The stakes are very high !!!

- Can we show that ANY r-Process material comes from ν-heated ejecta ??

- Are there ν-signatures in r-Process abundance systematics ??

⇓ ⇓ ⇓ ⇓

Yes ⇒ fantastic probe of ν physics

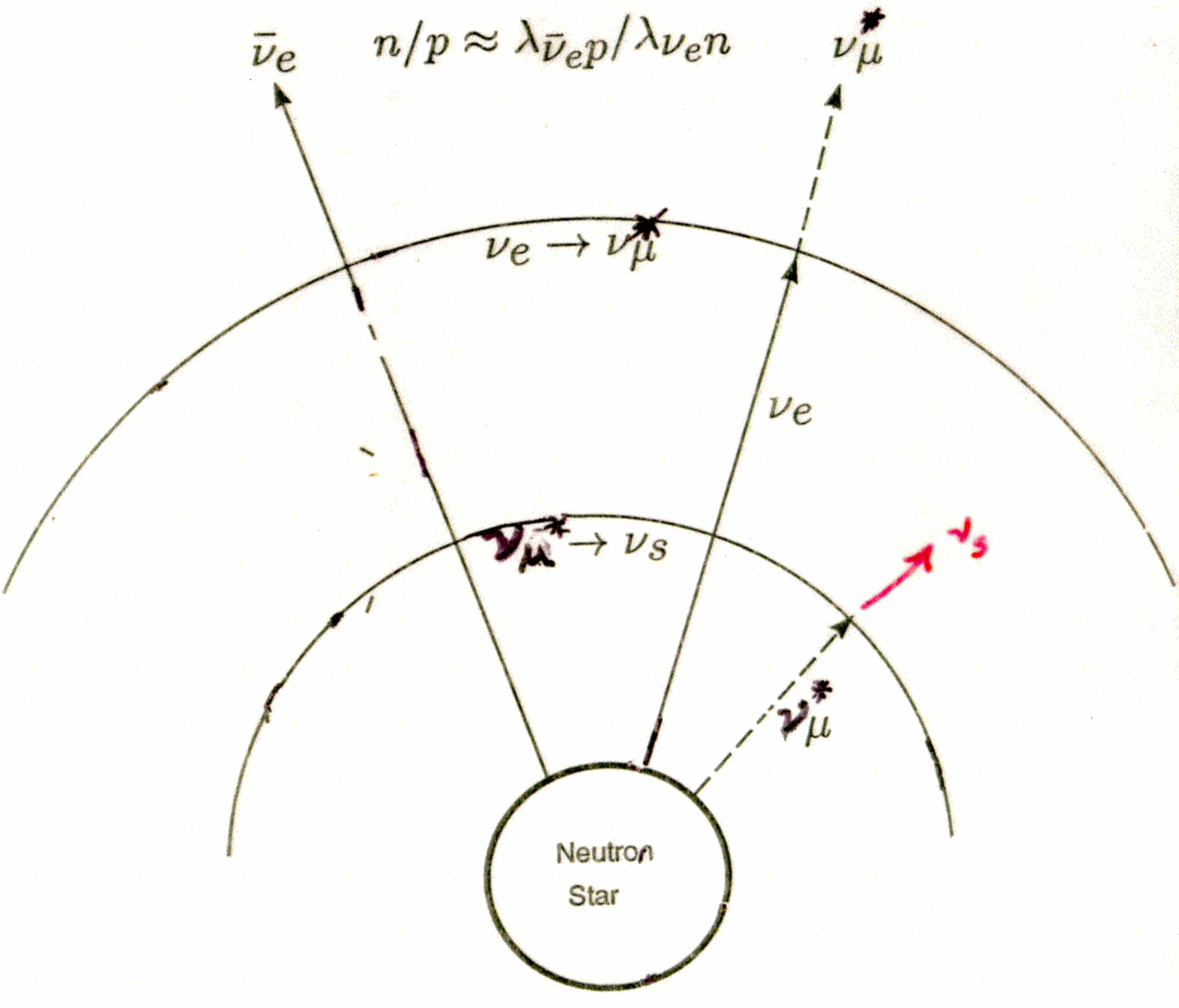
But we are not there yet.

Caldwell, Fuller, Qian (~~1997~~ 2000)

~~Caldwell (1994)~~

$t_{pb} \sim 10$ sec

r-process
nucleosynthesis region

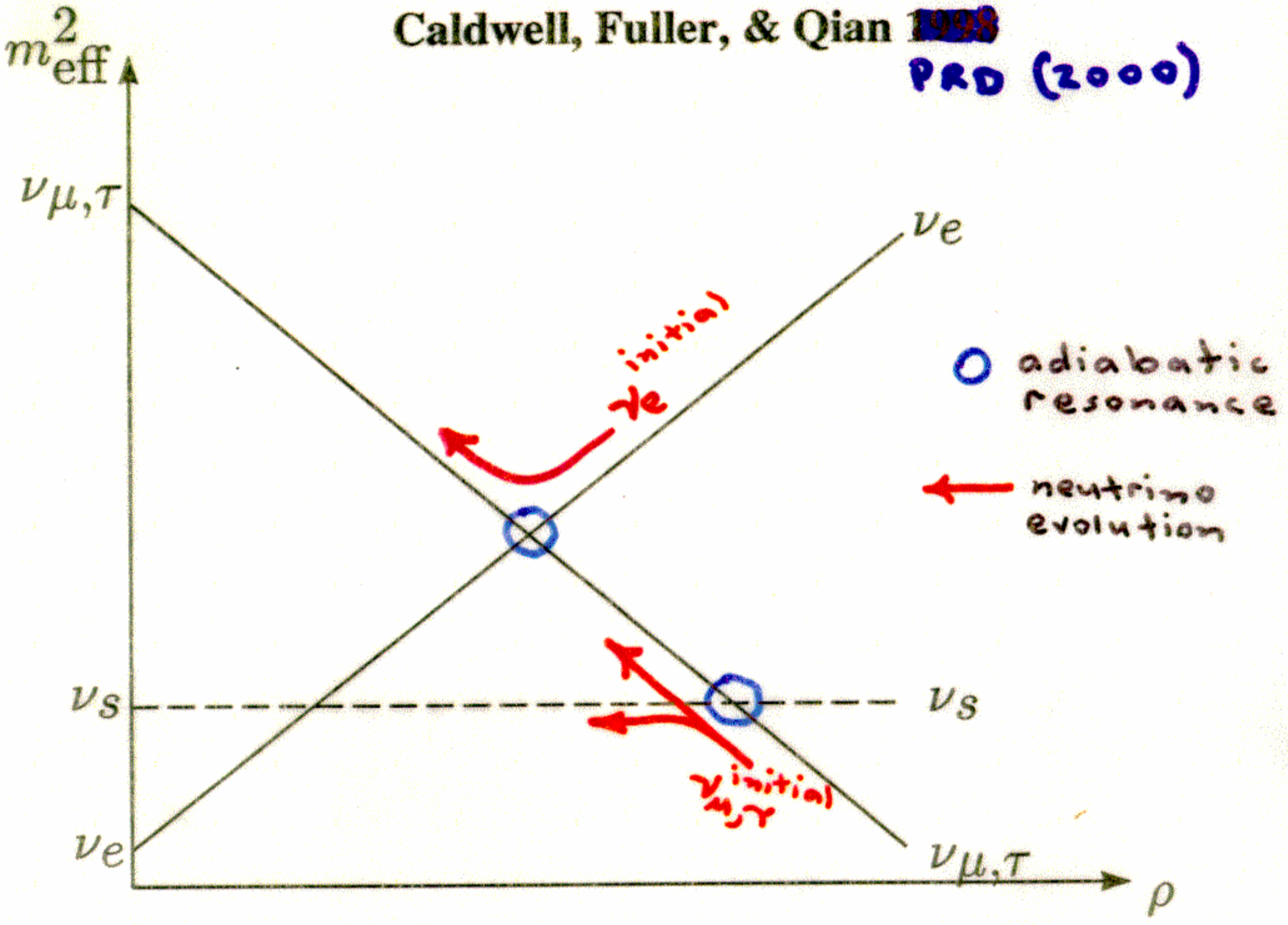


@ $t_{pb} < 1$ sec
use $\nu_e \rightleftharpoons \nu_s$ <u>twice</u>

see also
Peltoniemi
Petcov

$\nu_e \rightleftharpoons \nu_s$ [illegible] ν_e's $\Rightarrow$ proton-rich

Caldwell, Fuller, & Qian ~~1998~~ PRD (2000)



Fast expansion case: $\nu_{\mu,\tau} \rightleftharpoons \nu_s$ $(\nu_m^* \rightleftharpoons \nu_s)$

followed by $\nu_{\mu,\tau} \rightleftharpoons \nu_e$ $(\nu_m^* \rightleftharpoons \nu_e)$

In the fast expansion case, Y_e lags neutrino transformation. Therefore, the order of the level crossings does not change until all of the electron neutrinos are transformed.

Net Result:

at 1st resonance
- Probability $\nu_\mu \rightarrow \nu_\mu \Rightarrow 1/4$
- Probability $\nu_\mu \rightarrow \nu_\tau \Rightarrow 1/4$
- Probability $\nu_\mu \rightarrow \nu_s \Rightarrow 1/2$

after 2nd res.
- Probability $\nu_{\mu,\tau} \rightarrow \nu_e \Rightarrow 0$ (2nd resonance)

The key step is to define two linear combinations of ν_μ and ν_τ in this representation, and then transform into the new flavor basis defined by these states. The linear combinations are:

$$|\nu_\mu^*\rangle \equiv \frac{|\nu_\mu\rangle - |\nu_\tau\rangle}{\sqrt{2}}$$

$$|\nu_\tau^*\rangle \equiv \frac{|\nu_\mu\rangle + |\nu_\tau\rangle}{\sqrt{2}}$$

Armed with this new flavor basis, we can produce a new unitary transformation to the mass basis in vaccum:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_s\rangle \\ |\nu_\mu^*\rangle \\ |\nu_\tau^*\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi\cos\omega & \sin\phi\sin\omega & 0 \\ -\sin\phi & \cos\phi\cos\omega & \cos\phi\sin\omega & 0 \\ 0 & -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

$\Downarrow$ $\Downarrow$ $\Downarrow$

$\nu_\mu^* \rightleftharpoons \nu_e , \nu_s$

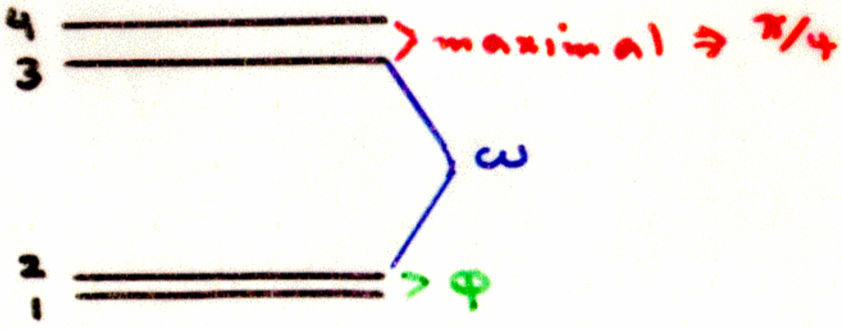
ν_τ^* "decoupled"

4 × 4 Mixing in Vacuum

CFQ '00
Balantekin & Fuller '99

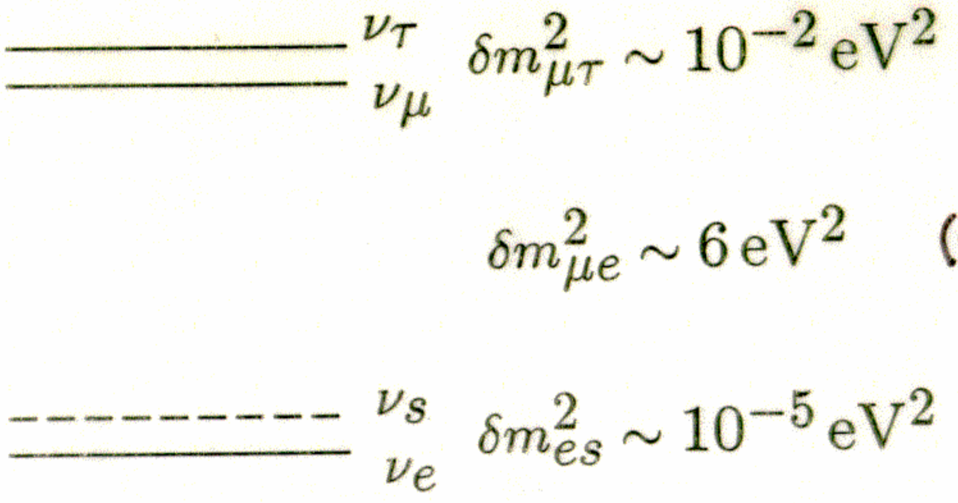
$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_s\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi\cos\omega & \sin\phi\sin\omega & 0 \\ -\sin\phi & \cos\phi\cos\omega & \cos\phi\sin\omega & 0 \\ 0 & -\sin\omega/\sqrt{2} & \cos\omega/\sqrt{2} & 1/\sqrt{2} \\ 0 & \sin\omega/\sqrt{2} & -\cos\omega/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

Note that the mixing between ν_e and ν_s is mostly determined by the angle ϕ, while ω controls the level of mixing between between the doublets, $\nu_{\mu,\tau}$ and $\nu_{e,s}$.



$$\underset{3 \rightleftharpoons 4}{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}} \underset{1 \rightleftharpoons 2}{\begin{pmatrix} c\varphi & s\varphi & 0 & 0 \\ -s\varphi & c\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}} \underset{2 \rightleftharpoons 3}{\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\omega & s\omega & 0 \\ 0 & -s\omega & c\omega & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}}$$

Caldwell, Fuller, and Qian ~~1998~~ 2000



ν_τ $\delta m^2_{\mu\tau} \sim 10^{-2}\,\mathrm{eV}^2$

ν_μ

$\delta m^2_{\mu e} \sim 6\,\mathrm{eV}^2$ $(0.2\,\mathrm{eV}^2 - 8\,\mathrm{eV}^2)$

ν_s $\delta m^2_{es} \sim 10^{-5}\,\mathrm{eV}^2$

ν_e

(like old C.& Mohapatra scheme for masses)

BBN: **OK** (very restricted !!!)

SNN: **Enables r-Process in neutrino-heated supernova ejecta; removes ν_e flux.**

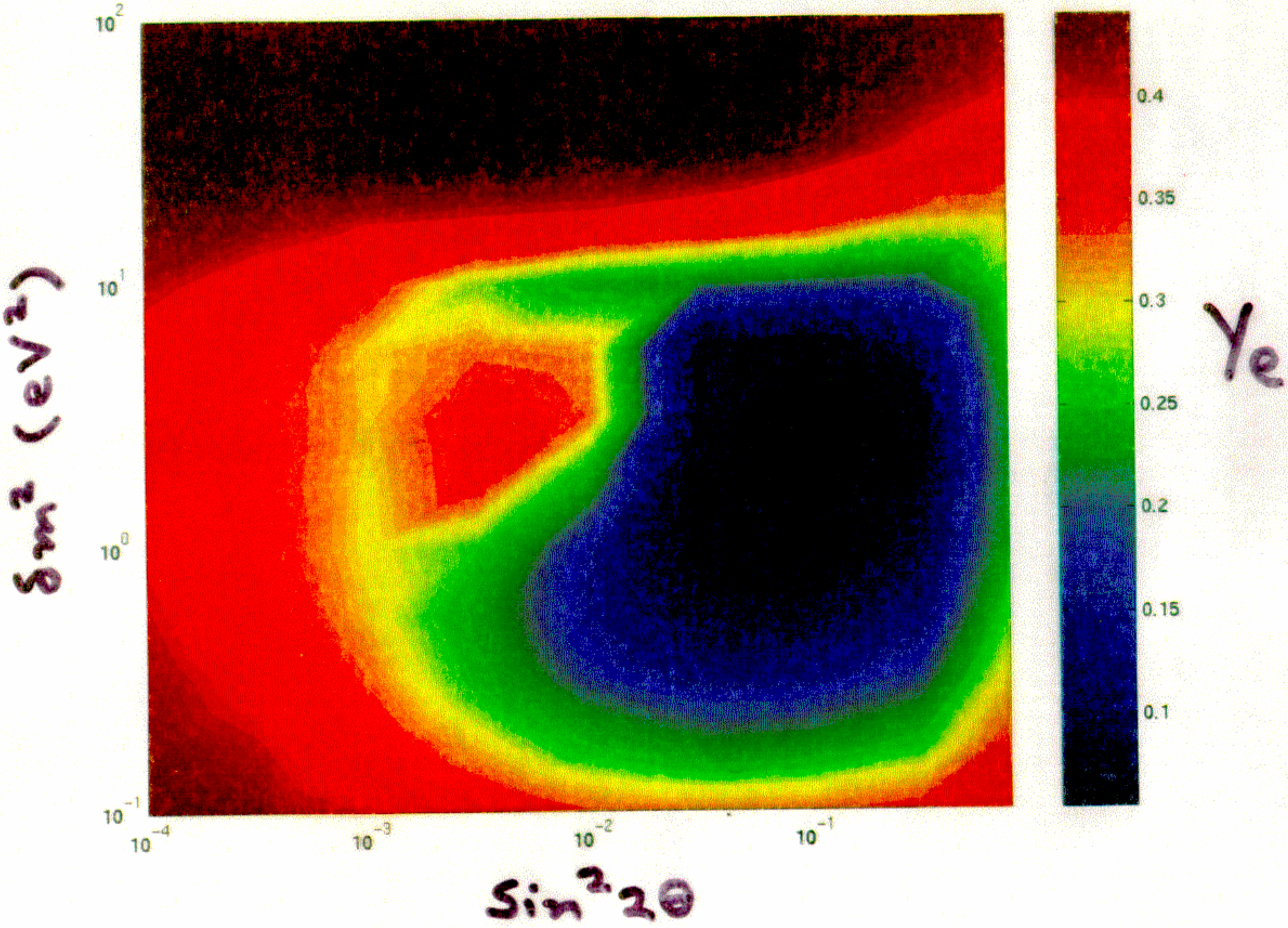
SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ **maximal vacuum mixing**

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_s$ **matter-enhanced**
(or $\nu_e \rightleftharpoons \nu_s$ "just so" $\delta m^2 \sim 10^{-10}\,\mathrm{eV}^2$)

LSND: $\nu_\mu \rightleftharpoons \nu_e$ **vacuum oscillations**

MFBF '93 EFFECT
Patel & Fuller

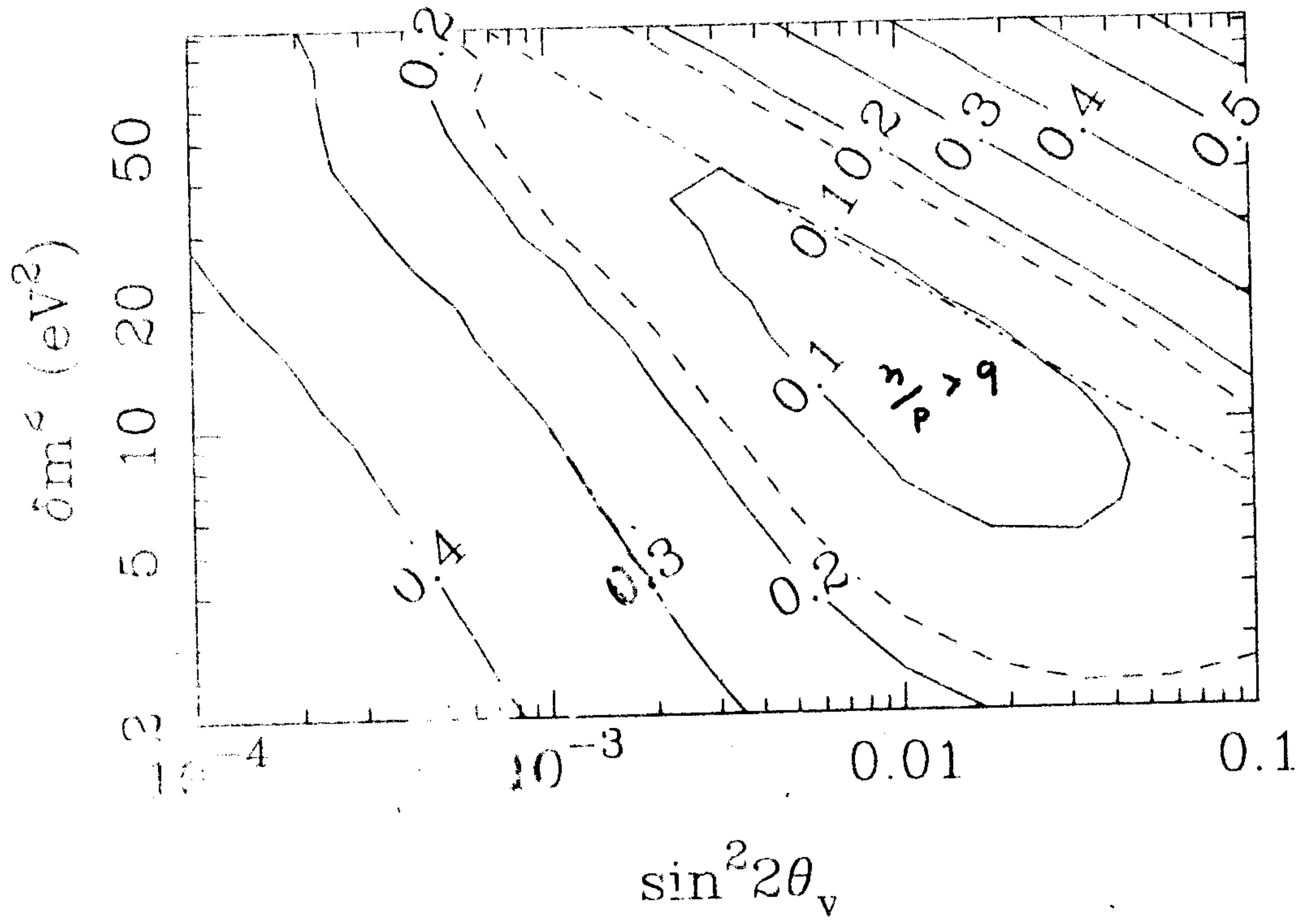
$\nu_e \rightleftharpoons \nu_s$
$\bar{\nu}_e \rightleftharpoons \nu_s$



MFBF '98

Final Y_e, $\tau = 0.3$ s

$\left.\begin{array}{c}\nu_e \rightleftharpoons \nu_s \\ + \\ \bar{\nu}_e \rightleftharpoons \bar{\nu}_s\end{array}\right\}$ Fetter, McLaughlin, Balantekin, G.M.F.



McLaughlin, Fetter, Balantekin, GMF
(MFBF), ~~submitted PRD~~
PRC 39, 2873,
(1999)

Balantekin, Fetter, Fuller,
McLaughlin 1998

?- - - - - - - - - - ν_s''?

?- - - - - - - - - - ν_s'?

For r-process "fix"

- - - - - - - - - - ν_s $100\,\mathrm{eV}^2 > \delta m^2_{es} > 6\,\mathrm{eV}^2$

?
could be $0.2\,\mathrm{eV}^2 - 200\,\mathrm{eV}^2$
depending on ν-spectra

ν_τ $\delta m^2_{\mu\tau} \sim 10^{-2}\,\mathrm{eV}^2$

ν_μ

ν_e $\delta m^2_{e\mu} < 10^{-4}\,\mathrm{eV}^2$

?
BBN: OK, may give interesting CMBR signal

SNN: Enables r-Process in neutrino-heated ejecta
"removes" ν_e flux

SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ **maximal vacuum mixing**

NO
not
if
we
want

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_{\mu,\tau}$ matter-enhanced or vacuum oscillations

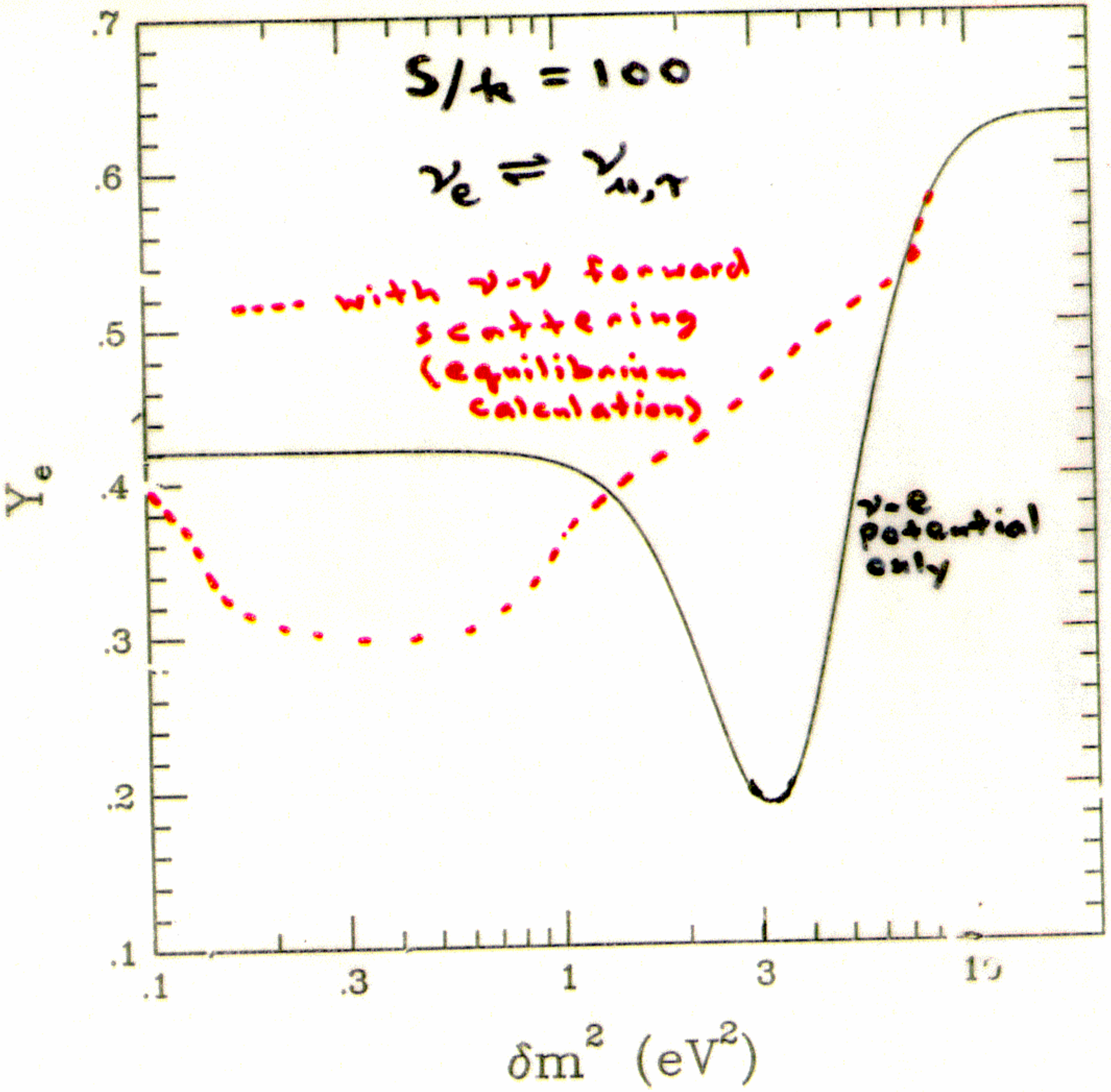
LSND: $\nu_\mu \to \nu_s \to \nu_e$ Indirect vacuum oscillations
(but note that oscillation channel
proceeds through sterile state)

troubled:

can effective two-ν mixing
be big enough? also BBN?

with ν-ν forward scattering, get ~10% reduction in Y_e for

$$\boxed{0.1\ \mathrm{eV}^2 \lesssim \delta m^2 \lesssim 1\ \mathrm{eV}^2}$$



Matter-Enhanced $\nu_{\mu(\tau)} \rightleftharpoons \nu_e$

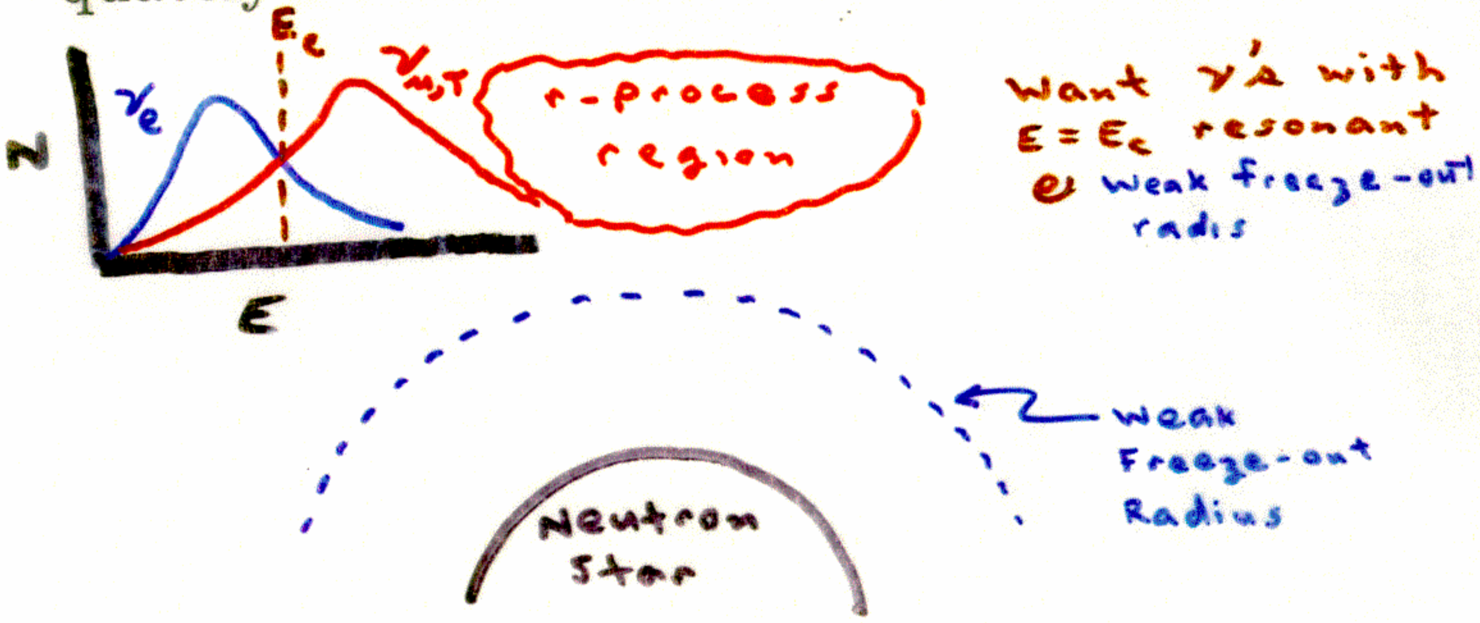
(Qian & Fuller 1997)

- Want only neutrinos with energies less than spectrum crossover energy E_c to transform inside the weak freeze-out radius.

- This will occur and decrease Y_e when

$$2\,\mathrm{eV}^2 \lesssim \delta m^2 S_{100} \lesssim 3\,\mathrm{eV}^2$$

e.g., when $S/k = 400$, Y_e decreased adequately for $\delta m^2 \approx 0.5\,\mathrm{eV}^2$.



Want ν's with $E = E_c$ resonant @ weak freeze-out radis

Y.-Z. Qian & G.M. Fuller
Phys. Rev. D51, 1479 (1995)

Qian & Fuller 1994

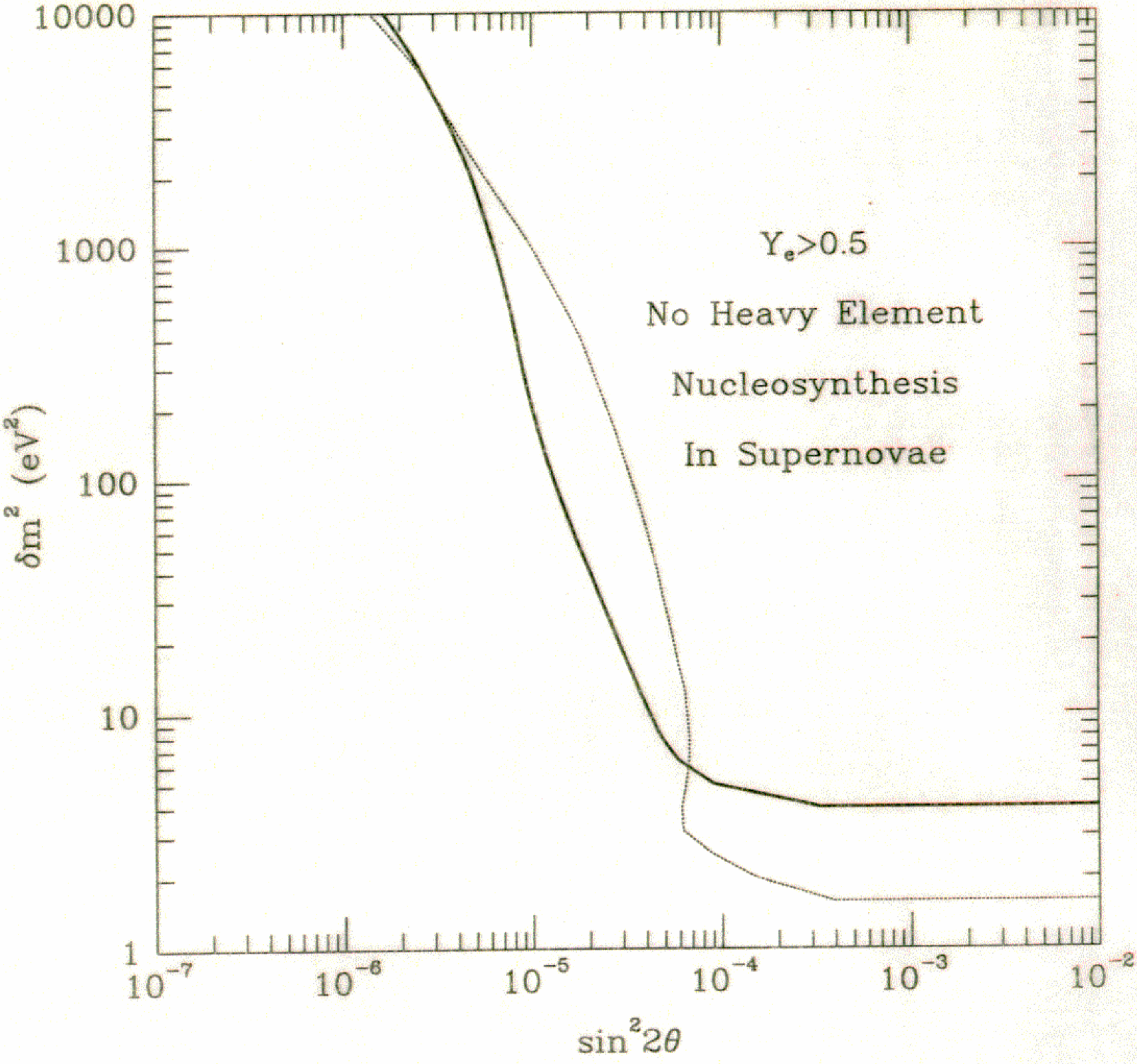


Fig. 9

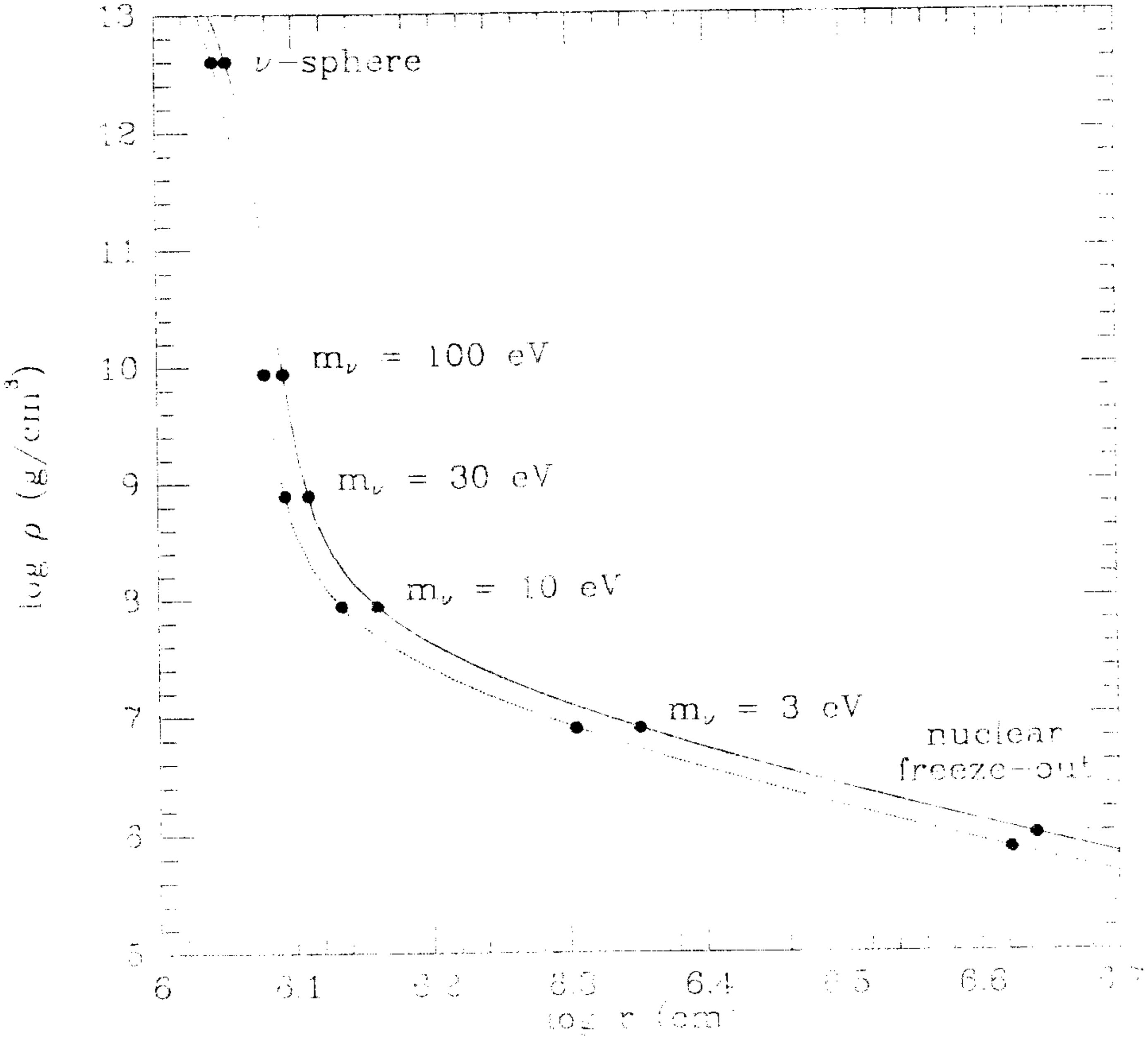
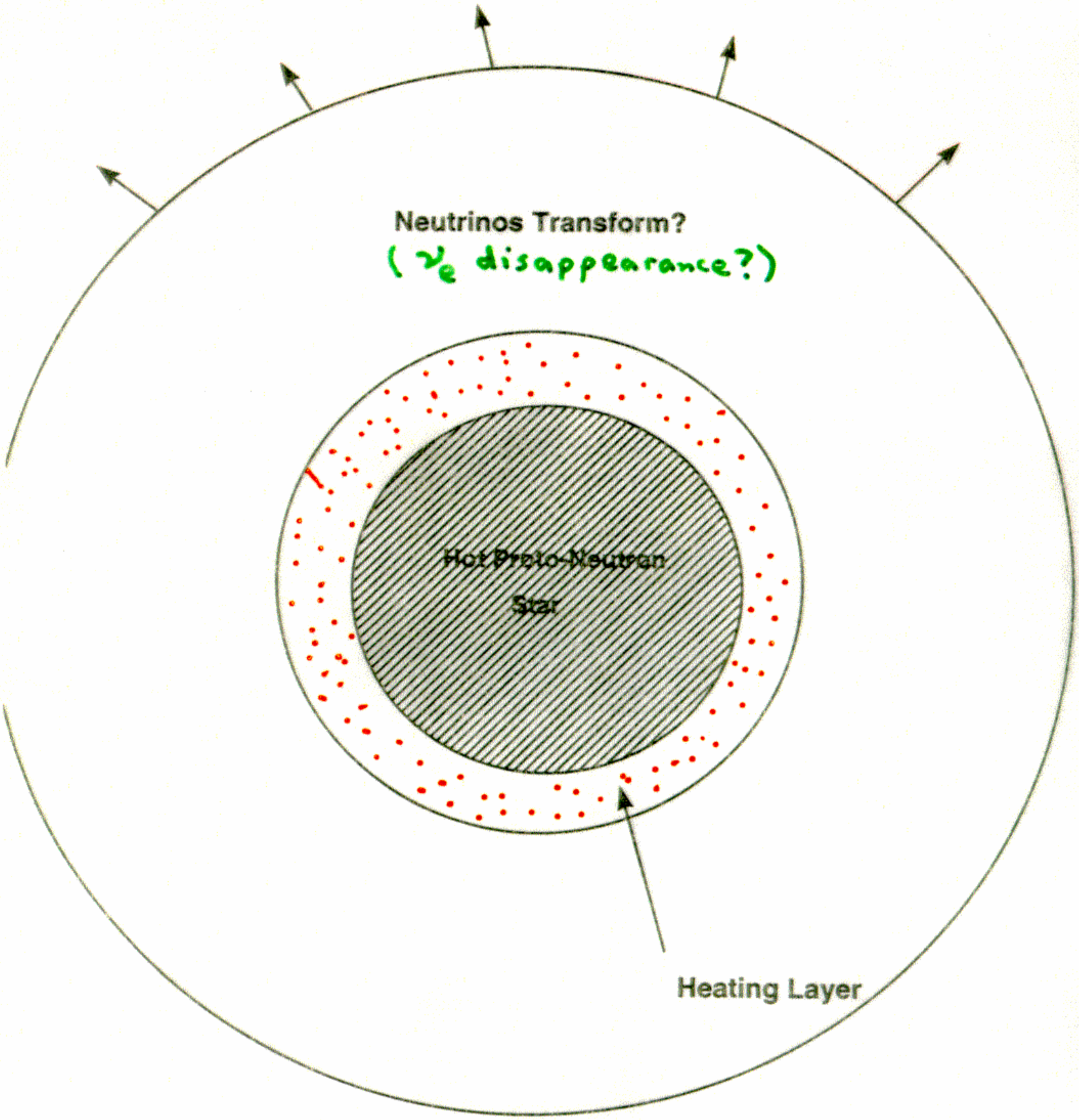

ν−sphere
m_ν = 100 eV
m_ν = 30 eV
m_ν = 10 eV
m_ν = 3 eV
nuclear
freeze−out
log ρ (g/cm³)
13
12
11
10
9
8
7
6
5
6
6.1
6.2
6.3
6.4
6.5
6.6
6.7
log r (cm)

Figure 1

Uranium
⋮
$\alpha + \alpha + n \rightarrow {}^9Be$
$2p + 2n \rightarrow \alpha$



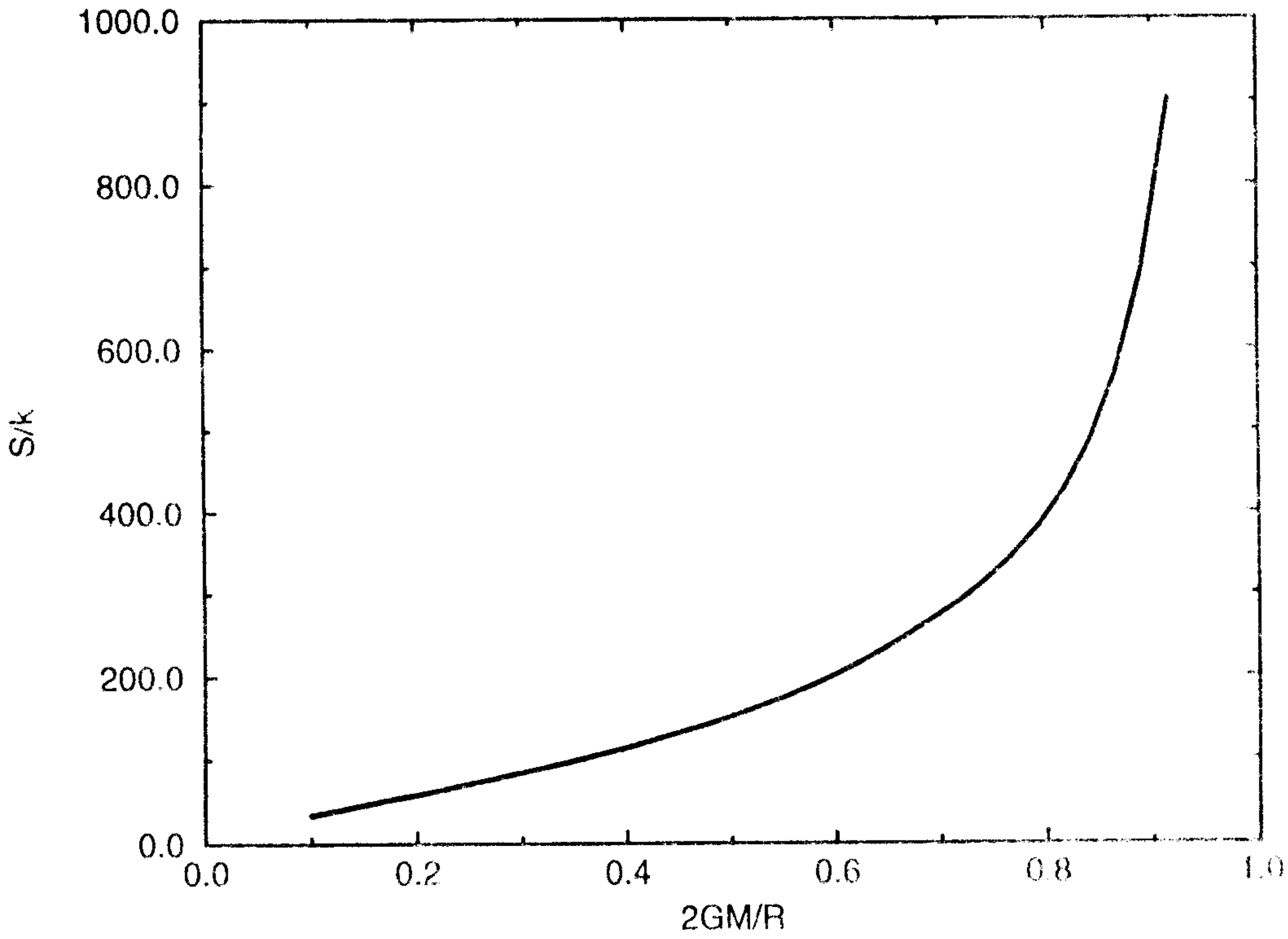
r-Process Region

Neutrinos Transform?
(ν_e disappearance?)

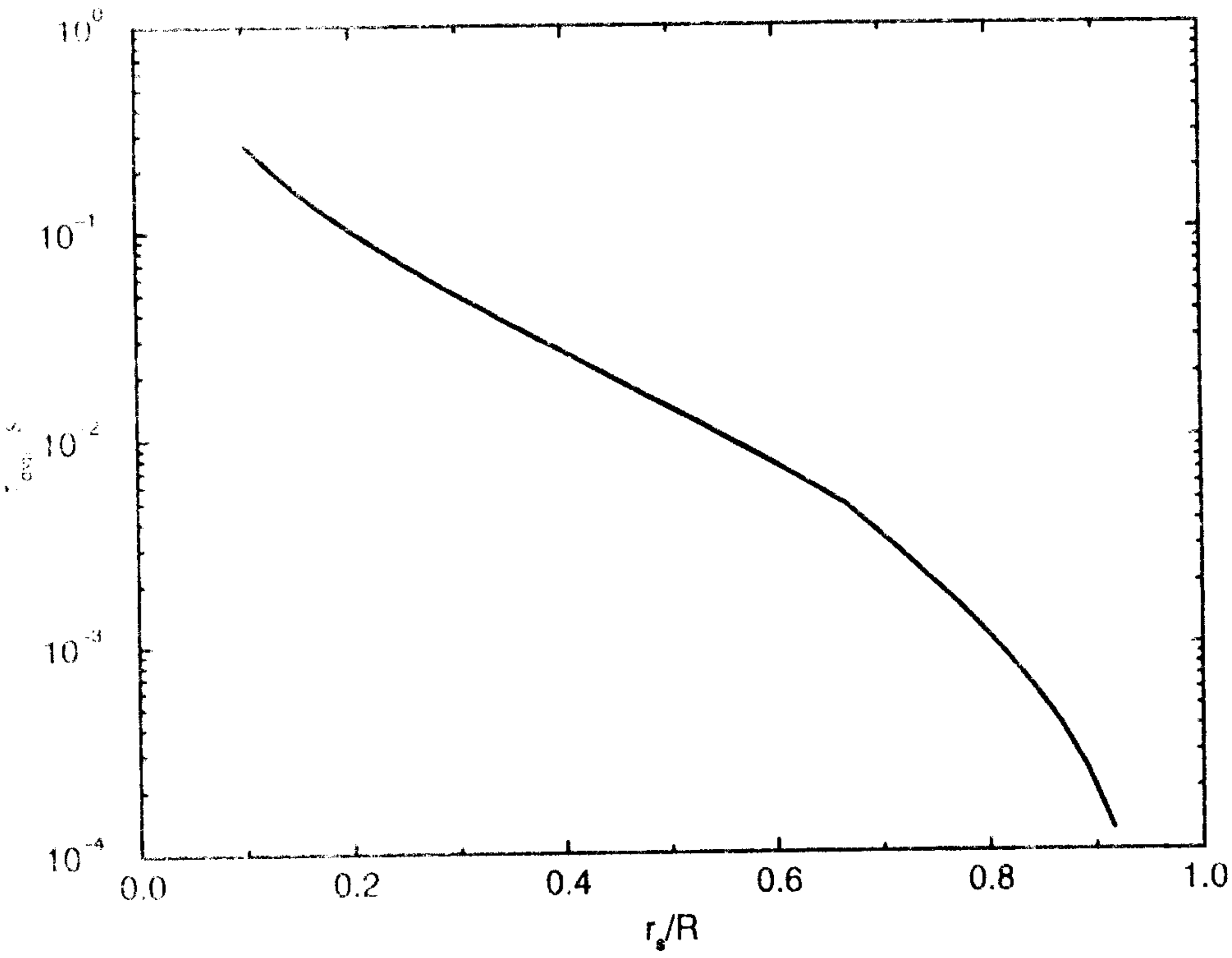
Hot Proto-Neutron Star

Heating Layer

Entropy per Baryon



Dynamical Time Scale



General Relativistic Effects

Cardall & Fuller 1996; Fuller & Qian 1996; Qian & Woosley 1996

Salmonson & Wilson 1999 ; T. Kajino et al '99

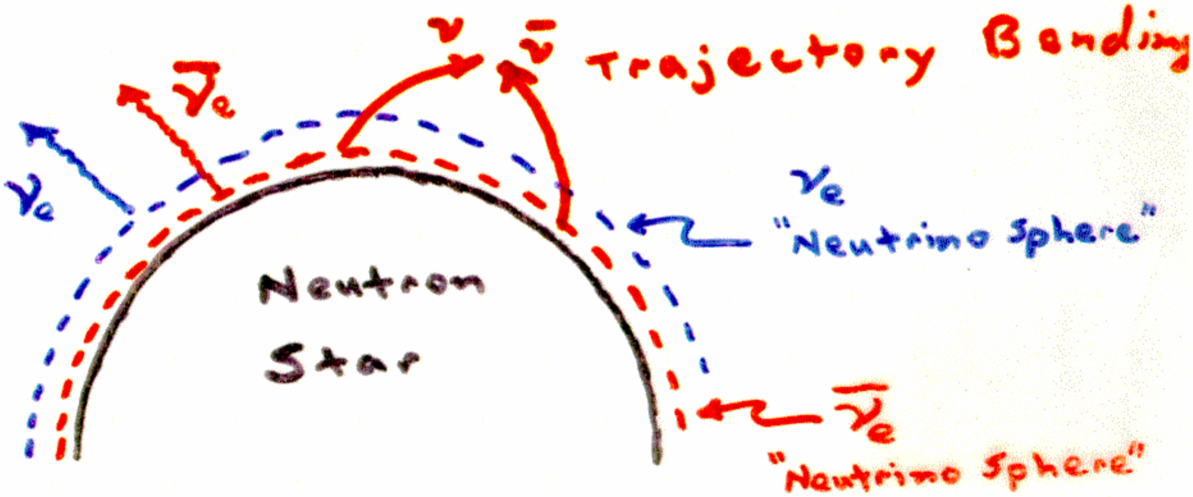
- Entropy of Outflow in Wind Increases:

$$Ts \approx GMm_b/r.$$

- Expansion Timescale Decreases

- Differential redshift of $\bar{\nu}_e$ and ν_e sets limit on how relativistic star can get and yet still have $Y_e < 0.5$.

$\Rightarrow$ $\bar{\nu}_e$ redshifted more than ν_e since $\bar{\nu}_e$ decouple deeper in gravitational potential well.

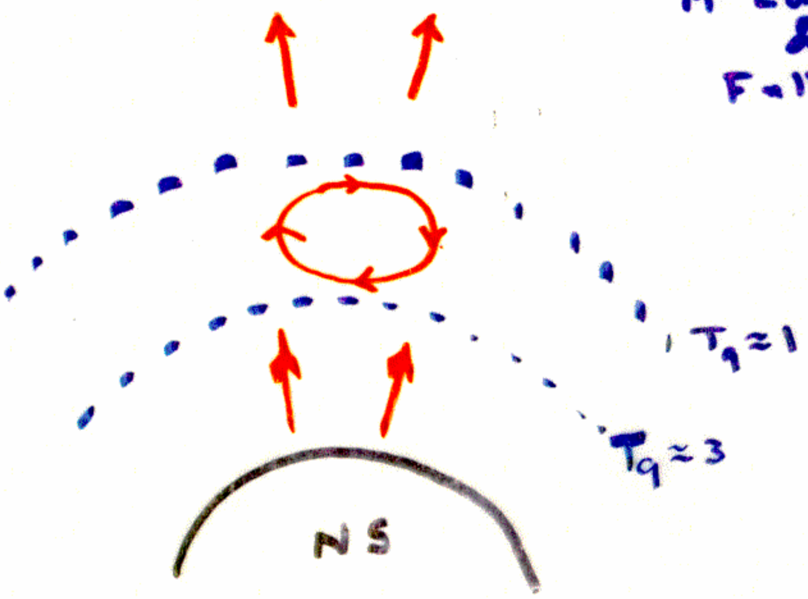


"Fast-Slow-Fast" Outflow

- Fast initial early outflow from Neutron Star ⇒ increase neutron-to-seed ratio

- Slow expansion during rapid neutron capture phase, so that weak steady flow equilibrium is established.

- After cessation of neutron capture, *may* need outflow speed to increase again so as to avoid too much neutrino post-processing.

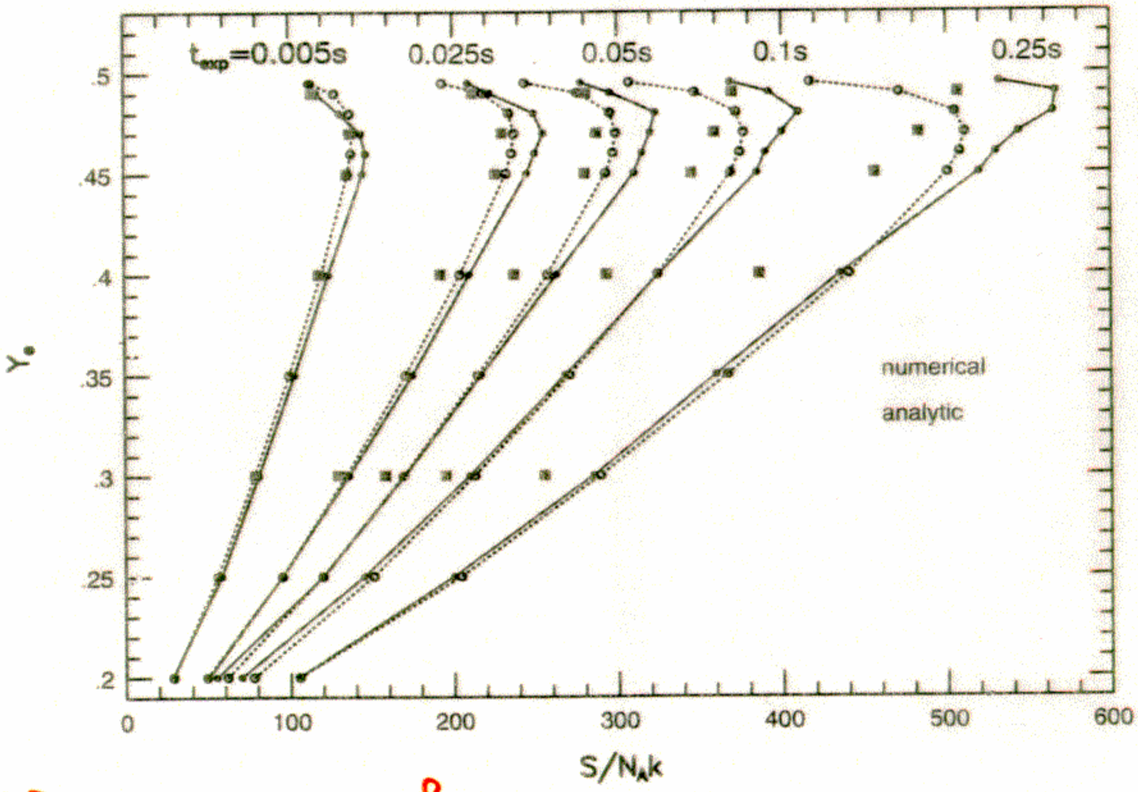


e.g., McLaughlin & Fuller (1997)

Required Entropy & Y_e & τ_{dyn}

Meyer et al. 1996

Hoffman et al. 1996



Hoffman, Woosley, & Qian 1996

Figure 1. The combination of electron fraction, entropy, and expansion time scale required for production of the $A \sim 195$ r-process peak nuclei. Points connected by lines are for fixed expansion time scales. The results from a simple analytic approximation (open circles) and two numerical surveys (filled circles and squares) are shown. All results assumed a constant entropy in deriving the density. For the circles, the approximation $S \propto T^3/\rho$ is used to solve for the density, whereas for the squares, a fully consistent equation of state is used.

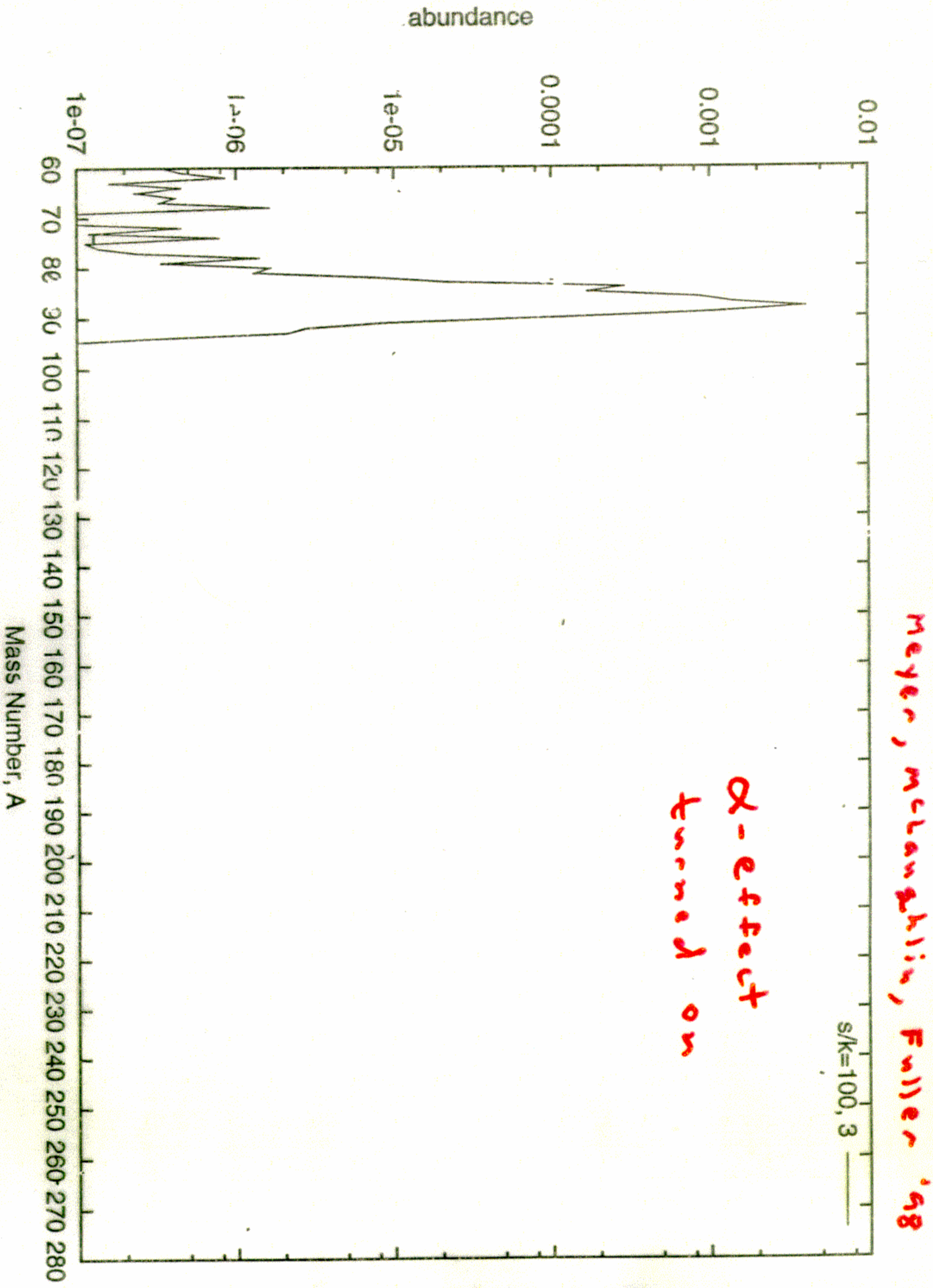
How to Fix the r-Process

(i.e., raise the neutron-to-seed nucleus ratio)

- **Decrease Y_e**
  (Increases n/p ratio.)

- **Increase Entropy**
  (More photo-dissociation hinders formation of seed nuclei.)

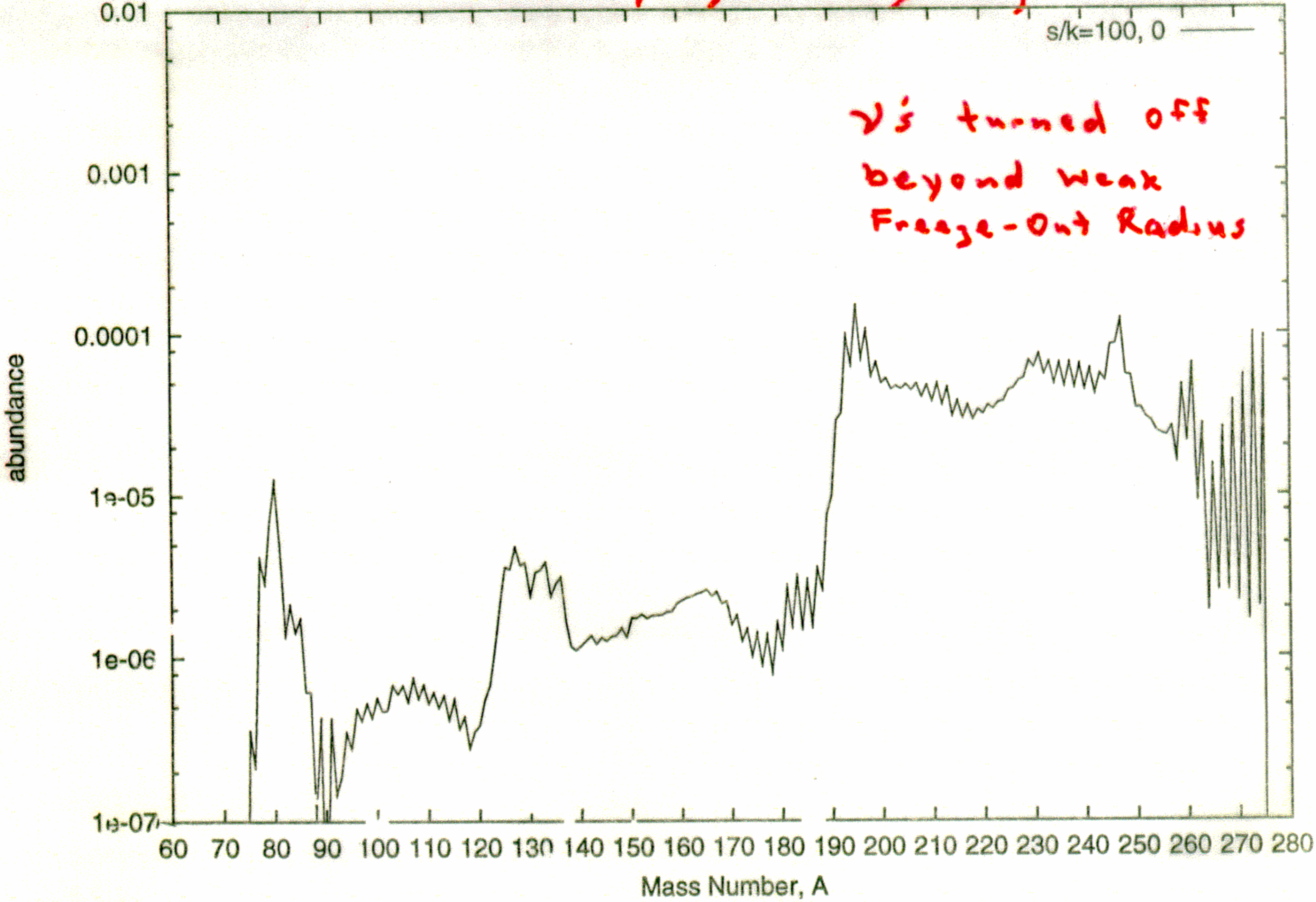
- **Decrease Expansion Timescale**
  (Fewer seed nuclei because there is less time for $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be}$.)



meyer, mclaughlin, Fuller '98

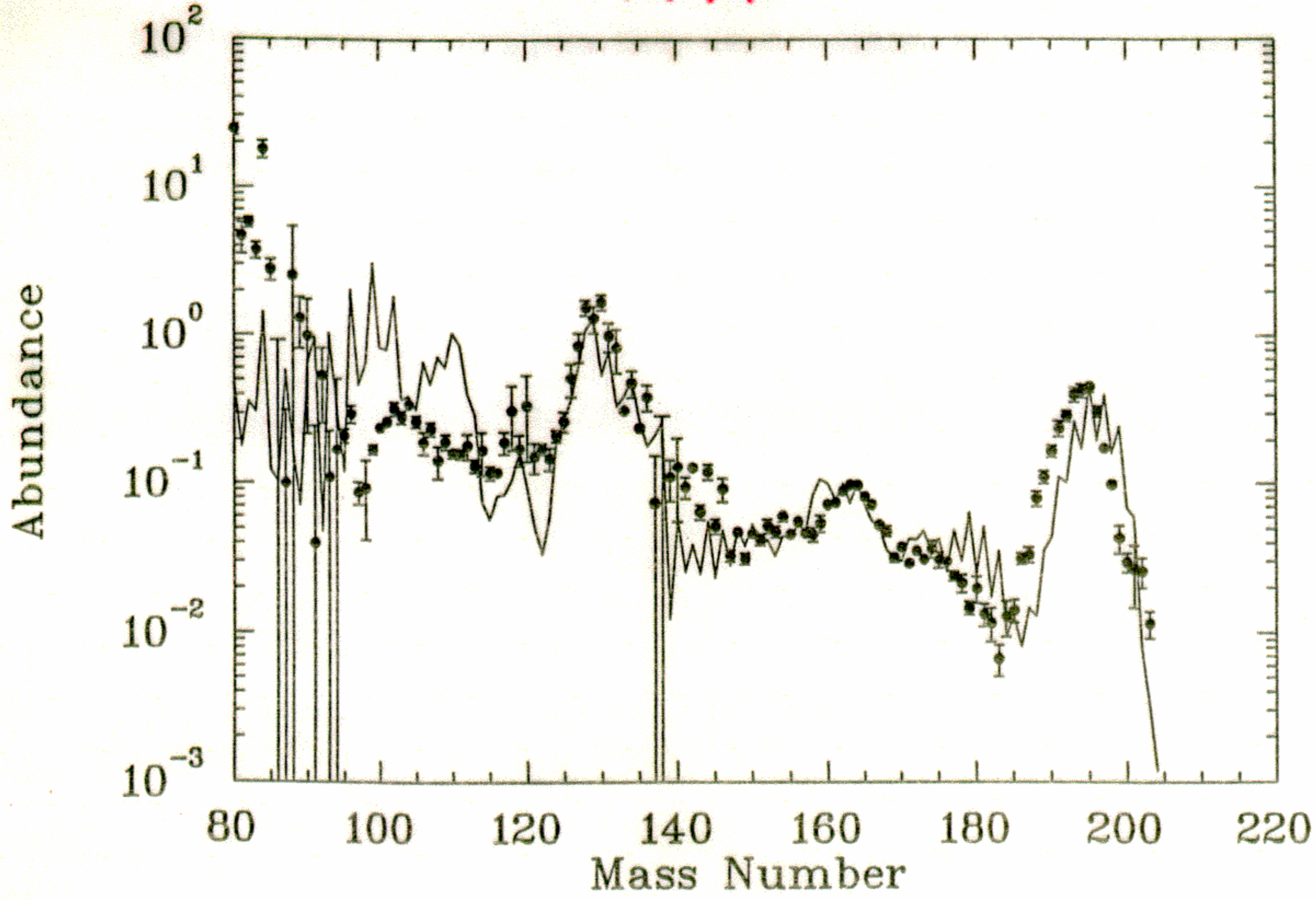
α-effect turned on

Meyer, McLaughlin, Fuller '98



ν's turned off beyond weak Freeze-Out Radius

Woosley, Wilson, Mathews, Hoffman, Meyer
1994

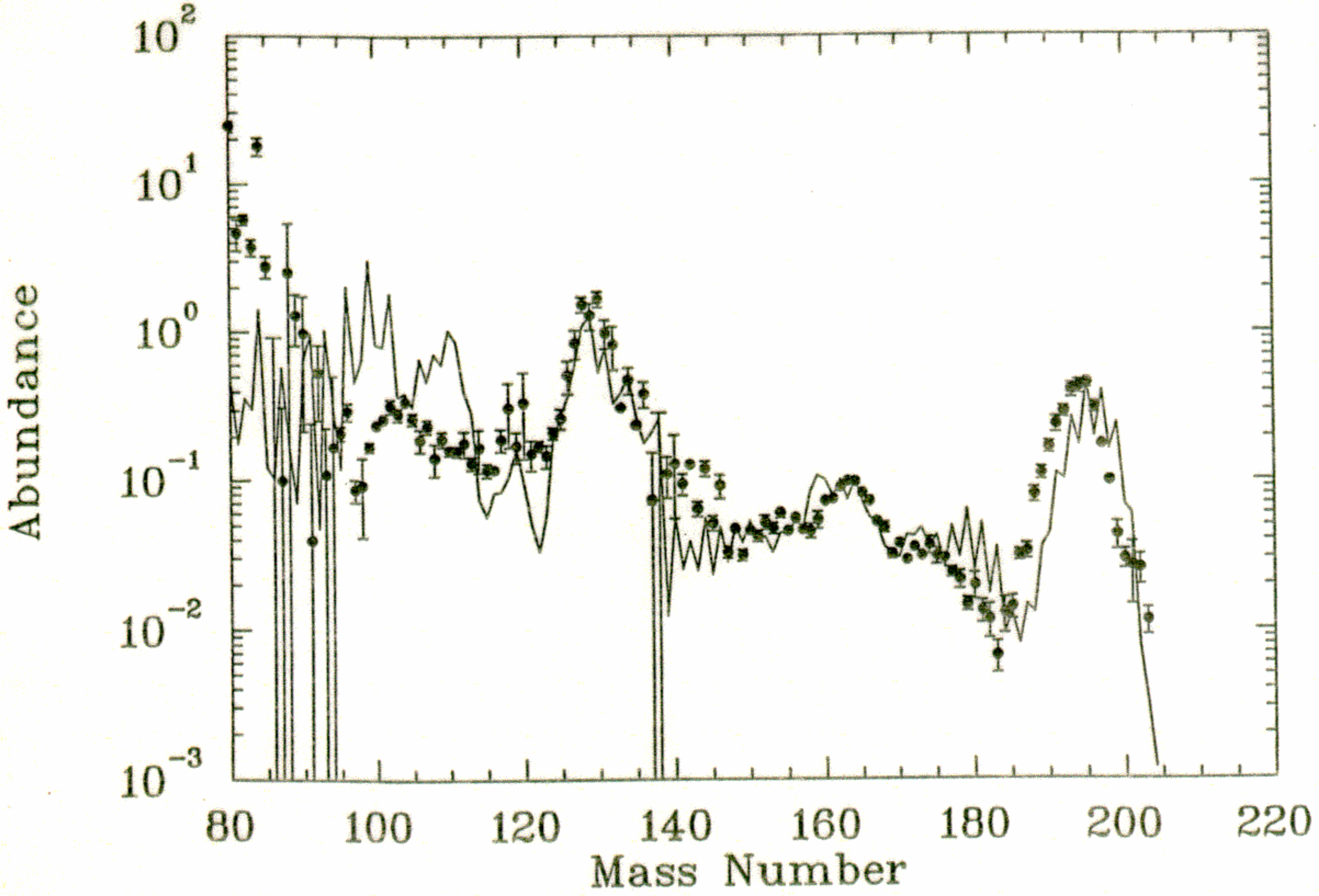


But $\frac{n}{\text{seed}}$ ratio artificially high here

Fig. 16

$\Rightarrow$ see Meyer 1995 $(\nu + \alpha \rightarrow {}^3H + p + \nu$
$\rightarrow \nu + {}^3He + n)$

Woosley, Wilson, Mathews, Hoffman, Meyer
1994



But $\frac{n}{seed}$ ratio artificially high here

Fig. 16

⇒ see Meyer 1995 ($\nu + \alpha \to {}^3H + p + \nu$
${}^3He + n$)

Average Neutrino Energy Hierarchy

- In the Absence of Neutrino Flavor Transformations, the Average Neutrino Energies Always Satisfy:

$$\langle E_{\nu_{\mu(\tau)}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

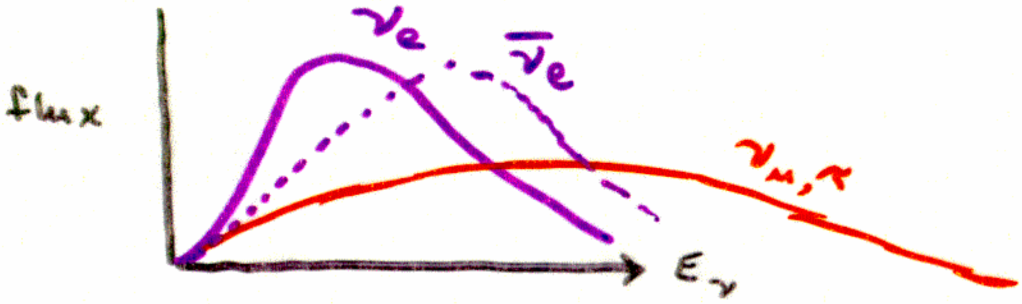
$$\Downarrow \qquad \Downarrow \qquad \Downarrow \qquad \Downarrow$$

$\Longrightarrow$ This Would Imply That Material Is Neutron-Rich, Since

$$Y_e \approx (1 + \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle)^{-1} < 0.5$$

OR

$$n/p \approx \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle > 1$$



Neutrinos Set Y_e

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

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

- Cross Sections: $\sigma \sim G_F^2 E_\nu^2$
- Rates: $\lambda =$ (Flux)·(Cross Section)

$$\lambda \sim (L_\nu / \langle E_\nu \rangle) \cdot \langle E_\nu \rangle^2 = L_\nu \langle E_\nu \rangle$$

$$\Downarrow \qquad \Downarrow \qquad \Downarrow \qquad \Downarrow$$

Integrate the Rate Equations ⇒

$$Y_e \approx \lambda_{\nu_e n} / (\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}) \sim (1 + \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle)^{-1}$$

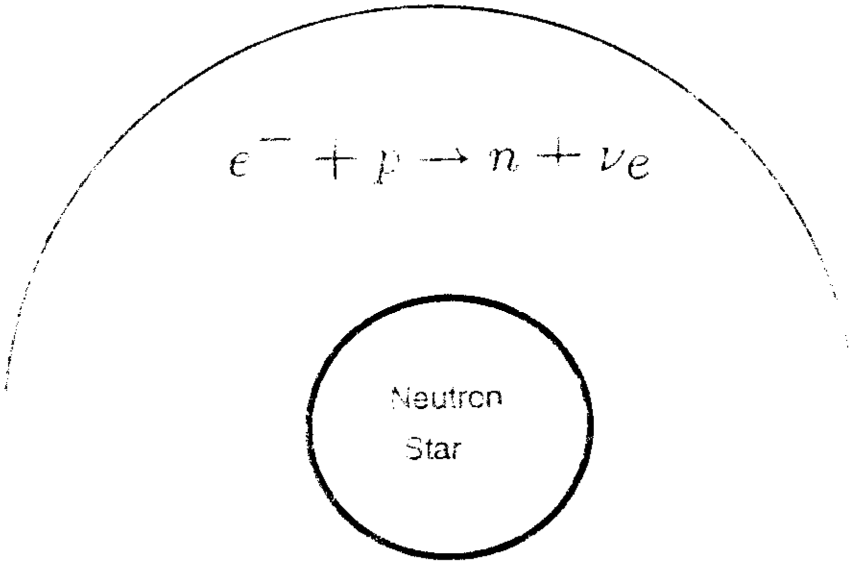
Where the Last Step Follows on Noting that at Late Times,

$$L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_{\mu(\tau)}}$$

WEAK FREEZE-OUT RADIUS ----

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

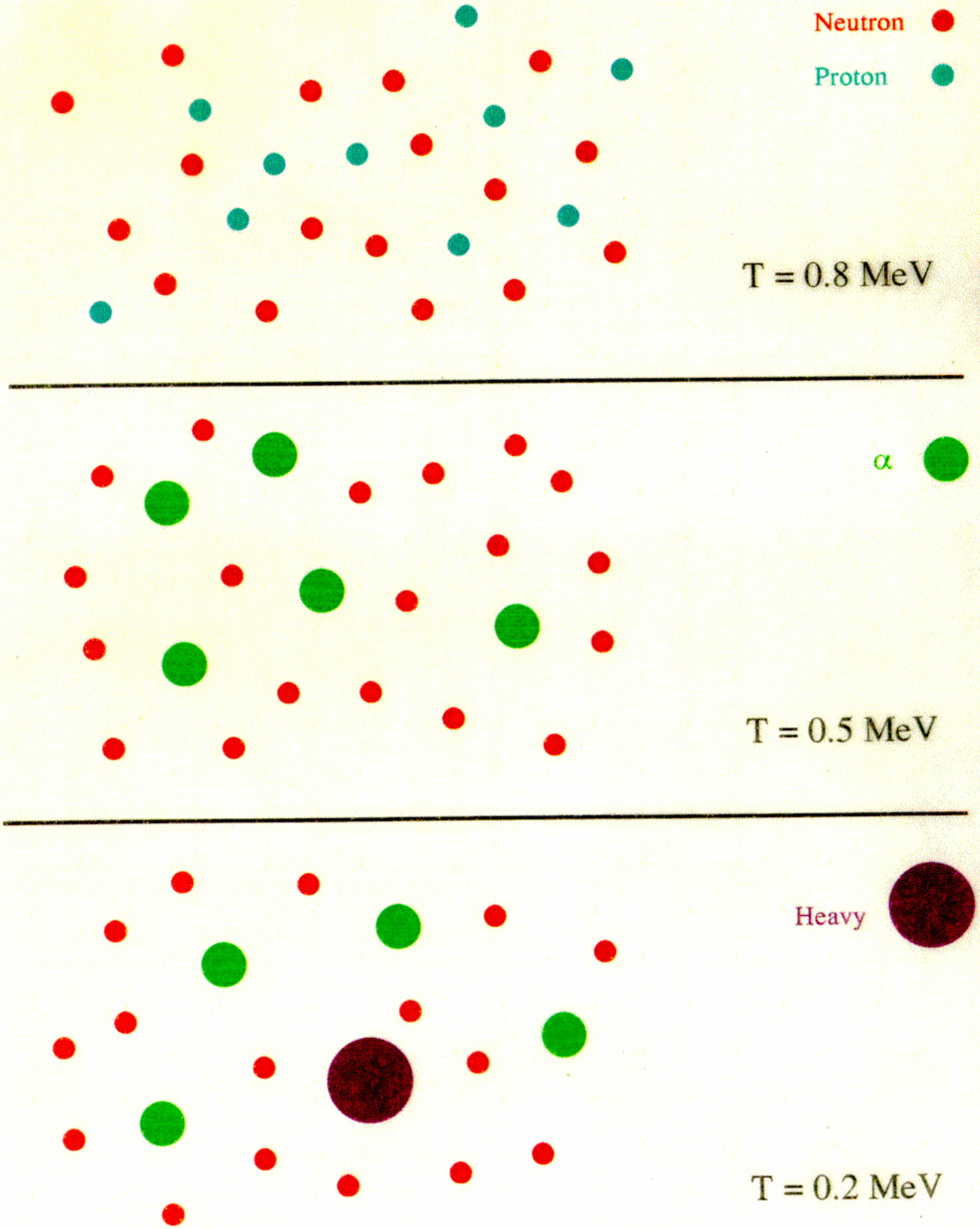
$$\bar{\nu}_e + p \rightarrow n + e^+$$



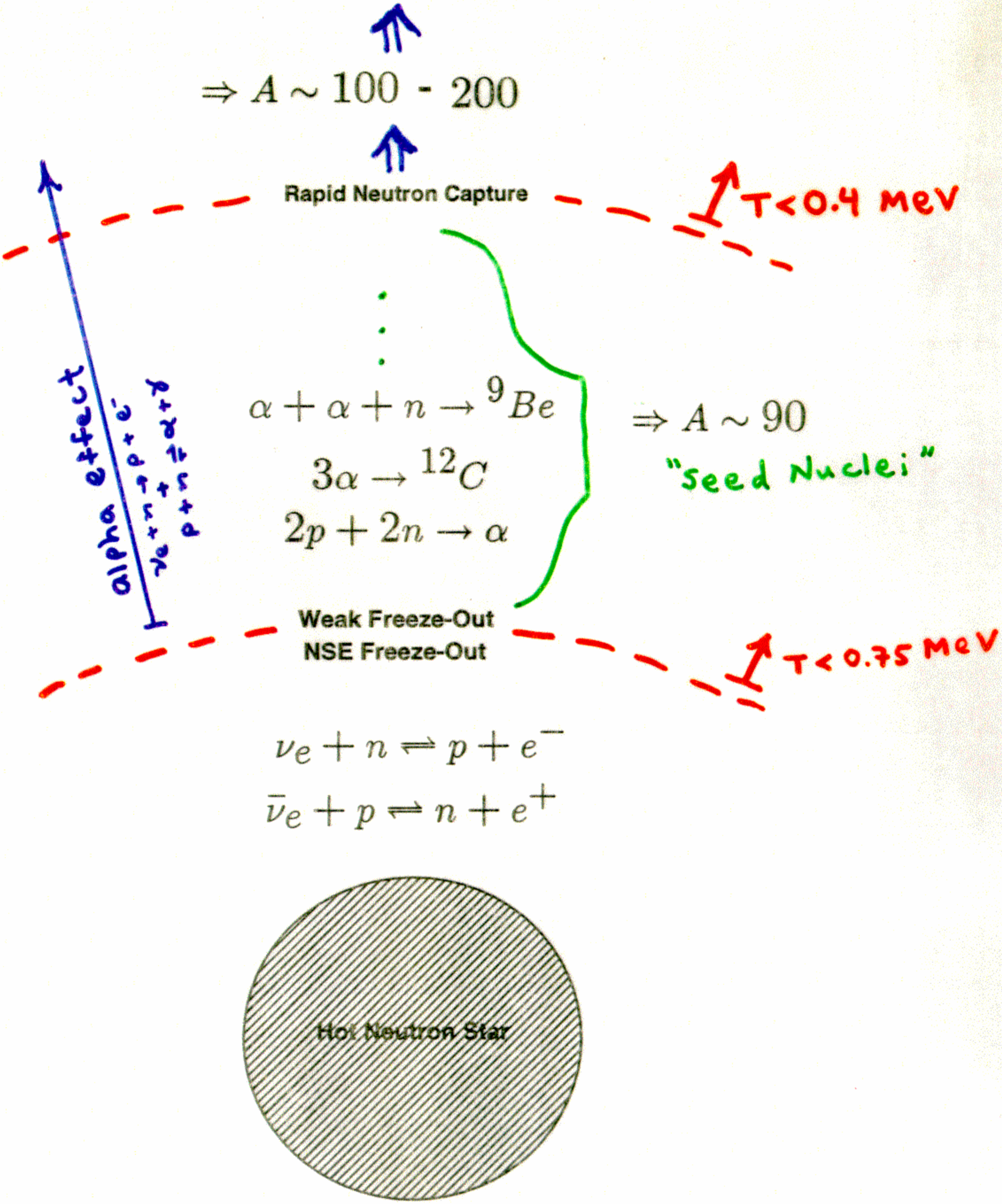
$$e^- + p \rightarrow n + \nu_e$$


$\lambda_\nu < \lambda_{exp}$

G. Fuller, SSI 2000



r-Process from Neutrino-Heated SN Ejecta



$$\Uparrow$$

$$\Rightarrow A \sim 100 \text{ - } 200$$

$$\Uparrow$$

Rapid Neutron Capture

$$\vdots$$

$$\alpha + \alpha + n \rightarrow {}^{9}Be$$

$$3\alpha \rightarrow {}^{12}C$$

$$2p + 2n \rightarrow \alpha$$

$$\Rightarrow A \sim 90$$

"Seed Nuclei"

Weak Freeze-Out
NSE Freeze-Out

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

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

- **ν-Heated Supernova Ejecta**

B. S. Meyer et al. 1992; K. Takahashi, Witti, & T. Janka 1994; S. E. Woosley et al. 1994.
Status: Troubled; neutrino heating leads to "alpha effect," which can only be circumvented via new neutrino physics, finely tuned GR, or non-neutrino ejection with high speeds.

- **Neutron Star Mergers**

e.g., C. Freiburghaus, S. Rosswog, & F. Thielemann '99
Status: Troubled; merger rate only 10^{-3} to 10^{-4} of SN rate, implying that we need $> 0.1\,\mathrm{M}_\odot$ of r-process material per event. Numerical calculations (e.g., Ruffert & Janka 1996; Wilson & Mathews 1996) suggests that much less is ejected and *that* is sometimes via neutrino heating (see above).

- **Jets/Globs of Low Y_e Material**

e.g., LeBlanc/Wilson jets; A. Burrows low Y_e lumps
Status: Troubled; only one SN in $\sim 10^3$ might do this.

- **Shock Induced r-Process in He or C/O Shells**

Truran & Cowan '00; Truran, Cowan, Cameron '78; Thieleman, Arnould, Hillebrandt 79; Blake, et al. '81
Status: Troubled; will make some lighter r-process, but heavy r-process species yield is sensitive to ^{13}C content, shock parameters.

The Riddle of Neutron-Rich Nuclei

$\Rightarrow$ Require synthesis environment with **abundant free neutrons.**

- **But** Neutrons Are Unstable!! $\tau \approx 887.0\,\mathrm{s}$

$\Rightarrow$ **Can Obtain Free Neutrons By:**

- "Spalling" Neutrons from Nuclei where they are Stabilized by the Strong Force:
  $\gamma + \mathrm{A(Z, N)} \mapsto \mathrm{A(Z, N-1)} + \mathrm{n}$
  But typical neutron binding $\sim 8\,\mathrm{MeV}$!

- "Spalling" Neutrons from Neutron Stars where they are Stabilized by "Gravity."
  (*e.g.*, Binary Neutron Star Coalescence)
  But typical neutron binding $\gtrsim 100\,\mathrm{MeV}$!!

- Weak Interaction $\bar{\nu}_e + \mathrm{p} \mapsto \mathrm{n} + e^+$
  But G_F is small!

Evidence for ν modification

W. Haxton, Y.-Z. Qian, K. Langanke, P. Vogel
'96

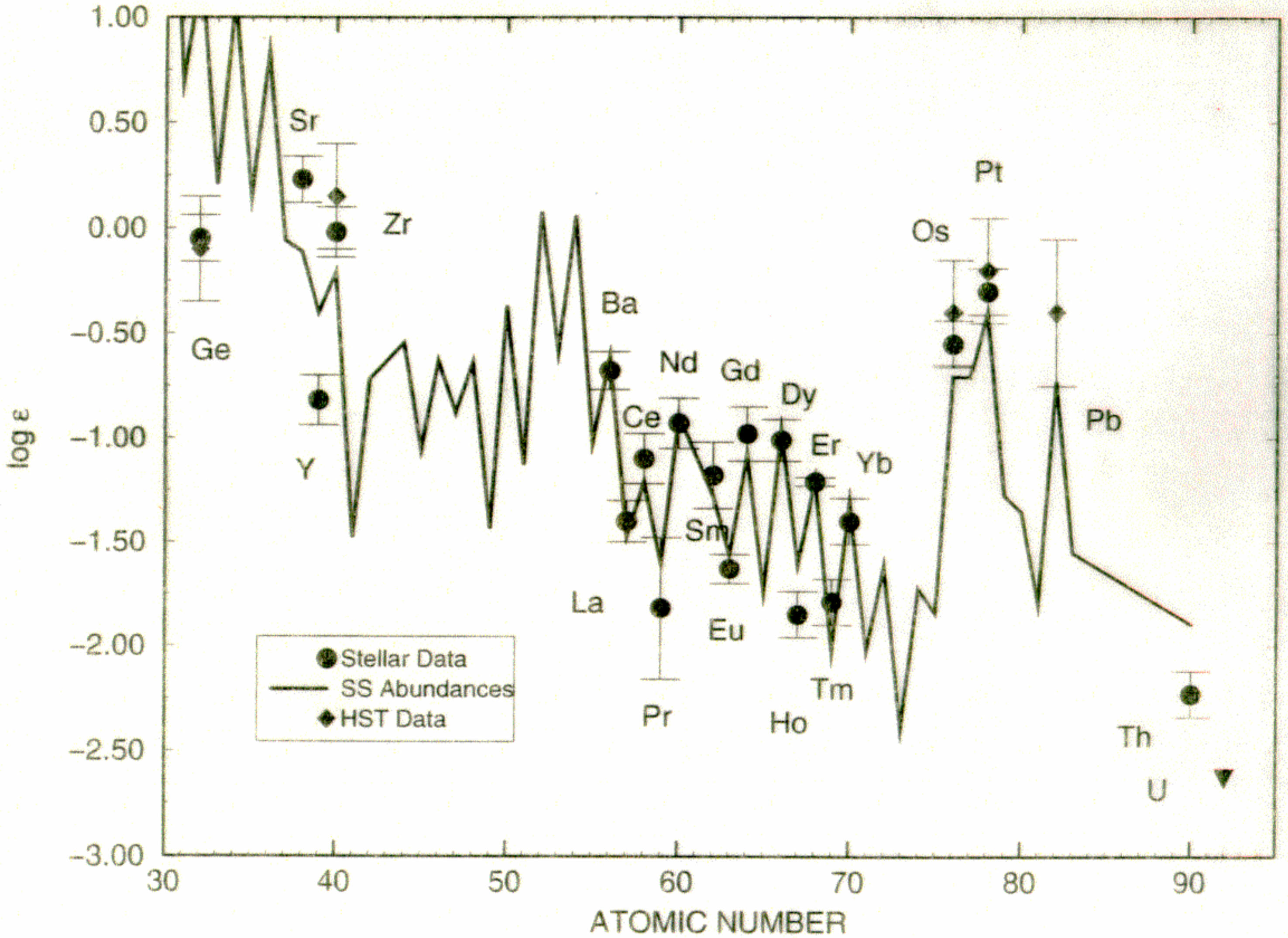
synthesis timescale "evidence"

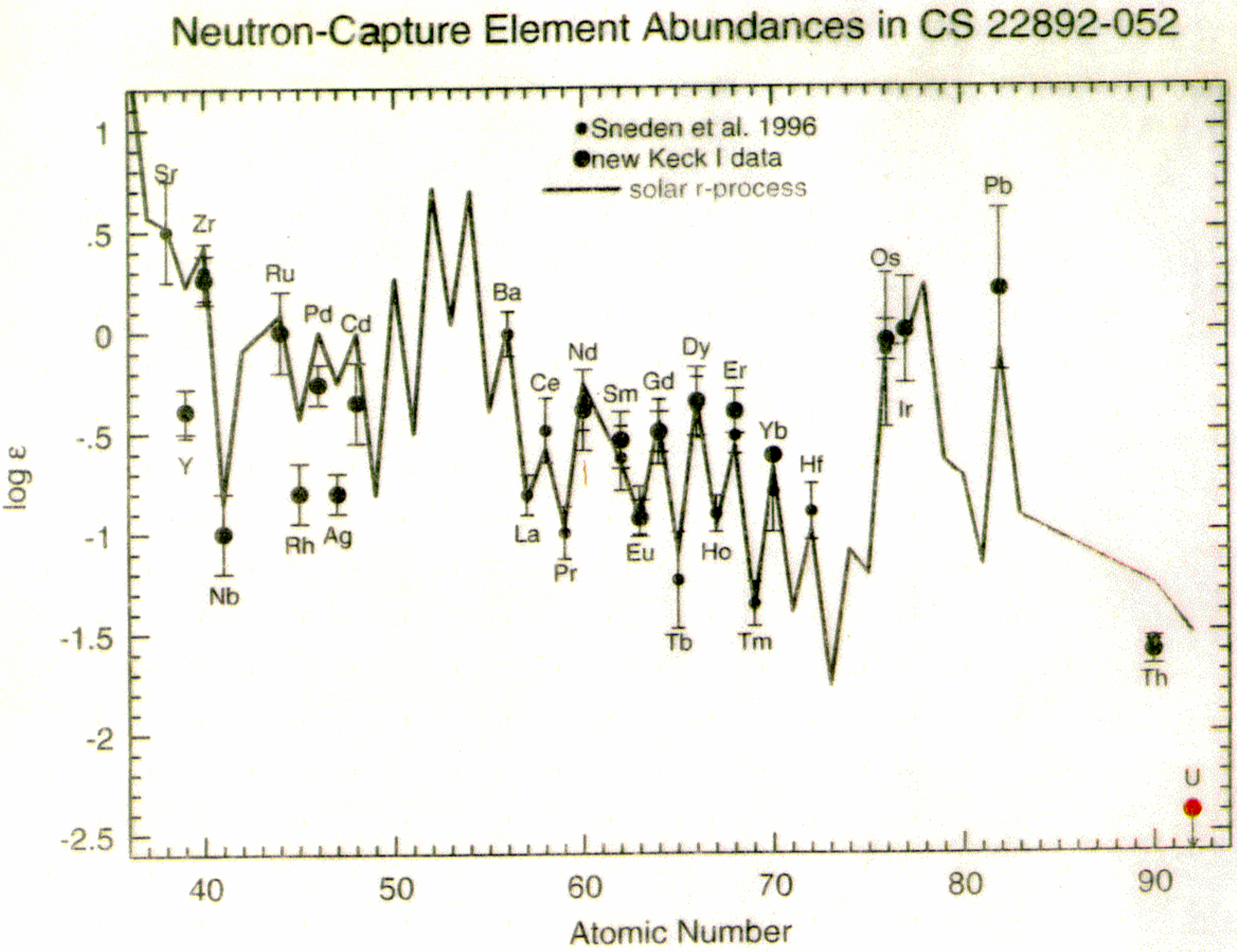
Qian . Vogel . Wasserburg '98

Sneden et al. 2000

NEW KECK Data

HD 115444: good match to scaled
s.s. r-process for $Z \geq 56$





Scaled solar-system r-process is not a godd match with data for $Z < 56$

unlikely to ever get elements in $Z \approx 50$ area

The stakes are very high !!!

- Can we show that ANY r-Process material comes from ν-heated ejecta ??

- Are there ν-signatures in r-Process abundance systematics ??

⇓ ⇓ ⇓ ⇓

Yes ⇒ fantastic probe of ν physics

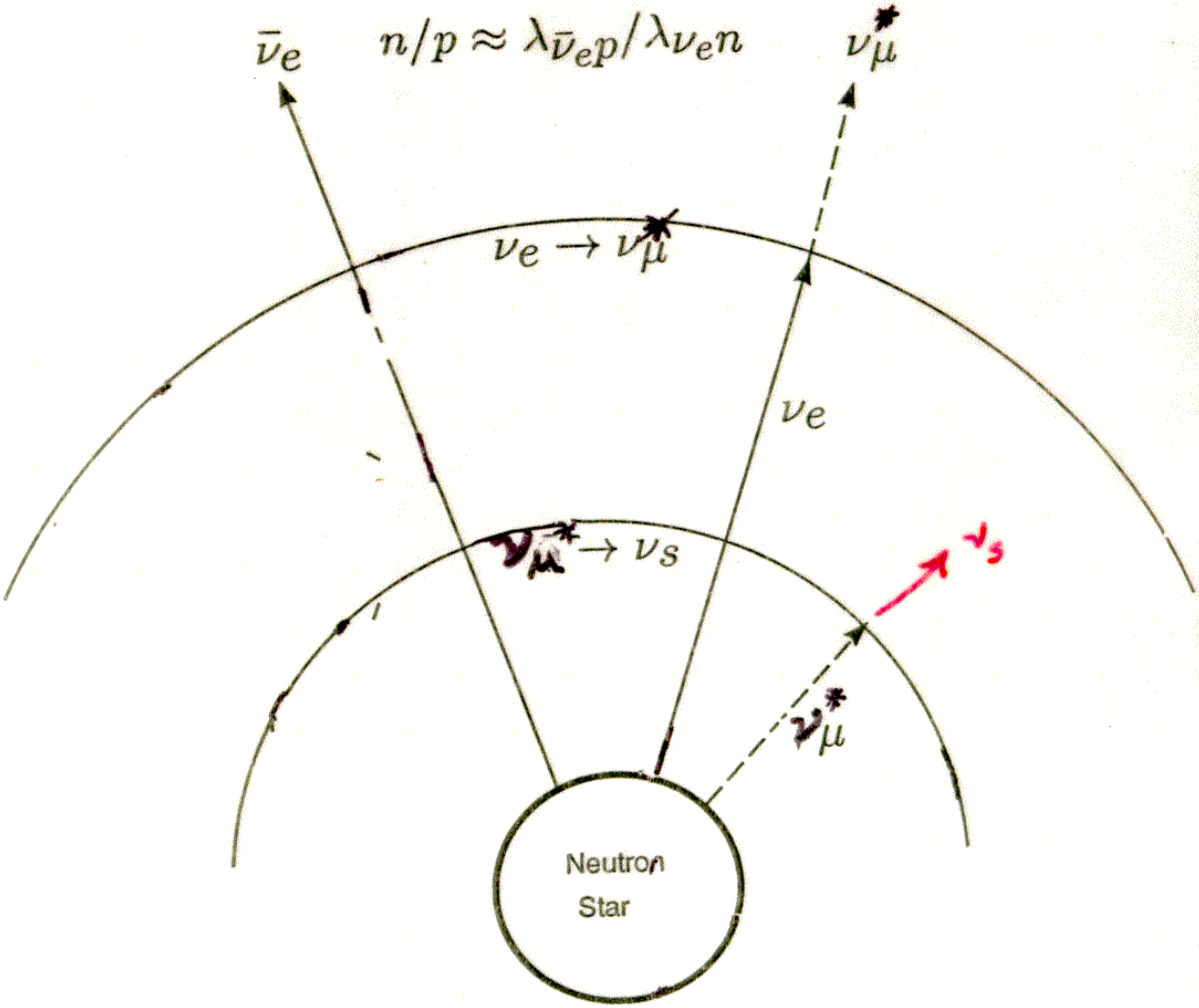
But we are not there yet.

Caldwell, Fuller, Qian (~~1997~~ 2000)

~~Caldwell (1994)~~

$t_{pb} \sim 10$ sec

r-process
nucleosynthesis region

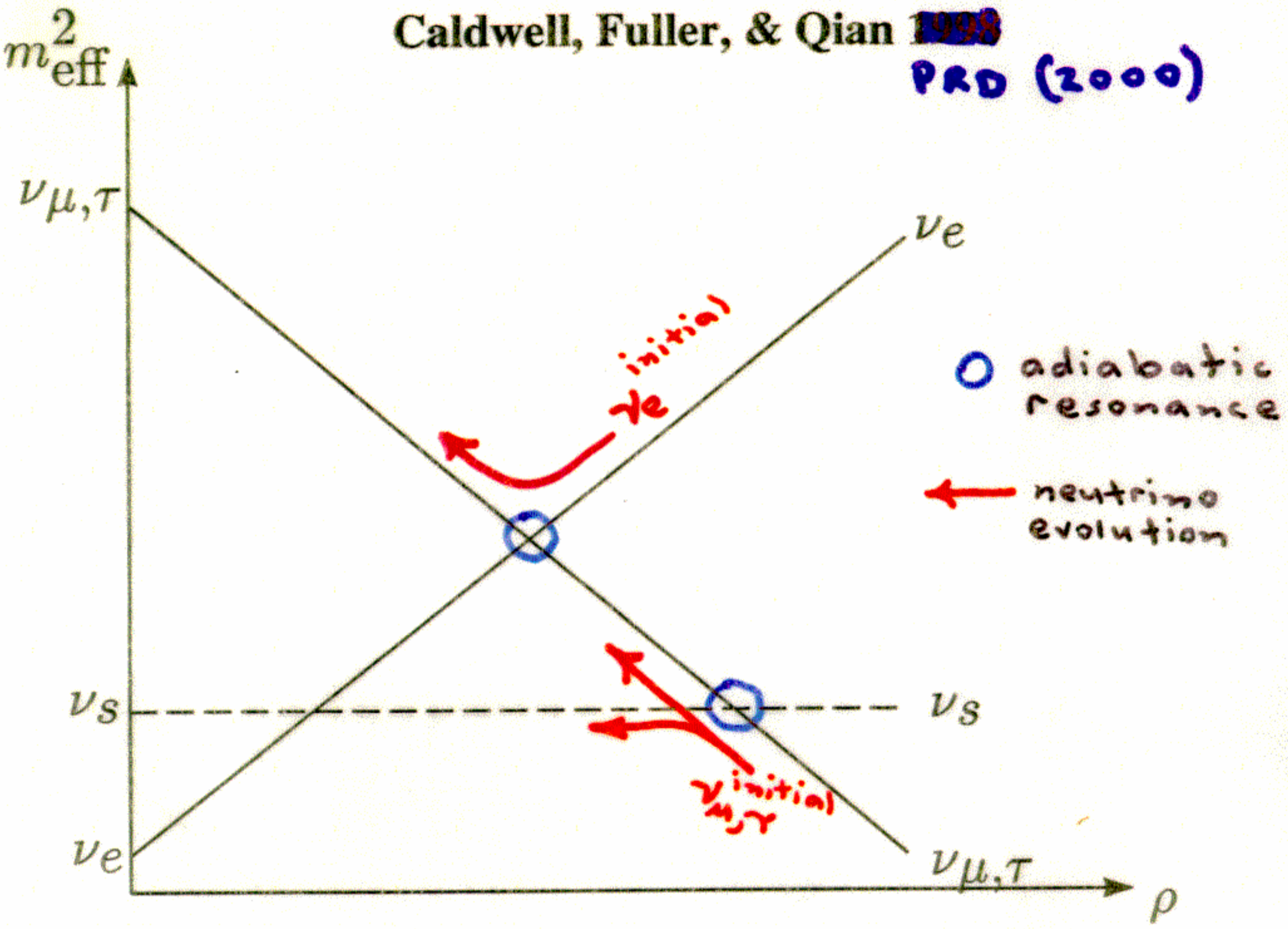


@ $t_{pb} < 1$ sec
use $\nu_e \rightleftharpoons \nu_s$ <u>twice</u>

see also
Peltoniemi
Petcov

$\nu_e \rightleftharpoons \nu_s$ ... ν_e's ⇒ proton-rich

Caldwell, Fuller, & Qian ~~1998~~
PRD (2000)



Fast expansion case: $\nu_{\mu,\tau} \rightleftharpoons \nu_s$ $(\nu_\mu^* \rightleftharpoons \nu_s)$

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Probability $\nu_\mu \to \nu_\mu \Rightarrow 1/4$
Probability $\nu_\mu \to \nu_\tau \Rightarrow 1/4$
Probability $\nu_\mu \to \nu_s \Rightarrow 1/2$

after 2nd res.
Probability $\nu_{\mu,\tau} \to \nu_e \Rightarrow 0$ (2nd resonance)

The key step is to define two linear combinations of ν_μ and ν_τ in this representation, and then transform into the new flavor basis defined by these states. The linear combinations are:

$$|\nu_\mu^*\rangle \equiv \frac{|\nu_\mu\rangle - |\nu_\tau\rangle}{\sqrt{2}}$$

$$|\nu_\tau^*\rangle \equiv \frac{|\nu_\mu\rangle + |\nu_\tau\rangle}{\sqrt{2}}$$

Armed with this new flavor basis, we can produce a new unitary transformation to the mass basis in vaccum:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_s\rangle \\ |\nu_\mu^*\rangle \\ |\nu_\tau^*\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi\cos\omega & \sin\phi\sin\omega & 0 \\ -\sin\phi & \cos\phi\cos\omega & \cos\phi\sin\omega & 0 \\ 0 & -\sin\omega & \cos\omega & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

$\Downarrow$ $\Downarrow$ $\Downarrow$

$\nu_\mu^* \rightleftharpoons \nu_e\,,\ \nu_s$

ν_τ^* "decoupled"

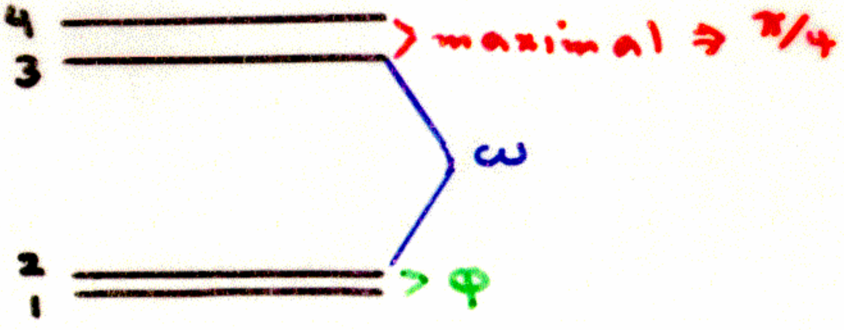
4×4 Mixing in Vacuum

CFQ '00

Balantekin & Fuller '99

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_s\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \cos\phi & \sin\phi\cos\omega & \sin\phi\sin\omega & 0 \\ -\sin\phi & \cos\phi\cos\omega & \cos\phi\sin\omega & 0 \\ 0 & -\sin\omega/\sqrt{2} & \cos\omega/\sqrt{2} & 1/\sqrt{2} \\ 0 & \sin\omega/\sqrt{2} & -\cos\omega/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \\ |\nu_4\rangle \end{pmatrix}$$

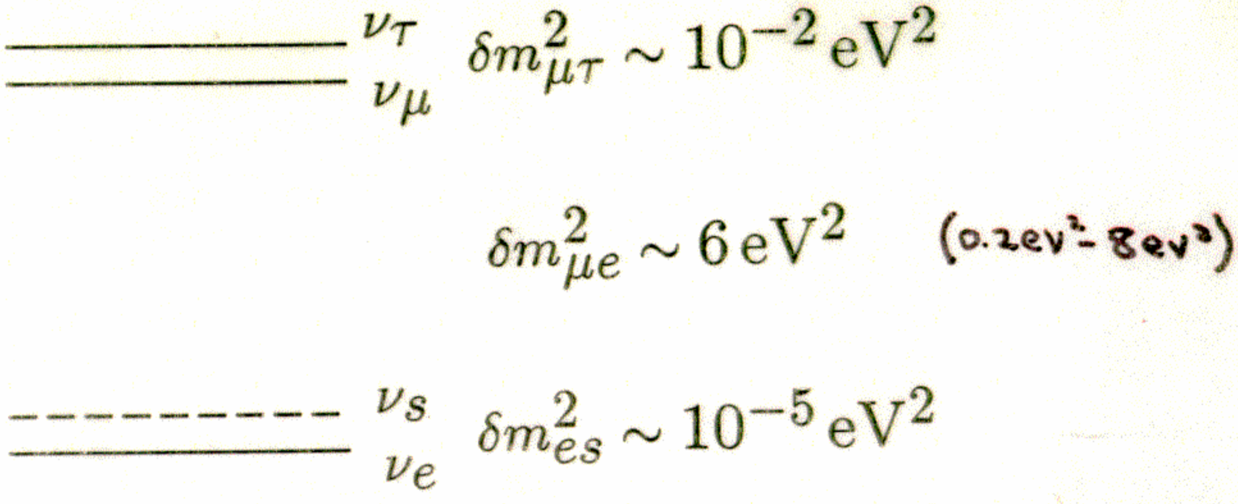
Note that the mixing between ν_e and ν_s is mostly determined by the angle ϕ, while ω controls the level of mixing between between the doublets, $\nu_{\mu,\tau}$ and $\nu_{e,s}$.



$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} c\varphi & s\varphi & 0 & 0 \\ -s\varphi & c\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c\omega & s\omega & 0 \\ 0 & -s\omega & c\omega & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$3 \rightleftharpoons 4$ $\qquad$ $1 \rightleftharpoons 2$ $\qquad$ $2 \rightleftharpoons 3$

Caldwell, Fuller, and Qian ~~1998~~ 2000



(like old C. & Mohapatra scheme for masses)

BBN: OK (very restricted !!!)

SNN: Enables r-Process in neutrino-heated supernova ejecta; removes ν_e flux.

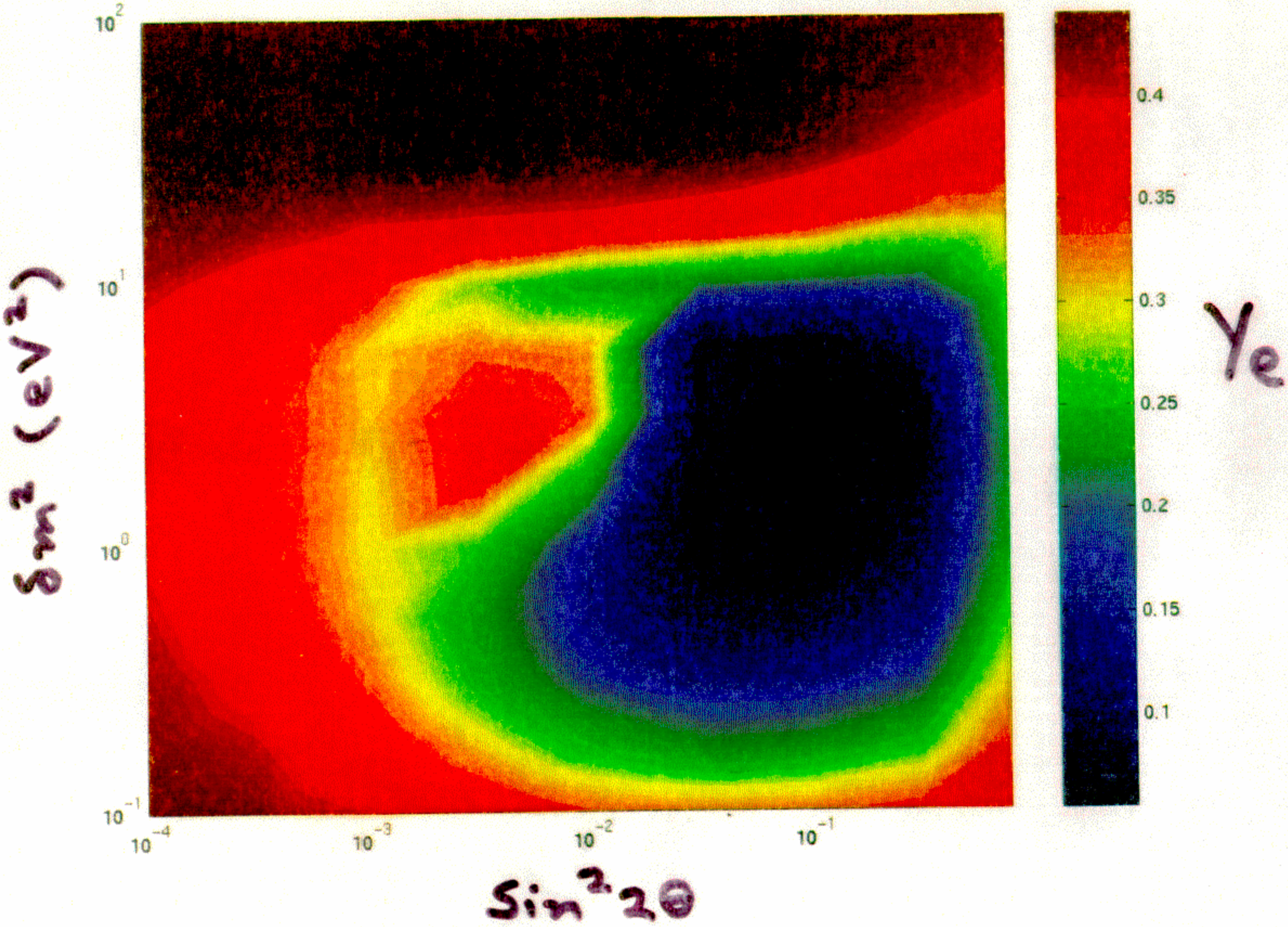
SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ maximal vacuum mixing

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_s$ matter-enhanced
(or $\nu_e \rightleftharpoons \nu_s$ "just so" $\delta m^2 \sim 10^{-10}\,\mathrm{eV}^2$)

LSND: $\nu_\mu \rightleftharpoons \nu_e$ vacuum oscillations

MFBF '92 EFFECT
Patel & Fuller

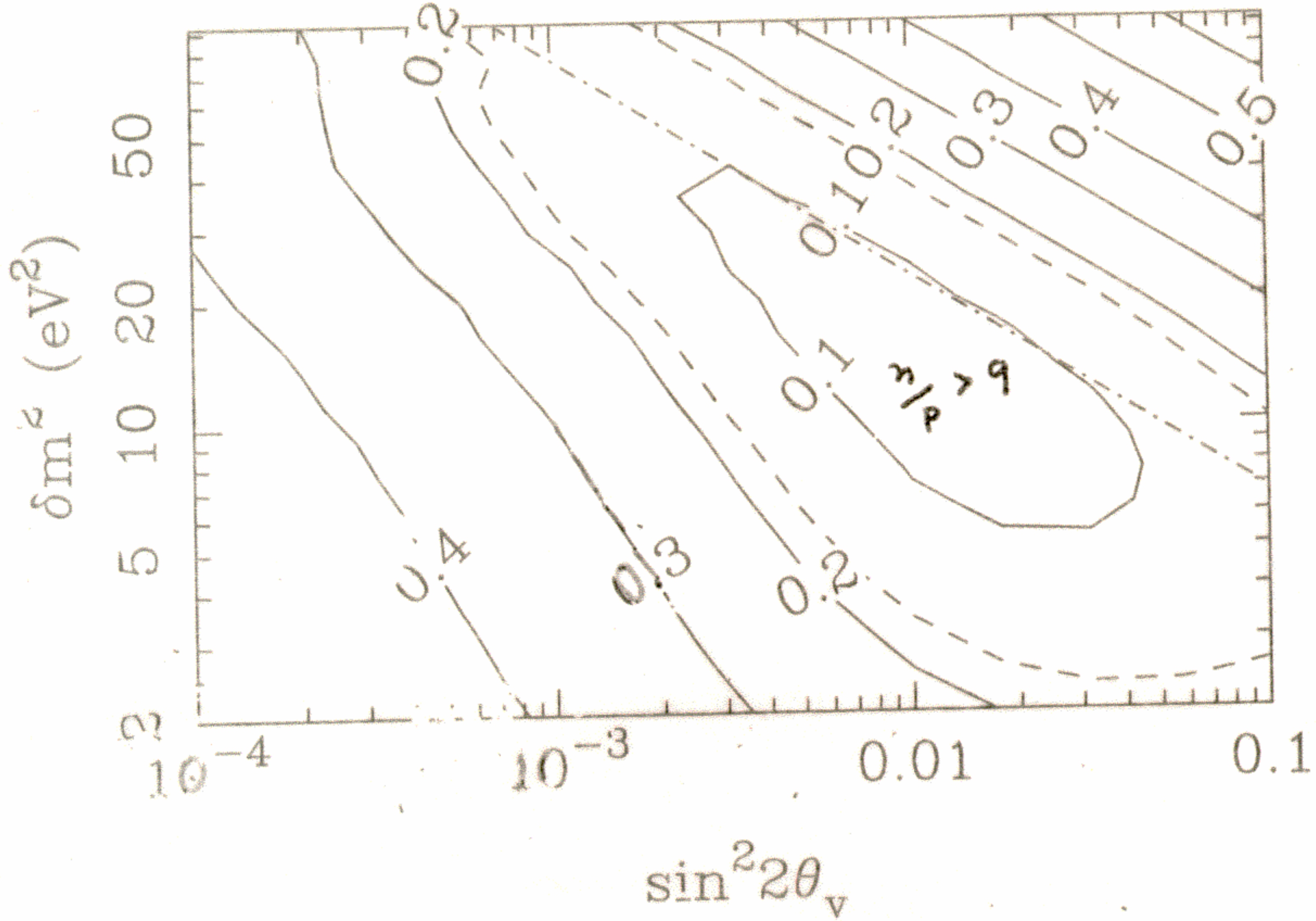
$\nu_e \rightleftarrows \nu_s$
$\bar{\nu}_e \rightleftarrows \nu_s$



MFBF '98

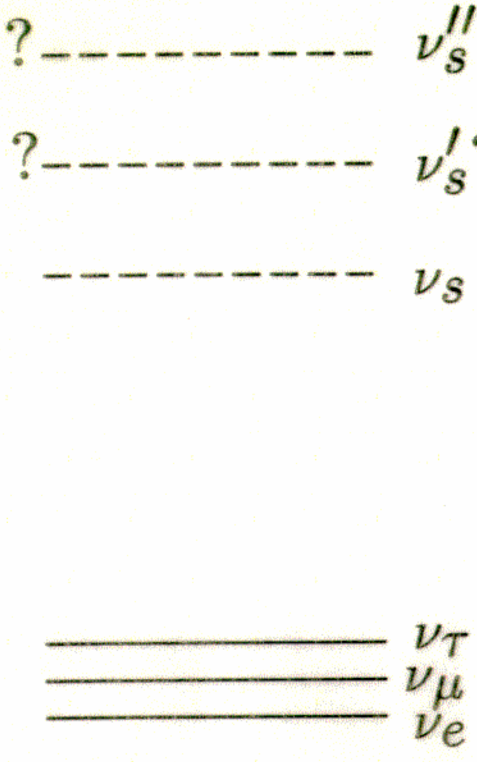
Final Y_e, $\tau = 0.3$ s

$\nu_e \rightleftharpoons \nu_s$ + $\bar{\nu}_e \rightleftharpoons \bar{\nu}_s$ } Fetter, McLaughlin, Balantekin, G.M.F



McLaughlin, Fetter, Balantekin, GMF
(MFBF), ~~submitted PRD~~
PRC 59, 2873,
(1999)

Balantekin, Fetter, Fuller,
McLaughlin 1998



For r-process "fix"

$$100\,\mathrm{eV}^2 > \delta m^2_{es} > 6\,\mathrm{eV}^2$$

?
could be 0.2eV² – 200eV²
depending on ν-spectra

$$\delta m^2_{\mu\tau} \sim 10^{-2}\,\mathrm{eV}^2$$

$$\delta m^2_{e\mu} < 10^{-4}\,\mathrm{eV}^2$$

BBN: OK, may give interesting CMBR signal ?

NO not if we want

SNN: Enables r-Process in neutrino-heated ejecta
"removes" ν_e flux

SuperK: $\nu_\mu \rightleftharpoons \nu_\tau$ **maximal vacuum mixing**

Solar Neutrinos: $\nu_e \rightleftharpoons \nu_{\mu,\tau}$ matter-enhanced or vacuum oscillations

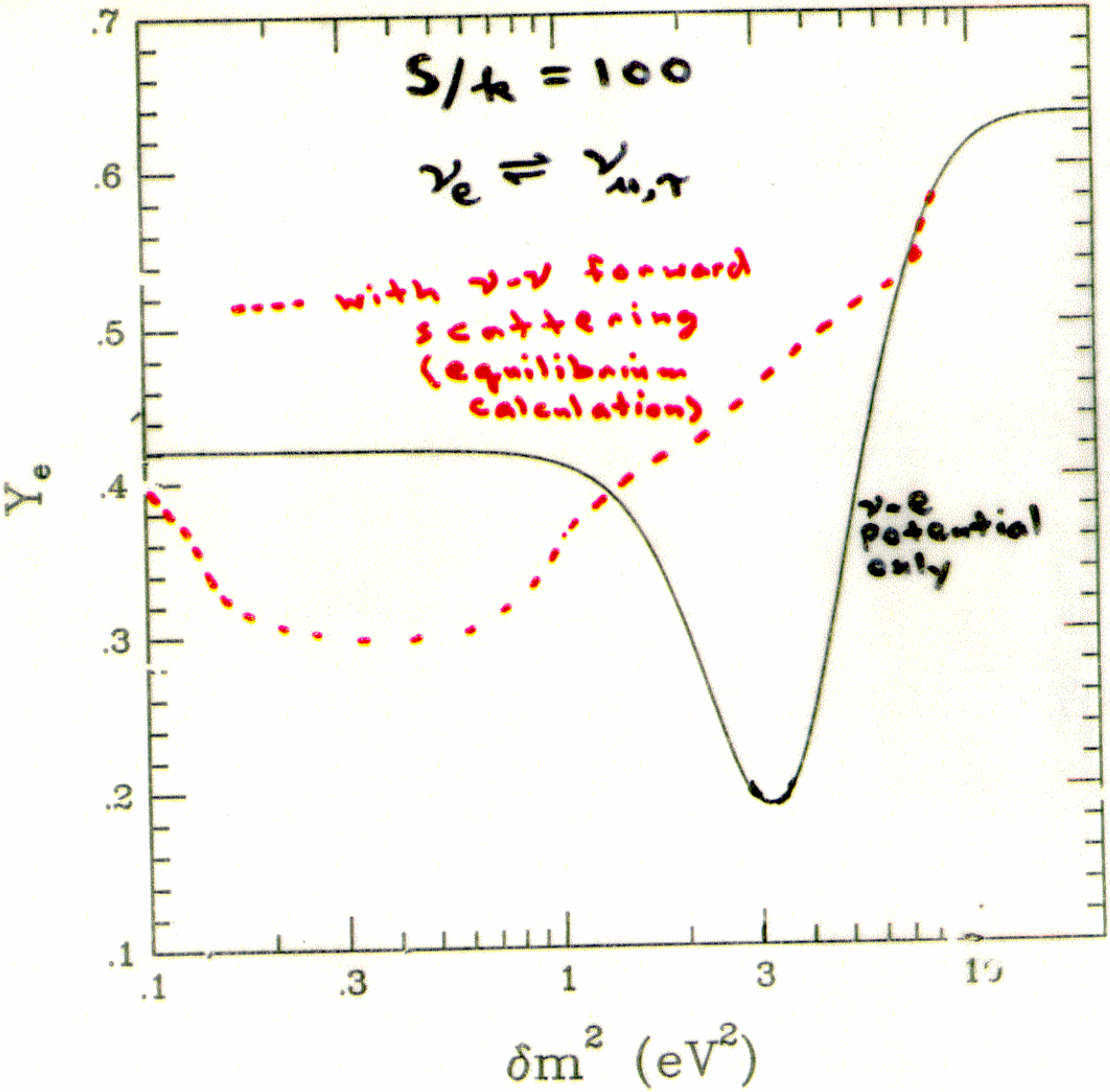
LSND: $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ Indirect vacuum oscillations (but note that oscillation channel proceeds through sterile state)

troubled:

can effective two-ν mixing be big enough? Also BBN?

with ν-ν forward scattering, get ~10% reduction in Y_e for

$$\boxed{0.1\ \mathrm{eV}^2 \lesssim \delta m^2 \lesssim 1\ \mathrm{eV}^2}$$



Matter-Enhanced $\nu_{\mu(\tau)} \rightleftharpoons \nu_e$

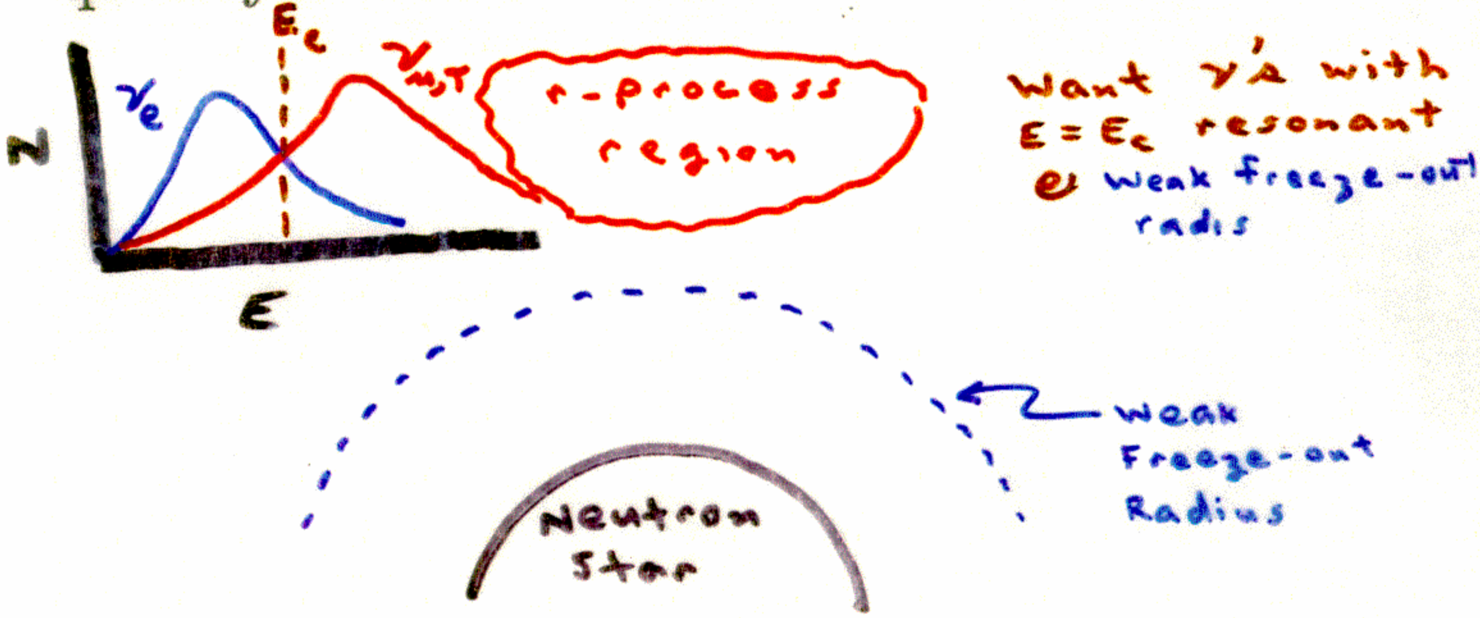
(Qian & Fuller 1997)

- Want only neutrinos with energies less than spectrum crossover energy E_c to transform inside the weak freeze-out radius.

- This will occur and decrease Y_e when

$$2\,\mathrm{eV}^2 \lesssim \delta m^2 S_{100} \lesssim 3\,\mathrm{eV}^2$$

e.g., when $S/k = 400$, Y_e decreased adequately for $\delta m^2 \approx 0.5\,\mathrm{eV}^2$.



Want ν's with $E = E_c$ resonant @ weak freeze-out radis

weak Freeze-out Radius

Y.-Z. Qian & G.M. Fuller
Phys. Rev. D51, 1429 (1995)

Qian & Fuller 1994

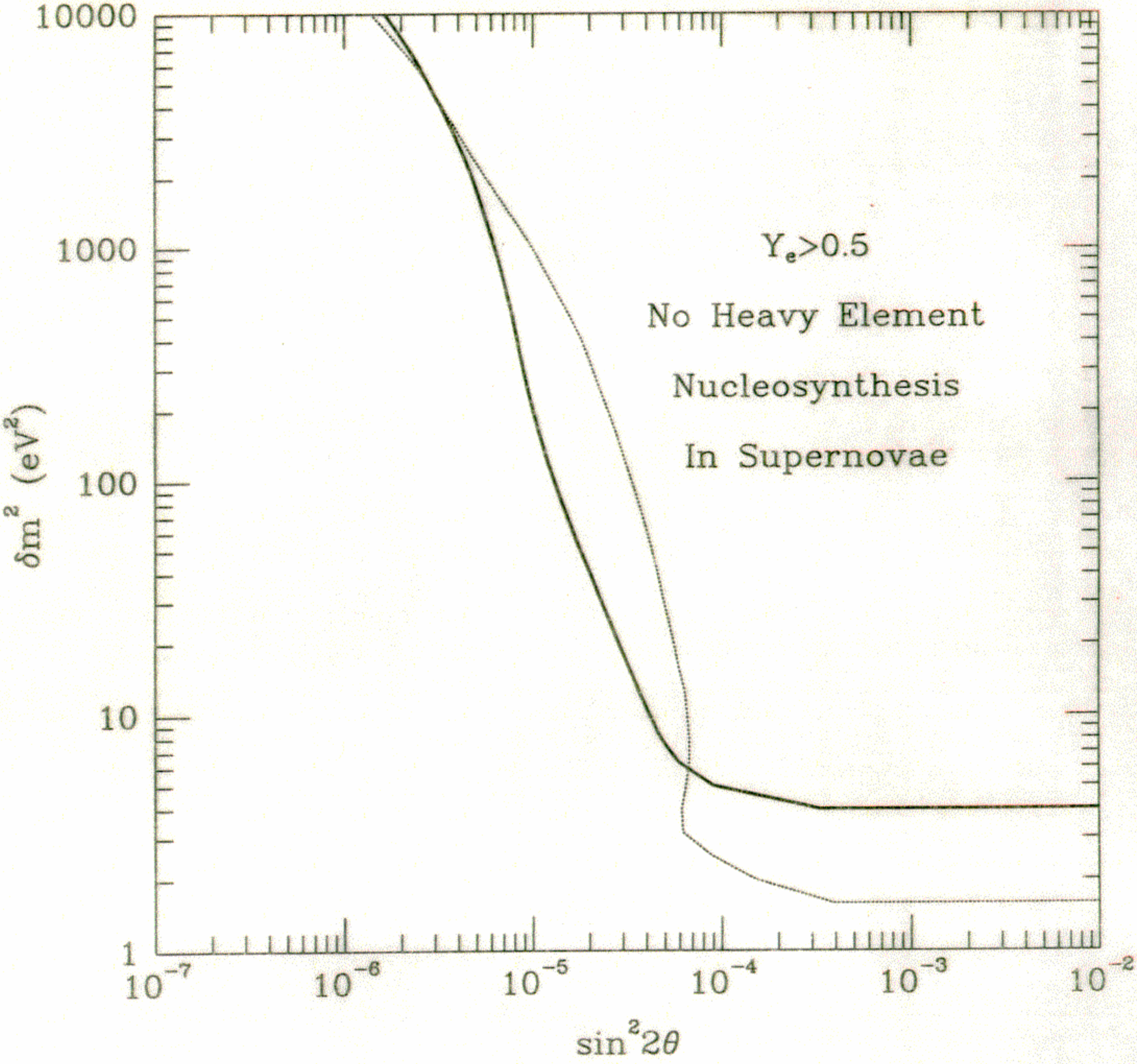


Fig. 9

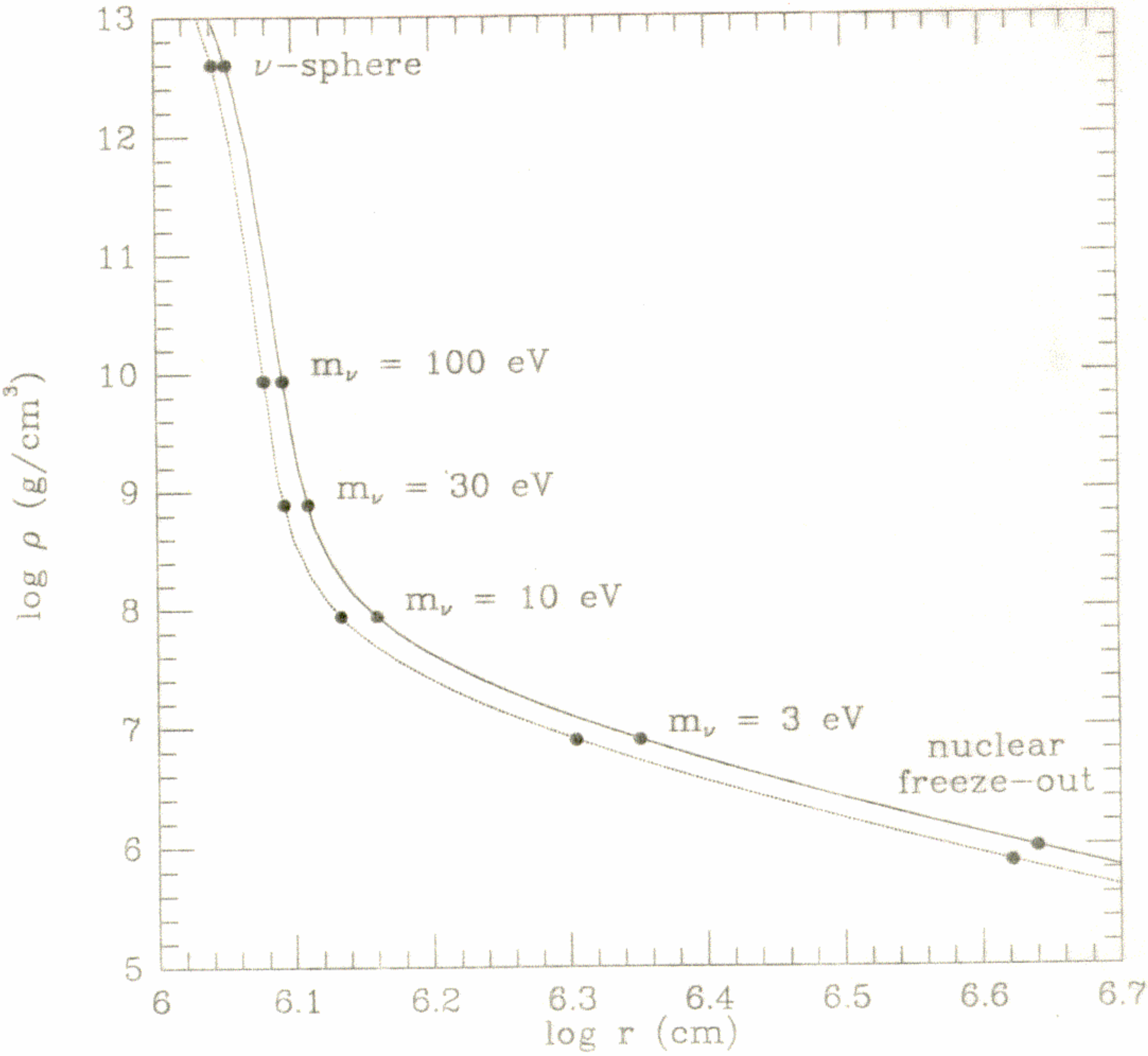

ν−sphere
m$_\nu$ = 100 eV
m$_\nu$ = 30 eV
m$_\nu$ = 10 eV
m$_\nu$ = 3 eV
nuclear
freeze−out
log ρ (g/cm^3)
13
12
11
10
9
8
7
6
5
6
6.1
6.2
6.3
6.4
6.5
6.6
6.7
log r (cm)

Figure 1

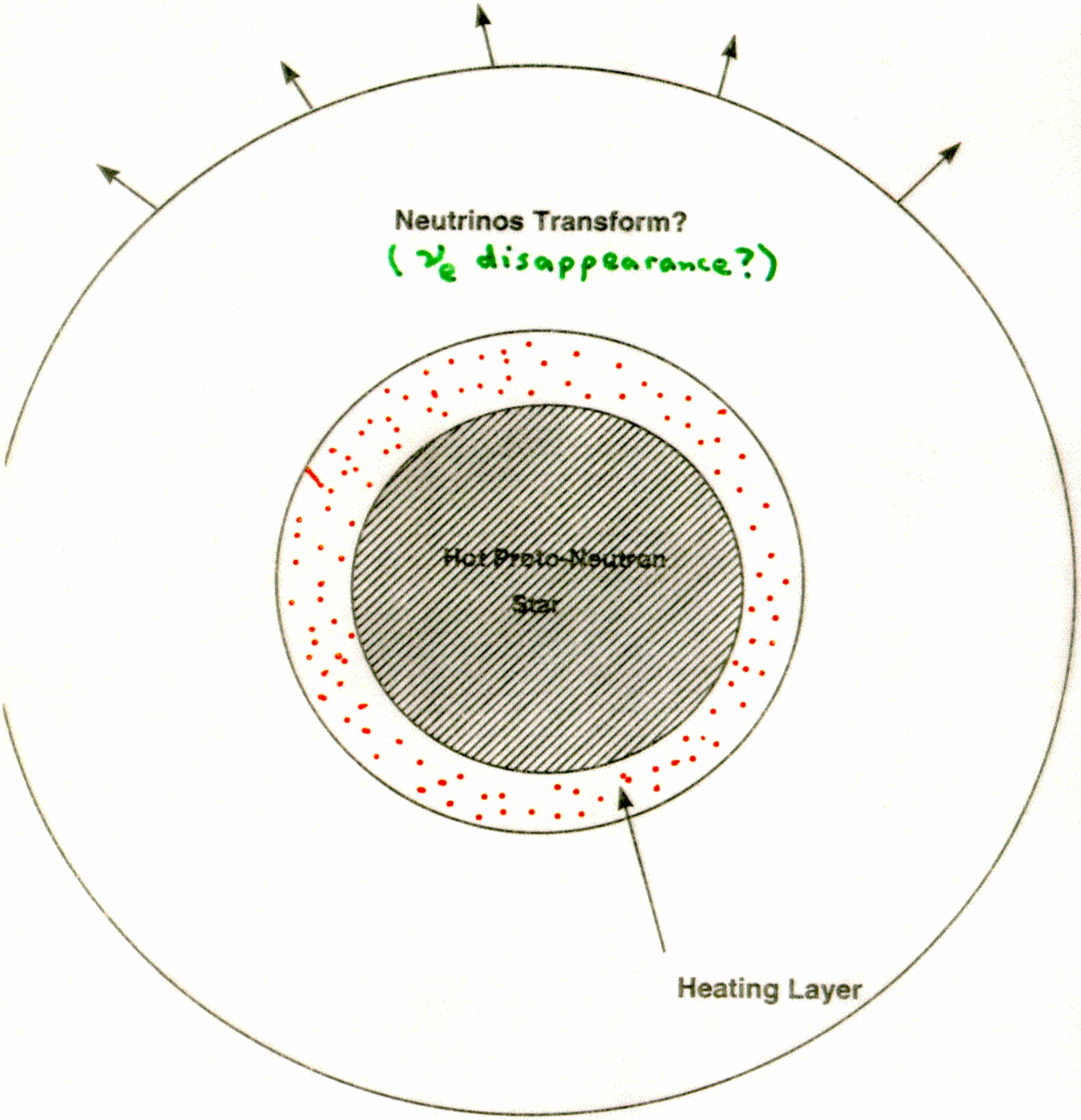
Uranium

$\vdots$

$\alpha + \alpha + n \rightarrow {}^{9}Be$

$2p + 2n \rightarrow \alpha$

r-Process Region

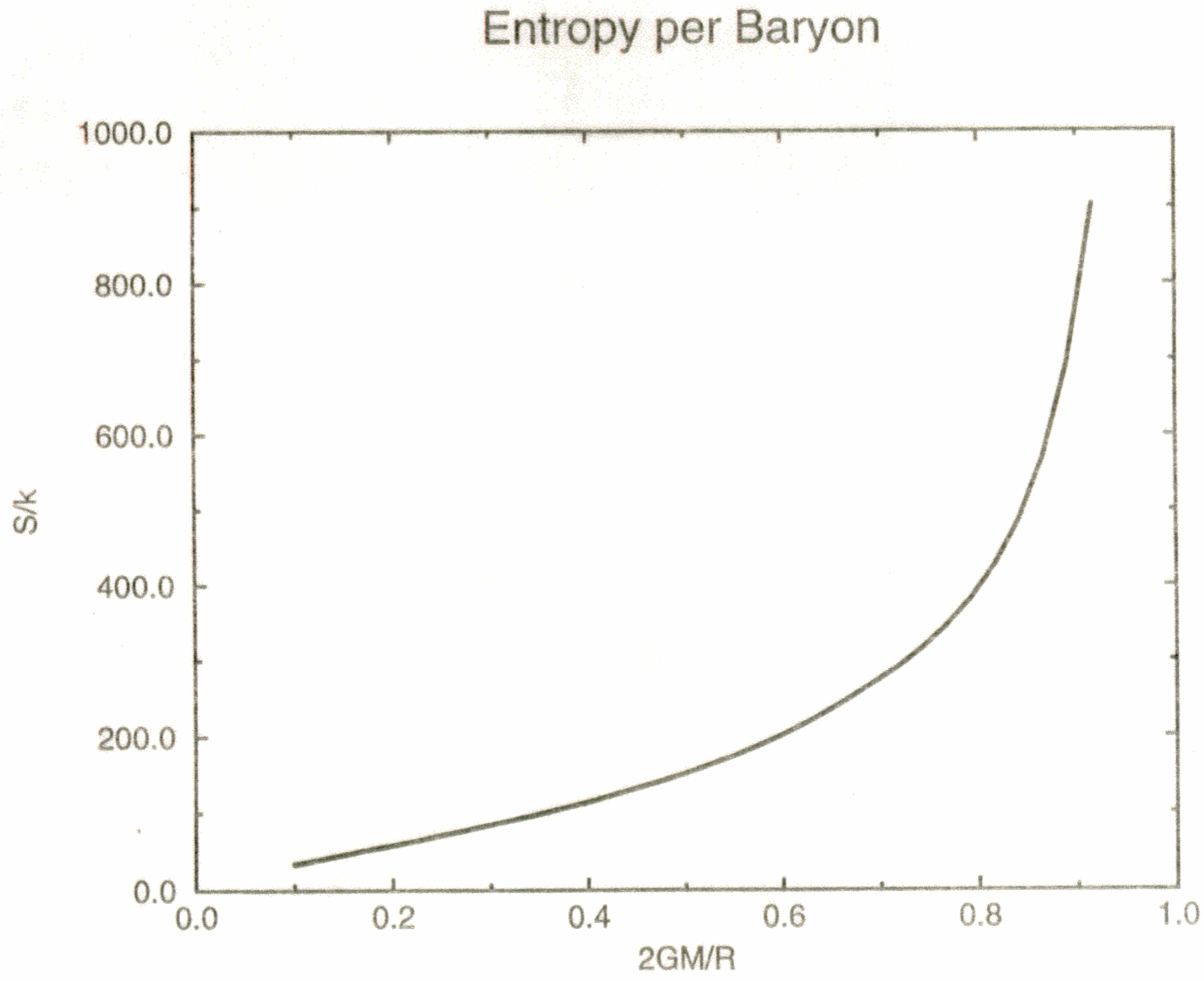


Neutrinos Transform?

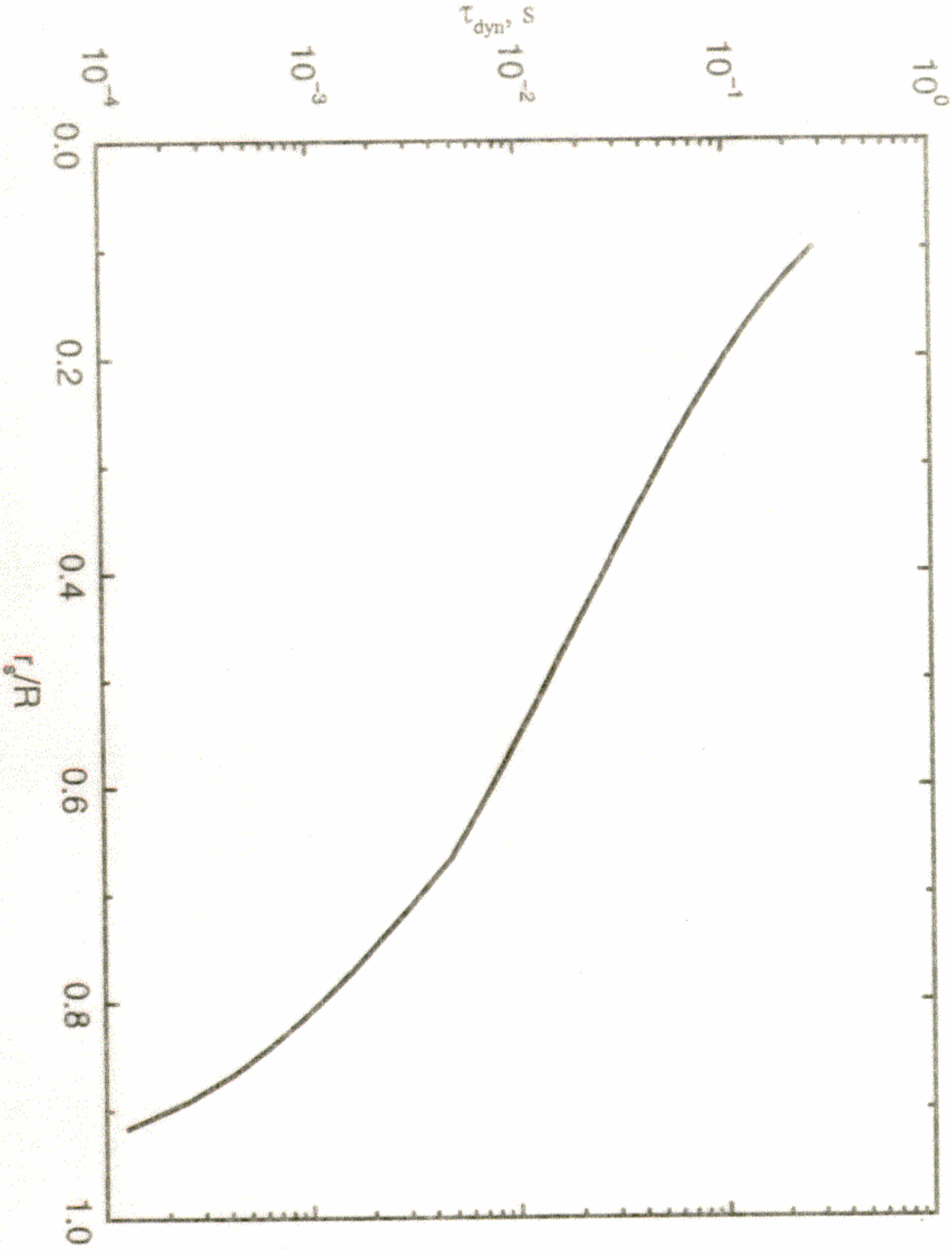
(ν_e disappearance?)

Hot Proto-Neutron Star

Heating Layer


Entropy per Baryon
S/k
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
0.2
0.4
0.6
0.8
1.0
2GM/R

Dynamical Time Scale



General Relativistic Effects

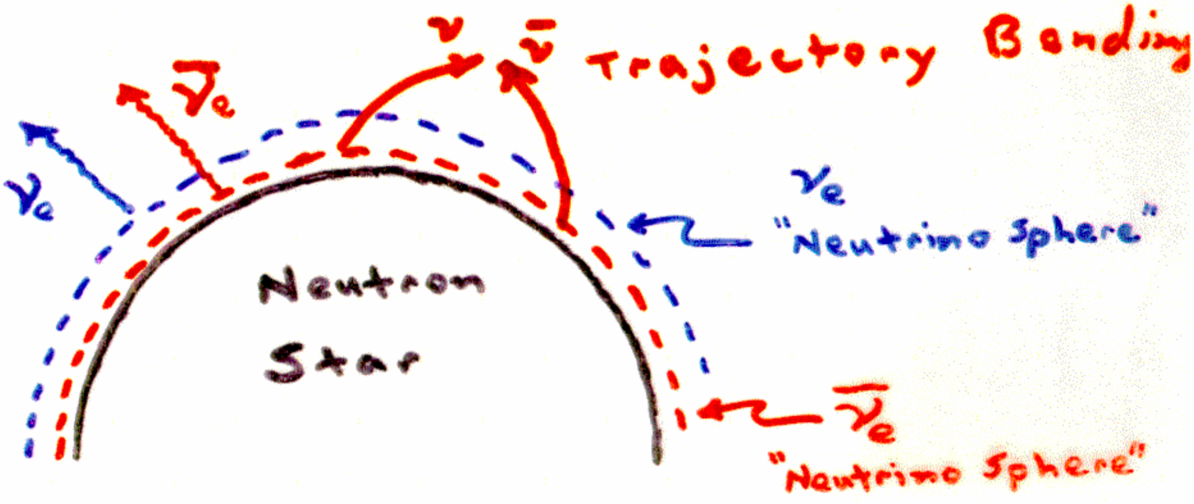
Cardall & Fuller 1996; Fuller & Qian 1996;
Qian & Woosley 1996
Salmonson & Wilson 1999 ; T. Kajino et al '99

- Entropy of Outflow in Wind Increases:

$$Ts \approx GMm_b/r.$$

- Expansion Timescale Decreases
- Differential redshift of $\bar{\nu}_e$ and ν_e sets limit on how relativistic star can get and yet still have $Y_e < 0.5$.

$\Rightarrow$ $\bar{\nu}_e$ redshifted more than ν_e
since $\bar{\nu}_e$ decouple deeper
in gravitational potential well.



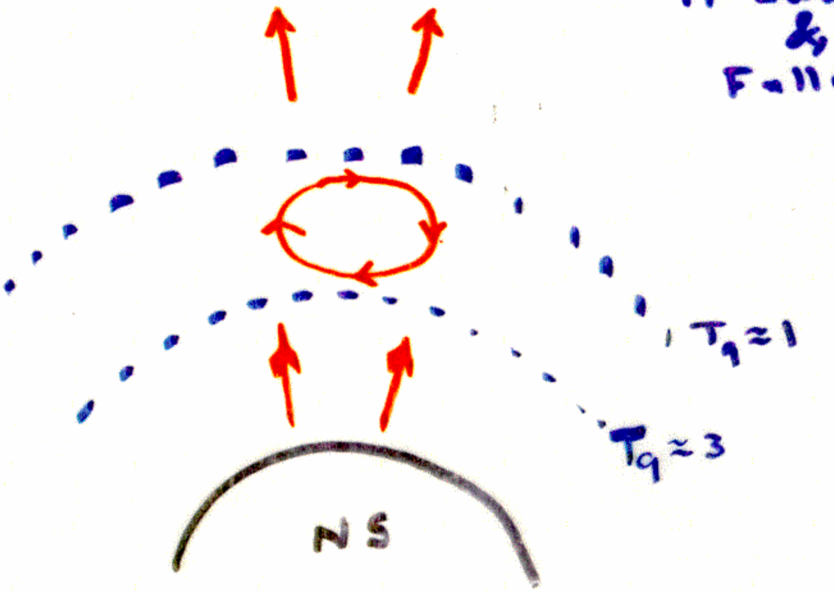
"Fast-Slow-Fast" Outflow

- Fast initial early outflow from Neutron Star ⇒ increase neutron-to-seed ratio

- Slow expansion during rapid neutron capture phase, so that weak steady flow equilibrium is established.

- After cessation of neutron capture, *may* need outflow speed to increase again so as to avoid too much neutrino post-processing.

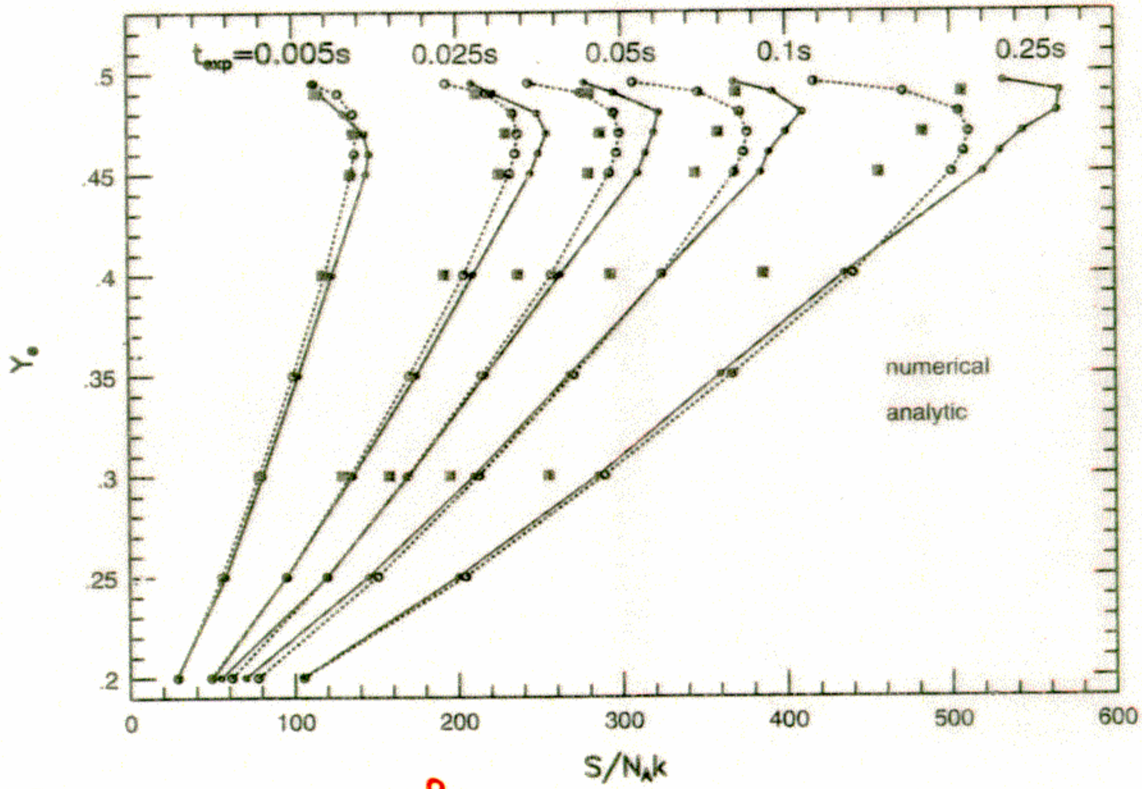
e.g.,
McLaughlin & Fuller (1997)



Required Entropy & Y_e & τ_{dyn}

Meyer et al. 1996

Hoffman et al. 1996



Hoffman, Woosley, & Qian 1996

Figure 1. The combination of electron fraction, entropy, and expansion time scale required for production of the $A \sim 195$ r-process peak nuclei. Points connected by lines are for fixed expansion time scales. The results from a simple analytic approximation (open circles) and two numerical surveys (filled circles and squares) are shown. All results assumed a constant entropy in deriving the density. For the circles, the approximation $S \propto T^3/\rho$ is used to solve for the density, whereas for the squares, a fully consistent equation of state is used.

How to Fix the r-Process

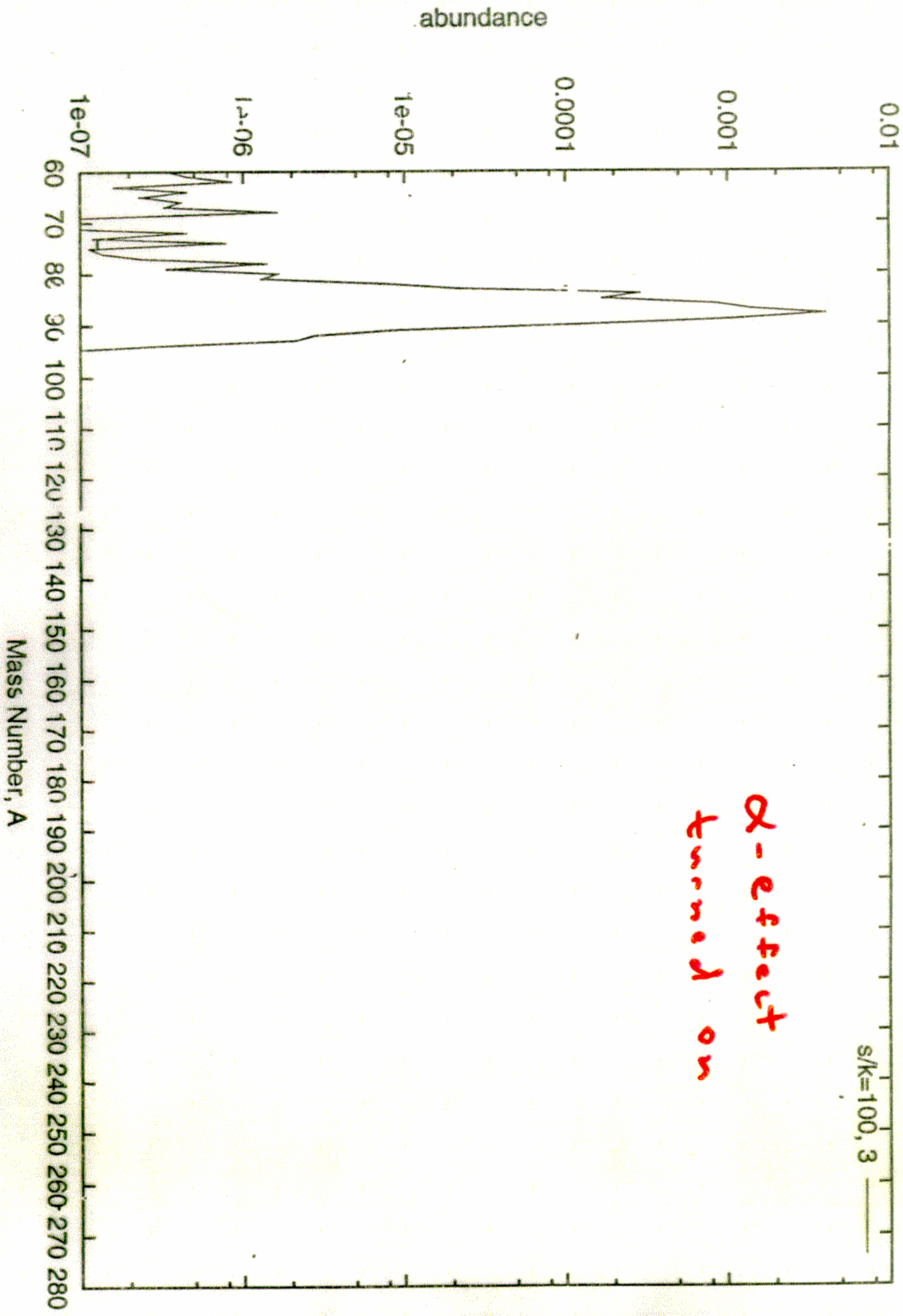
(i.e., raise the neutron-to-seed nucleus ratio)

- **Decrease Y_e**
  (Increases n/p ratio.)

- **Increase Entropy**
  (More photo-dissociation hinders formation of seed nuclei.)

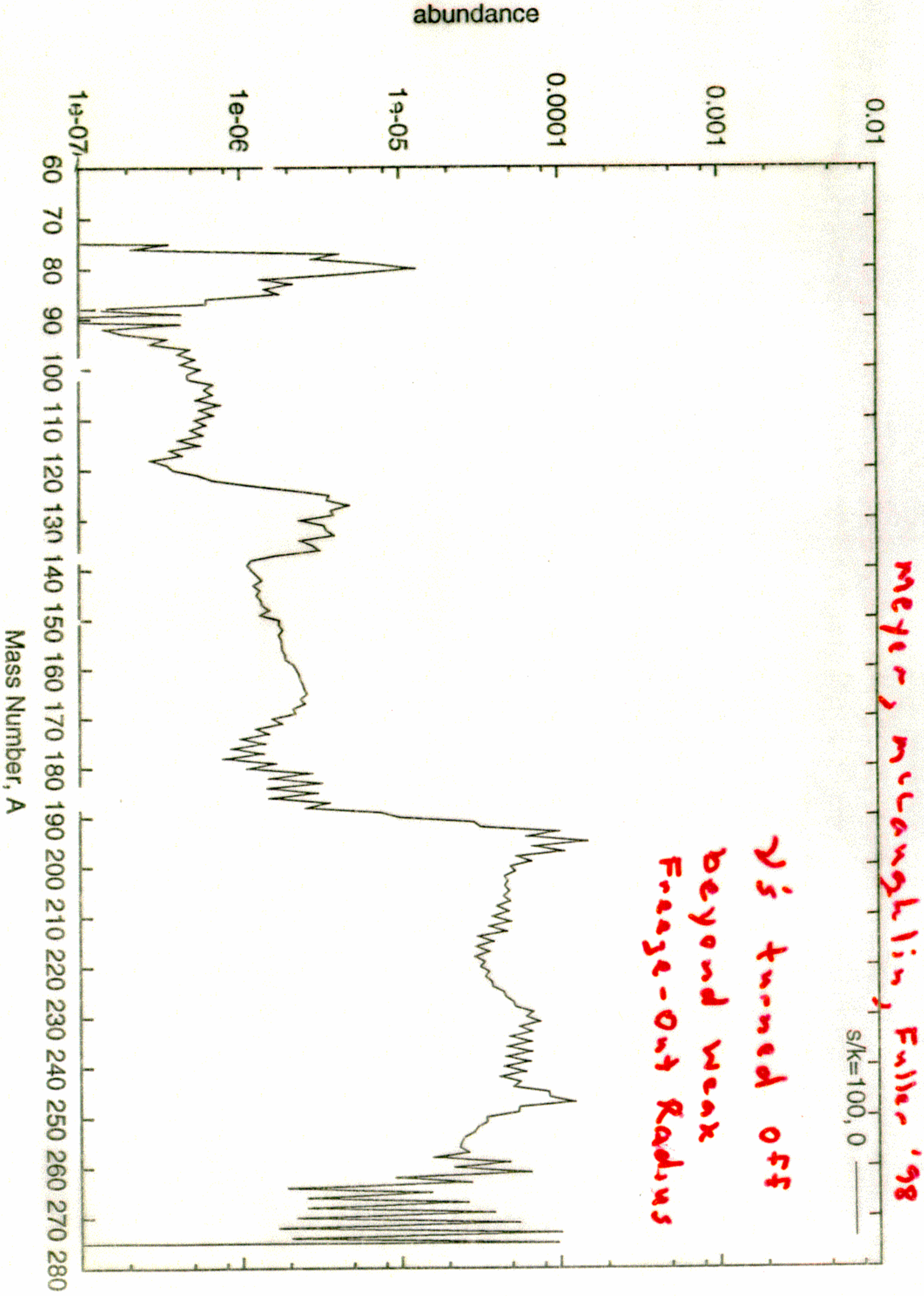
- **Decrease Expansion Timescale**
  (Fewer seed nuclei because there is less time for $\alpha + \alpha + n \rightarrow {}^9\mathrm{Be}$.)

G. Fuller, SSI 2000



Meyer, McLaughlin, Fuller '98

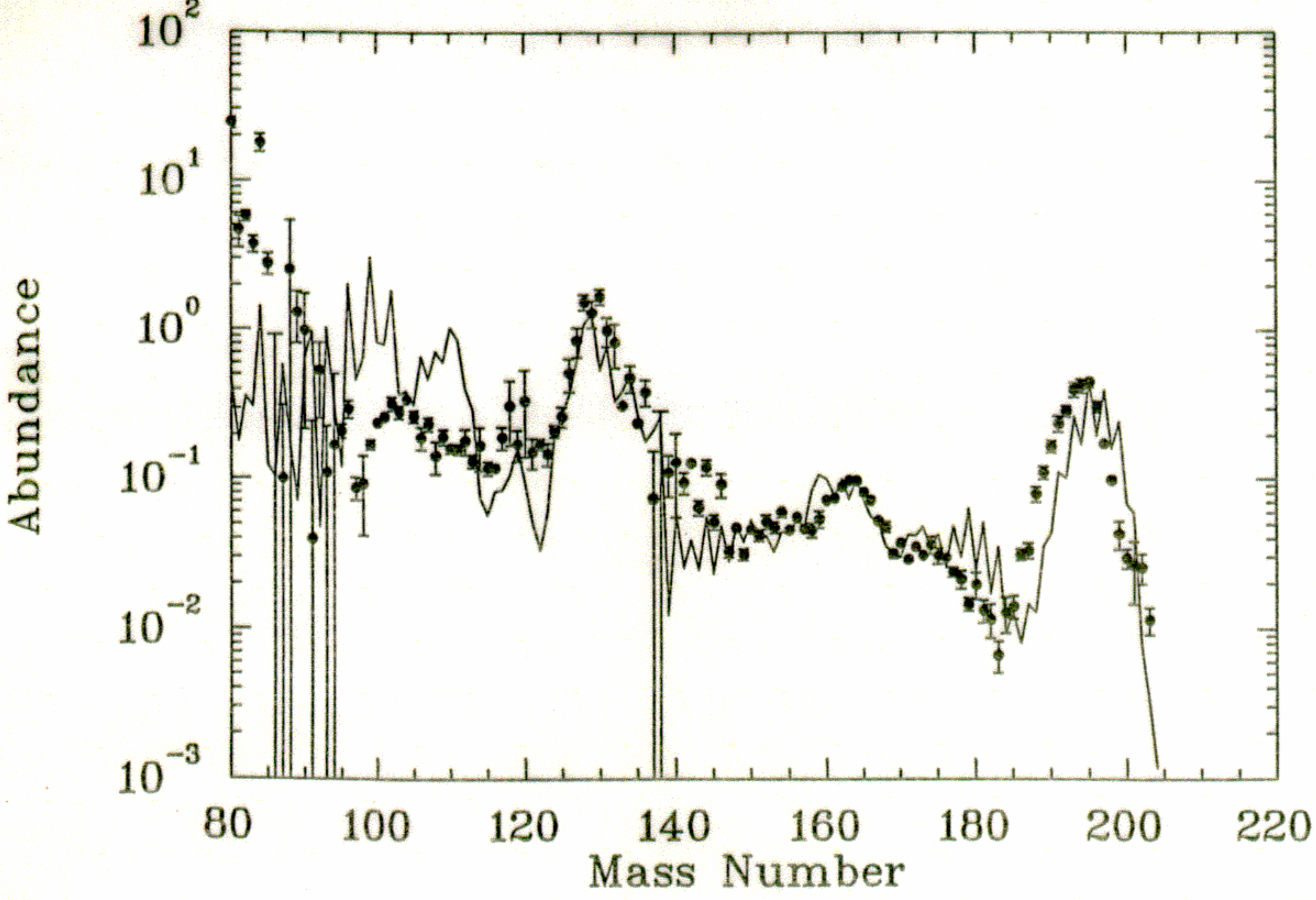
α-effect
turned on



Meyer, McLaughlin, Fuller '98

Y's turned off
beyond Weak
Freeze-Out Radius

Woosley, Wilson, Mathews, Hoffman, Meyer
1994

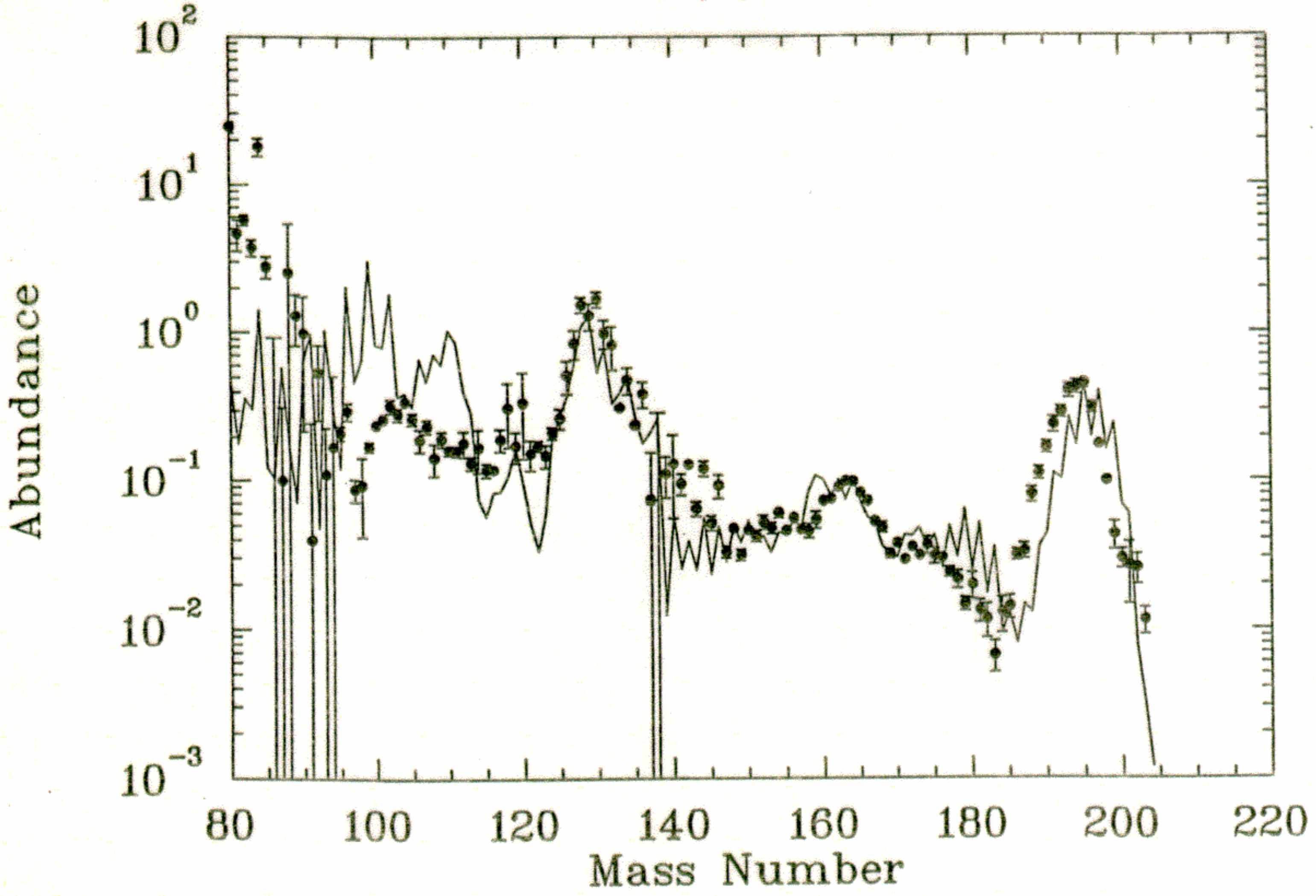


But $\frac{n}{\text{seed}}$ ratio artificially high here

Fig. 16

⇒ see Meyer 1995 $\left(\nu + \alpha \rightarrow {}^{3}H + p + \nu \rightarrow \nu + {}^{3}He + n \right)$

Woosley, Wilson, Mathews, Hoffman, Meyer
1994



But $\frac{n}{seed}$ ratio artificially high here

Fig. 16

$\Rightarrow$ see Meyer 1995 $(\nu + \alpha \to {}^{3}H + p + \nu$
${}^{3}He + n)$

Average Neutrino Energy Hierarchy

- In the Absence of Neutrino Flavor Transformations, the Average Neutrino Energies Always Satisfy:

$$\langle E_{\nu_{\mu(\tau)}} \rangle > \langle E_{\bar{\nu}_e} \rangle > \langle E_{\nu_e} \rangle$$

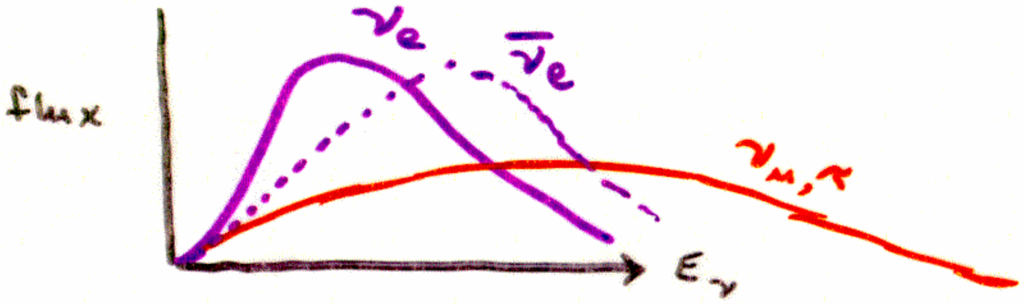
$$\Downarrow \qquad \Downarrow \qquad \Downarrow \qquad \Downarrow$$

$\Longrightarrow$ This Would Imply That Material Is Neutron-Rich, Since

$$Y_e \approx (1 + \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle)^{-1} < 0.5$$

OR

$$n/p \approx \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle > 1$$



Neutrinos Set Y_e

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

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

- Cross Sections: $\sigma \sim G_F^2 E_\nu^2$
- Rates: $\lambda =$ (Flux)$\cdot$(Cross Section)

$$\lambda \sim (L_\nu / \langle E_\nu \rangle) \cdot \langle E_\nu \rangle^2 = L_\nu \langle E_\nu \rangle$$

$$\Downarrow \qquad \Downarrow \qquad \Downarrow \qquad \Downarrow$$

Integrate the Rate Equations ⇒

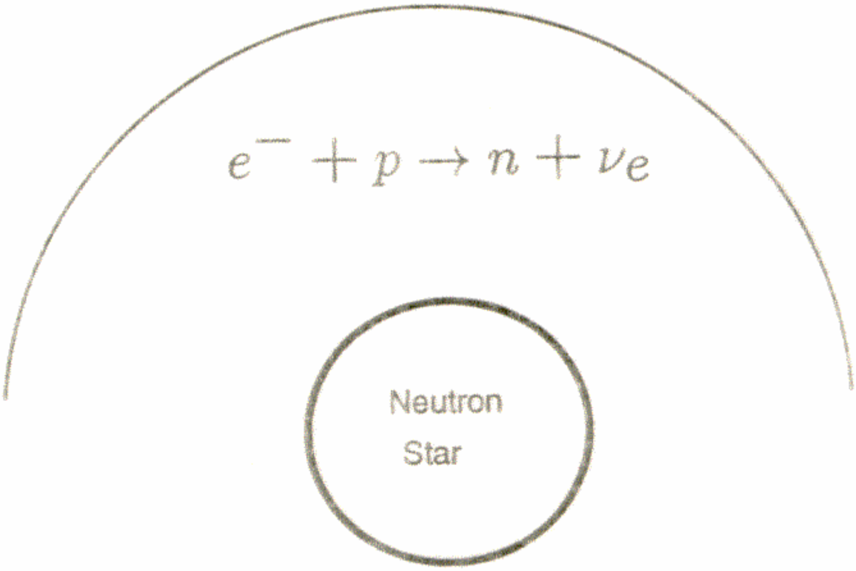
$$Y_e \approx \lambda_{\nu_e n} / (\lambda_{\nu_e n} + \lambda_{\bar{\nu}_e p}) \sim (1 + \langle E_{\bar{\nu}_e} \rangle / \langle E_{\nu_e} \rangle)^{-1}$$

Where the Last Step Follows on Noting that at Late Times,

$$L_{\nu_e} \approx L_{\bar{\nu}_e} \approx L_{\nu_{\mu(\tau)}}$$

WEAK FREEZE-OUT RADIUS

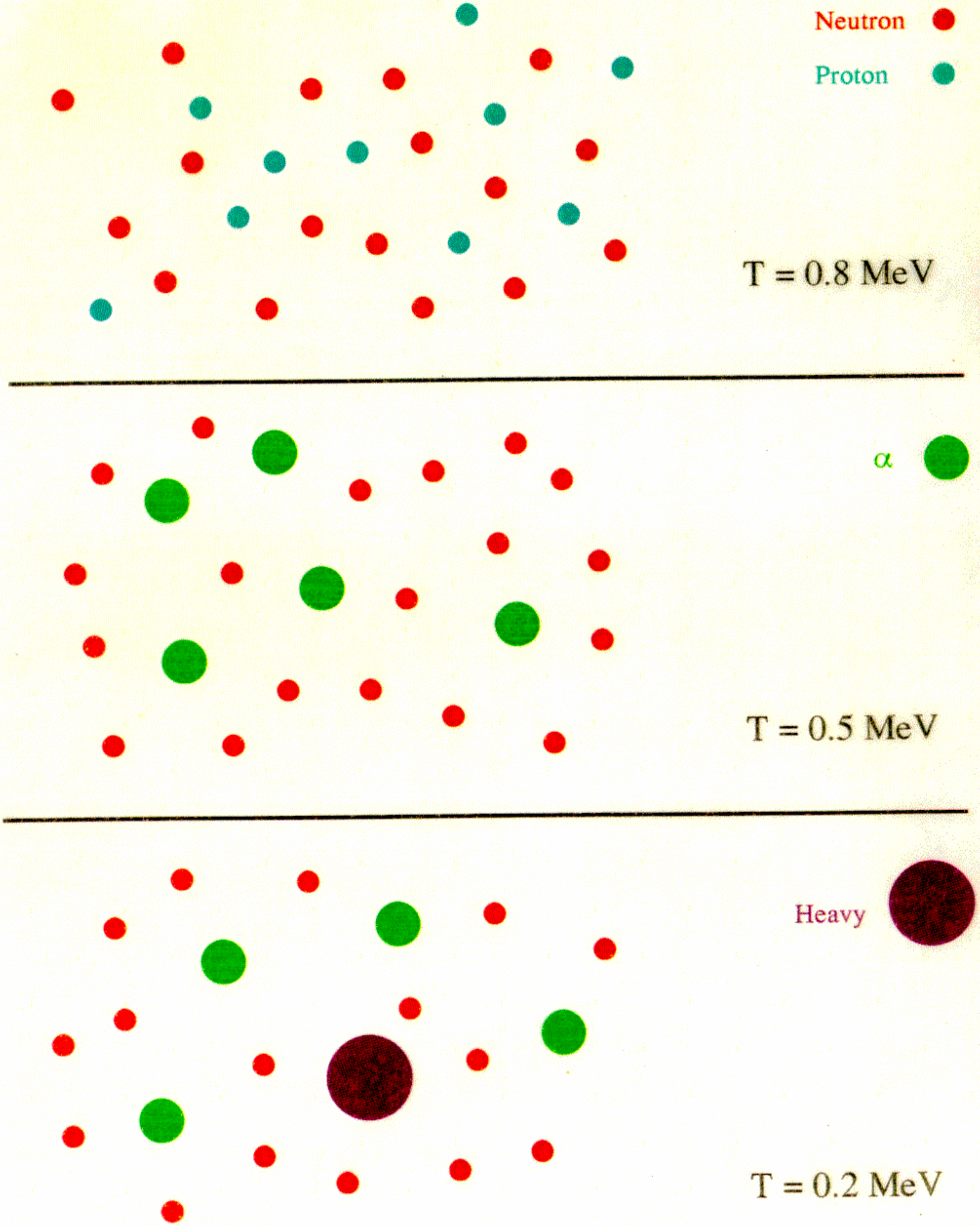
$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$



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

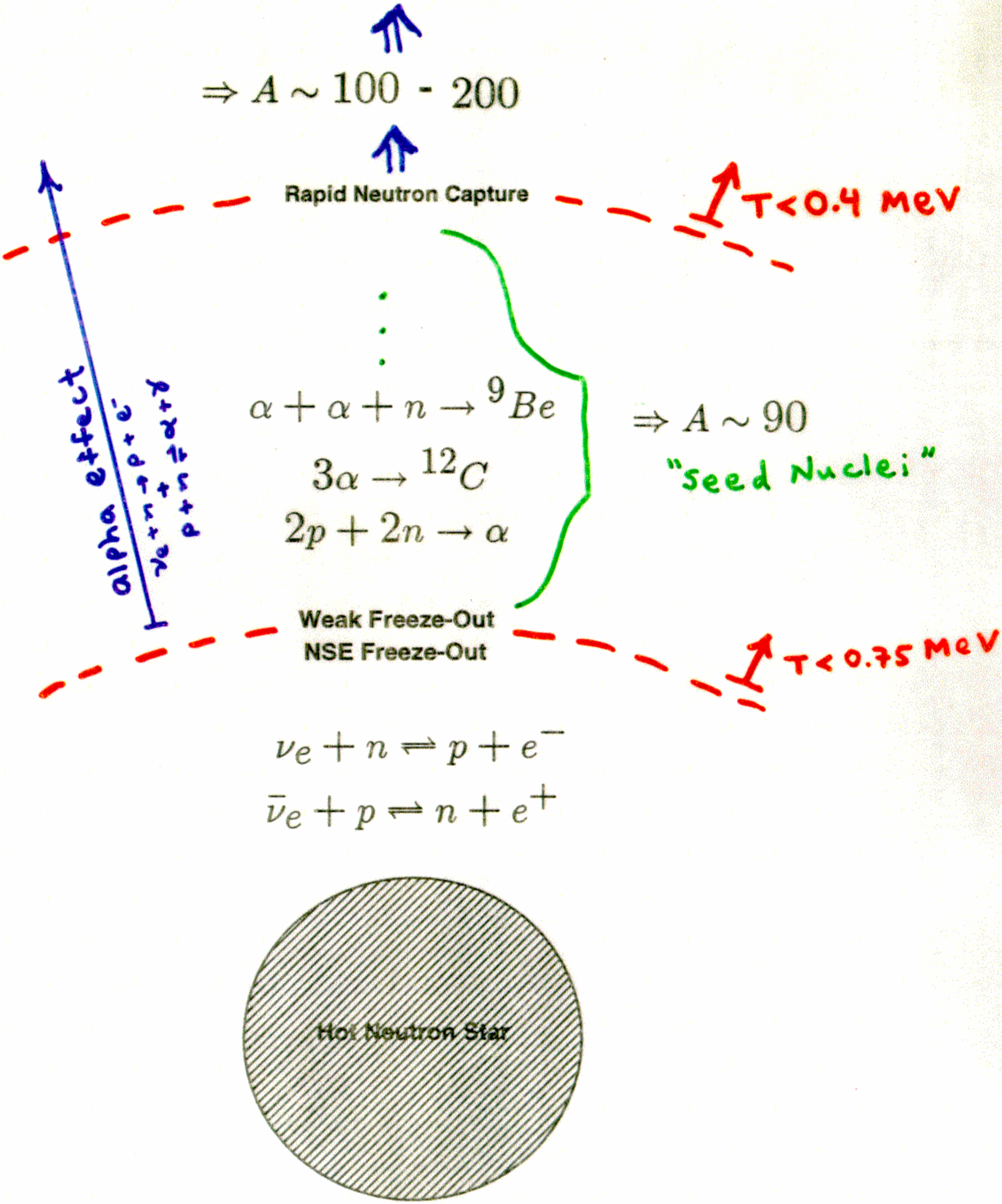

$\lambda_\nu < \lambda_{exp}$

G. Fuller, SSI 2000



G. Fuller, SSI 2000

r-Process from Neutrino-Heated SN Ejecta



$\Rightarrow A \sim 100$ - 200

Rapid Neutron Capture

T<0.4 MeV

$\alpha + \alpha + n \rightarrow {}^{9}Be$

$3\alpha \rightarrow {}^{12}C$

$2p + 2n \rightarrow \alpha$

$\Rightarrow A \sim 90$

"seed Nuclei"

alpha effect

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

$p + n \rightleftharpoons d + \gamma$

Weak Freeze-Out

NSE Freeze-Out

T<0.75 MeV

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

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

- **ν-Heated Supernova Ejecta**

B. S. Meyer et al. 1992; K. Takahashi, Witti, & T. Janka 1994; S. E. Woosley et al. 1994.
Status: Troubled; neutrino heating leads to "alpha effect," which can only be circumvented via new neutrino physics, finely tuned GR, or non-neutrino ejection with high speeds.

- **Neutron Star Mergers**

e.g., C. Freiburghaus, S. Rosswog, & F. Thielemann '99
Status: Troubled; merger rate only 10^{-3} to 10^{-4} of SN rate, implying that we need $> 0.1\,\mathrm{M}_\odot$ of r-process material per event. Numerical calculations (e.g., Ruffert & Janka 1996; Wilson & Mathews 1996) suggests that much less is ejected and *that* is sometimes via neutrino heating (see above).

- **Jets/Globs of Low Y_e Material**

e.g., LeBlanc/Wilson jets; A. Burrows low Y_e lumps
Status: Troubled; only one SN in $\sim 10^3$ might do this.

- **Shock Induced r-Process in He or C/O Shells**

Truran & Cowan '00; Truran, Cowan, Cameron '78; Thieleman, Arnould, Hillebrandt 79; Blake, et al. '81
Status: Troubled; will make some lighter r-process, but heavy r-process species yield is sensitive to ^{13}C content, shock parameters.

The Riddle of Neutron-Rich Nuclei

⇒ Require synthesis environment with **abundant free neutrons.**

- **But** Neutrons Are Unstable!! $\tau \approx 887.0\,\mathrm{s}$

⇒ **Can Obtain Free Neutrons By:**

- "Spalling" Neutrons from Nuclei where they are Stabilized by the Strong Force:
  $\gamma + \mathrm{A(Z,N)} \mapsto \mathrm{A(Z,N-1)} + \mathrm{n}$
  But typical neutron binding $\sim 8\,\mathrm{MeV}$!

- "Spalling" Neutrons from Neutron Stars where they are Stabilized by "Gravity."
  (*e.g.*, Binary Neutron Star Coalescence)
  But typical neutron binding $\gtrsim 100\,\mathrm{MeV}$!!

- Weak Interaction $\bar{\nu}_e + \mathrm{p} \mapsto \mathrm{n} + e^+$
  But G_F is small!

Evidence for ν modification

W. Haxton, Y.-Z. Qian, K. Langanke, P. Vogel
'96

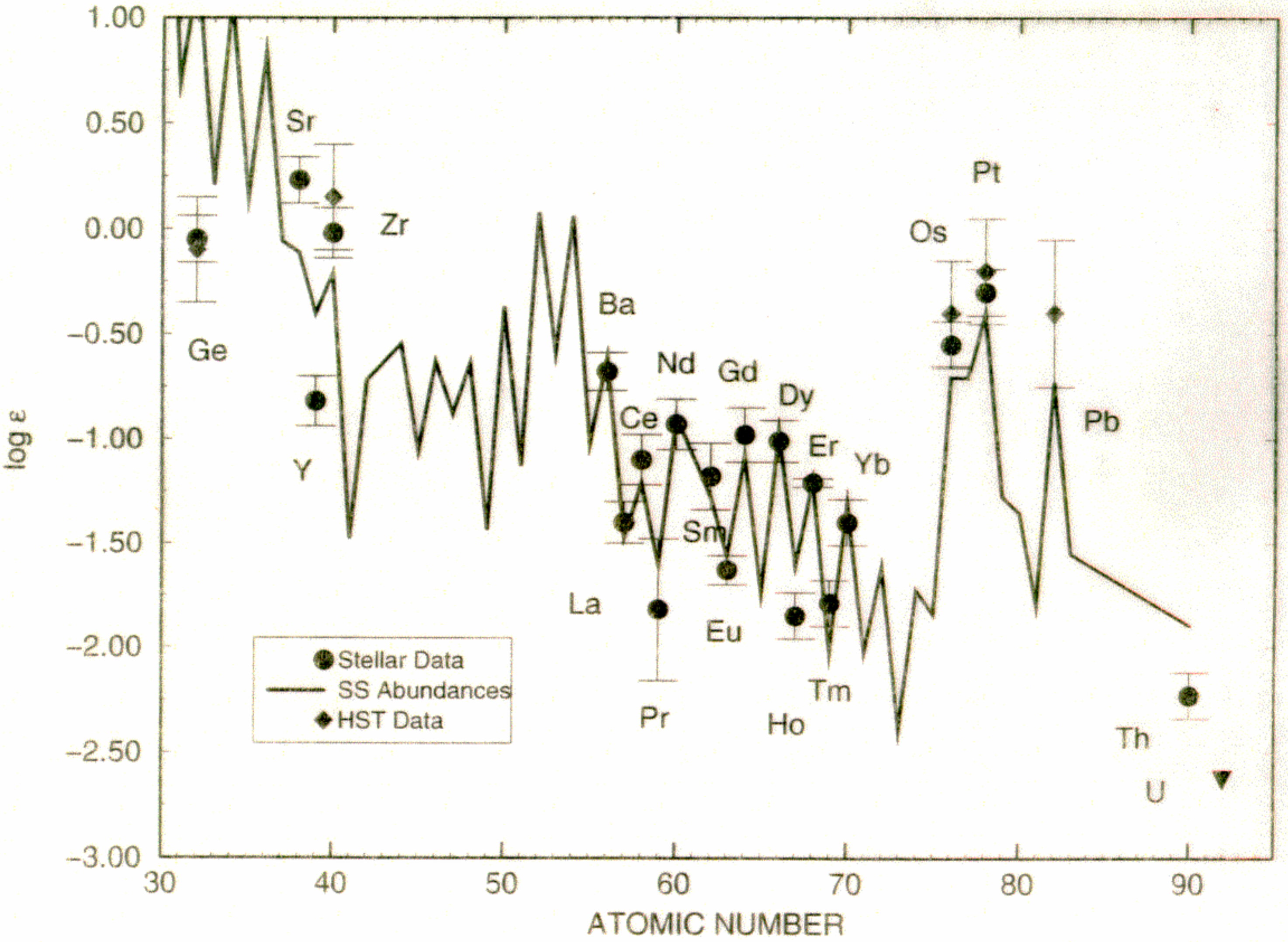
synthesis timescale "evidence"

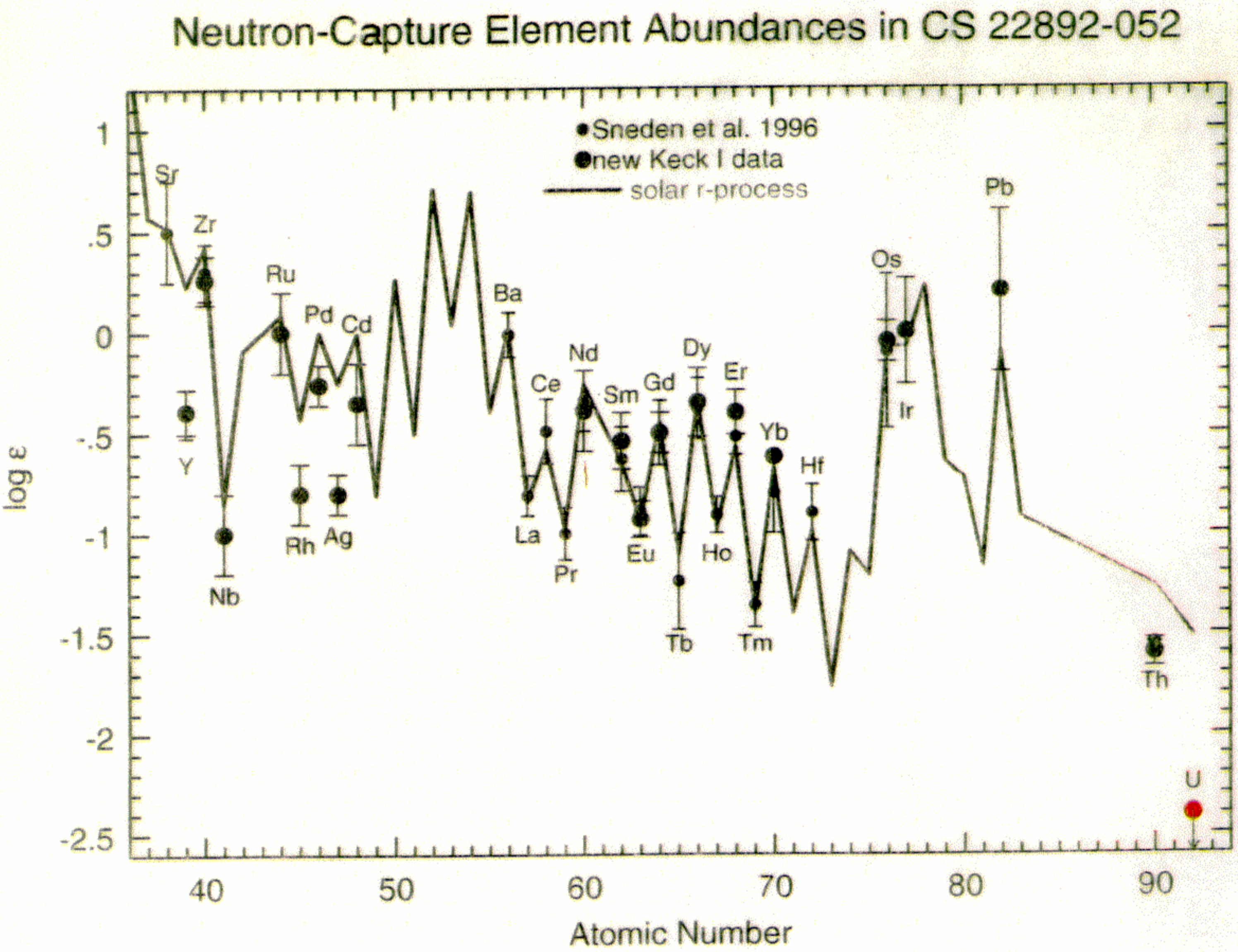
Qian, Vogel, Wasserburg '98

Sneden et al. 2000

NEW KECK Data

HD 115444: good match to scaled s.s. r-process for $Z \geq 56$





scaled solar-system r-process is not a godd match with data for $Z < 56$

unlikely to ever get elements in $Z \approx 50$ area