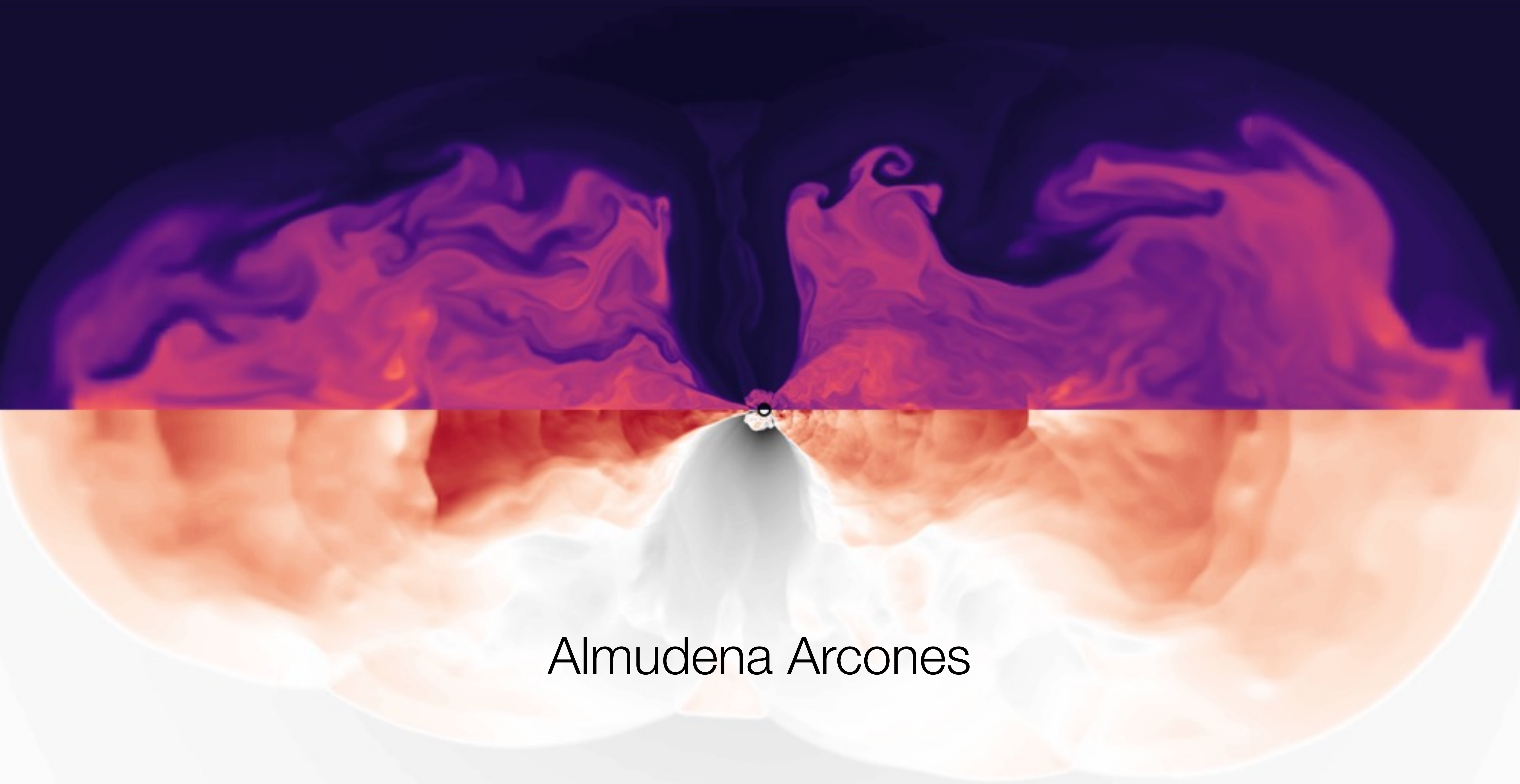
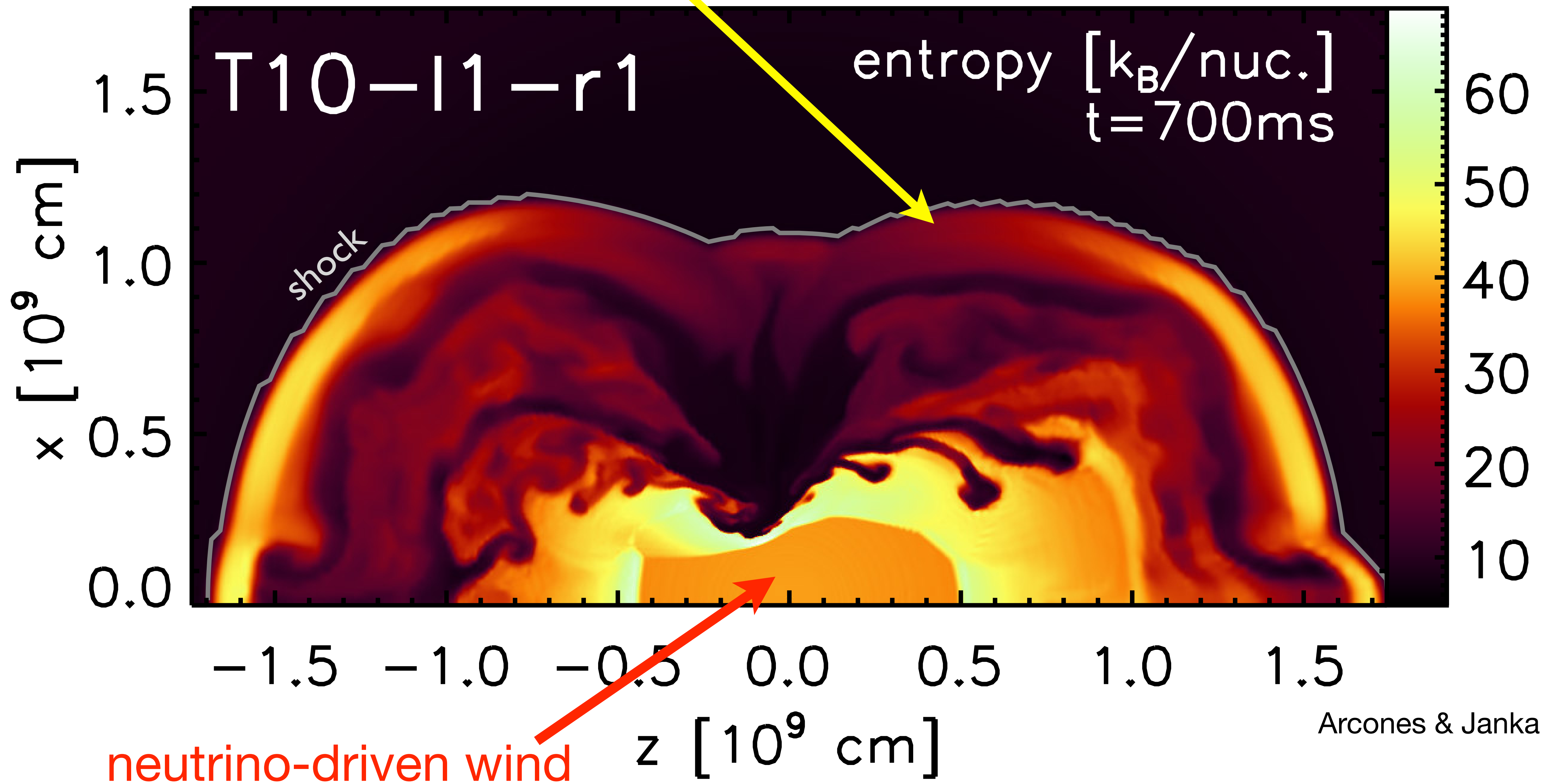
Nucleosynthesis in core-collapse supernovae



Almudena Arcones

Nucleosynthesis in core-collapse supernovae

Explosive nucleosynthesis: O, Mg, Si, S, Ca, Ti, Fe, p-process
shock wave heats falling matter



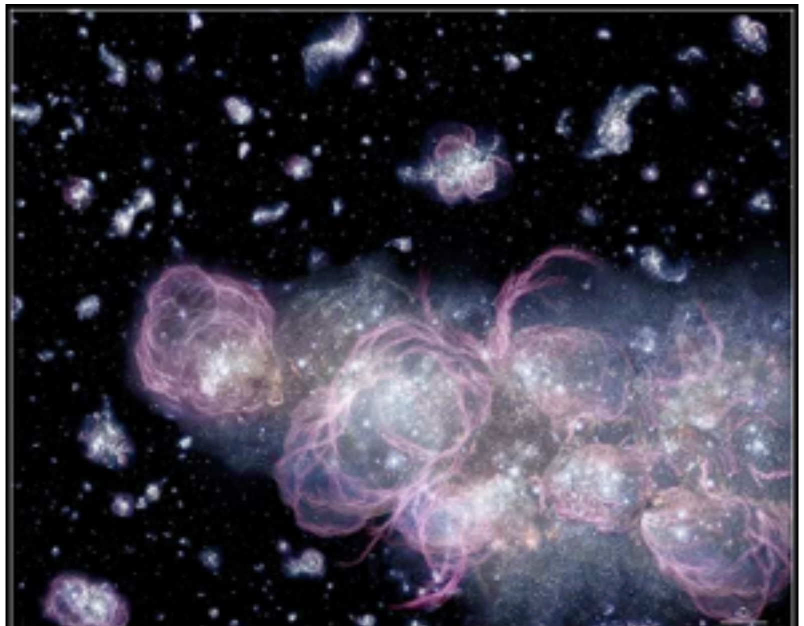
Arcones & Janka (2011)

neutrino-driven wind
heavy elements**?**

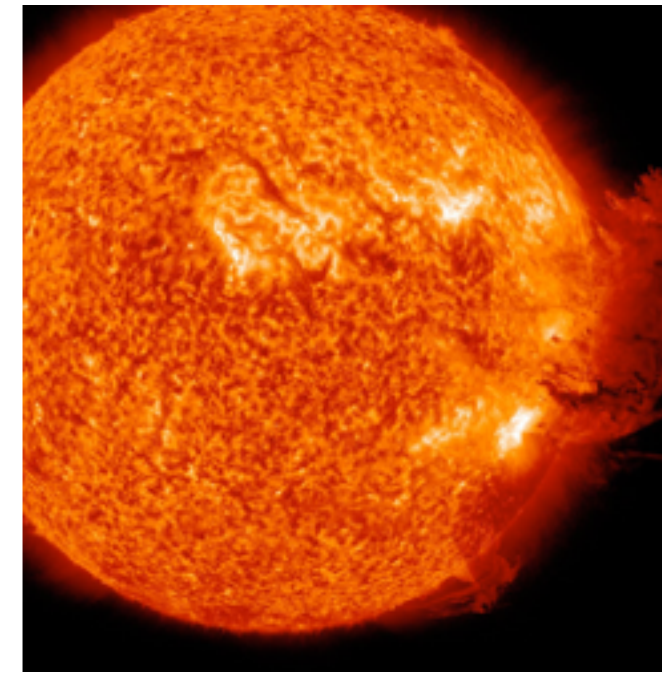
Galactic chemical evolution

First stars: H, He → Heavy elements ← New generation of stars

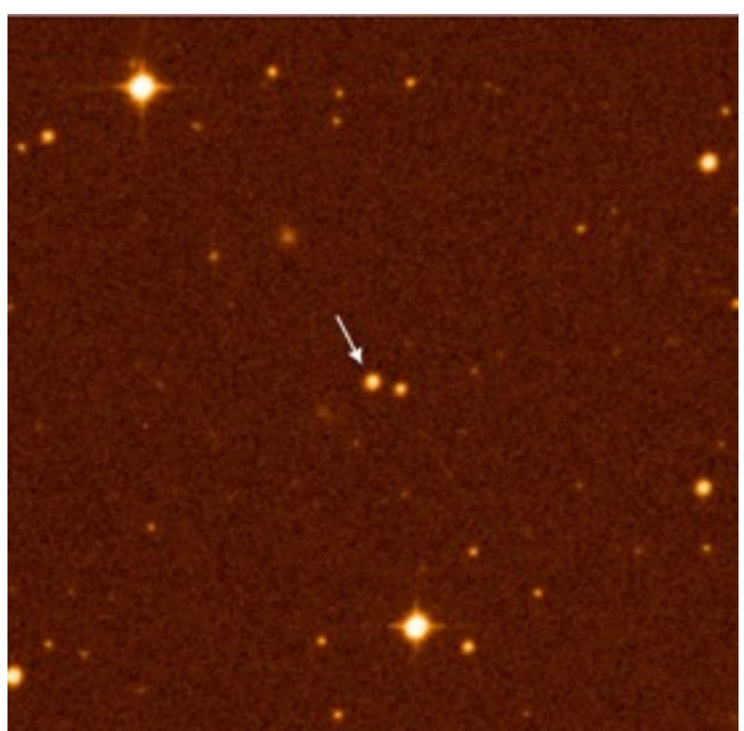
Interstellar medium (ISM)

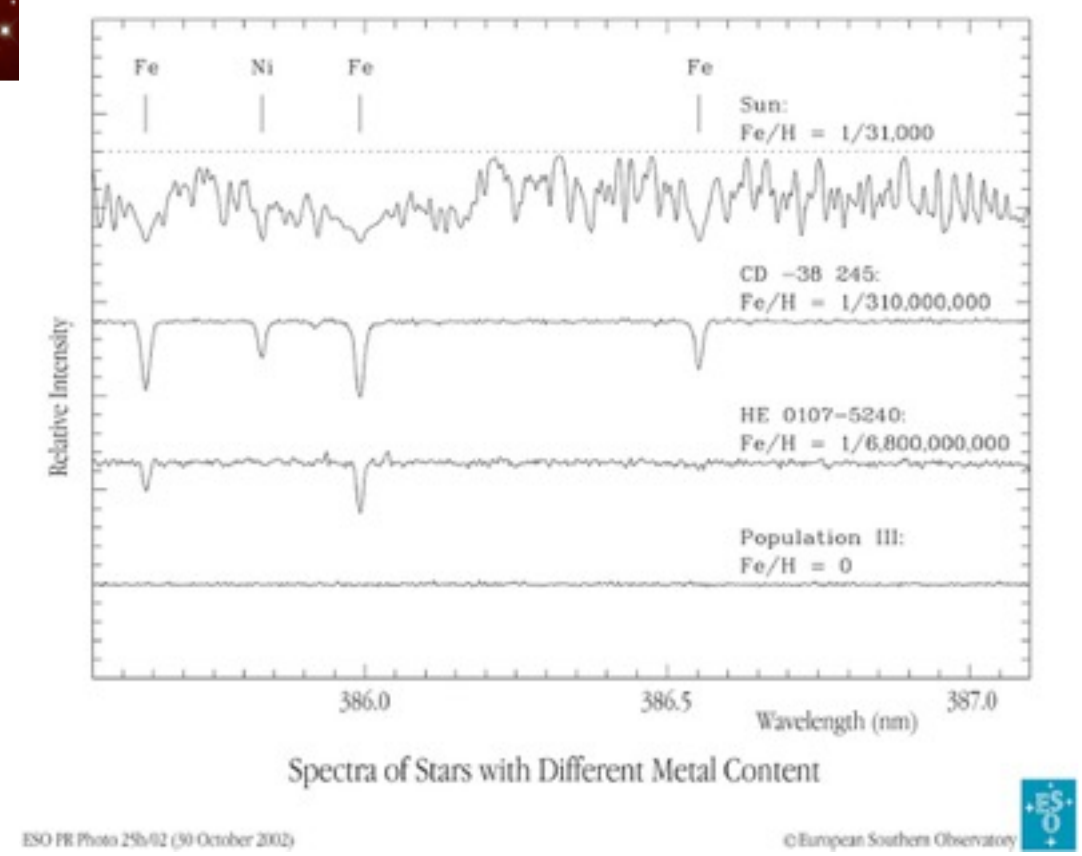


Artist's View of Star Formation in the Early Universe
Painting by Adolf Schaller • STScI-PRC02-02



The very metal-deficient star
HE 0107-5240
(Hamburg-ESO survey)

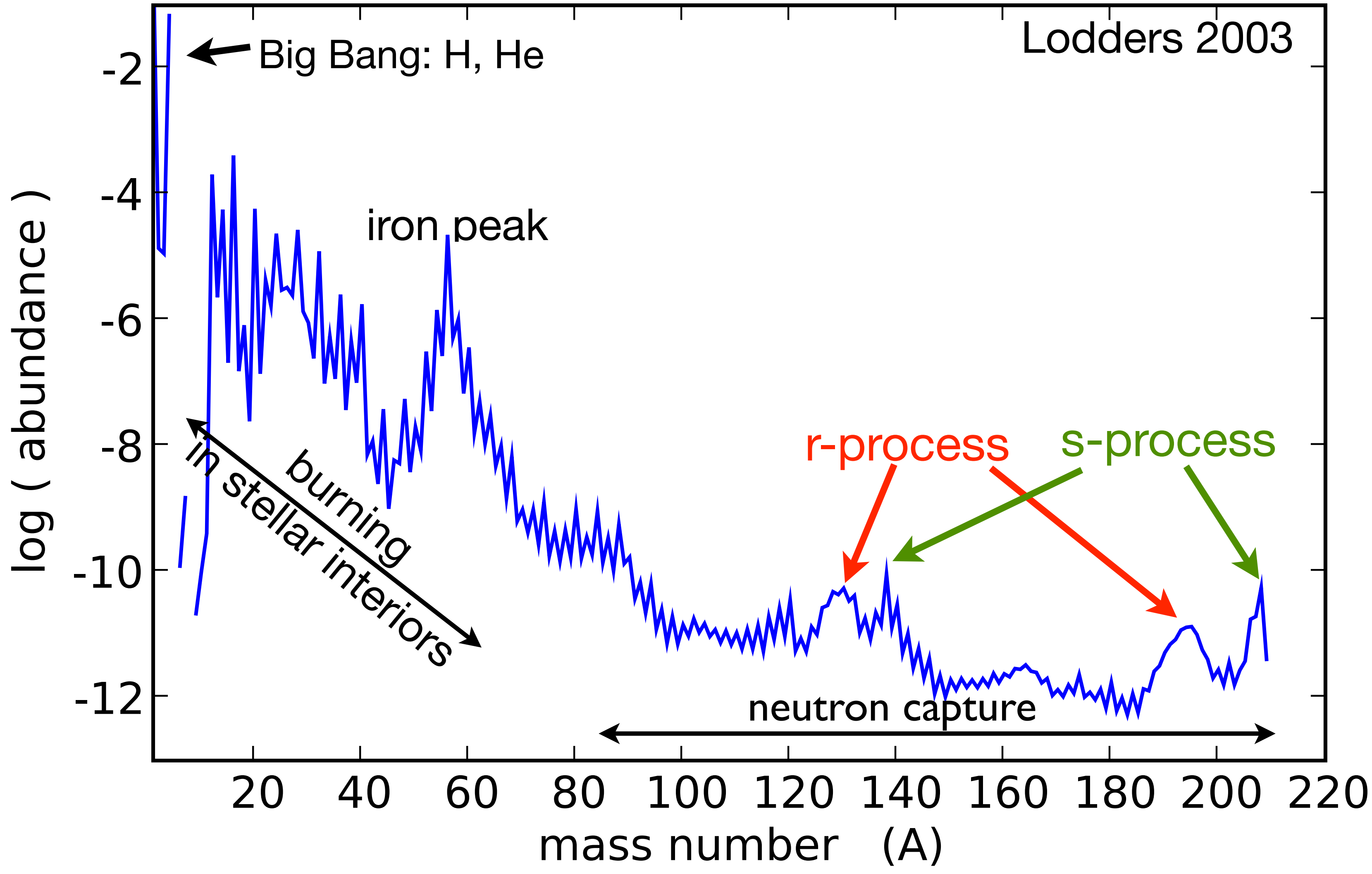


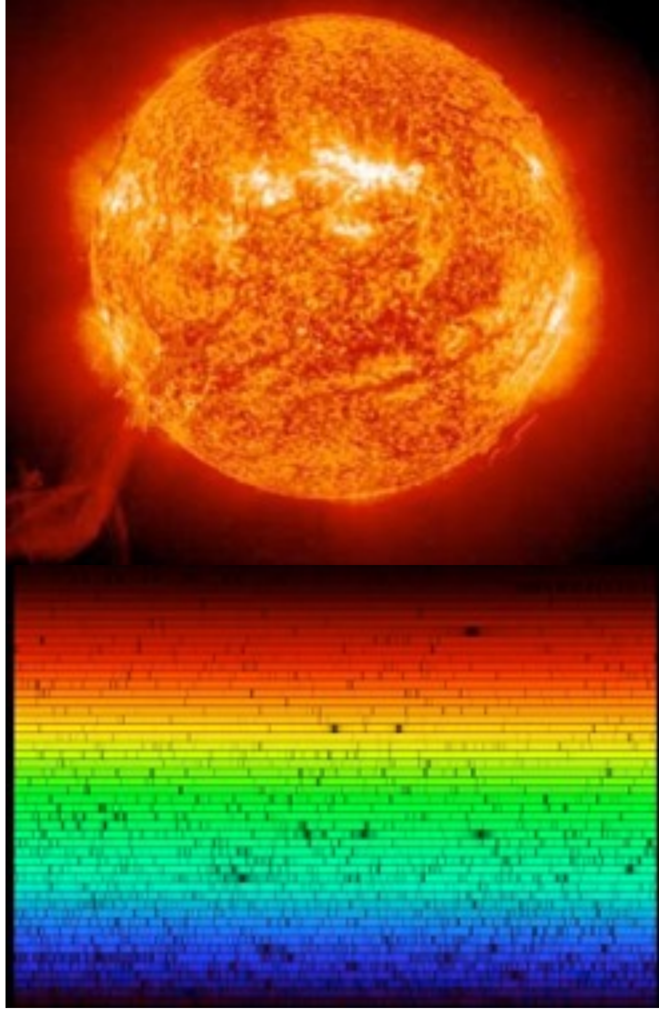


Solar system abundances

Solar photosphere and meteorites:
chemical signature of gas cloud where the Sun formed

Contribution of all nucleosynthesis processes



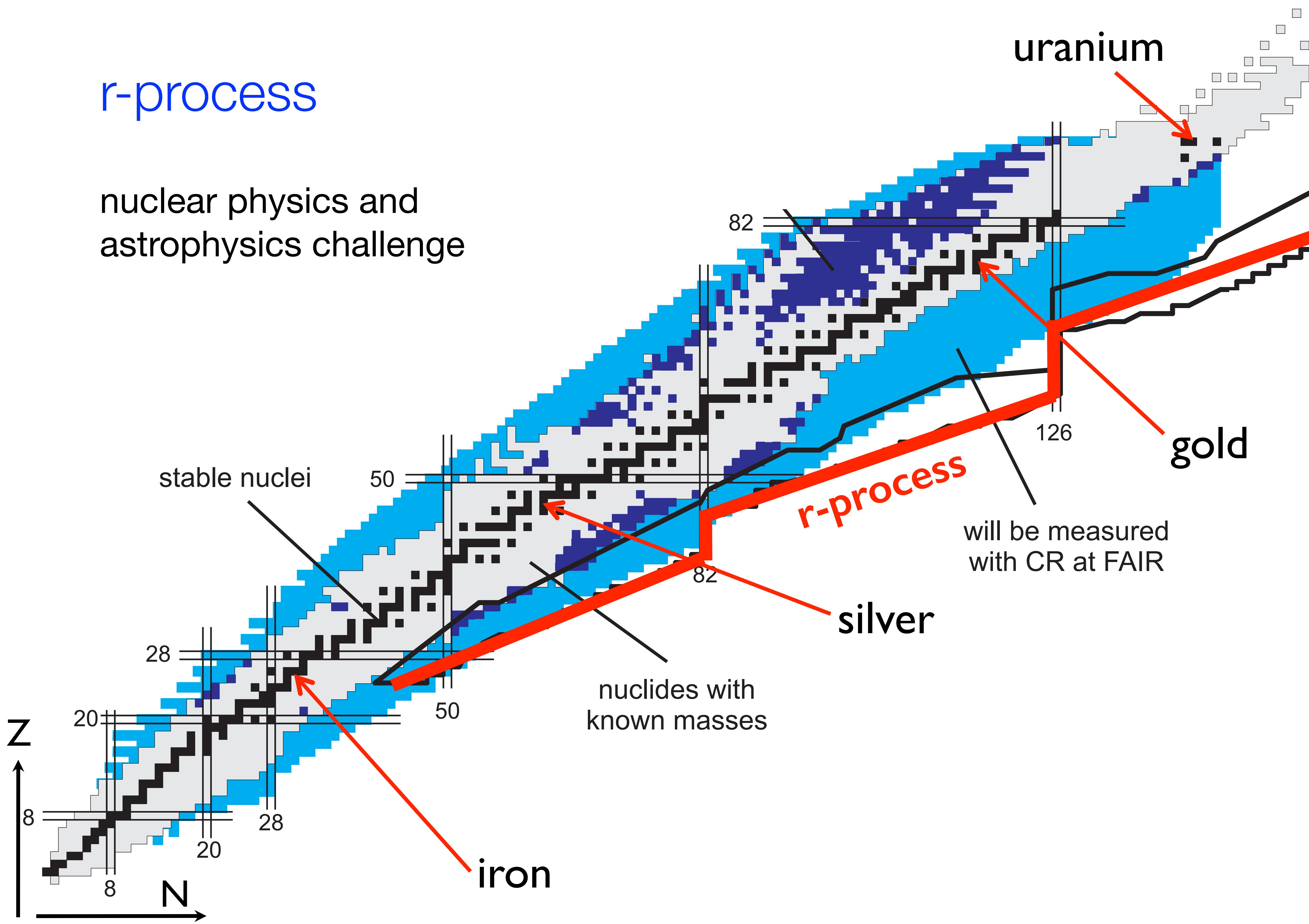


s-process:
slow neutron capture
r-process:
rapid neutron capture

abundance = mass fraction / mass number

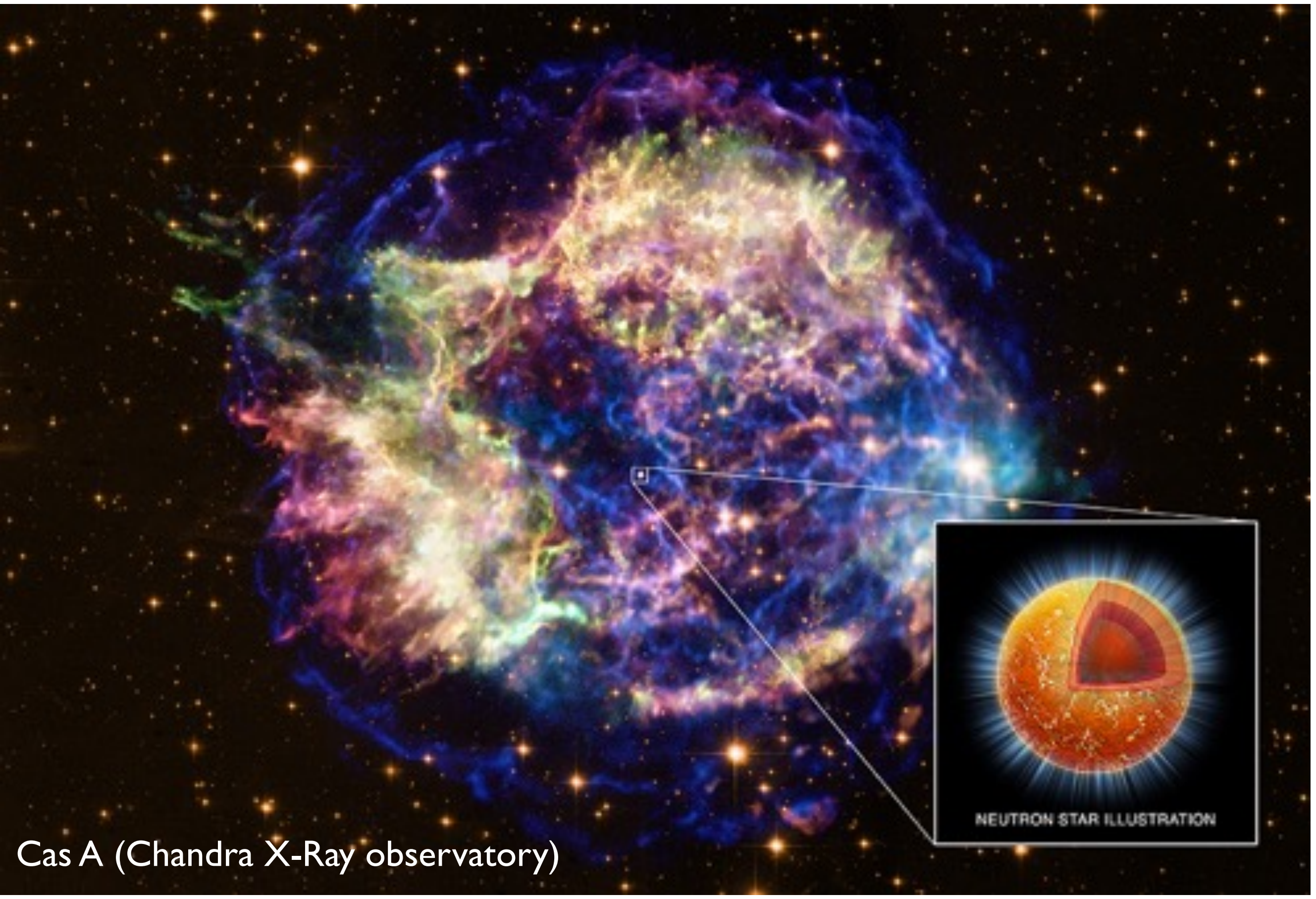
r-process

nuclear physics and
astrophysics challenge



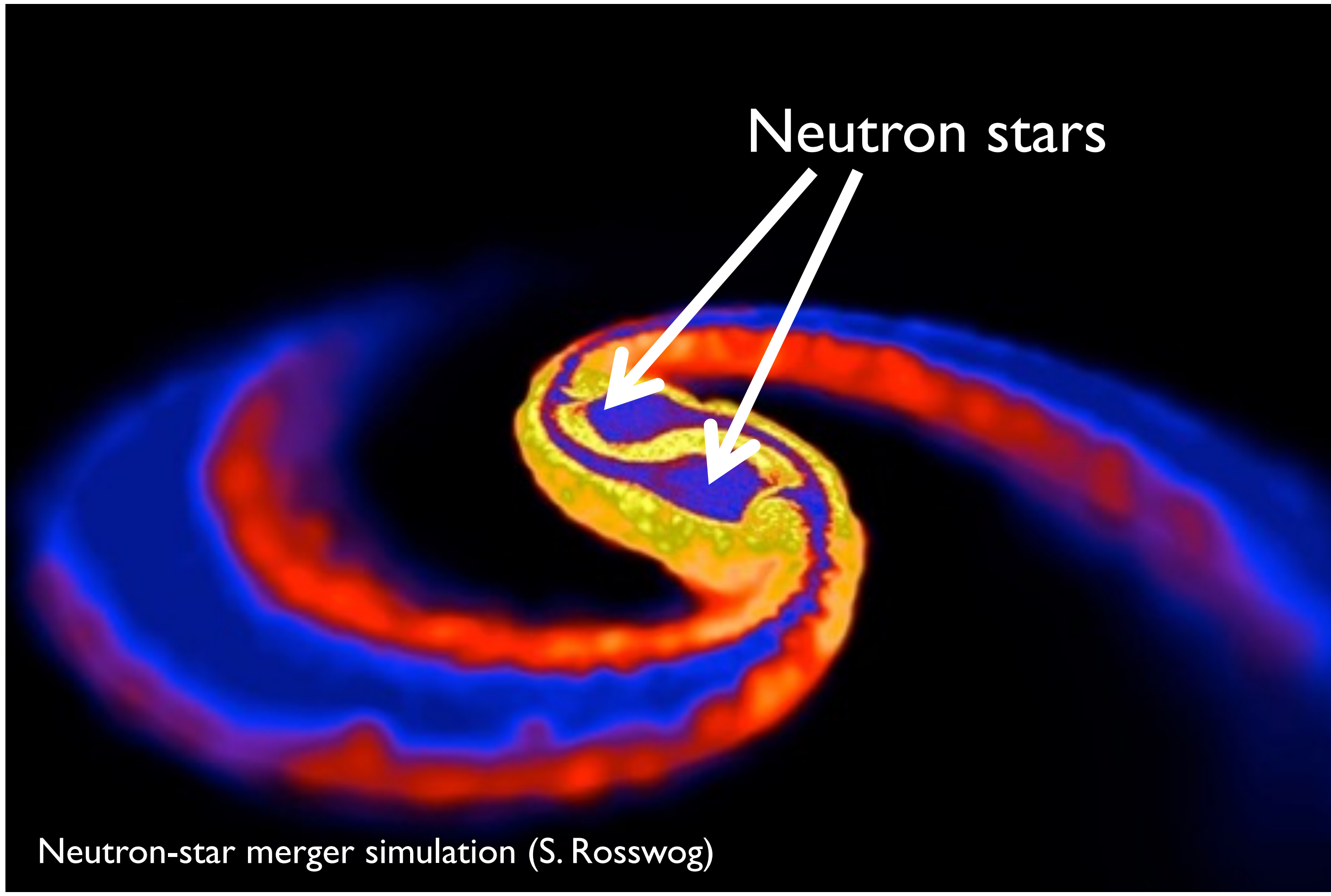
Where does the r-process occur?

Core-collapse supernovae



Cas A (Chandra X-Ray observatory)

Neutron star mergers



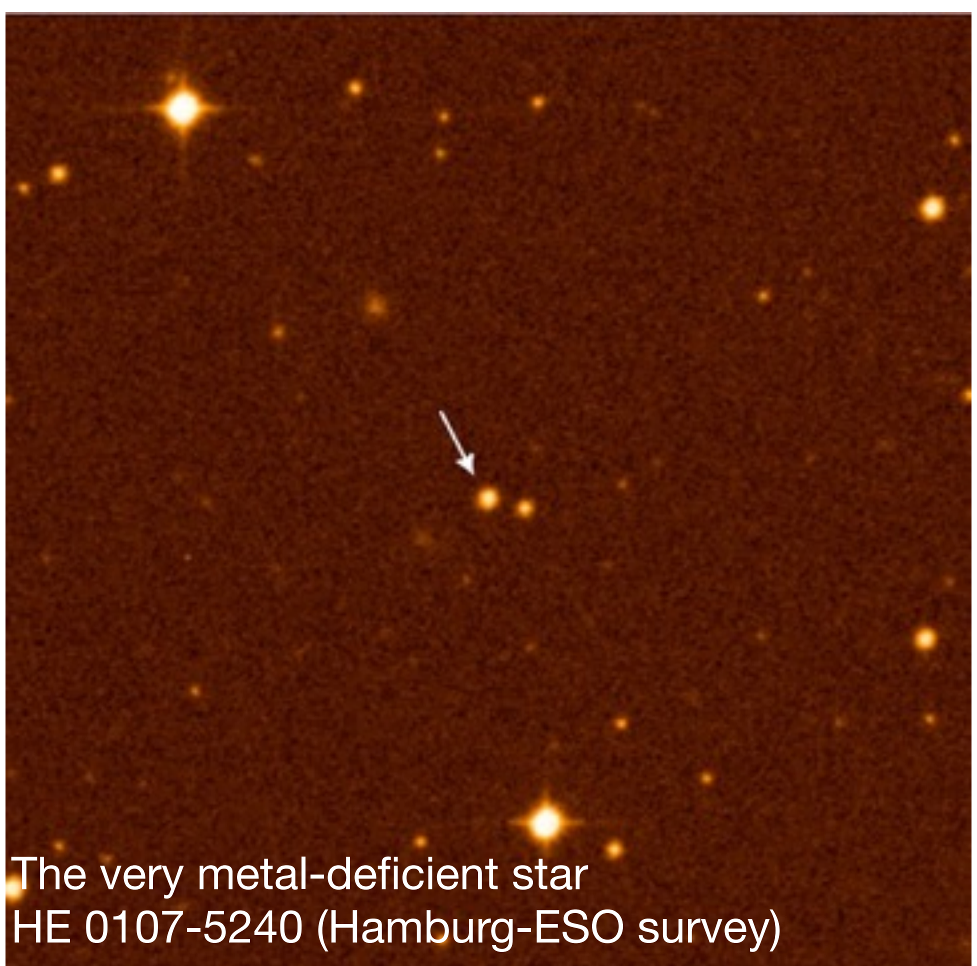
Neutron-star merger simulation (S. Rosswog)

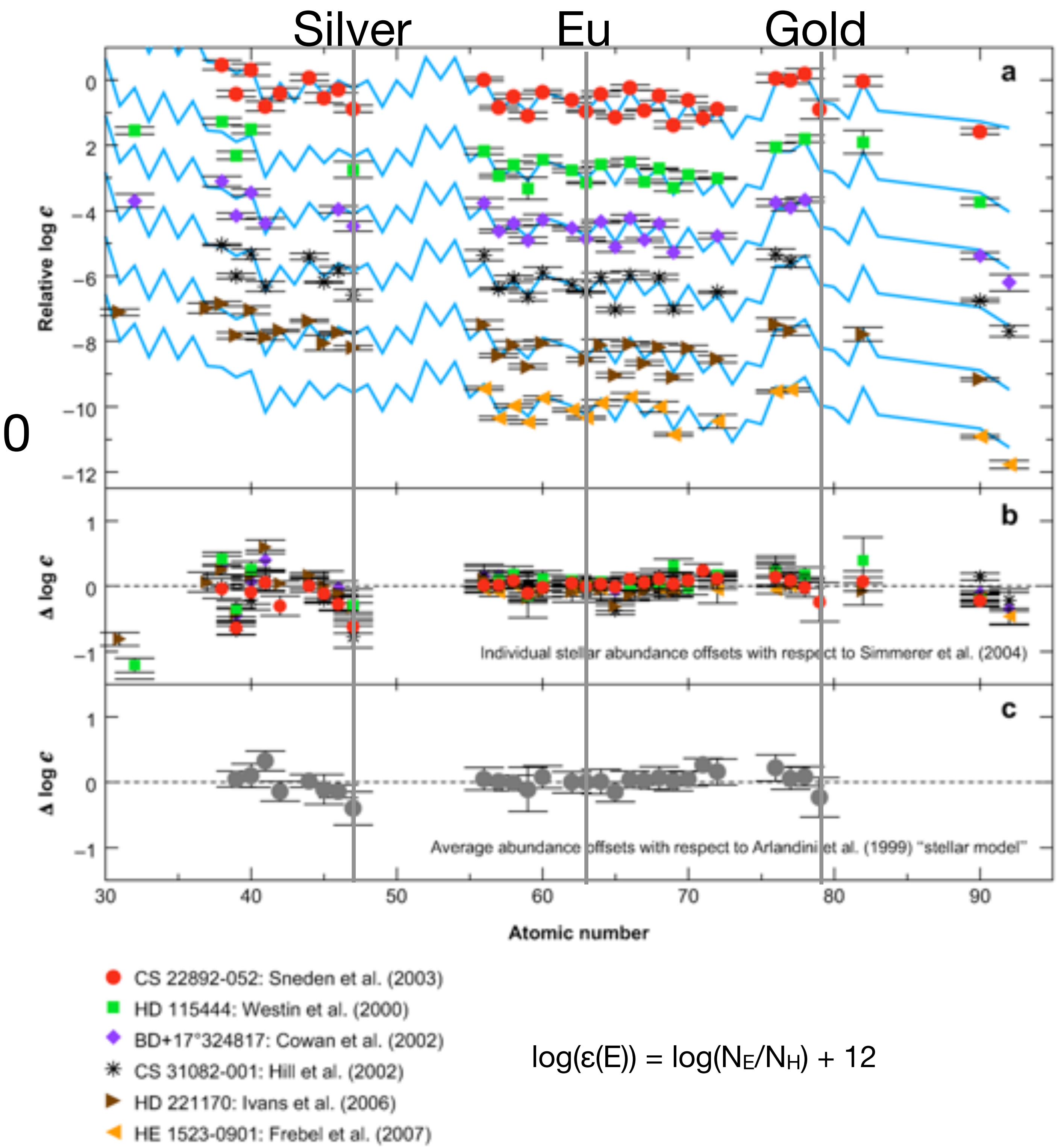
r-process in ultra metal-poor stars

Abundances of r-process elements in:
- ultra metal-poor stars and
- r-process solar system: N_{solar} - N_s

Robust r-process for 56<Z<83

Scatter for lighter heavy elements, Z~40

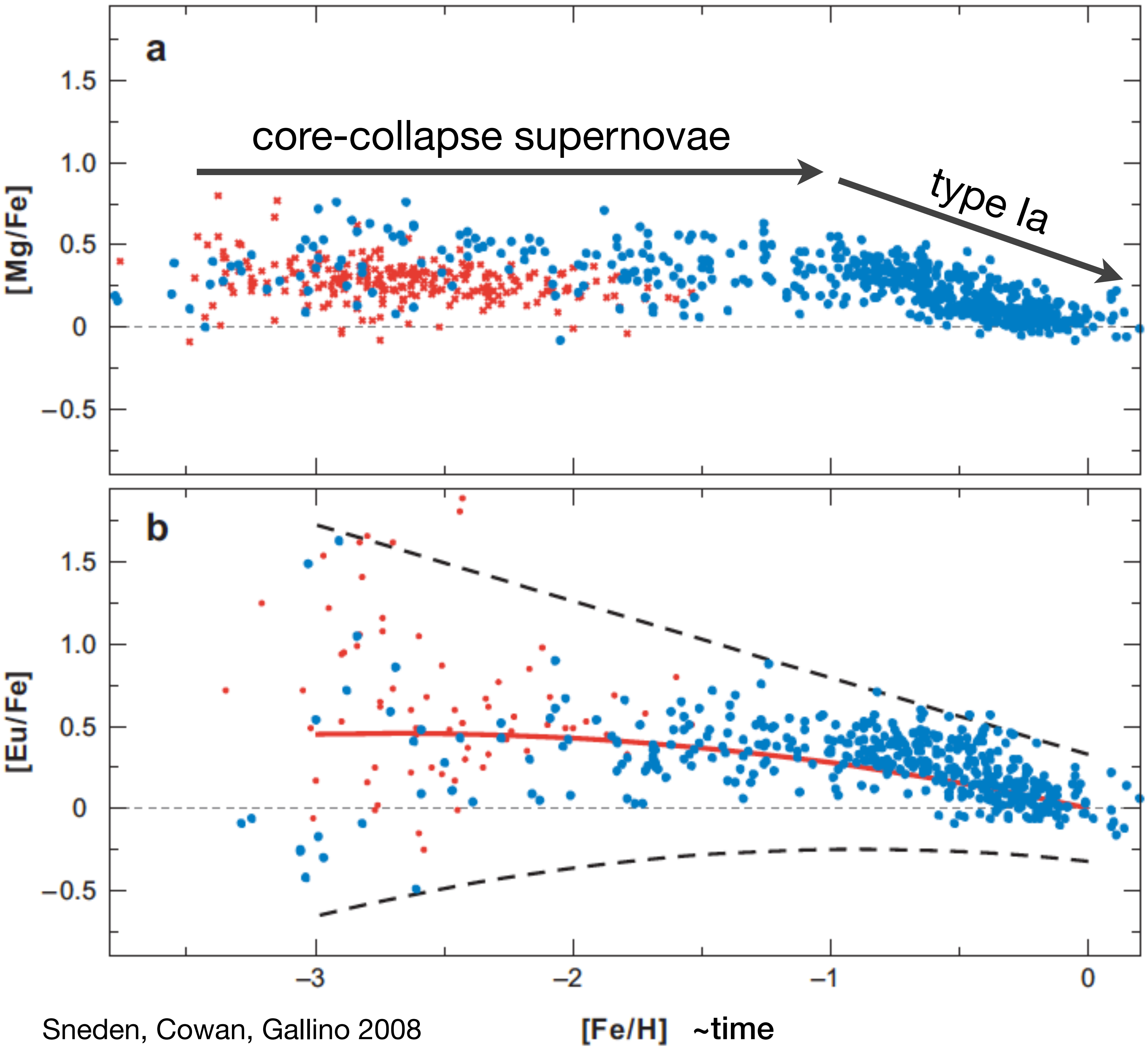

The very metal-deficient star
HE 0107-5240 (Hamburg-ESO survey)



$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Sneden, Cowan, Gallino 2008

Trends with metallicity



Sneden, Cowan, Gallino 2008

Fe and Mg produced in same site: core-collapse supernovae

Significant scatter at low metallicities

r-process production rare in the early Galaxy

Mg and Fe production is not coupled to r-process production

LETTER

doi:10.1038/nature17196

Recent near–Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe

A. Wallner[1], J. Feige[2]†, N. Kinoshita[3], M. Paul[4], L. K. Fifield[1], R. Golser[2], M. Honda[5], U. Linnemann[6], H. Matsuzaki[7], S. Merchel[8], G. Rugel[8], S. G. Tims[1], P. Steier[2], T. Yamagata[9] & S. R. Winkler[2]

nature COMMUNICATIONS

ARTICLE

Received 30 Mar 2014 | Accepted 26 Nov 2014 | Published 20 Jan 2015 DOI: 10.1038/ncomms6956 OPEN

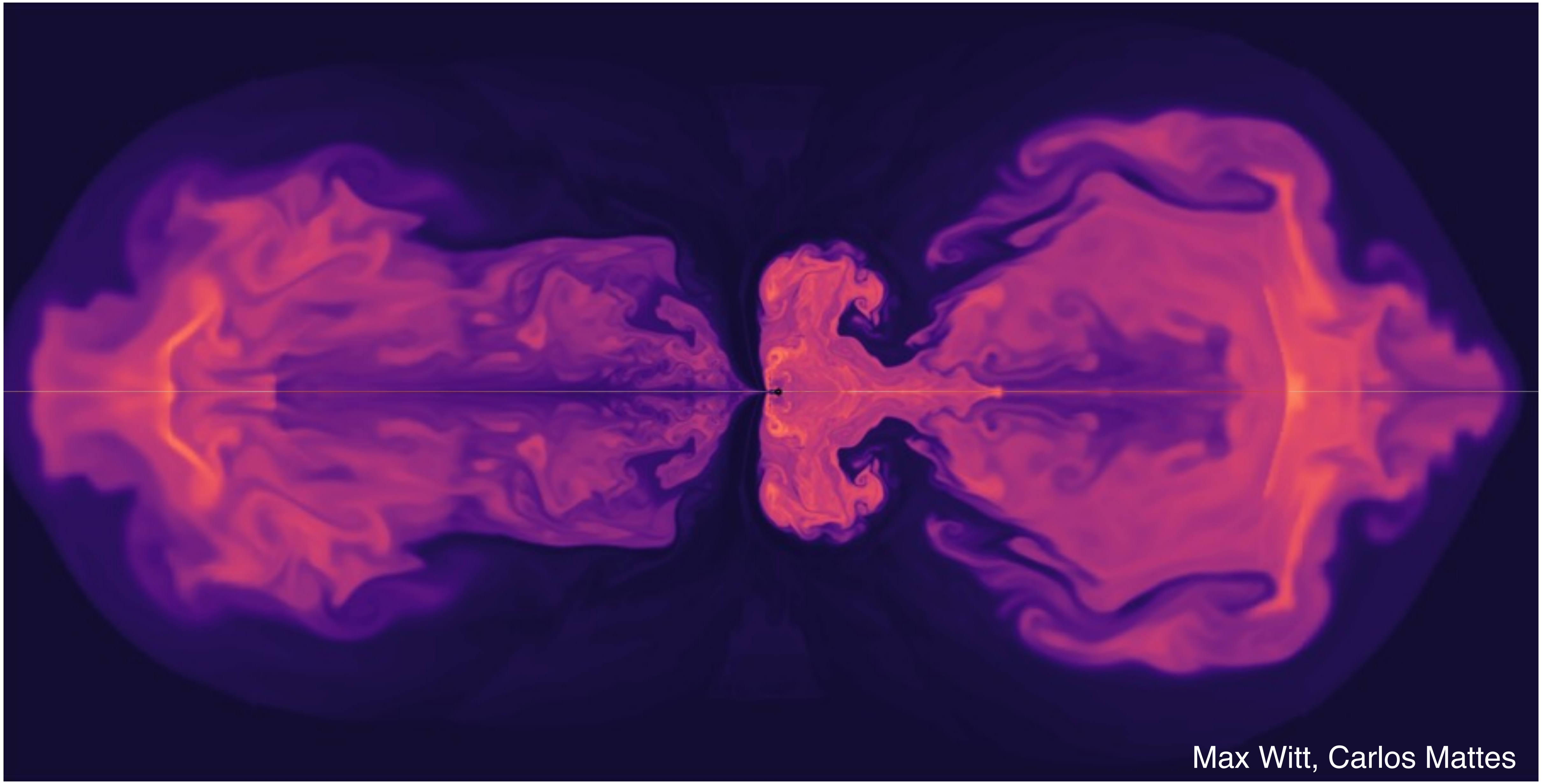
Abundance of live ^{244}Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis

A. Wallner[1,2], T. Faestermann[3], J. Feige[2], C. Feldstein[4], K. Knie[3,5], G. Korschinek[3], W. Kutschera[2], A. Ofan[4], M. Paul[4], F. Quinto[2,†], G. Rugel[3,†] & P. Steier[2]

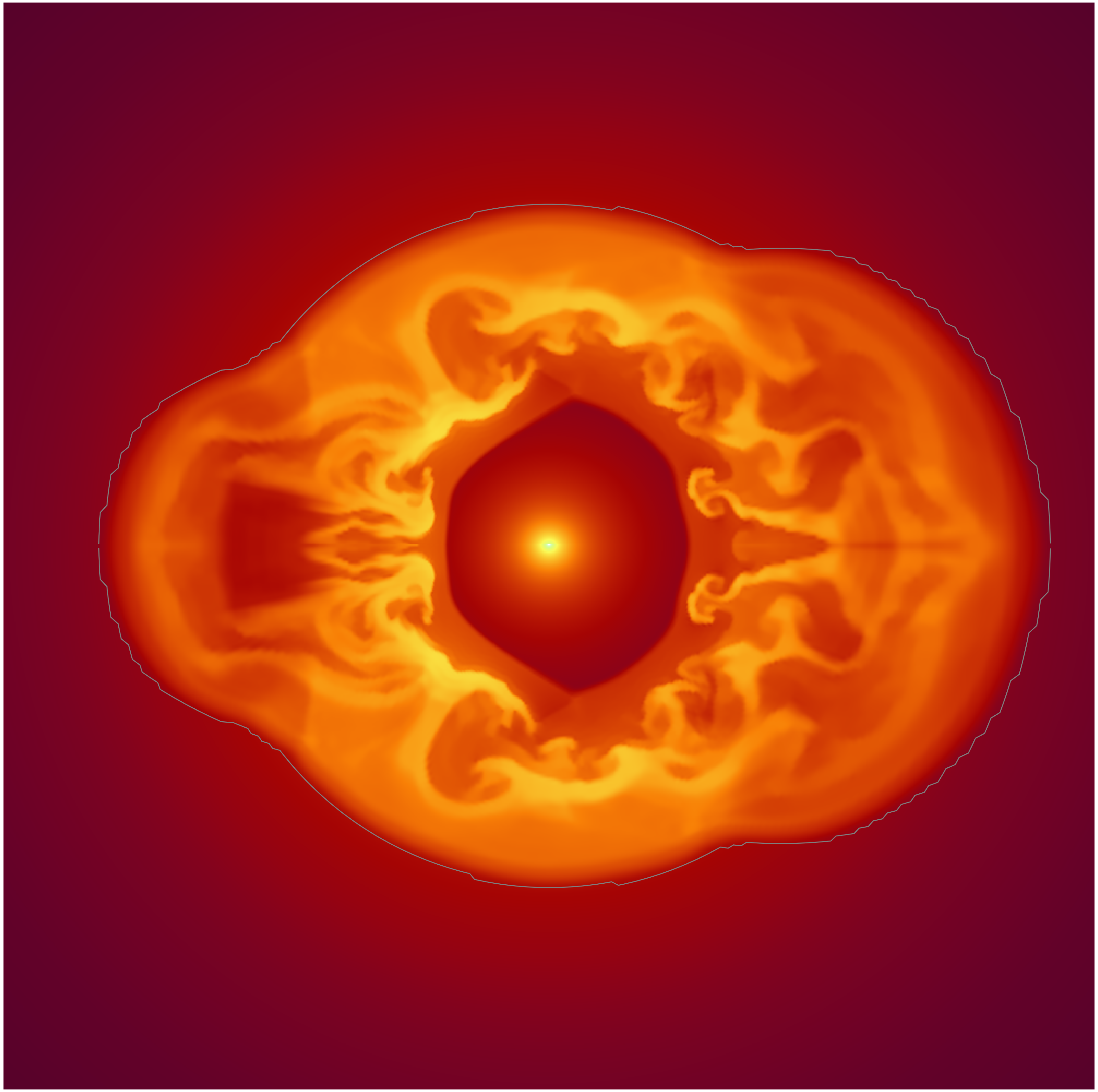
Core-collapse supernovae and r-process?

r-process is produced by rare event

No every core-collapse supernova produces heavy r-process nuclei

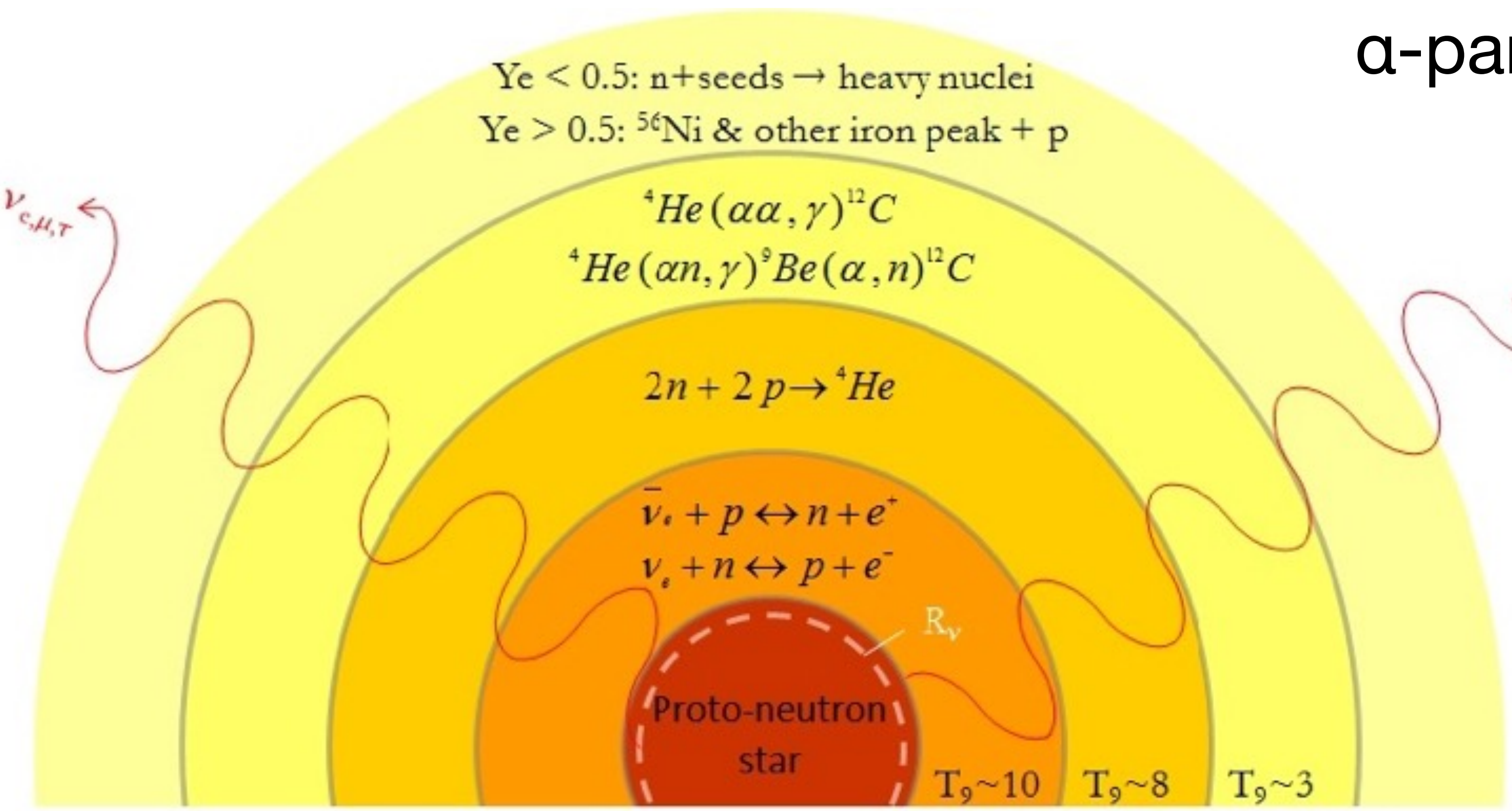


Neutrino-driven winds

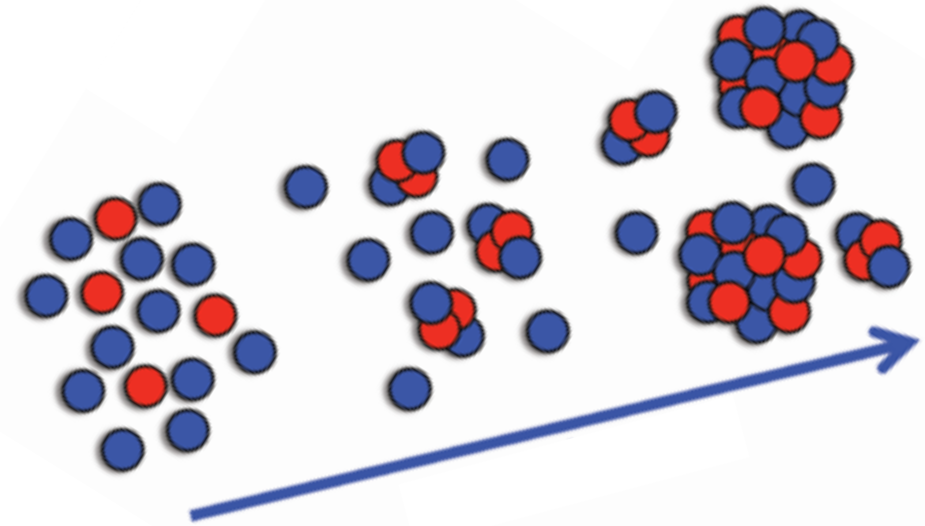


Arcones & Janka (2011)

Neutrino-driven winds



neutrons and protons form α-particles
α-particles recombine into seed nuclei



NSE → charged particle reactions / α-process → r-process

T = 10 - 8 GK   8 - 2 GK

weak r-process
νp-process

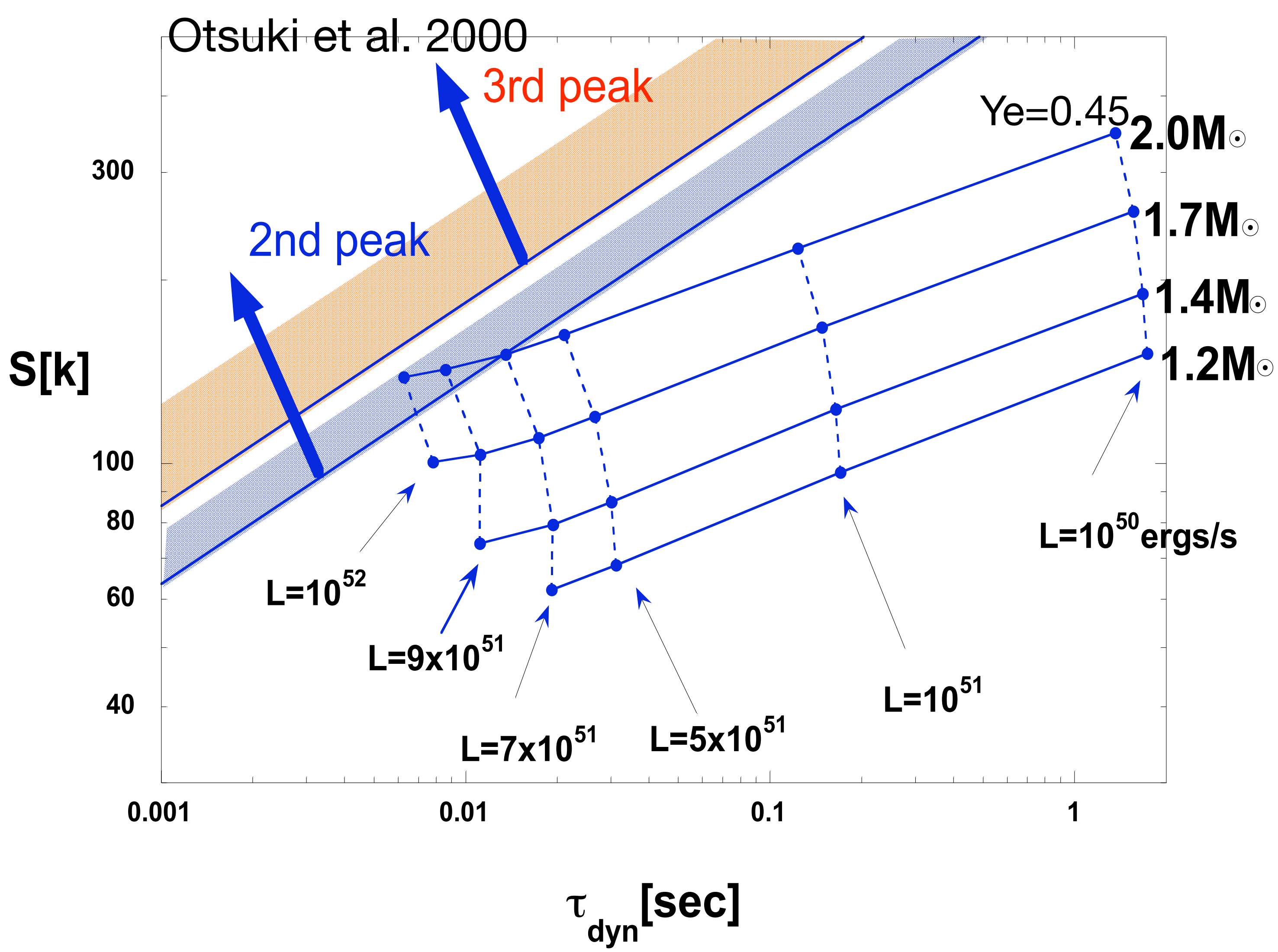
T < 3 GK

for a review see Arcones & Thielemann (2013)

Neutrino-driven wind parameters

r-process ⇒ high neutron-to-seed ratio (Y_n/Y_{seed}~100)

- Short expansion time scale: inhibit α-process and formation of seed nuclei
- High entropy: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e<0.5$



Conditions are not realized in hydrodynamic simulations

(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011, ...)

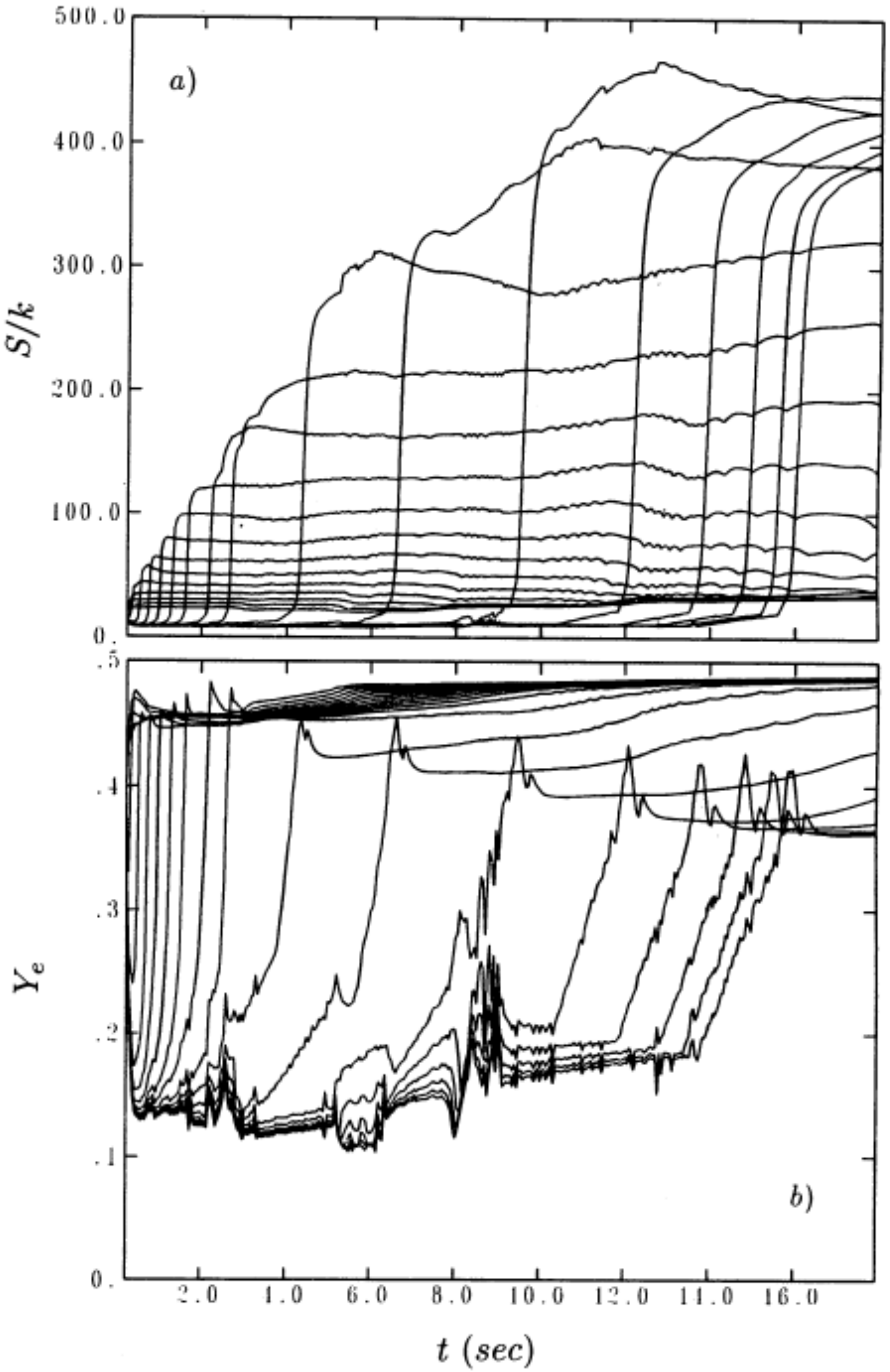
S_{wind} = 50 - 120 k_B/nuc

τ = few ms

Y_e ≈ 0.4 - 0.6?

Additional aspects:

wind termination, extra energy source, rotation and magnetic fields, neutrino oscillations



Wind and r-process

Meyer et al. 1992 and Woosley et al. 1994: r-process: high entropy and low Y_e

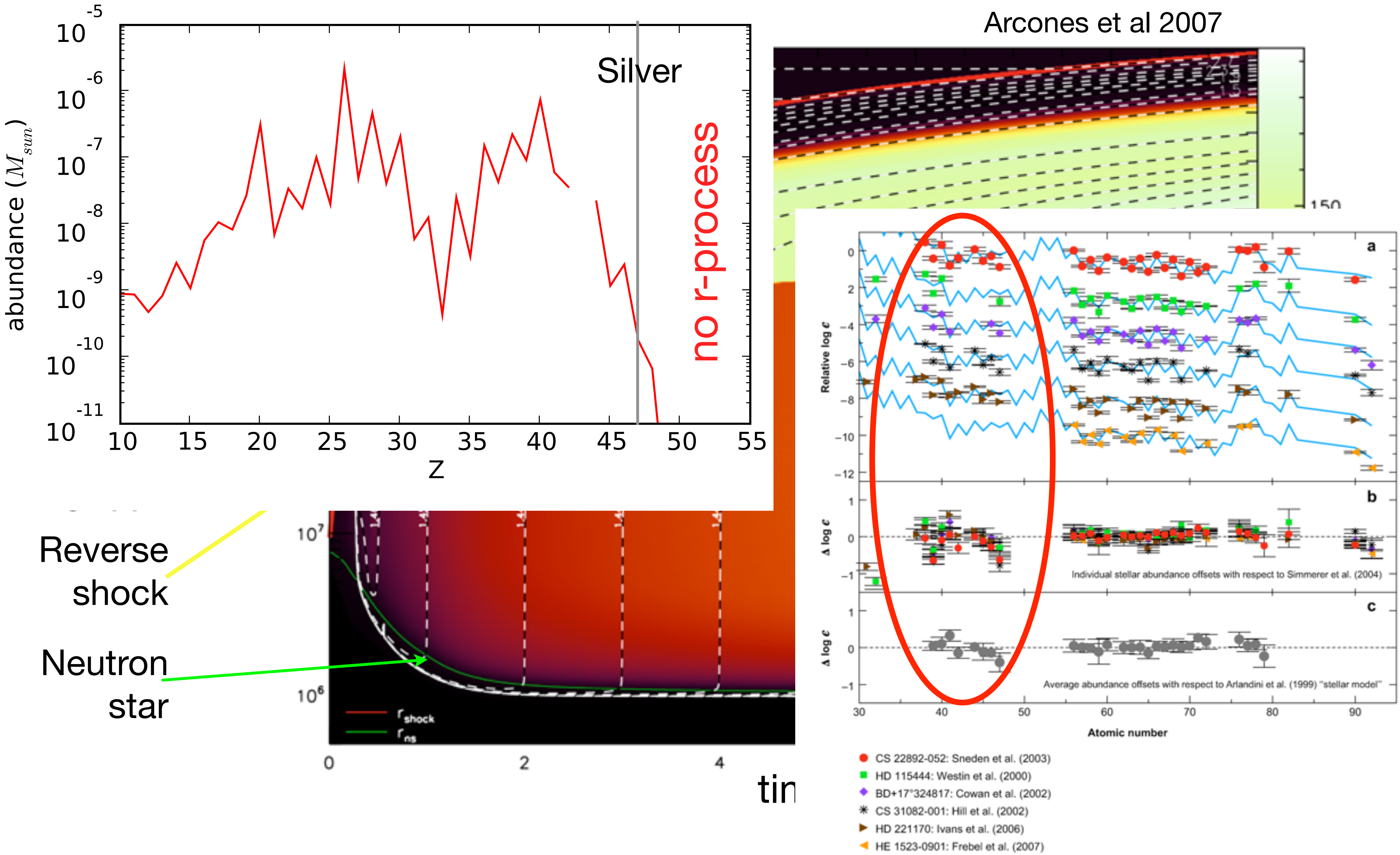
Witti et al., Takahasi et al. 1994 needed factor 5.5 increased in entropy

Qian & Woosley 1996: analytic model

$$\dot{M} \propto L_\nu^{5/3}\, \epsilon_\nu^{10/3}\, R_{ns}^{5/3}\, M_{ns}^{-2}\,,$$
$$s \propto L_\nu^{-1/6}\, \epsilon_\nu^{-1/3}\, R_{ns}^{-2/3}\, M_{ns}\,,$$
$$\tau \propto L_\nu^{-1}\, \epsilon_\nu^{-2}\, R_{ns}\, M_{ns}\,.$$

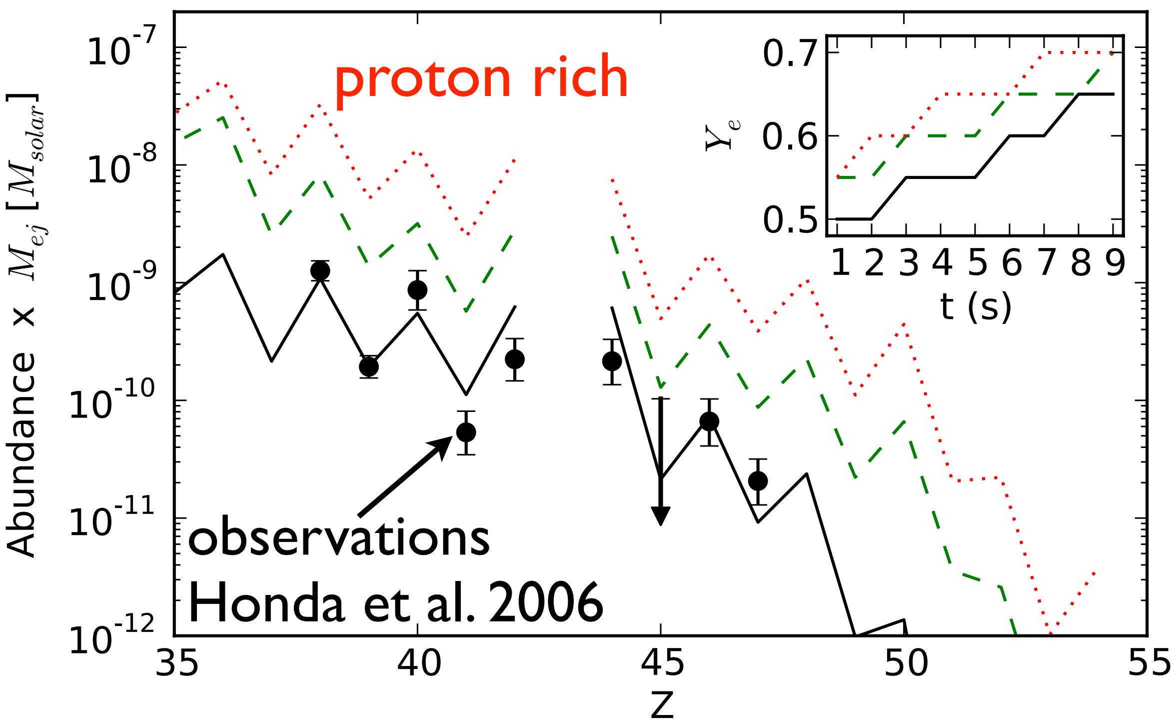
Thompson, Otsuki, Wanajo, ... (2000-...) parametric steady state winds

Which elements are produced in neutrino winds?



Lighter heavy elements in neutrino-driven winds

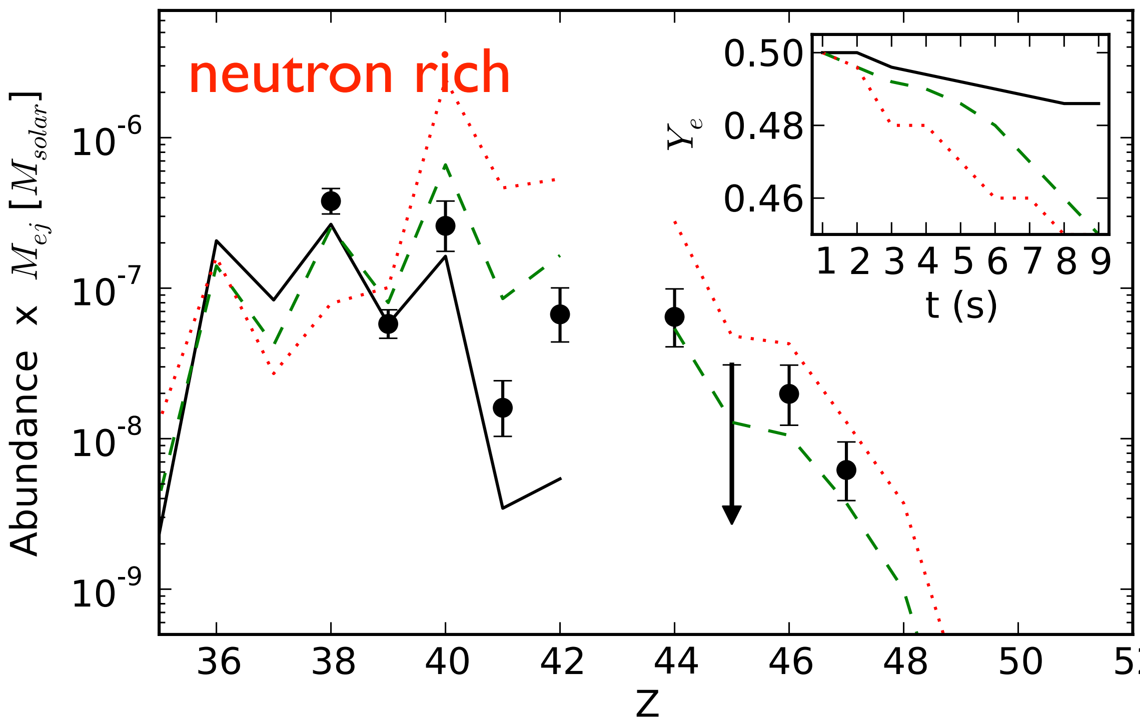
vp-process



Observation pattern reproduced!

Production of p-nuclei

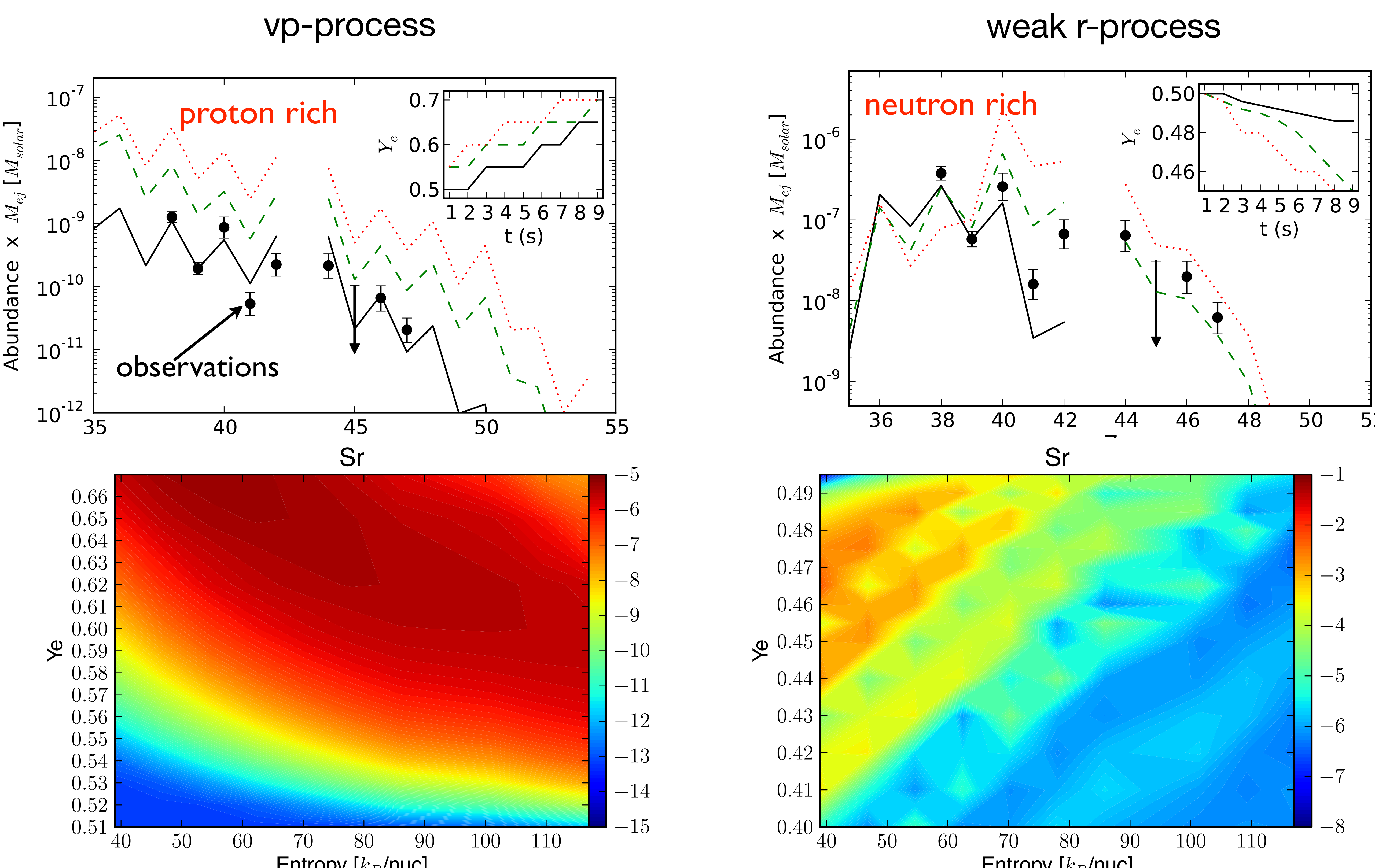
weak r-process



Overproduction at A=90, magic neutron number N=50 (Hoffman et al. 1996) suggests: only a fraction of neutron-rich ejecta (Wanajo et al. 2011)

Arcones & Montes (2011)
C.J. Hansen, Montes, Arcones (2014)

Lighter heavy elements in neutrino-driven winds

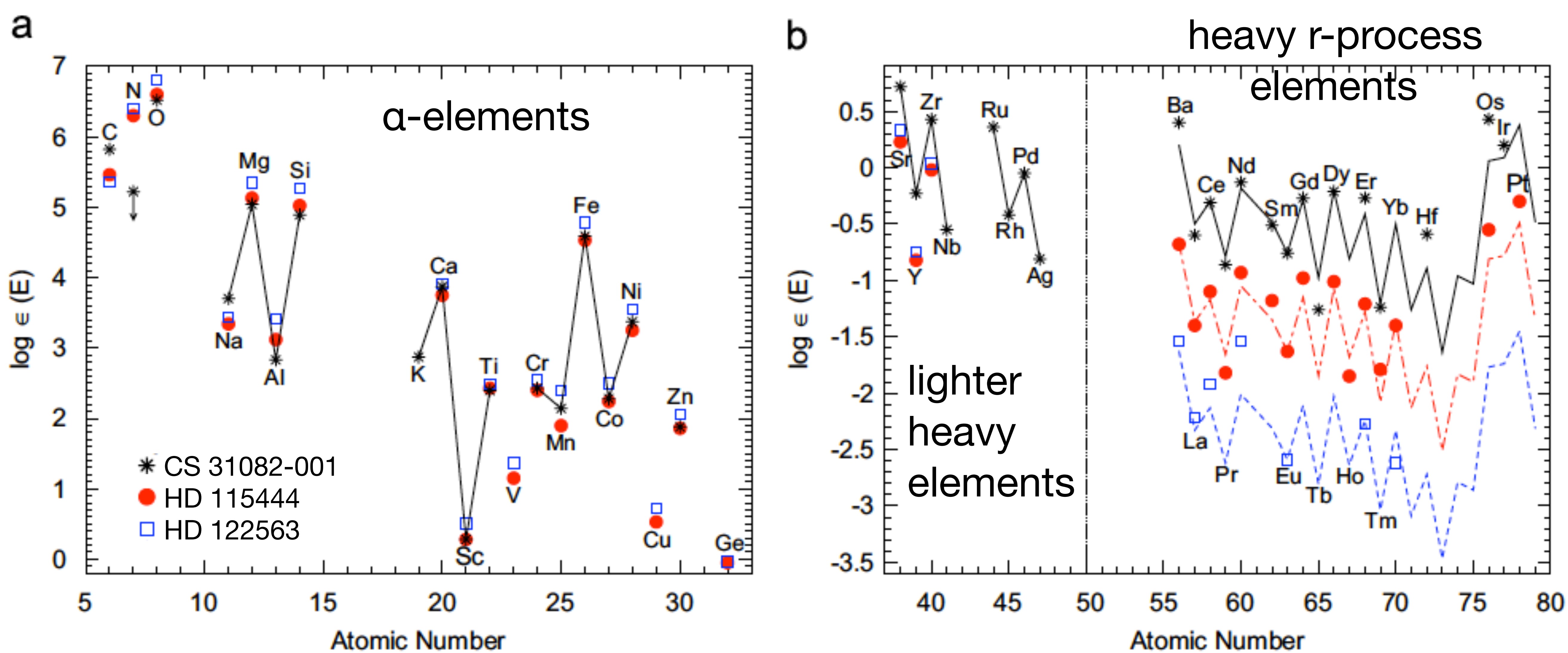


Arcones & Bliss (2014)

Elemental abundances in ultra metal-poor stars

Following Qian & Wasserburg 2007 three groups:

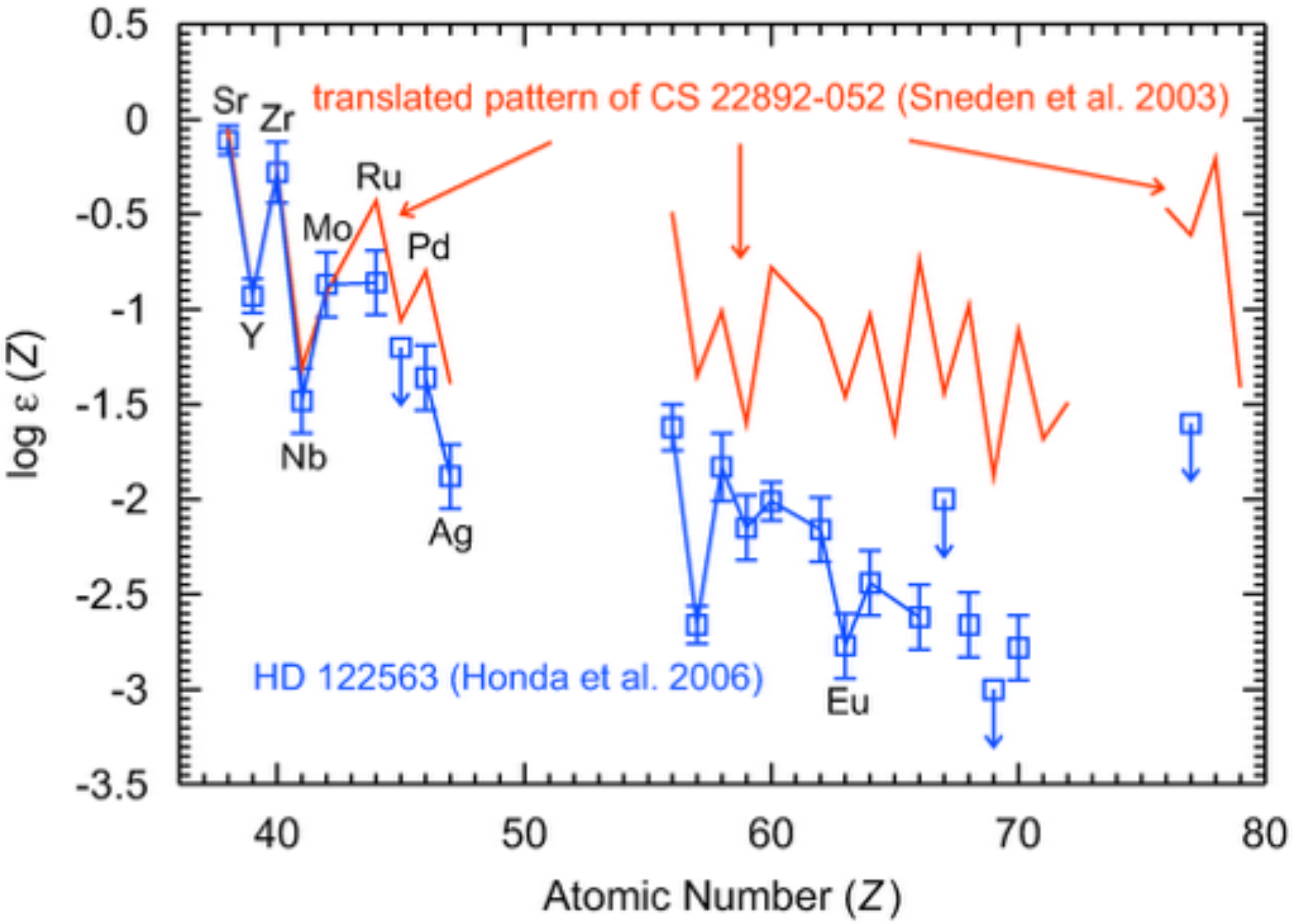
- Fe-like elements (A ~ 23 to 70): Na, Mg, Al, Si, ..., Fe, ..., Zn
- Sr-like elements (A ~ 88 to 110): Sr, Y, Zr, ..., Ag
- Eu-like elements (A > 130): Ba, ..., Eu, ..., Pt, ..., Th, ..., U



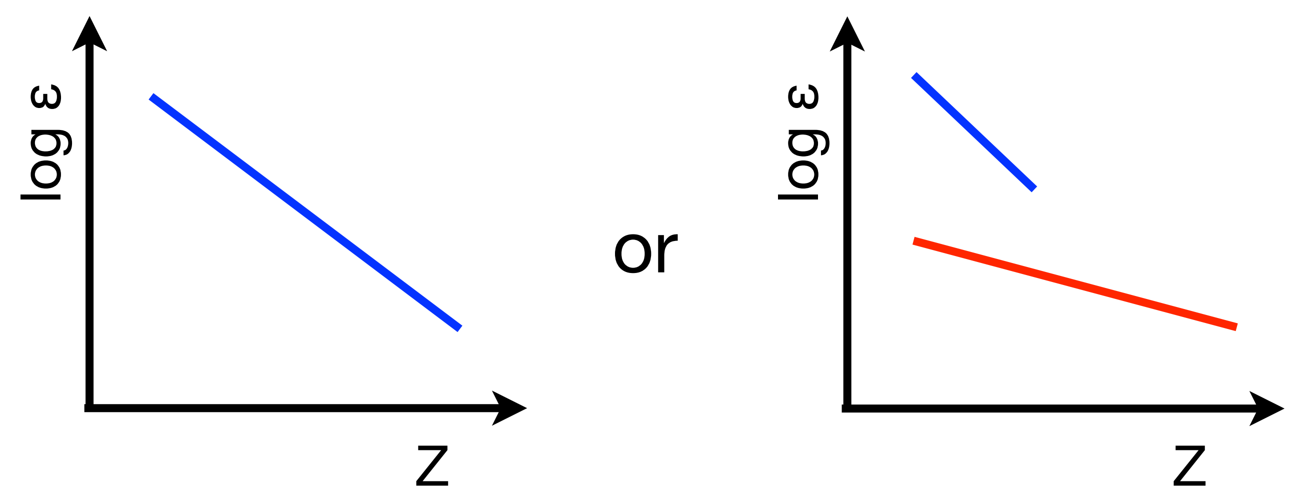
Qian & Wasserburg 2007

Lighter heavy elements: Sr - Ag

Ultra metal-poor stars with high and low enrichment of heavy r-process nuclei suggest: at least two components or sites (Qian & Wasserburg):



Are Honda-like stars the outcome of one nucleosynthesis event or the combination of several?

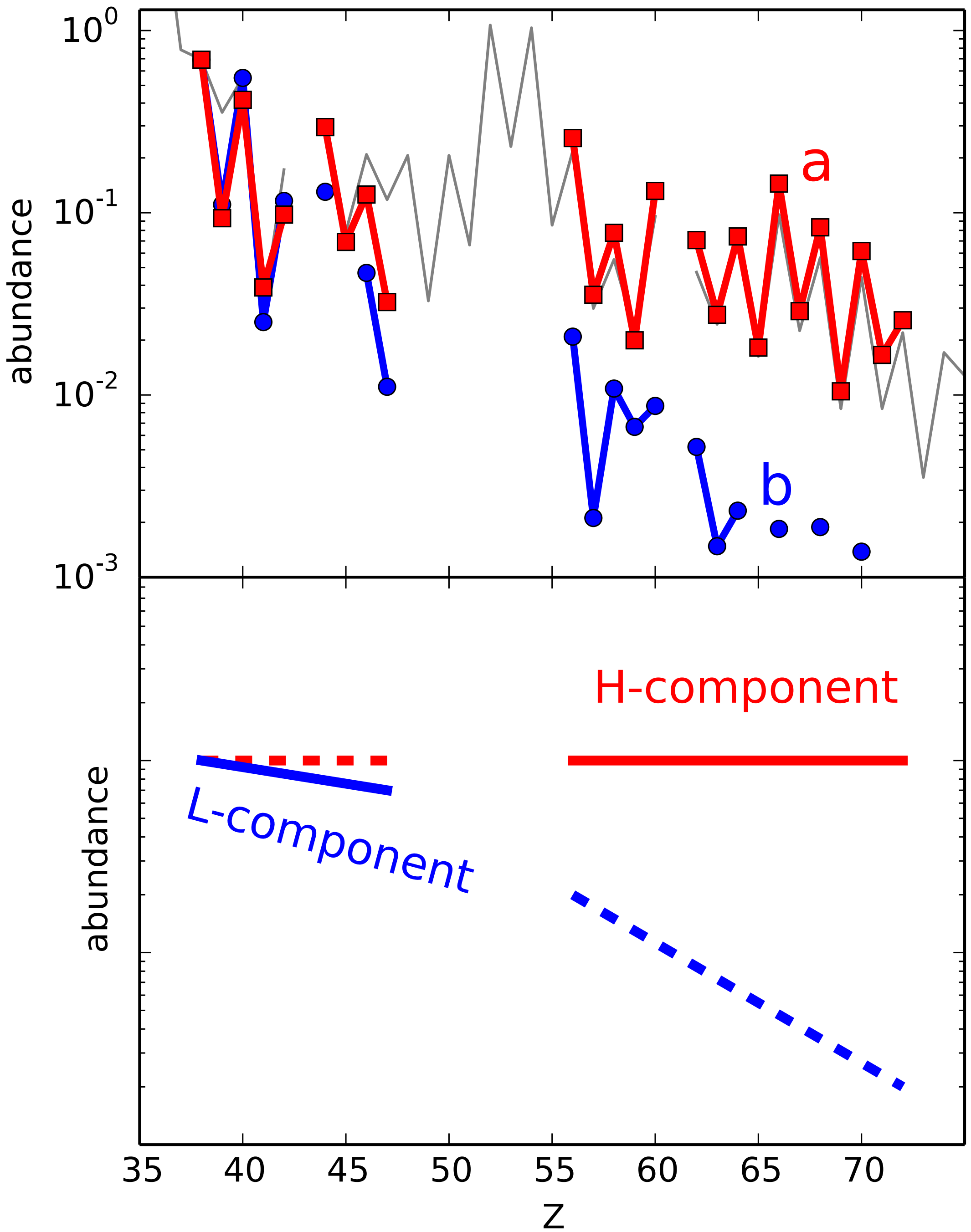


Travaglio et al. 2004: solar=r-process+s-process+LEPP

Montes et al. 2007: solar LEPP ~ UMP LEPP → unique

Nucleosynthesis components

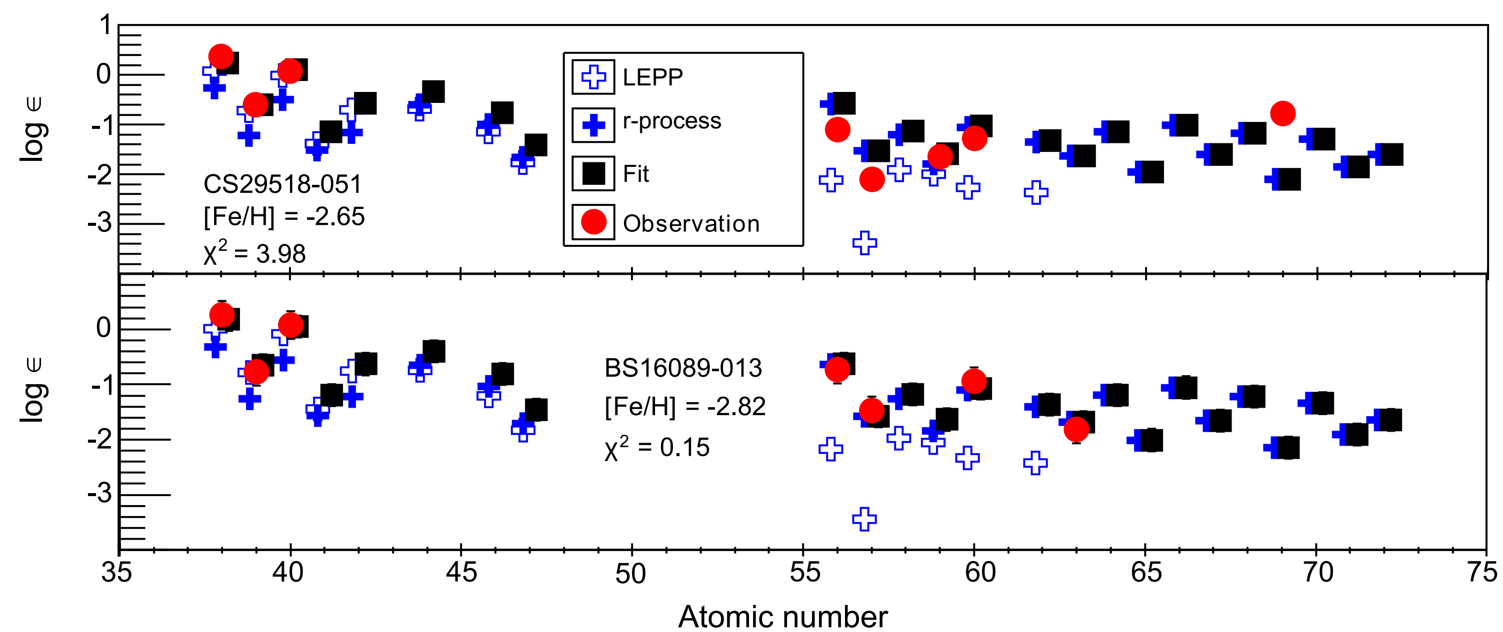
Abundance of many UMP stars can be explained by two components:



Component abundance pattern: Y_H and Y_L

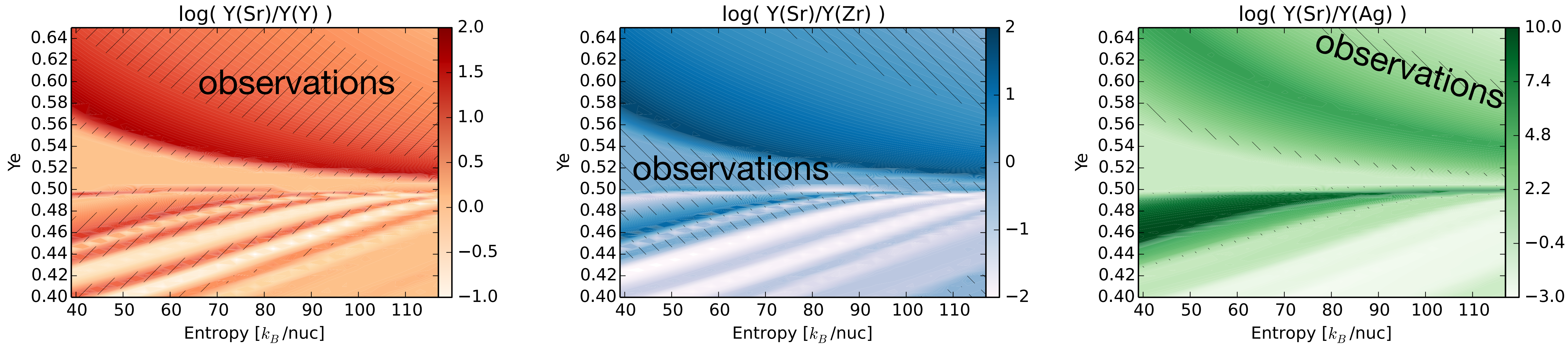
Fit abundance as combination of components:

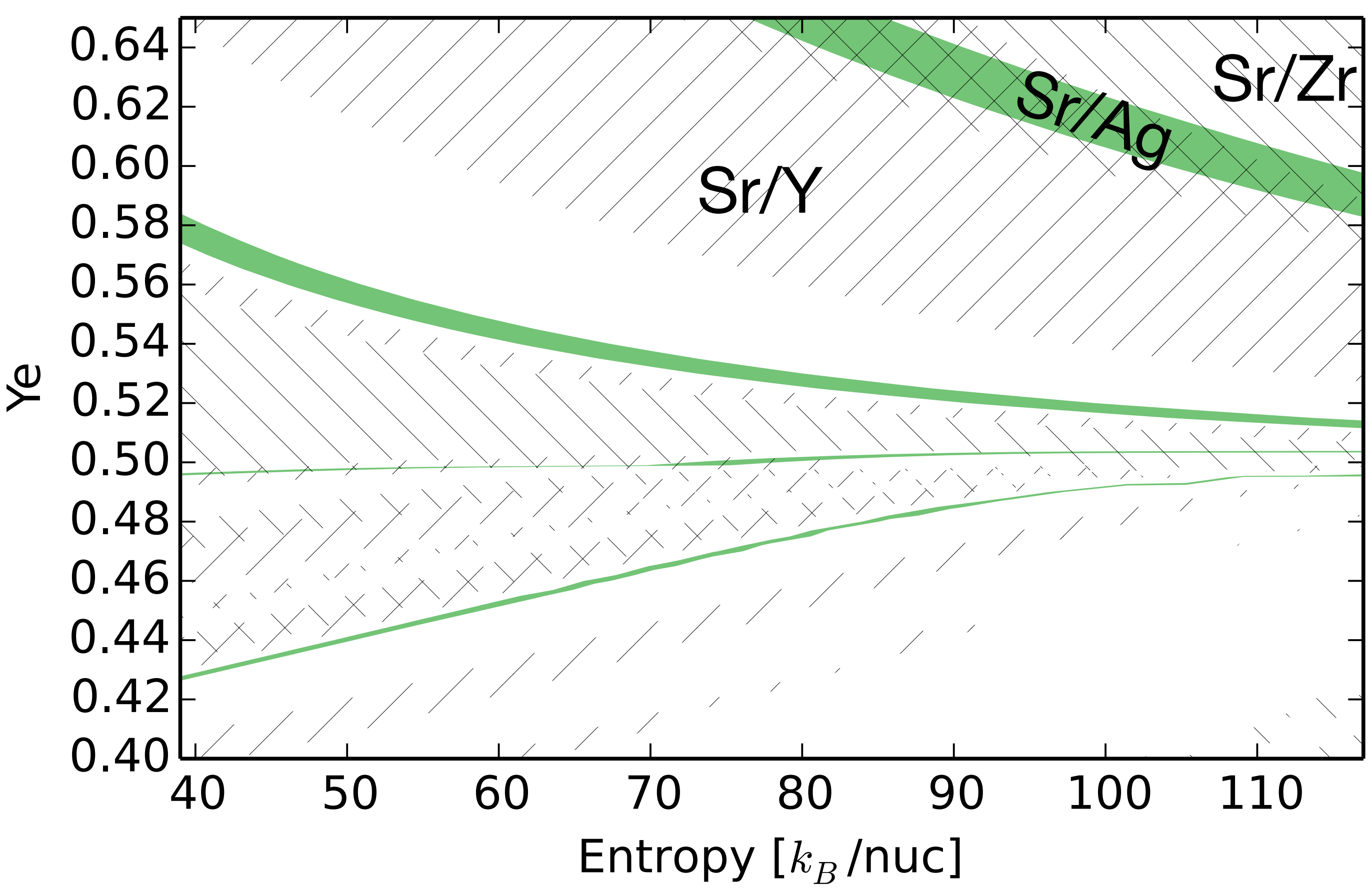
$$Y_{\rm calc}(Z) = (C_H Y_H(Z) + C_L Y_L(Z)) \cdot 10^{\rm [Fe/H]}$$



C.J. Hansen, Montes, Arcones (2014)

L-component in neutrino-driven winds



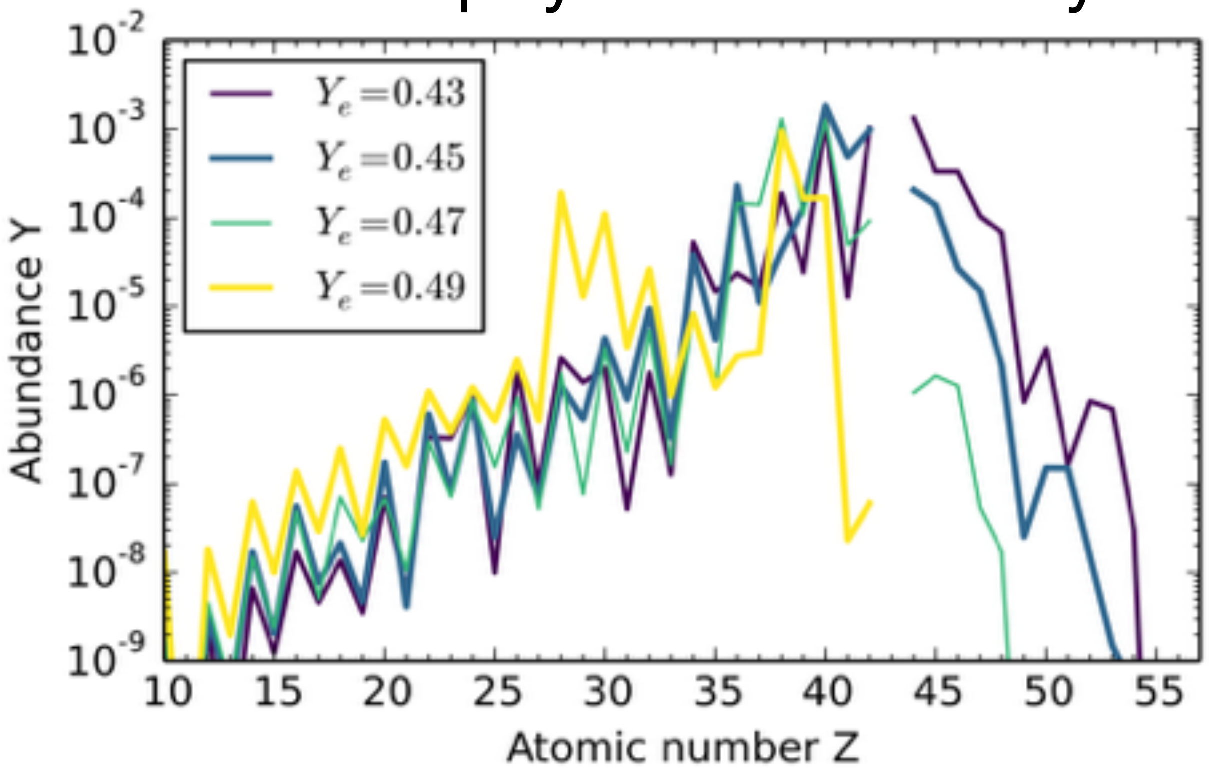


Observations point to proton-rich conditions

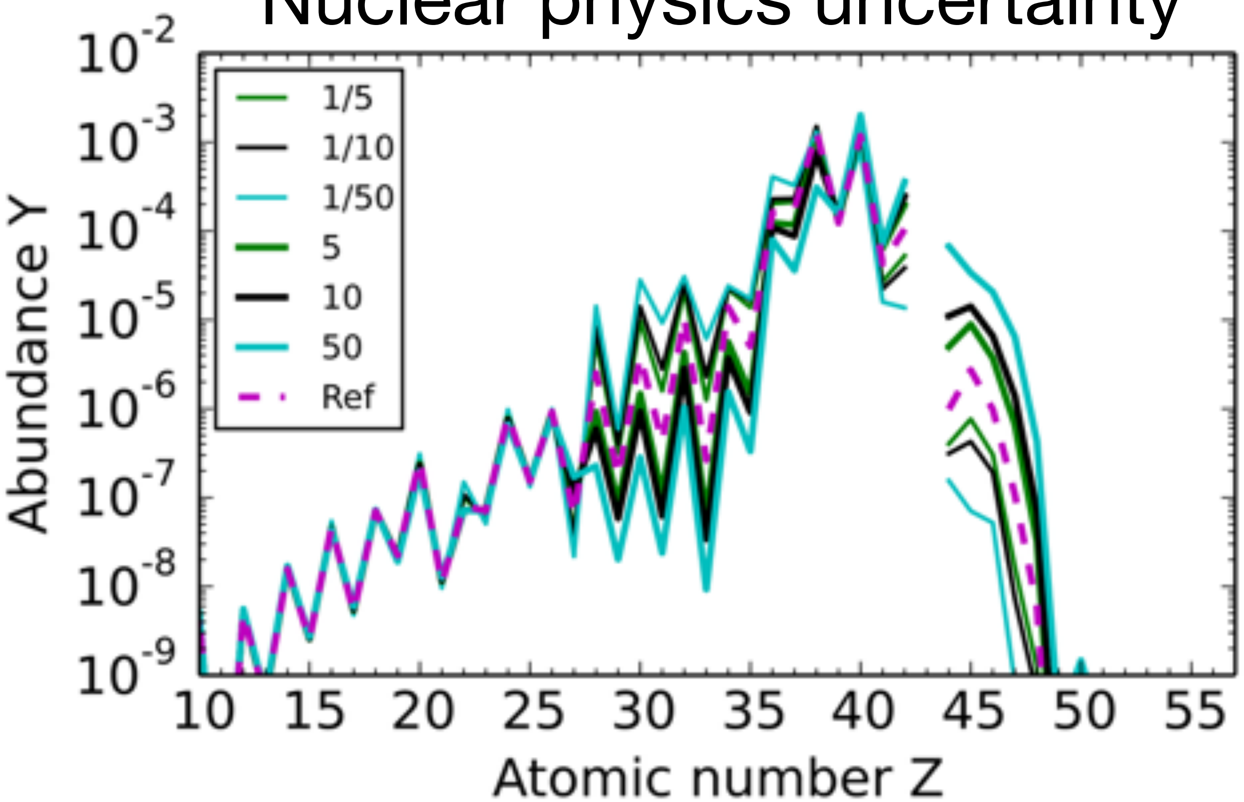
Nuclear physics uncertainties?

Astrophysics and nuclear physics uncertainties

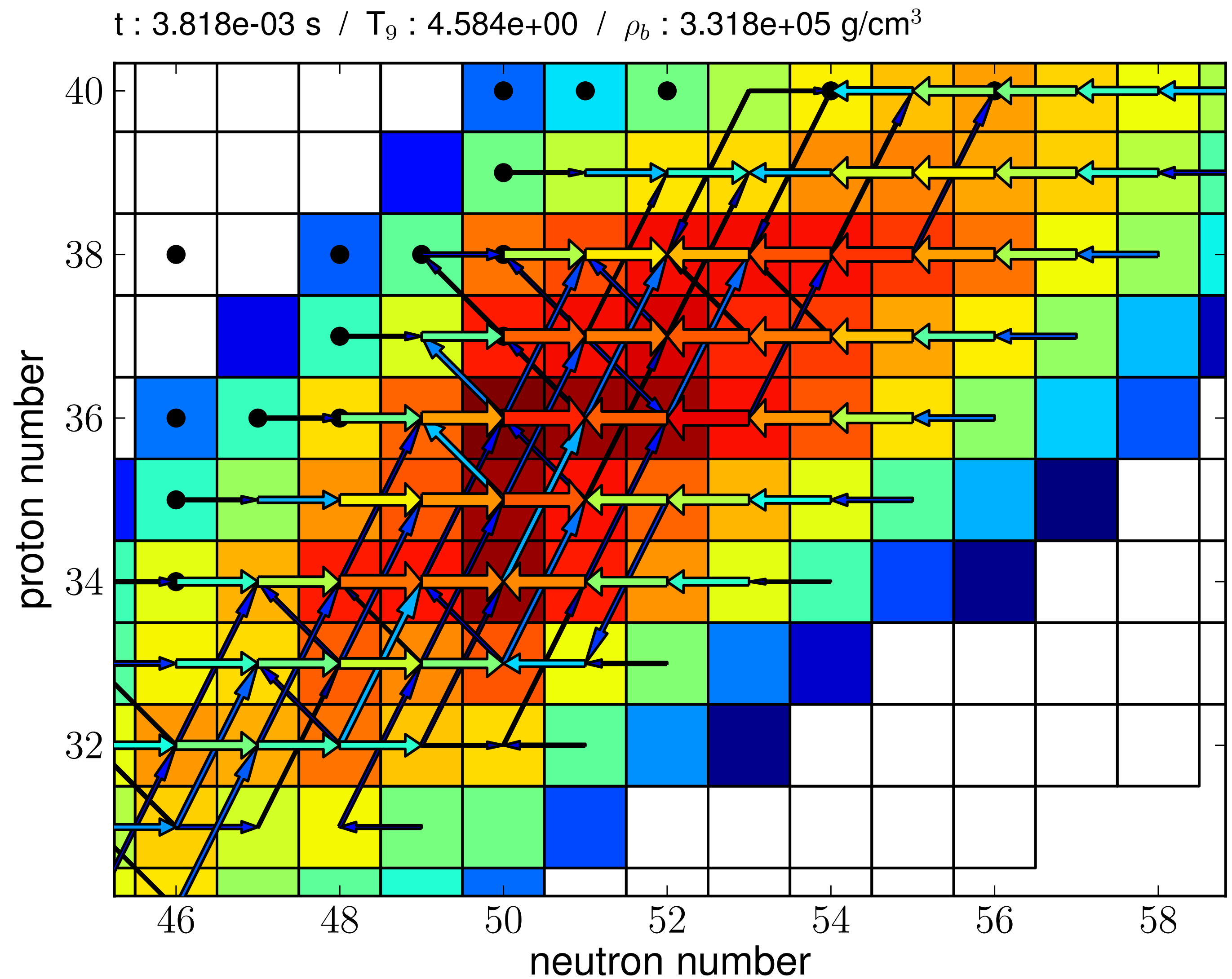
Astrophysics uncertainty



Nuclear physics uncertainty



(α,n)

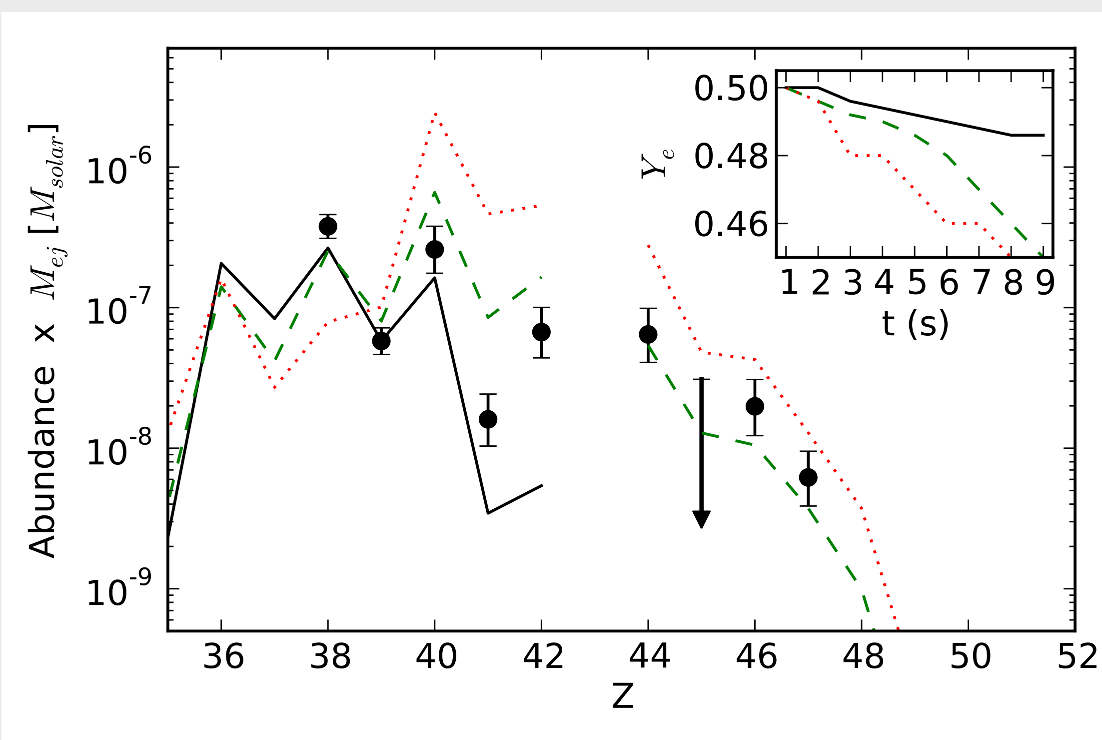


Bliss, Arcones, Montes, Pereira (in prep.)

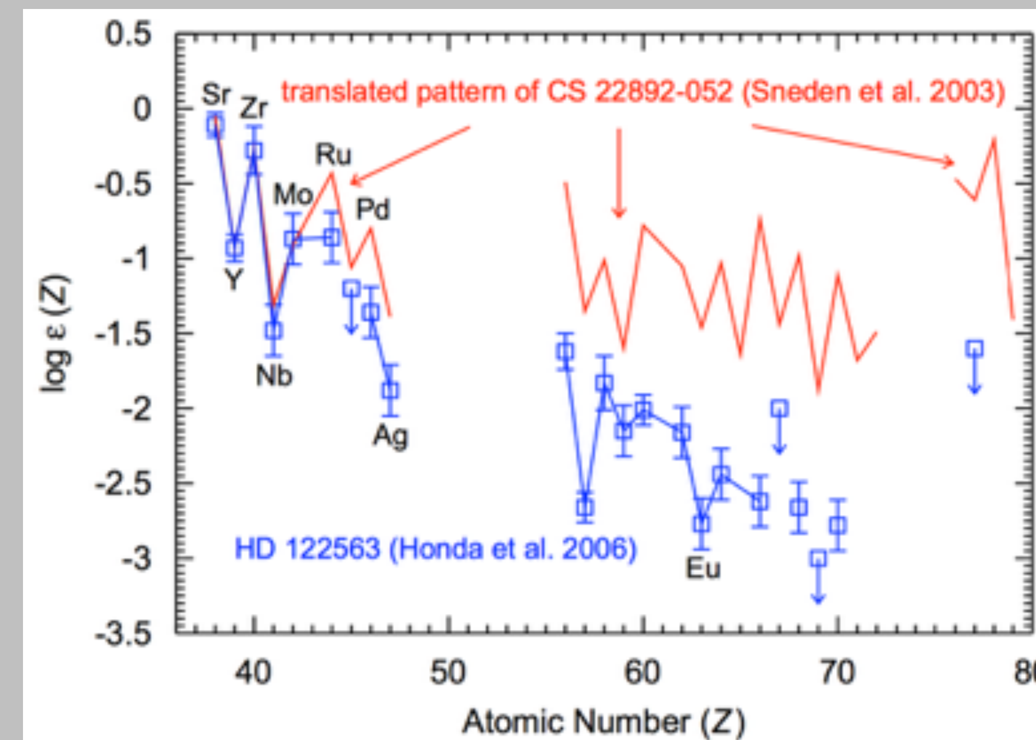
First experiment at ReA3:
^{75}Ga (α,n)^{78}As

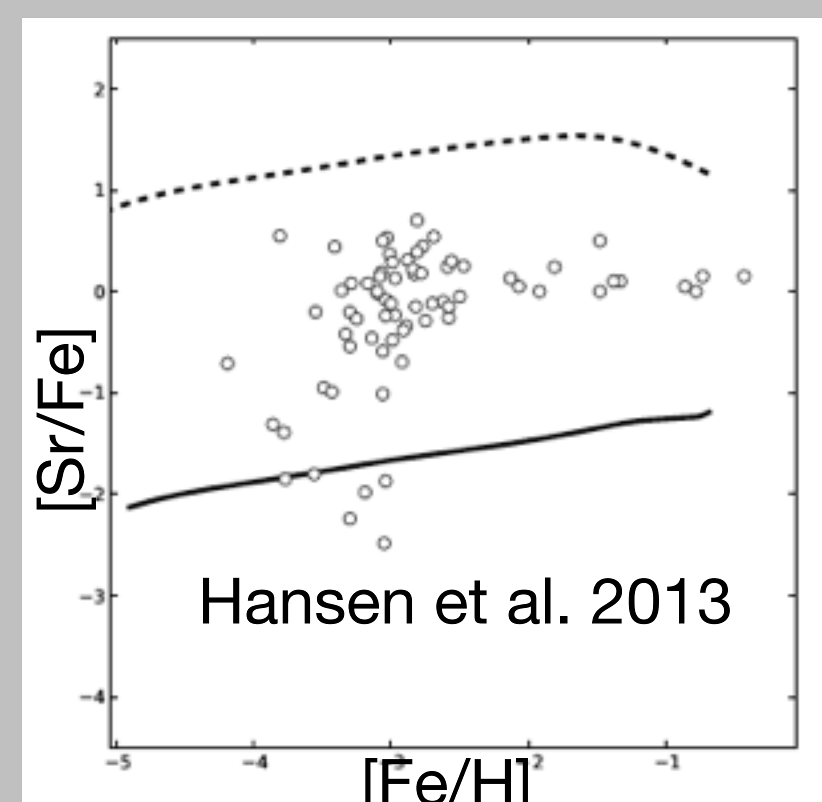
Origin of elements from Sr to Ag

Astrophysical site ⟷ Observations



Nucleosynthesis:
identify key reactions





Chemical
evolution