Chemically tagging the Milky Way

Prospects and issues

Sofia Feltzing
Lund Observatory

What is it?

- Builds on the understanding of
  - stars as time-capsules
    - ★ Solar-like stars retain, in their atmospheres, the same composition of elements as the gas cloud from which they formed.

  - each star formation event has a unique signature
    - ★ The chemistry in each star formation event is influenced by a unique set of chemical enrichment events.
  - star clusters dispers in the Galactic potential

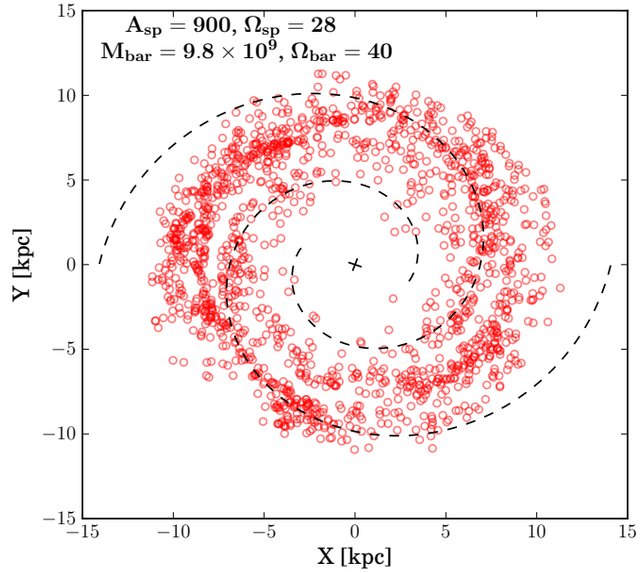
Freeman & Bland-Hawthorn 2002 ARA&A 40 487
Bland-Hawthorn et al. 2010 ApJ 713 166

What to do with it?

- Complementary (and necessary) information to understand the Milky Way as a galaxy.

- Formation signatures are lost in diffusion of orbits but chemical signatures remain.

Position of solar siblings after evolution in a non-axisymmetric Galactic potential
Liu et al. (submitted), simulation by Carmen Martínez-Barbosa.

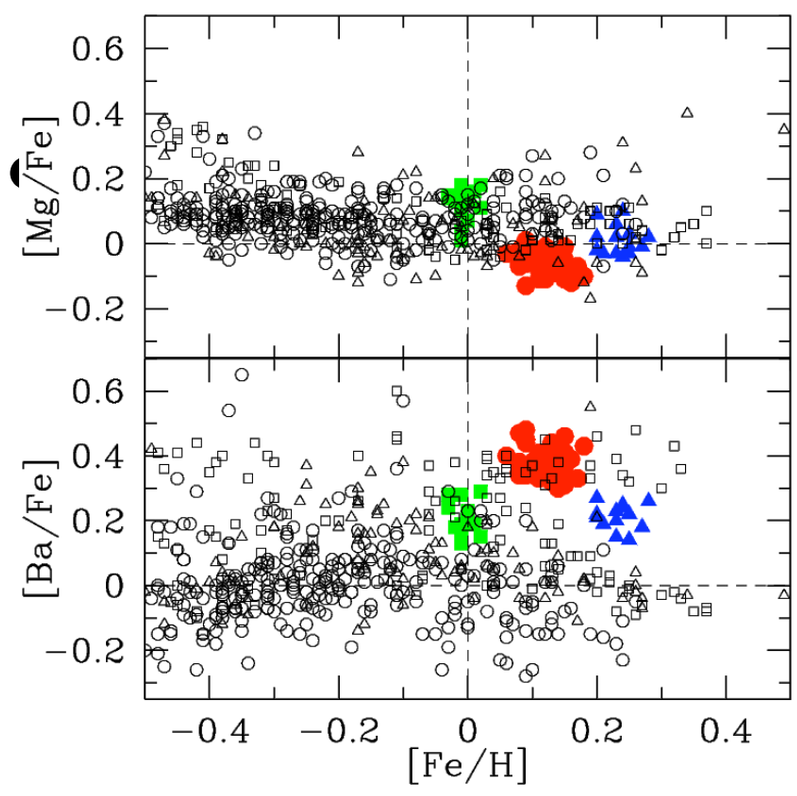


- Hence, use it to disentangle the whole formation history of the Milky Way.

Nomenclature

Chemical tagging

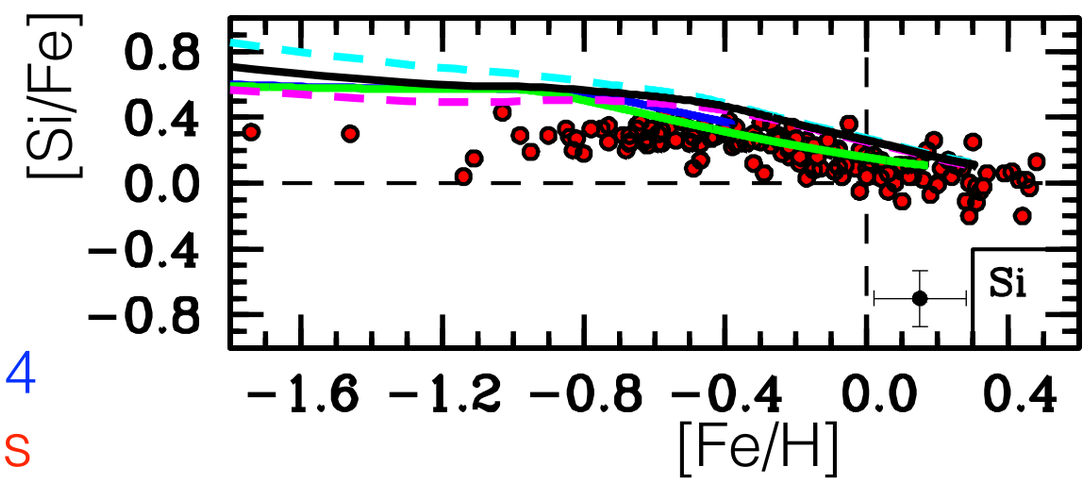
Chemical tracing



HR1614

Hyades

Collinder 261



De Silva et al. 2008 arXiv:0810.2287

Johnson et al. 2014 ApJ 148 67

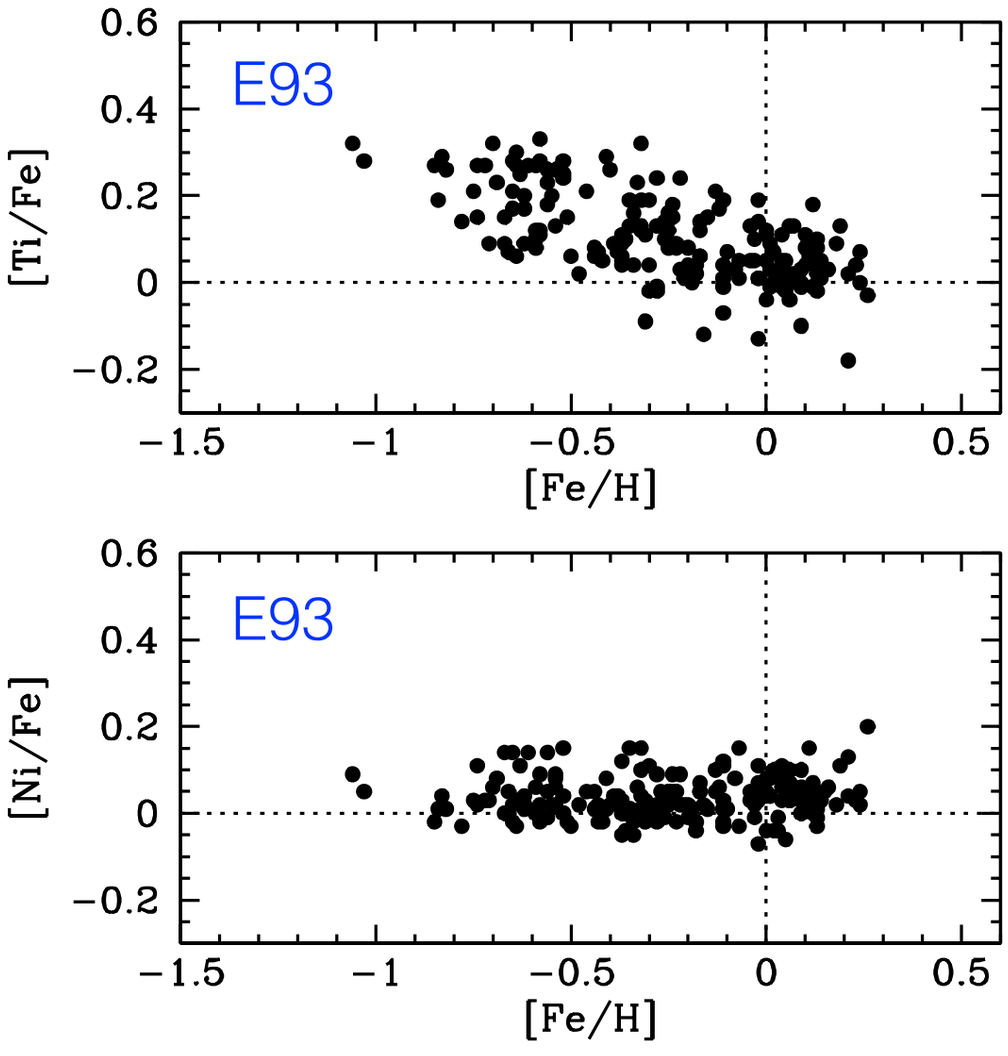
Does it work?

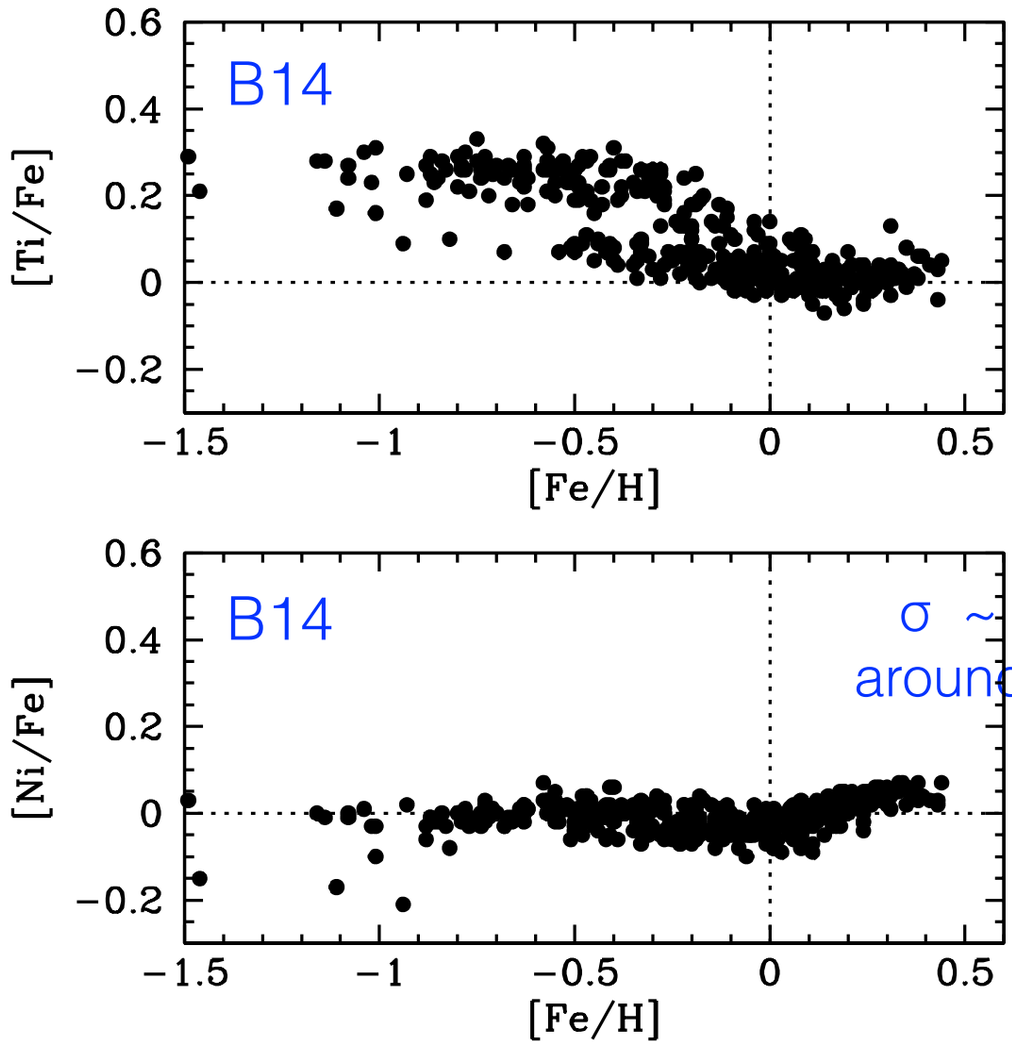
In summary, systematic differences between the stars and the Sun could arise due to the …

(i) analysis techniques (equivalent widths vs. spectrum synthesis)
(ii) stellar parameters
(iii) adopted grid of model atmospheres
(iv) treatment of line formation (LTE vs. NLTE)
(v) adopted gf-values
(vi) adopted line lists
(vii) spectral resolution
(viii) signal-to-noise ratio
(ix) problems with the spectrograph
(x) adopted solar spectrum (sky, Moon, moons of other planets, asteroids, solar atlas)
(xi) data reduction
(xii) determination of the continuum
(xiii) blends
(xiv) equivalent width measurements
(xv) adopted solar abundances

Meléndez et al. 2013 IAU Symp. 298, Eds. Feltzing, Zhao, Walton, Whitelock

Is it realistic to hope?





σ ~ 0.04 dex around the mean

Better data (S/N, larger λ-range, # lines)

Edvardsson, et al. 1993 A&A 275 101
Bensby et al. 2014 A&A 562 A71

Plot: Feltzing & Chiba 2013 NewAR 57 80

Is it realistic to hope?

18 Sco

Comparison of Stellar Parameters of 18 Sco

$T_{\rm eff}$ (K)	Error (K)	log g (dex)	Error (dex)	[Fe/H] (dex)	Error (dex)	Source
5823	6	4.45	0.02	0.054	0.005	This work
5816	4	4.45	0.01	0.053	0.003	Ramírez et al. (2014b)
5824	5	4.45	0.02	0.055	0.010	Monroe et al. (2013)
5810	12	4.46	0.04	0.05	0.01	Tsantaki et al. (2013)
5831	10	4.46	0.02	0.06	0.01	Meléndez et al. (2012)
5817	30	4.45	0.13	0.05	0.05	da Silva et al. (2012)
5826	5	4.45	0.01	0.06	0.01	Takeda & Tajitsu (2009)
5840	20	4.45	0.04	0.07	0.02	Meléndez et al. (2009)
5848	46	4.46	0.06	0.06	0.02	Ramírez et al. (2009a)
5818	13	4.45	0.02	0.04	0.01	Sousa et al. (2008)
5834	36	4.45	0.05	0.04	0.02	Meléndez & Ramírez (2007)
5822	4	4.451	0.006	0.053	0.004	Weighted mean from the literature

Meléndez et al. 2014 ApJ 791 14

Is it realistic to hope?

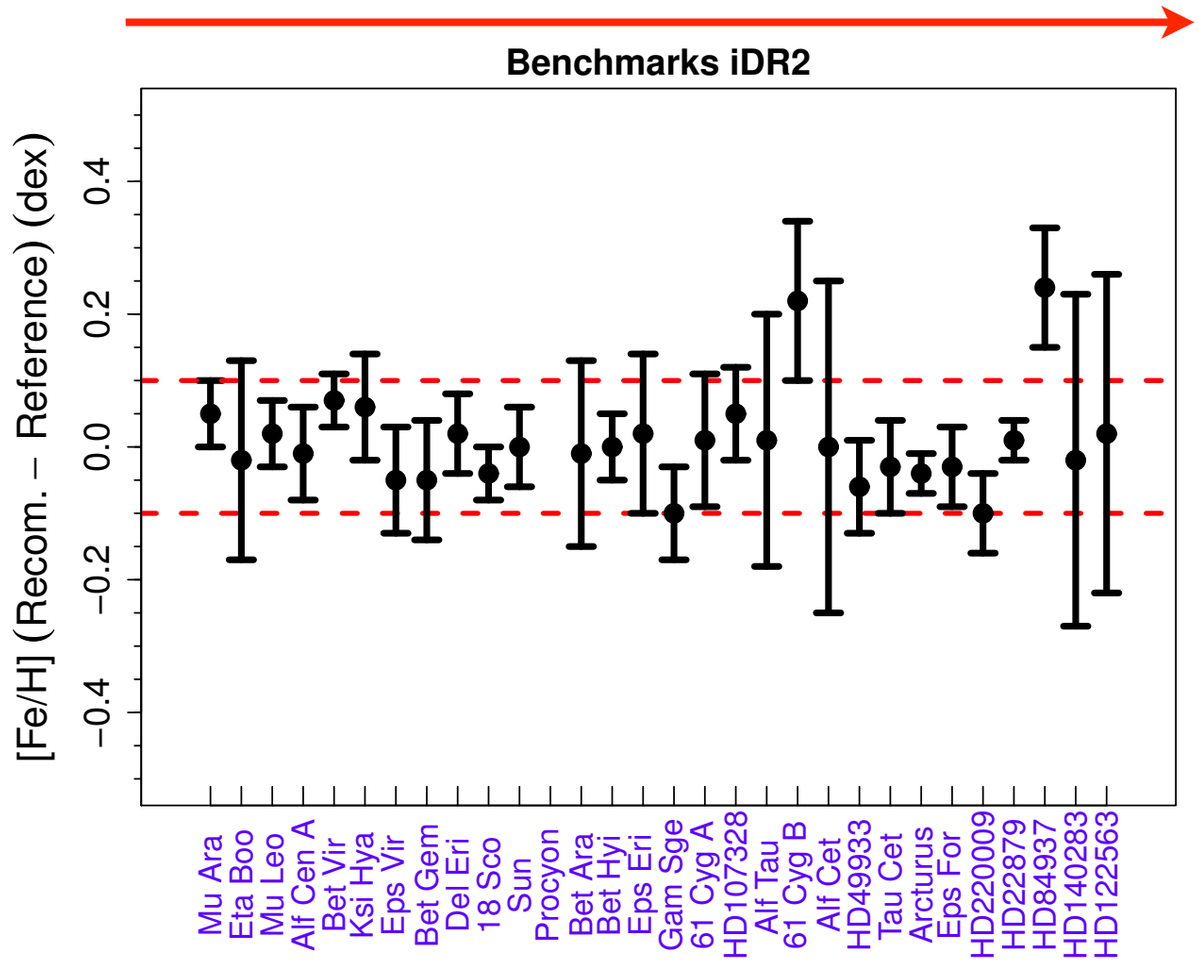
Comparison of Stellar Parameters of 18 Sco

$T_{\rm eff}$ (K)	Error (K)	log g (dex)	Error (dex)	[Fe/H] (dex)	Error (dex)	Source
5823	6	4.45	0.02	0.054	0.005	This work
5816	4	4.45	0.01	0.053	0.003	Ramírez et al. (2014b)
5824	5	4.45	0.02	0.055	0.010	Monroe et al. (2013)
5810	12	4.46	0.04	0.05	0.01	Tsantaki et al. (2013)
5831	10	4.46	0.02	0.06	0.01	Meléndez et al. (2012)
5817	30	4.45	0.13	0.05	0.05	da Silva et al. (2012)
5826	5	4.45	0.01	0.06	0.01	Takeda & Tajitsu (2009)
5840	20	4.45	0.04	0.07	0.02	Meléndez et al. (2009)
5848	46	4.46	0.06	0.06	0.02	Ramírez et al. (2009a)
5818	13	4.45	0.02	0.04	0.01	Sousa et al. (2008)
5834	36	4.45	0.05	0.04	0.02	Meléndez & Ramírez (2007)
5822	4	4.451	0.006	0.053	0.004	Weighted mean from the literature

Beware of the sheep
and sheep-goat effect

Gustafsson (2004)
Carnegie Observatories Astrophysics
Series 4. Eds. McWilliam & Rauch

Metallicity decreases, from >0.2 dex to –2.7 dex



Smiljanic et al. 2014 arXiv1409.0568
Meléndez et al. 2014 ApJ 791 14

Tagging: applications

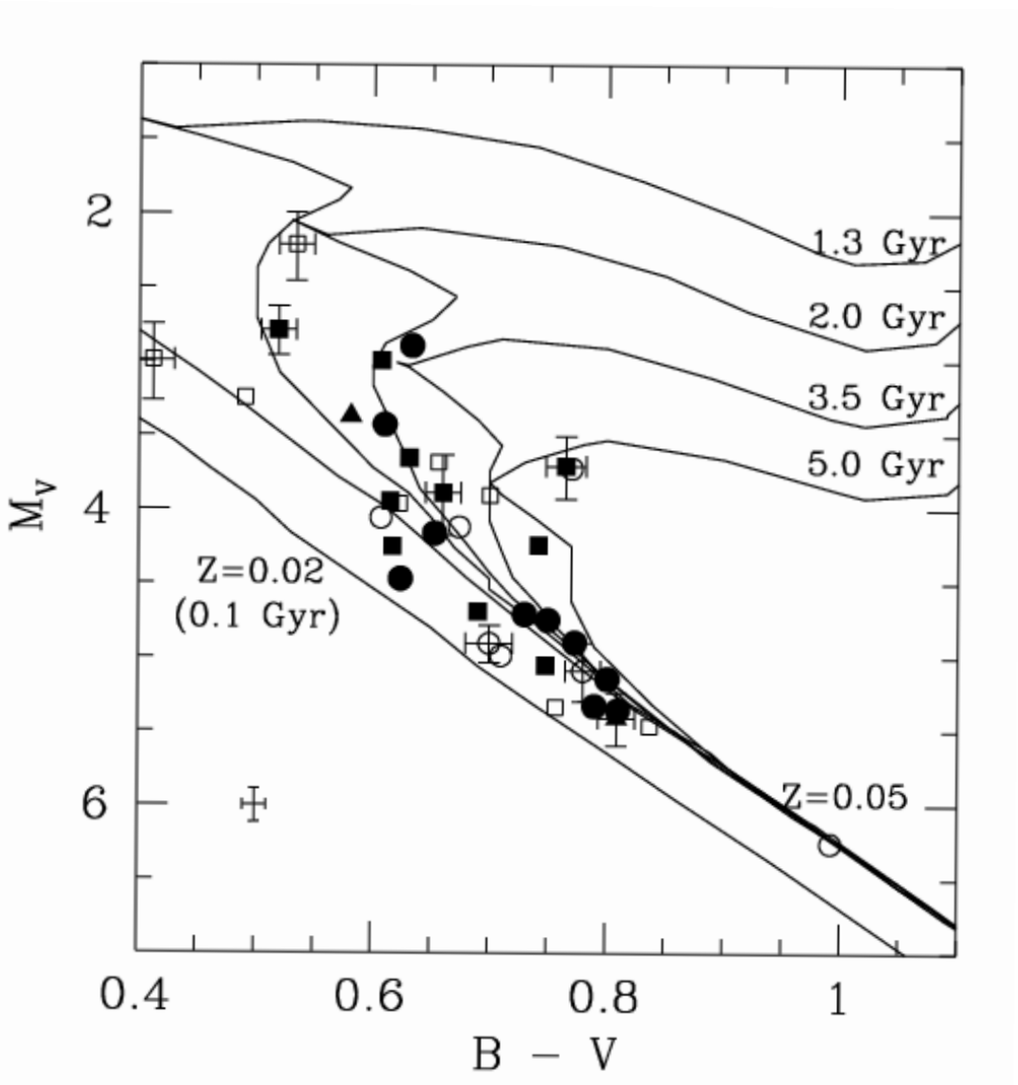
- Several studies have started to develop the analysis tools needed for chemical tagging and PC analysis in large data-sets.
  - Ting et al. 2012 MNRAS 421 1231 PC, various, incl. dSphs
  - Andrews et al. 2012 AcA 62 269 PC, Bensby et al. 2014
  - Mitschang et al. 2014 MNRAS 438 2753 Tagging, Bensby et al. 2014
  - Blanco-Cuaresma et al. in prep. Tagging, various incl. clusters, Gaia-ESO

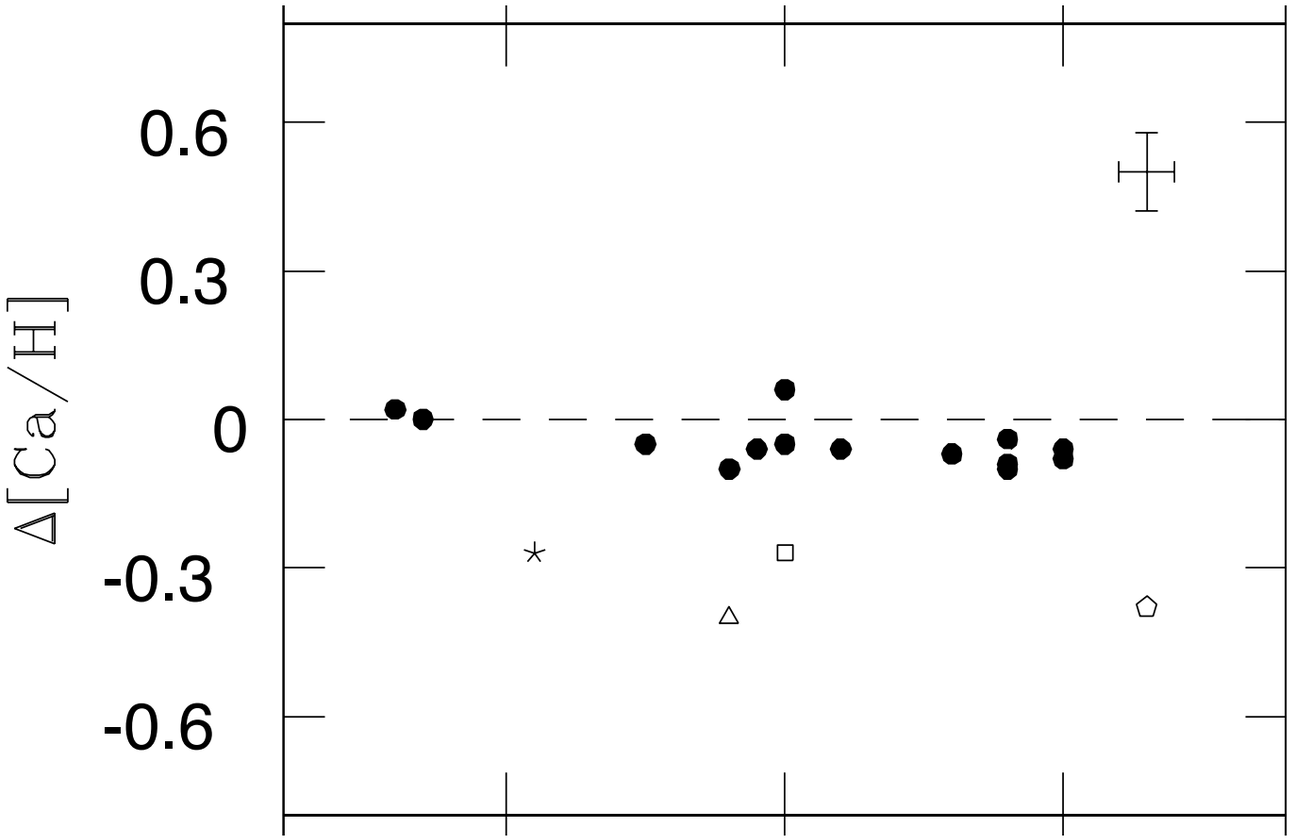
Inconclusive
Due to small samples

Two (old) examples

Dissolving cluster

HR1614

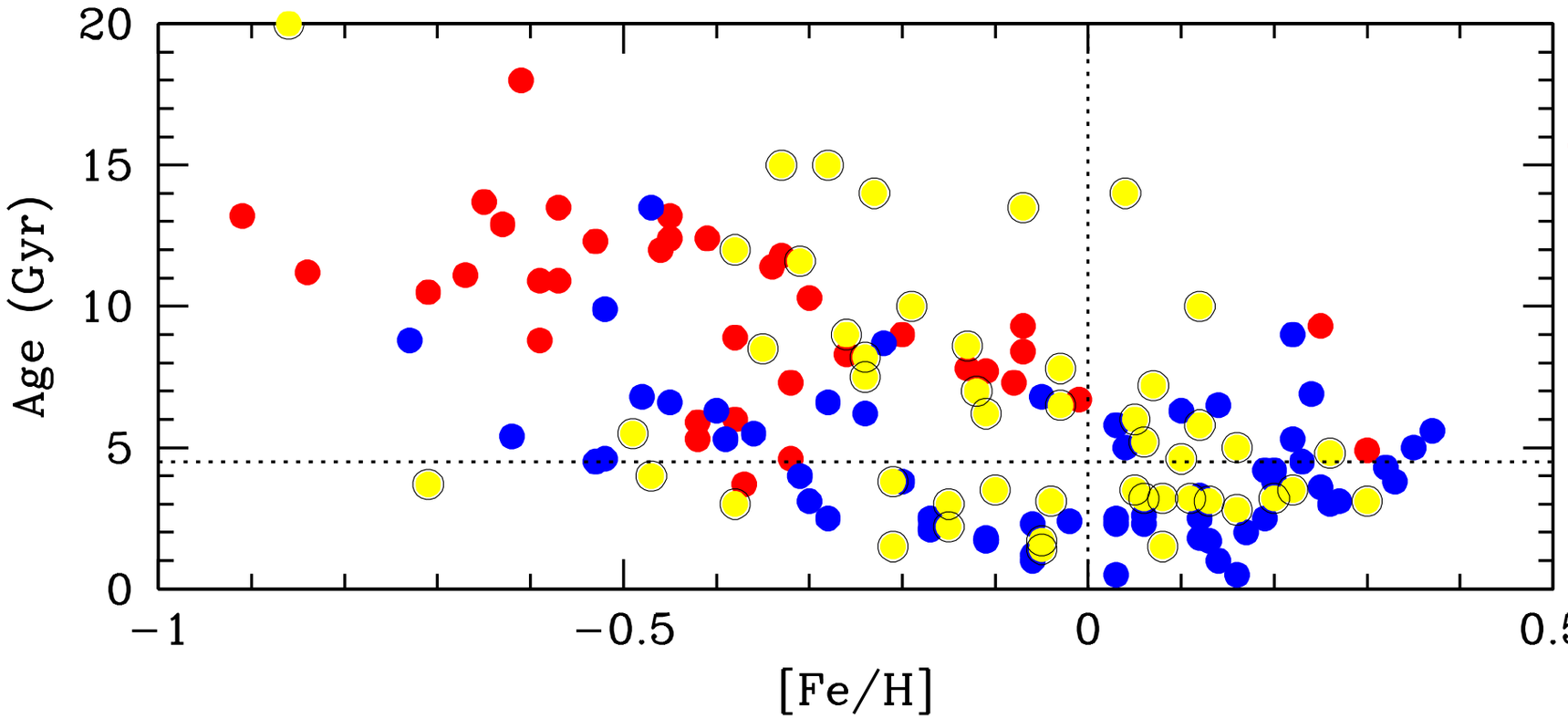




De Silva et al. 2007 AJ 133 694
Feltzing & Holmberg 2000 A&A 357 153

Dynamical structure

Hercules (in yellow)



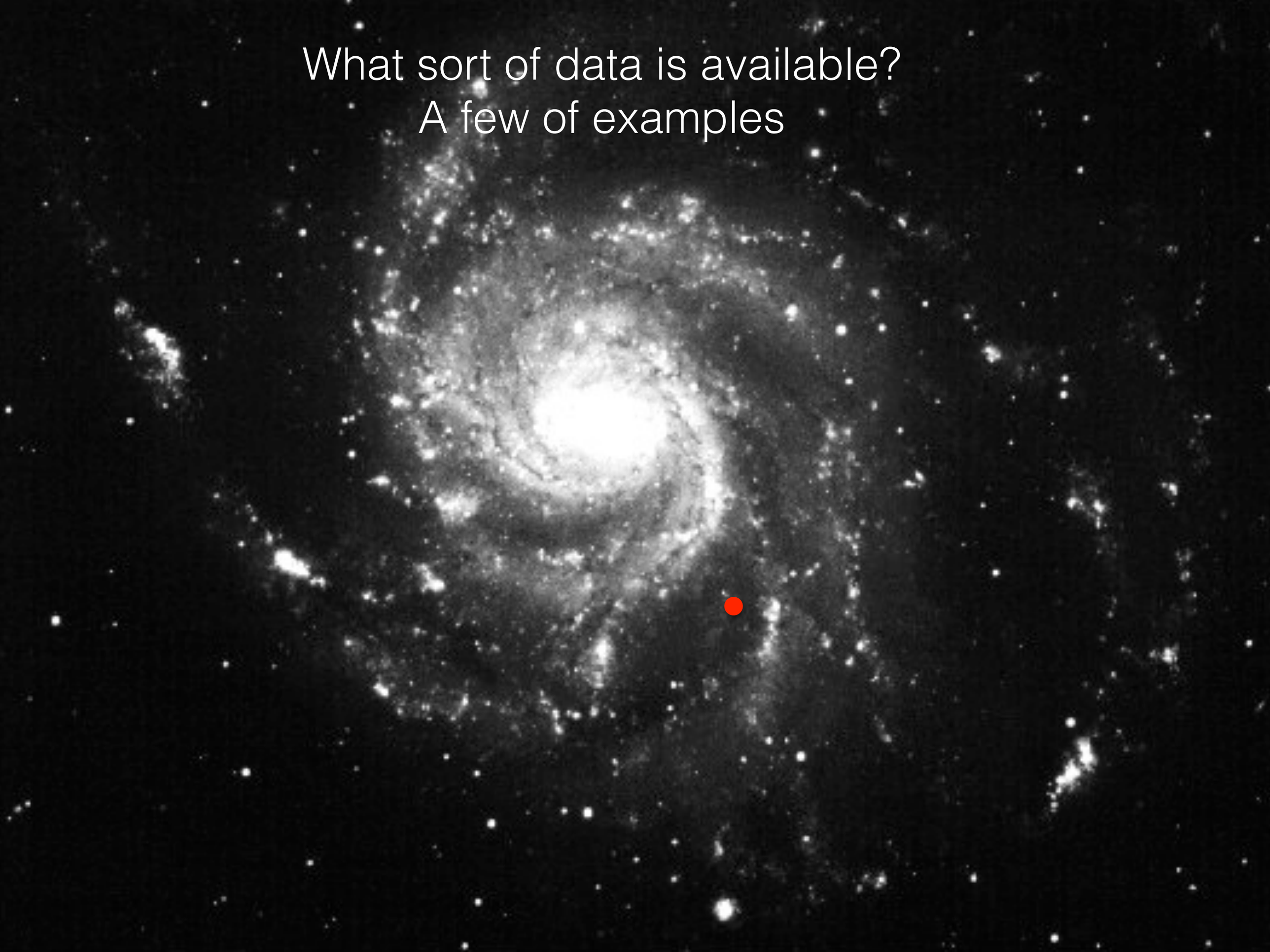
Thick disk

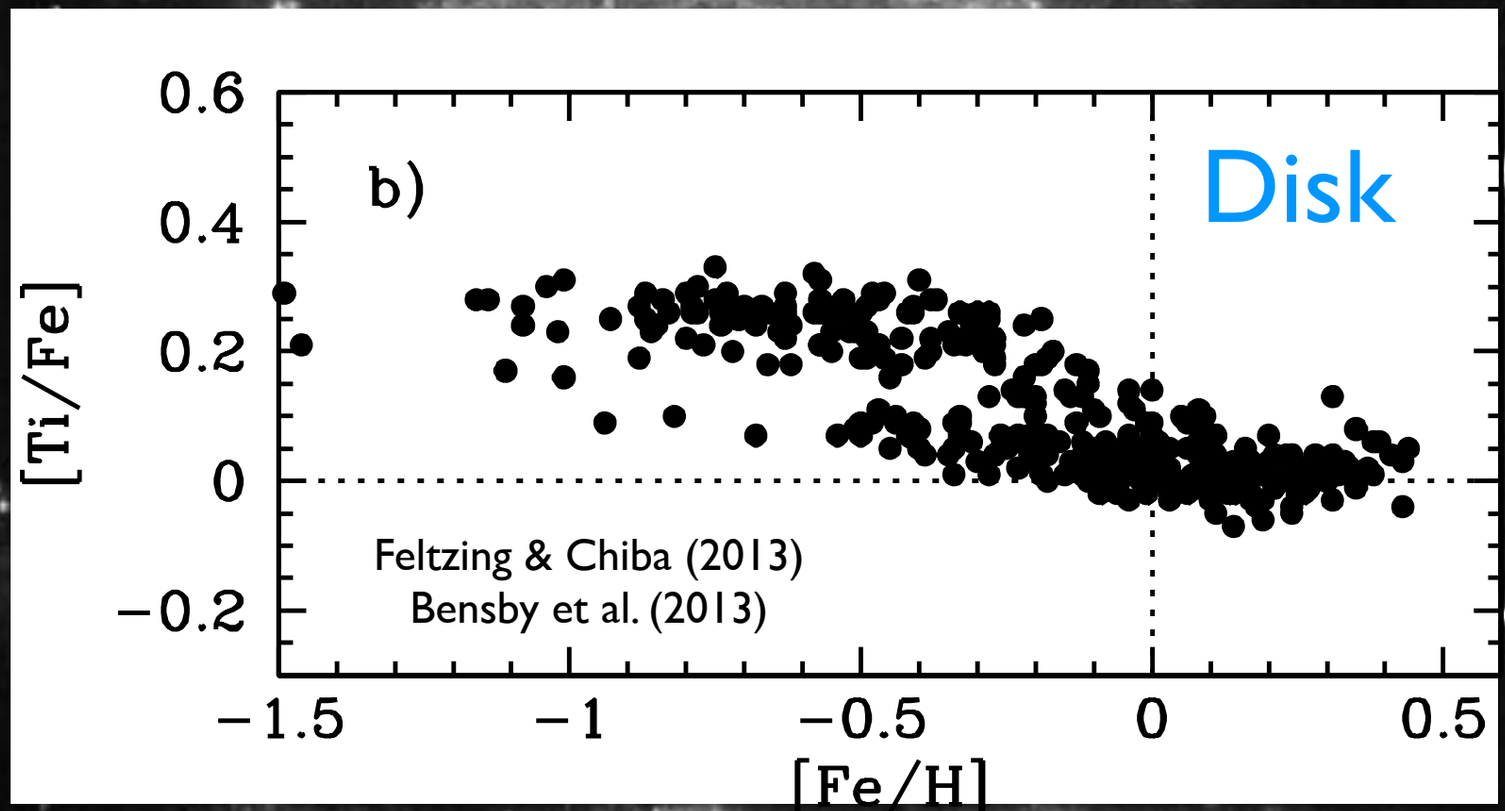
Thin disk

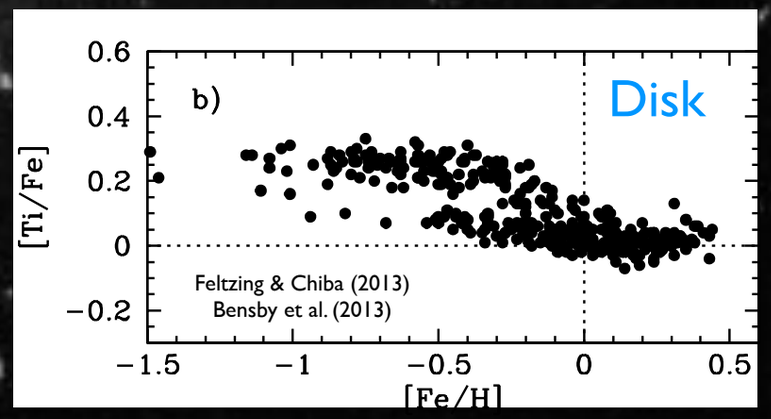
Not all “groups” dispersing are stellar clusters, some are dynamical features

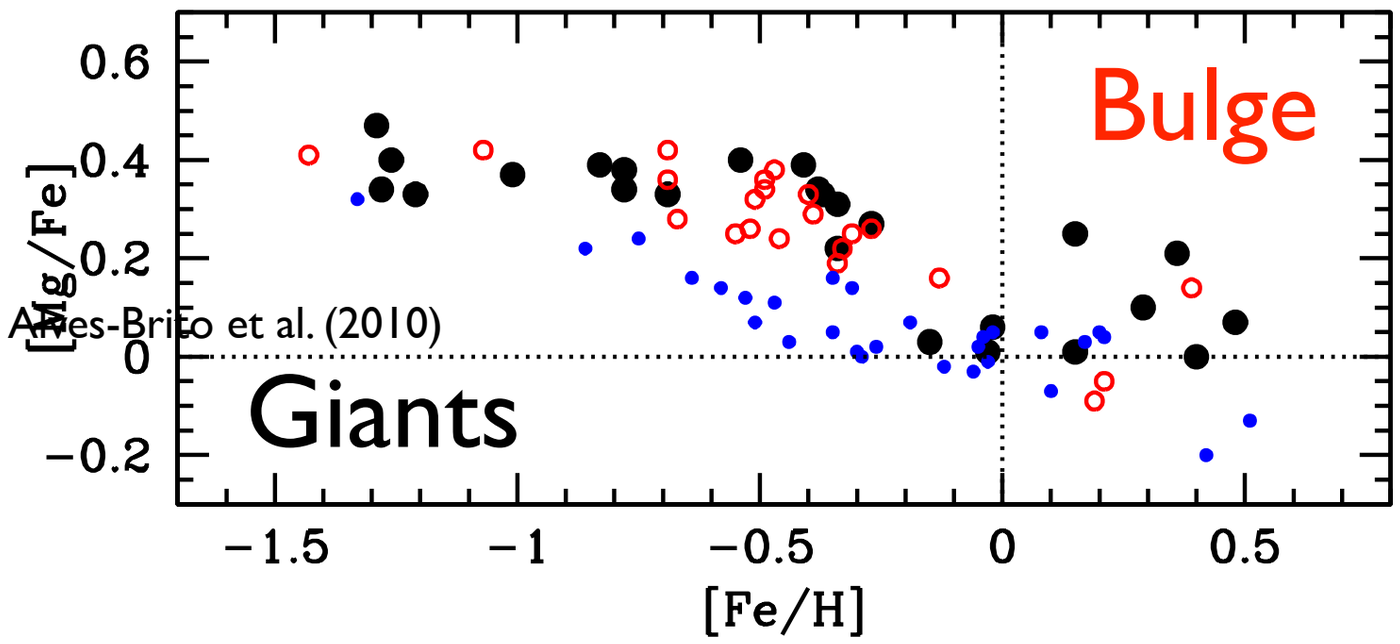
Bensby et al. 2007 ApJL 655 L89

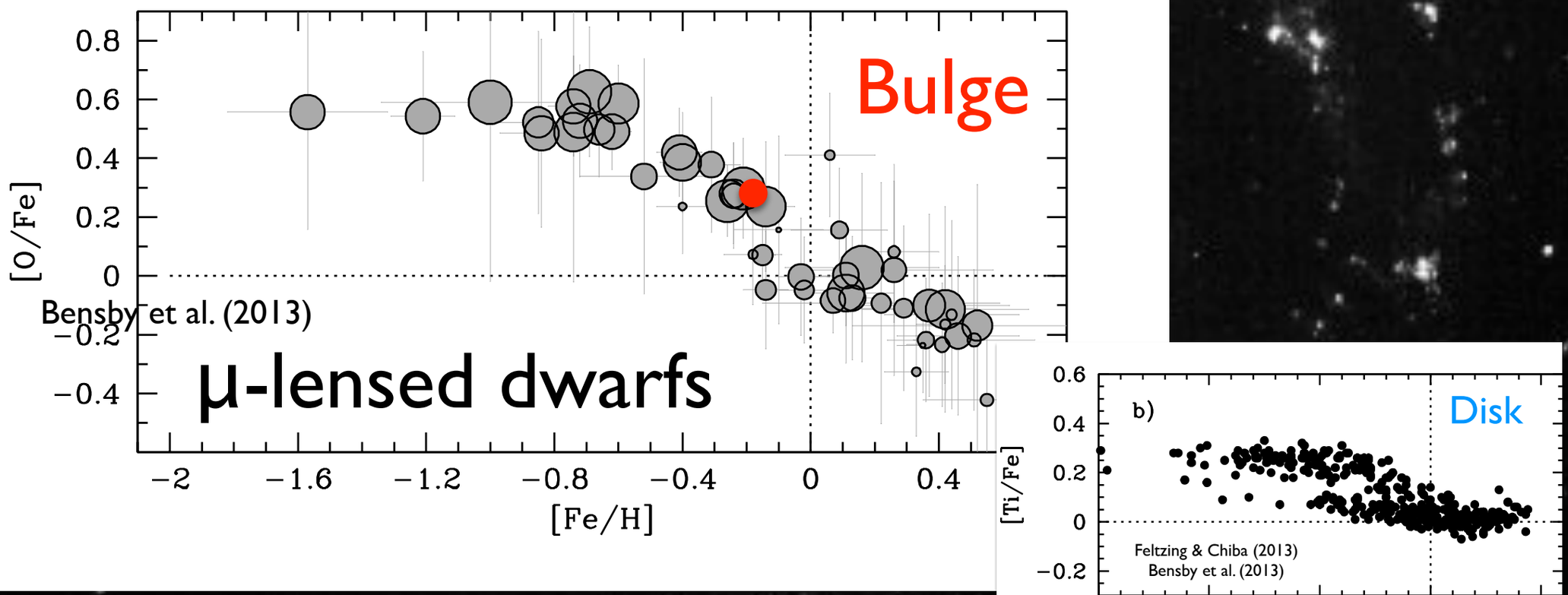
What sort of data is available?
A few of examples



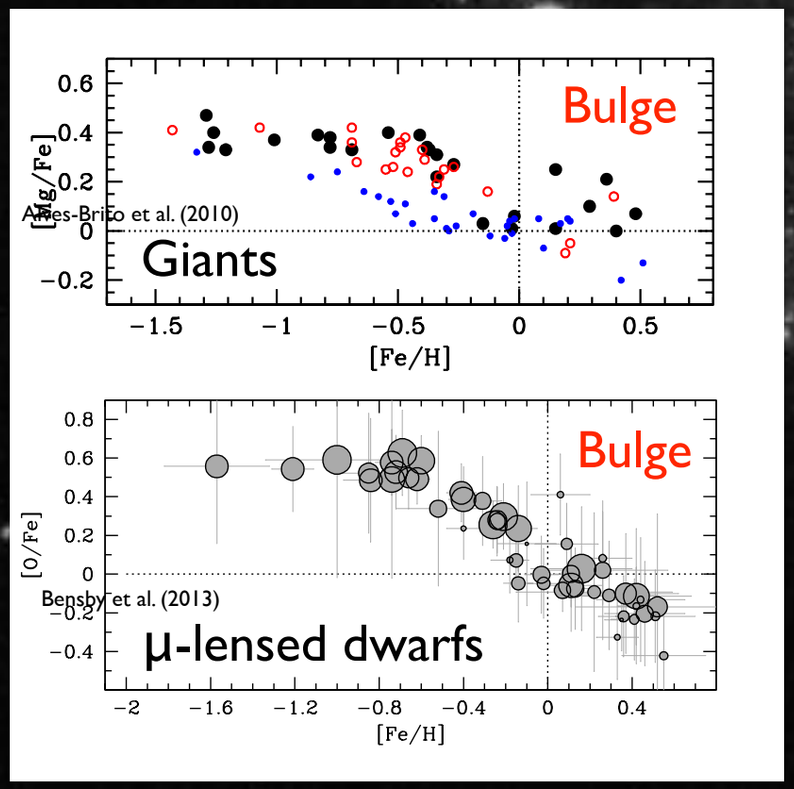

b)
Disk
0.6
0.4
0.2
0
−0.2
[Ti/Fe]
Feltzing & Chiba (2013)
Bensby et al. (2013)
−1.5
−1
−0.5
0
0.5
[Fe/H]

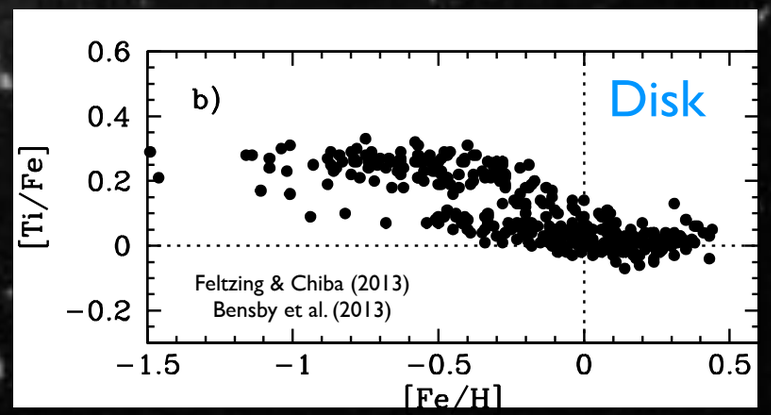

b)
Disk
0.6
0.4
0.2
0
−0.2
[Ti/Fe]
Feltzing & Chiba (2013)
Bensby et al. (2013)
−1.5
−1
−0.5
0
0.5
[Fe/H]


Bulge
Giants
Alves-Brito et al. (2010)
[Mg/Fe]
[Fe/H]
0.6
0.4
0.2
0
−0.2
−1.5
−1
−0.5
0
0.5

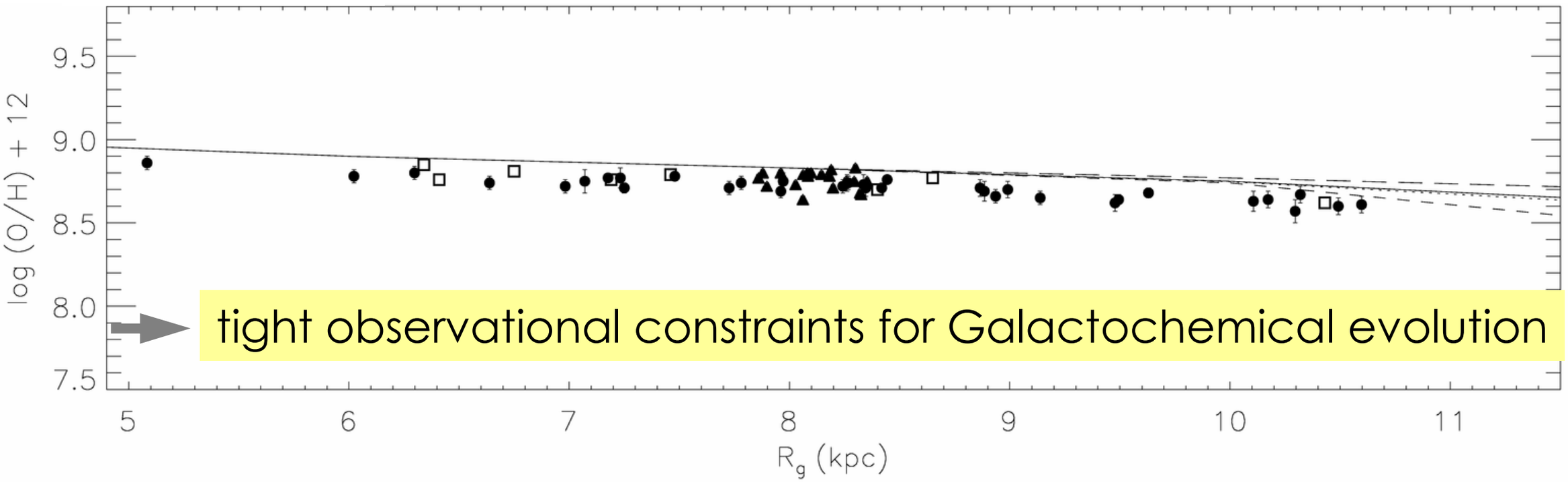

Bulge
μ-lensed dwarfs
Bensby et al. (2013)
[O/Fe]
[Fe/H]
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−2
−1.6
−1.2
−0.8
−0.4
0
0.4

b)
Disk
Feltzing & Chiba (2013)
Bensby et al. (2013)
[Ti/Fe]
[Fe/H]
0.6
0.4
0.2
0
−0.2
−1.5
−1
−0.5
0
0.5

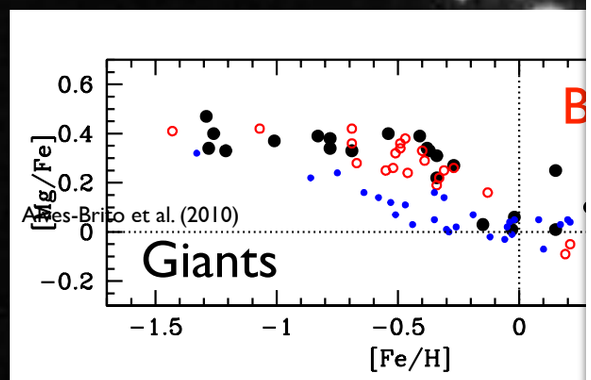

Bulge
Giants
Ares-Brito et al. (2010)
[Mg/Fe]
[Fe/H]
Bulge
μ-lensed dwarfs
Bensby et al. (2013)
[O/Fe]
[Fe/H]

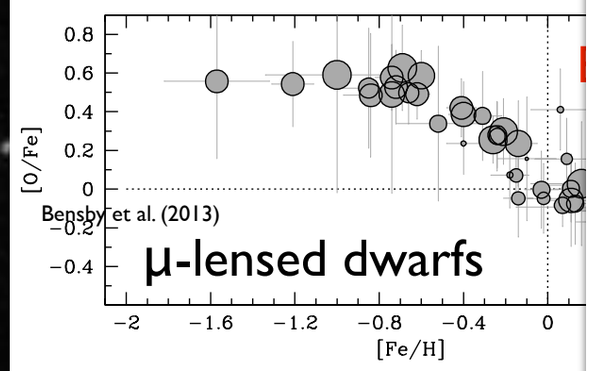

b)
Disk
Feltzing & Chiba (2013)
Bensby et al. (2013)
[Ti/Fe]
[Fe/H]

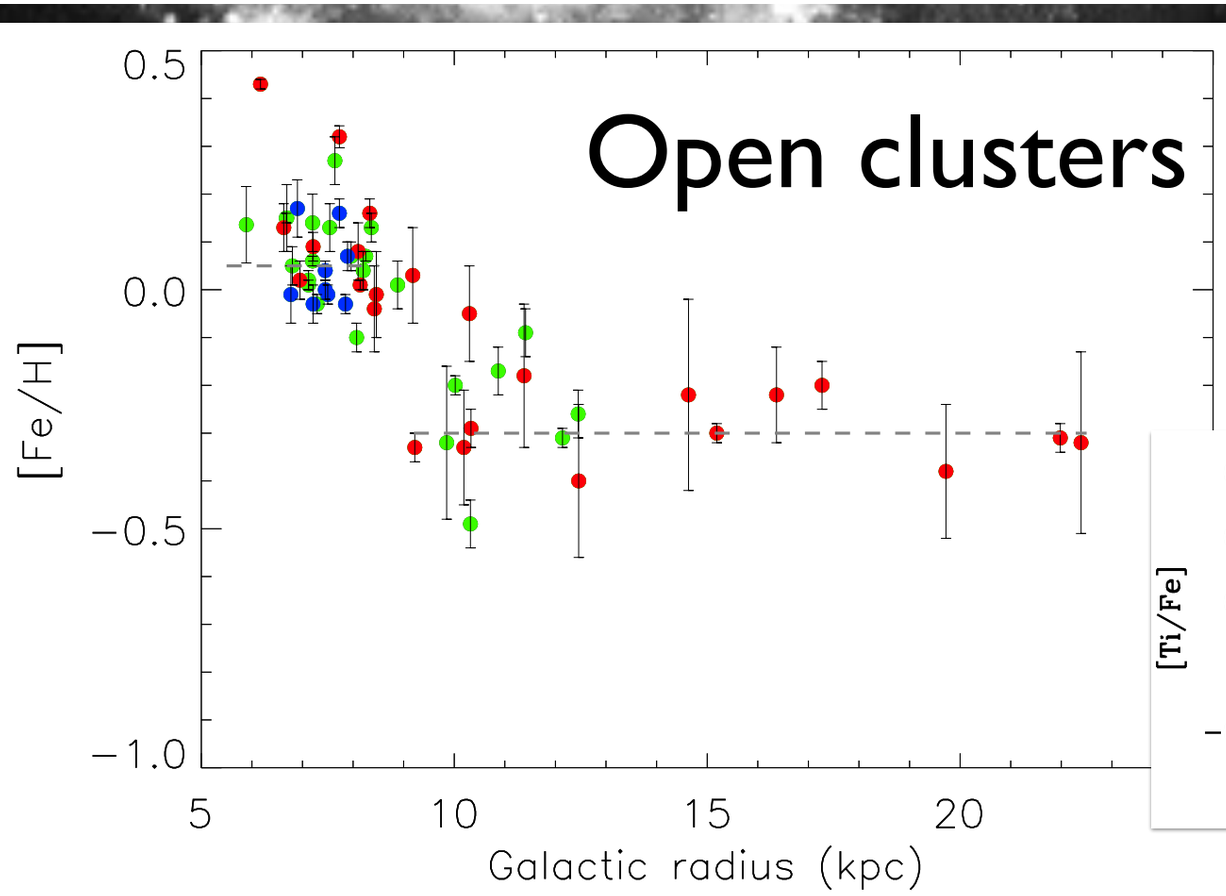
Nieva and Przybilla BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)

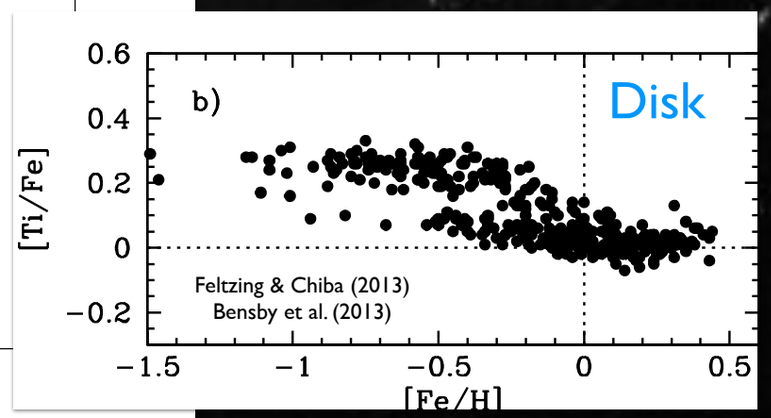


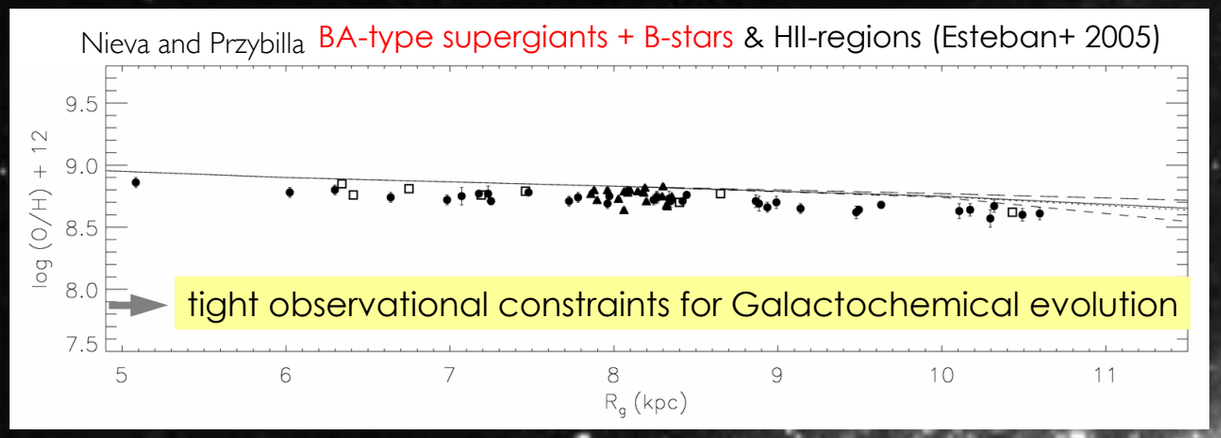
tight observational constraints for Galactochemical evolution

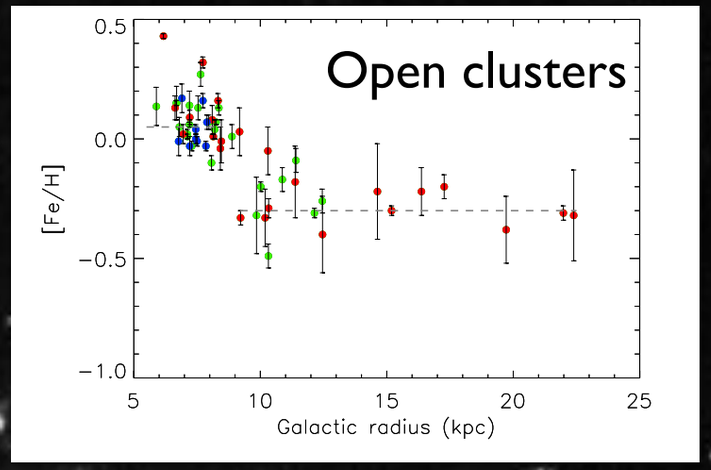


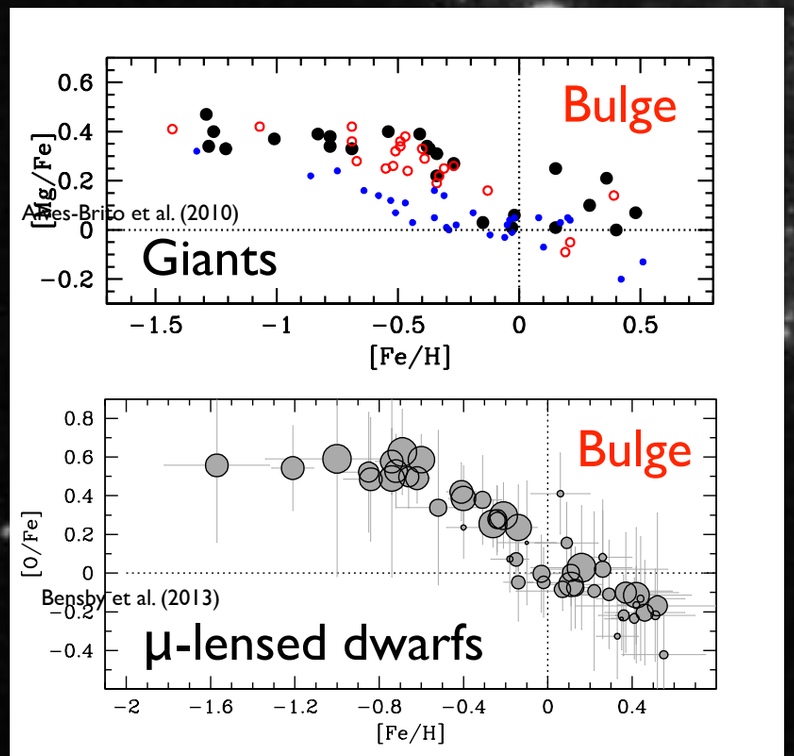


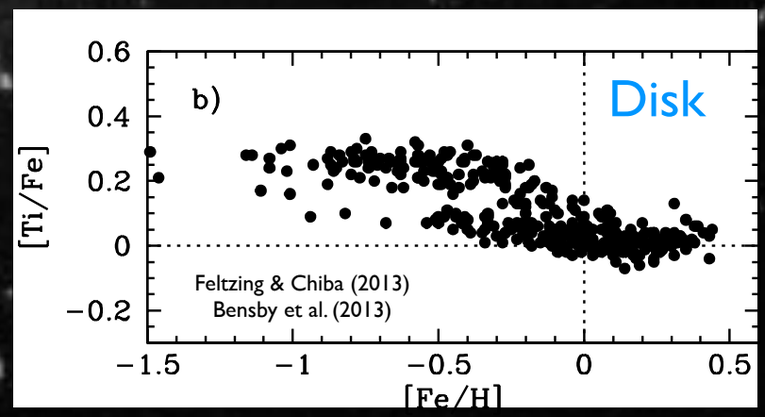


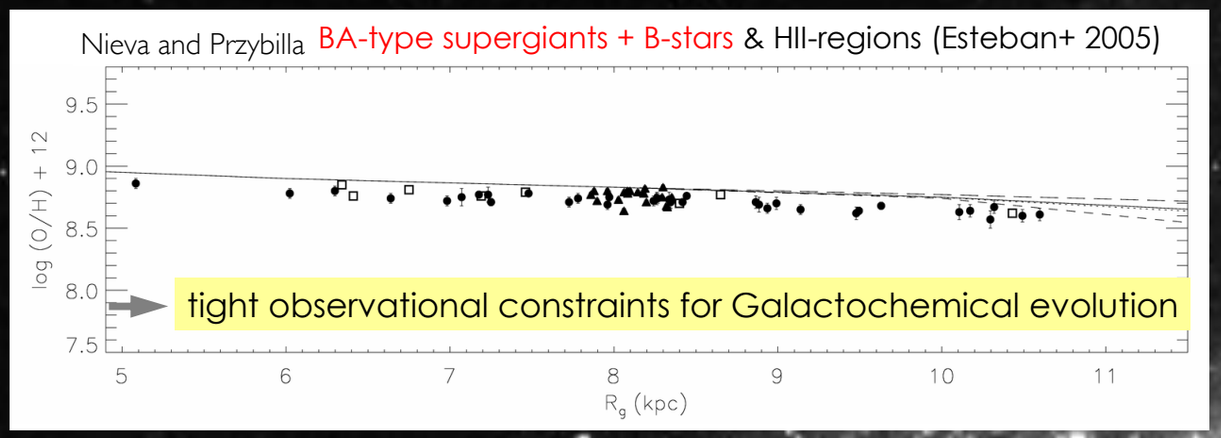


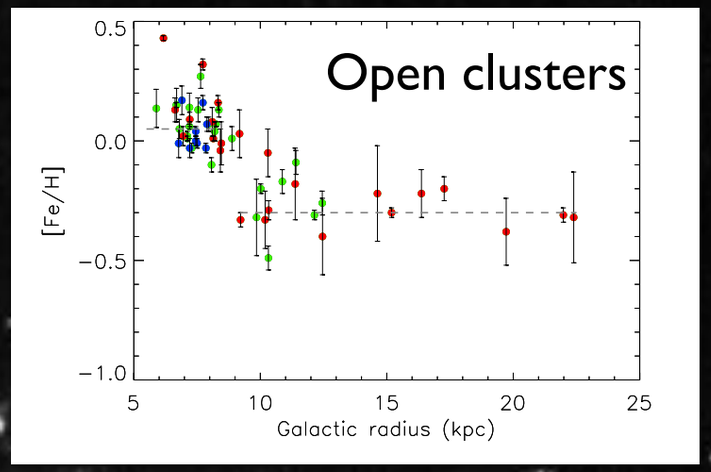

Nieva and Przybilla BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)
log (O/H) + 12
R_g (kpc)
tight observational constraints for Galactochemical evolution

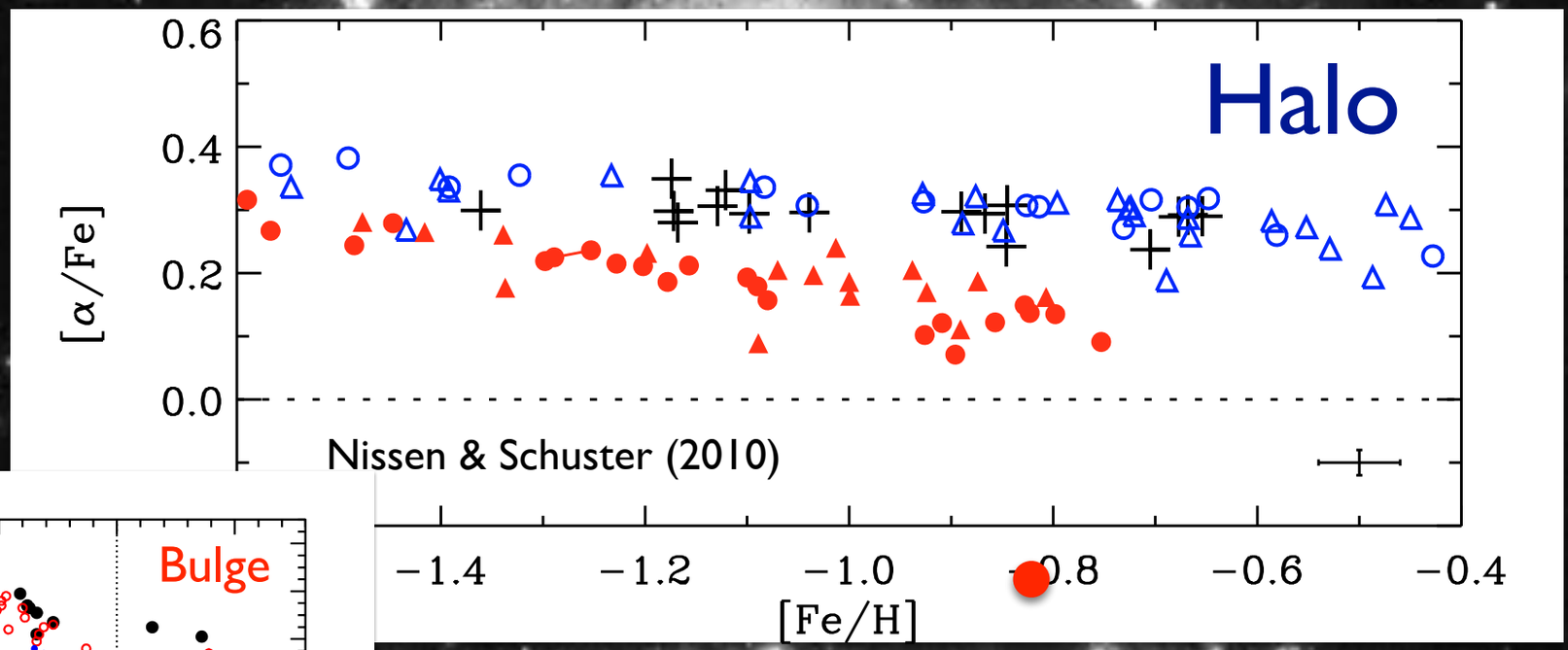

Open clusters
[Fe/H]
Galactic radius (kpc)

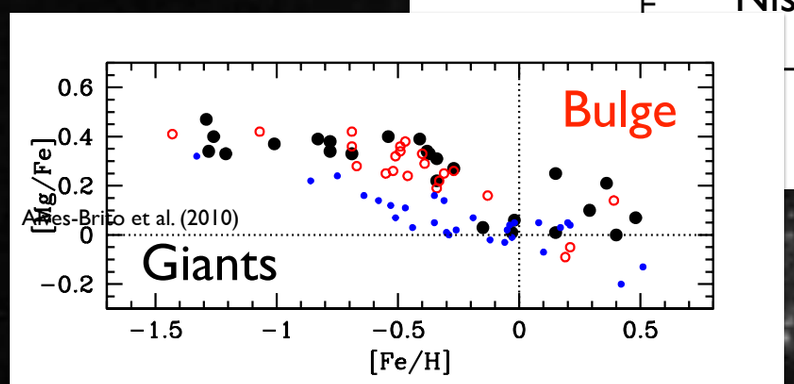

Bulge
Giants
Alves-Brito et al. (2010)
[Mg/Fe]
[Fe/H]
Bulge
μ-lensed dwarfs
Bensby et al. (2013)
[O/Fe]
[Fe/H]

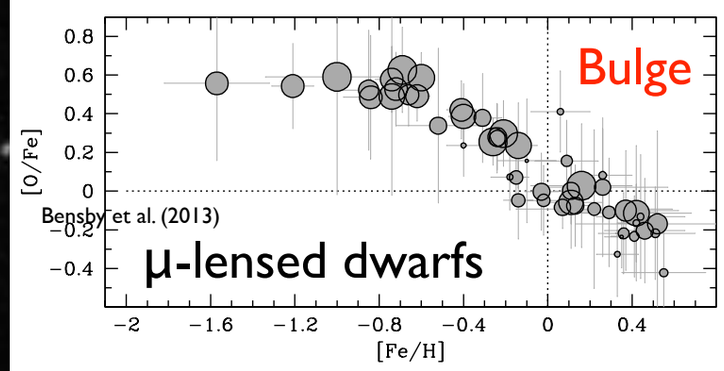

b)
Disk
Feltzing & Chiba (2013)
Bensby et al. (2013)
[Ti/Fe]
[Fe/H]

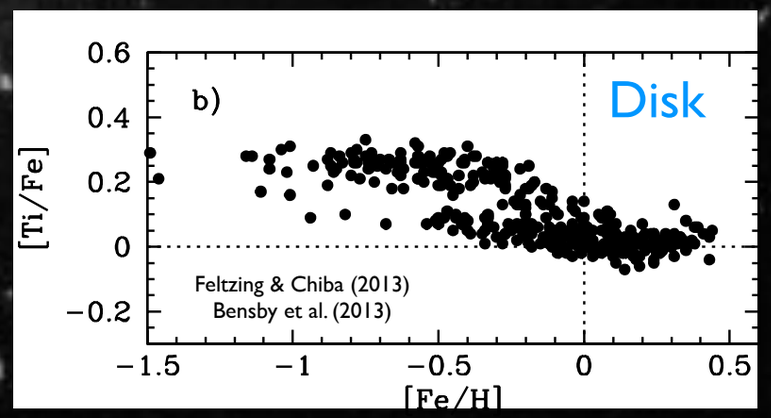

Nieva and Przybilla BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)
log (O/H) + 12
R_g (kpc)
tight observational constraints for Galactochemical evolution

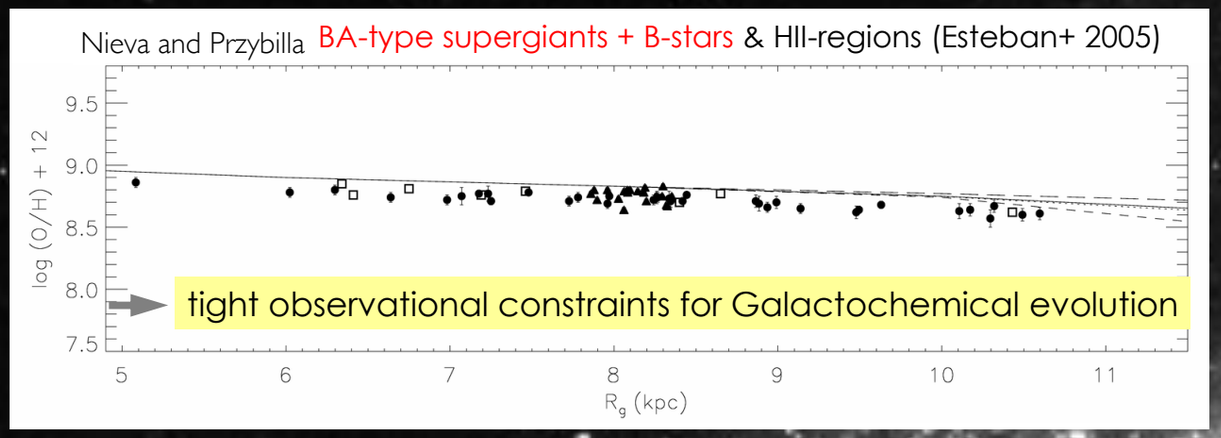

Open clusters
[Fe/H]
Galactic radius (kpc)

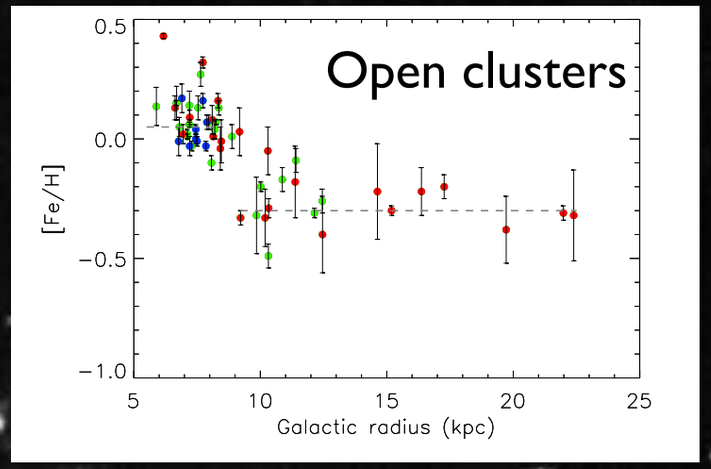

Halo
[α/Fe]
Nissen & Schuster (2010)
[Fe/H]

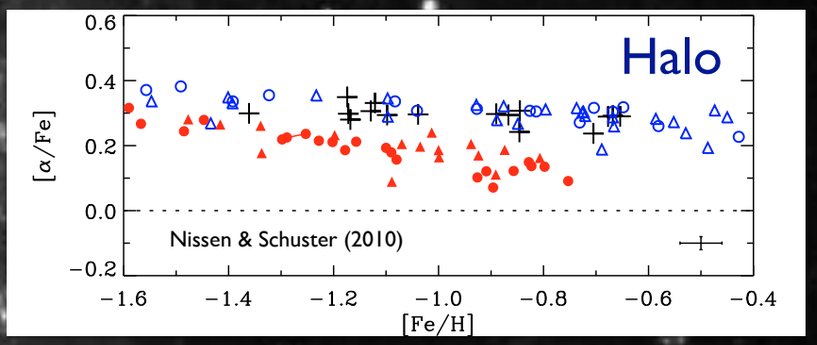

Bulge
[Mg/Fe]
Alves-Brito et al. (2010)
Giants
[Fe/H]


Bulge
[O/Fe]
Bensby et al. (2013)
μ-lensed dwarfs
[Fe/H]

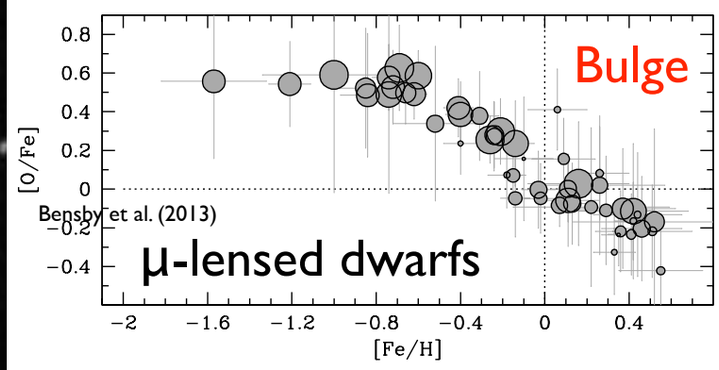

b)
Disk
[Ti/Fe]
Feltzing & Chiba (2013)
Bensby et al. (2013)
[Fe/H]

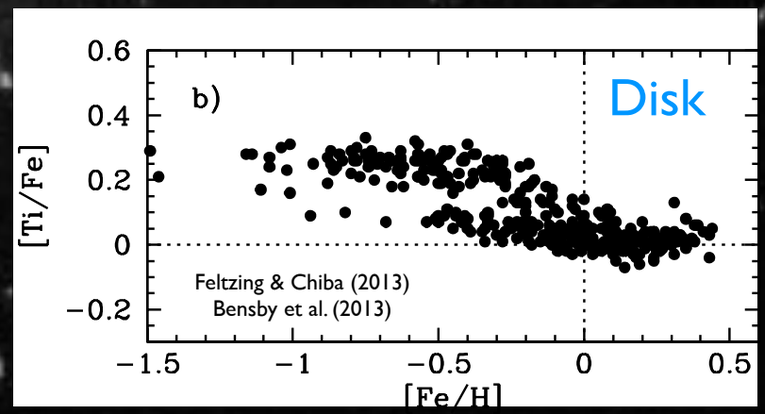

Nieva and Przybilla BA-type supergiants + B-stars & HII-regions (Esteban+ 2005)
log (O/H) + 12
R_g (kpc)
tight observational constraints for Galactochemical evolution


Open clusters
[Fe/H]
Galactic radius (kpc)


Halo
[α/Fe]
Nissen & Schuster (2010)
[Fe/H]

Bulge
[Mg/Fe]
Alves-Brito et al. (2010)
Giants
[Fe/H]


Bulge
[O/Fe]
Bensby et al. (2013)
μ-lensed dwarfs
[Fe/H]


b)
Disk
[Ti/Fe]
Feltzing & Chiba (2013)
Bensby et al. (2013)
[Fe/H]

Summary

- Most high precision data still confined to solar neighbourhood or Galactic bulge
- Chemical tagging has been applied in two ways
  - Simple “by-eye” tagging for specific project – successful
  - Detailed analysis of larger samples – un-successful so far
- We need surveys

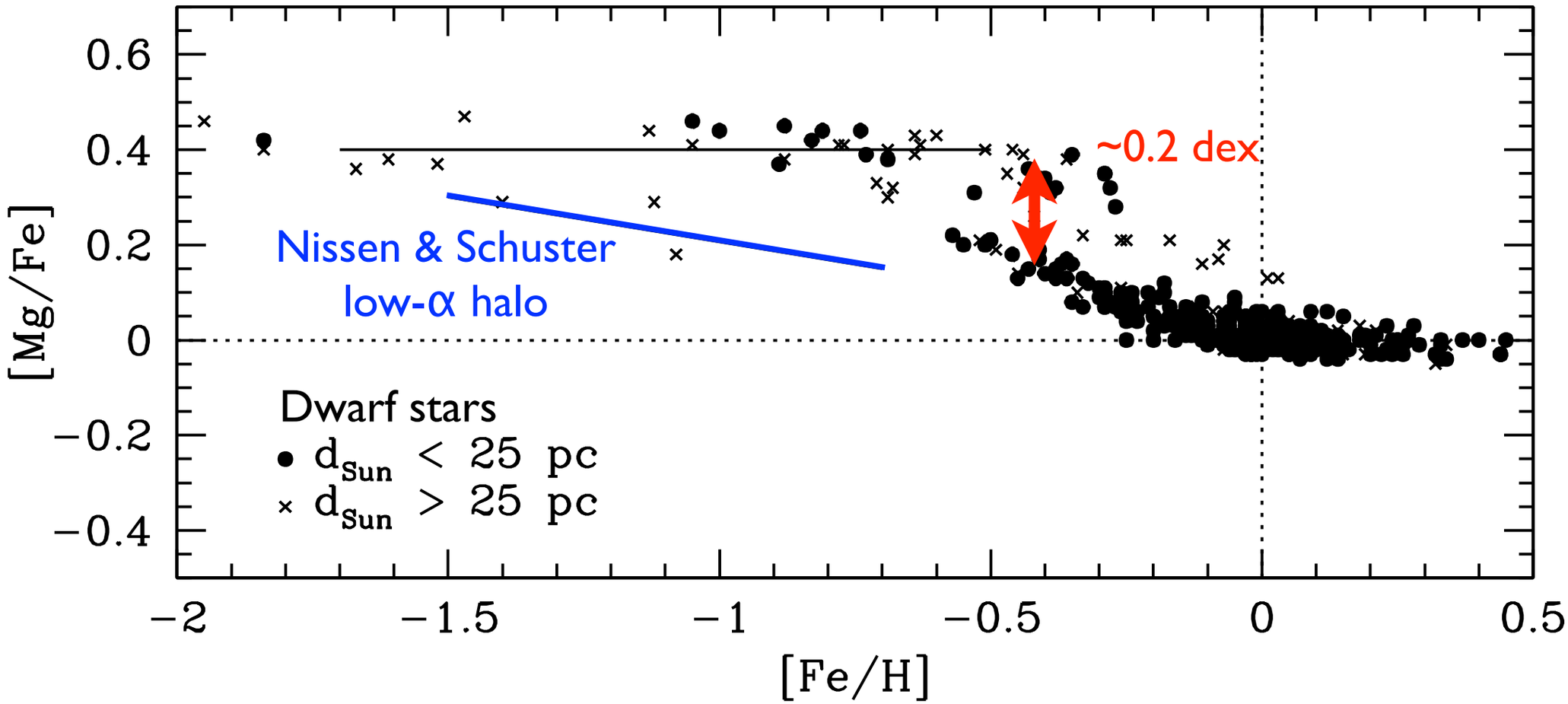
What should surveys deliver?

- Precision good enough to be able to detect the features we are interested in
  - Note – we do not necessarily know what we are looking for

- Samples large enough to address the questions we want to ask to the data
  - Normally this ends up with 10^5 to several 10^6 stars, depending on the problem

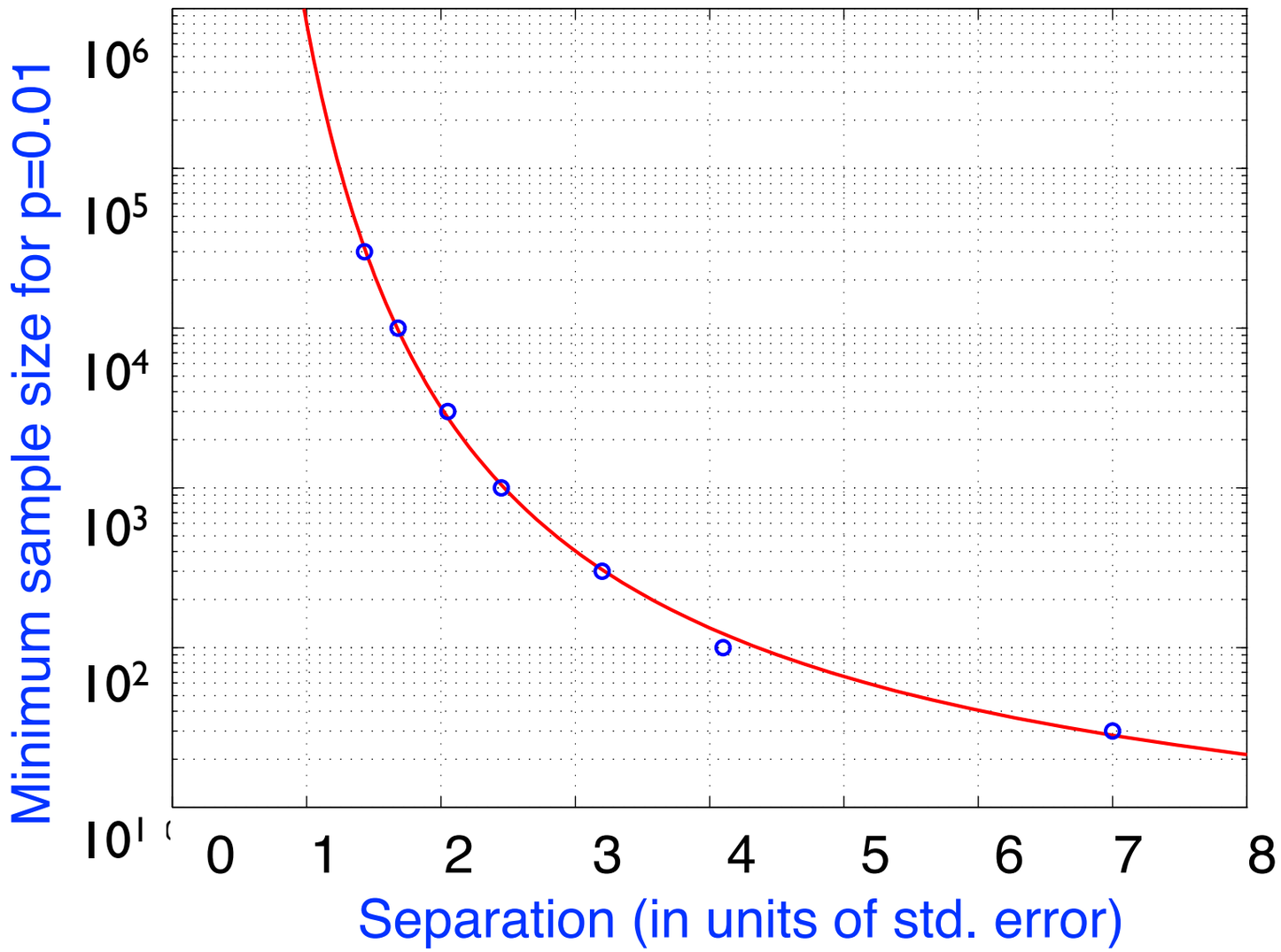
Size of features

We saw earlier that the size of features seen in abundance trends are of ~0.2 dex, or less



Plot based on data from Klaus Furhmann's studies (priv. comm.)

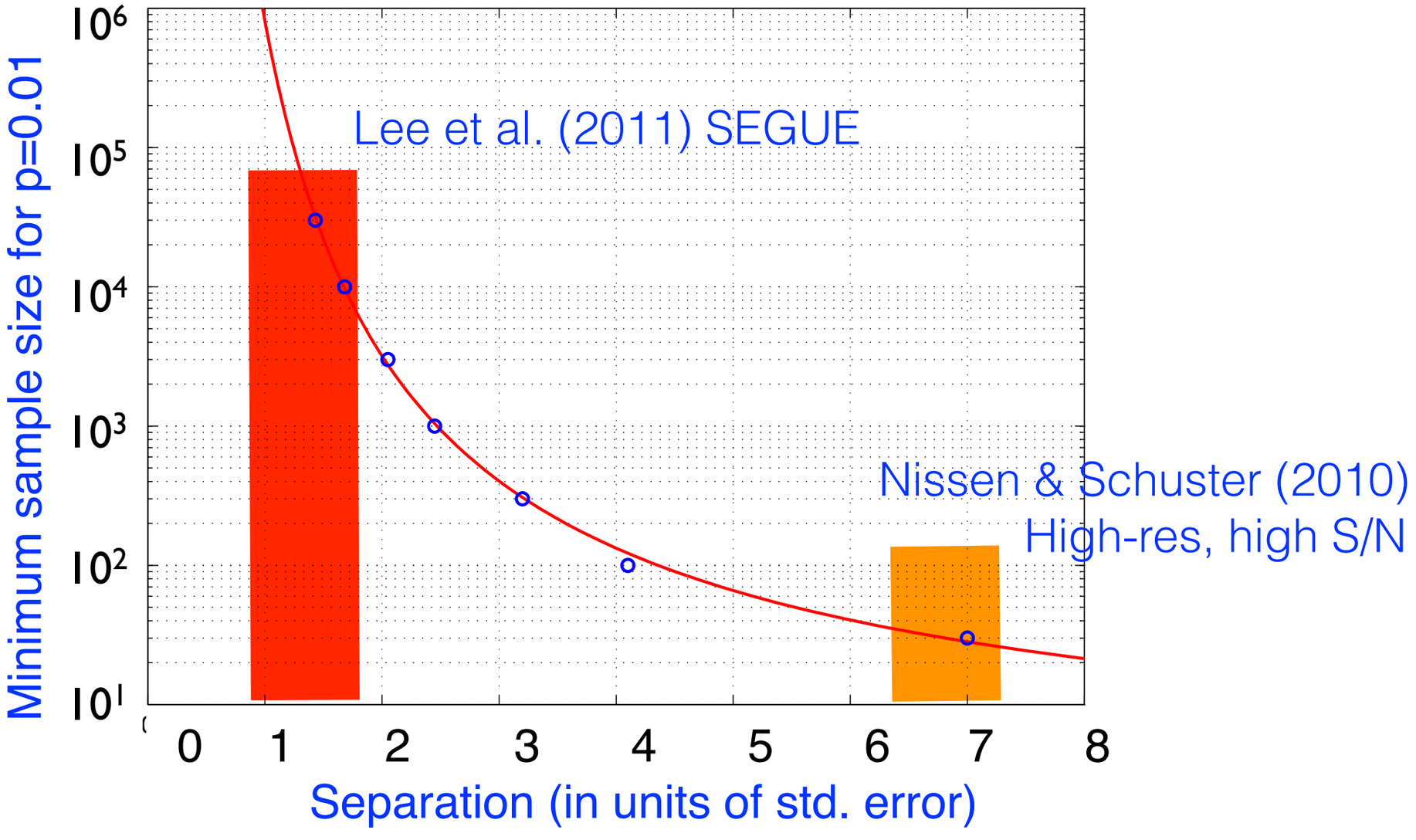
Precision vs # stars



Low probability of false detection (p = 0.01)

Lindegren & Feltzing 2013 A&A 553 A94

Precision vs # stars



Low probability of false detection (p = 0.01)

Lindegren & Feltzing 2013 A&A 553 A94

Summary

- Large samples are good
- But good precision is still required
- Cheer number does not compensate for poor data
- You must decide what precision your problem needs

Surveys that tag

- Currently available surveys include
  - SEGUE (SDSS 2.5m, Apache point)
  - RAVE (UK Schmidt, AAO)
  - APOGEE (SDSS 2.5m, Apache point)
  - Gaia-ESO Survey (VLT, Paranal)
  - GALAH on HERMES (AAT, AAO)

- Future surveys include those performed using
  - MOONS (VLT, Paranal)
  - WEAVE (WHT, La Palma)
  - 4MOST (VISTA, Paranal)

Surveys that tag

NIR

MOONS

NIR multifibre spectrograph being built for VLT

R ~ 5000 (0.64-1.8 μm)

R ~ 9000, 20 000, 20 000 (0.7-0.9, 1.17-1.26, 1.52-1.63 μm)

1024 fibres

Being built by consortium lead by ATC, UK

PI: Michelie Cirasuolo

http://www.roe.ac.uk/~ciras/MOONS/VLT-MOONS.html

Cirasuolo et al (SPIE, 2014)

UV

WEAVE

Multifibre spectrograph being built for WHT

R ~20 000 and R ~5000

800 fibres (switches R)

Gaia follow-up (4MOST in the North), extra-galactic science

Netherlands, UK, Spain, France, Italy

Project scientist: Scott Trager

http://www.ing.iac.es/weave/

UV

4MOST

Multifibre spectrograph to go on VISTA

R ~20 000 and R ~5000

800 + 1600 fibres

Gaia and eROSITA follow-up

10-20 million LR stars

1-2 million HR stars

LR to V~20 w SNR 10/Å

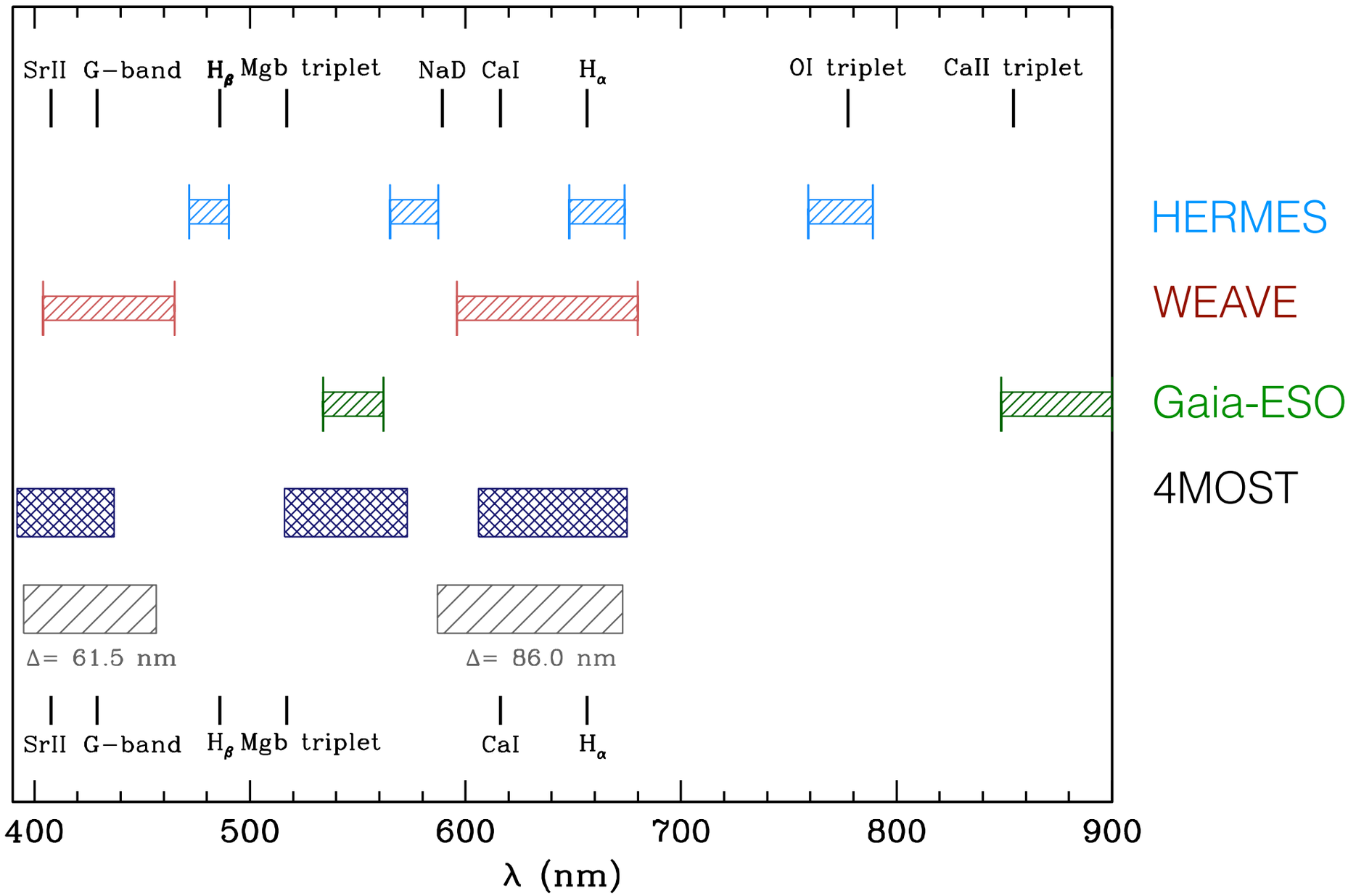
HR~16.5/17 w SNR of 170/Å

PI: Roelof de Jong

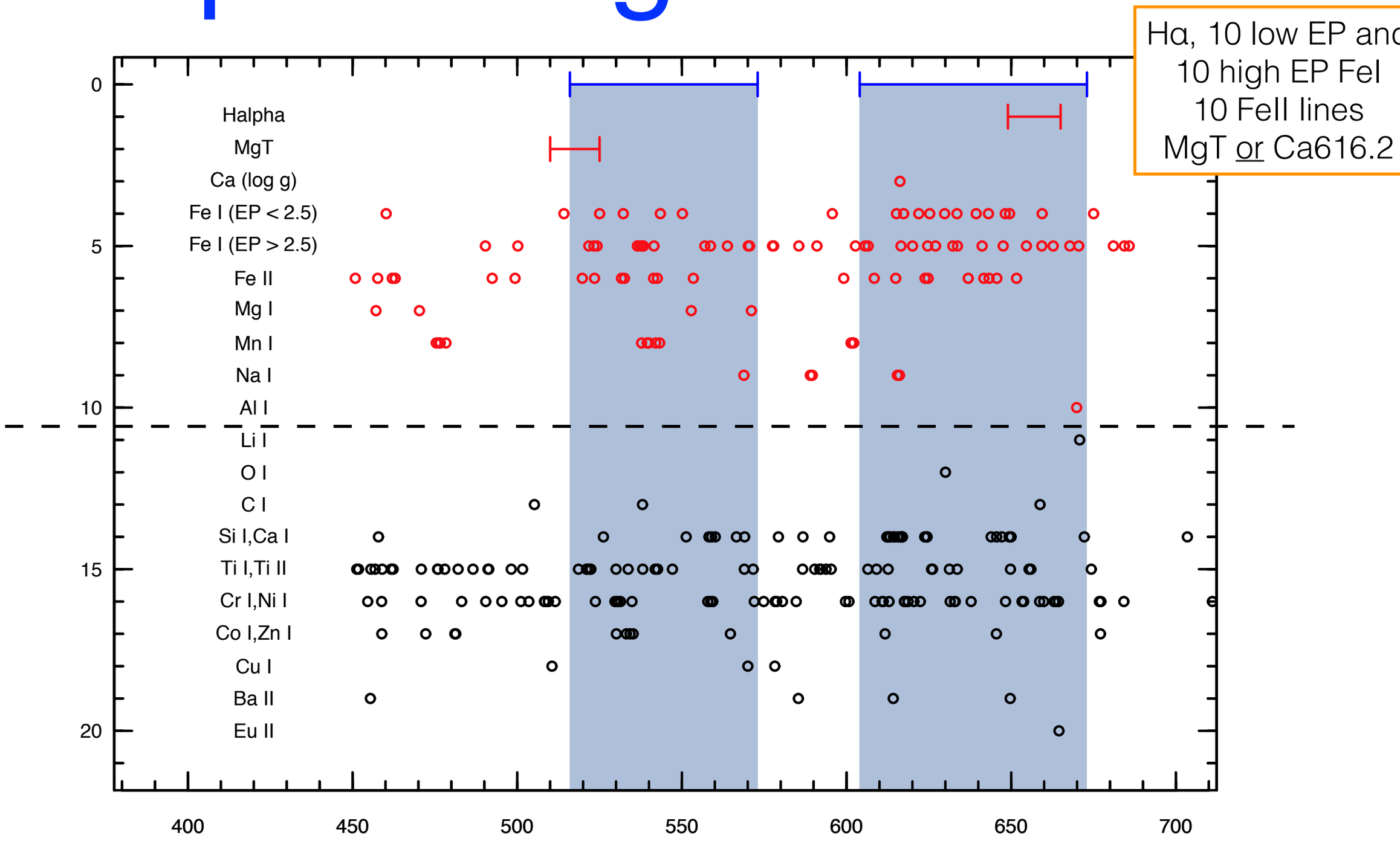
http://www.4most.eu

de Jong et al (SPIE, 2014)

λ-coverage (optical)



Optimizing 4MOST



Hα, 10 low EP and
10 high EP FeI
10 FeII lines
MgT or Ca616.2

Line-list wetted for science

Ruchti et al. (to be submitted)

But, will it really work?

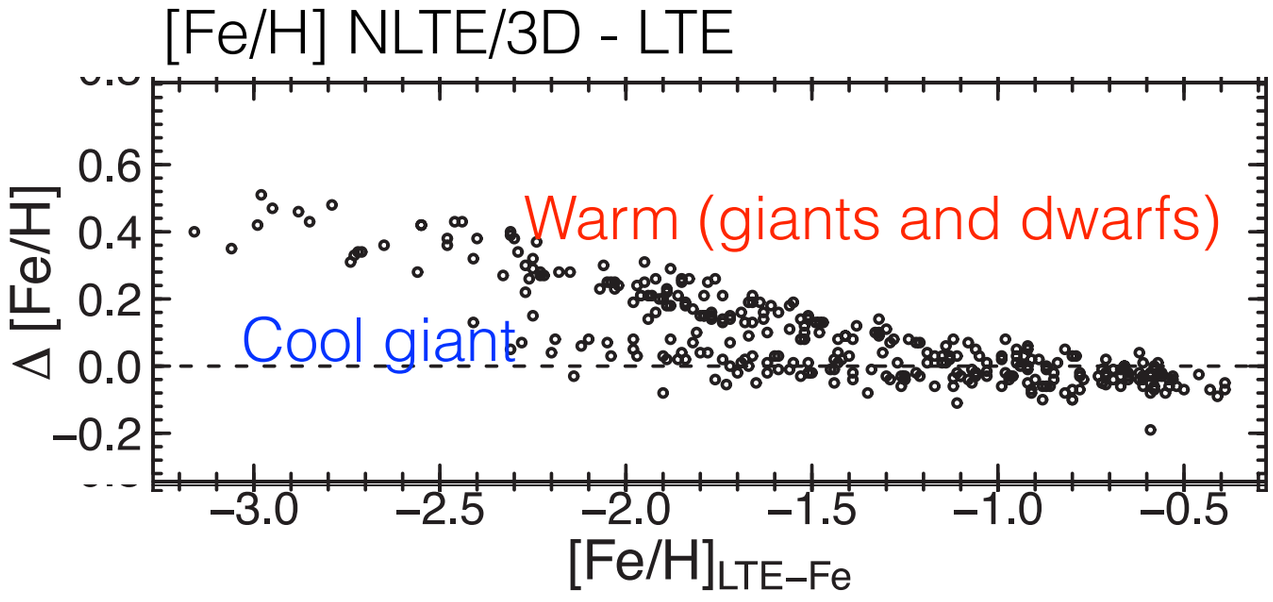
- Well …
- It does seem to work well when you compare apples with apples.
- What about the apples and oranges? That is less certain.

Two potential pitfalls ➔

Spanners in the works…

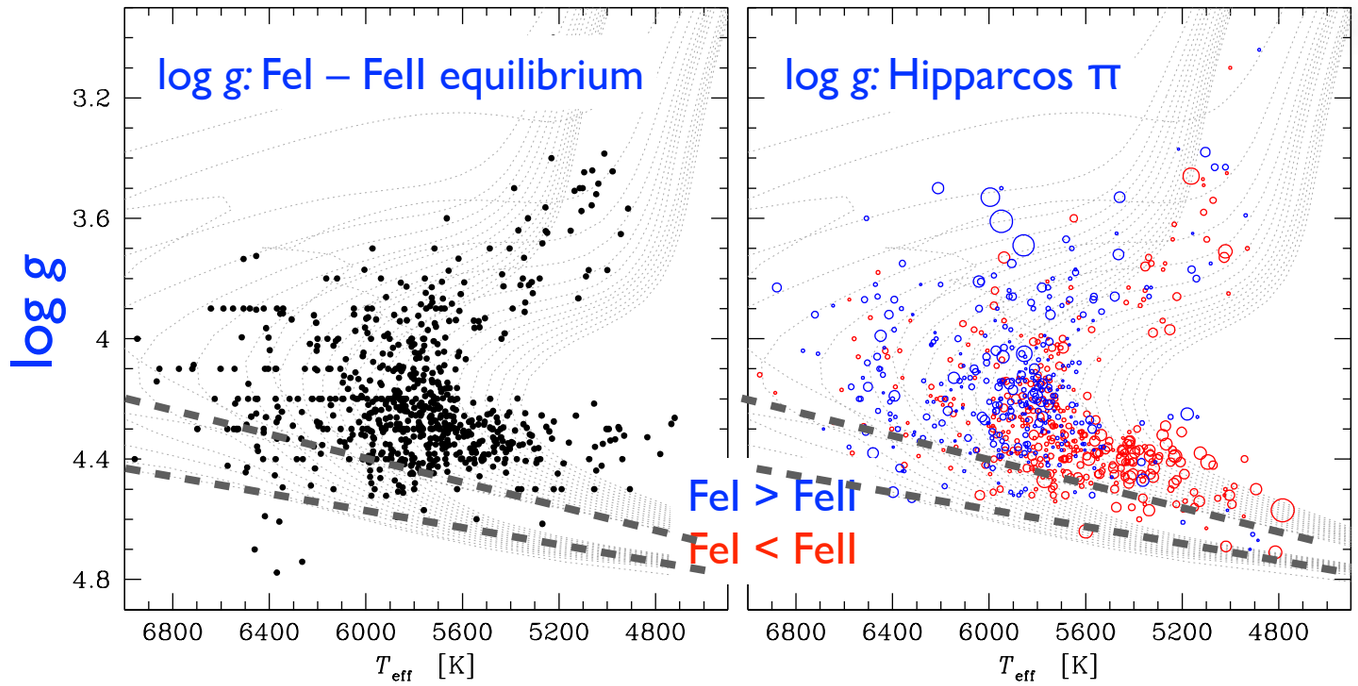
- Önehag et al. (2014) find tentative evidence that selective diffusion occurs in solar type stars at MS and TOP in M67
  - Variations up to 0.05 dex along the evolutionary sequence for some heavy elements

- NLTE, 3D effects can be severe, e.g., Ruchti et al. (2013)

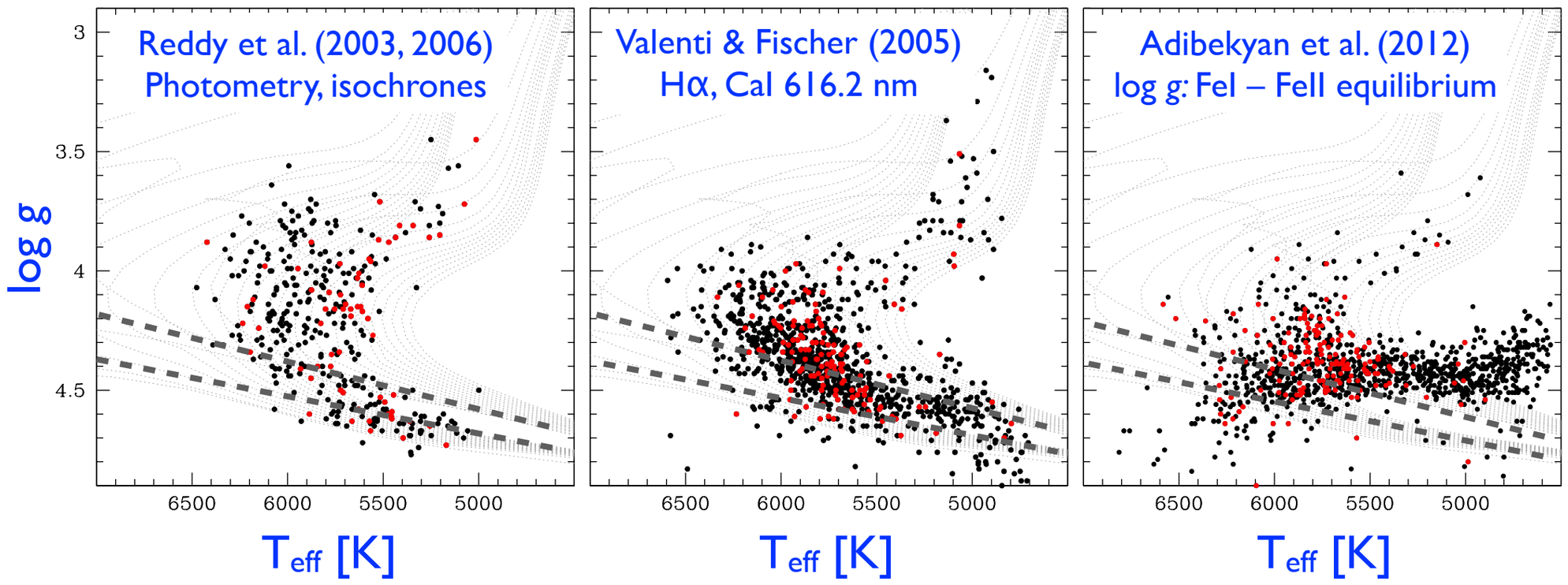


Önehag et al. 2014 A&A 562 A102
Ruchti et al. 2013 MNRAS 429 126

Spanners in the works...



Bensby et al. 2014 A&A 562 A71

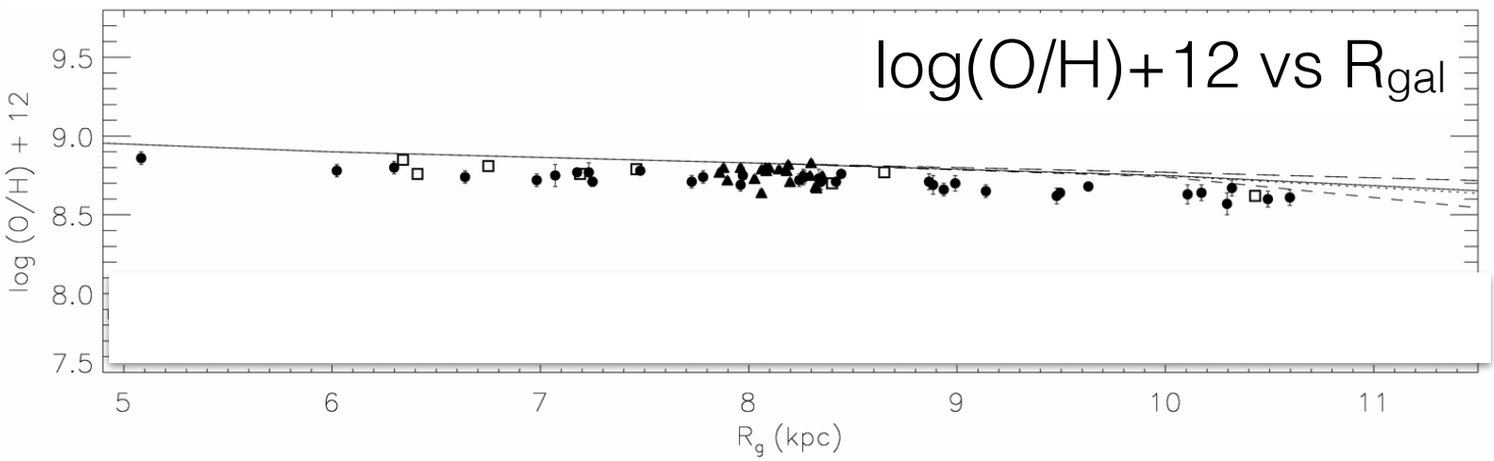


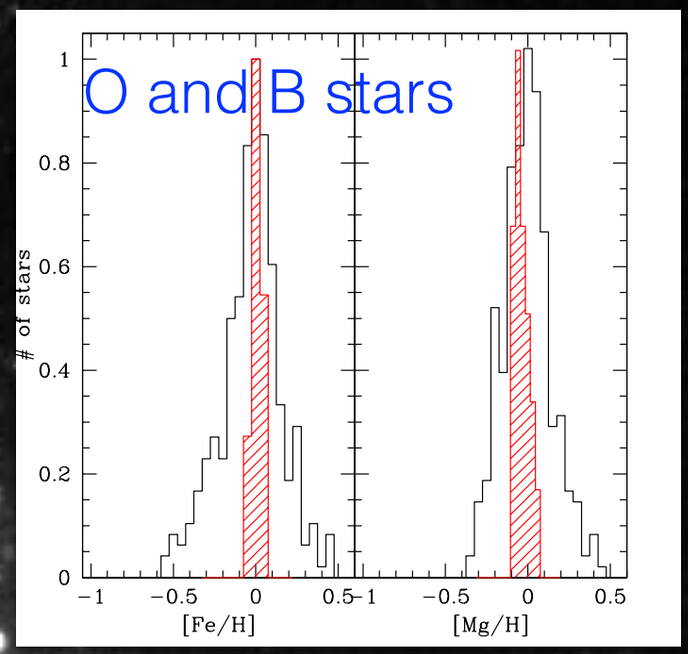
Summary

- Apples and oranges …
- Get your parameters right or select only one type of star (and consider NLTE, 3D …)
- How unique is a single star formation event? Are we “only” going to be able to recognise ensembles of star formation events?

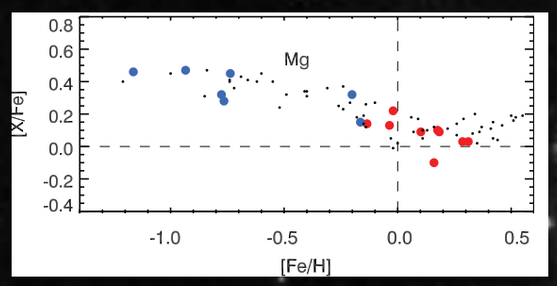
But see Feng & Krumholz 2014 Nature 513 523

Nieva and Przybilla A-type supergiants + B-stars & HII-regions (Esteban+ 2005)

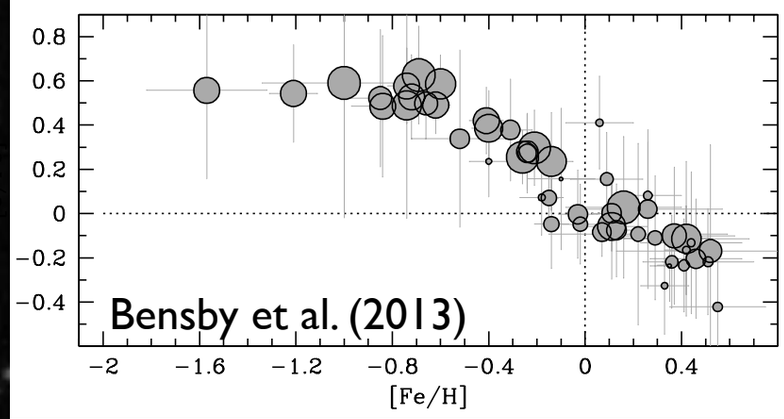


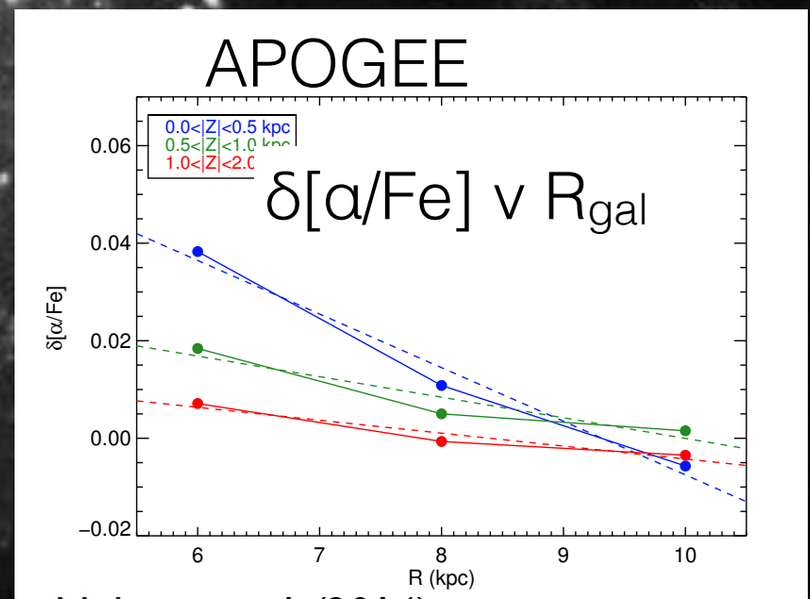


NIR-bulge, Ryde (2014)



μ-lensed dwarfs





Nidever et al. (2014)