Galactic Astroarchaelogy: constraints on formation and evolution of galaxies

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Outline of the talk

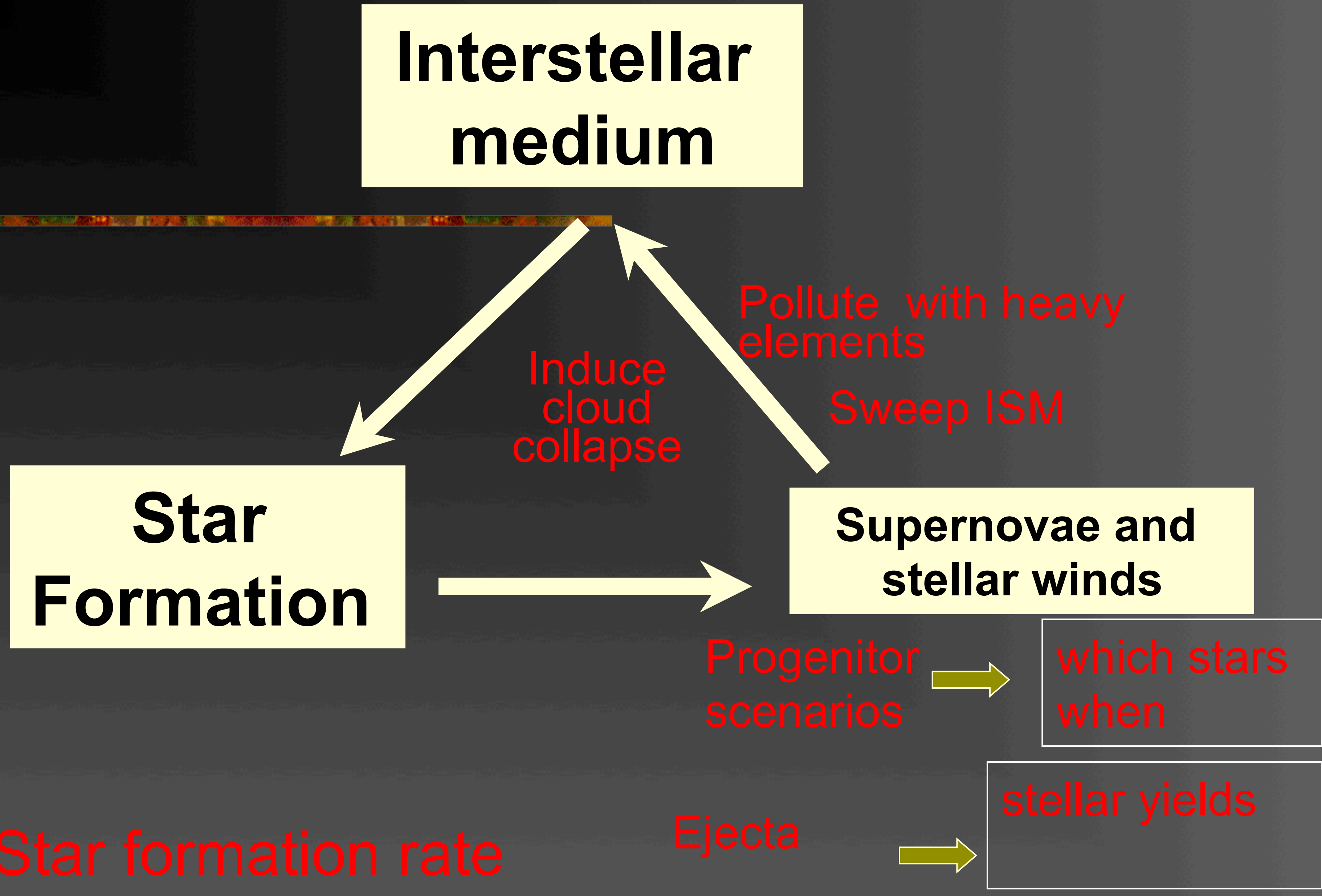
- Basic ingredients for building chemical evolution models
- Chemical abundances as tools to infer the star formation history of galaxies
- The Milky Way
- The dwarf spheroidals and ultra faint dwarfs of the Local Group

Astroarchaeology

- Chemical abundances tell us about the nucleosynthesis as well as the formation and evolution of galaxies
- Light elements (H, D, He, Li) were synthesized during the Big Bang
- All the elements with A>12 were formed inside stars
- Stars produce new elements and then restore them into the ISM. This process is called chemical evolution

Basic Ingredients of Chemical Evolution

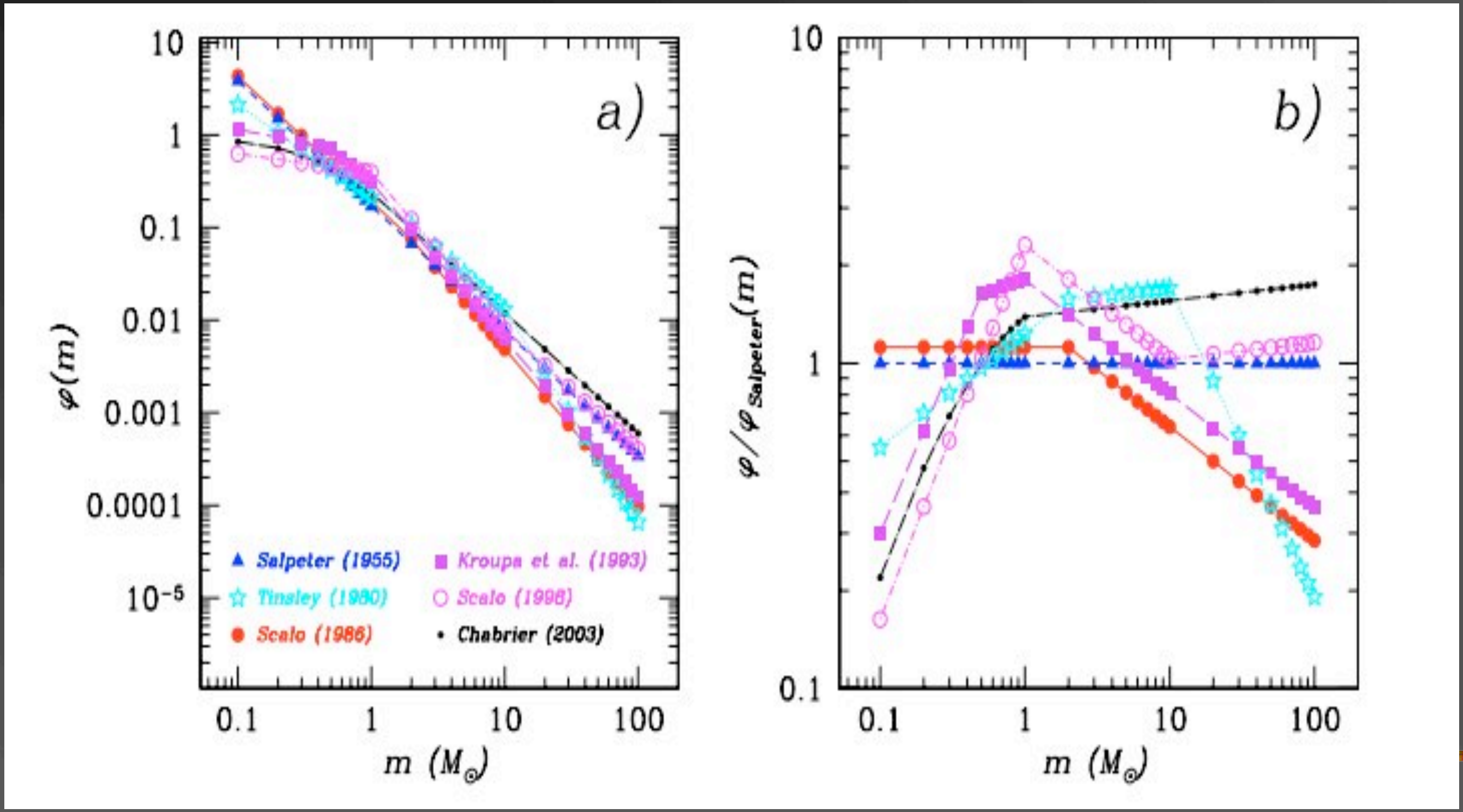
- Initial conditions (open/closed-box; initial chemical composition)
- The stellar birthrate function: SFRxIMF
- The stellar yields (i.e. the mass restored into the ISM by a star of a given mass in the form of a given chemical element
- Gas flows: infall, outflow, inflow



Star formation rate
Initial mass function

The Initial Mass Function

- The IMF has been derived for the solar vicinity and is expressed as a power law



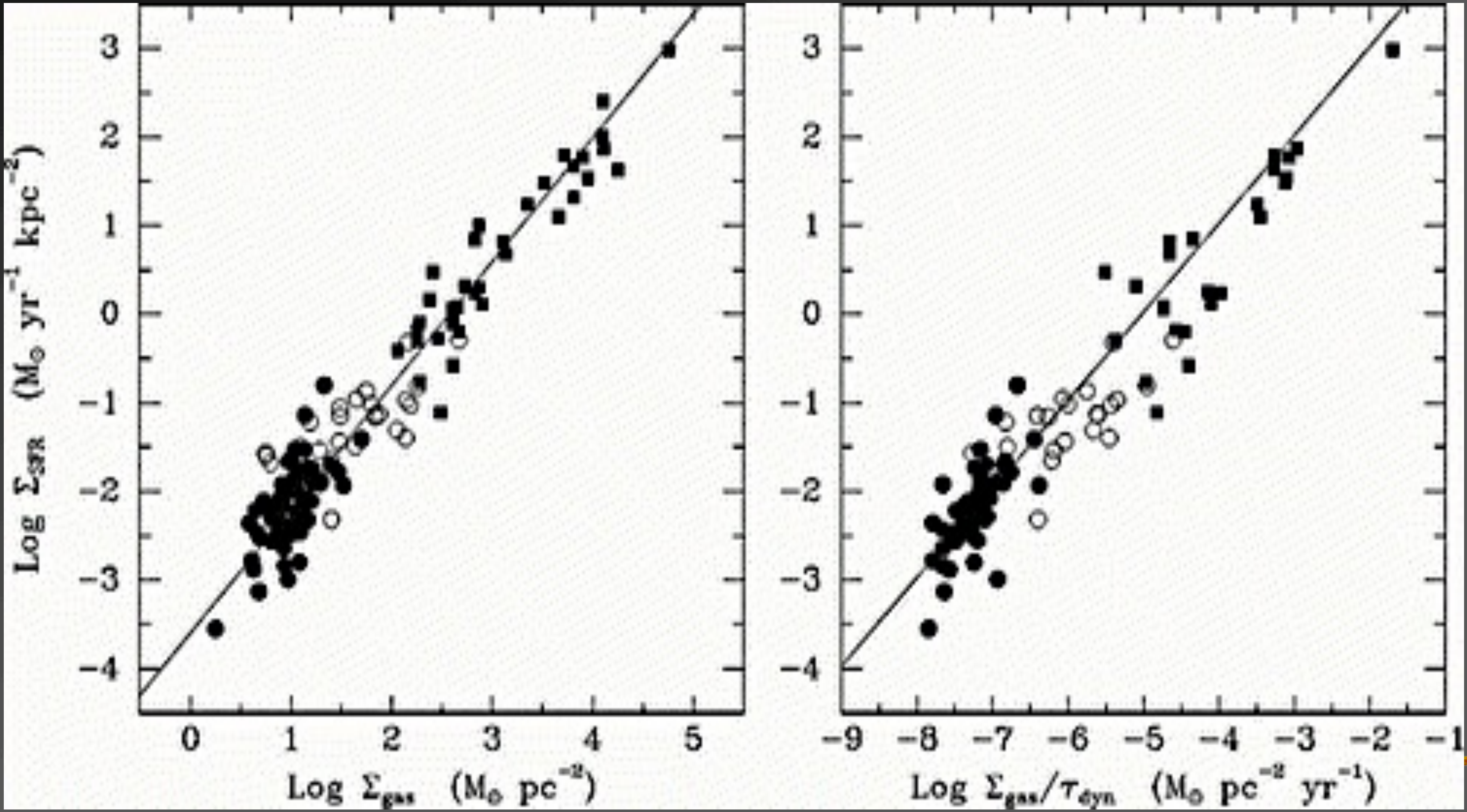
The parametrization of the SFR

- The most common parametrization is the so-called Schmidt (1959) law, where the SFR is proportional to some power of the gas density

$$SFR = \nu \sigma_{gas}^{k}$$

- Kennicutt (1998) suggested k=1.4 from studying star forming galaxies
- The constant in front of the gas density is the SF efficiency (expressed in time^{-1})

Kennicutt's law

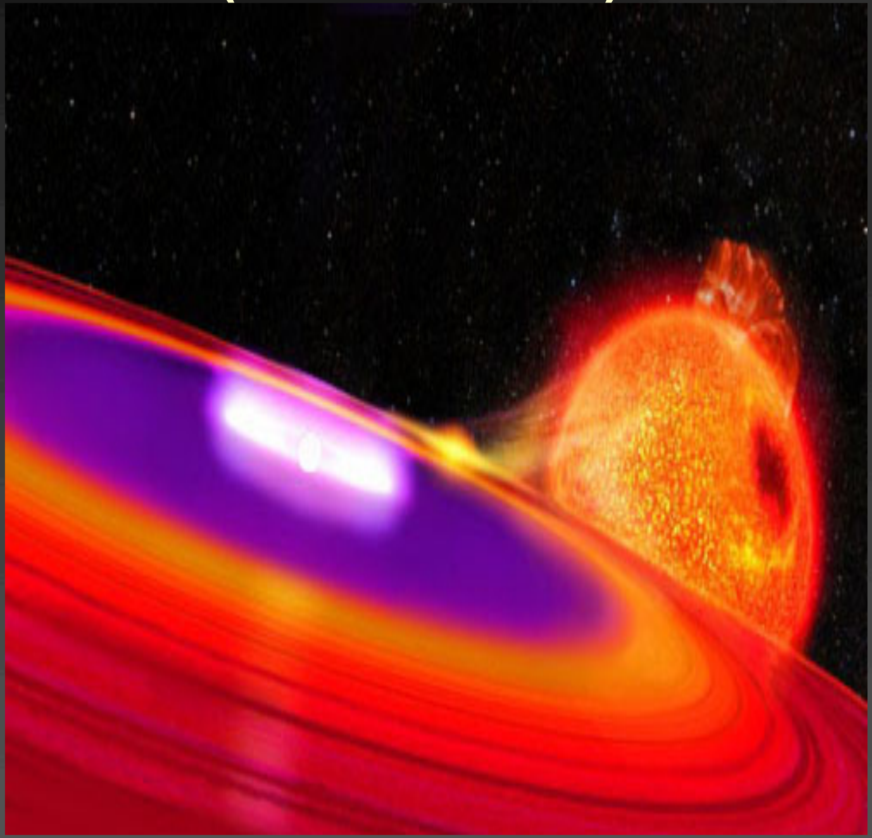


The Stellar Yields

- Low and intermediate mass stars (0.8-8 Msun): produce He, N, C and heavy s-process elements. They die as C-O WDs, when single, and can die as Type Ia SNe when binaries
- Massive stars (M>8-10 Msun, core-collapse SNe): they produce alpha-elements (O, Mg..), some Fe, light s-process elements and r-process elements
- Type Ia SNe produce mainly Fe (0.6-0.7Msun per SN)

Different supernovae

SN Ia (artistic view)

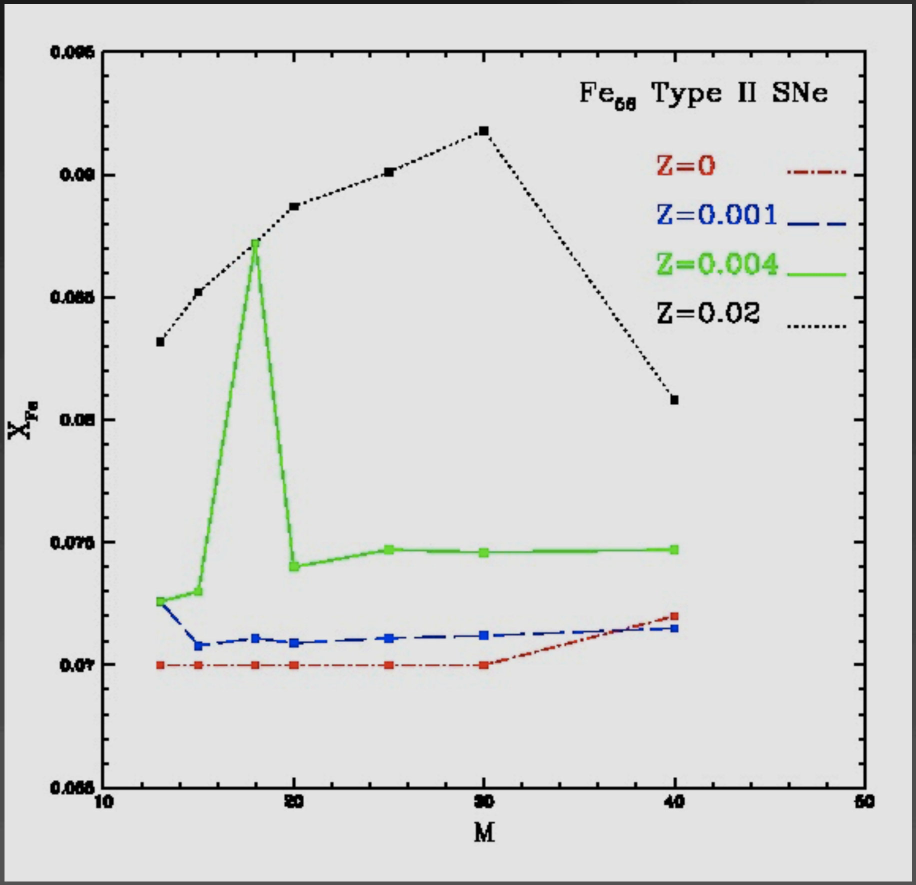


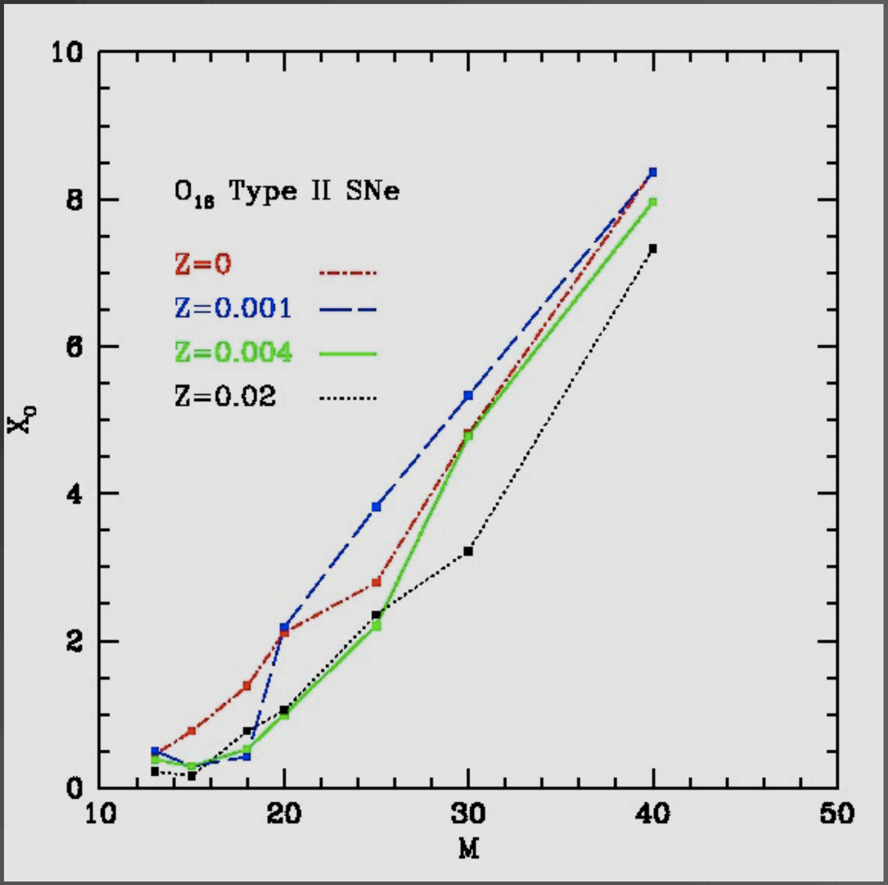
SN II (Cassiopea A)

Supernova Progenitors

- Core-collapse SNe originate from massive stars (M> 10Msun), they can be of Type II,Ib and Ic. They leave neutron stars or black holes as remnants. Type Ib/c SNe are the most massive and are connected to GRBs (lifetimes < 30Myr)
- Type I a SNe are thought to originate from C-O white dwarfs (WD) in binary systems (lifetimes >30 Myr)

Stellar yields: cc SNe Nomoto+06

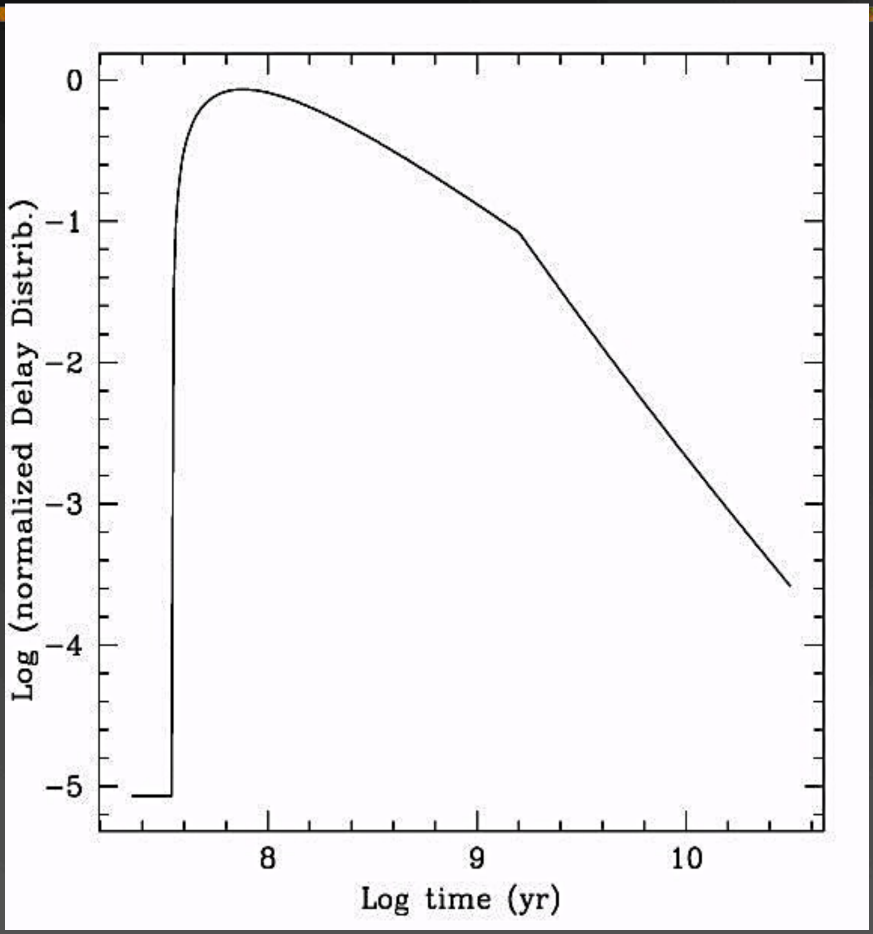


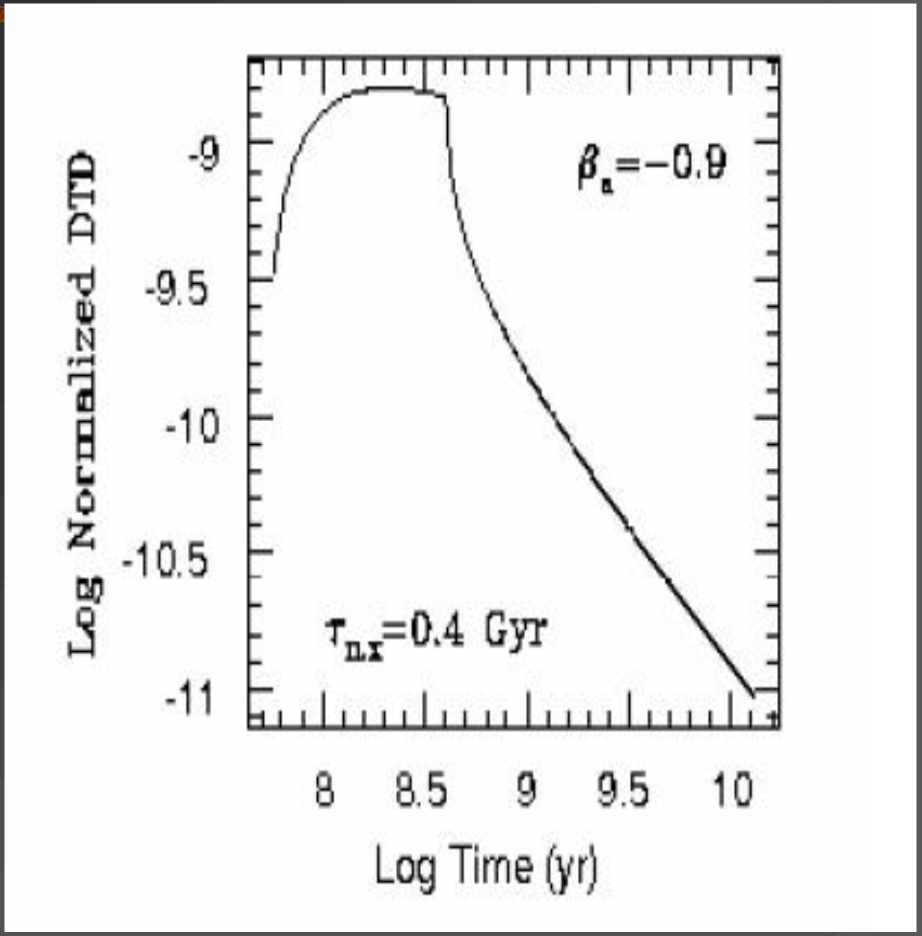


Type Ia Supernovae

- Double-Degenerate scenario (Iben & Tutukov, 1984): two C-O WDs merge after loosing angular momentum due to gravitational wave radiation
- Single-degenerate scenario (e.g. Whelan & Iben 1974): a binary system with a C-O white dwarf plus a MS star. When the star becomes RG it starts accreting mass onto the WD
- The explosion in both cases occurs when the Chandrasekhar mass is reached

Delay time distributions for Type Ia SNe (SD left DD right). Minimum delay 35Myr





Gas flows: infall

- Gas can be accreted or lost from a galaxy
- The most common parametrization of the accretion rate is an exponential law

$$IR = A(R)e^{-t/\tau(R)}$$

Gas Flows:outflow

- Outflows and galactic winds are seen in galaxies
- The most common parametrization is

Wind=CxSFR

- The wind rate is proportional to the star formation rate (Martin, 2000,2004)

Basic Equations: no IRA

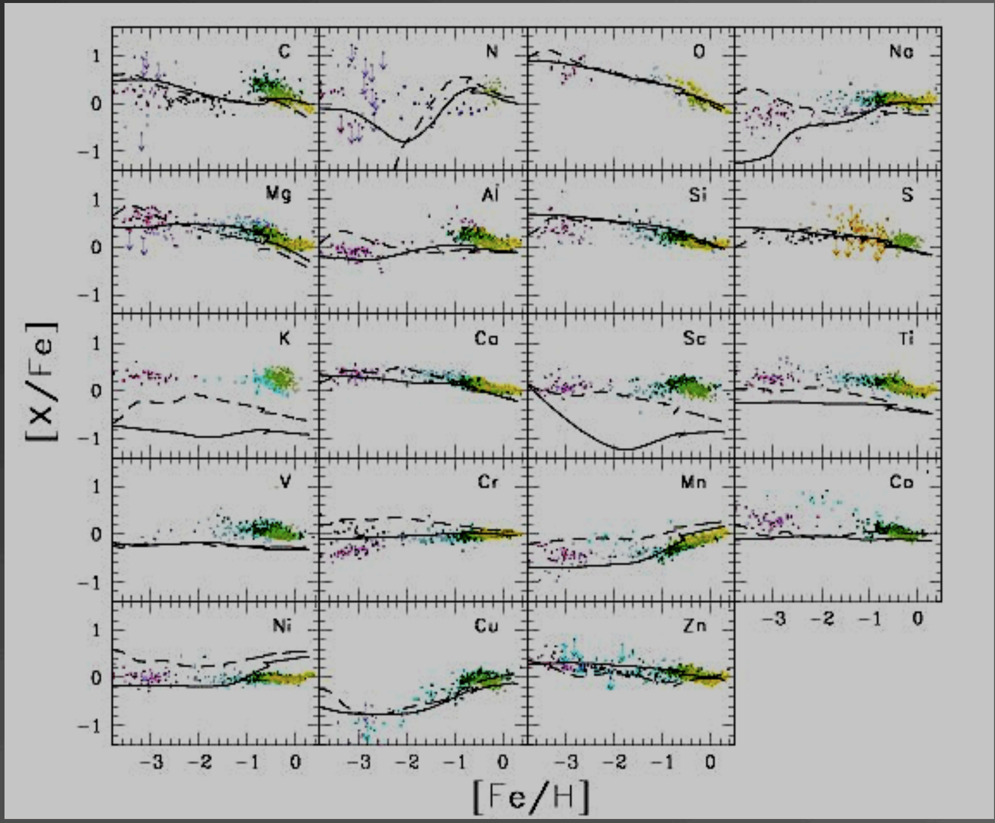
$$
\begin{aligned}
G_i(t) &= -\psi(t)X_i(t) \\
&+ \int_{M_L}^{M_{Bm}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+ A\int_{M_{Bm}}^{M_{BM}} \phi(m) \\
&\cdot[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})d\mu]dm \\
&+ B\int_{M_{Bm}}^{M_{BM}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+ \int_{M_{BM}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+ X_{A_i}A(t) - X_iW(t)
\end{aligned}
$$

How did the Milky Way form? The Formation of the MW from Astroarchaelogy

- The two-infall model of Chiappini, FM & Gratton (1997) predicts two main episodes of gas accretion
- During the first one the halo, bulge and all or part of thick disk formed, the second gave rise to the thin disk. SF efficiency is 1/Gyr
- This model can reproduce most of the observational data and allows us to derive the formation timescales

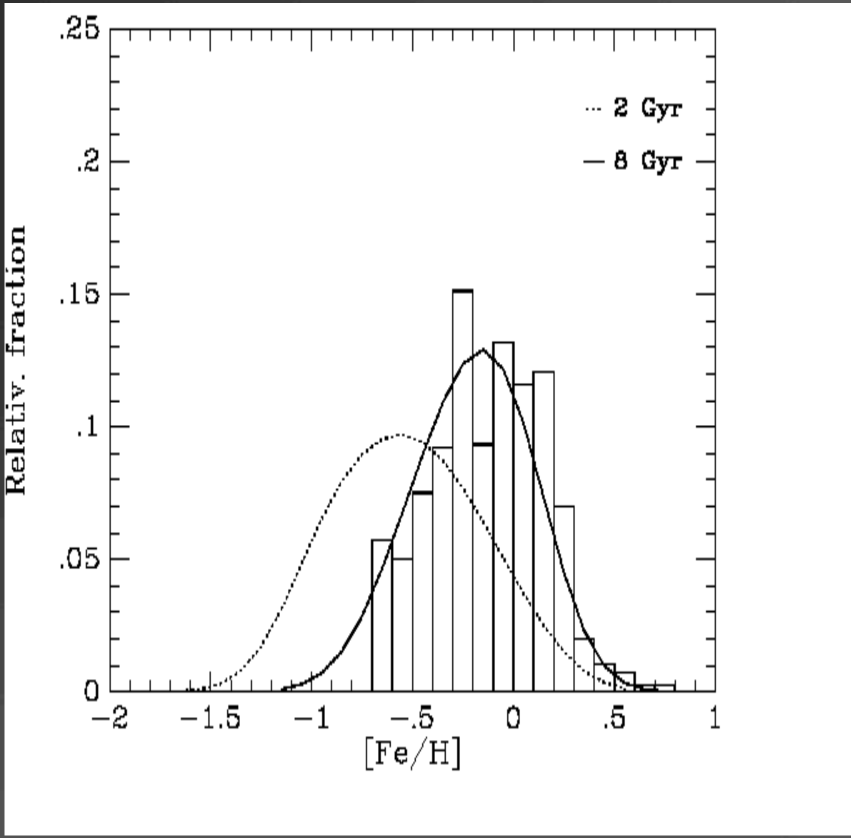
Chemical evolution of the Milky Way (Romano+10)

- Two sets of yields are tested in the framework of two-infall model
- The best are those represented by a continuous line: Kobayashi + 06 for massive stars and Geneva yields for rotating stars plus Karakas00 for LIMS
- The assumed IMF is that of Kroupa+93 which is the best for S.N.



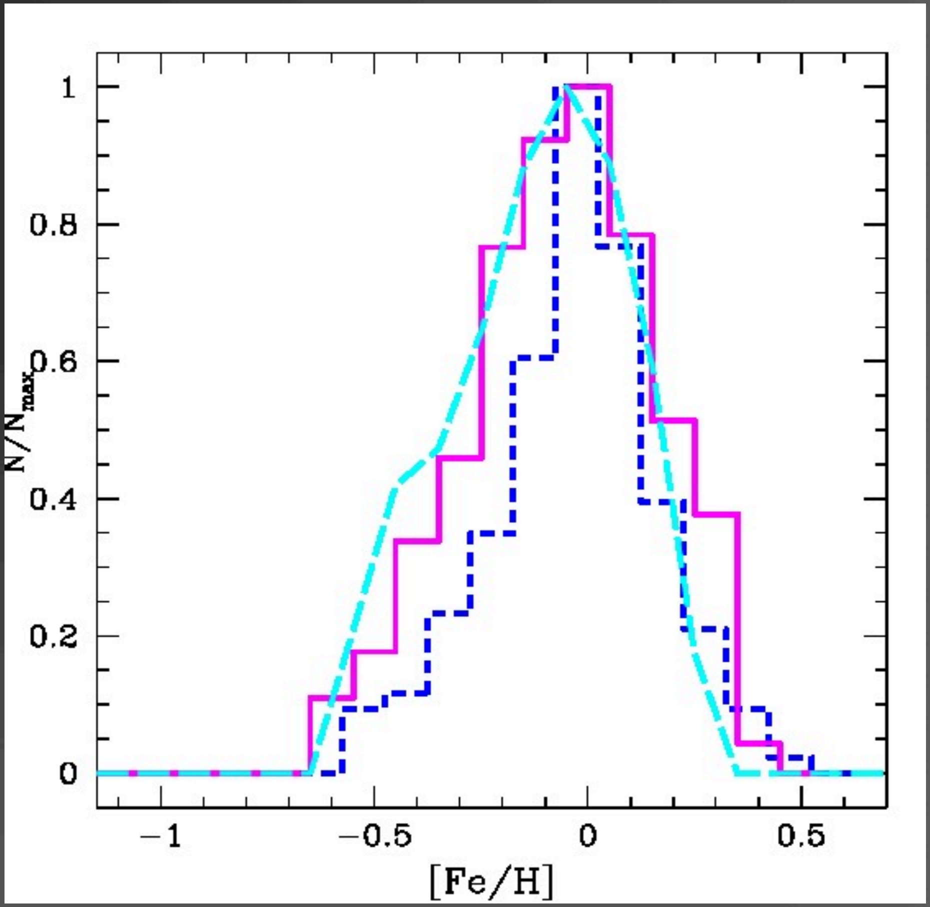
The G-dwarf Metallicity Distribution: the effect of the infall

- G-dwarf metallicity distribution compared with predictions of the two-infall model (Kotoneva et al. 2003)
- The assumed (8 Gyr) timescale for disk formation at solar ring is a very important parameter

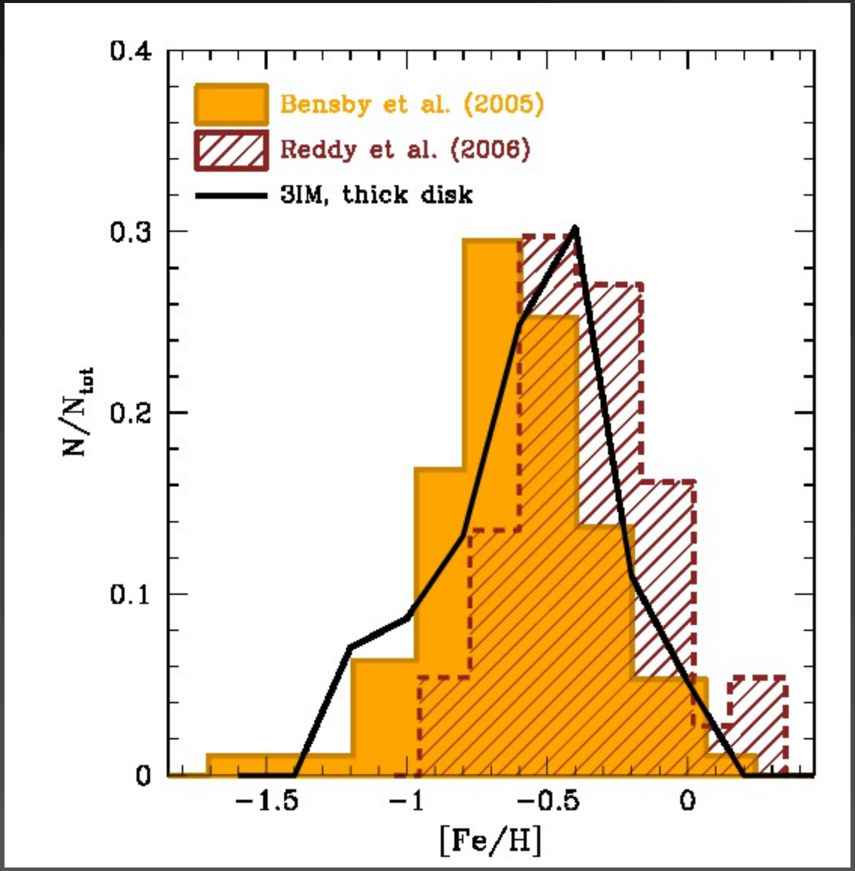


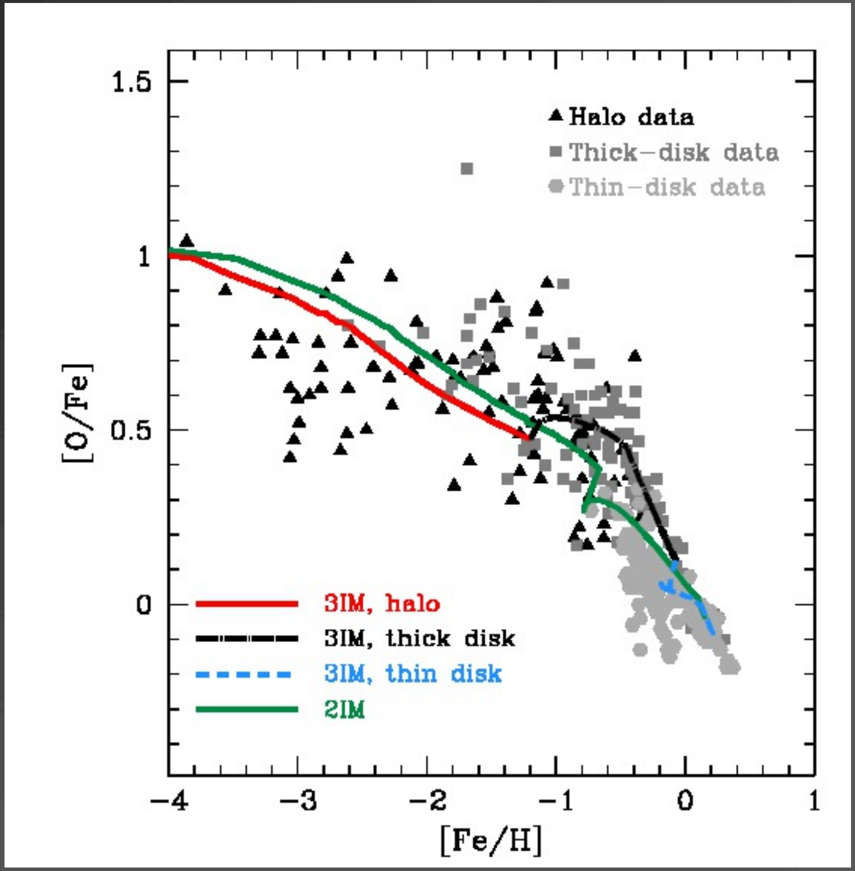
More recent data on G-dwarfs

- G-dwarf metallicity distribution by Adibekyan +2013 (pink histogram)
- Furhmann (2011) (blue histogram)
- Model with radial flows from Spitoni +2015 (cyan curve) no migration and always a timescale of 8 Gyr



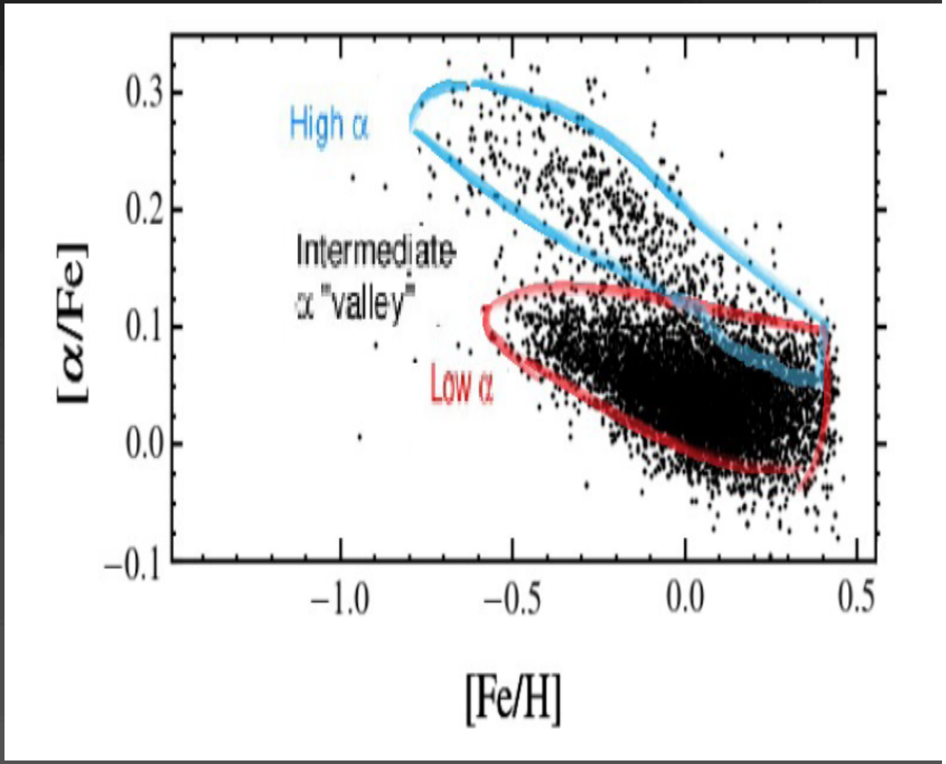
A three-infall model (Micali, FM +13: the thick disk)



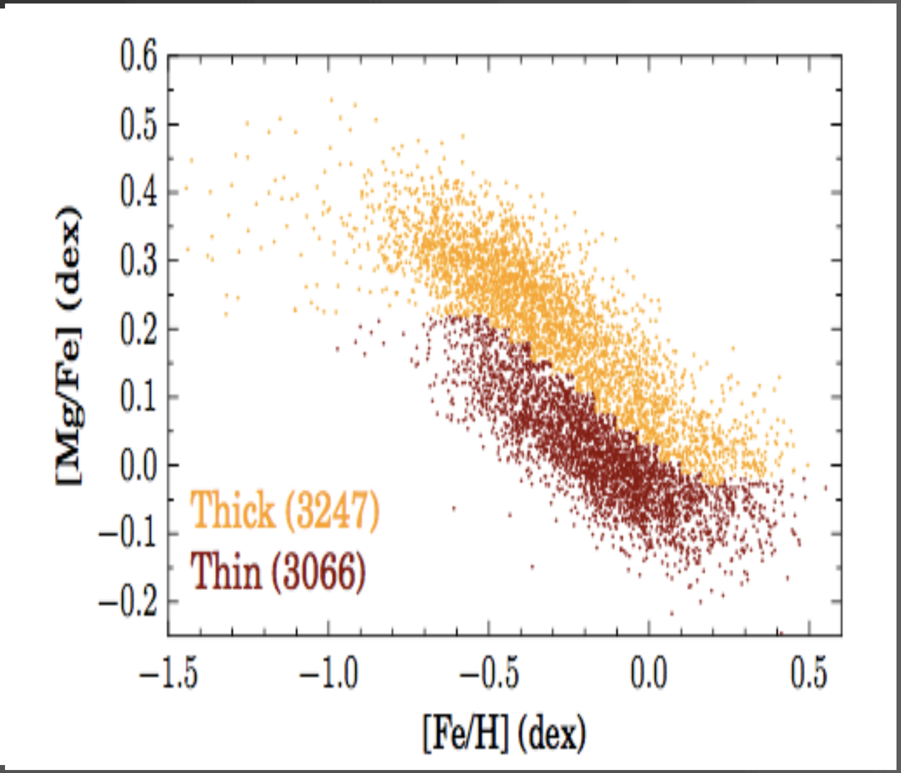


More recent data (two parallel sequences for thick and thin disk)

Apogee data (Hayden et al. 2015)

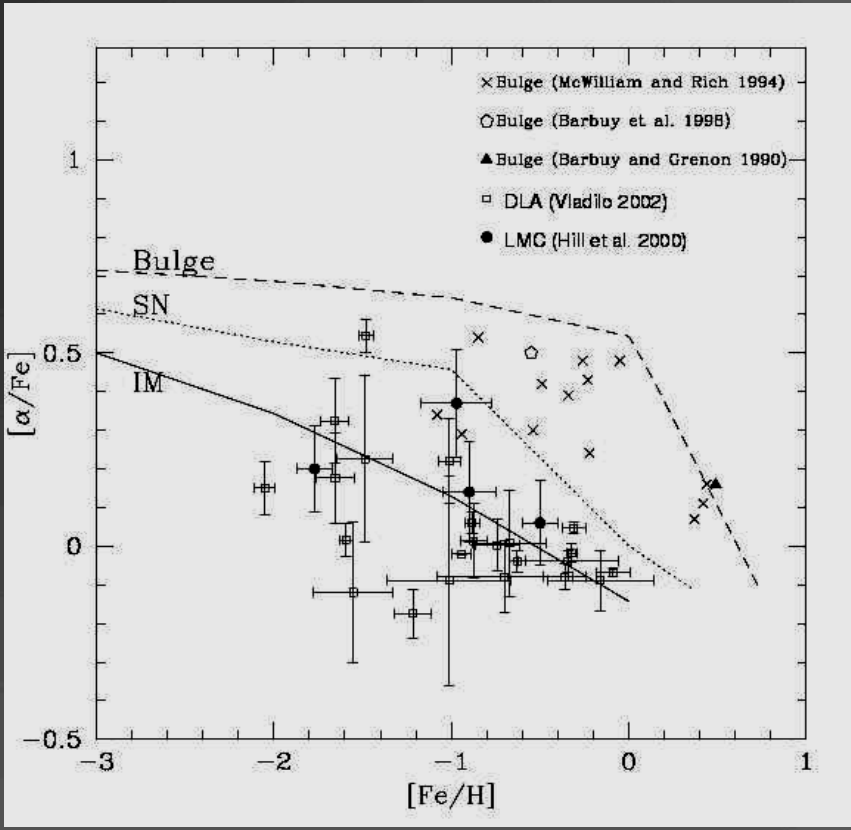


GES data (Rojas-Arriagata+ 2016)



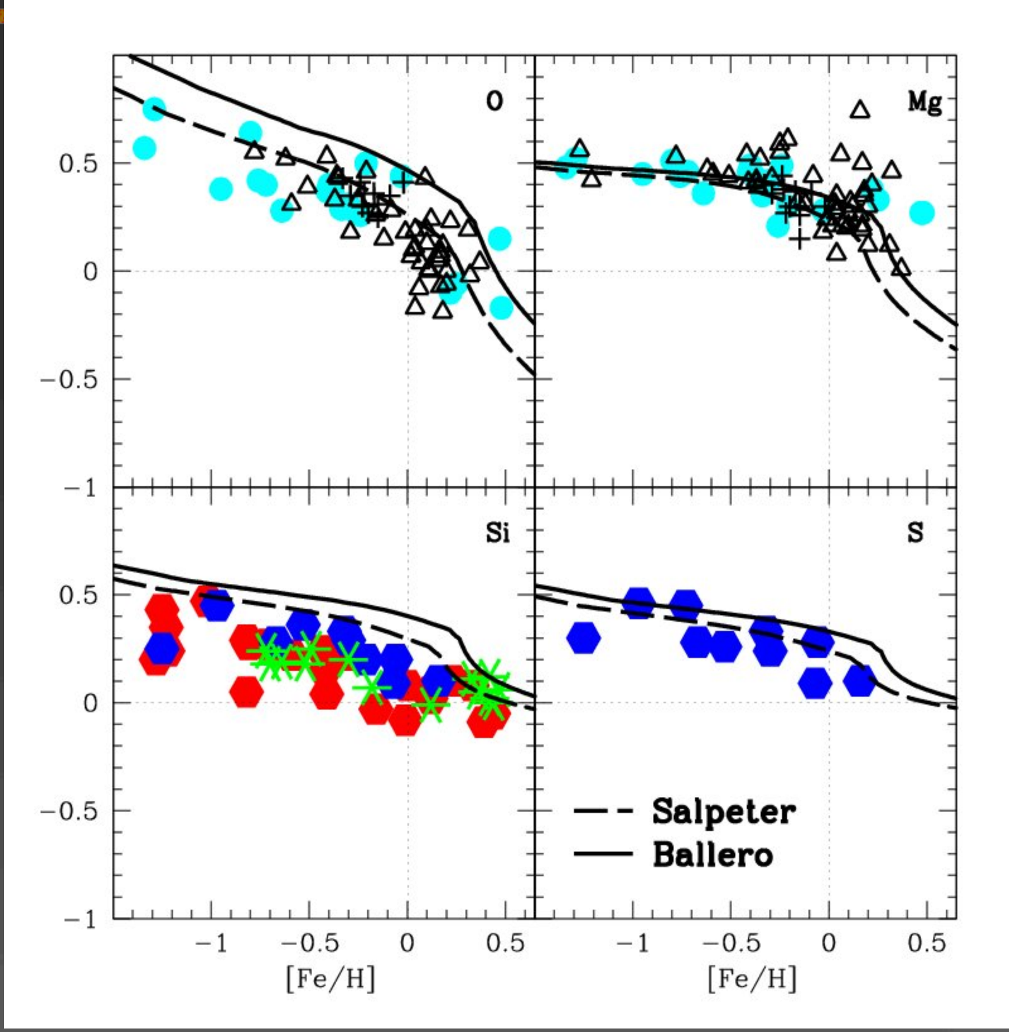
The time-delay model and the star formation rate in galaxies

- Predicted [alpha/Fe] ratios for different SFR histories (a more modern version of FM & Brocato 1990)
- A strong starburst (dashed line), a SFR like in the solar vicinity (dotted) and a slow SFR (continuous) like in Magellanic Irregulars or Dwarf Spheroidals



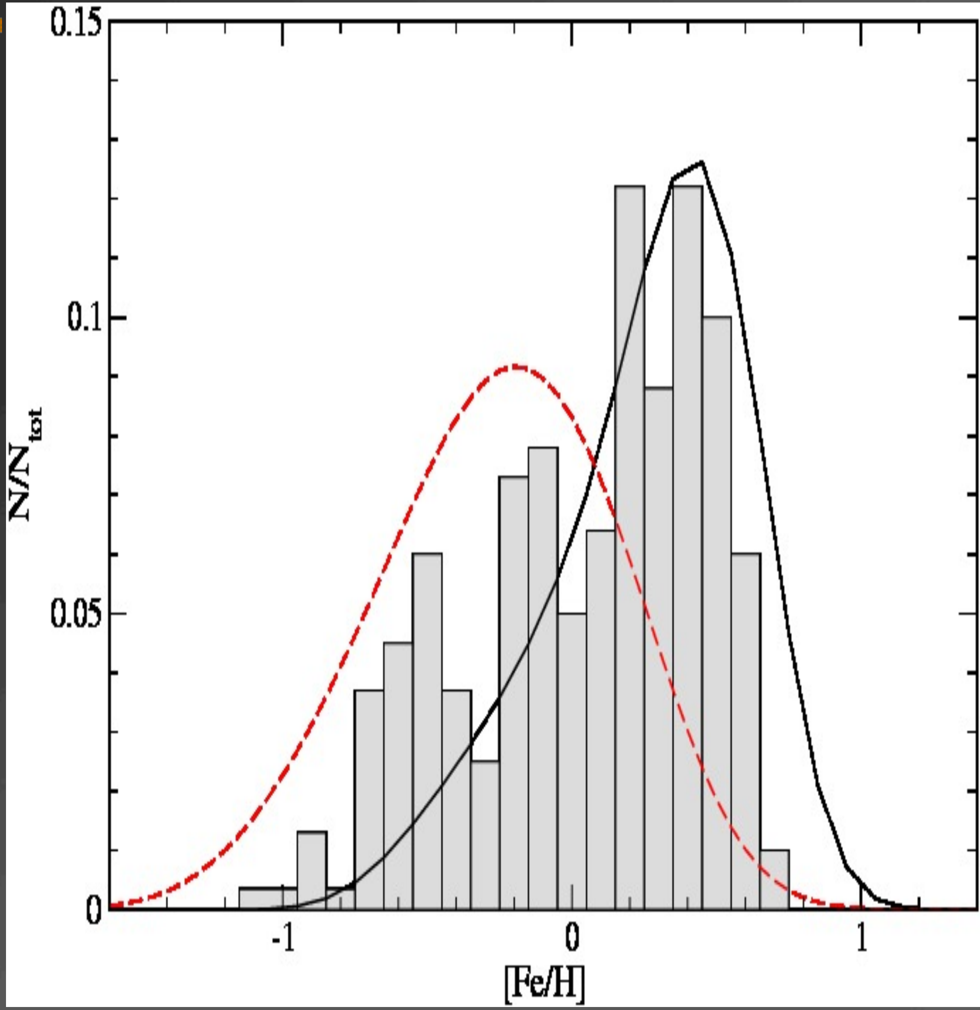
The Galactic Bulge

- Model (black, Cescutti & FM 2011): fast Bulge formation (0.3 -0.5Gyr) and IMF flatter than in S.N.
- High SF efficiency 20/Gyr
- Turning point at larger than solar Fe (effect of the time-delay model)
- Data from giants and dwarfs. Bensby & al. 2010; Alves-Brito & al. 2010



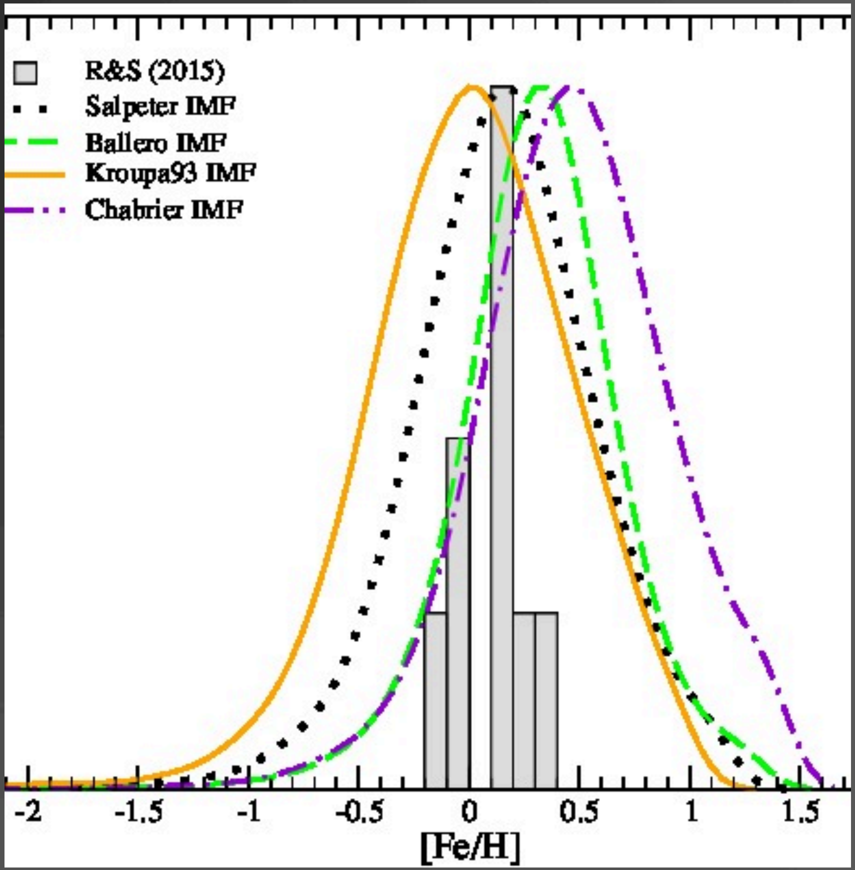
Two Bulge populations? Grieco +2012

- Two populations: i) classical bulge, fast formation (0.3 Gyr, red line), ii) younger stars related to the bar, longer formation (3-4 Gyr)
- Model by Grieco, FM & al. 12 compared to Hill & al's (2011) data
- Salpeter IMF
- MDF convolved with an error of 0.25 dex



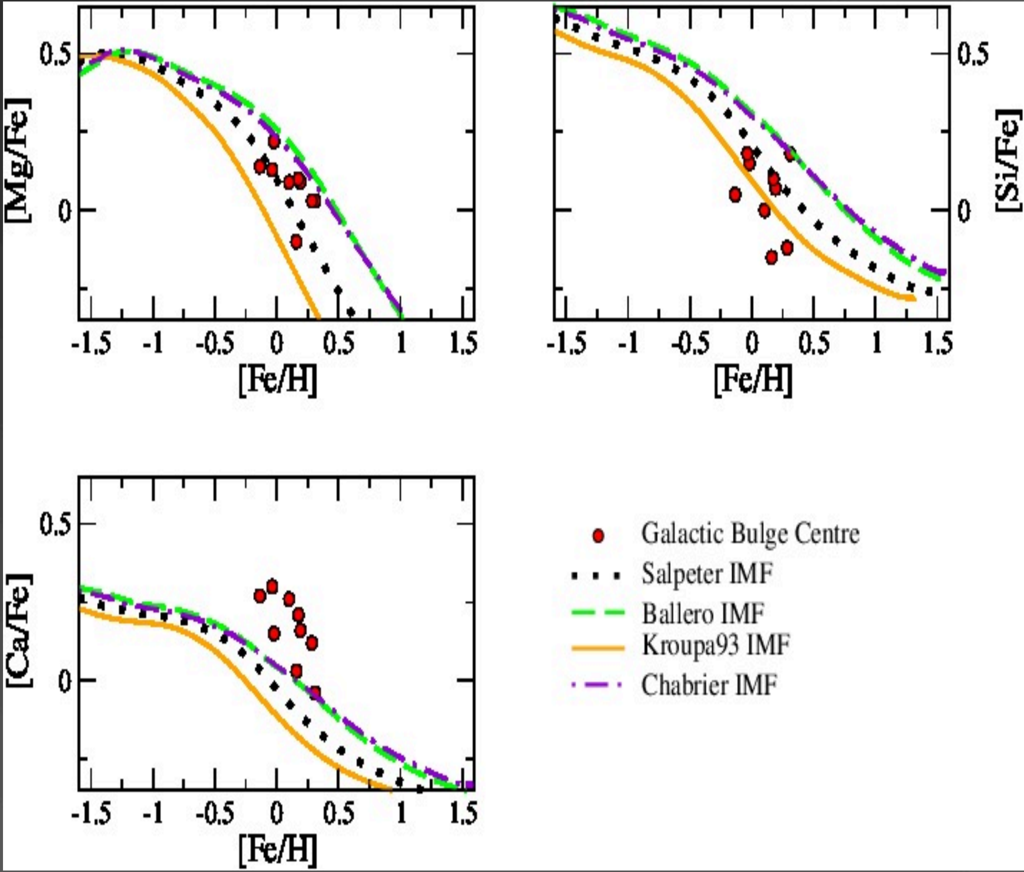
The Galactic centre (inner 200 pc)

- Grieco et al. (2015) modeled the chemical evolution of the Galactic centre (inner 200 pc)
- Data Ryde & Schultheis (2015), 9 M-giants
- The best agreement is reached by adopting a Salpeter IMF, a timescale of 0.7 Gyr and SF efficiency of 25 Gyr^{-1}



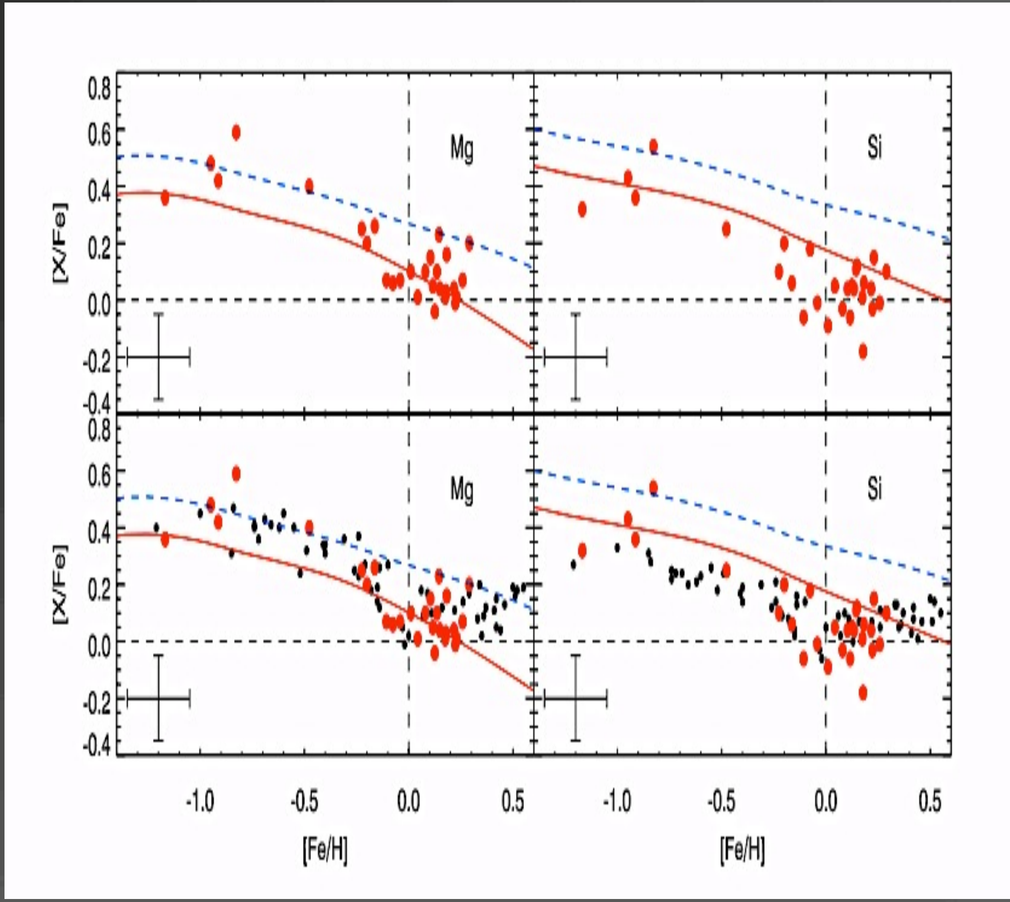
The Galactic centre ([alpha/Fe])

- The predicted [alpha/Fe] ratios for different IMFs, a SF efficiency of 25/Gyr and a timescale of 0.7 Gyr
- Ca seems to be a problem. Too lower stellar yields?



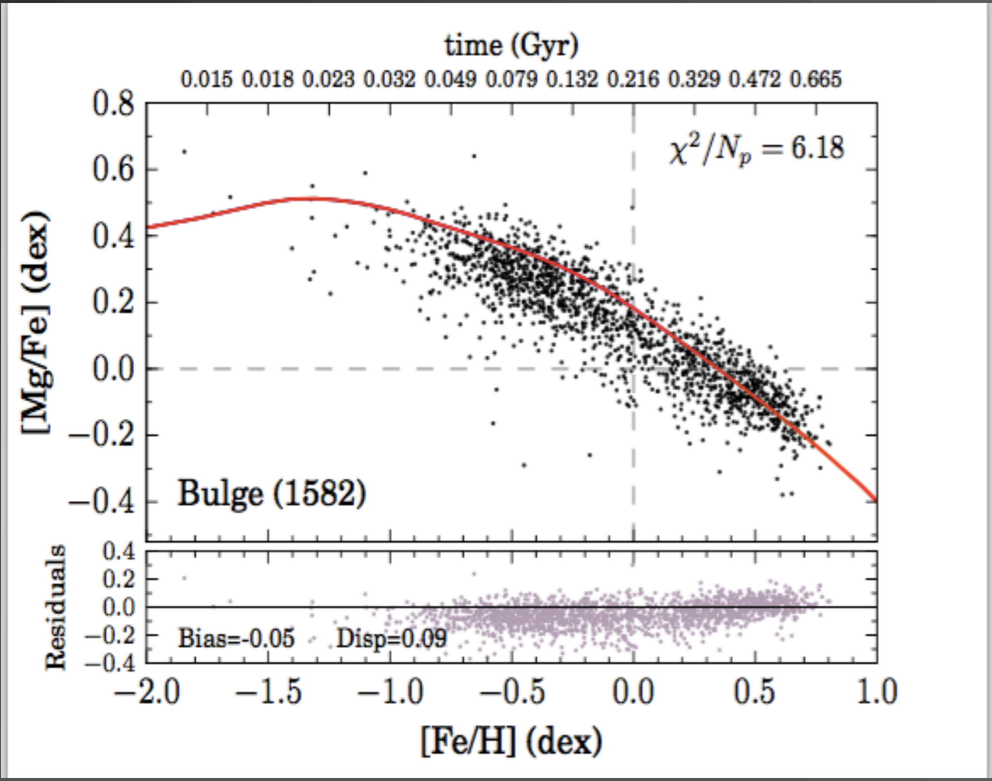
The inner Bulge

- Ryde et al. (2015) presented data for 28 M giants the inner 500 pc of the Bulge (red dots)
- Black dots are dwarfs from Bensby et al. (2013)
- The comparison with the model of Grieco+(2015) suggests a fast formation (0.7 Gyr), high SF efficiency (25 Gyr^{-1})
- Red line is a model with lower Mg and Si yields



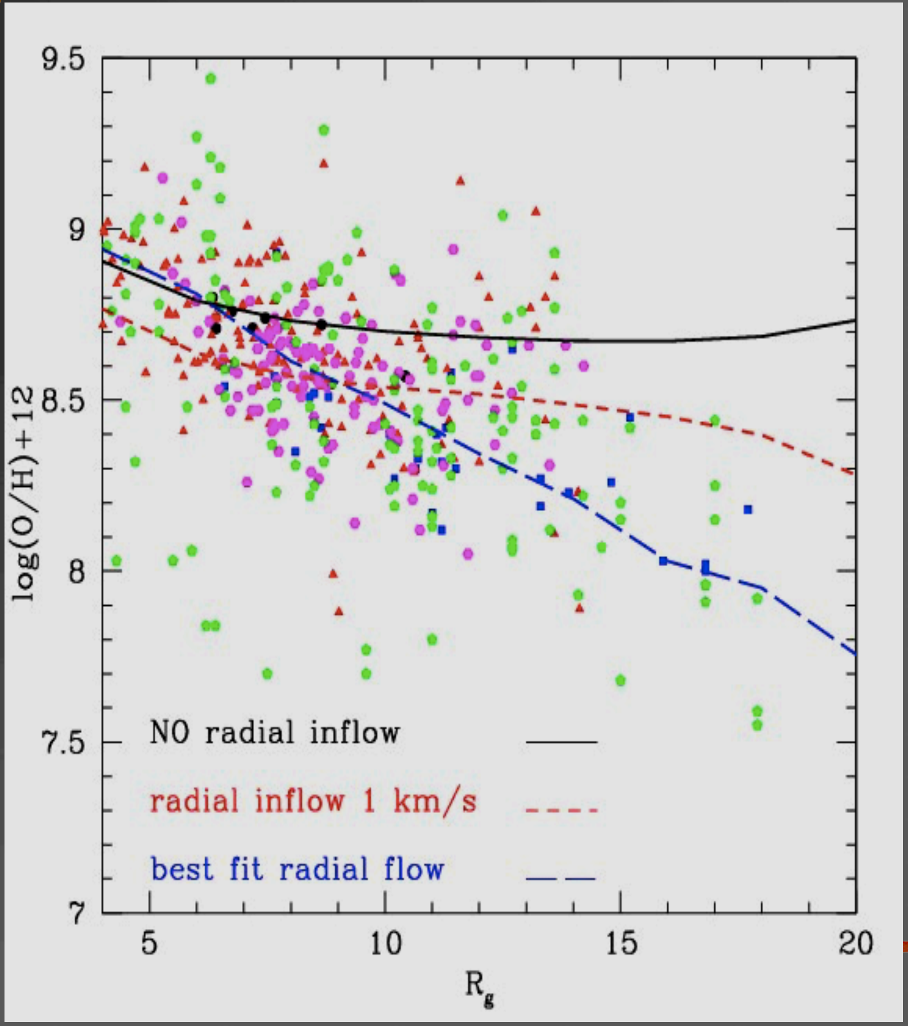
Last data on the Bulge from GES

- Data for the Bulge from Rojas-Arriagata+ 2016
- The red line is the model for the classical bulge from Grieco , FM et al. (2012, 2015), yields from Romano+(2000)
- The fit requires a timescale for Bulge formation of 0.3 Gyr and a Salpeter IMF, as already suggested for the classical Bulge



Abundance Gradients in the Galactic Disk: the effect of radial flows

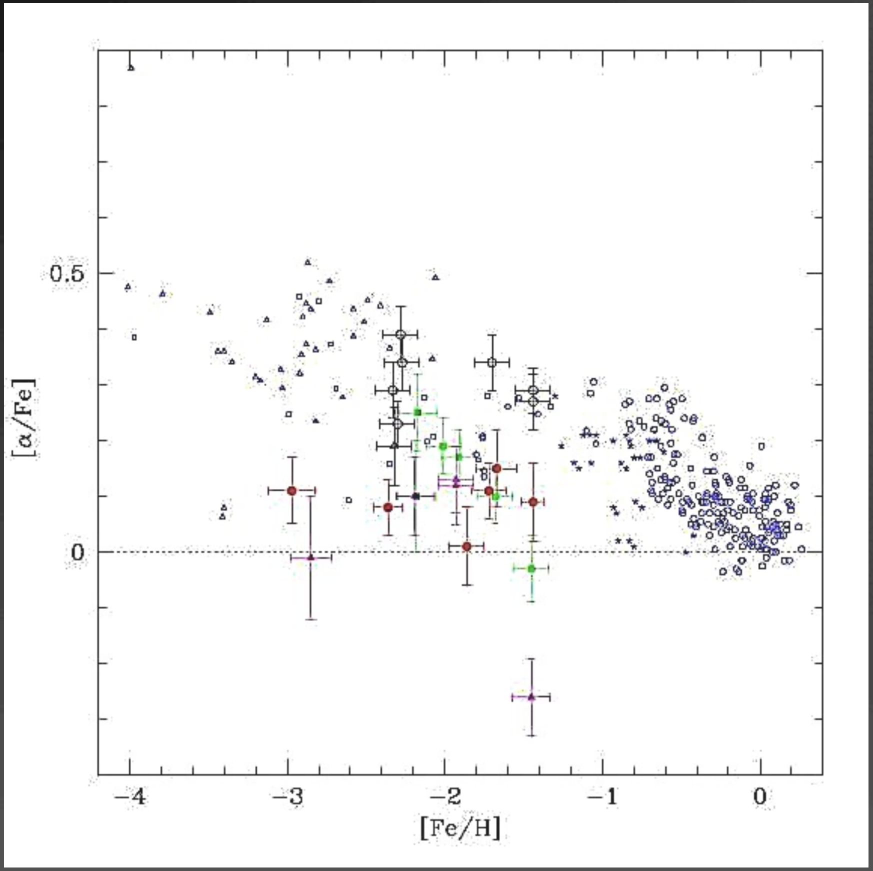
- Different models with and without radial inflows (Spitoni & FM 2011)
- Black line, (no flows no threshold, inside-out). Red line (radial flows of speed 1 Km/sec, inside-out)
- Blue line a variable speed for radial flows and inside-out



Time-scales from Galactic Astroarchaelogy

- The inner stellar Halo must have formed on a timescale of 1.5 Gyr whereas the outer Halo could have formed on a longer timescale
- The local disk must have assembled by gas accretion on a time scale from 6-8 Gyr and the timescale increases with galactocentric radius
- The thick disk must have formed more quickly than the thin disk (2-2.5 Gyr)
- The Bulge must have formed on a time no longer than 0.3-0.7 Gyr with flatter IMF than the solar neighbourhood

[Alpha/Fe] ratios in Dwarf Spheroidals (Shetrone+02)

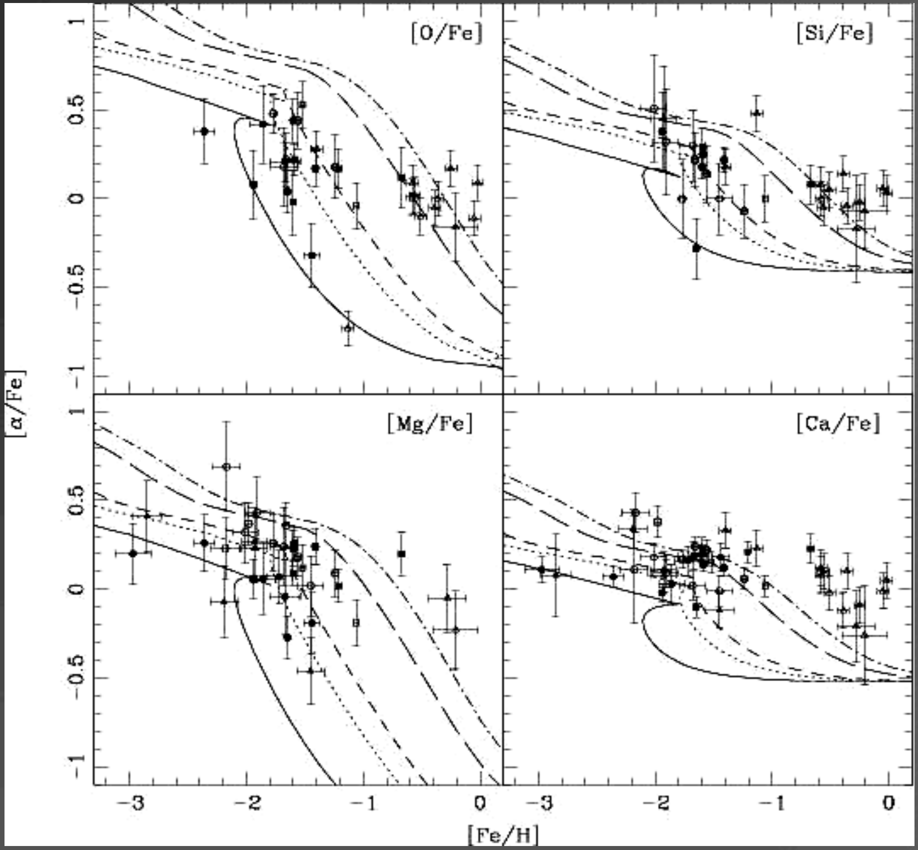


Dwarf Spheroidals vs. Milky Way

- The [alpha/Fe] ratios in dSphs evolve differently as a function of [Fe/H]
- There is some overlapping of the [alpha/Fe] ratios only at low metallicity
- Can the dSphs have been the building blocks of the Galactic halo?
- Chemical abundances should reveal it

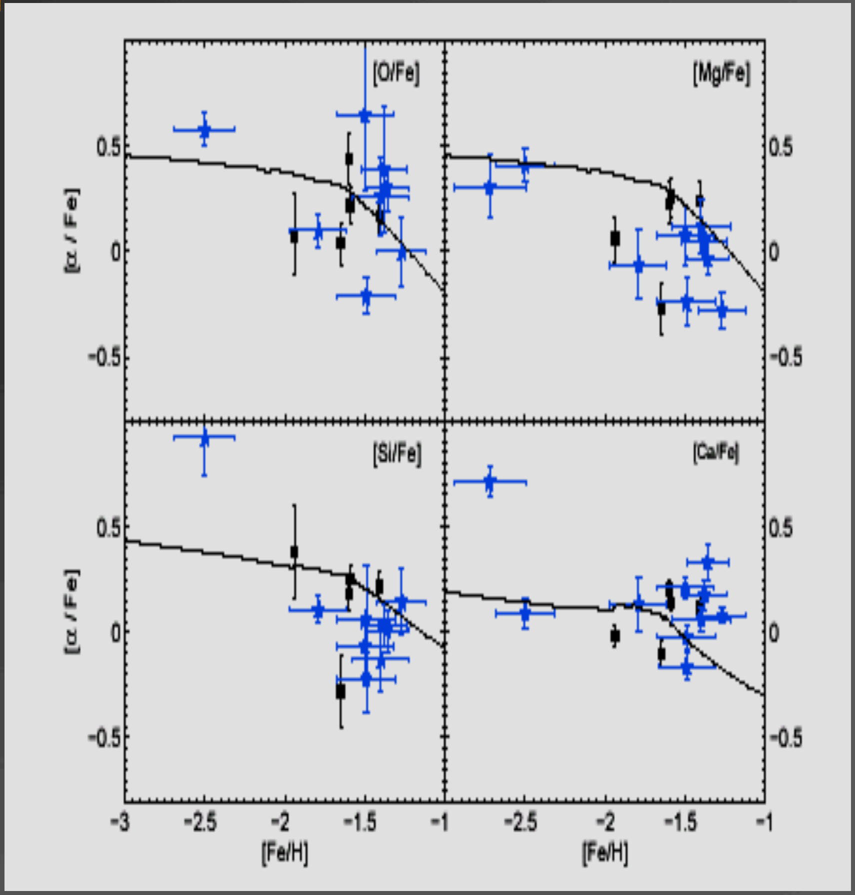
Chemical evolution of dSphs: standard model

- Lanfranchi & FM (2003, 2004) proposed a model which assumes a SFH as derived by the CMDs. Initial baryonic masses 5×10^8 Msun
- SN feedback induces a strong outflow. DM ten times LM but diffuse (M/L today of the order of 100)
- SFR less efficient than in the MW and going on for 8 Gyr



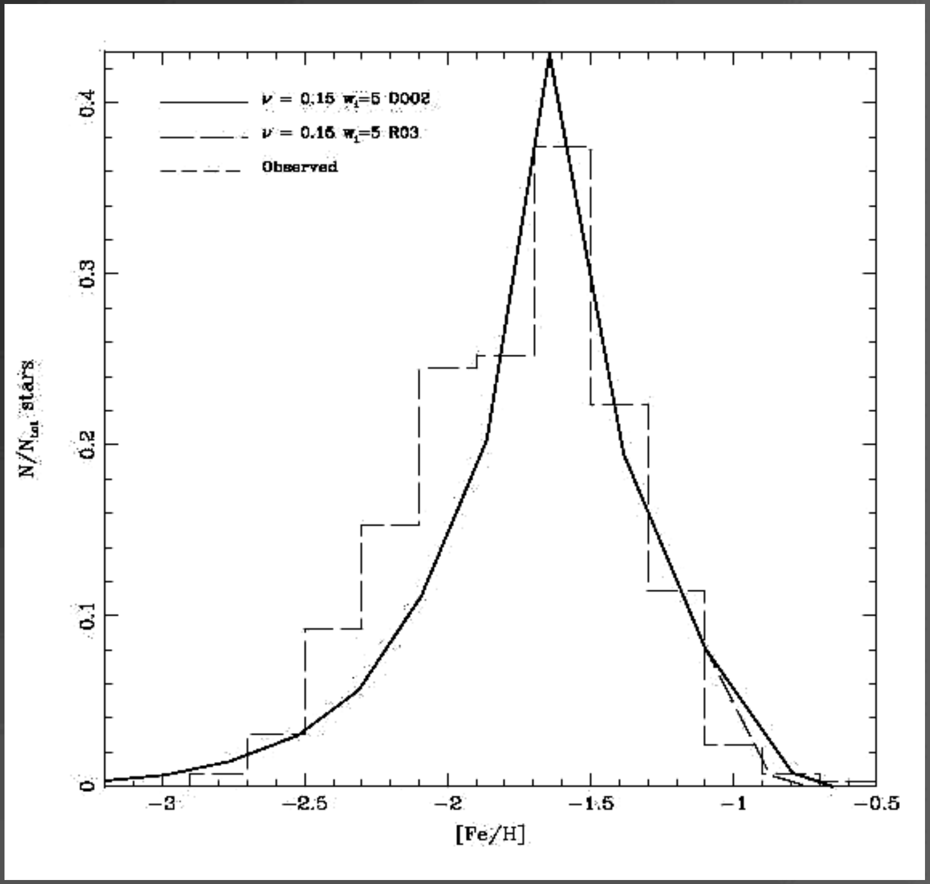
Specific Models for dSphs: Carina

- The best model for Carina by Lanfranchi, FM & Cescutti (2006) compared with data from Koch & al.(2008)
- Four bursts of SF are considered as suggested by the C-M diagram

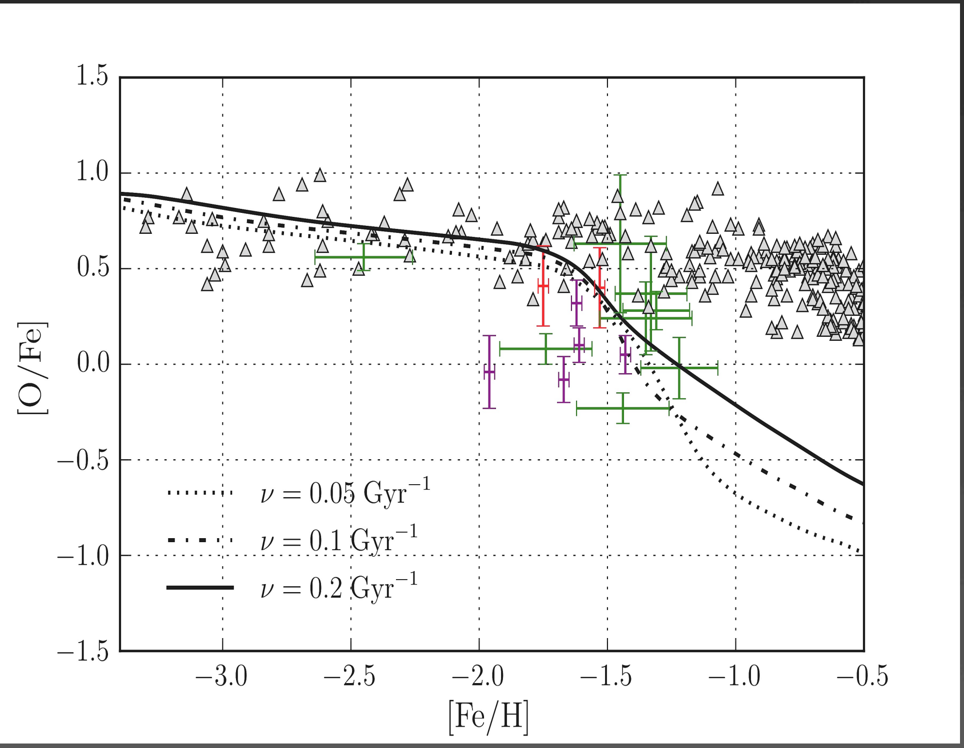


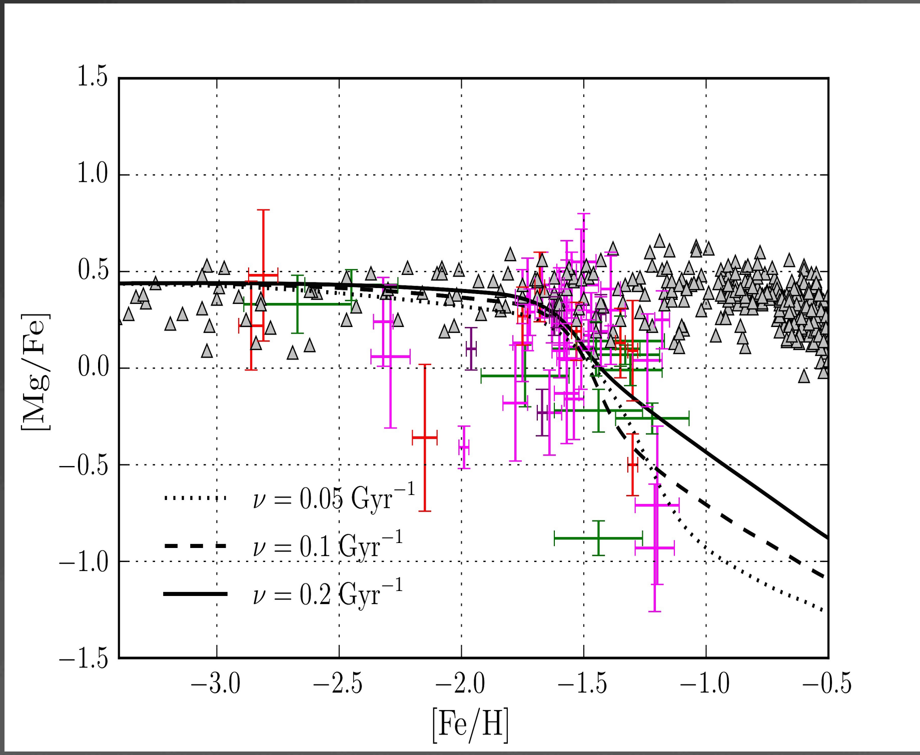
Specific Models for dSphs: Carina

- The stellar metallicity distribution predicted for Carina and observed by Koch & al. (2005)
- SF history from Rizzi et al. 03. Four bursts of 2 Gyr, SF efficiency of 0.15 Gyr^{-1}
- Salpeter IMF
- Wind=7xSFR



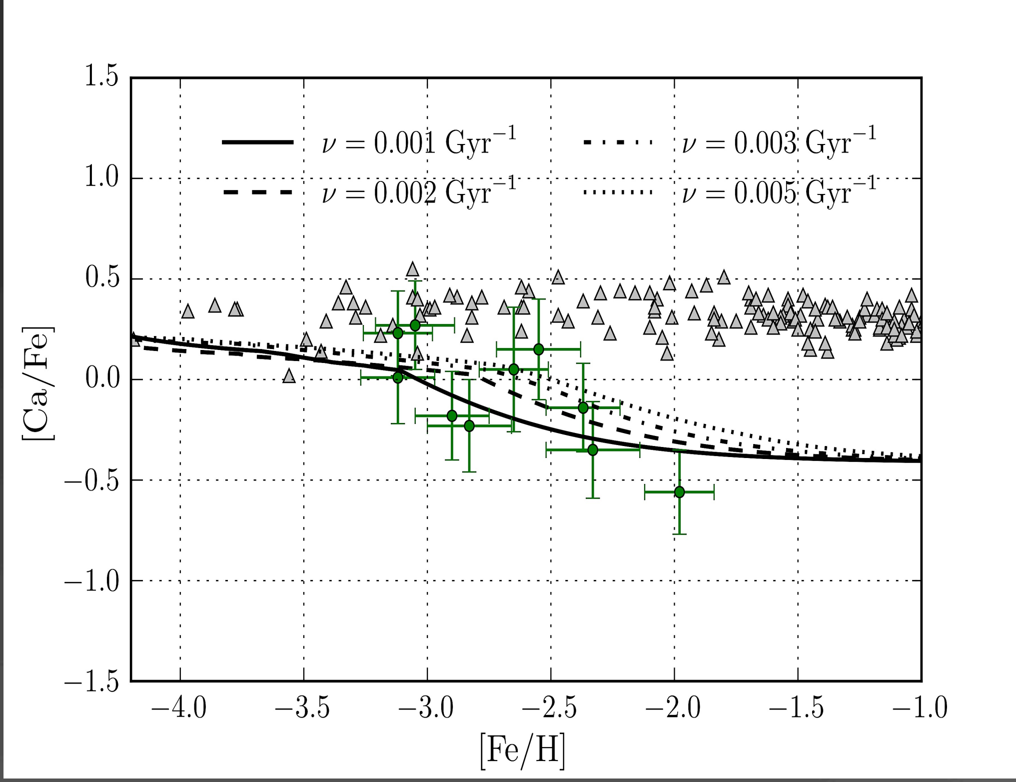
More recent models for Carina compared to the Milky Way (Vincenzo, FM et al. 2014). Data from:Shetrone+03,Koch+08,Venn +12,Lemasle+12





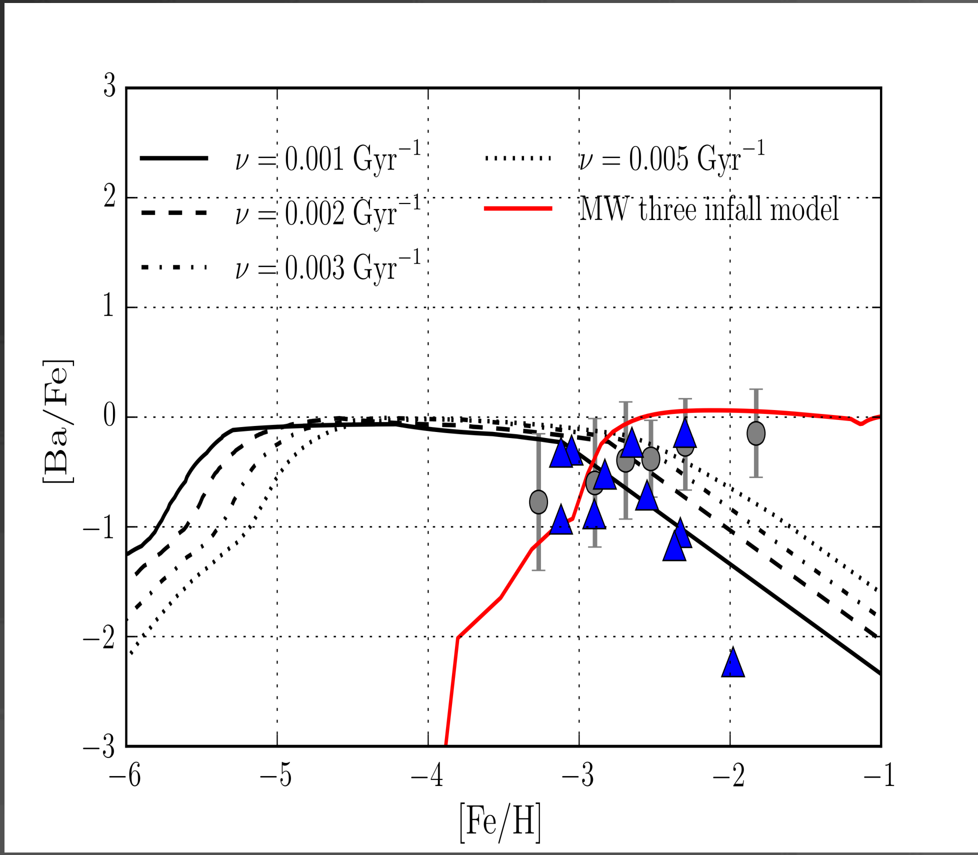
The Ultra Faint Dwarfs (Vincenzo, FM et al. 2014)

- Better candidates for the Galactic halo are the ultra-faint-dwarfs (UFD) ? No
- Dots from Aden+11 refer to Hercules, black points are the MW and blue points the dSphs
- Models with very low SF efficiency



The Ultra Faint Dwarfs (Vincenzo, FM+2014)

- Models for Hercules (grey) compared to the prediction of the two-infall model for the MW (red). Blue data for Hercules are from Koch et al. (2013). Grey dots are MW stars (Frebel+2009)
- The [Ba/Fe] ratio is quite different at low [Fe/H] in the MW and UfDs



Chemical evolution of dSphs from astroarchaeology

- The chemical evolution of dSphs in general can be reproduced by assuming an extended period of SF, a poorly efficient SFR and a quite efficient galactic wind from SN feedback
- The [X/Fe] ratios of alpha and heavy elements suggest different histories of SF in the MW, dSphs and UfDs
- Same [alpha/Fe] ratios at [Fe/H]<-3.0 dex is not necessarily a proof that the MW halo has formed by accretion of dSphs. Other abundance ratios such as [Ba/Fe] could solve the problem