The νp-Process: A LEPP candidate

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U.S. DEPARTMENT OF ENERGY

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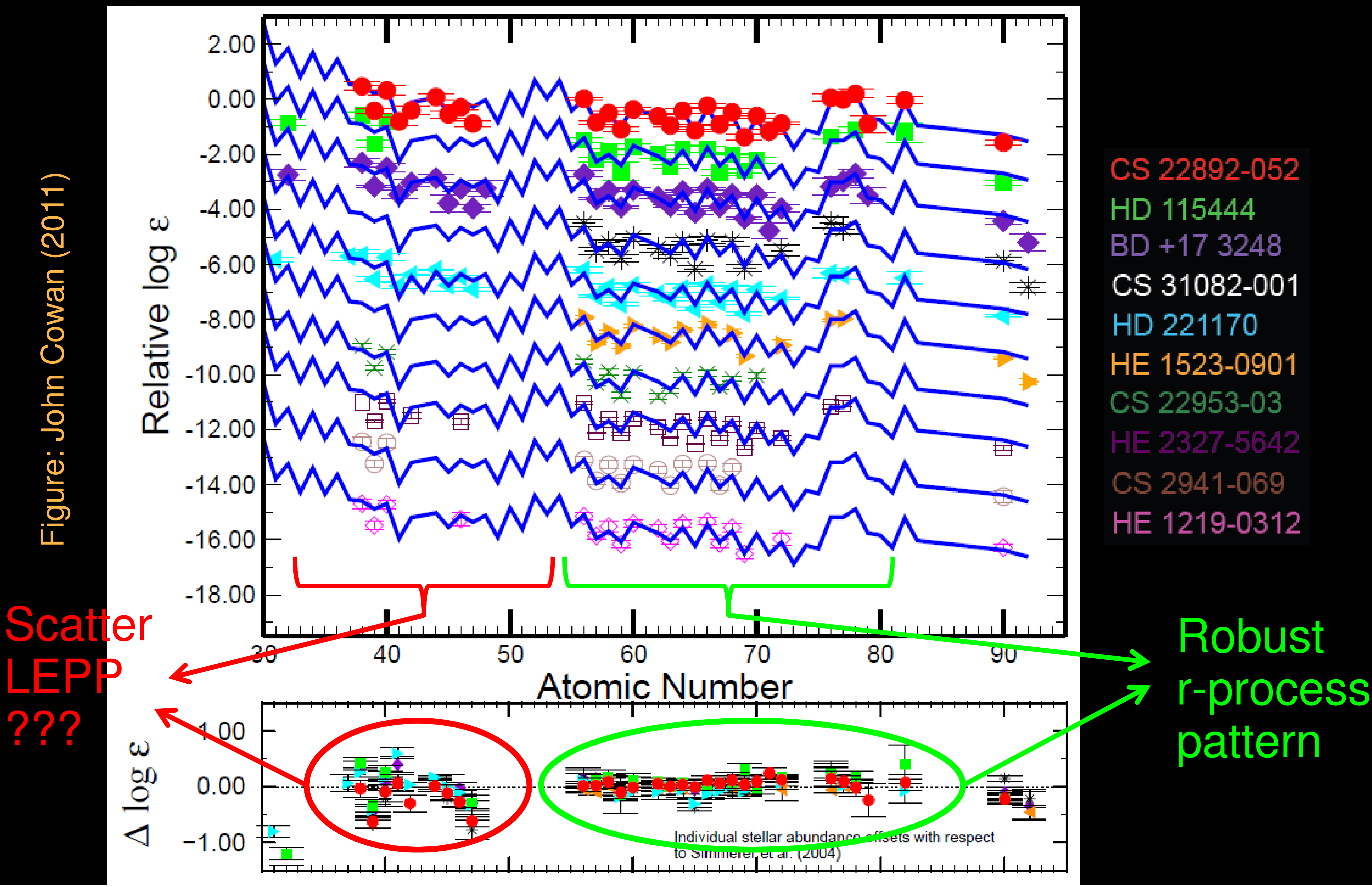
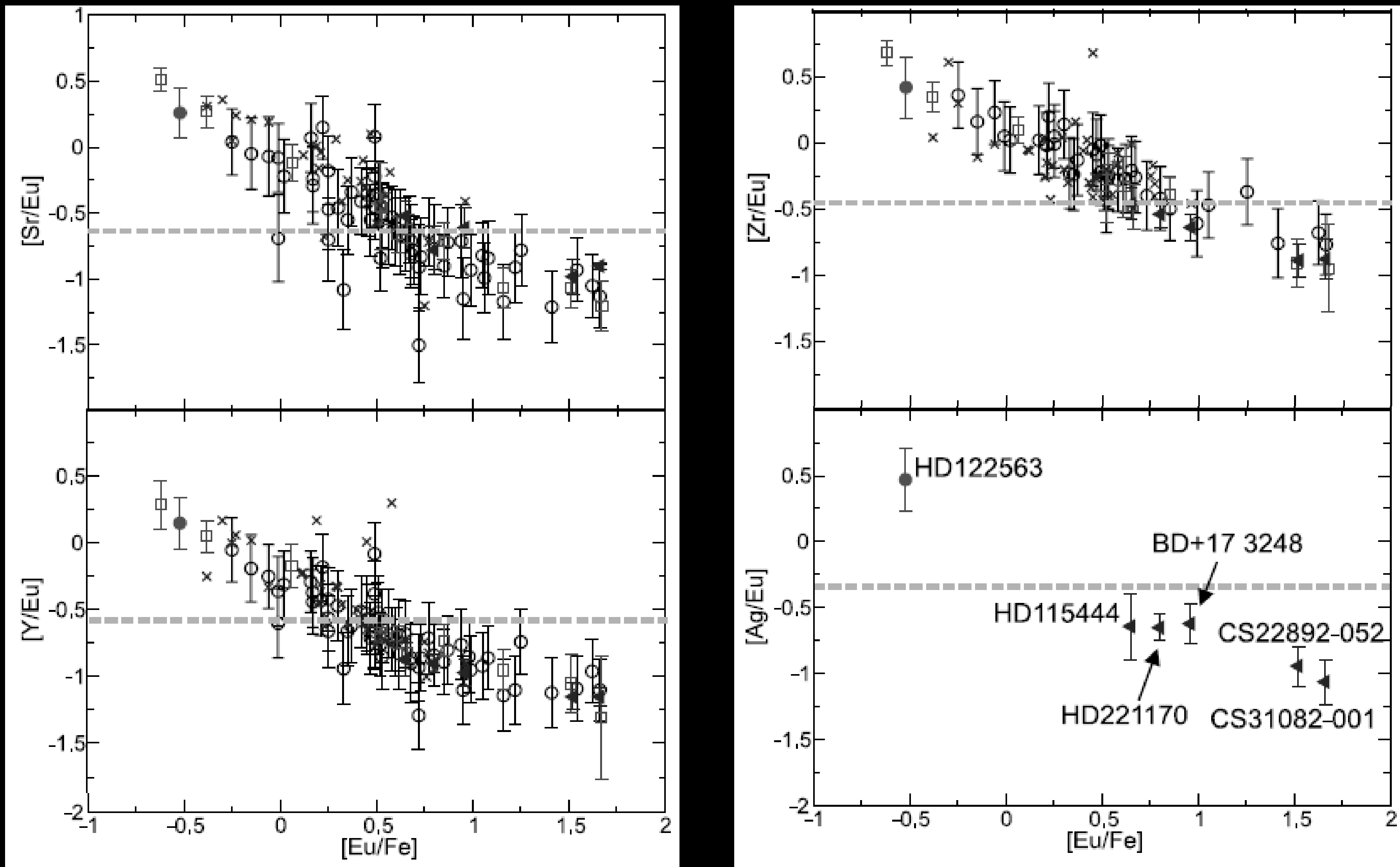
Observations of Metal-Poor Halo Stars



Observations of Metal-Poor Halo Stars

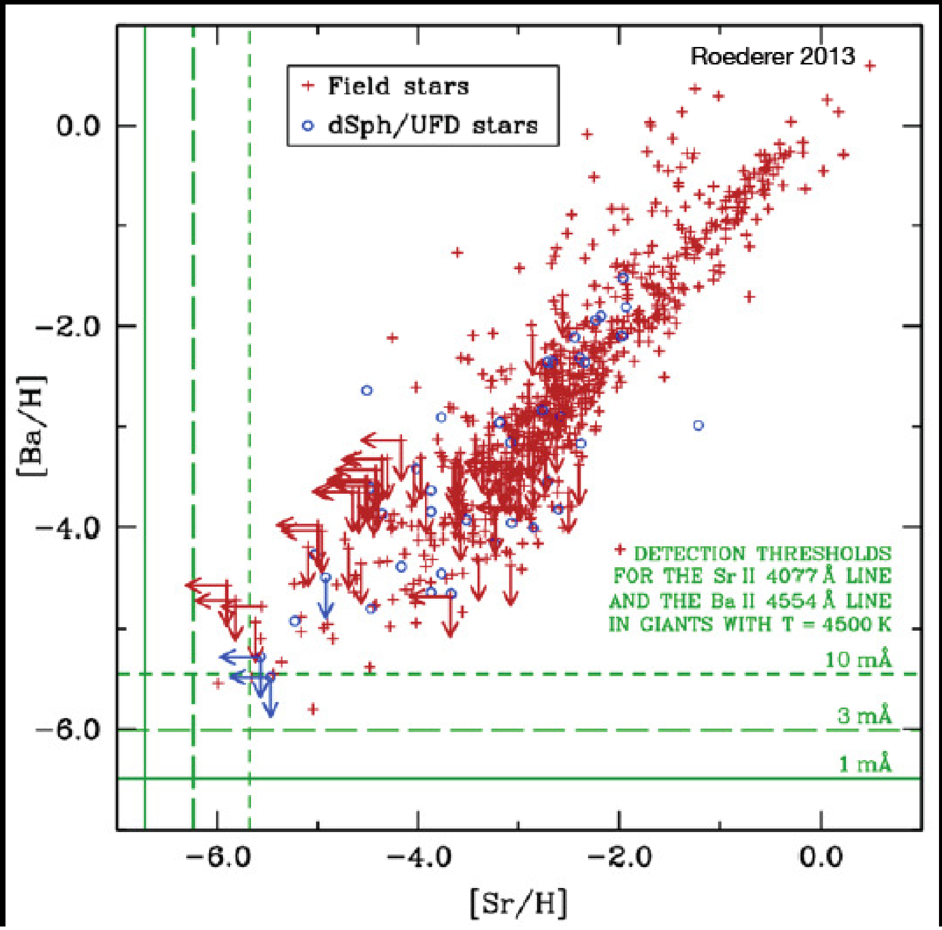
Montes et al (2007)



➔ 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?



Roederer 2013

Neutrino-driven winds

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

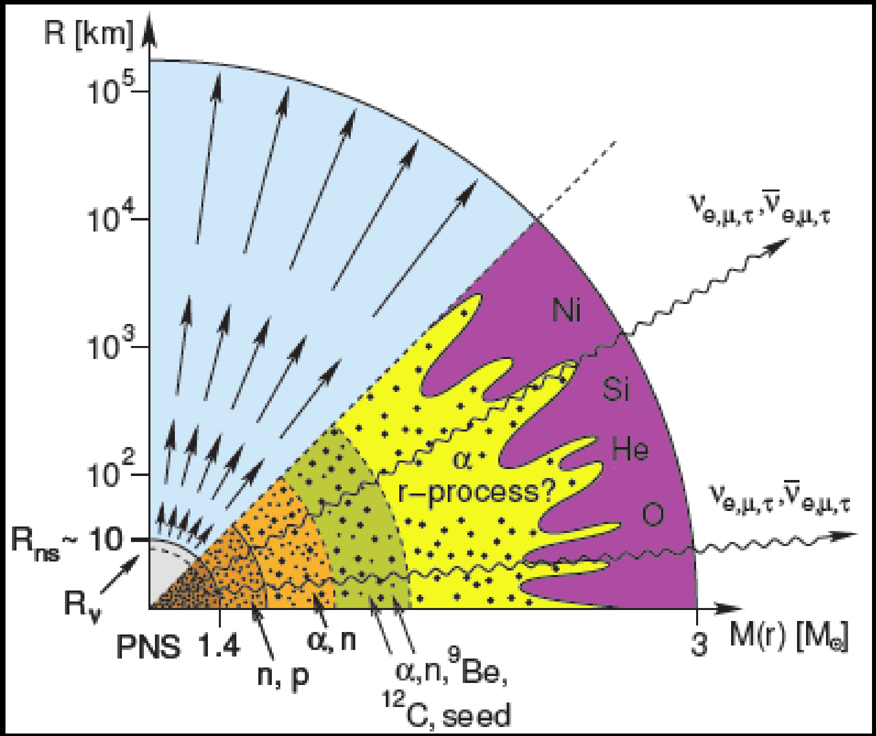


Figure: Janka

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

Questions

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

  Travaglio et al (2004): LEPP (solar LEPP)
  Montes et al (2007): solar LEPP ←→ stellar LEPP
  Qian & Wasserburg: two components or sites to r-process
  Frohlich et al (2006), Pruet et al (2006); Wanajo (2006): νp-process

→ Nuclear Physics: Exploring the Heart of Matter

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): νp-process

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- Is the νp-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

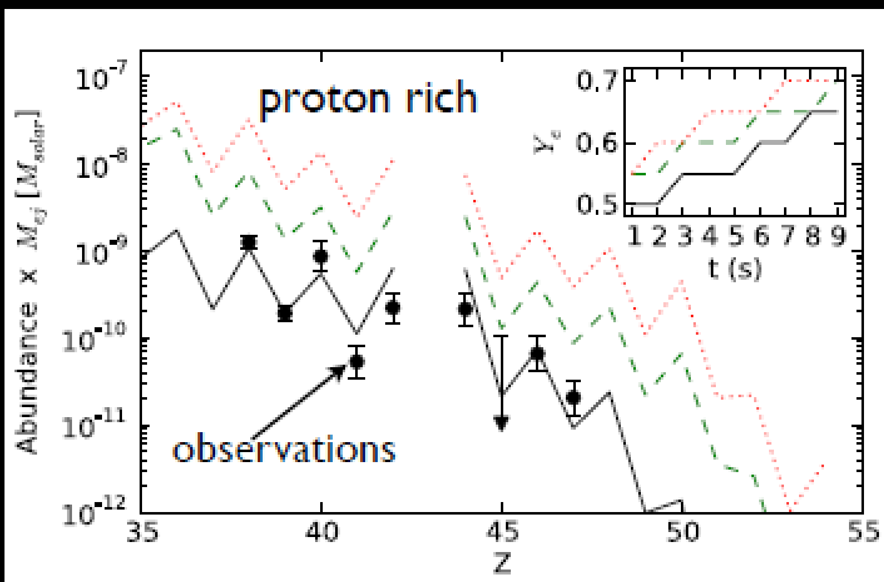
Clues from simulations

- 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)

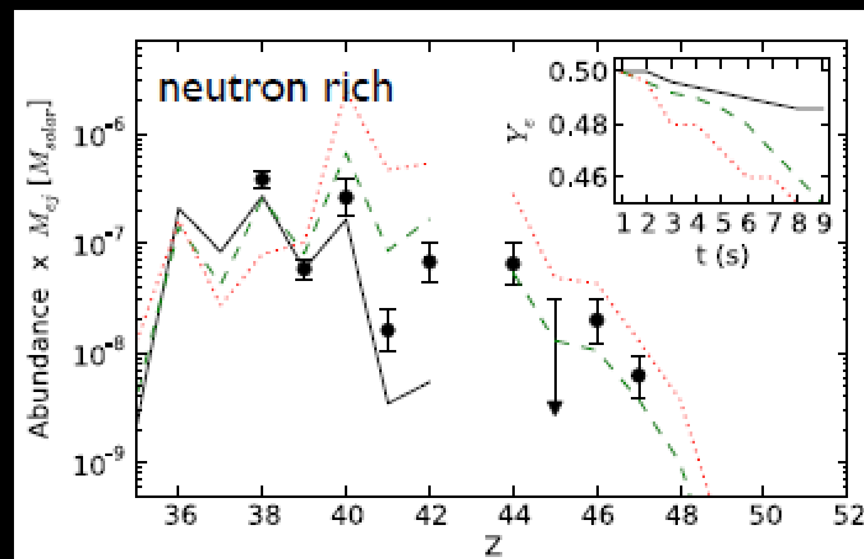
  - Nuclear physics:
    - trajectory independent predictions of critical inputs
      Frohlich & Rauscher (2012)
    - Nuclear masses I → affect abundances locally
      Weber et al (2008)
    - Nuclear masses II → new experimental efforts a Lanzhou
    - Nuclear reactions → experimental efforts

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)

Arcones & Montes (2011)

➔ Need some p-rich ejecta

Nucleosynthesis in neutrino-winds

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

$$\nu_e + \mathrm{n} \leftrightarrow e^- + \mathrm{p}$$
$$\overline{\nu}_e + \mathrm{p} \leftrightarrow e^+ + \mathrm{n}$$

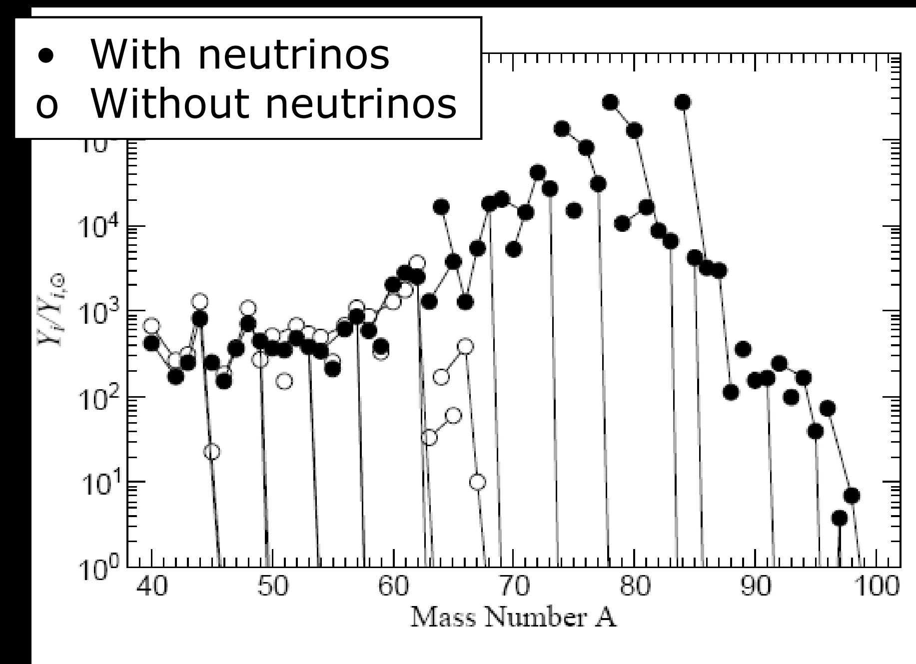
$$Y_e = \frac{Y_p}{Y_p + Y_n} = \frac{1}{1 + \frac{\lambda_{\bar{\nu}_e,p}}{\lambda_{\nu_e,n}}}$$

- 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. τ(64Ge)
- Neutron source:

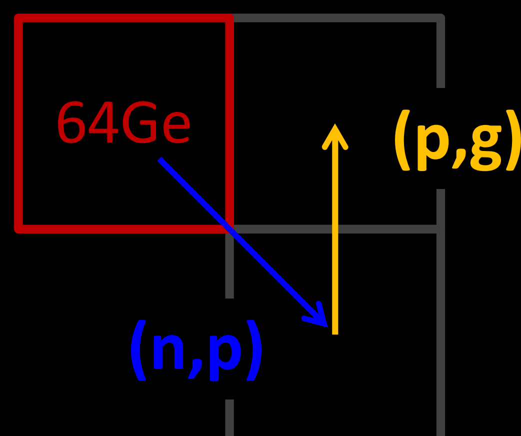
$$\overline{\nu}_e + p \rightarrow n + e^+$$

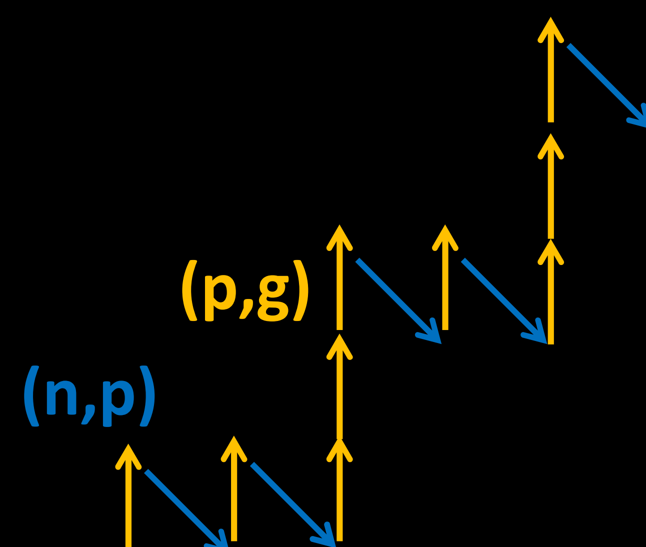


Frohlich et al (2006)

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

(n,p)
(p,γ)





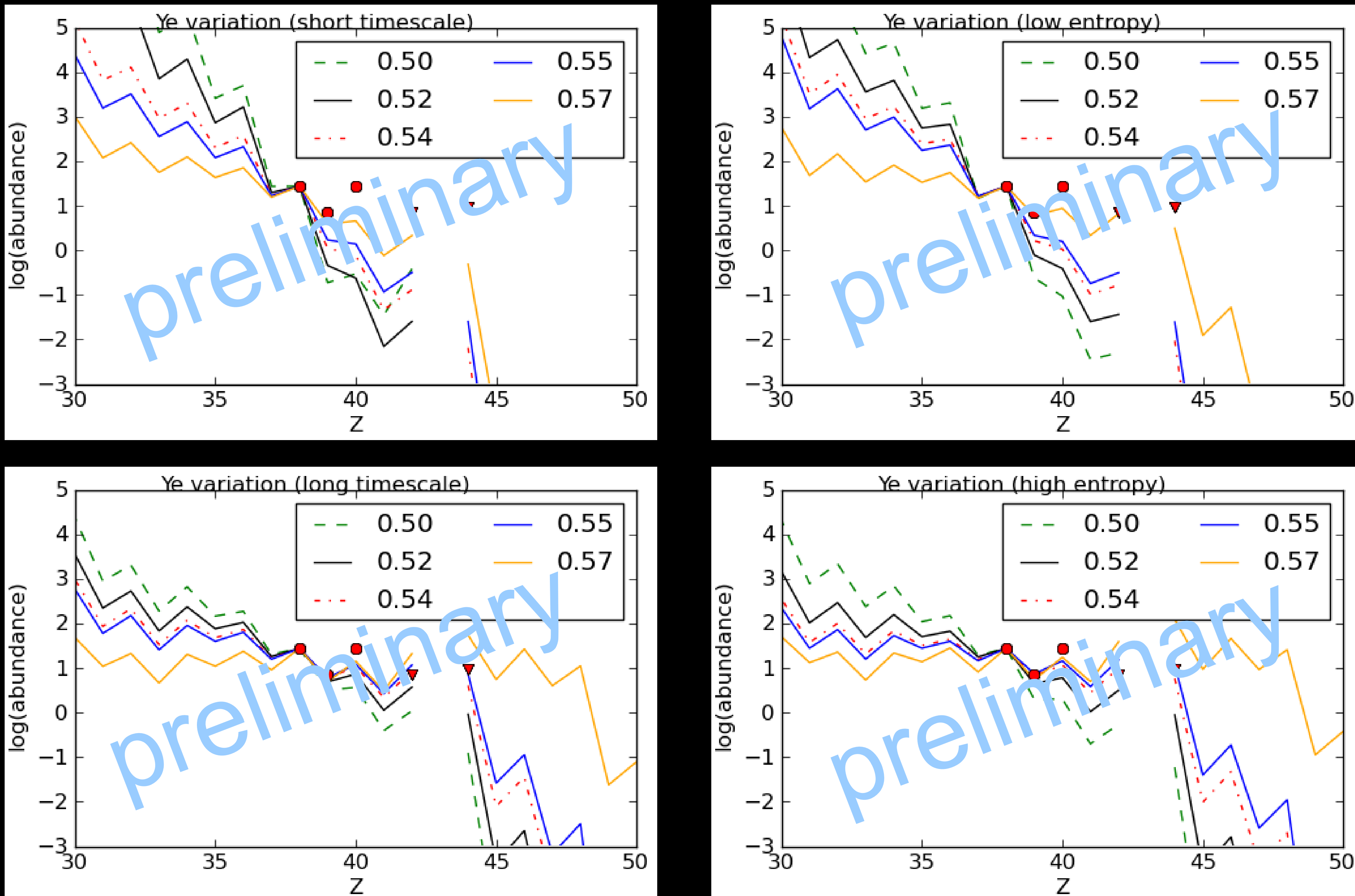
Electron fraction Ye

- 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 Ye:
  - Mostly smooth behavior as function of Ye for isotopes and elements
  - Yields up to Sn for some conditions

Electron fraction Ye



Samulski & Frohlich, in prep.

➔ If only one process and only from p-rich conditions: high Ye needed

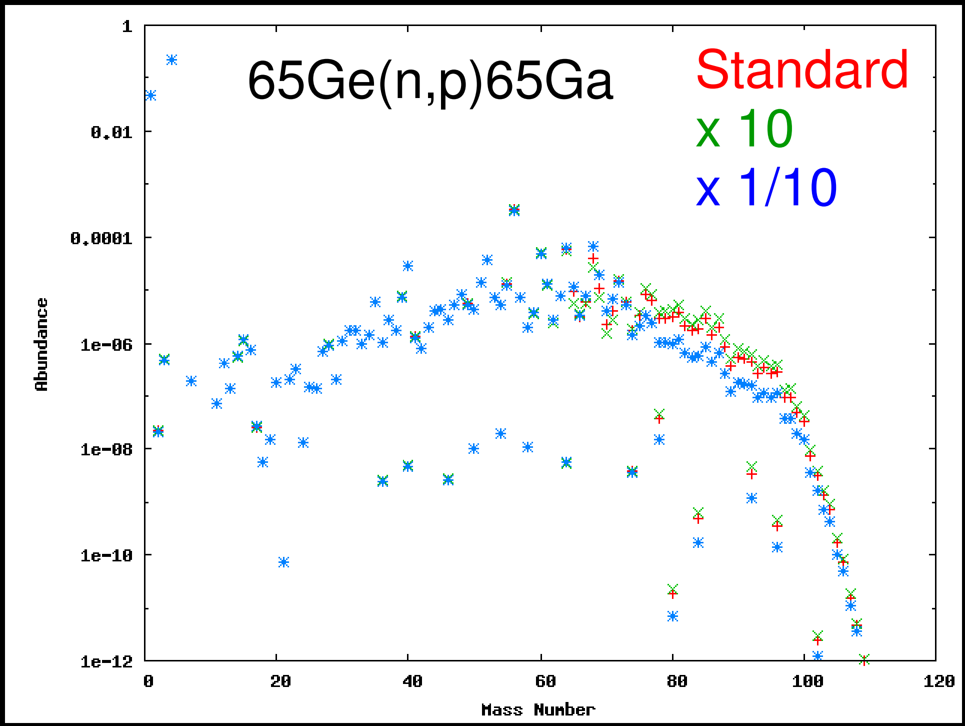
Nuclear physics

- 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)
  - 56Ni(n,p)

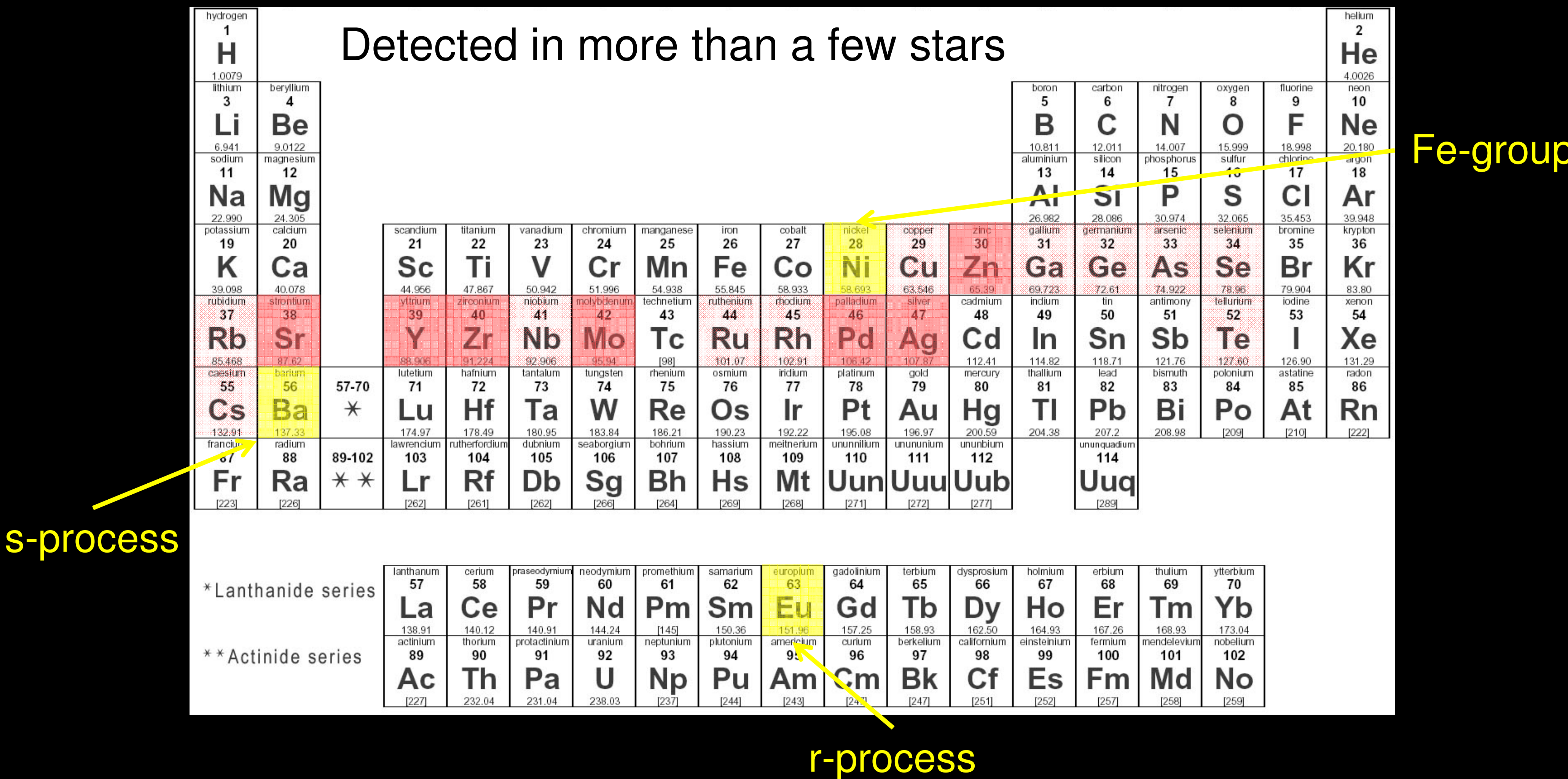
    Wanajo et al (2012); Frohlich+ (2012)
  - 64Ge(n,p)
  - 96Pd(n,p)

    Frohlich+ (2012)



Hatcher & Frohlich, in prep.

Clues from stars

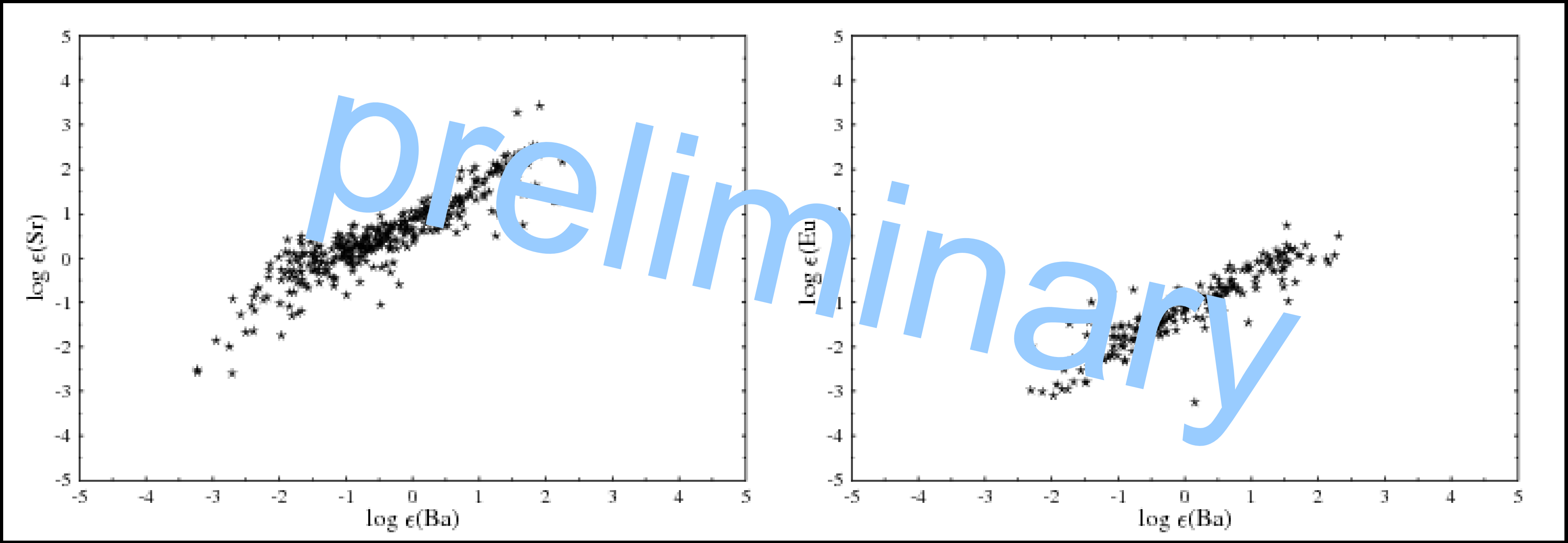


Our sample

- Compiled a large sample of abundances for distinct metal-poor stars from the literature & SAGA database
  - [Fe/H] < -1.0 → metal-poor
  - [Ba/Eu] < 0.2 → 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

Frohlich et al, in prep

Some examples



Frohlich et al, in prep

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