

# Neutrinos at the Spallation Neutron Source



**Kate Scholberg, Duke University**  
**RCNP Workshop, March 3, 2007**

# OUTLINE

## A free neutrino source!

- The SNS at Oak Ridge National Lab
- Neutrino source properties

## Supernova-related cross-sections

- Supernova physics
- Supernova neutrino detection

## The Nu-SNS project

- Site and collaboration
- Proposed detectors

## Other possible physics topics

- Coherent NC elastic scattering
- Sterile neutrino oscillations

## Progress and Prospects

# Spallation Neutron Source at Oak Ridge National Lab, Tennessee



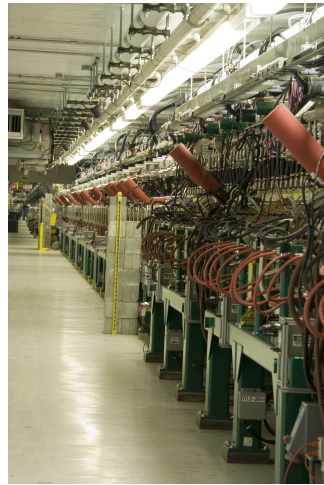


# Spallation Neutron Source



**1\$B facility for neutron science: most intense pulsed neutron beams in the world for chemistry, materials science, engineering, structural biology...**

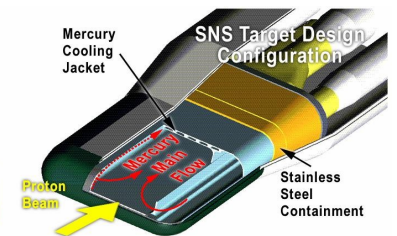
**Proton linear  
accelerator,  
initial operation  
at 1.0 GeV;  
upgrade to  
1.3 GeV planned**



**Accumulator ring,  
400 ns pulse width**



**Proton  
beam  
bombards  
liquid Hg  
target**



**$24 \mu\text{C}/\text{pulse}$  at 60 Hz  $\Rightarrow$  1.4 MW power**

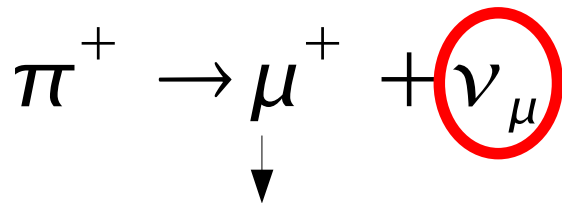
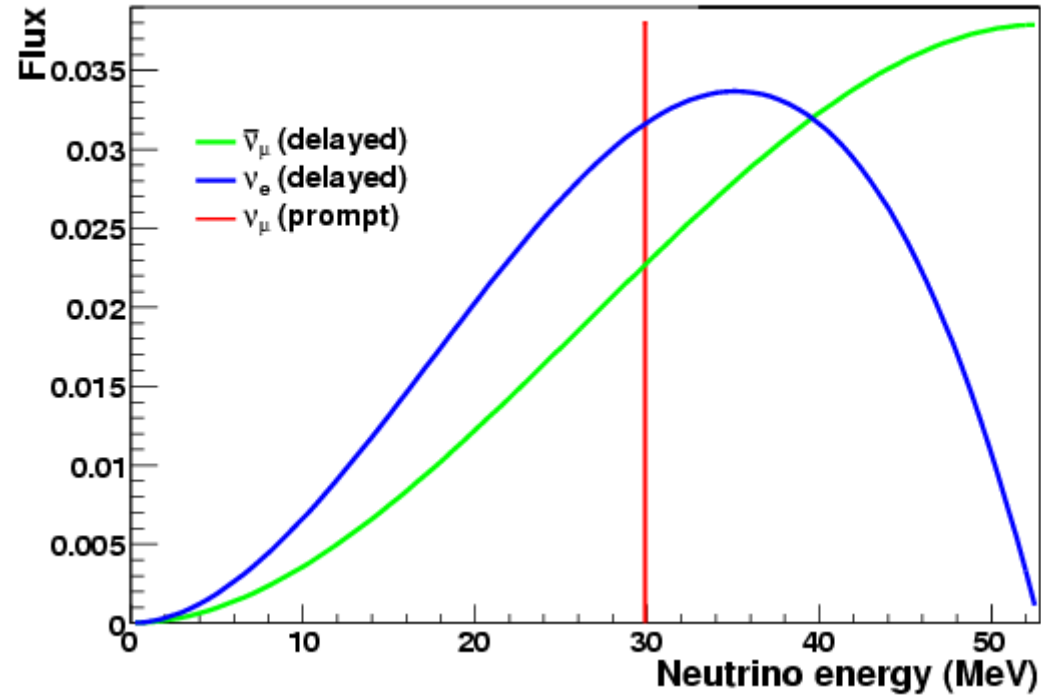
# SNS Status and Schedule

- beam construction basically complete  
(neutron instruments still under construction)
- first beam in 2006, up to 10 kW
- ramp up to 100 kW until April 2007,  
3500 hours of beam on target
- continue to ramp power beyond April 2007
- full power in 2009
- possible eventual upgrade to 2-5 MW (2012?)

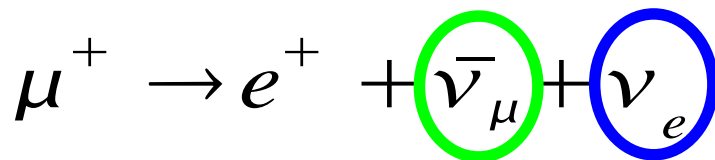
# Neutrinos are a free by-product!

~0.13 per flavor  
per proton

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



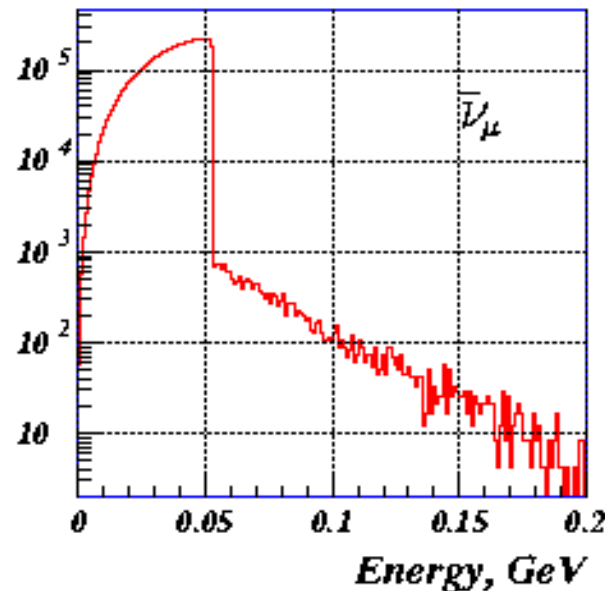
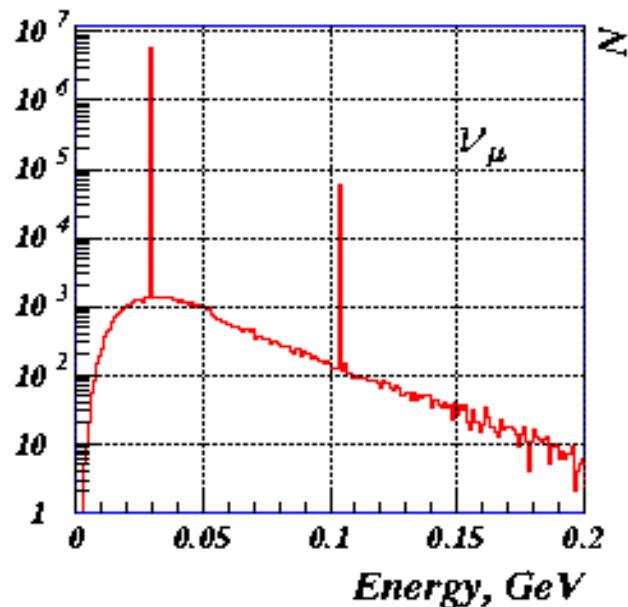
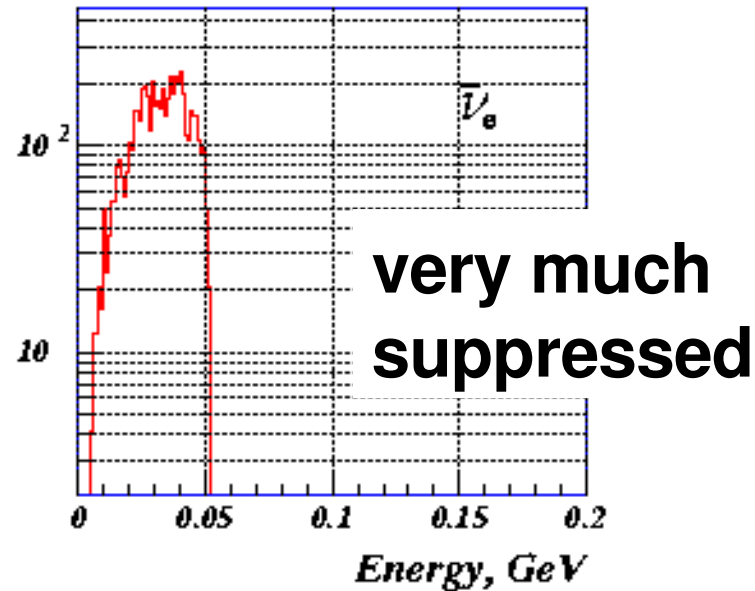
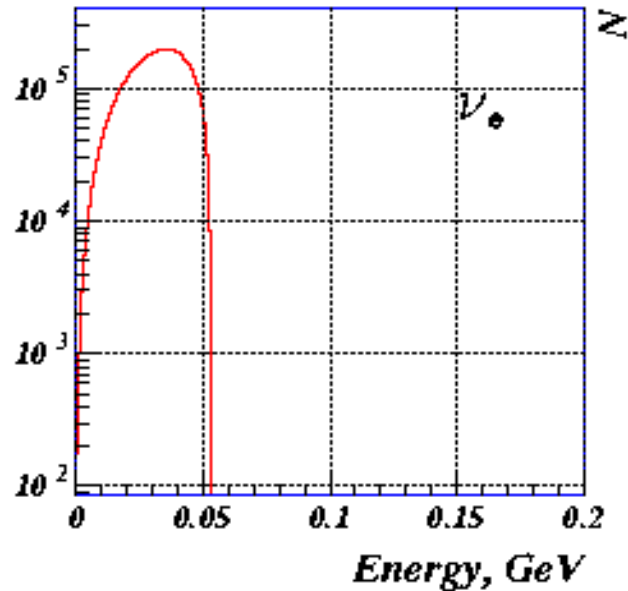
2-body decay: monochromatic 29.9 MeV  $\nu_\mu$   
**PROMPT**



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

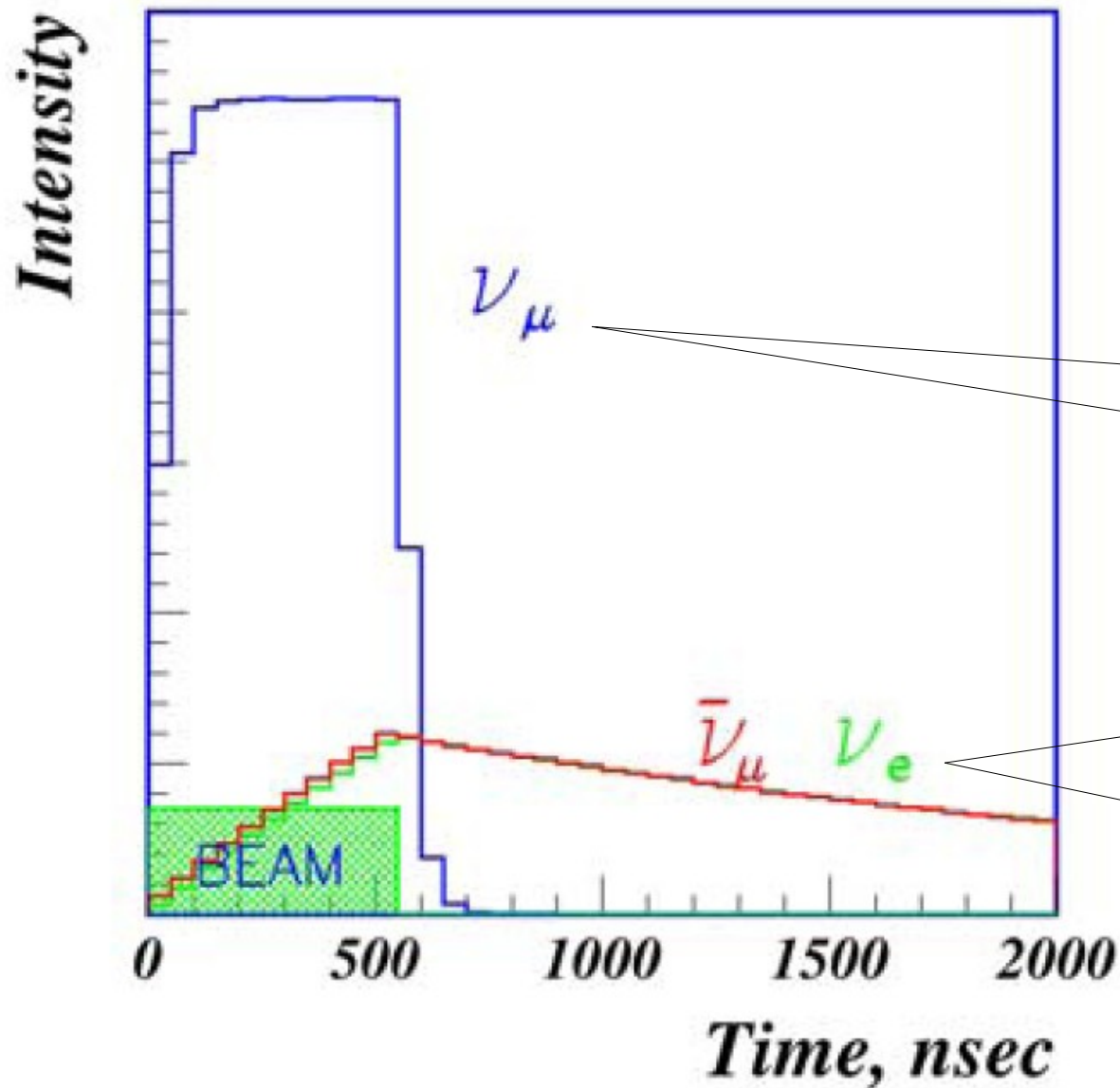
# More detailed calculation of the spectra

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



Neutrino flux: few times  $10^7$  /s/cm<sup>2</sup> at 20 m

# Time structure of the source



**60 Hz *pulsed* source**

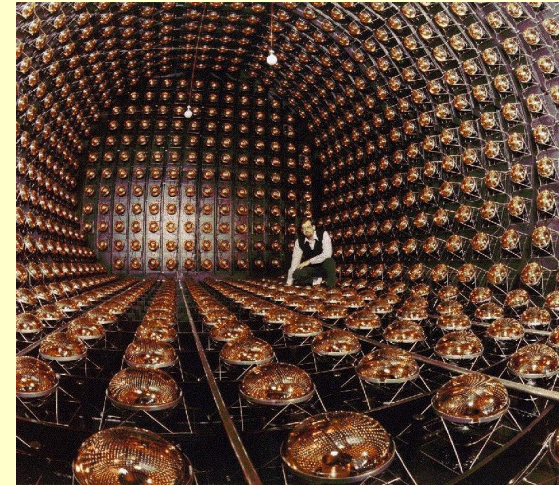
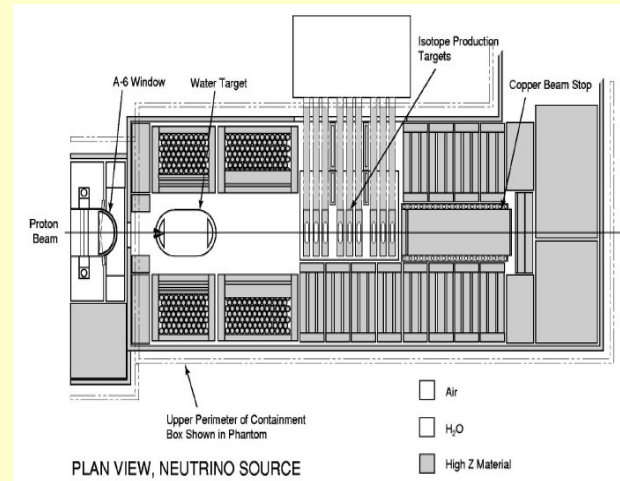
**in time  
with beam**

**delayed on  
 $\mu$  decay  
timescale  
(2.2  $\mu$ s)**

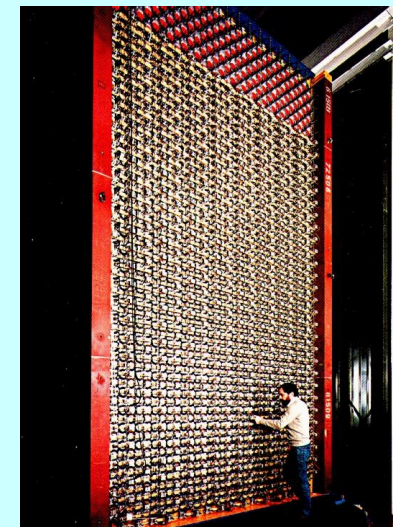
**Background rejection factor  $\sim \text{few} \times 10^{-4}$**

# Previous neutrino experiments at stopped-pion neutrino sources

## LSND at LANSCE (LANL)



## KARMEN at ISIS (RAL)

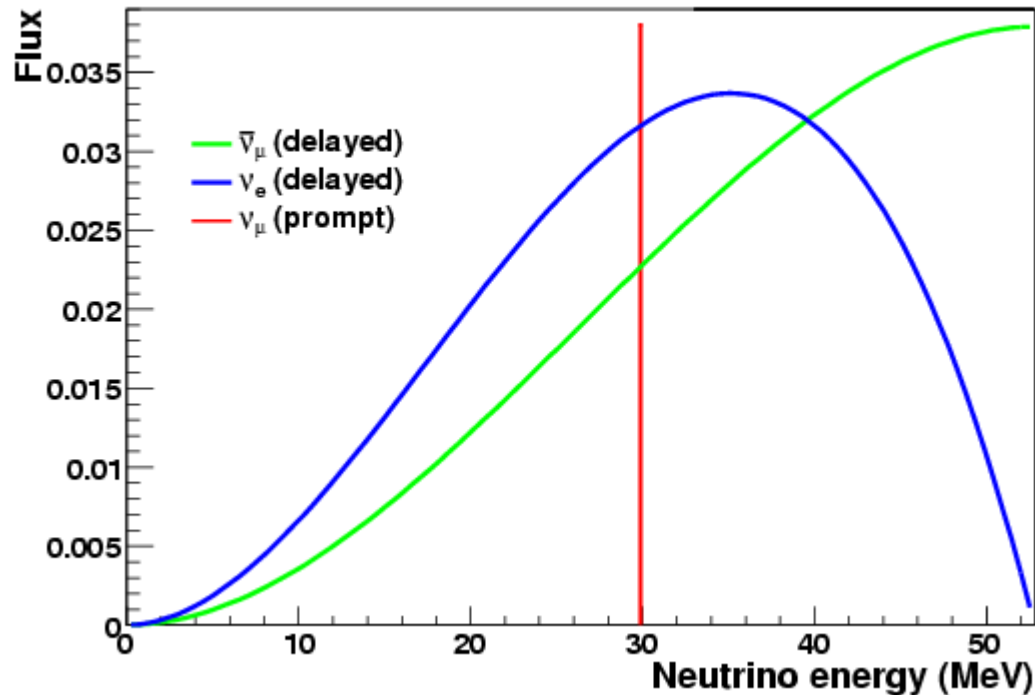


# Comparison of stopped-pion neutrino sources

|                        | <b>LANSCCE</b>              | <b>ISIS</b>                                   | <b>SNS</b>         | <b>JSNS</b>                |
|------------------------|-----------------------------|-----------------------------------------------|--------------------|----------------------------|
| <b>Location</b>        | <b>USA (LANL)</b>           | <b>UK (RAL)</b>                               | <b>US (ORNL)</b>   | <b>Japan (J-PARC)</b>      |
| <b>Proton energy</b>   | <b>0.8 GeV</b>              | <b>0.8 GeV</b>                                | <b>1 (1.3) GeV</b> | <b>3 GeV</b>               |
| <b>Beam current</b>    | <b>70 <math>\mu</math>A</b> | <b>0.2 mA</b>                                 | <b>1.1 mA</b>      | <b>0.33 mA</b>             |
| <b>Time structure</b>  | <b>Continuous</b>           | <b>Two 200 ns bunches separated by 300 ns</b> | <b>380 ns FWHM</b> | <b>1 <math>\mu</math>s</b> |
| <b>Repetition rate</b> | <b>N/A</b>                  | <b>50 Hz</b>                                  | <b>60 Hz</b>       | <b>25 Hz</b>               |
| <b>Power</b>           | <b>56 kW</b>                | <b>160 kW</b>                                 | <b>&gt;1 MW</b>    | <b>1 MW</b>                |
| <b>Target</b>          | <b>Various</b>              | <b>Water-cooled tantalum</b>                  | <b>Mercury</b>     | <b>Mercury</b>             |

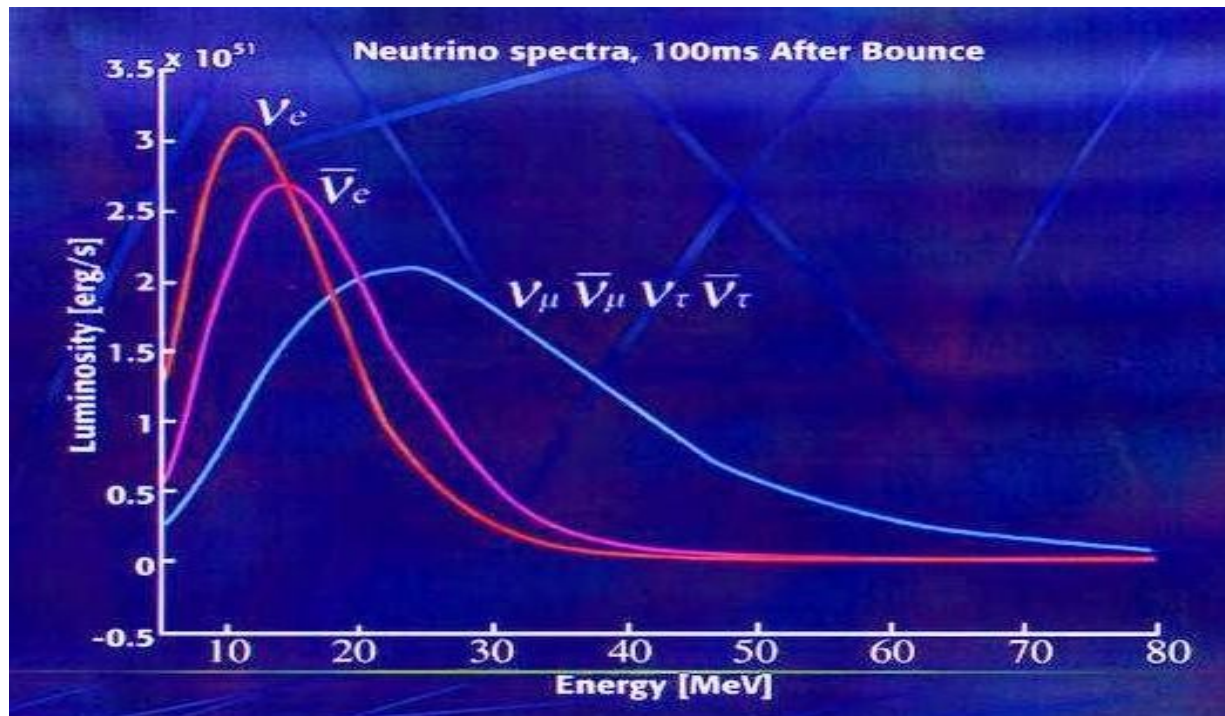
- very high intensity  $\nu$ 's
- ~below K threshold
- very little DIF
- narrow pulses

# What physics can we do with this intense, pulsed source of tens of MeV $\nu$ 's?



- supernova-related cross-section studies
- coherent NC scattering
- neutrino oscillation

# Supernova neutrino spectrum overlaps very nicely with stopped $\pi$ neutrino spectrum!



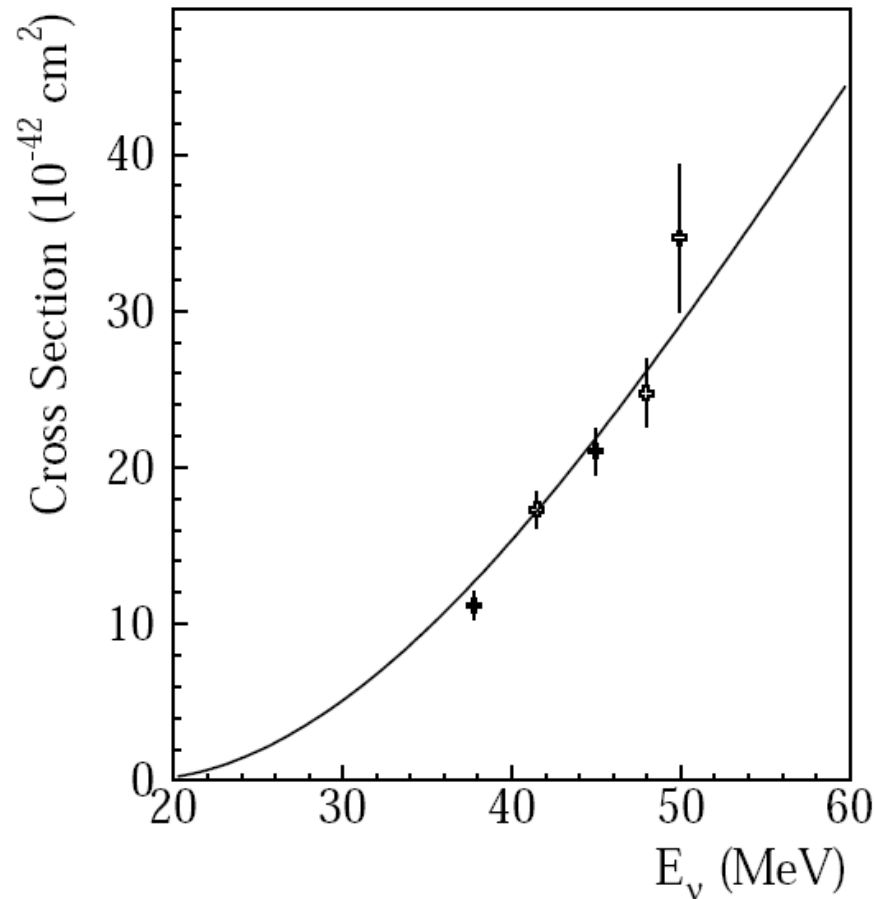
Study  
CC and NC  
interactions  
with various  
nuclei,  
in few to 10's  
of MeV range

1. Understanding of *core-collapse SN processes*,  
nucleosynthesis
2. Understanding of *SN  $\nu$  detection* processes

So far only  $^{12}\text{C}$  is the only heavy nucleus with  $\nu$  interaction cross-sections measured in the few tens of MeV regime!

e.g. **LSND**

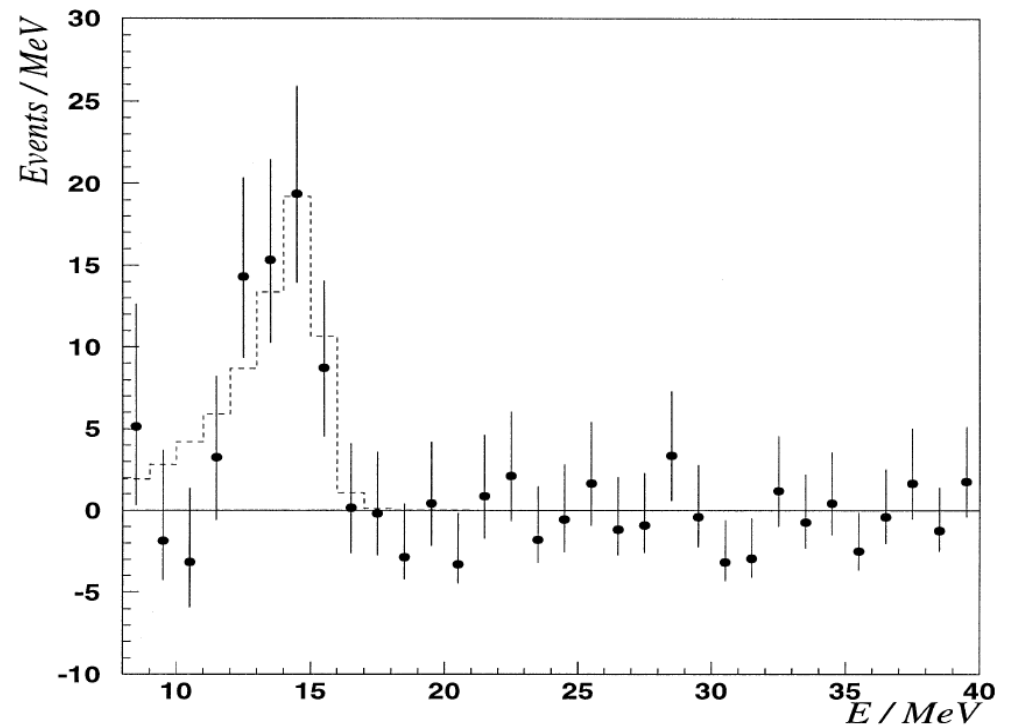
Phys. Rev. C 66 (2002) 015501



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

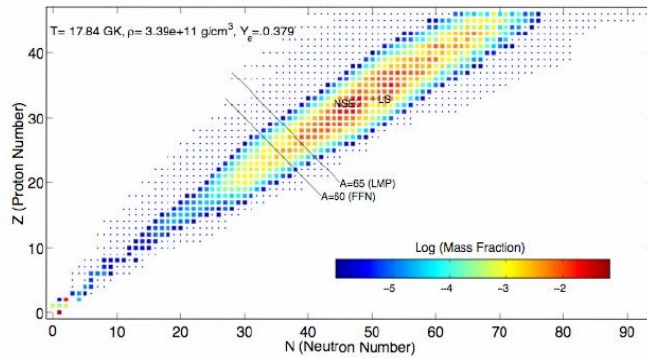
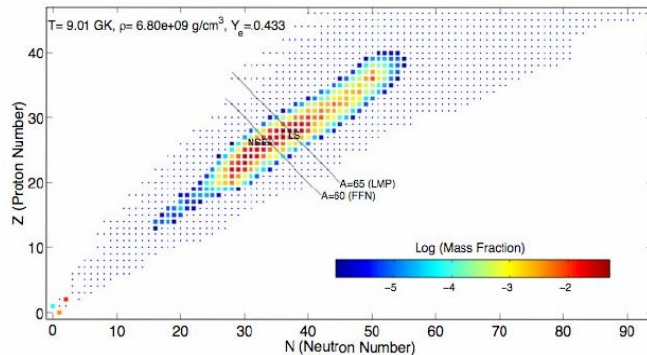
**Karmen**

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



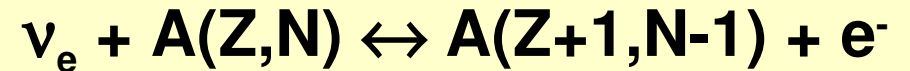
$^{12}\text{C}(\nu_\mu \nu'_\mu)^{12}\text{C}^*(1^+, 1; 15.1 \text{ MeV})$

# Core collapse dynamics



Liebendorfer *et al.*, 2001

Understanding of electron capture is vital for understanding the core collapse mechanism

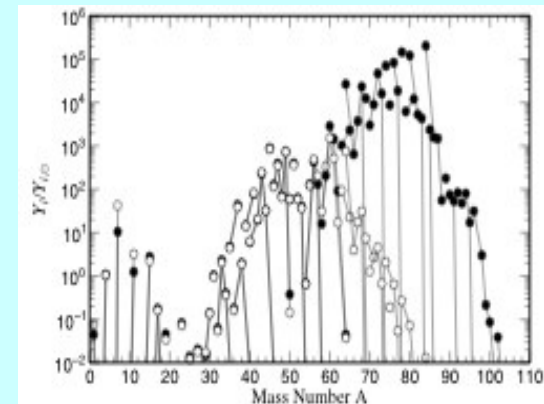


$\nu_e$  cross-sections on nuclei  
up to  $A \sim 100$  needed

Neutrino opacities are also important:  
help to understand prompt vs delayed  
explosion mechanism

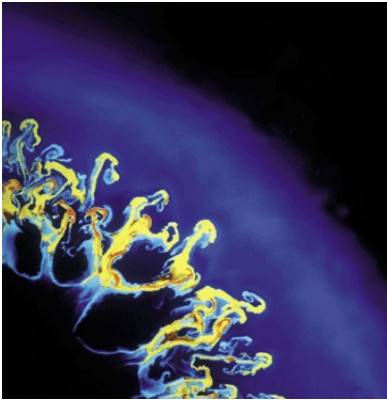
## Supernova nucleosynthesis

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

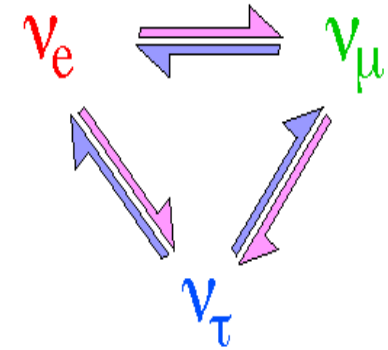


Fröhlich *et al.*, *Astrophys. J.* 637 (2006) 415-426

# Supernova neutrino detection



Learn about core collapse  
and neutrino properties  
from flavor, energy, time  
structure of the burst



Require NC sensitivity for  $\nu_{\mu,\tau}$ , since SN  $\nu$   
energies below CC threshold

Sensitivity to different flavors  
*and ability to tag interactions is key!*

$\nu_e$  VS  $\bar{\nu}_e$  VS  $\nu_x$

# Supernova neutrino detection channels

Inverse beta decay:  $\bar{\nu}_e + p \rightarrow e^+ + n$

- dominates for detectors with lots of free p (water, scint)
- $\bar{\nu}_e$  sensitivity; good E resolution; well known x-scns; some tagging, poor pointing



Elastic scattering: few % of inv $\beta$ dk, but point!



CC interactions w/ nuclei:

- lower rates, but still useful,  $\nu_e$  tagging useful
- x-scns not well known

$$\nu_e + (N, Z) \rightarrow (N-1, Z+1) + e^-$$

$$\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$$

?

NC interactions w/ nuclei:

- very important for physics, probes  $\mu$  and  $\tau$  flux
- some rate in existing detectors; new ones proposed
- x-scns not well known

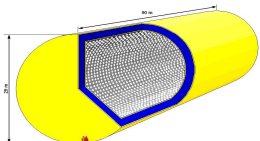
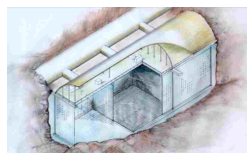
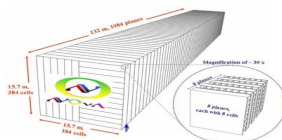
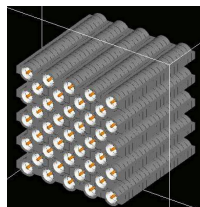
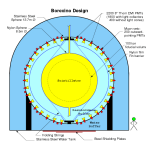
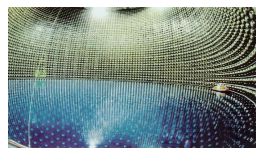
$$\nu_x + (A, Z) \rightarrow (A-1, Z) + n + \nu_x$$

$$\nu_x + (A, Z) \rightarrow (A, Z)^* + \nu_x$$

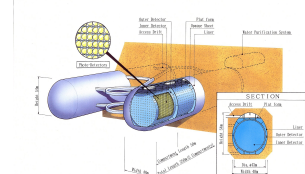
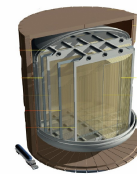
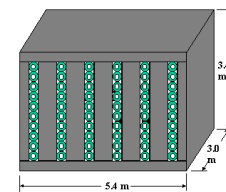
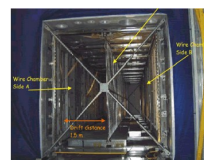
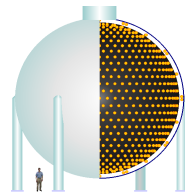
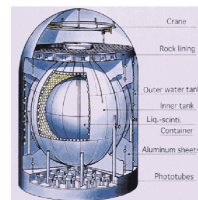
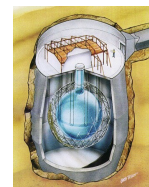
$\searrow$   $(A, Z) + \gamma$

?

# Supernova neutrino detectors, current & future



| <i>Detector</i>    | <i>Type</i>       | <i>Mass (kton)</i>                           | <i>Location</i> | <i>Events at 8.5 kpc</i> | <i>Status</i>                |
|--------------------|-------------------|----------------------------------------------|-----------------|--------------------------|------------------------------|
| Super-K            | Water             | 32                                           | Japan           | 7000                     | Running as SK III            |
| SNO                | Heavy water       | 1(D <sub>2</sub> O)<br>1.4(H <sub>2</sub> O) | Canada          | 400<br>450               | Running until<br>end of 2006 |
| LVD                | Scintillator      | 1                                            | Italy           | 200                      | Running                      |
| KamLAND            | Scintillator      | 1                                            | Japan           | 300                      | Running                      |
| Borexino           | Scintillator      | 0.3                                          | Italy           | 100                      | 200x                         |
| Baksan             | Scintillator      | 0.33                                         | Russia          | 50                       | Running                      |
| Mini-BooNE         | Scintillator      | 0.7                                          | USA             | 200                      | Running                      |
| AMANDA/<br>IceCube | Long string       | 0.4/PMT                                      | Antarctica      | N/A                      | Running                      |
| Icarus             | LAr               | 2.4                                          | Italy           | 200                      | 200x                         |
| CLEAN              | Ne, Ar            | 0.01                                         | Canada, USA?    | 30                       | proposed                     |
| HALO               | Pb                | 0.1                                          | Canada          | 40                       | proposed                     |
| SNO+               | Scintillator      | 1                                            | Canada          | 300                      | proposed                     |
| MOON               | <sup>100</sup> Mo | 0.03                                         | ?               | 20                       | proposed                     |
| NOVA               | Scintillator      | 20                                           | USA             | 4000                     | proposed                     |
| OMNIS              | Pb                | 2-3                                          | USA?            | >1000                    | proposed                     |
| LANND              | LAr               | 70                                           | USA?            | 6000                     | proposed                     |
| MEMPHYS            | Water             | 440                                          | Europe          | >100,000                 | proposed                     |
| UNO                | Water             | 500                                          | USA             | >100,000                 | proposed                     |
| Hyper-K            | Water             | 500                                          | Japan           | >100,000                 | proposed                     |
| LENA               | Scintillator      | 60                                           | Europe          | 18,000                   | proposed                     |
| HSD                | Scintillator      | 100                                          | USA             | 30,000                   | proposed                     |



**Most urgently needed supernova neutrino  
CC and NC cross-section measurements:  
(total and differential)**

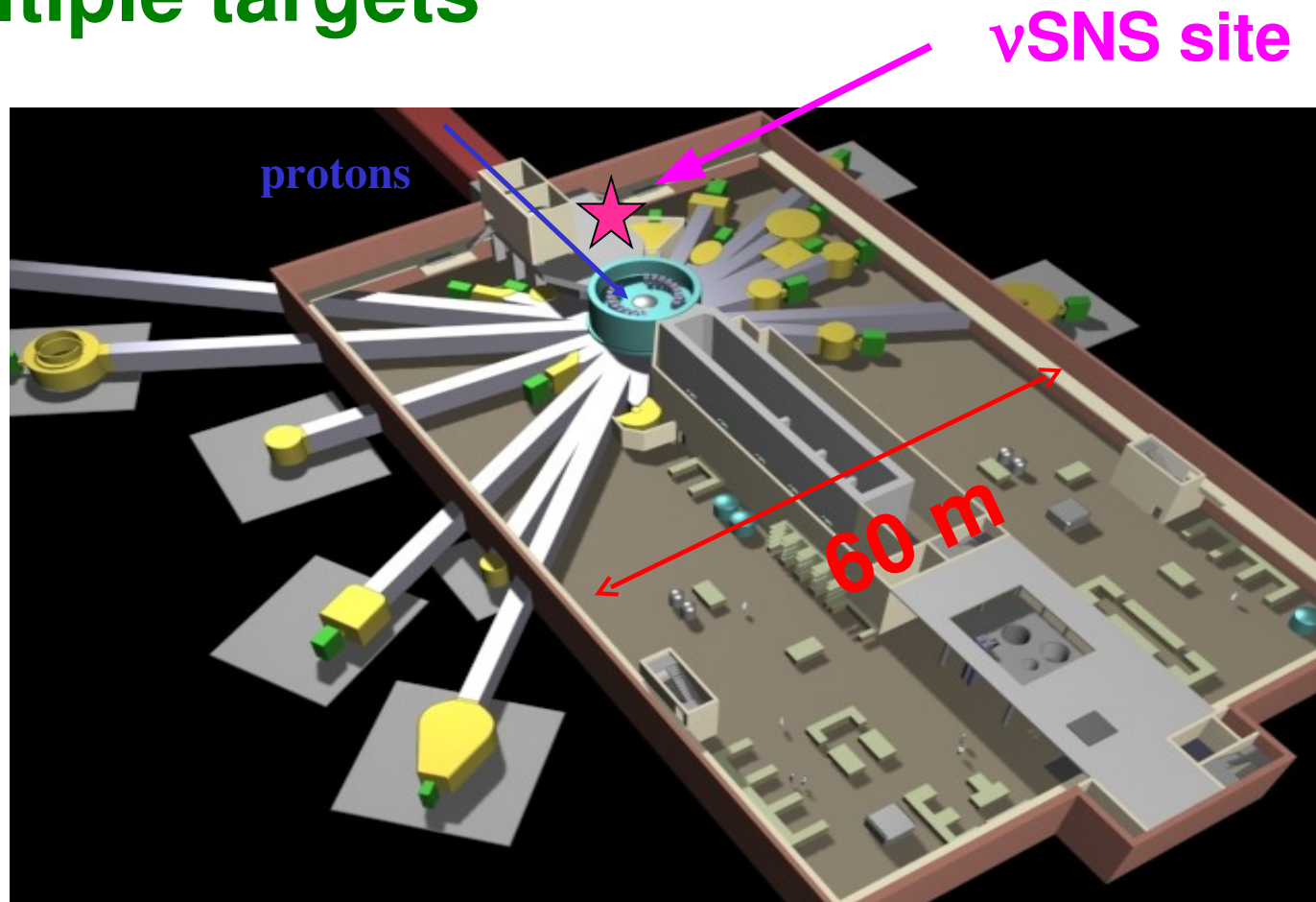
**oxygen, argon, lead,  
iron, (carbon), deuterium**

So, how can we address these needs?

## NuSNS (Neutrinos at the SNS)



A neutrino facility with capability to measure multiple targets



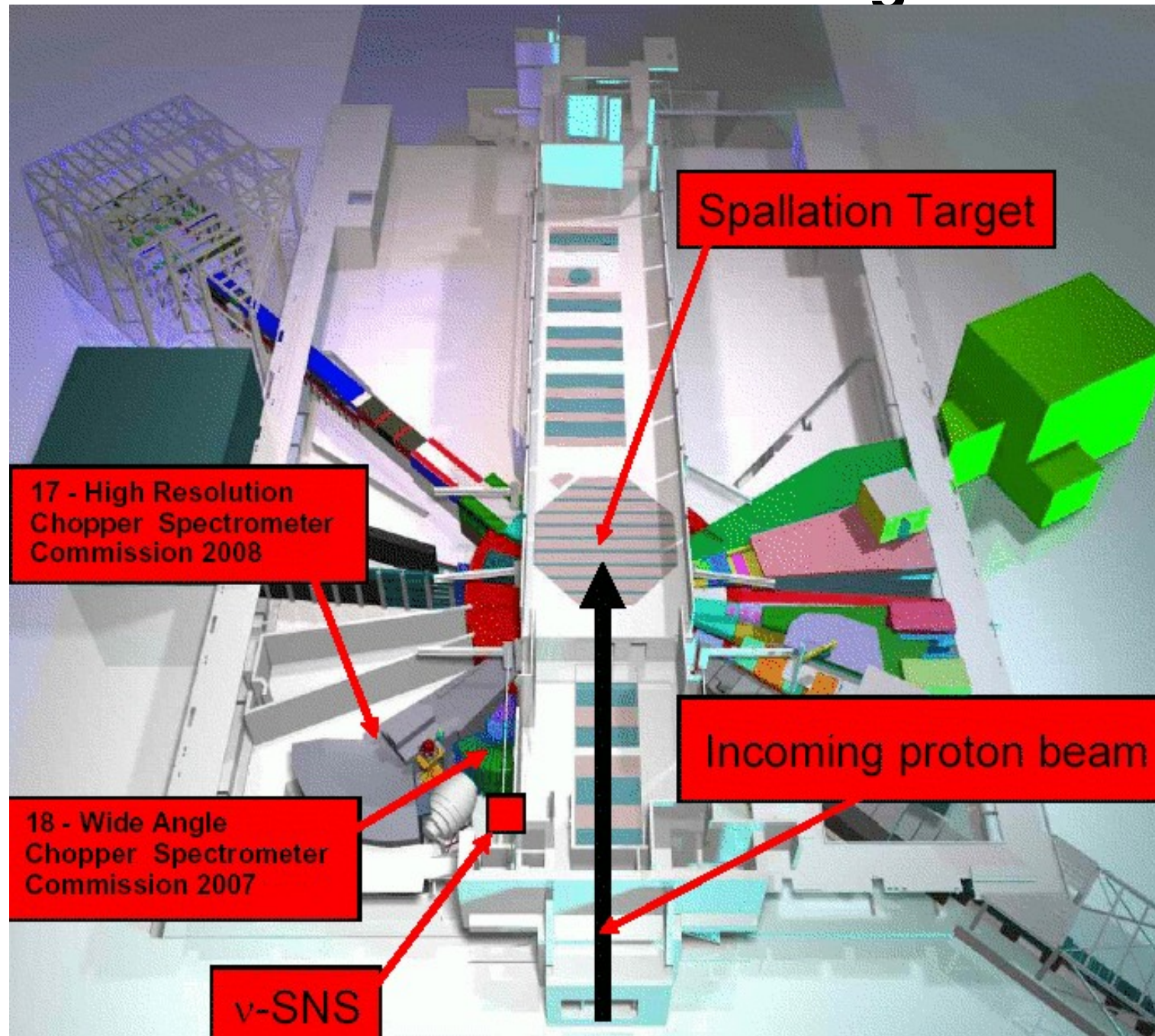
# NuSNS collaboration: 20 US institutions



| <i>System</i>        | <i>Lead</i>                     |
|----------------------|---------------------------------|
| Project manager      | Efremenko (Tenn)                |
| Bunker               | Cianciolo (ORNL)                |
| Segmented Detector   | Hungerford (Houston)            |
| Homogeneous Detector | Stancu (Alabama)                |
| $\nu$ A Scattering   | Scholberg (Duke)                |
| Veto                 | Greife (Mines)                  |
| SNS & Backgrounds    | Blackmon (ORNL)                 |
| Theory               | McLaughlin (NCSU)<br>Hix (ORNL) |

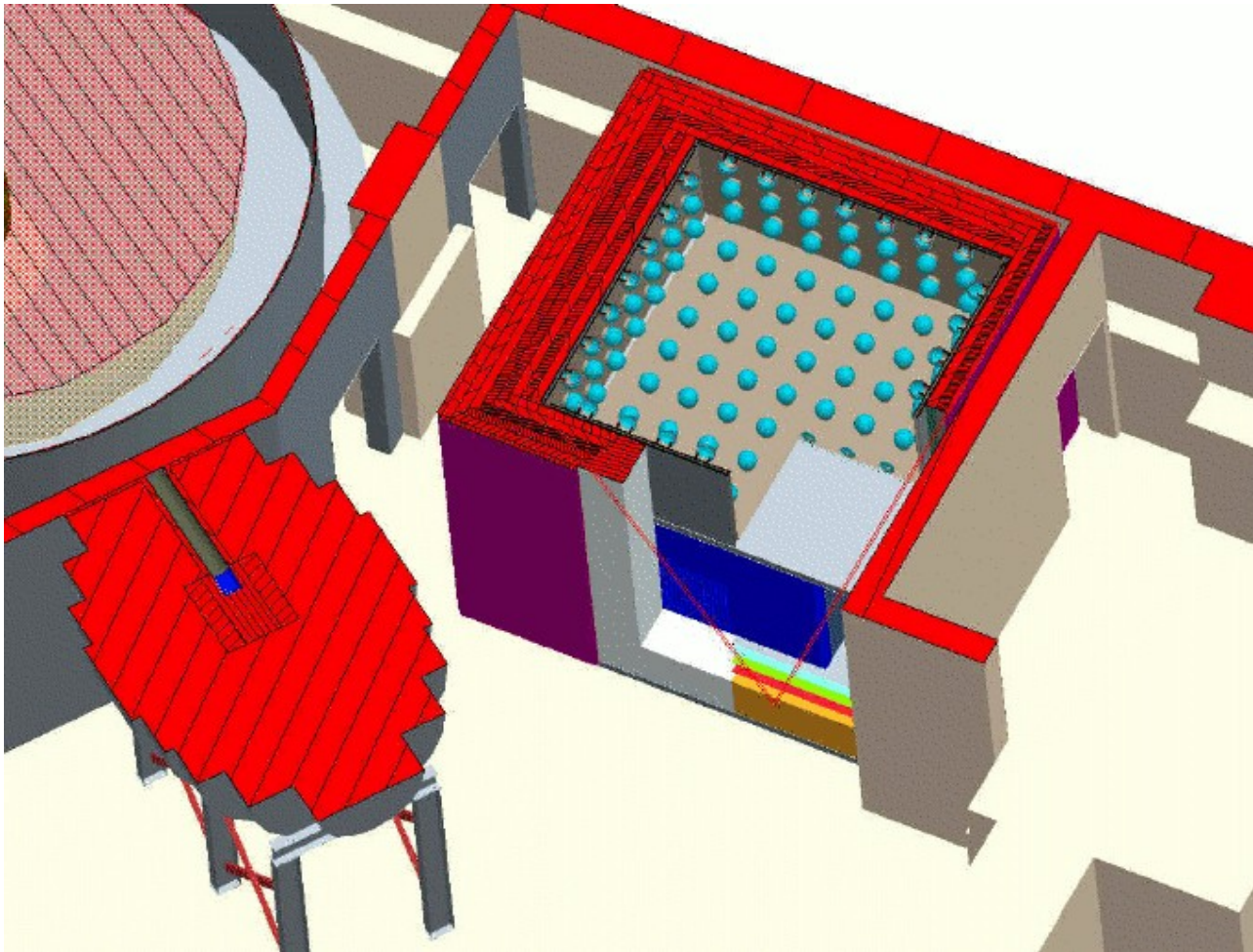
<http://www.phy.ornl.gov/nusns>

# Spot identified 20 m from the target



## Conventional ~10 ton detectors w/ few MeV thresholds:

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



Concrete  
+ steel  
bunker,  
1 m ceiling,  
0.5 m walls;  
inner  
4.5x4.5x6.5 m<sup>3</sup>  
volume

Aims to be 'user facility'

# The Homogeneous Detector: liquid targets

3.5m x 3.5m x 3.5m

steel vessel

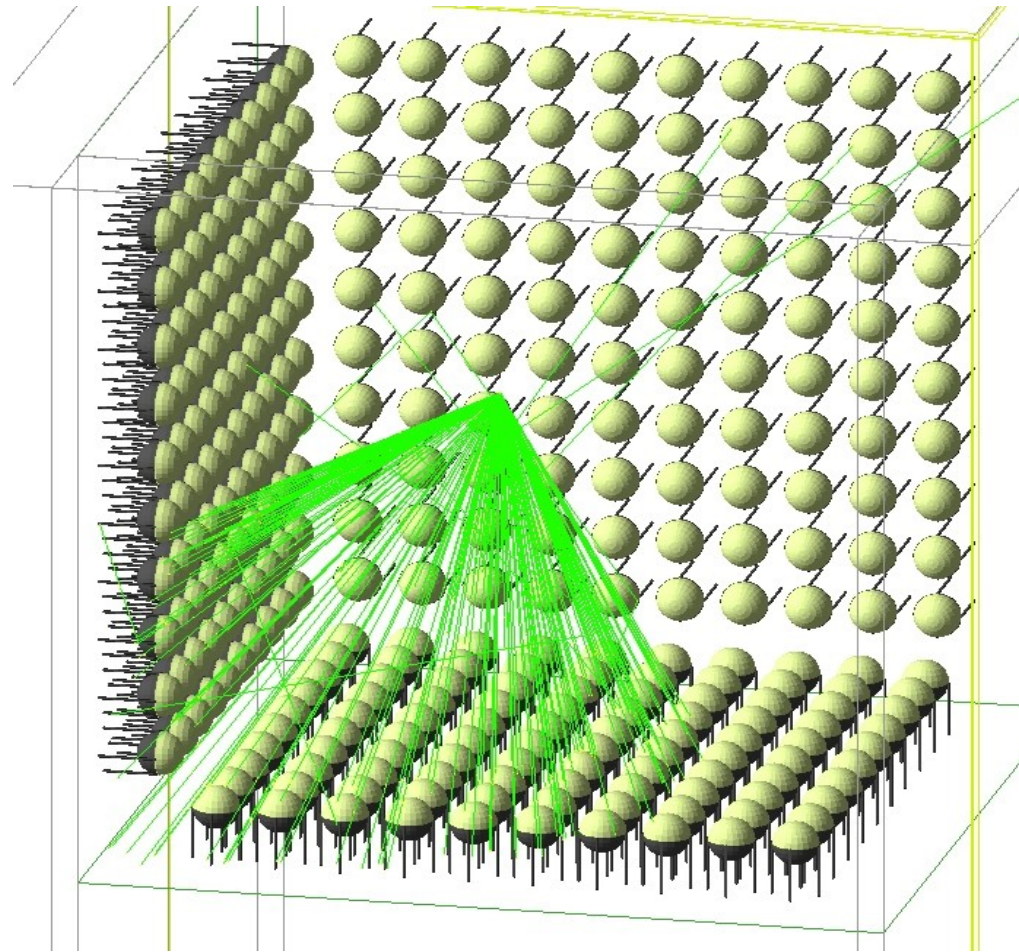
(43 m<sup>3</sup>, 15.5 m<sup>3</sup>

fiducial volume)

600 8" PMTs

(41% coverage)

Well known  
technology!



## Potential targets

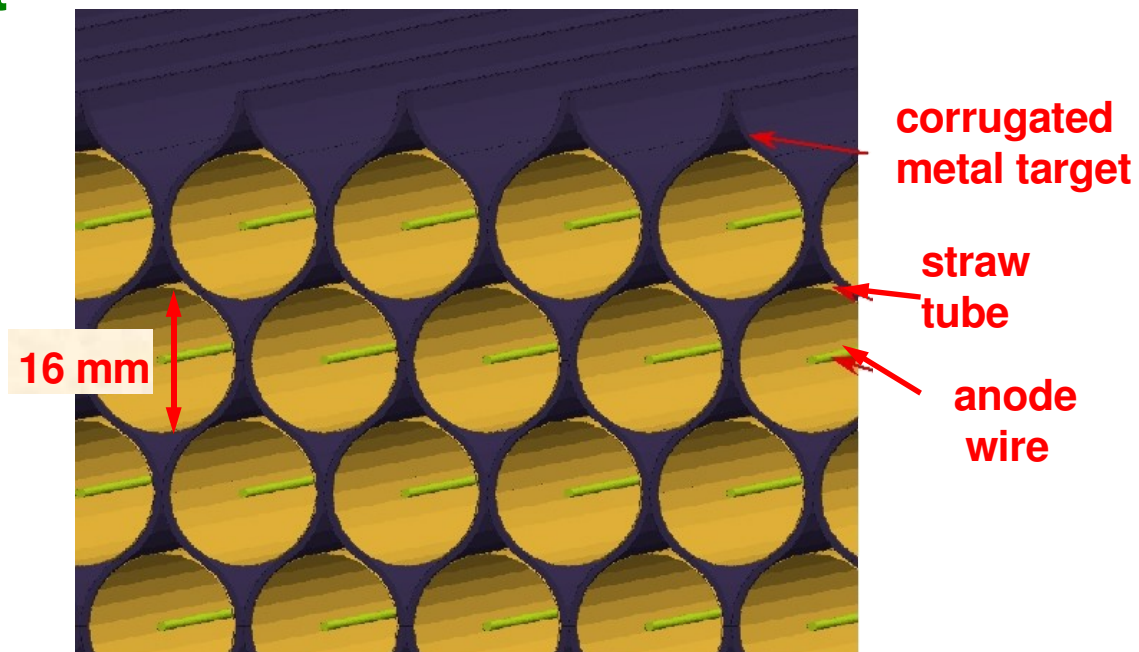
- 1300 events/yr  $\nu_e + {}^{12}\text{C} \rightarrow {}^{12}\text{N} + e^-$  (mineral oil)
- 450 events/yr  $\nu_e + {}^{16}\text{O} \rightarrow {}^{16}\text{F} + e^-$  (water)
- 1000 events/yr  $\nu_x + {}^2\text{H} \rightarrow p + n + \nu_x$  (heavy water)

# The Segmented Detector: metallic targets

Thin corrugated metal sheet  
(e.g. 0.75 mm-thick iron)

Total mass ~14 tons,  
10 tons fiducial

Detector:  $1.4 \times 10^4$  gas  
proportional counters  
(straw tube),  
3m long x 16mm diameter

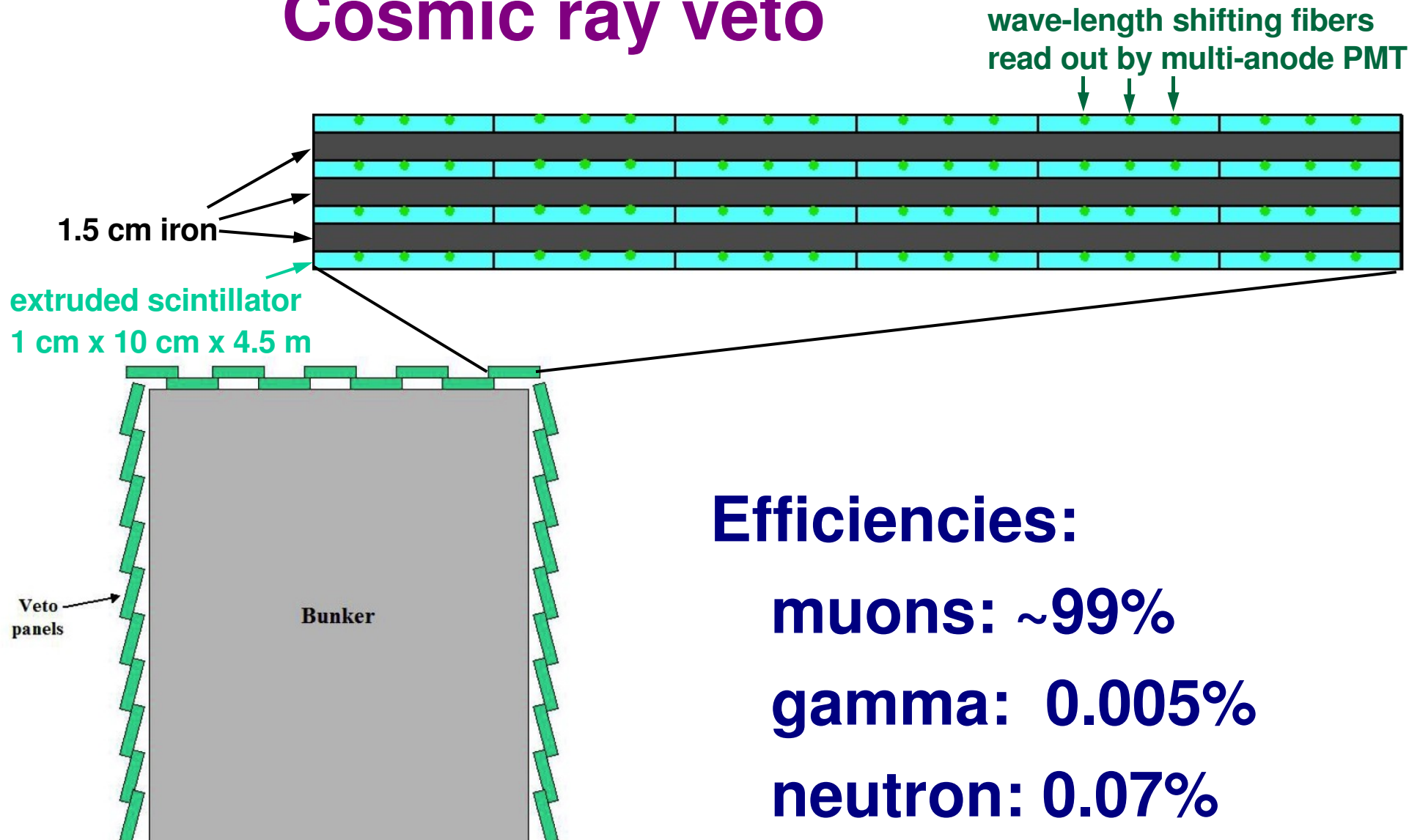


- 3D position by Cell ID & charge division
- PID and energy by track reconstruction

## Potential targets

- |                  |                                                 |
|------------------|-------------------------------------------------|
| • 1100 events/yr | $\nu_e + \text{Fe} \rightarrow \text{Co} + e^-$ |
| • 1100 events/yr | $\nu_e + \text{Al} \rightarrow \text{Si} + e^-$ |
| • 4900 events/yr | $\nu_e + \text{Pb} \rightarrow \text{Bi} + e^-$ |

# Cosmic ray veto



## Efficiencies:

**muons: ~99%**

**gamma: 0.005%**

**neutron: 0.07%**

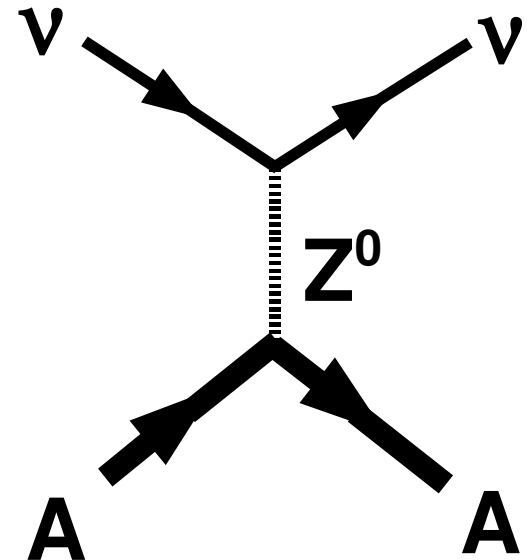
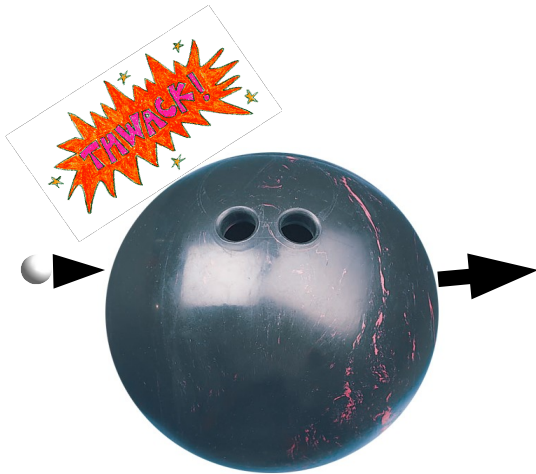
**Geant4 simulation & prototype  
studies underway for all subdetectors**

Another physics topic requiring a different detector technology:

## Coherent neutral current neutrino-nucleus elastic scattering

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a  $Z$ , and the nucleus recoils



- Neutral current, so flavor-blind
- Coherent up to  $E_\nu \sim 50$  MeV
- Important in SN processes & detection

# This process has a cross-section easily calculable in the Standard Model:

A. Drukier & L. Stodolsky, PRD 30, 2295 (1984)

Horowitz et al. astro-ph/0302071

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

And the cross-section is *large*!

~100 times inverse  $\beta$  dk in few-50 MeV range

keV<sup>-1</sup> s<sup>-1</sup>

0.00001

8 × 10<sup>-6</sup>

6 × 10<sup>-6</sup>

4 × 10<sup>-6</sup>

2 × 10<sup>-6</sup>

0.01

0.02

0.03

0.04

MeV

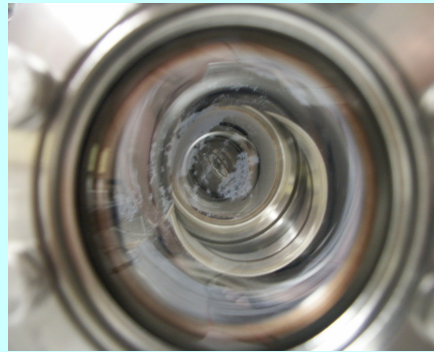
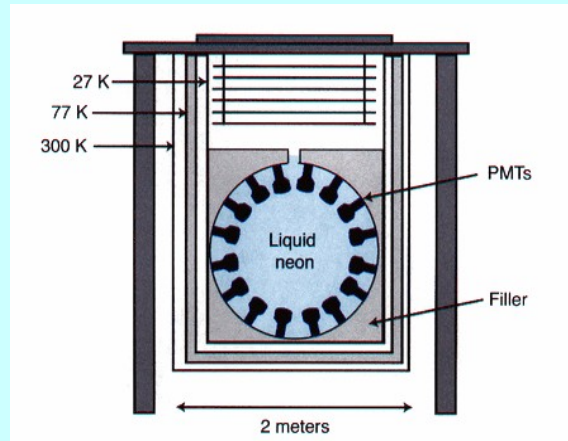
Nuclear recoil energy  
spectrum for 30 MeV  $\nu$

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

*Never before  
observed:  
huge rates  
but recoil  
energies  
are tiny!*

# Detector technologies that might work: (WIMPs)

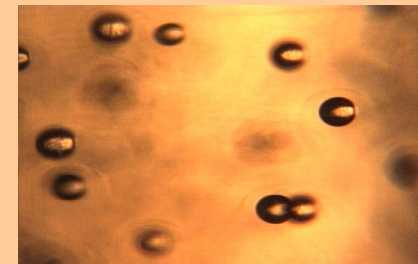
## Noble gas/liquid, single or dual-phase (Ne, Ar, Xe)



## Germanium

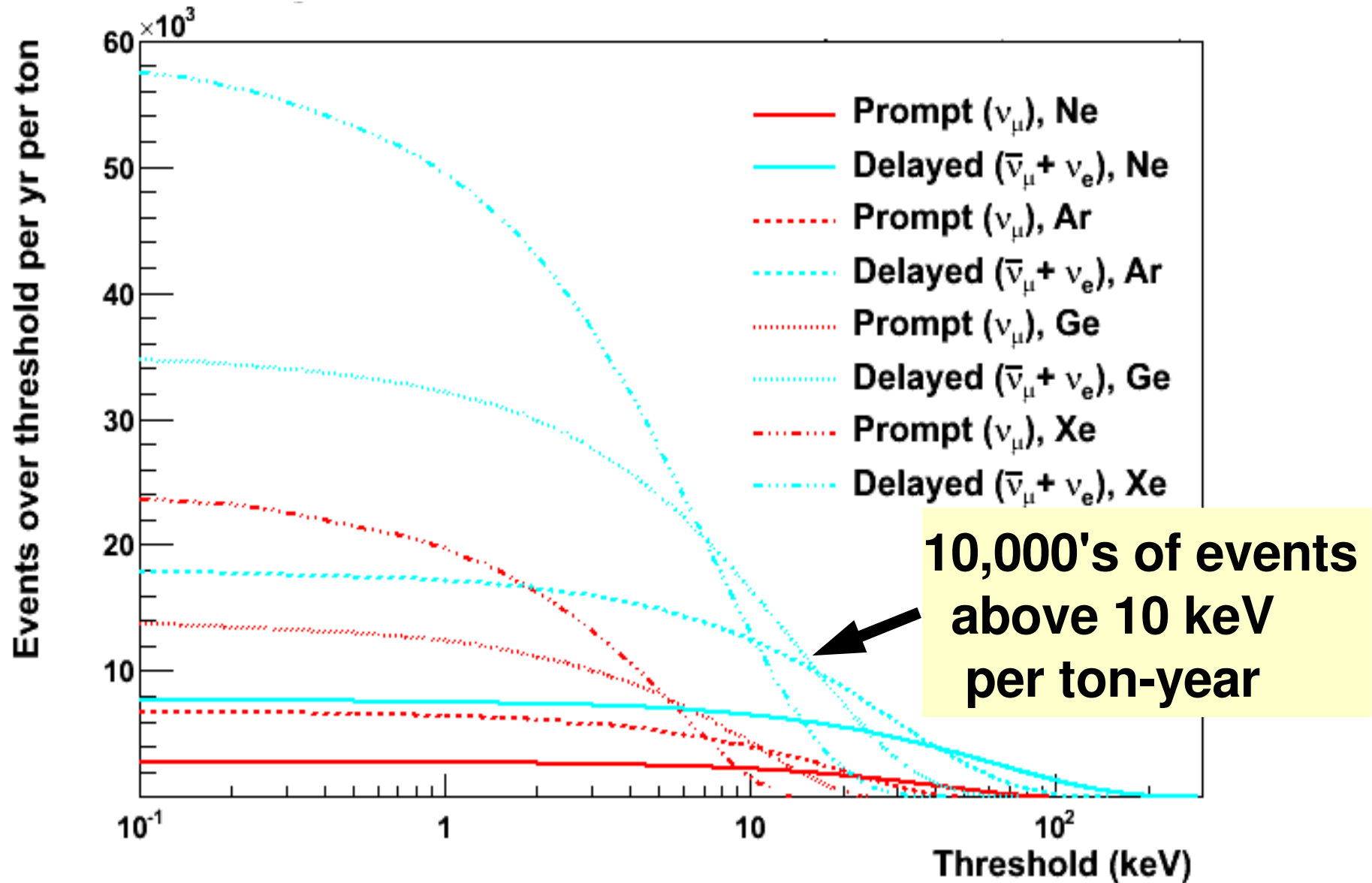


## Warm liquid/bubble



- 10 keV threshold achievable, good recoil selection
- large target masses may be possible
- bg requirements less stringent than for WIMPs

# Integrated yield for various targets vs threshold



Lighter nucleus  $\Rightarrow$  expect fewer interactions, but more at higher energy

So, the 'sanitized' rates look good...  
even with a few kg scale detector,  
one might make the first detection

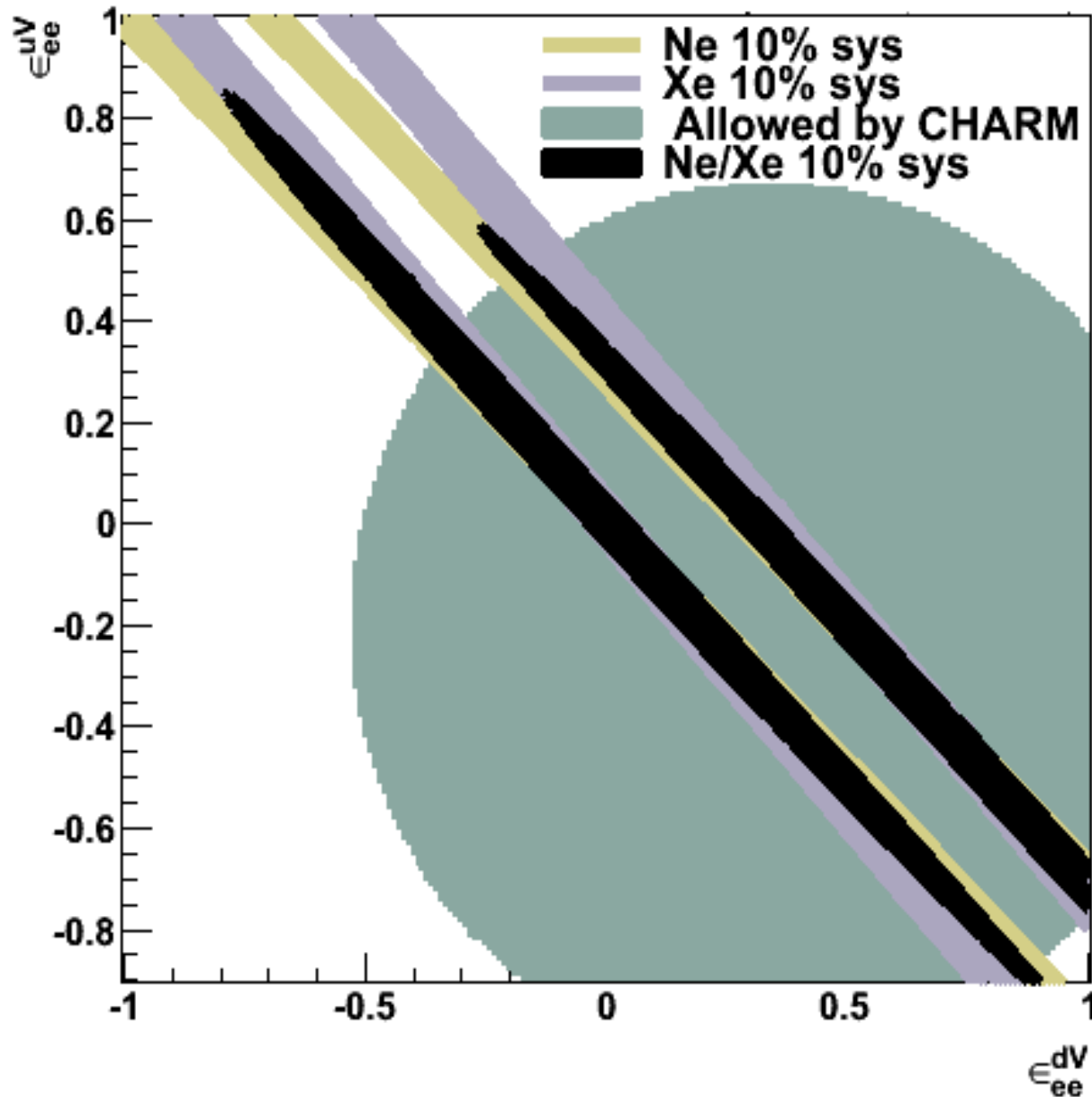
## What physics could be learned?

K. Scholberg, Phys. Rev D 73 (2006) 033005

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

- **Weak mixing angle:**  
could measure to  $\sim 5\%$
- **Non Standard Interactions (NSI) of neutrinos:**  
could significantly improve constraints
- **Neutrino magnetic moment:**  
hard, but maybe doable

# Example: sensitivity to NSI parameters

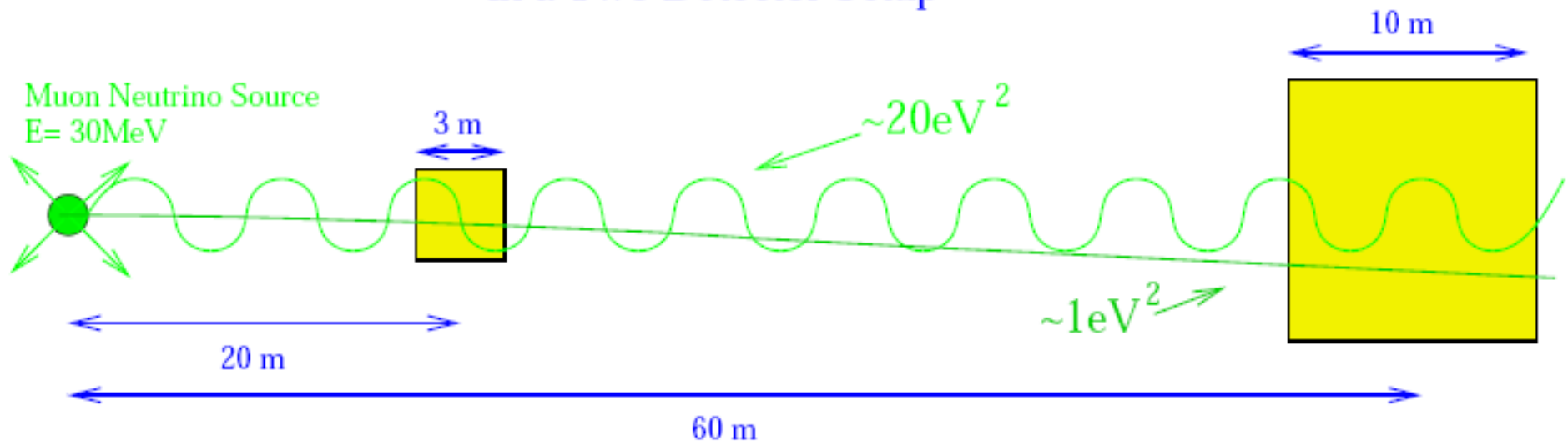


With  $\sim 100$  kg-yr,  
can significantly  
improve  
constraints on  
 $\epsilon_{ee}$  and  $\epsilon_{e\tau}$   
NSI parameters

# Final physics possibility: **Osc-SNS**

If mini-BooNE confirms LSND, can search for oscillations to sterile neutrinos using a second detector, by comparing NC events at near and far detectors

Neutral Current Disappearance Pattern  
in a Two Detector Setup



G. Garvey *et al.*, Phys. Rev D 72 (2005) 092001

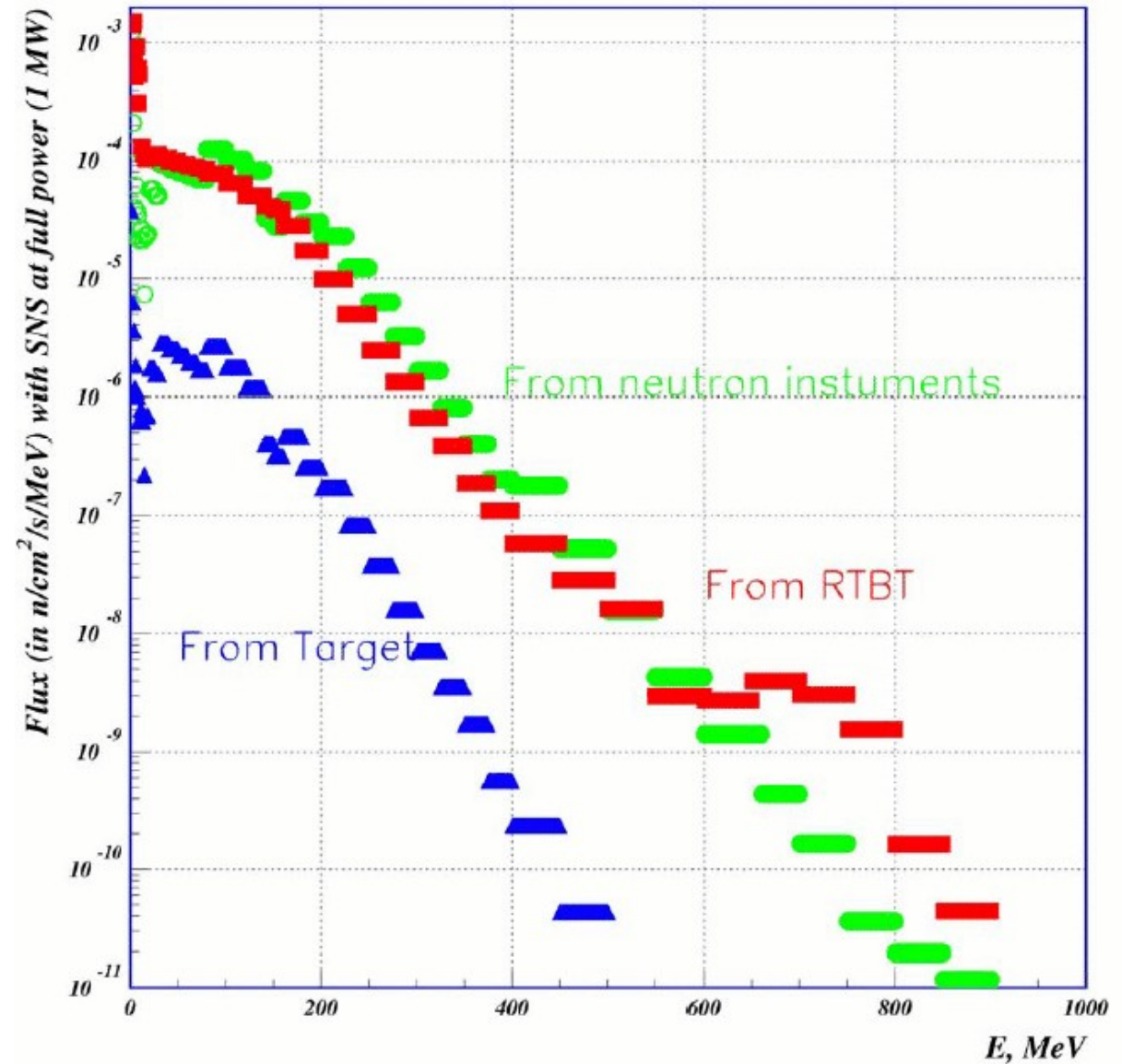
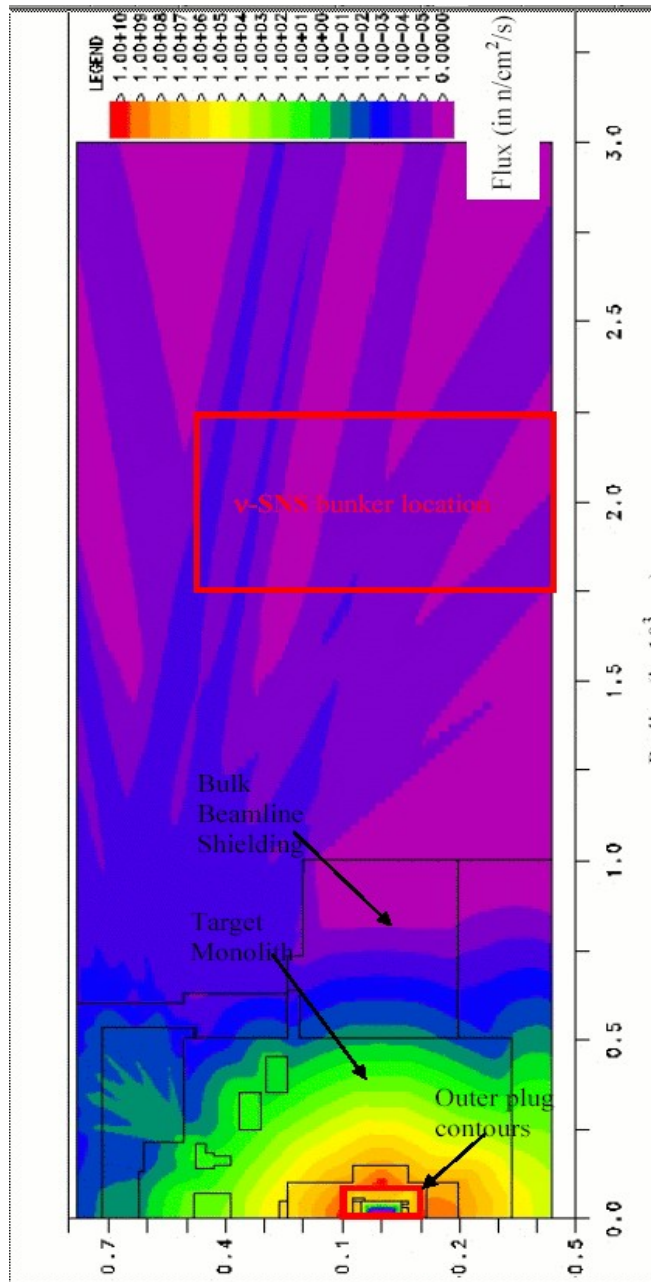
So, for all these physics topics,  
detectors are feasible, interaction rates good;  
we still need to fully understand **background:**

n's, e's,  $\gamma$ 's, instrumental...

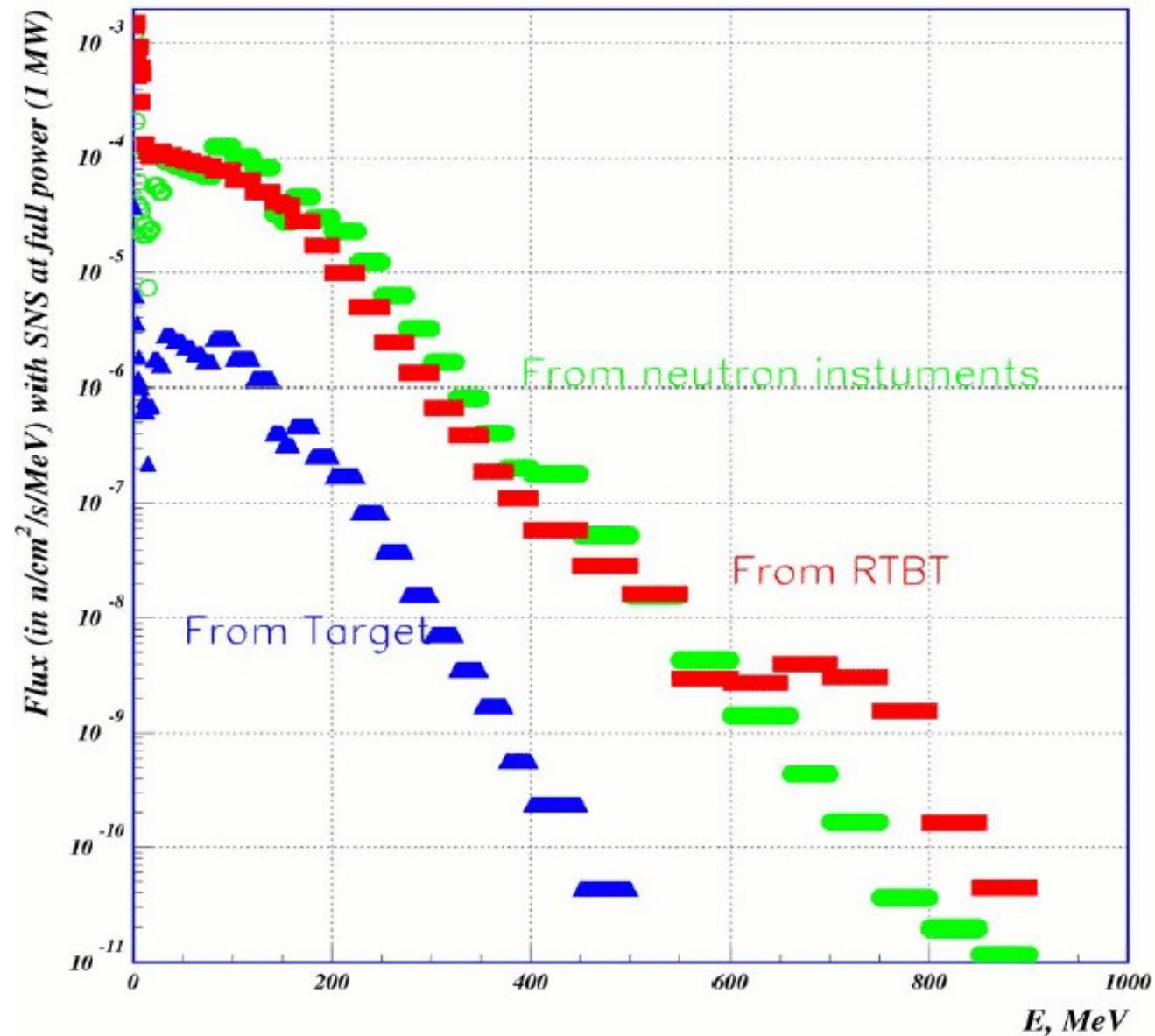
- Radioactivity (detector & ambient)
- Cosmic ray related
  - reduced by veto & bunker
- Beam-related neutrons

} subject  
to pulsed  
beam  
rejection  
factor  
( $10^{-4}$ - $10^{-3}$ )

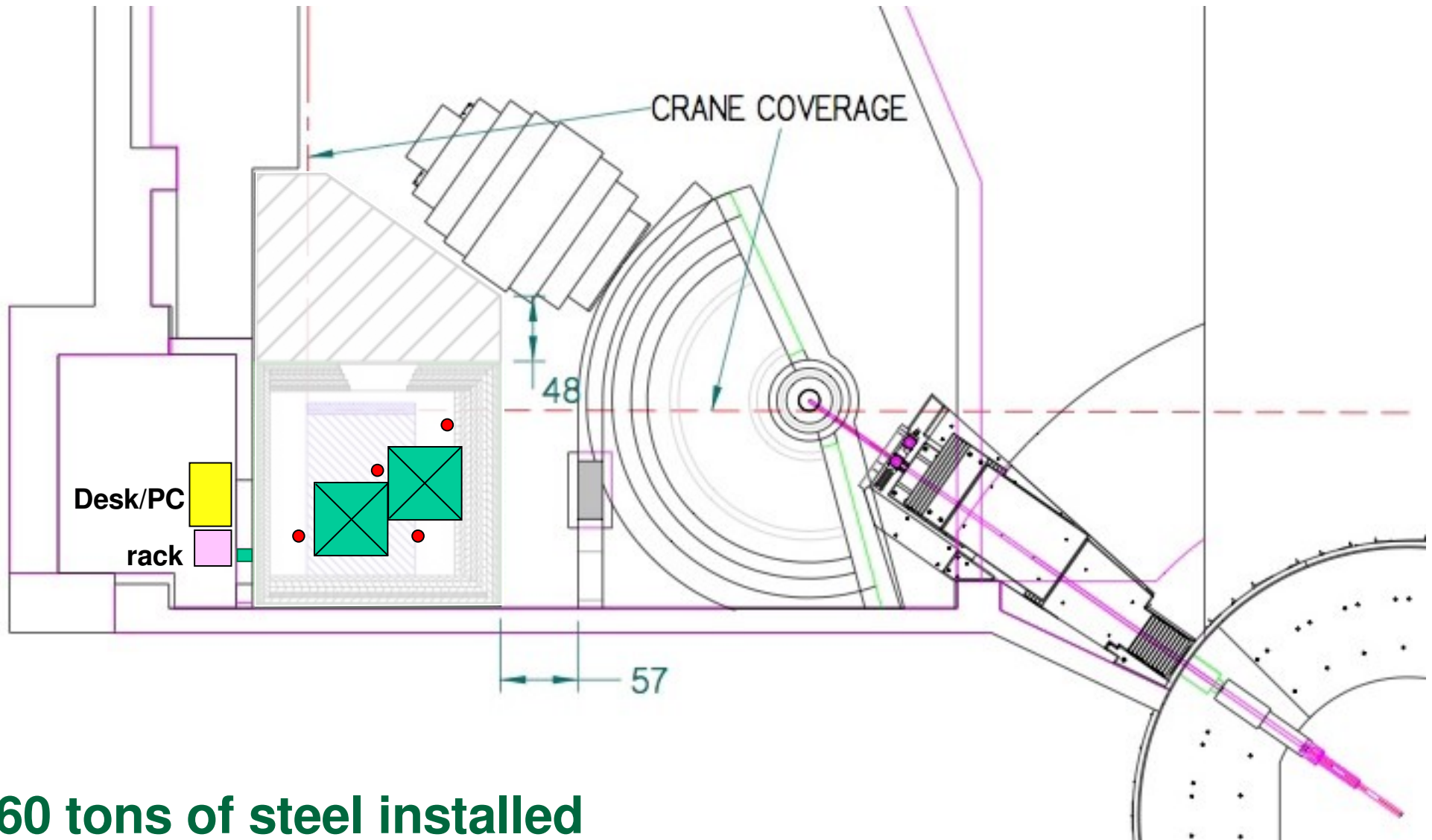
# Background neutron simulations by SNS neutronics group



For coherent NC scattering: need n flux  
in few MeV range, both energy & time dependence



# Background measurements 2006



**60 tons of steel installed**  
**2 stacks of shield block**  
**52" x 52" x 60" high**

**4 detector stations:**  
**5" liquid scintillator**



**Measurements ongoing as beam power ramps up in 2007**

# Summary

**The SNS at ORNL will provide a high-intensity stopped-pion neutrinos in the fews tens of MeV range**

**This is ideal for studies of supernova-relevant neutrino-nucleus interactions!**

**The Nu-SNS collaboration plans homogeneous and segmented detectors 20 m from the target:  
O, C, d, Pb, Fe**

**Also: coherent NC elastic scattering in low threshold detector may be possible**

**Background and prototype studies underway at the SNS**