The Chemical Evolution of the ICM

Chiosi C. Moretti A. Portinari L.

Astronomy Department, University of Padova, Italy

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The data

[Fe/H] = 0.2 - 0.3

[O/Fe] marginally overabundant

Mushotzky et al. 1996
Ishimaru & Arimoto 1997

Existence of gradients

The iron is produced in galaxies → $M_{ICM}^{Fe} \propto L_V^{E+S0}$

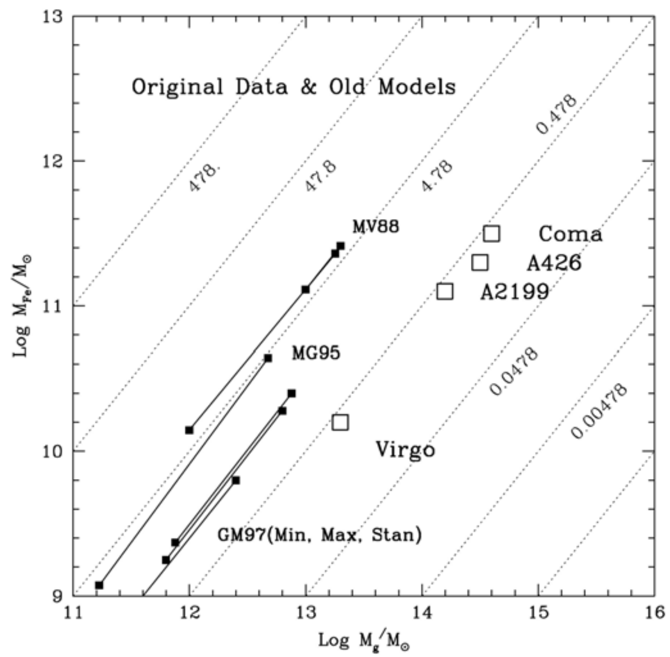
Arnaud et al. 1992

Constant IMLR
Independently from richness and temperature → **Galactic Wind scenario**

Total Iron and Gas Contents

- **Data and theoretical predictions.**
- **Open squares: data for four clusters.**
- **Solid lines & full dots: models by MV88, MG95, GM97.**
- **Dotted lines: loci of constant XFe/XFeO.**

Models matching the total Fe mass are too short in the total Gas mass.



The Old Models of ICM Evolution

Standard SNDGW (Larson 1974) galactic models & ejecta from Salpeter IMF.

Recipe based on the observed luminosity function of the galaxies and a certain red-shift of galaxy formation (say z=5): MV88, MG95, GM97.

$$\frac{M_i^T}{L_V^E} = \frac{\int_{y\min}^{\infty} M_i^{ej}(y)\exp(-y)dy}{\int_{y\min}^{\infty} L_V\, y^{\gamma}\exp(-y)dy}$$

where

$$y = L_V / L^*$$

The iron content is well reproduced, but a large amount of ICM should be of primordial composition (never involved in galaxy formation) if the total amount of gas in a cluster has to be matched.

To cope with this discrepancy an IMPORTANT contribution from Dwarf Galaxies to the enrichment of BOTH METALS AND GAS has been invoked.

The role of dwarf galaxies

Observational evidences from deep surveys of a large number of dwarfs in the galaxy luminosity functions of clusters (Trentham, 1998; Conselice et al, 2002).

Despite their large number, they actually do not much contribute to the global chemical enrichment of the ICM.

Furthermore in spite of their shallow potential well, after the first episode of galactic wind due to the SNII, owing to the lower energy input by type Ia SN, the gas cannot leave the galaxy (at least with the classic prescription for the energetics).

Similarities between the galactic problems and the ICM discrepancies

ICM

Top heavy IMF are able to eject more iron.

Matteucci & Gibson 1995

A bimodal SFR occurring in two major episodes with different IMF has the same effect.

Elbaz et al 1995

GALAXIES

Top heavy IMF are better suited to reproduce the photometric properties of elliptical galaxies.

Arimoto & Yoshii 1987

Systematic variations of the IMF with the mass of Elliptical Galaxies could explain the tilt of the Fundamental Plane.

Renzini & Ciotti 1993
Chiosi et al. 1998

…are there arguments **in favour of a non standard IMF** ?

Among others, two cases of variable IMF have been proposed, i.e. Larson (1998) and Padoan, Nordlund & Jones (1997, PNJ). Both have similar behavior.

Adopted PNJ-IMF

Chiosi et al 1998
Chiosi 2000

$$\frac{dN}{d\log M} = M^{-x} \exp(-M_S / M)$$

$$M_P = M_S / x$$

The peak mass M_p is related to the Jeans mass, i.e. the physical conditions of the environment in which stars are formed.

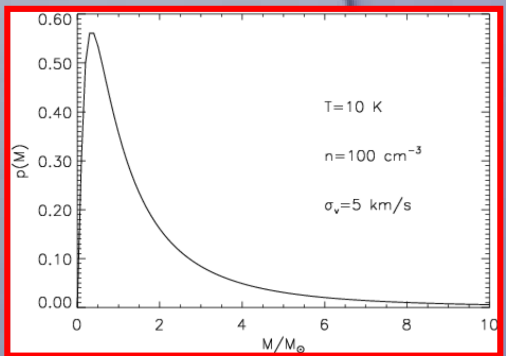
PNJ IMF : $M_p = 0.2\ M_o\ (T/10K)^2 (n/1000cm^{-3})^{-1/2} (\sigma/2.5km\ s^{-1})^{-1}$

The predictions from the PNJ IMF are as follows:

At **increasing galactic mass** the average density decreases and the typical peak mass increases.

Lower locked-up fraction

At **increasing redshift of formation,** the minimum T_{gas} increases following the behaviour of the T_{CMB}



M_p gets higher and the locked-up fraction lower.

Galactic models with variable IMF

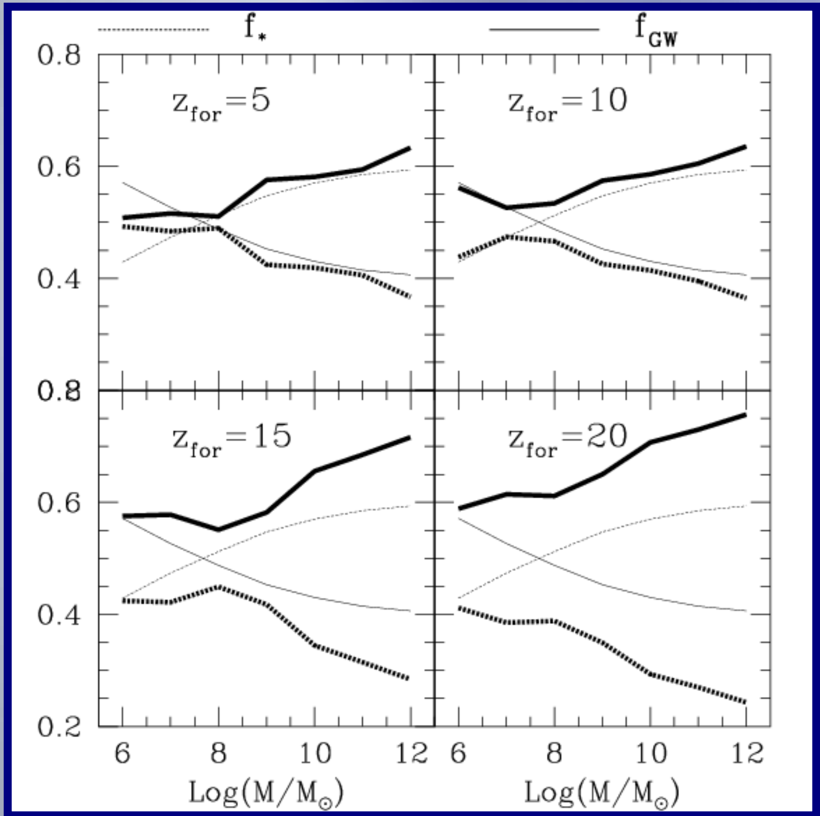
Variable IMF is not too different from standard IMF → **$M_p < 1\ M_{sol}$**

The high M_p-phase is limited to early galactic ages after which it becomes a standard IMF thus mimicking the bimodal behaviour of Elbaz et al. 1995.

Nevertheless it can explain many features of observed ellipticals:

- Tilt of Fundamental Plane
- Lack of low metallicity stars
- **BOTH** color magnitude relation **AND** trends in α-enhancement

The Galactic Ejecta



Mass fraction in stars and gas

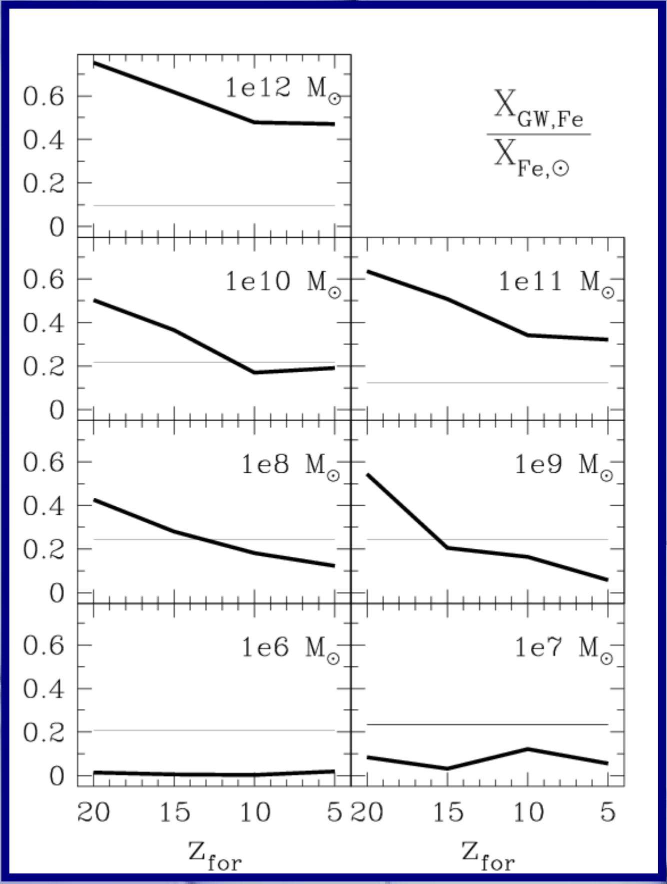
- Gas fraction is almost always larger than with the Salpeter IMF.
- The mass-trends are clearly opposite to those with the Salpeter IMF.

Thick line : PNJ IMF

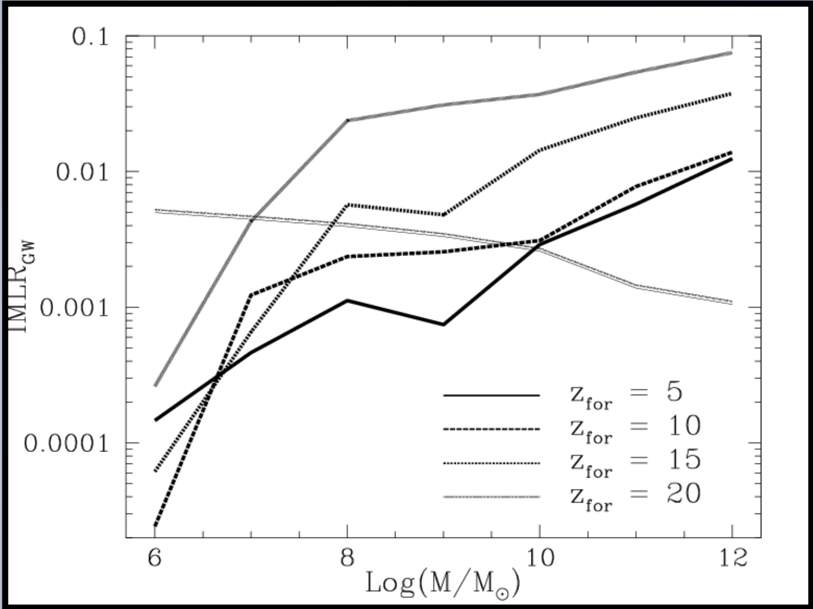
Thin line : Salpeter IMF

Consequences

- In most cases, models with PNJ are more metal rich than with Salpeter, especially for more massive galaxies and increasing redshift of formation.
- Dwarf galaxies do not much contribute to the enrichment.



Iron mass and luminosity

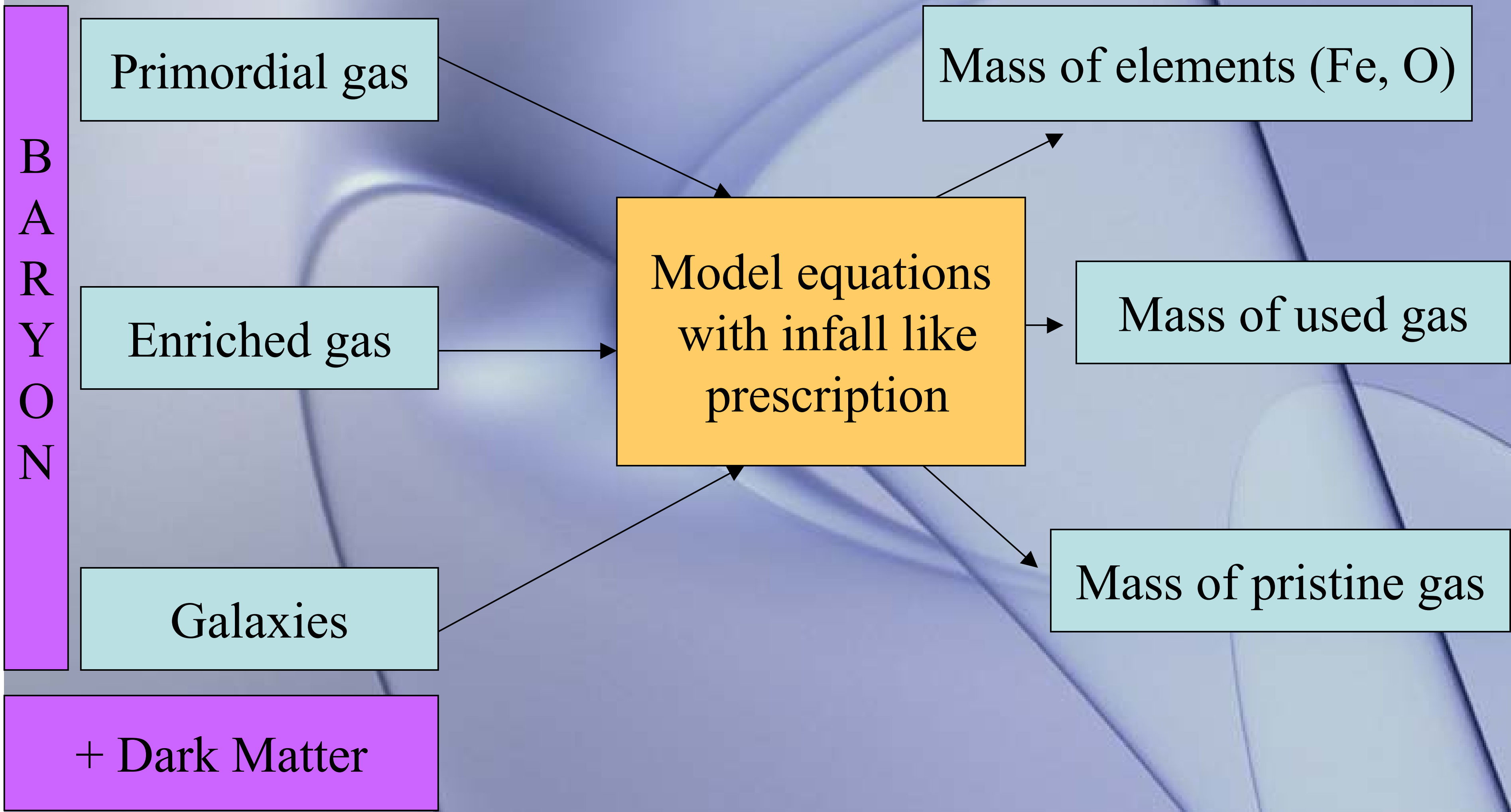


- The efficiency of metal production is measured by the so called IMLR:
- M^{Fe}_{ICM}=(0.01- 0.02)$h_{50}^{-1/2}$

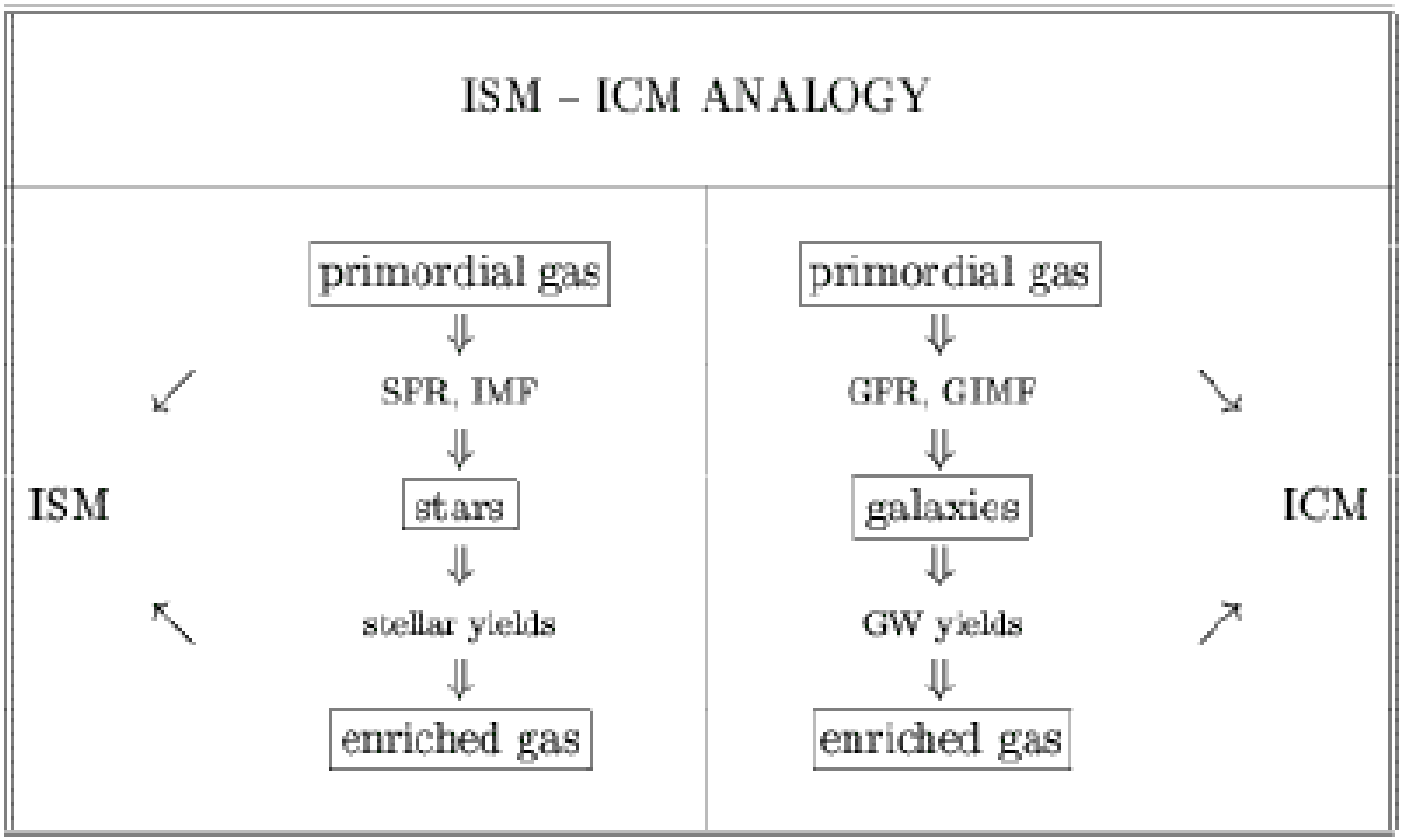
IMLR for single galaxies: the B luminosity is obtained attributing to the galactic remnant the M/L ratio of a solar SSP with the appropriate age.

With a variable IMF, Dwarf Galaxies do not significantly contribute to the enrichment process

The Chemical Model for the ICM



Analogy between ISM and ICM



An Integral Model

- Integral model by Chiosi (2000)
- Same galaxy models and ejecta.
- See below for the definition of f or GMF.
- [O/H]=-0.51, [Fe/H]=-0.41, [O/Fe]=-0.11
- Satisfactory agreement with variable IMF (the same adopted here) and 20% dilution with primordial gas.

$$M_i^T = \int_{zfor}^{0} dz \int_{M\min(z)}^{\infty} M_i^{ej} \frac{df(M, M_N^*, z)}{dM} dM$$

$$M_{Gal}^T + M_{Gas}^T + \alpha M_B^T = A_\alpha M_B^T$$

$$\alpha M_B^T = M_P$$

$$M_H^T = X_P M_B^T - (1-\alpha) M_{Gal}^T (z)_0$$

$$M_{Fe}^T = (1-\alpha) M_{Fe}^T (z)_0$$

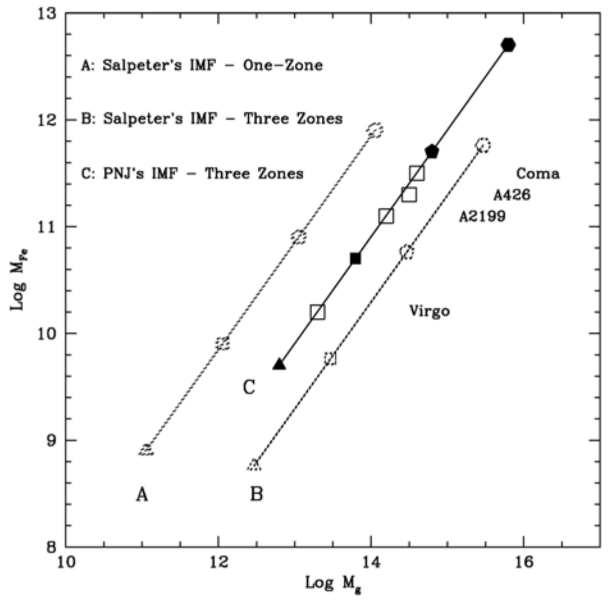
$$M_O^T = (1-\alpha) M_O^T (z)_0$$

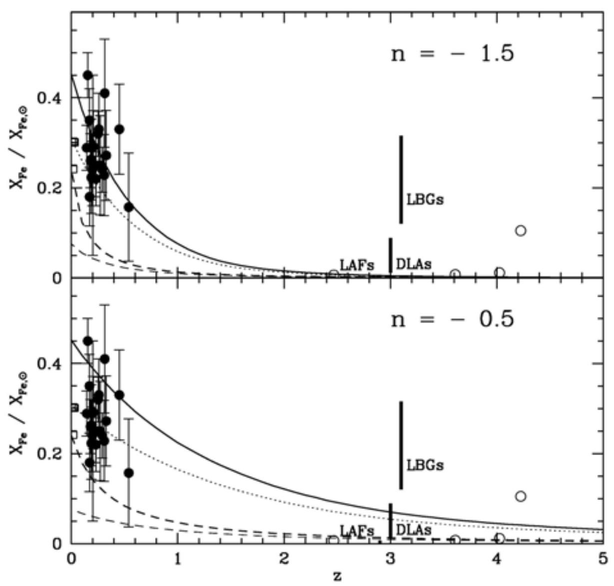
$$\alpha = 0.2$$

$$X_{Fe} / X_{Fe,\Theta} = 0.3$$

An Integral Model

The MFe *vs* Mg and XFe *vs* z relationships





Key Prescriptions for the ICM Model

- **Istantaneous Recycling Approximation: galaxies eject their wind istantaneously (TGW < TG).**

- **Only non interacting elliptical galaxies are taken into account: they are indeed the major sources of gas and metals.**

- **One zone model for the cluster as a whole: it describes only the average properties.**

- **Three phases for the ICM gas: hot primordial, cold primordial (simulated by the infall-like term), hot processed by star formation and ejected.**

Four Basic Assumptions of the IMC Model

- The primordial cold gas in the cluster is consumed by galaxy formation according to some Galaxy Formation Rate GFR.
- At each time step new galaxies, whose mass spectrum is according to the Galaxy Initial Mass Function (the Press & Schechter one) GIMF, can reach the star formation stage.
- Galaxies eject gas and metals via galactic wind (see details in Chiosi 2000 and Chiosi et al. 1998).
- Finally the enriched gas mixes with the primordial one never processed in stars.

The Infall - like Formalism

- Based on the suggestion by Pei & Fall 1995: an infall-like term describes the phase transition between hot and cold primordial gas. Only this latter can form stars.

Model equations

$$\frac{dM_{g,F}}{dt} = -\Psi_G(t) + \left[\frac{dM_{g,F}}{dt}\right]_{inf} \quad (1)$$

$$\frac{dM_{g,W}}{dt} = \Psi_G(t)\,Y_G(t) \quad (2)$$

$$\frac{dM_G}{dt} = \Psi_G(t)\,[1 - Y_G(t)] \quad (3)$$

$$A = \frac{1 - B\tau_2\left[\tau_2 - (\tau_2 + t_H - t_0)\,e^{-\frac{t_H - t_0}{\tau_2}}\right]}{\tau_1\left[\tau_1 - (\tau_1 + t_M)\,e^{-\frac{t_M}{\tau_1}}\right]}$$

$$\frac{dM_b}{dt} = \left[\frac{dM_{g,F}}{dt}\right]_{inf} = A\,t\,e^{-\frac{t}{\tau_1}} + B\,(t - t_0)\,e^{-\frac{t-t_0}{\tau_2}} \quad (4)$$

$$M_b(t_M) = M_{b,T} = 1 \quad (5)$$

Galactic Mass Function: GMF

Press & Schechter (1974) mass function according to Lacey & Cole (1994).

It holds for Dark Matter Haloes and depends on the spectral index n of the perturbations and the scale mass $M^*(z)$ varying with the redshift.

For the purpose of this study we assume that the same relation provides also the mass spectrum of galaxies forming at redshift z(t).

The ratio between baryonic and dark matter mass is assumed to be 0.1.
The ratio f= M/M*(z) is governed by

$$\frac{df[z(t)]}{d\ln M} = \left(\frac{2}{\pi}\right)^{\frac{1}{2}} \left(\frac{n+3}{6}\right) \left(\frac{M}{M^*(z)}\right)^{\frac{n+3}{6}} \exp\left[-\frac{1}{2}\left(\frac{M}{M^*(z)}\right)^{\frac{n+3}{2}}\right]$$

where $M^*(z) = M_N (1+z)^{-\frac{6}{n+3}}$ $\quad M_N = M^*(z=0)$

GMF: the Mass Limits

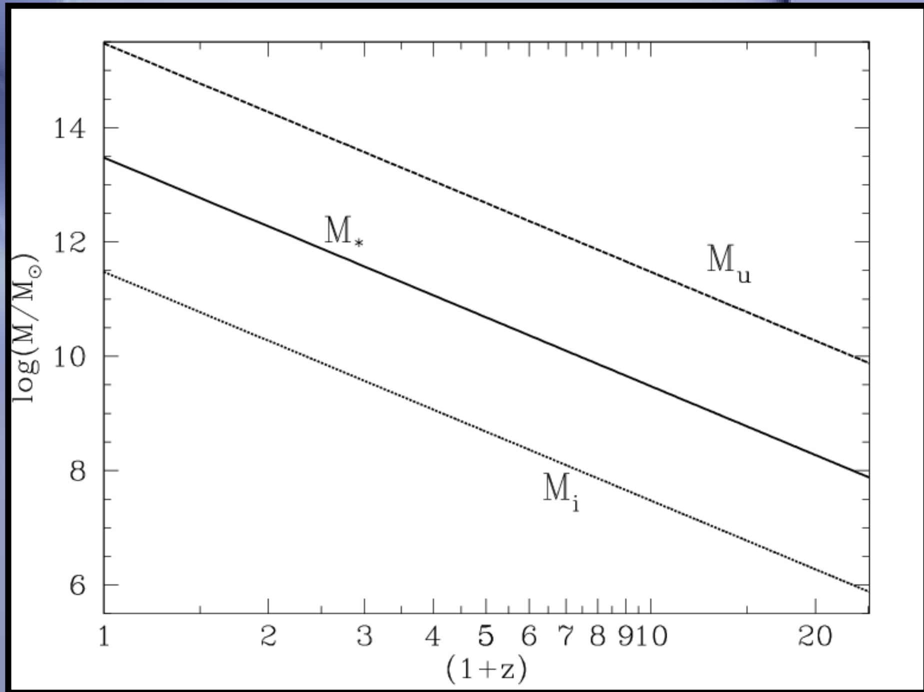
- The mass limits are as indicated

$$M_l = \gamma\, M^*(z)$$

$$M_u = M^*(z)/\, \gamma$$

$$\gamma \;= 100$$

Scale Mass M*(z)



Galaxy Formation Rate: GFR

Simple Schmidt-like law

$$\Psi_g = \nu M_{gas,prim}$$

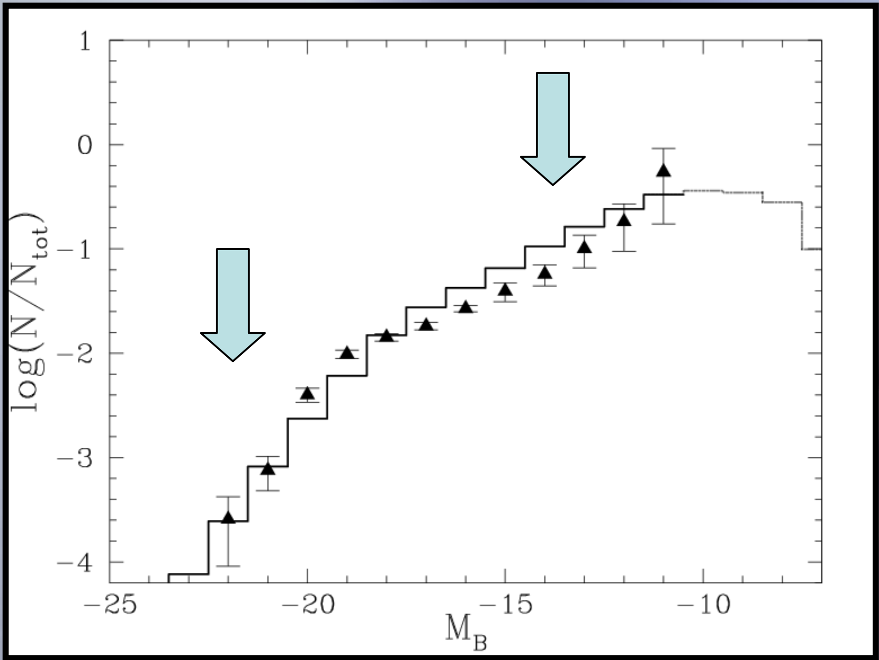
Under the combined effect of the infall-like term and gas consumption, the GFR first grows, reaches a peak value, and then decreases.

The galaxy formation history is supposed to start at z = 20 with a burst of Dwarf Galaxies (required to fit the LF) followed by a more gentle GFR during which galaxies of any mass can *form*.

It is halted when the characteristic mass becomes larger than the residual available cold primordial gas. Other laws are also tested.

Calibration

Mainly based on the **luminosity function by Trentham (1998)**



The large number of Dwarf Galaxies seems to require a **first episode of galaxy (star) formation** at high redshift, a feature which inspired our **double infall model.**

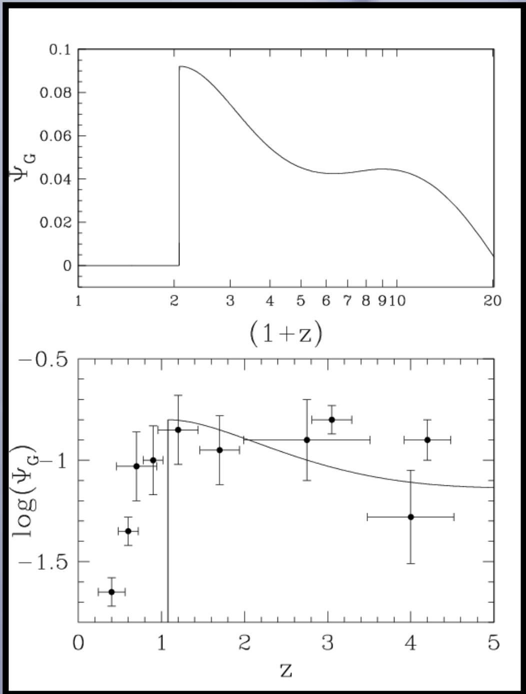
IMLR as a strong constraint…

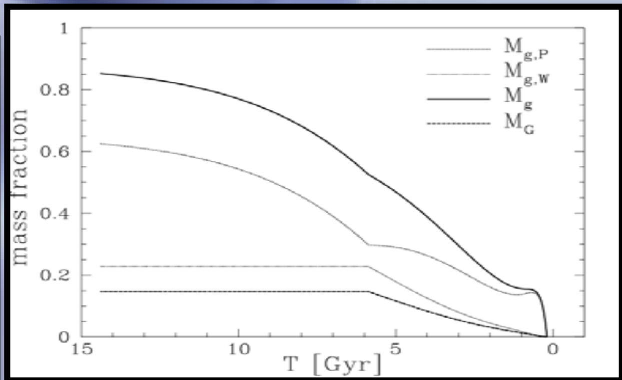
Finally the iron and oxygen enrichment

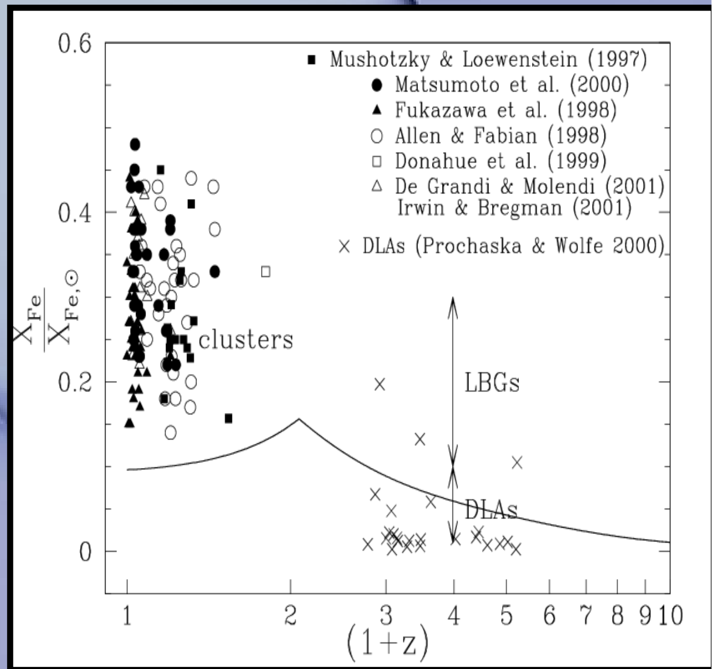
Results: Fiducial Model (A)

- $M_N = M_*(z=0) = 3 \times 10^{13}\ M_O$

IMLR	Mgal / LT	MGW / Mgal	MICM / LT	XFe ICM / XFe O	[O/FE]
0.0058	5.6	1.56	32.8	0.096	-0.061





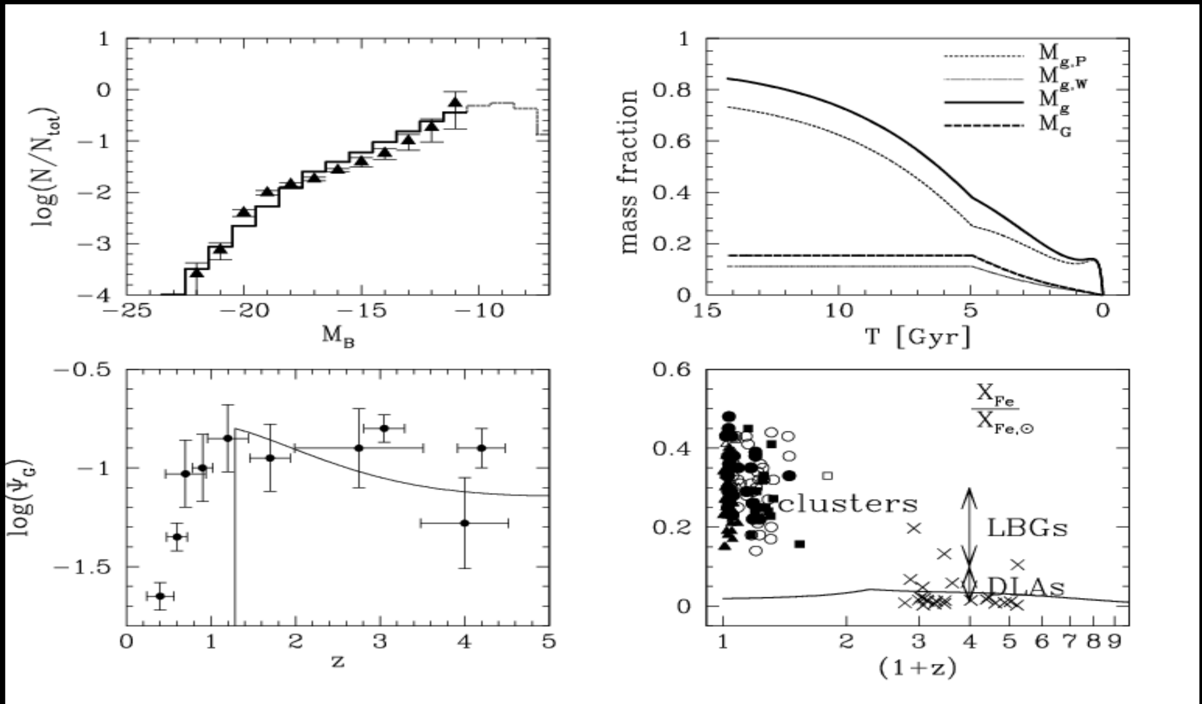


IMF: PNJ

Results: Fiducial Model (AS)

- $M_N = M_*(z=0) = 3 \times 10^{13} M_O$

IMLR	M_{gal}/L_T	M_{GW}/M_{gal}	M_{ICM}/L_T	$X_{Fe\,ICM}/X_{Fe\,O}$	[O/FE]
0.0013	7.1	0.72	38.8	0.019	-0.085



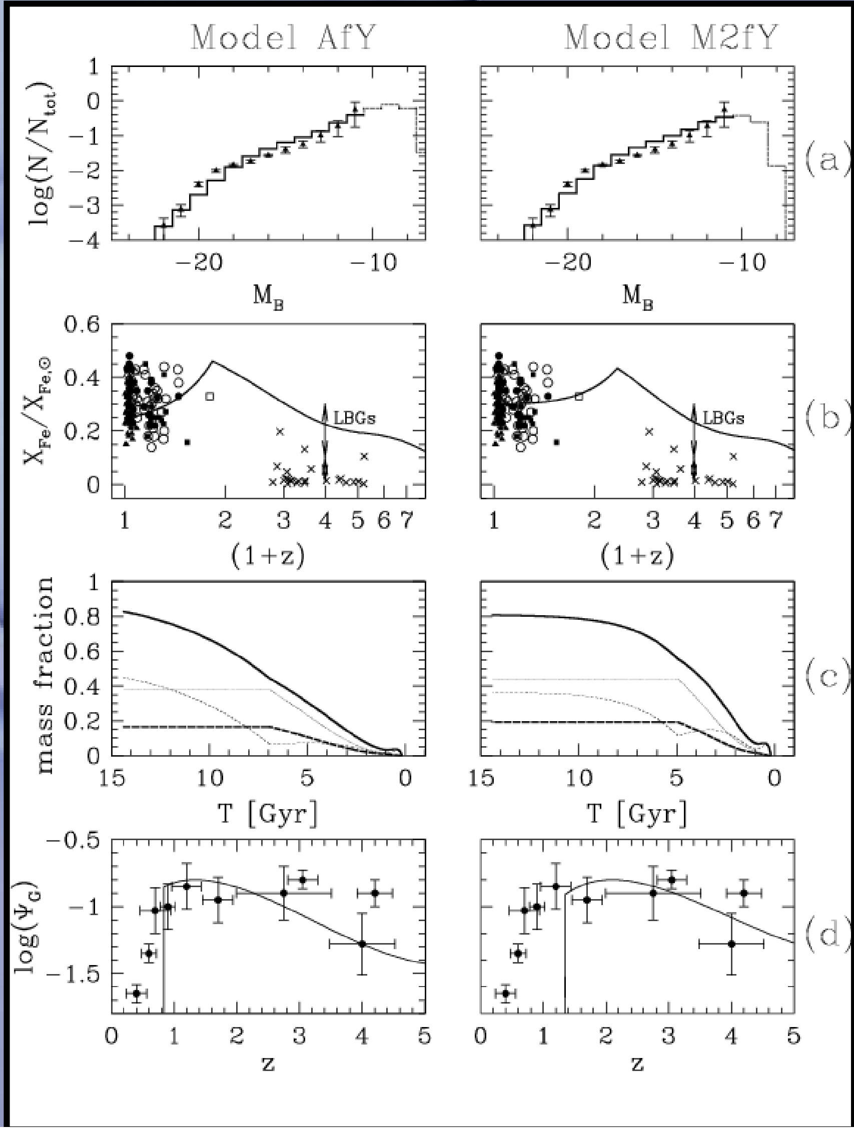
IMF: SALPETER

Results: Two Best Models (AfY & M2fY)

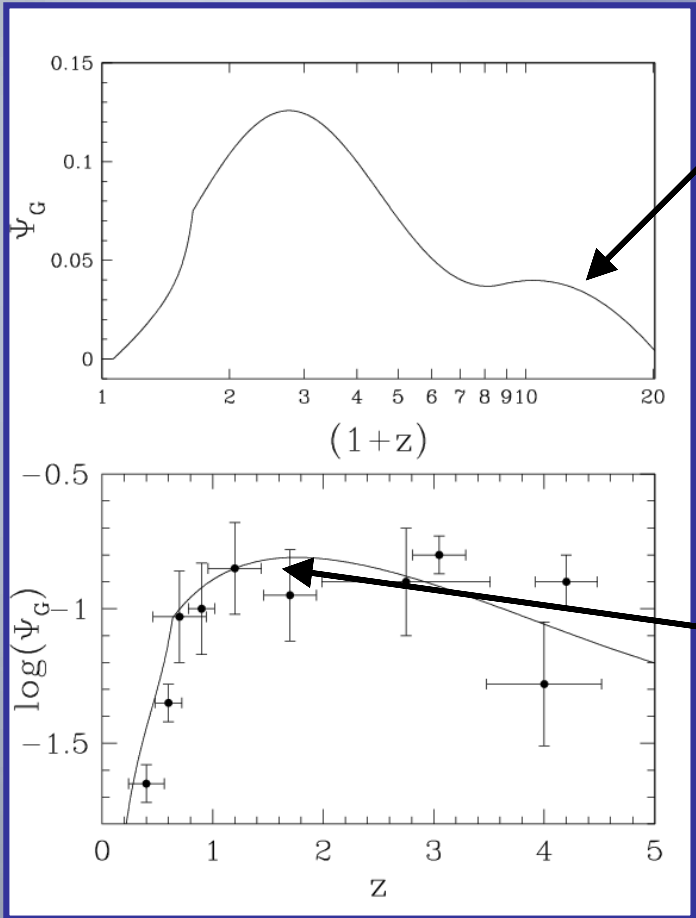
IMLR	0.0184	0.0215
Mgal LT	8.2	9.4
MGW Mgal	2.26	2.29
MICM LT	40.6	39.2
XFe ICM XFe O	0.247	0.299
[O/FE]	0.163	0.164

IMF: Flatter than PNJ

M_{nor} = 3E14 Mo



Results from Smoother GFRs



First episode of star formation during the first infall - **dwarf galaxies**

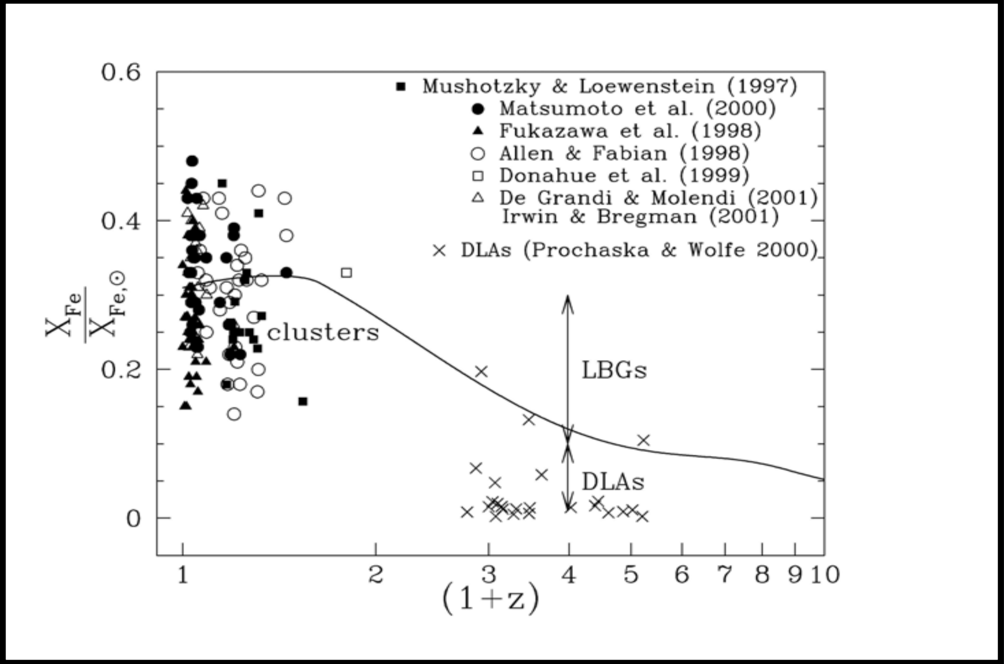
Possibly associated with the reionization epoch and to the reheating of the ISM?

Peak of the star formation activity at redshift 1-2, according to the Madau-plot

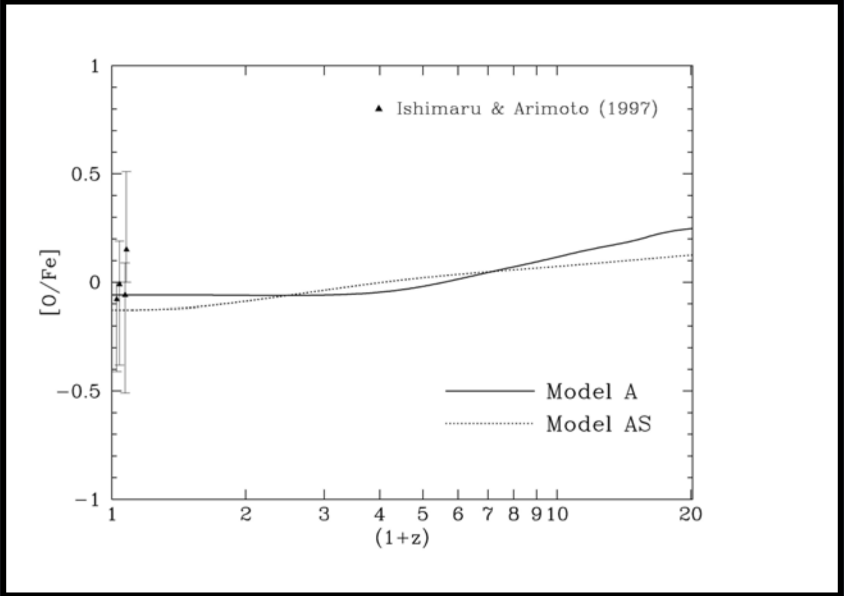
Is there any relationship ?

Results from Smoother GFRs

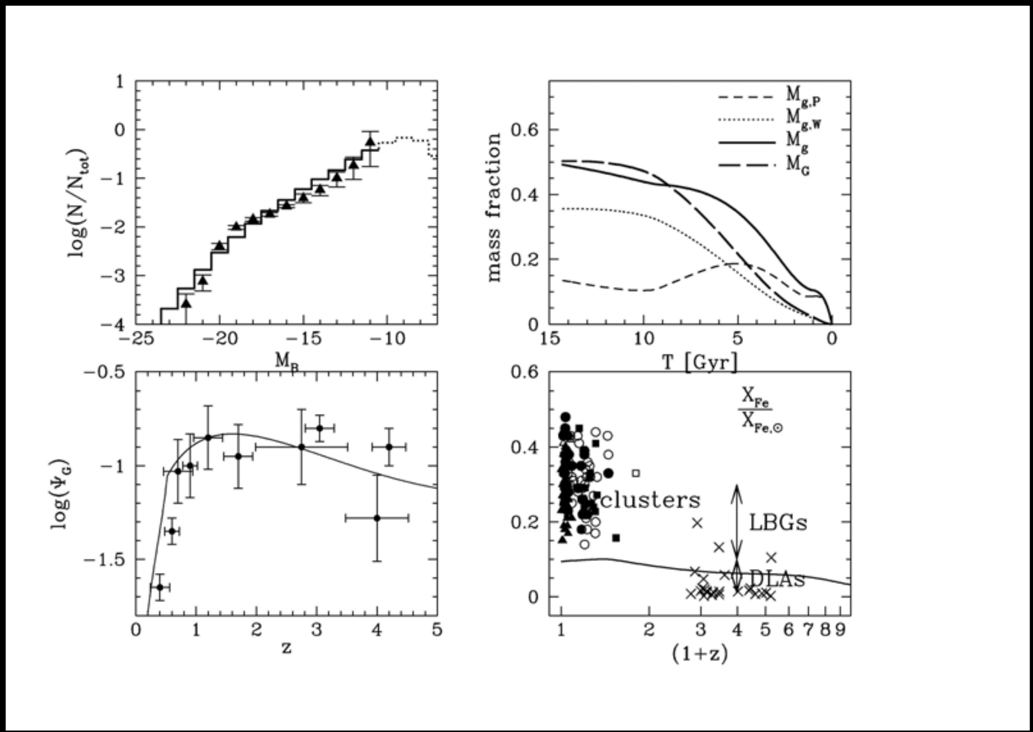
Iron abundance



[O/Fe] ratio



Results from Smoother GFRs
Comparison with the Salpeter IMF



All but the iron abundance is in agreement with observations…

Salpeter IMF is not able to reproduce both the iron and the gas content of the ICM a the same time

Can the *Salpeter* IMF explain the IMLR ?

Define $IMLR_{SSP} = M_{Fe} / L_B$

Single Slope Salpeter IMF with mass limits 0.1 – 100 Mo

This is already too efficient in metal production !!!!!
A steeper IMF at high masses would be better.

Tab 1. Metal Production by SSP with the Salpeter IMF

T (Gyr)	M(T)	N_Ia	MFe_Ia	N_Ia/N_II	MFe_Ia/MFe_II	MFe_T	[O/Fe]
1	2.2	5.5e-4	3.9e-4	0.09	0.8	0.9e-3	0.20
2	1.6	1.0e-3	7.0e-4	0.16	1.4	1.2e-3	0.08
5	1.2	1.4e-3	9.9e-4	0.22	2.0	1.5e-3	-0.01
10	1.0	1.5e-3	1.1e-3	0.24	2.2	1.6e-3	-0.04
15	0.9	1.6e-3	1.1e-3	0.25	2.2	1.6e-3	-0-04

Can the *Salpeter* IMF explain the IMLR? - 2

Remember that for the same IMLR and observed stellar metallicities, the same IMF with different M_L would yield much different amounts of looked up Fe and in turn different contributions to the ICM (Table 1 is for M_L=0.1 Mo).

IMLR for a Salpeter SSP can be compatible with that observed in clusters provided we are dealing with old SSP and provided a large part of the IMLR gets dispersed into the ICM (IMLR : 0.01—0.015).

Presence of young staff (spirals or late SFR) in the cluster would decrease IMLR. If dealing with an old SSP and Salpeter IMF, the M/L ratio is much lower than estimated by White et al. (1993) or Balogh (2001)…often used to get the partition in mass and metals between ICM and Galaxies.

Tab.2. Luminosity, IMLR & mass evolution of a SSP with Salpeter IMF

T (Gyr)	M_B	L_B	IMLR	M^*_{SSP}	M^*/L_B
1	2.50	0.094	9.2e-4	0.78	0.80
2	6.41	0.426	2.8e-3	0.75	1.74
5	7.43	0.167	9.0e-3	0.72	4.31
10	8.14	0.087	1.8e-3	0.71	8.16
15	8.55	0.059	2.7e-2	0.70	12.50

Can the *Salpeter* IMF explain the IMLR? - 3

Calculate the mass MFe* looked up in stars and MFeICM the dispersed mass; the same for O; finally the corresponding IMLRs.

In the SDGW model (Larson 1974), winds occur earlier than about 1 Gyr. The entries of Table 3 show that in this case little Fe is produced by stars. This is the reason why neglible amounts of Fe are obtained and much lower IMLRs are derived with the Salpeter IMF.

Models with the Salpeter IMF and early GWs CANNOT release sufficient Fe in the ICM if the observed solar stellar abundances are to matched at the same time.

Tab. 3 Based on the assumption that [Fe/H] is nearly solar

T (Gyr)	MFe*	MFe_{ICM}	IMLR*	$IMLR_{ICM}$	MO*	MO_{ICM}	$[O/Fe]_{ICM}$
1	9.4e-4	0	9.6e-4	0	1.0e-2	0	
2	9.0e-4	3.0e-4	2.1e-3	7.0e-4	1.0e-2	0	
5	8.6e-4	6.4e-4	5.0e-3	3.8e-3	9.6e-3	4e-4	-1.05
10	8.5e-4	7.5e-4	9.8e-3	8.6e-3	9.5e-3	5e-4	-1.02
15	8.4e-4	7.6e-4	1.5e-2	1.4e-3	9.4e-3	6e-4	-0.95

Can the Salpeter IMF explain the IMLR? – 4

However, if the total Fe production is available to be dispersed then it is possible for old SSPs to reach the observed IMLRs → MV88 who suggested that if all the Fe produced by SN Ia escapes the galaxies then MFe and ILMR of ICM can be reproduced. But Dark Matter….potential well.. SN Ia cannot escape the galaxy (however, Pipino et al. 2002 for opposite conclusion).

If star formation in EGs is of short duration (< 1 Gyr) → typical [O/Fe]=0.2. If [Fe/H] is solar → X_{O*} =1.33e-2 → Most Oxygen is looked in stars → little Oxygen left out to enrich ICM (see Tab. 3).

Tab.4 Based on the assumption that [O/H] is nearly solar

T (Gyr)	MO*	MO_{ICM}	MFe*	MFe_{ICM}	ILRM*	$ILRM_{ICM}$	$[O/Fe]_{ICM}$
1	6.5e-3	3.5e-3	5.8e-4	3.2e-4	5.9e-4	3.2e-4	0.19
2	6.2e-3	3.8e-3	5.6e-4	6.4e-4	1.3e-3	1.5e-3	-0.07
5	6.0e-3	4.0e-3	5.4e-4	9.6e-4	3.2e-3	5.7e-3	-0.22
10	5.9e-3	4.1e-3	5.3e-4	1.1e-3	6.1e-3	1.3e-2	-0.27
15	5.8e-3	4.2e-3	5.2e-4	1.1e-3	8.8e-3	1.9e-2	-0.27

Can the Salpeter IMF explain the IMLR? - 5

If we assume that [O/H] is nearly solar and [O/Fe] is still 0.2, we get the data of Tab.4. → The conclusion about $IMLR_{ICM}$ and the need of after GW enrichment from SN Ia remain unchanged.

We demostrated that unavoidably the Salpeter GW models give a negligible Fe and O enrichment of the ICM.

We have also shown that it is possible to reproduce the observed IMLR in thw ICM with a Salpeter IMF, provided all the metals ever produced (all SN Ia included) are expelled from the galaxy to enrich the ICM. However the corresponding [O/Fe] ratios are highly under-solar at odds with observations.

At early times the IMF had to be different.

Most likely in EGs (and ICM) the IMF is flatter if not top heavy and changing with the environment, time, etc..

Final Conclusions

High metallicity of ICM interpreted on the base of SNDGW model for EGs.

Toy model is presented connecting the final luminosity function to the metal enrichment history of ICM.

The observed LF can be reproduced with a Madau-like GHF peaking at z =1-2 plus a burst of formation of DG at high redshift.

Galaxy models calculated with a variable IMF favouring the formation of massive stars at high redshift and or in more massive.

At given galactic luminosity these EGs eject into the ICM eject more gas and metals than those based on the Salpeter IMF.

Conclusions (cont.)

The mass in wind-ejected gas is predicted to exceed the mass in galaxies by a factor of 1.5—2 and to constitutes roughly half of the ICM gas.

However even the kind of IMF we are using appears to be too mild to account for the observed metal production in clusters.

The high MFe/L of the ICM can be reproduced only by assuming a more dramatic variation of the stellar scale mass.

Although our model is still far from solving all the problems related to the ICM, perhaps it is on the right track….

Cum sint difficilia

………….. tria,

Quartum nescit penitus,

Quod est natura rerum

In multibus sideribus