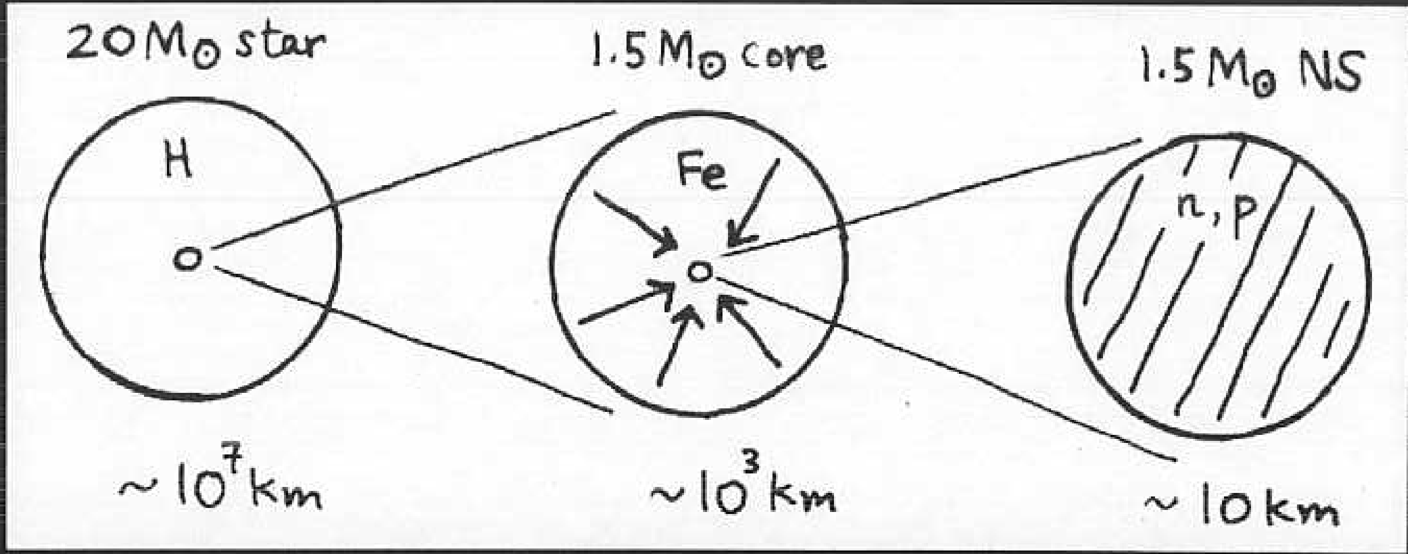
Supernova Neutrinos

GADZOOKS!

John Beacom, Fermilab

Supernova Energetics

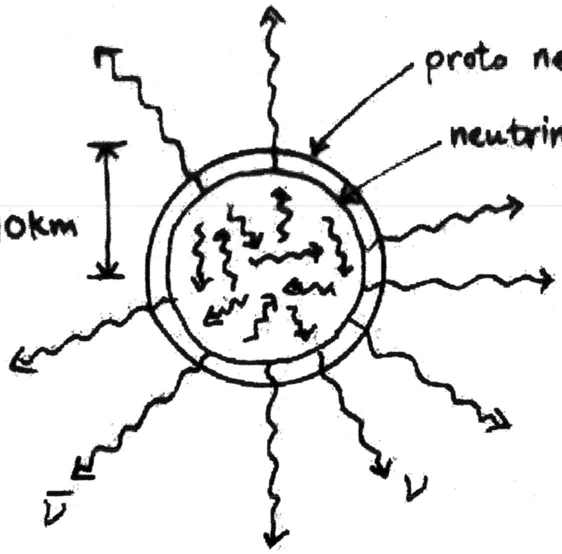


$$\Delta E_B \simeq \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} - \frac{3}{5}\frac{GM_{NS}^2}{R_{core}} \simeq 3\times10^{53}\ \text{ergs} \simeq 2\times10^{59}\ \text{MeV}$$

K.E. of explosion $\simeq 10^{-2}\,\Delta E_B$

E.M. radiation $\simeq 10^{-4}\,\Delta E_B$

Supernova Neutrino Emission



"cooling" by neutrino emission :

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

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

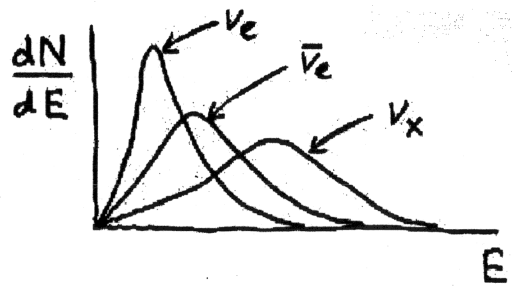
etc.

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

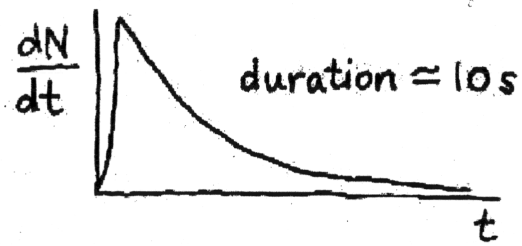
$\langle E_{\nu_e} \rangle \simeq 11$ MeV

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

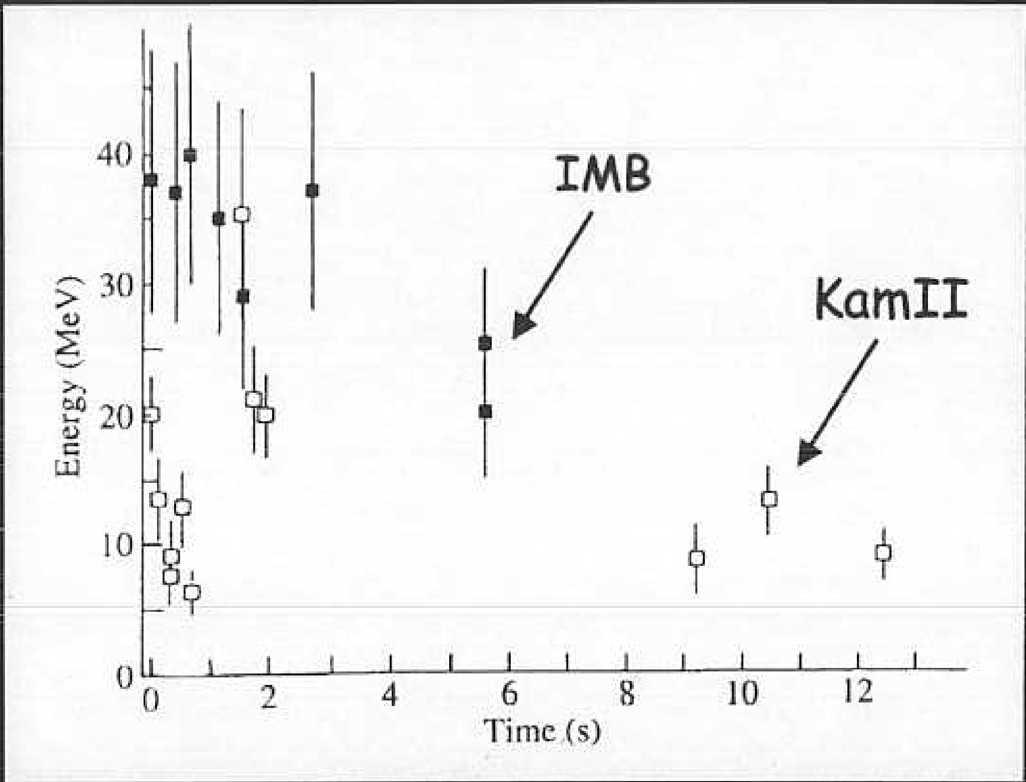
$\langle E_{\nu_x} \rangle \simeq 25$ MeV



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



Supernova Neutrino Detection



SN1987A :

$\sim 20\ \bar{\nu}_e p \rightarrow e^+ n$ events

SN200?? :

$\sim 10^4$ CC events

$\sim 10^3$ NC events

Supernova physics (models, black holes, progenitors...)

Particle physics (neutrino properties, new particles, ...)

The Hardware

Here's a fairly complete list of the expected supernova responses of the world's various neutrino detectors, including those being proposed (in red), under construction (in blue), and currently running (in green):

Total number of SN events at 10 kpc

Hyper–Kamiokande ∼300,000

UNO — ∼140,000

Super–K–III — ∼9,700

Super–K–II ∼8,400

OMNIS ∼2000

SNO ∼1,000

KamLAND ∼500

Borexino ∼200

MiniBooNE — ∼200

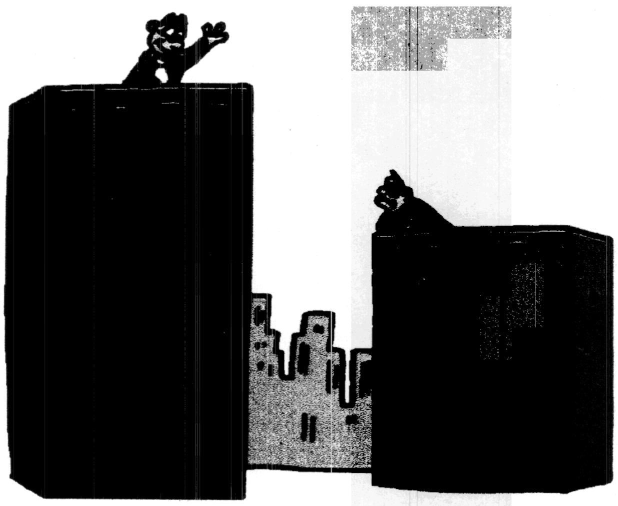
LVD ∼200

MOON ∼70

All transparencies in this format borrowed from my collaborator Mark Vagins (Irvine)

Same Detectors, Different Day

The list on the previous slide represents the current and near (?) future devices capable of recording individual supernova neutrino events. As is often the case, size matters:



Most of these detectors or detector ideas have been around for quite a while

But is there anything new under the exploding sun?

As it happens, there *are* a couple of new developments worth mentioning.

- A forgotten signal mode in water Cherenkov detectors is getting another chance.

- A possible upgrade for Super–K which could be applied to other water Cherenkov detectors is being studied.

The Lost Mode

In the immediate excitement after SN1987A, Wick Haxton published a paper [W. Haxton, Phys. Rev. D, **36**, 2283 (1987)] outlining various nuclear physics reactions which could occur in water during a galactic supernova

One of the most interesting was the charged current interaction,

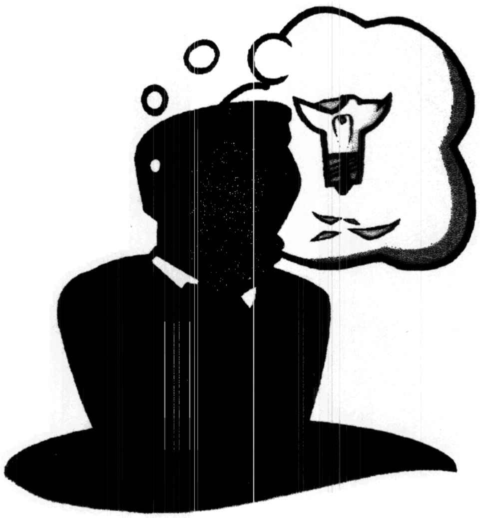
$$\nu_e + {}^{16}\mathrm{O} \rightarrow e \;\; + {}^{16}\mathrm{F}$$

These $O(\nu_e, e^-)F$ events have an E_ν threshold of 15.4 MeV and are somewhat backwards-peaked. They have *tremendous* sensitivity to the temperature of the supernova burst.

Back in 1987 there were just two problems:

Neutrinos would have to oscillate with near maximal mixing to get many events.

2. It was almost impossible to separate them from the more common inverse beta events.



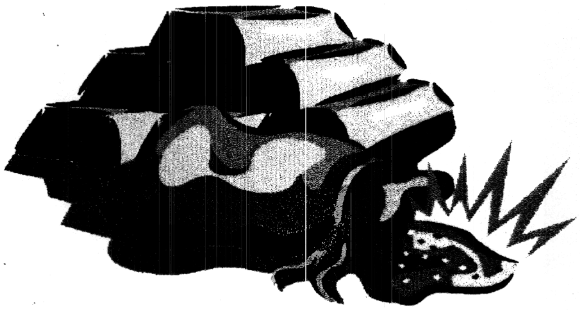
the idea was pretty much forgotten...

...until now.

1. Of course, sixteen years later it turns out that neutrinos *do* oscillate with near maximal mixing, and

2. There may in fact be a way to tag, *event-by-event*, the inverse beta supernova "background."

These are precious events, because one thing the world is lacking is a good SN ν_e detector



Leaving tagging aside for now, one can expect this many supernova ν_e events at 10 kpc:

Super–K–III: $\sim$700 O(ν_e, e^-)F + $\sim$100 e.s.

Super–K–II: $\sim$630 O(ν_e, e^-)F + $\sim$80 e.s.

SNO: $\sim$100

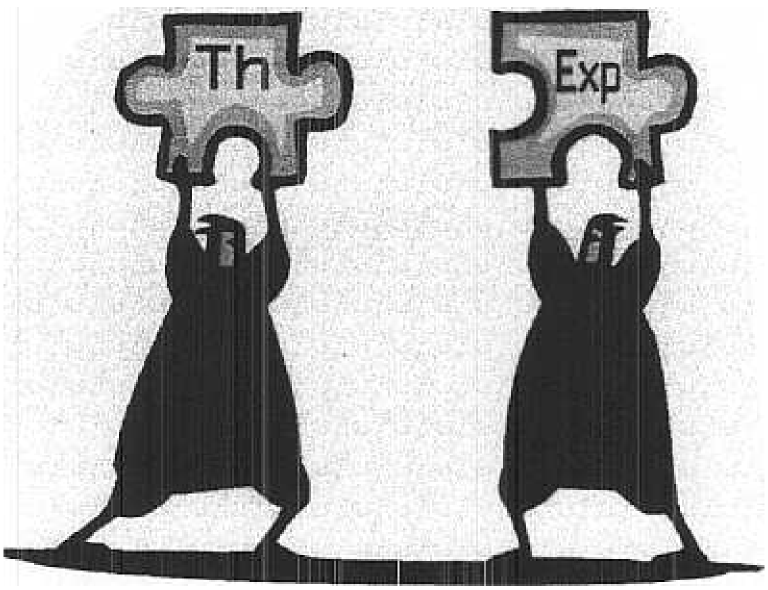
KamLAND: $\sim$30

Borexino: $\sim$15

So, What's This About Tagging $\bar{\nu}_e$'s?

In what began as a search for a new method of extracting the supernova relic neutrino signal without background issues, for close to a year now Fermilab's John Beacom and I have been tossing around ideas regarding modifying the Super–K detector.

It has proven to be a very fruitful partnership:



Everything which follows in this talk is the result of our ongoing, combined efforts.

The Initial Goal

it be great if we could **tag** *every* supernova relic neutrino," we thought

Well, the reaction we are looking for is:

$$\overline{\nu}_e + \mathrm{p} \rightarrow e^+ + \mathrm{n}$$

What if we could reliably identify the neutron?

The Challenge

Of course, it is well known that free neutrons in water get captured by free protons and emit 2.2 MeV gammas. If we could see these we'd be in business! They're pretty small, but...

Maybe we could just lower the threshold briefly after each regular trigger.

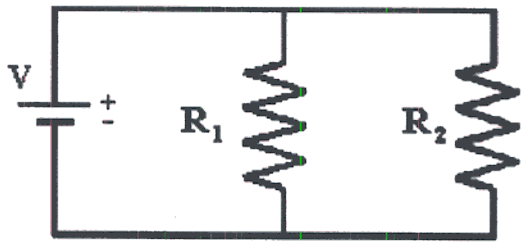
Possible, and no SK change except a new trigger board would be required, but efficiency will still be fairly low. SRN's are rare, so...

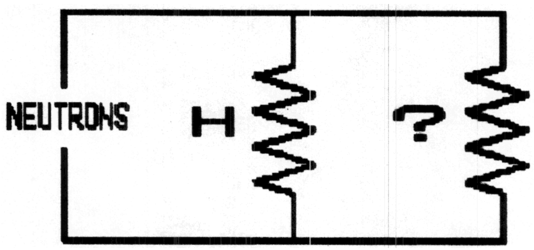
How can we get <u>all</u> of this signal?

The Next Approach

We need something which will compete with the hydrogen in capturing neutrons.

Such a process is very similar to resistors in parallel, and can be exactly calculated:





<u>When I'm 64</u>

We finally turned to the best neutron capture nucleus known: gadolinium. It has a nice 8.0 MeV gamma cascade, easily visible in SK.

Unlike metallic Gd, the compound gadolinium (tri)chloride, $GdCl_3$, is water soluble.

We found that in order to collect 50% of the neutrons on gadolinium and 50% on hydrogen you need to put just 9 tons of $GdCl_3$ in SK! That's exactly two cubic meters. No problem!

The 0.1% Solution

Even better to collect >90% of the neutrons on gadolinium you only need to put *100 tons* of $GdCl_3$ in Super K! That's about twenty cubic meters or a 0 1% concentration **of Gd in the** tank and with t **we can tag all the SRN events.**

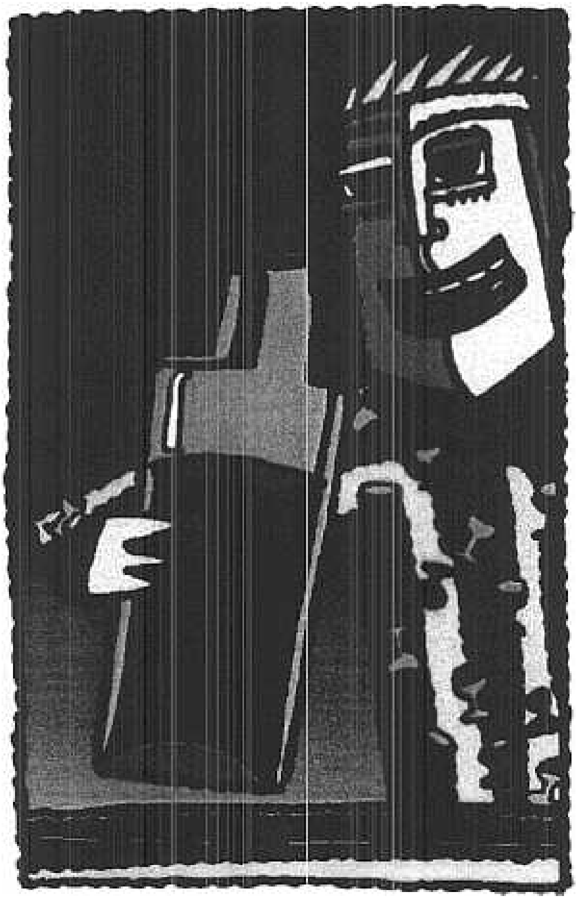
SK should see about five each year with no background at all! Now imagine Hyper K seeing 100+ supernova relic neutrinos every year!

But is the weird stuff in the water dangerous?

SK, With a Twist

The short answer is, *not at all.*

Both human and animal toxicology studies have been done, and the bottom line is that you could drink at least 12 liters of this solution every day straight from the tank and suffer no detectable effects from the $GdCl_3$.



The Price of Gd in China

Great, so it won't kill us, but can we **afford it?**

In 1984: \$4,000/kg → \$400,000,000
In 1993: \$485/kg → \$48,500,000
In 1999: \$115/kg → \$11,500,000
In 2002: \$4/kg → \$400,000

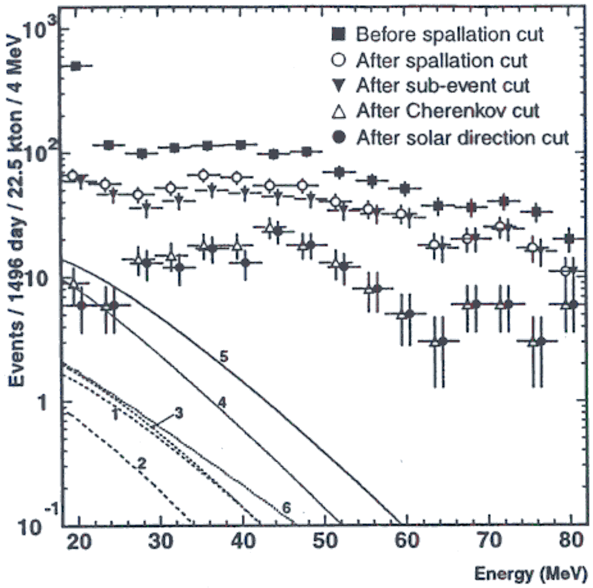


FIG. 1. Energy spectrum at each reduction step. In the final data set, the spallation cut and solar direction cut are applied only in the first four bins. The numbered lines represent the corresponding theoretical predictions from Table I.

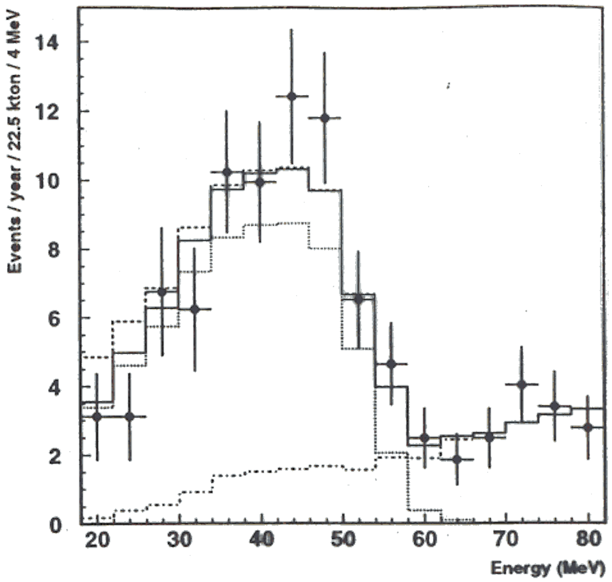


FIG. 2. Energy spectrum of SRN candidates. The dotted and dash-dotted histograms are the fitted backgrounds from invisible muons and atmospheric ν_e. The solid histogram is the sum of these two backgrounds. The dashed line shows the sum of the total background and the 90% upper limit of the SRN signal.

TABLE I. The SRN search results are presented for six theoretical models. The first column describes the method used to calculate the SRN flux. The second column shows the efficiency-corrected limit on the SRN event rate at SK. The third column is the flux limit set by SK, which can be compared with the theoretical predictions that are shown in the fourth column. The fifth column shows the flux predictions above a threshold of $E_\nu > 19.3$ MeV. Note that the heavy metal abundance calculation sets only a theoretical upper bound on the SRN flux [7].

Theoretical model	Event rate limit (90% C.L.)	SRN flux limit (90% C.L.)	Predicted flux	Predicted flux ($E_\nu > 19.3$ MeV)
Galaxy evolution [4]	<3.2 events/yr	$<130\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$44\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$0.41\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Cosmic gas infall [5]	<2.8 events/yr	$<32\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$5.4\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$0.20\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Cosmic chemical evolution [6]	<3.3 events/yr	$<25\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$8.3\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$0.39\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Heavy metal abundance [7]	<3.0 events/yr	$<29\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$<54\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$<2.2\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Constant supernova rate [4]	<3.4 events/yr	$<20\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$52\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$3.1\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Large mixing angle osc. [8]	<3.5 events/yr	$<31\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$11\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$0.43\ \bar{\nu}_e\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

What Else Can We Do With Gd?

Well, once we can identify $\overline{\nu}_e$'s, we can dramatically improve our search for solar $\overline{\nu}_e$'s.

John and I estimate a two-orders-of-magnitude improvement in sensitivity over our present result, so if there is as little as *one solar* $\overline{\nu}_e$ *out of 10,000 solar* ν_e*'s* we will know it!

Anatomy Of A Burst

Naturally, if we can do relics, we can do a great job with galactic supernovas, too. **With 0.1%** gadolinium in the SK tank,

1. The inverse betas get individually tagged, allowing us to study their spectrum and subtract them away from...

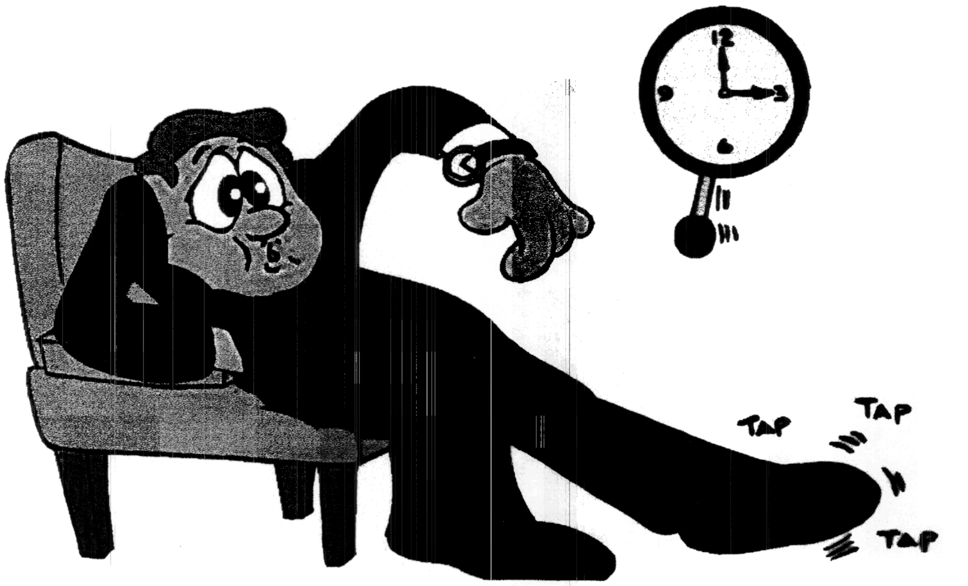
   the directional elastic scatters, which will double our pointing accuracy!

   The ^{16}O NC events no longer sit on a large background and are hence individually identified, and

   the O(ν_e, e^-)F events' backwards scatter can be clearly seen, providing a measure of burst temperature and oscillation angle.

Regarding Neutrino Oscillations...

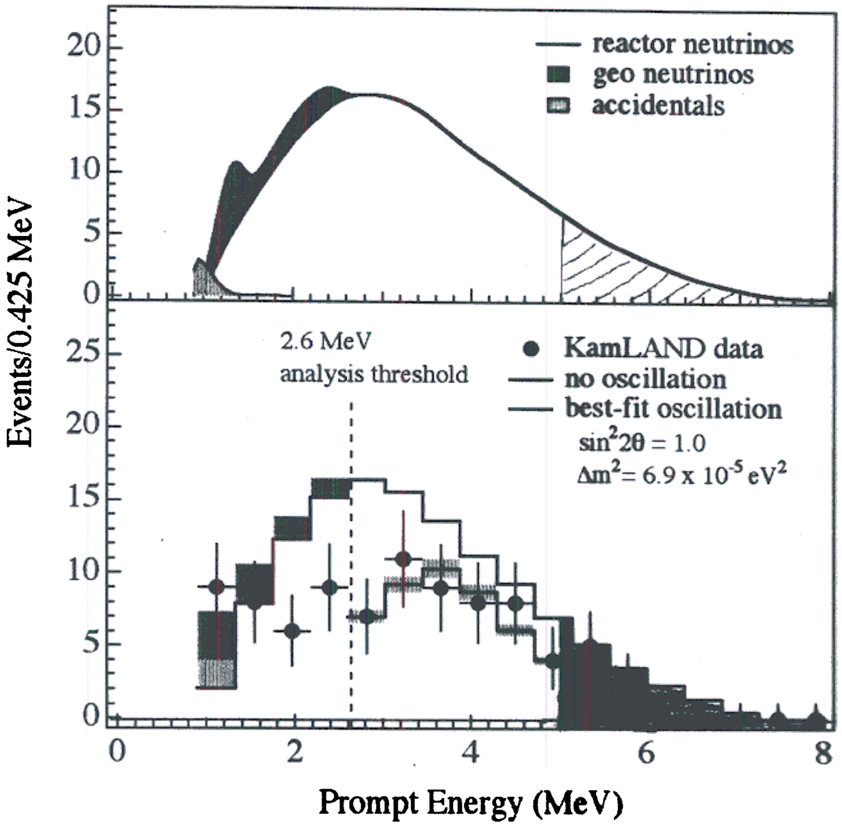
Okay, so maybe you're the impatient type, and don't want to wait for a galactic supernova burst to arrive or relic neutrinos to trickle in. And who knows if there are any solar $\overline{\nu}_e$'s, anyway?



That's fine. Do we have a signal for you...

Super-KamLAND!

Here's KamLAND's first published spectrum, based on about half a year of data.



Super–K with 0.1% gadolinium could collect this data in just three days!

Hyper–K with $GdCl_3$ could collect six KamLAND-years worth of data in just one day!

Gadzooks!

Since John and I were focusing on the low energy side of things, we haven't even gotten into how this solute should also allow our high energy friends to differentiate between atmospheric (or long baseline) neutrinos and antineutrinos of all species, reduce backgrounds to proton decay searches, and so on.

We propose calling this new project "GADZOOKS!" In addition to being an expression of surprise, here's what it stands for:

Gadolinium
Antineutrino
Detector
Zealously
Outperforming
Old
Kamiokande,
Super!

A Modest Proposal

Pouring a bunch of stuff into Super–K is a big step, and not to be done lightly, no matter how promising things may look initially.

Here's what comes next:

1) Spend the next year or so exploring the chemistry, stability, and optical properties of $GdCl_3$ in detail.
2) Understand any changes needed in the SK water system and Monte Carlo the modified detector's response using what's learned above as input.
3) Build a small test tank (one supermodule) with exactly the same materials as in SK. Put in PMT's, cables, water, and $GdCl_3$ and let it sit for two years. Check for $GdCl_3$-induced damage.
4) If everything looks good, in the last month(s) of SK–II put in 9 tons of $GdCl_3$ to make sure we really understand our backgrounds. Look for reactor antineutrinos!

Onward Ever Onward

Finally f every test *still* looks good mix 100 tons of $GdCl_3$ into SK–III and prepare for the bright new days of supernova and reactor neu trino data ahead!

John Beacom & Mark Vagins n preparation