The puzzling origin of the ^{6}Li plateau

Carmelo Evoli†, Stefania Salvadori & Andrea Ferrara

SISSA/International School for Advanced Studies, Via Beirut 4, 34100 Trieste, Italy

†evoli@sissa.it

XXIVth IAP Colloquium

from July 7th to 11th, 2008

ABSTRACT

We discuss the ^{6}Li abundance evolution within a hierarchical model of Galaxy formation which correctly reproduces the [Fe/H] distribution of metal poor halo stars (MPHS). Contrary to previous findings **[4]**, we find that neither the level (Log ^{6}Li/H= -11.2) nor the flatness of the ^{6}Li distribution with [Fe/H] can be reproduced under the most favorable conditions by any model in which ^{6}Li production is tied to a (data-constrained) Galactic star formation rate (SFR) via cosmic-ray spallation **[1]**. Thus the origin of the plateau might be due to some other early mechanism unrelated to star formation.

Introduction

The relative abundance of light elements synthesized during the Big Bang nucleosynthesis (BBN) is a function of a single parameter, η, namely the baryon-to-photon ratio. Given the WMAP constraint $\boldsymbol{\eta = (6.8 \pm 0.21) \times 10^{-10}}$, the light nuclei abundances can be precisely predicted by BBN (Spergel 2007; Yao & et al. 2006).

Despite a general agreement with the observed abundances of light elements, a discrepancy arise concerning ^{6}Li abundance for which the BBN predicts a value of $\boldsymbol{(^6\mathrm{Li/H})_{BBN} \sim 10^{-14}}$ whereas abundance of ^{6}Li observed in the atmospheres of Galactic Metal Poor Halo Stars (MPHS) reveal the presence of a plateau of **Log ^{6}Li/H = -11.2** for **-3 < [Fe/H] < -1** [3]. A primordial origin of ^{6}Li seems favored by the presence of the plateau; however, the high ^{6}Li value observed cannot be reconciled with this hyphotesis. We investigate then the production of ^{6}Li during Galaxy Formation. In this scenario ^{6}Li is synthesized by fusion reactions ($\alpha + \alpha \rightarrow {}^6$Li) when high-energy CR particles, accelerated by SNe, collide with the ambient gas.

Building the Milky Way

Hierarchical merger tree:

The code **GAMETE** (GAlaxy Merger Tree & Evolution) is a binary Monte Carlo algorithm with accretion mass able to reconstruct the hierarchical merger tree of the Galaxy **[2]**. Looking back in time at any time-step a halo can either lose part of its mass or lose mass and fragment into two progenitors. The mass below the resolution limit accounts for the ***Galactic Medium*** (GM) which represents the mass reservoir into which halos are embedded.

Simple but physically motivated prescriptions have been adopted in order to study the star formation history and the chemical evolution along the hierarchical tree:

i) Stars form in Lyα cooling halos ($\mathbf{T_{vir} > 10^4\ K}$).

ii) The SFR is taken to be proportional to the gas mass.

iii) Low-mass star formation is triggered by the presence of metals in the gas exceeding $\mathbf{Z_{cr} = 10^{-5\pm1}\ Z_{SUN}}$ (PopIII stars form if $Z \leq Z_{cr}$ and with a reference mass of 200 M_{SUN}, PopII/I stars form if $Z > Z_{cr}$ and according to a Larson IMF between 0.1 and 100 M_{SUN}).

iv) Stars, once formed, evolve instantaneously (IRA approximation).

v) Mechanical feedback is active if SN explosion energy overcomes the binding energy of the halo.

vi) Gas and metals ejected into the ISM, and eventually into the GM through mechanical feedback, are instantaneously and homogeneously mixed in it.

Model Calibration:

The model free parameters are fixed to match the global properties of the MW (stellar/gas mass and metallicity) and the Metallicity Distribution Function (MDF) of MPHS derived from the Hamburg-ESO Survey (**Fig. 1**).

Model Results:

In **Fig. 2** we show the derived SFR and the corresponding GM iron abundance evolution. Since **[2]** have shown that the majority of present-day iron-poor stars (**[Fe/H]<-2.5**) formed in halos accreting GM gas which was Fe-enhanced by previous SN explosions, the initial [Fe/H] abundance within a halo is set by the corresponding GM Fe-abundance at the virialization redshift.

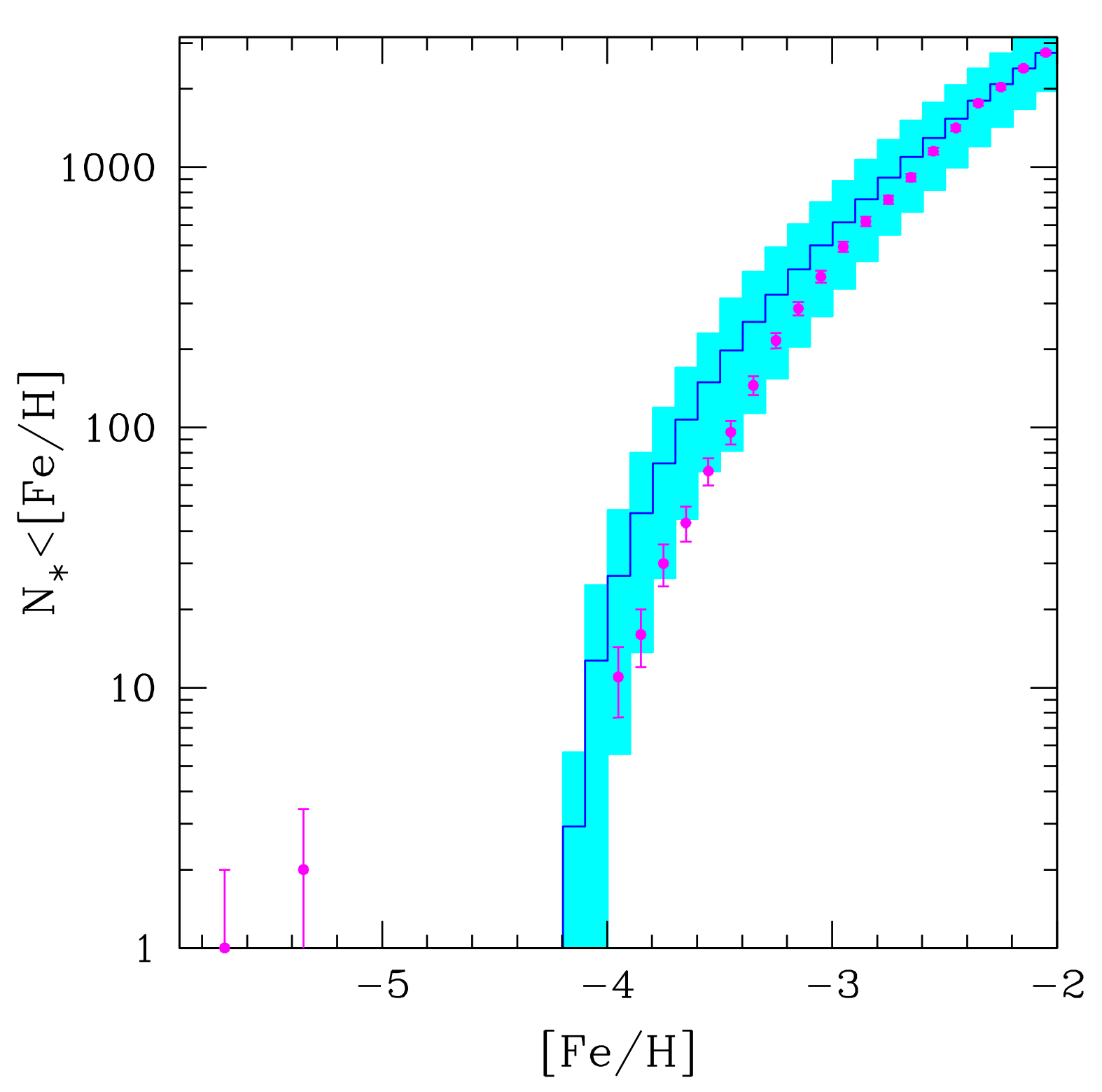

Figure 1. *Points:* The cumulative MDF for the Galactic halo stars as reported by Beers & Christlieb (2006) with the inclusion of the two hyper-metal poor stars (Christlieb et al. 2002; Frebel et al. 2005).
Histograms: Average value of the MDF over 200 realizations of the merger-tree. The shaded area represents ±1σ Poissonian errors.

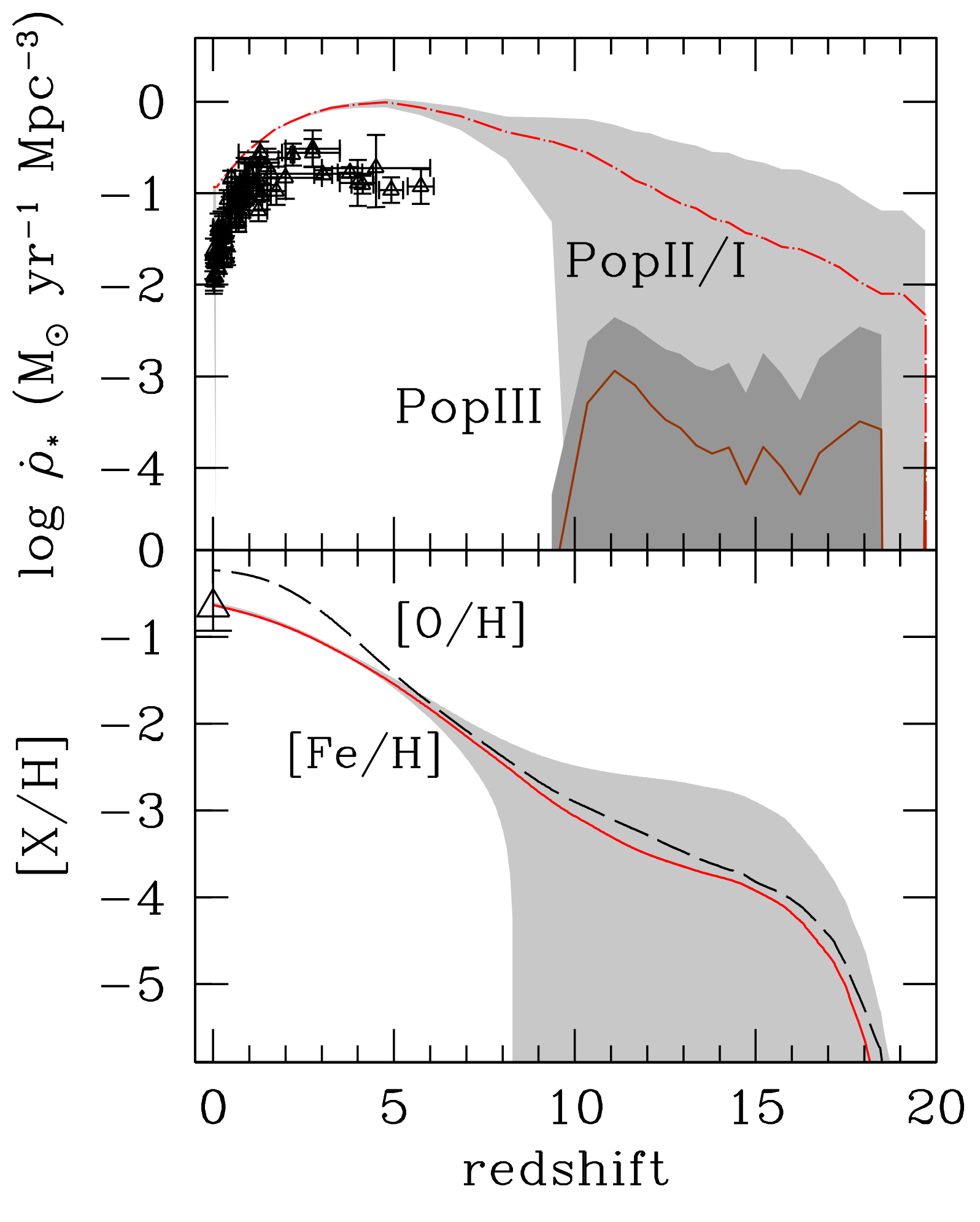

Figure 2. *Upper panel:* Comoving SFR density evolution for PopIII and Pop II/I stars. Points represent the low-redshift measurements of the cosmic SFR by Hopkins (2004).
Lower panel: Corresponding GM iron and Oxygen abundance evolution. The point is the measured [O/H] abundance in high-velocity clouds by Ganguly et al. (2005).

Lithium production

We describe the production of ^{6}Li assuming that primary CRs are spawned by SNe (PopIII + Pop II/I) with a power law in momentum between a minimum (E_{min}= 10^{-5} GeV/n) and a maximum energy (E_{max}= 10^6 GeV/n) and with a fraction of the total energy not emitted in neutrinos transferred to CRs by a single SN (ε) of 0.15. We make the hypothesis that primary CRs escape from parent galaxies on a timescale short enough to be considered as immediately injected in the GM, so their density evolution only depends on energy losses suffered in the GM. Finally we consider ^{6}Li as entirely secondary, i.e. purely produced by fusion of GM He-nuclei by primary α-particles. This gives ^{6}Li/H at any given redshift z (**Fig. 3**).

We now use the [Fe/H] predicted by GAMETE to convert redshift into [Fe/H] values and derive the GM ^{6}Li vs [Fe/H]. According to our semi-analytical model for the build-up of the MW, in fact, the GM elemental abundances reflect those of MPHS, which are predicted to form out of new virializing haloes accreting gas from the GM. This implies that the observed MPHS formed continuously within the redshift range $3 < z < 10$.

From **Fig. 4** we see that our fiducial model yields **Log ^{6}Li/H= -13.5**, about 3 orders of magnitude below the data. This discrepancy cannot be cured by simply boosting the free parameters to their maximum allowed values. This is also illustrated in the same Fig., where for the upper curve we assume **ε = 1**, that all the SN energy is transferred in **10 MeV/n** CRs (i.e. the energy at which the fusion cross section is the highest) and for the SFR the maximum value allowed by GAMETE within 1-σ dispersion. Although the discrepancy between observations and model results is less prominent in this case, we are still unable to fit the data, in particular at **[Fe/H] = -3** (i.e. at higher redshifts) only **Log ^{6}Li/H= -12.6** has had time to be produced, failing short by a factor of 30.

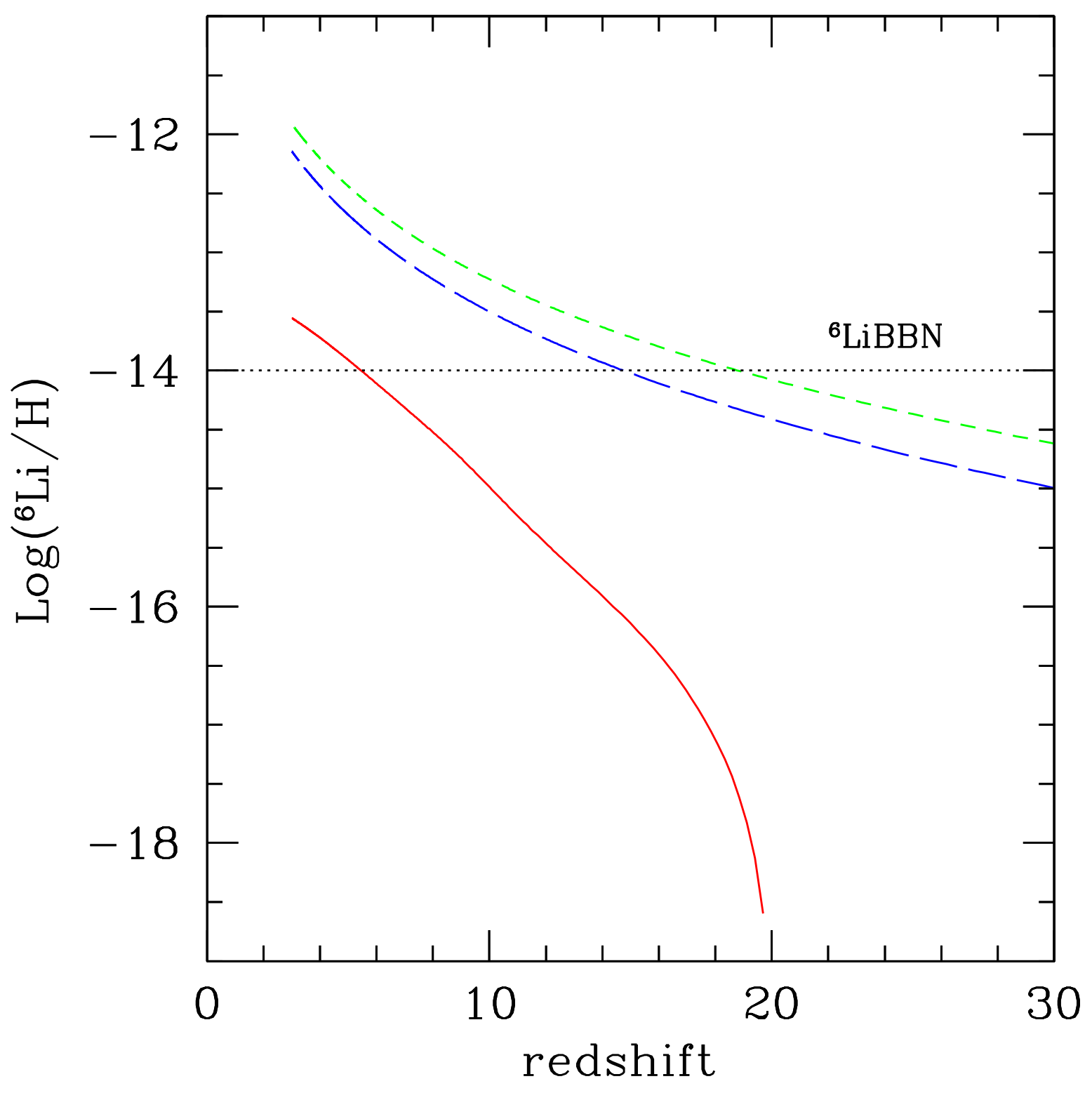

Figure 3. Redshift evolution of the GM ^{6}Li/H abundance for an analytical solution of a simplified model with no energy losses and destruction and constant SFR (**green line**), the same model including energy loss/destruction (**blue line**), the fiducial model with realistic SNR, ε = 0.15 and E_{min} = 10^{-5} MeV/n (**red line**).

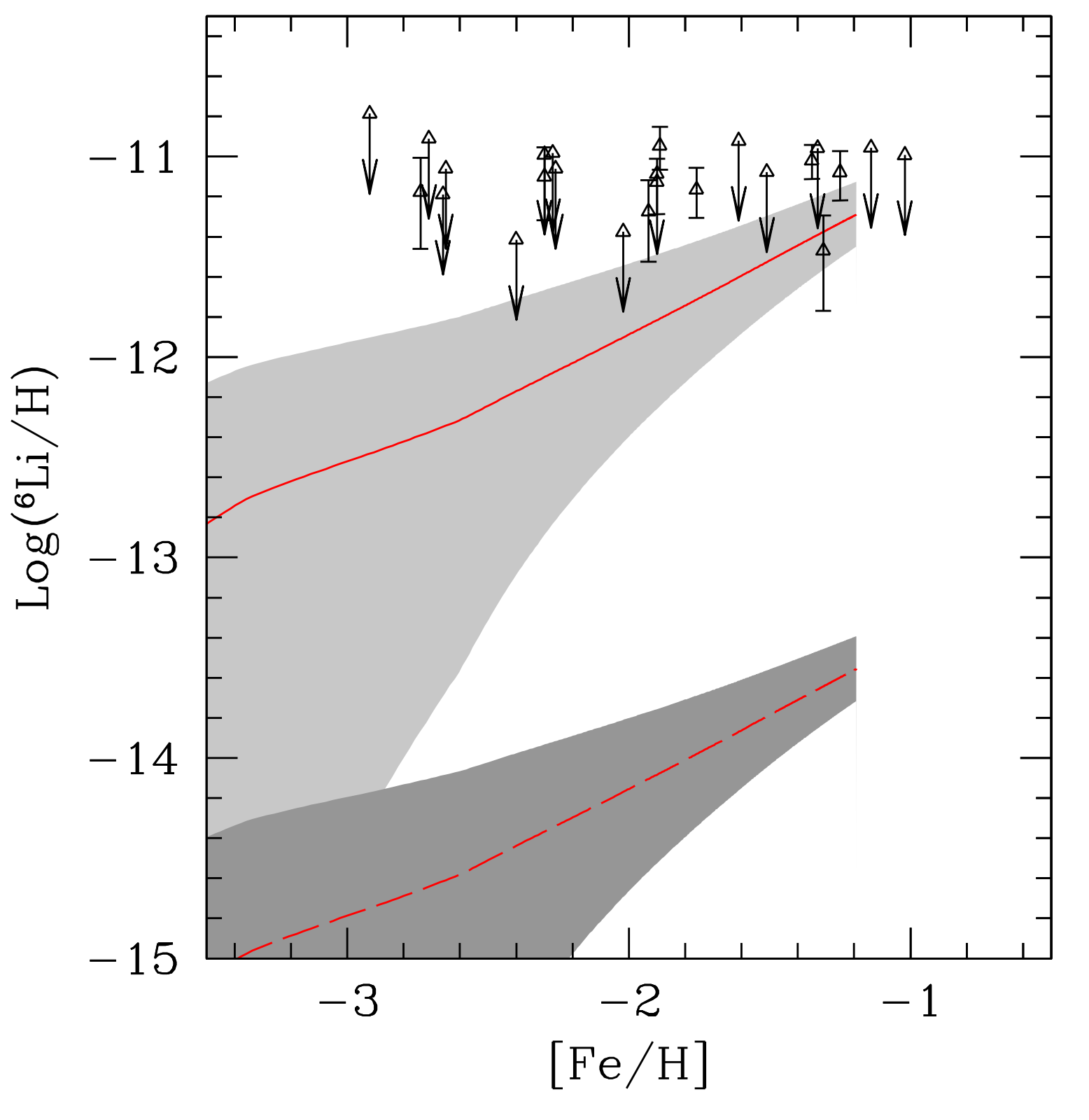

Figure 4. Redshift evolution of ^{6}Li/H vs [Fe/H] for the fiducial model (**dashed line**) and for the maximal model (**solid line**). Shaded areas denote ±1σ dispersion regions around the mean of the input SFR.

Conclusions

We have pointed out that both the level and flatness of the ^{6}Li distribution **cannot be explained** by CR spallation if these particles have been accelerated by SN shocks inside MW building blocks. Our model, which follows in detail the hierarchical build-up of the MW and reproduces correctly the MDF of the MPHS, predicts a monotonic increase of ^{6}Li abundance with time, and hence with [Fe/H]. Moreover, **our fiducial model falls short by three orders of magnitude in explaining the data**; such discrepancy cannot be cured by allowing the free parameters (E_{min}, ε) to take their maximum (physically unlikely) values. Apparently, a flat ^{6}Li distribution appears inconsistent with any (realistic) model for which CR acceleration energy is tapped from SNe: if so, ^{6}Li is continuously produced and destruction mechanisms are too inefficient to prevent its abundance to steadily increase along with [Fe/H].

Clearly, the actual picture could be more complex: for example, if the diffusion coefficient in the ISM of the progenitor galaxies is small enough, ^{6}Li could be produced in situ rather than in the more rarefied GM. This process might increase the species abundance, but cannot achieve the required decoupling of ^{6}Li evolution from the enrichment history. Alternative models in the literature have also been found to have some problems in explaining these observations, then one has to resort to more exotic models involving either suitable modifications of BBN or some yet unknown production mechanism unrelated to cosmic SF history.

FURTHER READINGS:

[1] Evoli C., Salvadori S., Ferrara A., 2008, MNRAS Letters accepted (arXiv:0806.4184)
[2] Salvadori S., Schneider R., Ferrara A., 2007, MNRAS, 381, 647
[3] Asplund M., Lambert D. L., Nissen P. E., Primas F., Smith V. V., 2006, ApJ, 644, 229
[4] Rollinde E., Vangioni E., Olive K. A., 2006, ApJ, 651, 658

Carmelo