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INAF - Astronomical Observatory of Trieste

Photochemical models for the dSph galaxy satellites of the MW

Fiorenzo Vincenzo

In collaboration with:
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Monica Tosi (Bologna, Italy)

Outline

- **Brief overview**: the dSph galaxy satellites of the MW
- **Modeling the chemical evolution of dSphs and UfDs**:
  Carina, Boötes I and Hercules
  (Vincenzo et al., 2014)
- **Lighting up stars in chemical evolution models**:
  the CMD of Sculptor dSph
  (Vincenzo et al., submitted)

Brief overview:

the dSph galaxy satellites of the MW

The dSph galaxy satellites of the MW

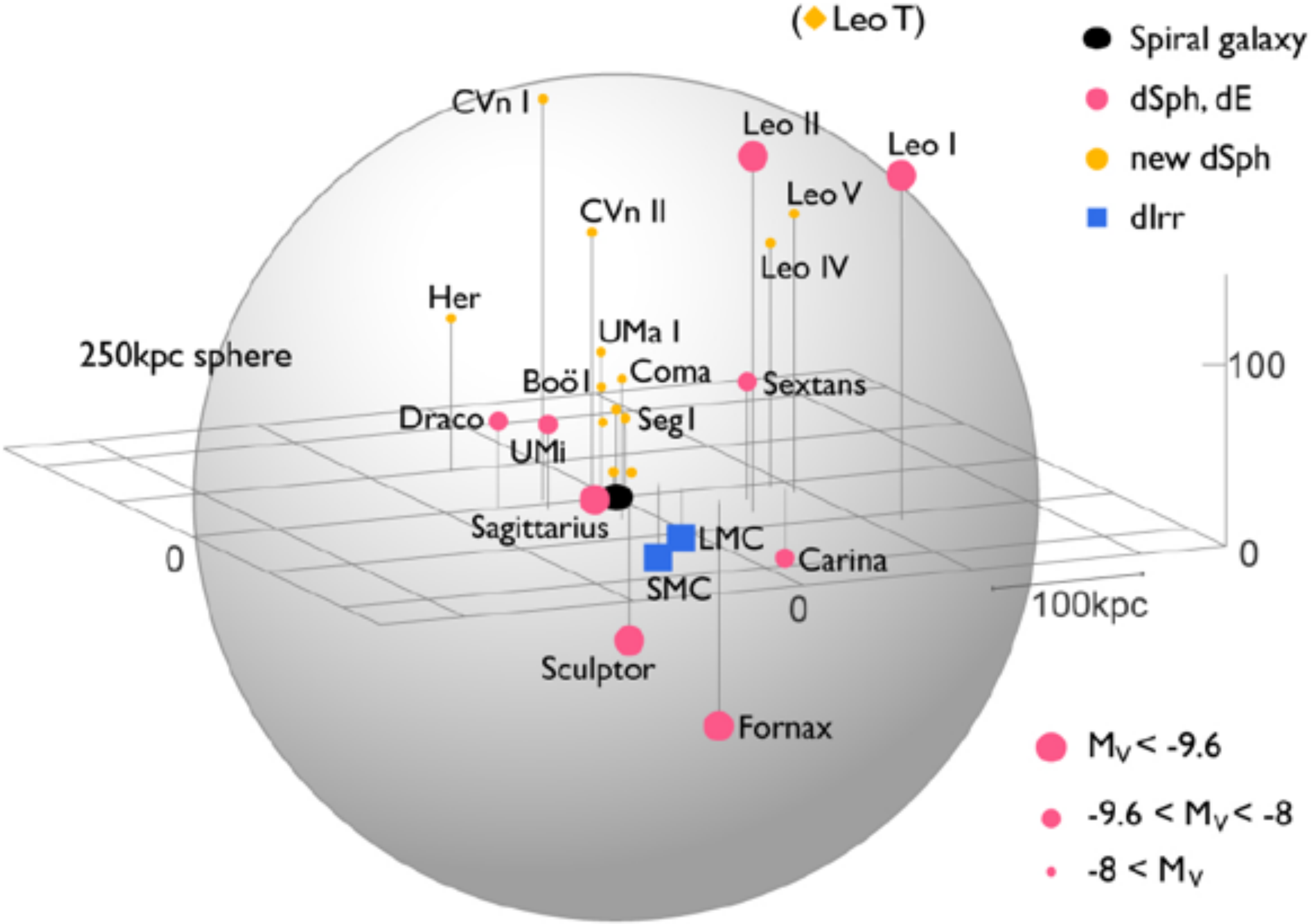

Figure from Okamoto (2011)

The dSph galaxy satellites of the MW

Classical dwarf spheroidal galaxies (dSph)

Photometry:

- $\langle \mu_V \rangle \gtrsim 22 \; mag \; arcsec^{-2}$

Mass content:

- $M_{tot} \sim 10^7 - 10^8 \; M_\odot$
- $10 \left(\frac{M}{L}\right)_\odot < \left(\frac{M}{L}\right)_V < 10^3 \left(\frac{M}{L}\right)_\odot$
- $M_{HI,obs} < 10^5 \; M_\odot$

Stellar population ages:

- $\gtrsim 5 - 7 \; Gyr$

Iron abundances:

- $-2.0 \; dex \leq \langle [Fe/H] \rangle \leq -1.3 \; dex$

Ultra-faint dwarf spheroidal galaxies (UfD)

Photometry:

- $\langle \mu_V \rangle \gtrsim 26 \; mag \; arcsec^{-2}$

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- $M_{tot} \sim 10^6 - 10^7 \; M_\odot$
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Stellar population ages:

- $\gtrsim 10 - 12 \; Gyr$

Iron abundances:

- $-3.3 \; dex \leq \langle [Fe/H] \rangle \leq -2.1 \; dex$

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Chemical evolution of galaxies

an astro-archaeological approach

Basic equations:

$$\boxed{\frac{\mathrm{d}M_{\mathrm{g},i}(t)}{\mathrm{d}t} = \underbrace{-X_i(t)\ \mathrm{SFR}(t)}_{\mathrm{SF}} + \underbrace{R_i(t)}_{\mathrm{yields}} - \underbrace{\Psi_i(t)}_{\mathrm{outflow}} + \underbrace{\Phi_i(t)}_{\mathrm{infall}}}$$

star formation: $\mathrm{SFR}(t) = \nu M_{\mathrm{g}}(t)$

outflow: $\Psi_i(t) = \omega_i\ \mathrm{SFR}(t)$

infall: $\Phi_i(t) = \frac{X_{\mathrm{inf},i}\, M_{\mathrm{inf}}\, e^{-t/\tau_{\mathrm{inf}}}}{\tau_{\mathrm{inf}}\left(1-e^{-t_{\mathrm{G}}/\tau_{\mathrm{inf}}}\right)}$, with $\sum_i \int_0^{t_{\mathrm{G}}} \Phi_i(t)dt = M_{\mathrm{inf}}$

Chemical evolution of dSphs and UfDs

Lanfranchi et al., 2004; Vincenzo et al., 2014

	dSphs	UfDs
SFE	0.1 - 1 Gyr^{-1}	0.001 - 0.1 Gyr^{-1}
M_{inf}	$\approx 10^{8}\ M_{\odot}$	$\lesssim 10^{7}\ M_{\odot}$
τ_{inf}	0.5 Gyr	Extremely low
SFH	Concentrated towards earlier and earlier epochs	

MDF peaked towards lower [Fe/H] abundances

Knee of the [α/Fe] ratios at lower [Fe/H] abundances

Smaller amount of gas and stellar mass at the present time

Chemical evolution of dSphs and UfDs

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dSphs → UfDs

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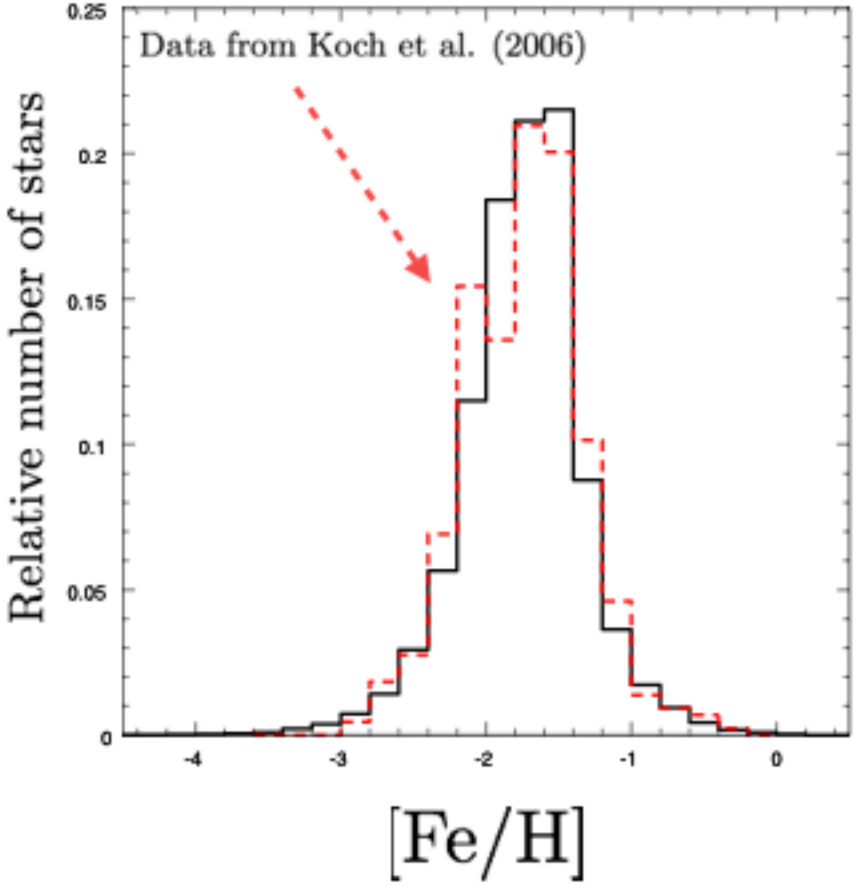
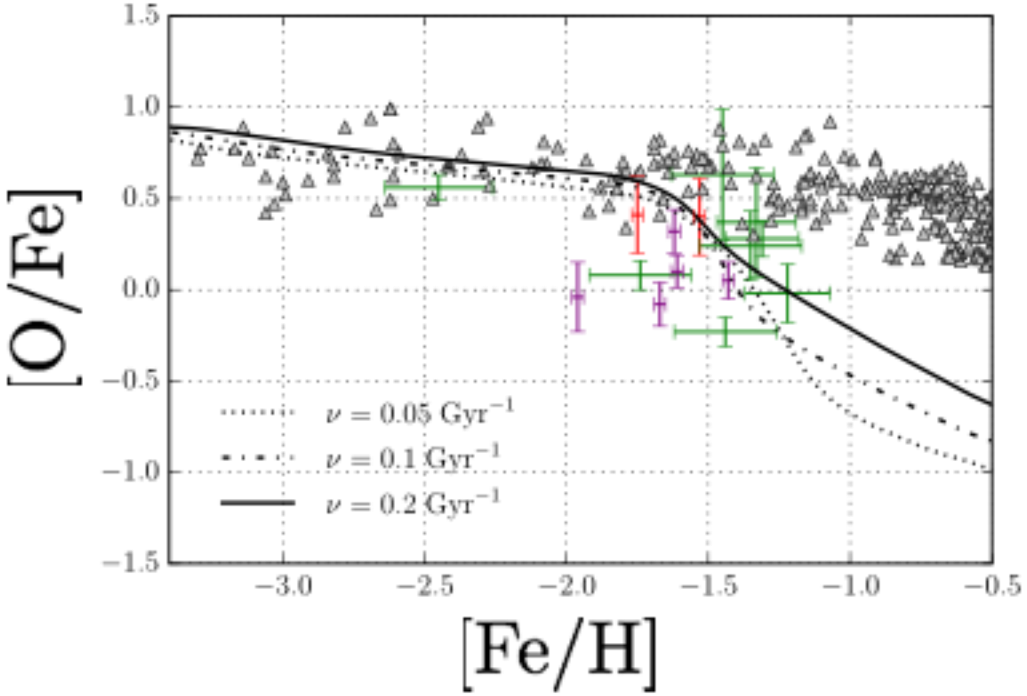
Modelling the chemical evolution of dSphs and UfDs:

Carina, Boötes I and Hercules

F. Vincenzo, F. Matteucci, S. Vattakunnel, G.A. Lanfranchi (2014)

Chemical evolution of Carina dSph





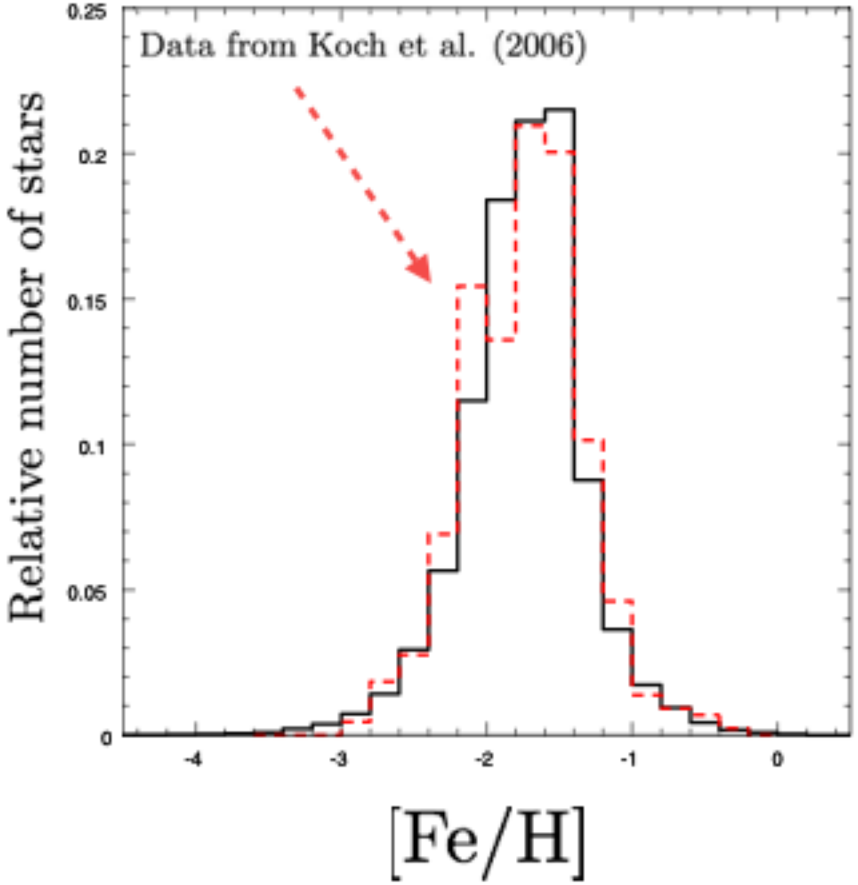
Reference parameters (Carina dSph)
star formation efficiency = 0.2 Gyr^{-1}
wind parameter = 10 Gyr^{-1}
infall time-scale = 0.5 Gyr
infall mass = 1.0 × 10^8 M$_\odot$

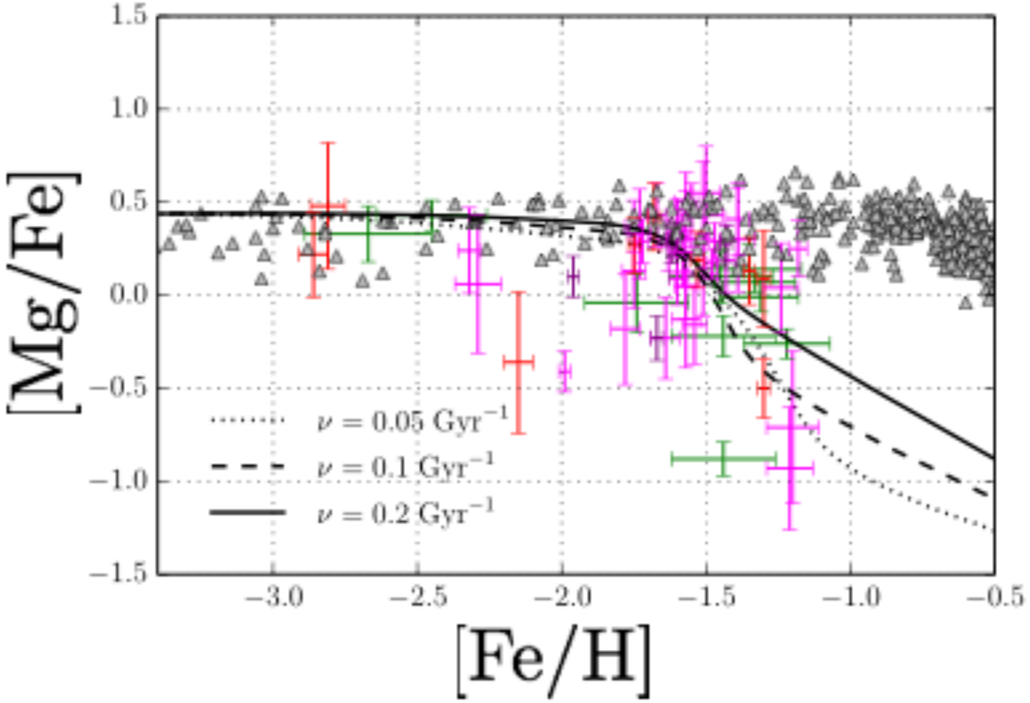
Data

MW stars (grey):
Bensby et al. (2014)
Gratton et al. (2003)
Akerman et al. (2004)
Cayrel et al. (2004)
Shi et al. (2009)

Carina stars:
Shetrone et al. (2003), purple
Koch et al. (2008), green
Venn et al. (2012), red
Lemasle et al. (2012), magenta

Chemical evolution of Carina dSph





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Carina stars:
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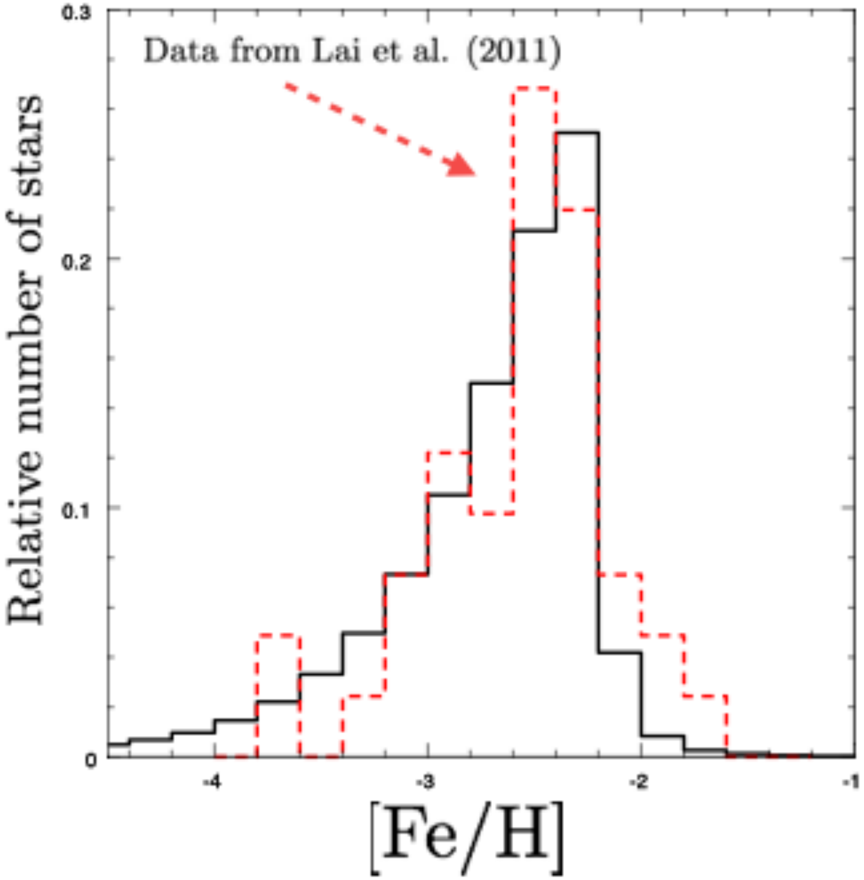
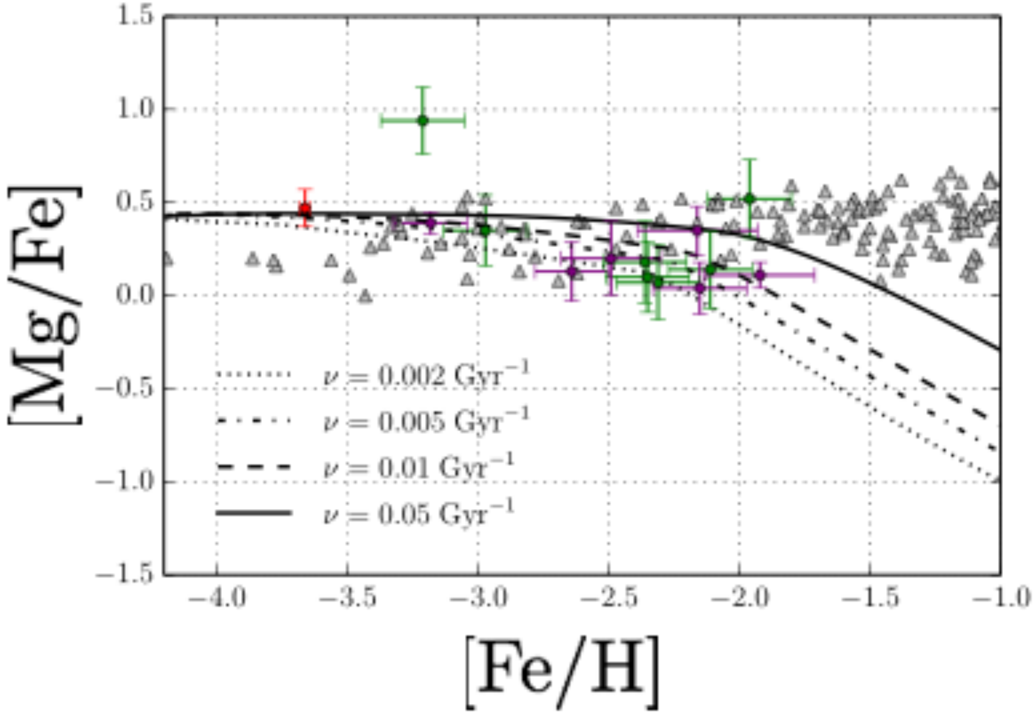
Koch et al. (2008), green
Venn et al. (2012), red
Lemasle et al. (2012), magenta

Chemical evolution of Boötes I UfD





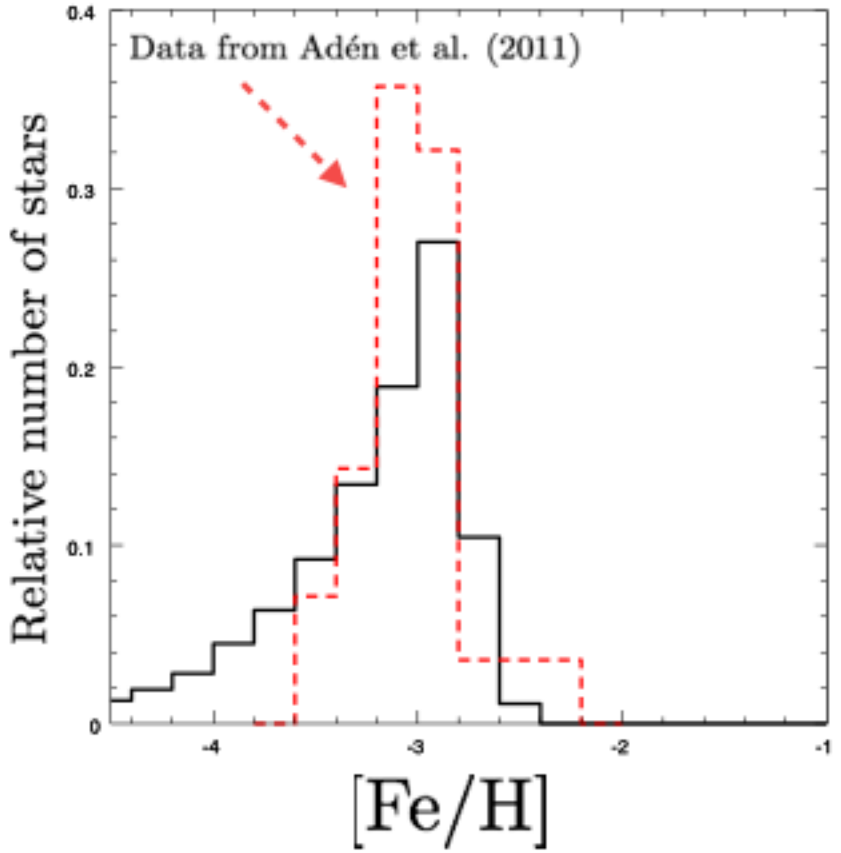
Reference parameters (Boötes I UfD)
star formation efficiency = 0.01 Gyr^{-1}
wind parameter = 10 Gyr^{-1}
infall time-scale = 0.005 Gyr
infall mass = 2.5×10^7 M$_\odot$

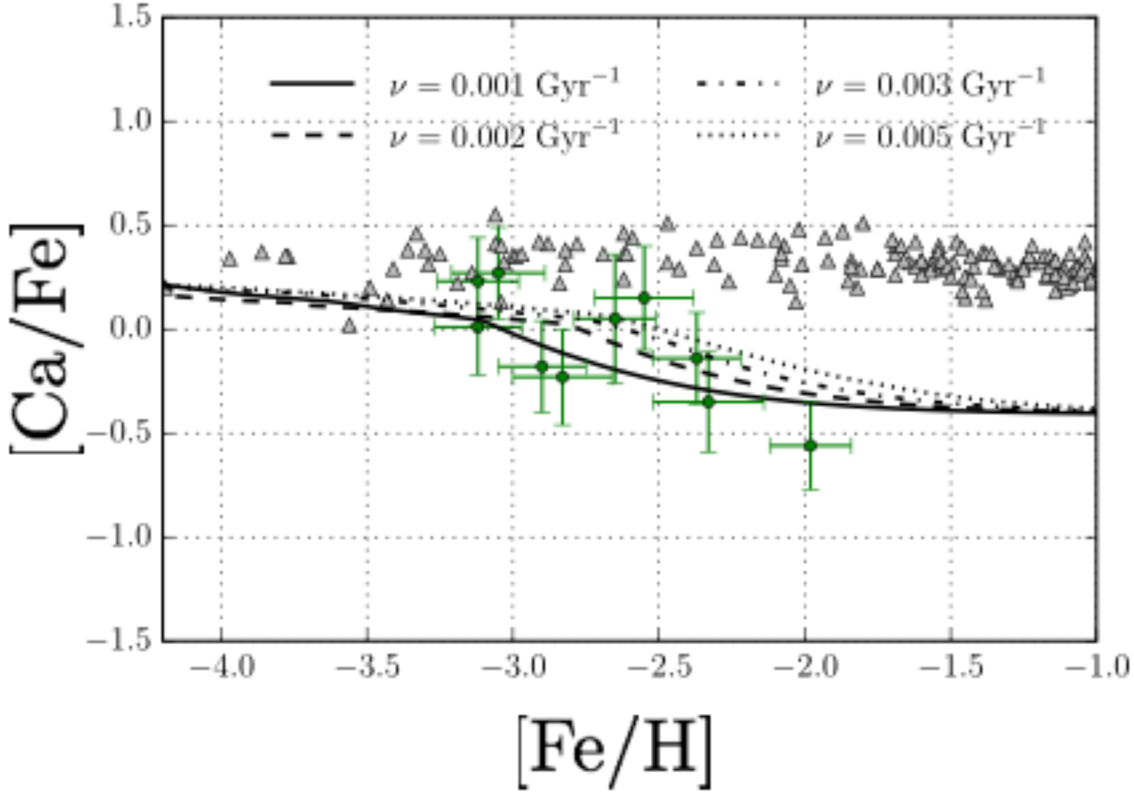
Data

MW stars (grey):
Bensby et al. (2014)
Gratton et al. (2003)
Akerman et al. (2004)
Cayrel et al. (2004)
Shi et al. (2009)

Boötes I stars:
Norris et al. (2010), red
Gilmore et al. (2013), green
Ishigaki al. (2014), purple

Chemical evolution of Hercules UfD





Reference parameters (Hercules UfD)

star formation efficiency = 0.003 Gyr^{-1}
wind parameter = 10 Gyr^{-1}
infall time-scale = 0.005 Gyr
infall mass = 1.0×10^7 M$_\odot$

Data

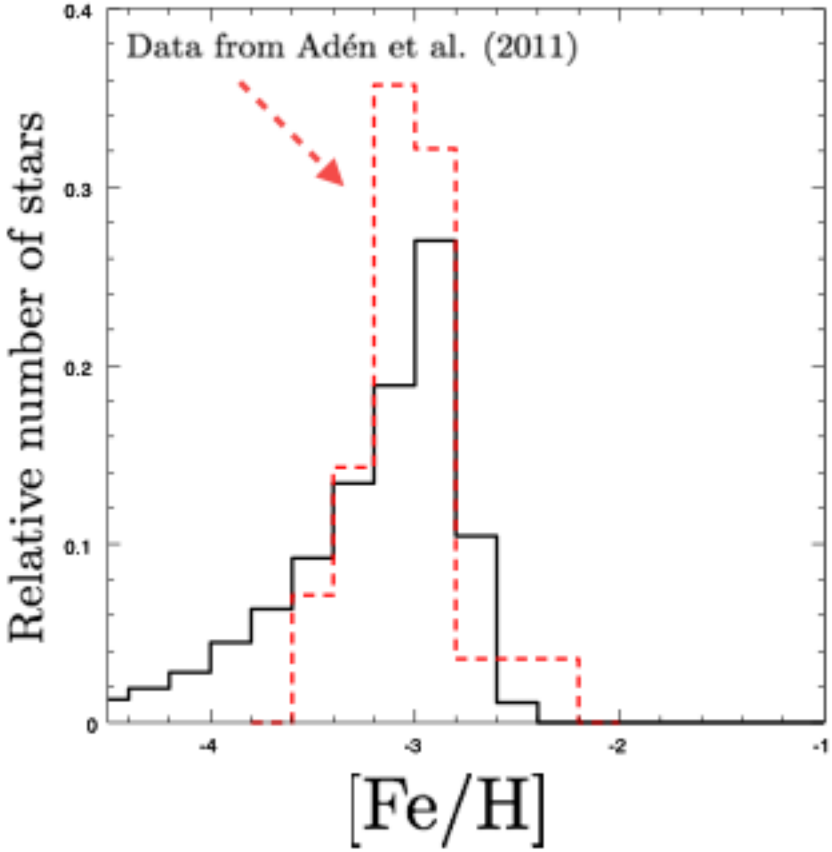
MW stars (grey):

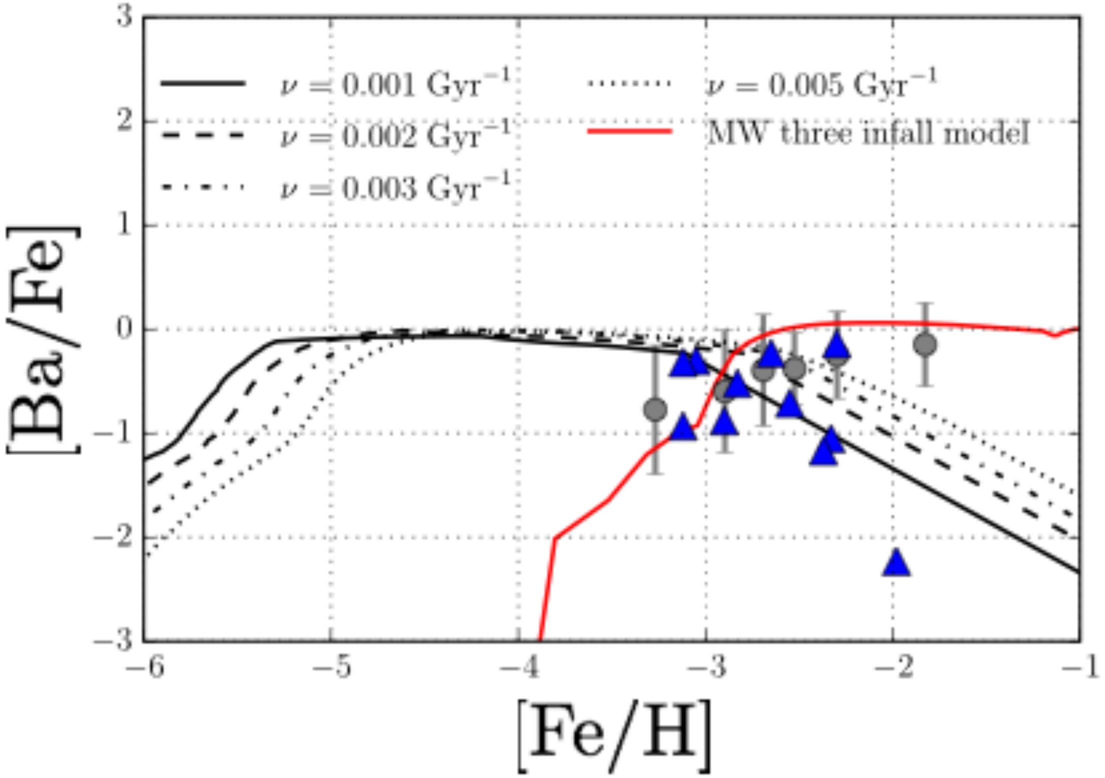
Bensby et al. (2014)
Gratton et al. (2003)
Akerman et al. (2004)
Cayrel et al. (2004)
Shi et al. (2009)

Hercules stars:

Adén et al. (2011), red

Chemical evolution of Hercules UfD





Reference parameters (Hercules UfD)
star formation efficiency = 0.003 Gyr^{-1}
wind parameter = 10 Gyr^{-1}
infall time-scale = 0.005 Gyr
infall mass = 1.0 × 10^7 $M_\odot$

Data

MW stars (grey):
Frebel et al. (2009),
as binned by Cescutti et al. (2010)

Hercules stars:
compilation from Koch et al. (2013), blue

Lighting up stars in chemical evolution models

the CMD of Sculptor

F. Vincenzo, F. Matteucci, T. de Boer, M. Cignoni, M. Tosi, *submitted*

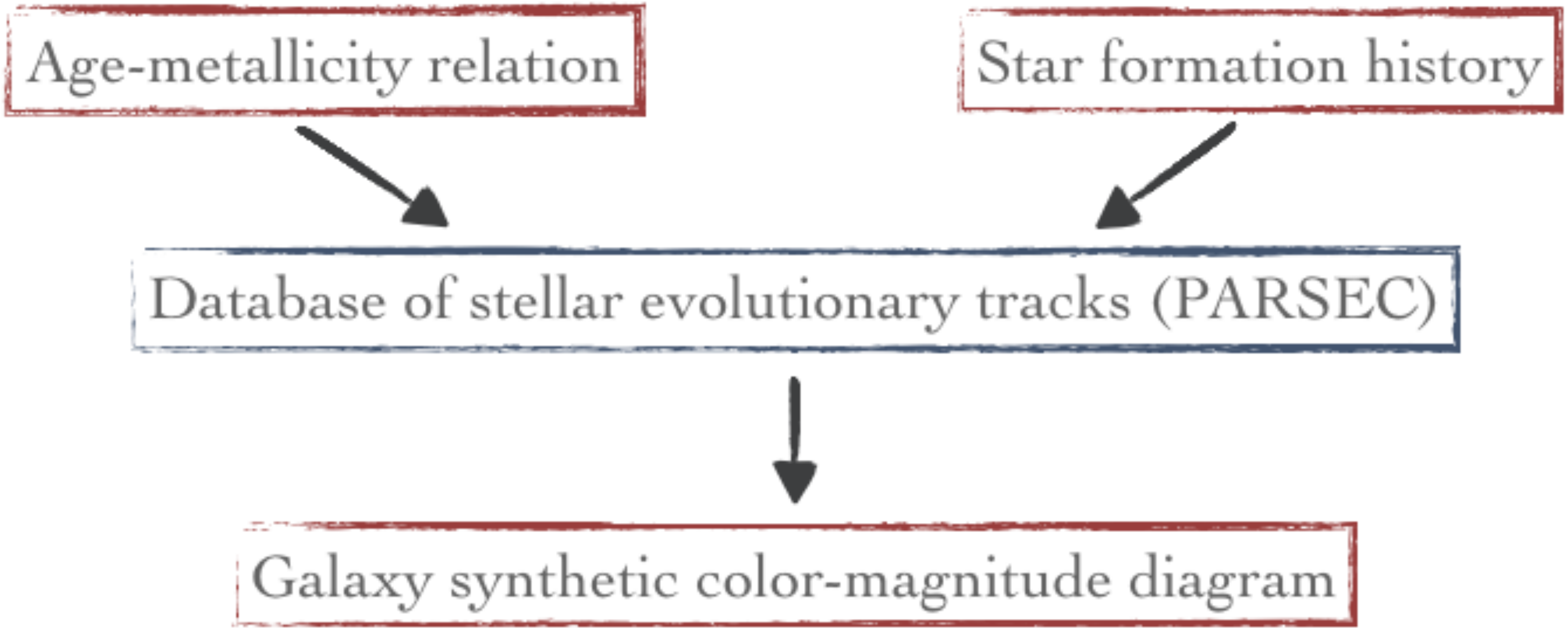
The photo-chemical model

stepwise structure

1. Statistically sampling the galaxy **predicted SFH**, to randomly extract an **age** for the formation of a given star
2. Sampling the **assumed IMF**, to assign a **mass** to the star
3. Making use of the **predicted age-metallicity relation** to find the stellar **metallicity**
4. **Question**: Given the age, mass and metallicity, is the star alive at the present time?
    - **Yes**: Draw it in the CMD
    - **No**: Refuse it
5. **Repeat** the cycle until the (corrected) synthetic CMD has the same number of stars as the observed CMD

Vincenzo et al. (2016)

The photo-chemical model



Age-metallicity relation

Star formation history

Database of stellar evolutionary tracks (PARSEC)

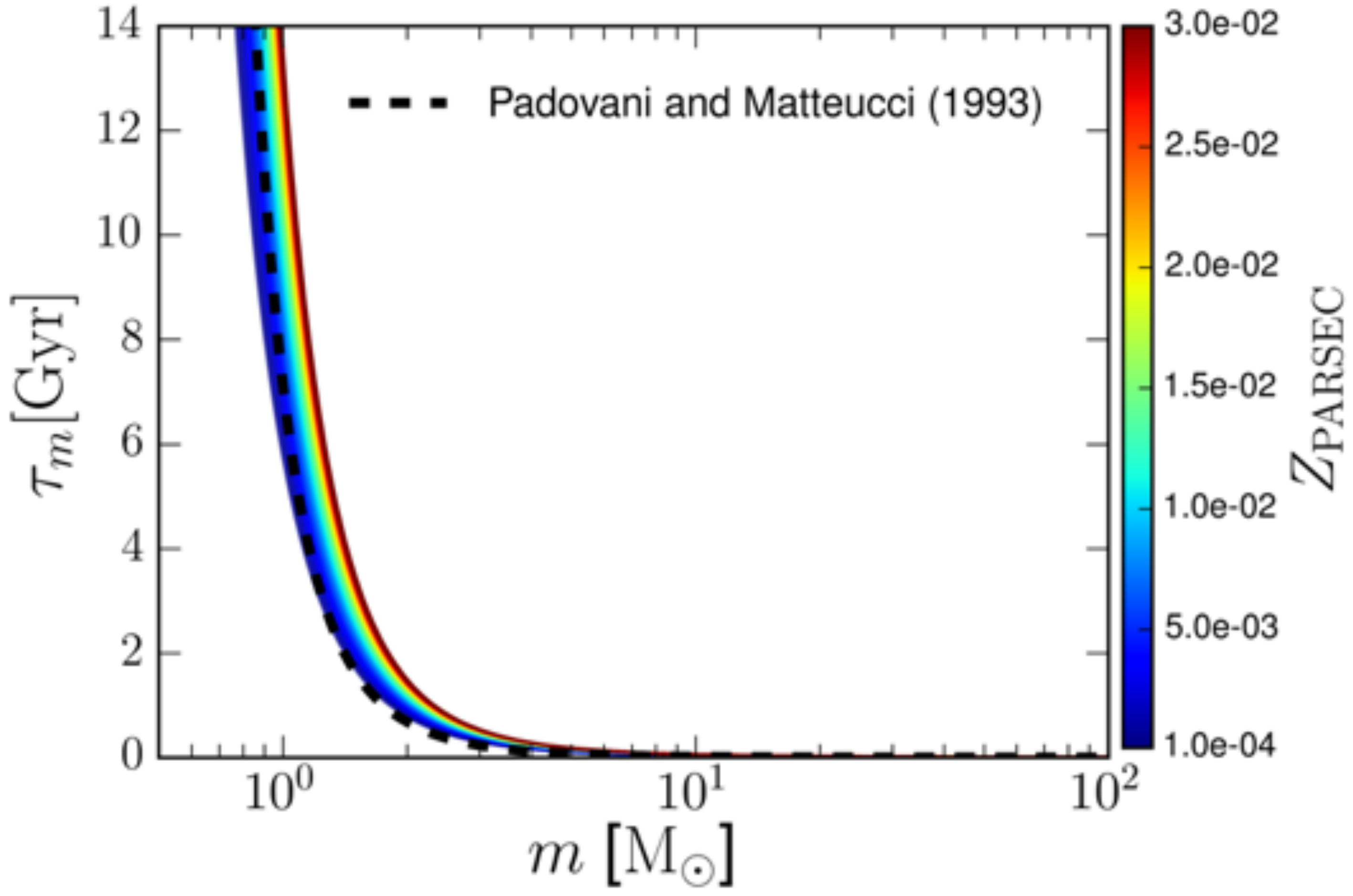
Galaxy synthetic color-magnitude diagram

New set of observational constraints for chemical evolution models

How does the assumed galaxy formation and evolution scenario affect the final configuration of the synthetic CMD?

Strength: very fine grid of stellar isochrones both in metallicity and in age

The assumed stellar lifetimes



Vincenzo et al. (2016)

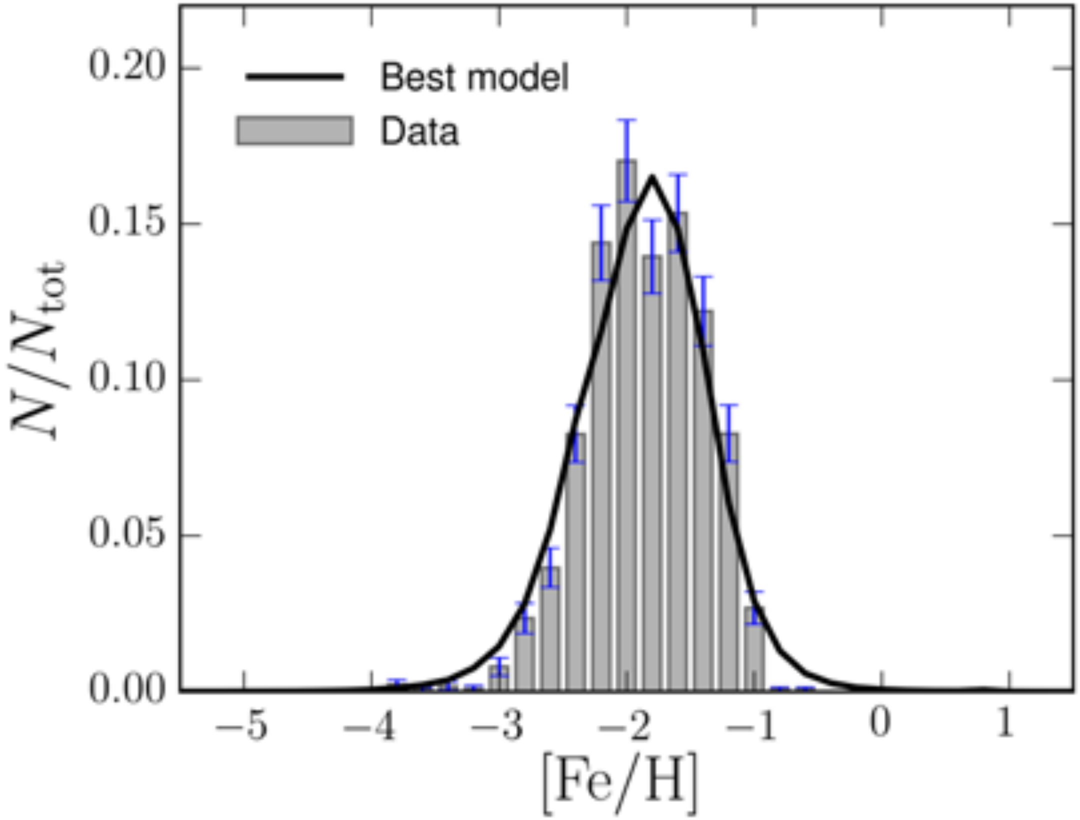
Fitting formula:

$$\tau_m(Z) = \mathrm{A}(Z) \times \exp\left[\mathrm{B}(Z)\, m^{-\mathrm{C}(Z)}\right]$$

Sculptor dwarf spheroidal galaxy

- It was discovered by Shapley (1938) as a stellar count excess in photographic plates
- It hosts **two main stellar populations** (e.g. Tolstoy et al., 2004):
  1. inner metal-rich, kinematically hot
  2. outer metal-poor, kinematically cold
- Average V-band surface brightness: $\langle \mu_V \rangle$ **= 23.5 ± 0.5 mag arcsec**$^{-2}$ (McConnachie, 2012)
- Absolute V-band magnitude: $\mathbf{M_V}$ **= -11.1 ± 0.5 mag** (McConnachie, 2012)
- Half light radius: $\mathbf{r_h}$ **= 285 ± 45 kpc** (McConnachie, 2012)
- Distance modulus: **μ = 19.62 ± 0.04 mag** (Martînez-Vàzquez et al., 2015)
- Distance: **d = 79 ± 4 kpc** (Koch, 2009)

The best Sculptor chemical evolution model



Vincenzo et al. (2016)

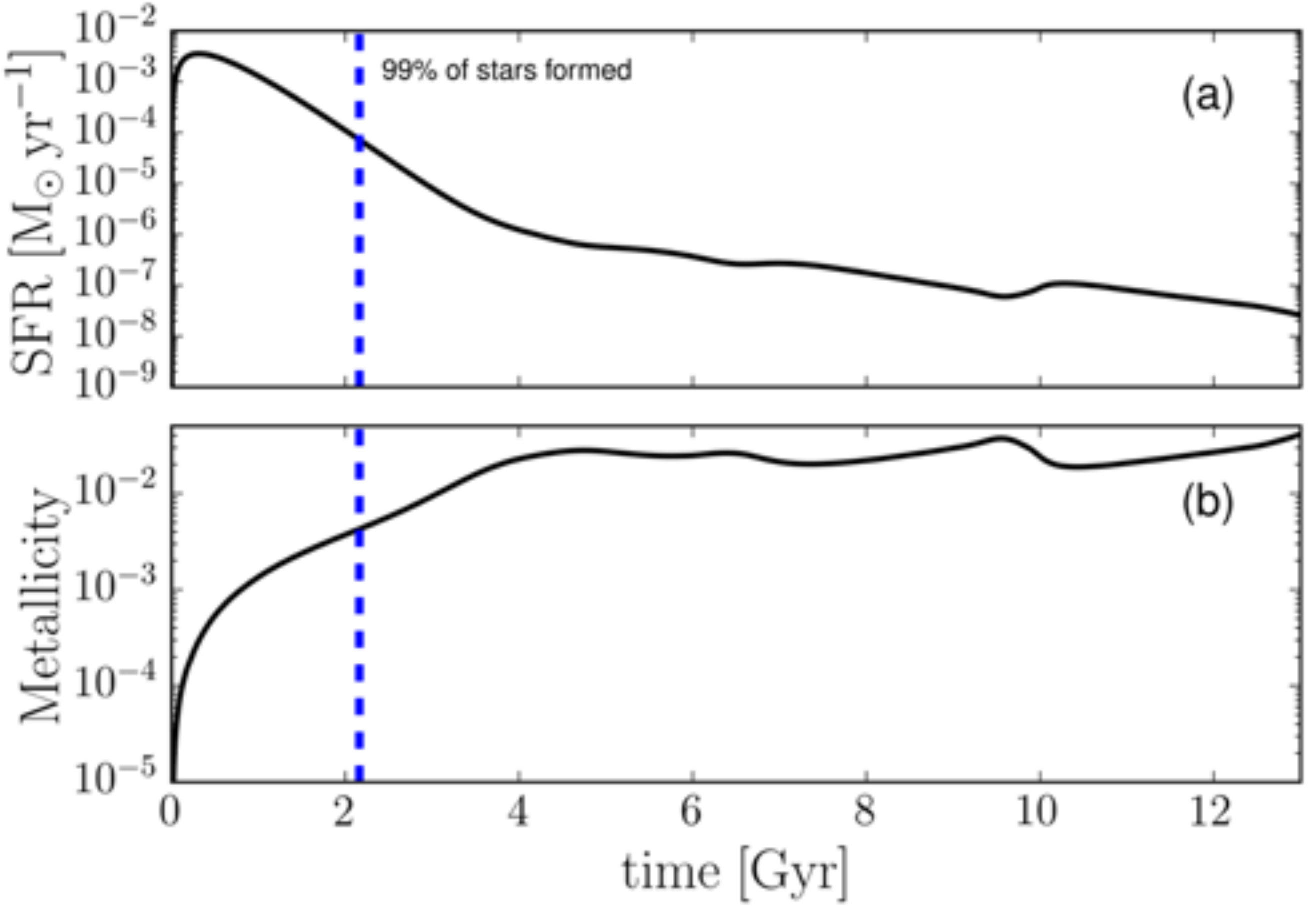
Best chemical evolution model:
star formation efficiency = 0.04 Gyr^{-1}
wind parameter = 3.0 Gyr^{-1}
infall time-scale = 0.3 Gyr
infall mass = $1.0 \times 10^{8}\ M_\odot$

Two observed main stellar populations:

- inner metal-rich, kinematically hot
- outer metal-poor, kinematically cold

Observed MDF from Romano & Starkenburg (2013)

The input of the photo-chemical model



Best chemical evolution model:

star formation efficiency = 0.04 Gyr^{-1}

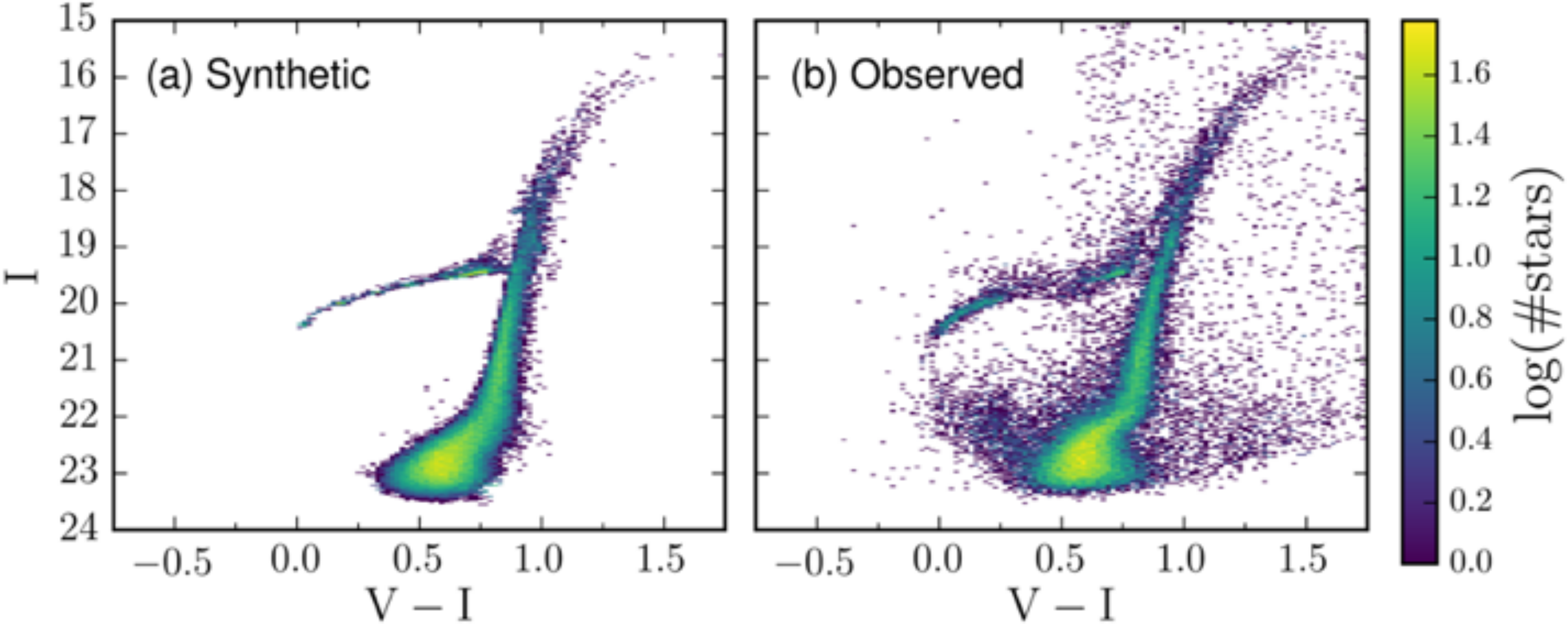
wind parameter = 3.0 Gyr^{-1}

infall time-scale = 0.3 Gyr

infall mass = $2.31 \times 10^8\ \mathrm{M}_\odot$

Vincenzo et al. (2016)

The Hess diagram of Sculptor

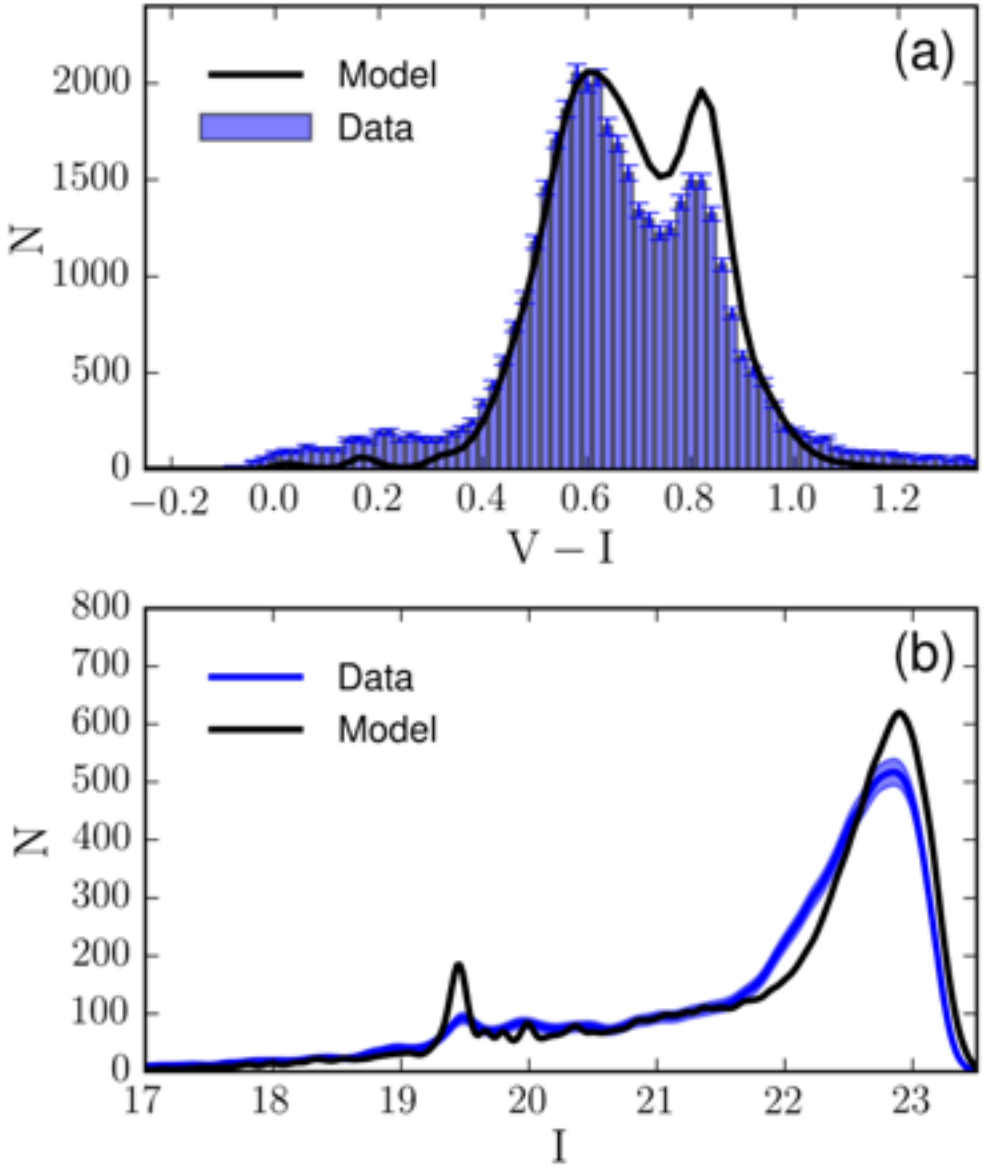


Vincenzo et al. (2016)

Data from de Boer et al. (2011)

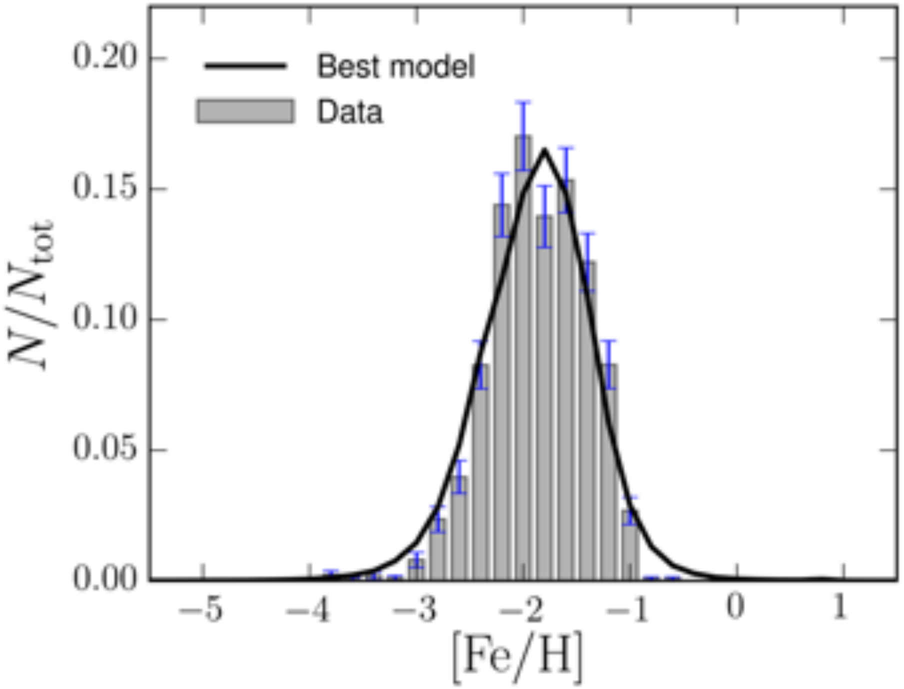
- The synthetic CMD has been convolved with the distribution of the observed photometric errors from de Boer et al. (2011)
- The completeness profile has been computed starting from the artificial star test of de Boer et al. (2012)

Comparing model and data



Vincenzo et al. (2016)

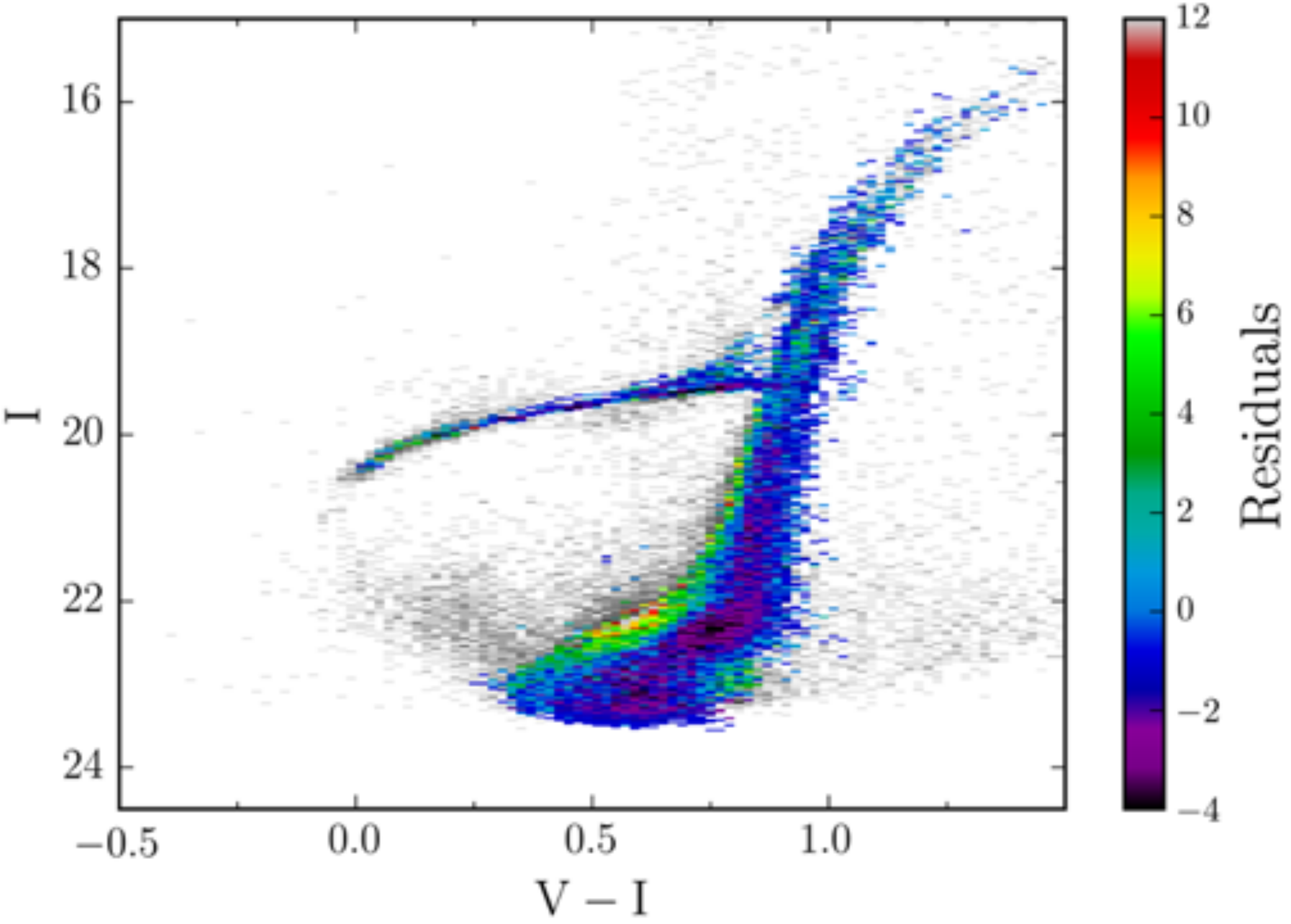
Memo:



Good agreement for the RGB and HB

Main discrepancy for the blue MSTO and SGB

Comparing model and data



Vincenzo et al. (2016)

Residual in the ij-th grid element

$$R_{ij} = \frac{n_{ij,\mathrm{obs}} - n_{ij,\mathrm{syn}}}{\sqrt{n_{ij,\mathrm{syn}}}}$$

Conclusions

I. Modelling the chemical evolution of dSphs and UfDs

- dSph stars exhibit lower [α/Fe] than the MW disc stars, with such difference diminishing when going down in metallicity towards halo stars

[α/Fe] vs. [Fe/H]

MDF

$M_\star$

dSphs ⇒ low SFEs

UfDs ⇒ very low SFEs

- They undergo **strong outflows**, which remove most of their gas and sharply reduce the SF activity

- [α/Fe] and [Ba/Fe] vs. [Fe/H] abundance patterns suggest MW halo component to have had **different** chemical evolution history with respect to UfD galaxies

Conclusions

II. Lighting up stars in chemical evolution models

- **Photo-chemical model**: a novel approach to draw the synthetic CMD of galaxies
- We 'light up' the stars in chemical evolution models, according to their initial mass, metallicity and age
- We can reproduce the main features of the observed Sculptor CMD
- Discrepancies in the blue MSTO and SGB are likely due to the following facts: **i)** we assumed a one-zone chemical evolution model; **ii)** intrinsic uncertainties in the completeness profile; **iii)** the IMF might host a lower number of low-mass stars than the assumed Salpeter (1955)