The Impact of improved Atomic Physics on the Chemical Compositions of Low Metallicity Stars

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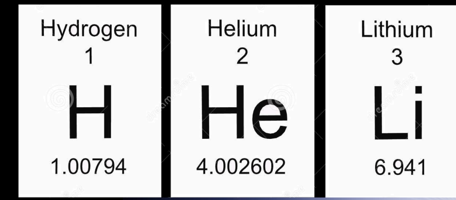
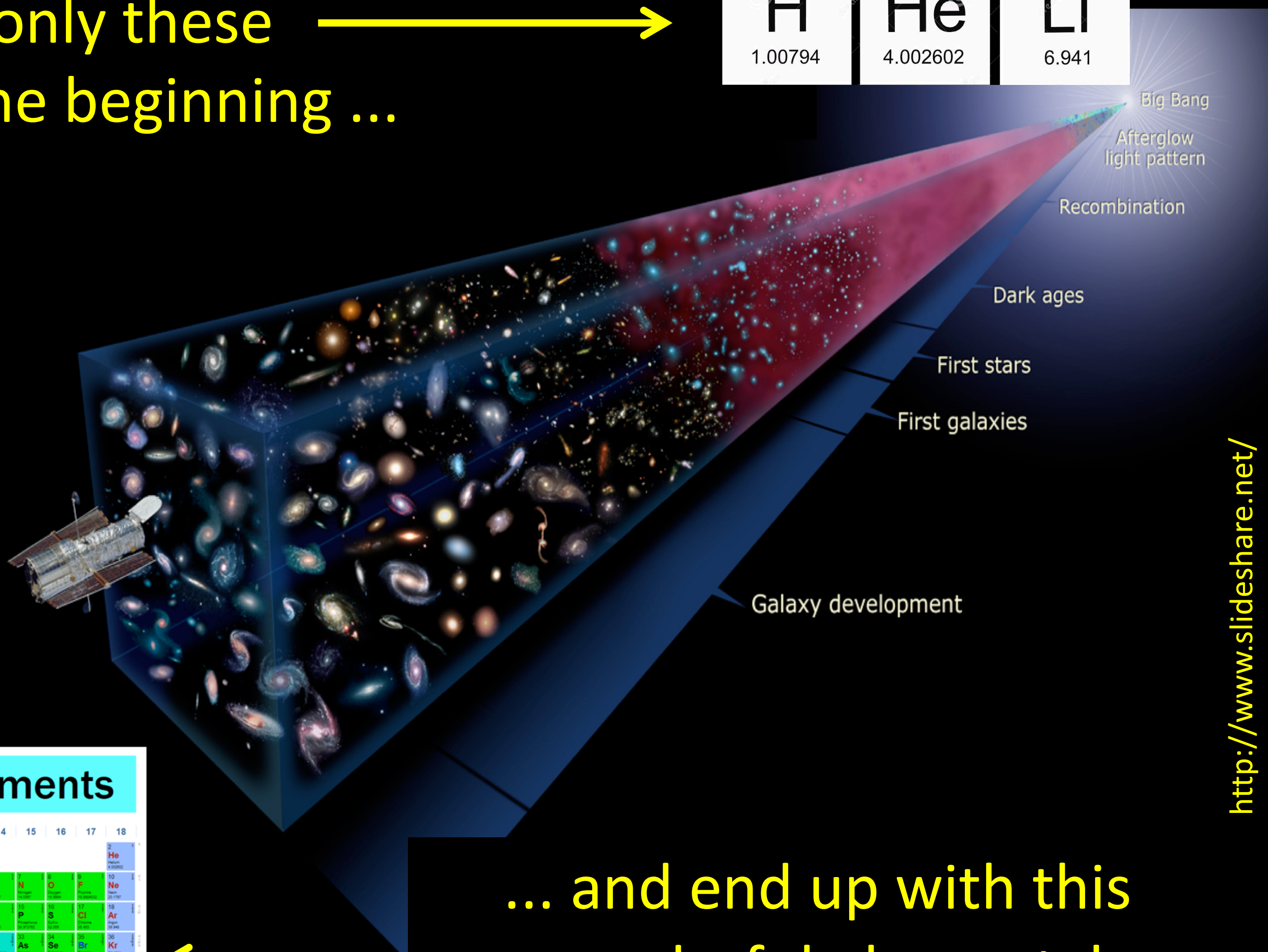
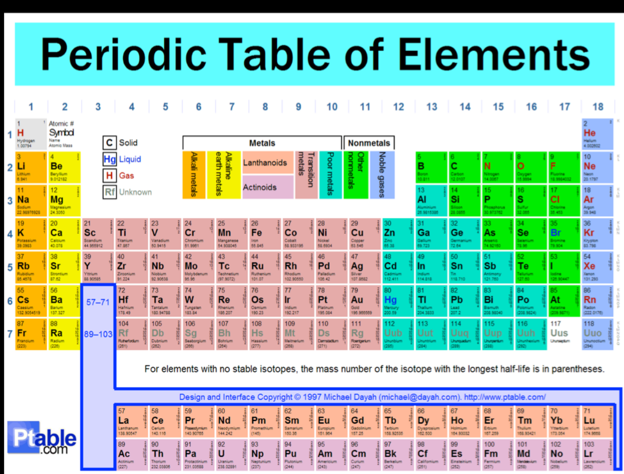
https://zeenews.india.com/tags/galactic-halo.html

How did the universe produce only these elements in the beginning ...



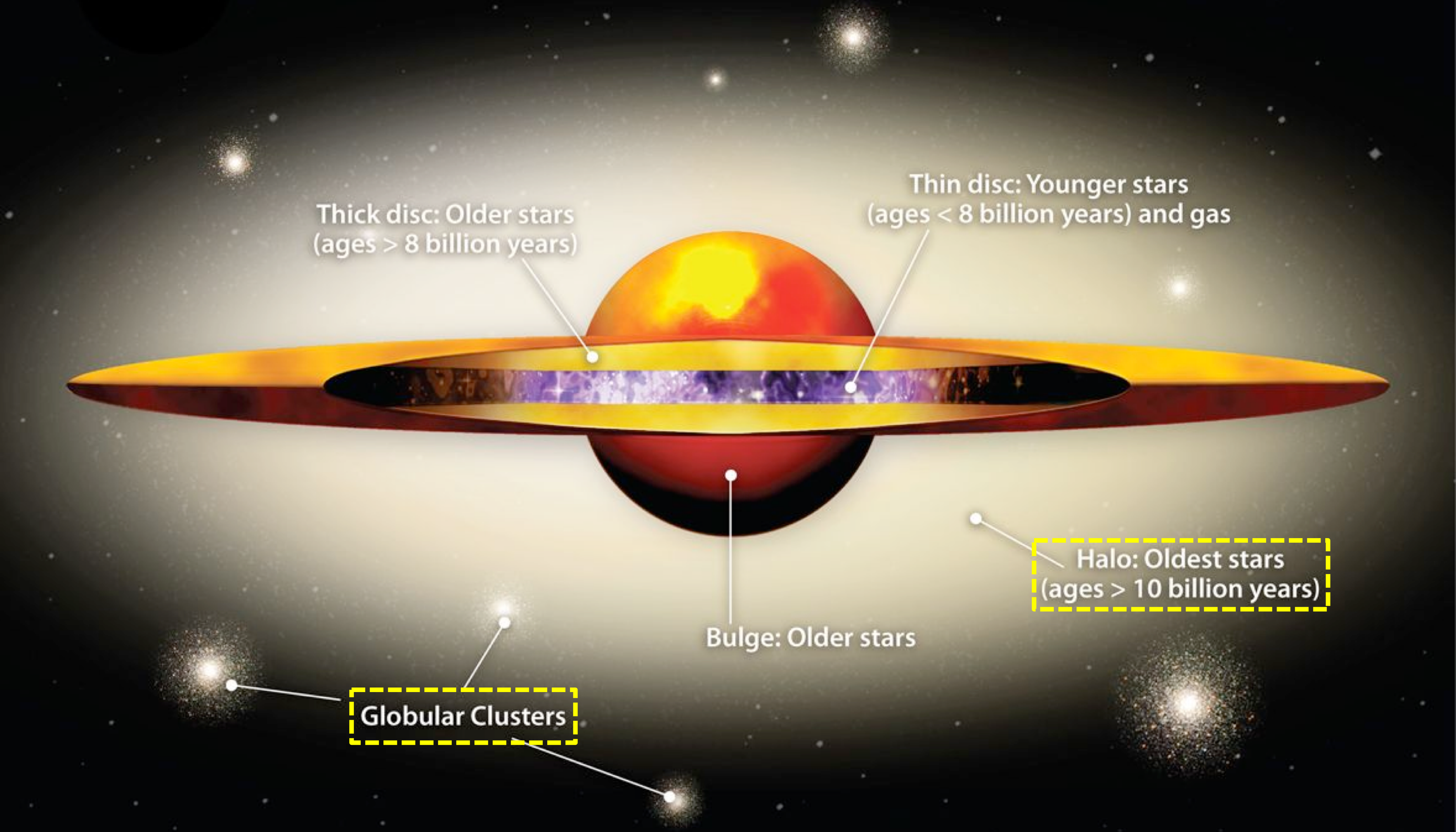


... and end up with this wonderful elemental complexity?



http://www.slideshare.net/

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



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

Outline of topics

- first, a general challenge on stellar chemical compositions
- neutron-capture elements: why do we care?
- r-process rich low metallicity stars: the leap forward in quality
- Fe-group elements: debunking (my!) past odd abundance claims
- don't stop now: attacking the lighter elements
- a wider look – what can we do with metal-rich neutron-capture elemets?

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; almost all my stars are very metal-poor, or [Fe/H] < –2

I'm speaking on behalf of MANY friends who have contributed decades to this work

a challenge from two decades ago ...
just as relevant today

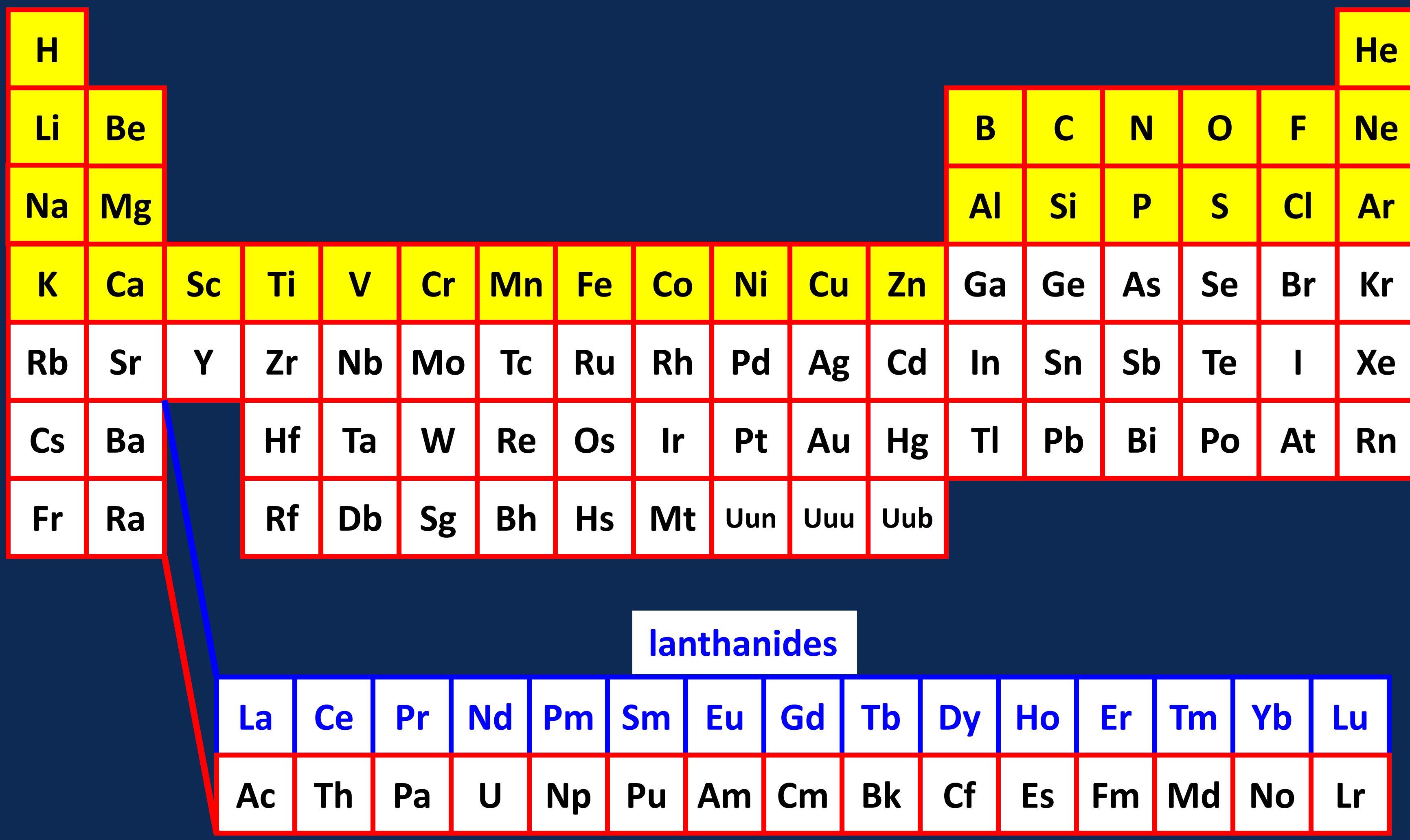
"So, even if the study of these surface layers appears rather boring to many of the astrophysicists, it cannot be neglected. As we have shown, even the most fundamental parameters of the most basic representation of stellar atmospheres suffer from significant uncertainties. The theoretical and observational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

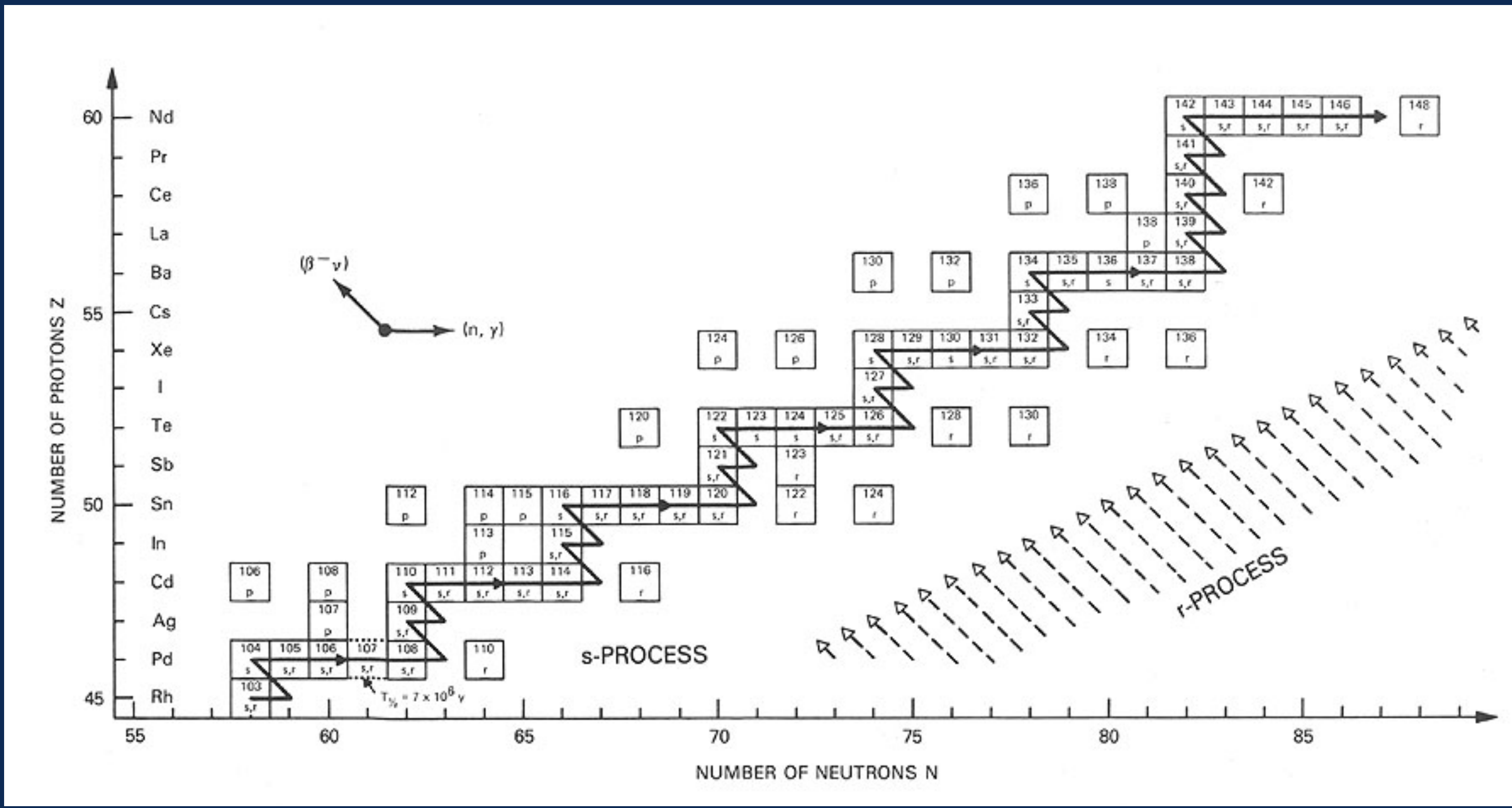
Let’s talk about neutron-capture elements

usually includes all elements with Z > 30



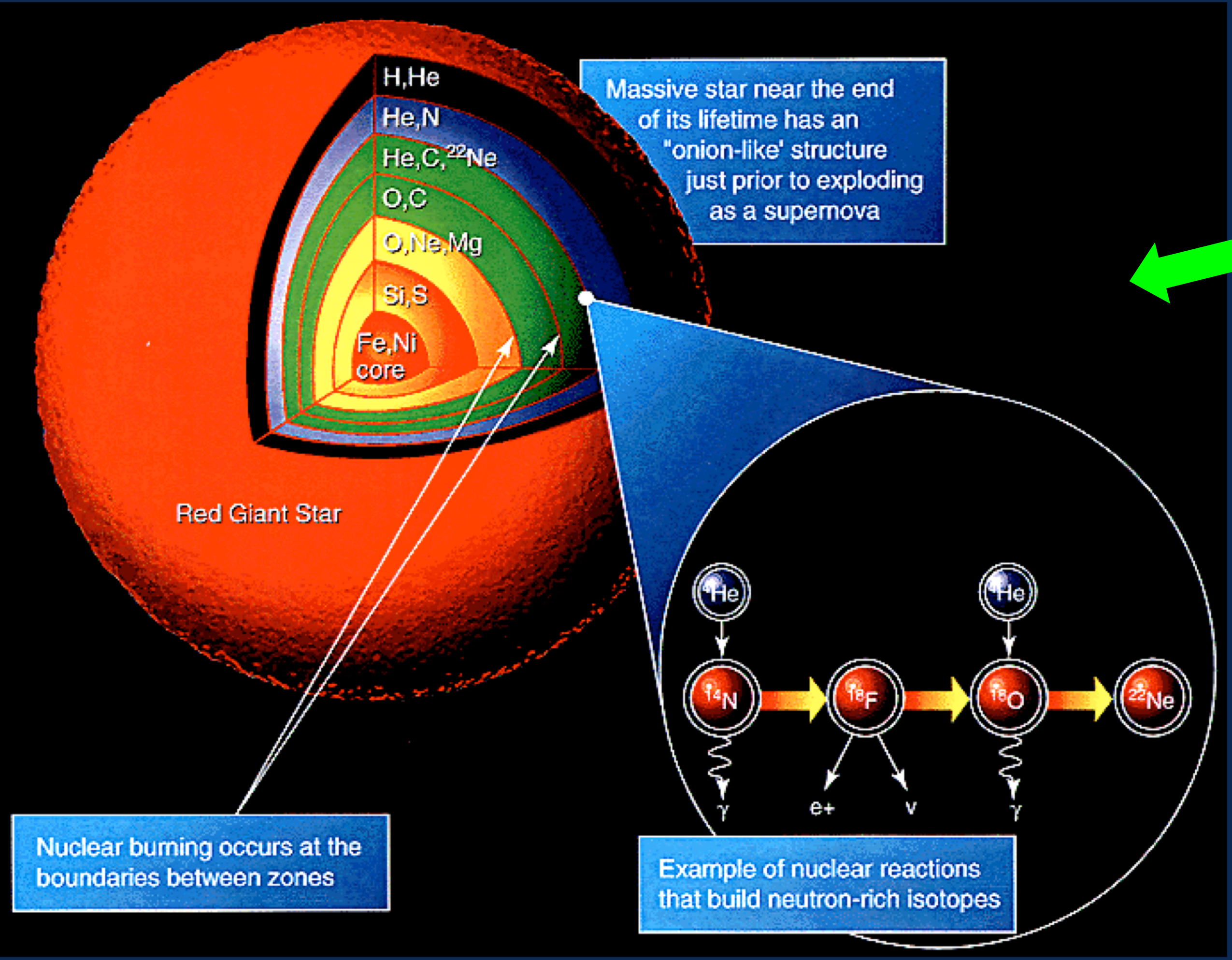
The basic neutron-capture (n-capture) paths

- *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)

Why the interest in n-capture elements? In the early Galaxy they had to be made by massive stars during Type II supernova, **right?**



classic cut-away picture of a massive star about to detonate

we are sure that these objects made Fe-group elements and especially the light "alpha" elements like Mg, Si, Ca

https://en.wikipedia.org/wiki/Stellar_nucleosynthesis

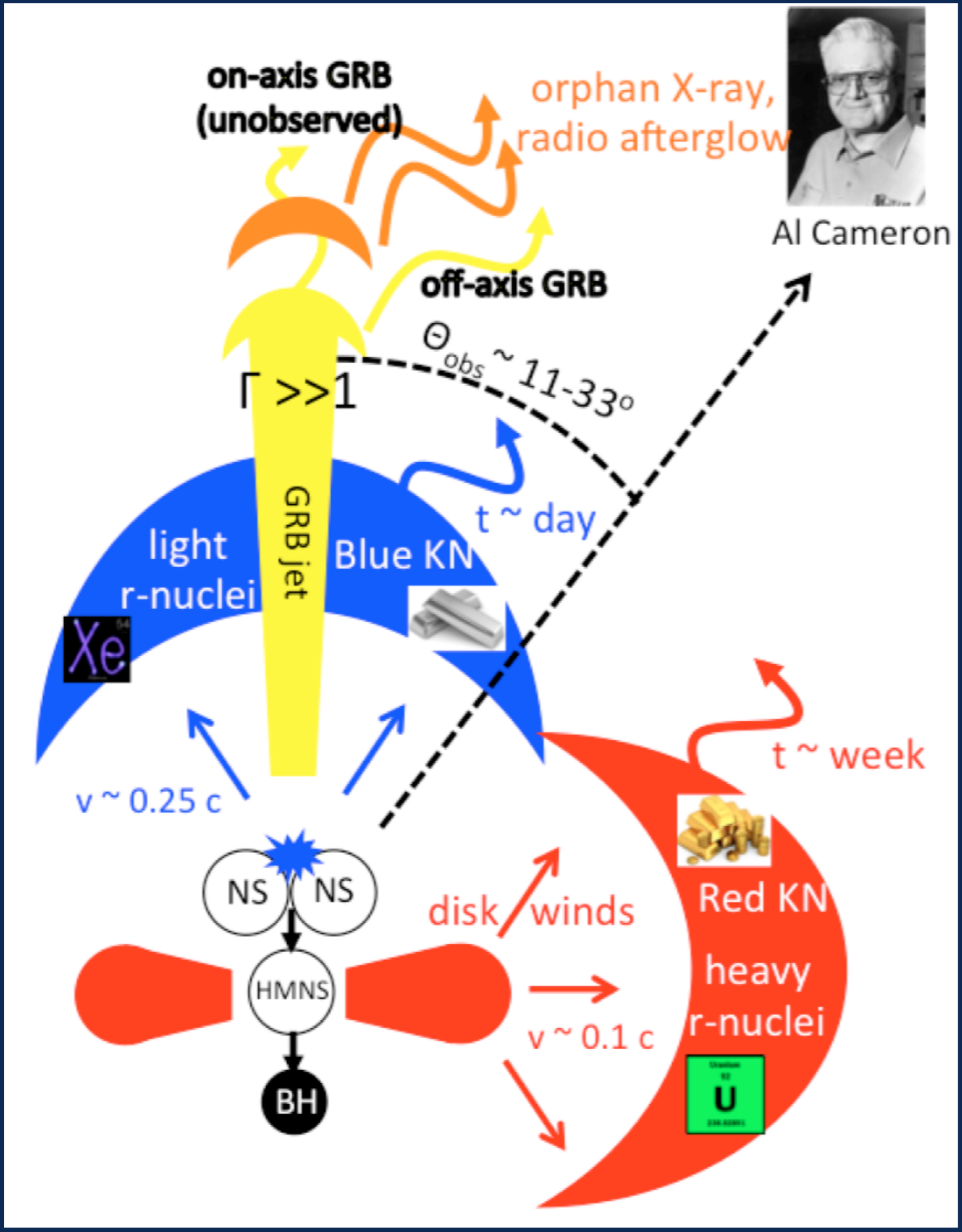
Then came the binary neutron-star merger

https://www.ligo.caltech.edu/news/ligo20180817

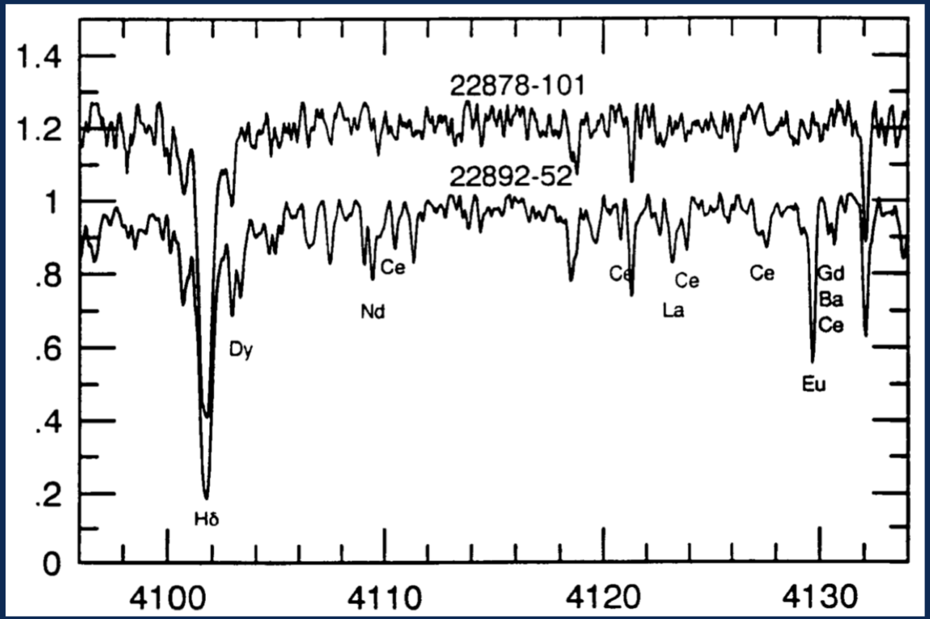
And headlines about creating lanthanides and GOLD

This was a true multi-messenger event from a "kilonova"

Within 11 hours, a bright but rapidly-fading thermal optical counterpart was discovered in NGC 4993. ... The rapid spectral evolution of the kilonova emission to near-infrared wavelengths demonstrates that a portion of the ejecta contains heavy lanthanide nuclei. Two weeks after the merger, rising non-thermal X-ray and radio emission were detected from the position of the optical transient.



Metzger+17a,b

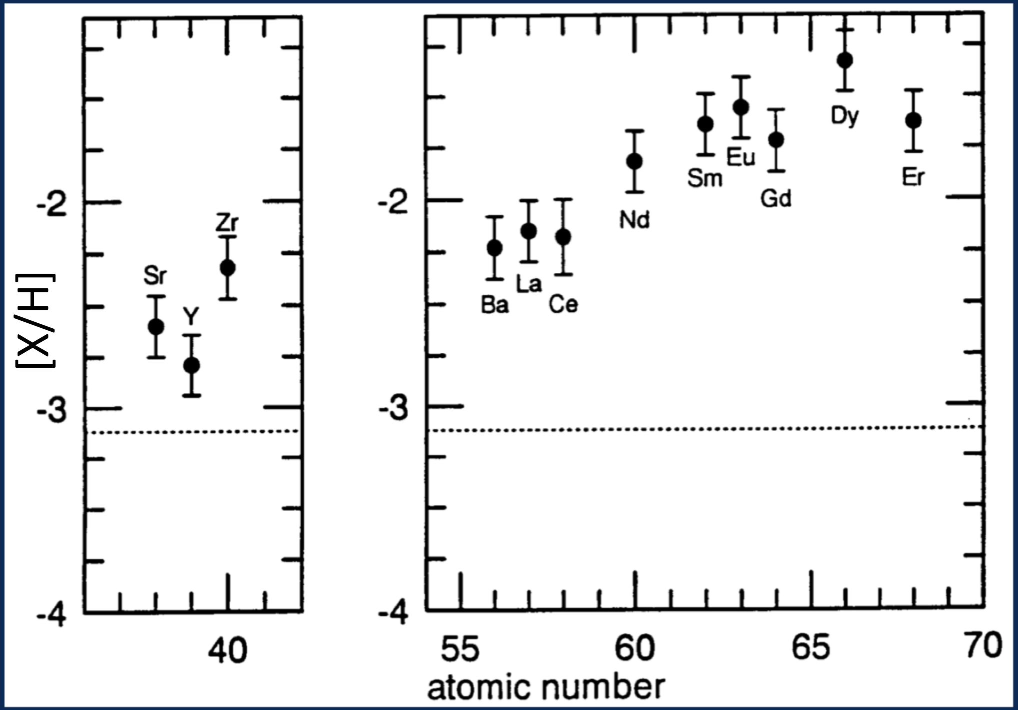


In 1994 a randomly observed halo star began a new major field of low metallicity, *r*-process-rich stars

high resolution, poor signal-to-noise; even so, the great strength of rare earth transitions are obvious

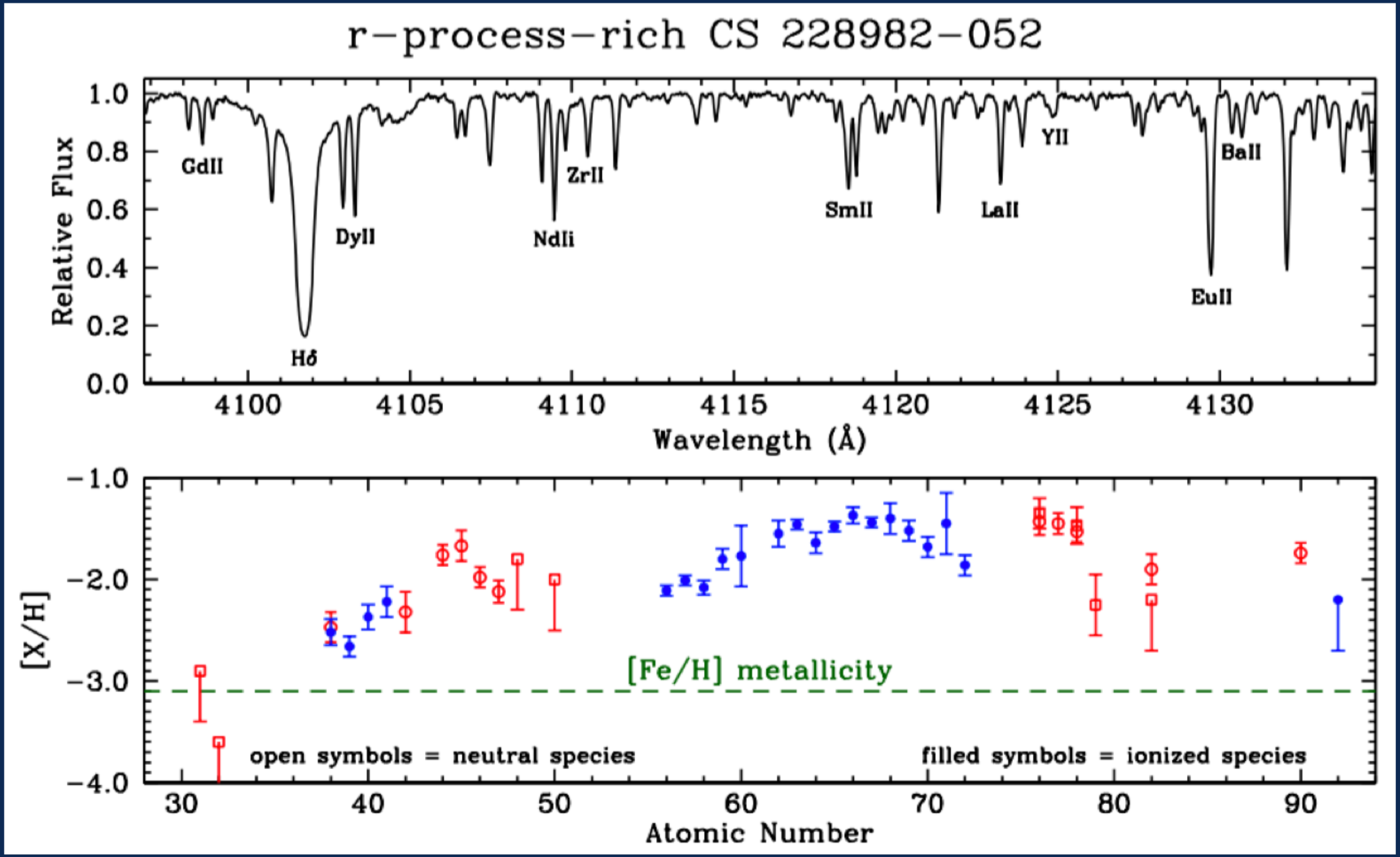
overabundances up to a factor of 30 (easy to spot)

increasing abundance with atomic number Z —> the *r*-process



Sneden, Preston, McWilliam, & Searle 1994

now look only a decade later



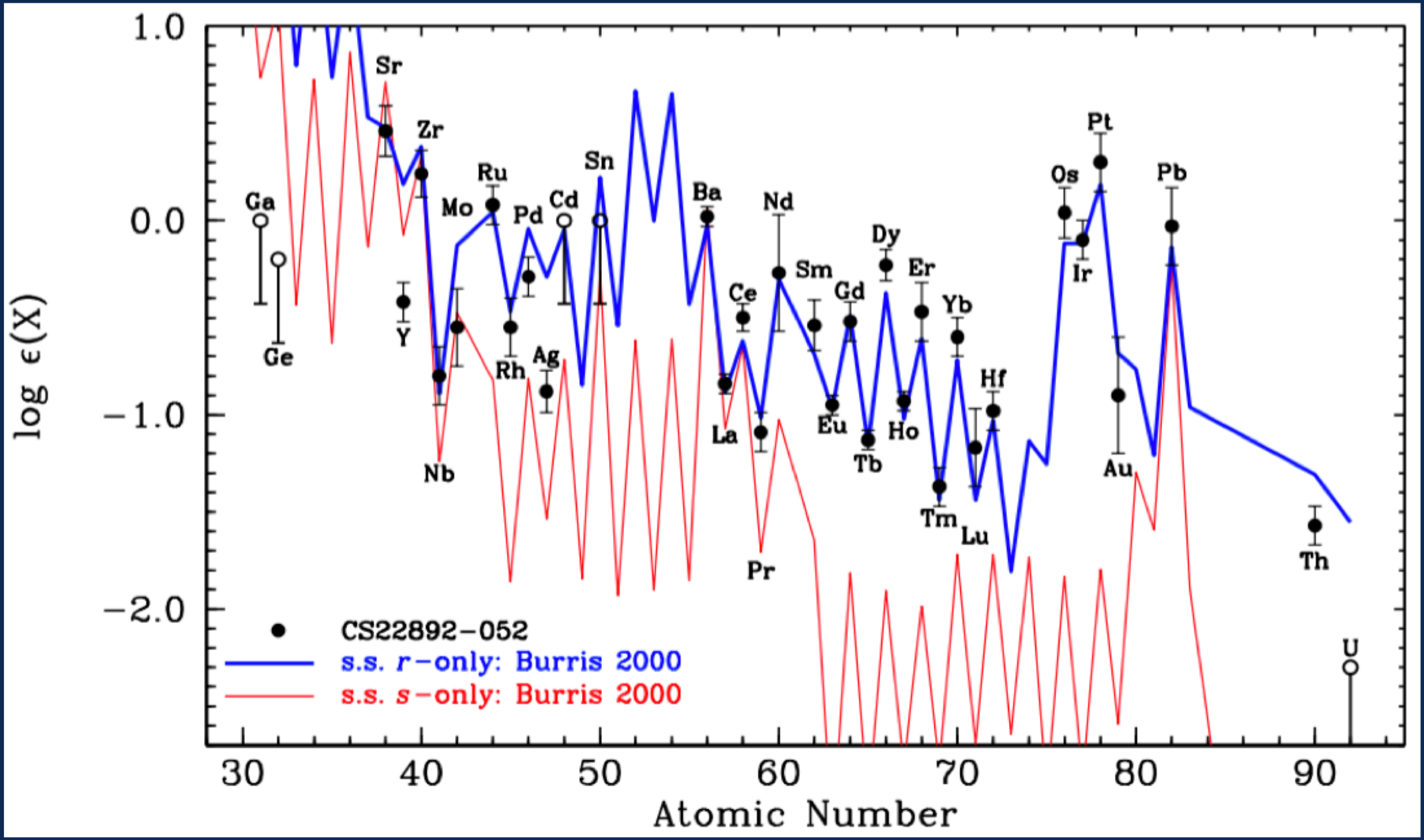
Sneden+ 2003

WHAT CHANGED? Much better instruments getting much better spectra

Improved model stellar atmospheres

a quiet revolution in laboratory and theoretical atomic physics for transitions accessible to cool-star spectroscopy

the abundance pattern is a near-perfect solar system *r*-process match

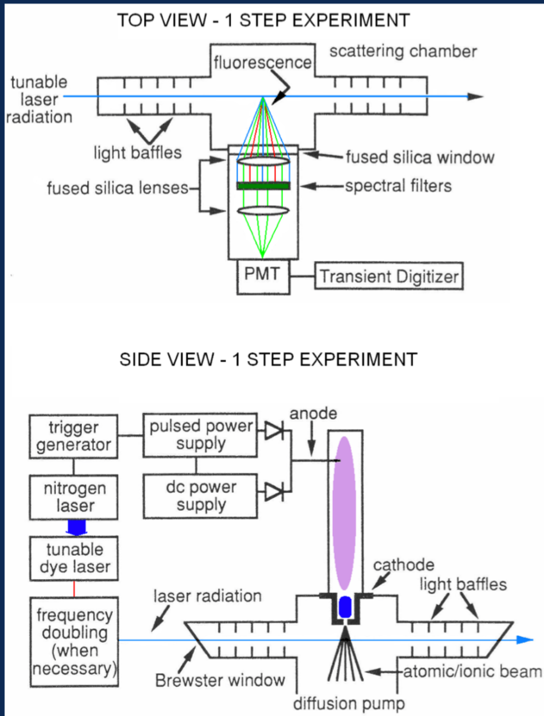


Sneden et al. 2003

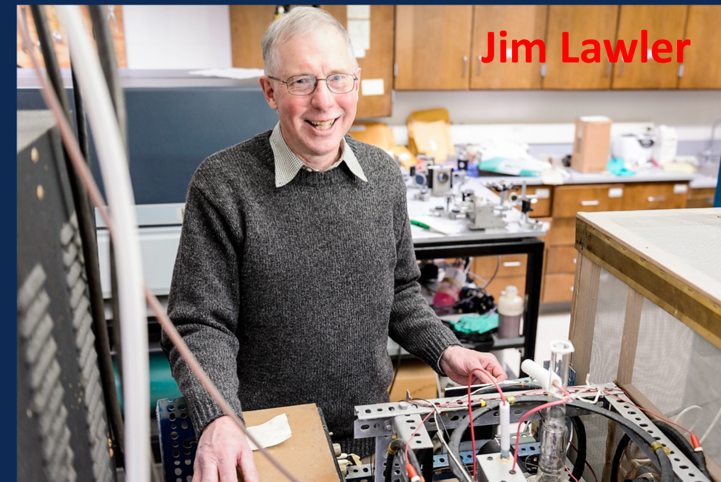
My focus has been to help on the transition data issue:

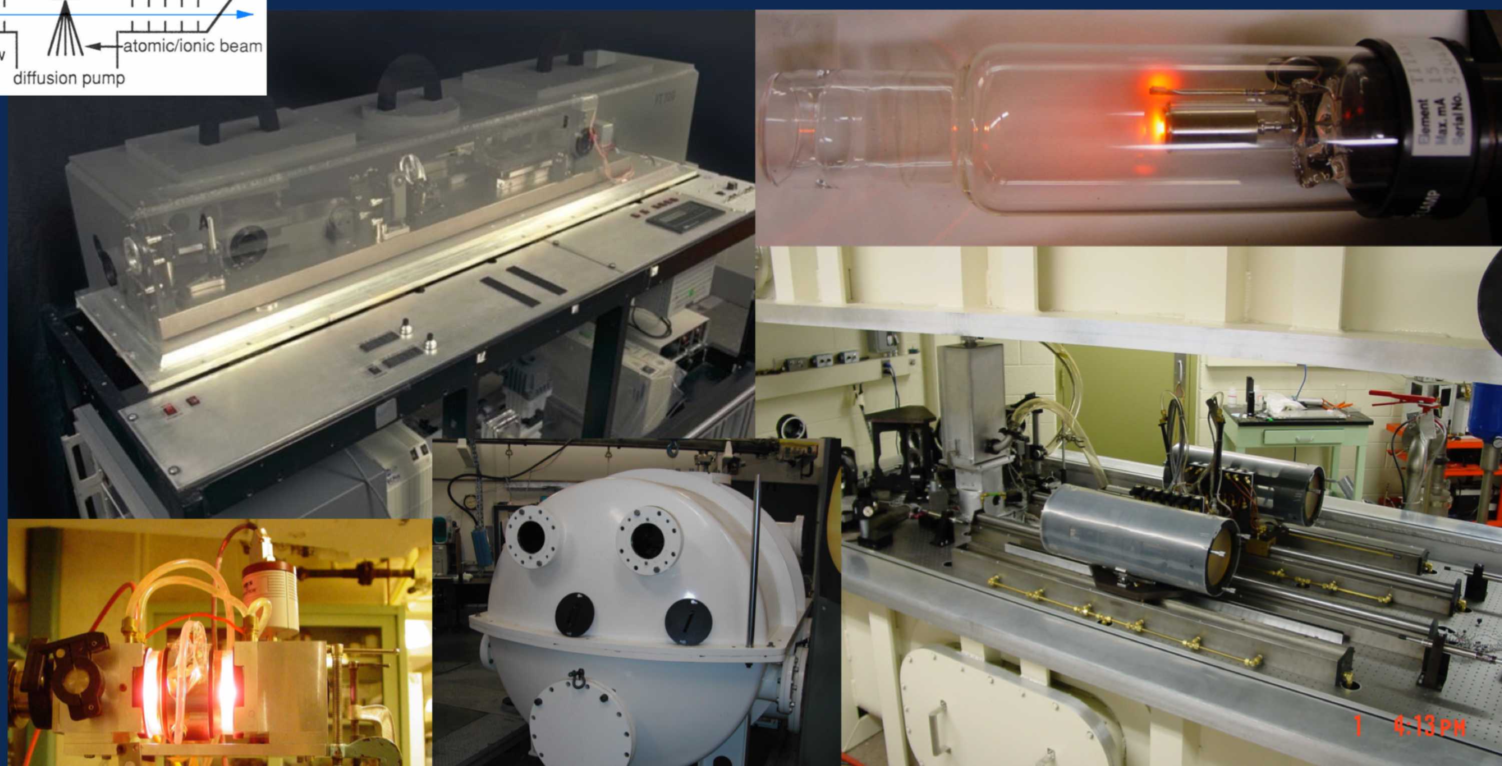
transition probabilities, hyperfine substructure; isotopic wavelength shifts

https://minds.wisconsin.edu/handle/1793/78307



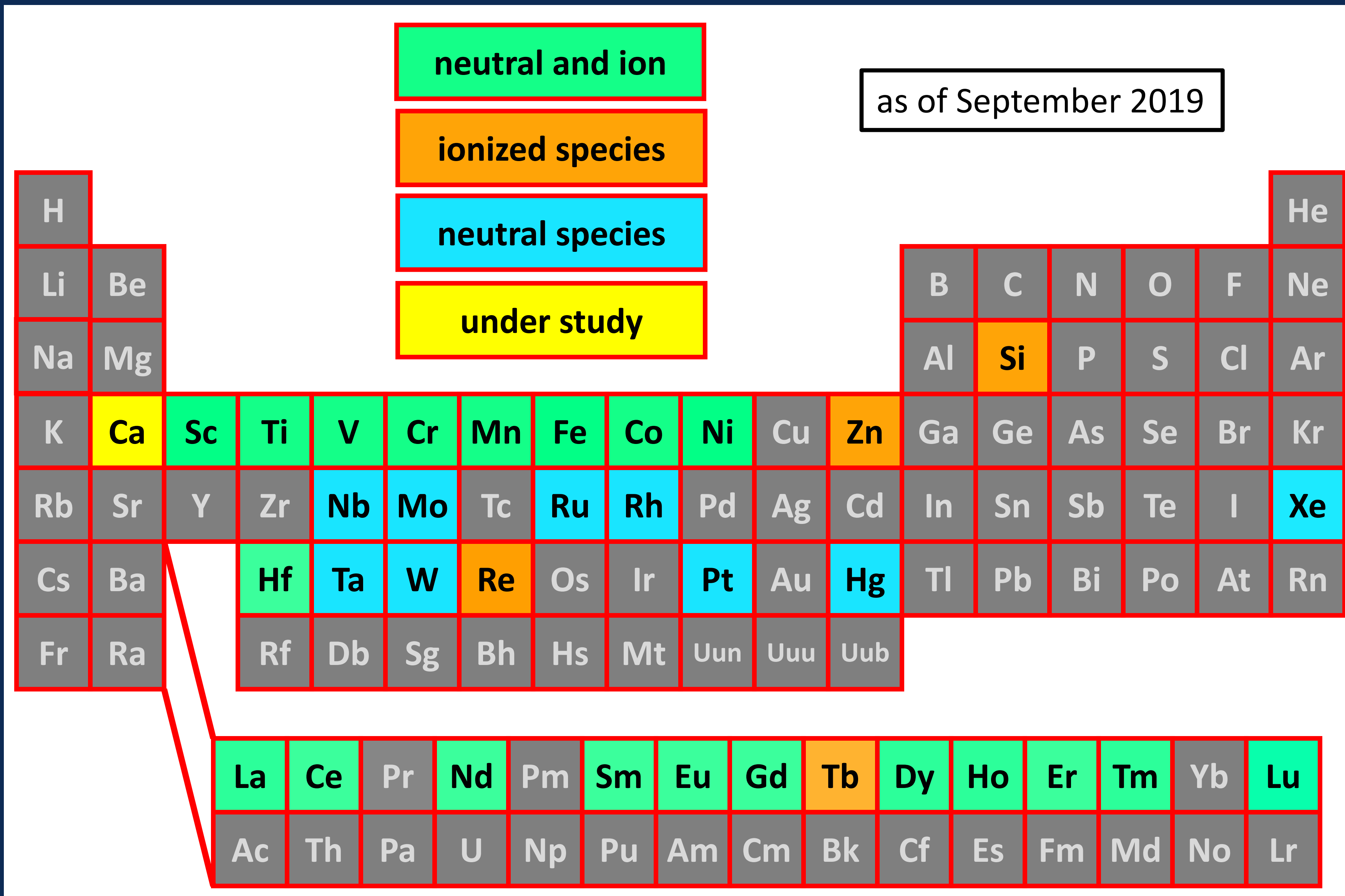
Wisconsin lab atomic physics studies have made major contributions to stellar spectroscopy



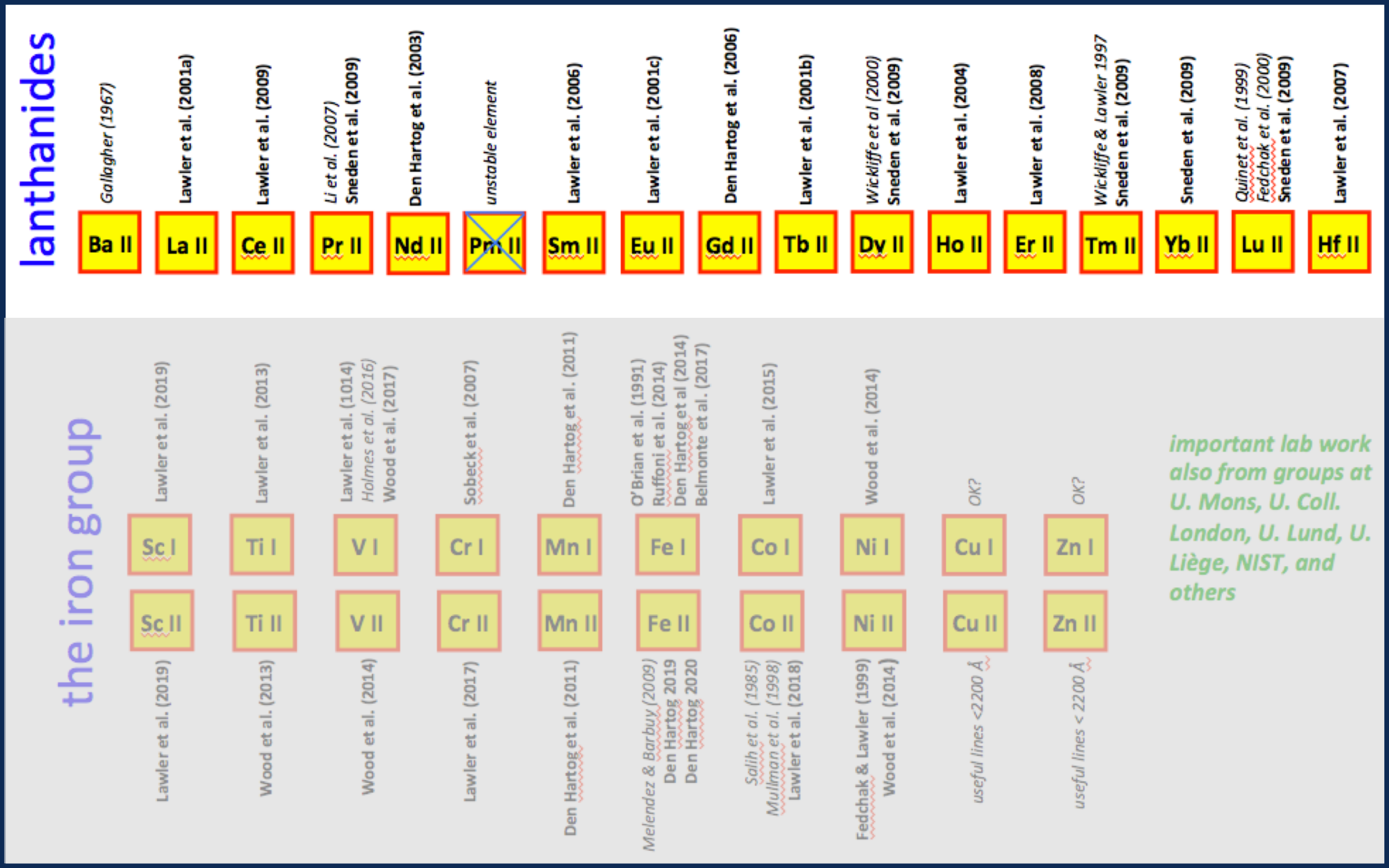


https://minds.wisconsin.edu/handle/1793/78313

University of Wisconsin-Madison lab atomic contributions



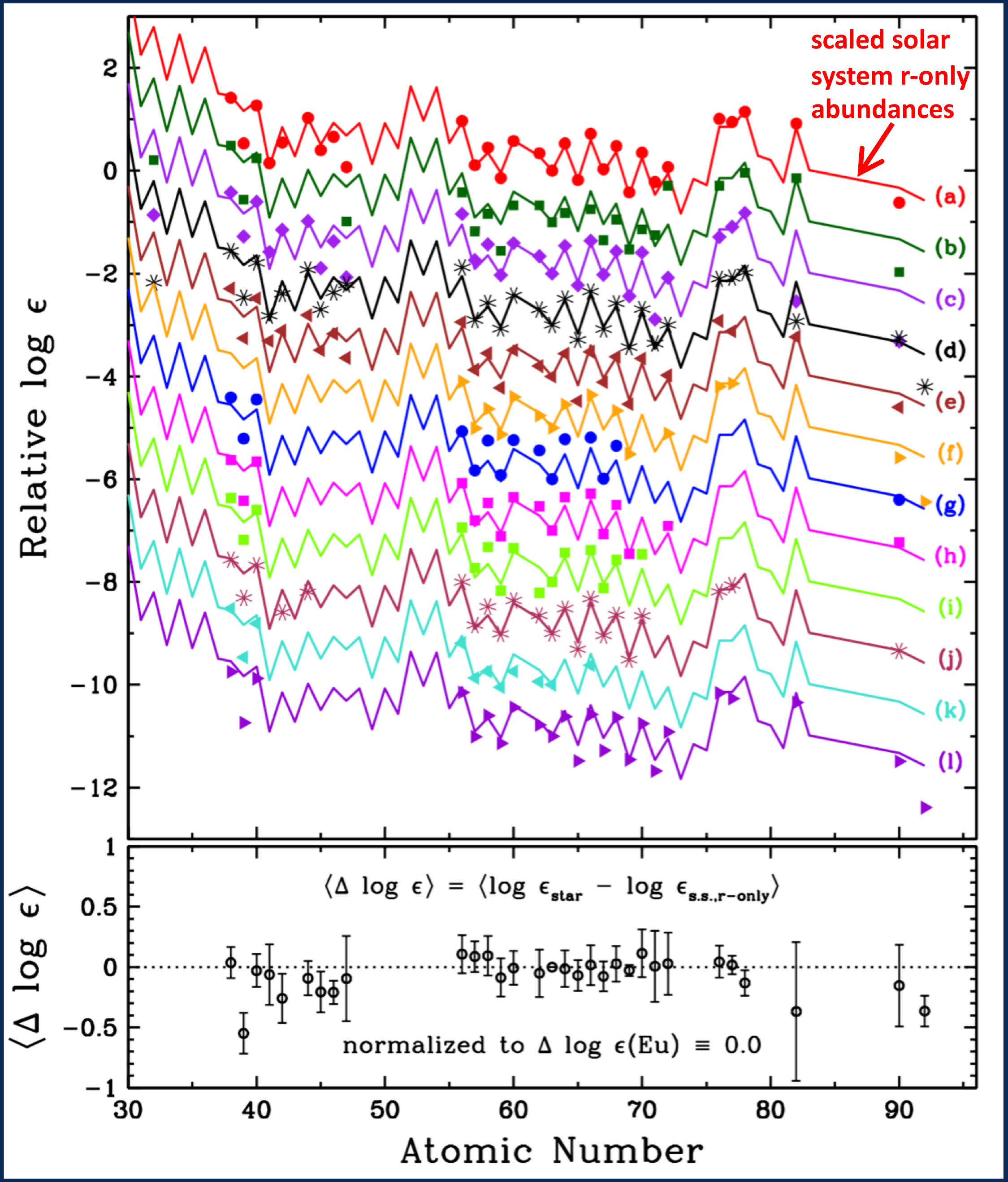
Wisconsin lab astro: major additions to reliable transitions of *n*-capture and Fe-group species



"No field of science places higher demand on the quantity and accuracy of atomic data than astrophysics" (Nave+2019)

what have we learned by applying these lab data to *r*-process-rich stars?

Così fan tutte?



Application of the vastly improved lab data:

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

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

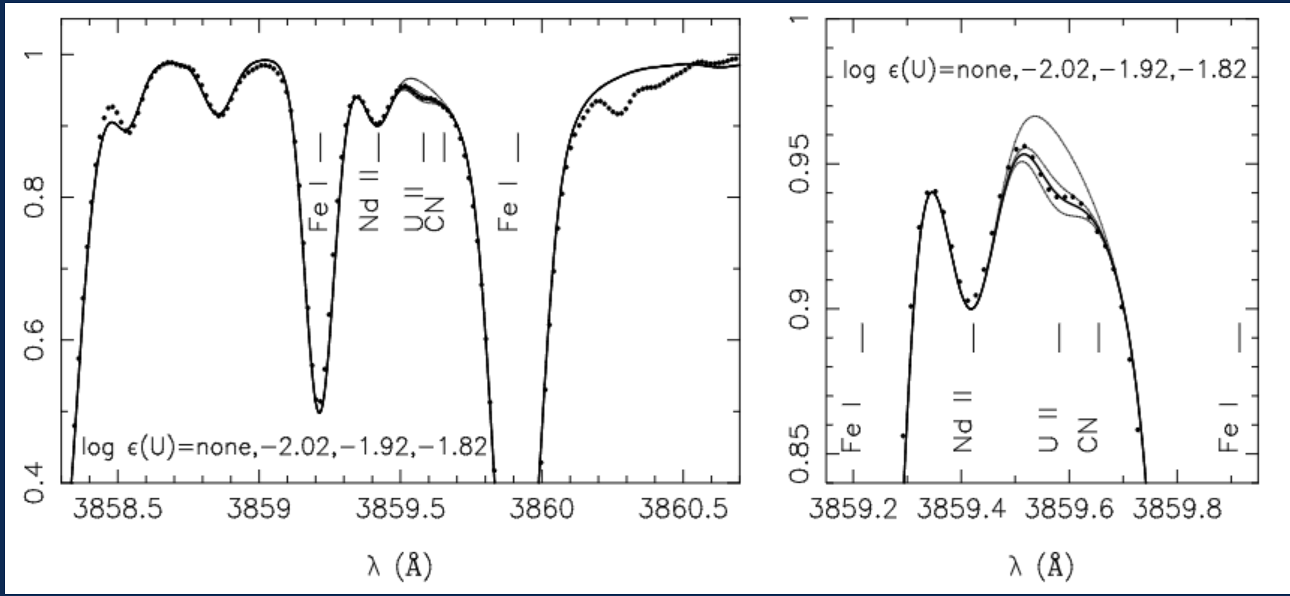
Lower panel: mean differences with respect to the solar *r*-process

Cowan+ 2020+

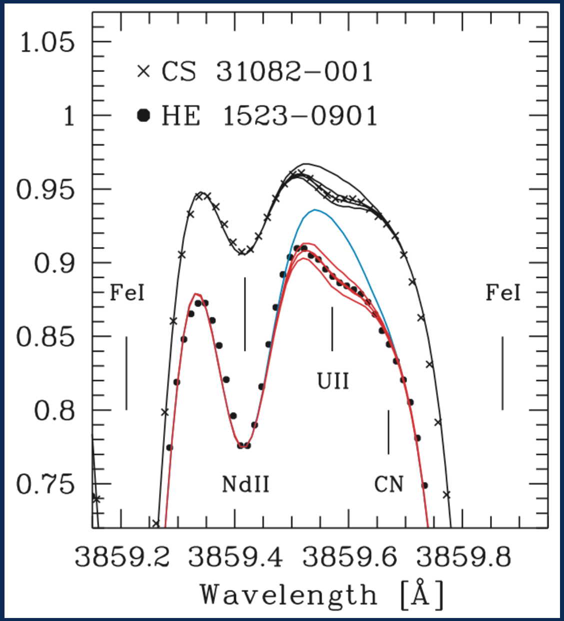
We have uranium detections in *r*-process-rich stars

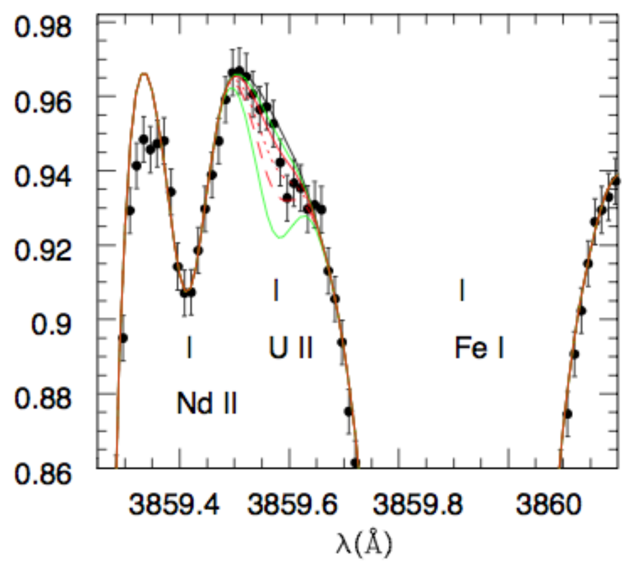
First detection:
- CS 31082-001
- (Hill et al. 2002)

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



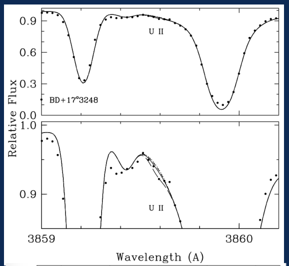
Frebel et al. 2007

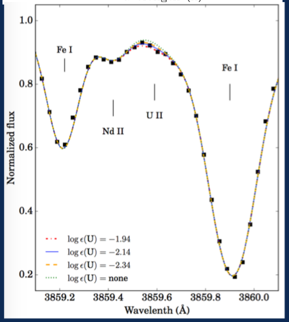




Hill et al. 2017

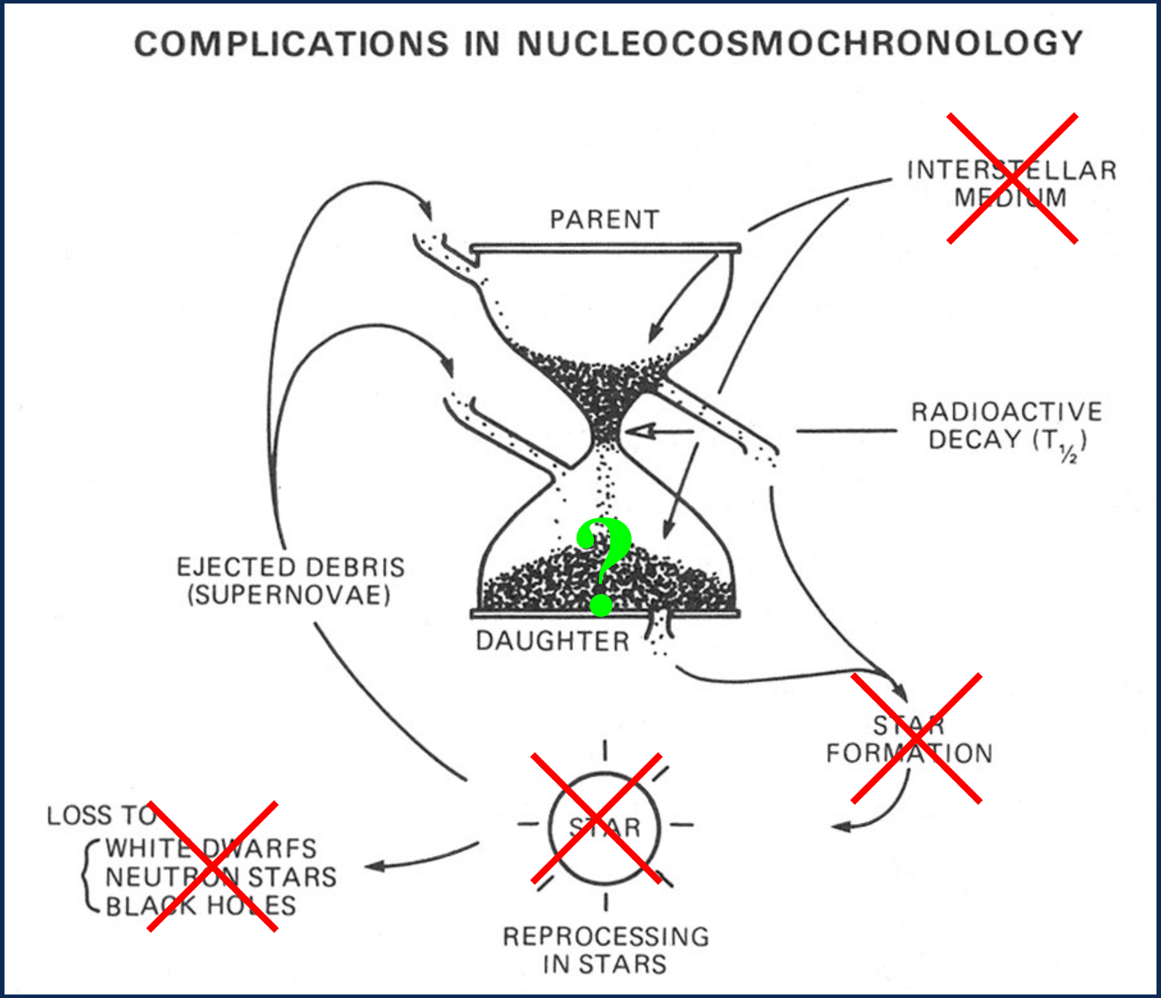
Cowan et al 2002





Placco et al. 2017

Radioactive cosmochronometry is *NOT* complex for metal-poor *r*-rich 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!

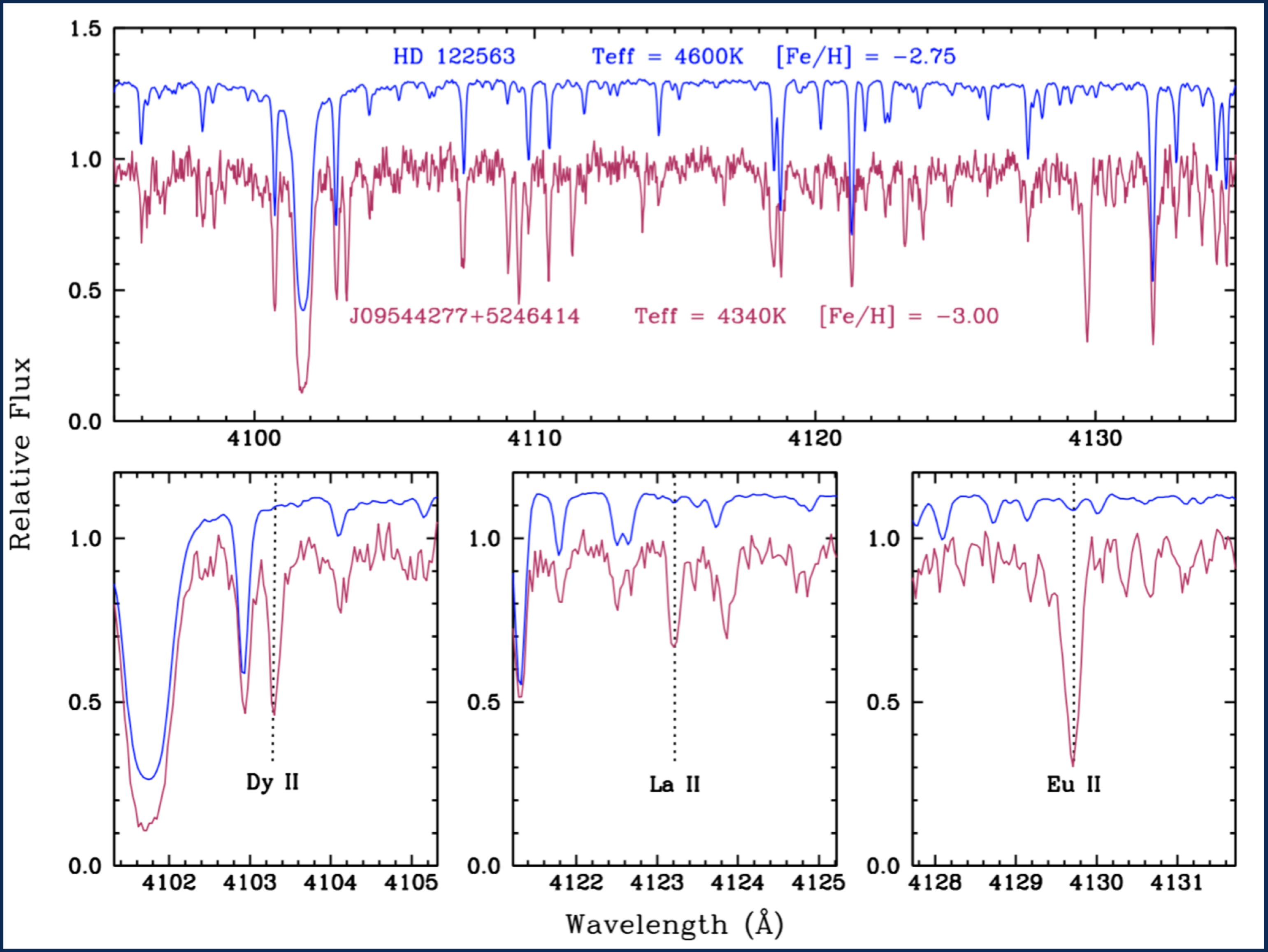
Rolfs & Rodney (1988)

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

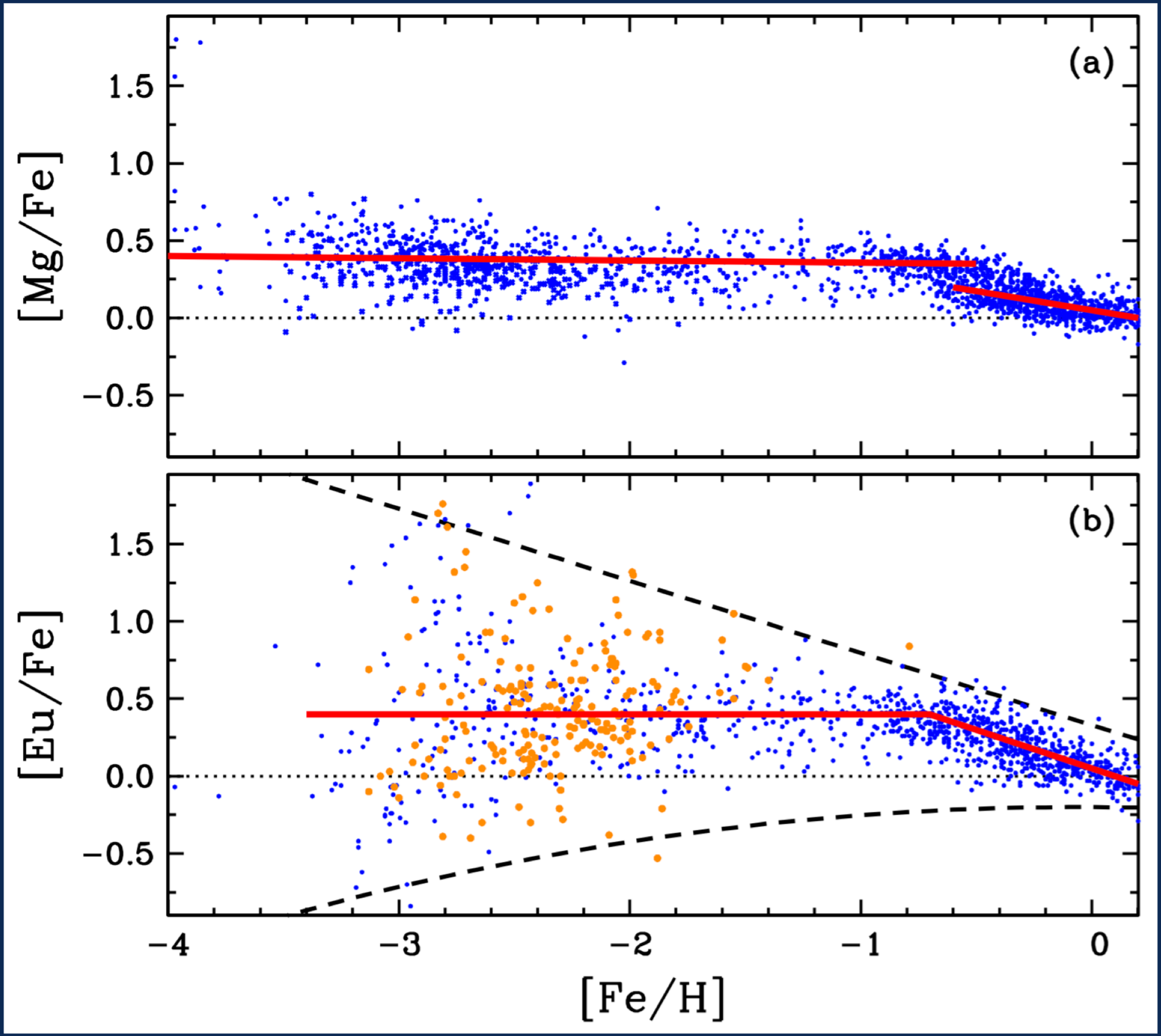
- **combines observations, theory and modeling, and experiments**
- **investigates different aspects of the r-process**
- **first goal: find the true halo distribution of r-process abundances**
- **want *approximate* totals to be:**
  - **100 *r*-II**
  - **500 *r*-I**
  - **100 *r*-limited**
- **these 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**

led by Tim Beers (U Notre Dame), with major effort by John Cowan, Rana Ezzeddine, Anna Frebel, Terese Hansen, Andrea Kunder, Vini Placco, Ian Roederer, Charli Sakari Kim Venn, Rosie Wyse, et al.!

Here is a typical low S/N snapshot spectrum of a new RPA *r*-II star



2019 version of a 2008 ARA&A figure on Eu/Fe



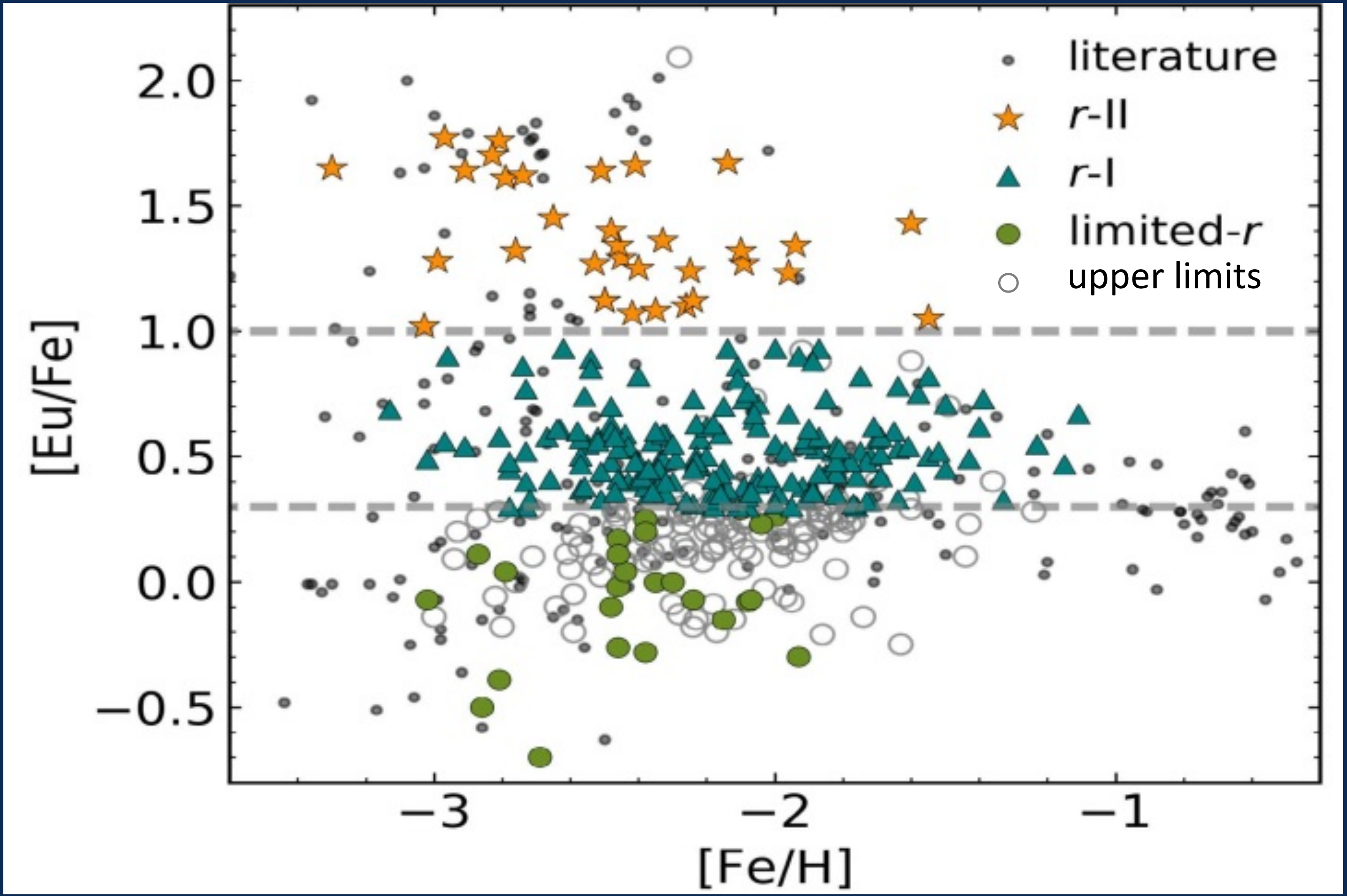
Hansen et al. 2018, Sakari et al. 2018 are the orange points

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

Overall Progress of RPA Snapshot High-Res Spectroscopy



30 NEW r-II STARS … and counting (~15 more in hand)

SUMMARY of N-Capture Results

neutron-capture elements were once neglected Periodic Table exotica

They have emerged as important signposts to explosive death stages of early Galactic element donors, particularly those parts created in the r-process

the developing statistical knowledge of the *r*-process occurrence will provide constraints on early Galactic chemical evolution

The Fe-group elements

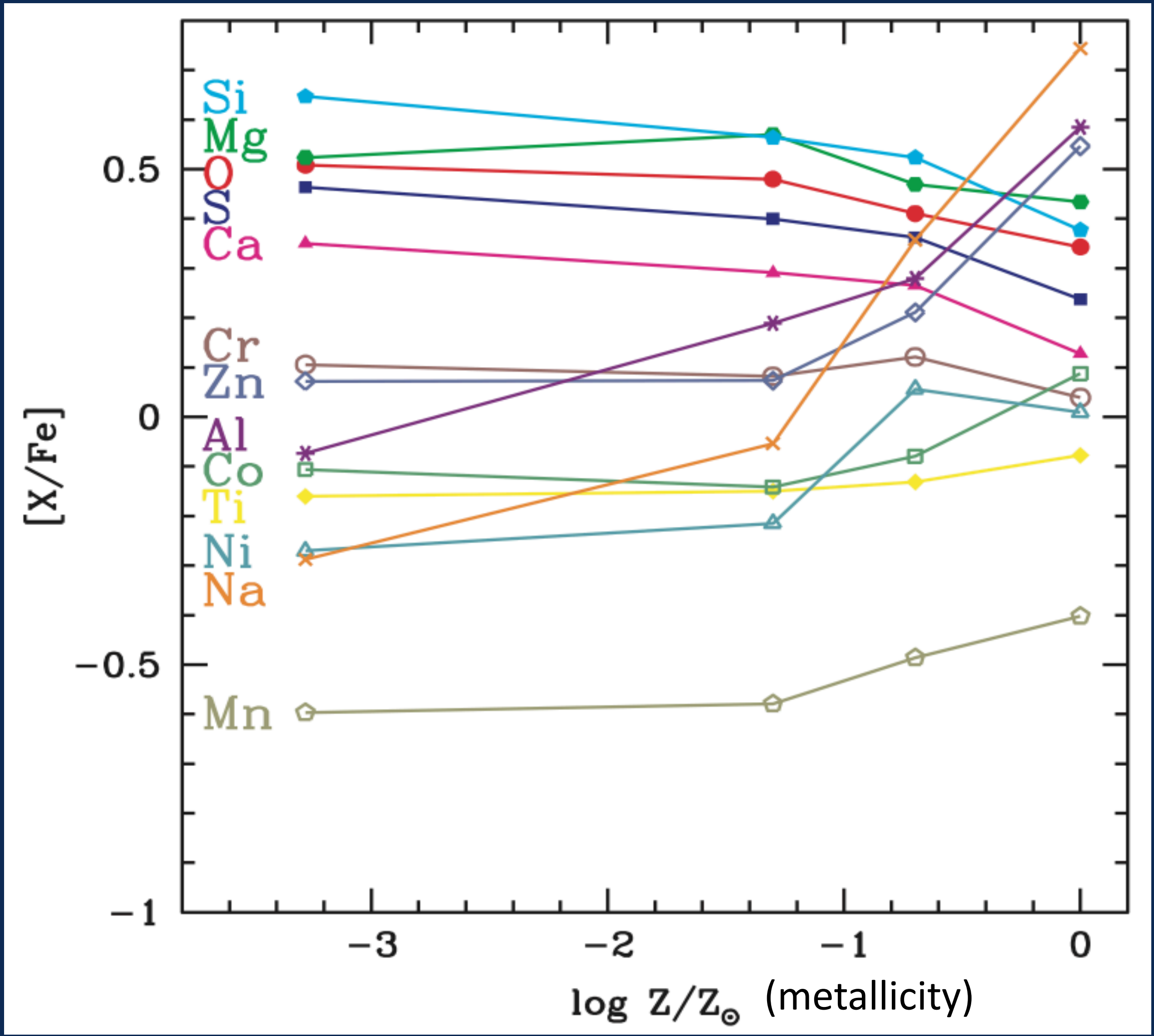
most abundant elements after H, He, C, N, O;
easily accessible spectroscopically (but ...);
many UV-optical lines in *various* metallicity stars

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

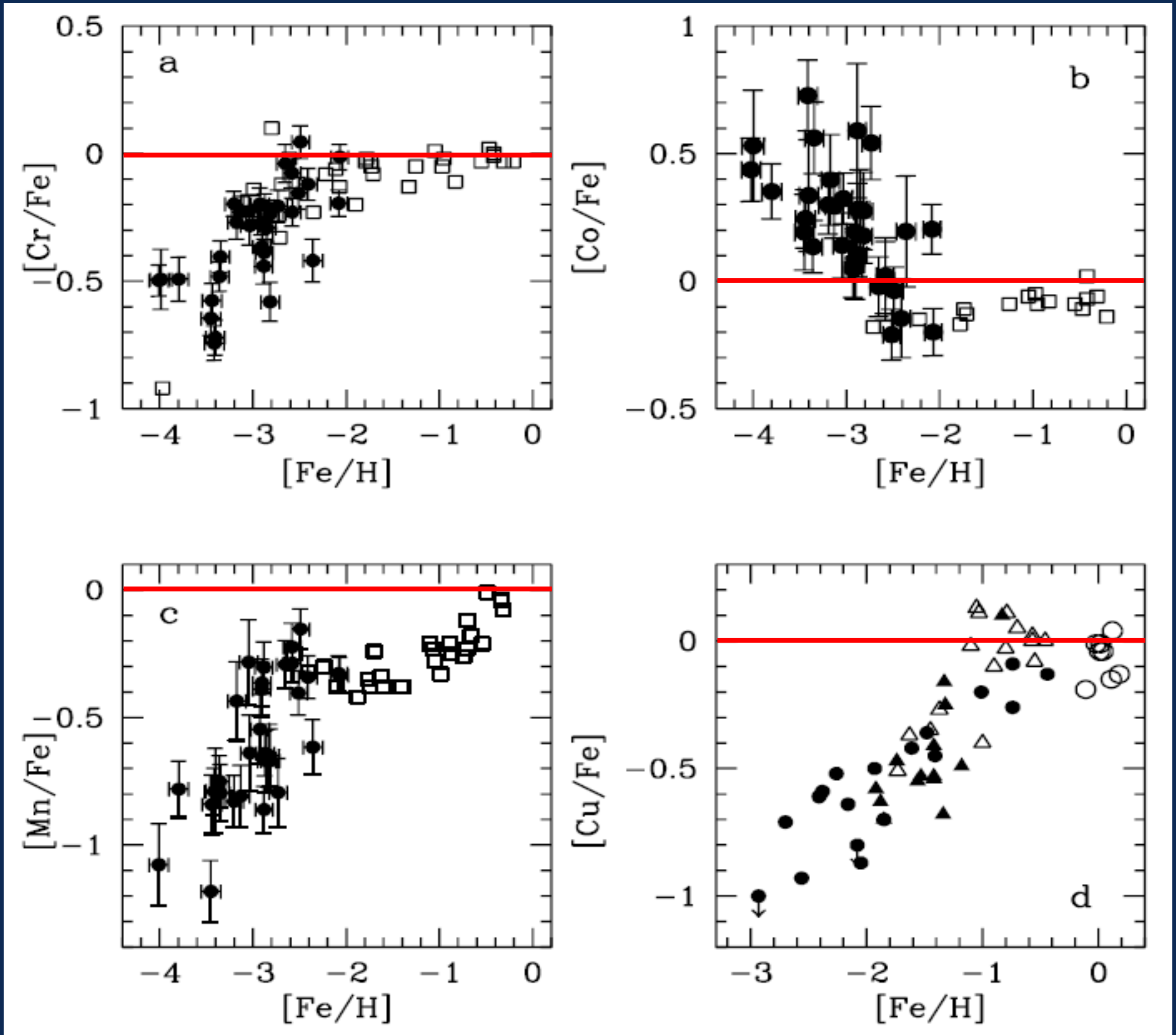
Wisconsin lab astro: major contributions to observable transitions of n-capture and Fe-group species

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, Mn, Cu are very underabundant w.r.t. Fe

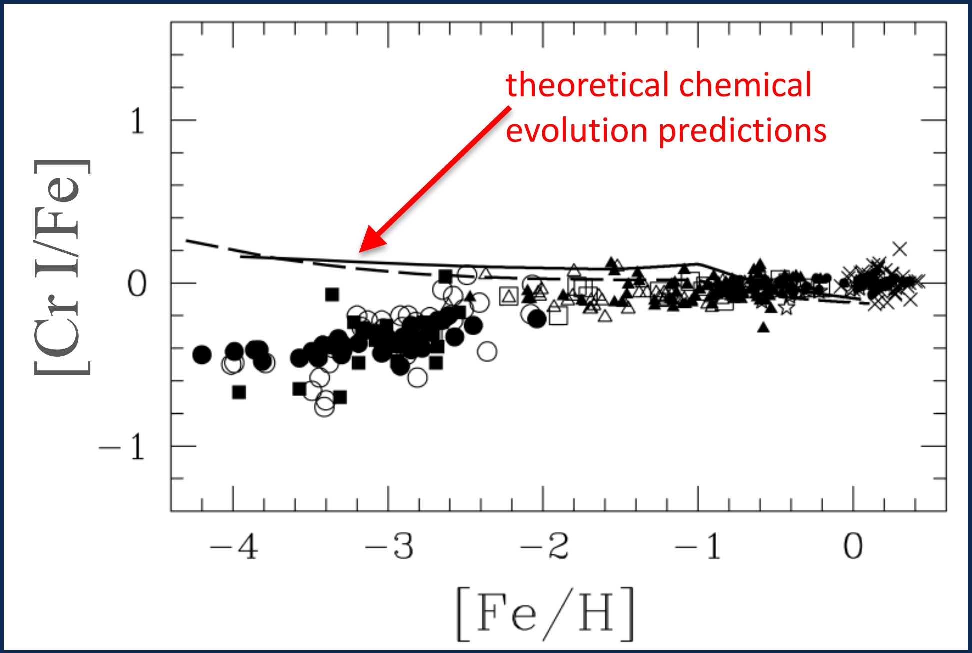
Co is very overabundant

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

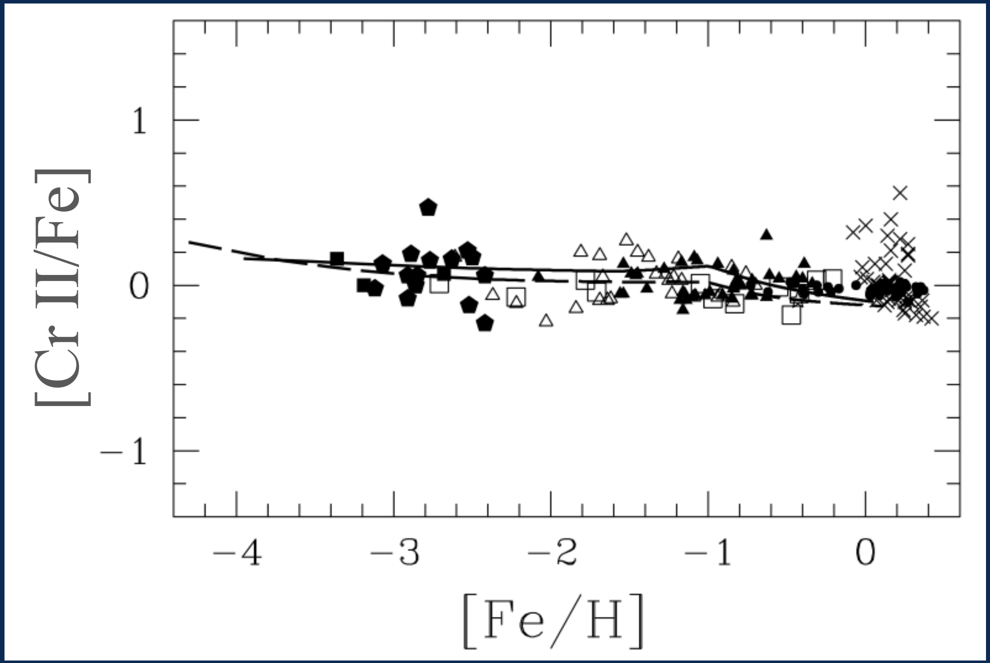
But massive star element synthesis models cannot reproduce most of these observed abundances!

Surveys with better spectra have always confirmed these trends

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



Kobayashi et al. 2006



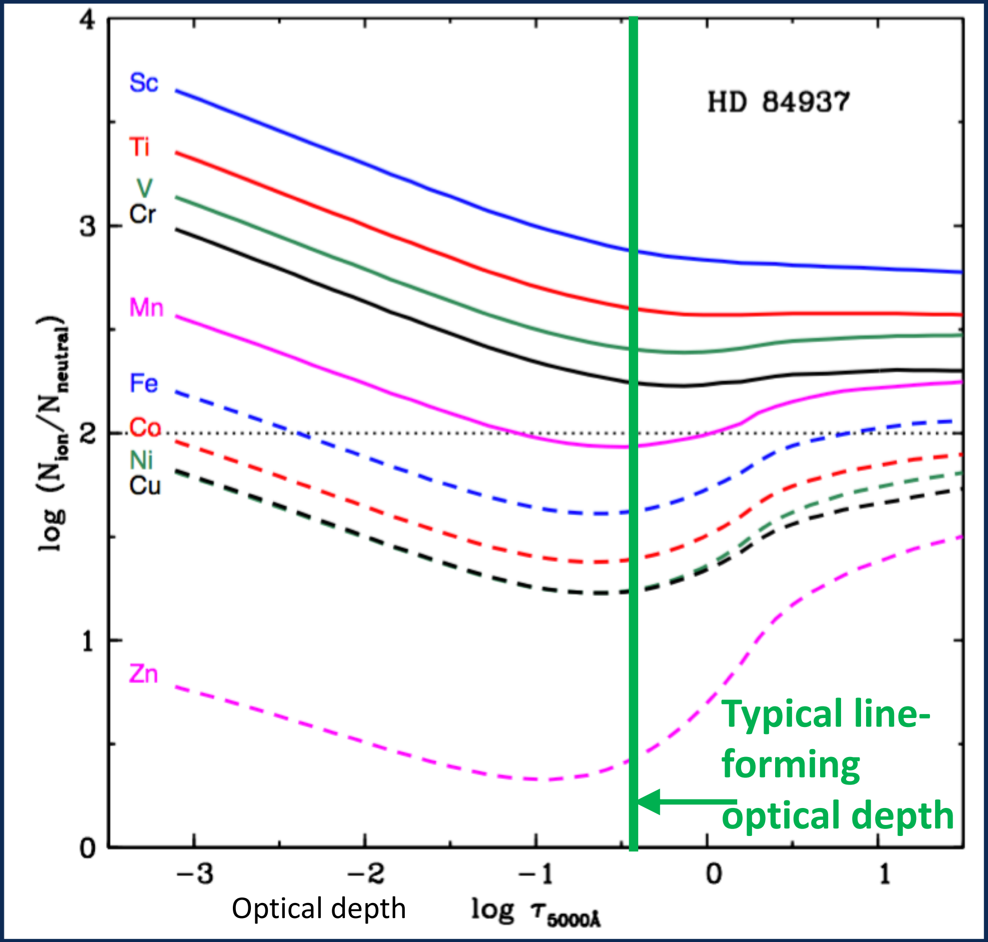
same theory, different observed species of an element

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?!

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

The “Saha” ionization balance



Sneden+2016

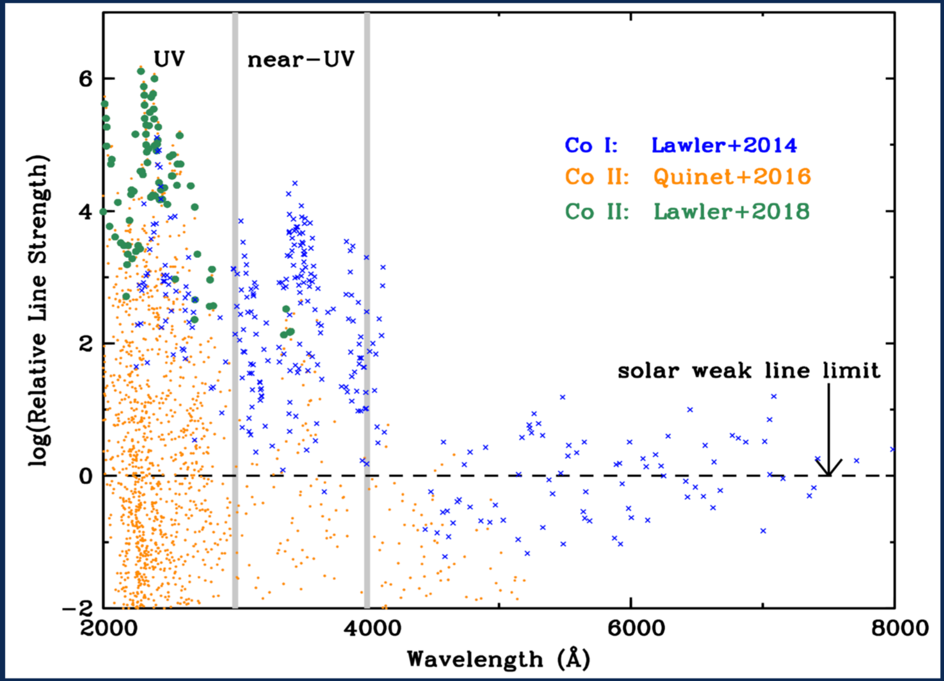
ions dominate Saha balances for Fe-group elements in warm metal-poor stars
The neutral species are mostly trace fractions ➔
big corrections from neutral number densities to elemental abundances

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"

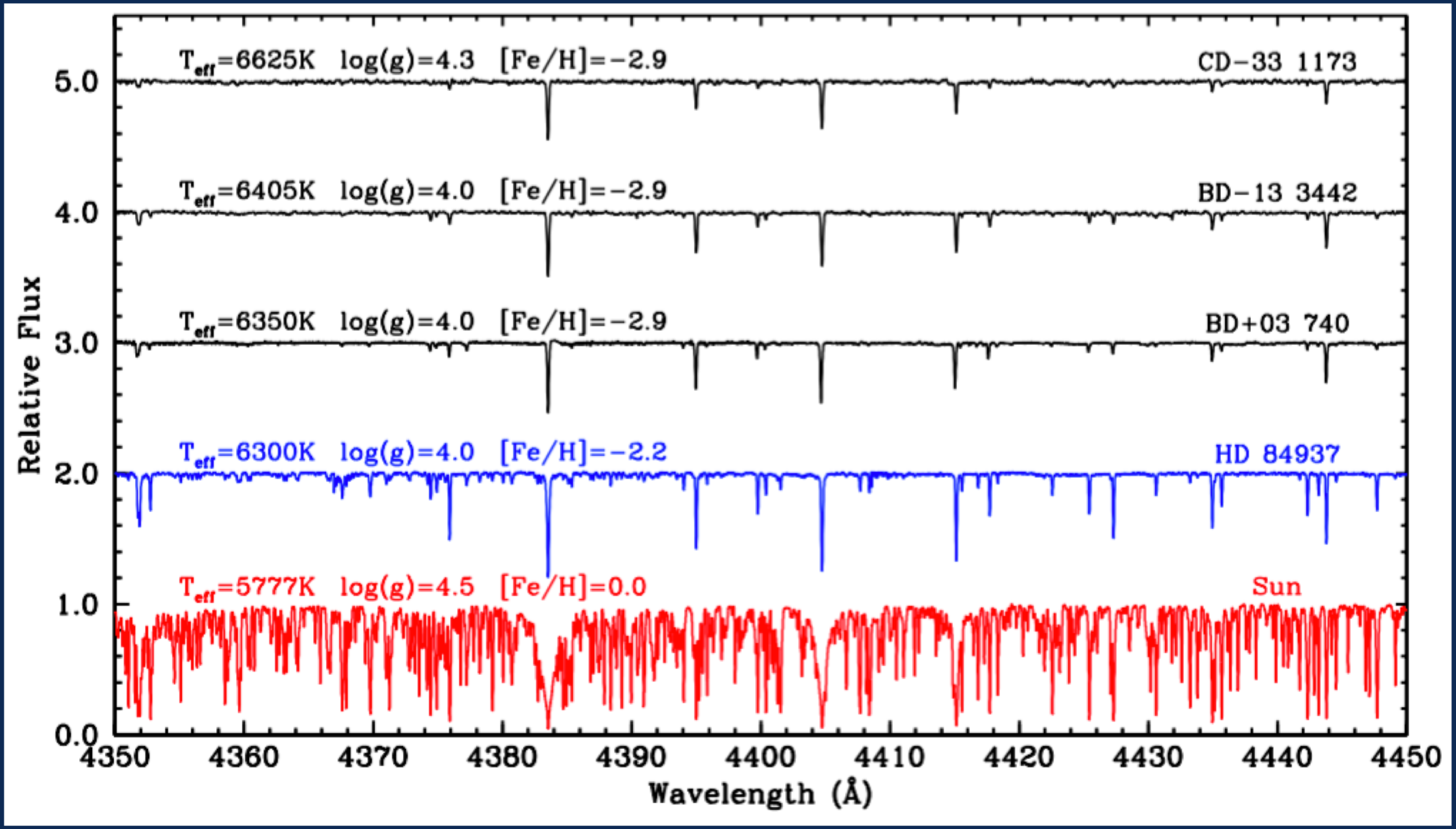
ionized-species lines are mostly in the UV



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

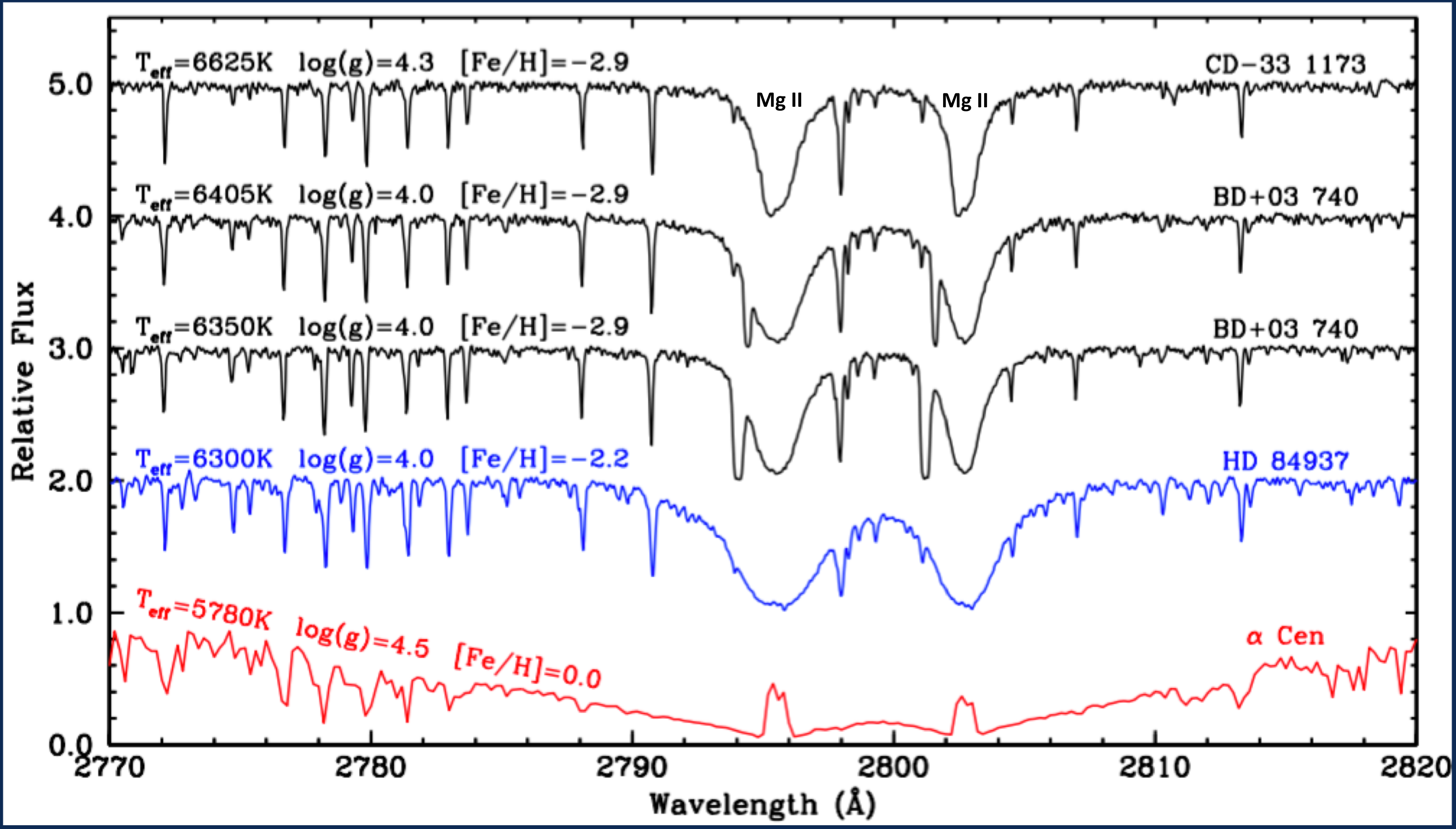
This means targeting warm main sequence stars, not red giants

The blue-yellow region is barren in low metallicity main sequence stars



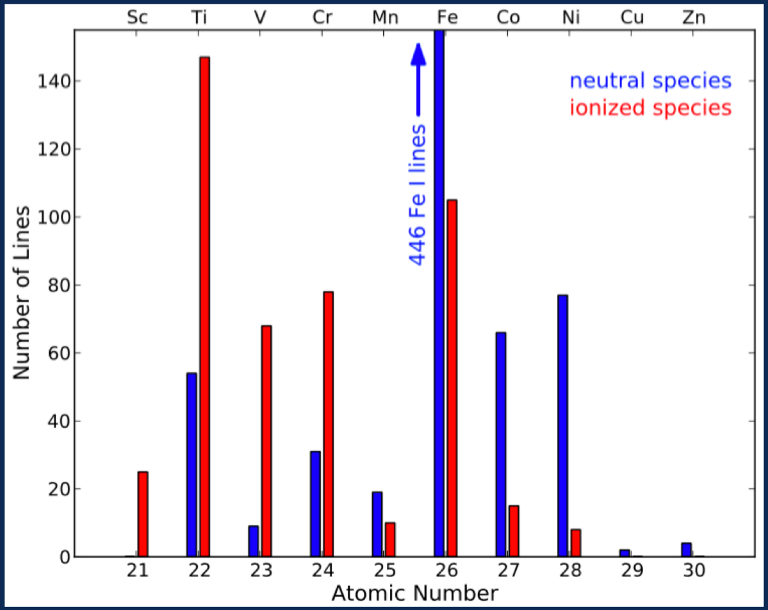
only Fe I, Fe II, and Ti II survive to be detected in these regions at [Fe/H] ~ –3

In the UV, metal-poor main sequence stars are very accessible for quantitative spectroscopy

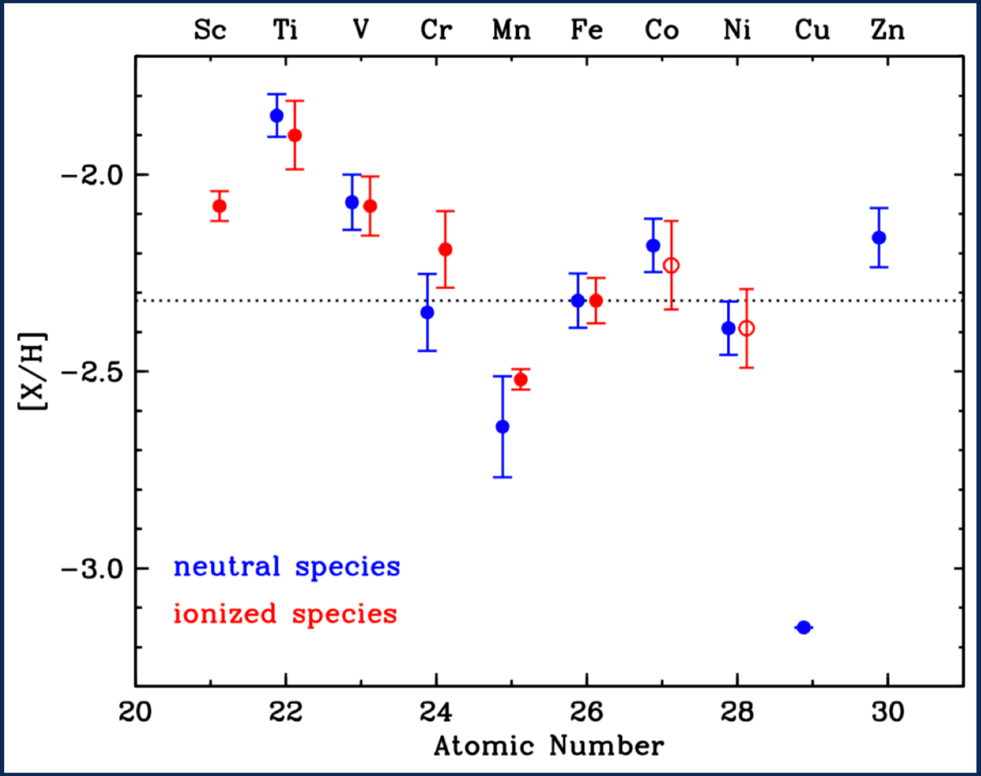


these are HST/STIS spectra: λ = 2300–3050 Å R = λ/Δλ = 25,000 S/N ≈ 70

First results: HD 84937



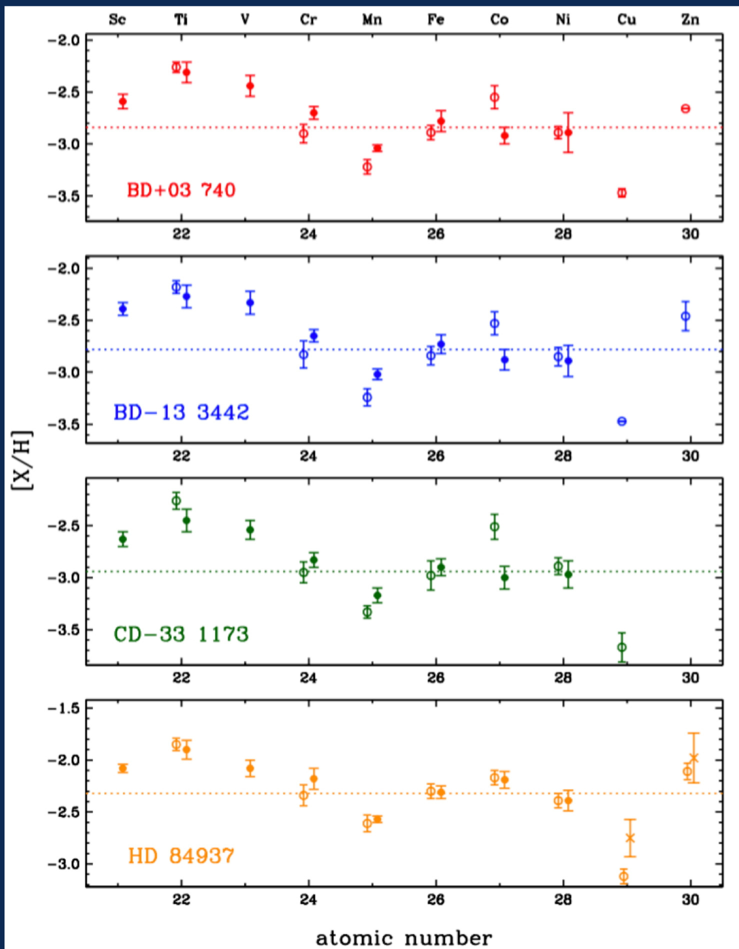
- *neutrals, ions give same abundances for 7 elements: good Saha balance*
- *standard LTE analysis shows no obvious breakdown*

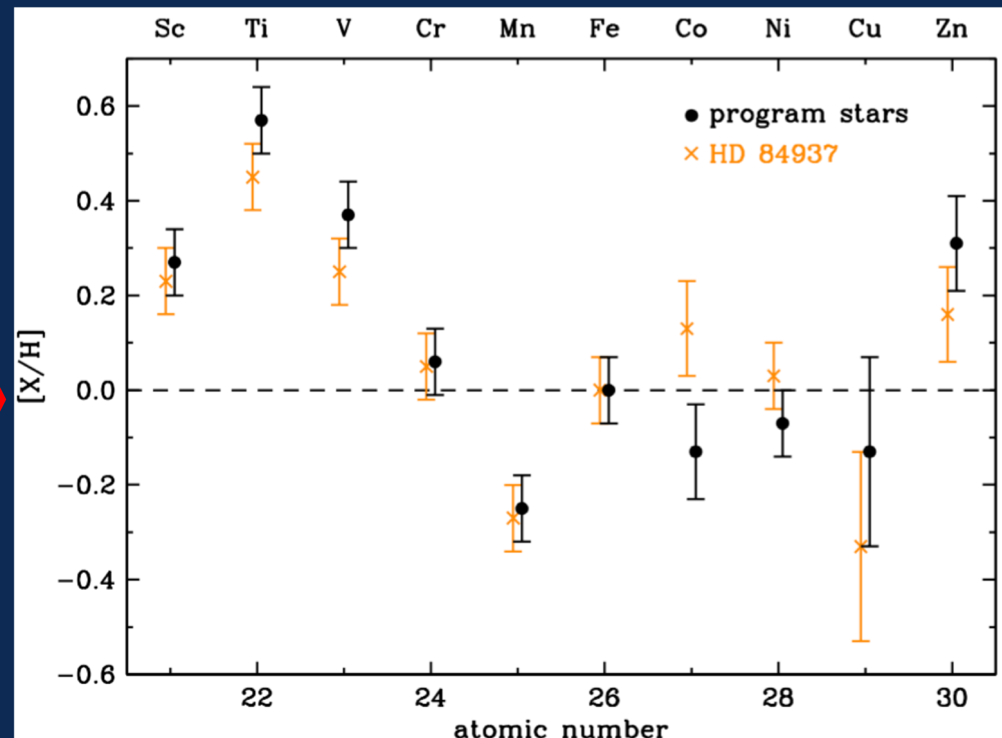


- *at [Fe/H] = –2.3 there is no sign of a Cr/Co abundance anomaly*
- *some details reveal possible NLTE effects in neutral species*
- *what about Sc, Ti, and V?*

Sneden+ 2016

the full "survey" of HST/STIS data on low metallicity main sequence stars

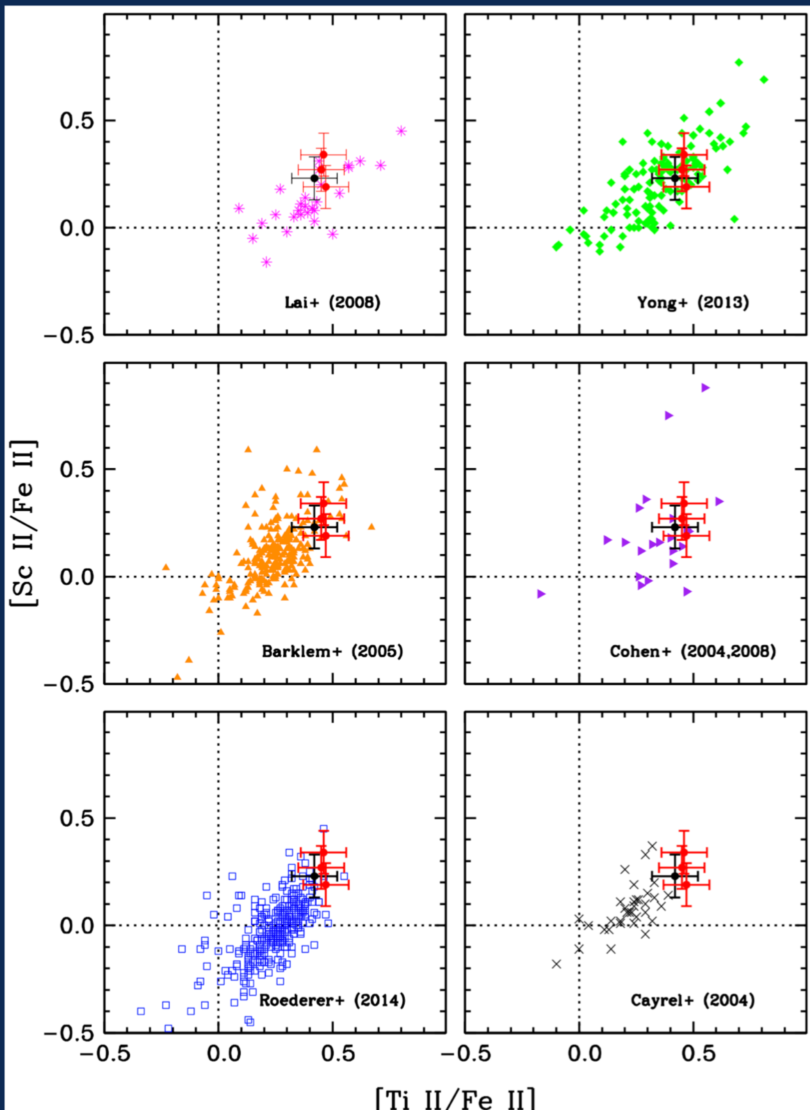


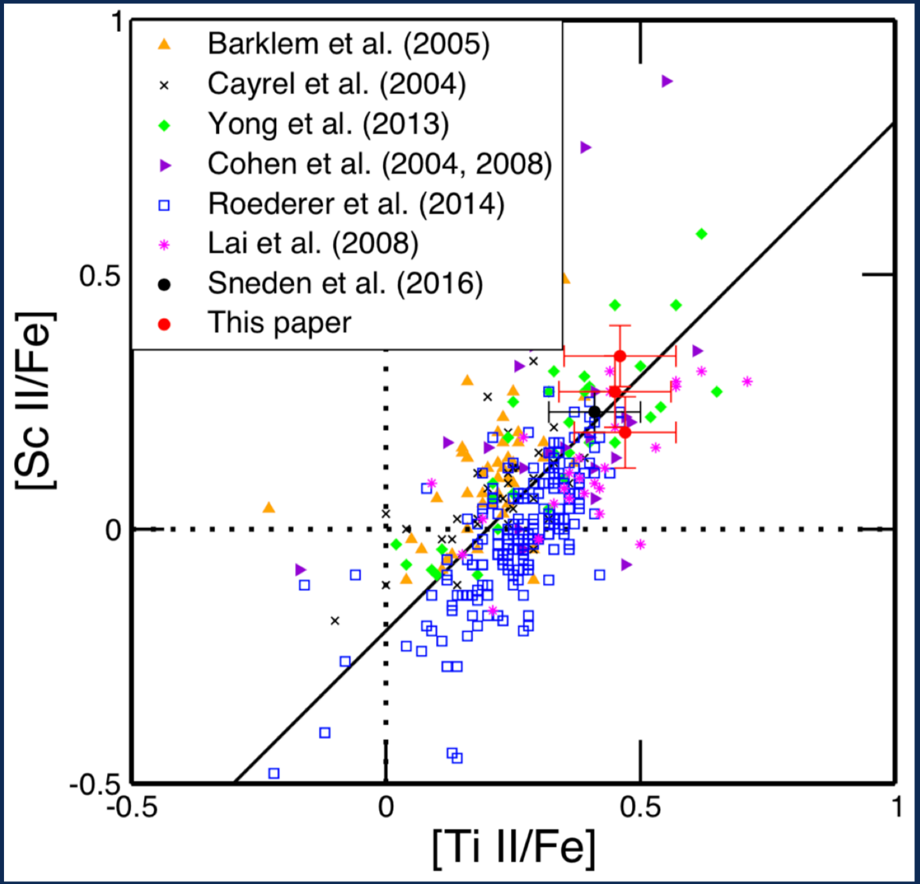


1) large overabundances of Sc, Ti, V
2) no Cr deficiency
3) Co overabundance ***only*** from Co I

Cowan+ 2020

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

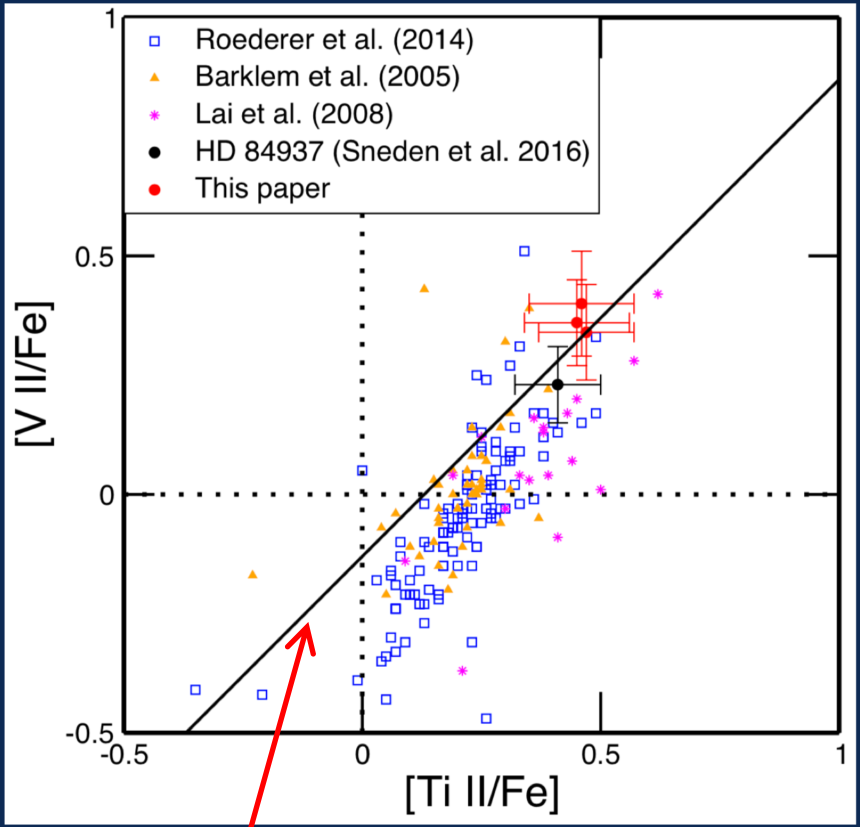




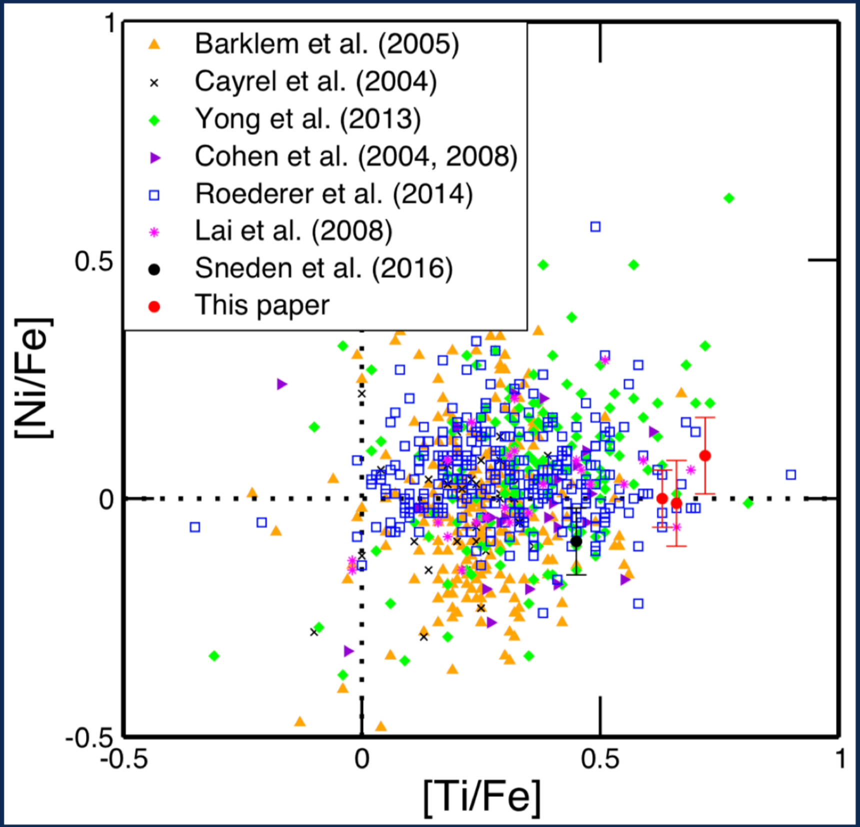
Cowan+ 2020

Is this the final “proof” that Ti is NOT an “alpha” element?

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

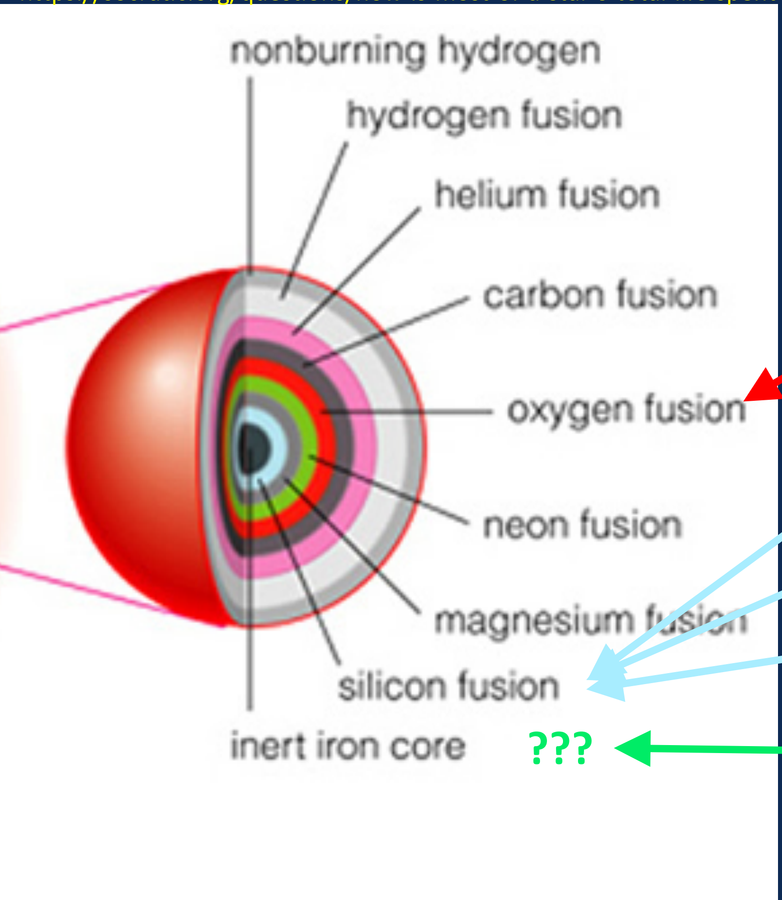


and no obvious correlation of [Sc,Ti.V/Fe] with [Cr/Fe], [Mn/Fe], [Co/Fe], ...

Cowan+ 2020

Where are the Fe-group elements 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

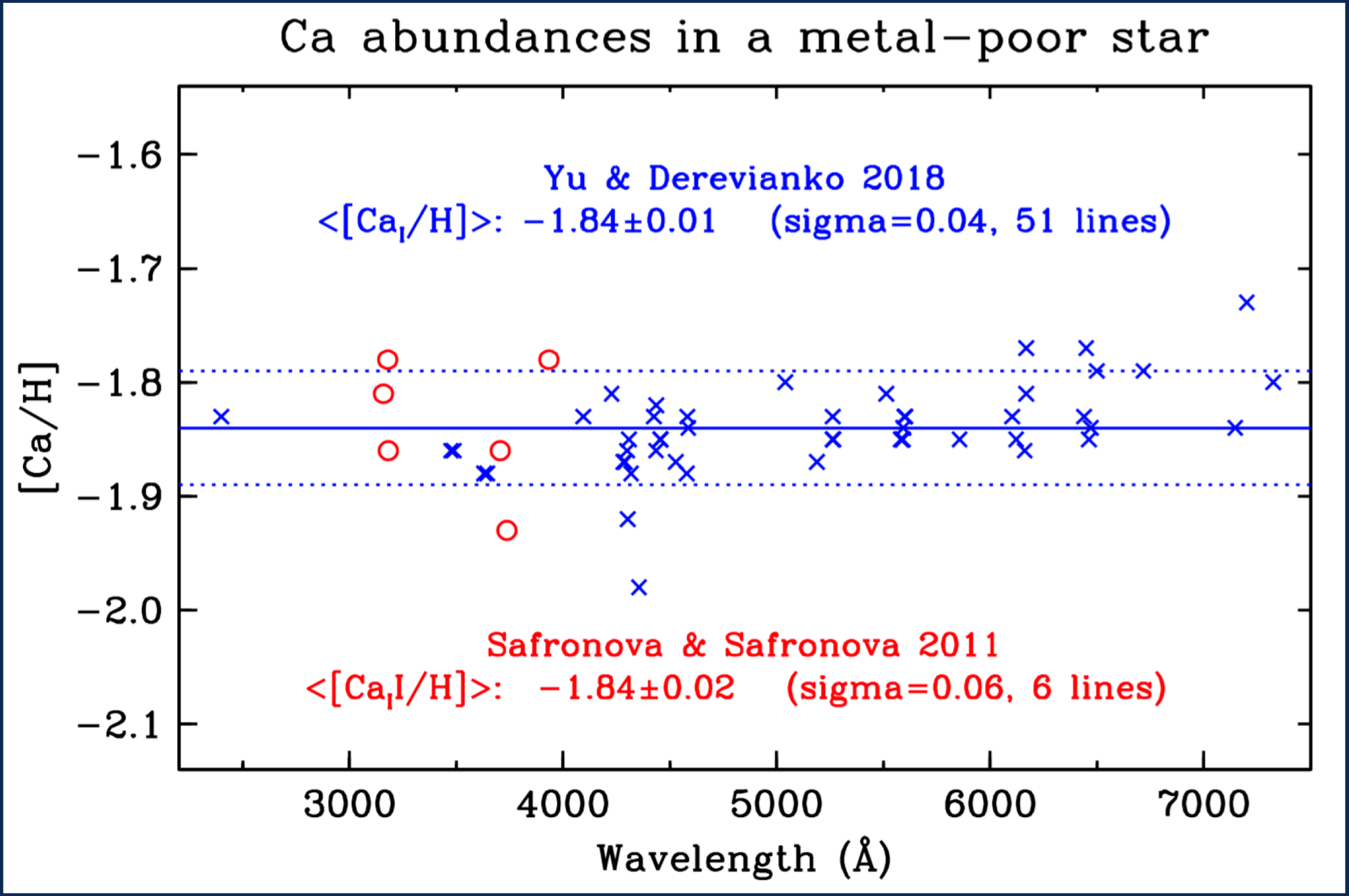
SUMMARY of Fe-group Results

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

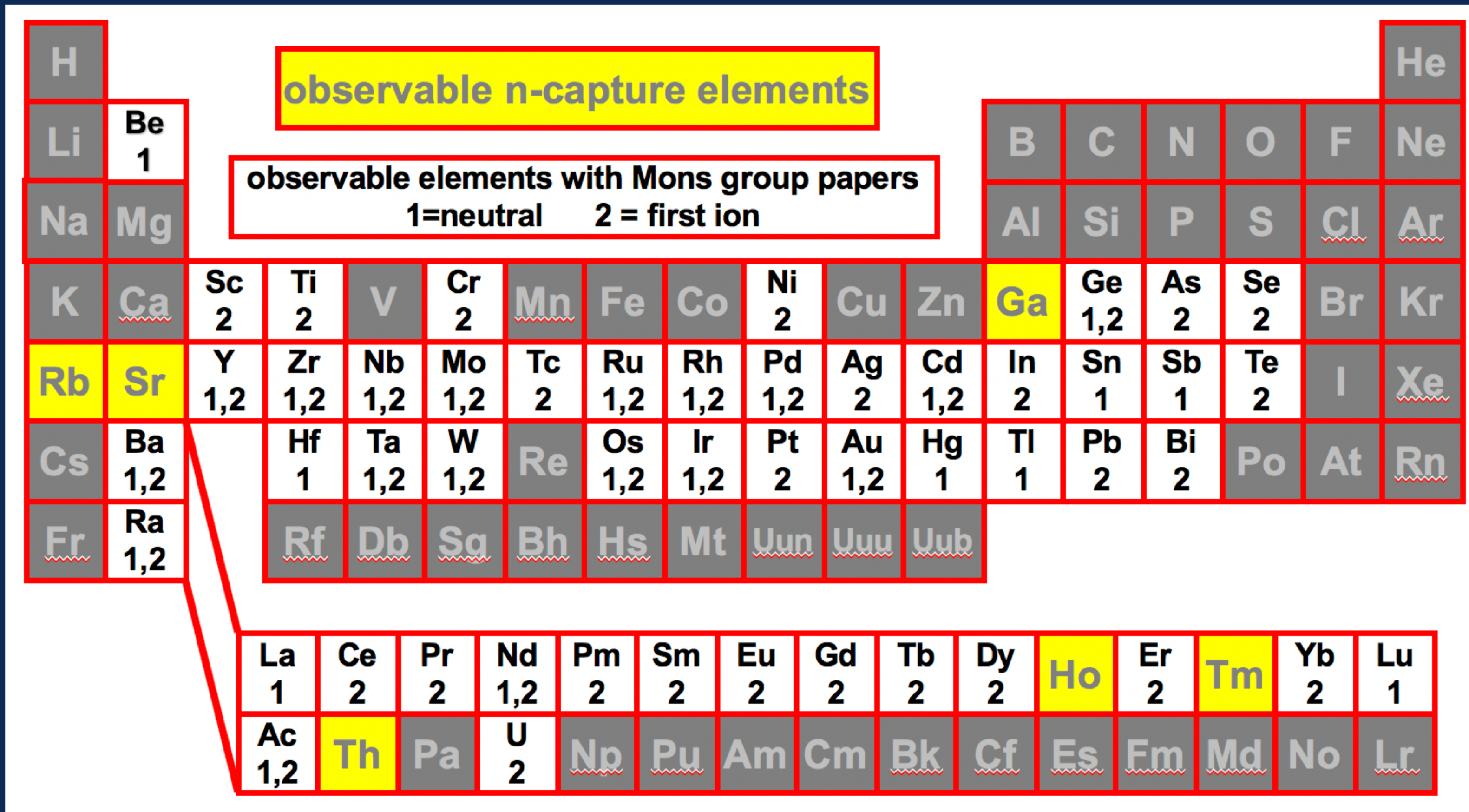
Sc, Ti, and V ARE correlated — hey nucleosynthesis people: it is time to get back to work

don't stop now! Many very common elements need modern transition data



the Wisconsin group is measuring new lifetimes for Ca

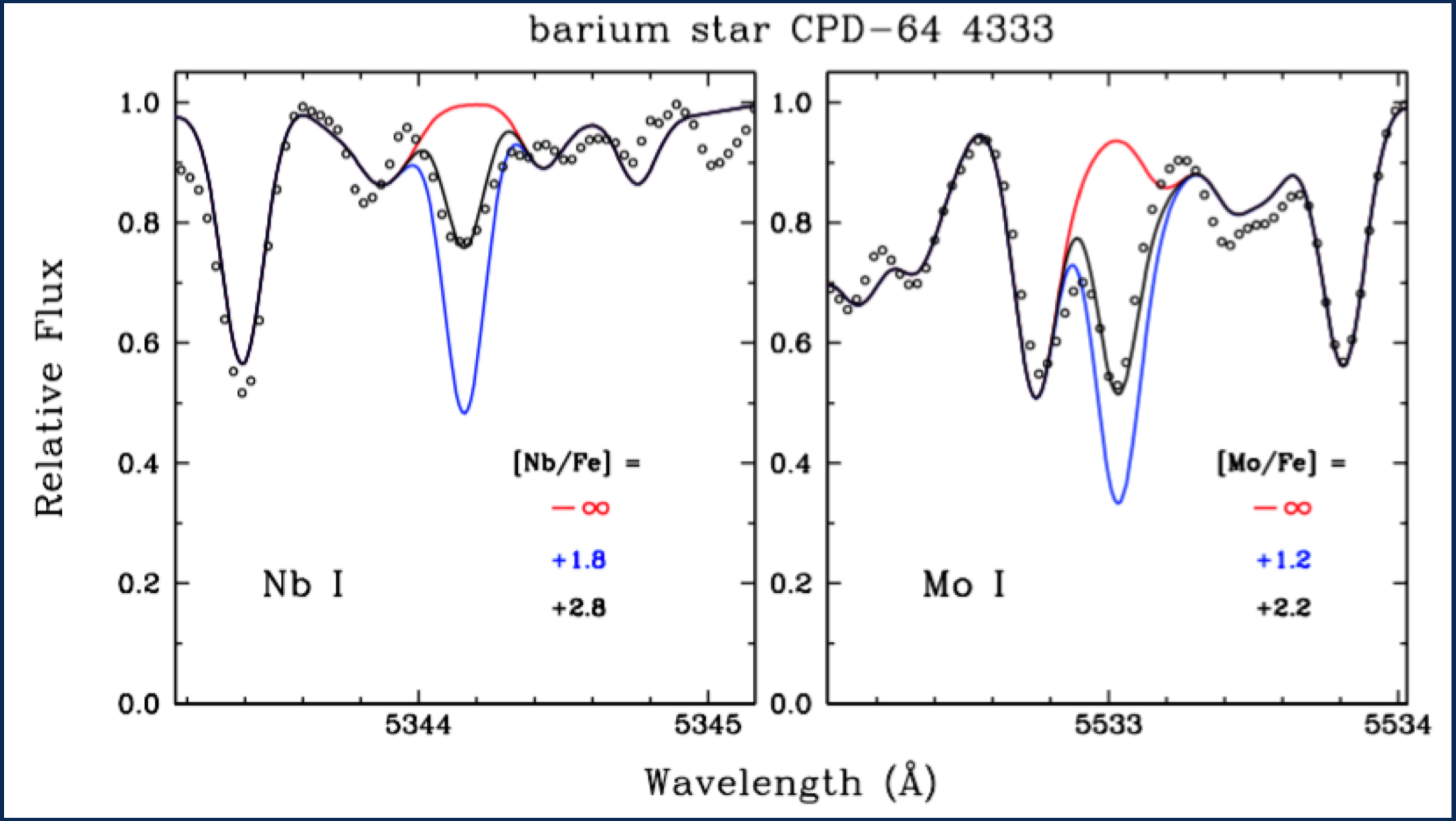
Université de Mons Atomic Physics has contributed greatly to the lab/theory improvements



Émile Biémont, Pascal Quinet, Patrick Palmeri, Michel Godefroid, and friends

this chart does not show their contributions to more ionized atomic species!

notice that many of their unique contributions have been for "neglected" species

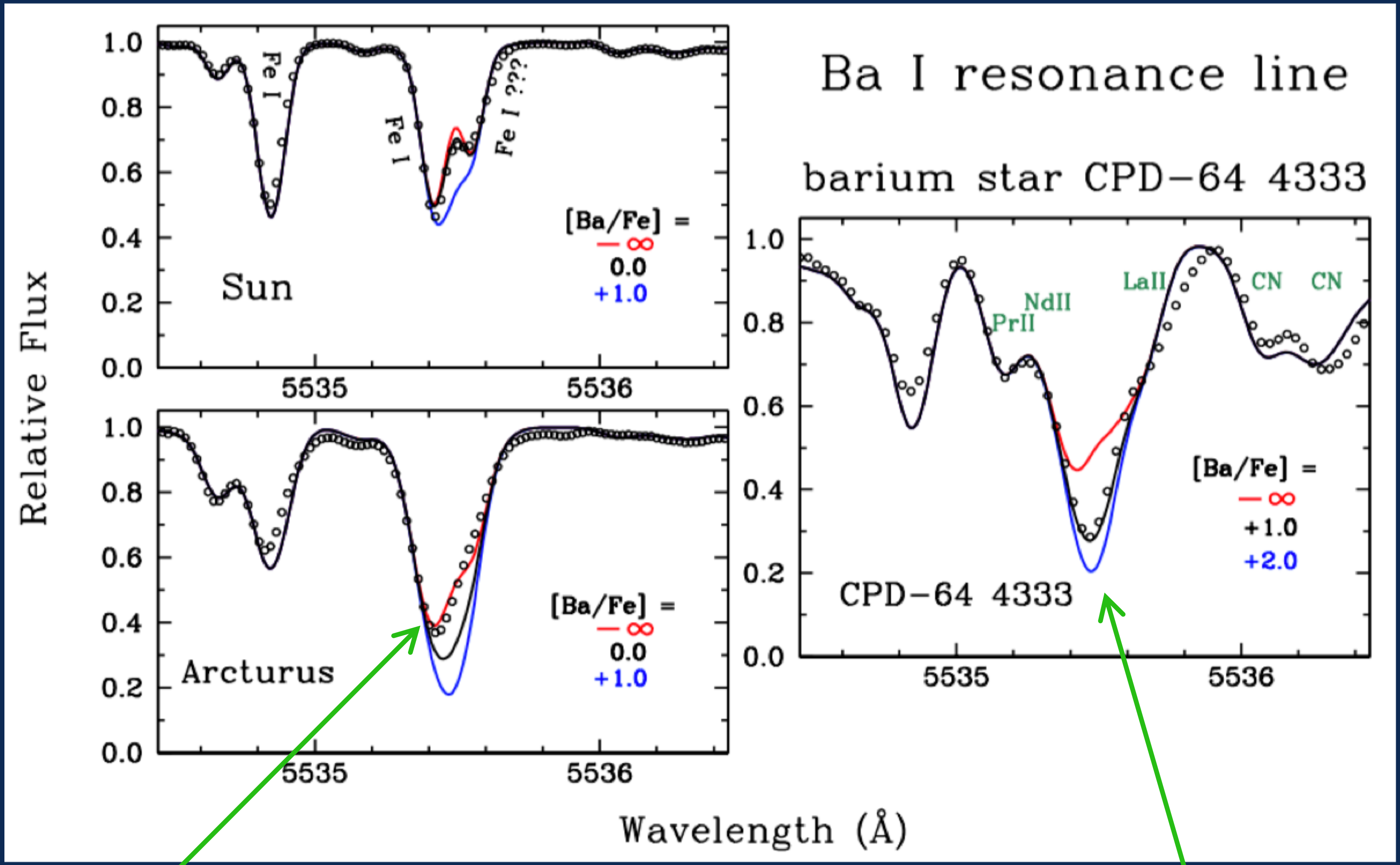


M. Roriz, C. Pereira et al., in prep

barium stars: high metallicity s-process-enhanced red giant stars

this is just "conscientiousness raising" with easy to detect transitions

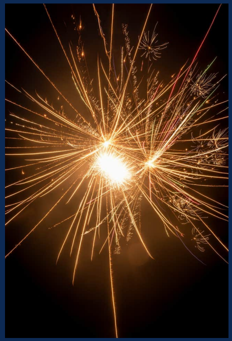
Even the very elusive neutral barium is detectable in the right kind of stellar atmosphere



M. Roriz, C. Pereira et al., in prep

Ba I is undetectable in ordinary stars

Simple detection with a rational abundance is a victory here



we really should be celebrating!

- all aspects of abundance studies in stars of all metallicities have greatly improved over the past several decades
- we are rapidly approaching true "precision" abundance results
- stellar abundances now can quantitatively confront nucleosynthesis theory

but we should not ignore a sobering reality

G. Nave et al. 2019, Bull. Am. Ast. Soc., 51, 1

- atomic spectroscopy has been shrinking … there could be no groups left at the end of the next decade unless significant effort is made to recruit and train new people
- by the time new UV telescopes are launched (e.g. LUVOIR) there will be no people left who know how to calibrate them or measure required data for the interpretation of their spectra
- ***What is the purpose of gathering higher spectral resolution observations if the origin of the spectrum is misunderstood and the wavelengths of the lines are not adequately known?***

MANY THANKS FOR INVITING ME TO SPEAK AT THIS MEETING