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 localization

(pointing toward the SN independently to or prior to 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

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)

$$\nu + e \to \nu + e$$

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

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

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

$$\nu + d \to n + p + \nu$$

<u>Time delay of the ν_τ and ν_μ signal</u>

$$\Delta t\,(E_\nu) = 0.515\,(m\,/E_\nu)^2\,(D/10\text{ kpc})$$

(m in eV, E_ν in MeV, $\Delta t\,(E_\nu)$ in seconds)

Assume: SN frequency - every 30 years
distance D=10 kpc
binding energy 3×10^{53} ergs
duration of the signal ~ 10 s
equal luminosity in each ν flavor

neutrino temperatures:

$T(\nu_e) = 3.5$ MeV ($\langle E_\nu \rangle = 11$ MeV)

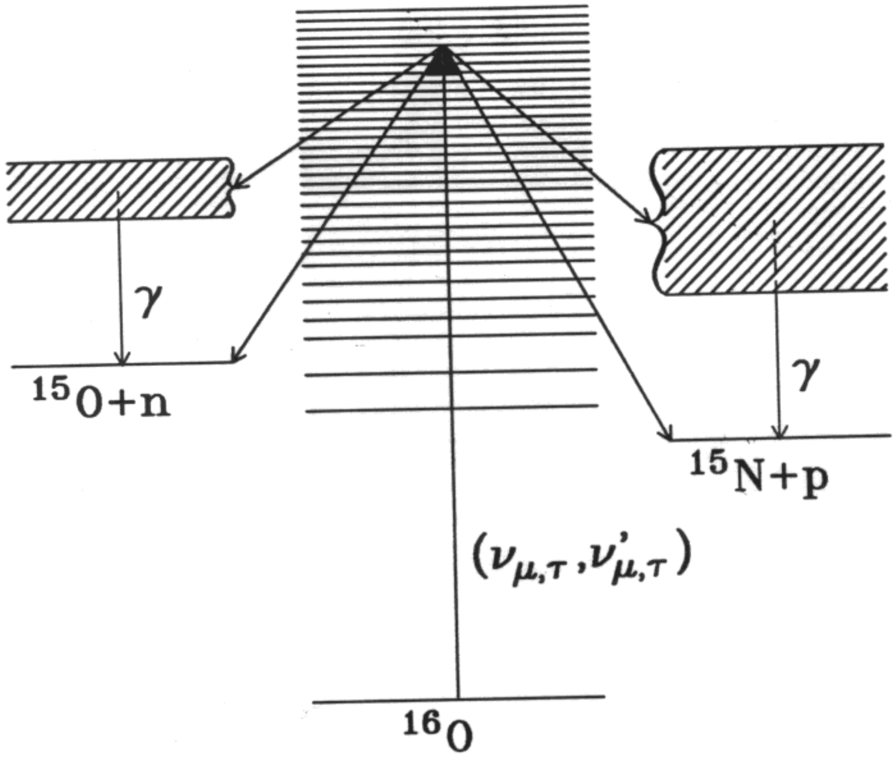
$T(\nu_e) = 5$ MeV ($\langle E_\nu \rangle = 16$ MeV)

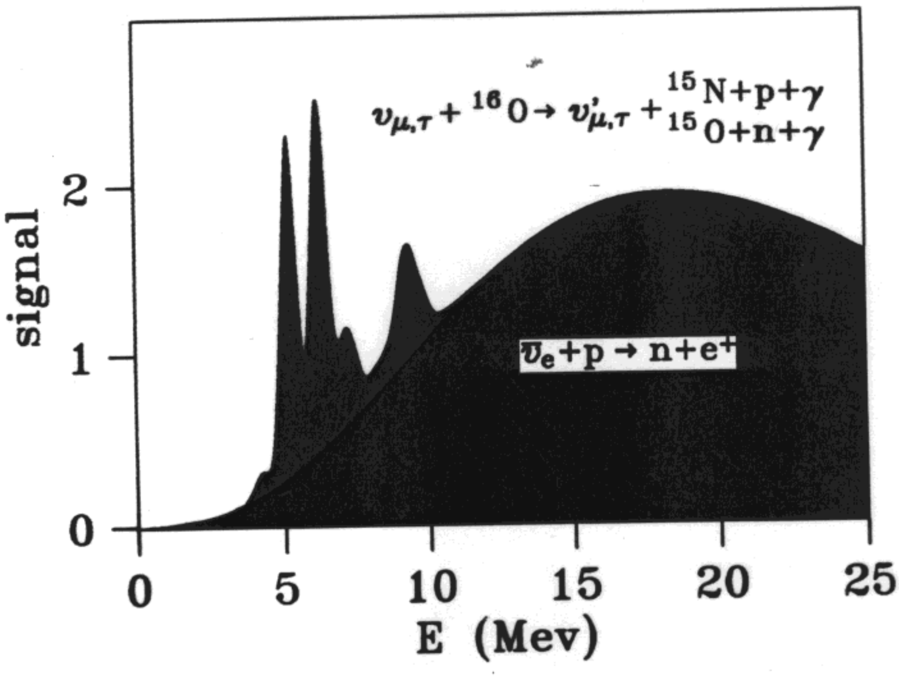
$T(\nu_\tau,\nu_\mu) = 8$ MeV ($\langle E_\nu \rangle = 25$ MeV)

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
$\bar{\nu}_e + p \to e^+ + n$	8300
$\bar{\nu}_e + p \to e^+ + n$ ($E_{e^+} \leqslant 10$ MeV)	530
$\nu_\mu + {}^{16}\mathrm{O} \to \nu_\mu + \gamma + X$ $\bar{\nu}_\mu + {}^{16}\mathrm{O} \to \bar{\nu}_\mu + \gamma + X$	355
$\nu_\tau + {}^{16}\mathrm{O} \to \nu_\tau + \gamma + X$ $\bar{\nu}_\tau + {}^{16}\mathrm{O} \to \bar{\nu}_\tau + \gamma + X$	355
$\nu_e + e^- \to \nu_e + e^-$ $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	200
$\nu_\mu + e^- \to \nu_\mu + e^-$ $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$	60
$\nu_\tau + e^- \to \nu_\tau + e^-$ $\bar{\nu}_\tau + e^- \to \bar{\nu}_\tau + e^-$	60

For ^{16}O excitations delayed signal / background = 355/885

ν, e scattering —— " —— 60/700

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Expected count rate in SNO

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

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

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

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 $L(\mathrm{t} - \Delta \mathrm{t}(E_\nu))$.

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:

$$dN/dt = C \int dE_\nu\, f(E_\nu)\, \sigma(E_\nu)\, L(t - \Delta t(E_\nu))$$

where $f(E_\nu)$ is the thermal neutrino spectrum,

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

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

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>

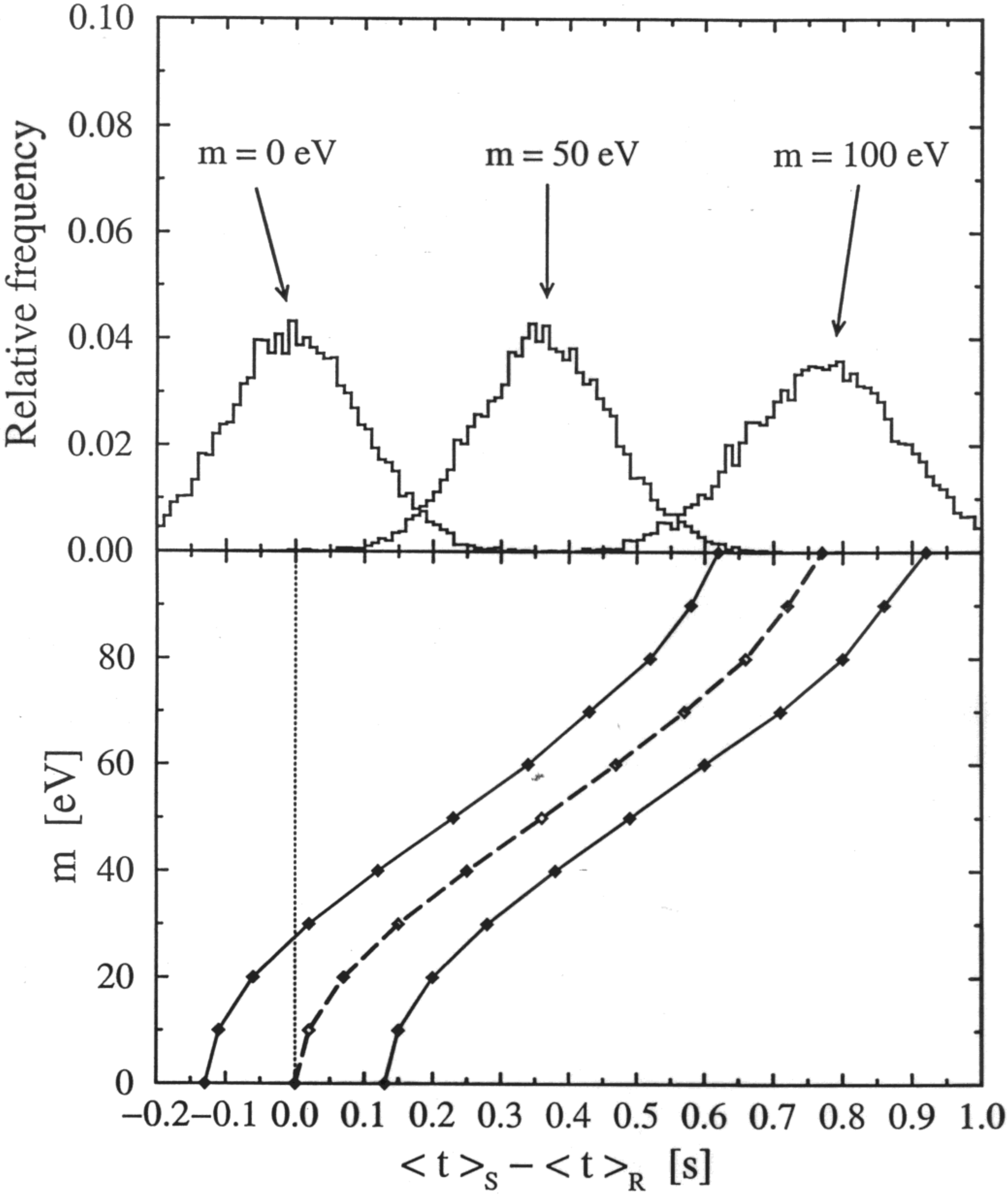
$\langle t \rangle_S = \Sigma_k t_k / N_S$ for the signal and

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

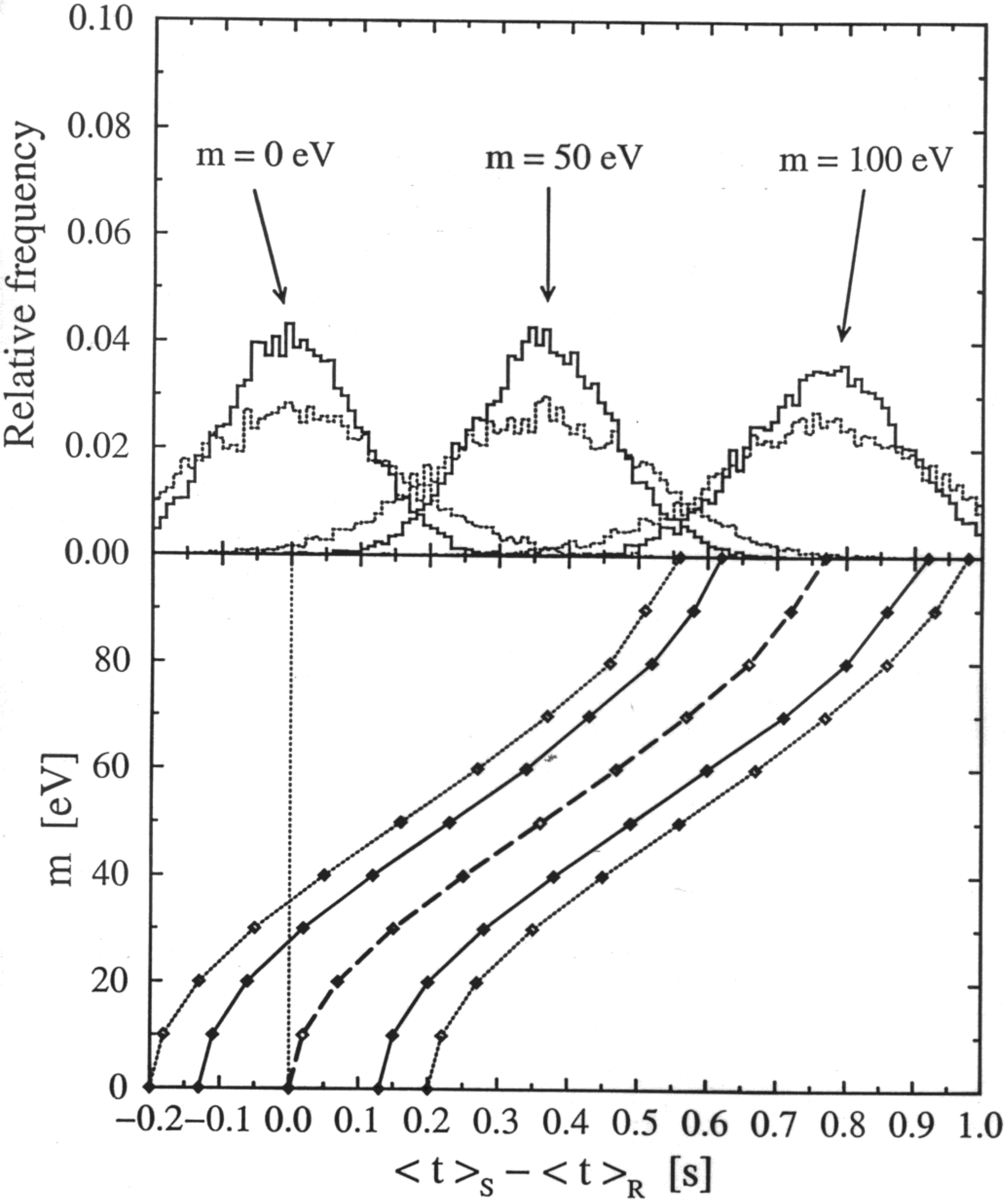
The signature of neutrino mass is thus

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

With significance beyond the statistical fluctuations.



Relative frequency
0.10
0.08
0.06
0.04
0.02
0.00
m = 0 eV
m = 50 eV
m = 100 eV
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]



Relative frequency
m = 0 eV
m = 50 eV
m = 100 eV
m [eV]
$< t >_S - < t >_R$ [s]

Analytic estimate of sensitivity to m_ν

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

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

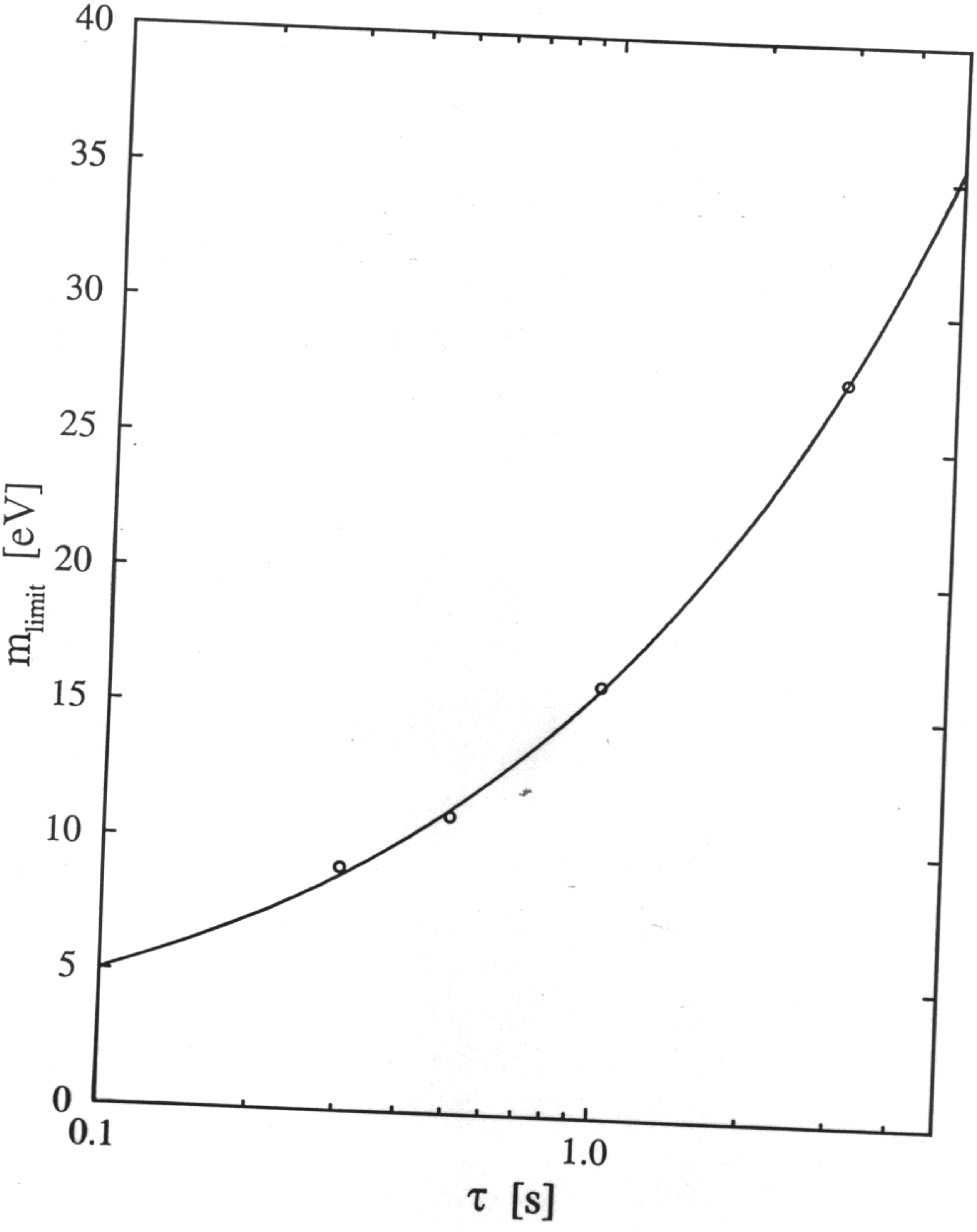
$\delta(\langle t \rangle_S - \langle t \rangle_R) \sim \tau/\sqrt{N_{signal}} \sim \tau D/\sqrt{T}$

Significance: $(\langle t \rangle_S - \langle t \rangle_R)/\,\delta(\langle t \rangle_S - \langle t \rangle_R)$

$m_{lim} \sim \sqrt{\tau} T^{3/4}$

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**.



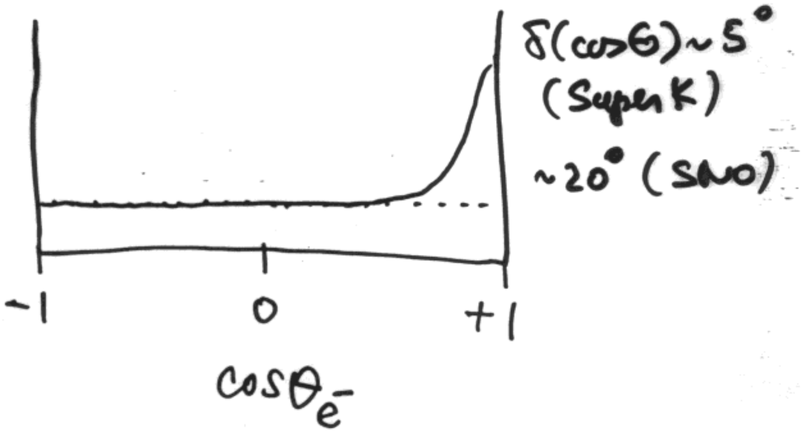
40
35
30
25
20
15
10
5
0
m_{limit} [eV]
0.1
1.0
τ [s]

J. Beacom and P. V.
astro-ph/9811350

SN Neutrino-Location :

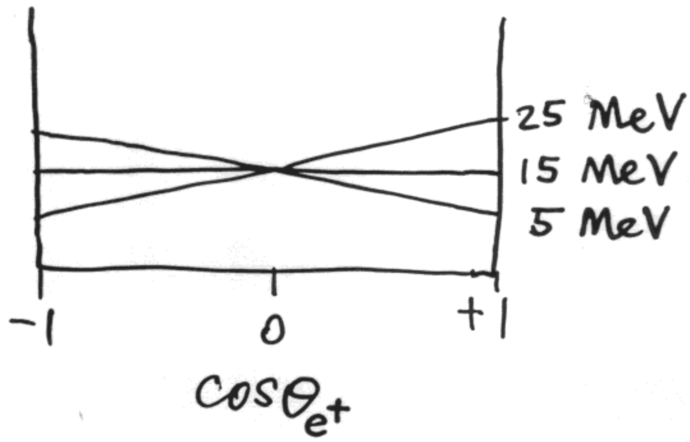
- $\boxed{\nu + e^- \rightarrow \nu + e^-}$

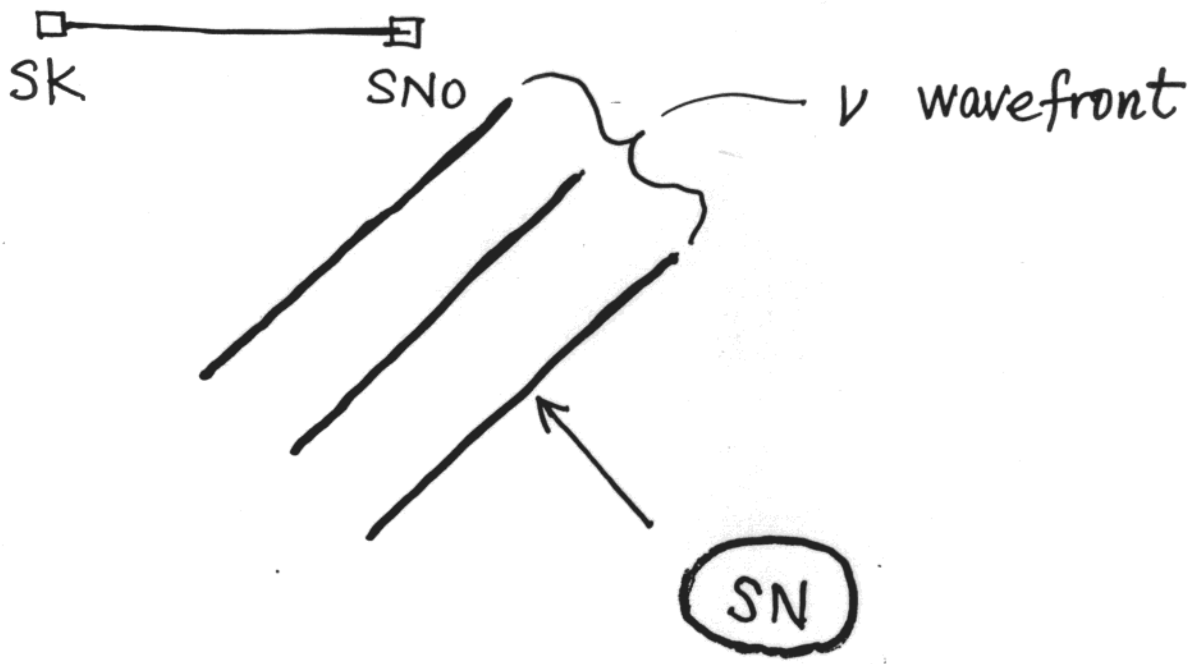
  $N \sim 300$



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

  $N \sim 10^4$



- 

Triangulation:

$$\cos\Theta = \frac{\Delta t}{d} \quad \begin{array}{l} \leftarrow \text{measured delay} \\ \leftarrow \text{distance} \end{array}$$

(Earth diameter $d = 40\,\text{ms}$)

error: $\delta(\cos\Theta) = \dfrac{\delta(\Delta t)}{d}$

Problem in statistics:

Is $\delta(\Delta t) \sim \dfrac{\tau}{N}$ or $\dfrac{\tau}{\sqrt{N}}$???

where τ is the signal duration

N number of events

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

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

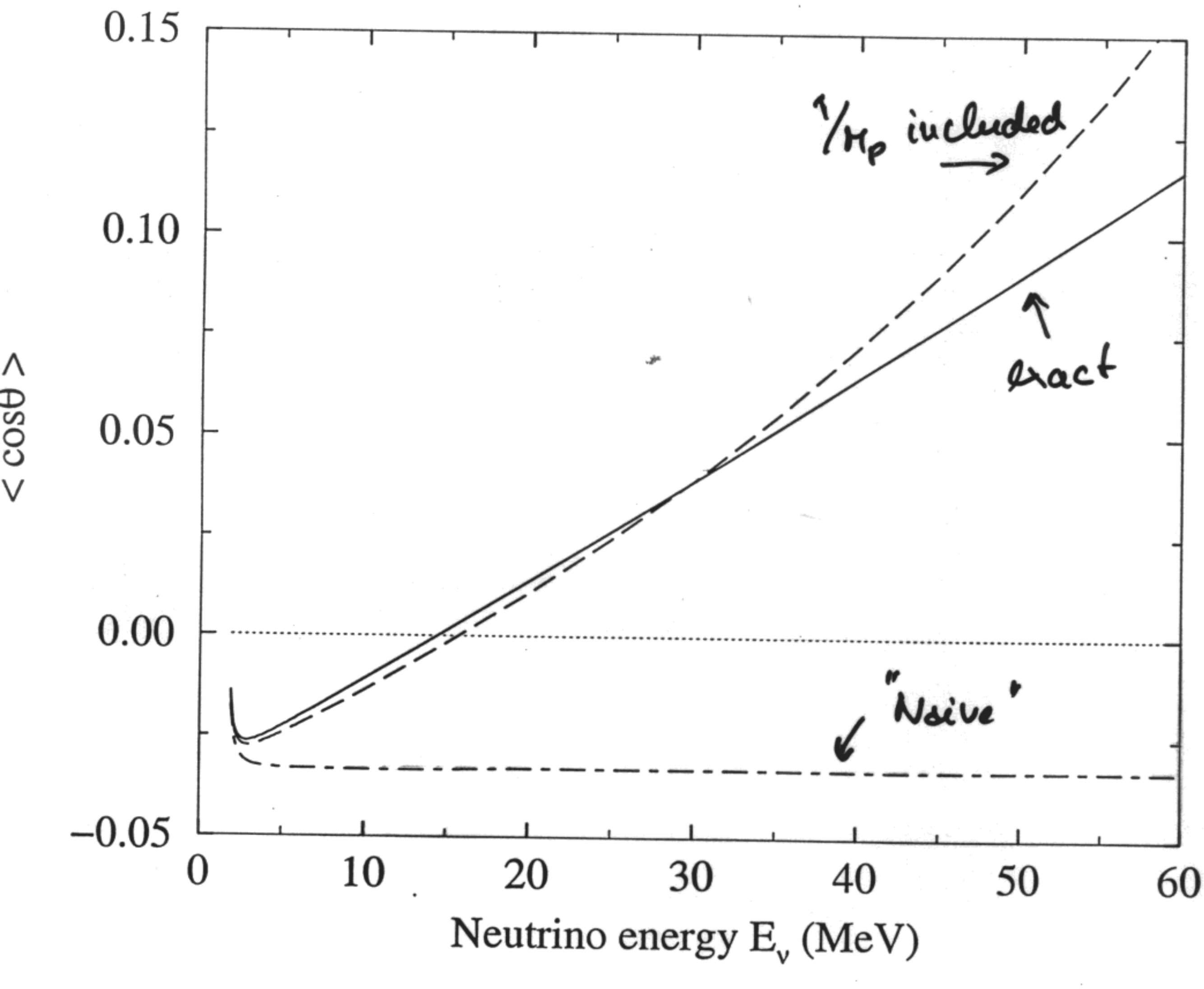
$$\langle \cos\Theta \rangle = \frac{v}{c}\,\frac{a}{3}$$

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

Uncertainty $\delta(\cos\Theta) \sim 0.2$ (SuperKamiokande) $\sim 35°$

~ 1.0 (SNO)

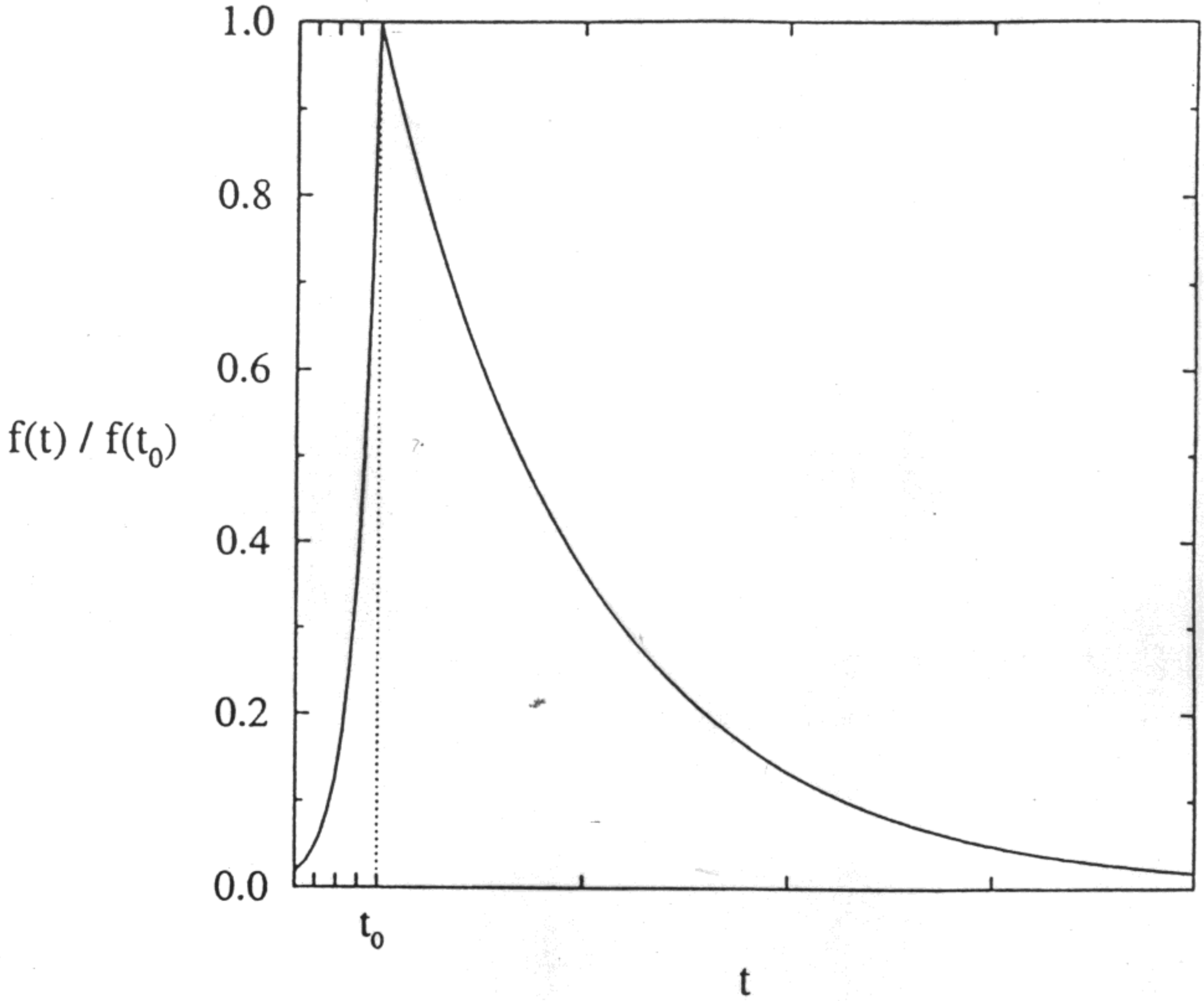
~ 0.5 using $\nu_e, \bar{\nu}_e + d$ in SNO



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 $\tau_1 << \tau_2$

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

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) $\nu_\tau + \nu_\mu$ SN signal can be isolated

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

3) $\nu + e$ scattering can be used for pointing with accuracy $\sim 5°$

4) $\bar{\nu}_e + p \to n + e^+$ can be used only very crudely for pointing

5) Triangulation appears to be difficult if the SN signal is going to last more than ~ 1 second