Neutrino Mass Constraints from Supernovae

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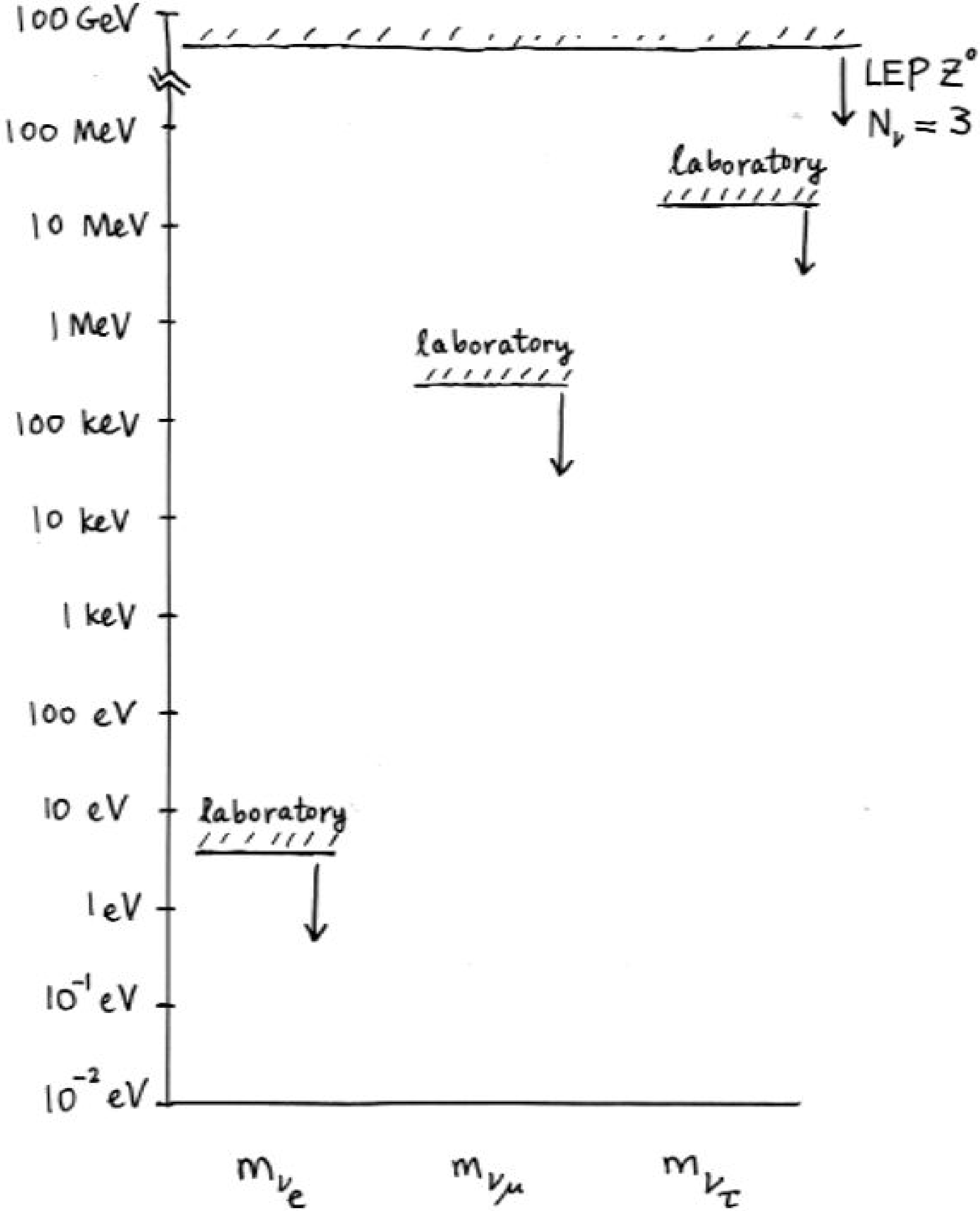
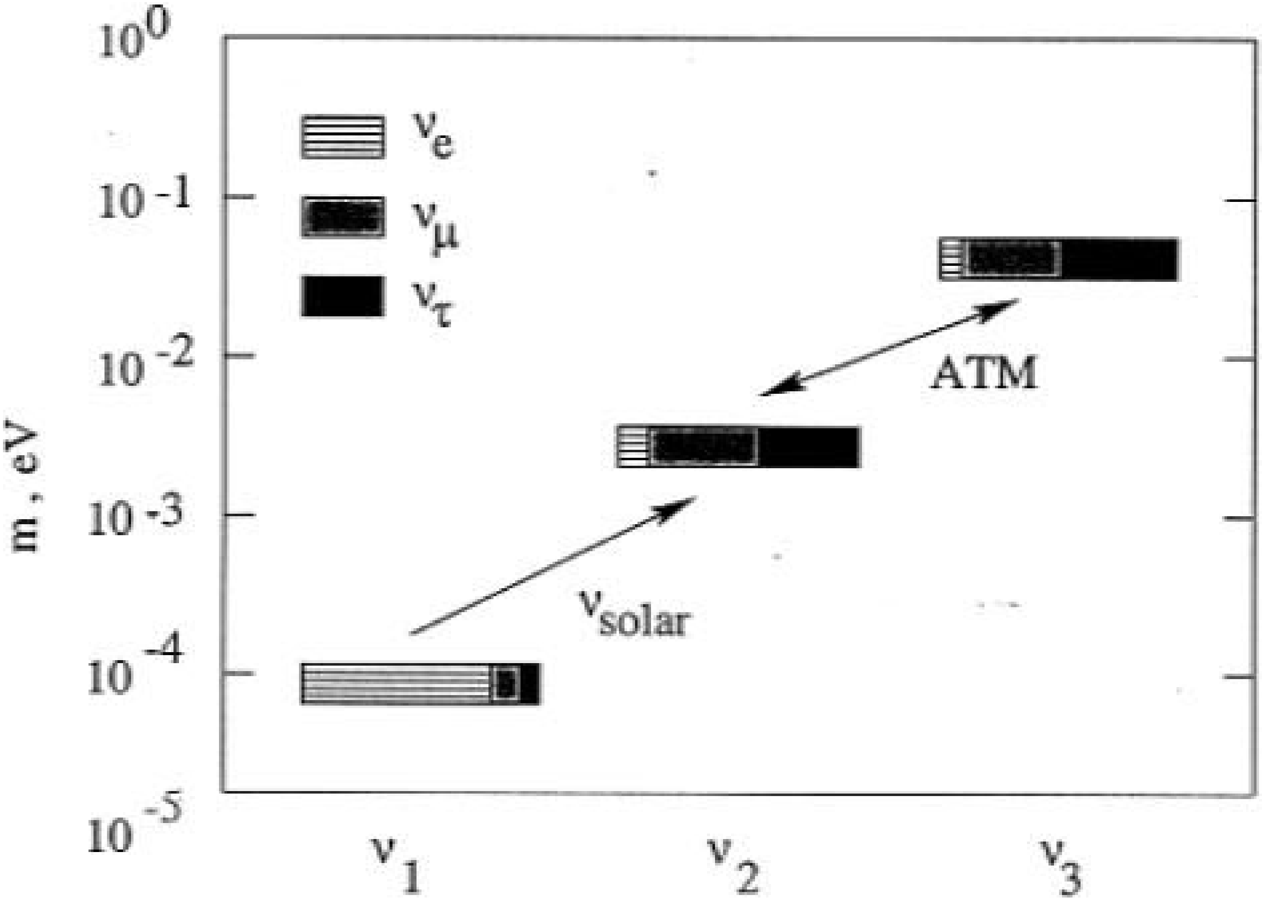


100 GeV
100 MeV
10 MeV
1 MeV
100 keV
10 keV
1 keV
100 eV
10 eV
1 eV
10^{-1} eV
10^{-2} eV
LEP Z^0
$N_\nu = 3$
laboratory
laboratory
laboratory
m_{ν_e}
m_{ν_μ}
m_{ν_τ}



(Fig. from A. Yu. Smirnov, hep-ph/9901208)

solar: small-angle MSW mixing

atmospheric: large-angle vacuum mixing

LSND: ignored

HDM: possible for quasi-degenerate masses

SN Rate

- Historical record in last 1000 years

year	name	distance (kpc)	
1006	Lupus	1.4	
1054	Crab	2.0	
1181?	3C 58	2.6	
1300?	(new)	0.2	^{44}Ti
1572	Tycho	2.5	
1604	Kepler	4.2	
1680?	Cas. A	3.0	^{44}Ti

$\boxed{\simeq 0.7 \,/\, \text{century in a restricted volume}}$

- Volume correction

  (Bahcall & Soniera 1980, Bahcall & Piran 1983)

  $g(R)$ = fraction of stars within distance R of Sun

  $$g(R \simeq 4\,\text{kpc}) \simeq 0.06$$

$$\boxed{\text{SN rate} \simeq \frac{0.7/\text{century}}{0.06} \simeq 10/\text{century} \ \text{in whole Galaxy}}$$

- Other estimates:

  (van den Bergh, Tammann, etc)

$$\boxed{\text{SN rate} \simeq (3 \pm 1)/\text{century}}$$

Supernova Neutrinos:

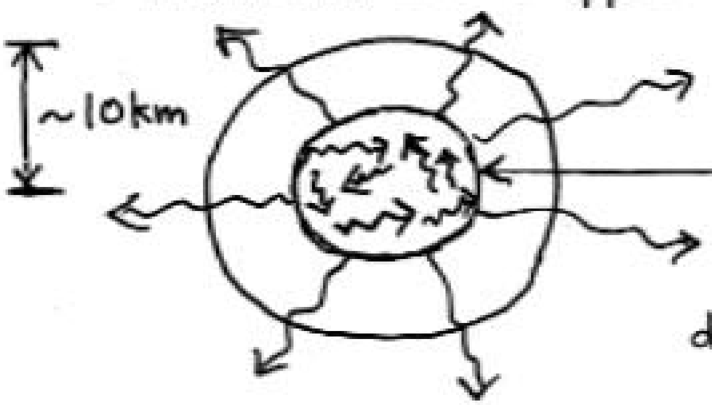
- type-II SN: core collapse of an $M > 8 M_\odot$ star

$$\Delta E_B \sim \frac{G M_\odot^2}{R_{NS}} - \frac{G M_\odot^2}{R_{core}} \sim 3 \times 10^{53}\ \text{ergs}$$

- "cooling" by neutrino emission:

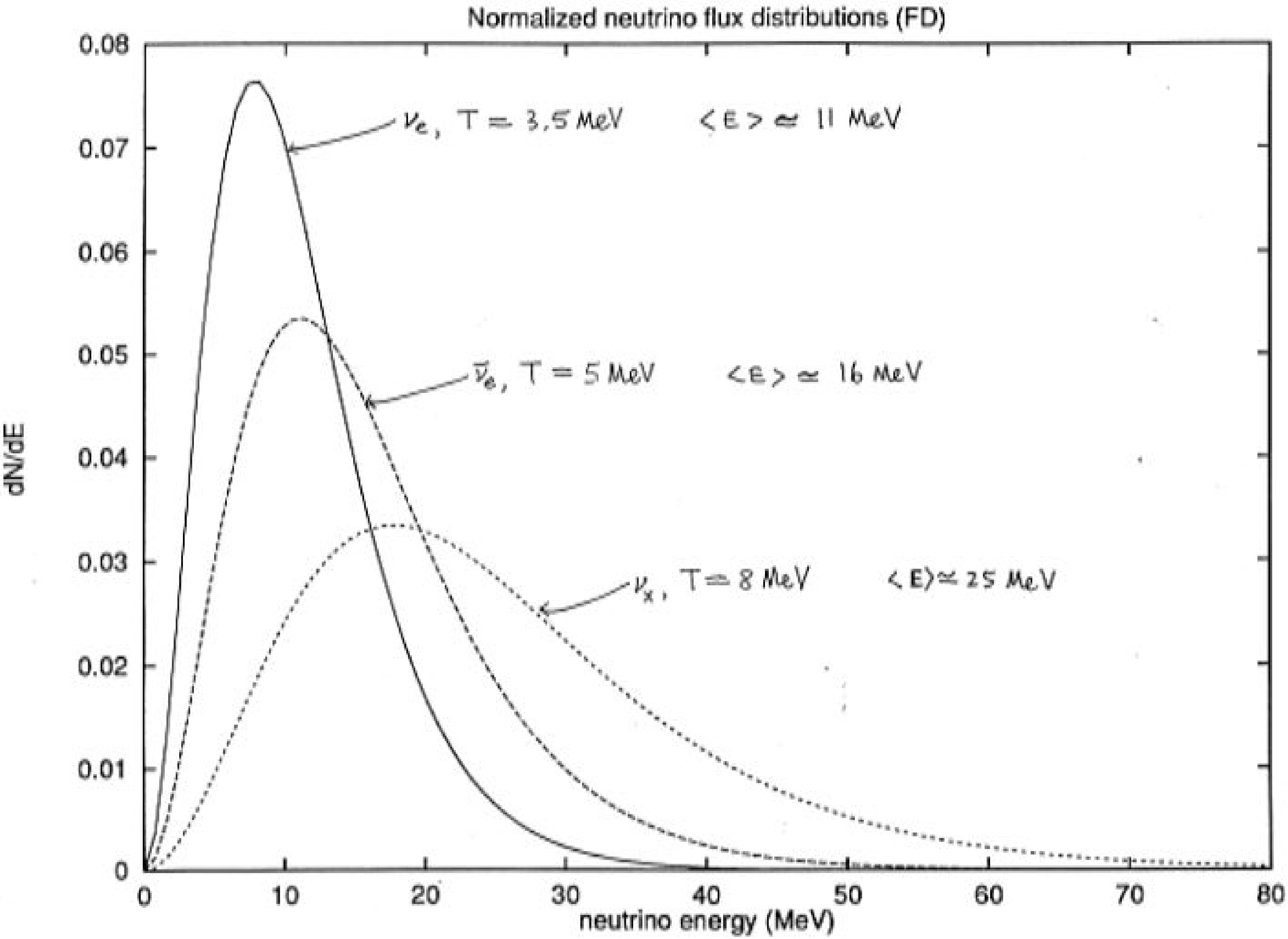
$$e^+ e^- \longrightarrow \nu_e \bar{\nu}_e,\ \nu_\mu \bar{\nu}_\mu,\ \nu_\tau \bar{\nu}_\tau$$

- Neutrinos are trapped for $\sim 10\,s$:



diffusion until $\lambda = 1/\rho\sigma$ from surface, then escape

$$\boxed{\begin{array}{c} T_{\nu_e} \simeq 3.5\ \text{MeV} \qquad T_{\bar{\nu}_e} \simeq 5\ \text{MeV} \qquad T_{\nu_x} \simeq 8\ \text{MeV} \\ L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t) \simeq L_0\, e^{-t/\tau} \\ \tau \simeq 3s \end{array}}$$


Normalized neutrino flux distributions (FD)
dN/dE
neutrino energy (MeV)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 10 20 30 40 50 60 70 80
ν_e, T = 3,5 MeV   <E> ≃ 11 MeV
$\bar{\nu}_e$, T = 5 MeV   <E> ≃ 16 MeV
ν_x, T = 8 MeV   <E> ≃ 25 MeV

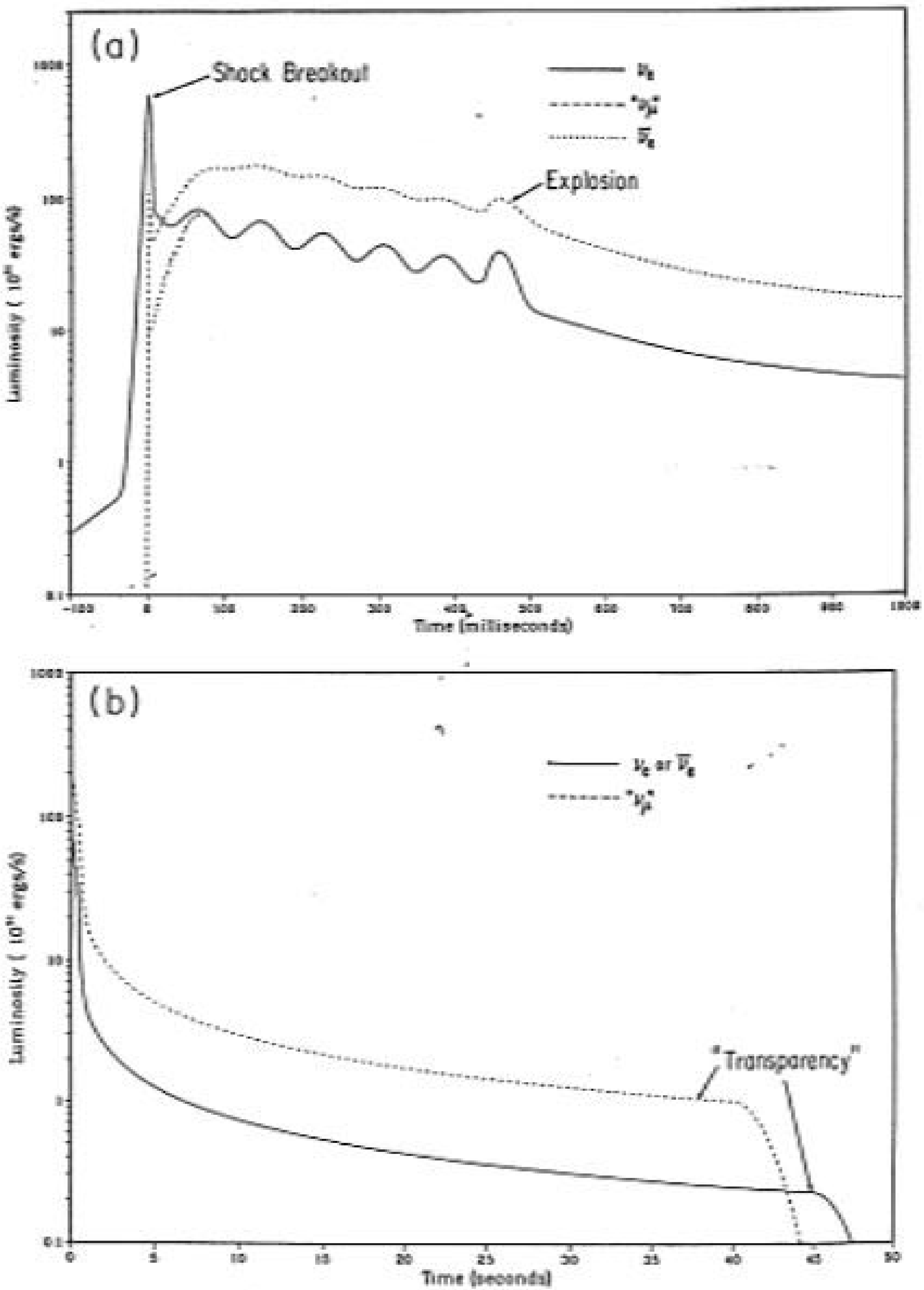


FIG. 3. (a) The luminosity (in ergs/sec) vs time (in msec) for the ν_e's, $\bar{\nu}_e$'s, and, collectively, the $\nu_\mu(\bar{\nu}_\mu)$'s and $\nu_\tau(\bar{\nu}_\tau)$'s during the first second of the neutrino burst in the generic model employed in this paper. (b) Same as (a), but for the first 50 sec. The various evolutionary phases are identified.

from Burrows, Klein, and Gandhi, PRD 45, 3361 (1992)

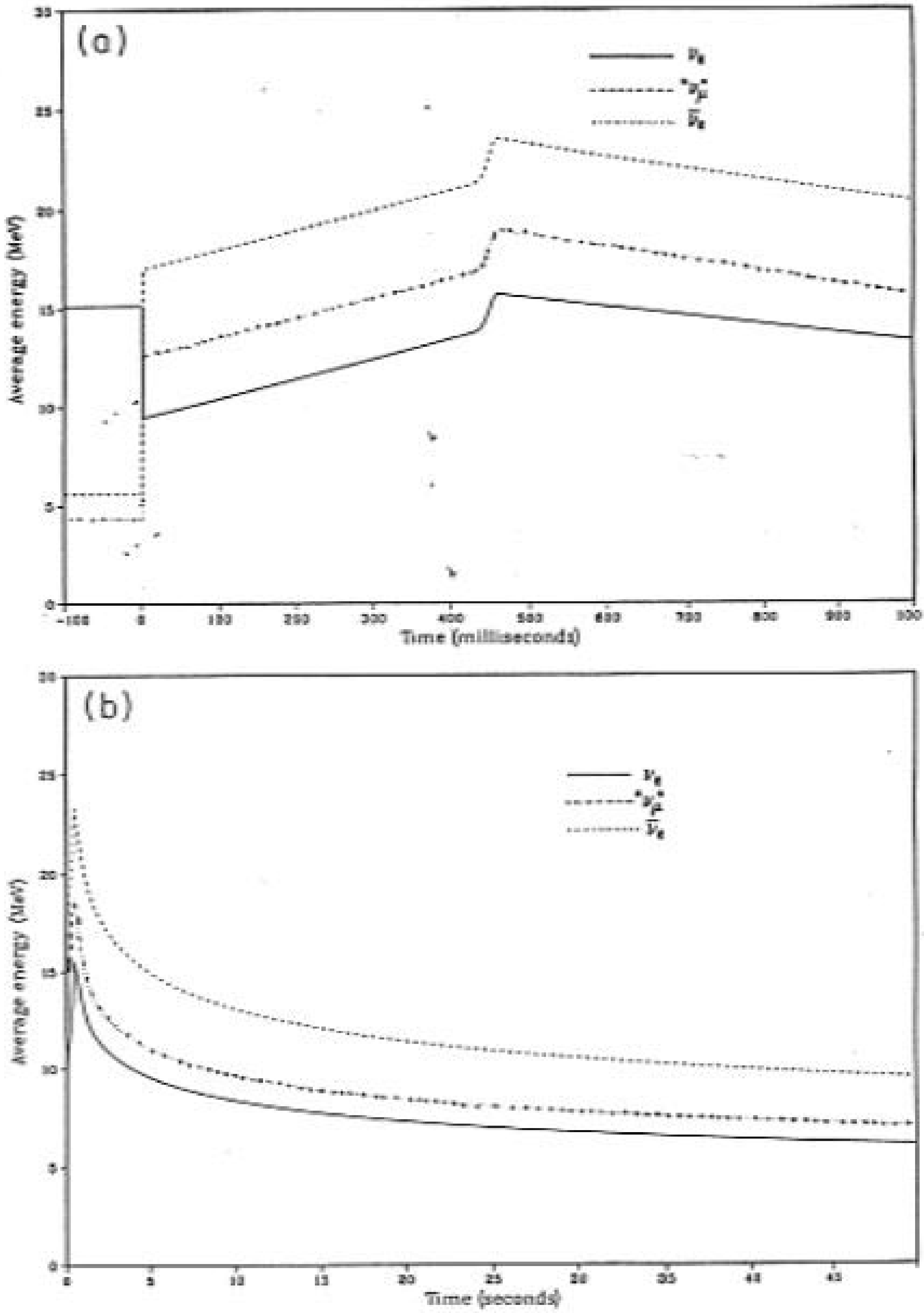


FIG. 4. (a) Same as Fig. 3(a), but for the average neutrino energy (in MeV) vs time. (b) Same as (a), but for the first 50 sec.

from Totani et al., ApJ 496, 216 (1998) [J. Wilson]

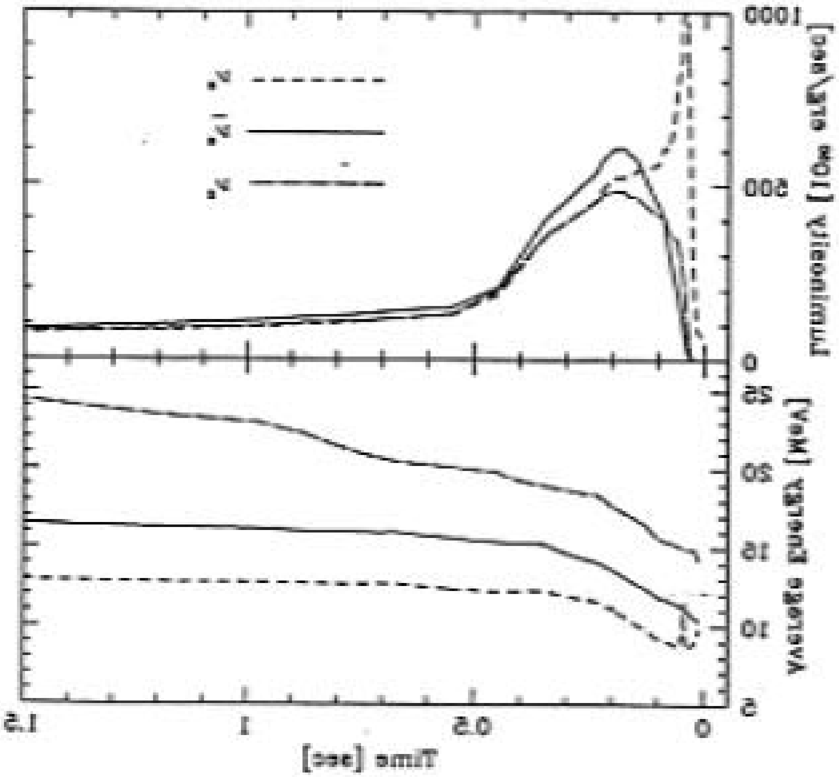


FIG. 4.—Same as Fig. 1, but for the early phase in linear coordinates

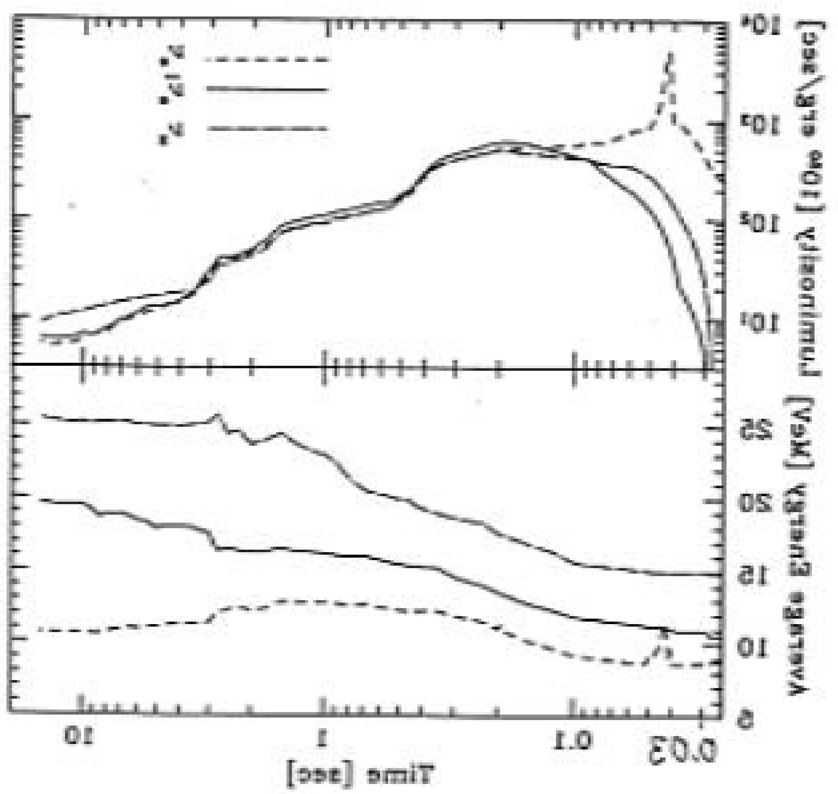


FIG. 1.—Time evolution of neutrino luminosity and average energy of the numerical supernova model used in this paper. The dashed line is for ν_e, solid line for $\bar{\nu}_e$, and dot-dashed line for ν_x (=each of $\nu_\mu, \nu_\tau, \bar{\nu}_\mu$, and $\bar{\nu}_\tau$). The core bounce time is 3–4 ms before the neutronization burst of ν_e's.

$$\Delta t = \frac{D}{v} - \frac{D}{c}$$

$$\boxed{\Delta t(E) \simeq 0.515 \left(\frac{m}{E}\right)^2 D} \sim [s]$$

$m \sim [eV]$ $E \sim [MeV]$ $D \sim [10\ kpc]$

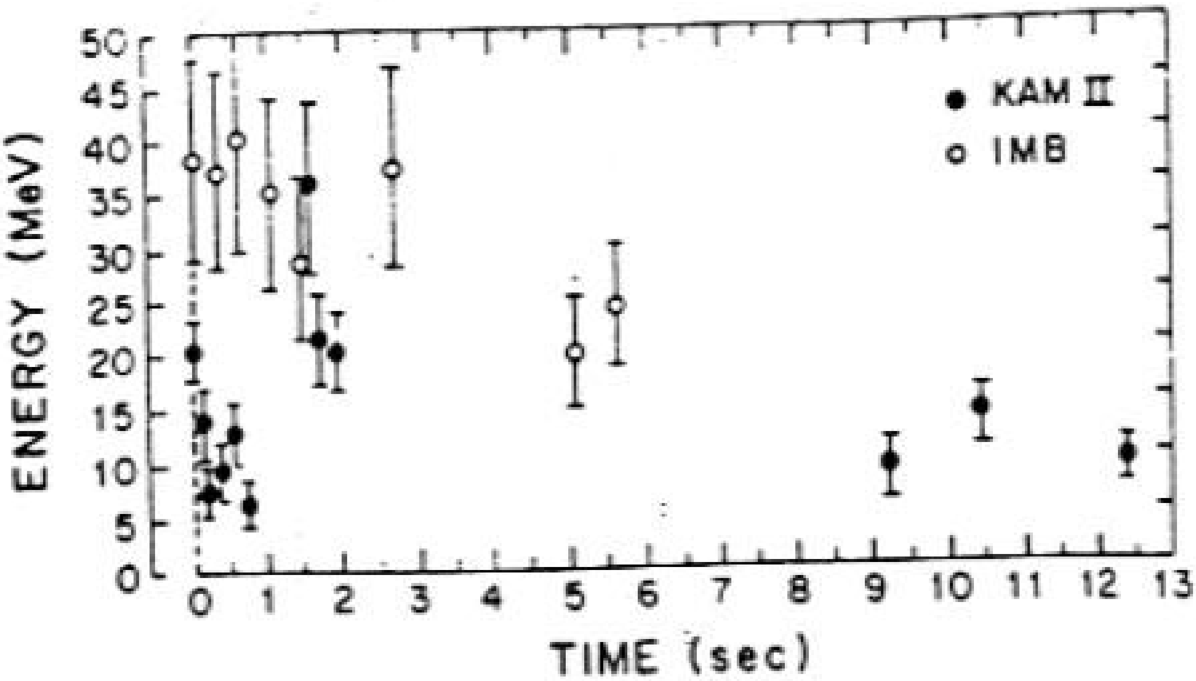


FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t = 0$.

What if $m \simeq 20\,eV$?

$$\Delta t \simeq 0.515 \left(\frac{m}{E}\right)^2 D$$

$$\Delta t\,(\mathrm{IMB}) \simeq 0.5 \left(\frac{20}{35}\right)^2 5 \simeq 1\,s$$

$$\Delta t\,(\mathrm{Kam\,II}) \simeq 0.5 \left(\frac{20}{15}\right)^2 5 \simeq 4\,s$$

$\longrightarrow$ signal separation $\simeq 3s$

not seen, so $m \lesssim 20\,eV$

Next SN, $\bar{\nu}_e$ mass limit :

$\simeq 8000$ $\bar{\nu}_e p \to e^+ n$ at 10 kpc

split into low-E (E_{lo}), high-E (E_{hi})

$$\langle t \rangle_{lo} - \langle t \rangle_{hi} \simeq 0.515 \left(\frac{m}{E_{lo}} \right)^2 D$$

$$\text{error} \simeq \frac{\tau}{\sqrt{N}} \simeq \frac{\tau}{\sqrt{8000}} D$$

If $m \simeq 0$, and $\langle t \rangle_{lo} - \langle t \rangle_{hi} \simeq 0$ measured,

$$\boxed{m_{lim} \simeq E_{lo} \sqrt{\frac{2\tau}{\sqrt{8000}}} \simeq 4\,\text{eV}}$$

- independent of D
- better than 87A by $\sqrt[4]{\frac{8000}{20}} \simeq 5$

TABLE I. Calculated numbers of events expected in SNO for a supernova at 10 kpc. The other parameters (e.g., neutrino spectrum temperatures) are given in the text. In rows with two reactions listed, the number of events is the total for both. The notation ν indicates the sum of ν_e, ν_μ, and ν_τ, though they do not contribute equally to a given reaction, and X indicates either $n+{}^{15}\mathrm{O}$ or $p+{}^{15}\mathrm{N}$.

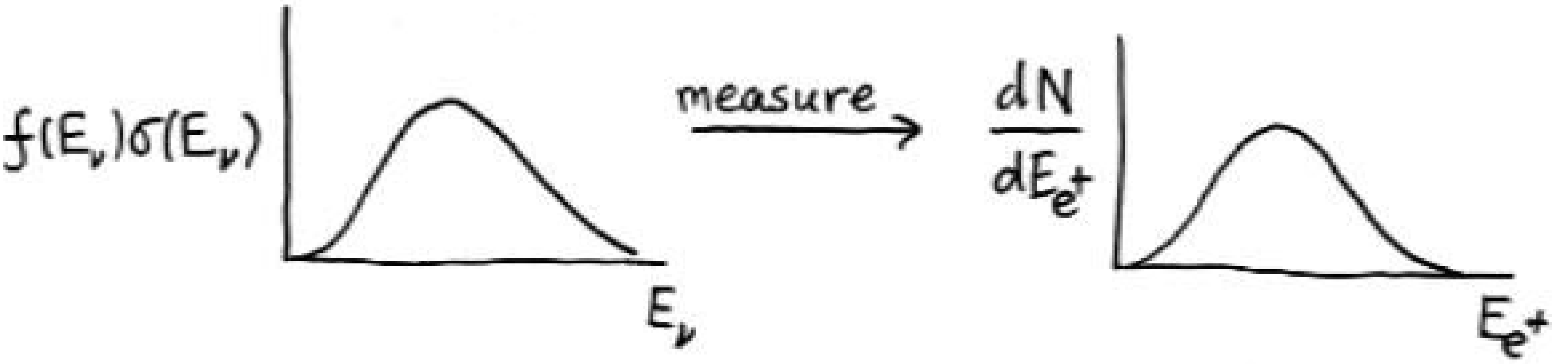
Events in 1 kton D_2O		
$\nu + d \to \nu + p + n$ $\bar{\nu} + d \to \bar{\nu} + p + n$	detected particle(s) : n	485
$\nu_e + d \to e^- + p + p$ $\bar{\nu}_e + d \to e^+ + n + n$	e^-, e^+nn	160
$\nu + {}^{16}\mathrm{O} \to \nu + \gamma + X$ $\bar{\nu} + {}^{16}\mathrm{O} \to \bar{\nu} + \gamma + X$	γ, γn	20
$\nu + {}^{16}\mathrm{O} \to \nu + n + {}^{15}\mathrm{O}$ $\bar{\nu} + {}^{16}\mathrm{O} \to \bar{\nu} + n + {}^{15}\mathrm{O}$	n	15
$\nu + e^- \to \nu + e^-$ $\bar{\nu} + e^- \to \bar{\nu} + e^-$	e^-	10
Events in 1.4 kton H_2O		
$\bar{\nu}_e + p \to e^+ + n$	e^+	365
$\nu + {}^{16}\mathrm{O} \to \nu + \gamma + X$ $\bar{\nu} + {}^{16}\mathrm{O} \to \bar{\nu} + \gamma + X$	γ	30
$\nu + e^- \to \nu + e^-$ $\bar{\nu} + e^- \to \bar{\nu} + e^-$	e^-	15

- detected particles
- NC : dominated by ν_μ, ν_τ

  CC : ν_e, $\bar{\nu}_e$ only

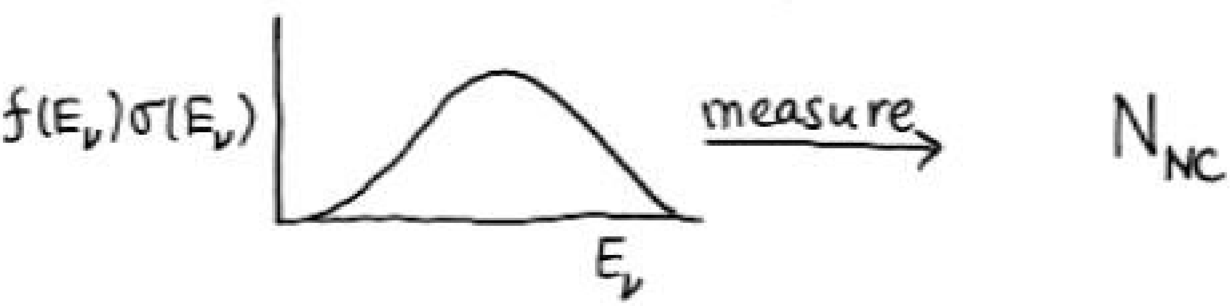
$$\boxed{N \sim \int dE_\nu \, f(E_\nu)\sigma(E_\nu)}$$

- charged-current, e.g., $\bar{\nu}_e p \to e^+ n$



since $E_{e^+} \simeq E_\nu - 1.8$ MeV

- neutral-current, e.g., $\nu d \to \nu p n$



E_ν <u>unknown</u>

Scattering Rate:

$\boxed{m=0}$

$$\frac{d^2N_\nu}{dE\,dt} = f(E)\,\frac{L(t)}{\langle E\rangle}$$

$$\longrightarrow \boxed{\frac{dN_{sc}}{dt} = C\cdot\left[\frac{L(t)}{E_B/6}\right]\cdot\int dE\, f(E)\left[\frac{\sigma(E)}{10^{-42}\,cm^2}\right]}$$

$\boxed{m>0}$

$$\frac{d^2N_\nu}{dE\,dt} = f(E)\,\frac{L(t-\Delta t(E))}{\langle E\rangle}$$

$$\boxed{\frac{dN_{sc}}{dt} = C\cdot\int dE\, f(E)\left[\frac{\sigma(E)}{10^{-42}\,cm^2}\right]\left[\frac{L(t-\Delta t(E))}{E_B/6}\right]}$$

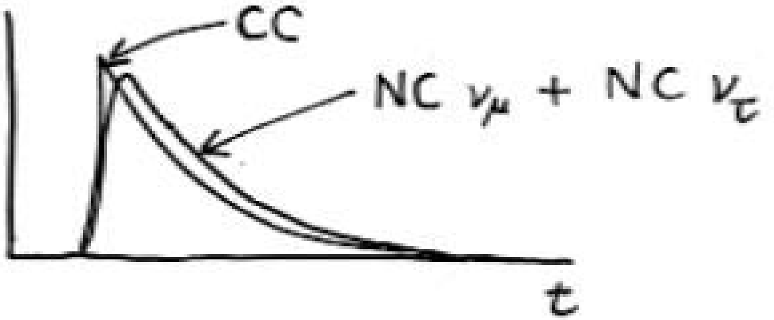
$$C = 9.28\left[\frac{E_B}{10^{53}\,ergs}\right]\left[\frac{1\,MeV}{T}\right]\left[\frac{10\,kpc}{D}\right]^2\left[\frac{det.\ mass}{1\,kton}\right]$$

For D_2O, use 8.28

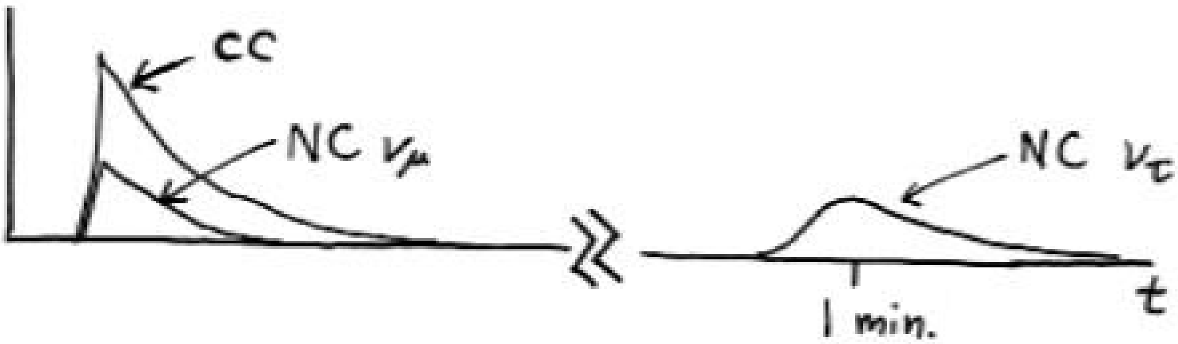
Mass Cases:

$$\boxed{\Delta t = 0.515 \left(\frac{m}{E_c}\right)^2 D}$$

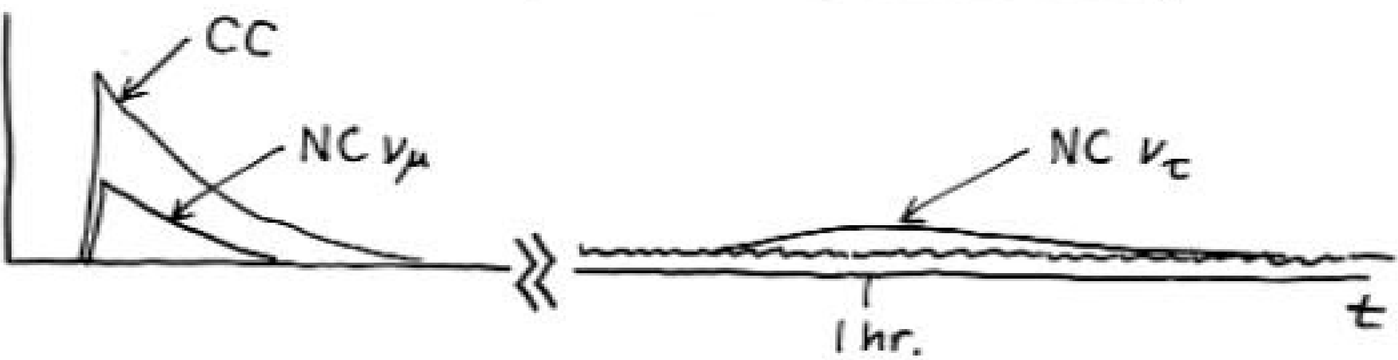
- $\boxed{m \simeq 30\,eV} \longrightarrow \boxed{\Delta t \simeq 0.5\,s}$

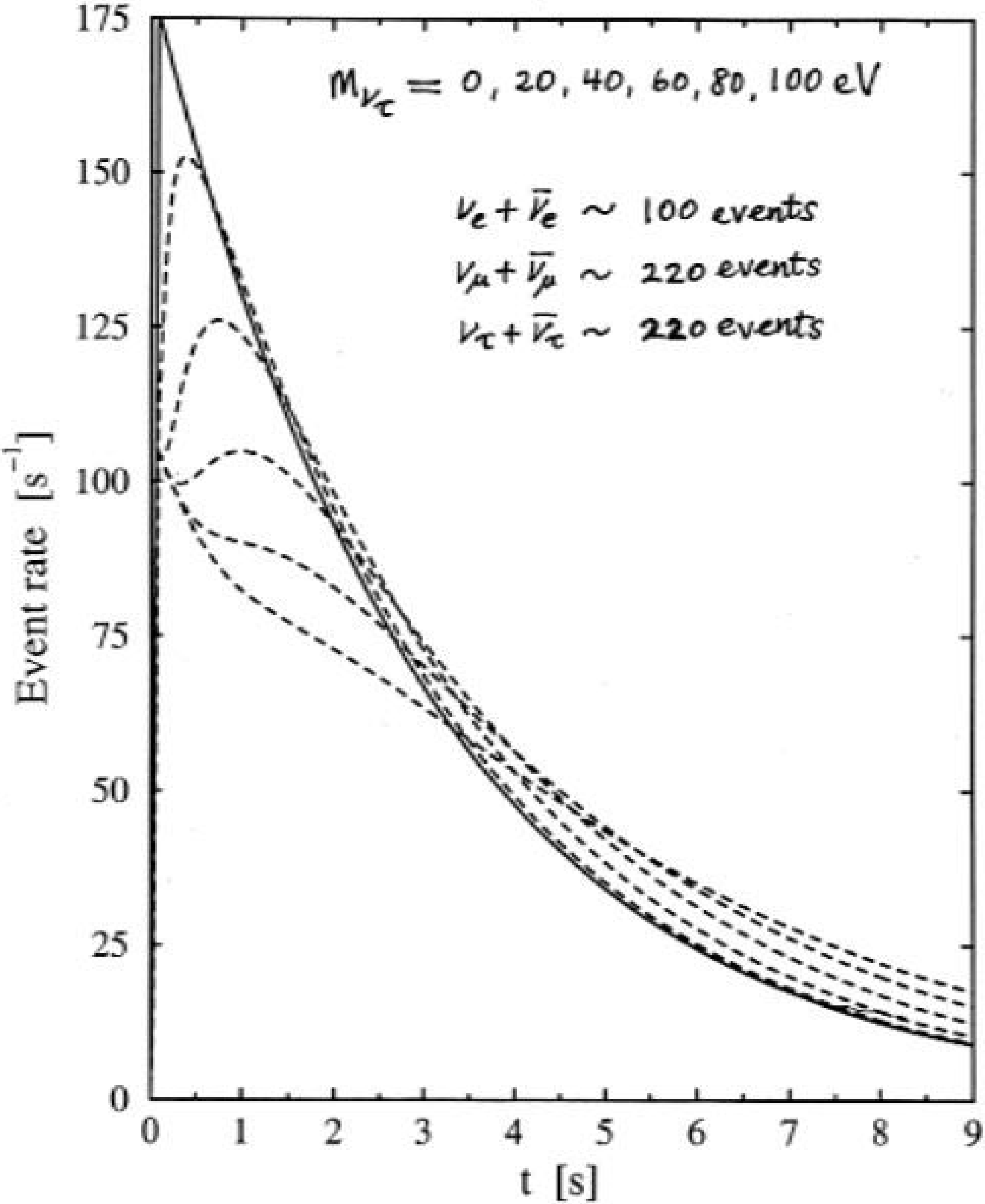


- $\boxed{m \simeq 300\,eV} \longrightarrow \boxed{\Delta t \simeq 50\,s \simeq 1\text{ min.}}$



- $\boxed{m \simeq 3000\,eV} \longrightarrow \boxed{\Delta t \simeq 5000\,s \simeq 1\text{ hr.}}$



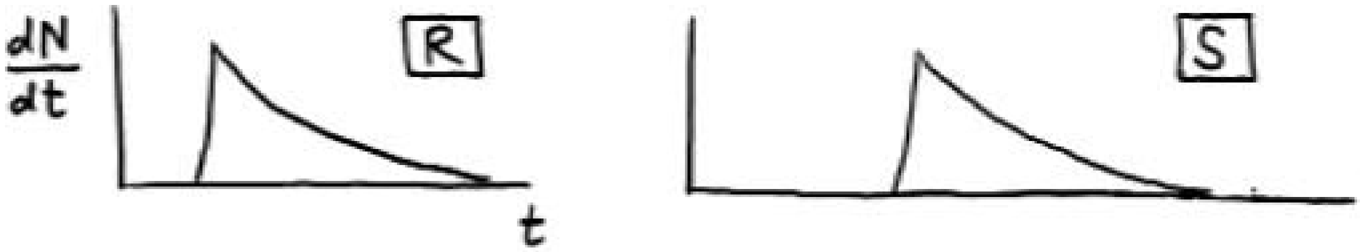


$M_{\nu_\tau} = 0, 20, 40, 60, 80, 100$ eV
$\nu_e + \bar{\nu}_e \sim 100$ events
$\nu_\mu + \bar{\nu}_\mu \sim 220$ events
$\nu_\tau + \bar{\nu}_\tau \sim 220$ events
Event rate [s^{-1}]
t [s]

Imagine

$$
m>0 : \boxed{\begin{array}{l} t_i \longrightarrow t_i + \Delta t(E) \\ \Delta t(E) = 0.515 \left(\frac{m}{E}\right)^2 D \end{array}}
$$

- Fixed E, one massive flavor :

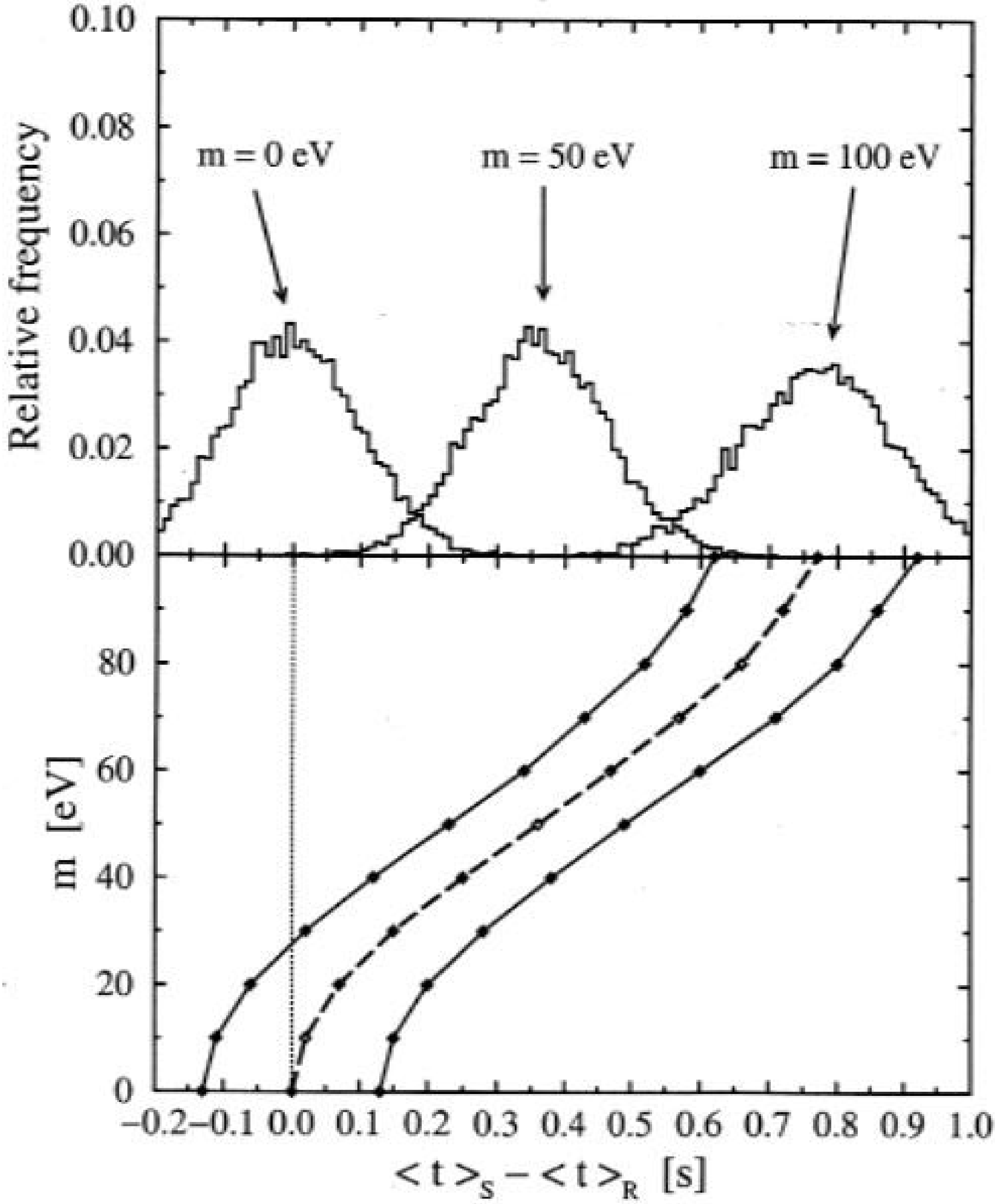


- Fixed E, one massive and one massless flavor

- Now also spectrum f(E)

$$
\boxed{\langle t \rangle_S = \langle t \rangle_R + \mathrm{frac}(m>0) \times \Delta t(E_c)}
$$

What about the other moments ?


m = 0 eV
m = 50 eV
m = 100 eV
Relative frequency
0.10
0.08
0.06
0.04
0.02
0.00
m [eV]
80
60
40
20
0
−0.2 −0.1 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
< t >S − < t >R [s]

explain

Analytic Estimate:

$$\langle t\rangle_S - \langle t\rangle_R \simeq \text{frac}(m>0) \times 0.515 \left(\frac{m}{E_c}\right)^2 D$$

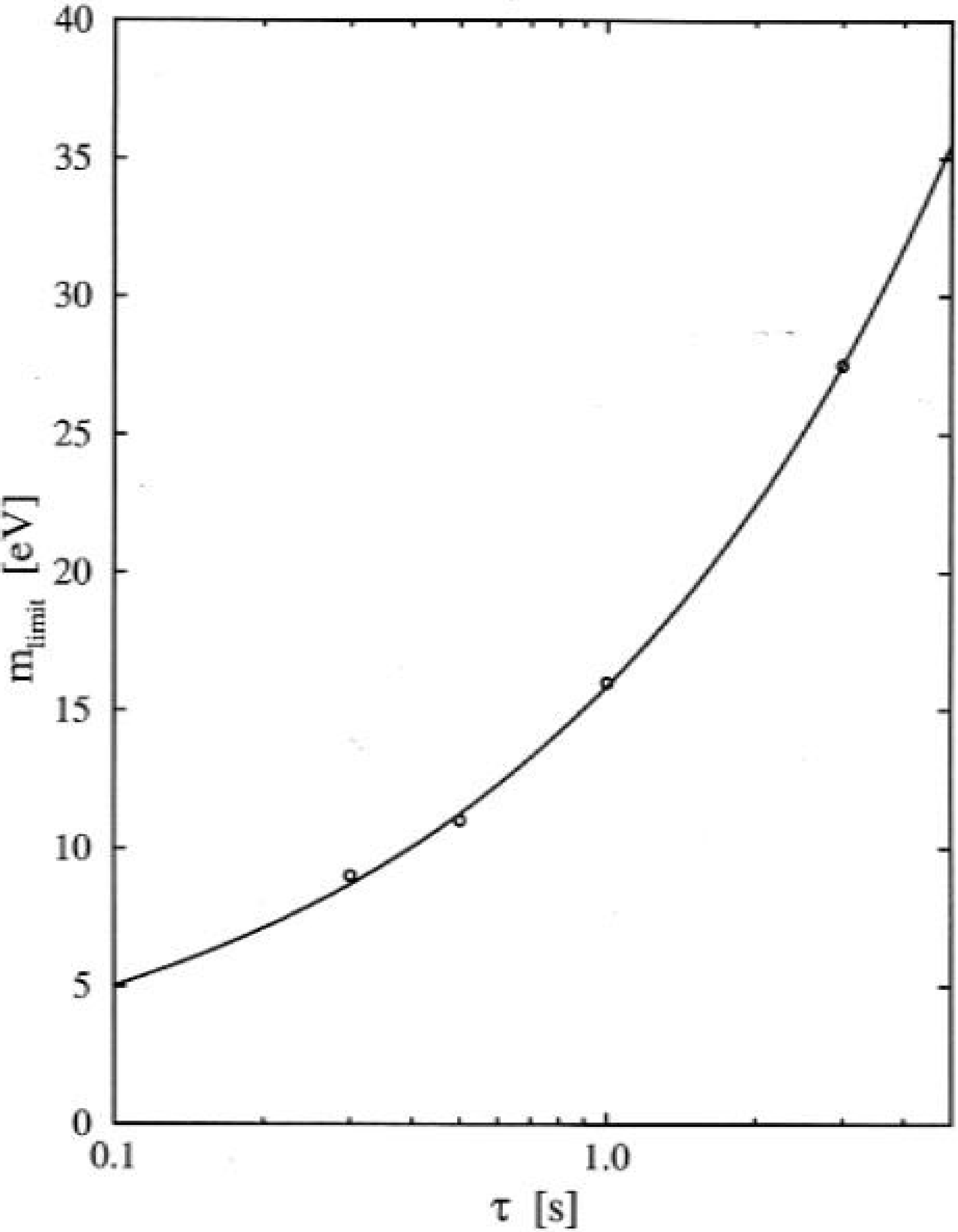
$$\delta\left(\langle t\rangle_S - \langle t\rangle_R\right) \simeq \frac{\tau}{\sqrt{N_{sig}}}$$

$$N_{sig} \sim \frac{\langle\sigma\rangle}{T} \frac{\epsilon_n}{D^2} \sim \frac{T}{D^2} \epsilon_n \qquad \text{for } \nu + d$$

$$\longrightarrow \boxed{\begin{array}{l} \text{delay } \langle t\rangle_S - \langle t\rangle_R \sim \dfrac{m^2}{T^2} D \\ \text{error } \delta\left(\langle t\rangle_S - \langle t\rangle_R\right) \sim \dfrac{\tau D}{\sqrt{T}} \dfrac{1}{\sqrt{\epsilon_n}} \end{array}}$$

$$\longrightarrow \boxed{m_{lim} \sim \sqrt{\tau}\, T^{3/4} \epsilon_n^{-1/4}}$$

independent of D



40
35
30
25
20
15
10
5
0
0.1
1.0
m_{limit} [eV]
τ [s]

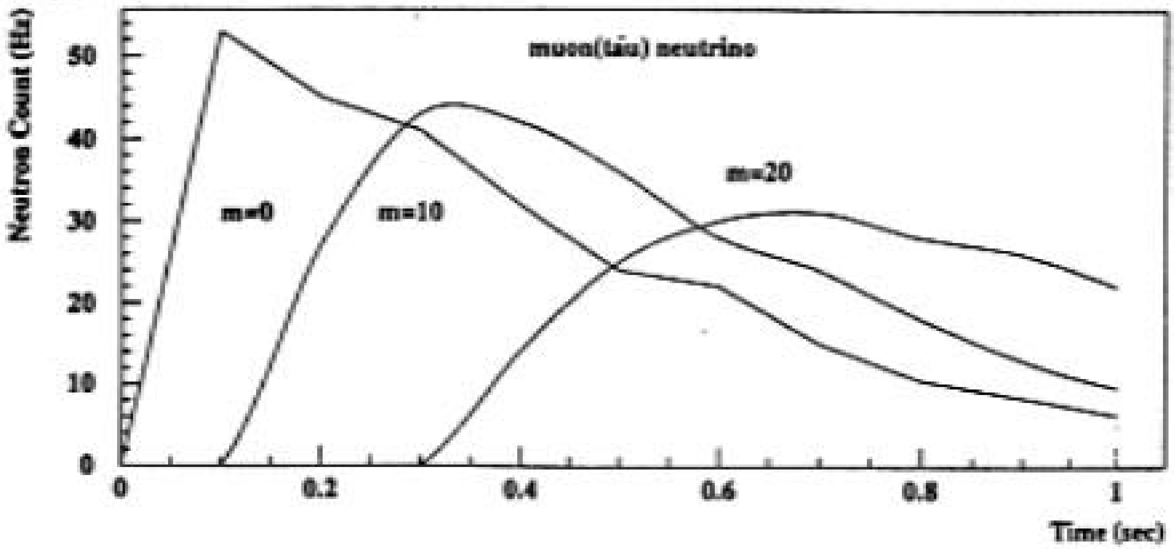


Fig. 1. Neutron count to be expected in LAND as a function of time within one second after initial burst.

LAND: Hargrove et al., Astroparticle Phys. 5, 183 (1996)

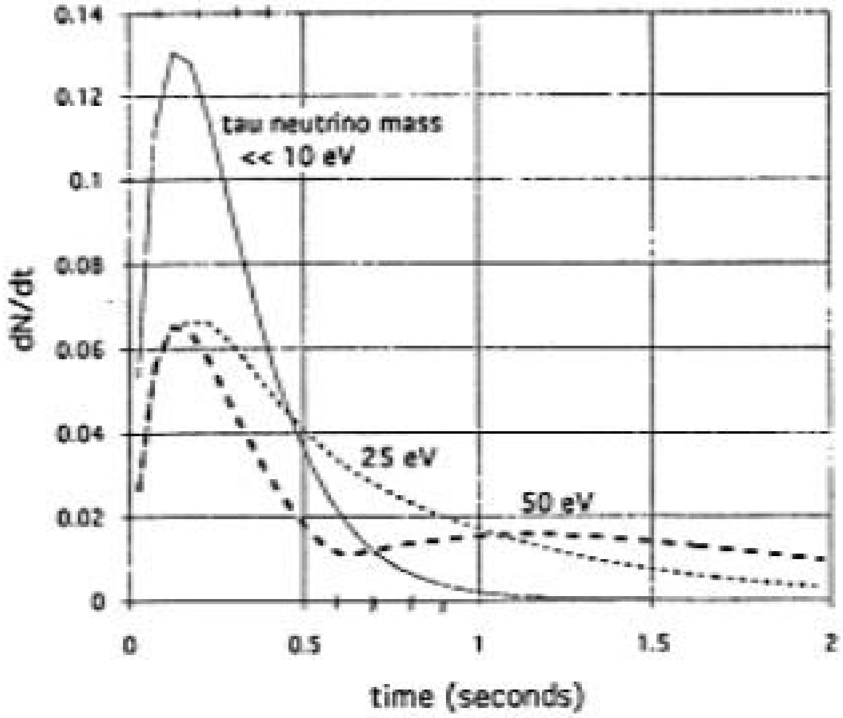
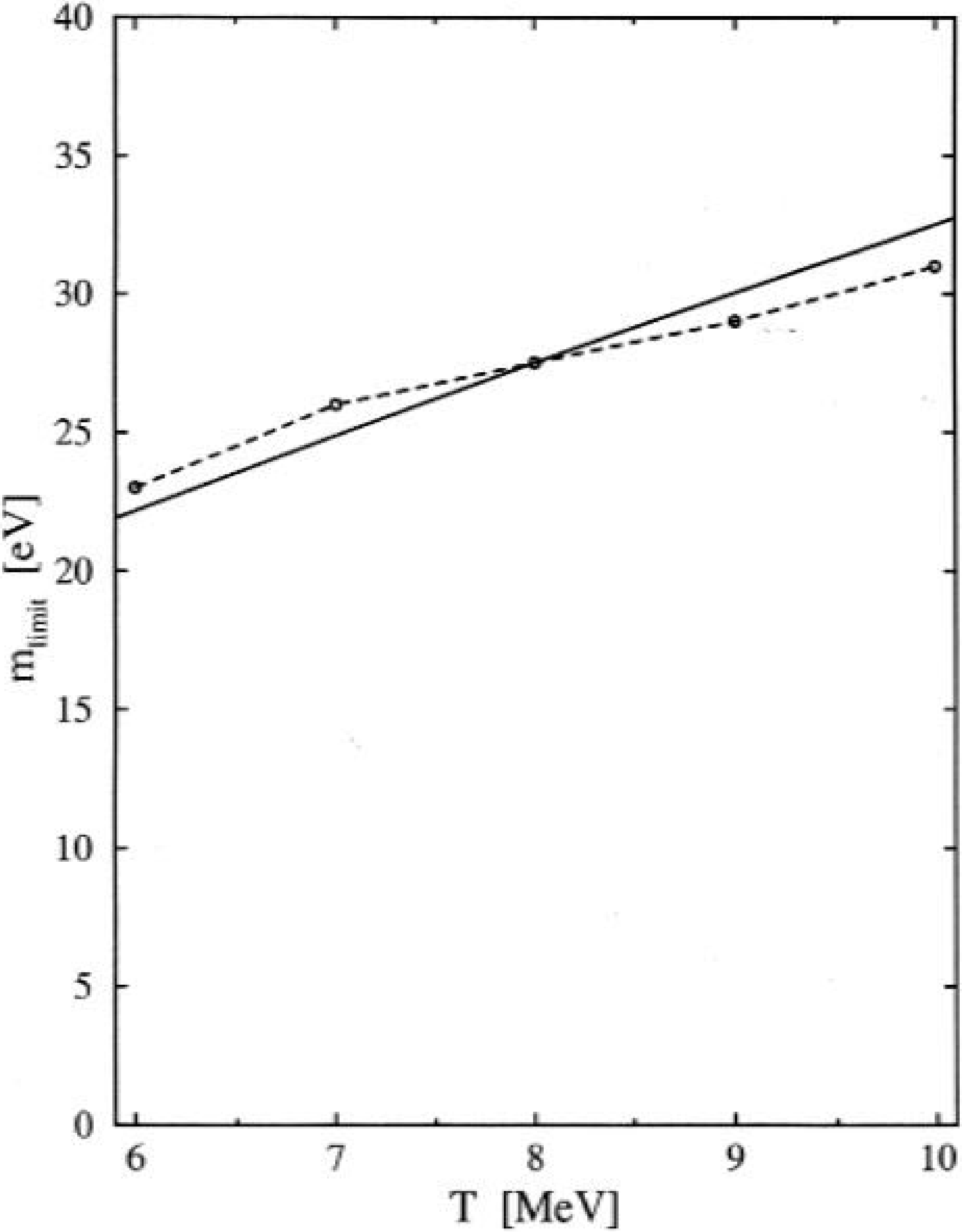
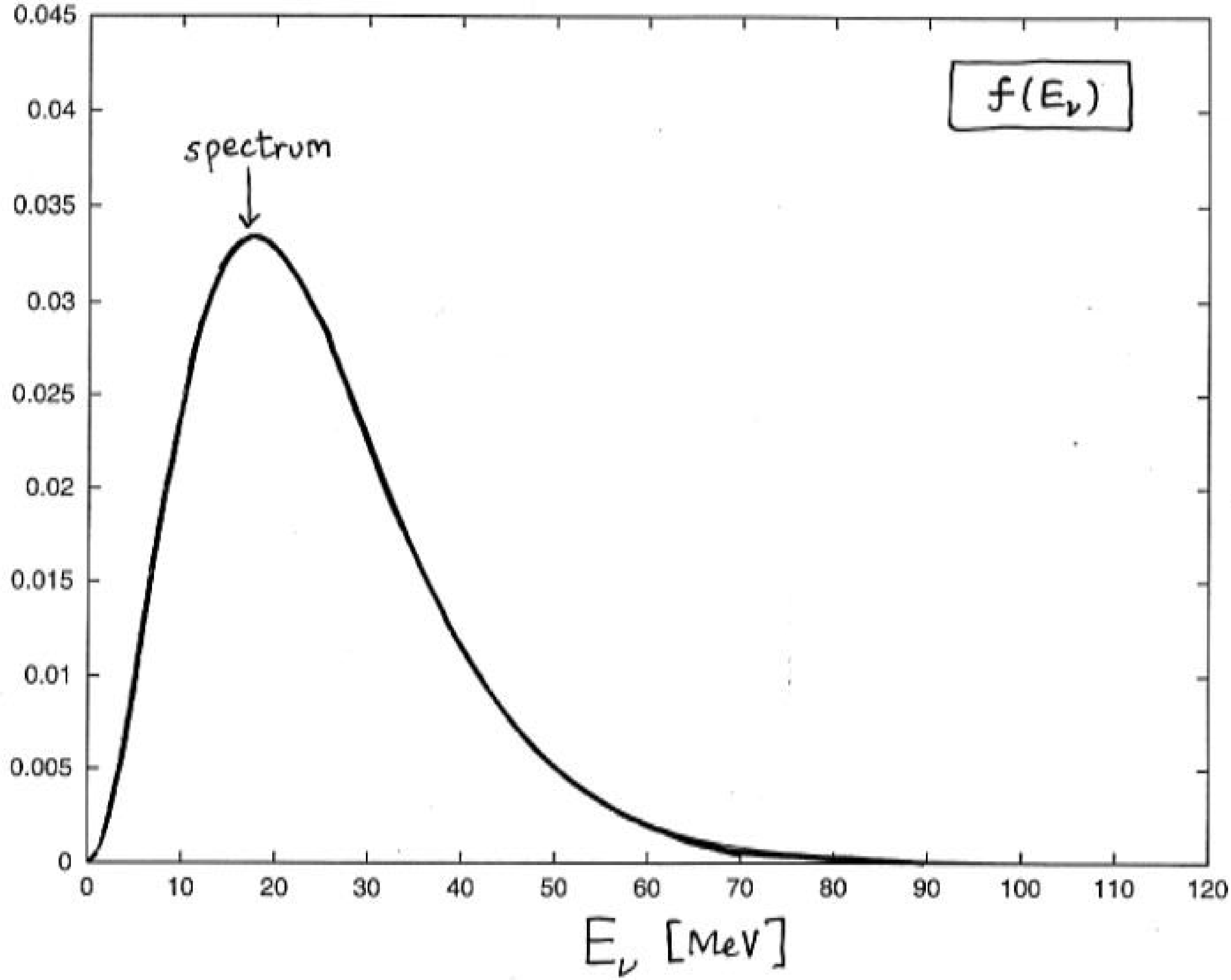


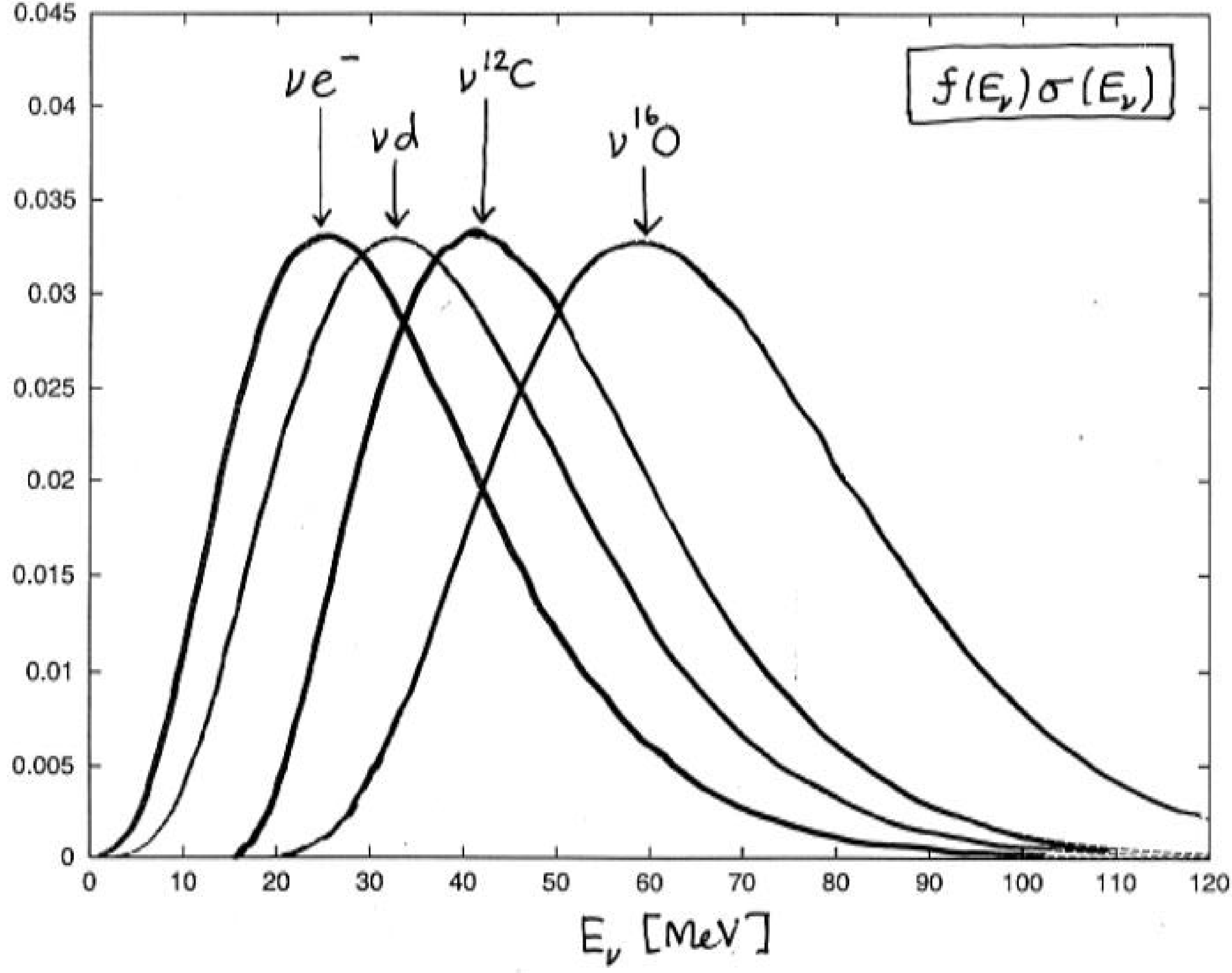
Fig. 3. Arrival time profile for mu and tau neutrinos from supernova at 8 kpc, showing effect of non-zero tau neutrino mass.

OMNIS: Smith, Astroparticle Phys. 8, 27 (1997)


m_{limit} [eV]
T [MeV]
0
5
10
15
20
25
30
35
40
6
7
8
9
10



f(E_ν)
spectrum
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
60
70
80
90
100
110
120
E_ν [MeV]



$f(E_\nu)\sigma(E_\nu)$
νe^-
νd
$\nu^{12}C$
$\nu^{16}O$
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 10 20 30 40 50 60 70 80 90 100 110 120
E_ν [MeV]

Conclusions

- For small $m_{\nu_\mu}, m_{\nu_\tau}$, only the <t> moment is affected, and it can be calibrated from the massless $\bar{\nu}_e$ events.

$\longrightarrow$ If $m_{\nu_\tau} \simeq 0$, get the following limits:

SNO, νd :	$m_{\nu_\tau} \lesssim 30$ eV
SK, $\nu\,^{16}O$:	$m_{\nu_\tau} \lesssim 45$ eV
SK, νe^- :	$m_{\nu_\tau} \lesssim 50$ eV
KamLAND, $\nu\,^{12}C$:	$m_{\nu_\tau} \lesssim 55$ eV
Borexino, $\nu\,^{12}C$:	$m_{\nu_\tau} \lesssim 75$ eV

J.F.B., P. Vogel, PRD 58, 053010 (1998)
J.F.B., P. Vogel, PRD 58, 093012 (1998)

The Future

- **Step One**: measure neutrino mixing

  atmospheric : K2K, MINOS

  solar : SNO, Borexino, Kamland

  accelerator : KARMEN, Mini Boone

- **Step Two**: measure the mass scale(s)

  tritium β^- : $m_{\nu_e} \lesssim 5\,eV$

  $\beta\beta$ decay : $\langle m_\nu \rangle \lesssim 0.2\,eV$

  astrophysics limits on $m_{\nu_\mu}, m_{\nu_\tau}$

- **Step Three**:

  What lies Beyond the Standard Model?