A Cold , Early r-process?

- Motivation: Metal-poor constraints on the r-process
- Our initial explorations
- Where else we might look

with Projjwal Banerjee and Yong-Zhong Qian

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

Standard "hot" 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?

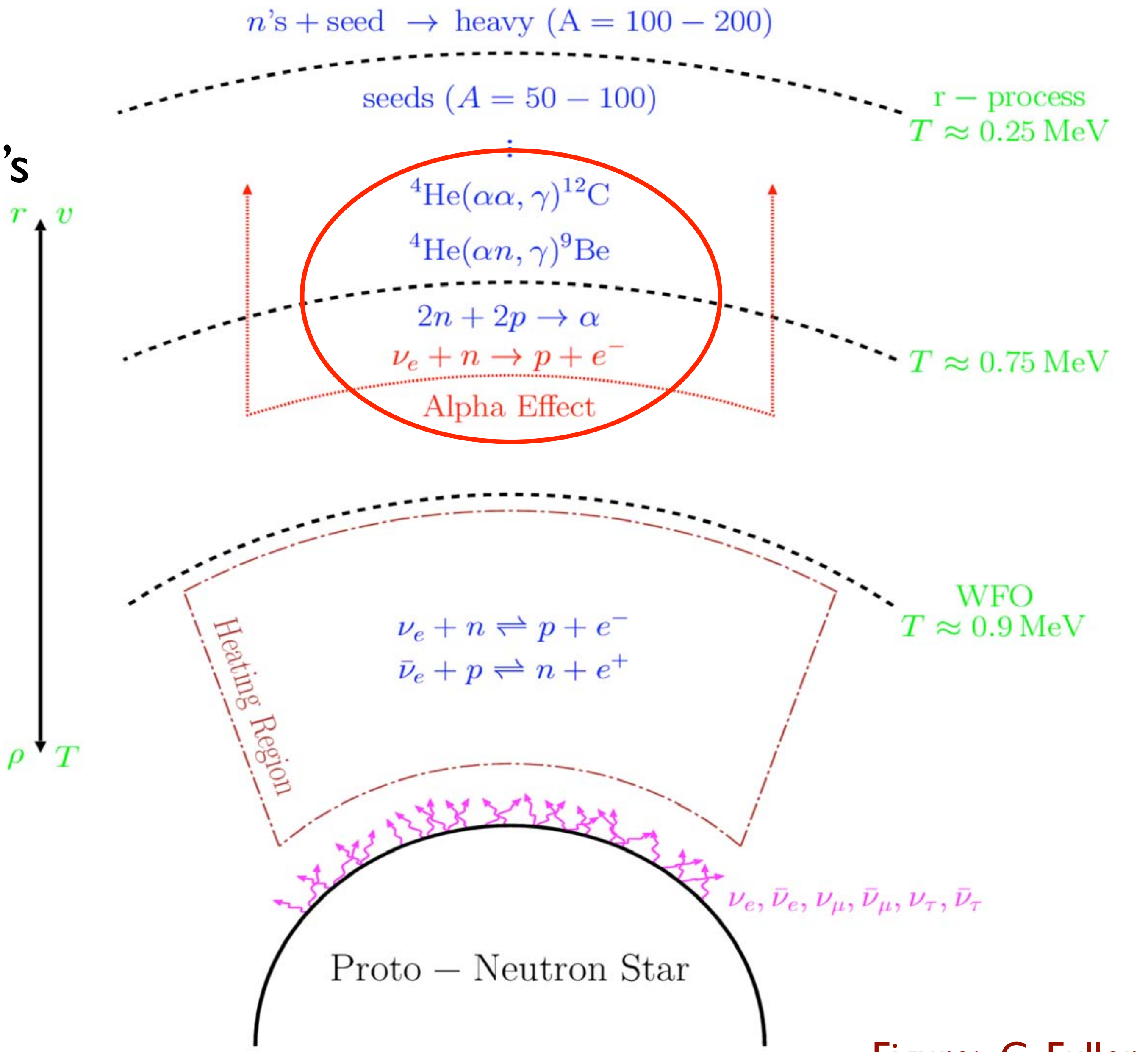

Figure: G. Fuller

- ❏ found to require very high entropies ~ 400 k, requiring fine-tuning in parametric studies, and 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

- ❏ three-body reactions (including those following ν breakup of ^{4}He) that increase the number of seeds, and thus diminish the n/seed ratio

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

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

very fast dynamic timescales required for expansion

- ❏ the α-process: the very 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

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

every ν reaction destroys two neutrons

INTEGRATED NUCLEOSYNTHESIS IN NEUTRINO DRIVEN WINDS

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

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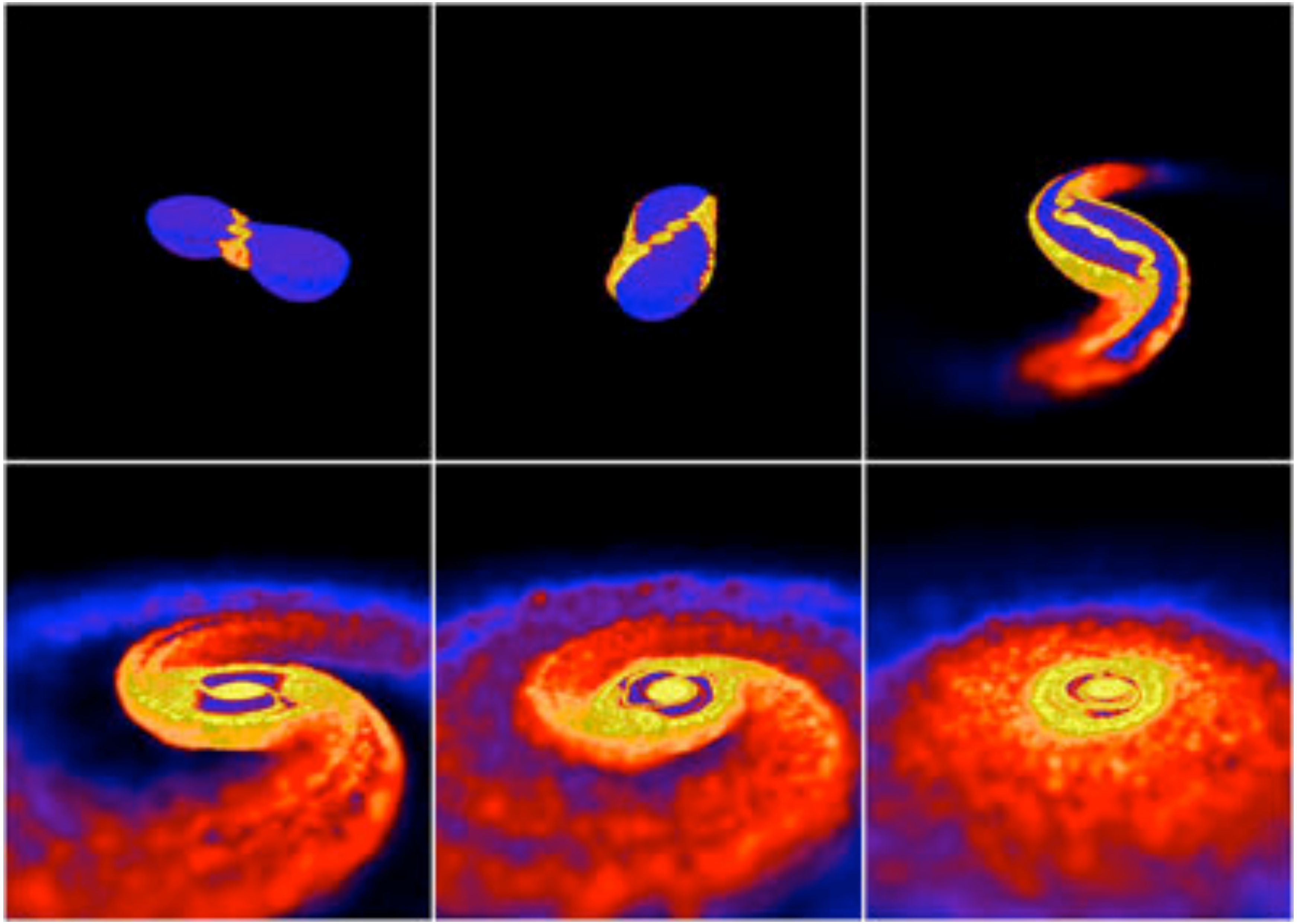
ABSTRACT

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.

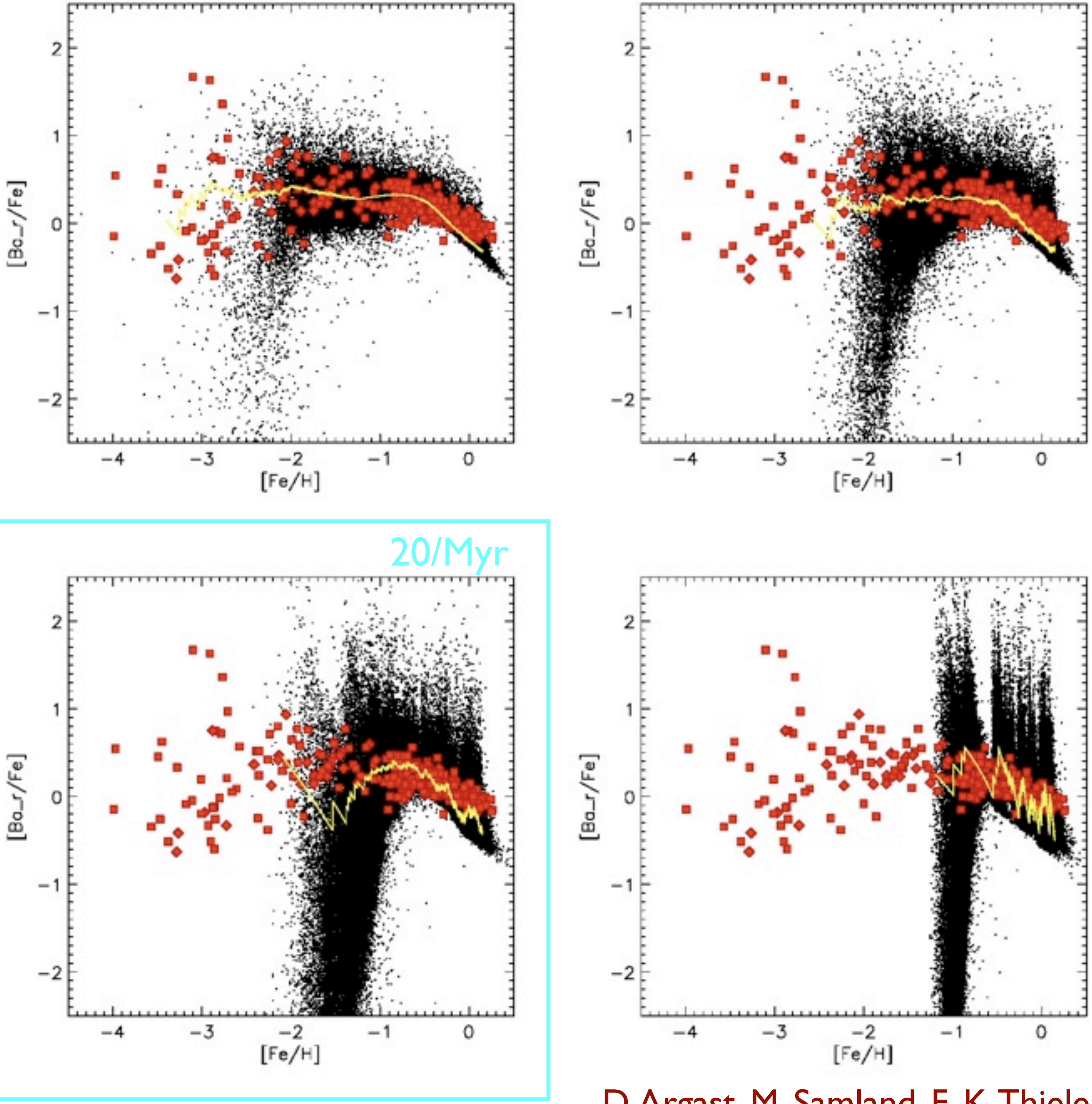
The issues appear to be rather generic for standard “hot” r-processes where the nucleon soup is initially at very high temperatures, where the neutron excess is modest, and where the neutrino flux is intense.

This is prompting reconsideration of other environments where the neutron/seed ratio might be easier to control, or where the neutron excess is so extreme that the neutron/seed ratio may not be problematic

One attractive alternate is NS mergers



neutron star merger: Flash Center, U of Chicago



galactic
chemical
evolution
constraints

Argast et al. 2004

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

Mixing: merger rate 10^{-2} - 10^{-3} that of SNII, while both kinds of events have similar ejection energies and thus mixing volumes

- ❏ any such mechanism will exhibit fluctuations at low metallicity reflecting local event-by-event statistics
- ❏ can be studied by looking at, e.g., r-process produces like Eu

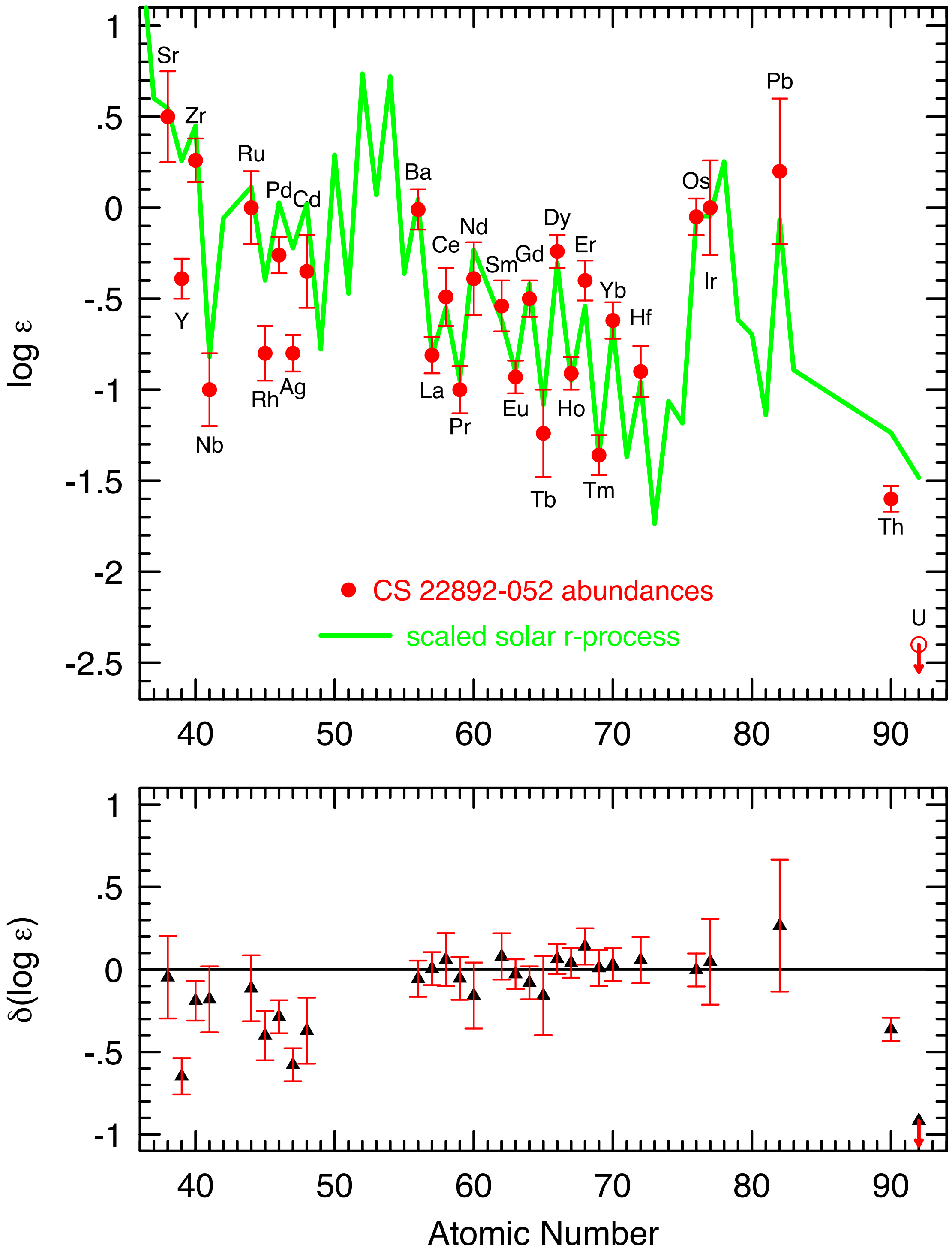
Statistics derived from MP star observations indicate a frequency ~ 1/100 y ~ SNII

Qian and Wasserburg

The NS mechanism is attractive in
1) having such large neutron excesses that it may not be subject to same kind of fine-tuning issues that arise for the hot bubble process;
2) having the potential to generate the bulk of r-process material.

But it has the two mentioned galactic chemistry issues that make it problematic as the source of MP star enrichments

Two other attributes of MP star data:

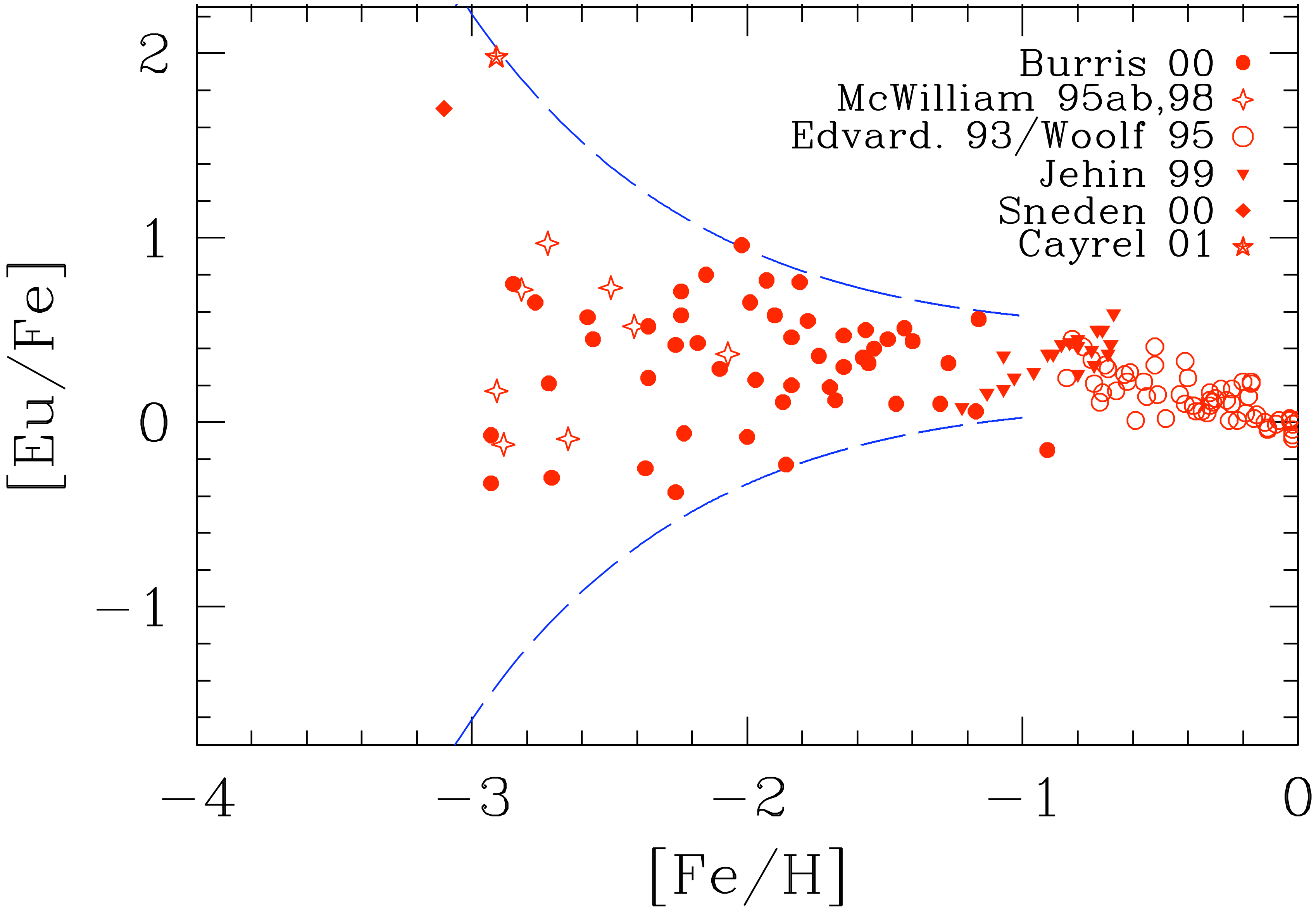


regularity of yields

scales to solar
r-process for
A > Ba

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

r-process yield to Fe variable in early stars



B. D. Fields, J. W. Truran, and J. J. Cowan, Ap. J. 575 (2002) 845

Appear to need an alternative SN mechanism, and we have some good hints as to its nature

❑ from the hot bubble "mechanism" we learn
  - the problem of seed proliferation is connected with the hot → cold nature of the explosive environments as well as the intense ν flux: no success in finding environments where the possible "work arounds" of high entropies and rapid expansions exist

❑ one might *want the robust universal r-process*, but what one *needs is an early r-process* with properties compatible with MP star data -- stable, SN associated, not rigidly co-produced with Fe
  - free NS (or other) mechanisms from MP star constraints
  - if one could bridge to Z ~ -2.5 and get lucky (no glitch in galactic chemical evolution at this Z) a multiple-site r-process explanation might emerge to solve a highly constrained problem

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

❏ based on two observations:
  - neutrons in the He zone of an SNII will capture efficiently on seeds
  - there is a neutron source, NC 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

❏ the n source is a continuous one, maintained in the star's He zone by the ν flux, with $\tau_{\nu\ \mathrm{cooling}} \sim 3\ \mathrm{s}$

R. Epstein, S. Colgate, W. C. Haxton, PRL 61 (1988) 2038

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 -- for reasons that require some explanation -- producing densities at or below ~ 10^{19} n/cm^3

- the path, while typical of other r-processes, is maintained by $(n,\gamma) \leftrightarrow \beta^-$ not $(n,\gamma) \leftrightarrow (\gamma,n)$
- the time needed to reach the transuranics is ~ 20 sec

❑ as advertised and explored previously, no neutron excess is produced: neutral currents separate n and p, under conditions where useful capture on Fe is fast compared with recombination channels

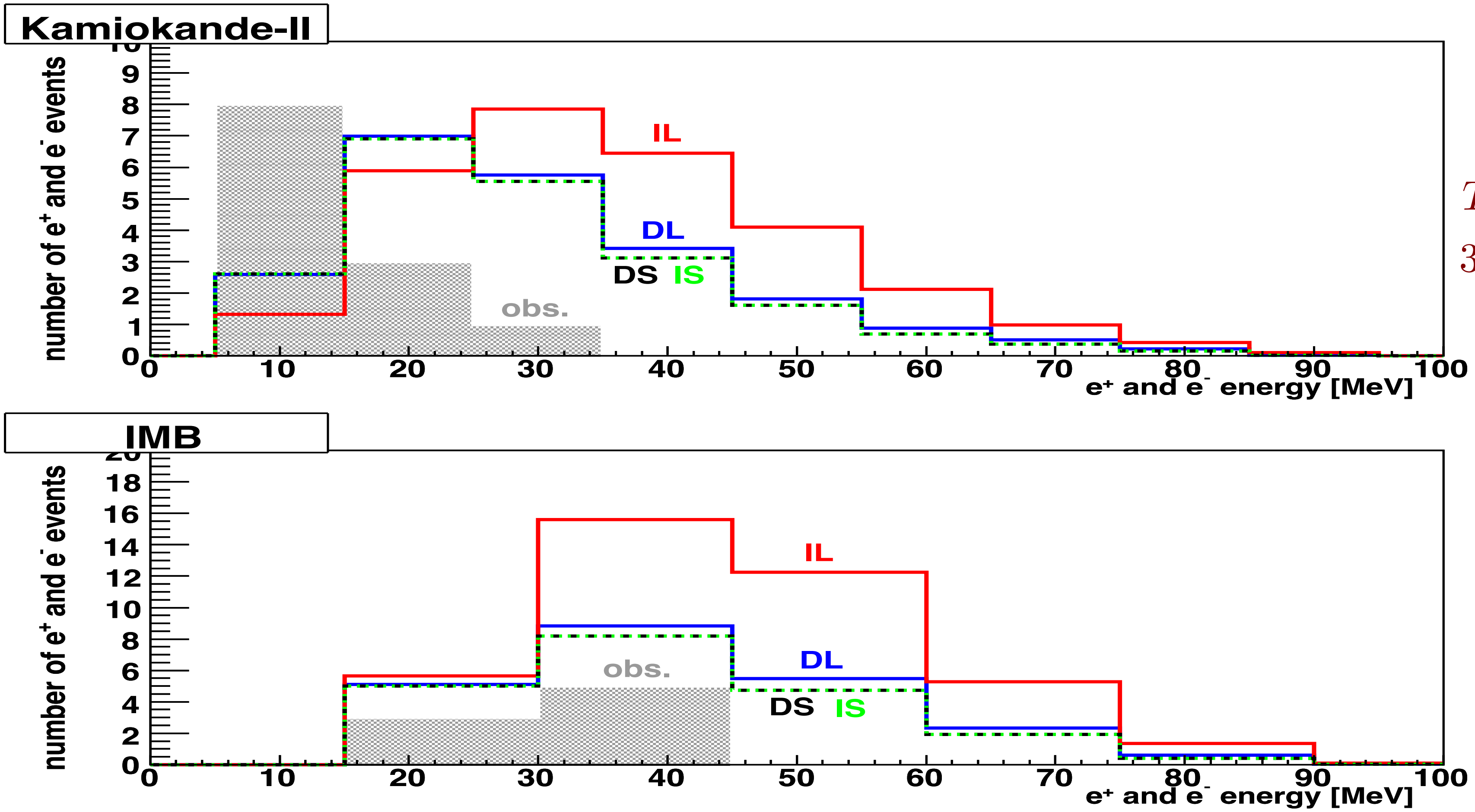
❑ however, the nuclear physics does not operate as advertised, as least in the simplest proposed environment, MP He shells

Contrasting Environments

ECH scenario	Current (Heger progenitor)
❑ r $\lesssim 10^9$ cm, $\rho \sim 3 \cdot 10^3 \text{ g/cm}^3$	❑ 10-17 $M_\odot,\ Z = 10^{-4} Z_\odot$ r $\sim 10^{10} \text{ cm},\ \rho \sim 50 \text{ g/cm}^3$
❑ T $\sim (2-3) \cdot 10^8 K$	❑ T $\sim 10^8 K$
❑ neutron poison: ^{14}N	❑ neutron poisons: $^{12}\text{C},\ ^{16}\text{O},\ ^{14}\text{N}$
❑ neutron source: NC	❑ neutron source: NC, CC oscillations
❑ $T_{\nu_{\text{heavy}}} \sim 9 \text{ MeV}$	❑ $T_{\nu_e}/T_{\bar{\nu}_e}/T\nu_{\text{heavy}} \sim 4/5.3/8 \text{ MeV}$ { SN1987A bounds inverted hierarchy

ok to view this
as a luminosity
fudge factor of ~ 3

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

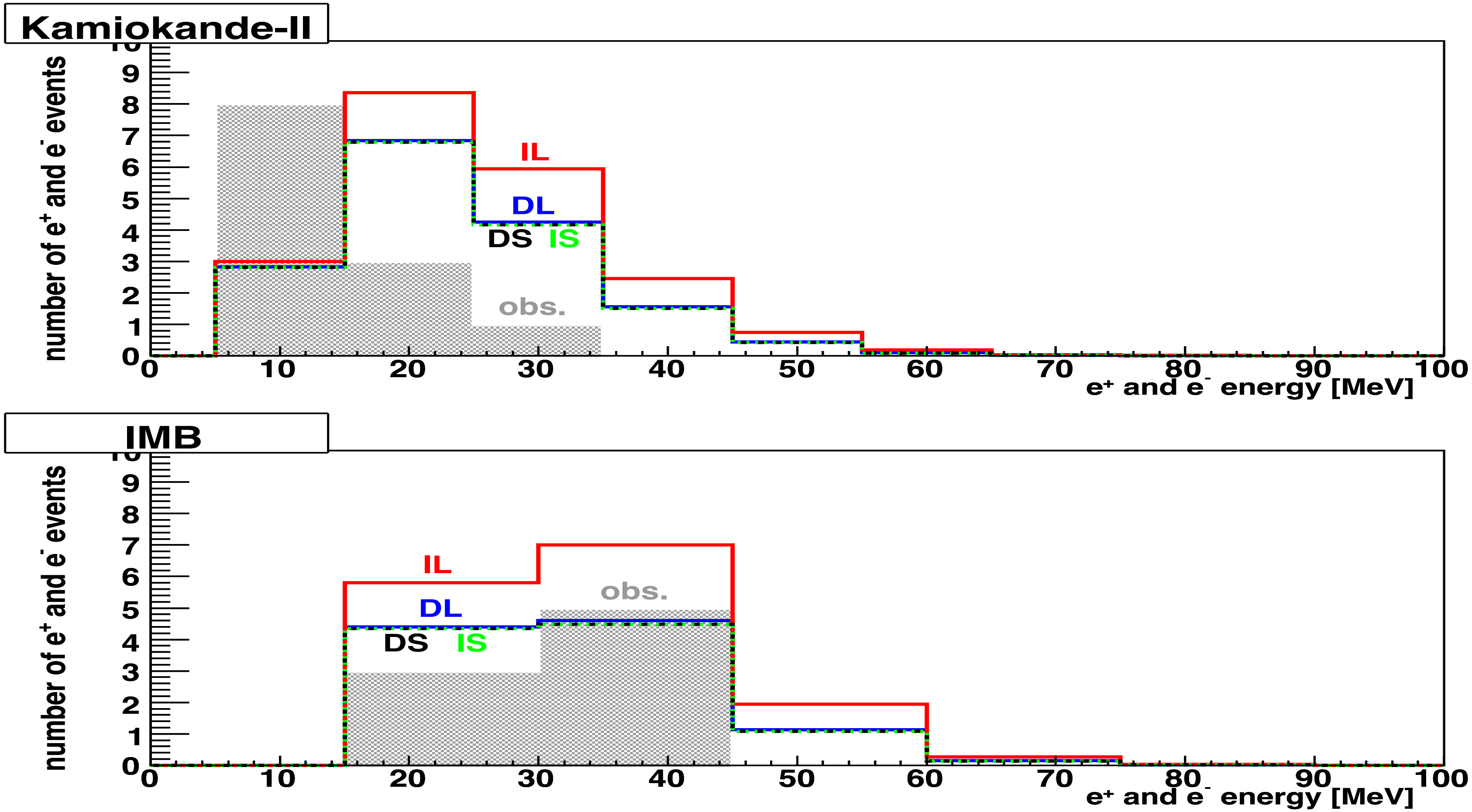


Fig. 3. The predicted e^+ and e^- energy spectra, in case the SN1987A production spectra are described by the "Analytic Fit Functions", for different combinations of mass hierarchy and Θ_{13}. For details see the description in Fig.2 and in text.

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

Contrasting Nuclear Physics

ECH scenario

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

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

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

Current

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

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

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

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

❑ three previous explorations of ECH were numerical: presumably did not recognize that few of the instantaneously NC-produced neutrons took part in the synthesis
    -- the theoretical efficiency of the mechanism could be significantly higher, if the Li sink were somehow avoided

❑ the CC current channel is significantly weaker, but would be enhanced through oscillations for an inverted hierarchy (IH)
    -- the degree depends on flavor temperature differences

❑ despite the losses, the process can work at very large radii
    -- the outer He shells of UMP Fe-core SN

❑ the process is calculable, and the astrophysical environment is realistic

❑ N, C, O not significant as neutron poisons

Dimensional checks of the dynamics

❑ He shell collapse time

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

❑ shock arrival time

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

❑ shock heating

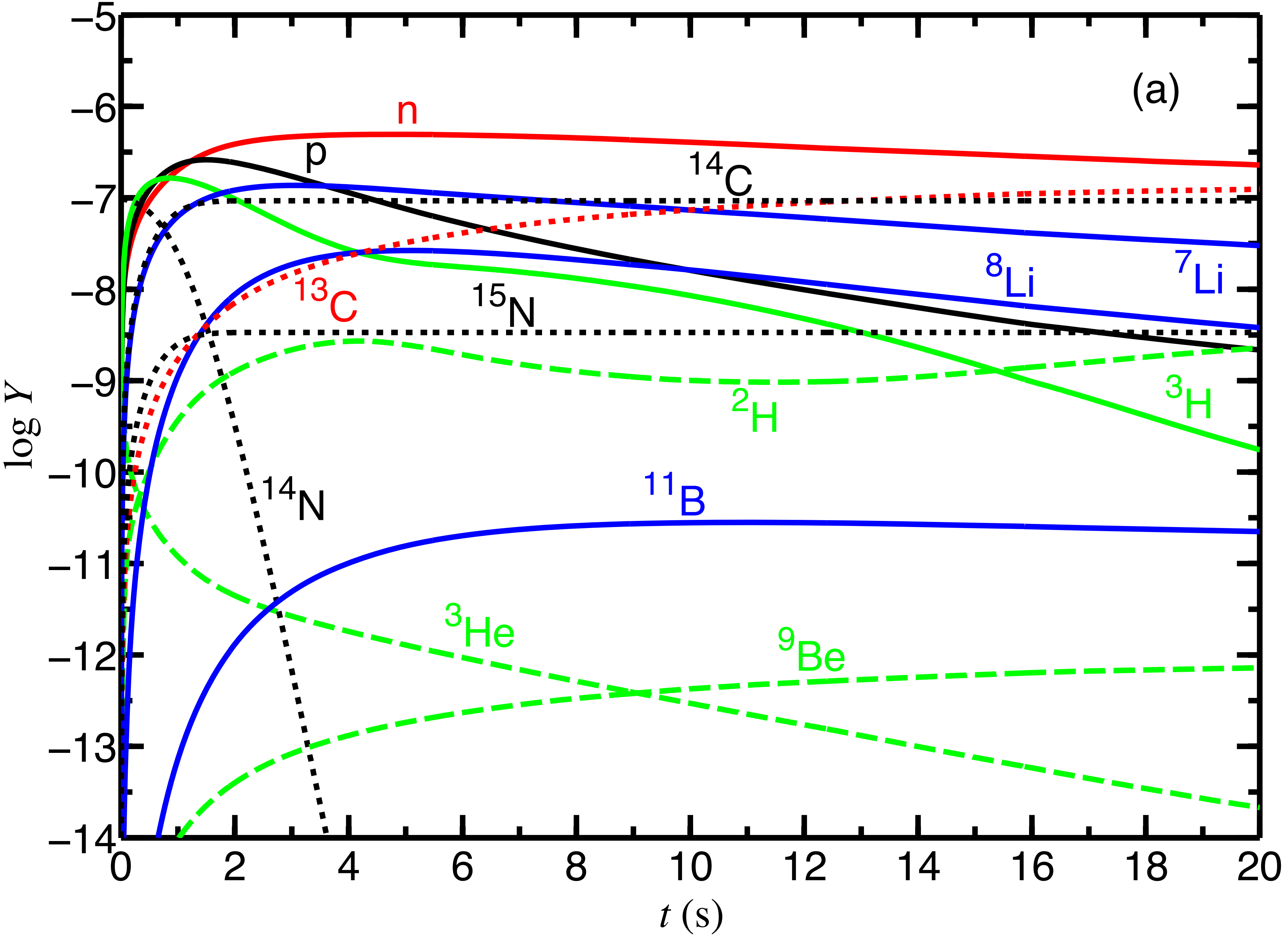
$$T_8^{\mathrm{peak}} \sim 2.4\ E_{50}^{1/4} r_{10}^{-3/4} < T_{\mathrm{r-process}}^{\mathrm{burnup}}$$

properties that relate synthesis to generic properties like the SN energy release ↔ high regularity possible

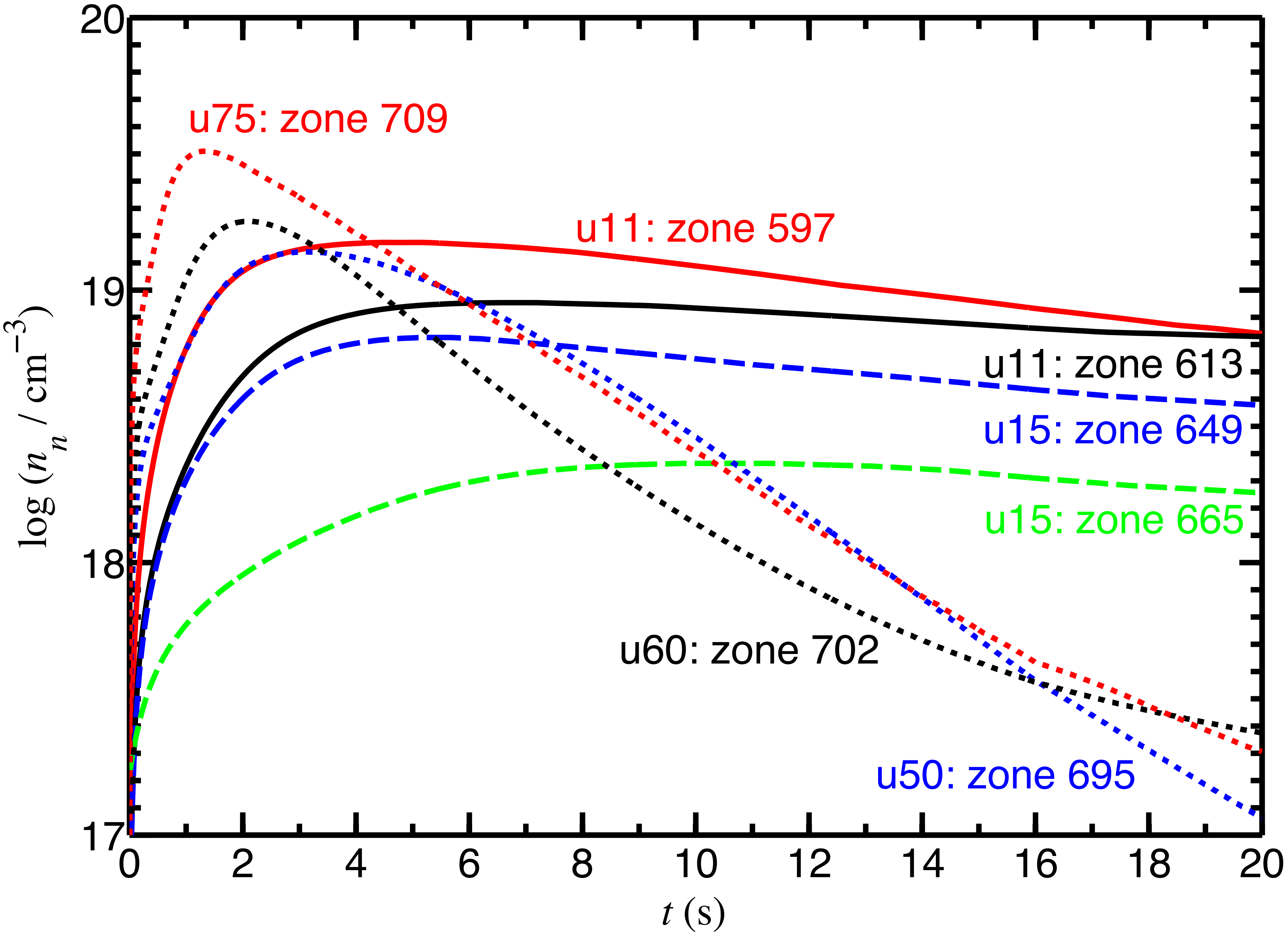
so outer He zones of Fe-core SN appear to be a particular simple environment for testing the mechanism

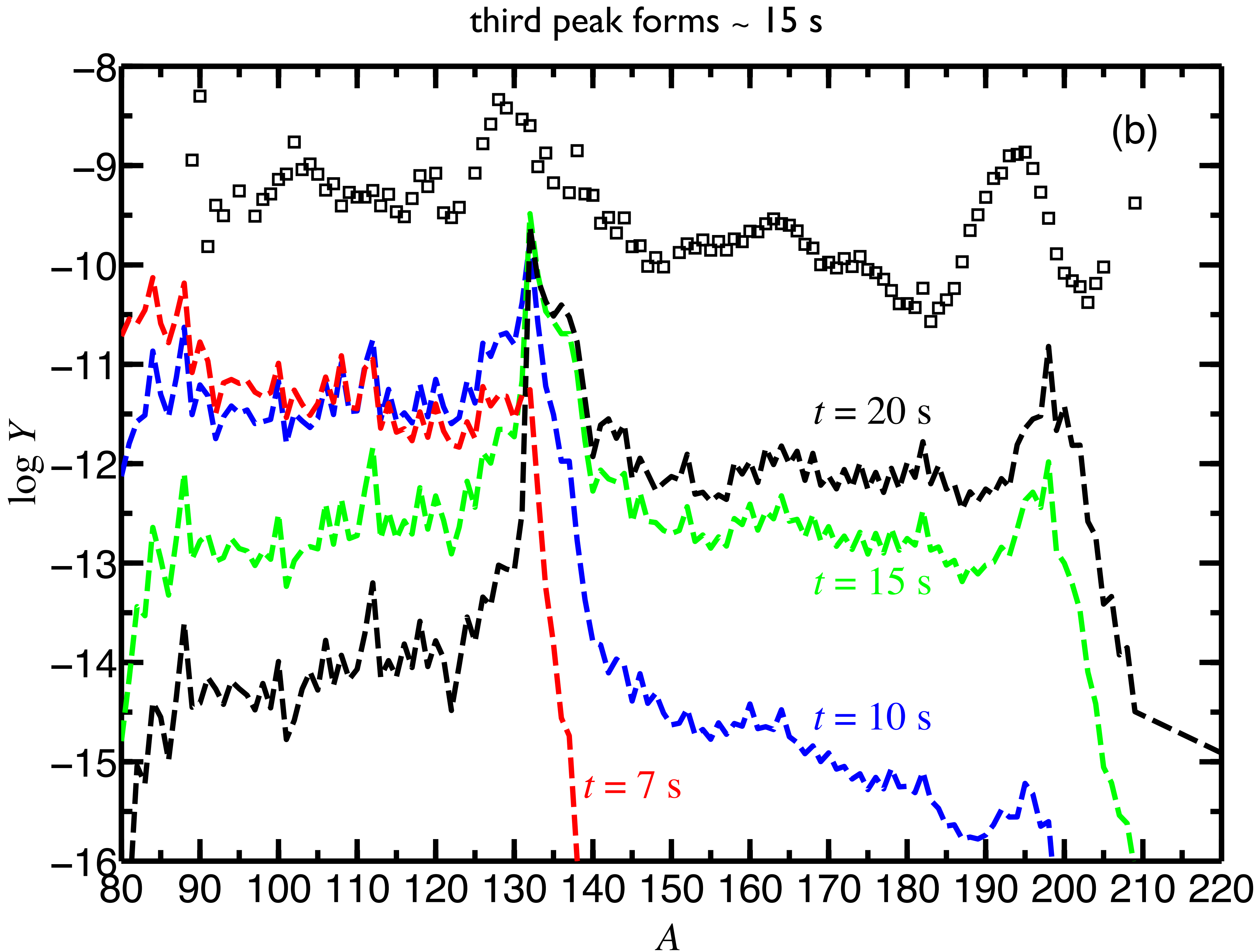
T_ν = 8 MeV, low-mass Fe core

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
(b)
log Y
A
−8
−9
−10
−11
−12
−13
−14
−15
−16
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
t = 20 s
t = 15 s
t = 10 s
t = 7 s

❑ long times not intrinsic to mechanism, but reflect 1) large radius 2) inefficiency of the NC channel 3) u11-u16 environment

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

❑ IH produces r-process conditions for Heger Fe-core models u11-u16 and u49-u75 for [Fe/H] between -4 and -3:
for u17-u48, H is an inhibiting n poison

❑ without oscillations, operates only near [Fe/H] ~ -4; with NH oscillations, the process does not operate [all conclusions in the context of standard MSW: no ν-ν effects]

❑ u49-u75 zones are hotter (2-3 $\times 10^8$K) and denser (200-600 g/cm^3), so that n-capture is completed in much shorter times

❑ IH yields at [Fe/H] = -4 are $\sim 10^{-8}$ M_{solar} which compares to the solar metal inventory of $\sim 4 \times 10^{-8}$ M_{solar}

❑ observed enrichments in MP stars with [Fe/H] < -2.5 are (3×10^{-4}) - 10^{-1} of solar: thus the ECH mechanism could be a candidate explanation

❑ r-process conditions are not found above [Fe/H] ~ -3

❑ yet neutron capture continues, mass continues to be added through such neutron bursts. This inventory greatly exceeds the r-process products discussed here, as it includes the integration over inner He and C/O shells, with both NC and CC neutron poison channels yielding ^{7}Li, ^{11}B, ^{13}C, ^{17}O, ... The consequences of such n "banks"...?

- new way to think of ν-process impact on galactic chemistry

❑ the post-shock phase is currently being explored, potentially interesting

- larger explosion energies > 1B limit the pre-shock phase to < 10s, and imply significant n densities in the compressed (×7) post-shock phase, where n-capture rates will be higher
- does the shock also produce unwelcome seeds?

❑ much stronger instantaneous neutron production is found in the inner He zone, where C and O are significant

  - neutrons are efficiently "banked" in the n sources ^{13}C, ^{17}O
  - are there conditions where subsequent shock-wave heating can release the neutrons, yet not lead to seed proliferation? (typical temperatures remain well below 10^9K)

❑ the original ECH proposal was to implement this process in more compact environments, below 10^9 cm, where neutron production is 100 times greater. The needed temperatures and radii are potentially available in expanding outflows, ONeMg core explosions, and in AI collapses. But what are the seed densities...?

Outlook

- ❑ several arguments suggest that a SN-associated r-process operated in the low-metallicity early galaxy
    - we have not been able to make the hot-bubble r-process work
    - the difficulties are associated with seed proliferation in highly explosive SN environments
    - these difficulties led us to explore an alternative, a cold SN r-process operating only at low metallicity

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

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

- ❑ does the mechanism operate in other, potentially more favorable sites (work in progress)? inner He zones, ONeMg core supernovae, late stages of neutrino-driven winds, ...

$$\text{figure of merit} \sim \left(\frac{T}{8\text{MeV}}\right)^5 \left(\frac{R}{10^{10}\text{cm}}\right)^2 \frac{\tau}{3\text{s}}$$

$$\text{plus adequate time for the nucleosynthesis}$$

❑ does it survive in the outer He zone when Kepler nuclear physics is improved?