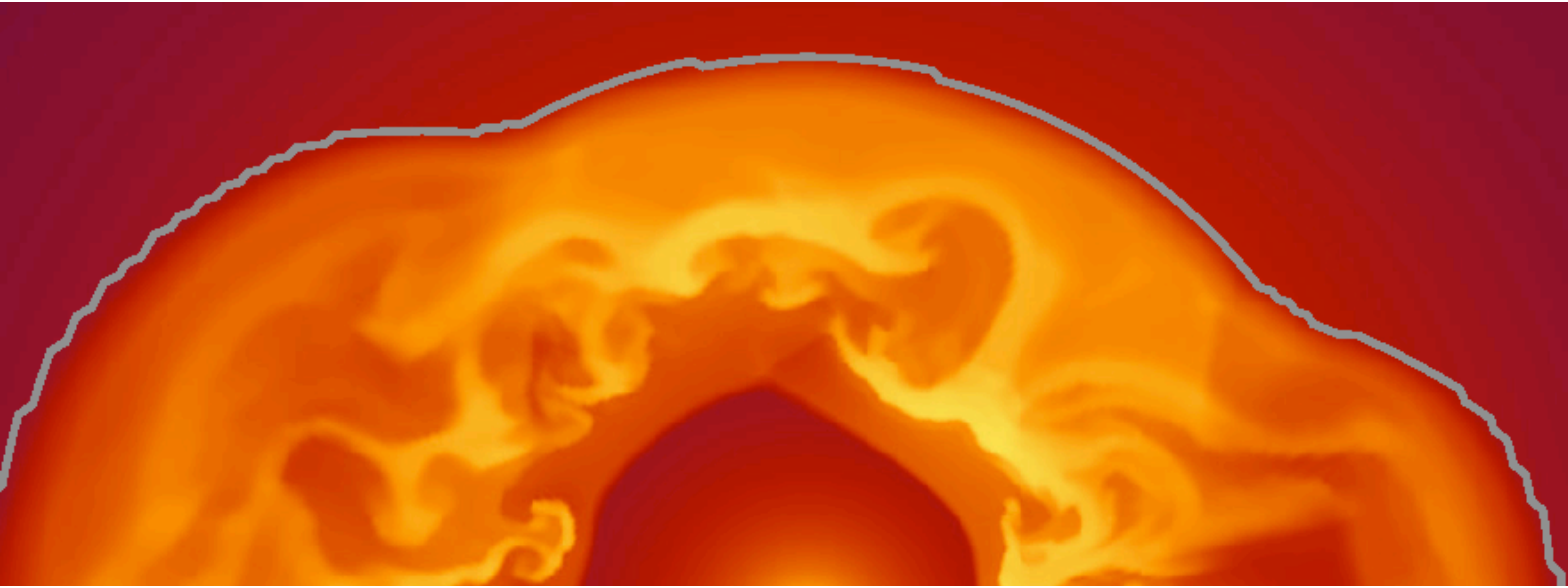
Lighter element primary process in neutrino-driven winds



HELMHOLTZ GEMEINSCHAFT

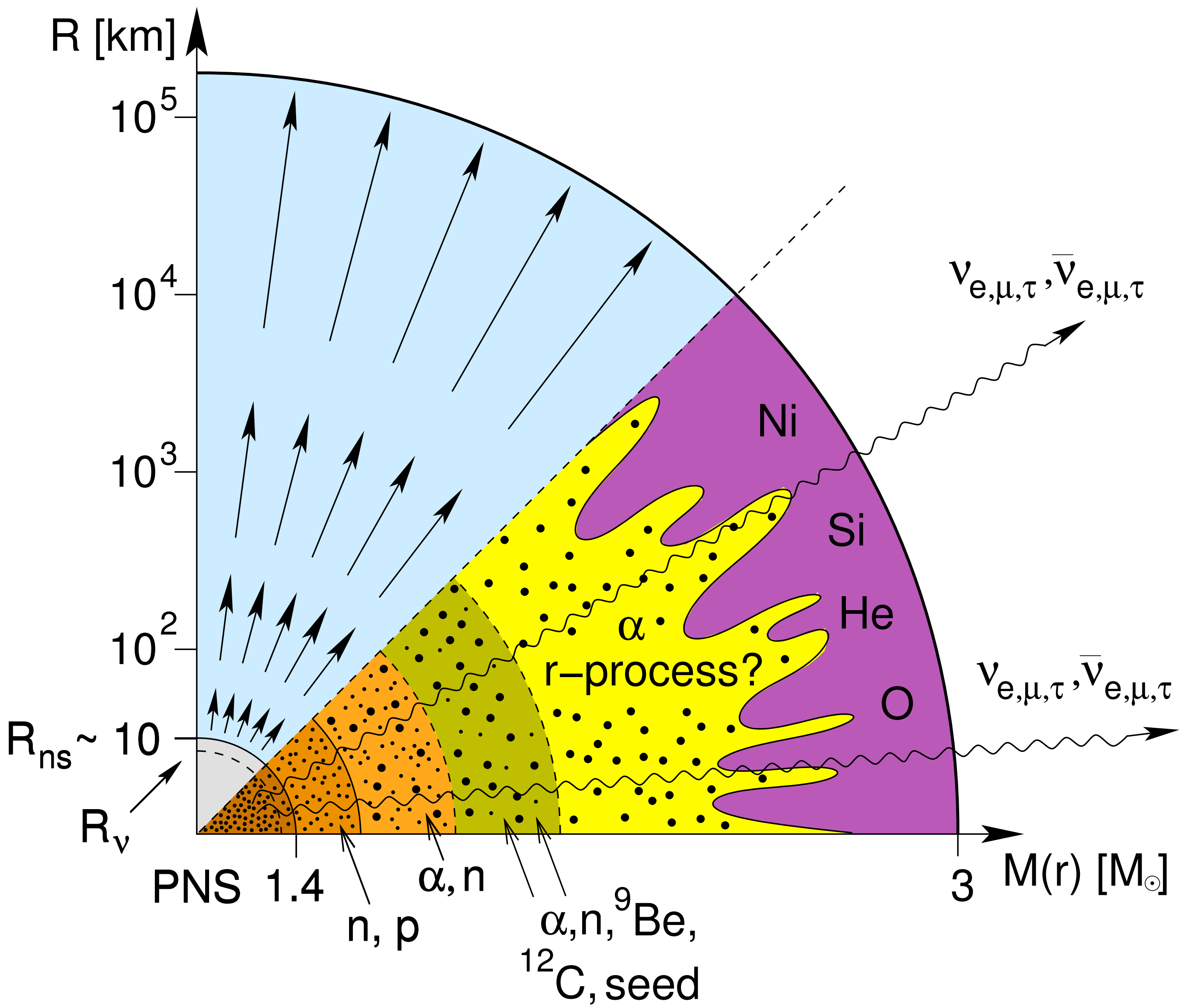
Almudena Arcones

Helmholtz Young Investigator Group

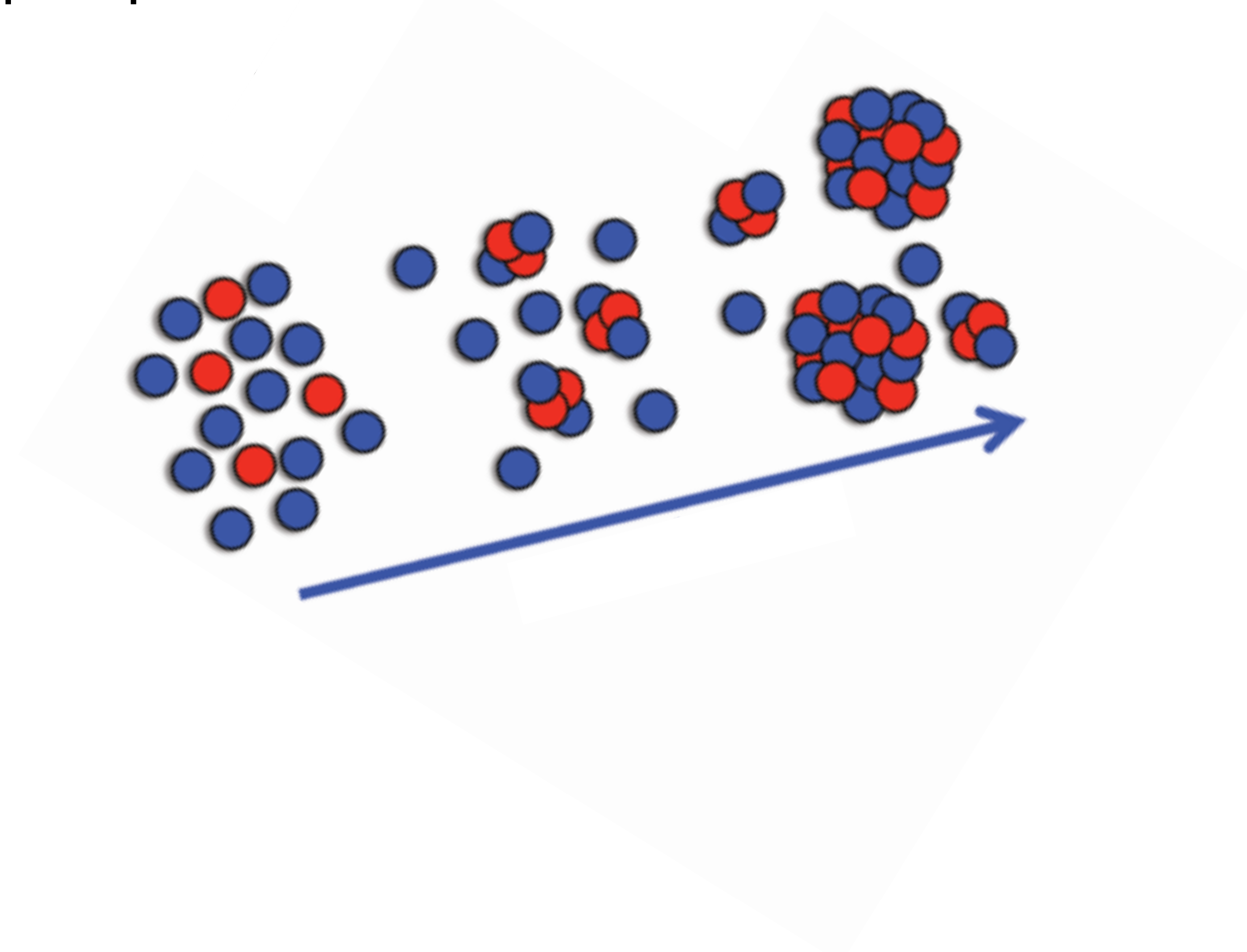
TECHNISCHE UNIVERSITÄT DARMSTADT

GSI

Neutrino-driven winds



neutrons and protons form alpha particles
alpha particles recombine into seed nuclei

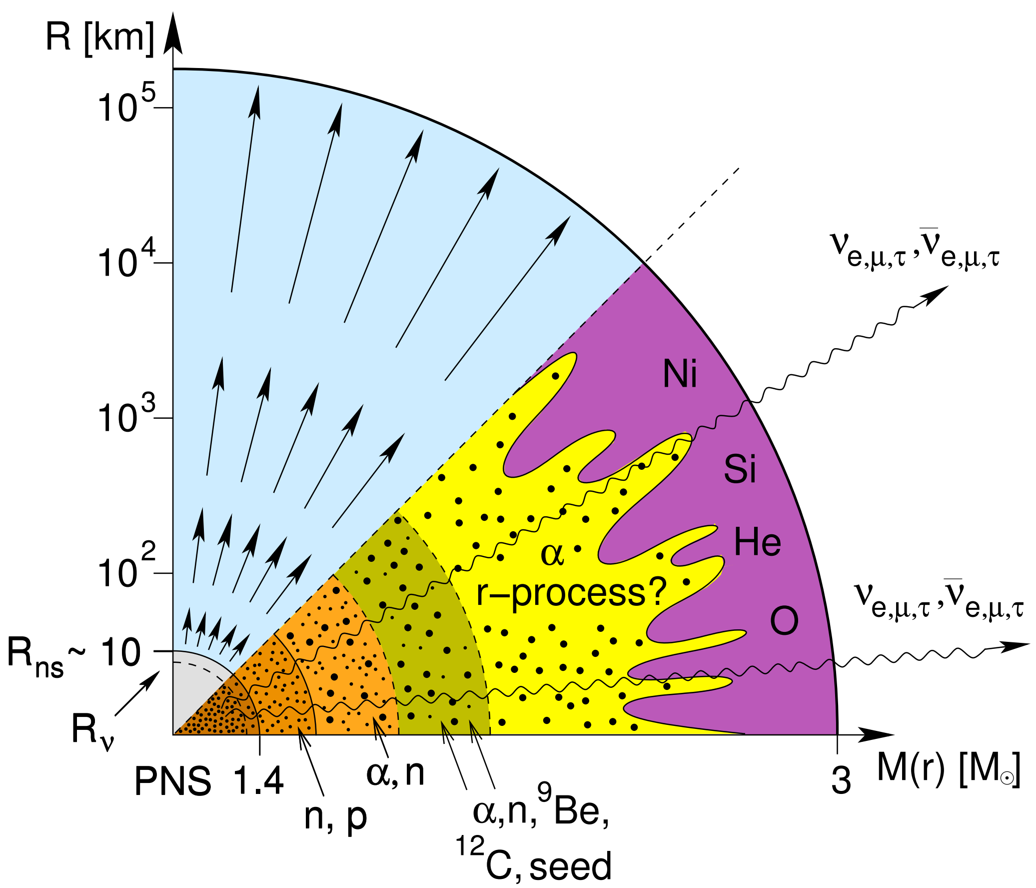


	NSE	→	charged particle reactions / α-process	→ r-process weak r-process νp-process
T =	10 - 8 GK		8 - 2 GK	T < 3 GK

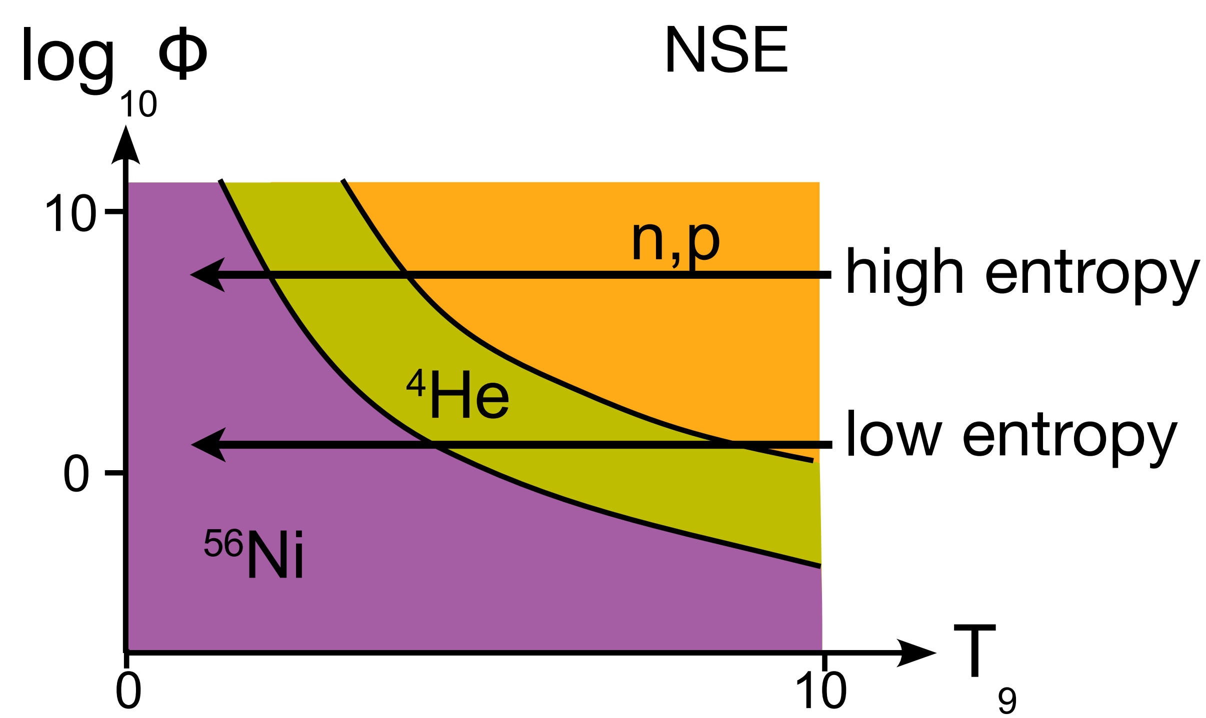
Neutrino-driven wind parameters

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

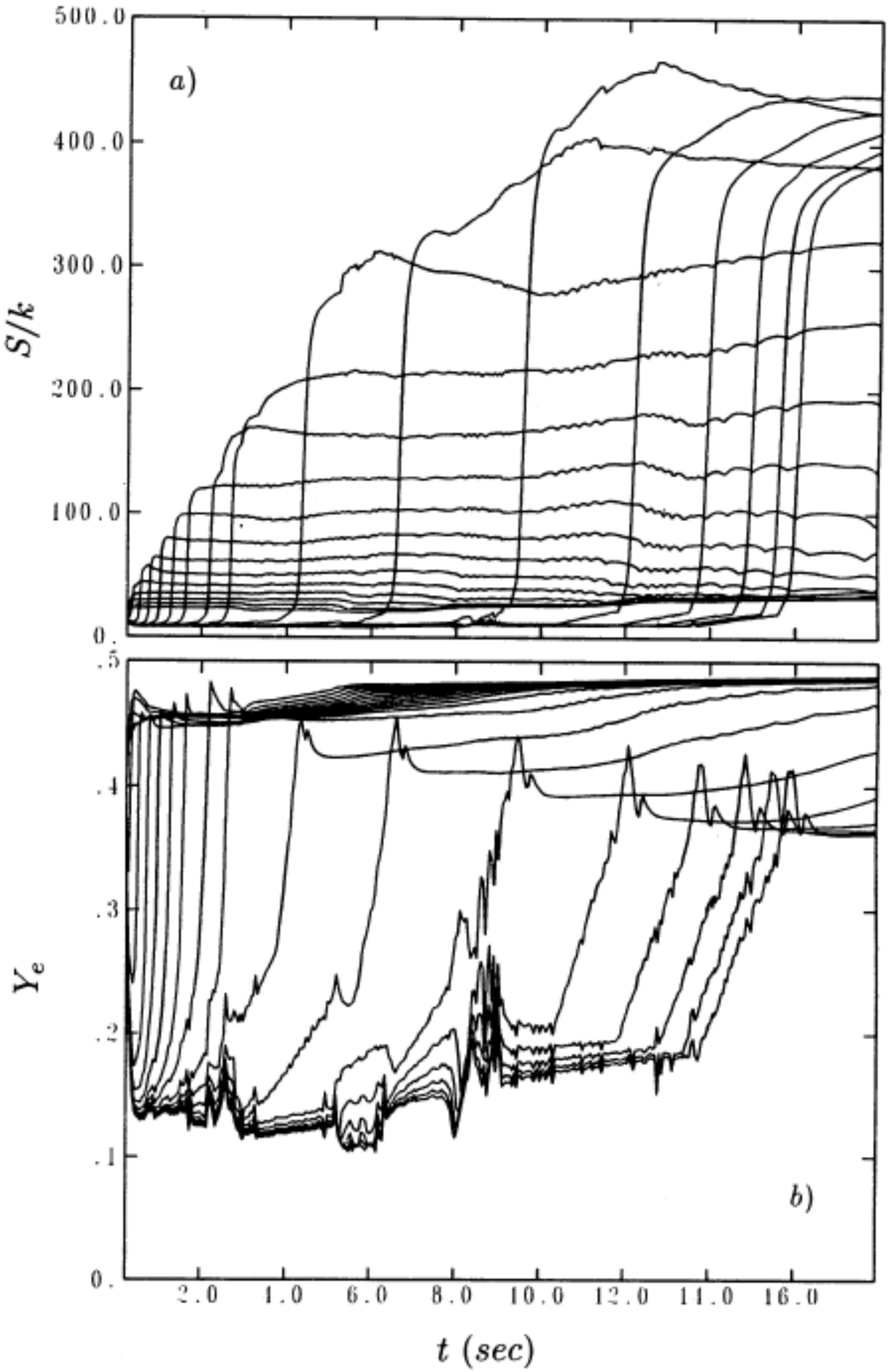
- Short expansion time scale to inhibit α-process and formation of seed nuclei
- High entropy is equivalent to high photon-to-baryon ratio: photons dissociate seed nuclei into nucleons
- Electron fraction: $Y_e<0.5$



Entropy per baryon in relativistic gas:
$s \propto (kT^3) / (\rho N_A) \Rightarrow s = 10/\Phi$



Photon-to-baryon ratio:
$\Phi = n_\gamma / (\rho N_A) \propto (kT^3) / (\rho N_A)$



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

Electron fraction

depends on accuracy of supernova neutrino transport and on details of neutrino interactions in outer layers of neutron star.

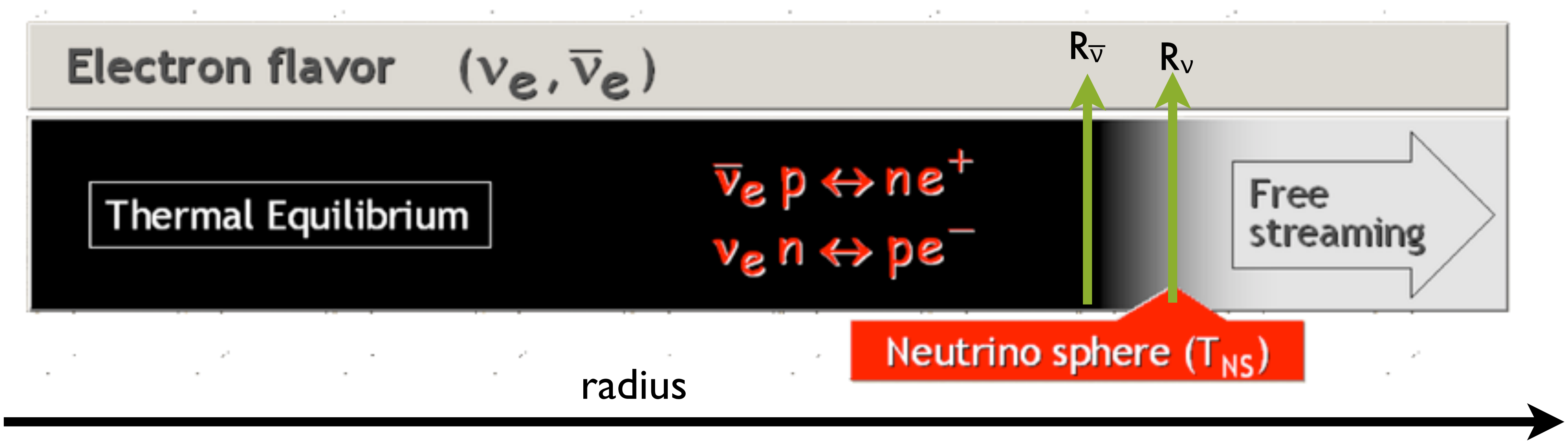
$$Y_e \approx \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta + 1.2\Delta^2/\epsilon_{\bar{\nu}_e})}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta + 1.2\Delta^2/\epsilon_{\nu_e})}\right]^{-1}$$

Qian & Woosley 1996

($\Delta = m_n - m_p$)

The neutrino energies are determined by the position (temperature) where neutrinos decouple from matter: neutrinosphere

Raffelt 2001



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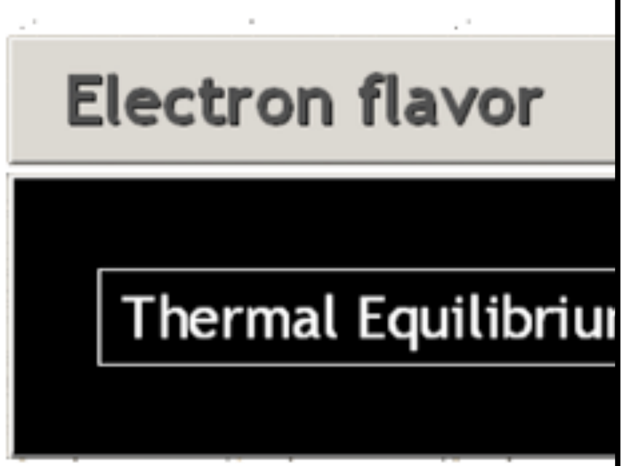
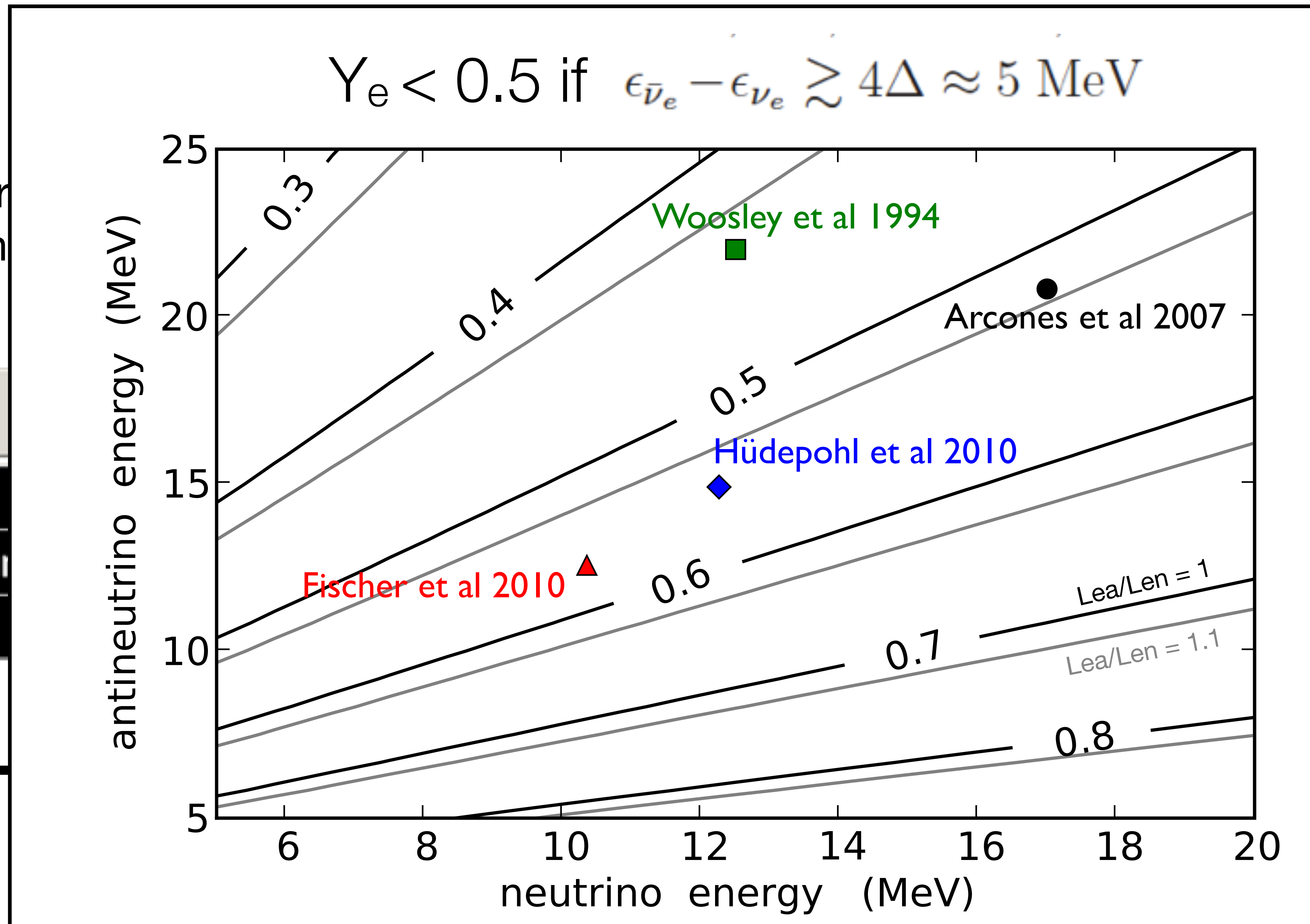




April 2012

Charged-current weak interaction processes in hot and dense matter and its impact on the spectra of neutrinos emitted from proto-neutron star cooling

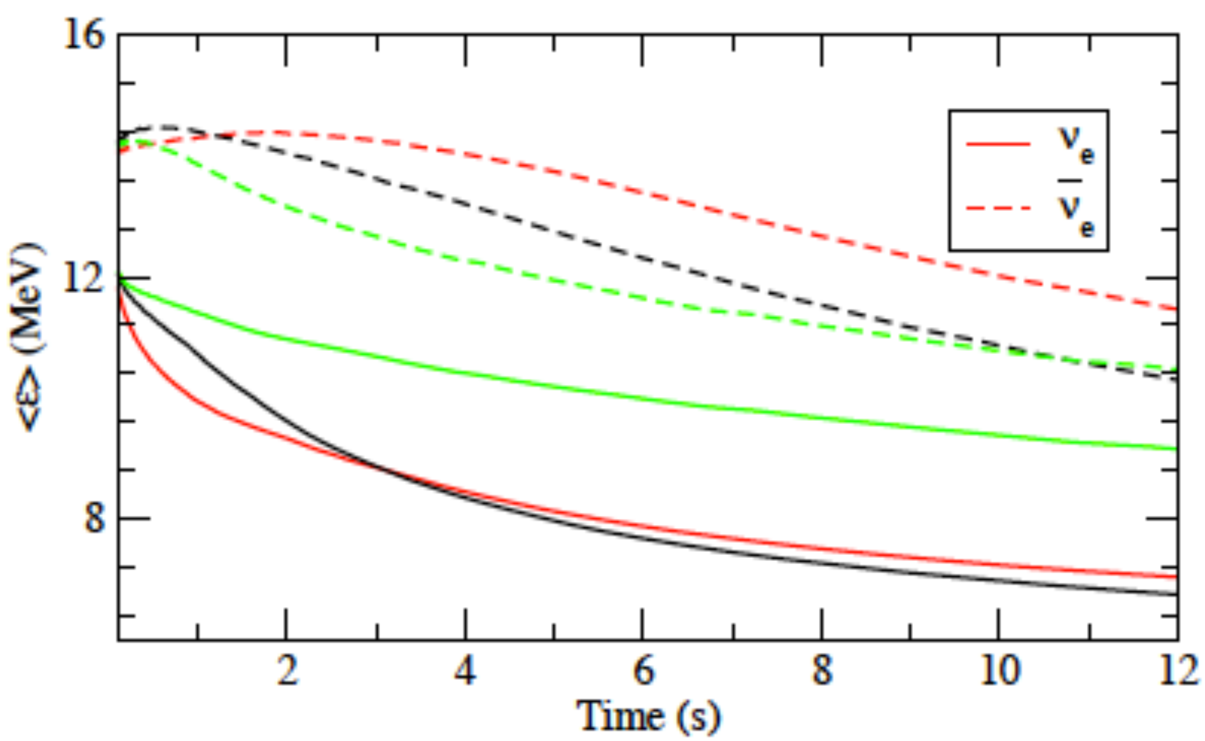
G. Martínez-Pinedo,[1,2] T. Fischer,[2,1] A. Lohs,[1] and L. Huther[1]

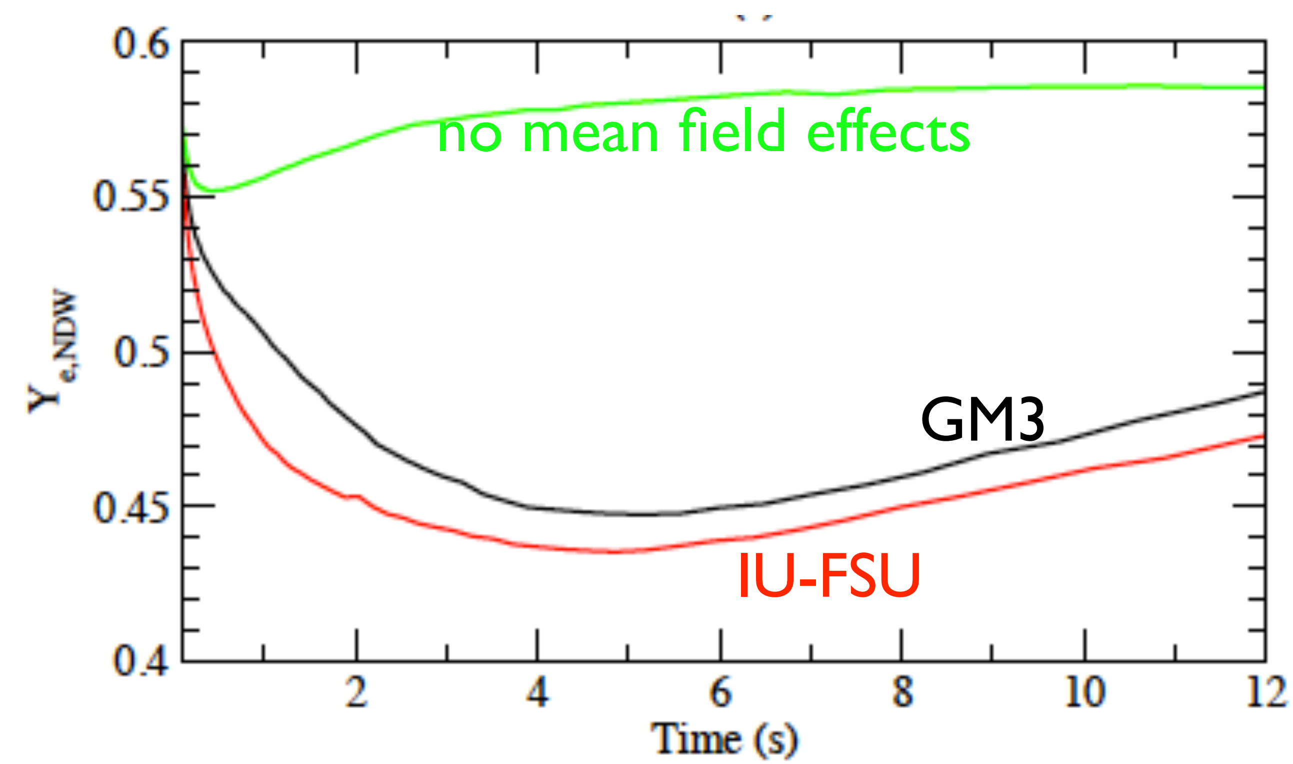
A NEW CODE FOR PROTO-NEUTRON STAR EVOLUTION

L. F. Roberts†

Medium modification of the charged current neutrino opacity and its implications

L. F. Roberts[1] and Sanjay Reddy[2]

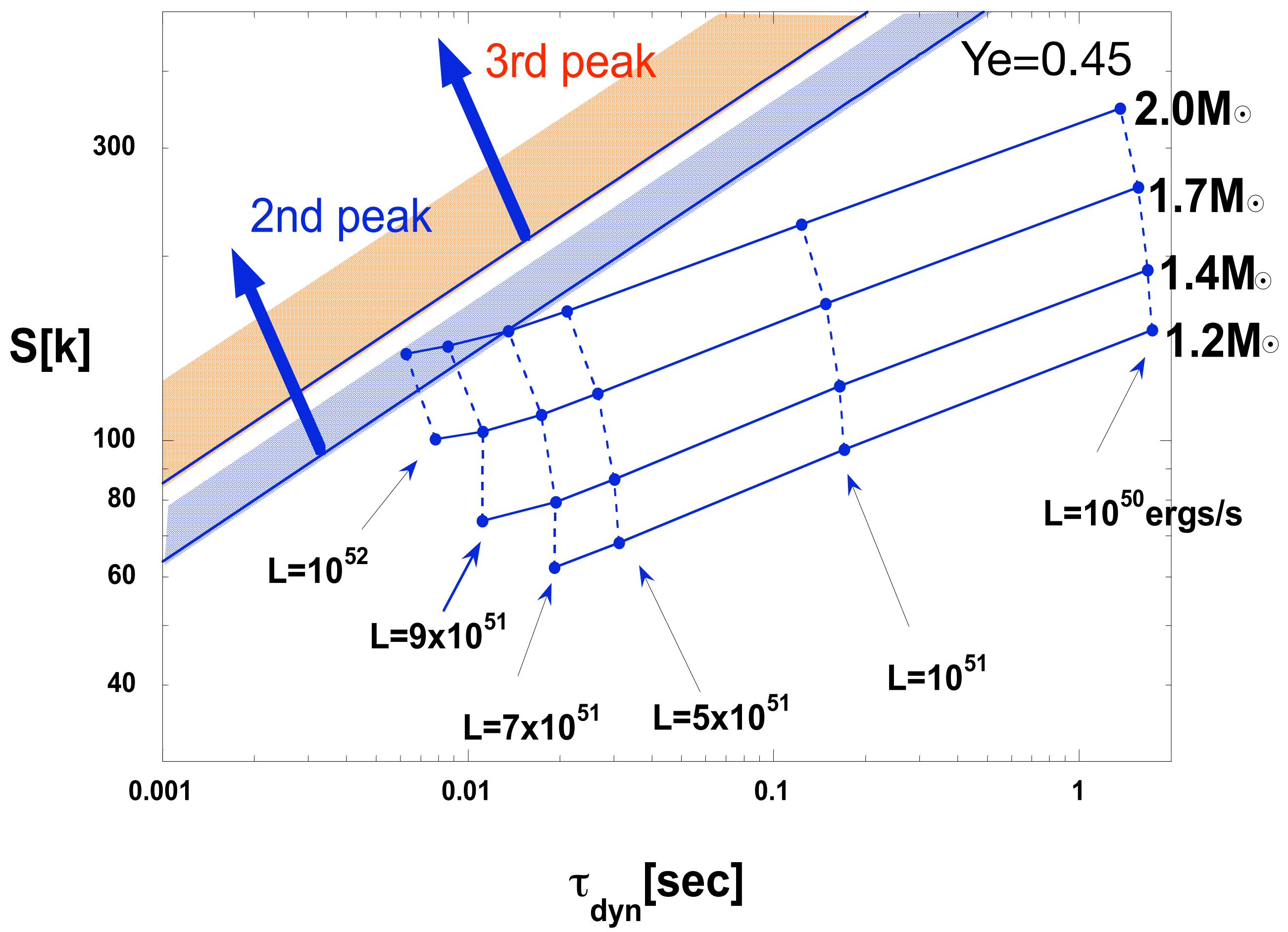


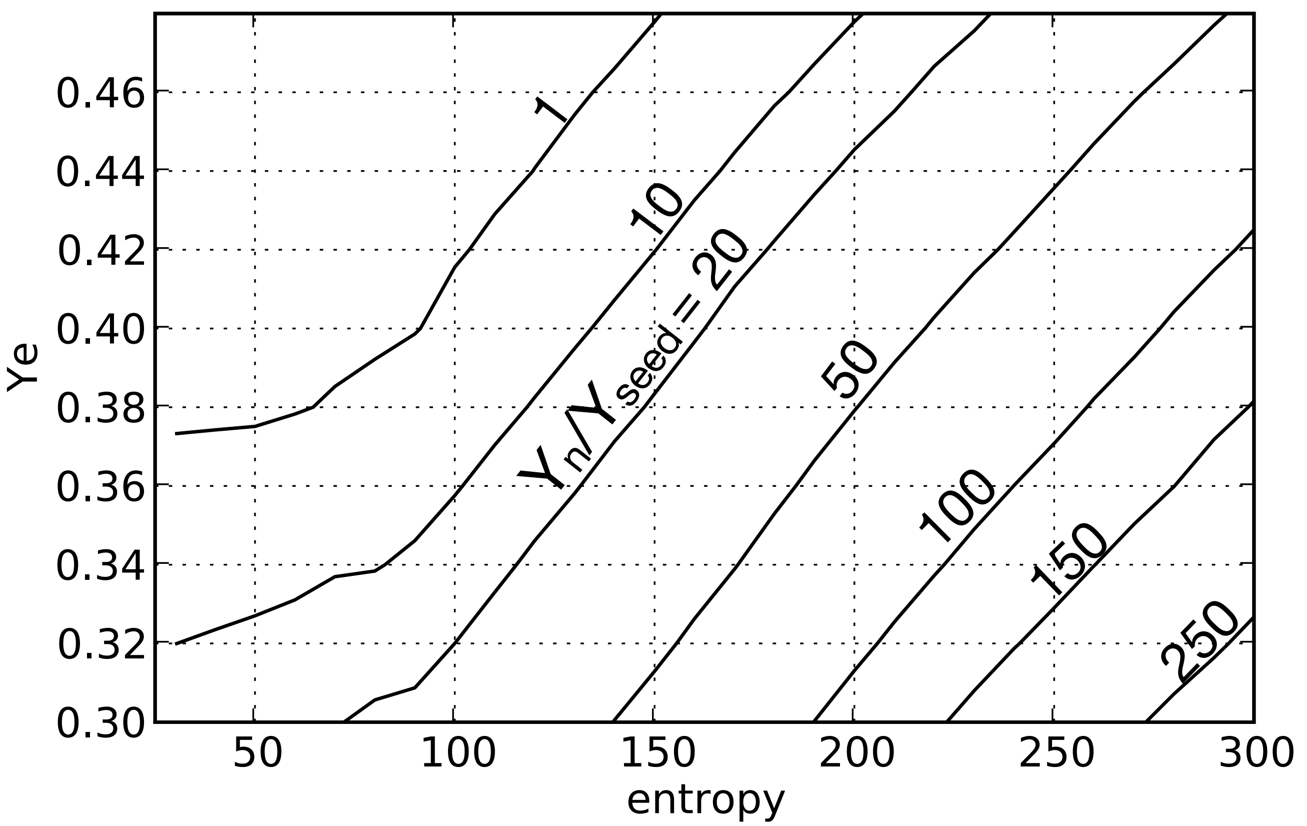


Wind parameters and r-process

Necessary conditions identified by steady-state models (e.g., Otsuki et al. 2000, Thompson et al. 2001)

Otsuki et al. 2000





Conditions are not realized in recent simulations

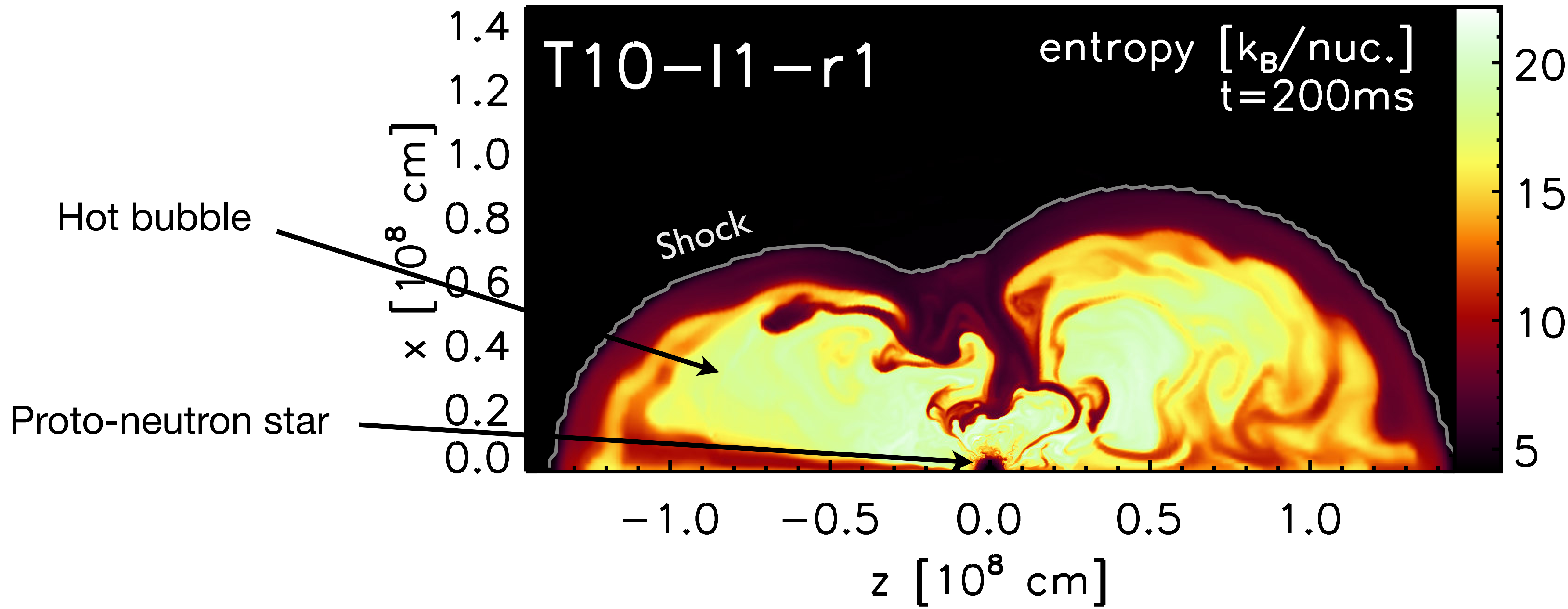
(Arcones et al. 2007, Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011)

S_{wind} = 50 - 120 k_B/nuc τ = few ms $Y_e > 0.5$?

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

Review: Arcones & Thielemann (arxiv: 1207.2527)

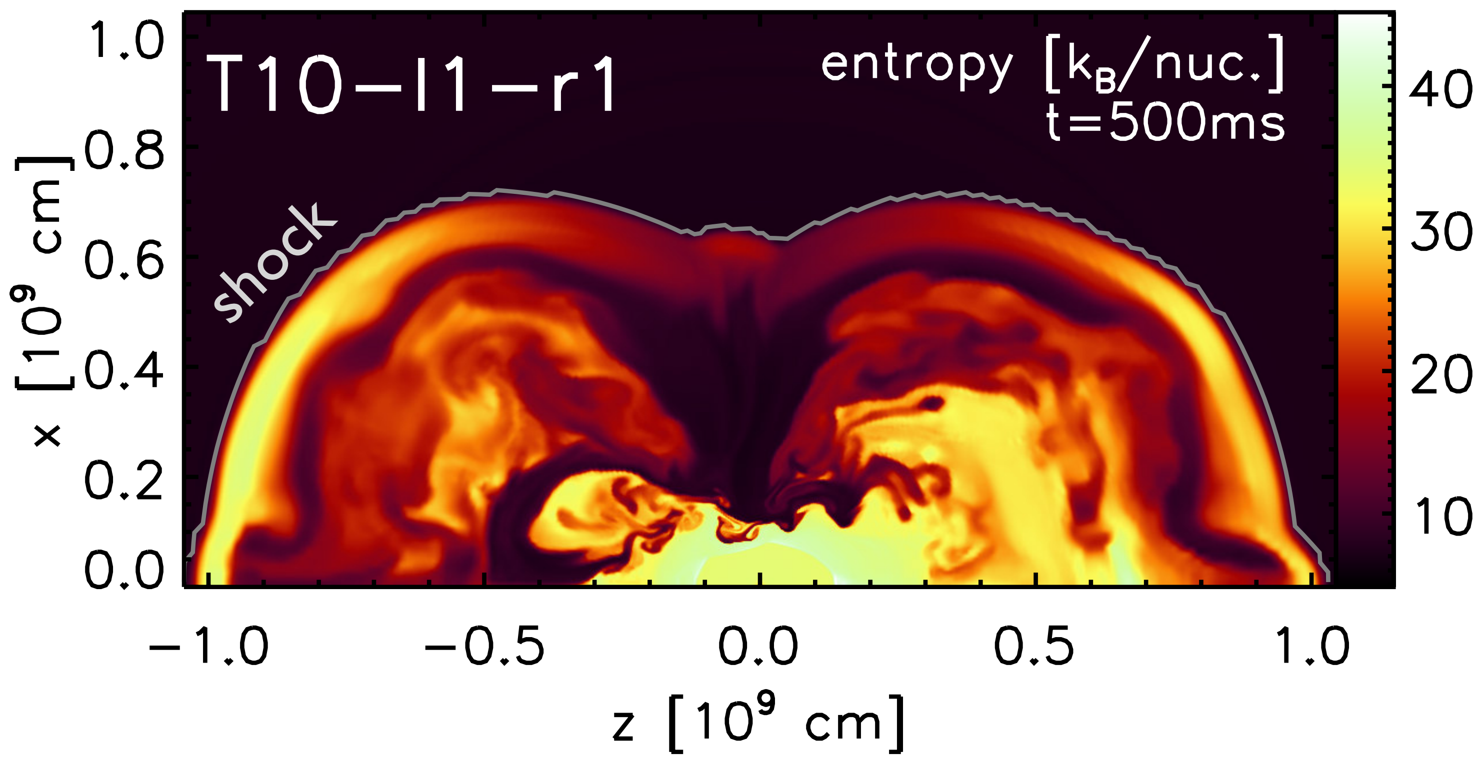
Core-collapse supernova simulations



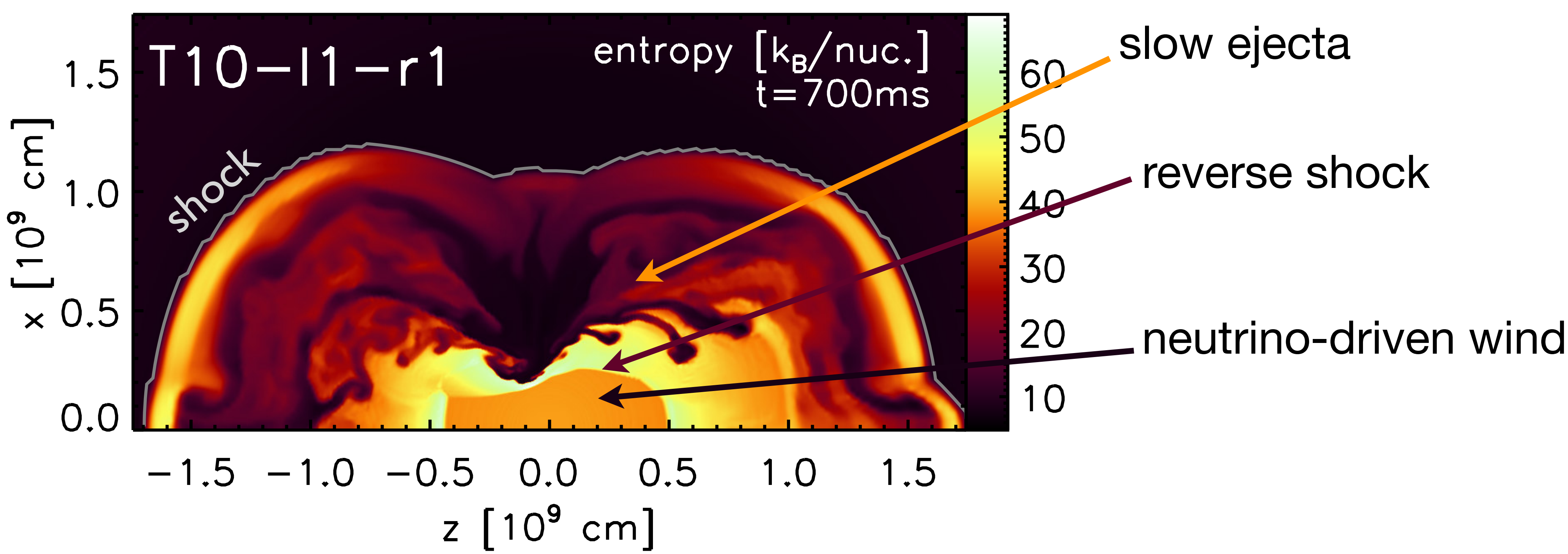
Long-time hydrodynamical simulations:

- ejecta evolution from ~5ms after bounce to ~3s in 2D (Arcones & Janka 2011)
  and ~10s in 1D (Arcones et al. 2007)
- explosion triggered by neutrinos
- detailed study of nucleosynthesis-relevant conditions

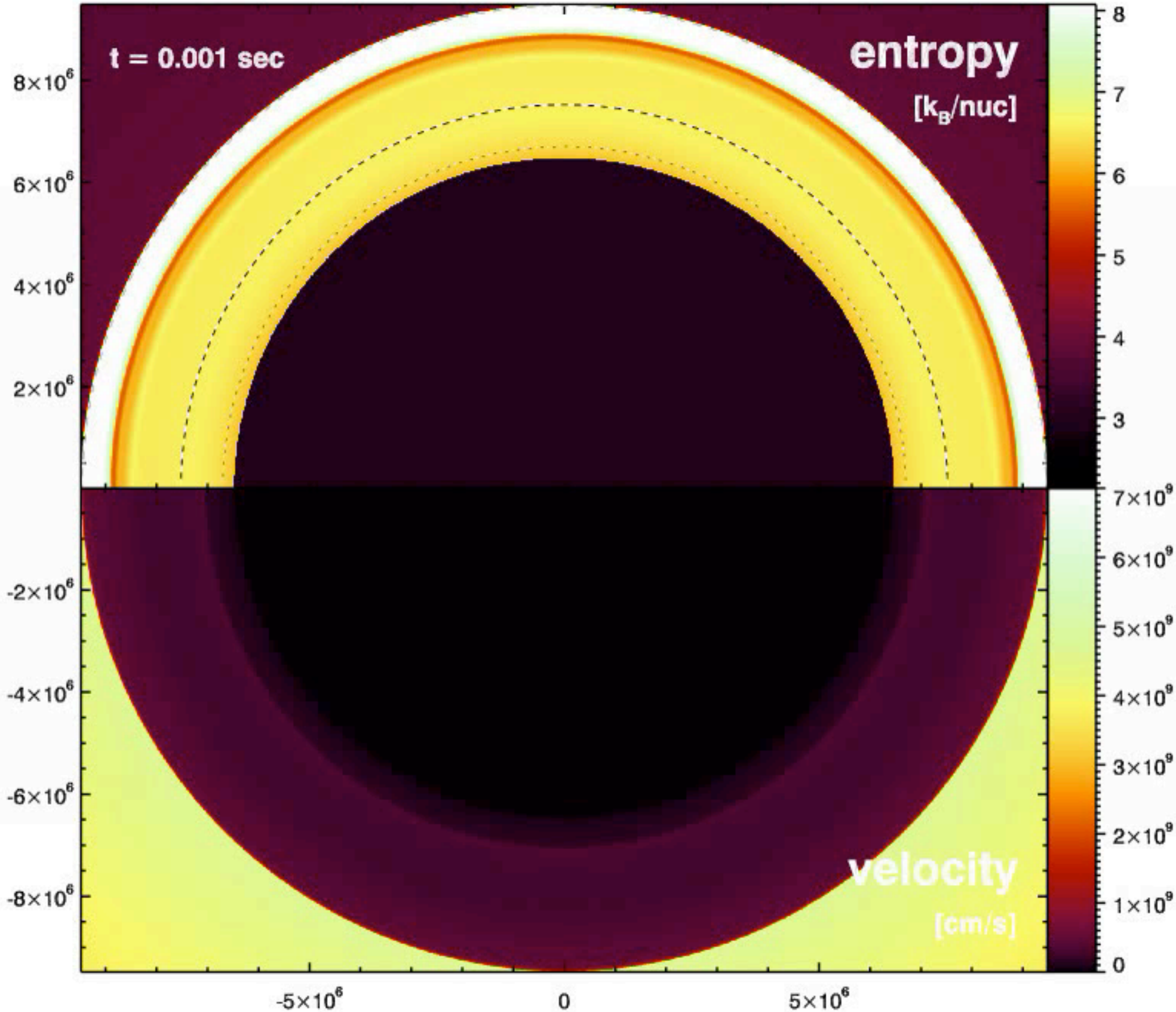
Neutrino-driven wind in 2D



Supersonic neutrino-driven wind collides with slow supernova ejecta: reverse shock

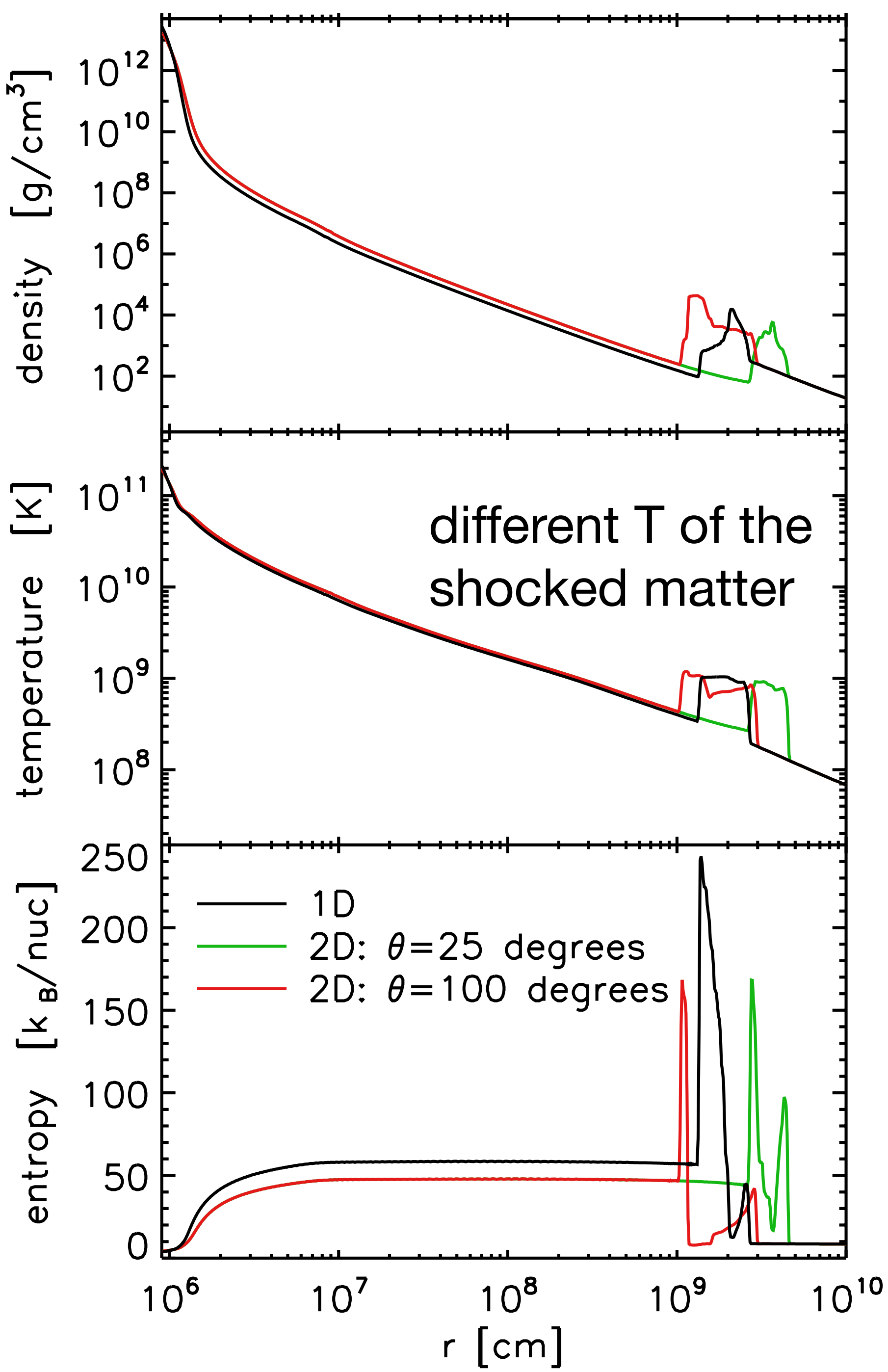


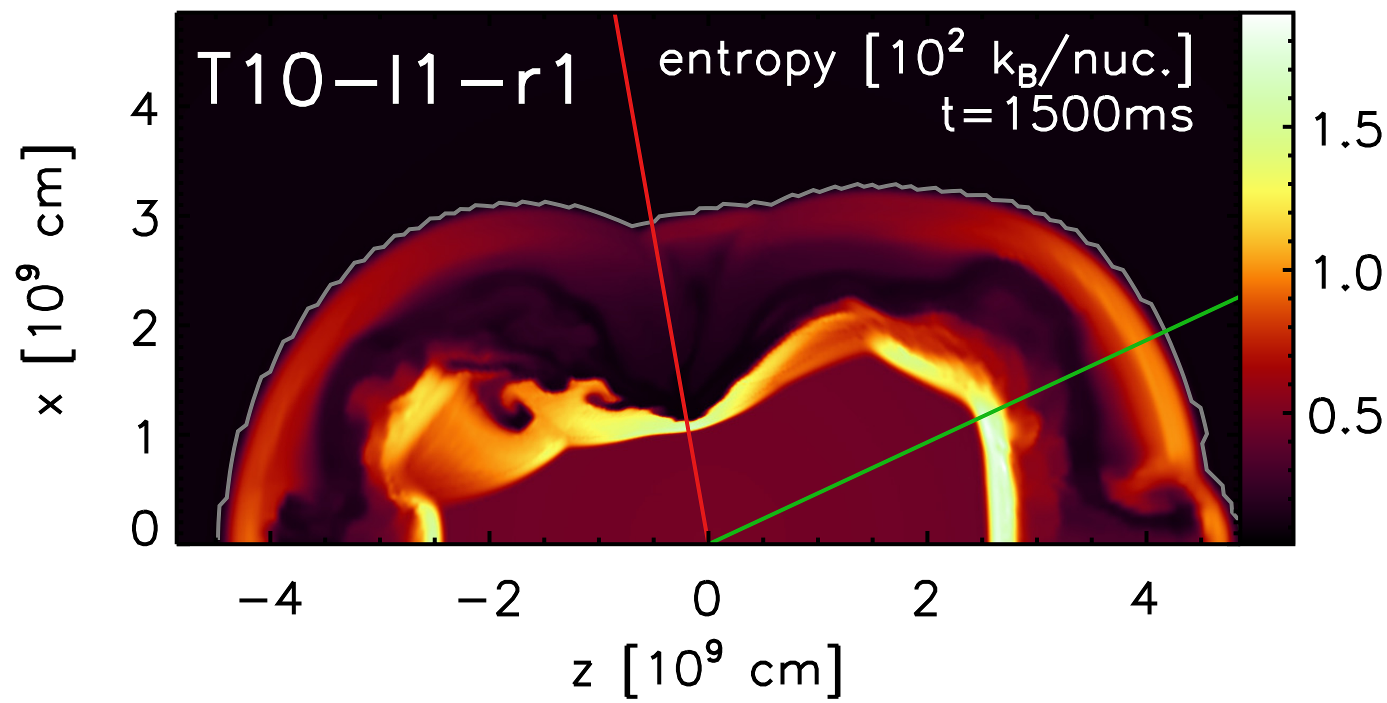
Arcones & Janka (2011)

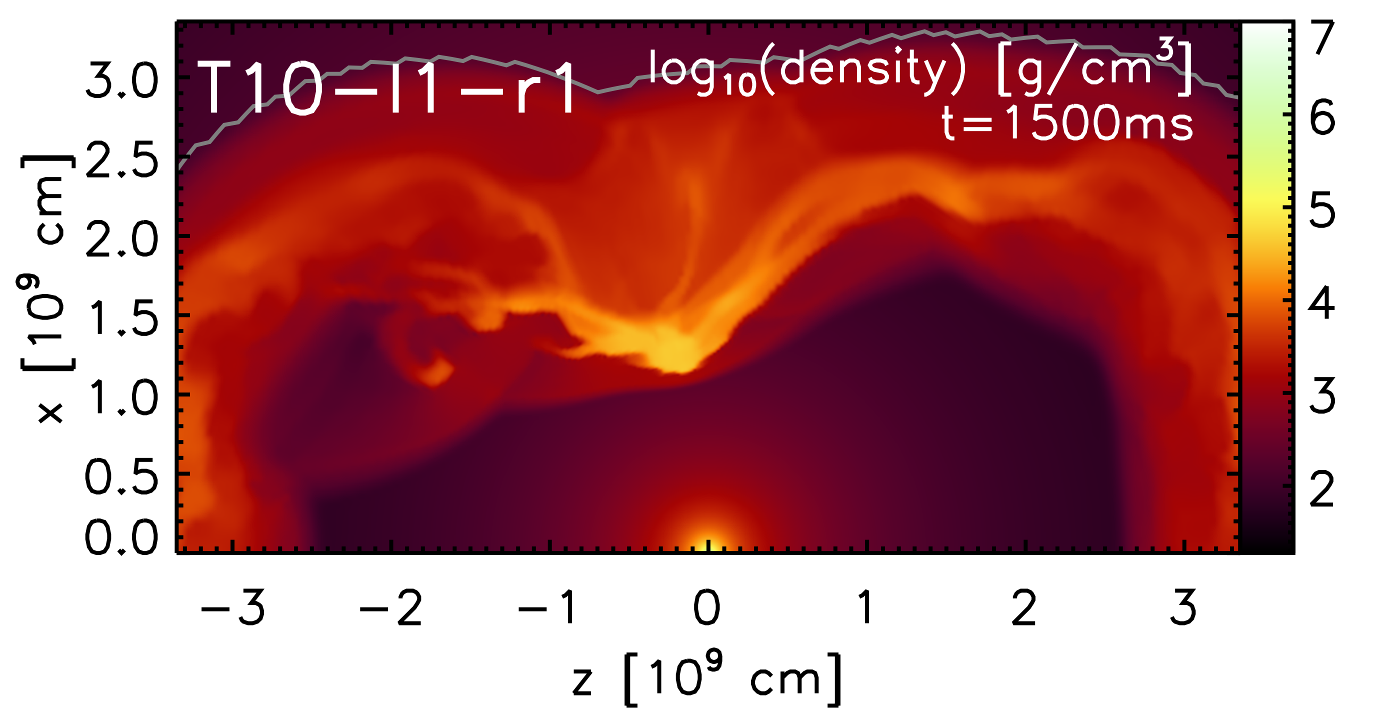


Neutrino-driven wind in 2D and 1D

Spherically symmetric wind

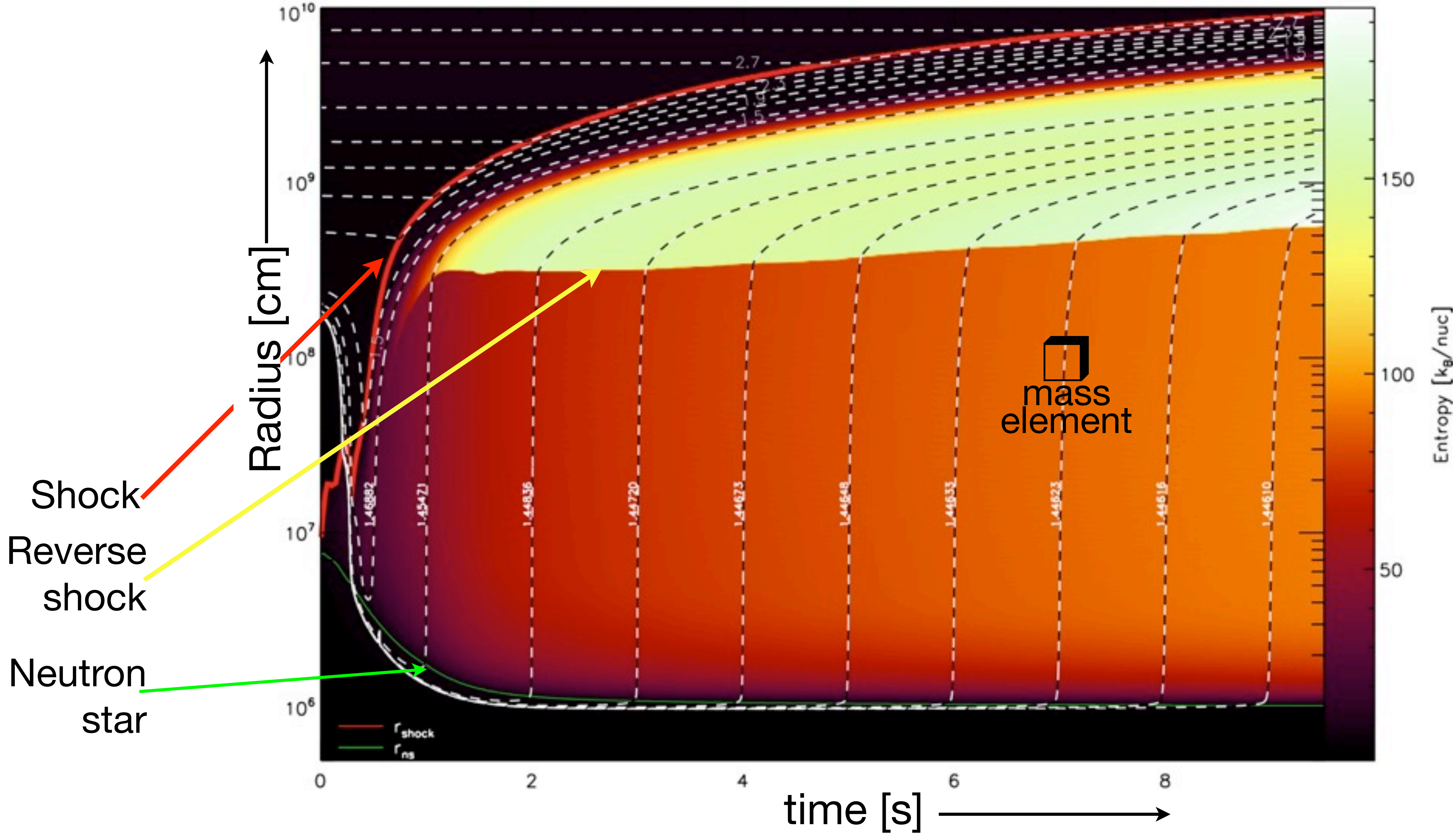






1D simulations for nucleosynthesis studies

Arcones et al 2007



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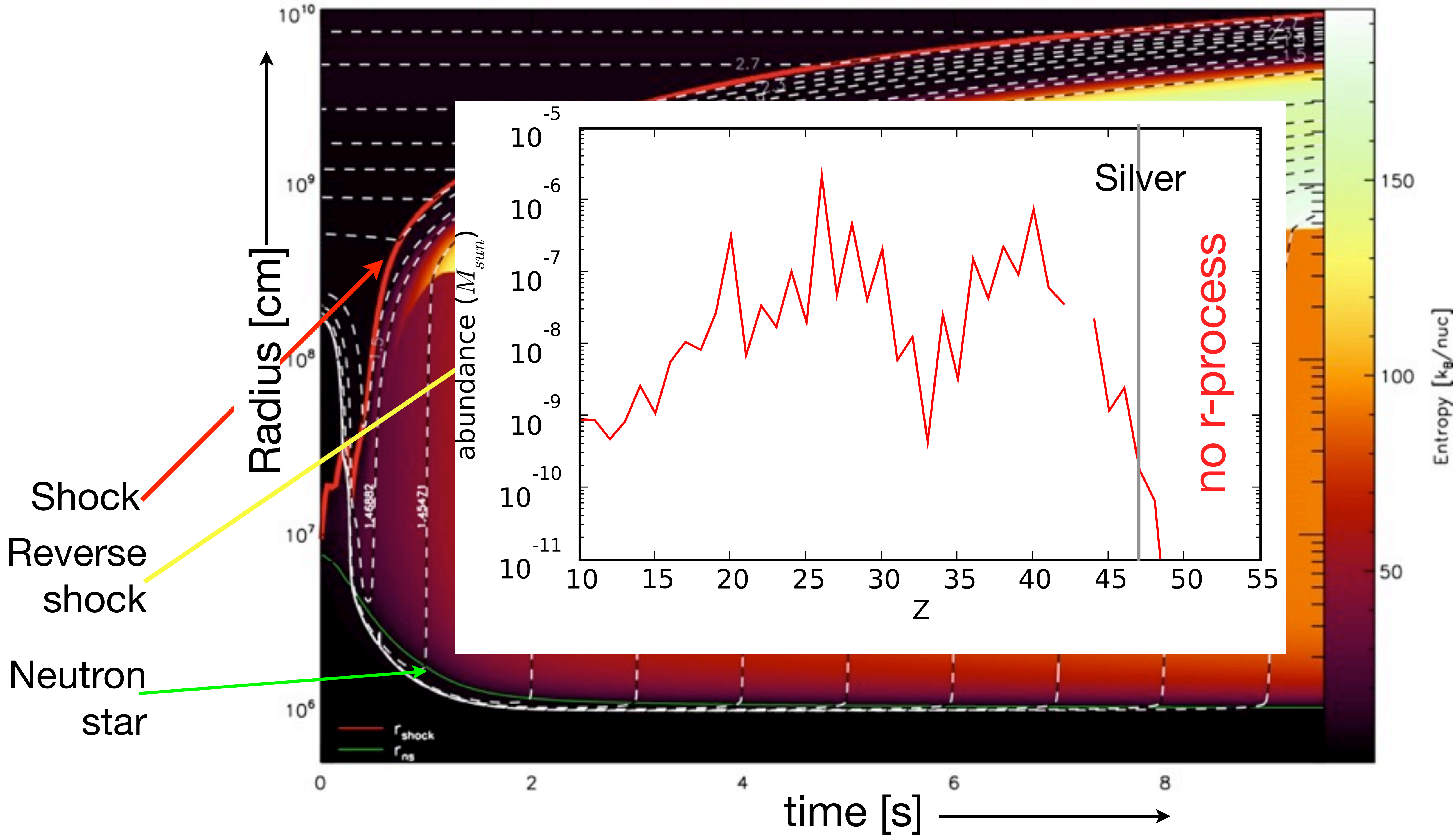
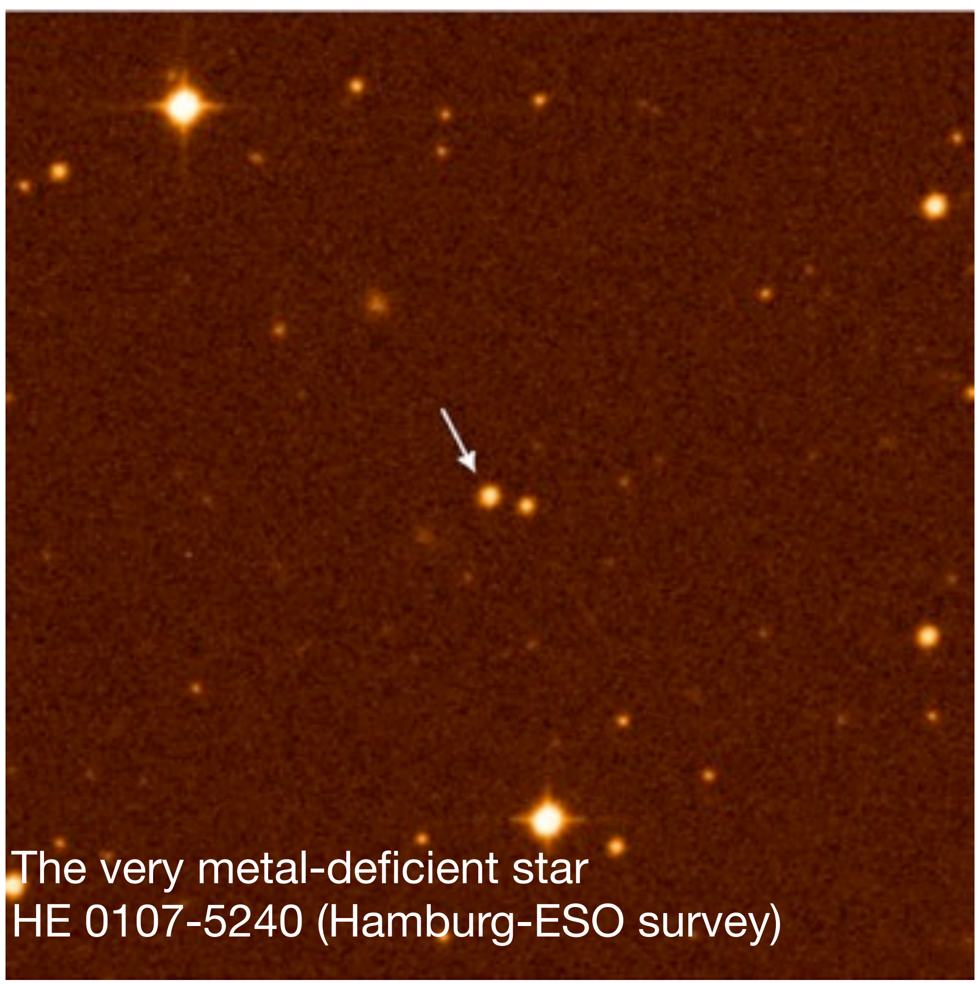


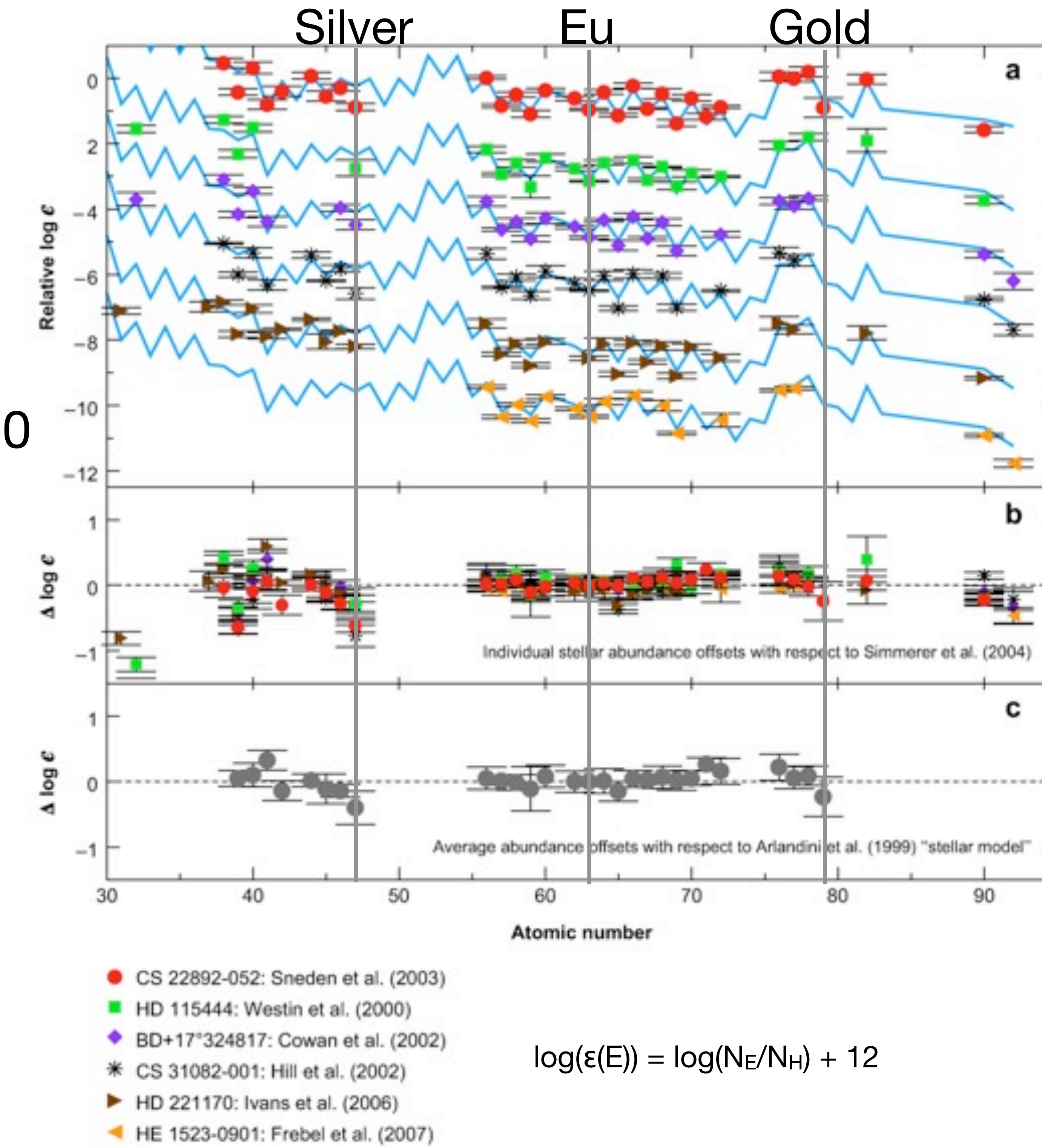
r-process in ultra metal-poor stars

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



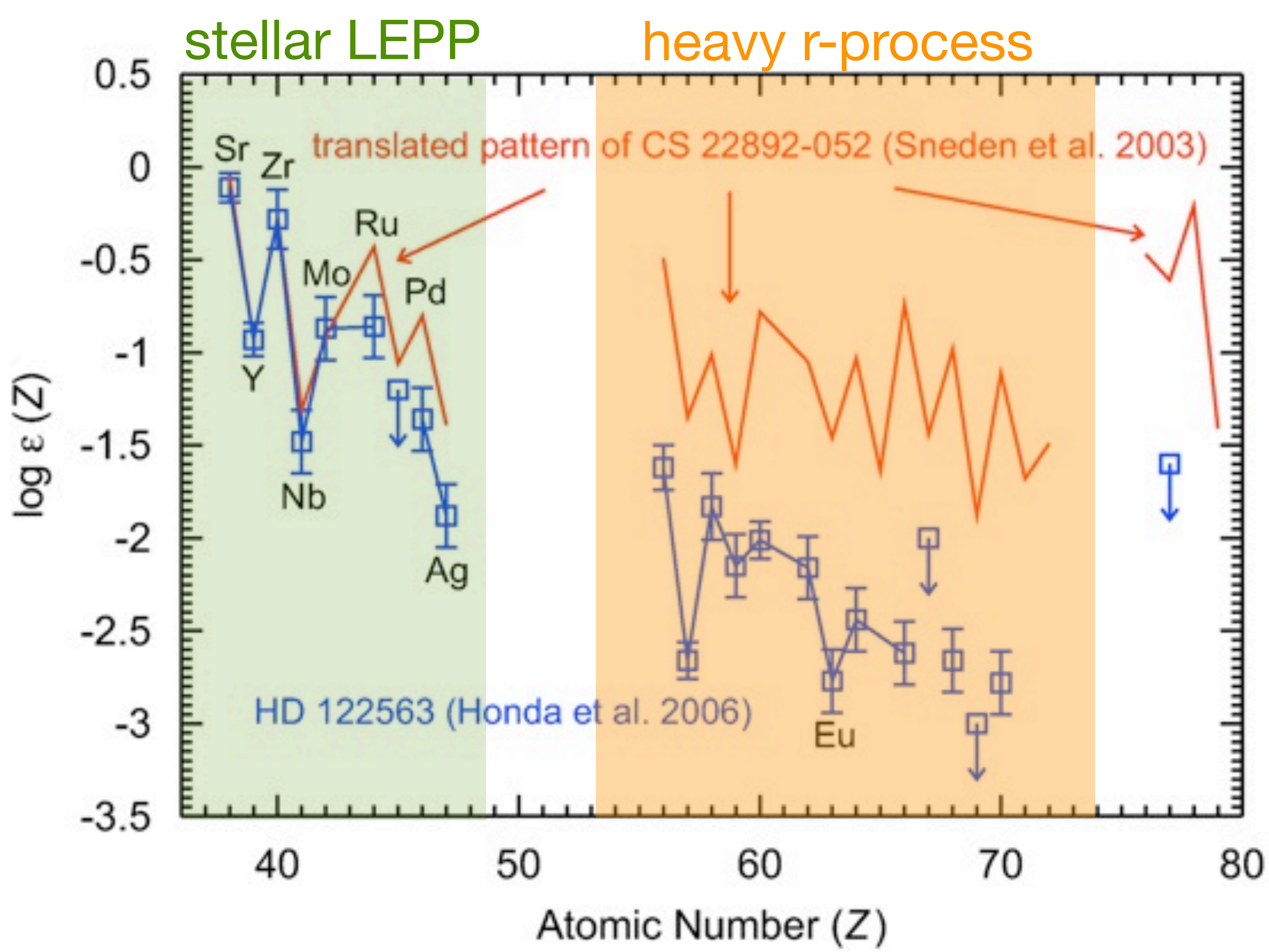


$\log(\varepsilon(E)) = \log(N_E/N_H) + 12$

Sneden, Cowan, Gallino 2008

LEPP: Lighter Element Primary Process

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



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

LEPP contributes 20-30% of solar Sr-Y-Zr and explains under-productions of "s-only" isotopes from ^{96}Mo to ^{130}Xe

Montes et al. 2007: solar LEPP ~ stellar LEPP → unique?

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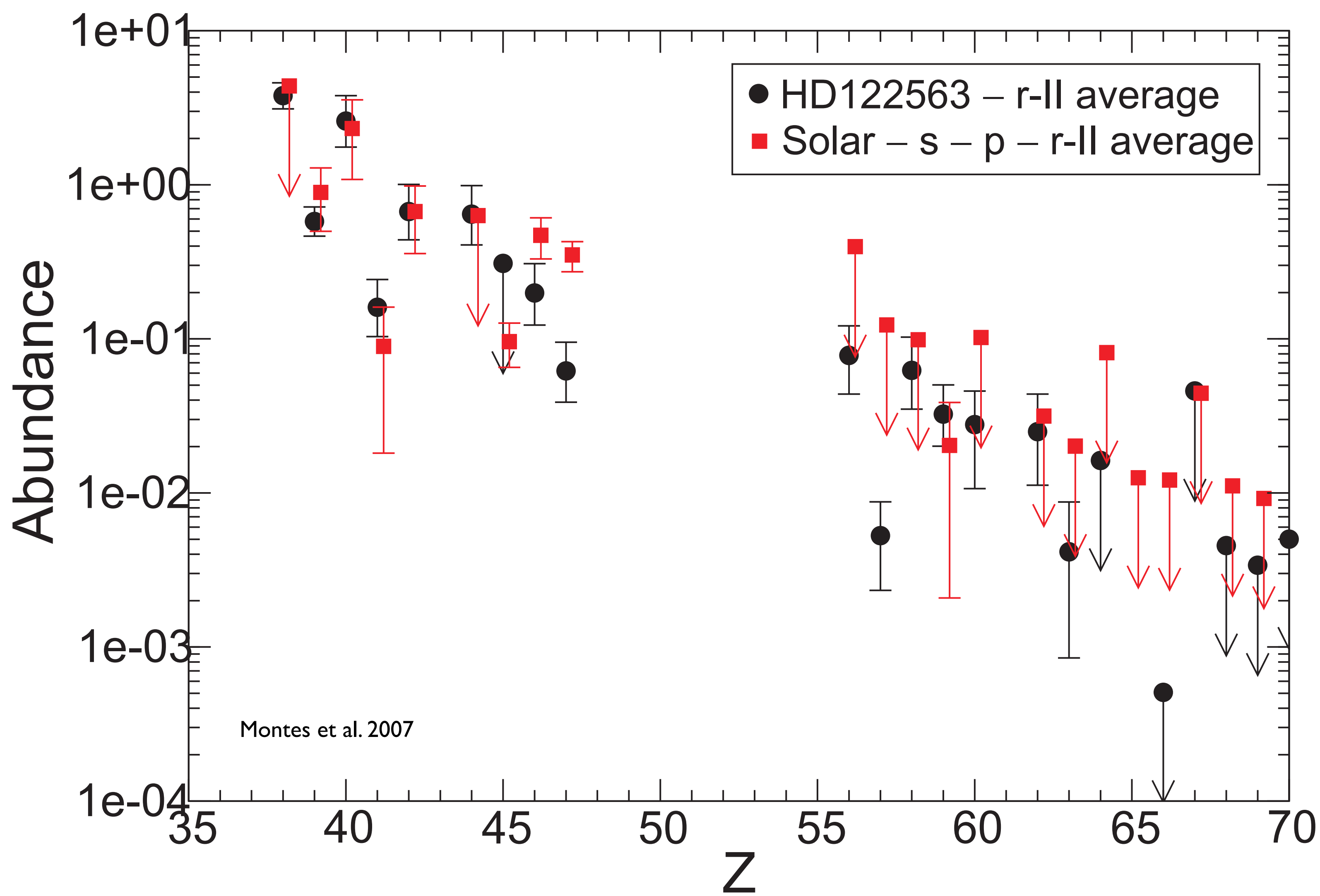

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LEPP in neutrino-driven winds

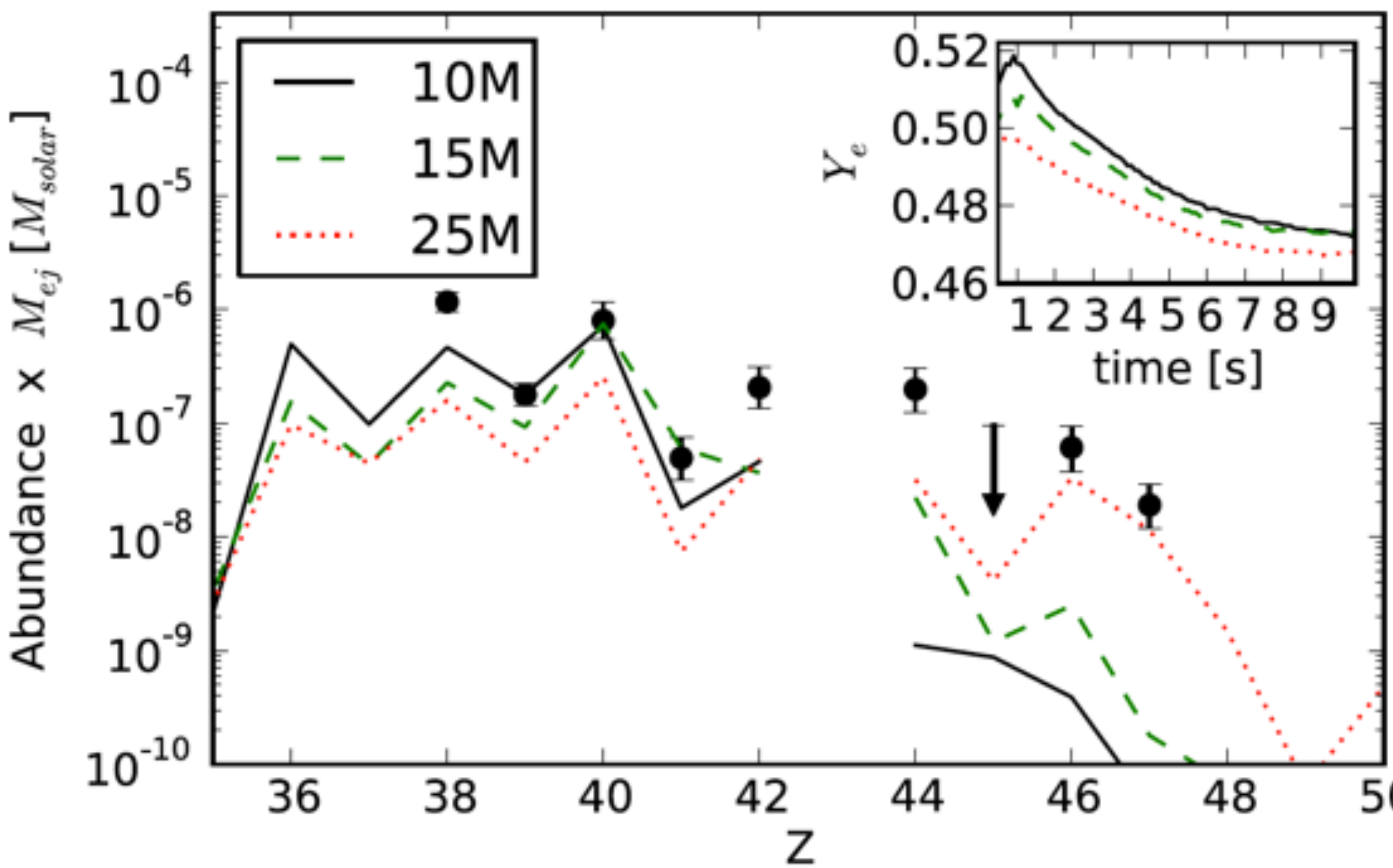
Integrated abundances for different progenitors

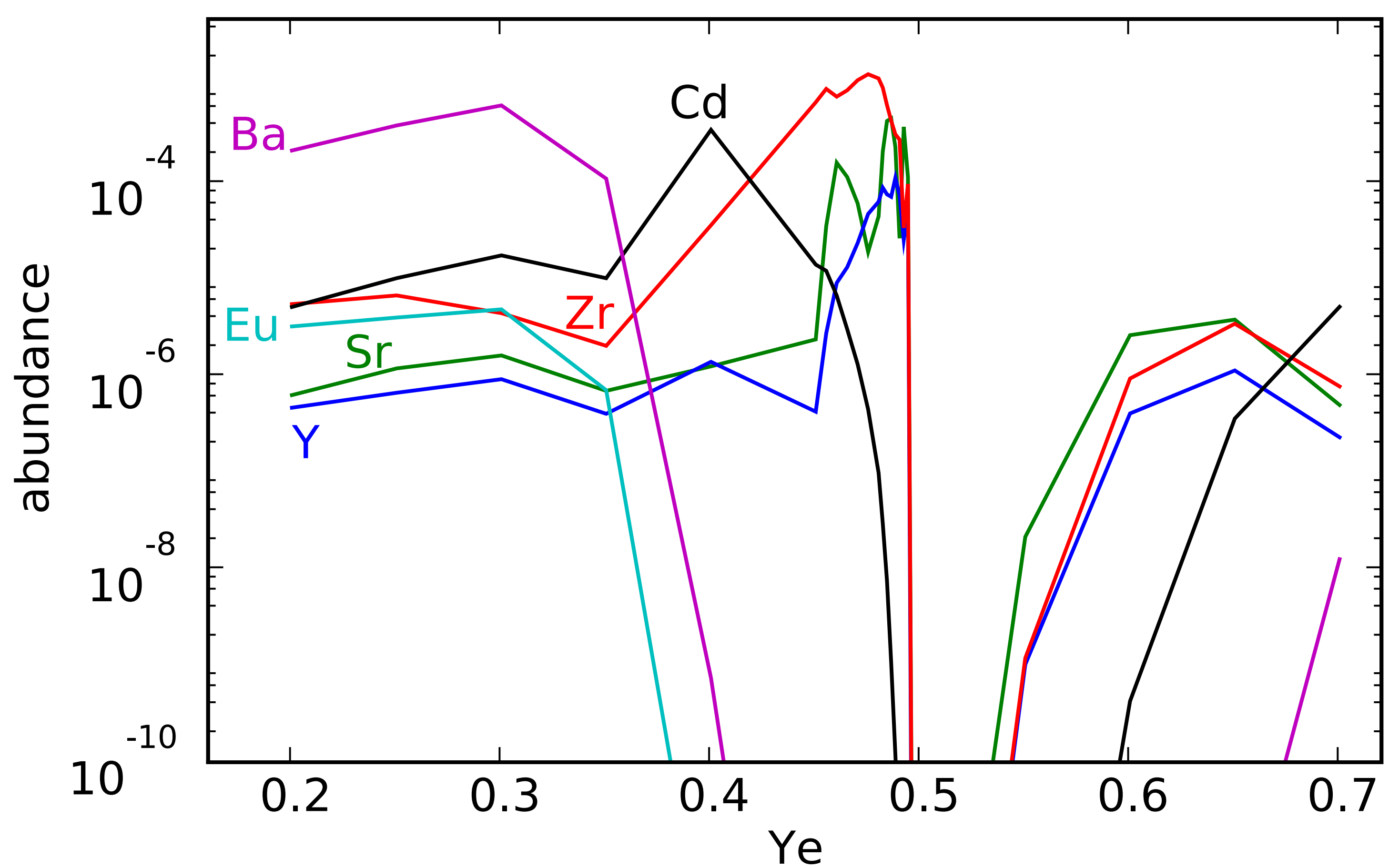
Massive progenitors:
higher entropy ⇒ heavier nuclei

Simplified neutrino transport:
approximated Y_e

Impact of Y_e on wind nucleosynthesis:
- r-process only for extreme low Y_e
- LEPP in neutron- and proton-rich conditions

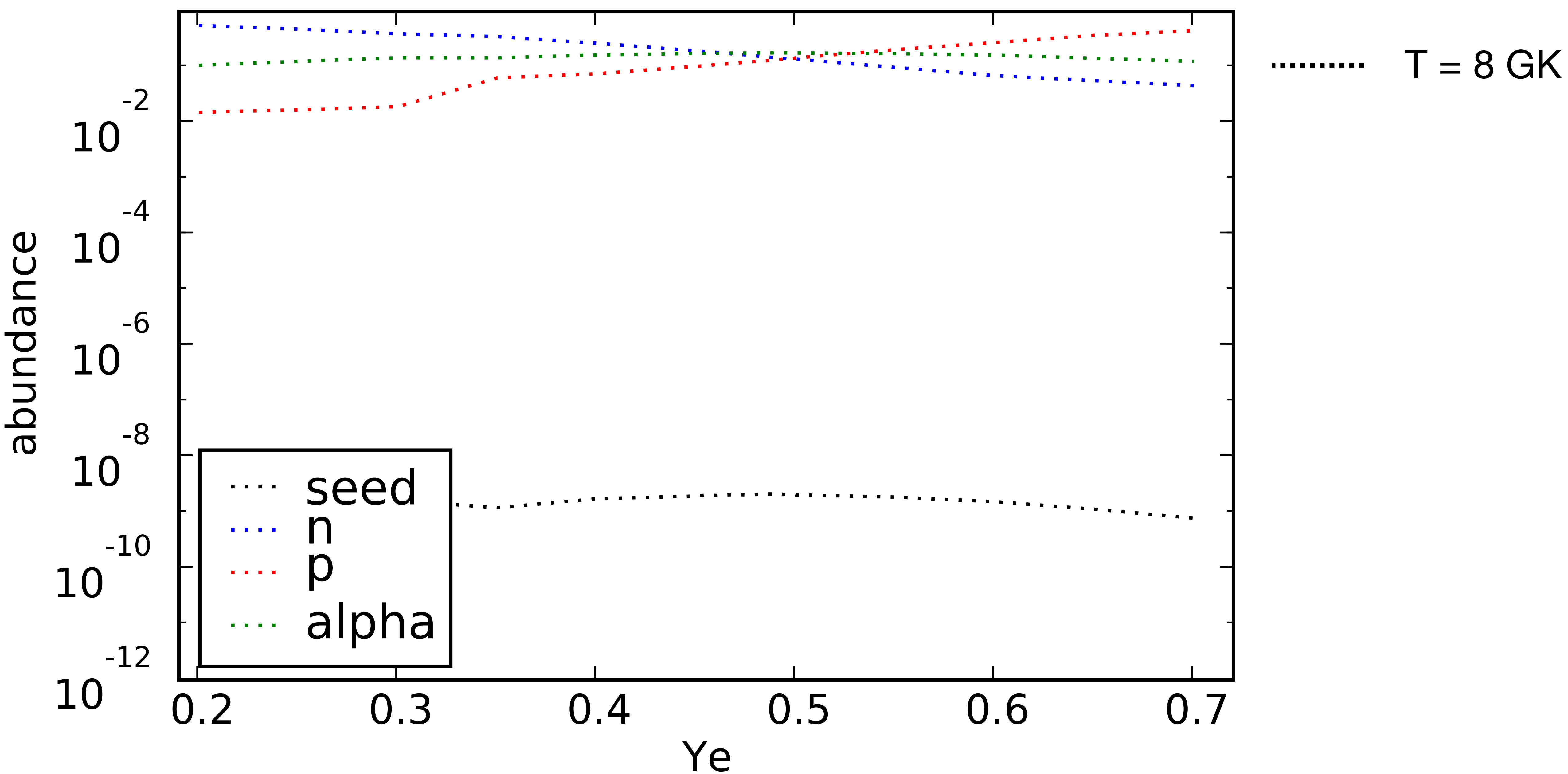
(Arcones & Montes, 2011)





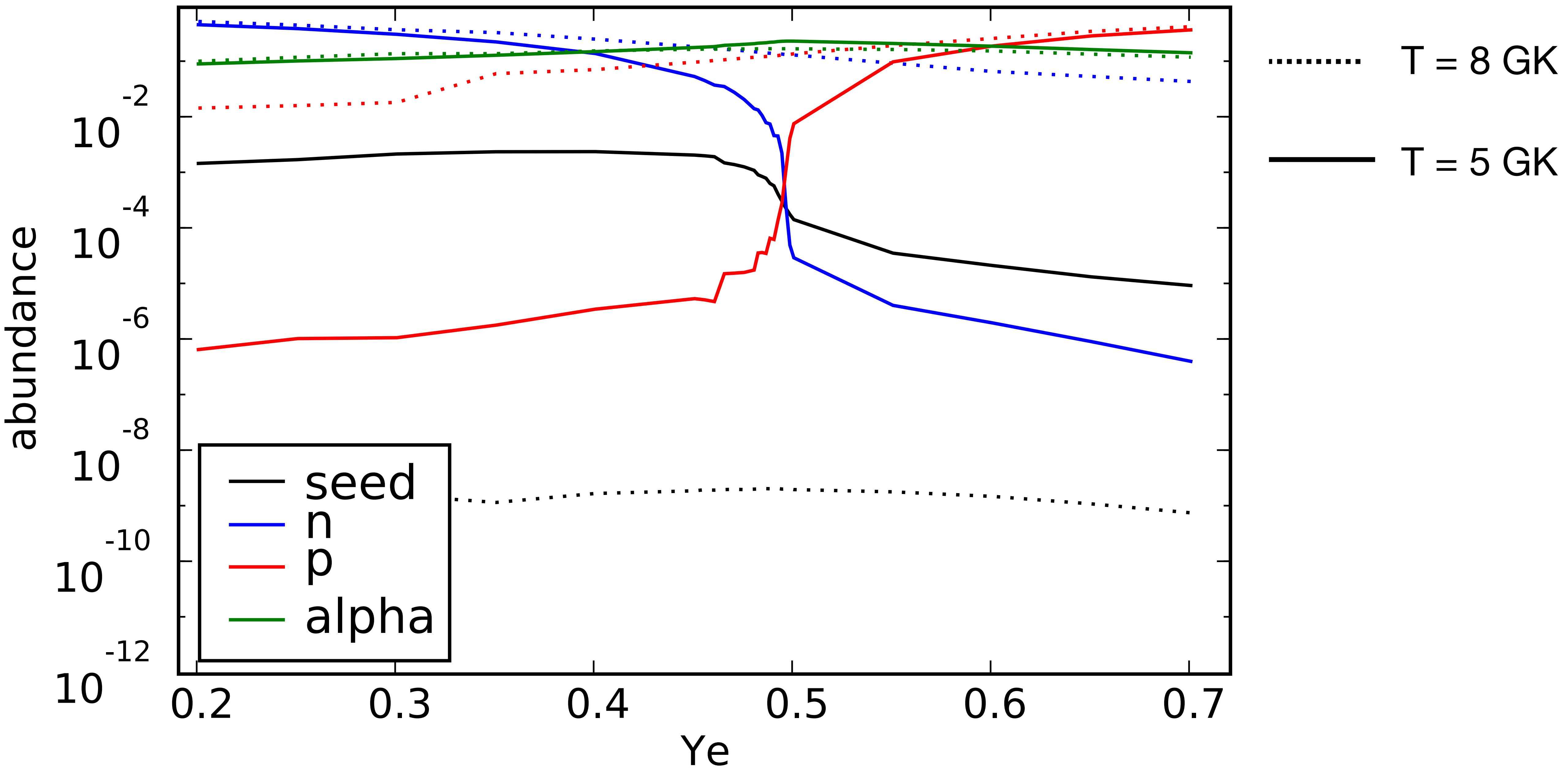
Wind nucleosynthesis and Y_e

Initial composition is given by NSE, at high temperatures only n, p and alphas.



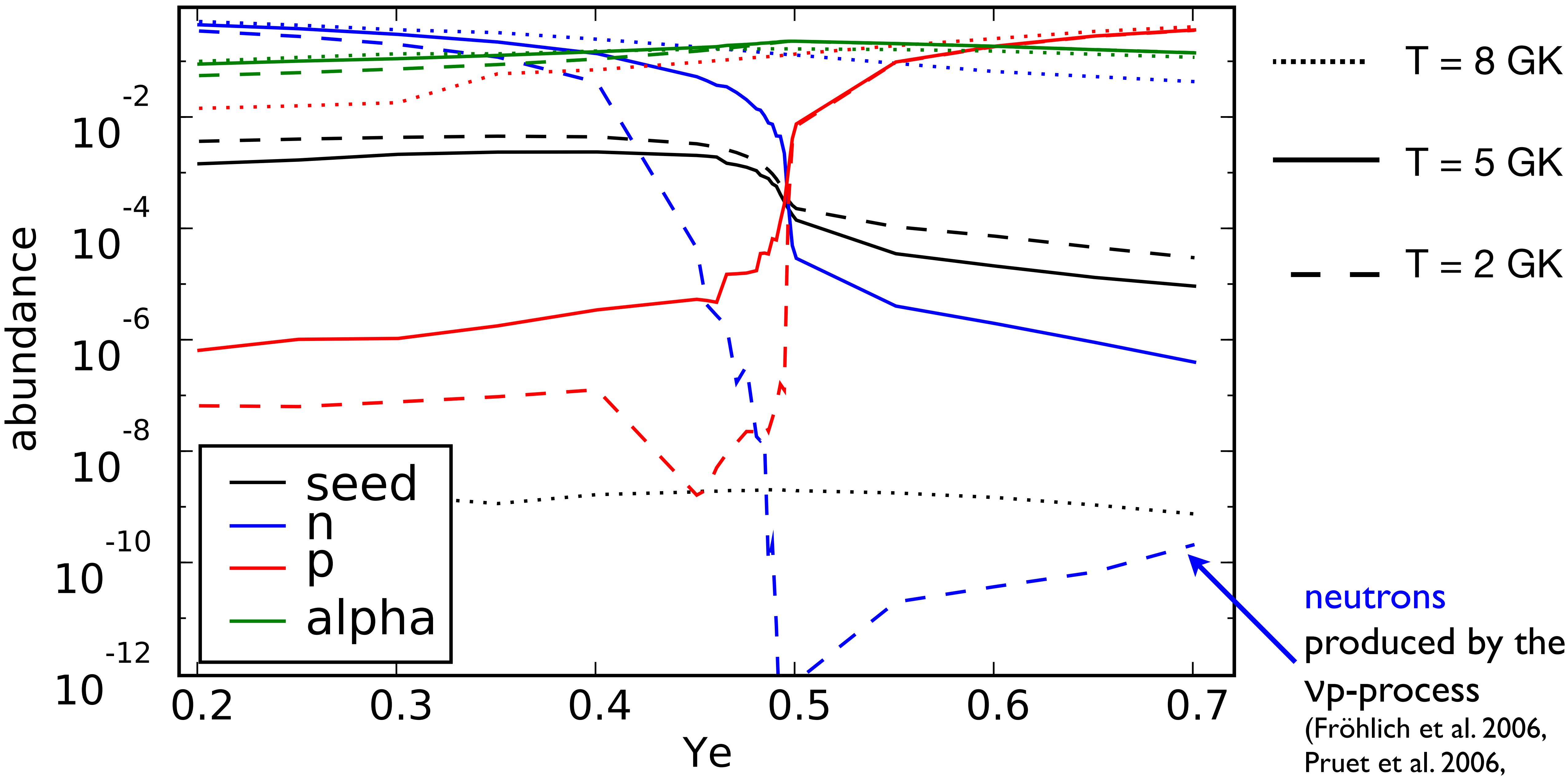
Wind nucleosynthesis and Y_e

Alpha particles recombine forming seed nuclei.



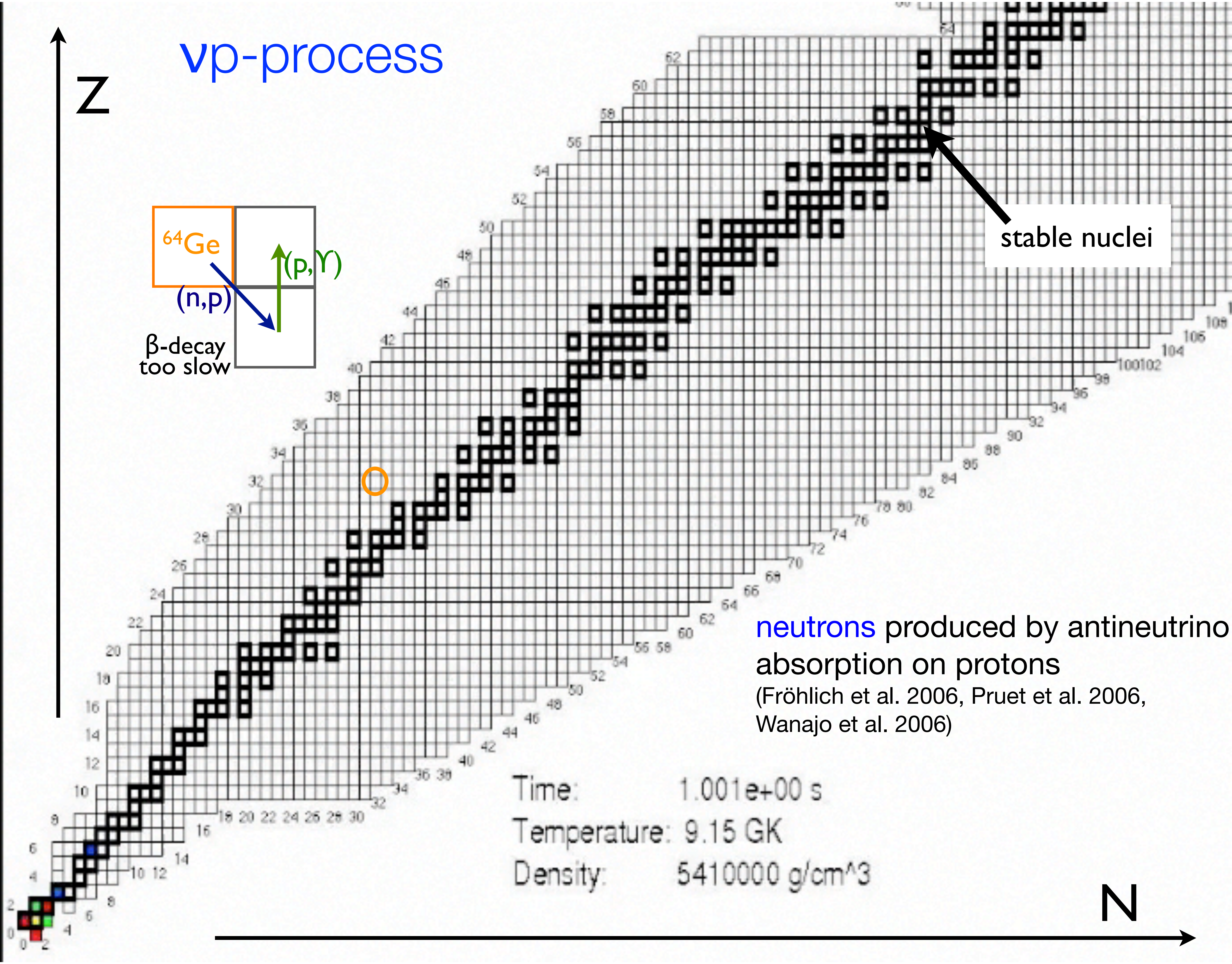
Wind nucleosynthesis and Y_e

At freeze-out neutron- and proton-to-seed ratio determine production of heavy elements.



neutrons produced by the νp-process (Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)

νp-process



neutrons produced by antineutrino absorption on protons

(Fröhlich et al. 2006, Pruet et al. 2006, Wanajo et al. 2006)

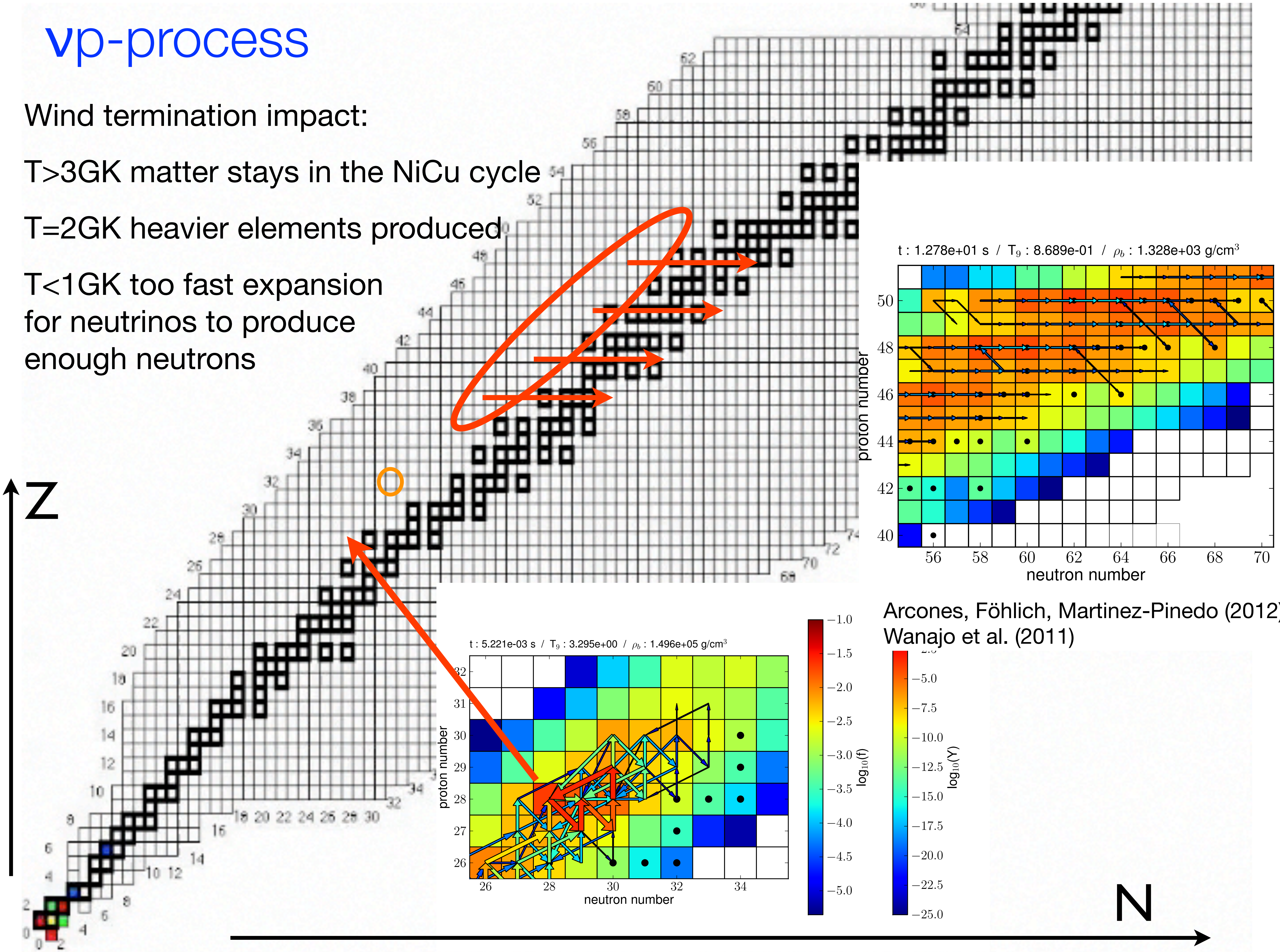
νp-process

Wind termination impact:

T>3GK matter stays in the NiCu cycle

T=2GK heavier elements produced

T<1GK too fast expansion for neutrinos to produce enough neutrons



Arcones, Föhlich, Martinez-Pinedo (2012)
Wanajo et al. (2011)

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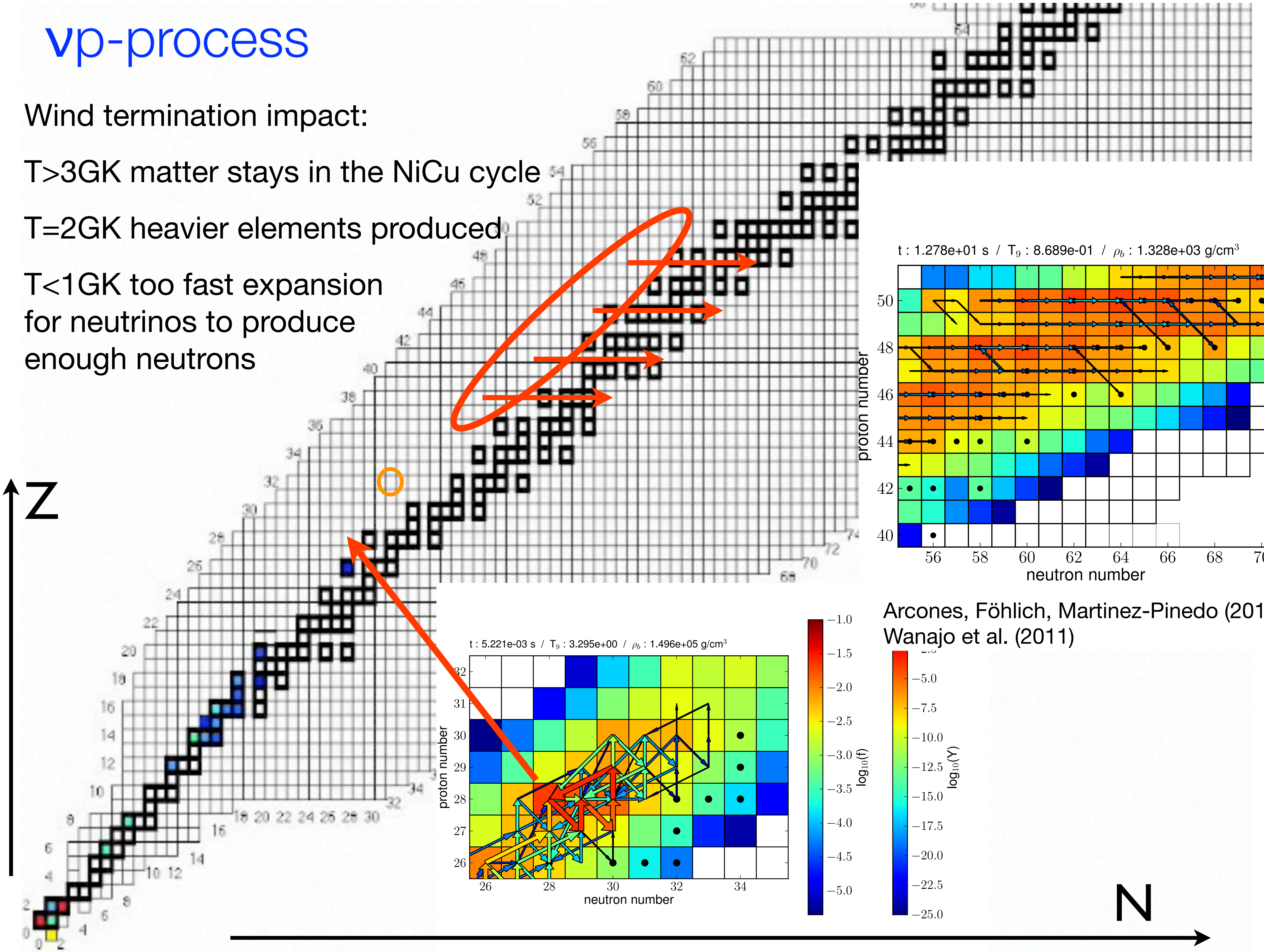

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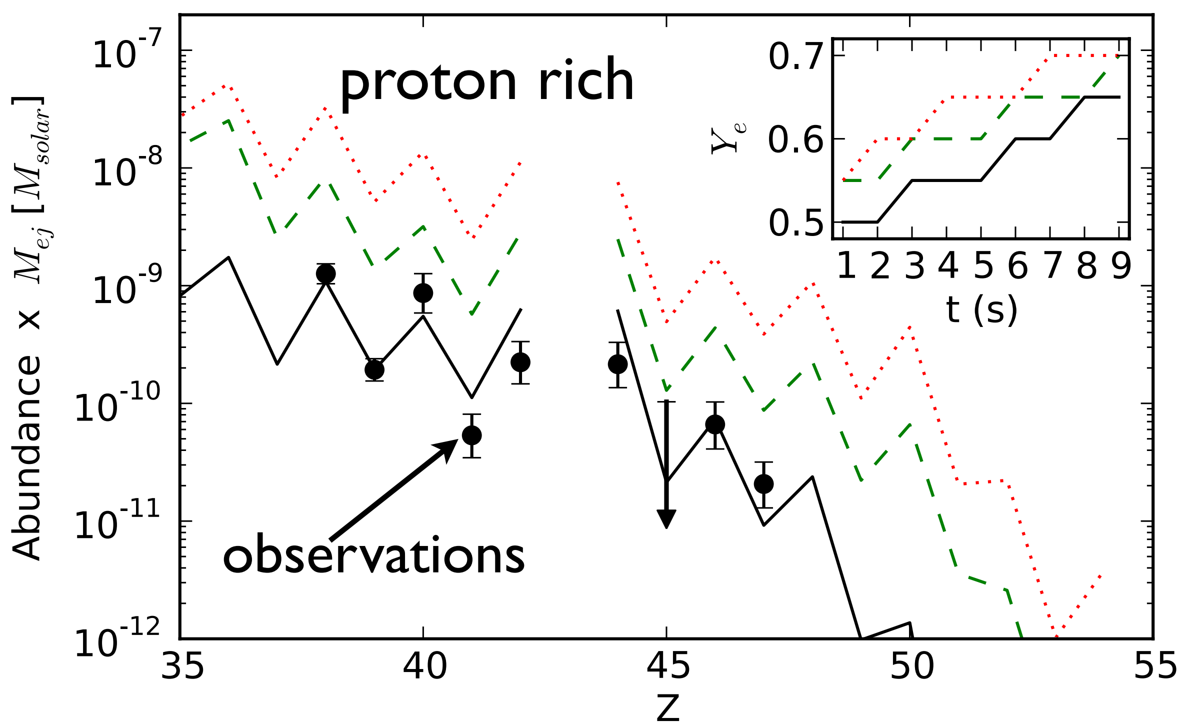
Lighter heavy elements in neutrino-driven winds

Can the LEPP pattern be produced based on neutrino-driven wind simulations?

Which nuclear process is the LEPP? Charged-particle reactions (Qian & Wasserburg 2001)

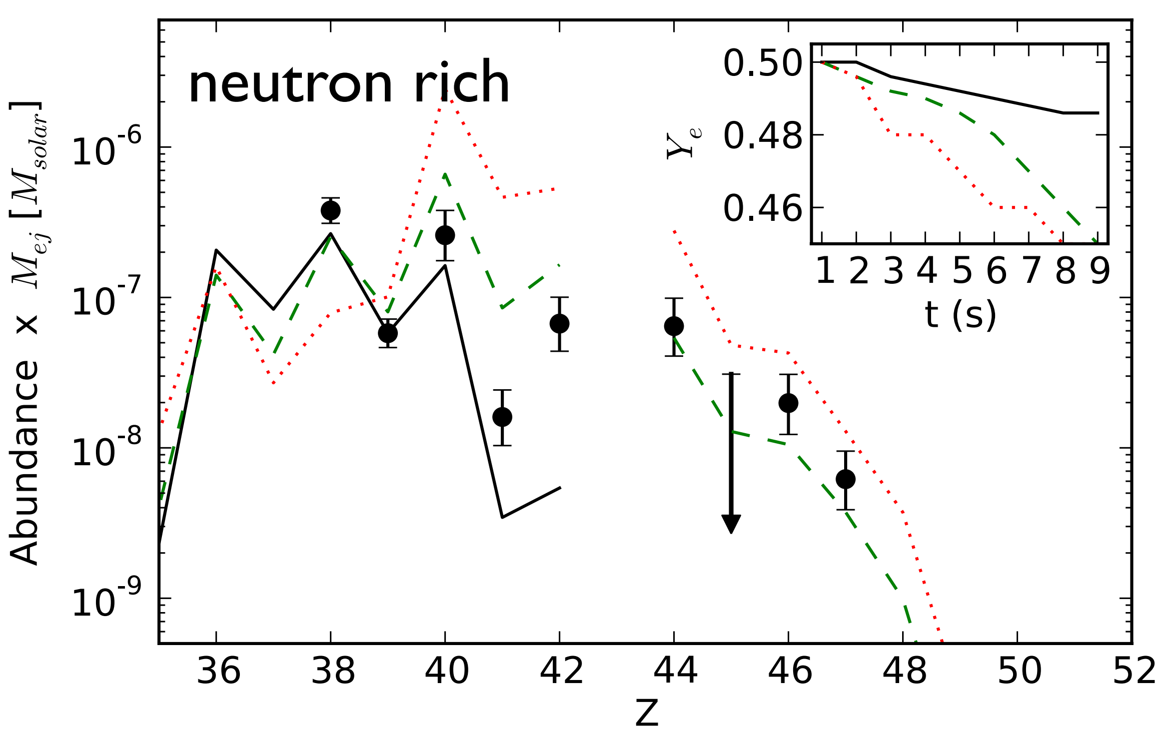
νp-process



Observation pattern can be 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

(Arcones & Montes, 2011)

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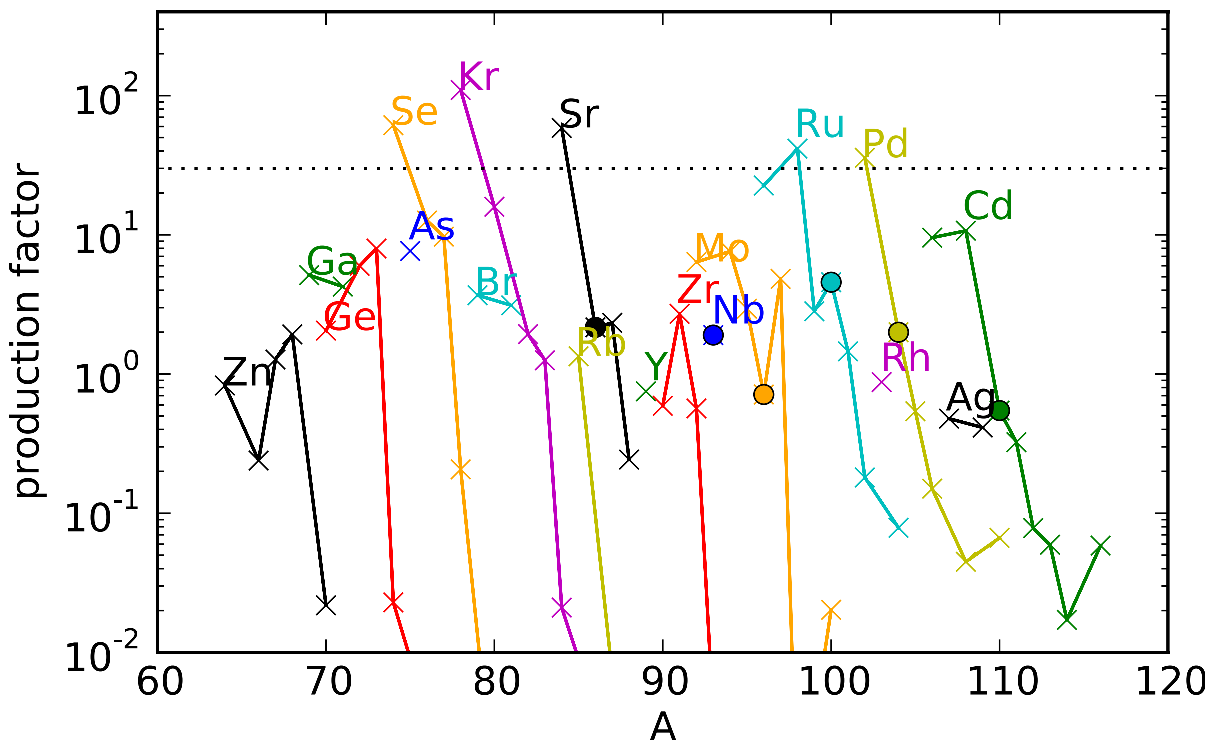

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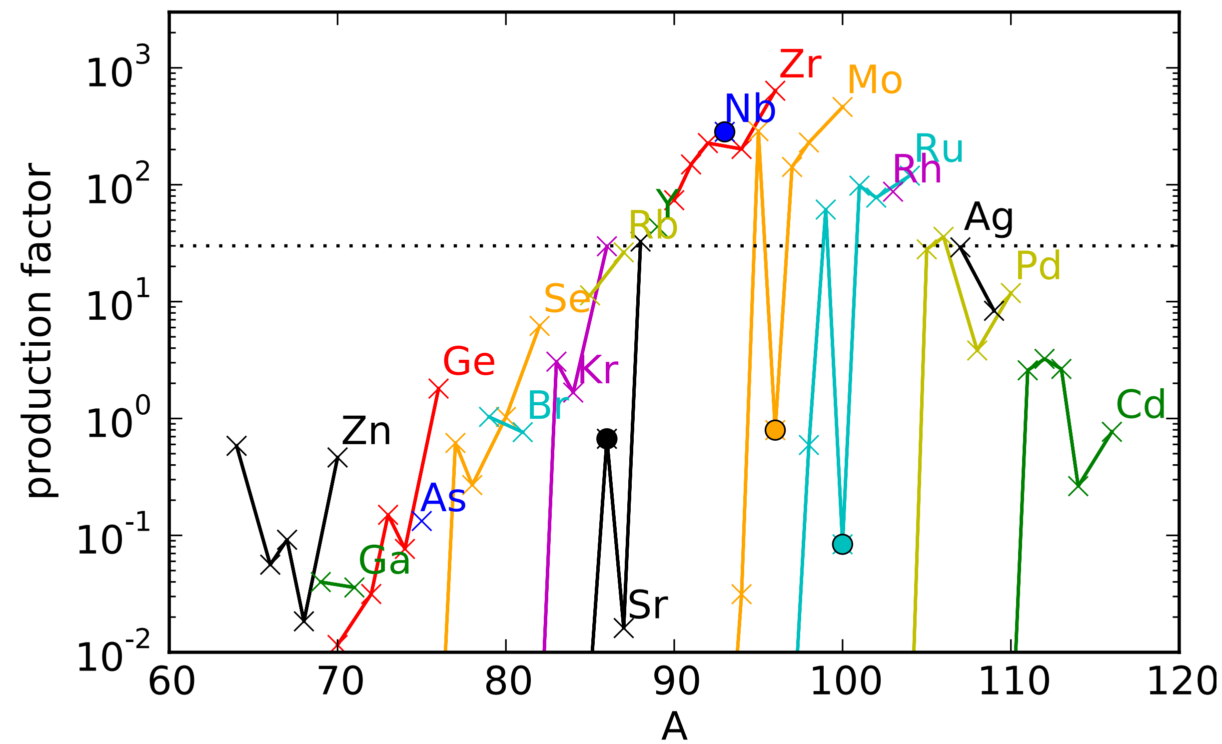

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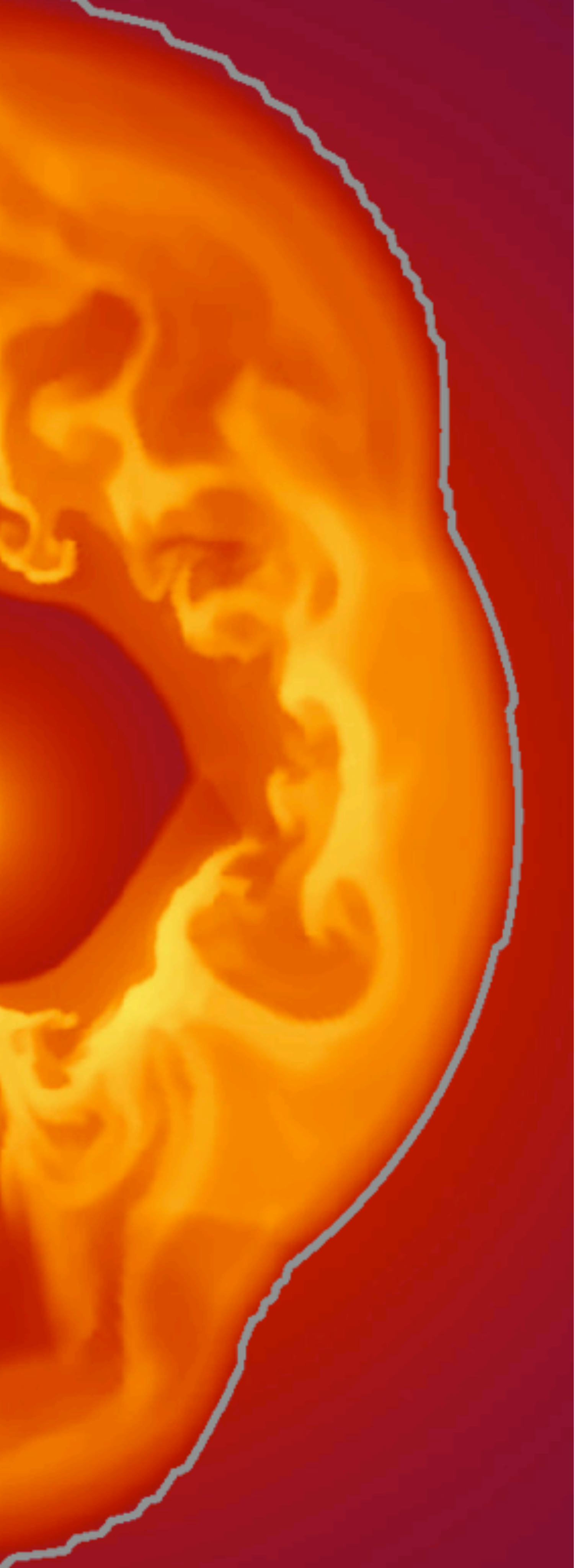
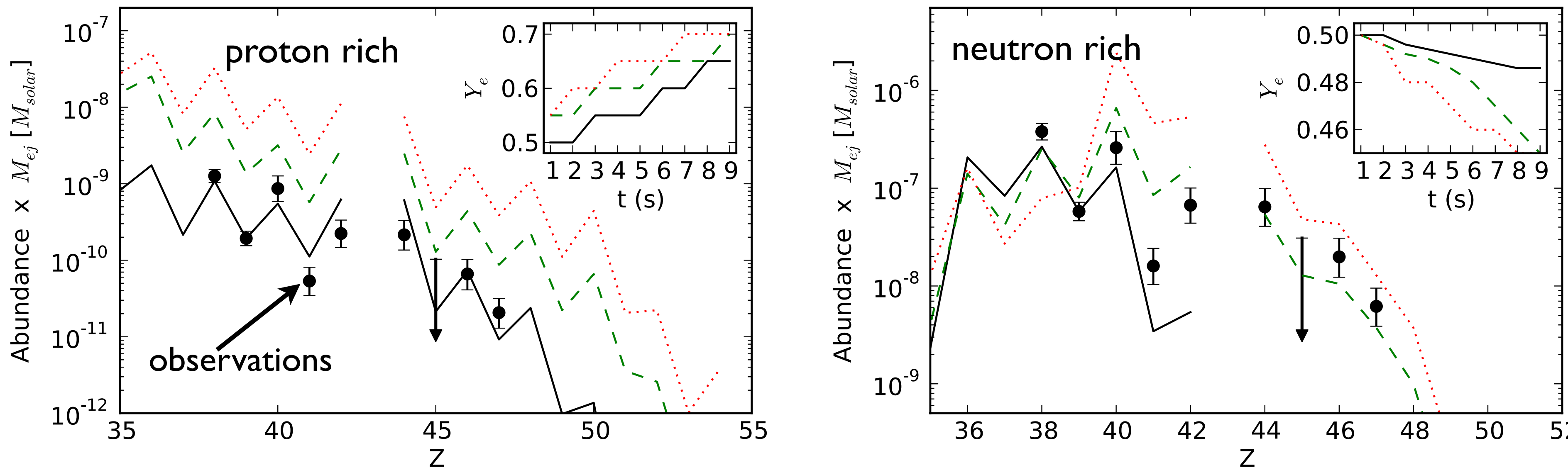


Conclusion

LEPP pattern can be produced based on neutrino-driven wind simulations



LEPP = charged-particle reactions + νp-process
weak r-process

Observations and better constraints on Y_e are required

Other possible LEPP sites: super-AGB stars at low Z (Herwig et al. 2011); fast rotating massive stars (Frischknecht et al. 2011)