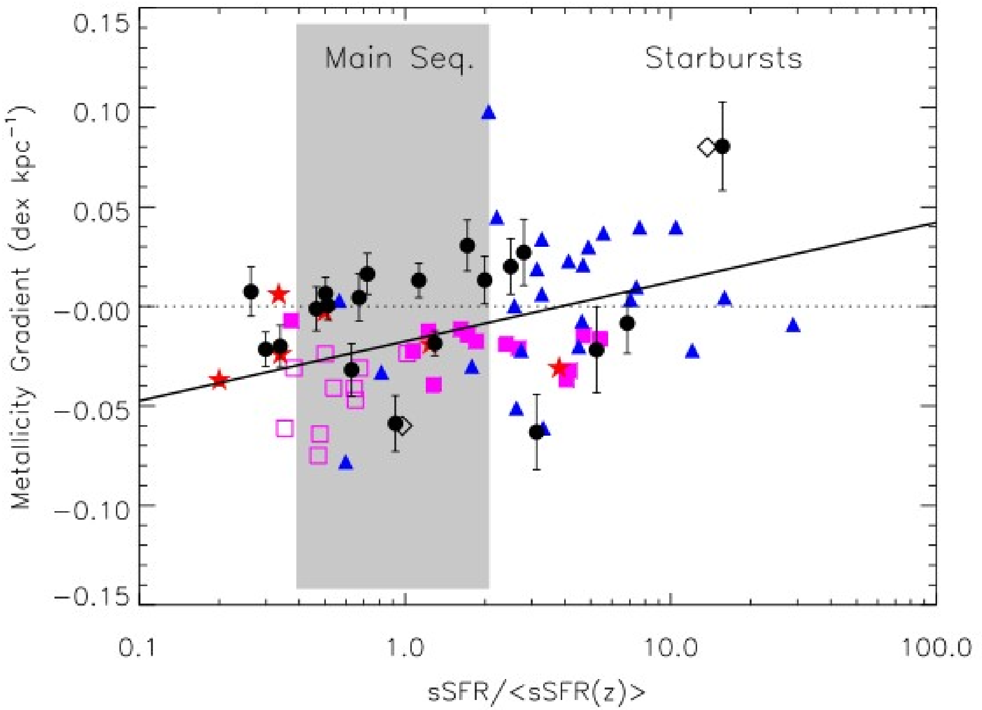


RADIUS

Yuan, Kewley, Swinbank et al., 2011

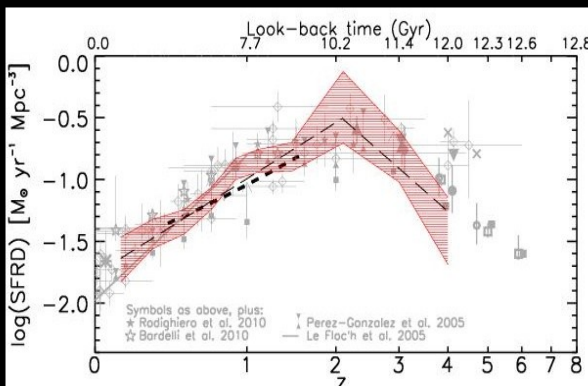
Stott et al. 2014 from K-mos 3D survey:



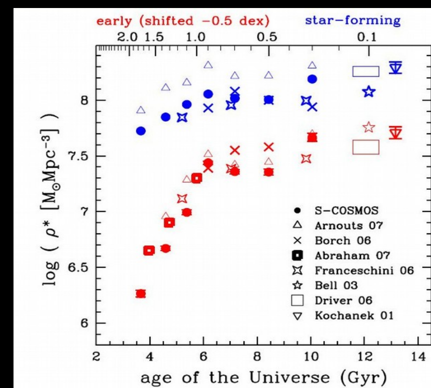


“Cosmic” chemical evolution:

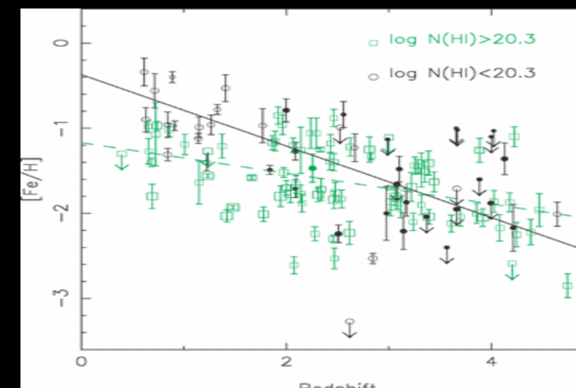
evolution with redshift (or with the age of the universe) of densities averaged over large volumes in the universe



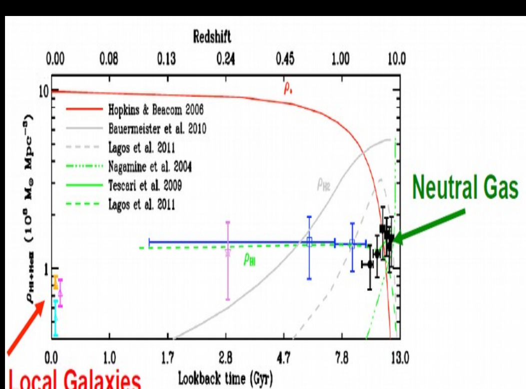
STAR FORMATION
(Cucciati et al., 2012)



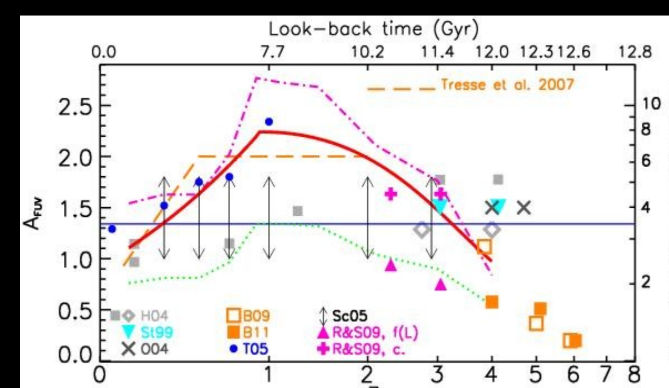
STELLAR MASS
(Ilbert et al., 2010)



ABUNDANCES
(Péroux et al., 2012)



GAS (Zafar et al., 2012)



DUST (Cucciati et al., 2012)

GALACTIC CHEMICAL EVOLUTION

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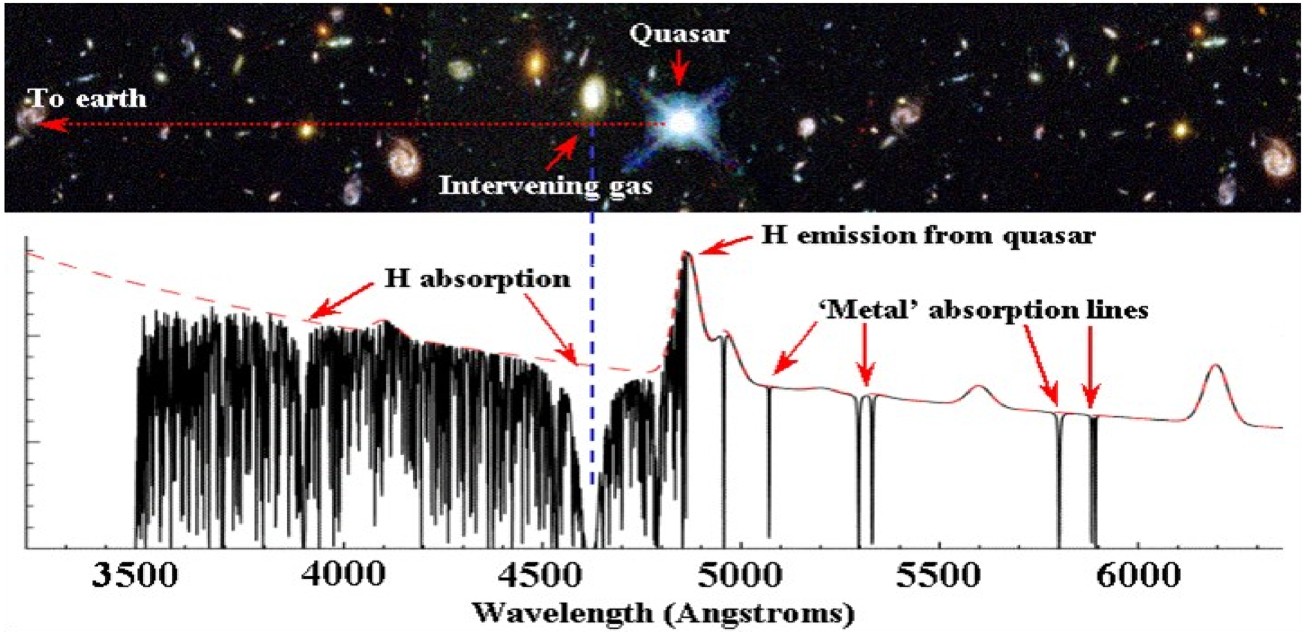
Measuring abundances

- Abundances in Stars (in the MW & very nearby galaxies)
- Average metallicity in a stellar population of a galaxy: stellar population synthesis techniques
- **Abundances in the gas.**
  - **In emission**
  - In absorption: powerful technique to probe the high z universe (Lyman Alpha forest, DLA)



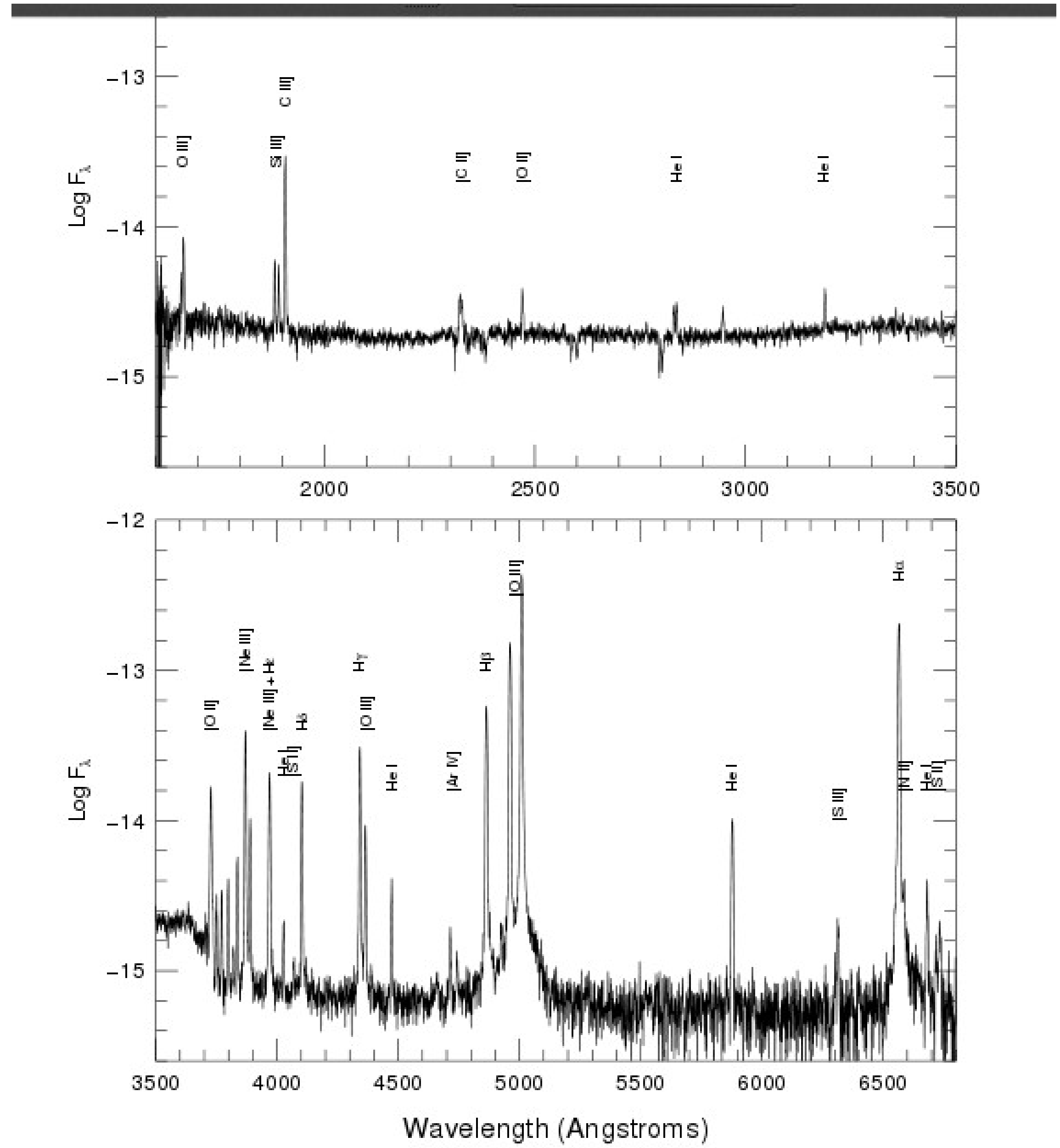
Measuring abundances

Emission lines (from individual HII regions, or global spectra of galaxies)

$$\frac{N(X^{+i})}{N(H^{+})} = \frac{I(\lambda)}{I(H\beta)} \frac{\epsilon(H\beta)}{\epsilon(\lambda)},$$

Atomic Properties

Te



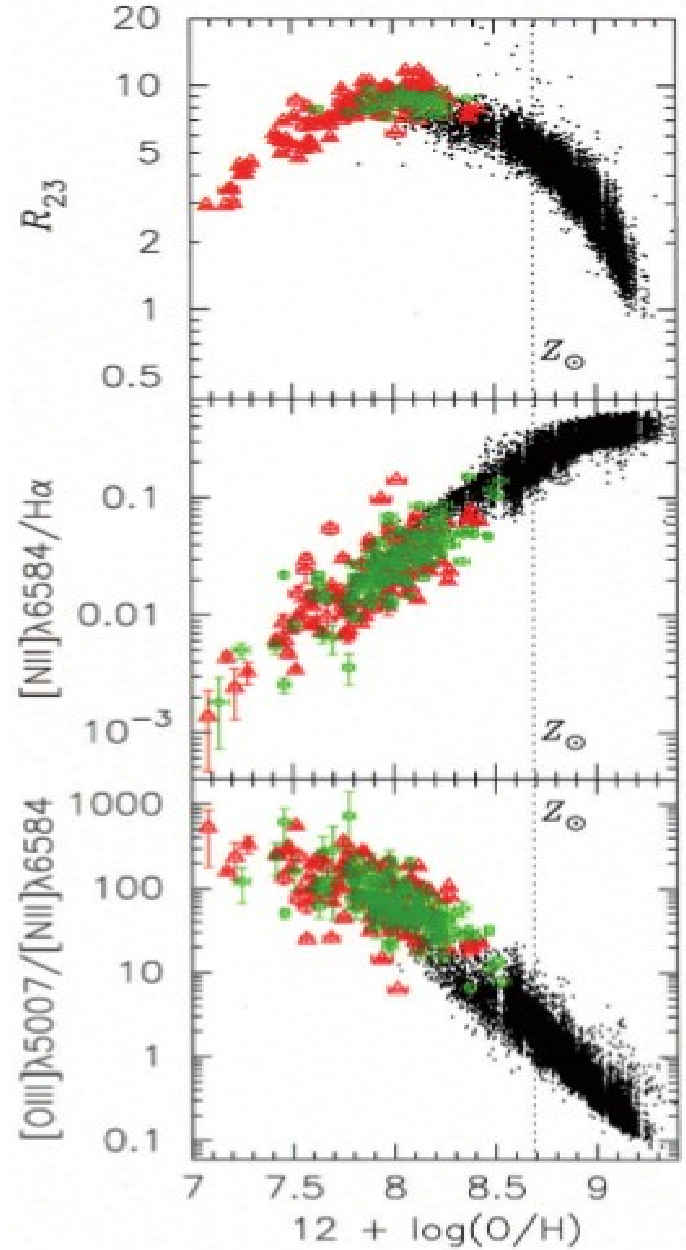
Garnett 2002

Measuring abundances

In the absence of Te-sensitive lines: use of "strong lines" empirical indicators

$$R_{23} = \frac{I([O\ II]\lambda3727) + I([O\ III]\lambda\lambda4959,5007)}{H\beta}$$

Double-branch : other diagnostics

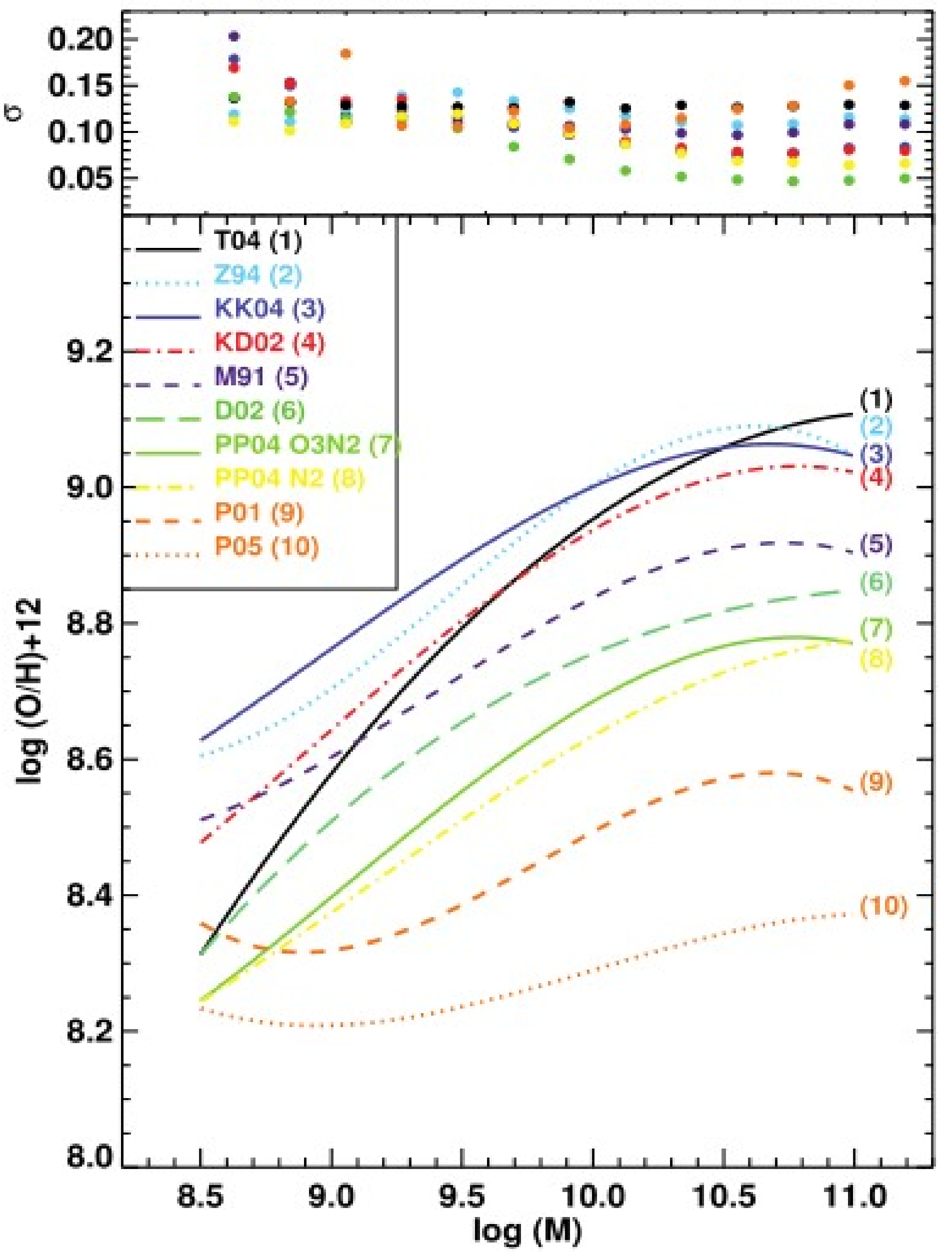


Nagao et al. 2006

Gas metallicity measurements

(Kewley Elysson 2008)

ID	Emission Lines	Calibration Class
T04[a]	[O II], Hβ, [O III], Hα, [N II], [S II]	Theoretical
Z94	R_{23}	Theoretical
KK04	R_{23}, [O III]/[O II]	Theoretical
KD02	[N II]/[O II], R_{23}, [O III]/[O II]	Theoretical
M91	R_{23}, [O III]/[O II]	Theoretical
D02	[N II]/Hα	Combined
PP04	[N II]/Ha, [O III]/Hβ	Empirical
PP04	[N II]/Ha	Empirical
P01, P05	R_{23}, [O III]/[O II]	Empirical
T_e	[O III] λ4363, [O III] λλ4959, 5007	Direct



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A FEW REFERENCES

- Pagel : nucleosynthesis & chemical evolution of galaxies

- Tinsley 1980, fundamentals of cosmic phyics

- An introduction by Nikos Prantzos: Prantzos (2007) http://fr.arxiv.org/abs/0709.0833

- Applets JAVA: http://astro.u-strasbg.fr/~koppen/apindex.html

How many stars form with mass M at time t ?

dM(M,t) = form(M,t) dM dt

Ψ(t)

Star Formation Rate
(Msol yr-1)

Φ(M)

Initial Mass Function
Description

$$\int_{M_l}^{M_u} M\,\Phi(M)\,dM = 1$$

m : total mass
mg : gas mass
m* : stellar mass
f : gas infall rate
o : gas outflow rate
E : mass ejected from stars
Xi : fraction of mass in form of element "i" in the gas
Ei : mass ejected in form of element "i"
Yi : yield of a star of mass M for the element "i"

WARNING : many Definition of "yields" :
net yield, true yield, effective yield

τ_M : lifetime of a star of mass M
C : mass of compact remnant of a star

GCE

$$\frac{dm}{dt} = [\, f - o \,]$$

infall outflow

Closed Box :

f=0

o=0

GCE

$$\frac{dm_G}{dt} = -\Psi + E + [\, f - o \,]$$

$$E(t) = \int_{M_t}^{M_U} (M - C_M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

GCE

$$\frac{d(m_G\ X_i)}{dt} = -\Psi X_i + E_i + [\ f X_{i,f} - o X_{i,o}\ ]$$

$$E_i(t) = \int_{M_t}^{M_U} Y_i(M)\ \Psi(t - \tau_M)\ \Phi(M)\ dM$$

$$Y_i(M) = y_i(M) + (M - C_M) X_i(t - \tau_M).$$

“Primary” yield depend only of M but “secondary” yields can depend on Xi

GCE

Instantaneous Recycling Approximation (IRA)

(good for O, for large gas fraction >50 %, still ok down to >~ 20%)

- Massive stars explodes « instantaneously » $\tau_M = 0$
- Others are "everlasting"

$$E(t) = \int_{M_t}^{M_U} (M - C_M)\, \Psi(t - \tau_M)\, \Phi(M)\, dM$$

Returned Fraction R ~ 0.3-0.4

$$E(t) = \psi(t) R \qquad R = \int_{M_T}^{M_U} (M - C_M)\, \Phi(M)\, dM$$

$$E_i(t) = R\psi(t)\, X_i(t) + (1 - R)\, p_i\, \psi(t)$$

$$p_i = \frac{1}{1 - R} \int_{m_t}^{m_s} y_i(m)\phi(m)dm.$$

GCE

In closed box :

$$X_i(t) - X_i(0) = -p_i \, ln(\sigma_g(t))$$

σ_g=Mg/M (fraction de gaz)

This relation links the gas fraction and the abundance , independently of the details of the history of star formation !

GCE

One more assumption
(schmidt like law)

$$\psi(t) = \epsilon M_G(t)$$

$$\sigma_g(t) = exp(-\epsilon\,(1 - R)\,t)$$

$$X_i\,(t) = X_i\,(0) + p_i\,\epsilon\,(1 - R)\,t$$

GCE

With IRA, it is possible to obtain similar relations under various assumptions :

- infall (f=-SFR)
- outflows (o=α SFR)

$$\sigma_g(t) = \frac{1}{1 + \epsilon\,(1 - R)\,t}.$$

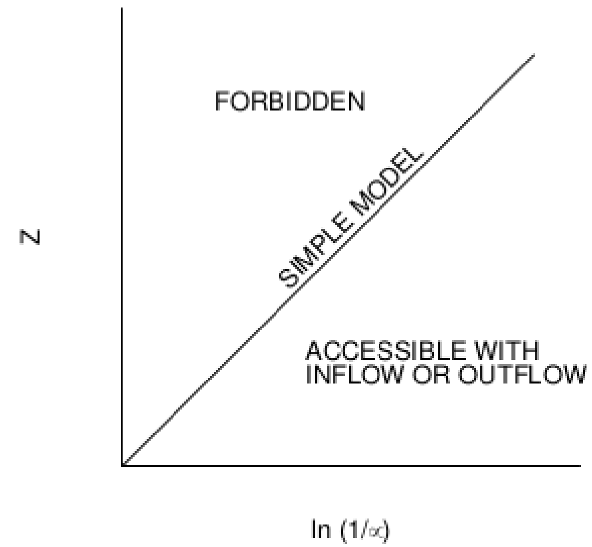
$$Z(t) = [Z(0) - (p_X + Z_f)]\, exp(-\epsilon\,(1 - R)\,t) + (p_X + Z_f).$$

$$Z(t) = [Z(0) - (p_X + Z_f)]\, exp\left(1 - \frac{1}{\sigma}\right) + (p_X + Z_f).$$

$$\sigma_g(t) = \frac{R - 1 - \alpha}{(R-1)exp(-\epsilon(R - 1 - \alpha)t) - \alpha}.$$

$$Z(t) = Z(0) + p_X\,\epsilon\,(1 - R)\,t$$

$$Z(t) = Z(0) + p_X \frac{1 - R}{1 - R + \alpha} ln\left[\left(\frac{1}{\sigma} + \frac{\alpha}{R - 1 - \alpha}\right)\left(\frac{1 - R + \alpha}{1 - R}\right)\right]$$



GARNETT 2002
Edmunds et al. 1990

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- Yields from massive stars

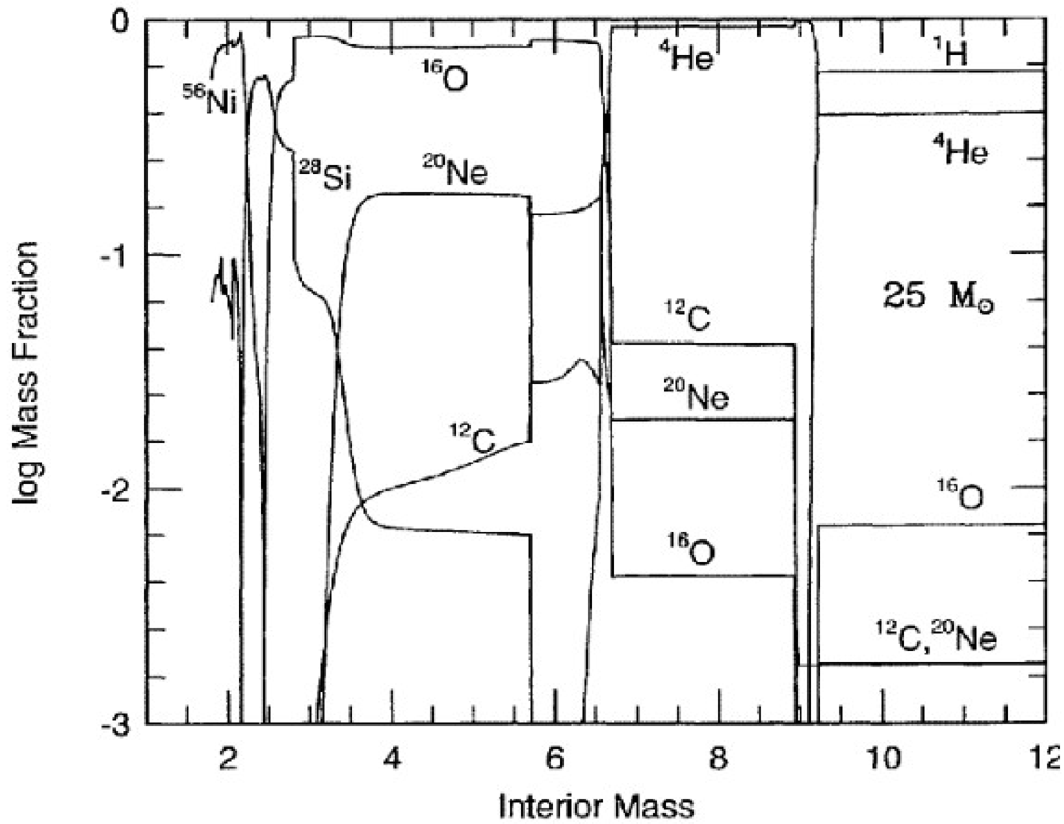


Fig. 3. Interior composition of a 25 $M_\odot$ star after its explosion; only major isotopes are displayed (from Woosley and Weaver 1995).

Yields quite uncertain

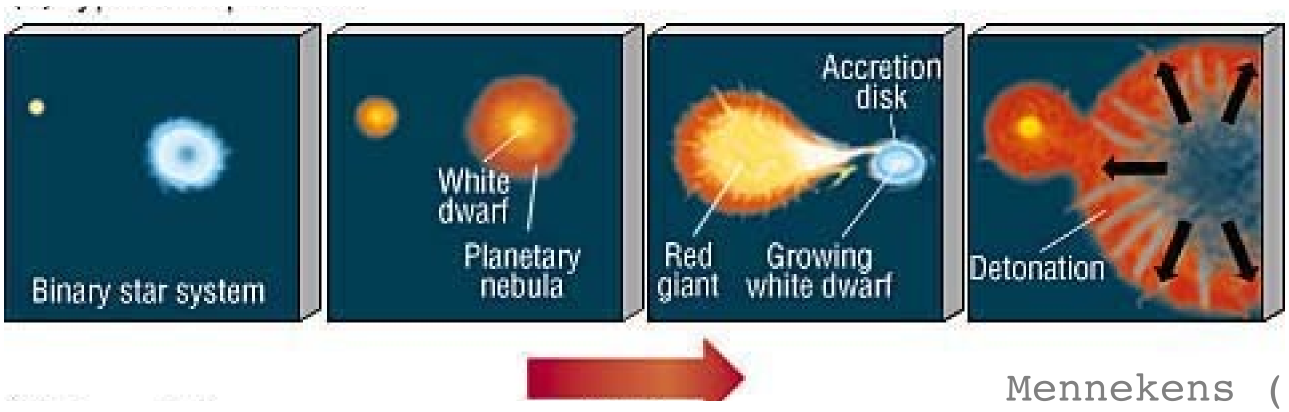
(factor 2 for O)

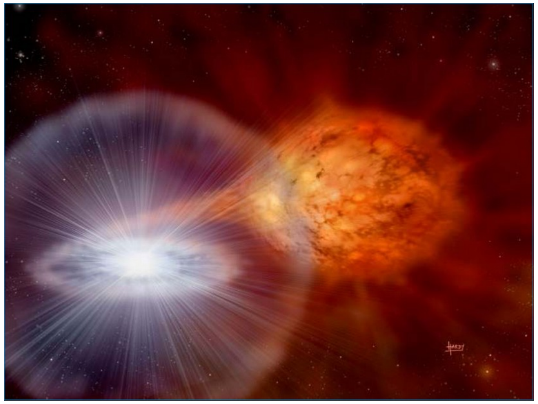
- Yields from intermediate-mass stars

Even more uncertain

Contributions to H,C,N,O isoptopes, s-process elements

- Yields from SN Ia





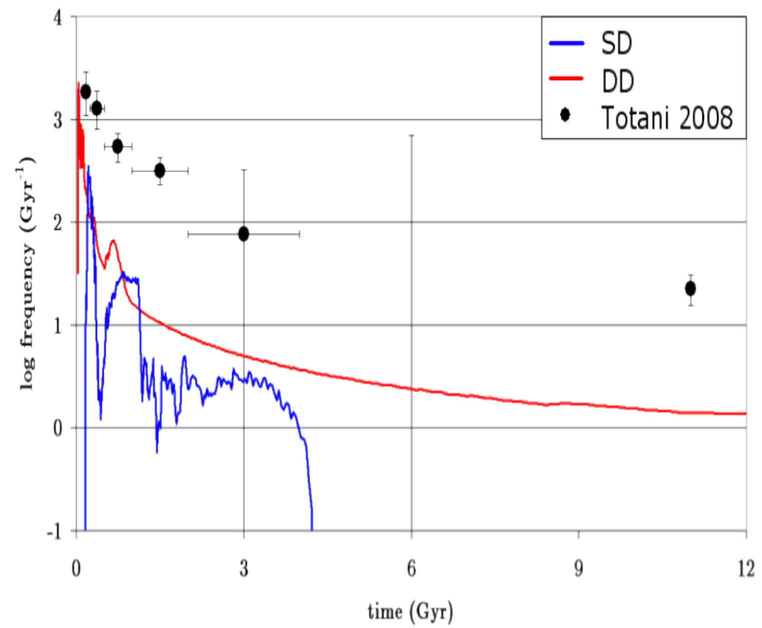
Mennekens (IAP Progenitor meeting)

Dominates Fe production, with a delay with respect to star formation !

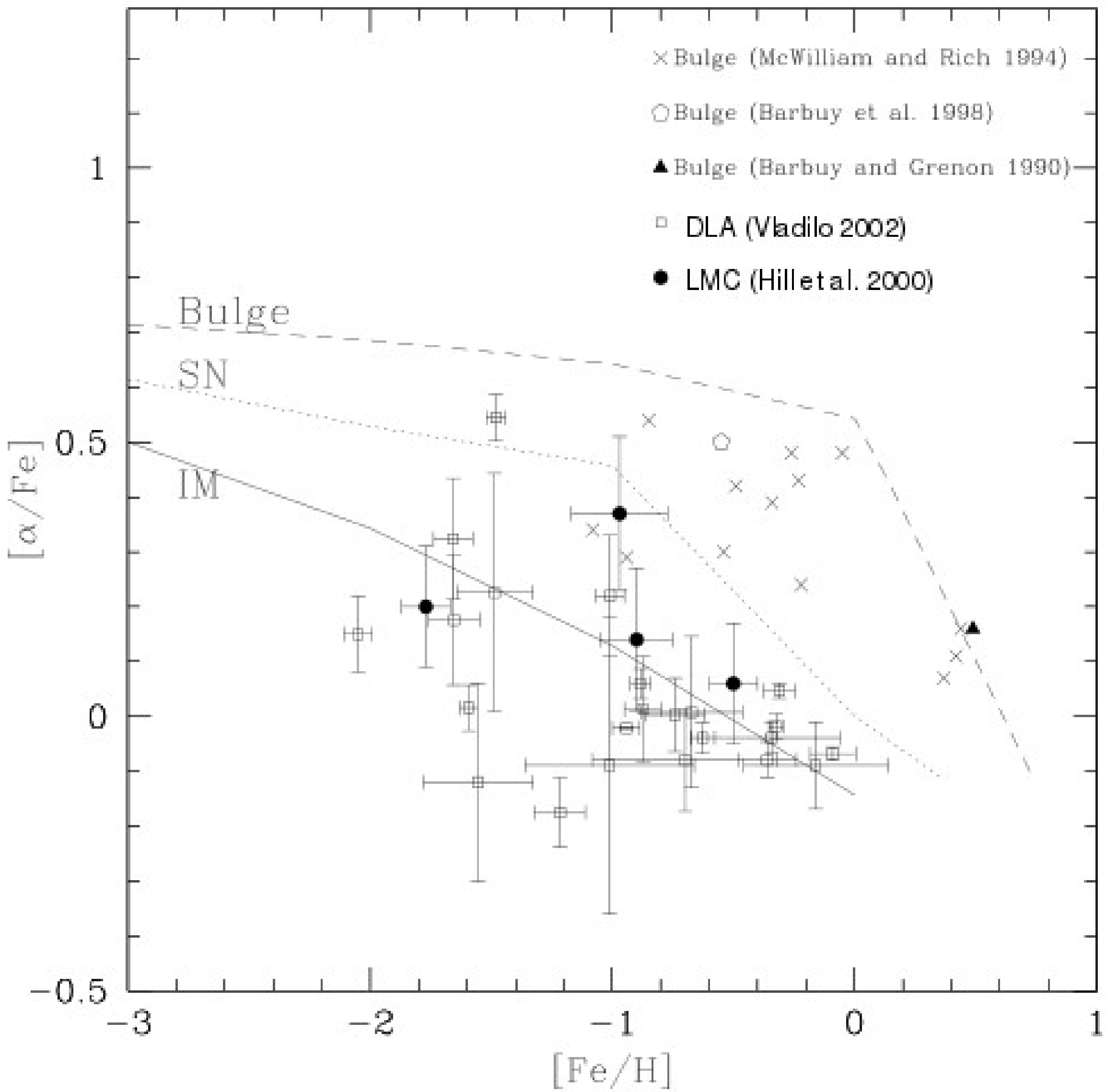
Prescription for inclusion in models
- Greggio & Renzini 1983:
  Based on binary system, evolution time for
  The primary star...

- Sannapieco & Bildsten 2005

$$\frac{\mathrm{SNR_{Ia}}(t)}{(100\ \mathrm{yr})^{-1}} = A\left[\frac{M_*(t)}{10^{10}\ M_\odot}\right] + B\left[\frac{\dot{M}_*(t)}{10^{10}\ M_\odot\ \mathrm{Gyr}^{-1}}\right], \quad (1)$$

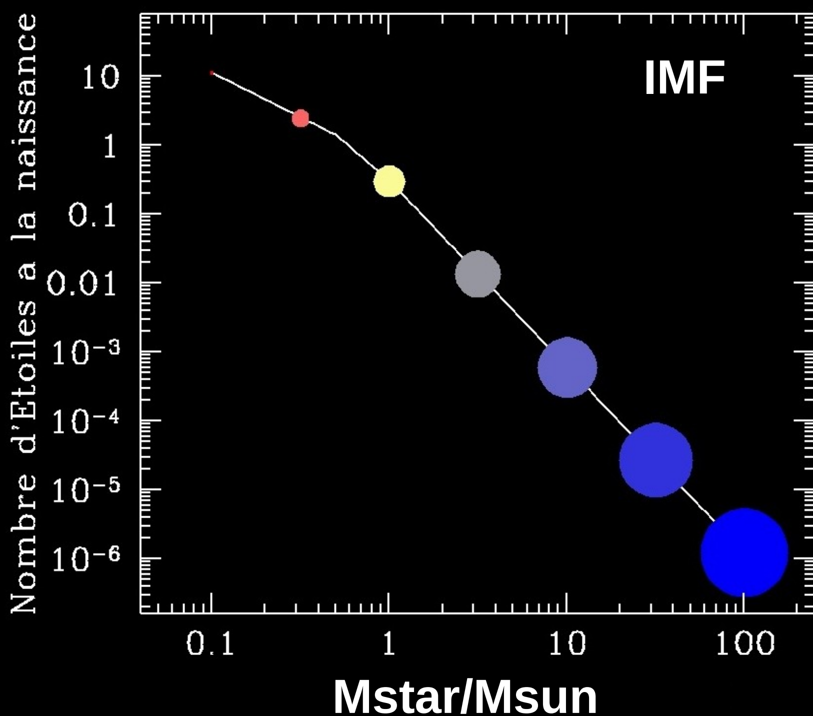


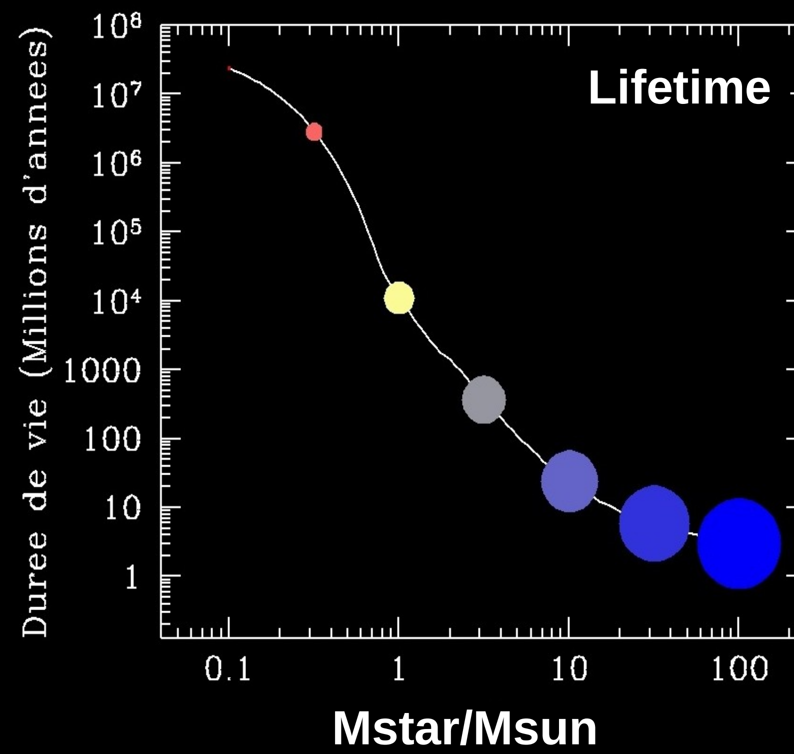
This delay in combination with different star formation histories can explain trends in e.g. O/Fe vs Fe/H

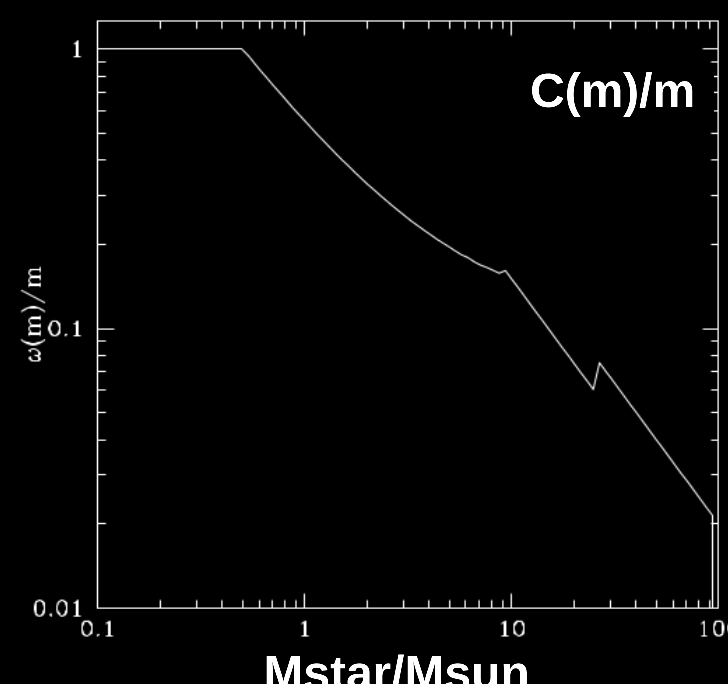


Matteucci 2003

IMF, Lifetimes, Remnant mass

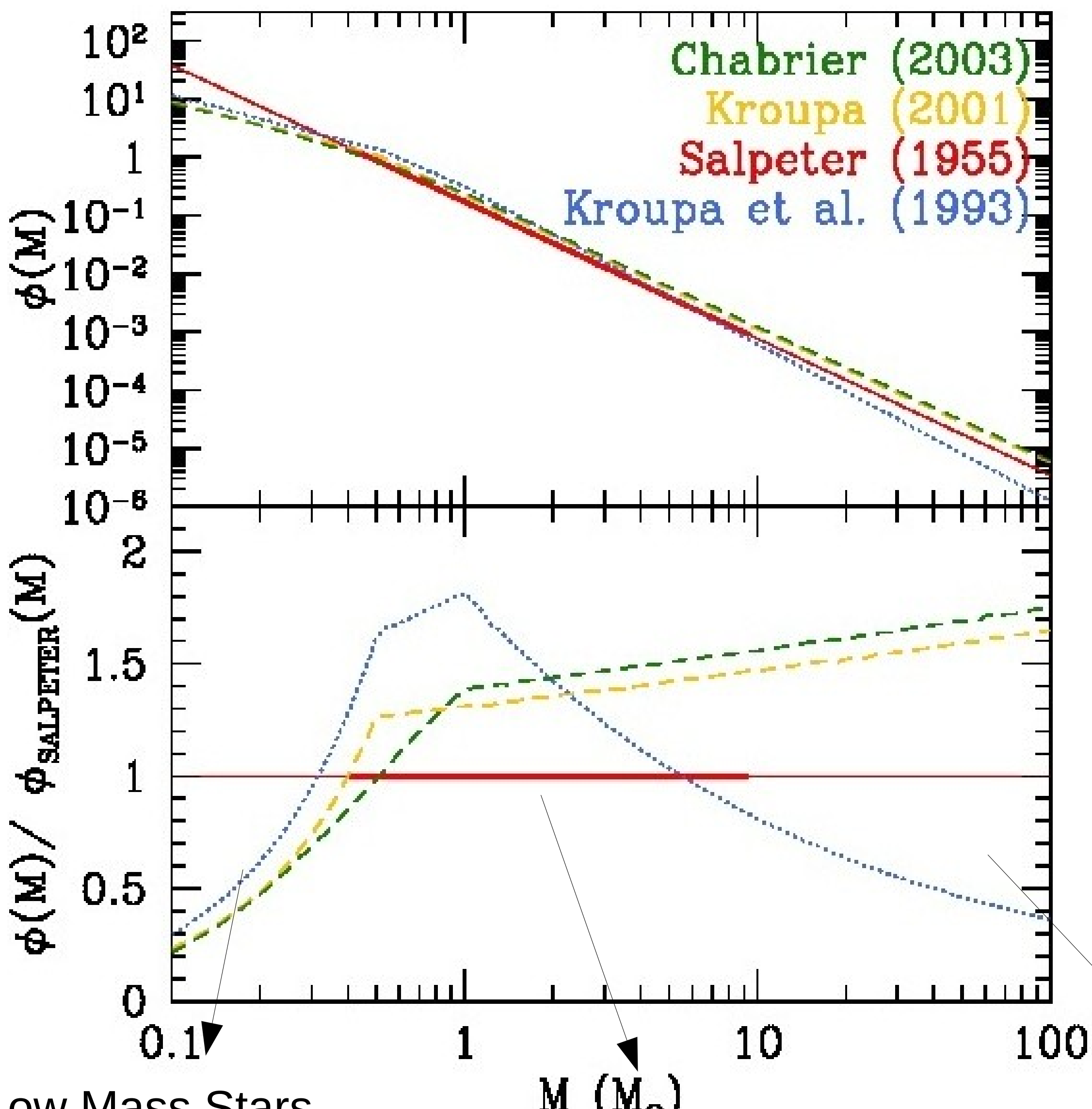






$$\Phi(M) = \frac{dN}{dM} = A \; M^{-(1+X)}$$

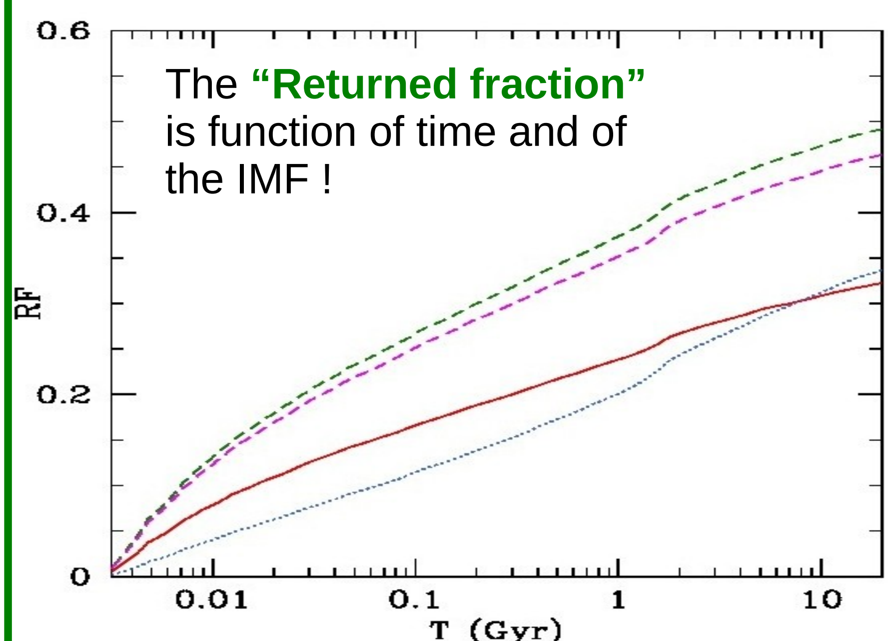
Slope of the Salpeter IMF: $X = 1.35$



Conversions SFR
(see lecture by V. Buat)

Boissier 2013

ψ(Kroupa 2001)	x 1.5	=	ψ(Salpeter)
ψ(Kroupa 2001)	x 1.59	=	ψ(truncated Salpeter)
ψ(Chabrier 2003)	x 1.5	=	ψ(Salpeter)
ψ(Kroupa 2001)	x 1.5	=	ψ(Salpeter)
ψ(Kroupa 2001)	x 0.88	=	ψ(Chabrier 2003)



<u>Low Mass Stars</u>
fraction of mass locked and the nir output

<u>Intermediate Mass Stars:</u>
during some phases, important light providers

<u>Massive stars:</u>
light output in SFR tracers, metal output

See also Review by Bastian 2010

Is the IMF universal ? Constant in time ?

- The Integrated Galaxial Initial Mass Function of stars

(e.g. Weidner & Kroupa 2005)

Basics : stars form within clusters

"Canonical IMF"

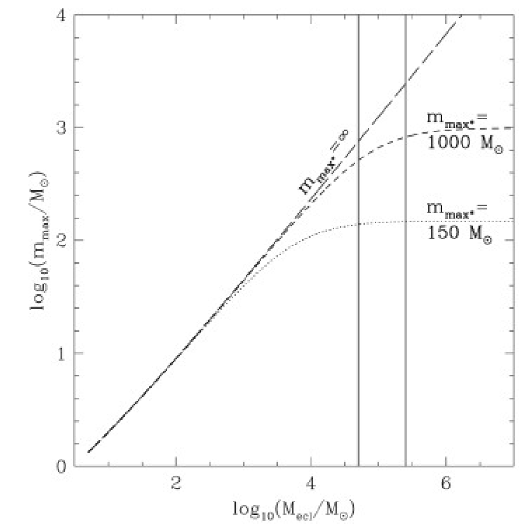
Max. Mass of stars f(Mcluster)

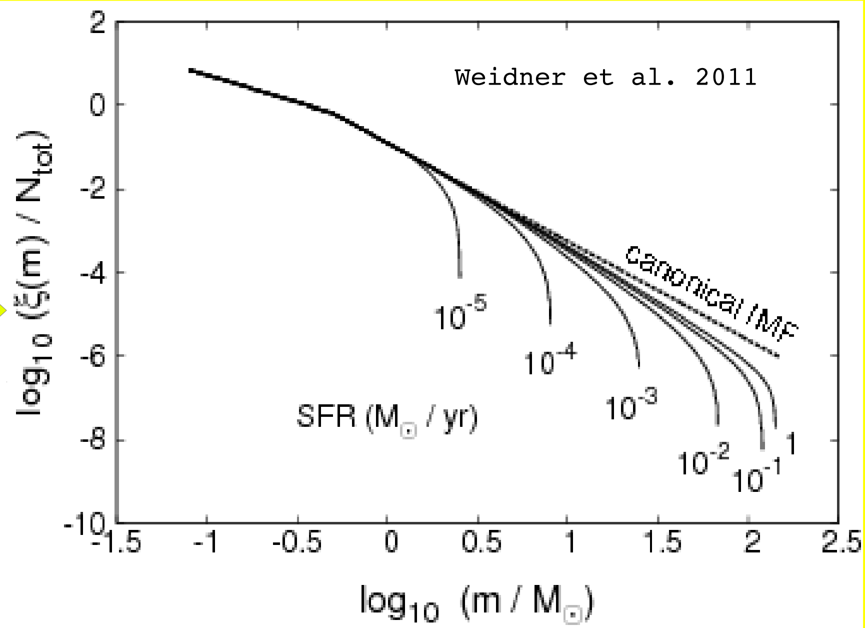
$$\xi_{\mathrm{IGIMF}}(m,t) = \int_{M_{\mathrm{ecl,min}}}^{M_{\mathrm{ecl,max}}(SFR(t))} \xi(m \le m_{\mathrm{max}})\,\xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\,dM_{\mathrm{ecl}}.$$

Cluster mass function

Maximum mass of a cluster:

$$\log M_{\mathrm{ecl,max}} = \log k_{\mathrm{ML}} + (0.75 \pm 0.03)\log \mathrm{SFR} + (6.77 \pm 0.02),$$





- Evolution with redshift ?

e.g. Wilkins et al. 2008

But see Ilbert et al. 2013

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“Galactic” Ingredients

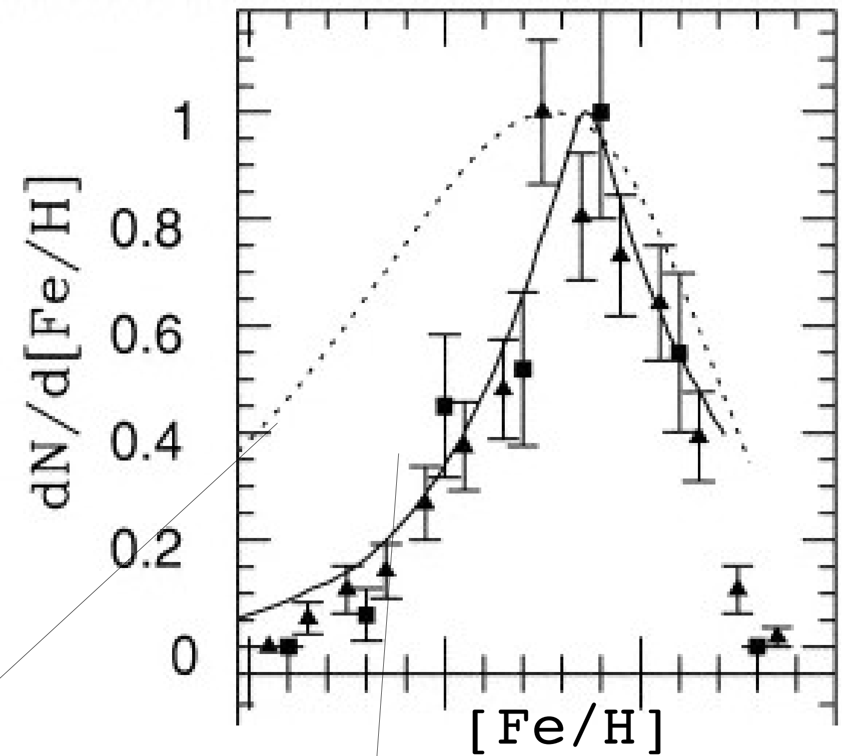
- Infall
  - In the MW: the G-dwarf problems
  - In other galaxies : History of accretion
    (backward, vs “cosmological”)
- Outflows

  Winds from massive stars vs potential of the galaxies
- The Star Formation Rate :

  see next lecture!

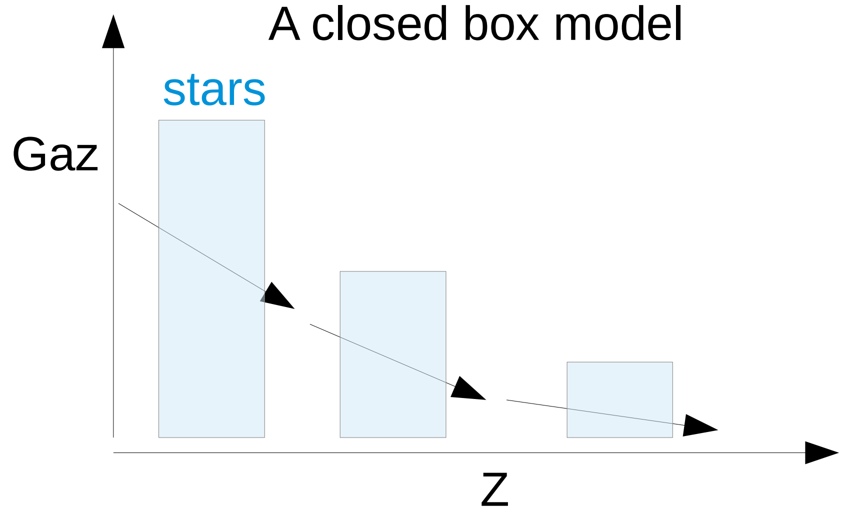
Infall in the Milky Way

e.g. Prantzos & Silk 1998

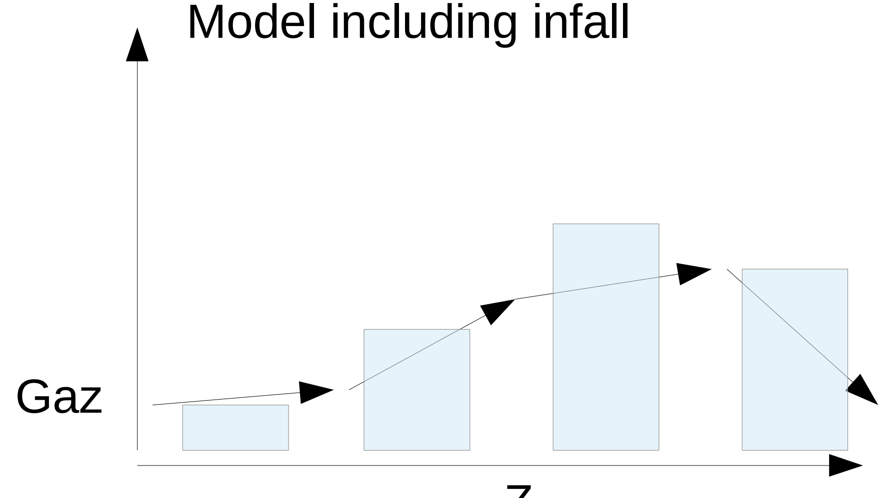


"The G-Dwarf problem" in the solar neighborhood.

A closed box model

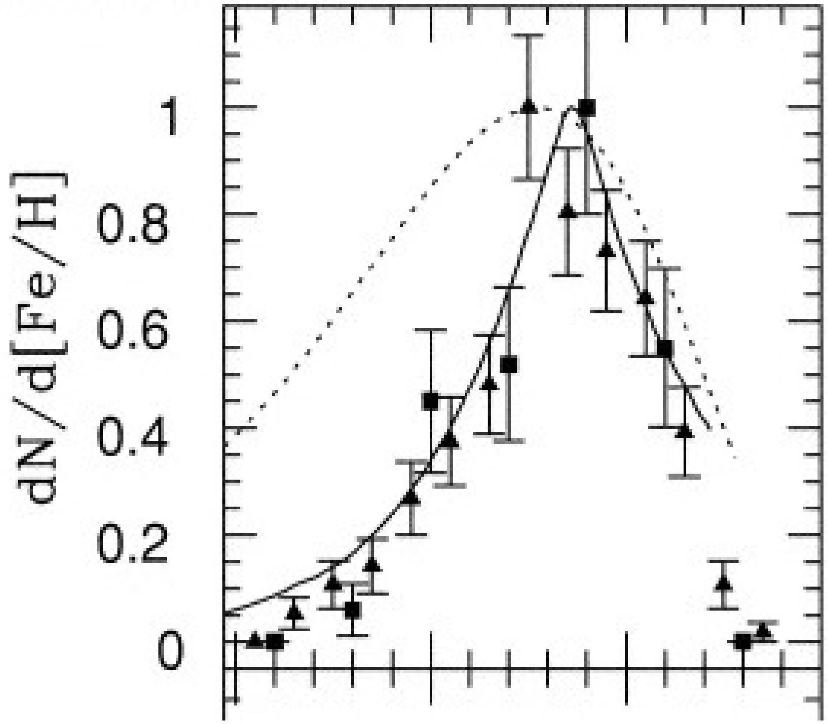


Model including infall



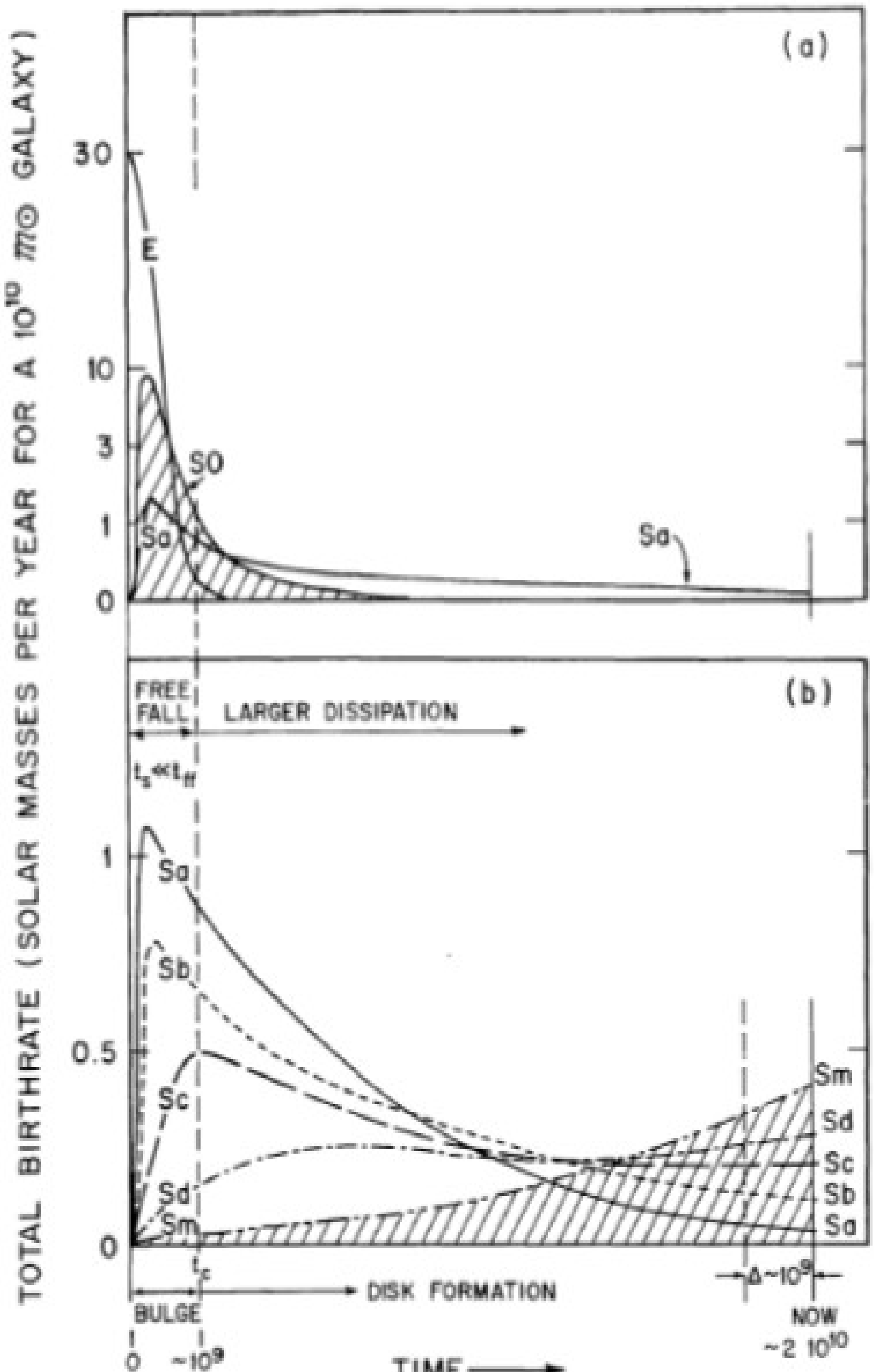
Infall in the Milky Way

"The G-Dwarf problem" in the solar neighborhood.



But see Haywood et al. 2014:
The thick disk is a significant contributor to the Milky Way + star migration

Infall in nearby galaxies

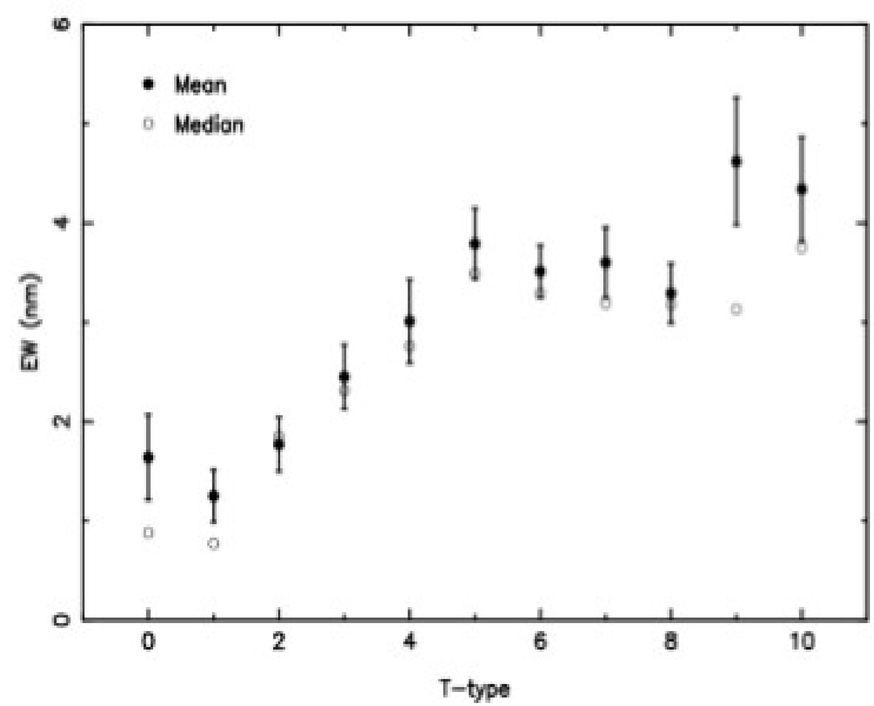


b = SFR / <SFR>

SSFR=SFR/M*

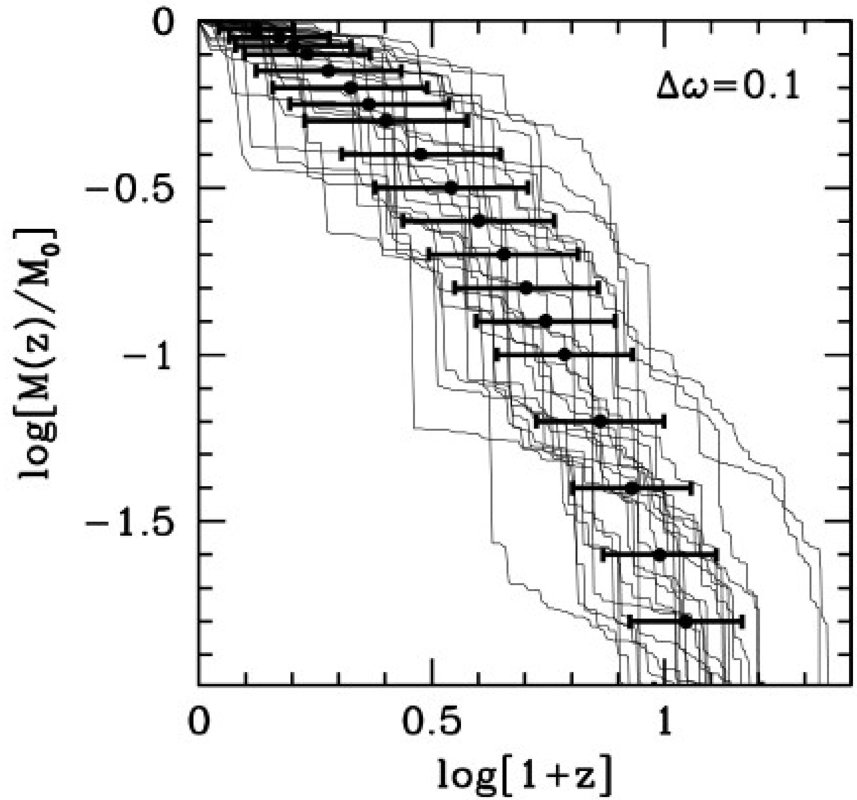
IRA: b= T (1-R) SSFR

Indicates long time-scales for SFR history of spirals -> long “formation” time



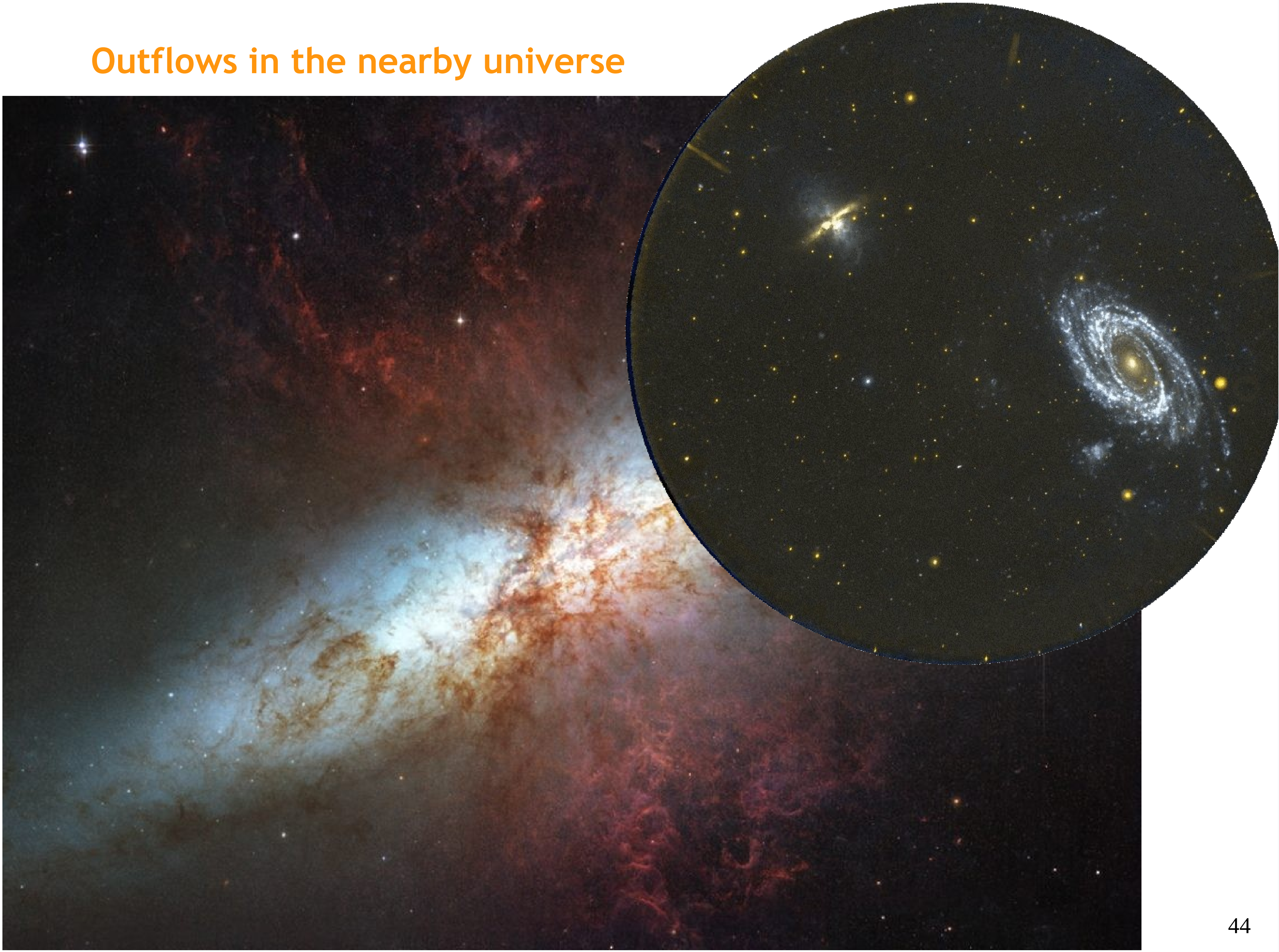
Infall in a cosmological context

See other lectures !



Van Den Bosch 2001

Outflows in the nearby universe



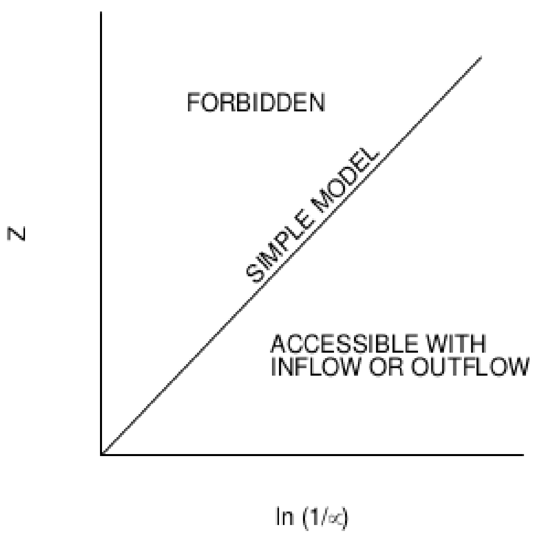
Outflows in the nearby universe

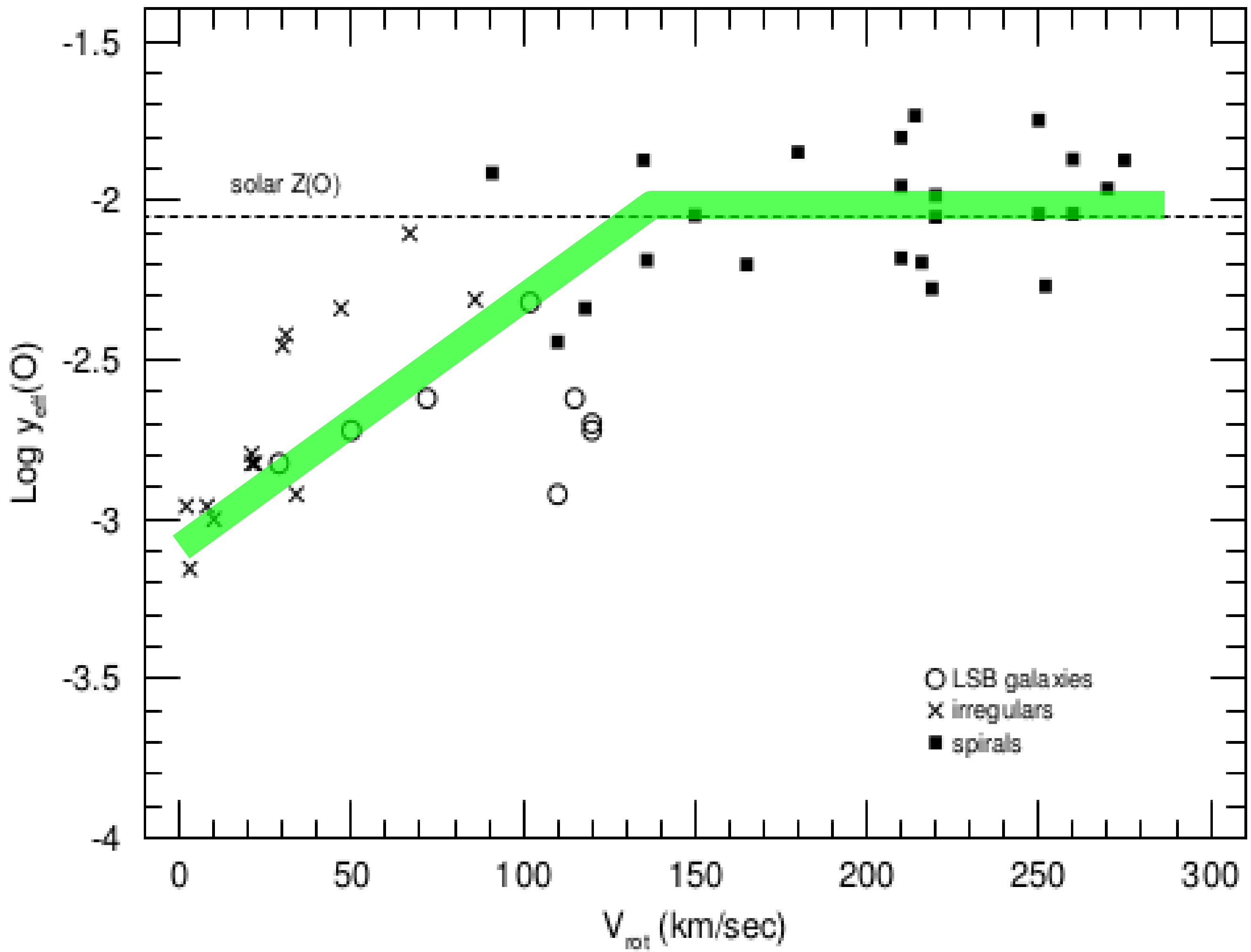
Observations

$$Z_X(t) - Z_X(0) = -p_X ln(\sigma_a(t))$$

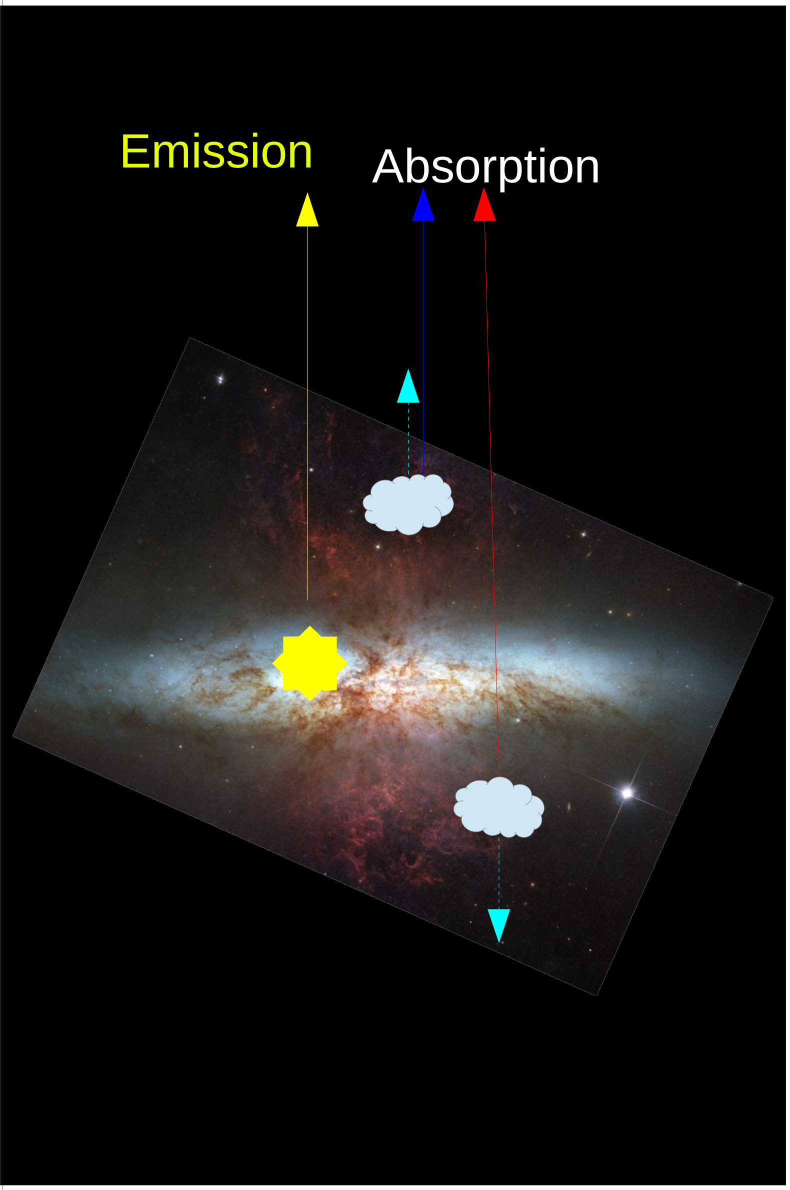
Garnett 2002

Definition of
“effective yield”





Outflows in the distant universe



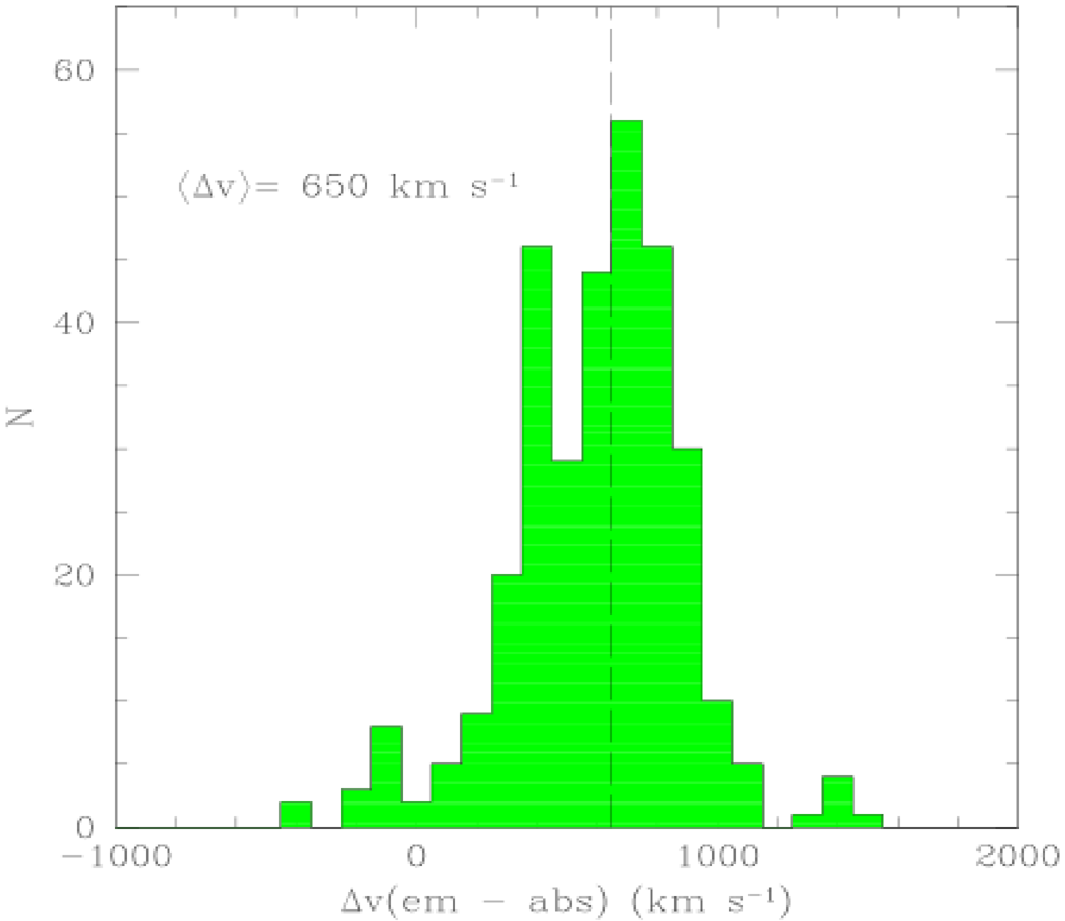


FIG. 1.— The distribution of velocity offsets between Lyα emission and low-ionization interstellar absorption. The most straightforward indication that LBGs are experiencing large-scale outflows of their interstellar material is the velocity offset measured in individual spectra between Lyα emission and interstellar absorption lines. This histogram shows the distribution of velocity offsets for the 323 galaxies with spectra in which both types of features are detected. The mean velocity offset (redshift difference) is $\Delta v = 650$ km s^{-1} ($\Delta z = 0.008$).

Shapley et al. 2003

A galactic ingredient ....

... THE Star Formation Rate

See next lecture