A Future 1-kiloton Lead Detector

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for the HALO-2 collaboration

INT Workshop 15 August 2016

HALO-1 at SNOLAB was a “detector of opportunity” constructed from the ^{3}He neutron detectors from the 3rd phase of the SNO experiment, and 79 metric tons of lead from a decommissioned cosmic ray monitoring station.

Now another opportunity beckons, with the availability of 1300 tons of lead from the decommissioned OPERA experiment at Gran Sasso.

Aim: to build a kiloton-class Pb detector for supernova neutrinos which is

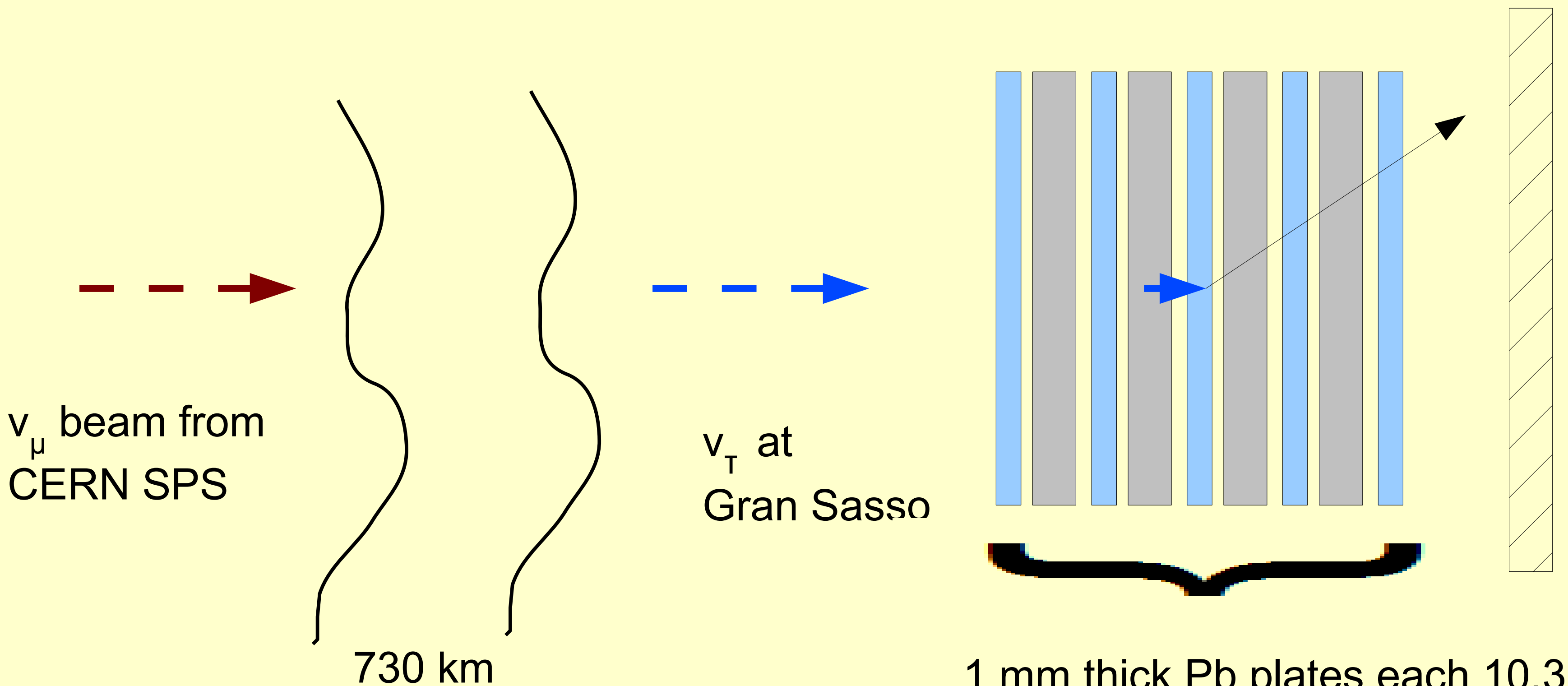
- robust
- relatively low cost (≤ a few million $)
- low maintenance
- high livetime
- with a projected life of > 50 years

OPERA = Oscillation Project with Emulsion-tRacking Apparatus

a long baseline neutrino oscillation experiment, from CERN to Gran Sasso, to observe oscillation $\nu_\mu \rightarrow \nu_\tau$

Charged current reaction produces τ leptons: $\nu_\tau + N \rightarrow \tau + X$

τ's leave very short tracks (~ 1 mm) in emulsion and decay products leave more tracks in downstream emulsions and electronic tracking chambers



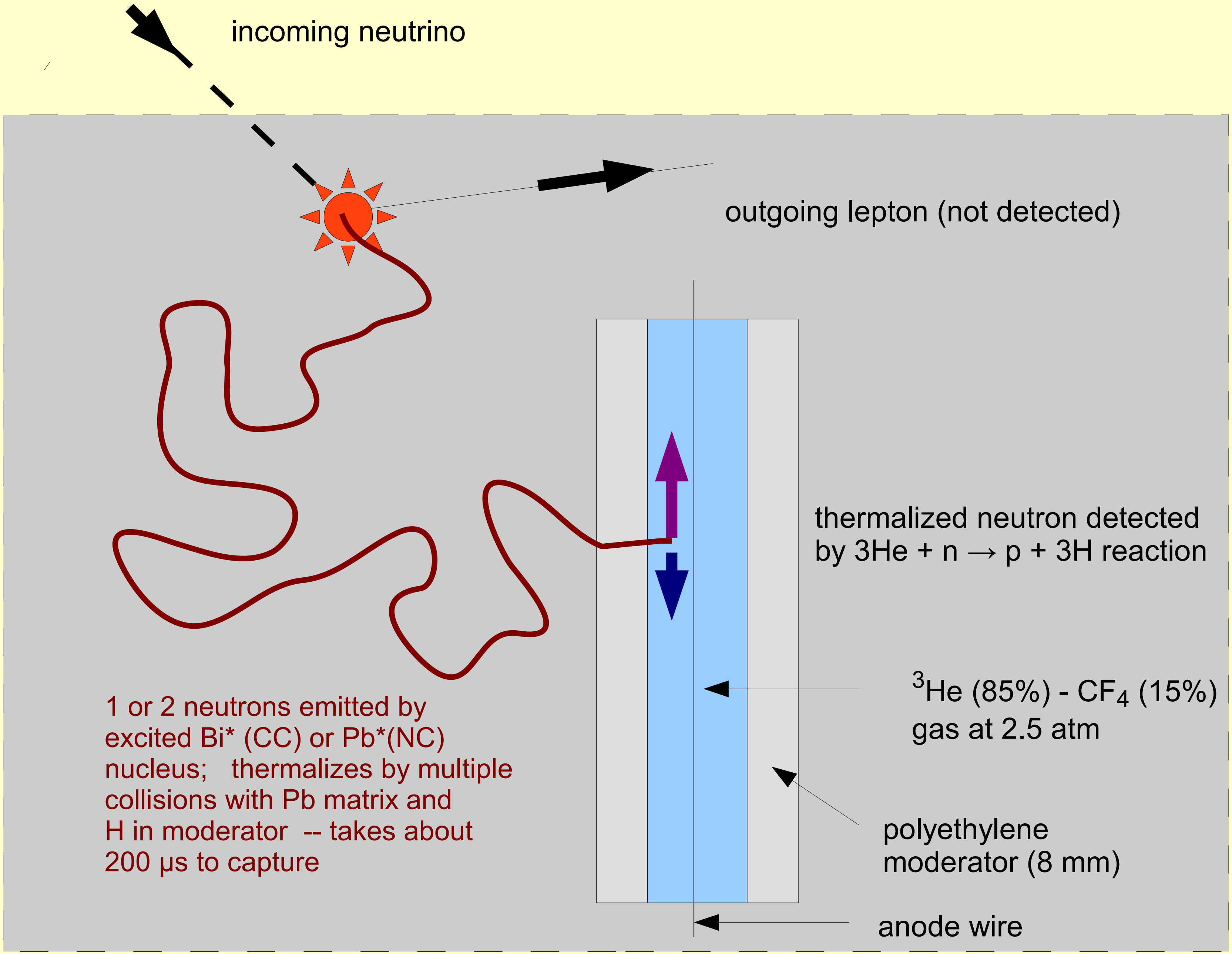
1 mm thick Pb plates each 10.3 x 12.8 cm
sandwiched between
sheets of emulsion
56 sheets of Pb in 1 “brick”

Available for use from the OPERA detector::
8.7 million of these Pb plates, totaling 1300 metric tons
This is lead that is naturally lower in radioactive ^{210}Pb, worth > $2.6 million USD.

Also available:

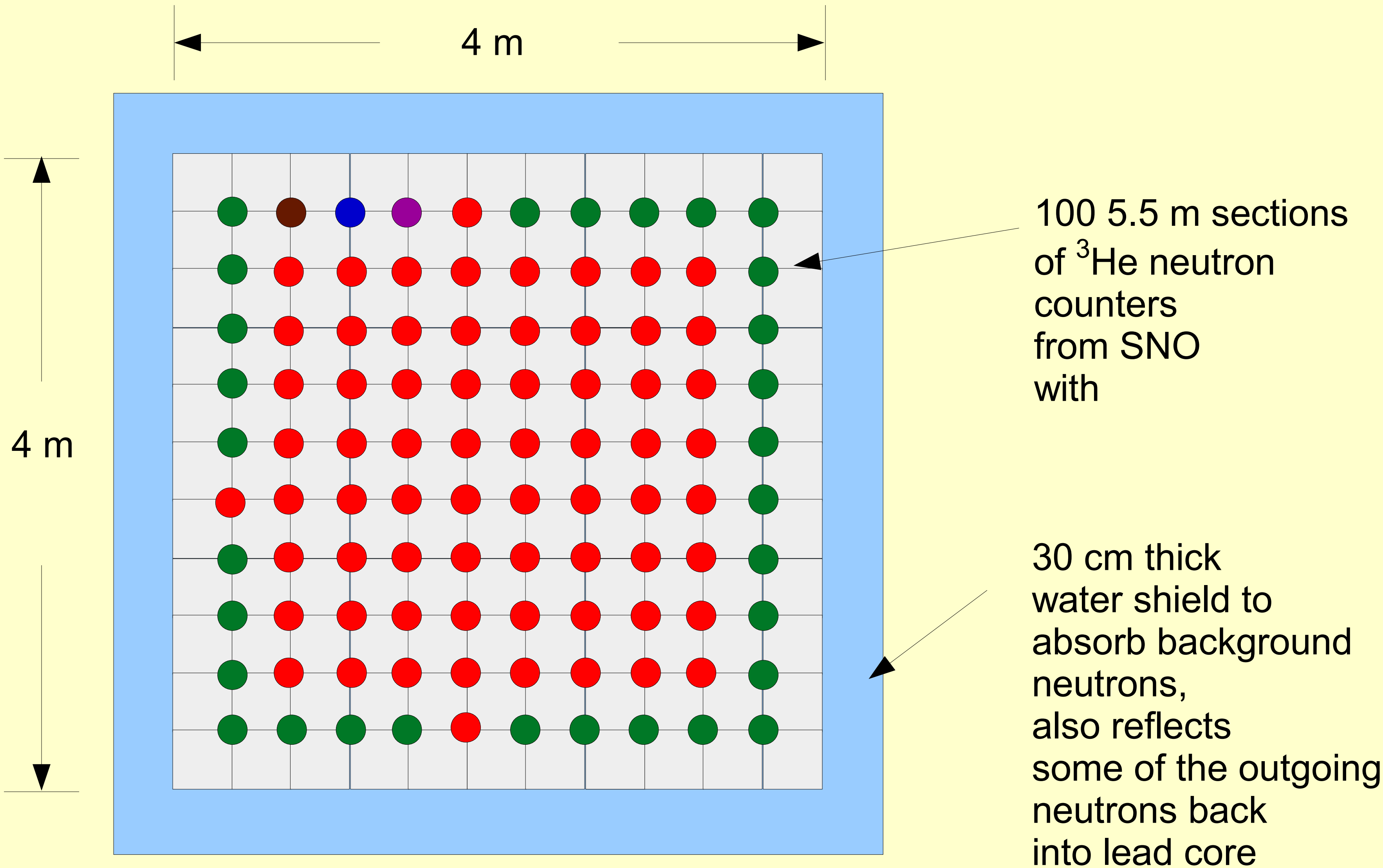
- about 500 metres of tubular ^{3}He-filled proportional neutron counters from the SNO experiment, of which 380 metres are currently deployed in HALO
    - 5.0 cm diameter, filled to 2.5 atmosphere of 85% ^{3}He, 15% CF_4;
    - These were built by U of Washington for the SNO experiment, and refurbished for use in HALO.
    - the lowest radioactivity neutron detectors in the world
    - value > $6 million USD for the ^{3}He isotope alone at 2012 prices; not feasible to build more of these

- about 50 2-metre $^{10}BF_3$-filled neutron counters, each with about 36% the neutron absorbing power of a 3-metre ^{3}He tube.



Energy threshold for 2-neutron emission higher than for 1-neutron emission, so ratio of number of 2-n events to 1-n events gives a measure of the average neutrino energy.

Baseline design: Use the lead and ^{3}He neutron detectors we have on hand
1 kT of Lead = 4 m x 4 m x 5.5 m "cube"



Simulations by Paul Voytas and Peter Gumplinger:
Neutron detection efficiency = **24%** [11Jan16]
42% absorb on Pb, 30% absorbed in water shield.
Need more neutron detectors to compete with absorption on Pb!

Because absorption on Pb is significant, more neutron detectors improves efficiency. Many permutations tried in Monte Carlo (Paul Voytas)

A. 26 x 26 array of detectors, with outer perimeter populated by 3He and inner 24 x 24 populated by BF3 containing 130 moles of BF3 = doubling neutron absorbancy ($0.5M-$1.5M) [25Jan16]

Efficiency = 37.5%

B. same as A above, but BF3's containing 260 moles of BF3 ($1.0M-$3.0M) [25Jan16]

Efficiency = 47% (27% captured on Pb, 16% captured on water)

C. same as B above, but 8 mm polypropylene moderator replaced by 48 mm graphite moderator [09Feb16]

Efficiency = 55%

D. Active water shield – embed BF3 counters in the water shield [23Feb16]

14 x 14 array of 3He or BF3 equivalents in lead core
103 BF3 in water shield (18 on each side, 16 on each end,
18 cm diameter x 1 STP = 641 moles of BF3)
Efficiency = 48.7%

Quite hopeful we can achieve efficiency > 50%. Efficiency for detecting the 2-n emission events ~ (one-neutron efficiency)^2 so high efficiency is important.

^3He now too expensive, no prospect of building more ^3He neutron detectors
3 alternatives being pursued in parallel

boron coated straws filled with $Ar\text{-}CO_2$ gas (Proportional Technologies Inc.)	BF_3 gas proportional chambers @TRIUMF	Gd-coated plastic scintillator bars + lead converter @ Argonne/Fermilab
new commercial product, robust and no known safety hazards	50-year old proven technology, simple and robust, ~\$0.5 million to equal neutron absorbing power of our ^3He detectors	early stage of development
cost unknown, large surface area of straws poses potential alpha background from materials	BF_3 gas is toxic and corrosive; safety concerns; BF_3 absorbs electrons so does not permit high gas gain or long drift distances to the anode wire	can gammas from Gd(n,γ) be efficiency detected?
test and evaluate at SNOLAB (summer/fall 2016)?	grant application fall 2016; prototypes in summer 2017?	simulation work under way extrusion of bars at Fermilab and testing (fall 2016)

Boron-coated straws with anode wire in each straw
(Jeffrey Lacy, IEEE Report)

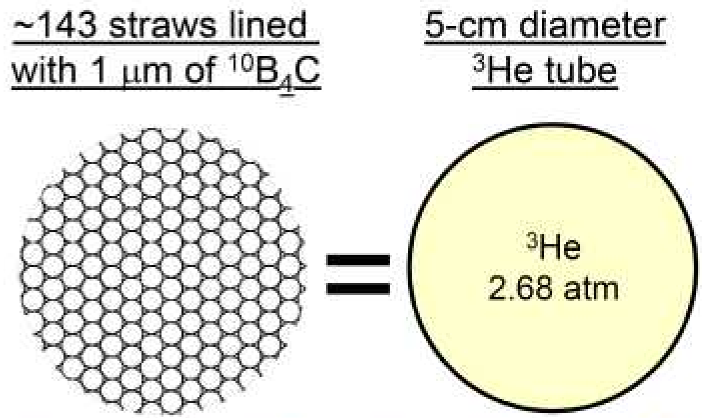


Fig. 1. Stopping power equivalence between straw detectors (4 mm diameter) lined with 1 μm of $^{10}B_4C$, and ^{3}He gas.

$^{10}B + n \rightarrow {}^{7}Li + \alpha$ charged particles ionize the Ar-CO_2 gas, but in small straws, they don't fully stop in the gas, so poor energy resolution

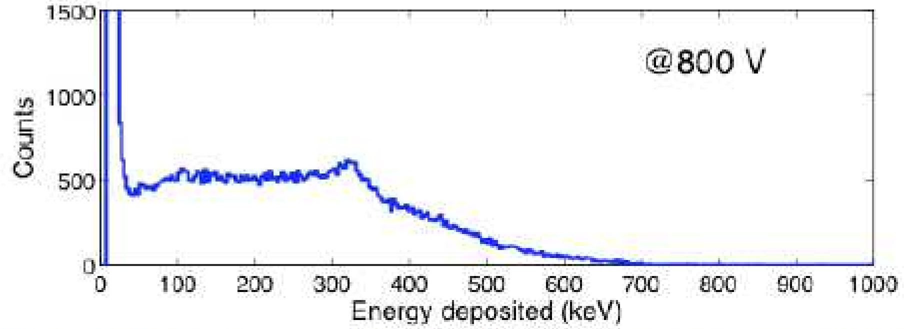


Fig. 2. Pulse height spectra measured in a close-packed array of BCS detectors, with a moderated ^{252}Cf source. The same spectrum is calibrated for charge generated in the detectors (*top*) and for the energy deposited (*bottom*).

BF_3 gas proportional counters

- BF_3 absorbs electrons, hence collection of ionization charge and thus energy resolution deteriorates as gas pressure increases; possible worsening of discrimination between neutrons and low-energy gammas

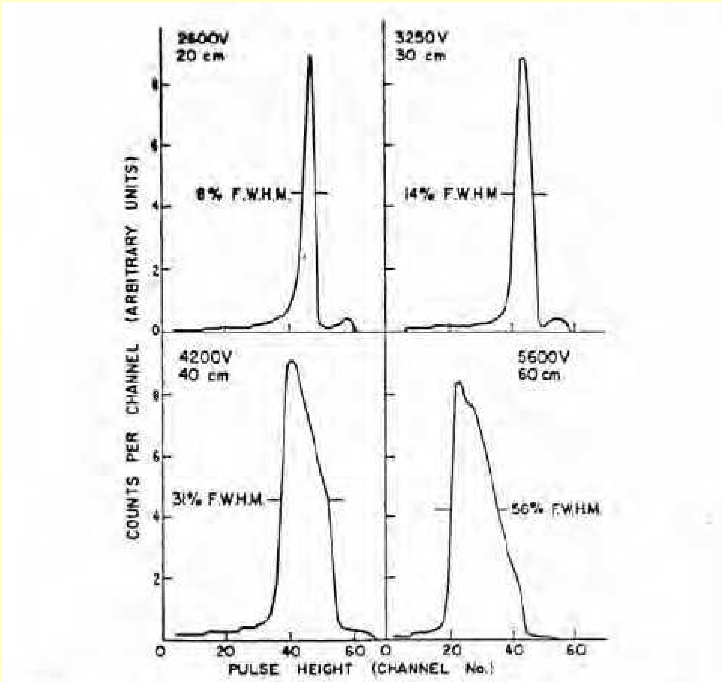
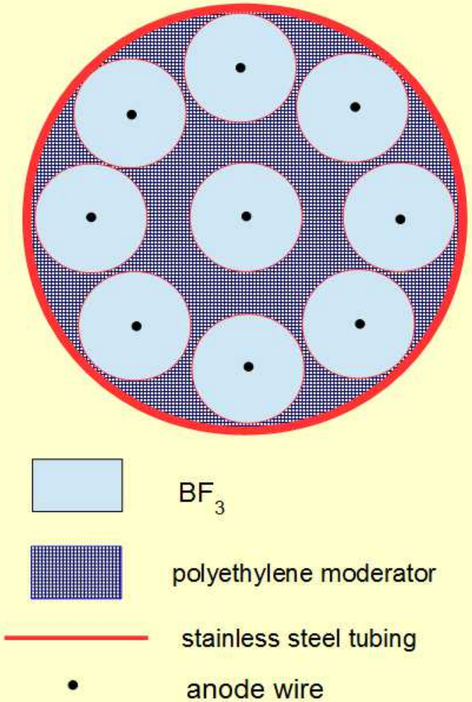


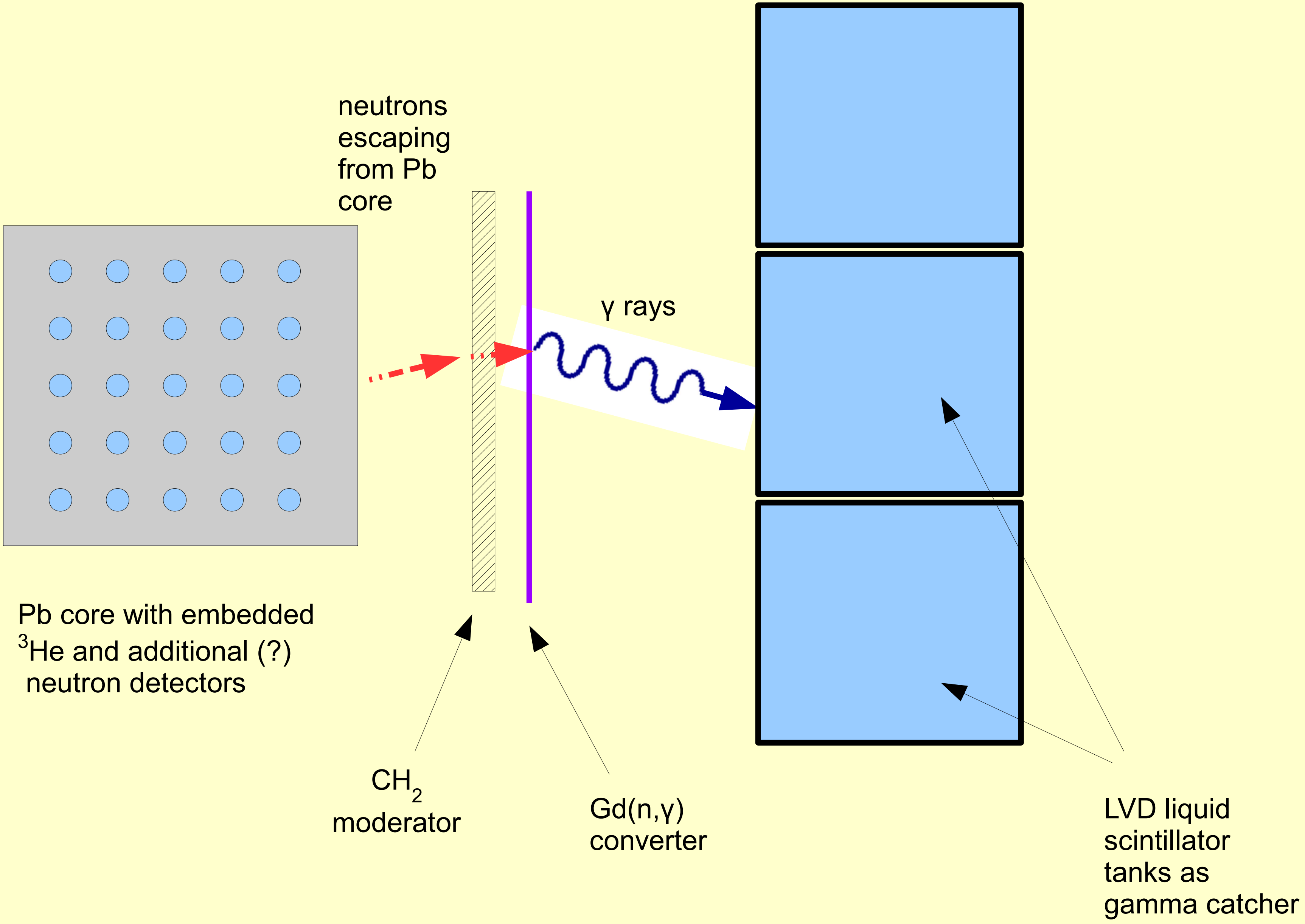
FIG. 6. Pulse-height distribution curves of counters with pure BF_3 fillings at, respectively, 20, 30, 40, and 60 cm Hg pressure.

I.L Fowler, Rev Sci Instrum. 34 (1962) 731.

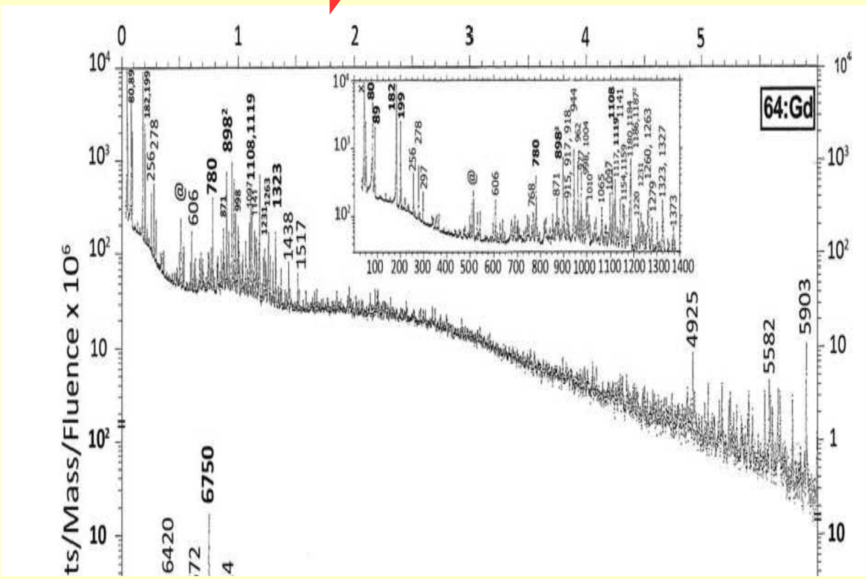
Possible solution in segmenting the gas volume to reduce drift distance?

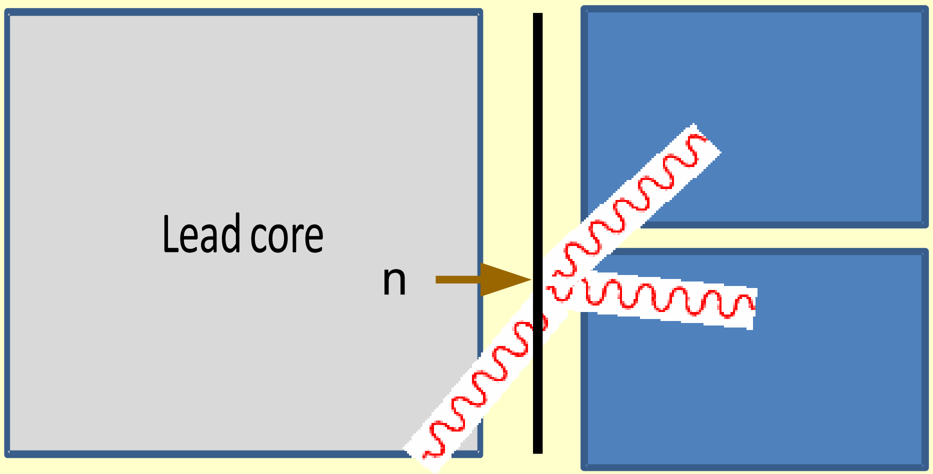


“LVD+” scheme: put the lead core inside the existing LVD detector at Gran Sasso, convert them to gammas using Gd, detect the gammas with the LVD scintillator tanks. Could we do this with high efficiency? Threshold for LVD tanks is 4 MeV in trigger, 0.5 MeV if gated by other activity.



Gd(n,γ) results in a cascade, emitting an average of 3.2 gamma rays,
with a range of energies, some of which head in the wrong direction and miss the scintillator,
most of which are below the 4 MeV primary threshold of LVD.





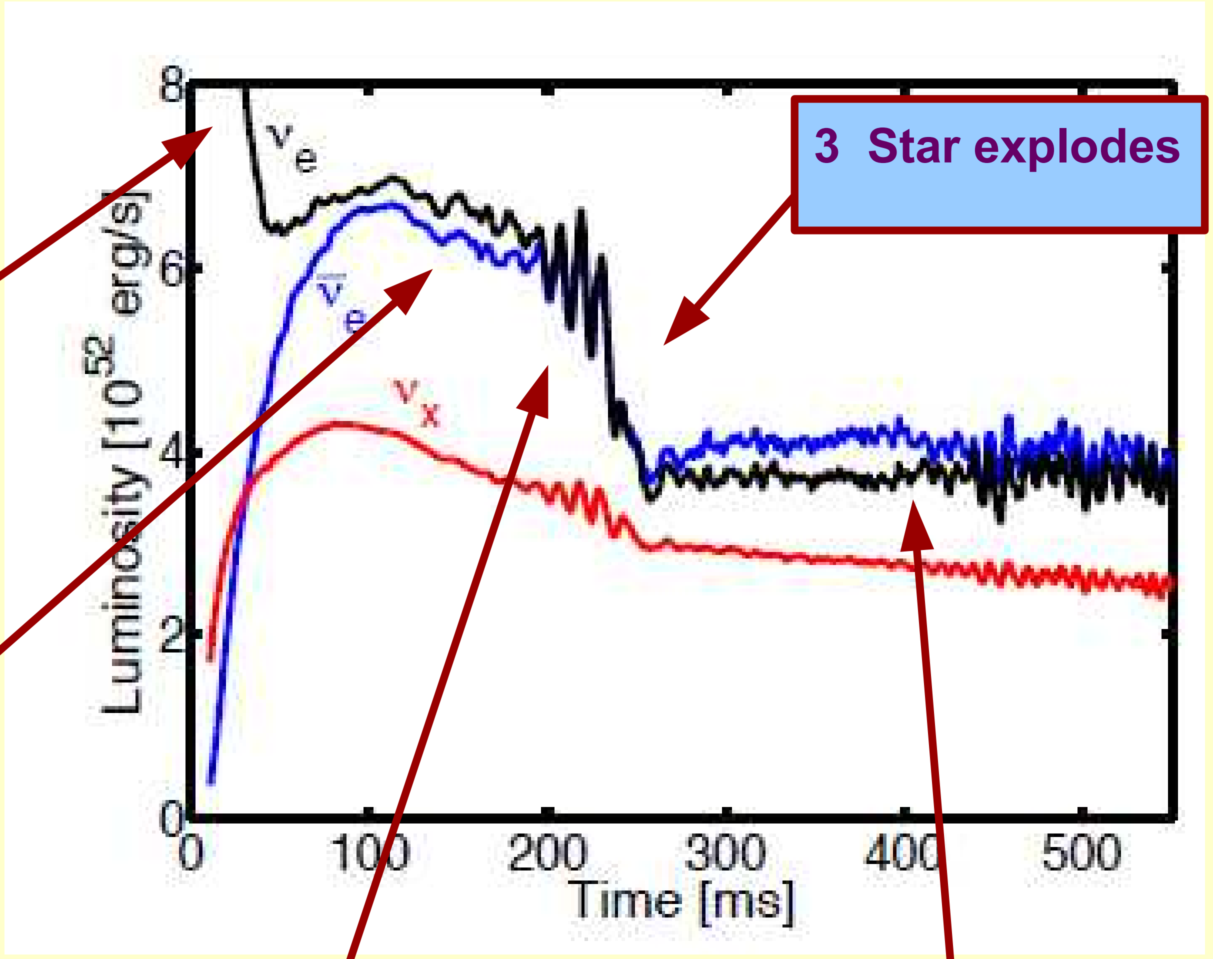
This scheme might be useful to detect second neutron from a 2-n emission event, where the first neutron has been detected already by the lead core detectors, and the threshold lowered to 0.5 MeV for 1 ms to catch the second neutron's gamma cascade.

Unstacking the hundreds of 1.5 ton LVD modules in order to place a lead mass inside a daunting task!

Physics signals from a 1.3 kT lead detector

1 Burst phase:

short (~20 msec) spike of ν_e from free and bound protons absorbing electrons; stellar core collapses and shrinks; neutron star is formed



3 Star explodes

2 Accretion phase:

ν_e and anti- ν_e emission while material is raining down onto neutron star; hydrodynamic instability as inward pull of gravity balanced by outgoing shock and neutrino heating; increasingly large dipole oscillations of the stellar core

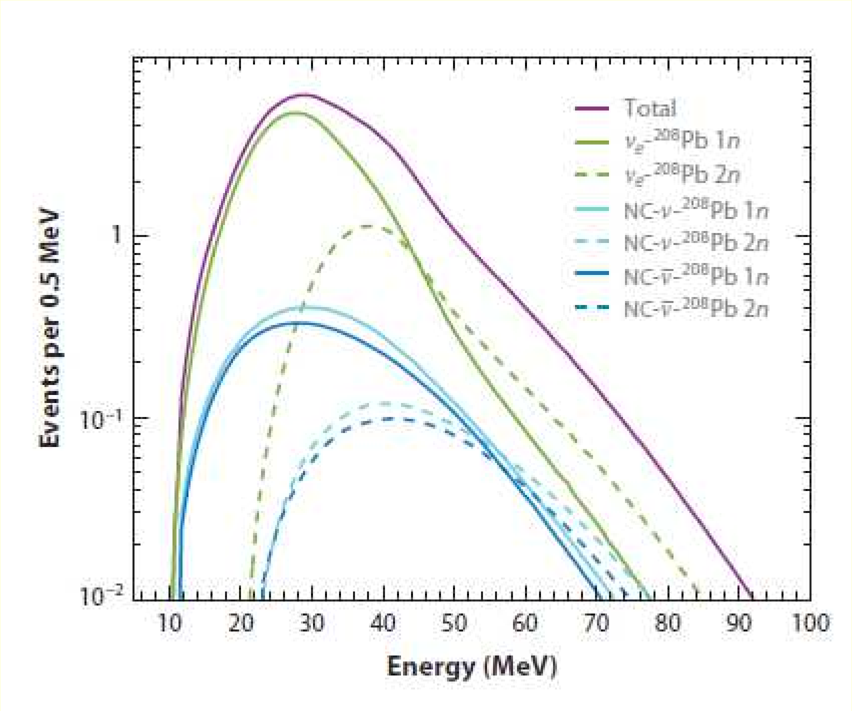
2b SASI oscillations

Millisecond-scale oscillations of increasing amplitude due to **S**tanding **A**ccretion **S**hock **I**nstability; observable in HyperK and ICECUBE?

4 Cooling phase

Neutron star cools by emitting neutrinos of all flavors equally; lasts ~20 seconds; source of 90% of SN neutrinos

How many events could we expect in 1.3 kT of Pb?



From K. Scholberg, Ann. Rev. Nucl. Part. Sci. 2012 Vol 62 81-103

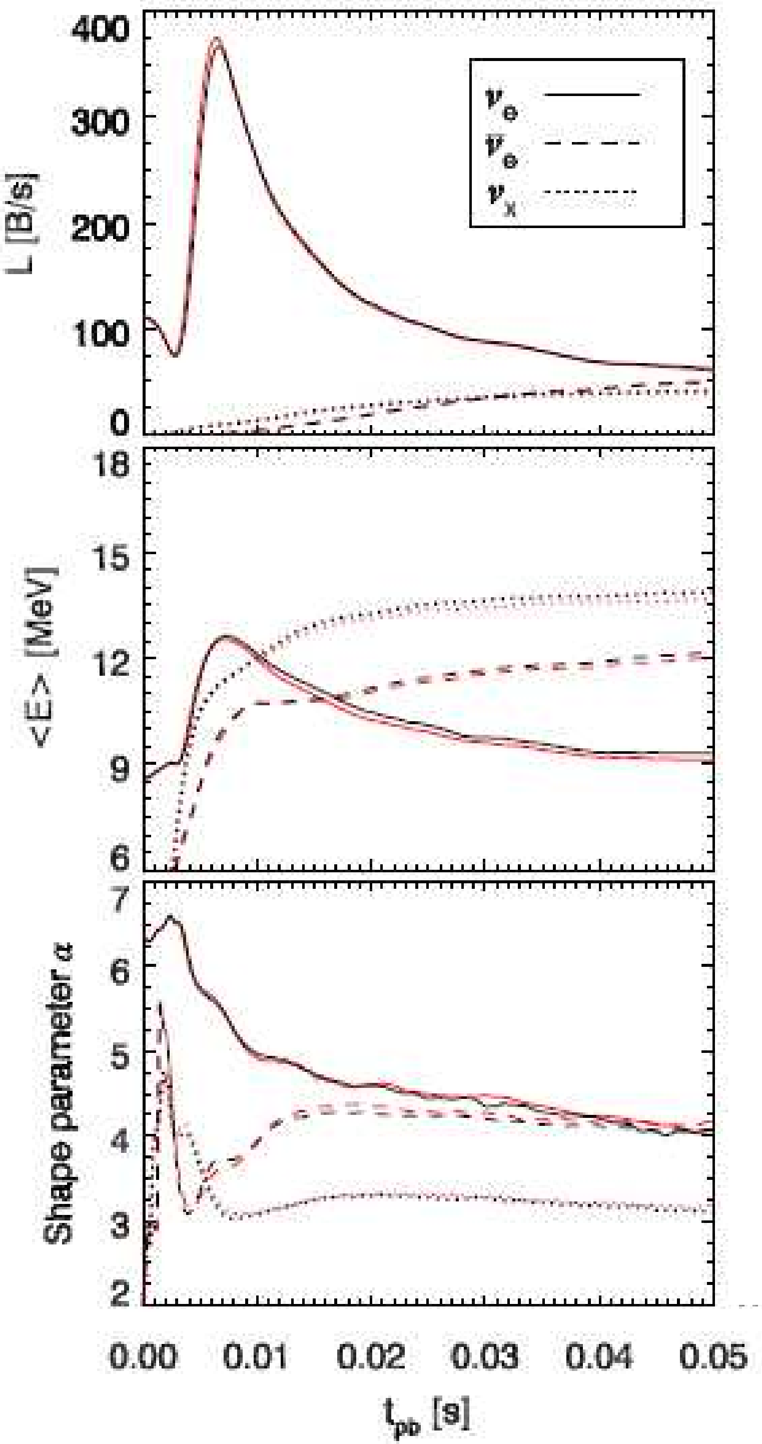
rates based on Gava-Kneller-Volpe-McLaughlin model, Phys. Rev Lett. 103:071101 (2009)

Total of **366 events** from a SN at 10 kpc; will be reduced by detector inefficiency.

Note strong dominance of ν_e interactions over NC interactions of non- ν_e flavors -- Pb is dominantly a ν_e detector.

GKVM model includes effects of collective and MSW flavor oscillations, but does not model in detail the early ν_e spike from burst phase.

This early ν_e spike is hard to measure in a water or organic scintillator detector, which is primarily sensitive to anti-ν_e. Can a 1.3 kT Pb detector observe this?



To evaluate the number of events in the initial spike of ν_e we use the calculation of Mirizzi et al. Riv. Nuovo Cim. 39 (2016) no.1-2, 1 arXiv:1508.00785 [astro-ph.HE] whcih give the parameters of the neutrino emission as a function of time.

L Luminosity in Bethe/sec at time t, where
1 Bethe = 10^{51} erg = 10^{44} Joule = 6.25×10^{56} MeV

<E> Mean energy of neutrinos at time t

α Pinching (shape) parameter at time t

a large distance from the radiating source:

$$f_\alpha(E) = \left(\frac{E}{\langle E\rangle}\right)^\alpha e^{-(\alpha+1)E/\langle E\rangle}, \tag{9}$$

where

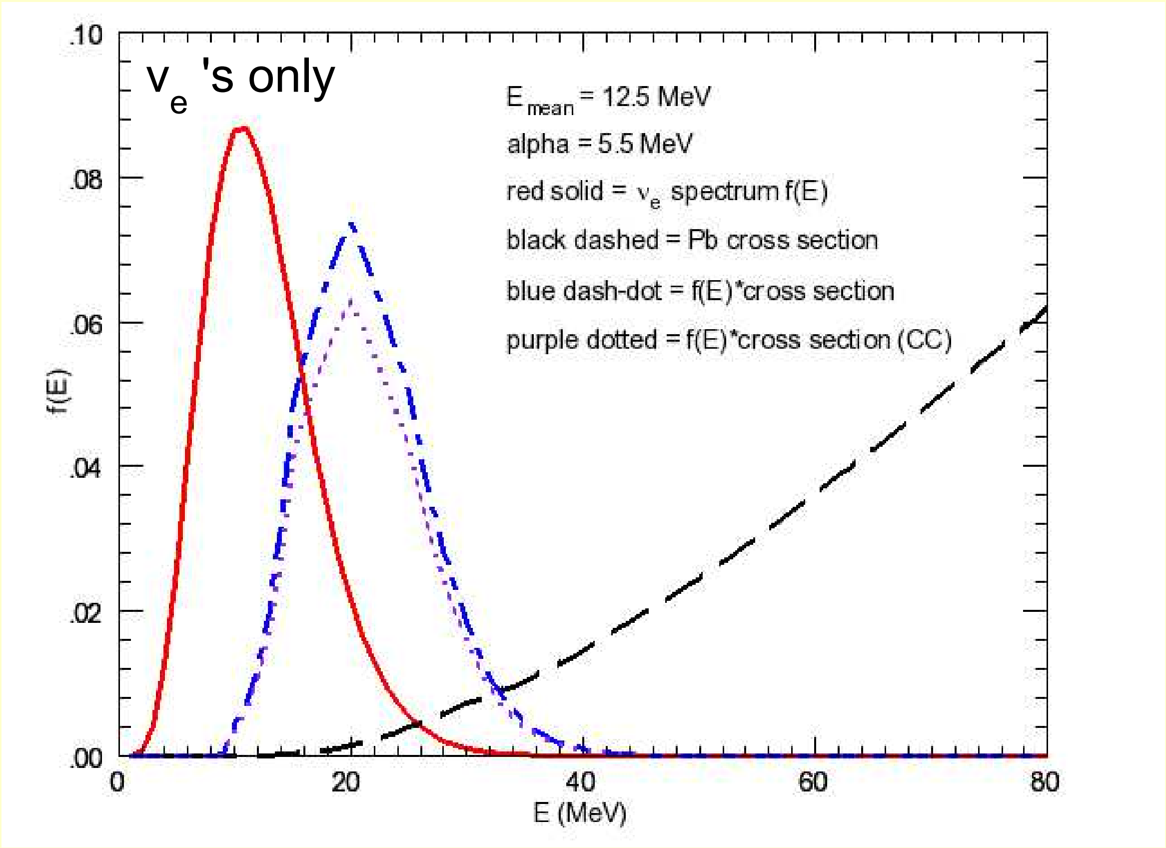
$$\langle E\rangle = \frac{\int_0^\infty dE\, E f(E)}{\int_0^\infty dE\, f(E)} \tag{10}$$

is the average energy([4]). The parameter α represents the amount of spectral pinching and can be computed from the two lowest energy moments of the spectrum, $\langle E\rangle$ and $\langle E^2\rangle$, by

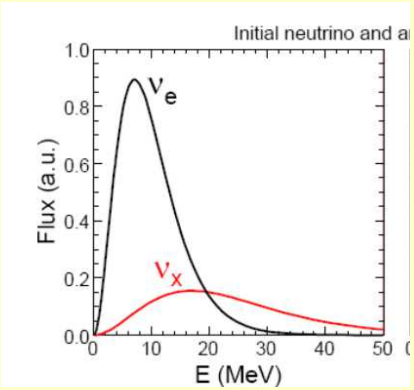
$$\frac{\langle E^2\rangle}{\langle E\rangle^2} = \frac{2+\alpha}{1+\alpha}. \tag{11}$$

We take the calculated neutrino-Pb cross sections of Engel, McLaughlin & Volpe arXiv:hep-ph/0209267v2 20 Oct 2002, and multiply it by the ν_e spectrum.

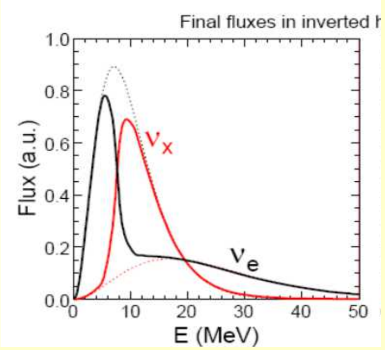
Shown is the plot at time = 7 ms time. It is evident that the Pb detector is mainly sensitive to the high energy tail of the spectrum. It is also evident that the CC contribution (purple dash) constitutes most of the total reaction rate (blue dash-dot).



t = 7 ms



E. Lisi,
TAUP'07



Observed events are sampling mainly the high energy tail of the ν spectrum -- very sensitive to enhancements of the tail due to flavor swapping between the initially cool ν_e spectrum and the initially hot ν_x spectrum due to collective ν-ν effects

Result of integrating initial ν_e spike over 0 – 50 ms:

Get **12 events** from ν_e interactions (CC+NC) with 1.3 kiloton of Pb, in first 50 msec. with no flavor oscillations taken into account.

This is assuming 100% neutron detection efficiency; in reality, ~50% might be achievable, giving us only ~6 events.

We're aiming for a background rate of 6.7 Hz in the HALO-2 detector to be low enough for SNEWS (0.34 events in 50 msec window), so 6 events in 50 msec (1/20 sec) is easily distinguishable.

Failure of ν's to thermalize in SN could lead to higher energy ν_e 's and a larger number of events?

Small statistics, but still a worthwhile thing to observe!

MSW oscillations at larger radii will reduce this numberr:

Effect of MSW oscillations, assuming adiabatic transition in outer envelope of supernova (from Raffelt, 2015)

	NORMAL MASS HIERARCHY	INVERTED MASS HIERARCHY
ν_e survival probability	0	$\sin^2\theta_{12} \approx 0.3$
anti-ν_e survival prob.	$\cos^2\theta_{12} \approx 0.7$	0

1. Absence of ν_e detected during neutronization burst implies normal mass hierarchy

2. Iff inverted mass hierarchy, only expect to detect 0.3 x 6 ≈ 2 neutrons in a 50 msec window in 1.3 kT lead detector -- still observable above expected background of 0.34 events in 50 msec window, but marginal statistics

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A K. Hirata et al.

TABLE I. Measured properties of the twelve electron events detected in the neutrino burst. The electron angle in the last column is relative to the direction of SN1987A. The errors on electron energies and angles are one-standard-deviation Gaussian errors.

Event number	Event time (sec)	Number of PMT's (N_{hit})	Electron energy (MeV)	Electron angle (degrees)
1	0	58	20.0 ± 2.9	18 ± 18
2	0.107	36	13.5 ± 3.2	15 ± 27
3	0.303	25	7.5 ± 2.0	108 ± 32
4	0.324	26	9.2 ± 2.7	70 ± 30
5	0.507	39	12.8 ± 2.9	135 ± 23
6	0.686	16	6.3 ± 1.7	68 ± 77
7	1.541	83	35.4 ± 8.0	32 ± 16
8	1.728	54	21.0 ± 4.2	30 ± 18
9	1.915	51	19.8 ± 3.2	38 ± 22
10	9.219	21	8.6 ± 2.7	122 ± 30
11	10.433	37	13.0 ± 2.6	49 ± 26
12	12.439	24	8.9 ± 1.9	91 ± 39

First 2 events point back to Large Magellanic Cloud, consistent with ν-e scattering, Are these 2 events actually ν_e ?

If so, already signature of Inverted Mass Hierarchy?

Comparison with, e.g. Pb detector could establish flavor of ν's involved.

other 10 events isotropic, consistent with $\bar{\nu}_e + p \rightarrow e^+ + n$

Measuring number of 1n and 2n emission events can constrain models
Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225v3 [astro-ph.SR]

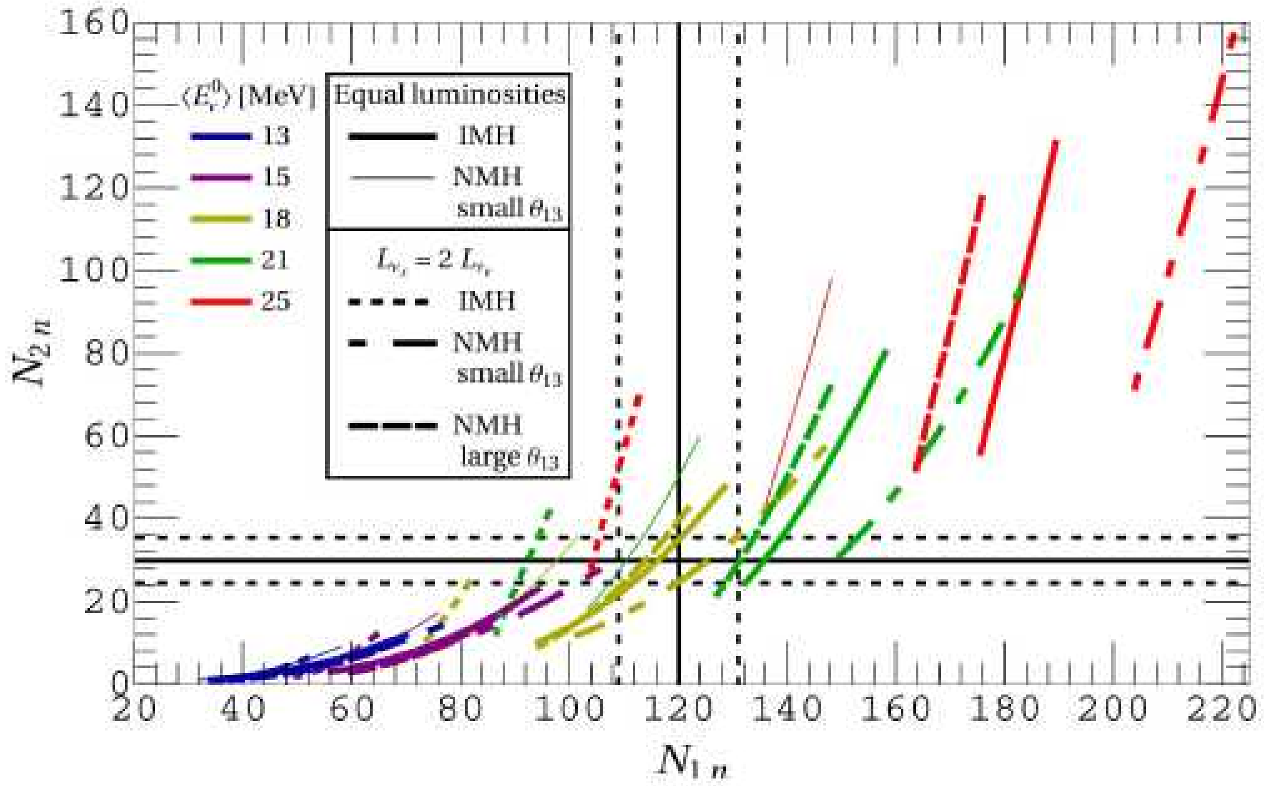


Figure 12. (Color online) One- and two-neutron emission event rates with different values of the primary non-electron neutrino pinching parameter α_{ν_x}: at the top of each curve $\alpha_{\nu_x} = 2$, at the bottom $\alpha_{\nu_x} = 7$. Results include $\nu - \nu$ interactions, the MSW effect and decoherence. Different colors correspond to different non-electron type primary average energies (as in figure 6), solid lines are for equal luminosities (thick IMH, thin NMH with small θ_{13}), others for $L_{\nu_x} = 2L_{\nu_e}$: dotted IMH, dashed NMH with large θ_{13} and dash-dotted NMH with small θ_{13}. The total time-integrated luminosity is taken to be 10^{53} erg ($\sim$ total events during the cooling phase), distance to the supernova 10 kpc, a target mass 1 kton of ^{208}Pb and 100 % detection efficiency is assumed. Notice that the results in the case of equal luminosities in NMH with large θ_{13} are the same as the ones in IMH. In addition is shown an example measurement case with 120 one-neutron and 30 two-neutron events (solid black lines) together with estimated statistical errors (dashed black lines).

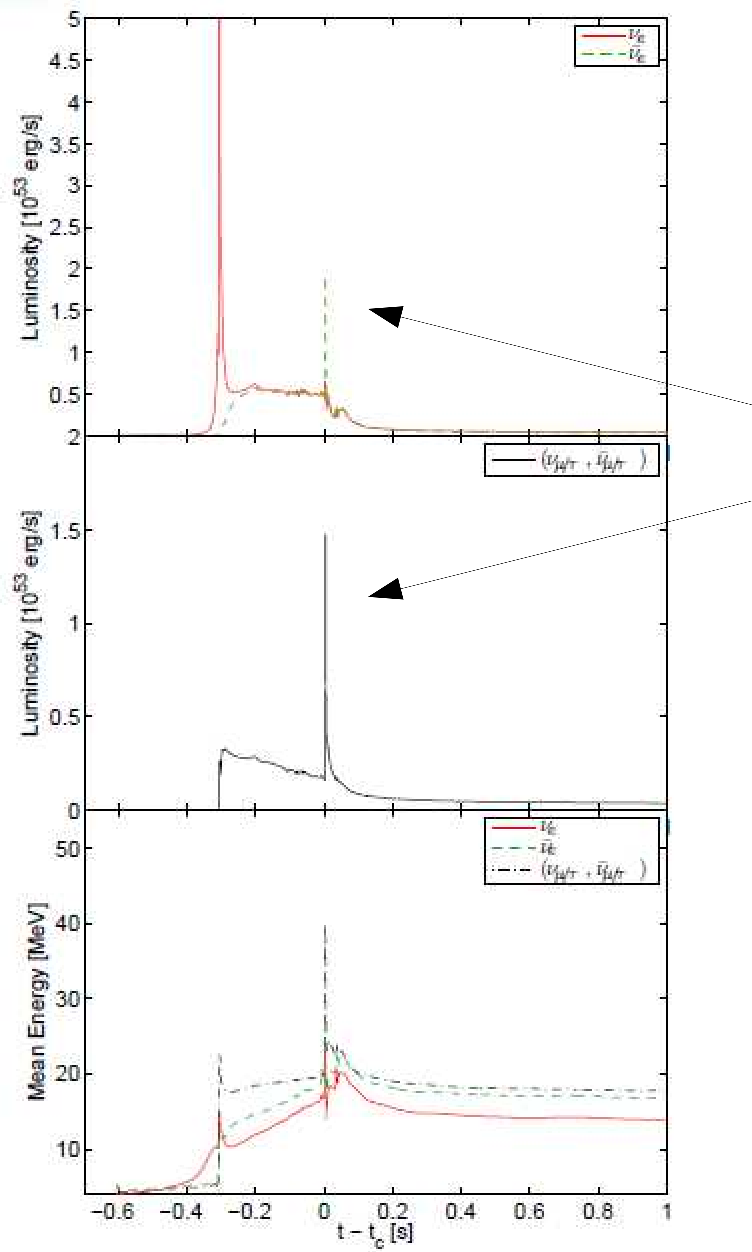


FIG. 21.— Luminosities and mean neutrino energies for the 15 M$_\odot$ progenitor model using the hybrid EOS3. The time gauge t_c is again the moment when the maximum central density is obtained during the PNS collapse.

Second neutrino burst due to QCD phase transition?

(T. Fischer, I Sagert et al. arXiv:1011.3409v2 [astro-ph.HE]

flux mainly in $\bar{\nu}_e$ and $\nu_{\mu\tau}$, might still be observable in Pb detector via neutral current excitation -- note high energy of $\nu_{\mu\tau}$ which would result in a large fraction of 2-neutron emissions

Maybe QCD transition already observed in SN 1987A if you believe the early signal from Mont Blanc?

Important to observe in different flavors to test models.

What I'd like to get from the theory community:

1. Starting from a theoretical model encompassing all phases of a SN, make predictions of the signal in lead, LAr, Water Cerenkov, Scintillator detectors as a function of time, to cover the different phases (neutronization, accretion, cooling, QCD phase transition), for SN of different masses.

2. Make predictions of each stage in above list, for different oscillation scenarios

   - collective neutrino effects or not

   - with and without MSW

   - normal or inverted mass hierarchy

   - sterile neutrino ?

Specifically for a lead detector, the observables are the rate of 1-n and 2-n events as a function of time.

In the same way that the gravitational wave people built up ahead of time a set of templates of different scenarios to compare the GW signal with,

we too, should build up a set of “signature templates” for the worldwide array of different detectors of different flavor sensitivities, for different astrophysical / oscillation scenarios, so that when the next galactic SN occurs, we'll be able to match the observed signal to these templates and quickly come to a conclusion.

Summary

- 1.3 kT of lead available from the OPERA detector

- Design aiming for overall neutron detection efficiency of ~ 50%

- Continued simulation effort to optimize design.

- Testing and evaluation of different neutron detection technologies over next 2 years.

- Full proposal in ~2 years time.

More collaborators needed !

Please contact Clarence Virtue cjv@snolab.ca
or Stan Yen stan@triumf.ca