Cosmic Star Formation, Reionization, and Constraints on Global Chemical Evolution

GRB rate at high z

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(see Daigne et al. 2004, astroph 0405355)

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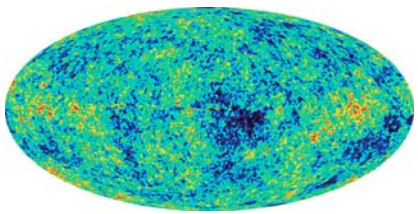
Introduction



WMAP : ΛCDM cosmology
TE cross-correlation power spectrum consistent with a large optical depth due to electron scattering : $\tau_e = 0.17 \pm 0.04$ (Kogut et al. 03)

This suggests a very early epoch (z ~ 20) of reionization in the IGM.

It is often suggested that this early reionization is initiated by very massive pop. III stars (e.g. Oh et al. 01; Cen 03; Bromm 04).

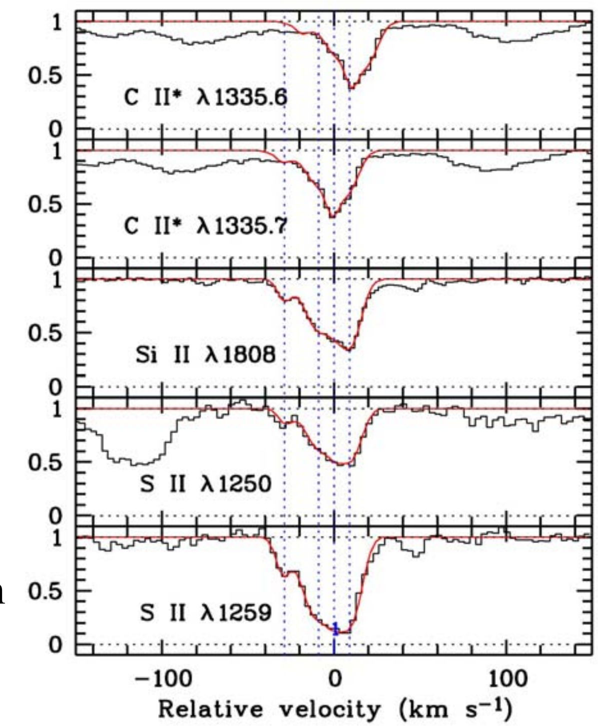
Metal abundances are now measured not only locally but also at high redshift :

- In massive star forming galaxies (Shapley et al. 04),
- In the Lyman α forest (Songaila 01; Simcoe et al. 04; Aguirre, Schaye et al. 04),
- In DLA systems (Pettini et al. 02; Ledoux et al. 03; Prochaska et al. 03).

These new observations strongly constrain the cosmic evolution of the stellar formation.

Additional possible constraints on the early star formation come from the observation of **extremely metal-poor stars**, as for instance :

HE 0107-5240 ([Fe/H]~ -5.3) (Christlieb et al. 04)
CS 22949-037 ([Fe/H] ~ -4) (Depagne et al. 02)



DLA in Q0405-43 at z=2.8
(Ledoux, Petitjean & Srianand 03)

Understanding the early star formation

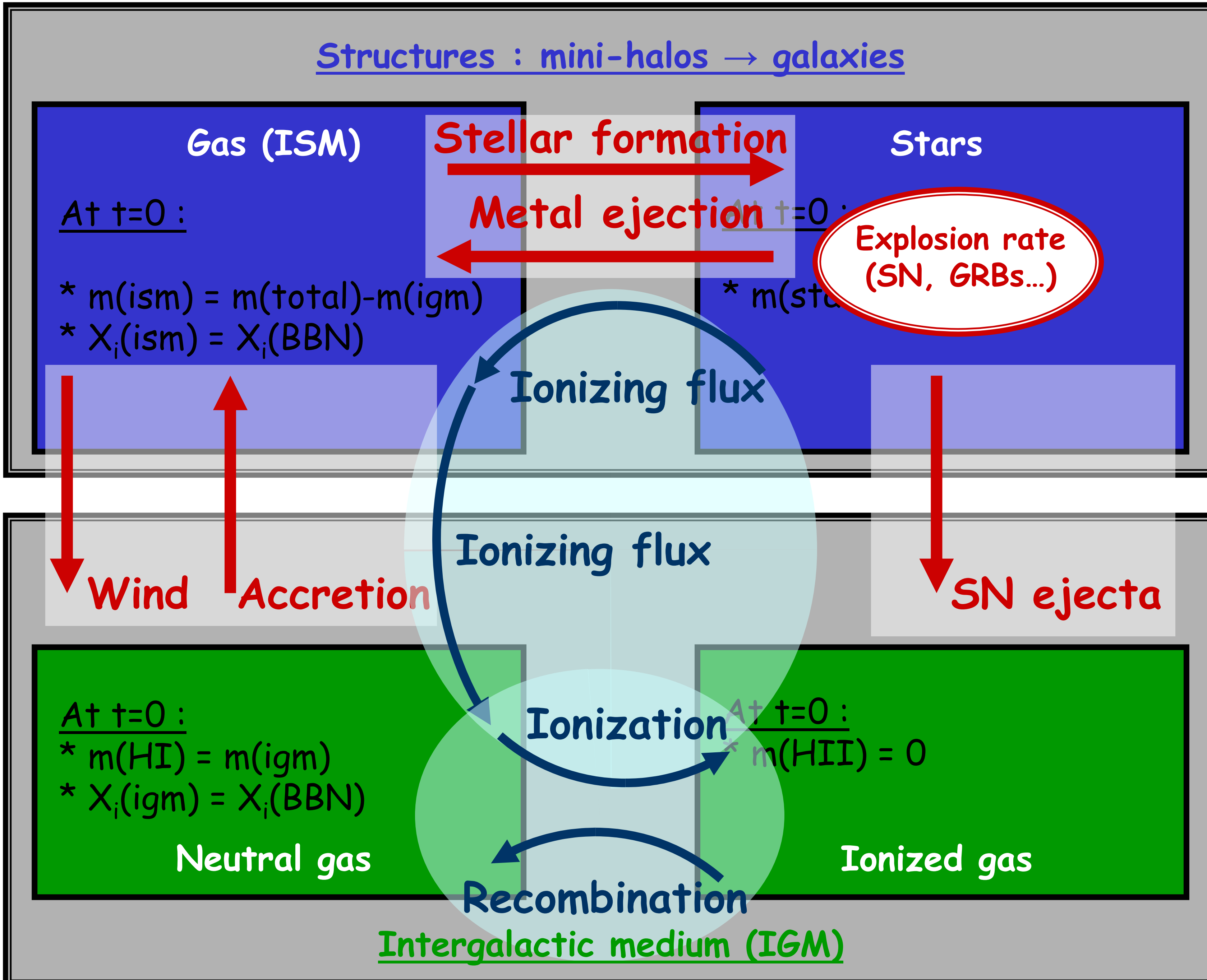
- Motivated by these new observations, we consider several cosmic star formation scenarios which are capable to reionize the early IGM, in the framework of the so-called concordance cosmological model.

- **We have developed a model which follows consistently the metal production, the explosion rates and the ionizing photon flux from the epoch of formation of the first stars (z ~ 20) up to now (z=0).**

Precisely, we compute the global SFR, the ionizing flux (H^+, He^+ and He^{++}), the stellar explosion rates (SN Ia, SNII, Ibc and GRBs), and the evolution of the abundances of D, ^4He, C, N, O, Si, S, Fe and Zn both in the gas in the structures (ISM) and in the intergalactic medium (IGM) as a function of time/redshift.

- This new approach allows to test several scenarios of cosmic star formation (SFR and IMF) and to distinguish models which can reionize the early IGM and simultaneously reproduce all the observed constraints.

- An important by-product of this model is the capacity to predict the rate of GRBs at high redshift. These very energetic phenomena should be observed at z > 6~8 in the coming years and are therfore a very promising tool to probe the high redshift Universe.


Structures : mini-halos → galaxies
Gas (ISM)
Stellar formation
Stars
Metal ejection
At t=0 :
At t=0 :
Explosion rate
(SN, GRBs…)
* m(ism) = m(total)-m(igm)
* X_i(ism) = X_i(BBN)
* m(sta
Ionizing flux
Ionizing flux
Wind
Accretion
SN ejecta
Ionization
At t=0 :
* m(HI) = m(igm)
* X_i(igm) = X_i(BBN)
At t=0 :
* m(HII) = 0
Neutral gas
Ionized gas
Recombination
Intergalactic medium (IGM)

Parameters

i. Initial redshift at which star formation begins : $z_{init} = 20$

$\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$ and $h = 0.71$ (Spergel et al. 2003)

$$\frac{dt}{dz} = \frac{9.78\ h^{-1}\ \mathrm{Gyr}}{(1+z)\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

Parameters

i. Initial redshift at which star formation begins : $z_{init} = 20$

ii. SFR and IMF

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i. Initial redshift at which star formation begins : $z_{init} = 20$

ii. SFR and IMF

iii. Cosmic baryon accretion rate :

Initial $a_{init} \sim 1$ % of baryons in mini-halos at $z = 20$ (Mo & White 02)

Present time : ~ 10-15 % (Fukugita, Hogan & Peebles 98 ; Dickinson et al. 03)

Structure formation :

Early slow or fast : $$a_b(t) = \frac{a}{\tau_s} M_{tot} \exp\left(-t/\tau_s\right)$$

Late and fast : $$a_b(t) = a M_{tot} \, \delta(t - t_0)$$

Parameters

i. Initial redshift at which star formation begins : $z_{init} = 20$

ii. SFR and IMF

iii. Cosmic baryon accretion rate

iv. Gas outflow (structures → IGM) : two components

Global outflow powered by stellar explosions (galactic wind)

\+ Fraction of SN ejecta (« chimneys »)

Parameters

ii. SFR and IMF

iii. Cosmic baryon accretion rate

Parameters

i. Initial redshift at which star formation begins : $z_{init} = 20$

ii. SFR and IMF

iii. Cosmic baryon accretion rate

iv. Gas outflow (structures → IGM)

We follow as a function of time/redshift :

- the mass of each baryon reservoir (IGM ; structures = ISM + stars)

$$\frac{dM_{\rm igm}}{dt} = -a_{\rm b}(t) + o(t) \qquad \frac{dM_{\rm struct}}{dt} = a_{\rm b}(t) - o(t) \qquad \frac{dM_{\rm ism}}{dt} = (-\psi(t) + e(t)) + (a_{\rm b}(t) - o(t))$$

- the chemical composition of the ISM and the IGM
- the cosmic star formation rate
- the production of ionizing photons by stars
- the stellar explosion rates (SN Ia, SNII, GRBs)

Model 0 : a standard model

IMF 0 : 0.1 – 100 $M_\odot$ $\phi(m) \propto m^{-(x+1)}$ $x = 1.7$

SFR 0 : $\propto$ gas mass fraction in the structures (timescale 5 Gyr)

Model 1 : model 0 + massive mode

IMF 0 + IMF 1 : 40 – 100 $M_\odot$

SFR 0 + SFR 1: exponentially decreasing mode (timescale 50 Myr)

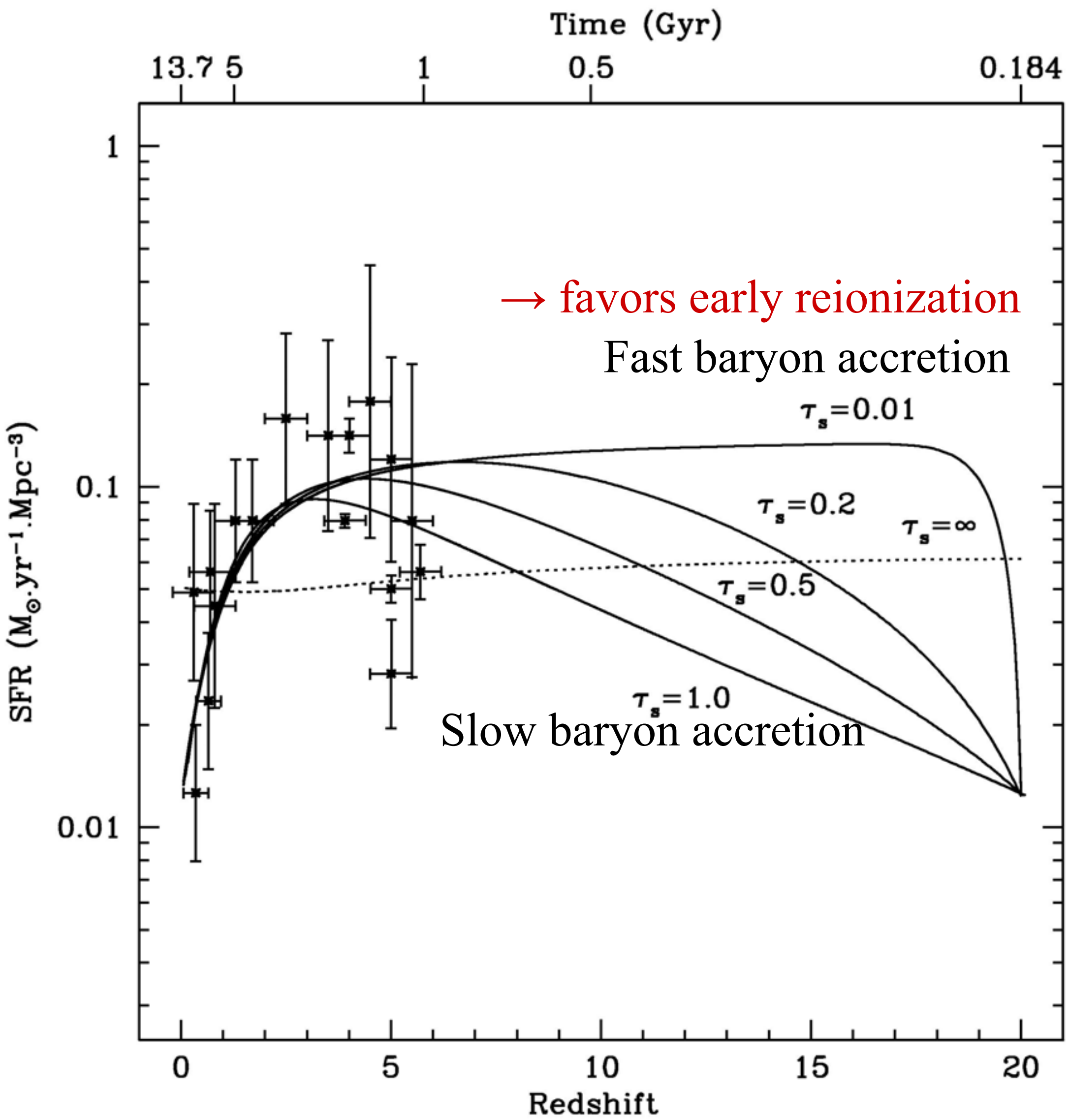
Model 2 : model 0 + very massive mode

IMF 0 + IMF 2a : 140 – 260 $M_\odot$ or 270 – 500 $M_\odot$

SFR 0 + SFR 2a,b : exponentially decreasing mode (timescale 50 Myr)

Stellar yields are taken from van den Hoek & Groenewegen 97,
Woosley & Weaver 95 and Heger & Woosley 02.

Cosmic Star Formation Rate



Model 0 : « standard model »

Mass range :

IMF 0 : 0.1-100 $M_\odot$

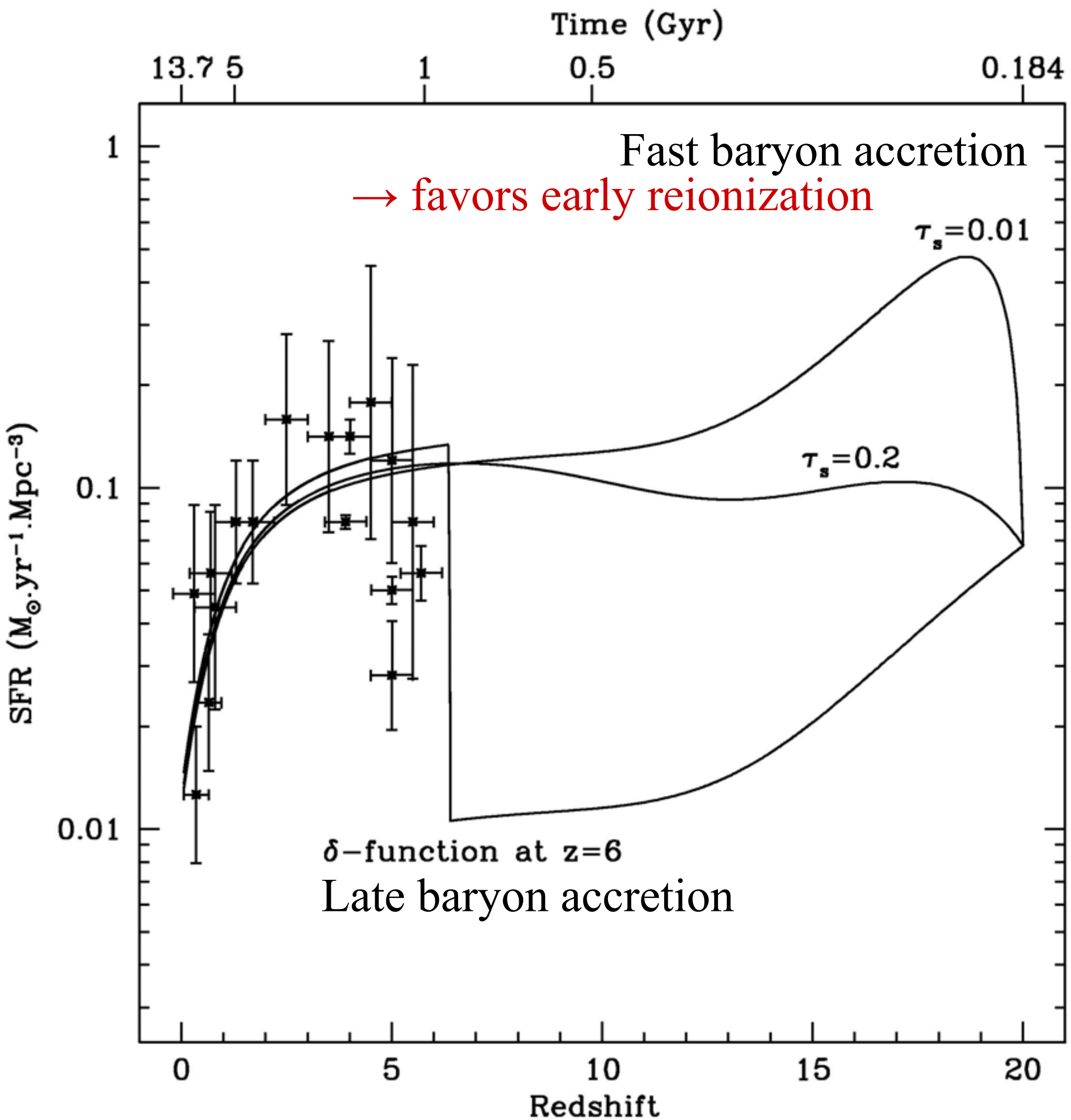
The accretion of baryons by the structures has to be finished before ~ 1 Gyr.

Characteristic SFR timescale :

SFR 0 : 5 Gyr

SFR data : Lilly et al. 96 ; Pascarelle et al. 98 ; Iwata et al. 03 ; Ouchi et al. 03 and Giavalisco et al. 04

Cosmic Star Formation Rate



Model 1 : model 0
+ massive stars

Mass range :

IMF 0 : 0.1-100 $M_\odot$

\+ IMF 1 : 40-100 $M_\odot$

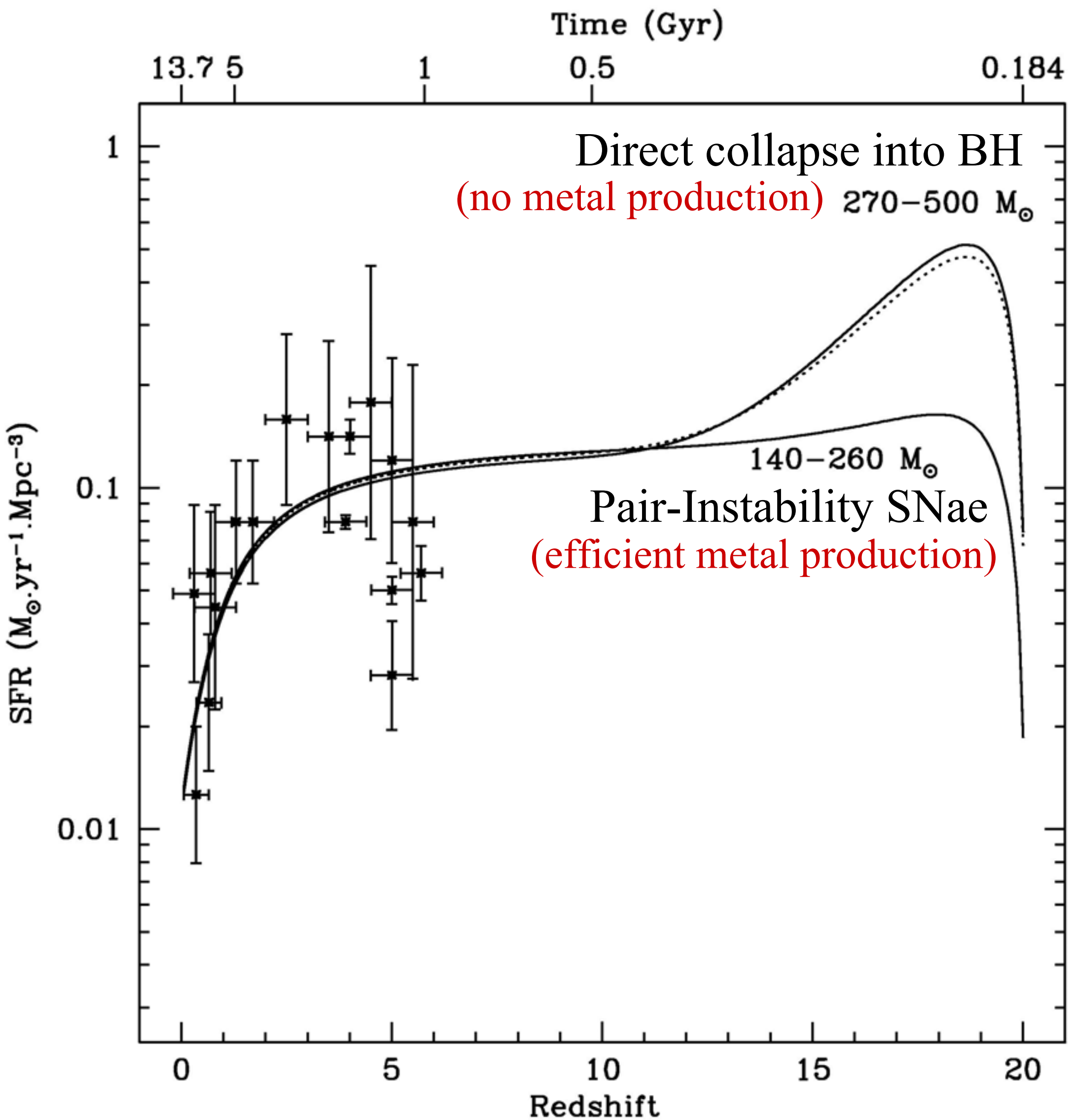
Characteristic SFR timescale :

SFR 0 : 5 Gyr

SFR 1 : 50 Myr

SFR data : Lilly et al. 96 ; Pascarelle et al. 98 ; Iwata et al. 03 ; Ouchi et al. 03 and Giavalisco et al. 04

Cosmic Star Formation Rate



Model 2 : model 0

+ very massive stars

Mass range :

IMF 0 : 0.1-100 $M_\odot$

\+ IMF 2a : 140-260 $M_\odot$

or IMF 2b : 270-500 $M_\odot$

Characteristic SFR timescale :

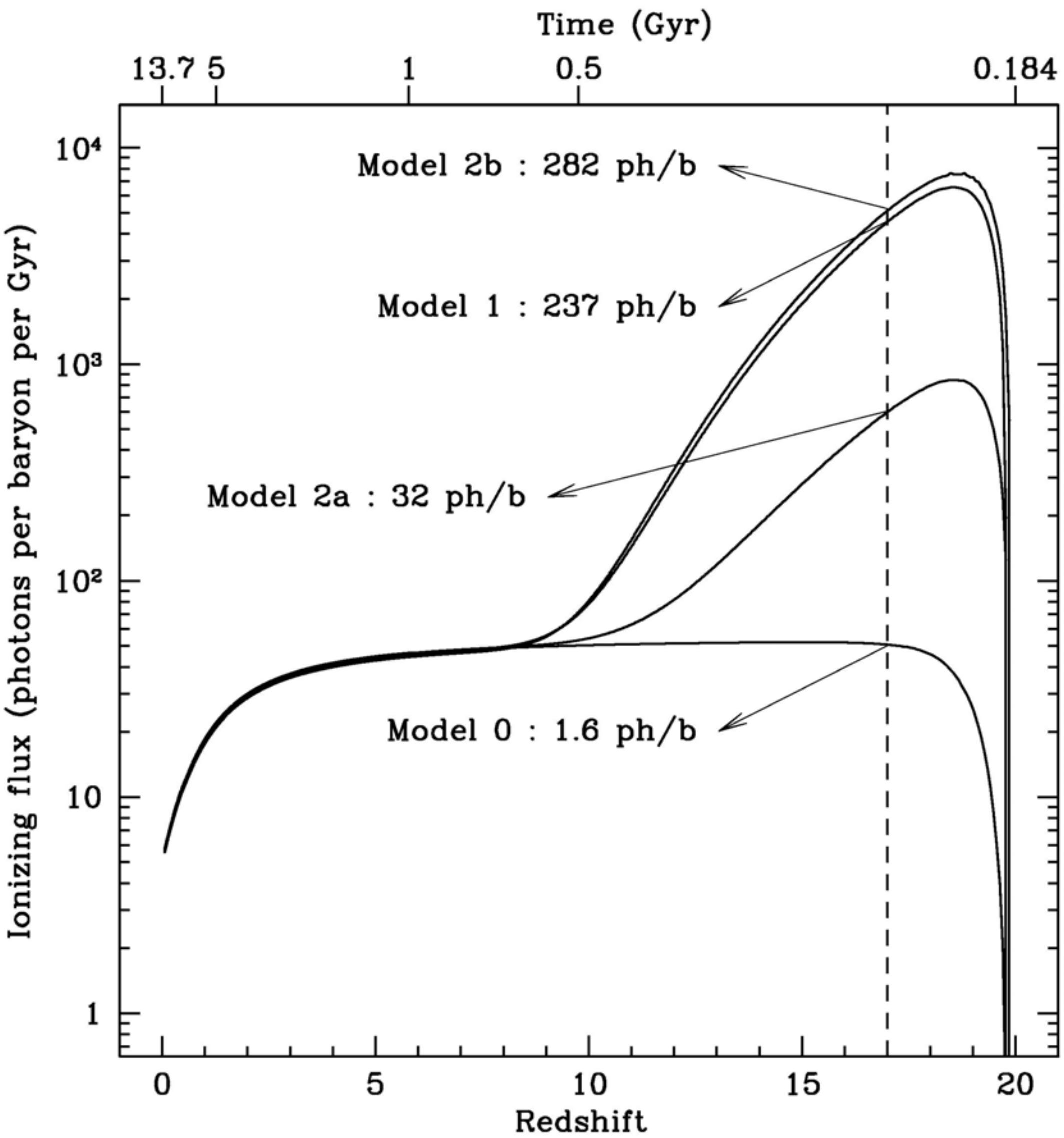
SFR 0 : 5 Gyr

SFR 2 : 50 Myr

SFR data : Lilly et al. 96 ; Pascarelle et al. 98 ; Iwata et al. 03 ; Ouchi et al. 03 and Giavalisco et al. 04

Ionizing flux

Uncertainty : only a fraction $f_{esc} \sim 0.03 - 0.5$ of these ionizing photons escape the structures and contribute to the reionization of the IGM.

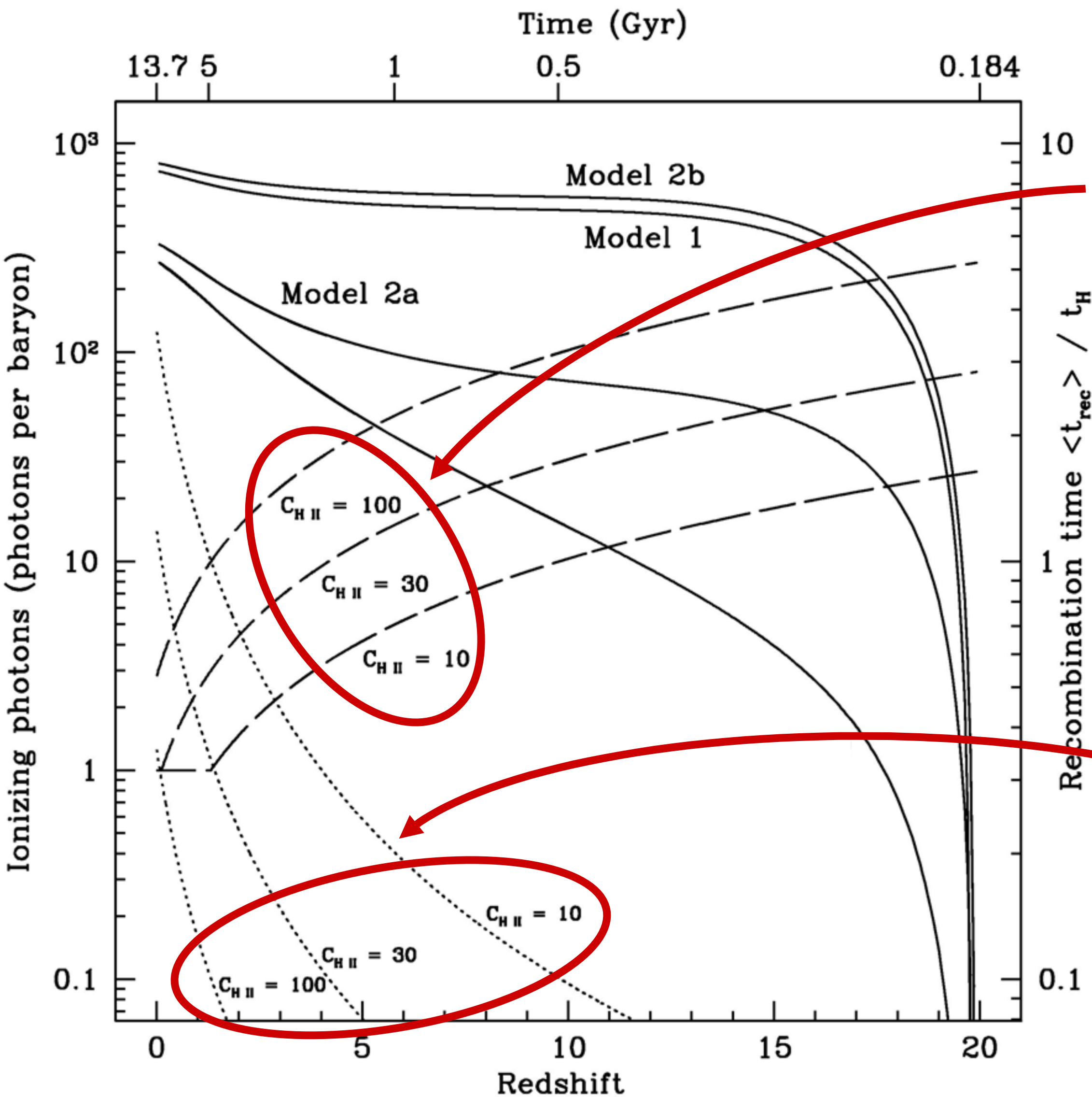


Model 1 and model 2a,b allow an early reionization of the IGM.

A massive mode is required !

Model 0 alone cannot reionize the IGM at early times.

Ionizing photons per baryon

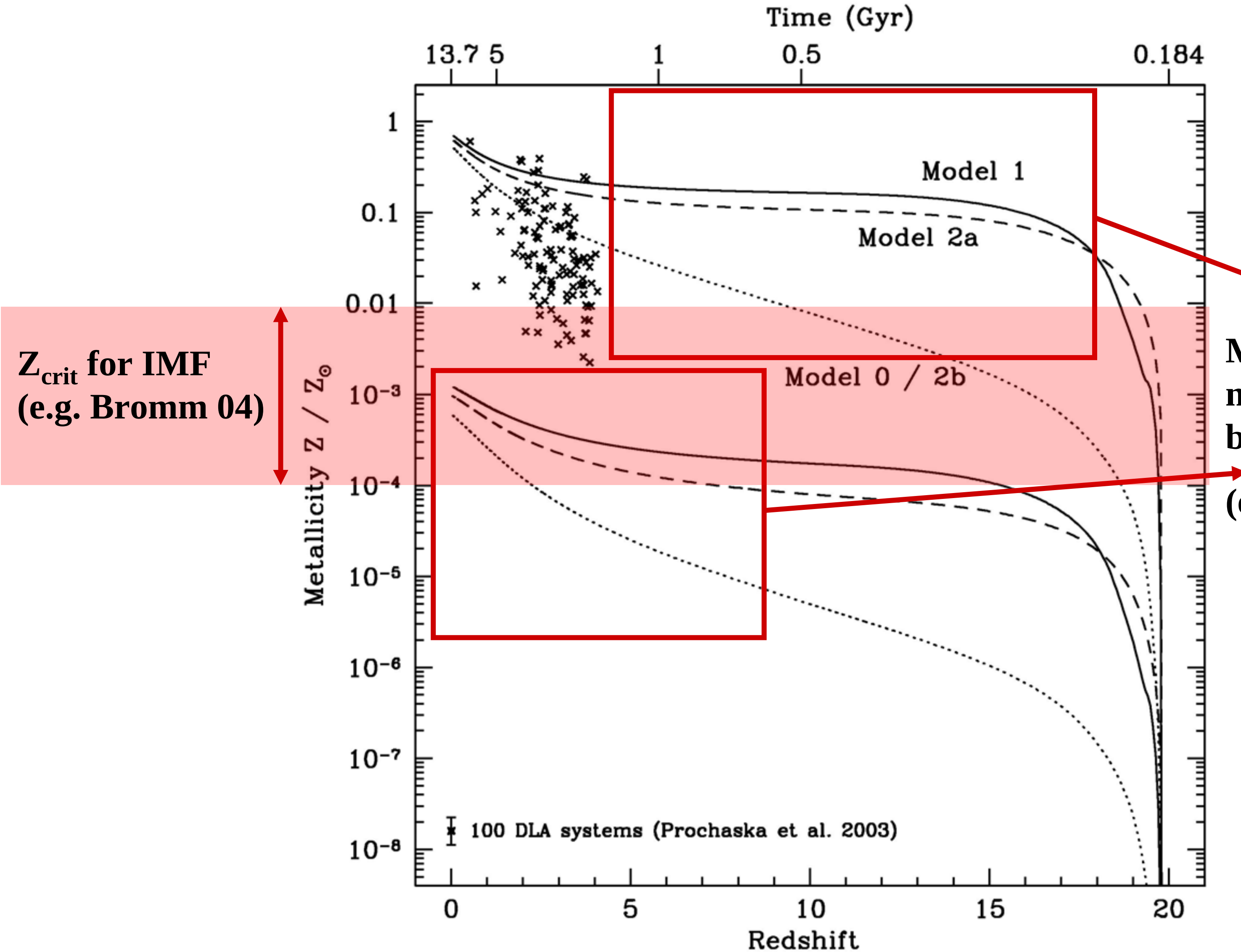


$$
\begin{aligned}
n_{\gamma,\,\mathrm{min}} &= \left(\frac{\langle t_{\mathrm{rec}}\rangle}{t_{\mathrm{H}}}\right)^{-1} \\
&= 22\left(\frac{1+z}{18}\right)^{1.5}\left(\frac{C_{\mathrm{H\,II}}}{10}\right)\ \text{ph/b if } \langle t_{\mathrm{rec}}\rangle < t_{\mathrm{H}} \\
&= 1\ \text{ph/b otherwise}
\end{aligned}
$$

Model 1 and 2b allow an early reionization of the IGM even for a high clumpiness factor.

$$
\frac{\langle t_{\mathrm{rec}}\rangle}{t_{\mathrm{H}}} = 0.046\left(\frac{1+z}{18}\right)^{-1.5}\left(\frac{C_{\mathrm{H\,II}}}{10}\right)^{-1}
$$

Global metallicity

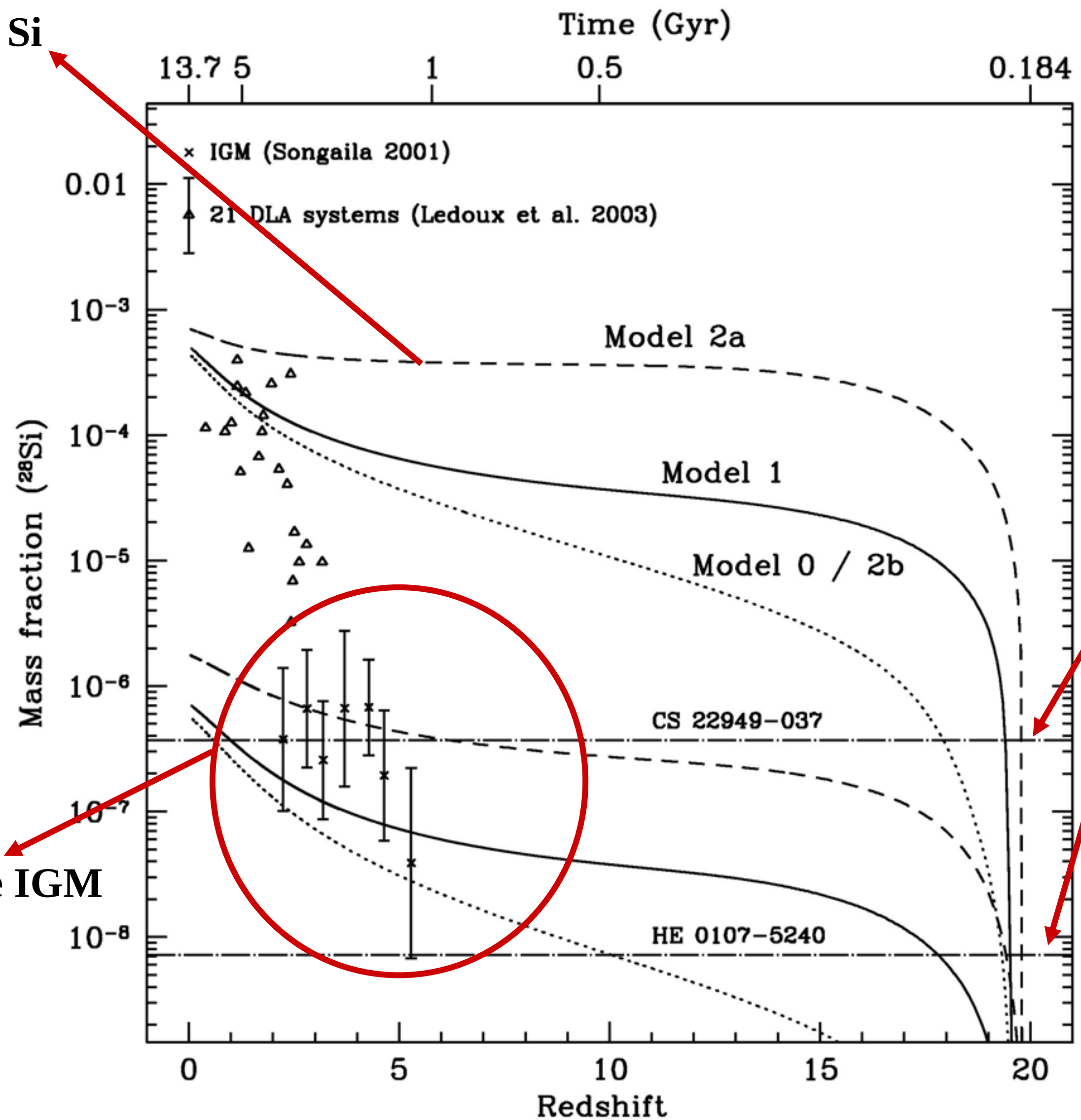


More observations are needed to distinguish between the models.

(especially at high z!)

Silicon

PISNae stars overproduce Si

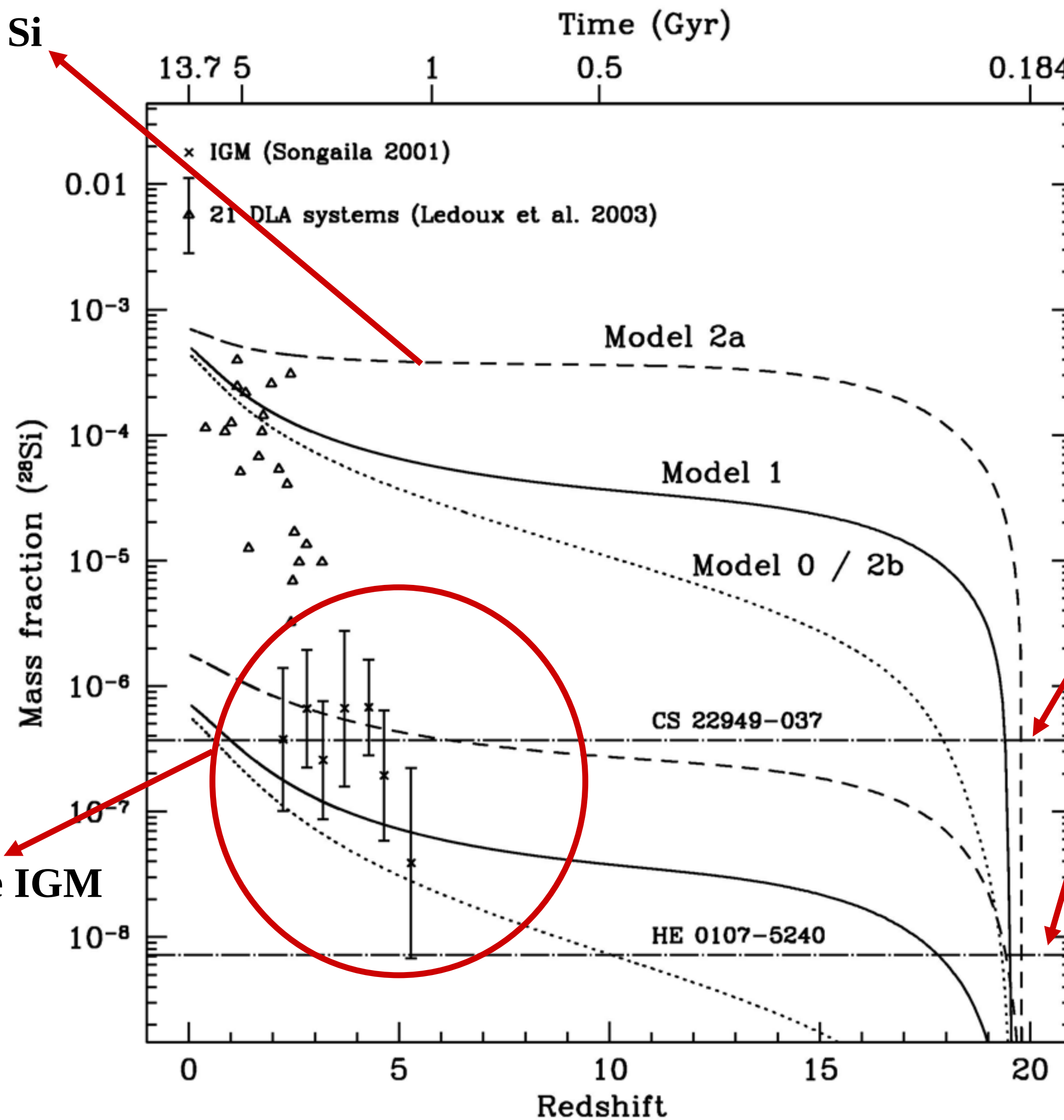


Extremely metal-poor halo stars could trace the early metal enrichment by pop. III stars.

Abundance determination in the IGM are now available.

Silicon

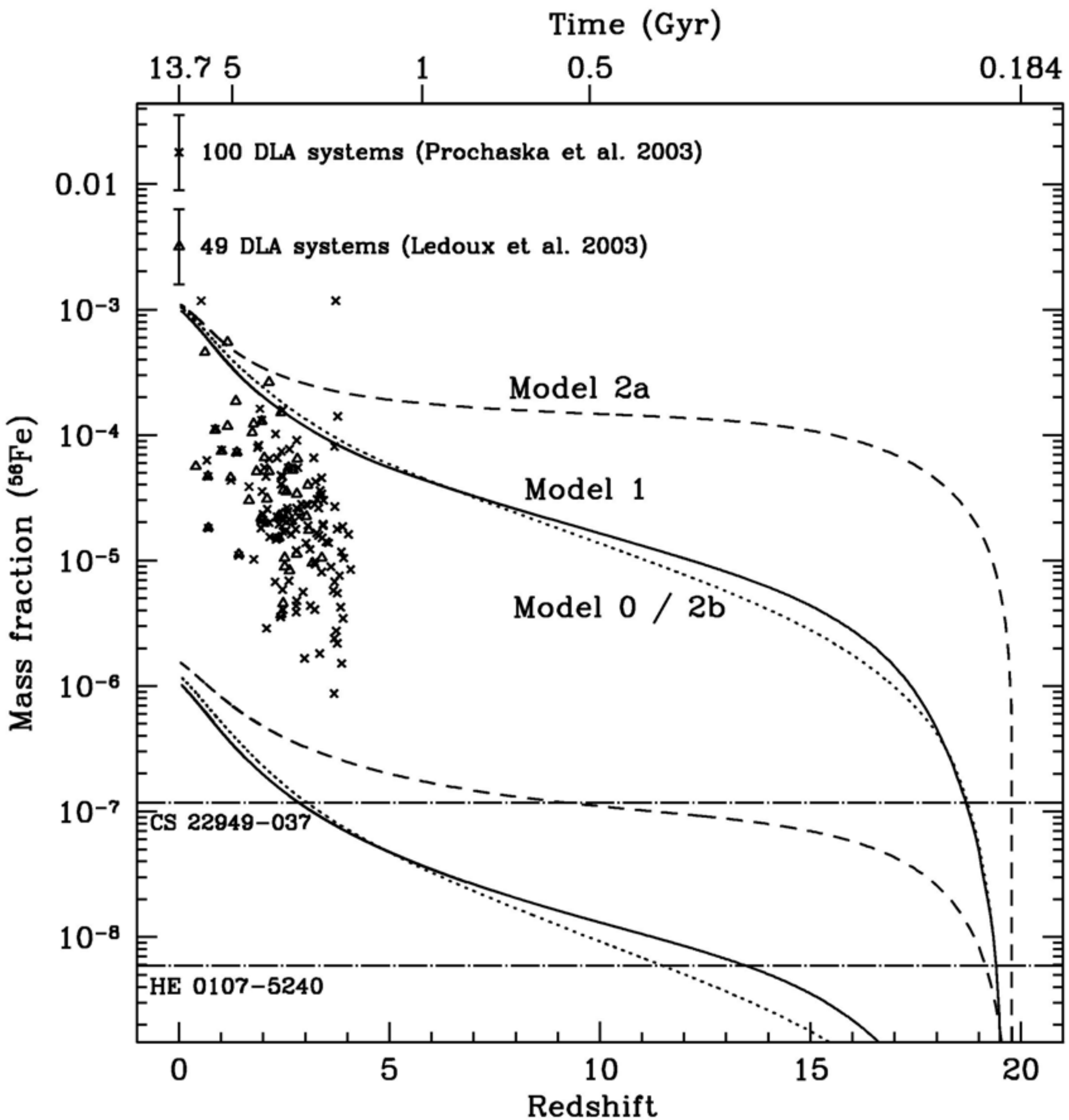
PISNae stars overproduce Si



Extremely metal-poor halo stars could trace the early metal enrichment by pop. III stars.

Abundance determination in the IGM are now available.

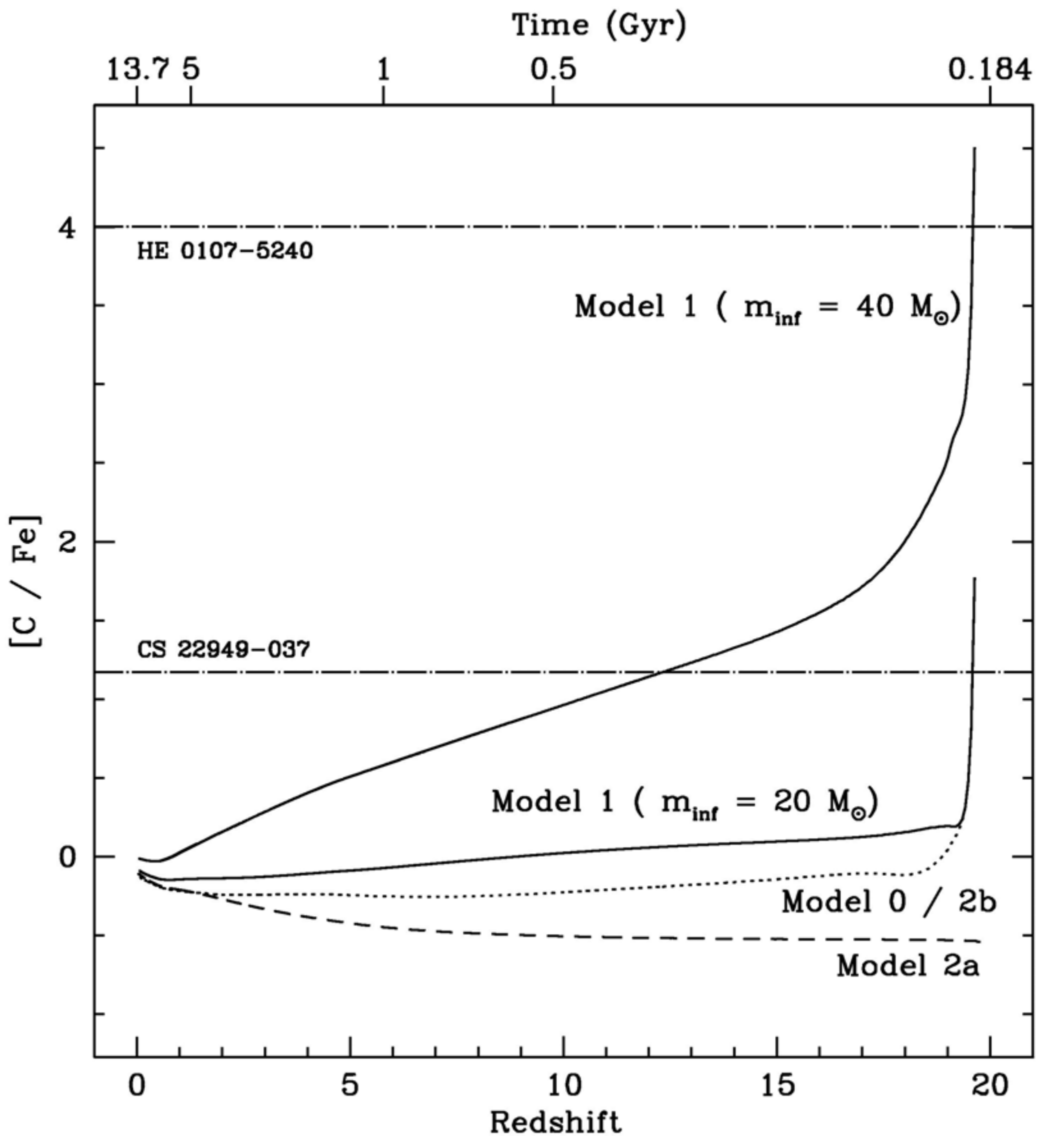
Iron



Time (Gyr)
13.7
5
1
0.5
0.184
100 DLA systems (Prochaska et al. 2003)
49 DLA systems (Ledoux et al. 2003)
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Mass fraction (^{56}Fe)
Model 2a
Model 1
Model 0 / 2b
CS 22949-037
HE 0107-5240
0
5
10
15
20
Redshift

Carbon to Iron ratio

If extreme metal-poor halo stars are used as tracers of the high-z star formation, their very peculiar abundance ratios put severe constraints on the pop. III stellar mass range.



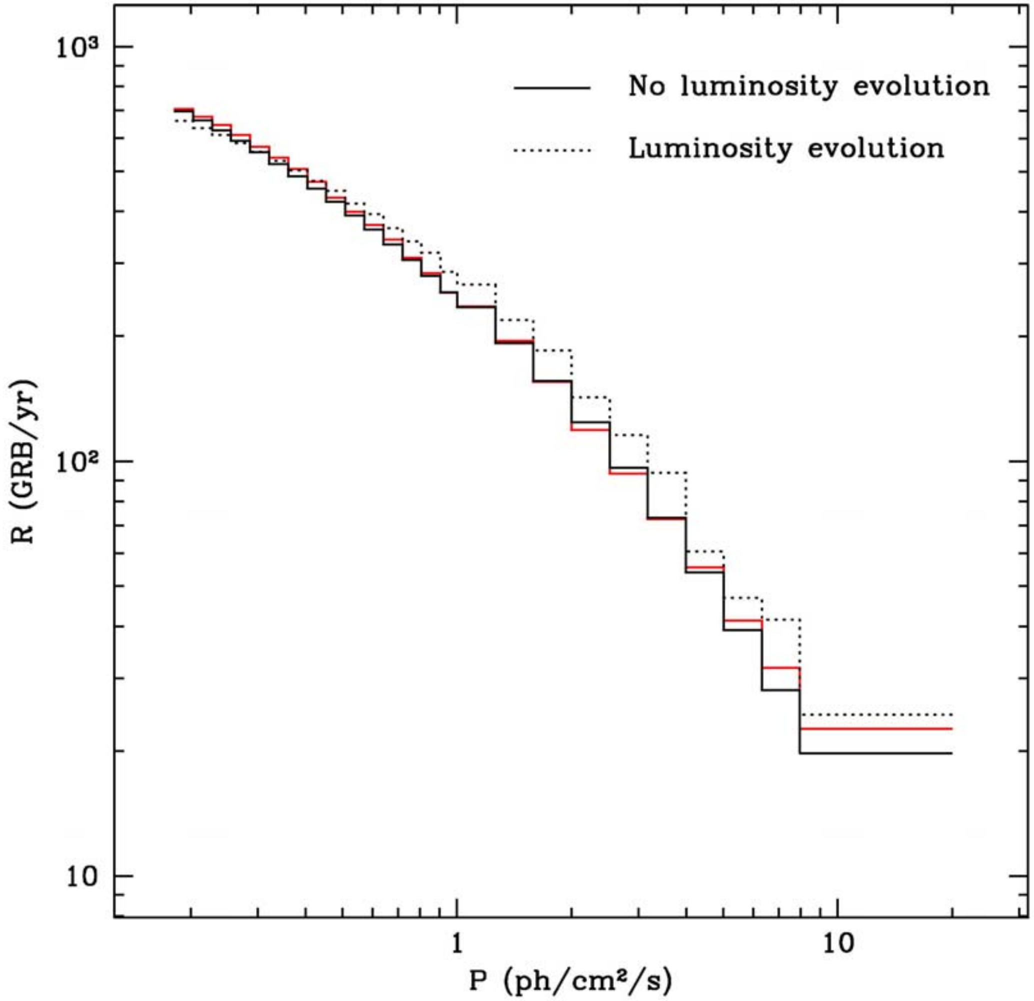
Model 1 can explain [C/Fe] in extremely metal-poor halo stars and it is even possible to constraint the lower mass of the massive mode.

Model 0 and 2a,b cannot explain [C/Fe] in extremely metal-poor halo stars.

Gamma-ray bursts

Assumption : (long) GRBs are produced by collapsars, i.e. the collapse of massive stars into a BH.

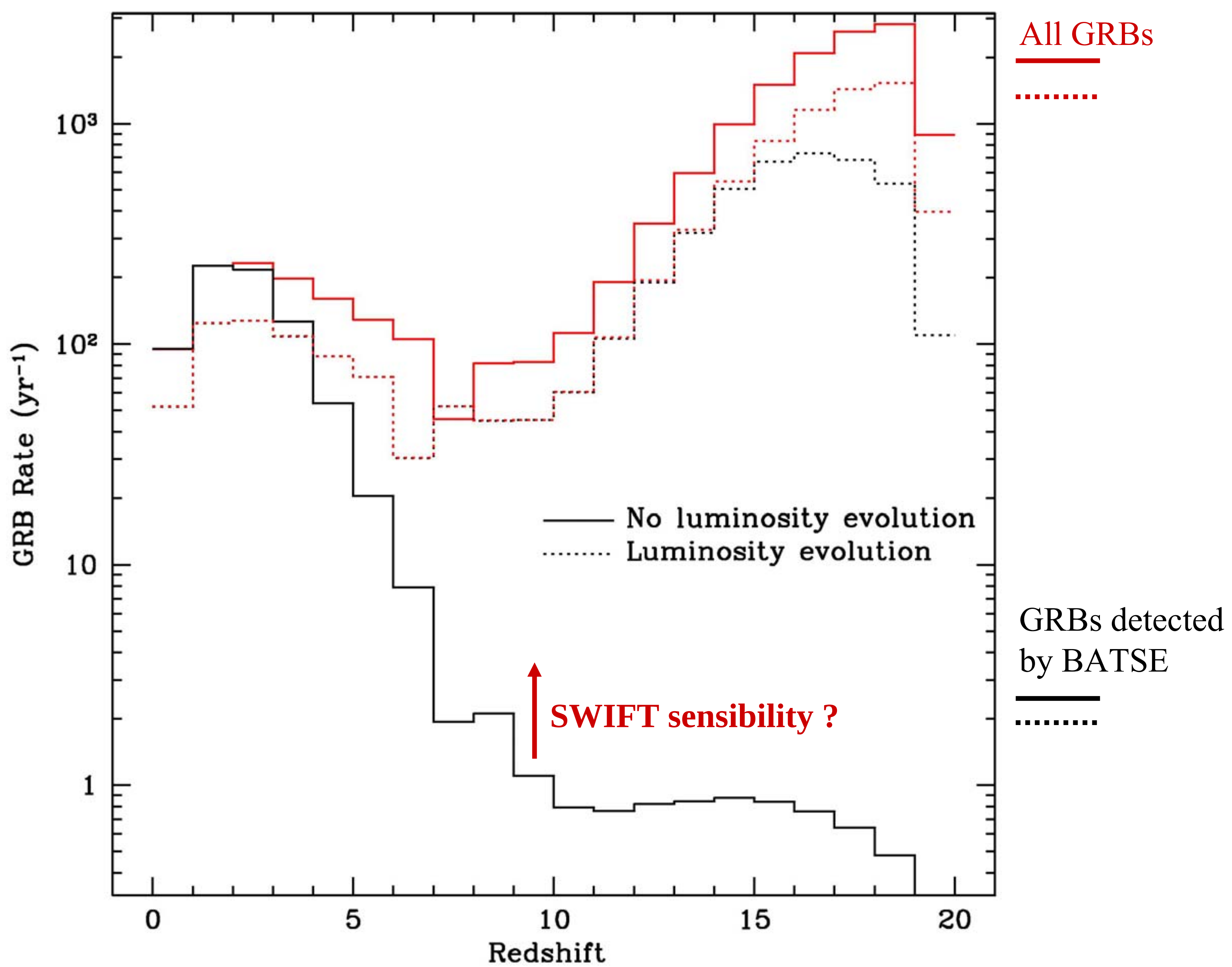
Because of unkown conditions (rotation, binarity, … ?), only a fraction **f** of these stars can produce a GRB. We adjust **f** to fit the observed **log N – log P** diagram (BATSE data). We can then predict the observed rate of GRB as a function of redshift.



$f \sim (3\text{-}6) \times 10^{-5}$

Gamma-ray bursts

Model 1



Summary

We have calculated the combined effect of an early population of massive stars on the reionization history and chemical enrichment history of the early cosmic structures and of the IGM.

Our main results are : (see Daigne et al. **astroph 0405355**)

- We confirm the need for an early burst of massive star formation to reionize the IGM at z ~15-20.

- We use other constraints to precise the mass range of pop. III stars : our model 1 with an IMF in the range 40-100 $M_\odot$ is preferred over a scenario which includes a component with very massive stars above 100 $M_\odot$.

This « best model » is well suited to account for the observed abundances of C, O, Si, S, Fe and Zn in DLAs as well as C, Si in the IGM, and also for most elements in extremely metal-poor halo stars. It is also capable to reionize the early IGM with a escape fraction of UV photons from the structures of only about 5 %.

- A massive starburst relying mostly on PISNae stars (140-260 $M_\odot$) requires a lower SFR intensity to avoid the overproduction of metals and therefore leads to a weaker ionizing flux. Even so, the overproduction of specific elements (S and Si) seems unavoidable and the peculiar abundance ratios observed in extremely metal-poor halo stars cannot be reproduced.

- A massive starburst relying mostly on very massive stars which collapse entirely into black holes can easily reionize the early IGM but cannot reproduce the cosmic chemical evolution without another massive stellar component.

- If GRB luminosity depends on the initial mass/metallicity of the pregenitor, it is possible that a large fraction of GRBs observed by BATSE occured at high redshift ($z > 10$). The observation of the afterglow of such GRBs is a very promising tool to probe the high-z Universe in the near future (SWIFT).