Supernova Location by Neutrinos

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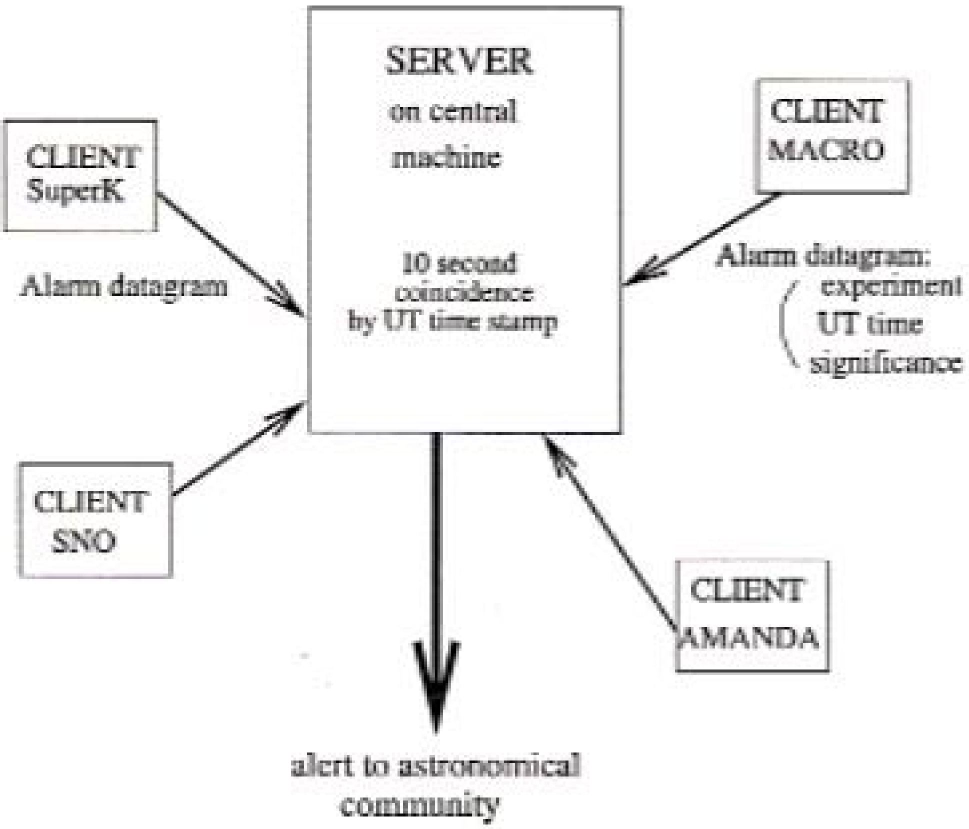
Outline:

- Introduction
    - SN early alert network
    - expected neutrino signals
- $\nu + e^-$ scattering
- ν + nucleus scattering
    - $\bar{\nu}_e p \rightarrow e^+ n$, e^+ distribution
    - $\bar{\nu}_e p \rightarrow e^+ n$, n distribution
    - $\nu_e d \rightarrow e^- pp$, $\bar{\nu}_e d \rightarrow e^+ nn$, $e^\pm$ distributions
- Triangulation
- Conclusions

Implementation of an international coincidence

Use the Internet!

Client/server code using UDP protocol; datagrams sent via socket.



Portable, tested on many platforms.

Could upgrade to dedicated phone line(s), but may not be necessary. Multiple servers possible.

	Investigator	Institution	Country
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CoI:	Dr. Leif Robinson	*Sky & Telescope* Magazine, Sky Publishing	US
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CoI:	Dr. Mark Vagins	University of California, Irvine	US

Total number of investigators: 15

Observing Summary:

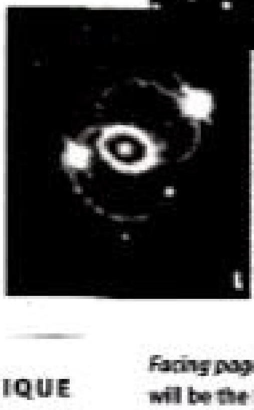
Target	RA	DEC	V	Configuration,mode,aperture spectral elements	Total orbits	Flags
SN1999XX			−6 to 15	STIS/CCD ACCUM 52X0.1 G230LB	4	TOO
SN1999XX			−6 to 15	STIS/FUV ACCUM SLITLESS/ND3 G140L	4	TOO
SN1999XX			−6 to 15	WFPC2 IMAGE F255W,F450W,F606W,F814W	4	TOO
SN1999XX			−6 to 15	WFPC2 IMAGE F469N,F588N,F656N,F658N,F673N	4	TOO
				Grand total orbit request	16	

SUPERNOVAE, NEUTRINOS, AND AMATEUR ASTRONOMERS

> *They give birth astride a grave, the light gleams an instant, then it's night once more.*
>
> — Samuel Beckett, *Waiting for Godot*

HE LAST PERSON TO SEE AND CHRONICLE A SUPERNOVA outburst in our galaxy was Johannes Kepler. That was in 1604, when the star now named after him rivaled Venus in brightness. By some measures we're overdue for another brilliant supernova, yet the next star to explode in our galaxy is more likely to be a visual pipsqueak compared to Kepler's Star. Yet even a dim supernova is unlikely to be overlooked; its birth will be trumpeted by physicists' subterranean particle detectors rather than by astronomers' telescopes.

Supernovae are stars that brighten by a dozen magnitudes or so and at their peak are some 10,000 times more luminous than ordinary novae. (The physical processes operating during these two explosions are completely different: supernovae blow themselves to smithereens; ordinary novae don't.) The enormous luminosity of supernovae at their brightest makes it possible to readily spot them in distant galaxies — for weeks they can match the light output from all the other stars in a hefty system like our own Milky Way. Indeed, the identification of supernovae as a unique phenomenon had to wait until the 1920s, when galaxies themselves were recognized as independent star systems.



Above: The supernova that was spotted in the Large Magellanic Cloud in 1987 reached 3rd magnitude and was the brightest to grace our skies in 383 years.

Left: What's seen today are the faded star and two surrounding rings of gas that it has lit up. This three-color Hubble Space Telescope composite is from several images taken in 1994, 1996, and 1997.

AMATEUR ASTRONOMERS HAVE A UNIQUE OPPORTUNITY TO FIND THE NEXT NEARBY SUPERNOVA. ▸ BY LEIF J. ROBINSON

Facing page: Neutrino observatories like this one at Sudbury, Ontario, will be the first to know when a Type II supernova explodes in our galaxy or a nearby neighbor. Incoming neutrinos interact with deuterium atoms and produce flashes of light that are recorded by photomultiplier tubes. Some 10,000 of these line this 18-meter-diameter sphere.

Sky & Telescope, Aug. '99

Supernova Neutrinos:

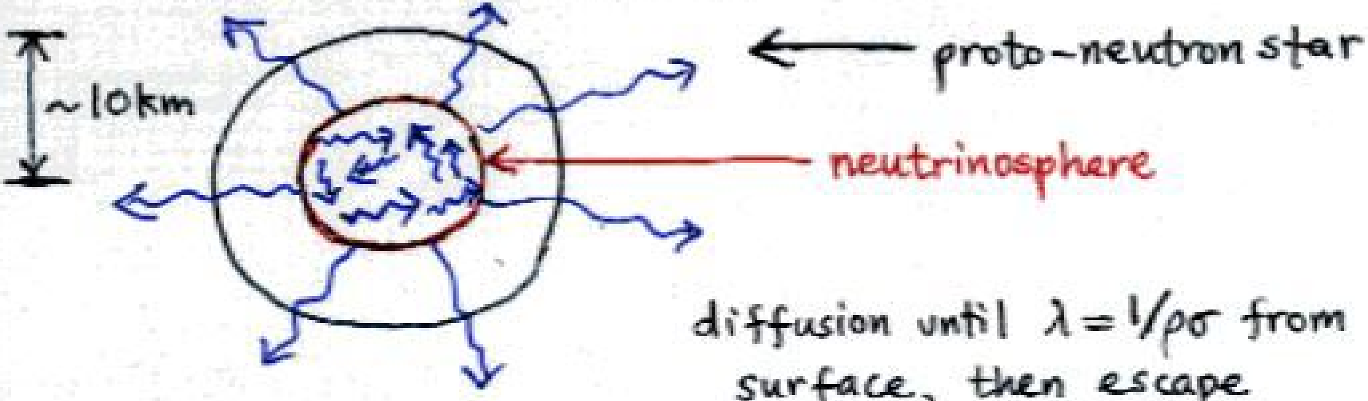
- type-II SN: core collapse of an $M > 8 M_\odot$ star

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

- "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 ~ 10s:



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

$$T_{\nu_e} \simeq 3.5 \text{ MeV} \qquad T_{\bar{\nu}_e} \simeq 5 \text{ MeV} \qquad T_{\nu_x} \simeq 8 \text{ MeV}$$

$$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t) \simeq L_0 e^{-t/\tau}$$

$$\tau \simeq 3 s$$

TABLE I. Calculated numbers of events expected in SK with a 5 MeV threshold and 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 second row is a subset of the first row that is an irreducible background to the reactions in the third and fourth rows.

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

[redacted]

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 $n+{}^{15}O$ or $p+{}^{15}N$.

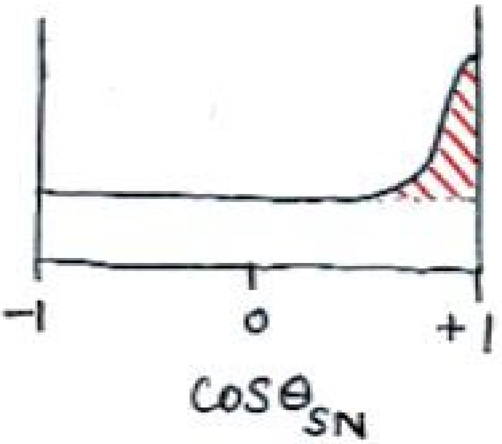
Events in 1 kton D_2O		
$\nu + d \rightarrow \nu + p + n$ $\bar{\nu} + d \rightarrow \bar{\nu} + p + n$	detected particle(s) : n	485
$\nu_e + d \rightarrow e^- + p + p$ $\bar{\nu}_e + d \rightarrow e^+ + n + n$	e^-, e^+nn	160
$\nu +^{16} O \rightarrow \nu + \gamma + X$ $\bar{\nu} +^{16} O \rightarrow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

- detected particles
- NC : dominated by ν_μ, ν_τ

  CC : ν_e, $\bar{\nu}_e$ only

SN ν-Location

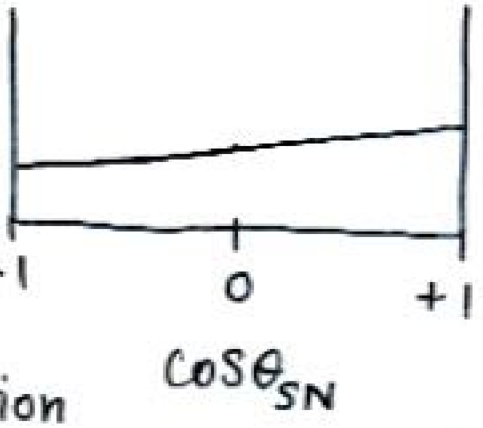
- $\boxed{\nu + e^- \rightarrow \nu + e^-}$



N $\simeq$ 300 forward

but large background

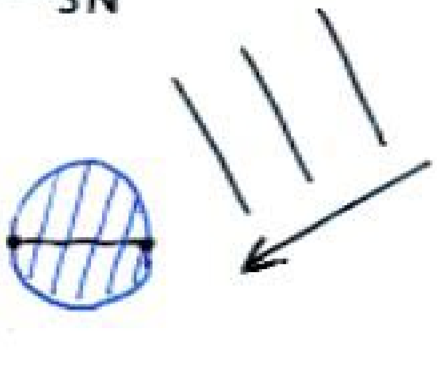
- $\boxed{\bar{\nu}_e + p \longrightarrow e^+ + n}$



$N \simeq 10^4$

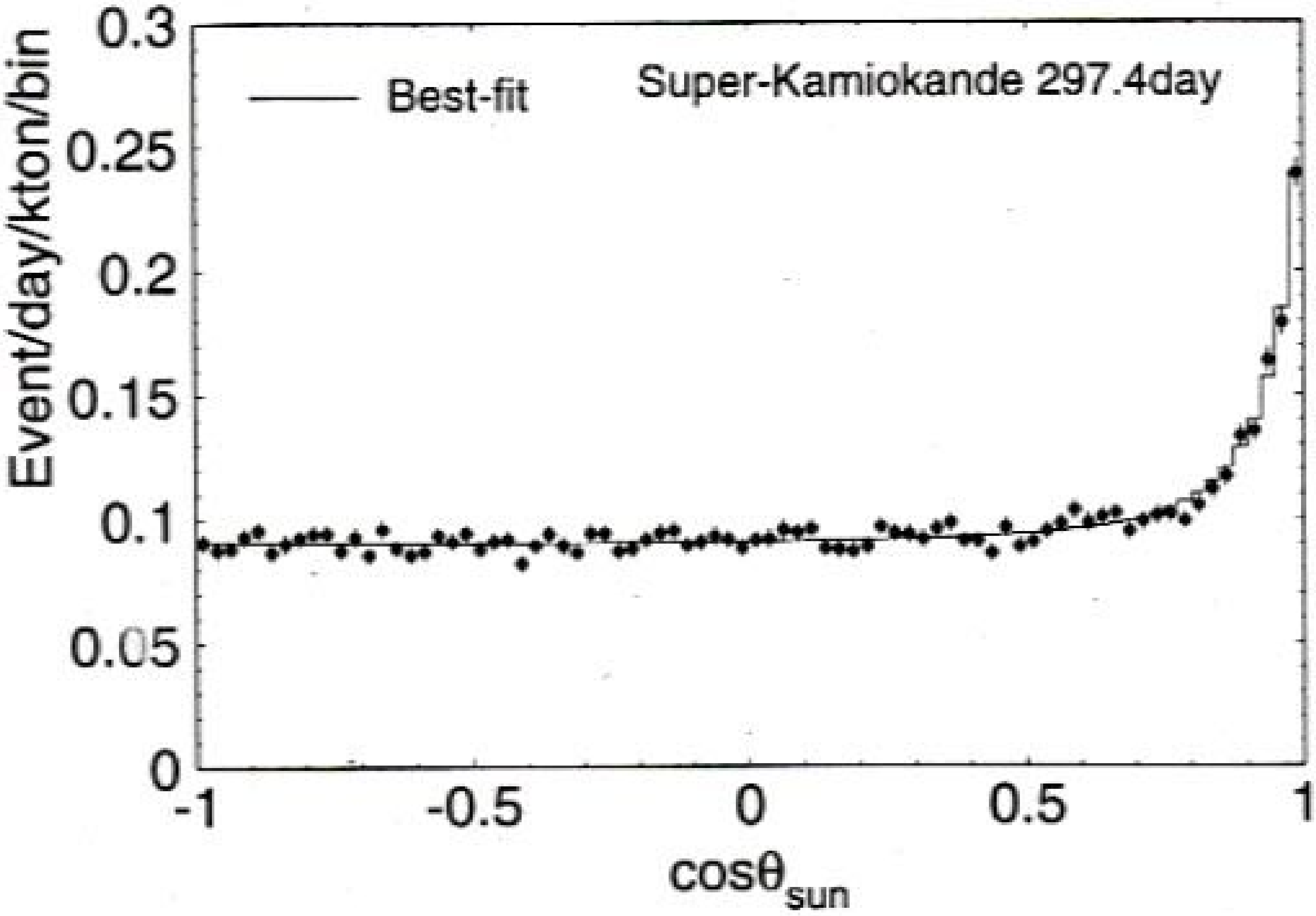
but weak angular distribution

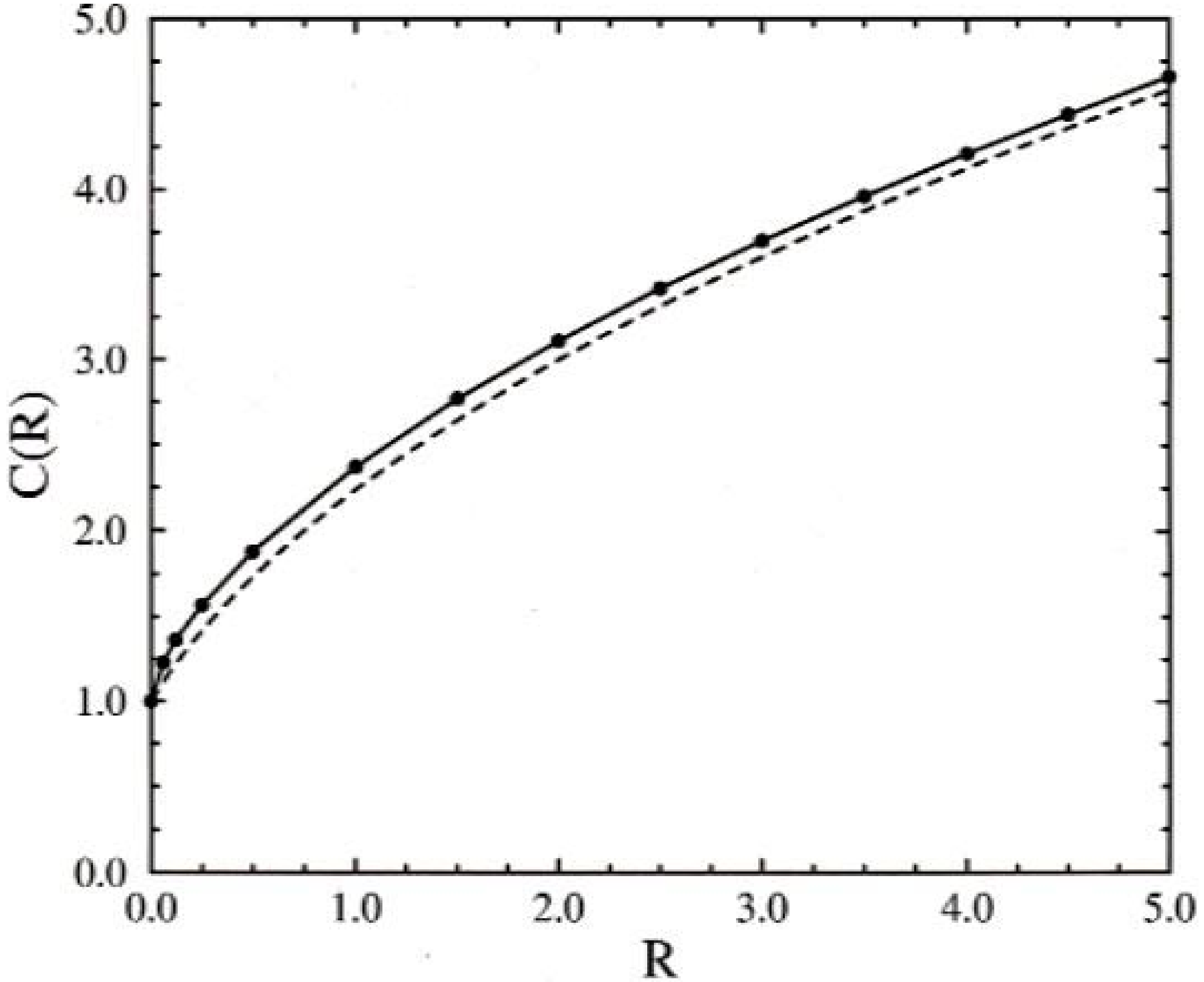
- $\boxed{\text{arrival time triangulation}}$



separate detectors in network

but pulse duration >> Earth diameter


Best-fit
Super-Kamiokande 297.4day
Event/day/kton/bin
0.3
0.25
0.2
0.15
0.1
0.05
0
-1
-0.5
0
0.5
1
$\cos\theta_{sun}$



$$\delta\theta \simeq \frac{25^\circ}{\sqrt{N_S}} \cdot C(R)$$

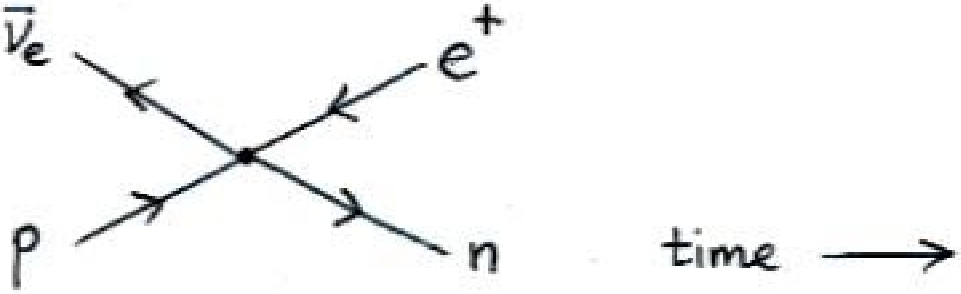
$$R = \frac{(25^\circ)^2}{2} \frac{N_B}{N_S} = \frac{\text{background}}{\text{signal (at peak)}}$$

$$\boxed{C(R) \simeq \sqrt{1+4R}}$$

SK ≃ 5°

SNO ≃ 20°

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

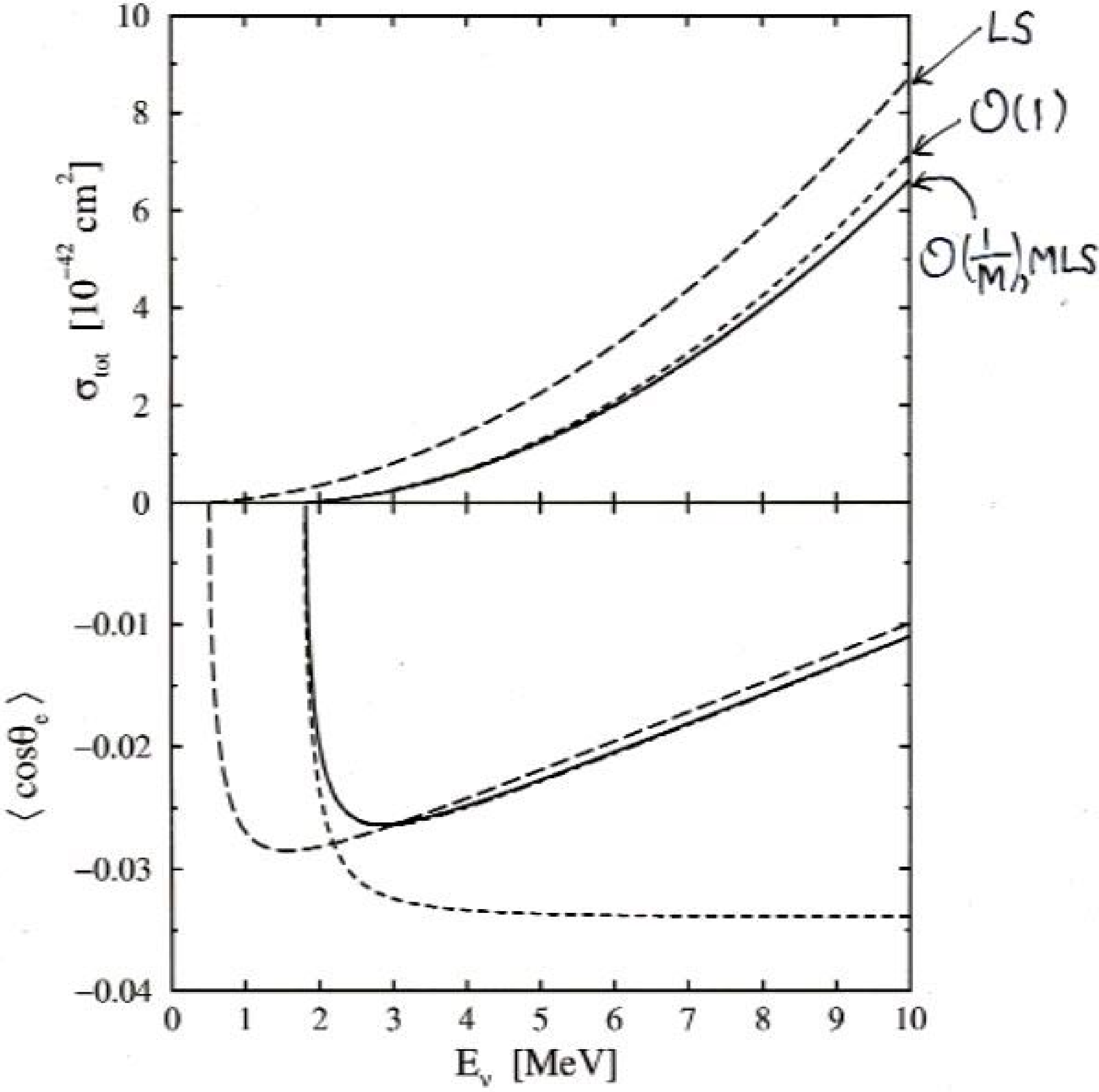


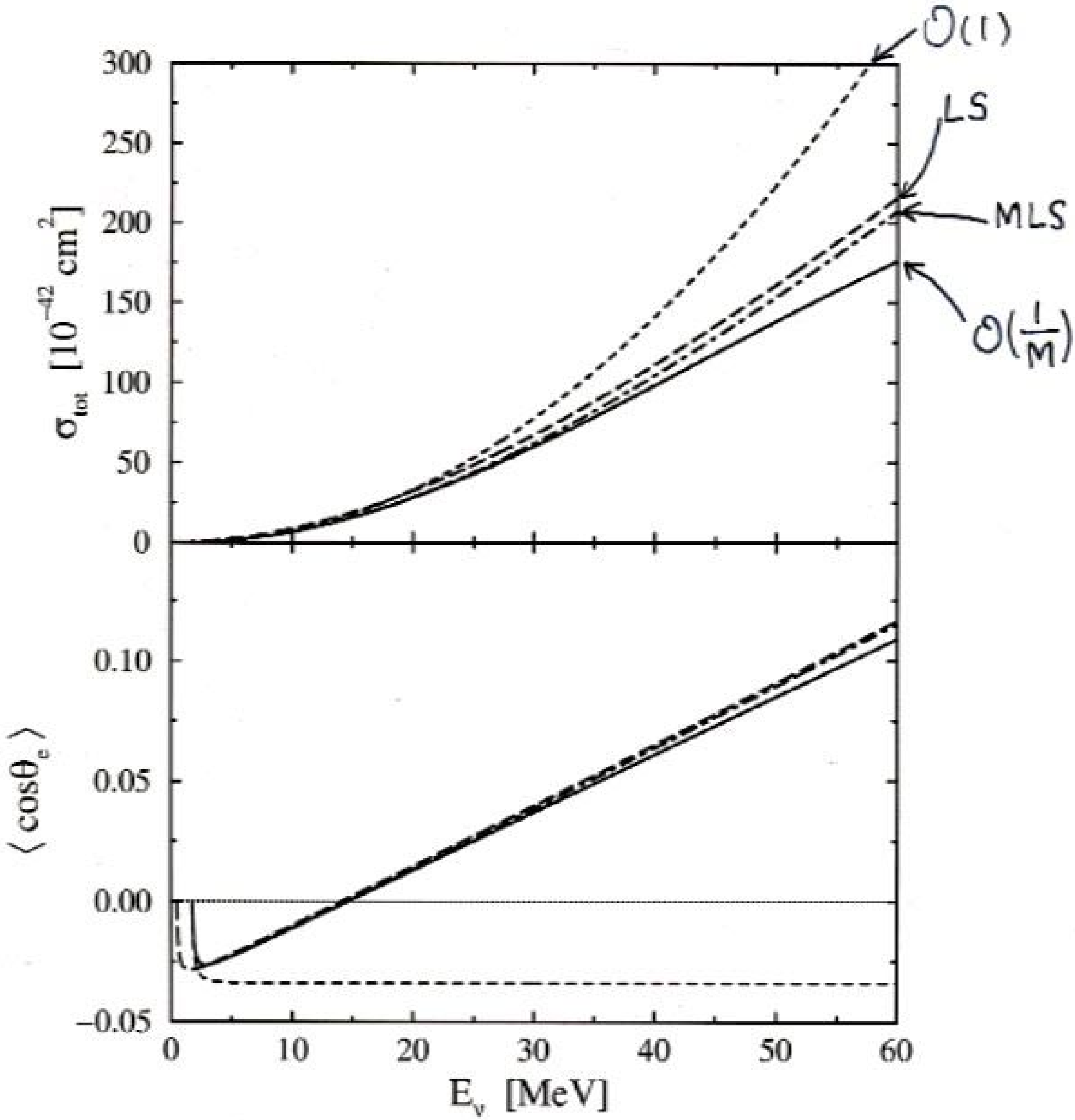
$$\mathcal{M} = \frac{G_F \cos\theta_c}{\sqrt{2}} \left[\bar{v}_\nu \gamma^\mu (1-\gamma_5) v_e \right]$$

$$\cdot \left[\bar{u}_n \left(f\gamma_\mu - g\gamma_\mu\gamma_5 - \frac{f_2}{2M} i\sigma_{\mu\nu} q^\nu \right) u_p \right]$$

$$\frac{d\sigma}{d\cos\theta} \sim (1 + a\cos\theta) \qquad \langle\cos\theta\rangle = \frac{a}{3}$$

$$\boxed{\langle\cos\theta\rangle \simeq \underbrace{\frac{1}{3}\left(\frac{f^2-g^2}{f^2+3g^2}\right)}_{\text{naive}} + \underbrace{\frac{E_\nu}{M}}_{\text{recoil}} + \underbrace{\frac{4}{3}\left(\frac{(f+f_2)g}{f^2+3g^2}\right)\frac{E_\nu}{M}}_{\text{weak magnetism}}}$$


LS
$\mathcal{O}(1)$
$\mathcal{O}(\frac{1}{M})$ MLS
σ_{tot} [10^{-42} cm^2]
$\langle \cos\theta_e \rangle$
E_ν [MeV]
0
2
4
6
8
10
−0.01
−0.02
−0.03
−0.04
0
1
2
3
4
5
6
7
8
9
10



$\mathcal{O}(1)$
LS
MLS
$\mathcal{O}(\frac{1}{M})$
σ_{tot} [10^{-42} cm^2]
300
250
200
150
100
50
0
$\langle \cos\theta_e \rangle$
0.10
0.05
0.00
−0.05
0
10
20
30
40
50
60
E_ν [MeV]

Candidate $\bar{\nu}_e$ events

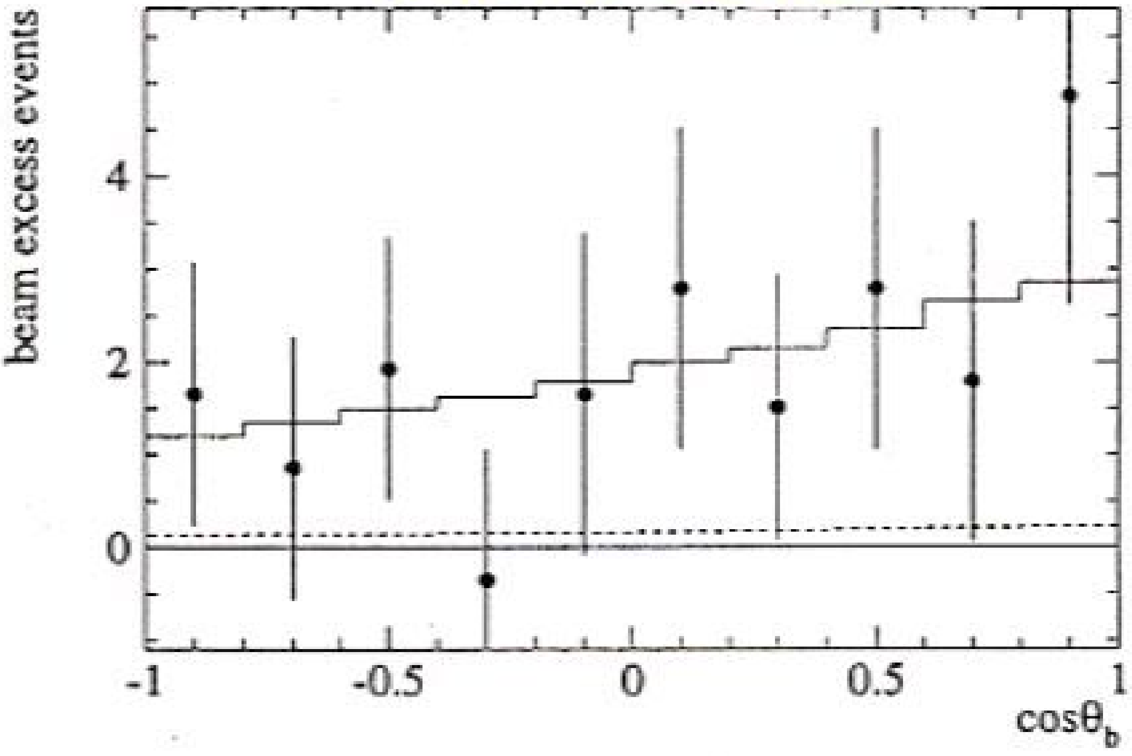


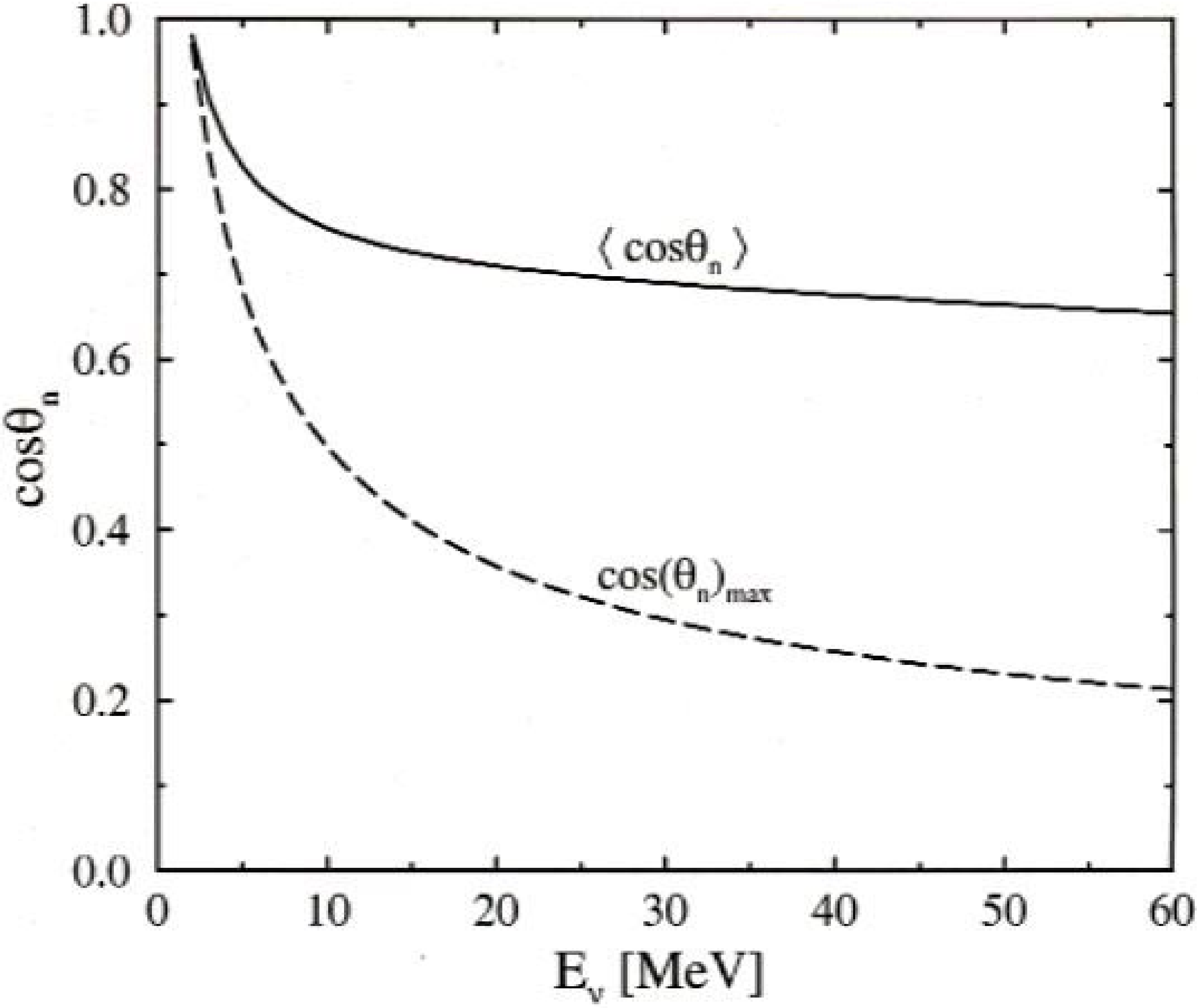
FIG. 21. The $\cos\theta_b$ distribution for beam-excess data events with $36<E_e<60$ MeV and $R>30$ and that expected for neutrino oscillations at large Δm^2 (solid). The dashed curve is the estimated neutrino background. θ_b is the e^+ angle with respect to the neutrino direction.

$$\boxed{\langle\cos\theta\rangle = 0.20 \pm 0.13 \qquad \text{(LSND, 1996)}}$$

$\langle\cos\theta\rangle = 0.08$ theory

$\langle\cos\theta\rangle = 0.16$ theory + LSND corrections

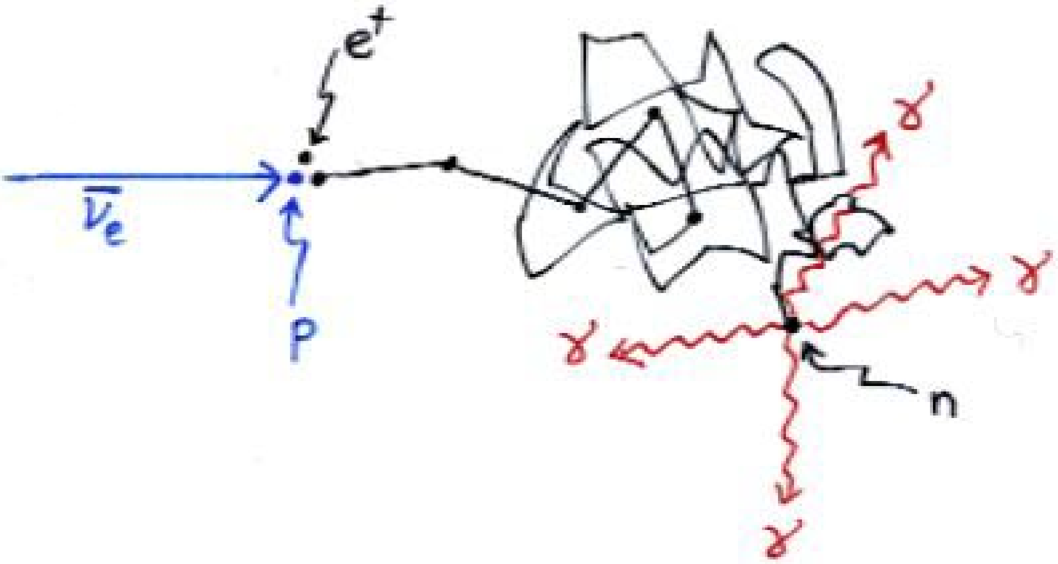
[redacted]



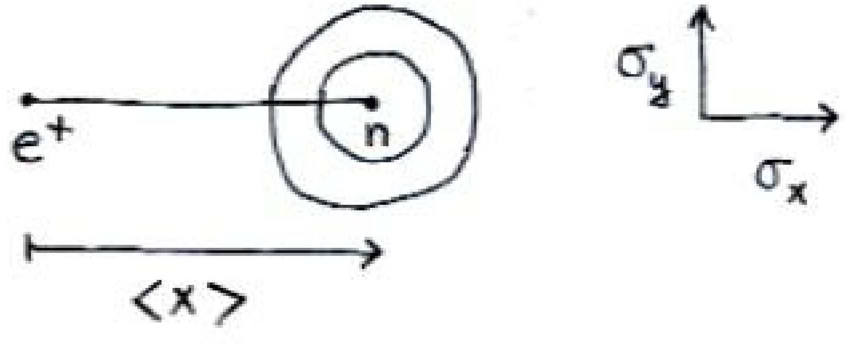
$$\cos(\theta_n)_{max} \simeq \frac{\sqrt{2E_\nu\Delta - (\Delta^2 - m_e^2)}}{E_\nu}$$

$$\simeq \frac{\sqrt{2(E_\nu - \Delta - m_e)\Delta + (\Delta + m_e)^2}}{E_\nu}$$

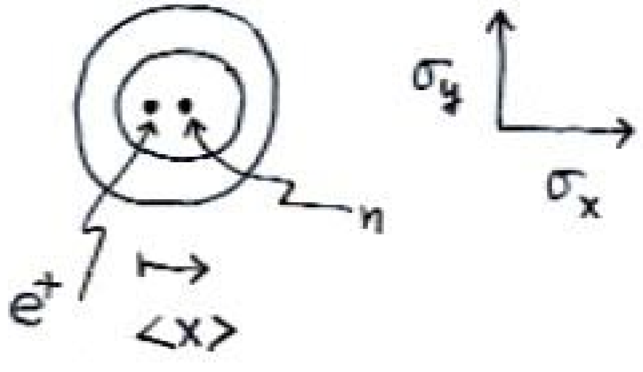
Neutron – Positron Separation

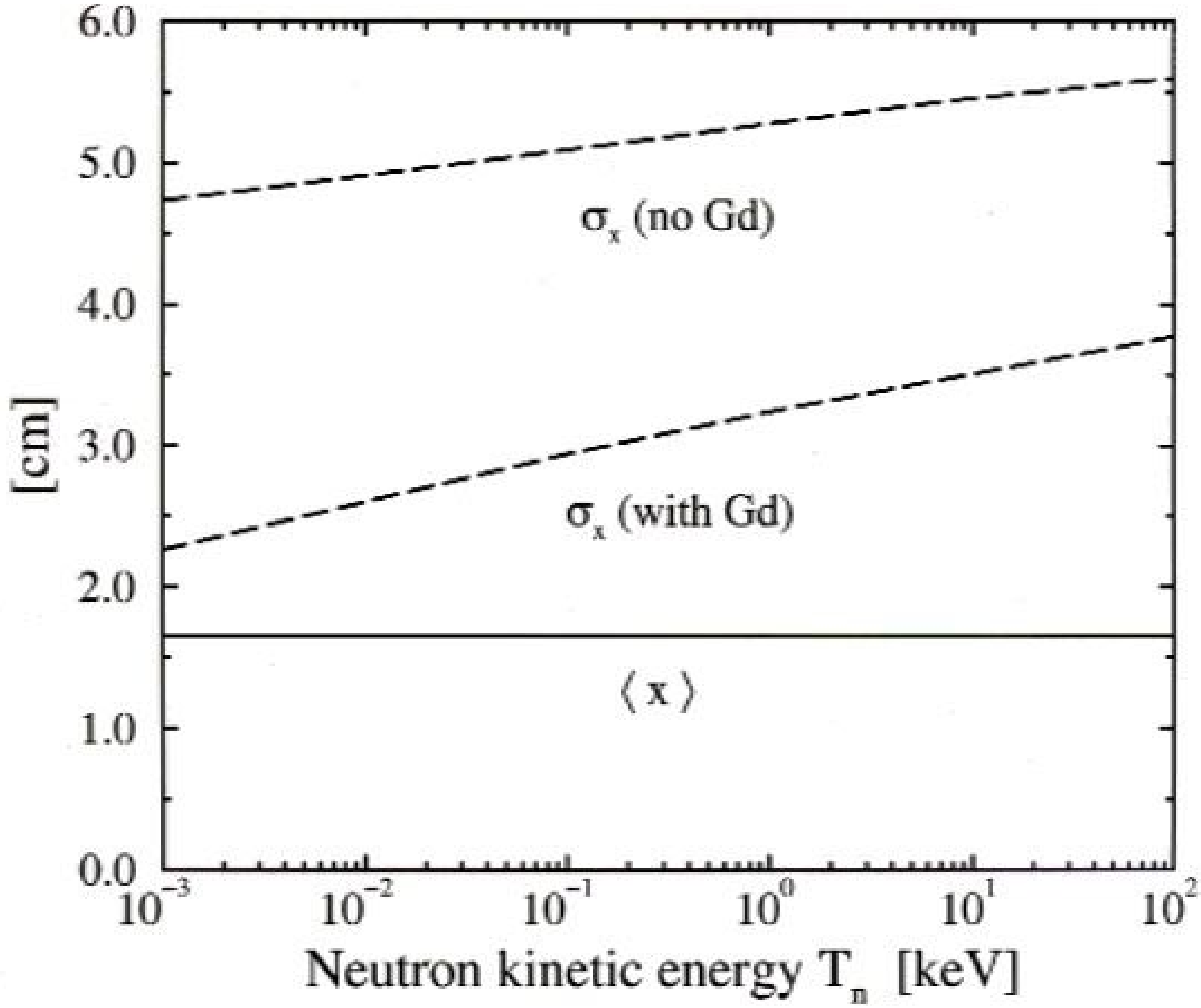


ideal case :



real case :





$$T_n \simeq \frac{E_\nu E_e^{(0)}}{M}\left(1 - v_e^{(0)}\cos\theta\right) + \frac{(\Delta^2 - m_e^2)}{2M}$$

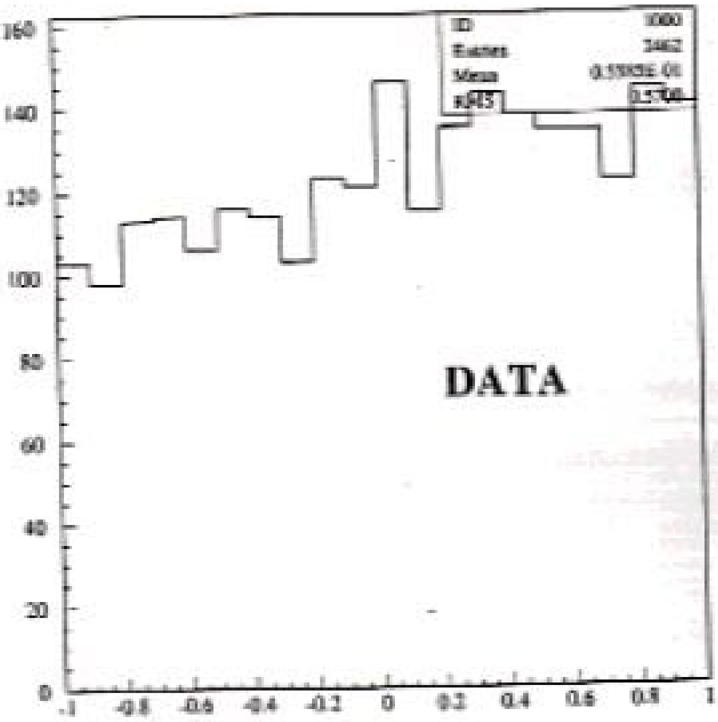


Figure 4: Distribution of the projection of the positron-neutron unit vector along the known neutrino direction.

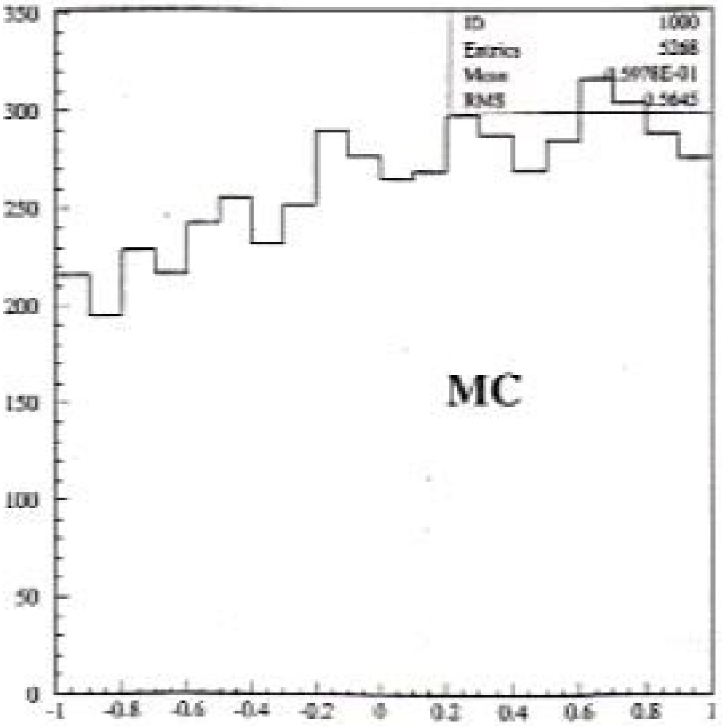
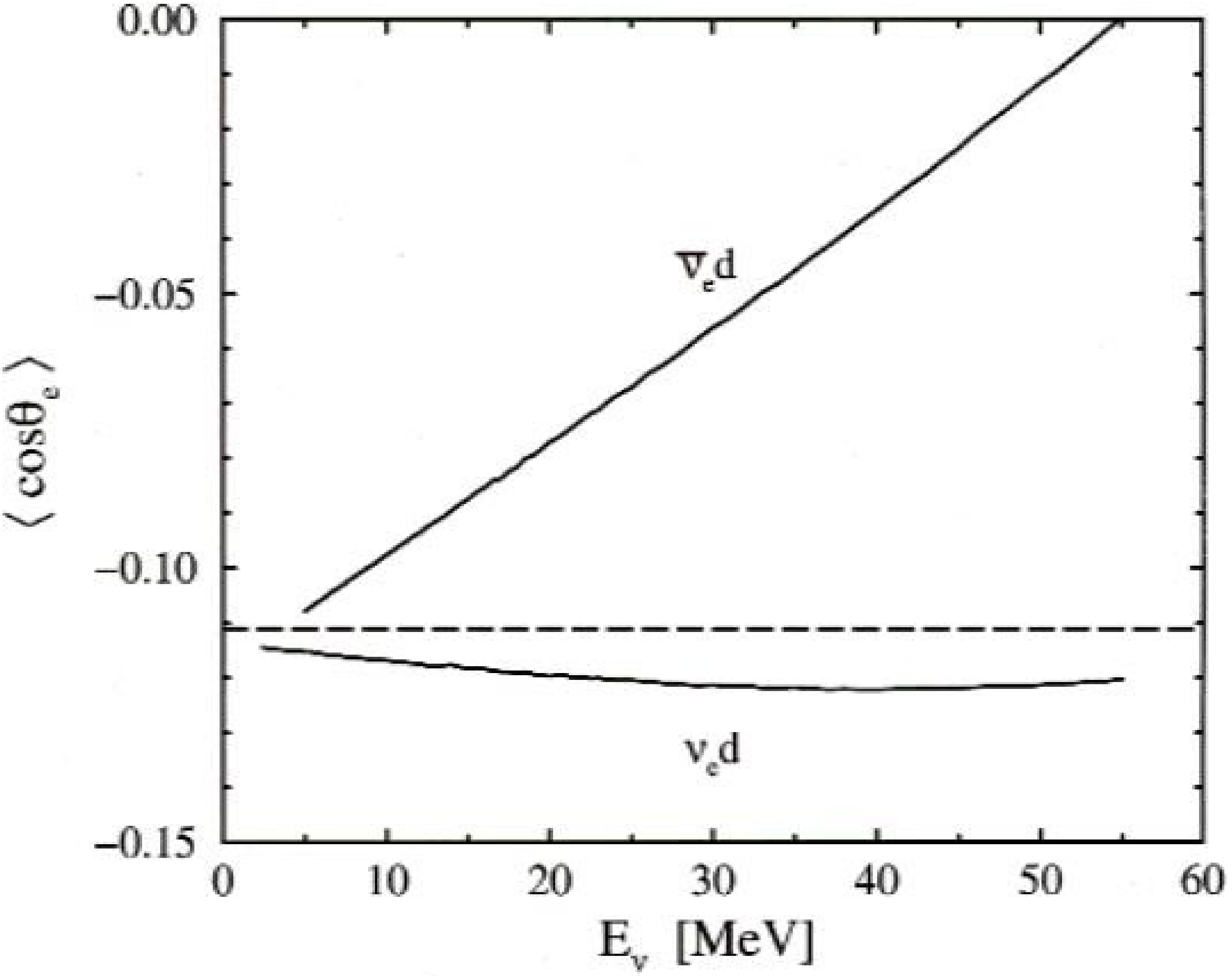


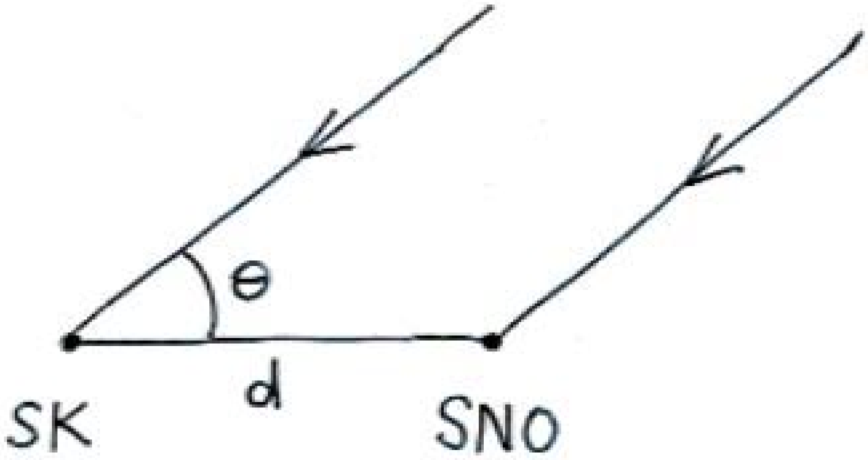
Figure 5: Distribution of the projection of the Montecarlo positron-neutron unit vector along the known neutrino direction.

CHOOZ, hep-ex/9906011



$$\langle \cos\theta \rangle \simeq -\frac{1}{9} + \frac{2}{3}\frac{E_\nu}{M} \pm \frac{8}{27}\frac{f_2}{g}\frac{E_\nu}{M}$$

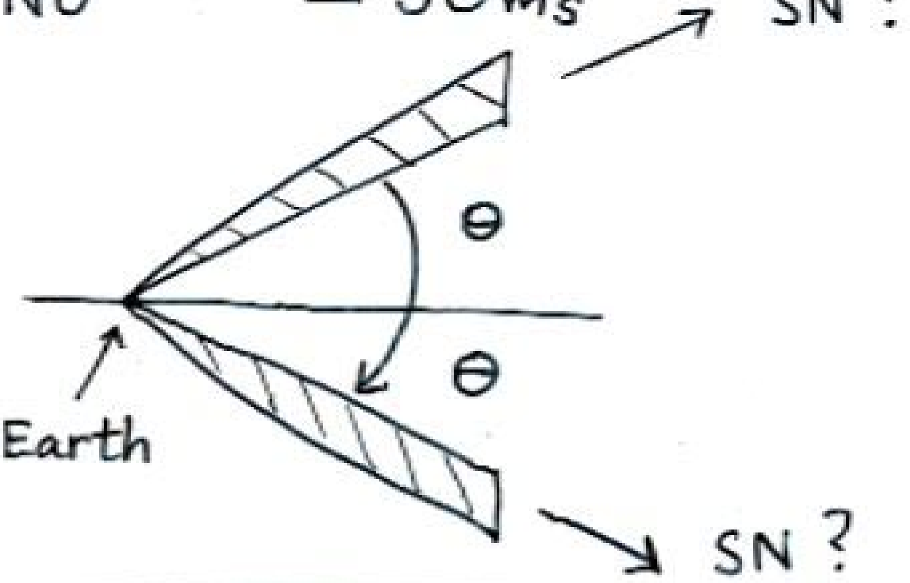
Triangulation

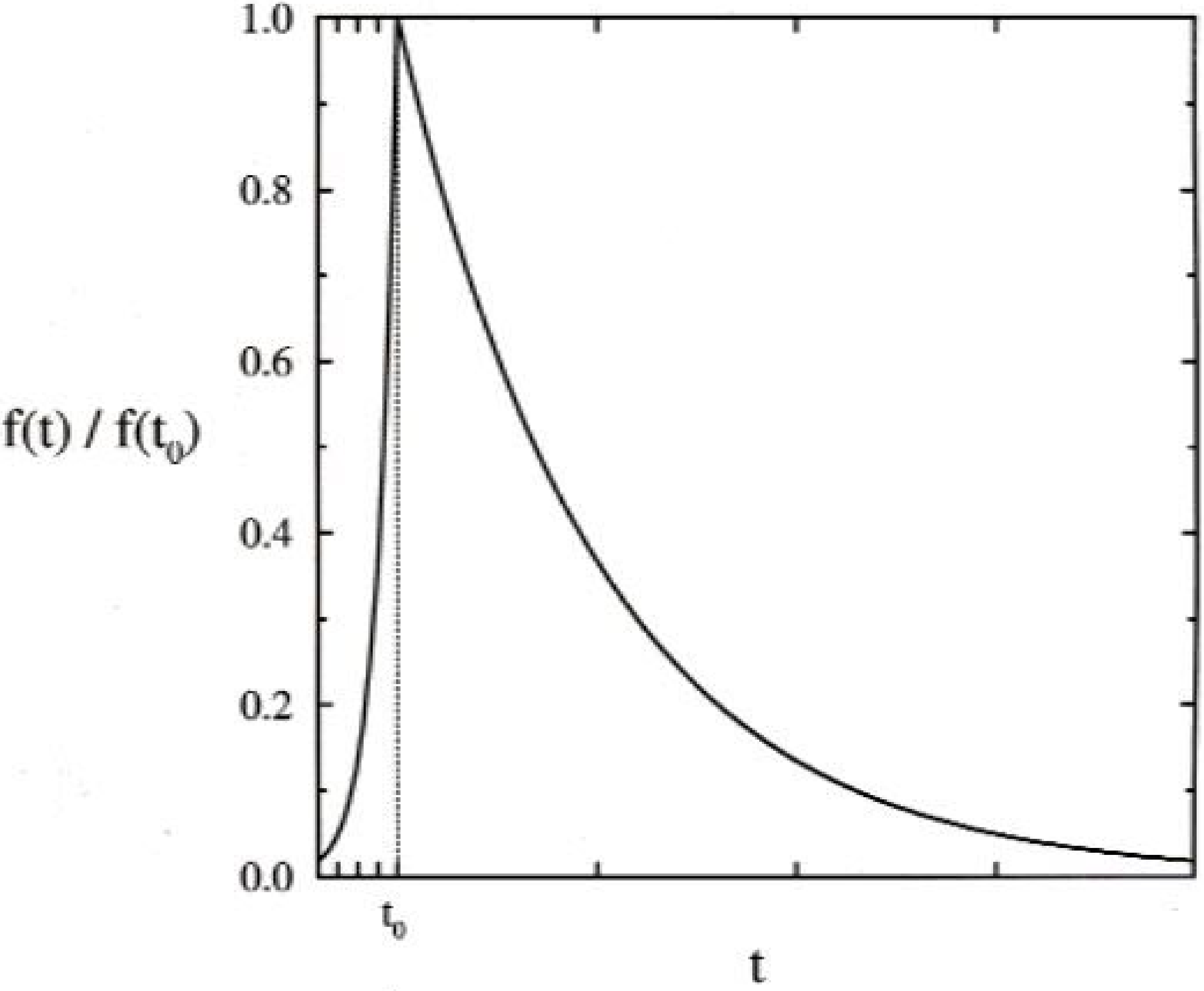


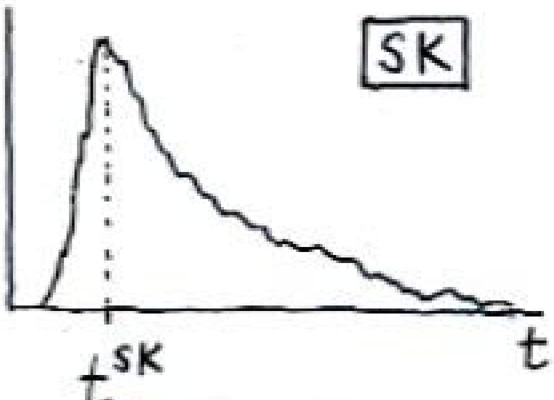
$$\boxed{\cos\theta = \frac{\Delta t}{d}} \qquad \boxed{\delta(\cos\theta) = \frac{\delta(\Delta t)}{d}}$$

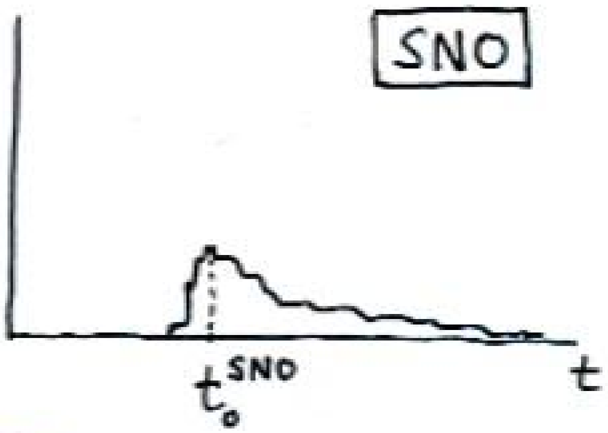
Earth diameter $\simeq$ 40 ms

SK − SNO $\simeq$ 30 ms





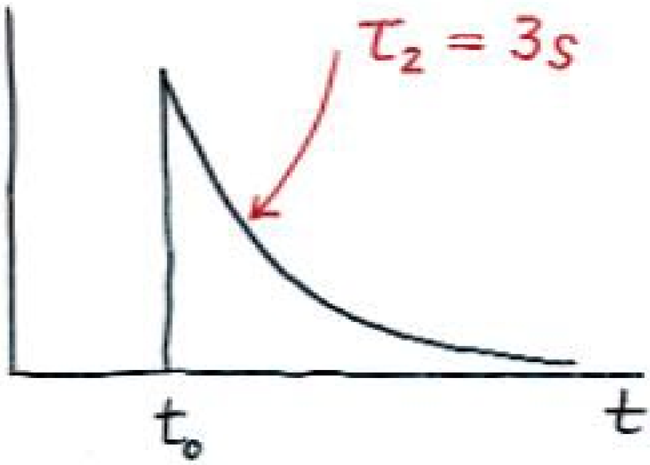




$$\boxed{\Delta t = t_0^{SK} - t_0^{SNO}}$$

$$\boxed{\delta(\Delta t) \simeq \delta(t_0^{SNO})}$$

- zero risetime



$$t_0 = t_{i=1} - \frac{\tau_2}{N}$$

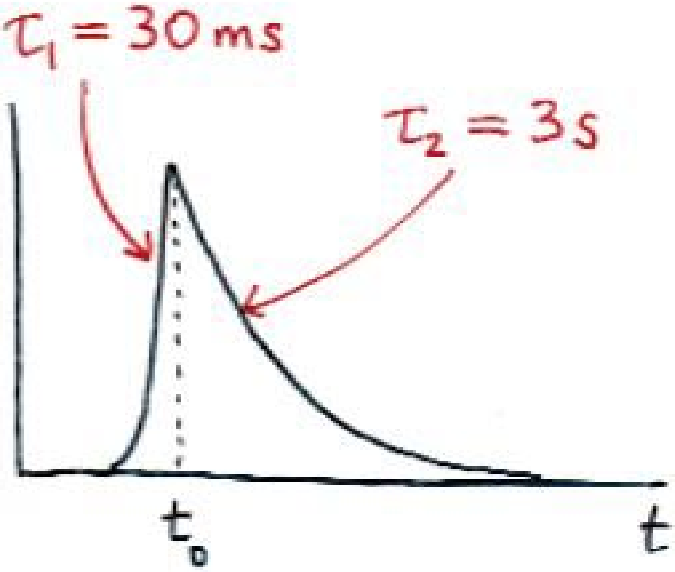
$$\boxed{\delta t_0 = \frac{\tau_2}{N}} \quad = \text{ event spacing at peak}$$

$$\delta t_0^{SK} \simeq \frac{3s}{10^4} \simeq 0.3 \text{ ms}$$

$$\delta t_0^{SNO} \simeq \frac{3s}{400} \simeq 7.5 \text{ ms}$$

$$\boxed{\delta(\cos\theta) \simeq 0.25} \quad \sim \frac{1}{N} \sim D^2$$

- nonzero risetime



t_0 determination straightforward

$$\boxed{\frac{1}{(\delta t_0)^2_{\min}} = N \int dt \; f(t,t_0) \left[\frac{\partial \ln f(t,t_0)}{\partial t_0}\right]^2}$$

Rao-Cramer

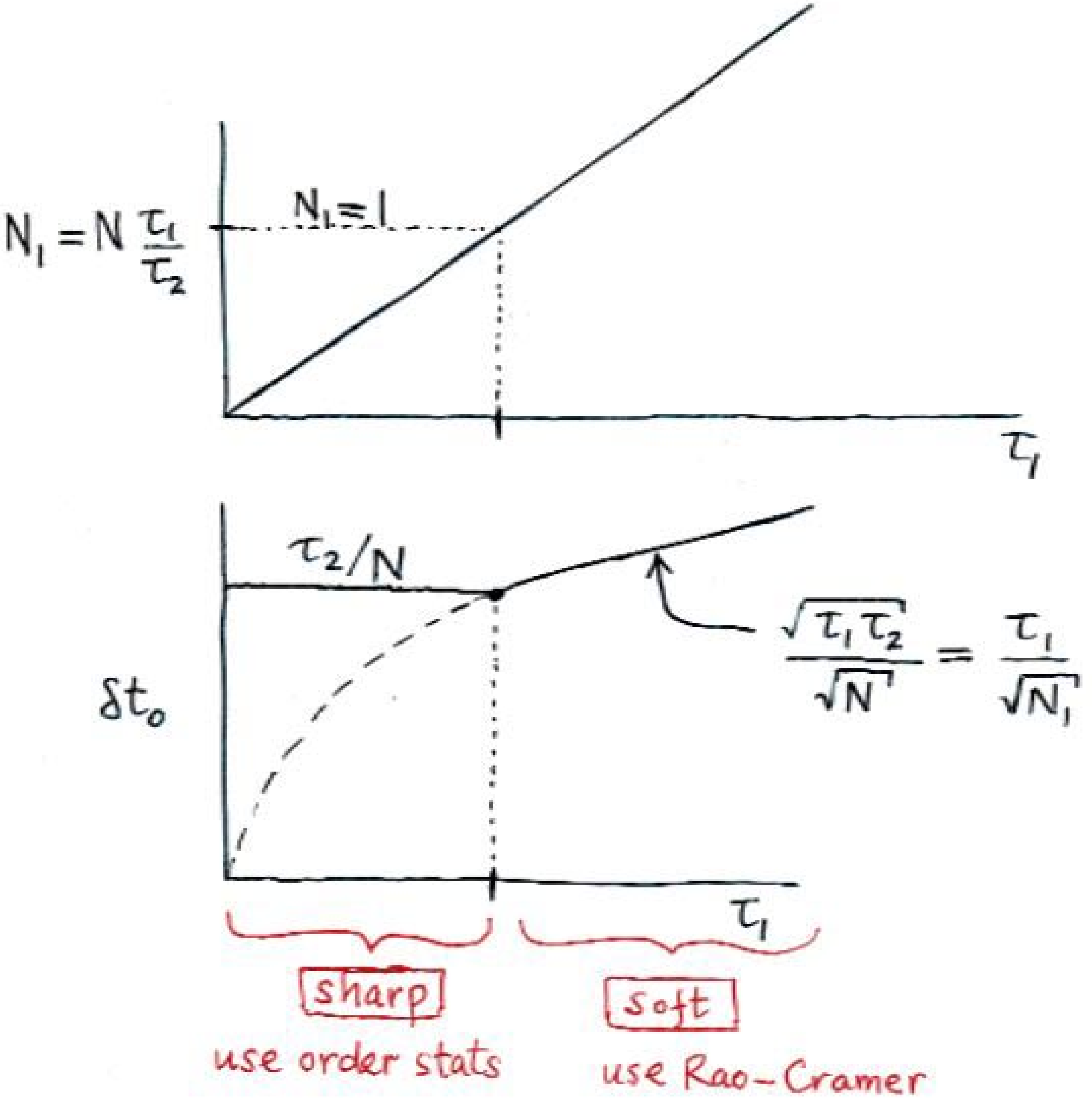
$$\boxed{(\delta t_0)_{\min} \simeq \frac{\sqrt{\tau_1 \tau_2}}{\sqrt{N}} \simeq \frac{\tau_1}{\sqrt{N_1}}}$$

$$N_1 \simeq N \frac{\tau_1}{\tau_2}$$

$$\delta t_0^{SK} \simeq \frac{30\,\mathrm{ms}}{\sqrt{100}} \simeq 3\,\mathrm{ms} \qquad \delta t_0^{SNO} \simeq \frac{30\,\mathrm{ms}}{\sqrt{4}} \simeq 15\,\mathrm{ms}$$

$$\boxed{\delta(\cos\theta) \simeq 0.5} \sim \frac{1}{\sqrt{N}} \sim D$$

Sharp vs. Soft Edge



At $D = 10$ kpc:

technique	error	
νe^- SK	$\delta(\cos\theta) \simeq 4 \times 10^{-3}$	$(\delta\theta \simeq 5^\circ)$
νe^- SNO	$\delta(\cos\theta) \simeq 6 \times 10^{-2}$	$(\delta\theta \simeq 20^\circ)$
$\bar{\nu}_e p$ SK	$\delta(\cos\theta) \simeq 0.2$	
$\bar{\nu}_e p$ SNO	$\delta(\cos\theta) \simeq 1.0$	
$\bar{\nu}_e d$, $\nu_e d$ SNO	$\delta(\cos\theta) \simeq 0.5$	
SK-SNO timing	$\delta(\cos\theta) \simeq 0.5$	

- "Small" recoil and weak magnetism corrections can be large.

$\longrightarrow$ The e^+ angular distribution from $\bar{\nu}_e p \longrightarrow e^+ n$ is energy-dependent and very different from the naive result.

P. Vogel, J.F.B., PRD 60, 053003 (1999)

- Earth diameter ($\simeq 40$ ms) is small compared to timescales of SN pulse.

$\longrightarrow$ Realistic statistics say that SN location by triangulation is much less precise than previously thought.

J.F.B., P. Vogel, PRD 60, 033007 (1999)