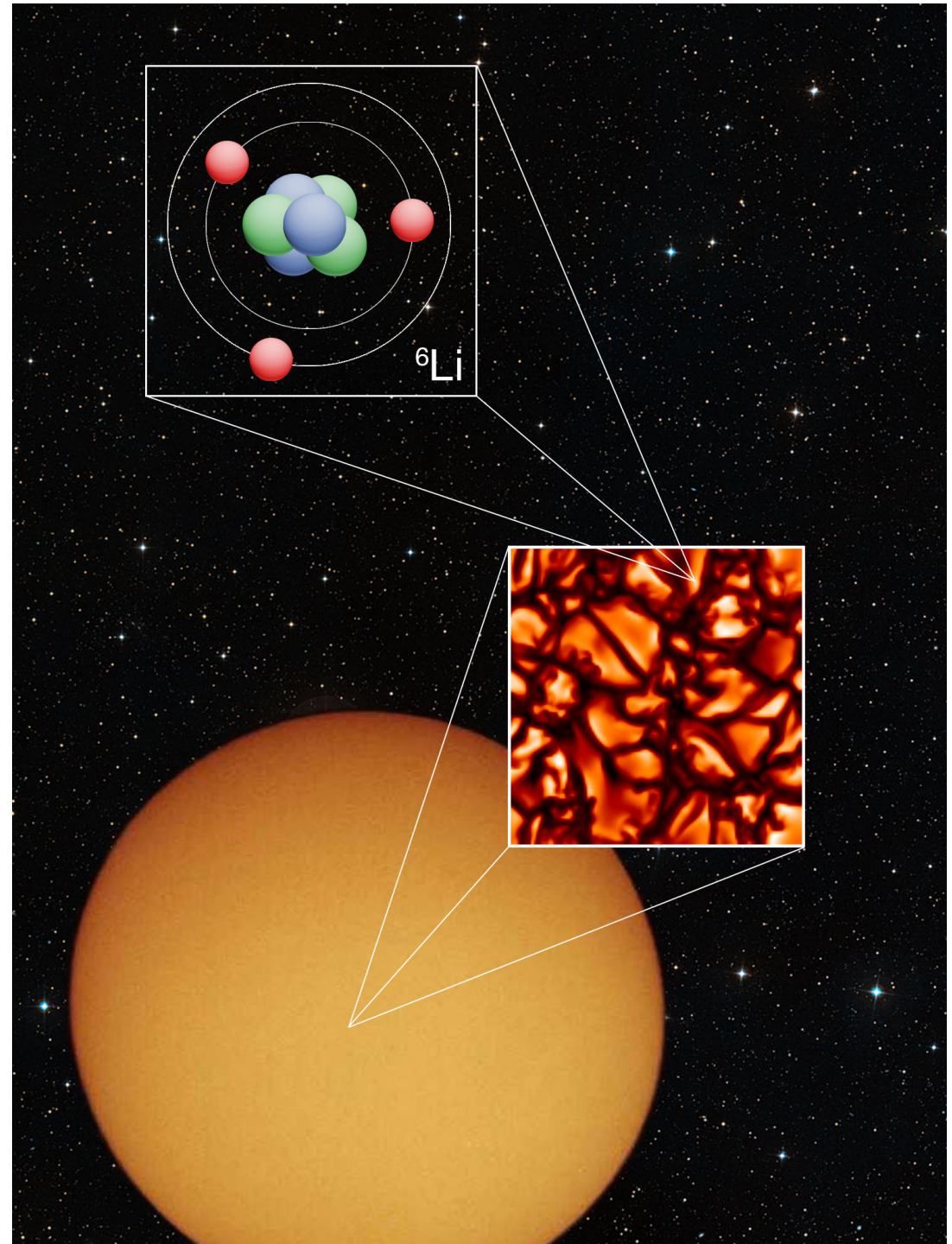


Isotope Ratios in Stars

Karin Lind
IoA Cambridge



$$1 < Z < 5$$



Shifts for atomic lines:

$$H - D \sim 2\text{\AA}$$

$${}^3\text{He} - {}^4\text{He} \sim 0.5\text{\AA}$$

$${}^6\text{Li} - {}^7\text{Li} \sim 0.1\text{\AA}$$

$${}^{10}\text{B} - {}^{11}\text{B} \sim 25\text{m\AA}$$

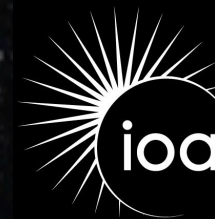
hydrogen 1 H 1.0079																helium 2 He 4.0026		
lithium 3 Li 6.941	beryllium 4 Be 9.0122										boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180		
sodium 11 Na 22.990	magnesium 12 Mg 24.305										aluminum 13 Al 26.982	silicon 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]	ununilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

* Lanthanide series

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
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** Actinide series

Hydrogen



Spite et al. 1983

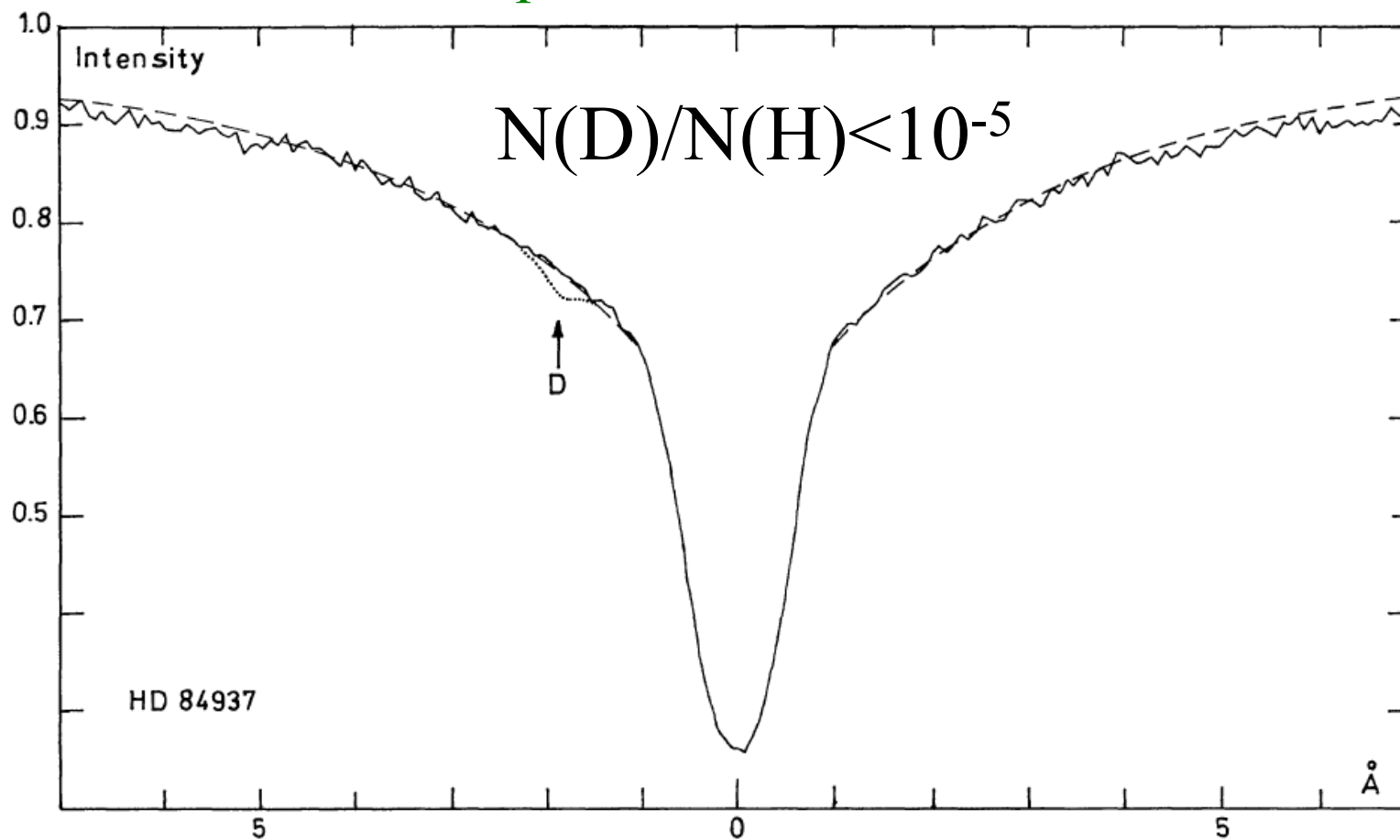
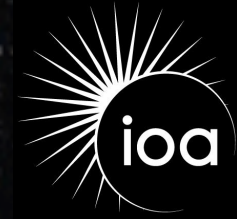
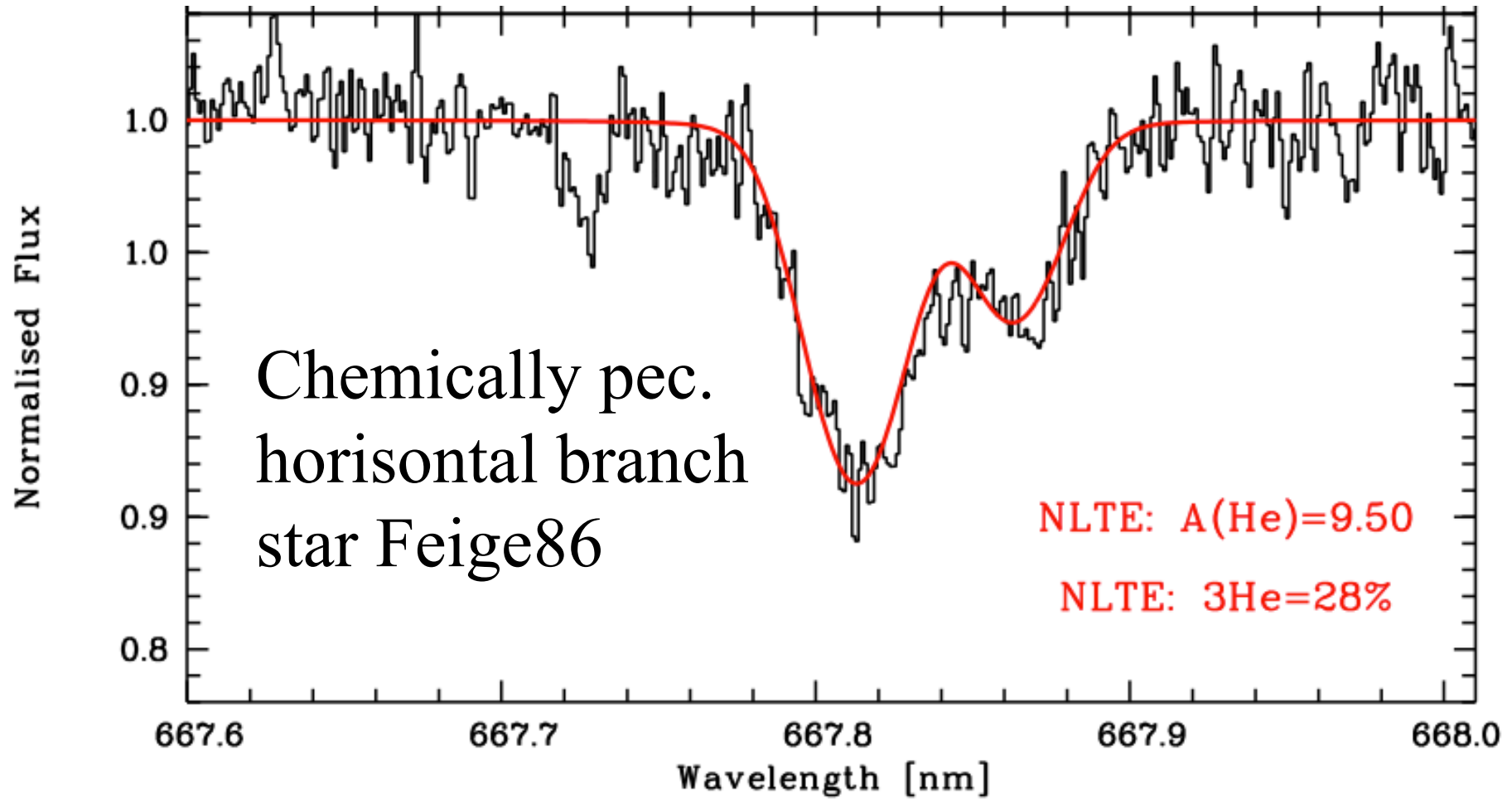


Fig. 2. Same as in Fig. 1 but for HD 84937: the hottest and more massive star of the sample

Helium



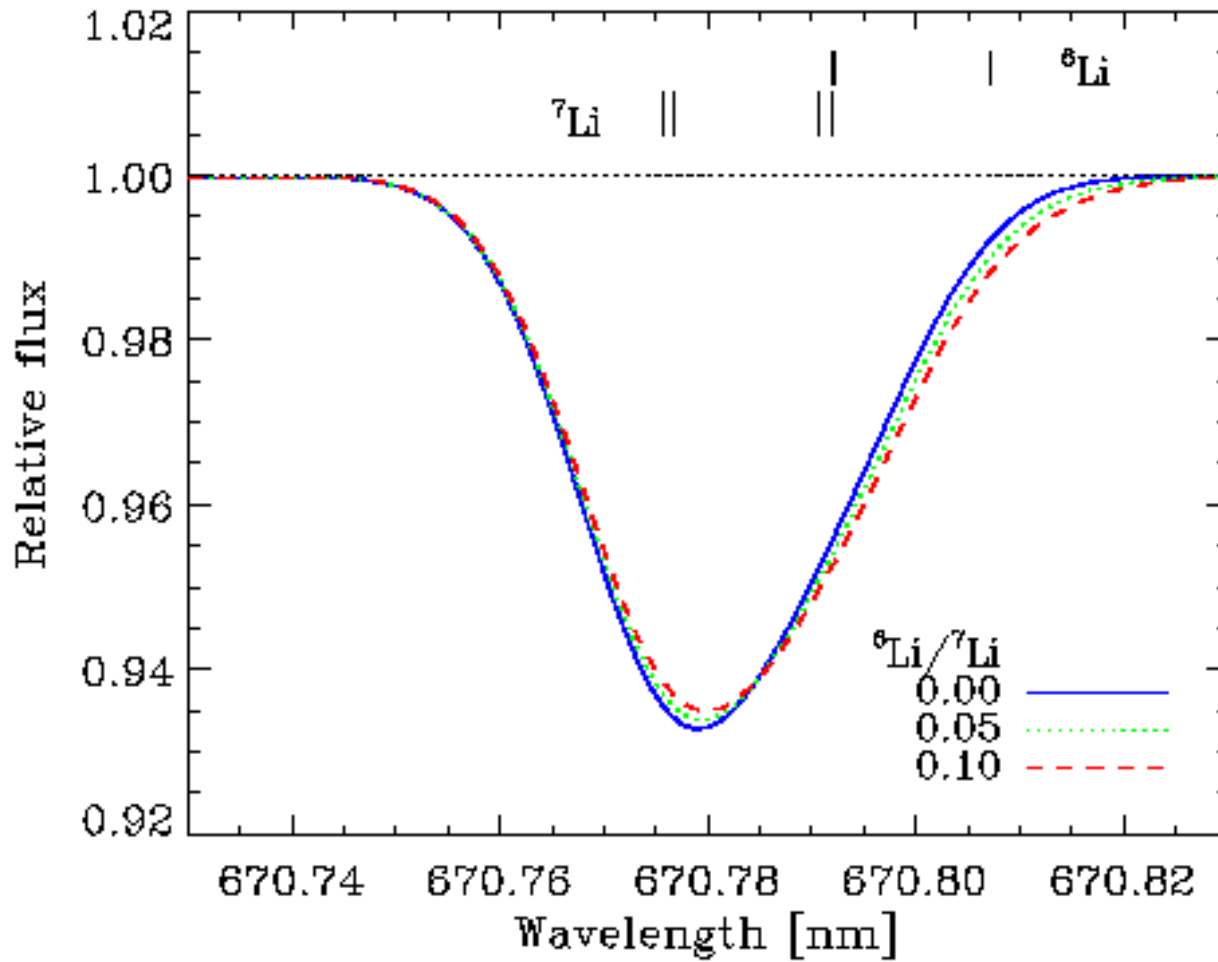
Caffau et al. 2013



Lithium



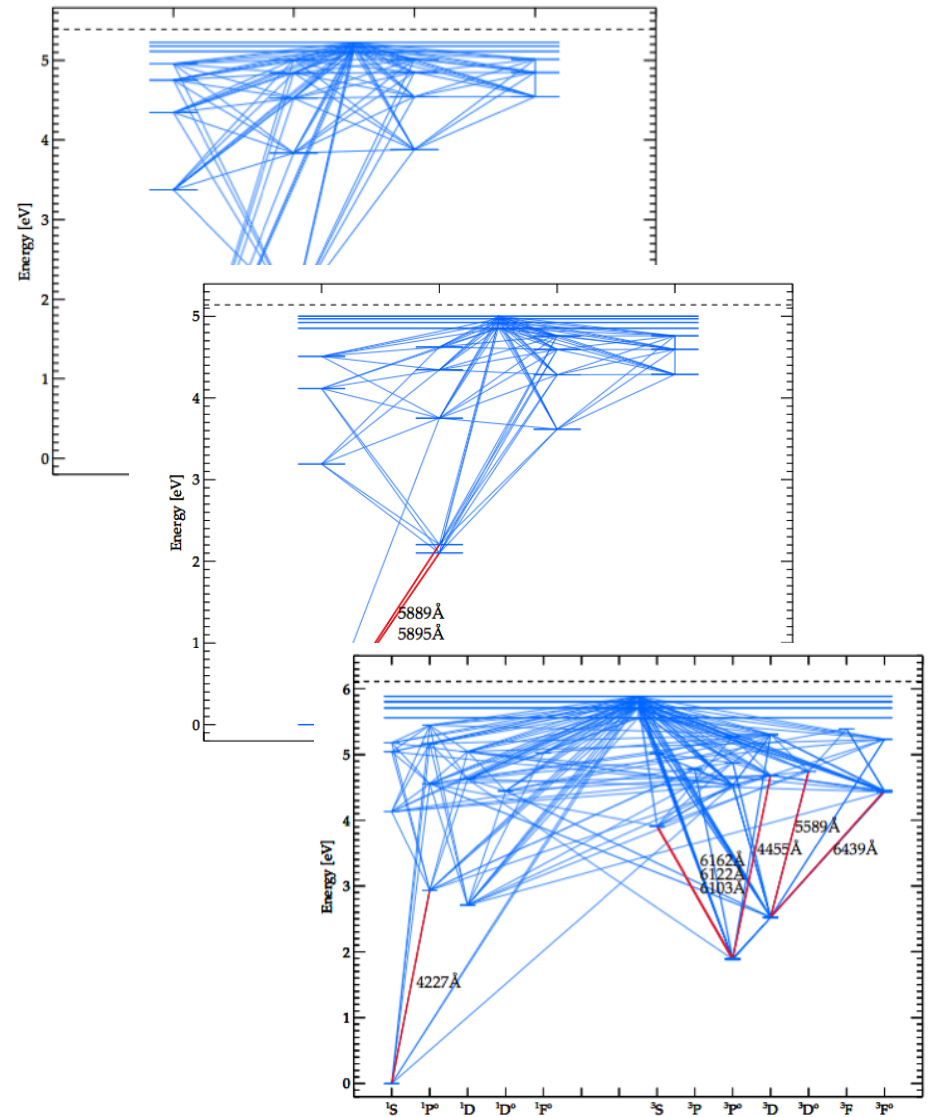
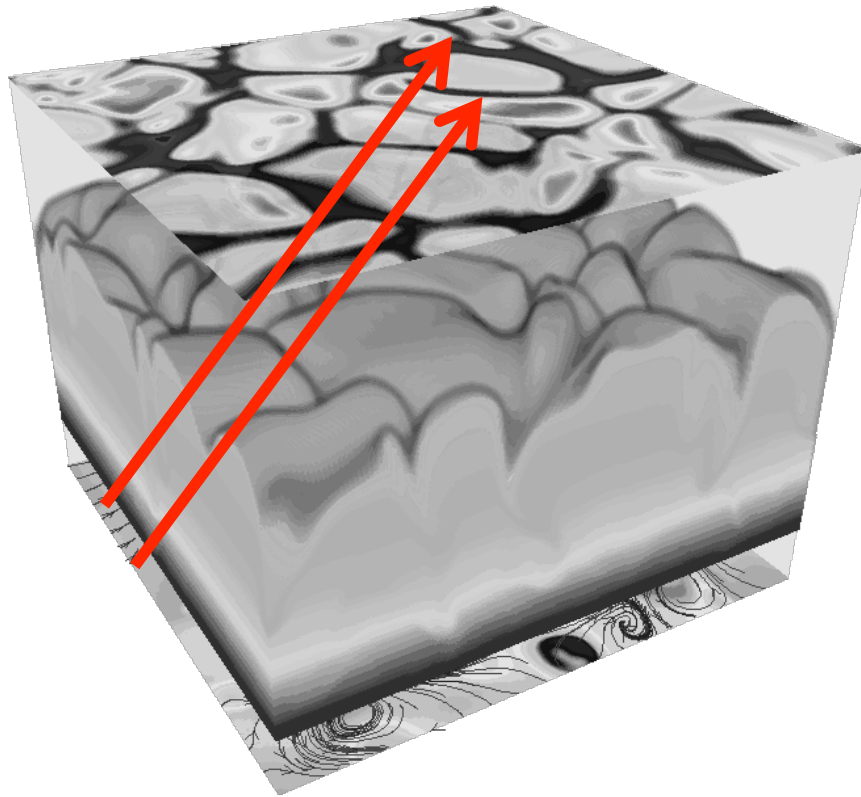
M. Asplund



Lithium



Lind et al. 2013

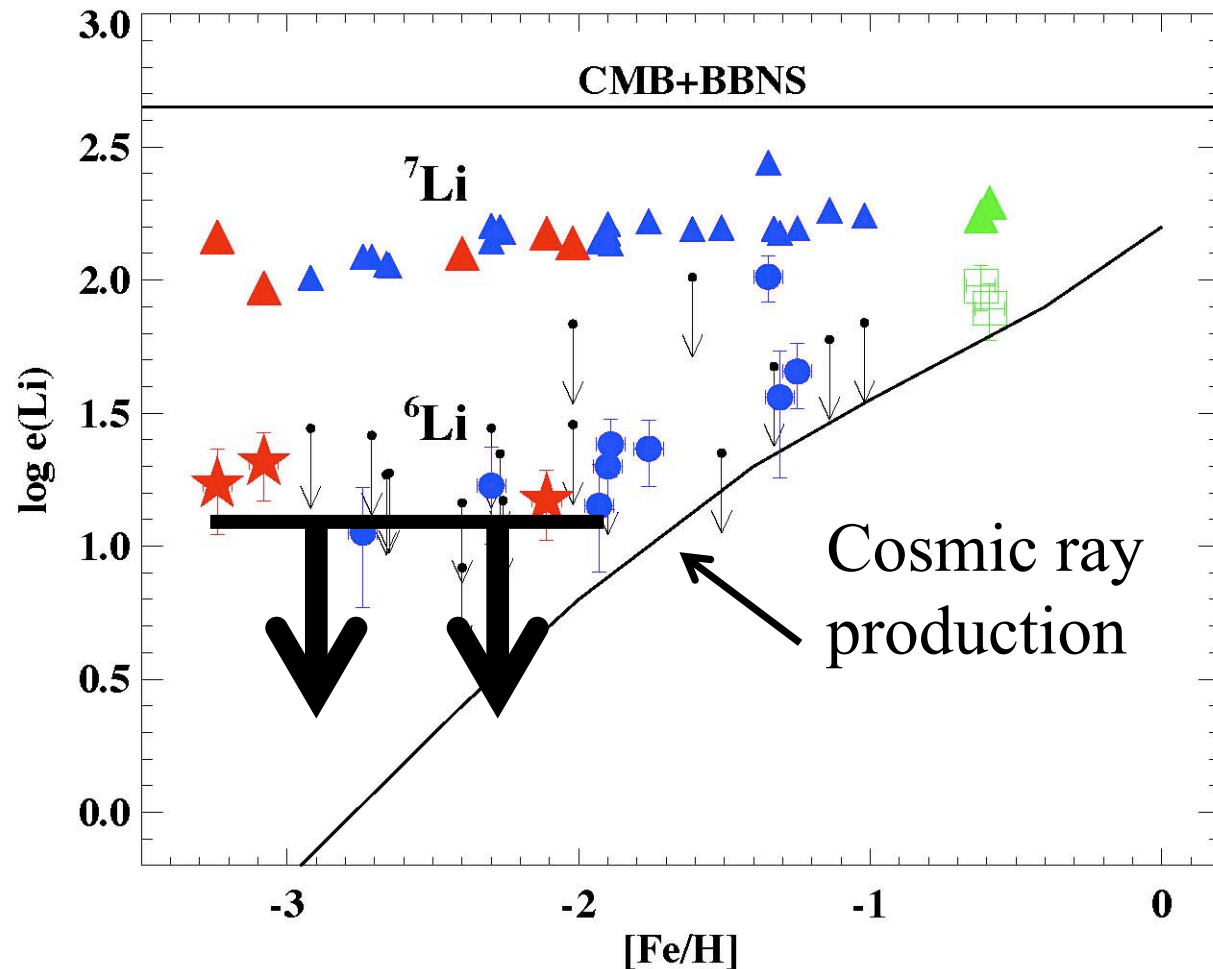


Lithium

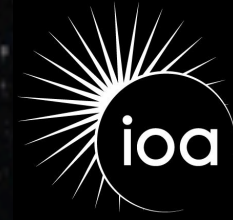


Lind et al. (2013)

Li isotopic ratios overestimated by LTE modelling.
No observational support for a Big Bang origin



Boron



Rebull et al. 1998

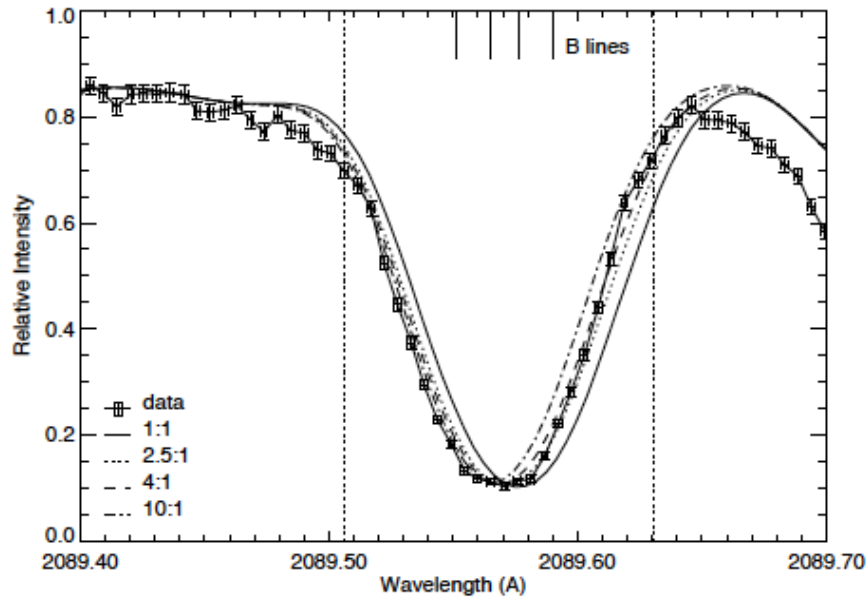


FIG. 4a

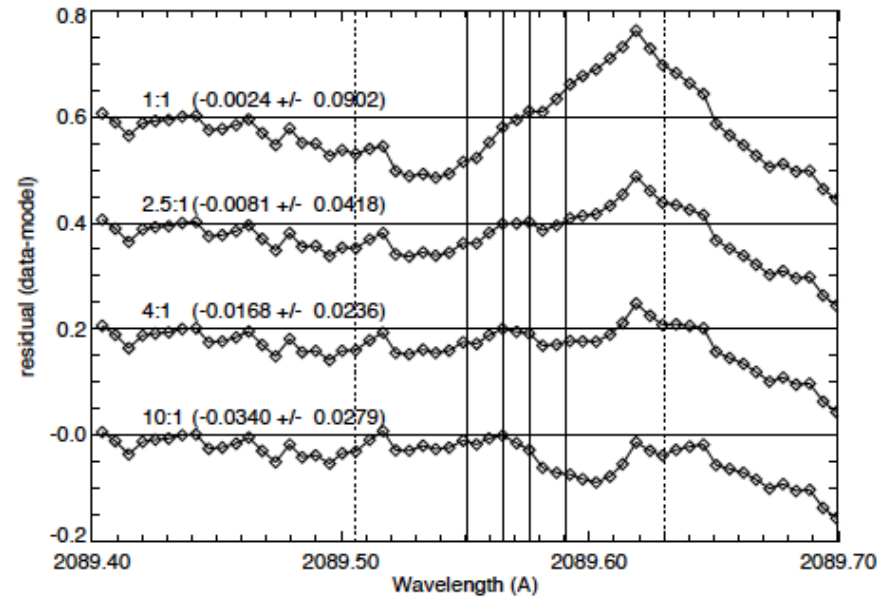


FIG. 4b

High $^{11}\text{B}/^{10}\text{B}$ isotopic ratios slightly favoured in HD76932, a $[\text{Fe}/\text{H}]=-1$ dwarf star. GCR spallation not enough?

6 < Z < 22



CH, CN, CO, MgH, SiO, TiO

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																	aluminum 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
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		57-70 *																		57-70 *			
		89-102 **																		89-102 **			

* Lanthanide series

** Actinide series

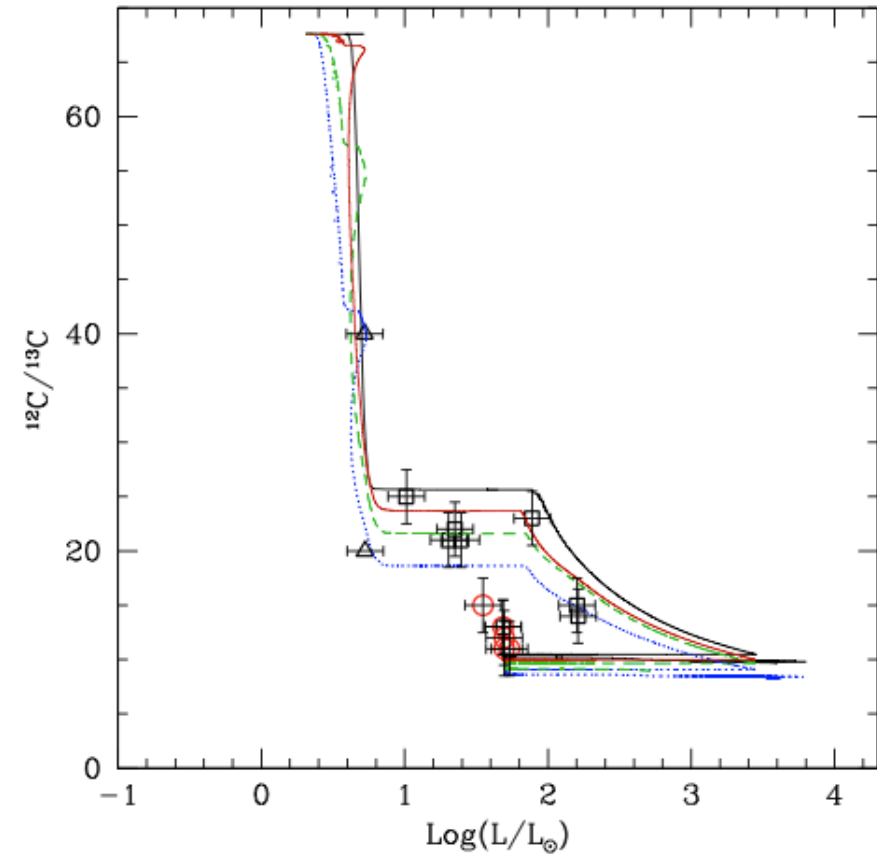
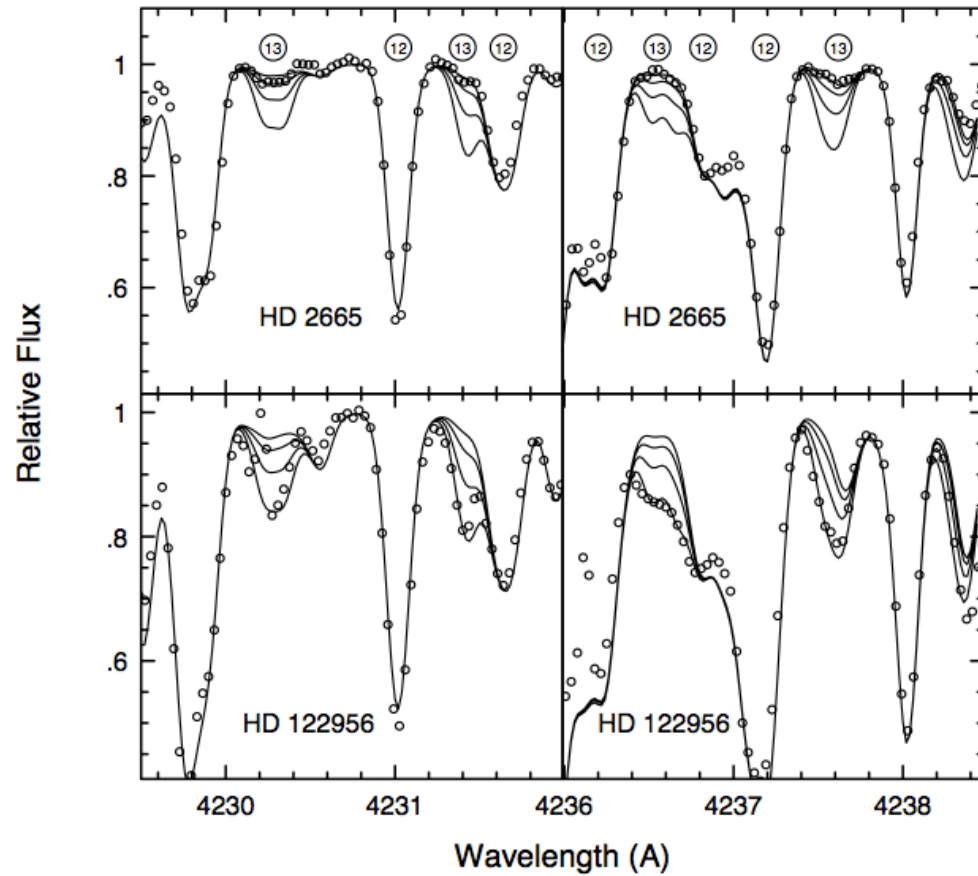
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
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Carbon



Gratton et al. 2000

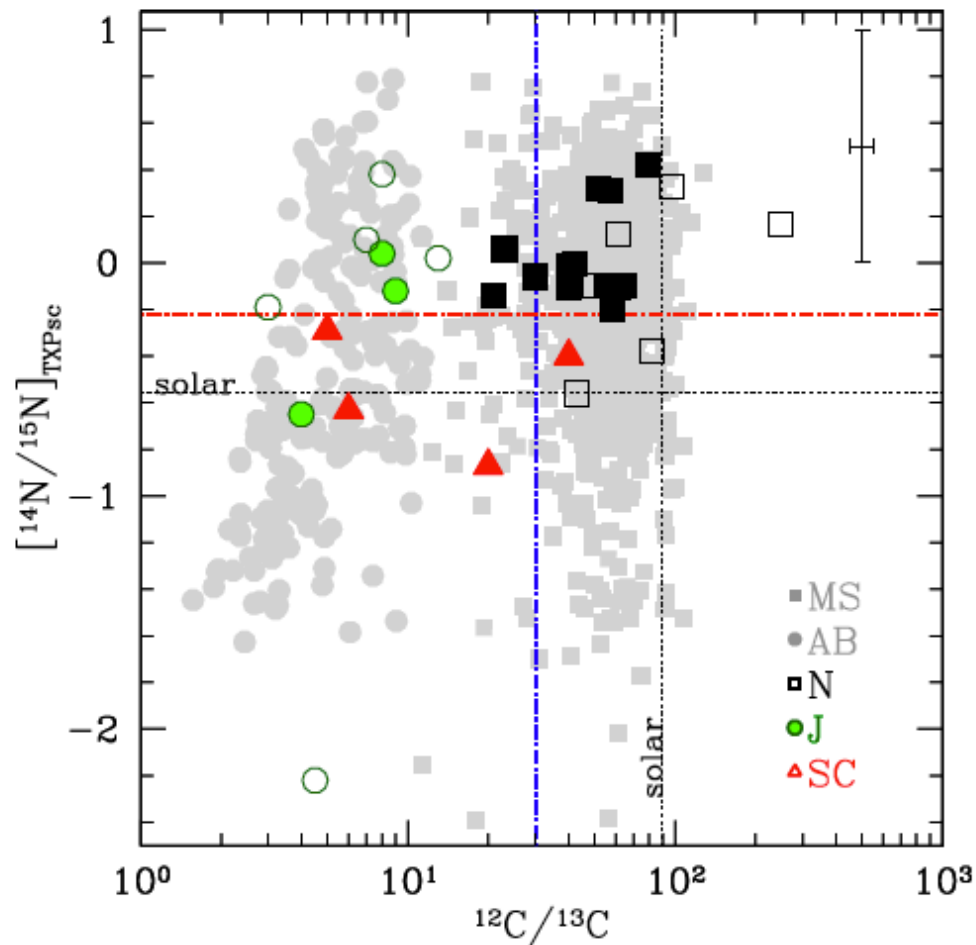
Charbonnel & Lagarde 2010



Nitrogen

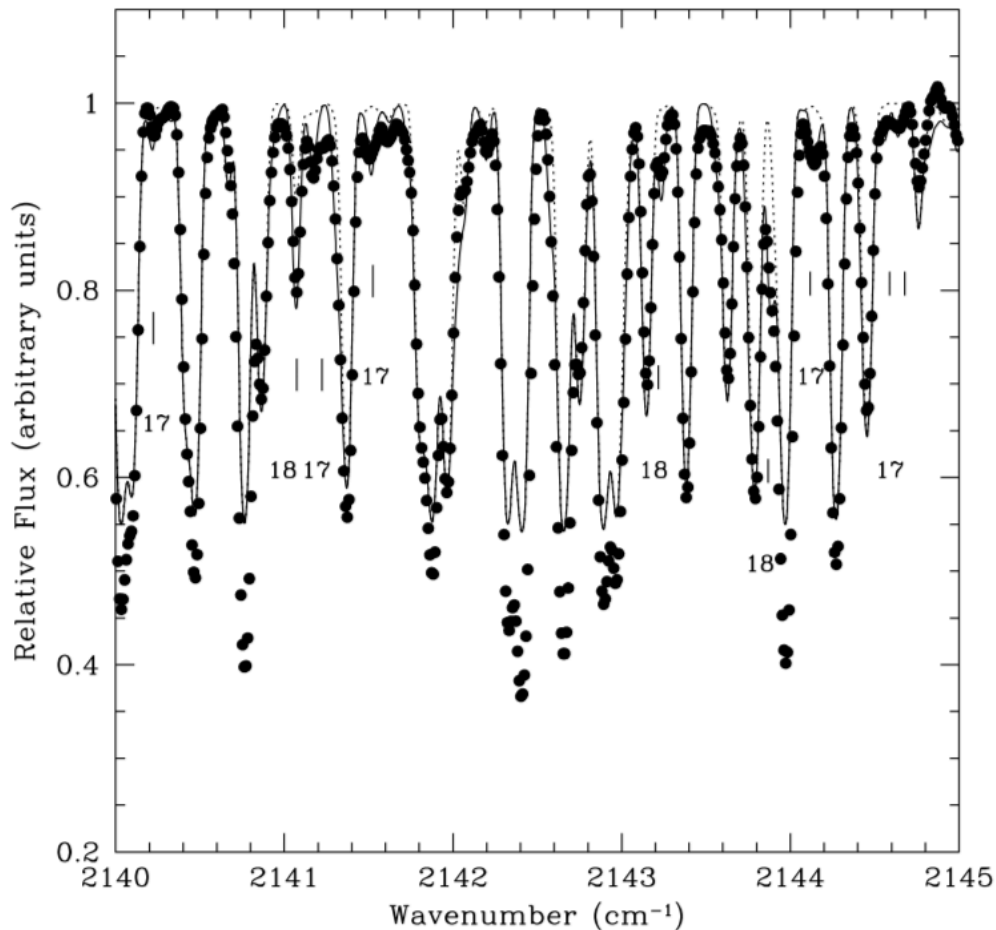


Hedrosa et al. 2012



$^{14}\text{N}/^{15}\text{N}$ ratios measured
in AGB C-stars from CN
bands at $\sim 8000\text{\AA}$
Range in agreement with
SiC grains

Oxygen



Abia et al. 2012

Measured from CO bands near 5 μ m in Arcturus and Aldebaran

→ First dredge up not sufficient to explain carbon and oxygen ratios

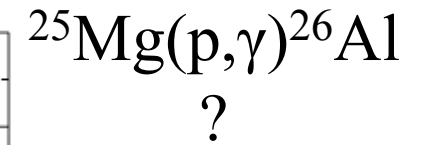
Arcturus :

Dotted: Only ¹⁶O, Solid: Best-fit

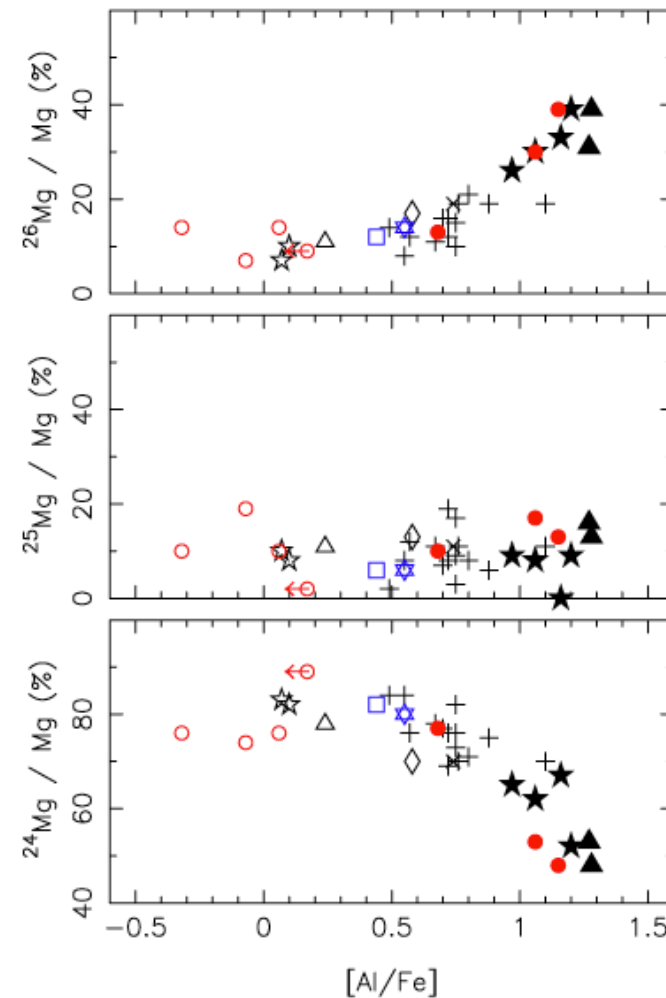
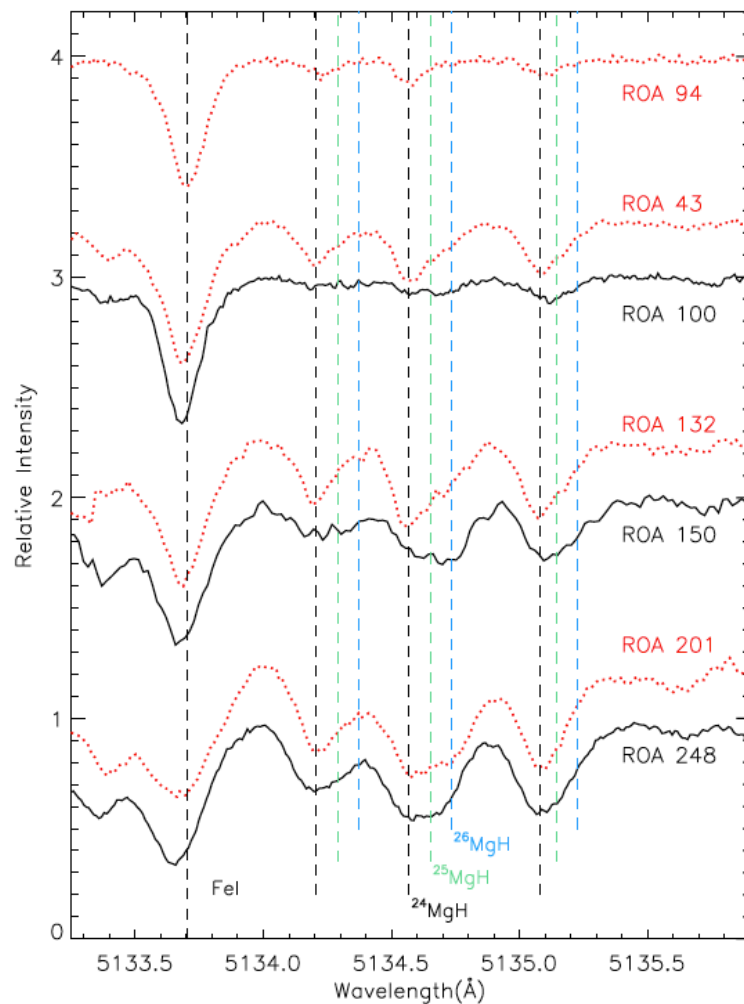
Magnesium



Isotopic ratios measured for GC red giants → Increased rate of



Da Costa
et al. 2013

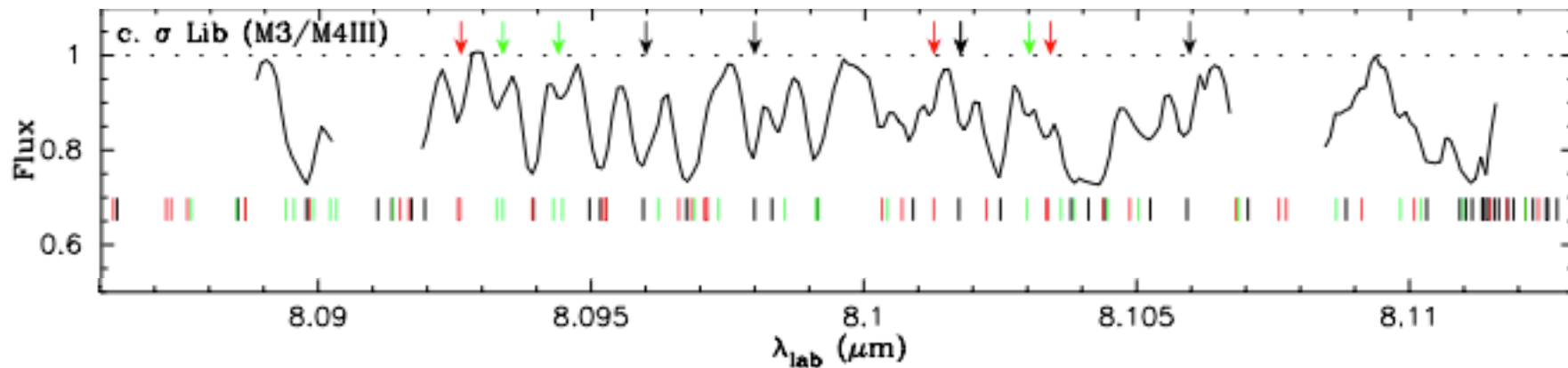


Silicon



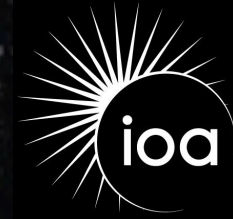
Isotopic ratios measured from SiO bands for K-M giants → meteoritic, but with large ($\sim 30\%$) error bars

Ohnaka 2013



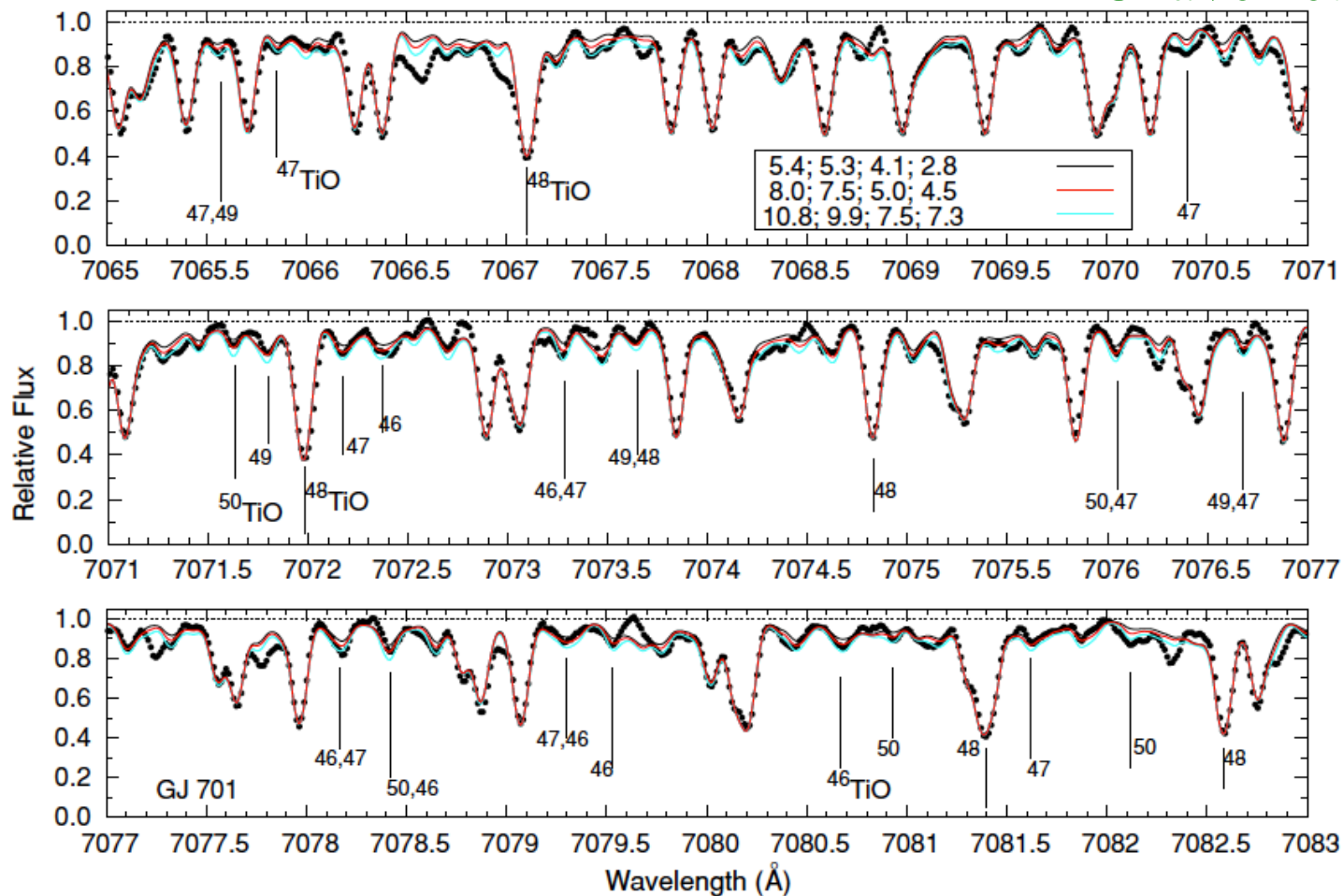
^{28}Si Black — ^{29}Si Green — ^{30}Si Red

Titanium



Approximately constant ratios over one dex in $[Fe/H]$,
measured from TiO bands in 11 M dwarfs

Chavez et al. 2009



Z=28



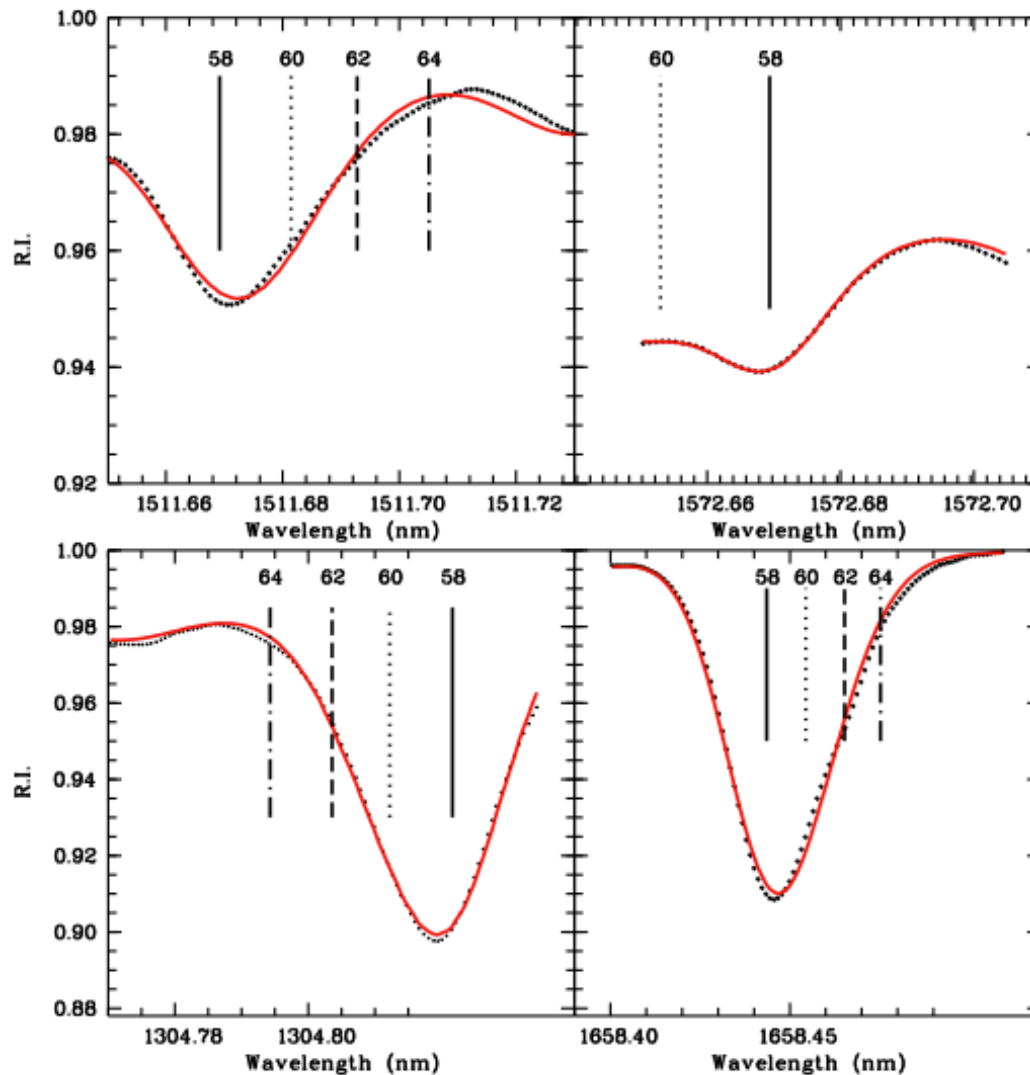
hydrogen 1 H 1.0079																	helium 2 He 4.0026												
lithium 3 Li 6.941	beryllium 4 Be 9.0122																	boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180						
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* Lanthanide series

** Actinide series

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
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Nickel



Caffau et al. 2013

Solar $^{58}\text{Ni}/^{60}\text{Ni}$ ratio
measured from 5 IR
NiI lines.

→ Results in good
agreement with
meteoritic values
except for $1658\mu\text{m}$

56 < Z < 63



Incl. HFS

Ba ~ 0.05 Å

Nd ~ 0.05 Å

Sm ~ 0.05-0.1 Å

Eu ~ 0.2-0.3 Å

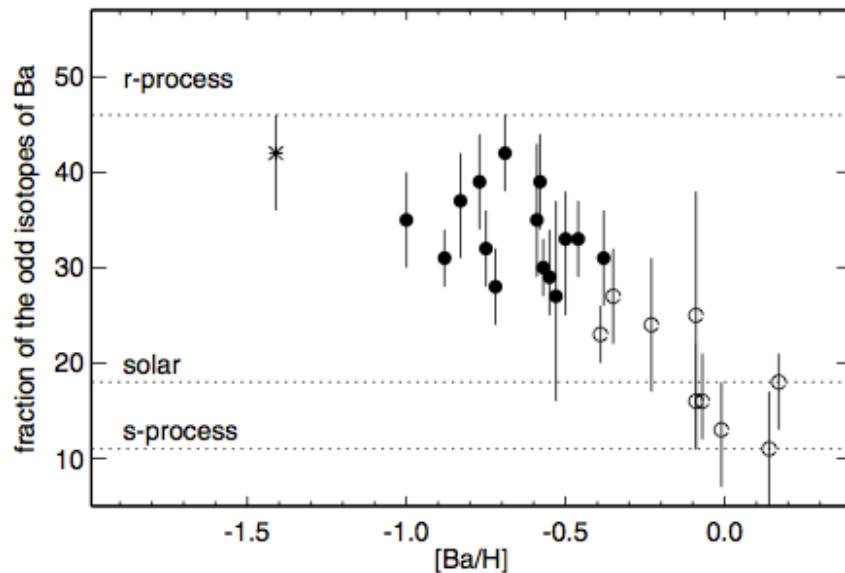
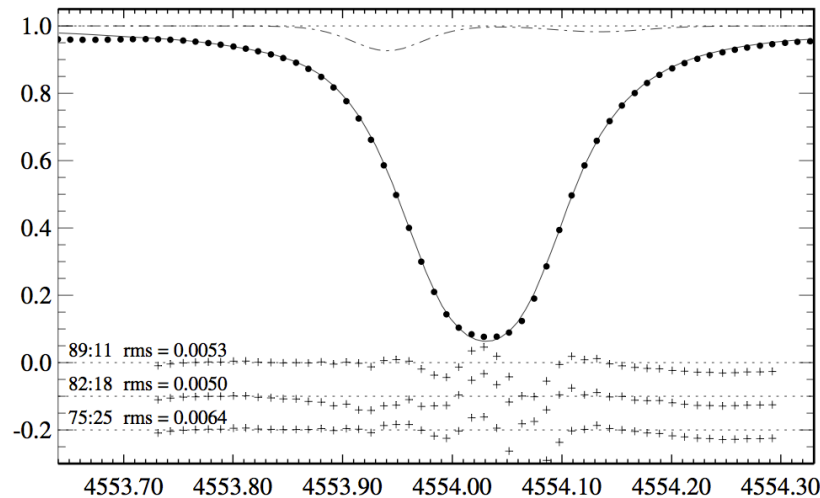
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caesium 55 Cs 132.91	barium 56 Ba 137.33	* 57-70	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 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]			
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** Actinide series

Barium

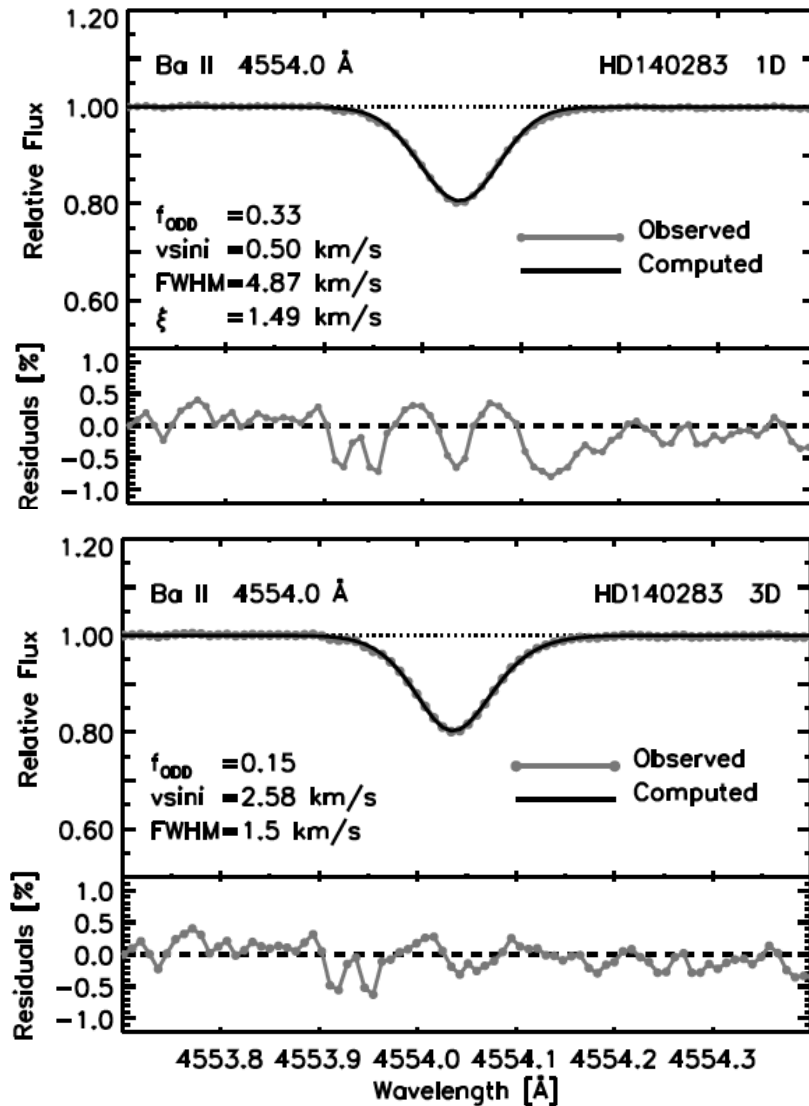


Mashonkina & Zhao 2006

Even-to-odd isotopic ratio measured from the Ba II 4554 Å in 25 cool dwarfs

→ Higher ratios in the thick disk (filled) compared to thin disk (open) indicate higher contribution of the r-process

Barium

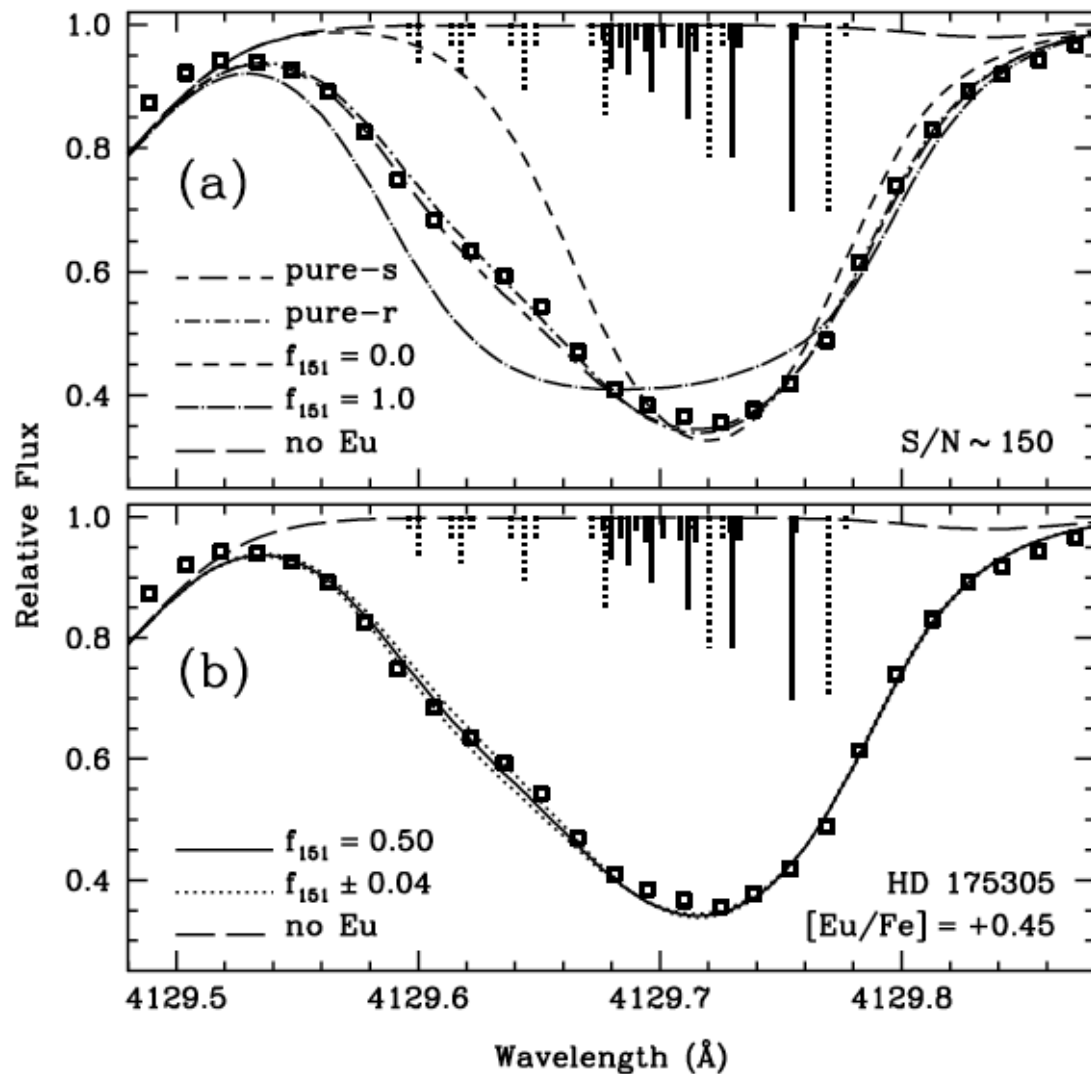
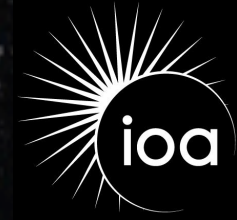


Collet et al. 2009

Even-to-odd isotopic ratio measured in 1D and 3D from the Ba II 4554 Å in metal-poor subgiant HD140283

→ 3D analysis points to s-process origin at $[\text{Fe}/\text{H}] = -2.5$ (!)

Europium



Roederer et al. 2007

Pure r and pure s-process fractions are similar.

→ Results for r-process enhanced star in agreement with both

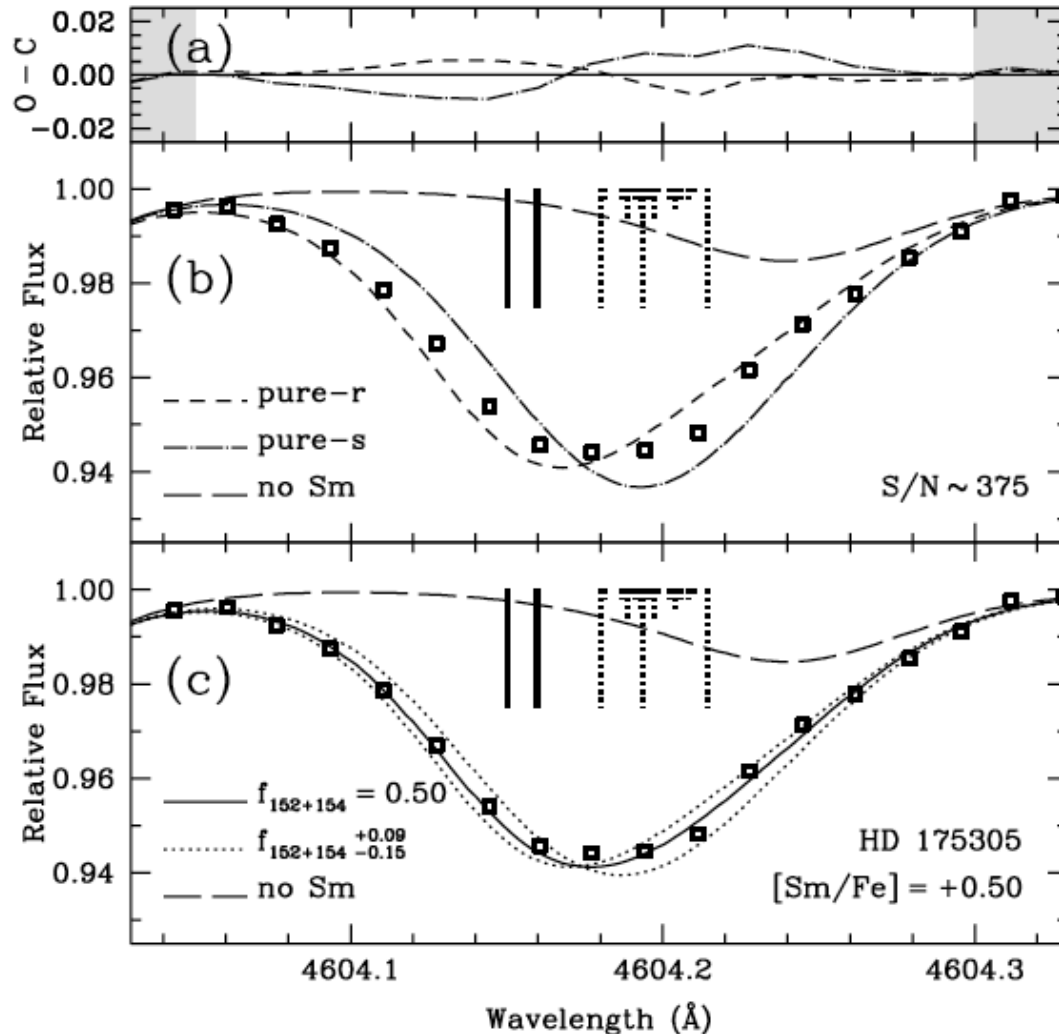
Samarium



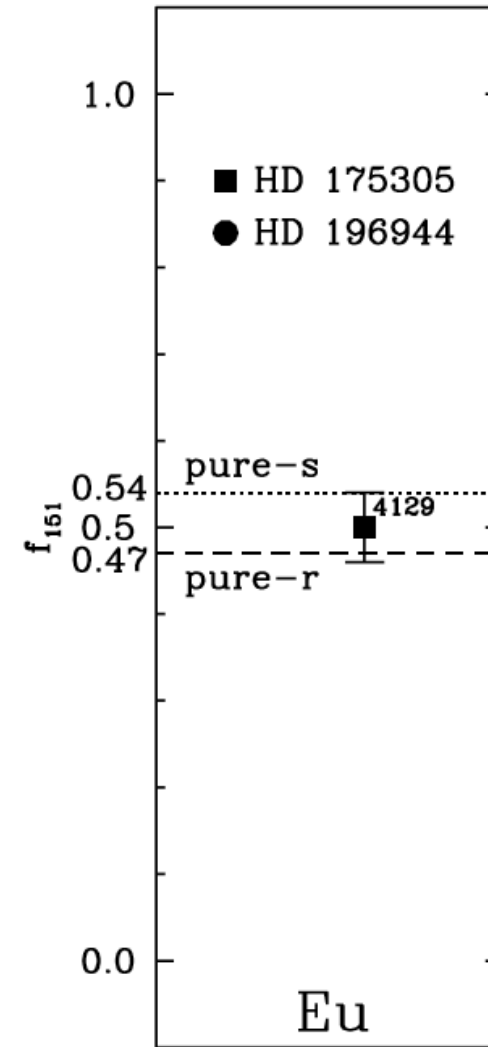
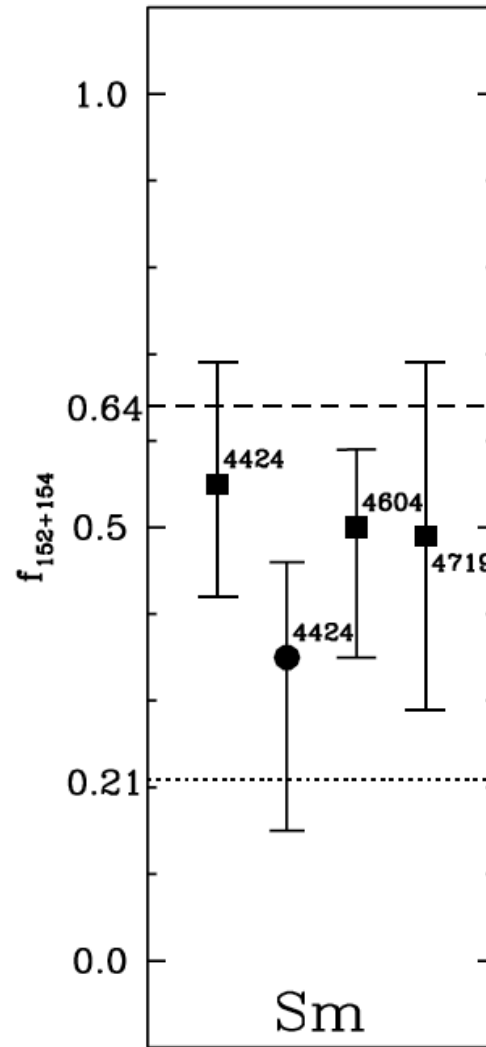
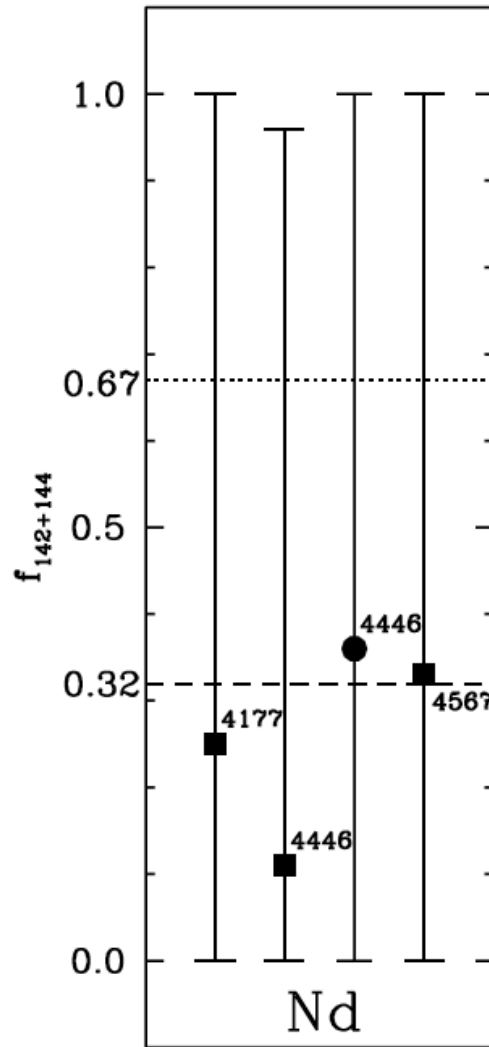
Roederer et al. 2007

Pure r and pure s-process fractions are more different than Eu.

→ Ratios for two metal-poor giants support their respective r- and s-process origin.



Neodymium



Roederer et al. 2007

Summary



- **H, He, Li, B** isotopic ratios are constrained by atomic lines. Implications for Big Bang, GCR spallation, mixing in low mass stars
- **C, N, O, Mg, Si, Ti** isotopic ratios measured from molecular bands. Low-mass stellar evolution, AGB/SN nucleosynthesis etc.
- **Ni** isotopic ratio measured from IR lines (Sun).
- **Ba, Nd, Sm, Eu** isotopic ratios measured from HFS-sensitive singly ionised lines. Ba and Sm can provide additional constraints for the r and s-process channels.