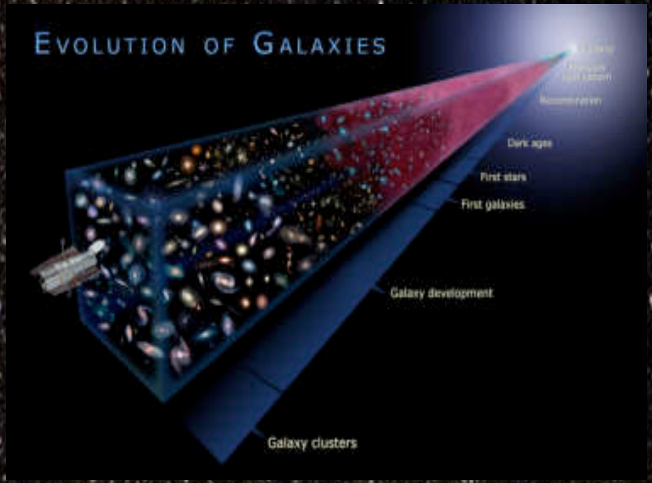
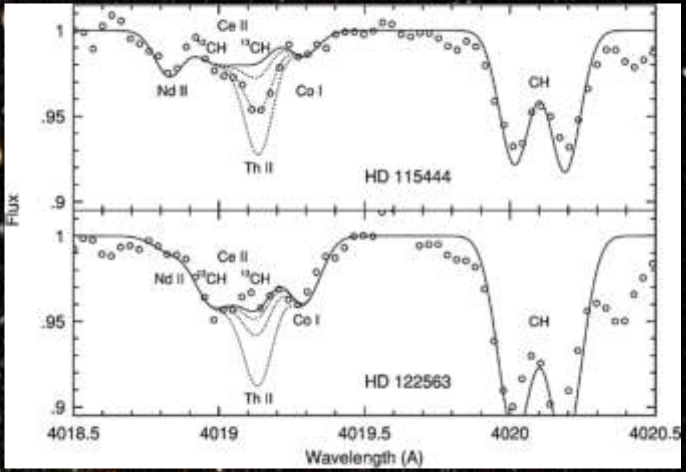


hubblesite.org



Nissen & Gustafsson 2018

Nuclear Astrophysics: a Stellar Spectroscopist's View

Chris Sneden

Department of Astronomy & McDonald Observatory
University of Texas, Austin

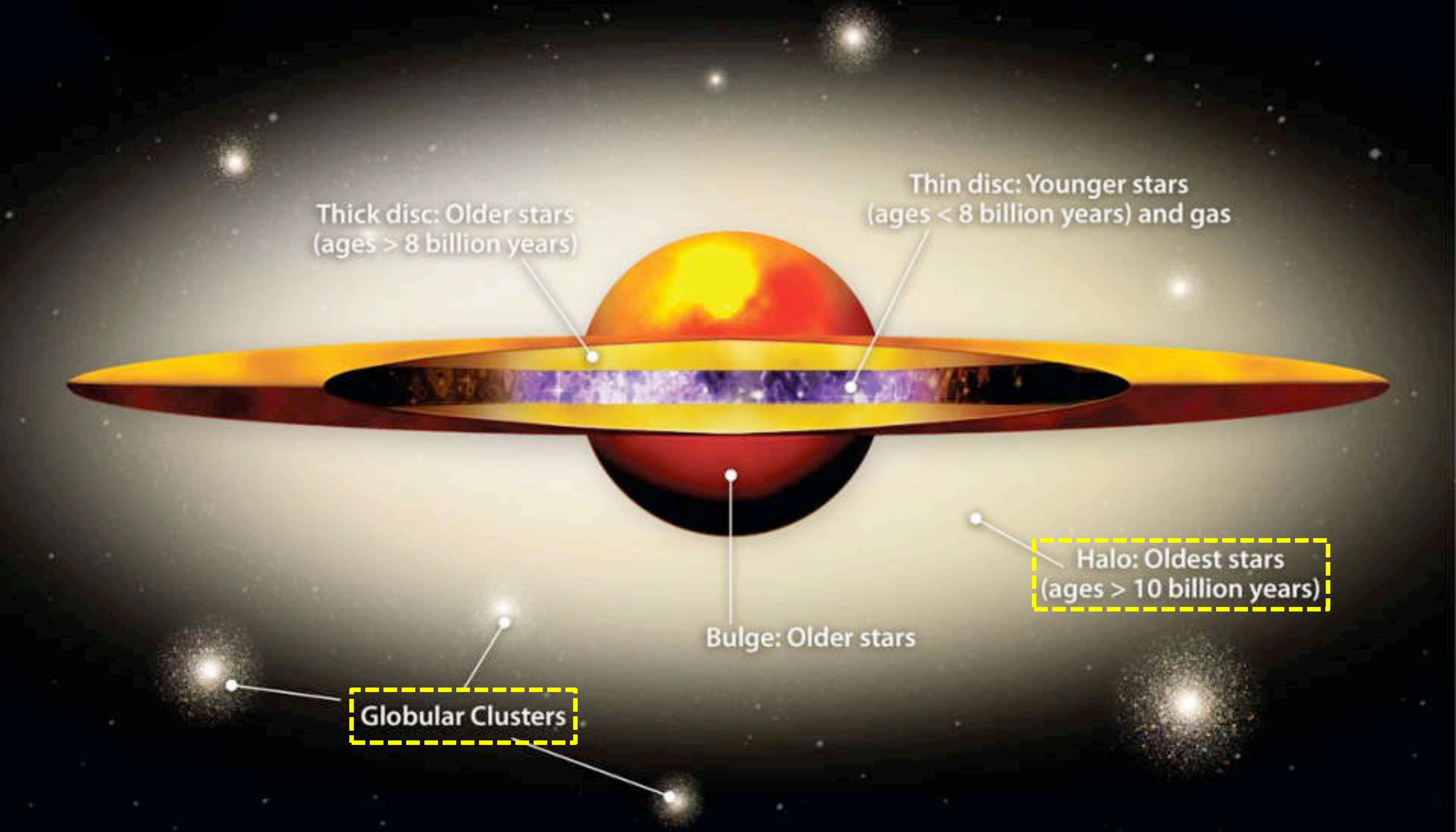
Galactic Definitions

- Disk populations: thin disk, thick disk, [old disk], bulge
- halo populations: inner, outer, accreted, dissipated
- kinematic versus chemical composition separations
- sub-populations from abundance peculiarities

Abundance Definitions

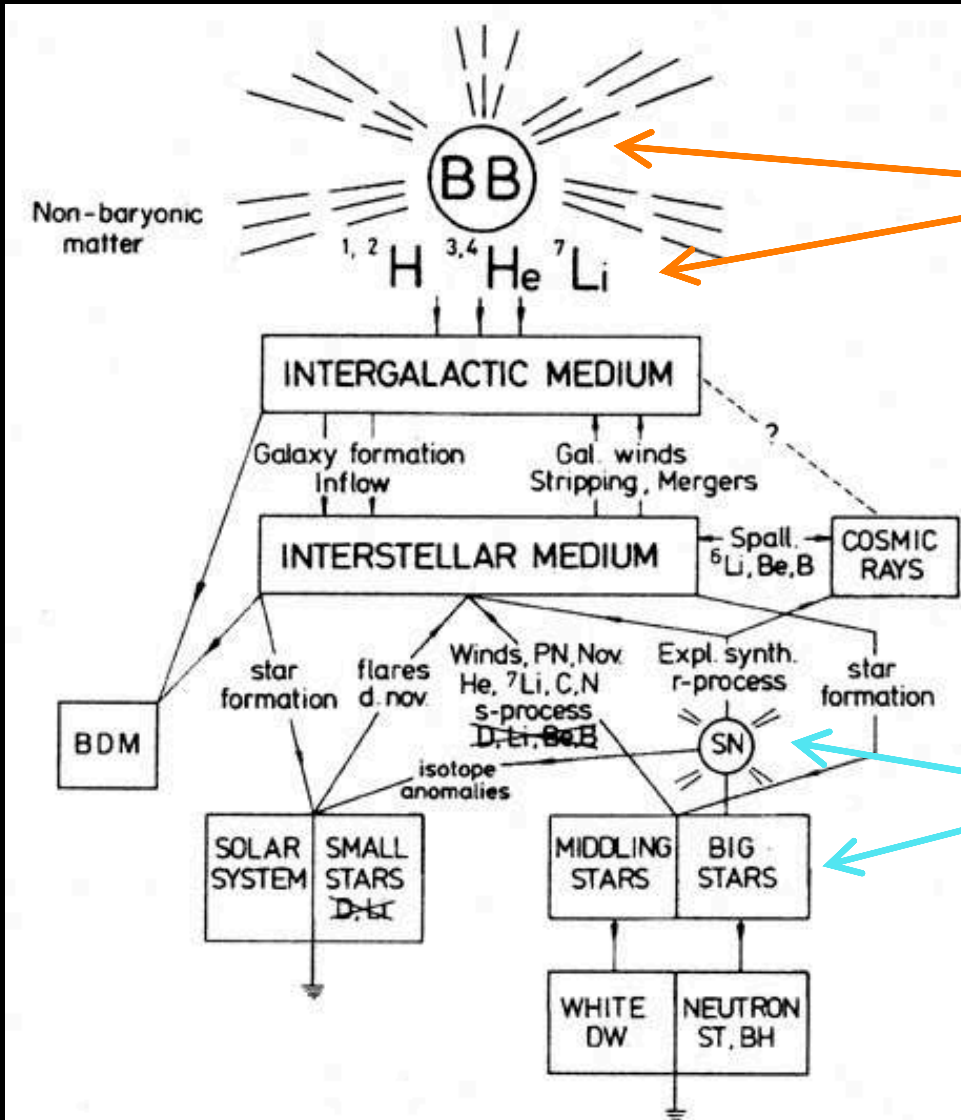
- $\log \varepsilon(X) = \log_{10}(N_X/N_H) + 12$ for element "X"
- $[X/Y] = \log_{10}(N_X/N_Y)_{\star} - \log_{10}(N_X/N_Y)_{\odot}$
- metallicity: the [Fe/H] value by common usage; all my stars are very metal-poor, or [Fe/H] < –2
- adjectives of various utility:
  - metal-poor: [Fe/H] < –0.5 or <–1.0 maybe,
  - very metal-poor: [Fe/H] < –2
  - extremely metal-poor: [Fe/H] < –3
  - these are mostly qualitative descriptions

detailed spectroscopy of halo stars reveals 1st Galactic element creation events



http://members.nova.org/~sol/solcom/x-objects/lum-halo.htm

Why I will concentrate on metal-poor halo stars



https://ned.ipac.caltech.edu/level5/Pagel/Pagel1_1.html

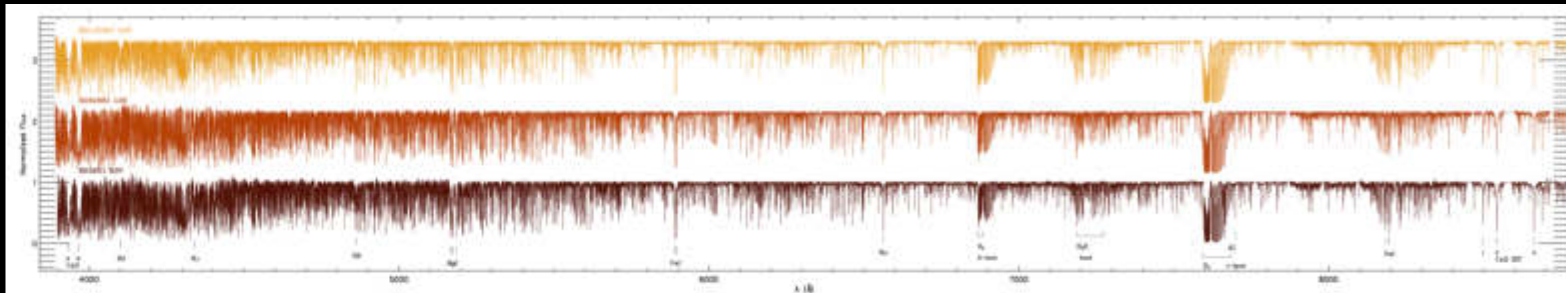
this begins the entire show

all these things come into play to produce the solar system chemical composition

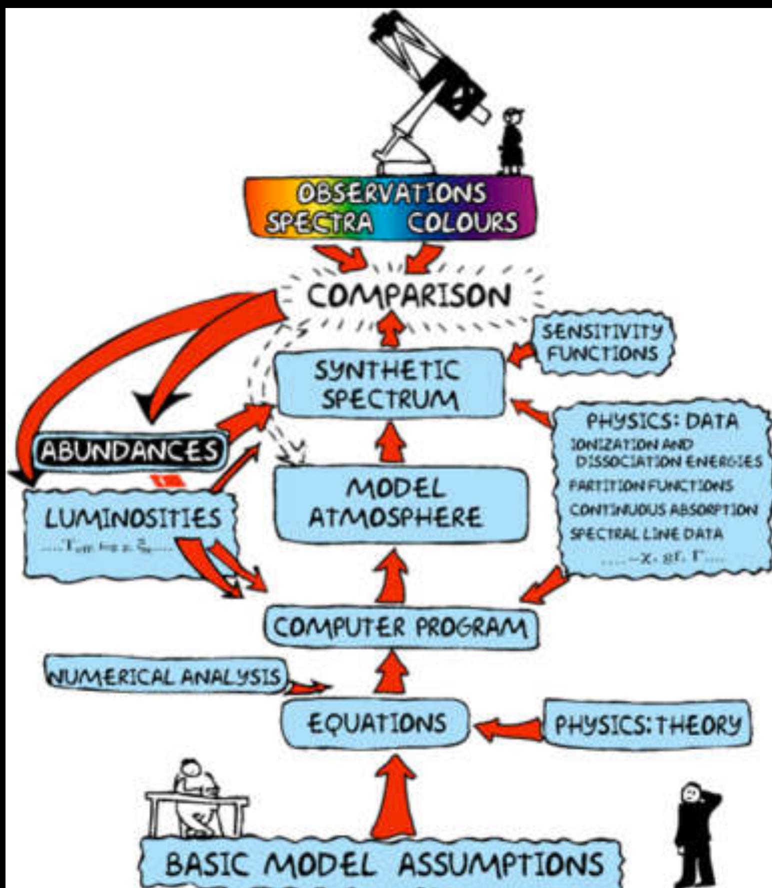
at very low metalicity the scenario is MUCH simpler

exceptions will be noted as needed (e.g., some neutron-capture rich stars)

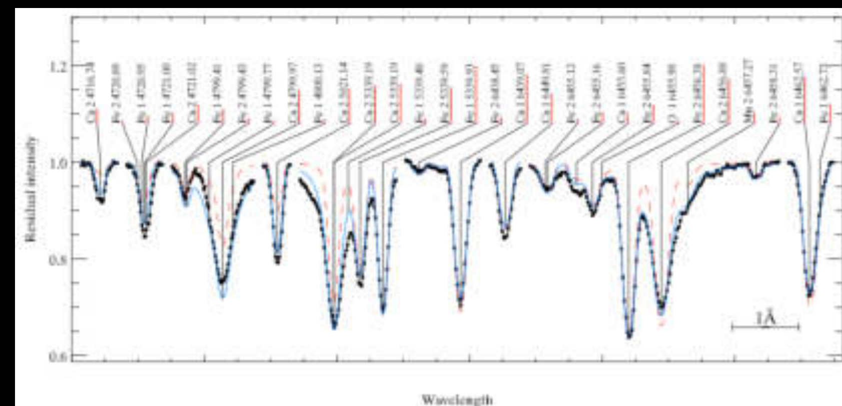
Chemical composition analysis (what I do) in one slide



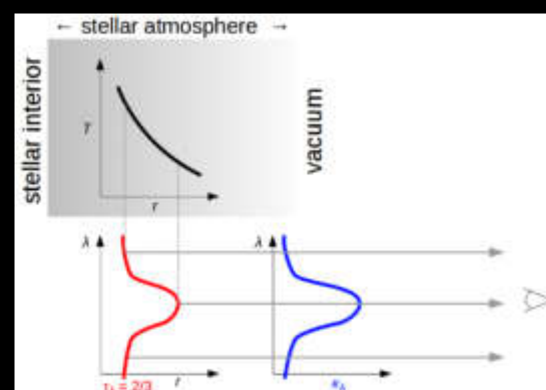
http://webs.ucm.es/info/Astrof/invest/actividad/spectra.html



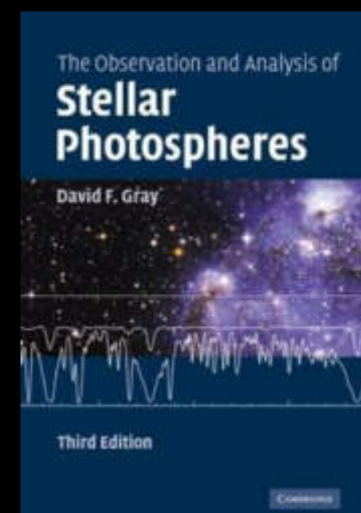
https://en.wikipedia.org/wiki/Model_photosphere (Bengt Gustafsson)



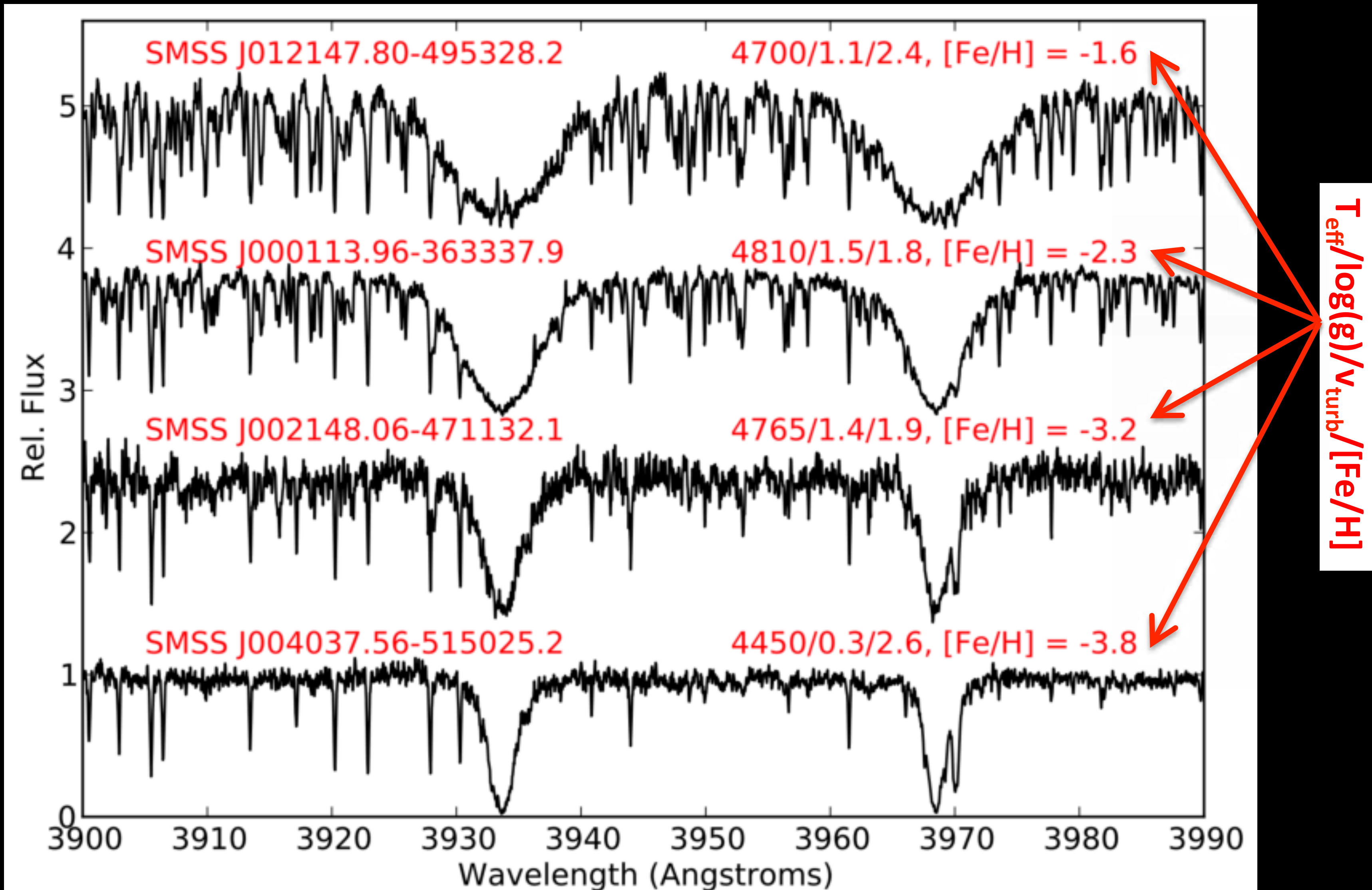
Ryabchikova+ 2005



http://www-star.st-and.ac.uk/~pw31/education.html



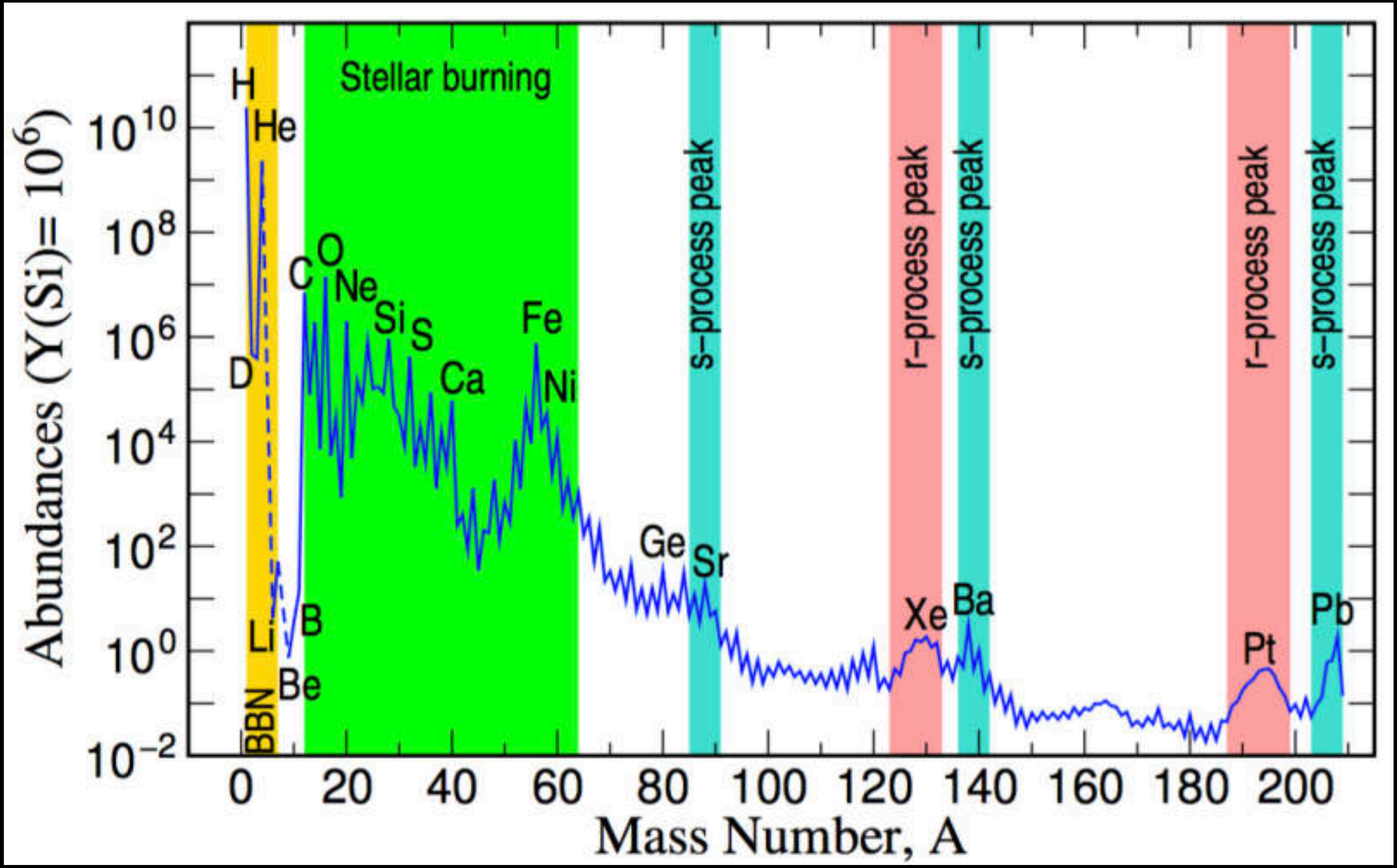
Overall metallicities can be obvious if done well



Jacobson+ 2015

Greater interest in abundance ratios in element groups

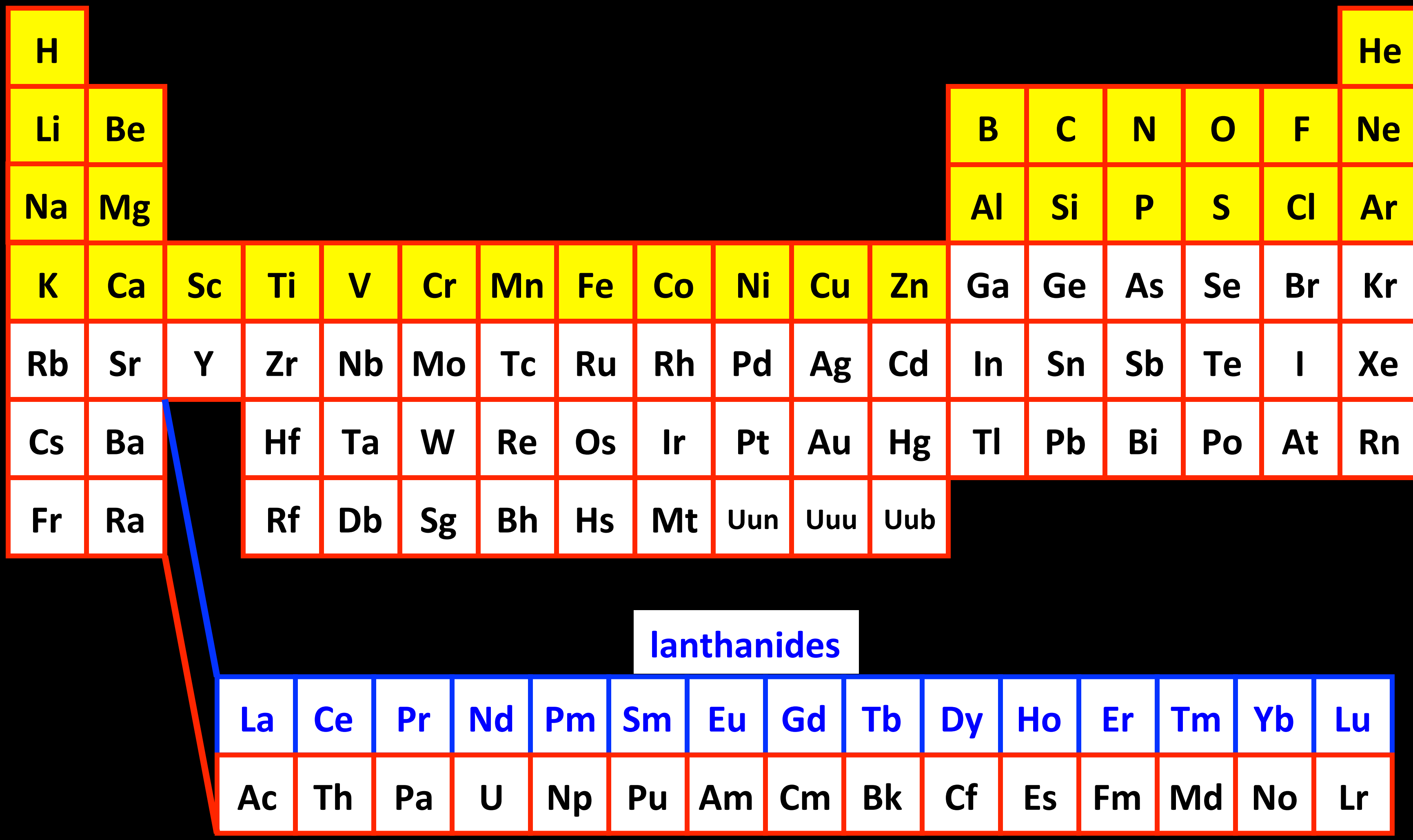
today's focus: neutron-capture and Fe-peak elements



Cowan et al. 2021, RMP, 93, 015002 (arXiv:1901.01410)

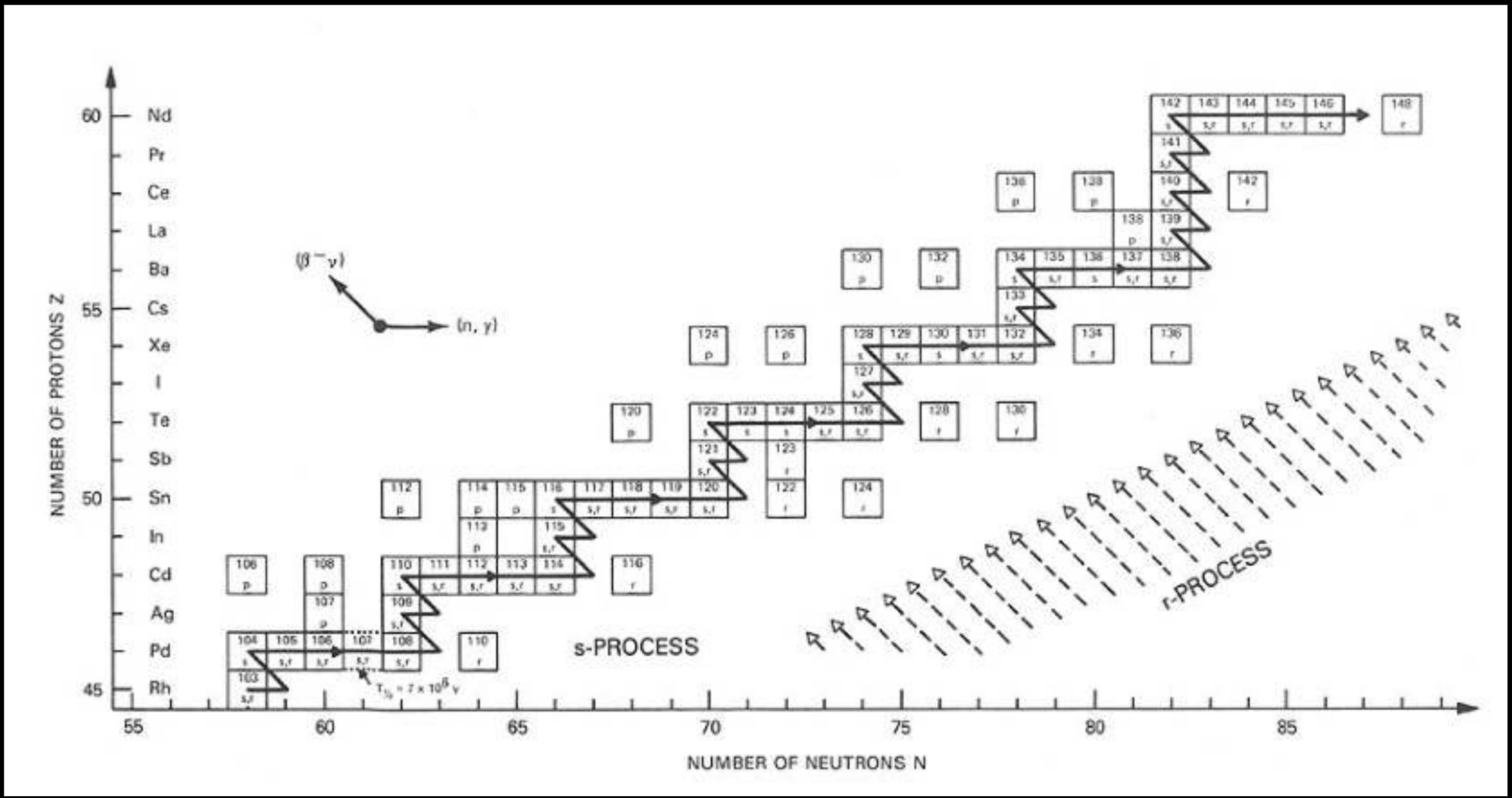
First: neutron-capture elements

usually includes all elements with Z > 30



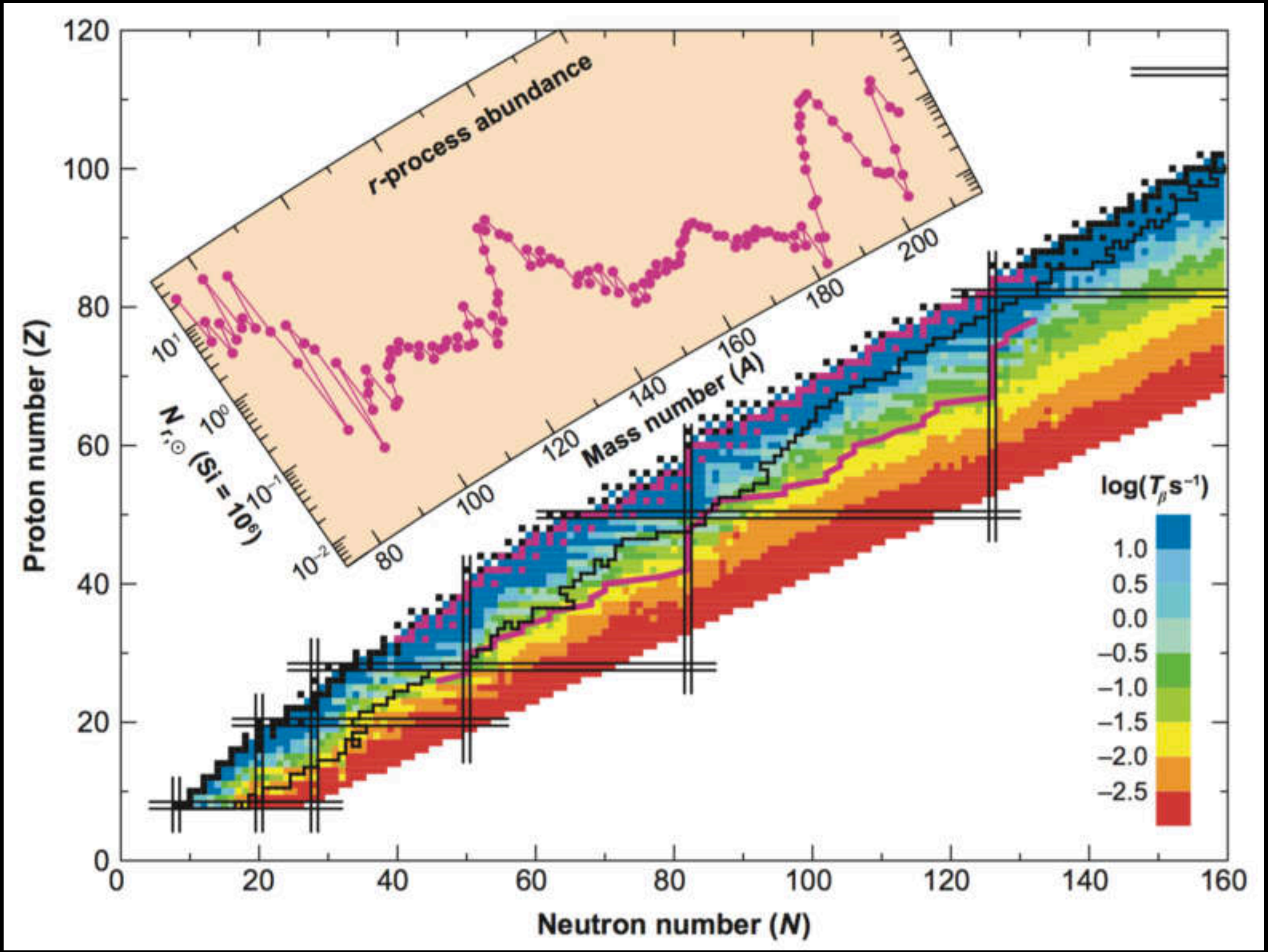
The basic neutron-capture (n-capture) paths

- *these elements can't be made in standard charged-particle fusion:*
  - *Coulomb barriers; endothermic reactions*
- *s*-process: β-decays occur between successive n-captures
- *r*-process: rapid, short-lived neutron blast overwhelms β-decay rates
- *r*- or *s*-process element: ***solar-system*** dominance by r- or s- production



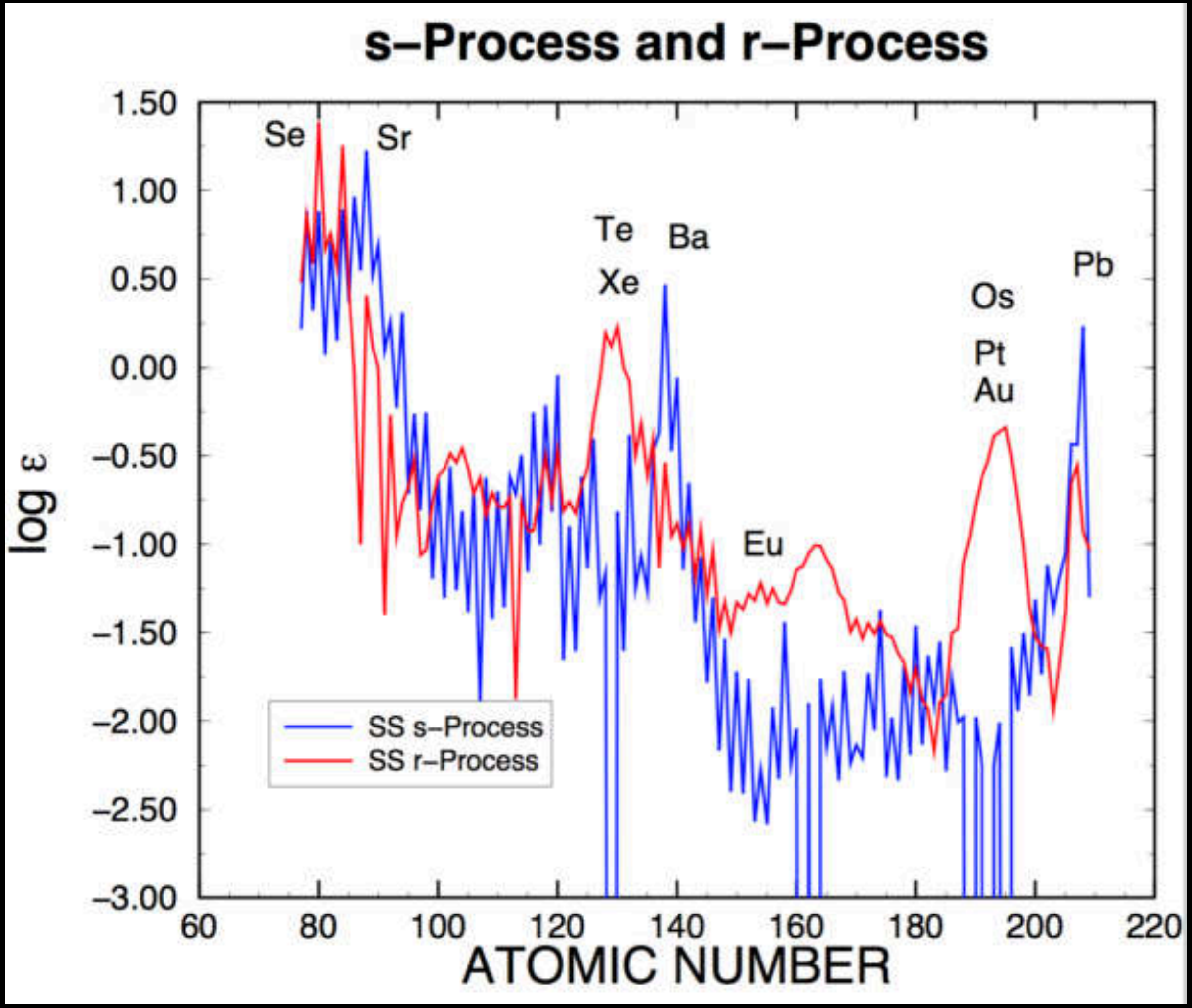
Rolfs & Rodney (1988)

illustrating the *r*-process pathway



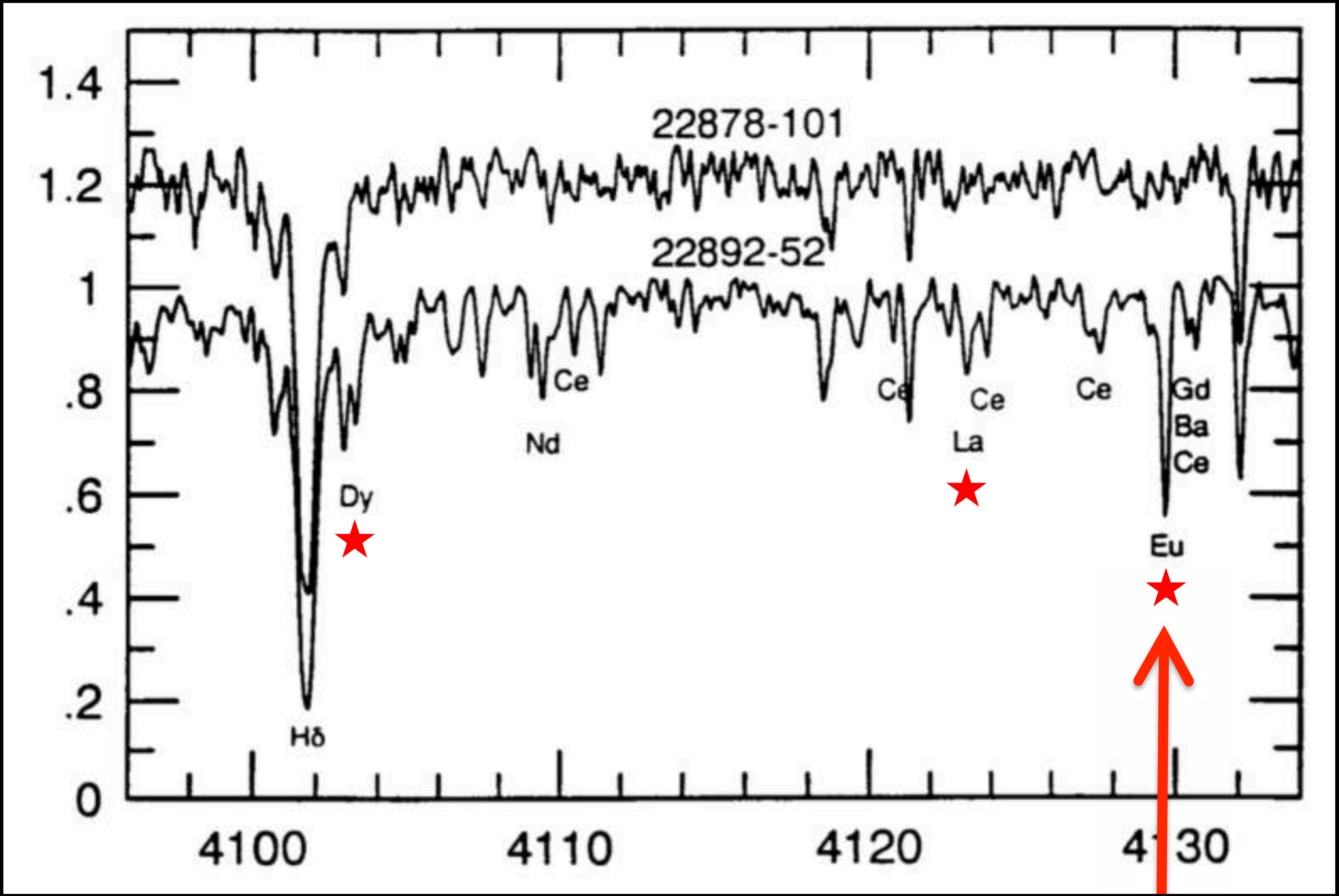
Sneden+08, after Möller+97

here is the solar system *r*- and *s*- breakdown



these two processes each contributed about 50% of solar n-capture abundances

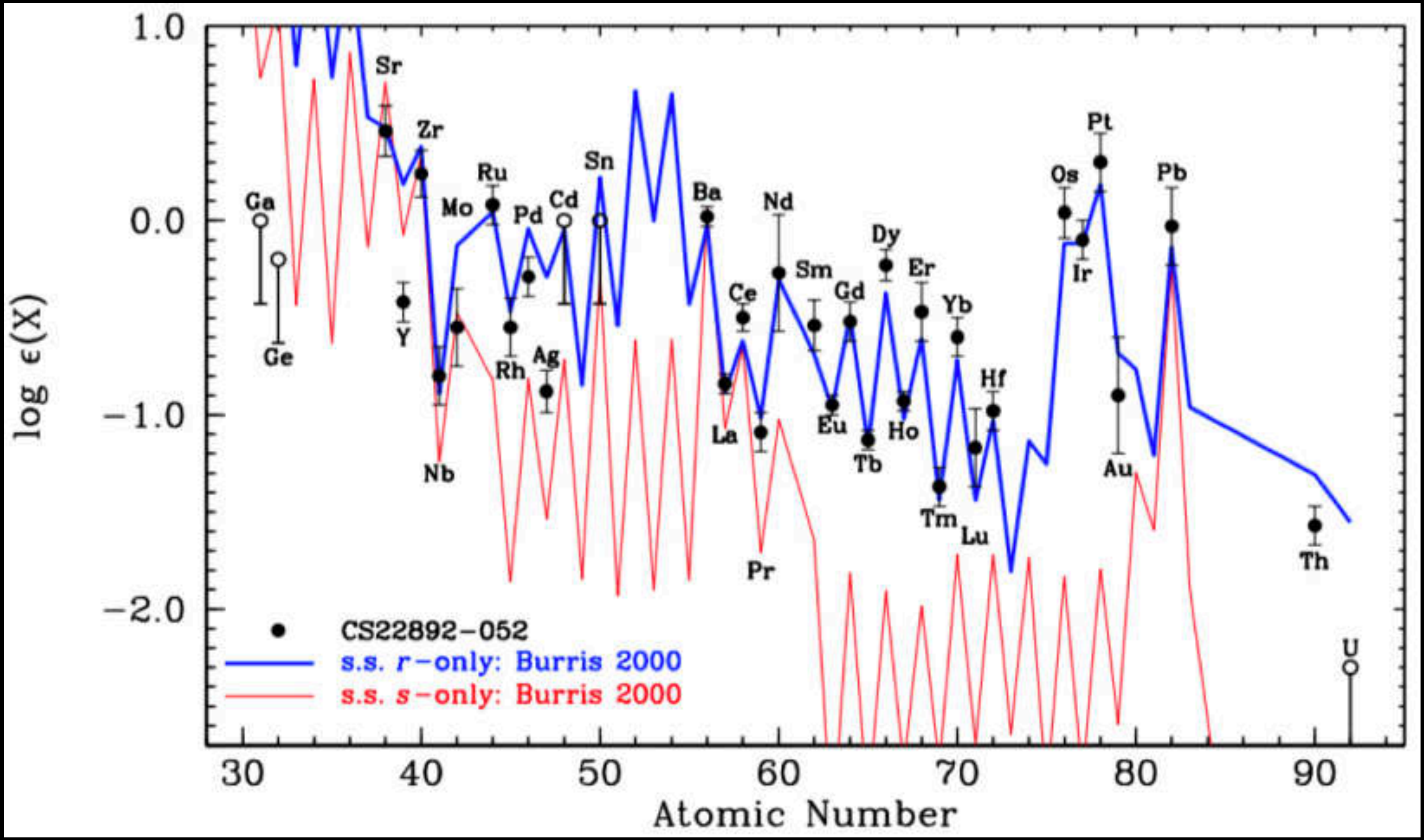
metal-poor stars with *gross* excesses of r-process elments are now well known



Sneden et al. 1994

* Beers et al. 1985, Beers et al. 1992

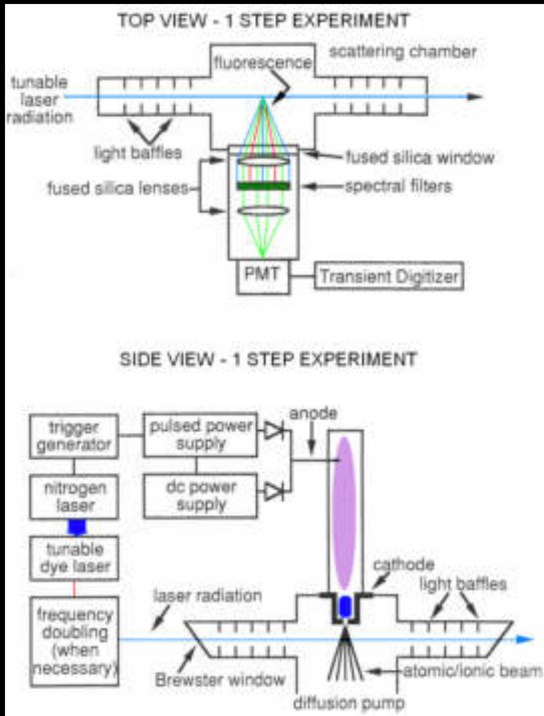
abundances of r-process-rich stars are near-perfect solar system *r*-process matches



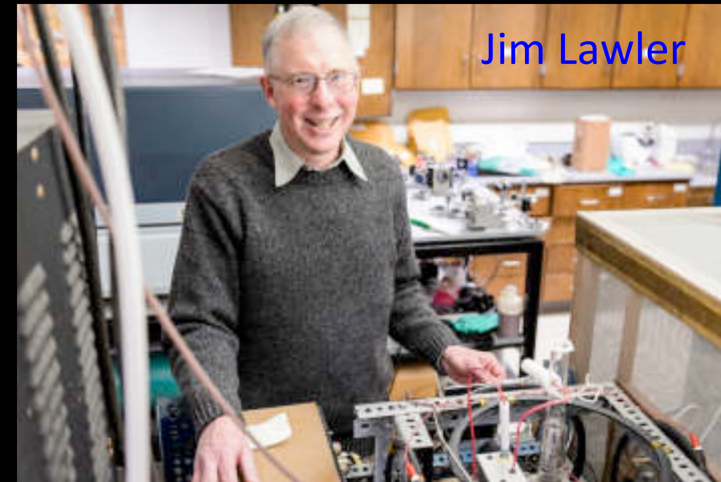
Sneden et al. 2003

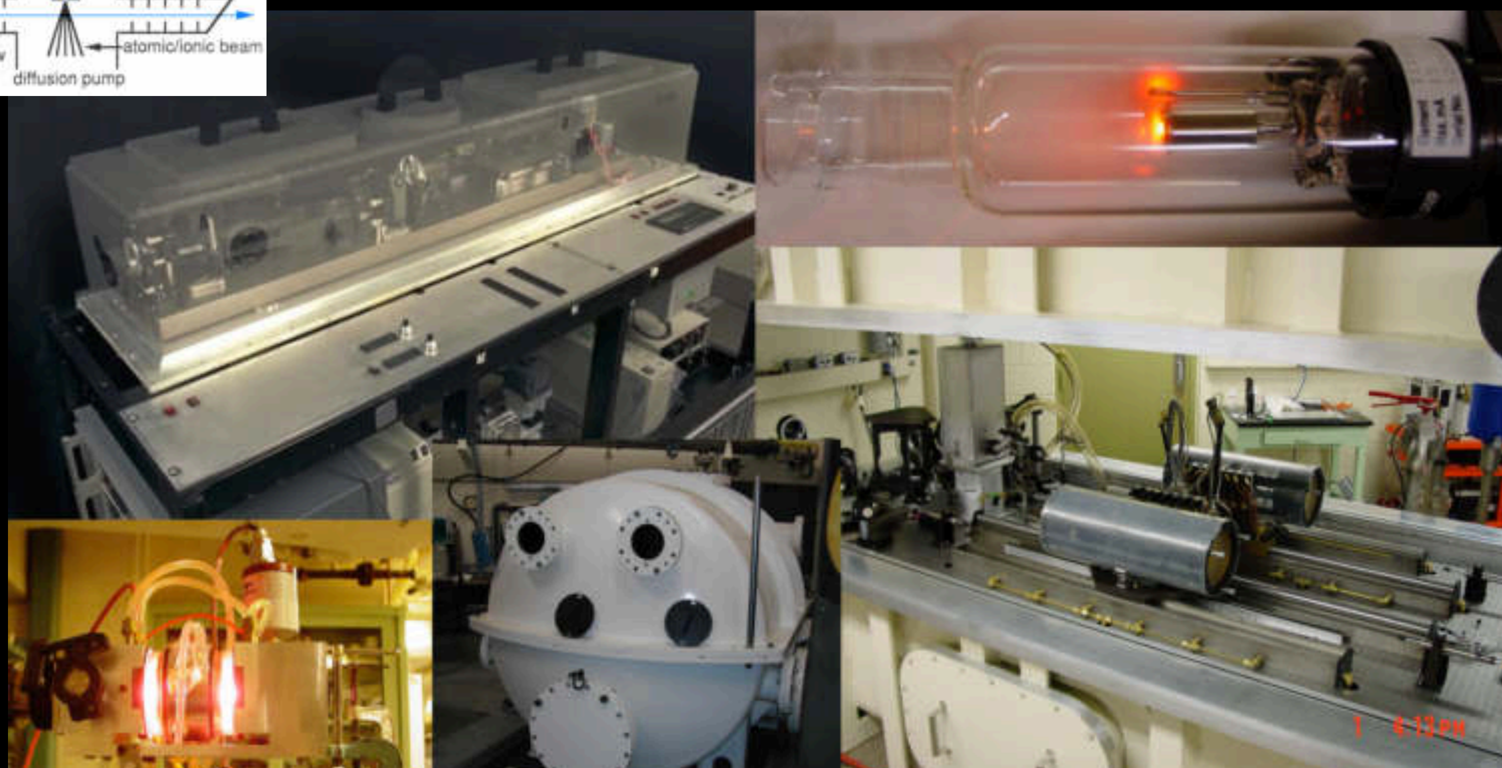
WHY are there so many elements with such good error bars?

(a) bigger telescopes; (b) better instruments; (c) [somewhat] better analytical methods; and **(d) a quiet revolution in laboratory atomic physics** https://minds.wisconsin.edu/handle/1793/78307



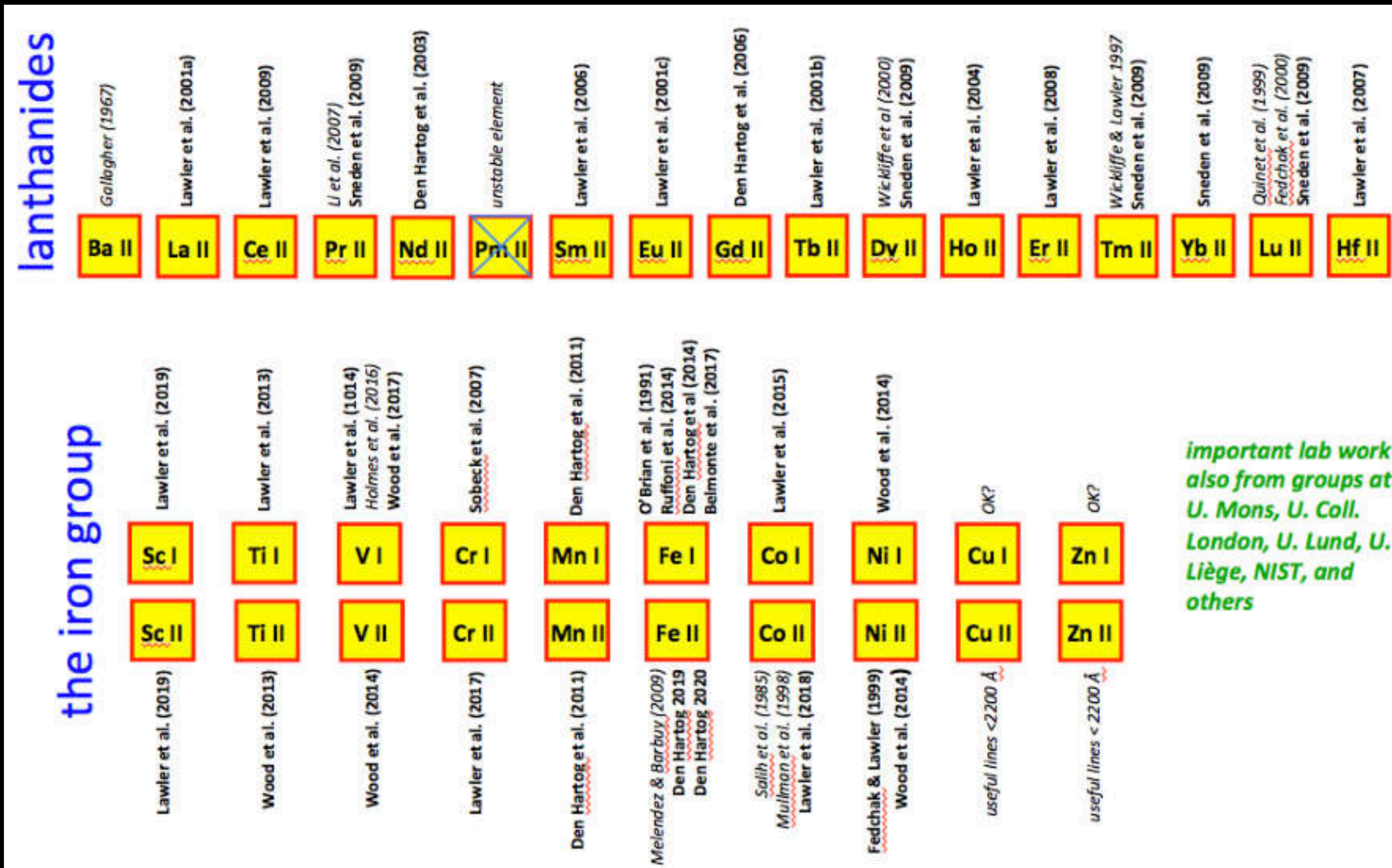
Wisconsin lab atomic physics studies have made major contributions to stellar spectroscopy





https://minds.wisconsin.edu/handle/1793/78313

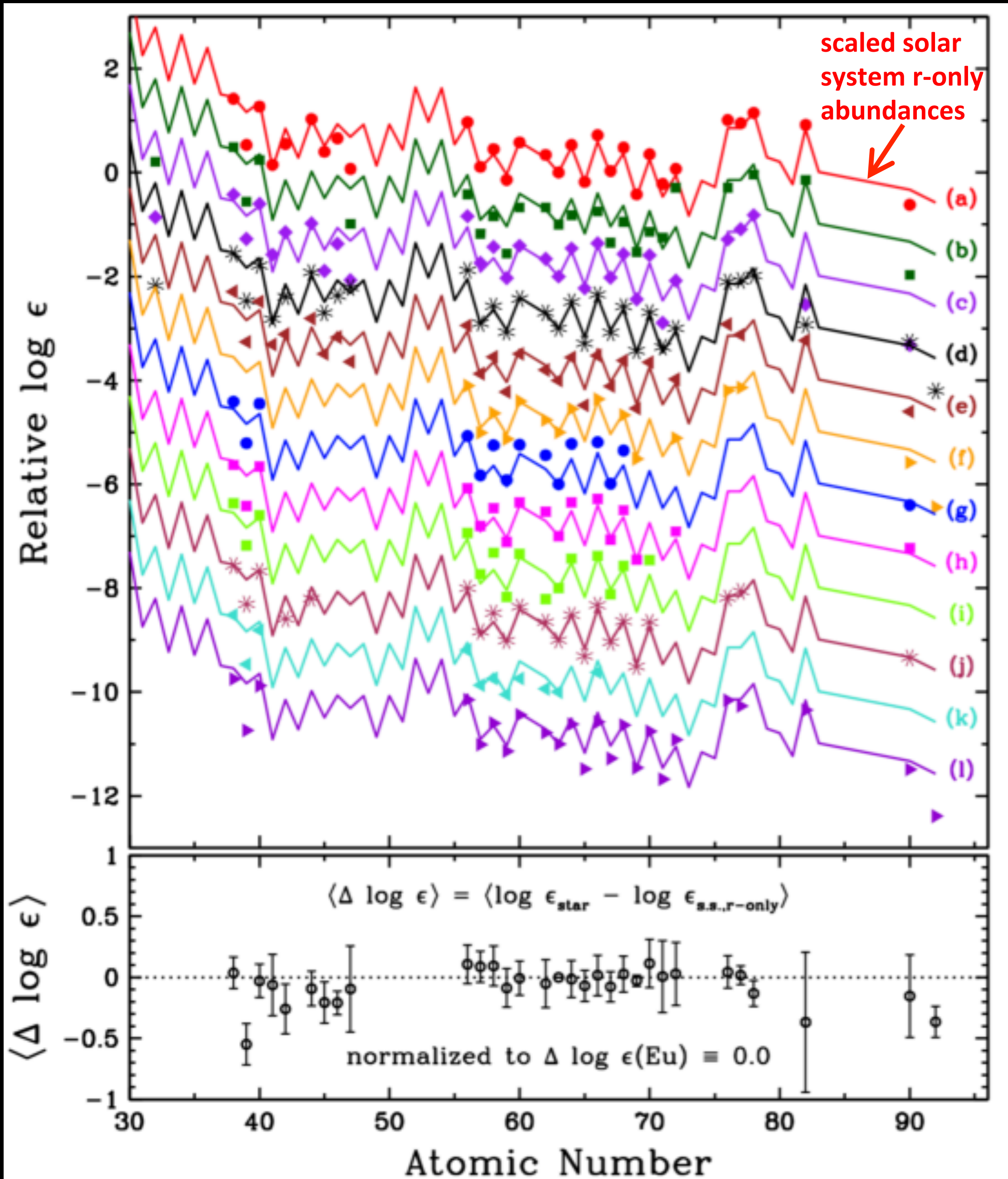
University of Wisconsin lab astro and stellar spectroscopy



Lots of *r*-rich stars are now known ...
here are some highlights

- the overall pattern is boring! Yawn?
- neutron-capture elements: “always” detected???
- Th & U abundances: reliable cosmochronometry?
- LEPP (Lighter Element Primary Process)
- lanthanide-poor but still r-process?
- what are the *r*-process statistics at low metallicity?
- time only to mention dwarf spheriodal n-capture elements

Mozart:
Così fan Tutte ???



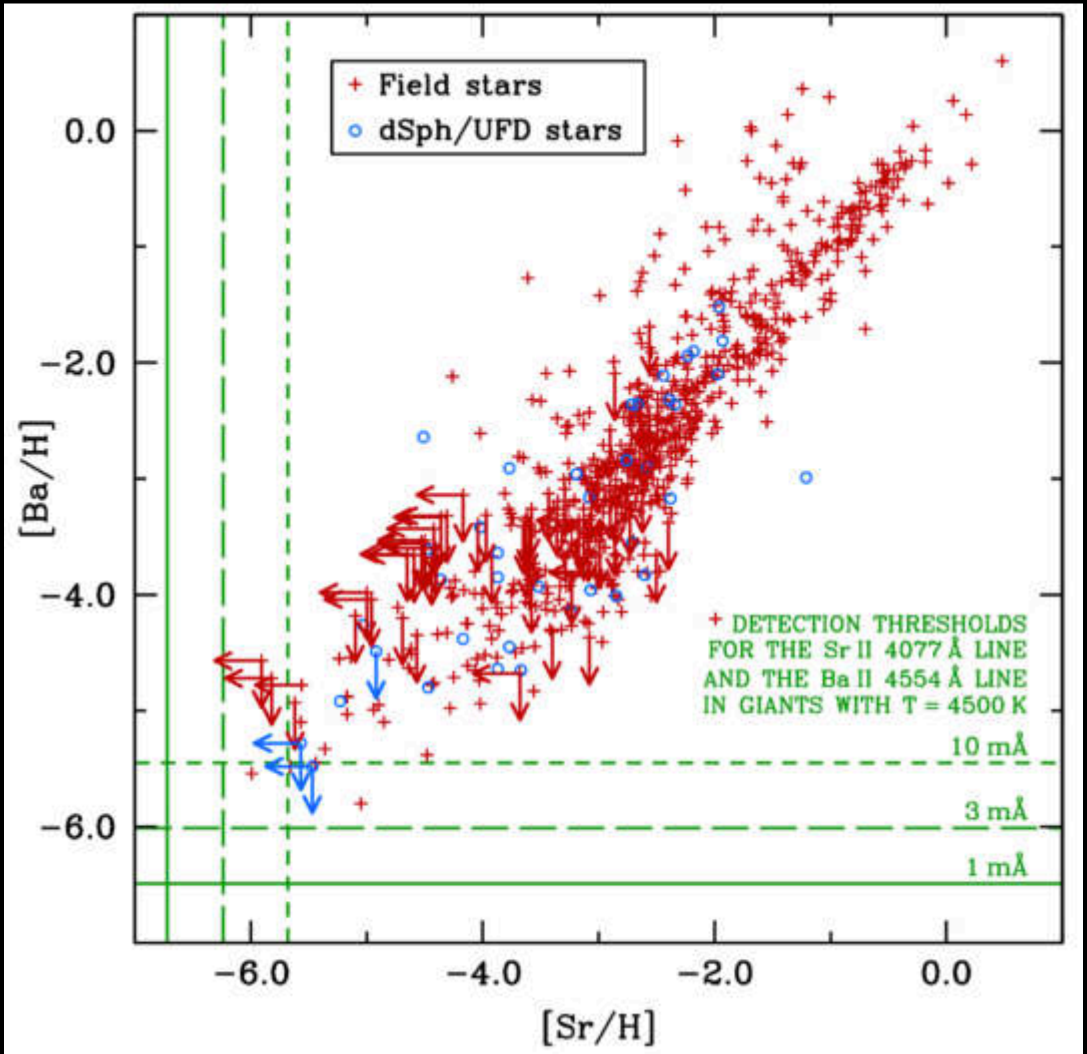
very *r*-rich stars have the same 2nd and 3rd peak relative abundances

upper panel:
13 *r*-II abundance distributions and the scaled solar *r*-process distribution

Lower panel: mean differences with respect to the solar *r*-process

Cowan et al. 2021

How metal-poor do you need to go before there are no neutron-capture elements?

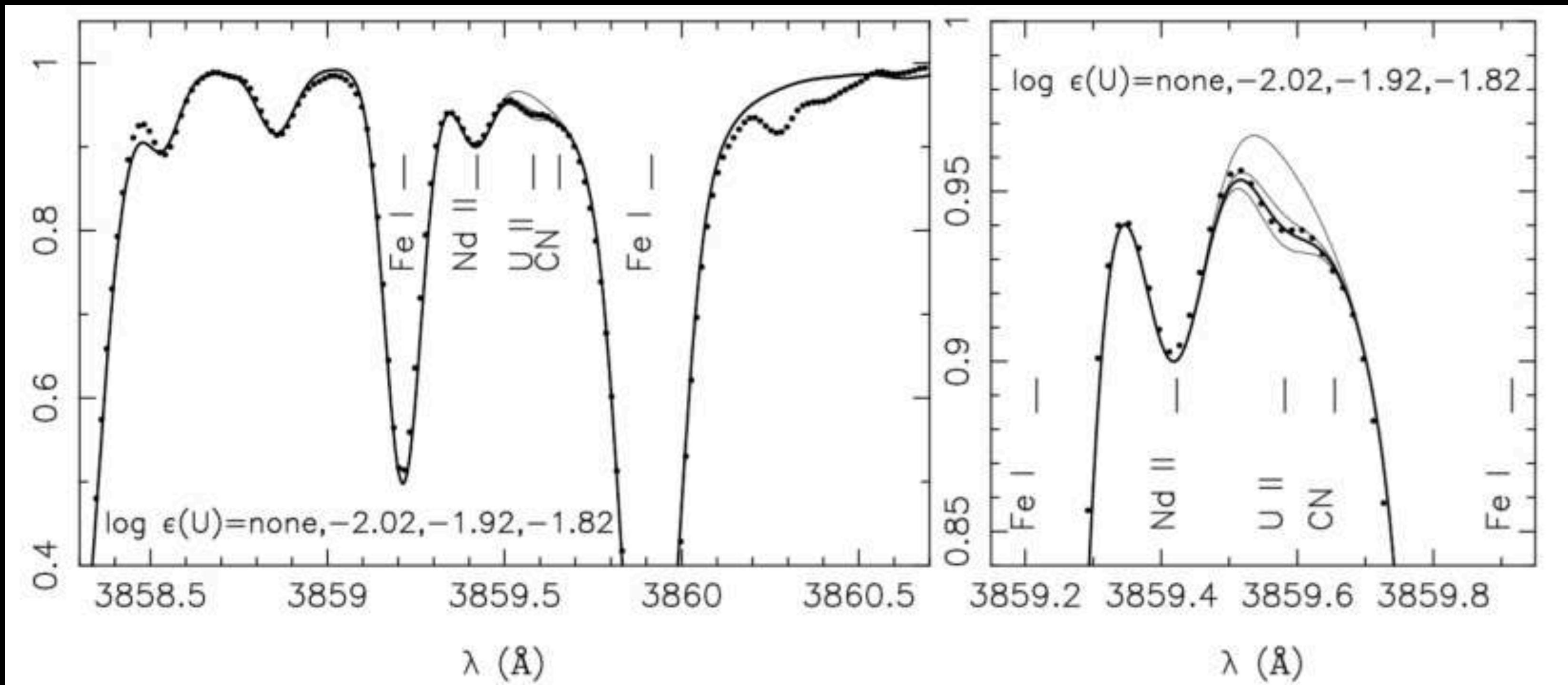


Roederer 2013

see this paper for details, but simply:

if the spectra are good enough, the presence of Sr and/or Ba “always” can be detected in VERY metal-poor stars

uranium detection: vital for nuclear cosmochronometry



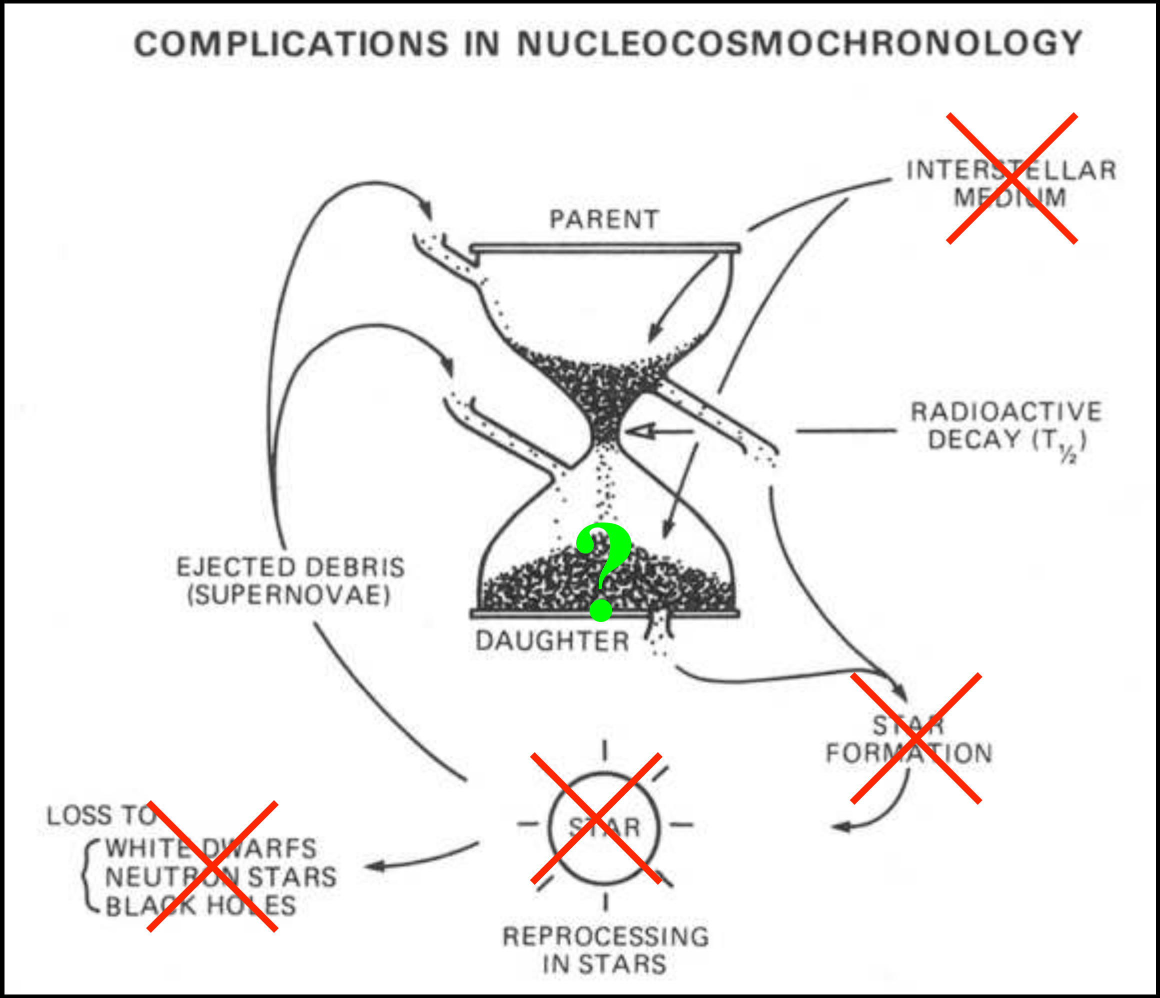
Hill et al. 2002

Too bad! This is a crowded spectral region with many contaminants that must be adjusted to make sense of the spectrum

Also this is in the near-UV spectral region, where stellar fluxes and spectrograph efficiencies are weaker than at longer wavelengths

This line may be the only U II transition strong enough for analysis ???

Radioactive cosmochronometry is *not* complex for metal-poor stars



Galactic chemical evolution effects do not matter for radioactive elements Th and U "frozen" into ***metal-poor stars born near the start of the Galaxy.***

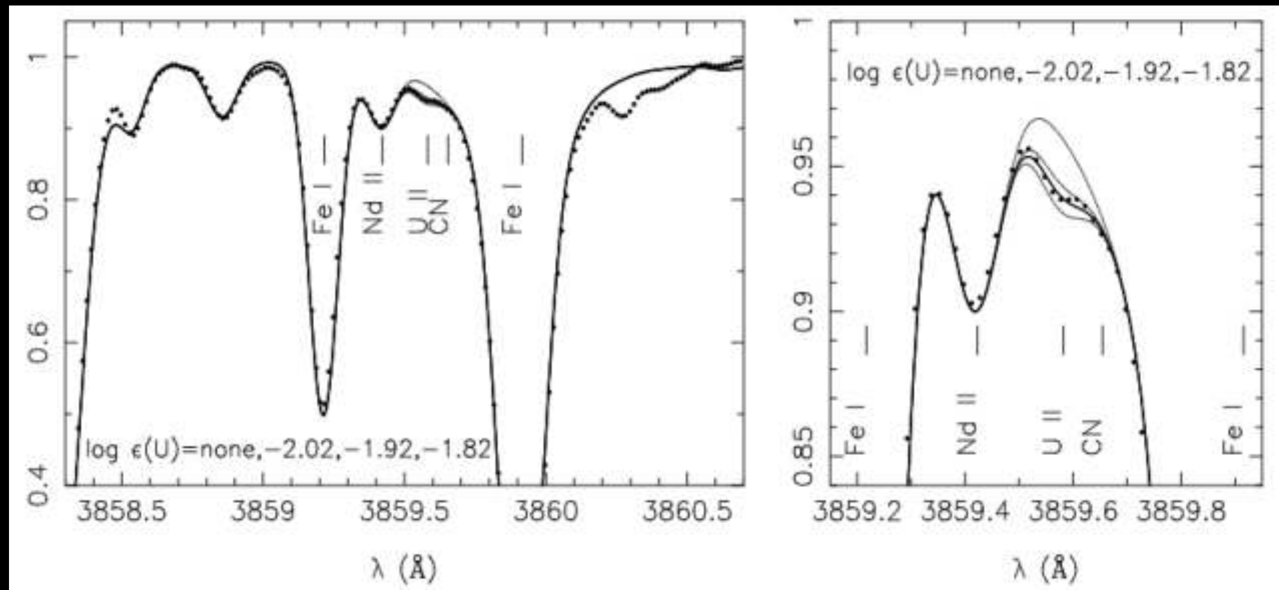
Daughter product Pb is also a direct *n*-capture synthesis product; it is a complex mess!

Rolfs & Rodney (1988)

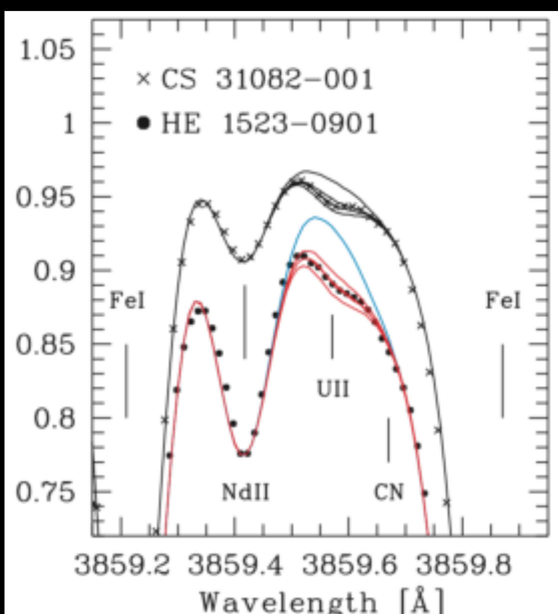
some uranium detections and meaningful limits

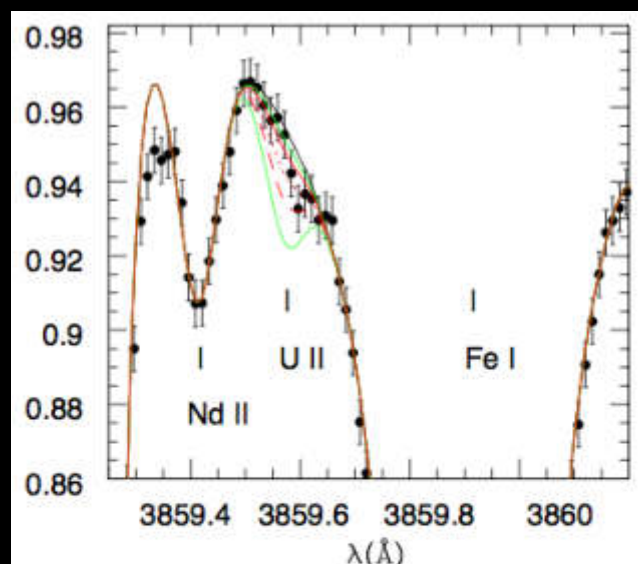
First detection:
- CS 31082-001
- (Hill et al. 2002)

The single U II line:
- it is weak!
- it is blended!
- only with weak CN!



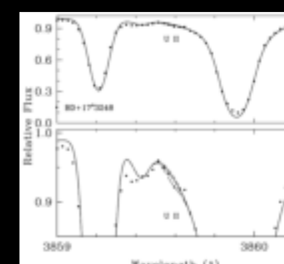
Frebel et al. 2007

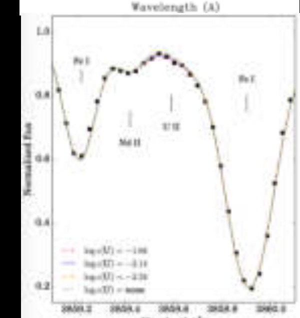




Hill et al. 2017

Cowan et al 2002





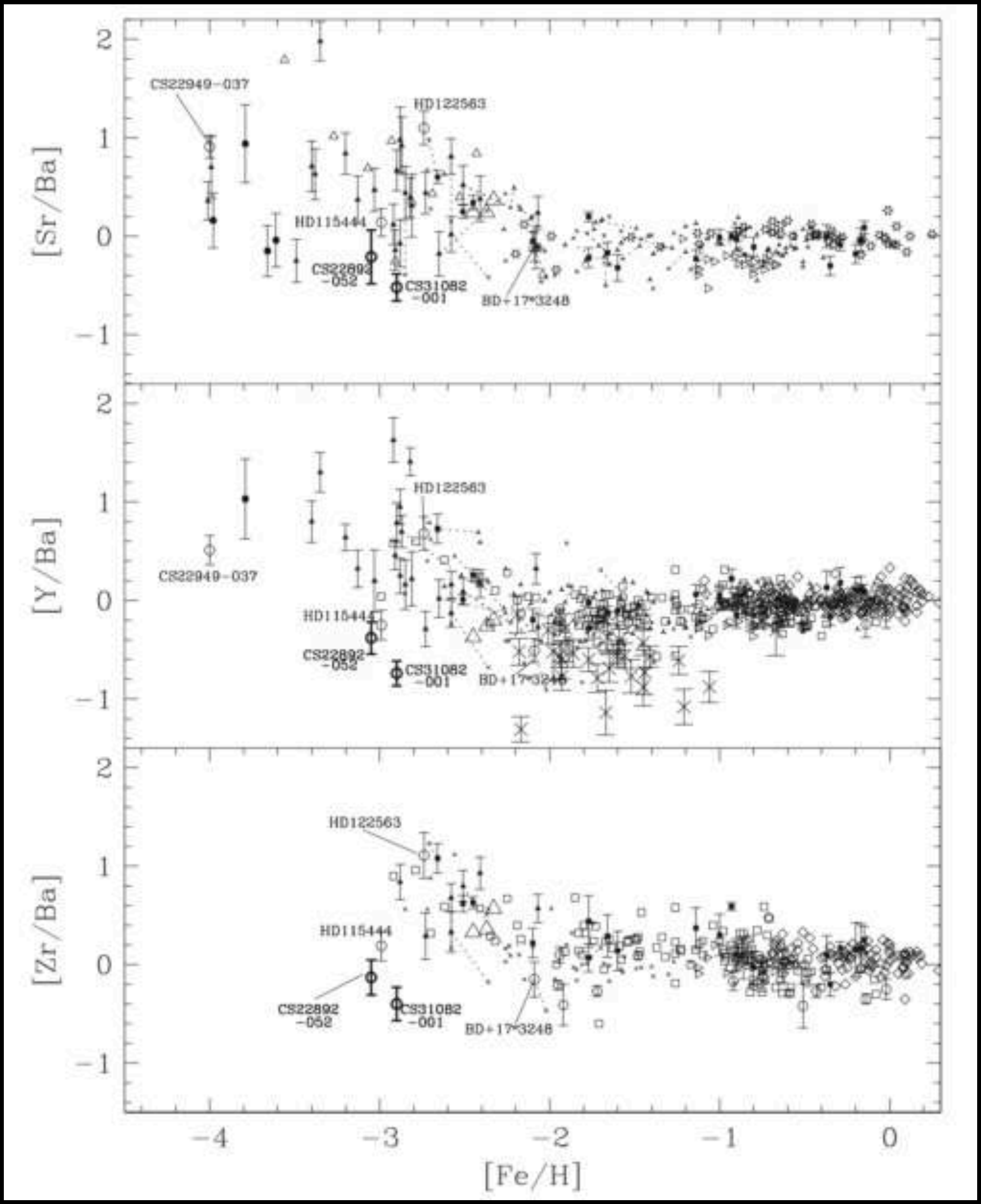
Placco et al. 2017

LEPP: Lighter Element Primary Process

invented by Travaglio et al. 2004 to "*explain*" the scatter of 1[st] peak elements with respect to 2[nd] & 3[rd] peak ones

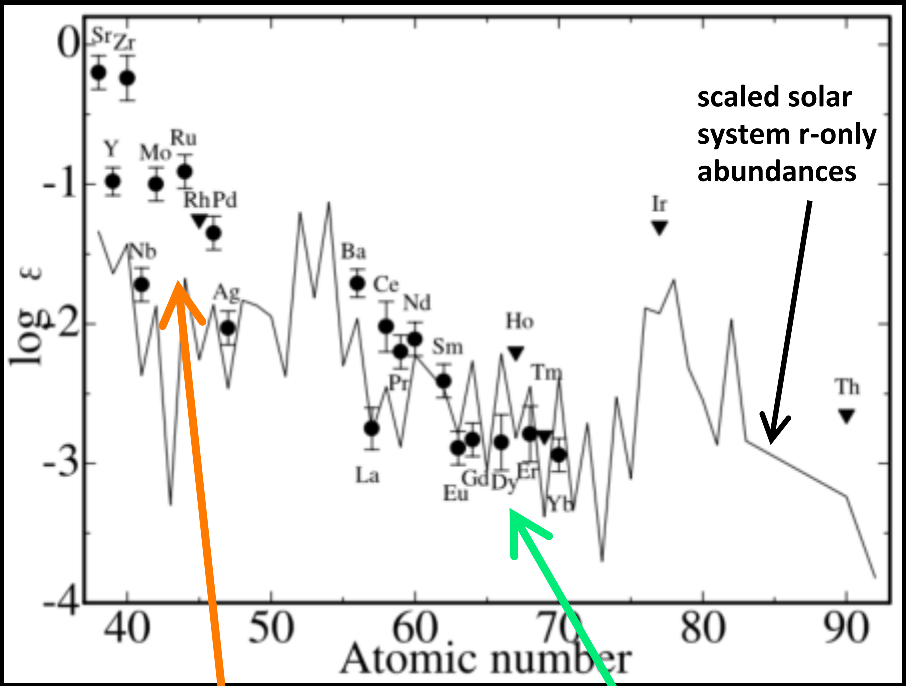
- **"weak" *s*-process?**
- **explosive He-burning?**
- ***i*-process *n*-capture?**
- **neutrino-driven wind?**

LEPP probably is a cover for a number of different nucleosynthesis mechanisms

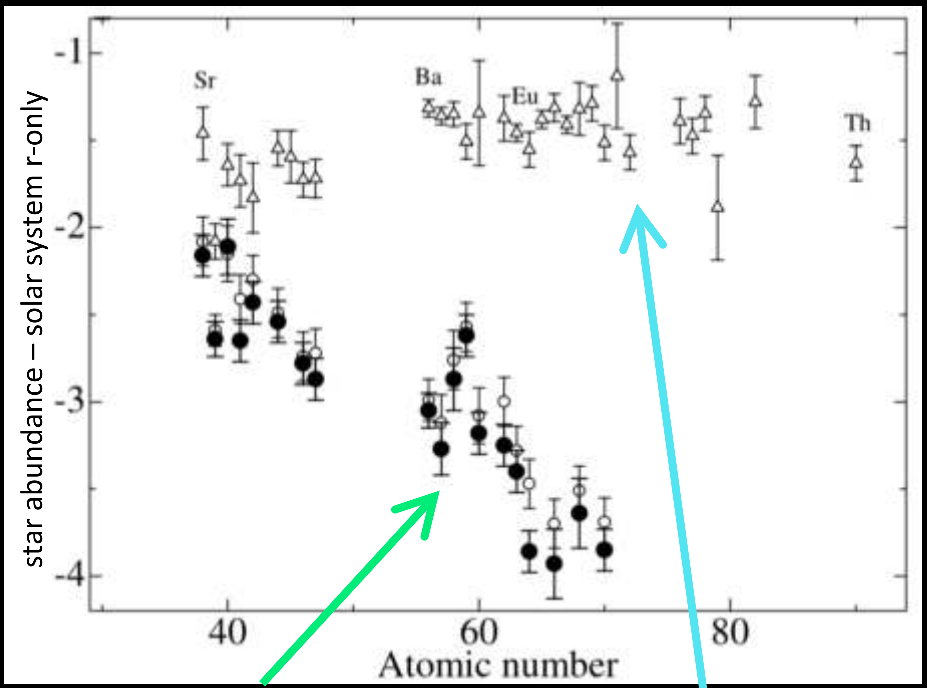


a rare but important low metallicity class identified by close analysis of two well-known giants

HD 88609



HD 88609 & HD 122563



lots of light n-capture elements compared to heavier ones

but a reasonable match to the solar-system r-process pattern

but the r-process is weak and dying in HD 88609 and HD 122563

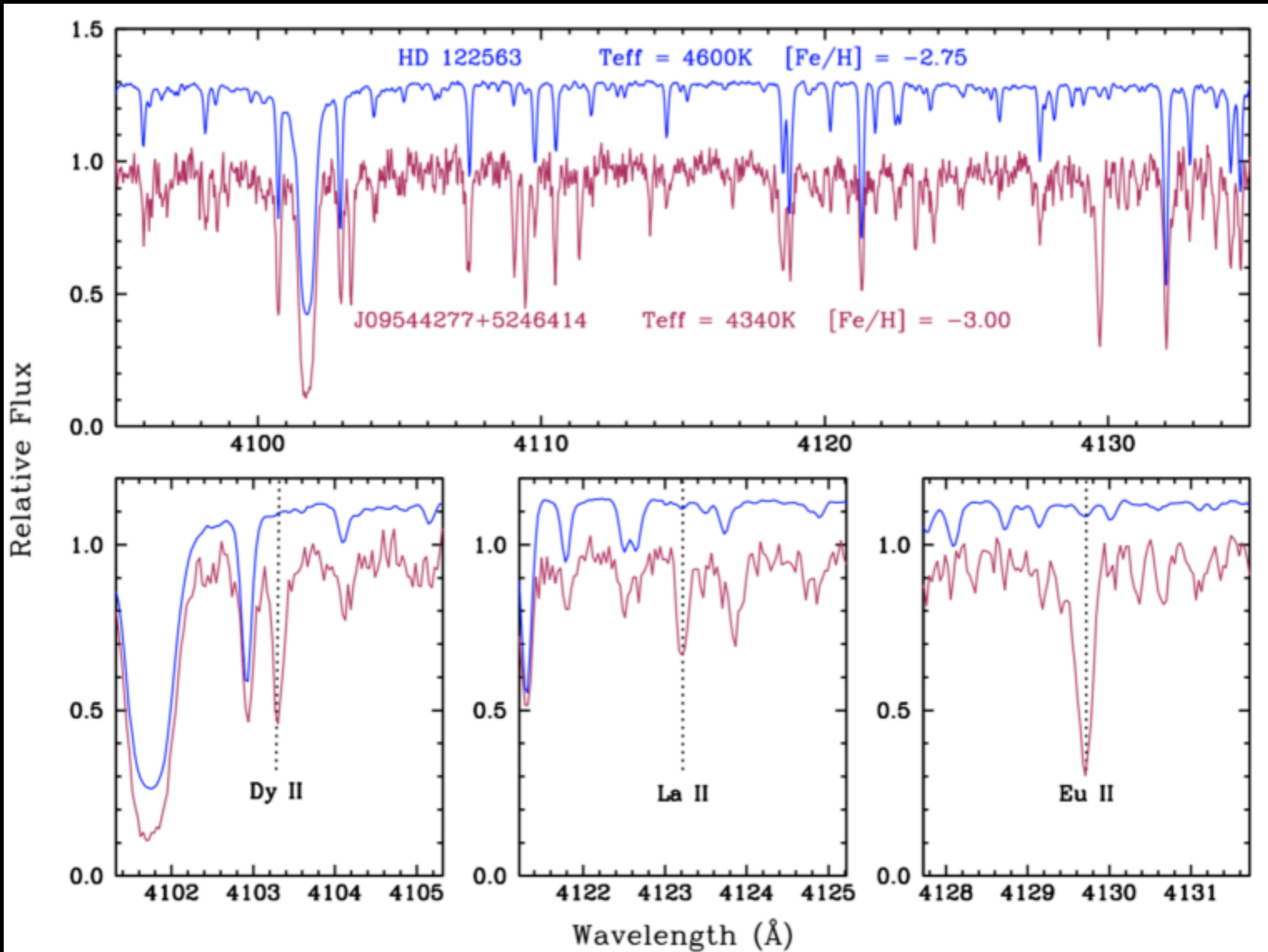
CS 31082-001 (r-rich) is good match to solar system r-only abundances

Honda et al. 2007

The hunt to better understand the r-process: the *R*-Process Alliance (RPA)

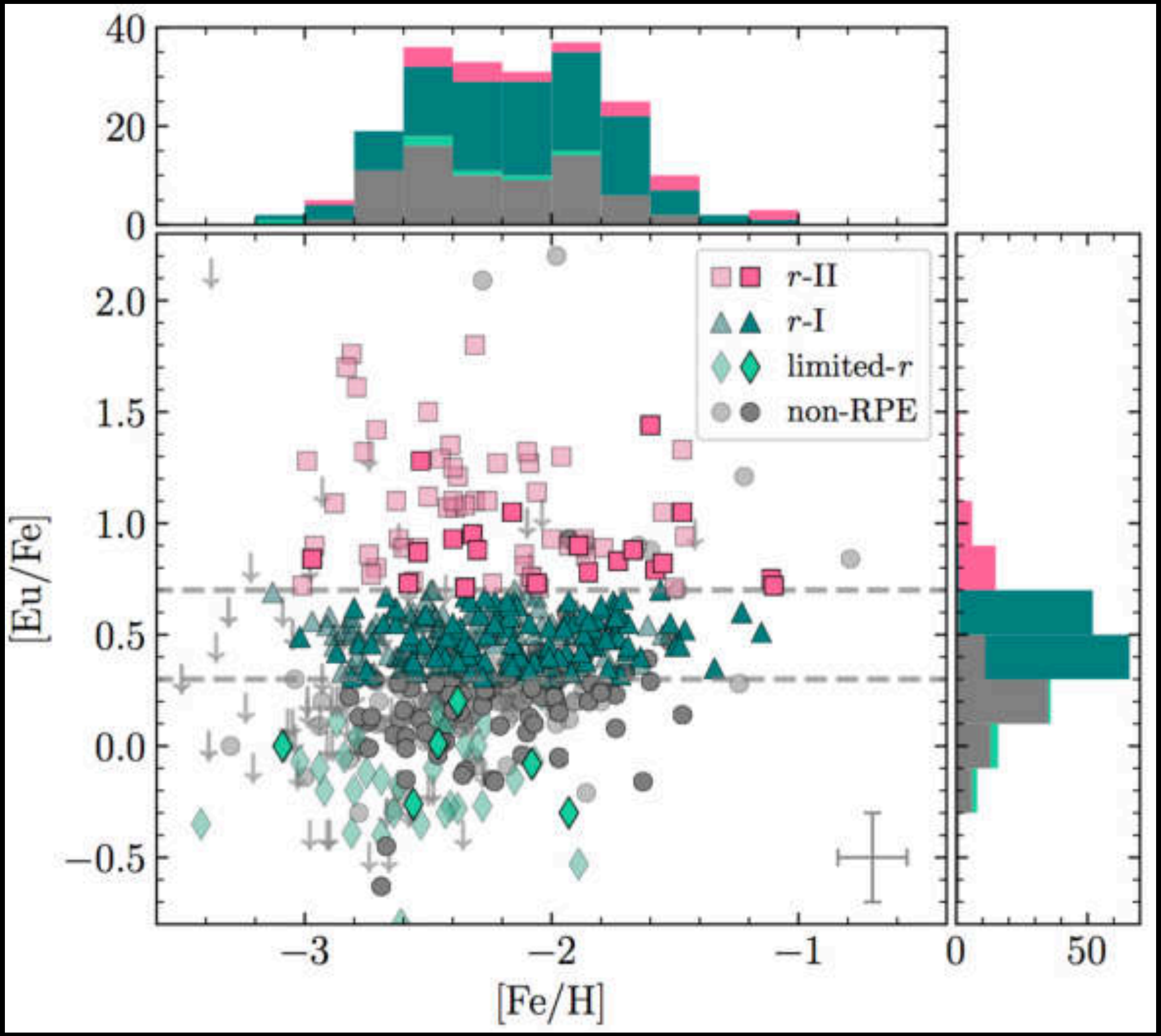
- **combines observations, theory and modeling, and experiments**
- **investigates different aspects of the r-process**
- **first goal: find the true halo distribution of r-process abundances**
- **want *approximate* totals to be:**
  - **100 *r*-II stars: [Eu/Fe] ≥ +0.7**
  - **500 *r*-I stars: +0.3 < [Eu/Fe] < +0.7**
  - **100 *r*-limited stars: [Eu/Fe] ≤ +0.3**
- **these totals can facilitate real statistics for the first time**
- **can potentially lead to more U detections**
- **can try to understand the 1st peak abundance distributions**
- **can look for "imperfections" in the *r*-II abundance sets**

RPA low S/N, high resolution snapshot spectra can easily find r-II stars



the spectrum for Holmbeck+ 2018

RPA so far: Eu abundances in 595 stars



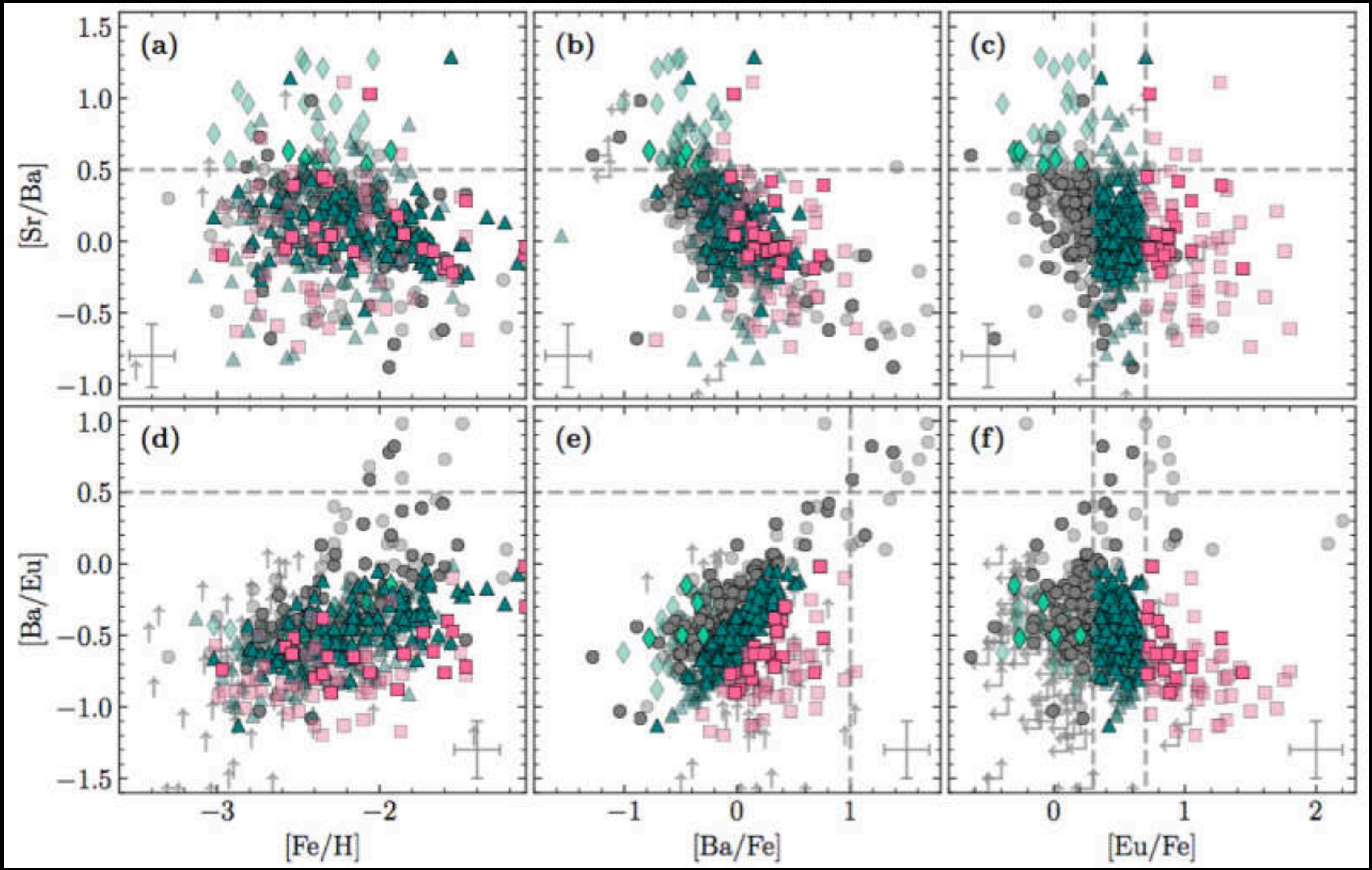
Holmbeck+ 2020

72 r-II stars

232 r-I stars

(ignore the color shading; it is meaningless for our purposes)

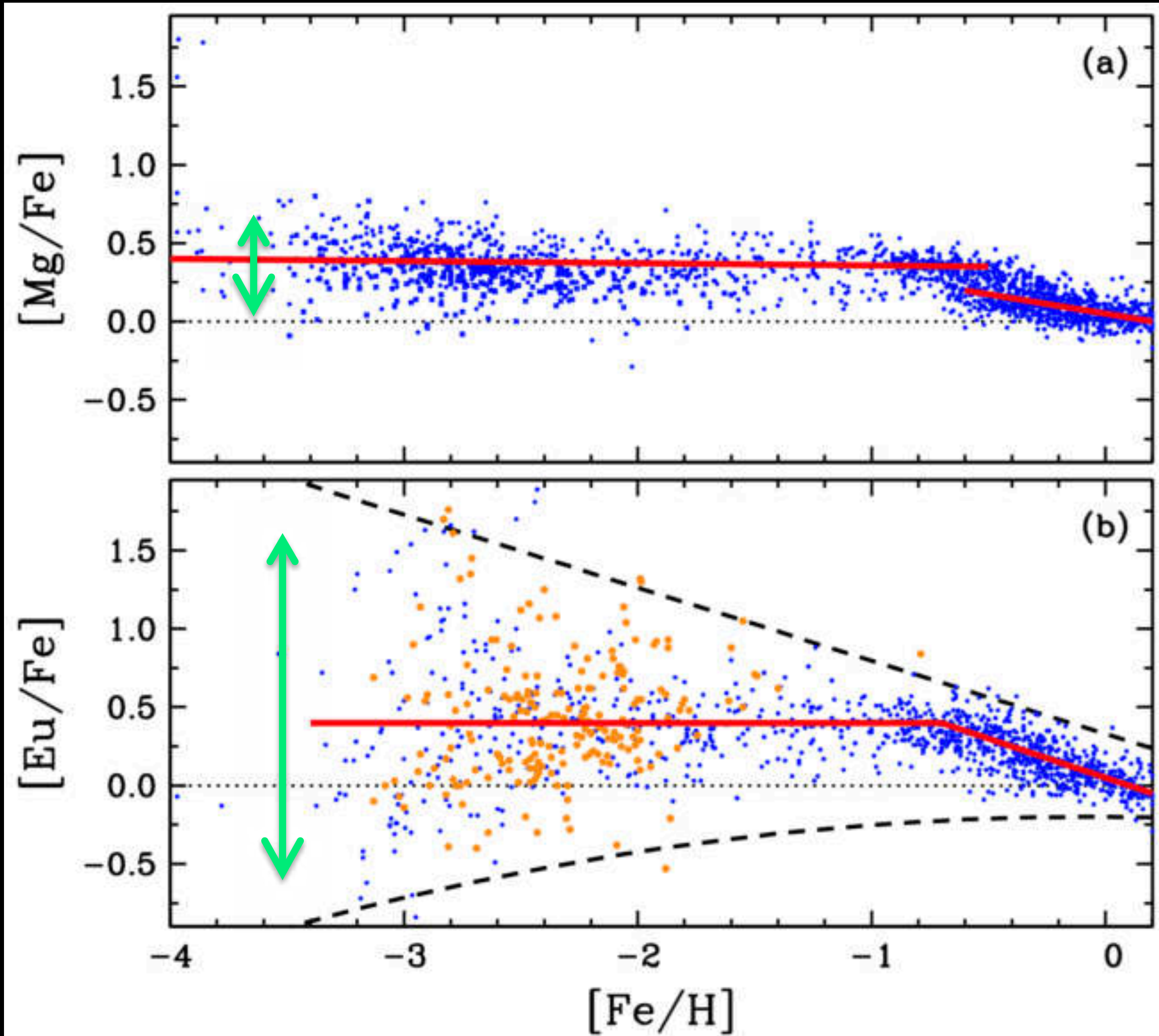
RPA results so far: information for nuclear astro



Holmbeck+ 2020

A simple 1st conclusion: the correlations deteriorate for r-limited stars; the r-process simply has not created all the n-capture elements in these cases

Finally, don't forget this simple, crucial Eu scatter



the 2-dex [Eu/Fe] spread is now confirmed with large samples

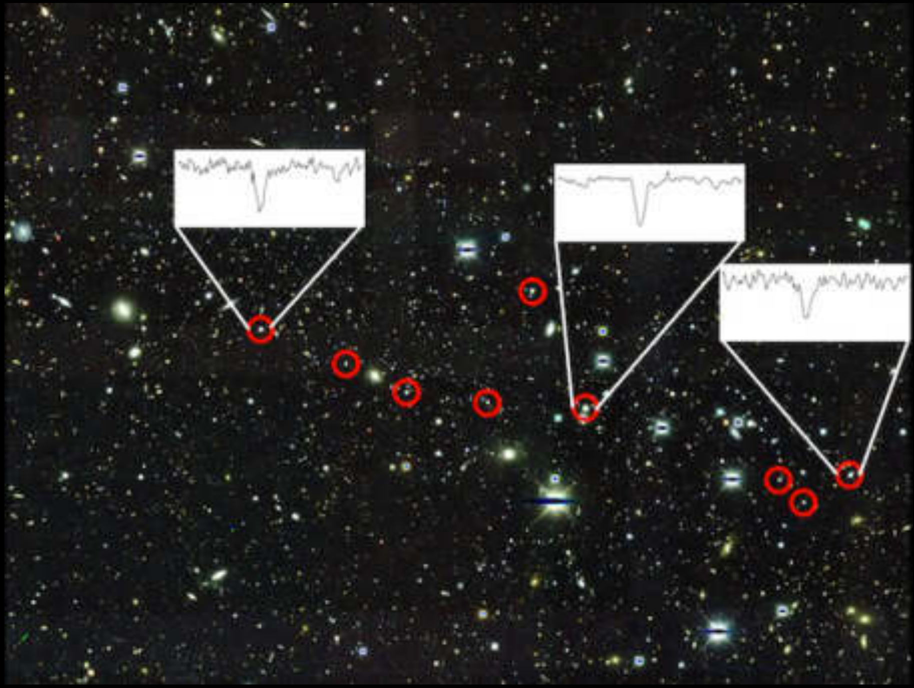
the lack of points for [Fe/H] < –3.4 is probably just a detection issue

note: relatively few stars with [Eu/Fe] < –0.3

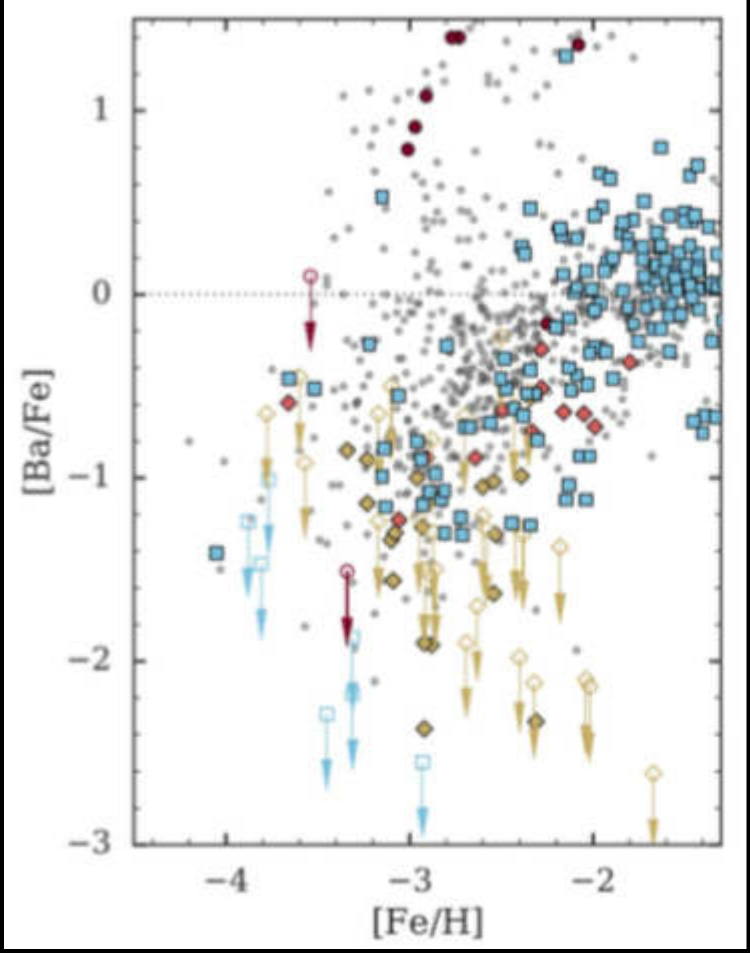
Cowan+ 2021; Hansen+ 2018, Sakari+ 2018 are the orange points

We have no time to talk about dwarf spheroidals and the r-process

Several giants in dSph Reticulum II have large Eu overabundances



Ji et al. 2016

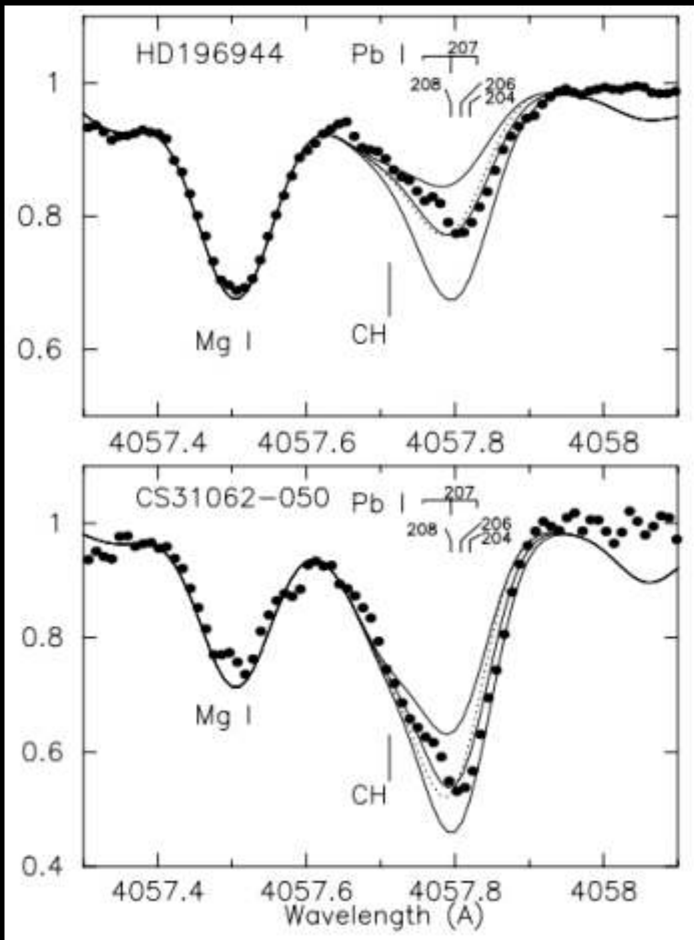


Brauer et al. 2019

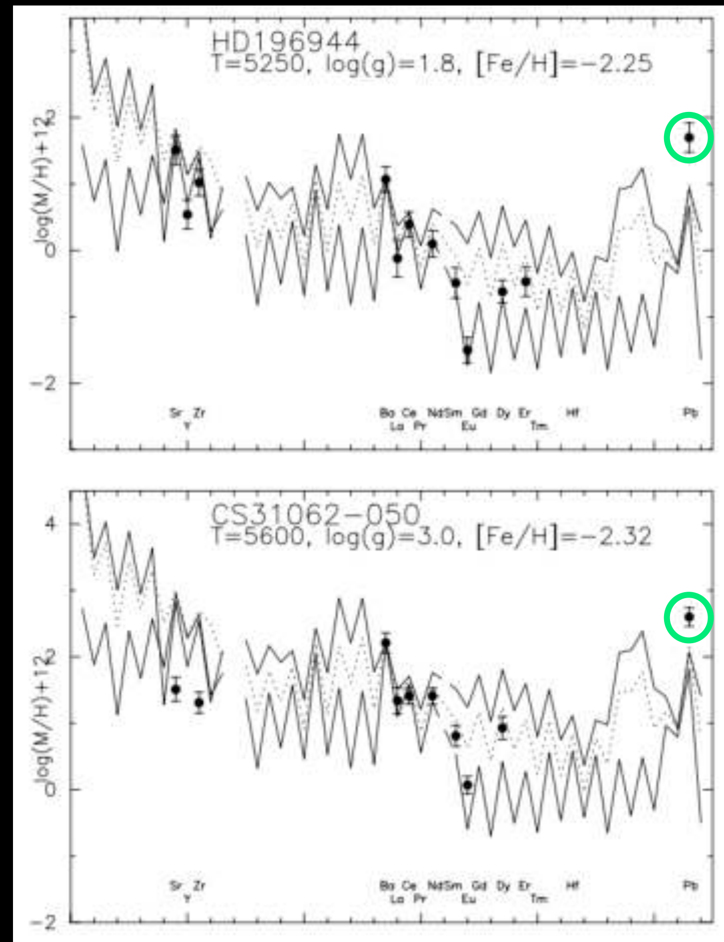
And lots of s-process-rich stars are known

- carbon-enhanced metal-poor (CEMP) stars: many types
- CEMP-s: s-process enriched (lots of Ba, La, Pb)
- most (all) are binaries, with donor star a white dwarf
- s-process means we can model the nuclear burning
- LOTS of modeling knobs to turn
- actually have detected Bi (Z = 83); last stable element
- sorry, no time to discuss the other CEMP subtypes

s-process-rich stars: lead spectra, abundances



Aoki+ 2002



[Pb/Fe] = +1.9

[Ba/Eu] = +0.5

[Pb/Fe] = +2.9

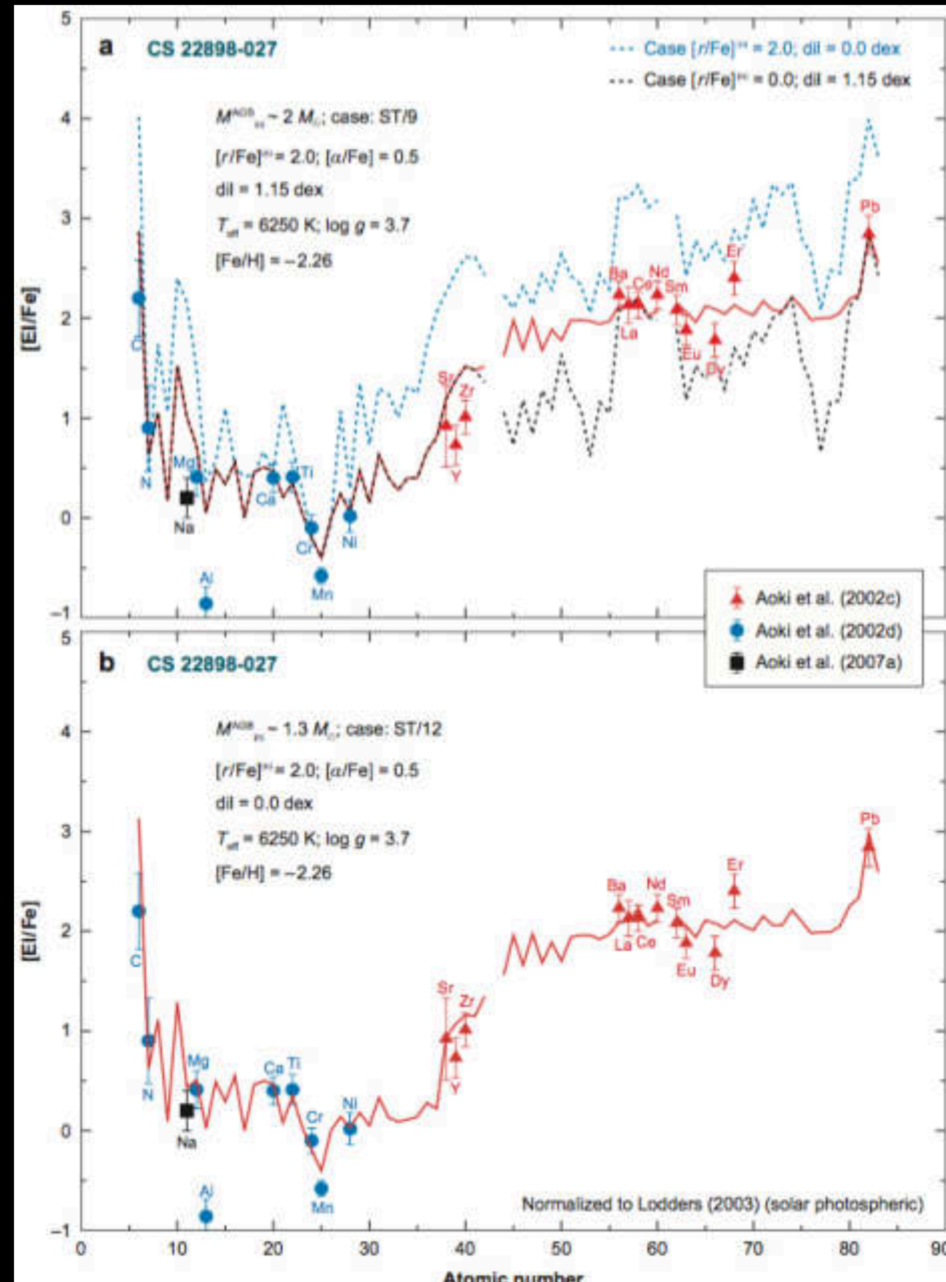
[Ba/Eu] = +0.8

messy syntheses, but do-able

these abundance ratios are typical
in low metallicity s-rich stars

almost more parameters than abundance points

- dilution factor
- donor stellar mass
- ^{13}C envelope pocket size
- metallicity
- r-process addition?
- ratio of light/heavy elements
- CNO abundances
- etc., etc., ...



But the takeaway is simple: rational choices of well understood parameters can lead to solid abundance matches

The Fe-group elements

most abundant elements after H, He, C, N, O;
easily accessible spectroscopically (but ...);
many UV-optical lines in *various* metallicity stars

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

The Fe-group in metal-poor stars? Aren't their abundances well known?
In short: NO!

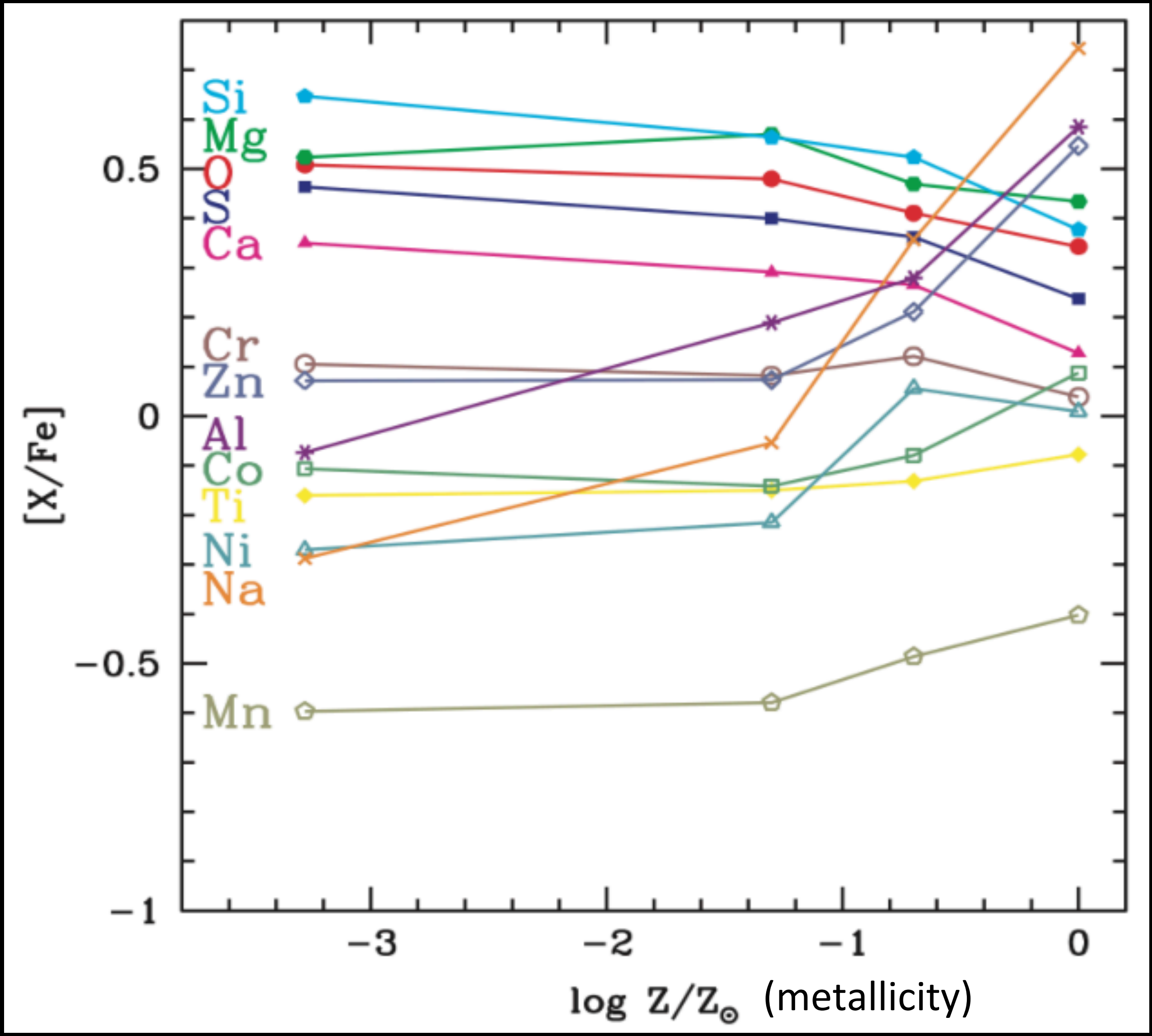
Their abundances can be predicted quantitatively!

Signs that the usual observational results are inadequate

Major recent advances in lab atomic data of useful transitions

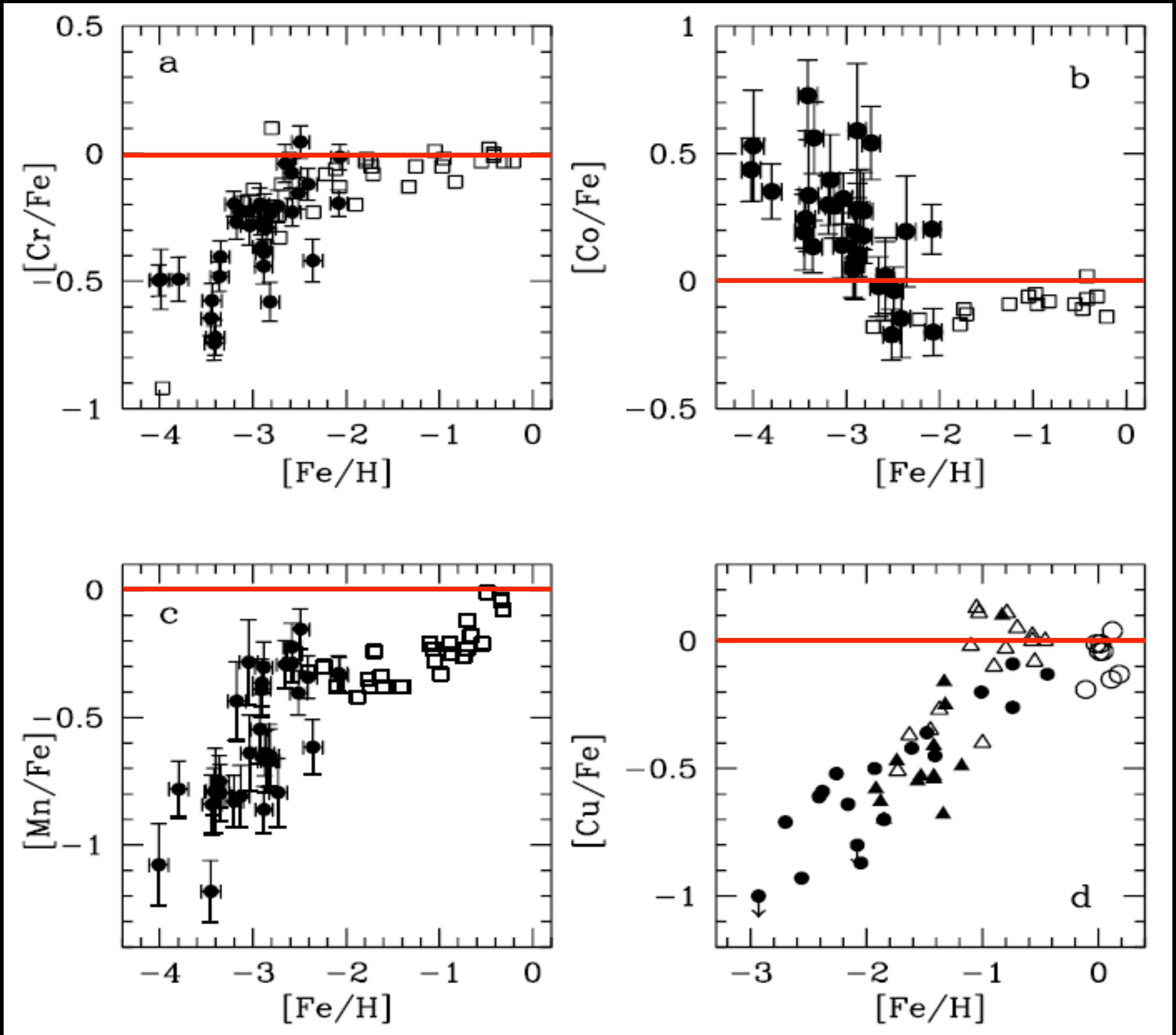
The observable spectroscopic wavelength window has greatly increased

theoretical high-mass star models generate abundances that can be compared to observed trends



Kobayashi et al. 2006

those predictions clash with past claims of non-solar abundance ratios at low metallicity



[Cr/Fe], [Mn/Fe], [CuFe] are very low when [Fe/H] < –2.5

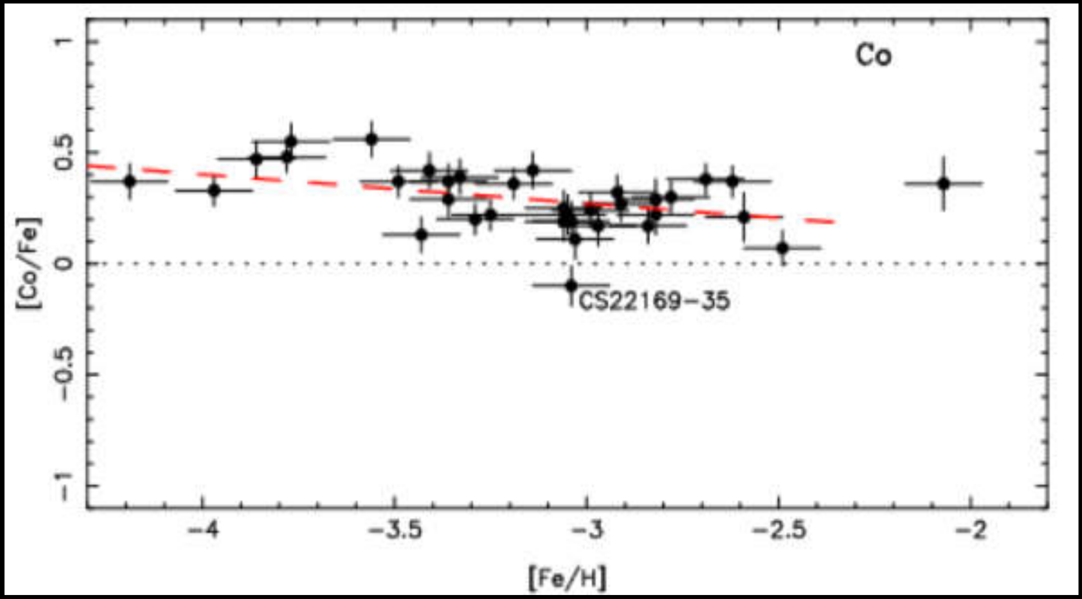
[Co/Fe] is very high

McWilliam 1997, but mostly based on Mcwilliam, Preston, Sneden, & Searle 1995

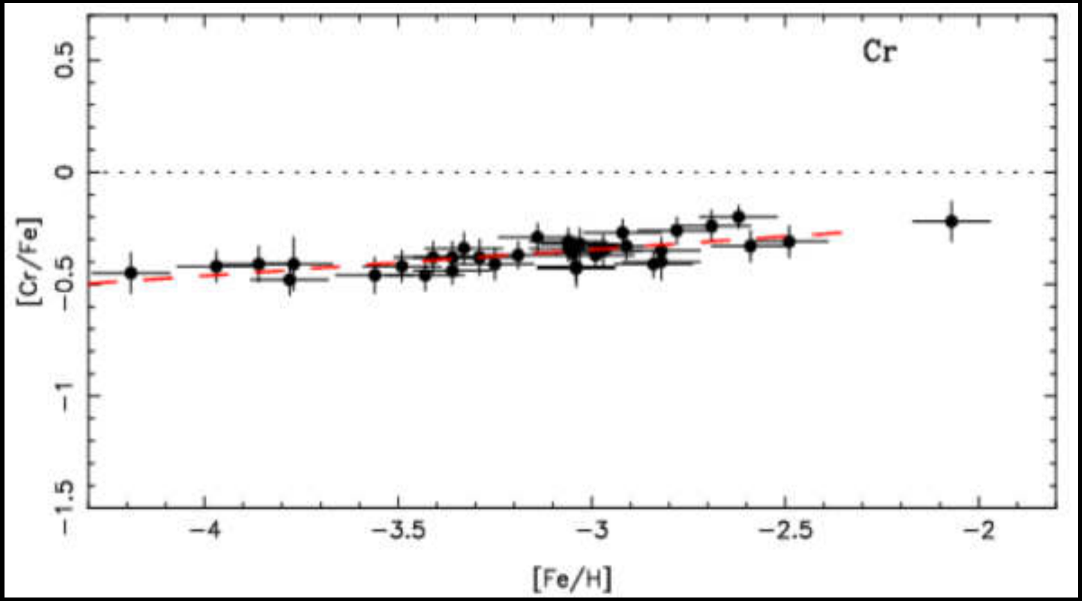
But massive star element synthesis models cannot reproduce most of these observed abundances!

Surveys with better spectra have always confirmed these trends

McWilliam+95 led to other surveys with better spectra



Cayrel et al. 2004



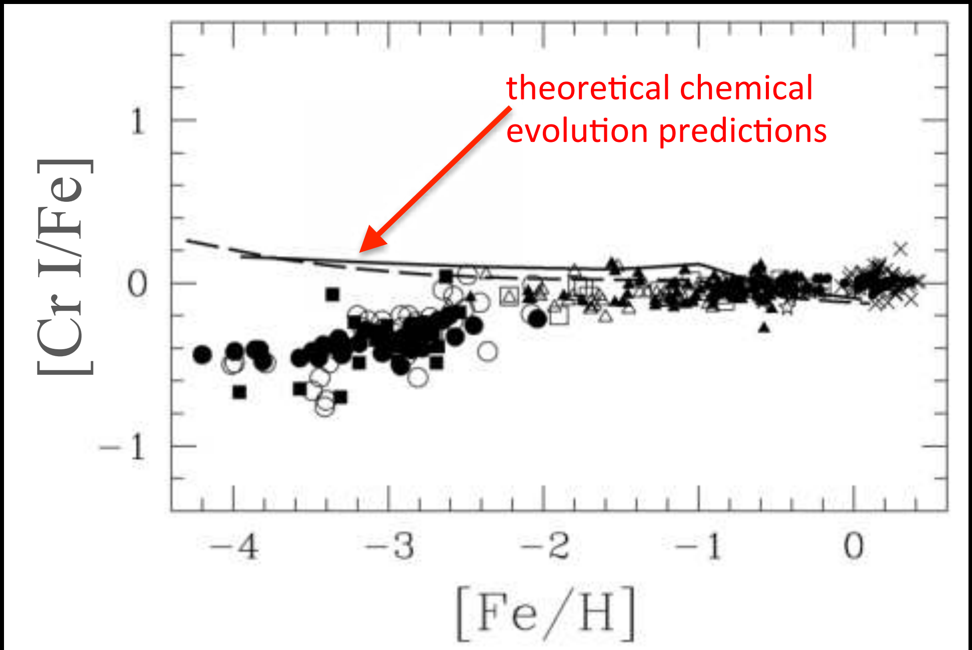
the "First Stars" survey refined the quantitative answers but the qualitative trends stayed the same

Importantly, the star-to-star scatter was decreased from McWilliam's study, suggesting efficient mixing of early Galaxy nucleosynthetic Fe-group products

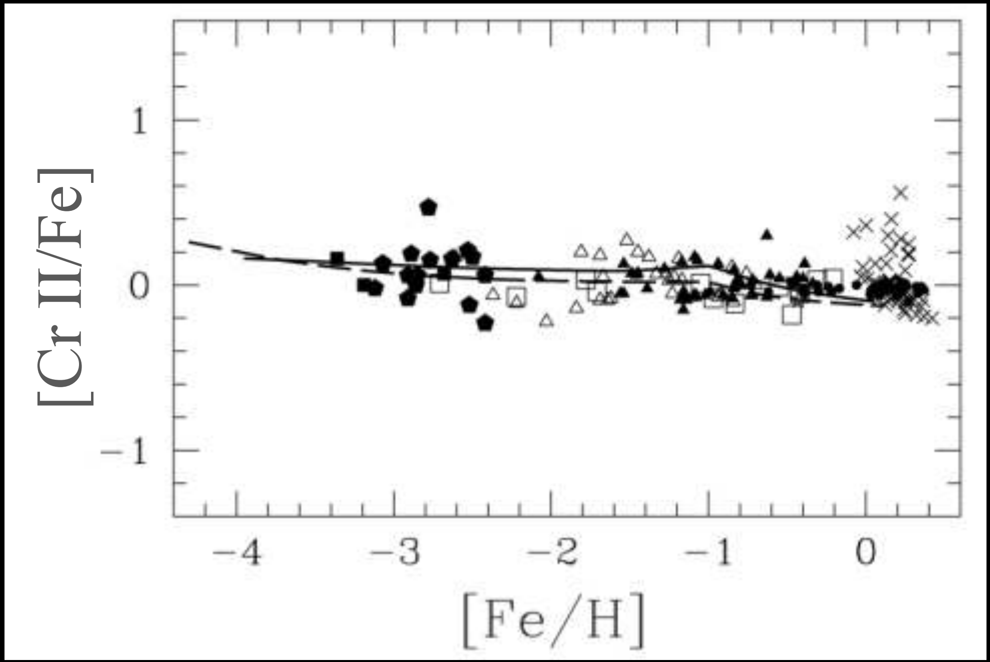
And the "spectroscopy secret" that is not obvious here is *how few* transitions of several elements were used for these abundances

theoretical predictions cannot reproduce these trends

But something was clearly amiss: neutral and ionized Cr transitions gave different answers



Kobayashi et al. 2006

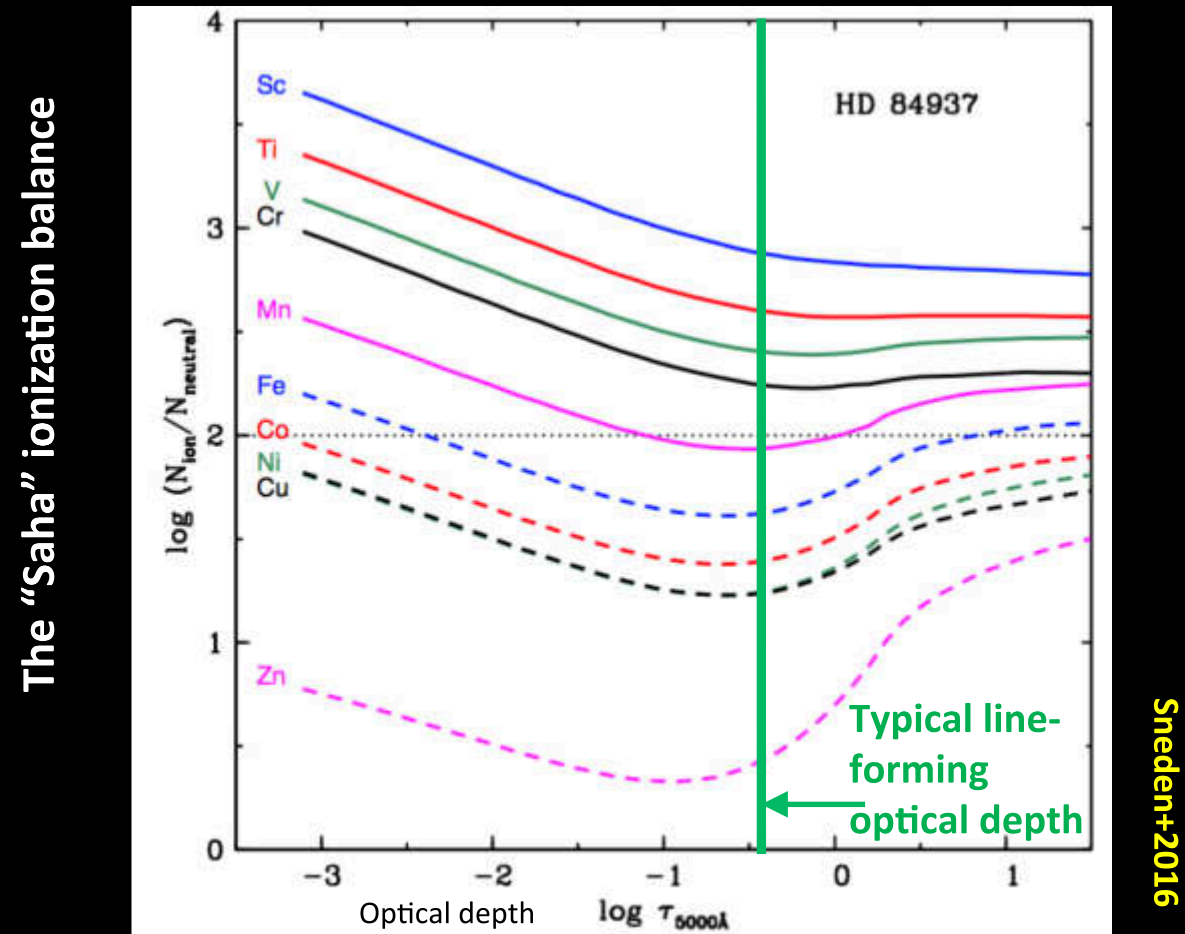


same theory, different observed species of an element

example: at [Fe/H] = –3
[Cr/Fe] ≈ –0.4 from neutral lines
[Cr/Fe] ≈ 0.0 from ionized lines

which abundance is right? or maybe neither of them?!

BIG issue: one must use ionized species for fundamental abundances in low metallicity stars



ions dominate Saha balances for Fe-group elements in warm metal-poor stars

The neutral species are mostly trace fractions →

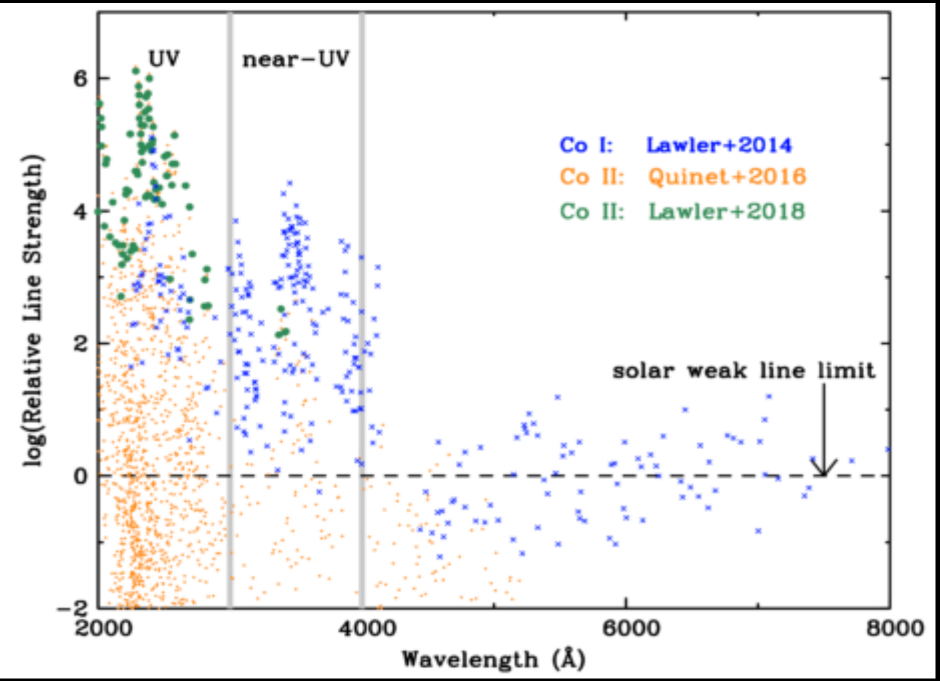
big corrections from neutral number densities to elemental abundances

remember the American philosopher-criminal Willie Sutton

Sutton's Law: A famous apocryphal story is that Sutton was asked why he robbed banks. Allegedly he replied:

"Because that's where the money is"

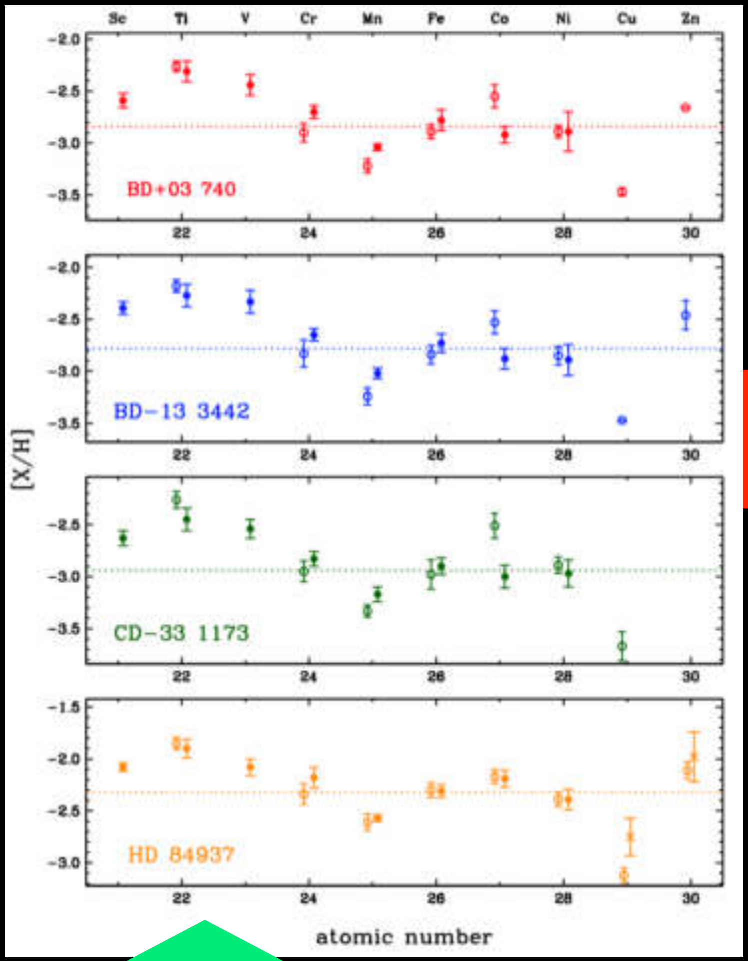
ionized-species lines are mostly in the UV



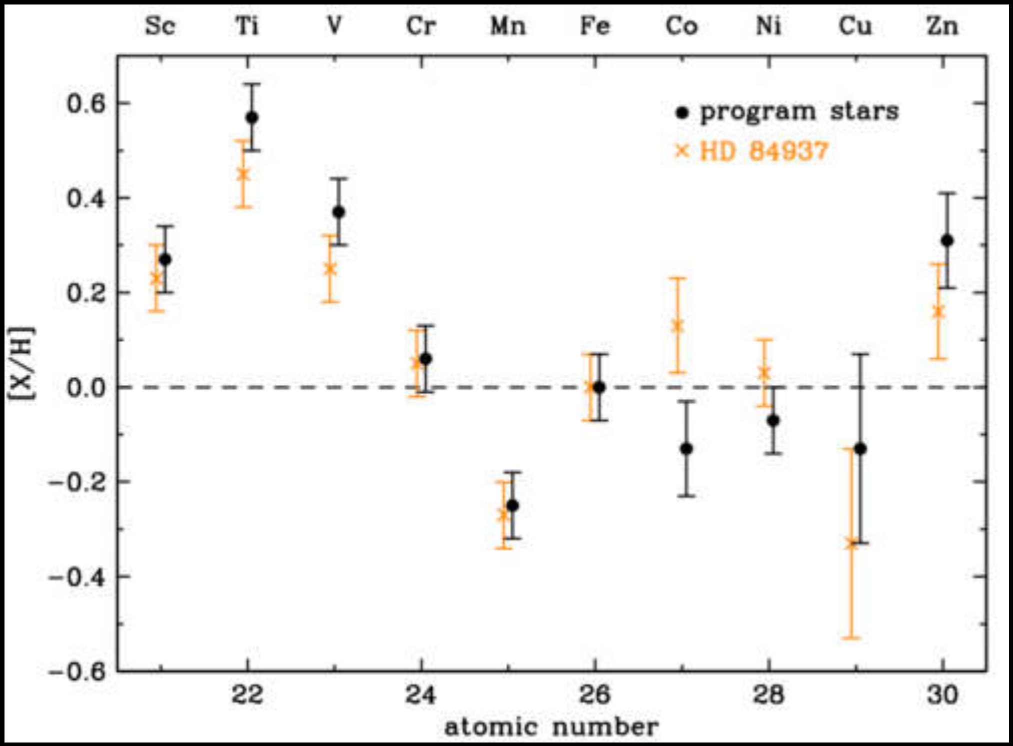
Sounds easy: explore near-UV and especially UV spectral regions

This means targeting warm main sequence stars, not red giants

a very quick summary of a "survey" of HST/STIS data on very metal-poor stars



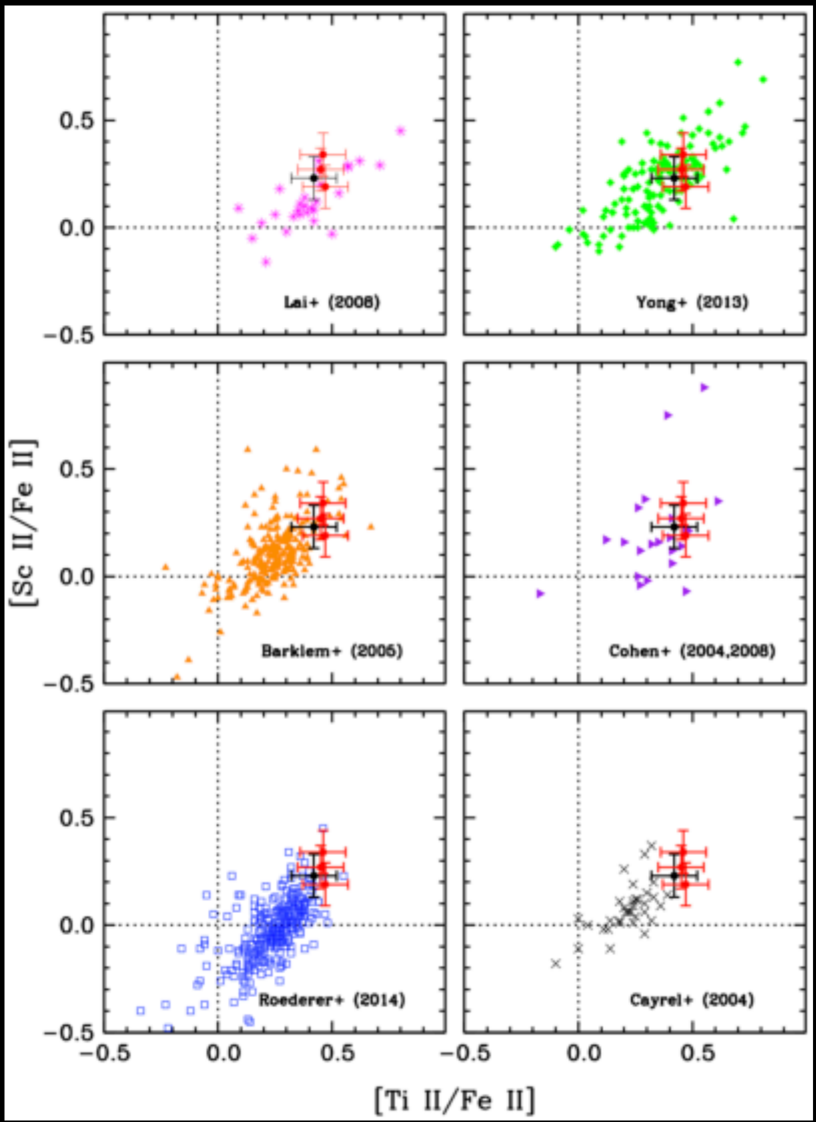
open circles = neutral species
filled circles = ionized species

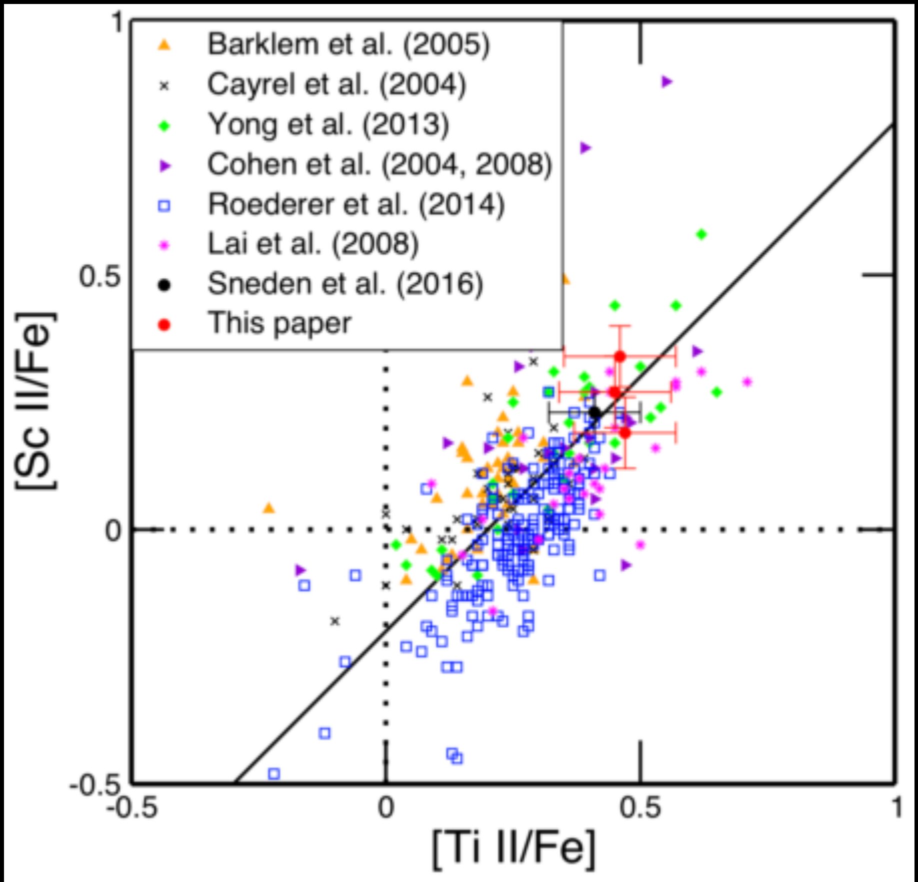


1) large overabundances of Sc, Ti, V
2) no Cr deficiency
3) Co overabundance ***only*** from Co I

Cowan+ 2020

Correlated Sc-Ti exists in large surveys, but have not been much noticed

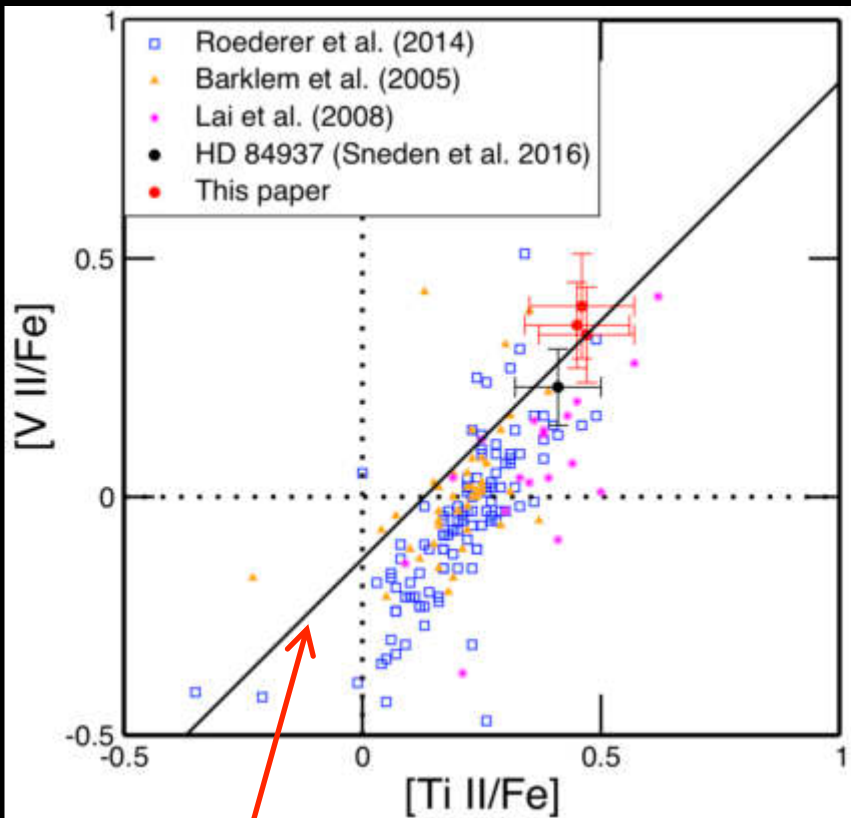


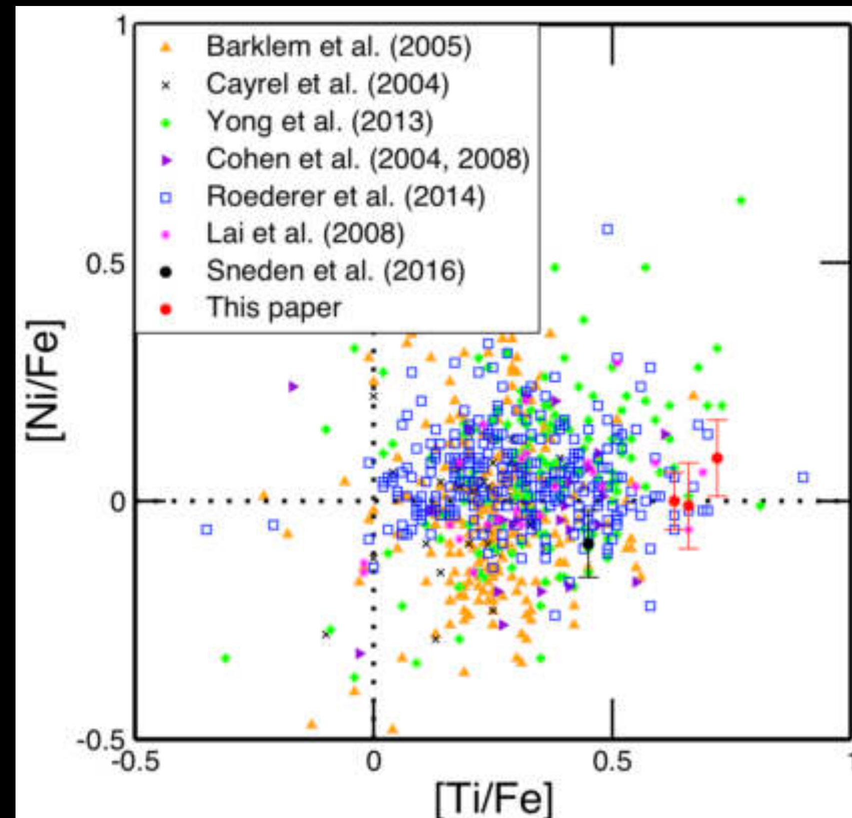


final “proof” that Ti is NOT an alpha element

Cowan+ 2020

The correlation of Ti with V is also clear, but it is absent with heavier Fe-group elements





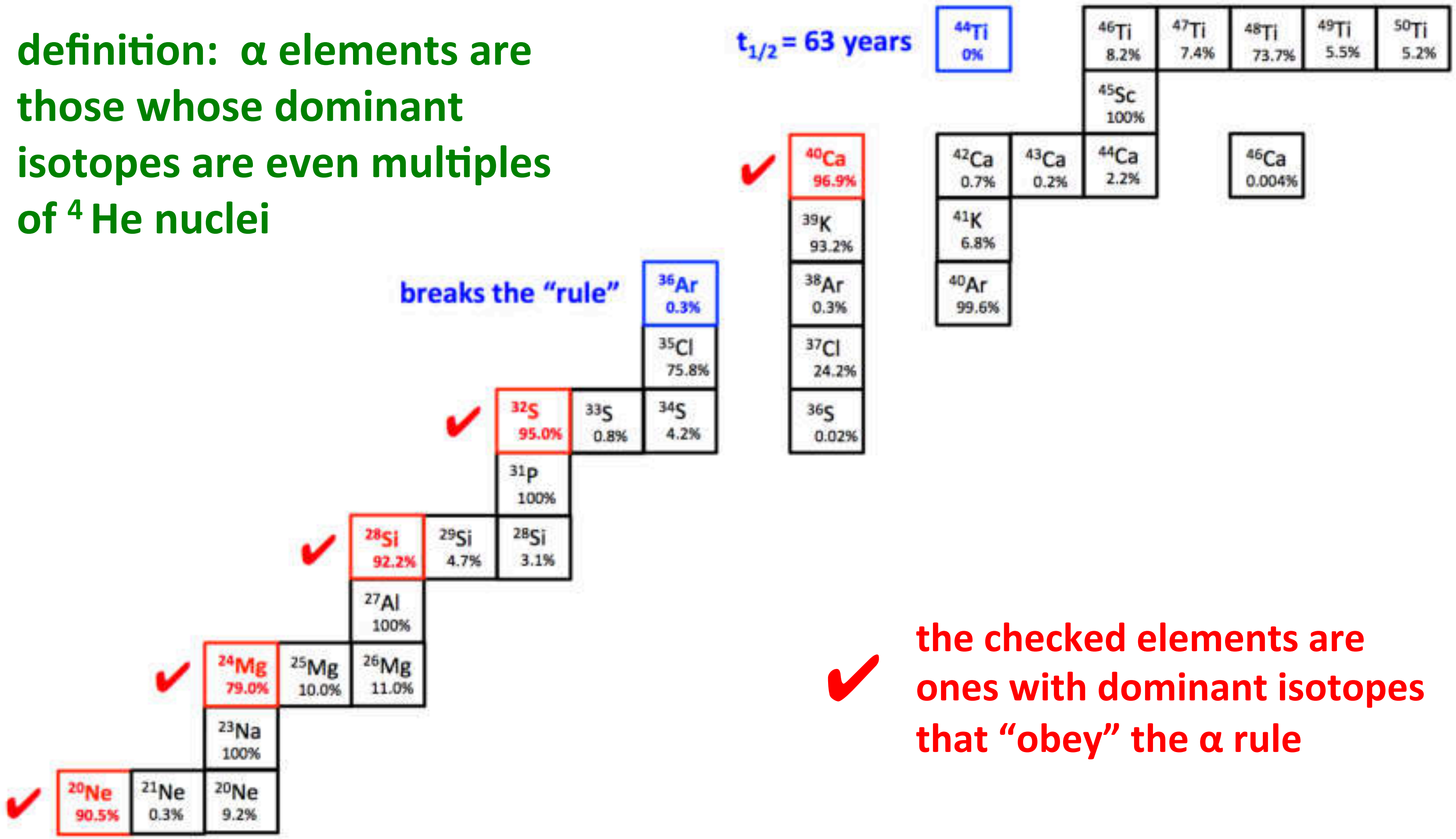
The 45º line is arbitrarily shifted to go through the mean of our 4 stars

and no obvious correlation of [Sc,Ti.V/Fe] with [Cr/Fe], [Mn/Fe], [Co/Fe], ...

Cowan+ 2020

For the last time … Ti is NOT an “alpha” element

definition: α elements are those whose dominant isotopes are even multiples of ^{4}He nuclei

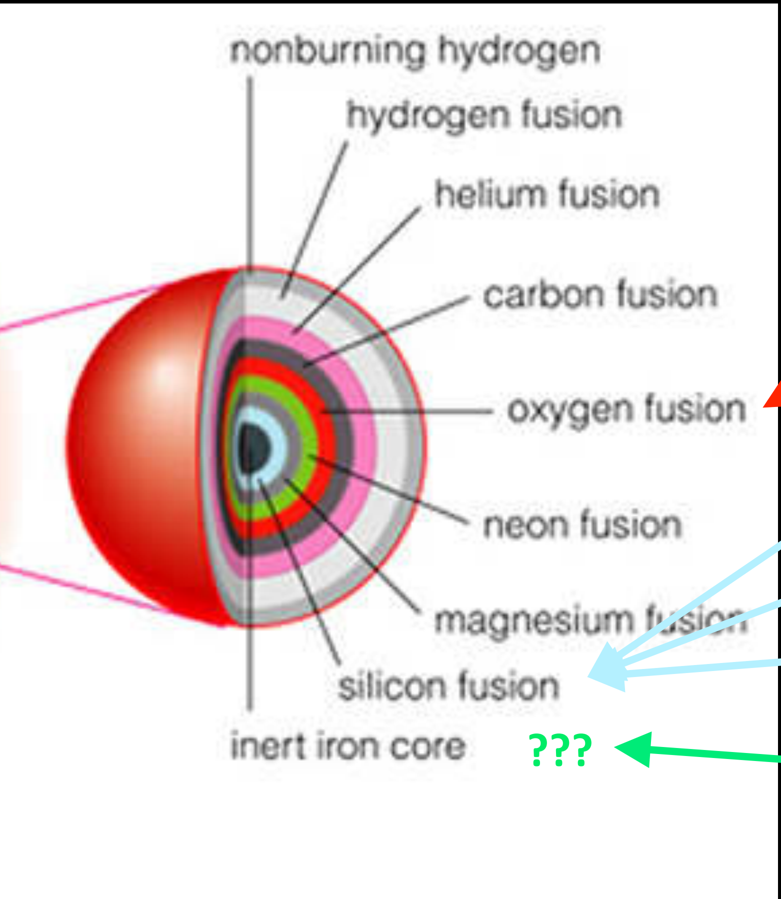


✔ **the checked elements are ones with dominant isotopes that “obey” the α rule**

(we start with Ne (Z=10, N=20) because lighter potential α elements (C and O) also are involved in hydrogen burning, which can significantly alter their abundances)

Where is the Fe-group synthesized in massive stars?

https://socratic.org/questions/how-is-most-of-a-star-s-total-life-spent



Probable synthesis site for:

Si, S, Ar – oxygen fusion

Ca, Mn – "incomplete Si fusion"

Ti, Fe, Co, Ni, (Cu) – Si fusion

V, Cr, Zn – Si fusion with $Y_e > 0.5$

Sc – "inner layers with $Y_e > 0.5$"

see Curtis et al. 2019

Y_e = proton/nucleon ratio … strongly affected during the explosion by neutrino and anti-neutrino captures on protons and neutrons

But wait a minute: this is not my problem!

Fe-group summary

for the first time Fe abundances in metal-poor stars are being derived from (a) enough lines, and (b) with the right (ionized) species

We do not believe past claims of large [Co/Fe] abundances at low metallicity

Sc, Ti, and V ARE correlated in this small sample, so:

For the near future: a large sample because the nucleosynthesis theories must be really tested

But nuclear astro people need us to “certify” the lighter elements at low metallicity ... back to work

a challenge from two decades ago …
just as relevant today

"So, even if the study of these surface layers appears rather boring to many of the astrophysicists, it cannot be neglected. As we have shown, even the most fundamental parameters of the most basic representation of stellar atmospheres suffer from significant uncertainties. The theoretical and observational tools needed to solve these problems are, to a large extent, available

It is therefore mostly a matter of will: there is still a lot to be done in the study of stellar atmospheres, what is needed is researchers who wish to tackle these problems."

Pierre Magain, 1995, in "Stellar Evolution: What Should be Done", Proc. 32nd Liège Int. Astrophysical Colloq, ed. A. Noels, D. Fraipont-Caro, M. Gabriel, N. Grevesse, and P. Demarque. Liege: Universite de Liege, Institut d'Astrophysique, 1995., p.139