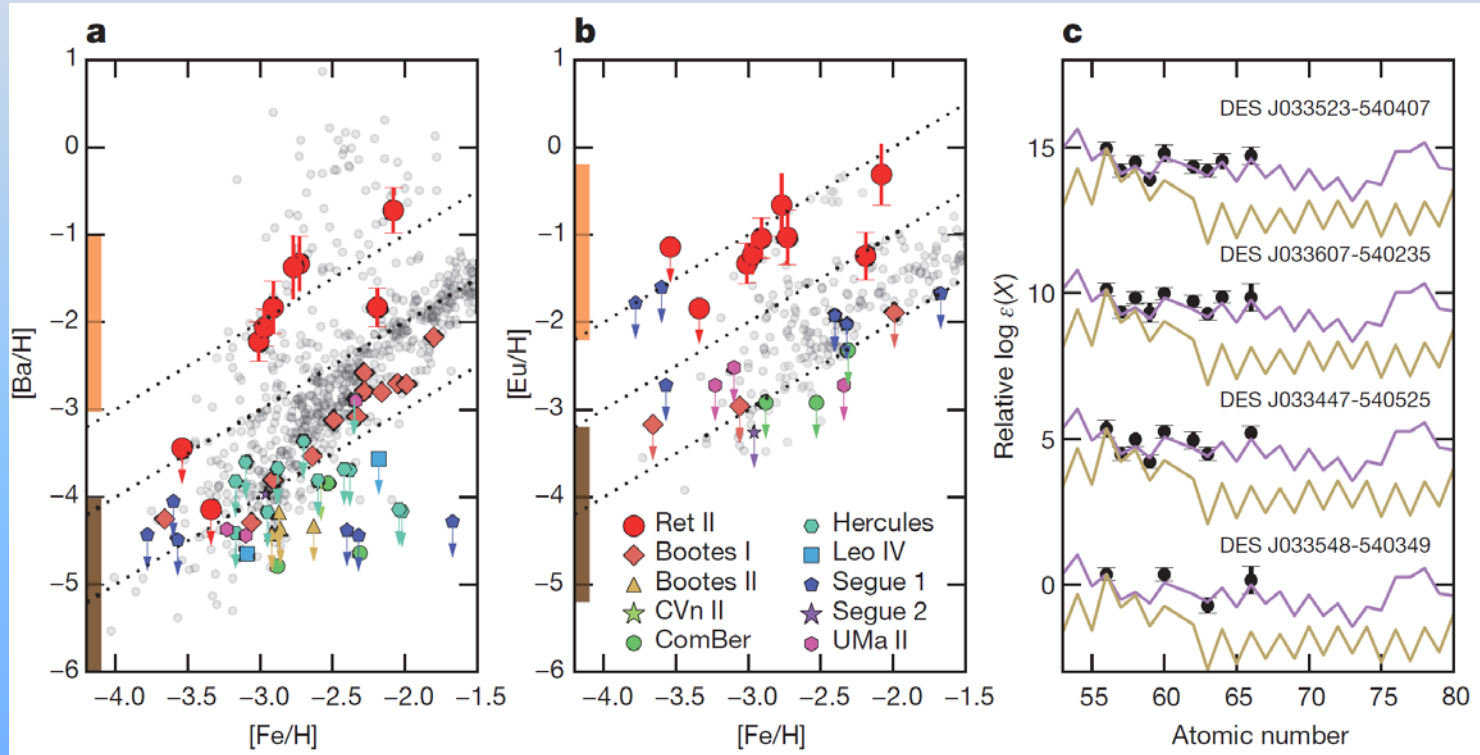
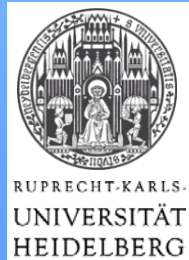


Constraints on nucleosynthesis processes and their sites from stellar abundances

Norbert Christlieb (ZAH, U Heidelberg)



(Ji et al. 2016, Nature 531, 610)



Deutsche Forschungsgemeinschaft
DFG



Contents

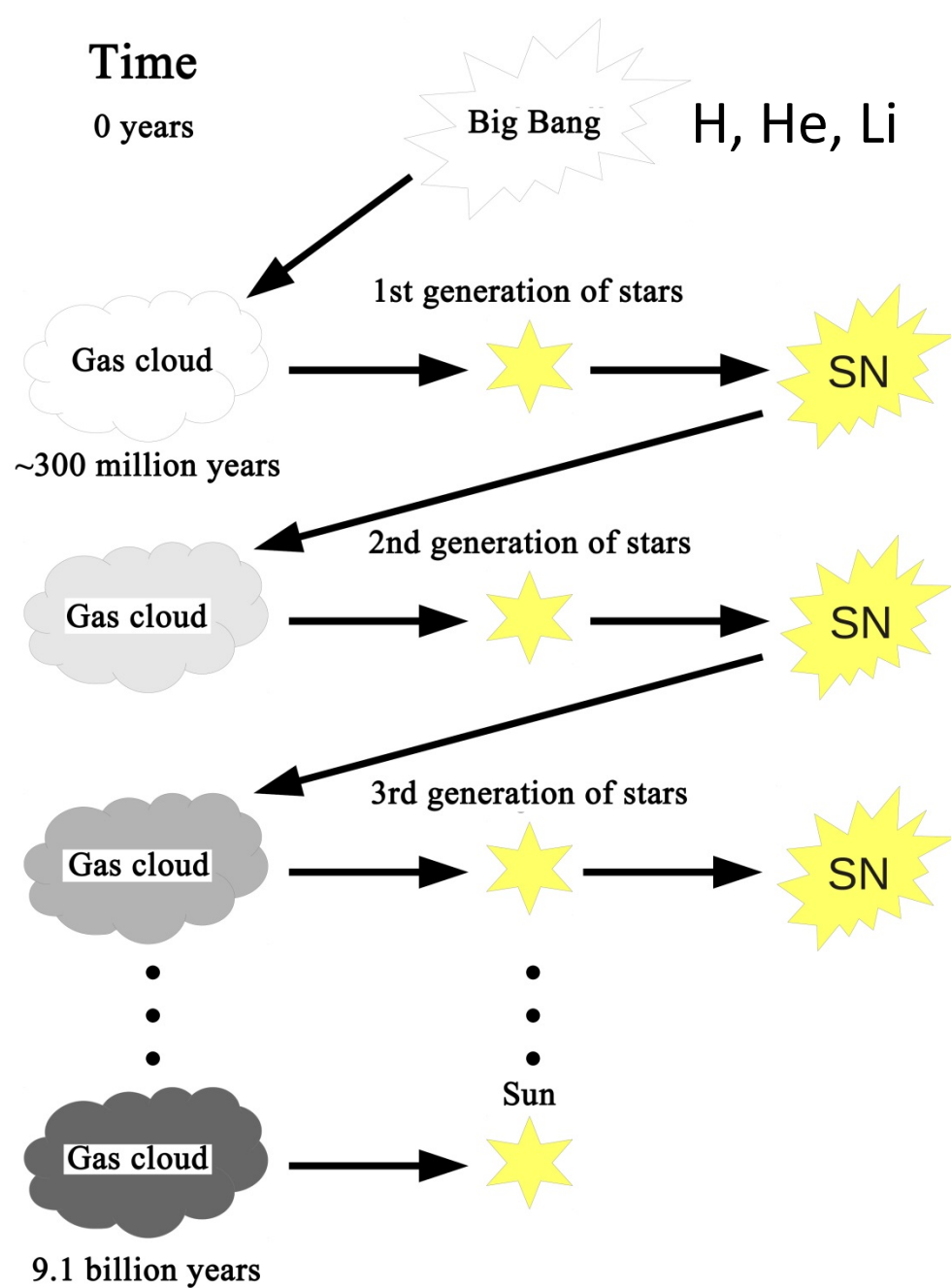
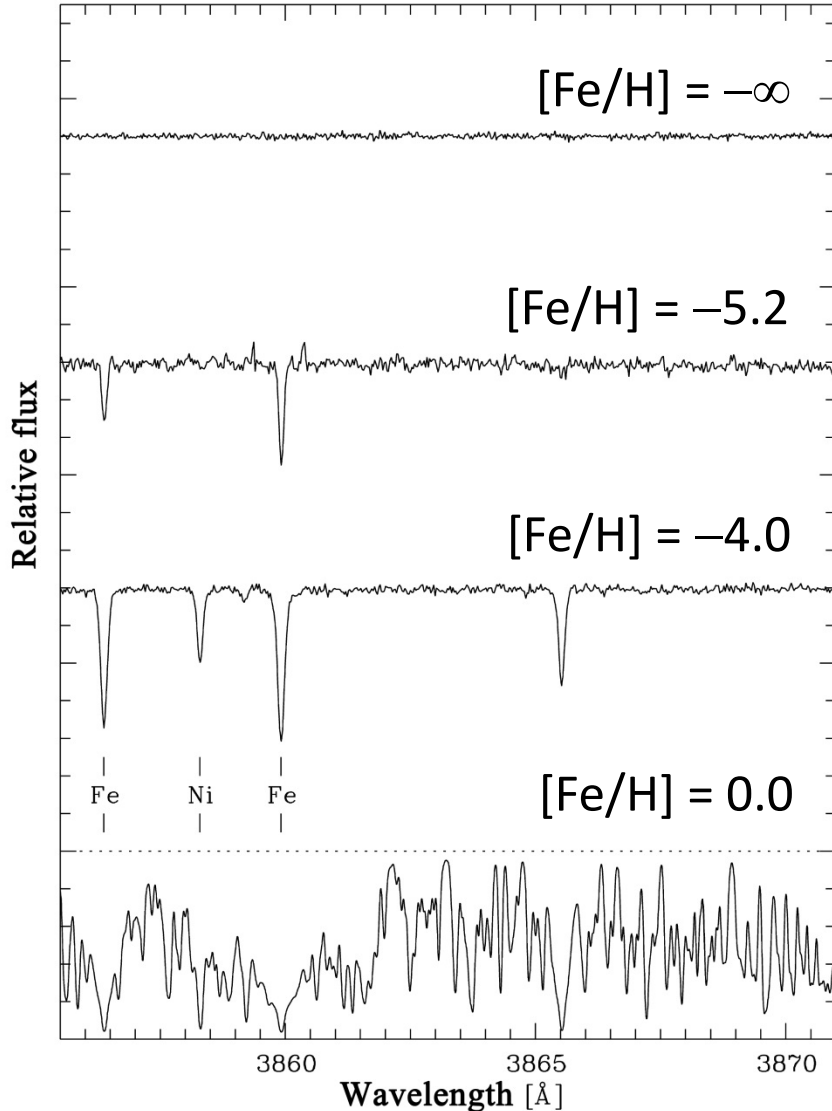
- Introductory remarks
- Measurements of elemental abundances and isotopic ratios in metal-poor stars
- Outlook

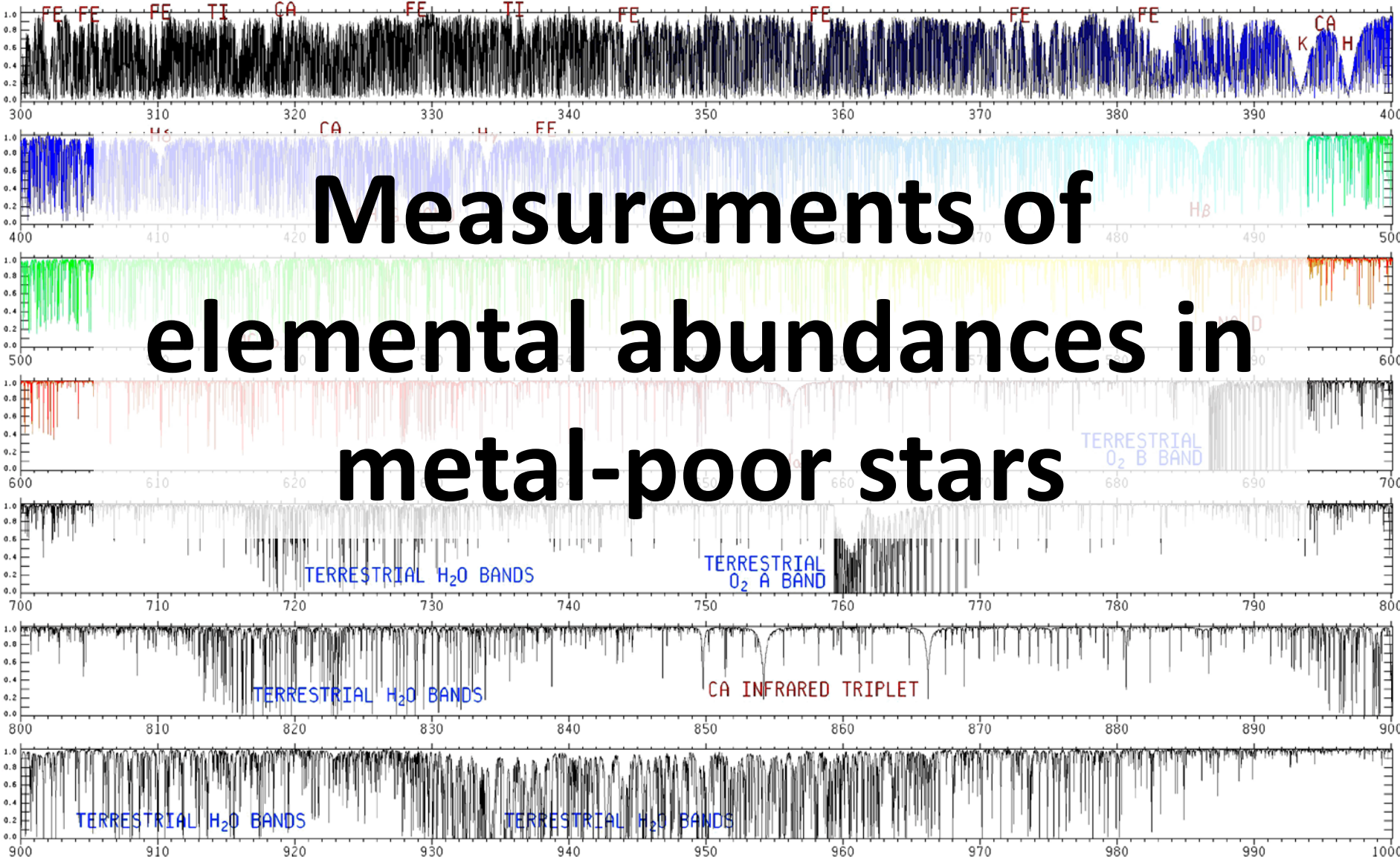
Examples (main-sequence stars)

Mass	$10 M_{\text{Sun}}$	$0.8 M_{\text{Sun}}$
Radius	$4 R_{\text{Sun}}$	$0.9 R_{\text{Sun}}$
T_{eff}	20,000 K	5200 K
Luminosity	$3000 L_{\text{Sun}}$	$0.6 L_{\text{Sun}}$
Spectral type	B2	K0
MS lifetime	10^7 yr	$2 \cdot 10^{10}$ yr

- Use hot stars if you want to study present-day cosmic abundances.
- Use old, cool stars if you want to study chemical enrichment history of the Universe.

Chemical enrichment of the Universe





Measurements of elemental abundances in metal-poor stars

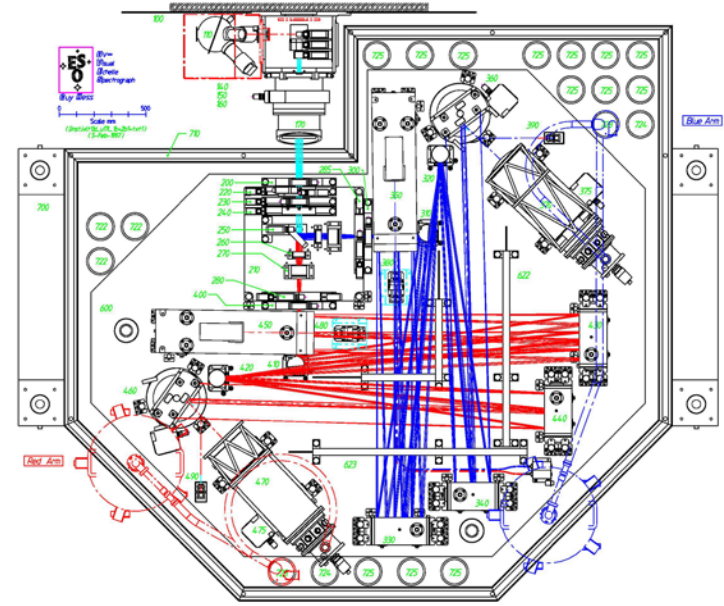




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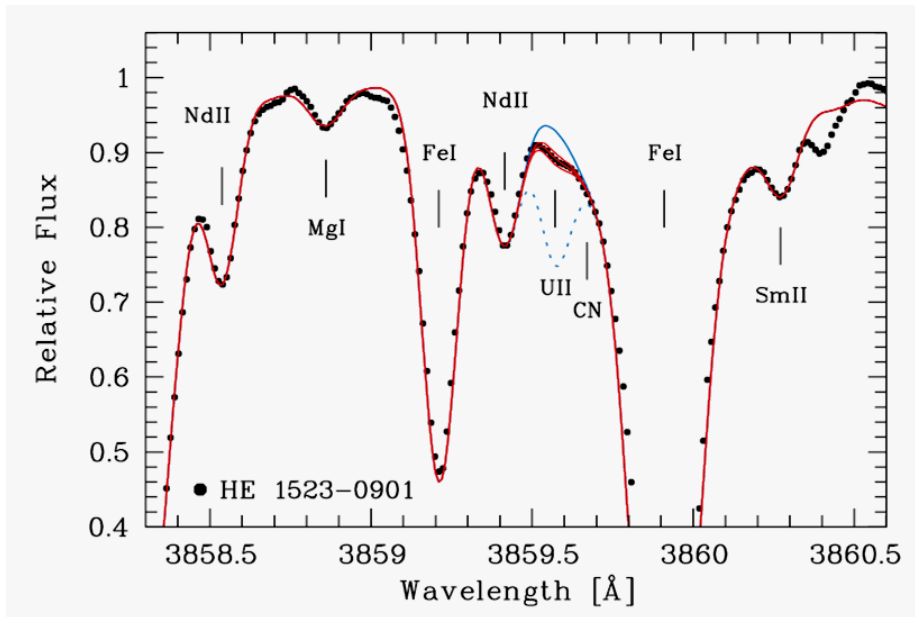
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UVES

(two-arm cross-dispersed
Échelle spectrograph =>
high spectral resolution
and large wavelength
coverage)

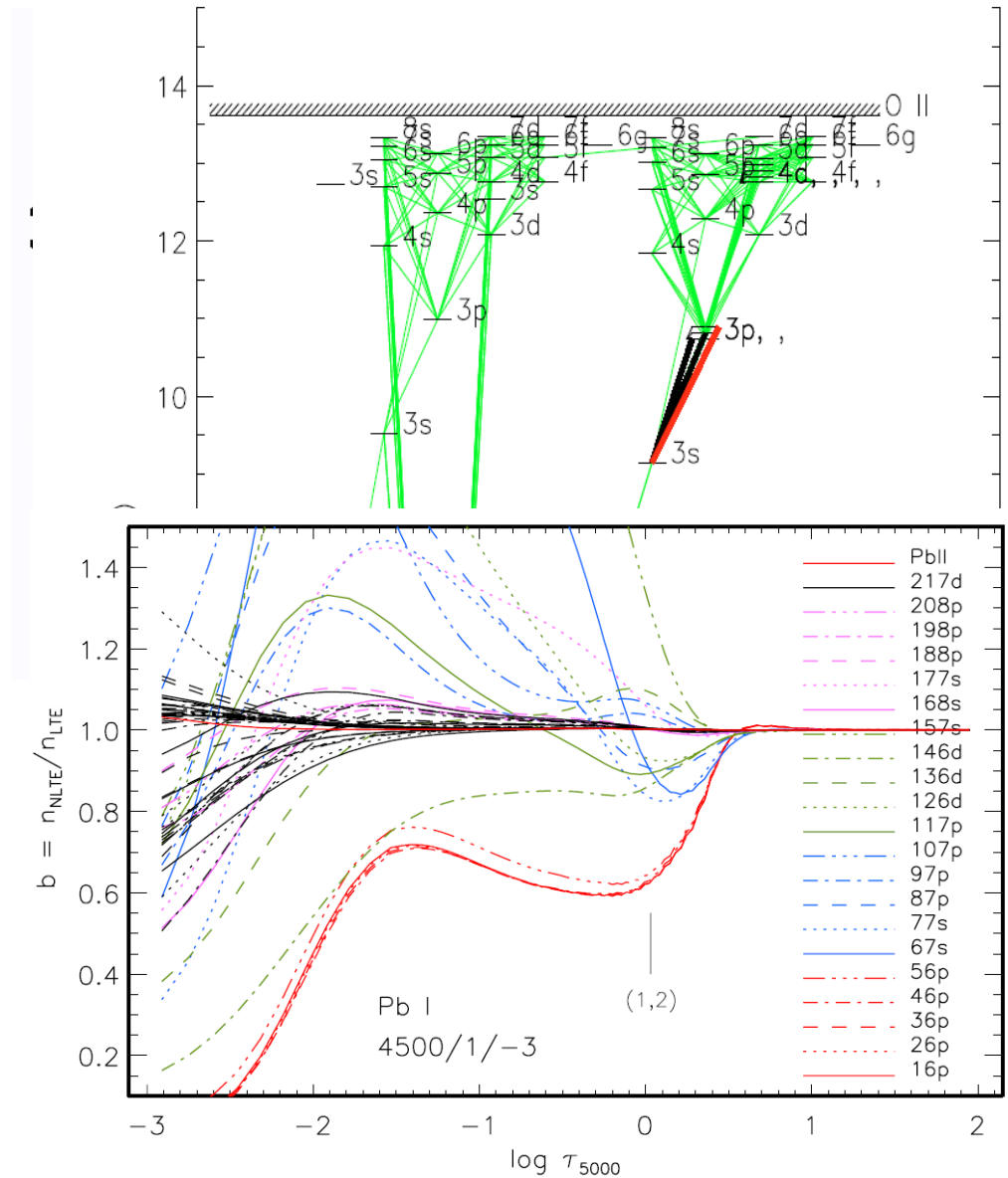
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From spectra to abundances

Ingredients:

- Stellar parameters:
 T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$
- Model atmospheres
(1D? <3D>? 3D?)
- Atomic data ($\log gf$,
 λ , χ , partition
functions...)
- Line formation
calculations (NLTE?)



Elements measured in metal-poor stars

hydrogen 1 H 1.0079																	helium 2 He 4.0026				
lithium 3 Li 6.941	beryllium 4 Be 9.0122															boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305															aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80				
rubidium 37 Rb 85.468	strontium 38 Sr 87.62	yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29				
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]			
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]							

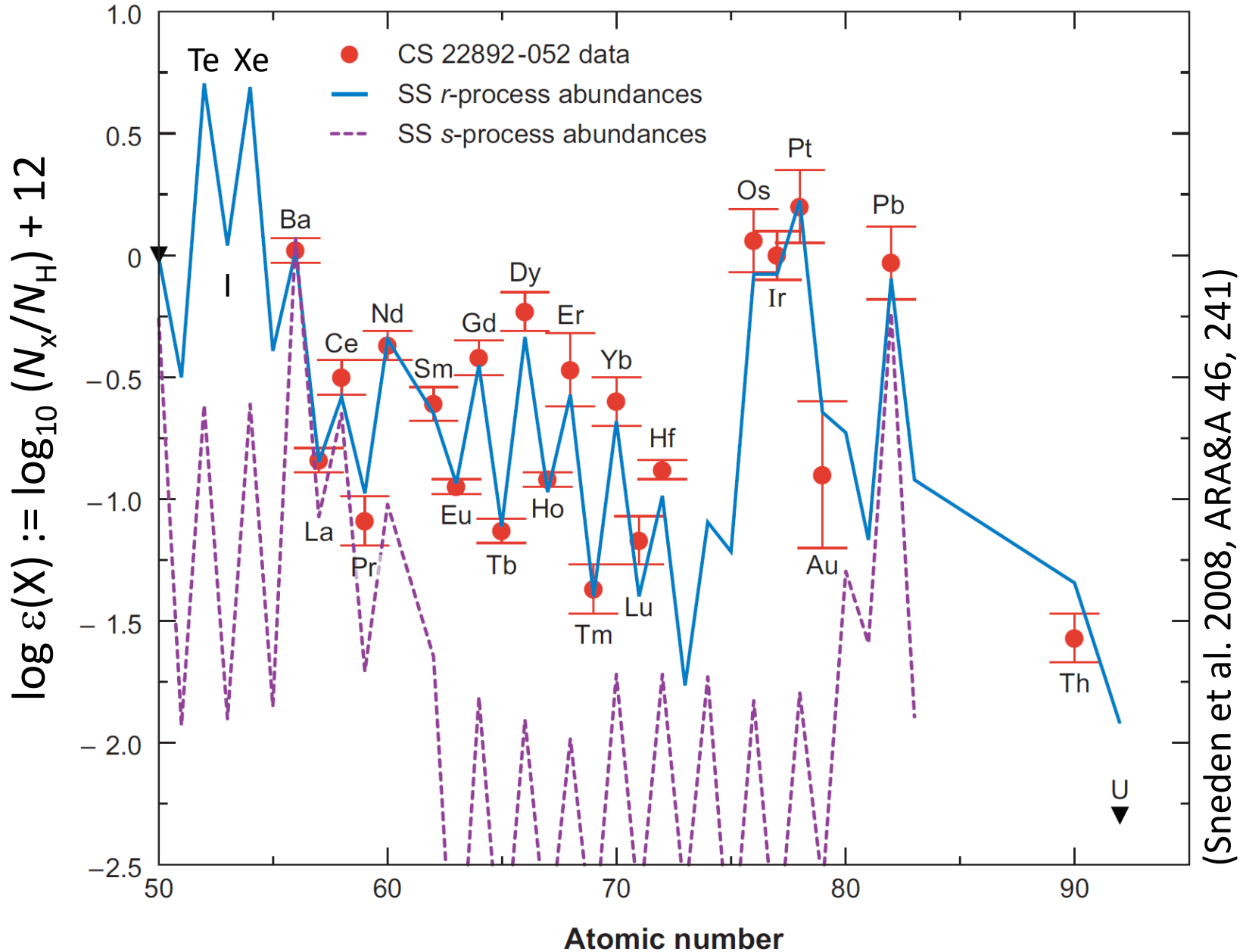
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

* Lanthanide series

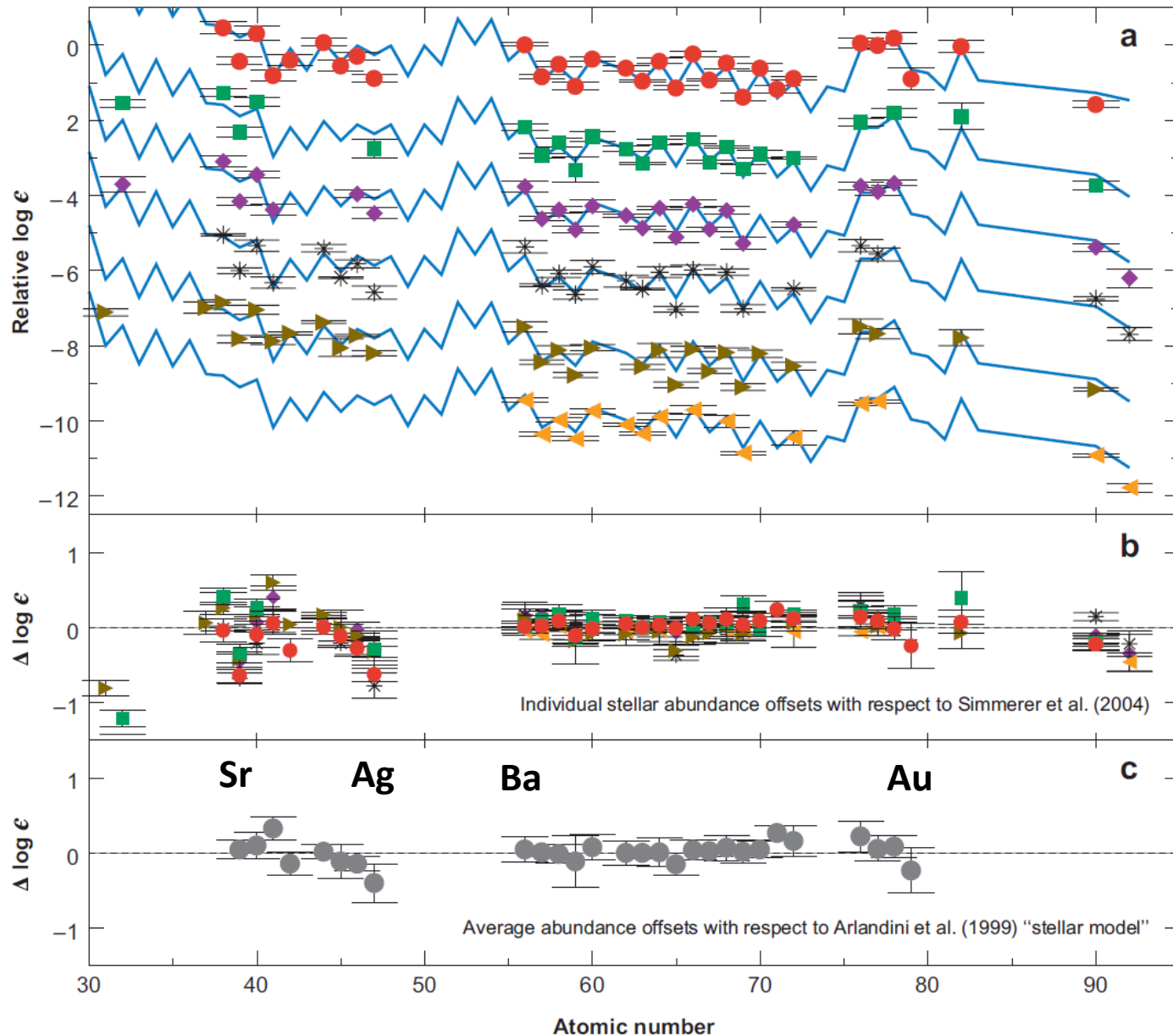
** Actinide series

9 July 2013

Strongly r-process enhanced stars



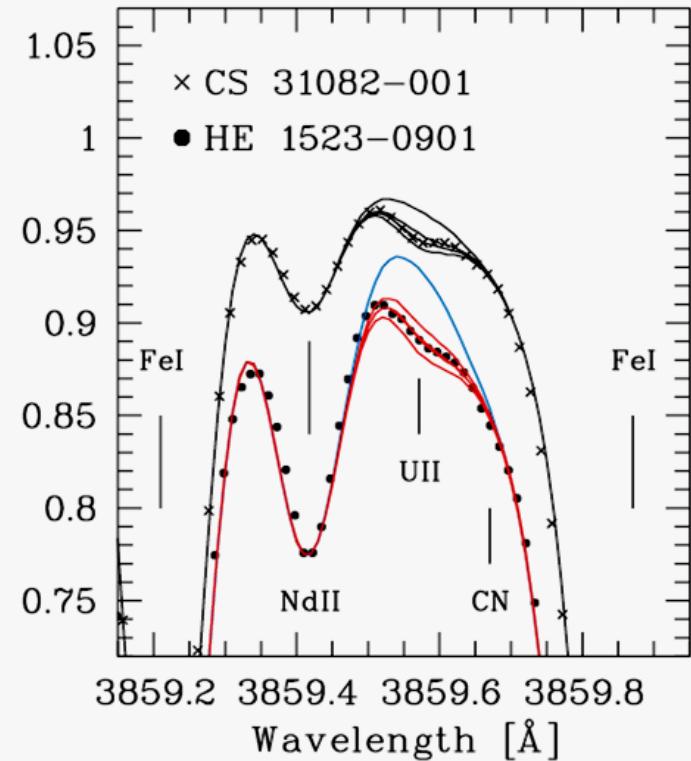
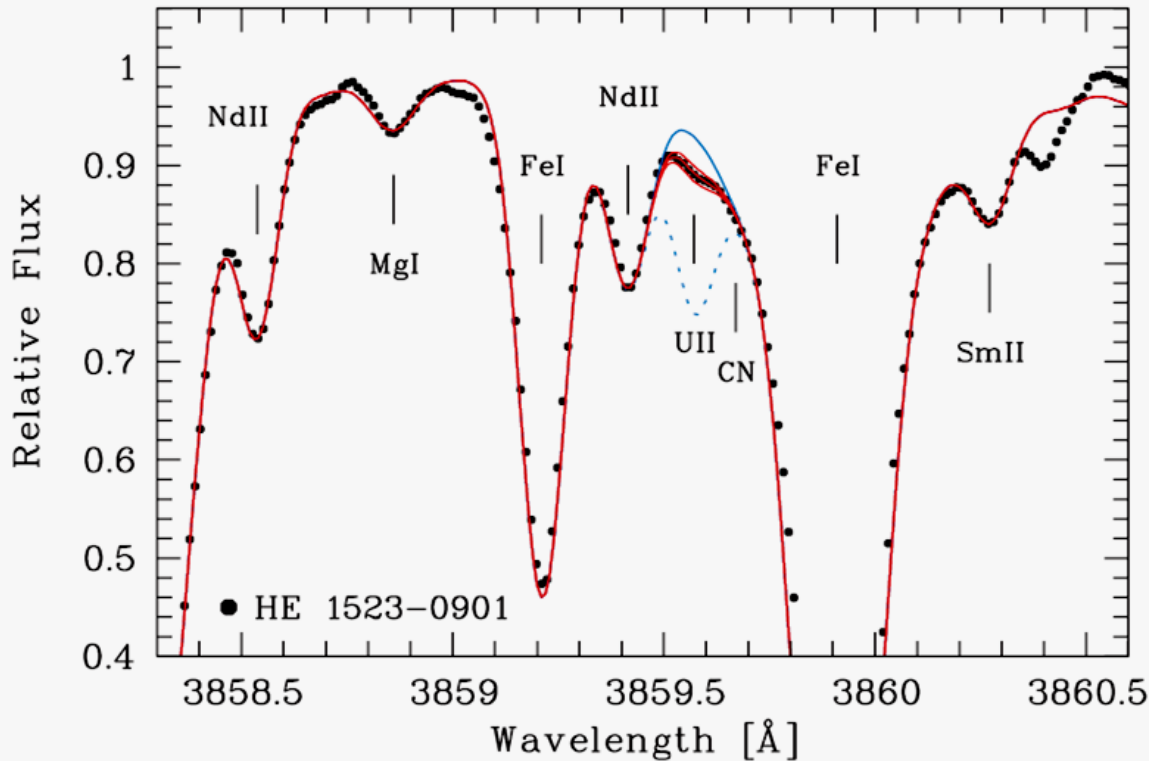
Strongly r-process enhanced stars



(Sneden, Cowan & Gallino 2008, ARA&A 46, 241)

Detection of uranium

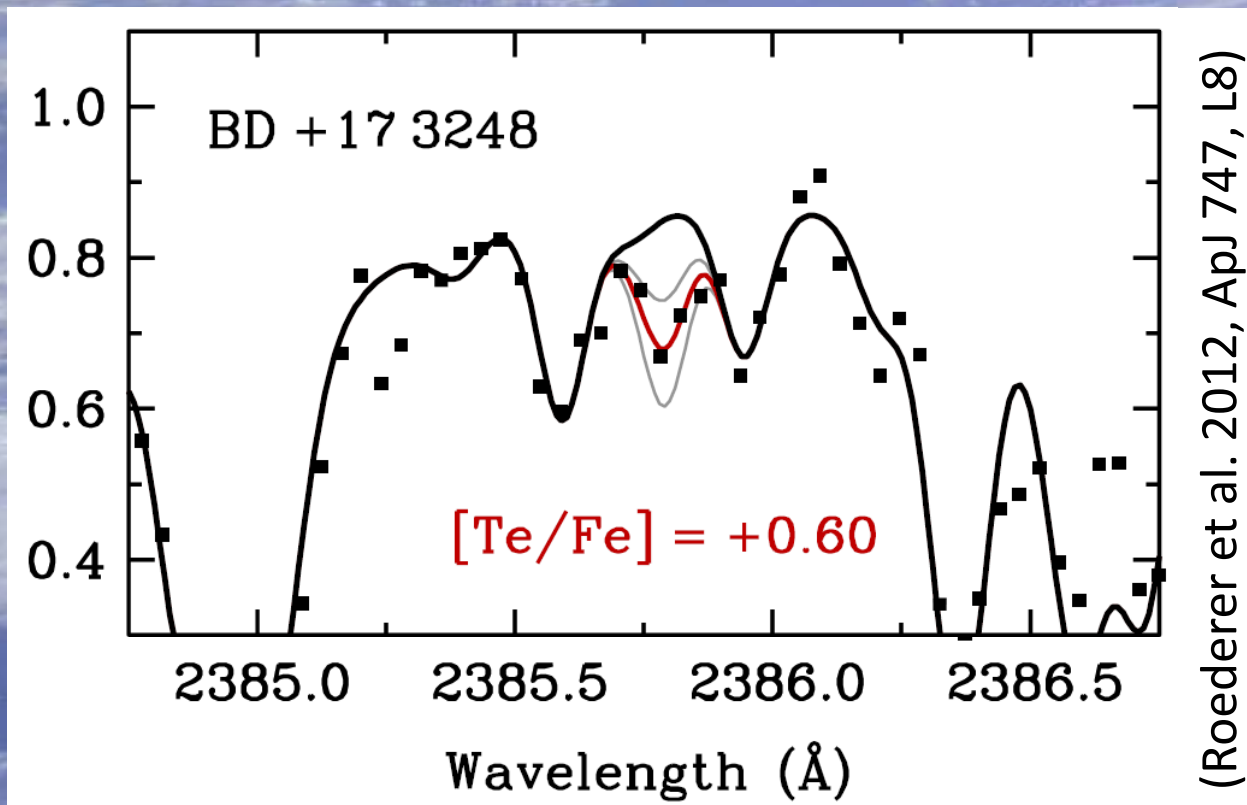
(Frebel et al. 2007, ApJ 660, L117)



$$\log \varepsilon(\text{U}) = -2.1, \text{ where } \log \varepsilon(X) := \log_{10} (N_X/N_H) + 12$$

1 U atom in 10^{14} H atoms!

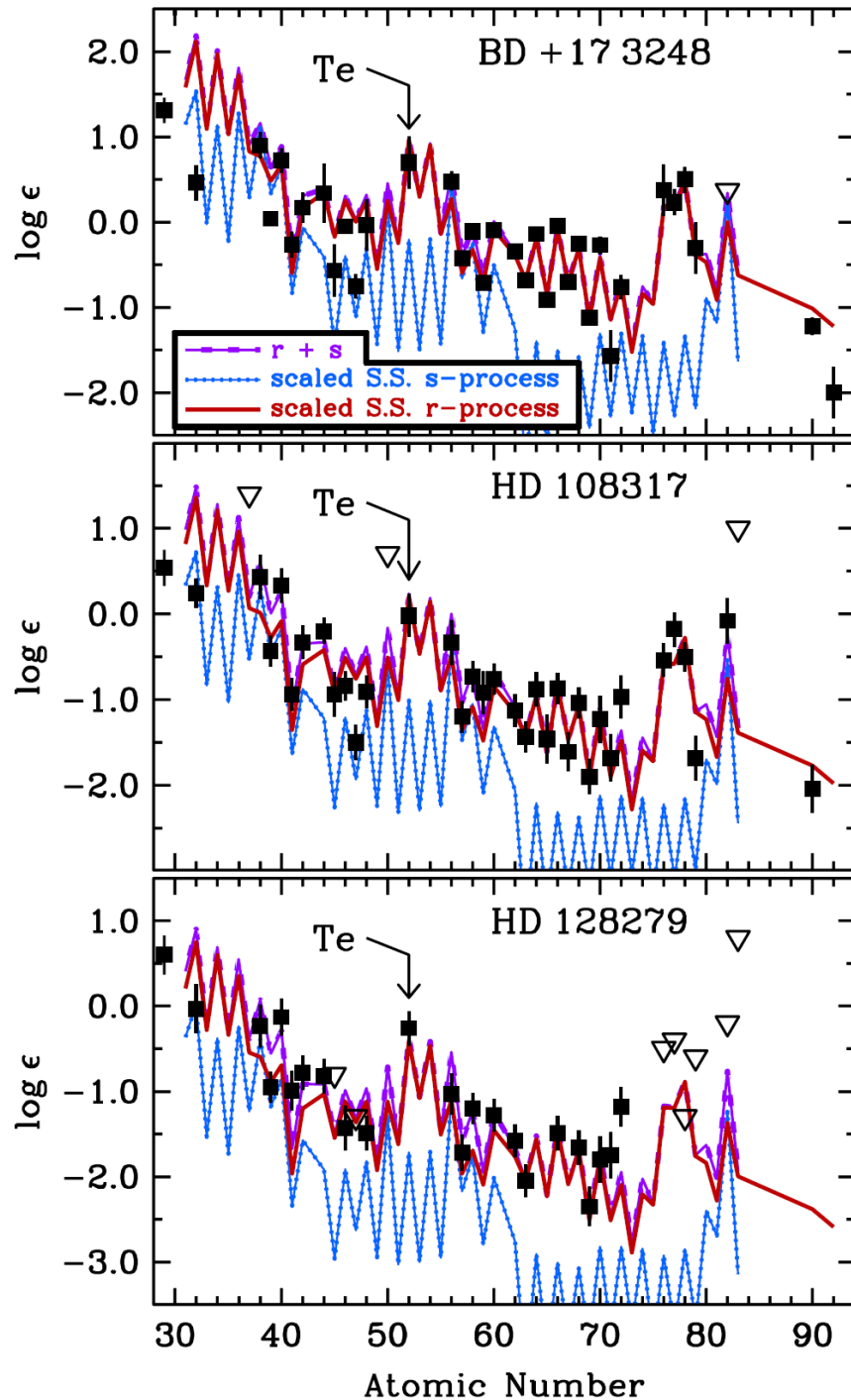
HST observations of Te



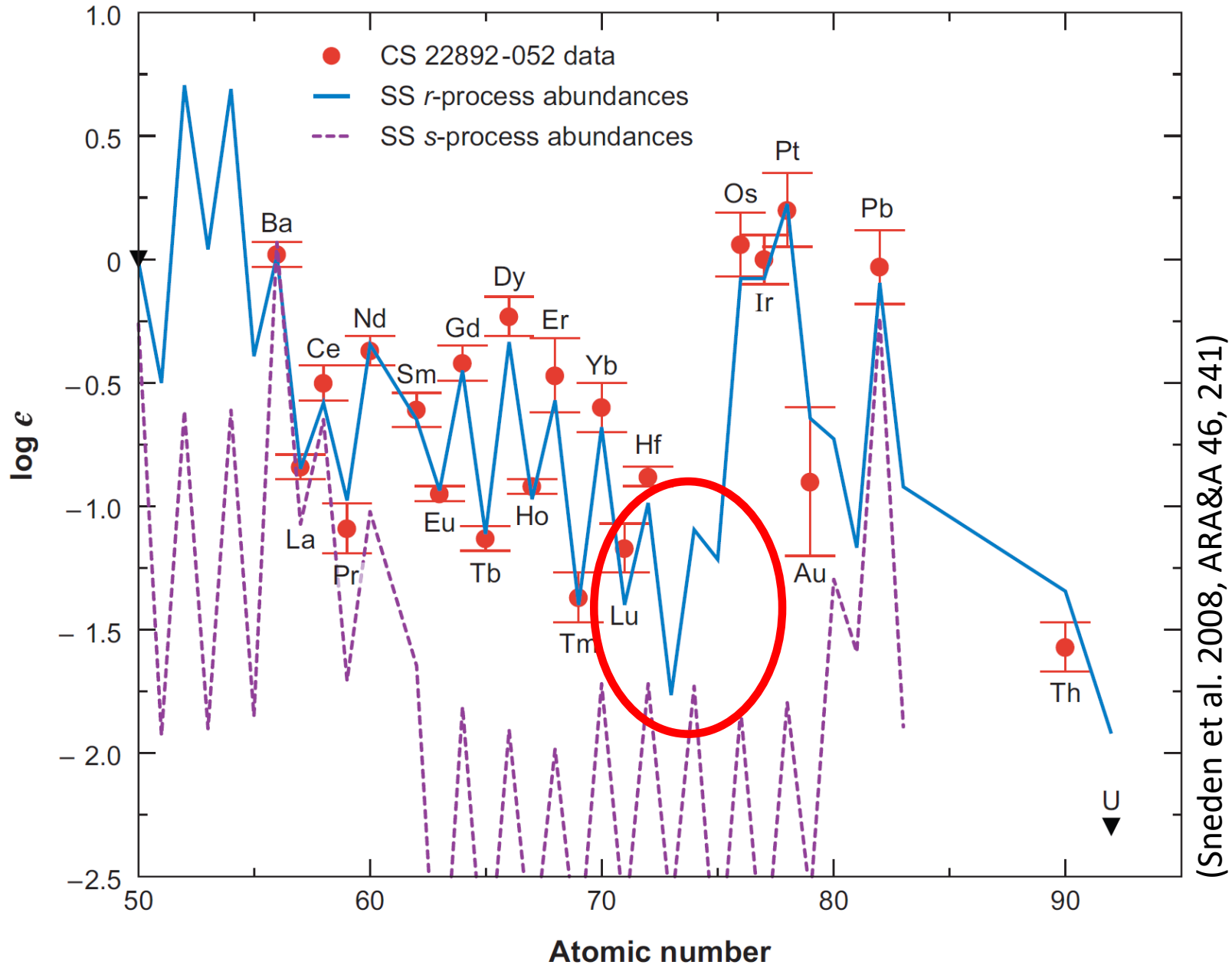
Tellurium

- Roederer et al. (2012, ApJ 747, L8): Observed abundances of Te match scaled Solar “r-process” abundance pattern well.

The stars observe from space you shall!

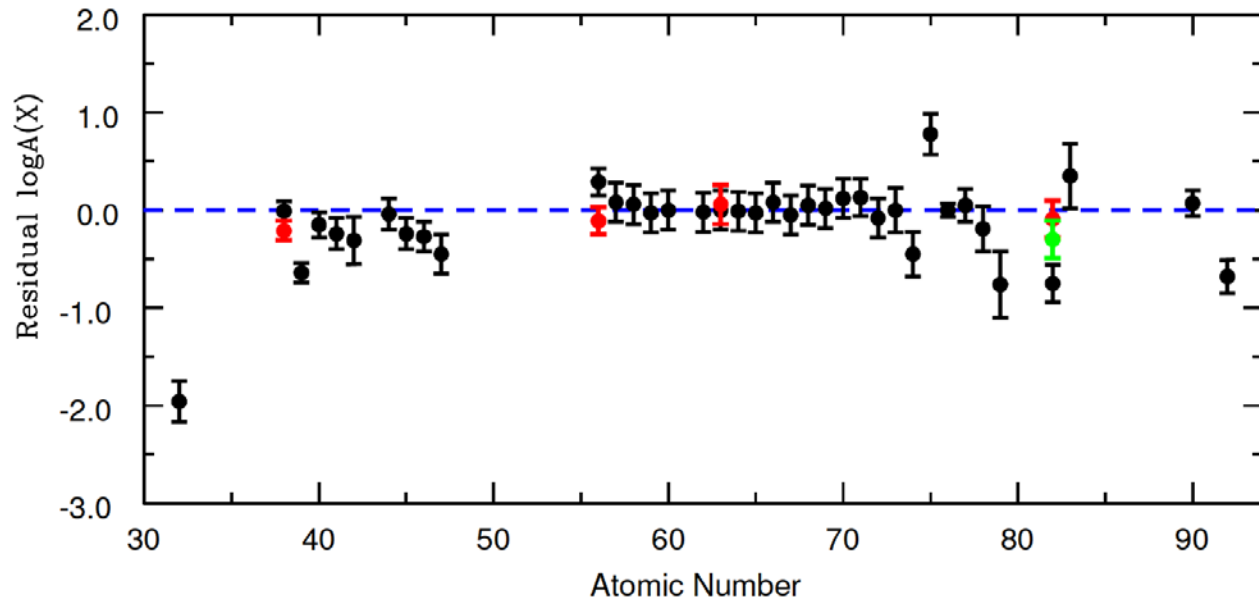
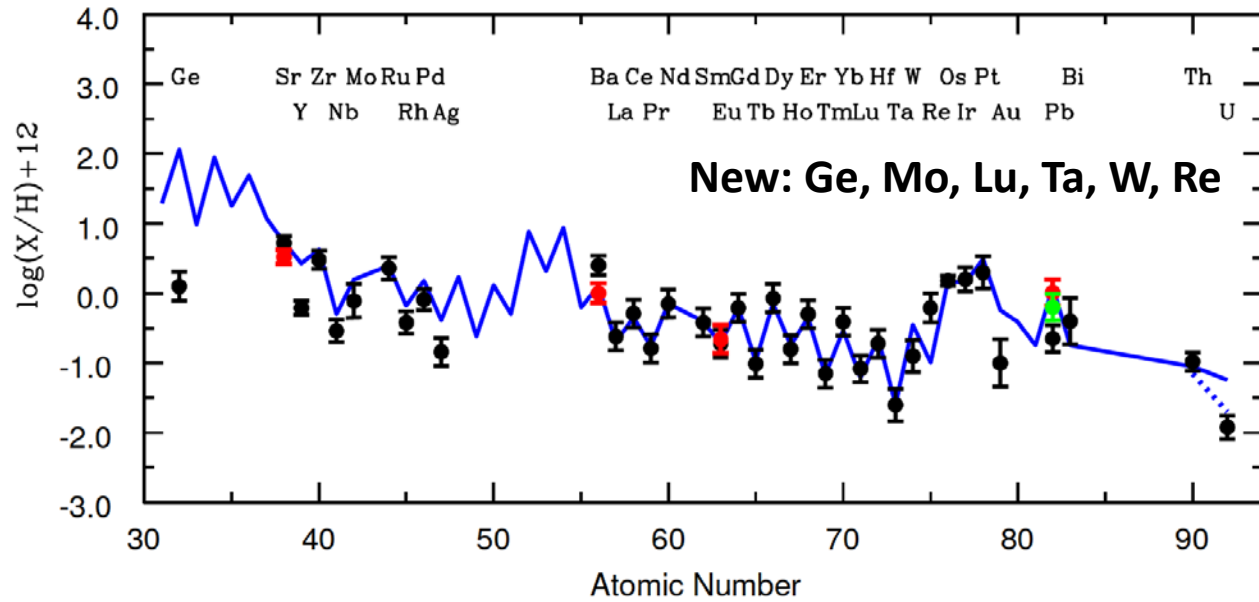


CS 22892–052, the “classical” r-II star



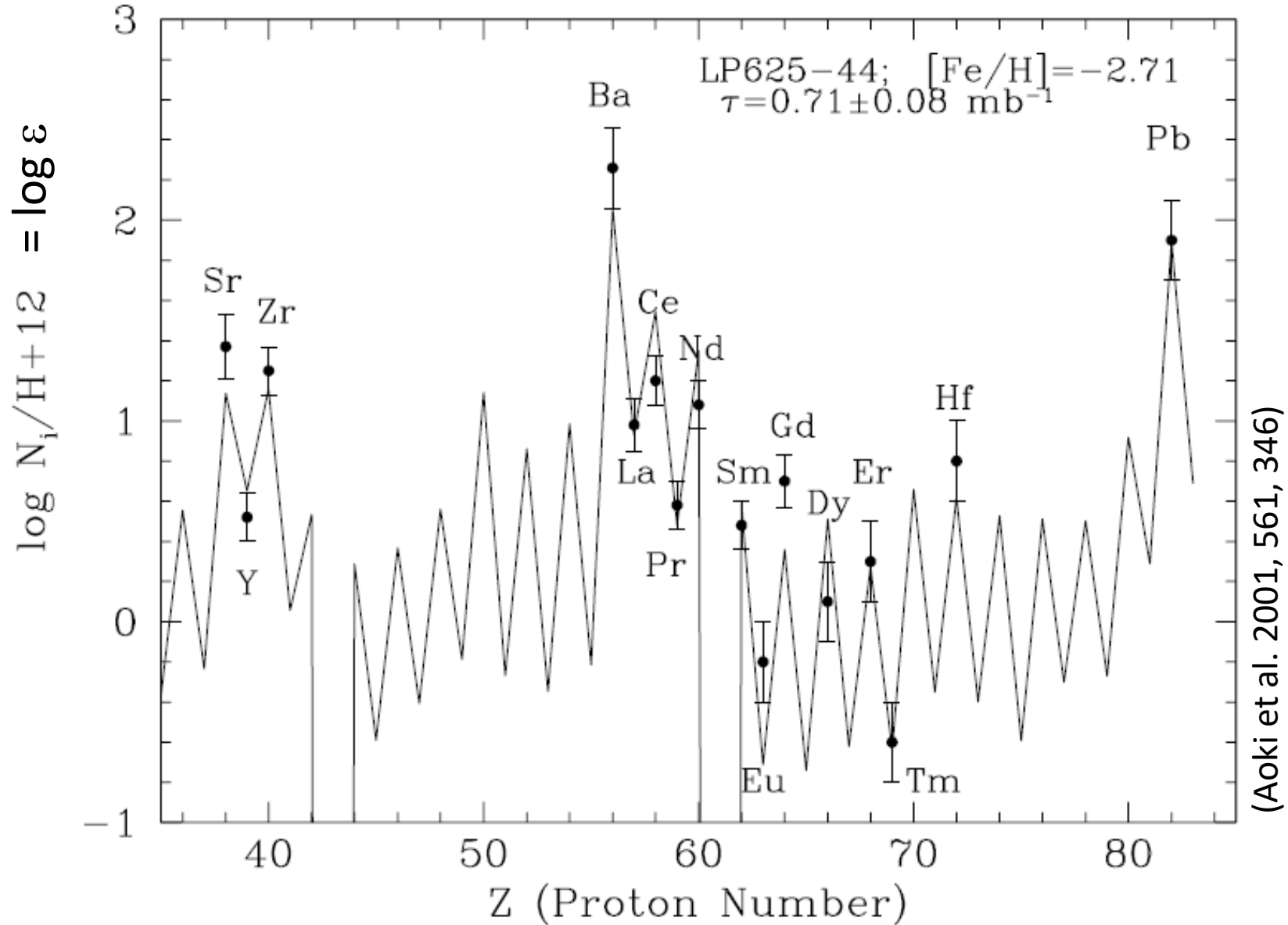
(Snedden et al. 2008, ARA&A 46, 241)

HST/STIS observations of CS31082-001

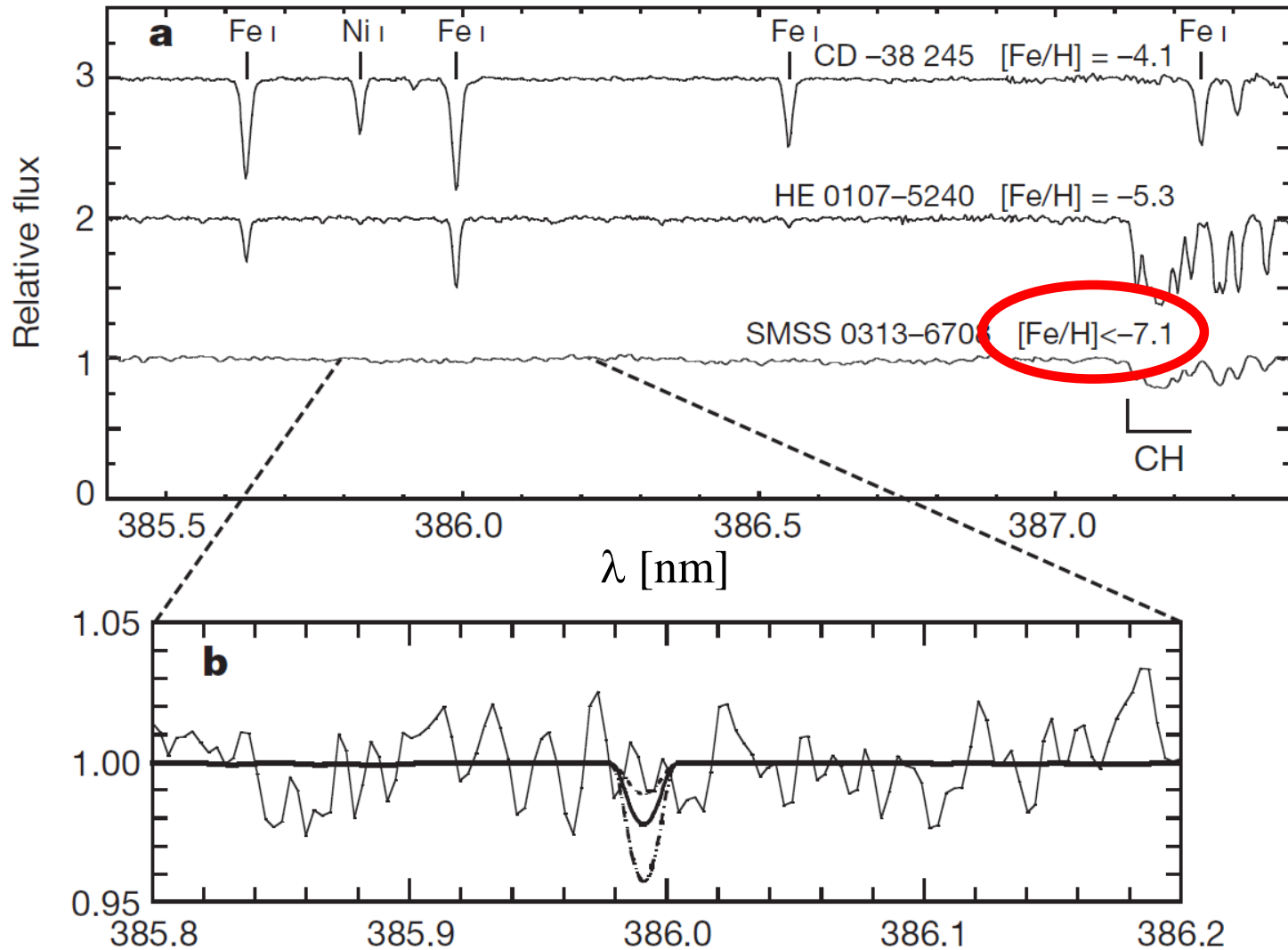


(Siqueira Mello et al. 2013, A&A 550, A122)

Strongly s-process enhanced stars

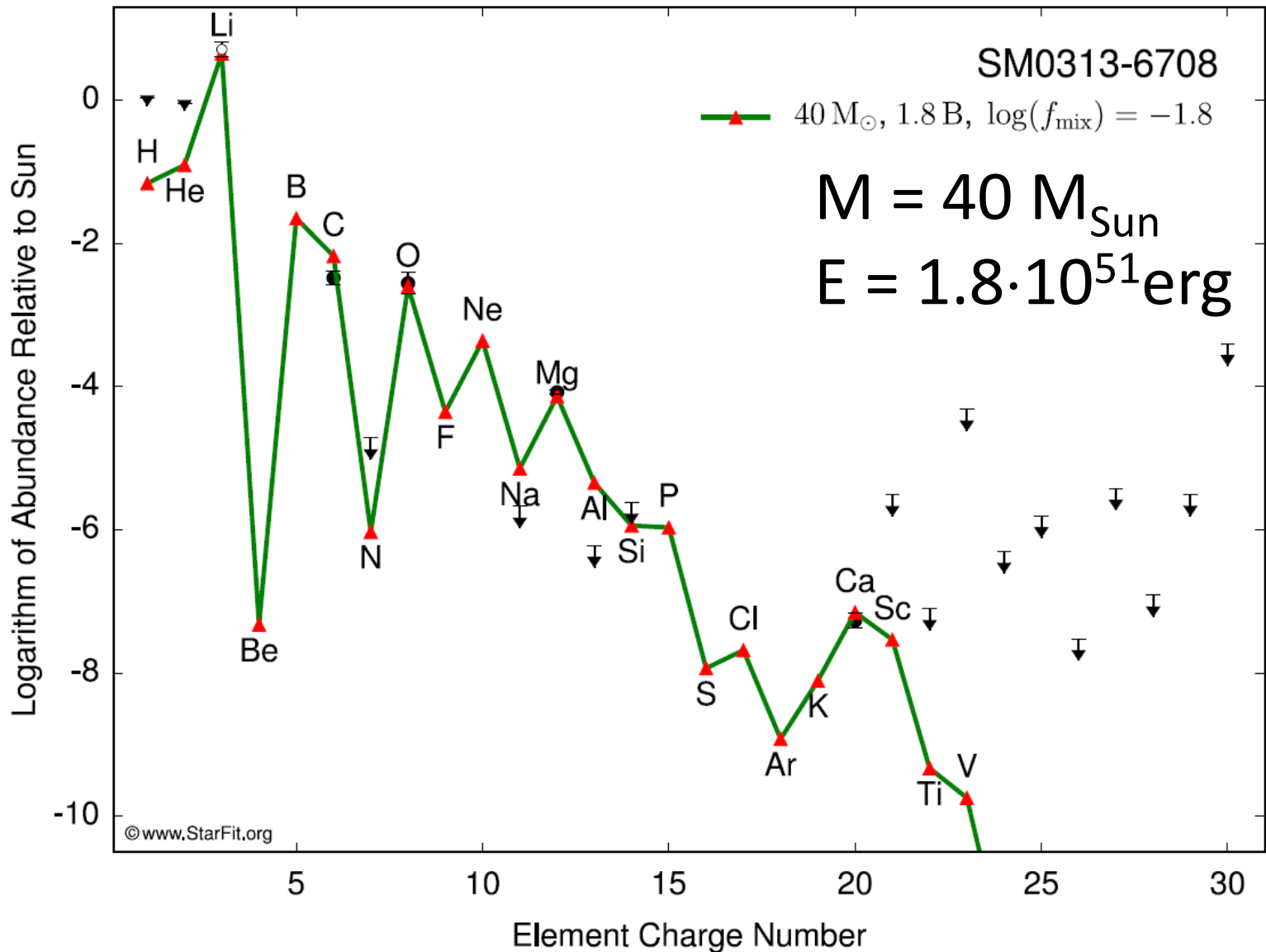


SMSS 0313–6708



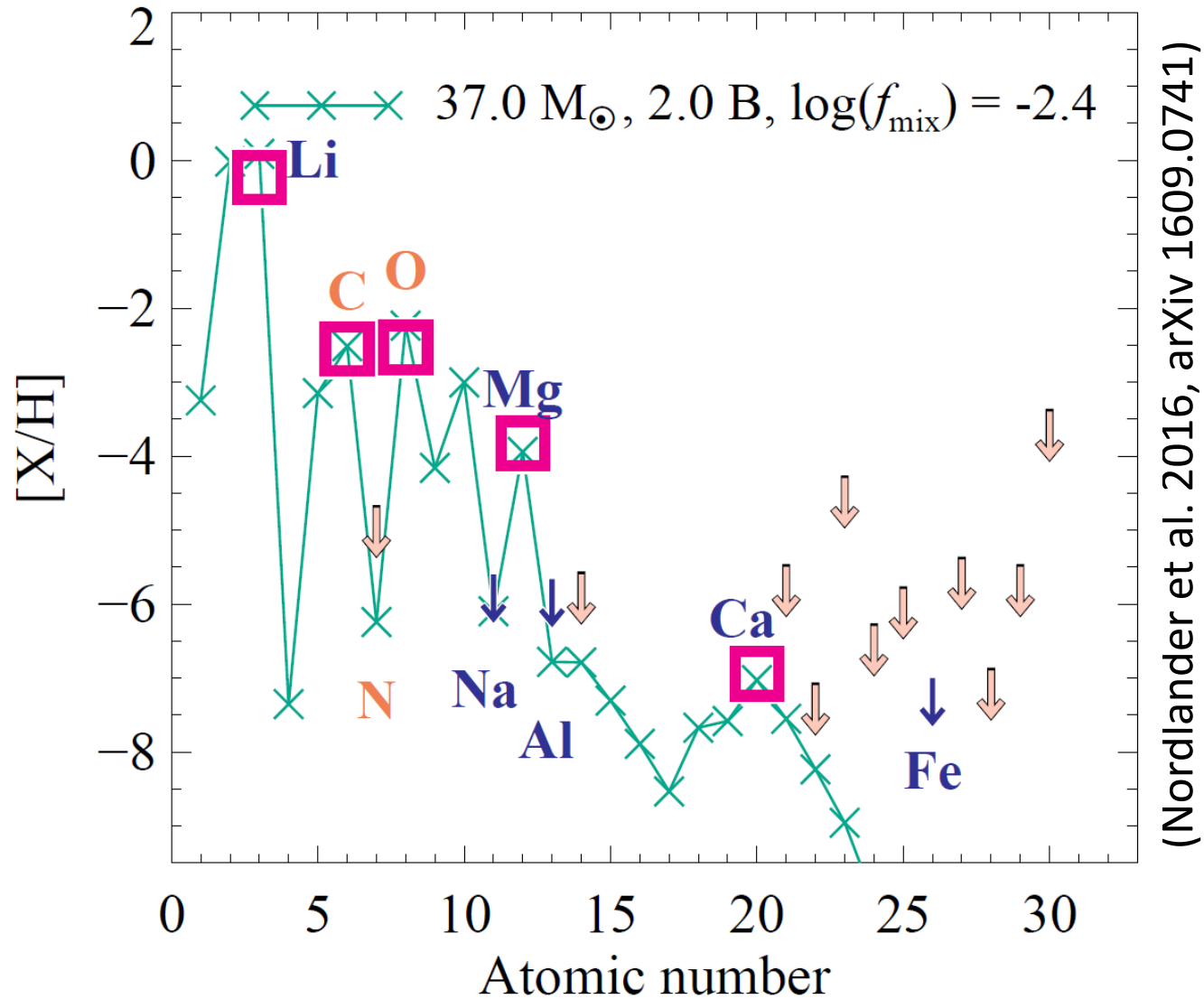
(Keller et al. 2014, Nature 506, 463)

SMSS 0313–6708: Abundance pattern



(Bessell et al. 2015, ApJ 806, L16)

SMSS 0313–6708: 3D NLTE abundance pattern



(Nordlander et al. 2016, arXiv 1609.0741)

Isotopic ratios measured in metal-poor stars

hydrogen 1 H 1.0079																						helium 2 He 4.0026	
lithium 3 Li 6.941	beryllium 4 Be 9.0122											boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180						
sodium 11 Na 22.990	magnesium 12 Mg 24.305											aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948						
potassium 19 K 39.098	calcium 20 Ca 40.078	scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80						
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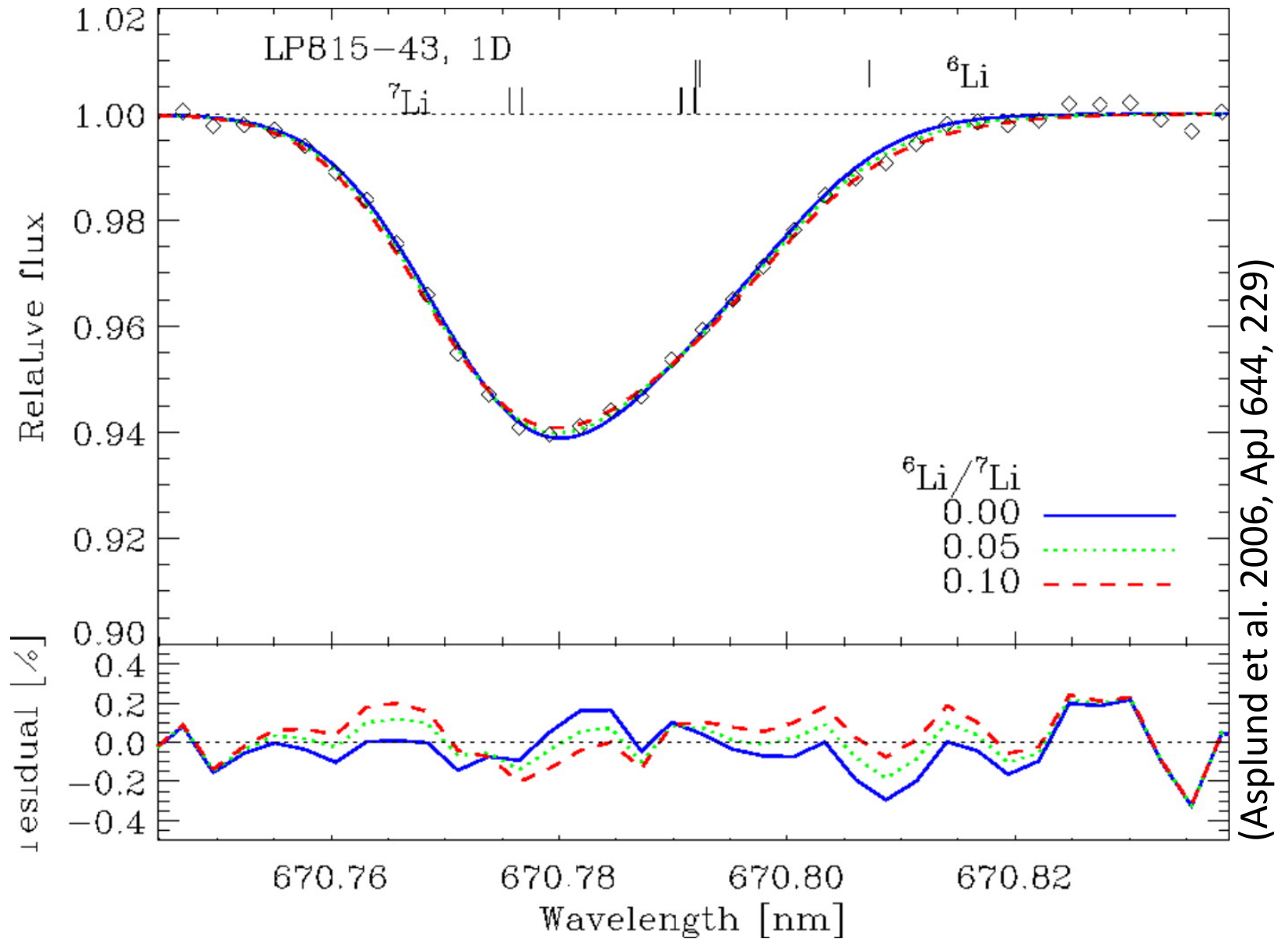
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* Lanthanide series

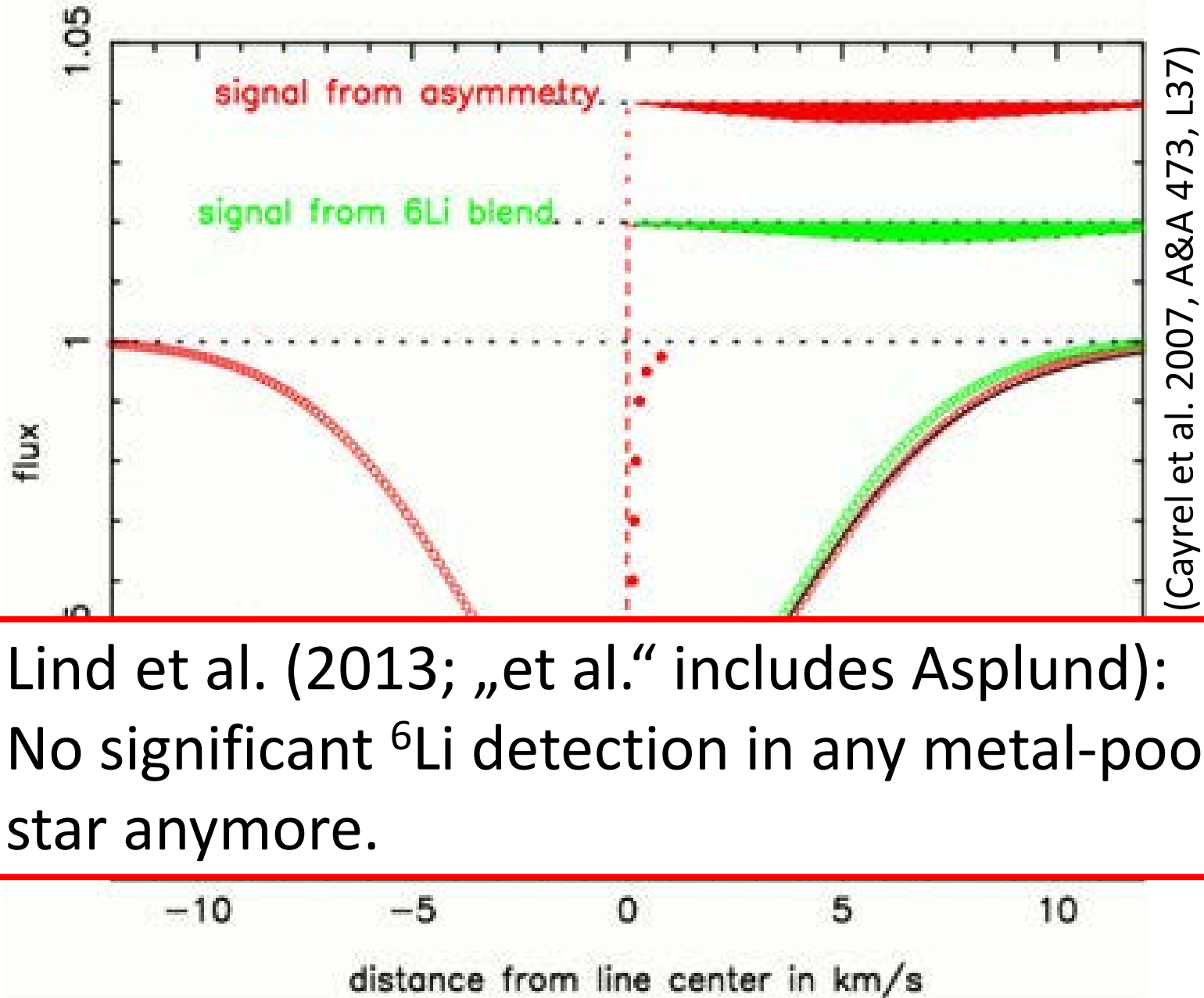
** Actinide series

23 March 2013

Lithium isotopic ratio

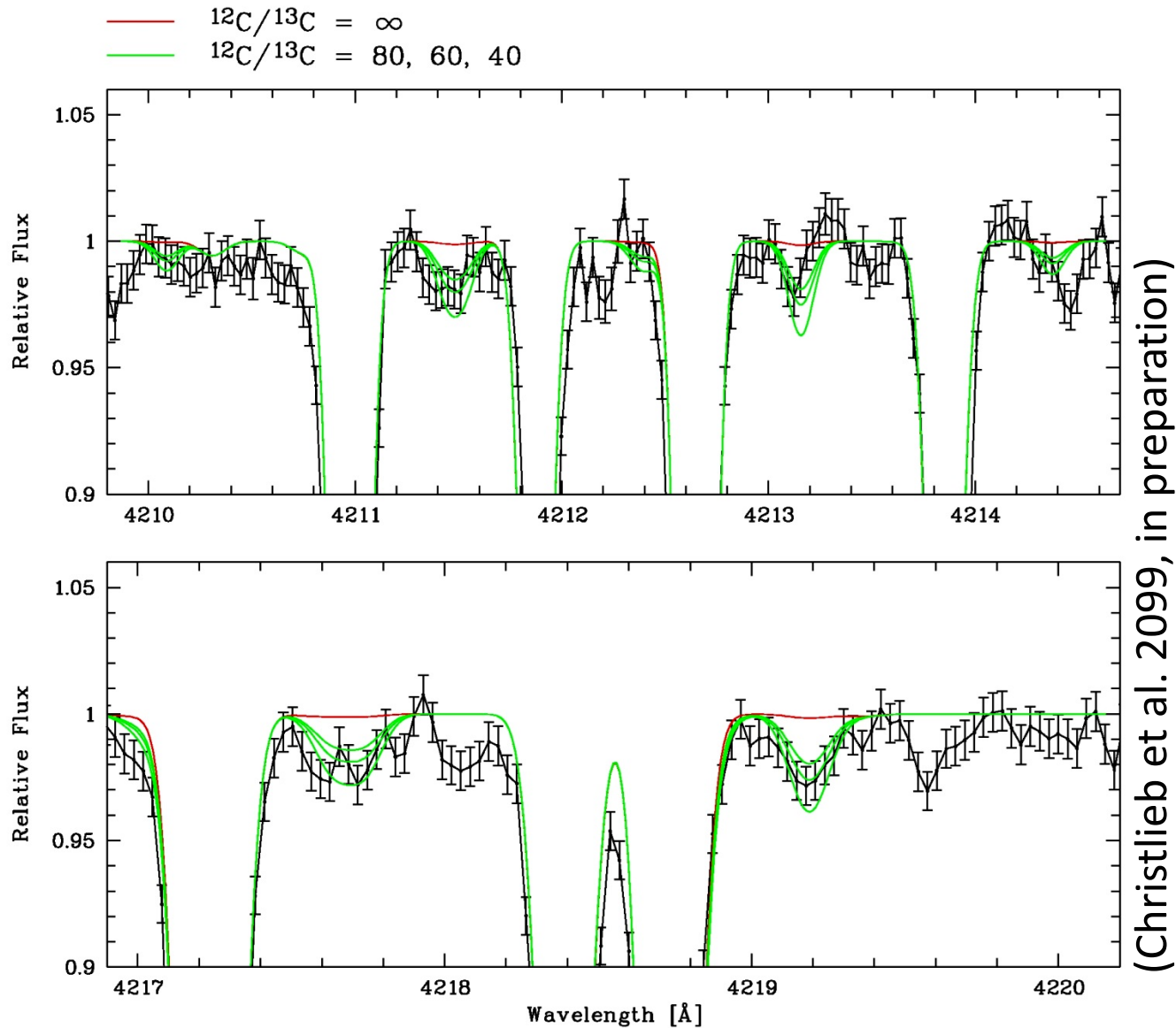


But...



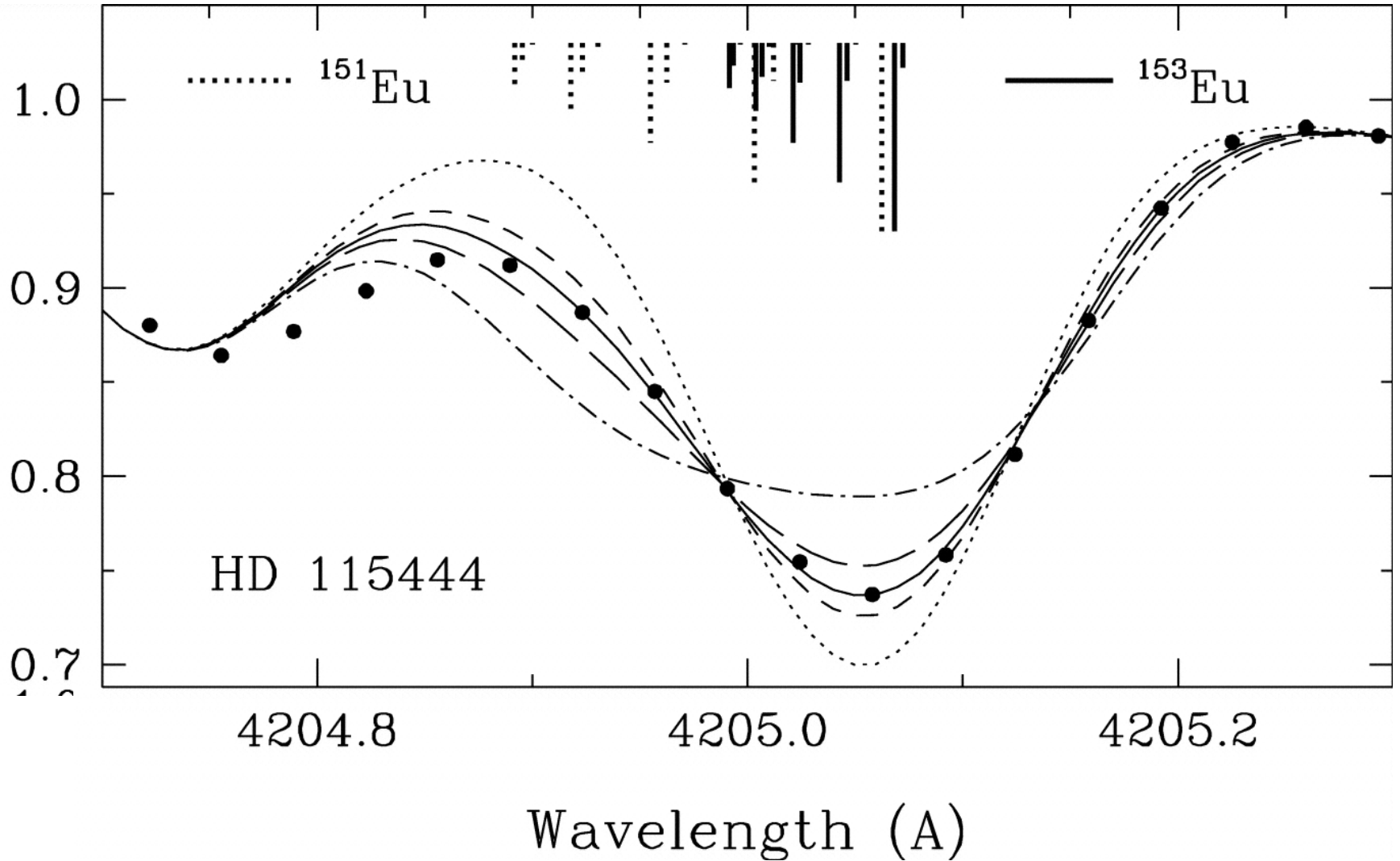
Lind et al. (2013; „et al.“ includes Asplund):
No significant ${}^6\text{Li}$ detection in any metal-poor star anymore.

^{13}C in HE 0107–5240

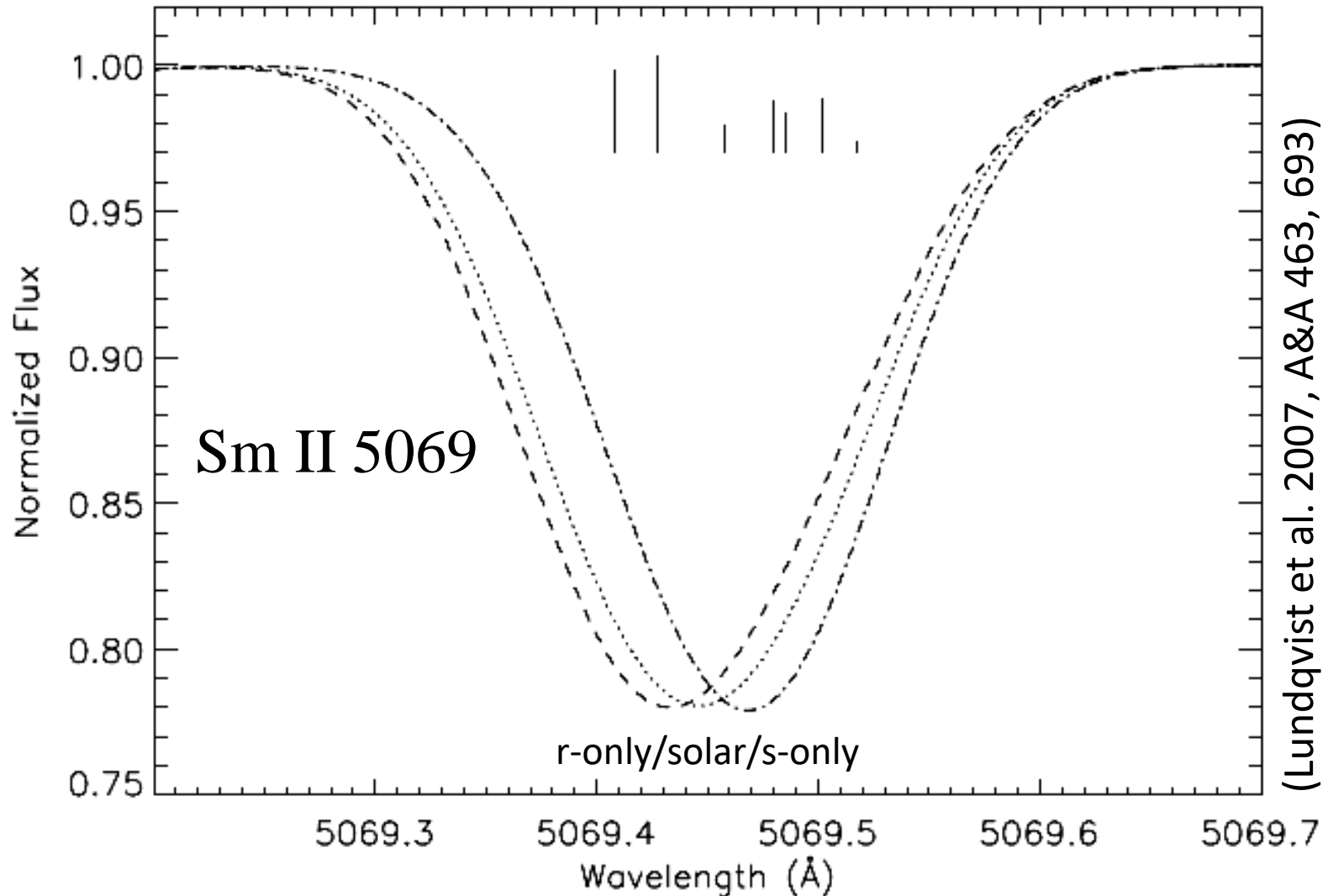


Europium isotopic ratio

(Sneden et al. 2002, ApJ 566, L25)



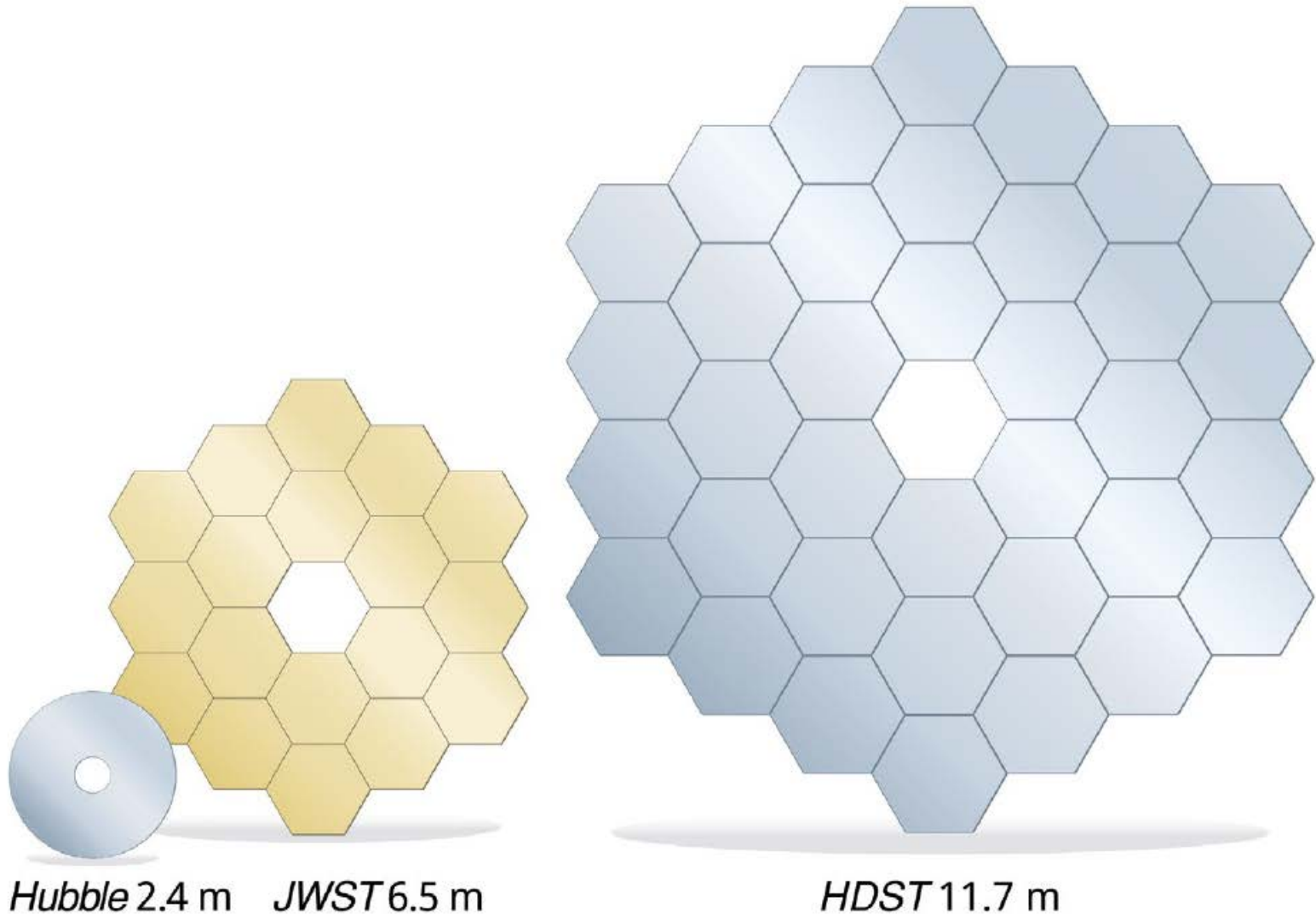
Isotopic ratio of samarium



Outlook: Expected progress

- **3D models; NLTE calculations**
=> more accurate abundances and isotopic ratios
- **Multi-object spectrographs** at 4-8m telescopes;
e.g., 4MOST/VISTA, WEAVE/WHT, ngCFHT.
=> larger samples of stars; lower [Fe/H]
- **CUBES**: a joint ESO-Brazil high-resolution UV spectrograph for the VLT. => more light in the UV
- **E-ELT HIRES**: Crossed-dispersed optical/IR Èchelle spectrograph. => More photons
- **High-Definition Space Telescope (HDST)**:
=> UV observations from space after HST

High-Definition Space Telescope (HDST)



(Dalcanton et al. 2015, AURA report)

30m-class telescope projects

- **European Extremely Large Telescope (E-ELT)**
www.eso.org/sci/facilities/eelt/
 - ESO
 - 798 hexagonal primary mirror segments of 1.4 m $\Leftrightarrow D = 39$ m
 - Site: Cerro Armazones, Chile
 - First Light: “mid-2020ies”
- **Thirty Meter Telescope (TMT; www.tmt.org)**
 - USA + Canada + China + Japan
 - 492 hexagonal primary mirror segments of 1.4 m $\Leftrightarrow D = 30$ m
 - Site: Mauna Kea, Hawai’i
 - First Light: 2022?
- **Giant Magellan Telescope (GMT; www.gmto.org)**
 - USA + Australia + Korea
 - 7 round mirrors of 8.4 m $\Leftrightarrow D = 22$ m
 - Site: Las Campanas, Chile
 - First Light: “2022”

Telescope primary mirrors



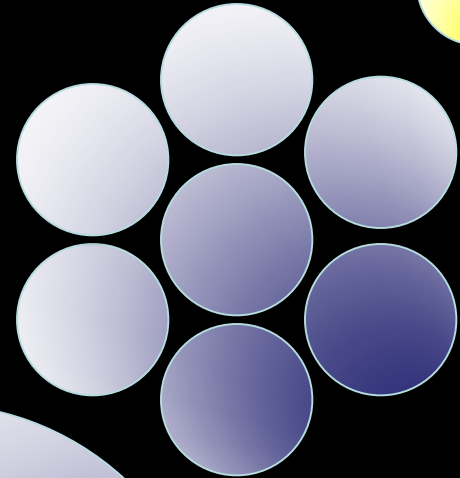
HST
2.4m



JWST
6.5m



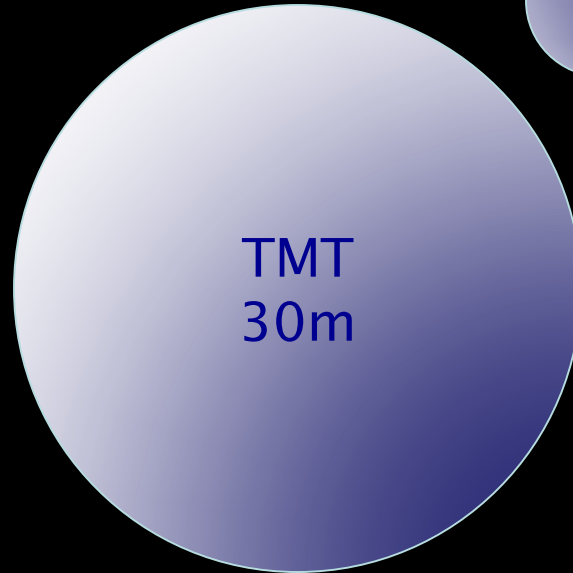
GMT
24m



E-ELT
39m



TMT
30m



VLT
8m



Summary

- Elemental abundances of old, metal-poor stars in our Galaxy provide observational constraints on nucleosynthesis processes in the early Universe, and their sites.
- Outlook:
 - (a) 3D NLTE
 - (b) larger samples of stars
 - (c) more light in the UV from ground and space
 - (d) higher quality spectra quality for more stars.