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The chemical evolution of Sagittarius: the effect of different IMFs

Chemical and dynamical evolution of the Milky Way and Local Group galaxies

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Outline

- The Sagittarius dSph: *some observational properties*

- Basic equations of chemical evolution

- Our work on the Sgr dwarf
  - The integrated galactic initial mass funtion: *a SFR- and metallicity-dependent IMF (Recchi et al., 2014; review: Kroupa, 2013)*
  - Eu from neutron star mergers: *a new formation scenario (Matteucci et al., 2014)*
  - Main source of uncertainties in models: *stellar yields*

- Conclusions

The Sagittarius dSph

some observational properties

- Second closest known satellite galaxy of the MW
  - $D_\odot = 26 \pm 2\ \mathrm{kpc}$ (*Simon et al., 2011*)
- Very low central surface brigthness
  - $\mu_V = 25.2 \pm 0.3\ \mathrm{mag\ arcsec^{-2}}$ (*Majewski et al. 2003*)
- Small total amount of gas
  - $M_{HI} \sim 10^4\ \mathrm{M_\odot}$ (see *McConnachie et al., 2012*)
- Two main, distinct stellar populations
  - The old blue horizontal branch population, with ages $> 10\ \mathrm{Gyr}$ (*Monaco et al., 2003*)
  - The so-called Pop A, of intermediate age, dating back to $8 \pm 1.5\ \mathrm{Gyr}$ (*Bellazzini et al., 2006*)
- Mean iron abundance
  - $\langle [Fe/H] \rangle = -0.5 \pm 0.2\ \mathrm{dex}$ (*Cole et al., 2001*)

Basic equations of chemical evolution

Ejected mass returned per unit time by stars in advanced stages of their evolution

$$\dot{M}_{\mathrm{g},i} = \underline{-\psi(t)X_i(t)} + \boxed{R_i(t)} + \underline{(\dot{M}_{\mathrm{g},i})_{\mathrm{inf}}} - \underline{(\dot{M}_{\mathrm{g},i})_{\mathrm{out}}}$$

Star formation rate:

$$\psi(t) = \left(\frac{dM_g}{dt}\right)_{SF} = \nu M_g^k(t)$$

Infall rate:

$$\left(\frac{dM_{g,i}}{dt}\right)_{inf} = A \cdot X_{i,inf} e^{-t/\tau}$$

Outflow rate:

$$\left(\frac{dM_{g,i}}{dt}\right)_{out} = \omega_i \psi(t) = \cdots = \lambda_i M_g^k(t)$$

References:

Lanfranchi et al. (2004)

Vincenzo et al. (2014)

Different IMFs in Sgr dwarf

- McWilliam et al. (2013) measured high-res abudances for α-elements (O, Mg, Ca, Si) and Eu
- They concluded that to explain all the abundances in this galaxy an IMF deficient in massive stars is required
- We tested several IMFs (*Salpeter*, *Chabrier* and *IGIMF*); in particular, the IGIMF predicts less massive stars in a regime of low star formation, as in dSphs

Different IMFs in Sgr dwarf

Observed facts:

Similar [Eu/Fe] ratios in MW disk stars and in Sagittarius

Enhanced [Eu/O] ratios in Sagittarius with respect to the MW disk stars

Proposed explanations (McWilliam et al. 2013):

i) The IMF in Sagittarius is deficient in high-mass stars

ii) The Eu-producers are stars less massive than the O-producers

The set of stellar yields of Romano et al. (2010)

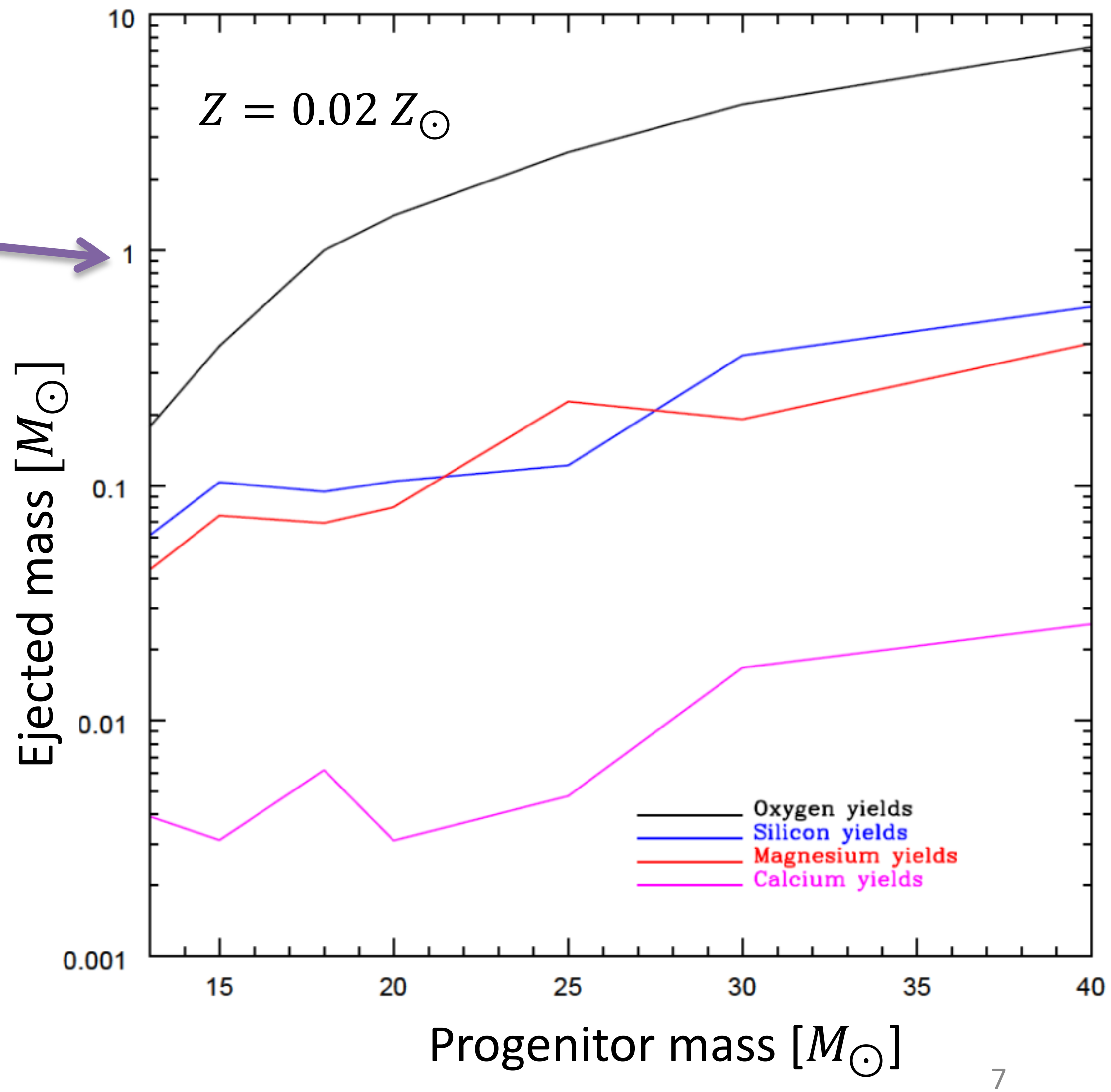
Massive star yields:

i) For He, C, N and O, we assume the metallicity-dependent stellar yields of the Geneva group (*see Romano et al., 2010 for more references*)

ii) For heavier elements, the metallicity-dependent stellar yields of Kobayashi et al. (2006)

LIM star yields:
i) The metallicity-dependent stellar yields of Karakas (2010)

Type Ia SNe:
i) Iwamoto et al. (1999)



The integrated galactic initial mass function (IGIMF)

Review: Kroupa (2013)

$$\xi_{\mathrm{IGIMF}}(m, \psi(t), [Fe/H]) = \int_{M_{\mathrm{ecl,min}}}^{M_{\mathrm{ecl,max}}(\psi(t))} dM_{\mathrm{ecl}}\, \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}}) \phi(m \leqslant m_{\max}, [Fe/H])$$

The embedded cluster mass function:

$$\xi_{ecl} \propto M_{ecl}^{-\beta}$$

where

$$\log(M_{ecl,max}) = 4.83 + 0.75 \cdot \log\left(\frac{\psi(t)}{M_{\odot} yr^{-1}}\right)$$

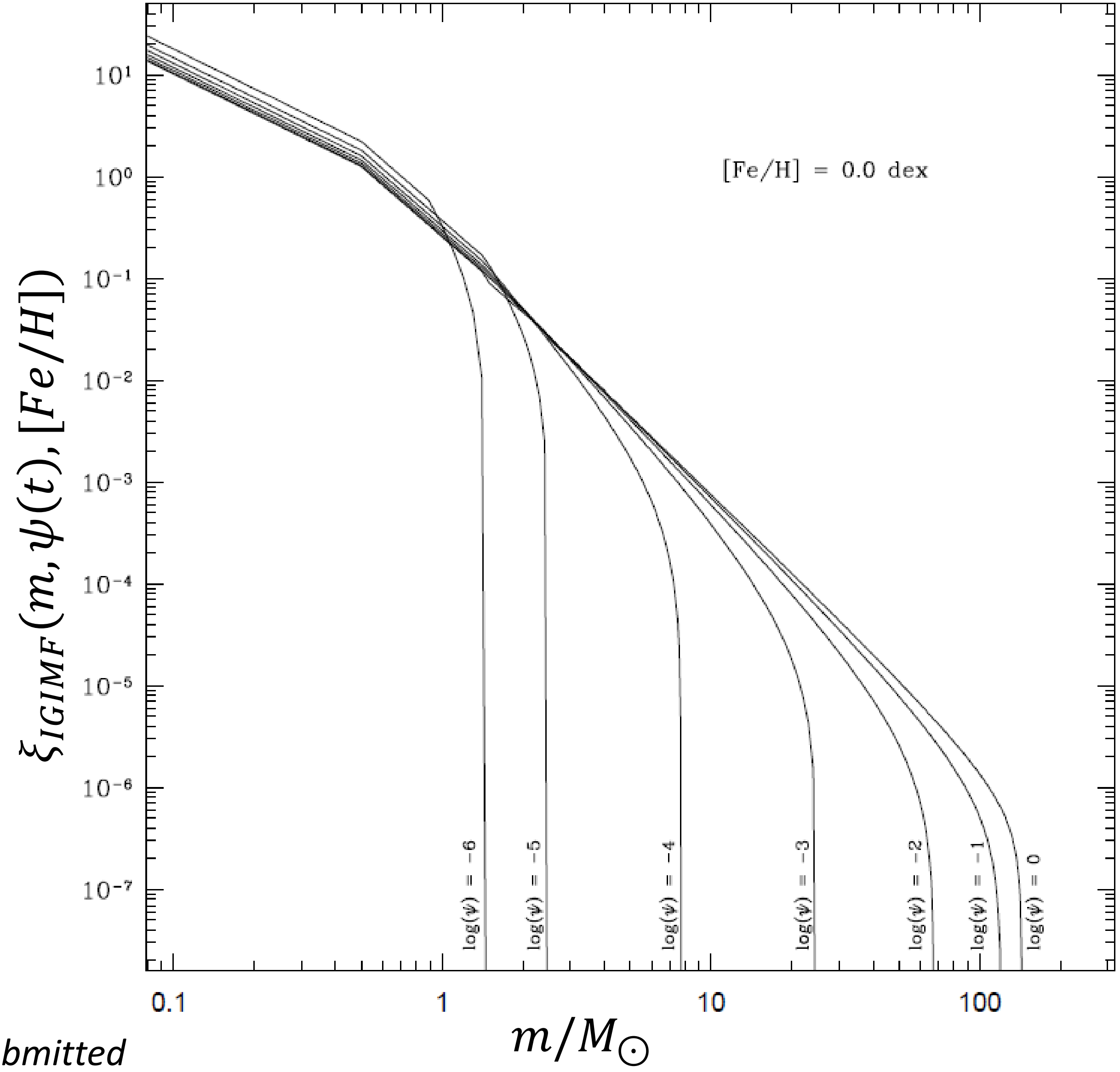
Kroupa & Weider (2003)
Weidner & Kroupa (2004)
Recchi et al. (2009)
Zhang and Fall (1999)

The initial mass function:

$$\phi(m, [Fe/H]) \propto \begin{cases} m^{-1.3}, & 0.08\ M_{\odot} \leq m < 0.5\ M_{\odot} \\ m^{-2.3+k\cdot\left[\frac{Fe}{H}\right]}, & 0.5\ M_{\odot} \leq m < m_{max} \end{cases}$$

Recchi et al. (2014)

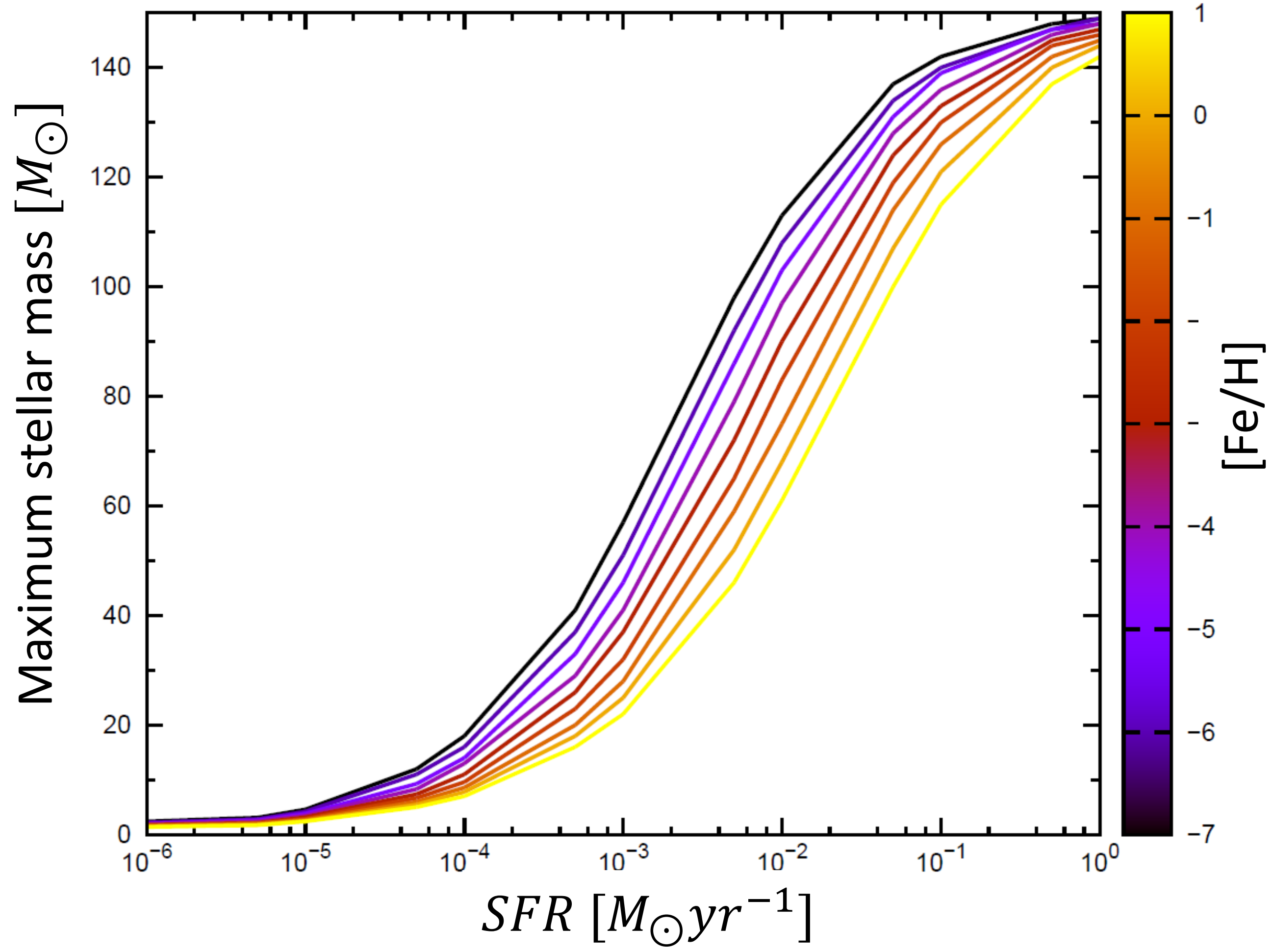
The IGIMF of Recchi et al. (2014)



Vincenzo et al., submitted

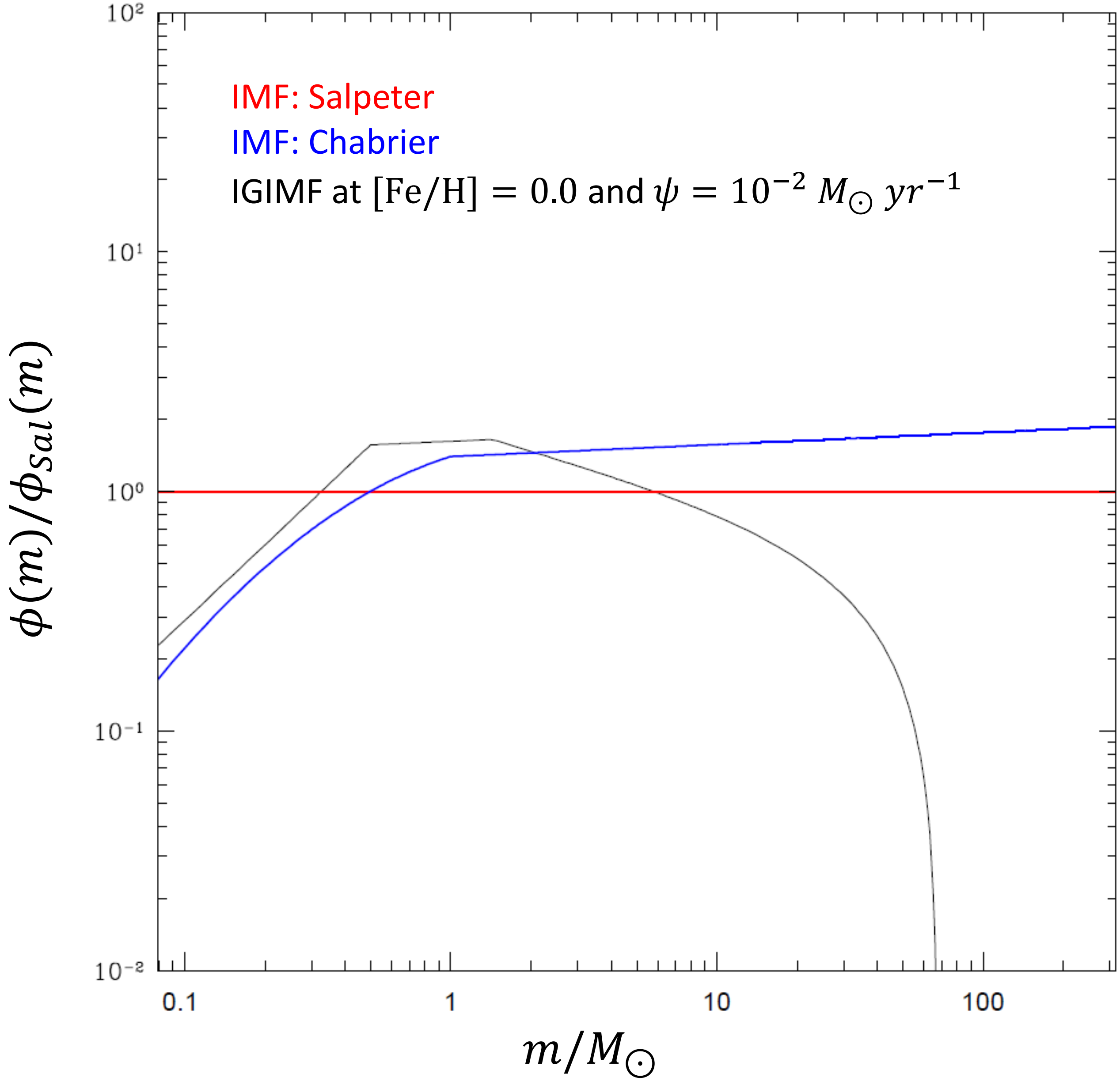
The IGIMF of Recchi et al. (2014)

Its main effect

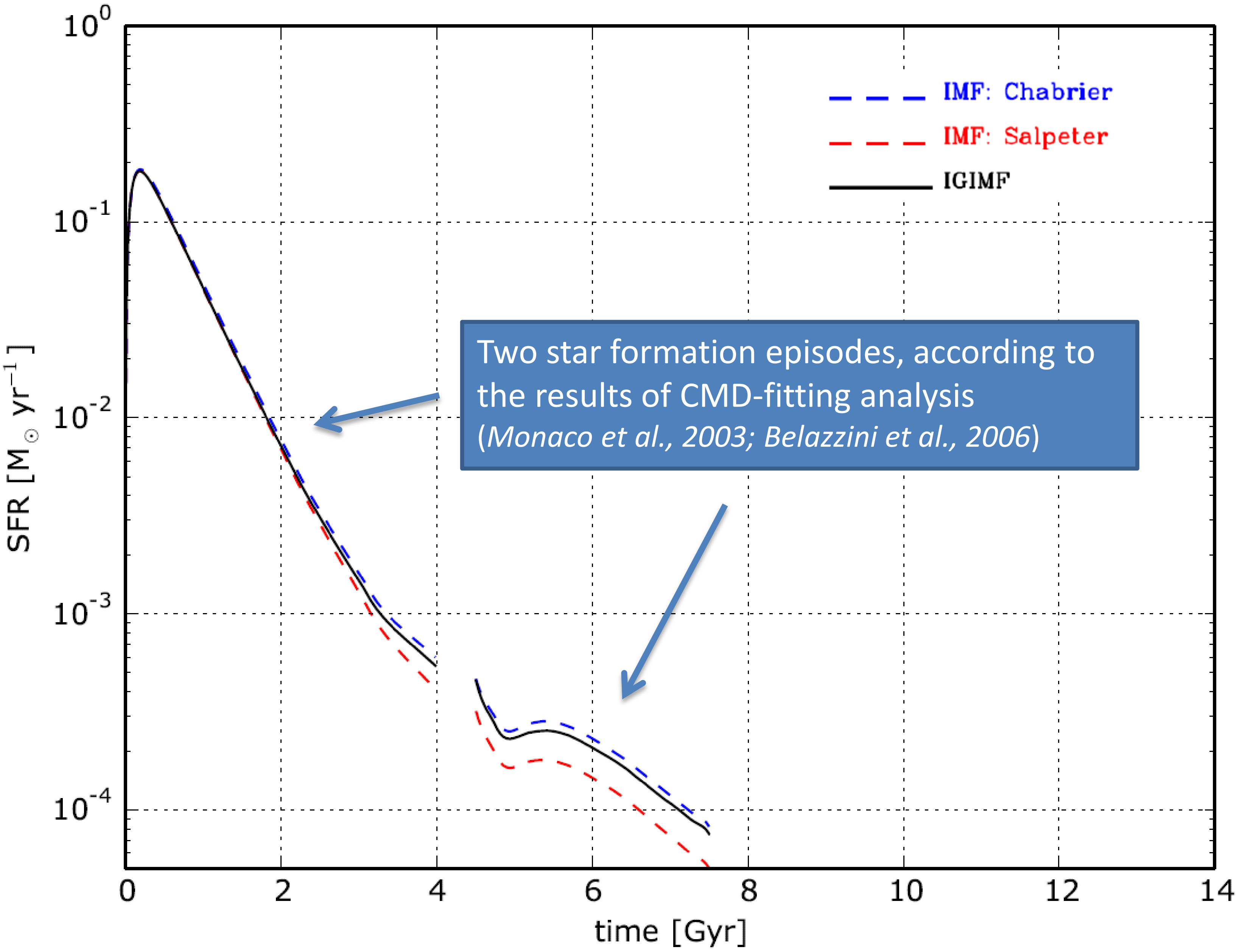


Vincenzo et al., submitted

The IGIMF with respect to classical IMFs

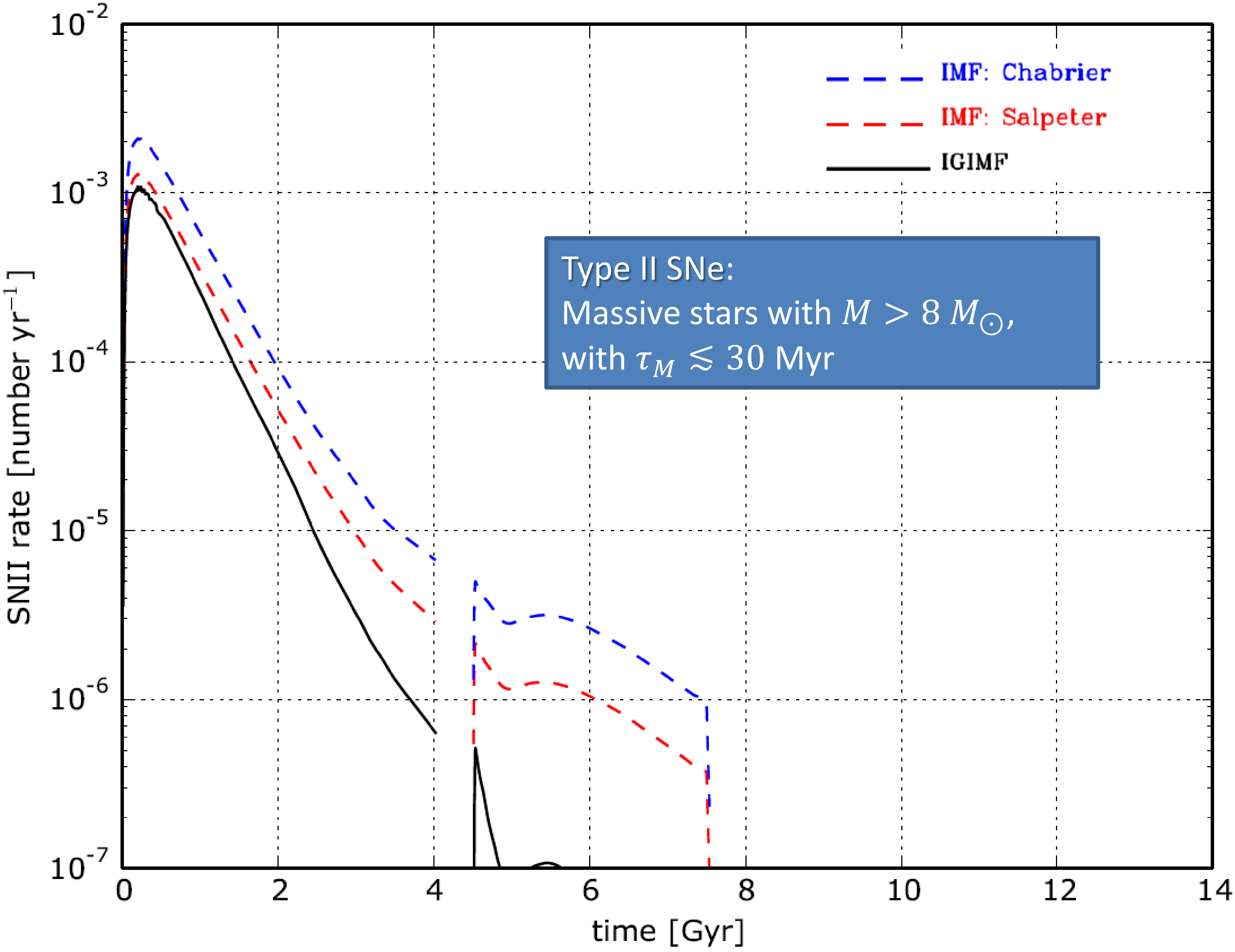


The predicted SFHs



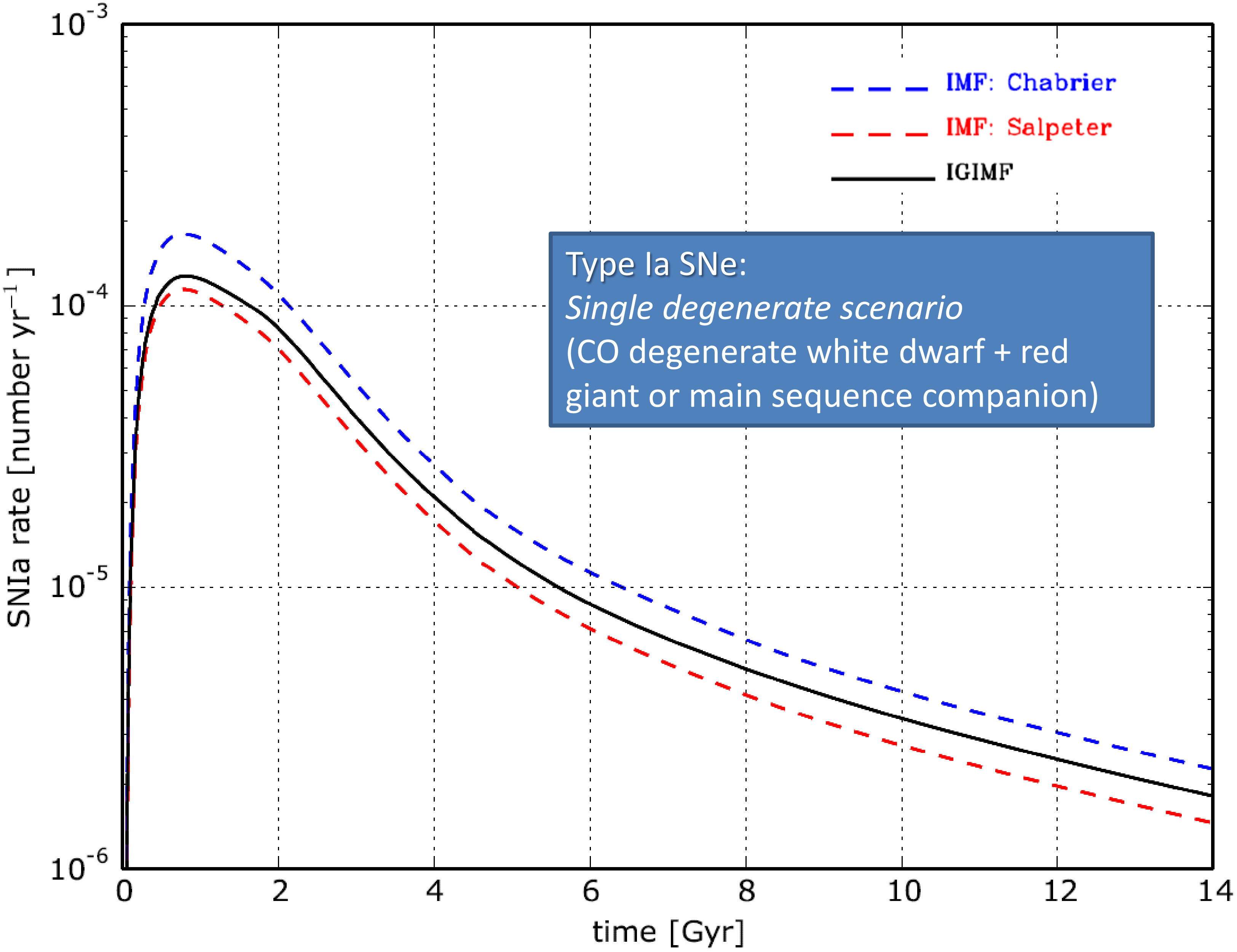
Two star formation episodes, according to the results of CMD-fitting analysis (*Monaco et al., 2003; Belazzini et al., 2006*)

The predicted Type II SN rates



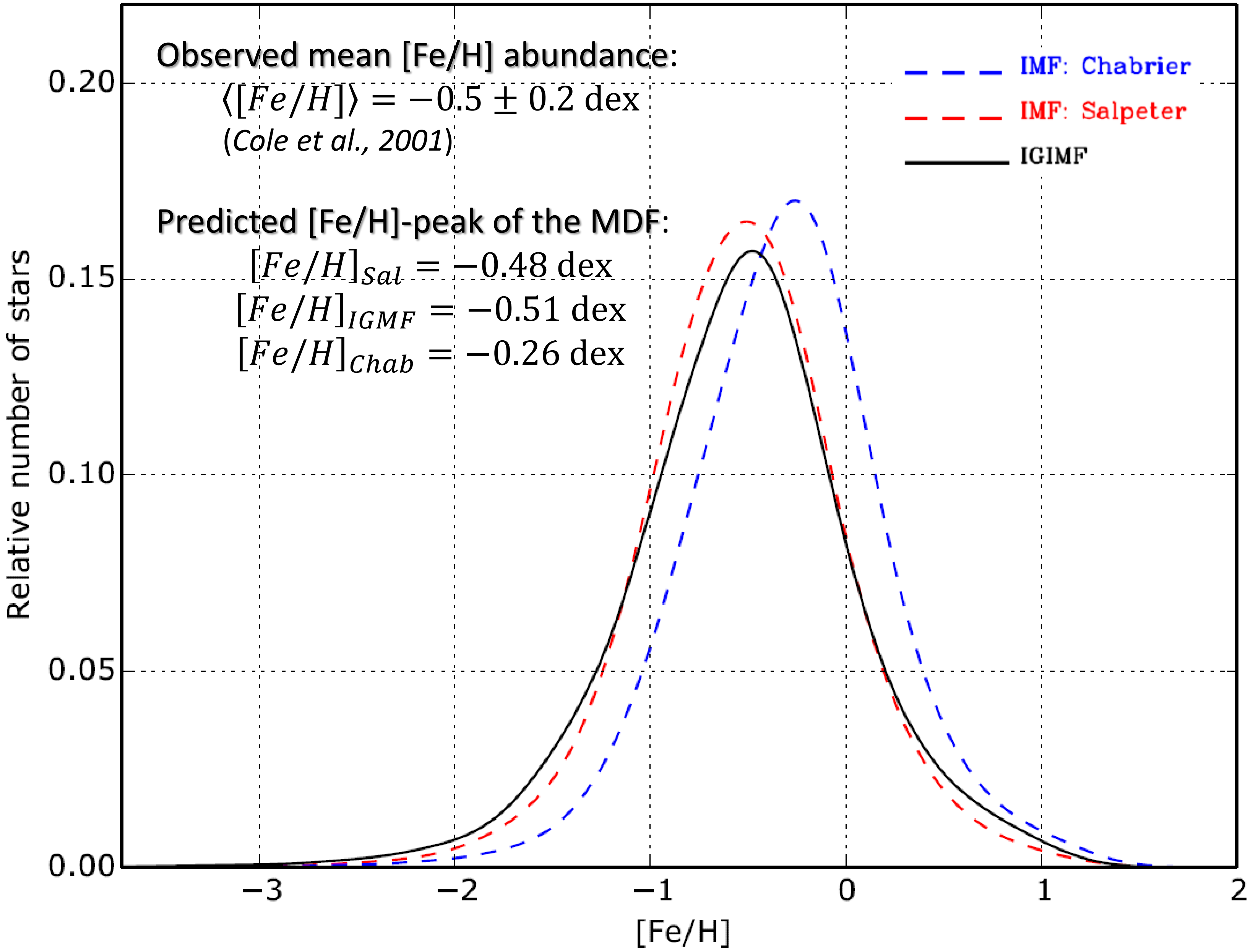
Type II SNe:
Massive stars with $M > 8\ M_{\odot}$,
with $\tau_M \lesssim 30$ Myr

The predicted Type Ia SN rates



Type Ia SNe:
Single degenerate scenario
(CO degenerate white dwarf + red giant or main sequence companion)

The predicted MDFs



Observed mean [Fe/H] abundance:

$$\langle [Fe/H] \rangle = -0.5 \pm 0.2 \text{ dex}$$

(*Cole et al., 2001*)

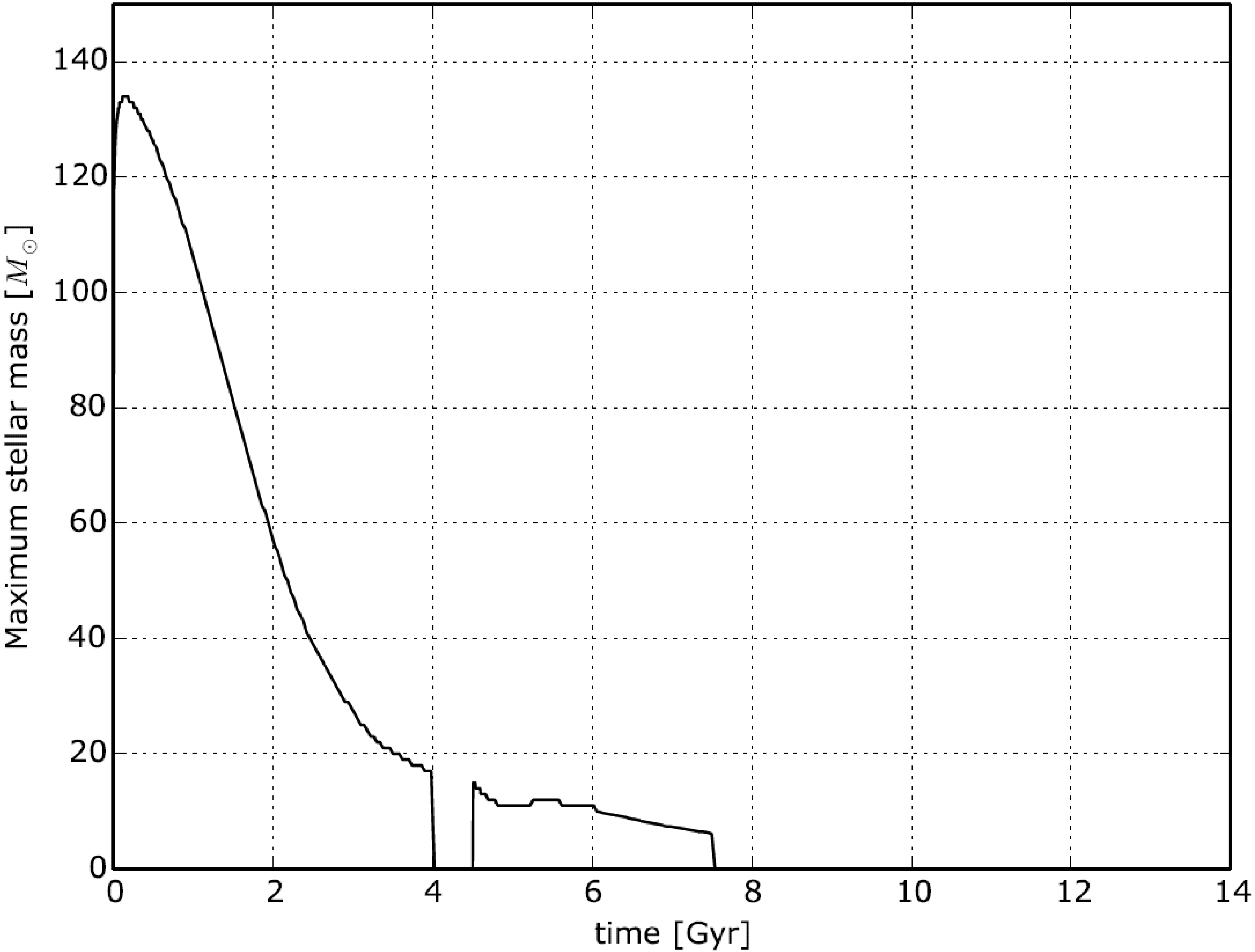
Predicted [Fe/H]-peak of the MDF:

$$[Fe/H]_{Sal} = -0.48 \text{ dex}$$

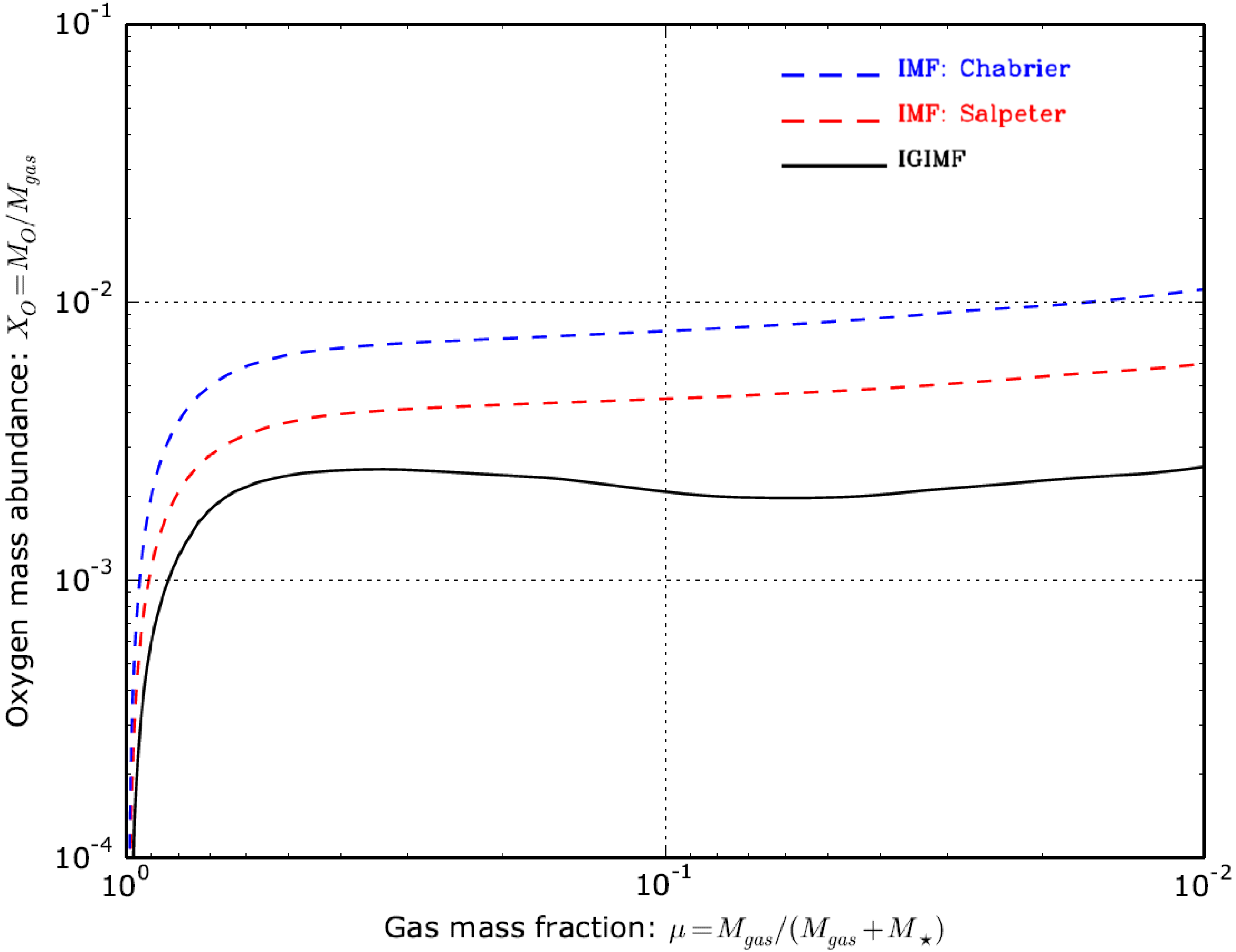
$$[Fe/H]_{IGMF} = -0.51 \text{ dex}$$

$$[Fe/H]_{Chab} = -0.26 \text{ dex}$$

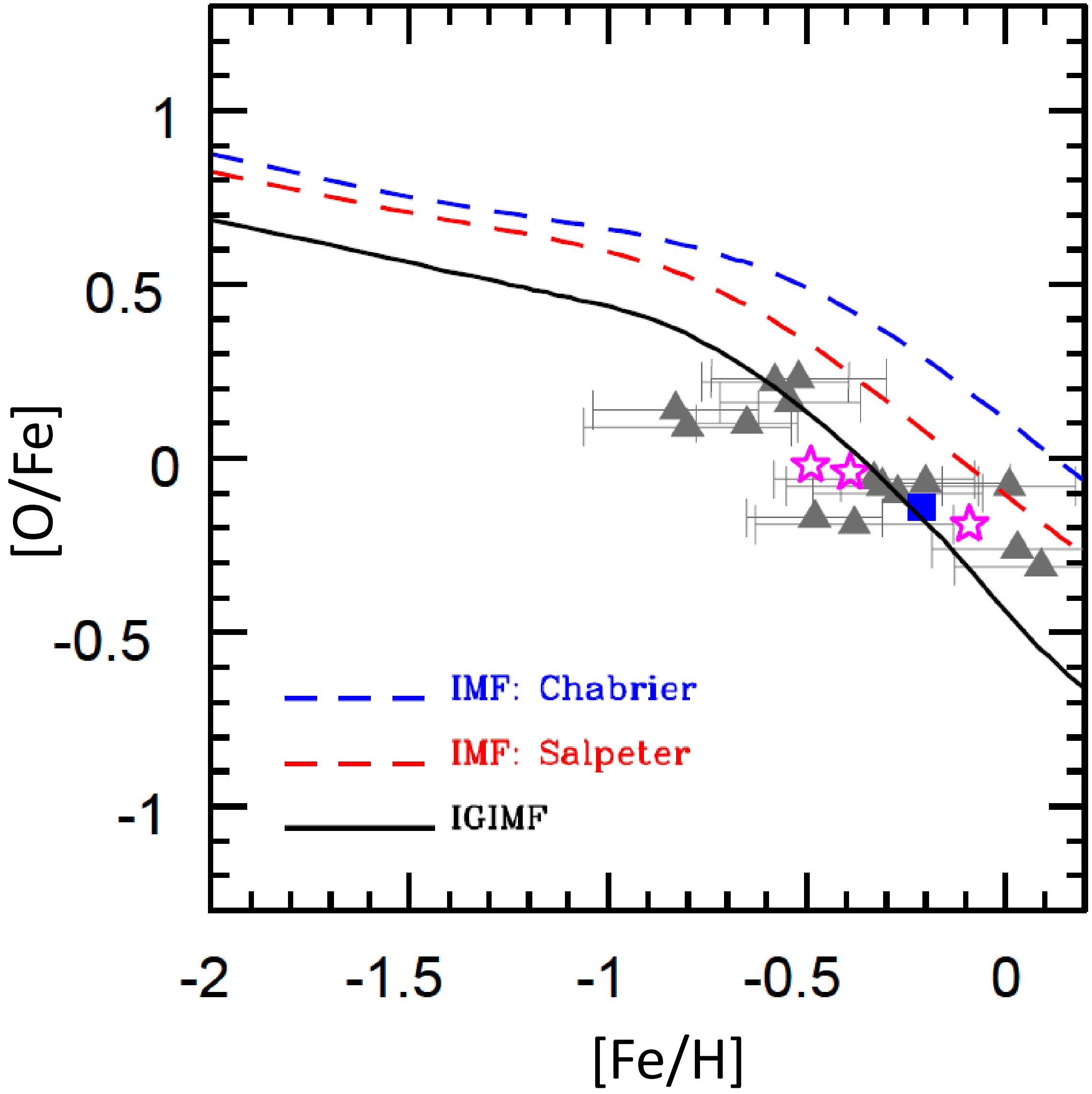
The evolution of the maximum stellar mass in Sgr, as predicted when assuming the IGIMF



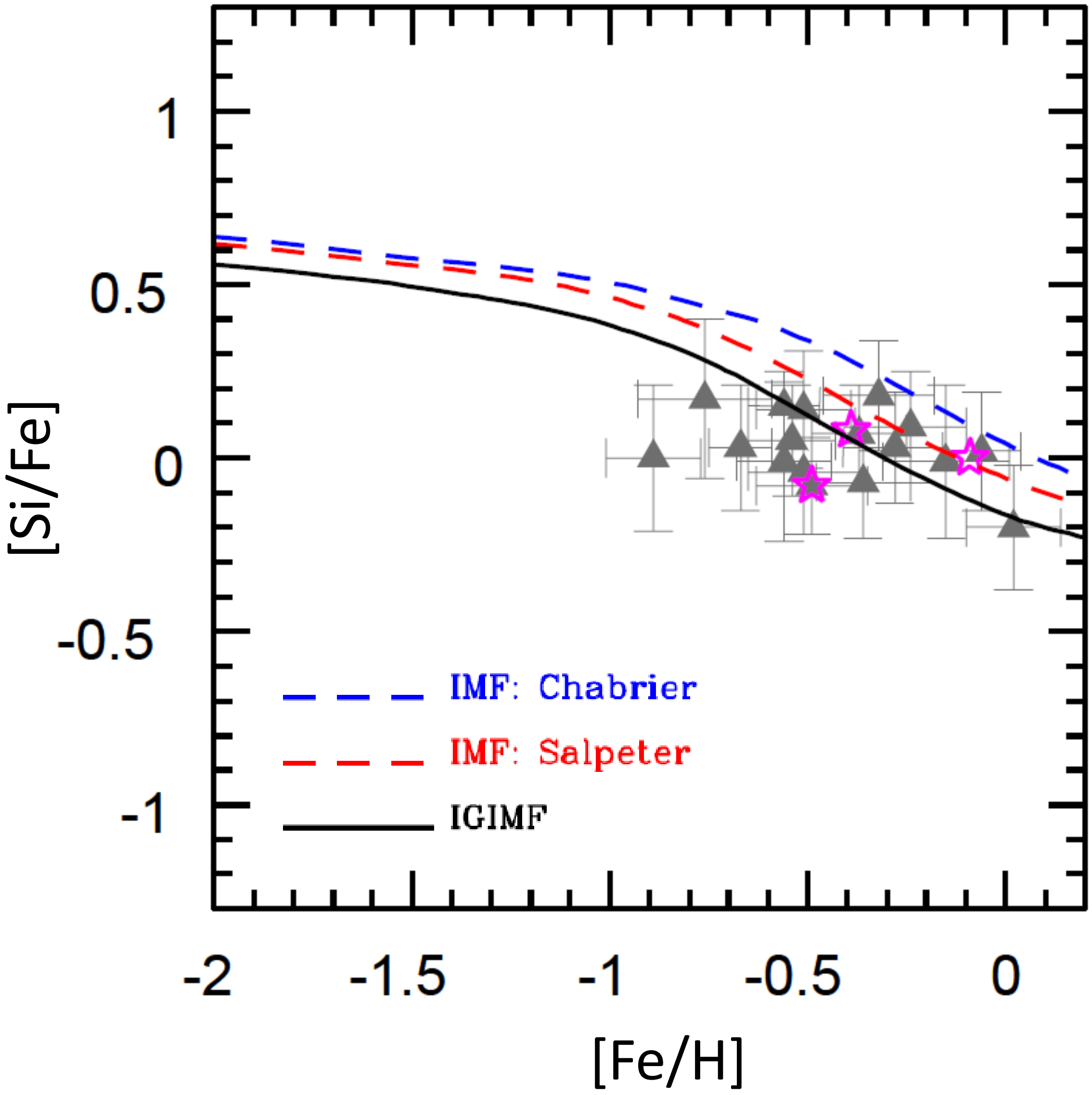
Oxygen mass abundance vs. gas mass fraction



The [O/Fe] vs. [Fe/H] in the Sgr dwarf

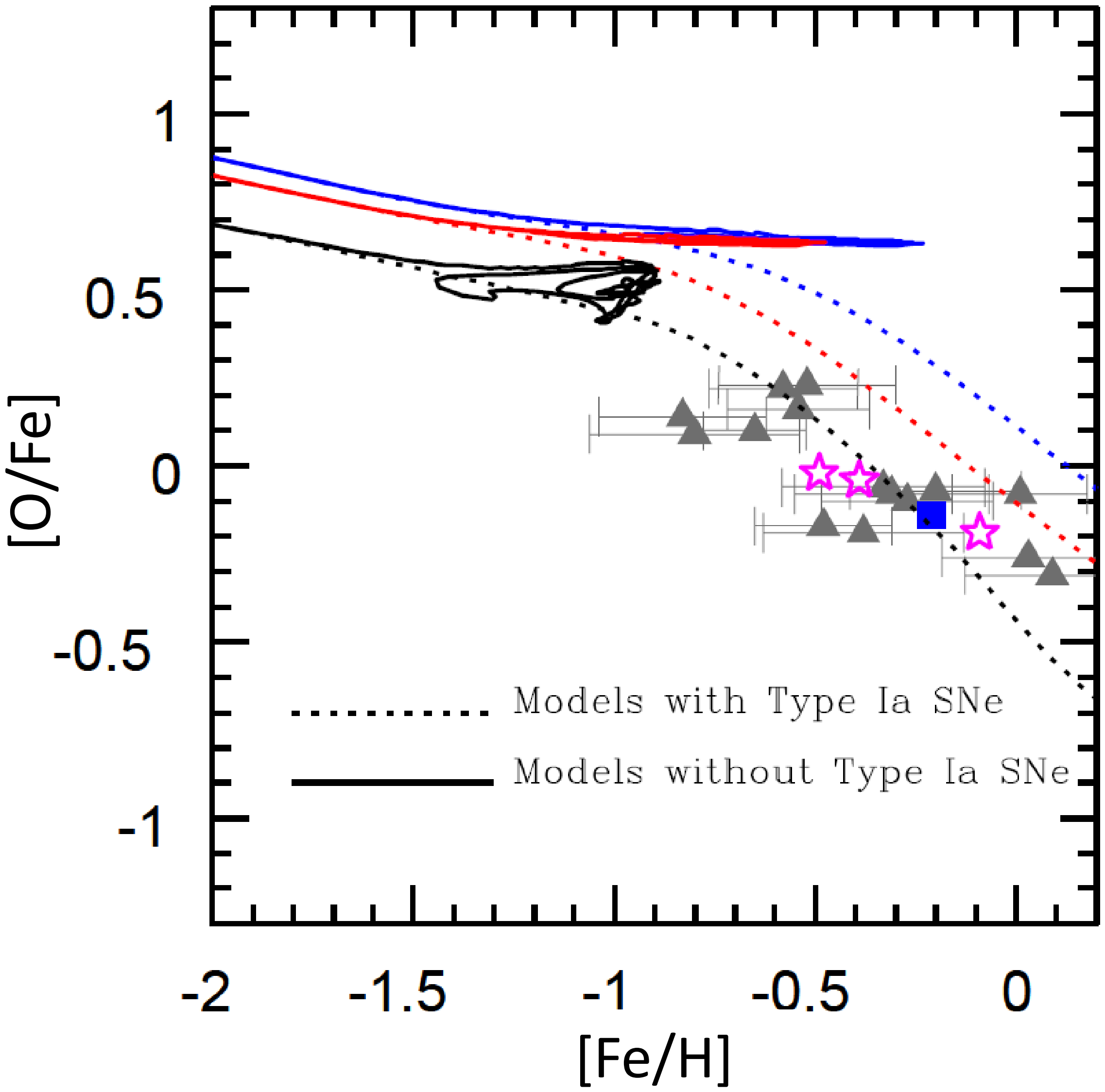


The [Si/Fe] vs. [Fe/H] in the Sgr dwarf



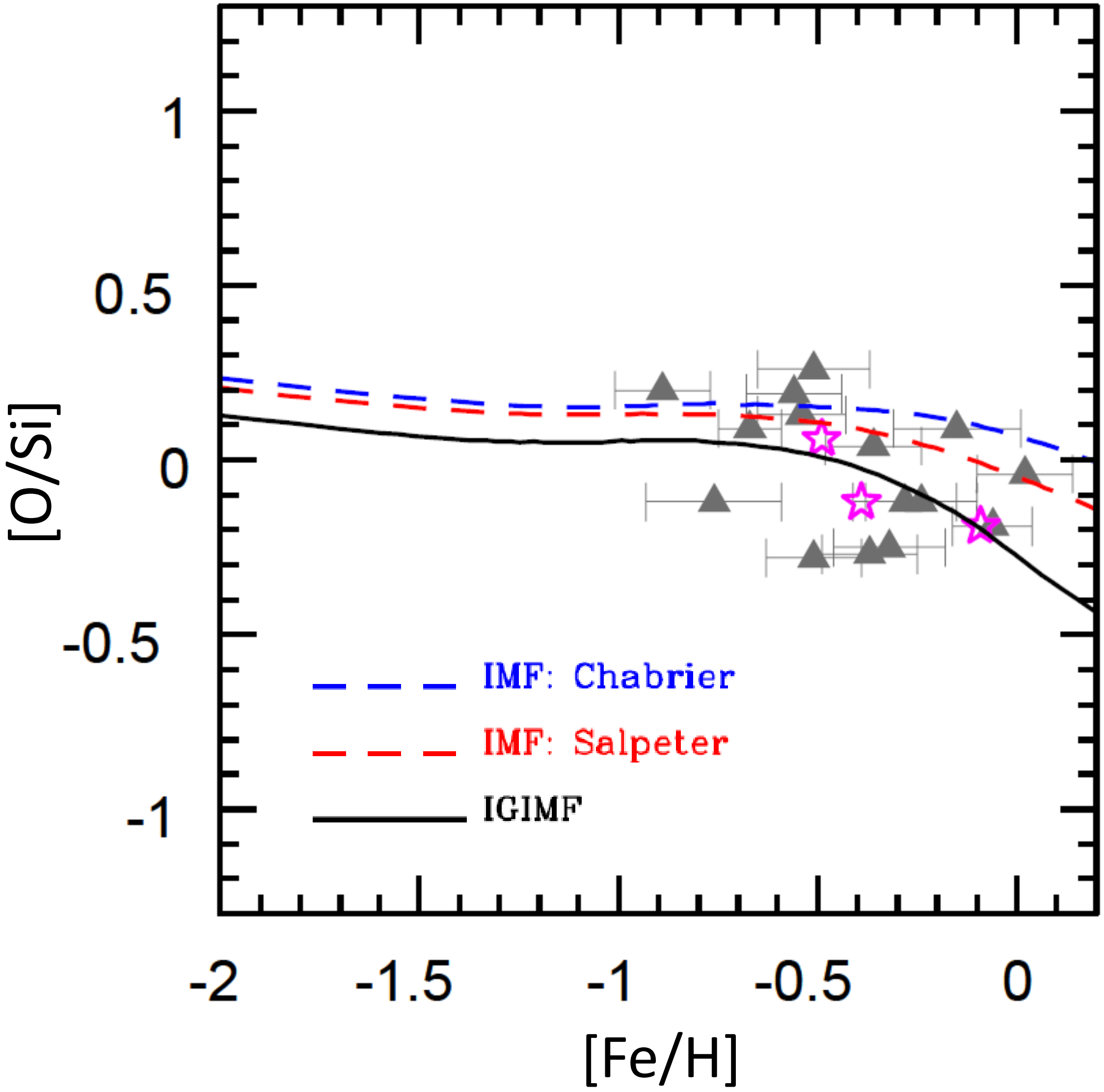
The time-delay model in dSphs

Bulk of Fe from SNe Ia + low SFRs



Hydrostatic-to-explosive α-element ratios

indicators of a truncated IMF (see McWilliam et al., 2013)



Eu nucleosynthetic prescriptions

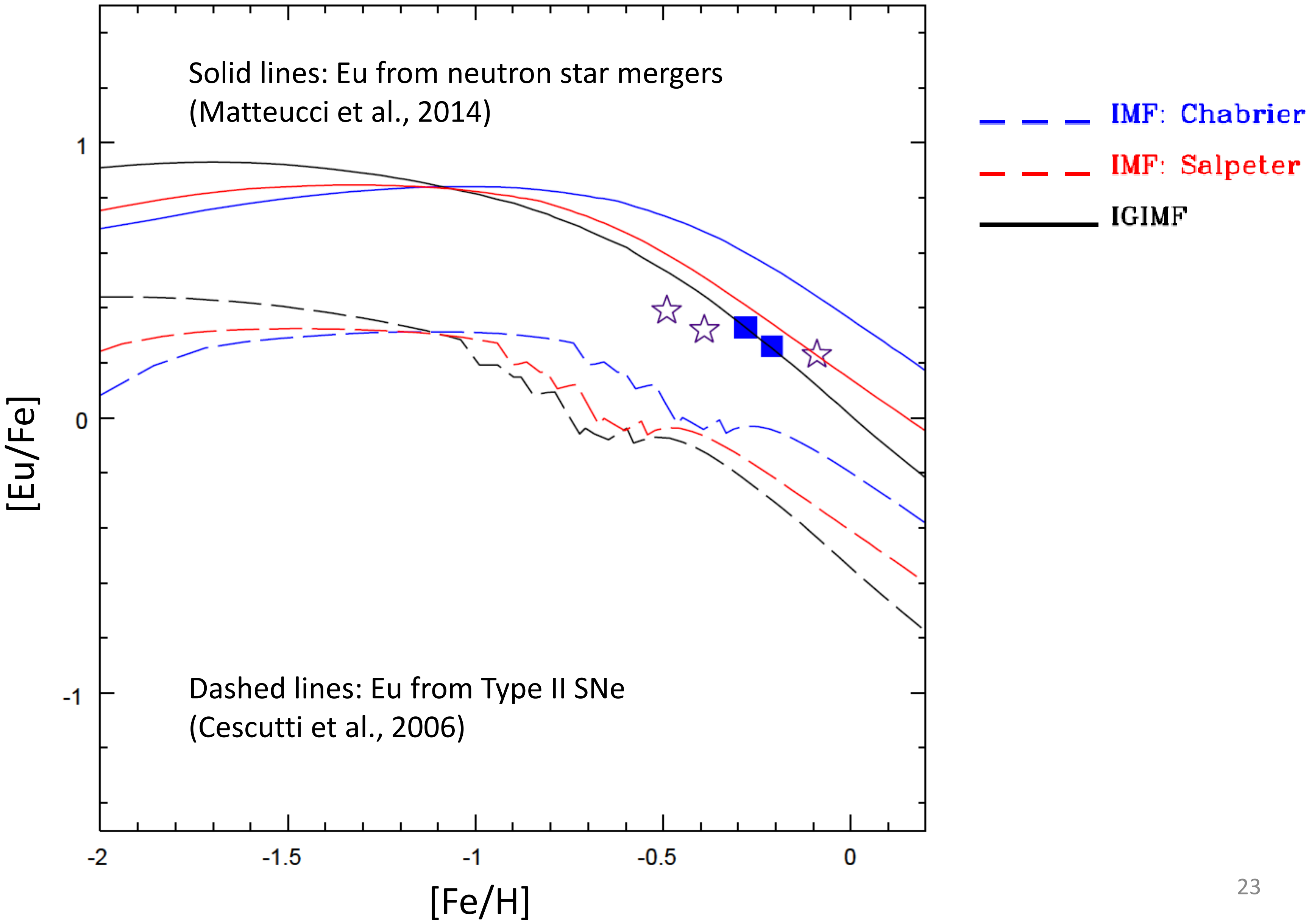
- *Cescutti et al. (2006)*: core-collapse SNe with mass in the range $M = 12 - 30\ M_\odot$

$M_\star/M_\odot$	X_{Eu}^{new}
12.0	$4.50 \cdot 10^{-8}$
15.0	$3.00 \cdot 10^{-9}$
30.0	$5.00 \cdot 10^{-10}$

- *Ishimaru et al. (2004)*: core-collapse SNe with mass in the range $M = 8 - 10\ M_\odot$
  - $X_{Eu}^{new} = 1.1 \cdot 10^{-6}\ M_\odot/M_\star$

- *Matteucci et al. (2014)*: neutron star mergers
  - Each NSM release $M_{Eu}^{new} = 2.2 \cdot 10^{-6}\ M_\odot$

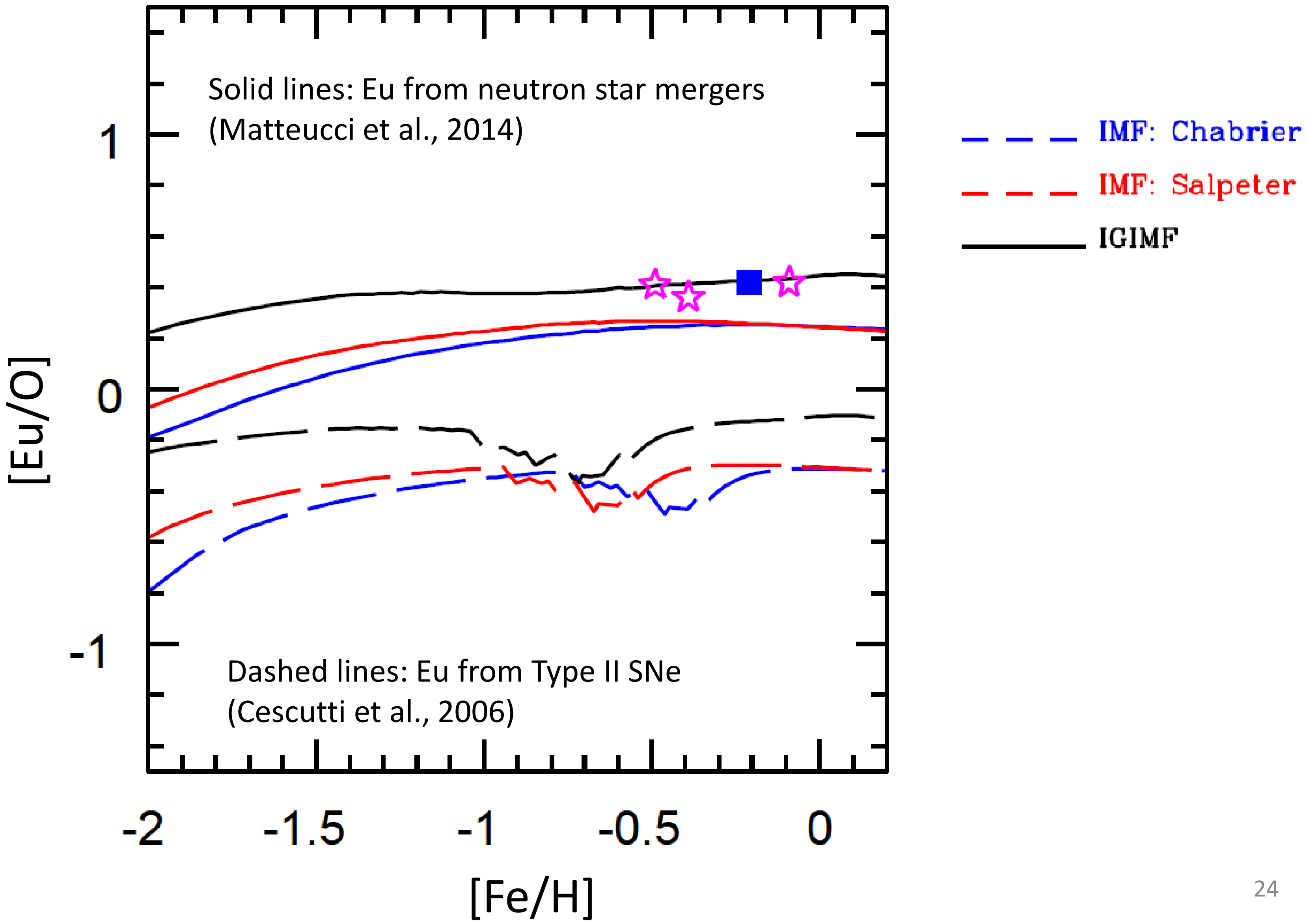
The [Eu/Fe] vs. [Fe/H] in the Sgr dwarf



Solid lines: Eu from neutron star mergers
(Matteucci et al., 2014)

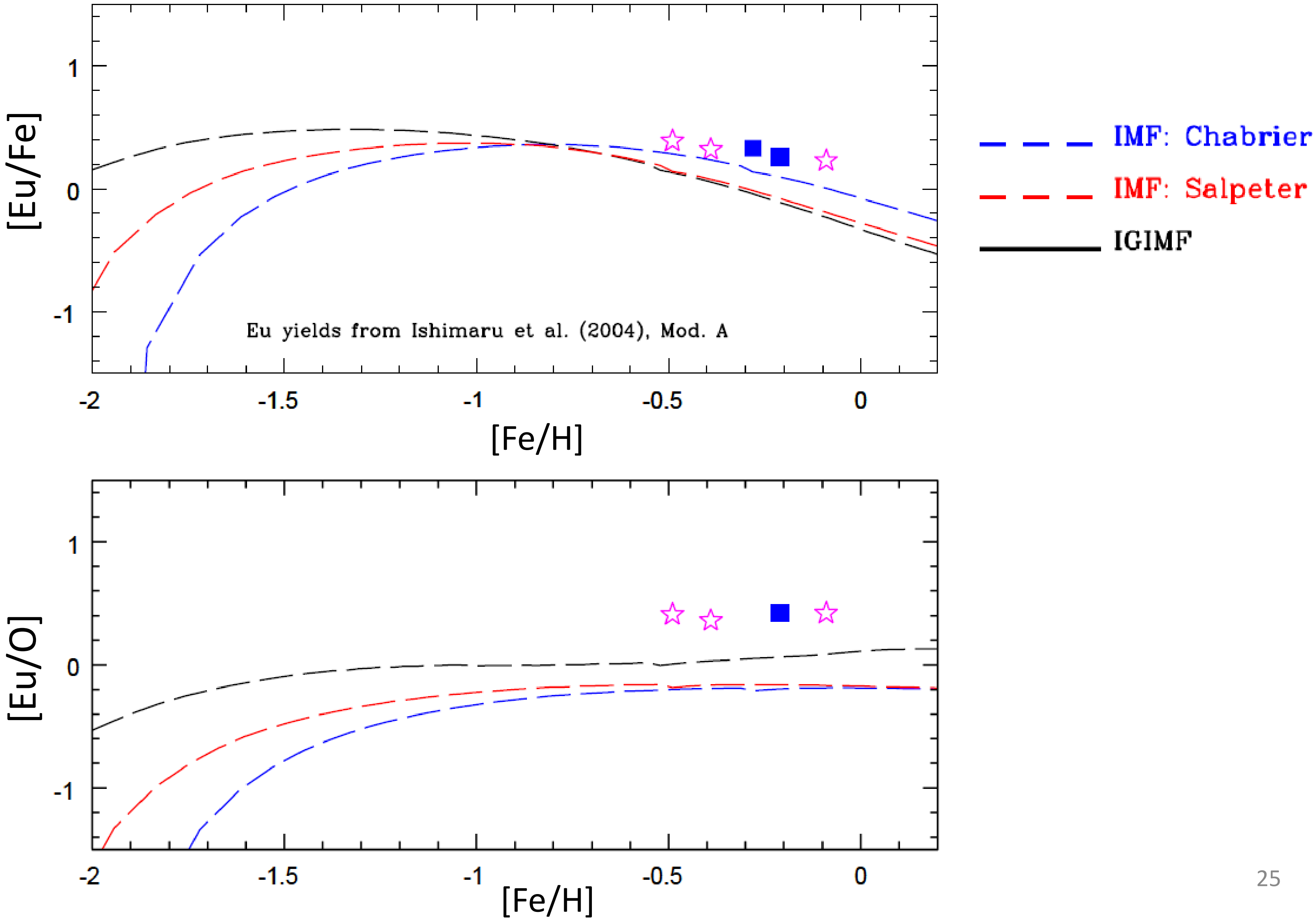
Dashed lines: Eu from Type II SNe
(Cescutti et al., 2006)

The [Eu/O] vs. [Fe/H] in the Sgr dwarf



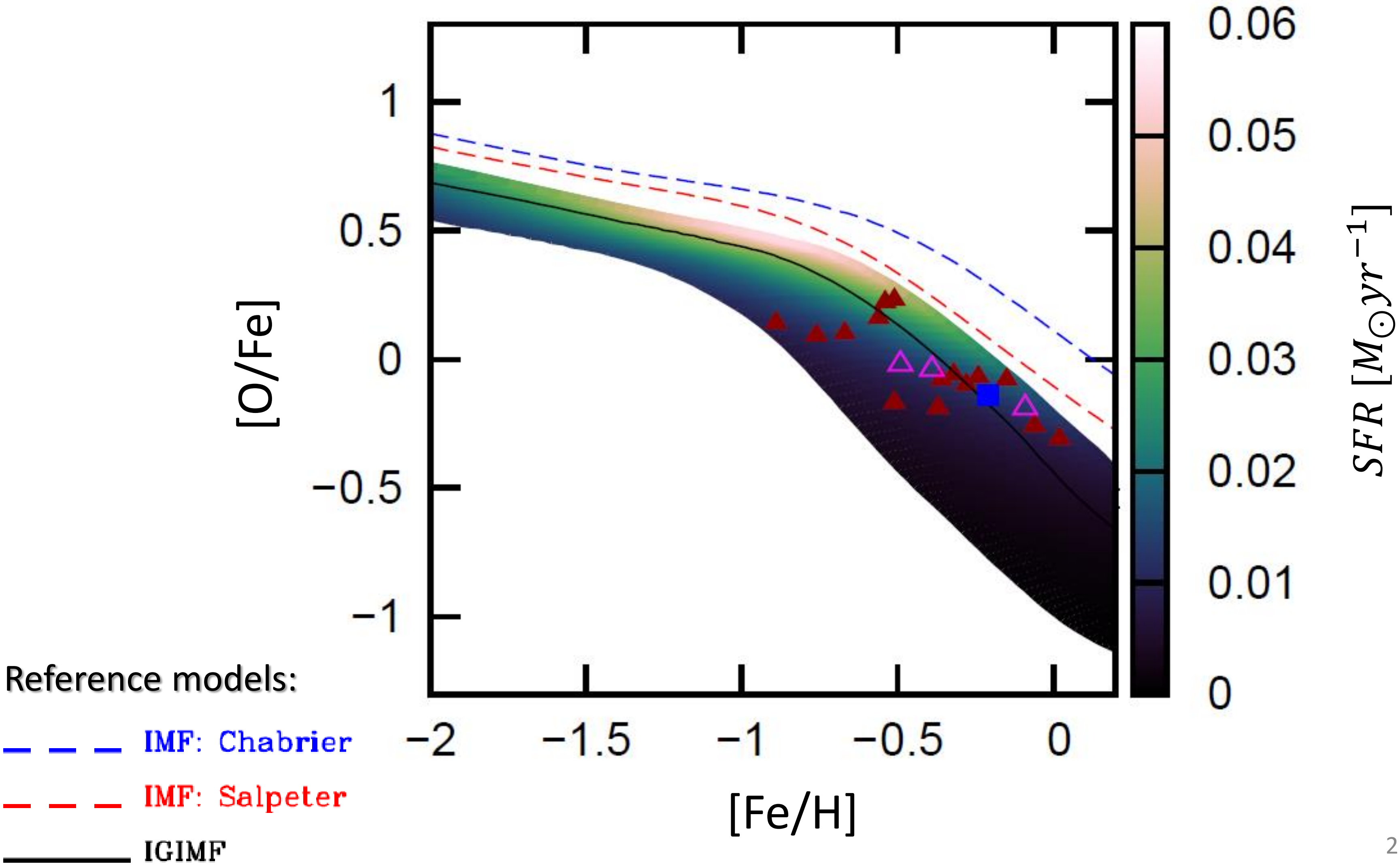
The Ishimaru (2004) yields for Eu:

low mass core-collapse SNe



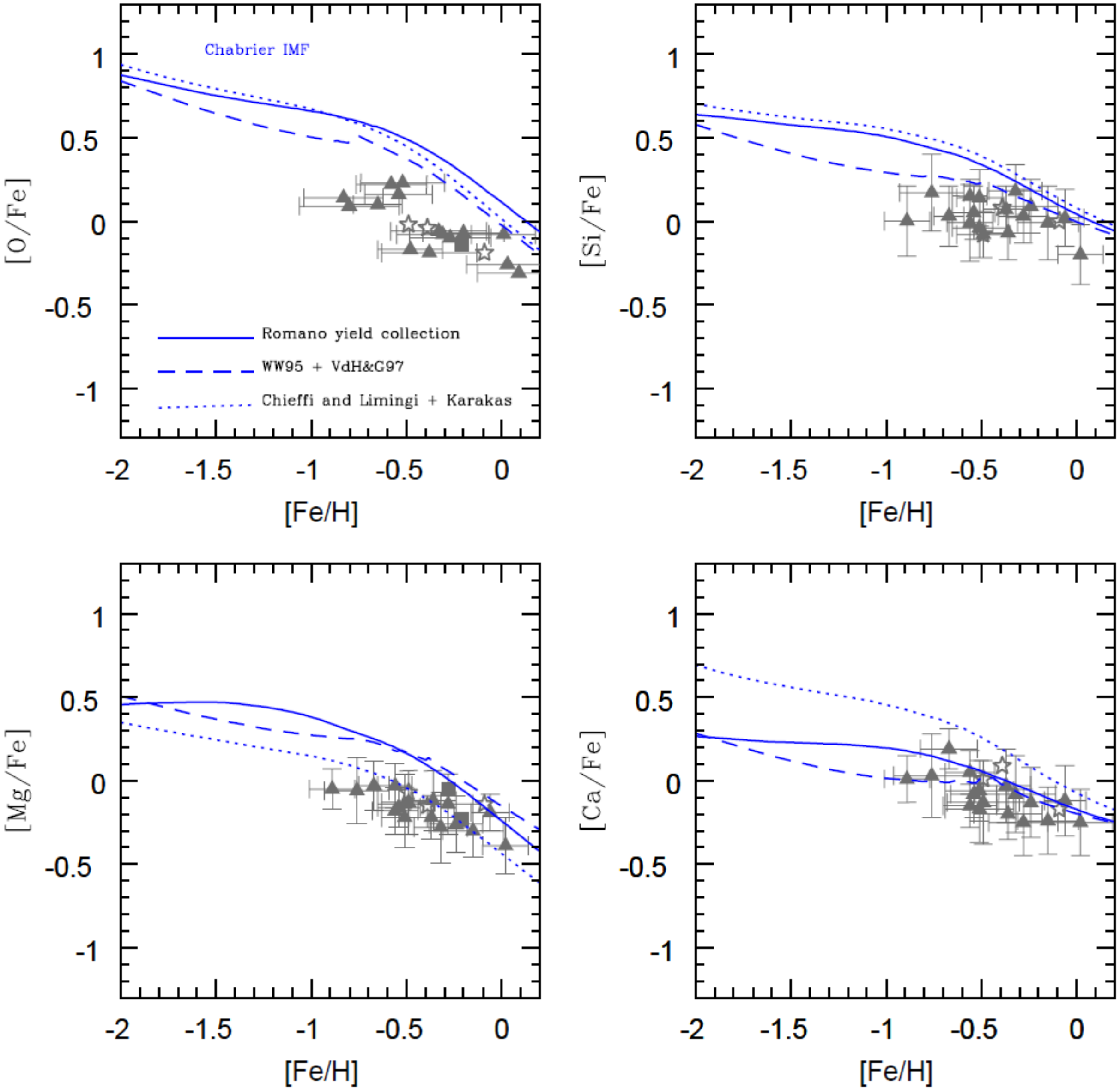
Exploring the parameter space

varying the star formation efficiency in the models with the IGIMF



Uncertainties in the models

the stellar yields (fixing the IMF, here Chabrier)



In this figure, we compare:

i) The Romano et al. (2010) set of stellar yields (*solid lines*)

ii) The WW95 stellar yields for massive stars, with the corrections of Francois et al. (2004) + VDH&G97 for LIM stars (*dashed lines*)

iii) The most recent Chieffi and Limongi stellar yields (priv. comm.) for massive stars with $v_{rot} = 0.0\ km\ s^{-1}$ (*dotted lines*)

Conclusions

- A truncated IMF in Sgr provides a better qualitative agreement between predicted an observed abundance ratios
- The time-delay model is necessary to explain the trends of the [α/Fe] and [Eu/Fe] ratios. However, it turns out to be not sufficient to explain the observations in this galaxy
- The hydrostatic-to-explosive α-element abundance ratios can retain a well defined signature of a truncated IMF and might support the idea of a truncated IMF in Sgr
- All our model with Eu coming from core-collapse SNe are not able to reproduce the [Eu/Fe] and [Eu/O] ratios at the same time, which are well matched when the NSM mechanism and the IGIMF are assumed