Progenitors of Supernovae Type Ia in SPH galaxy simulations: Can we constraint their identity by studying the chemical abundance patterns of the host galaxy?

Noelia Jimenez,[1,2] **Patricia B. Tissera**[2,3] **& Francesca Matteucci**[4]
1- School of Physics & Astronomy, University of St. Andrews, Scotland, UK (*nj22@st-andrews.ac.uk*).
2-Instituto de Astronomia y Fisica del Espacio, Buen os Aires, Argentina. 3-Departamento de Ciencias Fisicas, Universidad Andres Bello, Chile.
4- Dipartamento di Fisica, Universidad de Trieste, Italy

Abstract

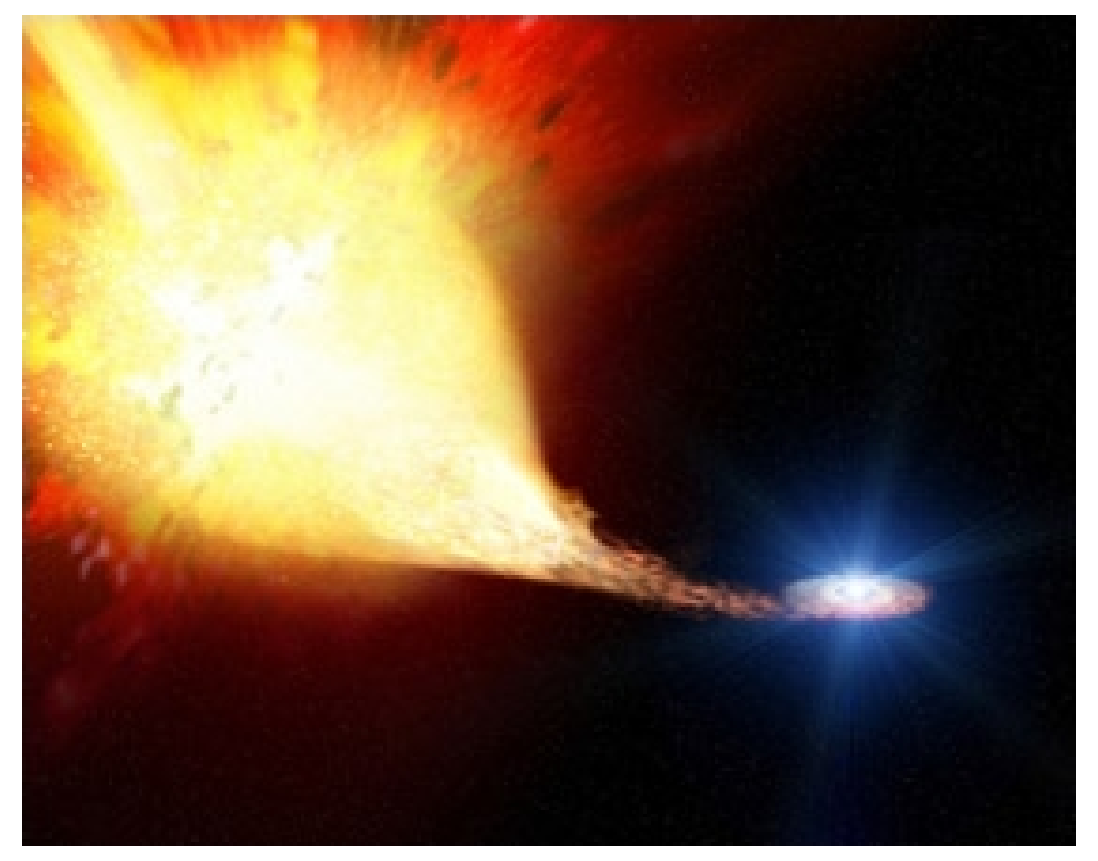
The nature of the Type Ia supernovae (SNIa) progenitors remains still uncertain. This is a major issue for galaxy evolution models since chemical and energetic feedback play a major role in the overall stellar evolution. SNIa events occur following a distribution of explosion times which is known as the Delay Time Distribution (DTD). It is suggested that different progenitor scenarios will create particular chemical abundance patterns in their host galaxies. We explore this point and implement 5 different DTDs in SPH galaxies dominated by a rapid quenching of the star formation, displaying the majority of the stars concentrated in the bulge component. We find that not every DTD is able to reproduce simultaneously the observed SNIa rates of spheroidal/bulge-type galaxies, the [O/Fe] ratios shown displayed by the Bulge of the Milky Way and the observed correlation between the specific SNIa rate and the specific star formation rate. Our results suggest that SNIa observations in galaxies with very low and very high specific star formation rates can help to impose more stringent constraints on the DTDs and therefore on SNIa progenitors.

Motivation

One of the major astrophysical problems is the uncertain identity of the SNIa progenitors. This is a matter of concern not only in galaxy formation theory but also in modern cosmology. Core-Collapse supernovae (SNeII) produced by massive short-lived stars (M> 8 M⊙) inject the ISM with energy and the so-called alpha-elements – O, Ne, Mg, Si, S and Ca –. On the other hand, the SNeIa are the main contributor of the Fe in the Universe (Greggio & Renzini 1983; Matteucci & Greggio 1986; Cappellaro et al. 1997). This element is usually considered to be a tracer of the metallicity in stars. Furthermore, the production and the time-delay between SNeII and SNeIa injection of chemical elements in the ISM, creates important patterns which can be used as clocks to tag particular events in the formation histories of galaxies.

Among the two most popular scenarios for explaining SNIa based on a thermonuclear explosion of a Carbon -Oxigen White Dwarf, there is the **Single Degenerate (SD) scenario** – a WD exceeding the Chandrasekhar mass through accretion from a non-degenerate companion star– where the mass accretion can assume many configurations (Main Sequence star, a subgiant star, a helium star or red giant star)(Greggio & Renzini 1983)

The second most popular scenario involving a thermonuclear explosion of a C-O WD is the **Double Degenerate (DD) scenario** – two WDs that loose angular momentum and energy by emitting gravitational waves and eventually merge. If the exceed the Chandrasekhar mass they ignite as SNIa (Iben & Tutukov 1984. Greggio 2005).



Lately, many empirical DTDs have been proposed. The **Bimodal** model by Mannucci et al.(2006) considers a DTD with two populations of progenitors of SNIa, one dominated by the “prompt” component that explodes within 100Myrs after the formation of their progenitors, and the “tardy” component exploding on a wide period of time extending up to 10 Gyr . Moreover, similar power law **DTDs (~t^1)** have been recovered from different observational survey (i.e.: **Totani** et al. 2008, **Maoz** et al. 2012, **Pritchet** et al. 2008) . We explore all these DTDs in this work.

The DTD represents a powerful tool, not only for testing models and helping to constraint the progenitor SNIa scenarios, but also for obtaining an accurate description of the chemical and energetic feedback from SNIa. We wish to test which is the best scenario for SNIa in the framework of cosmological simulations.

Methodology & Results

We estimate the rate of SNIa usign the formulation of Matteucci & Recchi (2001) (see the Equation below), where adopt the IMF of Salpeter and assume that the life-times of the stars exploding as SNIa are comprised in the mass range of 0.8 − 8M⊙. The total mass of the bynary system is MB = M1 +M2 (M1 is the primary and M2 the secondary) and the Star Formation Rate (SFR) is evaluated at the life-time of the M2 star. The only free parameter A is the fraction of binary systems able to produce SNeIa in the mass range 3-16M⊙. The DTD results:

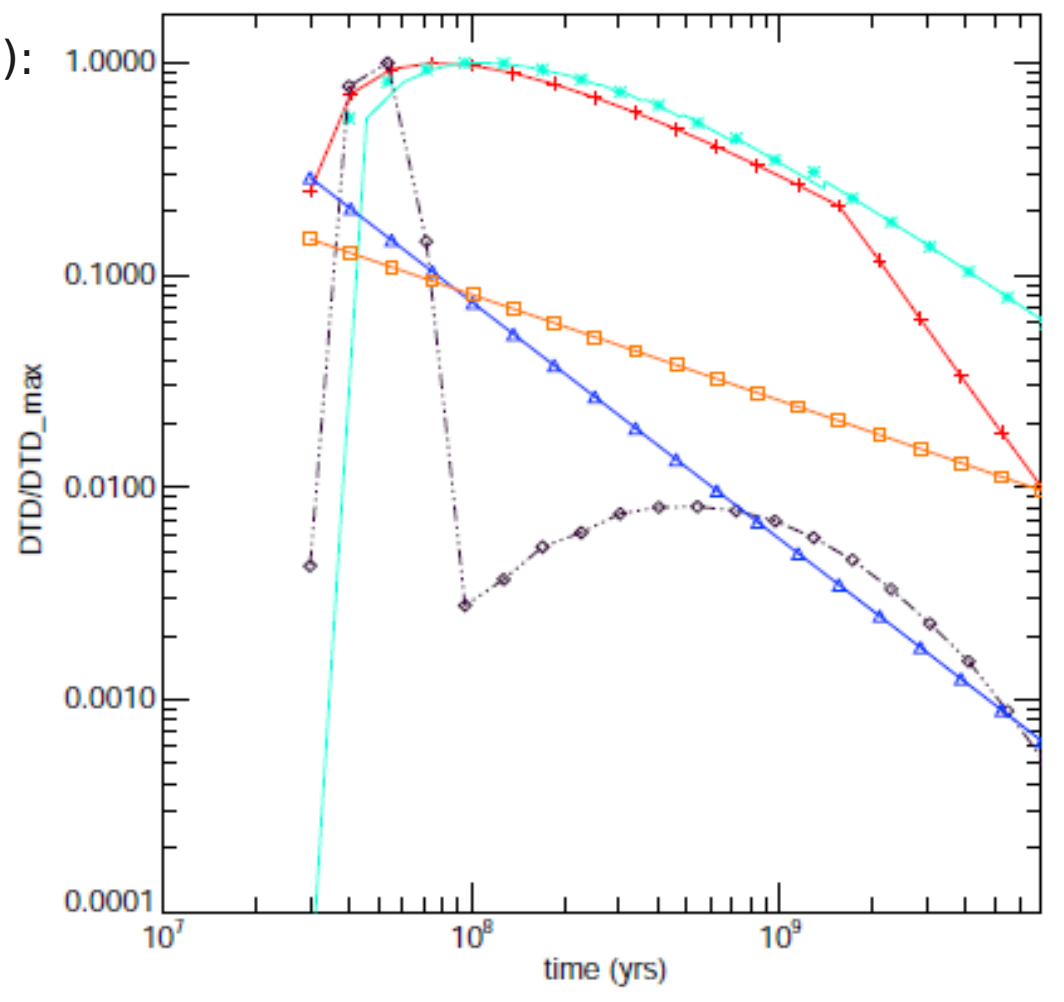
$$R_{\rm Ia}(t) = A \int_{M_{\rm B,inf}}^{M_{\rm B,sup}} \phi(M_{\rm B}) \int_{\mu_{\rm min}}^{\mu_{\rm max}} f(\mu)\psi(t-\tau_{M_2})d\mu\, dM_{\rm B} \tag{1}$$

The Simulations

Here we use an extended version of Tree-PM SPH code GADGET-3 (Springel 2005), which includes metal-dependent cooling (Sutherland & Dopita 1993), star formation, chemical enrichment, supernova feedback and a multiphase model for the gas component (Scannapieco et al. 2006). We analyse the performance of 5 different DTDs in galaxies within isolated dark matter haloes. The virial mass of the systems is 10^{11} M⊙, with 10% of this mass in form of baryons. Initially, the gas is distributed in the disc component and represents > 65% of the total baryonic mass of the galaxy. The analysis of the SFR of the bulge shows that the stars formed during the strong star-bursts, where the cold gas is exhausted within less than 1 Gyr. The new stars remain concentrated within ~3 kpc. The Bulge+Disk stellar mass is nearly 3.5×10^{10} M⊙, typical of a small ellipticals or spiral galaxy bulges. We explore the space parameter of A, within each DTD, that reproduces observed rates by Li et al. (2011), for bulges and spheroids ~ 0.0017 SNIa per year.

The DTDs implemented (see the Figure on the right):

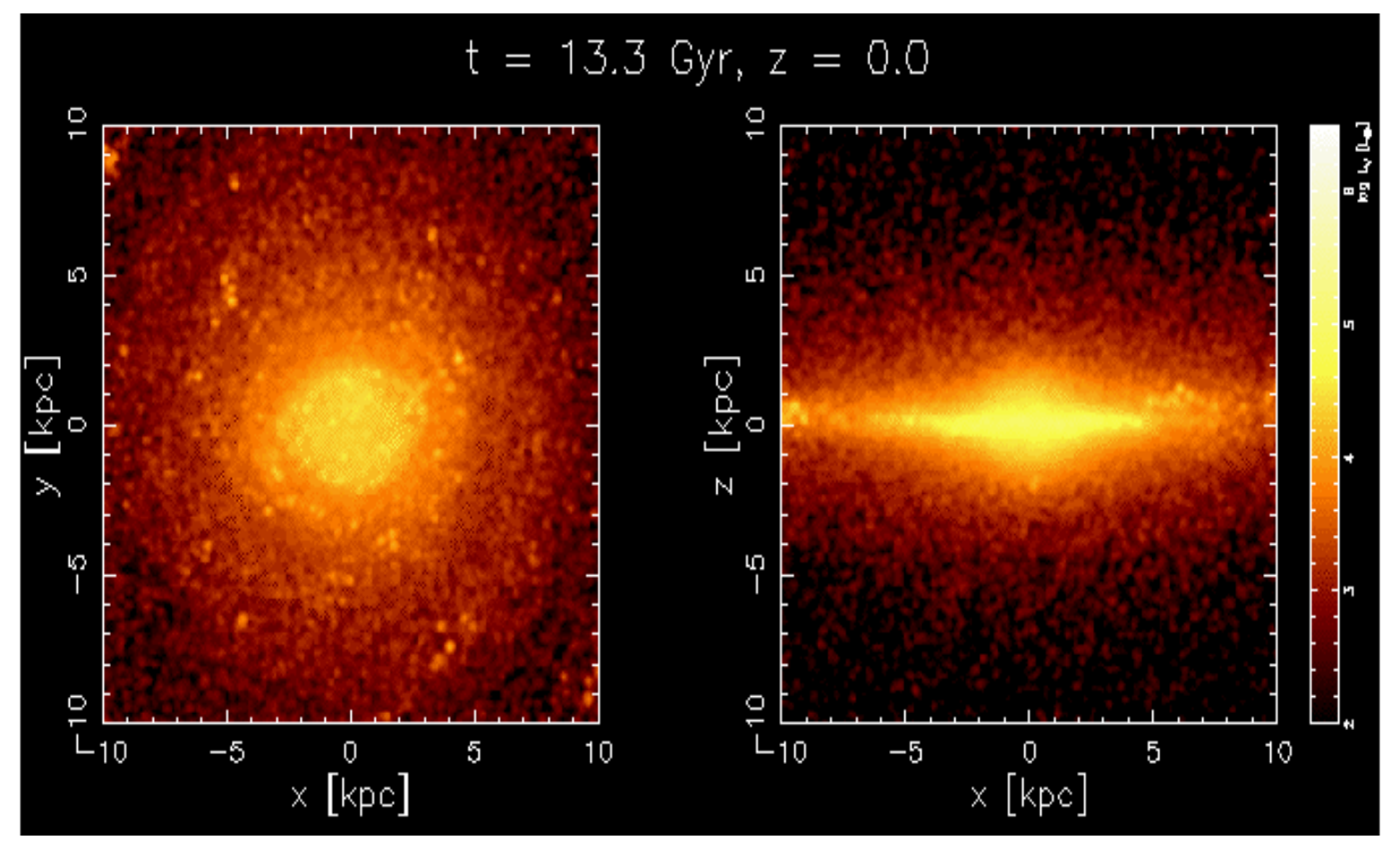
- Sinlge Degenerate (SD, cyan)
- Double Degenerate (DD, red)
- Bimodal DTD (purple)
- Power Law DTD from Maoz (equivalent to Totani, in orange)
- Power Law from Pritchet (blue)



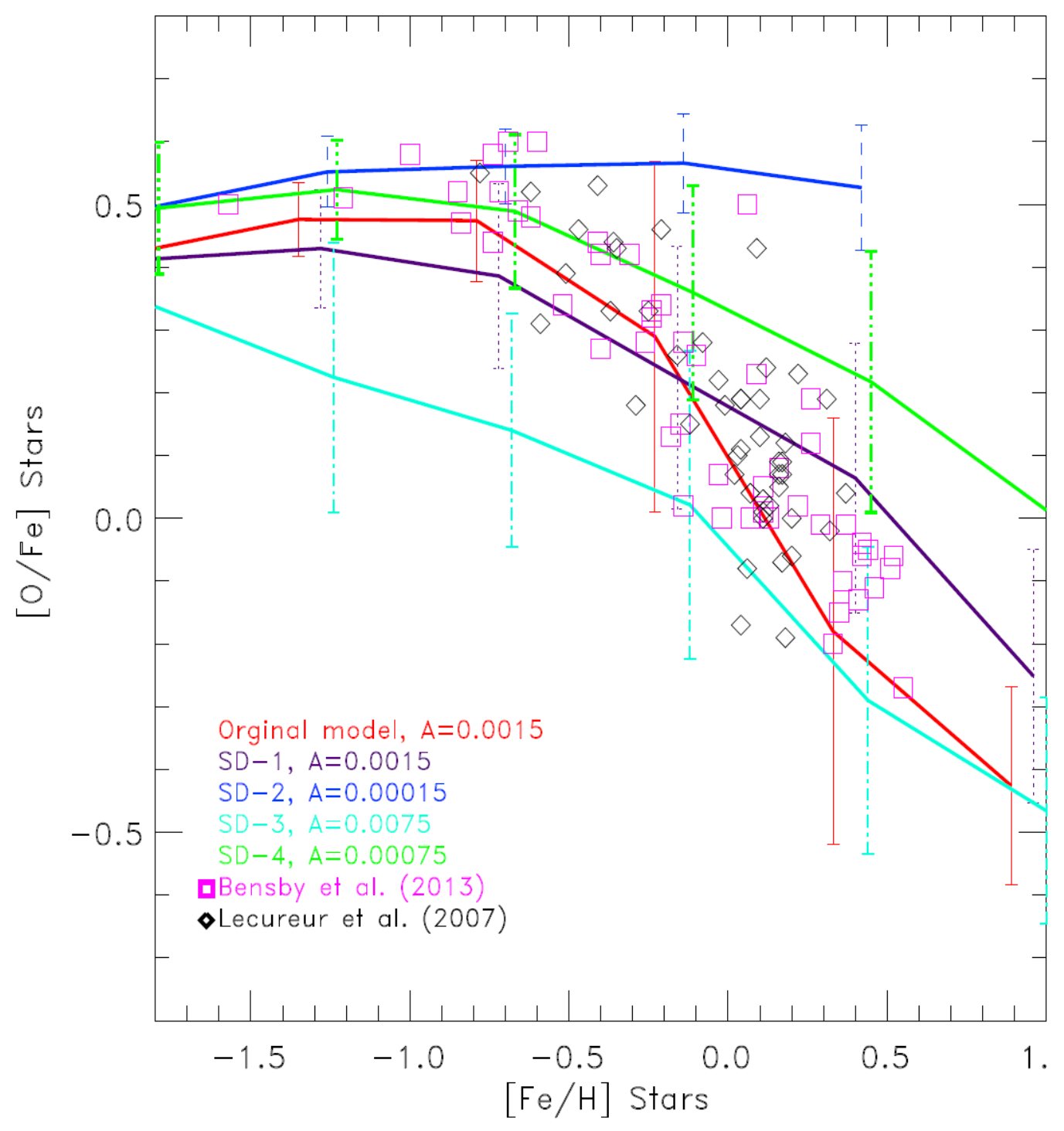
The [O/Fe] vs. [Fe/H] diagram

We compute the average stellar mass abundance of [Fe/H] and [O/Fe] for the stars in the bulges of each of the DTDs (with different A values) and compare them to a sample of dwarfs and subgiant stars from the Galactic Bulge (Bensby et al. 2013), and Red Giants stars from Lecureur et al. (2007).

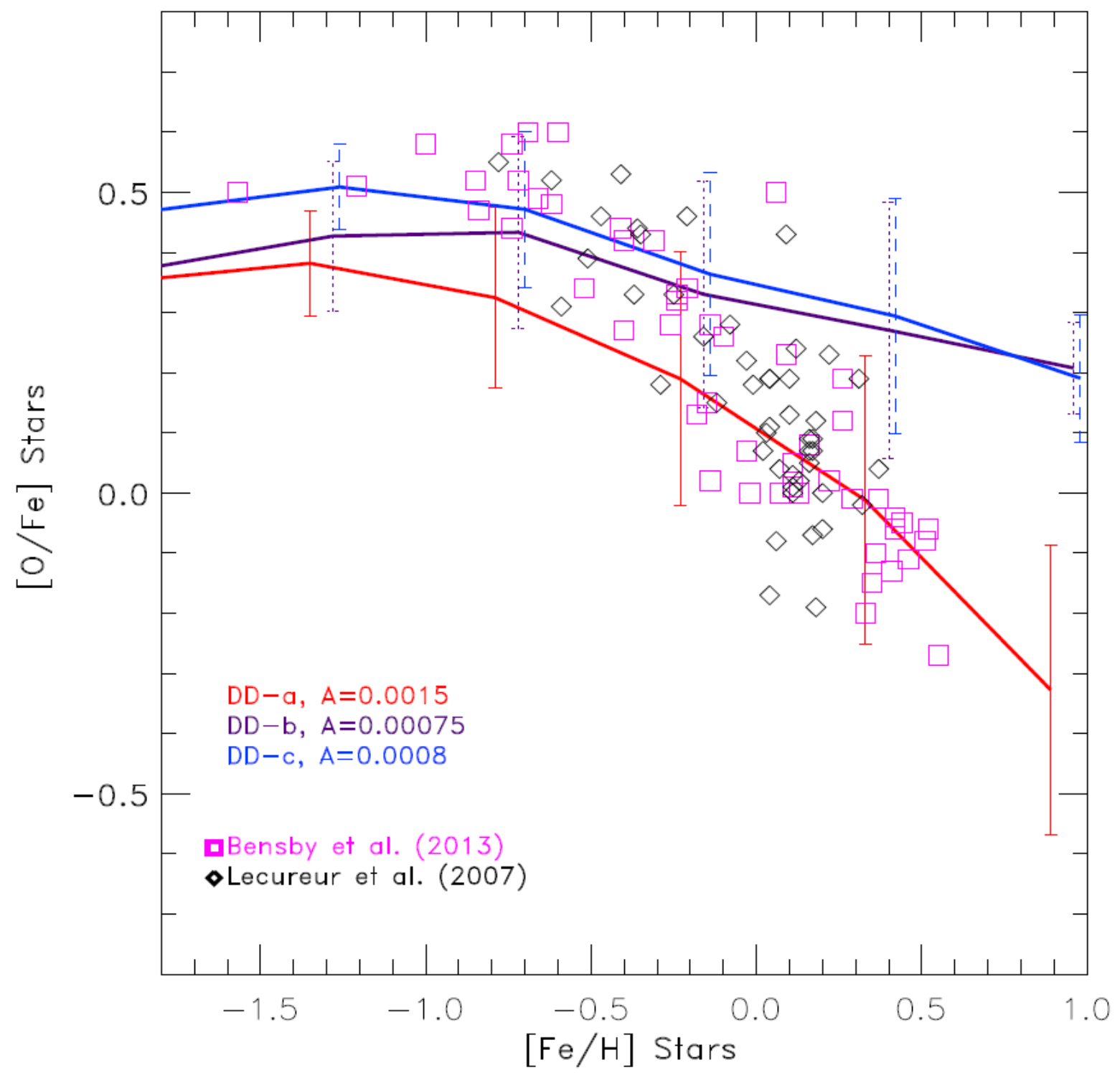
As an expample of what the simulations predict, we analyse in detail the SD scenario (Figure on the top right). The observed data points lying in between the curves displayed by models SD-3 and SD-2, corresponding to the highest and low-est values of A, respectively. However, model SD-2 predicts a too flat [O/Fe] ratio, meaning that the fraction of SNIa is too low. On the other hand, model SD-3 is an extreme case where there are too many SNeIa and it predicts, in fact, a continuous decrease of the [O/Fe] ratio, at odds with the observations. The data are best represented by the models SD-4 and SD-1. The former model (SD-4) fits the zero point of the data following the observed trend up to [Fe/H]> −0.25. Meanwhile,SD-1 matches the slope and passes through the data better. **These models predict a long plateau for the [O/Fe] ratio and a knee occurring at high [Fe/H], as observations suggest.** However, at high metallicity the slopes of both models do not so nicely follow the observed [O/Fe] ratios. This is perhaps a consequence of yields adopted in this work. The Wosley & Weavier (1995) yields do not include mass loss from massive stars, which is particularly important for Wolf-Rayet stars and for supersolar metallicity. Its effect is to increase the yields of Carbon and Helium and to depress that of Oxygen (McWilliam et al. 2008). The original model (of Scannapiecco 2006), albeit simple with no DTD,fits the data in the whole range. In the rest of the Figures we show other DTDs and their predictions for the chemical evolution.

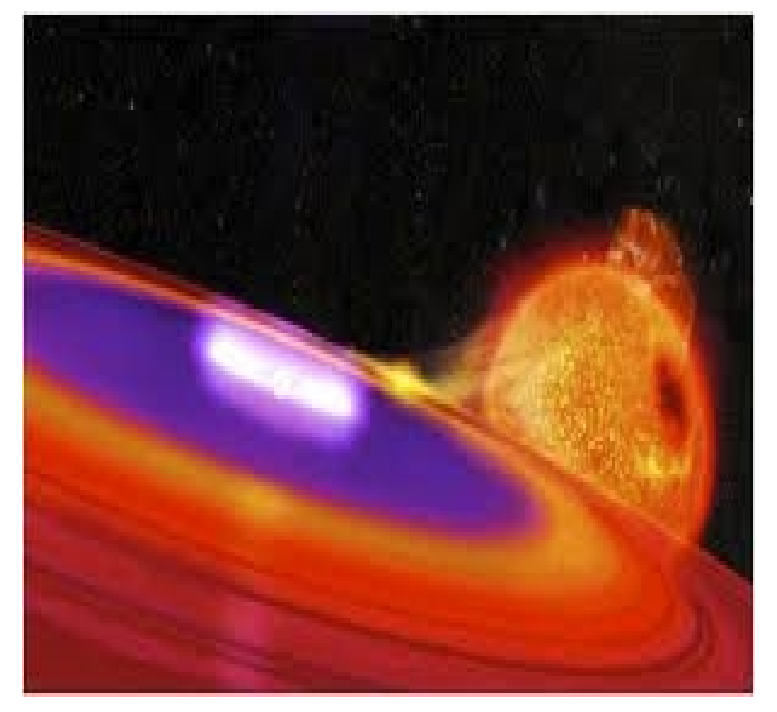


Single Degenerate

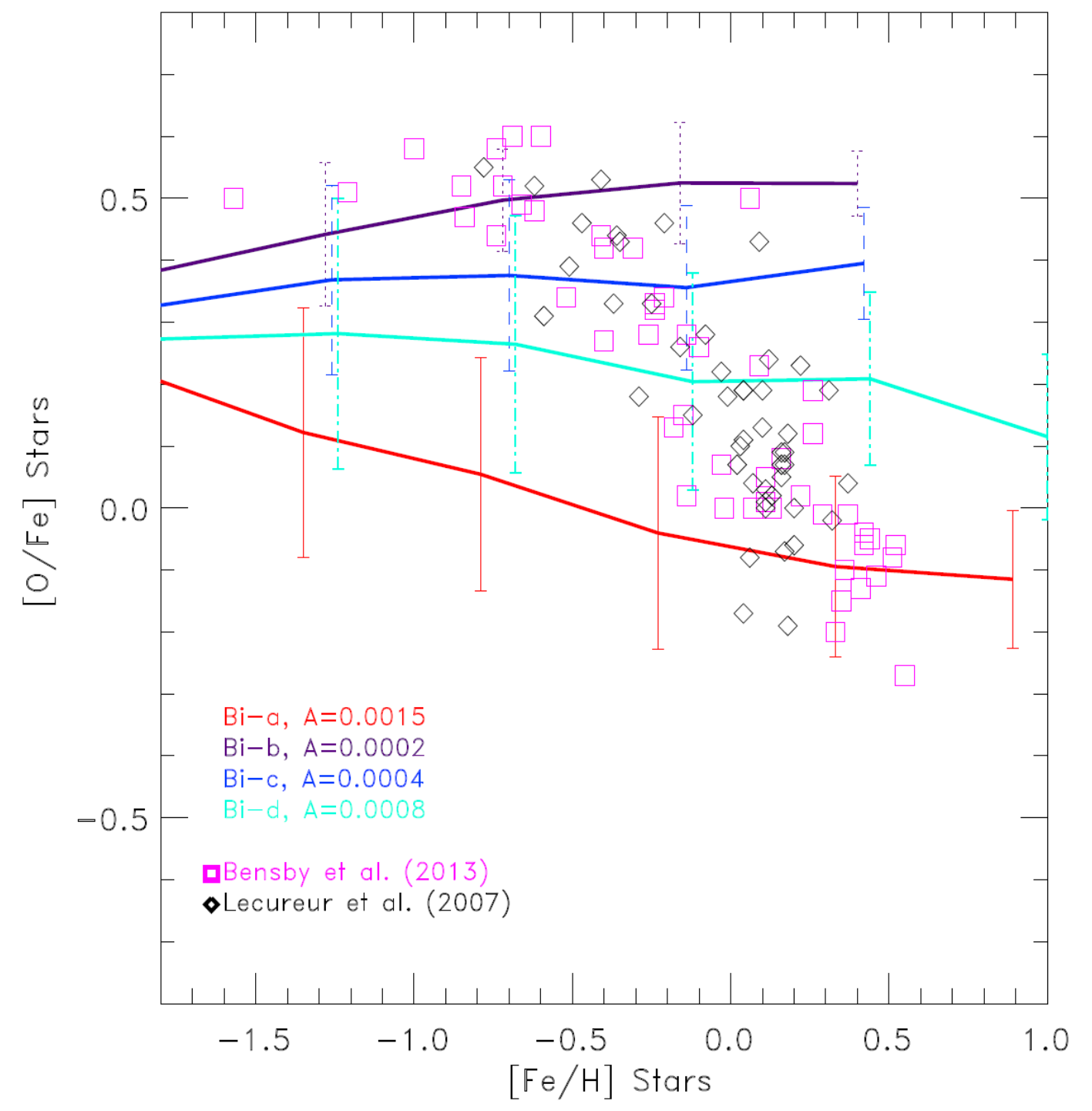


Double Degenerate

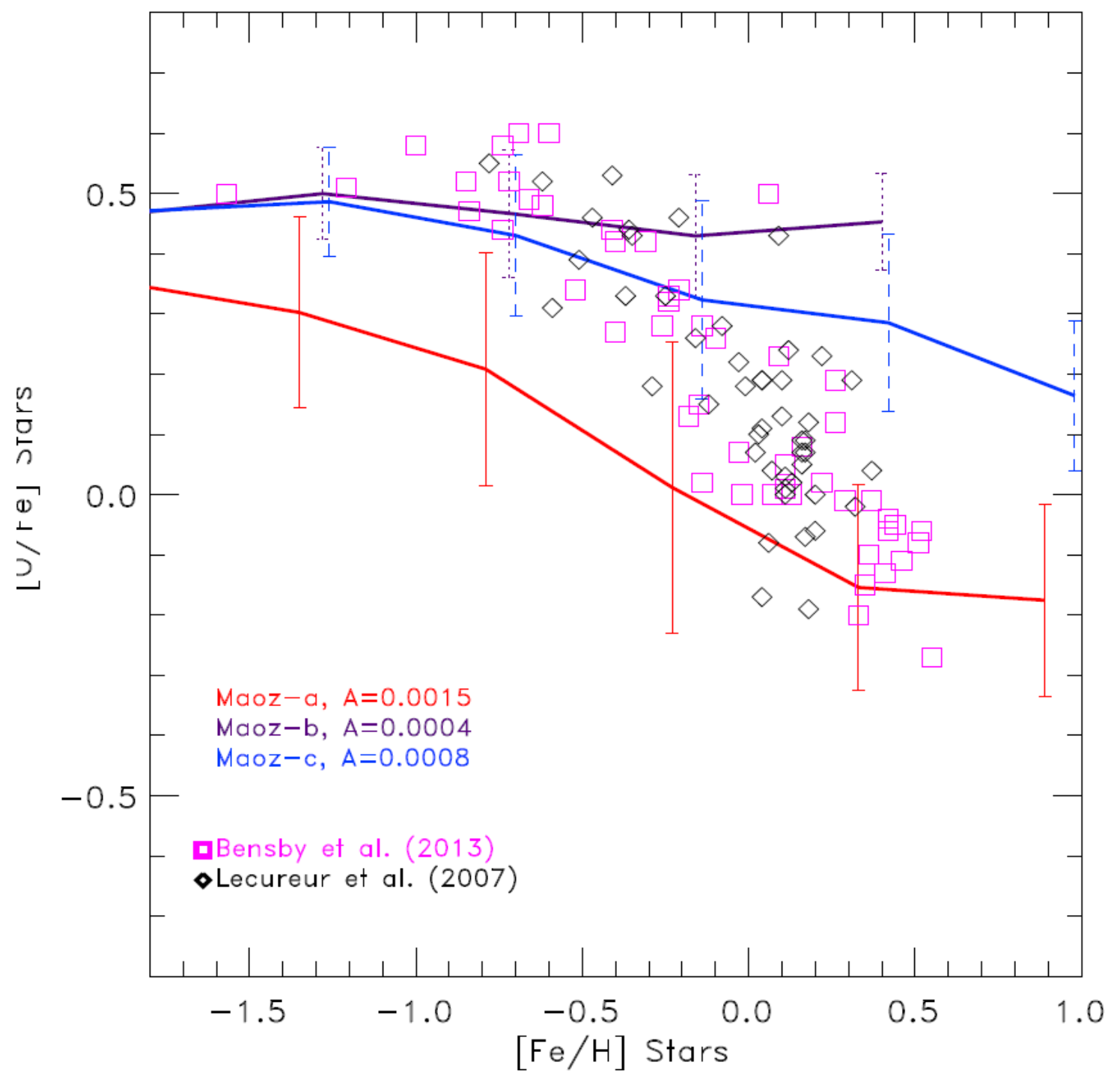




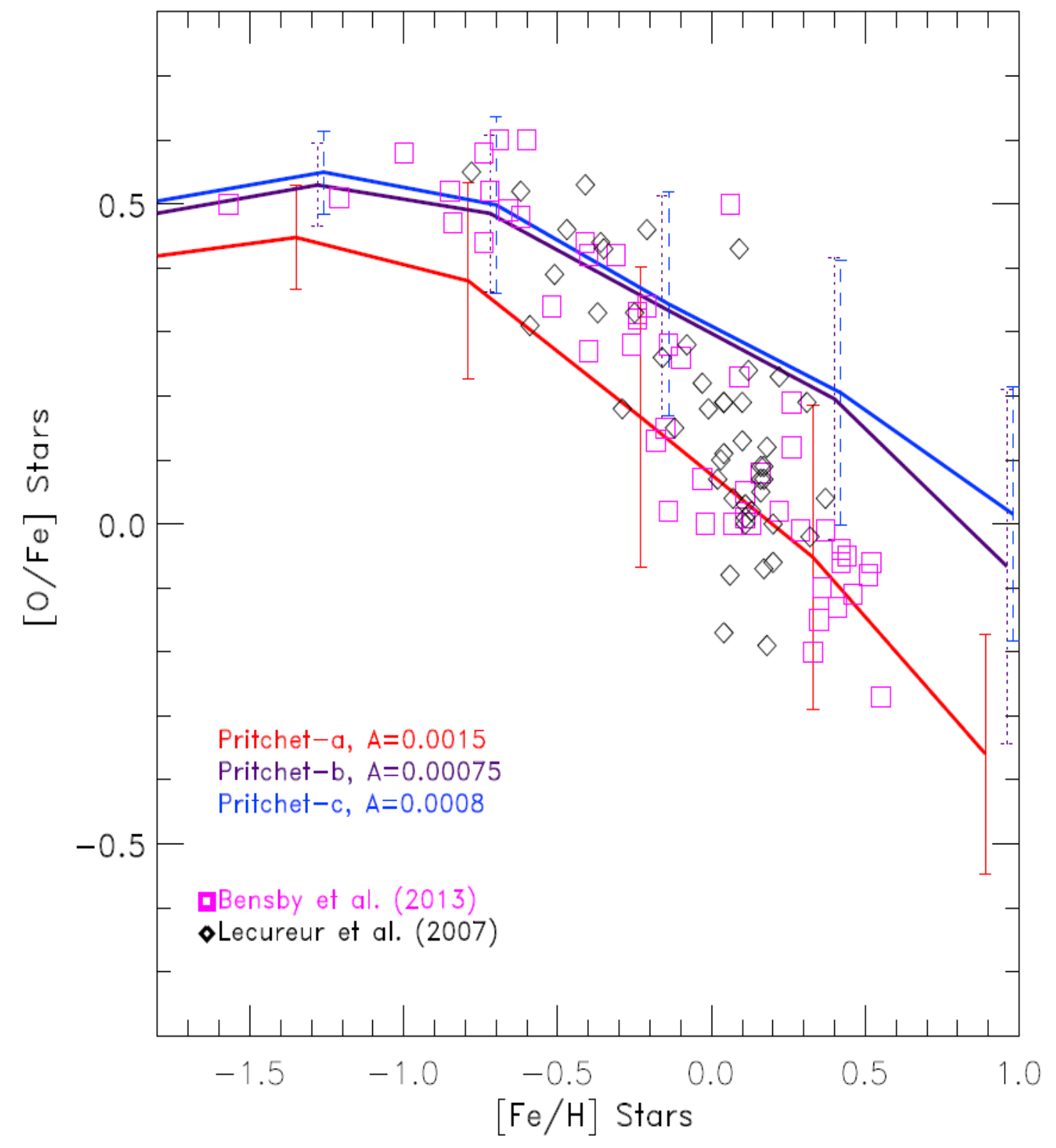
Bimodal DTD

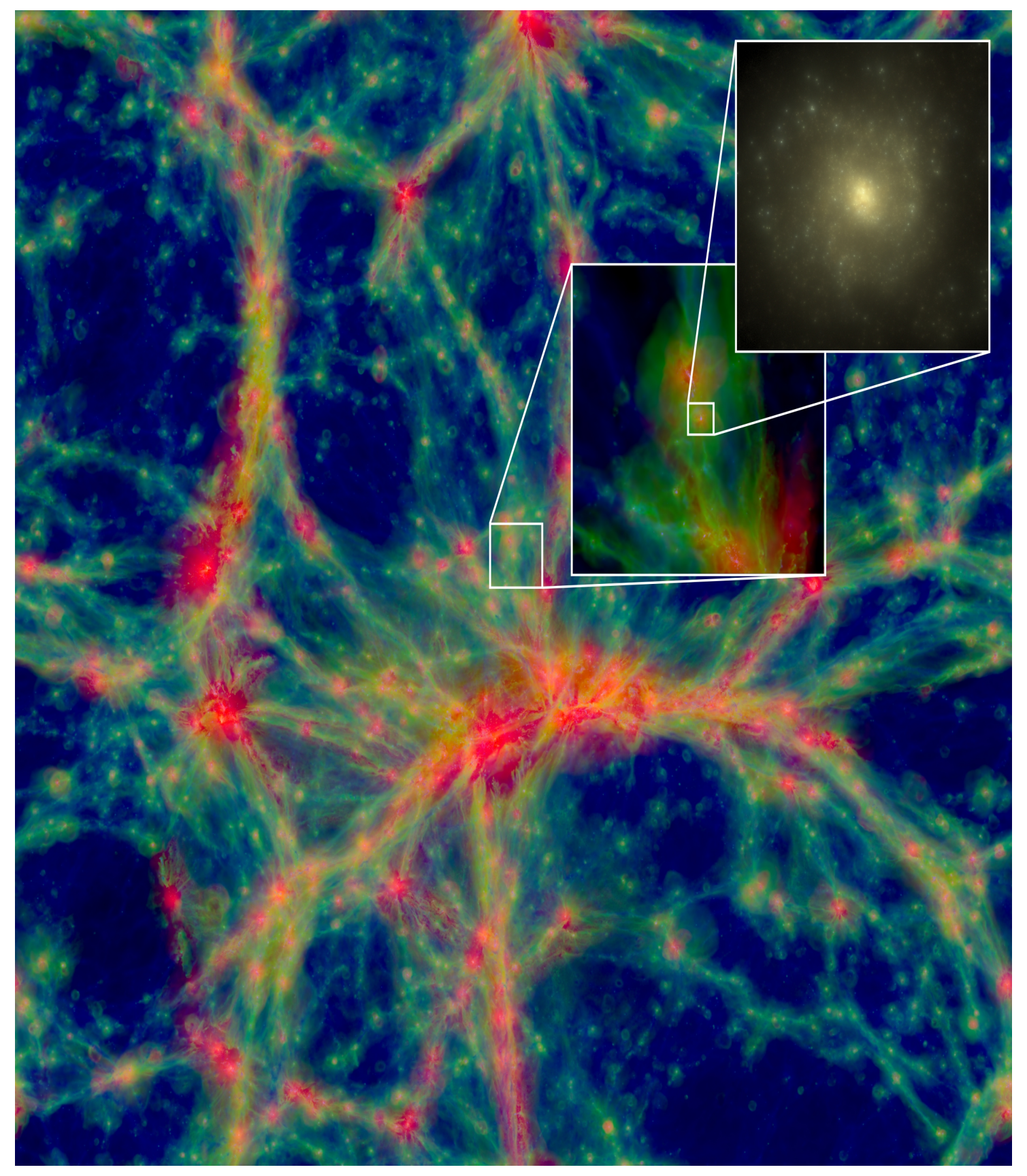


Power law– Maoz DTD



Power law– Pritchet DTD





Conclusions

We present the results of galaxy simulations performed with Tree-PM SPH-GADGET-3 (Springel 2005; Scannapieco et al. 2006), to study the impact of the SNIa feedback implementing 5 different DTDs. This involves the calibration of a free parameter A which represents the fraction of binary systems in one stellar generation giving rise to SNIa events. Chemical evolution models generally fix A according to the SFR and the present day SNIa rates of the galaxy under study. However in a cosmological simulations A acts at a particle basis. Thus, it is assumed to be the same for all single stellar populations, while the final SNIa rates or any relation between the SNIa rates and the galaxy properties – or the chemical abundance patterns –should come out as a prediction of the simulations. Therefore,i t is necessary to explore a range of suitable A values and their impact on the properties of galaxies, by using simple initial conditions as isolated galaxies.

The [O/Fe] ratios predicted for the stars in the bulge of the simulated galaxies are compared to data from the Galactic Bulge (although this comparison is just indicative). For all the models, at high metallicity there an effect due to yields adopted in this work (see Methodology & Results). The space parameter for A, within each DTD is fixed using the observed rates for spheroidal galaxies from Li et al. (2011). For each scenario we find:

- SD: the best agreement with observations is provided by the SD-1 and SD-4 models. These models predict a long plateau for the [O/Fe] ratio and a knee occurring at high [Fe/H], as observations suggest.
- DD: the observed [O/Fe] vs. [Fe/H] ratios lie between the models DD-a and DD-c. Meanwhile DD-a matches the slope and passes through the data at high metallicity, DD-c fits the zero point of the data at low metallicity and follows the observed trend up to [Fe/H]> −0.15. Only DD-a predicts a long plateau for the [O/Fe] ratio and a knee occurring at high [Fe/H], as observations suggest.
- Bimodal: the data lies between the models Bi-a and Bi-b, but the slopes do not follow the observed trend. The rates for various models are of the order of magnitude with the observed ones, but at variance with chemical evolution models (e.g. Matteucci et al. 2006) this does not guaranties in SPH simulations a good fit to the observed [O/Fe]vs. [Fe/H] diagram.
- Maoz Power law: (similar to Totani) shows a range of A for which is possible to match the zero point, but not the trend followed by the data. For model Maoz-a there is too many SNeIa that will produce a flattening of the slope at low metallicty in the [O/Fe] vs. [Fe/H] diagram. The model, Maoz-c shows a good fitting to the zero point, but can not follow the observed trend at high metallicty.
- Pritchet Power law: within a range of values of A can fit very well both the rates and the data in [O/Fe] vs. [Fe/H] diagram.

In conclusion, SD, DD and Pritchet DTDs can reproduce simultaneously the observables. Our next goal is to run cosmological simulation and analyse the chemical properties of galaxies of different masses and assembly histories.

NJ acknowledges support from the European Research Council Starting Grant (SEDmorph; P.I.V. Wild).