Prospects for (Non-Oscillation) Neutrino Physics at the Spallation Neutron Source

Kate Scholberg, Duke University

Fundamental Symmetries & Neutrinos Workshop, August 2012

Outline

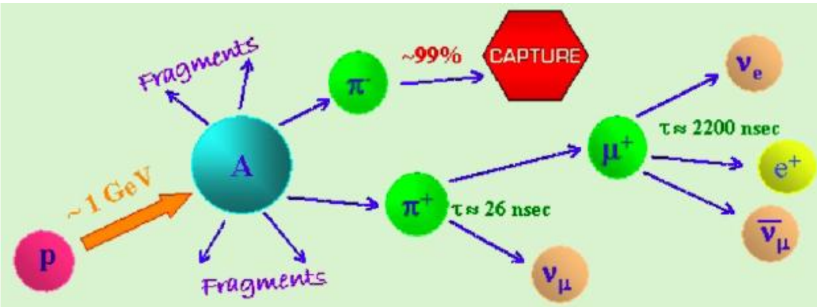
- Neutrinos from the SNS
  - Nature of the source
  - Global context

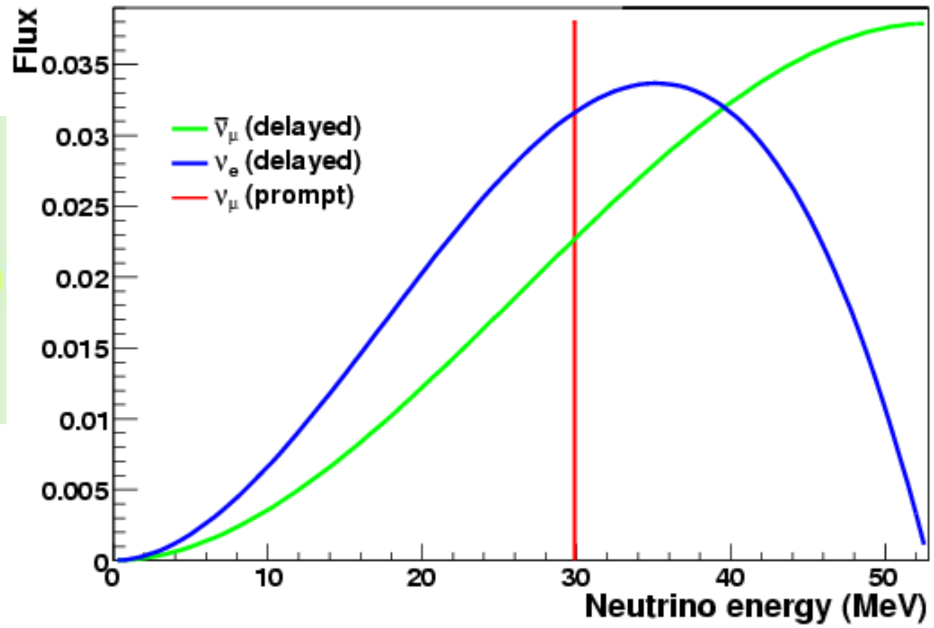
- Physics that could be explored
  - Supernova-relevant cross-sections
  - Coherent-elastic νA scattering
  - And more...

] some examples

The SNS as a Stopped-Pion Neutrino Source

F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

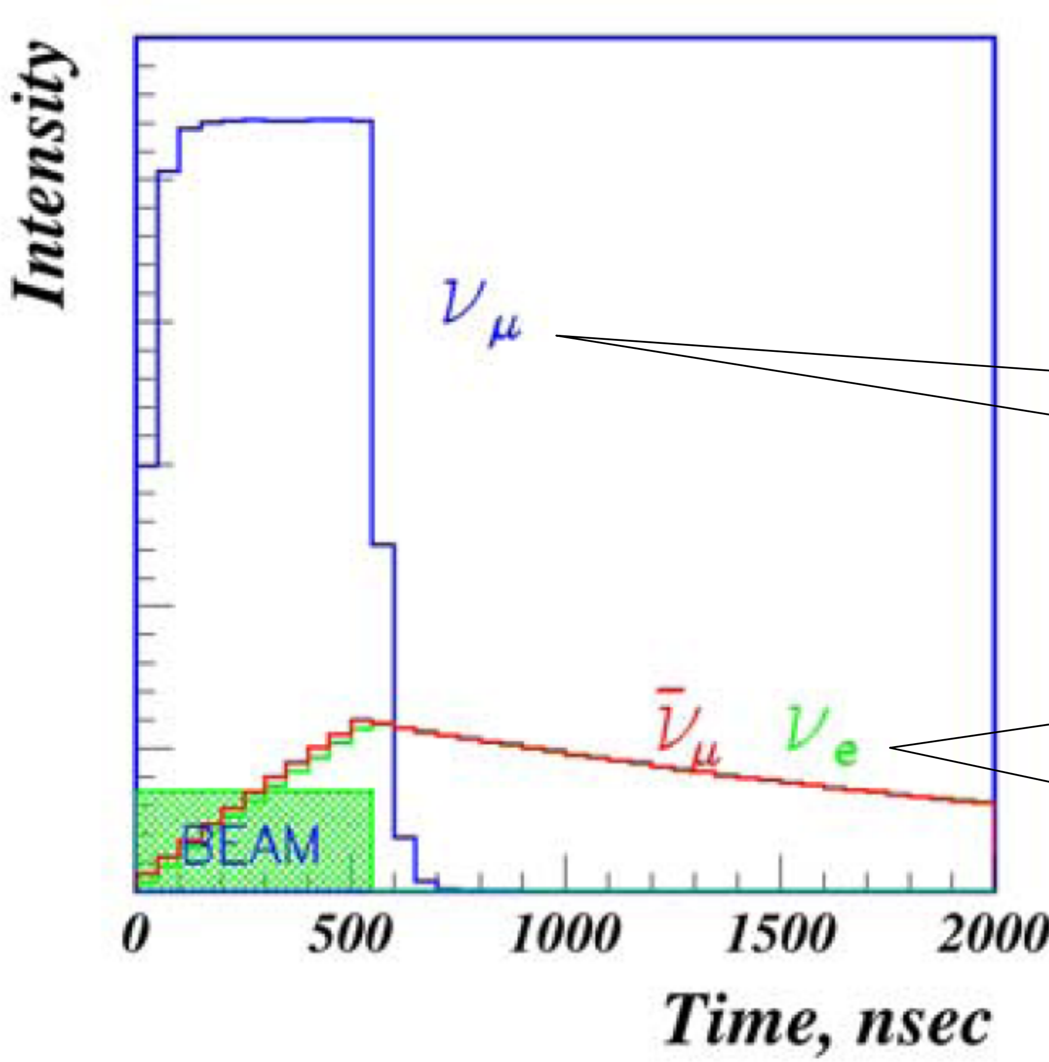
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Neutrino flux: few times 10^7 /s/cm^2 at 20 m

~0.13 per flavor per proton

Time structure of the source



60 Hz *pulsed* source

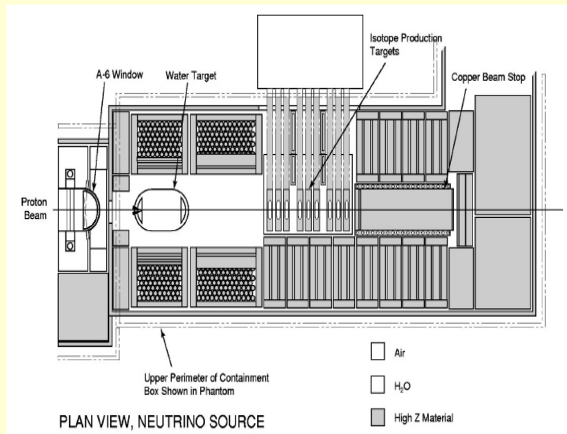
in time with beam

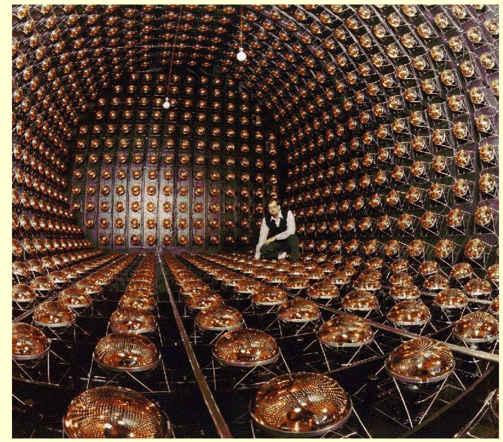
delayed on μ decay timescale (2.2 μs)

Background rejection factor ~few x 10^{-4}

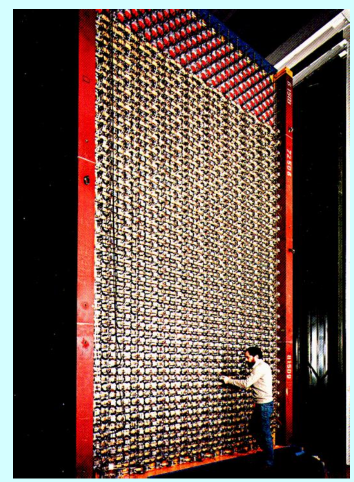
Previous neutrino experiments at stopped-pion neutrino sources

LSND at LANSCE (LANL)





KARMEN at ISIS (RAL)



Comparison of stopped-pion neutrino sources

	LANSCE	ISIS	SNS	JSNS	ESS
Location	USA (LANL)	UK (RAL)	US (ORNL)	Japan (J-PARC)	Sweden
Proton energy	0.8 GeV	0.8 GeV	1 (1.3) GeV	3 GeV	1.3 GeV
Time structure	Continuous	Two 200 ns bunches separated by 300 ns	380 ns FWHM	2 60-100 ns bunches	(1.4 μs)/2.0ms
Repetition rate	N/A	50 Hz	60 Hz	25 Hz	(50 Hz)/17 Hz
Power	56 kW	160 kW	> 1 MW	1 MW	(5 MW)/5 MW
Target	Various	Water-cooled tantalum	Mercury	Mercury	Mercury

Plus: MB far-off-axis (?), DAEδALUS cyclotrons

Want:
- **very high intensity ν's**
- **~below kaon threshold**
- **nearly all decay at rest**
- **narrow pulses**

Workshop on Neutrinos at the Spallation Neutron Source

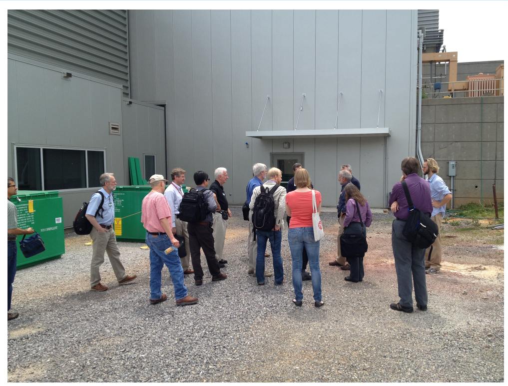
An informal workshop will be held on **May 3-4, 2012** at the Spallation Neutron Source at Oak Ridge National Laboratory, to explore future possibilities for neutrino measurements at the SNS. The discussion will be primarily on cross-section measurements in the few tens of MeV range. The aim for this workshop is to solicit from the community ideas for small-scale first-generation experiments that could be done on a relatively short time scale. Farther-future possibilities will also be discussed.

We expect that the workshop will generate a white paper that could guide future developments.

Whitepaper in progress

Topics for discussion:

- Supernova neutrino physics
- Supernova neutrino detection
- Short baseline neutrino oscillations
- Standard model tests
- Measurements of cross-sections on nuclear targets relevant for existing and future supernova detectors
- Detector technologies for coherent elastic neutrino-nucleus scattering
- Potential experiment sites and needs



http://www.phy.duke.edu/~schol/sns_workshop

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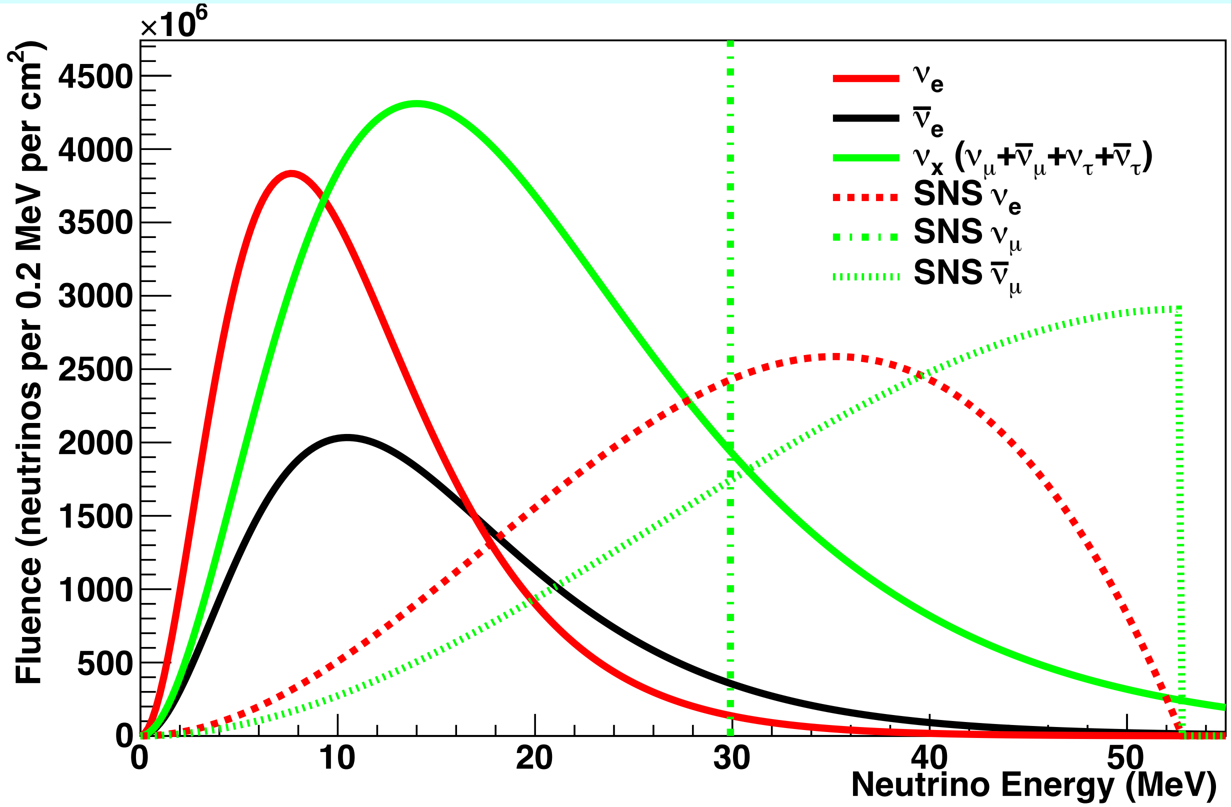
A. Bolozdynya, F. Cavanna, Y. Efremenko, G. T. Garvey, V. Gudkov,
A. Hatzikoutelis, R. Hix, J. M. Link, W. C. Louis,
D. Markoff, G. B. Mills, K. Patton, K. Scholberg, R. G. Van de Water,
C. Virtue, D. H. White, J. Yoo

I will focus on a few topics; please see the document for others

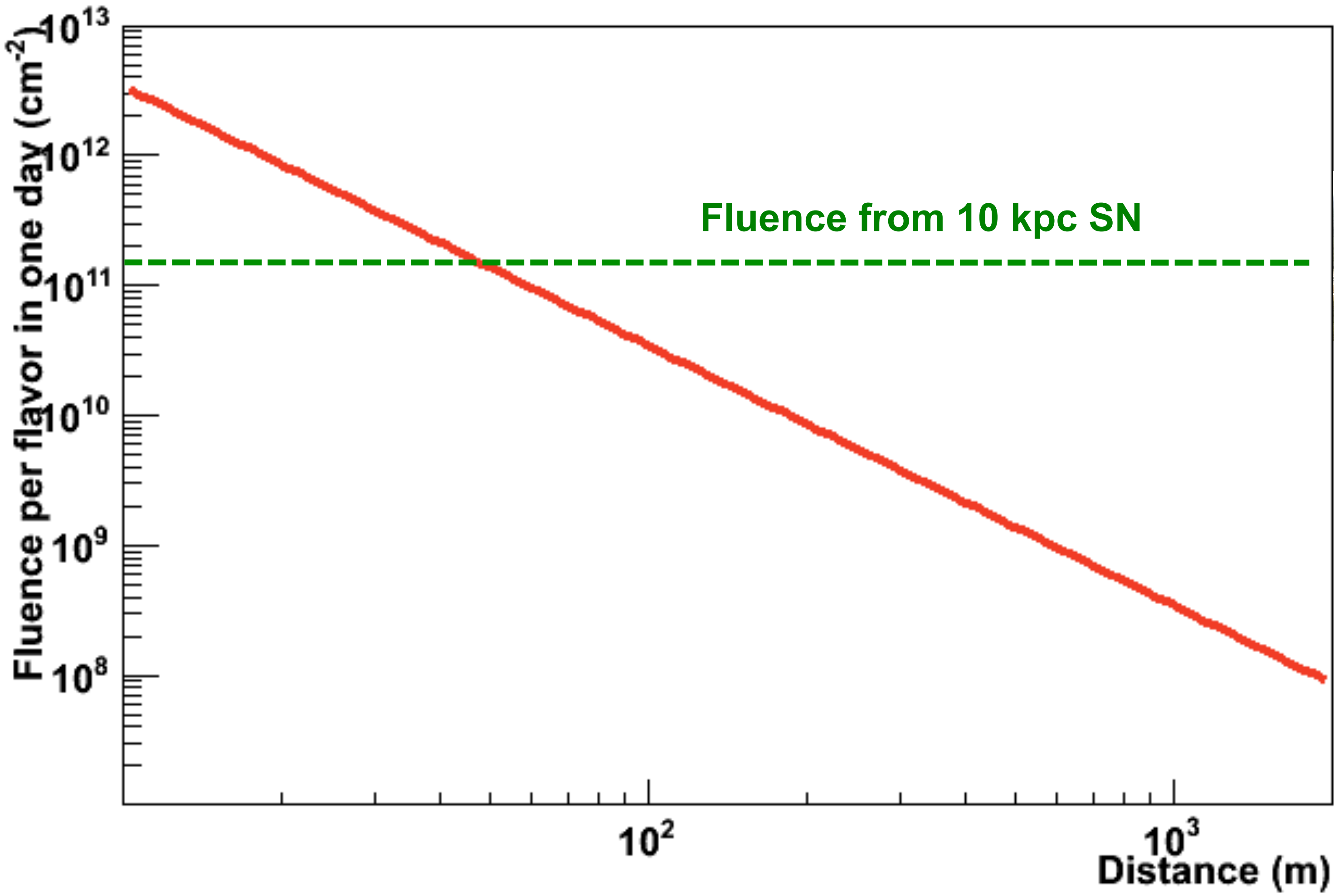
Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



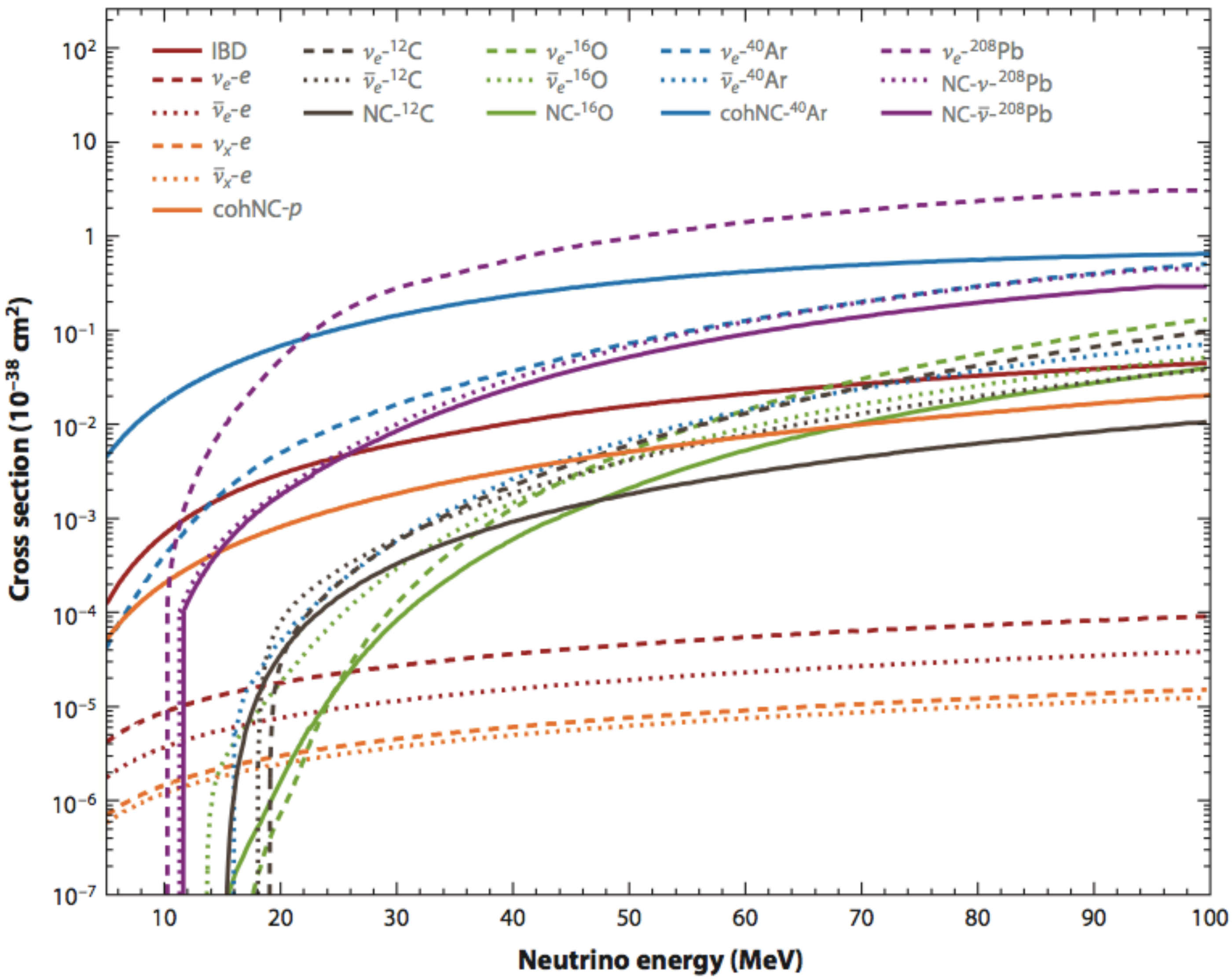
Study CC and NC interactions with various nuclei, in few to 10's of MeV range

1. Understanding of *core-collapse SN processes*, nucleosynthesis
2. Understanding of *SN ν detection* processes

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!



SN-relevant cross sections in this energy range



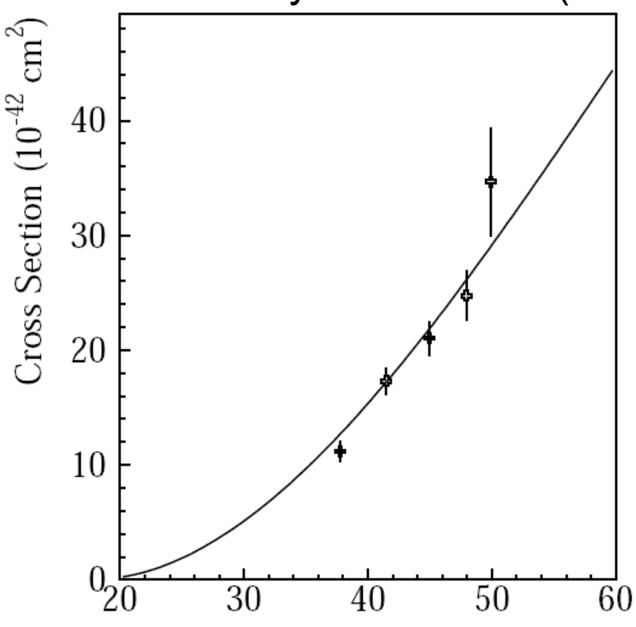
Of these, only IBD, ν-e ES are known at the few % level

So far only ^{12}C is the *only* heavy nucleus with ν interaction x-sections well (~10%) measured in the tens of MeV regime

e.g.

LSND

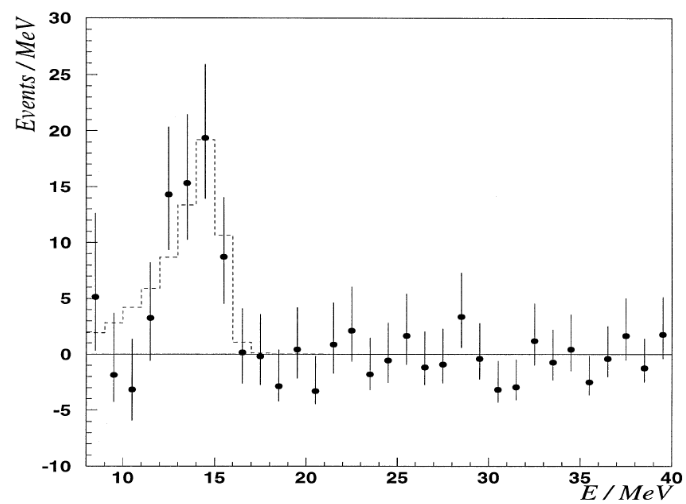
Phys. Rev. C 66 (2002) 015501



$$^{12}C(\nu_e, e^-)^{12}N_{g.s.}$$

Karmen

Phys. Lett. B 423 (1998) 15-20

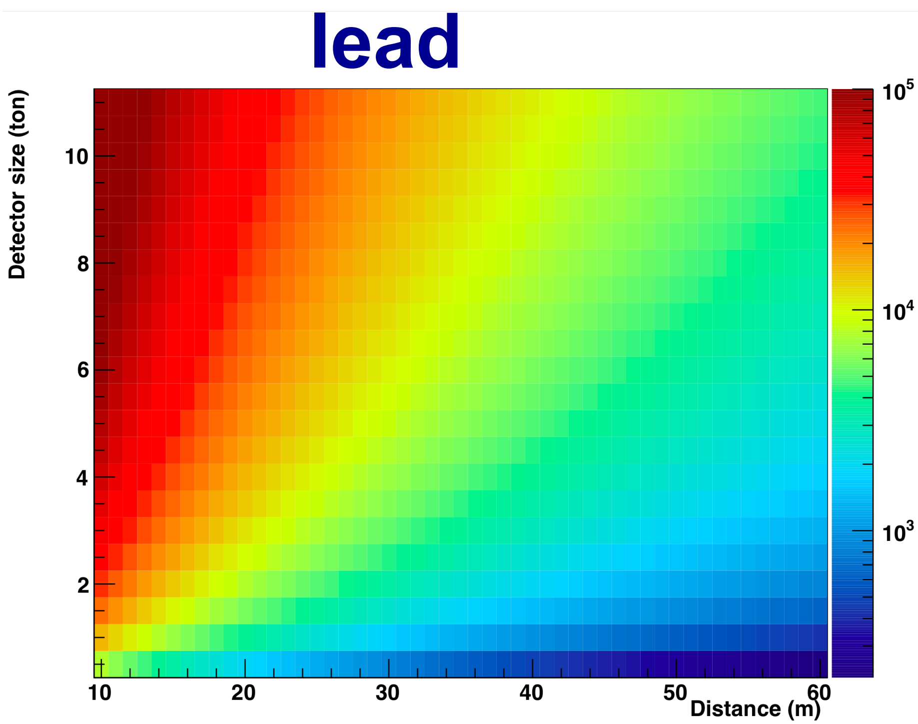


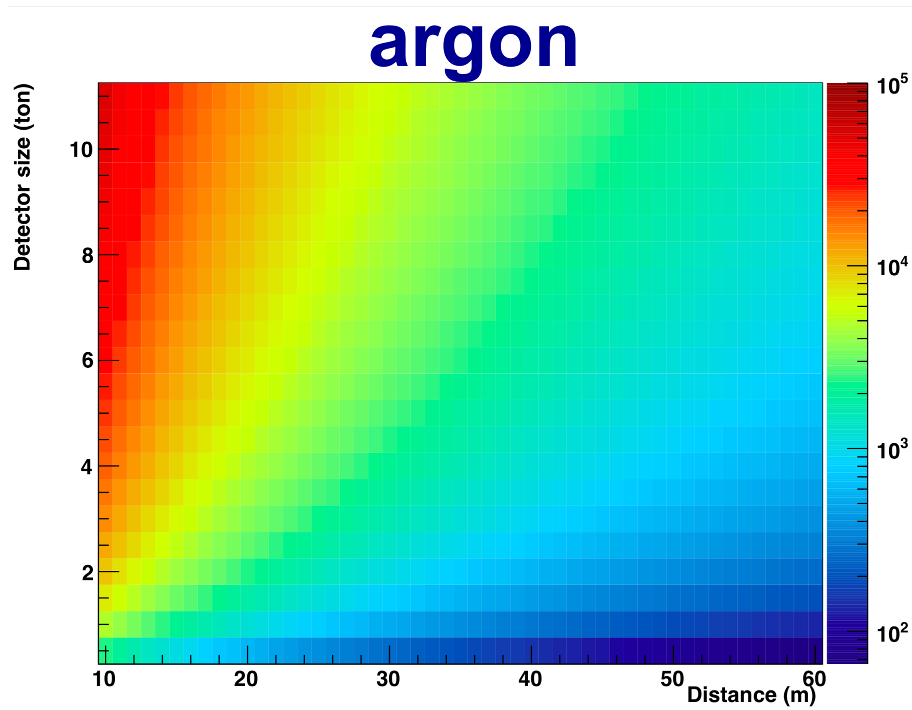
$$^{12}\mathrm{C}(\nu_\mu \nu'_\mu)\,^{12}\mathrm{C}^*(1^+, 1; 15.1\ \mathrm{MeV})$$

Need: oxygen (water), lead, iron, argon...

Total events per year at the SNS as a function of distance and mass

just scaling as $\alpha\ 1/R^2$, α M





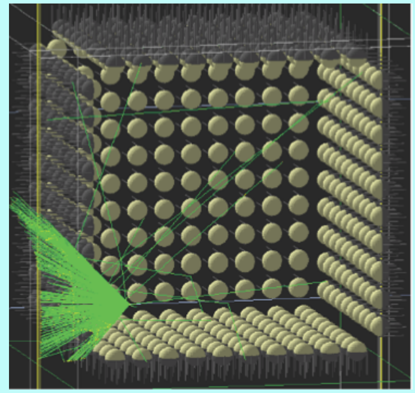
~10^3 events per few tons at 30 m

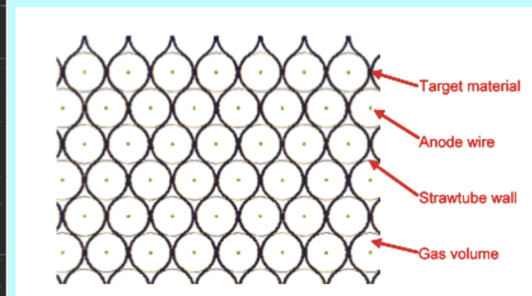
Possible Experiments for CC/NC Measurements

NuSNS:

interchangeable targets

- homogeneous detector for transparent liquids
- foils + strawtubes for metallic targets



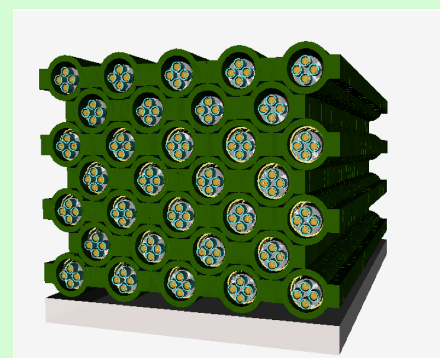


Small LAr TPC

ArgoNeut?
LBNE
prototype?

Small lead + n detector

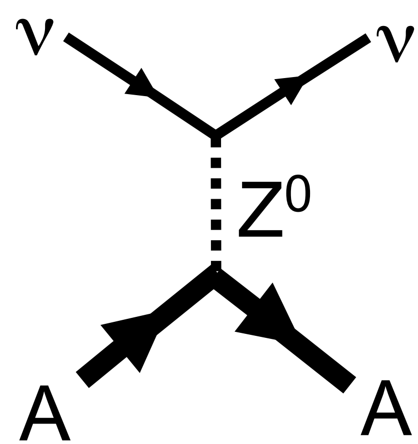
HALO-inspired

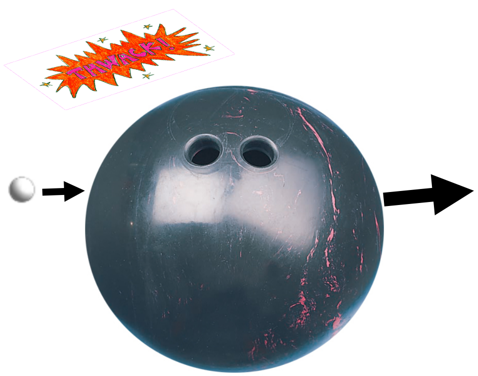


Coherent neutral current neutrino-nucleus elastic scattering

$$\nu + A \longrightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils;
coherent up to $E_\nu \sim 50$ MeV



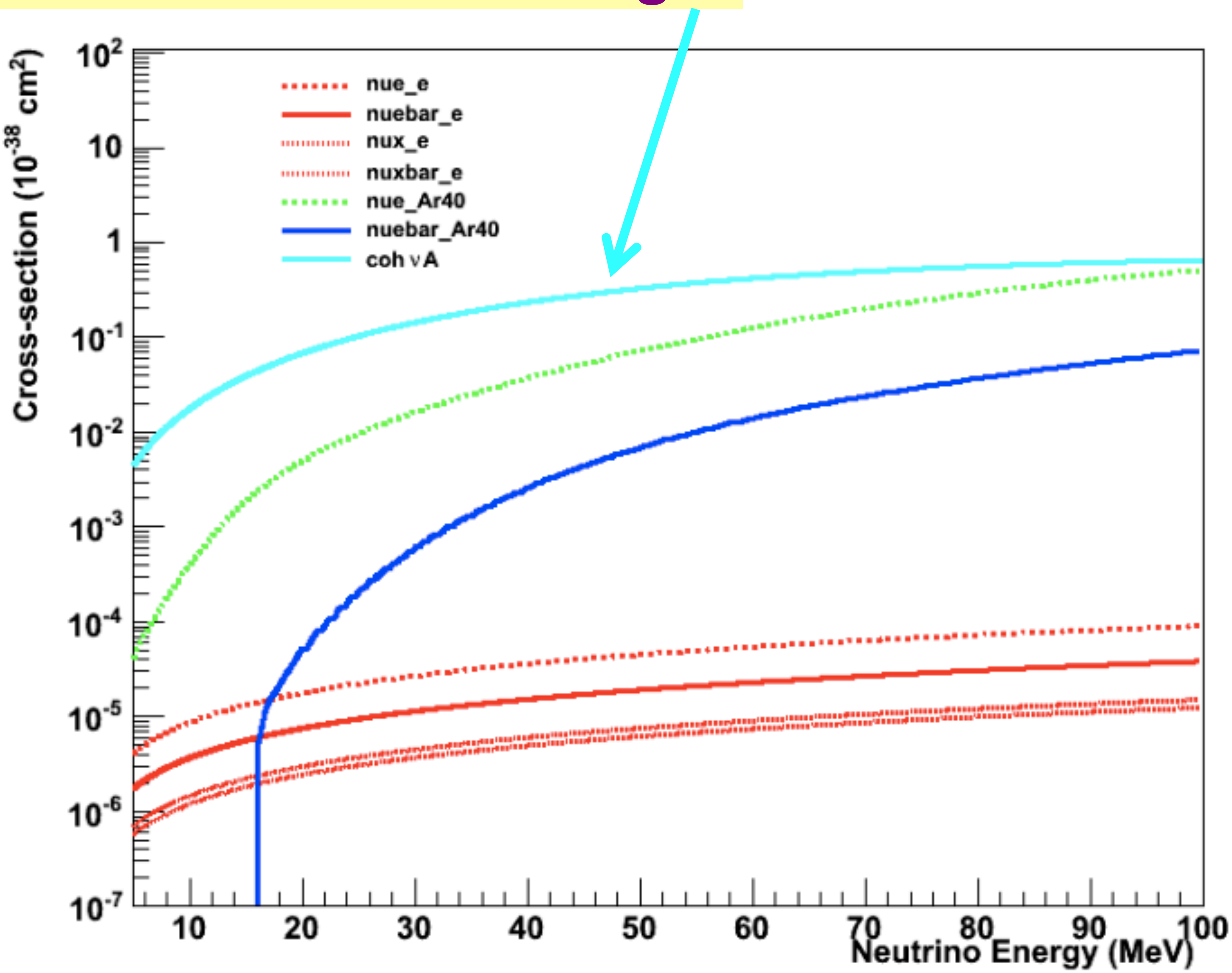


- Important in SN processes & detection
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Possible applications (reactor monitoring)

A. Drukier & L. Stodolsky, PRD 30:2295 (1984)
Horowitz et al. , PRD 68:023005 (2003) astro-ph/0302071

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

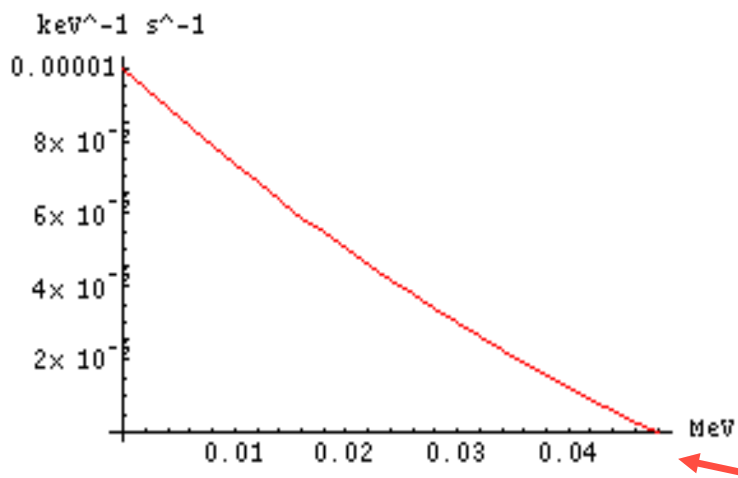
The cross-section is *large*



But this coherent ν A elastic scattering has never been observed...

Why not?

Nuclear recoil energy spectrum for 30 MeV ν



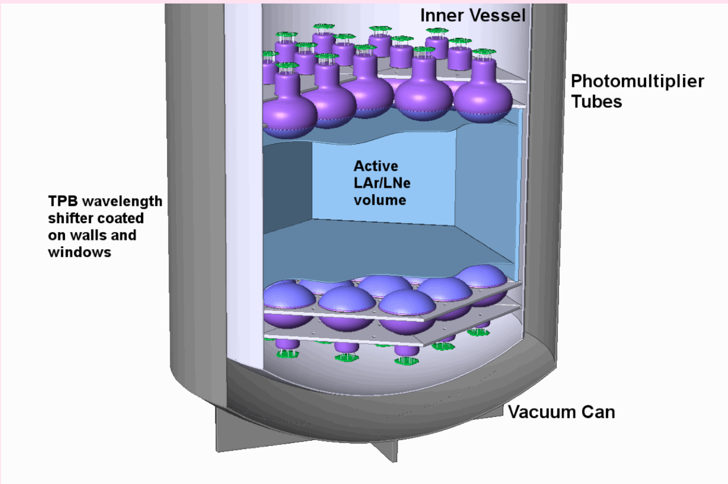
Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)

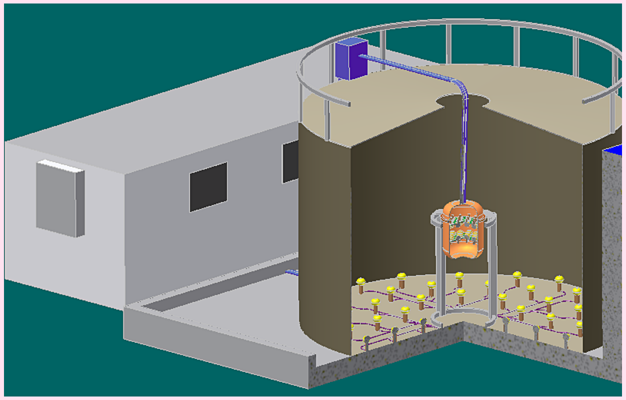
Recoil energies are tiny!

Most neutrino detectors (water, gas, scintillator) have thresholds of at least ~MeV: so these interactions are hard to see

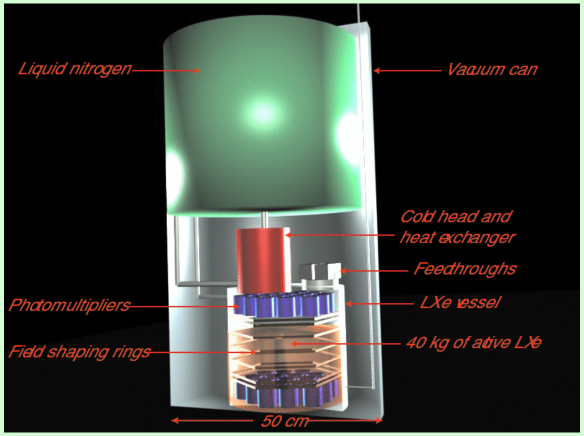
Detector possibilities: various DM-style strategies

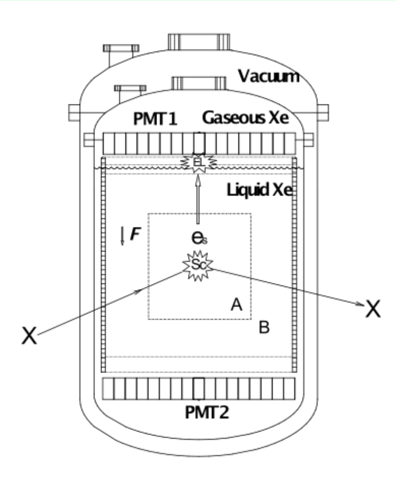
Single-phase Ar/Ne (CLEAR)



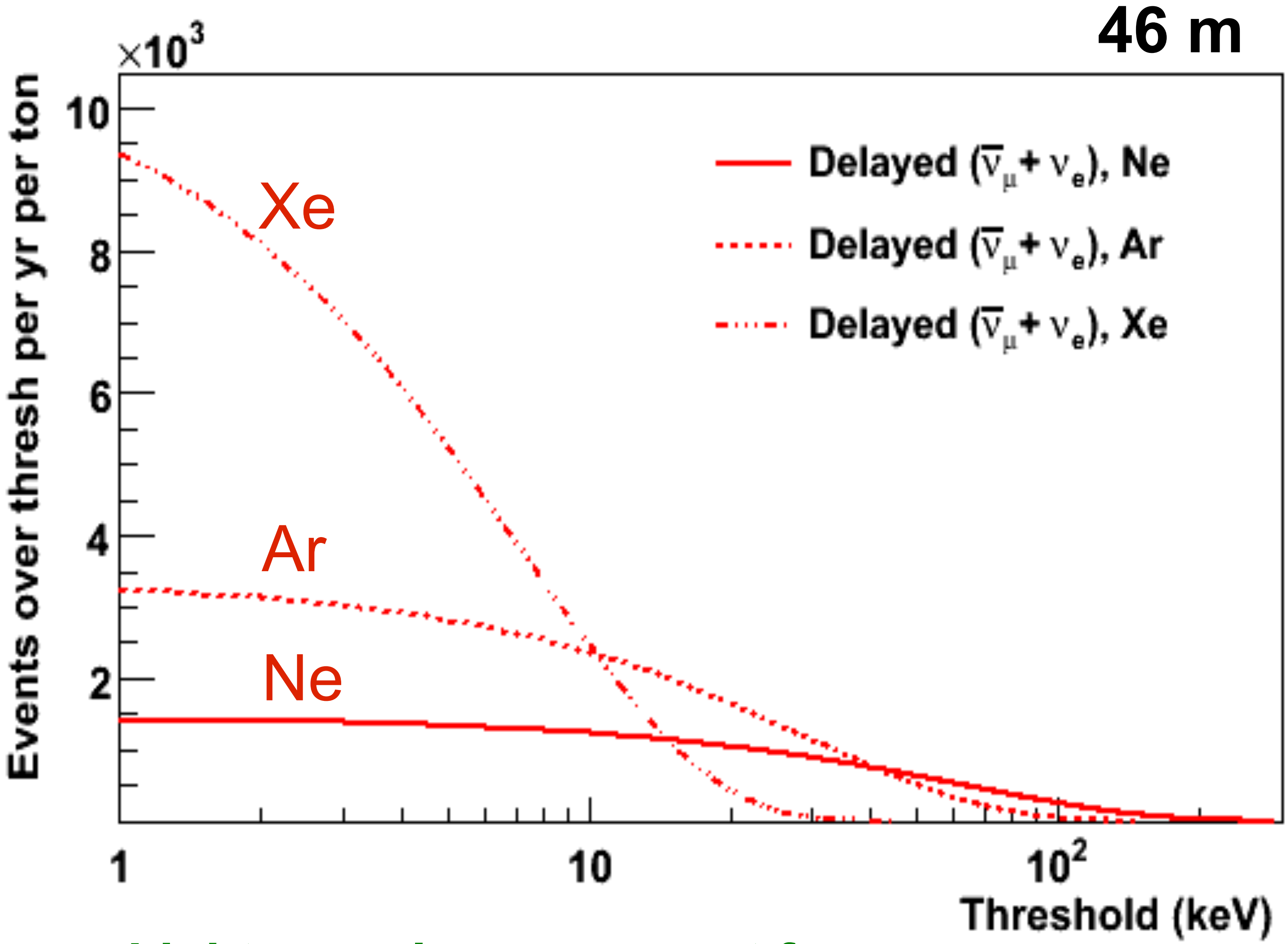


Xe dual-phase TPC





Integrated SNS yield for various targets



Lighter nucleus ⇒ expect fewer interactions, but more at higher energy

What major scientific discoveries have occurred in your research area since the 2007 LRP?

- No xscn measurements... no measurements the few tens of MeV range, no coherent νA scattering measurements;
  but measurements are more motivated than ever
  due to new SN detectors (lead [HALO], argon [LBNE])
- Recent low-energy recoil detectors have improved
- Recent new exploration of “hidden sector”

What compelling and unique science is to be done in the next five years?

- First measurements of CC & NC inelastic xscns in several nuclei (lead, argon, water)
- First measurement of coherent νA scattering, SM tests, NSI exclusion
- Possible “hidden sector program”

What science would you expect to pursue in the program in 2020 and beyond?

- List of interesting supernova-relevant targets
  is nearly inexhaustible
- SM tests from precision measurements
- Studies of neutron distributions with coherent νA scattering
- ...

What is the international context, and how does it affect your vision?

- Possible other stopped-pion sources: JSNS, DAEδALUS, ESS, FNAL

The existing SNS is the best of these in terms of combined high ν-intensity and excellent timing characteristics (...and it exists)

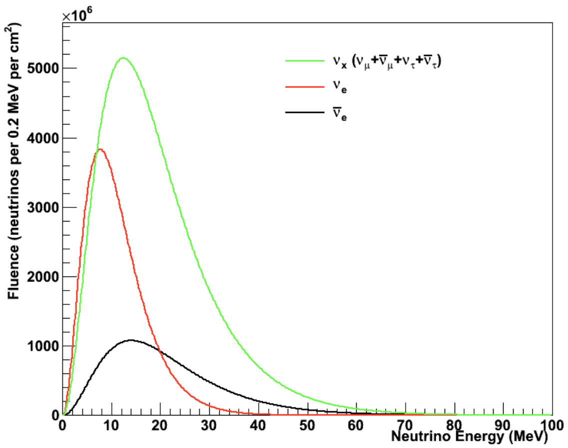
Let's not waste those free neutrinos!

These are *not* crummy old cast-off neutrinos...

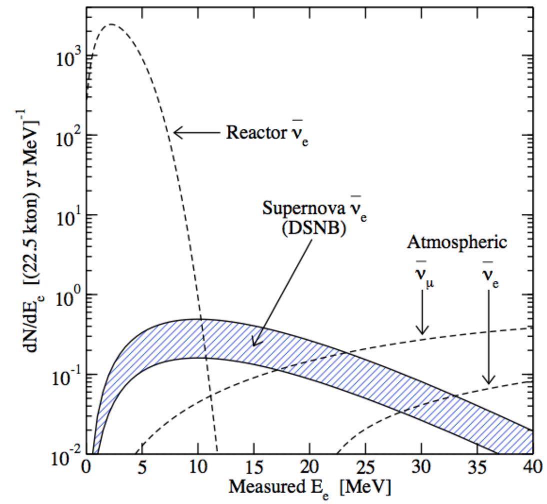
They are of the highest quality!

Backups/extras

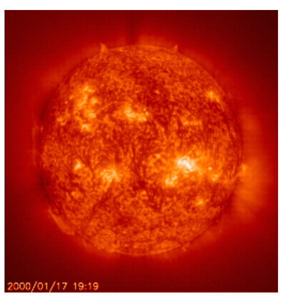
Neutrino interactions in the few-100 MeV range are relevant for:

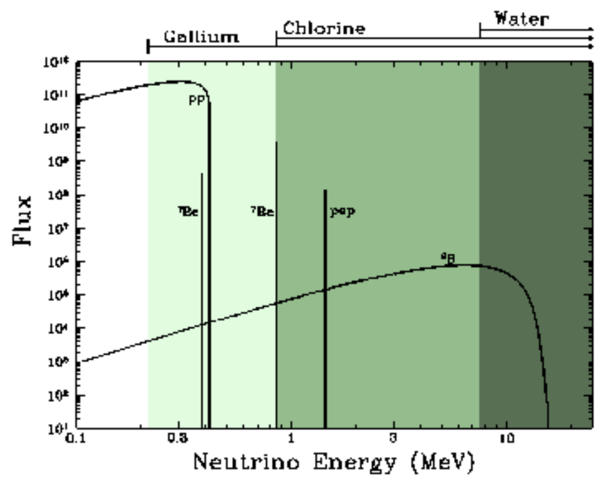


supernova neutrinos, burst & relic

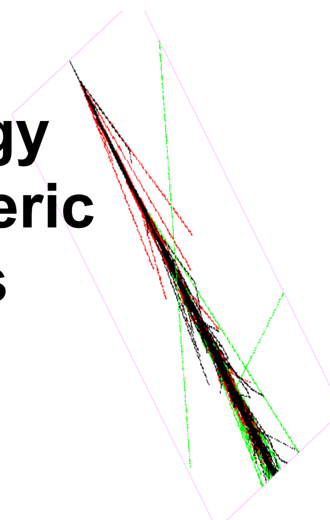


solar neutrinos



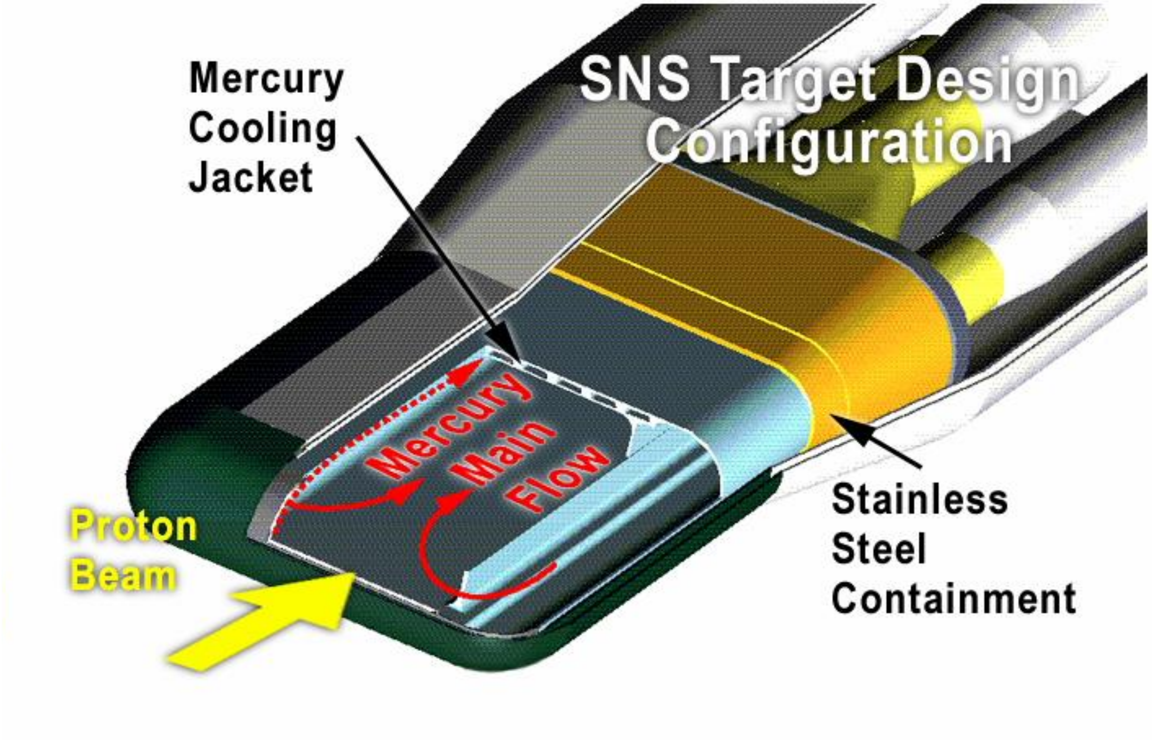


low energy atmospheric neutrinos

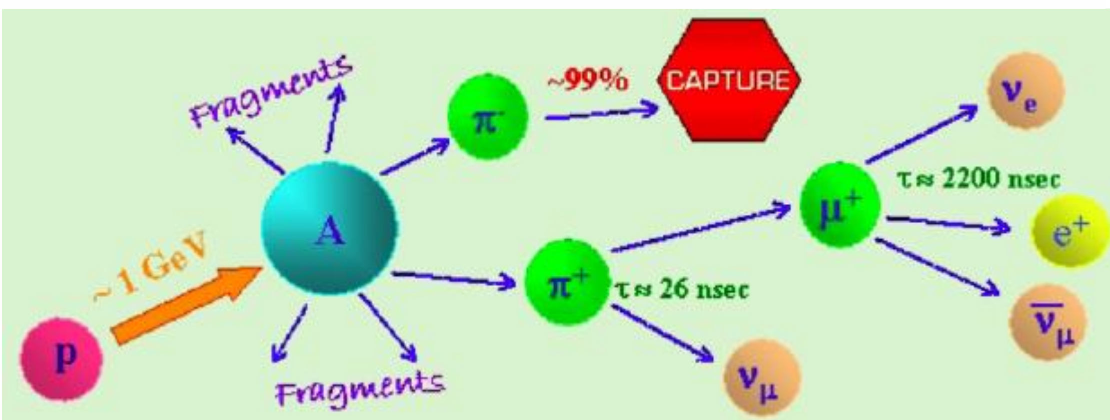


oscillation, astrophysics

Neutrinos are a free by-product!



In addition to kicking out neutrons, protons on target create copious pions:
π^- get captured;
π^+ slow and decay at rest



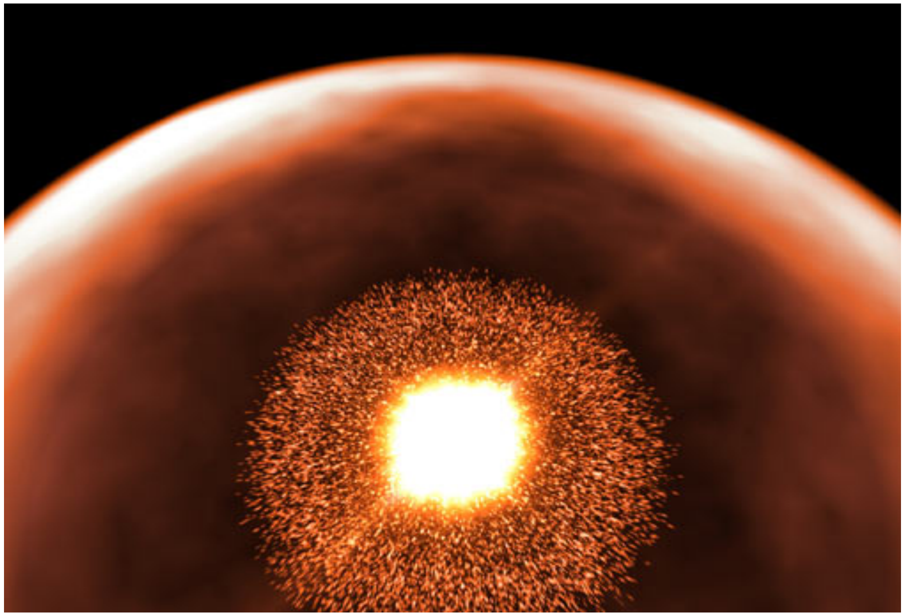
NEUTRINOS FROM CORE COLLAPSE

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~MeV energies

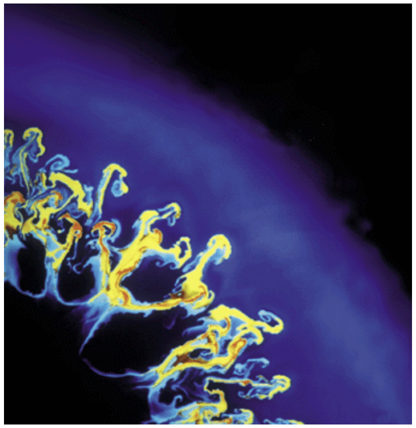
(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

Timescale: *prompt* after core collapse, overall Δt~10's of seconds



What We Can Learn

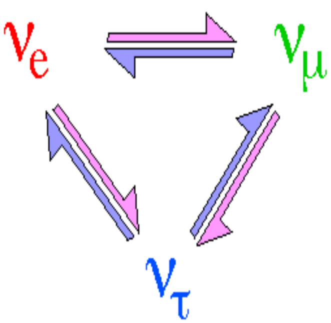


CORE COLLAPSE PHYSICS

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

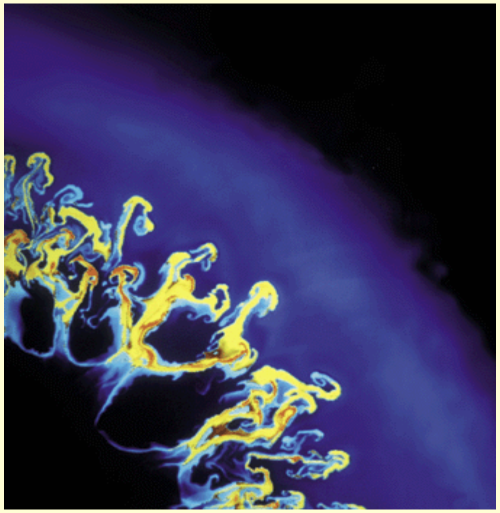
from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS



- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
  (' θ_{13} the lucky and patient way')
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

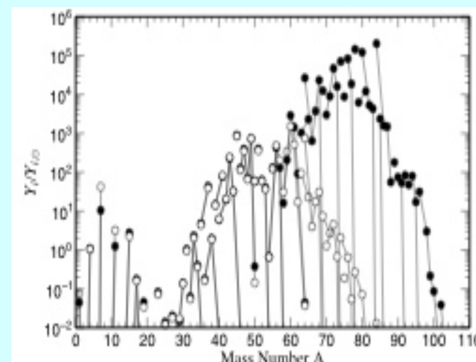


Supernova explosion

Neutrinos are intimately involved in the post-collapse explosion, which is not fully understood

Supernova nucleosynthesis

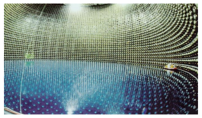
Neutrino reactions affect the distribution of SN-produced elements, and may produce rare isotopes

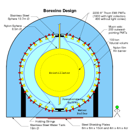


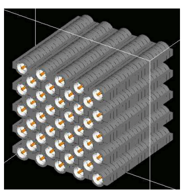
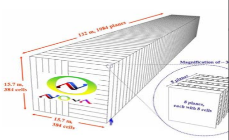
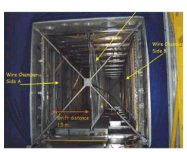
Fröhlich *et al*., Astrophys. J. 637 (2006) 415-426

Understanding of neutrino interactions with matter is crucial!

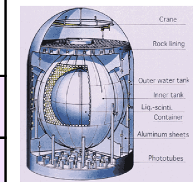
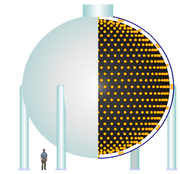
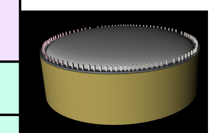
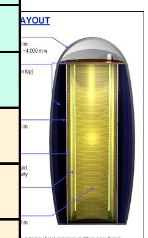
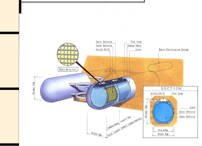
Supernova neutrino detectors, current & future





Detector	Type	Location	Mass (kton)	Events @ 8 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	0.4/PMT	N/A	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running
HALO	Lead	Canada	0.076	85	Under construction
Icarus	Liquid argon	Italy	0.6	230	Almost ready
NOvA	Scintillator	USA	15	3000	Construction started
SNO+	Scintillator	Canada	1	300	Funded
LBNE LAr	Liquid argon	USA	17	1500	Proposed
LBNE WC	Water	USA	300	78,000	Proposed
MEMPHYS	Water	Europe	440	120,000	Proposed
Hyper-K	Water	Japan	500	130,000	Proposed
LENA	Scintillator	Europe	50	15,000	Proposed
GLACIER	Liquid argon	Europe	100	38,000	Proposed


To make the most of a Galactic SN neutrino detection, we need to understand how the neutrinos interact with detector materials

Tool for evaluating neutrino event rates

To evaluate sensitivity to different features of flux/physics, we need to fold

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

Software package to make use of the GLoBES front-end rate engine (*not* the oscillation sensitivity part)

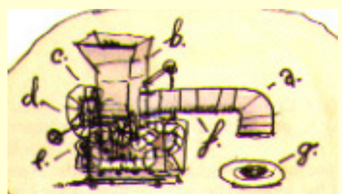
flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOw GLoBES



interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

what we're after

SNOwGLoBES package contents

- driving script
- data files:
  - cross-section files for O, Ar, C, Pb (+...)
  - smearing and efficiency files for several detector configurations (100kt, LAr, scint, HALO)
  - example flux file(s)
- example plotting scripts
- documentation w/refs

A. Beck, F. Beroz, R. Carr, KS, W. Johnson, A. Moss, D. Reitzner, D. Webber, R. Wendell
A. Dighe, H. Duan, A. Friedland, J. Kneller

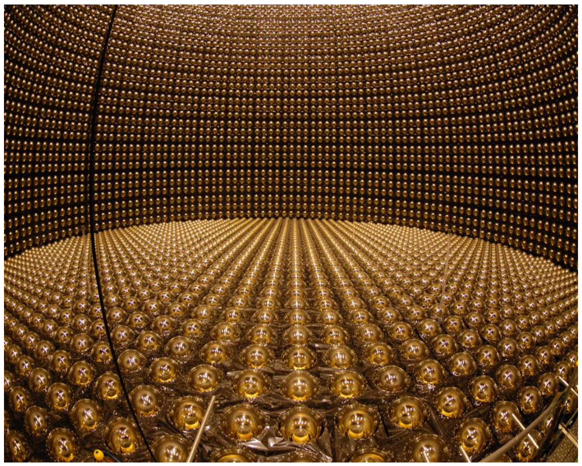
- Smearing and efficiency files provided are based on:
  - published information (resolutions etc.), reasonable assumptions, simulation output where available
- Users (typically) would provide their own fluxes
- Users could use the packaged detector smearing datafiles, or provide their own

http://www.phy.duke.edu/~schol/snowglobes

- Test version available

Example 1: interactions on oxygen nuclei

CC interactions



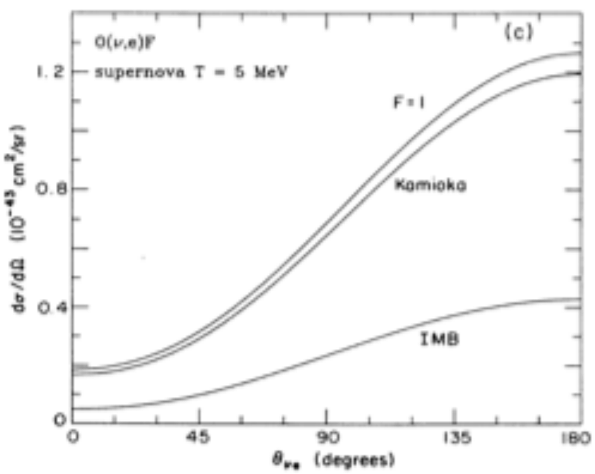
few % of SN signal

Kolbe, Langanke, Vogel: PRD 66, (2002) 013007

TABLE III. Partial cross sections for charged-current neutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=4$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

Neutrino reaction	$\sigma, T=4$ MeV	$\sigma, T=8$ MeV
total	1.91 (−1)	1.37 (+1)
$^{16}O(\nu_e, e^- p)^{15}O$(g.s.)	1.21 (−1)	6.37 (+0)
$^{16}O(\nu_e, e^- p\gamma)^{15}O^*$	4.07 (−2)	3.19 (+0)
$^{16}O(\nu_e, e^- np)^{14}O^*$	3.92 (−4)	1.76 (−1)
$^{16}O(\nu_e, e^- pp)^{14}N^*$	2.61 (−2)	3.26 (+0)
$^{16}O(\nu_e, e^- \alpha)^{12}N^*$	1.16 (−3)	1.31 (−1)
$^{16}O(\nu_e, e^- p\alpha)^{11}C^*$	2.17 (−3)	5.66 (−1)
$^{16}O(\nu_e, e^- n\alpha)^{11}N(p)^{10}C^*$	1.11 (−6)	3.28 (−3)

Angular distributions are interesting



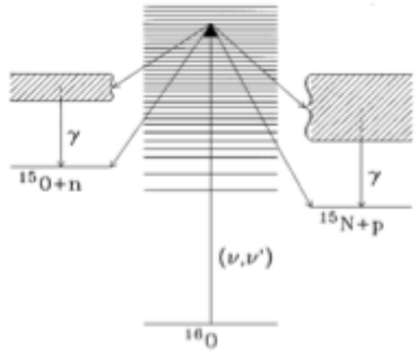
Haxton: PRD 36, (1987) 2283

TABLE IV. Partial cross sections for charged-current antineutrino-induced reactions on ^{16}O. Fermi-Dirac distributions with $T=5$ MeV and $T=8$ MeV and zero chemical potential have been assumed. The cross sections are given in units of 10^{-42} cm^2, exponents are given in parentheses.

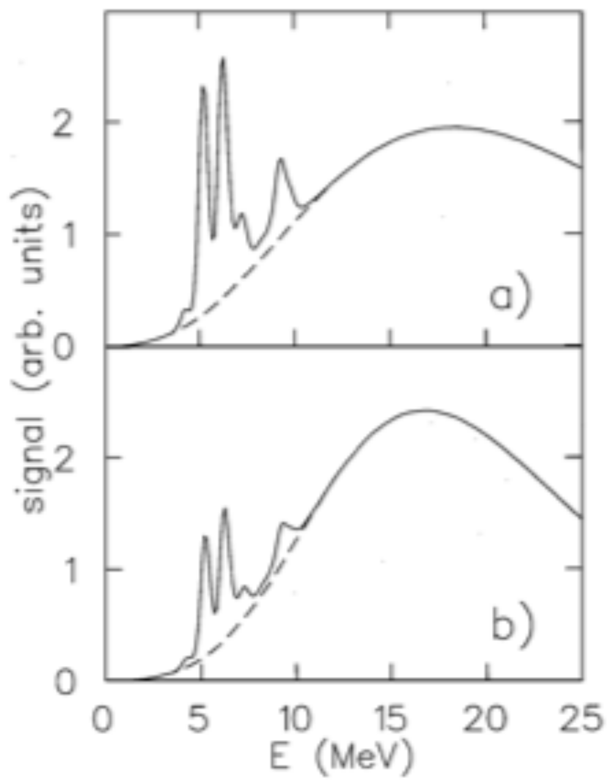
Neutrino reaction	$\sigma, T=5$ MeV	$\sigma, T=8$ MeV
total	1.05 (+0)	9.63 (+0)
$^{16}O(\bar{\nu}_e, e^+)^{16}N$(g.s.)	3.47 (−1)	2.15 (+0)
$^{16}O(\bar{\nu}_e, e^+ n)^{15}N$(g.s.)	5.24 (−1)	4.81 (+0)
$^{16}O(\bar{\nu}_e, e^+ n\gamma)^{15}N^*$	1.47 (−1)	1.90 (+0)
$^{16}O(\bar{\nu}_e, e^+ np)^{14}C^*$	4.56 (−3)	1.38 (−1)
$^{16}O(\bar{\nu}_e, e^+ nn)^{14}N^*$	5.50 (−3)	1.81 (−1)
$^{16}O(\bar{\nu}_e, e^+ \alpha)^{12}B^*$	1.07 (−2)	1.91 (−1)
$^{16}O(\bar{\nu}_e, e^+ n\alpha)^{11}B^*$	6.20 (−3)	2.16 (−1)

NC interactions on oxygen nuclei

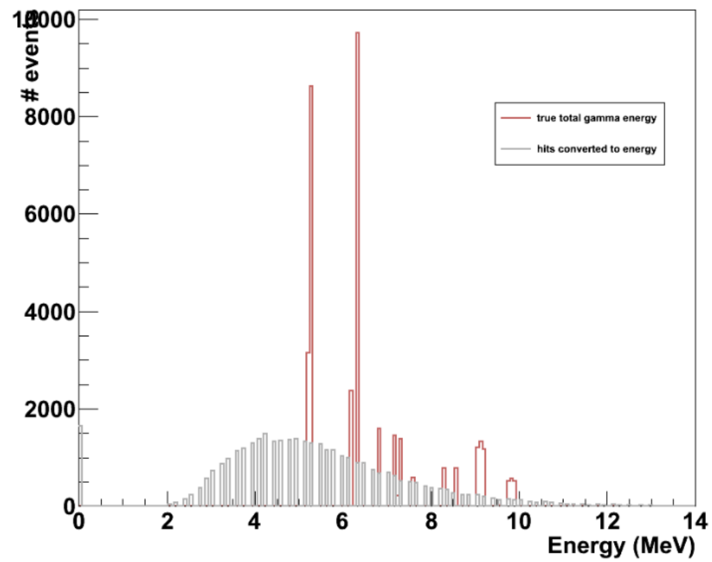
Final states from NC excitation



Langanke, Vogel, Kolbe: PRL 76, (1996) 2629

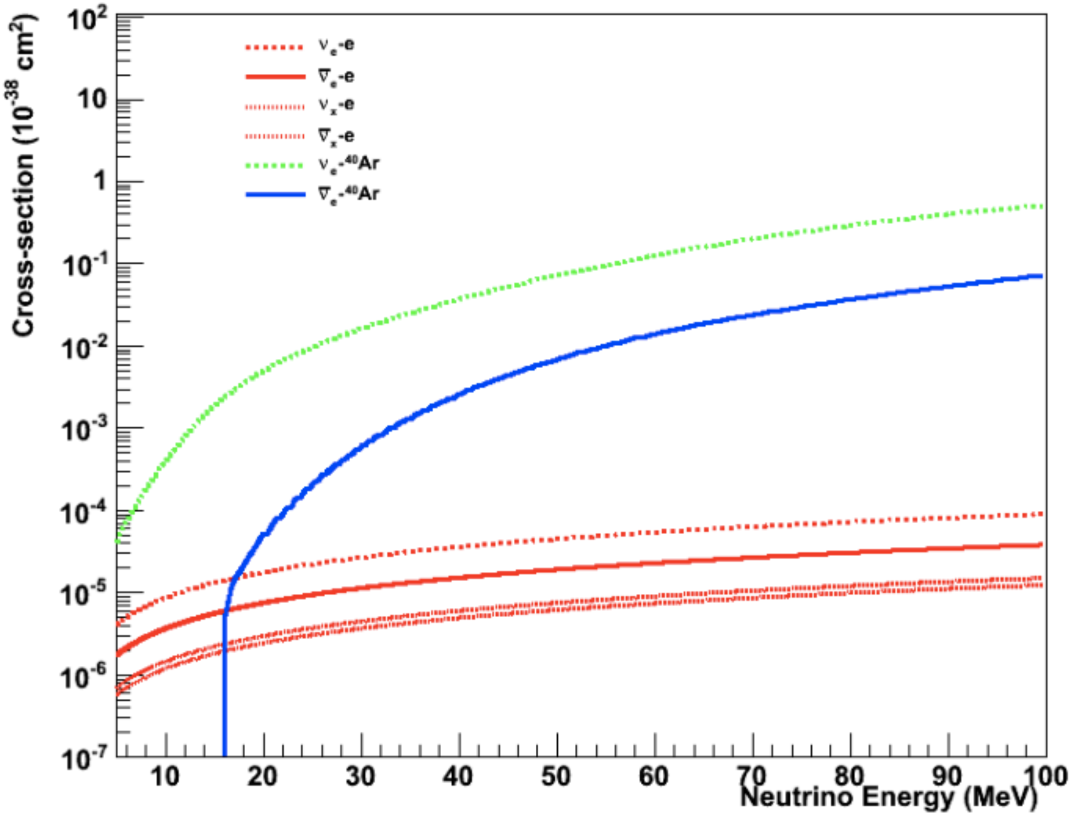


Observed γ energy per event



large fraction of the γ energy is lost in Compton scatter

<u>Example 2:</u> interactions on argon nuclei



M. Sajjad-Athar & S.K. Singh,
Phys. Lett. B 591 (2004) 69

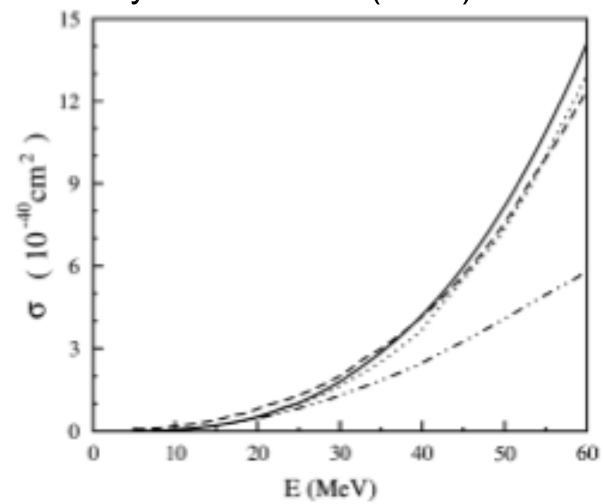


Fig. 3. Total cross section σ vs. E for $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$ reaction with Fermi function (solid line), modified effective momentum approximation (dashed line), Ormand et al. [12] (dashed-double dotted line) and Bueno et al. [13] (dotted line).

$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$
$$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$$
$$\nu_x + {}^{40}\text{Ar} \rightarrow \nu_x + {}^{40}\text{Ar}^*$$

Again, final states include ejected nucleons and deexcitation γ's
... are these observable?

Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; find out more?

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

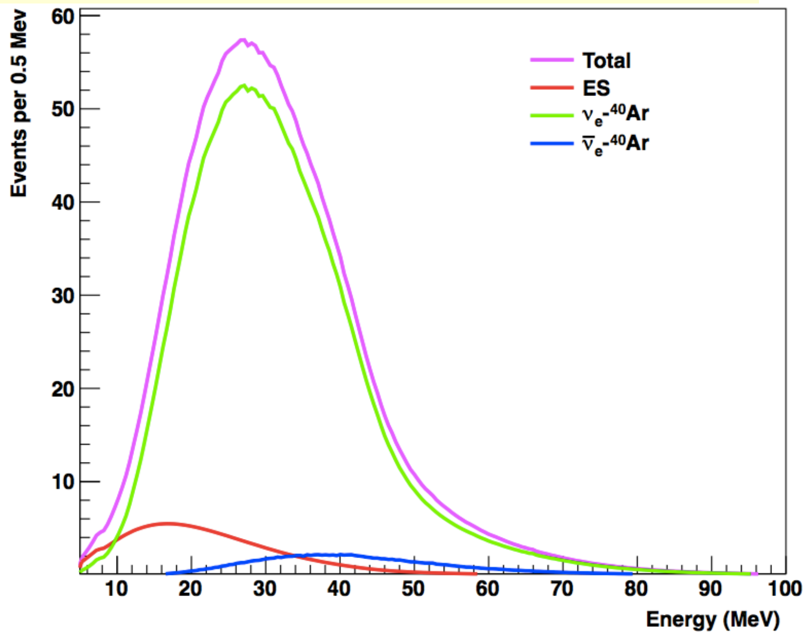
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...
- however no assumptions made about this so far

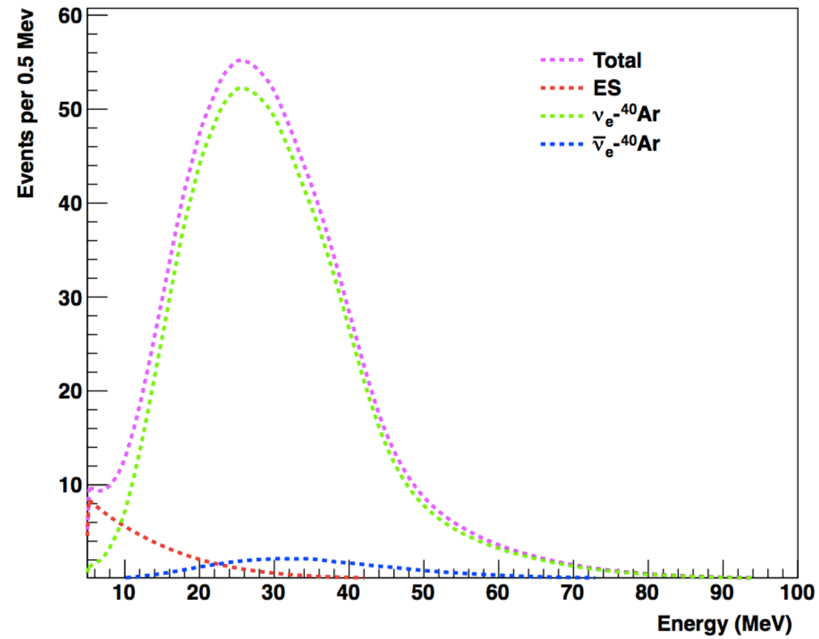
Supernova signal in LAr

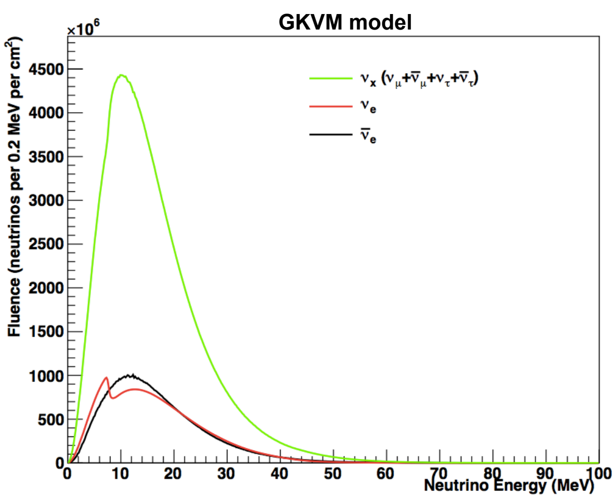
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy





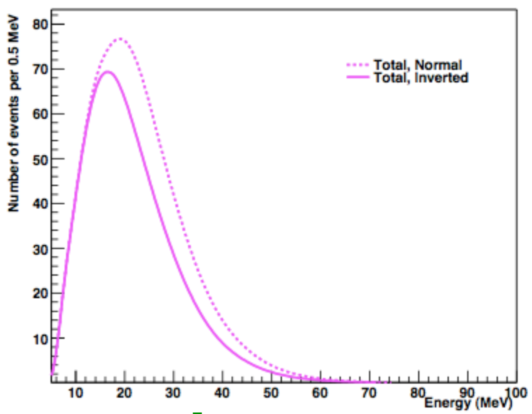
Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

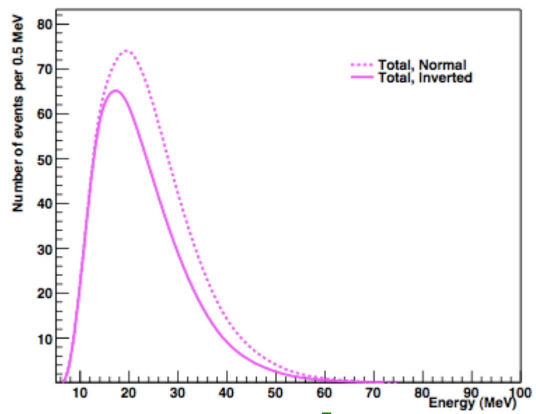
Dominated by ν_e

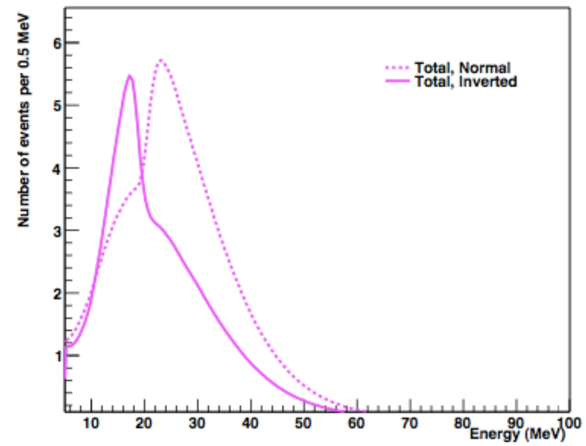
Observability of oscillation features in a SN burst: example from LBNE physics working group study

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice)







Differences, but no sharp features in water; 15% and 30% ~equally sensitive

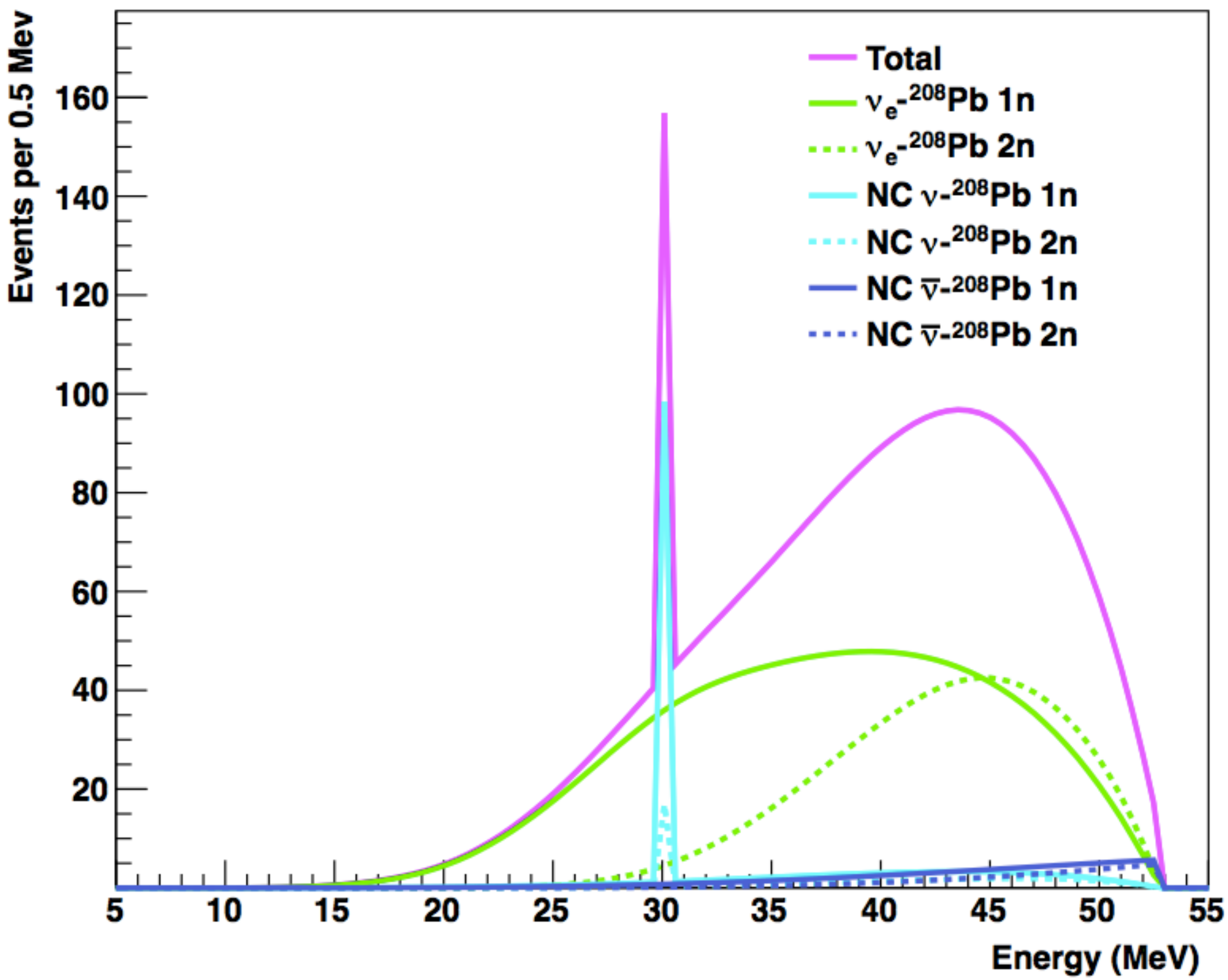
LAr shows dramatic difference

But need to understand the cross-section!

Event rates for lead

per ton per year at 20 m

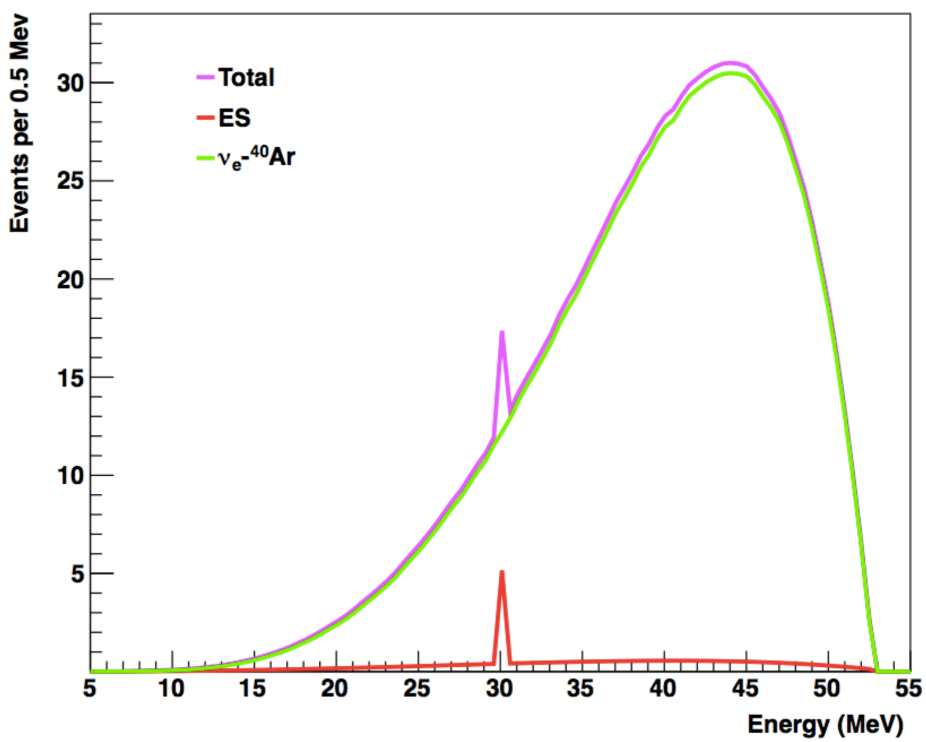
Interactions, as a function of neutrino energy



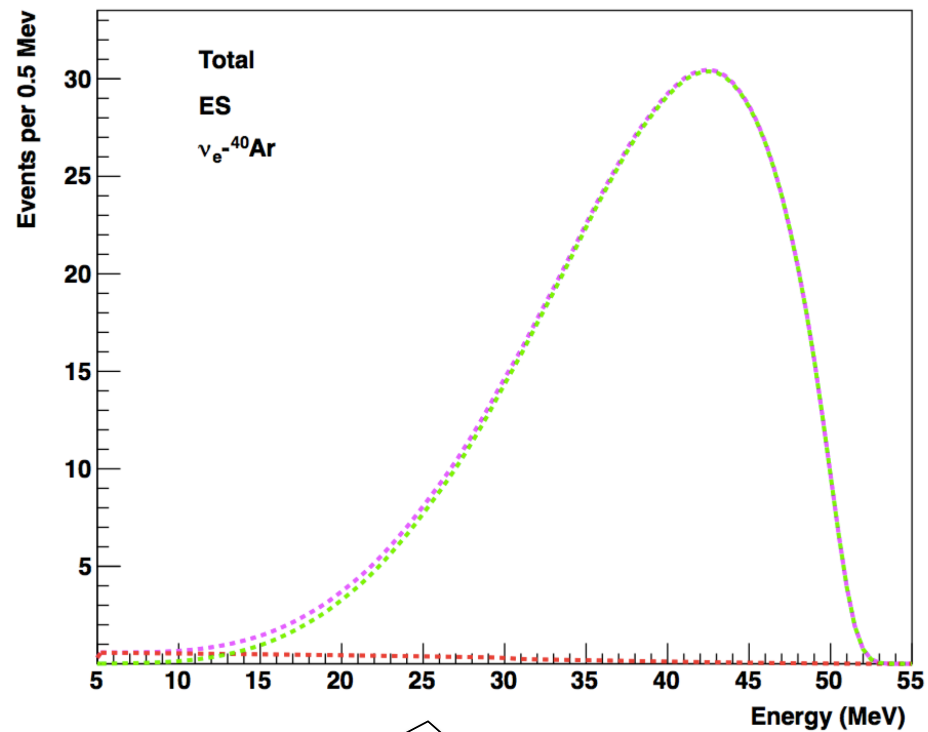
Event rates for argon

per ton per year at 20 m

Interactions, as a function of neutrino energy



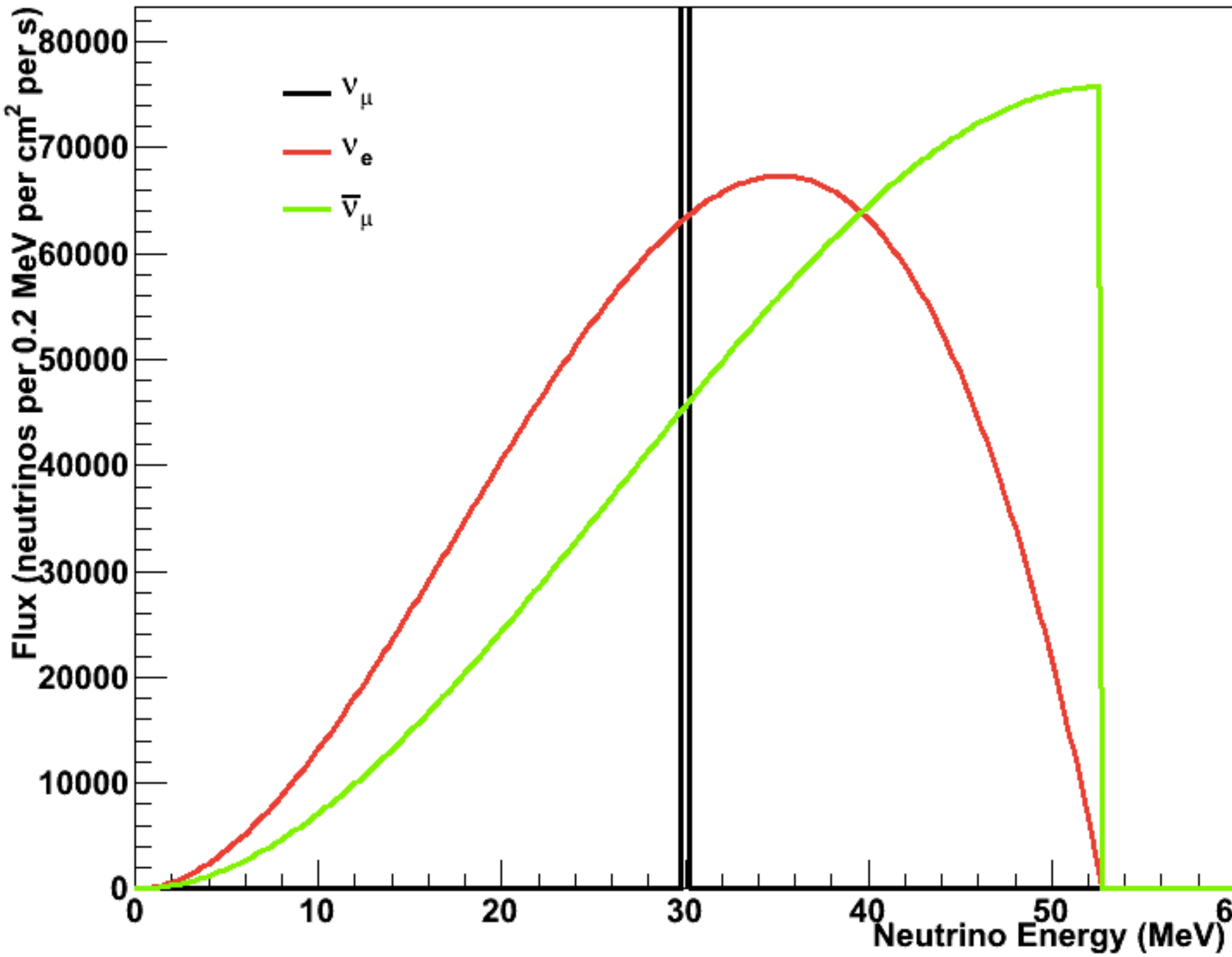
Events seen, as a function of observed energy



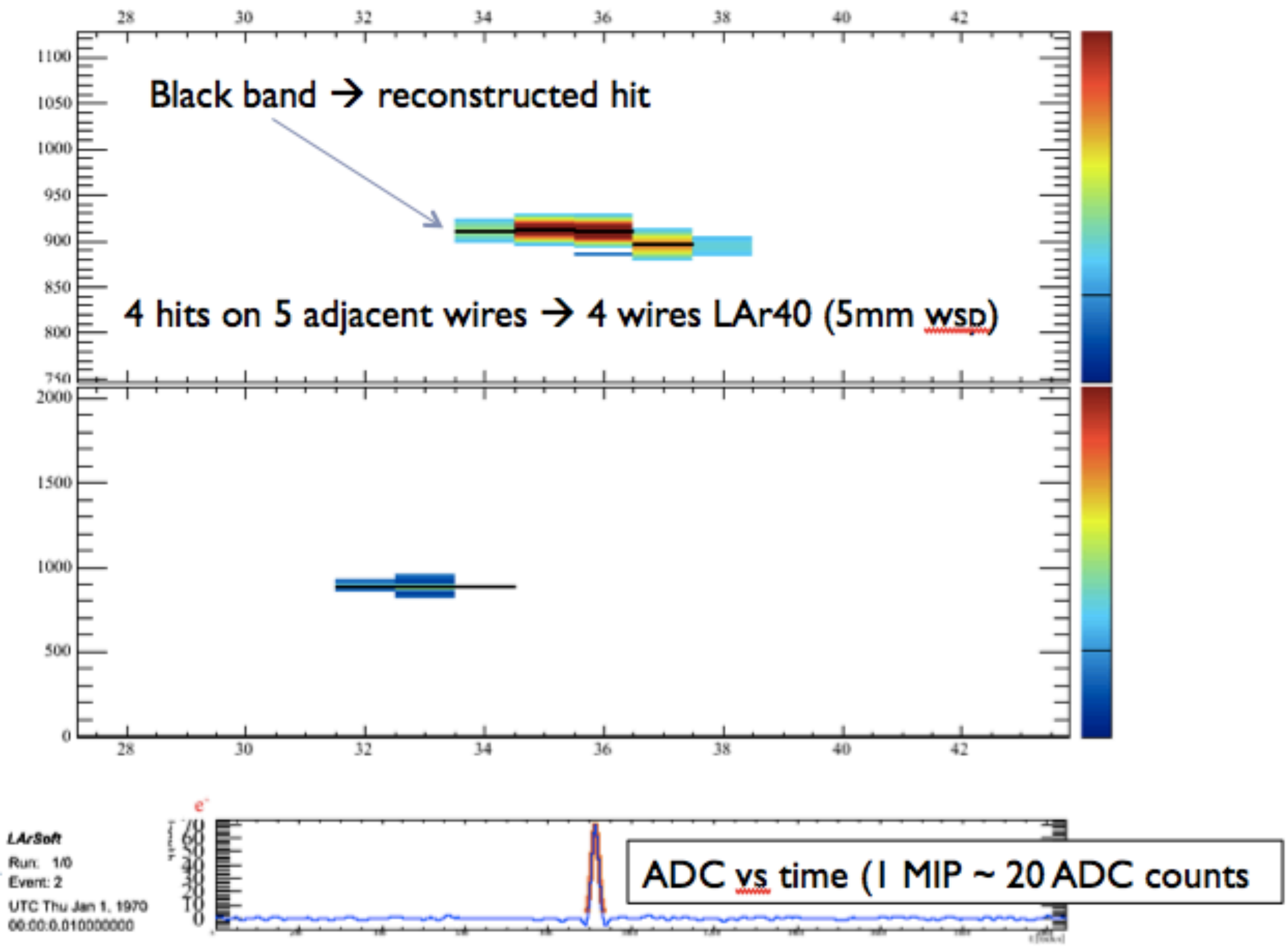
Assumes 100% efficiency,resolution from Amoruso et. al. (ICARUS)

SNS Flux for SNOwGLoBES

Normalized to 10^7 per cm^2 per s per flavor at 20 m

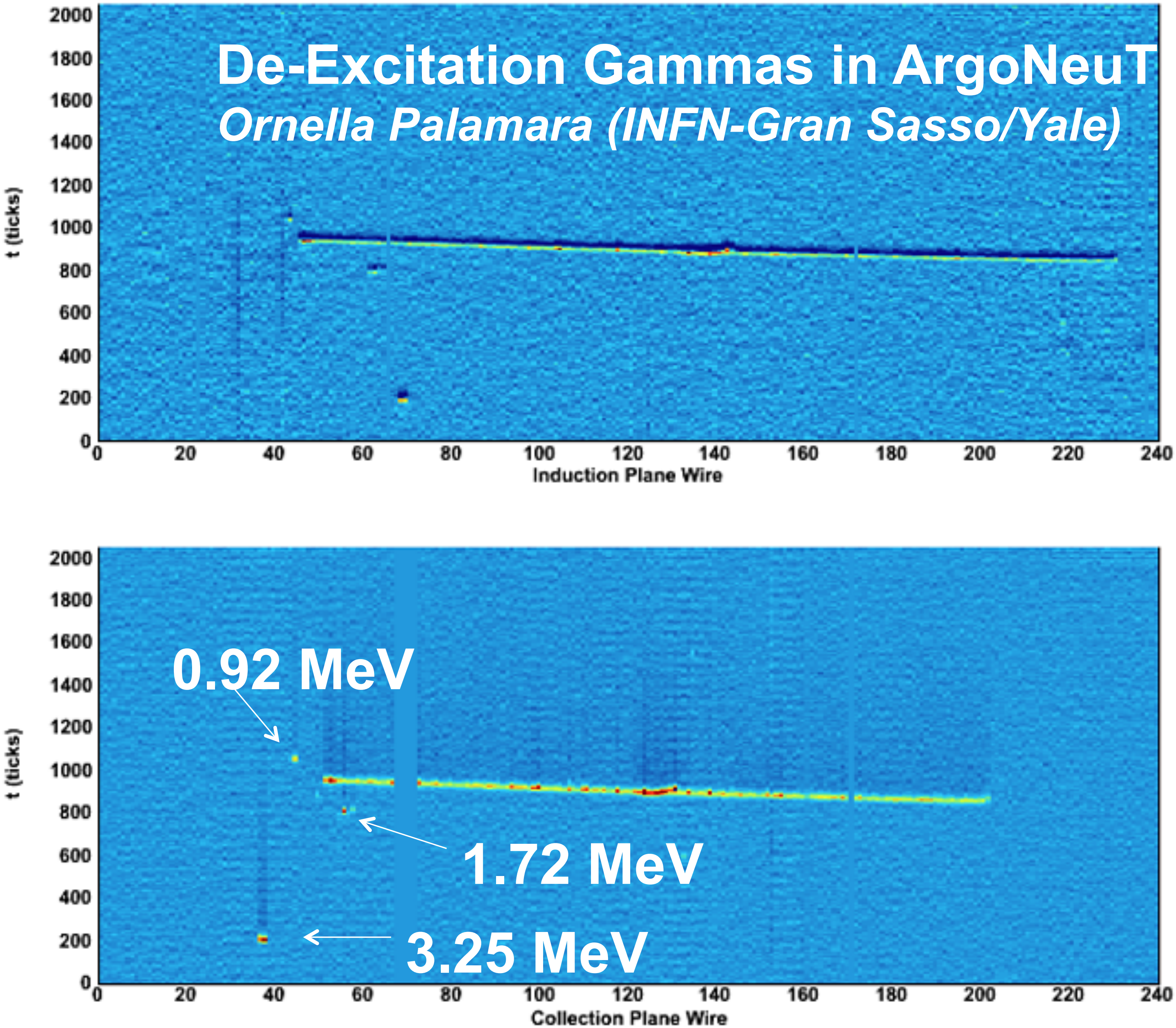


MC - 10 MeV Electron in ArgoNeuT/LArSoft 4 mm wire spacing *Bruce Baller*



De-Excitation Gammas in ArgoNeuT

Ornella Palamara (INFN-Gran Sasso/Yale)



Example 3: Interactions on lead nuclei

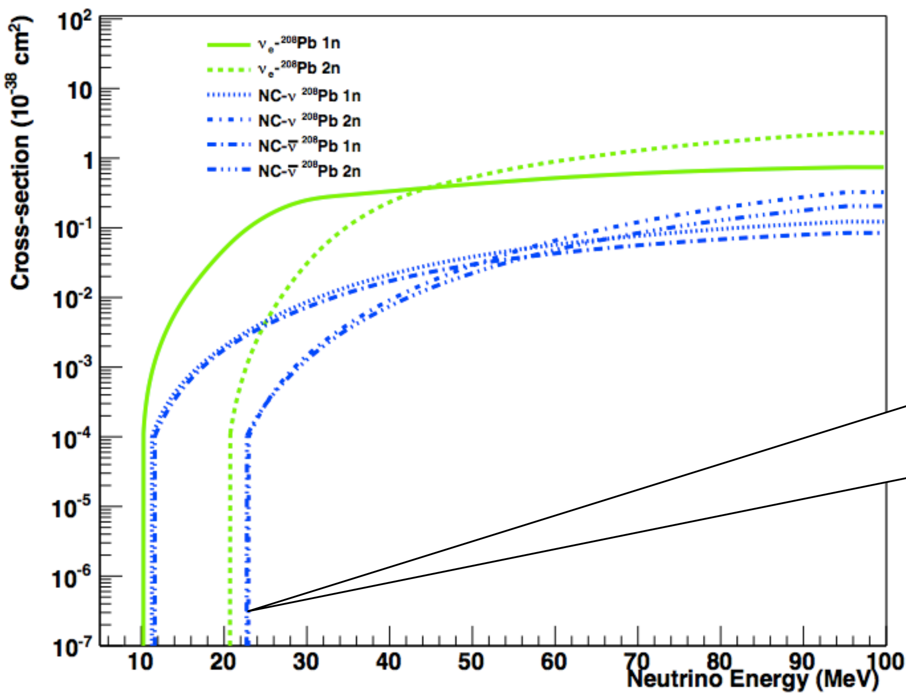
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

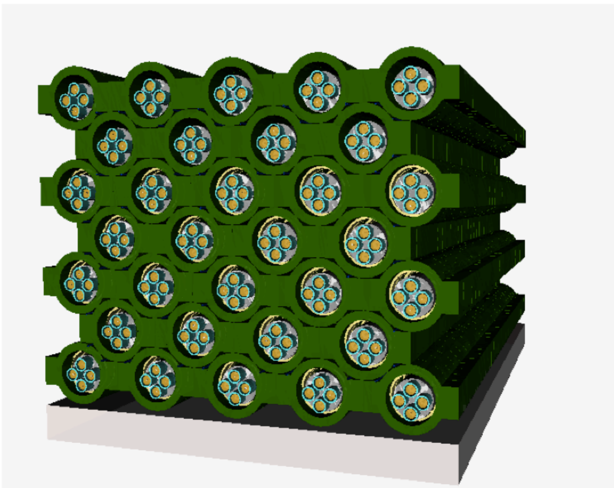
Observe single and double ~few MeV neutron events in the ^{3}He counters

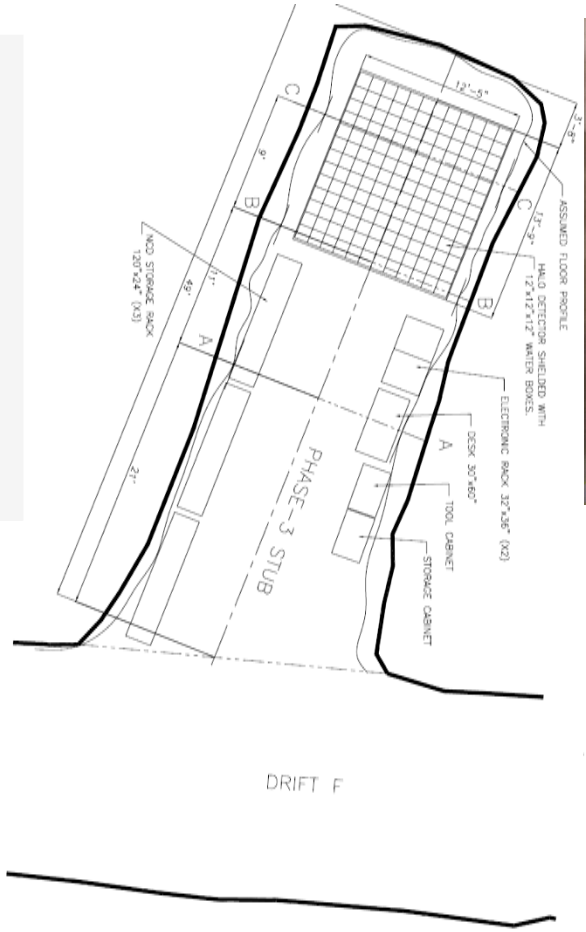


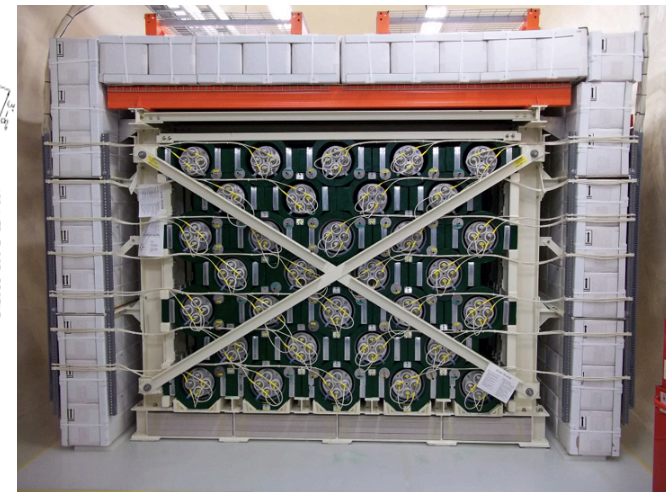
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

(similar for other lead isotopes)

HALO at SNOLAB





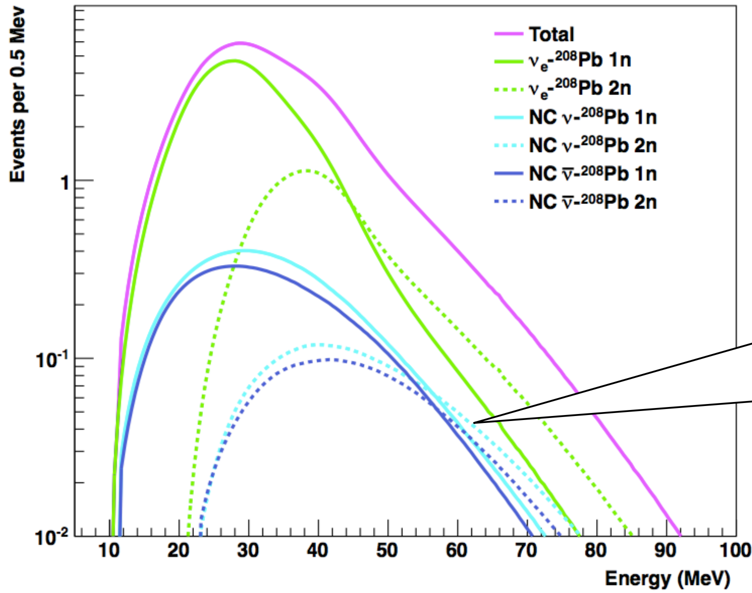


talk by Clarence Virtue tomorrow

SNO ^{3}He counters + 79 tons of Pb: ~40 events @ 10 kpc

Example of event rates for particular models

http://www.phy.duke.edu/~schol/snowglobes



2n events sample higher neutrino energies

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

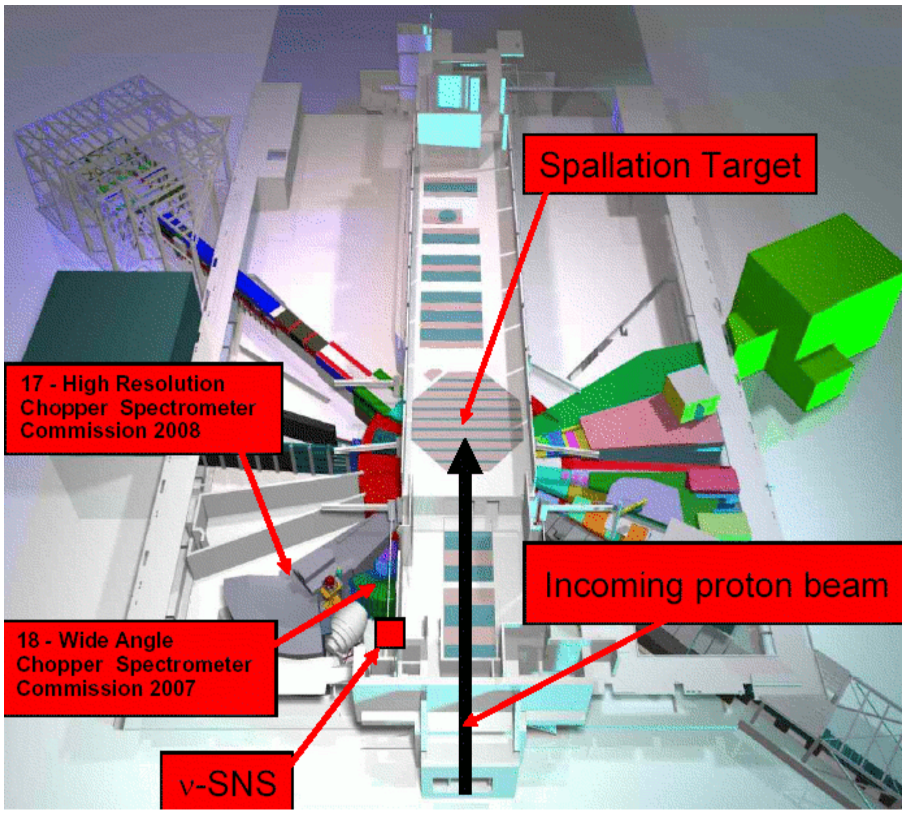
expect a few hundred events per kton @ 10 kpc

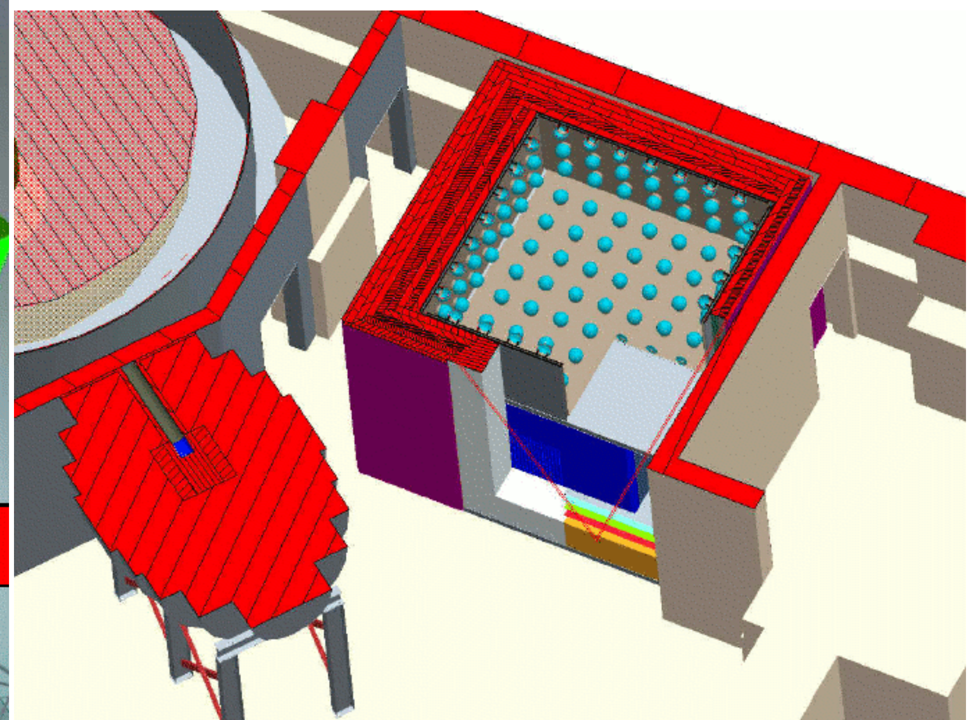
NuSNS (Neutrinos at the SNS)

Conventional ~10 ton detectors w/ few MeV thresholds:

- -liquid target + PMTs
- -strawtube gas tracker+ target sheets
- -cosmic ray veto

} changeable targets





What physics could be learned from measuring this?

KS, Phys. Rev D 73 (2006) 033005

Basically, any deviation from SM cross-section is interesting...

- Weak mixing angle
- Non Standard Interactions (NSI) of neutrinos
- Neutrino magnetic moment (hard)
- Nuclear physics

Summary of physics reach

Basically, any deviation from SM x-scn is interesting...

- Standard Model weak mixing angle:

could measure to ~5% (new channel)

- Non Standard Interactions (NSI) of neutrinos:

could significantly improve constraints

- Neutrino magnetic moment:

hard, but conceivable

- Neutron form factor:

also hard but conceivable

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105, 2009 hep-ph.0707.4191

Bottom line signal and background for CLEAR

Signal events/year: ~1100 in 456 kg of Ar >20 keVr
~450 in 391 kg of Ne >30 keVr

SNS neutronics group calculation of beam n spectrum
+ Fluka sim through shielding (T. Empl, Houston)
+ noble liquid detector sim (J. Nikkel, Yale)