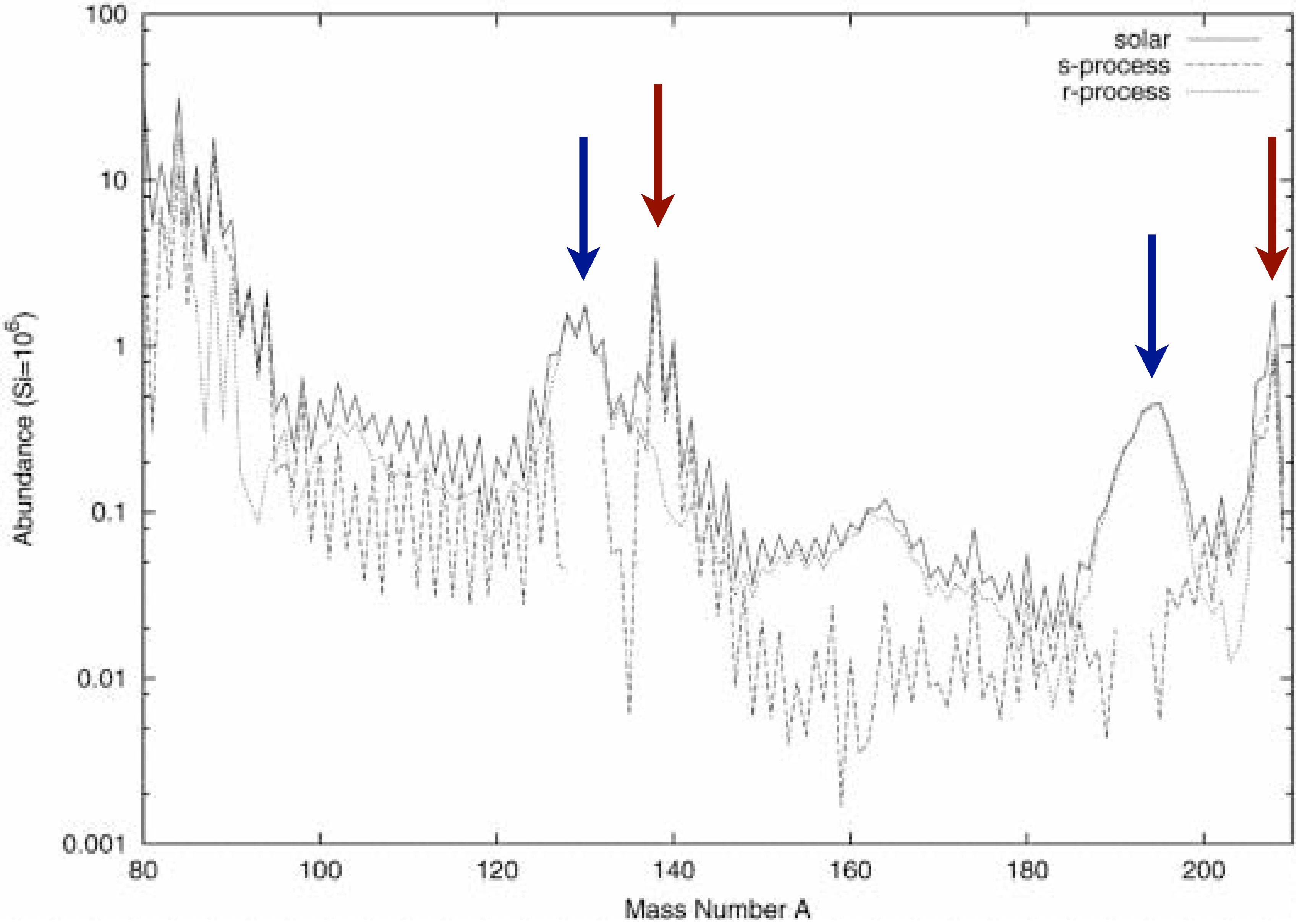
A Cold , Early r-process under not-so-extreme conditions

- What we have learned about the r-process
- The puzzle of its site
- A possible two-site solution, dependent on new neutrino physics

with Projjwal Banerjee and Yong-Zhong Qian

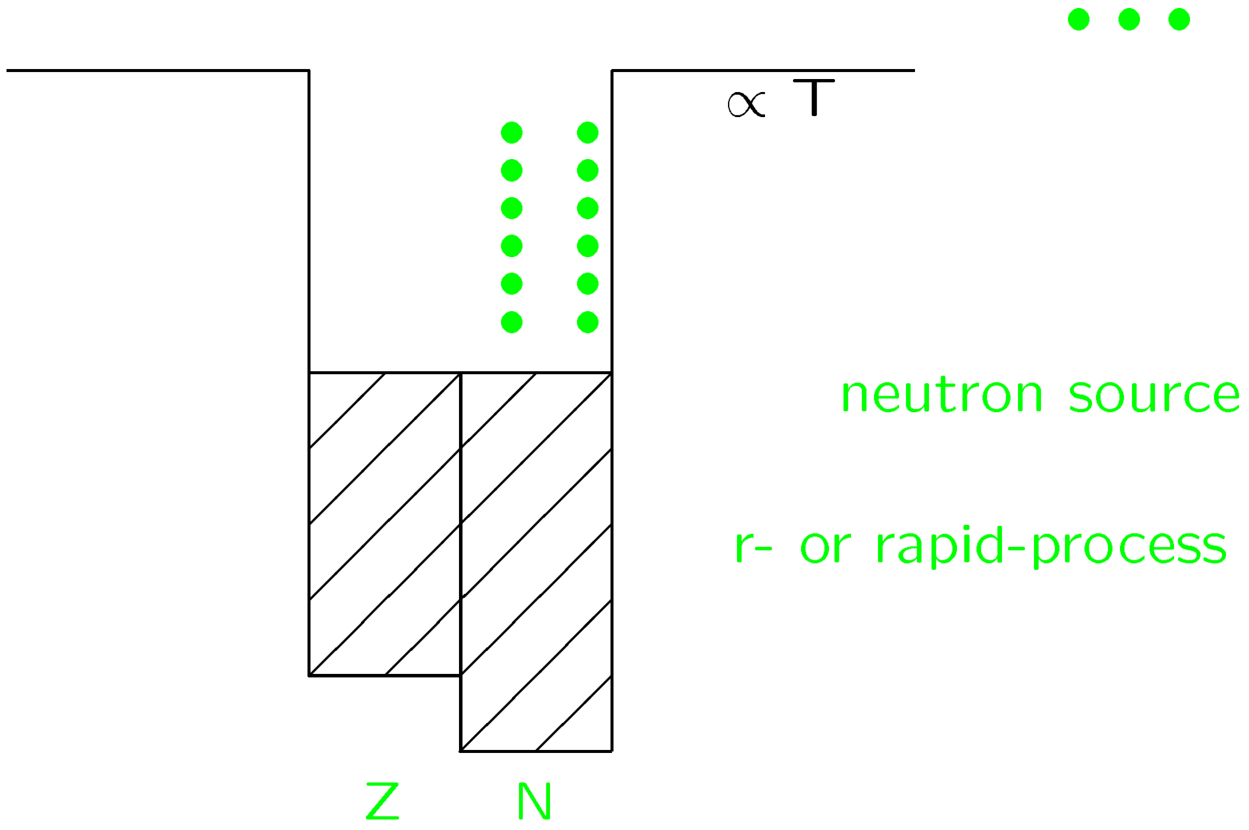
Wick Haxton *EMMI@GSI* *8 November 2011*

Identifying the astrophysical sites where the heavy elements were created



BBFH RMP 1957

the explosive (hot) r-process, as usually described

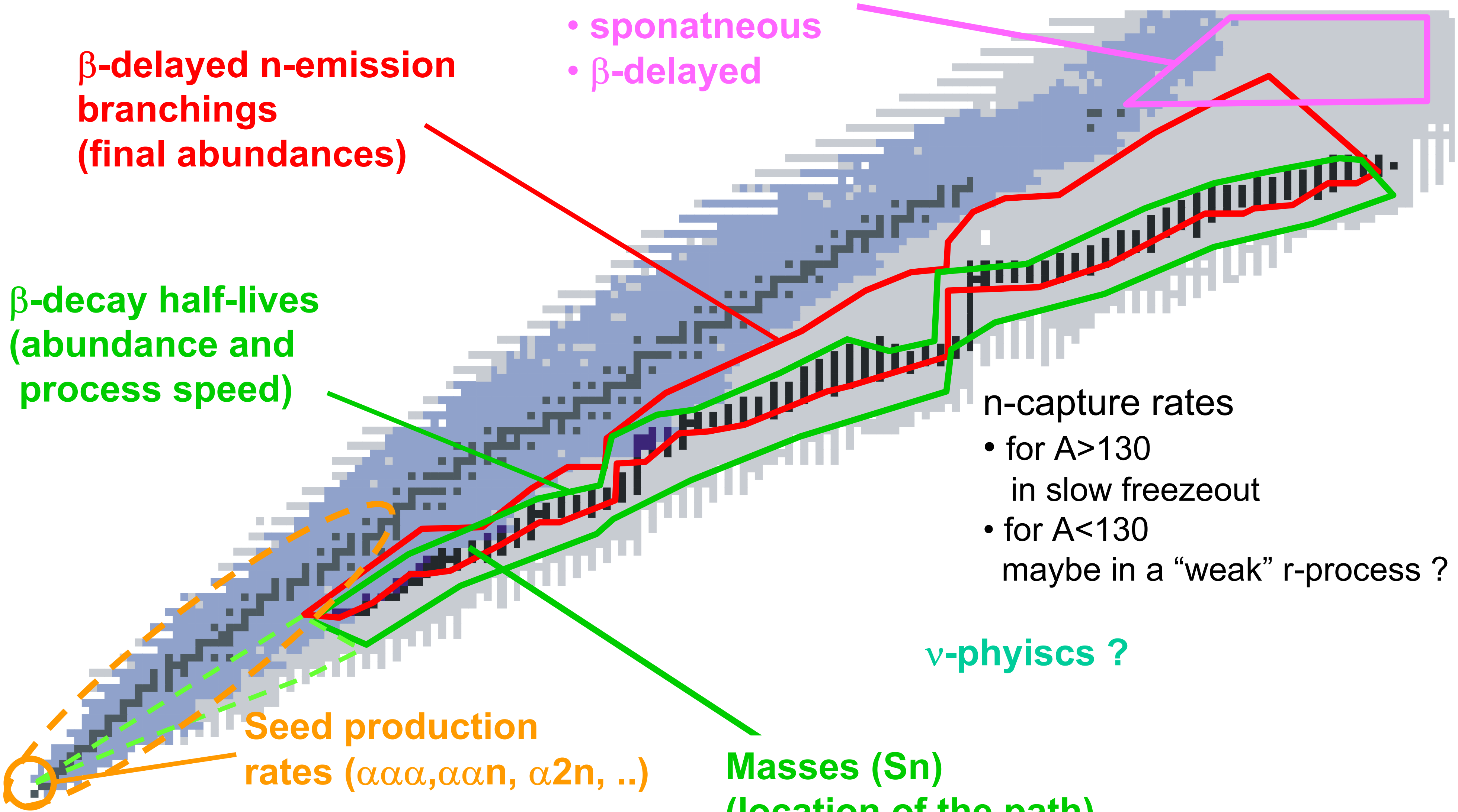


neutron source

r- or rapid-process

- n-capture fast, β decay slow ⇒ the equilibrium is (n,γ) ↔ (γ,n)
- nucleosynthesis rate ∝ β^- rate ⇒ through exotic, neutron-rich nuclei
- abundance A(Z,N) ∝ $[\omega_\beta(Z,N)]^{-1}$ for equilibrated mass flow

From Schatz



Fission rates and distributions:
- **n-induced**
- **sponatneous**
- **β-delayed**

β-delayed n-emission branchings (final abundances)

β-decay half-lives (abundance and process speed)

n-capture rates
- for A>130 in slow freezeout
- for A<130 maybe in a “weak” r-process ?

ν-phyiscs ?

Seed production rates ($\alpha\alpha\alpha$,$\alpha\alpha$n, α2n, ..)

Masses (Sn) (location of the path)

the r-process site

❑ generally modeled with condition where

$$\rho(\mathrm{n}) \sim 10^{20}\ /\mathrm{cm}^3 \qquad T \sim 10^9\ \mathrm{K} \qquad t \sim 1\ \mathrm{s}$$

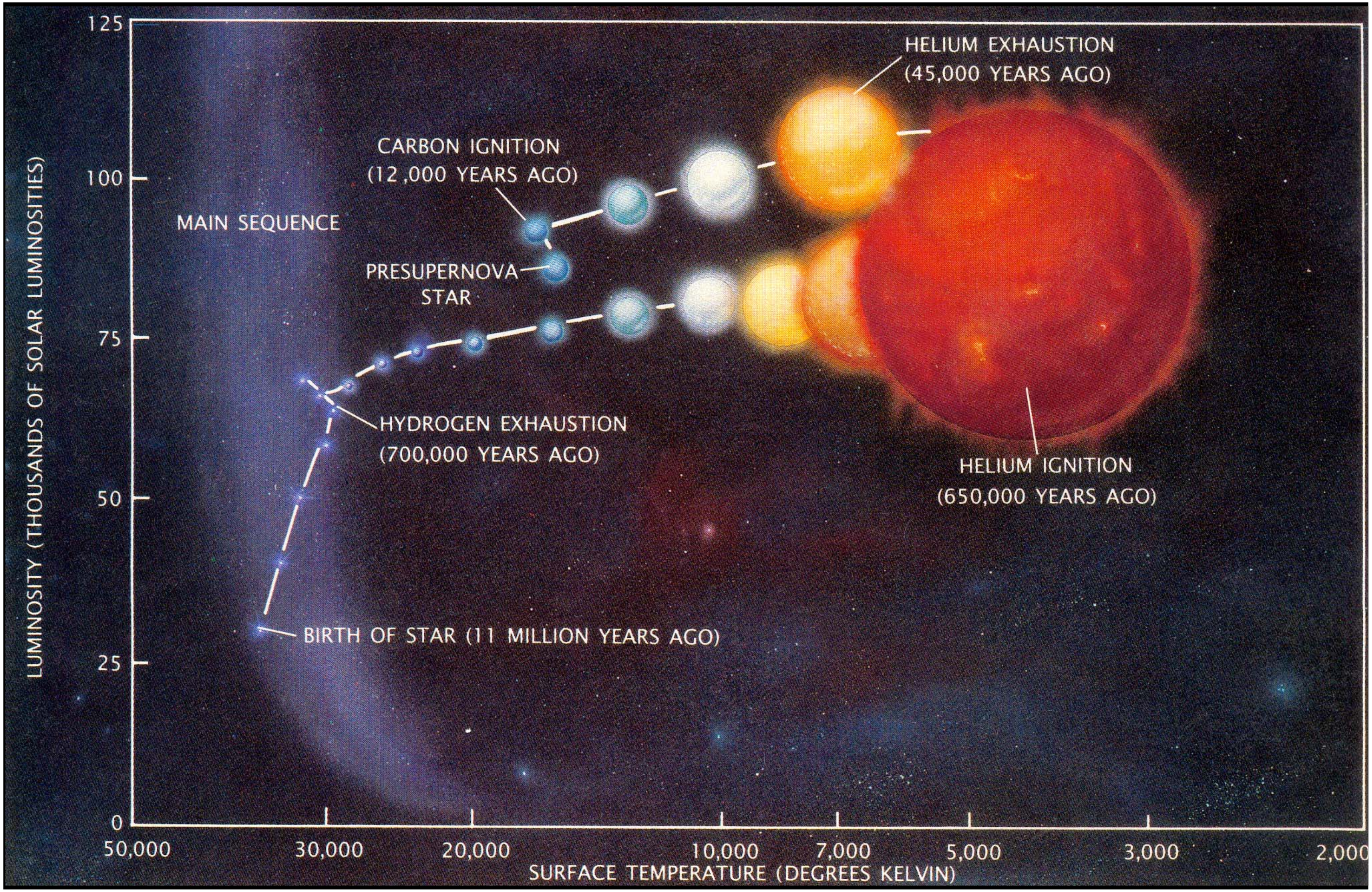
❑ both primary and secondary sites have been proposed

primary: no pre-enrichment of metal “seeds” required
secondary: n-capture occurs on s-process seeds

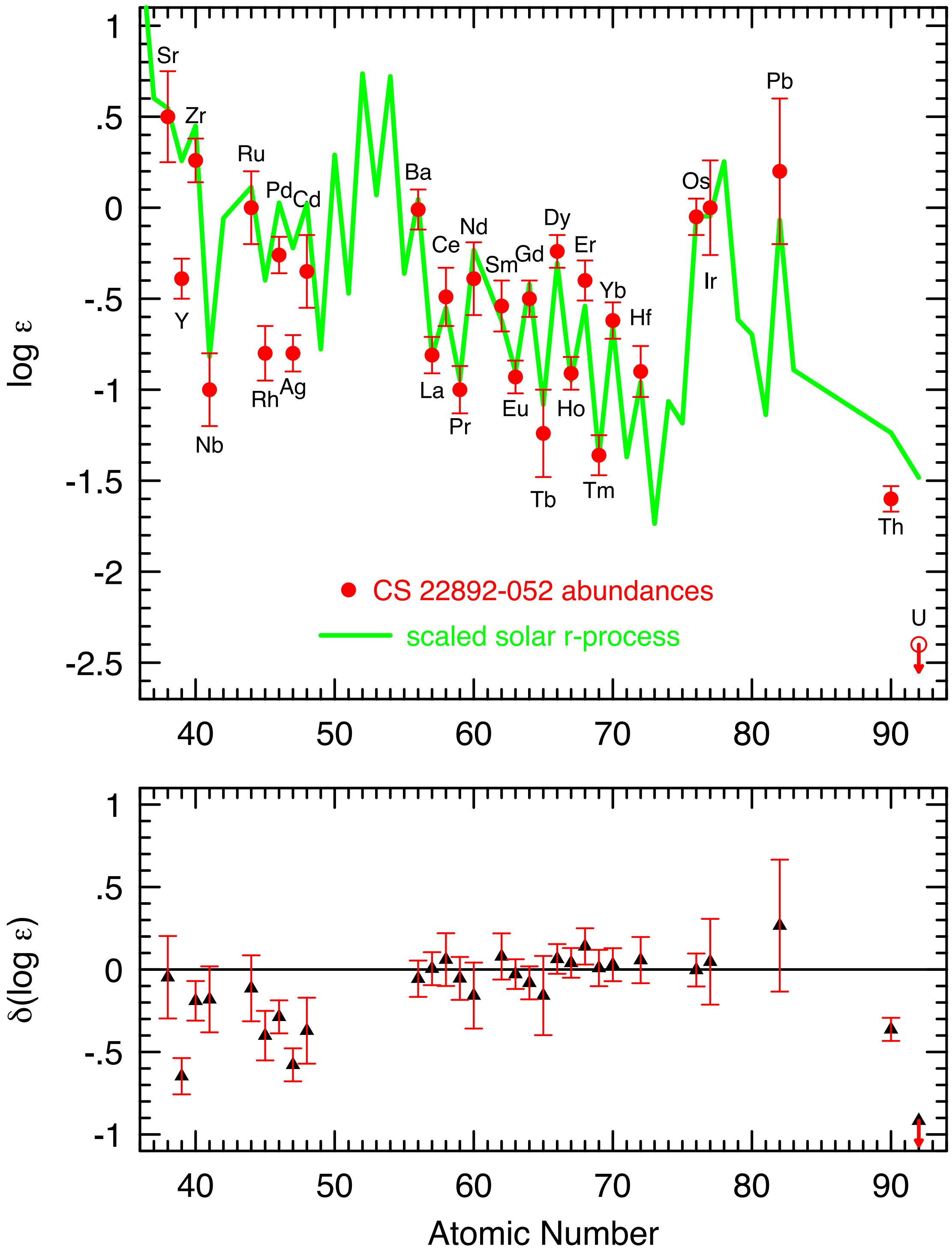
❑ studies of galactic evolution argue that the process is either primary, or involves a neutron source that is primary

❑ the two obvious sites -- supernovae and neutron star mergers -- have proven problematic, despite the recent accumulation of astrophysical information about the r-process

core-collapse supernovae: end state of rapidly evolving massive stars



Woosley and Weaver, 1987



much of our information comes from the early (metal poor) galaxy

regularity of yields

scales to solar r-process for A > Ba

J. J. Cowan, C. Sneden, et al.

Recent studies of metal-poor stars have made SNIIs an increasingly likely r-process site

❑ surfaces of such stars are "museums" preserving the pattern of the galaxy's individual, early, local nucleosynthetic events

❑ they show a pattern of heavy elements above Ba that is remarkably similar to the solar pattern -- the result of many such events occurring over the lifetime of our galaxy

❑ the r-process operated when the galaxy was very young, containing 10^{-4} of its current metals

❑ it occurred frequently: from the event-by-event statistics on the abundance of r-process isotopes like Eu, $\tau \sim 1/100$ y (Qian and Wasserburg)

❑ the typical r-process yield associated with SNIIs could generate the galaxy's present metal content, given typical yields of $10^{-6}\ M_\odot$/event

S. E. Woosley and R. D. Hoffmann, Ap. J. 395 (1992) 202

Standard "hot" SNII r-process:

hot bubble conditions provide α's and excess n's

α+A processing up to medium masses

followed by n capture on these heavy seeds

require ~ 100 neutrons/seed

neutrino wind "lifts" baryons off star

problems?

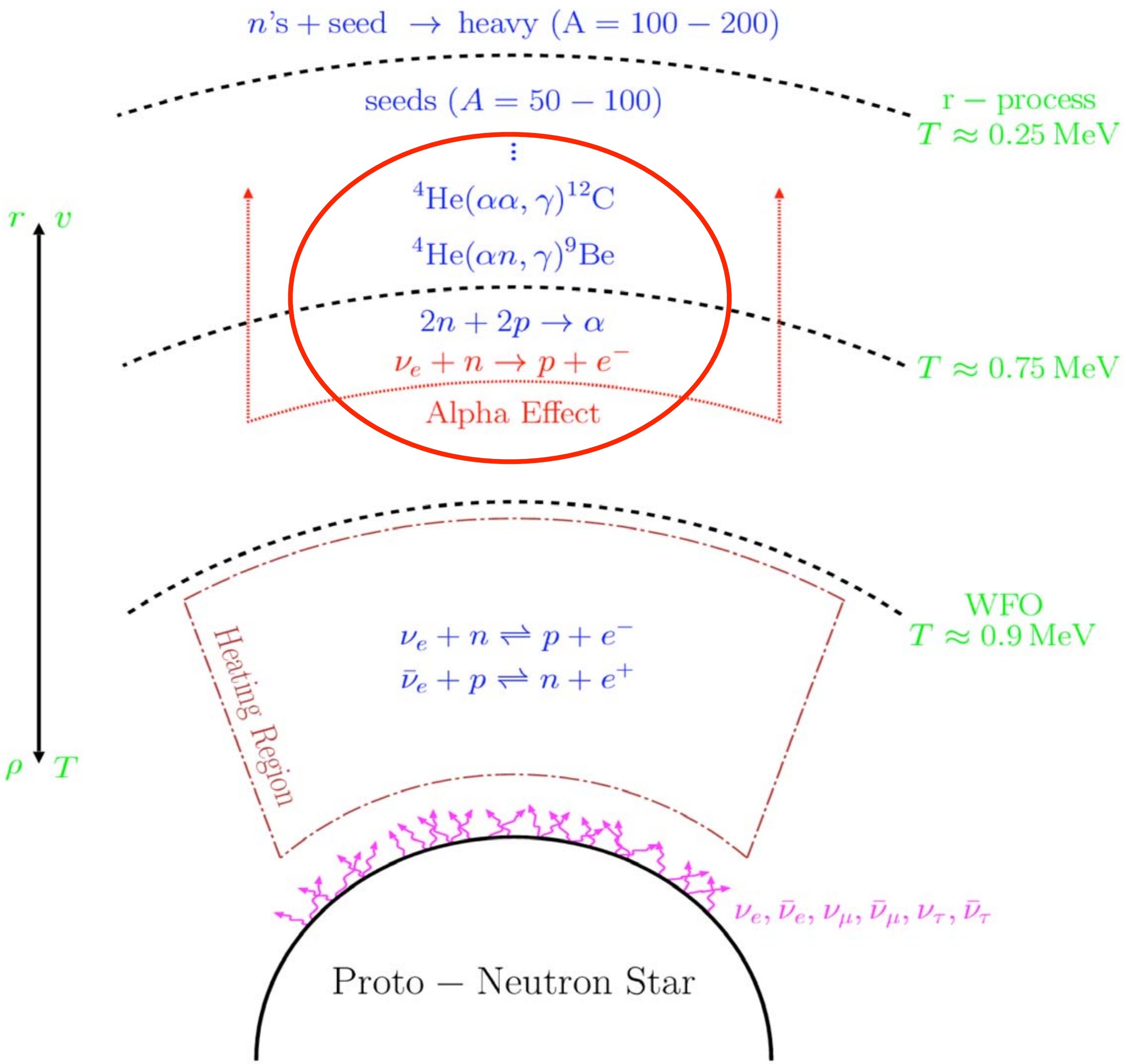


Figure: G. Fuller

A fundamental requirement for the site is a n/seed ratio ≥ 100

- ❏ early parametric studies succeeded only for high entropies ~ 400 k, requiring fine-tuning: at variance with realistic simulations

J. Witti, H.-T. Janka, and K. Takahashi, A. & A. 286 (1994) 841
K. Takahasi, J. Witti, and H.-T. Janka, A. & A. 286 (1994) 857

- ❏ the high T, high ρ environment leads to three-body reactions that increase the number of seeds, and thus diminish the n/seed ratio

B. S. Meyer, Ap. J. Lett. 449 (1995) 55

$$(\alpha\alpha\alpha,\gamma)^{12}\mathrm{C} \qquad (\alpha\alpha n,\gamma)^{9}\mathrm{Be}$$

avoided only for very fast expansions off the star

- ❏ the α-process: the same νs that are driving the wind and are thus needed for the ejection, destroy the neutron excess

G. M. Fuller and B. S. Meyer, Ap. J. 453 (1995) 792

$$\nu_e + \mathrm{n} \rightarrow e^- + \mathrm{p} \qquad 2\mathrm{p} + 2\mathrm{n} \rightarrow ^4\mathrm{He} + \gamma$$

each ν reaction destroys ~ two neutrons

INTEGRATED NUCLEOSYNTHESIS IN NEUTRINO DRIVEN WINDS

L. F. Roberts[1], S. E. Woosley[1], and R. D. Hoffman[2]

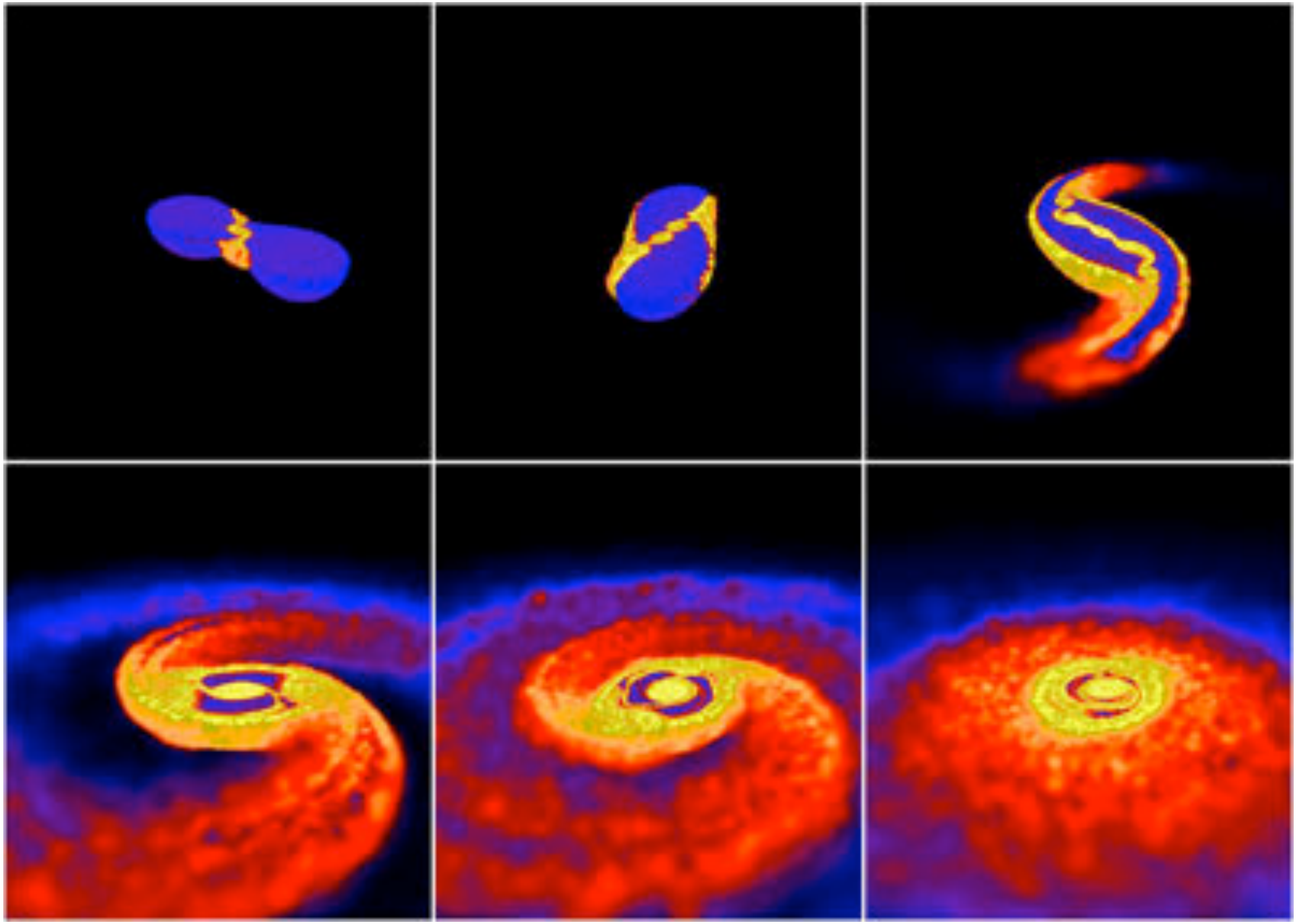
Draft version April 29, 2010

ABSTRACT

Although they are but a small fraction of the mass ejected in core-collapse supernovae, neutrino-driven winds (NDWs) from nascent proto-neutron stars (PNSs) have the potential to contribute significantly to supernova nucleosynthesis. In previous works, the NDW has been implicated as a possible source of r-process and light p-process isotopes. In this paper we present time-dependent hydrodynamic calculations of nucleosynthesis in the NDW which include accurate weak interaction physics coupled to a full nuclear reaction network. Using two published models of PNS neutrino luminosities, we predict the contribution of the NDW to the integrated nucleosynthetic yield of the entire supernova. For the neutrino luminosity histories considered, no true r-process occurs in the most basic scenario. The wind driven from an older $1.4 M_\odot$ model for a PNS is moderately neutron-rich at late times however, and produces ^{87}Rb, ^{88}Sr, ^{89}Y, and ^{90}Zr in near solar proportions relative to oxygen. The wind from a more recently studied $1.27 M_\odot$ PNS is proton-rich throughout its entire evolution and does not contribute significantly to the abundance of any element. It thus seems very unlikely that the simplest model of the NDW can produce the r-process. At most, it contributes to the production of the $N = 50$ closed shell elements and some light p-nuclei. In doing so, it may have left a distinctive signature on the abundances in metal poor stars, but the results are sensitive to both uncertain models for the explosion and the masses of the neutron stars involved.

arXiv:1004.4916v1 [astro-ph.HE] 27 Apr 2010

There are attractive alternates, e.g., NS mergers



neutron star merger: Flash Center, U of Chicago

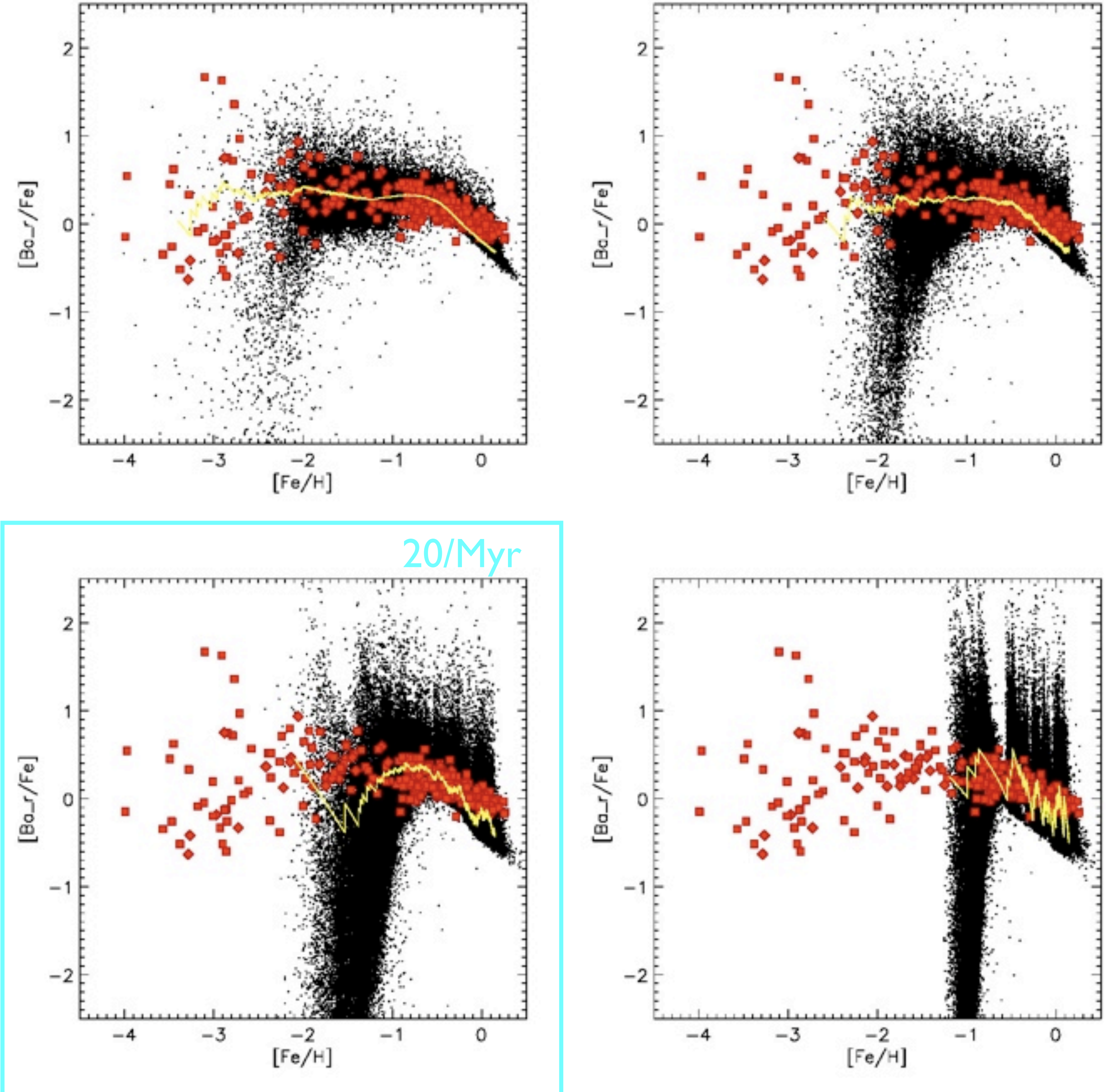
The NS mechanism offers

- such large neutron excesses that it may not be subject to the fine-tuning issues that arise for the hot bubble process
- the capacity to generate the bulk of r-process material
- the possibility of producing a stable pattern, through fission cycling

But this site likely cannot account for the metal-poor star data

- neutron star mergers expected to be rare in the early galaxy
- their galactic rate even today is not 10^{-2}/y, but 10^{-4}-10^{-5}/y
- unlikely to account for the highly variable early yield of Ba/Fe

a very puzzling and frustrating situation after 50 years of work...



galactic chemical evolution constraints

Argast et al. 2004

D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian, A. & A. 416 (2004) 997

So perhaps we are looking at things the wrong way...

❑ The evidence for a early SN-associated r-process is strong: but the data only demand that SN dominated r-process synthesis then

❑ The metal-poor-star data do not necessarily constraint "the r-process" but only the r-process as it occurred in the early galaxy. If those data can be explained by an early mechanism, later mechanisms like NS mergers would then not be constrained by MP star results

❑ The basic difficult with the SN "hot bubble" r-process is the difficulty of avoiding seed proliferation in hot explosions

❑ There are two ways to generate a good neutron/seed ratio: 1) many neutrons (explosive) or 2) fewer seeds (low Z), where one might manage with somewhat more modest neutron fluxes

❑ Any SN mechanism that depends on low Z will natural die away as the universe ages and becomes metal rich

Motivated us to re-examine the little-studied ECH mechanism

R. Epstein, S. Colgate, WH, PRL 61 (1988) 2038

❑ based on three observations:

- as we learned in BBN, the absence of a stable nucleus at A=5 restricts nucleosynthesis: neutrons in He just scatter
- neutrons in the SN He zone will thus capture efficiently on seeds
- there is a potential neutron source, ν breakup of ^{4}He

❑ ν reactions were harmful to the hot-bubble r-process, leading to excess seeds: ECH found the nuclear physics changes for $T_{He} < 2.5 \times 10^8$ K

$$^4\mathrm{He}(\nu,\nu' n)^3\mathrm{He} \qquad ^4\mathrm{He}(\nu,\nu' p)^3\mathrm{H}$$

$$^3\mathrm{He}(n,p)^3\mathrm{H}$$

$$^3\mathrm{H} + {}^3\mathrm{H} \rightarrow {}^4\mathrm{He} + 2n$$

every ν reaction produces one neutron

$$\tau_{\nu\ \mathrm{cooling}} \sim 3\ \mathrm{s}$$

❑ this n source is very stable, connected to the Chandrasekhar mass

Properties

- it is a cold r-process - the material does not experience an explosion - consequently the usual SN seed proliferation problem is avoided

- the neutron source is a weak one, yet because n-capture is slow, densities typical of other r-processes are produced, ~ 10^{19} n/cm^3
  - the path, while similar to that of other r-processes, is maintained by $(n,\gamma) \leftrightarrow \beta^-$ not $(n,\gamma) \leftrightarrow (\gamma,n)$

- this r-process is effective but requires time: there are few seeds and no other sink for neutrons. A substantial inventory of neutrons is produced. Abundances remain high for long times, as they are consumed
  - the time needed to reach the transuranics is ~ 10-100 sec

- the nuclear physics does not operate as described in ECH, at least in the simplest proposed environment, MP He shells

Contrasting Environments

ECH scenario

- r $\lesssim 10^9$ cm, $\rho \sim 3 \cdot 10^3 \ \mathrm{g/cm^3}$
  $Z \sim Z_\odot$
- T $\sim (2-3) \cdot 10^8 K$
- neutron poison: $^{14}\mathrm{N}$
- neutron source: NC νs
- $T_{\nu_{\mathrm{heavy}}} \sim 9 \ \mathrm{MeV}$

Current (Heger progenitor)

- 10-17 $M_\odot, \ Z = 10^{-4} Z_\odot$
  r $\sim 10^{10} \ \mathrm{cm}, \ \rho \sim 50 \ \mathrm{g/cm^3}$
- T $\sim 10^8 K$
- neutron poisons: $^{12}\mathrm{C}, \ ^{16}\mathrm{O}, \ ^{14}\mathrm{N}$
- neutron source: NC, CC νs
  + oscillations
- $T_{\nu_e}/T_{\bar{\nu}_e}/T\nu_{\mathrm{heavy}} \sim 4/5.3/8 \ \mathrm{MeV}$

inverted hierarchy

Contrasting Nuclear Physics

ECH scenario
(separate, maintain n+p)

$$\left\{\begin{array}{l} {}^4\mathrm{He}(\nu,\nu' p)^3\mathrm{H} \\ {}^4\mathrm{He}(\nu,\nu' n)^3\mathrm{He}(n,p)^3\mathrm{H} \end{array}\right.$$

$$^3\mathrm{H} + ^3\mathrm{H} \rightarrow {}^4\mathrm{He} + 2n$$

NC: charge separation maintained,
but as free protons + ^{7}Li, ^{11}B, ...

New scenario
create net neutrons

$$\left\{\begin{array}{l} {}^4\mathrm{He}(\nu,\nu' p)^3\mathrm{H} \\ {}^4\mathrm{He}(\nu,\nu' n)^3\mathrm{He}(n,p)^3\mathrm{H} \end{array}\right.$$

$$^3\mathrm{H} + ^3\mathrm{H} \not\rightarrow {}^4\mathrm{He} + 2n$$

inefficient

$$^3\mathrm{H}(^4\mathrm{He},\gamma)^7\mathrm{Li}$$

$$^7\mathrm{Li}(^3\mathrm{H}\cancel{,}2n)2^4\mathrm{He}$$

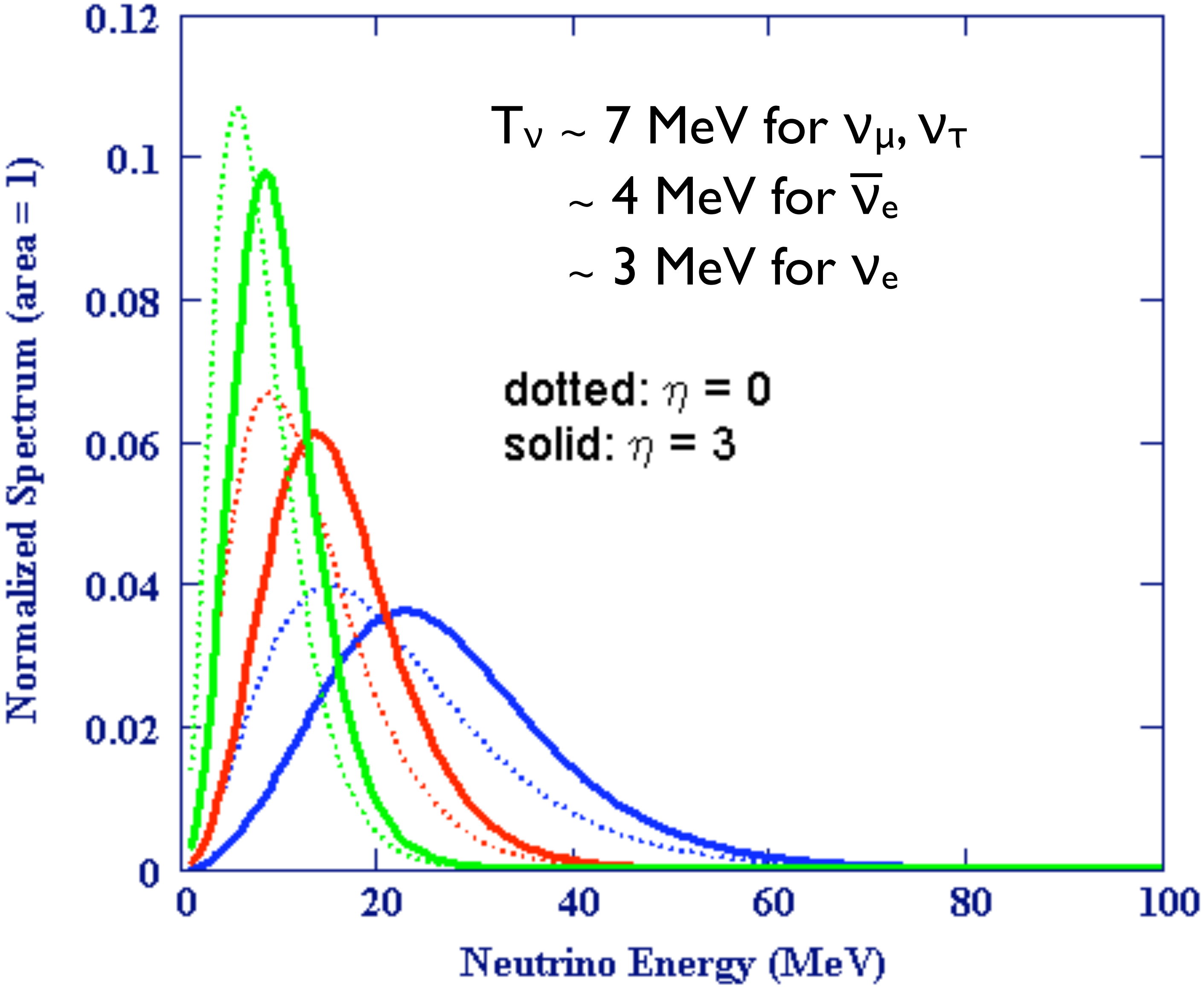
inefficient

CC: n + ^{7}Li

$$^4\mathrm{He}(\bar{\nu}_e, e^+ n)^3\mathrm{H} \quad ^3\mathrm{H}(^4\mathrm{He},\gamma)^7\mathrm{Li}$$

The neutrino spectrum depends on flavor

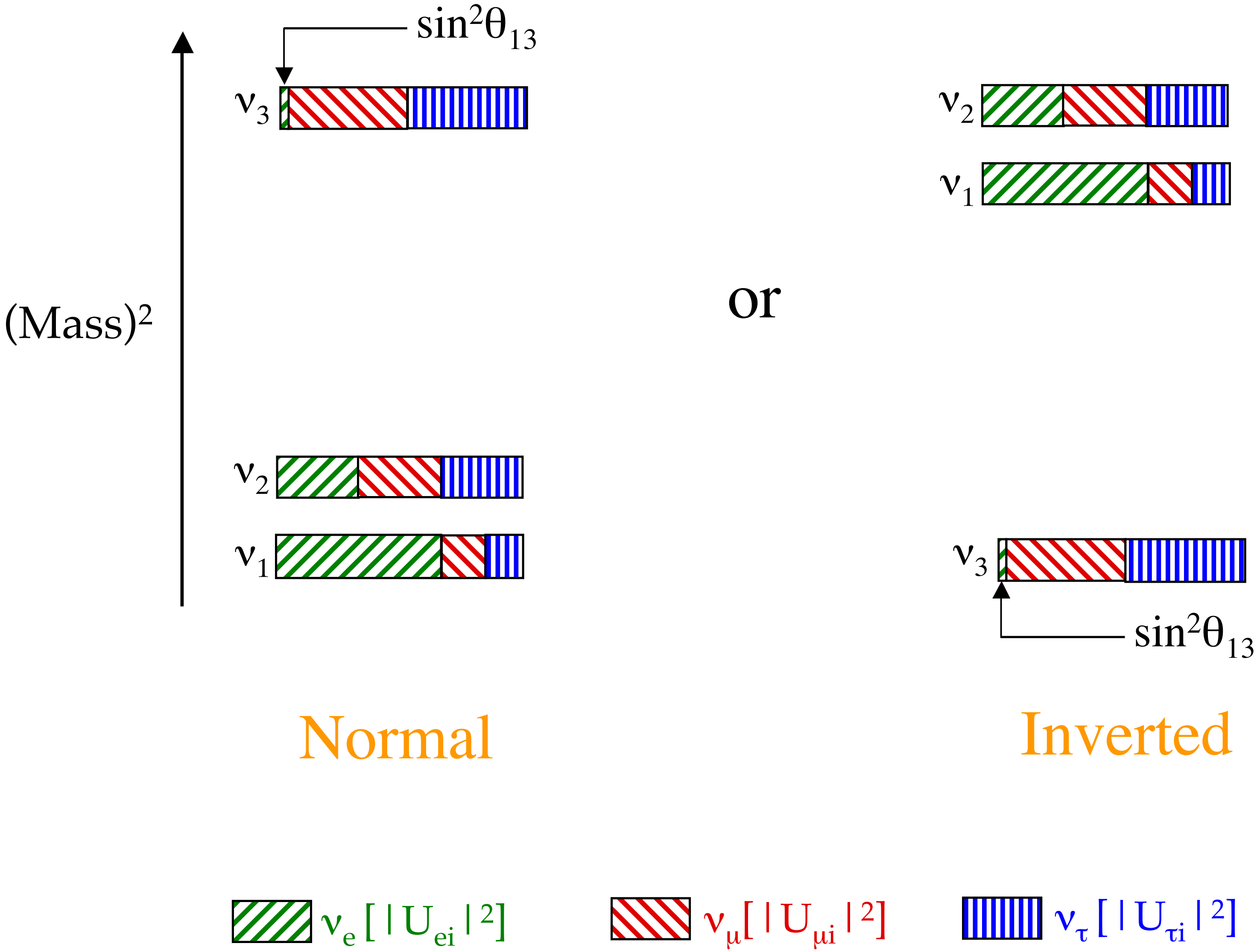
$$(weakly\ coupled)\quad T_{heavy flavor} > T_{\bar{\nu}_e} > T_{\nu_e} \quad (neutron\ rich)$$



T_ν ~ 7 MeV for ν_μ, ν_τ
~ 4 MeV for $\bar{\nu}_e$
~ 3 MeV for ν_e

dotted: $\eta = 0$
solid: $\eta = 3$

And the spectrum flips in flavor depending on a critical unkown, the <u>Hierarchy</u>



(artwork: Boris Kayser)

Dimensional analysis of relevant dynamic times

- ❑ He shell collapse time

$$\tau_{\text{collapse}} \sim 102 \text{ s} \left(\frac{0.6}{\alpha}\right) \left(\frac{M_\odot}{M}\right)^{1/2} r_{10}^{3/2} \gg \tau_{\text{r-process}}$$

- ❑ shock arrival time

$$\tau_{\text{shock}} \sim 21.8 \text{ s} \left(\frac{M - M_{NS}}{M_\odot}\right)^{1/2} \frac{r_{10}}{E_{50}^{1/2}} \sim \tau_{\text{r-process}} \gg \tau_\nu$$

- ❑ shock heating

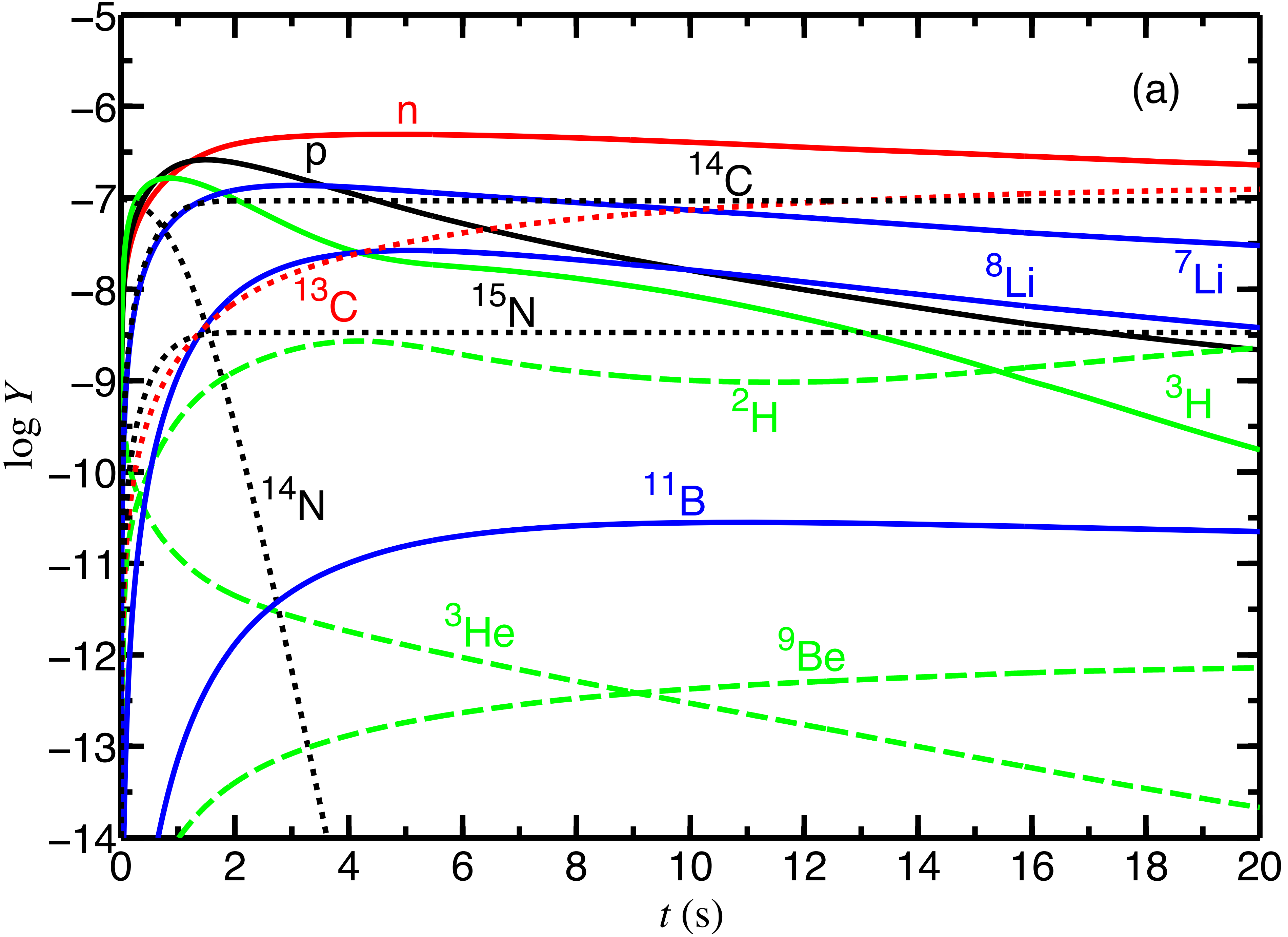
$$T_8^{\text{peak}} \sim 2.4 \; E_{50}^{1/4} r_{10}^{-3/4} < T_{\text{r-process}}^{\text{burnup}}$$

the nucleosynthetic environment depends on generic SN properties like the SN energy release, progenitor mass ↔ no tuning, can be modeled

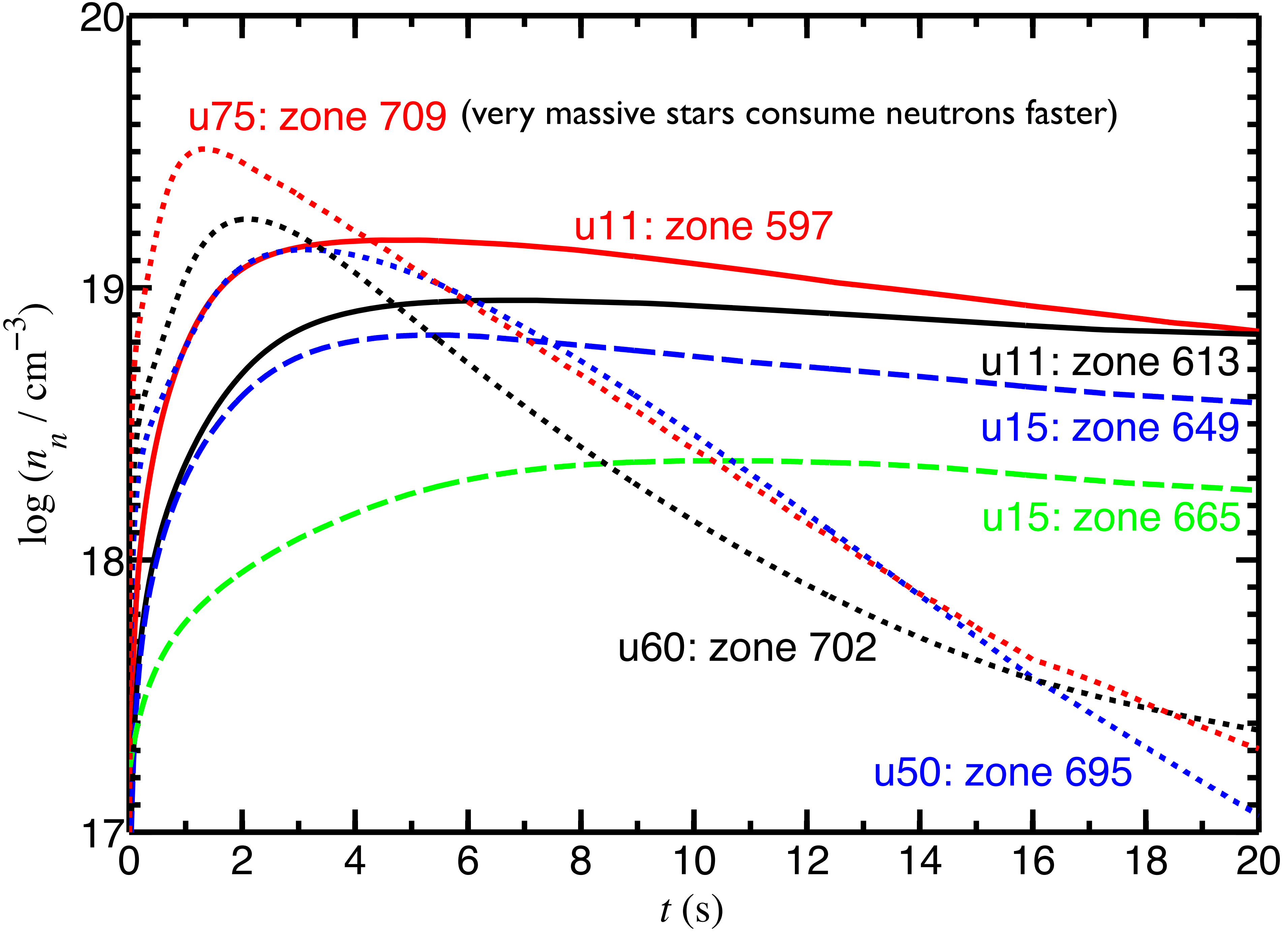
so outer He zones of Fe-core SN appear to be a particular simple environment for testing the mechanism

T_ν = 8 MeV, low-mass Fe core

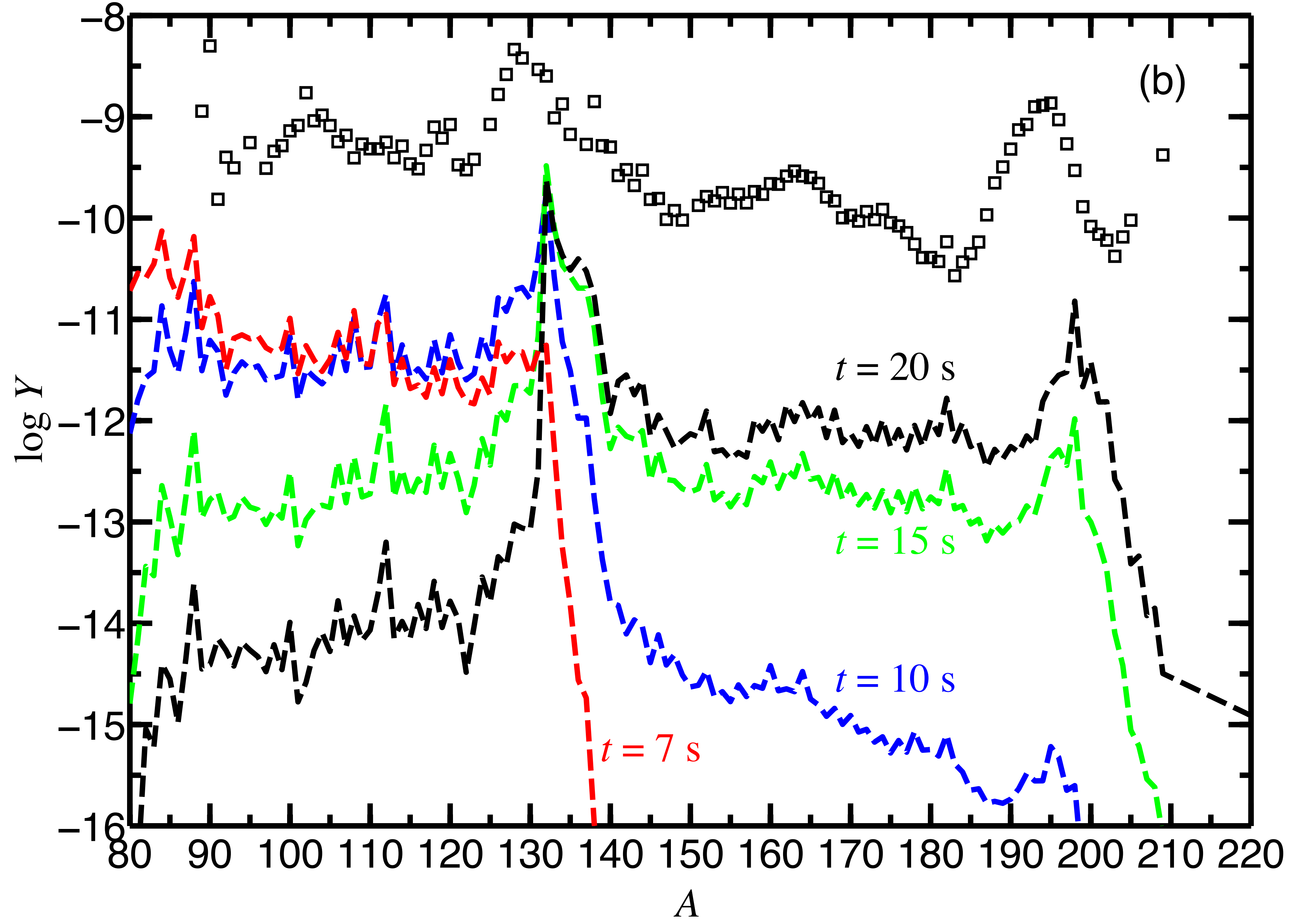
can be calculated with some certainty



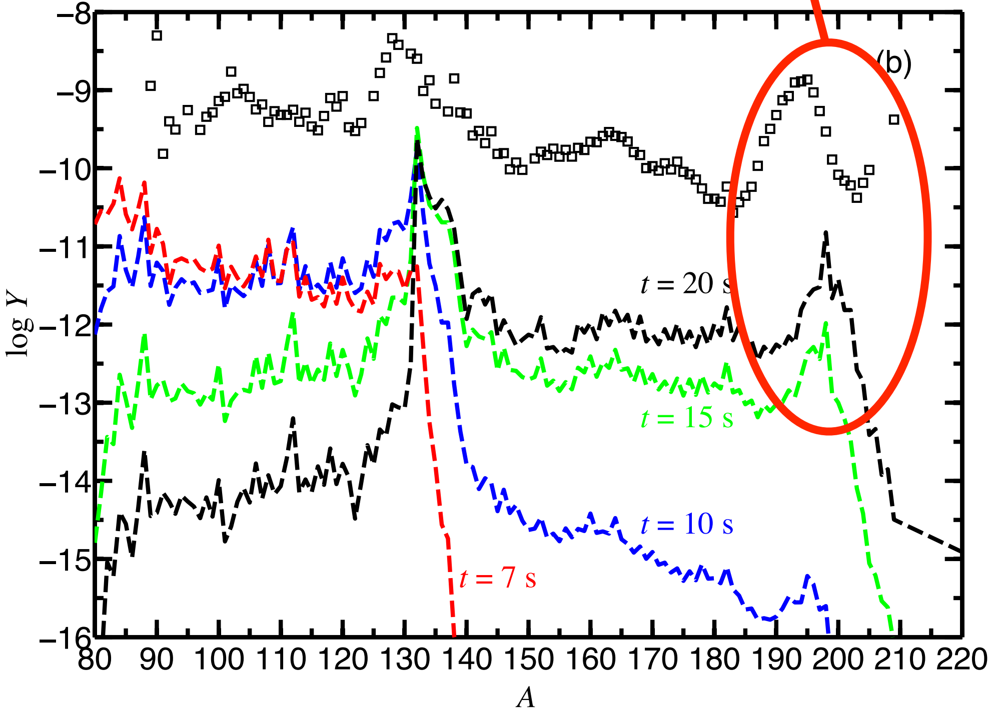
11-75 M_{solar}, wide variety of zones ⇒ neutron densities of $10^{18\text{-}19}/cm^3$ maintained

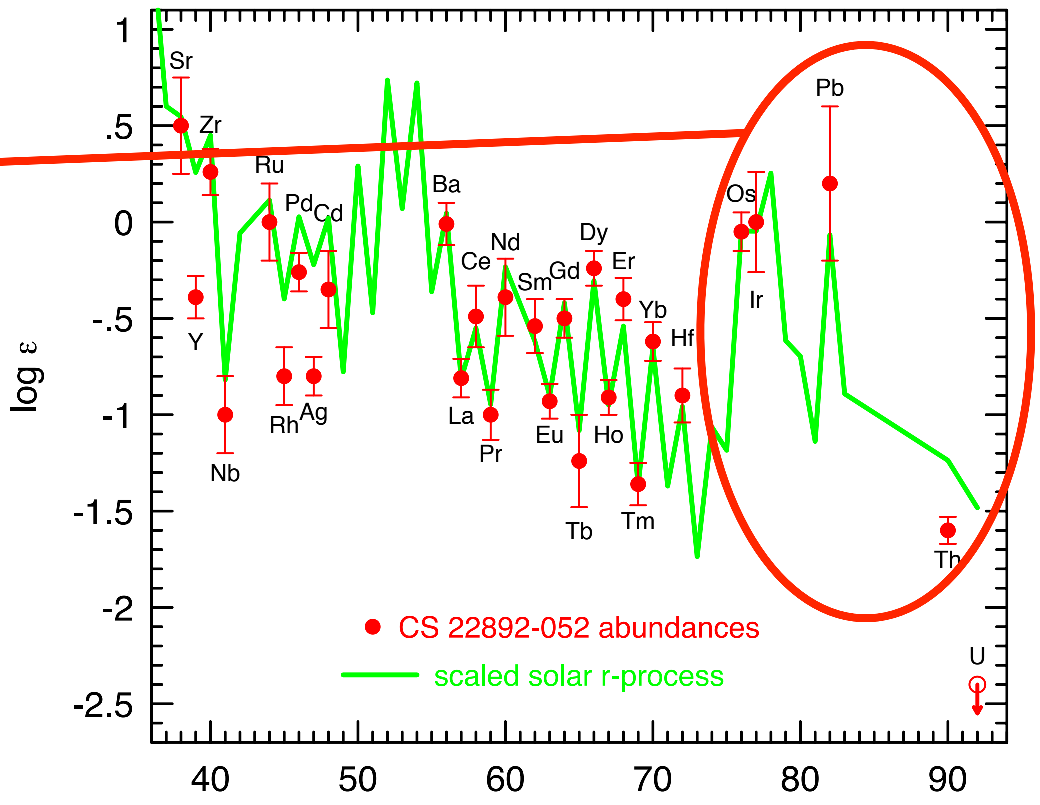


third peak forms ~ 15 s



third peak position/shape potentially a diagnostic of such a cold r-process





- the long times reflect the low metallicity and low density of the u11-u16 environment: neutrons must search for a "seed"

- corresponding neutron capture rate ~ 10/Fe "seed"/s

- r-process condition found for IH in Fe-core models u11-u16 and u49-u75 for [Fe/H] between -4 and -3 (for u17-u48, H is a poison)

- without oscillations, operates only for UMP conditions: [Fe/H] ~ -4

- with NH oscillations, the process does not operate, as least in the context of standard MSW (no ν-ν effects)

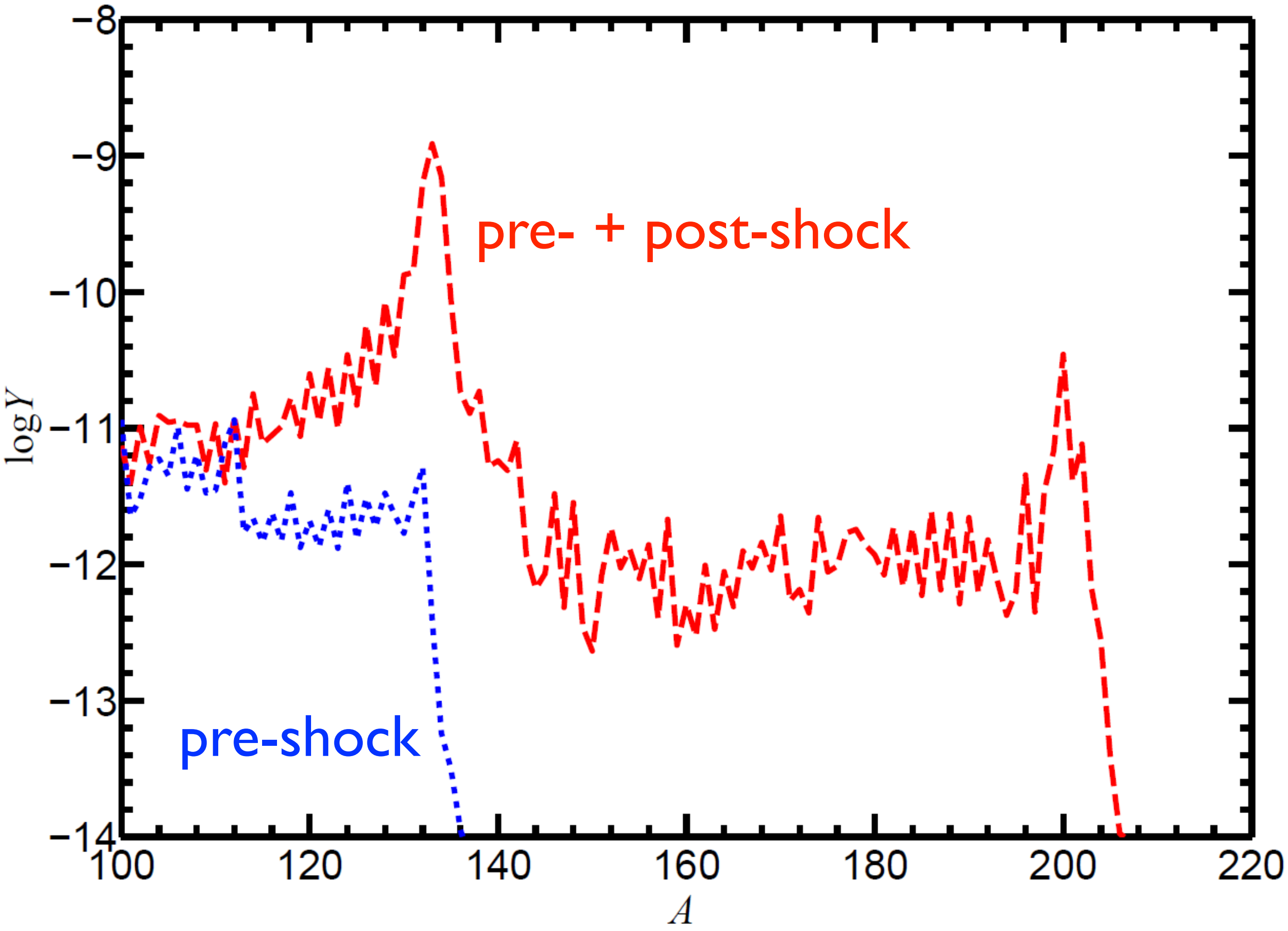
- IH yields at [Fe/H] = -4 are $\sim 10^{-8}$ M_{solar}, similar to the solar metal inventory of $\sim 4 \times 10^{-8}$ M_{solar} Process turns off above [Fe/H] ~ -3

- observed MP star enrichments for [Fe/H] < -2.5 are (3×10^{-4}) - 10^{-1}, consistent with the generated enrichments

The results shown were pre-shock: what happens when the shock arrives before the n inventory has been exhausted?

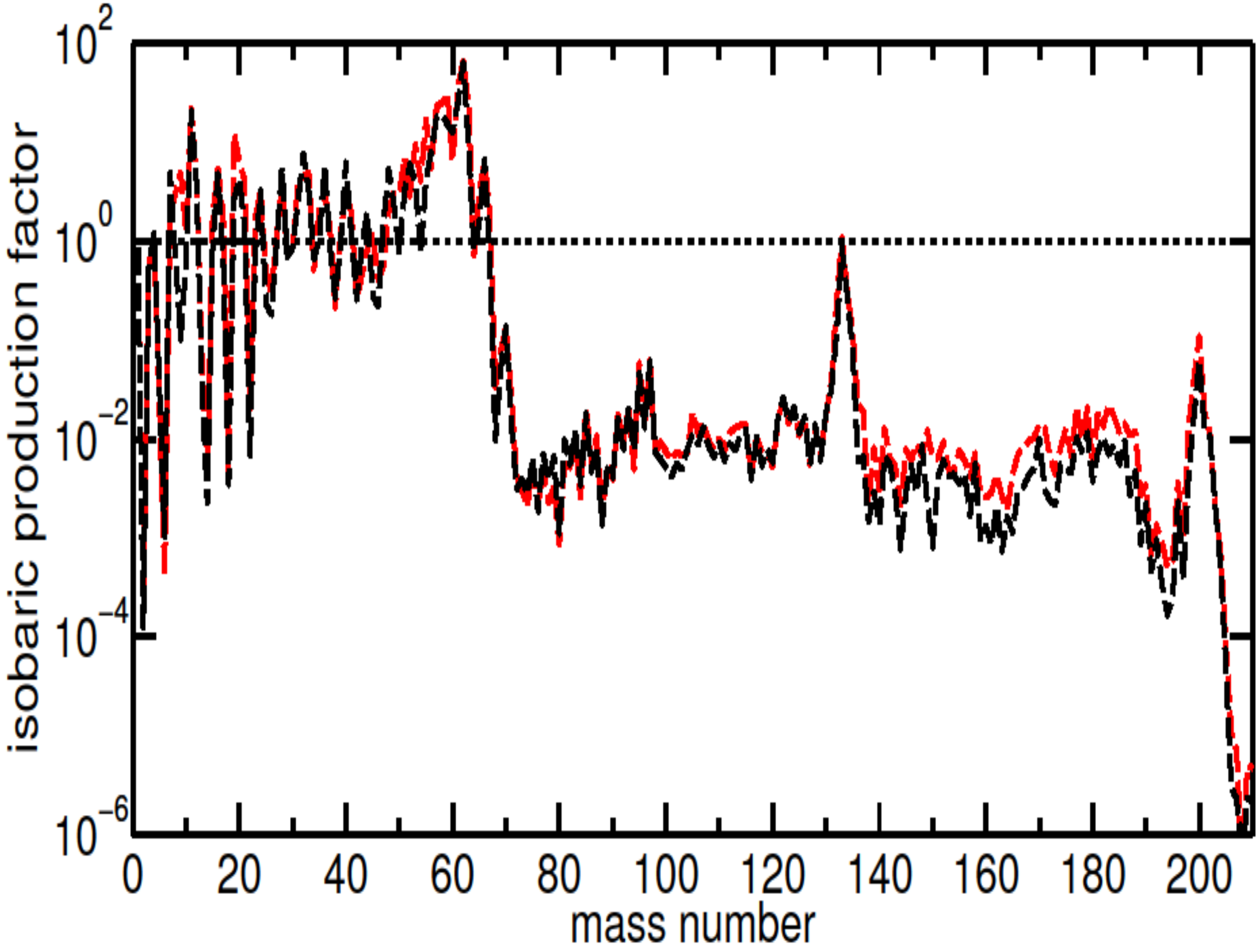
- for explosion energies > 1B the pre-shock phase provides only ~ 10 s for nucleosynthesis
- so neutrons will remain post-shock, while shock wave compression (×7) will increase post-shock reaction rates
- but there is also some heating that potentially could increase the number of seeds

Effects of the Shock



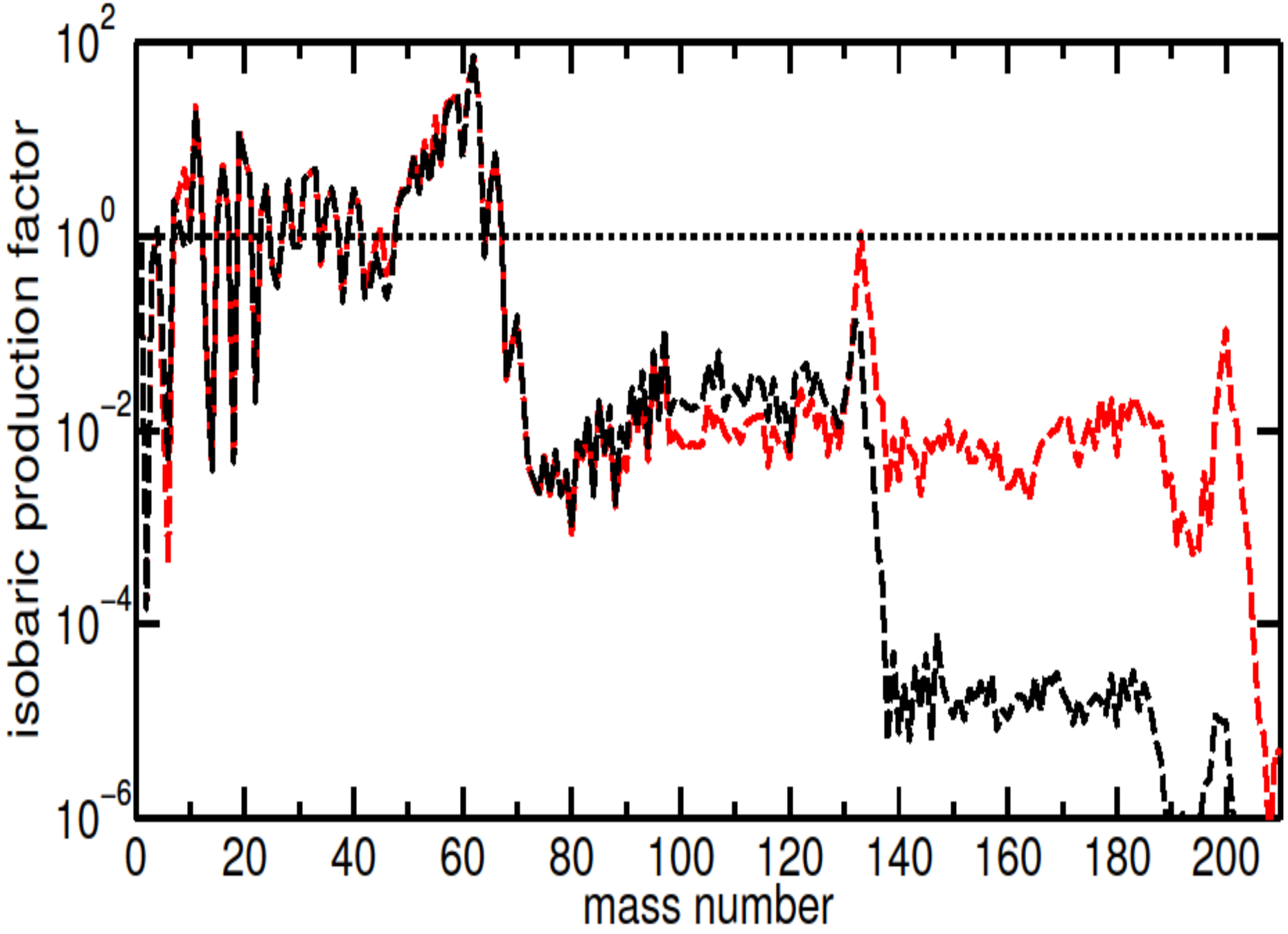
the r-process continues for 60-70 s!

Effects of the Explosion Energy:
Minor



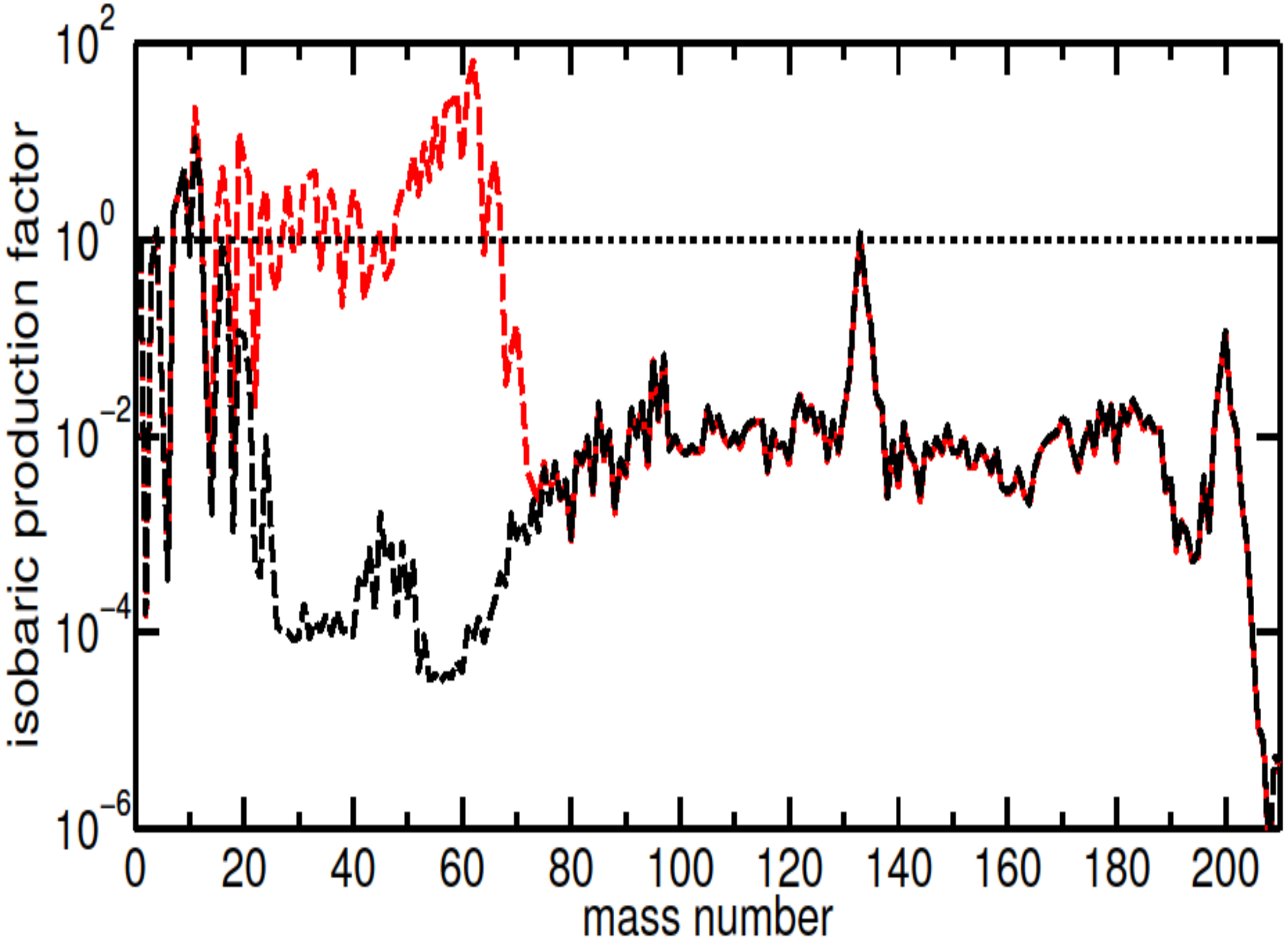
u11 mode: E = 1 × 10^{50} ergs (red) or 10 × 10^{50} ergs (black)

Effects of the Initial Composition: Significant



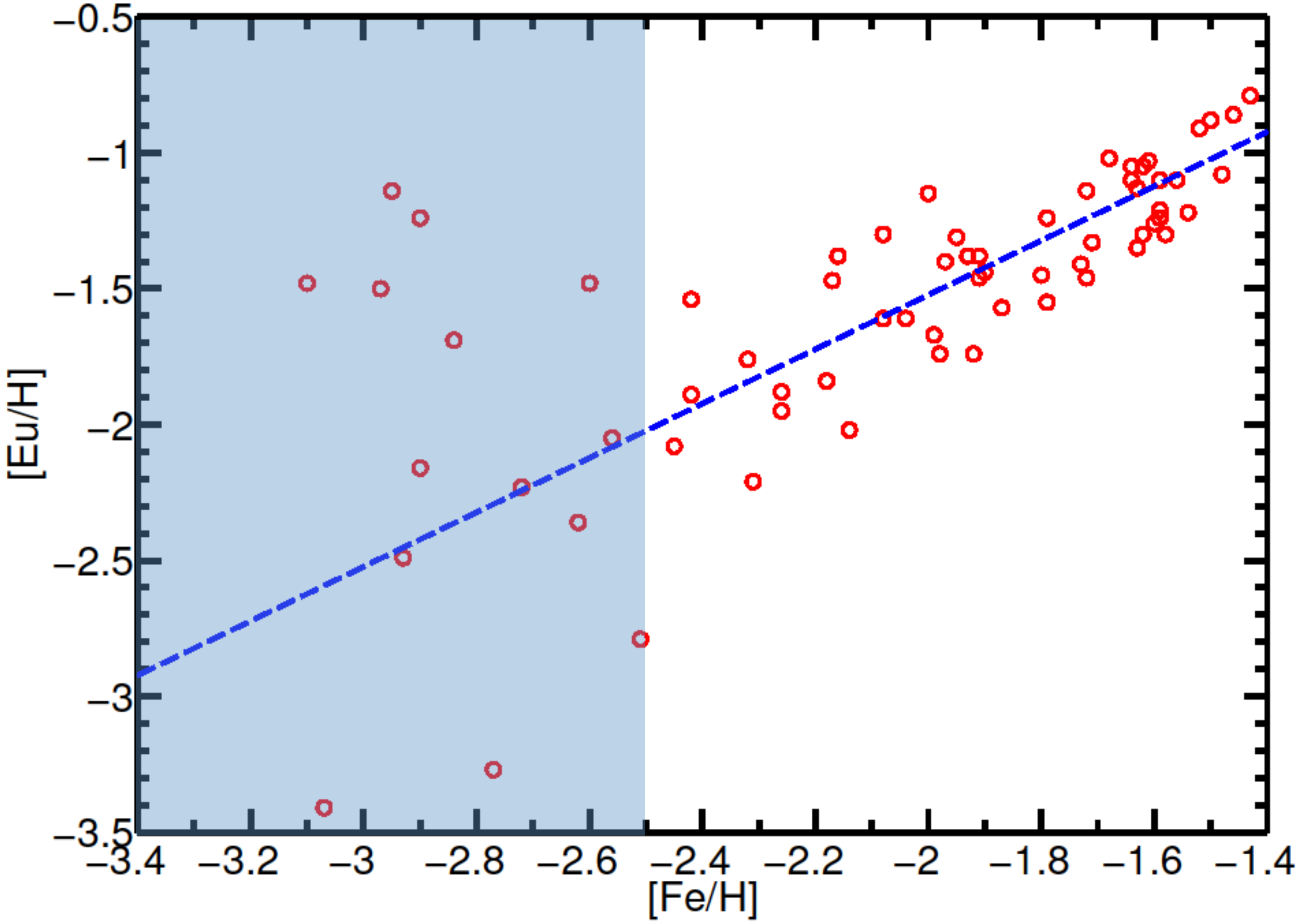
u11 mode: E = 1 × 10^{50} ergs black: introduced new poisons ^{28}Si, ^{32}S

Effects of Fallback: Significant and Intriguing



Black: with fallback

Observed Nonuniform Mixing in Early Galaxy



Roederer et al., Ap J 724 (2010) 975

Outlook

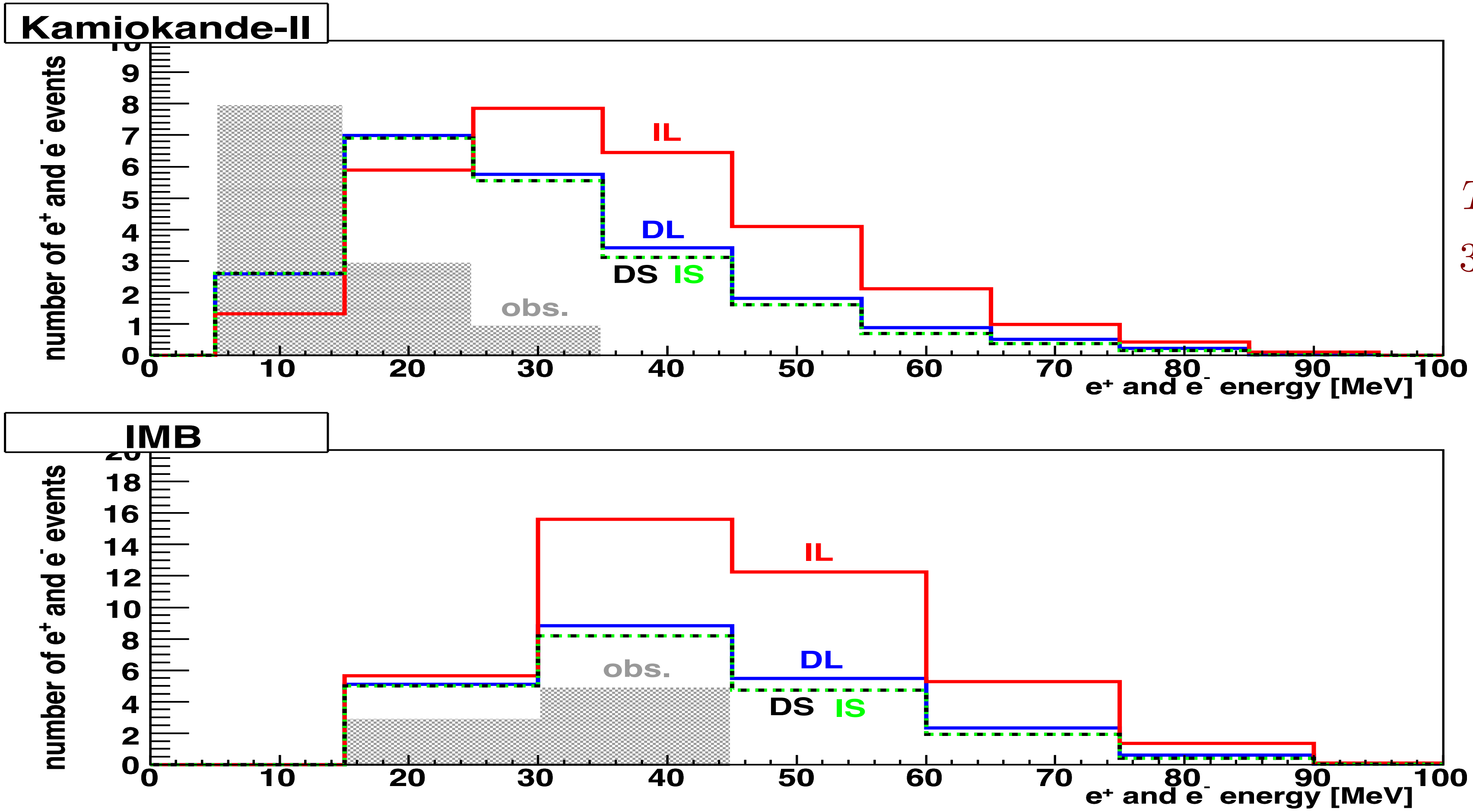
- ❏ several arguments suggest that a SN-associated r-process operated in the low-metallicity early galaxy
  - the hot bubble process seems not to produce the necessary enrichments
  - we explored an alternative, a cold and slow SN r-process that operates at low Z in the star's mantle

- ❏ its features match requirements: a very stable astrophysical environment, associated with a subclass of Fe-core supernovae, producing a solar-like distribution, and variable Z/Fe. The process is calculable

- ❏ success would open "phase space" for complementary r-processes to account for the bulk of metals in the contemporary galaxy

- ❏ it works - in the scenarios so far explored - for an inverted hierarchy and a hard but not unreasonable heavy-flavor ν spectrum

Bekman,
Holeczek,
& Kisiel
2006



$T_{\nu_e}/T_{\bar{\nu}_e}/T_{\nu_x} \sim$
$3.5/5/8$ MeV

Fig. 2. The predicted e^+ and e^- energy spectra, in case the SN1987A production spectra are described by the thermal Fermi–Dirac functions, for different combinations of mass hierarchy and Θ_{13} (DL — Direct mass hierarchy and *Large* Θ_{13}, IL — Inverted mass hierarchy and *Large* Θ_{13}, DS — Direct mass hierarchy and *Small* Θ_{13}, IS — Inverted mass hierarchy and *Small* Θ_{13}). The shaded areas show the histograms of observed SN1987A events. For details see the description

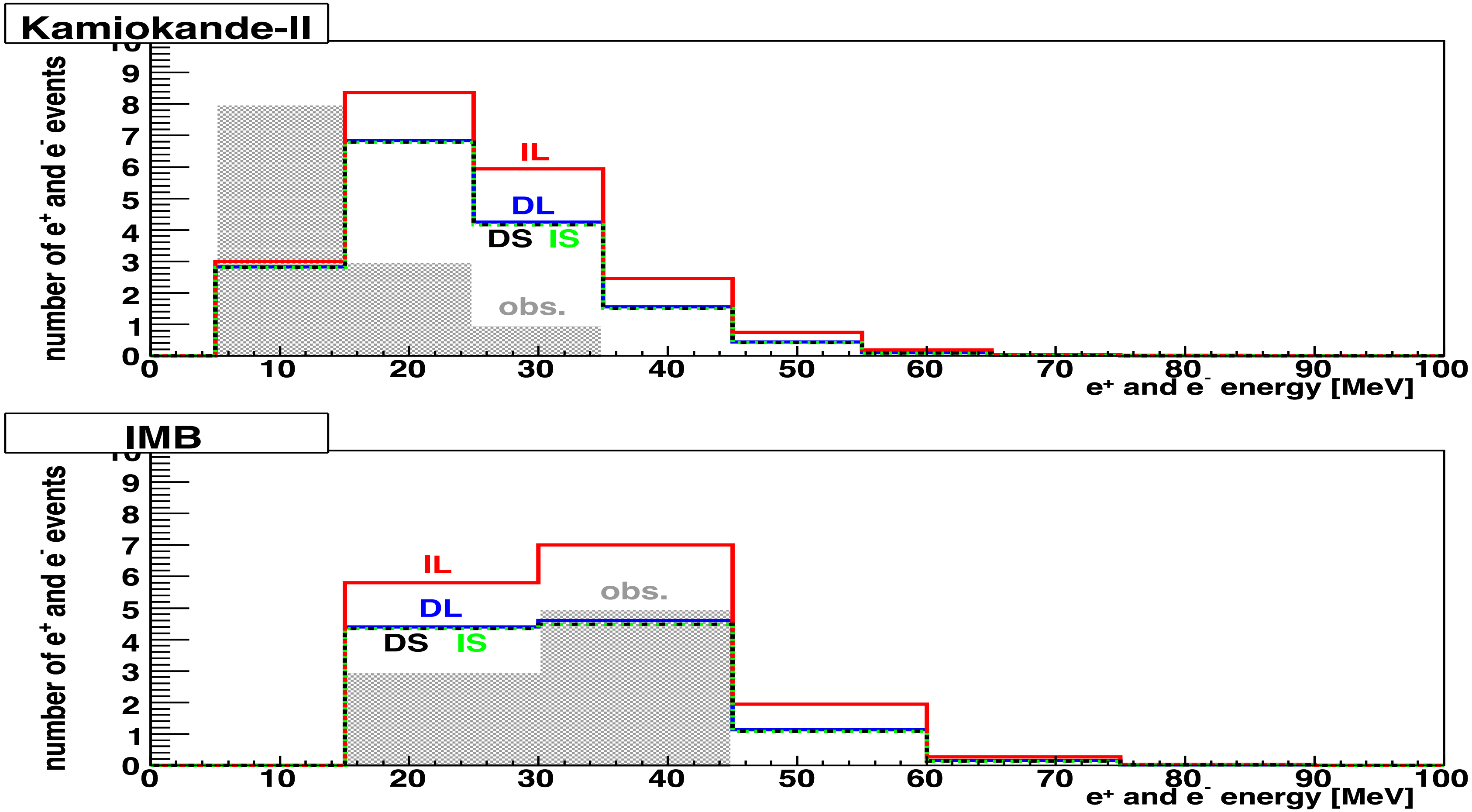


Fig. 3. The predicted e^+ and e^- energy spectra, in case the SN1987A production spectra are described by the "Analytic Fit Functions", for different combinations of mass hierarchy and Θ_{13}. For details see the description in Fig.2 and in text.

1) hierarchy insensitivity 2) KII-IBM tension 3) K-II favors disfavors higher T but is also generally discrepant