Future galactic supernova neutrino signal
What can we learn?

a) Mass of ν_τ and or ν_μ
(determining neutrino mass from the time delay)

b) Supernova properties
(determining temperatures and luminosities of the individual neutrino flavors)

c) Supernova localization
(pointing toward SN independently of the optical observation)

Physics of these tasks is straightforward, but there are complications due to:

a) Finite statistics of the signal

b) Finite time duration of the signal

c) Nuclear cross sections - not discussed today

References - all with John Beacom
PRD58, 053010(1998); PRD58, 093012(1998);
PRD60, 033007(1999); PRD60, 0530003(1999);
and the last paper in preparation

Neutrinos from SN1987A

Feb. 23, 1987

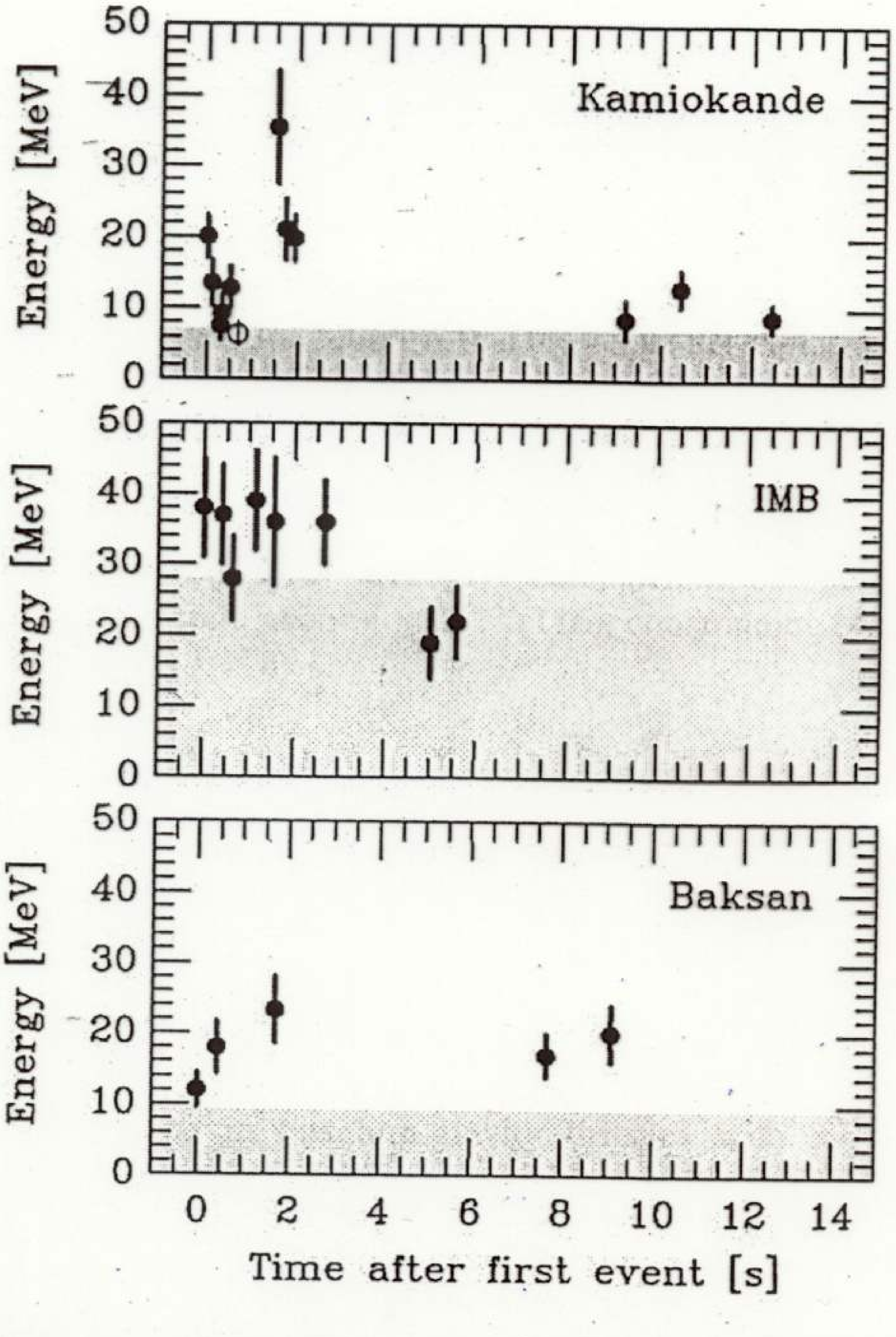


Figure 7 SN 1987A neutrino observations at Kamiokande (93), IMB (94), and Baksan (95). The energies refer to the secondary positrons from the reaction $\bar{\nu}_e p \rightarrow ne^+$. In the shaded area, the trigger efficiency is less than 30%. The clocks have unknown relative offsets; in each case, the first event was shifted to $t = 0$. In Kamiokande, the event marked as an open circle is attributed to background.

Brief lifetime (~7My) of a large star (~$25M_o$)

Burning sequence: H, ^{4}He, $3\alpha \rightarrow {}^{12}$C, ^{16}O, ^{28}Si, ^{56}Ni

(note that the A~56 have maximum binding/nucleon, there is no more gain in energy in fusion after that.)

Last stage, Si burning, takes only ~days.

Core properties: $M \sim (1-1.5)M_o$, $\rho \sim 10^9$ g/cm^3

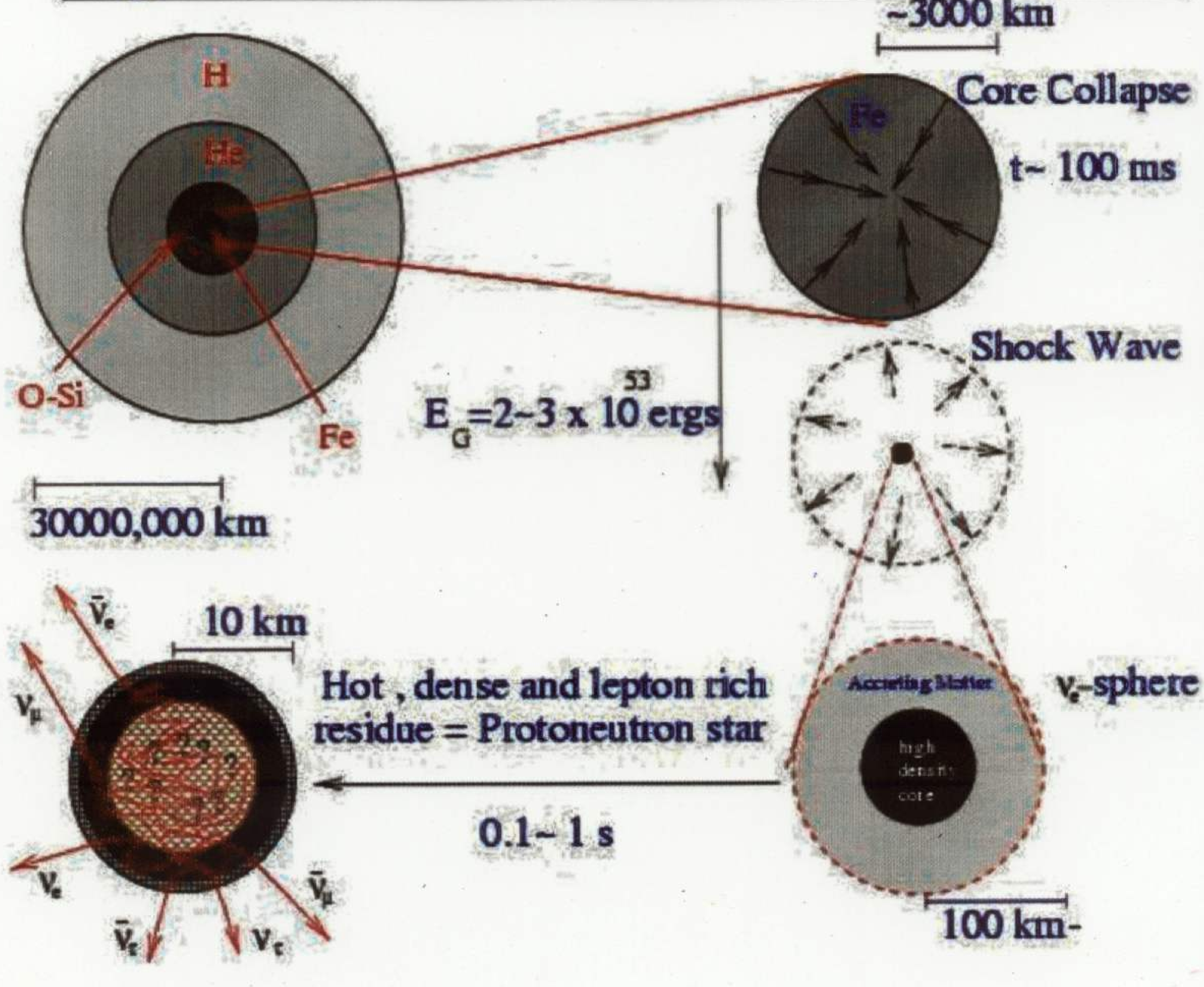
$R \sim 10^3$ km, $kT \sim 0.5$ MeV

Once there is no more heat source, free infall follows

Neutrino trapping occurs at $\rho \sim 10^{12}$ g/cm^3

Bounce follows at $\rho \sim 10^{14}$ g/cm$^3 > \rho_{nucl}$

Supernovae – Neutrinos – Neutron Stars



Understanding basic SN parameters

- **Binding energy:** $E_B \simeq \frac{3}{5}\frac{G_N M^2}{R} \sim 3 \times 10^{53}$ **erg**

- **Trapping:** mean free path $\lambda = \frac{1}{\rho\sigma}$ should be comparable to the scale height $h = \frac{kT}{M_n \times g}$
For $g = 2 \times 10^{12}\mathrm{ms}^{-2}$ (this is the g of the protoneutron star) and $T = 5$ MeV , $h \sim 200$ m

- The average density for $R \sim 10$ km is $\rho \sim 10^{38}$ nucleons/cm^3.
Since $\sigma \sim 10^{-41}$ cm^2 $\Longrightarrow$ $\lambda \sim$ meter or less.
Hence the trapping extends up to $\sim$ 100 km.

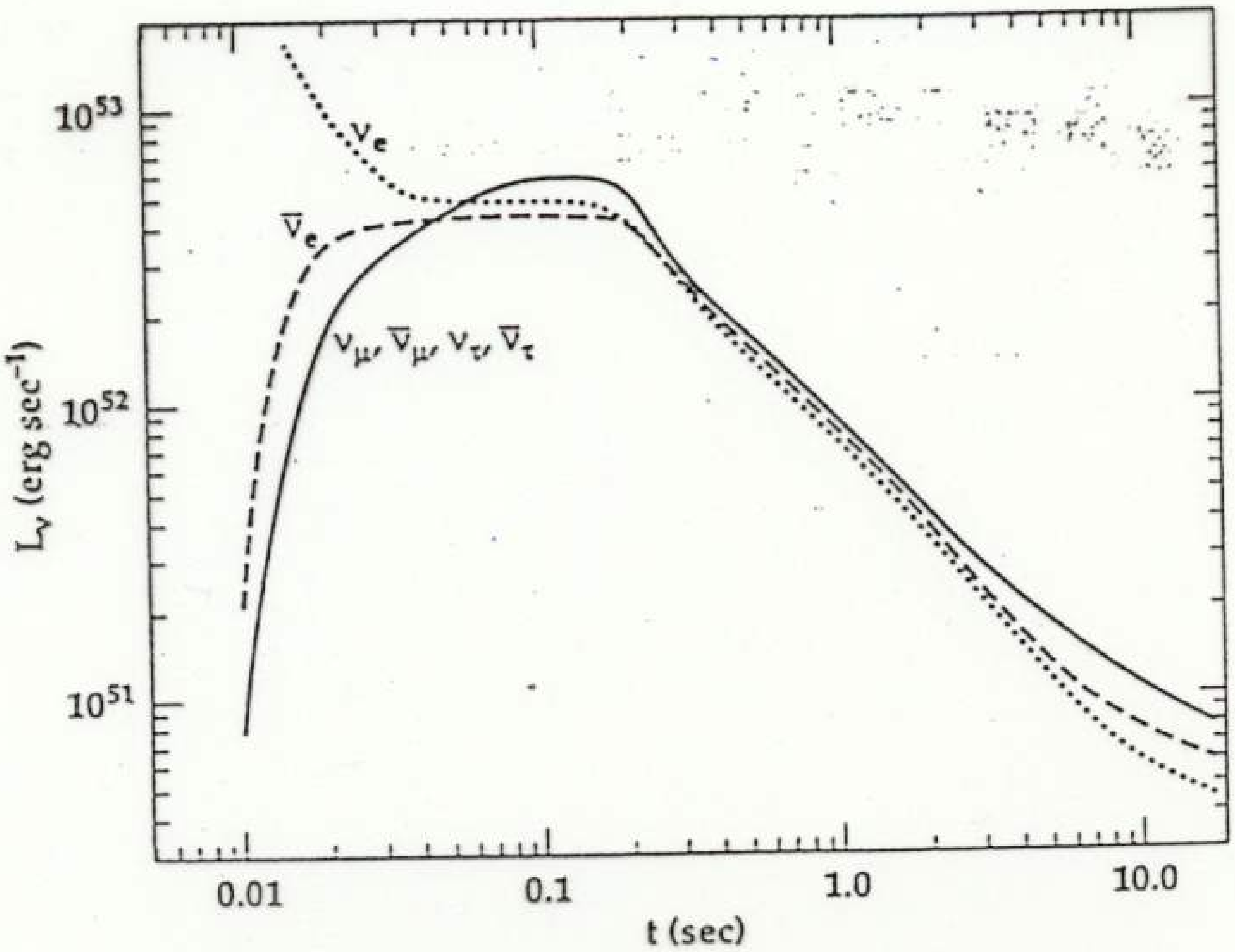
- Diffusion time: Crude estimate is $\tau = \frac{R^2}{\lambda^2}\frac{\lambda}{c}$.
Hence, $\tau \simeq 10$ s.

- The explosion energy is $\sim 10^{51}$ erg, and the energy in optical emission is $\sim 10^{49}$ erg. Thus these manifestations of the SN are just a side-show to the neutrino cooling.

- Hierarchy: Since ν_μ and ν_τ have only NC, and $\bar{\nu}_e$ interact with protons, we expect that $\lambda(\nu_x) > \lambda(\bar{\nu}_e) > \lambda(\nu_e)$.
Hence the 'neutrinosphere' for ν_x will be farther inside than for $\bar{\nu}_e$ which further will be deeper than for ν_e
$\Longrightarrow T(\nu_x)(\sim 8\mathrm{MeV}) > T(\bar{\nu}_e)(\sim 5\mathrm{MeV}) > T(\nu_e)(\sim 3.5\mathrm{MeV})$.

- At the same time, one expects that the total luminosity will be equally shared by all neutrino flavors,
$\bar{L}_\nu \simeq E_B/(6\tau) \simeq 5 \times 10^{51}$ erg/s.

Woosley et al. ApJ 433, 229 (1994)



$L \sim e^{-t/\tau}$

$\tau \sim 3s$

FIG. 2.—Neutrino luminosity L_ν for the six neutrino types as labeled as a function of time in the 20 $M_\odot$ supernova model.

$$\varepsilon_\nu = \frac{\langle E^2 \rangle}{\langle E \rangle} \sim 4T$$

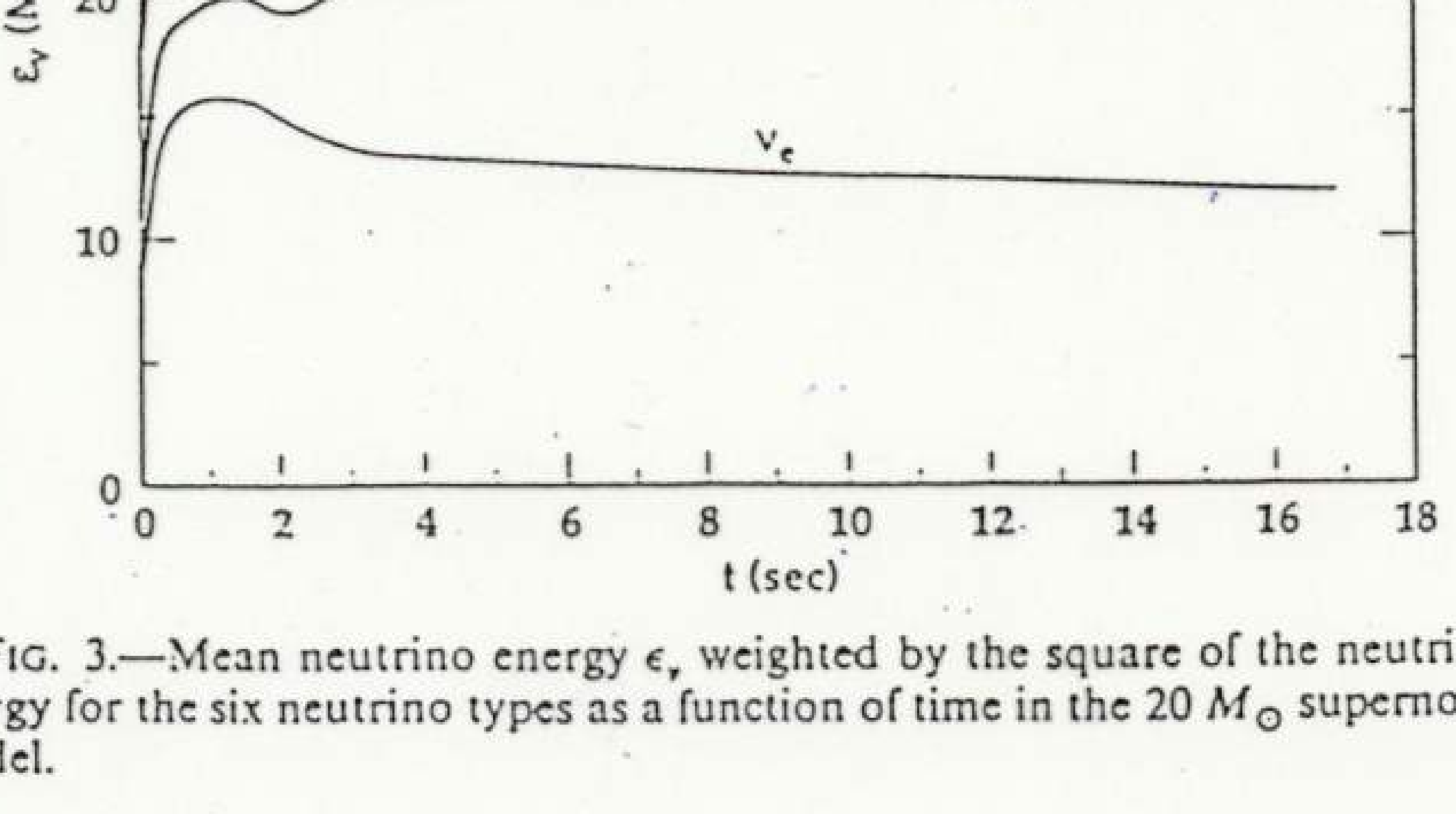


FIG. 3.—Mean neutrino energy ϵ_ν weighted by the square of the neutrino energy for the six neutrino types as a function of time in the 20 $M_\odot$ supernova model.

Aside: 10^{53} erg is an enormous energy

and 10^{51} erg/s is an enormous luminosity

Comparison:

Solar luminosity is 3.8×10^{33} erg/s

Total solar energy output over 10^{10} years $\sim 10^{51}$ erg

visible galactic luminosity $\sim 5 \times 10^{44}$ erg/s

Curiosity: with 3 SN/century we have 10^{54} erg/century

but the visible galactic energy/century is

$5 \times 10^{44} \times 3 \times 10^{9} \sim 10^{54}$ erg/century

SN Rates

Historical record in last 1000 years

Year	name	distance (kpc)
1006	Lupus	1.4
1054	Crab	2.0
1181?	3C58	2.6
1300?	doubtful	0.2
1572	Tycho	2.5
1604	Kepler	~~3.0~~ 4.4
1680?	Cas.A	3.0

about 0.7/century in a restricted volume

we take 3/century in the entire galaxy

this agrees with other estimates, but has a large uncertainty

Limits on neutrino masses

Evidence is accumulating that at least some neutrinos are massive. This comes from the searches for neutrino oscillations. Oscillations depend on $\Delta m^2 = m_1^2 - m_2^2$. One cannot determine m absolutely. This can be done only, on earth, in kinematic tests.

$m_{\nu_\tau} \leq 18$ MeV (from τ decay)

$m_{\nu_\mu} \leq 170$ keV (from $\pi^+ \to \mu^+ + \nu_\mu$)

$m_{\nu_e} \leq 3$ eV (from tritium beta decay)

Cosmological bound

from $\Omega \leq 1$ and for stable neutrinos

$\Sigma m_\nu \leq 50$ eV (depends on H)

Moreover, assuming that neutrinos can be at best responsible for only "hot dark matter"

$\Sigma m_\nu \leq 5 - 10$ eV.

Time delay of the ν_τ and ν_μ signal.

• Neutrinos of mass m_ν and energy E_ν travel over a distance D with the velocity

$$\frac{v_\nu}{c} = \frac{p_\nu c}{E_\nu} \simeq 1 - \frac{m_\nu^2 c^4}{2E_\nu^2} .$$

Hence there will be a time delay in their arrival, compared to the $m_\nu = 0$ case, of

$$\Delta t \simeq \frac{m_\nu^2 c^4}{2E_\nu^2} D .$$

• In proper units this delay is

$$\Delta t(s) = 0.515 \left(\frac{m_\nu(\mathrm{eV})}{E_\nu(\mathrm{MeV})}\right)^2 \left(\frac{D}{10\mathrm{kpc}}\right) .$$

• So we need to know the arrival time of the $m_\nu = 0$ neutrinos. We can use the robust $\bar{\nu}_e$ signal for that purpose.

• Next we need to separate the ν_τ and ν_μ signal from everything else.

• And finally we have to measure the time delay.

Mass of ν_τ and/or ν_μ

ν_τ and ν_μ can be detected only through neutral current reactions:

a) $\underline{\nu}$ scattering on electrons
(all detectors, but difficult to separate from the charged current scattering)

$$\nu + e \rightarrow \nu + e$$

b) $\underline{\nu}$ neutral current excitation of oxygen in water (SuperKamiokande and SNO)

$$\nu + {}^{16}O \rightarrow X + \nu + \gamma$$

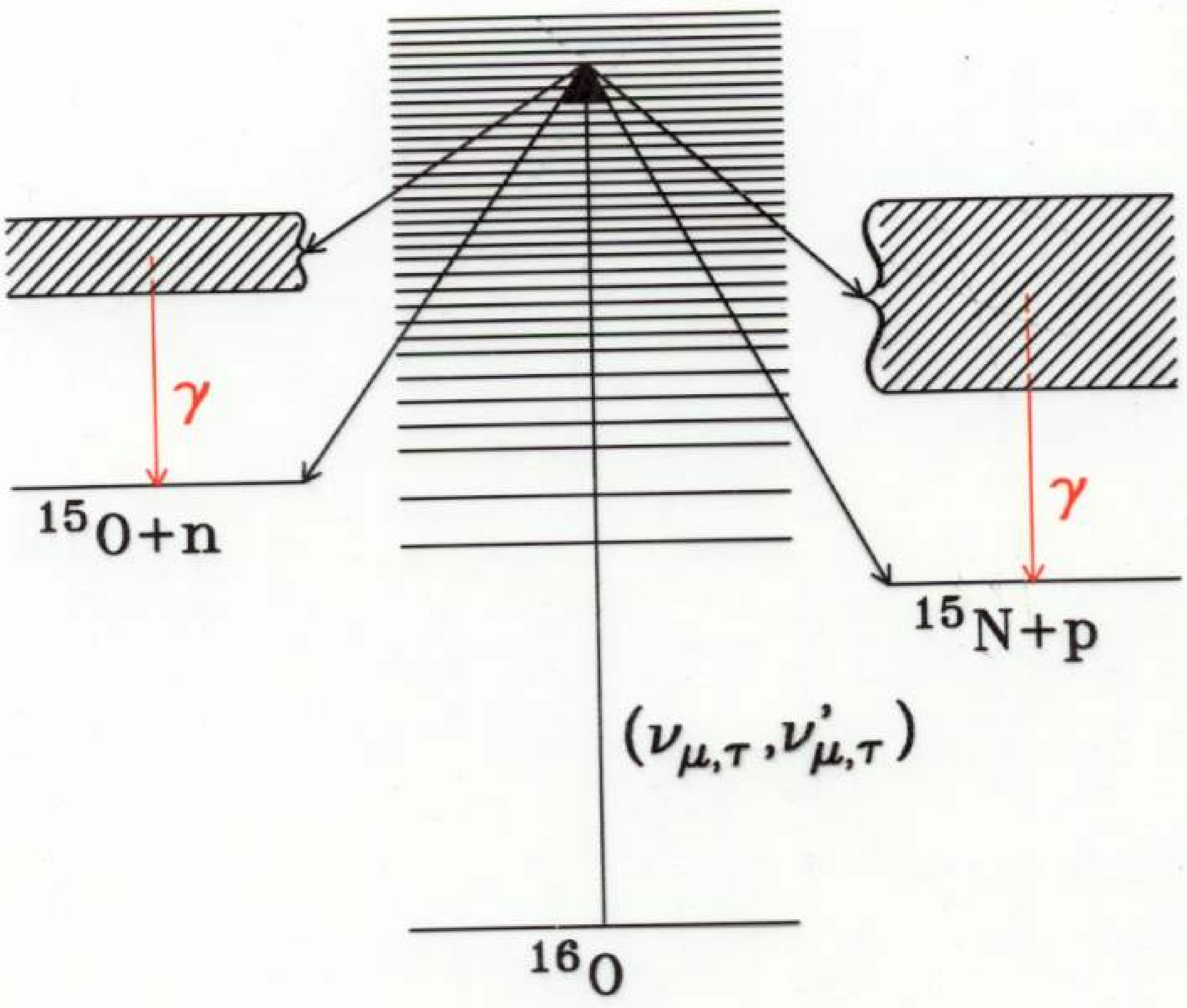
c) $\underline{\nu}$ neutral current deuteron dissintegration (SNO)

$$\nu + d \rightarrow n + p + \nu$$

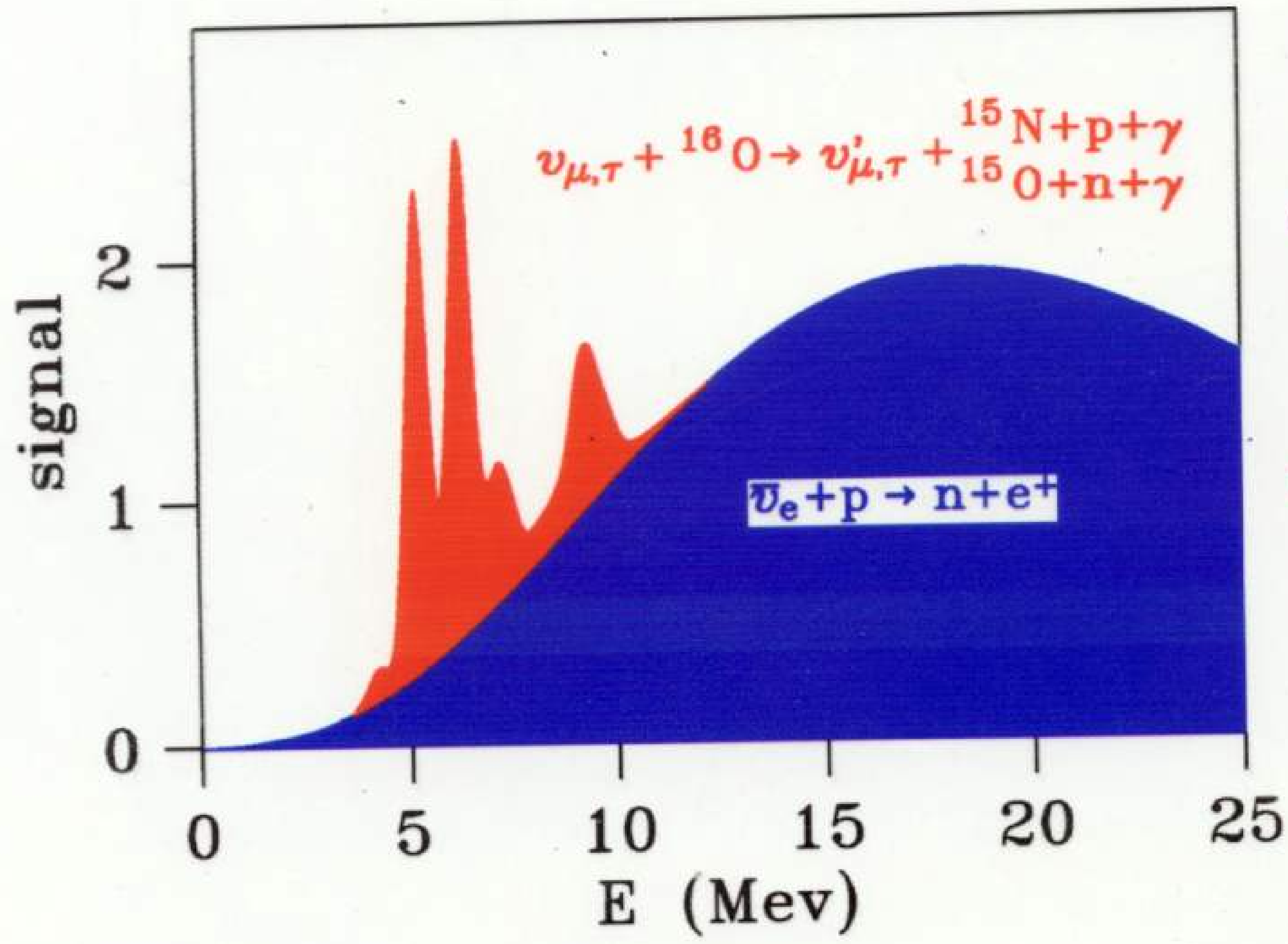
d) $\underline{\nu}$ scattering on protons - detect proton recoil

$$\nu + p \rightarrow \nu + p$$

SUPERNOVA NEUTRINO SIGNAL IN SUPERKAMIOKANDE



LANGANKE
VOGEL
KOLBE
(PRL 76, 2629 (1996))



~ 8000 counts from $\bar{\nu}_e$

~ 400-800 counts from $\nu_\mu + \nu_\tau$

Expected count rates in Superkamiokande
(see J. Beacom and P.V., Phys. Rev. D58, 053010 (1998))

Reaction	No. of events
$\bar{\nu}_e + p \rightarrow e^+ + n$	8300
$\bar{\nu}_e + p \rightarrow e^+ + n$ ($E_{e^+} \leqslant 10$ MeV)	530
$\nu_\mu + {}^{16}O \rightarrow \nu_\mu + \gamma + X$ $\bar{\nu}_\mu + {}^{16}O \rightarrow \bar{\nu}_\mu + \gamma + X$	355
$\nu_\tau + {}^{16}O \rightarrow \nu_\tau + \gamma + X$ $\bar{\nu}_\tau + {}^{16}O \rightarrow \bar{\nu}_\tau + \gamma + X$	355
$\nu_e + e^- \rightarrow \nu_e + e^-$ $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	200
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$	60
$\nu_\tau + e^- \rightarrow \nu_\tau + e^-$ $\bar{\nu}_\tau + e^- \rightarrow \bar{\nu}_\tau + e^-$	60

only ν_τ massive — For ^{16}O excitations: delayed signal / background = 355/885

ν, e scattering: — " — 60/700

both ν_τ and ν_μ massive:

^{16}O --- 710/530

ν, e ... 120/640

Expected count rate in SNO

(see J. Beacom and P.V, Phys. Rev. D58, 093012 (1998))

Events in 1 kton D_2O	
$\nu + d \rightarrow \nu + p + n$ $\bar{\nu} + d \rightarrow \bar{\nu} + p + n$	485
$\nu_e + d \rightarrow e^- + p + p$ $\bar{\nu}_e + d \rightarrow e^+ + n + n$	160
$\nu + {}^{16}O \rightarrow \nu + \gamma + X$ $\bar{\nu} + {}^{16}O \rightarrow \bar{\nu} + \gamma + X$	20
$\nu + {}^{16}O \rightarrow \nu + n + {}^{15}O$ $\bar{\nu} + {}^{16}O \rightarrow \bar{\nu} + n + {}^{15}O$	15
$\nu + e^- \rightarrow \nu + e^-$ $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$	10
Events in 1.4 kton H_2O	
$\bar{\nu}_e + p \rightarrow e^+ + n$	365
$\nu + {}^{16}O \rightarrow \nu + \gamma + X$ $\bar{\nu} + {}^{16}O \rightarrow \bar{\nu} + \gamma + X$	30
$\nu + e^- \rightarrow \nu + e^-$ $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$	15

For $\nu + d$ NC delayed signal / background = 219/316

both ν_μ and ν_τ massive 438/97

Assume that the SN luminosity (i.e. also the neutrino flux) varies as $L(\mathrm{t})$.

The arrival time of massive neutrinos will then follow $L(\mathrm{t} - \Delta\mathrm{t}(\mathrm{E}_\nu))$.

In neutral current scattering one cannot determine the incoming neutrino energy E_ν.

Hence the only information available is the <u>time distribution</u> of the events:

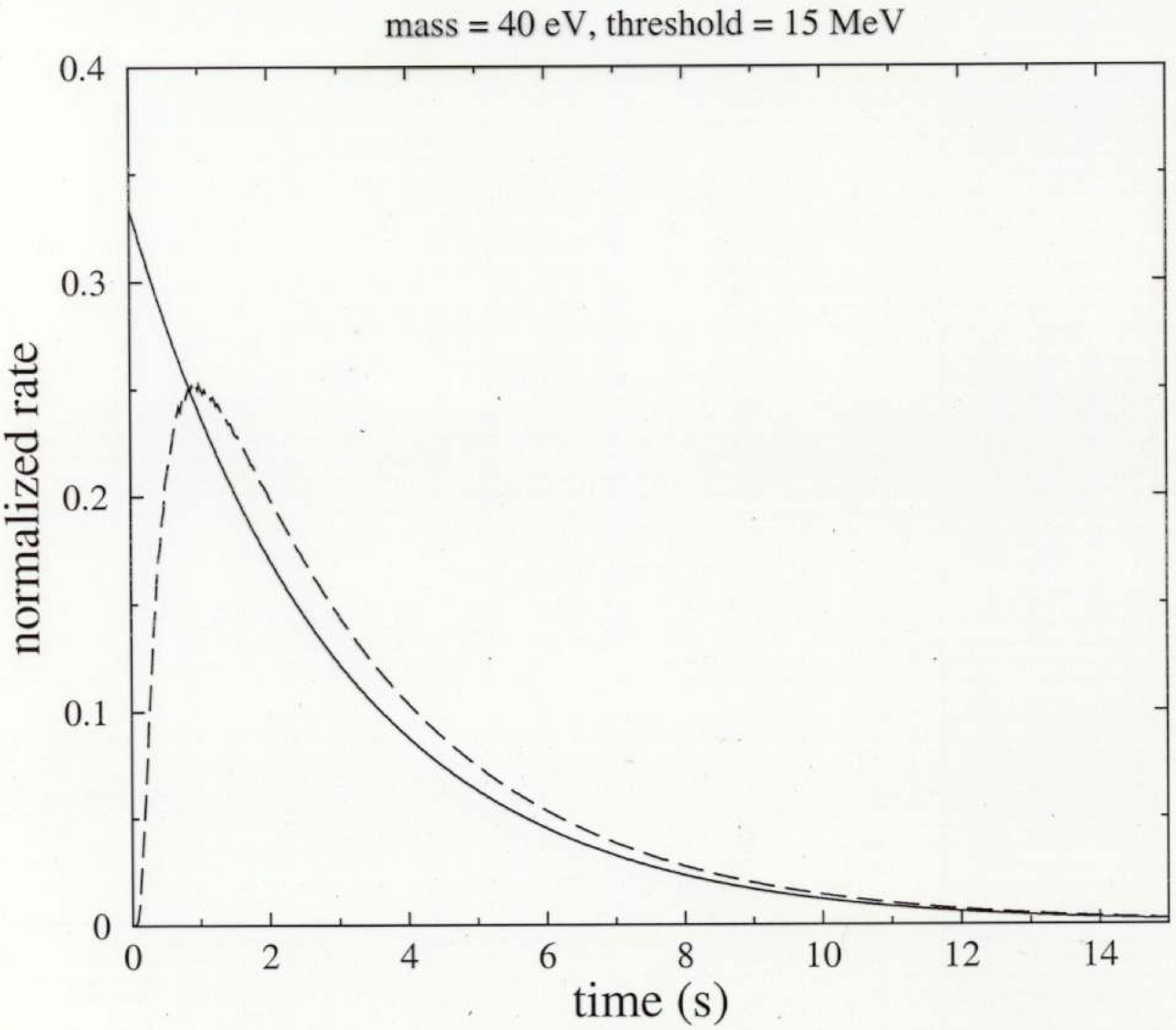
$$\mathrm{dN/dt} = \mathrm{C} \int \mathrm{dE}_\nu\, \mathrm{f}(\mathrm{E}_\nu)\, \sigma(\mathrm{E}_\nu)\, L(\mathrm{t} - \Delta\mathrm{t}(\mathrm{E}_\nu))$$

where $\mathrm{f}(\mathrm{E}_\nu)$ is the thermal neutrino spectrum,

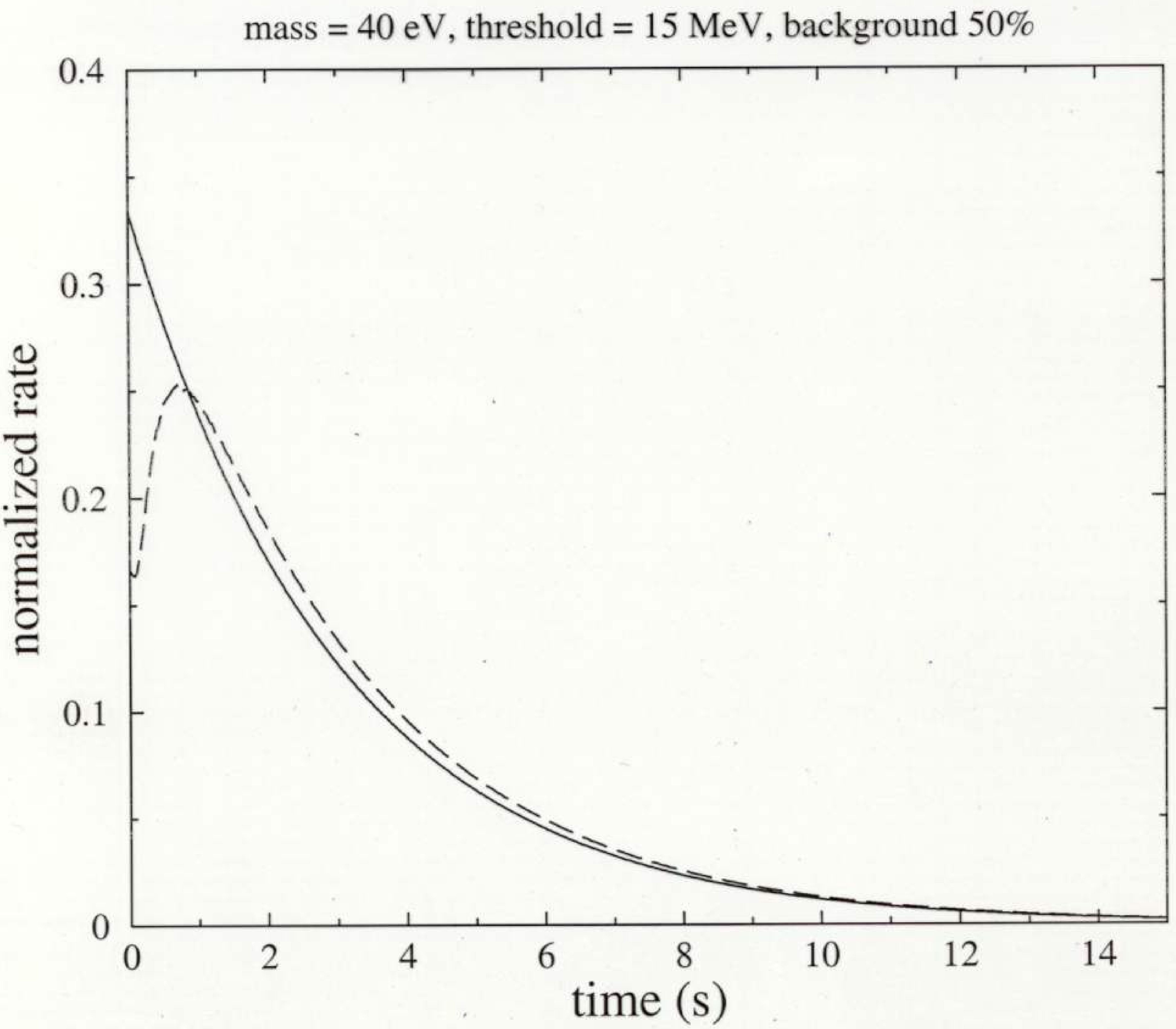
$\sigma(\mathrm{E}_\nu)$ is the cross section in $10^{-42}\ \mathrm{cm}^2$, and

$$\mathrm{C} \approx 174/(\mathrm{D}^2 \times \mathrm{T})\ (\text{det. mass}/1\ \text{kton})$$

Signal without a delay (full) and with delay (dashed)



Signal without a delay (full) and with delay (dashed)



The only way we can decide whether there is a time delay or not is to compare this (dominantly) NC signal with the refence signal that is certainly not delayed, because it is caused by the (essentially) massless $\bar{\nu}_e$ and ν_e.

The most efficient way to do that is also the simplest one, i.e. to use the difference in the <u>mean arrival time:</u>

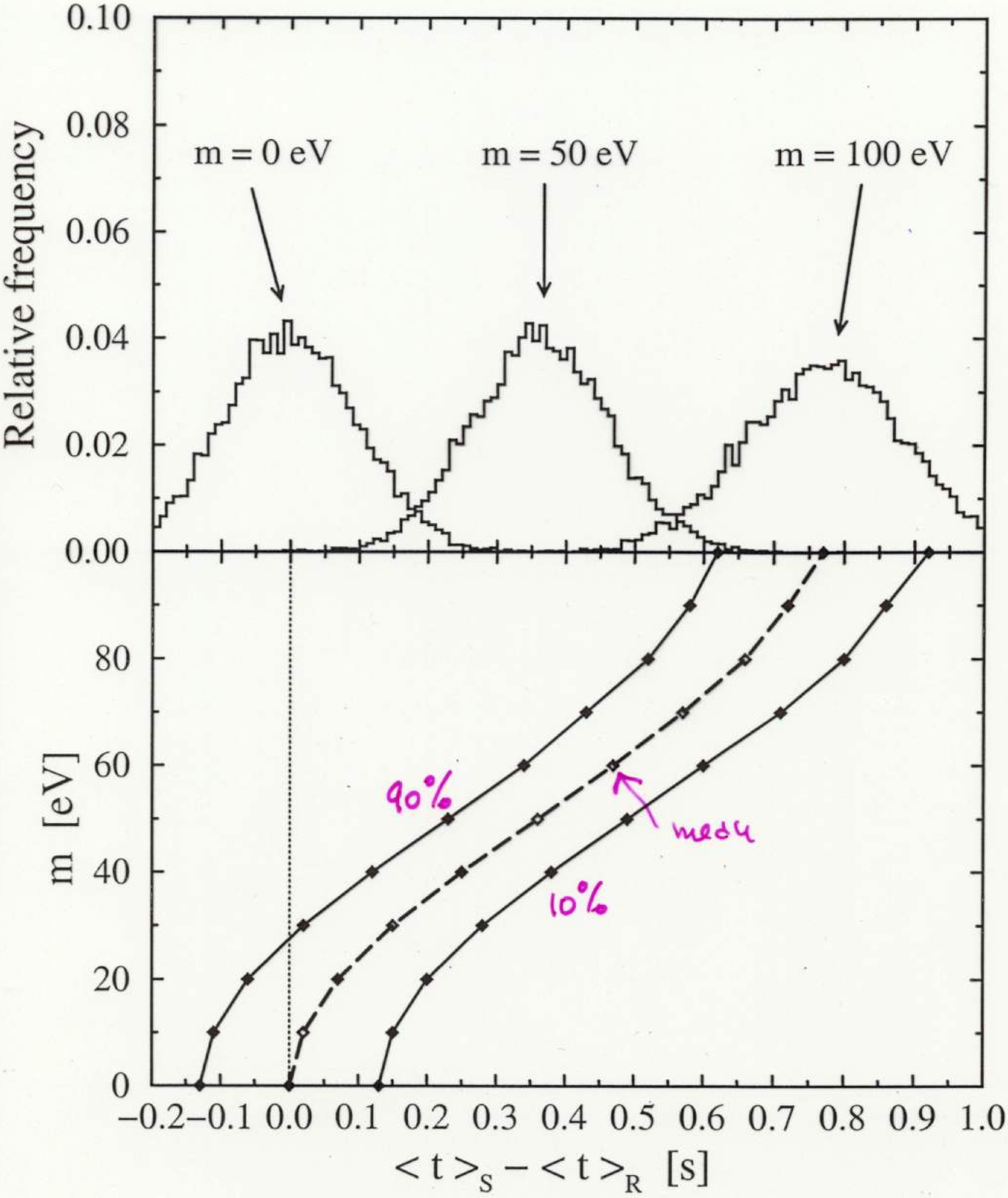
$\langle t \rangle_S = \Sigma_k t_k / N_S$ for the signal and

$\langle t \rangle_R = \Sigma_k t_k / N_R$ for the reference

The signature of neutrino mass is thus

$\langle t \rangle_S > \langle t \rangle_R$

With significance beyond the statistical fluctuations.



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
90%
medn
10%
−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]

Analytic estimate of sensitivity to m_ν

Time delay: $\langle t \rangle_S - \langle t \rangle_R \sim (m/T)^2 D$

$N_{signal} \sim T/D^2$

$\delta(\langle t \rangle_S - \langle t \rangle_R) \sim \tau/\sqrt{N_{signal}} \sim \tau D/\sqrt{T}$

Significance: $(\langle t \rangle_S - \langle t \rangle_R)/\delta(\langle t \rangle_S - \langle t \rangle_R) \sim \frac{m^2}{\tau \cdot T^{3/2}}$

$m_{lim} \sim \sqrt{\tau} T^{3/4}$ also $m_{lim} \sim 1/(\text{mass of detector})^{1/2}$

where T is the neutrino temperature,
D is the distance to the supernova
τ is the duration of the neutrino signal

The limit on neutrino mass is independent on the supernova distance **D**, and depends only relatively mildly on the duration of the neutrino pulse τ and on the temperature **T**.

Determining SN parameters:

We would like to determine the temperature and luminosity for each of the three flavors: ν_x, ν_e and $\bar{\nu}_e$. Having all luminosities we can evaluate the total emitted energy, and hence e.g. the radius if the mass is known.

For $\bar{\nu}_e$ this is easy since SupeK will have ~ 8000 events from $\bar{\nu}_e + p \to e^+ + n$. The $\bar{\nu}_e$ energy can be measured in each event. The temperature $T_{\bar{\nu}_e}$ can measured to $\sim 1\%$.

For ν_e we need a neutron target. In SNO there will be ~ 80 $\nu_e + d \to e^- + p + p$ events. This is probably enough to check that $T_{\nu_e} < T_{\bar{\nu}_e}$.

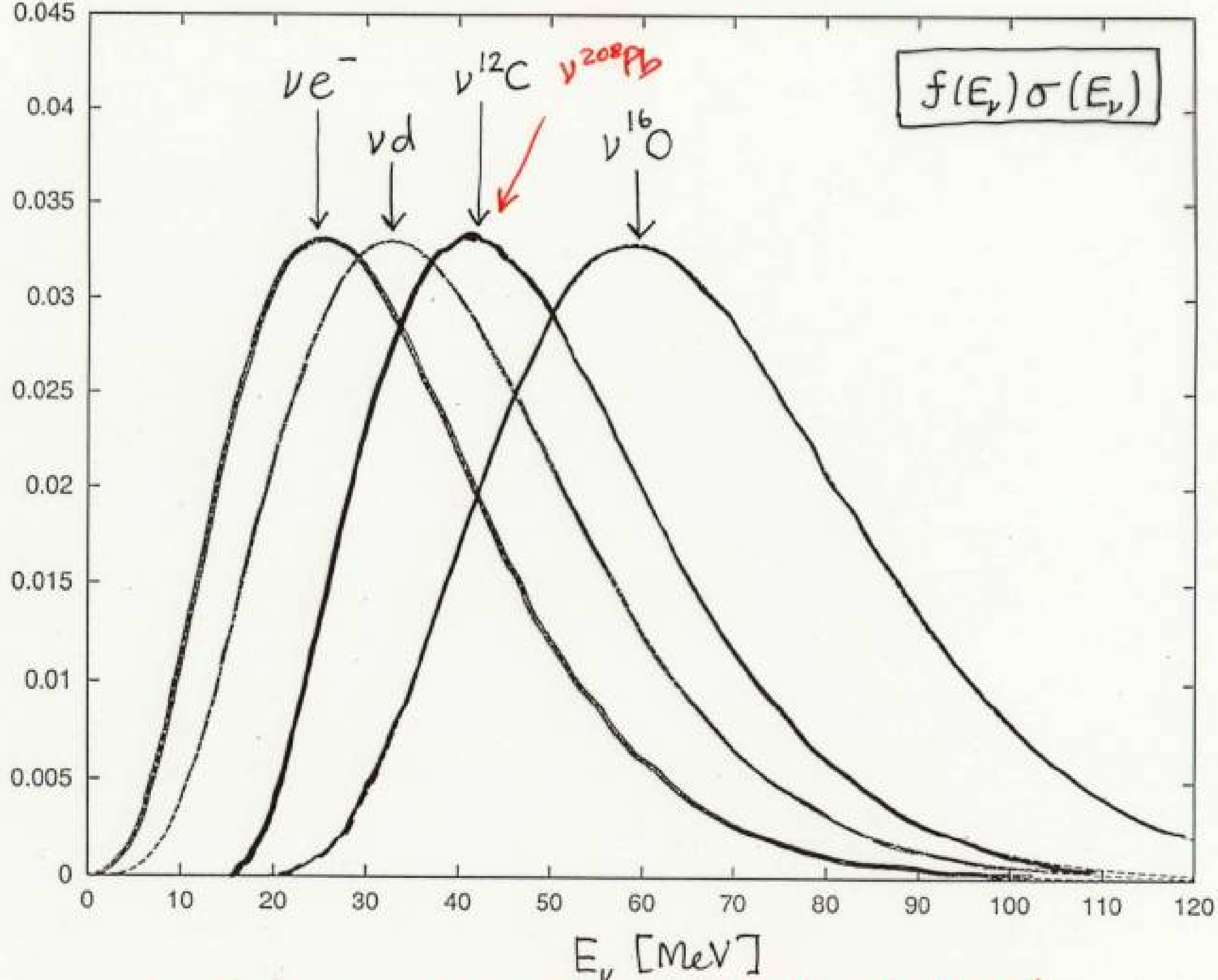
For ν_x there is no spectral information. Only the number of events that depends both on the luminosity and temperature.

$N \sim \frac{L}{D^2 T} \int f(T)\sigma(T) \mathrm{d}E_\nu$

However, different reactions probe different parts of the ν_x spectrum. By combining results of several detectors we can fit for T_{ν_x}.

In the scintillator detectors with low threshold (e.g. Kamland) one can (hopefully) observe ν_x elastic scattering on protons, which would allow separate determination of the ν_x temperature and luminosity.

How to determine the T of SN ν_μ and ν_τ?



Neutral current reactions on different targets

Supernova neutrino signals at Kamland

1) Electron antineutrinos $\bar{\nu}_e$ detected by
$\bar{\nu}_e + p \rightarrow e^+ + n$

2) All neutrinos detected by the charged and neutral current reactions on ^{12}C, leading to the $T, I^\pi = 1, 1^+$ triad. In particular the neutral current excitation of the 15.1 MeV state in ^{12}C, dominated by the ν_x flux. (Possible only with liquid scintillator)

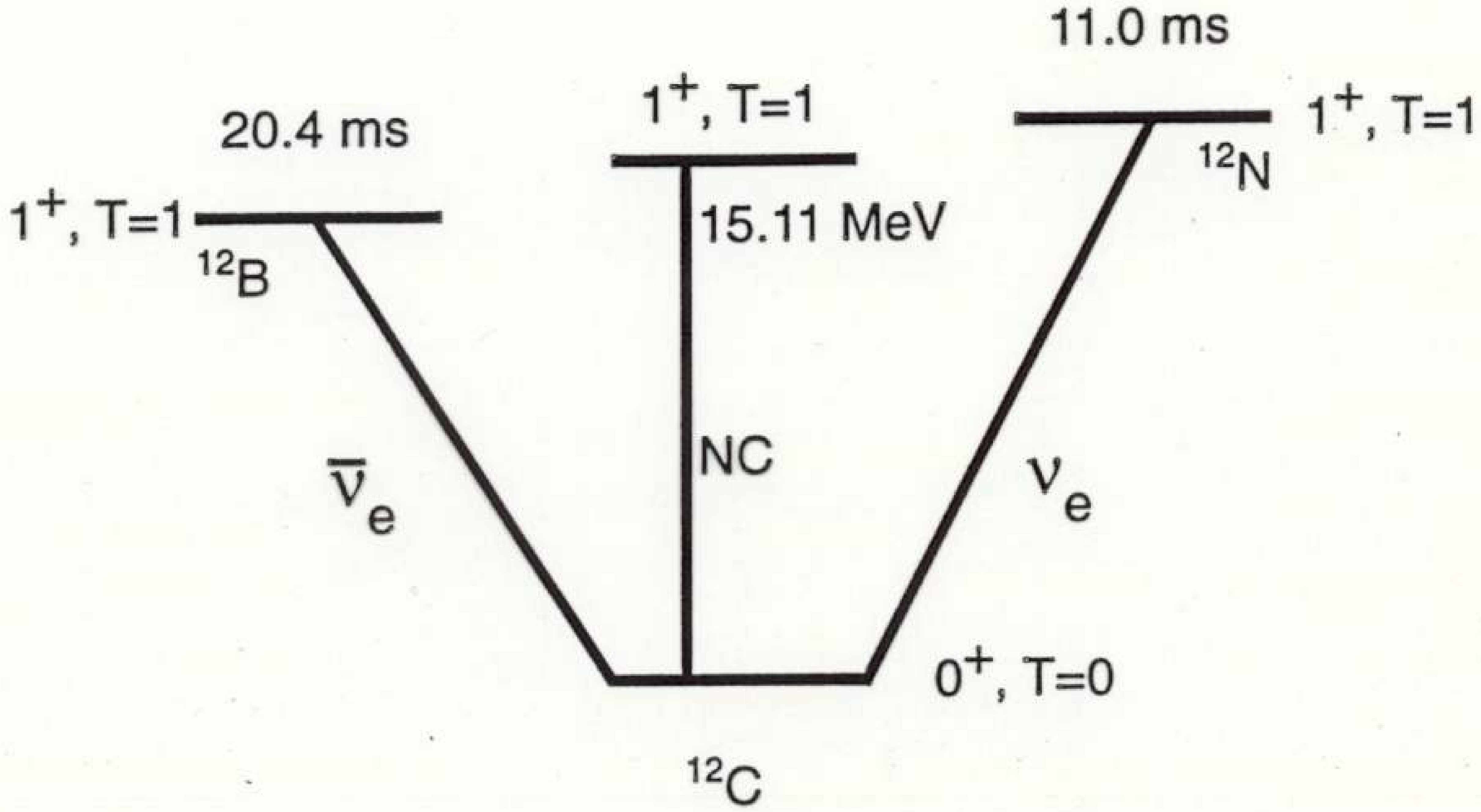
3) All neutrinos detected through the elastic scattering on protons,
$\nu + p \rightarrow \nu + p$ and $\bar{\nu} + p \rightarrow \bar{\nu} + p$,
dominated by ν_x and $\bar{\nu}_x$, with detection of the spectrum of recoil protons. This is ossible only in a liquid scintillator due to the very low threshold.

Event rates

1) $\bar{\nu}_e + p \rightarrow e^+ + n$: 330 events, (300 ev. $>$ 10 MeV)

2) ν^{12}C: $\sim$ 10 events (CC), $\sim$ 60 events (NC).
However, with oscillations $\sim$ 20 - 40 CC events.

3) $\nu_x(\bar{\nu}_x) + p \rightarrow \nu(\bar{\nu}_x) + p$:$\sim$300 events above 150 keV


20.4 ms
1+, T=1
12B
1+, T=1
15.11 MeV
NC
11.0 ms
1+, T=1
12N
ν̄e
νe
0+, T=0
12C

Neutrino elastic scattering on protons, a chance for scintillator based detectors

Neutrinos will scatter on protons according to (to order E_ν/M)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T_p} = \frac{G_F^2 M}{\pi}\left[(c_A^2 + c_V^2) - (c_A^2 - c_V^2)\frac{T_p M}{2E_\nu^2} - (c_V \mp c_A)^2\frac{T_p}{E_\nu} \pm 2c_M c_A \frac{T_p}{E_\nu}\right] ,$$

where $c_V = 1/2 - 2\sin^2\theta_W = 0.0375,\ c_A = 1.26/2,\ c_M \simeq -\mu_n/2.$

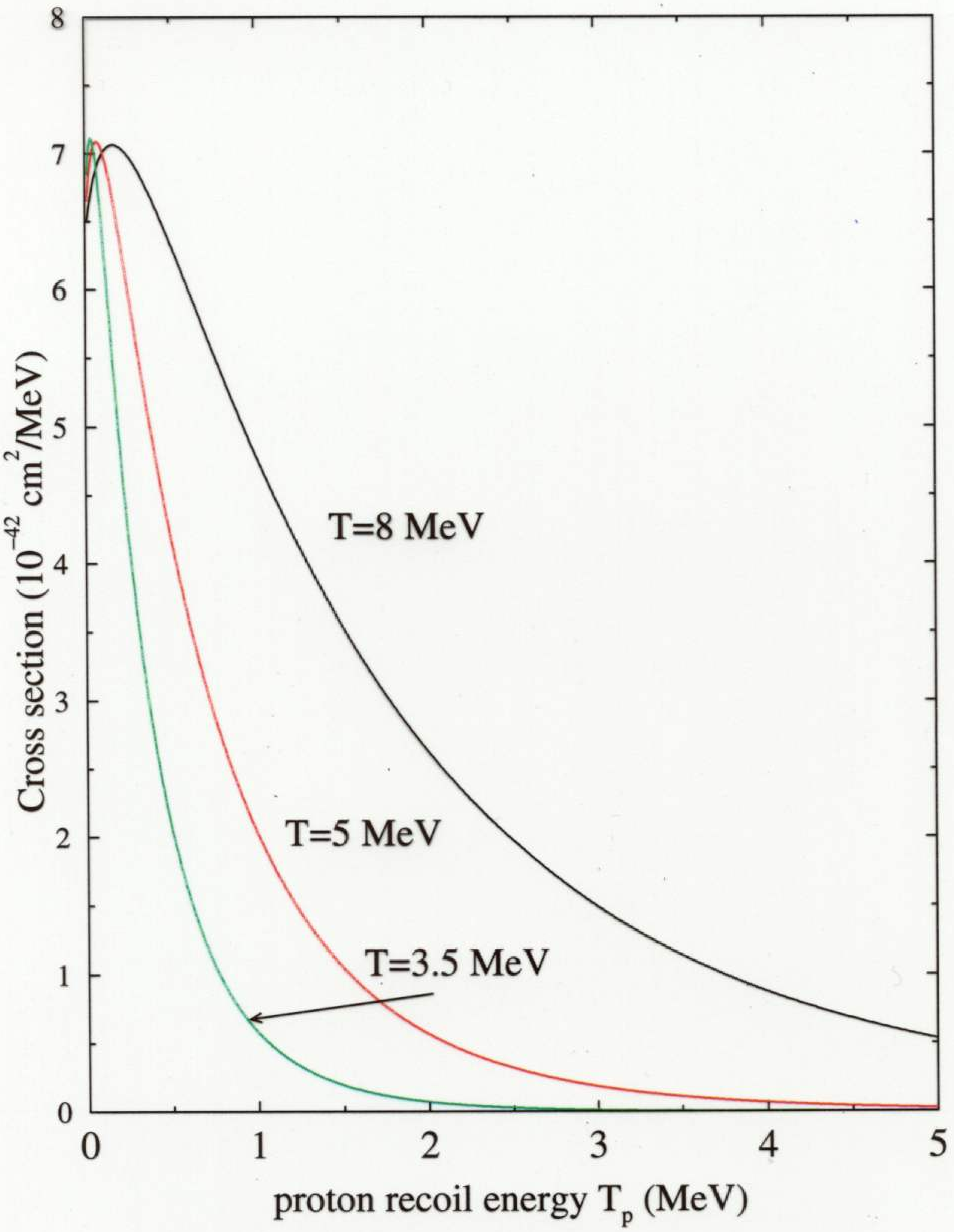
The proton recoil kinetic energy T_p is restricted from above by $\sim 2E_\nu^2/M$. Only the first two terms in the cross section formula are relevant for $E_\nu \ll M$.

The recoiling protons do not emit Čerenkov radiation, but they will scintillate. However, the scintillation light is quenched, compared to electrons or γ. Thus, the relevant energies are ≤ 1 MeV.

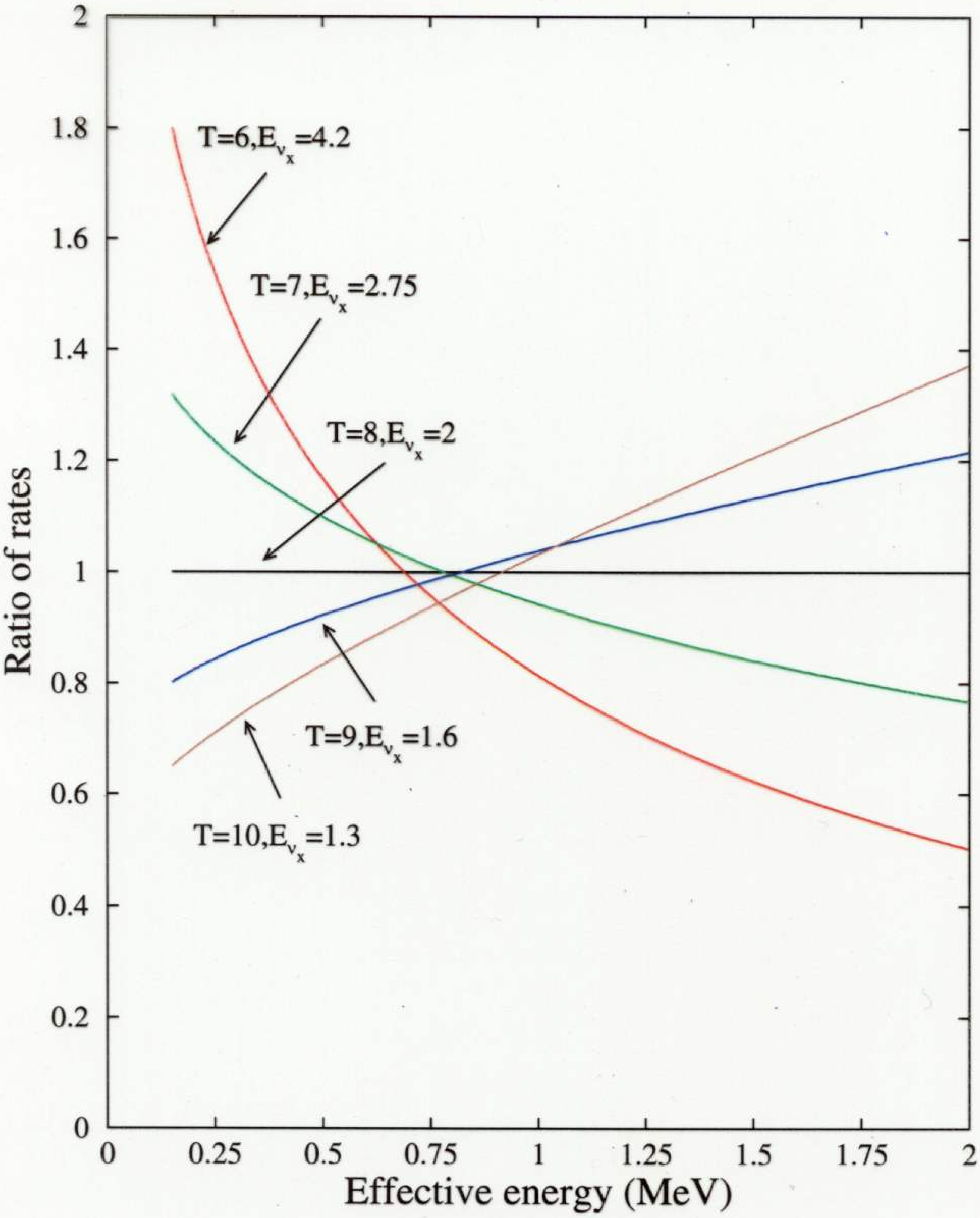
The total cross section is proportional to E_ν^2, so the signal will be dominated by ν_x, particularly above reasonable detection thresholds.

In a sensitive detector one might be able not only to count the number of events, but observe the proton recoil spectrum. In that case one will be able to determine <u>both</u> the ν_x temperature and luminosity.

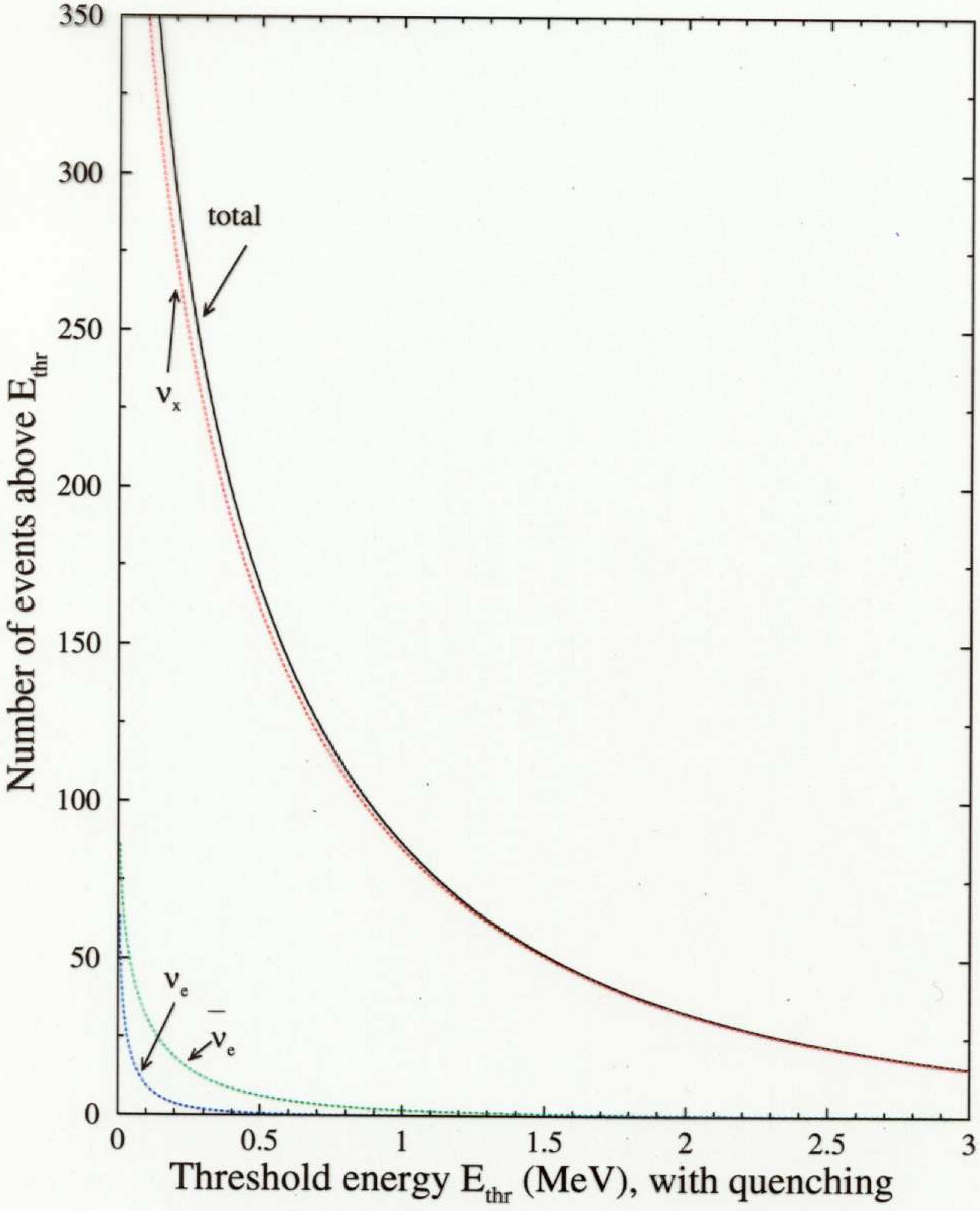
dσ/dT_p averaged over F–D spectrum

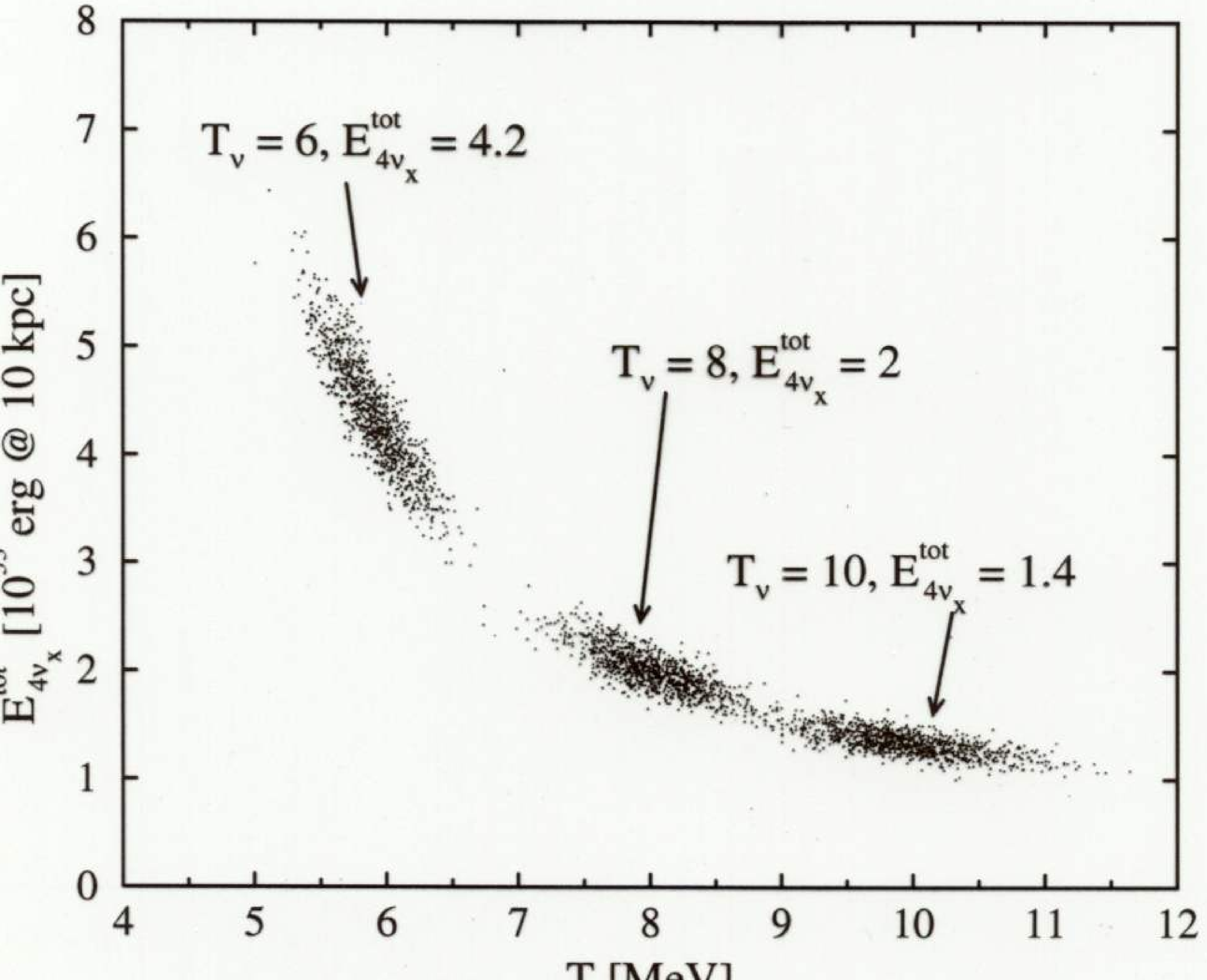


All these combinations of T and E_{ν_x} give ~260 events / 1 kton for E_{thr} = 200 keV



For ν_x, $T = 8$ MeV, $E_{\nu_x} = 2 \times 10^{53}$ erg





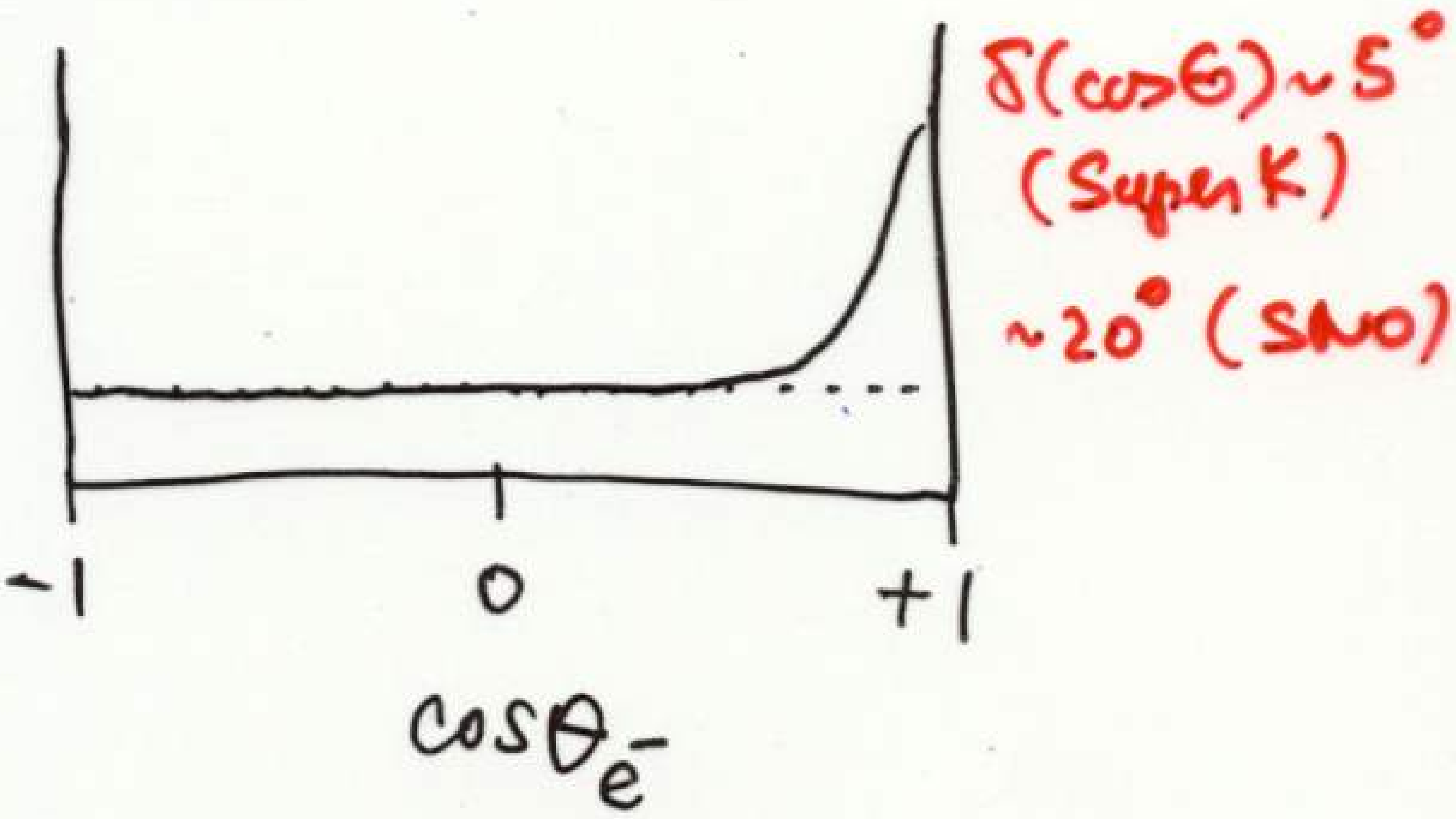
$T_\nu = 6, E^{tot}_{4\nu_x} = 4.2$
$T_\nu = 8, E^{tot}_{4\nu_x} = 2$
$T_\nu = 10, E^{tot}_{4\nu_x} = 1.4$
$E^{tot}_{4\nu_x}$ [10^{53} erg @ 10 kpc]
T [MeV]
0
1
2
3
4
5
6
7
8
4
5
6
7
8
9
10
11
12

J. Beacom and P. V.
astro-ph/9811350
Phys. Rev. D60, 033007

SN Neutrino-Location:

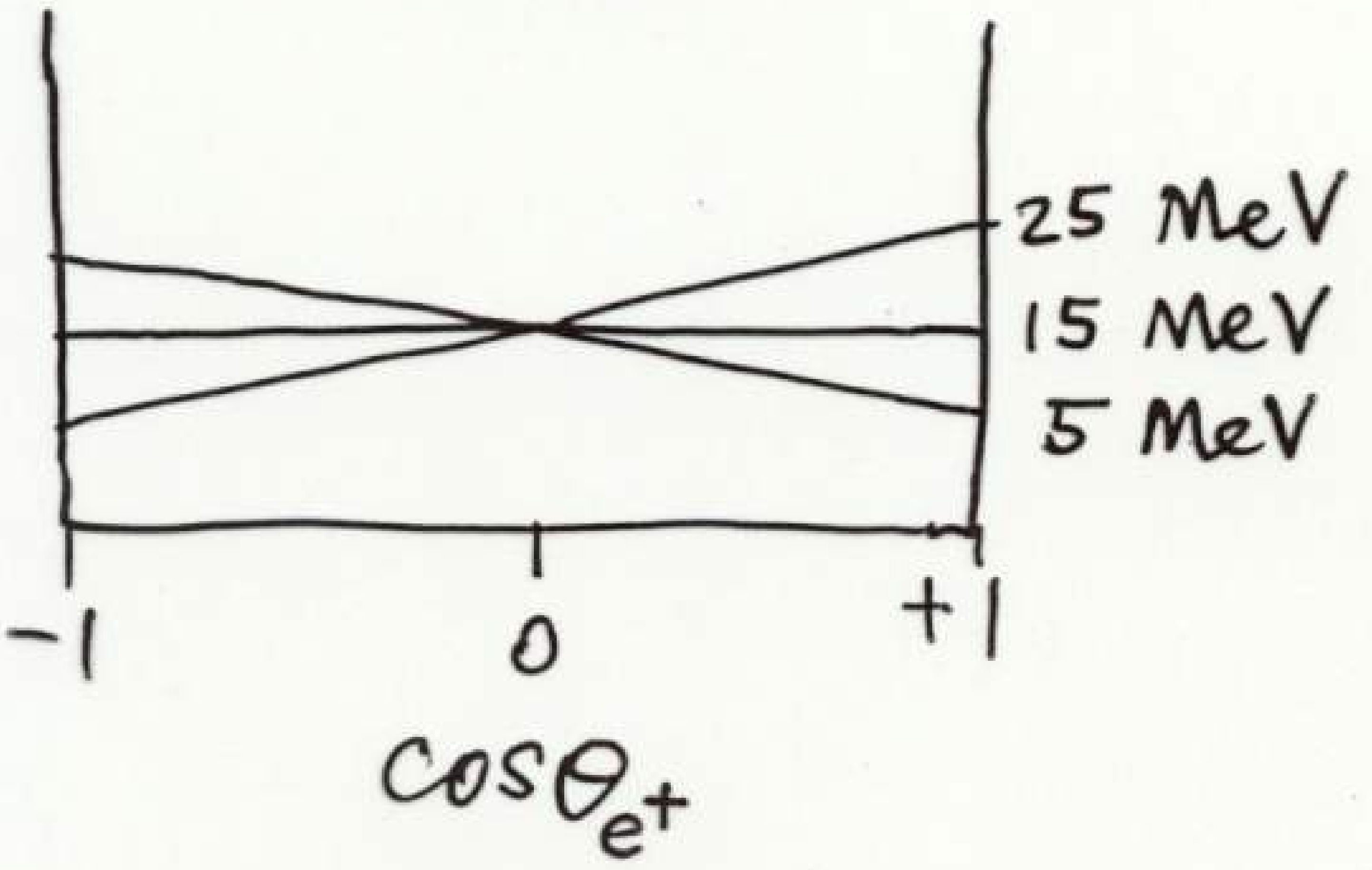
- $\nu + e^- \rightarrow \nu + e^-$

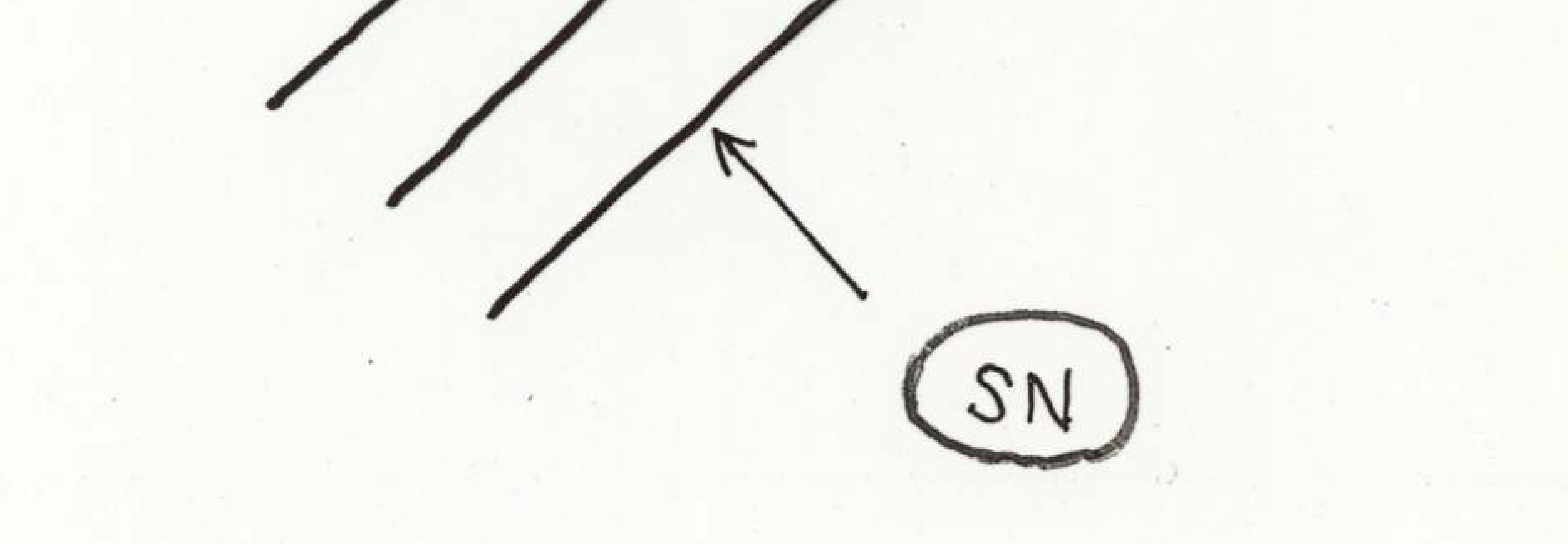
  $N \sim 300$



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

  $N \sim 10^4$



- 

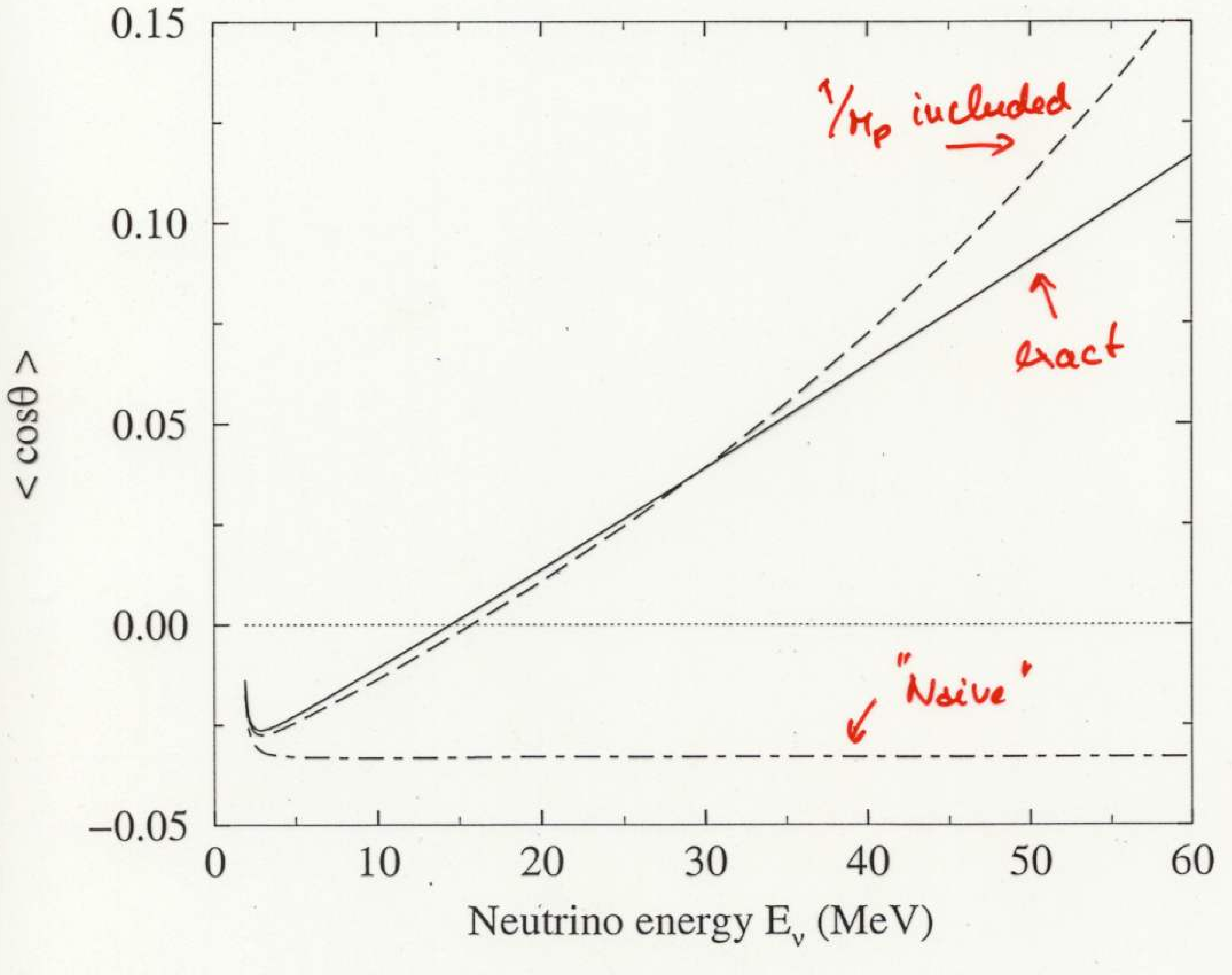
$\bar{\nu} + p \to n + e^+$, use positron angular distribution

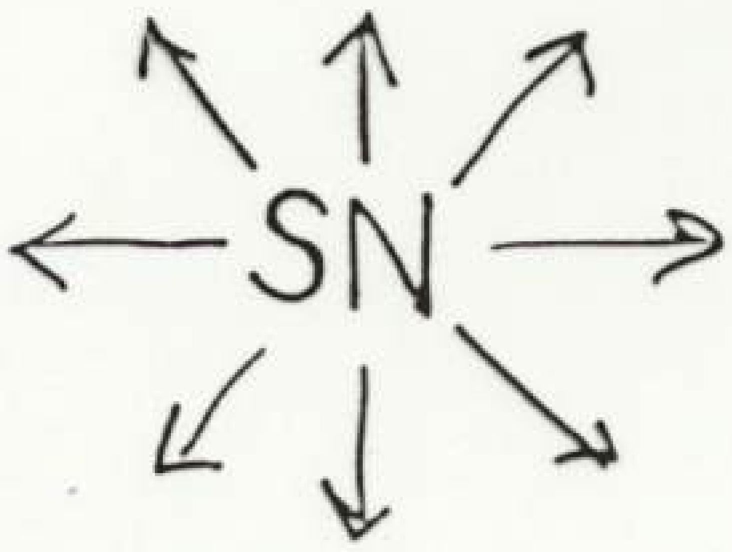
$$\frac{d\sigma}{d\Theta} \sim N\left(1 + a\cos\Theta \cdot \frac{v}{c}\right)$$

$$\langle \cos\Theta \rangle = \frac{v}{c}\,\frac{a}{3}$$

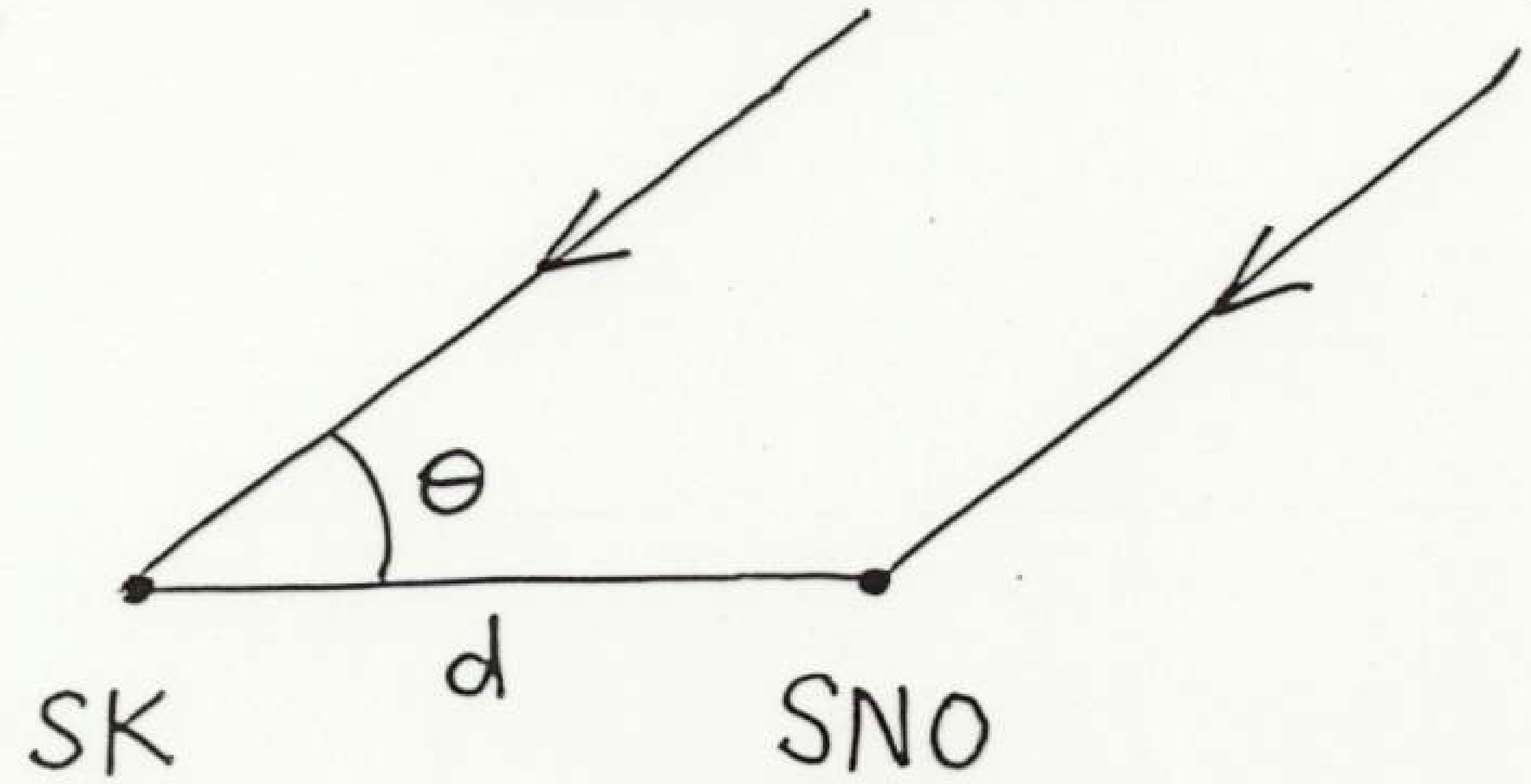
"Naive", i.e. $M_p \to \infty$ $\quad a = \frac{f^2 - g^2}{f^2 + 3g^2} \simeq -0.1 \quad \frac{g}{f} \approx 1.26$

Uncertainty $\delta(\cos\Theta)$ ~ 0.2 (SuperKamiokande) ~ 35°
~ 1.0 (SNO)
~ 0.5 using $\nu_e, \bar{\nu}_e + d$ in SNO





Triangulation

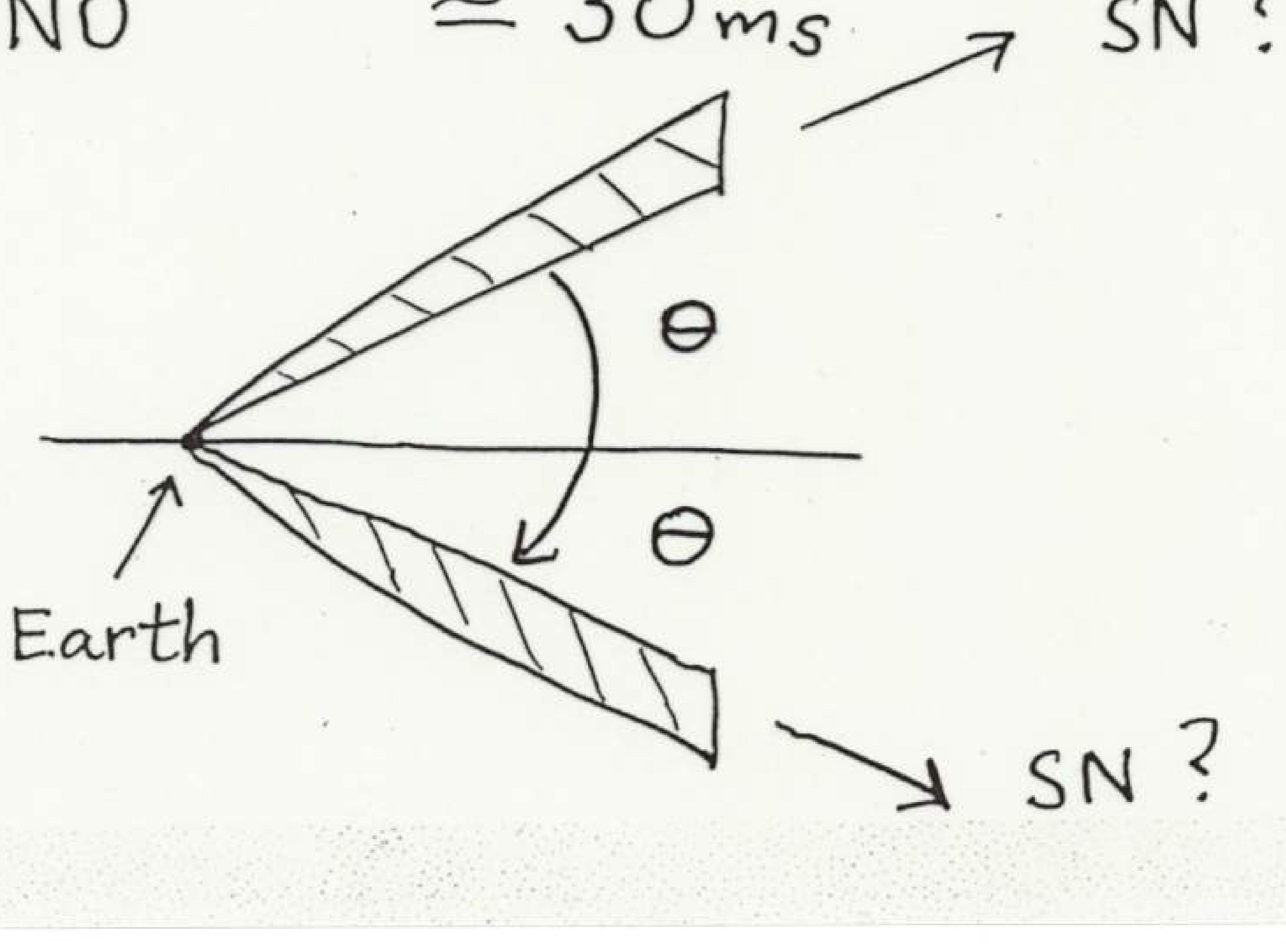


$$\cos\theta = \frac{\Delta t}{d}$$

$$\delta(\cos\theta) = \frac{\delta(\Delta t)}{d}$$

Earth diameter $\simeq$ 40 ms

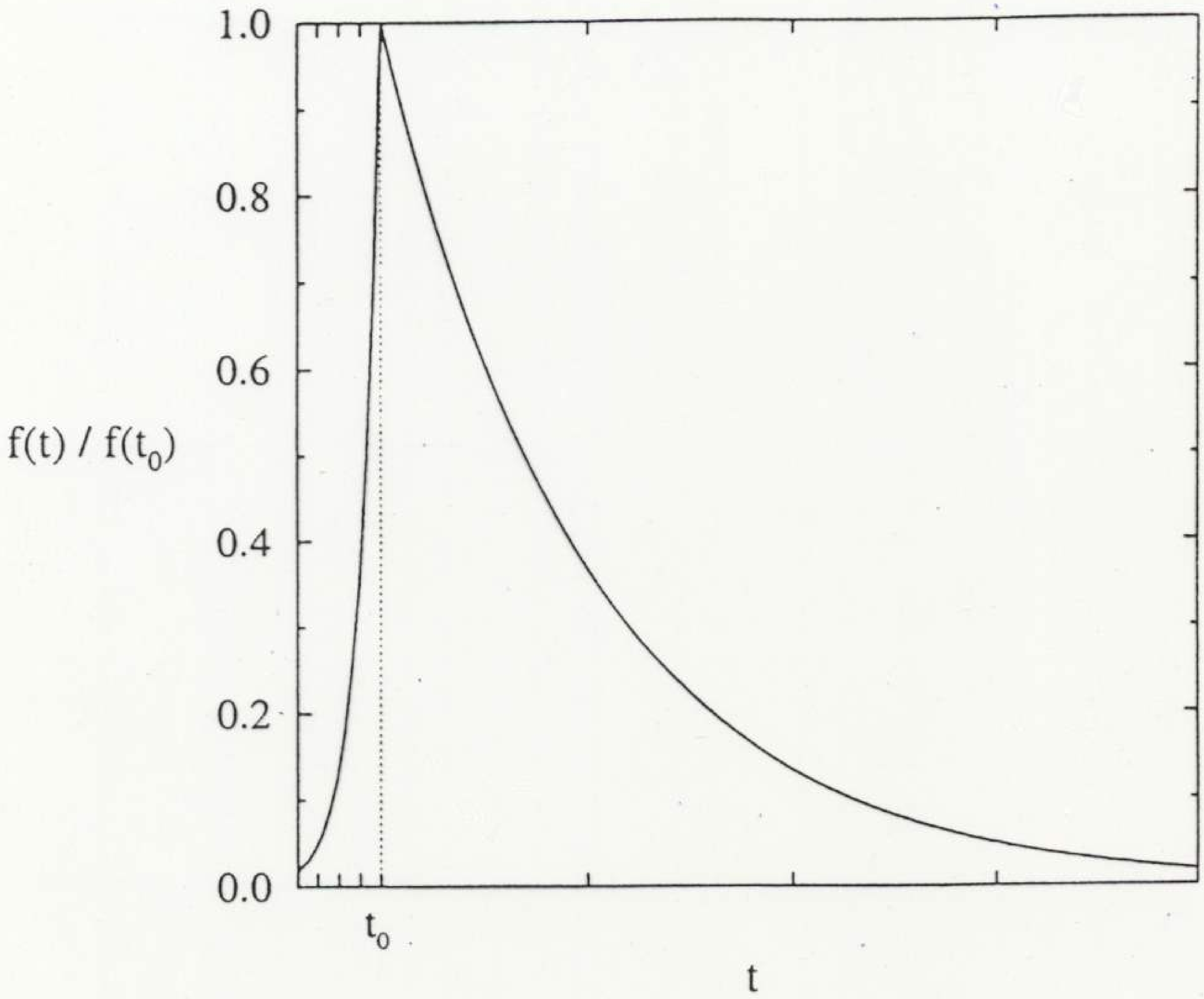
SK − SNO $\simeq$ 30 ms



Generic event rate:

sharp rise ... $\tau_1 \sim 30$ ms

slow decline $\tau_2 \sim 3$ s



if $\tau_1 \to 0$ (unrealistic sharp edge)

$\delta(t_0) = \frac{\tau_2}{N}$ ... about 8 ms for SNO

However - any tail will spoil it, since a bigger detector will see it sooner

When τ_1 (leading edge) $\neq 0$
the best strategy is to determine t_0

Then rigorously the best you can do

$$\frac{1}{(\delta t_0)^2_{min}} = \frac{N}{\tau_1 + \tau_2} \left(\frac{1}{\tau_1} + \frac{1}{\tau_2} \right)$$

and for $\tau_1 \ll \tau_2$

$$(\delta t_0)_{min} \simeq \sqrt{\frac{\tau_1 \tau_2}{N}} \approx \frac{\tau_1}{\sqrt{N_1}}$$

where N_1 is the number of counts in the leading part.

For SK $\quad N_1 \sim 100 \quad \delta t_0 \sim 3$ ms

for SNO $\quad N_1 \sim 4 \quad \delta t_0 \sim 15$ ms

CONCLUSIONS:

1) SN signal corresponding to ν_τ and ν_μ neutrinos can be isolated.

2) By determining the average arrival time $\langle t \rangle$, one will be able to determine (conservatively) $m_{\nu_\tau} \leq 30 - 50$ eV. This is an improvement by 10^6!!

3) Moreover, if ν_τ and ν_μ are maximally mixed with $\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 as the atmospheric neutrino study suggests, the limits for both flavors are improved to $\sim$ 20 - 35 eV.

4) By combining the signal of several detectors one will be able to determine the temperature of each neutrino flavor.

5) Provided that the νp elastic scattering is really observable in KamLAND, both the luminosity and temperature of ν_x can be determined, and hence the total energy emitted by SN in neutrinos.

6) $\nu + e$ scattering can be used for pointing with $\sim 5^o$ accuracy, while $\bar{\nu}_e + p$ can be used only very crudely for pointing.

7) Triangulation appears to be difficult if the SN signal is going to last more than $\sim$ 1 second.