Metal Poor Stars:
A Review for Non-Observers

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Outline

- Summary: What we know and have discussed already

- How should we interpret published stellar abundances?
  - Martin Asplund et al.: NOT “observed abundances”

- What data can we hope to get in the future?
  - Near future: New surveys, new interesting targets
  - Next few decades: New telescopes
  - Moving outside of the Milky Way

Part I: What we’ve discussed this week

(the observations)

Reminder: Anna’s Talk

- Log epsilon vs. [X/H] vs. [X/Fe]

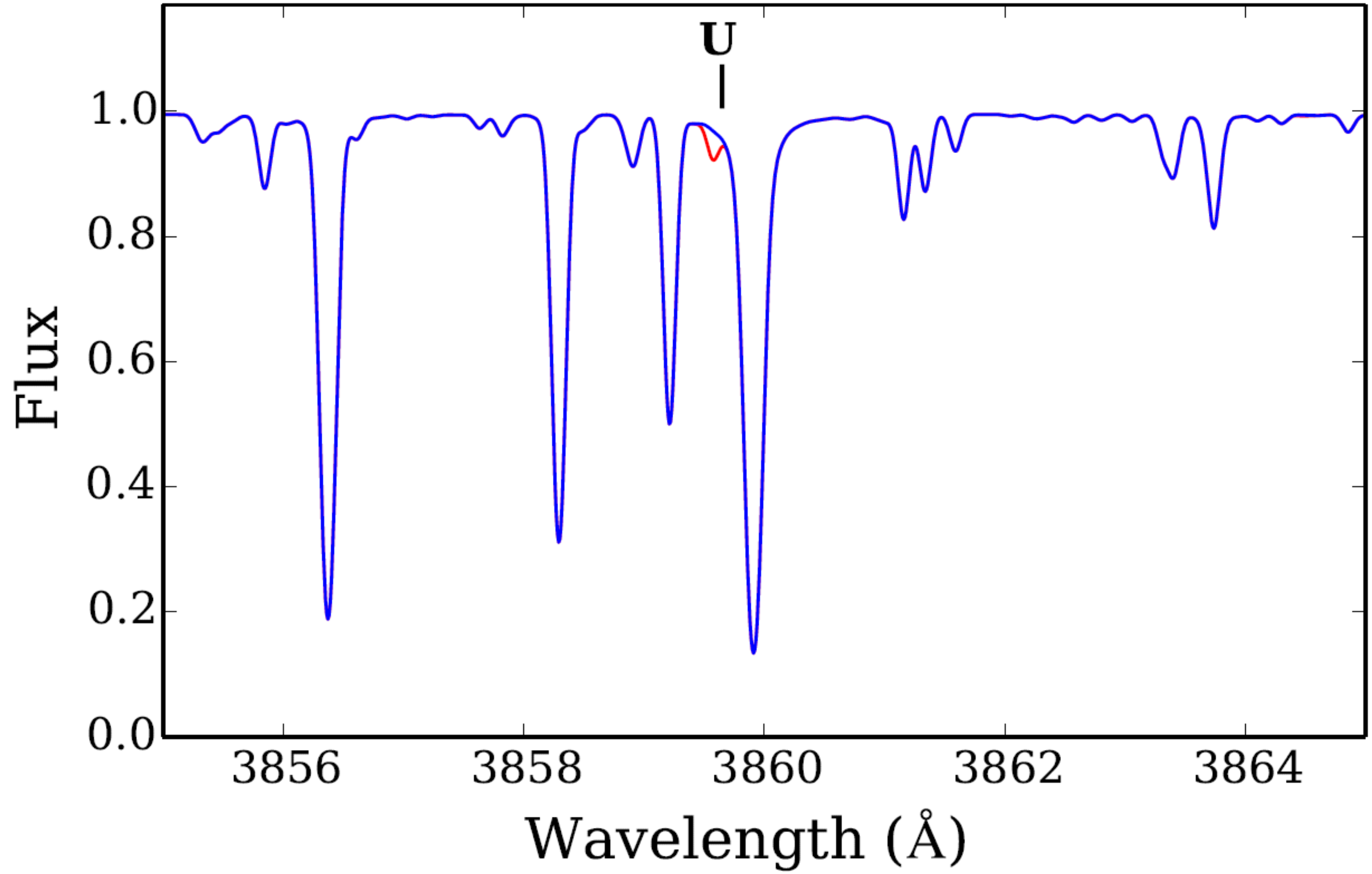
$$\log \varepsilon_X = \log\left(\frac{N_X}{N_H}\right)+12$$

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right] = \log \varepsilon_X - \log\varepsilon_{X,\odot}$$

Reminder: Anna's Talk

- Log epsilon vs. [X/H] vs. [X/Fe]
- Stellar evolution
- Chemical evolution
- Classifications of stars

Promising Sites to Study the r-Proc



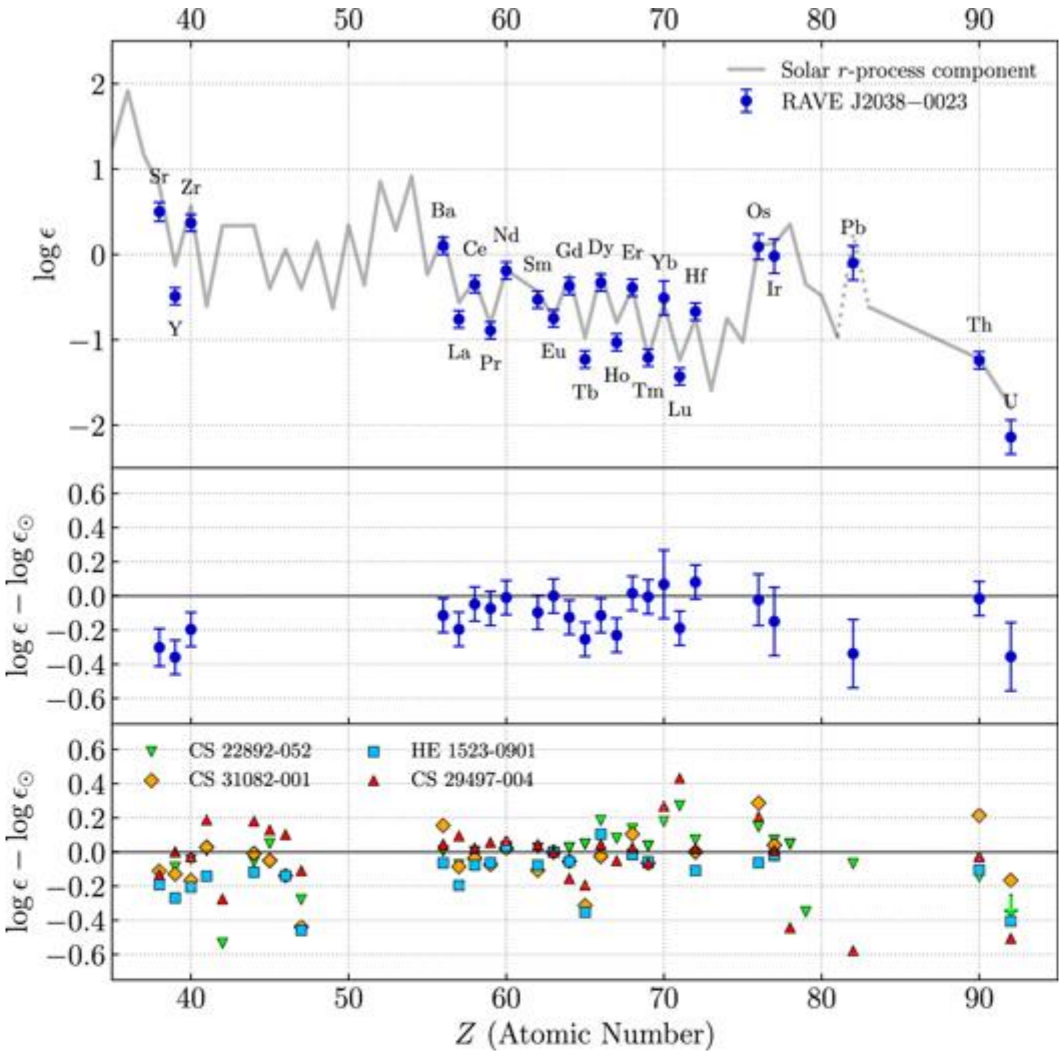
Promising Sites to Study the r-Proc

r-proc enhanced stars:
[Ba/Eu] < 0

r-I stars:
0.3 < [Eu/Fe] < 1

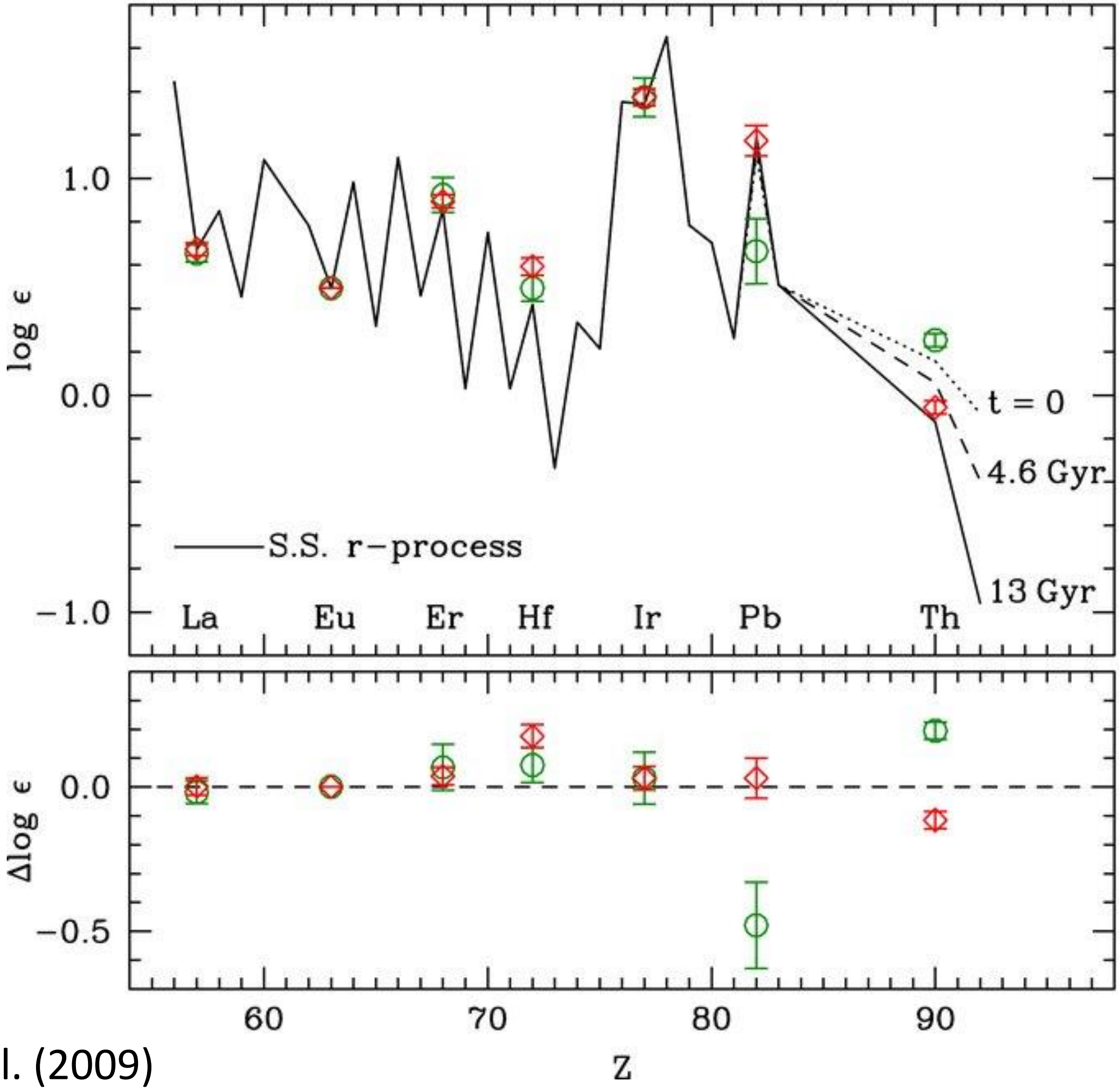
r-II stars
[Eu/Fe] > 1

Plus CEMP versions with [C/Fe] > 0.7



Placco et al. (2017)

Actinide Boost

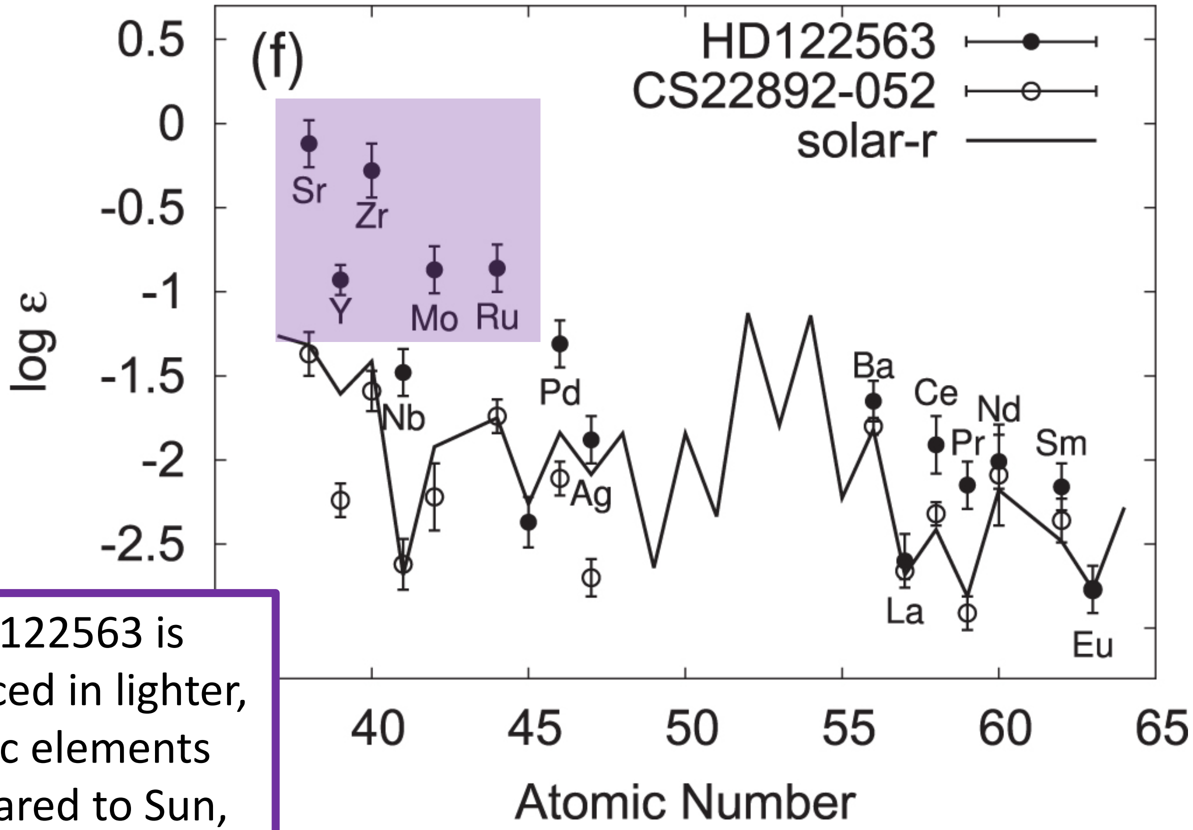


Mean: “Normal” r-proc enhanced stars

Mean: Actinide boost stars

Roederer et al. (2009)

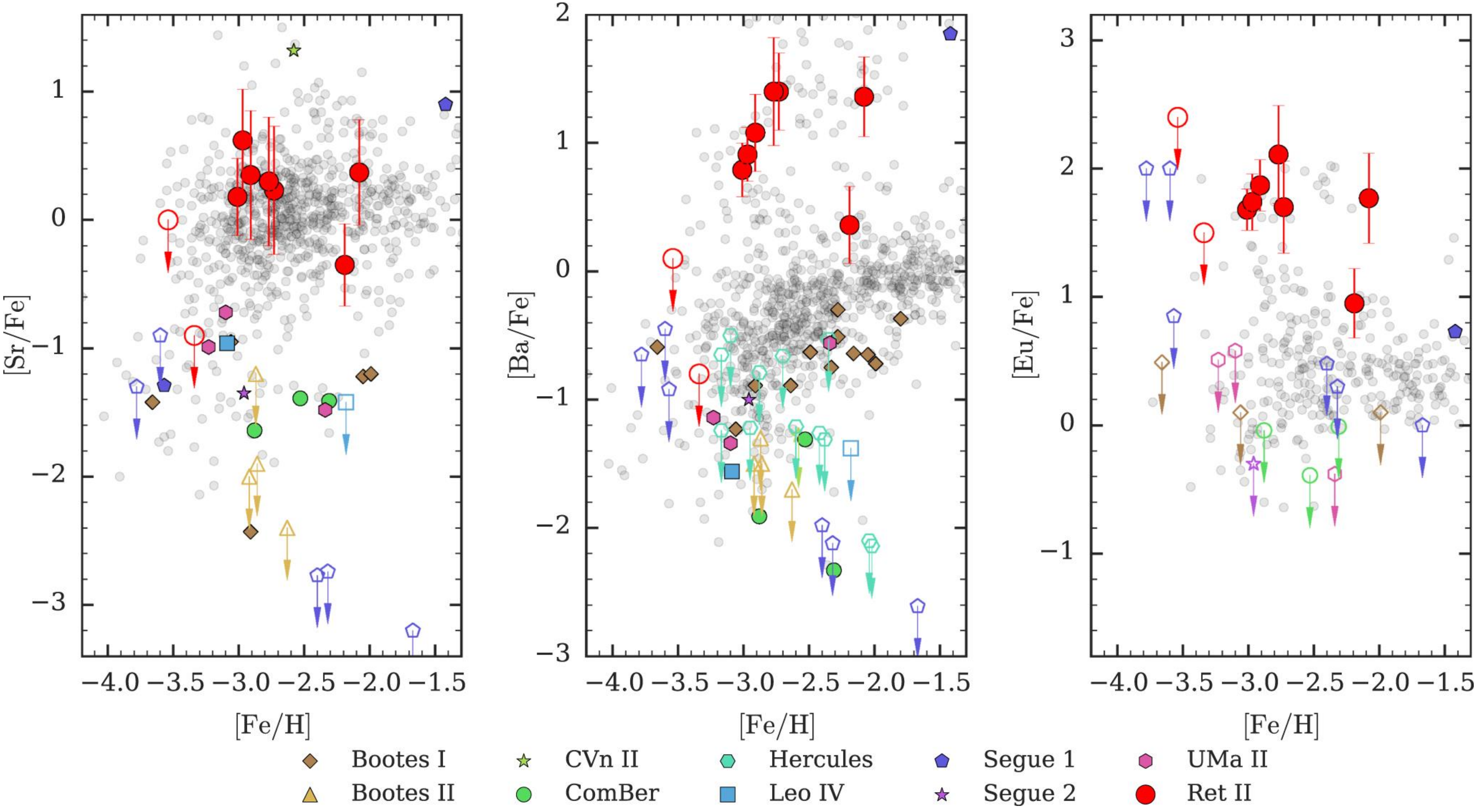
Terminal QSE, weak-r process



HD 122563 is enhanced in lighter, r-proc elements compared to Sun, r-II stars

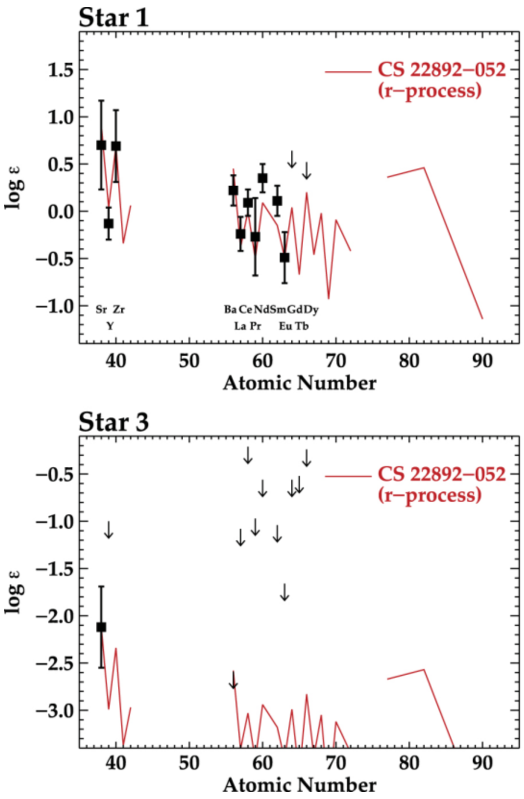
Aoki et al. (2017)

Reticulum II

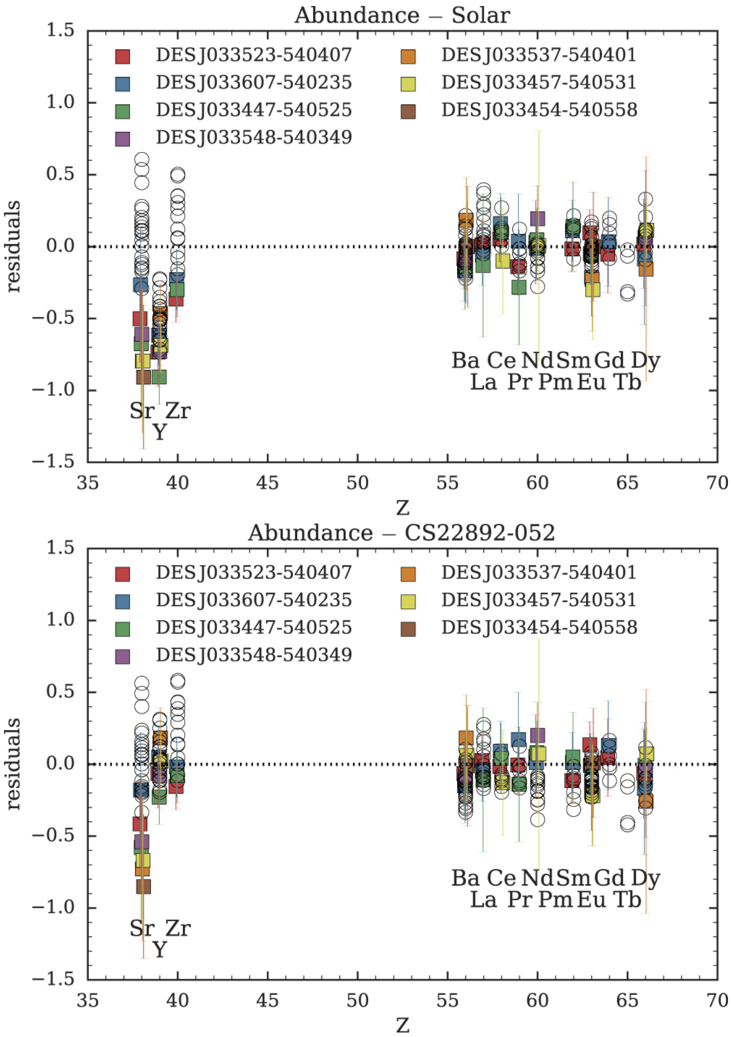


Ji et al. (2016)

Reticulum II



Roederer et al. (2016)



Ji et al. (2016)

Part II: How do we interpret and use abundances from the literature?

Interpreting Literature Abundances

How can theorists, experimentalists, modelers, etc. use abundances from the literature?*

- How should I interpret uncertainties? (E.g., “random” vs. “systematic”)
- Which values should I use? (E.g., log ε, [X/H], [X/Fe]?)
- How do I compare different studies?

*Based on discussions at the JINA meeting “Forging Connections: From Nuclei to the Cosmic Web”

Interpreting Errors

Typically these “random” errors come from line-to-line dispersion due to, e.g., S/N, uncertainties in line measurements or continuum placement, cosmic ray or sky line contamination, (atomic data uncertainties,) etc.

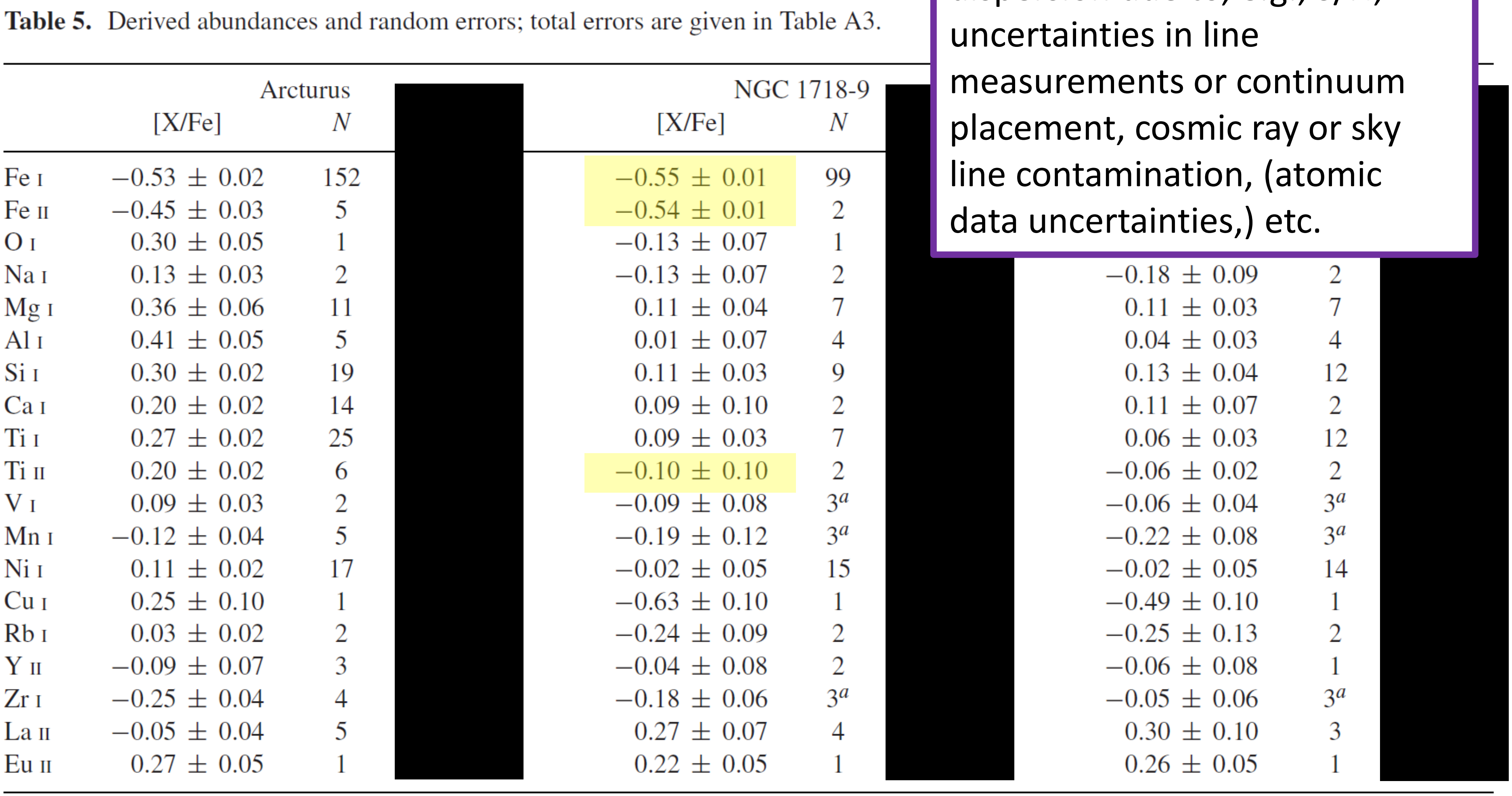


Table 5. Derived abundances and random errors; total errors are given in Table A3.

	Arcturus			NGC 1718-9					
	[X/Fe]	*N*	[redacted]	[X/Fe]	*N*	[redacted]			[redacted]
Fe I	−0.53 ± 0.02	152	[redacted]	−0.55 ± 0.01	99	[redacted]			[redacted]
Fe II	−0.45 ± 0.03	5	[redacted]	−0.54 ± 0.01	2	[redacted]			[redacted]
O I	0.30 ± 0.05	1	[redacted]	−0.13 ± 0.07	1	[redacted]			[redacted]
Na I	0.13 ± 0.03	2	[redacted]	−0.13 ± 0.07	2	[redacted]	−0.18 ± 0.09	2	[redacted]
Mg I	0.36 ± 0.06	11	[redacted]	0.11 ± 0.04	7	[redacted]	0.11 ± 0.03	7	[redacted]
Al I	0.41 ± 0.05	5	[redacted]	0.01 ± 0.07	4	[redacted]	0.04 ± 0.03	4	[redacted]
Si I	0.30 ± 0.02	19	[redacted]	0.11 ± 0.03	9	[redacted]	0.13 ± 0.04	12	[redacted]
Ca I	0.20 ± 0.02	14	[redacted]	0.09 ± 0.10	2	[redacted]	0.11 ± 0.07	2	[redacted]
Ti I	0.27 ± 0.02	25	[redacted]	0.09 ± 0.03	7	[redacted]	0.06 ± 0.03	12	[redacted]
Ti II	0.20 ± 0.02	6	[redacted]	−0.10 ± 0.10	2	[redacted]	−0.06 ± 0.02	2	[redacted]
V I	0.09 ± 0.03	2	[redacted]	−0.09 ± 0.08	3^a	[redacted]	−0.06 ± 0.04	3^a	[redacted]
Mn I	−0.12 ± 0.04	5	[redacted]	−0.19 ± 0.12	3^a	[redacted]	−0.22 ± 0.08	3^a	[redacted]
Ni I	0.11 ± 0.02	17	[redacted]	−0.02 ± 0.05	15	[redacted]	−0.02 ± 0.05	14	[redacted]
Cu I	0.25 ± 0.10	1	[redacted]	−0.63 ± 0.10	1	[redacted]	−0.49 ± 0.10	1	[redacted]
Rb I	0.03 ± 0.02	2	[redacted]	−0.24 ± 0.09	2	[redacted]	−0.25 ± 0.13	2	[redacted]
Y II	−0.09 ± 0.07	3	[redacted]	−0.04 ± 0.08	2	[redacted]	−0.06 ± 0.08	1	[redacted]
Zr I	−0.25 ± 0.04	4	[redacted]	−0.18 ± 0.06	3^a	[redacted]	−0.05 ± 0.06	3^a	[redacted]
La II	−0.05 ± 0.04	5	[redacted]	0.27 ± 0.07	4	[redacted]	0.30 ± 0.10	3	[redacted]
Eu II	0.27 ± 0.05	1	[redacted]	0.22 ± 0.05	1	[redacted]	0.26 ± 0.05	1	[redacted]

Sakari , McWilliam, & Wallerstein (2017): Analysis of an LMC star cluster

Differential Analyses

(E.g., McWilliam et al. 2013)

Derived in the same way, same atomic data, same model atmosphere (Different from adopting, e.g., Asplund et al. 2009)

- For each spectral line:
  - Determine log ε in the Sun for that line
  - Find log ε in a standard star, calculate [X/H] with solar abundance
  - In the target stars, calculate Δlog ε ([X/H]) with respect to the standard
- With all lines, find an average Δ[X/H] for the target stars
- Apply that Δ[X/H] offset to the standard's [X/H] (which was likely derived with more lines)

Can do this for the atmospheric parameters as well!!!

Differential Analyses

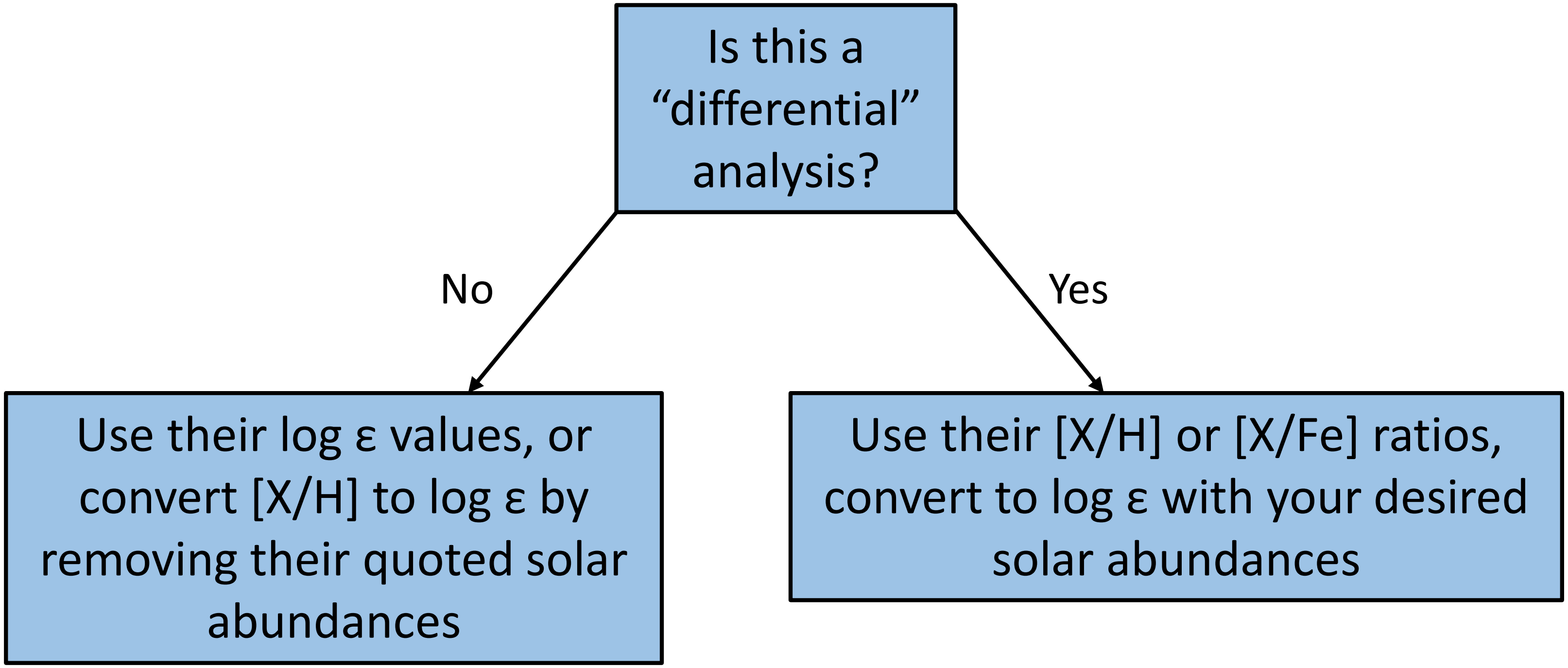
Differential [X/H] ratios are likely to be MORE accurate than the log ε values that come straight from MOOG, if done well

But…

- Cannot do this for all lines (solar lines too weak or too strong)
- Have to assume a solar pattern for some lines, e.g., Asplund et al. 2009
- May depend on how similar the standard is to the targets (in atmospheric parameters, metallicities, abundances)

Too Much Information!

I just want to use the abundances to test my models!!!



Is this a “differential” analysis?

No

Use their log ε values, or convert [X/H] to log ε by removing their quoted solar abundances

Yes

Use their [X/H] or [X/Fe] ratios, convert to log ε with your desired solar abundances

Interpreting Errors

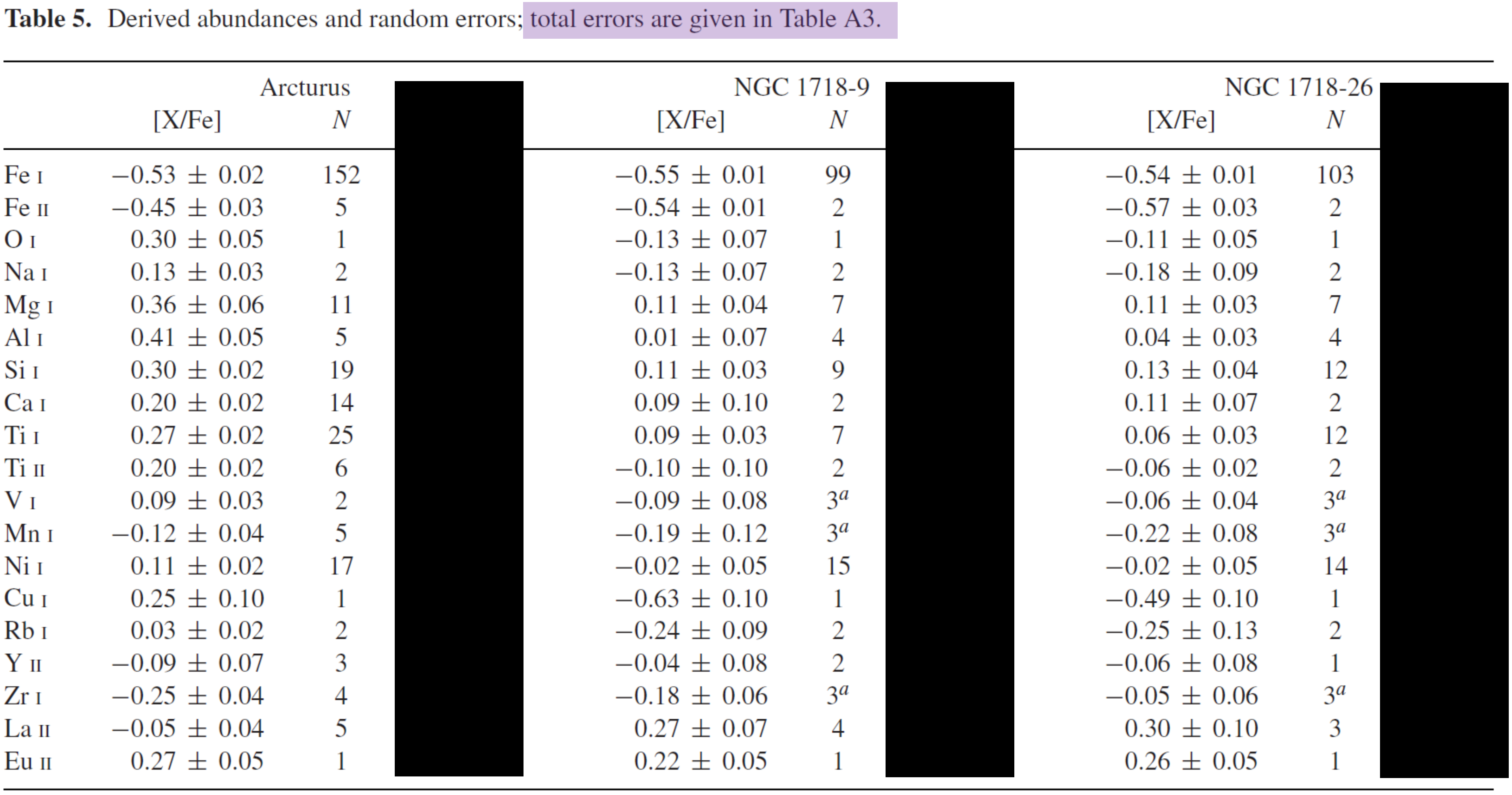


Table 5. Derived abundances and random errors; total errors are given in Table A3.

	Arcturus			NGC 1718-9			NGC 1718-26		
	[X/Fe]	*N*	[redacted]	[X/Fe]	*N*	[redacted]	[X/Fe]	*N*	[redacted]
Fe I	−0.53 ± 0.02	152	[redacted]	−0.55 ± 0.01	99	[redacted]	−0.54 ± 0.01	103	[redacted]
Fe II	−0.45 ± 0.03	5	[redacted]	−0.54 ± 0.01	2	[redacted]	−0.57 ± 0.03	2	[redacted]
O I	0.30 ± 0.05	1	[redacted]	−0.13 ± 0.07	1	[redacted]	−0.11 ± 0.05	1	[redacted]
Na I	0.13 ± 0.03	2	[redacted]	−0.13 ± 0.07	2	[redacted]	−0.18 ± 0.09	2	[redacted]
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V I	0.09 ± 0.03	2	[redacted]	−0.09 ± 0.08	3^a	[redacted]	−0.06 ± 0.04	3^a	[redacted]
Mn I	−0.12 ± 0.04	5	[redacted]	−0.19 ± 0.12	3^a	[redacted]	−0.22 ± 0.08	3^a	[redacted]
Ni I	0.11 ± 0.02	17	[redacted]	−0.02 ± 0.05	15	[redacted]	−0.02 ± 0.05	14	[redacted]
Cu I	0.25 ± 0.10	1	[redacted]	−0.63 ± 0.10	1	[redacted]	−0.49 ± 0.10	1	[redacted]
Rb I	0.03 ± 0.02	2	[redacted]	−0.24 ± 0.09	2	[redacted]	−0.25 ± 0.13	2	[redacted]
Y II	−0.09 ± 0.07	3	[redacted]	−0.04 ± 0.08	2	[redacted]	−0.06 ± 0.08	1	[redacted]
Zr I	−0.25 ± 0.04	4	[redacted]	−0.18 ± 0.06	3^a	[redacted]	−0.05 ± 0.06	3^a	[redacted]
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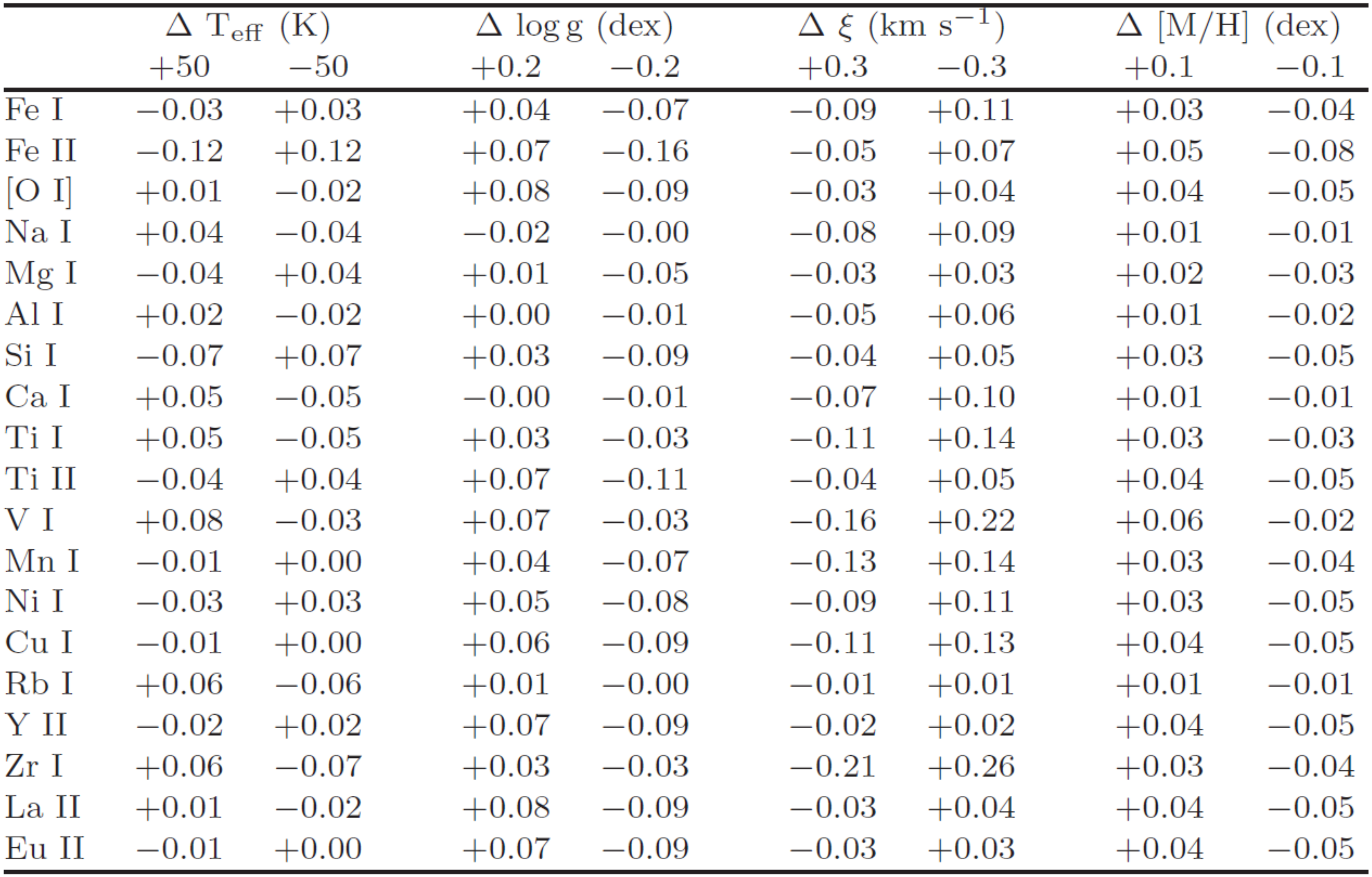
Sakari , McWilliam, & Wallerstein (2017): Analysis of an LMC star cluster

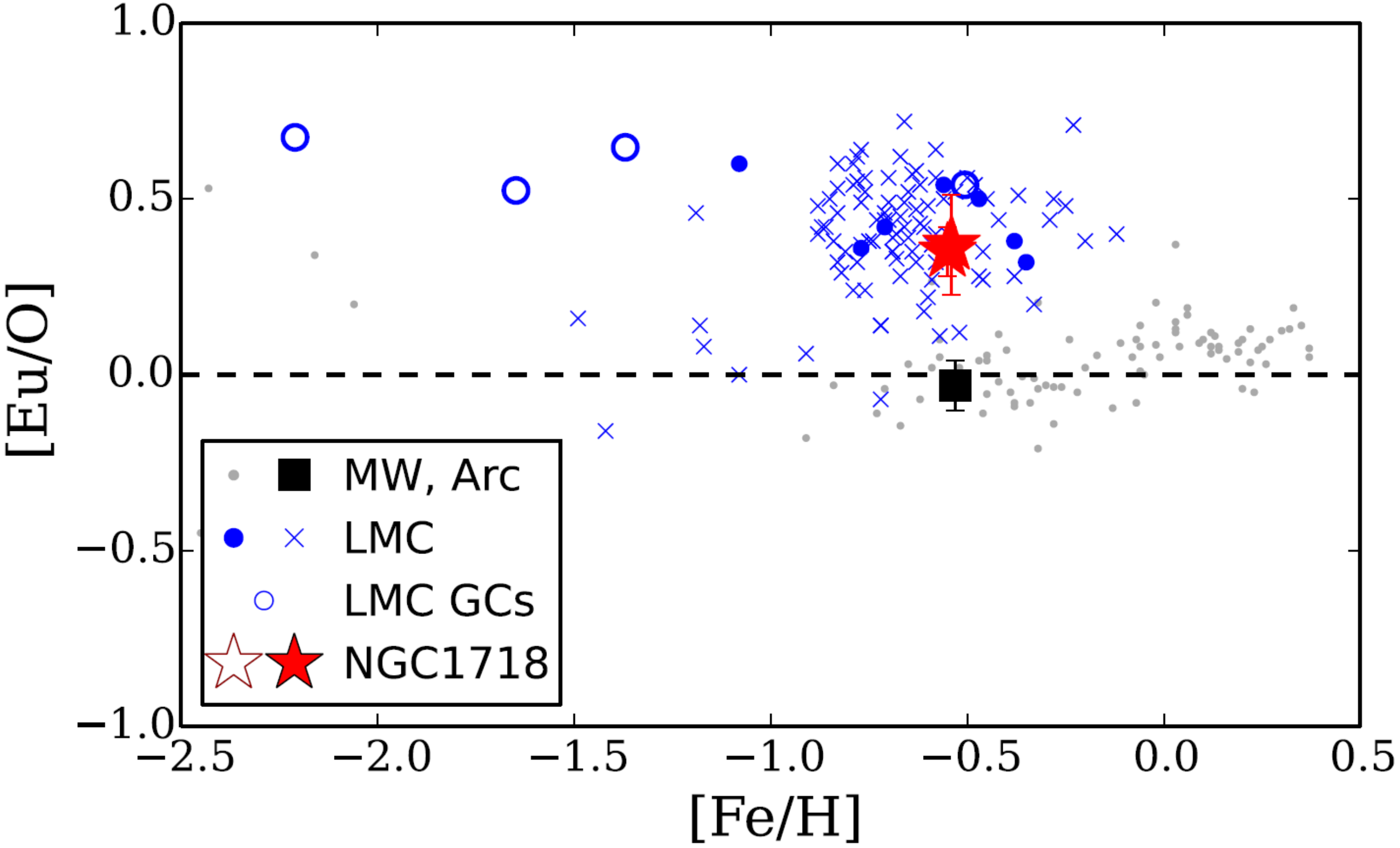
“Systematic” Errors



	Δ $T_{\rm eff}$ (K)		Δ $\log g$ (dex)		Δ ξ (km s^{-1})		Δ [M/H] (dex)	
	+50	−50	+0.2	−0.2	+0.3	−0.3	+0.1	−0.1
Fe I	−0.03	+0.03	+0.04	−0.07	−0.09	+0.11	+0.03	−0.04
Fe II	−0.12	+0.12	+0.07	−0.16	−0.05	+0.07	+0.05	−0.08
[O I]	+0.01	−0.02	+0.08	−0.09	−0.03	+0.04	+0.04	−0.05
Na I	+0.04	−0.04	−0.02	−0.00	−0.08	+0.09	+0.01	−0.01
Mg I	−0.04	+0.04	+0.01	−0.05	−0.03	+0.03	+0.02	−0.03
Al I	+0.02	−0.02	+0.00	−0.01	−0.05	+0.06	+0.01	−0.02
Si I	−0.07	+0.07	+0.03	−0.09	−0.04	+0.05	+0.03	−0.05
Ca I	+0.05	−0.05	−0.00	−0.01	−0.07	+0.10	+0.01	−0.01
Ti I	+0.05	−0.05	+0.03	−0.03	−0.11	+0.14	+0.03	−0.03
Ti II	−0.04	+0.04	+0.07	−0.11	−0.04	+0.05	+0.04	−0.05
V I	+0.08	−0.03	+0.07	−0.03	−0.16	+0.22	+0.06	−0.02
Mn I	−0.01	+0.00	+0.04	−0.07	−0.13	+0.14	+0.03	−0.04
Ni I	−0.03	+0.03	+0.05	−0.08	−0.09	+0.11	+0.03	−0.05
Cu I	−0.01	+0.00	+0.06	−0.09	−0.11	+0.13	+0.04	−0.05
Rb I	+0.06	−0.06	+0.01	−0.00	−0.01	+0.01	+0.01	−0.01
Y II	−0.02	+0.02	+0.07	−0.09	−0.02	+0.02	+0.04	−0.05
Zr I	+0.06	−0.07	+0.03	−0.03	−0.21	+0.26	+0.03	−0.04
La II	+0.01	−0.02	+0.08	−0.09	−0.03	+0.04	+0.04	−0.05
Eu II	−0.01	+0.00	+0.07	−0.09	−0.03	+0.03	+0.04	−0.05

Sakari, McWilliam, & Wallerstein (2017)

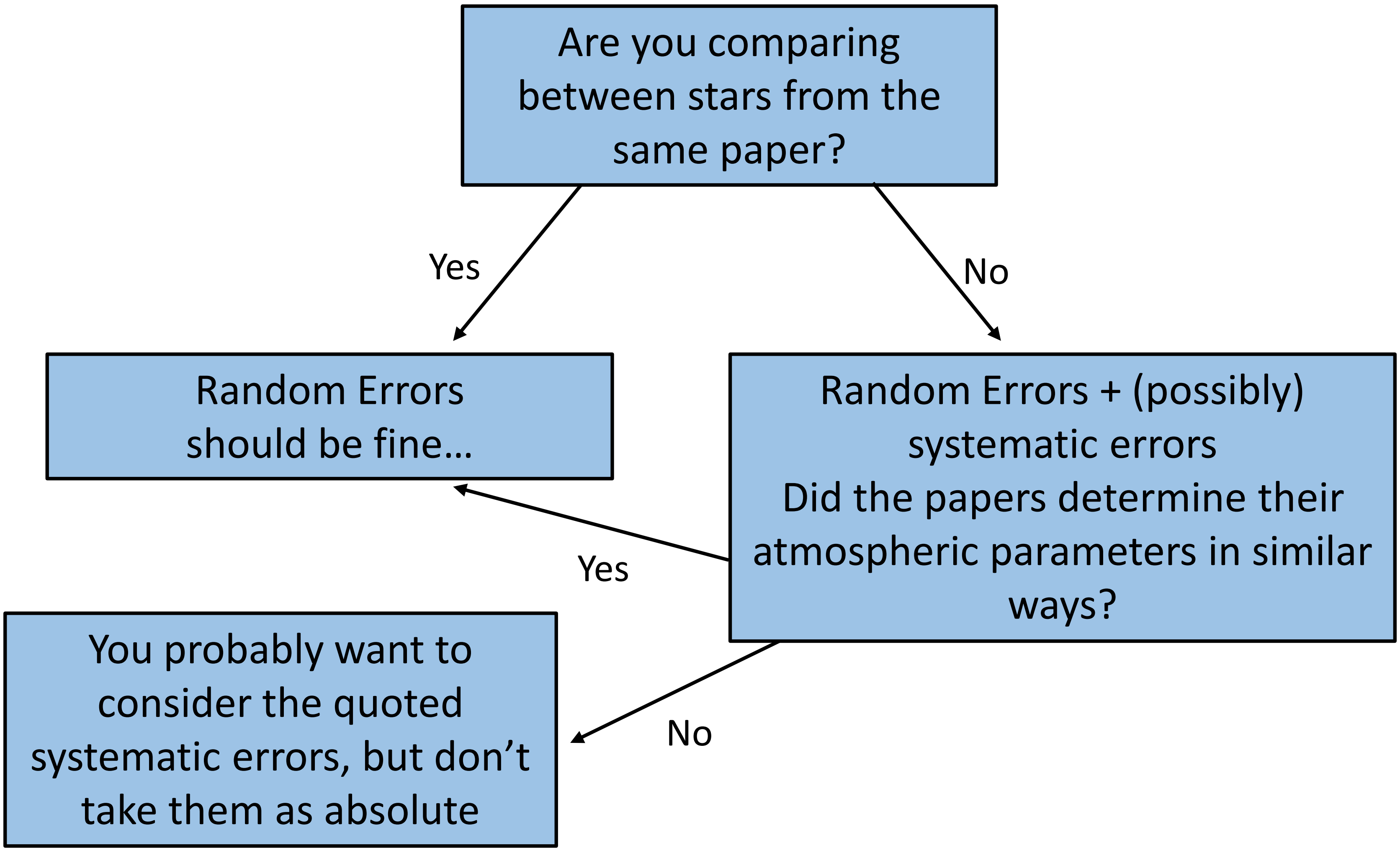
“Systematic” Errors



Sakari, McWilliam, & Wallerstein (2017)

Too Much Information!

Which errors should I use?



Are you comparing between stars from the same paper?

Yes

Random Errors should be fine…

No

Random Errors + (possibly) systematic errors
Did the papers determine their atmospheric parameters in similar ways?

Yes

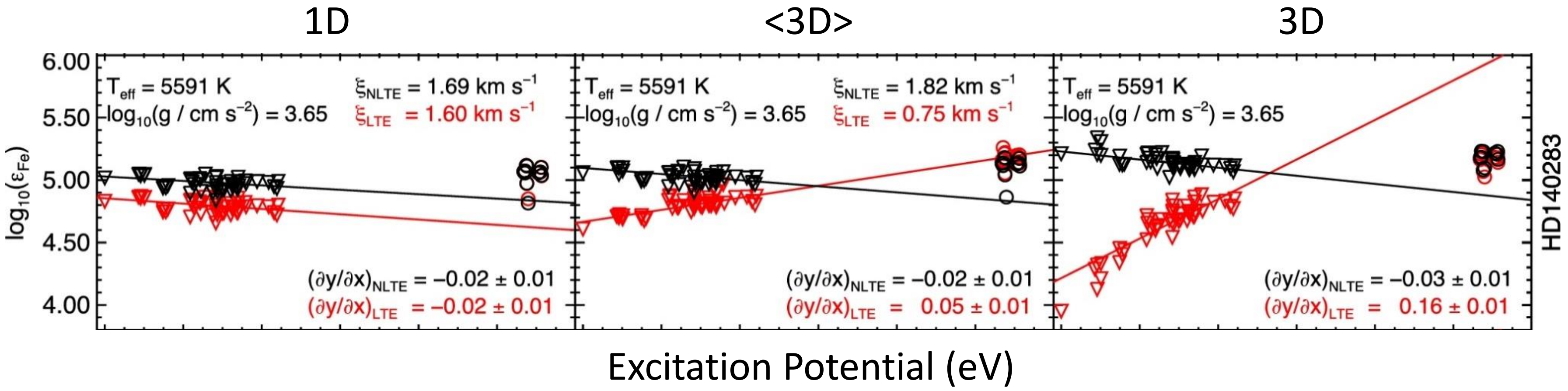
Random Errors should be fine…

No

You probably want to consider the quoted systematic errors, but don’t take them as absolute

More problems with atmospheric parameters…

- The "traditional" way of determining abundances requires the assumption of LTE, which is wrong
    - *How* wrong depends on the star
    - Various authors deal with this in different ways



🔴 LTE

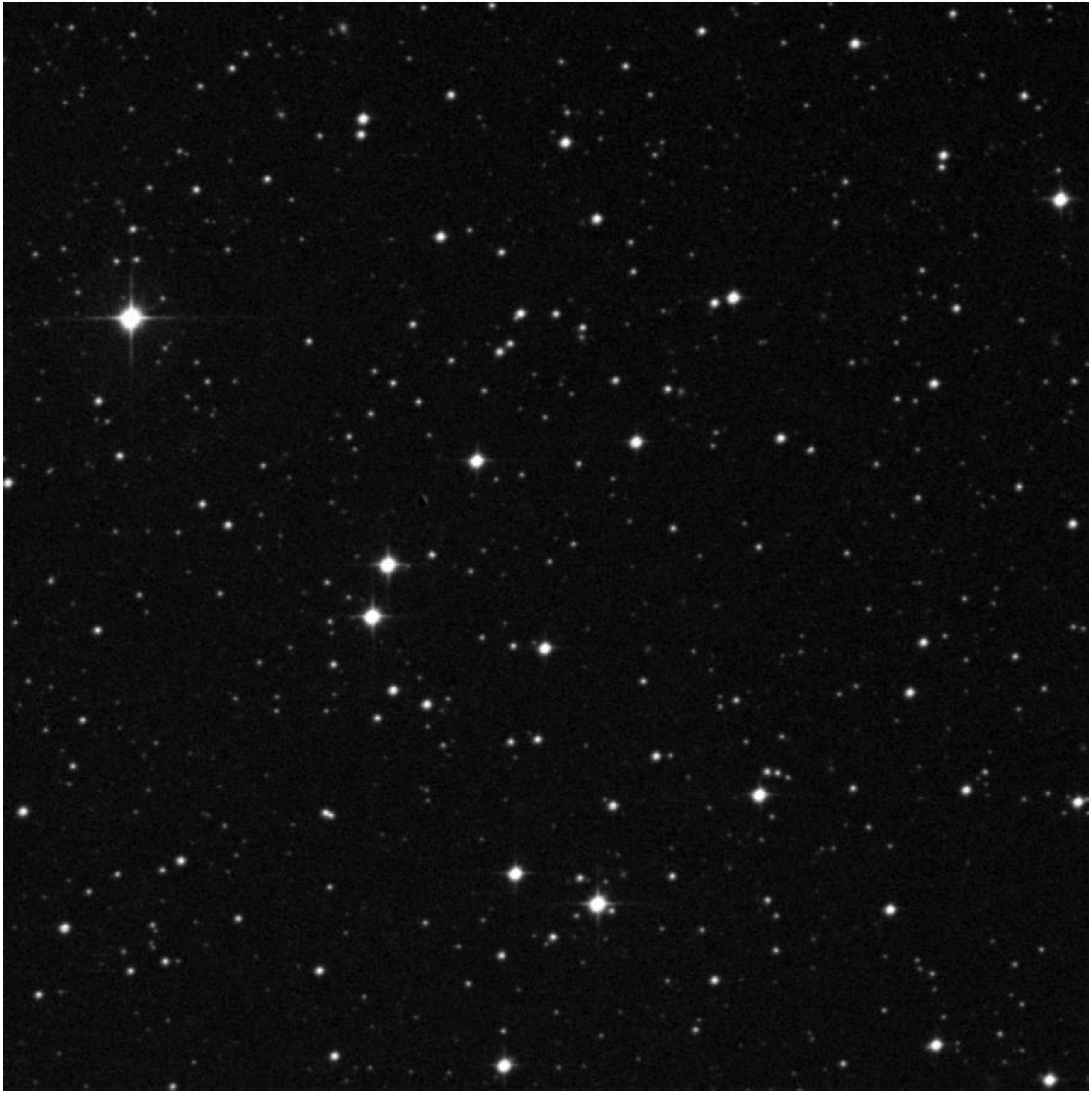
⚫ NLTE

Amarsi et al. (2016)

Part III: Okay great, now we know how to interpret the observations.

When can we get better data for more stars?
Can we get Element X in Environment Y?

(E.g., Te in an environment like Ret II?)



Digitized Sky Survey: 15’ x 15’

More Data: The Near Future

- Large Surveys will find new metal-poor stars:
  E.g., RAVE, APOGEE, GALAH, GAIA-ESO, Skymapper, Pristine, others…

Limited to MW and nearest neighbors

- Medium resolution spectroscopic follow-up
  Can provide rough abundances of some elements (Fe, C, etc.)
- High resolution follow-up (R~30,000)
  Some neutron capture elements: e.g,. Y, Ba, Eu
- Higher resolution follow-up (R~80,000)
  More elements: e.g., U
- UV observations (requires *HST*)
  Even more r-process elements: Ge, Mo, Cd, Te, Pt, Au, Bi

Very limited to the brightest, nearby stars

Finding new r-I and r-II stars

- In the Milky Way:
  - Survey with Terese Hansen, Anna Frebel, Tim Beers, Vini Placco, and others
  - I will talk about this more on Tuesday, August 1
  - Briefly, we expect to significantly increase the number of known r-I and r-II stars
- Attempts to find new UFDs may find a new Reticulum II…

Okay, but we really want the detailed r-process patterns…

More Data: The Near Future

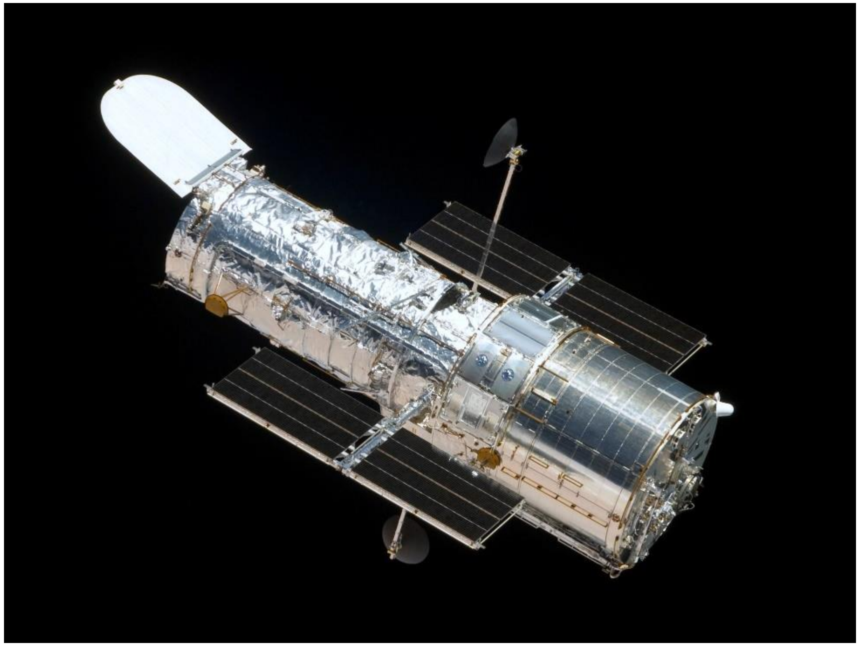
Limited to MW and nearest neighbors

- Large Surveys will find new metal-poor stars:
  E.g., RAVE, APOGEE, GALAH, GAIA-ESO, Skymapper, Pristine, others…
- Medium resolution follow-up may be necessary
  Can provide rough abundances of some elements (Fe, C, etc.)
- High resolution spectroscopic follow-up (R~30,000)
  Some neutron capture elements: e.g,. Y, Ba, La, Nd, Sm, Gd, Dy, Th
- Higher resolution follow-up (R~80,000)
  More elements: e.g., U
- UV observations (requires *HST*)
  Even more r-process elements: Ge, Mo, Cd, Te, Pt, Au, Pb, Bi

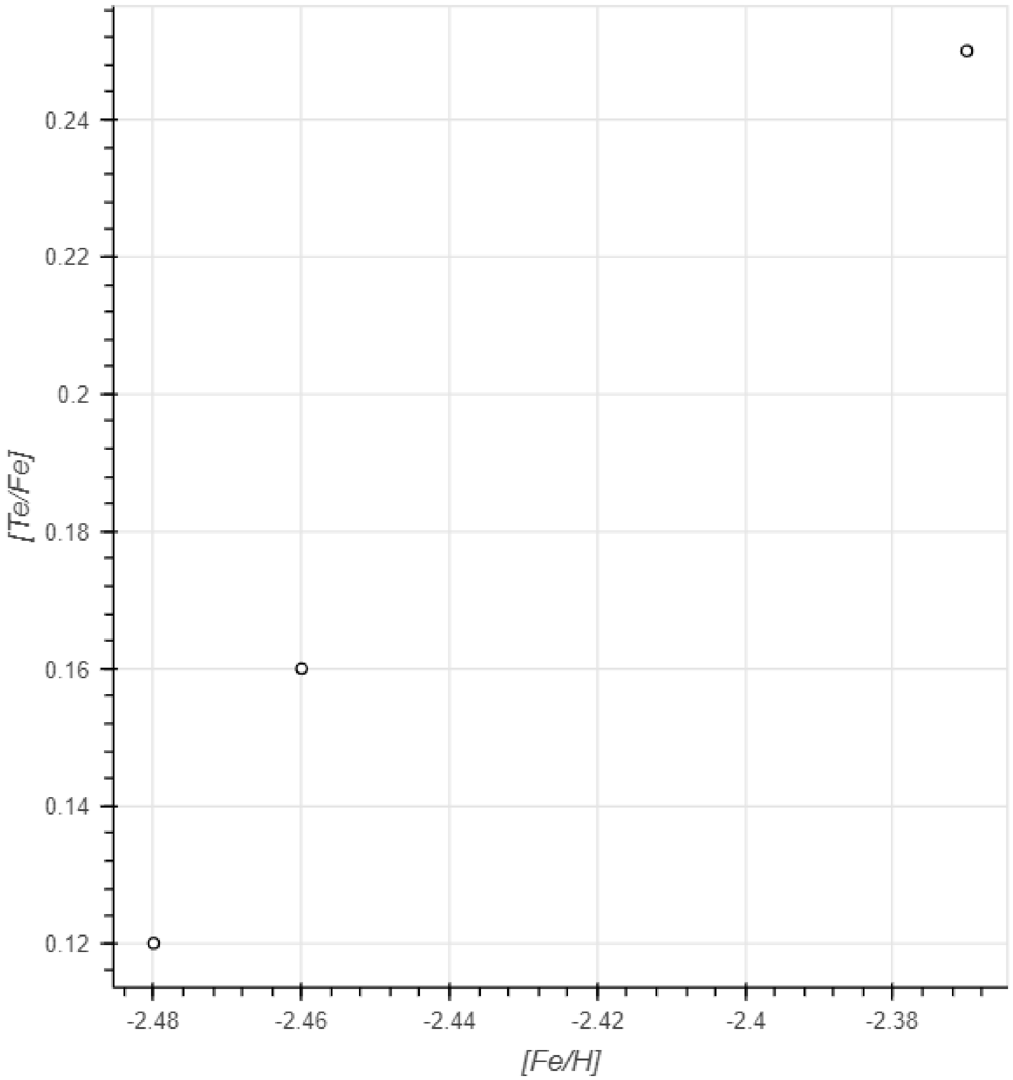
Very limited to the brightest, nearby stars

Hubble Space Telescope

- Certain elements are only accessible with *HST*
- Time is very competitive
- Only possible for the brightest stars
- Eventually *HST* will die

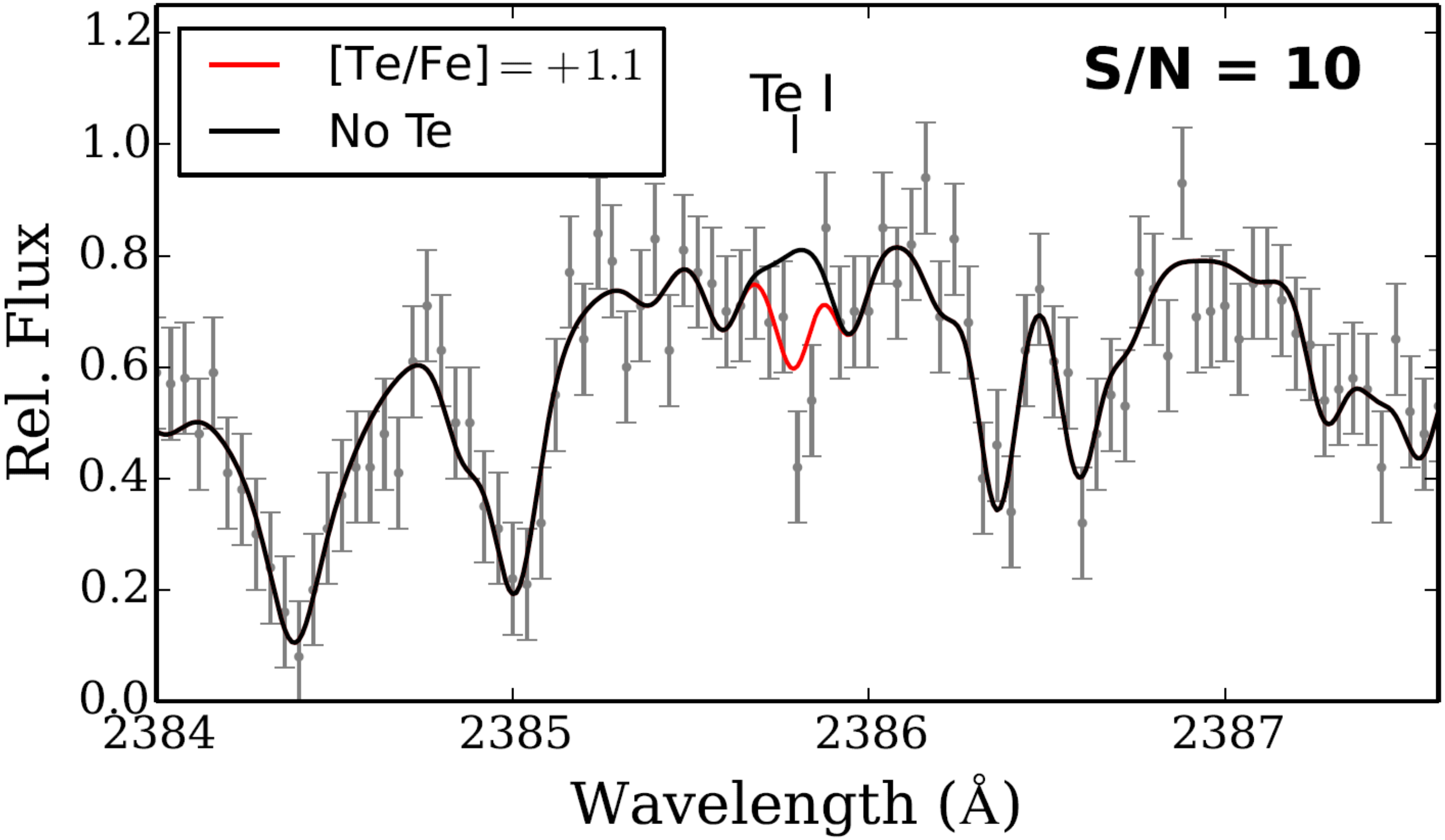


Tellurium in JINAbase



All have V<9.4
One is an r-I,
the others are
not r-proc
enhanced
(Roederer et al.
2012, 2014)

Tellurium with *HST*

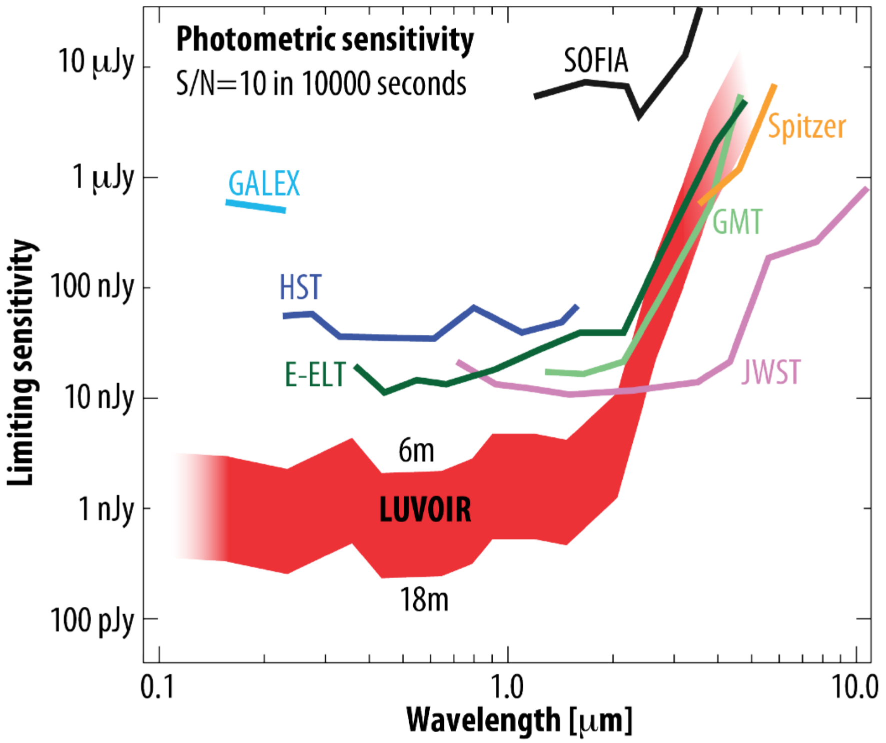


Predicted spectrum for V = 10.9 with 44 orbits

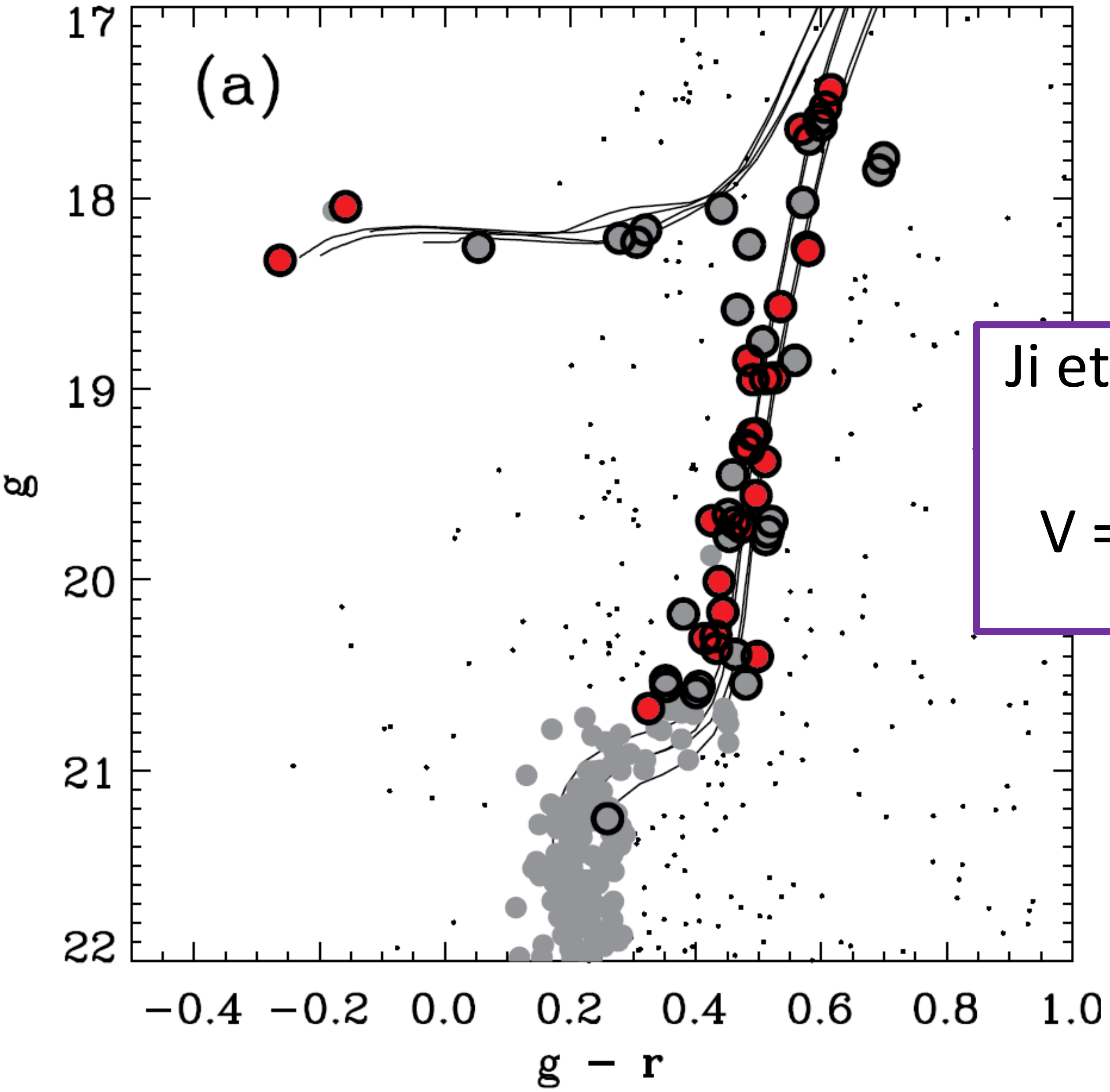
LUVOIR:

Large UV/Optical/Infrared Surveyor

- Large mirror aperture (8 – 16 m)
- Primary Science Case: Detecting habitable exoplanets
- LUVOIR UV MultiObject Spectrograph (LUMOS), with R~30,000-50,000 (possibly 100,000)



Limiting sensitivities for some current and future facilities. LUVOIR values are computed assuming a 280K temperature and a range of telescope diameters (based on Dalcanton et al., 2015).



Ji et al. (2016) stars:

V = 16-18.7

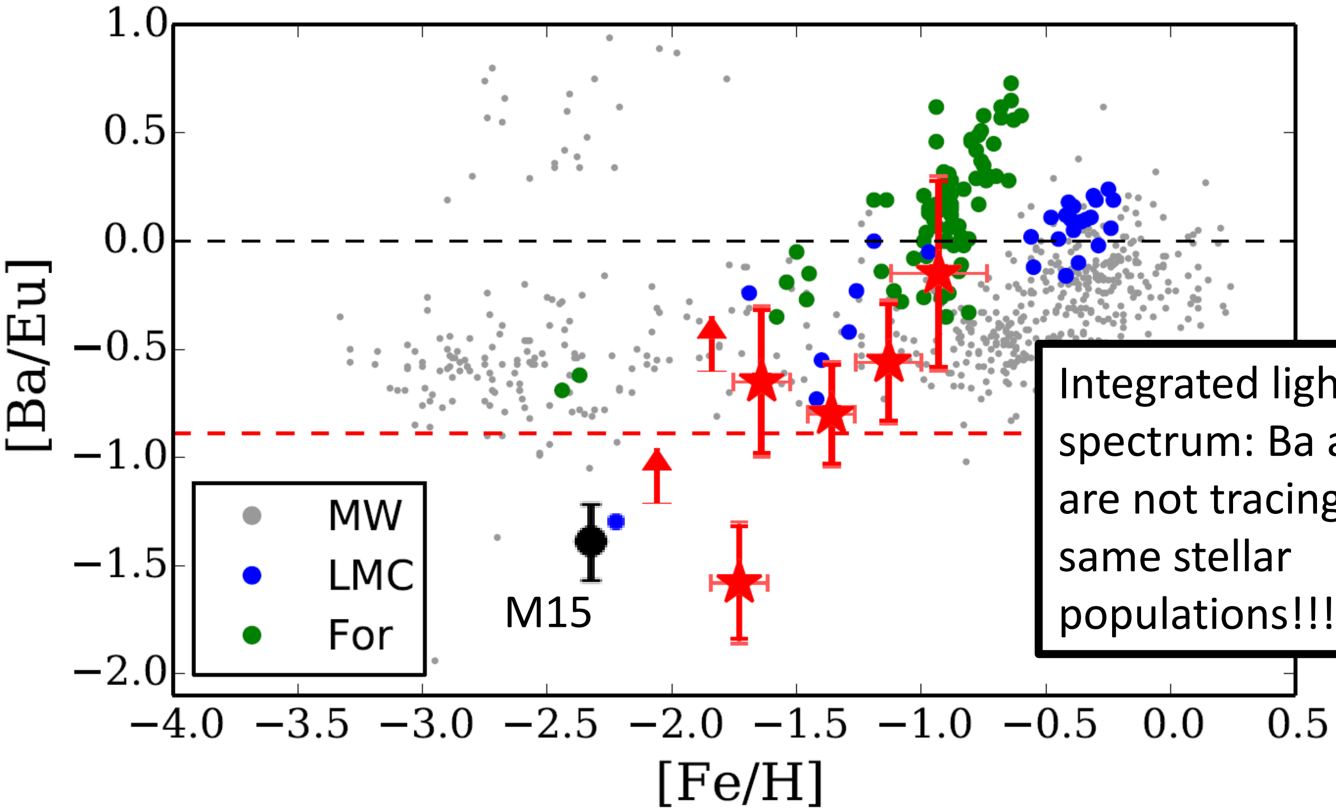
Simon et al. (2015)

LUMOS

- ETC simulator
- No giant template spectra
- No metal-poor template spectra
- No gratings that extend to high resolution or past 2000 Å
- But with a 12 m aperture, a G2V (solar?) template, a grating with R = 30,000, and a 1 hour exposure:
  - S/N = 80-90 for V = 16 at 1800 Å
  - S/N = 20-30 for V = 18.7 at 1800 Å
  - Both are better than we can currently (reasonably) do for the *brightest* r-II stars, and should be better for low [Fe/H]

Going even further…

- r-process enhanced stars in an M31 globular cluster



Integrated light spectrum: Ba and Eu are not tracing the same stellar populations!!!

Sakari et al. (2015)

“Systematic” Errors

- Often describes the effects of the atmospheric parameters (Teff, log g, microturbulent velocities, metallicities) on the abundances
- But these parameters are NOT independent, should take covariances into account

$$\sigma(\overline{\varepsilon_1/\varepsilon_2})^2 = \sigma_r(\overline{\varepsilon_1/\varepsilon_2})^2 + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial T}\right)^2 \sigma_T^2 + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial g}\right)^2 \sigma_g^2 + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial \xi}\right)^2 \sigma_\xi^2 + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial [M/H]}\right)^2 \sigma_{[M/H]}^2 +$$

$$2\left[\left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial T}\right)\left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial g}\right)\sigma_{Tg} + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial T}\right)\left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial \xi}\right)\sigma_{T\xi} + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial g}\right)\left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial \xi}\right)\sigma_{g\xi} + \left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial [M/H]}\right)\left(\frac{\partial\overline{\varepsilon_1/\varepsilon_2}}{\partial T}\right)\sigma_{T[M/H]}\right]$$

McWilliam et al. (2013)

Sakari, McWilliam, & Wallerstein (2017)

“Systematic” Errors

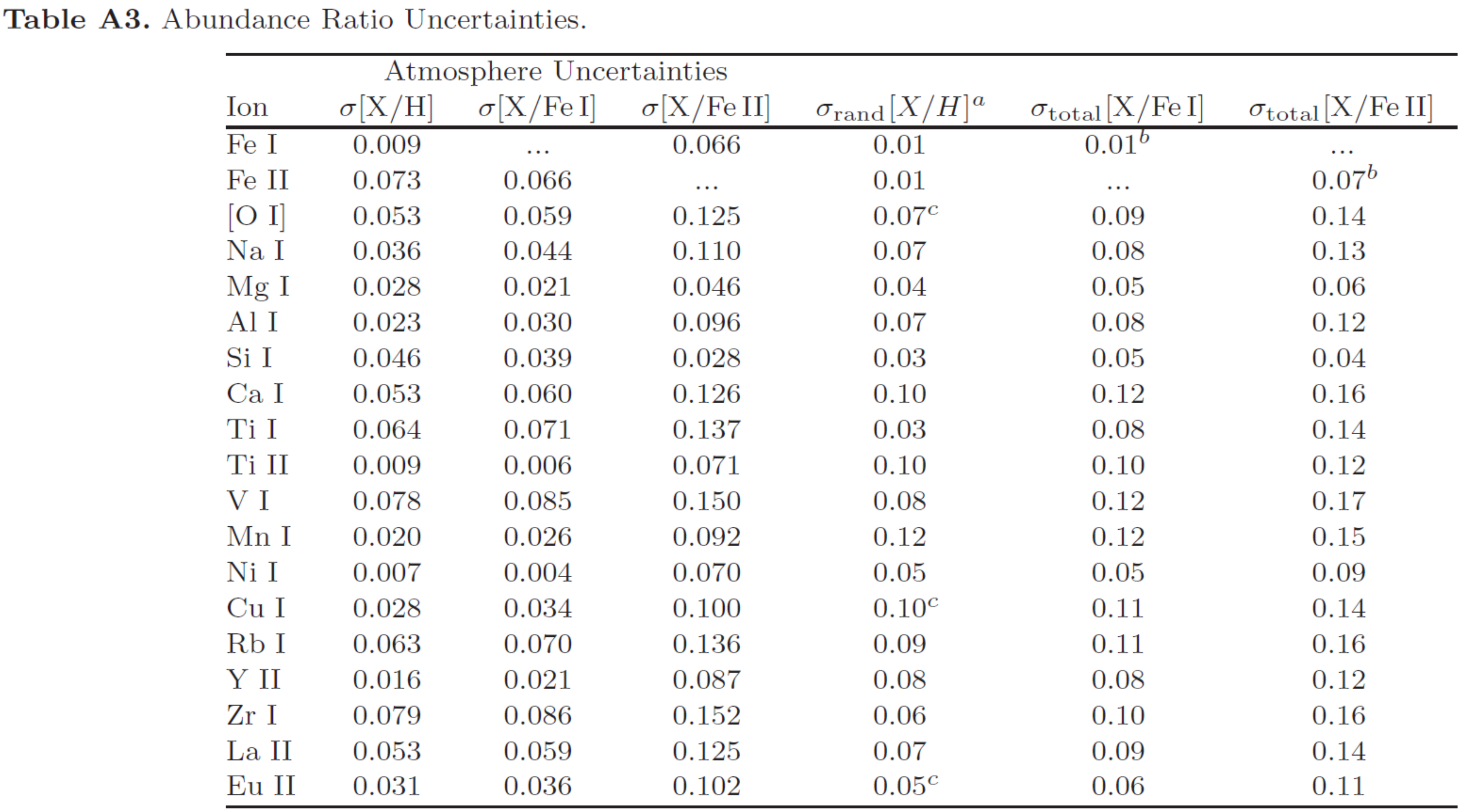


Table A3. Abundance Ratio Uncertainties.

	Atmosphere Uncertainties					
Ion	σ[X/H]	σ[X/Fe I]	σ[X/Fe II]	$\sigma_{\rm rand}[X/H]^a$	$\sigma_{\rm total}$[X/Fe I]	$\sigma_{\rm total}$[X/Fe II]
Fe I	0.009	...	0.066	0.01	0.01^b	...
Fe II	0.073	0.066	...	0.01	...	0.07^b
[O I]	0.053	0.059	0.125	0.07^c	0.09	0.14
Na I	0.036	0.044	0.110	0.07	0.08	0.13
Mg I	0.028	0.021	0.046	0.04	0.05	0.06
Al I	0.023	0.030	0.096	0.07	0.08	0.12
Si I	0.046	0.039	0.028	0.03	0.05	0.04
Ca I	0.053	0.060	0.126	0.10	0.12	0.16
Ti I	0.064	0.071	0.137	0.03	0.08	0.14
Ti II	0.009	0.006	0.071	0.10	0.10	0.12
V I	0.078	0.085	0.150	0.08	0.12	0.17
Mn I	0.020	0.026	0.092	0.12	0.12	0.15
Ni I	0.007	0.004	0.070	0.05	0.05	0.09
Cu I	0.028	0.034	0.100	0.10^c	0.11	0.14
Rb I	0.063	0.070	0.136	0.09	0.11	0.16
Y II	0.016	0.021	0.087	0.08	0.08	0.12
Zr I	0.079	0.086	0.152	0.06	0.10	0.16
La II	0.053	0.059	0.125	0.07	0.09	0.14
Eu II	0.031	0.036	0.102	0.05^c	0.06	0.11

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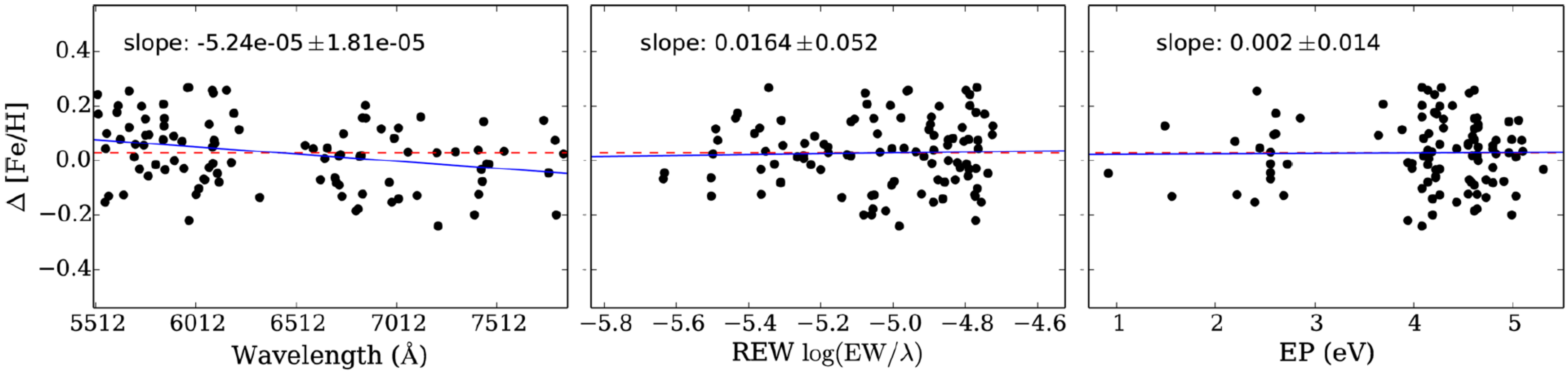
Line-to-line Scatter



Sakari , McWilliam, & Wallerstein (2017): Analysis of an LMC star cluster