First stars, feedback and dSph

Goal: quantify astrophysical feedback in small DM-dominated systems:

hope to constrain astro-particle physics of dark matter
– near-field equivalent of LSS neutrino limits

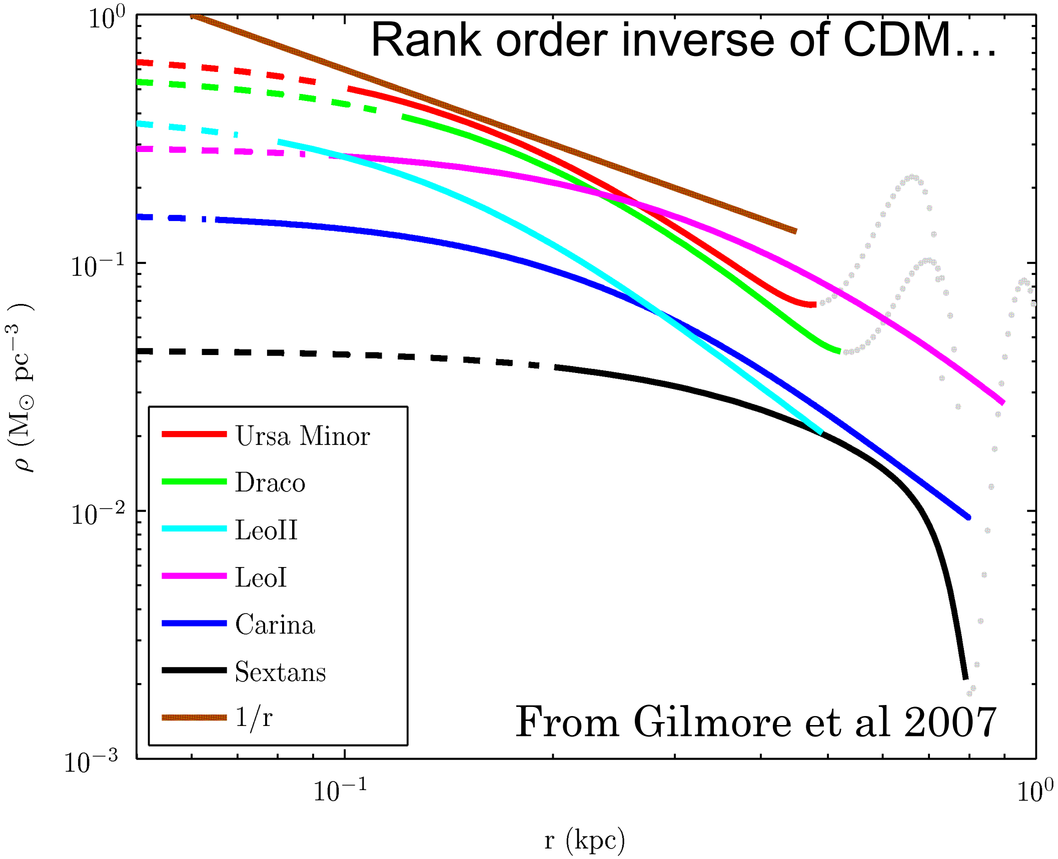
Georges Kordopatis
PI: Gerry Gilmore
IoA Cambridge,
AIP Potsdam

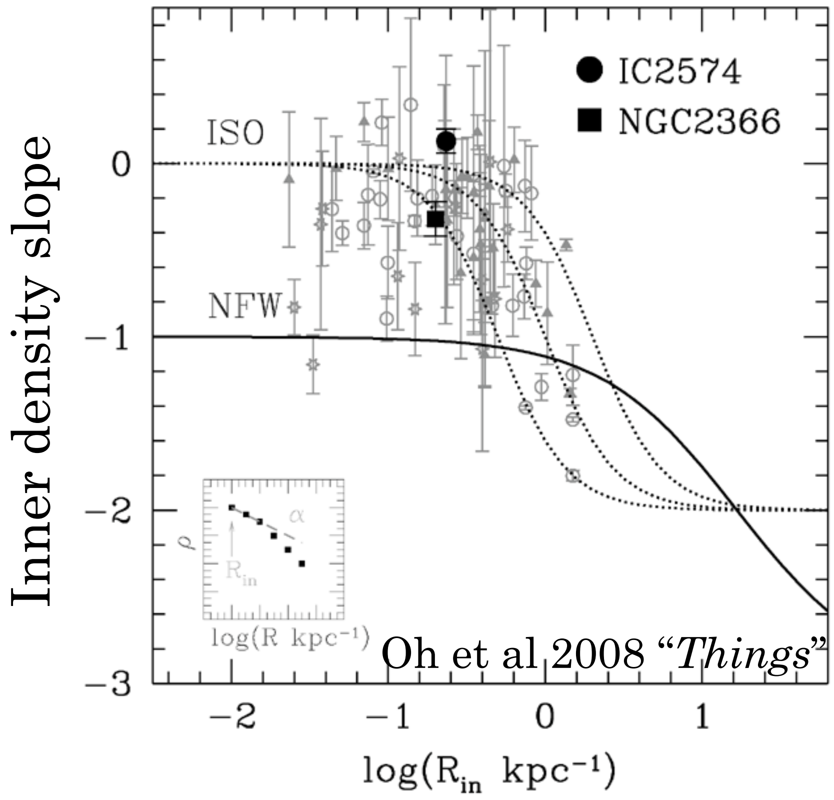
Rainbows of the Southern Sky, ESO HQ, 8th October 2015

Derived mass density profiles

Jeans' equation with assumed isotropic velocity dispersion:
Now the challenge is to **explain, not to refute.**

CDM "predicts" slope of -1.3 at 1% of virial radius and asymptotes to -1 (eg Diemand et al. 04)





- Characteristic Density ~10GeV/c²/cm³
  - **cores are always seen –DM physics or are they evidence of violent histories?**

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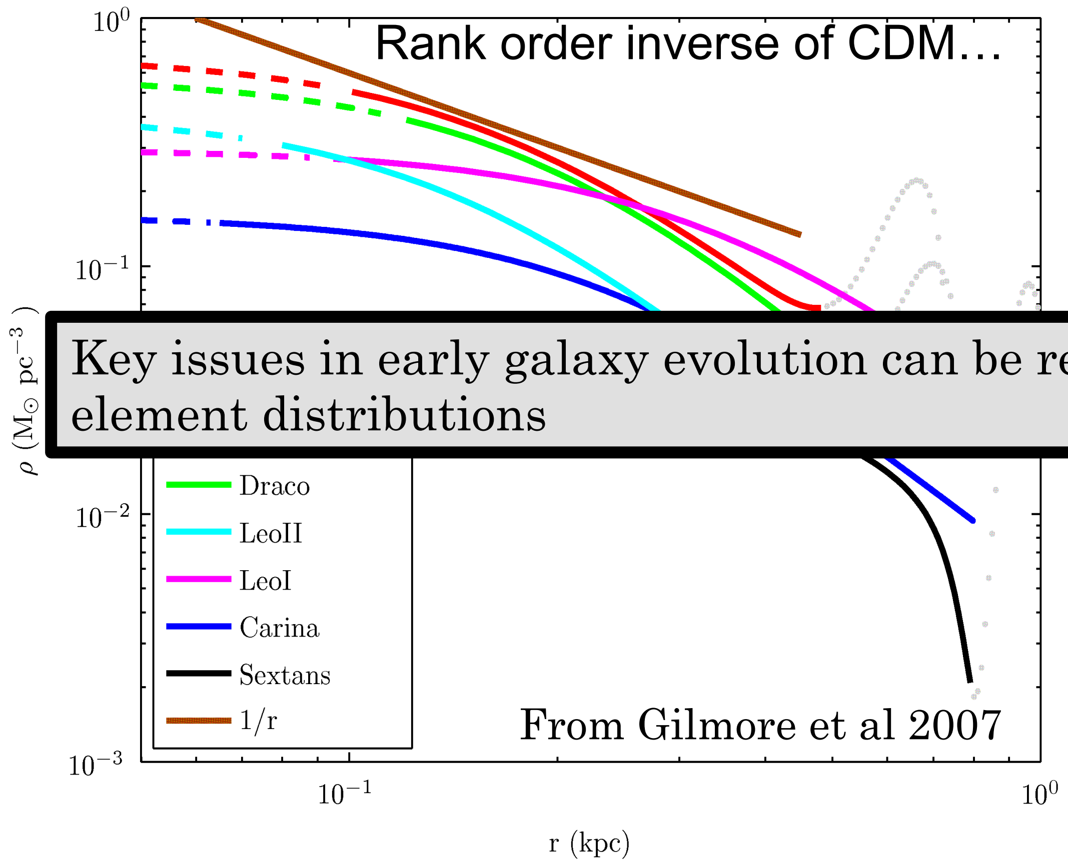
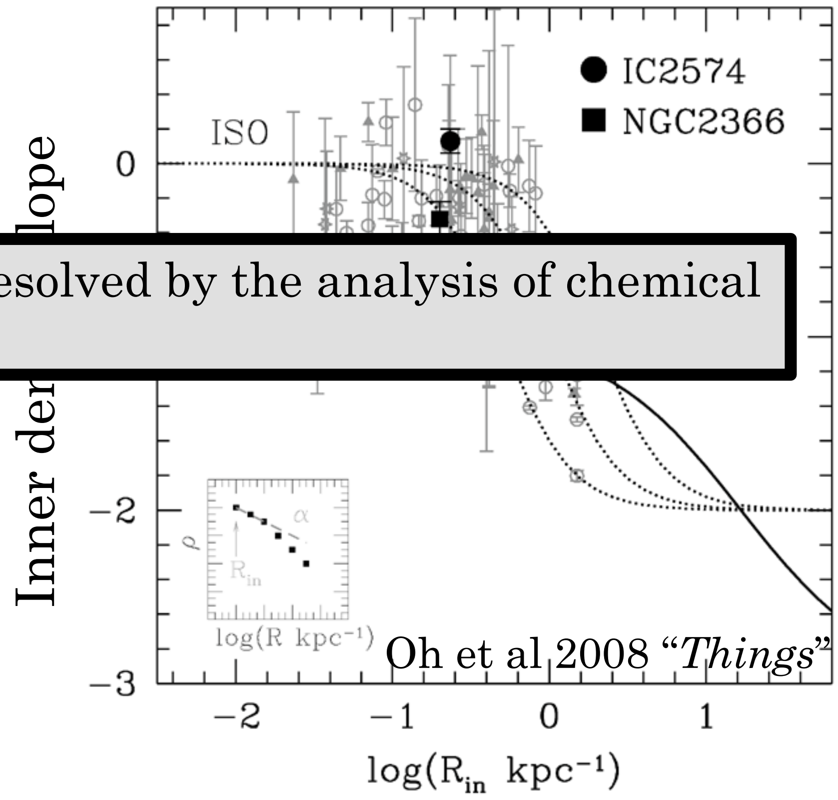




Key issues in early galaxy evolution can be resolved by the analysis of chemical element distributions

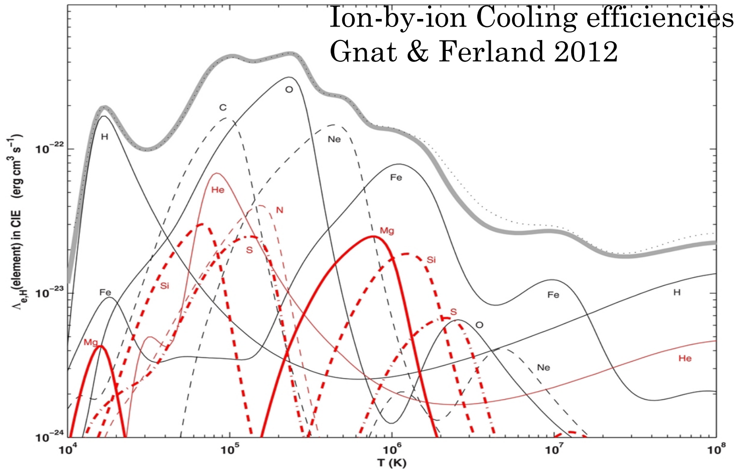
- Characteristic Density ~10GeV/c²/cm³
  - **cores are always seen –DM physics or are they evidence of violent histories?**

The information in chemistry

- Abundances define the cooling curve, defining possible star formation rates

Component	Temperature	Density	Tracers and IR lines
Cold gas	10-100 K	1-1000 cm-3	H2, CO, PAH's
Diffuse HI	100-1000 K	1 cm-3	HI 21cm, [CII], [OI]
HII regions	1000-10000 K	3-300 cm-3	H$ \alpha$, [OII], [OIII]

Signal of first SNe? May be very high C, O, very low Fe



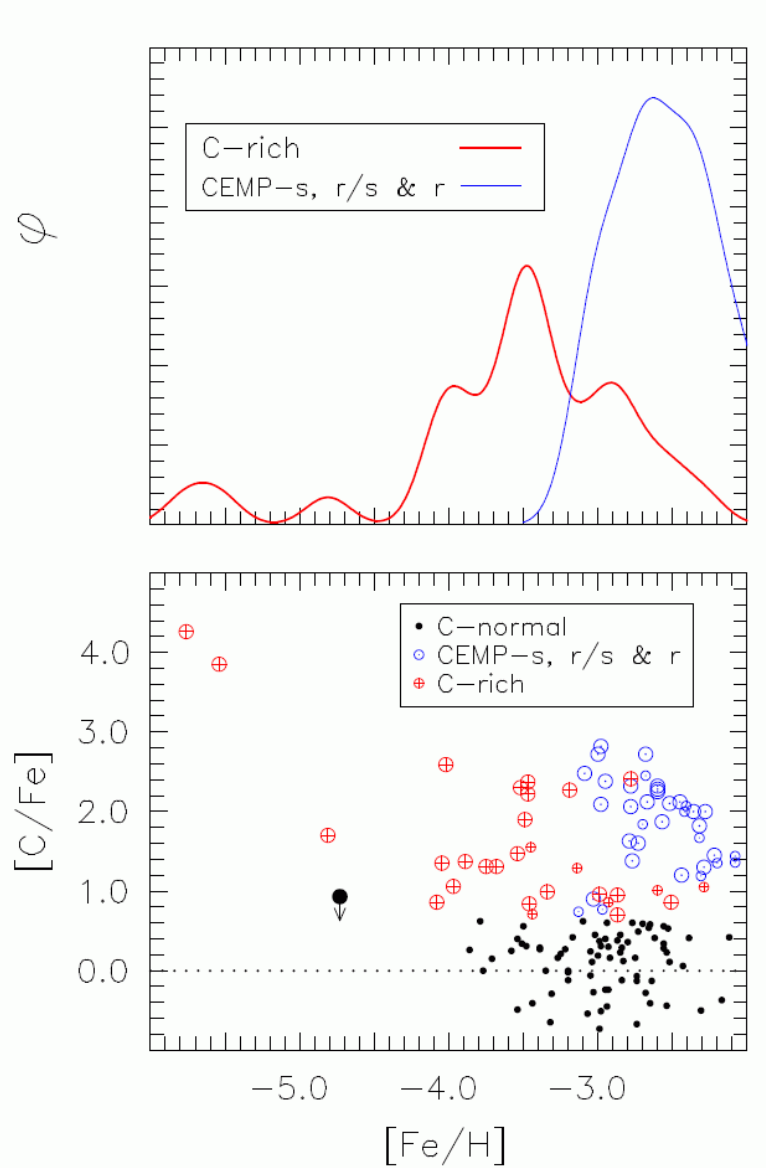
Ion-by-ion Cooling efficiencies
Gnat & Ferland 2012

Cooling is dominated by carbon & oxygen

The information in chemistry

- Abundances define the cooling curve, defining possible star formation rates

- Special abundance patterns identify PopIII SNe enrichment
  ➔very early stars



The information in chemistry

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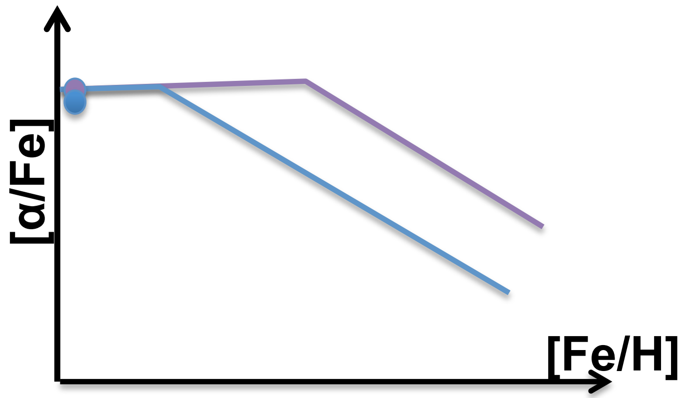
- α-elements define the high-mass IMF slope



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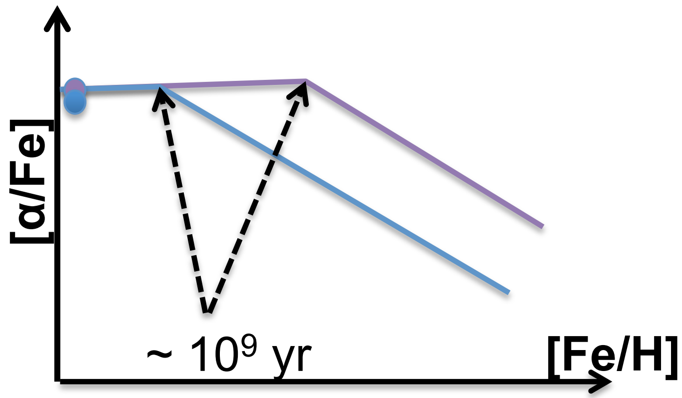
- α-elements define the high-mass IMF slope

- α-element “break” defines enrichment at ~1Gyr
  ➔star formation rate



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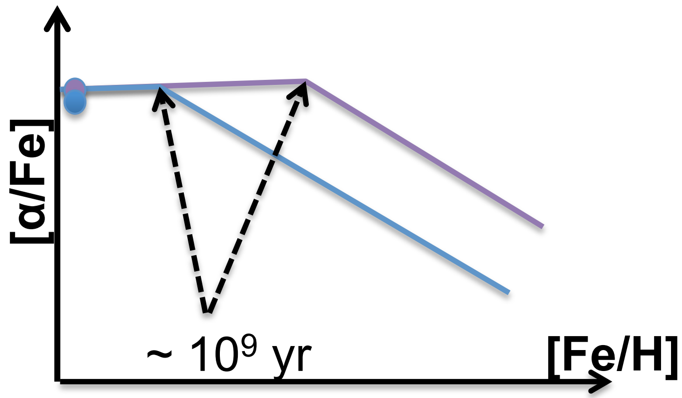


- Metallicity Distribution Function defines gas-loss fraction
  ➔impact on chemistry and kinematics

We are determining elemental abundances for stars in dSph galaxies to map chemical evolution, mass loss, and feedback energy rates.

➔ **Carina, Fornax and Bootes-I**

Fornax 413 stars in high res

THE METAL-POOR KNEE IN THE FORNAX DWARF SPHEROIDAL GALAXY†

Benjamin Hendricks[1], Andreas Koch[1], Gustavo A. Lanfranchi[2], Corrado Boeche[3], Matthew Walker[4], Christian I. Johnson[5,6], Jorge Peñarrubia[7], Gerard Gilmore[8]

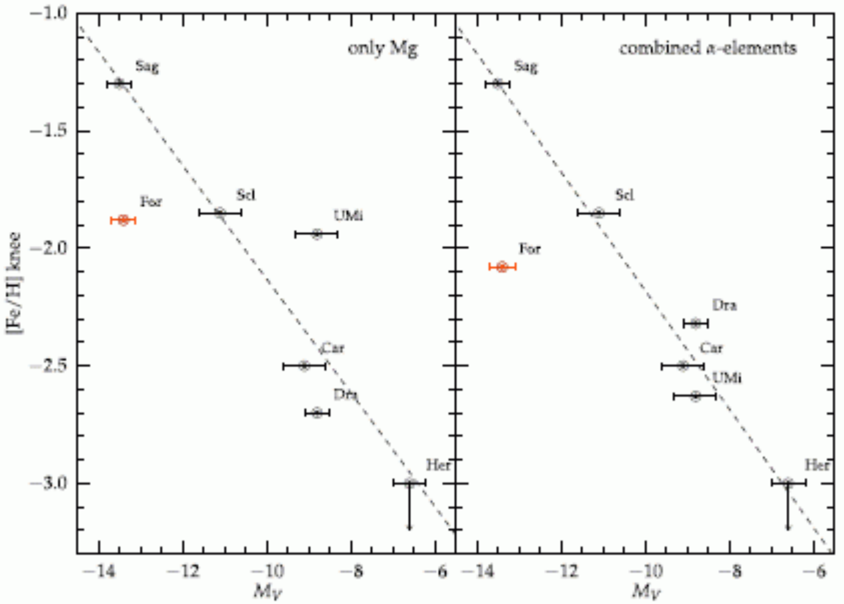
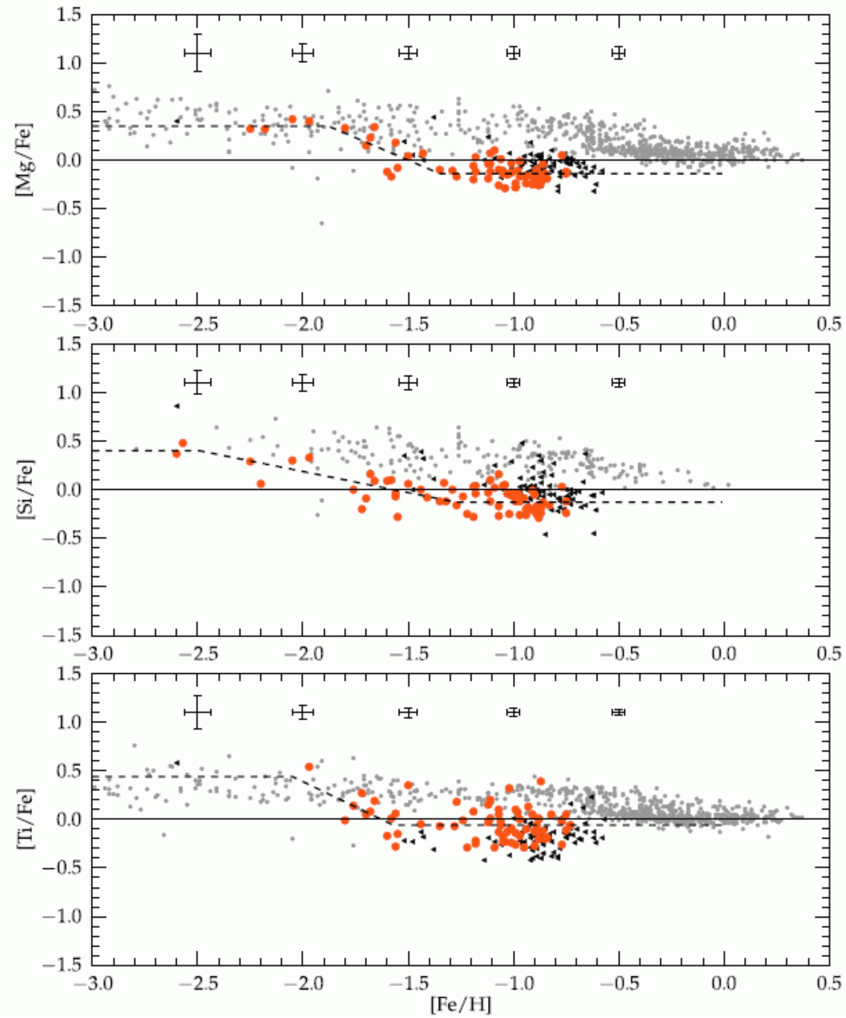


Fig. 3.— Position of the knee in the α-element distribution in several dwarf galaxies as a function of absolute magnitude. Uncertainties in M_V have been adopted from McConnachie (2012). Note, that Sagittarius might have been as much as two magnitudes more luminous in the past (Niederste-Ostholt, et al. 2010). In the left panel we only use [Mg/Fe], in the right panel we use a combination of all available α-elements. The dashed line indicates the best fitting linear relation, when we exclude Fornax from the sample. The metal-poor knee of Fornax does not fall in an otherwise linear relation and either questions the formation scenario of this galaxy, or the understanding of chemical enrichment in dSphs.



Very slow SFR (opposite than would be required for cusp-core transformation)

Carina 90 UVES stars, 1000 Giraffe

Norris, Masseron, Venn, Yong, GK, GG

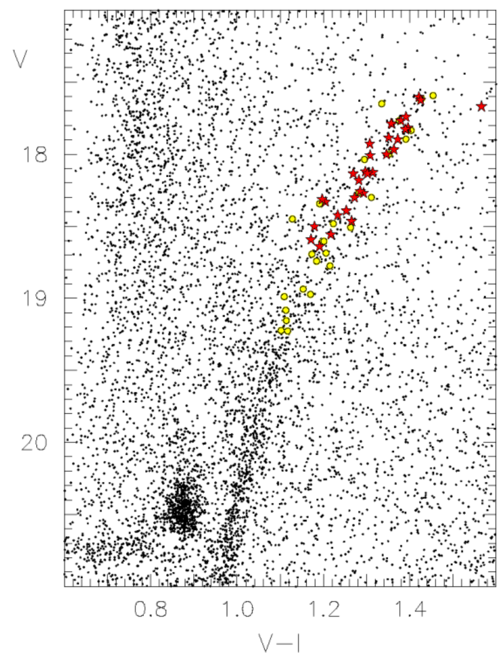
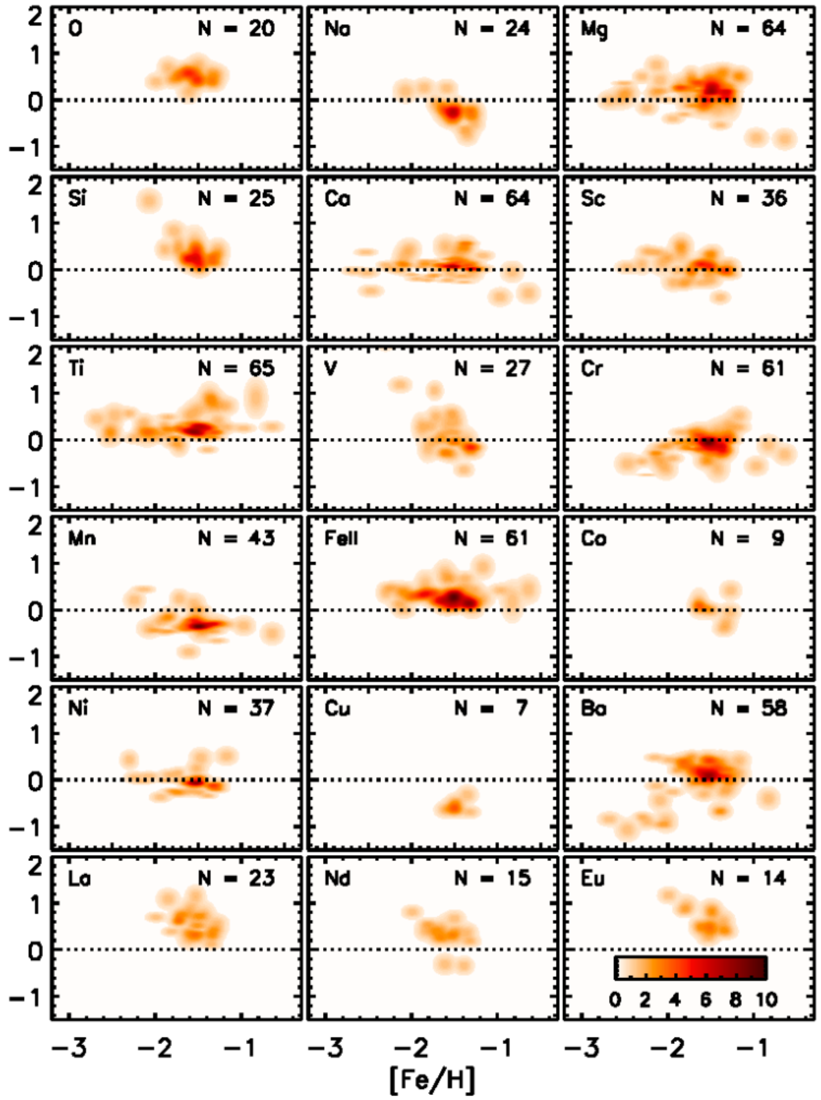


Fig. 1.— The Carina (V, $V-I$) color−magnitude diagram for stars observed in our initial photometric survey. The high quality photometry presented here have been made available by P.B. Stetson. The small black symbols present results for the general survey; large red star symbols represent objects observed spectroscopically at high-resolution in the present work; and large yellow circles stand for independent stars in the literature having spectroscopy of a similar quality.

Key points: expanded UVES sample to all archive Keck & Magellan, to get 90 stars
Find: evidence for Ia enrichment, direct age-metallicity relation, long time-scale, no globular cluster-like relations. Definitive chemical study.

Carina - High Res sample



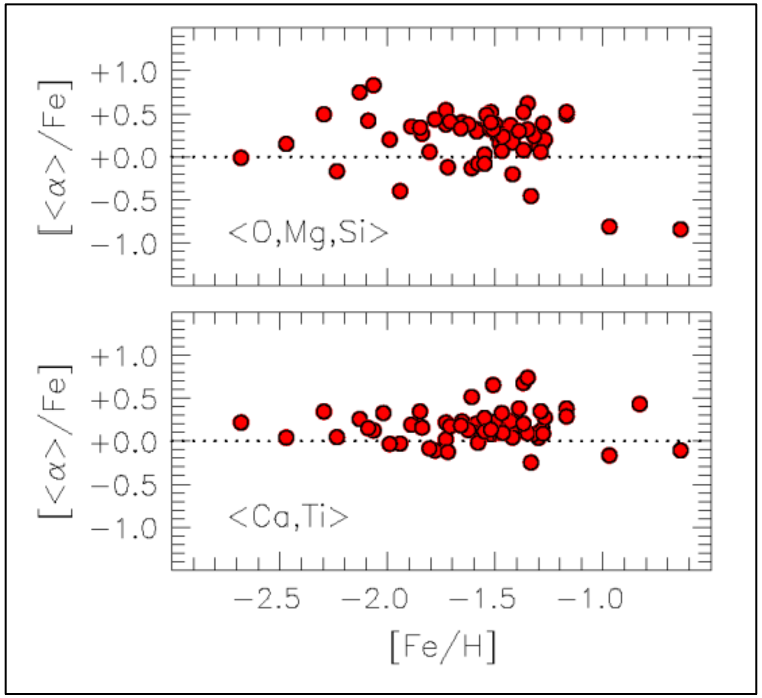
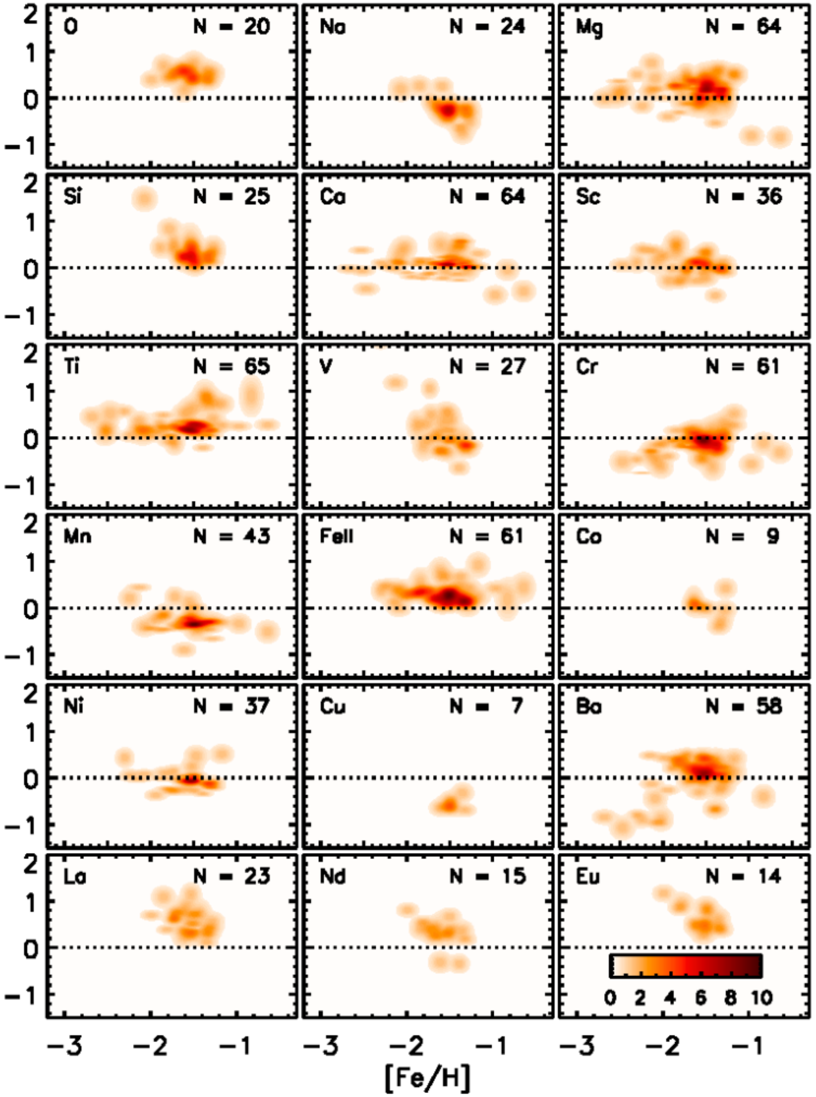
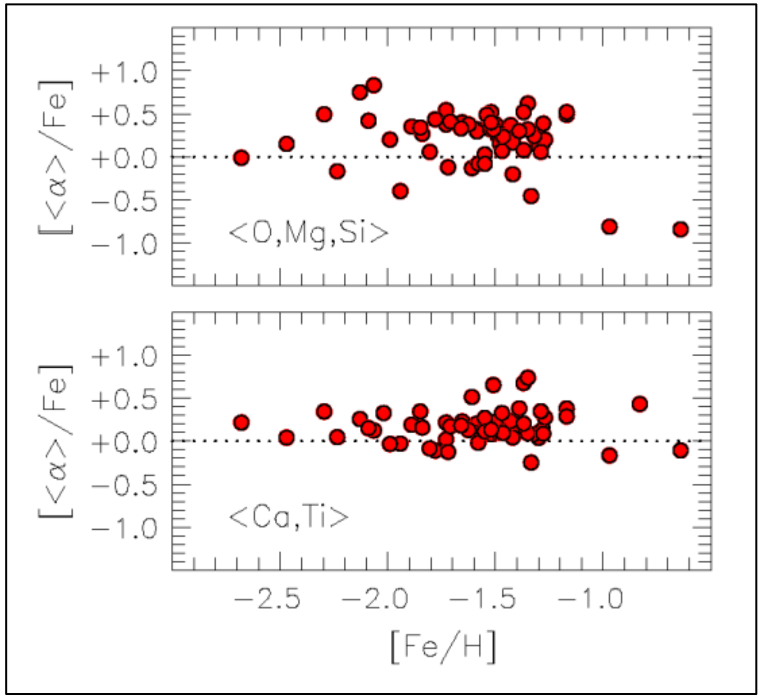


Fig. 12.— Contours of relative abundance – [X/Fe] vs. [Fe/H]. Here each star is represented by a double Gaussian having kernels equal to the total observational errors.

Carina - High Res sample





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Direct evidence for Type Ia SN enrichment

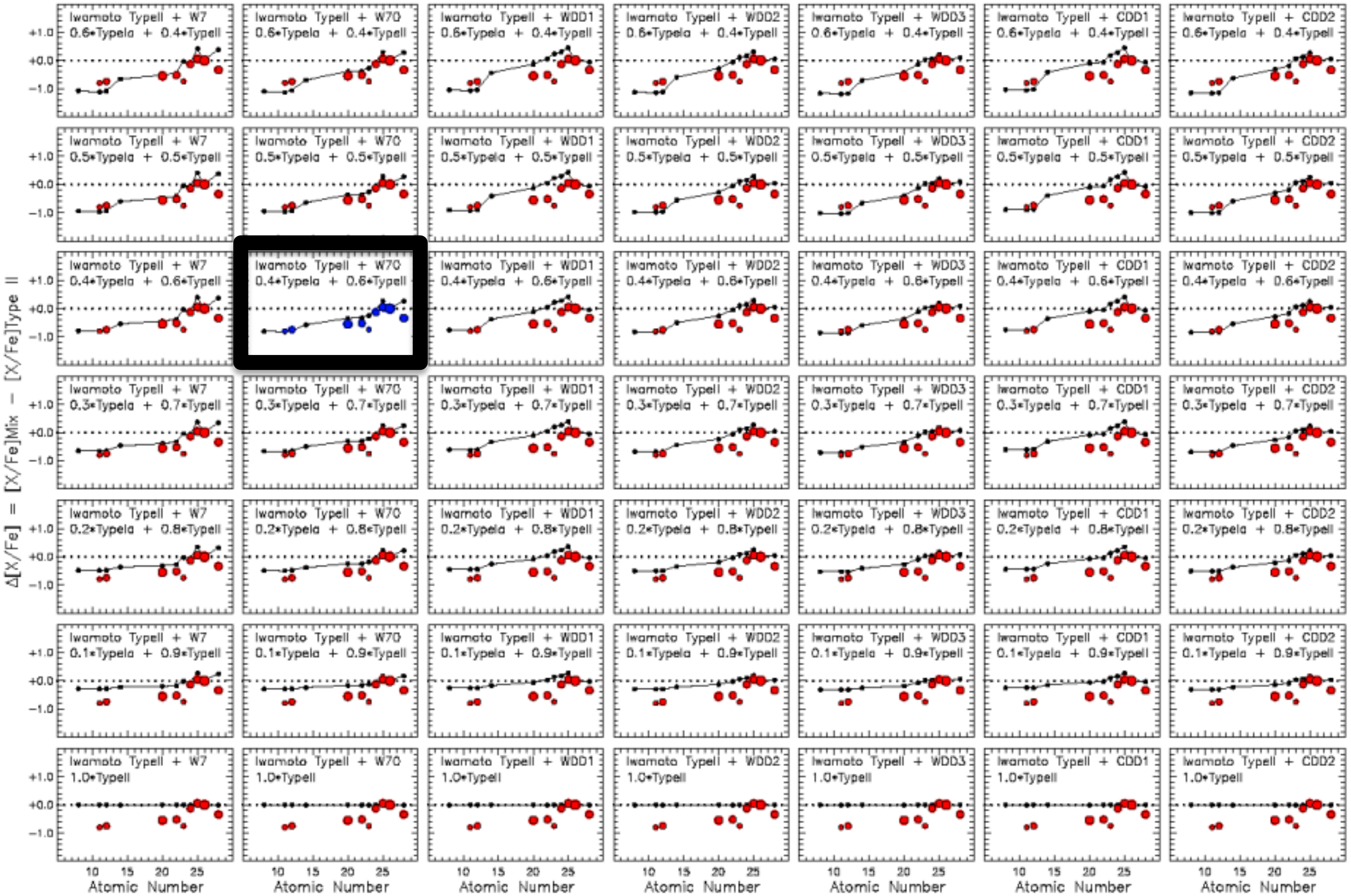


Fig. 14.— The comparison of model admixtures of Type Ia and Type II SNe (small black dots) and observed abundances (red circles) as a function of atomic number for Car-612 = CC_07452. Blue symbols are used for the best fit case. The sizes of the observational symbols are proportional to the square of the inverse of obsrvational errors. See text for more details.

Direct evidence for Type Ia SN enrichment

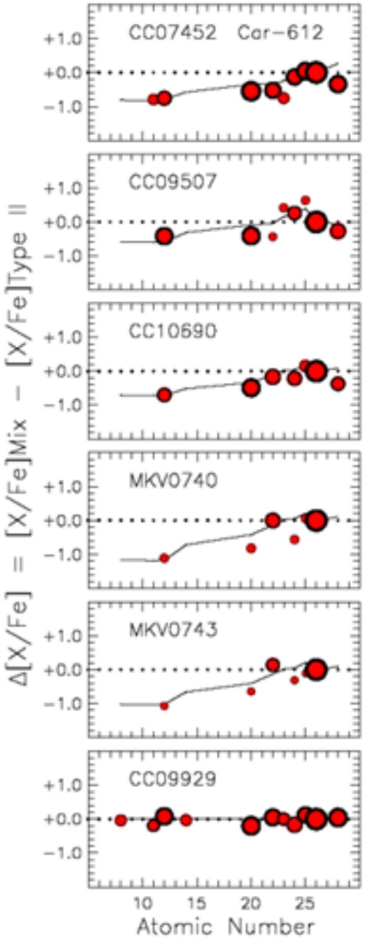


Fig. 16.— (Top five panels) The comparison between best fit Iwamoto et al. (1999) Type II and Type Ia mixture models (black line) with observations (red circles, size proportional to error of measurement) of the five Carina giants showing strongest evidence for Type Ia enhancement. Results for a typical red giant with no Type Ia enhancement is shown for comparison in the bottom panel. The ordinates are as described in Figure 14.

The Carina age-metallicity relation

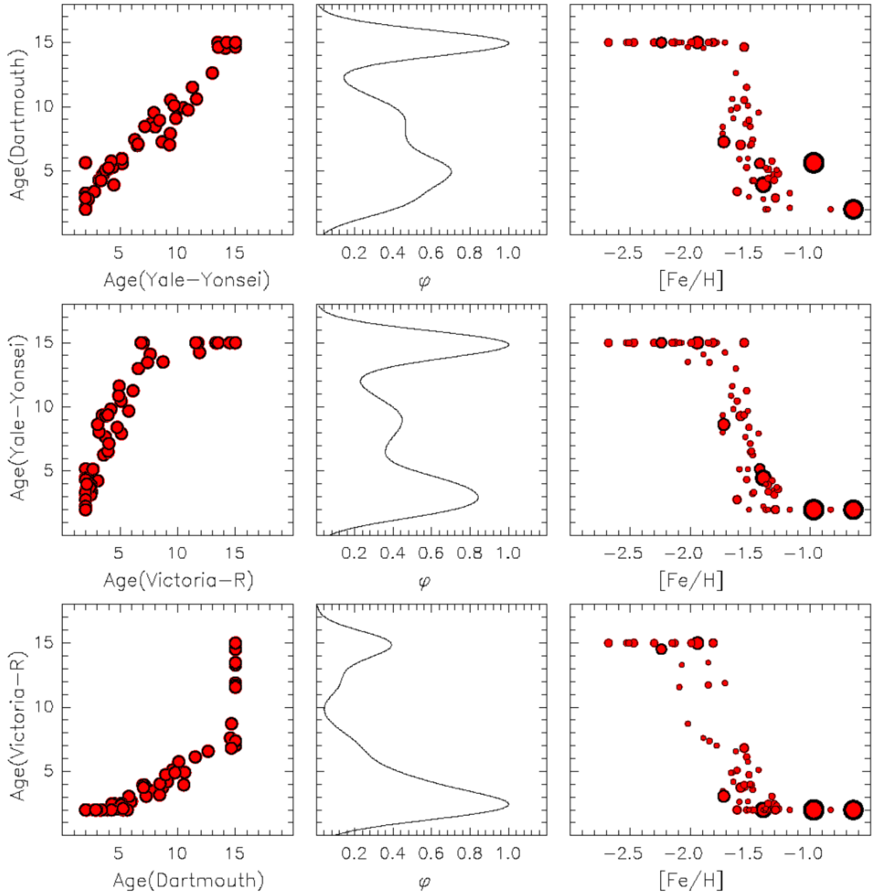


Fig. 17.— The interdependence of age, [Fe/H], [Ca/Fe], and Type Ia enrichment for the Carina red giants. In the left column, ages have been determined using the isochrones of Dotter et al. (2008) (Dartmouth), Demarque et al. (2004) (Yale-Yonsei), and Vandenberg et al. (Victoria-Regina). The middle column contains the resulting age histograms, while the right column presents (age, metallicity) dependences. The symbol size in the rightmost column is proportional to the fraction of the star that initially comprised Type Ia material.

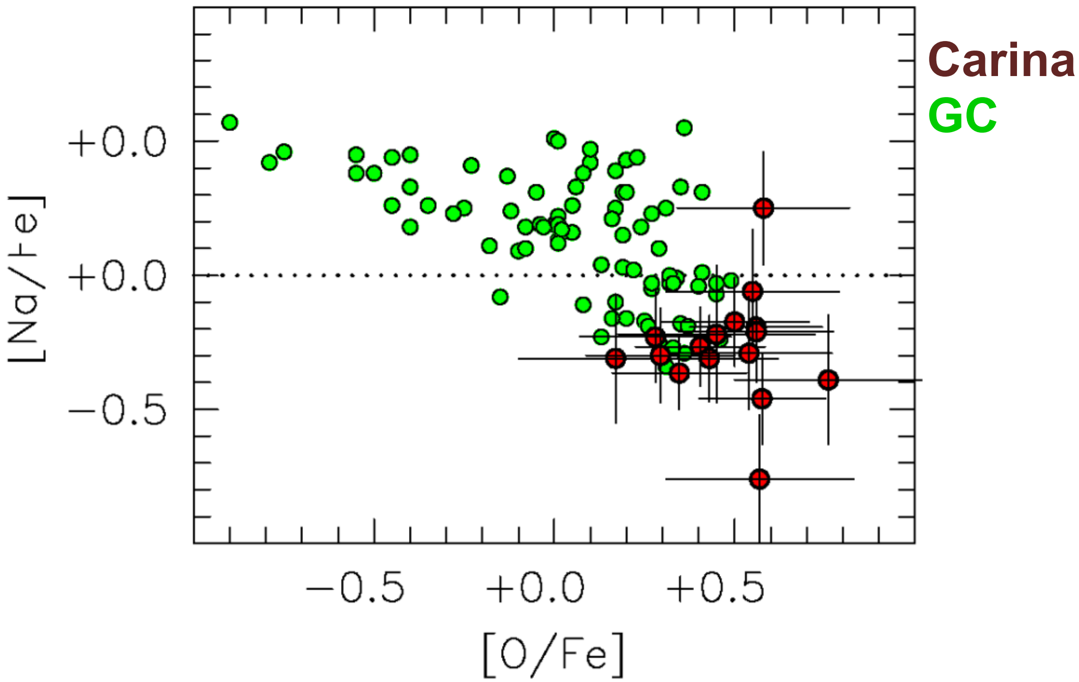
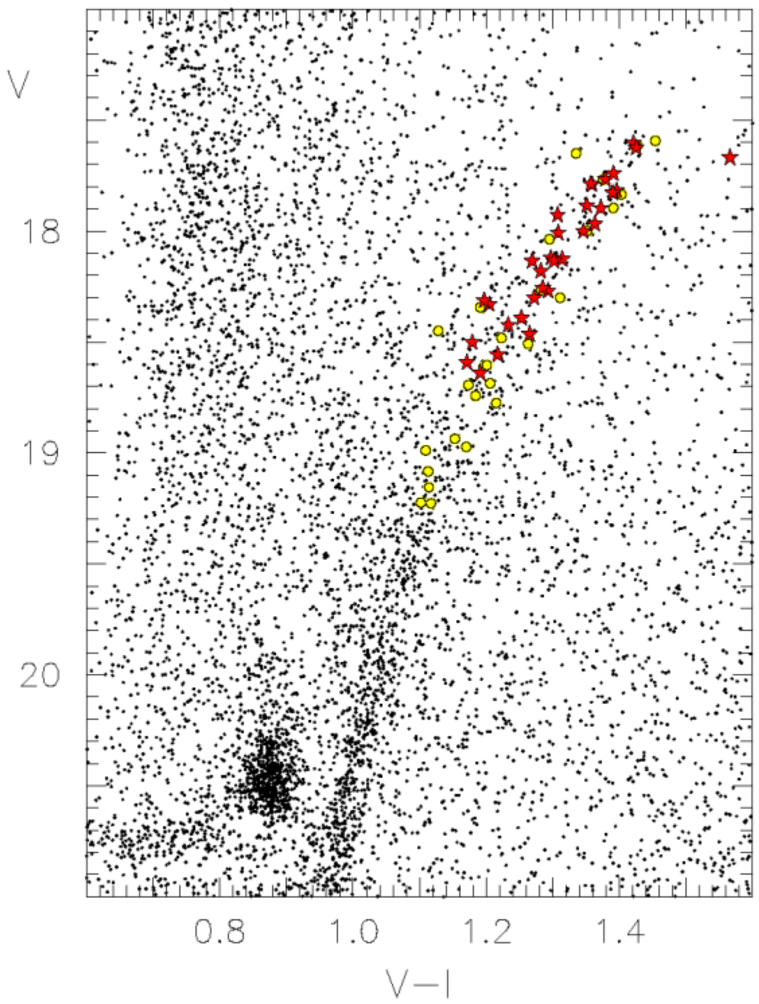
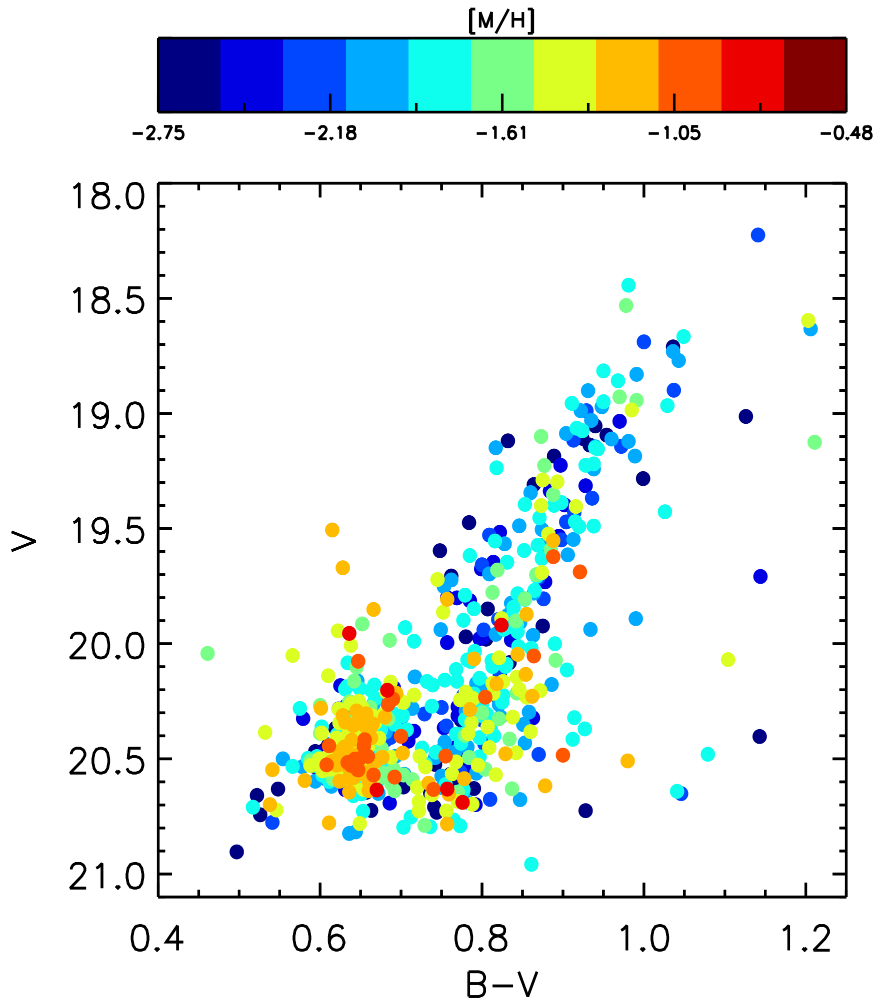


Fig. 18.— LTE relative abundances [Na/Fe] vs. [O/Fe] for red giants in Carina (large red symbols, present work) and in the globular clusters M3, M4, M5, M13 (small green symbols, data from Kraft et al. 1992, Kraft et al. 1997, Ivans et al. 1999, and Ivans et al. 2001).

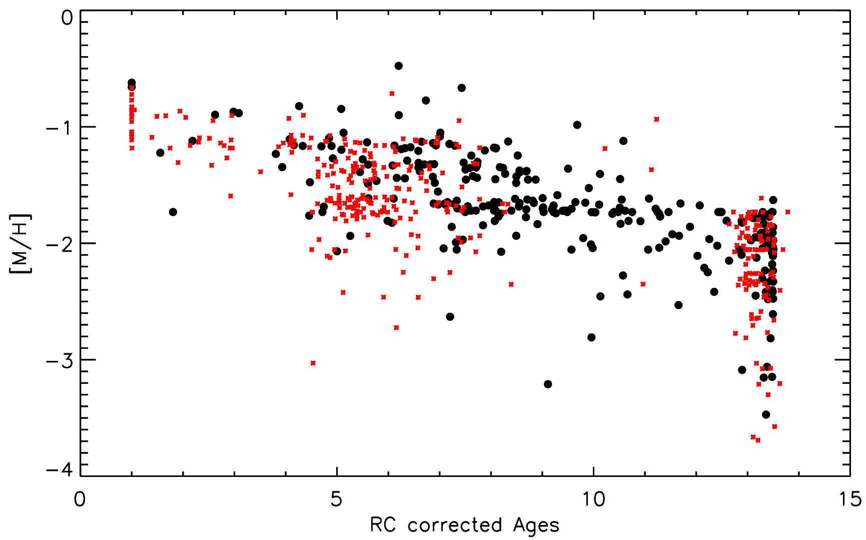
No evidence for globular cluster-like Na-O relation: Why these differences in the evolution of the stars?

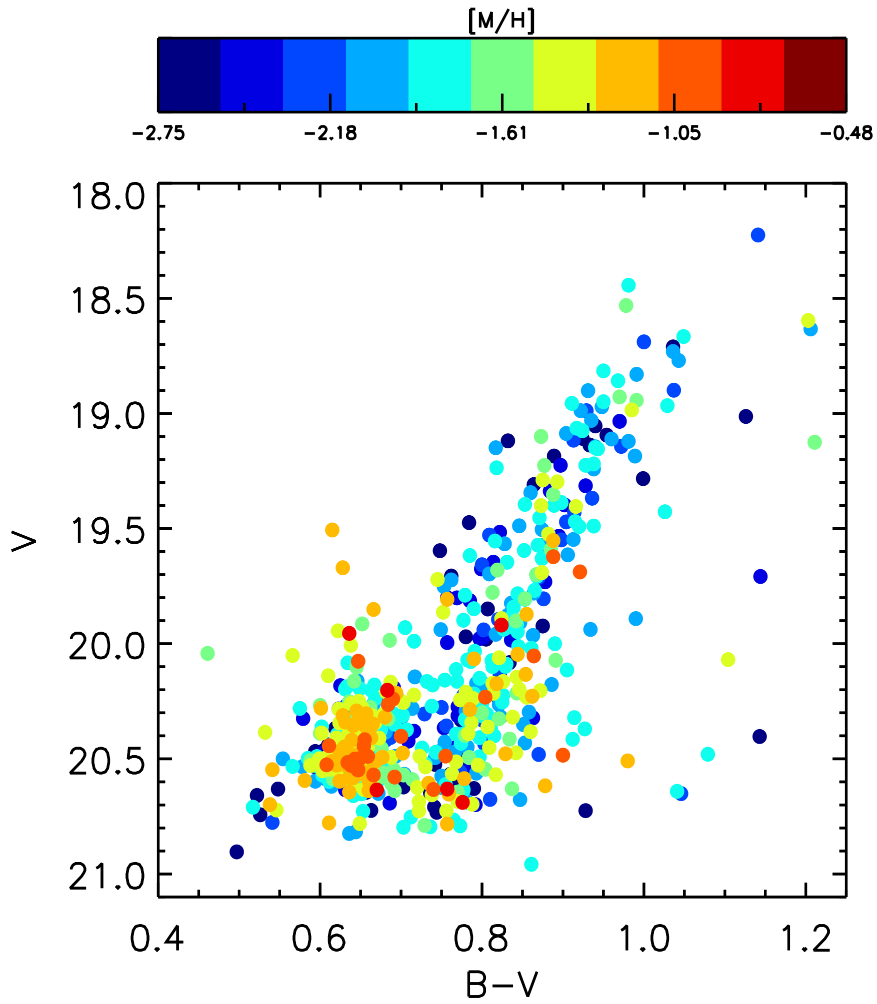
Carina Low-res study





Carina Low-res study





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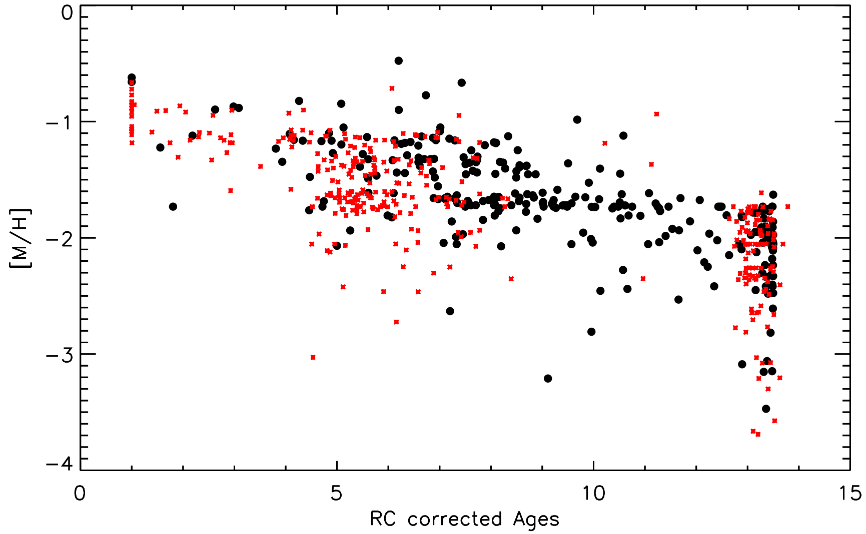
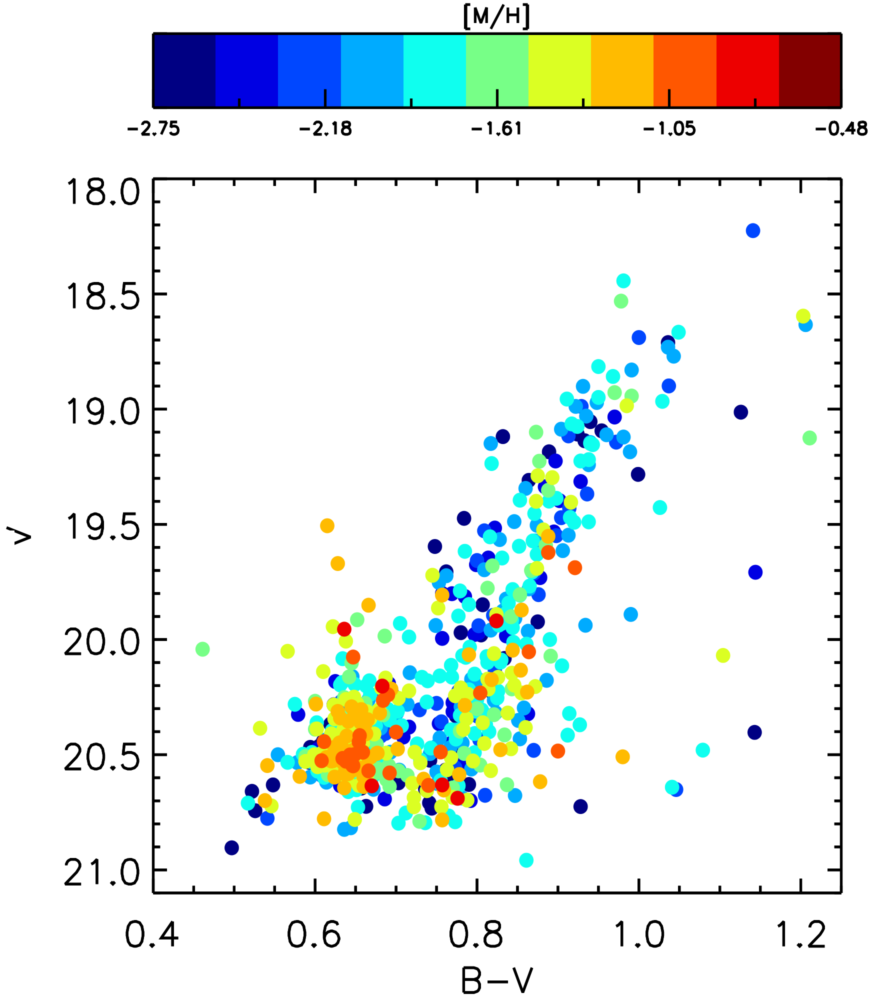
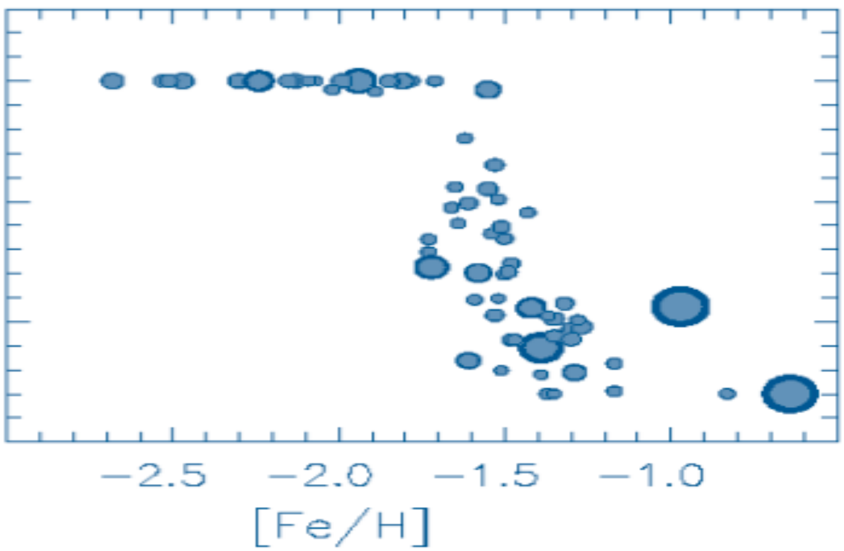
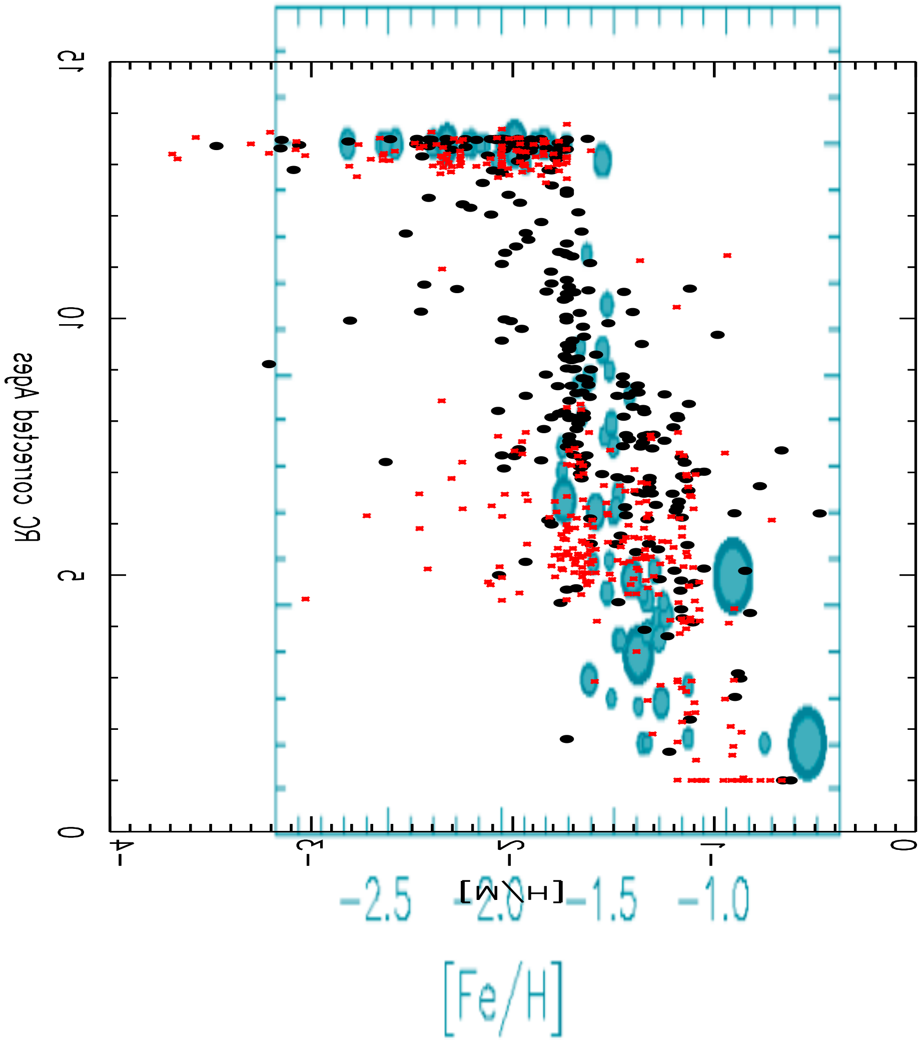
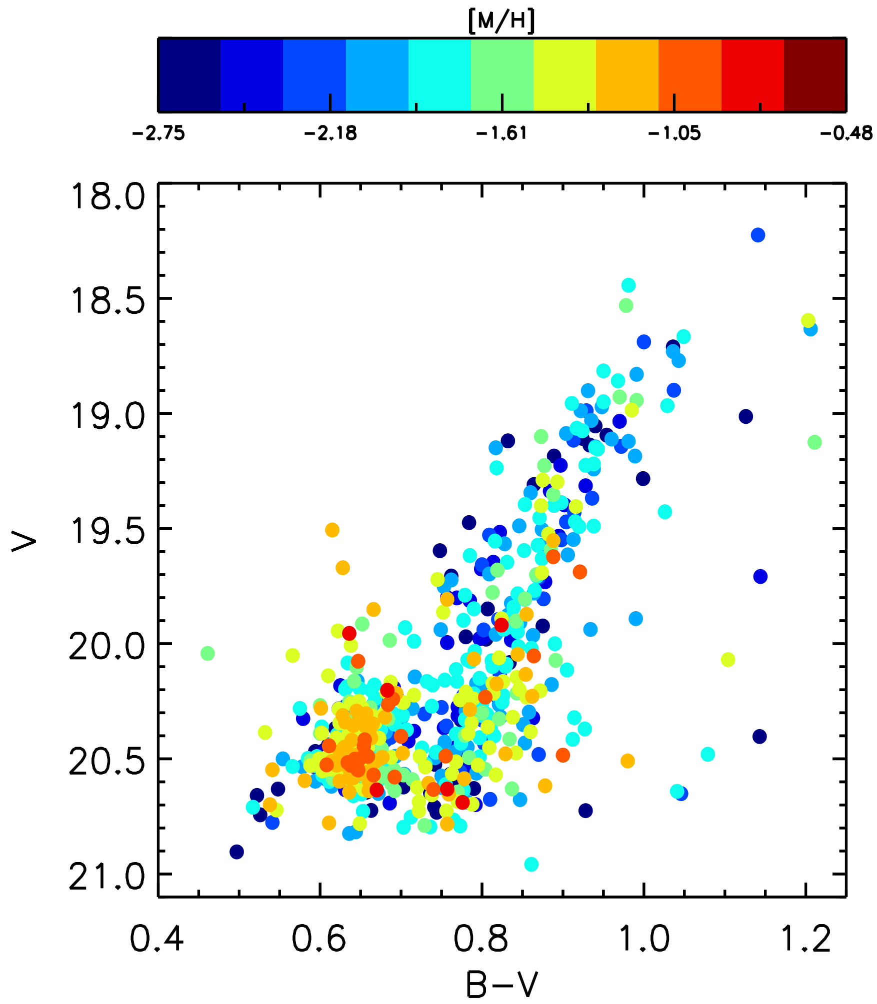






Carina Low-res study





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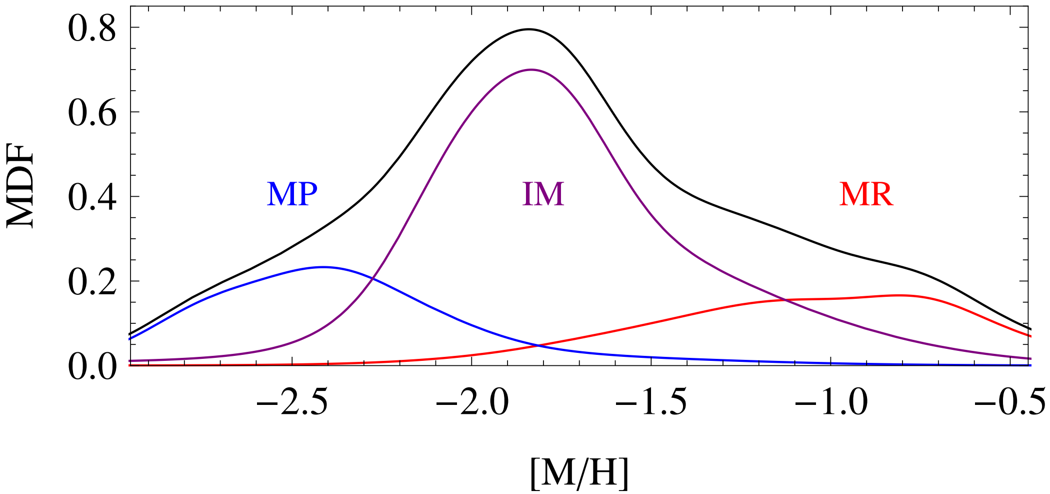
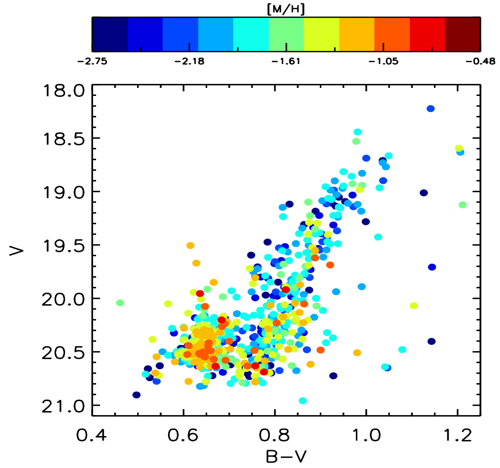
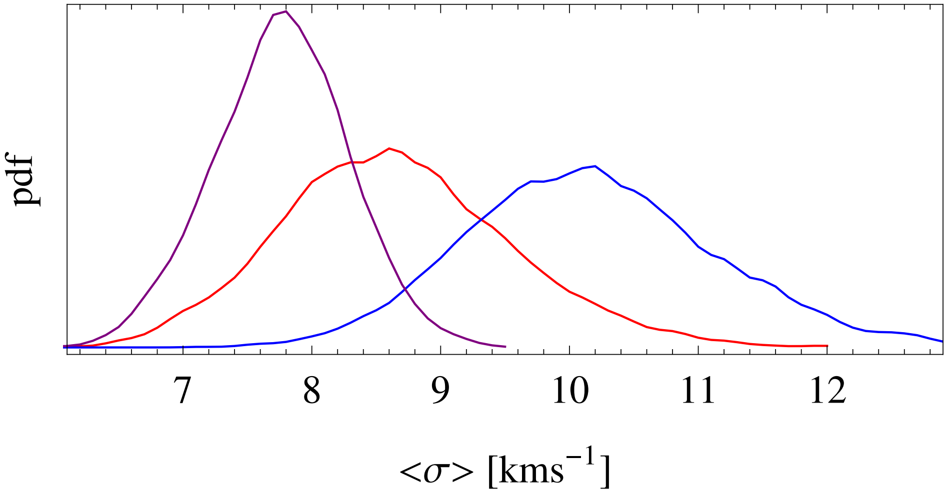
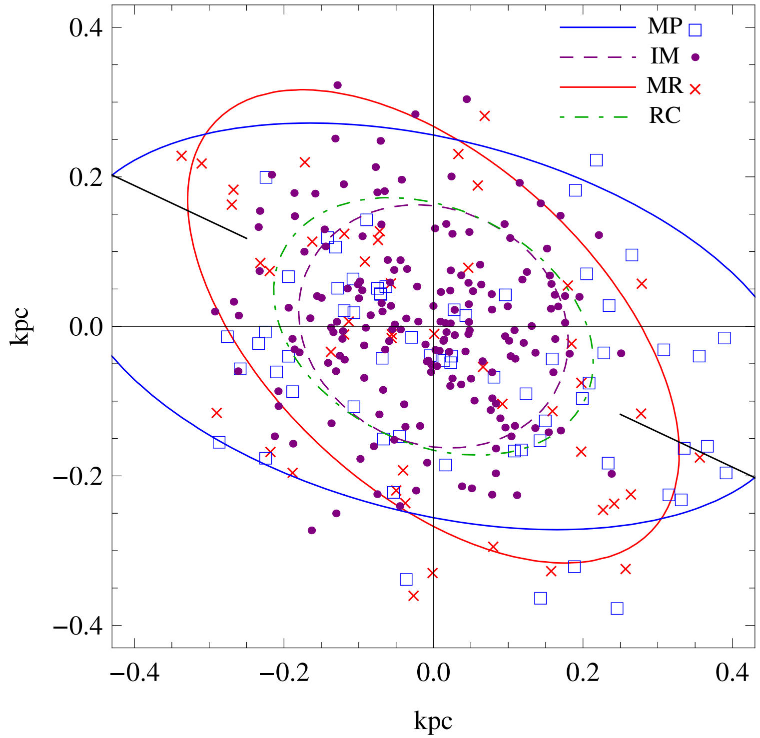




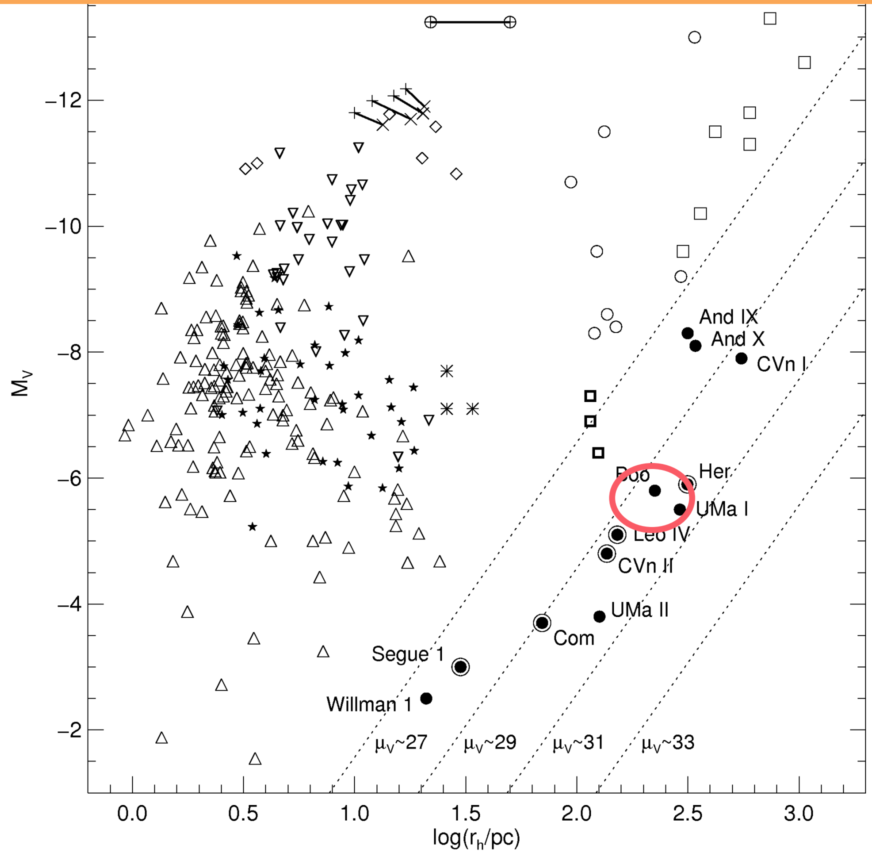




First time that a there is not a complete parallel ordering of the metallicity

Bootes I

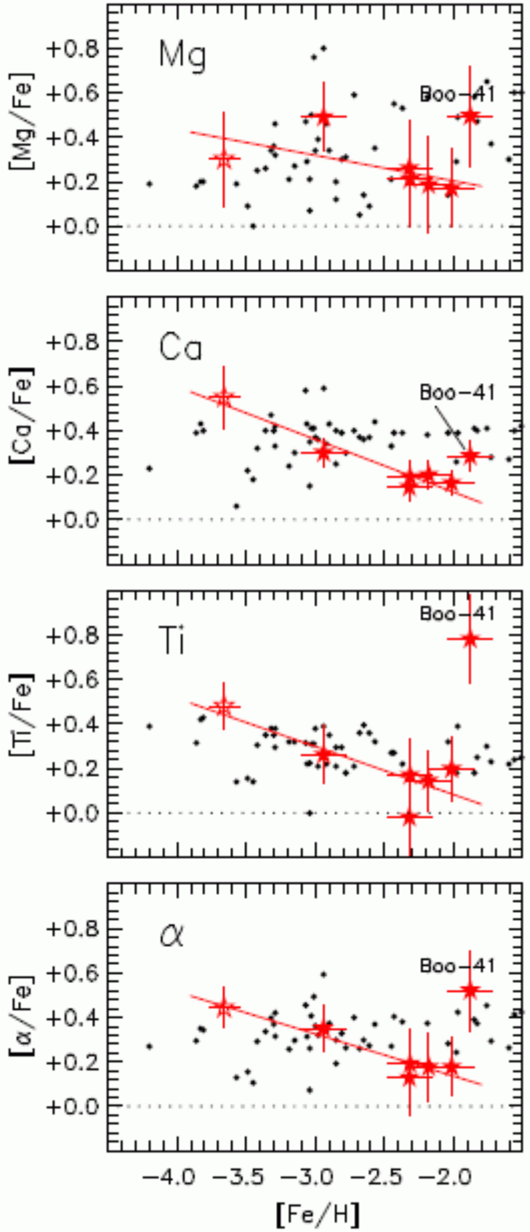
Bootes 1: a large, low-luminosity, metal-poor, system with very metal-poor stars. Fainter than a typical GC.
First discovery of CEMP-no stars in a small system
allows study of the chemical evolution of a DM-dominated dSph



Bootes I
M_v = -6.3
[Fe/H] = -2.5
M = 3-7 $10^4 M_{sun}$
Log Rc = 2.3
σ_v~3km/s
dist=65kpc

very faint, very large, very cold very metal-poor

Belokurov et al. 2007 ApJ, 654, 897 / Martin et al. 2008, ApJ, 684, 1075
Koposov, Gilmore, et al 2011 (kinematics),
Norris, Gilmore, et al 2010a,b, 2011, 2012; Gilmore et al 2013 (chemistry)



ELEMENTAL ABUNDANCES AND THEIR IMPLICATIONS FOR THE CHEMICAL ENRICHMENT OF THE BOÖTES I ULTRA-FAINT GALAXY[1]

GERARD GILMORE[1], JOHN E. NORRIS[2], LORENZO MONACO[3], DAVID YONG[2], ROSEMARY F.G. WYSE[4], AND D. GEISLER[5]

ApJ 2013 763 61

The *α* - “plateau” is flat or (2-sigma) declining.
➔total Duration <~1Gyr

halo amplitude ➔ “standard” IMF

Low-*ish* scatter ➔ efficient mixing

The element consistency ➔ slow SFR, with time to mix ejecta from several SNe during continuing star formation

Bootes-I has <10^6 stars, formed over ~1 Gyr

➔ **very low SFR**

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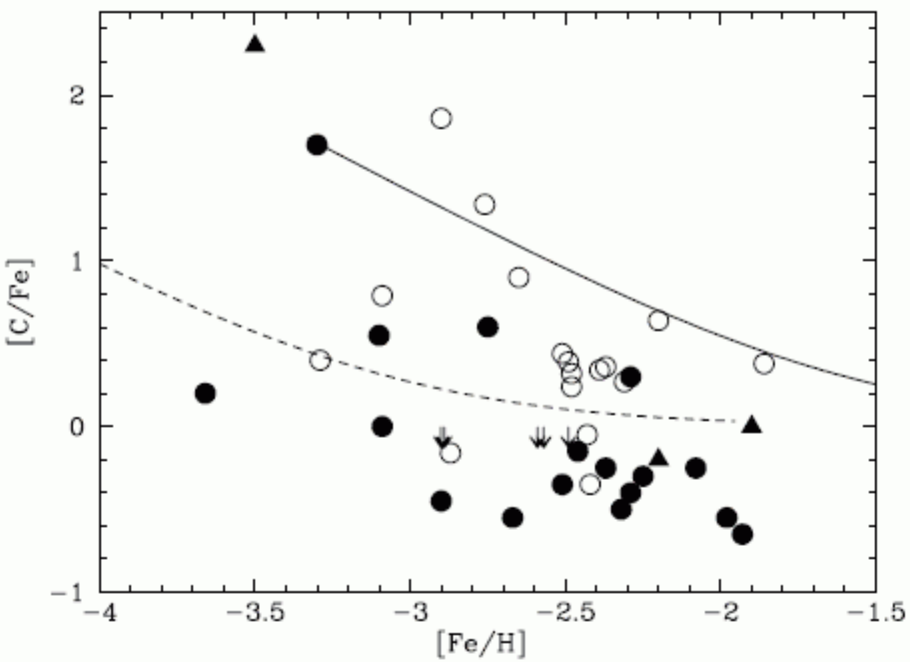
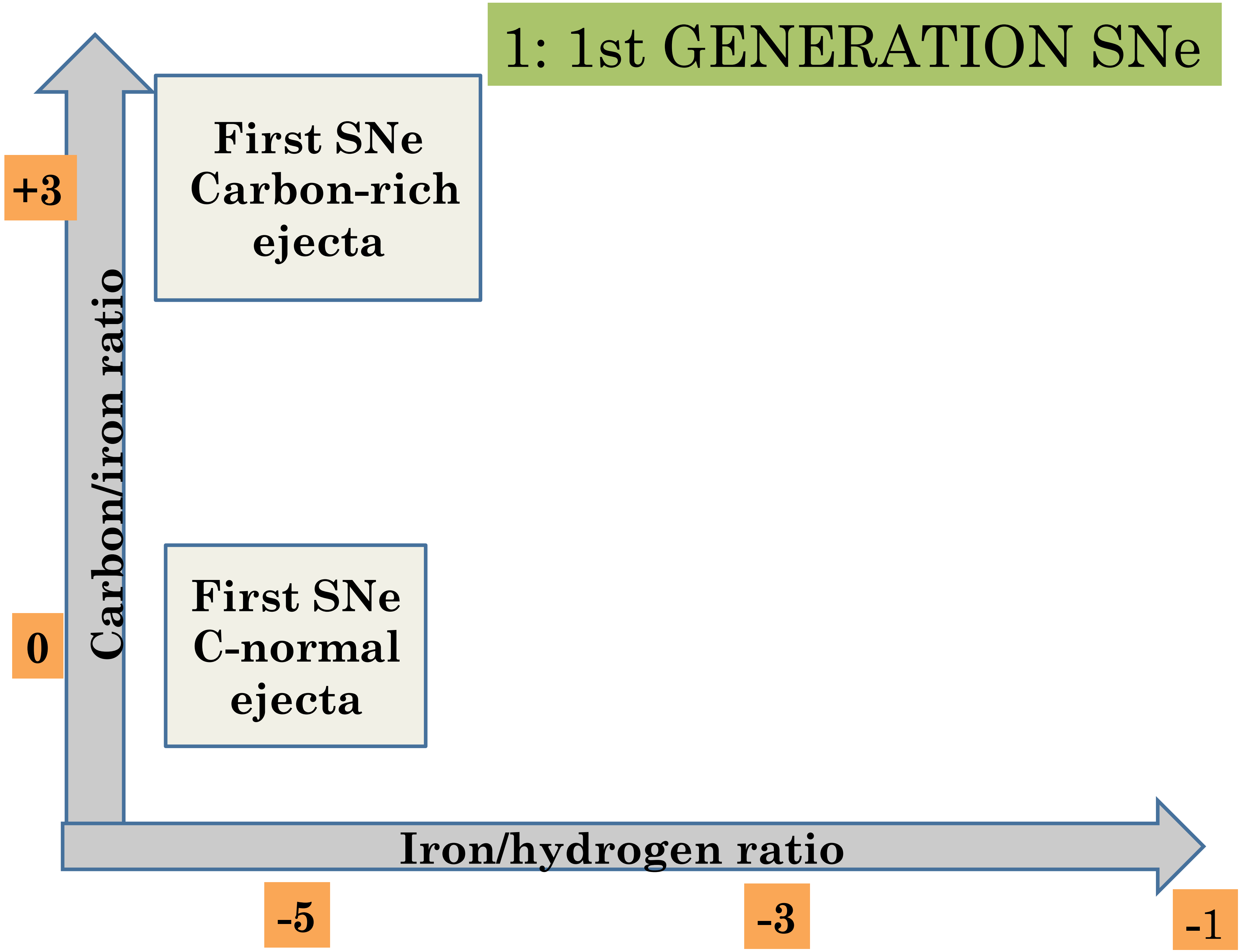
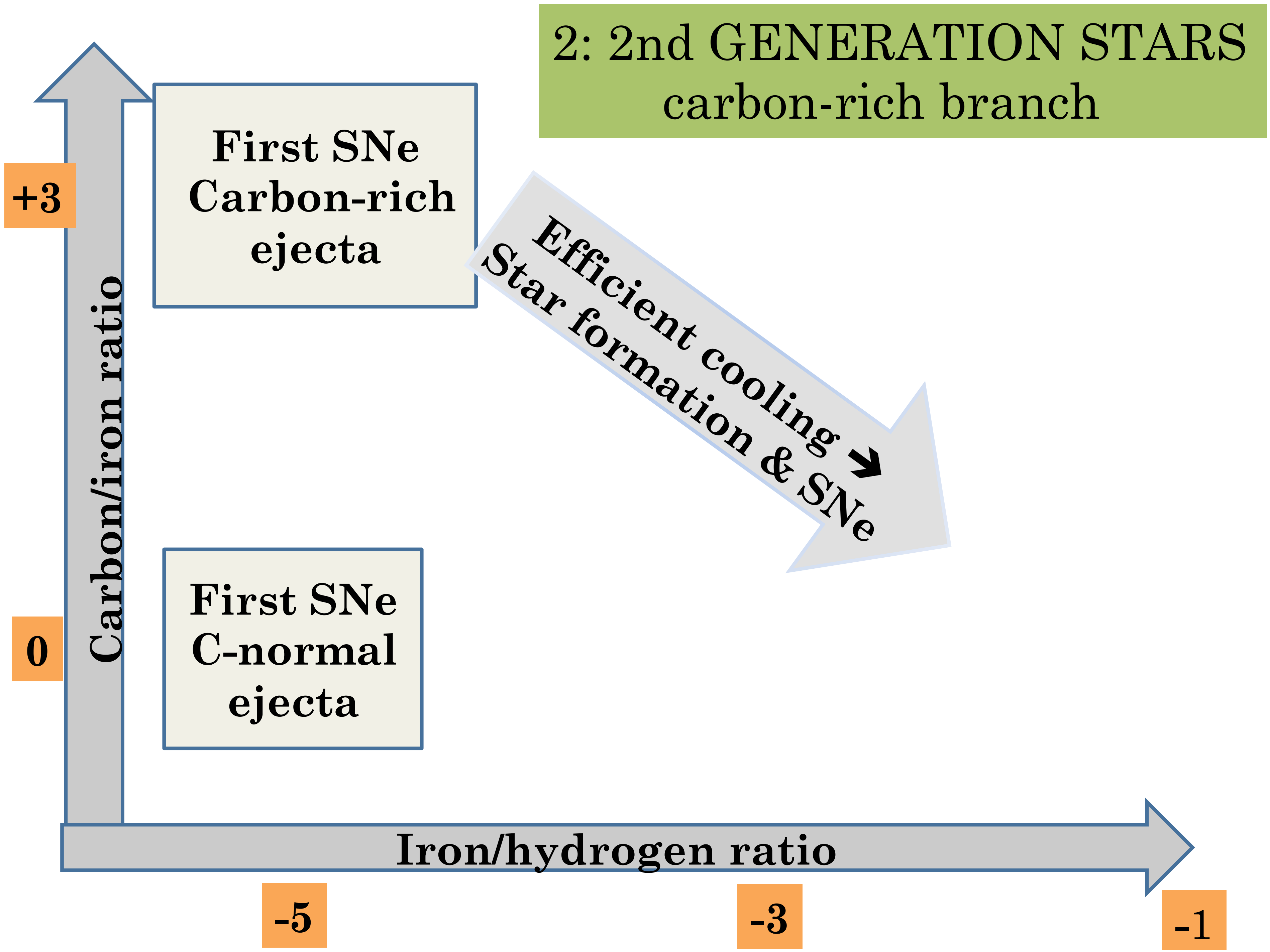


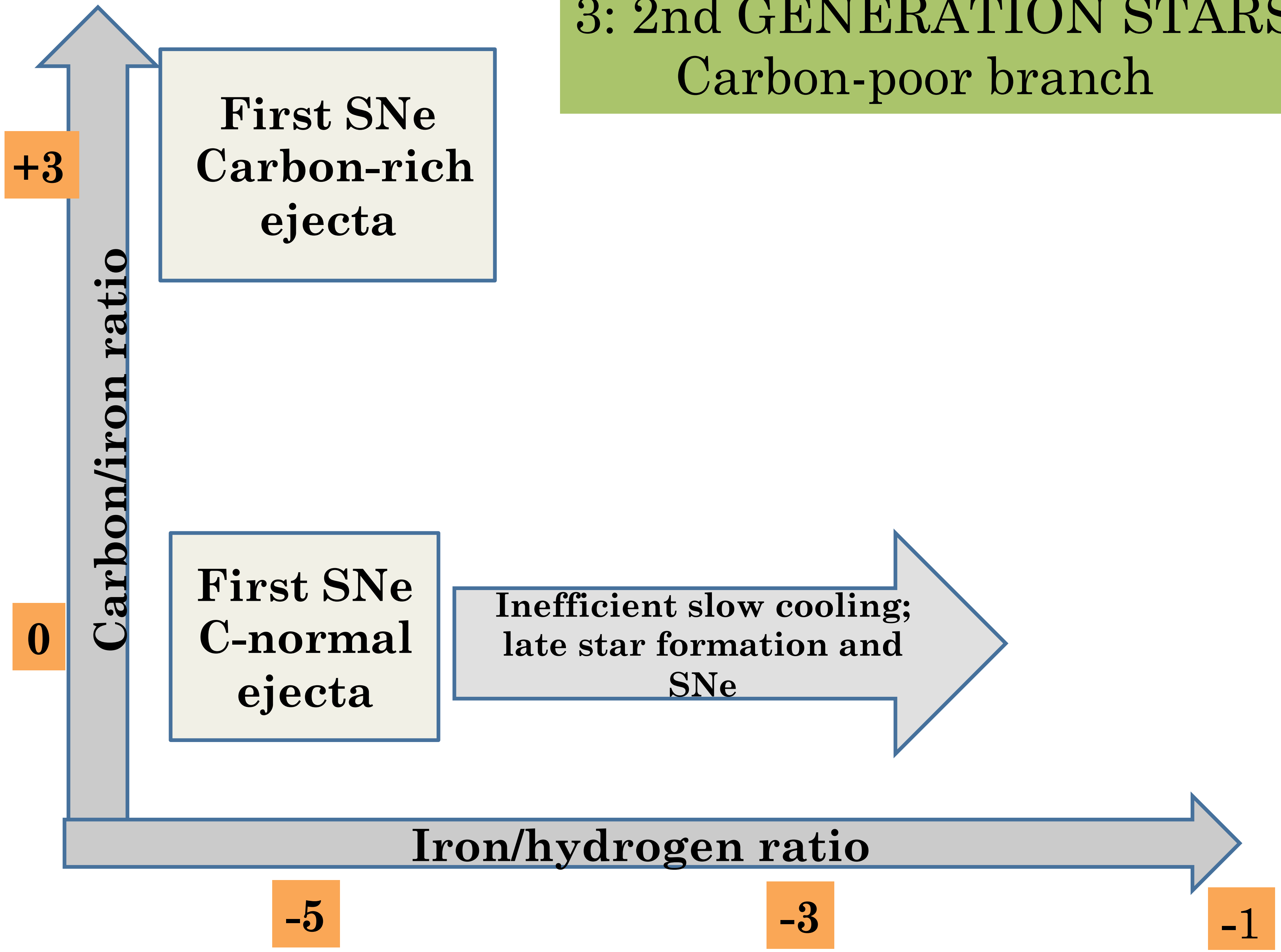
Fig. 11.— [C/Fe] vs. [Fe/H] for stars in the Boötes I dwarf galaxy (filled circles represent data of Norris et al. (2010b), with the exception of the CEMP-no star Boo-119, which has been plotted adopting the carbon abundance from Lai et al. (2011) and the iron abundance from the present work; open circles and upper limits represent data from Lai et al. (2011)) and for the Segue 1 dwarf galaxy (filled triangles, data from Norris et al. (2010b,a)). The smooth curve starts at Boo-119, and tracks the expected evolution due to continuing star formation in gas to which carbon and iron are added in the solar ratio, consistent with normal core-collapse supernovae. As discussed in the text, the data suggest two distinct channels of enrichment, one carbon-rich, and one carbon-normal.

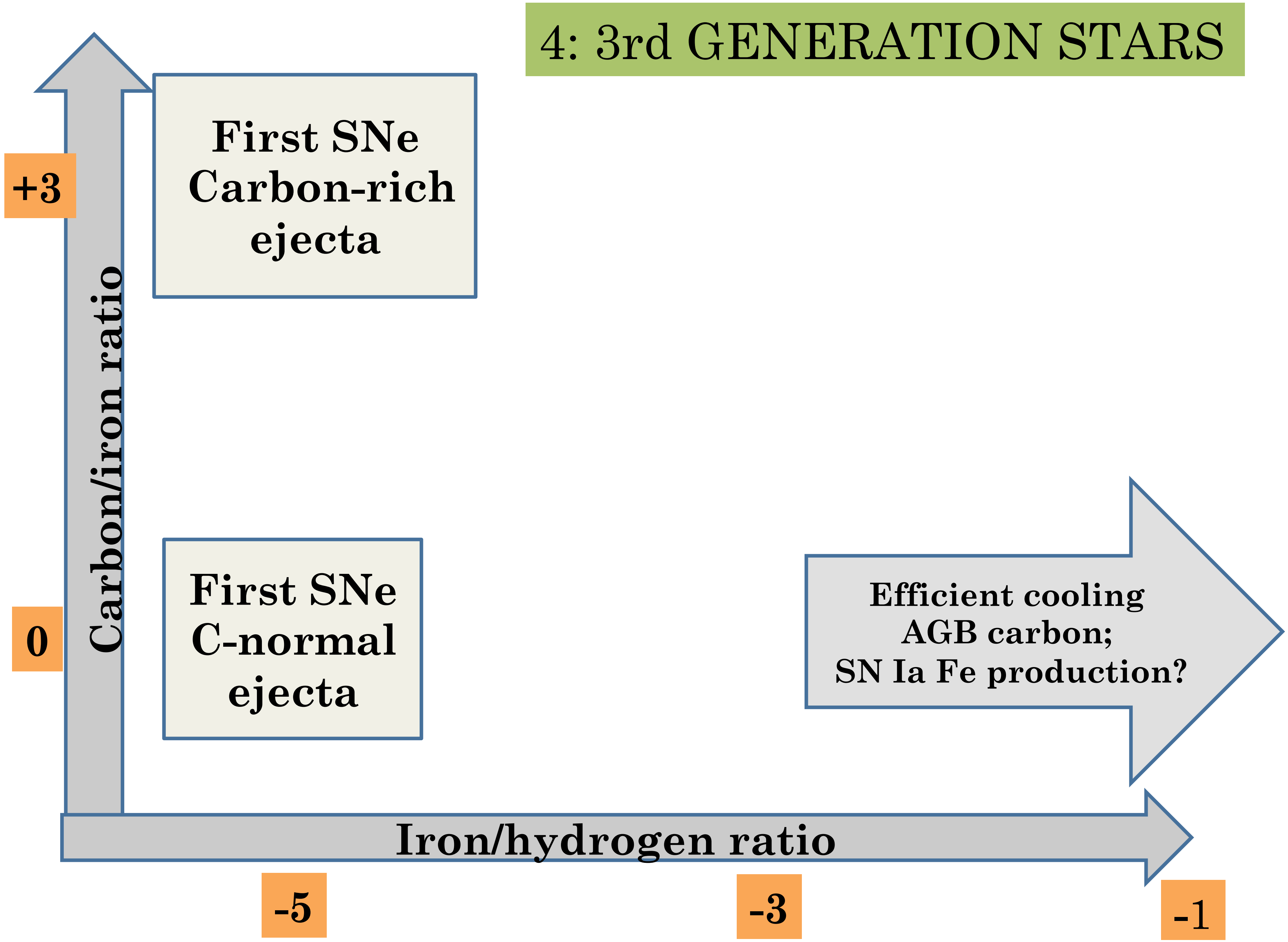


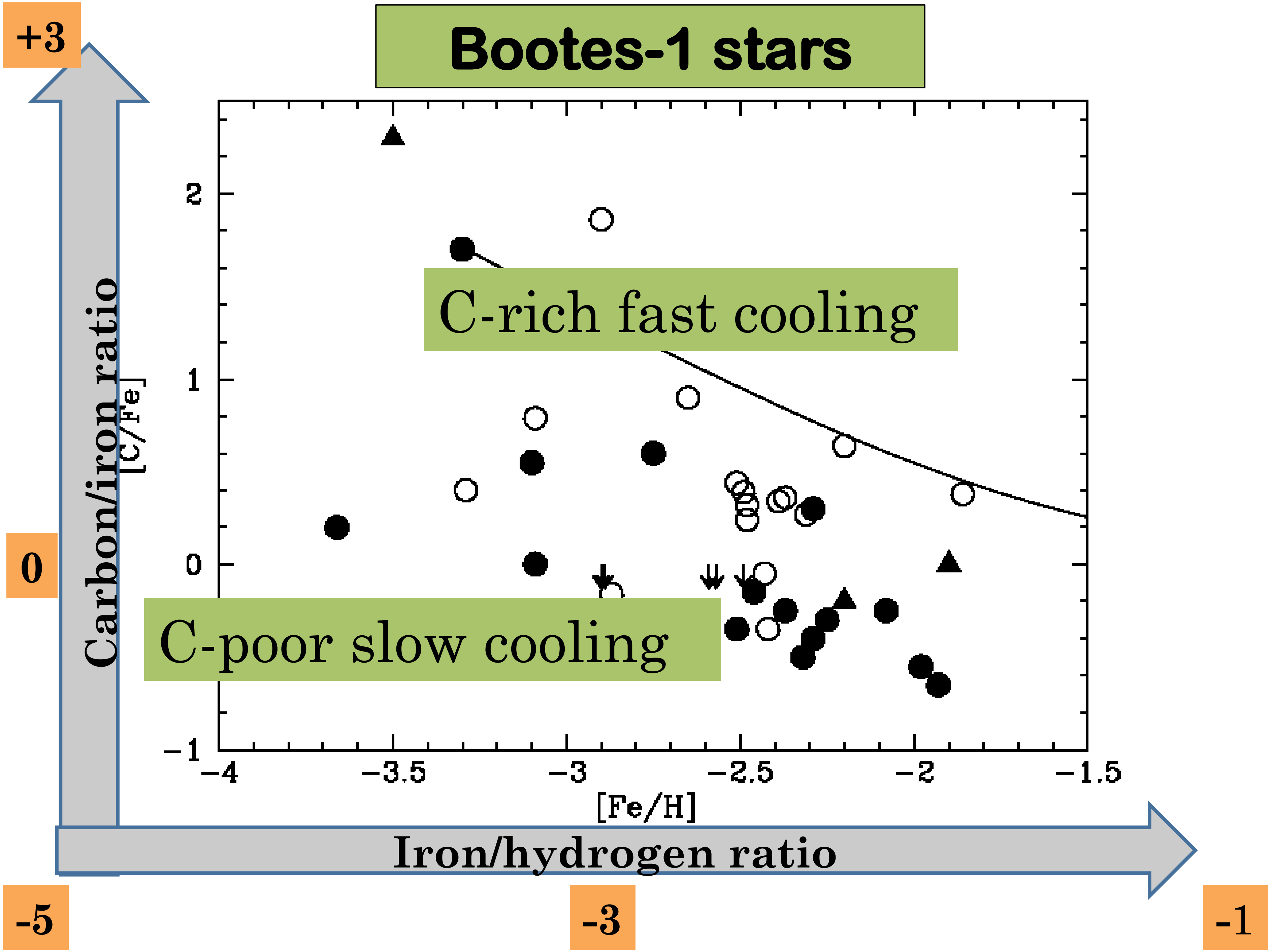
1: 1st GENERATION SNe
First SNe Carbon-rich ejecta
First SNe C-normal ejecta
Carbon/iron ratio
+3
0
Iron/hydrogen ratio
-5
-3
-1


2: 2nd GENERATION STARS
carbon-rich branch
First SNe
Carbon-rich
ejecta
Efficient cooling ➔
Star formation & SNe
+3
Carbon/iron ratio
0
First SNe
C-normal
ejecta
Iron/hydrogen ratio
-5
-3
-1

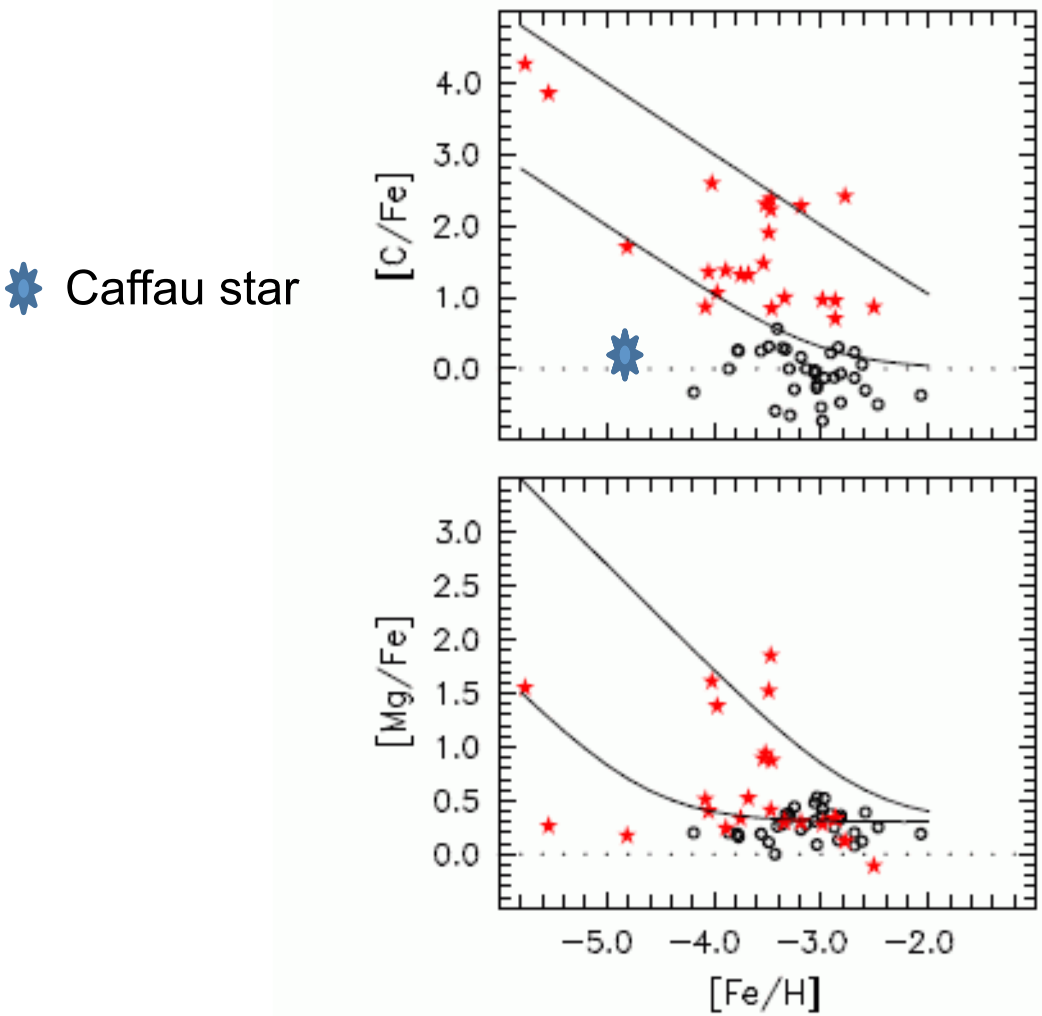
3: 2nd GENERATION STARS
Carbon-poor branch




4: 3rd GENERATION STARS
First SNe
Carbon-rich
ejecta
First SNe
C-normal
ejecta
Efficient cooling
AGB carbon;
SN Ia Fe production?
Carbon/iron ratio
+3
0
Iron/hydrogen ratio
-5
-3
-1


Bootes-1 stars
C-rich fast cooling
C-poor slow cooling
[C/Fe]
[Fe/H]
Carbon/iron ratio
Iron/hydrogen ratio
+3
0
-5
-3
-1
2
1
0
−1
−4
−3.5
−3
−2.5
−2
−1.5

ApJ 2013 763 61



Does the model fit field stars?

The two-channel model is consistent with all halo field data, but cannot be deduced from that – the history of each star is unknown.

This is the special feature of Bootes-I, a self-enriching system whose history is preserved.

Fig. 12.— [C/Fe] and [Mg/Fe] vs. [Fe/H] for Galactic halo CEMP-no stars (star symbols, from Norris et al. 2012) and C-normal red giants (circles, from Cayrel et al. 2004 and Caffau et al. 2011). The lines represent dilution trajectories, as C-rich and Mg-rich material produced at the earliest times is mixed with C-normal and Mg-normal halo material. As [Fe/H] increases to –2.5, early C-rich and Mg-rich signatures are no longer evident. See text

So what does this mean?

- Ultra-faint dSph show clear chemical evidence of low rate star formation, with standard IMF, continuing up to many Gyr. Most baryons are blown out, slowly
- This feedback is consistent with mass-metallicity relation
- There are two cooling/star formation channels at low [Fe/H].
- CEMP-no enrichment is created **only** at extremely low [Fe/H] (= pop3?) then drives rapid cooling ➔ explains lack of CEMP-no stars at high [Fe/H]
- C-normal low-[Fe/H] stars take longer to form – unmixed ISM

Dynamical DM feedback must be sub-dominant: this isn't forming cores ➔ potential for astro-particle physics?