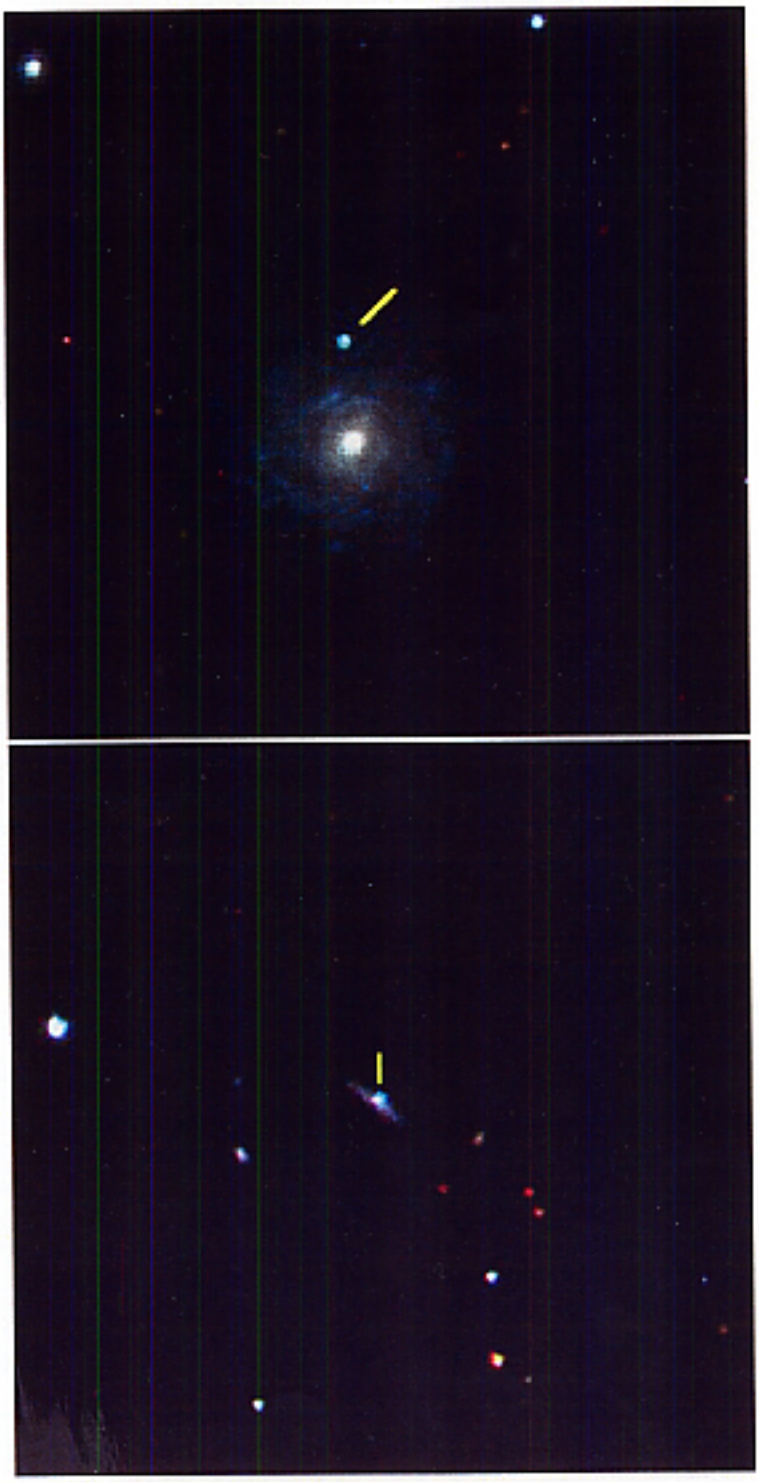
Supernovae in the SDSS



SN 1999dk

$z = 0.015$

$D \simeq 65$ Mpc

new!

$z = 0.049$

$D \simeq 210$ Mpc

D. Vanden Berk et al. (2001)

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)

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

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

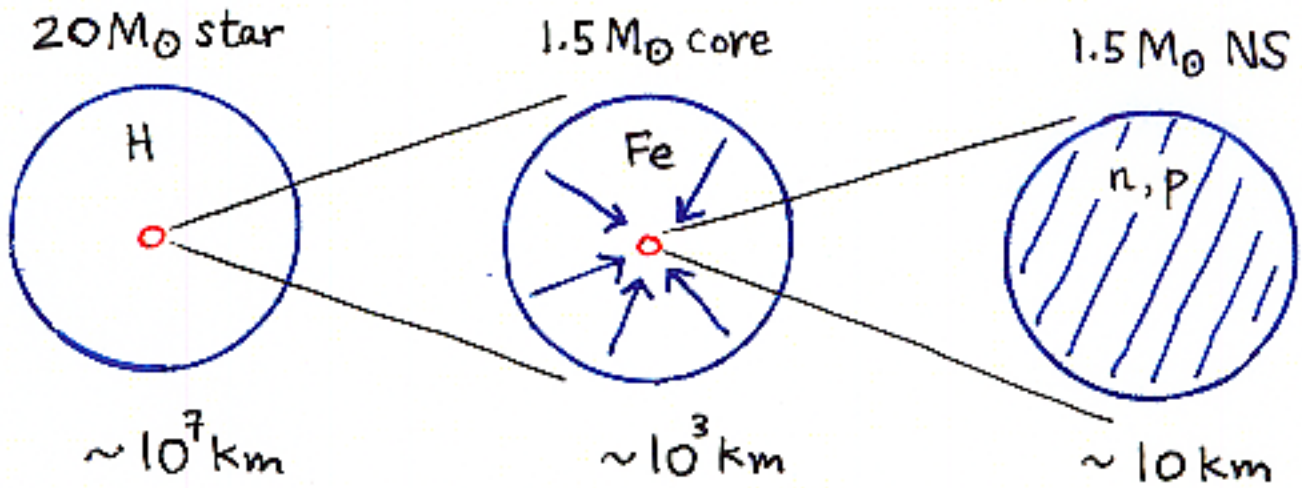
$$\boxed{\text{SN rate} \simeq \frac{0.7/\text{century}}{0.06} \simeq 10/\text{century in whole Galaxy}}$$

- Other estimates:

  (van den Bergh, Tammann, etc)

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

Supernova: Core-Collapse



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

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

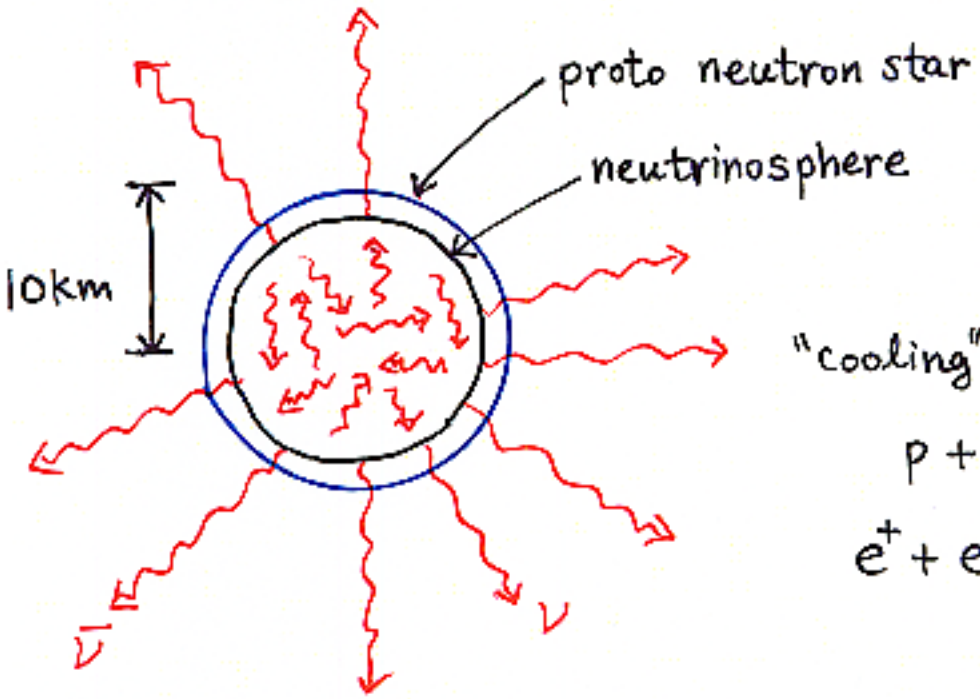
$$\simeq 2 \times 10^{59} \text{ MeV}$$

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:

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

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

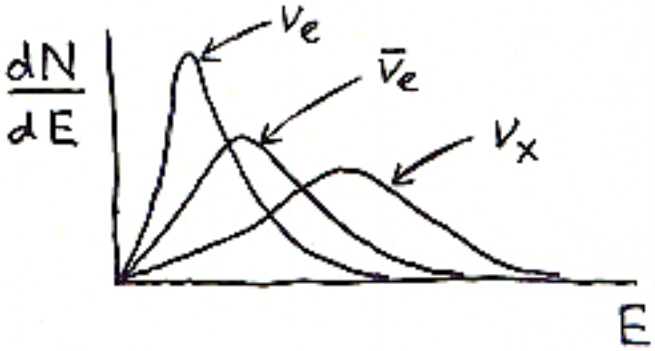
etc.

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

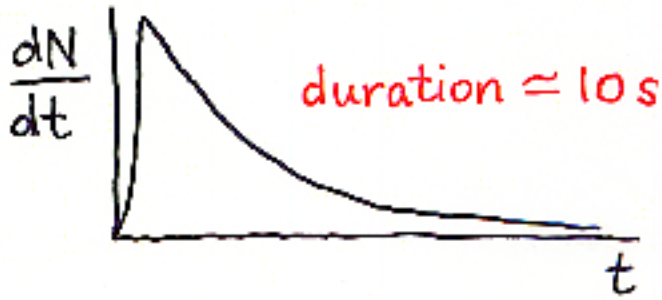
$\langle E_{\nu_e} \rangle \simeq 11$ MeV

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

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



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



September 19, 2001 Jobs with TSI at SUNY-SB

- Senior Research Scientist
- Postdoctoral Research Associate

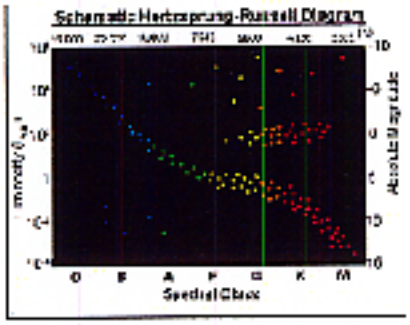
September 5, 2001 The Terascale Supernova Initiative unveils new website

The Terascale Supernova Initiative is a multidisciplinary collaboration of one national lab and eight universities to develop models for core collapse supernovae and enabling technologies in radiation transport, radiation hydrodynamics, nuclear structure, linear systems and eigenvalue solution, and collaborative visualization.

TSI is sponsored by the Department of Energy's Office of Science Scientific Discovery Through Advanced Computing program.

Private site

Stellar Evolution

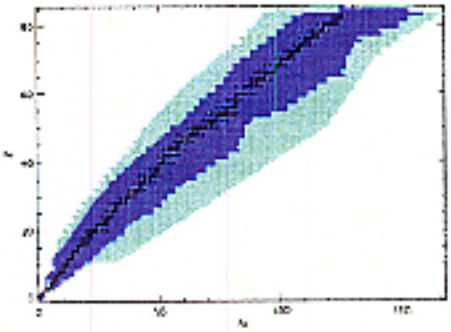


Hertzsprung-Russell Diagram

Supernovae

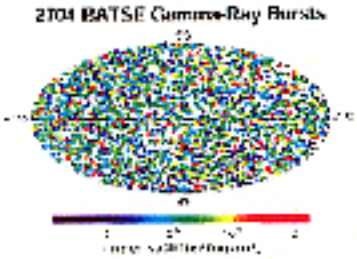
Stellar Montage
Credit:A. Burrows ,University of Arizona

Nucleosynthesis & Nuclear Astrophysics



The Whole Thing:
Nucleosynthesis network including *all* stable isotopes (black)

GRBs & XRBs



BATSE GRB Final Sky Map
Credit: G. Fishman et al., BATSE, CGRO,NASA

ANNOUNCEMENTS:

- Welcome to the new Supernova Science Center
- Please remember this is is still under construction

Sponsored by:
The Department of Energy
Scientific Discovery Through Advanced Computing

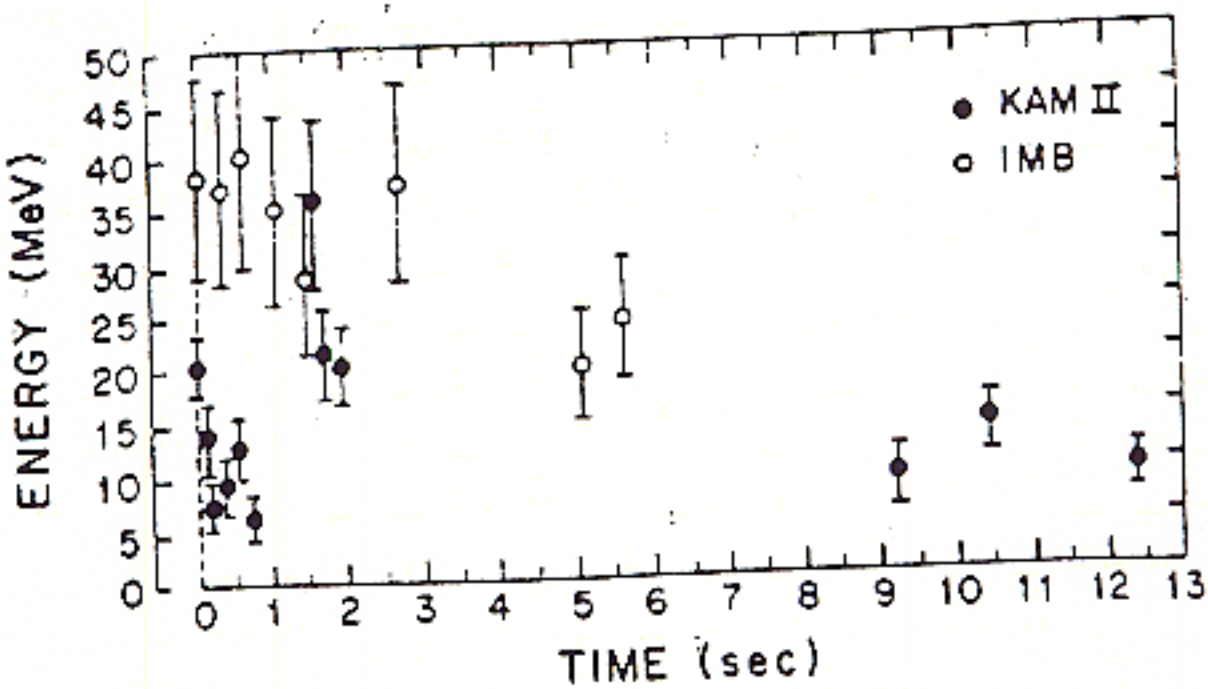


FIG. 15. Scatter plot of energy and time of the 12 events in the burst sample observed in Kamiokande-II, and the 8 events in the burst sample observed in the IMB detector. The earliest event in the sample of each detector has, arbitrarily but not unreasonably, been assigned $t = 0$.

What if $m \simeq 20\,\text{eV}$?

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

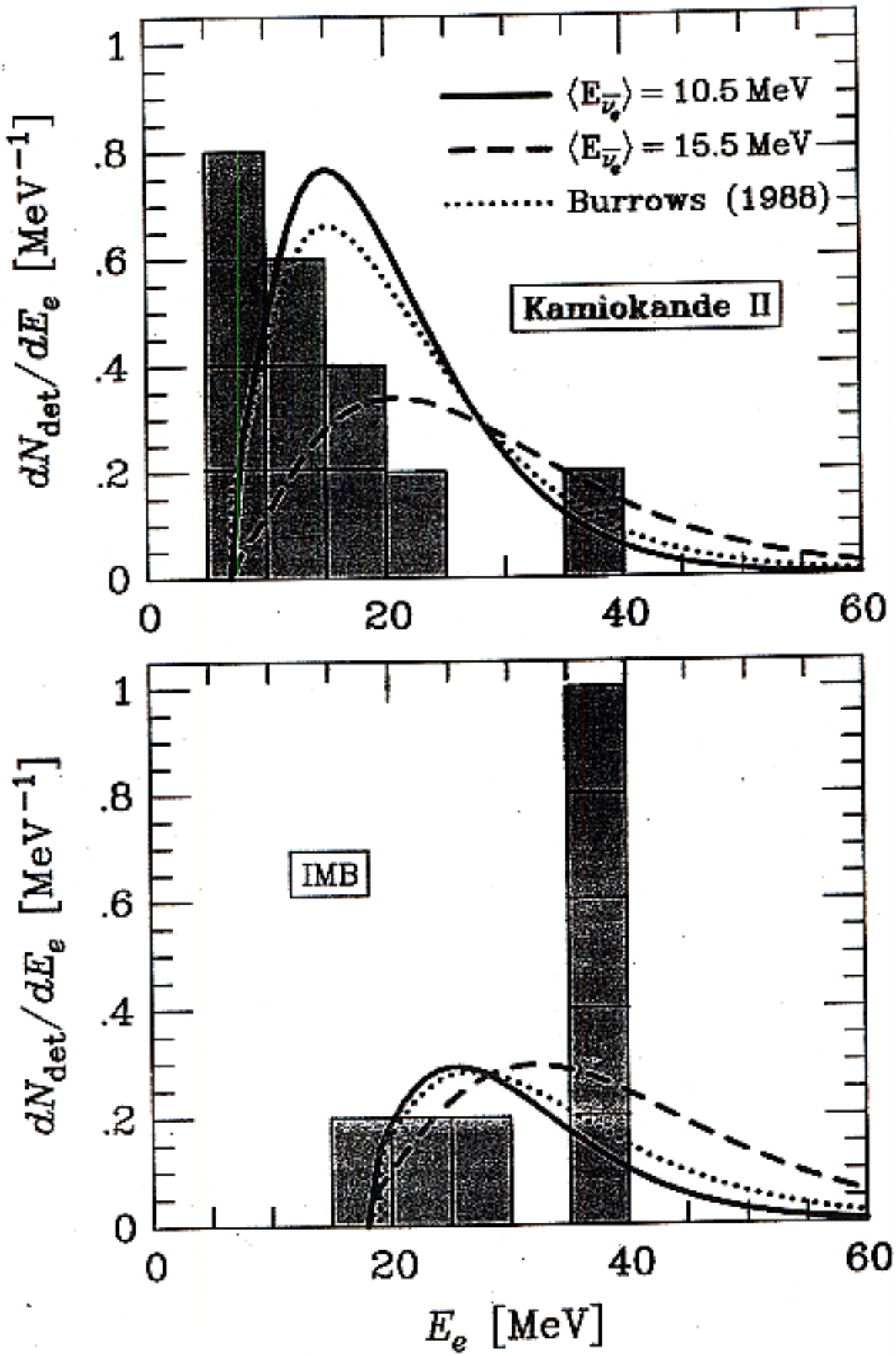
$$\Delta t(\text{IMB}) \simeq 0.5 \left(\frac{20}{35}\right)^2 5 \simeq 1\,s$$

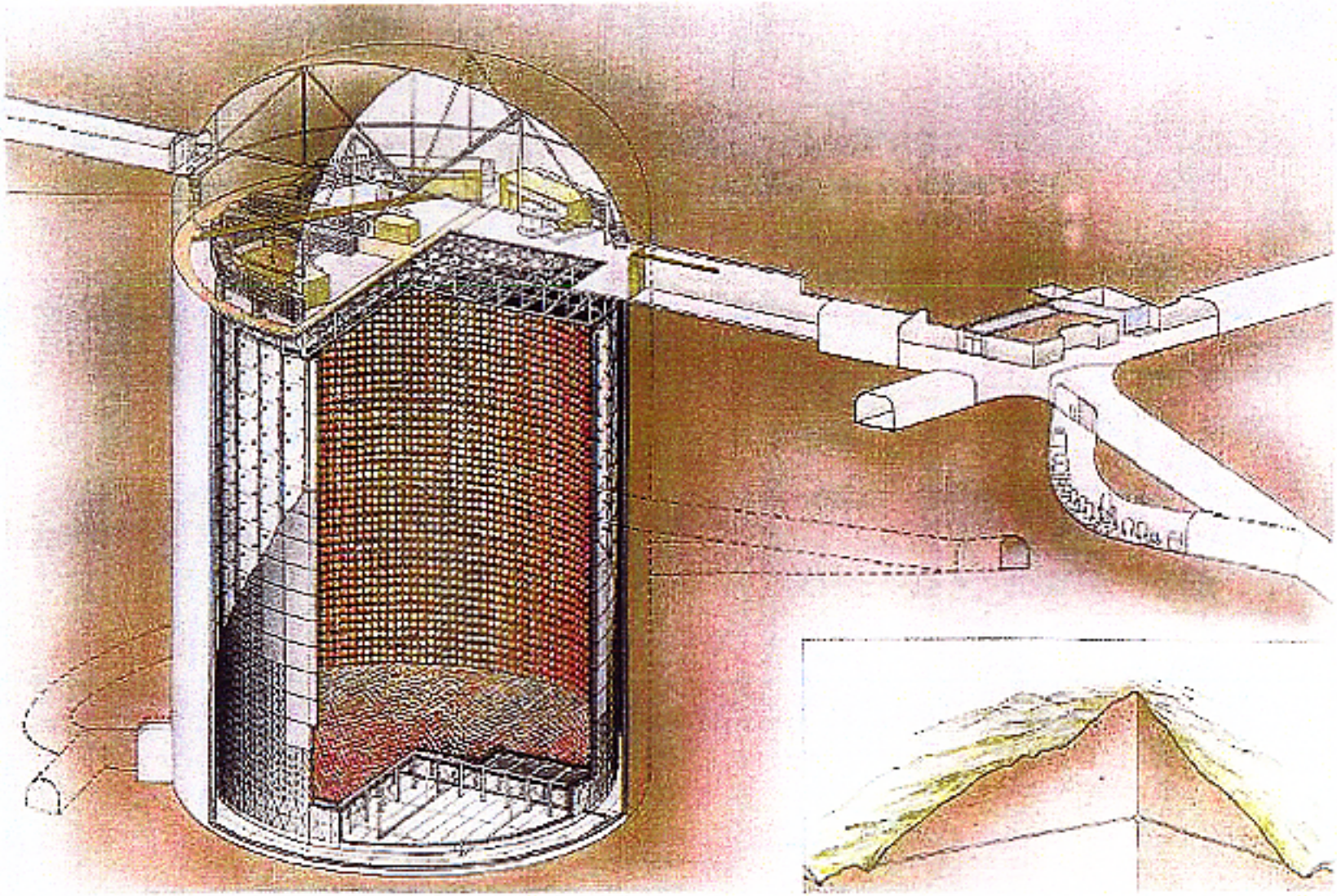
$$\Delta t(\text{KamII}) \simeq 0.5 \left(\frac{20}{15}\right)^2 5 \simeq 4\,s$$

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

not seen, so $m \lesssim 20\,\text{eV}$

SN 1987 A Neutrino Signal





SUPERKAMIOKANDE [illegible] ICRR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

[illegible]

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
$\bar{\nu}_e + p \rightarrow e^+ + n$ ($E_{e^+} \leq 10$ 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

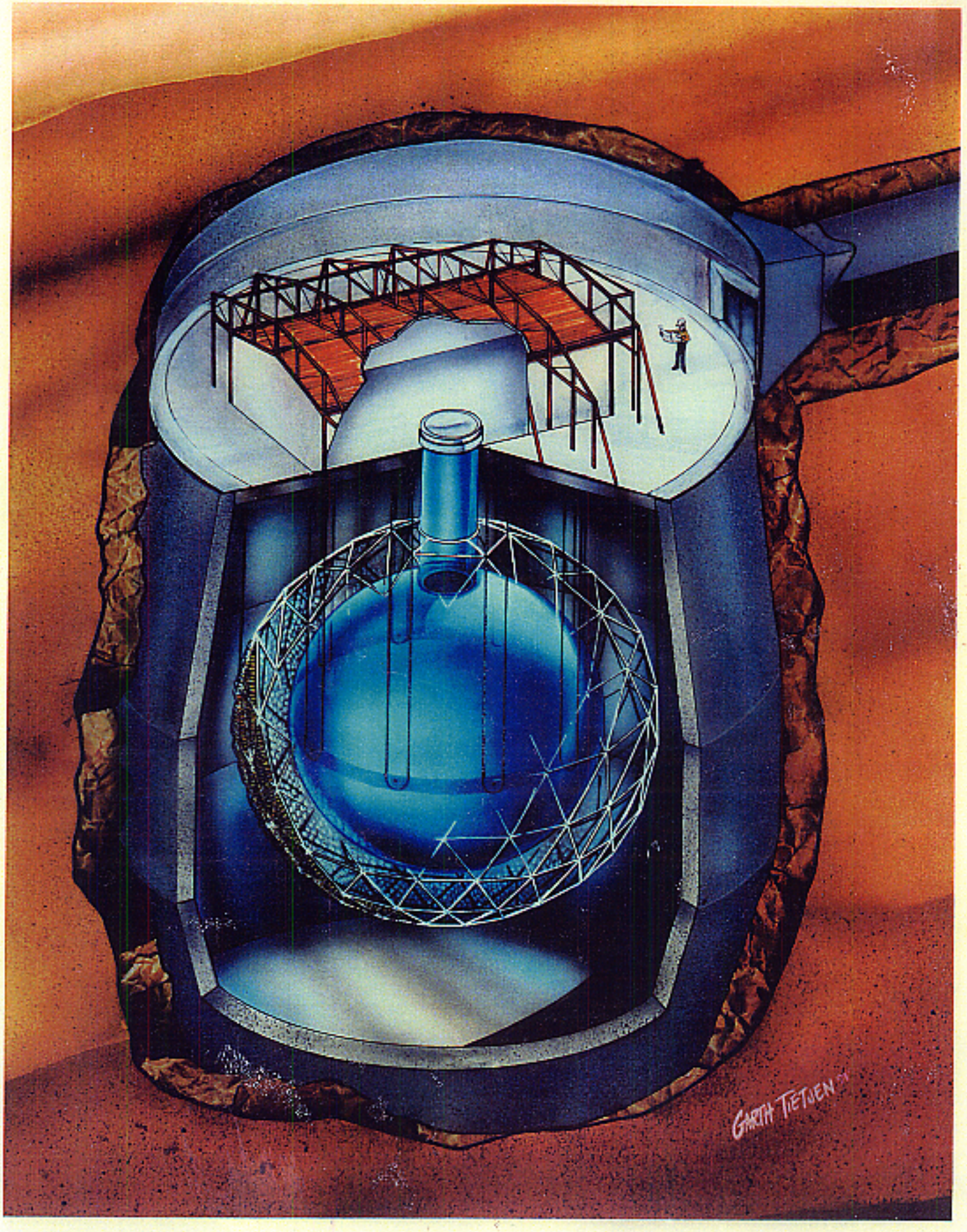

GARTH TIETJEN

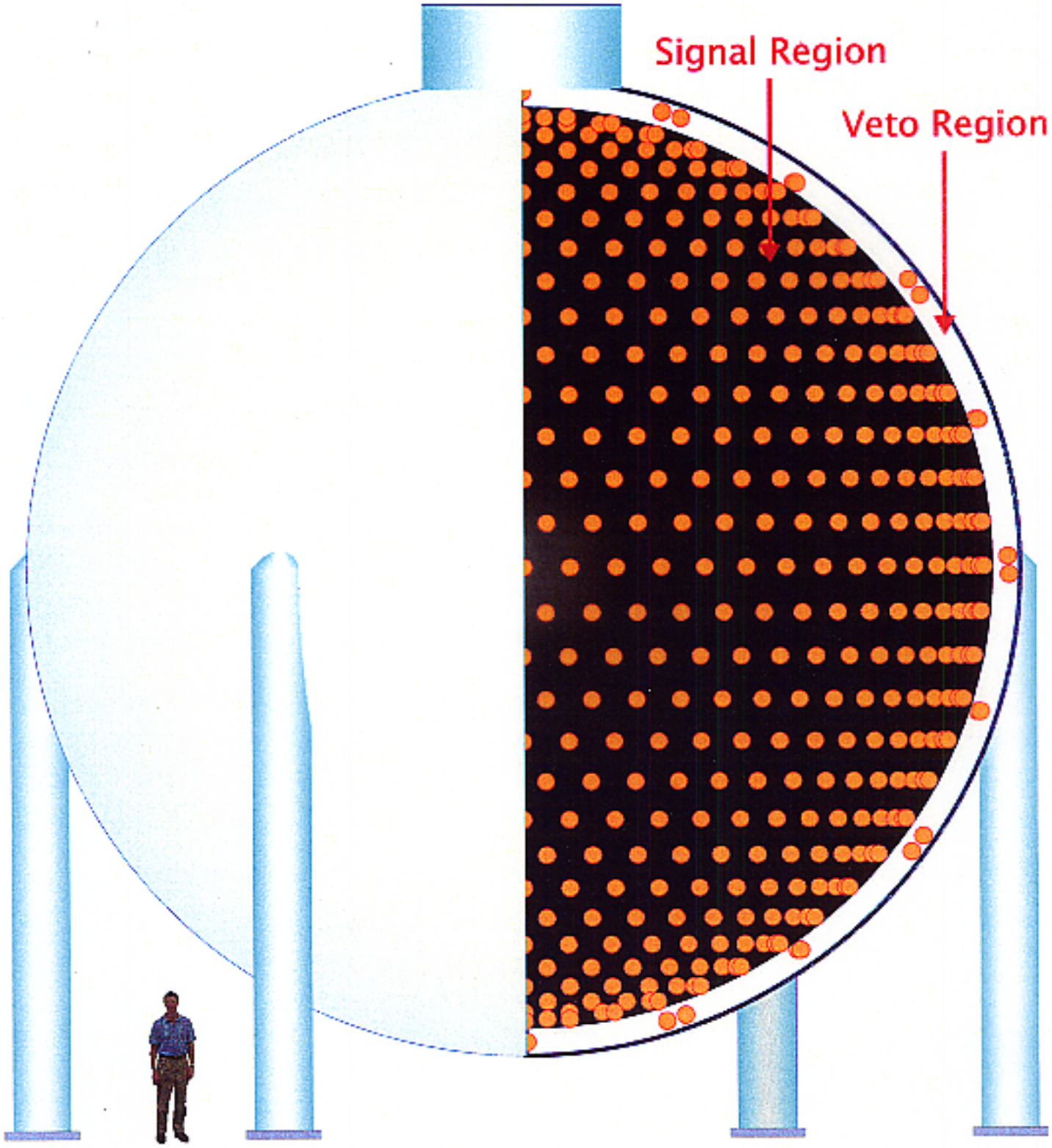
TABLE I. Calculated numbers of events expected in SNO for a supernova at 10 kpc. The other parameters (e.g., neutrino spectrum temperatures) are given in the text. In rows with two reactions listed, the number of events is the total for both. The notation ν indicates the sum of ν_e, ν_μ, and ν_τ, though 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		
$\nu + d \rightarrow \nu + p + n$ $\bar{\nu} + d \rightarrow \bar{\nu} + p + n$	detected particle(s) : n	485
$\nu_e + d \rightarrow e^- + p + p$ $\bar{\nu}_e + d \rightarrow e^+ + n + n$	e^-, e^+nn	160
$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \gamma + X$ $\bar{\nu} + {}^{16}\mathrm{O} \rightarrow \bar{\nu} + \gamma + X$	$\gamma, \gamma n$	20
$\nu + {}^{16}\mathrm{O} \rightarrow \nu + n + {}^{15}\mathrm{O}$ $\bar{\nu} + {}^{16}\mathrm{O} \rightarrow \bar{\nu} + n + {}^{15}\mathrm{O}$	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
$\nu + {}^{16}\mathrm{O} \rightarrow \nu + \gamma + X$ $\bar{\nu} + {}^{16}\mathrm{O} \rightarrow \bar{\nu} + \gamma + X$	γ	30
$\nu + e^- \rightarrow \nu + e^-$ $\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$	e^-	15

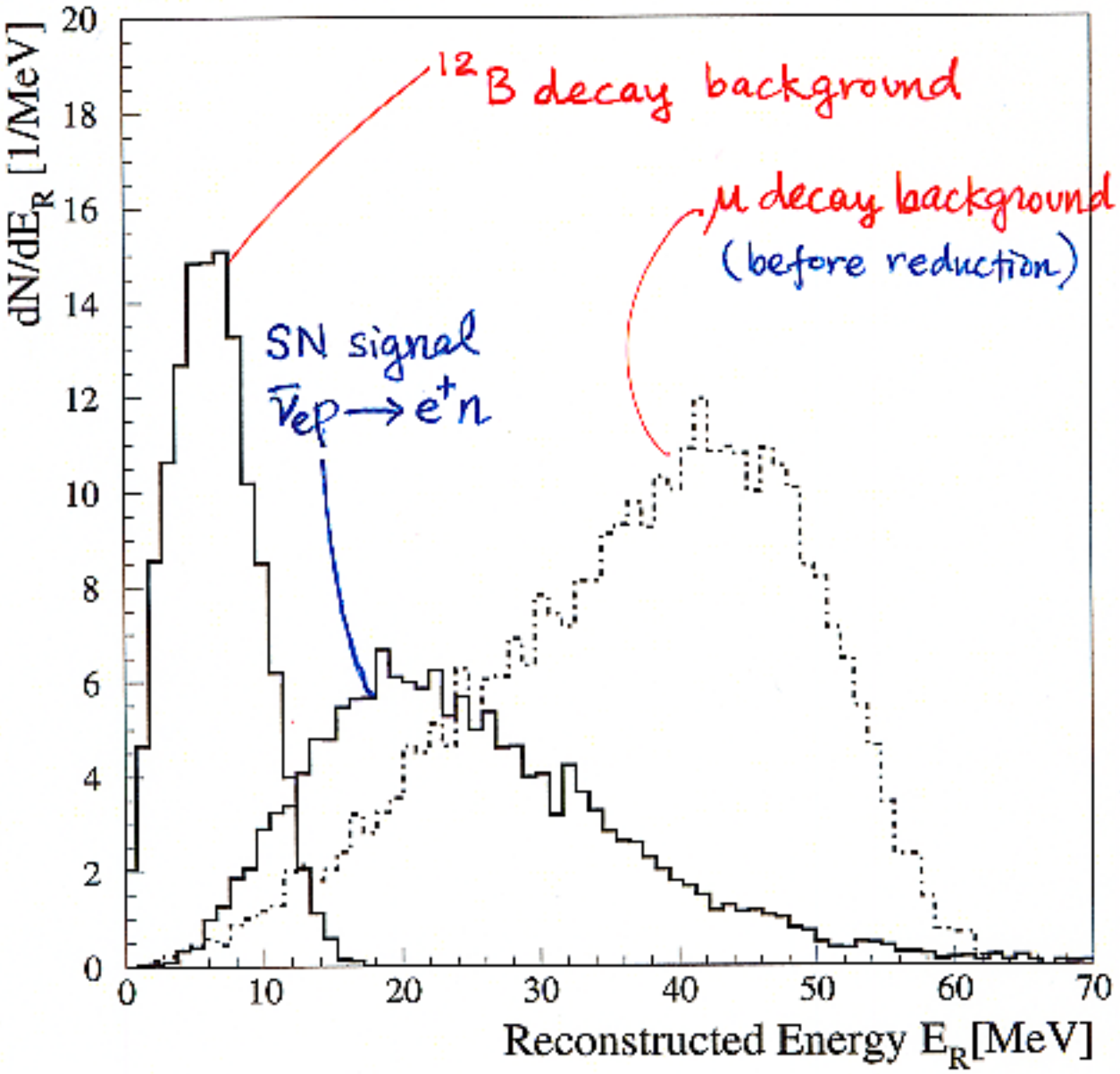
- detected particles
- NC : dominated by ν_μ, ν_τ

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

MiniBooNE Detector



Supernova Neutrinos in Mini-Boone



M. Sharp, J. Beacom, J. Formaggio

Early Alert Network

Expect a blizzard of emails....

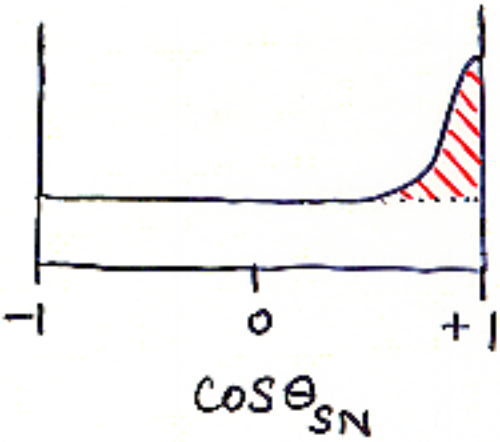
- When and where did it happen?
- How long did it last?
- What is the mass of the newly-formed object?
- Which of two types is it?

... and ...

- Do we know anything about the progenitor?

SN ν-Location (SK)

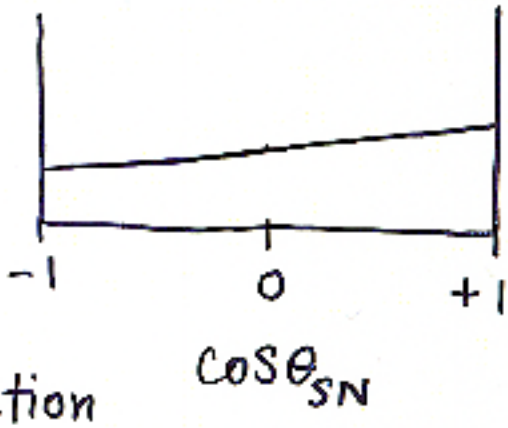
- $\boxed{\nu + e^- \rightarrow \nu + e^-}$



$N \simeq 300$ forward

but large background

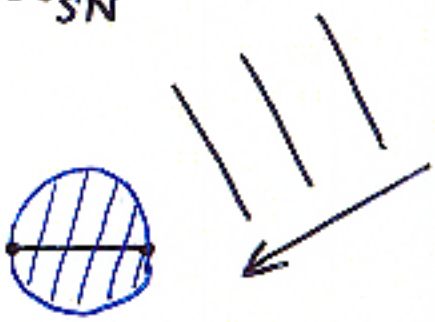
- $\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$



$N \simeq 10^4$

but weak angular distribution

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



separate detectors in network

but pulse duration >> Earth diameter

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

hep-th/0006071

arXiv:hep-th/0006071 v1 10 Jun 2000

Noncommutative Tachyons And String Field Theory

Edward Witten

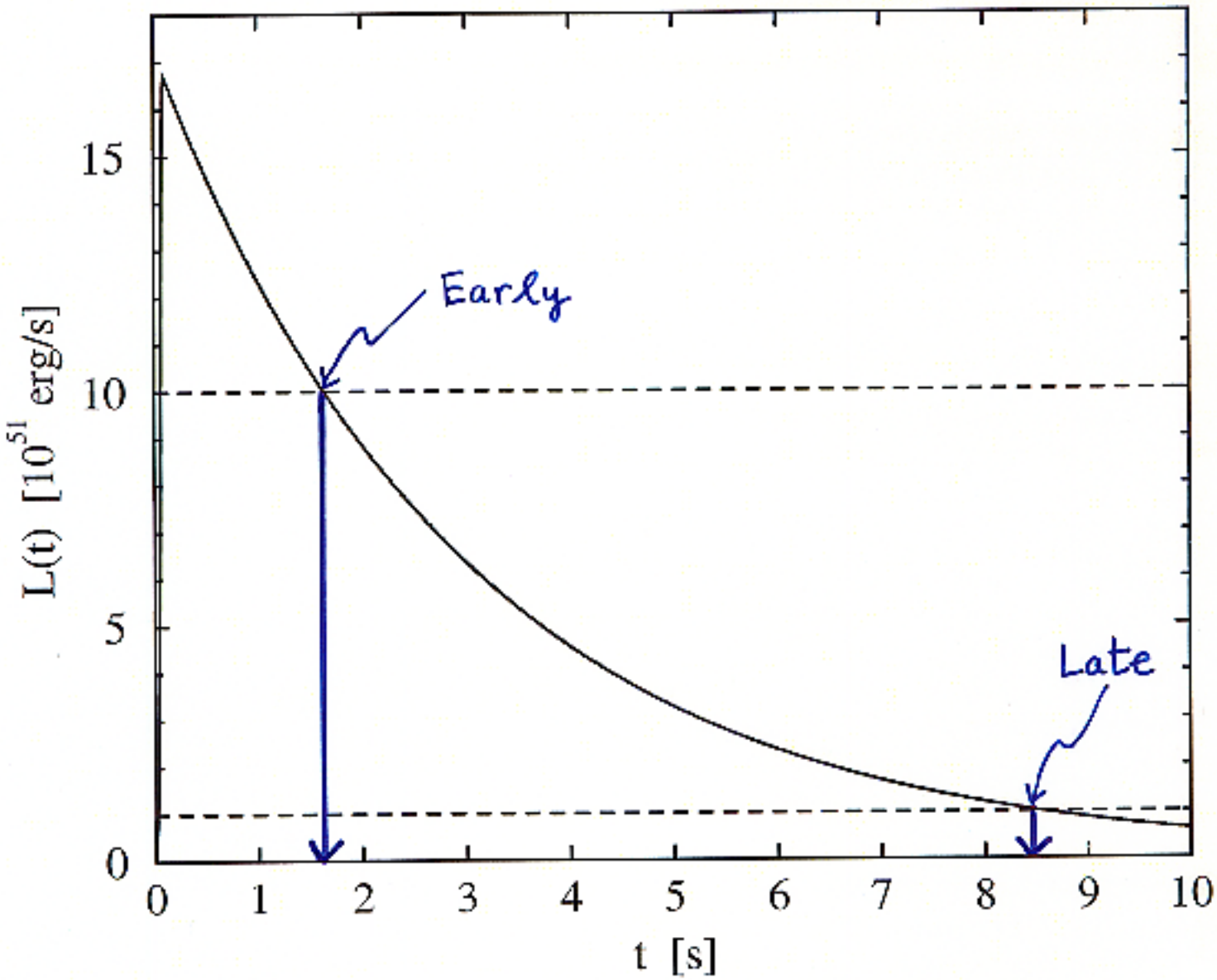
Dept. of Physics, Cal Tech, Pasadena, CA

and

CIT-USC Center For Theoretical Physics, USC, Los Angeles CA

It has been shown recently that by turning on a large noncommutativity parameter, the description of tachyon condensation in string theory can be drastically simplified. We reconsider these issues from the standpoint of string field theory, showing that, from this point of view, the key fact is that in the limit of a large B-field, the string field algebra factors as the product of an algebra that acts on the string center of mass only and an algebra that acts on all other degrees of freedom carried by the string.

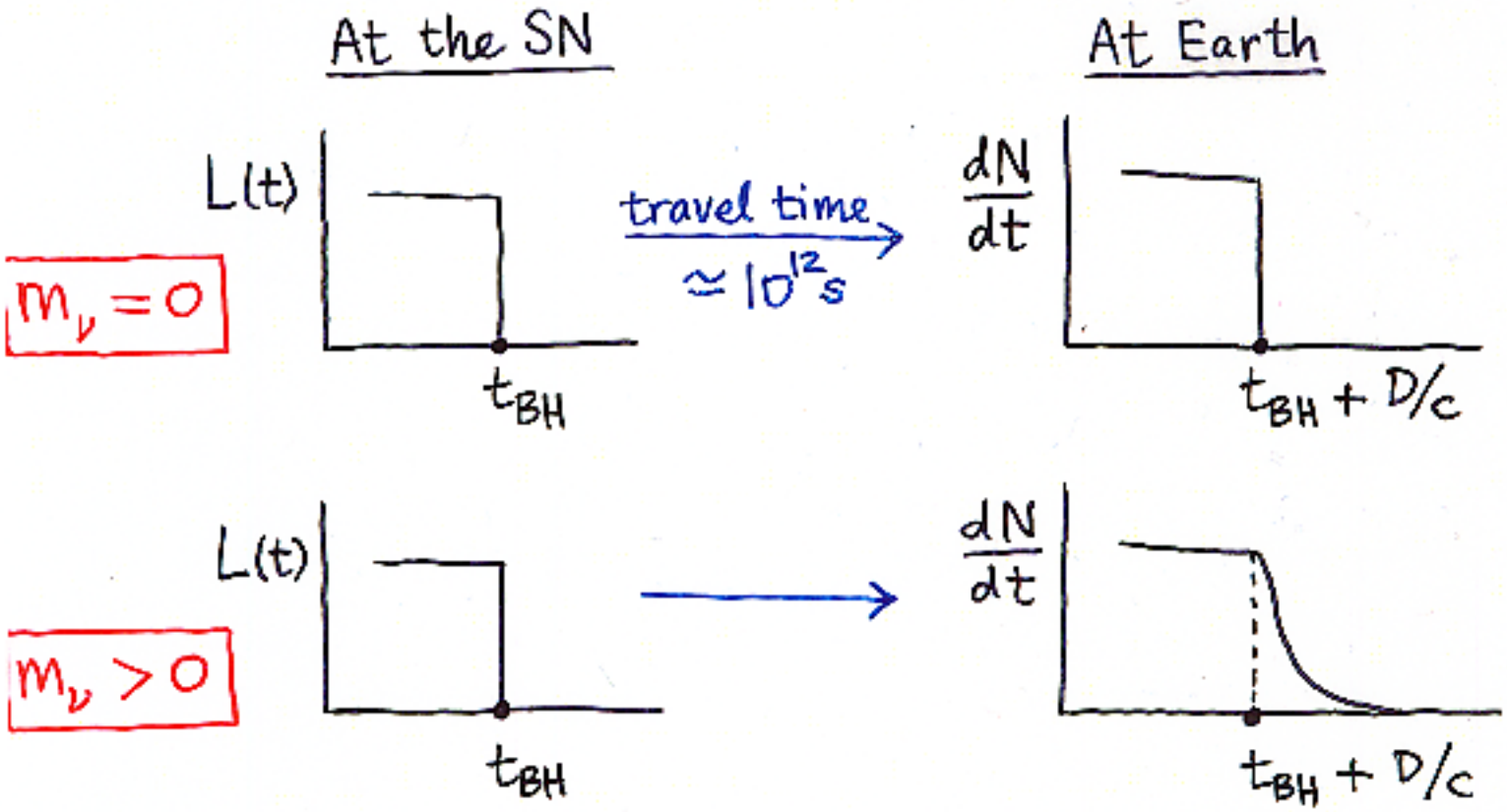
June, 2000



Early : $L_{BH} = 10^{52}$ erg/s per flavor

Late : $L_{BH} = 10^{51}$ erg/s per flavor

BH Measurement of m_ν



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

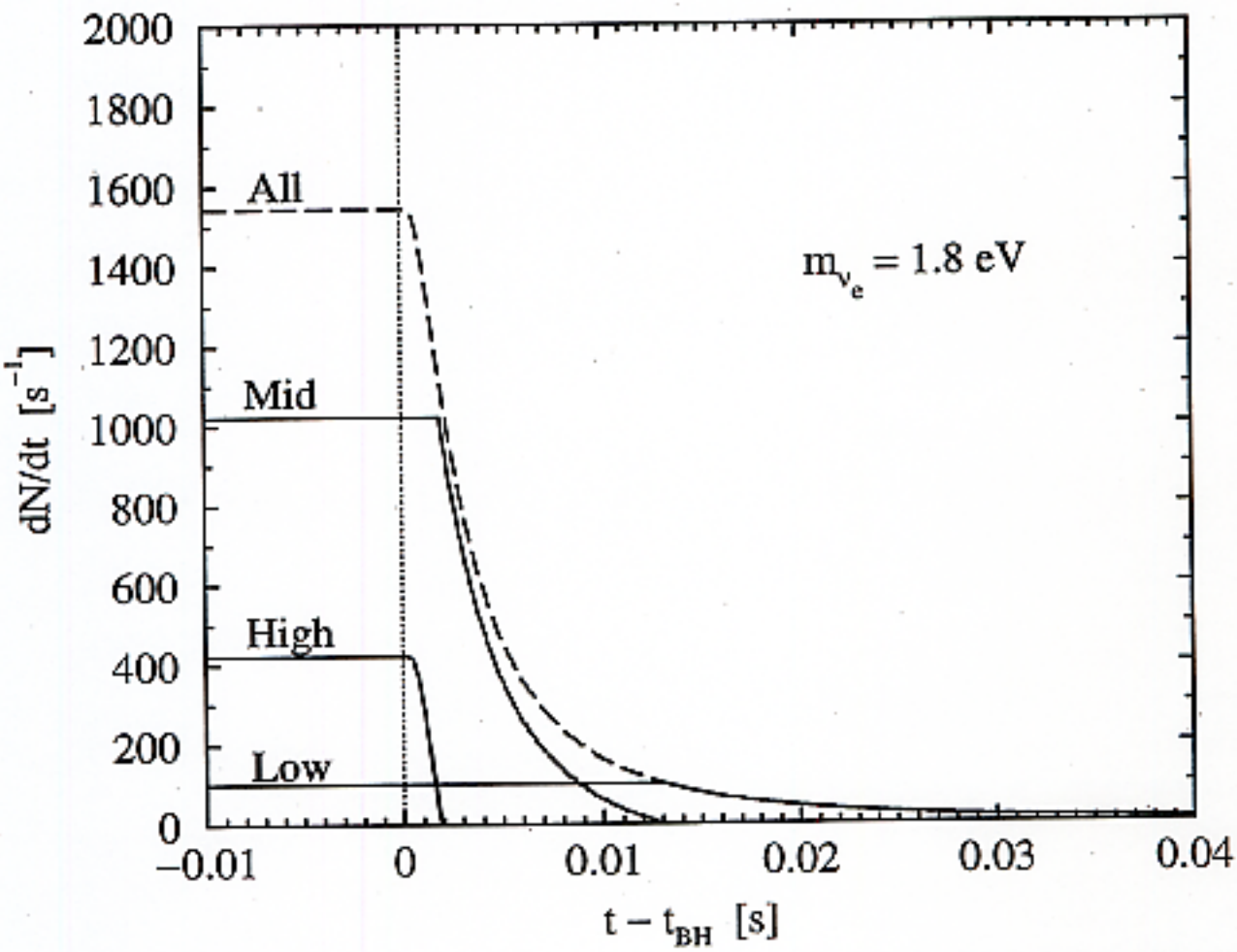


FIG. 1. The event rate due to $\bar{\nu}_e + p \to e^+ + n$ in SK, in the Early case, with an assumed distance of 10 kpc. Note that only the rate after about t_{BH} is shown, and that the range of $t - t_{BH}$ is very short. We took $m_{\nu_e} = 1.8$ eV, which is close to the minimum mass that can be discerned from this data. The labels "Low" (contains 2.4 events past the true t_{BH}), "Mid" (4.8 events), "High" (0.5 events), and "All" (7.7 events) refer to ranges of neutrino energy defined in the text.

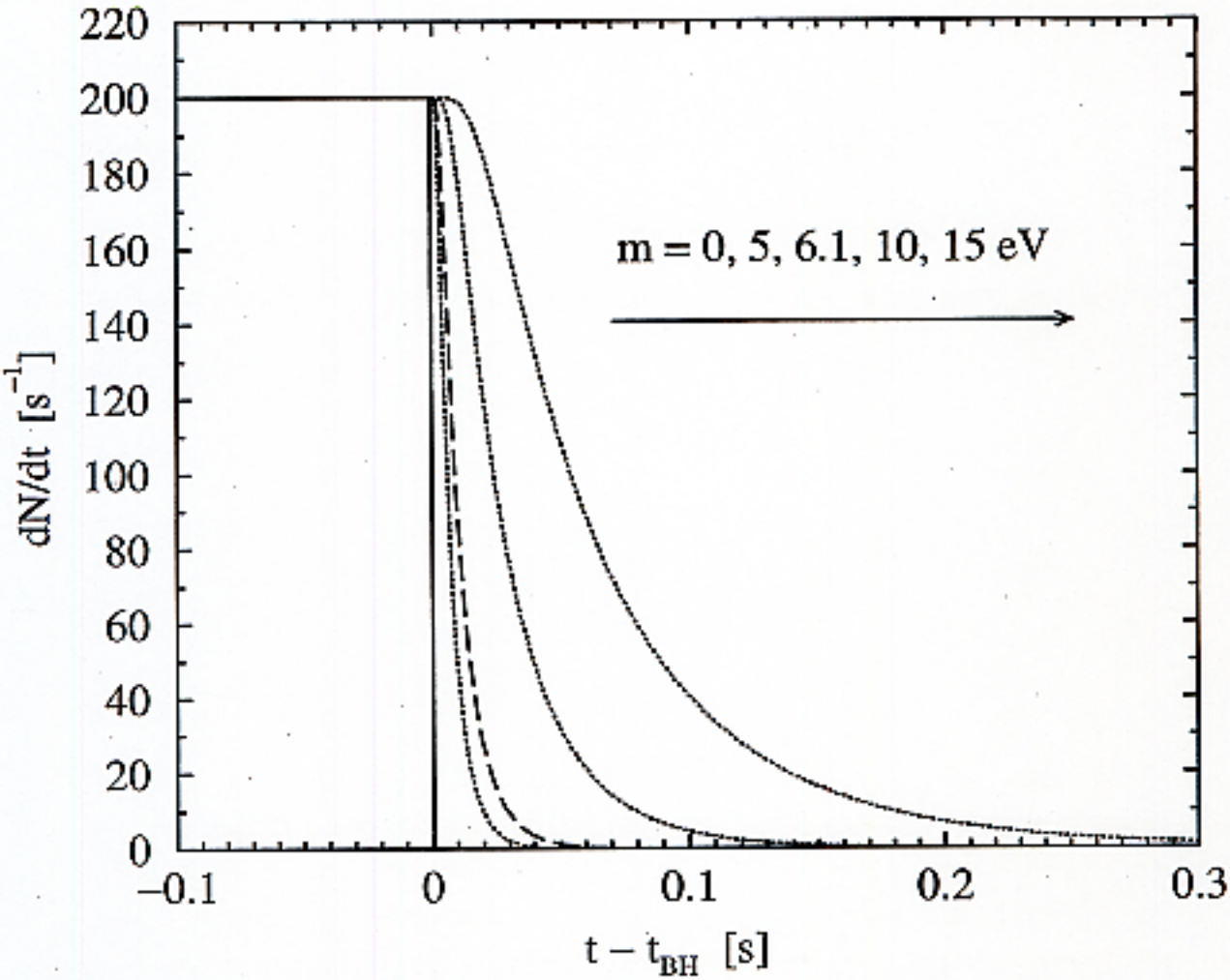


FIG. 2. The results for the combined 1-n neutral-current event rate due to ν_μ, ν_τ, $\bar{\nu}_\mu$, and $\bar{\nu}_\tau$ in OMNIS. Note that only the rate after about t_{BH} is shown. The Early case is assumed, with t_{BH} occurring a few (~ 1) seconds after core collapse, and luminosities of 10^{52} erg/s per flavor at t_{BH}. The assumed distance is 10 kpc. Before t_{BH}, there are other reactions that produce neutrons; they are not included here, and those events will have to be statistically subtracted from the measured neutron rate. Maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing with small δm^2 is assumed, so $m \simeq m_{\nu_2} \simeq m_{\nu_3}$. The $m = 0$ case is drawn with a solid line. The $m = 6.1$ eV case, with 2.3 events expected in the tail, is the first case that can be reliably distinguishable from $m = 0$, and is drawn with a long-dashed line. The results for other masses are drawn with dotted lines.

Neutrino Oscillations :

Status :

solar : $\nu_e \longrightarrow ?$ $\qquad \delta m^2 \simeq 10^{-5}\,eV^2$

atmospheric : $\nu_\mu, \bar{\nu}_\mu \longrightarrow ?$ $\qquad \delta m^2 \simeq 10^{-3}\,eV^2$

LSND : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\nu_\mu \longrightarrow \nu_e$ $\qquad \delta m^2 \simeq 1\,eV^2$

Future :

- confirm or deny signal
- measure δm^2, $\sin^2 2\theta$
- make flavor identification

solar : SNO, Borexino, KamLAND

atmospheric : K2K, MINOS

LSND : Mini-BOONE

Are there sterile neutrinos?

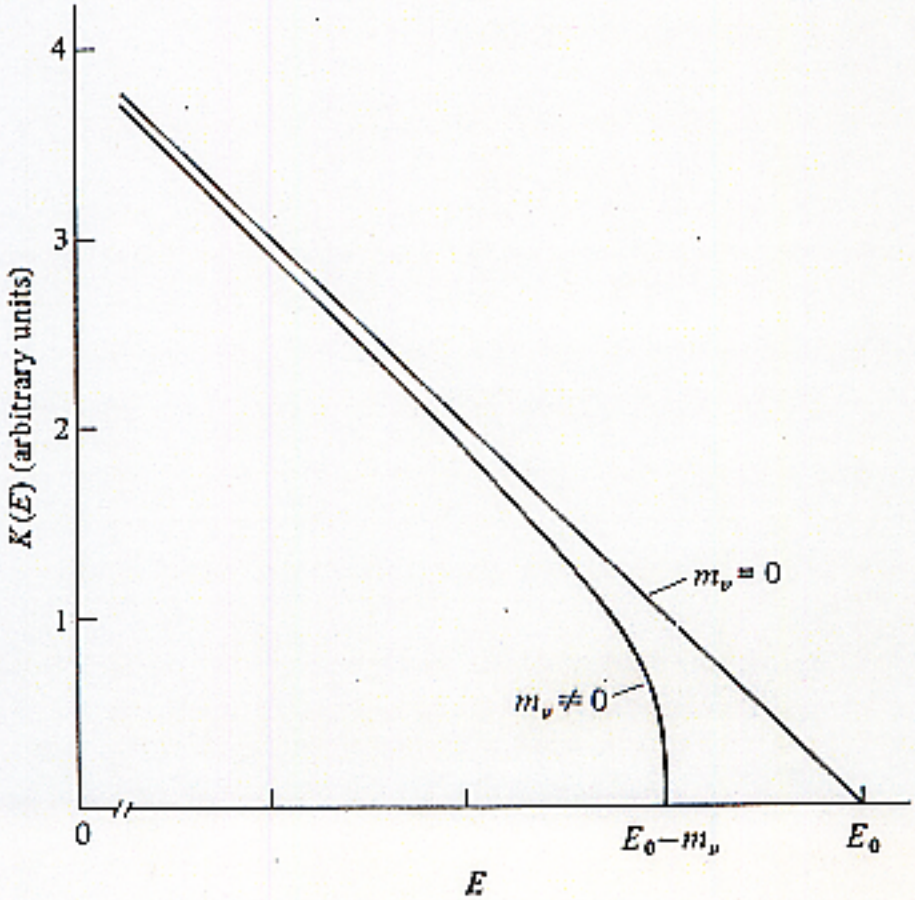
m_{ν_e} Measurement:

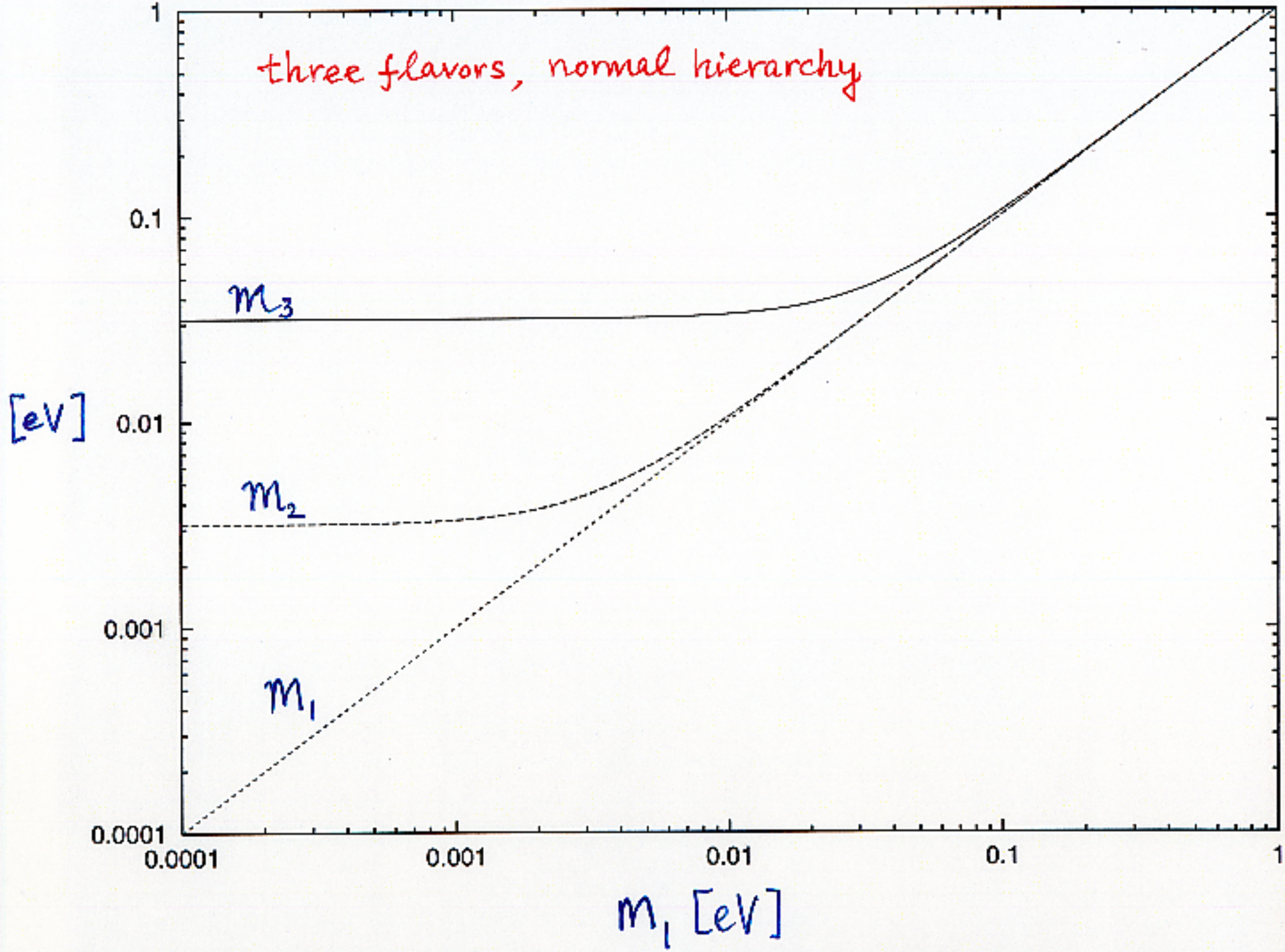
$$^3H \longrightarrow {}^3He + e^- + \bar{\nu}_e \qquad Q \simeq +18\,\text{keV}$$

$$\hookrightarrow \text{recoil energy} \lesssim \frac{(18\,\text{keV})^2}{2\,(3\,\text{GeV})} \lesssim 0.05\,\text{eV}$$

$$\boxed{\text{Maximum } E_e \text{ is lower for } m_\nu > 0}$$

Figure 2.1. Illustration of linearized beta spectrum near the endpoint for neutrino mass $m_\nu = 0$ and $m_\nu \neq 0$.



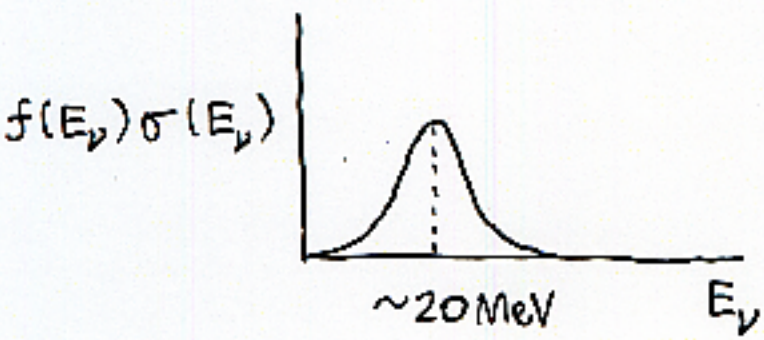

three flavors, normal hierarchy
m_3
m_2
m_1
[eV]
1
0.1
0.01
0.001
0.0001
0.0001
0.001
0.01
0.1
1
m_1 [eV]

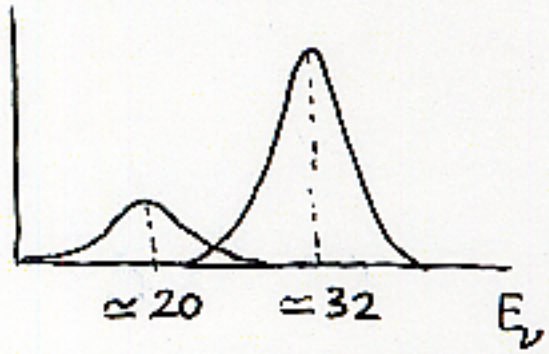
SN Neutrino Oscillations:

- 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

<u>Example</u>: $\bar{\nu}_e p \longrightarrow e^+ n$ $\qquad \sigma(E_\nu) \sim E_\nu^2$





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

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

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

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

CC Measurements:

At 10 kpc:

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

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:

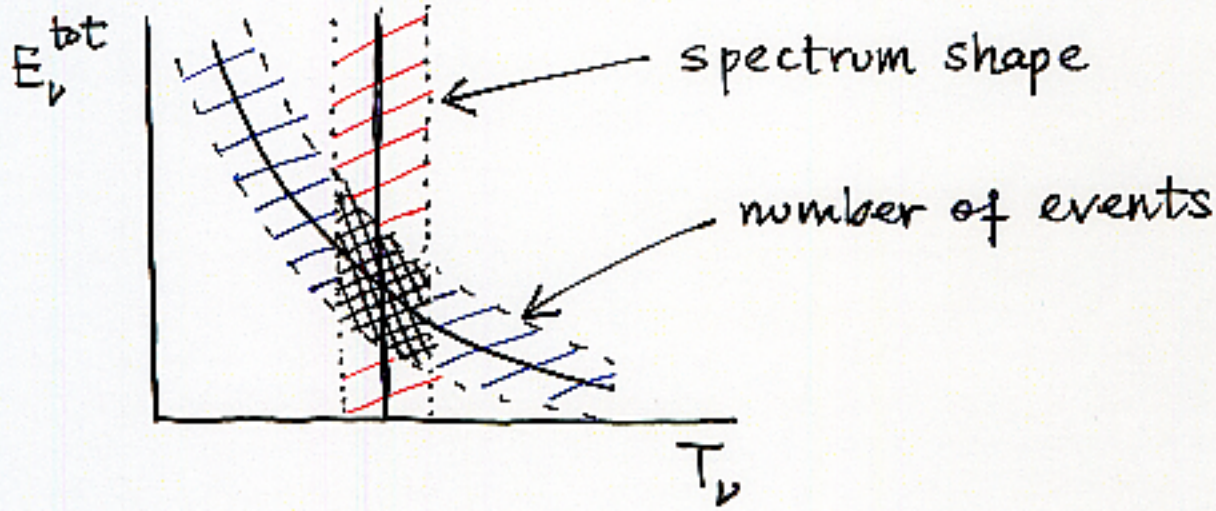
$$\frac{\delta T}{T} \sim \frac{\delta \langle E_\nu \rangle_{f\sigma}}{\langle E_\nu \rangle_{f\sigma}} \sim \frac{\delta \langle E_e \rangle}{\langle E_e \rangle} \sim \frac{1}{\sqrt{N}}$$

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

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

recoil spectrum
very hard to separate events

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

detect n capture

SK: $\simeq 700$ $\quad \nu + {}^{16}O \longrightarrow {}^{15}O + n + \gamma$, ${}^{15}N + p + \gamma$

Kolbe
Langanke
Vogel

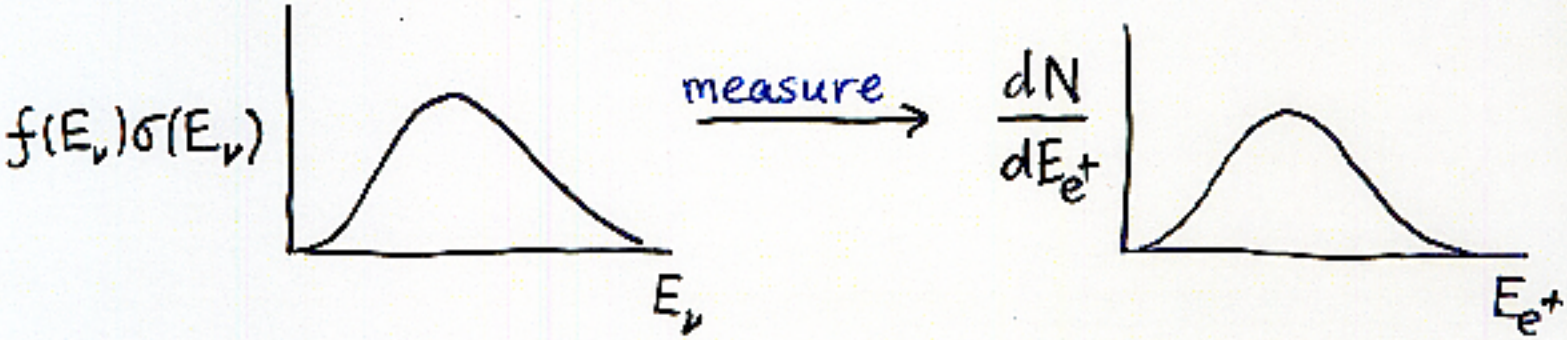
$E_\gamma \simeq 5-10$ MeV

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

$E_\gamma = 15.11$ MeV

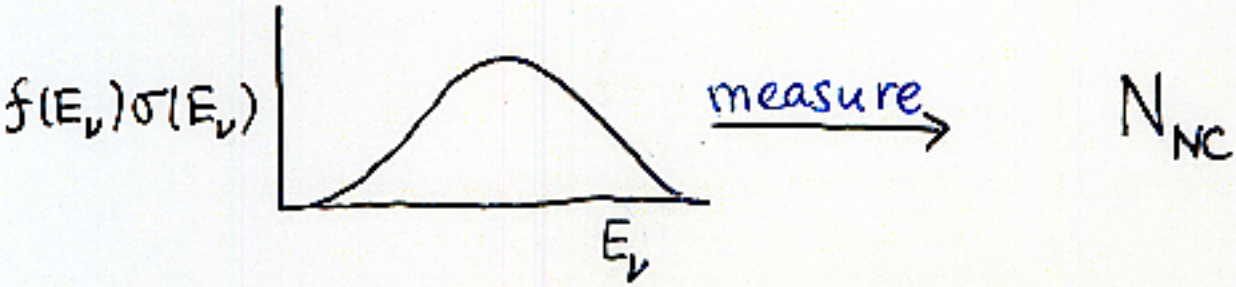
$$\boxed{N \sim \int dE_\nu \; f(E_\nu)\sigma(E_\nu)}$$

- 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., $\nu d \rightarrow \nu p n$

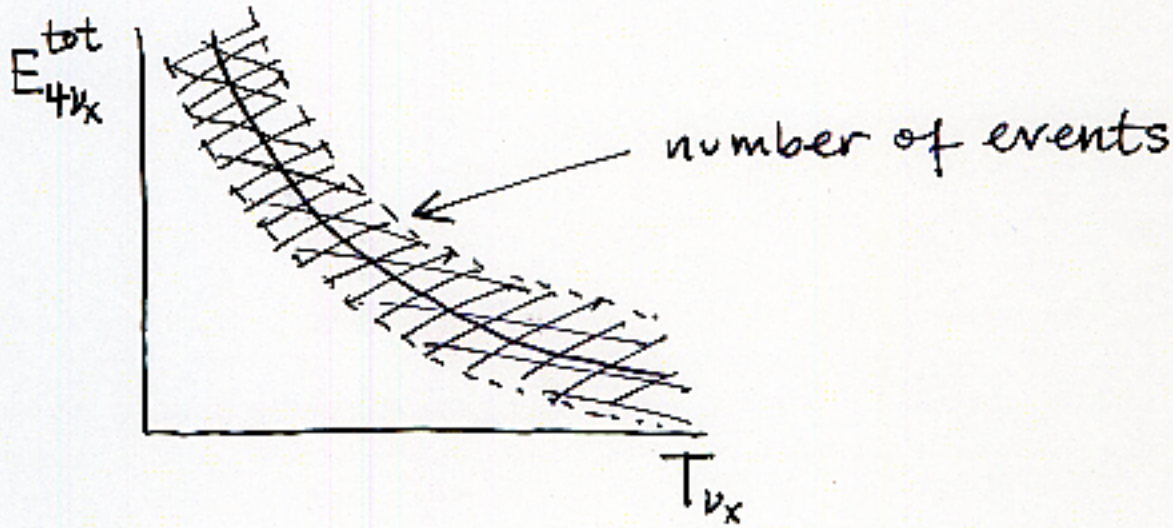


E_ν <u>unknown</u>

So, can only measure

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

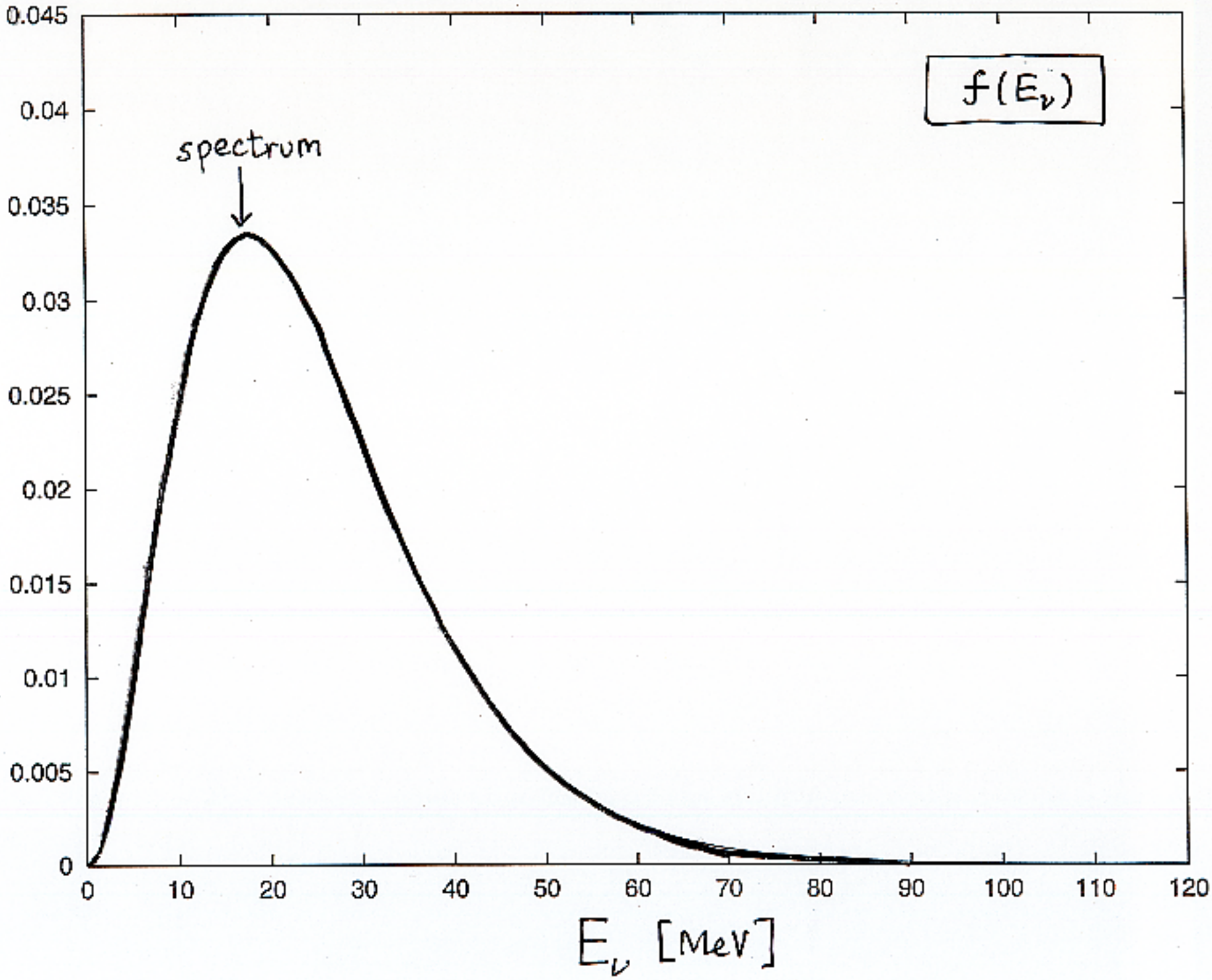
$$\longrightarrow \boxed{N \sim E^{tot}_{4\nu_x} T_{\nu_x}} \quad \text{for } \sigma \sim E_\nu^2$$



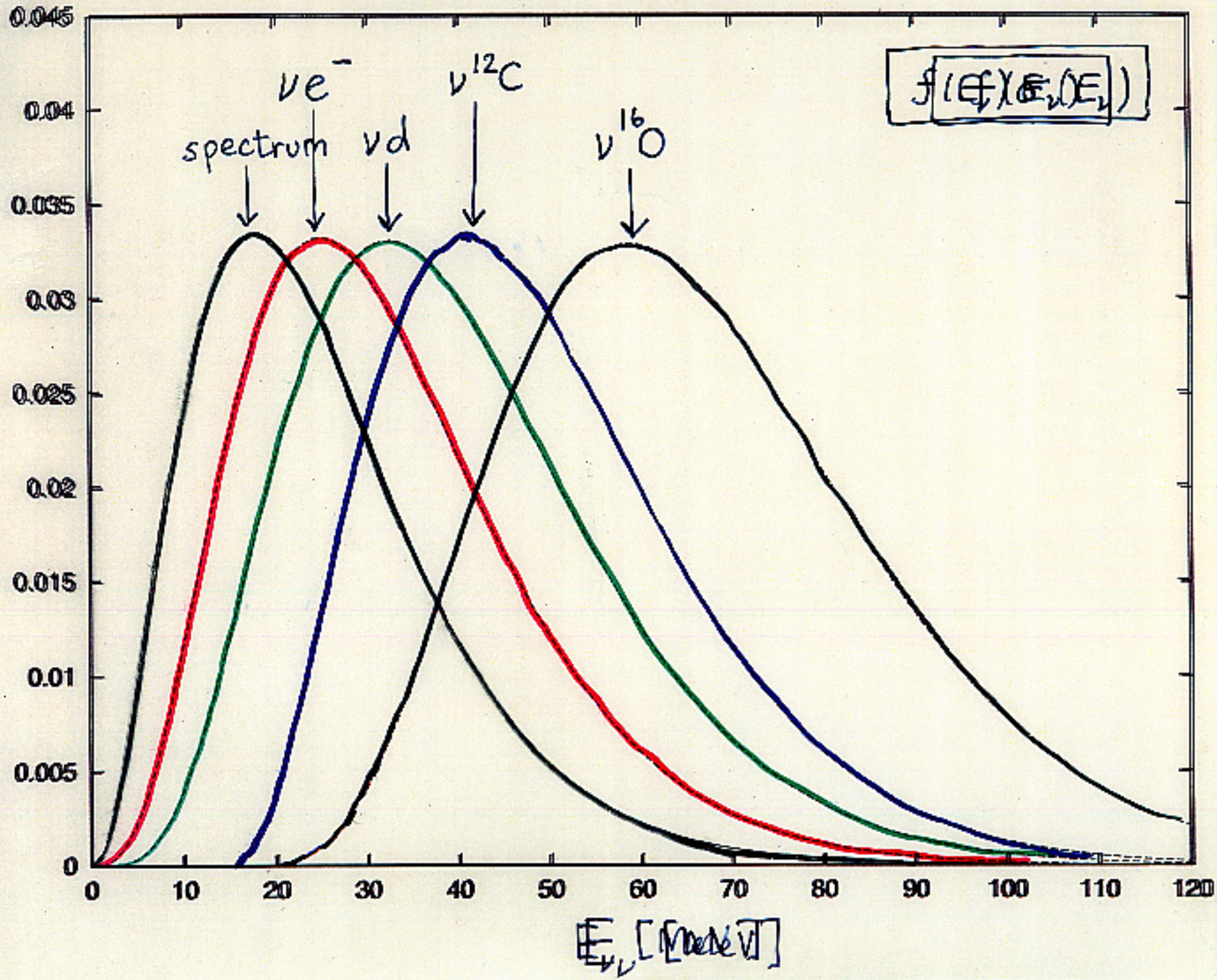
How can we break the degeneracy?

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

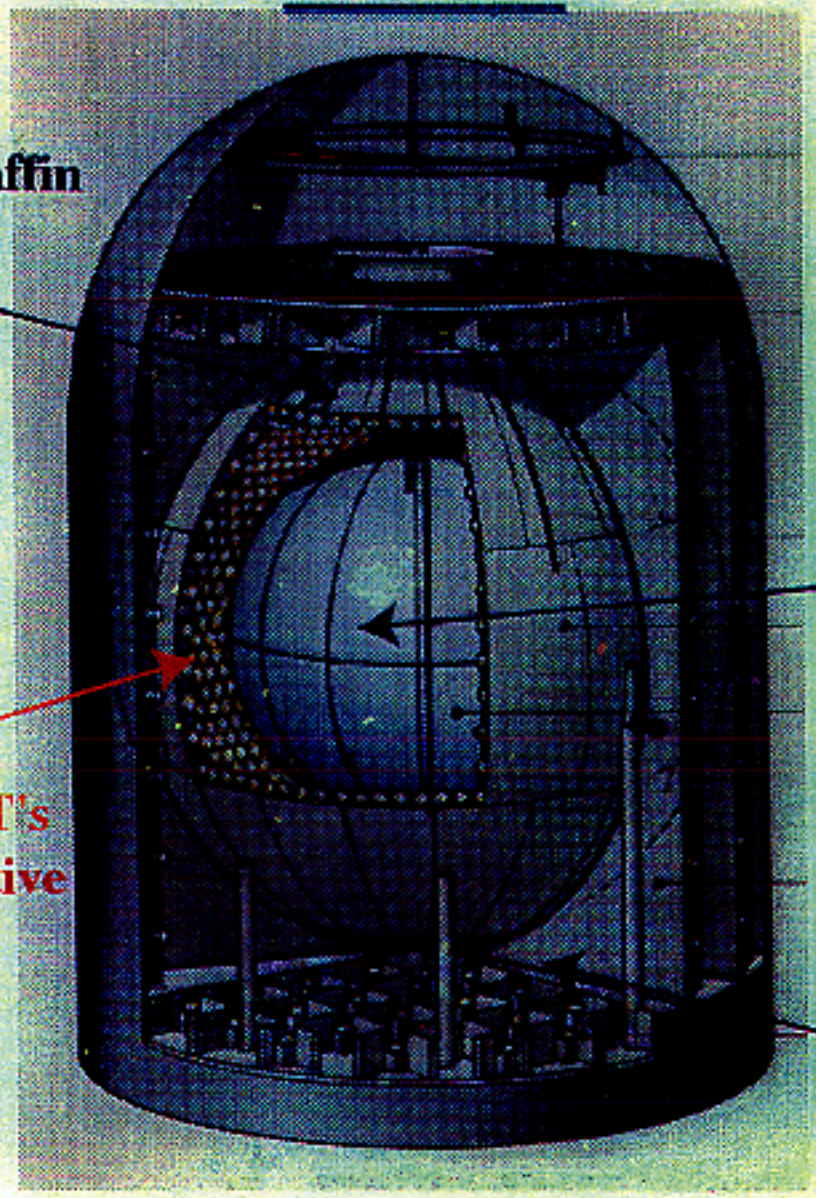
<u>Option B</u>: see below


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. $T_p \sim \frac{E_\nu^2}{M_p} \sim$ 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 $\bar{\nu}_e + p \longrightarrow e^+ + n$, $\nu + e^- \longrightarrow \nu + e^-$, $\nu + {}^{12}C \longrightarrow \nu + {}^{12}C + \gamma$, etc	6'. easy to separate in practice

flavor	$E_{thr} = 0$	$E_{thr} = 0.2\,MeV$
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

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

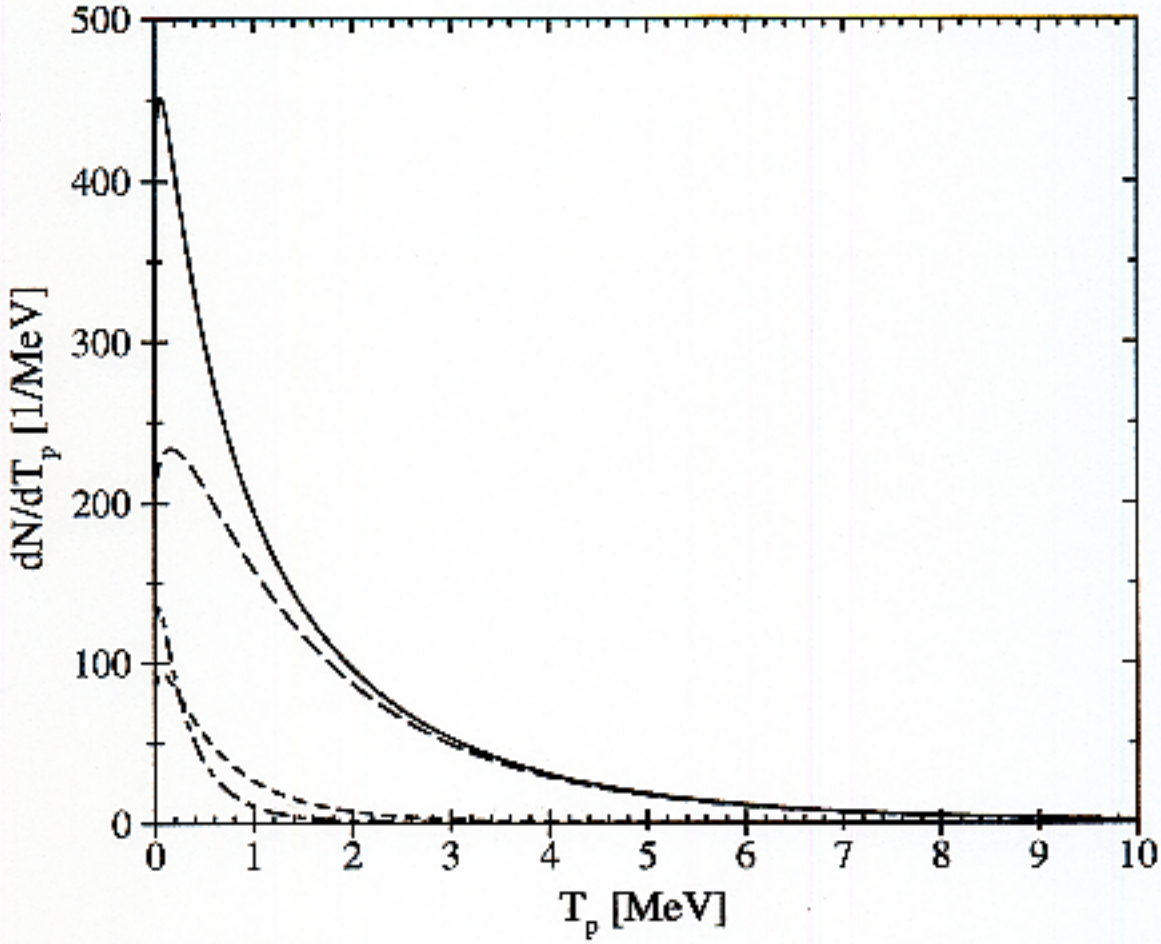


FIG. 3. The ideal struck proton spectrum assuming temperatures as in Table I. From top to bottom, we have events from all flavors (solid line), events from $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ (long-dashed), events from $\bar{\nu}_e$ (short-dashed), and events from ν_e (dashed-dot). This figure assumes ideal detector resolution, no threshold, and no quenching.

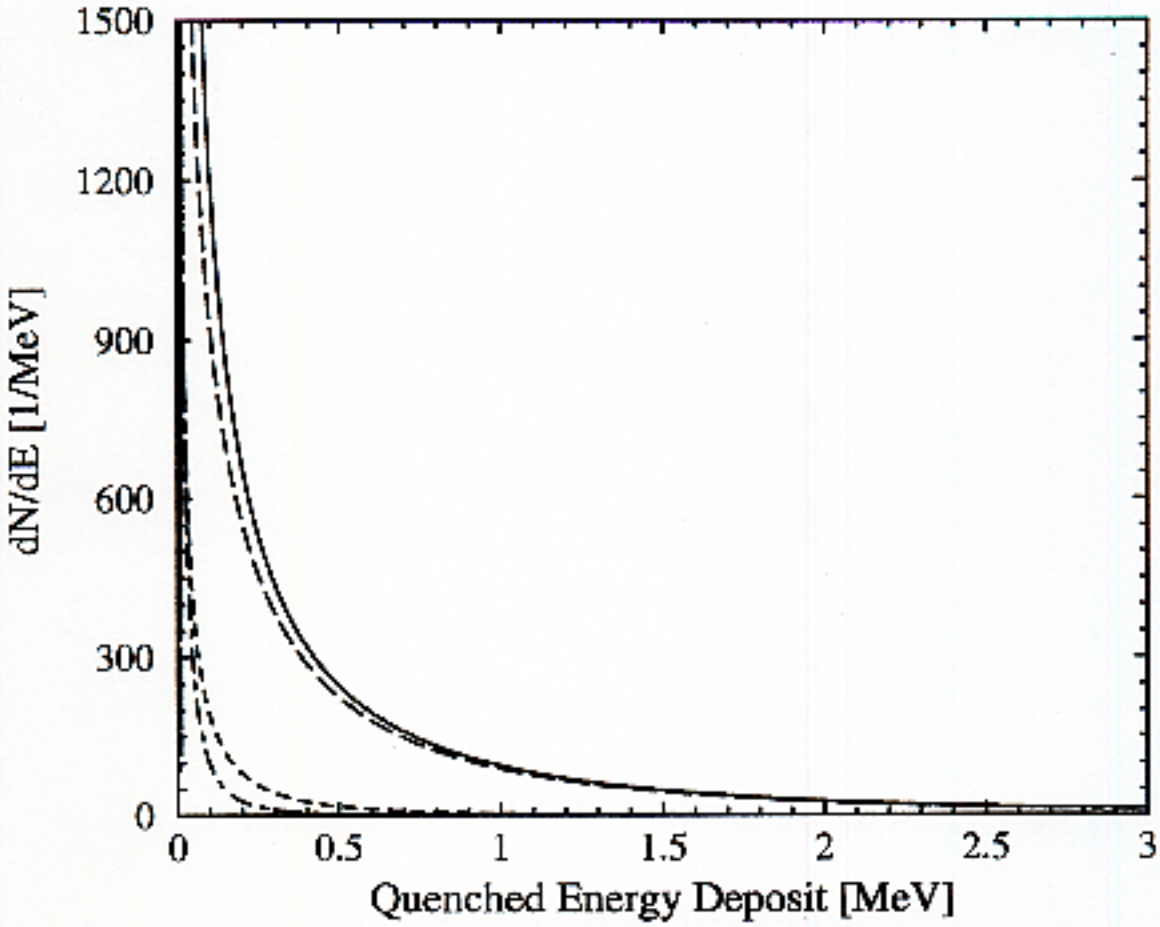


FIG. 5. Analogous to Fig. 3; the struck proton spectrum for the different flavors, but with quenching effects taken into account. From top to bottom we have the events from all flavors (solid line), events from $\nu_{\mu,\tau}$ and $\bar{\nu}_{\nu,\tau}$ (long-dashed), events from $\bar{\nu}_e$ (short-dashed), and events from ν_e (dashed-dot). Quenching reduces the contribution of ν_e and $\bar{\nu}_e$ significantly above threshold. The anticipated KamLAND threshold is 200 keV electron equivalent.

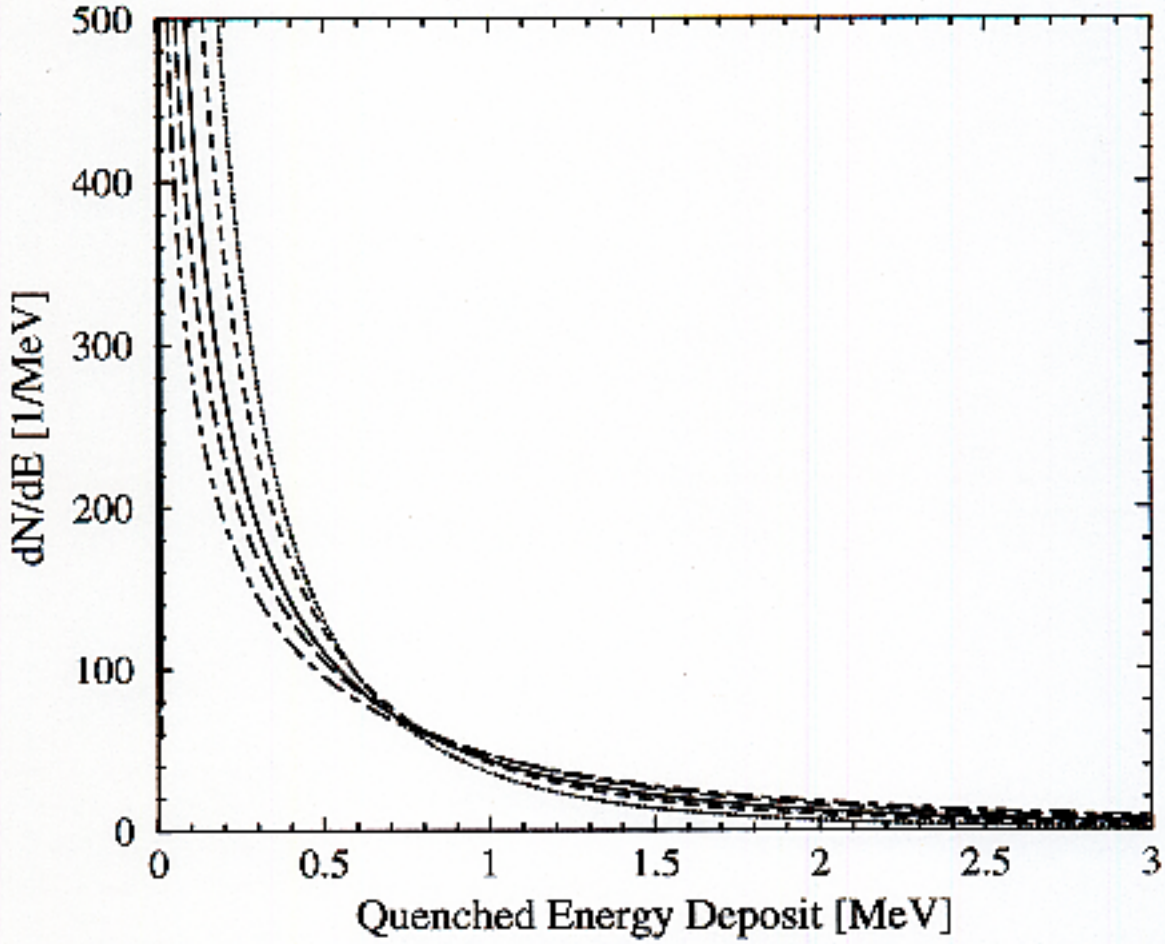


FIG. 7. Spectra produced by the various T_ν and $E^{tot}_{4\nu_x}$ used in the fits in Figs. 8, 9, 10. From left to right, at 200 keV, the cases are: $T_\nu = 6$, $E^{tot}_{4\nu_x} = 4.2$, $T_\nu = 7$, $E^{tot}_{4\nu_x} = 3.2$, $T_\nu = 8$, $E^{tot}_{4\nu_x} = 2$, $T_\nu = 9$, $E^{tot}_{4\nu_x} = 1.6$, $T_\nu = 10$, $E^{tot}_{4\nu_x} = 1.4$, with T_ν in MeV and $E^{tot}_{4\nu_x}$ in 10^{53} erg at 10 kpc. These values were chosen to keep the number of events above 1.2 MeV constant.

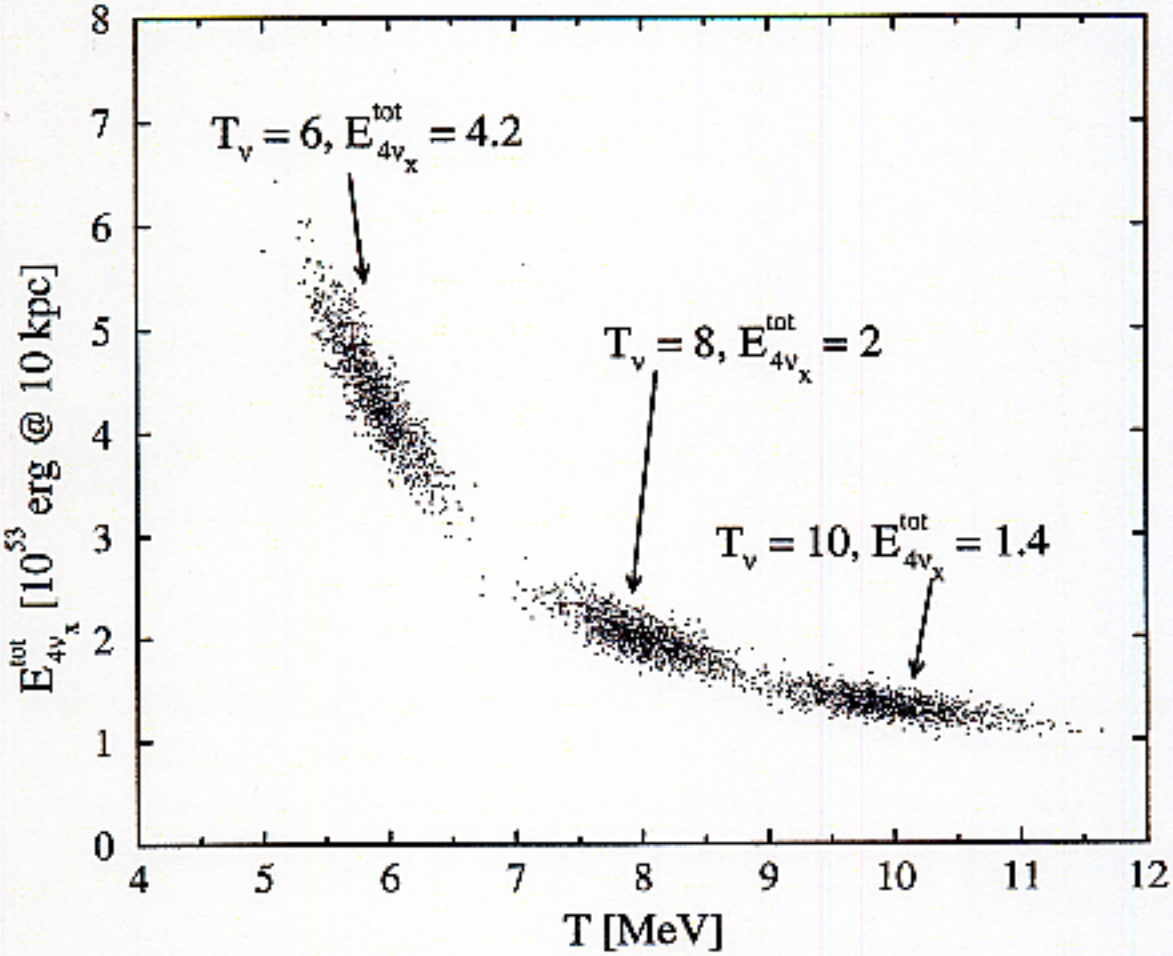
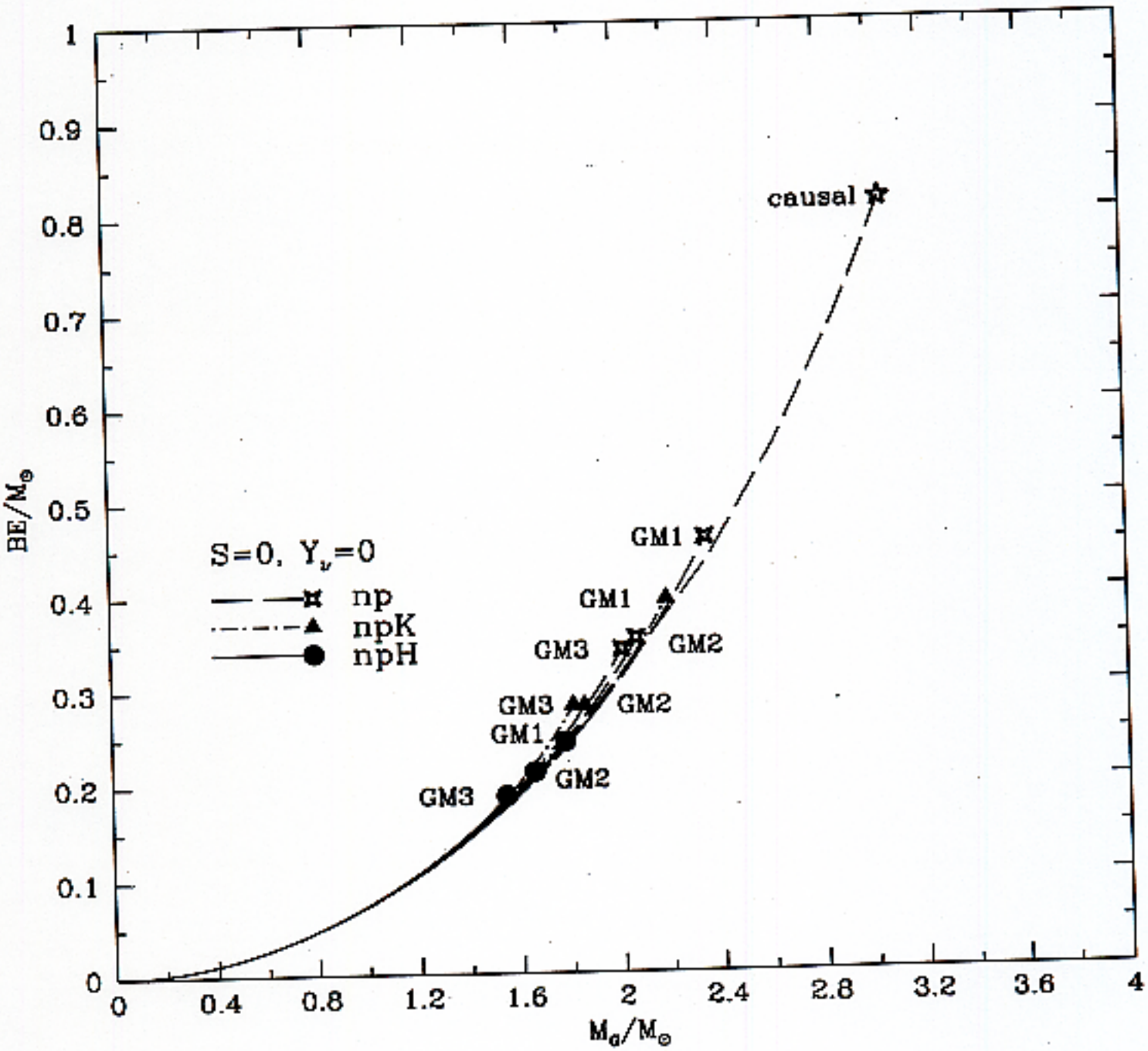


FIG. 8. Scatterplots in the $E^{tot}_{4\nu_x}$ and T_ν plane of 10^4 fits to each of the listed energy release and temperature values. Values of $E^{tot}_{4\nu_x}$ and T_ν were chosen such that the total number of neutrinos of each flavor above a threshold of 1.2 MeV would remain constant, rendering futile a simple event-count approach. Counting events places one roughly on the hyperbola $E^{tot}_{4\nu_x} T_\nu = const$; being able to fit for a shape picks out a section along the T_ν axis from this hyperbola.

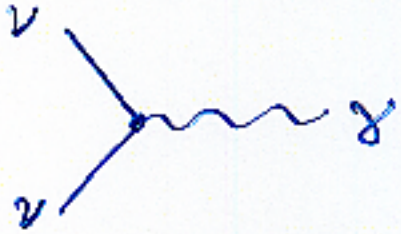
Beacom, Farr, and Vogel, in preparation

$$\boxed{\frac{\delta T_{\nu_x}}{T_{\nu_x}} \sim 10\%}$$

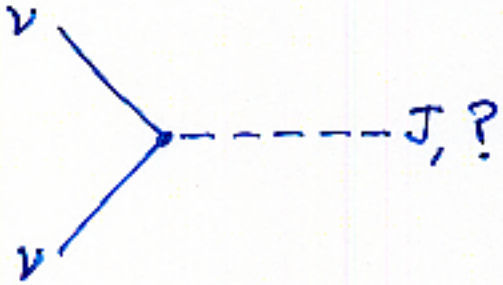

causal
GM1
GM2
GM3
S=0, Y_ν=0
np
npK
npH
BE/$M_\odot$
$M_G/M_\odot$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.4
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4

Searches for New Physics

- "Standard" neutrino mixing
- CPT violation in mixing
- Neutrino magnetic moments



- New couplings



- Novel energy loss channels:

  KK gravitons
  axions
  sterile neutrinos
  LGM

Conclusions

- Can detect supernova neutrinos from anywhere in the Galaxy
- Yield should be $\sim 10^4$ events from all flavors, seen in several detectors
- The supernova rate is low, but manageable
- The neutrinos are well worth the wait:
  - key to understanding explosion and its aftermath
  - unprecedented tests of neutrino properties
  - tests of other new physics if the "beam" is understood