Supernova Neutrinos

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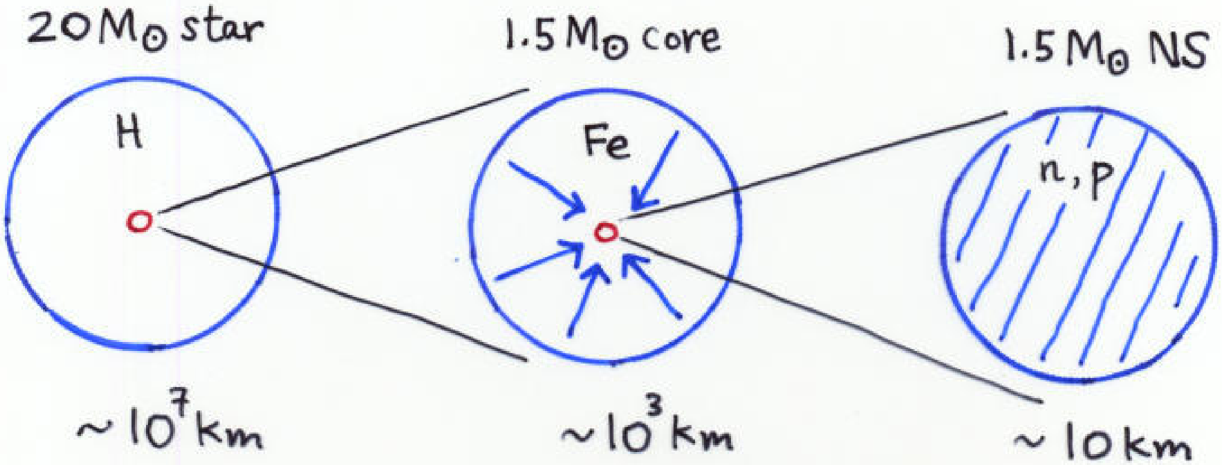
Executive Summary:

No supernova neutrinos detected recently.

Supernova: Core-Collapse



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

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

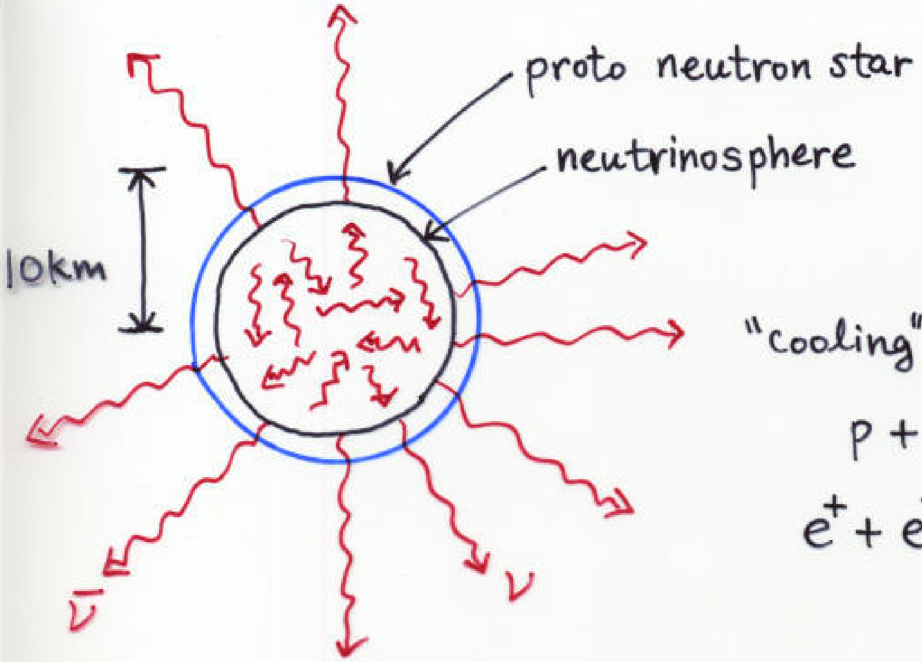
$$\simeq 2 \times 10^{59} \text{ MeV}$$

observations :

kinetic energy of explosion $\simeq 10^{-2} \cdot \Delta E_B$

electromagnetic radiation $\simeq 10^{-4} \cdot \Delta E_B$

Supernova: Energy Release



"cooling" by neutrino emission:

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

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

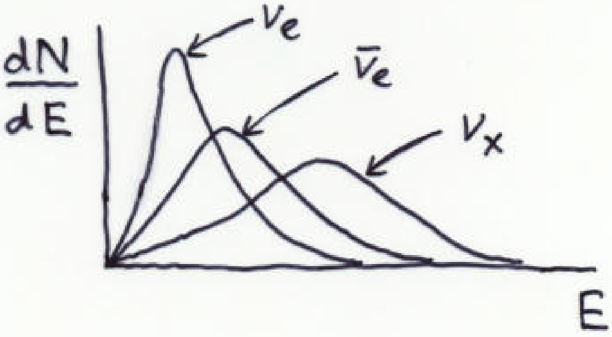
etc.

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

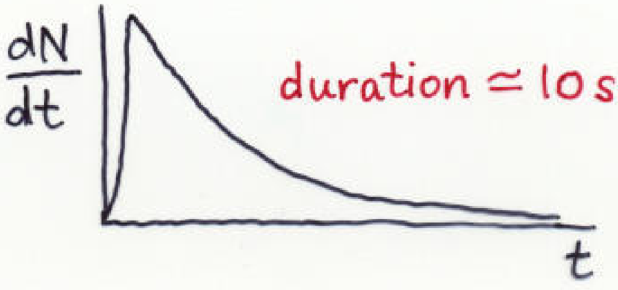
$\langle E_{\nu_e} \rangle \simeq 11$ MeV

$\langle E_{\bar{\nu}_e} \rangle \simeq 16$ MeV

$\langle E_{\nu_x} \rangle \simeq 25$ MeV



$$L_{\nu_e}(t) \simeq L_{\bar{\nu}_e}(t) \simeq L_{\nu_x}(t)$$



duration $\simeq 10$ s

Supernova Models:

Bad news: Supernovae explode in nature, but not in computers.

Good news: Lots of progress.

1d models with full Boltzmann transport and Newtonian or full GR gravity don't explode.
[Janka et al.; Mezzacappa et al.]

Next: 1d → 2d → 3d.

Lots of work on emissivities and opacities.
[Janka; Raffelt; Horowitz; others

This is a very important problem.

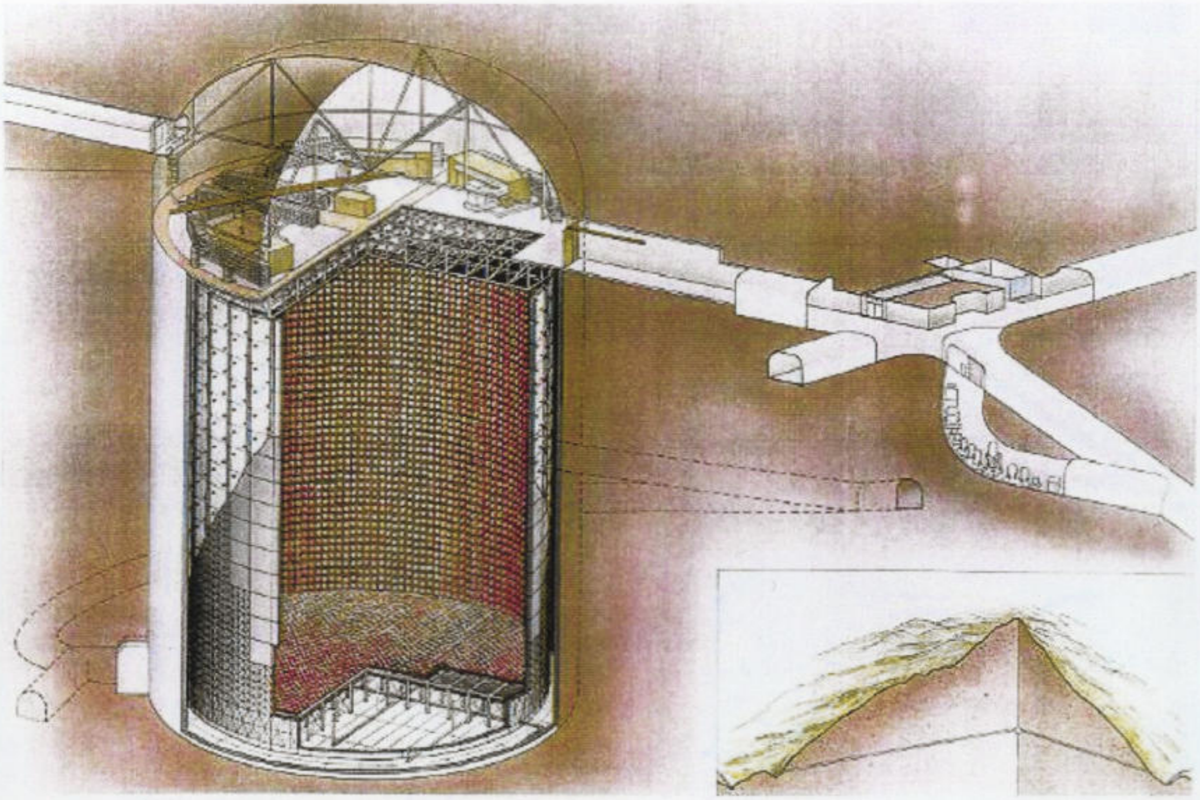
Detectors :

water	Super-Kamiokande	32 kton H_2O
	SNO	1 kton D_2O
		1.4 kton H_2O
	AMANDA	lots of ice
oil	LVD	1 kton
	KamLAND	1 kton
	MiniBooNE	0.6 kton
	Borexino	0.3 kton
	Baksan	0.2 kton

Biggest yield: $\bar{\nu}_e p \rightarrow e^+ n$, ~300 events/kton

Some other proposed targets :

Pb (OMNIS), Ar (ICARUS), Mo (MOON),
Cl (Homestake Hybrid), ~1 Mton H_2O



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKEI

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

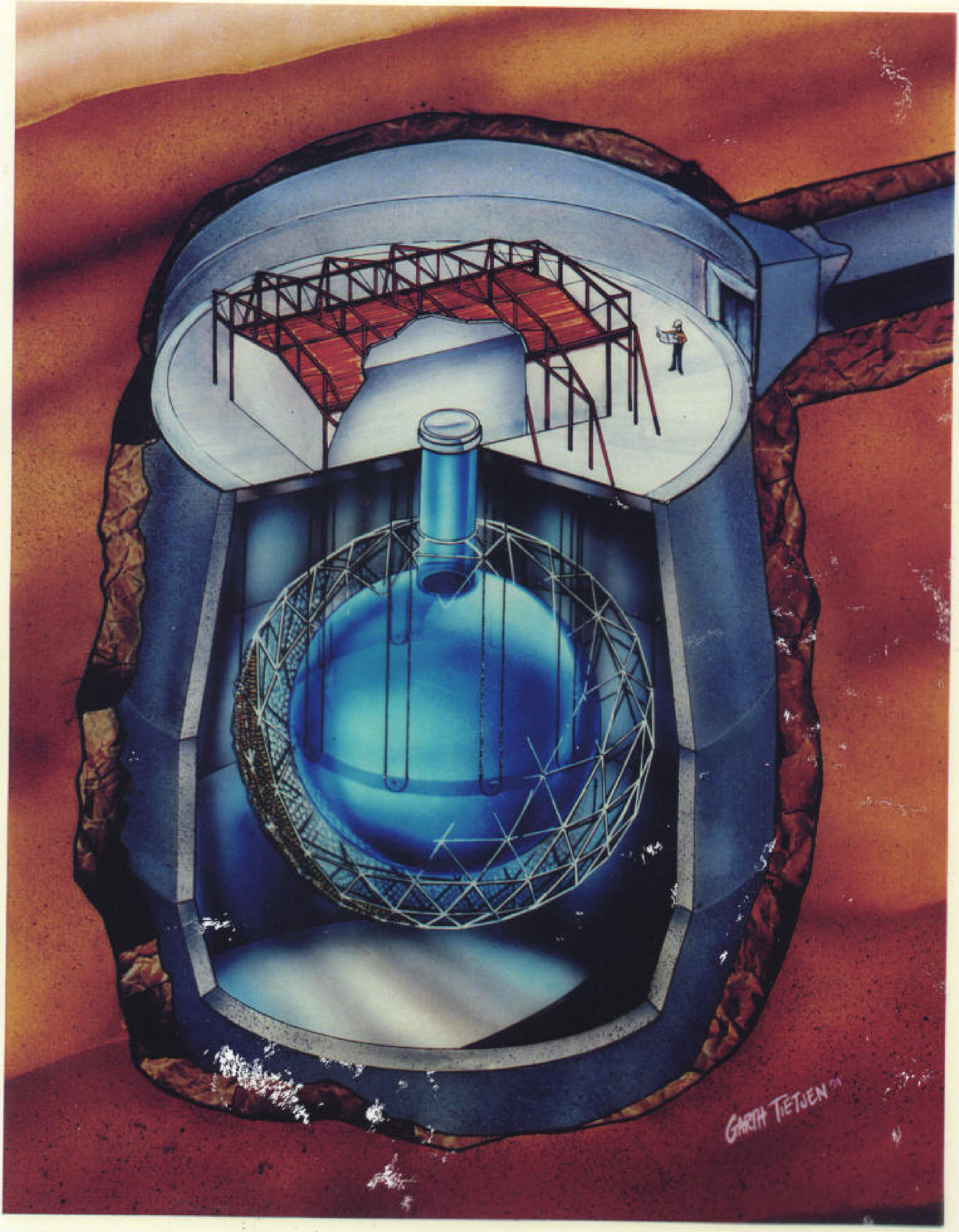

GARTH TIETJEN '91

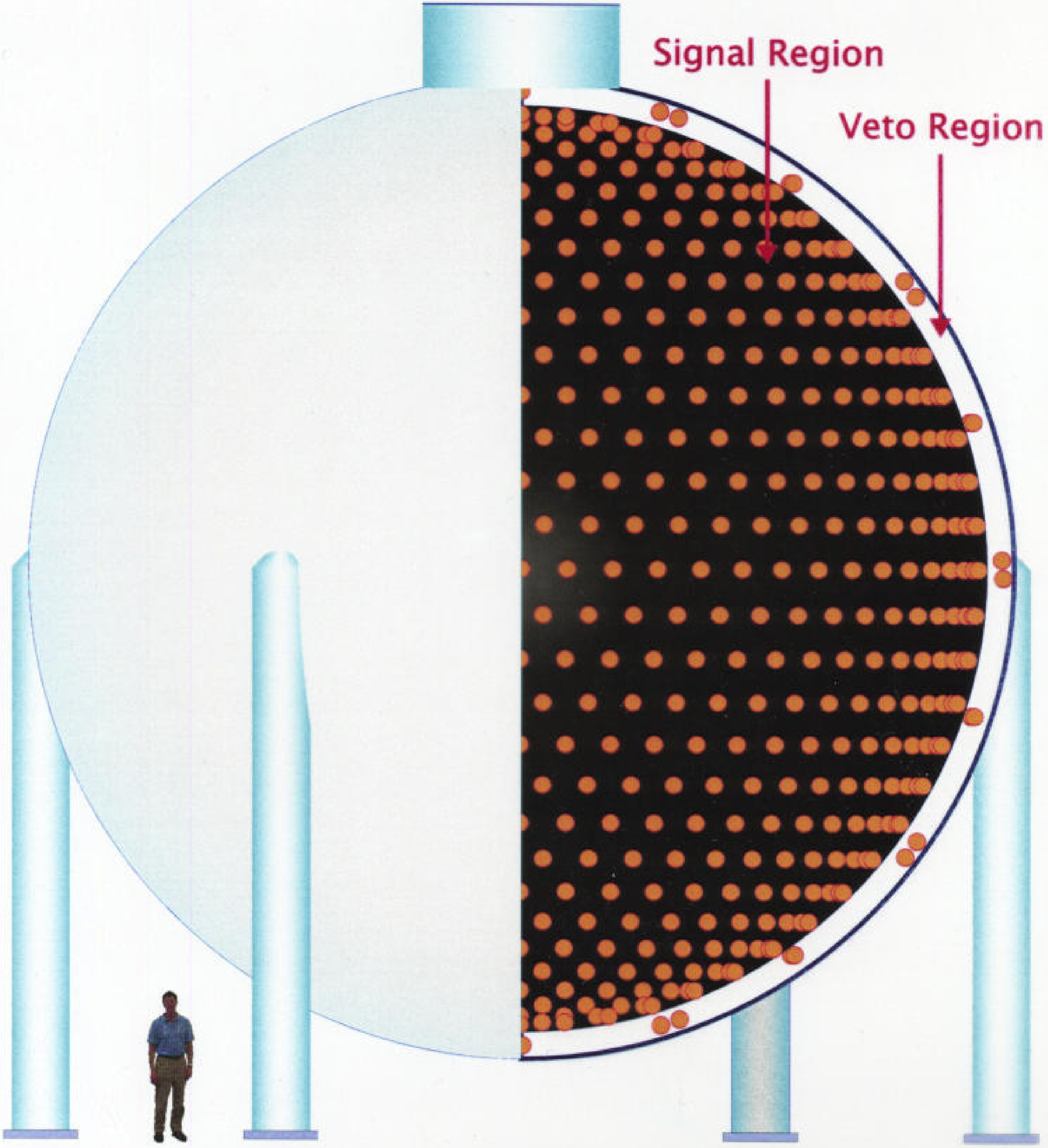
TABLE I. Calculated numbers of events expected in SNO for a supernova at 10 kpc. The other parameters (e.g., neutrino spectrum temperatures) are given in the text. In rows with two reactions listed, the number of events is the total for both. The notation ν indicates the sum of ν_e, ν_μ, and ν_τ, though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

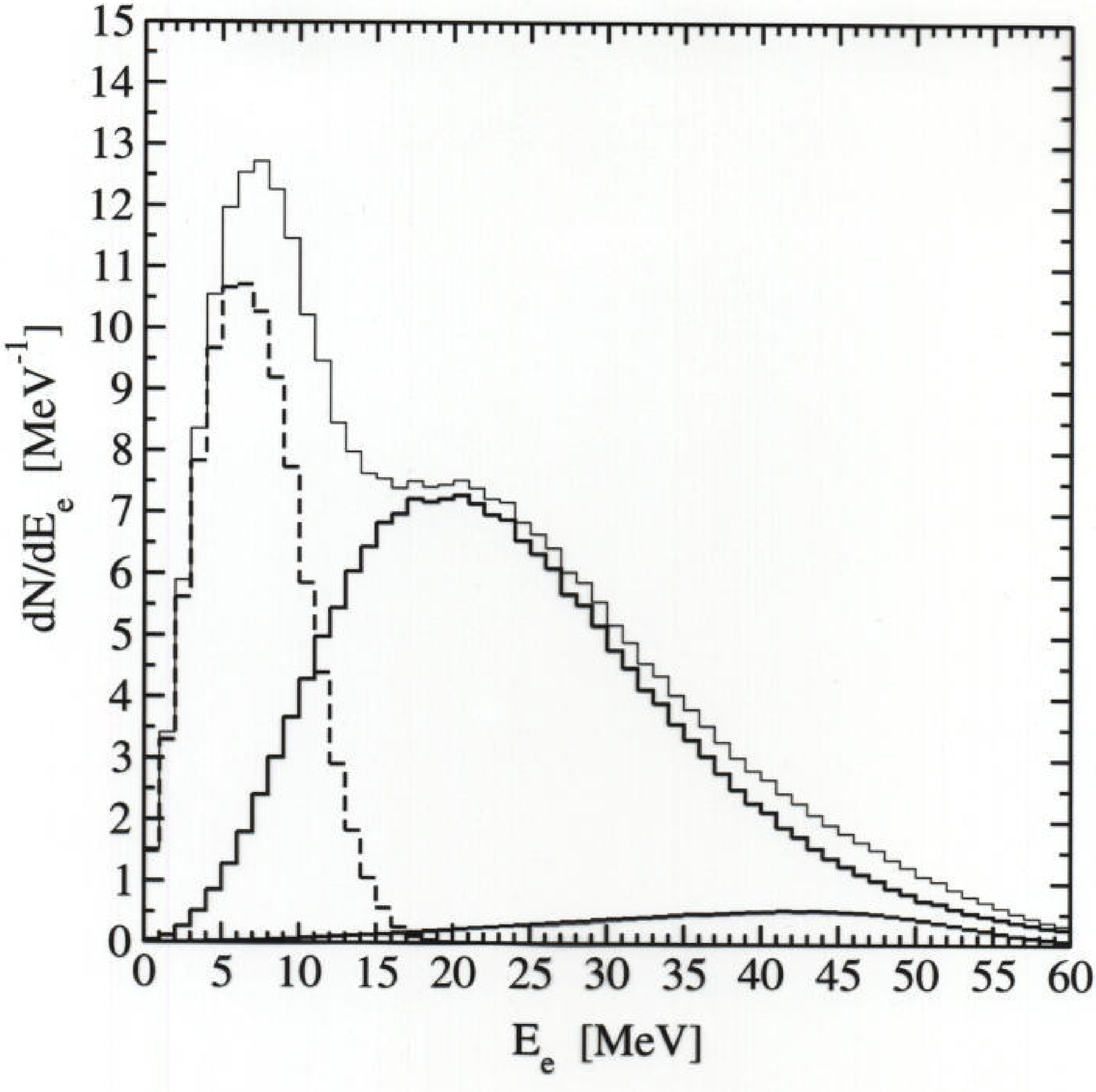
Events in 1 kton D_2O		
$\nu + d \to \nu + p + n$ $\bar{\nu} + d \to \bar{\nu} + p + n$	detected particle(s) : n	485
$\nu_e + d \to e^- + p + p$ $\bar{\nu}_e + d \to e^+ + n + n$	e^-, e^+nn	160
$\nu +^{16} O \to \nu + \gamma + X$ $\bar{\nu} +^{16} O \to \bar{\nu} + \gamma + X$	γ, γn	20
$\nu +^{16} O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

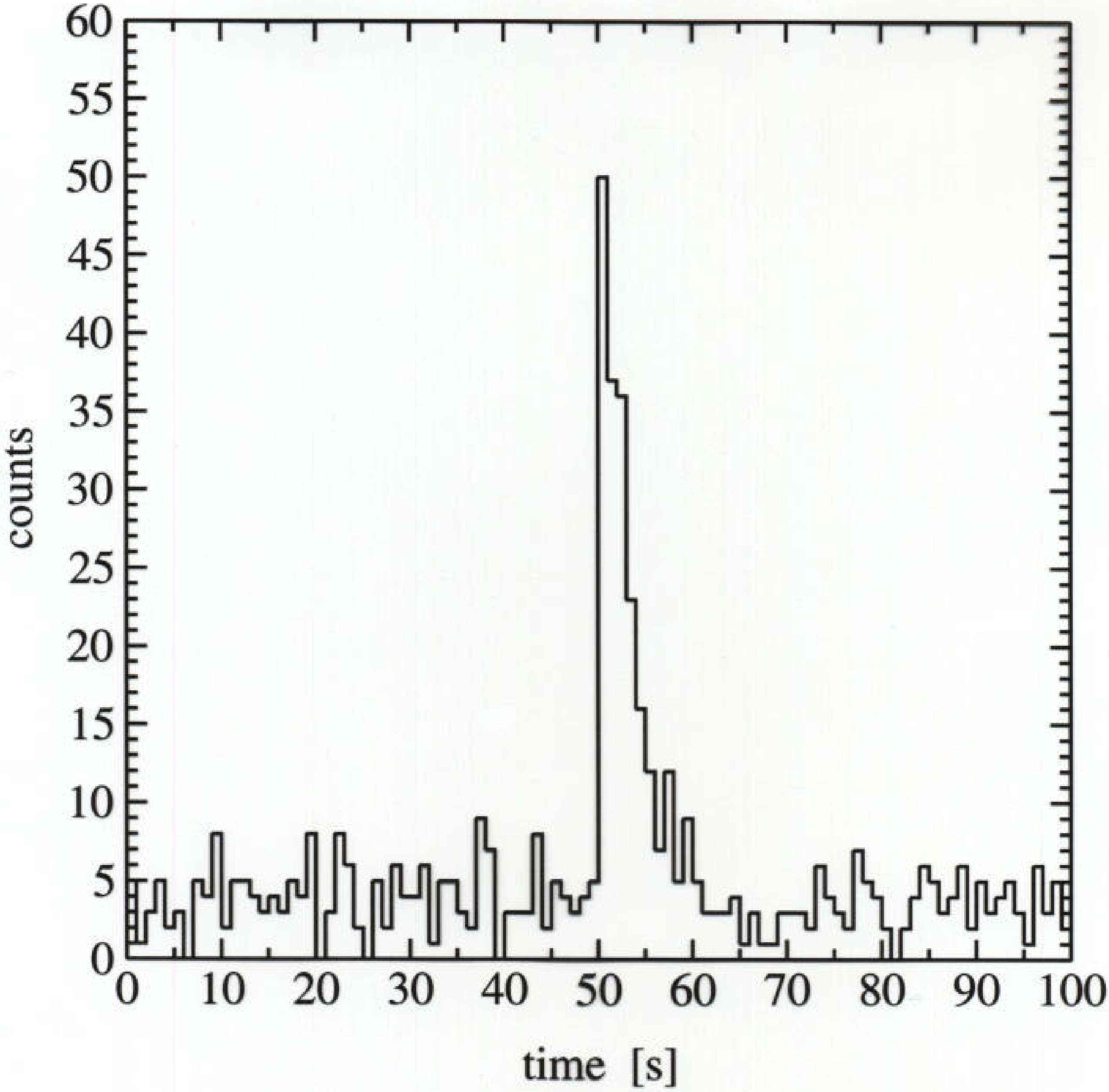
  CC : ν_e, $\bar{\nu}_e$ only
- CC, NC separation easy

MiniBooNE Detector





dN/dE$_e$ [MeV^{-1}]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
0
5
10
15
20
25
30
35
40
45
50
55
60
E$_e$ [MeV]


counts
time [s]
0
5
10
15
20
25
30
35
40
45
50
55
60
0
10
20
30
40
50
60
70
80
90
100

CC Measurements :

At 10 kpc :

$$\left.\begin{array}{lll} \text{SK}: & \simeq 8000 & \bar{\nu}_e + p \to e^+ + n \\ \text{SNO}: & \simeq 80 & \nu_e + d \to e^- + p + p \end{array}\right\} \text{"clean" reactions}$$

spectral quality :

$$E_\nu = E_e + \Delta + \mathcal{O}(1/M_p)$$

$$\longrightarrow \boxed{\frac{dN_e}{dE_e} \sim f(E_\nu)\,\sigma(E_\nu)}$$

shape :

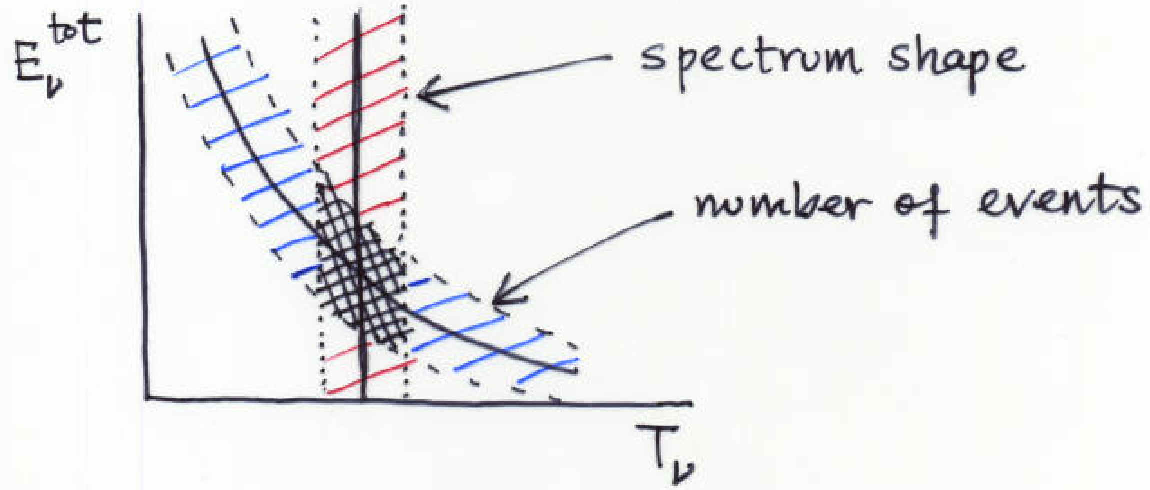
$$\frac{\delta T}{T} \sim \frac{\delta \langle E_\nu \rangle_{f\sigma}}{\langle E_\nu \rangle_{f\sigma}} \sim \frac{\delta \langle E_e \rangle}{\langle E_e \rangle} \sim \frac{1}{\sqrt{N}}$$

$$\longrightarrow \boxed{\begin{array}{l} \dfrac{\delta T_{\bar{\nu}_e}}{T_{\bar{\nu}_e}} \sim 1\% \quad \text{SK} \\[2ex] \dfrac{\delta T_{\nu_e}}{T_{\nu_e}} \sim 10\% \quad \text{SNO} \end{array}}$$

normalization:

$$N \sim \frac{E_\nu^{tot} \langle \sigma \rangle}{T_\nu}$$

$$\longrightarrow \boxed{N \sim E_\nu^{tot} T_\nu} \quad \text{for } \sigma \sim E_\nu^2$$



These are the most basic observables (model comparisons, E_B, r-process oscillations).

Next step: time dependence

$$\frac{dN}{dt}(t) \sim L(t), \text{ modulo } T(t) \text{ effects}$$

NC Measurements :

$\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$: no CC reactions

: dominate the NC signals

Why are these so important?

- $\simeq \frac{2}{3}$ of binding energy is radiated in these flavors
- not observed in SN1987A
- equipartition untested
- temperature controversial
- generally unaffected by oscillations
- needed for computing $E_B \sim \frac{GM^2}{R}$

BUT ..... E_ν not measured in NC reactions!

at 10 kpc:

SK: $\simeq 120$ $\nu + e^- \longrightarrow \nu + e^-$

recoil spectrum

very hard to separate events

SNO: $\simeq 500$ $\nu + d \longrightarrow \nu + p + n$

detect n capture

SK: $\simeq 700$ $\nu + {}^{16}O \longrightarrow \begin{matrix} {}^{15}O + n + \gamma \\ {}^{15}N + p + \gamma \end{matrix}$

Kolbe
Langan
Vogel

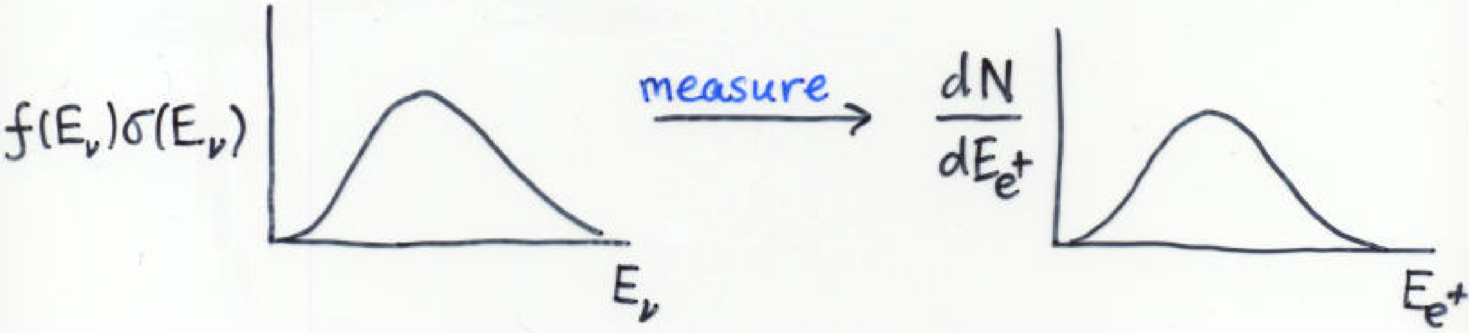
$E_\gamma \simeq 5-10$ MeV

KamLAND: $\simeq 60$ $\nu + {}^{12}C \longrightarrow \nu + {}^{12}C + \gamma$

$E_\gamma = 15.11$ MeV

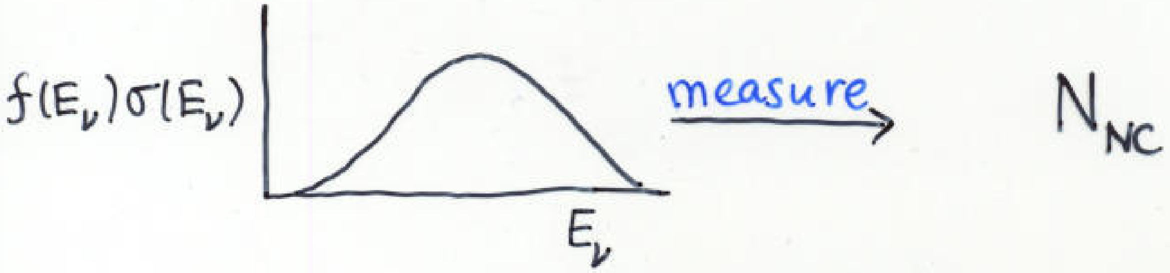
$$\boxed{N \sim \int dE_\nu \; f(E_\nu)\sigma(E_\nu)}$$

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



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

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

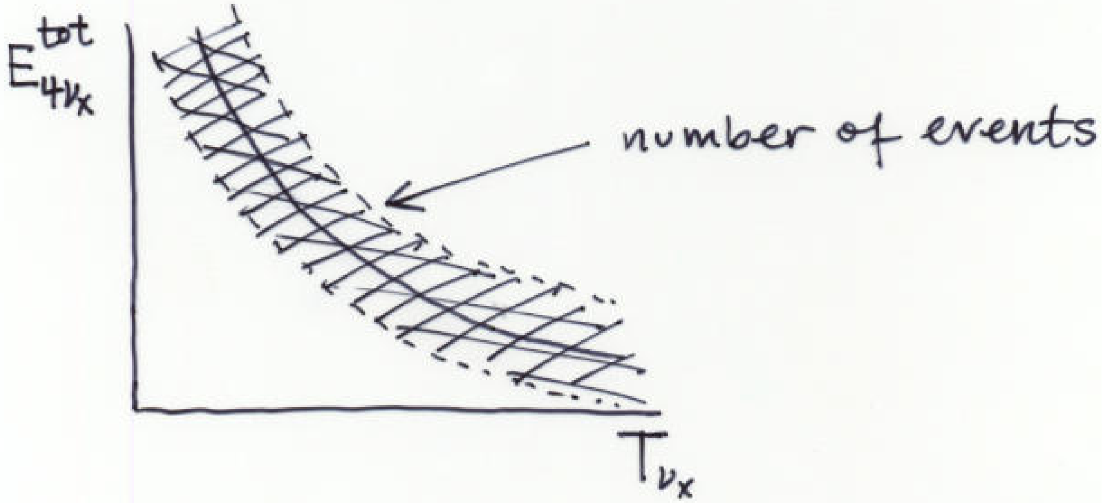


E_ν <u>unknown</u>

So, can only measure

$$N \sim E^{tot}_{4\nu_x} \frac{\langle\sigma\rangle}{T_{\nu_x}}$$

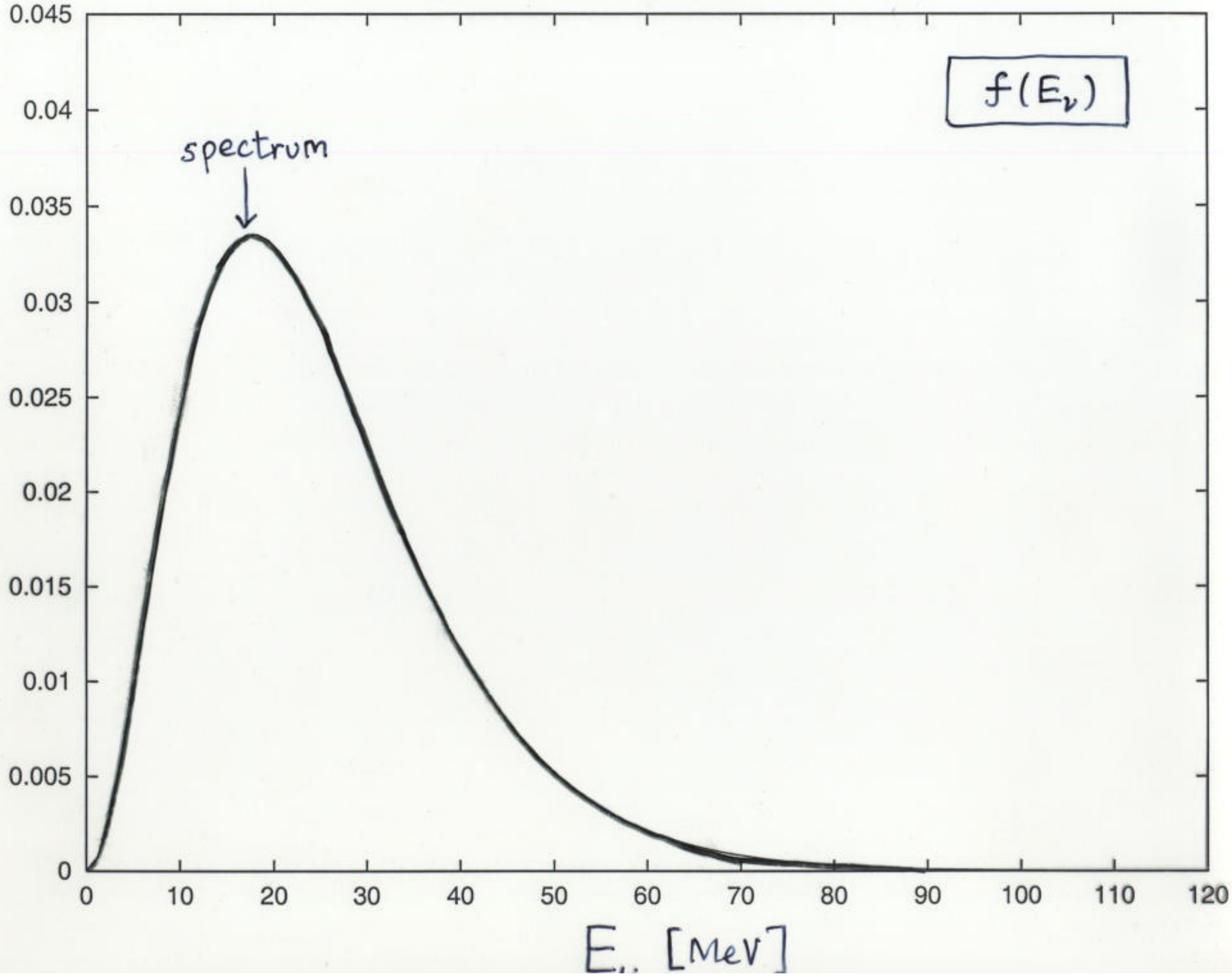
$$\longrightarrow \boxed{N \sim E^{tot}_{4\nu_x} T_{\nu_x}} \quad \text{for } \sigma \sim E_\nu^2$$



How can we break the degeneracy?

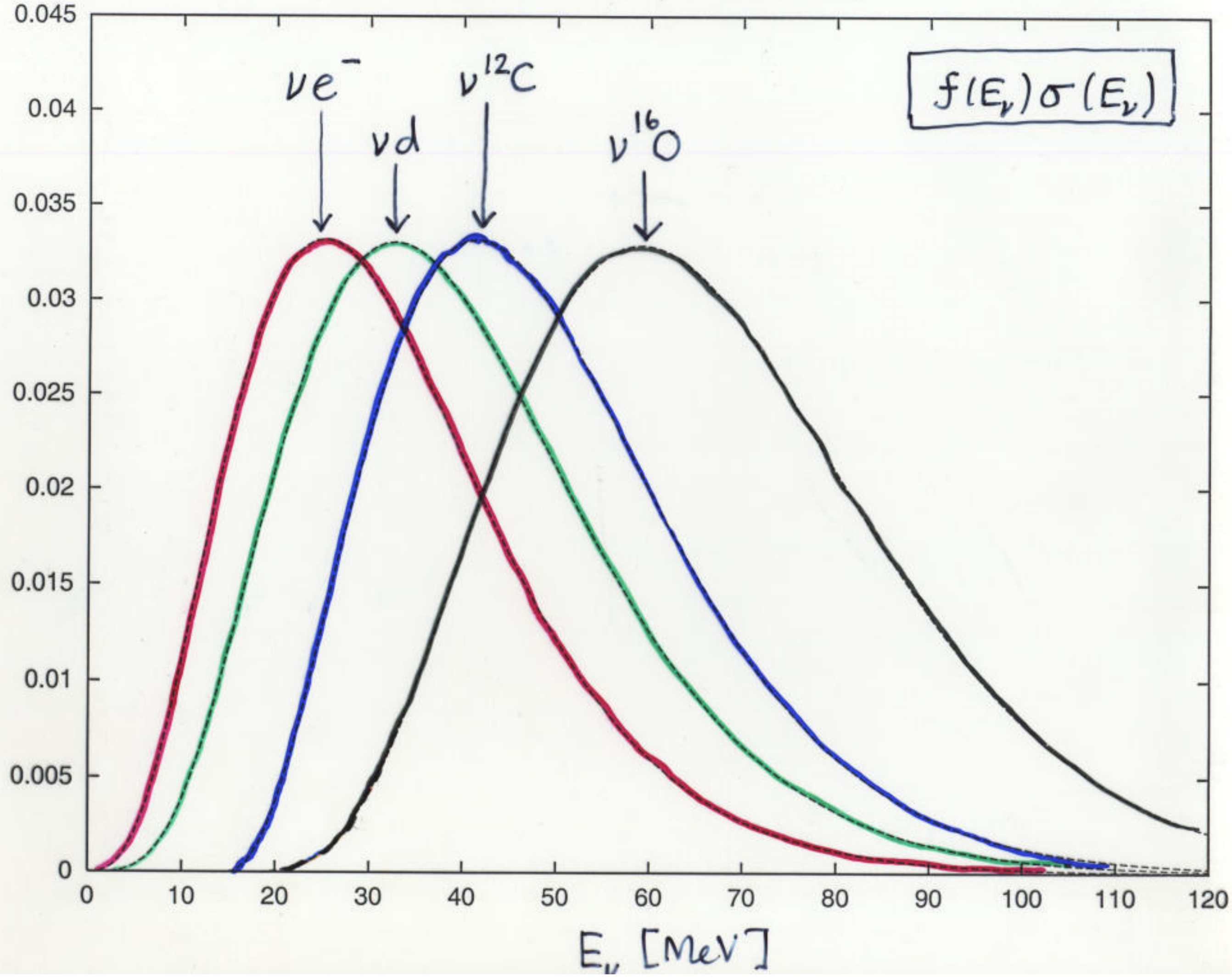
<u>Option A</u>: exploit different spectral responses

<u>Option B</u>: see below

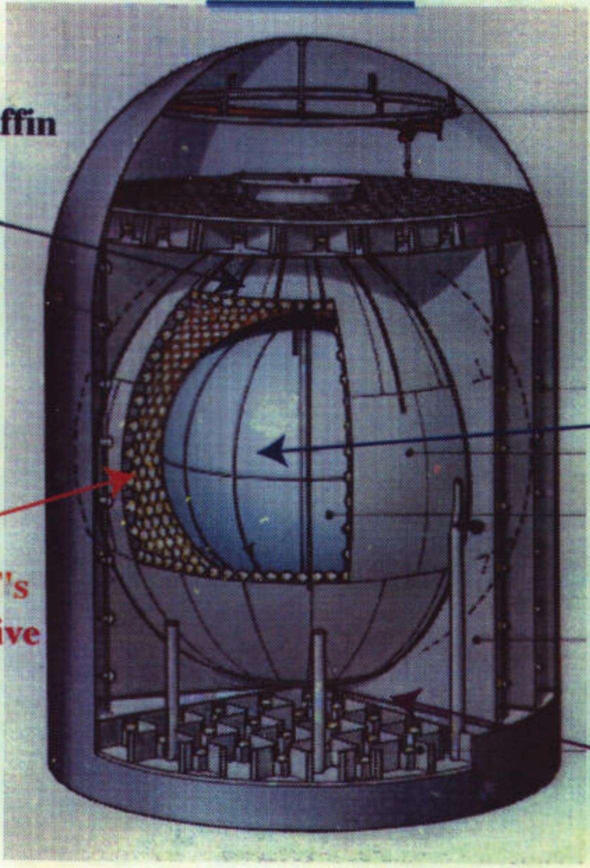


0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
10
20
30
40
50
60
70
80
90
100
110
120
$f(E_\nu)$
spectrum
E_ν [MeV]

J.F. Beacom, hep-ph/9909231



Detector



3,000 m^3 Isoparaffin Buffer Tank

1,200 m^3 Scintillator Balloon

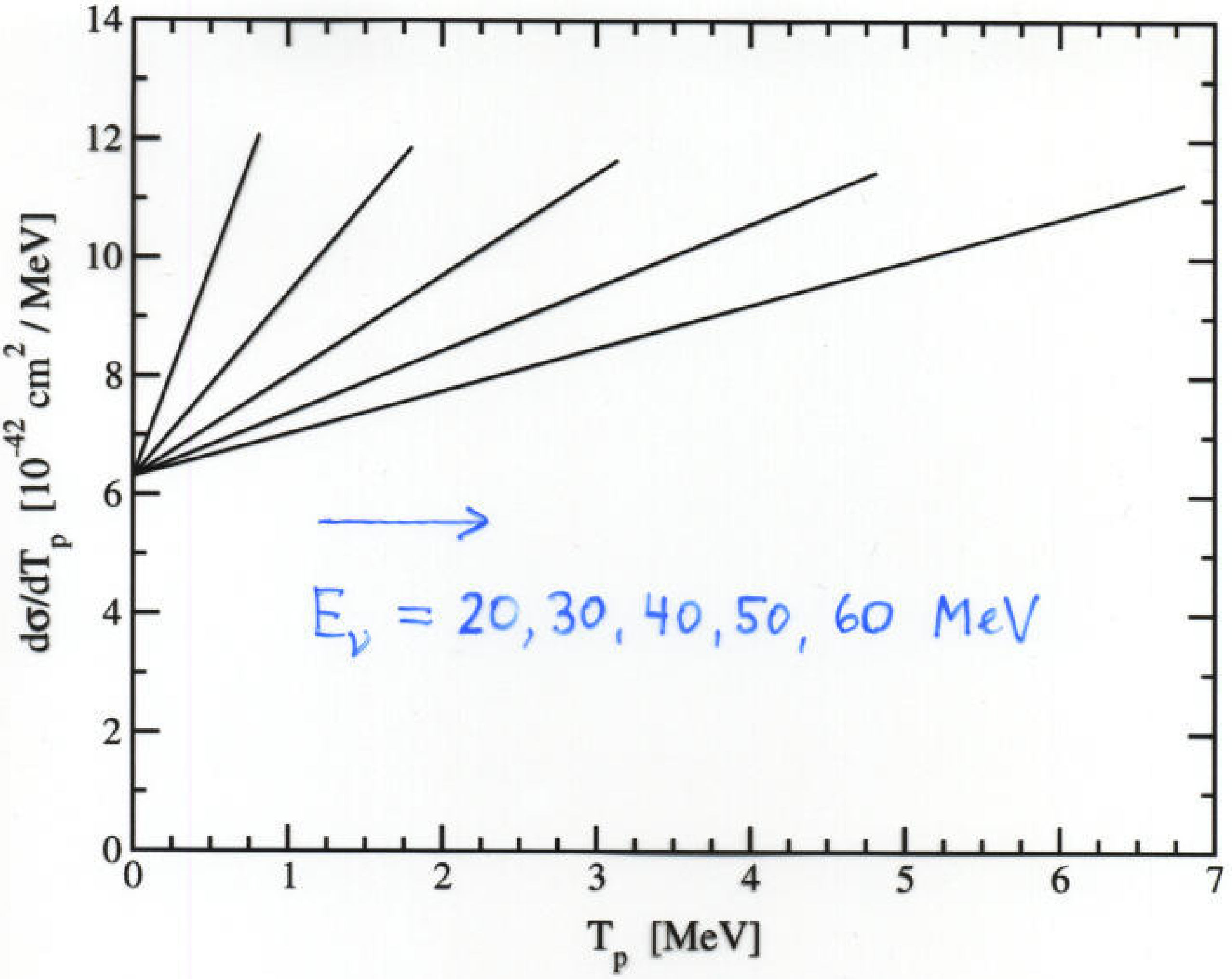
1,280 17 inch-PMT's (~ 22% photosensitive coverage)

+
630 PMTs
(U.S plan)

Water Cherenkov Anti-Counter

$\nu + p \longrightarrow \nu + p$ in KamLAND:

Why this seems crazy ……but……	why it isn't
1. $T_p \sim \frac{E_\nu^2}{M_p} \sim \text{MeV}$	1′. scintillation detector
2. light quenching ($\simeq 14$ for alphas)	2′. quenching $\simeq 4$ for protons, threshold $\simeq 0.2$ MeV
3. NC vector coupling $\sim 1 - 4\sin^2\theta_W \simeq 0$	3′. NC axial coupling ok, favors large T_p
4. NC cross section $\simeq \frac{1}{4}$ CC $\bar{\nu}_e + p$ cross section	4′. 4 flavors contribute, E_ν is higher
5. $\nu_e, \bar{\nu}_e$ NC contributions	5′. $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ dominate
6. confusion with $\bar{\nu}_e + p \rightarrow e^+ + n$ $\nu + e^- \rightarrow \nu + e^-$ $\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma$ etc	6′. easy to separate in practice



$\nu p \longrightarrow \nu p$ (and $\bar{\nu} p \longrightarrow \bar{\nu} p$)

$$\frac{d\sigma}{dT_p} \simeq \frac{G_F^2 M_p}{\pi}\left(1 + \frac{T_p}{T_p^{max}}\right) C_A^2$$

$$T_p^{max} \simeq \frac{2E_\nu^2}{M_p}$$

$$\sigma^{tot} \simeq \frac{G_F^2 E_\nu^2}{\pi} \cdot 3 C_A^2$$

Comparison to $\nu A \to \nu A$:

(Freedman 1974, Drukier & Stodolsky 1984)

$E_\nu \lesssim 50$ MeV $\longrightarrow$ $\lambda_\nu \gtrsim 4$ fm

coherent scattering from whole ^{12}C nucleus

$$\sigma^{tot}_{\nu\,^{12}C} \simeq \frac{G_F^2 N^2 E_\nu^2}{\pi} \sim \sigma^{tot}_{\nu p}$$

but

(i) $T^{max}_{\nu\,^{12}C} = \frac{1}{12} \cdot T^{max}_{\nu p}$

(ii) $\frac{d\sigma}{dT}$ strongly favors $T = 0$

(iii) light output from recoil ^{12}C
is heavily quenched

Comparison to $\nu e^- \to \nu e^-$:

Easy to detect an event.

Simple two-body kinematics.

but

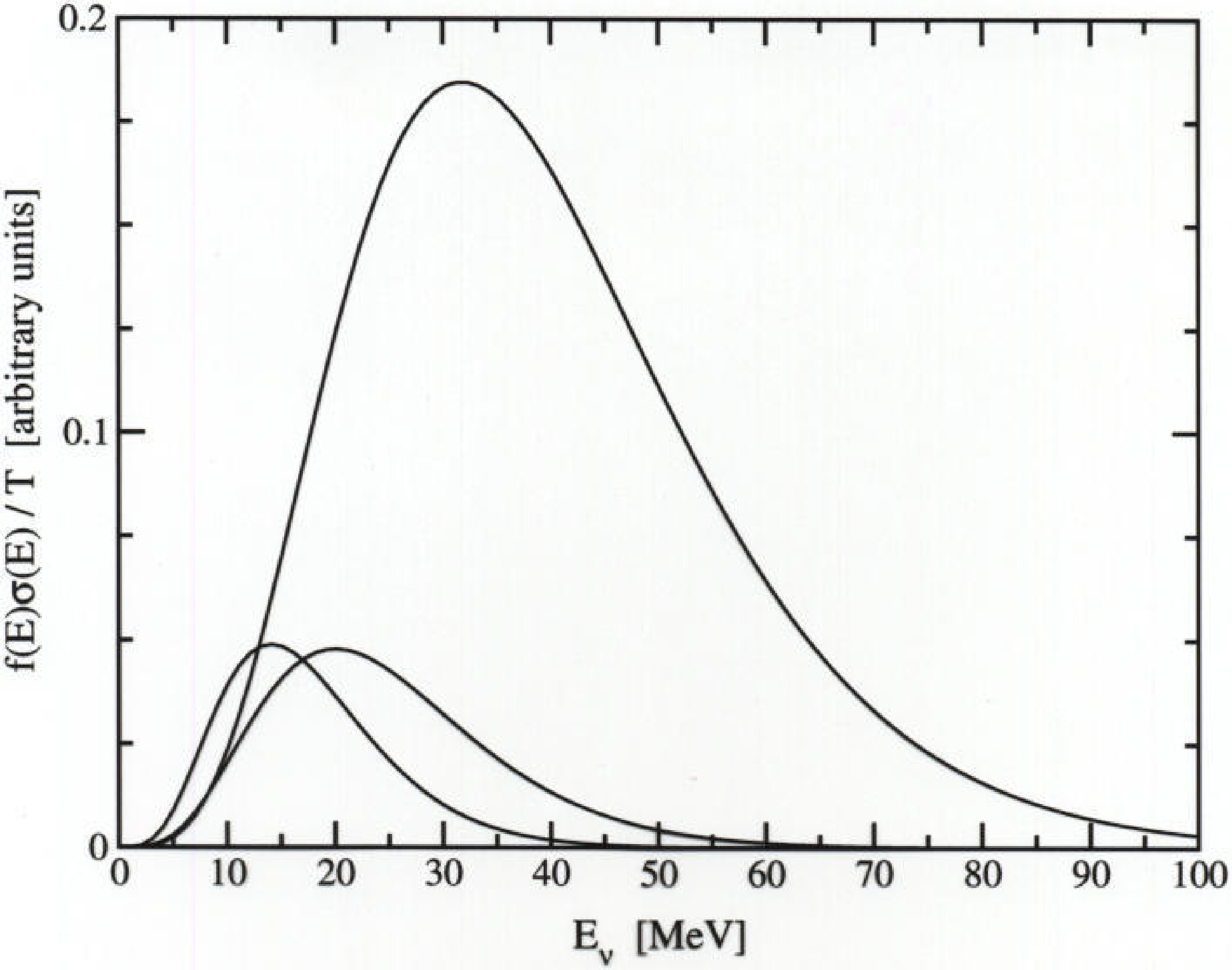
(i) Can't measure E_ν for each event.

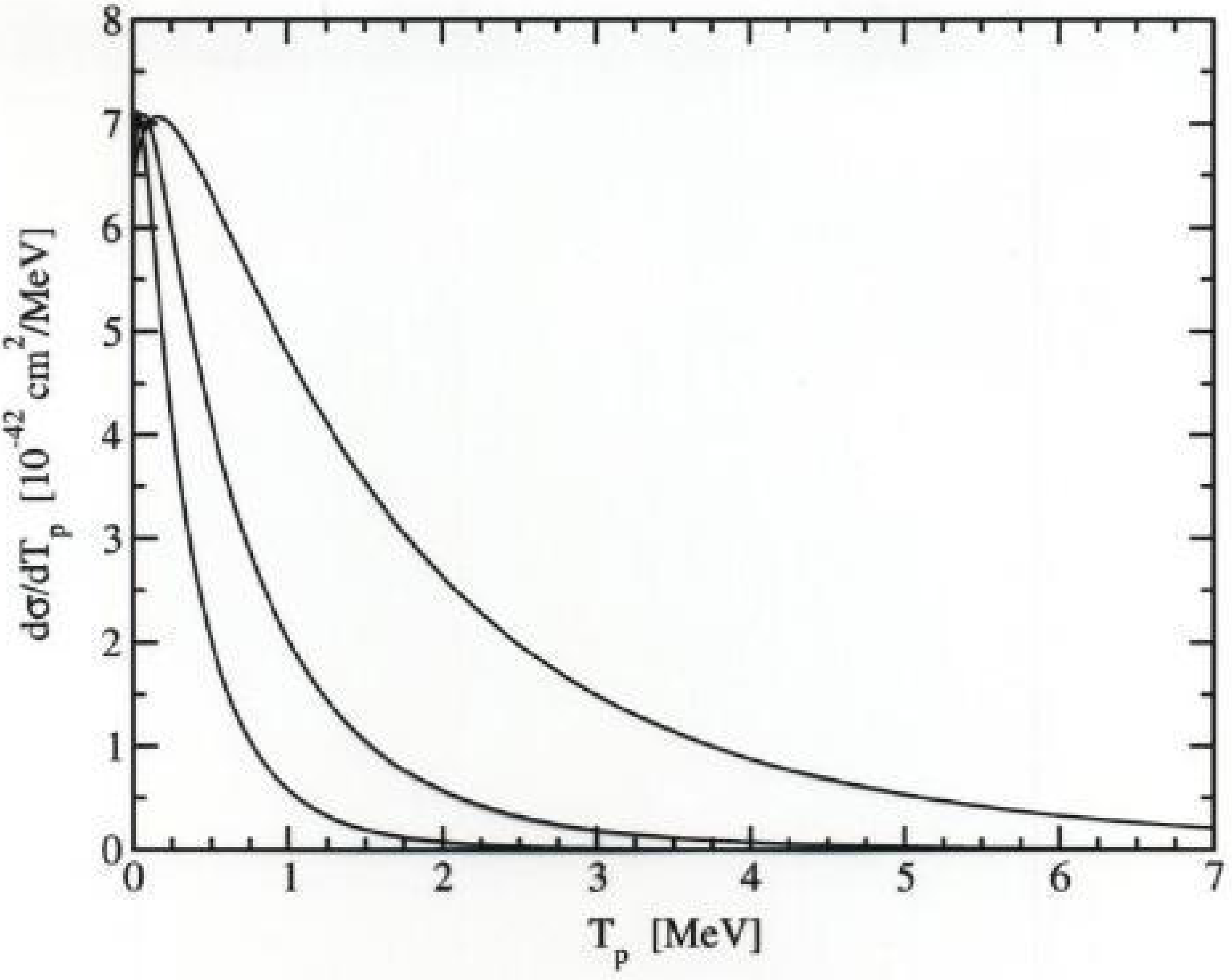
(ii) Hard to measure spectrum well.

(iii) $\sigma^{tot}_{\nu e^-} \sim \frac{m_e}{E_\nu} \cdot \sigma^{tot}_{\nu p}$

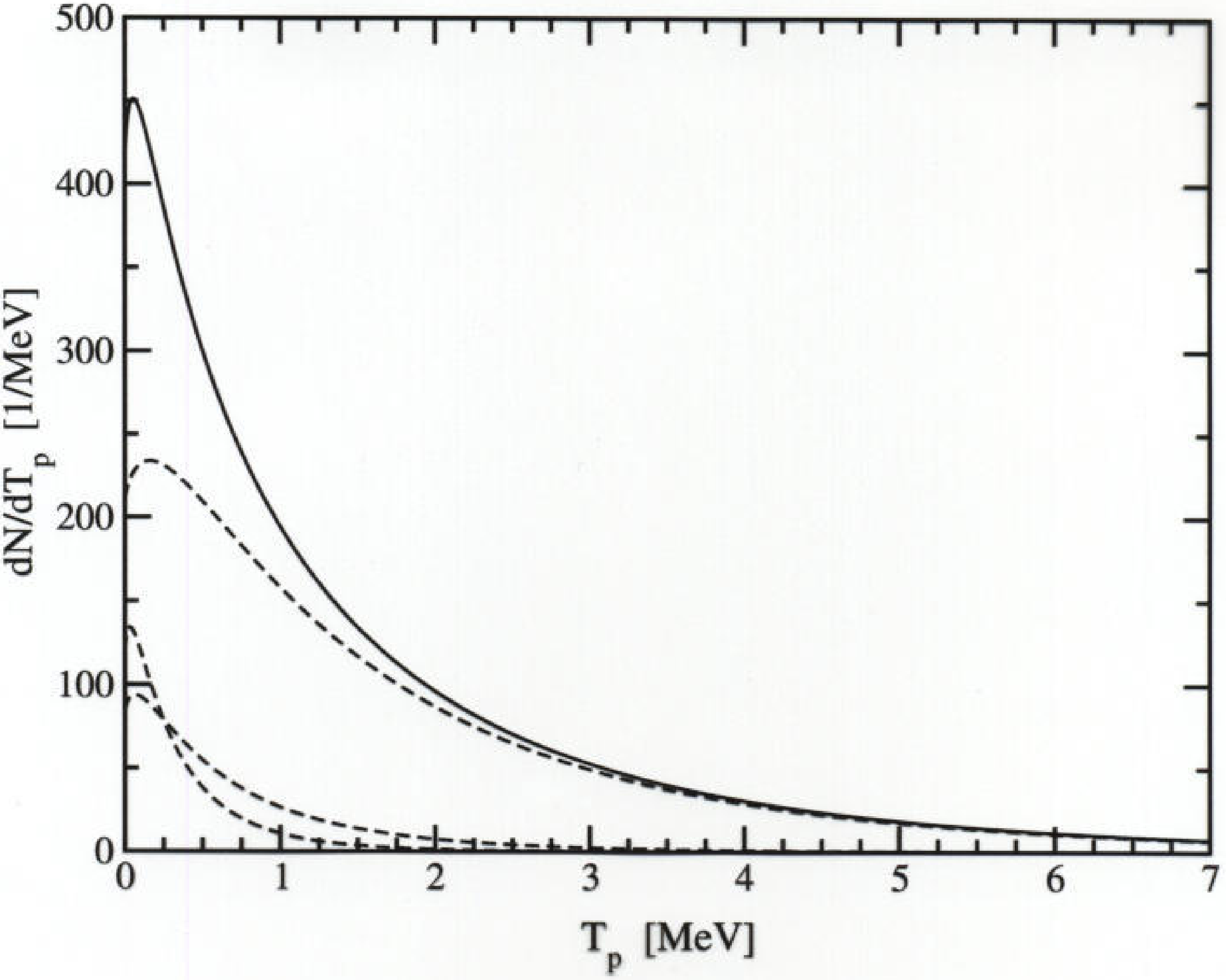
(iv) $T^{max}_{\nu e^-} \simeq E_\nu$ vs. $T^{max}_{\nu p} \simeq \frac{2E_\nu^2}{M_p}$

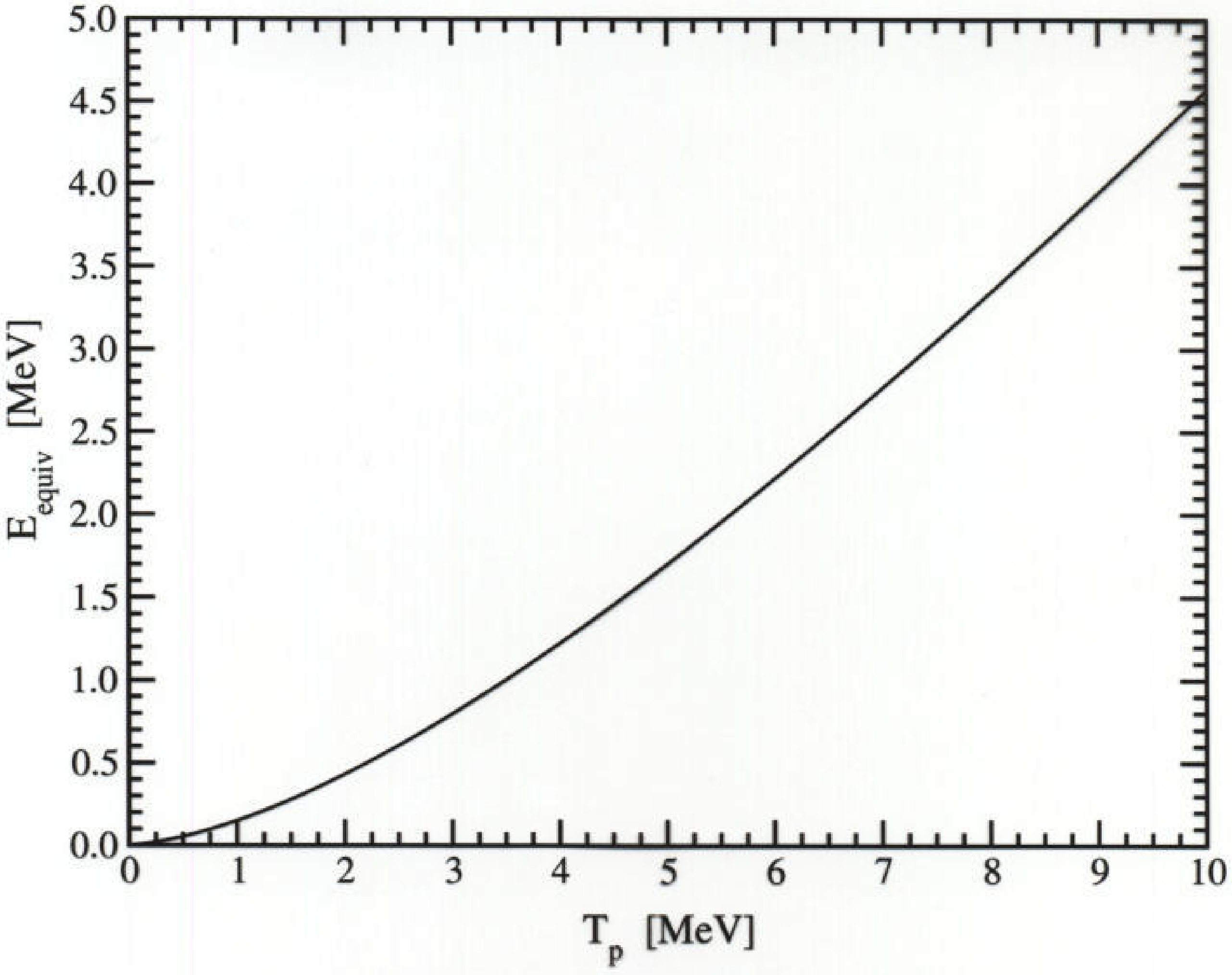
(v) $\frac{d\sigma}{dT}$ weakly favors $T=0$


0.2
0.1
0
f(E)σ(E) / T [arbitrary units]
0
10
20
30
40
50
60
70
80
90
100
E_ν [MeV]

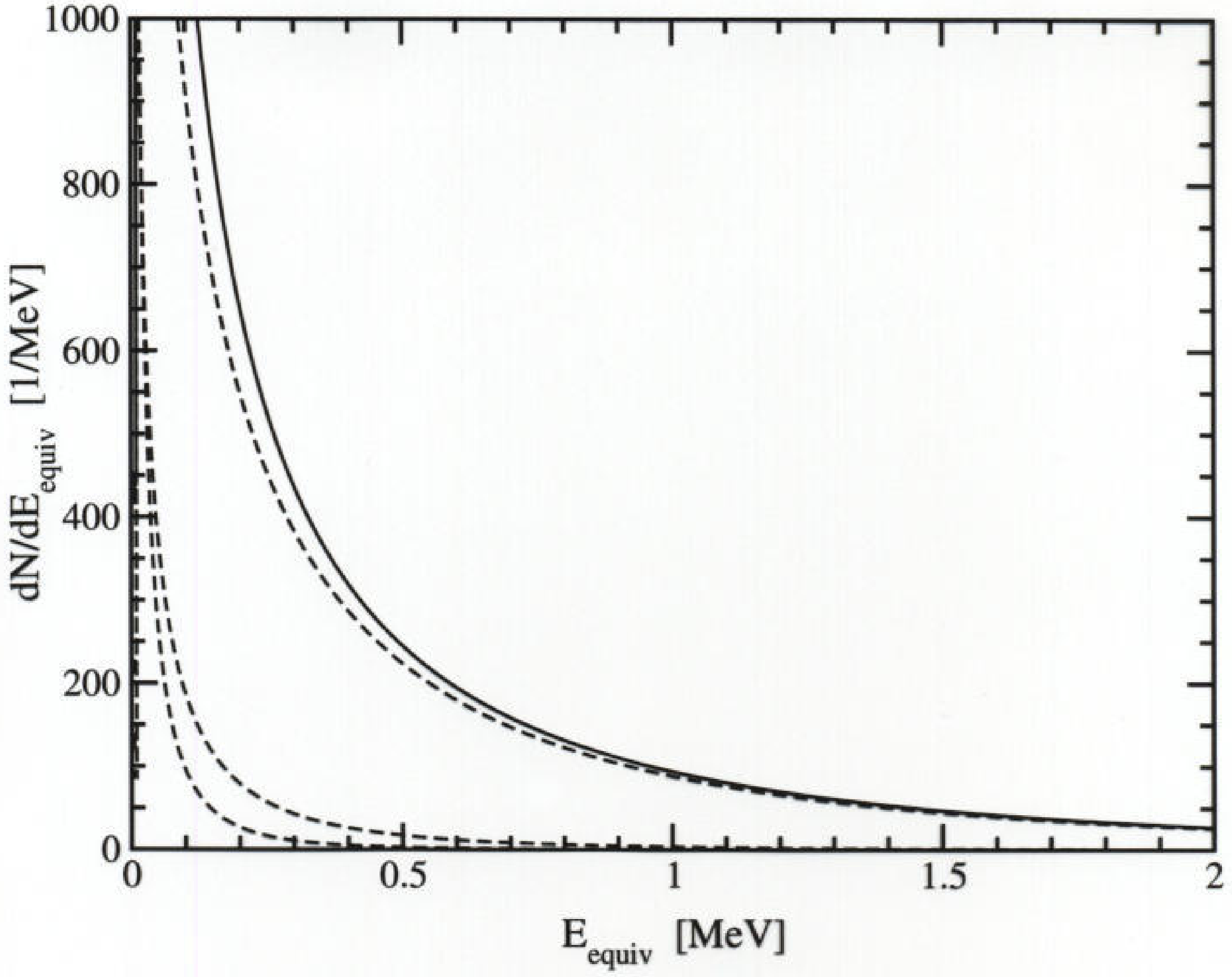


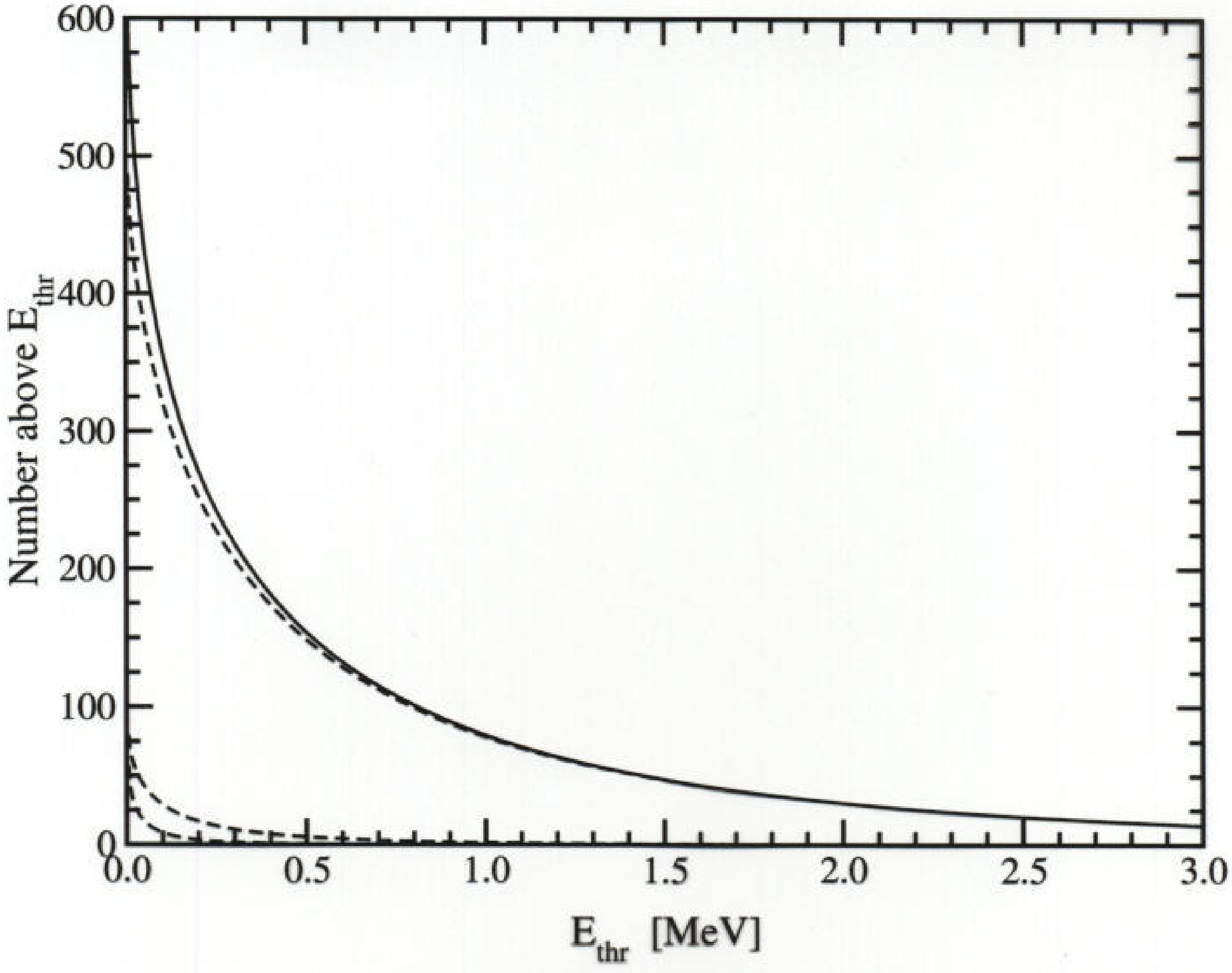
$d\sigma/dT_p$ [10^{-42} cm^2/MeV]
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
6
7
T_p [MeV]


dN/dT_p [1/MeV]
T_p [MeV]
0
100
200
300
400
500
0
1
2
3
4
5
6
7



$$\frac{E_{equiv}}{T_p} = \text{"quenching factor"}$$


1000
800
600
400
200
0
0
0.5
1
1.5
2
dN/dE_equiv [1/MeV]
E_equiv [MeV]


600
500
400
300
200
100
0
Number above E_{thr}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
E_{thr} [MeV]

flavor	$E_{thr} = 0$	$E_{thr} = 0.2\,\mathrm{MeV}$
ν_e	60	5
$\bar{\nu}_e$	80	20
$\nu_\mu + \nu_\tau + \bar{\nu}_\mu + \bar{\nu}_\tau$	490	250
ALL	630	275

bottom line:

- large NC sample
- totally clean
- proton recoil spectrum reflects the incoming neutrino spectrum

→ $\boxed{\text{Probably the best way to measure } E^{tot}_{4\nu_x} \text{ and } T_{\nu_x}.}$

Two Sanity Checks:

- $\nu + p \longrightarrow \nu + p$

  $E_\nu \simeq 45 \text{ MeV} \longrightarrow T_p \simeq 4 \text{ MeV}$

or

  $n + p \longrightarrow n + p$

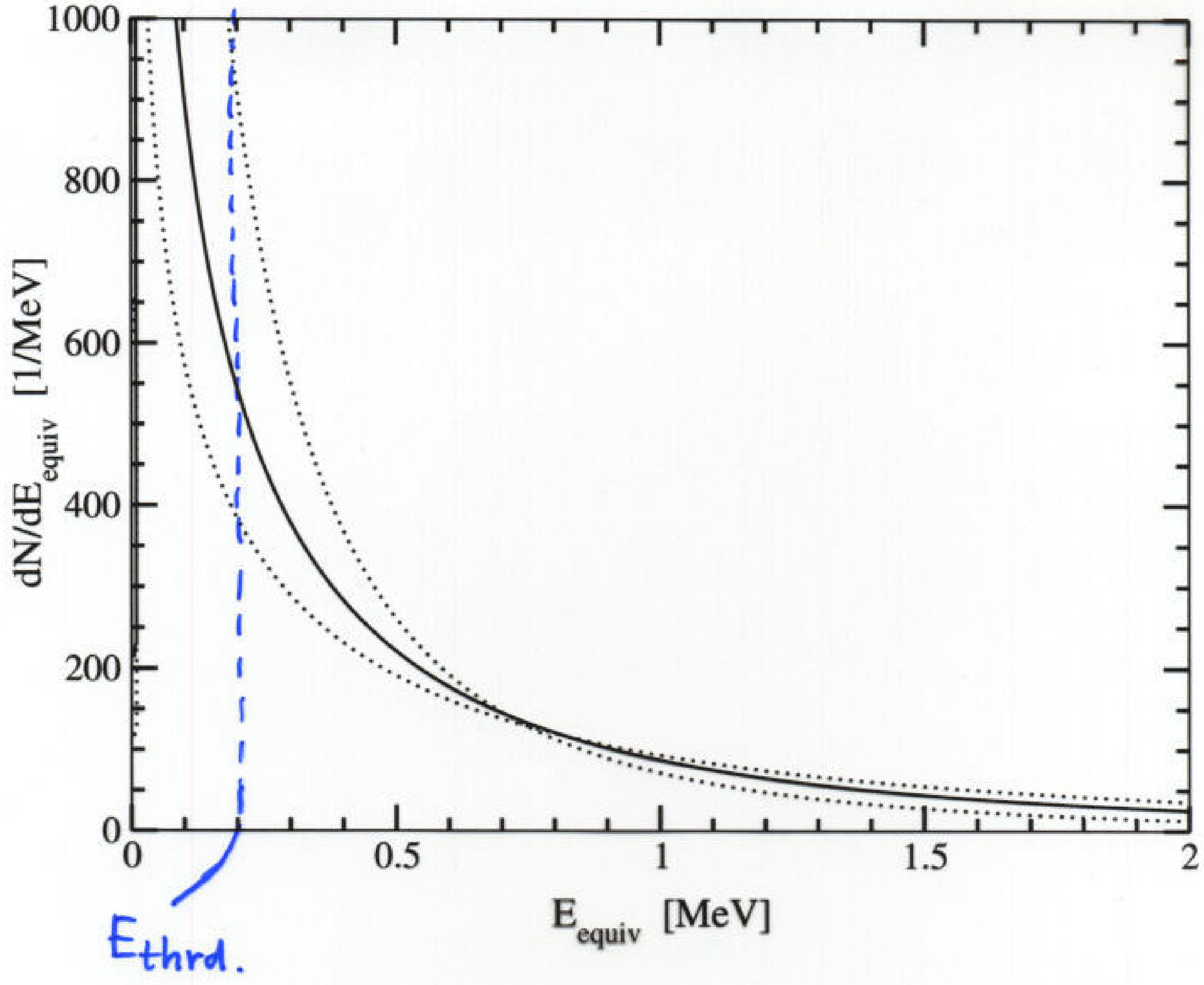
  $T_n \simeq 8 \text{ MeV} \longrightarrow T_p \simeq 4 \text{ MeV}$

  All aspects of detection are identical

- KamLAND solar background requirement above a similar threshold is

  $$\text{Rate} \lesssim 10^{-3} \text{ Hz}.$$

  We only need Rate $\lesssim$ 1 Hz.

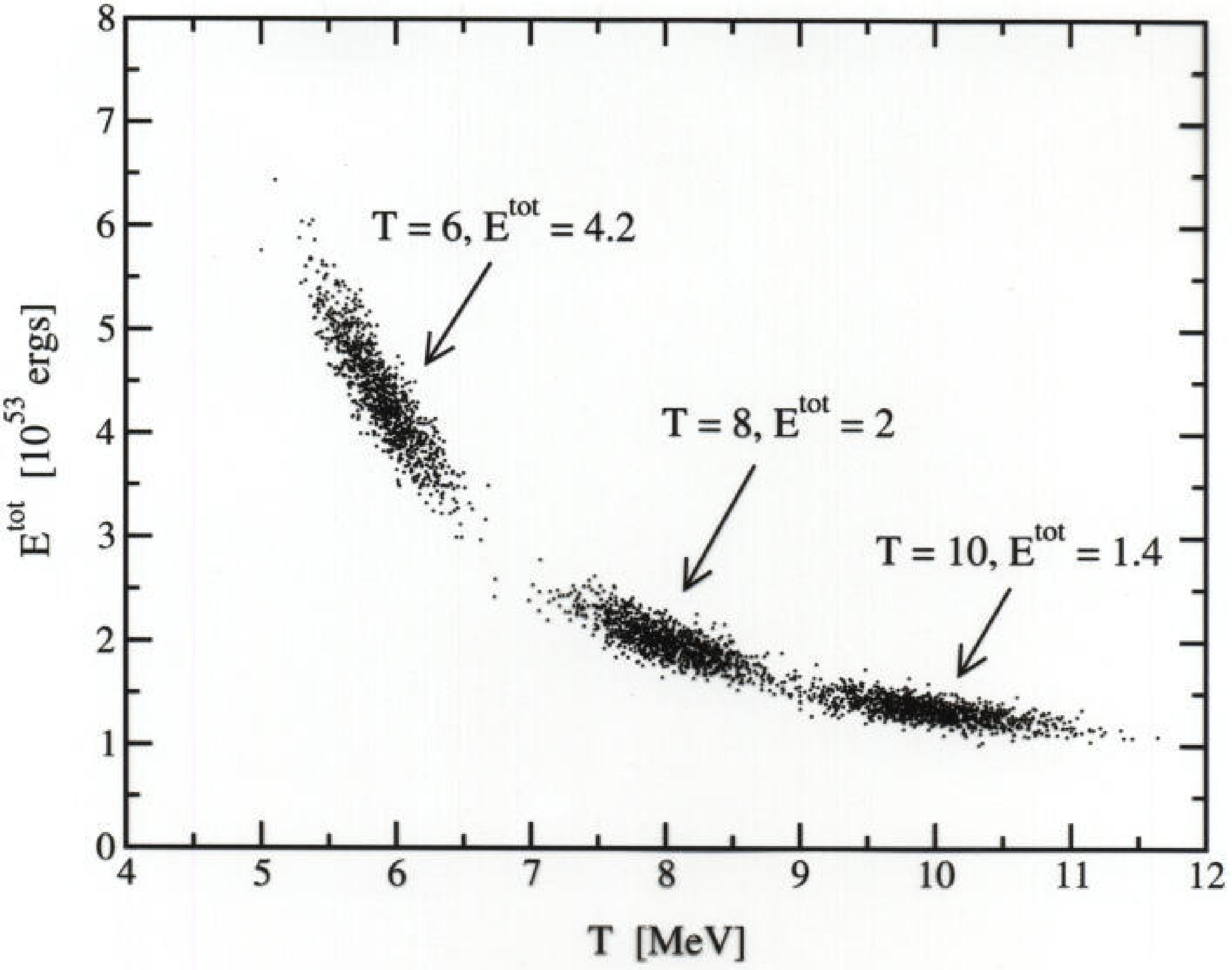


Solid line: $E^{tot} = 2 \times 10^{53}$ ergs, T = 8 MeV

upper line: $E^{tot} = 1.4 \times 10^{53}$ ergs, T = 10 MeV

lower line: $E^{tot} = 4.2 \times 10^{53}$ ergs, T = 6 MeV

All with the <u>same</u> number of events in E_{equiv} in [0.2MeV, ∞).



If supernova distance is unknown, must marginalize over E^{tot}.

$$\boxed{\delta E^{tot}, \delta T \sim 10\%}$$

10^3 events used in each Monte Carlo.

Conclusions

- E^{tot} and T for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ are presently quite uncertain. A lot of present work depends on assumptions.

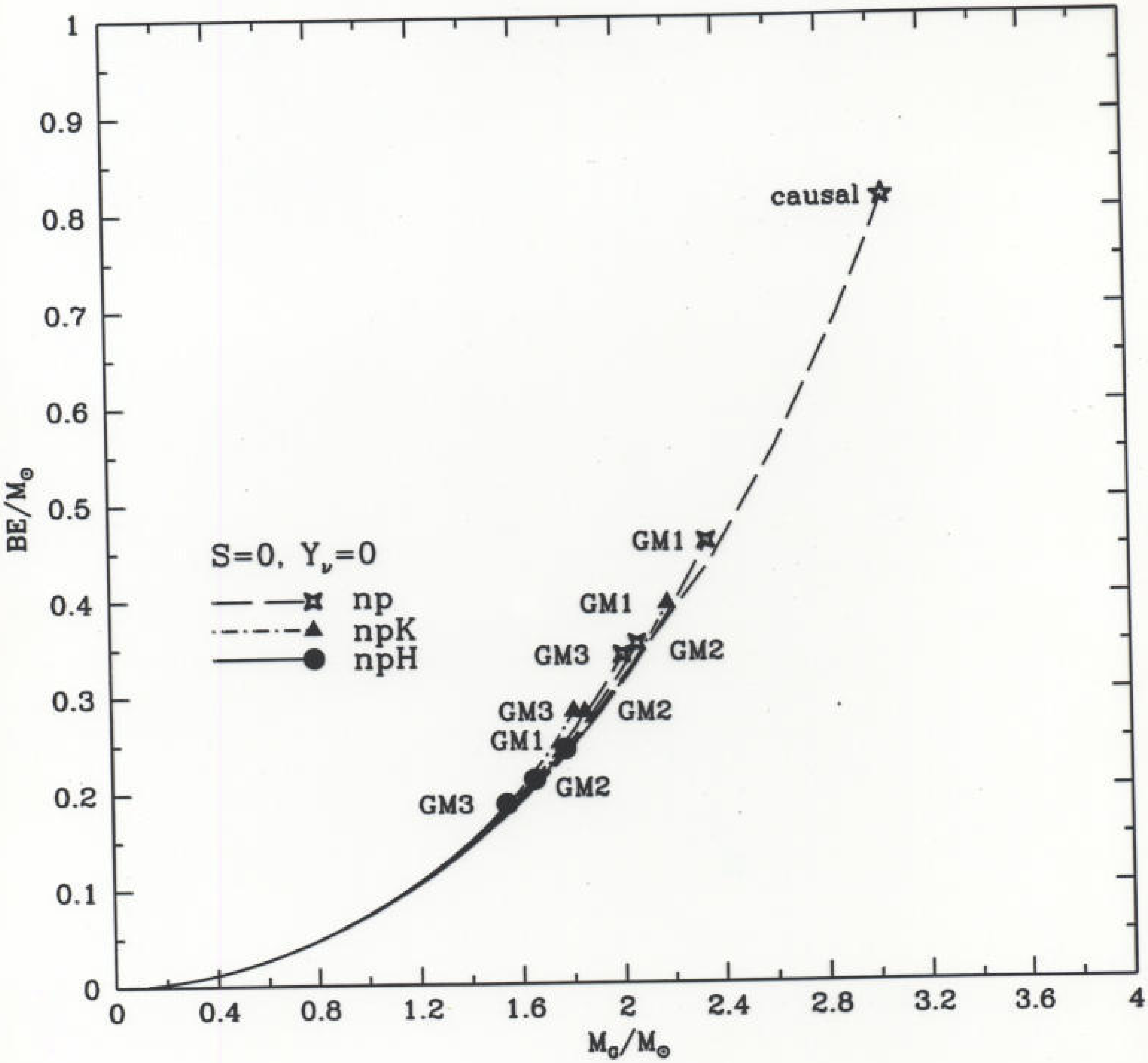
- $\nu + p \rightarrow \nu + p$ and $\bar{\nu} + p \rightarrow \bar{\nu} + p$ can be measured in KamLAND and Borexino, making them premier SN neutrino observatories.

$$\boxed{E^{tot}, T \text{ can be measured to} \sim 10\%.}$$

- Crucial for

  Comparison to SN models
  Neutrino oscillations
  Total binding energy

Beacom, Farr, and Vogel, hep-ph/020522



Lattimer & Prakash

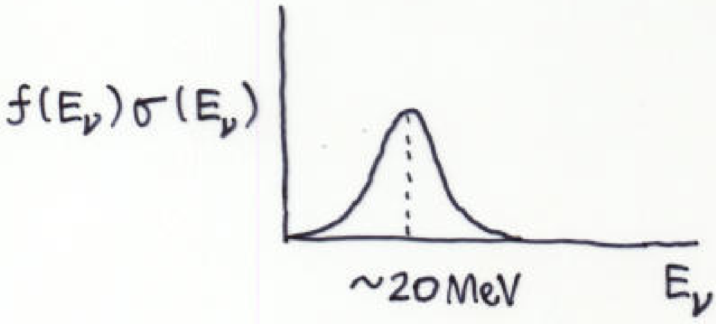
$$BE \simeq \frac{3}{5}\frac{GM_{NS}^{2}}{R_{NS}}$$

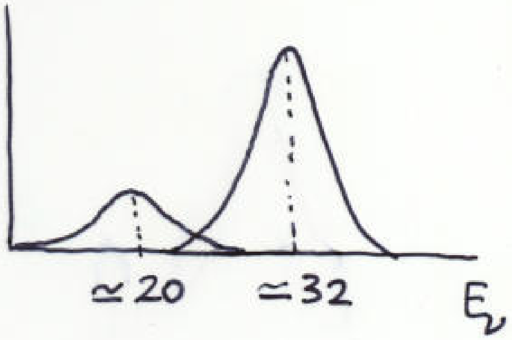
SN Neutrino Oscillations:

- Oscillations to steriles reduce numbers of events
- Oscillations among $\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau$ irrelevant
- Oscillations $\nu_e \longleftrightarrow \nu_\mu, \nu_\tau$ or $\bar{\nu}_e \longleftrightarrow \bar{\nu}_\mu, \bar{\nu}_\tau$:

  Main effect is to swap in a "hot" spectrum

Example: $\bar{\nu}_e p \longrightarrow e^+ n$ $\quad \sigma(E_\nu) \sim E_\nu^2$





$$\boxed{\begin{array}{l}\text{peak at } \simeq 4T \\ \text{integral} \simeq \dfrac{\langle\sigma\rangle}{T} \simeq T\end{array}}$$

$T_{\bar{\nu}_e} \simeq 5\,\text{MeV}$

$T_{\nu_x} \simeq 8\,\text{MeV}$

- Similar for $\nu + d, {}^{12}C, {}^{16}O, {}^{208}Pb, \ldots\ldots$

SN Neutrino Oscillations (cont.)

See recent papers by

Barger, Marfatia, Wood
Minakata, Nunokawa, Tomas, Valle
Akmedhov, Lundardini, Smirnov
Sato et al.
Balantekin et al.
Fogli et al.
Schirato and Fuller

and many others....