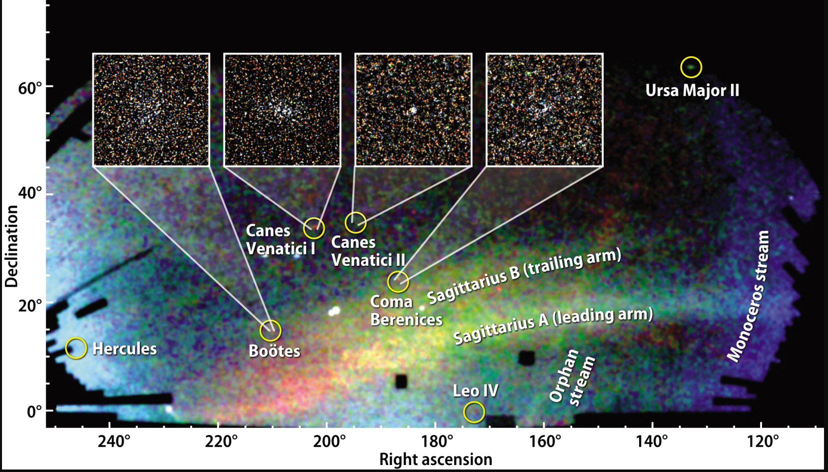

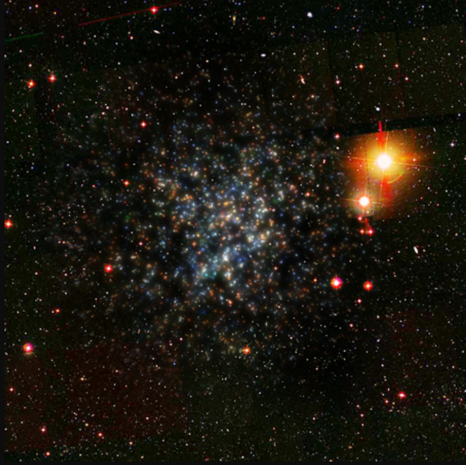

The chemical evolution of the smallest Milky Way satellites: Boötes I

Donatella Romano
INAF–Osservatorio Astronomico di Bologna

Collaborators: M. Bellazzini (OABo), E. Starkenburg (UVIC), R. Leaman (IAC)
F. Calura (OABo), A. D'Ercole (OABo), C. G. Few (UExeter)

Image credits: *left:* **Alexander Jamieson (Celestial Atlas, 1822);** *center and right:* **V. Belokurov and SDSS-II collaboration**

Outline of the talk

- Basic facts about Boötes I
- Chemical evolution models
- Comparison: model predictions *vs* observations
- Conclusions
- Future work

Basic facts

- Recently discovered (Belokurov+06)

THE ASTROPHYSICAL JOURNAL, 647: L111–L114, 2006 August 20

A FAINT NEW MILKY WAY SATELLITE IN BOOTES

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Received 2006 April 17; accepted 2006 June 30; published 2006 August 15

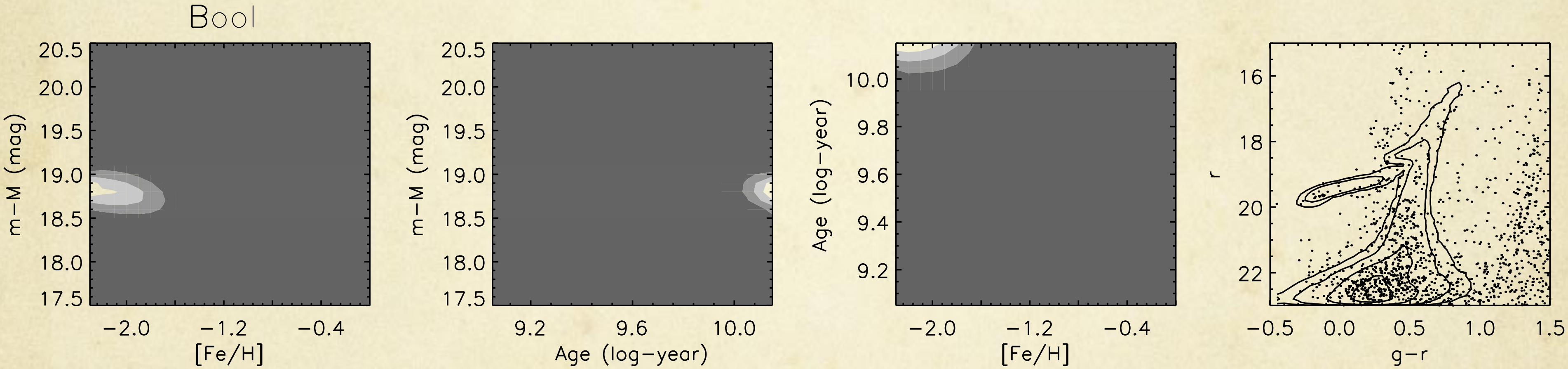
ABSTRACT

We announce the discovery of a new satellite of the Milky Way in the constellation of Bootes at a distance of ~60 kpc. It was found in a systematic search for stellar overdensities in the north Galactic cap using Sloan Digital Sky Survey Data Release 5. The color-magnitude diagram shows a well-defined turnoff, red giant branch, and extended horizontal branch. Its absolute magnitude is $M_V \sim -5.8$ mag, which makes it one of the faintest galaxies known. The half-light radius is ~220 pc. The isodensity contours are elongated and have an irregular shape, suggesting that Boo may be a disrupted dwarf spheroidal galaxy.

Subject headings: galaxies: dwarf — galaxies: individual (Bootes) — Local Group

Basic facts

- Recently discovered (Belokurov+06)
- Old stellar population (de Jong+08; Hughes+08)



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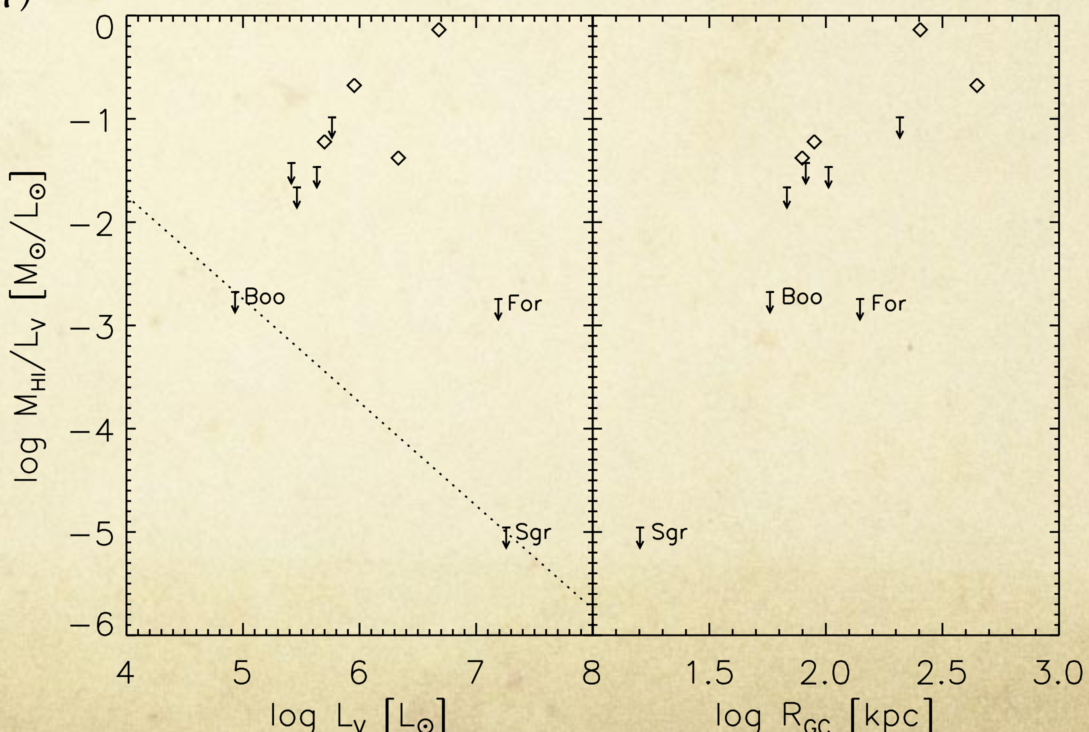

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- $r_h = 242 \pm 21$ pc (McConnachie 2012)
- $M_{dyn}(\leq r_h) = (0.081-2.36) \times 10^7\ M_\odot$ (Wolf+10; Koposov+11)

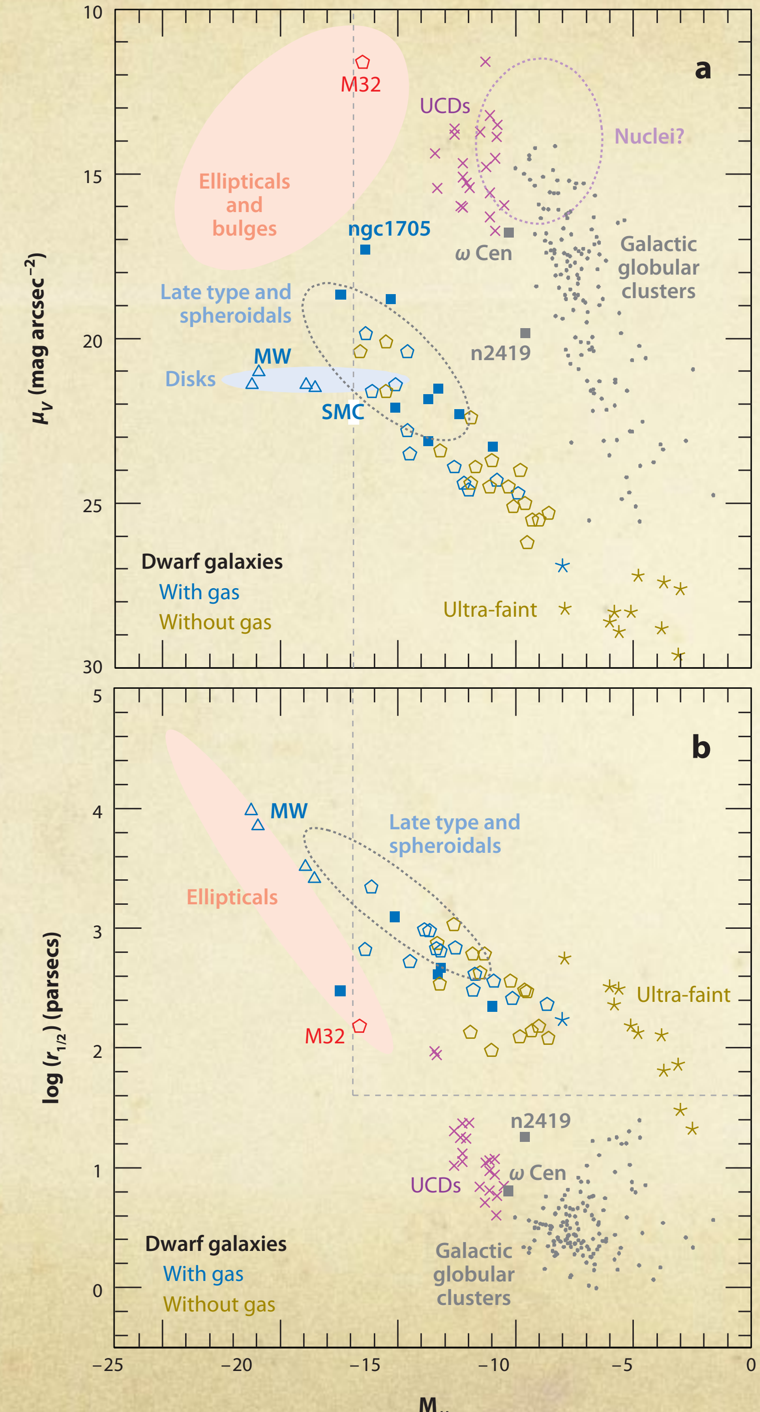

Figure from Tolstoy, Hill & Tosi (2009)

Chemical composition

- Large star-to-star variation in Fe (Norris+08; Feltzing+09; Norris+10; Lai +11; Gilmore+13; Ishigaki+14), in stark contrast with the lack of evidence for [Fe/H] variations in GGCs of similar mass (Gratton +04)

Ability to retain metals

- Type Ia SN signature (declining [α/Fe] abundance ratio)?
- Inhomogeneities?

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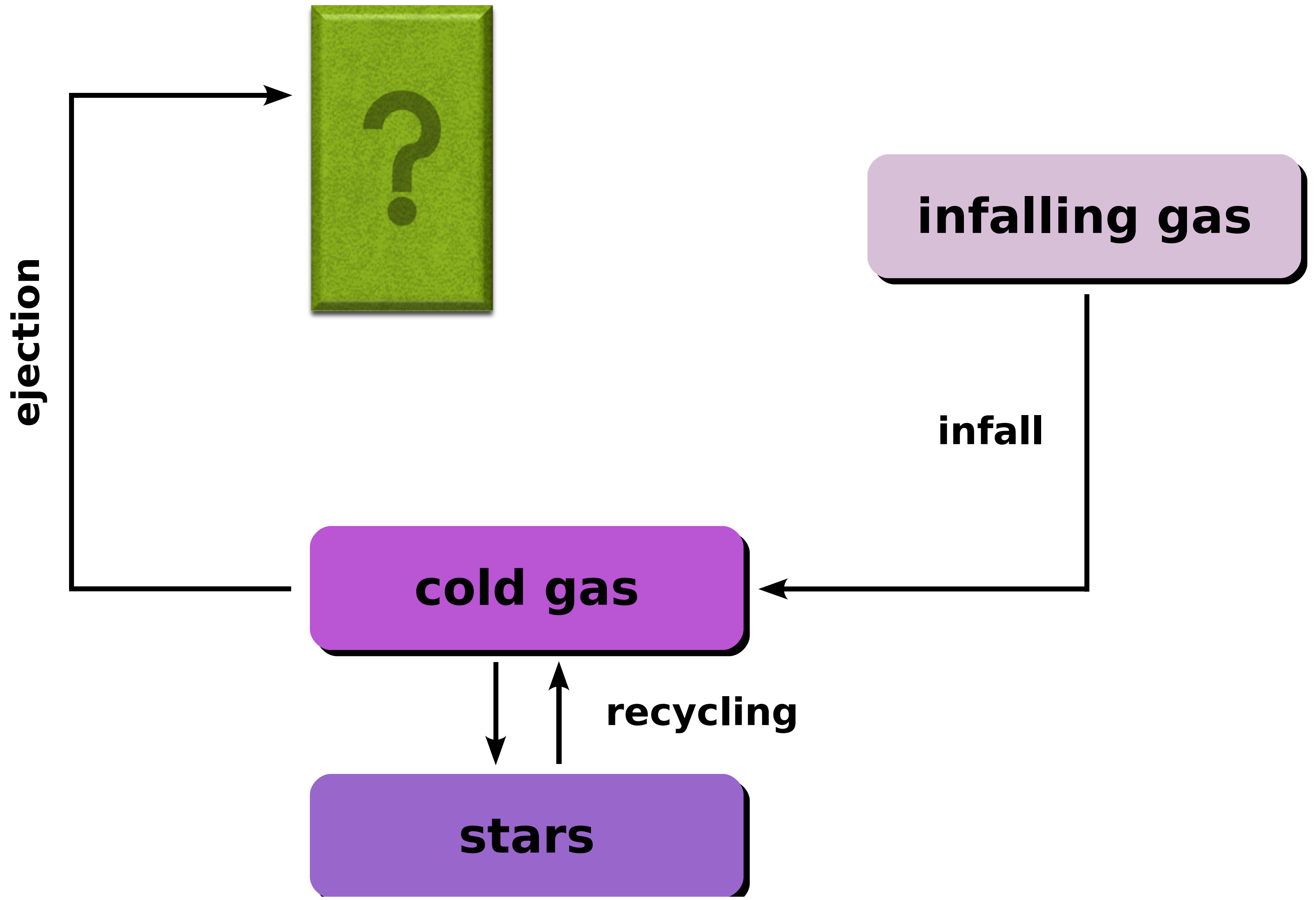
Ability to retain metals

- Type Ia SN signature (declining [α /Fe] abundance ratio)?
- Inhomogeneities? Anti-correlations?

Chemical evolution models

- Follow the evolution of the abundances of several elements (H, He, C, N, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, Cr, Mn, Co, Ni, Fe, Cu, Zn, Eu)
- Model assumptions:
  - Inflow of gas of primordial chemical composition provides the raw material for star formation (exponentially decreasing in time, $e^{-t/\tau}$)
  - Galactic outflows remove gas from the system
  - The stellar IMF (Kroupa 2001) is constant in space and time
  - Finite stellar lifetimes taken into account

Baryon flows



Model parameters

Model	M_b ($M_\odot$)	τ (Myr)	r_h/r_{DM}	M_{DM} ($M_\odot$)	ε_{th}	ν_{SF} (Gyr^{-1})	Δt_{SF} (Gyr)	<[Fe/H]>
Boo1	2×10^6	50	0.1	2×10^6	0.01	0.02	1	−2.24
Boo2	2×10^6	50	0.1	2×10^6	0.1	0.02	1	−2.25
Boo3	2×10^6	50	—	—	0.01	0.02	1	−2.24
Boo4	2×10^6	50	0.1	2×10^6	0.01	0.04	1	−1.92
Boo5	1.1×10^7	50	0.1	1.1×10^8	0.1	0.013	1	−2.44
Boo6	1.1×10^7	50	0.1	1.1×10^8	0.1	0.026	0.5	−2.52
Boo7	1.1×10^7	50	0.1	1.1×10^8	0.01	0.053	0.25	−2.60
Boo8	1.1×10^7, 10^5	50	0.1	1.1×10^8	0.01	0.053, 4.0	0.25, 0.02	−2.60 −2.46
Boo9	1.1×10^7	50	0.1	6.5×10^7	0.1	0.013	1	−2.44

Stellar MDF

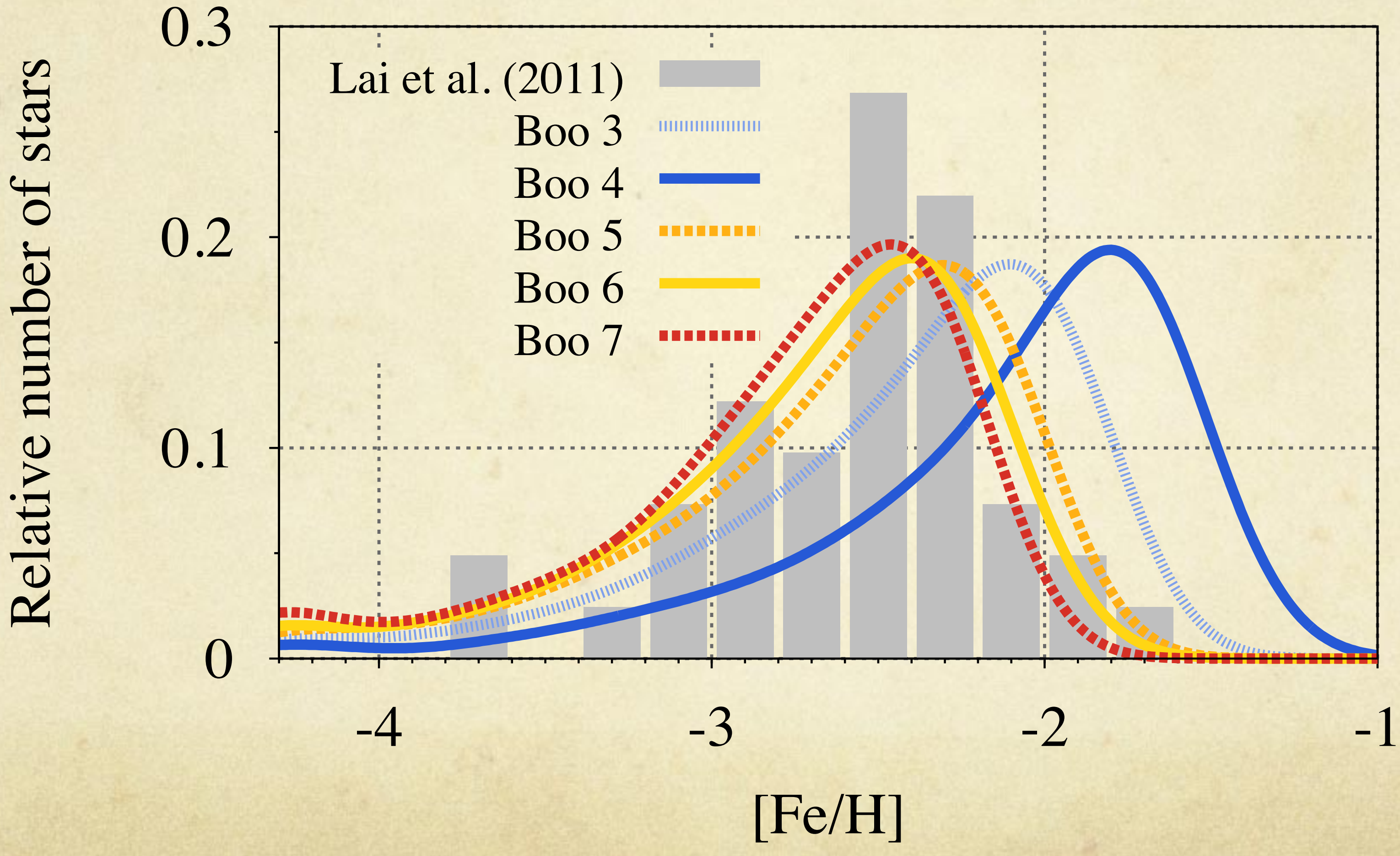
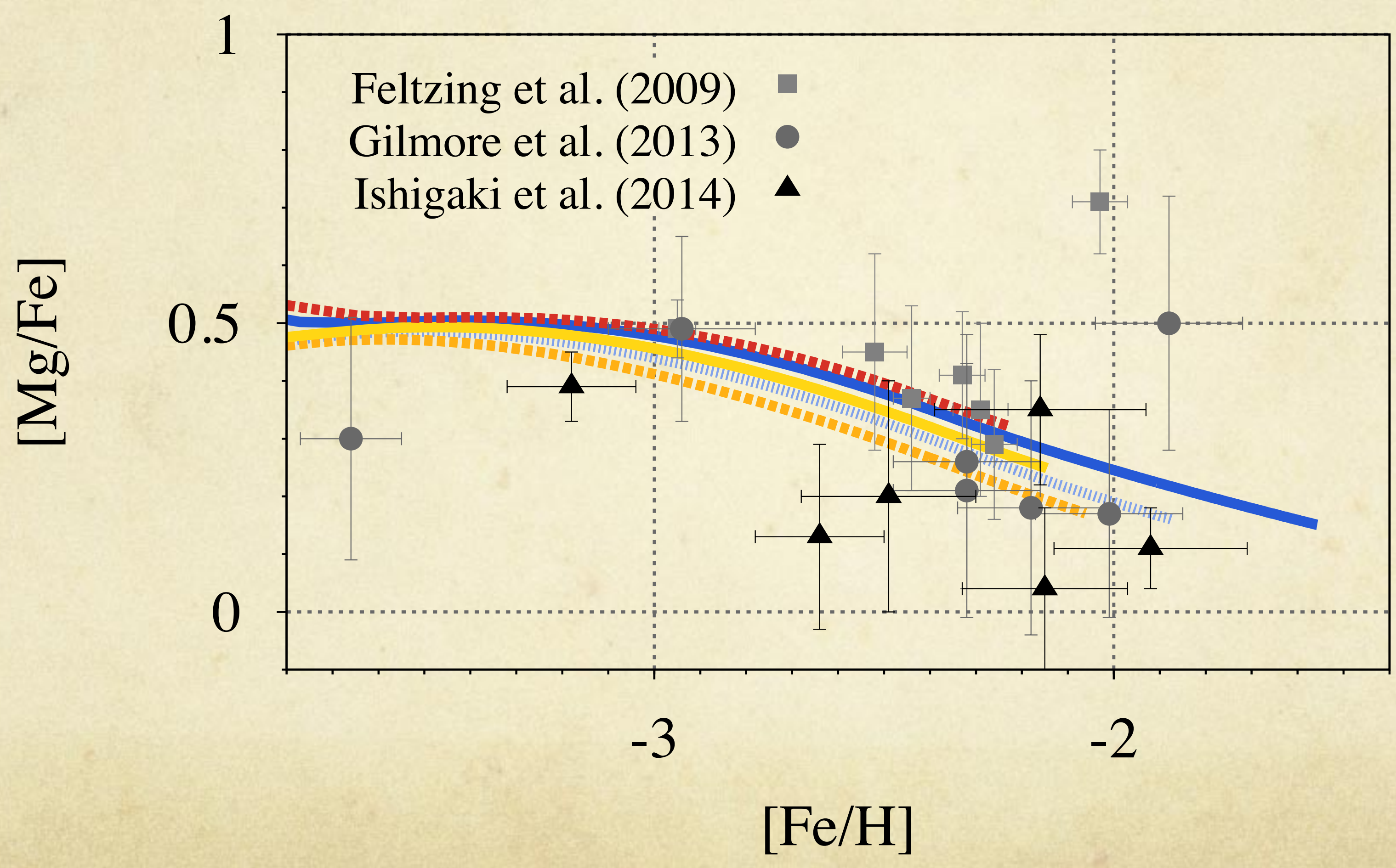


Figure from Romano+15

[Mg/Fe] versus [Fe/H]



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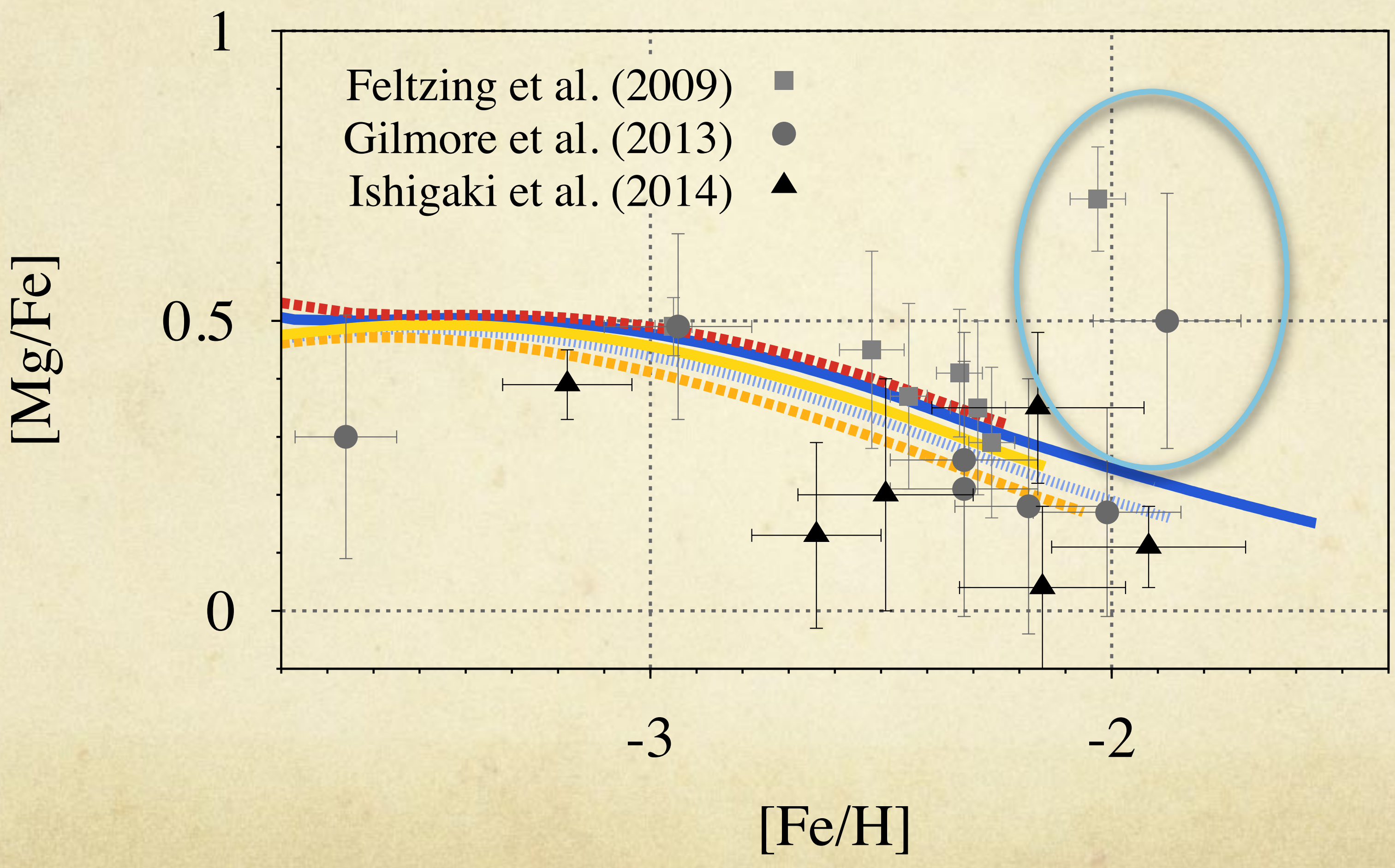

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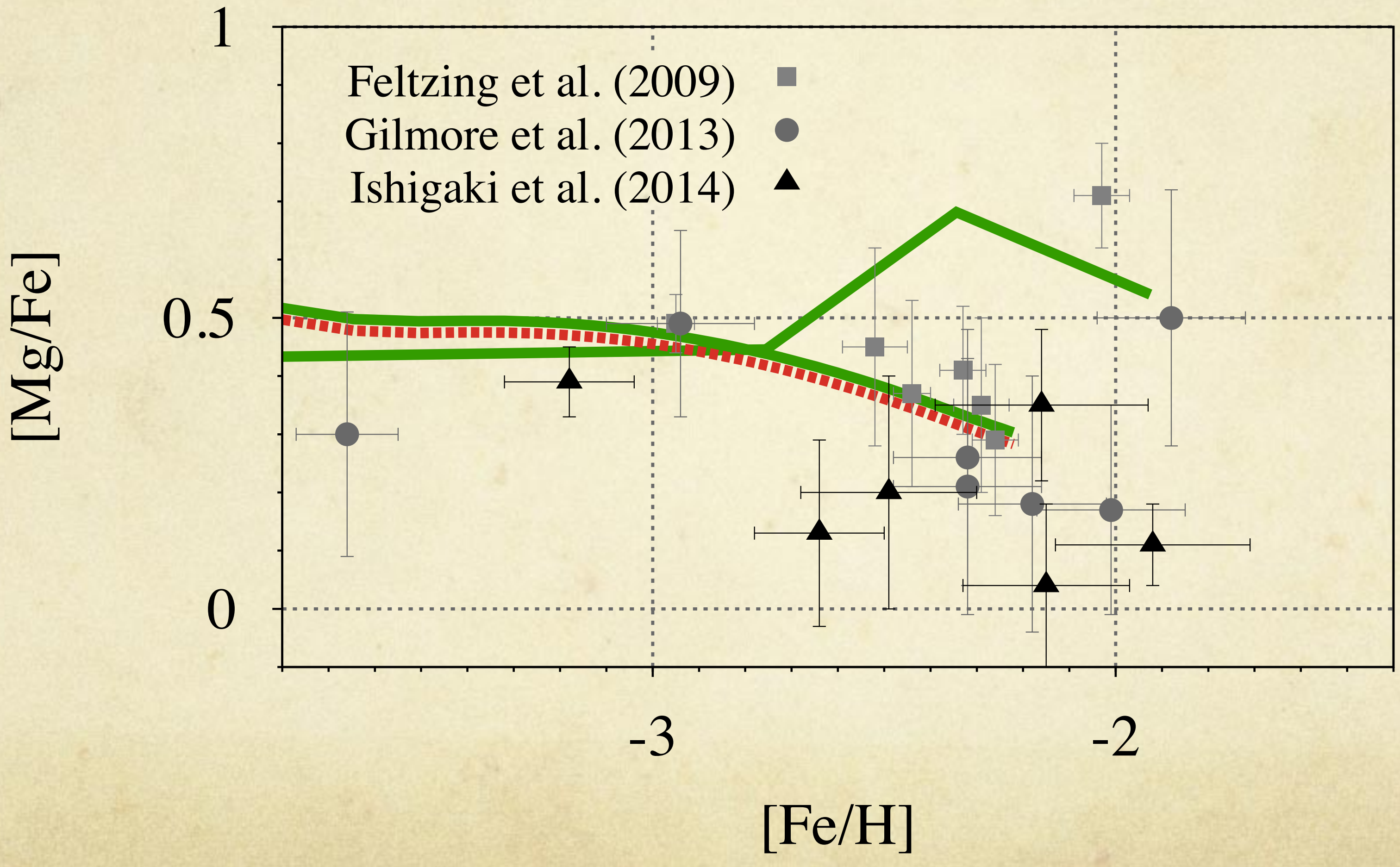


Figure from Romano+15

Inhomogeneities: empirical relation

(Leaman 2012)

THE ASTRONOMICAL JOURNAL, 144:183 (13pp), 2012 December

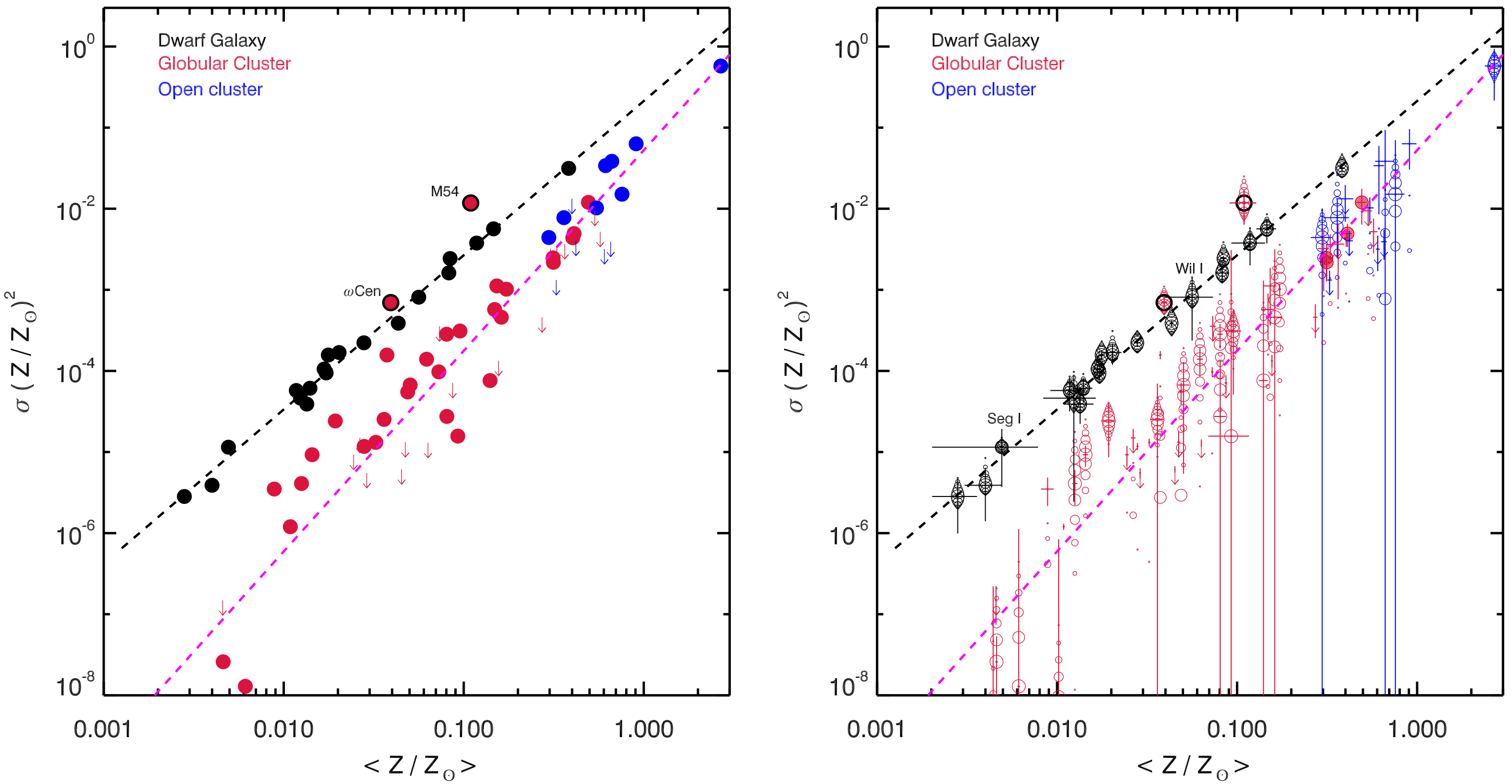
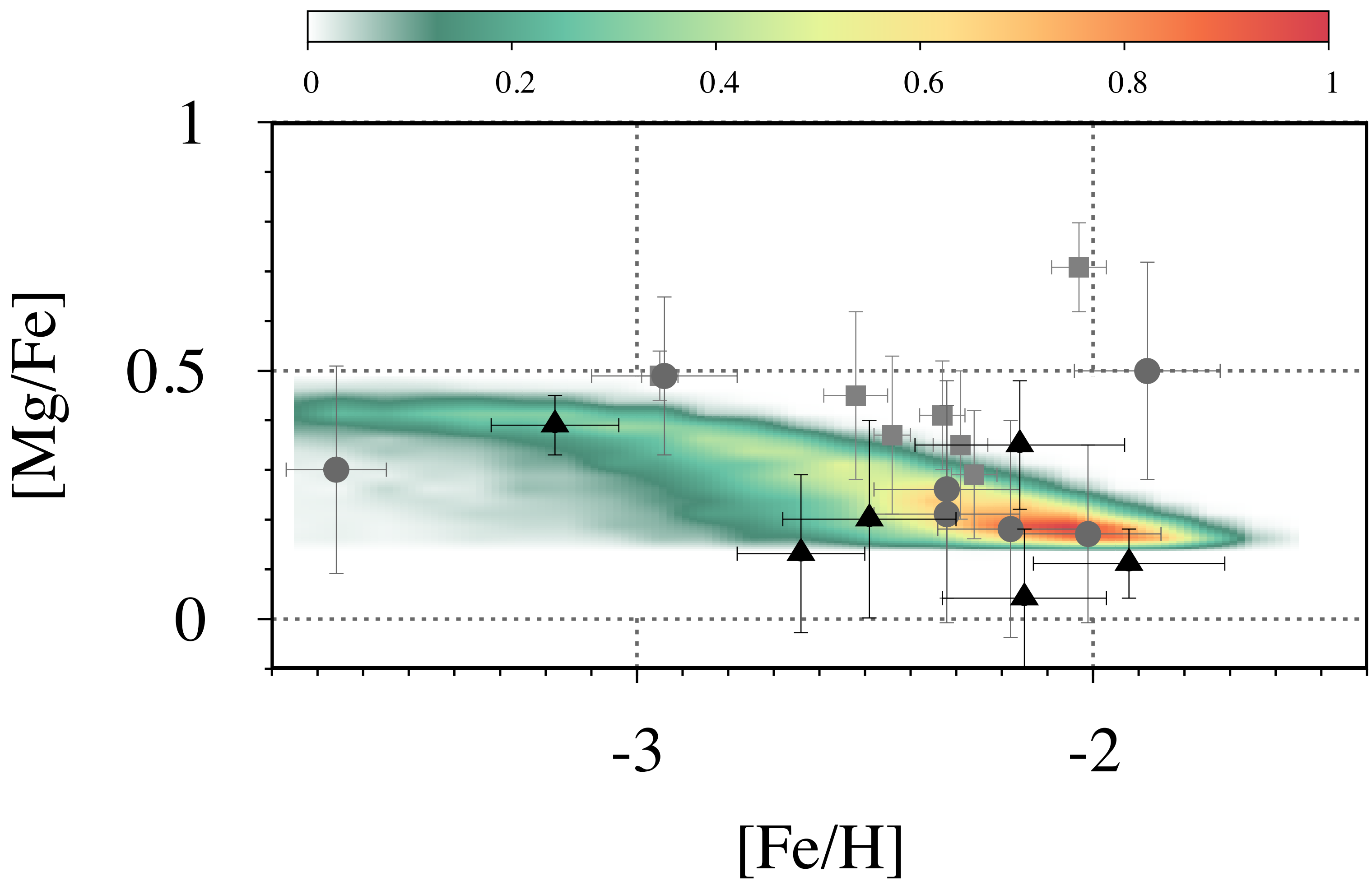


Figure 2. Intrinsic variance $\sigma(Z)^2$ in Z vs. $\bar{Z}$, the mean Z for dwarf galaxies and star clusters. Dashed lines represent a linear least-squares fit to the dwarf galaxies (black) and star clusters (magenta). Arrows indicate upper limits to the intrinsic dispersions. There is a clear separation between the dwarf galaxy and star cluster seq… erro…

Form stars following a Gaussian distribution in Z values with

$$\log\ \sigma(Z)^2 = a + b \log(<Z>) \qquad a=-0.6888970,\ b=1.88930$$

[Mg/Fe] versus [Fe/H]



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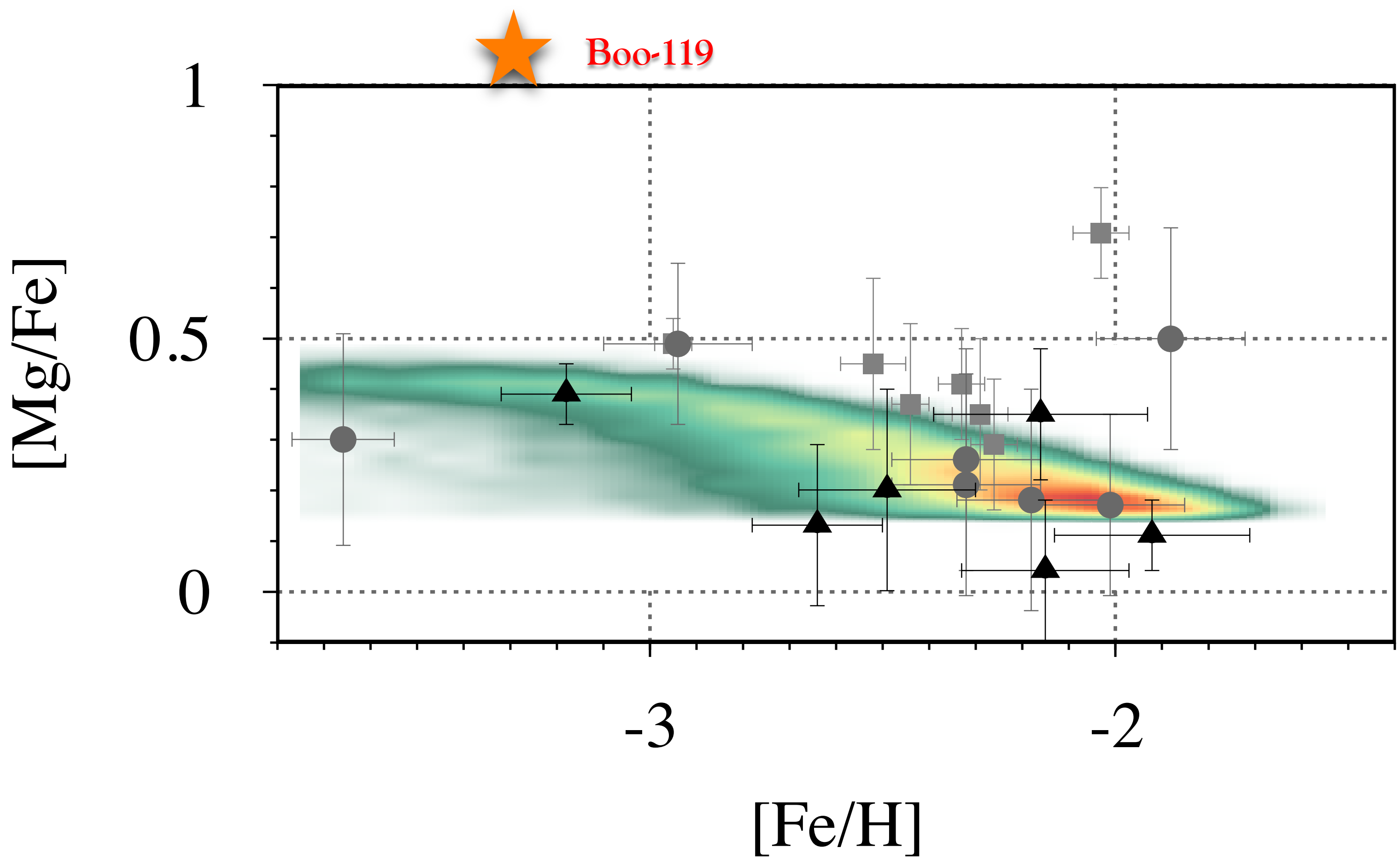

Figure from Romano+15

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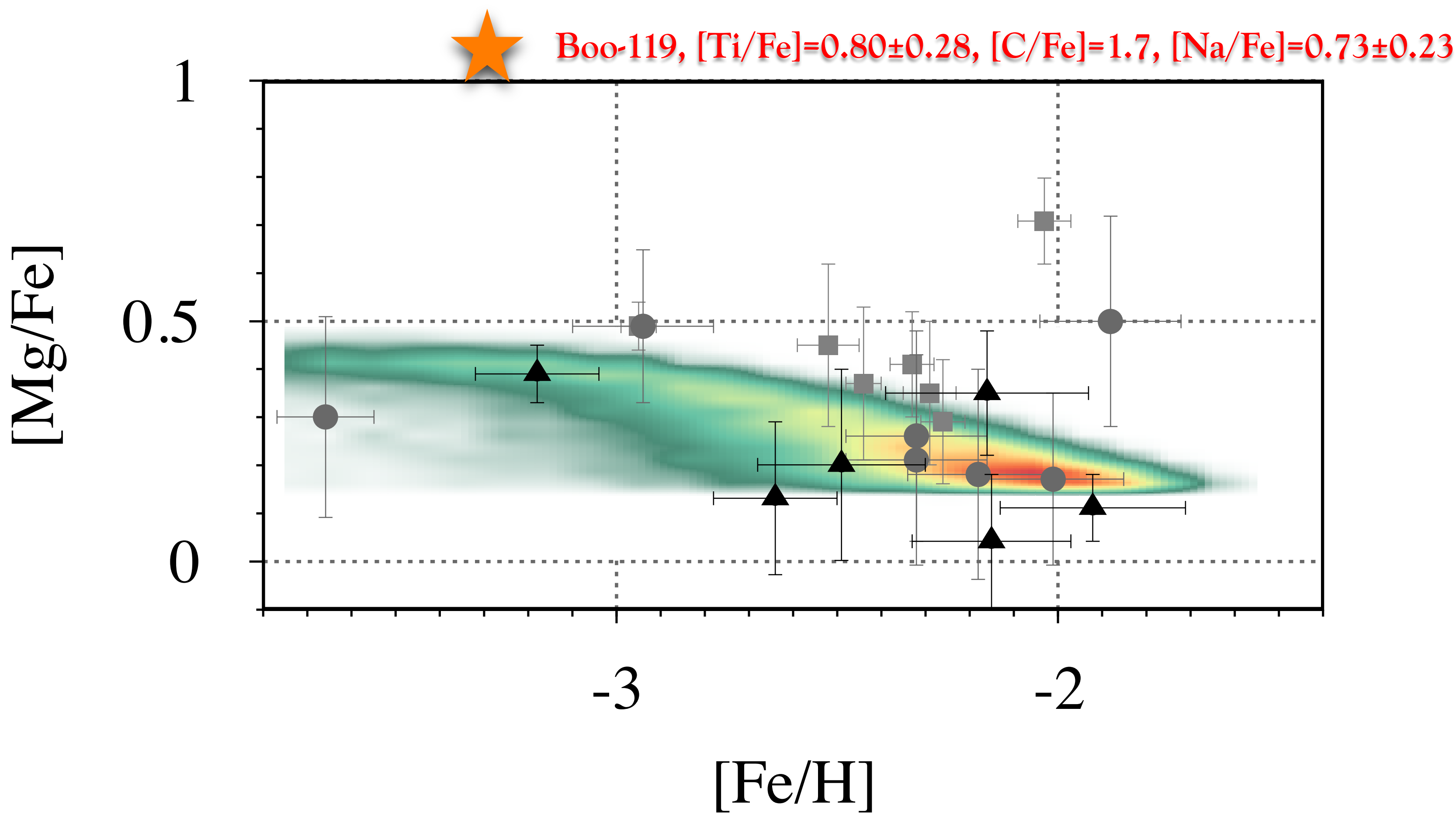

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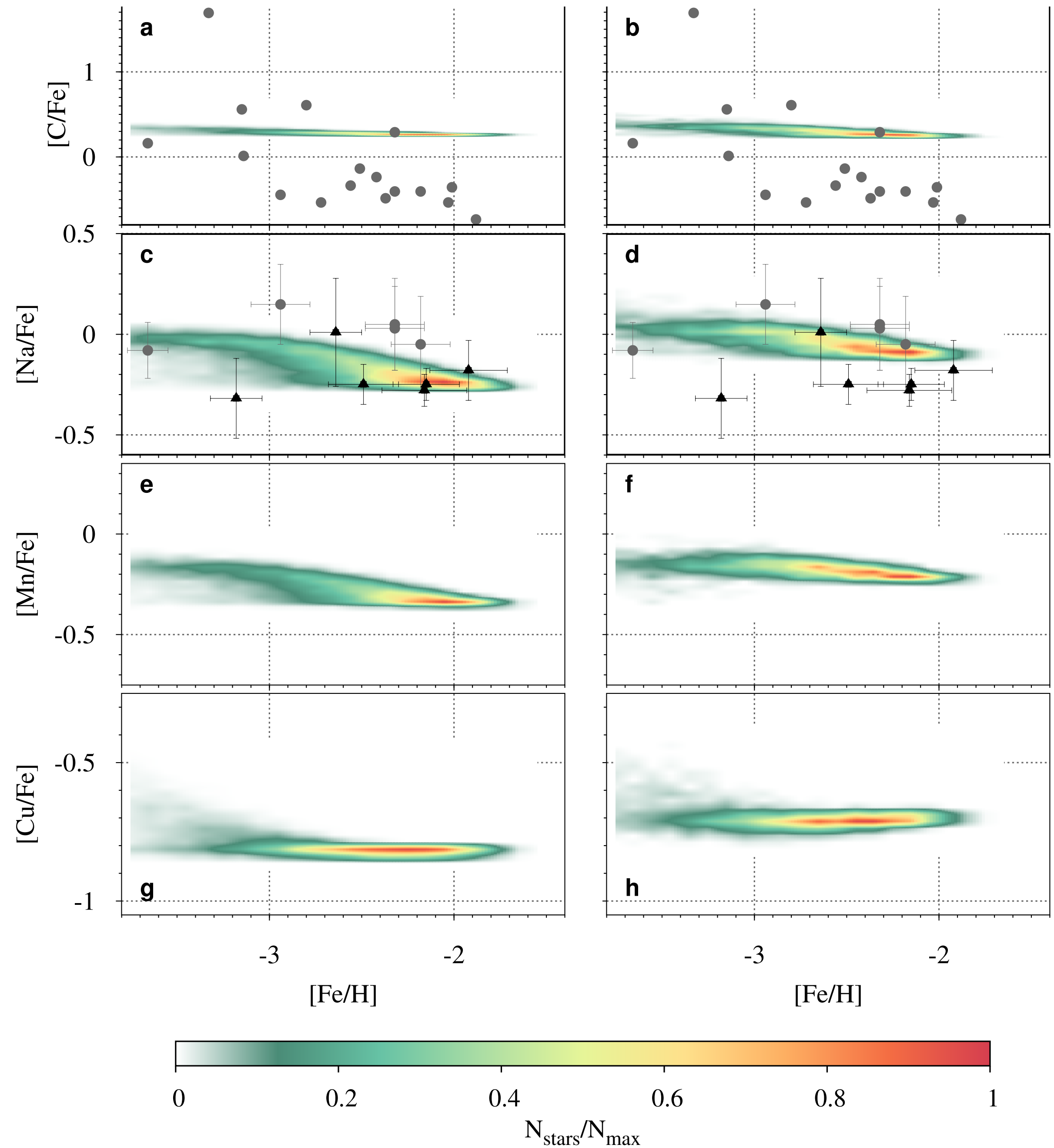


Figure 9. Same as Fig. 8 for C (panels a, b), Na (panels c, d), Mn (panels e, f) and Cu (panels g, h). Carbon data from Norris et al. (2010a) and Lai et al. (2011, one star).

[Mn/Fe] versus [Fe/H]

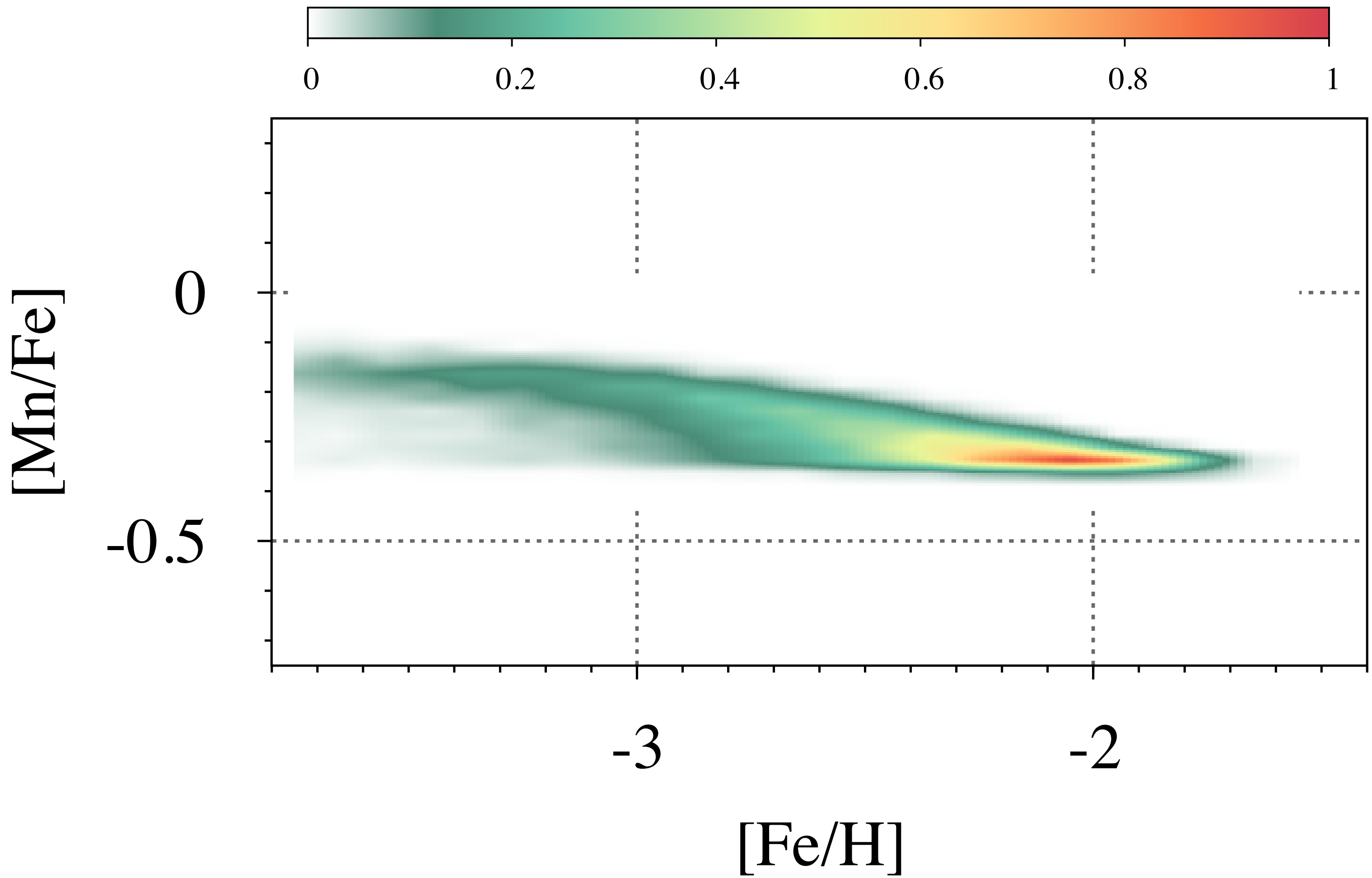


Figure from Romano+15

[Mn/Fe] versus [Fe/H] in different systems

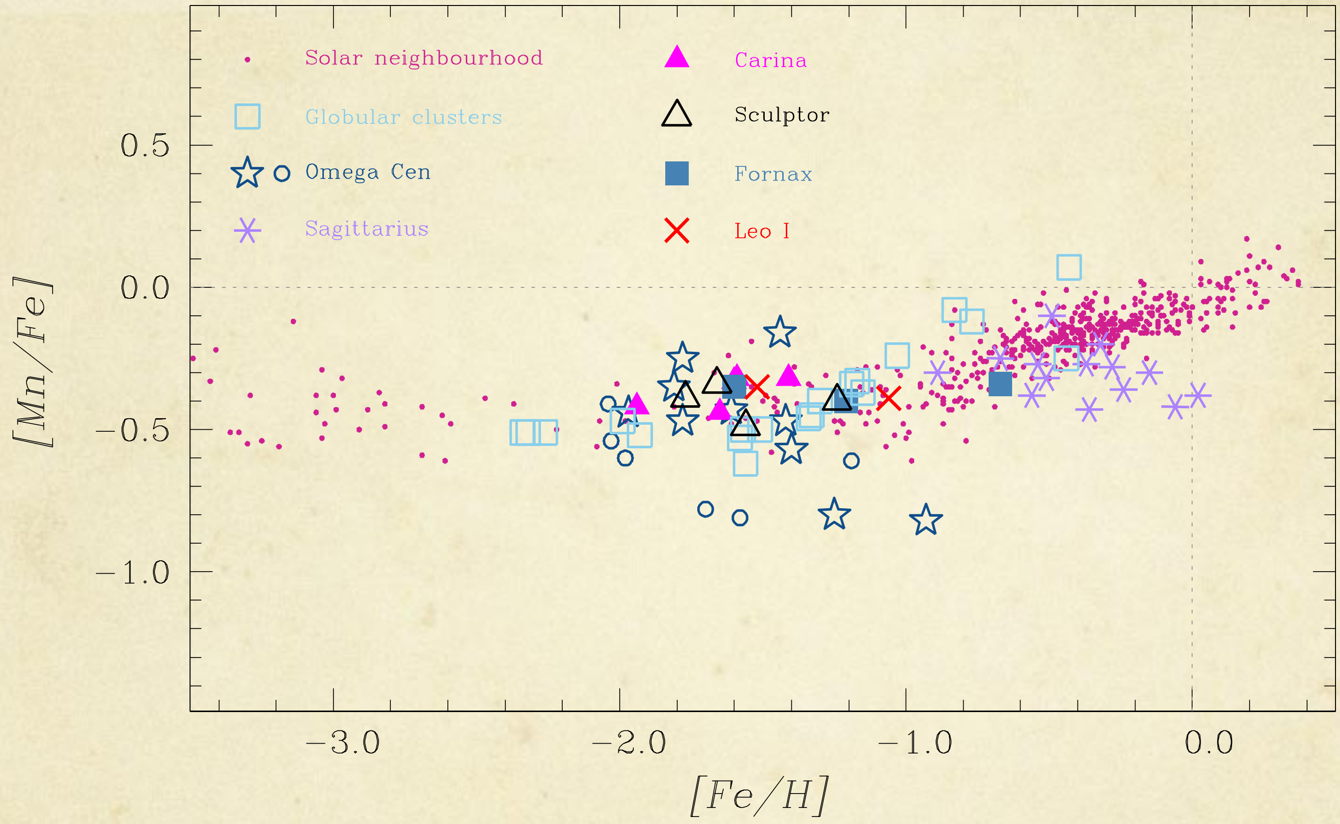
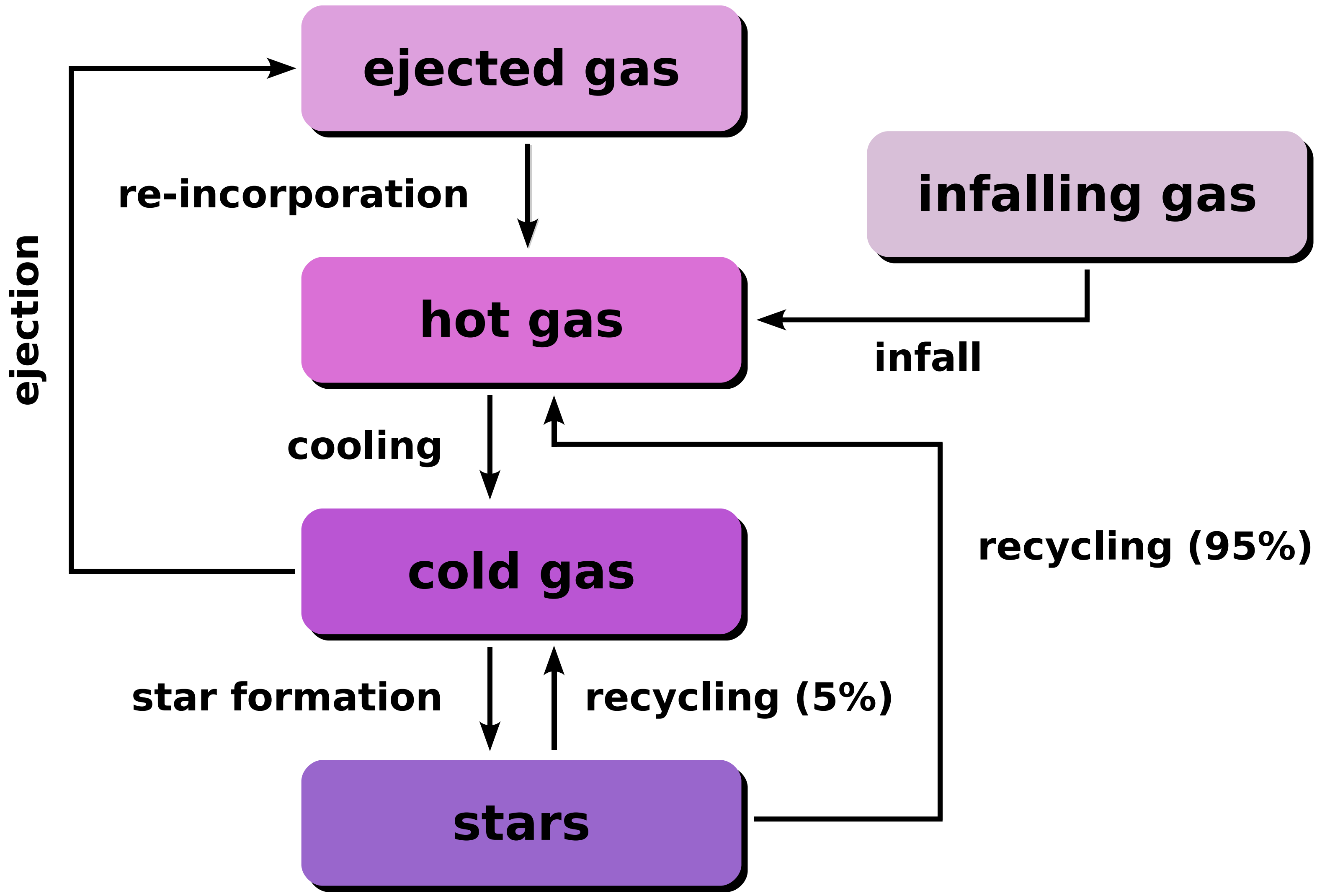


Figure 3. Observational [Mn/Fe] versus [Fe/H] relationships for field stars in the solar neighbourhood (filled circles; Cayrel et al. 2004; Gratton et al. 2003; Reddy et al. 2003, 2006; Feltzing et al. 2007), 20 Galactic globular clusters (open squares; Gratton et al. 2006; Carretta et al. 2007; Carretta 2010, private communication), ω Cen (stars: Cunha et al. 2010; open circles: Pancino et al. 2011), Sagittarius (main body and Terzan 7, asterisks; Sbordone et al. 2007) and 4 dSphs of the Local Group (filled triangles: Carina; open triangles: Sculptor; filled squares: Fornax; crosses: Leo I; Shetrone et al. 2003).

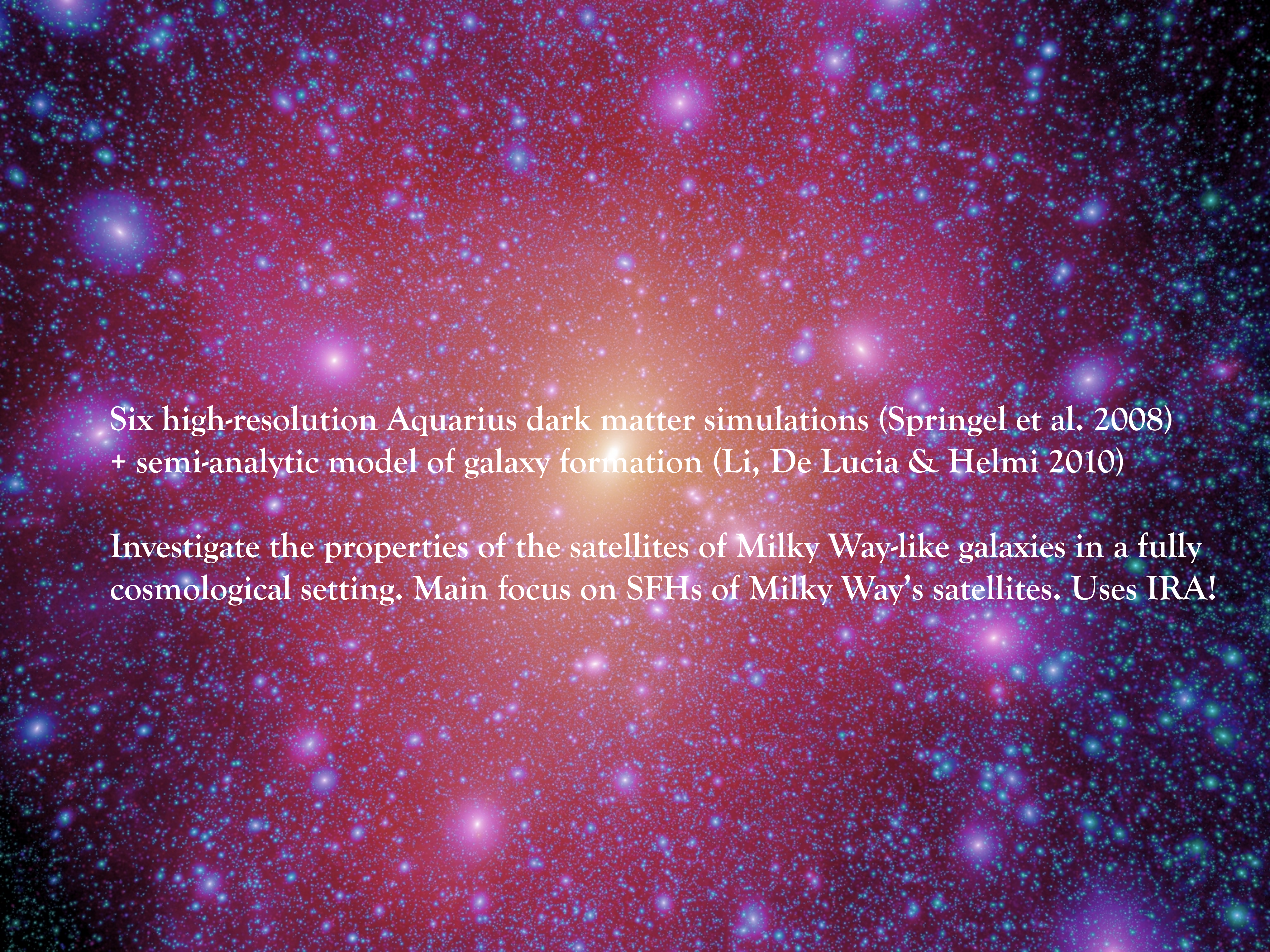
Figure from Romano+11

Chemical evolution in a full cosmological context:



Cosmological context

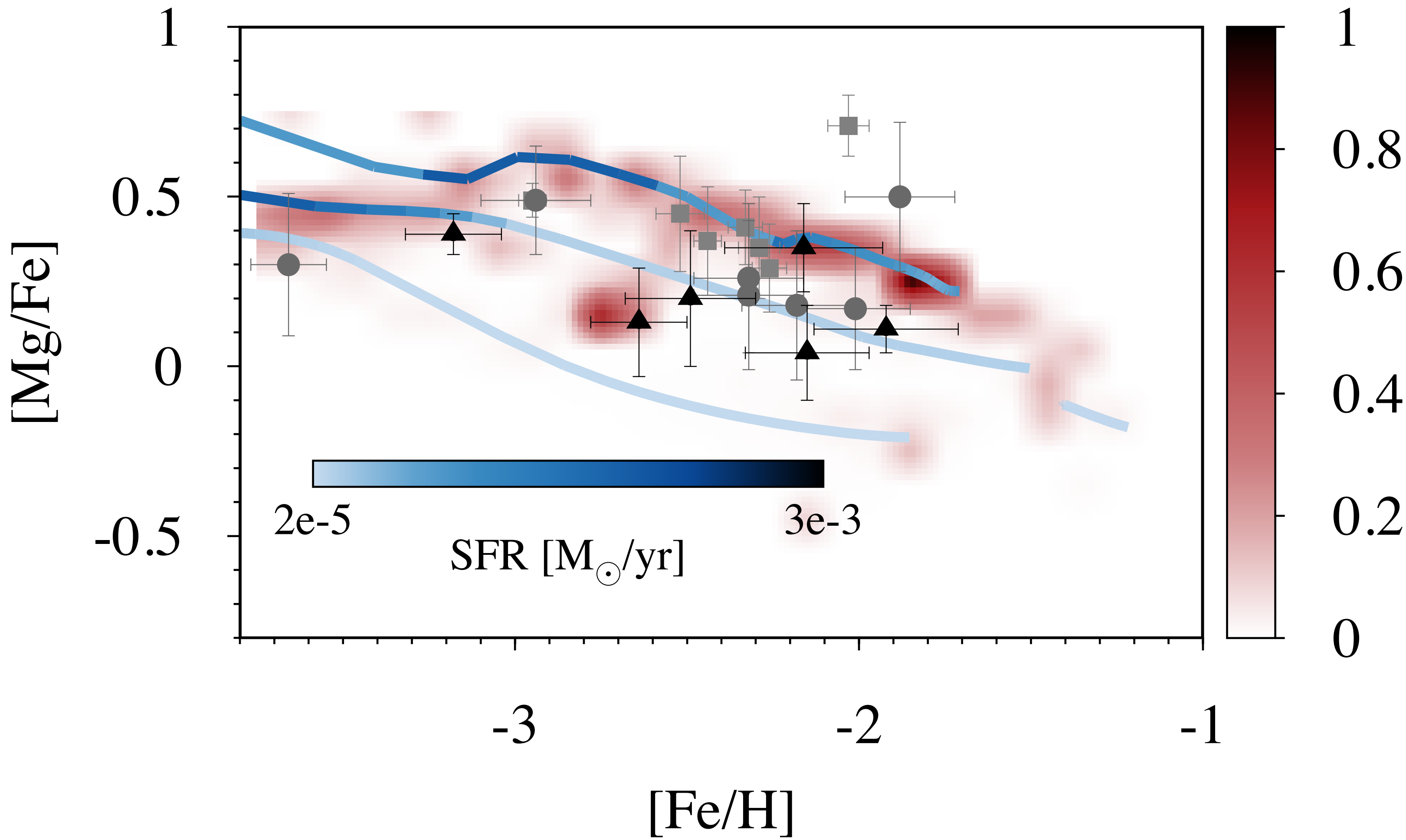
- Take into account the effect of the environment (mergers, ram-pressure stripping, tidal stripping)
- Identify Boötes I candidates in the mock catalogue by Starkenburg+13 basing on rather loose criteria:
  - M_V in the range −6.5,−6.0 mag
  - Mostly old stellar populations (80% of stars older than 10 Gyr)
  - The galaxy is a Milky Way satellite and no further out than 150 kpc today
- Post-process for detailed chemical properties (see Romano & Starkenburg 2013)



Six high-resolution Aquarius dark matter simulations (Springel et al. 2008)
+ semi-analytic model of galaxy formation (Li, De Lucia & Helmi 2010)

Investigate the properties of the satellites of Milky Way-like galaxies in a fully cosmological setting. Main focus on SFHs of Milky Way's satellites. Uses IRA!

[Mg/Fe] versus [Fe/H]



Conclusions

- Boötes I must have been much more massive (2 orders of magnitude) in the past
  - Gas needed to dilute the supernova ejecta
- Only a few per cent of its baryons were converted into stars (see also Salvadori & Ferrara 2009; Vincenzo+ 2014)
- It is unlikely that supernova feedback can sustain galactic-scale outflows and vent out all the gas left over from the star formation process (but see Vincenzo et al. 2014)
  - Interaction with the environment play a fundamental role

Next step (work in progress)

F. Calura *(OABo)*

A. D'Ercole *(OABo)*

C. G. Few *(UExeter)*

- 3D hydrodynamical simulations using RAMSES (Teyssier 2002) to study the evolution of bubbles and mixing of ejecta
- Long-term: contrast and compare GC vs UFD formation and evolution