

The νp -Process: A LEPP candidate

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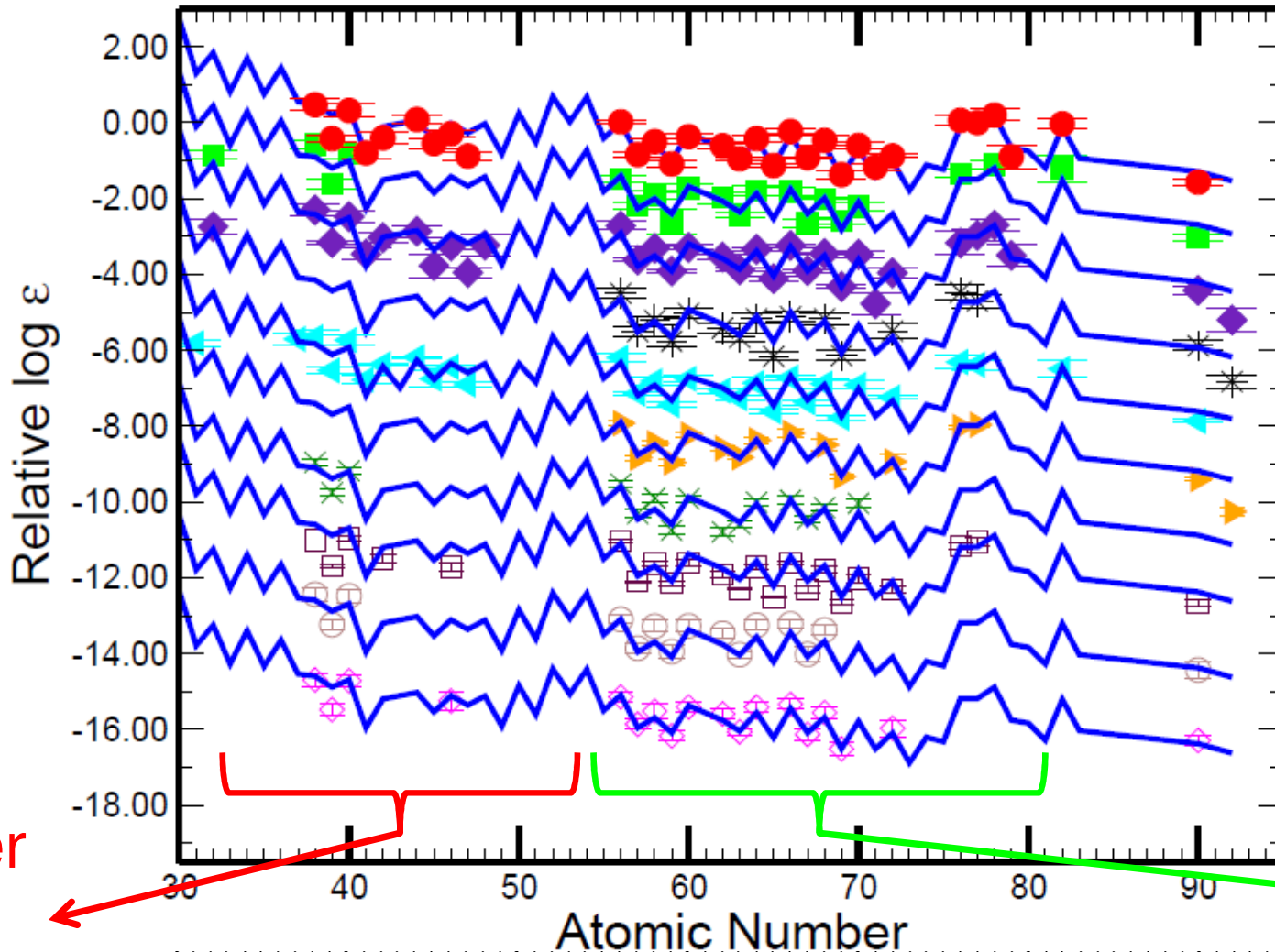


INT Workshop



Observations of Metal-Poor Halo Stars

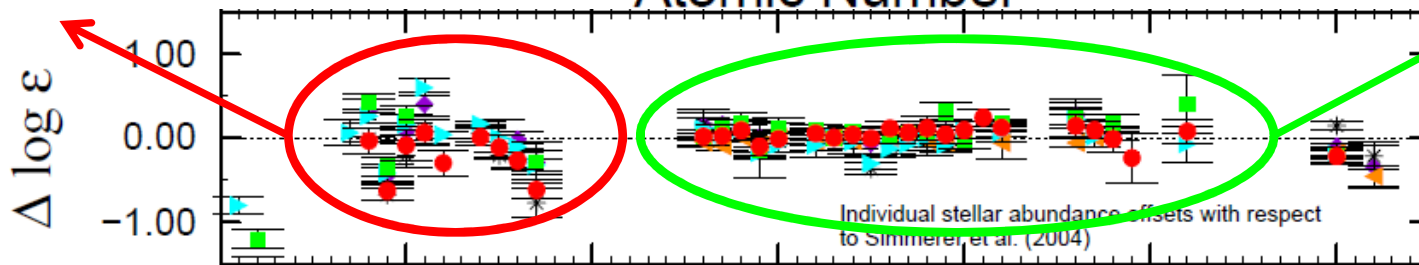
Figure: John Cowan (2011)



- CS 22892-052
- HD 115444
- BD +17 3248
- CS 31082-001
- HD 221170
- HE 1523-0901
- CS 22953-03
- HE 2327-5642
- CS 2941-069
- HE 1219-0312

Robust
r-process
pattern

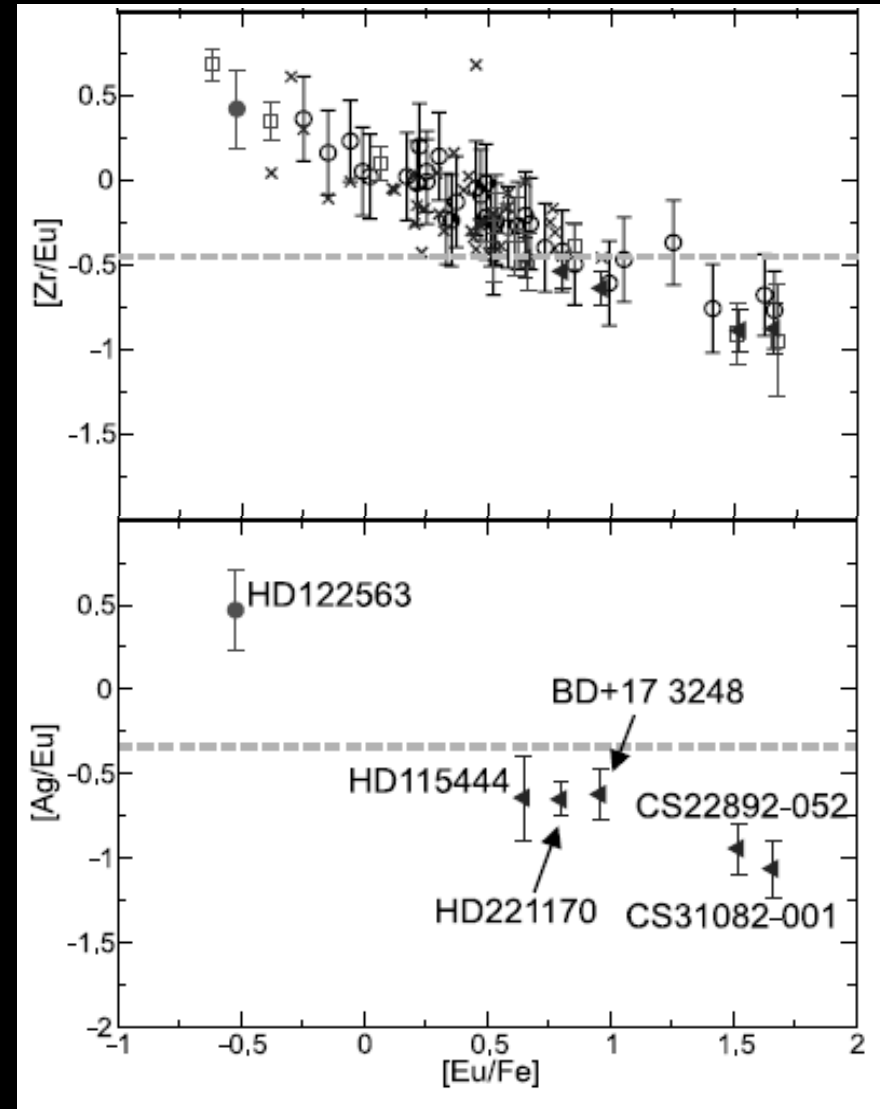
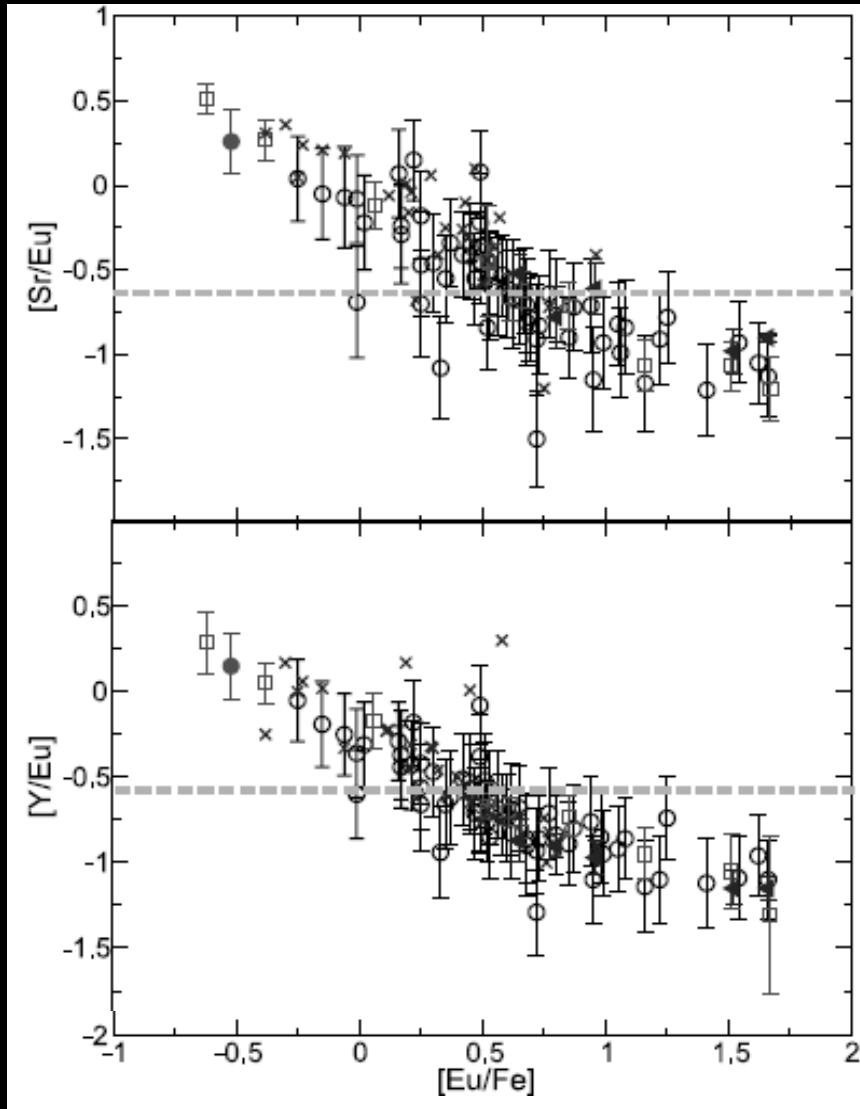
Scatter
LEPP
???



Individual stellar abundance offsets with respect to Simmerer, et al. (2004)

Observations of Metal-Poor Halo Stars

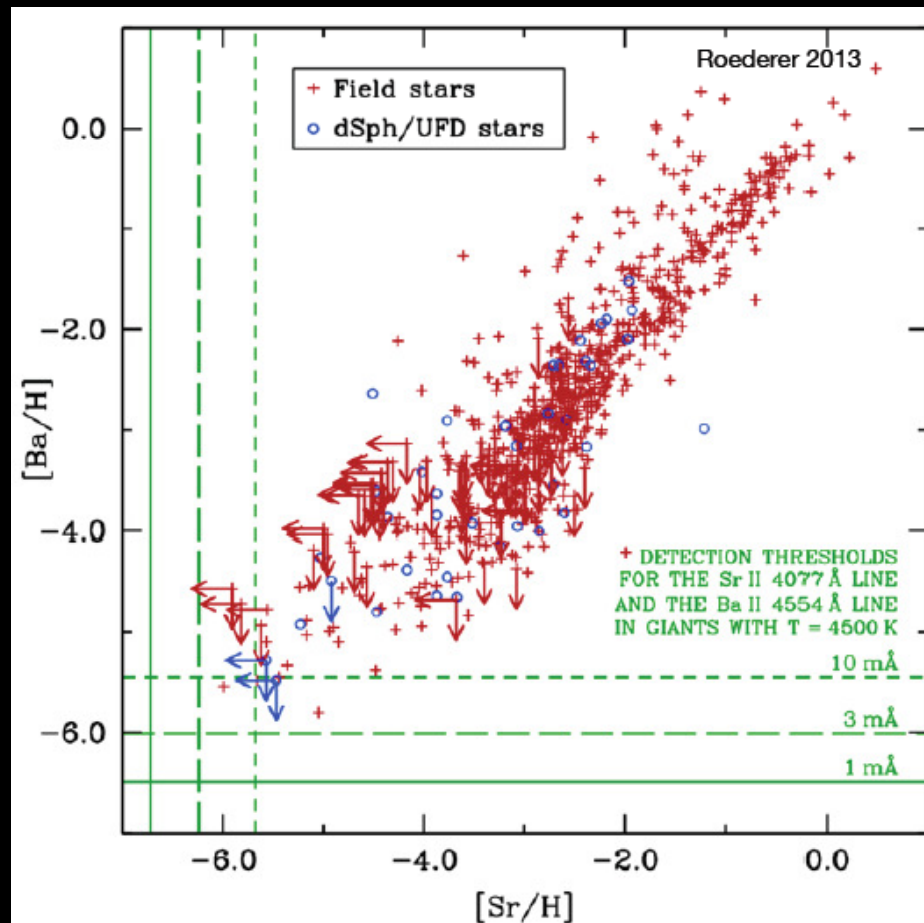
Montes et al (2007)



→ Non-correlation between $[X/Fe]$ and $[Eu/Fe]$ for Sr, Y, Zr, Pd and Ag in metal-poor halo stars

Sr and Ba in metal-poor stars

- Large scatter in Sr/Ba at low metallicities
→ evidence for an independent process producing Sr but not Ba at low metallicities
- No known metal-poor star without n-capture elements?



Neutrino-driven winds

- Strong neutrino flux from PNS
- Drives matter-outflow behind shock wave
- Nucleosynthesis:
 - NSE ($T=10-8\text{GK}$)
 - Charged-particle reactions ($8-2\text{GK}$)
 - R-process and vp-process nucleosynthesis ($3-1\text{GK}$)

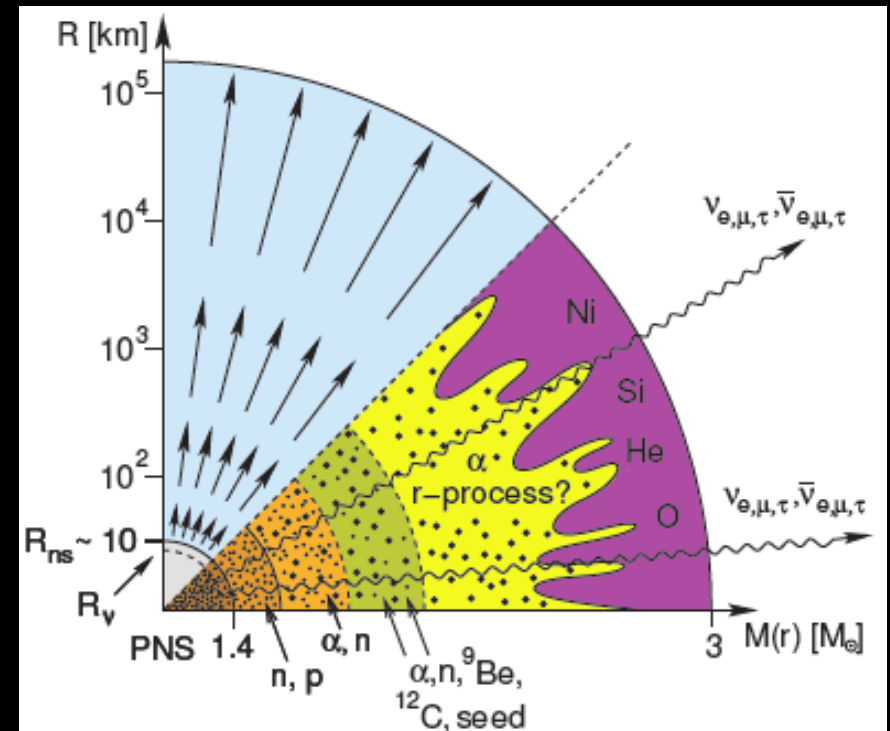


Figure: Janka

Conditions in wind determine details of nucleosynthesis (Y_e , entropy, timescale)

Questions

- Are there additional nucleosynthesis processes creating heavy elements?
→ Lighter Element Primary Process (LEPP)

Travaglio et al (2004): LEPP (solar LEPP)

Montes et al (2007): solar LEPP \leftrightarrow stellar LEPP

Qian & Wasserburg: two components or sites to r-process

Frohlich et al (2006), Pruet et al (2006); Wanajo (2006): vp-process

Heavy element nucleosynthesis

Processes other than s- and (main) r-process:

- Weak r-process: in electron-capture SNe
e.g. Wanajo et al (2011)
- Neutron-capture processes (other than r- and s-process)
e.g. Herwig (2014)
- Neutrino-p-process (proton-rich environment!)
e.g. Frohlich et al (2006), Pruet et al (2006); Wanajo (2006): vp-process

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- Is the vp-process the LEPP?
- What are the contributions from neutrino-driven winds?
- What is the underlying nuclear physics?

→ Nuclear Physics: Exploring the Heart of Matter

Clues from simulations

Clues from simulations

- What nucleosynthesis is possible in neutrino-driven winds?

- hydrodynamics / reverse shock

Arcones, Frohlich, Martinez (2012)
Wanajo et al (2012)

- Neutron-rich winds

Arcones & Montes (2011)
Bliss & Arcones (2014)

- Nuclear physics:

- trajectory independent predictions of critical inputs

Frohlich & Rauscher (2012)

- Nuclear masses I → affect abundances locally

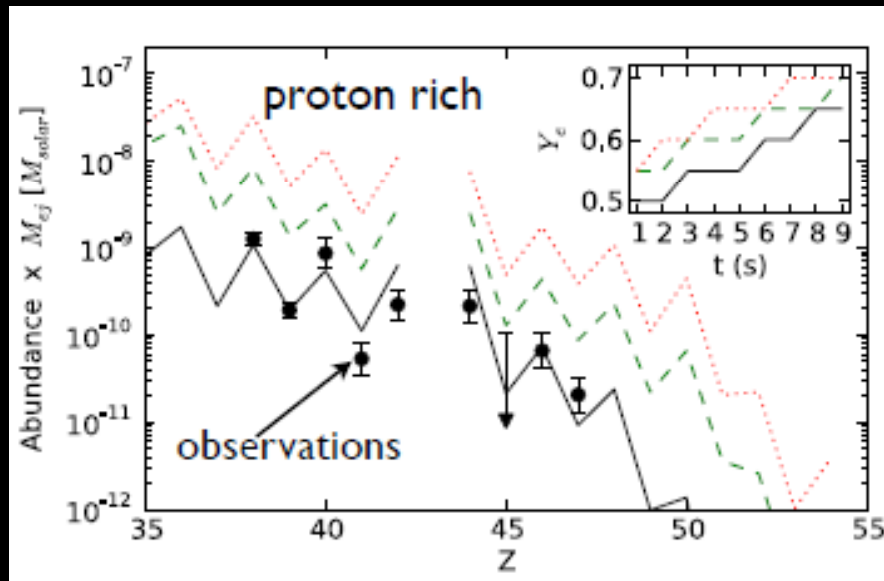
Weber et al (2008)

- Nuclear masses II → new experimental efforts at Lanzhou

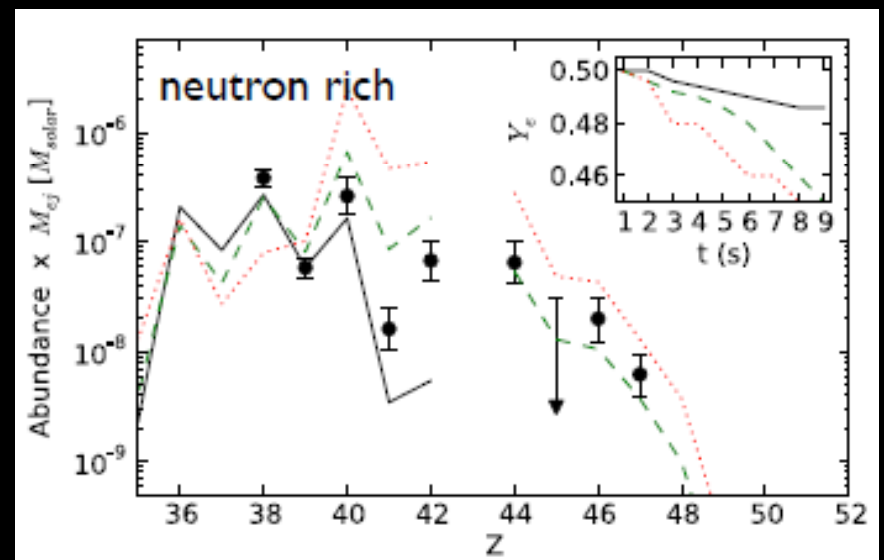
- Nuclear reactions → experimental efforts

Nucleosynthesis in ν -winds

- How does the abundance pattern from ν -driven wind simulations compare to the observed pattern in metal-poor stars.



Observed pattern reproduced
Production of p-nuclei

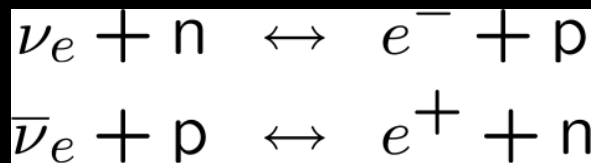


Overproduction of $A=90$ ($N=50$)
→ Only a fraction of neutron-rich ejecta (Hoffman et al 1996)

→ Need some p-rich ejecta

Nucleosynthesis in neutrino-winds

- Entropy s : 50-120 kB/nuc in recent SN simulations \rightarrow no full r-process
- Timescale τ : few milliseconds
- Electron fraction Y_e : set by weak interactions

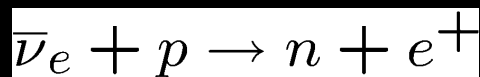


$$Y_e = \frac{Y_p}{Y_p + Y_n} = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e, p}}{\lambda_{\nu_e, n}}}$$

- Luminosity ratio $L_{\bar{\nu}_e}/L_{\nu_e}$
- Difference in neutrino energies: $\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e}$
- Details of nuclear physics (nuclear potentials, etc)

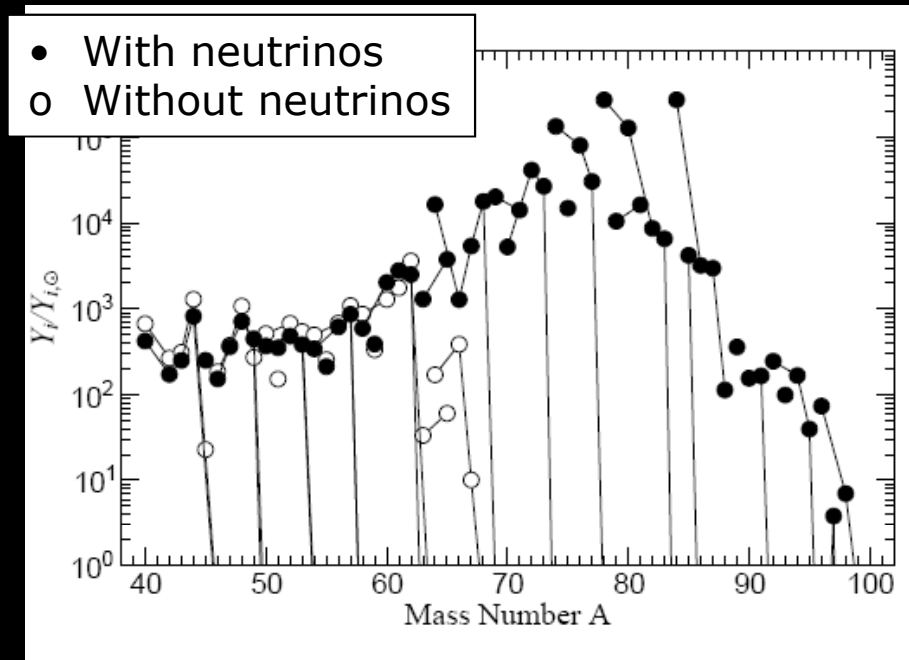
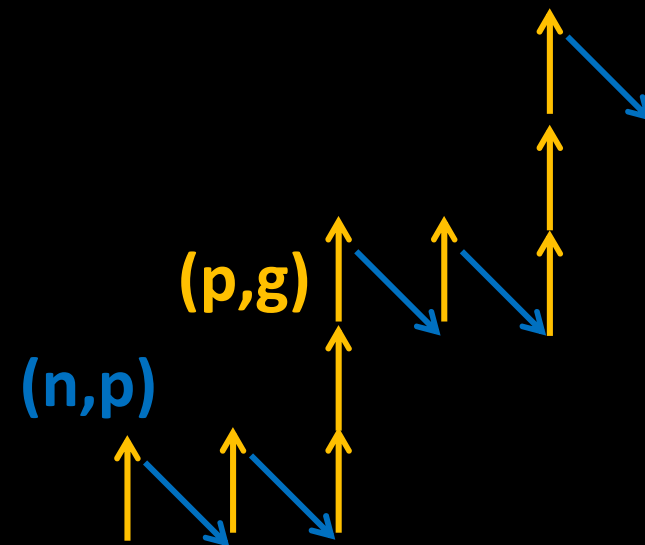
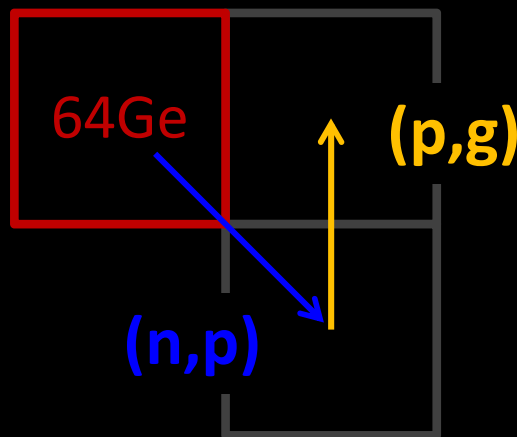
The νp -Process

- proton-rich matter is ejected under the influence of neutrino interactions
- true rp-process is limited by slow β decays, e.g. $\tau(64\text{Ge})$
- Neutron source:



- Antineutrinos help bridging long waiting points via (n,p) reactions:

(n,p)
(p, γ)

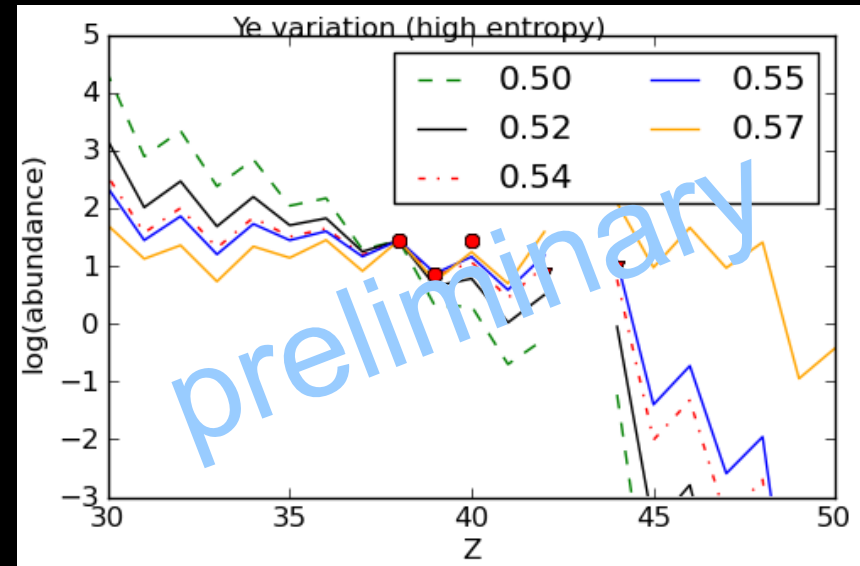
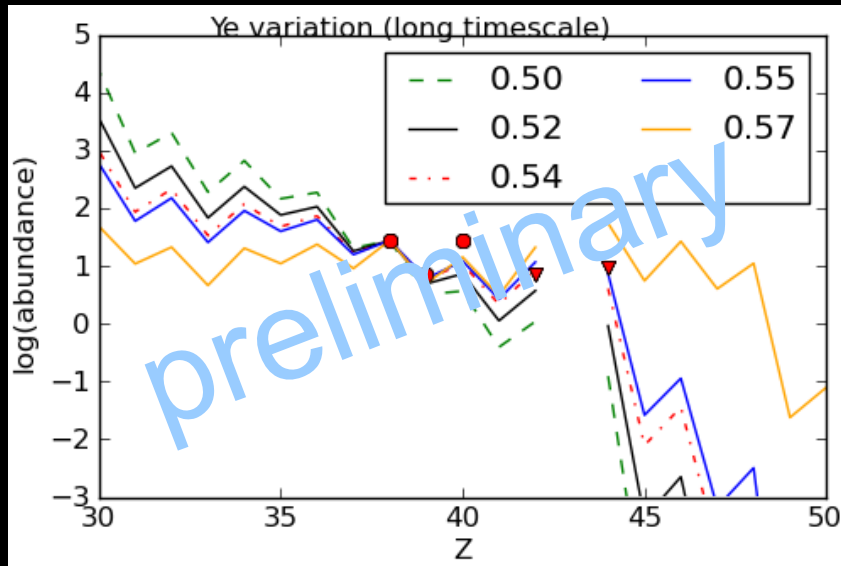
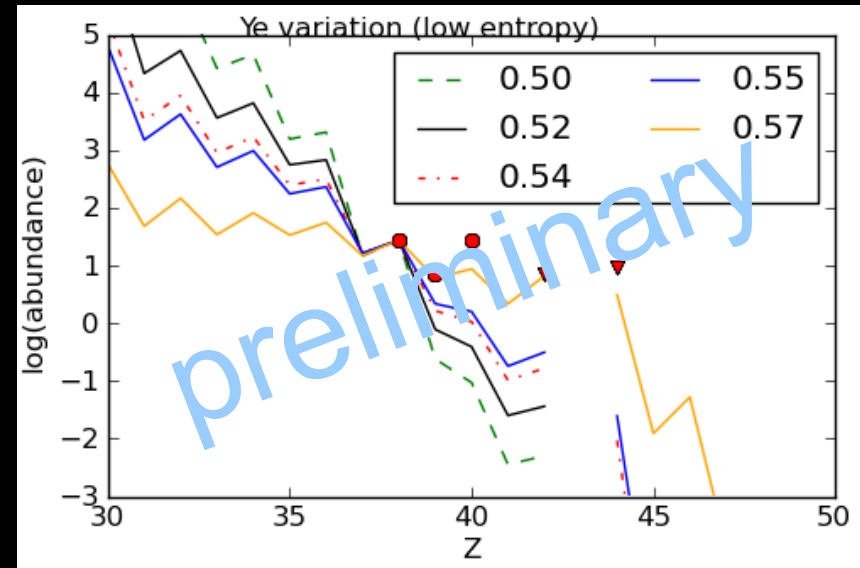
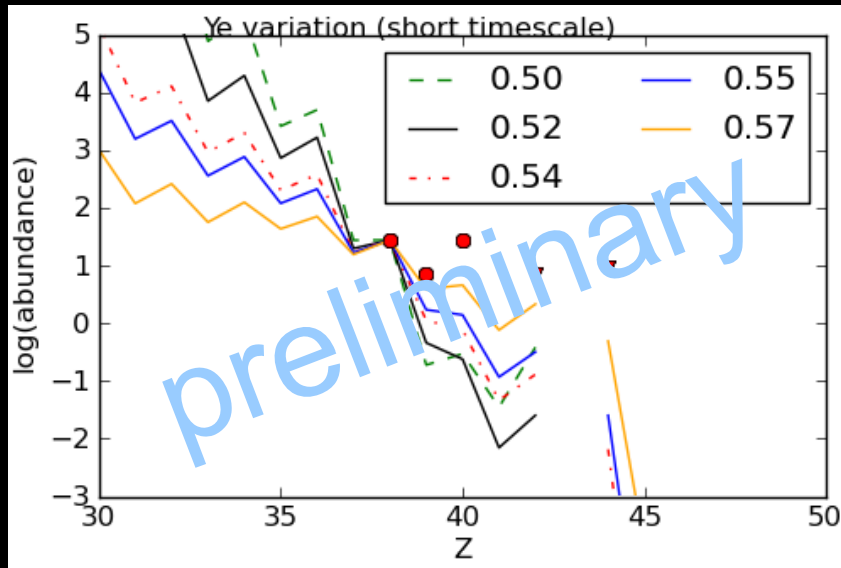


Frohlich et al (2006)

Electron fraction Y_e

- Parameterized studies of (p-rich) wind nucleosynthesis
 - Ratio of neutrino luminosities
 - Neutrino mean energies and electron fraction
 - Strength of νp -process depends on how many protons available and how many are converted to neutrons (for (n,p) reactions)
- Dependence of abundances on Y_e :
 - Mostly smooth behavior as function of Y_e for isotopes and elements
 - Yields up to Sn for some conditions

Electron fraction Y_e

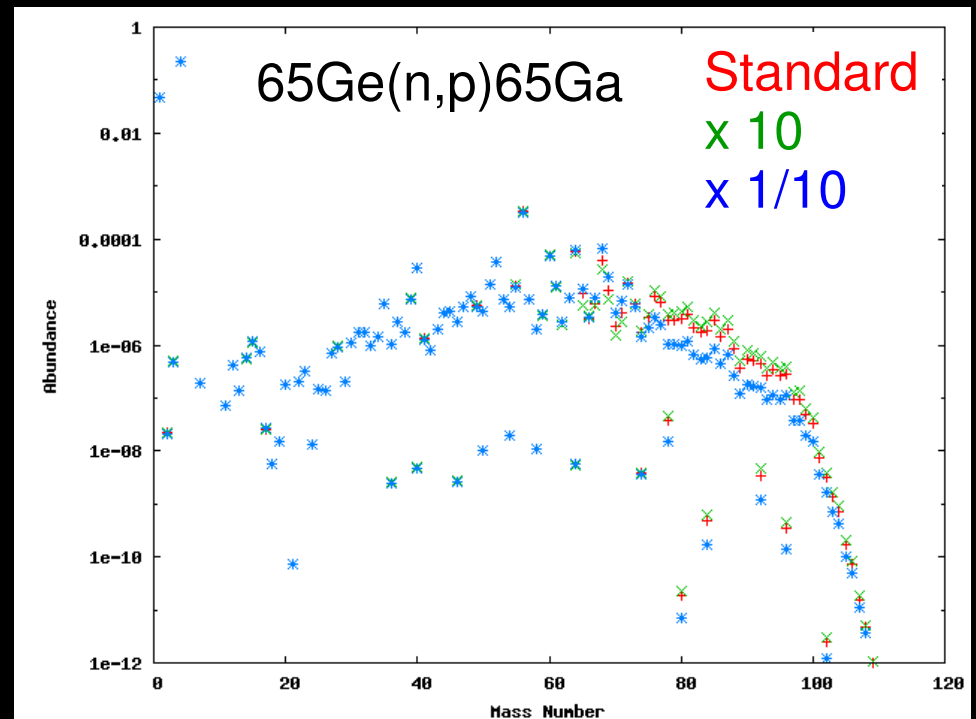


→ If only one process and only from p-rich conditions: high Y_e needed

Nuclear physics

- All important reaction rates from Hauser-Feshbach predictions
- Systematic sensitivity study:
 - (n,p) reactions are important for p-rich conditions → uncertainties in rates changes abundances locally

- Previous work:
 - Reactions on light nuclei
Wanajo et al (2012)
 - $^{56}\text{Ni}(n,p)$
Wanajo et al (2012); Frohlich+ (2012)
 - $^{64}\text{Ge}(n,p)$
Frohlich+ (2012)
 - $^{96}\text{Pd}(n,p)$



Clues from stars

Detected in more than a few stars

hydrogen 1 H 1.0079	Detected in more than a few stars																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]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]	ununquadium 114 Uuq [289]					

Fe-group

s-process

* Lanthanide series

* * Actinide series

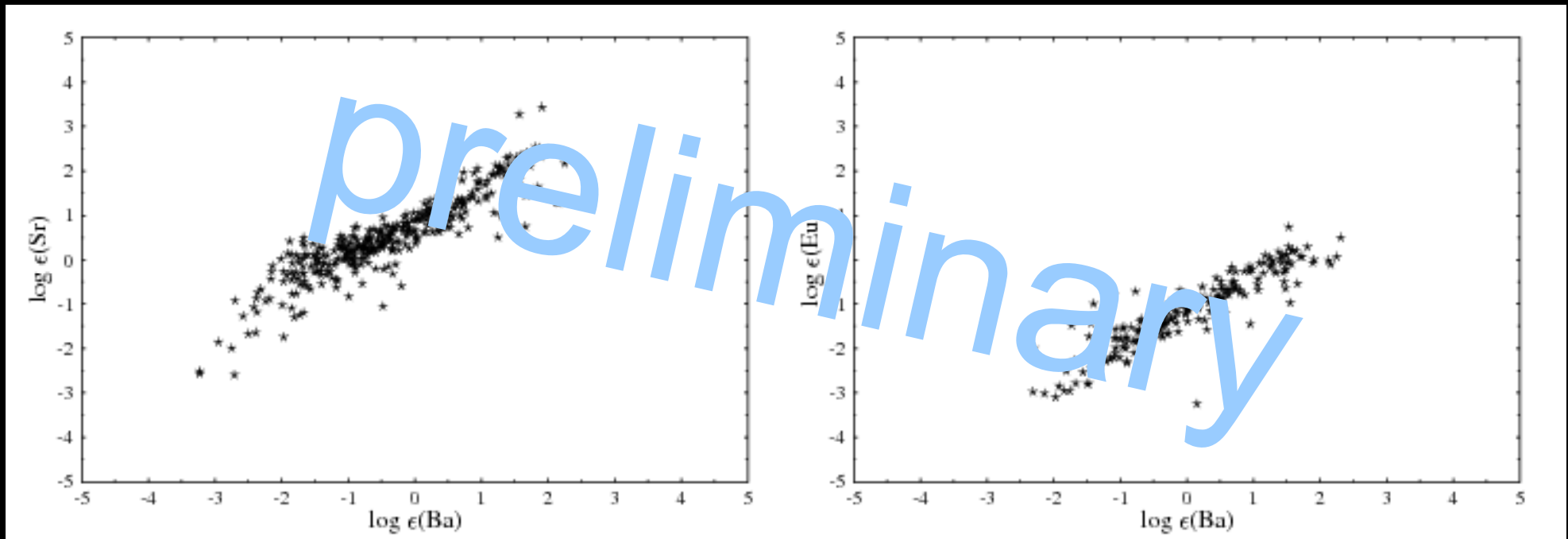
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70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

r-process

Our sample

- Compiled a large sample of abundances for distinct metal-poor stars from the literature & SAGA database
 - $[\text{Fe}/\text{H}] < -1.0 \rightarrow$ metal-poor
 - $[\text{Ba}/\text{Eu}] < 0.2 \rightarrow$ r-process enriched
 - No binaries
- Includes several LEPP stars
 - Low enhancement in heavy n-capture elements
 - High enhancement in light n-capture elements
 - HD122563, HD88609

Some examples



Summary

- Abundances in metal-poor stars:
 - 2nd and 3rd r-process peak: very robust
 - “lighter heavy elements” or light n-capture elements: interesting situation → how to explain?
- Nucleosynthesis calculations:
 - Need some p-rich ejecta but cannot only be p-rich
 - Understand dependence of yields on conditions, but what conditions are found in SNe?
 - Nuclear physics: important to be constrained experimentally; only local effects on abundances