Neutrinos and Nucleosynthesis

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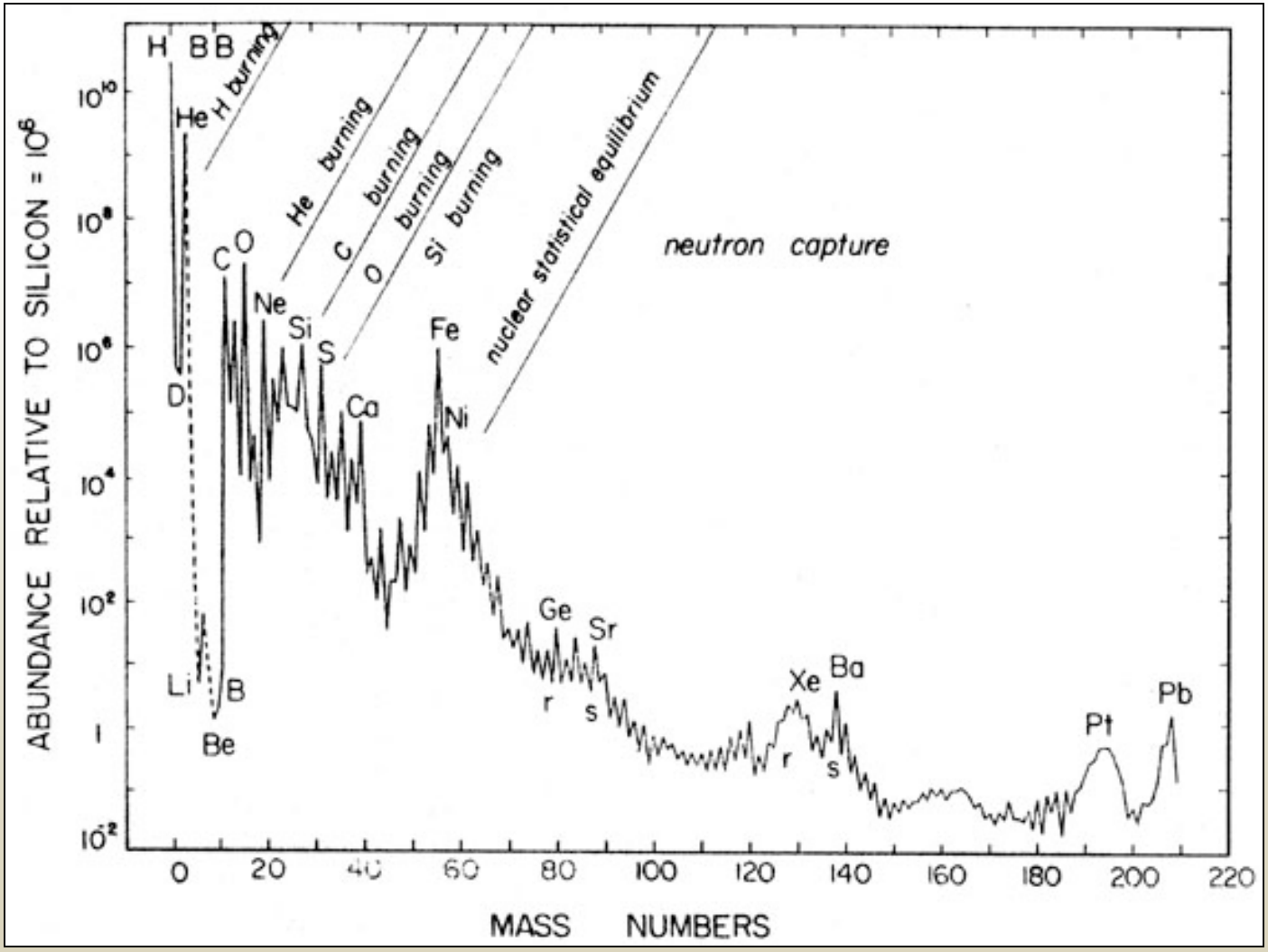
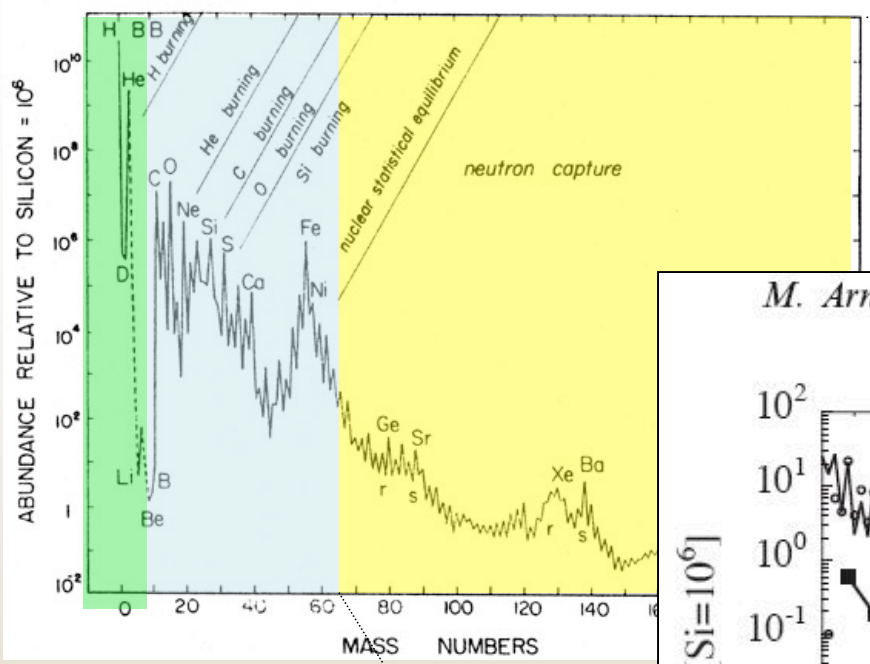
the astrophysical formation of the elements

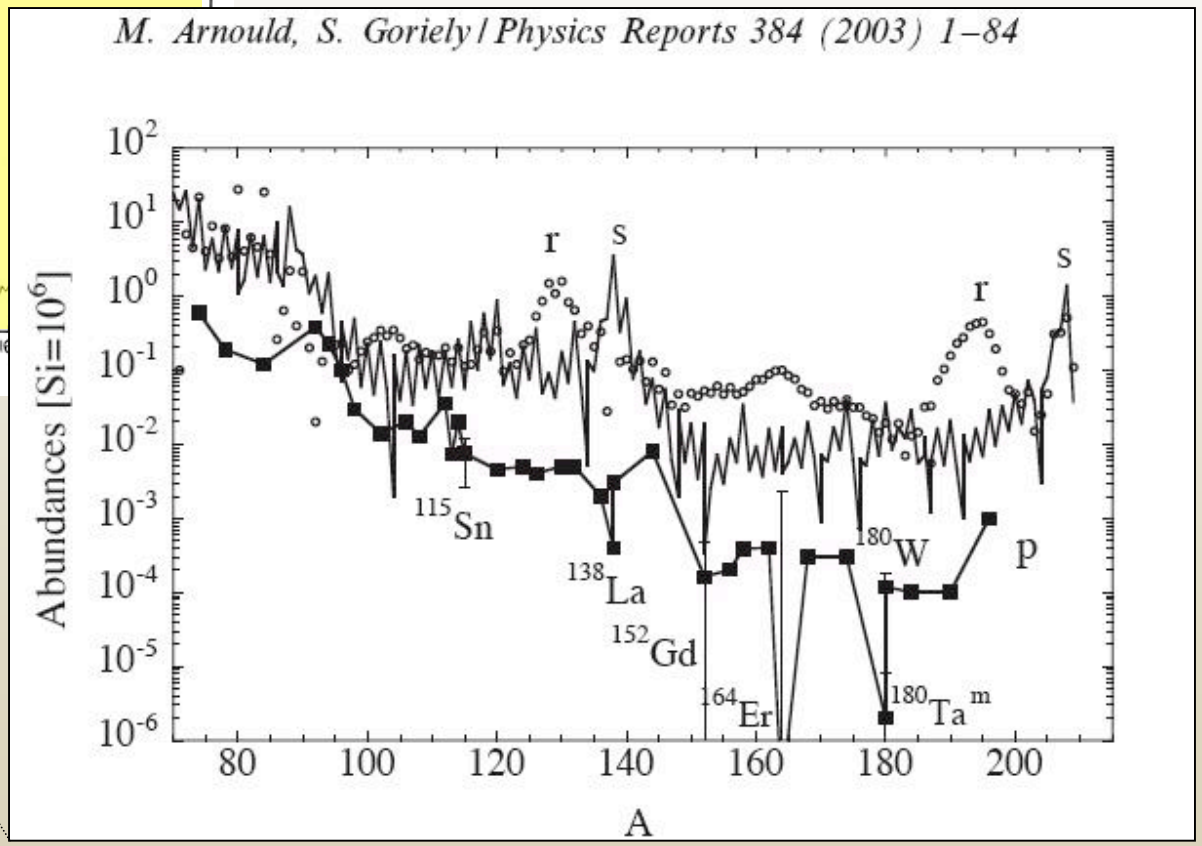


solar system abundances

http://nedwww.ipac.caltech.edu/level5/Pagel/Figures/figure1_4.jpeg

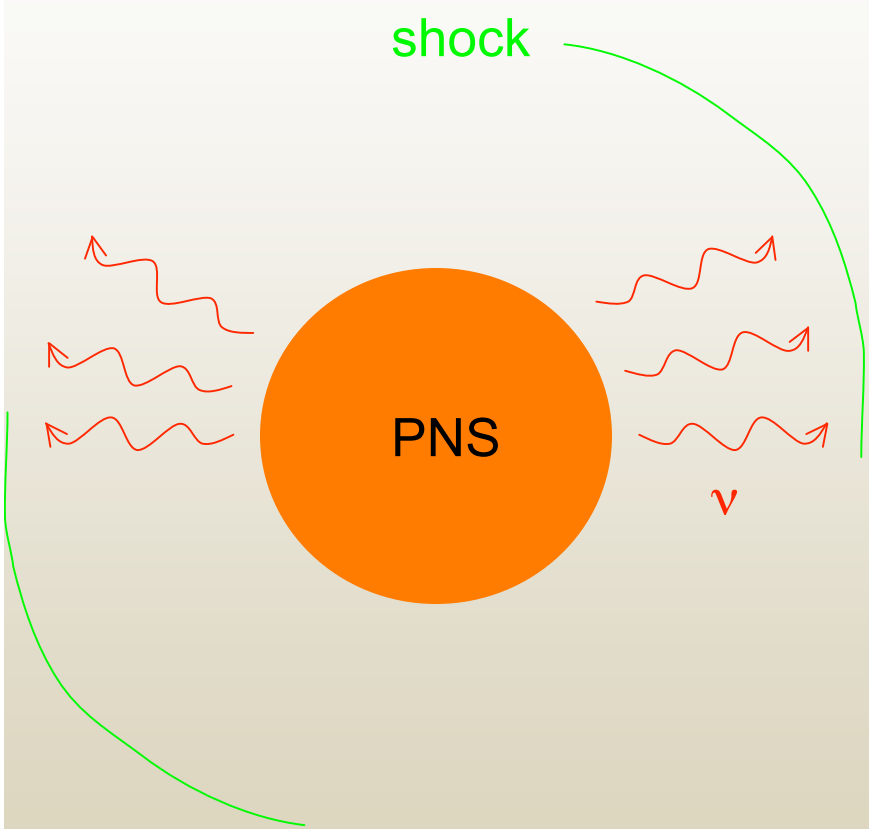
heavy element synthesis



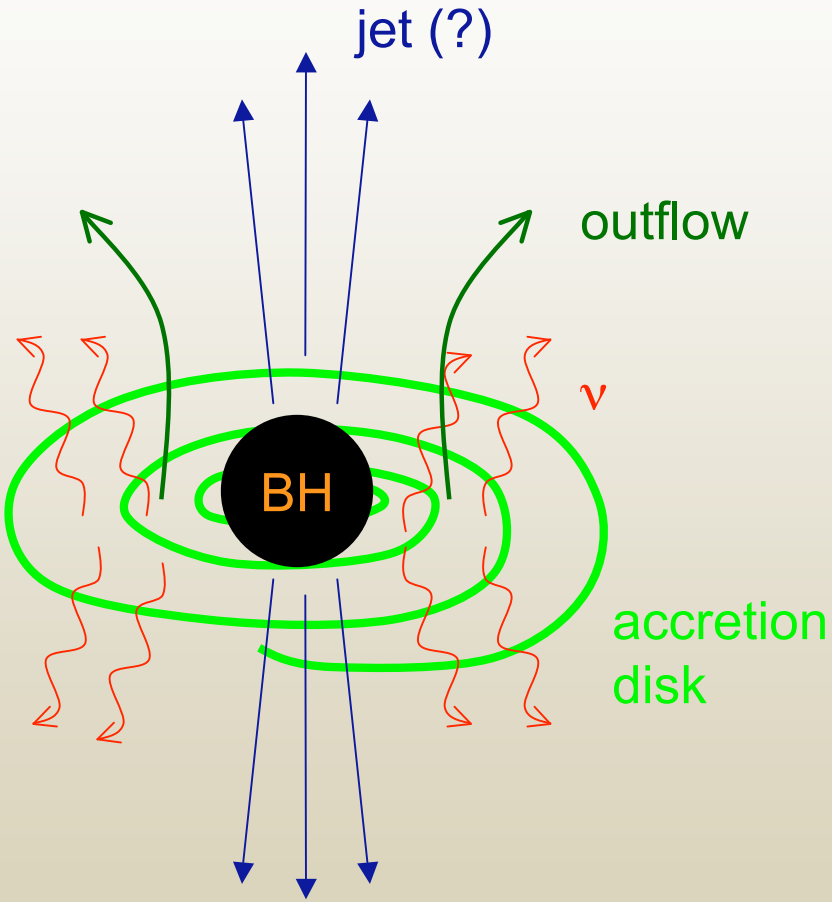


ν-rich environments for heavy element synthesis

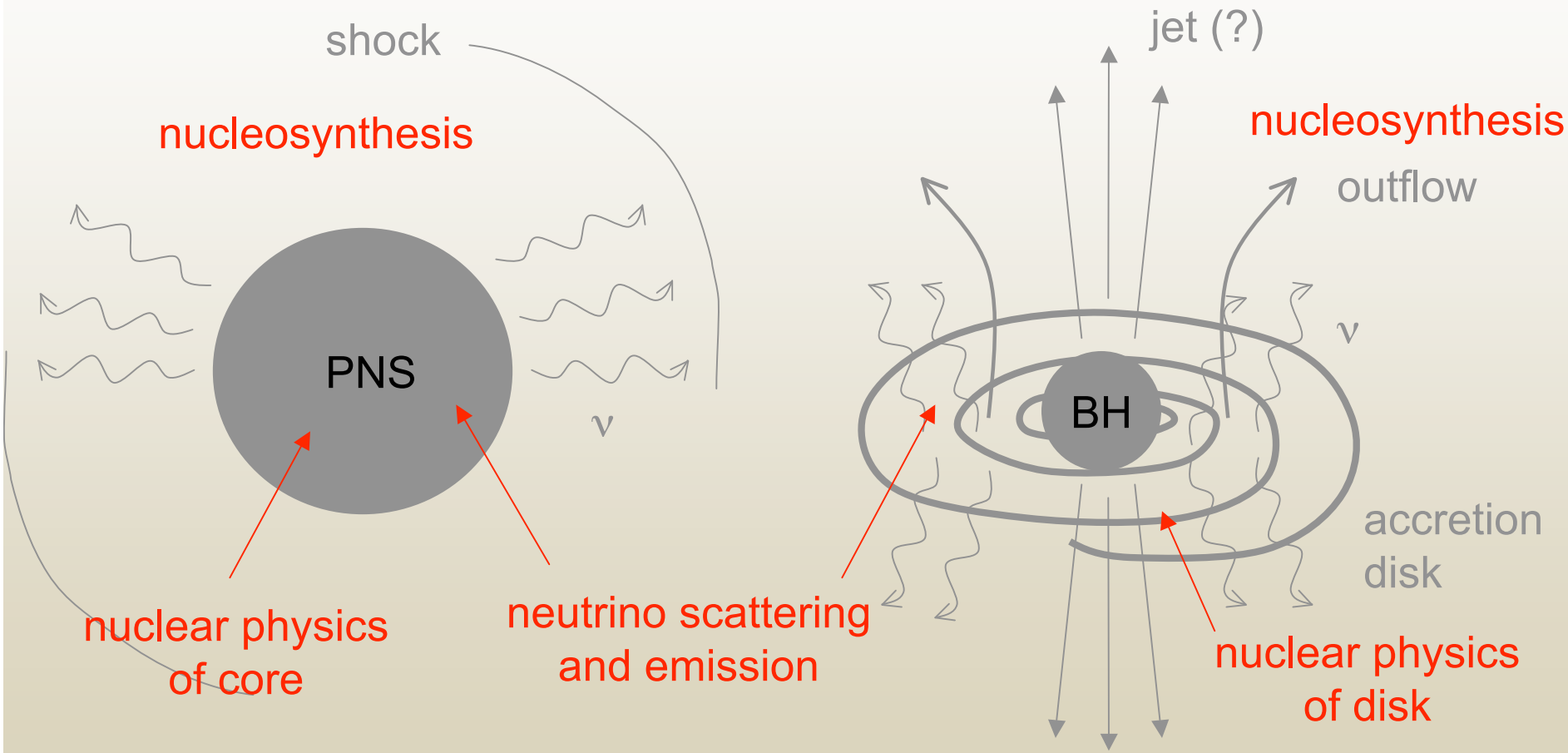
core-collapse supernova



black hole accretion disk



ν-rich environments for heavy element synthesis



stages of heavy element synthesis

(1) free neutrons and protons

$$p + e^- \leftrightarrow n + \nu_e$$

$$n + e^+ \leftrightarrow p + \bar{\nu}_e$$

(2) assembly of alpha particles

$$p,\ n \rightarrow \alpha\text{'s} + \text{excess } p \text{ or } n$$

(3) assembly of seed nuclei

$$\alpha\text{'s} + \text{excess } p \text{ or } n \rightarrow \text{iron peak nuclei} + \text{remaining } p \text{ or } n$$

(4) free nucleon capture on seeds

$$\text{iron peak nuclei} + \text{remaining } p \text{ or } n \rightarrow \text{heavy nuclei}$$

(1) free neutrons and protons

$p + e^- \leftrightarrow n + \nu_e$

$n + e^+ \leftrightarrow p + \bar{\nu}_e$

ν can set the neutron to proton ratio, n/p

n/p determines the subsequent nucleosynthesis

(2) assembly of alpha particles

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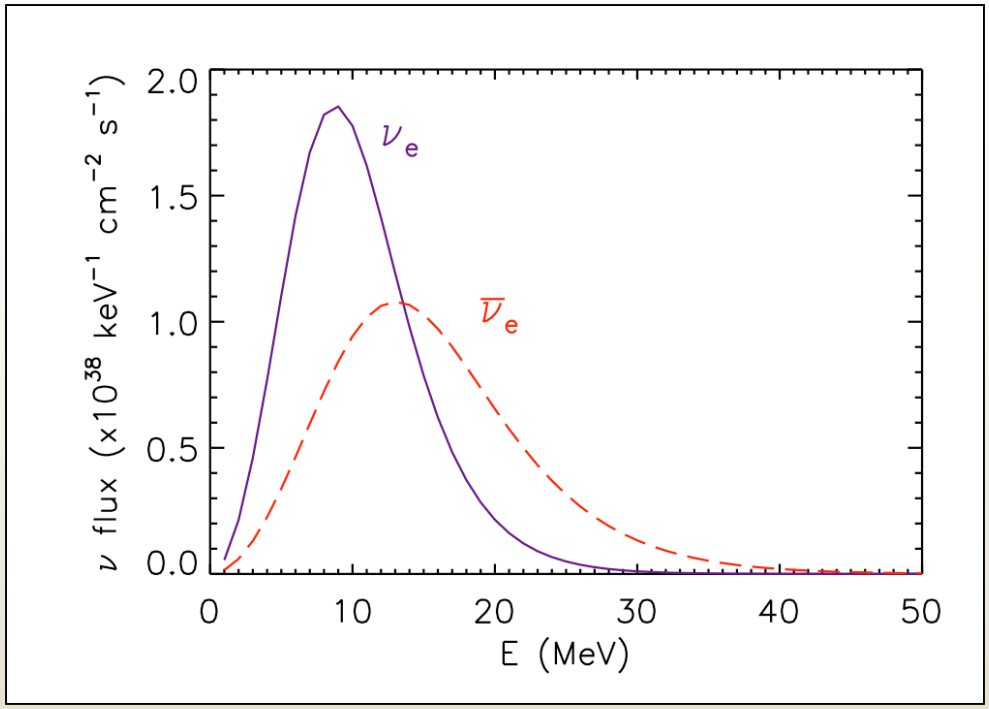
ν can continue to convert the excess p or n

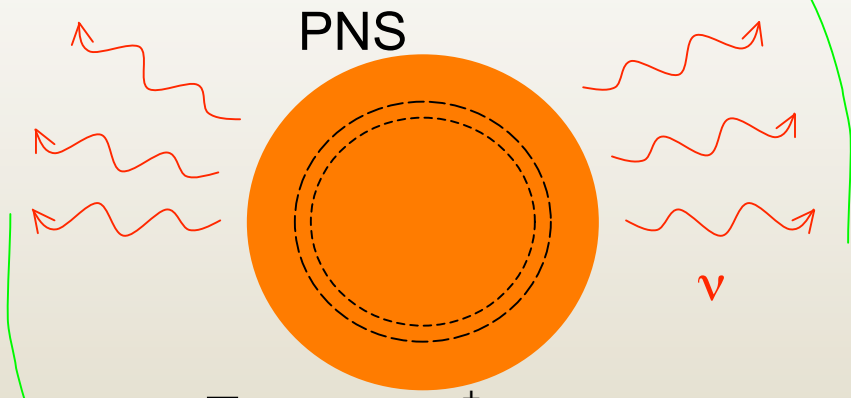
this alters the free nucleons available for capture onto seeds
e.g., 'alpha effect'

the supernova neutrino-driven wind



late-time ν fluxes from Keil et al (2003)

$$\langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

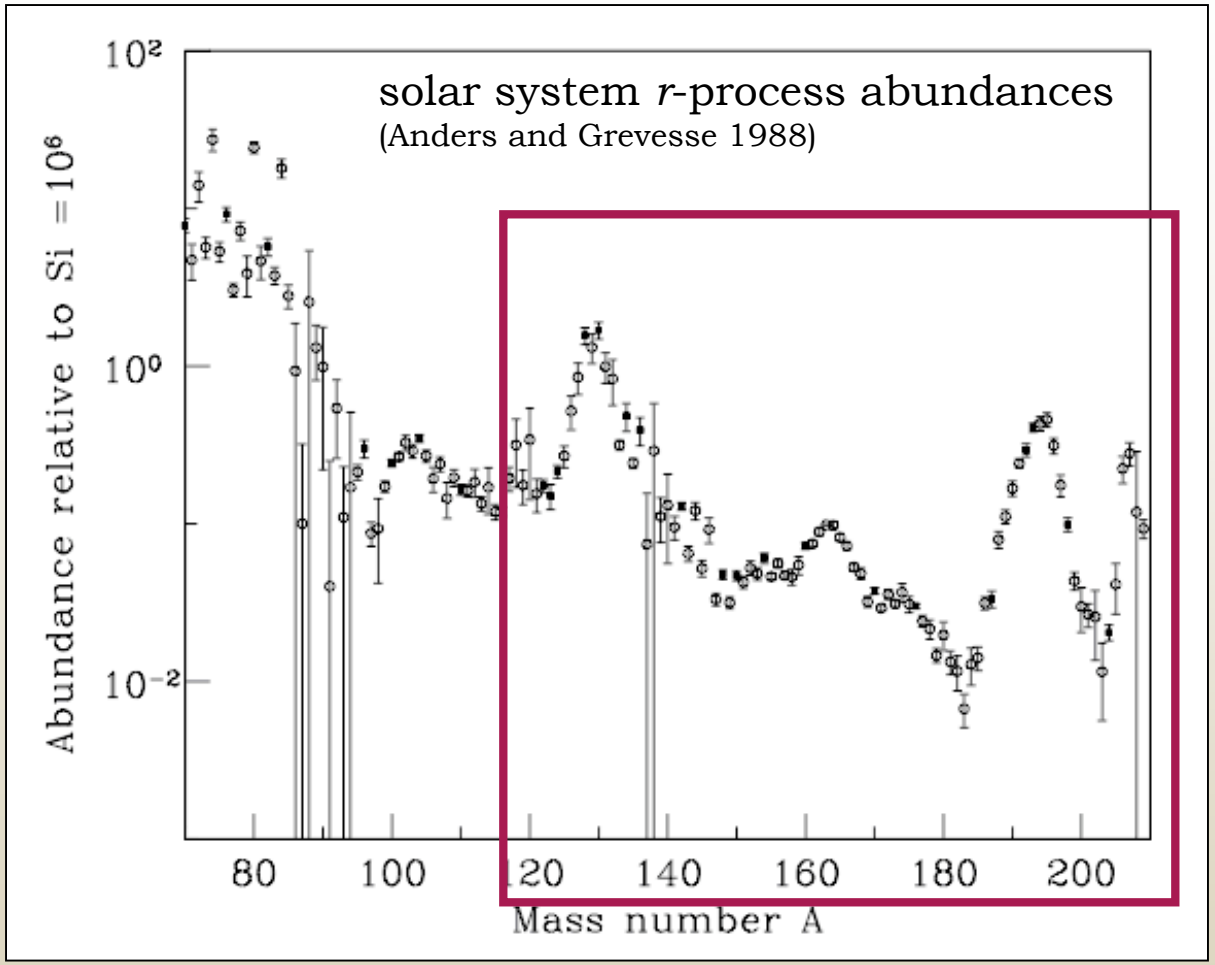


$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n + \nu_e \leftrightarrow p + e^-$$

$p, n \rightarrow \alpha, n \rightarrow$ seed nuclei + $n \rightarrow r$ process

the supernova neutrino-driven wind



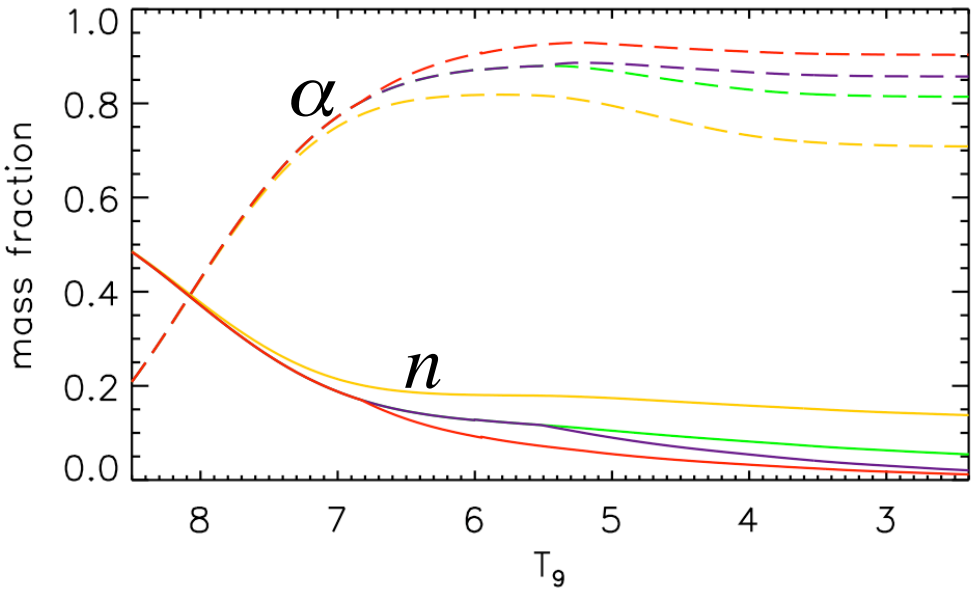
Hydrodynamic conditions required to build the heaviest nuclei are difficult to achieve, in part due to the neutrino-induced alpha effect.

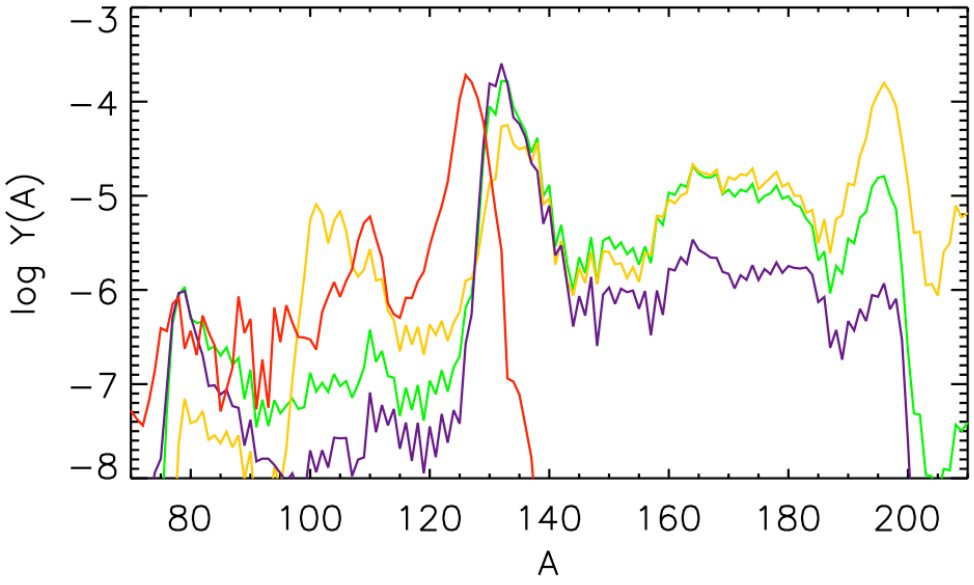
In the standard SNe energy heirarchy, neutrino oscillations only enhance the role of neutrinos.

$$\langle E_{\nu_x} \rangle \geq \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

$p, n \rightarrow \alpha, n \rightarrow$ seed nuclei + $n \rightarrow r$ process

a toy model





Duan, Friedland, McLaughlin, & Surman, in preparation (2010)

No ν for $T < 9\times10^9$ K

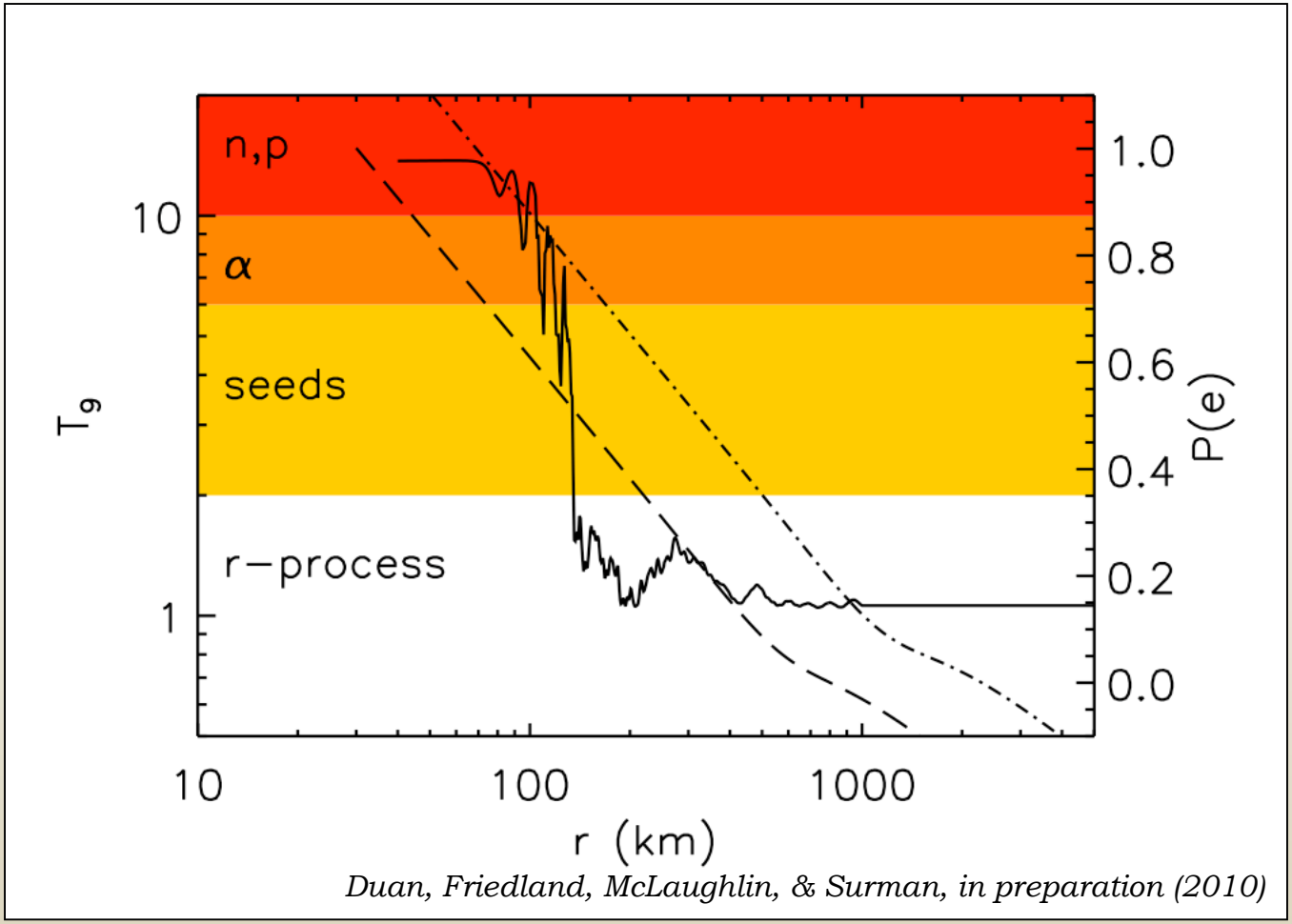
No oscillations

Test swap at seed assembly

Test swap at alpha assembly

$f_{\nu_e}(E)$ replaced by $f_{\nu_\mu}(E)$

where does each nucleosynthesis stage take place?



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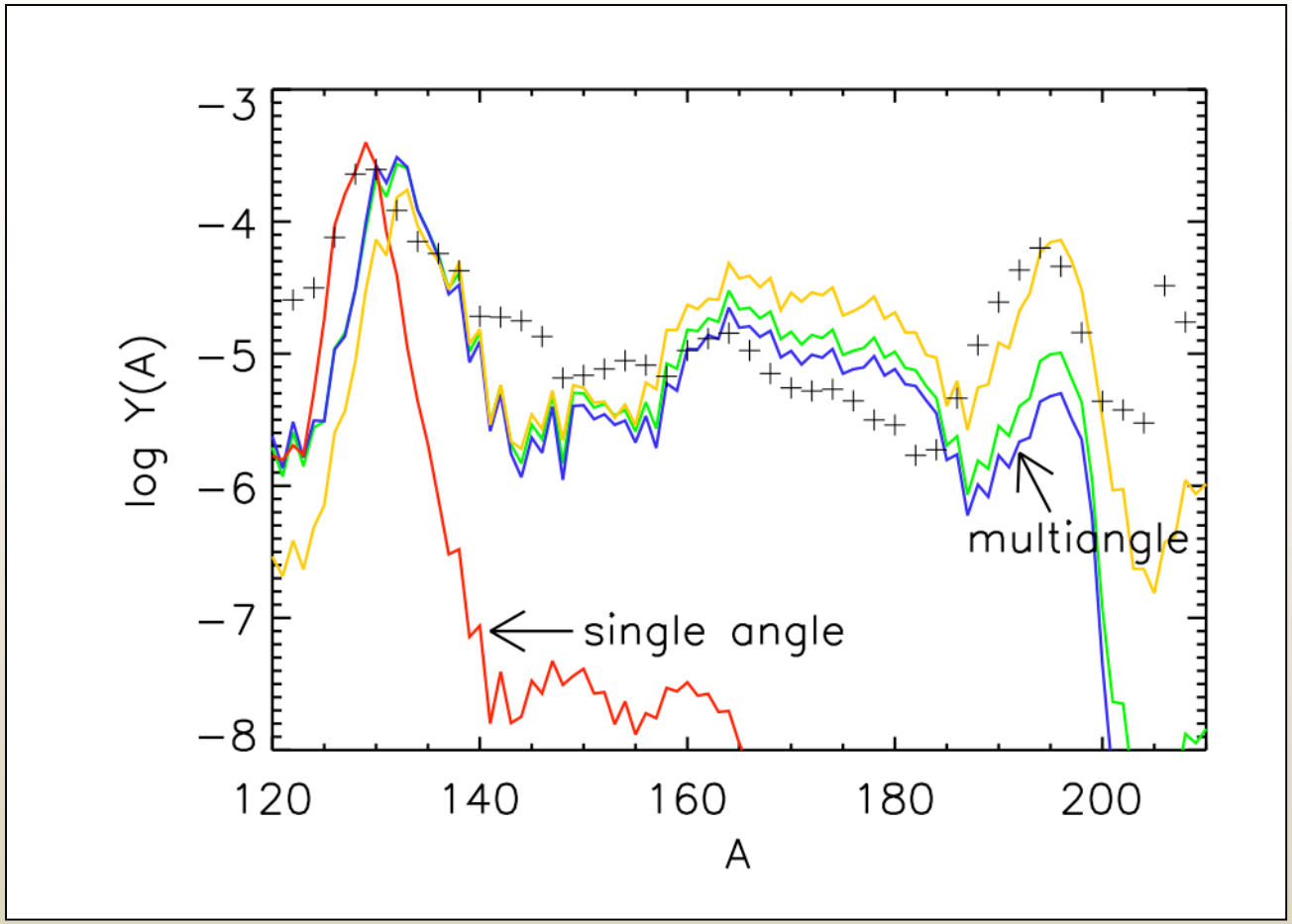
ν oscillation calculation by Huaiyu Duan and Alex Friedland
(as in hep-ph/10062359)

a full neutrino oscillation + *r*-process calculation



No ν for $T_9 < 9$

No oscillations

Multiangle ν oscillation calculation

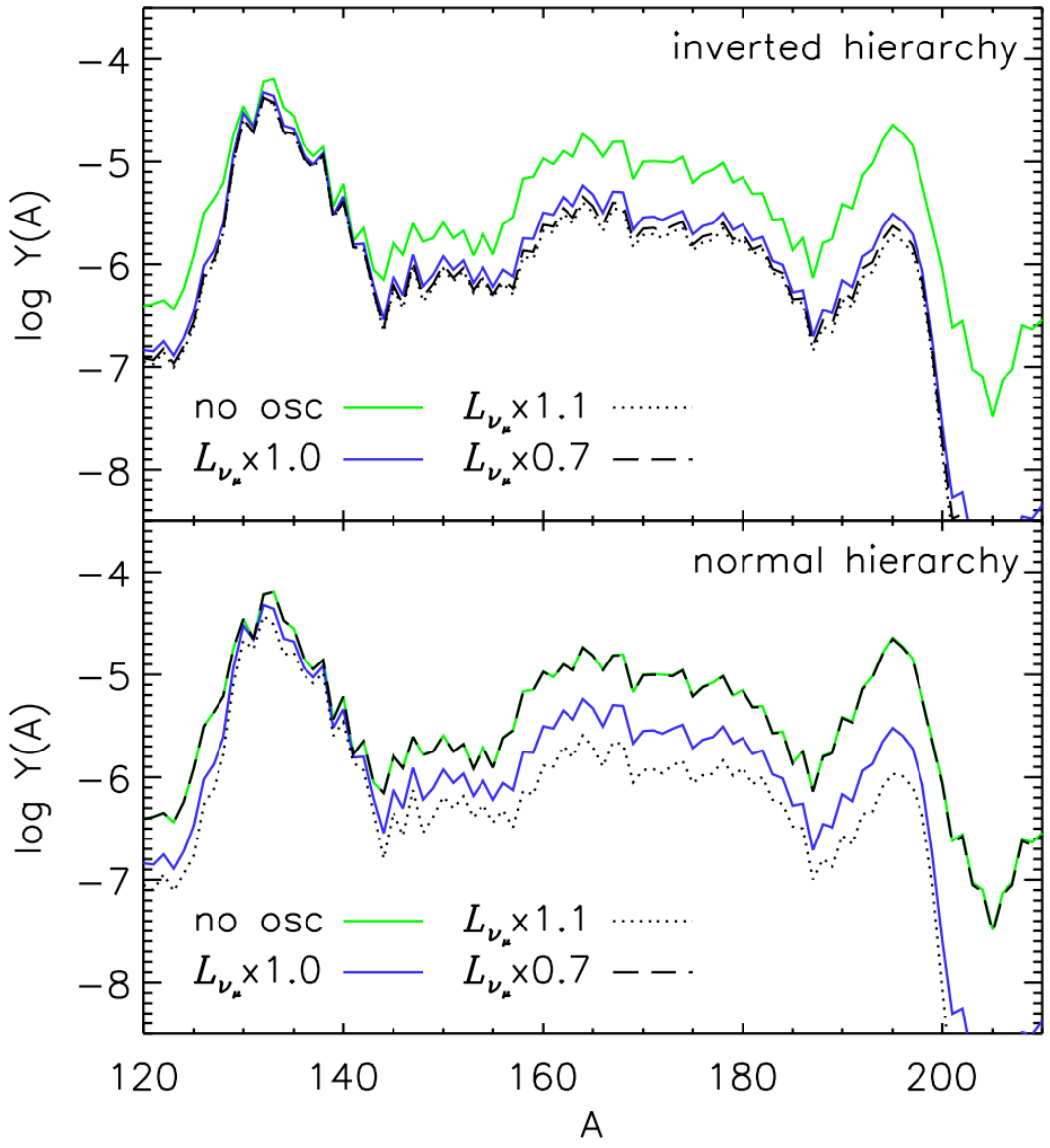
Single angle ν oscillation calculation

$s/k = 200$

$\tau = 18$ ms

Duan, Friedland, McLaughlin, & Surman, in preparation (2010)

mass hierarchy



Duan, Friedland, McLaughlin, & Surman, in preparation (2010)

$s/k = 300$

$\tau = 35$ ms

summary

Neutrino interactions on nucleons play an important role in heavy element synthesis in extreme environments

Supernova nucleosynthesis calculations cannot (safely) ignore neutrino oscillations

⇒ act only increase the importance of neutrino interactions

⇒ the influence is the greatest at the earliest stages of nucleosynthesis

⇒ correctly predicting the radius at which the flavor transformations occur is of key importance for the nucleosynthesis - this requires a multiangle ν oscillation calculation