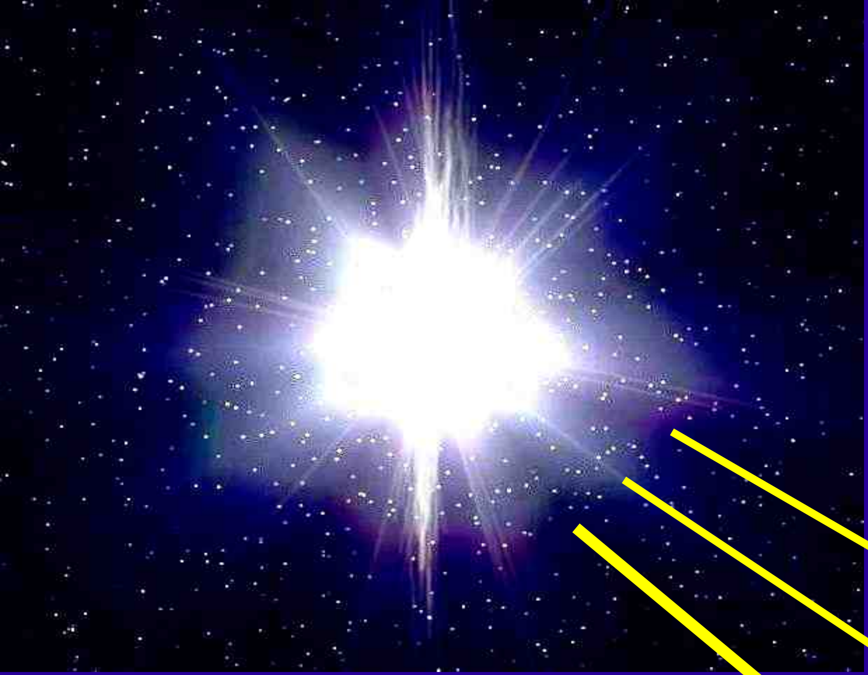
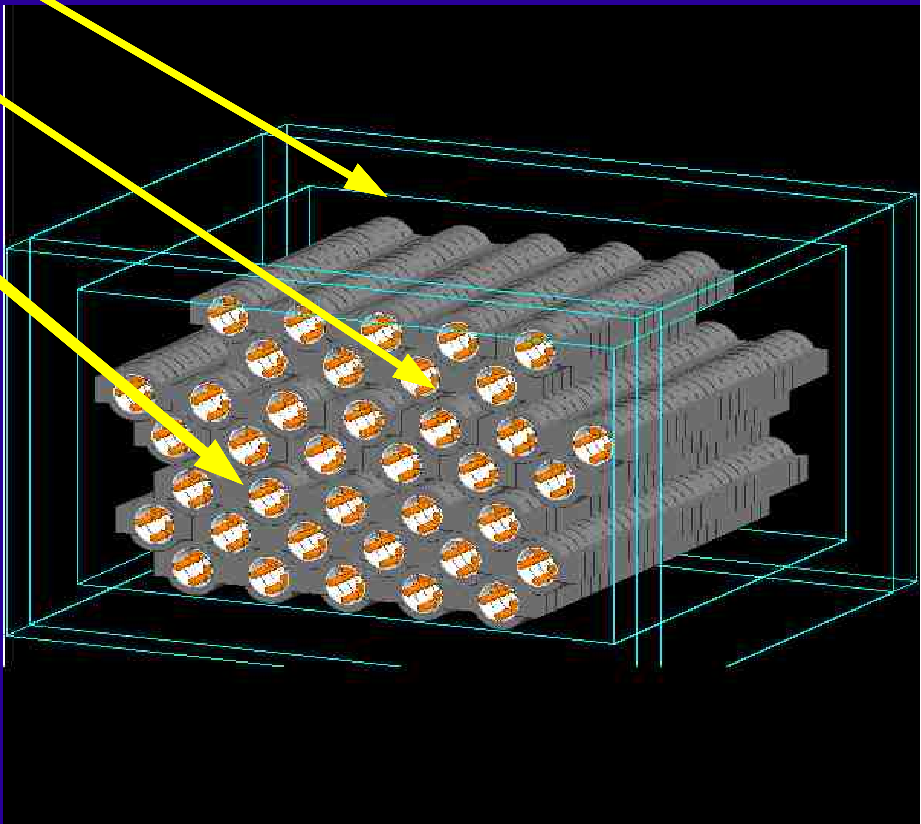


Helium
And
Lead
Observatory

for supernova neutrinos

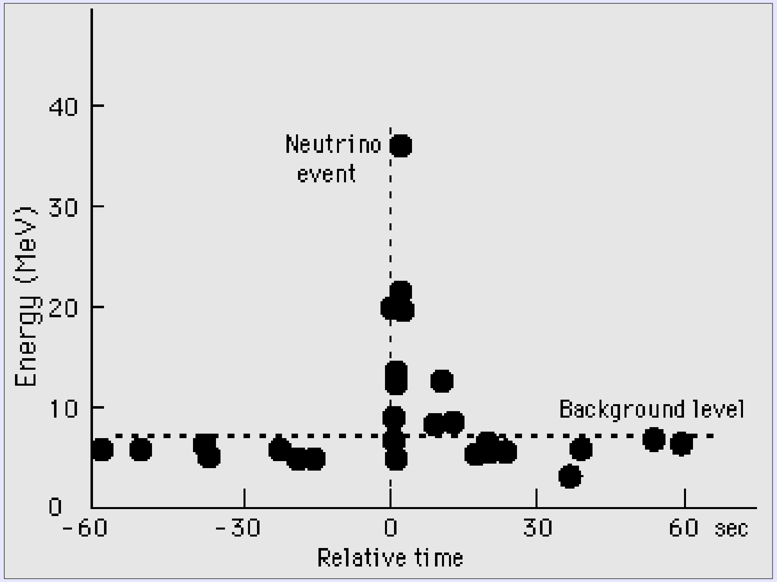


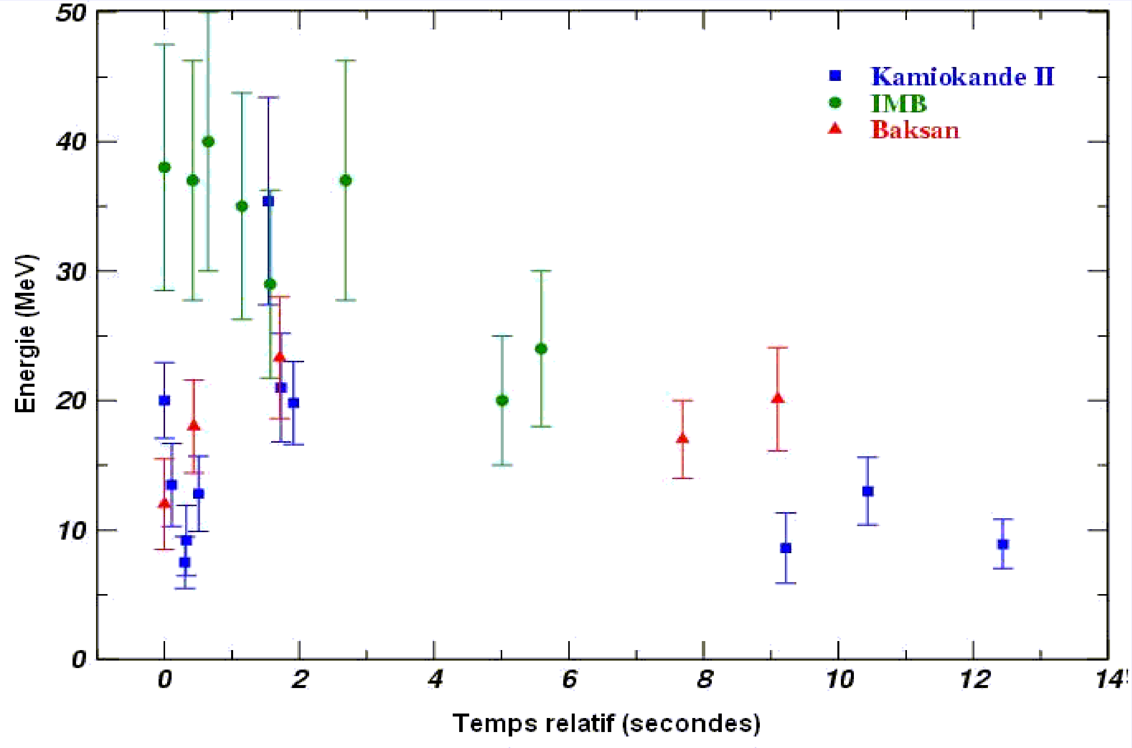
Stanley Yen, TRIUMF
Int Workshop
July 2012

Outline

1. Introduction
2. Lead as a SN neutrino detection medium
3. Construction of the HALO detector
3. Extracting SN physics from HALO
4. Ideas for a future HALO-2

Neutrino astronomy of supernovae is in its infancy





SN 1987A 22 neutrinos detected in 3 detectors

Hard: neutrino detectors are very inefficient because neutrinos interact only via the weak interaction

visible light mean free path~microns

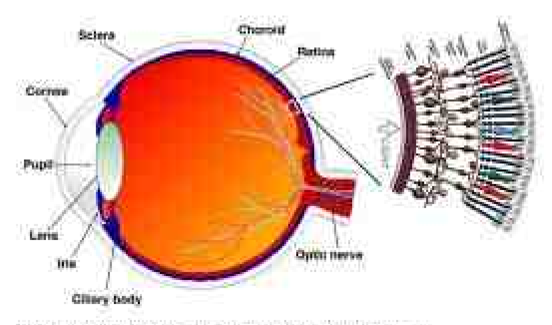
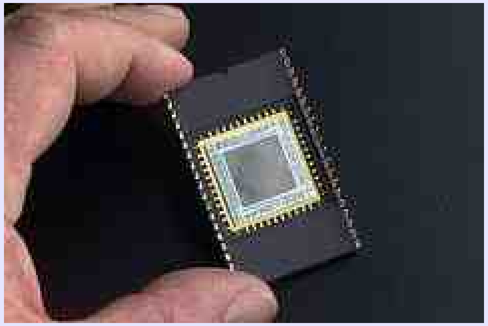
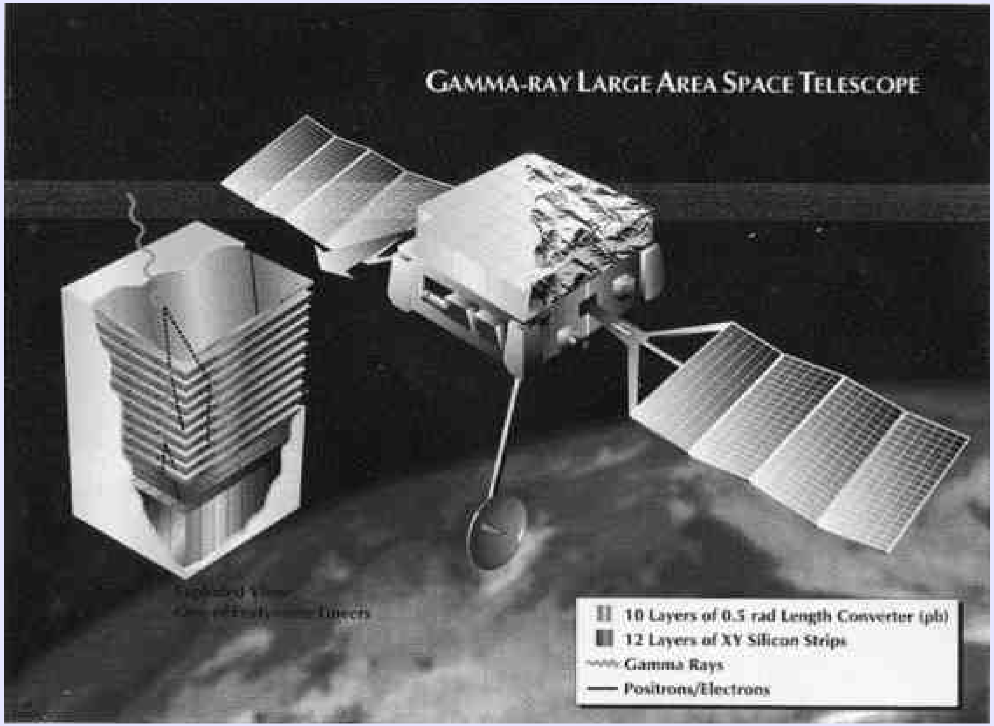


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

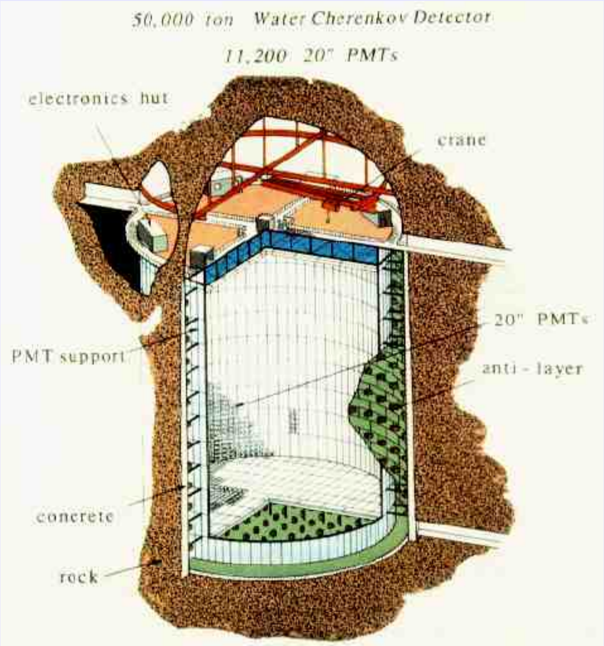


gamma rays mfp ~ 10's of cm



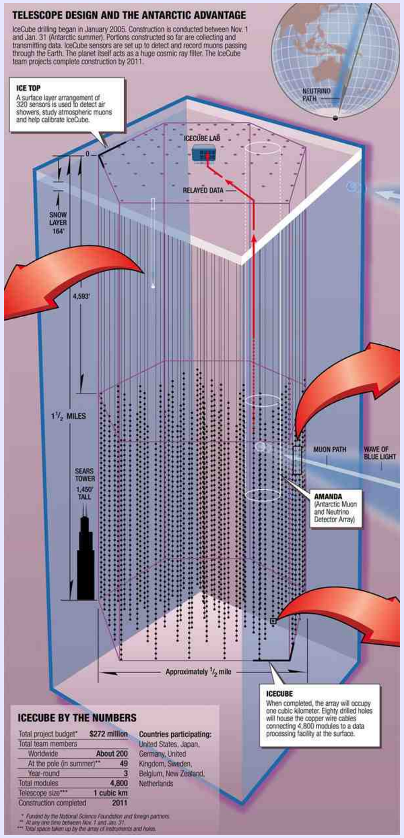
neutrinos: mfp ~ hundreds of parsecs

so even the largest neutrino detectors intercept only an infinitesimal fraction of the incident neutrinos, and sample only our galaxy and maybe a few nearby ones.



Super-Kamiokande
50,000 tonnes
of water

ICECUBE
~ 1 km^3 of
Antarctic ice
cap



TELESCOPE DESIGN AND THE ANTARCTIC ADVANTAGE

IceCube drilling began in January 2005. Construction is conducted between Nov. 1 and Jan. 31 (Antarctic summer). Portions constructed so far are collecting and transmitting data. IceCube sensors are set up to detect and record muons passing through the Earth. The planet itself acts as a huge cosmic ray filter. The IceCube team projects complete construction by 2011.

ICE TOP
A surface layer arrangement of 320 sensors is used to detect air showers, study atmospheric muons and help calibrate IceCube.

AMANDA
(Antarctic Muon and Neutrino Detector Array)

ICECUBE
When completed, the array will occupy one cubic kilometer. Eighty drilled holes will house the copper wire cables connecting 4,800 modules to a data processing facility at the surface.

ICECUBE BY THE NUMBERS

Total project budget*	**$272 million**
Total team members	
Worldwide	**About 200**
At the pole (in summer)**	49
Year-round	3
Total modules	4,800
Telescope size***	1 cubic km
Construction completed	2011

Countries participating: United States, Japan, Germany, United Kingdom, Sweden, Belgium, New Zealand, Netherlands

* *Funded by the National Science Foundation and foreign partners.*
** *At any one time between Nov. 1 and Jan. 31.*
*** *Total space taken up by the array of instruments and holes.*

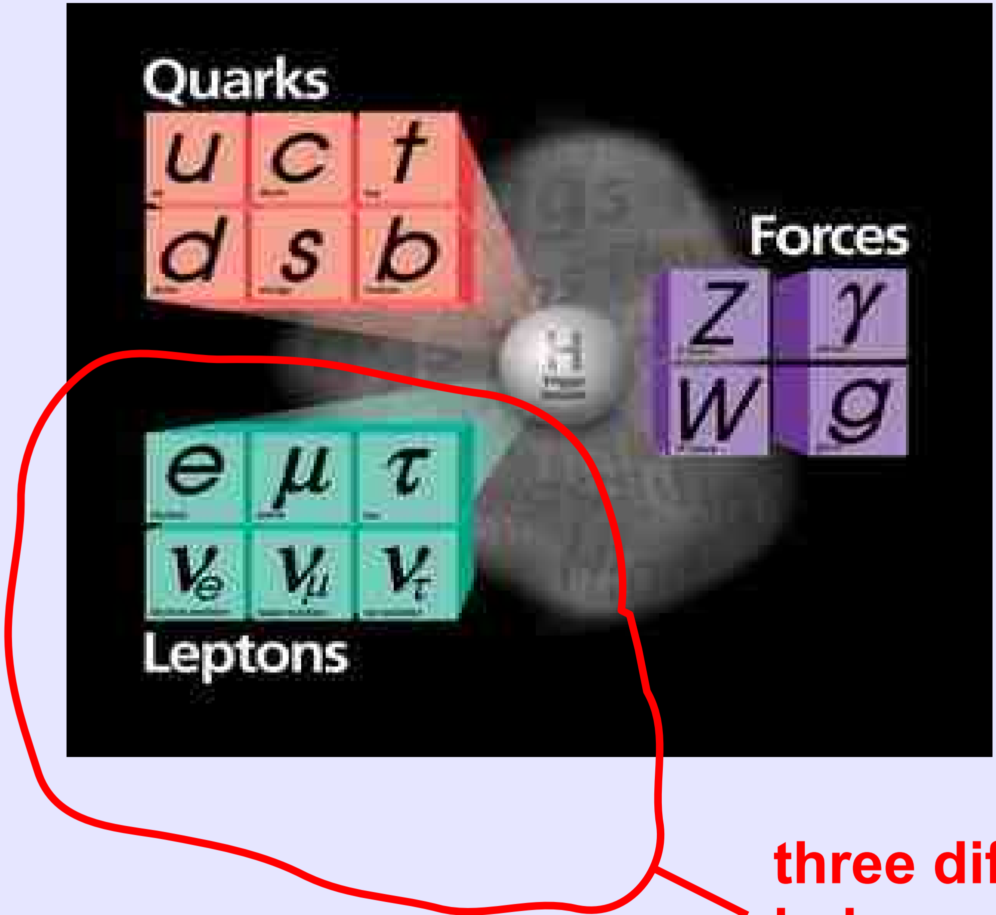
SN occur in our galaxy roughly every 30-50 years, so any detector of SN neutrinos must either

- piggyback on a detector primarily built and operated for other physics objectives (e.g. ICECUBE,Super-K, Borexino, SNO+)

OR

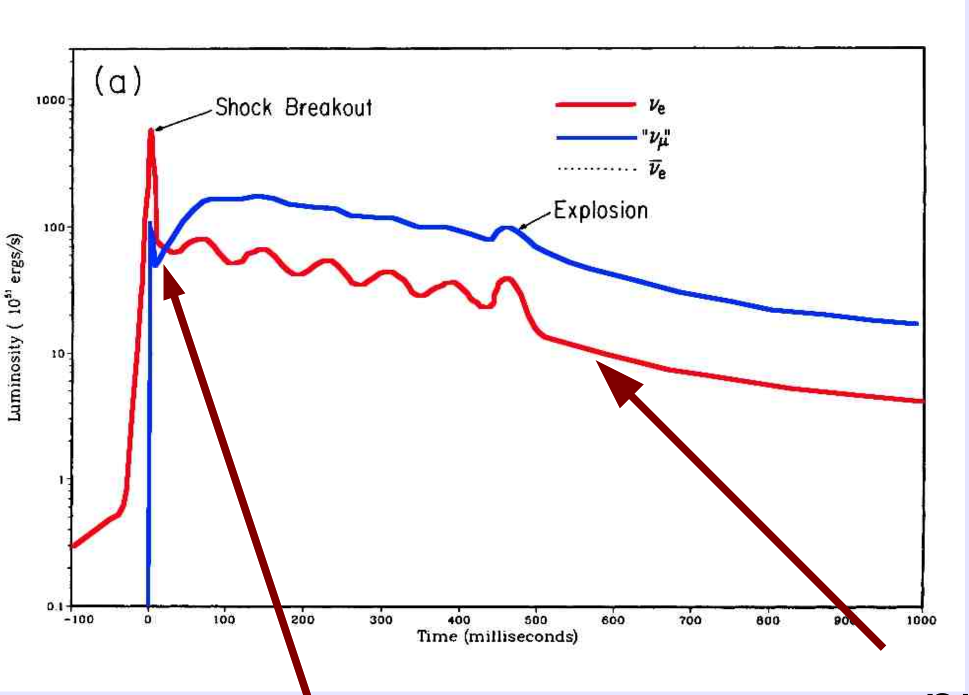
- be assembled from surplus parts to make a cheap dedicated SN neutrino detector (HALO)

A <u>dedicated</u> SN detector like HALO and LVD can patiently wait for decades without long downtime for calibrations and reconfigurations due to changing physics goals. This maximizes the chances of catching the SN neutrino burst of < 1 minute in duration.



three different neutrino flavors which behave differently in a supernova

For next galactic SN we would like precise information on
- time
-direction
-neutrino flavor
-neutrino energy

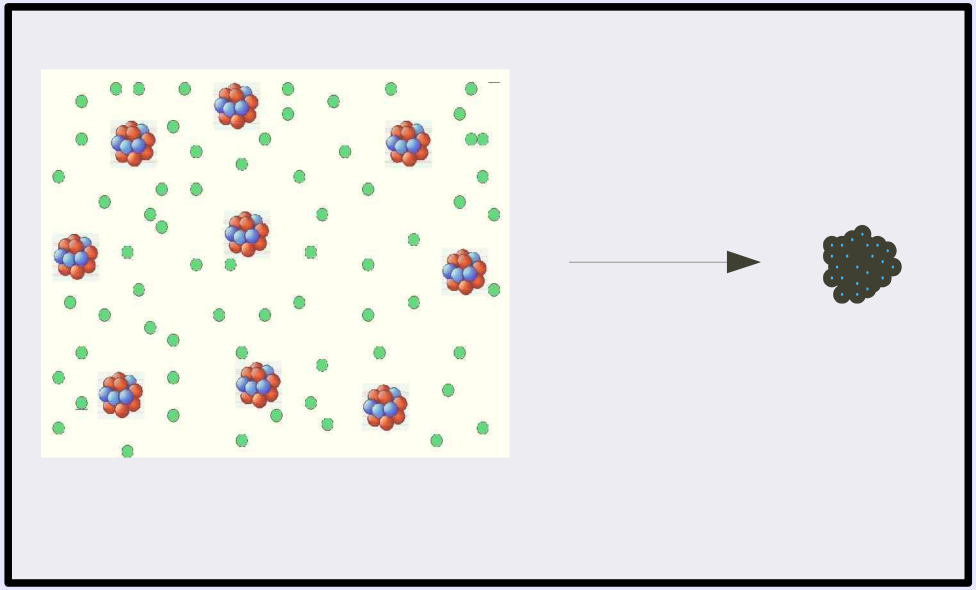


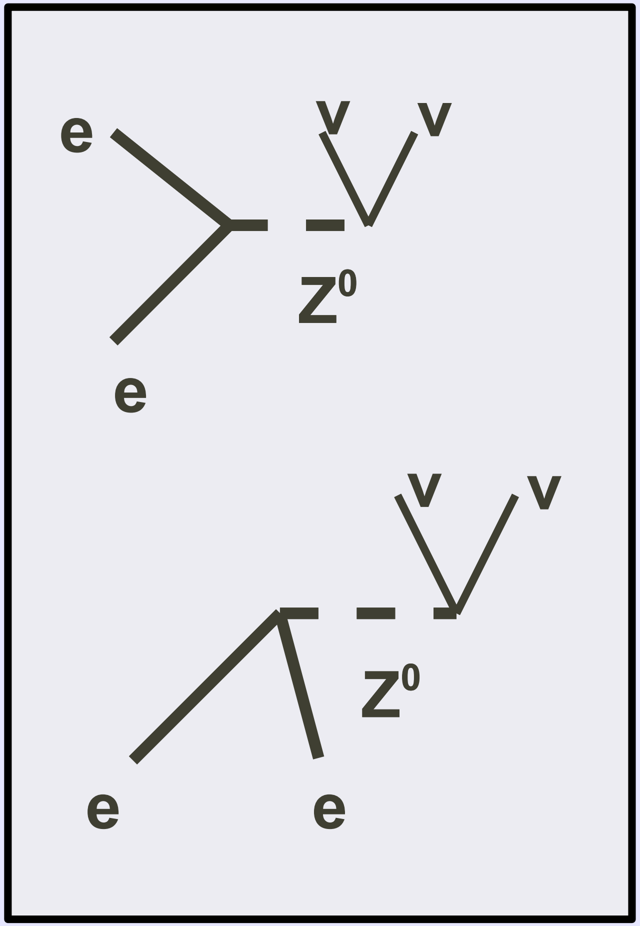
Neutrino luminosity in first 1 second (without neutrino oscillations).

Burrows et al. PRD **45** 33361 (1992)

e capture on protons
emits ν_e

ν pair
production
all flavors





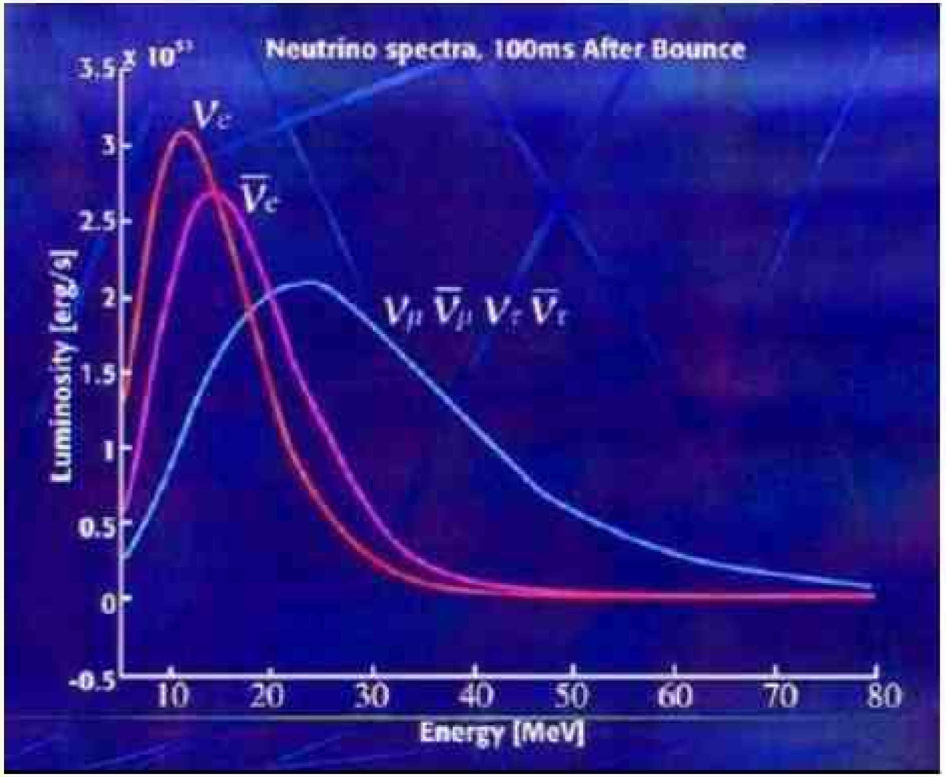
mfp of neutrinos in nuclear density matter < 1 km < radius of proto-neutron star

so neutrinos are trapped and thermalize

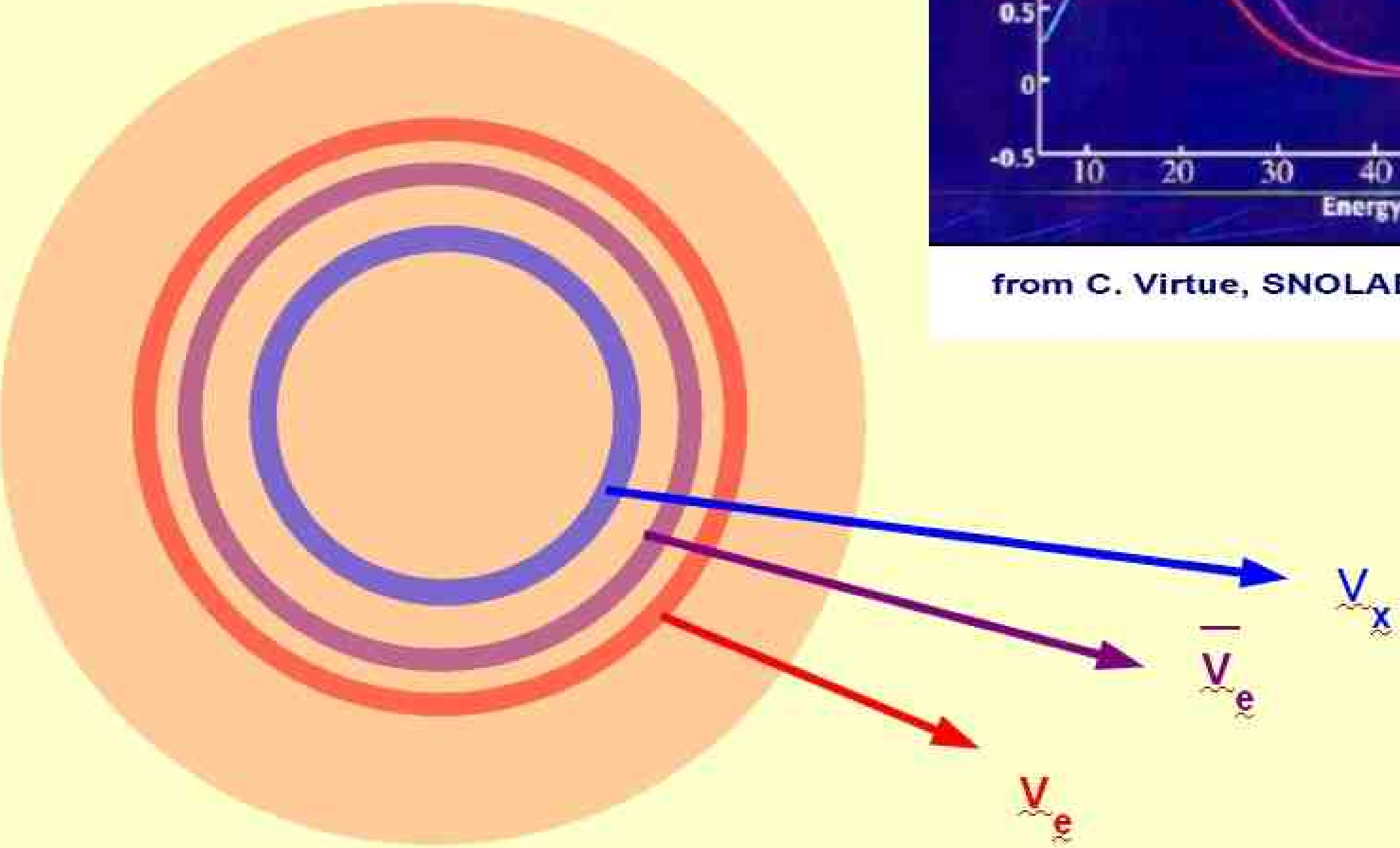
mfp (ν_e) < mfp ($\bar{\nu}_e$) < mfp (ν_x) $x=\mu, \tau$

Neutrinosphere = surface of last scattering

$T(v_e) < T(\text{anti-}v_e) < T(v_x)$



from C. Virtue, SNOLAB workshop, Aug 06



Quark supernova ?

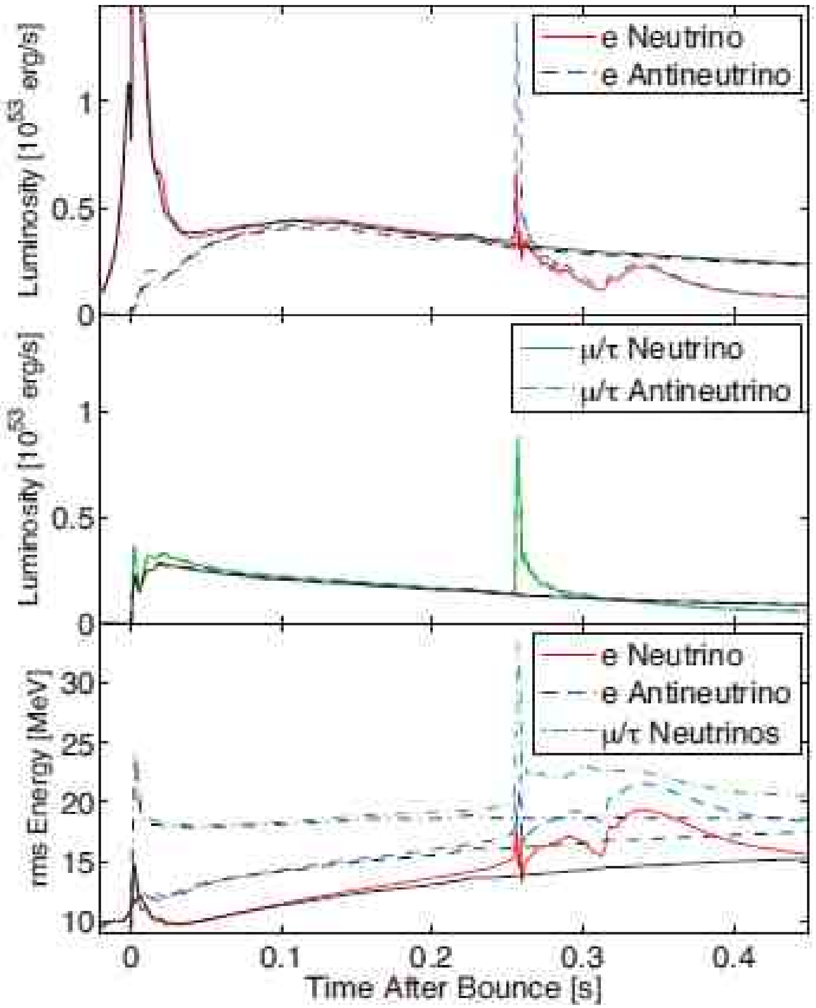
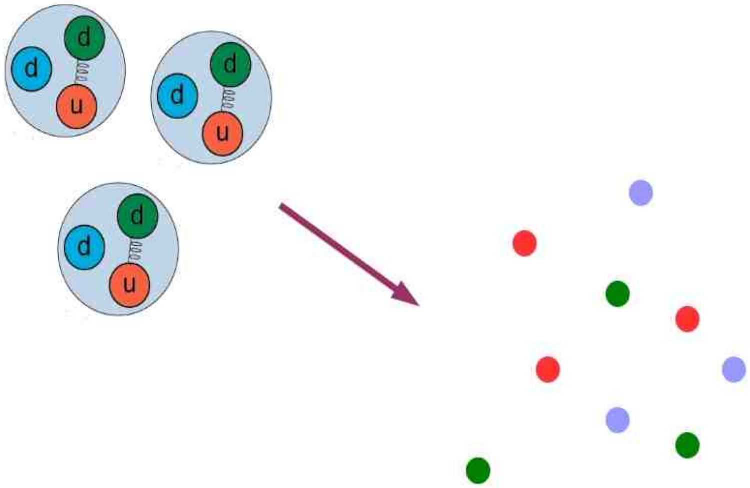


Figure 6. The neutrino spectrum without a phase transition (thick lines) and with a phase transition (thin lines). The case with a phase transition to strange quark matter results in a second peak in antineutrinos. The average energies of the emitted neutrinos increases also. Reprinted figure with permission from [26]. Copyright (2009) by the American Physical Society.



Sagert et al. arXiv:0902.2084v2 [astro-ph.HE] transition from neutron matter to uds quark matter would yield a second peak of electron anti-neutrinos.

Different physical processes for different neutrino flavors
→ need detectors with appropriate flavor sensitivity

Moreover
The initial neutrino composition and spectra are affected by flavor changes.

1. neutrino oscillations (MSW) induced by weak interaction with electrons in matter

2. collective neutrino-neutrino interactions
    - only place in the universe where we can observe the effects of neutrinos scattering off each other

→ neutrino flavor swapping

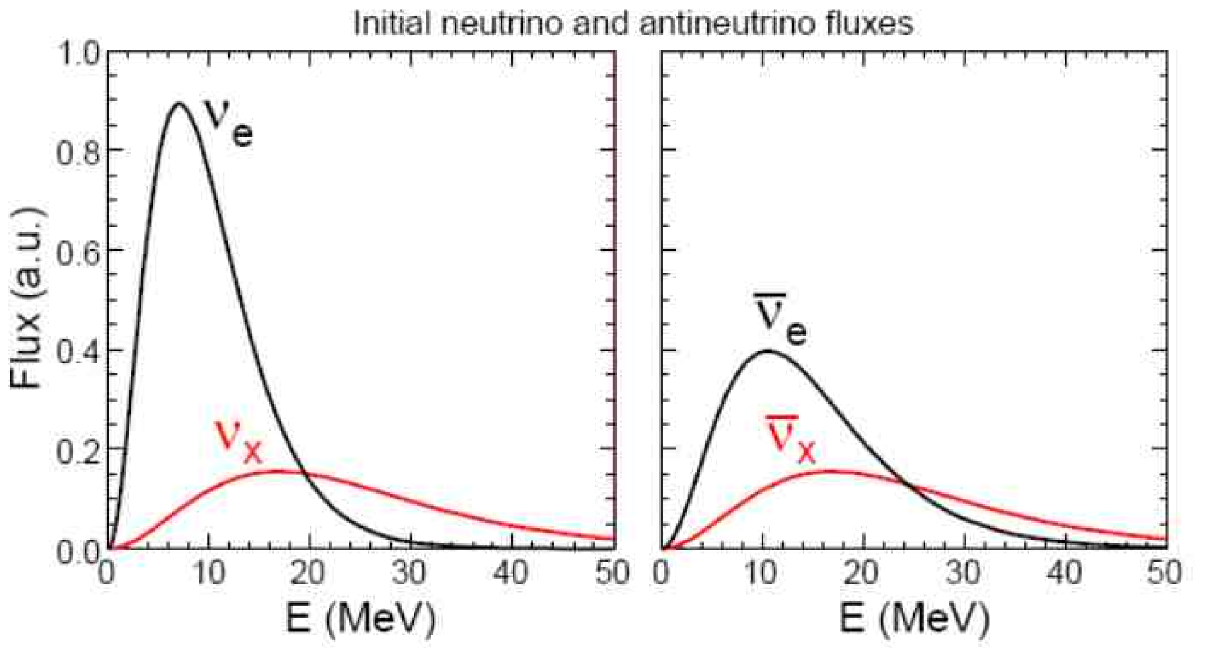


Figure 1. Initial fluxes (at $r = 10$ km, in arbitrary units) for different neutrino species as a function of energy. The fluxes are all proportional to $\phi^i(E)/\langle E\rangle$.

Single spectral split: valid when $L(\nu_e) > L(\nu_x)$ and IH

From Lisi, TAUP07

Initial spectra:

Cool ν_e Hot ν_x

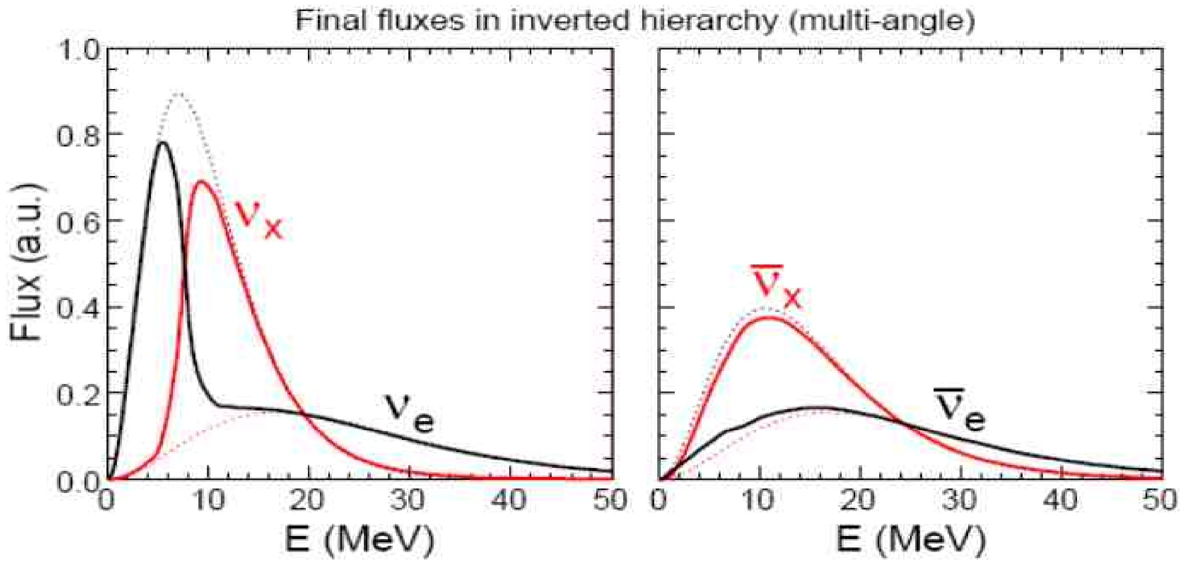


Figure 8. Multi-angle simulation in inverted hierarchy: Final fluxes (at $r = 200$ km, in arbitrary units) for different neutrino species as a function of energy. Initial fluxes are shown as dotted lines to guide the eye.

Final spectra with ν-ν collective effects, inverted hierarchy

Hot ν_e Cool ν_x

↓

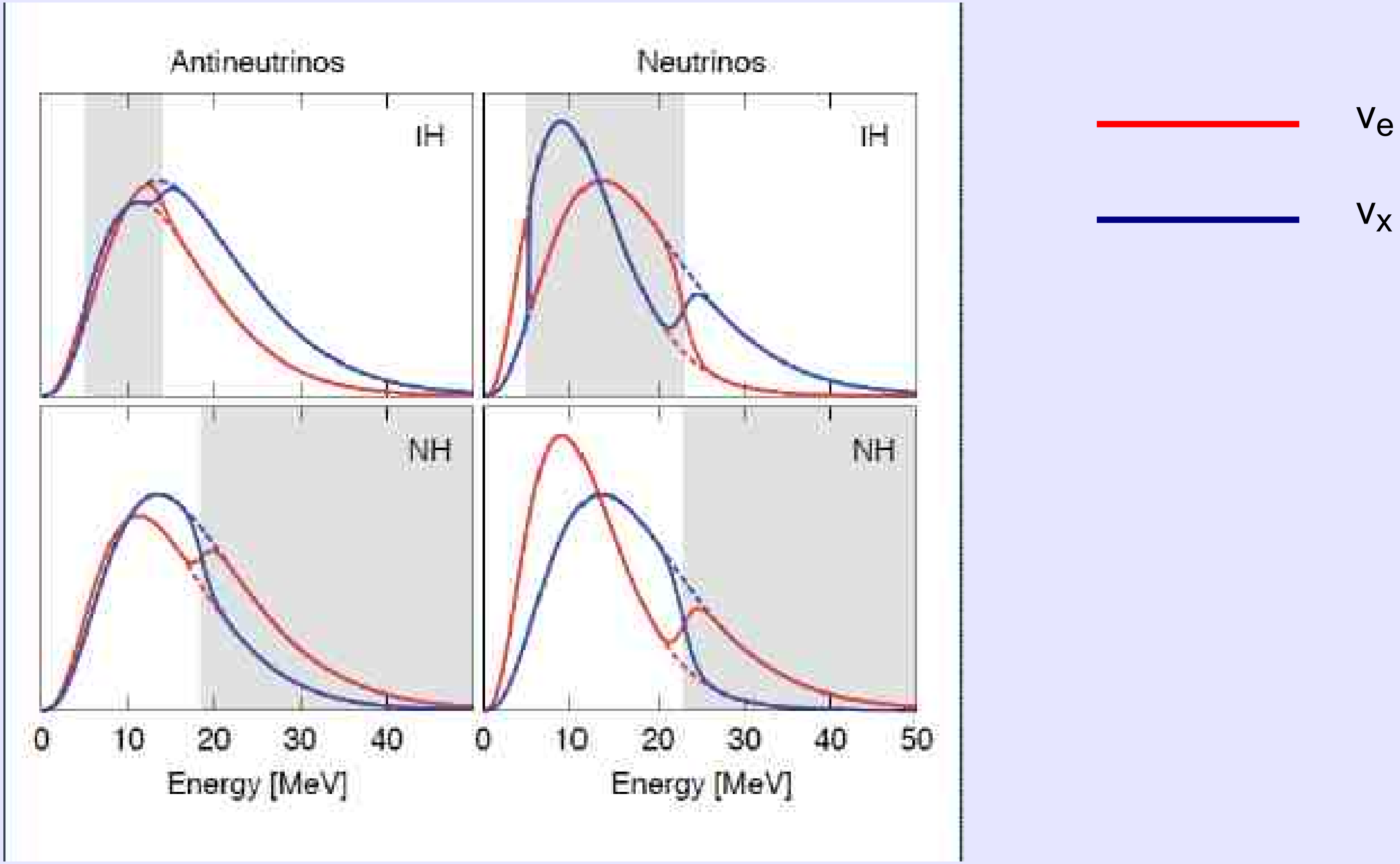
important effects on SN dynamics & R-process nucleosynthesis

In this picture, the most dramatic effect occurs in the v_e channel because the coolest species (v_e) swaps with the hottest species (v_x).

Less dramatic in the anti-neutrino sector.

→ we want a v_e - sensitive detector

In the more general case when luminosity of electron-types do not dominate, more complicated multiple spectral splits, different for normal and inverted hierarchies.



from B. Dasgupta, JIGSAW10 conference, Mumbai

Need to have neutrino detectors with different flavor sensitivities

anti-ν_e proton rich detectors (scintillator, water Cerenkov)

CC: anti-$\nu_e + p \rightarrow e^+ + n$

Well covered by SK, ICECUBE, LVD, BOEXINO,SNO+.

ν_e neutron rich detectors (lead)

CC: $\nu_e + n \rightarrow e^- + n$

$\nu_e + Pb \rightarrow e^- + Bi^* \rightarrow Bi + \text{neutron(s)}$

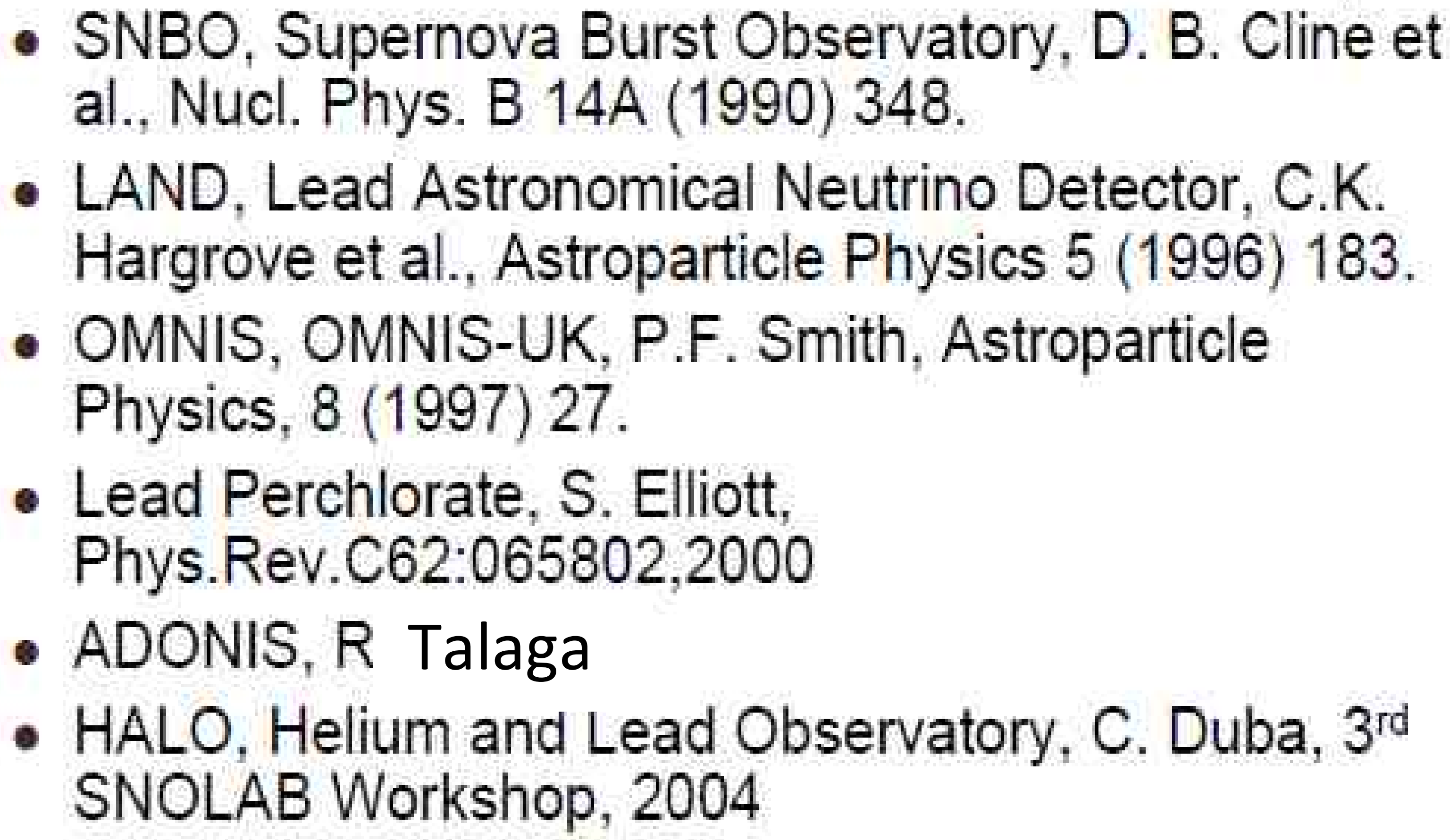
ν_{any} $N \approx Z$ e.g. D, C or Fe

NC: $\nu_{any} + D \rightarrow \nu_{any}' + p + n$

$\nu_{any} + {}^{12}C \rightarrow \nu_{any}' + {}^{12}C^*(15.11\ \text{Mev}) \rightarrow \gamma$

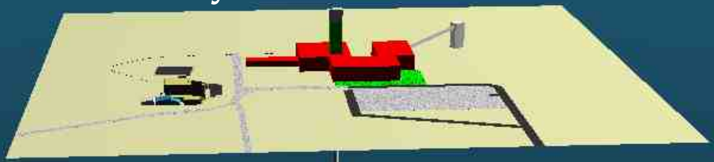
$\nu_{any} + Fe \rightarrow \nu_{any}' + Fe^* \rightarrow \text{neutrons}$

History of proposals for using lead as a neutrino detection medium



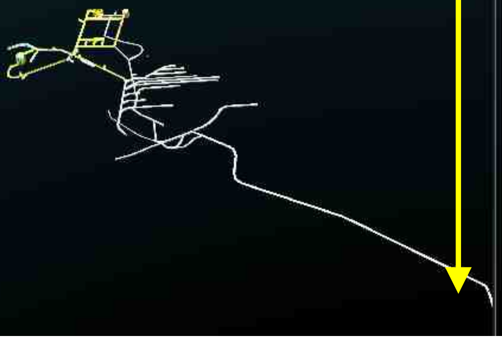
- SNBO, Supernova Burst Observatory, D. B. Cline et al., Nucl. Phys. B 14A (1990) 348.
- LAND, Lead Astronomical Neutrino Detector, C.K. Hargrove et al., Astroparticle Physics 5 (1996) 183.
- OMNIS, OMNIS-UK, P.F. Smith, Astroparticle Physics, 8 (1997) 27.
- Lead Perchlorate, S. Elliott, Phys.Rev.C62:065802,2000
- ADONIS, R Talaga
- HALO, Helium and Lead Observatory, C. Duba, 3rd SNOLAB Workshop, 2004

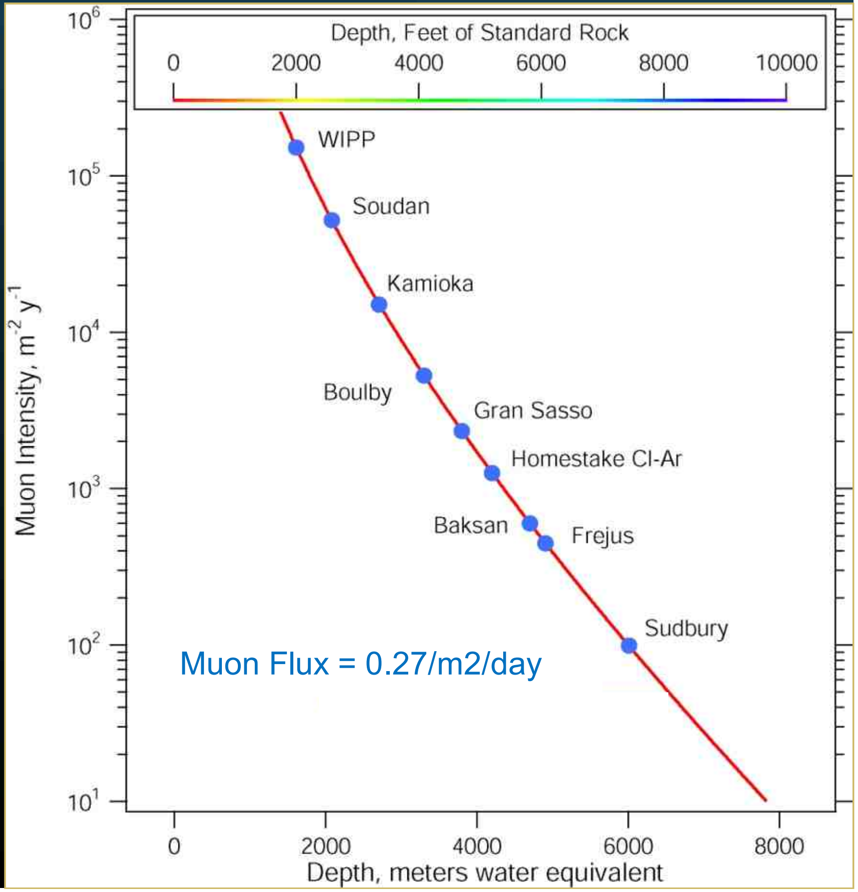
Surface Facility



2km flat
overburden
(6000mwe)

Underground
Laboratory





Muon Flux = 0.27/m2/day

Underground Facilities

All clean spaces operated as class 2000 cleanrooms

HALO (lead)

2 detectors with SN capabilities

SNO+ (liquid scint.)

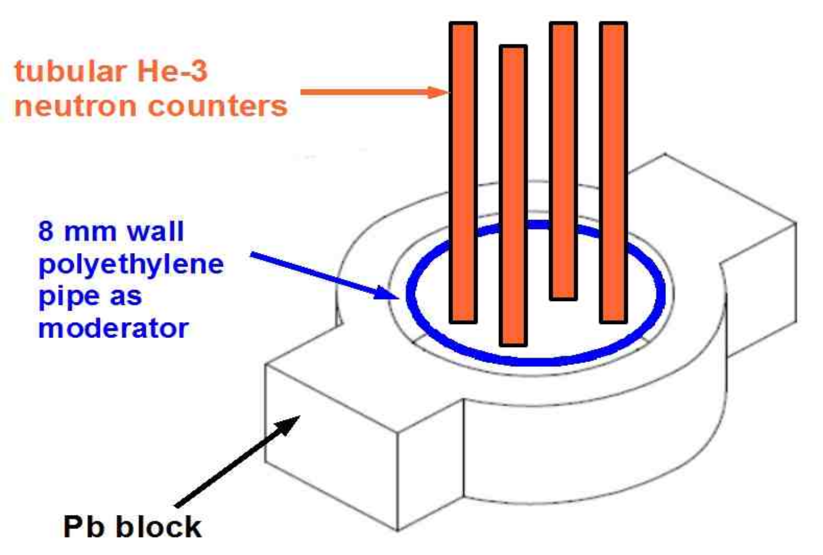
plus a suite of dark matter search experiments

HALO (Helium And Lead Observatory)

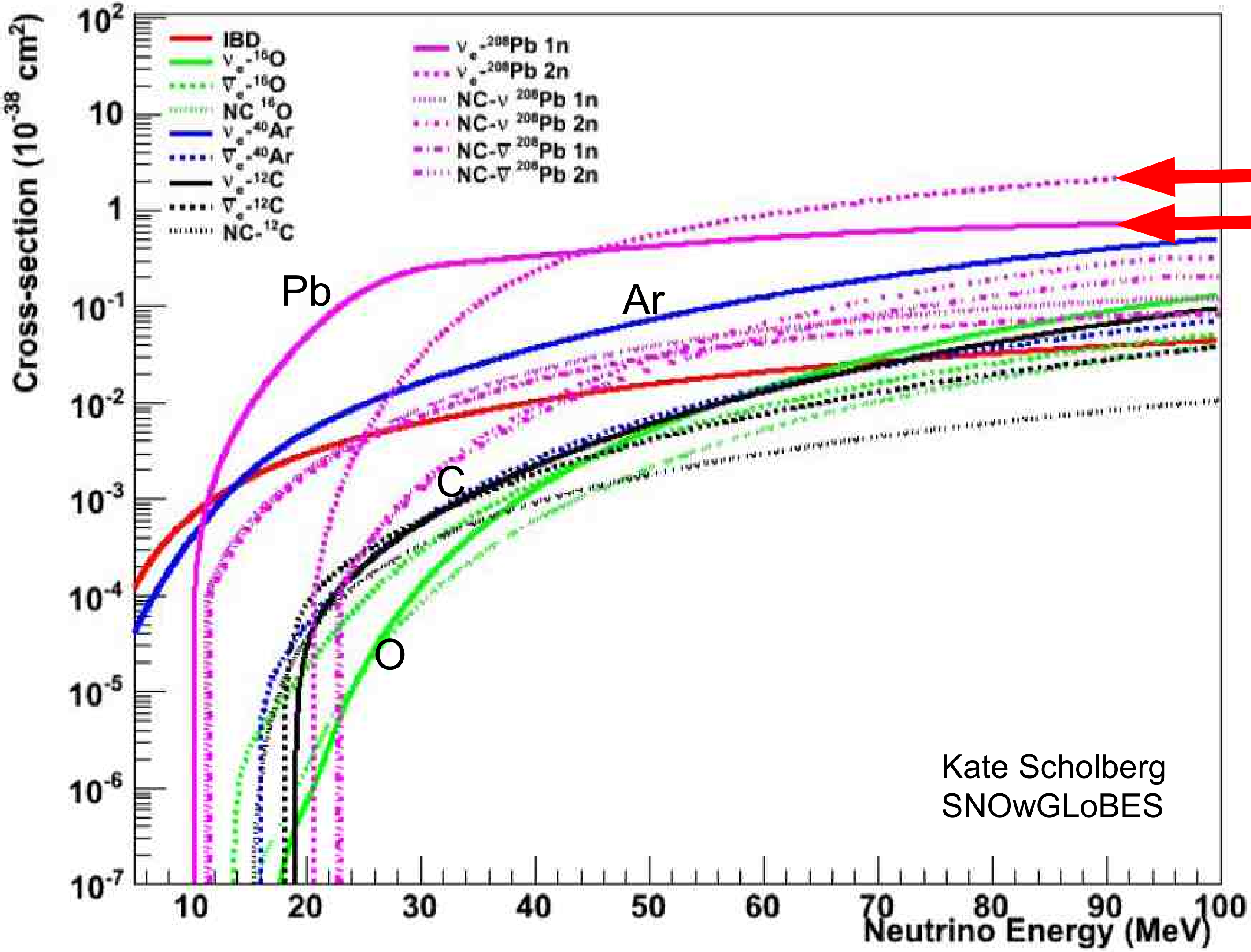
A detector of opportunity in SNOLAB
assembled from surplus equipment

- 79 tons of hollow lead blocks from a decommisioned cosmic ray monitoring station (value $1 M)
- the ^{3}He neutron detectors from the 3rd phase of the SNO experiment (value $6 M)
- the SNO electronics

– neutrino interactions with Pb knocks out neutrons which thermalize and are then detected by the ^{3}He counters – no direct measurement of neutron or ν energy



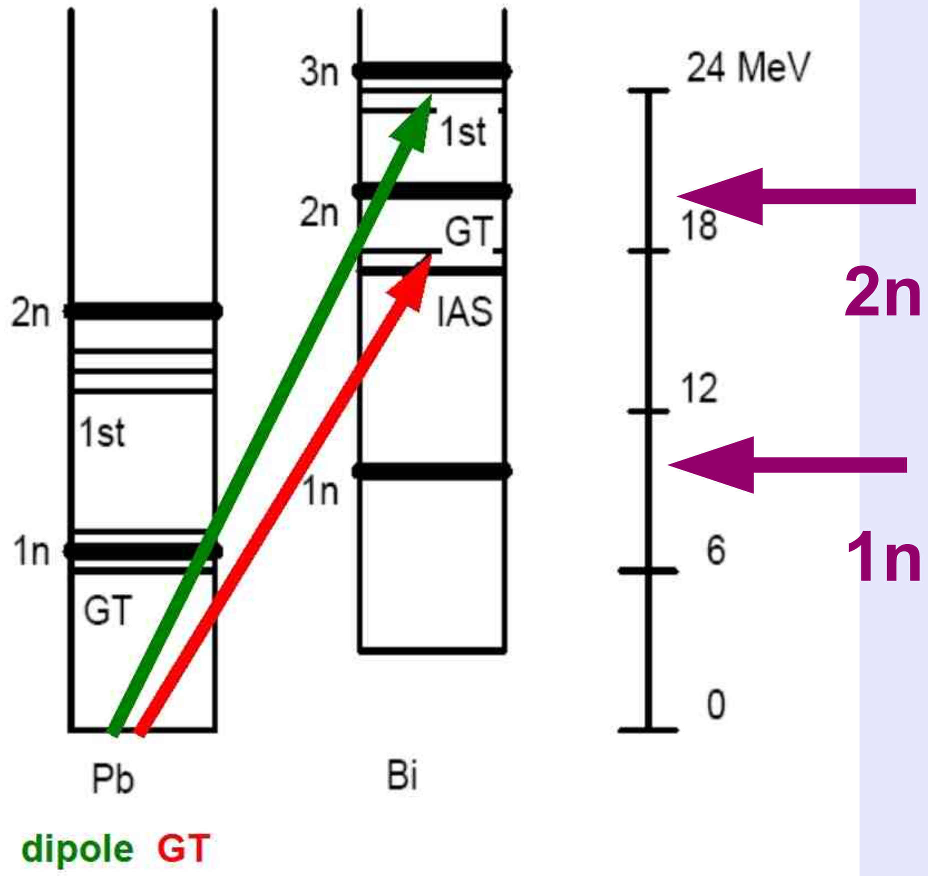
Comparative ν-nuclear cross-sections



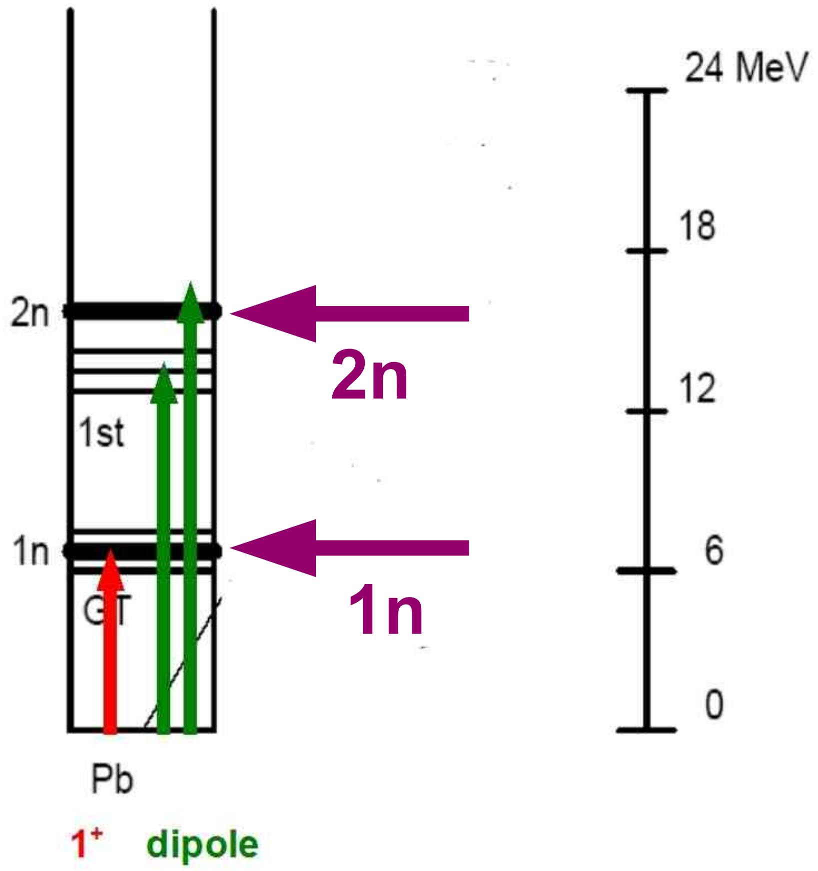
from C. Virtue, Havse11 Conference

Large Z of Pb nucleus pulls in outgoing electron wavefunc, enhances cross sec for CC interaction

CC Excitation of Pb

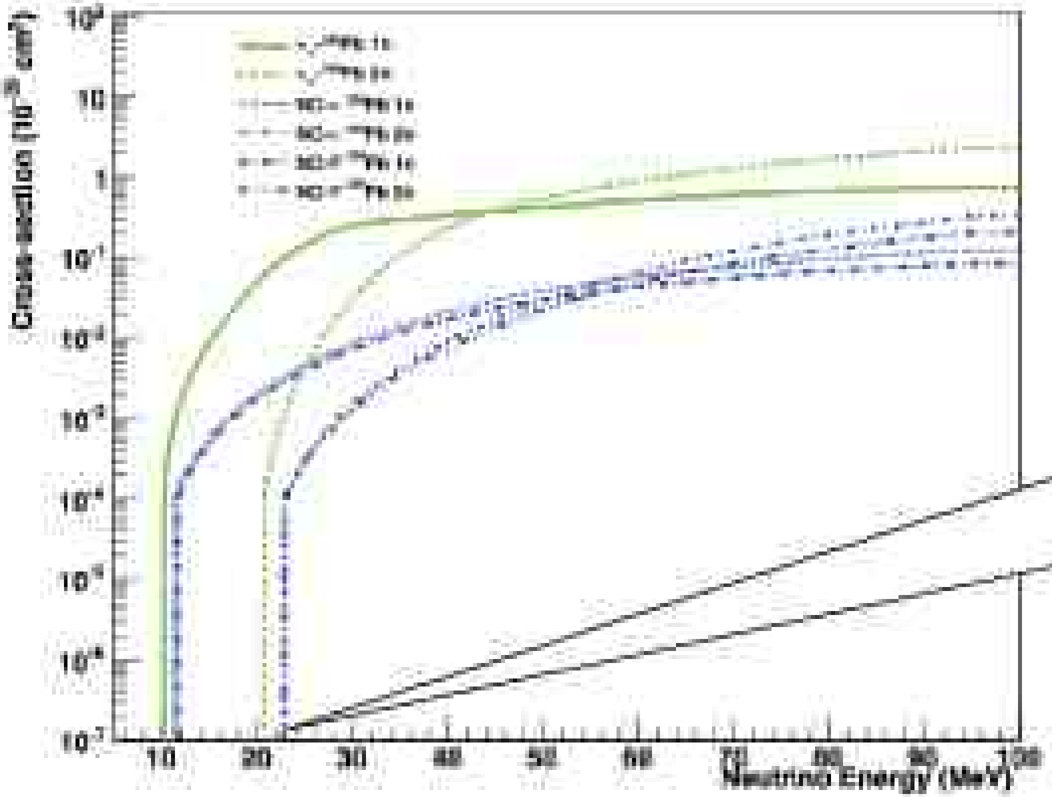


NC Excitation of Pb



Adapted from S. Elliot et al.

ratio of 2n : 1n emissions gives a rough measure of neutrino energy



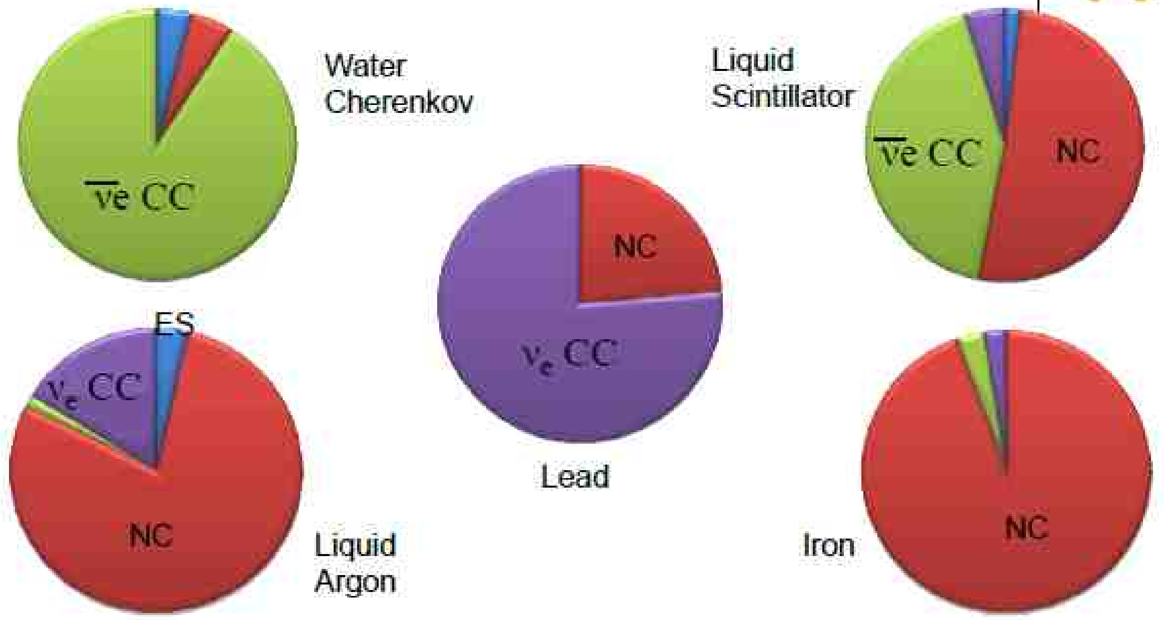
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

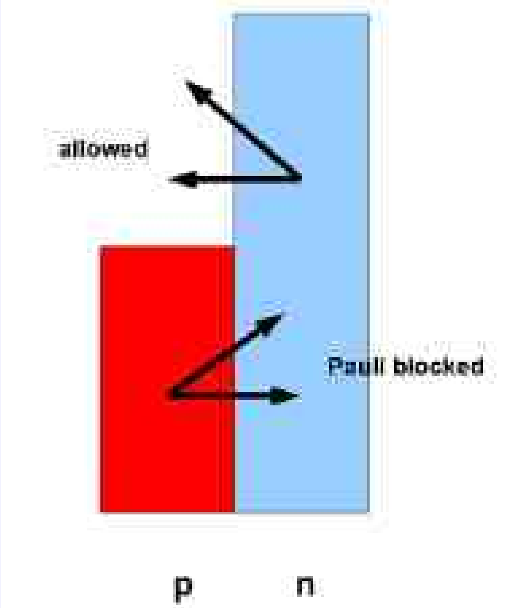
(similar for other lead isotopes)

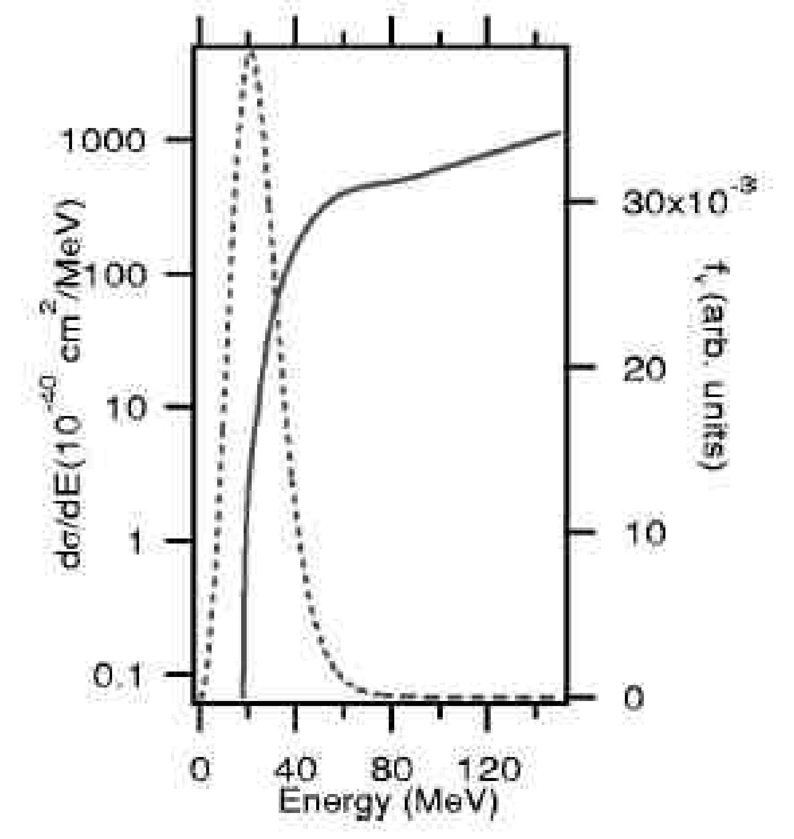
Roughly speaking, the hotter the neutrino energy spectrum, the larger the ratio 2n : 1n (but depends on SHAPE of spectrum as well).

figure from K. Scholberg,
plotted from cross section calc. of Engel, McLaughlin and Volpe, PRD 67, 013005

Flavour Sensitivities

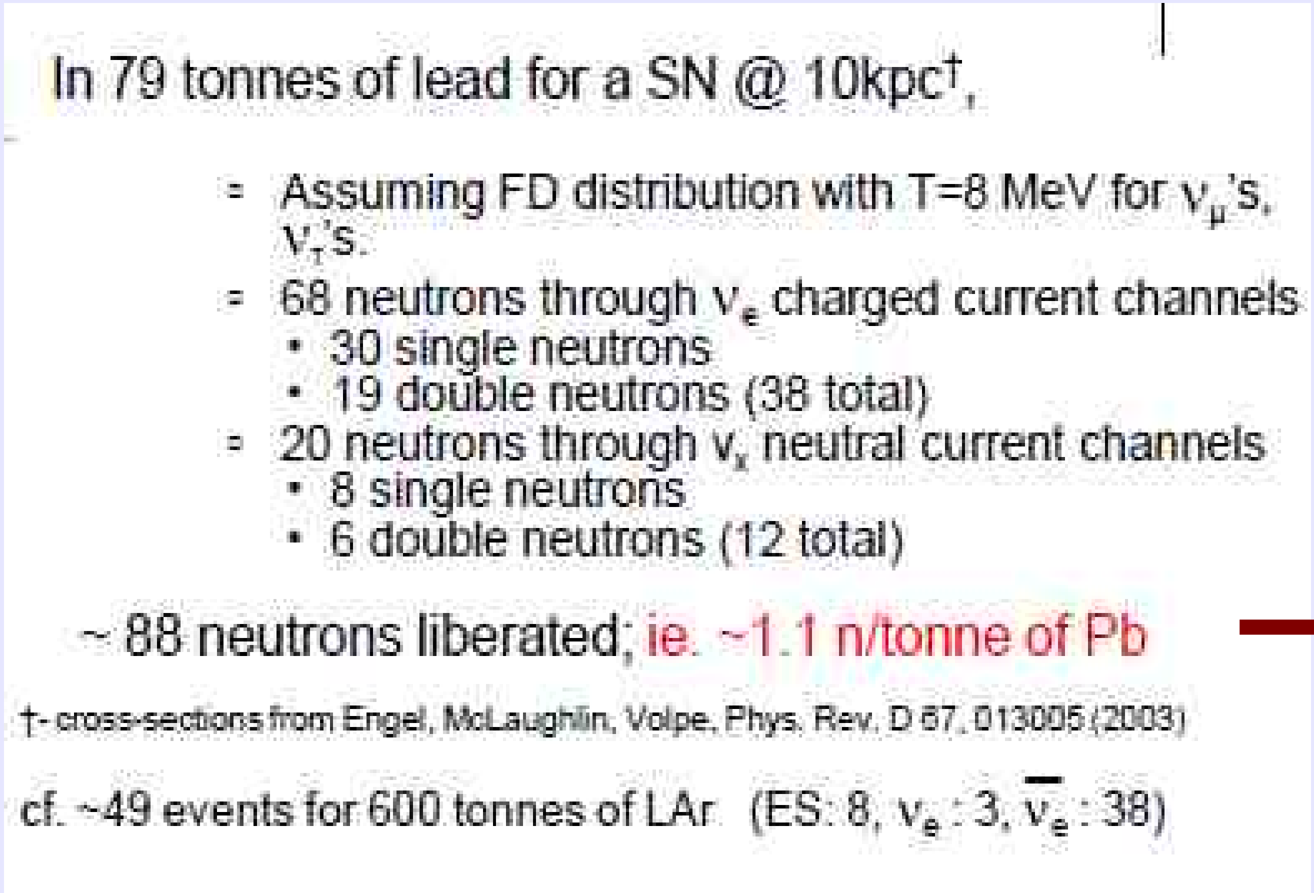






Large neutron excess blocks p→ n nuclear transition, favours n→p, thus sensitive to ν_e CC

σ a rapid function of E, sensitive to enhancement of high E tail of ν_e (fig. from S. Elliot et al.) csx from Engel, McLaughlin and Volpe)



In 79 tonnes of lead for a SN @ 10kpc[†],

- Assuming FD distribution with T=8 MeV for ν_μ's, ν_τ's.
- 68 neutrons through ν_e charged current channels
  - 30 single neutrons
  - 19 double neutrons (38 total)
- 20 neutrons through ν_x neutral current channels
  - 8 single neutrons
  - 6 double neutrons (12 total)

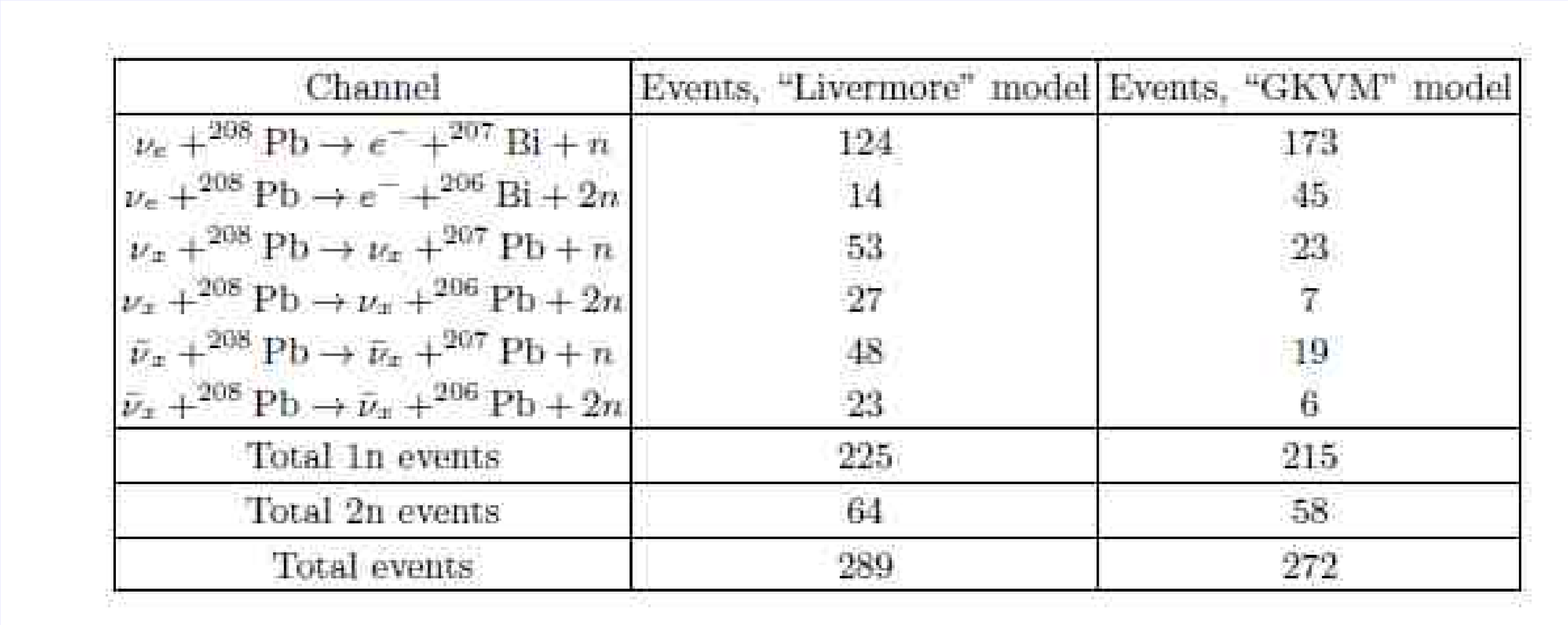
~ 88 neutrons liberated; ie. ~1.1 n/tonne of Pb

[†]- cross-sections from Engel, McLaughlin, Volpe, Phys. Rev. D 67, 013005 (2003)

cf. ~49 events for 600 tonnes of LAr (ES: 8, ν_e : 3, $\overline{\nu}_e$: 38)

multiplied by neutron detection efficiency of 43% = 38 neutrons detected

Another rate estimate, K. Scholberg



Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + {}^{208}\mathrm{Pb} \to e^- + {}^{207}\mathrm{Bi} + n$	124	173
$\nu_e + {}^{208}\mathrm{Pb} \to e^- + {}^{206}\mathrm{Bi} + 2n$	14	45
$\nu_x + {}^{208}\mathrm{Pb} \to \nu_x + {}^{207}\mathrm{Pb} + n$	53	23
$\nu_x + {}^{208}\mathrm{Pb} \to \nu_x + {}^{206}\mathrm{Pb} + 2n$	27	7
$\bar{\nu}_x + {}^{208}\mathrm{Pb} \to \bar{\nu}_x + {}^{207}\mathrm{Pb} + n$	48	19
$\bar{\nu}_x + {}^{208}\mathrm{Pb} \to \bar{\nu}_x + {}^{206}\mathrm{Pb} + 2n$	23	6
Total 1n events	225	215
Total 2n events	64	58
Total events	289	272

events per kiloton of Pb.
Multiply by 0.08 for HALO

Livermore: Totani et al., APJ 496, 216 (1998) , astro-ph/9710203

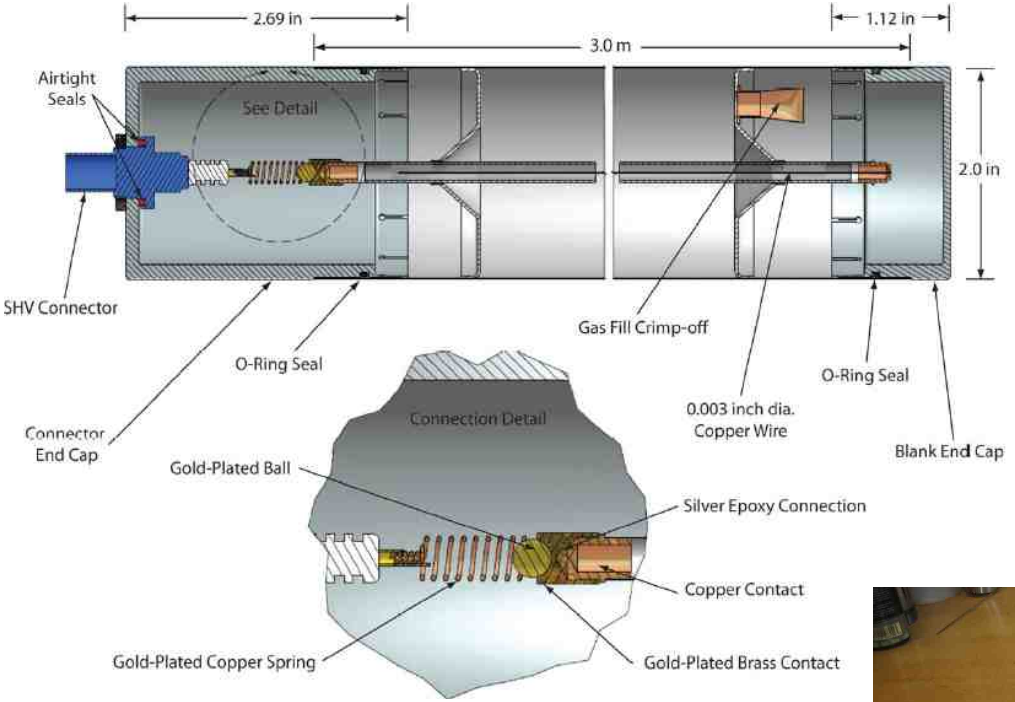
GKVM: Gava, Kneller, Volpe and McLaughlin PRL 103, 071101 (2009)

Pb blocks cleaned and painted to immobilize white lead carbonate powder

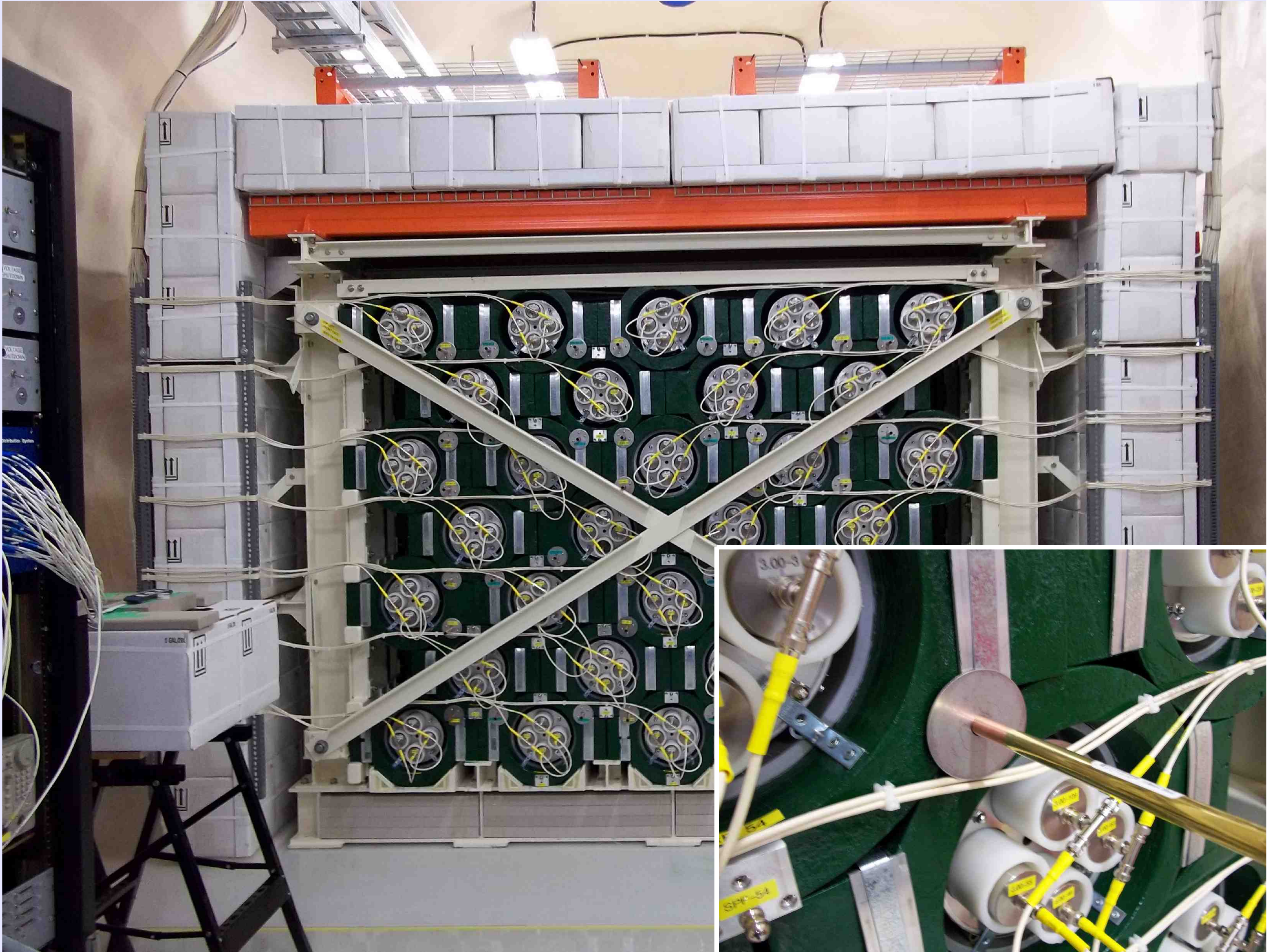
LITE

3He neutron detectors

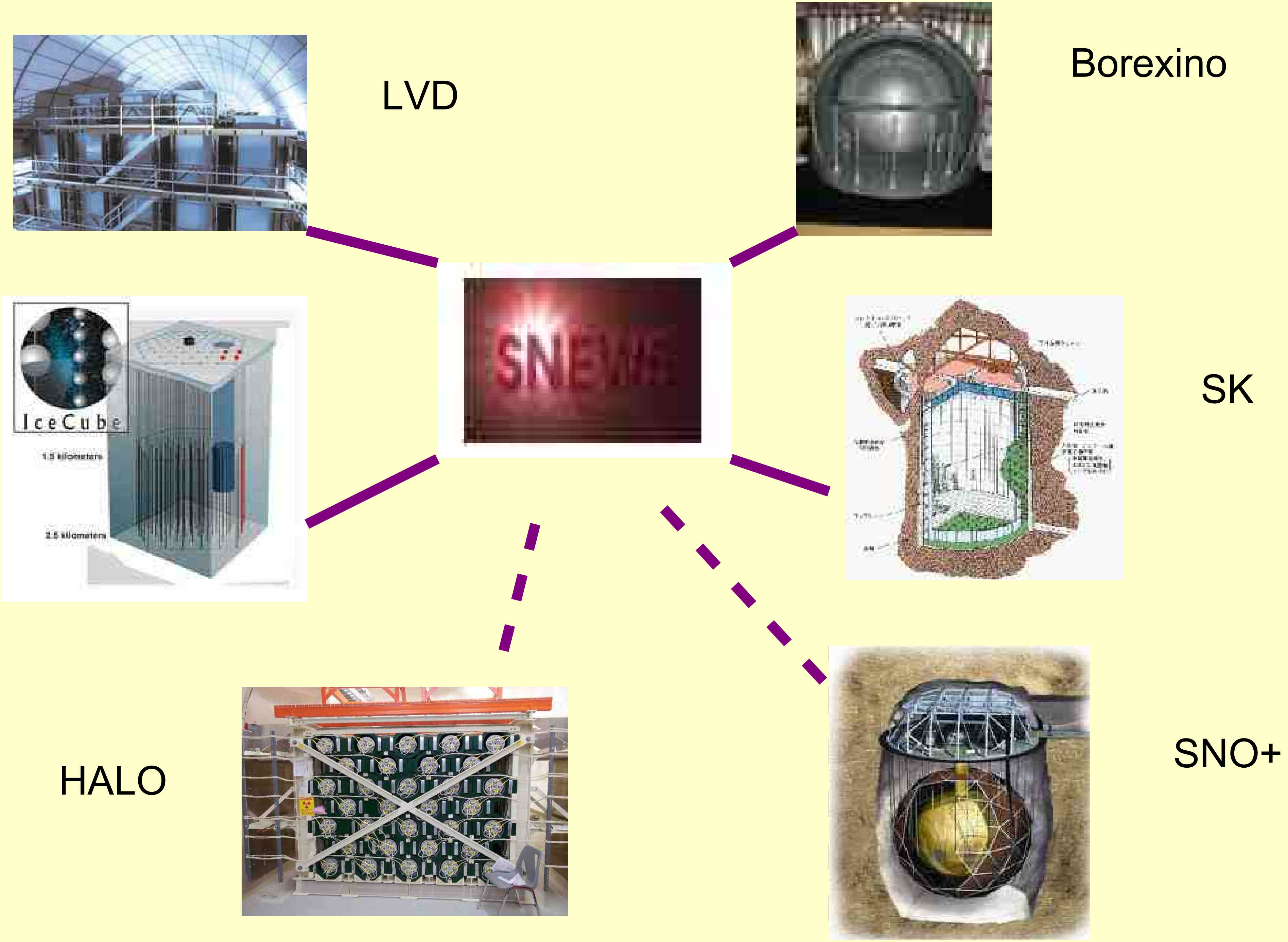
- made for SNO expt by UW, the most sensitive, lowest radioactivity neutron detectors in the world



Cutting apart welded sections from SNO installation and adding new endcaps. Six months of careful work!
Refurbished with new endcaps and preamps from UW.


VOLTAGE SHUTDOWN
VOLTAGE SHUTDOWN
5 GAL/20L
3.00-3
SPF-54

Super Nova Early Warning System



LVD

Borexino

SK

SNO+

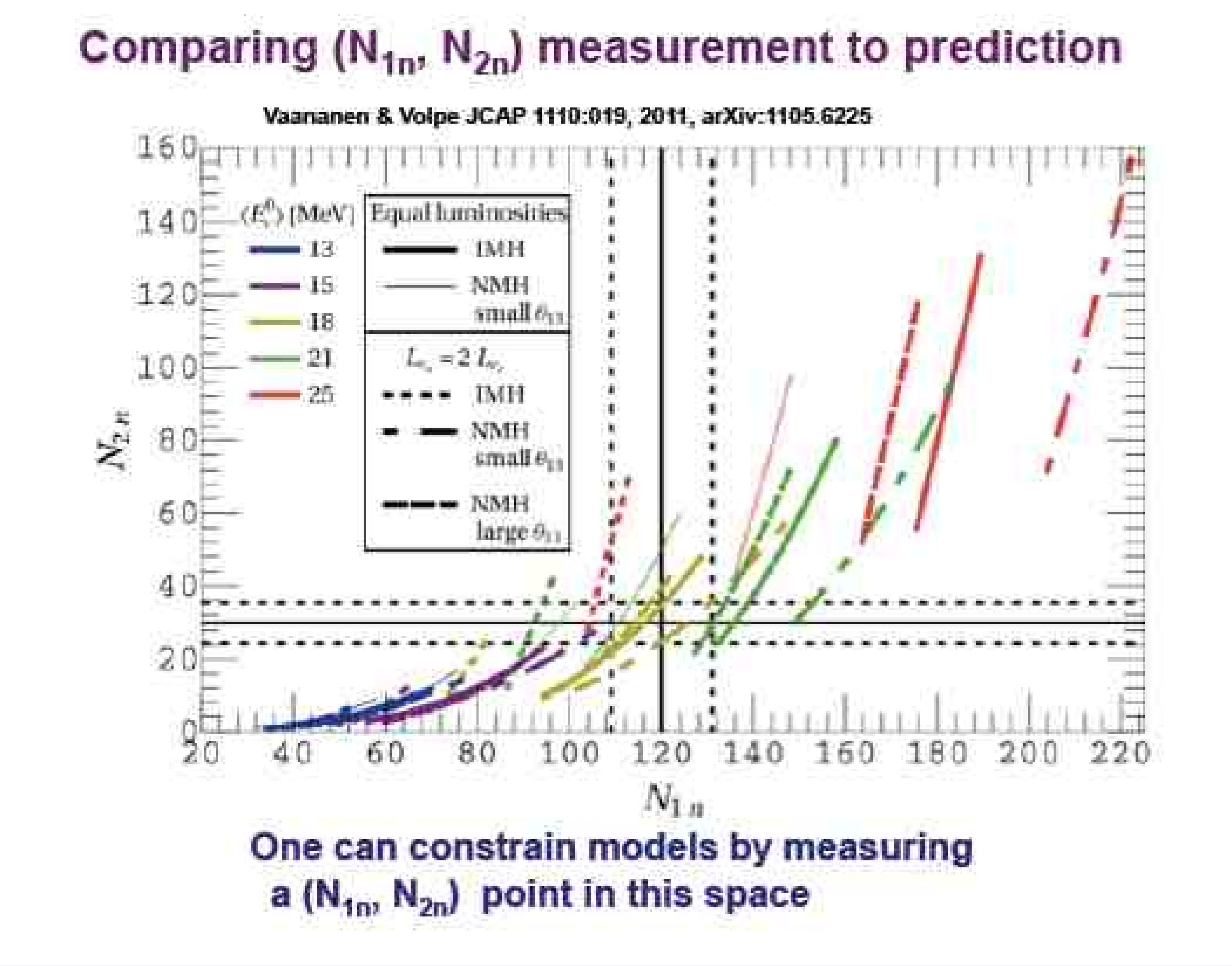
HALO

Backgrounds and SNEWS

- A trigger condition of 6 neutrons in a 2 second window gives sensitivity out to ~ 20 kpc (for T=8 MeV)
- Fast and thermal neutrons in SNOLAB occur at 4000 and 4100 neutrons/m^2/day respectively
- A background event rate of 150 mHz from all sources will randomly satisfy the trigger condition once per month. We take this as the target false alert rate for SNEWS (presently at 170 mHz with partial shielding)
- Bulk α contamination in the CVD nickel tubes gives a negligible 22 +/- 1 events in neutron window per day for the whole array
- Cosmic ray muon rate is < 2 per day, some of which will cause create neutrons through spallation

Would HALO be sensitive to mass hierarchy and flavor swapping?

Constraining models with 2n : 1n ratio



Comparing (N_{1n}, N_{2n}) measurement to prediction

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

One can constrain models by measuring a (N_{1n}, N_{2n}) point in this space

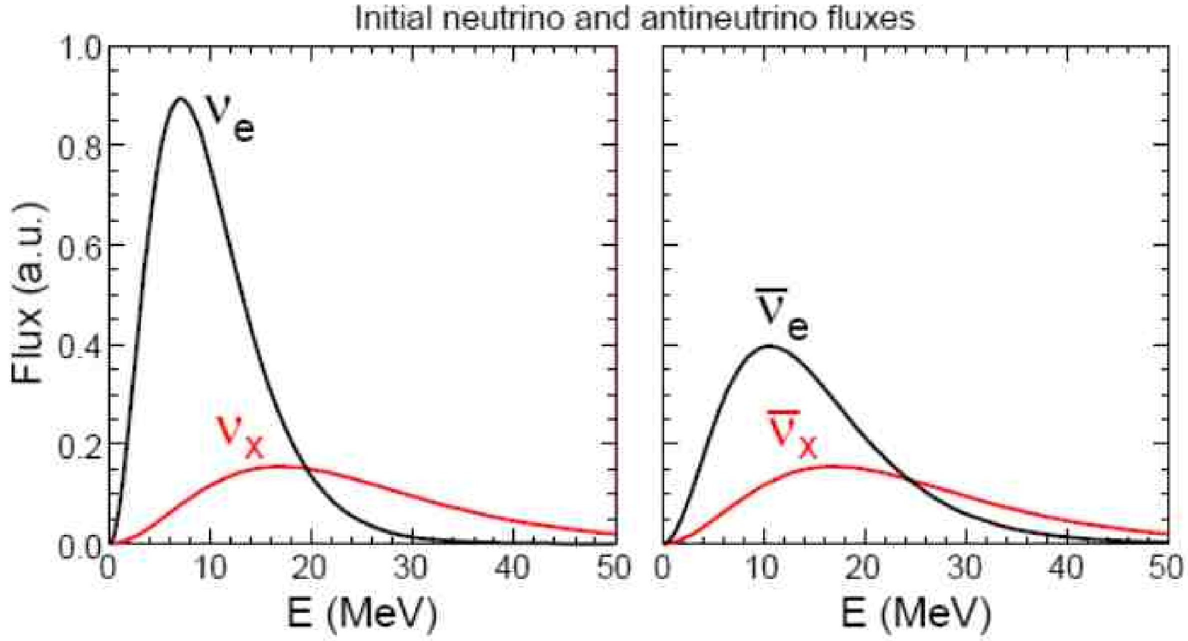


Figure 1. Initial fluxes (at $r = 10$ km, in arbitrary units) for different neutrino species as a function of energy. The fluxes are all proportional to $\phi^i(E)/\langle E\rangle$.

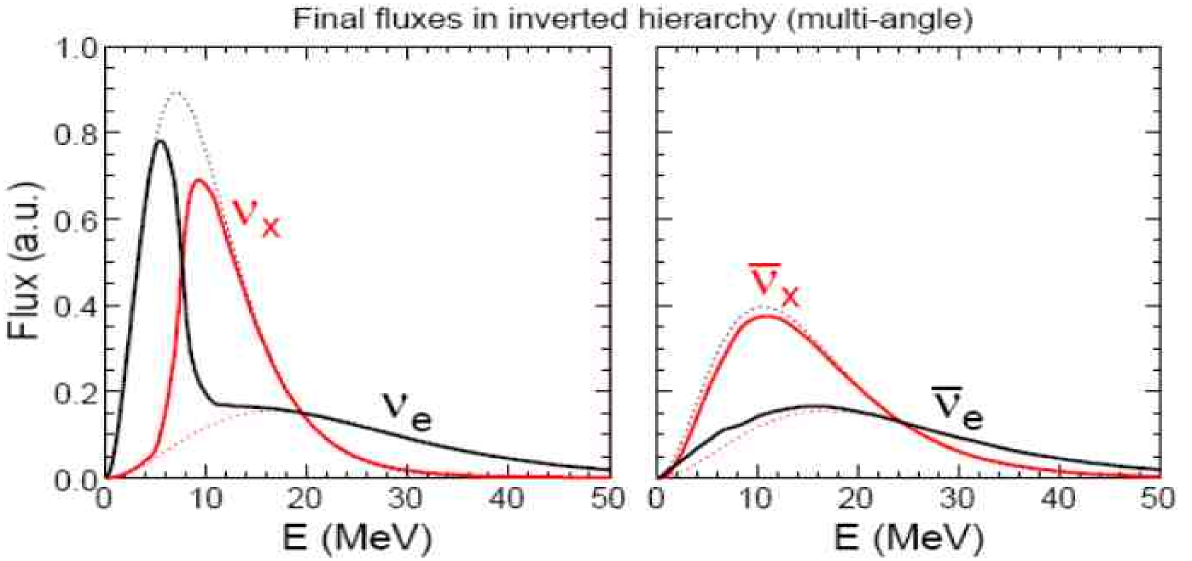


Figure 8. Multi-angle simulation in inverted hierarchy: Final fluxes (at $r = 200$ km, in arbitrary units) for different neutrino species as a function of energy. Initial fluxes are shown as dotted lines to guide the eye.

Total neutron rate in Pb increased by x3.7

2n : 1n ratio increased by 2.1

But we don't know a priori the absolute neutrino flux, the neutrino temperature at the time of emission, maybe not even the distance to the SN.

To say that we see 3.7 times as many neutrons in HALO as predicted by model X fluxes could either mean there is flavor swapping, or that the the model X fluxes are wrong, or we got the distance to the SN wrong.

To say that the measured 2n : 1n ratio is larger than predicted by model X and hence the neutrino spectrum is hotter than expected, could mean flavor swapping, or that the neutrino source is hotter than the model predicts.

A more robust signature of flavor swapping is obtained if we compare data from detectors of different flavor sensitivities. A hot v_e spectrum (higher rate than expected in Pb) together with a cold v_x spectrum (lower rate than expected for neutral current scattering) is more robust signature of flavor swappping.

Experimental Observables:

- v_e CC (+NC) rate and 2n:1n ratio in Pb (HALO)

- anti-v_e CC rate and energy spectrum on Hydrogen (SuperK, SNO+)

- some neutral current processes (excitation of 15.11 MeV state in ^{12}C, vp elastic scattering in SNO+)

HALO What's hot

- low cost; assembled from surplus equipment
- low maintenance, high livetime (~ 30 years between galactic SN)
- flavour selective - primary sensitivity to ν_e

HALO What's not

- no pointing capability
- cannot distinguish CC (pure ν_e) from NC (all flavours)
- high trigger threshold ~ 18 MeV for CC
- no measure of neutrino energy except by 1n to 2n ratio
- no measurements of ν_e- Pb cross sections
- small mass of only 79 metric tonnes = 600 t LAr (ICARUS)
  - expect ~25 - 40 neutrons detected from a SN at galactic centre

- high cost of ^{3}He makes scaling up impractical

A Future SN ν_e Detector?

- LAr TPC offers good resolution, low trigger threshold,
  sensitivity to ν_e if e^- can be distinguished from e^+
  but not cheap to operate for decades
  (See D. Cline, next talk)

- water Cerenkov loaded with Pb salts?

- after demise of SNO, no NC detector
  - an iron detector ? (instrument MINOS with neutron counters)
  - NC excitation of 15.11 state in ^{12}C in liquid scint.
  - ν-p elastic scattering (hard; very little light)

An idea from the past: Cerenkov detector with lead perchlorate solution

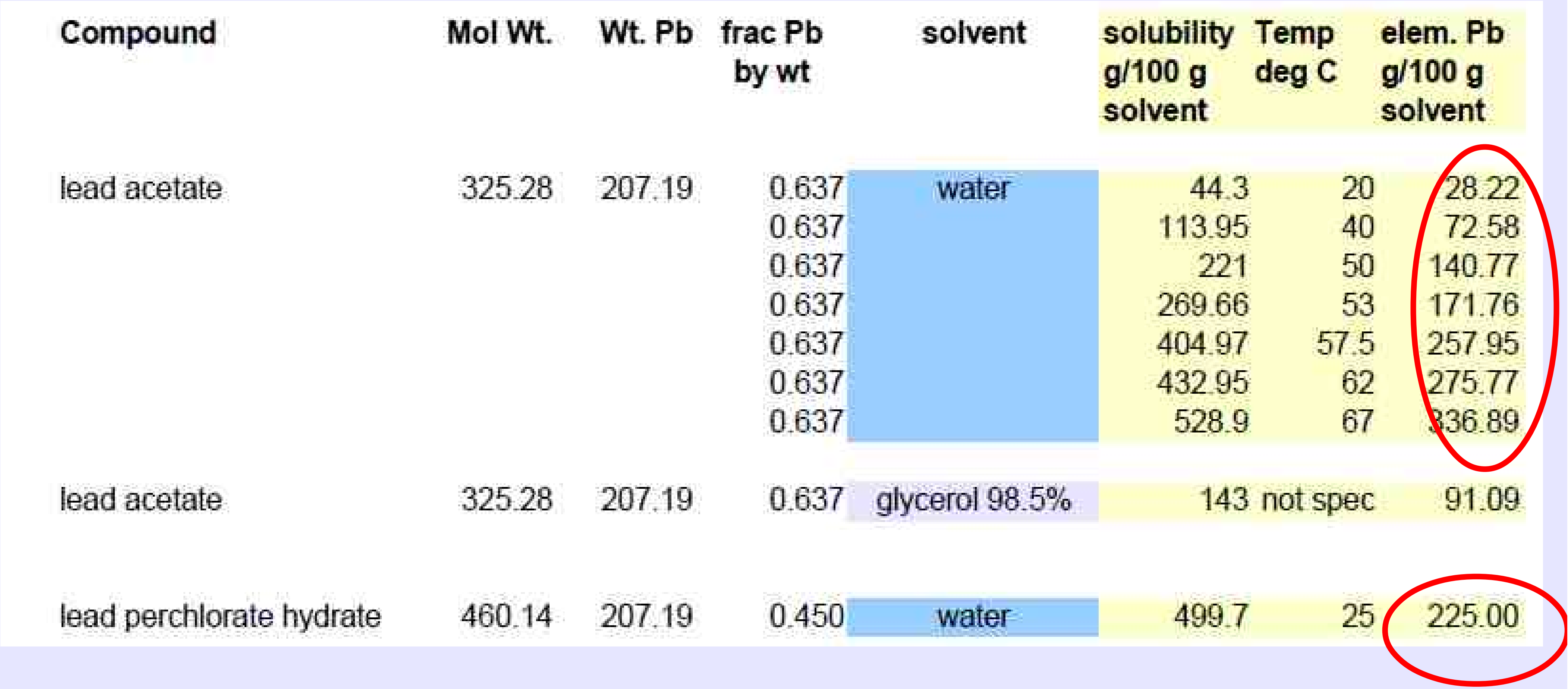
Steve Elliot, “Measuring Supernova Neutrino Temperatures with Lead Perchlorate”, Phys Rev C62, 065802 (2000)

- Pb perchlororate hydrate $Pb(ClO_3)_2.3H_2O$
  has very high solubility in water 499.7 grams / 100 g water
  (225 g of elemental Pb per 100 g water)

- rate (v_e on Pb) : rate (anti-v_e on H) ~ 3:1

- measuring amount and direction of Cerenkov light produced by outgoing electron gives a measure of the direction and energy of the neutrino and selects only CC channel

- unfortunately a dangerously unstable and reactive substance which would never be allowed in an underground laboratory



Compound	Mol Wt.	Wt. Pb	frac Pb by wt	solvent	solubility g/100 g solvent	Temp deg C	elem. Pb g/100 g solvent
lead acetate	325.28	207.19	0.637	water	44.3	20	28.22
			0.637		113.95	40	72.58
			0.637		221	50	140.77
			0.637		269.66	53	171.76
			0.637		404.97	57.5	257.95
			0.637		432.95	62	275.77
			0.637		528.9	67	336.89
lead acetate	325.28	207.19	0.637	glycerol 98.5%	143	not spec	91.09
lead perchlorate hydrate	460.14	207.19	0.450	water	499.7	25	225.00

hot aqueous lead acetate?

lead acetate in water at 55 deg C is as good as lead perchlorate at room temperature; rock at SNOLAB naturally at 42 C

glycerol+lead acetate?

lead acetate more soluble in glycerol than water, but temperature dependence is unknown – gives yellow solution

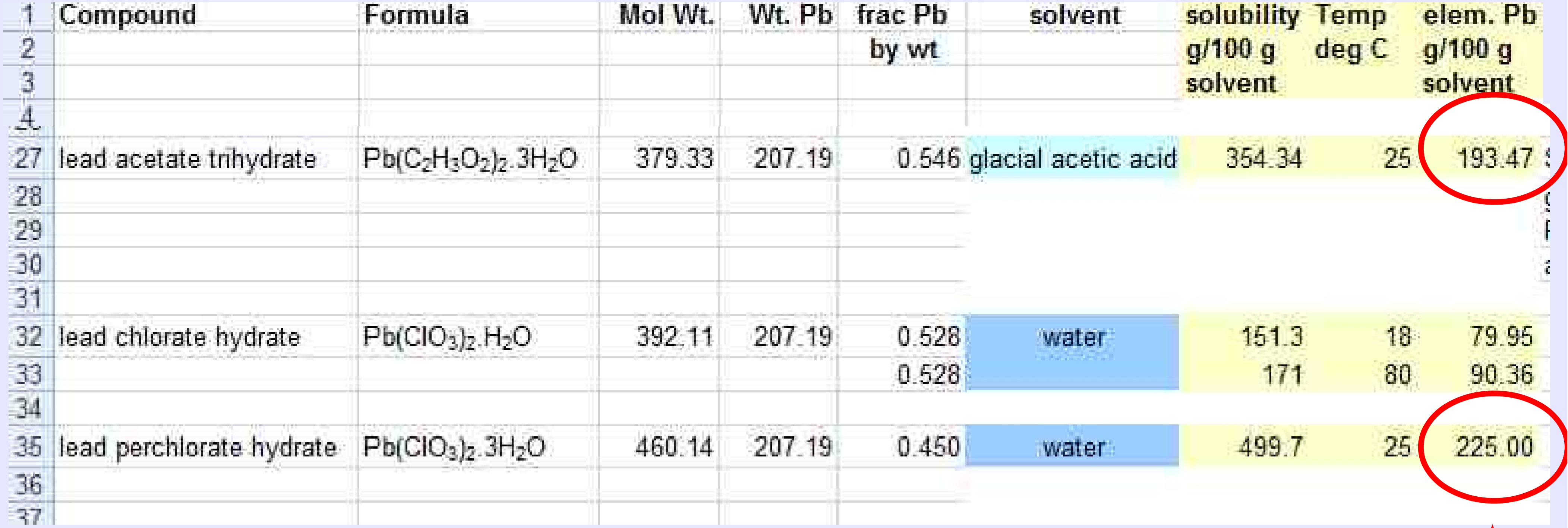
Lead acetate in water

Temp	rate(Pb):rate(H)
20 C	0.37 : 1
40 C	0.96 : 1
55 C	3 : 1

Even at 20 C, a PbAc solution would give a substantial and recognizable signal → one of the modules of Hyper-K ?

A more familiar use of lead acetate....

even though lead acetate is listed as toxic and carcinogenic!
Will they be a corporate sponsor of our next detector?

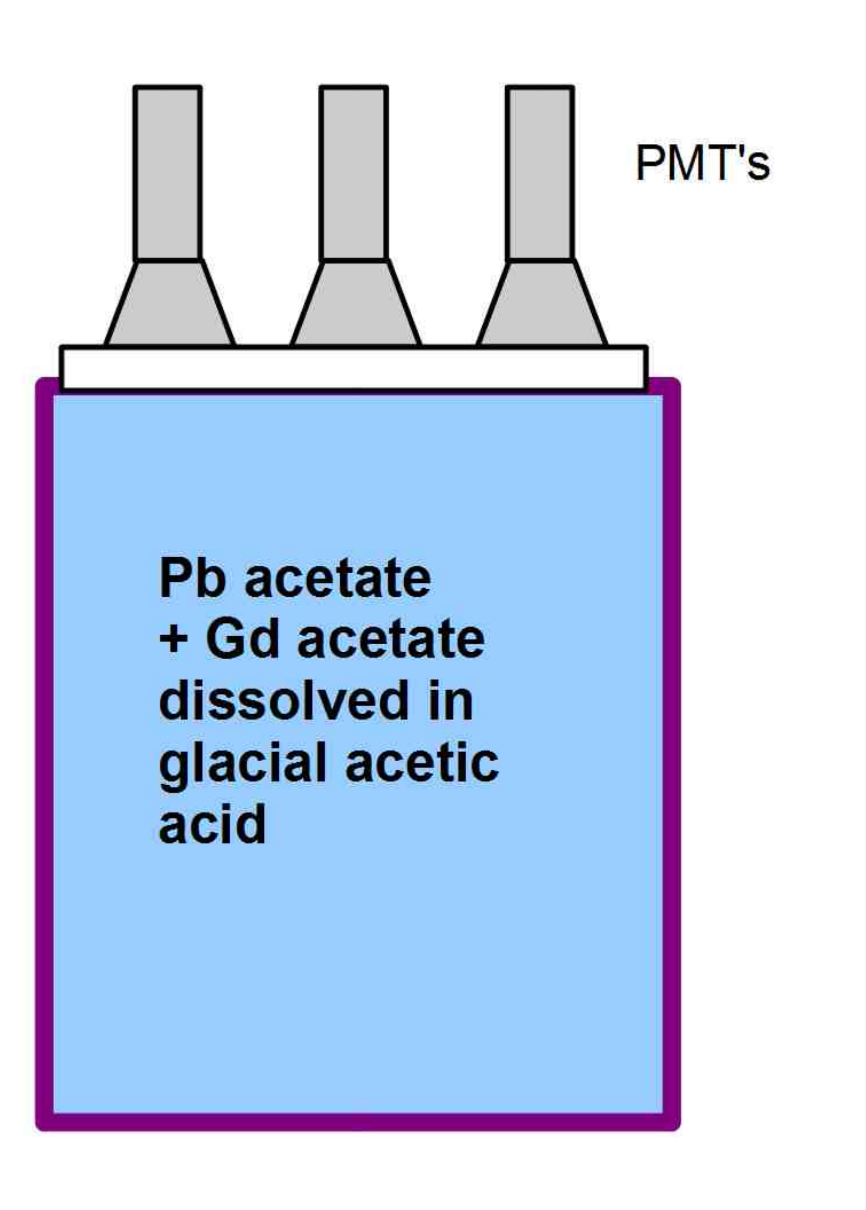


	Compound	Formula	Mol Wt.	Wt. Pb	frac Pb by wt	solvent	solubility g/100 g solvent	Temp deg C	elem. Pb g/100 g solvent
4									
27	lead acetate trihydrate	$Pb(C_2H_3O_2)_2.3H_2O$	379.33	207.19	0.546	glacial acetic acid	354.34	25	193.47
28									
29									
30									
31									
32	lead chlorate hydrate	$Pb(ClO_3)_2.H_2O$	392.11	207.19	0.528	water	151.3	18	79.95
33					0.528		171	80	90.36
34									
35	lead perchlorate hydrate	$Pb(ClO_3)_2.3H_2O$	460.14	207.19	0.450	water	499.7	25	225.00
36									
37									

lead acetate trihydrate highly soluble in glacial acetic acid

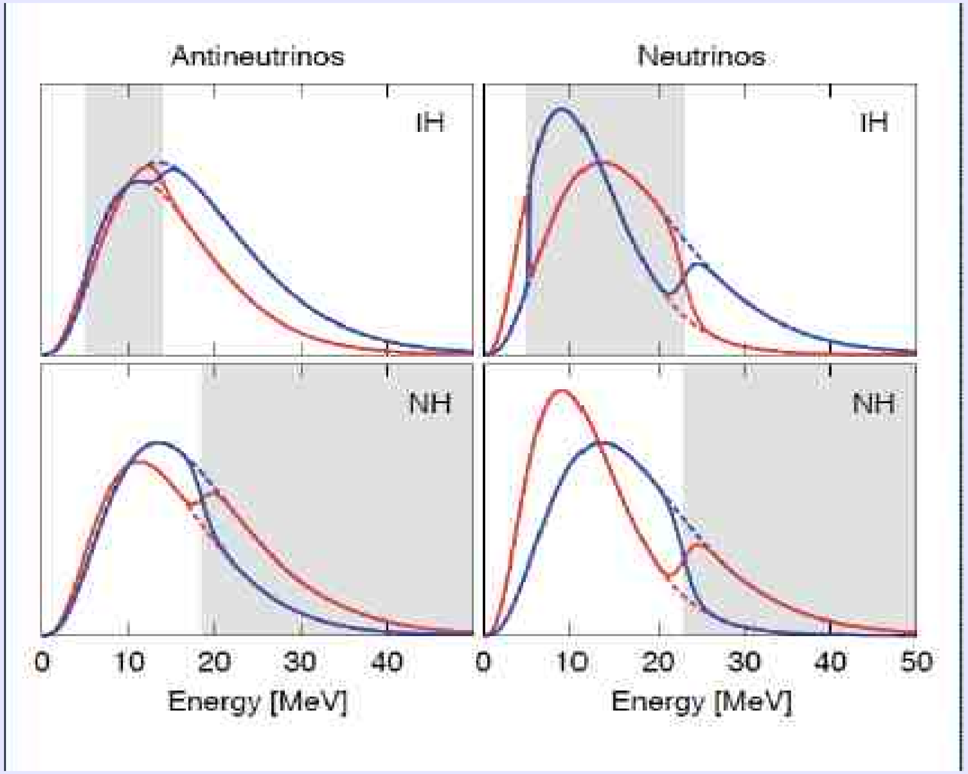
makes clear transparent solution

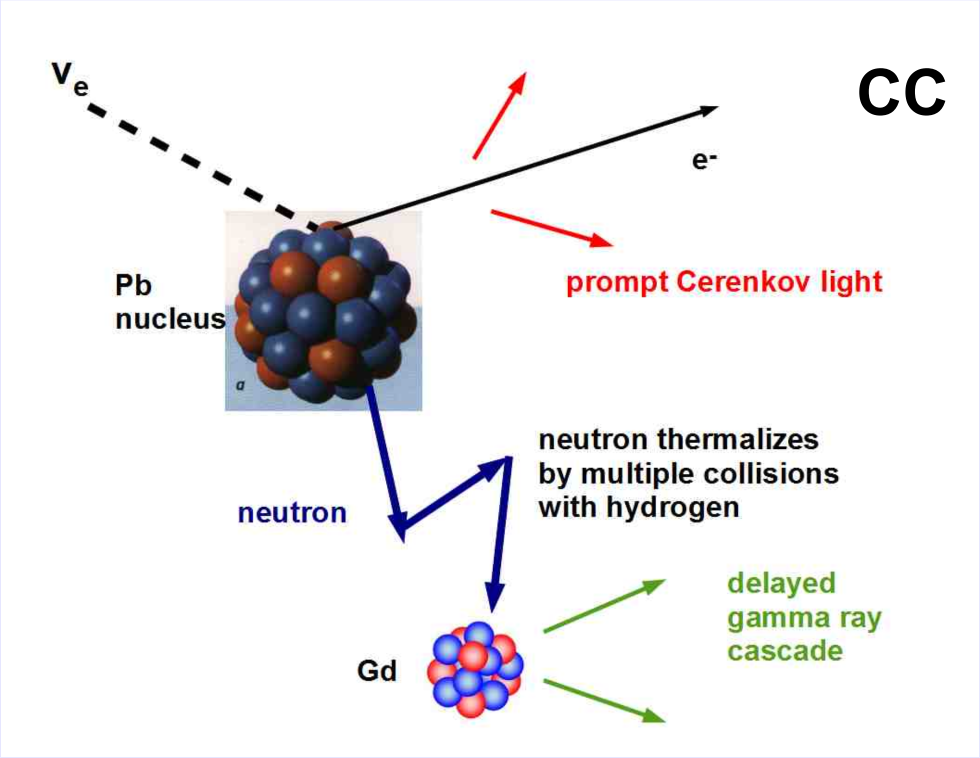
85% as good as lead perchlorate



Future lead acetate Cerenkov detector ???

Anyone have surplus PMT's ?

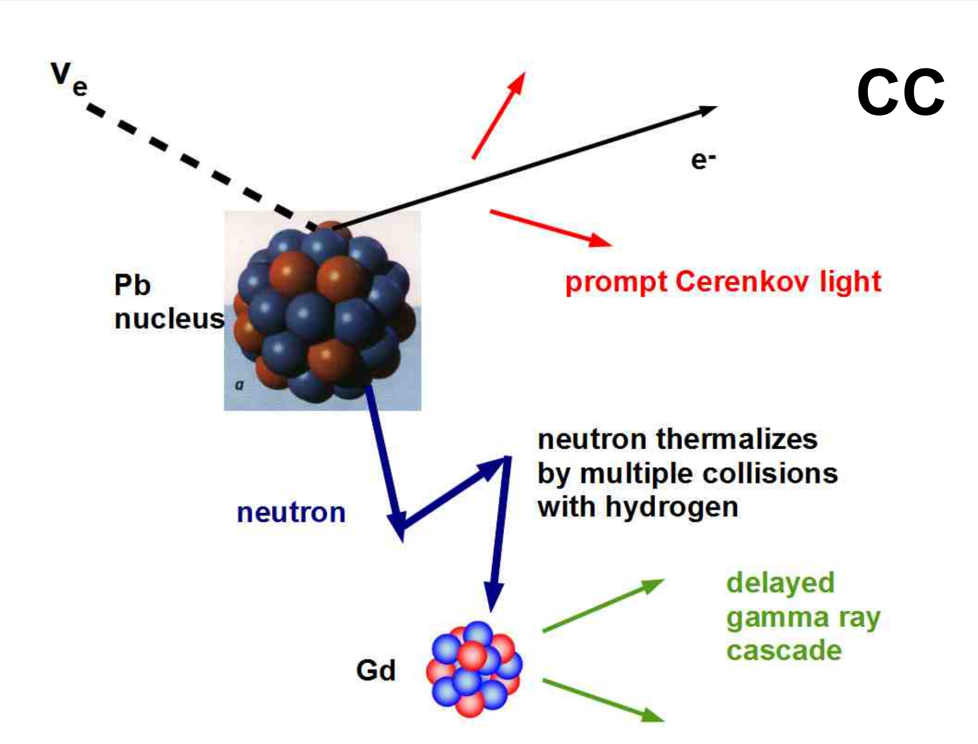


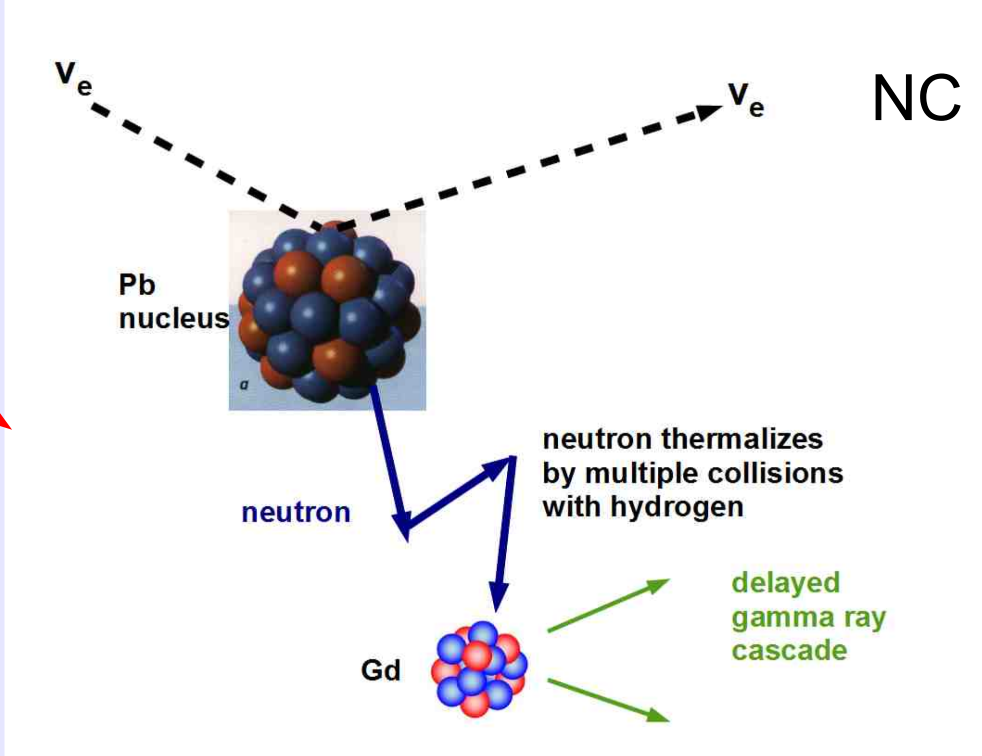


Amount of prompt Cerenkov light from outgoing electron measures the electron and hence the neutrino energy

→ observe the spectral splits that are the hallmark of flavor swapping

time structure of light output discriminates CC from NC





Summary

- a variety of neutrino detectors with different flavor sensitivitiewill be required to do a flavor decomposition of the neutrino flux from the next supernova in our galaxy
- HALO is the first SN neutrino detector with primary sensitivity to ν_e
- some ideas for bigger and better versions

The HALO Collaboration

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