Fast Stars in Gaia DR2

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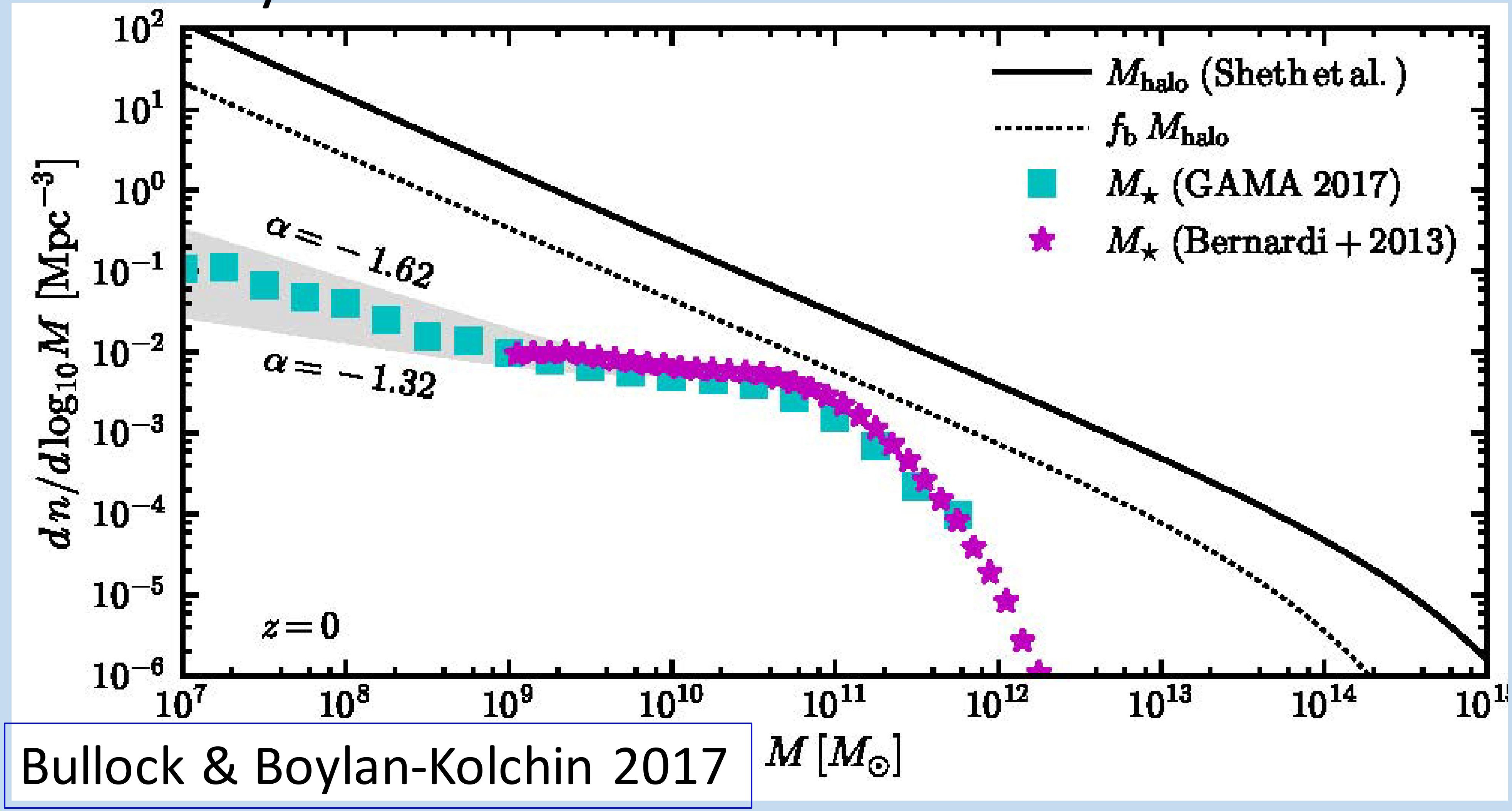
- Fast Stars:
  - Important probes of energetic phenomena within the Galaxy e.g. 3-body interaction between binary and central SMBH (Hills 1988; Brown et al 2005), other multi-body interactions, supernova explosions
  - Possibly contain interlopers from beyond the Galaxy e.g. LMC (e.g. Erkal et al 2019)
  - High-velocity tail of halo provides estimate of escape velocity curve
  - Constraints on total mass

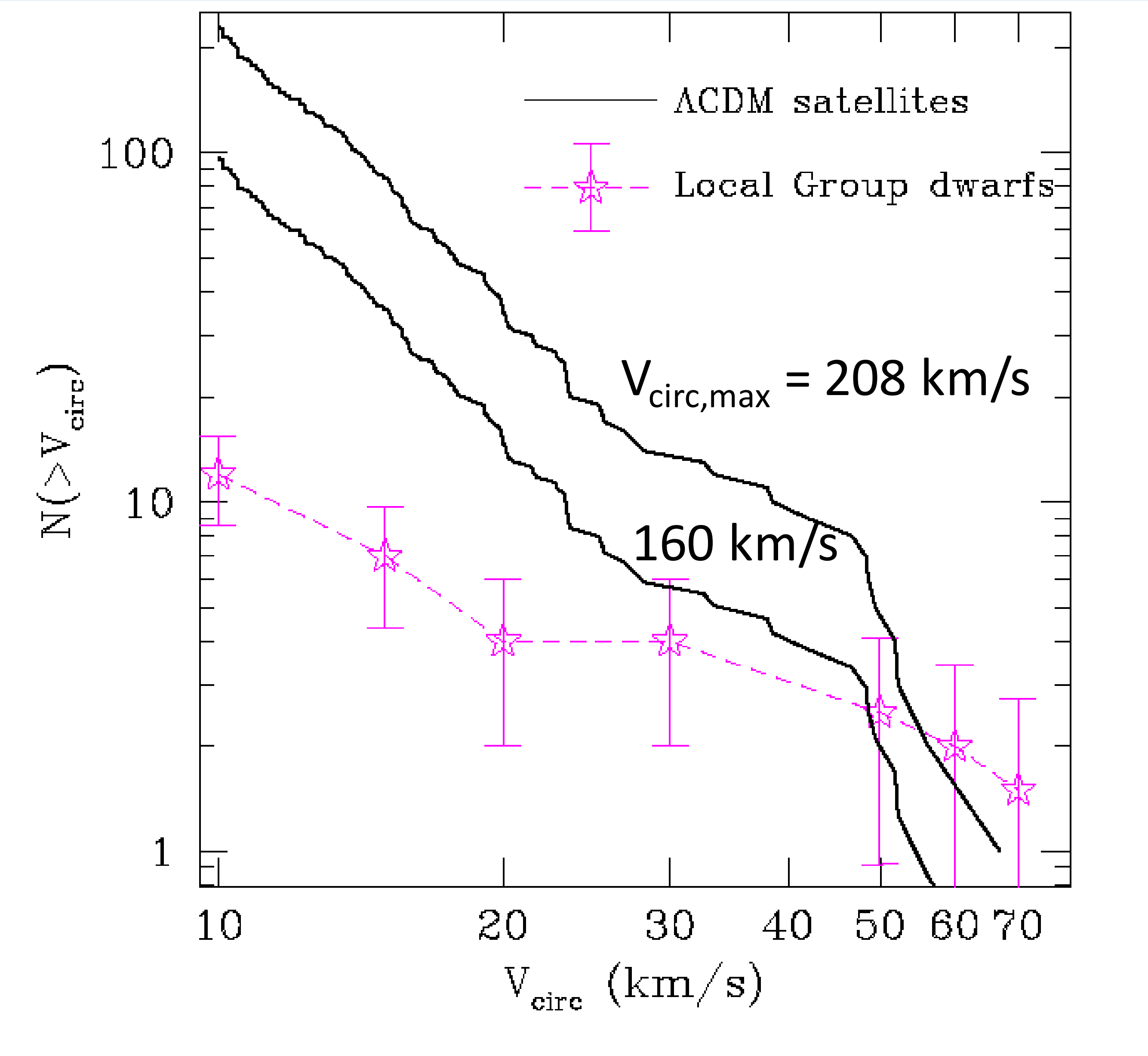
- Mass of the Galaxy:
  - Baryon fraction – feedback efficiency
  - Abundance-matching techniques – associating galaxies with dark-matter halos (e.g. Behroozi et al 2013)
  - Expected substructure – `missing satellite problem', 'too-big to fail problem' (e.g. Bullock & Boylan-Kolchin 2017)

- Need `feedback' at both high- and low-mass ends
- Milky Way normalization important -- increased dark mass decreases baryon fraction



Bullock & Boylan-Kolchin 2017

Kravtsov 2009



- Increased mass (or circular velocity) of Milky Way dark halo implies more substructure

Fast Stars: how to identify them?

- Gaia DR2 provides a wonderful dataset for the selection of candidate extreme-velocity stars
- 6D phase space information for over 7 million stars (with RV in Gaia DR2)
  - Plus ~2 billion with 5D phase space information
- Three main analyses of space motions that isolated `reliable' extreme velocity stars
  - Marchetti et al 2018
  - Hattori et al 2018
  - Bromley et al 2018

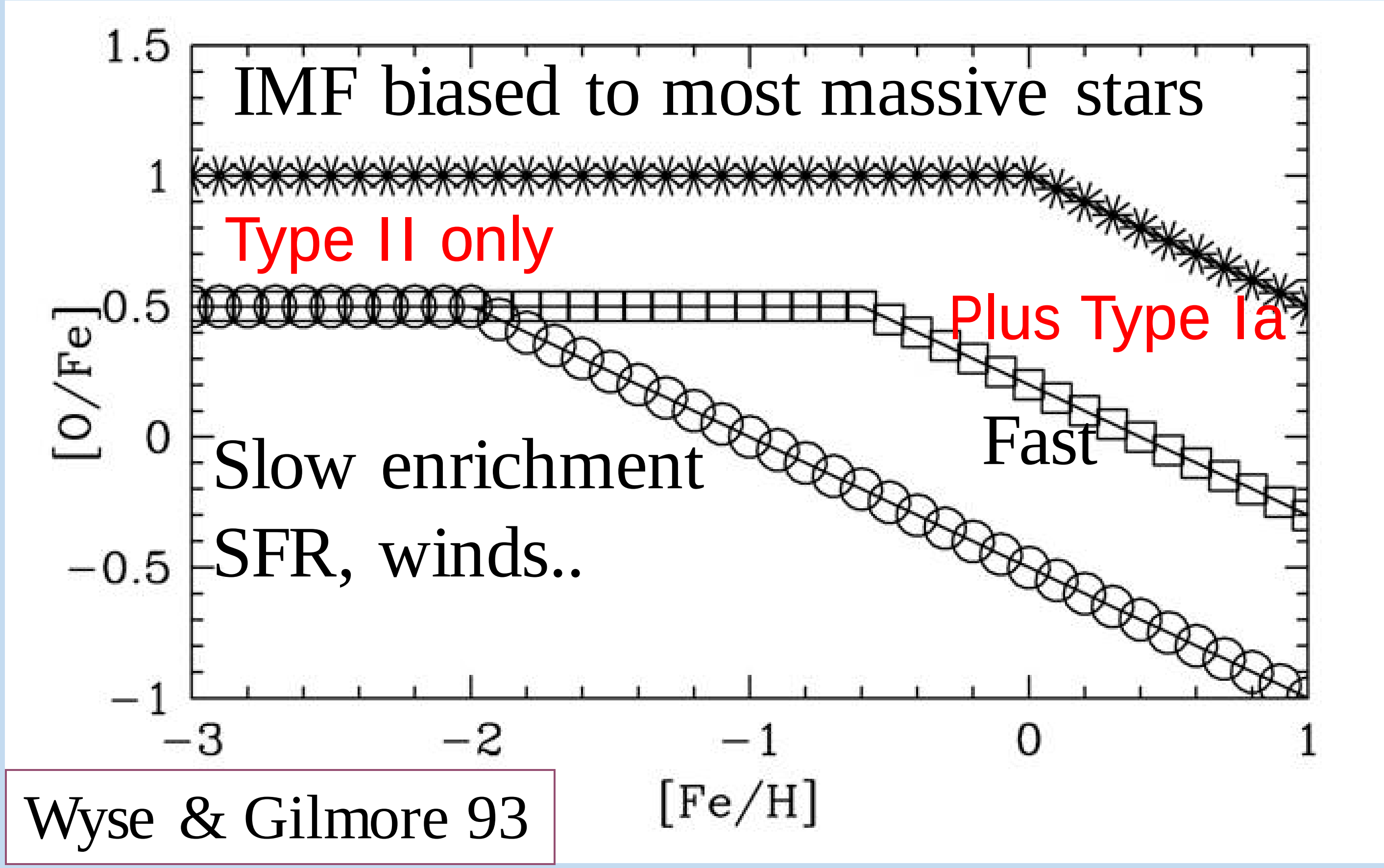
Fast Stars: how to understand them

- Mass and Evolutionary state of star provide constraints on formation mechanisms
  - 3-body Hills mechanism requires a very close binary, favors dwarf main sequence stars, disfavors giants
    - Important to establish surface gravity
- Chemical abundance ratios provide unique insight into birth location of stars and underlying parent stellar population

→ high-resolution spectroscopic study of candidate extreme velocity stars

Elemental Abundances: star formation history and enrichment history

Alpha element (core-collapse SNe) and iron (Type Ia SNe)



Self-enriching star-forming region, non-bursty star formation.
Model assumes good mixing so massive-star IMF average yields

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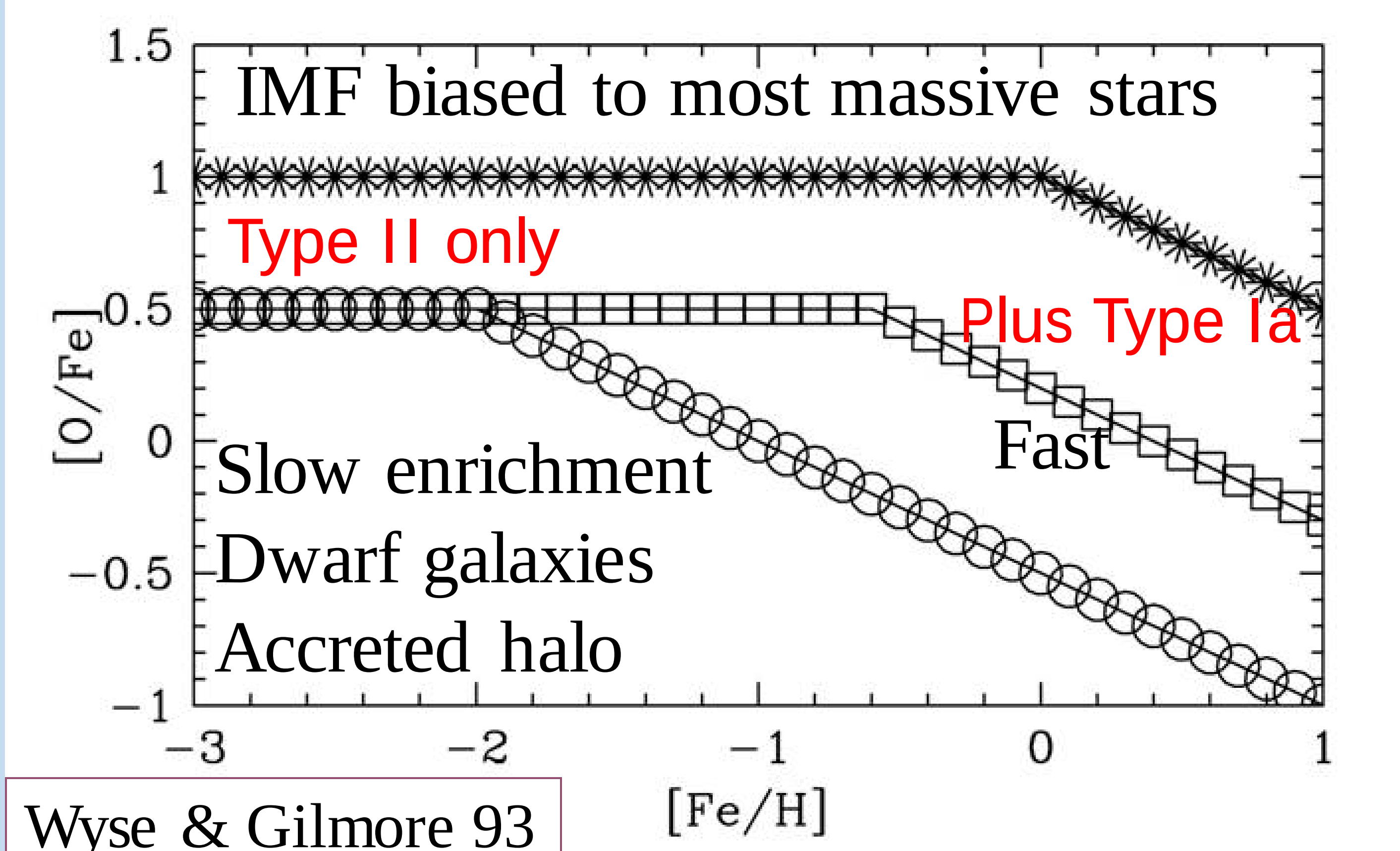
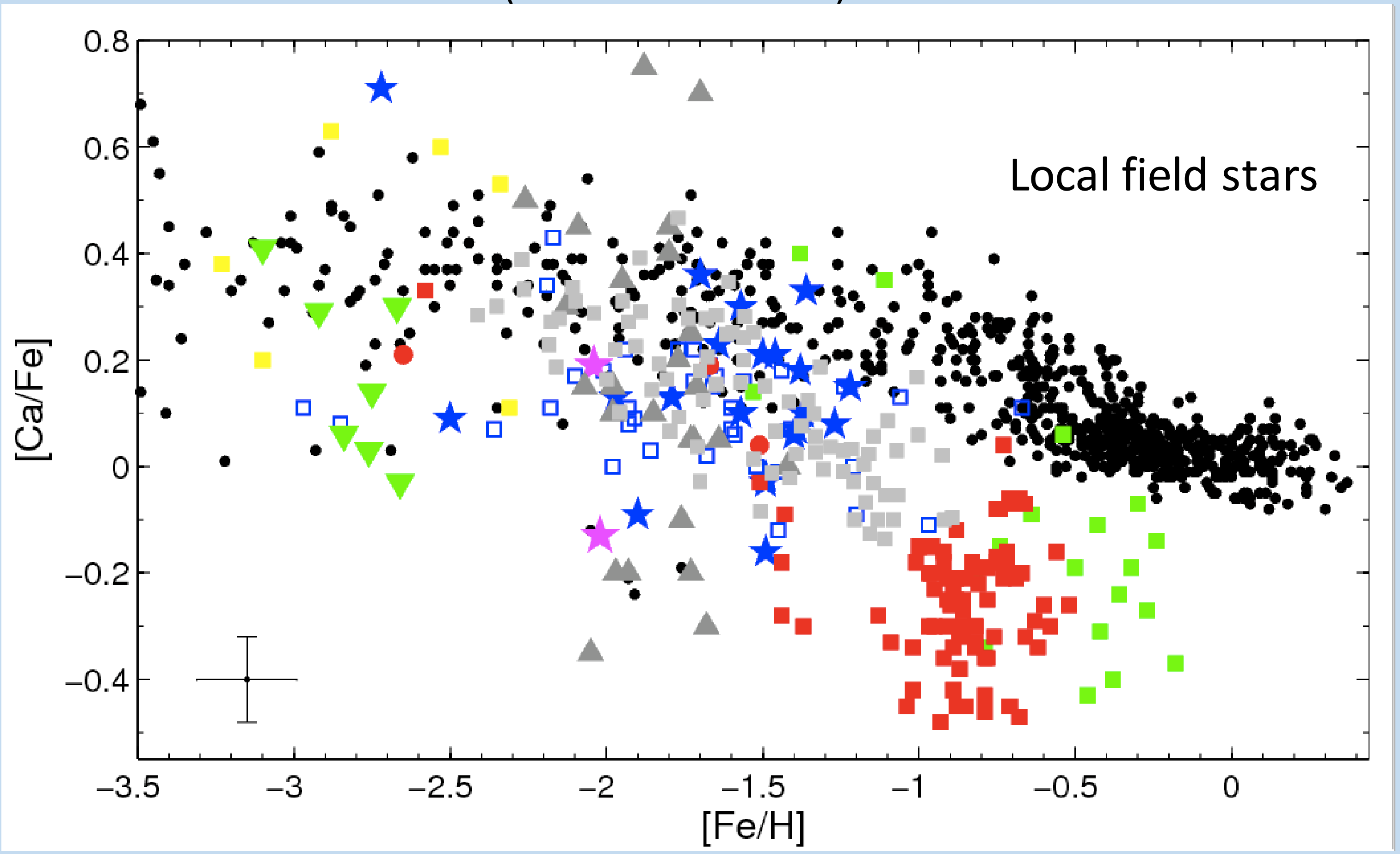


Wyse & Gilmore 93

Self-enriching star-forming region, non-bursty star formation.
Model assumes good mixing so massive-star IMF average yields

dSphs vs. MWG abundances

(from A. Koch)



Shetrone et al. (2001, 2003): 5 dSphs

Sadakane et al. (2004): Ursa Minor

Monaco et al. (2005): Sagittarius

Koch et al. (2006, 2007): Carina

Letarte (2006): Fornax

Koch et al. (2008): Hercules

Shetrone et al. (2008): Leo II

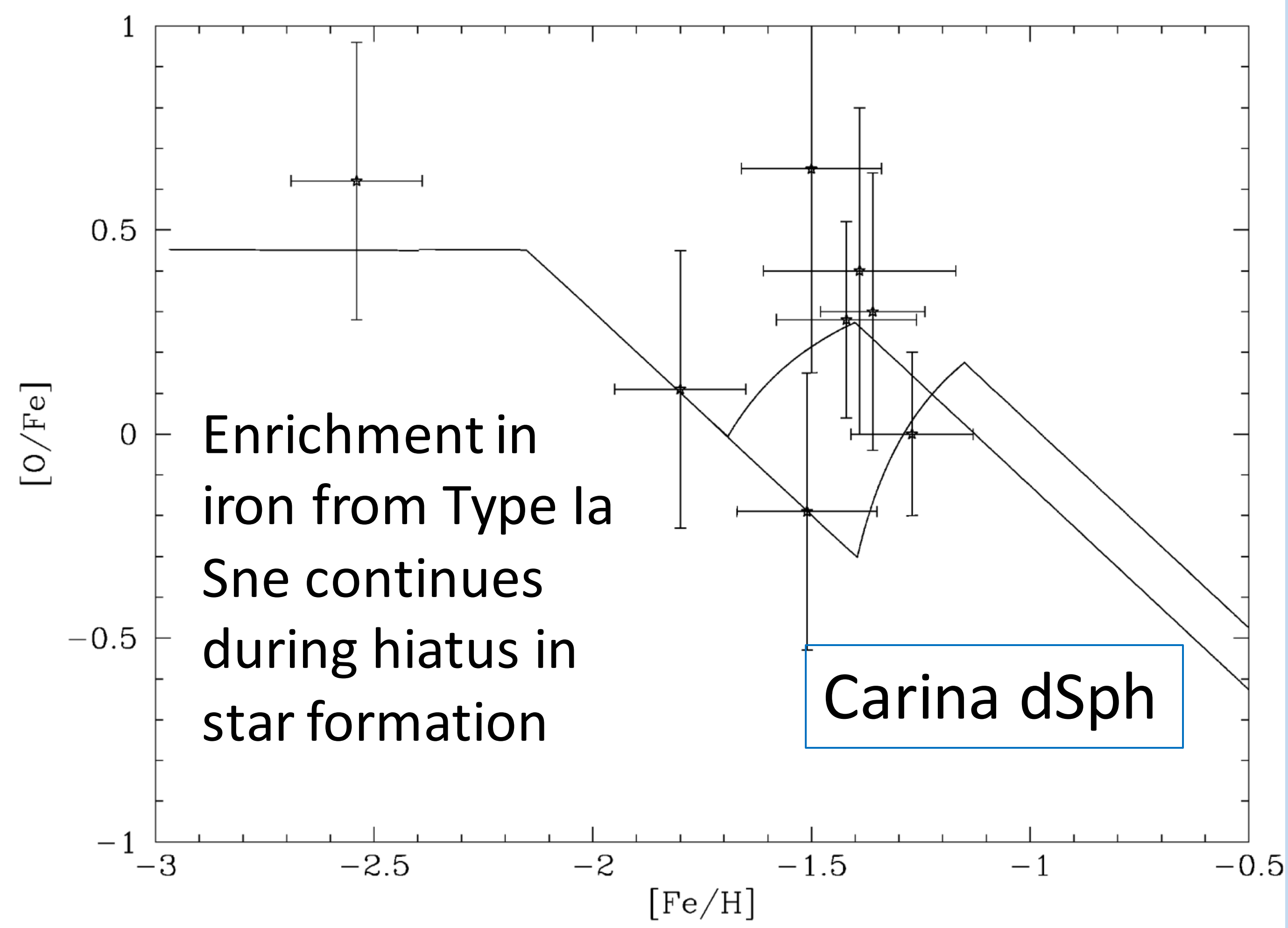
Frebel et al. (2009): Coma Ber, Ursa Major

Aoki et al. (2009): Sextans

Hill et al. (in prep): Sculptor

Elemental abundances with bursts of star formation

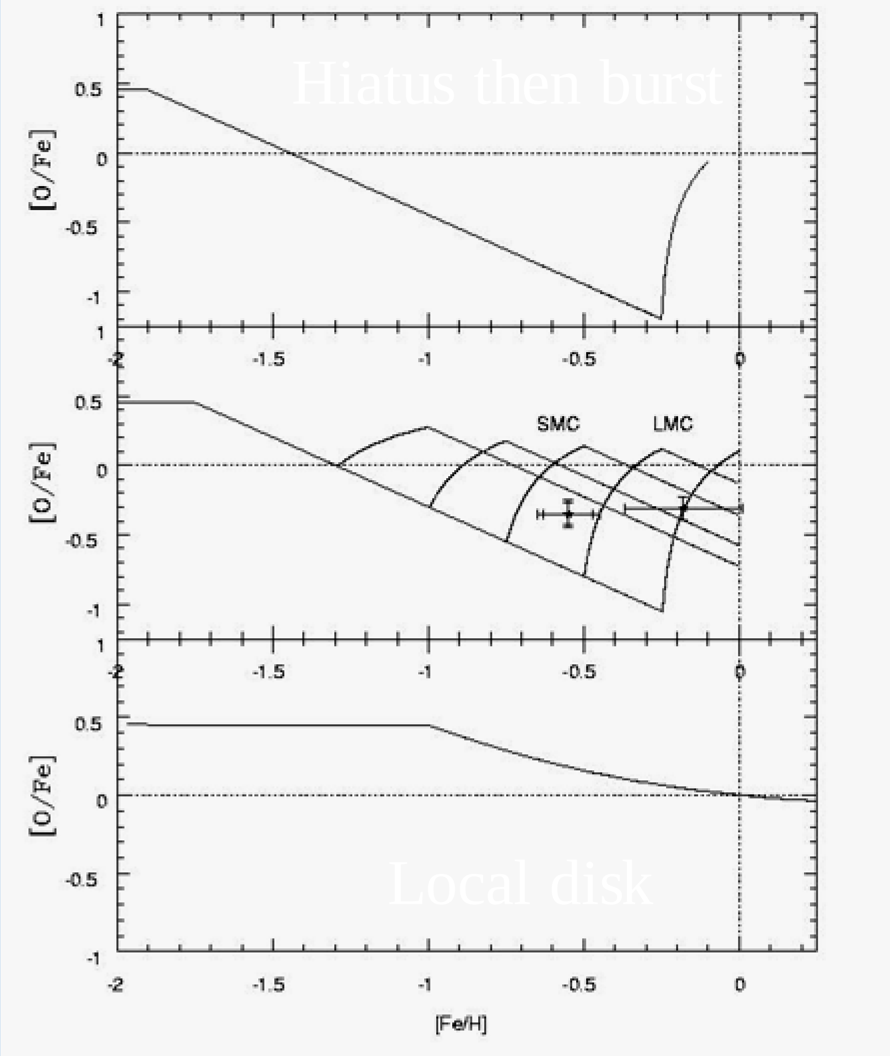
Gilmore & Wyse 1991



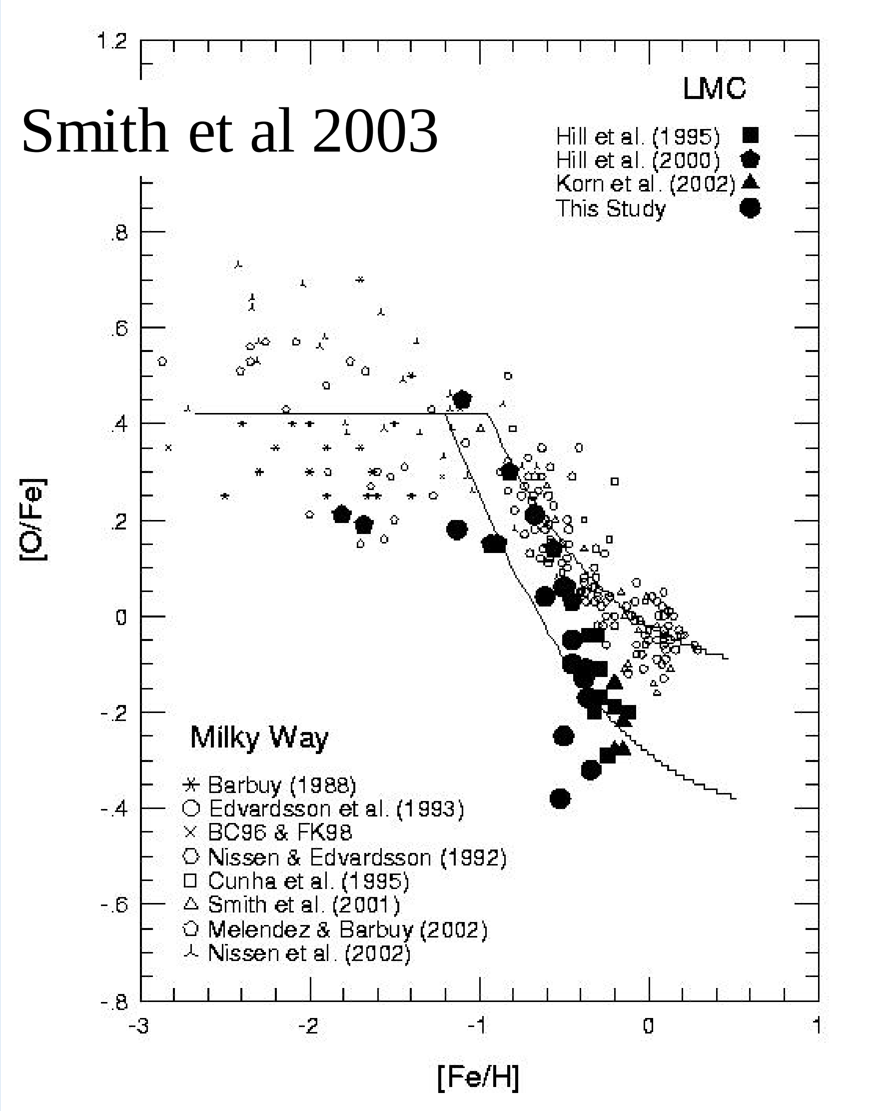
Massive star IMF invariant

Koch et al 2008

Extended, low-rate star formation and slow enrichment with gas retention, leads to expectation of ~solar (or below) ratios of [α/Fe], such as in LMC stars



Gilmore & Wyse 1991



Smith et al 2003

Fast Stars: how to identify them?

- Our sample from Marchetti, Rossi & Brown (2018 arXiv v1 + v2 version)

➔ 7 million reduced to 165 stars with 'reliable' derived median total space motion greater than 450km/s

➔ Further reduced to 28 stars with more than 50% probability of being 'unbound', based on escape velocity curve derived by Williams et al 2017, local escape speed ~520km/s → Marchetti et al (v1) Table 1

➔ Marchetti et al (v2) recalculated escape velocity curve with Gala potential, local escape velocity ~ 550km/s

→ Table 1 (v2) is 20 stars with greater than 80% probability of being unbound

- Obvious sensitivities to distance uncertainties, definition of `unbound', but likely high-velocity stars

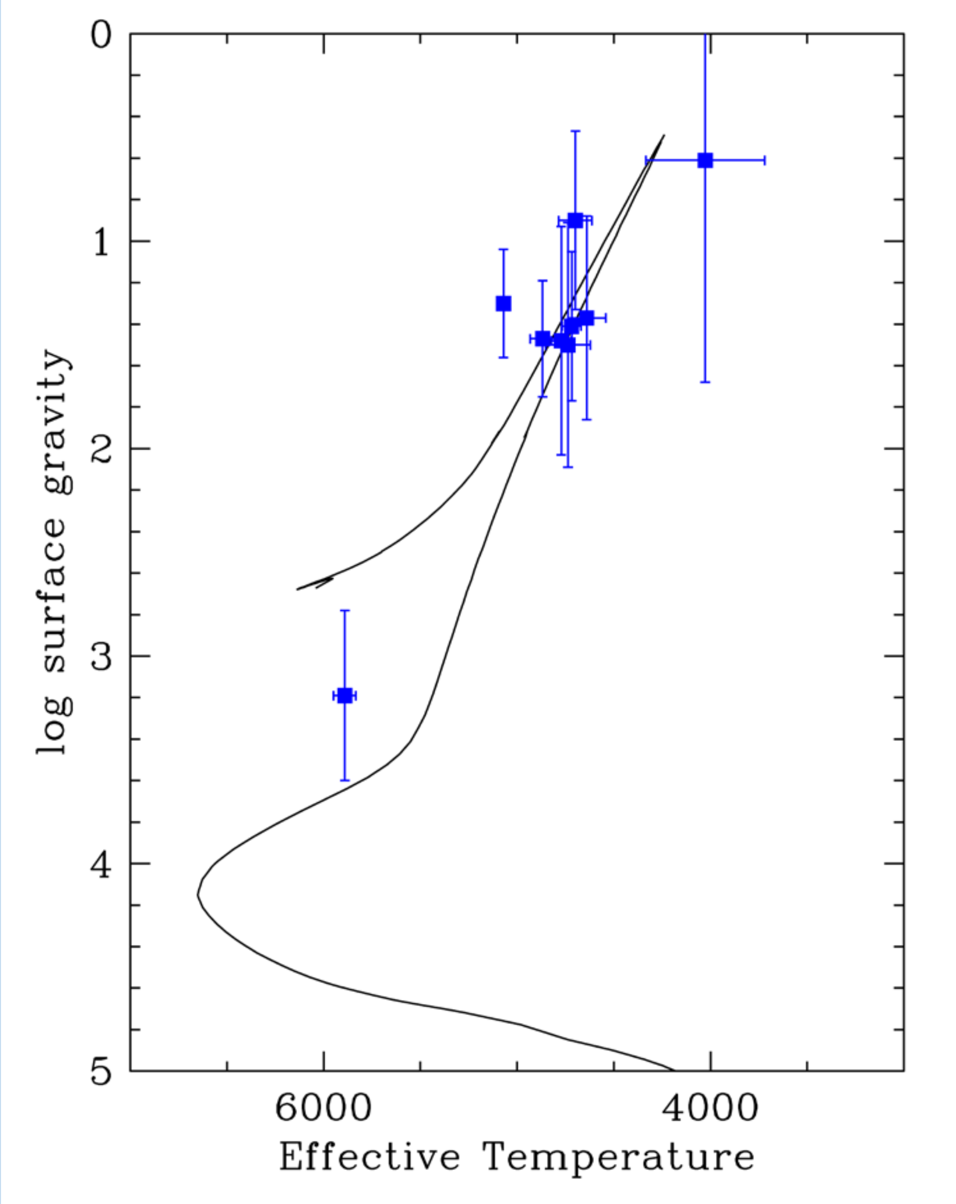
- We (Hawkins & Wyse 2018; 2019) selected 9 candidate extreme velocity stars, including one `100% probability unbound, of extragalactic origin’ (Marchetti et al, Bromley et al)
- Galactocentric distances 7-12kpc, heliocentric distances 4-10kpc
- Follow-up high-resolution spectroscopy with echelle spectrograph at Apache Point 3.5m telescope, $\mathcal{R} = \Delta\lambda/\lambda \sim 31500$

➔ Derived radial velocities agree very well with those in Gaia DR2

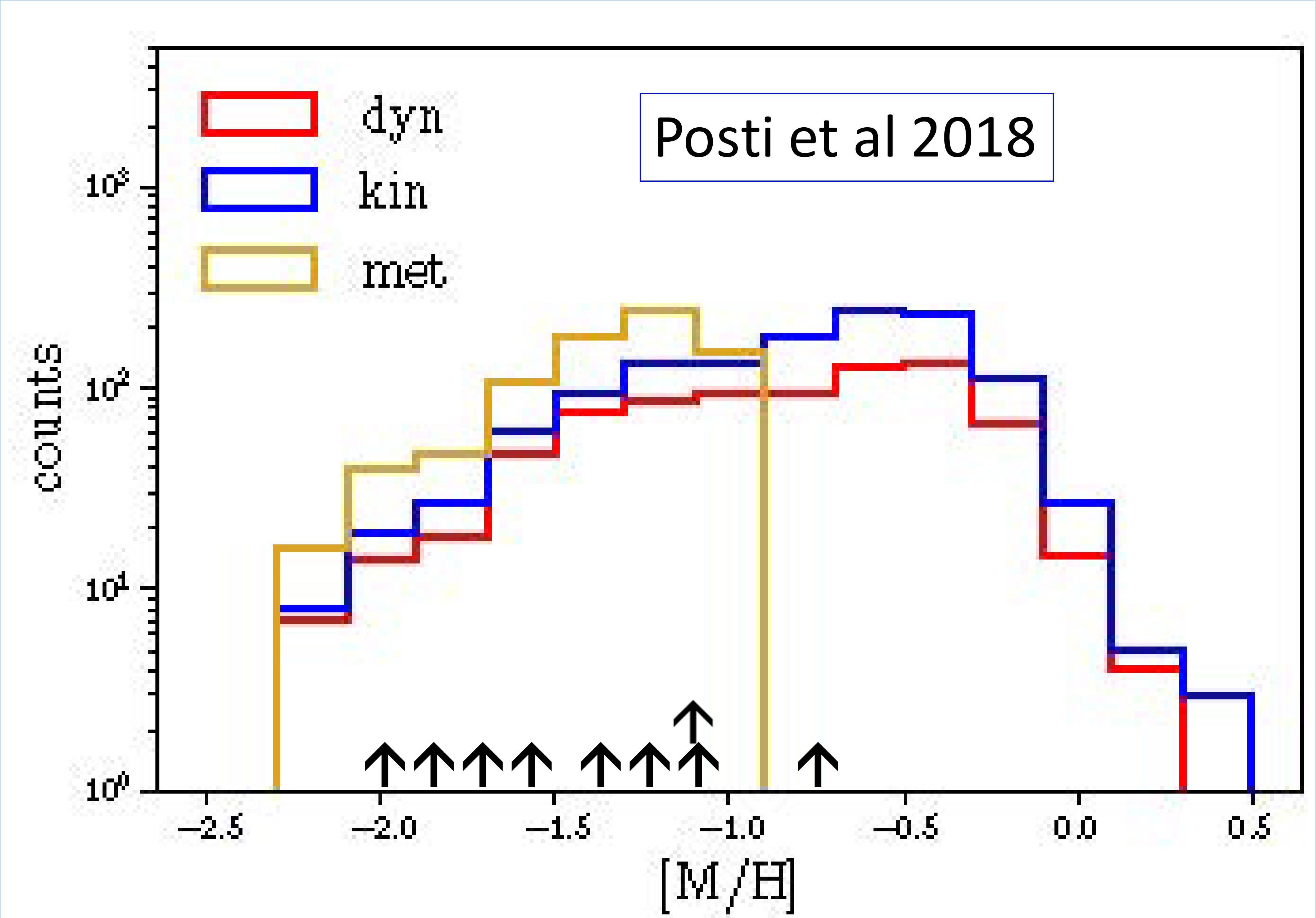
➔ Approximately 2/3 are on retrograde orbits

- Spectroscopic analysis used BACCHUS (Masseron, Merle & Hawkins 2016)
  - Derives effective temperature, surface gravity and iron abundance assuming LTE and using iron excitation-ionization equilibrium technique
  - Systematics in [Fe/H] ~0.1 dex from analysis of metal-poor Gaia FGK benchmark stars
  - These values adopted for synthetic spectra of different elemental abundance ratios
- Chemical abundances for up to ~ 22 species, alpha-elements, iron-peak elements

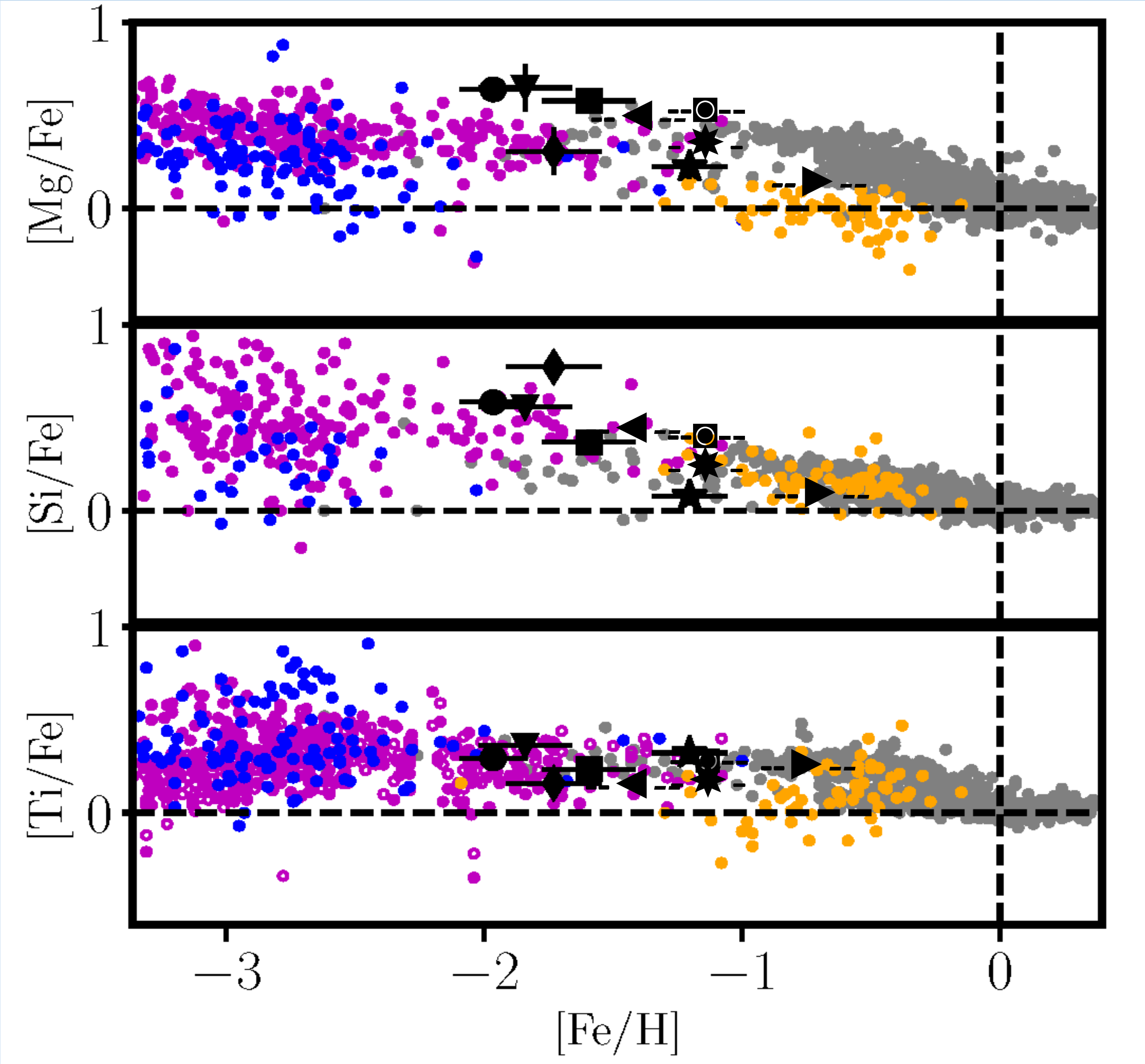
- Most stars have low metallicity, low gravity and cool effective temperatures, placing them on (old) metal-poor red giant branches



- PARSEC 10Gyr, -1.75 dex metallicity
- Consistent with location on colour-absolute magnitude plot (cf. Hattori et al 2018)
- Large stellar radius of giant phase argues against tight binary-SMBH 3-body process
    - Long timescales of stellar evolution argue against dwarf → giant while in transit across galaxy (100km/s ~ 100kpc/Gyr)

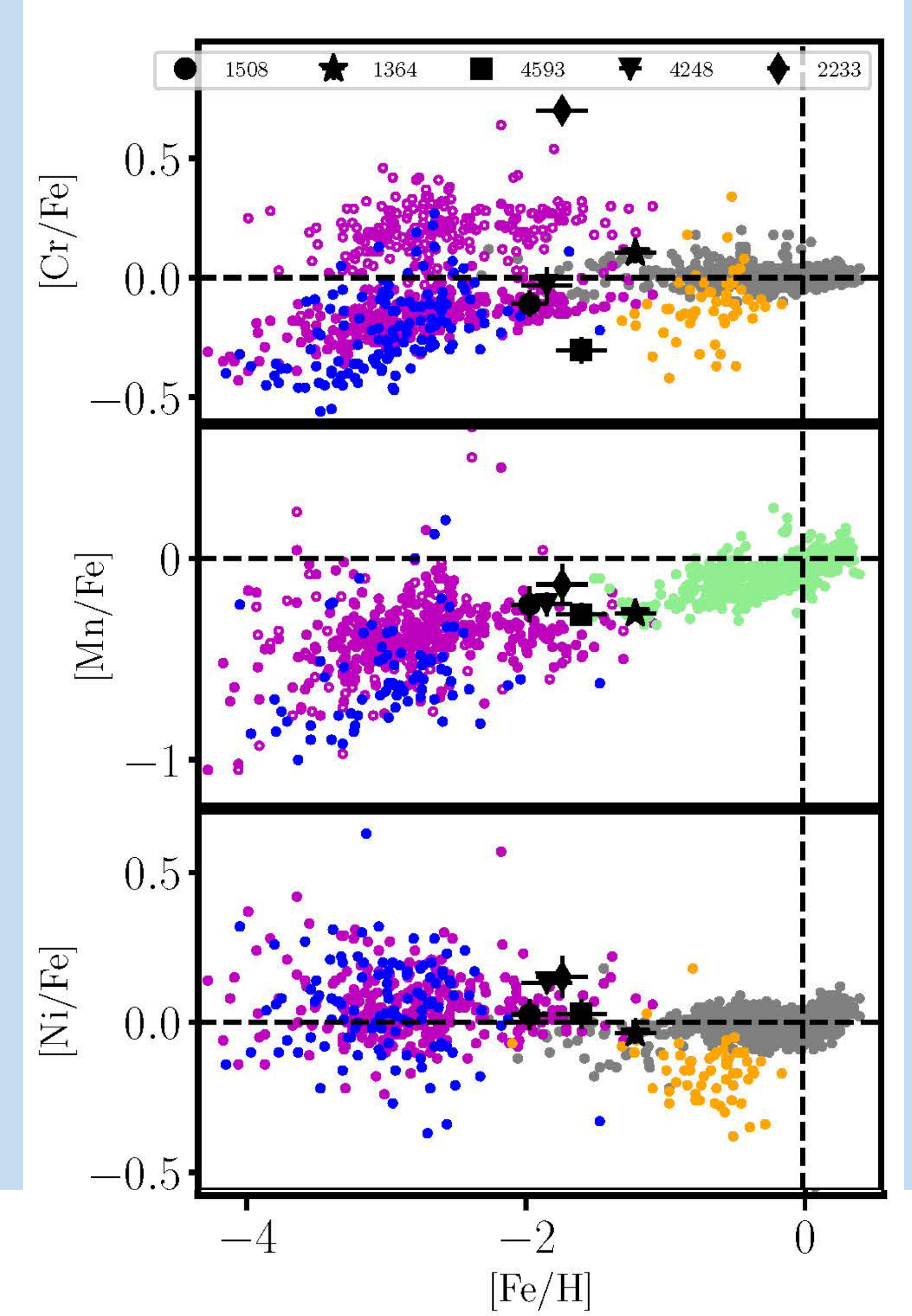


Extreme-velocity stars (↑) have metallicities typical of halo



- Candidate extreme-velocity stars fall within locus of halo (or metal-poor thick disc) in the alpha-elements

- Blue/magenta: halo stars (Roederer et al 14/Yong et al 13)
- Grey: discs stars (Bensby et al 14)
- Orange: LMC stars (Van der Swaelman et al 13)



- Candidate extreme-velocity stars also fit within locus of halo stars in the iron-peak elements

- Blue/magenta: halo stars (Roederer et al 14/Yong et al 13)
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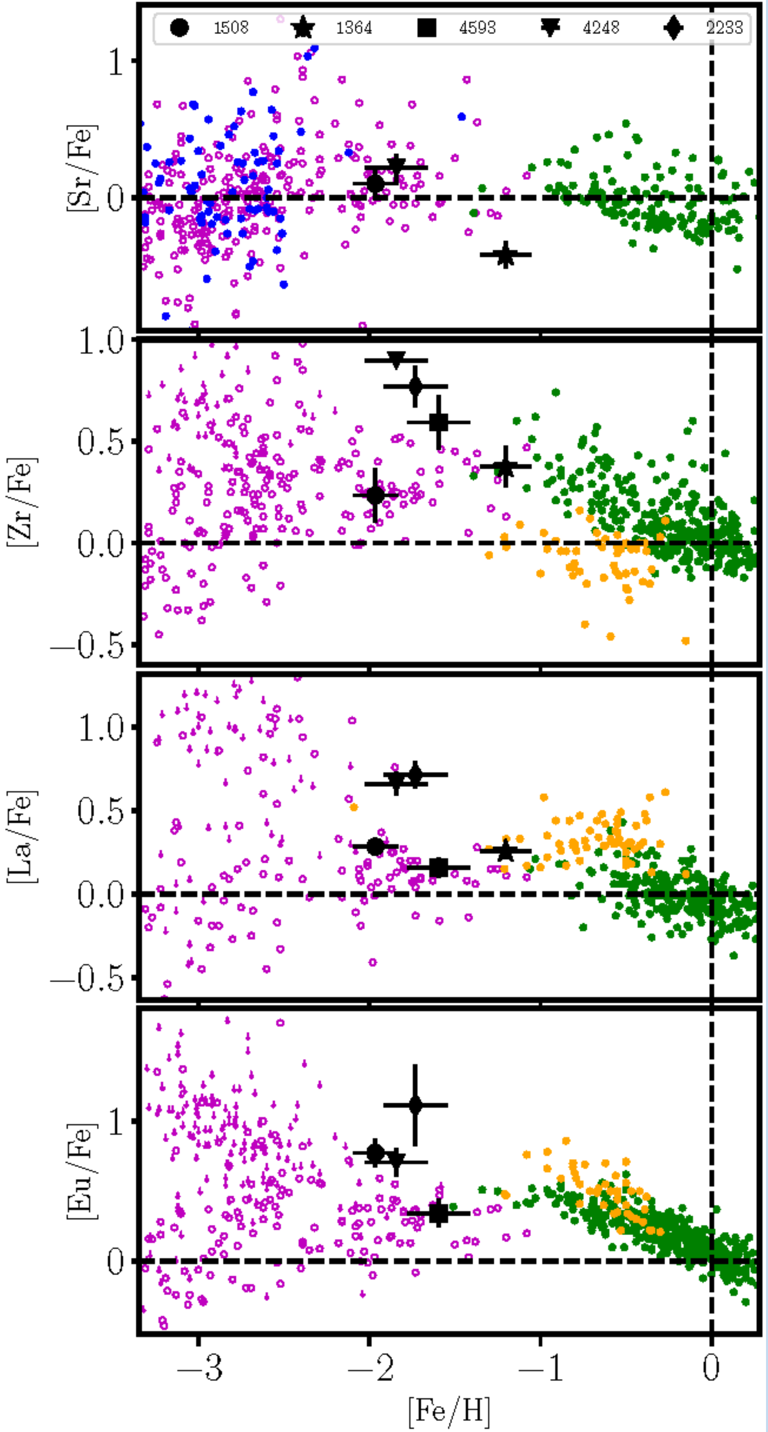
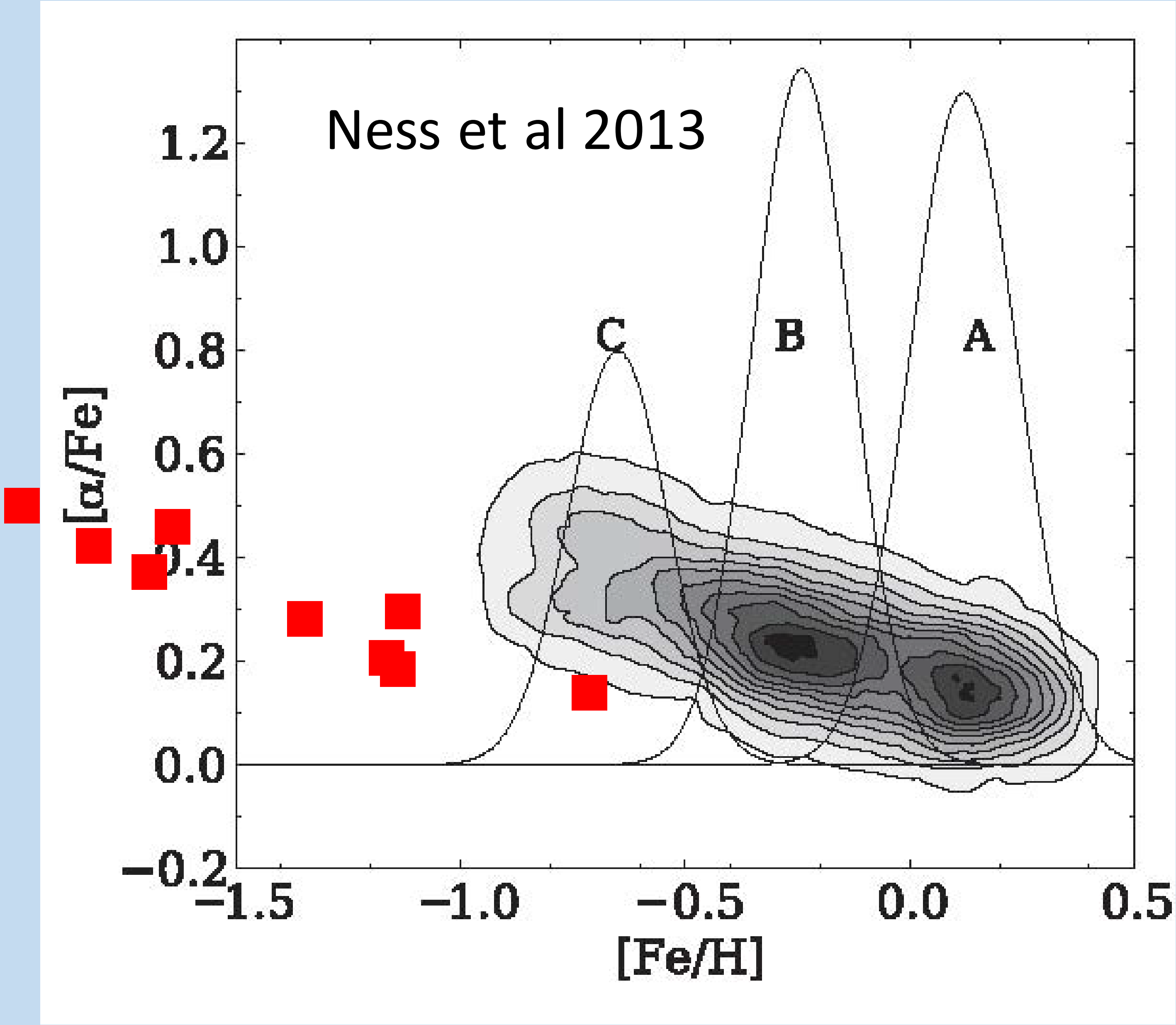
- Orange: LMC stars (Van der Swaelman et al 13)
- Green: discs stars (Battistini & Bensby 2016)



- Candidate extreme-velocity stars also fit within locus (scatter) of halo stars in the neutron-capture elements

- Blue/magenta: halo stars (Roederer et al 14/Yong et al 13)
- Orange: LMC stars (Van der Swaelman et al 13)
- Green: discs stars (Battistini & Bensby 2016)



Extreme-velocity stars (■) fall far from bulge stars in alpha-abundances and metallicity

- Cross-matched Marchetti (v1) Table 1 with public datasets of large spectroscopic surveys
  - Three in RAVE, one in APOGEE+LAMOST
  - All (three) with spectroscopic estimates of the atmospheric parameters are metal-poor giants, [Fe/H] ~ -1.70
  - APOGEE target is alpha-enhanced, typical halo star
- **See also Du et al (2018) LAMOST sample**
- Late-type extreme velocity stars with elemental abundance data are consistent with typical halo stars, inconsistent with origin in dwarf galaxies, LMC, Galactic central regions or being second population globular cluster stars

- Sample of candidate `unbound' stars consists of typical metal-poor giants, element ratios matching those of members of the stellar halo or thick disc

  ➔ **simply high-velocity tail of bound population (+ errors)**

- Need to increase amplitude of estimated escape velocity curve, mass of Milky Way (cf. Hattori et al 2018)
- Analysis of Gaia RVS dataset finds high mass, > 1.2 x $10^{12} M_\odot$; Monari et al. inc RFGW 2018)
- Radially biased velocity ellipsoid allows lower mass ~ $10^{12} M_\odot$ (Deason et al 2019)