Nucleosynthesis in Our Neighborhood

- Neutrino process
- Neutrino-generated neutrons: cold r-process, ^{9}Be
- ^{10}Be and the Cameron-Truran Hypothesis

Wick Haxton *INT* *18 August 2016*

Much of nucleosynthesis driven by neutron sources

❏ Big Bang: neutrons post beta-equilibrium
- capture in a proton-rich environment

❏ $p + p \rightarrow d + \gamma$ beta decay in main sequence stellar evolution
- regulates He synthesis, stellar evolution timescale

❏ s- and r-processes
- neutron-rich environments created by compression of nuclear matter, or by pre-existing sources like ^{13}C

Otherwise, neutrons are bound in metals, generally not available for driving nucleosynthesis

Neutrino process: SN neutrino sources can overcome nuclear binding energies, generating new nuclei and producing fluxes of spallation neutrons, protons

Neutrino process

❑ most of the interesting examples come from free-steaming neutrinos irradiating the C, Ne, He zones

❑ typically cross sections are dominated by neutral currents

$$\nu + A \to \nu' + A^* \qquad 3 \times 10^{-41} \mathrm{cm}^2/\mathrm{flavor}$$

typical energy transfers are 15-20 MeV (giant resonances)

heavy-flavor fluence through the middle of the Ne zone

$$\phi \sim \frac{4 \cdot 10^{57}}{4\pi (20000 \ \mathrm{km})^2} \sim 10^{38}/\mathrm{cm}^2$$

❑ consequently productions at the level of 1/300th of the major He-stable isotopes expected

Domagatsky and Nadyozhin, Ap. Space Sci. 1980
Woosley and Haxton, Nature 1988
Woosley, Hartmann, Hoffman, Haxton, Ap. J. 1990

One of the original examples is ^{19}F

- ❑ abundance relative to Ne: $\frac{^{19}\mathrm{F}}{^{20}\mathrm{Ne}} \sim \frac{1}{3100}$

- ❑ giant resonance excitation leads to breakup

typical energy transfers are 15-20 MeV (giant resonances)

$$^{20}\mathrm{Ne}(\nu,\nu')^{20}\mathrm{Ne}^* \rightarrow ^{19}\mathrm{Ne} + \mathrm{n} \rightarrow ^{19}\mathrm{F} + \mathrm{e}^+ + \nu_e + \mathrm{n}$$

$$^{20}\mathrm{Ne}(\nu,\nu')^{20}\mathrm{Ne}^* \rightarrow ^{19}\mathrm{F} + \mathrm{p}$$

- ❑ must follow the chemistry in a network calculation

$$^{15}\mathrm{O}(\mathrm{n},\mathrm{p})^{15}\mathrm{N} \quad ^{19}\mathrm{Ne}(\mathrm{n},\alpha)^{16}\mathrm{O} \quad ^{20}\mathrm{Ne}(\mathrm{n},\mathrm{p})^{19}\mathrm{F} \quad ^{19}\mathrm{Ne}(\mathrm{n},\mathrm{p})^{19}\mathrm{F} \qquad \sim 10^{-8}\mathrm{sec}$$

$$^{15}\mathrm{N}(\mathrm{p},\alpha)^{12}\mathrm{C} \quad ^{19}\mathrm{F}(\mathrm{p},\alpha)^{16}\mathrm{O} \quad ^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne} \qquad \sim 10^{-6}\mathrm{sec}$$

- ❑ burn-up when shock passes $^{19}\mathrm{F}(\gamma,\alpha)^{15}\mathrm{N}$

$[^{19}\mathrm{F}/^{20}\mathrm{Ne}]/[^{19}\mathrm{F}/^{20}\mathrm{Ne}]_\odot$	$T_{\mathrm{heavy}\ \nu}(\mathrm{MeV})$	
0.14	4	protected by 23Na
0.6	6	
1.2	8	
1.1	10	F destroys itself
1.1	12	

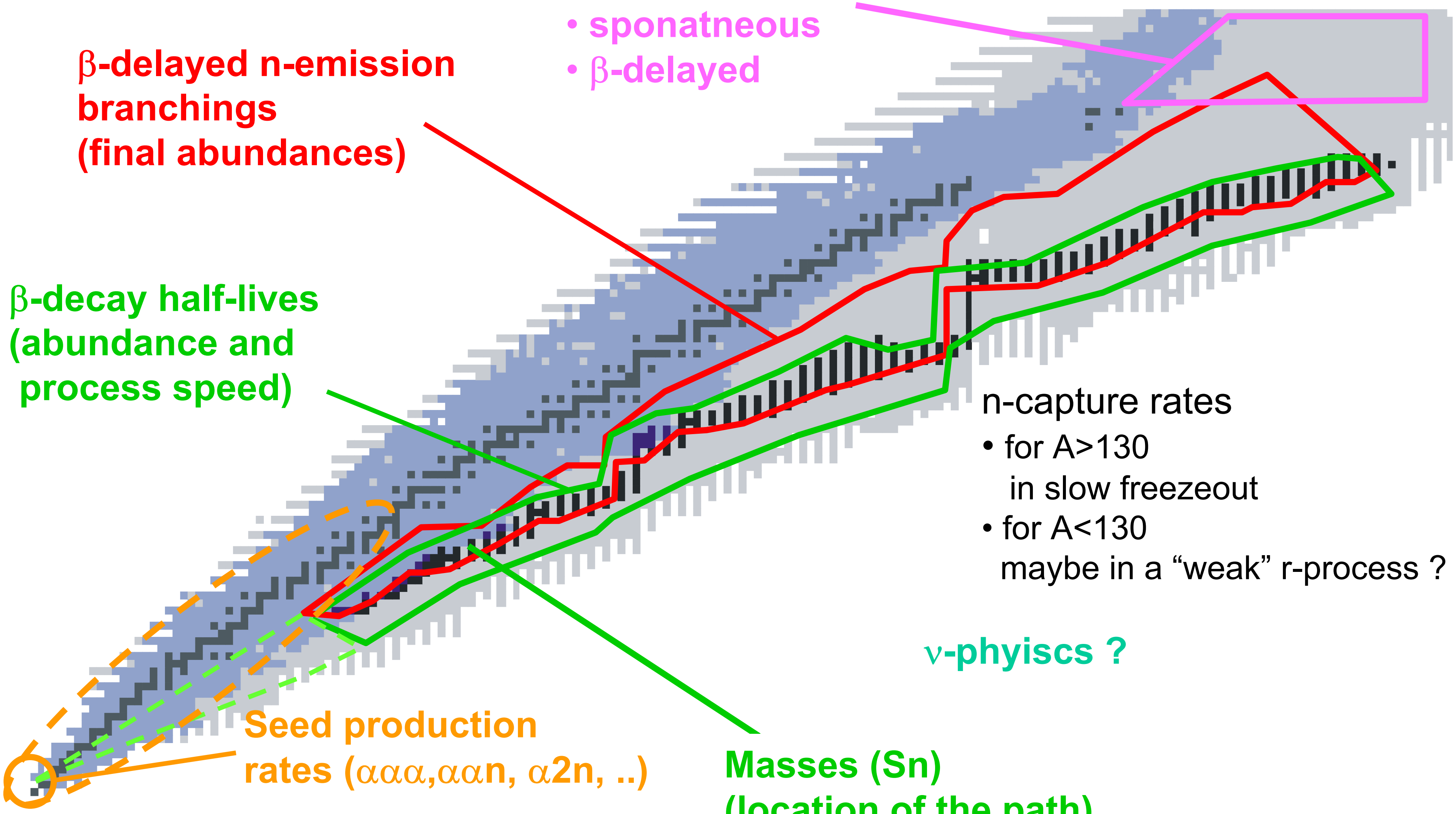
TABLE II: Production factor relative to solar normalized to ^{16}O production as a function of T_{ν_e} (for charged current only) and using 6 MeV for the μ and τ neutrinos.

star	product	(no ν)	(no ν_e)	4 MeV	6 MeV	8 MeV
15 $M_\odot$	^{11}B	0.011	1.509	1.899	3.291	—
	^{15}N	0.396	0.480	0.486	0.530	—
	^{19}F	0.375	0.577	0.643	0.914	—
	^{138}La	0.190	0.279	0.974	1.734	2.456
	^{180}Ta	0.599	1.016	2.751	4.628	6.026
25 $M_\odot$	^{11}B	0.004	0.828	1.170	2.384	—
	^{15}N	0.039	0.112	0.118	0.157	—
	^{19}F	0.105	0.300	0.366	0.643	—
	^{138}La	0.106	0.192	0.901	1.604	2.244
	^{180}Ta	1.382	2.360	4.238	6.238	7.102

charge current products

Heger, Kolbe, Haxton, Langanke, Martinez-Pinedo,Woosley,

Renewed interest in nu-process: r-process motivation



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 (ααα,ααn, α2n, ..)

Masses (Sn) (location of the path)

From Schatz

P. Banerjee, WH, Y-Z Qian, PRL 106, 201104 (2011)

Neutrino-wind supernova r-process

- entropies higher than those typical produced in simulations needed

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

- fast dynamic timescales to inhibit three-body seed-forming reactions

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

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

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

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

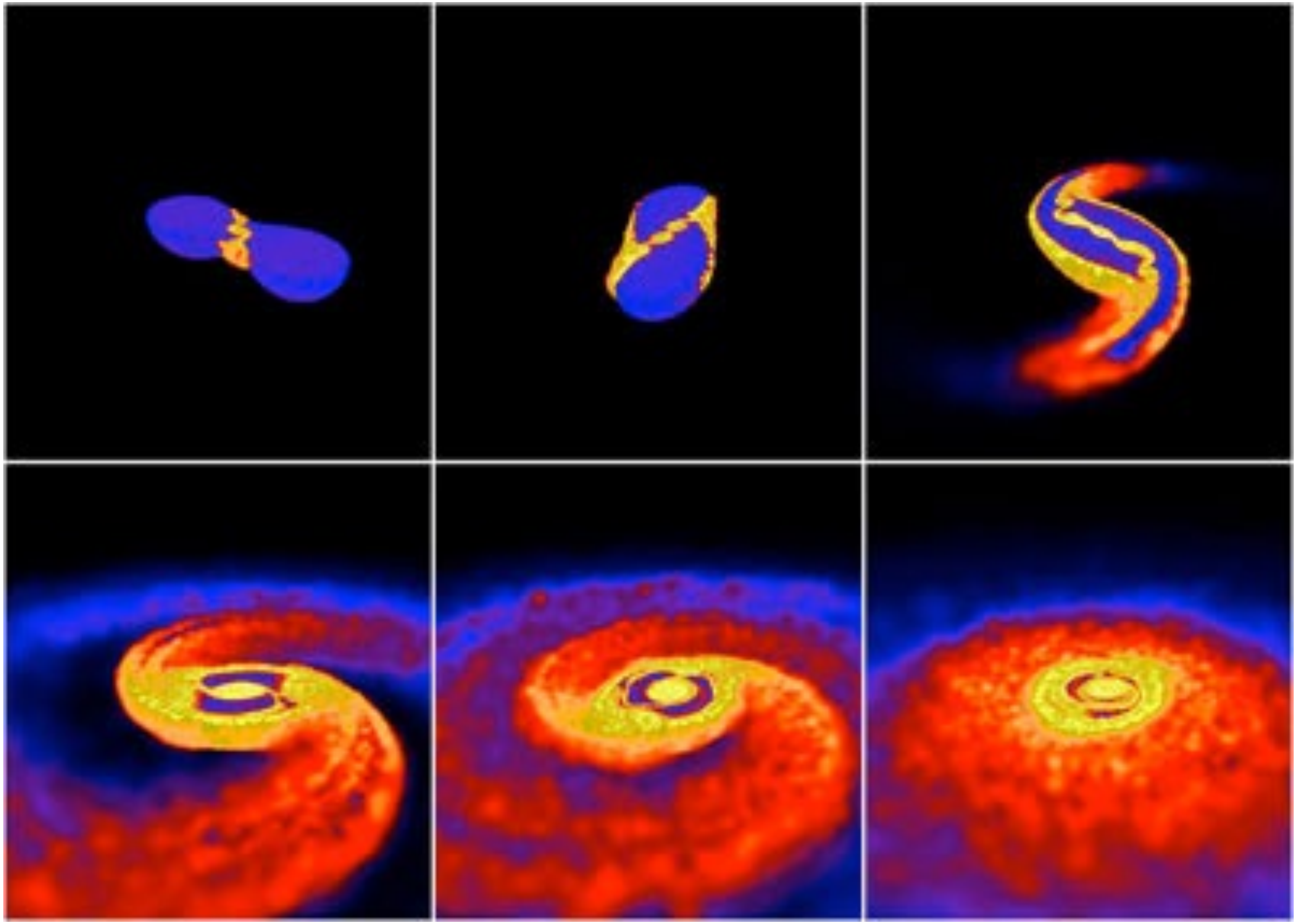
every ν reaction destroys two neutrons

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

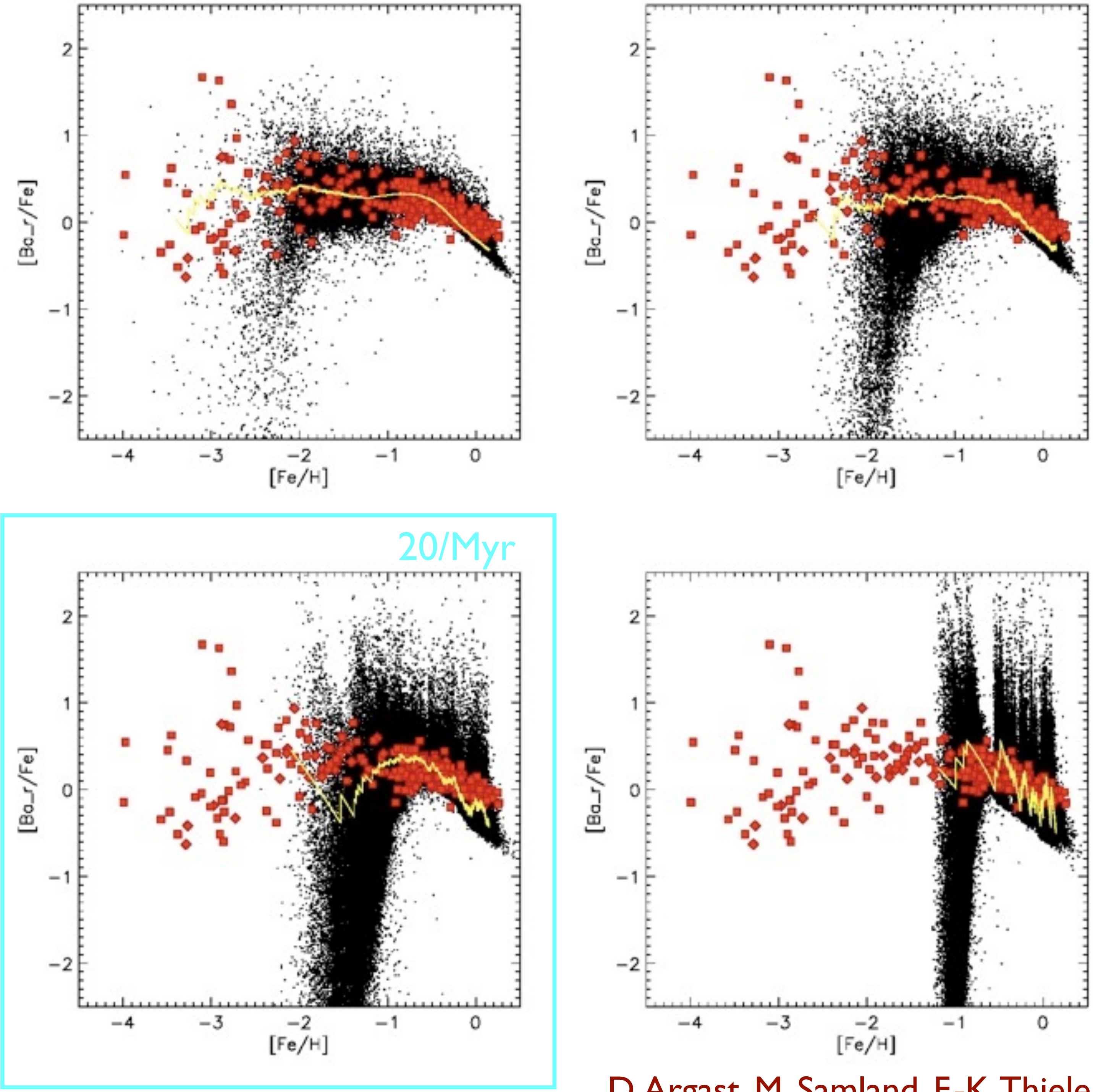
- productions may be limited to N=50 closed-shell nuclei

L. Roberts, S. Woosley, R. Hoffman

Neutron star mergers: alternative site, very neutron-rich



neutron star merger: Flash Center, U of Chicago



galactic
chemical
evolution
constraints

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

Both kinds of events have similar ejection energies, mixing volumes

But NS mergers thought to be 10^2-10^3 times less frequent
consequently they must produce proportionately more r-process material, and thus yield local larger local enrichments early in our galaxy's history, before it was chemically mixed

Europium statistics uncertain, but perhaps suggest a frequency of nucleosynthetic events in the early galaxy closer to SN rates than to NS merger rates Qian and Wasserburg

Thus a combination of arguments led us to examine the scenario:

- NS mergers manufacturing the bulk of galactic metals, with the vast majority of synthesis occurring at [Fe/H] > 0.01
- SNe contributing an early times, where the neutron/seed ratio is favorable, through a mechanism that avoids seed proliferation

Key ideas:

- the well-known physics of BBN, where neutrons introduced in He persist for long times due to the absence of A=5
- that the figure of merit, n/seed ratio, is easier to achieve at very low metallicity

ECH mechanism of a neutrino-driven r-process in the SN's He shell, but with better nuclear physics and focused on environments where [Fe/H] << 0.01 $[\mathrm{Fe/H}]_\odot$

parameters: $\tau_{\text{collapse}} \sim 100\ \text{sec}$ (quasi-static process)

$$\tau_{\text{shock}} \sim \frac{22\ \text{sec}}{E_{50}^{1/2}}$$ (mostly pre-shock)

$$T_{\text{peak}} \sim 2.4 \times 10^8\ \text{K}$$ (products survive)

neutron production primarily via: $^4\text{He}(\bar{\nu}_e, e^+\text{n})^3\text{H}$

As the standard MSW "atmospheric" crossing occurs in the C zone, the mechanism is sensitive to oscillations, potentially enhanced given an inverted hierarchy $\bar{\nu}_x \leftrightarrow \bar{\nu}_e$

The path is a cold one: $(\mathrm{n}, \gamma) \leftrightarrow \beta^-$ equilibrium

Neutron abundances are modest: $\sim 10^{19}/\mathrm{cm}^3$

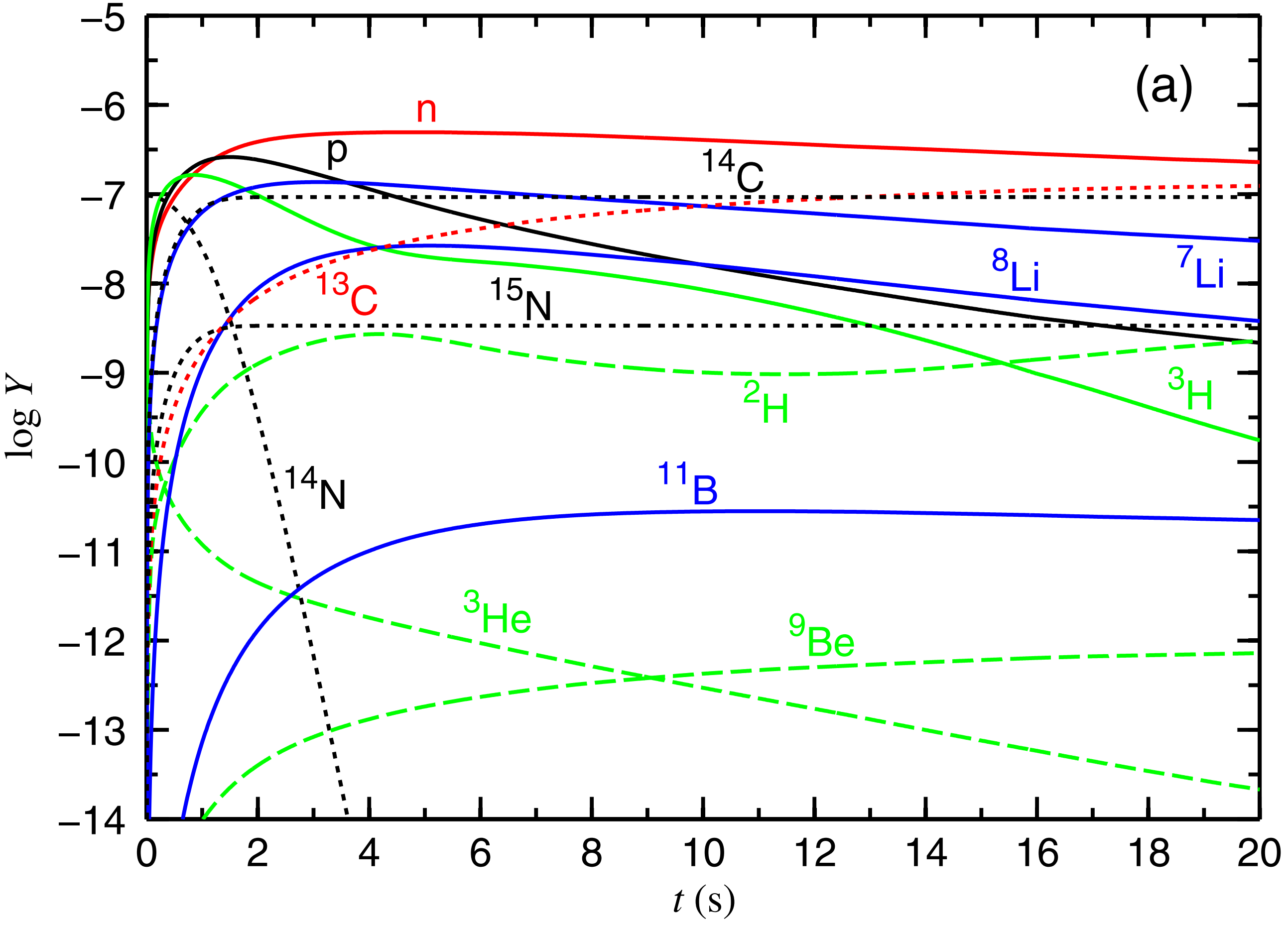
Neutron lifetimes are very large, to and beyond 100 sec

Thus the abundance is established in the explosion, then depleted over much longer times

The neutrons are consumed in all scenarios: e.g., absorbed on metals (smoothing distributions), banked as ^{13}C, …

Three parameters can be played off against one another

- the effective $\bar{\nu}_e$ temperature: production scales as T^5
- the radius of the He shell: $\phi \sim 1/R^2$
- the metallicity: n/Fe ratio plus competing poisons



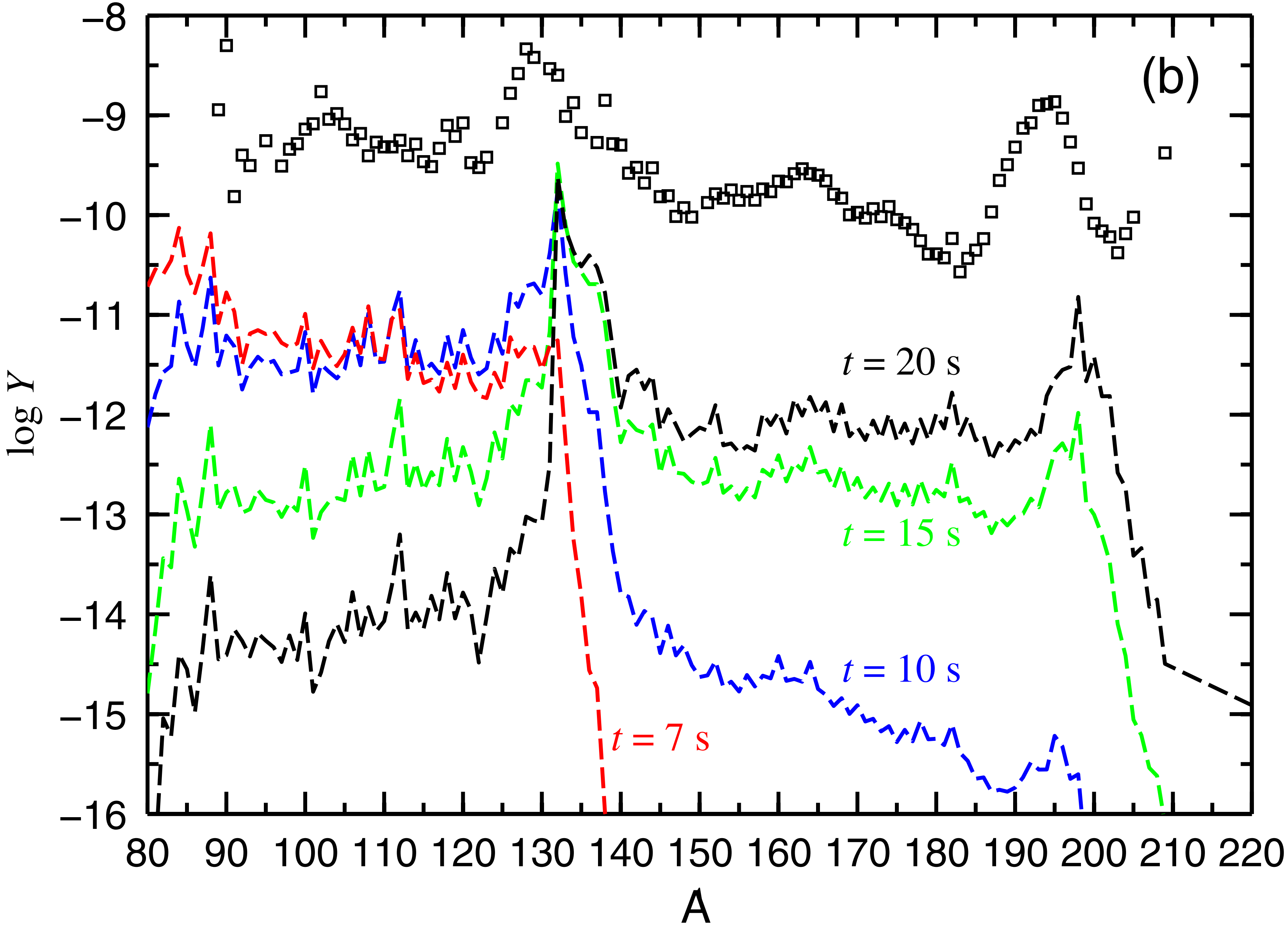
11 solar mass

[Fe/H] = 10^{-4}

r = 1.1 10^{10} cm

but

$T_{\bar{\nu}_e}^{\rm eff} = 8$ MeV


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

As one turns down $T_{\bar{\nu}_e}^{\text{eff}}$, the synthesis remains interesting, but falls short of a full r-process

If one requires the A=130 mass peak to form, e.g., then

$$[\text{Fe}/\text{H}] \sim 10^{-4} \qquad T_{\bar{\nu}_e}^{\text{eff}} \sim 5 \text{ MeV}$$

forms a minimum baseline.

Oscillations with a normal hierarchy turn off the production entirely.

Total yields of r-process material is typically 10^{-8} $M_\odot$

Under metallicity conditions that rule out an r-process, the net increase in heavy mass would remain 10^{-8} $M_\odot$

P. Banerjee, Y-Z Qian, WH, A Heger, PRL 110, 141101 (2013)

^{9}Be production

Long-running debate about the original of the rare light isotopes LiBeB

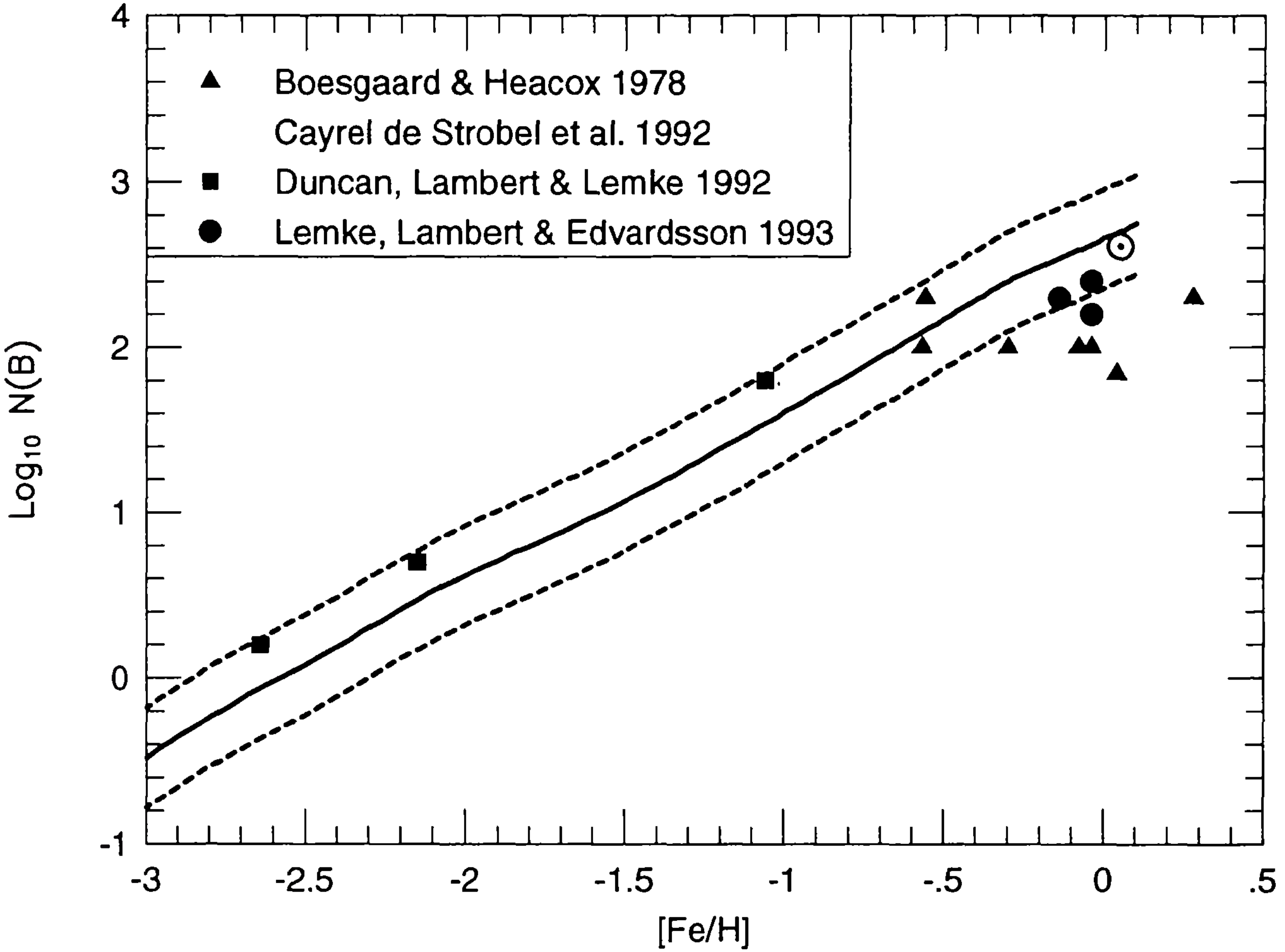
Classic explanation has been cosmic-ray production: high-energy protons interacting with C, O in the interstellar medium, fragmenting the target

The neutrino process, however, was found to produce a great deal of ^{11}B and very significant ^{7}Li

As a high-energy process, the CR mechanism tends to produce comparable amounts of the various isotopes, e.g., $^{10}\mathrm{B}/^{11}\mathrm{B} \gtrsim 0.5$

Neutrino process is low-energy, produces $^{10}\mathrm{B}/^{11}\mathrm{B} \sim 0.1$

Observed abundance ratio is $^{10}\mathrm{B}/^{11}\mathrm{B} \sim 0.24$



Timmes,
Woosley,
Weaver
ApJ Suppl 98, 617

Growth of B abundance roughly linear with [Fe/H], at least at low metallicity: more consistent with a primary process (like the ν process) than a secondary process (like CR spallation)

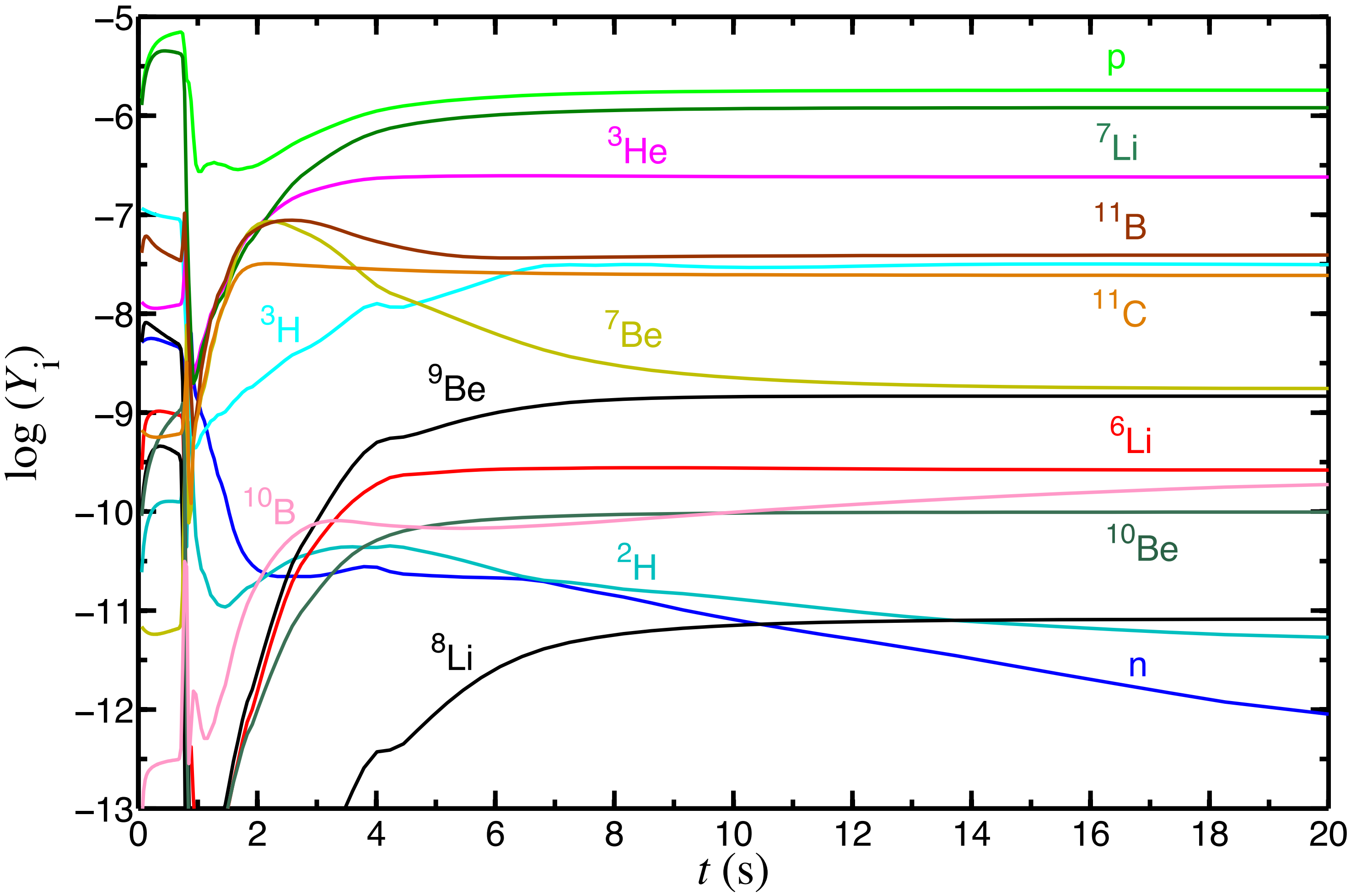
Perhaps the most consistent explanation would be roughly equal contributions from the two processes, the ν process likely dominating at early times, the CR process turning on later:

Isotopic ratios like ^{10}B/^{11}B and ^{6}Li/^{7}Li then might evolve in interesting ways

The counterargument to this has been the rarest isotope ^{9}Be - thought to be a CR product exclusively, and thus requiring the CR process to operate in the early galaxy

Yet log(Be/H) runs linearly (with a slope of 0.9-1.0) with log(O/H), log(Mg/H), log(Ti/H), log(Fe/H), all primary CCSN products

In fact, two SN mechanisms for producing ^{9}Be emerged from the recent ν process studies



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

Low metallicity, weak explosions yields a kind of mini-r-process:

$$^7\mathrm{Li}(\mathrm{n},\gamma)^8\mathrm{Li}(\mathrm{n},\gamma)^9\mathrm{Li}(e^-\bar{\nu}_e)^9\mathrm{Be}$$

that operates prior to shock arrival, survives shock hearing

But also $^7\mathrm{Li}(^3\mathrm{H},\mathrm{n}_0)^9\mathrm{Be}$ after shock arrival, in the expanding wind

The data and available mechanisms seem to suggest:

1. early production of 9Be in SN, with a linear growth in the integrated yield
2. later production by CRs, which could lead to a steeper growth with metallicity
3. comparable yields for the two processes, to account for the Li and B isotopic ratios

the last would suggest that the isotopic ratios evolve with metallicity

P. Banerjee, Y-Z Qian, A Heger, WH, submitted to Nature Comm.

A Supernova Trigger for Solar System Formation?

Suggestion by Cameron and Truran, prompted by the observation of very large enrichments of ^{26}Mg, daughter of ^{26}Al $(\tau \sim 1 \text{ Myr})$, in solar system solids

The shock wave from the parent SN would then be the event that triggered collapse of the SS's primordial gas cloud

Scenario consistent with simulations

But the pattern of SLRs (short-lived radioisotopes) confusing, when compared to theoretical studies employing (typically) CCSN models $\gtrsim 15 M_\odot$

Problems:

1) excessive isotope shifts in stable isotopes - Mg, Si, Ca, Fe, Ni

2) difficulties is matching the relative abundances of ^{10}Be, ^{26}Al, ^{41}Ca - with ^{10}Be assumed to be a spallation product from an early solar system episode of intense radiation, also affecting ^{26}Al, ^{41}Ca

3) significant overproduction of ^{53}Mn, ^{60}Fe

Most of these problems due to assumptions in previous work
- earlier studies focused on the wrong class of supernovae
- assumed ^{10}Be synthesized by intense irradiation/spallation, when in fact it is produced readily by $^{12}\mathrm{C}(\nu,\nu' pp)^{10}\mathrm{Be}$

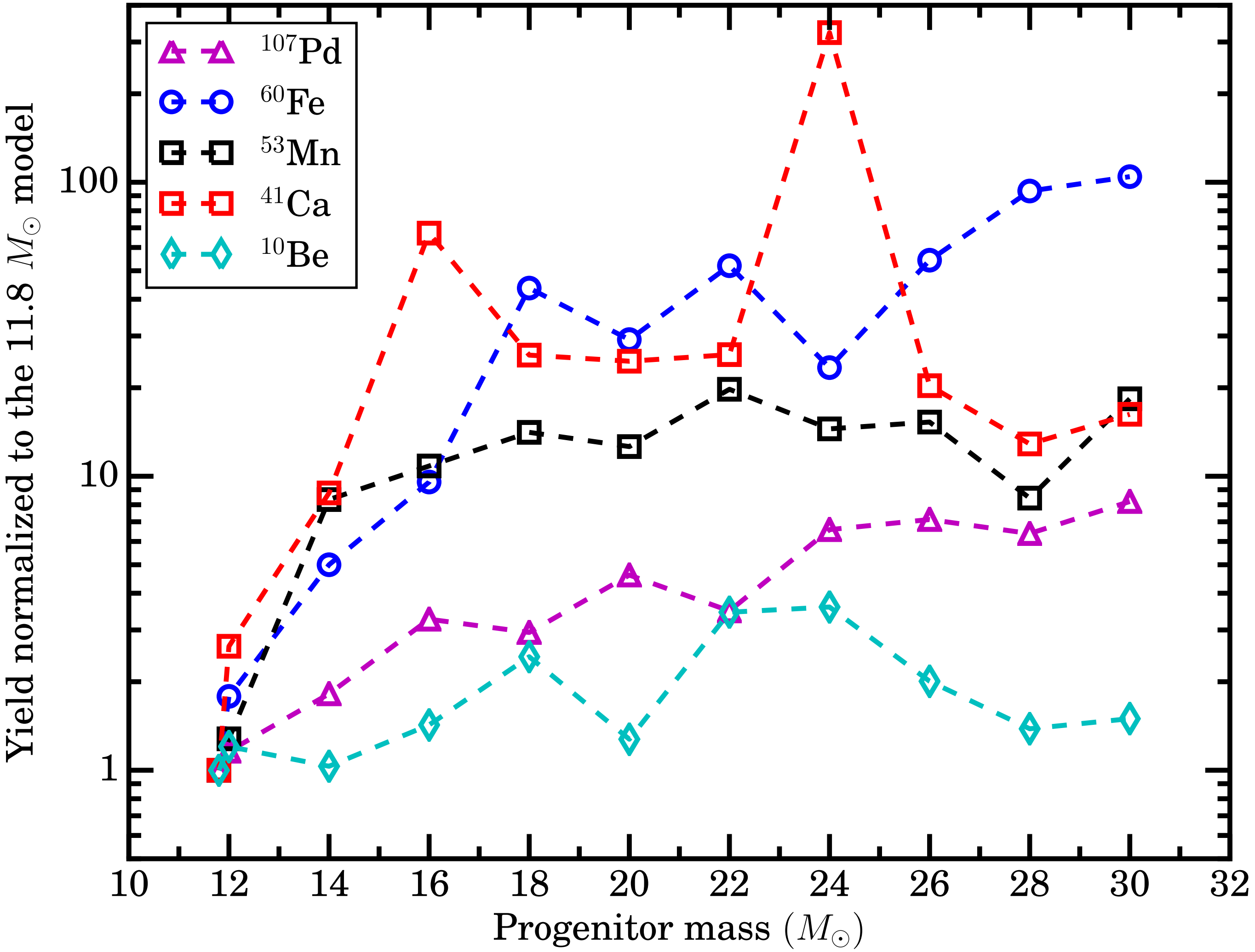
ν process production remains high in low-mass Fe-core SNe - lower C-zone masses compensated by more favorable 1/R^2

Simulations done with Kepler

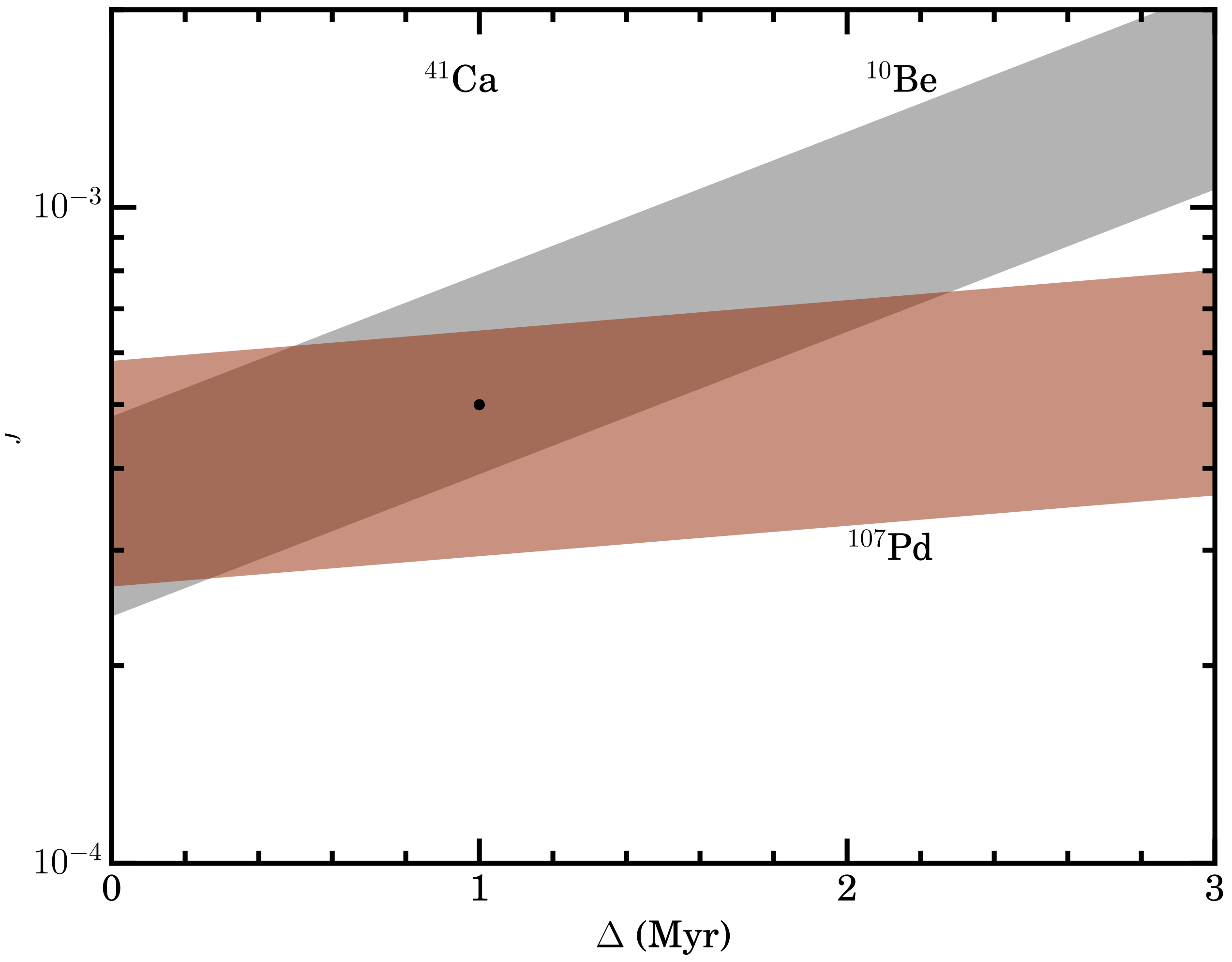
Explosion modeled by a piston, with the velocity matched to the explosion energies from more sophisticated calculations

Neutrino temperatures:

$$T_{\nu_e} \sim 3\ \mathrm{MeV},\ T_{\bar{\nu}_e} \sim T_{\nu_\mu} \sim T_{\nu_\tau} \sim T_{\bar{\nu}_\mu} \sim T_{\bar{\nu}_\tau} \sim 5\ \mathrm{MeV}$$



^{60}Fe, ^{53}Mn overproductions + small stable isotope anomalies + ^{10}Be all seem to point to a very light iron-core SN



11.8 M$_\odot$

occurring 1 Myr
before SS solids
formed

This scenario seems to improve every aspect of the fit to the data

And the overall picture simplifies - no need, for example, for an additional mechanism for ^{10}Be

Still some issues: while the overproduction of ^{53}Mn is significantly mitigated - reduced by an order of magnitude - there remains an overproduction by a factor of 60

This requires more work: ^{53}Mn originates from very deep within the star — the innermost 0.01 $M_\odot$ of the ejecta

No other production is associated with this inner material.

More realistic simulations might be able to test whether this material is indeed ejected

Summary

The Cameron-Truran observation that SN-associated isotopes in SS solids suggests a trigger for SS formation, appears to be in much better shape than previously believed

Several lines of argument suggest a very low mass progenitor

The one clear and remaining discrepancy is ^{53}Mn - though even that problem is now less severe

This isotope is unusual in its production, a fact that might motivate more sophisticated explosion modeling

THANKS to my collaborators! P. Banerjee, Y.-Z. Qian, A. Heger
(and to Sanjay's TC that triggered these collaborations)