Galactic Archeology

Prospects and issues

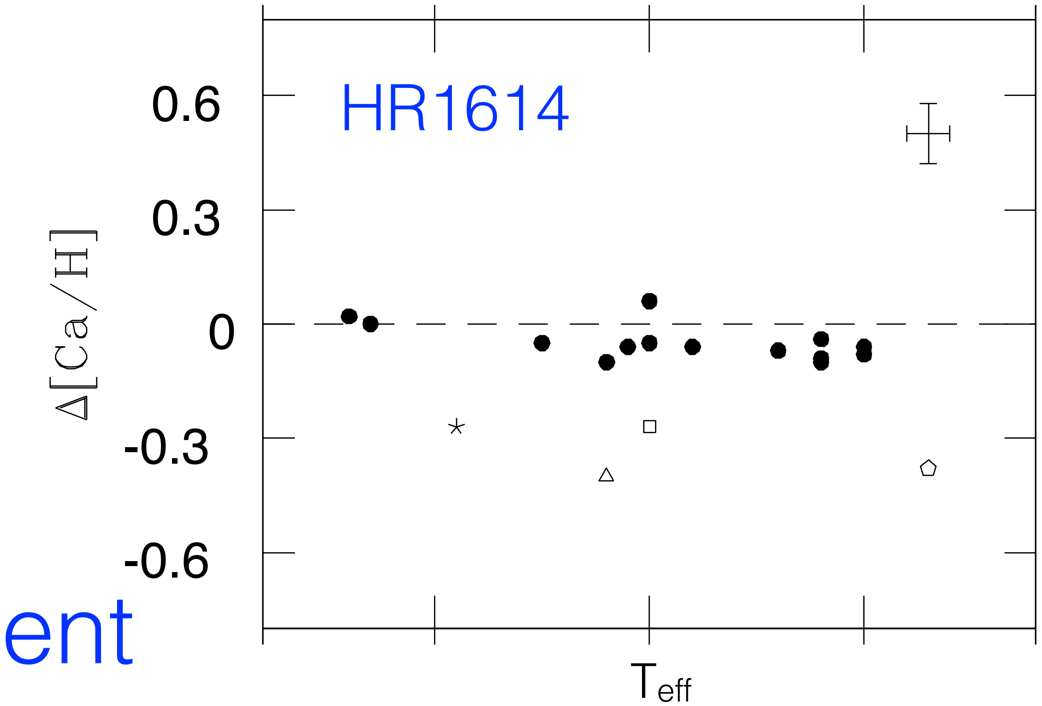
Sofia Feltzing
Lund Observatory

Galactic Archeology

- 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 disperse in the Galactic potential

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

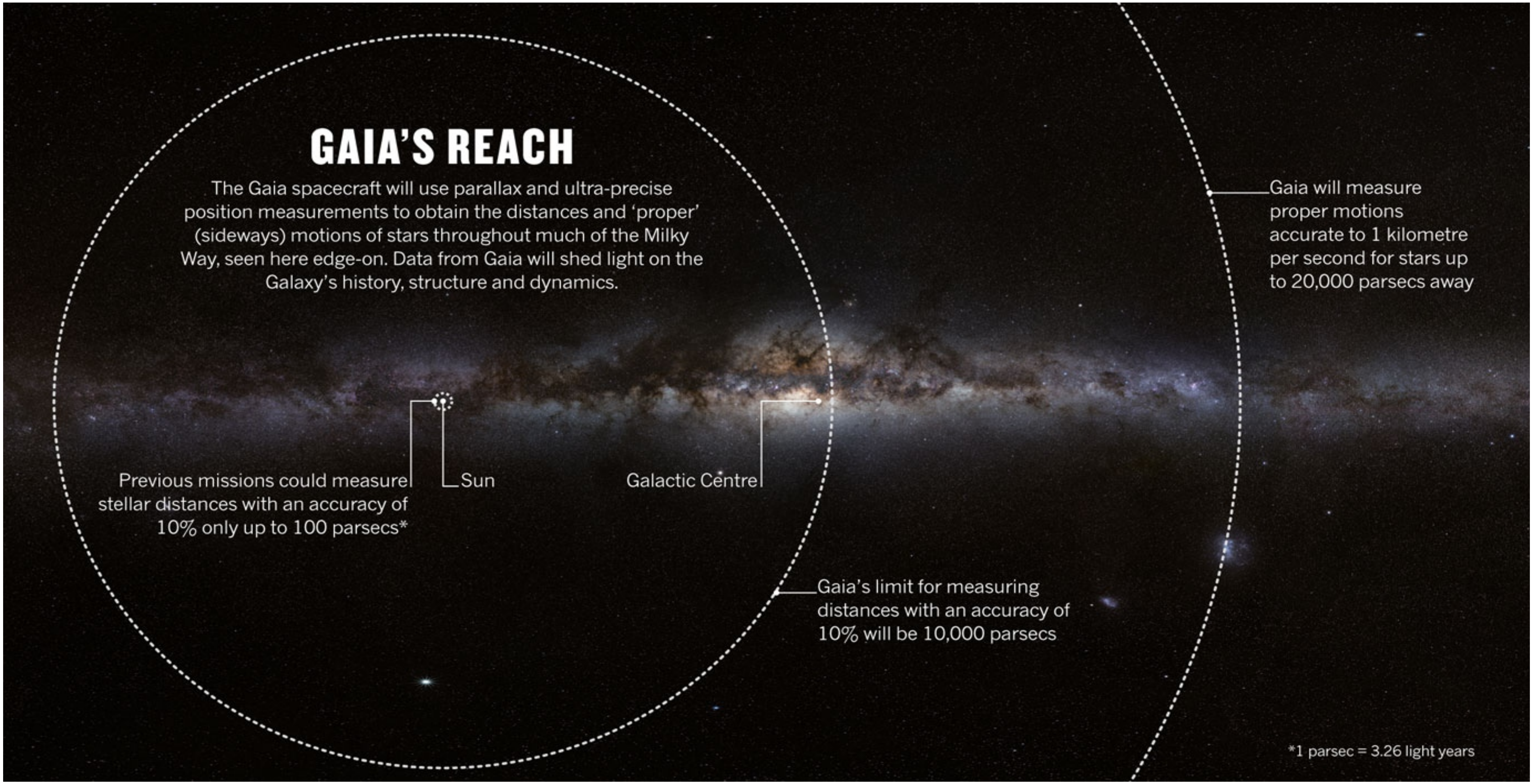


- So far we have likely
  - truly identified 1 (one!) such event
    - ★ The moving group HR1614 (de Silva et al.)
  - we have disproved several, e.g.,
    - ★ Herculus moving group (Bensby et al.)
    - ★ KFR08 stream (Liu, Ruchti, Feltzing)
  - have we just been unlucky or is it really hard to do this? (see also Mitschang et al. 2014, Ting et al. 2012)

de Silva et al. 2007 AJ 133 694
Bensby et al. 2007 ApJLetters 655 L89
Liu, Ruchti, Feltzing A&A, in referee process

Mitschang et al. 2014 MNRAS 438 2753
Ting et al. 2012 MNRAS 421 1231

Gaia changes all



From A. Helmi @ ESO in 2020

★ Ground-based follow-up to Gaia is essential as not all stars will have spectra and hence will not have, e.g., [Fe/H] derived

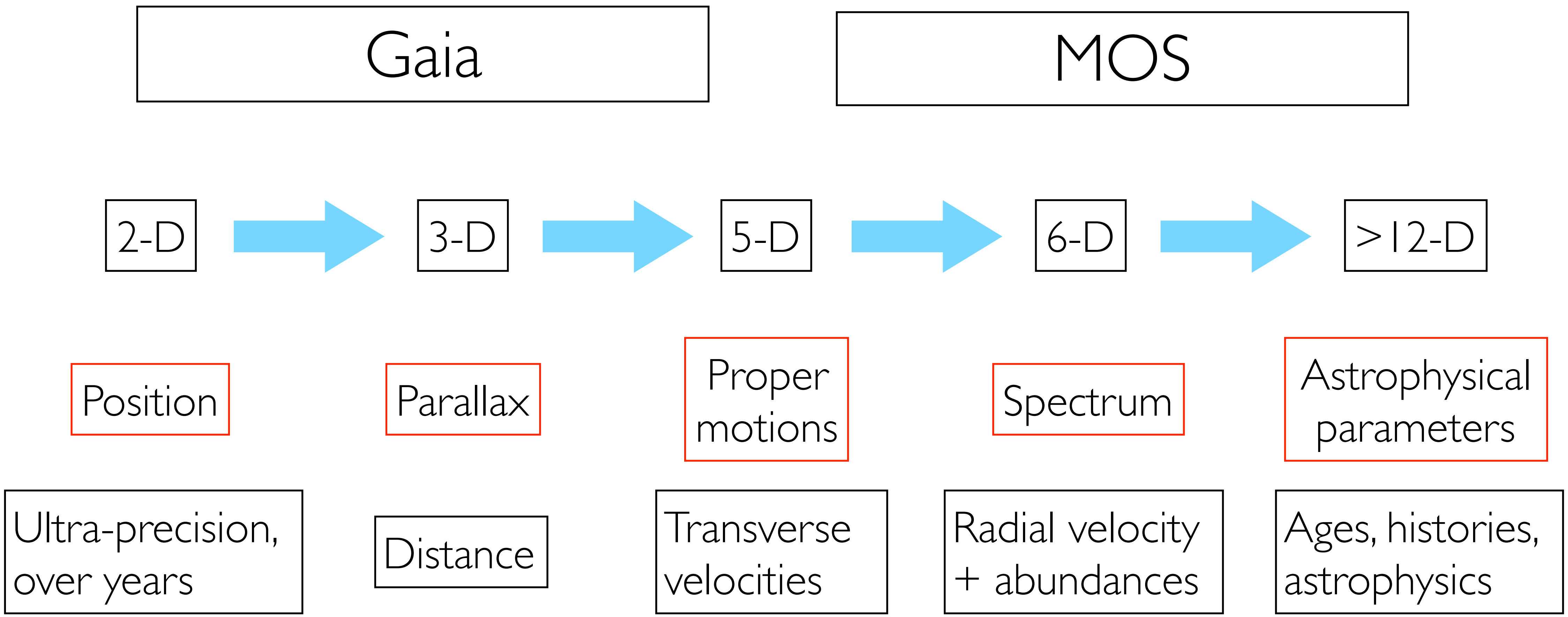
Measurement	Accuracy
Astrometry	7 μarcsec at $V = 10$
	12 – 25 μarcsec at $V = 15$
	100 – 300 μarcsec at $V = 20$
Photometry	low resolution prism spectra to $V = 20$
Radial velocities	1 – 15 km s^{-1} to $V \lesssim 17$

Ca II infra-red triplet (847 – 874 nm)

RVs down to ~15.2 and abundances to 11

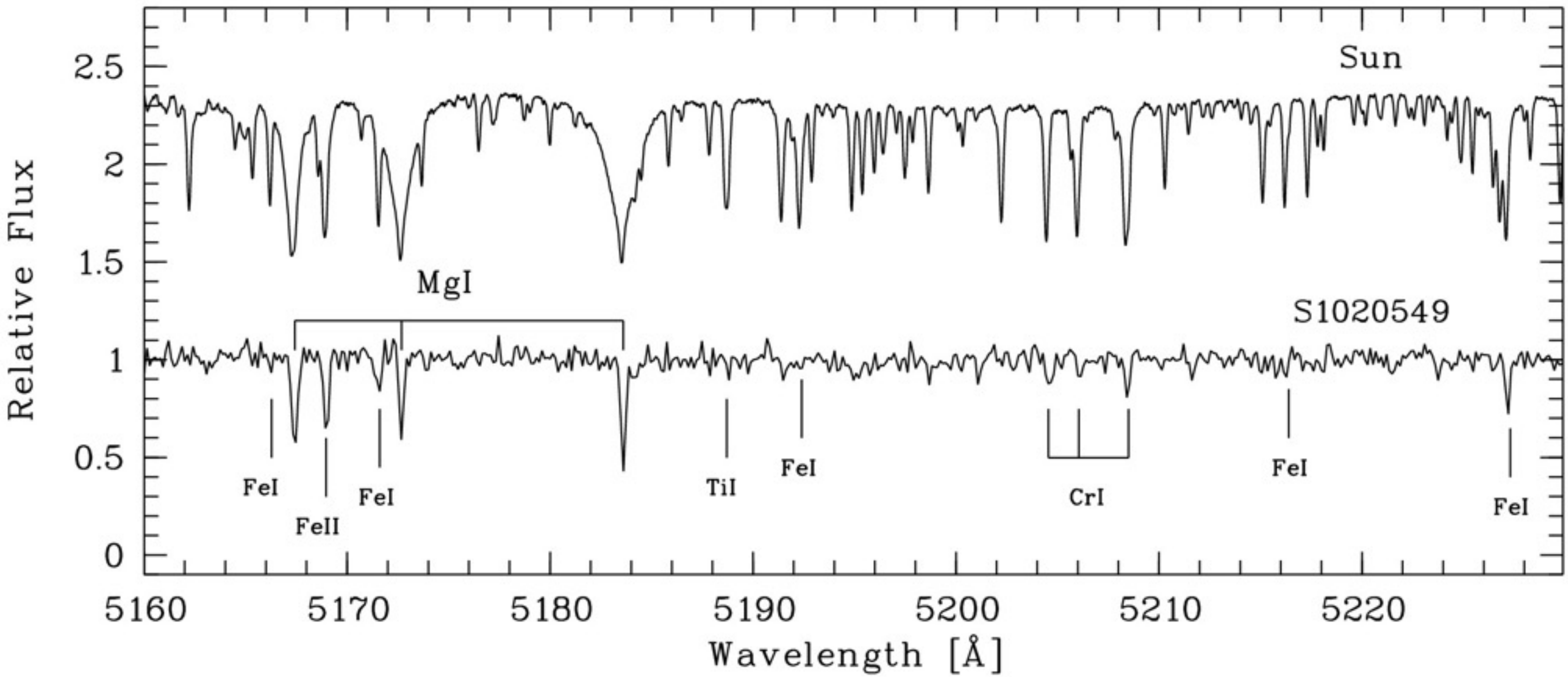
Pre-launch estimates

Ground-based follow-up

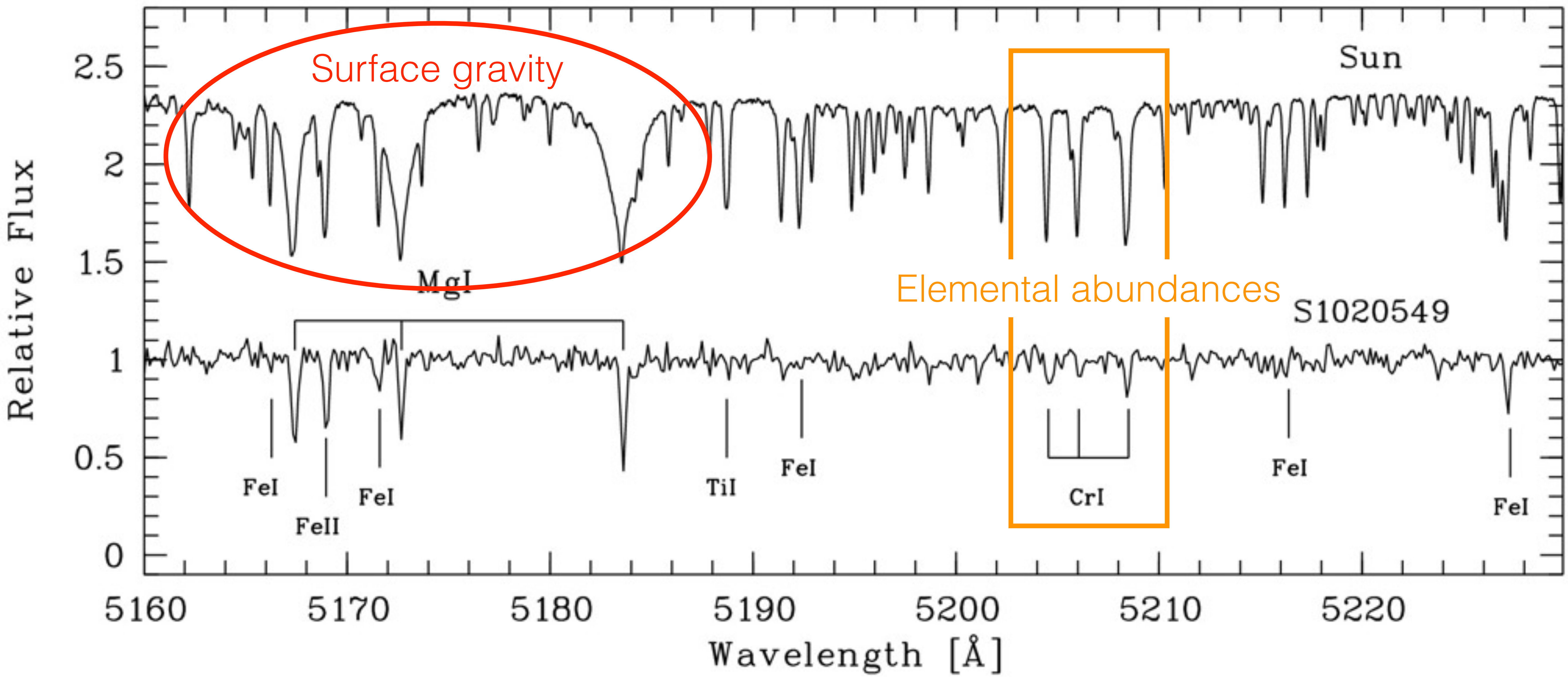


Adapted from Gilmore et al. (2012)

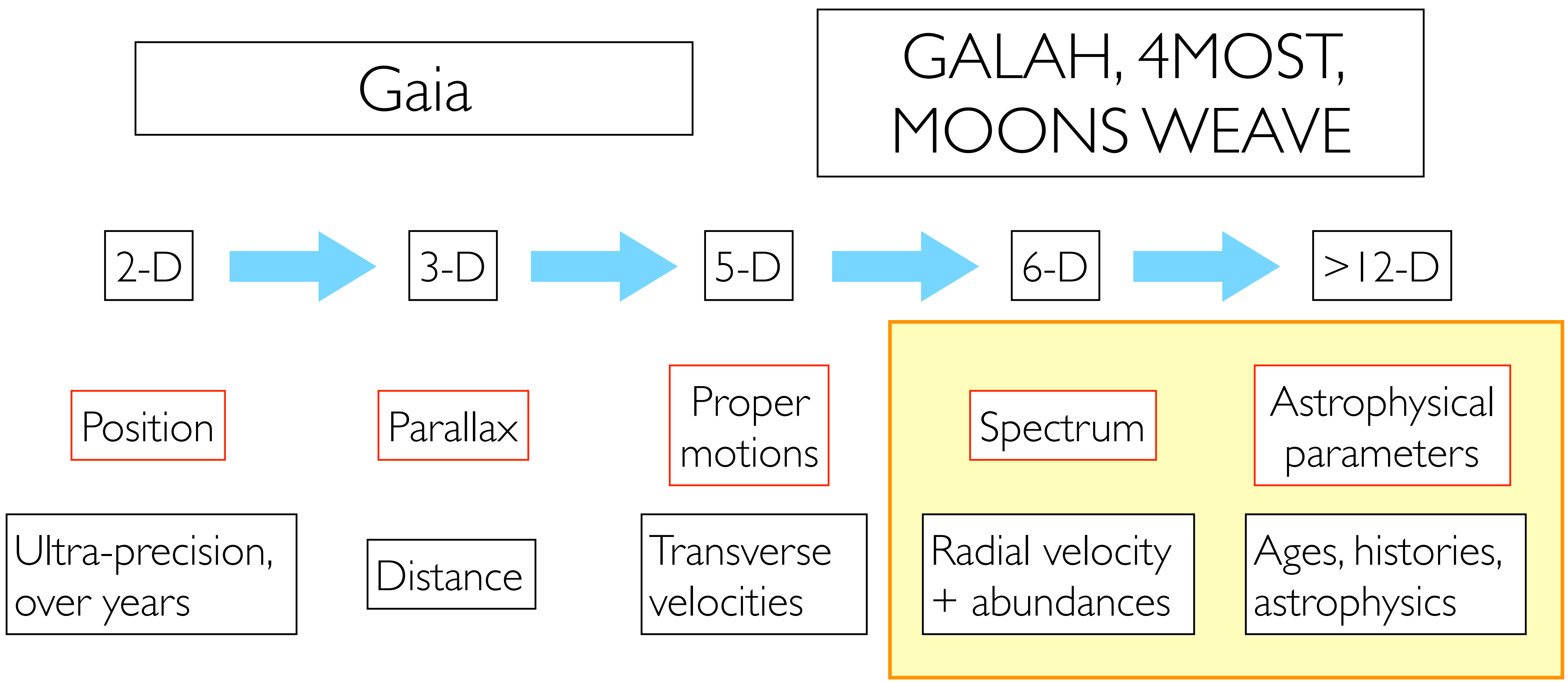
Ground-based follow-up



Ground-based follow-up



Ground-based follow-up



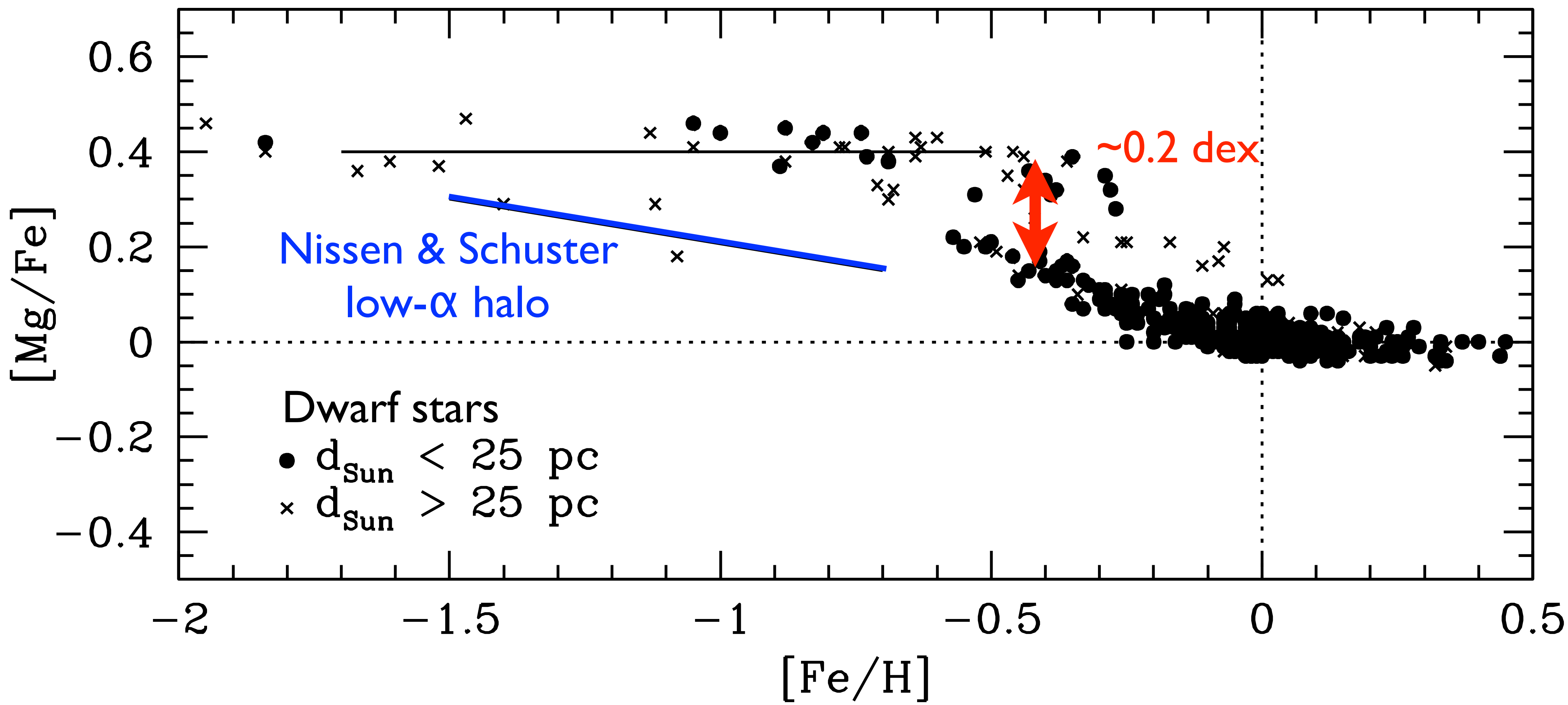
Requirements on spectrographs come from how well we need to know elemental abundances and stellar parameters.

Adapted from Gilmore et al. (2012)

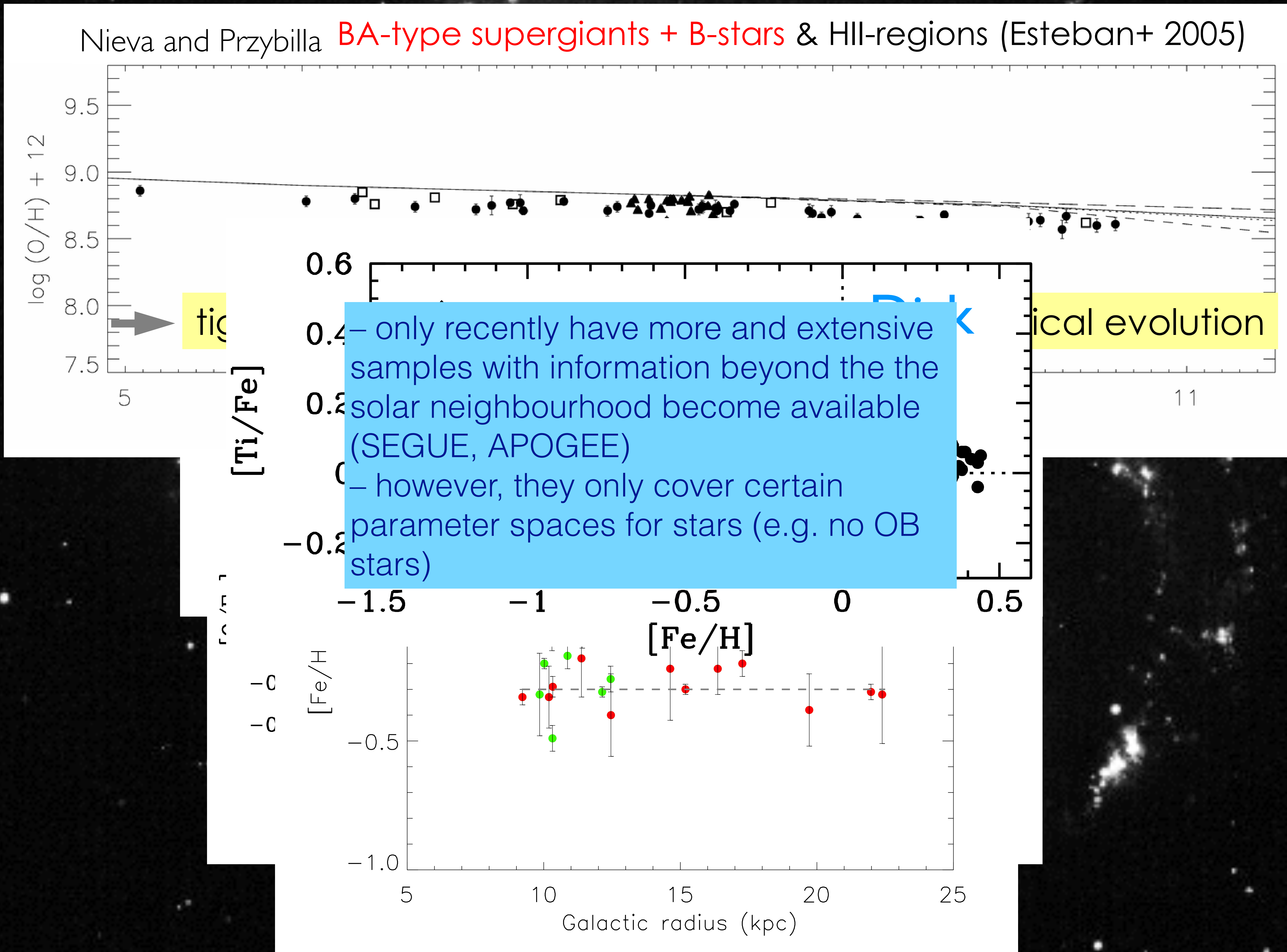
Size of features

Example of the precision/accuracy you wish to have.

The typical 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.)

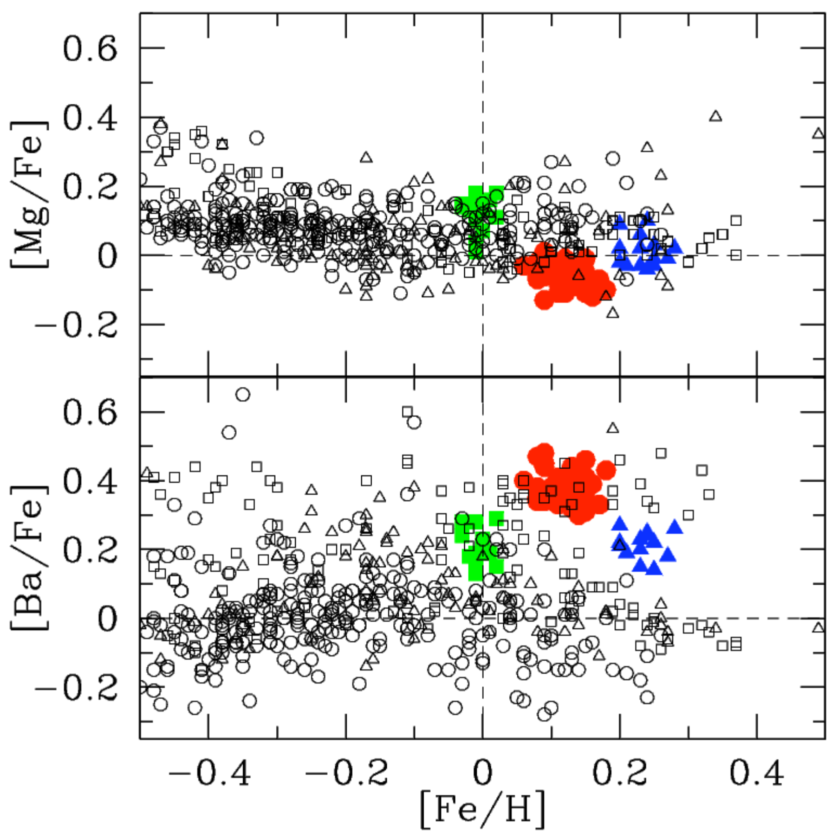


– only recently have more and extensive samples with information beyond the the solar neighbourhood become available (SEGUE, APOGEE)

– however, they only cover certain parameter spaces for stars (e.g. no OB stars)

Sizes to measure

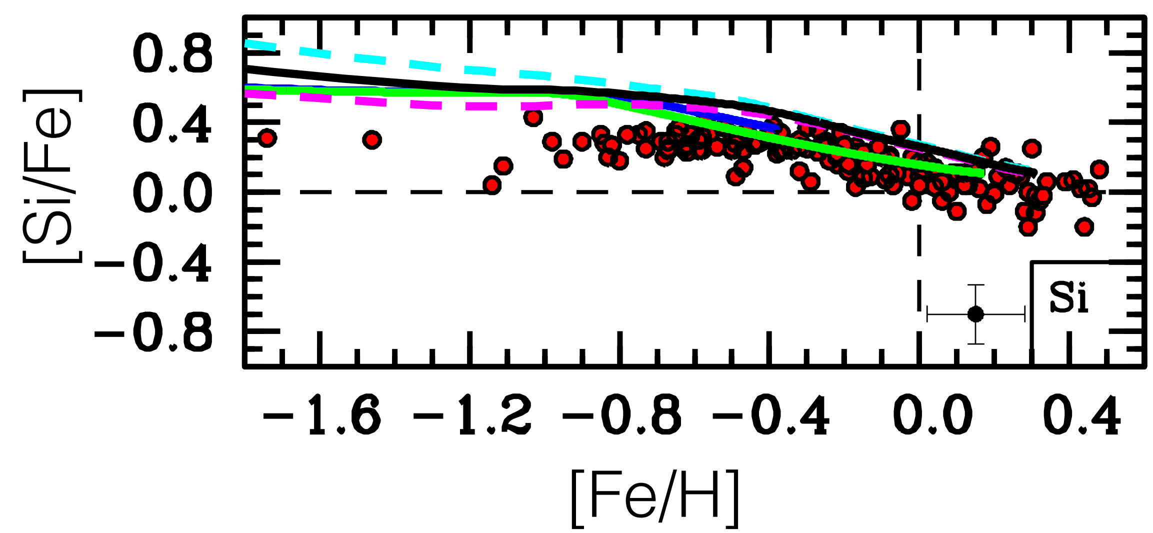
Chemical tagging



HR1614
Hyades
Collinder 261

σ ≤ 0.05 dex

Chemical tracing



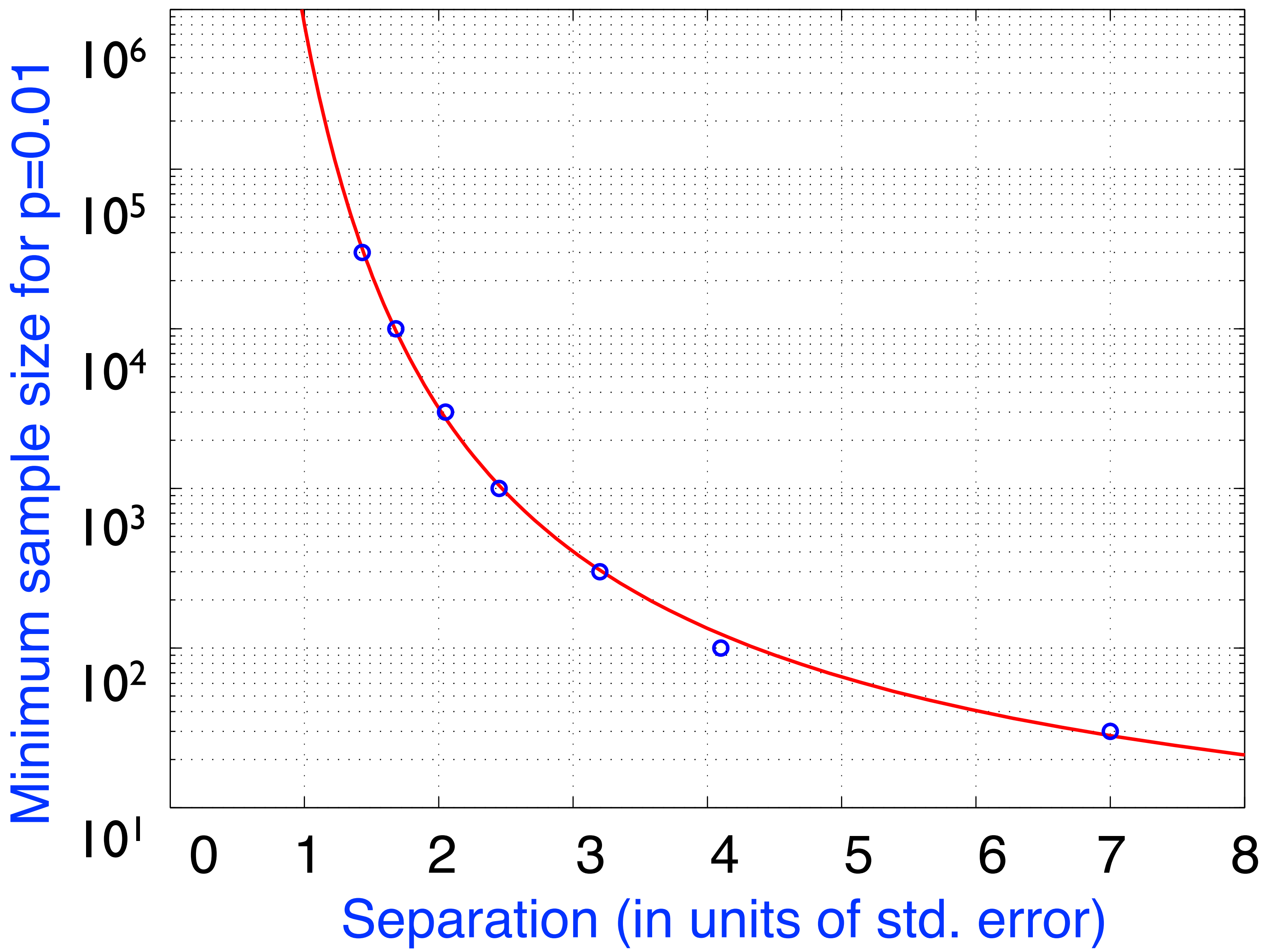
σ ≤ 0.1 - 0.2 dex

De Silva et al. 2008 arXiv:0810.2287

Johnson et al. 2014 ApJ 148 67

Size of survey

Precision vs. # of stars.

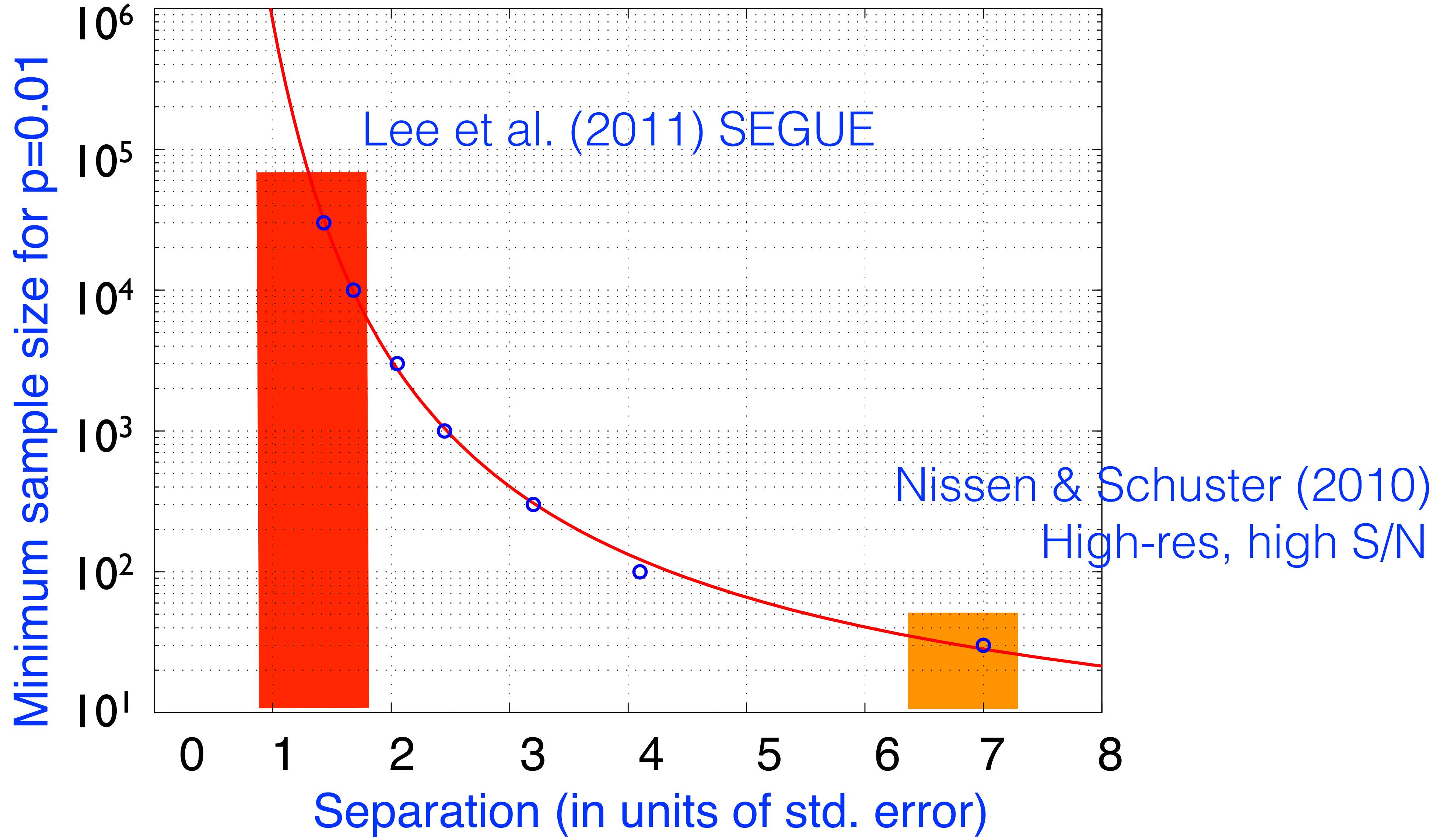


Low probability of false detection (p = 0.01)

Lindegren & Feltzing 2013 A&A 553 A94

Examples

Precision vs. # of stars.



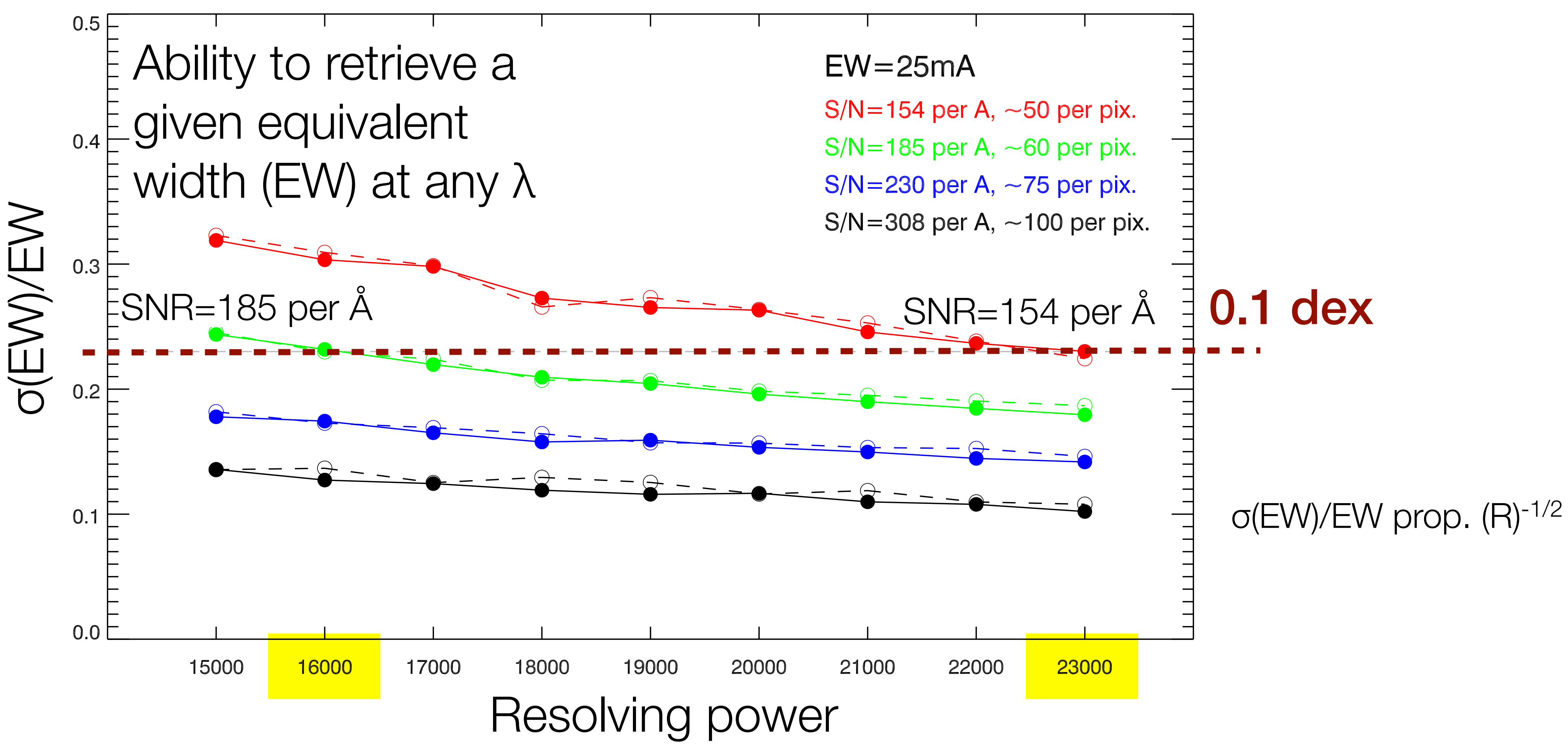
Low probability of false detection (p = 0.01)

Lindegren & Feltzing 2013 A&A 553 A94

R ⟷ SNR

Assuming we know what σ we want

Resolution vs. Signal-to-Noise ratio in spectra for abundance determination

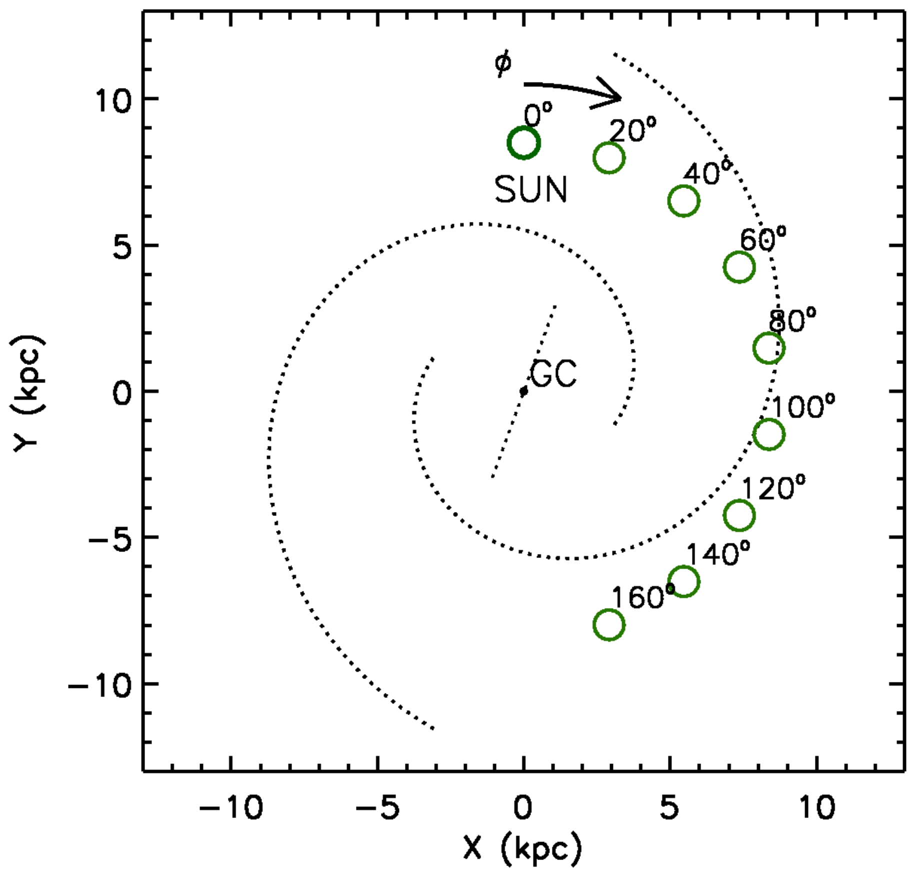


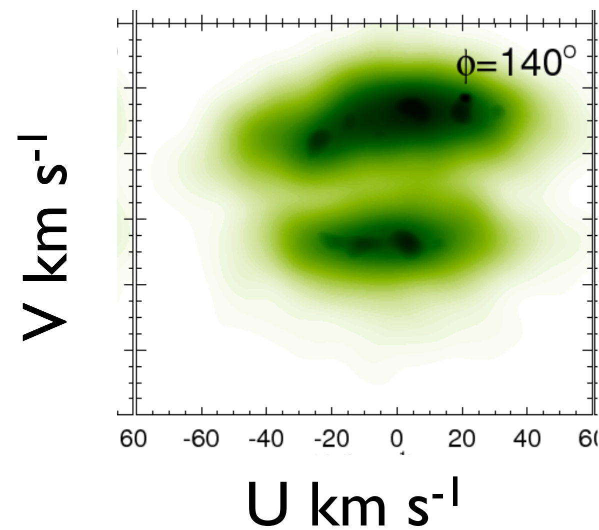
Luca Sbordone for 4MOST consortium, used for PDR
See also Gustafsson (1992)

Galactic Archeology

- Builds on the understanding of
  - stars as time-capsules
  - each star formation event has a unique signature
  - star clusters disperse in the Galactic potential
- Pure dynamical studies can also lead us further
  - Most knowledge is from the solar neighbourhood

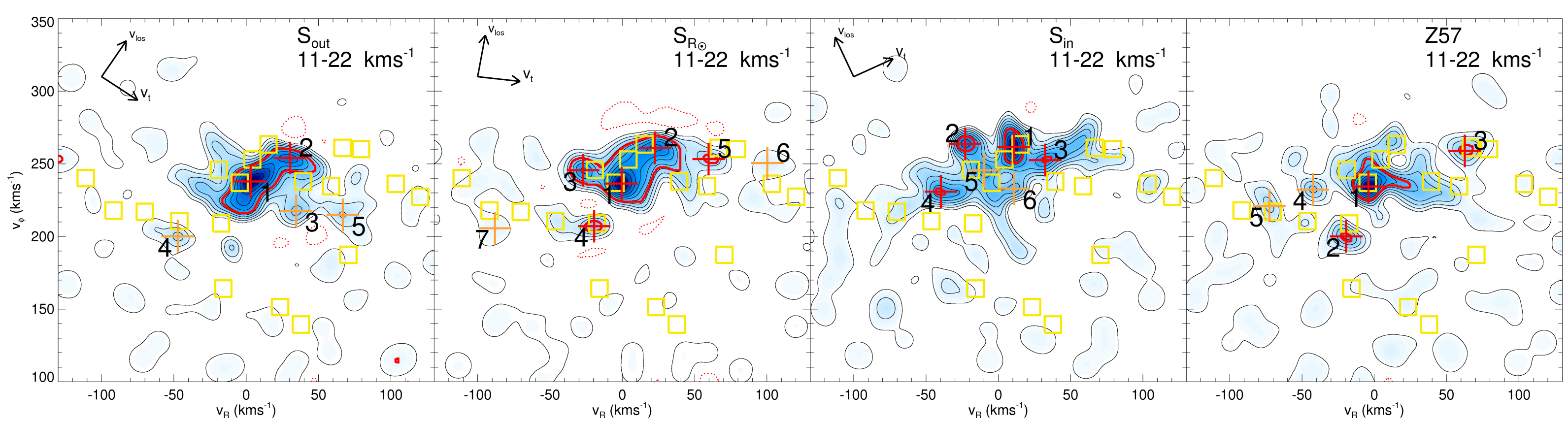
Disk dynamics





Expectation: Bar and spiral arms in the model ➙ makes for more complex velocity-plane

Antoja thesis



Kinematic structures prevail at ~1 kpc (RAVE, Antoja et al. arXiv:1205.0546)

Galactic Archeology II

- "Quantifying the strength of radial migration in the Milky Way is one of the most pertinent action items for the next generation of Milky Way surveys"
  - … but, how do you that?
    - ★ What stars should we select?
    - ★ What properties of the stars should we measure?
    - ★ …
  - Do we have an answer to such questions?

Rix & Bovy 2013 A&Arv 21 61

Existing instruments

NIR	UV	UV
APOGEE (I+II)	**HERMES**	**FLAMES**
Multifibre spectrograph part of SDSS	Multifibre spectrograph on AAT	Multifibre spectrograph on VLT
R ~ 22 500 (1.51 -1.70 µm)	R ~28 000 a	R ~20 000
300 fibres	390+ fibres	> 100 fibres
https://www.sdss3.org/future/apogee2.php	http://www.mso.anu.edu.au/galah/home.html	
Survey: APOGEE – 10^5 stars	Survey: GALAH – 10^6 stars	Survey: Gaia-ESO – 10^5 stars

Upcoming survey instruments

NIR	UV	UV
MOONS	**WEAVE**	**4MOST**
NIR multifibre spectrograph being built for VLT	Multifibre spectrograph being built for WHT	Multifibre spectrograph to go on VISTA
R ~ 5000 (0.64-1.8 μm)	R ~20 000 and R ~5000	R ~20 000 and R ~5000
R ~ 9000, 20 000, 20 000 (0.7-0.9, 1.17-1.26, 1.52-1.63 μm)	800 fibres (switchable R)	800 + 1600 fibres (sim.)
1024 fibres	Gaia follow-up (4MOST in the North), extra-galactic science	Gaia and eROSITA follow-up
Being built by consortium lead by ATC, UK	Netherlands, UK, Spain, France, Italy	10-20 million LR stars
PI: Michelie Cirasuolo	Project scientist: Scott Trager	1-2 million HR stars
http://www.roe.ac.uk/~ciras/MOONS/VLT-MOONS.html	http://www.ing.iac.es/weave/	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

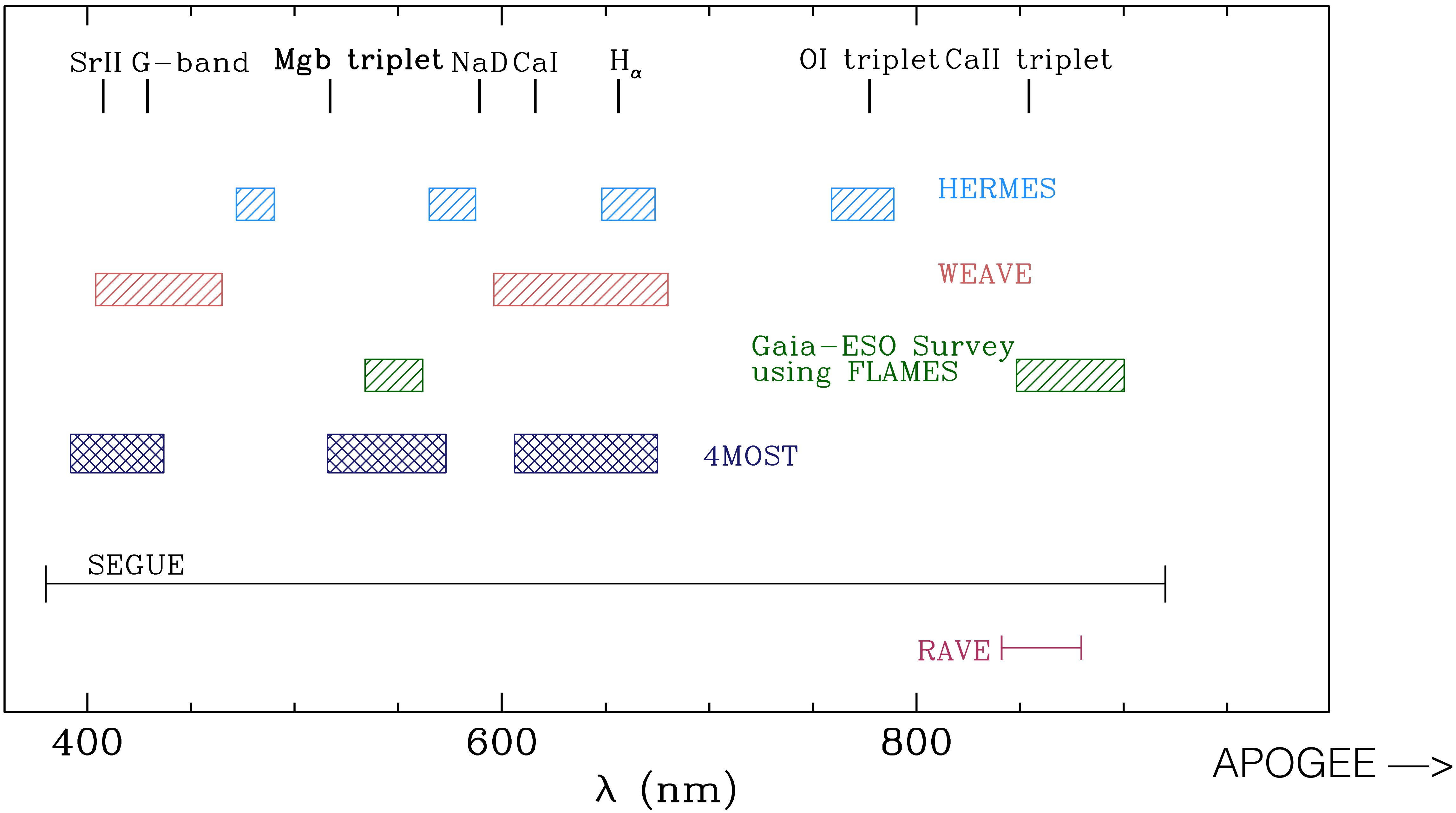
Cirasuolo et al (SPIE, 2014)

de Jong et al (SPIE, 2014)

Complementarity

- Many of the surveys are highly complementary
  - North <—> South being an obvious one
  - NIR vs Optical; but not the same stars studied (so far)
  - magnitude range (i.e. GALAH does everything down to V=14, 4MOST almost starts there)
- Cross-calibration not so well developed

λ-coverage



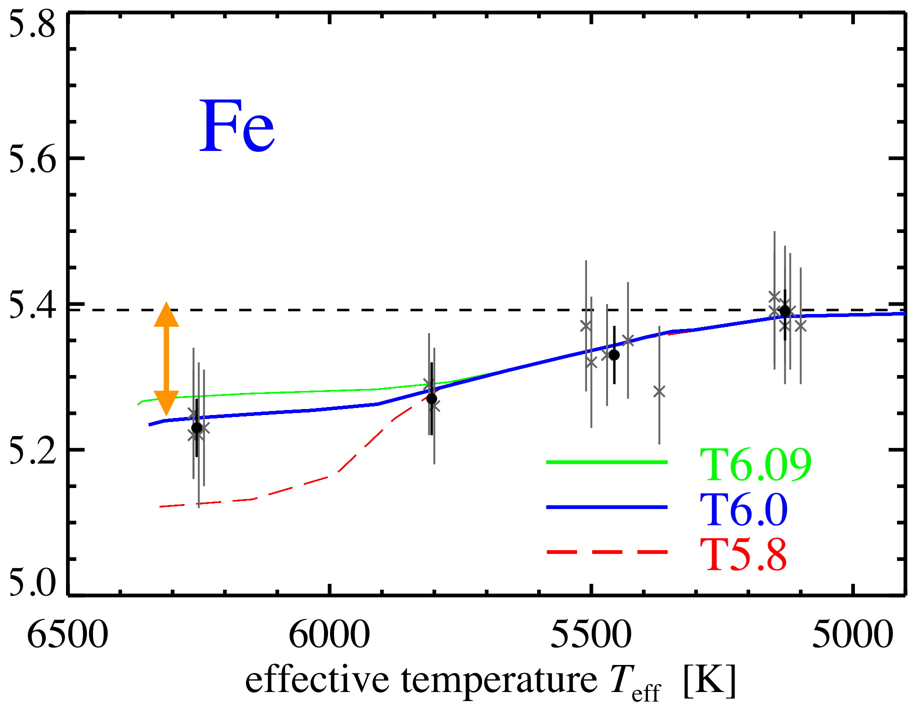
WEAVE and 4MOST similar coverage in LRS as SEGUE

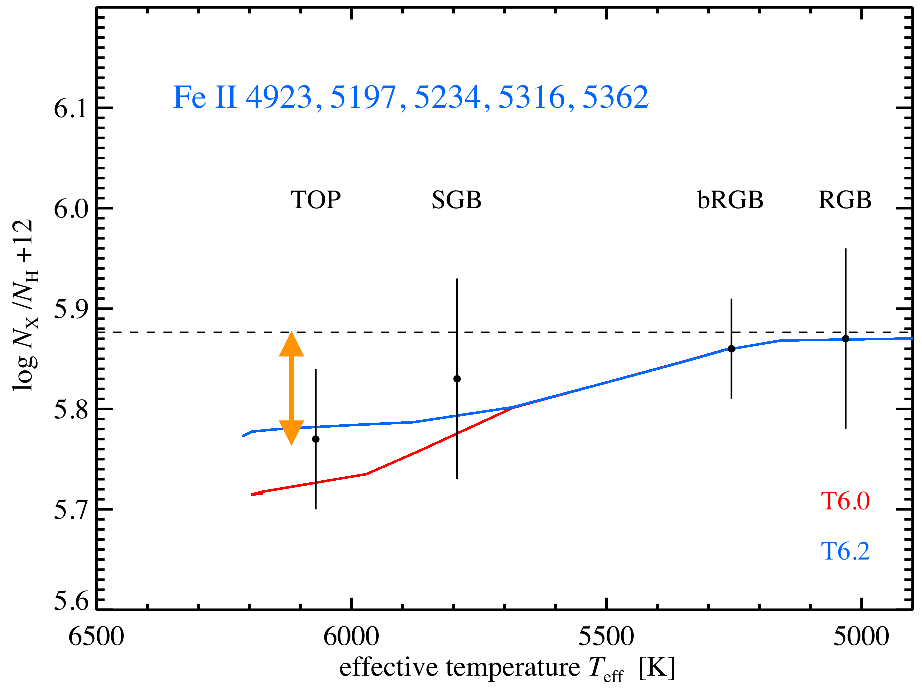
Can such precision in abundances be achieved?

- Lets take a step back and consider the limitations
  - stars as time-capsules
    - ★ Solar-like stars retain, in their atmospheres, the same composition of elements as the gas cloud from which they formed.

  - but do we measure the “true” values of the elemental abundances?
    - ★ Lets look at a few examples that are both discouraging and heartening

Diffusion changes abundance patterns

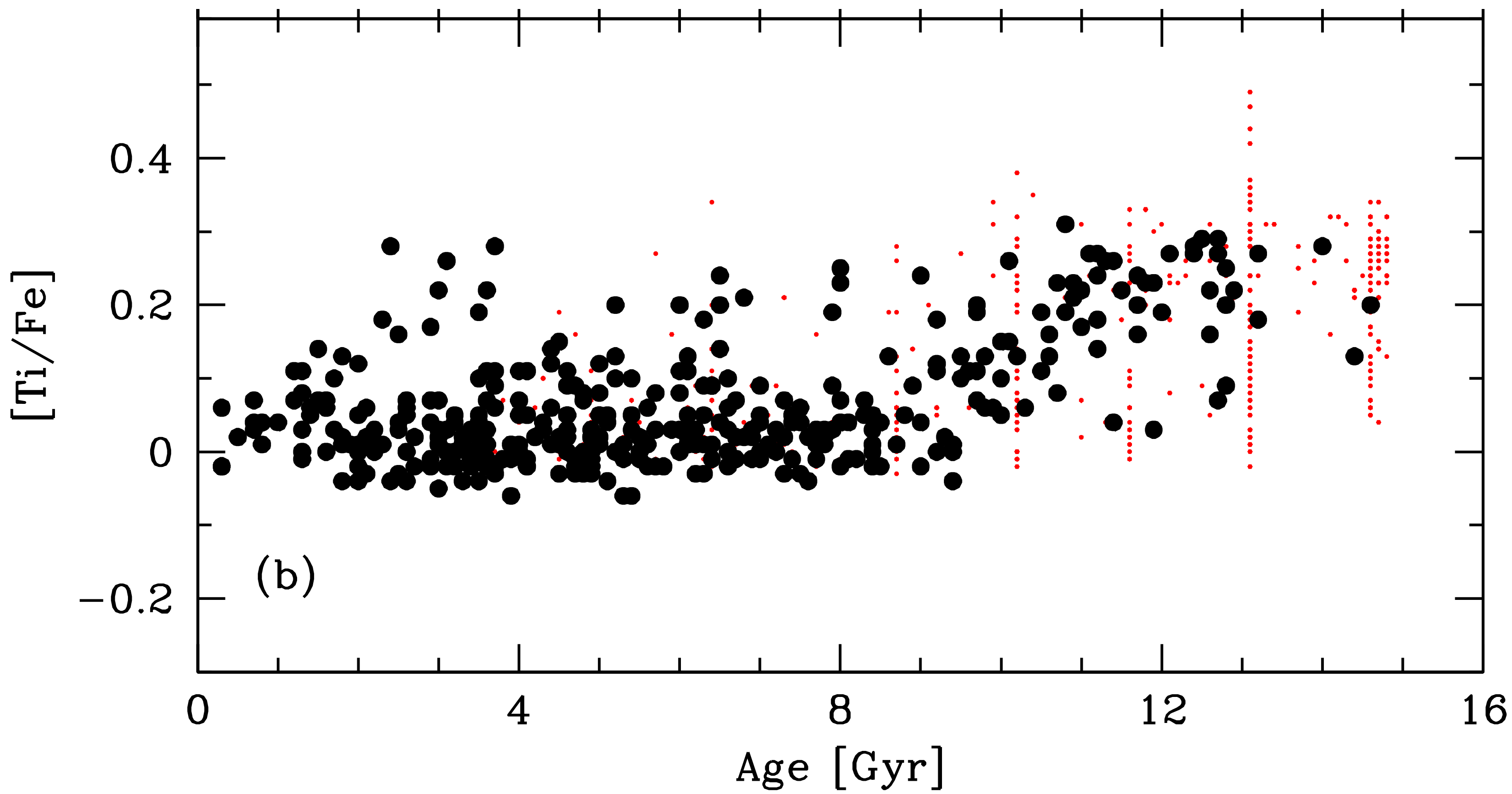




- Effects of stellar evolution.
- Evidence that selective diffusion occurs in stars at MS and TOP in globular clusters and M67.
- Up to 0.2 dex.

Önehag et al. 2014 A&A 562 A102
Korn et al. 2007 ApJ 671 402
Gruyters et al. 2013 A&A 555 A31

Is the trend real?

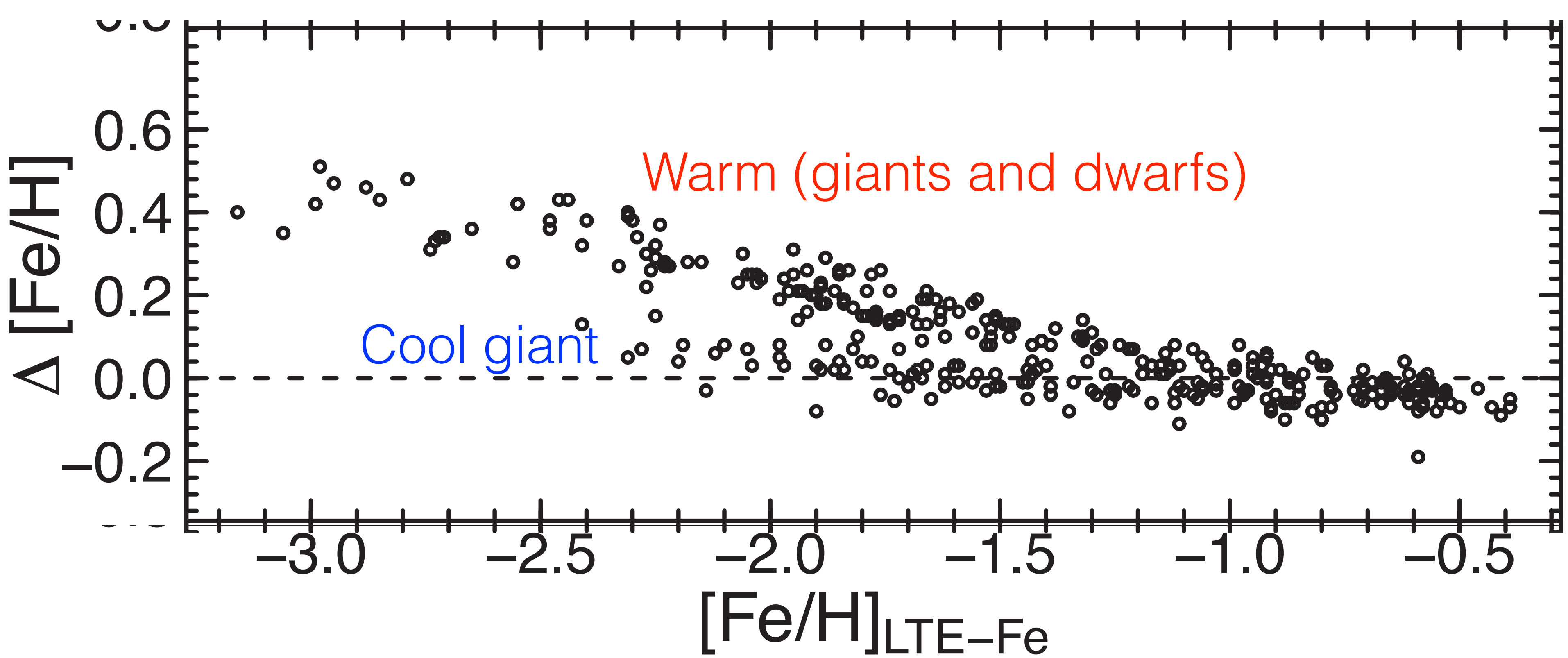


Δage < 4 Gyr

Bensby et al. 2014 A&A 562 A71
see also Haywood et al (2014) for interpretation of such trends

NLTE – 3D

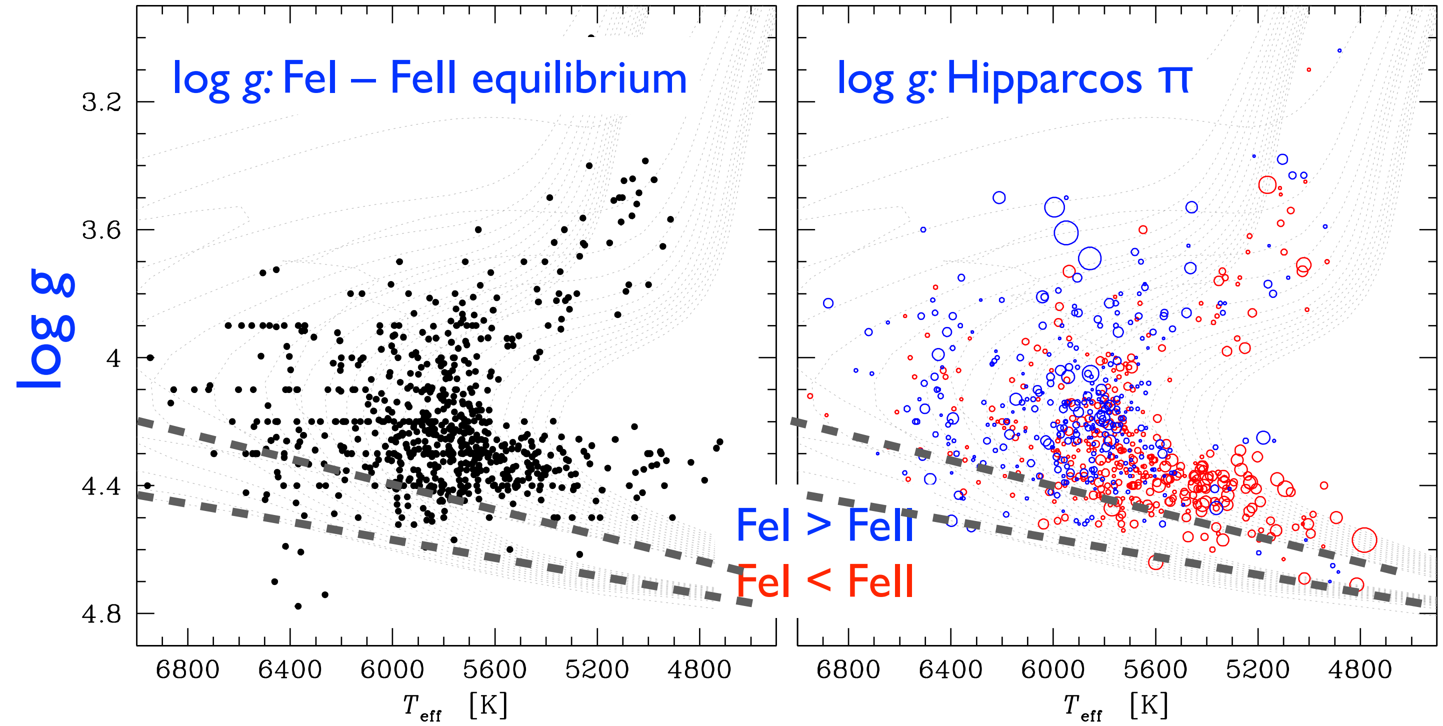
[Fe/H]: NLTE/3D - LTE



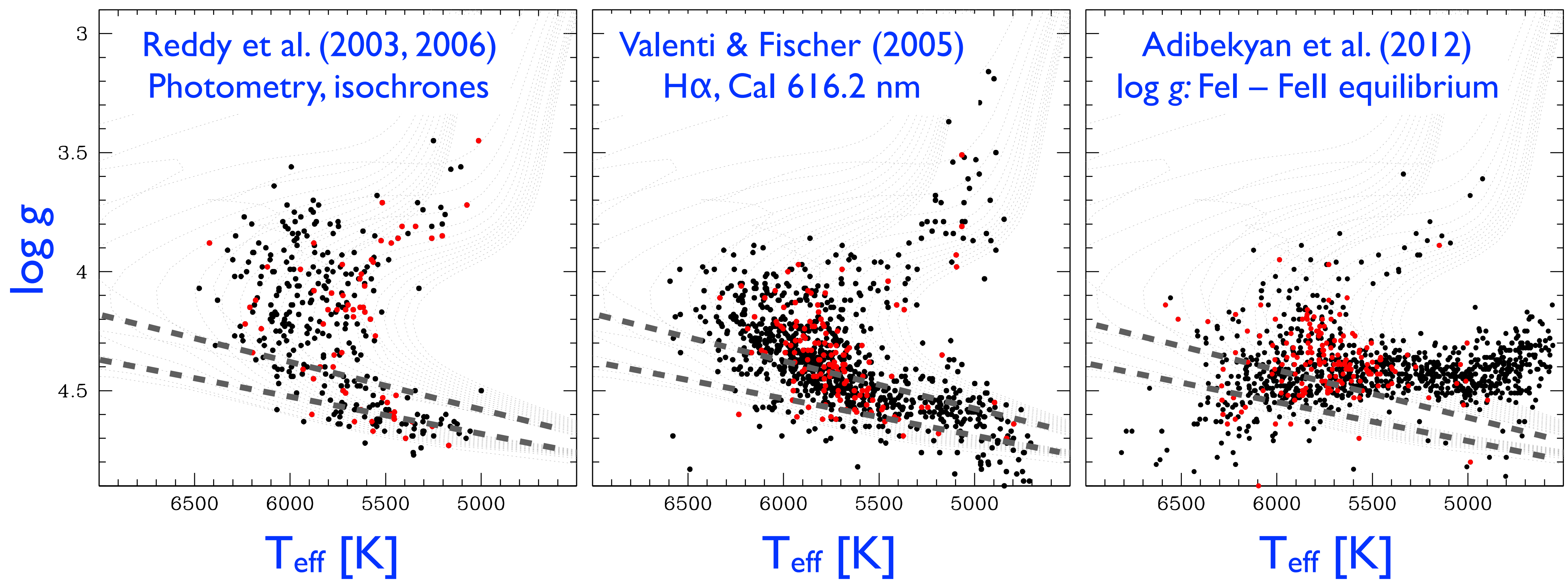
- NLTE, 3D effects can be severe, e.g., Ruchti et al. (2013).

Ruchti et al. 2013 MNRAS 429 126

Stellar parameters



Bensby et al. 2014 A&A 562 A71



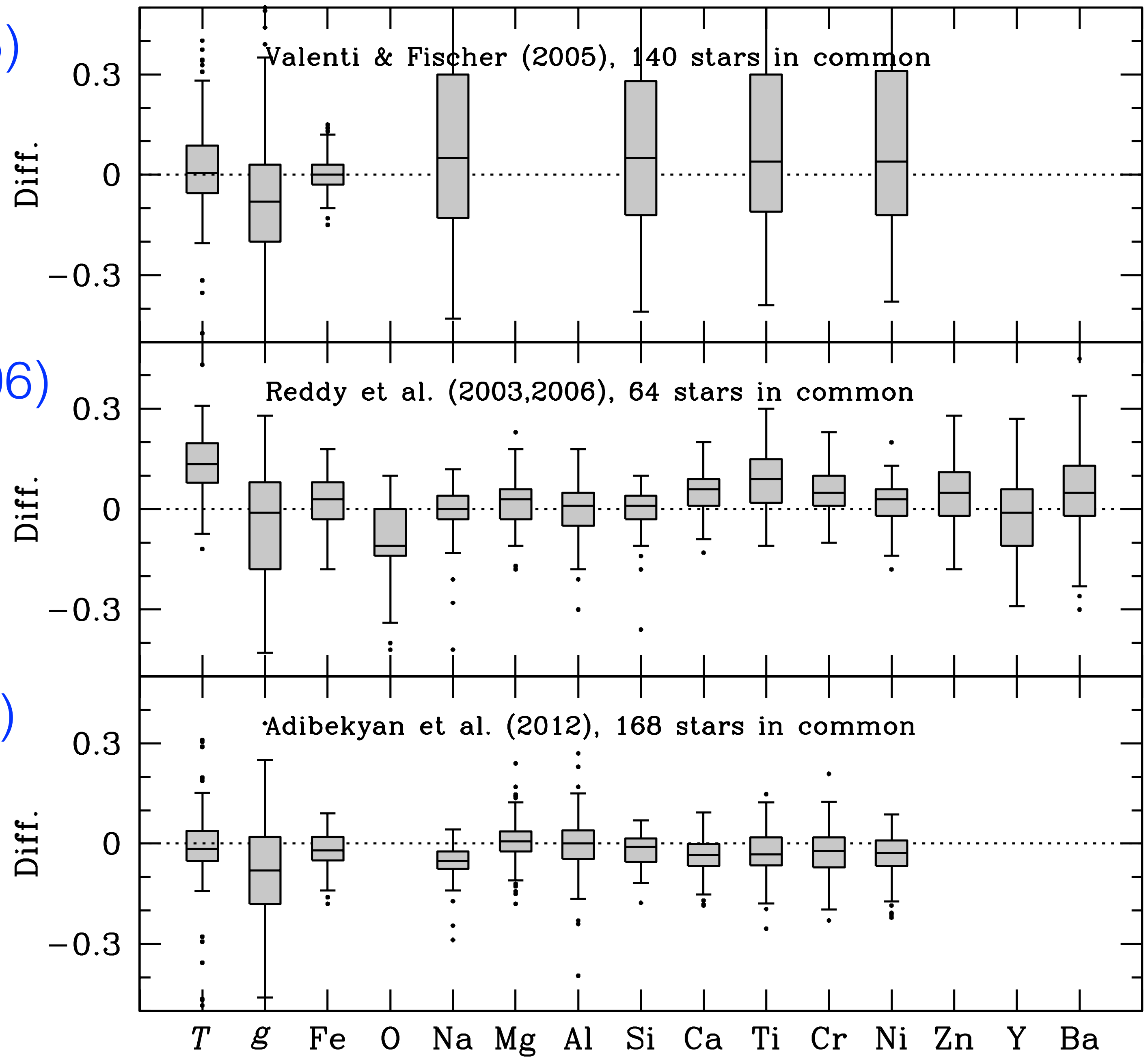
… but abundances work

Comparison Bensby et al (2014) and :

Valenti & Fischer (2005)
140 stars

Reddy et al. (2003,2006)
64 stars

Adibekyan et al. (2012)
168 stars

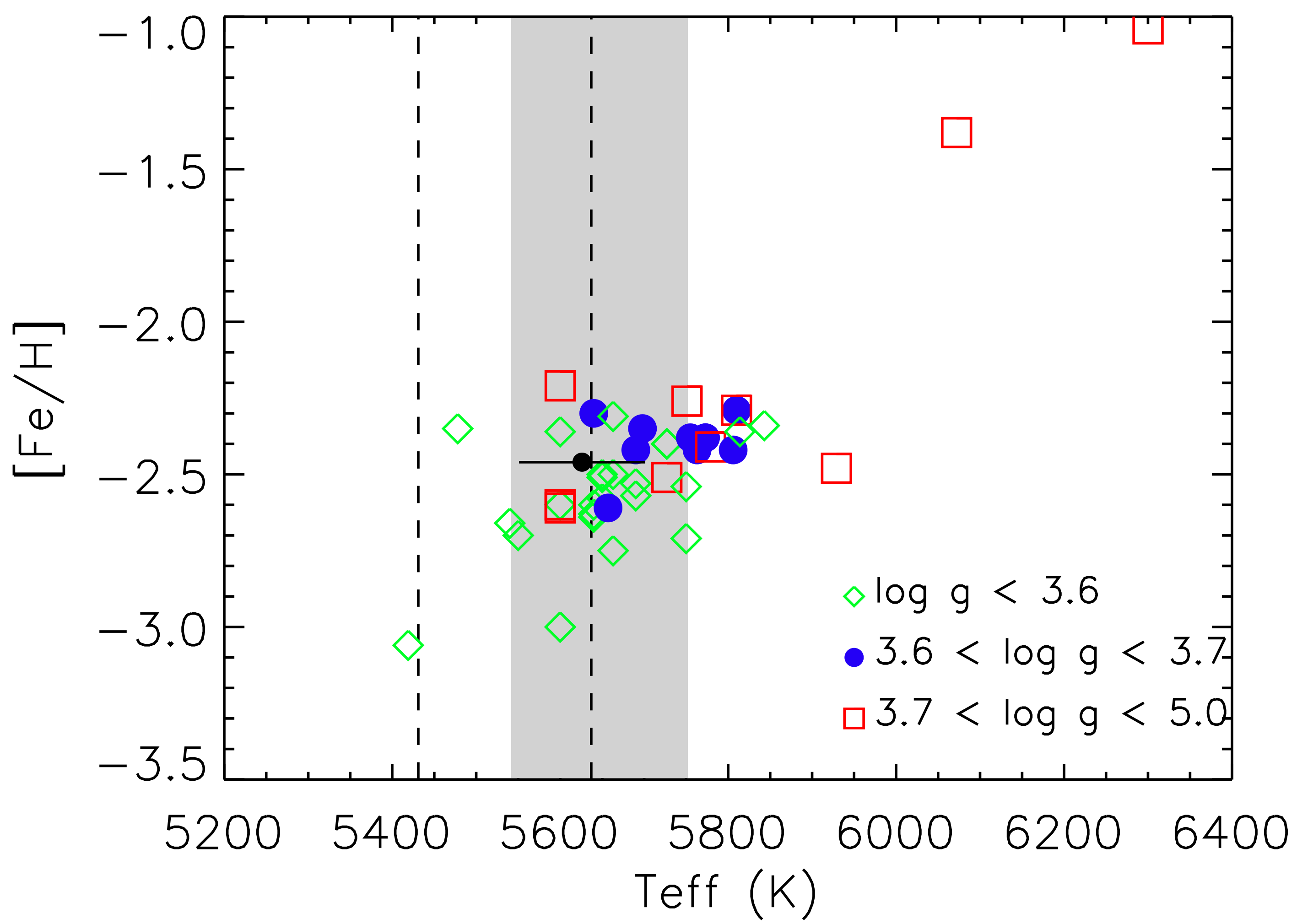


Offsets are small

Bensby et al. 2014 A&A 562 A71

HD140283

A metal-poor sub-giant star (Gaia Benchmark star)



T_{eff} from Hα wings

Interferometric measurements, with reddening

Uncertainty in understanding and measurement of E(B-V) causes severe limitations for absolute results

Creevy et al. 2014 arXiv:1410.4780v2

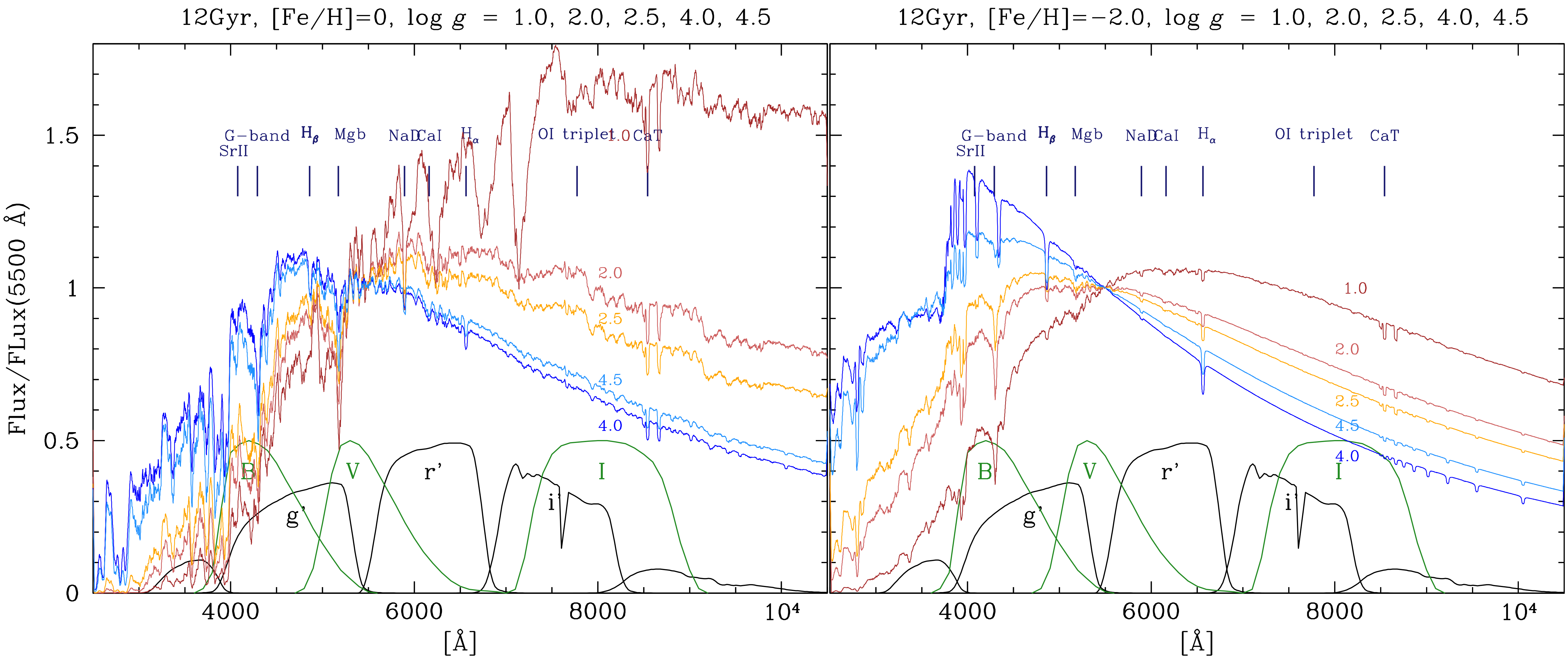
We should

- Spend some time and money on
  - Understanding the stars better or at least
    - ★ Obtain suitable corrections that puts stars of different kinds onto the same scales
  - Obtain suitable stellar samples to cross-calibrate the surveys. This means thousands of stars.
    - ★ Cannon-Fodder is starting

What about the design of the surveys?

- Surveys will inherently be limited due to selection effects
  - Common examples are when you have a magnitude limited sample (compare next slide)
    - ★ Dwarfs and giants sample different volumes
  - Another issue is to define what an observable is
    - ★ There is potentially a sliding scale here, but would suggest that we are very careful (compare slide after next and Creevy et al)

Solar | Very-metal poor



Spectral lines as well as SEDs vary significantly w. spectral type. Metallicity also plays a major role.

What is an observable?

- This seems to need a better definition or at least when you design your survey you need to think about it
  - parallax, proper motion, observed magnitudes
  - spectra themselves (?)
  - position and velocity?
  - Temperature, log(g), [Fe/H]
  - But is then [Mg/Fe] and observable or a derived parameter?

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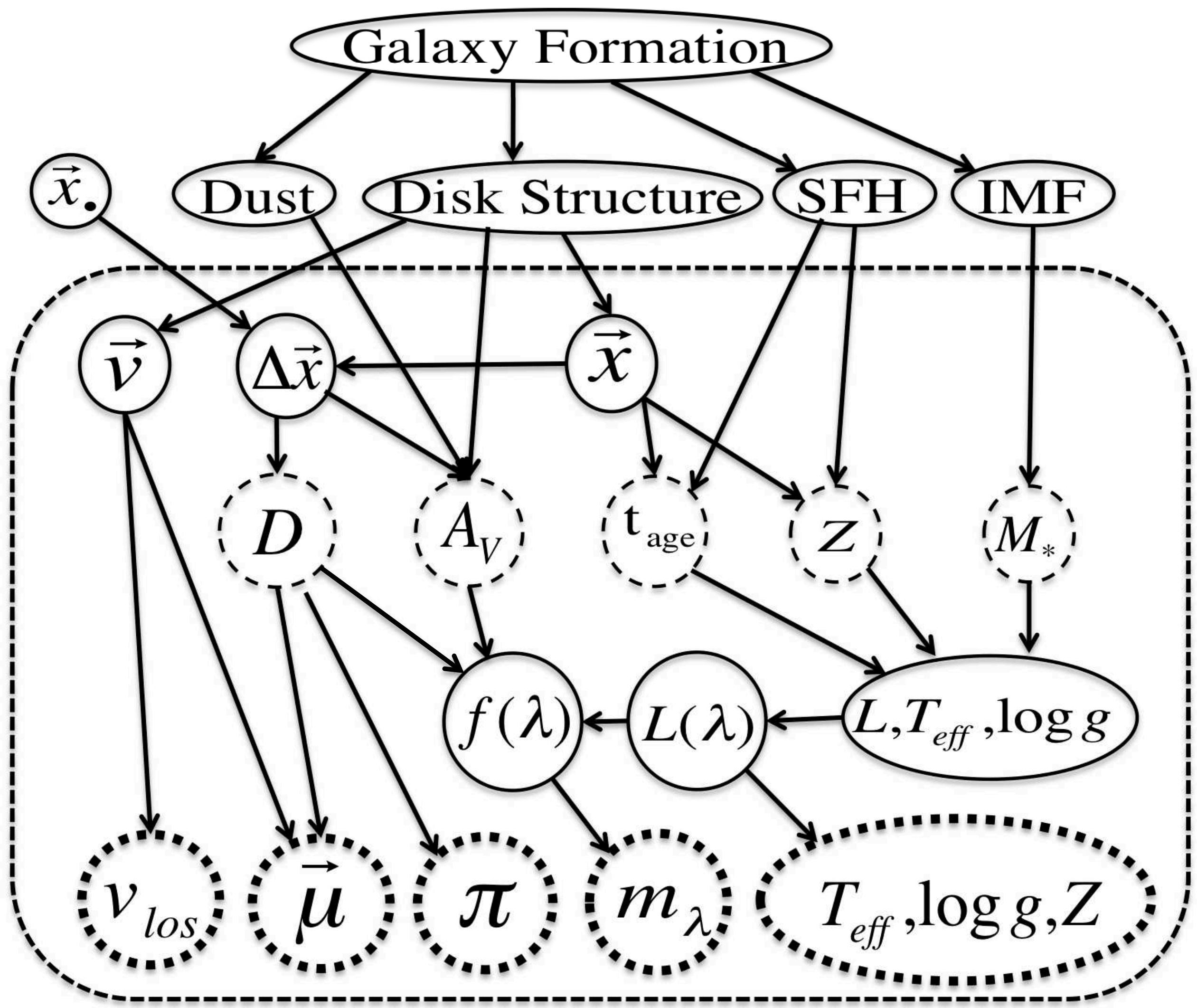
- Answers to these questions are likely at the core of how we chose to make progress



Desirables

Observables

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So far

Past	Now	Soon	Future
RAVE	Gaia-ESO	4MOST	E-ELT MOS
SEGUE	APOGEE I	WEAVE	What else?
	GALAH	APOGEE II	
	LAMOST	PFS	

Resolution

targets

?

Starting to step outside MW (PFS)

Beyond

- What do we want beyond the currently operational and planned instrumentation?
- What is more important to make progress?
  - ★ Larger samples?
  - ★ Smaller σ?
  - ★ More Milky Way or other galaxies?

ELT era

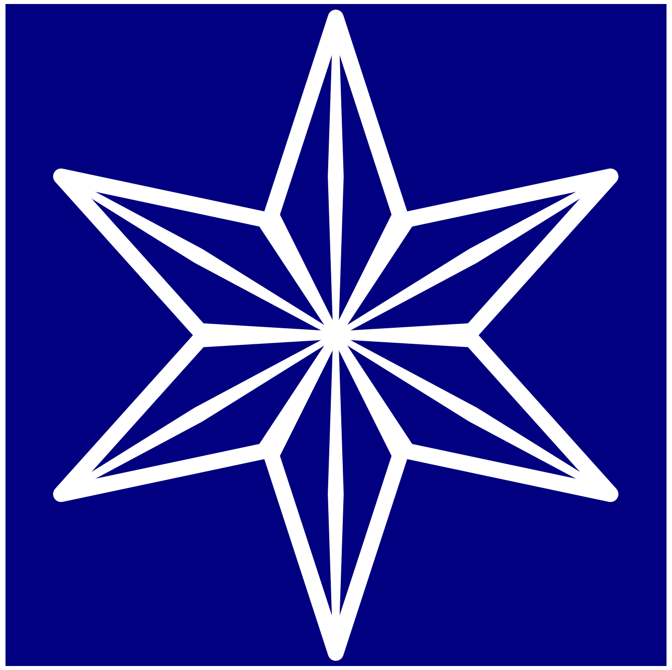
- What will the ELT era bring for Galactic Archeology?
  - Move fully outside the Milky Way – for the first time allow proper comparisons from spectroscopic studies between MW and other galaxies (N.B. we will be back to Edvardsson et al rather than moving towards Melendez et al.)
  - With AO - studies of very crowded regions, such as Bulge and clusters, down to the turn-off and below

Potential ideas

- A single slit spectrograph on an 8-10m, dedicated to following up the surveys [= better σ]
- A very specialised MOS on an 8-10m; e.g., very high resolution of Eu line (weak lines, hfs, only direct probe of *r*-process) [= better σ]
- LSST follow-up/variable

Potential ideas

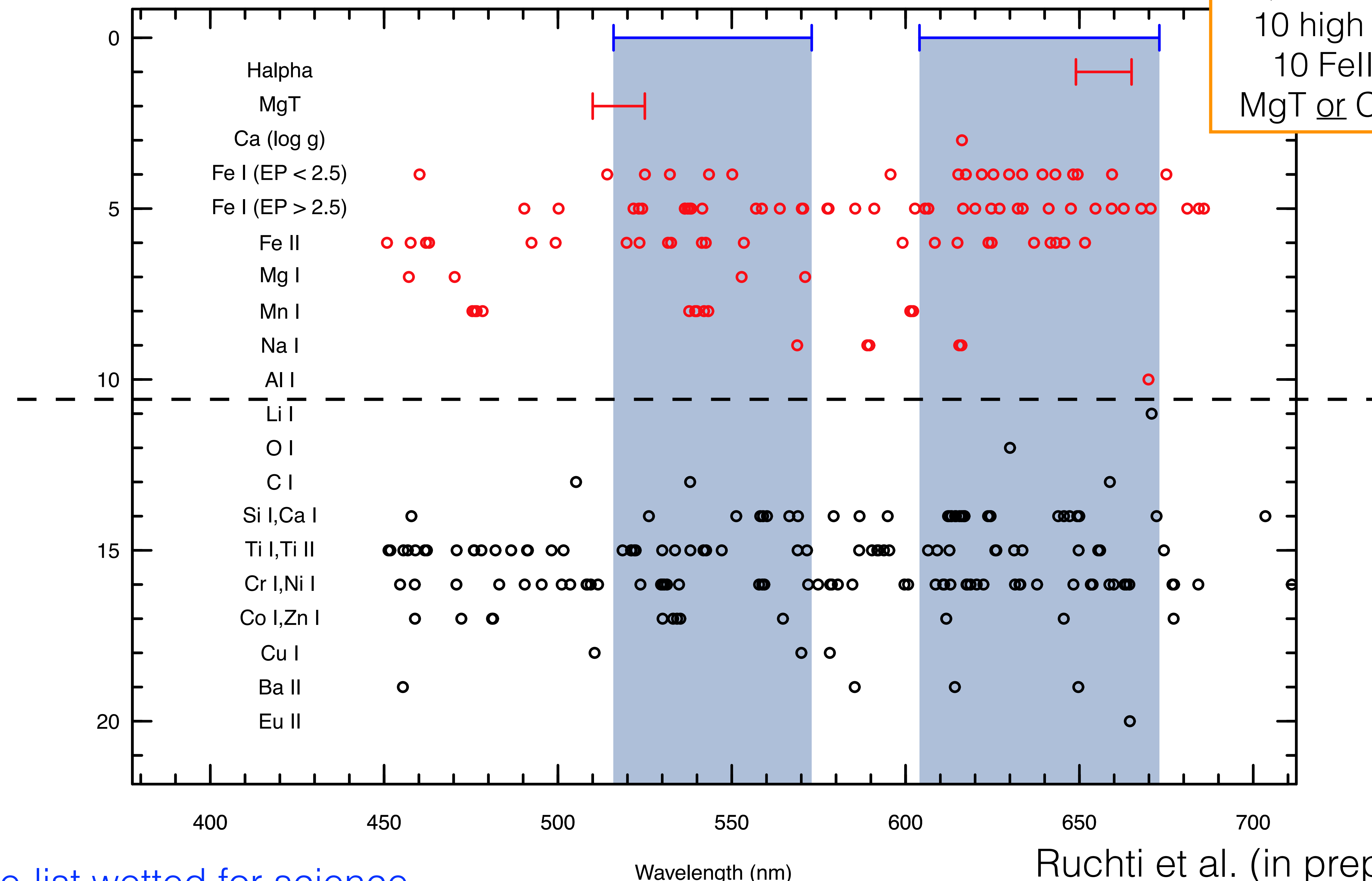
- A single slit spectrograph on an 8-10m, dedicated to following up the surveys [= better σ]
- A very specialised MOS on an 8-10m; e.g., very high resolution of Eu line (weak lines, hfs, only direct probe of *r*-process) [= better σ]
- LSST follow-up/variable sky
- But - perhaps better spend our energy on the analysis/stellar understanding
  - Follow-up for asteroseismology?
  - More interferometry?
  - Models?



Type of object

- Mixing different types of tracers can be (very) hard if you aim for high precision.
- This is because (many) analysis methods have been developed in the context of one particular type of star.
  ➡ There are good reasons for this – the stellar spectra are rather different and challenges differ depending on evolutionary phase and metallicity.

Optimizing 4MOST



Hα, 10 low EP and 10 high EP FeI 10 FeII lines MgT <u>or</u> Ca616.2

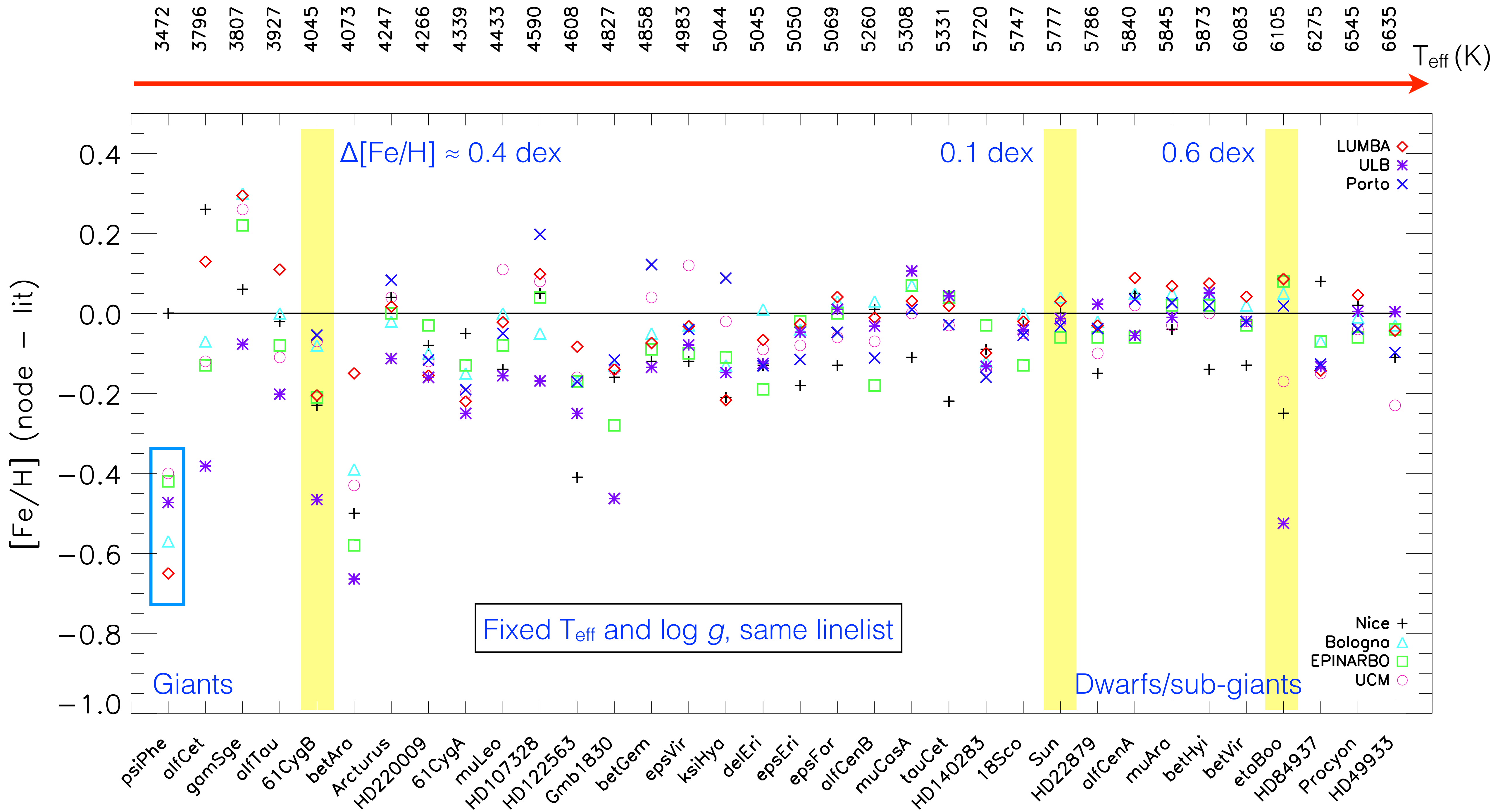
Ruchti et al. (in prep.)

Line-list wetted for science

Abundance analysis

- Traditional so called “fine analysis” (Drake 1992) baed on W_λ.
- Full spectrum synthesis.
- Finding best matching template spectrum.
- Get stellar parameters from independent source, and only analyse the atomic/molecular lines.
- …

Gaia Benchmark stars – sheep/goats



Jofré et al. 2014 A&A 564 A133

We need “standards”

- This has woefully been lacking in spectroscopic analysis.
- Yes, “everyone” analysis the sun, perhaps Arcturus or μLeo – but this covers a *very* limited set of stellar properties.
- The Gaia-Benchmark stars are a first, but not final, step in the right direction.
- In addition, the proper establishing of equatorial spectroscopic fields should be a high priority (could include open clusters).

A wider plan?

- Not only do we need common stars and clusters.
  - Reduced spectra need to be available for all to analyse.
  - Analysis codes should be well documented in the public domain and also, preferably, in some form of “open source”.
  - Analysis codes should be kept on version control and DR-codes kept.

For now…

- Do not mix apples and oranges – make life simple!
- Make the analysis self-consistent
  - Differential studies – useful for many things, absolute values not necessarily needed.
- (arbitrary) re-calibrations of derived parameters/abundances
  - Leaves us not knowing what we are actually looking at – will not be reproducible/compatible/possible to compare with (certainly not with other methods).

and …

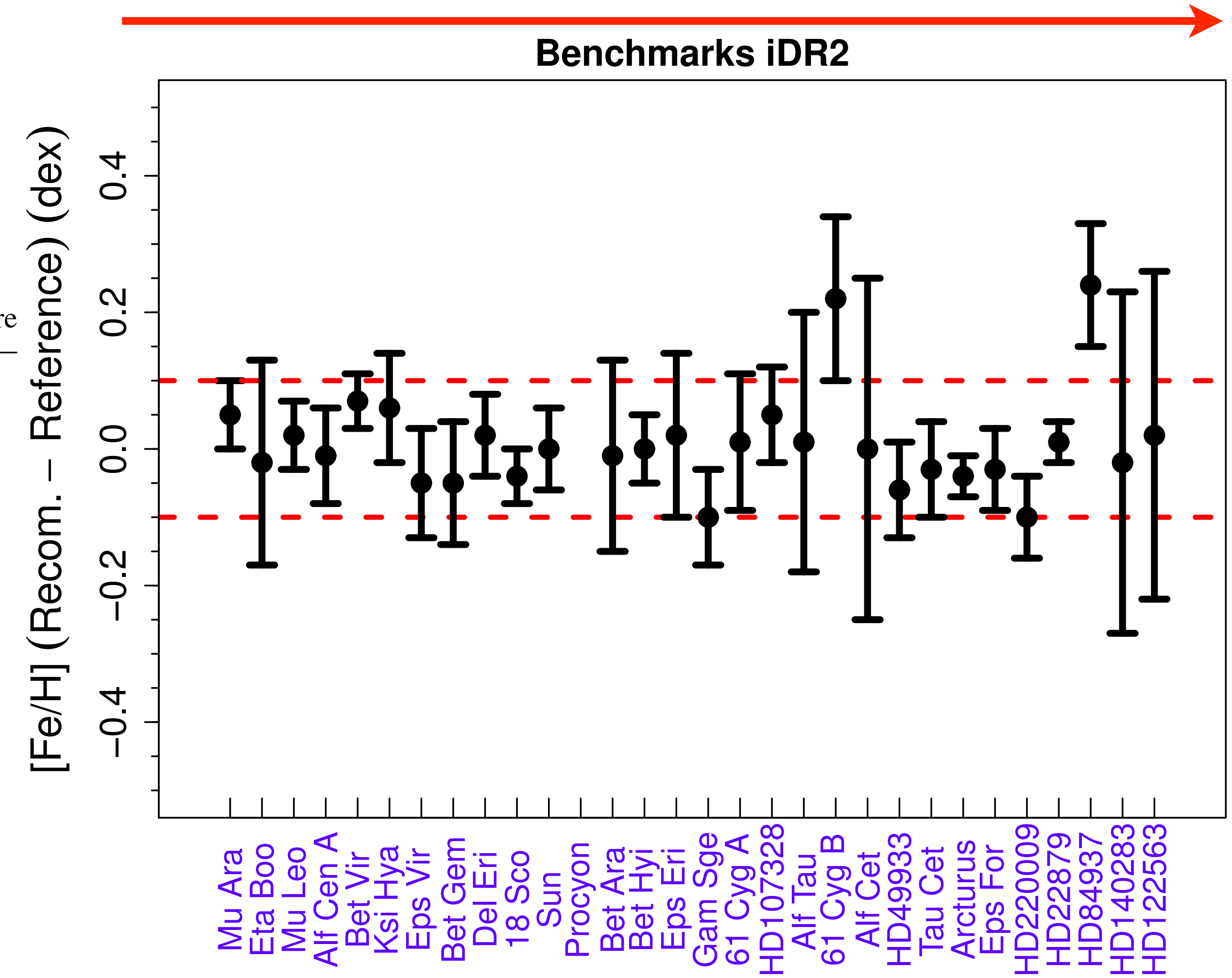
- An ultimate goal of all the large on-going and up-coming surveys will be to join the data in order to achieve a much bigger data-set
  - This requires that the results are reproducible such that
    - Each survey can analyse both their own and other spectra for the same star(s), i.e. spectra are publicly available.
    - Results are fully documented and reproducible.

Sheep and goats

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

Metallicity decreases, from >0.2 dex to –2.7 dex

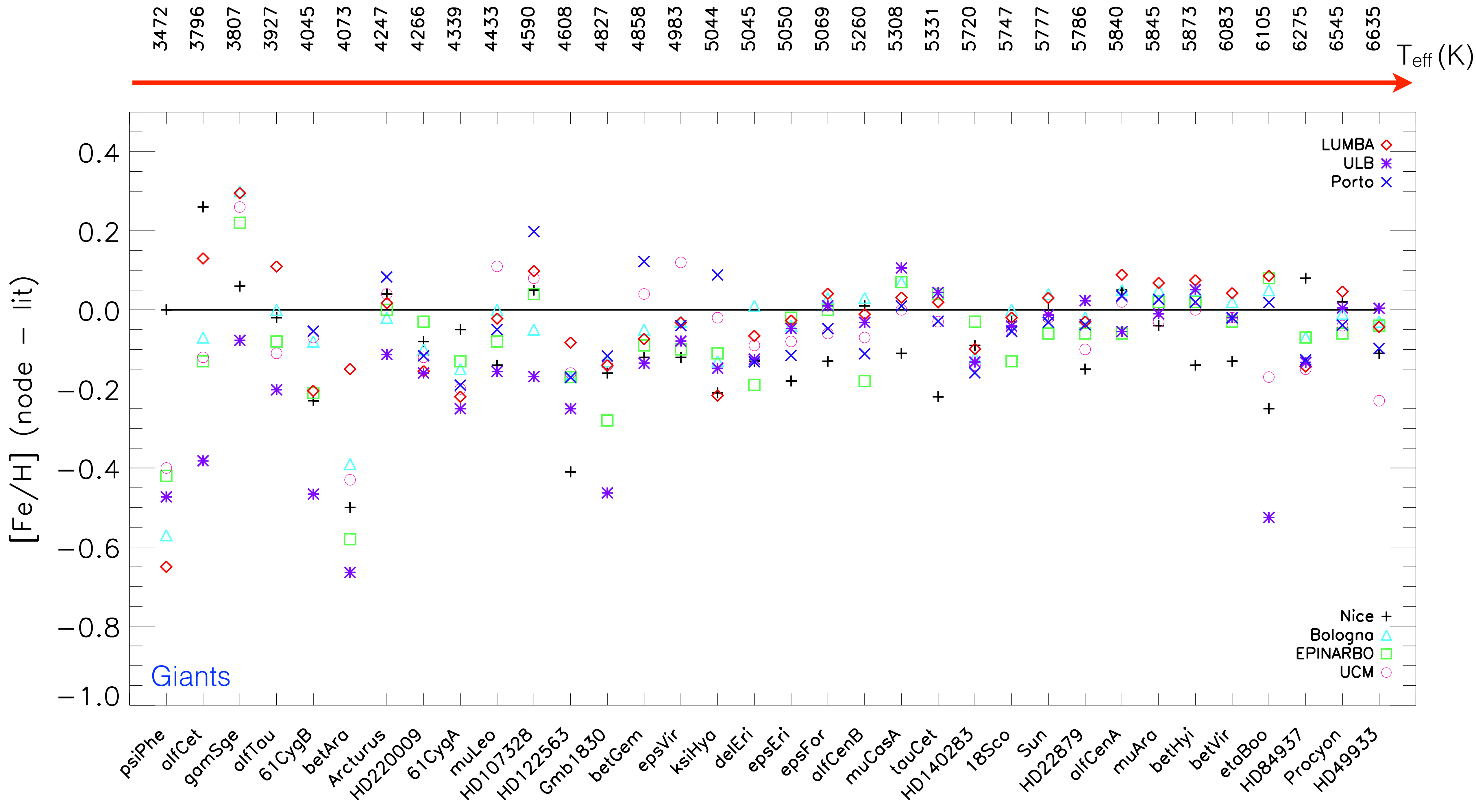


Beware of the sheep and sheep-goat effect

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

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

Not only apples and oranges different methods give different results too



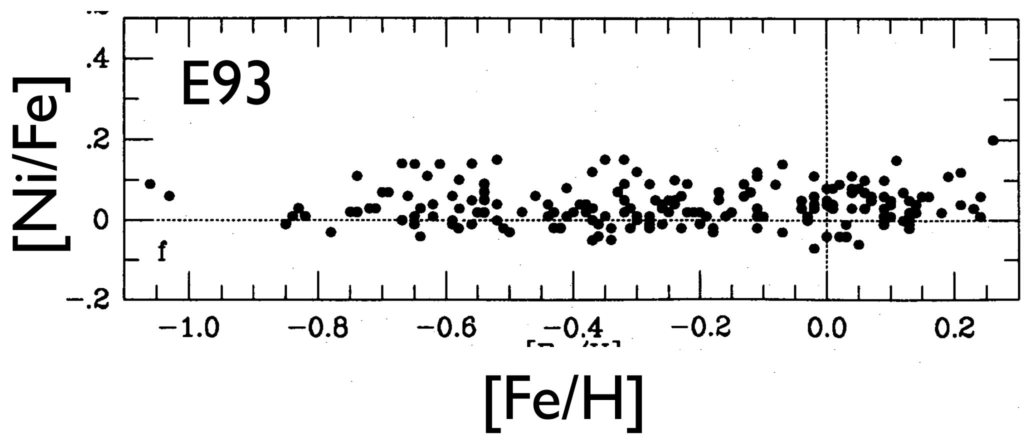
Apples and oranges

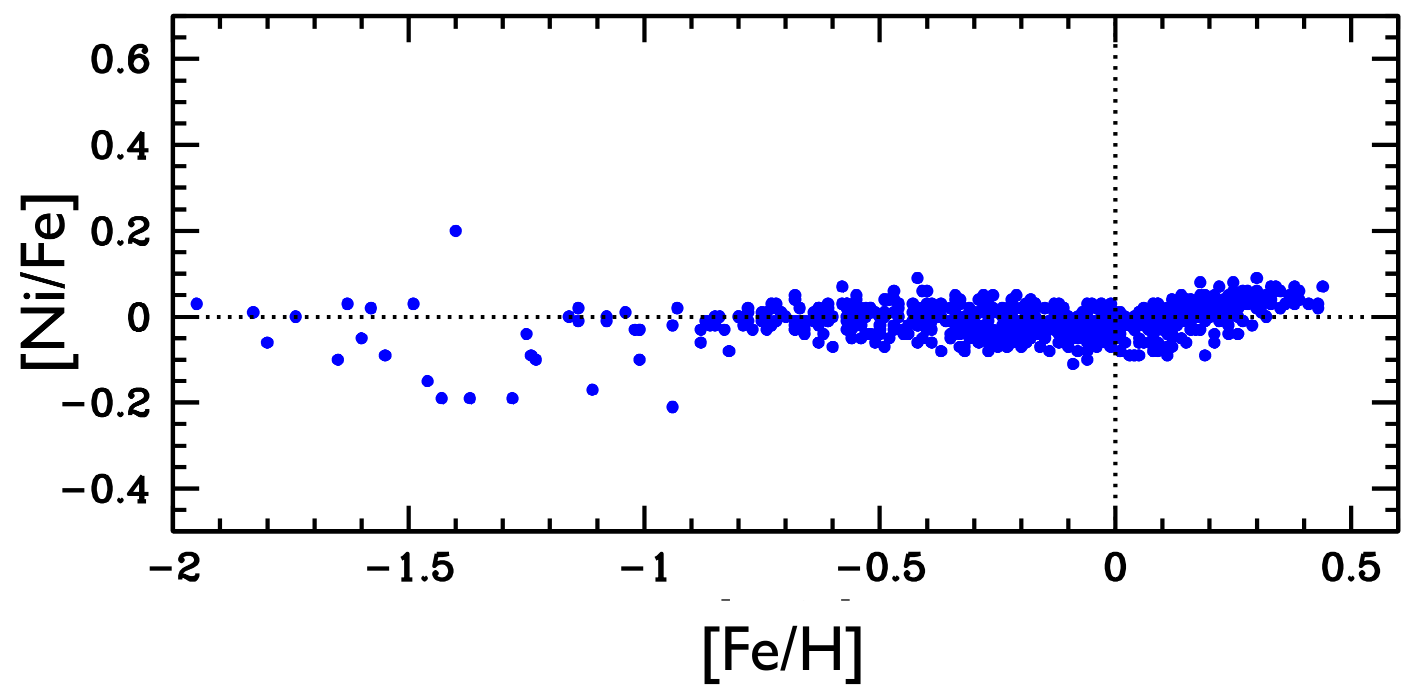
- Mixing different types of tracers can be (very) hard if you aim for high precision.
- This is because (many) analysis methods have been developed in the context of one particular type of star.

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





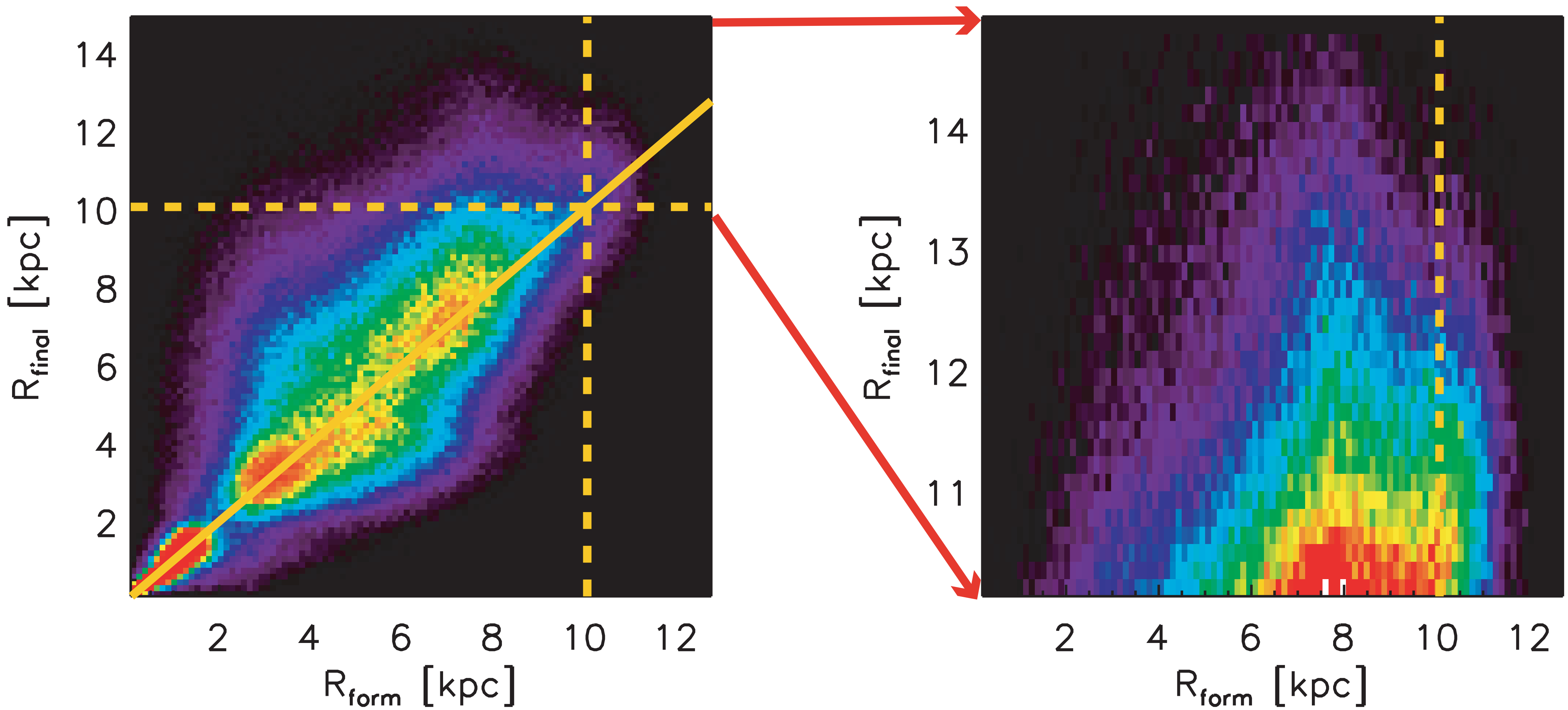
σ ~ 0.04 dex around the mean

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

Edvardsson, et al. 1993 A&A 275 101

Bensby et al. 2014 A&A 562 A71

And stars move



Rŏskar et al. 2008 ApJ 675 L65