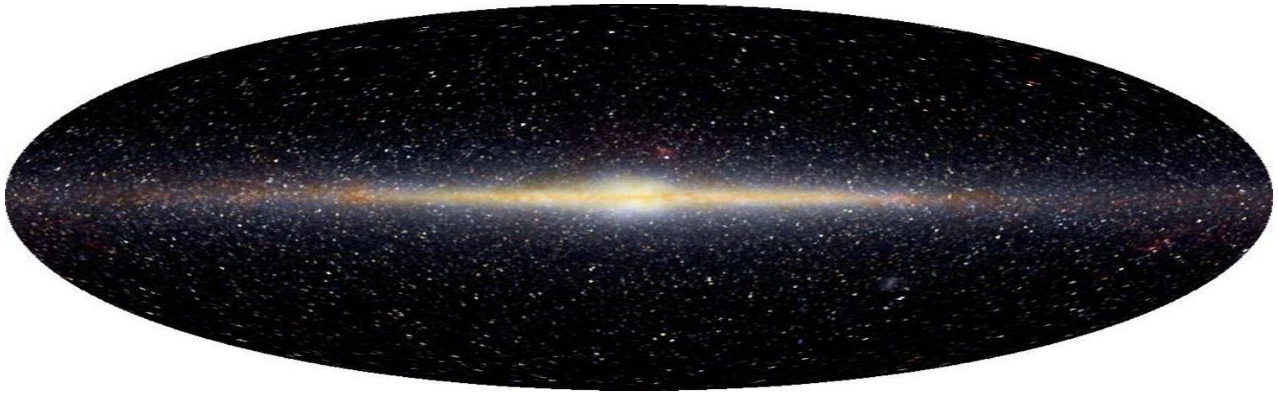
The Galactic Chemical Evolution: an observation overview



Alan Alves Brito

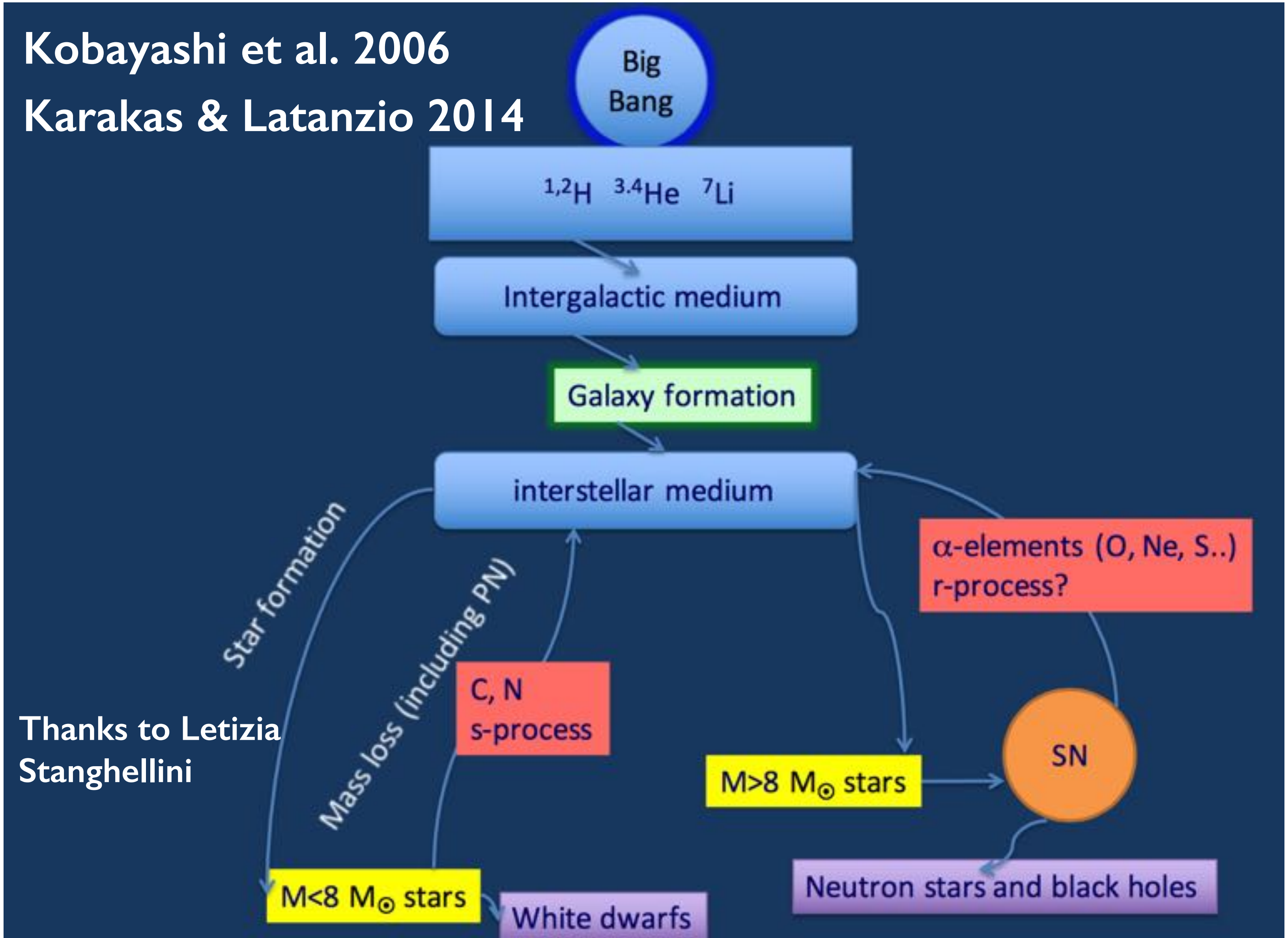
Precision Spectroscopy 2016

Porto Alegre, September 20

UFRGS
UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

DEPARTAMENTO DE Astronomia
INSTITUTO DE FÍSICA - UFRGS

Chemical Evolution



Summary

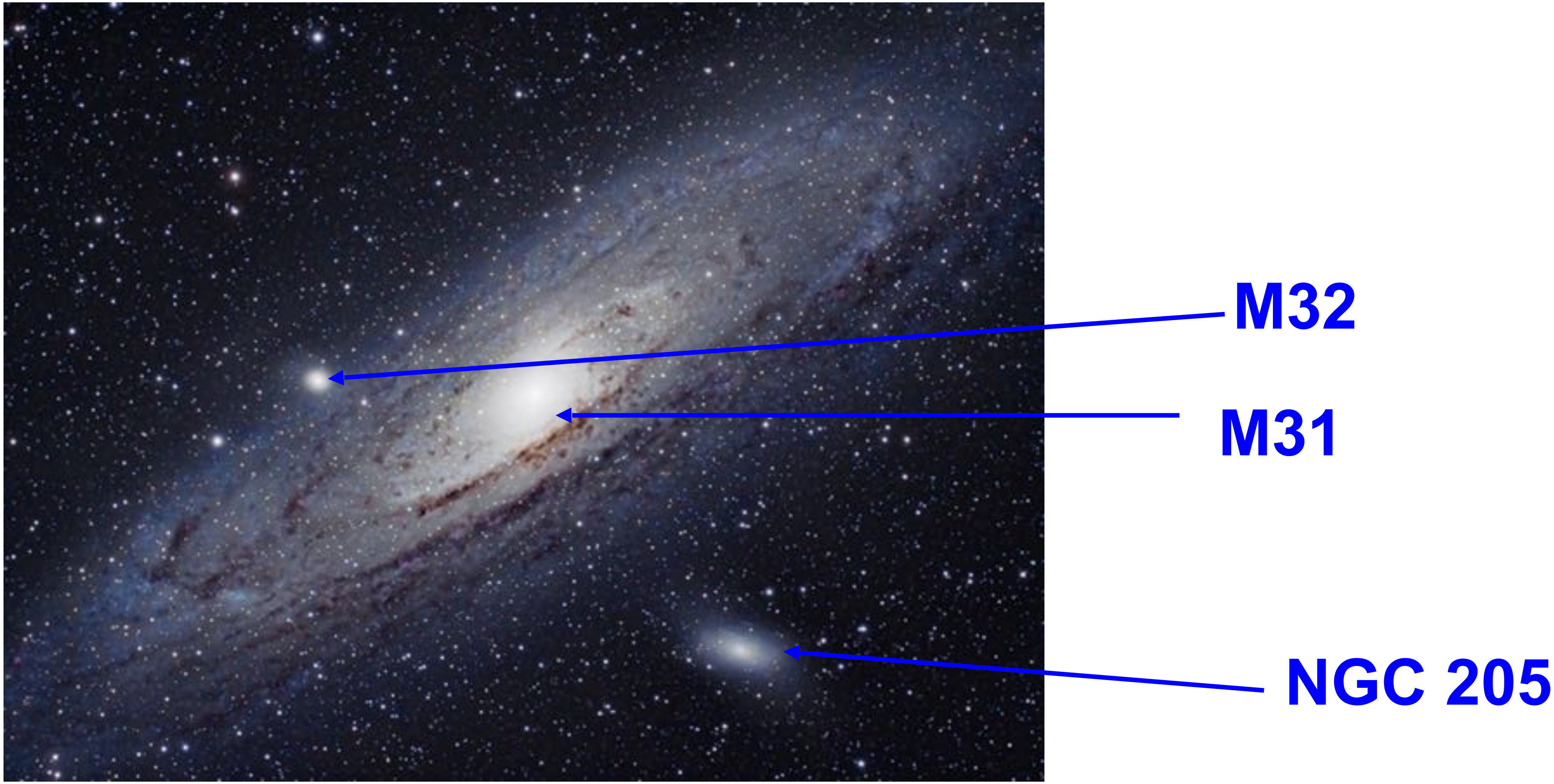
- Introduction
- "Biased" Main Results
- Stellar PoPs: fundamental problems/concerns/ questions
  - high precision spectroscopy: abundances, nucleosynthesis and chemical evolution

Chiaki Kobayashi (chemical evolution models)

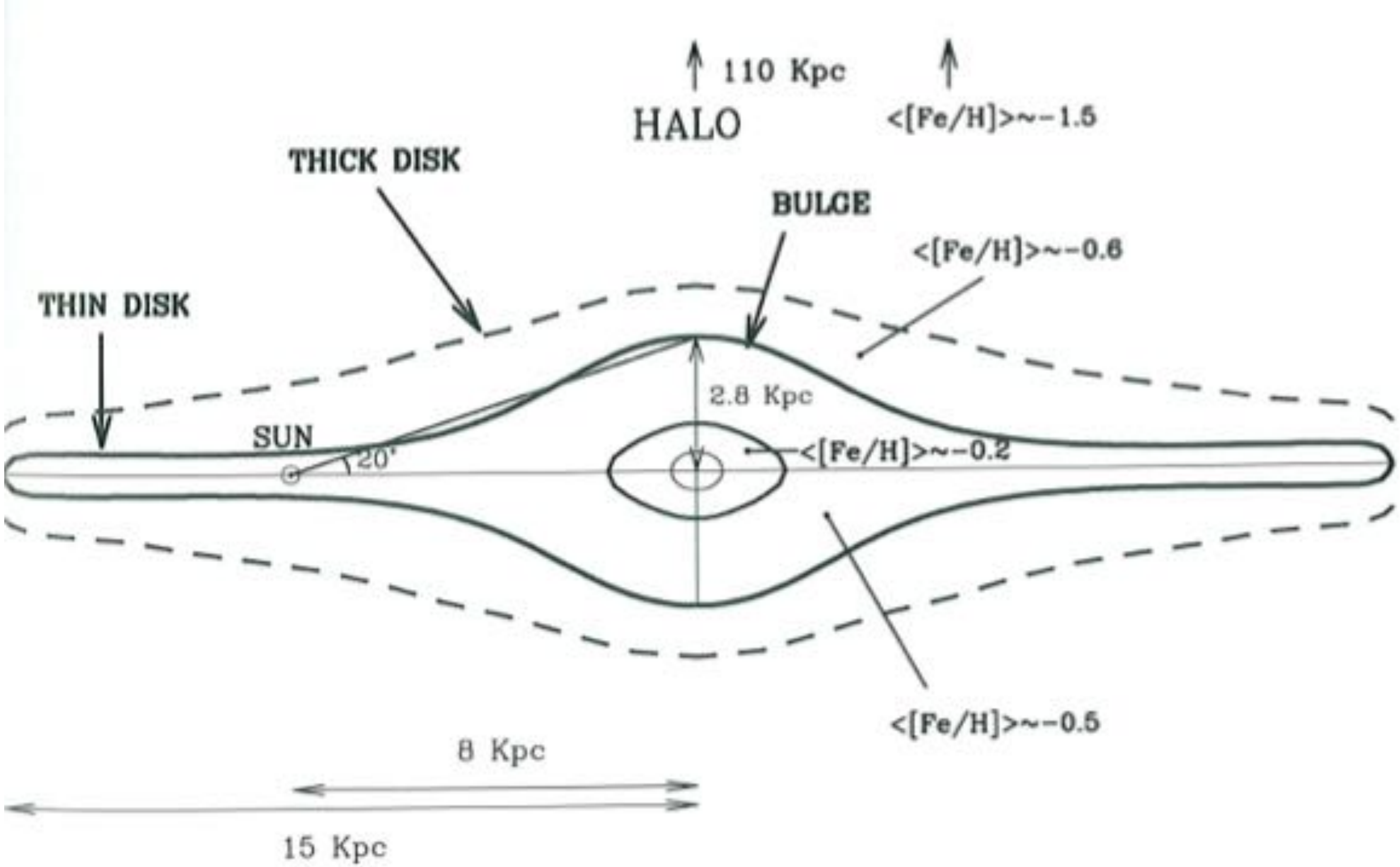
Amanda Karakas (heavy elements)

Stellar Populations

Walter Baade, in 1944



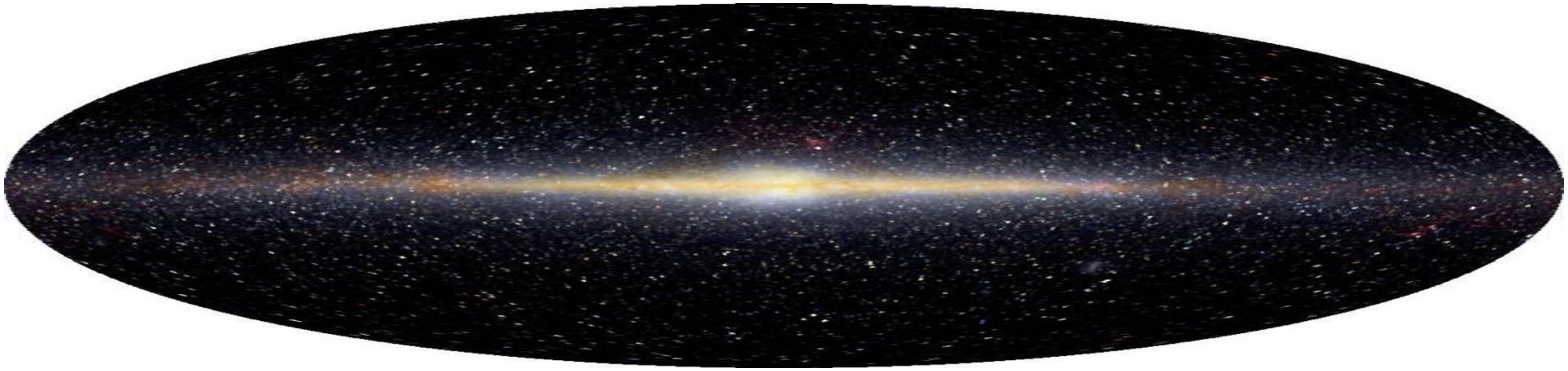
The Milky Way



- age
- kinematics
- dynamics
- chemical enrichment

Matteucci 2003

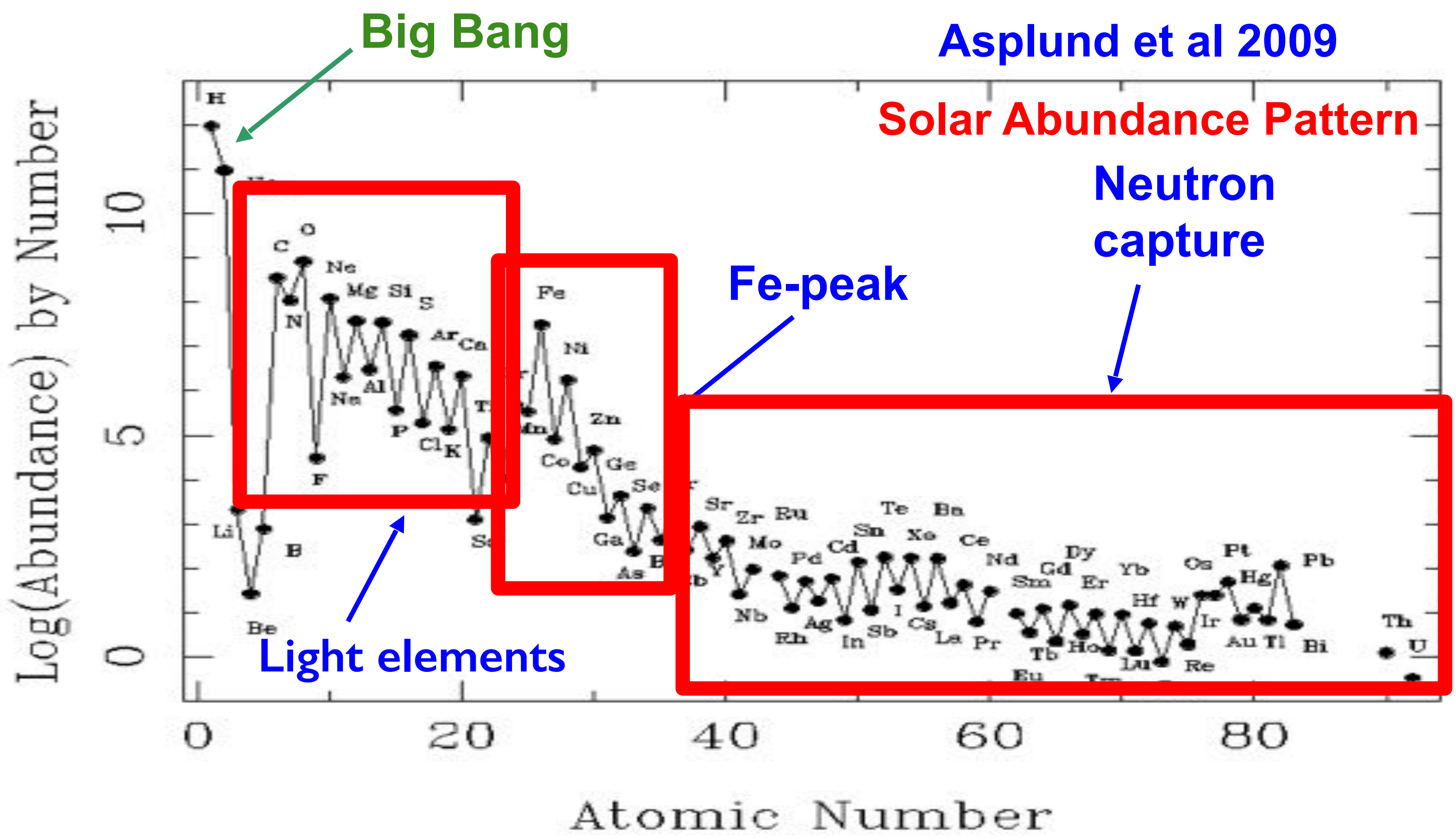
Galactic Tracers



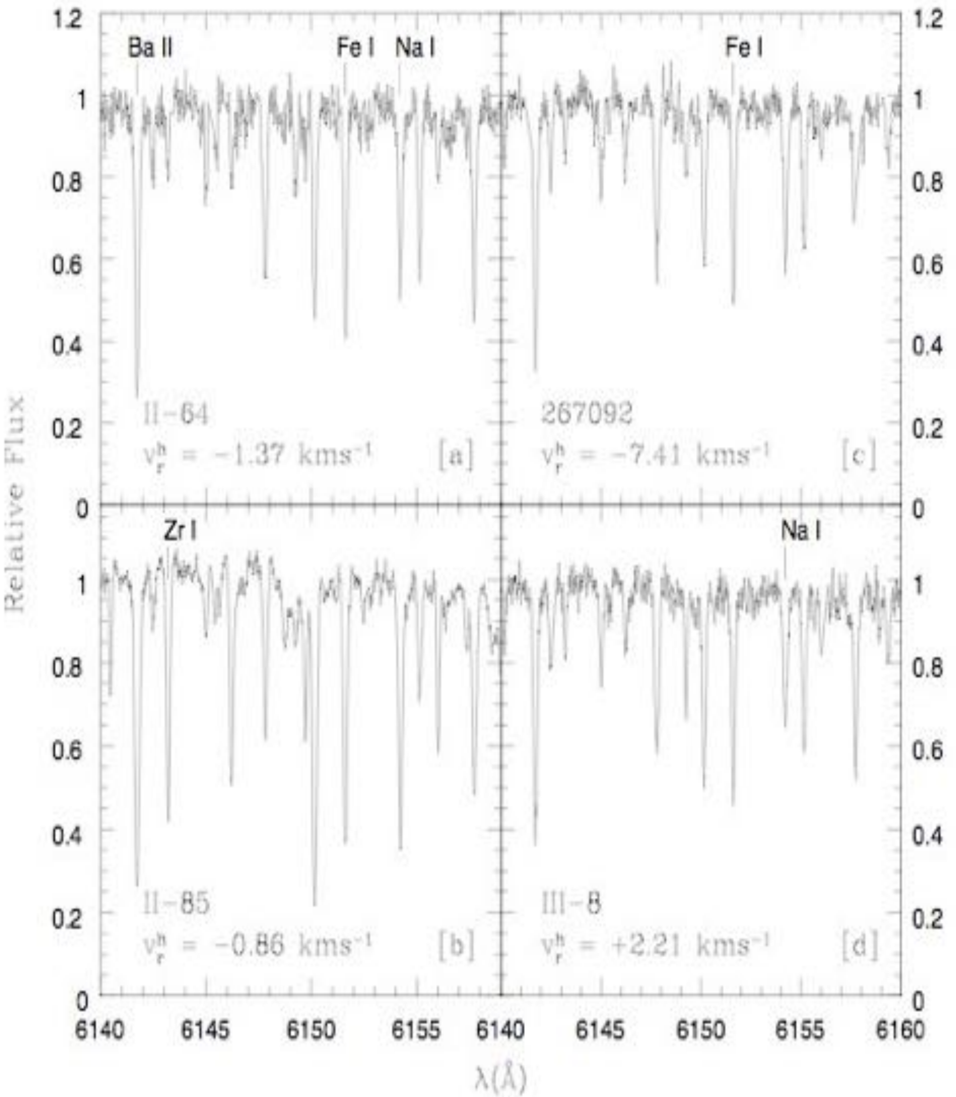
- F, G, K and M: dwarf, sub-giant and giant stars
- Dwarves, sub-giants and giants in star clusters
- Dwarf, sub-(giant) stars in gravitational microlenses
- Other tracers: Cepheids, OB stars, PNe, satellite dwarf galaxies, etc

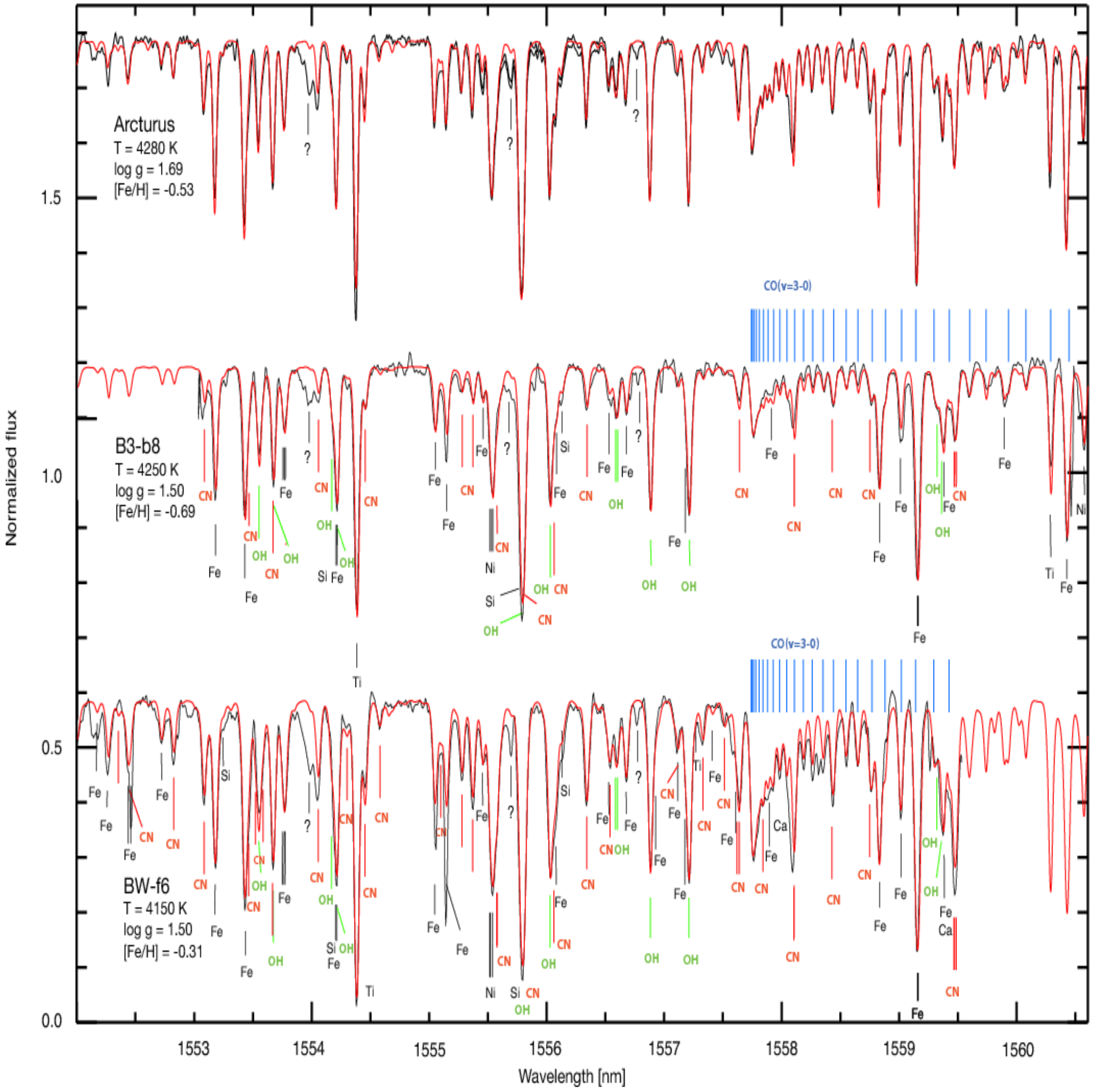
Main goal: Galactic Archeology

Grevesse & Sauval 1998;
Asplund et al 2009



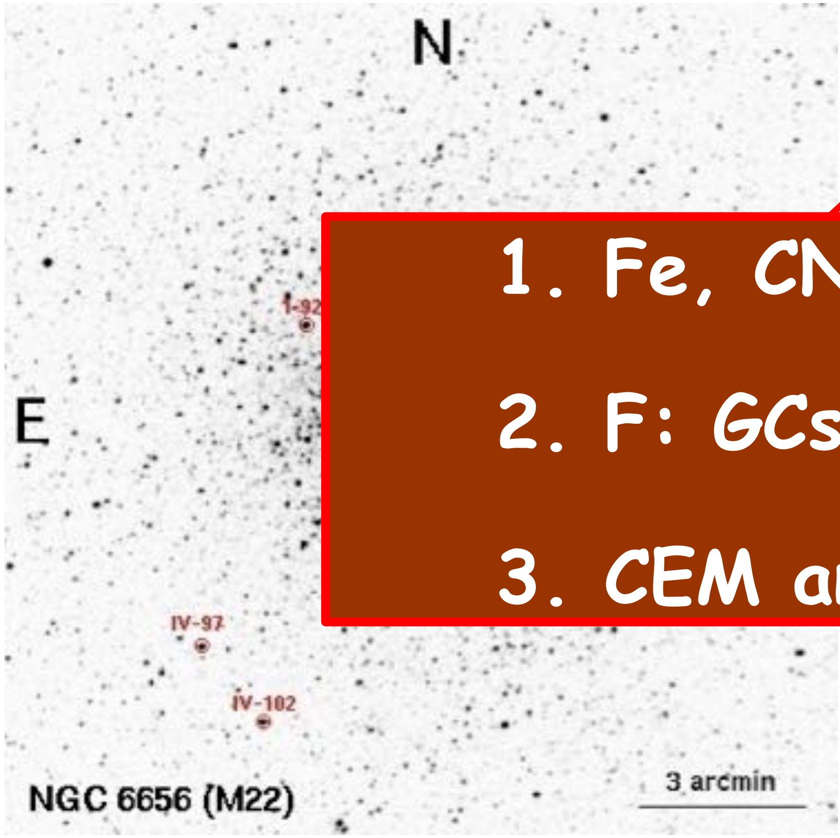
High Resolution Spectroscopy

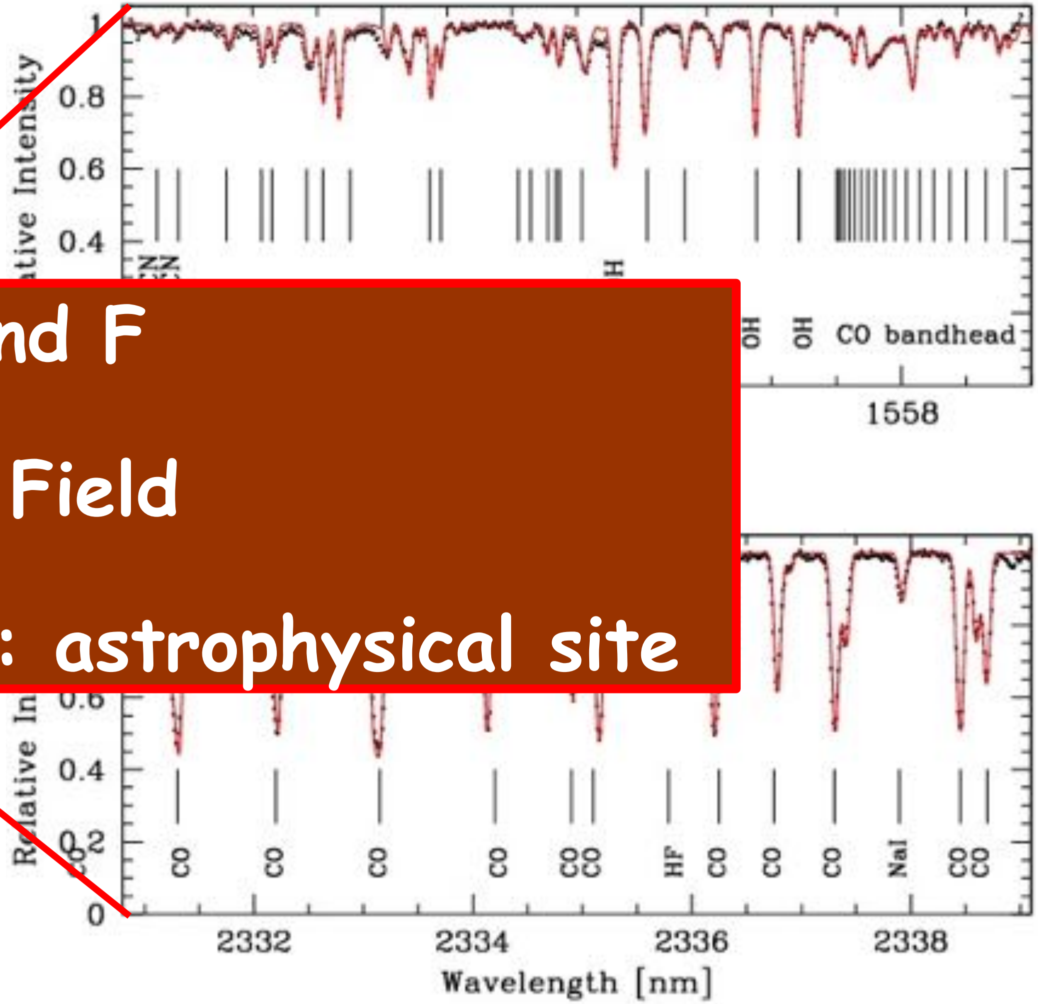




UVES@VLT: Alves-Brito et al. 2006 **CRIRES@VLT: Ryde … Alves-Brito et al. 2010**

High Resolution Spectroscopy

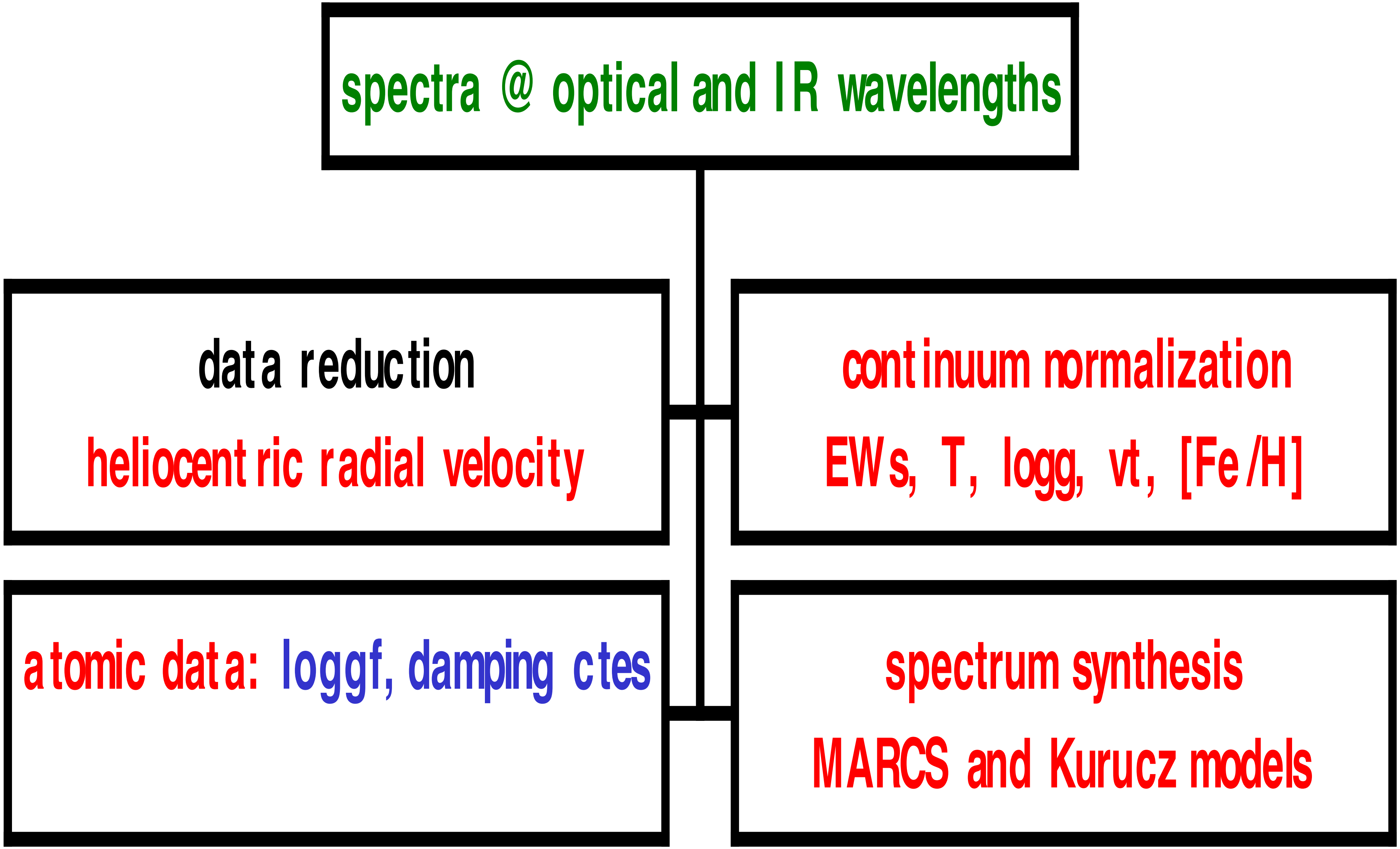




1. Fe, CNO and F
2. F: GCs vs. Field
3. CEM and F: astrophysical site

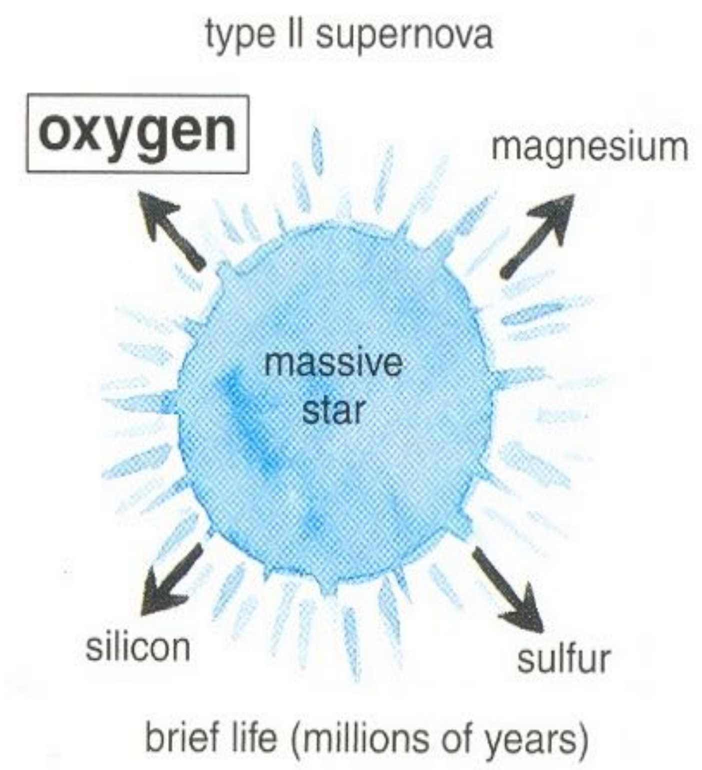
Alves-Brito et al. 2012; see also Dorazi+ 2013

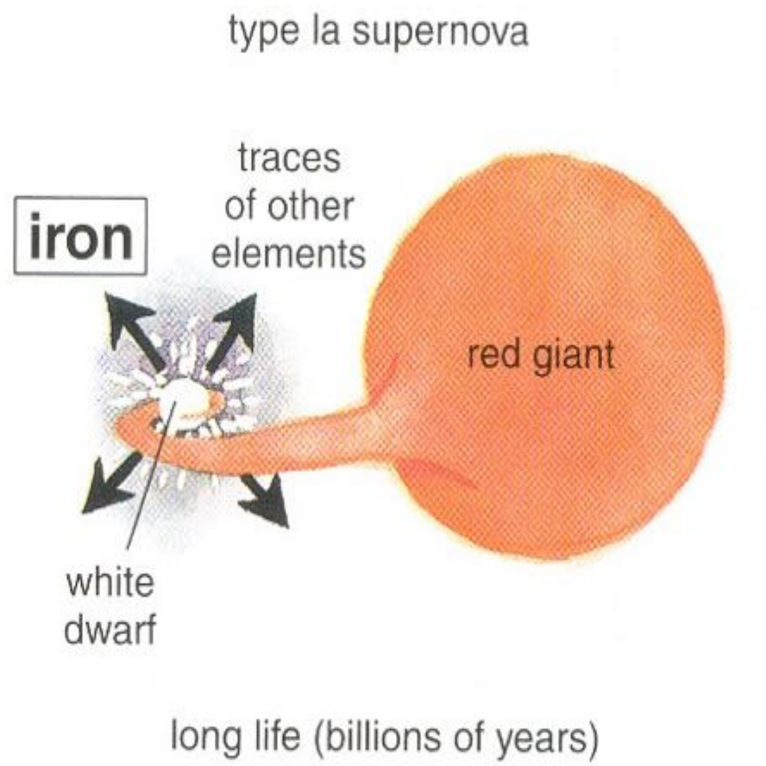
Methods


spectra @ optical and IR wavelengths
data reduction
heliocentric radial velocity
continuum normalization
EWs, T, logg, vt, [Fe/H]
atomic data: loggf, damping ctes
spectrum synthesis
MARCS and Kurucz models

Chemical Enrichment: [X/Fe] ~ SF

e.g. Tinsley 1979; Chiappini et al. 2004; Kobayashi et al. 2006





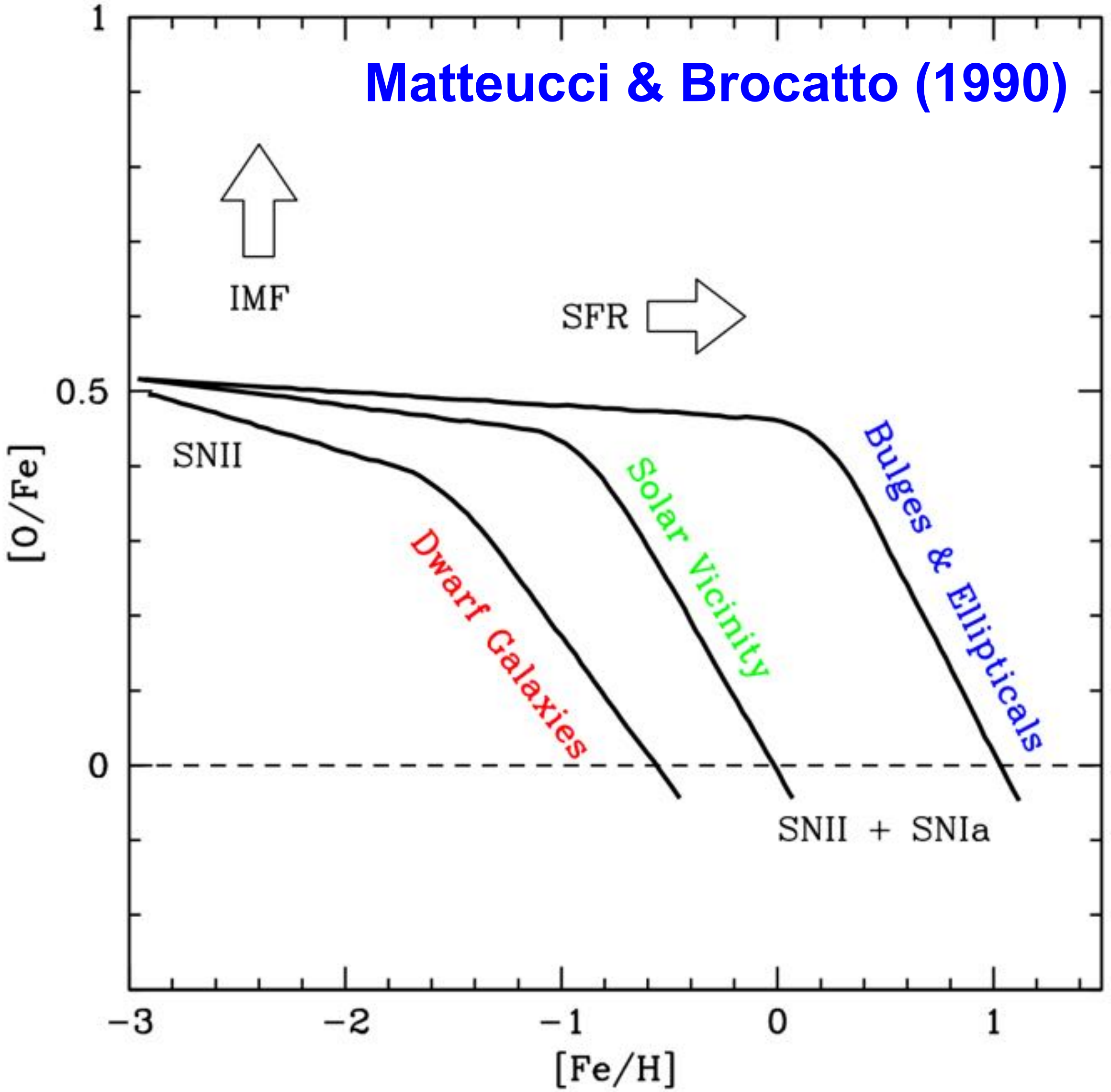
O (million of years)

Fe (billion of years)

$[Fe/H] = \log(Fe/H)_{star} - \log(Fe/H)_{Sun}$:

$[O/Fe] = \log(O/Fe)_{star} - \log(O/Fe)_{Sun}$

Chemical Enrichment: [X/Fe] ~ SF



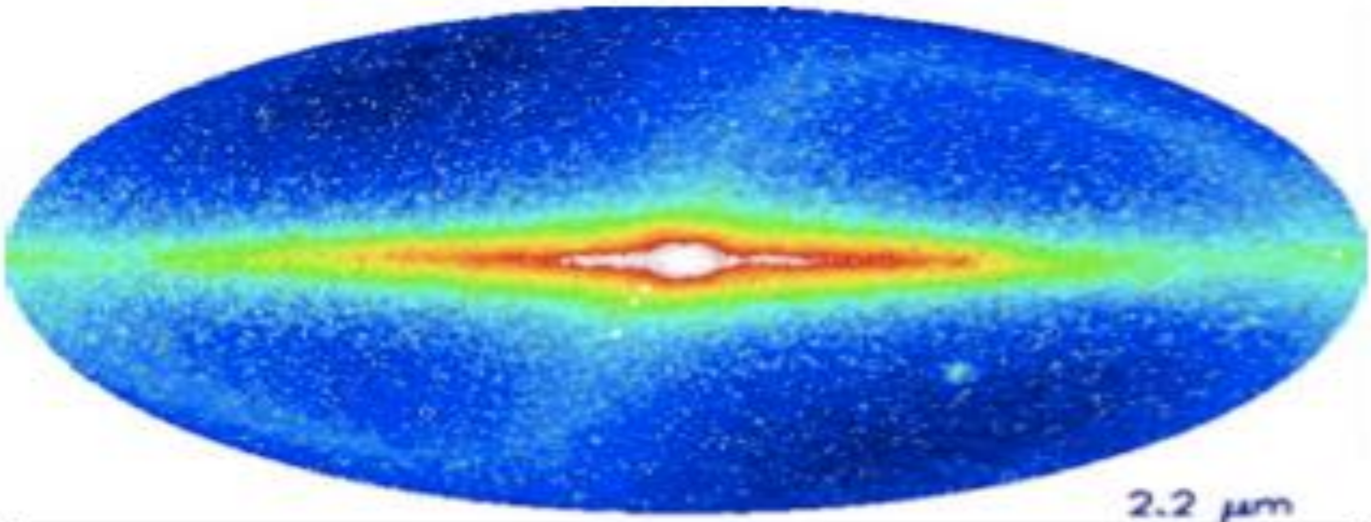
Observational Constraints

- Solar abundance pattern
- MDF: distribution of stars vs fe/h, age-fe/h and SFH
- Evolution of abundance ratios
- SFR and SN rates
- Age-metallicity relationship
- Gas and abundance gradient
- Isotopic abundance

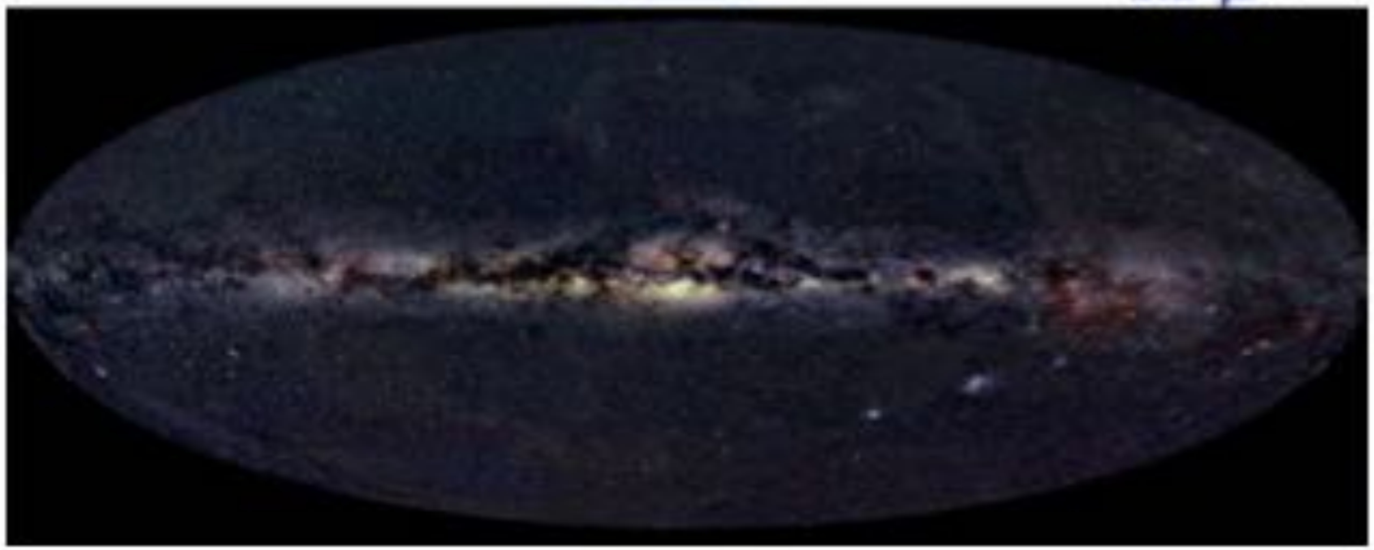
the distribution of stars as a function of metallicity, since this represents the convolution of the age–metallicity relationship and the star formation history

Results for the Galactic Bulge

When and how the Galactic bulge was formed?



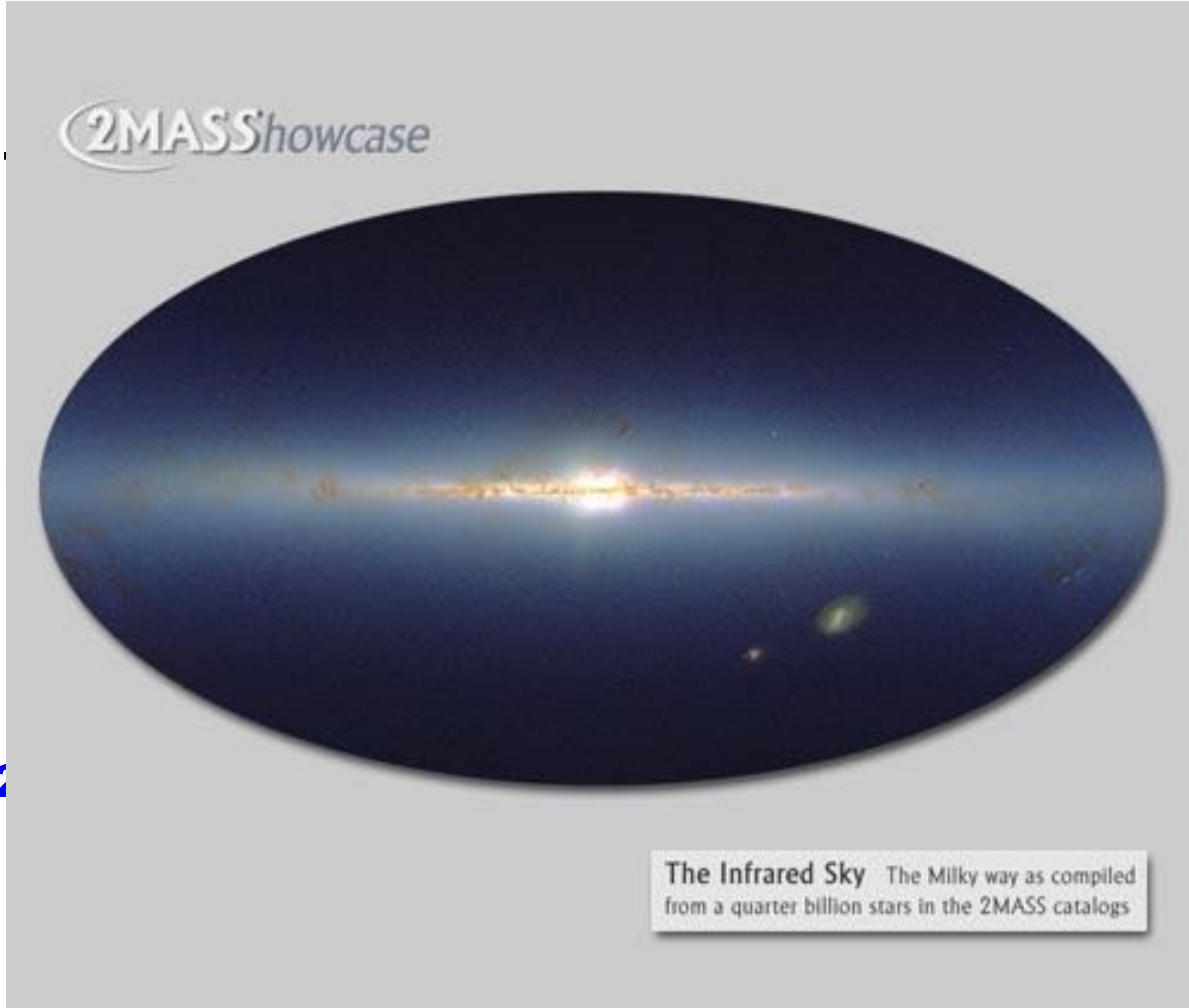
DIRBE@COBE
Dwek et al. 1995



OPTICAL IMAGE
Axel Mallenhoff 2001

When and how the Galactic bulge was formed?

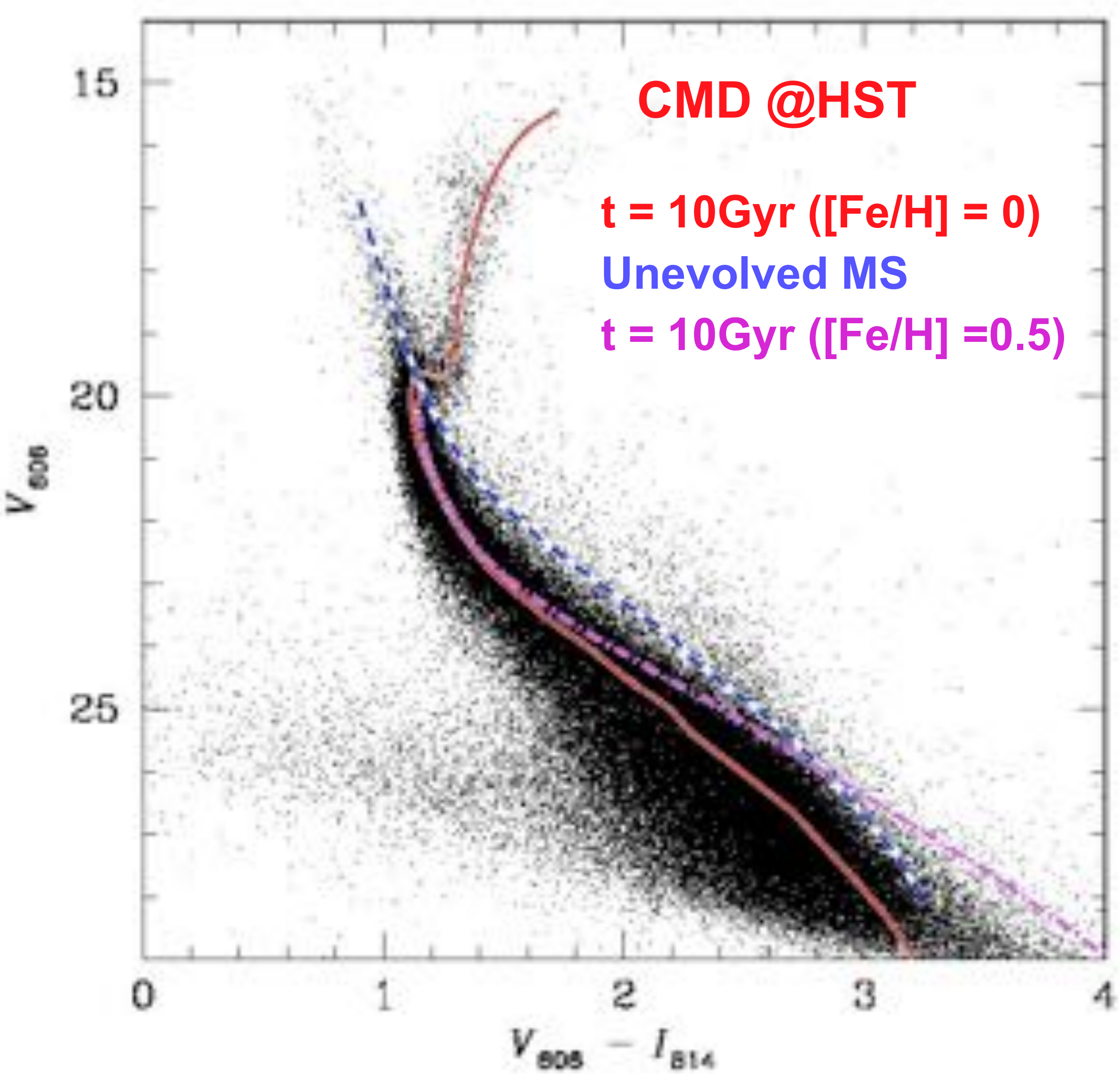
stellar conten
(classical)
vs.
morphology
(dynamical
instability)



Kormendy & Kennicutti 2

see also Elmegreen et al.

Bulge Colour Magnitude Diagram



t = GC +- 2.5 Gyr

(Ortolani et al. 1995; Zoccali et al. 2003)

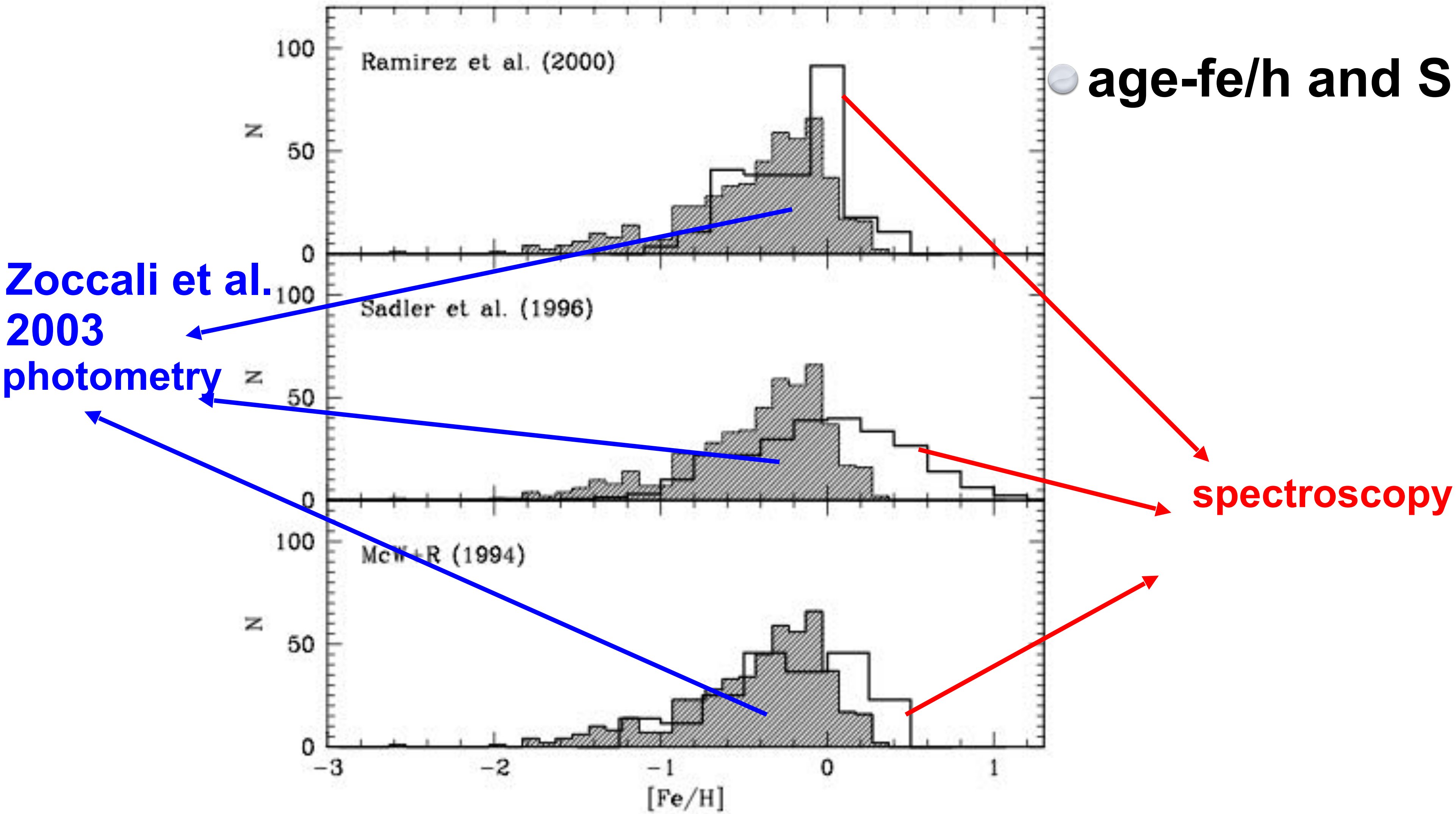
~245,000 stars

l,b = $1^0.25,-2^0.65$

Sahu et al. 2006

Bulge Metallicity Distribution Function

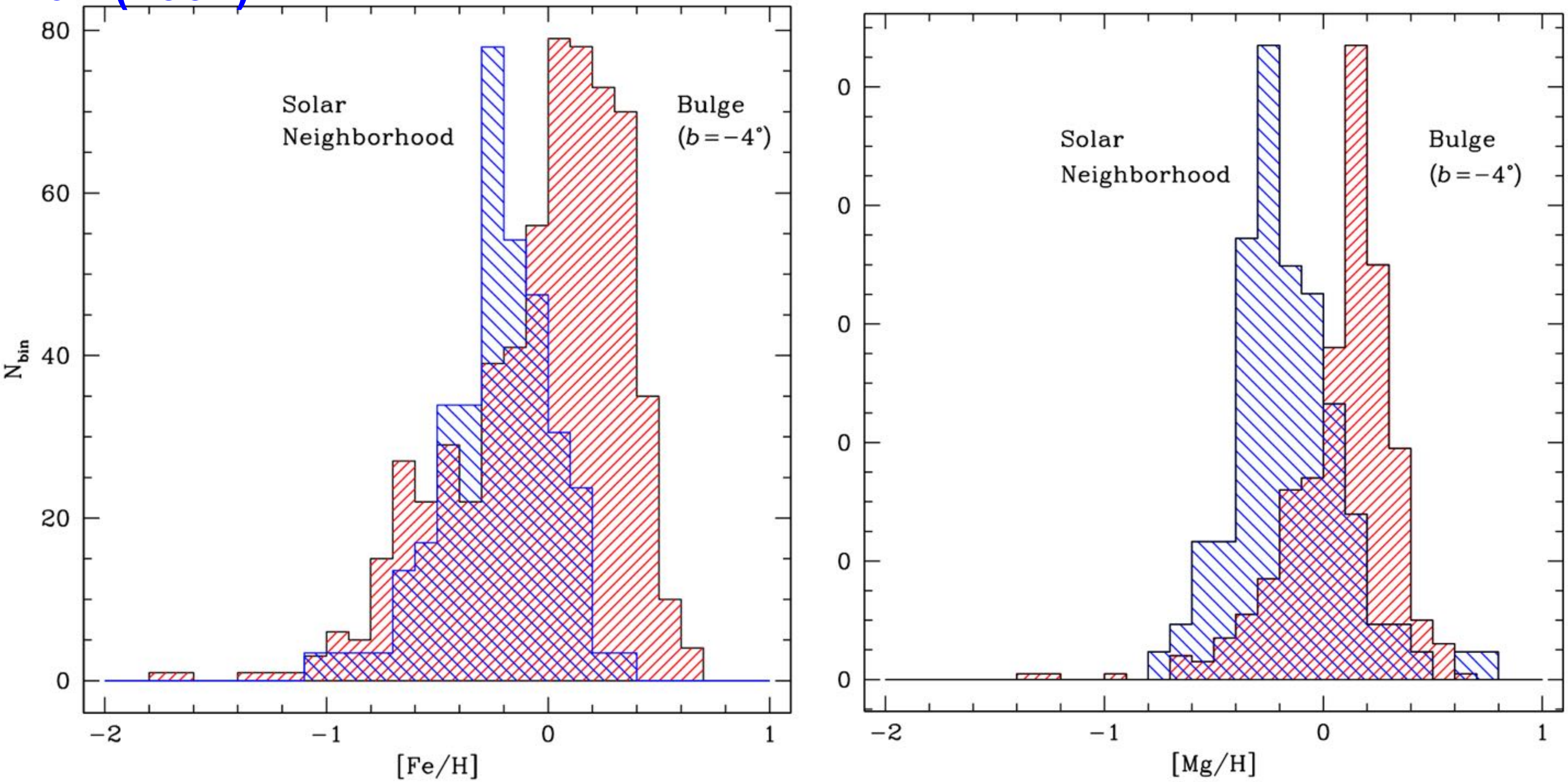
- **age-fe/h and SFH**



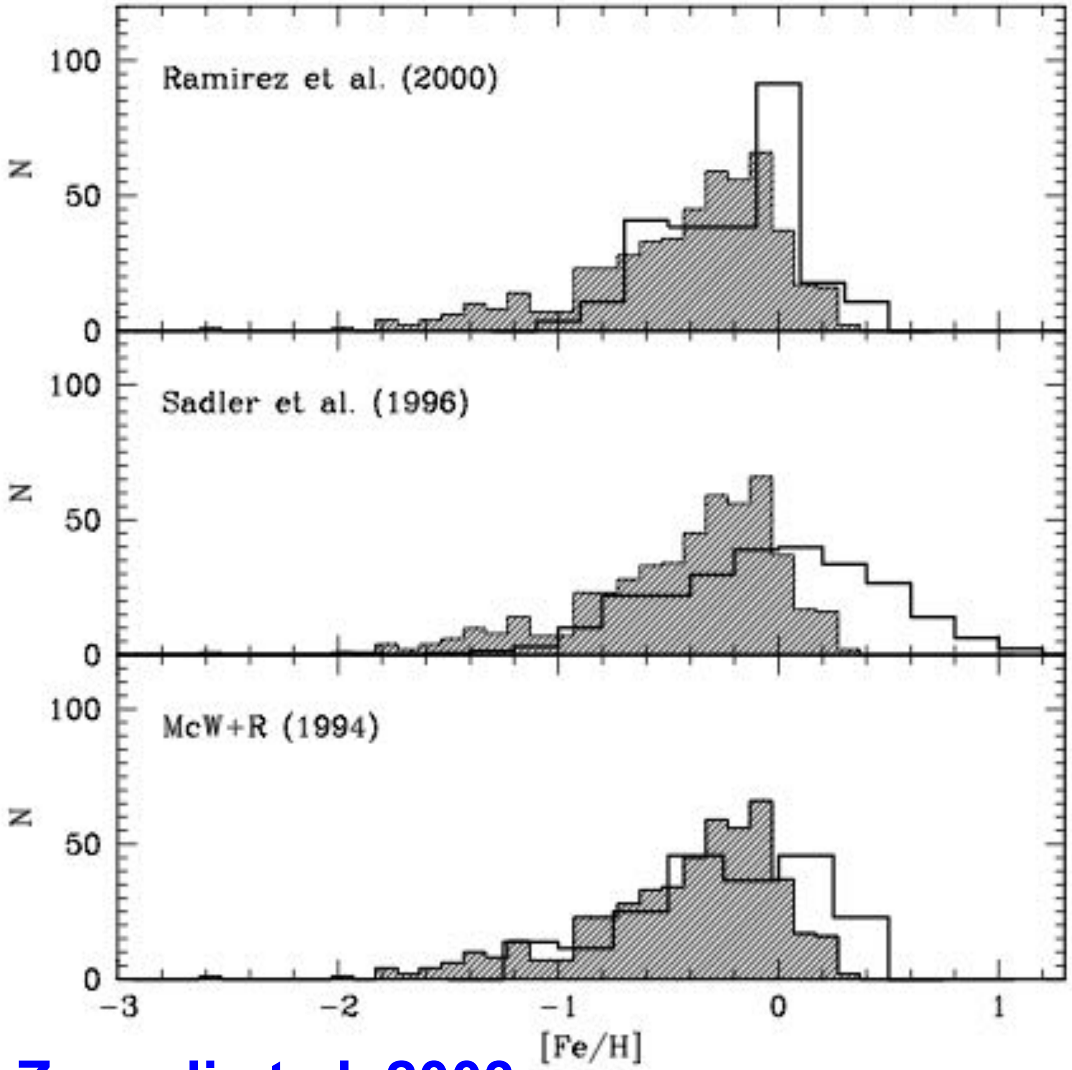
Bulge Metallicity Distribution Function

Solar, scaled to the peak number of bulge stars : Allende Pietro et al. (2004)

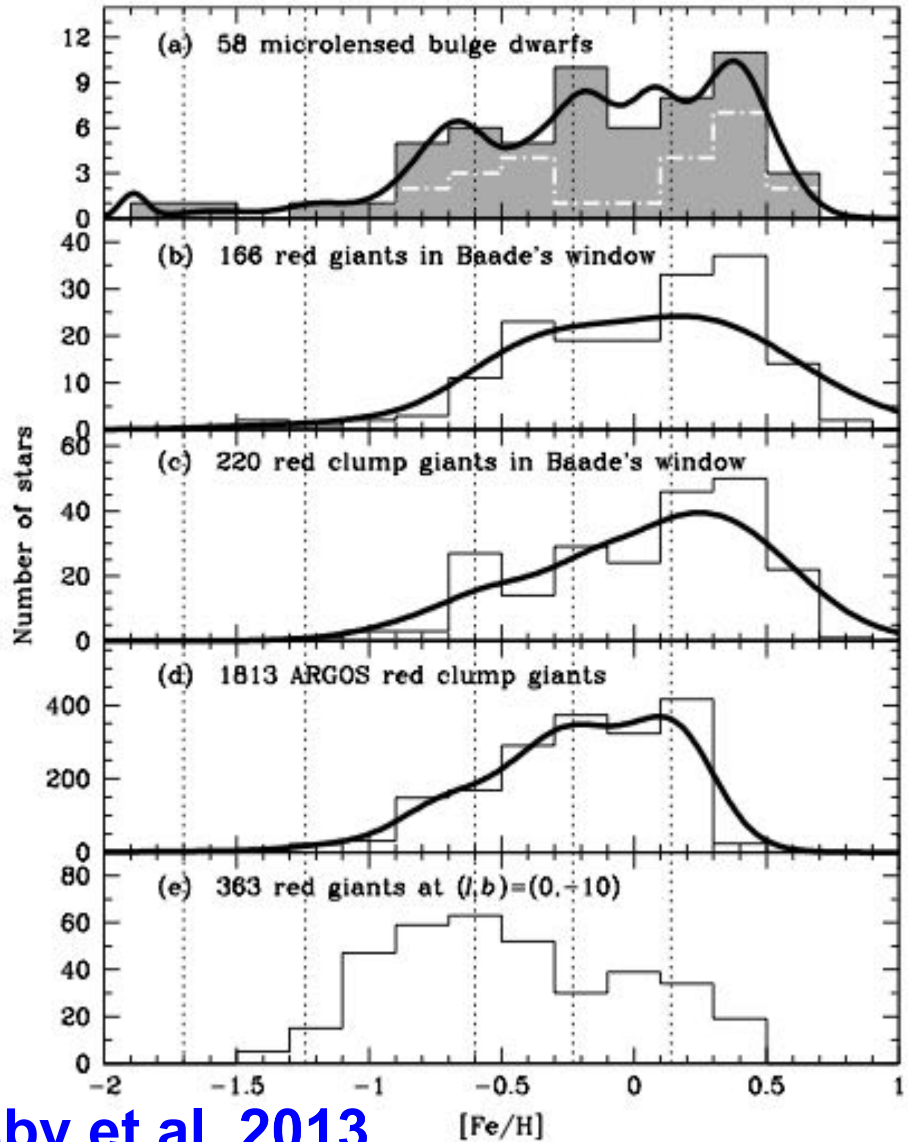
Bulge: Gonzalez+ (2015) and Hill+ (2011)



Bulge Trouble

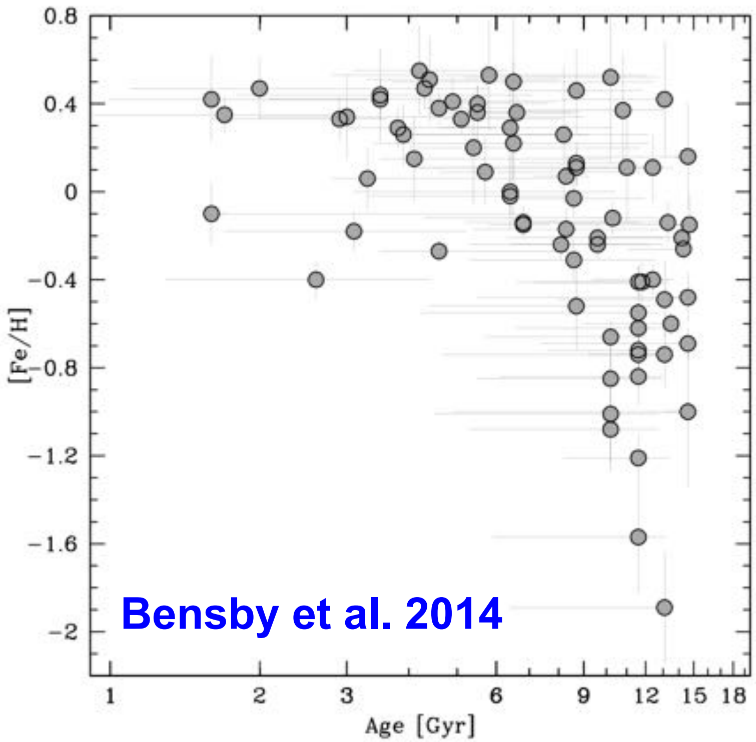


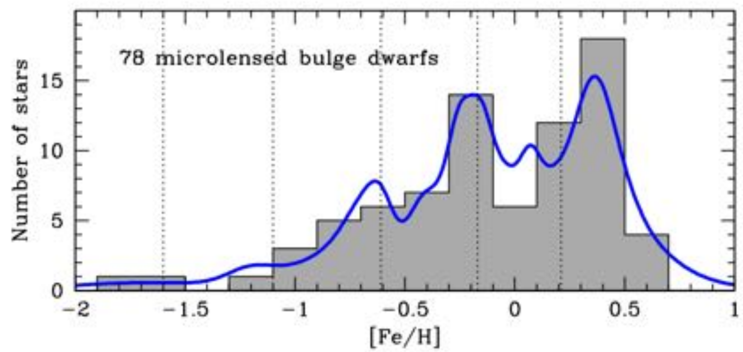
Zoccali et al. 2003

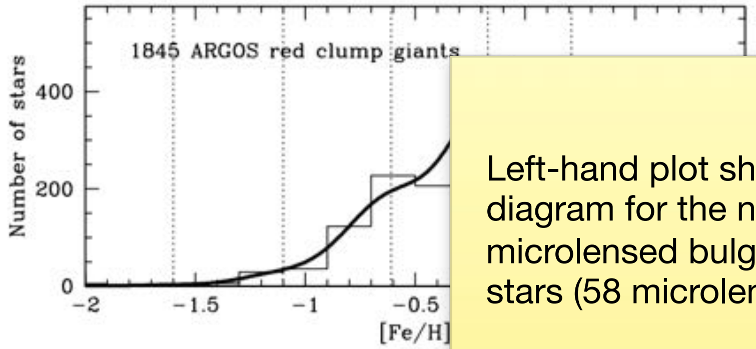


Bensby et al. 2013

Bulge Trouble







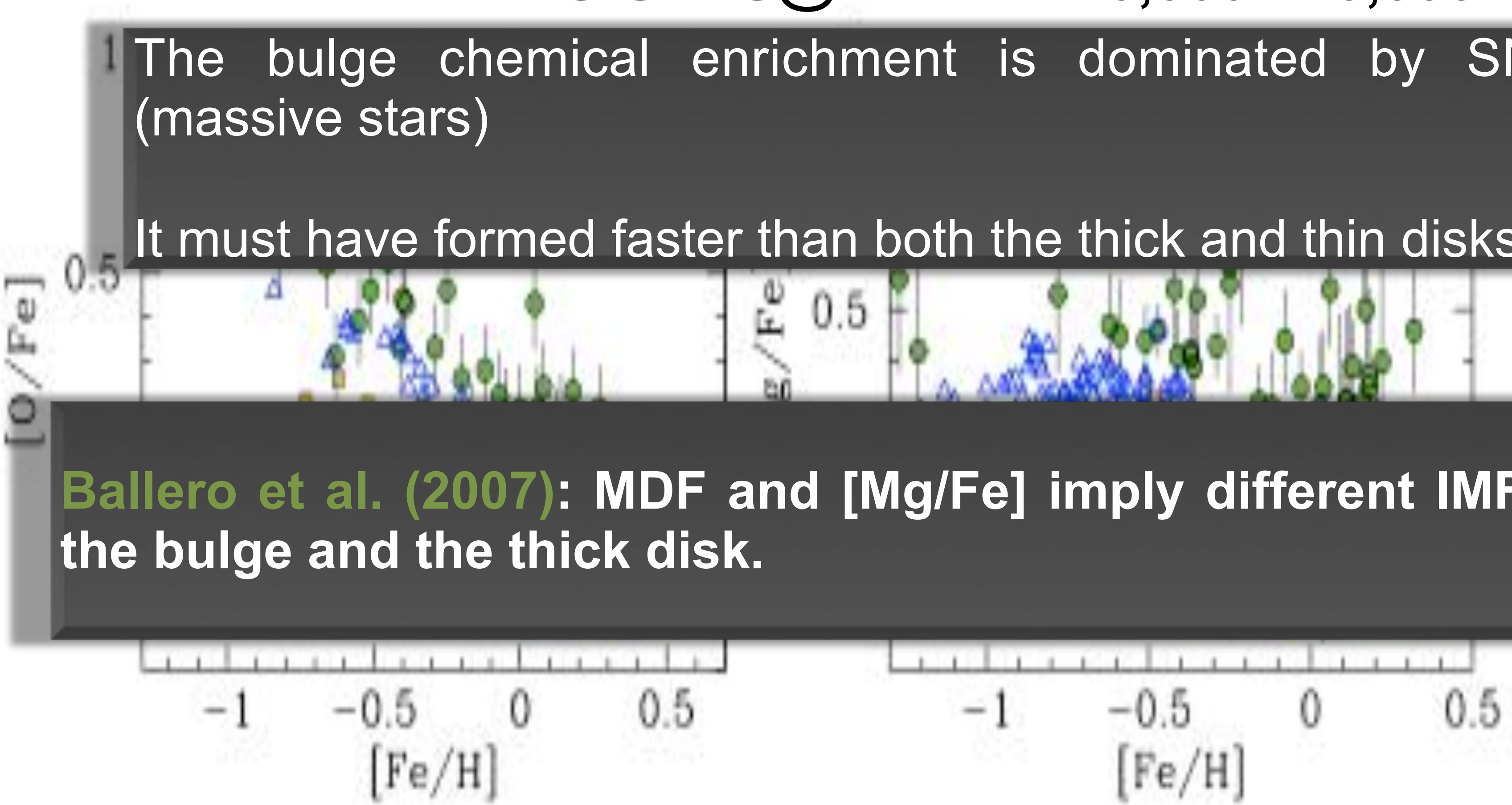
Left-hand plot shows the age-metallicity diagram for the now in total 78 microlensed bulge dwarf and subgiant stars (58 microlensed dwarf stars from

- See Dékány et al 2015, for Cepheidas (ag
- latitudes b = −5° , −7.5° , −10° (integrated over the whole range o longitudes −15° ≤ l ≤ 15°)
- 5 gaussians: A, B, C, D and E; [Fe/H]=0.1,-0.3,-0.7,-1.2,-1.7 dex

Bulge (giants) vs. Disks (dwarves)

Lecureur et al. 2007 and previous works

FLAMES:UVES@VLT: R = 20,000 - 40,000



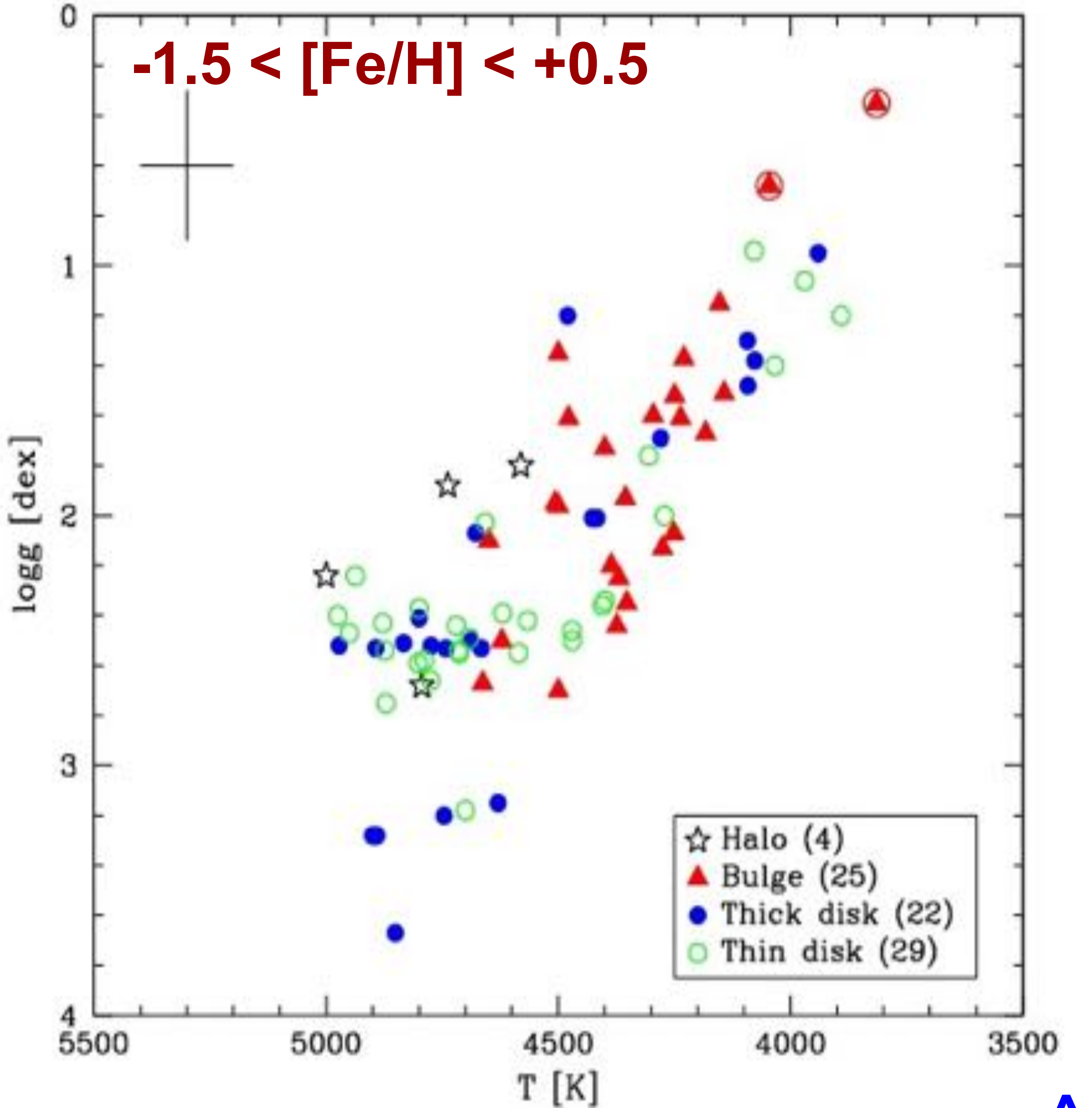
The bulge chemical enrichment is dominated by SNII (massive stars)

It must have formed faster than both the thick and thin disks

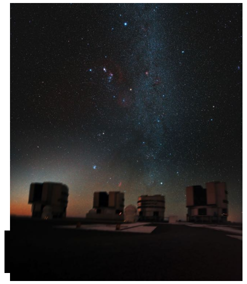
Ballero et al. (2007): MDF and [Mg/Fe] imply different IMFs for the bulge and the thick disk.

$[O/Fe] = \log(O/Fe)_{star} - \log(O/Fe)_{Sun}$

High Resolution Spectra: Innovation



PHOENIX@Gemini
MIKE@Magellan
UVES@VLT
ELODIE@OHP
2dcoude@McDonal
HIRES@Keck

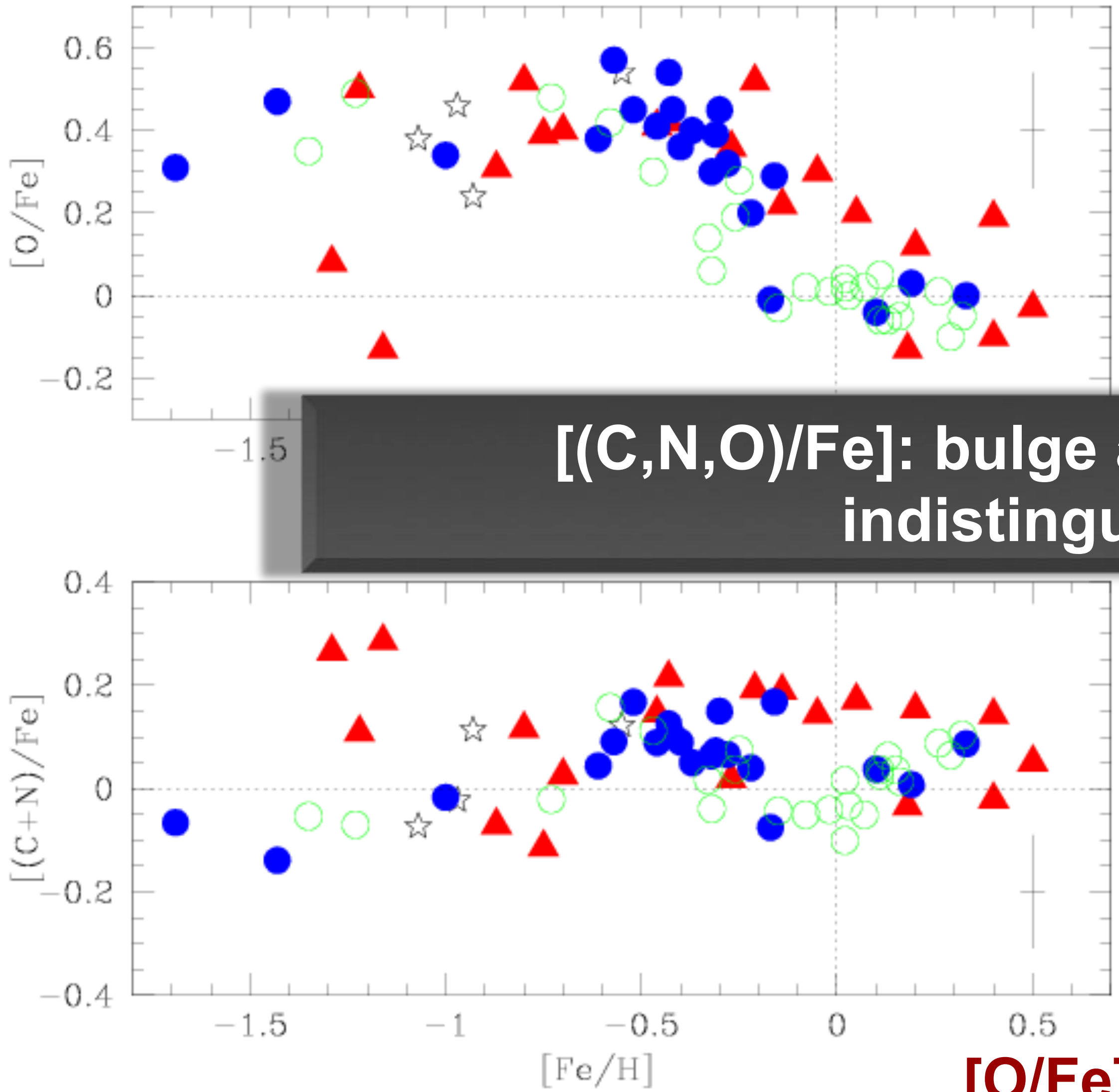


R ≥ 60,000

Alves-Brito et al. (2010)

Infrared Results

Meléndez, Asplund, Alves-Brito et al. 2008, A&A, L484, 2



[(C,N,O)/Fe]: bulge and thick disk are indistinguishable

Phoenix@Gemini-S : R = 50,000

e/H]

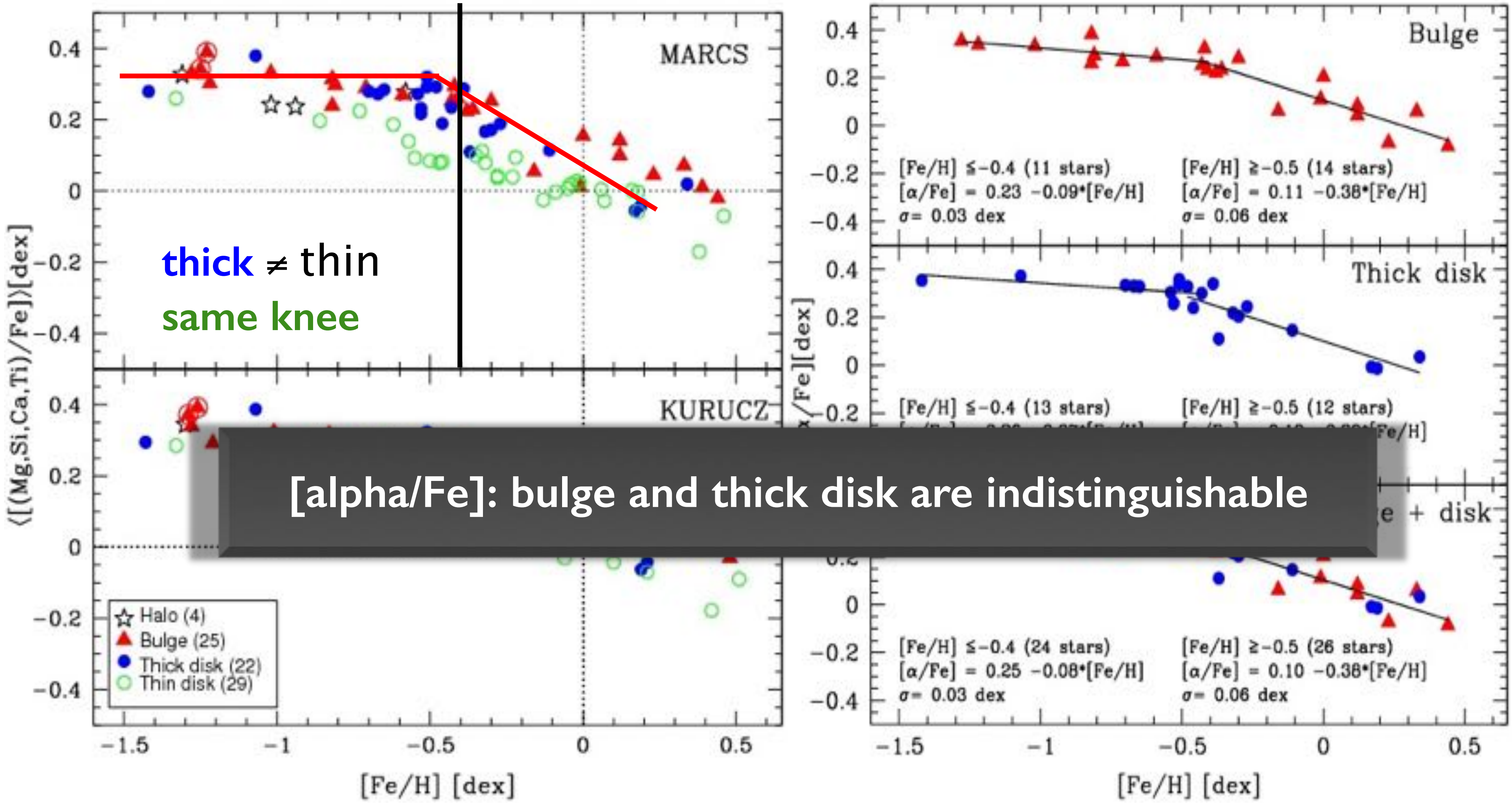
[O/Fe] = 0.39 - 0.01*[Fe/H]

Δ[O/Fe] = 0.03 ± 0.09 dex

[O/Fe] = log(O/Fe)_star– log(O/Fe)_sun

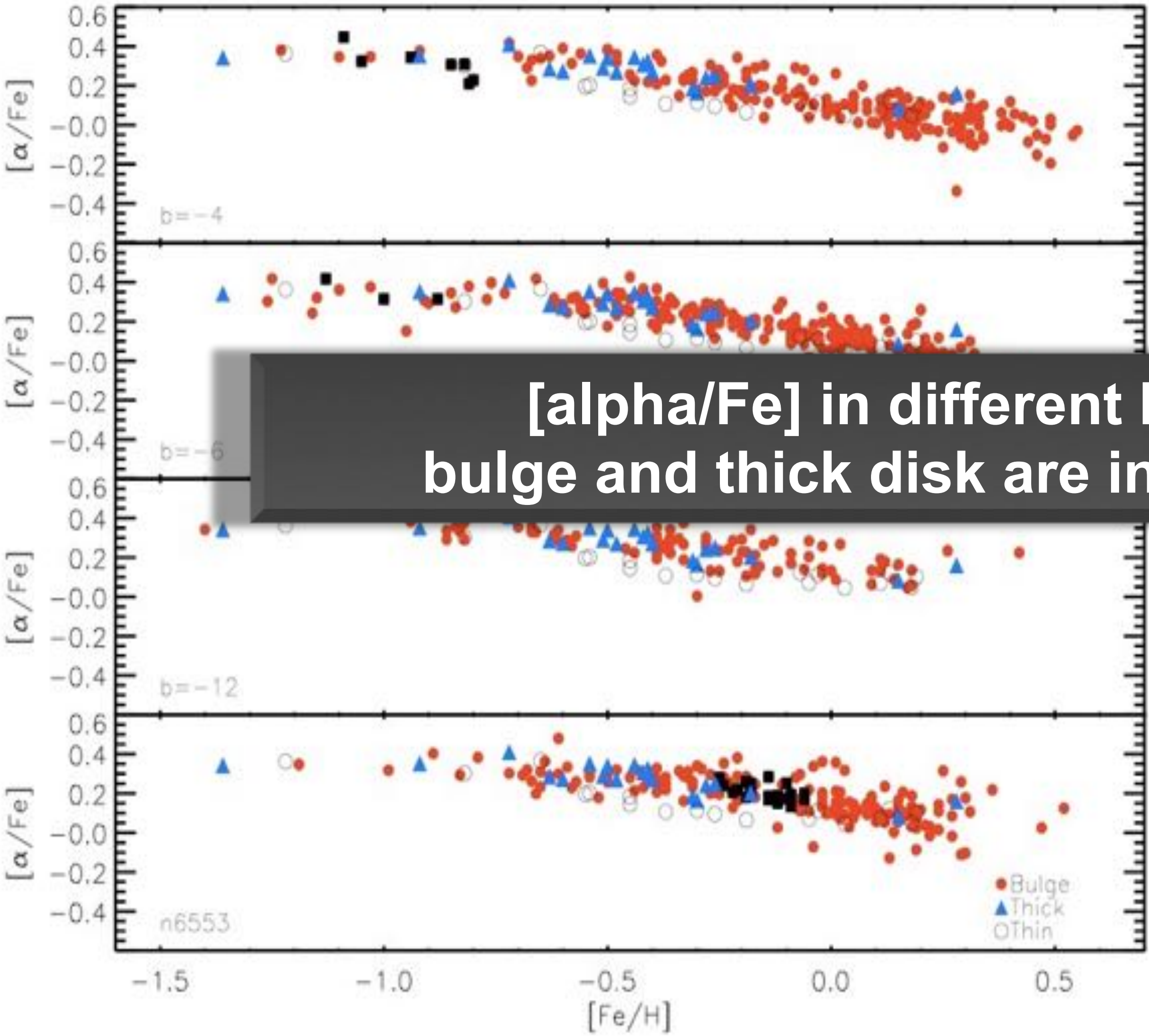
Optical Results

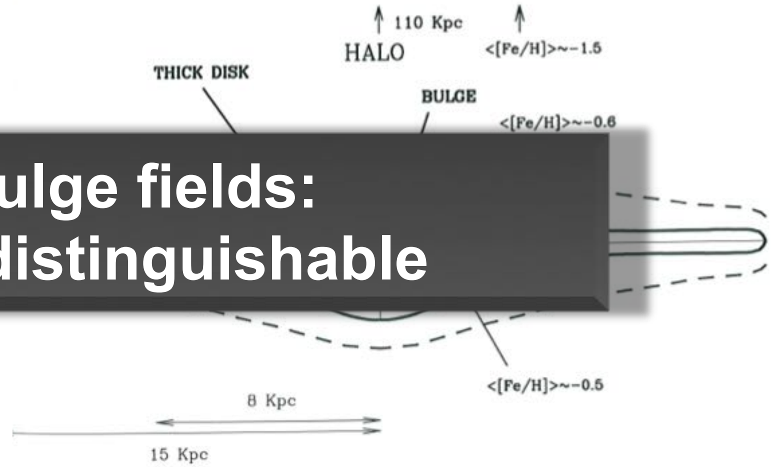
Alves-Brito et al. 2010, A&A, 513, 35



Optical Results

Gonzalez, …, Alves-Brito et al. 2011, A&A, 530, 54





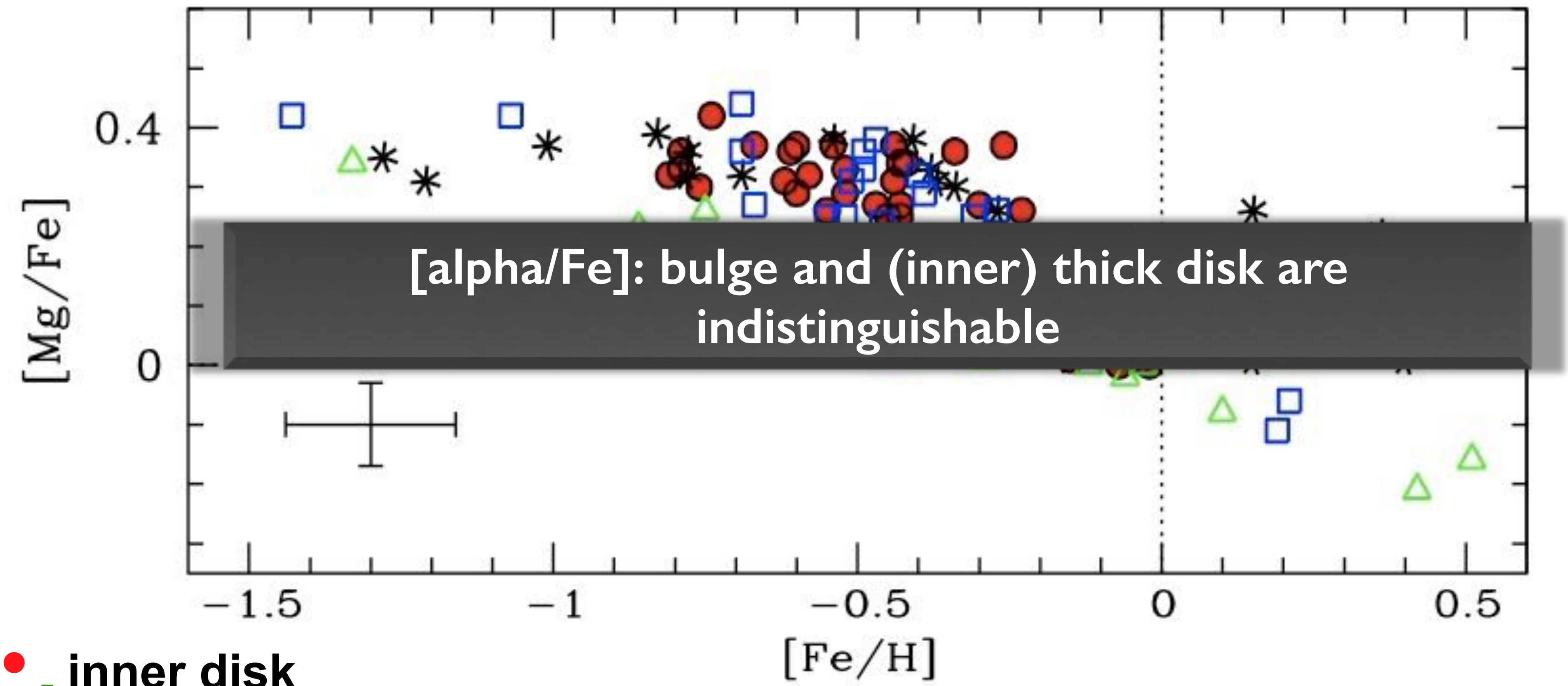
[alpha/Fe] in different bulge fields:
bulge and thick disk are indistinguishable

FLAMES@VLT
~700 estrelas
4 fields

Optical Results: Inner Disk

Bensby, Alves-Brito, Oey et al. 2010, A&A, 516, 13

MIKE@Magellan: R = 55,000 : S/N = 100 (44 giants : 3-7 kpc)



• inner disk

▯, Δ local thick- and thin-disk

*** bulge**

Old Bulge

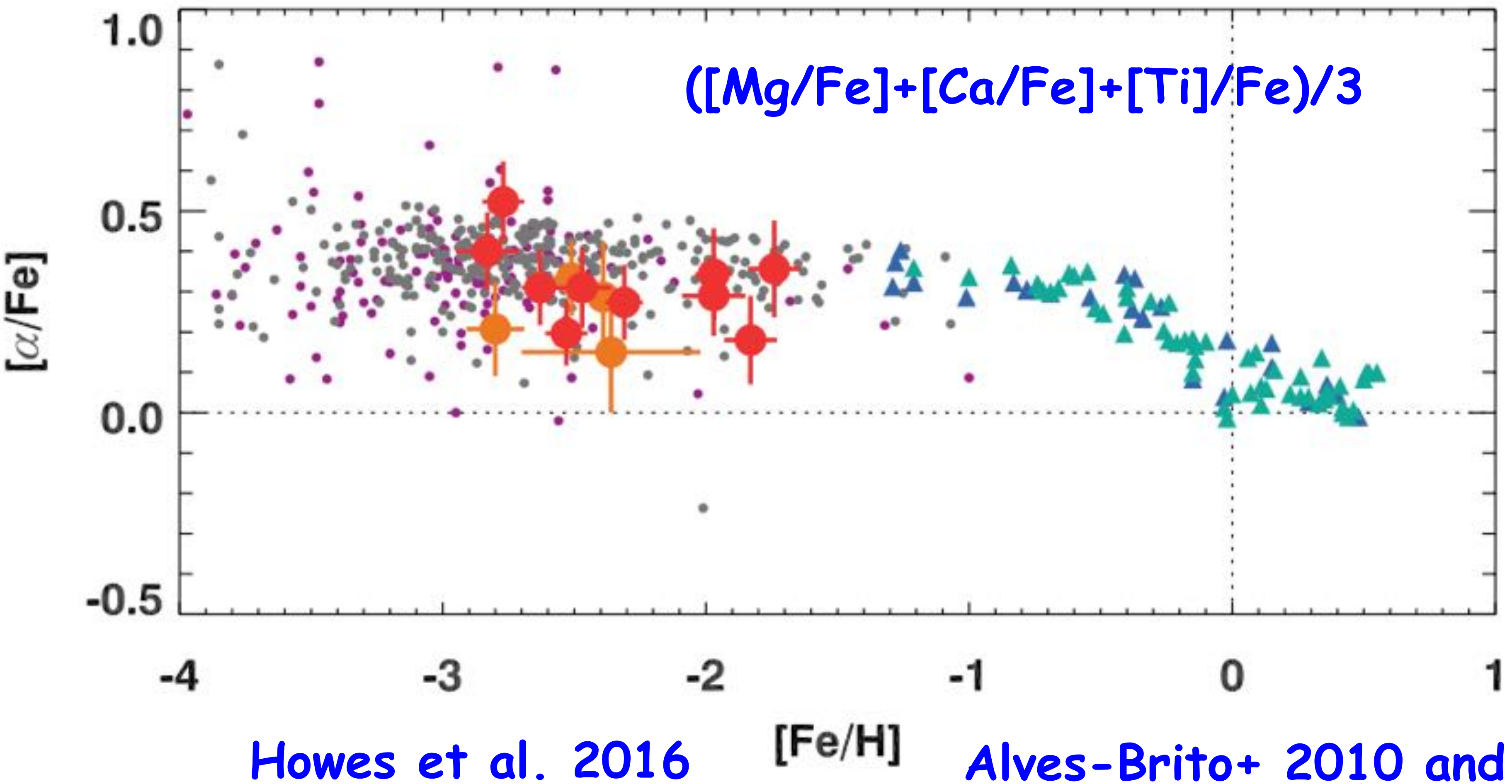
Howes et al. 2016

- The EMBLA (Extremely Metal-poor BuLge stars with AAOmega) Survey successfully searched for old, metal-poor stars by making use of the distinctive SkyMapper photometric filters to discover candidate metal-poor stars in the bulge

- Their metal-poor nature was then confirmed using the AAOmega spectrograph on the AAT

- 10 bulge stars with $-2.8<[Fe/H]<-1.7$ from MIKE/Magellan observations

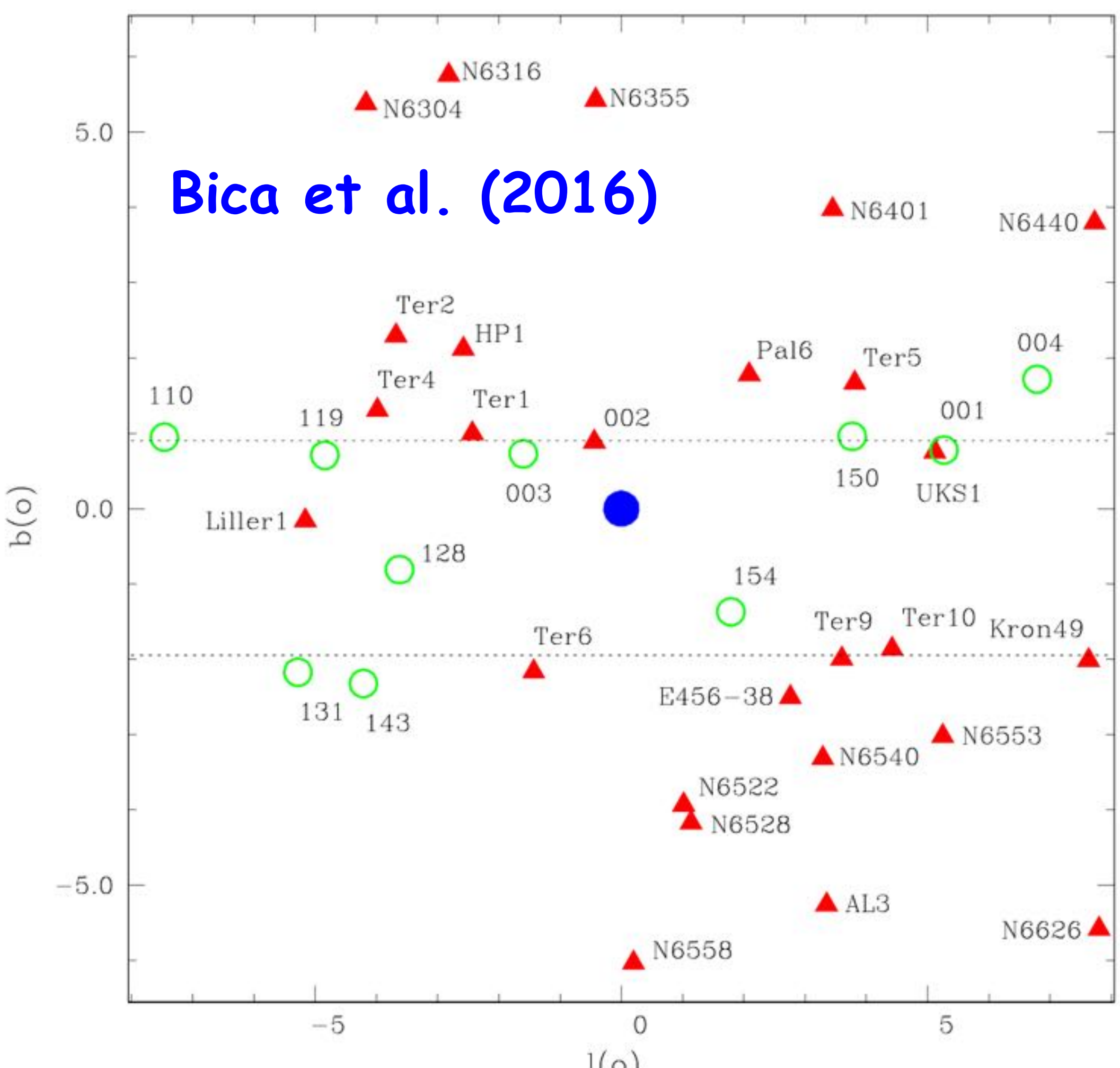
Old Bulge



Howes et al. 2016

Alves-Brito+ 2010 and others

Old Bulge (Globular Clusters)



Projected bulge clusters in Galactic coordinates.

Red filled triangles: bulge

GCs Open circles: VVV clusters and candidates

Blue filled circle: Galactic center

Dotted lines: encompass the so-called forbidden zone for optical globular clusters.

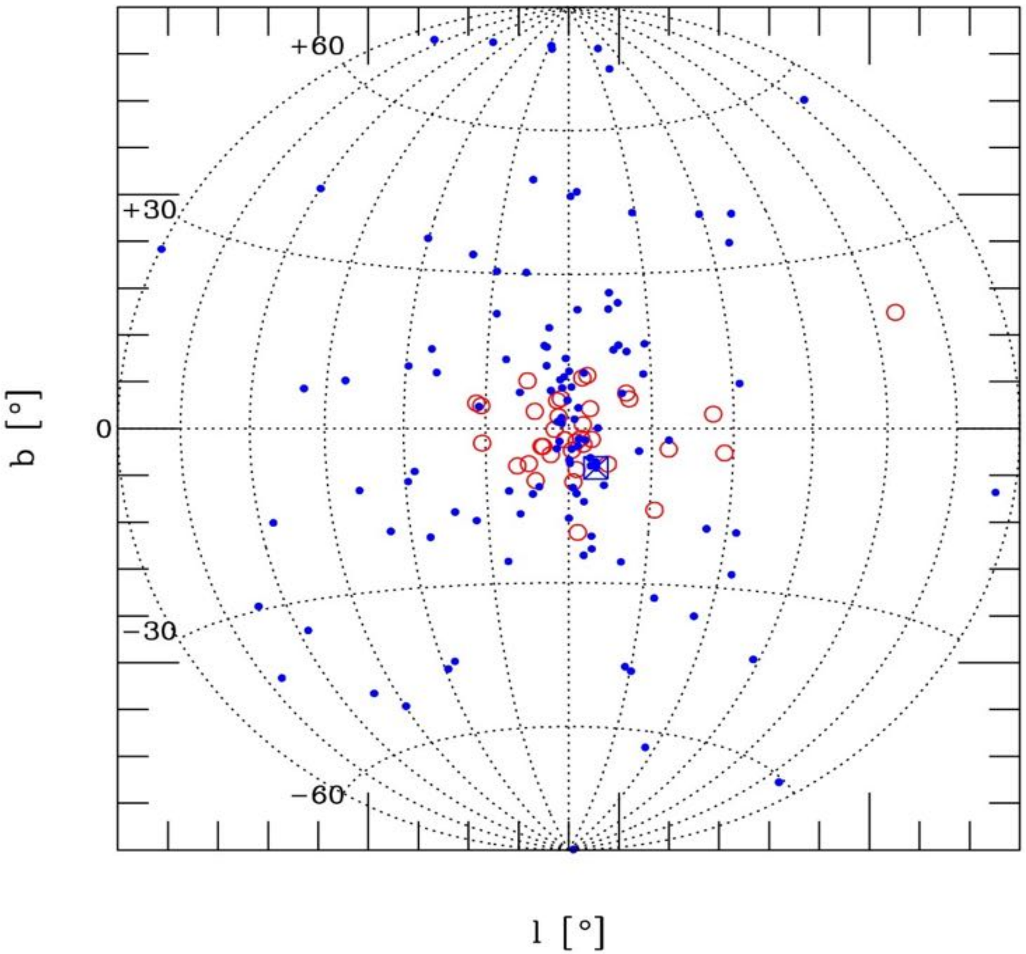
Globular Clusters

Gravitationally-bound systems of ~10^5Msun

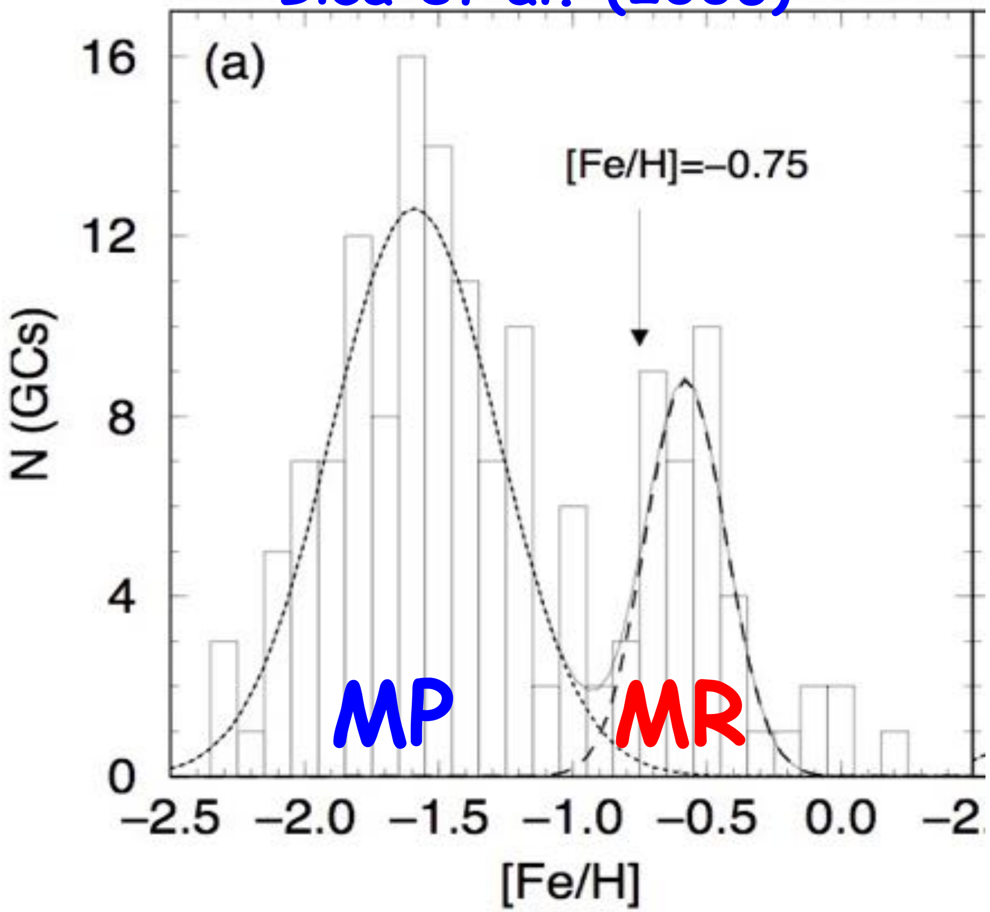
- **Among the oldest objects in the universe**
- **Very bright in external galaxies**
- **Present in all Hubble morphological types**

Harris 1991; Gratton et al. 2004; Brodie & Strader 2006

Globular Clusters



Bica et al. (2006)



- Catalogue used: Harris 1996

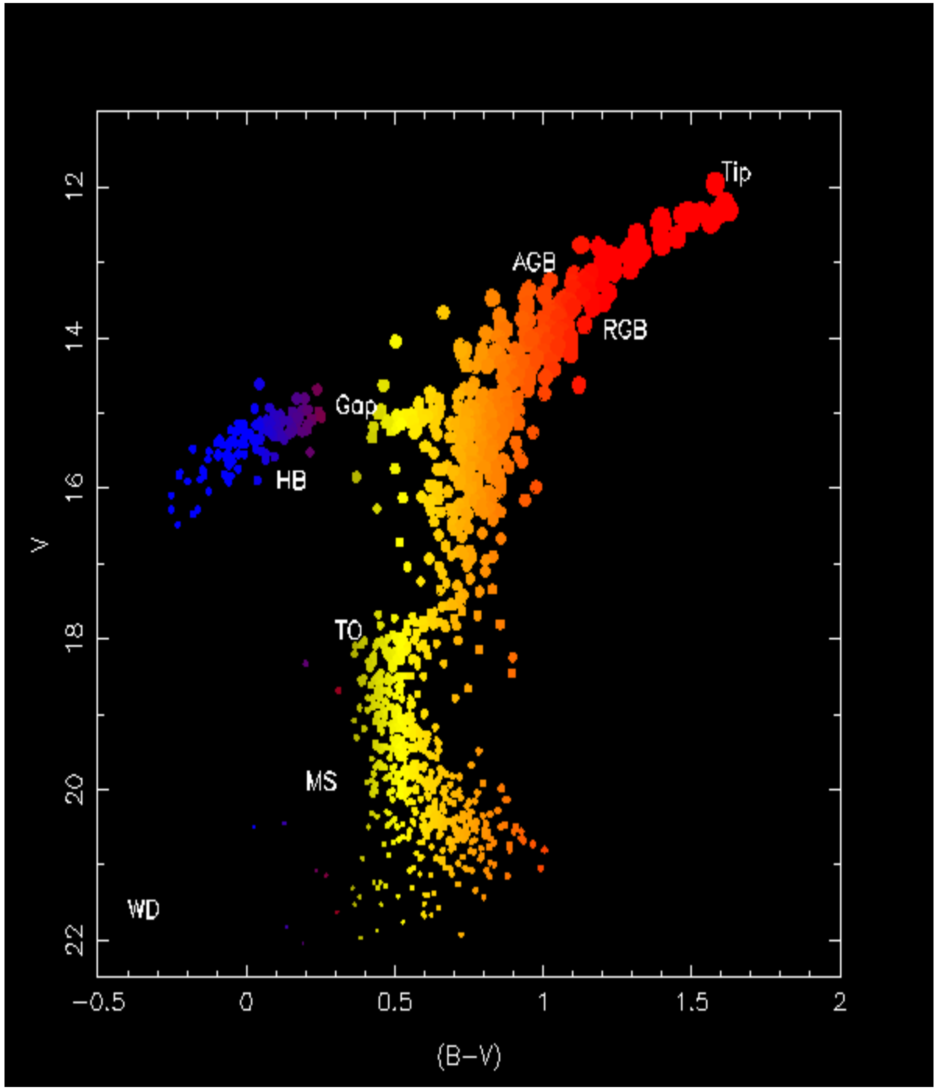
[Fe/H] = log(Fe/H)_star - log(Fe/H)_sun

Globular Clusters

Characterizing a SSP:

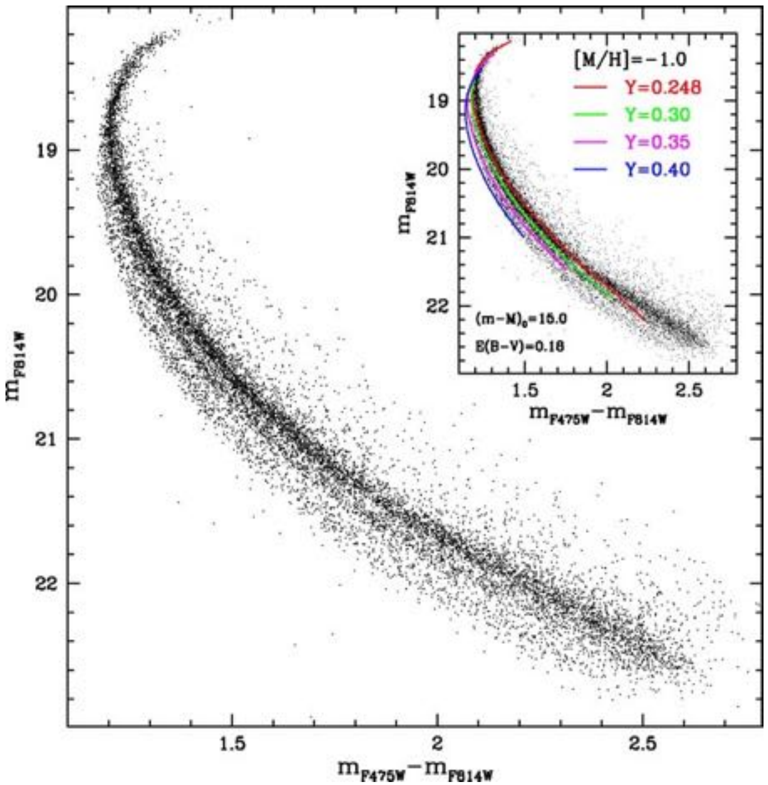
(Renzini & Buzzoni 1986)

- Age
- Composition (Y and Z)
- IMF



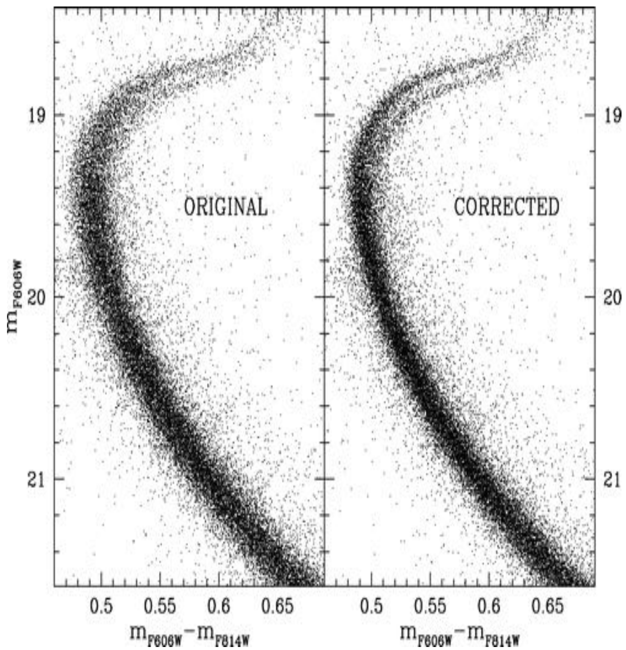
Globular Clusters

Galactic



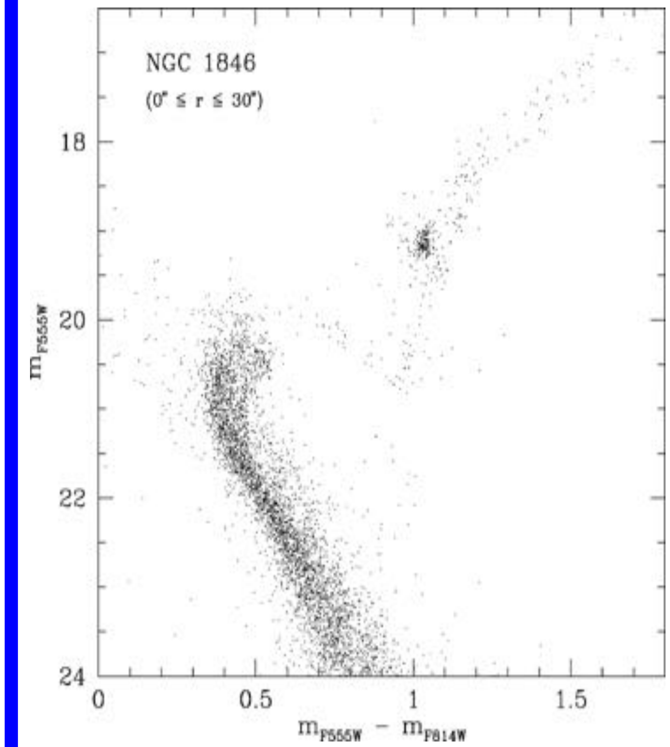
NGC2808: Piotto et al. 2007

NGC1851: Milone et al. 2008



See also Gratton+ 2004; 2012; Piotto et al. 2015

Extragalactic

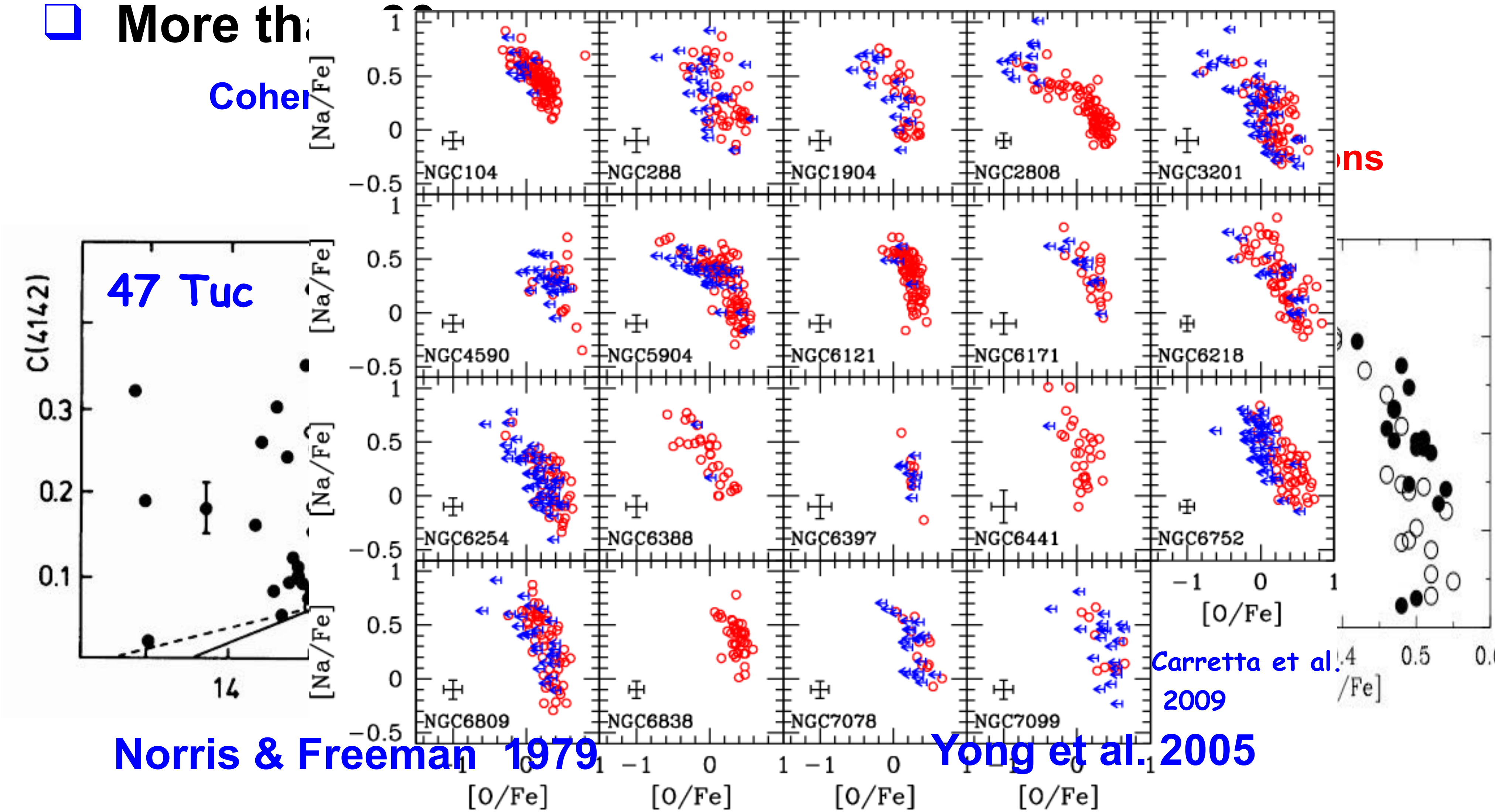


LMC NGC1846:

Mackey et al. 2007

Globular Clusters

- More tha



Norris & Freeman 1979

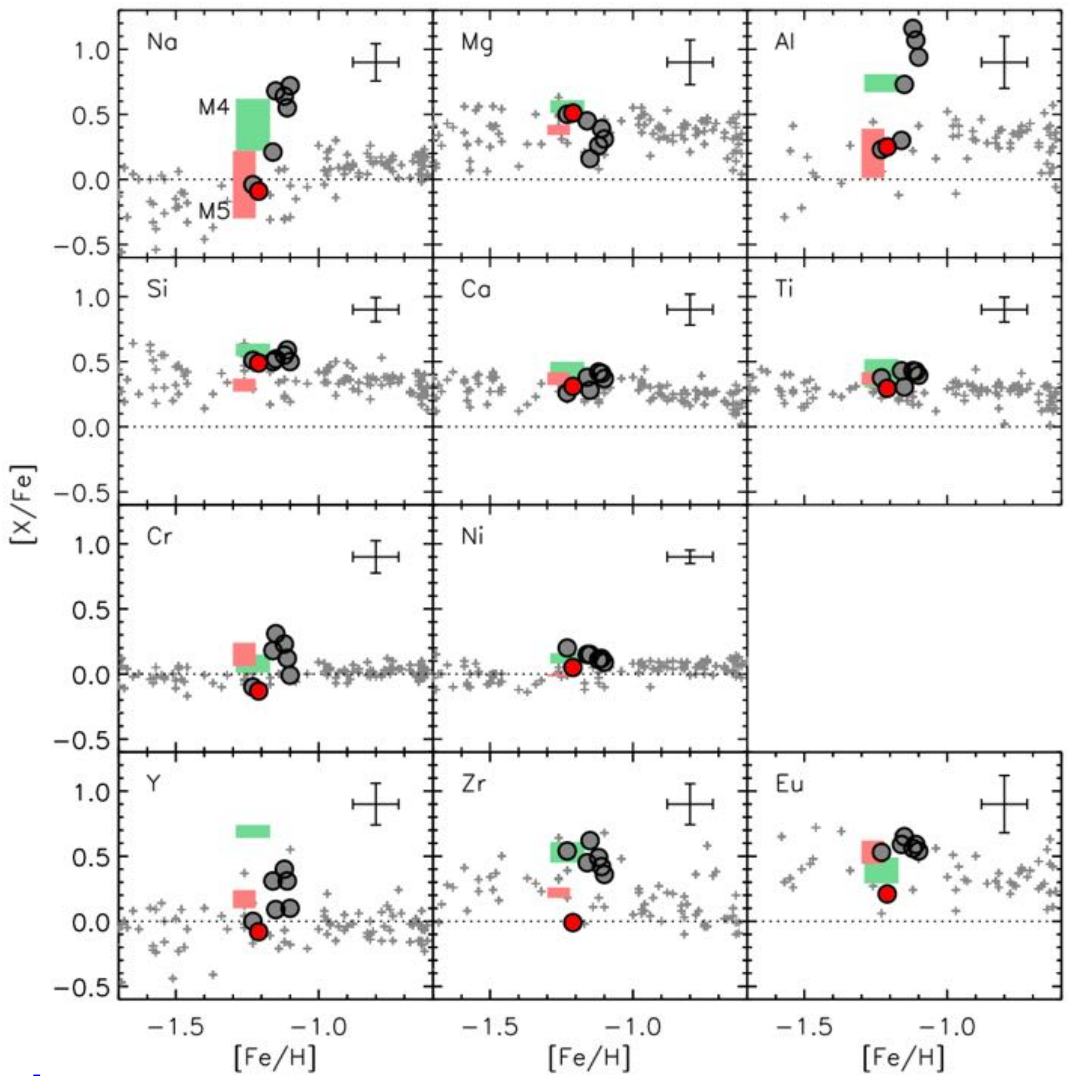
Yong et al. 2005

Carretta et al. 2009

Globular Clusters

Yong, Alves-Brito et al. 2014

- Our analysis reveals no evidence for an intrinsic metallicity dispersion in **M62**.
- The globular clusters with metallicity dispersions are preferentially the more luminous objects and tend to have extended horizontal branches.



NGC 6366: Puls, Alves-Brito et al. 2016, in progress

Globular Clusters

MD mul,modal sequences : C-N, O-Na, Mg-Al anticorrelations

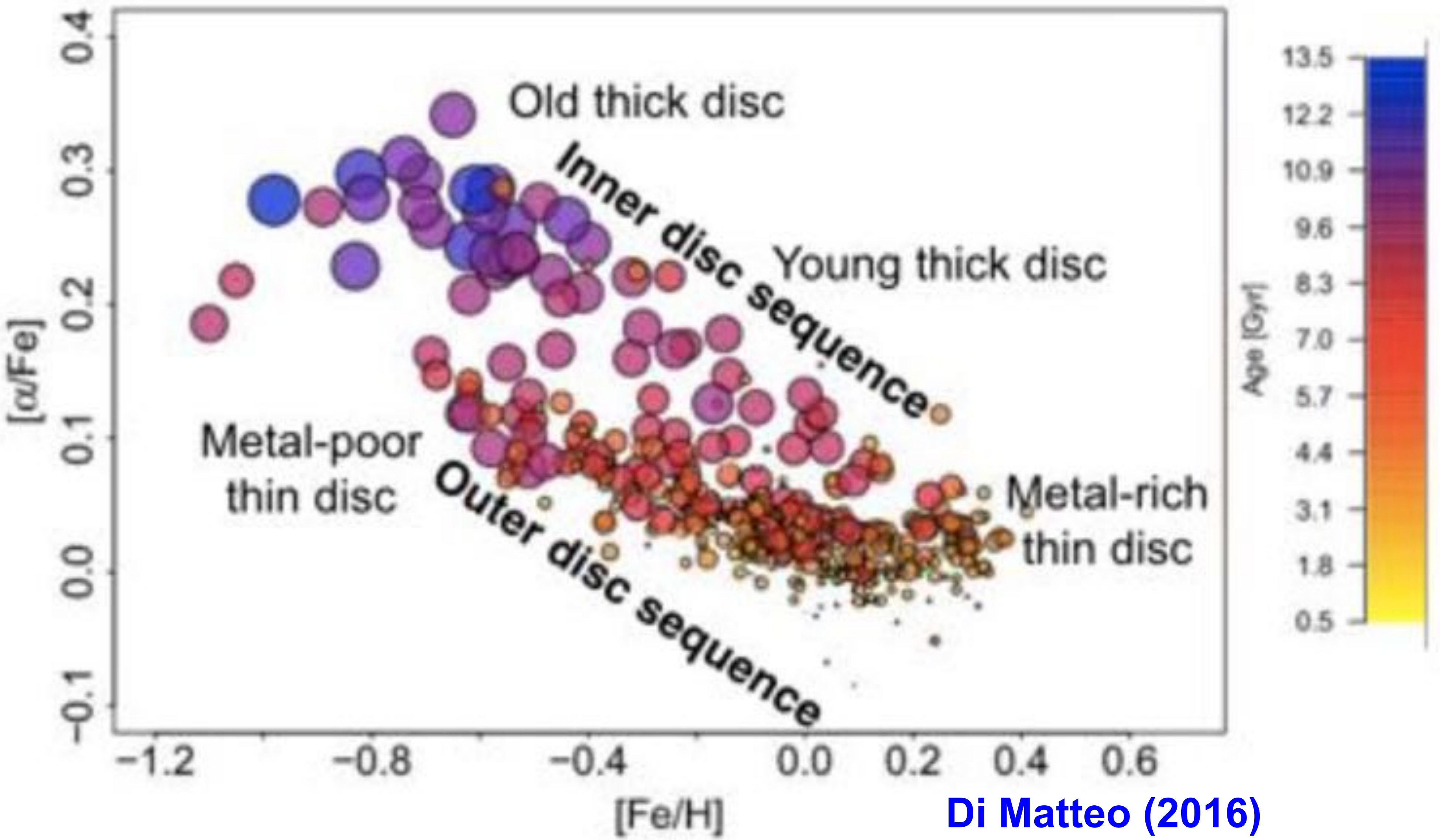
- Self-enrichment early on
- H-burning ashes (2P)
- 1P: more massive fast-evolving stars

Polluters

* Massive AGB stars: M~6–11M¤
* Supermassive stars
* Massive stars in close binaries
* Fast-Rotating Massive Stars: Minit > 25M¤
* High-mass interacting binaries (10-20M¤)

Results for the Galactic Disk (dwarfs+giants)

[alpha/Fe]-[Fe/H] relation

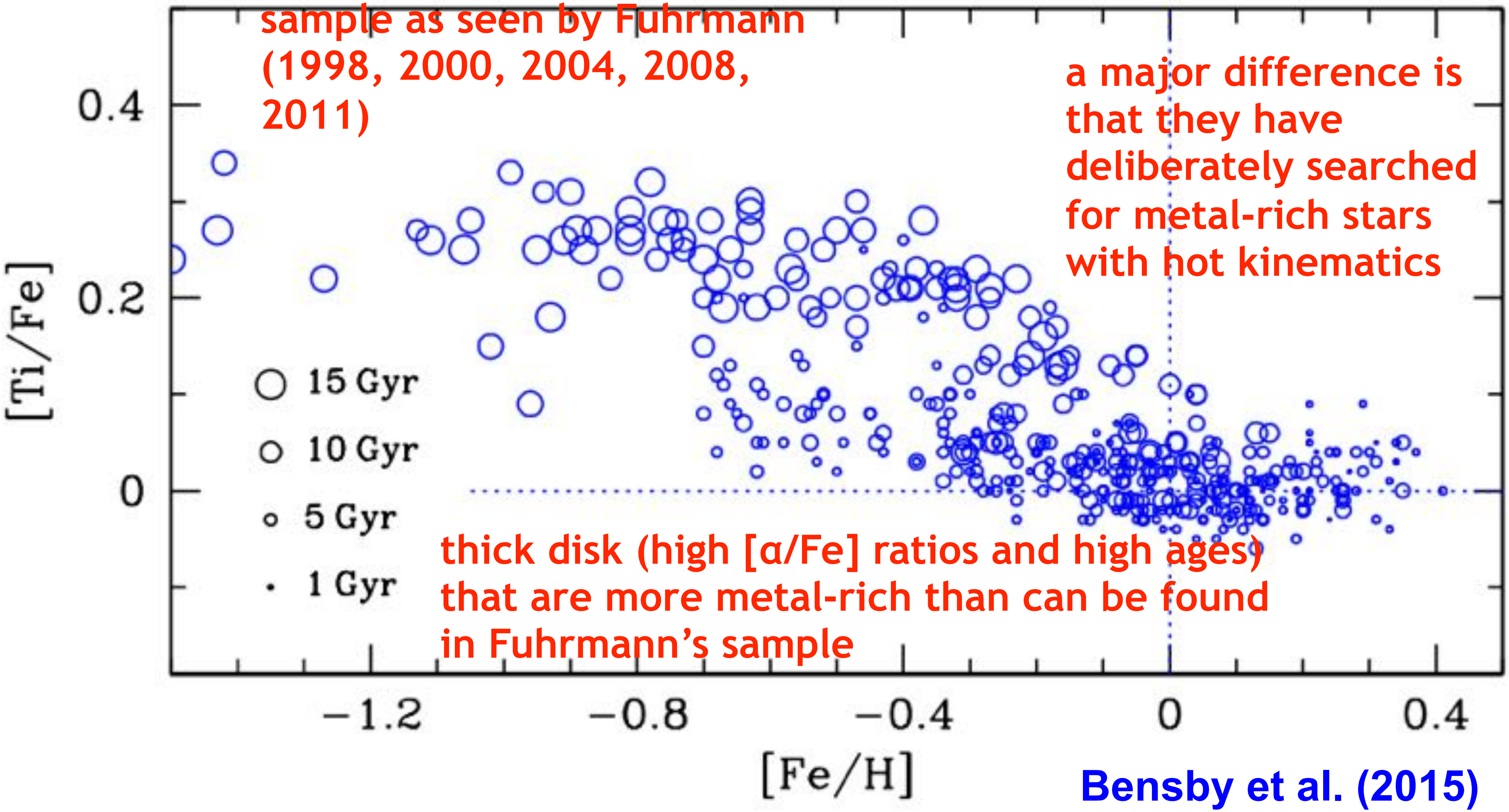


Di Matteo (2016)

[alpha/Fe]-[Fe/H]-Age relation

Similar division of the stellar sample as seen by Fuhrmann (1998, 2000, 2004, 2008, 2011)

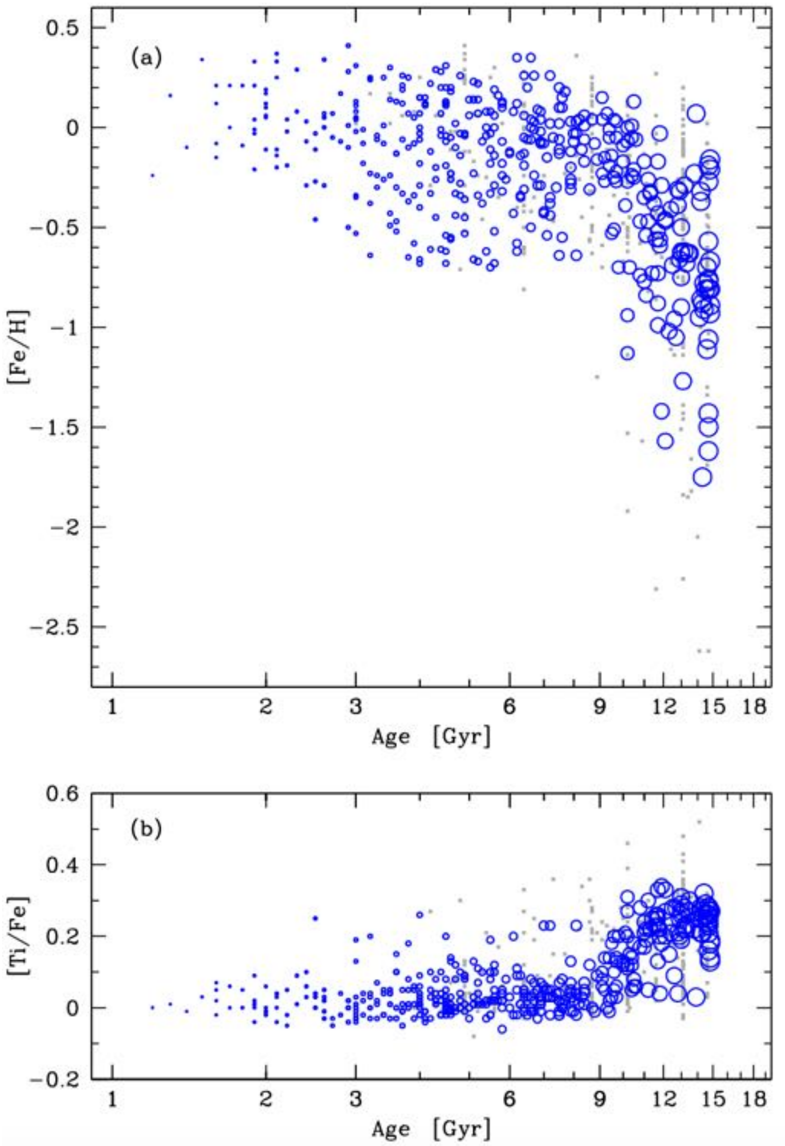
a major difference is that they have deliberately searched for metal-rich stars with hot kinematics



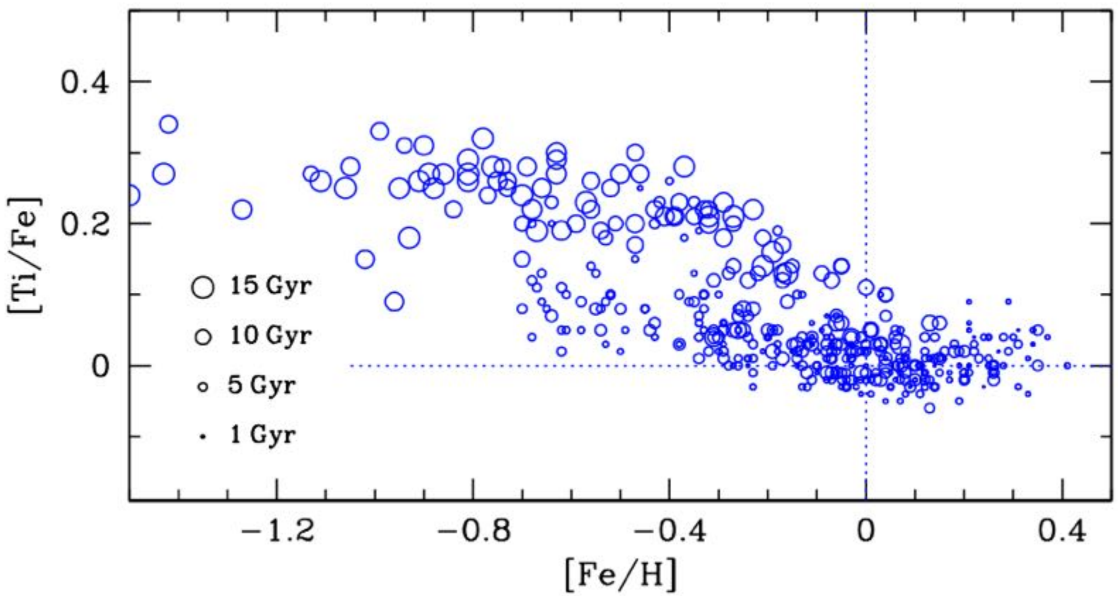
thick disk (high [α/Fe] ratios and high ages) that are more metal-rich than can be found in Fuhrmann’s sample

Bensby et al. (2015)

Age-[Fe/H] relation

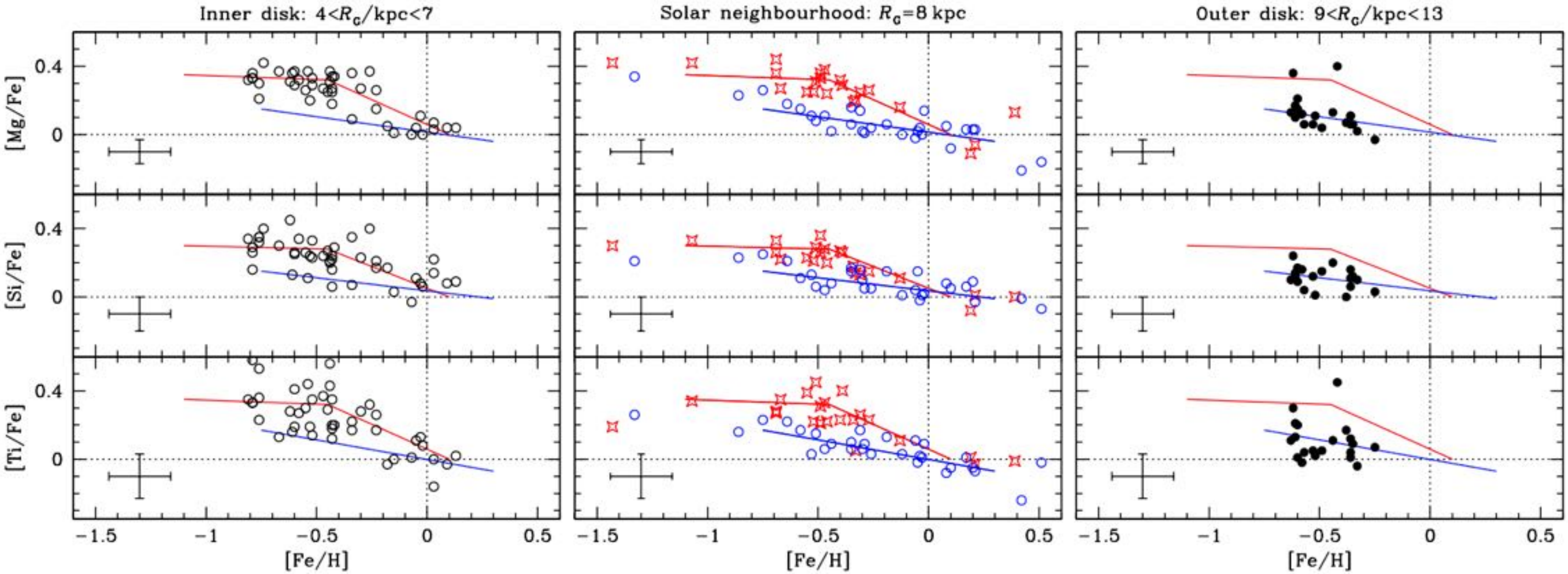


Bensby et al. (2015)



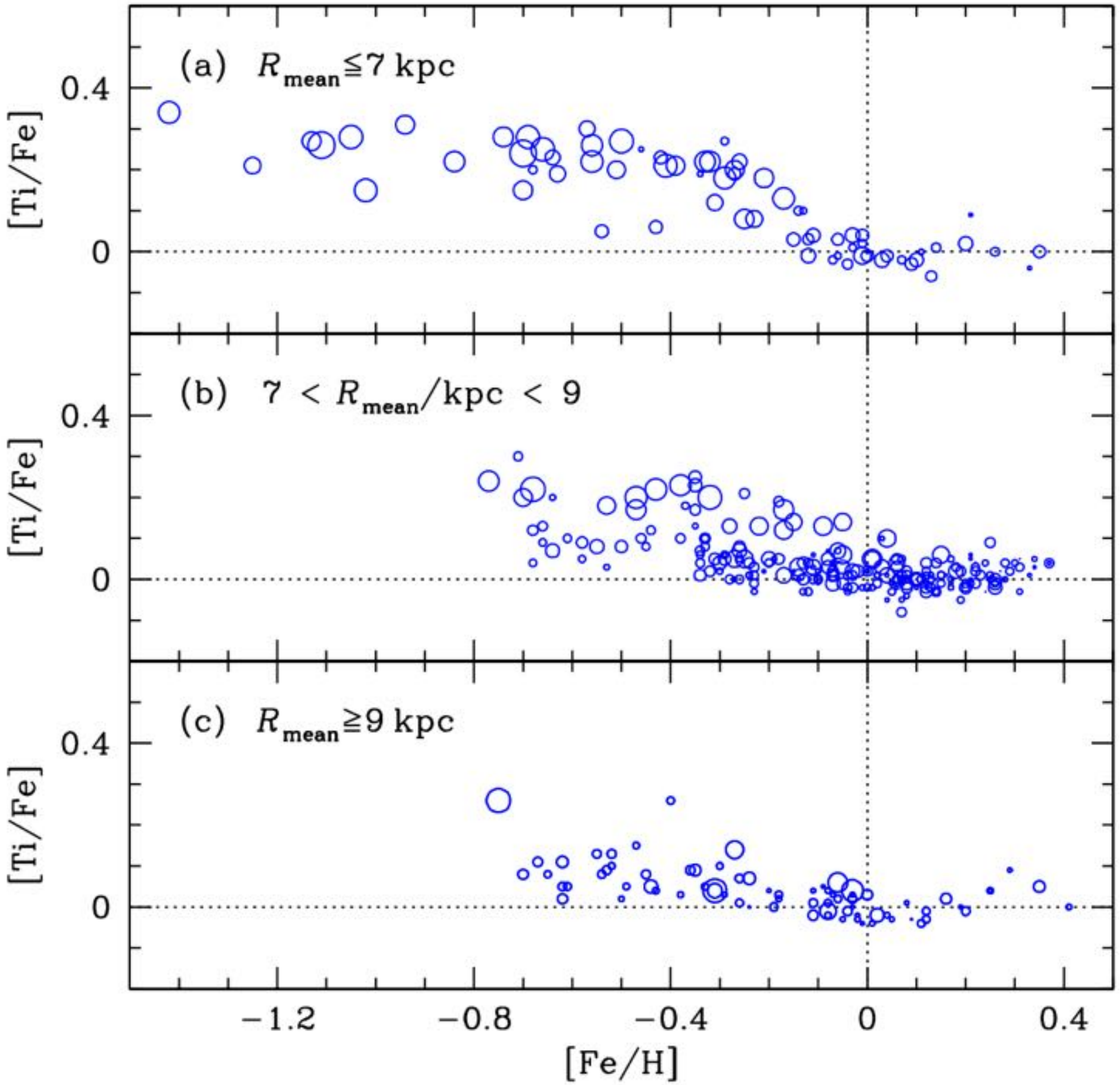
[alpha/Fe]-[Fe/H] relation

Bensby, Alves-Brito et al. 2010; 2011



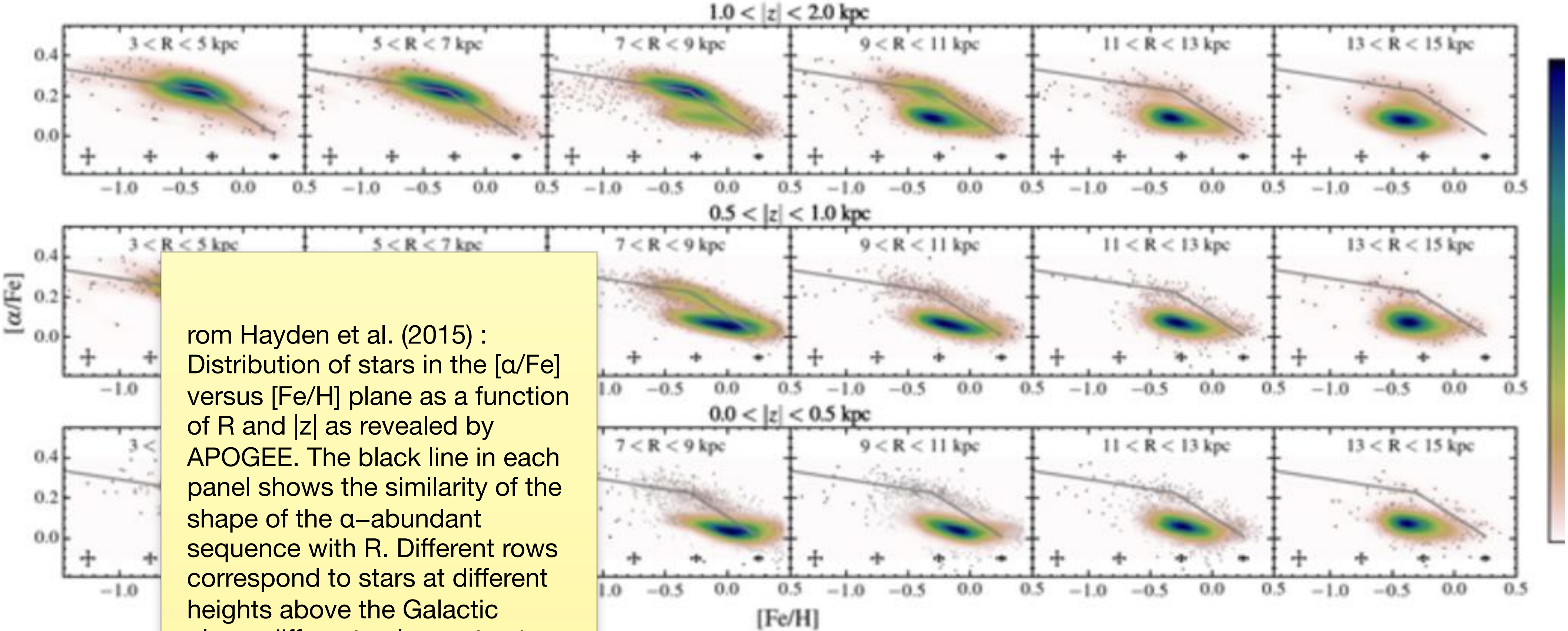
Shortly thereafter, Cheng et al. (2012) used 5650 stars from the SEGUE survey and confirmed the short scale-length of the thick disk.

[alpha/Fe]-[Fe/H]-radius relation



Bensby et al. (2015)

[alpha/Fe]-[Fe/H]-radius relation

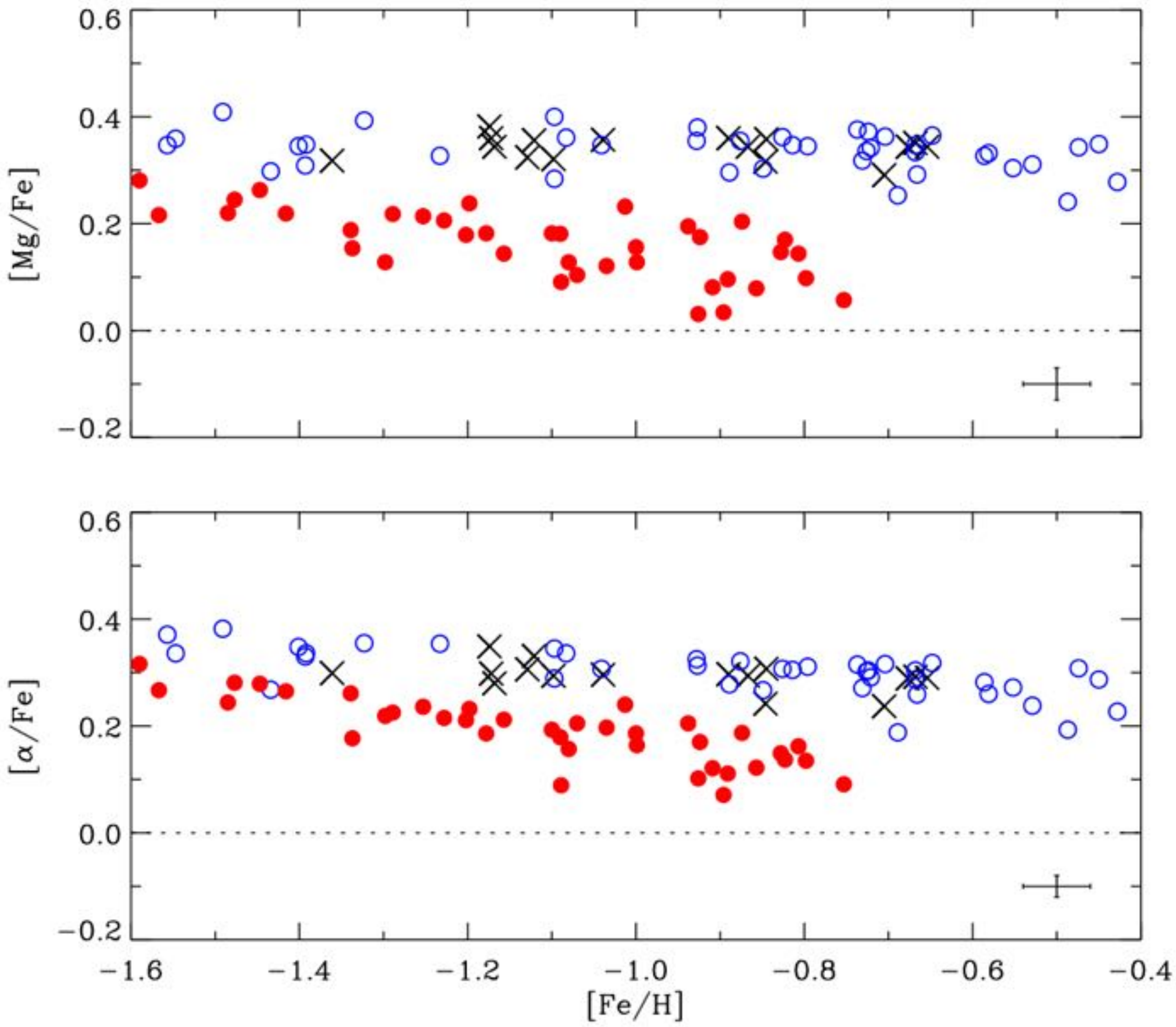


rom Hayden et al. (2015) : Distribution of stars in the [α/Fe] versus [Fe/H] plane as a function of R and |z| as revealed by APOGEE. The black line in each panel shows the similarity of the shape of the α–abundant sequence with R. Different rows correspond to stars at different heights above the Galactic plane, different columns to stars in different radial bins.

Hay ... **GEE confirming our results (giants)**

Results for the Galactic Halo

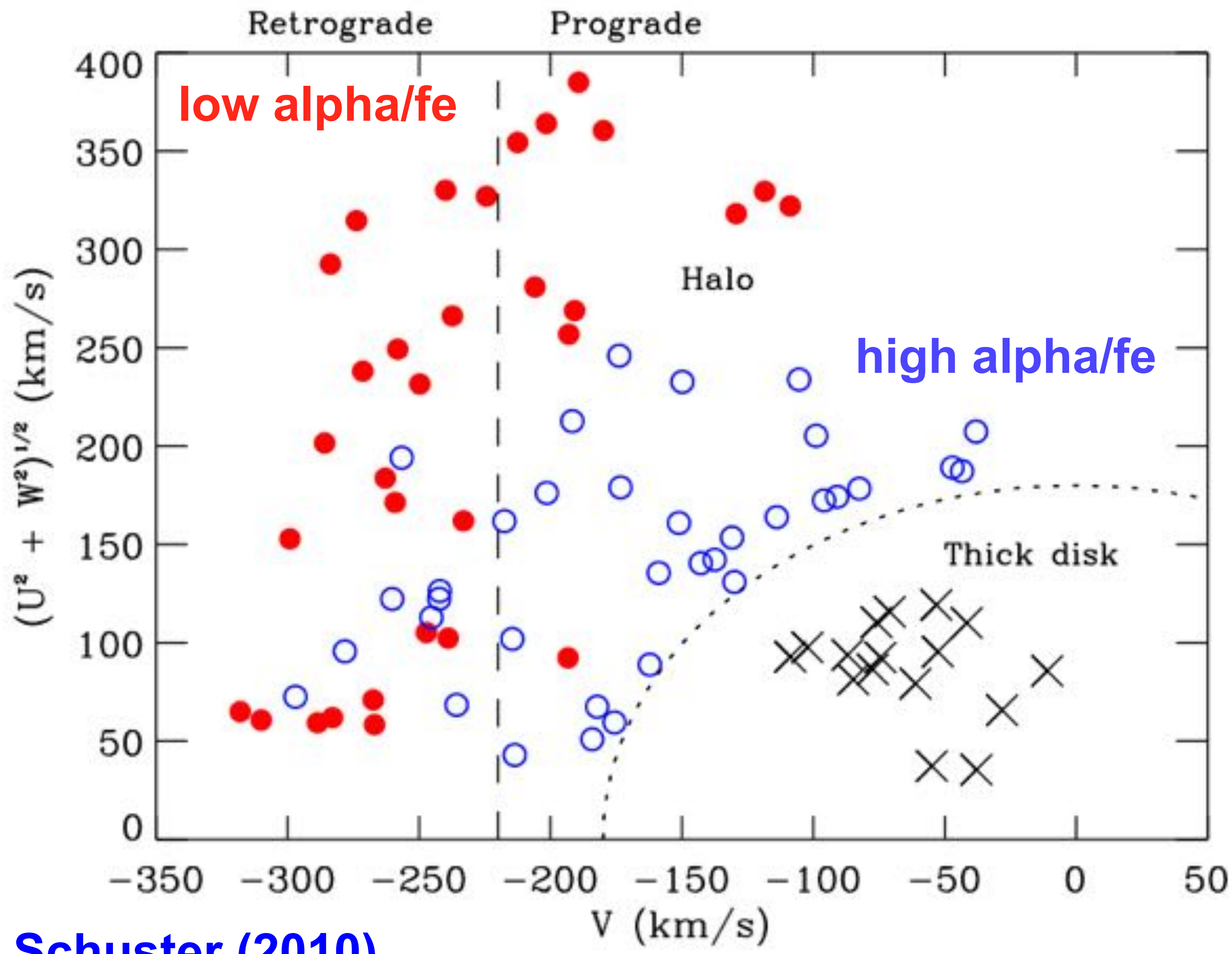
Nissen & Schuster (2010)



Halo stars are divided into low-α stars (red circles), and high-α stars (open blue) circles

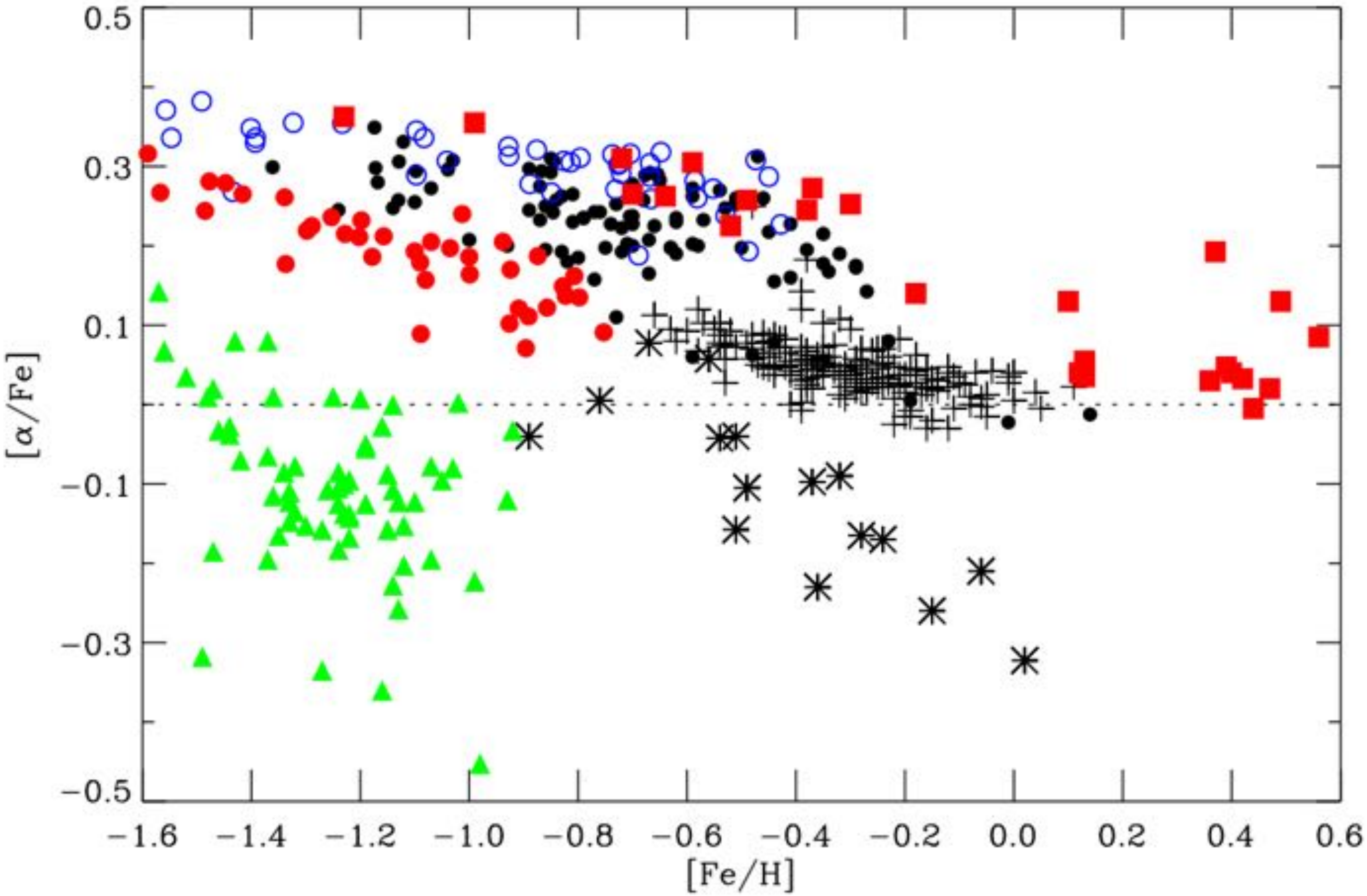
What is the different degrees of SNe Ia contribution to the production of Mg, Si, Ca, and Ti?

Toomre Diagram: [Fe/H] > −1.4



Nissen & Schuster (2010)

[alpha/Fe] in different galactic populations



Plus symbols: Thin-disk stars from Reddy et al. (2003)

Filled circles: thick-disk stars from Reddy et al. (2006) and Nissen & Schuster (2010).

Filled red squares: microlensed bulge stars from Bensby et al. (2011).

Open blue circles: high- α from Nissen & Schuster (2010)

Asterisks: stars in the Sagittarius dSph galaxy (Sbordone et al. 2007)

Filled green triangles: data for stars in the Sculptor dSph galaxy from Kirby et al. (2009)

Ground-based Surveys

Ground-based Surveys

- Gaia-ESO Survey (Gilmore+ 2012, Randich & Gilmore 2013)
- APOGEE (Allende-Prieto+ 2008)
- SDSS (York et al. 2000)
- SEGUE (The Sloan Extension for Galactic Understanding and Exploration Survey; ≈240,000 moderate-resolution, R ~ 1800; Yanny et al. 2009)
- RAVE (Steinmetz et al. 2006)

Ground-based Surveys

Forthcoming multi-object spectroscopy instruments

- LAMOST (Zhao et al. 2006; Cui et al. 2012)
- WEAVE (wide-field multi-object spectrograph for the William Herschel Telescope; R = 20000, Dalton et al. 2012; Balcells 2014)
- MOONS (the Multi-Object Optical and Near-infrared Spectrograph for the VLT; R = 8,000 and R = 20000; Cirasuolo et al 2011)
- 4MOST (4-metre Multi-Object Spectroscopic Telescope is a very large field (goal > 5 square degrees) multi-object spectrograph with up to 3000 fibres and spectral resolutions of 5000 and 20 000, proposed for the New Technology Telescope (NTT) or the VISTA survey telescope; de Jong et al. 2014)

Concerns/Problems

Concerns

- Giants (bulge) vs. dwarves (disks): Teff
- Zero points on stellar parameters
- Line list (different lines, atomic data)
- Solar abundances
- Methods of analysis

Concerns

- Parameters degeneracies (very high quality spectra; independent information)
- Oscillator strengths (Line-lists are full of theoretical f-values. Uncertainties can exceed a factor of ten)
- 1D LTE Modelling (realistic modelling of convection, radiation, and the statistical equilibria of atoms, without important free parameters)

Concerns

- [Fe/H] fundamental across astronomy
- Careful selection of lines and atomic data
- NLTE effects: different Teff, logg, [Fe/H]
- New crucial collisional data available
- 3D NLTE now possible

Concerns: extragalactic

- Oxygen as a proxy for metallicity
- Extragalactic oxygen abundances
- Strong Line Methods: dependence upon calibration
- Te: large discrepancies and saturation effects.
- "Abundance Discrepancy Factor" (CEL vs RL).
- Is O truly representative of "metallicity" ?

Questions

Questions

- The low and high [Fe/H]: bulge and disks
- Bulge vs Thin/Thick disk in the Galactic center
- [X/Fe] in very metal-poor ([Fe/H] ~-2.5 to -2.0) stars in the bulge/disk (?)
- MDF: How many components are there in the bulge?
- The critical -0.3 < [Fe/H] < +0.3 range

Questions

- Chemical inhomogeneities in globular clusters
- Heavy elements in different Galactic components
- Age spread, kinematics and chemical abundances can constrain different models of galaxy formation

Perspectives

- Gaia mission (from 2014-): ~1 billion of stars to V=20. 3D map of our Galaxy
- ESO-Gaia (optical)
- APOGEE (IR)
- ELTs
- High precision abundances

Thank You