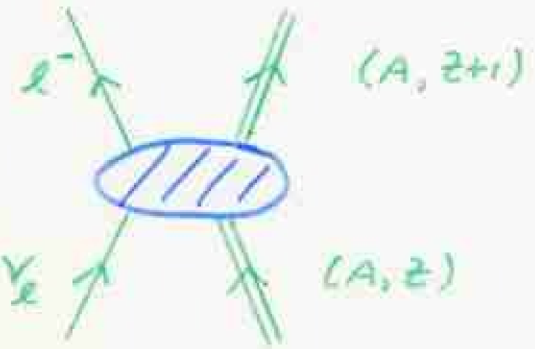
TMU
June 10
1998

THE NUCLEAR PHYSICS OF SOLAR AND SUPERNOVA NEUTRINO DETECTION

- nuclear responses to low energy neutrinos
- ^{37}Cl as an example
- supernova neutrinos
- the r-process & the ν-process

review of neutrino-nucleus interaction



standard model at low energies $\underset{\text{effectively}}{\longrightarrow}$

$$H(x) = \frac{G_F}{\sqrt{2}} J_\mu(x) J^\mu(x)$$

$$\frac{G_F}{\sqrt{2}} \sim \frac{e^2}{M_W^2}$$

$$H \longrightarrow \frac{G_F}{\sqrt{2}} \bar{u}(\ell) \gamma_\mu (1-\gamma_5) u(\nu_\ell) \int e^{i(k_f - k_i)x} J^\mu(x)$$

$J^\mu(x)$ is nuclear current operator

$$\underset{\text{schematically}}{\sim} \sum_{i=1}^{A} j^\mu(x_i) + \text{corrections}$$

	V	A
charge	$e_i \delta(\vec{x}-\vec{x}_i)\, \tau_+(i)$	$g_A\, \delta(\vec{x}-\vec{x}_i)\, \vec{\sigma}_i \cdot \frac{\vec{p}_i}{M}\, \tau_+(i)$
3-current	$\frac{\vec{p}_i}{M}\, \delta(\vec{x}-\vec{x}_i)\, \tau_+(i)$	$\vec{\sigma}_i\, \tau_+(i)$

$$\Rightarrow \quad O(1) + O\left(\tfrac{v^2}{c^2}\right) \qquad O\left(\tfrac{v}{c}\right) + O\left(\tfrac{v}{c}\right)$$

$$O\left(\tfrac{v}{c}\right) + O\left(\tfrac{v}{c}\right) \qquad O(1) + O\left(\tfrac{v^2}{c^2}\right)$$

but constrained by current conservation

where the "corrections" are contributions due to two-body currents, e.g.

$\Rightarrow$ lots of work in nuclear physics to do low energy nuclear physics rigorous in language of effective field theories: systematic treatments of relativity, multibody currents, ... P/A long wave length response of nuclei

$$e^{i(\vec{k}_f-\vec{k}_i)\cdot\vec{x}} \sim 1$$

$$\Rightarrow |(\vec{k}_f-\vec{k}_i)| << \frac{1}{R_{nucleus}}$$

$$\sim \frac{1}{\text{few fermis}} \quad (197\,\text{MeV-f})$$

$$\sim 40\,\text{MeV}$$

non-relativistic limit $\frac{v}{c}\Big|_{\text{nucleons in nucleus}} \sim 0.1 \sim 0$

$\Rightarrow$ only two operators remain

Fermi operator $\sum_{i=1}^{A} \tau_+(i) = T_+$ (J_0^{vector})

Gamow-Teller operator $\sum_{i=1}^{A} \vec{\sigma}(i)\tau_+(i)$ $(\vec{J}^{axial})$

$\Rightarrow$ control response of detectors to solar neutrinos $E_\nu \lesssim 15$ MeV

Isospin a good approximate symmetry of the nucleus ⇒ Fermi operator can be evaluated independent of any details of nuclear wave function

e.g.

$^{17}O(gs)$ $\xrightarrow{\text{Fermi}}$ $^{17}F(gs)$ $T = \frac{1}{2}$ $m_T = -1/2$

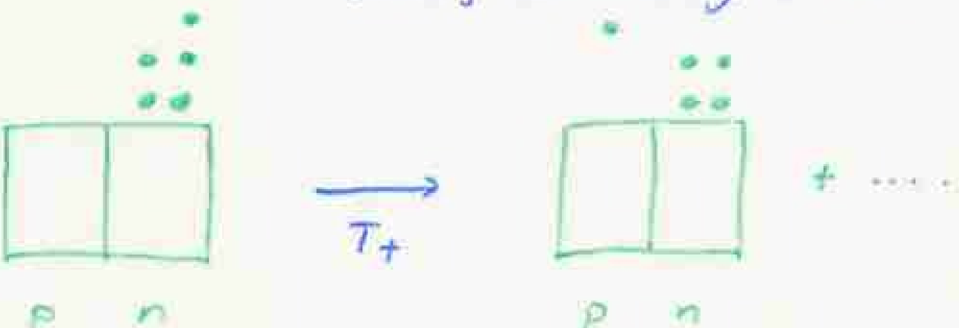
$T = \frac{1}{2}$ $m_T = -\frac{1}{2}$

$$\left| \langle ^{17}F | \sum_{i=1}^{A} \tau_+(i) | ^{17}O \rangle \right|^2 = 1$$

$= |N - Z|$ ← sum rule

sum rule exhausted by one state, the analog state

e.g.



$T = 5/2$
$m_T = -5/2$

(clearly the analog state,
$T = 5/2$
$m_T = -3/2$,
is an excited state

g.s. has $T = 3/2$ $m_T = -3/2$

Gamow-Teller operator much more complicated

- $g_A \sum_{i=1}^{A} \sigma(i)\tau_+(i)$ can connect parent nucleus ground state to many states in final nucleus

GT resonance $\langle E_{ex} \rangle \sim 15$ MeV

- satisfies Ikeda sum rule

$$\sum_f \left(|\langle f| \sum_{i=1}^{A} \sigma(i)\tau_+(i) |i\rangle|^2 - |\langle f| \sum_{i=1}^{A} \sigma(i)\tau_-(i) |i\rangle|^2 \right)$$

$$= 3(N-Z)$$

$\sim$ (ν_e, e^-) − $(\bar{\nu}_e, e^+)$ response constrained

often very small: blocked by neutron excess

⇒ generally need to find some way to measure or accurately calculate this for neutrino detectors

Supernova neutrinos $\langle E_{\text{HEAVY FLAVOR } \nu} \rangle \sim 25$ MeV
(0-80 MeV)

$\Rightarrow$ momentum transfer to nucleus is sufficiently high to begin to see radial profile of nucleus, not just total spin, isospin

e.g. $e^{i\vec{k}\cdot\vec{x}} \sim 1 + i\vec{k}\cdot\vec{x}$

$\Rightarrow$ get a series of operators

$$\sum_{i=1}^{A} \vec{x}_i \, \tau_+(i)$$

$$\sum_{i=1}^{A} [\vec{x}_i \otimes \sigma(i)]_{J=0,1,2} \, \tau_+(i)$$

and include v/c corrections

$$\Rightarrow \sum_{i=1}^{A} \vec{\sigma}_i \cdot \frac{\vec{\nabla}_i}{M} \, \tau_+(i) \qquad \text{axial charge}$$

together called first forbidden operators

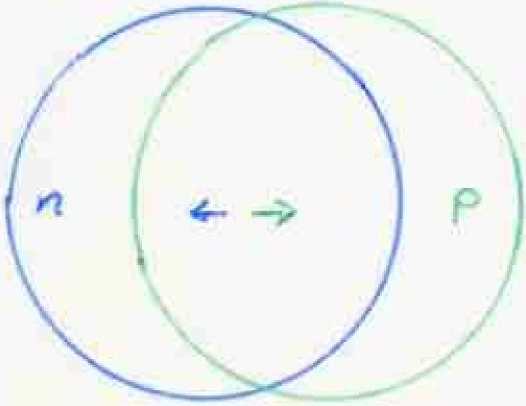
generate negative parity transition

e.g., consider analogous E1 operator of electromag.

$$\sum_{i=1}^{A} \vec{x}(i)\, \tau_3(i)$$

↑ moves protons, neutrons in opposite direction

⇒ collective resonance



harmonic mode

$\hbar\omega \sim 20$ MeV

↑ determined by the "spring constant" – calculable from the nuclear symmetry energy

+ various axial generalizations

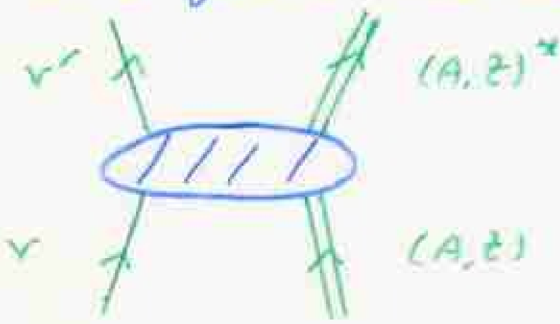
$$n\uparrow p\downarrow \longleftrightarrow n\downarrow p\uparrow$$

- related in spin-isospin SU(4) models
- satisfy TRK sum rule & spin generalization

$$\sum_f |\langle f| \sum_{i=1}^{A} x(i)\tau_+(i) |i\rangle|^2 \sim \frac{NZ}{A} \sim \frac{A}{4}$$

- highly collective

• could continue same game with neutral currents



essentially same except

• no analog of Fermi operator for inelastic scattering
(coherent scattering only)

• isovector axial current is purely isovector

$$\Rightarrow GT_{NC} \sim \sum_{i=1}^{A} \sigma(i)\, \tau_3(i)$$

• could continue with higher multipoles, etc. ⇒ Fermi gas response examples of nuclear physics issues: solar & supernova neutrino physics

solar neutrinos

- $p+p \rightarrow D + e^+ + \nu_e$ must be calculated, including two-body current (~2%) ...

- what is the cross section for Cl detector? Ga detector?

- 6% of all solar neutrino reactions in SuperK are off trace quantities of ^{18}O (abundance 0.2%) Is this a problem? (HW)

supernova mechanism

- how does a core collapse supernova produce a neutron star?

  electron capture on nuclei ⟺
  neutrino production and trapping ⟺
  nuclear excitations and the entropy

Solar Fusion Cross Sections

Eric G. Adelberger, Sam M. Austin, John N. Bahcall, A. B. Balantekin, Gilles Bogaert, Lowell S. Brown, Lothar Buchmann, F. Edward Cecil, Arthur E. Champagne, Ludwig de Braeckeleer, Charles A. Duba, Steven R. Elliott, Stuart J. Freedman, Moshe Gai, G. Goldring, Christopher R. Gould, Andrei Gruzinov, Wick C. Haxton, Karsten M. Heeger, Ernest Henley, Calvin W. Johnson, Marc Kamionkowski, Ralph W. Kavanagh, Steven E. Koonin, Kuniharu Kubodera, Karlheinz Langanke, Tohru Motobayashi, Vijay Pandharipande, Peter Parker, R. G. H. Robertson, Claus Rolfs, R. F. Sawyer, N. Shaviv, T. D. Shoppa, K. A. Snover, Erik Swanson, Robert E. Tribble, Sylvaine Turck-Chièze, John F. Wilkerson

astro-ph/9805121 (Rev. Mod. Phys., October 1998)

Two recommendations:

$S_{17}(0) = 22.4$ eV b $\rightarrow$ 19^{+4}_{-2} eV b, 1σ

$S_{34}(0)$: $\begin{cases} 0.507 \pm 0.016 \text{ keV b} \\ 0.572 \pm 0.026 \text{ keV b} \end{cases}$ capture γ activity

$\rightarrow$ 0.53 ± 0.05 keV b

- neutrino reheating of matter: delayed shock mechanism
- neutrino generated convection

supernova neutrino detection

- how ^{16}O in SuperK provides a test of $\nu_e \leftrightarrow \nu_\tau$ oscillation

- how do we experimentally determine the flux and flavor of the neutrinos emitted in the next supernova?

nucleosynthesis

- origin of Li/Be/B $\leftrightarrow$ HST measurements

- the origin of the heavy elements

Detector cross section

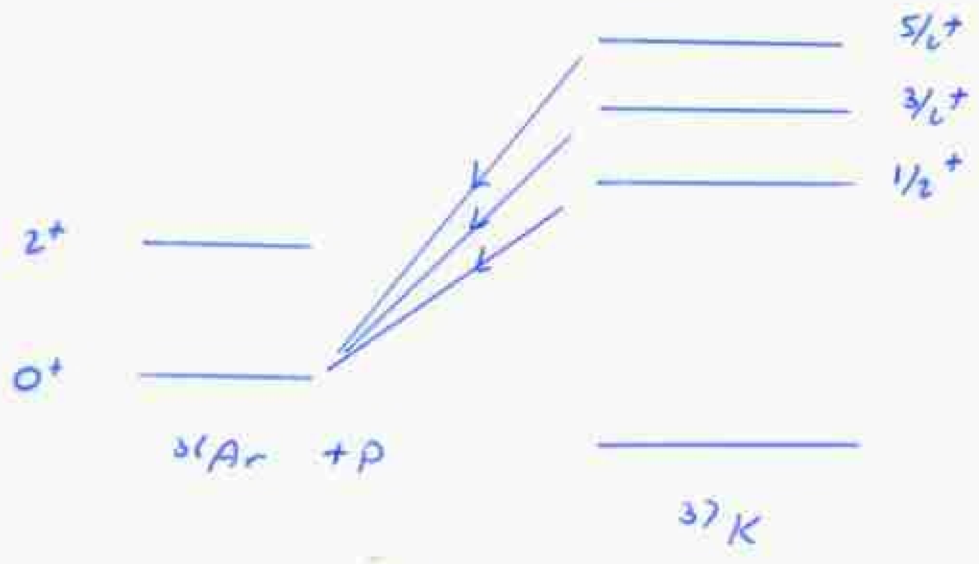
• $^{37}_{17}Cl_{20}(\nu,e)^{37}_{18}Ar_{19}$ ⟶ $^{37}_{20}Ca_{17} \to {}^{37}_{19}K^{*}_{18}$

$\hookrightarrow p + {}^{36}Ar$

β

delayed protons give strength and position of GT transition

model-dependent part of cross section



Garcia et al ⇒ ISOLDE $p + \gamma$ coincidence

$\sim 3\%$ uncertainty in $\sigma(^8B)$

Technique could be applied to $A = 40$

⇒ ICARUS

Neutrino observatories $\tau \gtrsim 30$ years
for supernova $\nu_e \leftrightarrow \nu_\mu$

- Super K

  - $E_{\bar{\nu}_e}$

  - $\nu_e + e^- \to \nu_e + e^-$ rate $\propto L_{\nu_e}$

    $\Rightarrow$ not affected by oscillation

    look for more "hard" events,
    but difficult...

  - $\nu_e + {}^{16}O \to {}^{16}F + e^-$

    $\Rightarrow$ modest back angle enhancement
    of $e^+ + e^-$ events

- Iodine ν_e flavor specific detector

  - Ken Lande's 1 kiloton detector
    $\gtrsim 100$ events for galactic supernova

  - recent IUCF GT measurements

$$\frac{\sigma^{\text{oscillations}}}{\sigma^{\text{no oscillations}}} \sim 6.4 - 6.9$$

$\Rightarrow$ rate increase of ~ 2.9

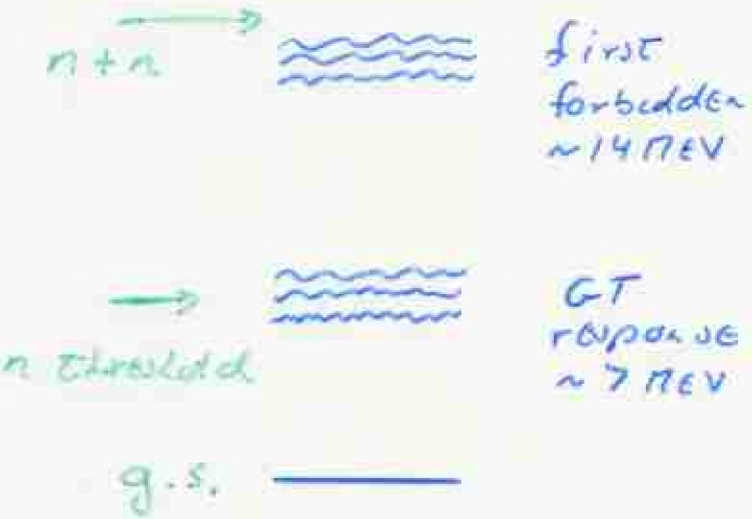
- neutron spallation detectors (OMNIS, LAND)
  - attractive experimentally because large volumes can be actively instrumented
  - generally not well suited to $\nu_e \Leftrightarrow \nu_\tau$ studies: not flavor specific

charged + neutral current responses ⟷ spectrum slope, $\bar{E}$ uncertainties

difficult to disentangle

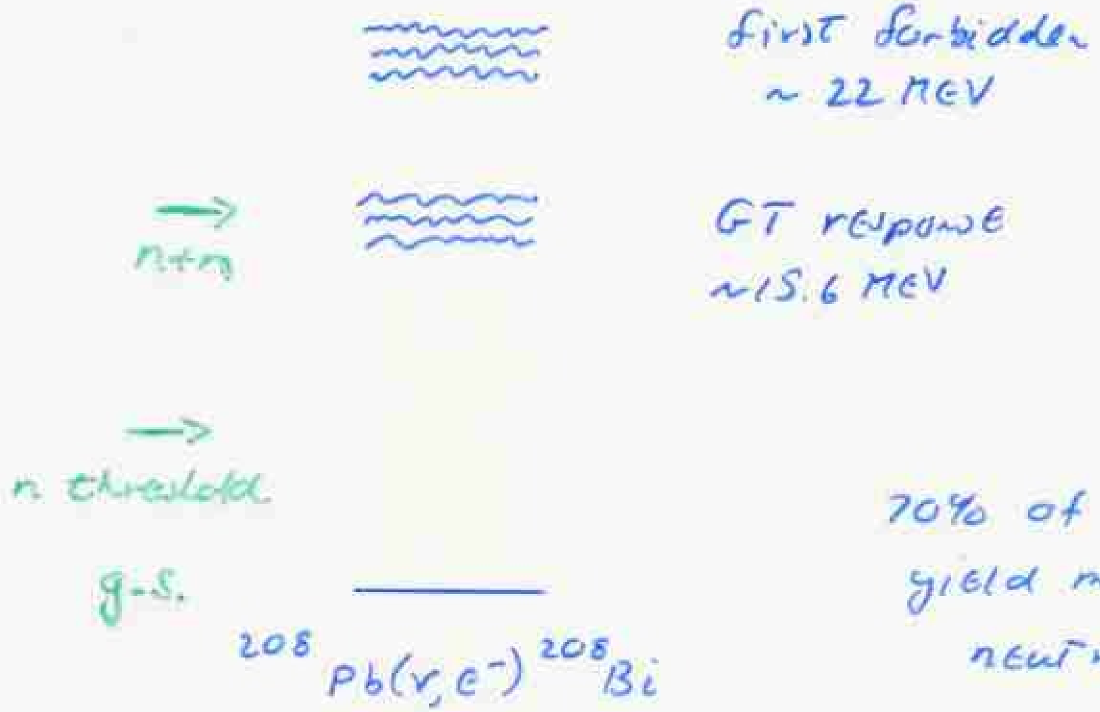
nice exception: n+n emission in Pb

G. Fuller
WH
G. McLaughlin



3% of neutral current events lead to n+n

Pb neutral current response



70% of events yield multiple neutrons

count multiple neutron events!

- nearly ν_e flavor specific reactions
- very high effective threshold

$\Rightarrow$ $\nu_e \leftrightarrow \nu_\tau$ oscillation increases multiple n rate by ×40

$$\sigma_{\nu_e}\Big|_{oscillation} = 3.95 \cdot 10^{-39}\,cm^2$$

Need to start planning detection schemes

The r-process: site & neutrino physics implication

- recall big-bang ^4He synthesis

  - expanding, radiation-dominated, proton-rich gas

    $n \to p + e^- + \bar{\nu}_e$ below $T \sim 1 MeV$

  - freezeout occurs at $T \sim 100 keV \sim 10^9 K$

    $n + p \to d + \gamma$ ...

    $^4He/_H \leftrightarrow n/p$ ratio at freezeout

  - dilute nucleon gas $\Rightarrow$ two-body reactions

    this plus mass gaps at $A = 5, 8$ terminate reaction chains

    $\alpha + \alpha \not\to$ $\qquad$ $\alpha + p \not\to$

- exists a fossil record of this physics in present-day abundances of H, $^3He/d$, ^4He, ^7Li

- this + galactic chemical evolution studies ⇒

  primordial abundances

⇒ constraints on important cosmological & particle physics parameters

$\eta = \frac{\# B}{\# \gamma}$ $\qquad$ # ν generations

- remarkably similar situation exists in Type II supernovae near mass cut

  - expanding, radiation dominated, neutron-rich gas

    $p + e^- \rightarrow n + \nu_e^{\text{escaping}}$

  - freezeout occurs at $T \sim (300-100)\,\text{keV}$
    $\sim (3-1) \cdot 10^9 K$

    $n/p \leftrightarrow$ nucleosynthesis

- nucleon gas is less dilute ⇒ bridge mass gap at A = 8

$$\alpha + \alpha + \alpha \to {}^{12}C$$
$$\alpha + \alpha + n \to {}^{9}Be$$

⇒ seeds + excess neutrons

- will claim that there exists a fossil record of this synthesis in the distribution of r-process nuclei

this + HST results ⇒ know the "primordial" abundances

⇒ constraints on important astrophysical and particle physics parameters

galactic chemical evolution ⇔ supernova rate

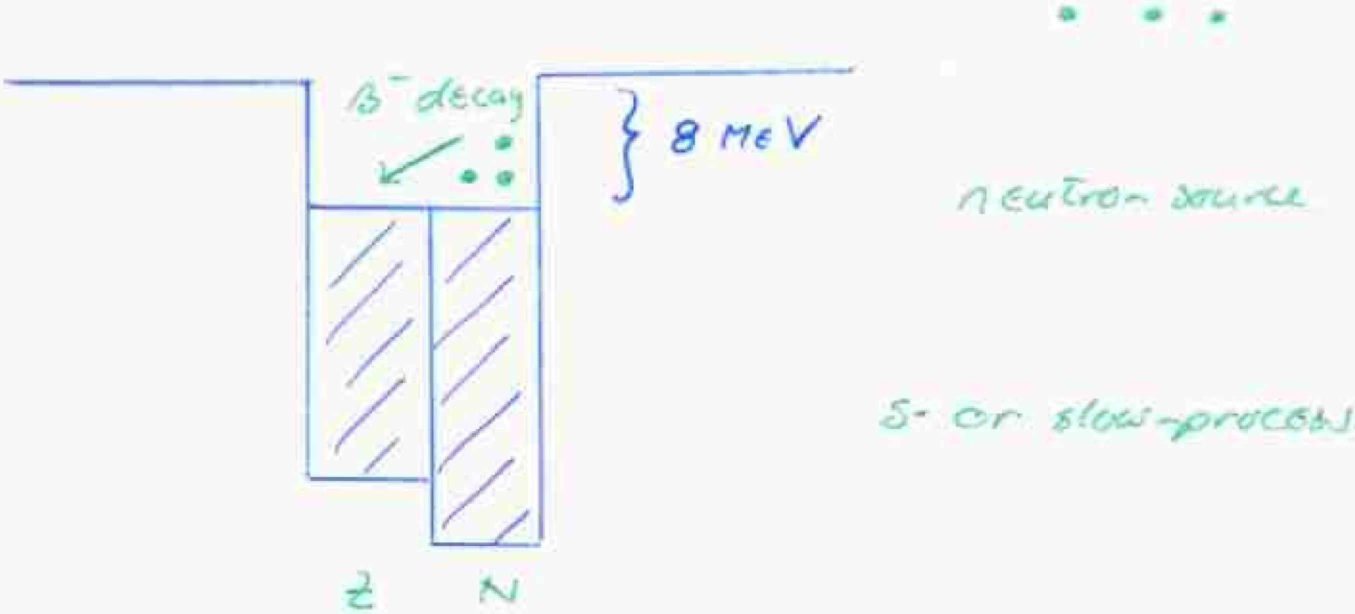
mass of m_{ν_τ} in a cosmologically interesting window

new: detailed link between Type II supernovae ⇔ r-process

What is the r-process?

consider stellar environment where neutrons are present with nuclei

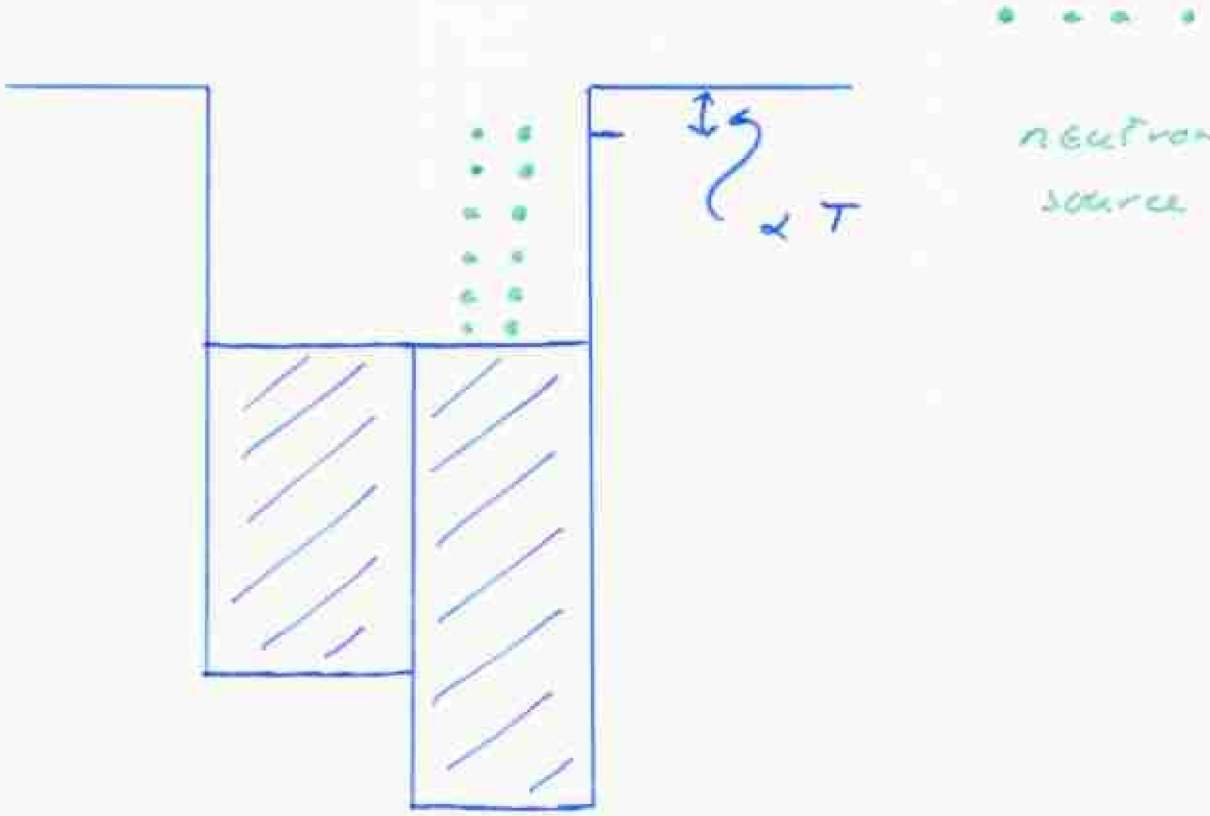
usual case:



- neutron capture slow compared to nuclear β-decay ⇒
- weak interactions maintain Z-N equilibrium ⇒
- nucleosynthesis rate ∝ n capture rate
- nucleosynthesis path is along the path of stable nuclei

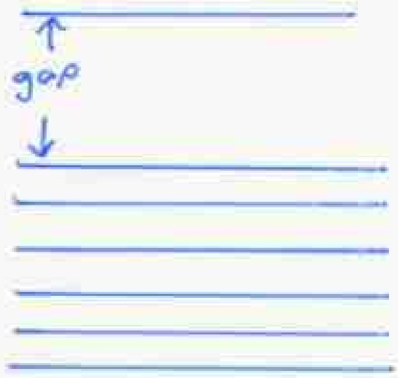
more exotic case: r-process

n, nuclei in a thermal bath



- neutron capture fast compared to β-decay
- the equilibrium maintained is $(n,\gamma) \leftrightarrow (\gamma,n)$
- the nucleosynthesis rate ∝ β^- decay rate
- the nucleosynthesis path is along very exotic neutron rich nuclei
- abundance $A(Z,N) \propto [\omega_\beta(Z,N)]^{-1}$


β⁻


gap

- neutron exposure ends or neutrons are exhausted

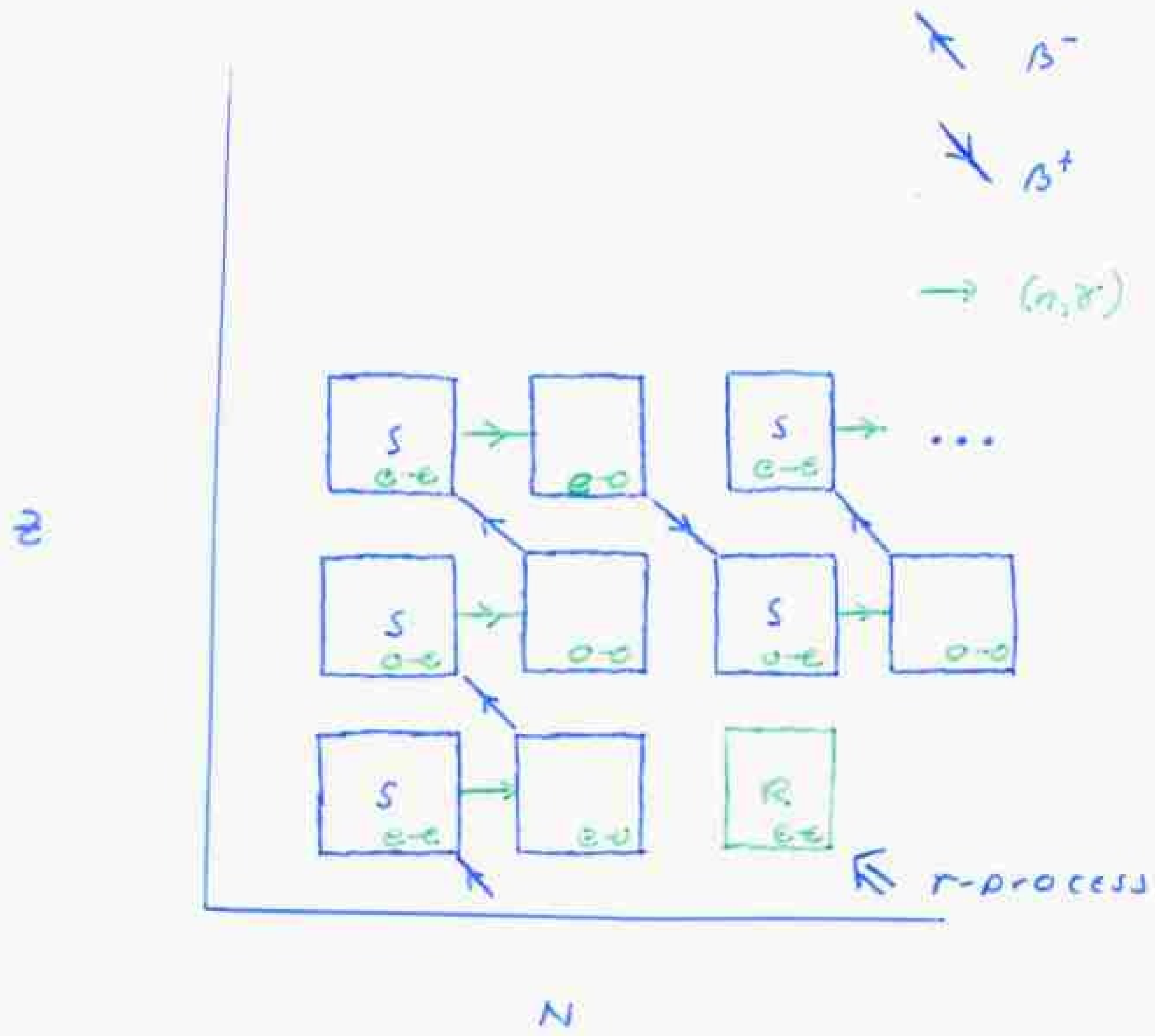
$$(Z, N) \xrightarrow[\beta\ \text{decay}]{} (Z+\Delta, N-\Delta)$$

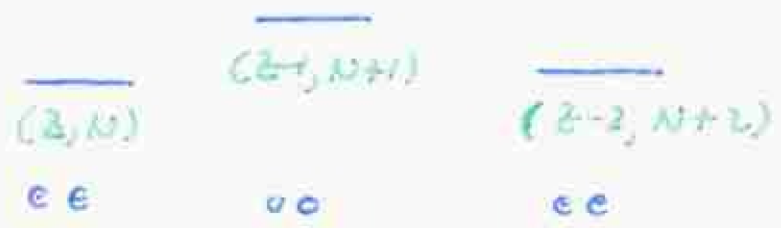
↑ β stable species

- about half of all nuclei ≳ 80 can only be made in this way

- shell gaps and waiting points

typical s-process path





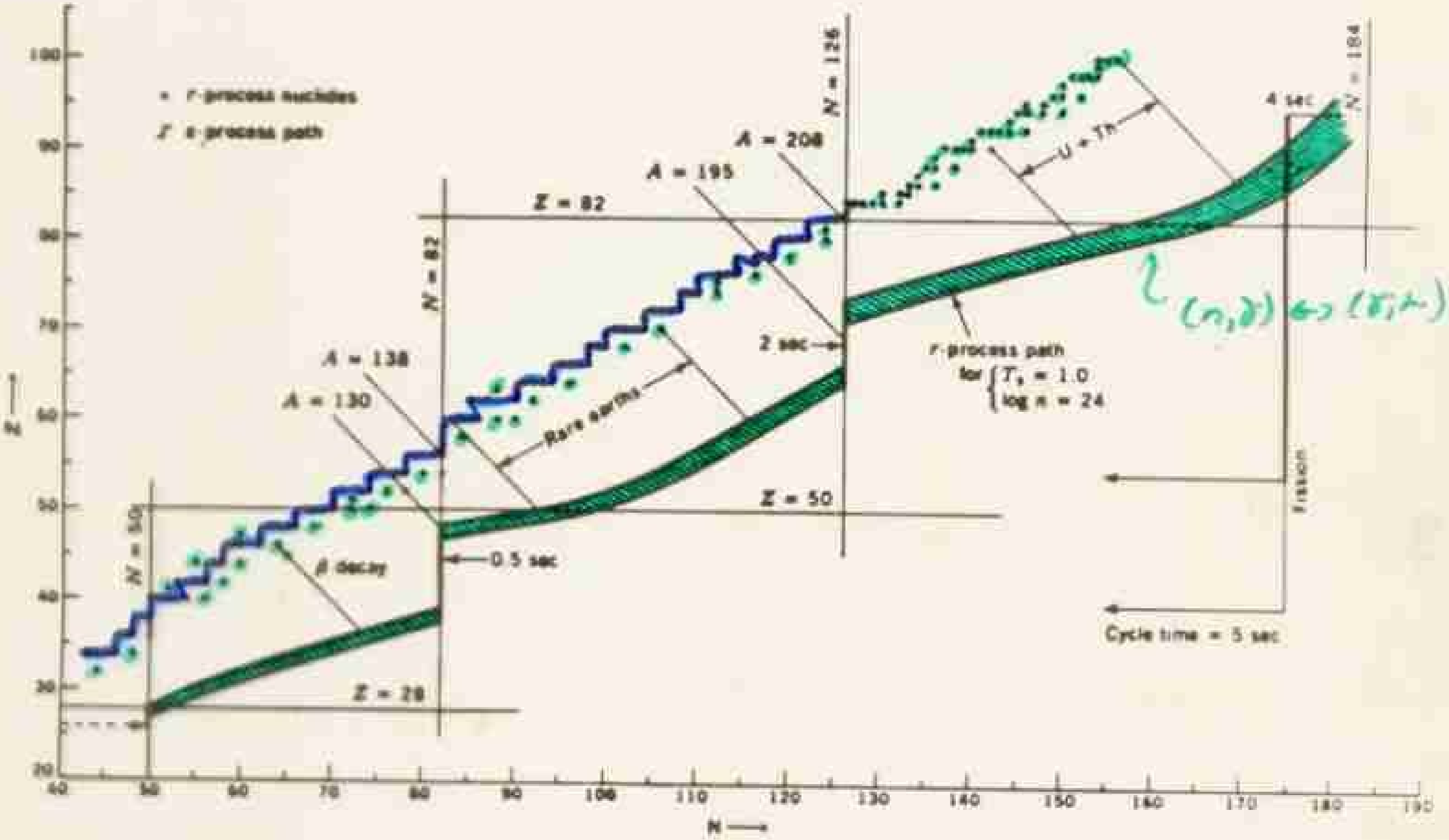


Fig. 7-28 Neutron-capture paths for the *s* process and the *r* process. The *s* process follows a path in the *NZ* plane along the line of beta stability. The neutron-rich progenitors to the stable *r*-process nuclei, which are here shown as small circles, are formed in a band in the neutron-rich area of the *NZ* plane, such as the shaded area shown here. This *r*-process path was calculated for the case $T_9 = 1.0$ and $\log n_n = 24$. After the synthesizing event the nuclei in this band beta-decay to the stable *r*-process nuclei. The abundance peaks at $A = 80$, 130, and 195 are attributed to abundance peaks in the neutron-rich progenitors having $N = 50$, 82, and 126. Neutron capture flows upward from the lower left-hand corner along the shaded band until neutron-induced fission occurs near $A = 270$. [*P. A. Seeger, W. A. Fowler, and D. D. Clayton, Astrophys. J. Suppl.*, 11:121 (1965). *By permission of The University of Chicago Press. Copyright 1965 by The University of Chicago.*]

s process

r process

- growing body of evidence favoring primary supernova site

1) HST discovery of very-metal-poor halo stars enriched in r-process material

C. Sneden et al.

  - [Fe/H] ~ (-1.7) - (-3.12)

  - abundance pattern matching solar r-process distribution

  ⇒ primary process, operating in early galaxy, producing a unique distribution/event

2) galactic chemical evolution models showing that the growth of r-process elements is consistent with low-mass Type II supernovae rate, distribution

Mathews & Cowan

3) more convincing modeling of an r-process occurring in the expanding neutron-rich matter near the mass cut in supernovae

Woosley et al.

- supernova r-process

  - massive star ~ $20 M_\odot$ evolves to form iron core

  - undergoes nearly free-fall collapse, rebounding at $\sim 5 \cdot 10^{14}\ g/cm^3$

    shock wave + neutrino wind ⇒ mantle ejection

  - conditions near mass cut

    - expanding, high entropy, n-rich gas

    - He synthesis, then α-process to moderately heavy Z

    - result in a neutron/seed ratio ~100

  - resulting r-process material driven off by neutrino wind astrophysics

- r-process requires spectacularly explosive conditions

$$\rho_n \gtrsim 10^{20}/cm^3$$

$$T \gtrsim (1\text{-}3)\cdot 10^9\,K$$ known for ~40 years

$$\tau \sim 1 sec$$

- suggested primary sites
  - neutronized atmosphere above protoneutron star in Type II supernova ⇐
  - neutron-rich jets from supernovae or neutron star mergers
  - inhomogeneous big bangs

  ⋮

- secondary sites (where ρ_n can be lower)
  - He/C zones in Type II supernovae
  - red giant He flash

⇒ • reasonable r-process distribution

• $\sim 10^{-5} M_\odot$ of material ejected : correct

⇒ • worries about the required high entropies ($S \gtrsim 300$)

characteristics

• r-process T: $3 \cdot 10^9 K \to 1 \cdot 10^9 K$

• freezeout radius 600 - 1000 km

• $L_\nu \sim (0.015 - 0.005) \cdot 10^{51} ergs/(100km)^2 s$

• $\tau \sim 3$ sec

⇒ neutrino fluence after freezeout

$(0.045 - 0.015) \cdot 10^{51} ergs/(100km)^2$

∴ the ejection of r-process material is predicted to occur in an intense neutrino flux

- supernova neutrinos

  - infall: when $\rho \gtrsim 10^{12}\, g/cm^3$,

    $\tau_\nu^{\text{DIFFUSION}} > \tau^{\text{COLLAPSE}}$

    $\Rightarrow$ $3 \cdot 10^{53}$ ergs of gravitational energy trapped in the protoneutron star

    $T_{\text{central}} \gtrsim 100$ MeV

  - after core bounce, neutrinos random walk out of neutron star

    $\Rightarrow$ flavor equilibrium

    $\Rightarrow$ equipartition of energy / flavor

  - weak decoupling from matter flavor dependent

$\nu_x + e^- \leftrightarrow \nu_x + e^-$

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

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

decoupling at 10^{12} g/cm^3

$\Rightarrow$ $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ decouple at higher density, temperature

$T_{\nu_\mu, \nu_\tau} \sim 8$ MeV
$T_{\bar{\nu}_e} \sim 4.5$ MeV
$T_{\nu_e} \sim 3.5$ MeV

but $\bar{L}_{\nu_e} \sim \bar{L}_{\nu_\mu} \sim \bar{L}_{\nu_\tau}$

- heavy-flavor neutrinos are responsible for novel nucleosynthesis

Woosley + WH
Domogatskii et al.

e.g. $\nu + A \rightarrow \nu' + A^*$ cross section $\sim 3 \cdot 10^{-41}$ cm^2/flavor

($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)

flux in middle of Ne shell

$$\phi = \frac{4 \cdot 10^{57}\ \nu\text{'s}}{4\pi\,(20{,}000\ \text{km})^2} \sim 10^{38}/\text{cm}^2$$

$\Rightarrow \frac{1}{300}$ of Ne nuclei excited by (ν, ν')

$\Delta E_{excit} \sim 20$ MeV

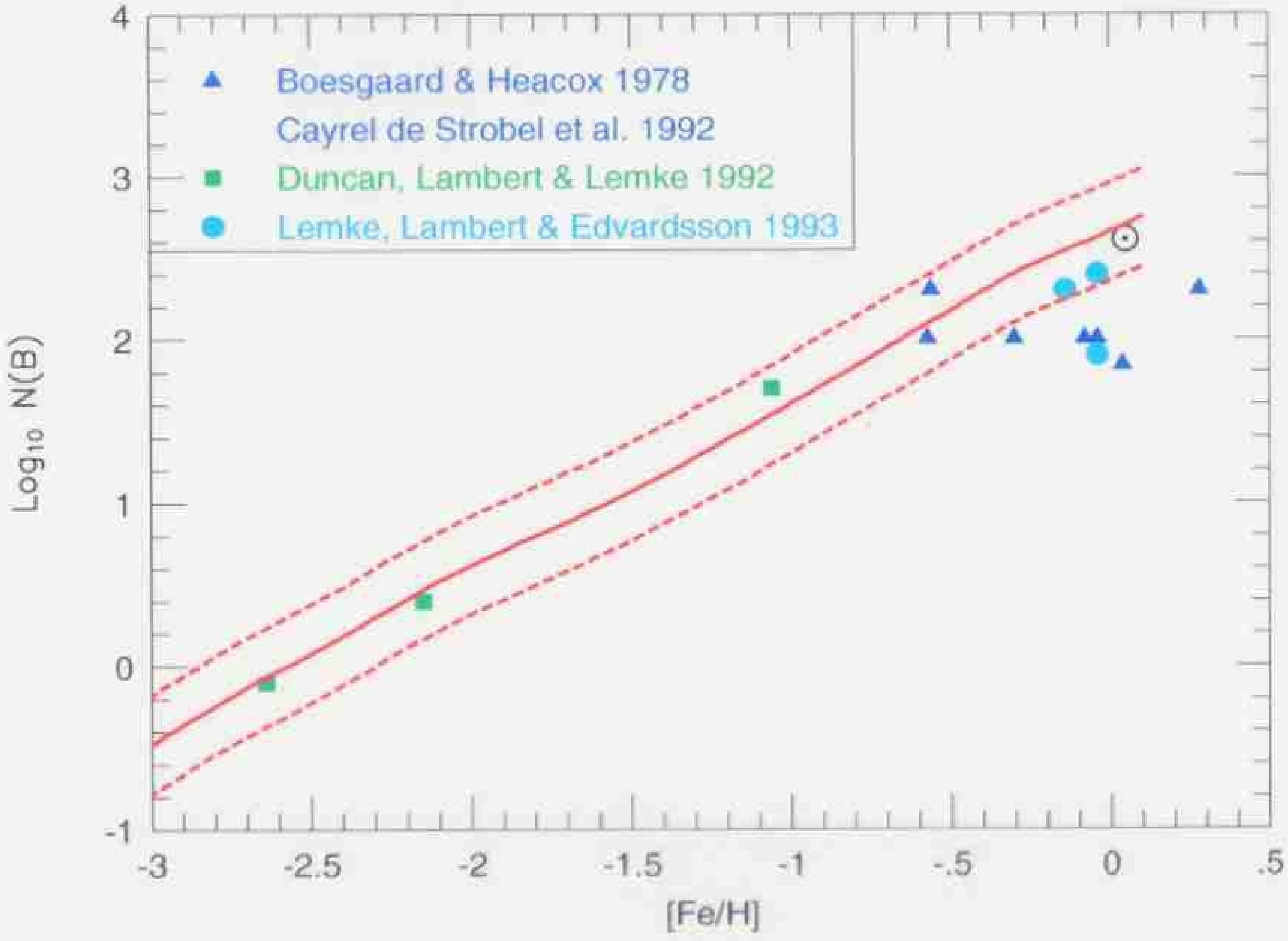
$$\Rightarrow {}^{20}\text{Ne}(\nu,\nu')\,{}^{20}\text{Ne}^* \rightarrow {}^{19}\text{Ne} + n$$
$$\hookrightarrow_{\beta^+} {}^{19}\text{F}$$

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

more careful modeling $\Rightarrow$

$$T_{\nu_\mu,\nu_\tau} = 8\ \text{MeV} \Rightarrow [{}^{19}\text{F}/{}^{20}\text{Ne}]_{produced} = 1.2\,[{}^{19}\text{F}/{}^{20}\text{Ne}]_{solar}$$

origin of F in our galaxy "neutrino process" from F. Thevenin



POINT: Nuclear processes occurring in the vicinity of protoneutron star can be altered in subtle but calculable ways by neutrino flux

QUESTION: If the r-process occurs so close to the protoneutron star, is there a neutrino "fingerprint" to prove this?

1) signatures during r-process will be erased

$$A(\nu,\nu')A^* \leftrightarrow A(\gamma,\ )A^*$$

2) signatures after freezeout of r process?

would'nt any signatures be buried in the noise of our incomplete understanding of the r-process?

If r-process freezes out in an intense neutrino fluence ⇒

neutrino interaction followed by emission of multiple neutrons

⇒ shifts distribution of r-process nuclei

Expect this to be a small effect

except for the now peaks and associated valleys

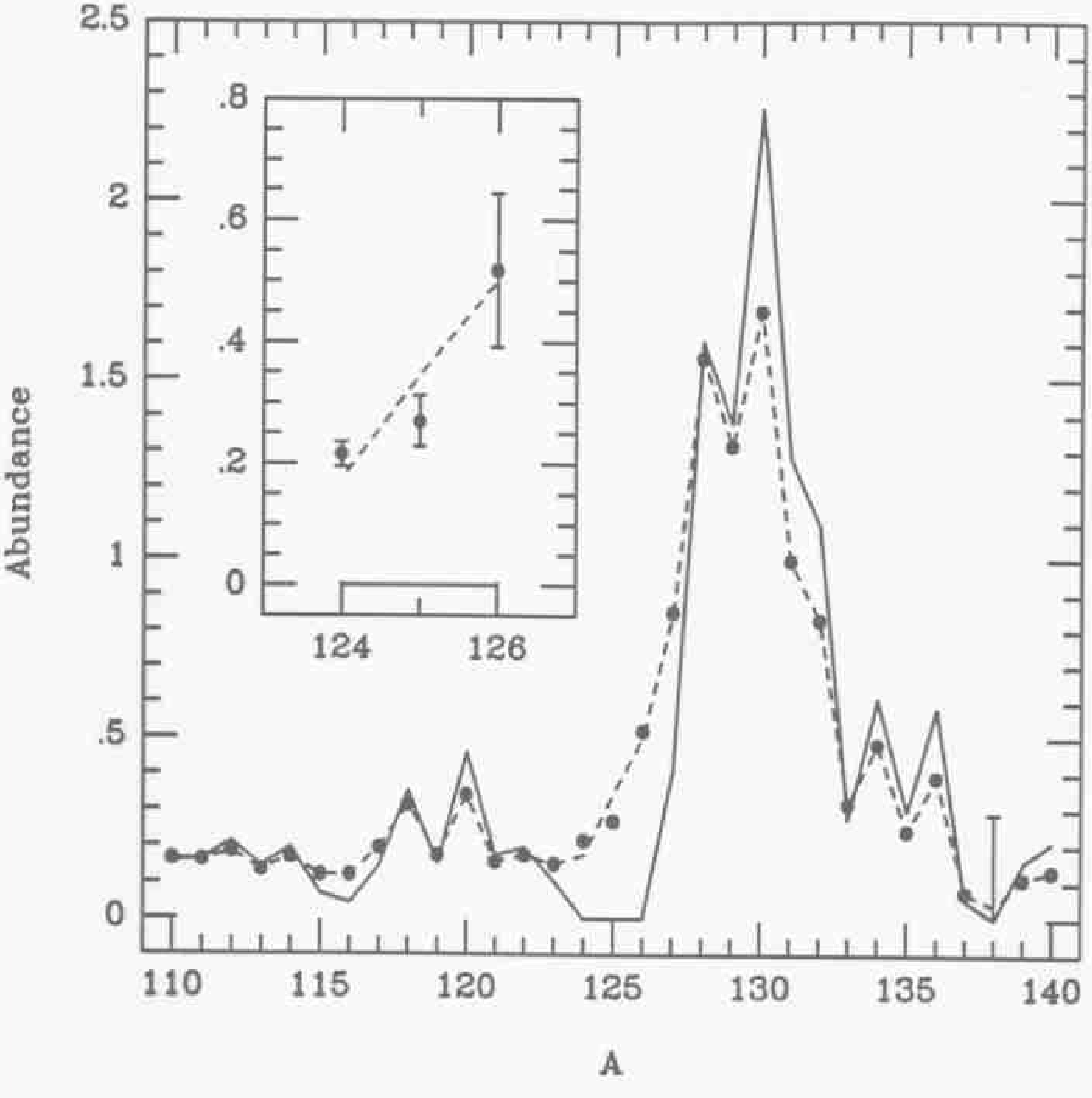
Can evaluate the effects independent of all the many hydrodynamic and nuclear physics uncertainties

WH, Qian, Langanke, Vogel

work backward, from observed solar r-process abundances to time of freezeout by unfolding neutrino physics

⇒ 8 special isotopes, immediately sensitive to neutrinos

124-126   183-187



2.5
2
1.5
1
.5
0
Abundance
.8
.6
.4
.2
0
124
126
110
115
120
125
130
135
140
A

Fig. 2

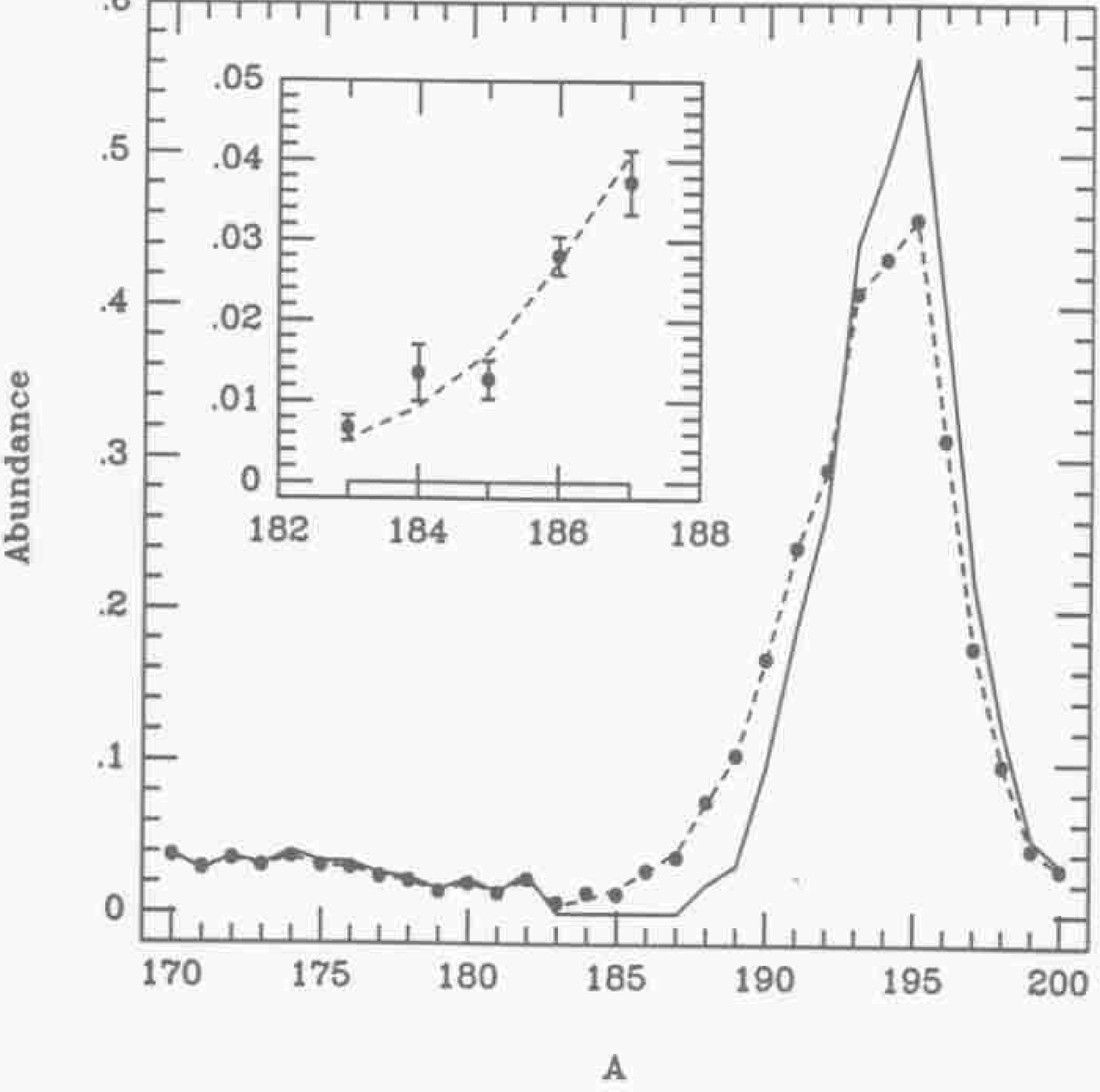

.6
.5
.4
.3
.2
.1
0
Abundance
170
175
180
185
190
195
200
A
.05
.04
.03
.02
.01
0
182
184
186
188

Fig. 3

⊙ oscillations of supernova neutrinos

solar neutrinos: $\nu_e \to$ "ν_μ"
↑ but could also be "ν_τ"

implicitly assumed $\nu_e \sim \nu_1$ $m_1 < m_2$
$\nu_\mu \sim \nu_2$

ν_e became heavier in matter

⇒ crossing

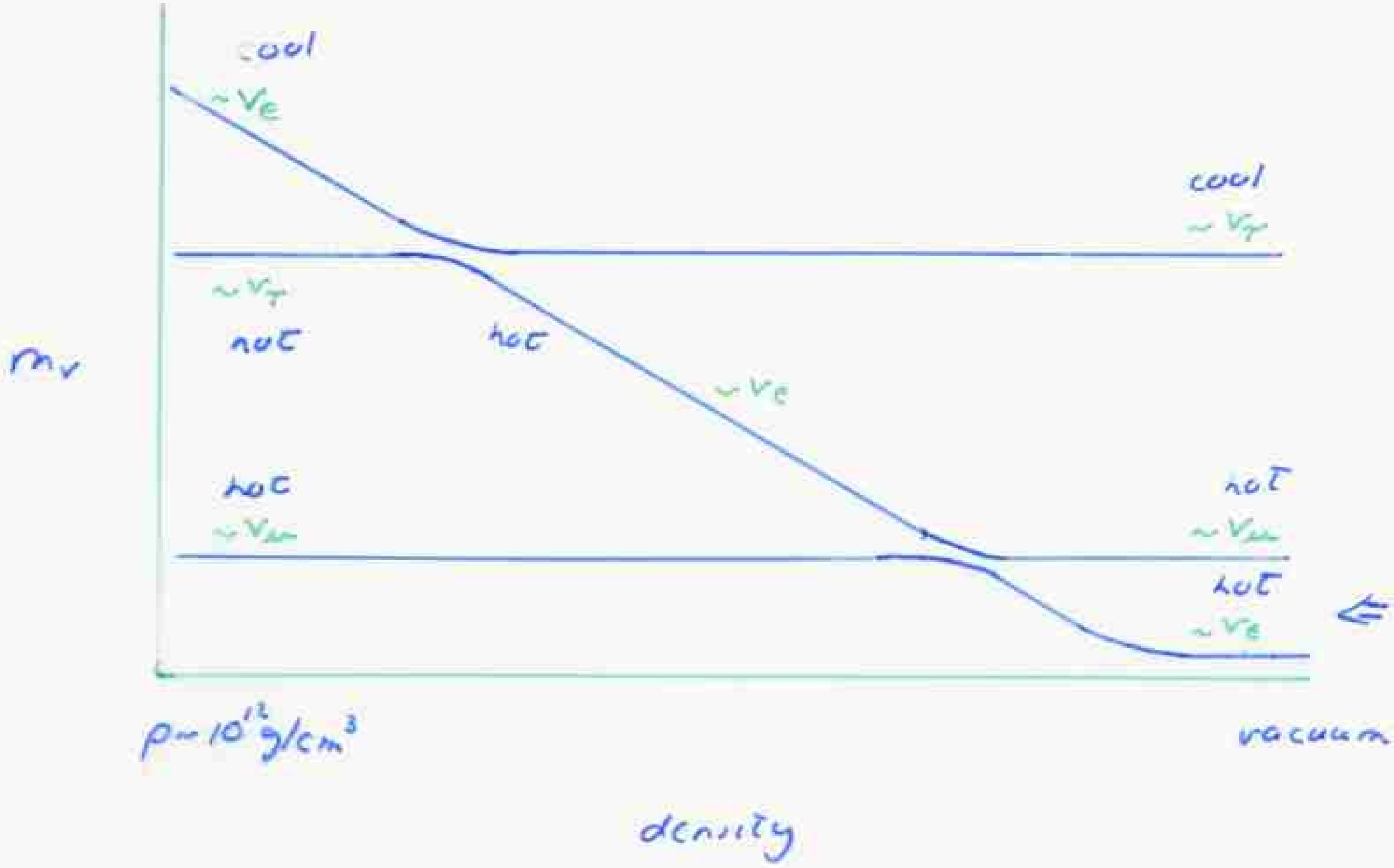
supernovae: ν_e, ν_μ, ν_τ $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

assume again $m_1 < m_2 < m_3$

sign of effective interaction flips for antineutrinos

⇒ $\bar{\nu}_e$ becomes even lighter in matter
⇒ no crossing

but neutrinos?



cosmologically interesting ν_τ's
have level crossings outside
neutrinosphere

But $T_{\nu_\mu, \nu_\tau} \sim 8$ MeV

$T_{\bar{\nu}_e} \sim 5$ MeV — without oscillations

$T_{\nu_e} \sim 4$ MeV

$\Rightarrow$ $T_{\nu_e}^{MSW} \sim 8 \text{ MeV} \gg T_{\bar{\nu}_e}$

$\therefore$ in the presence of oscillations $\left\{ \begin{array}{l} \sigma \propto T^2 \\ \text{flux} \cdot T = \text{const} = L \end{array} \right.$

augmented by $\frac{T_{\nu_e}^{MSW}}{T_{\bar{\nu}_e}}$ $\rightarrow$ $\nu_e + n \rightarrow e^- + p$

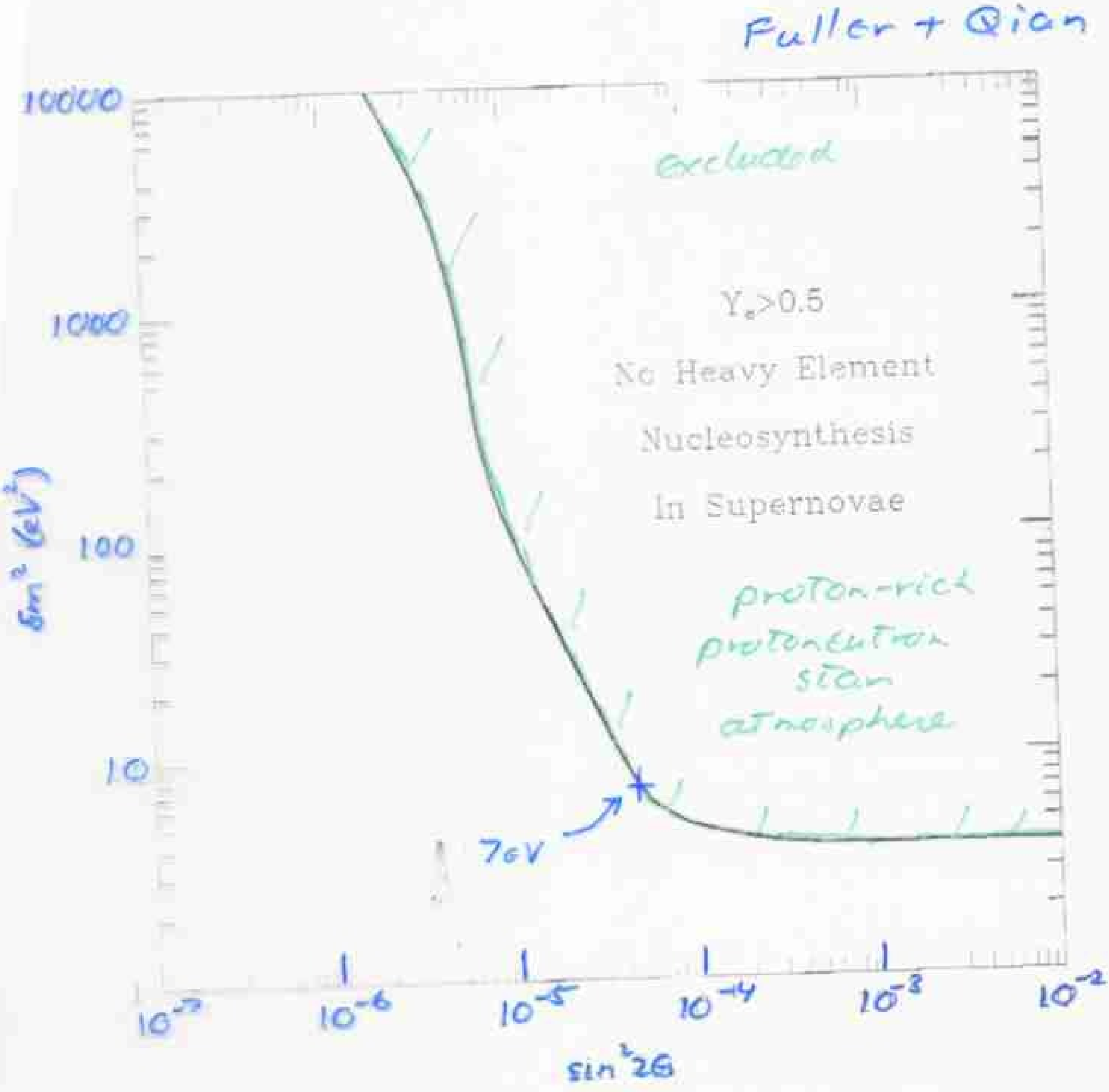
vs

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

} matter outside neutrinosphere is driven proton rich

a cosmologically interesting ν_τ
and
a supernova r-process

likely cannot both happen


Fuller + Qian
10000
1000
100
10
δm² (eV²)
excluded
Ye>0.5
No Heavy Element
Nucleosynthesis
In Supernovae
proton-rich
protoneutron
star
atmosphere
7eV
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
sin²2θ

Leads to lots of interesting possibilities

- supernova r-process ⇒

  - m_{ν_τ} small $\lesssim$ few eV

  - $\theta_{e\tau}$ small $\lesssim 0.003$

    ↳ not implausible

    $0.002 < V_{ub} < 0.007$
    $0.003 < V_{td} < 0.018$

  but not good news experimentally for terrestrial $\nu_e \to ?$ disappearance experiments

- r-process occurs elsewhere ...