# Neutrinos at the Spallation Neutron Source

**Kate Scholberg, Duke University**

**NUINT 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

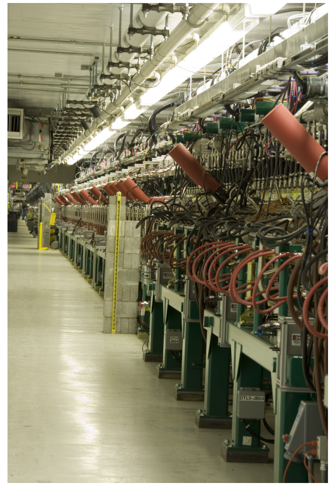
**Progress and Prospects**

# Spallation Neutron Source at Oak Ridge National Lab, Tennessee


# Spallation Neutron Source

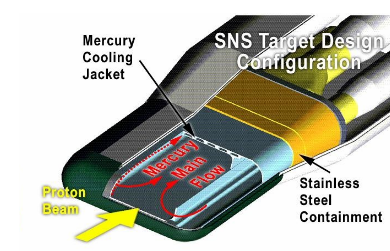

**1$B facility for neutron science: most intense pulsed neutron beams in the world for chemistry, materials science, engineering, structural biology...**

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 μC/pulse at 60 Hz ⇒ 1.4 MW power

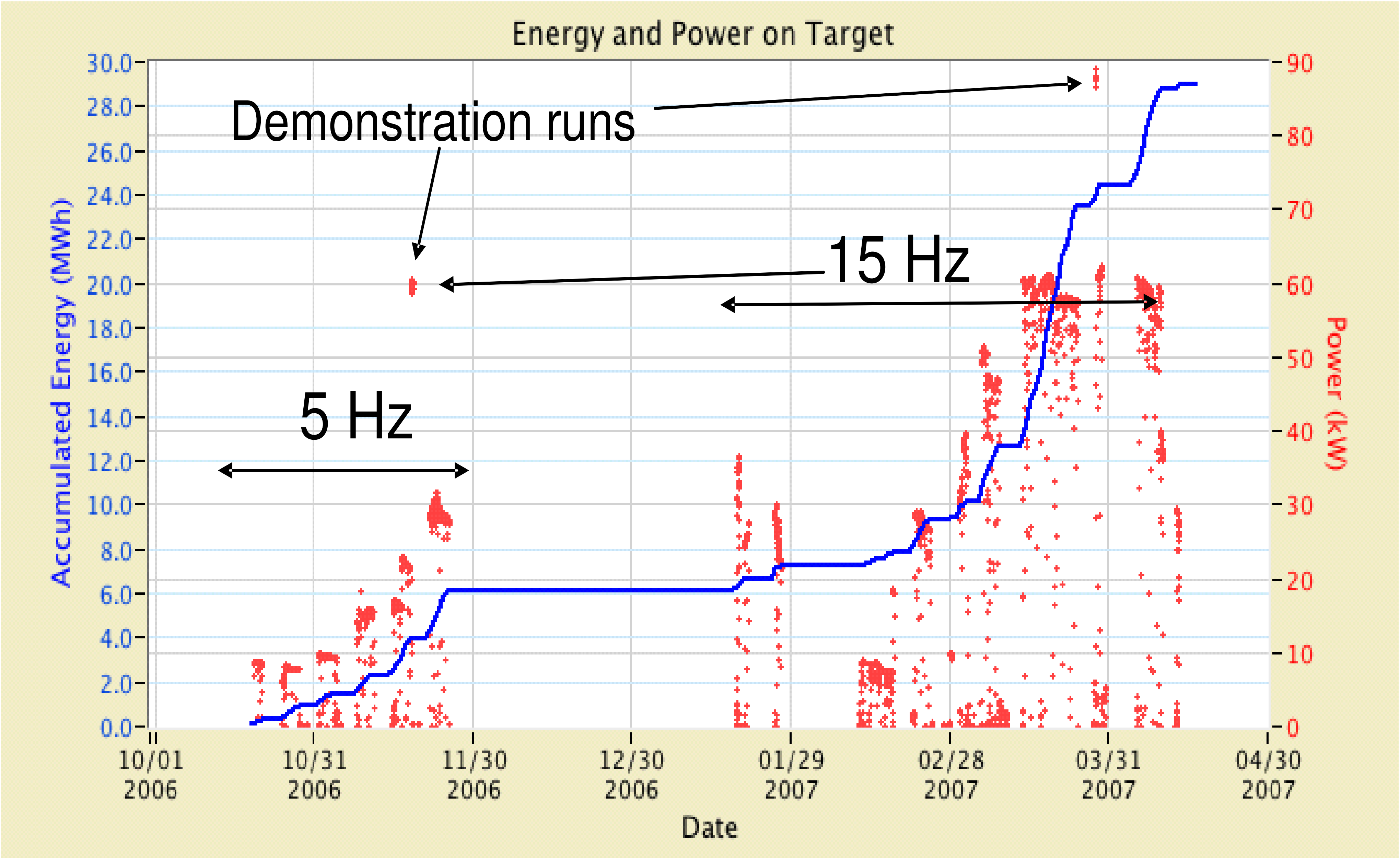
# SNS Status and Schedule

- beam construction basically complete
  (neutron instruments still under construction)
- first beam in 2006, up to 10 kW

- attained 100 kW in April 2007

- continuing to ramp up, 175 kW in Sept?
- full power in 2009
- possible eventual upgrade to 2-5 MW (2012?)

# SNS Beam History



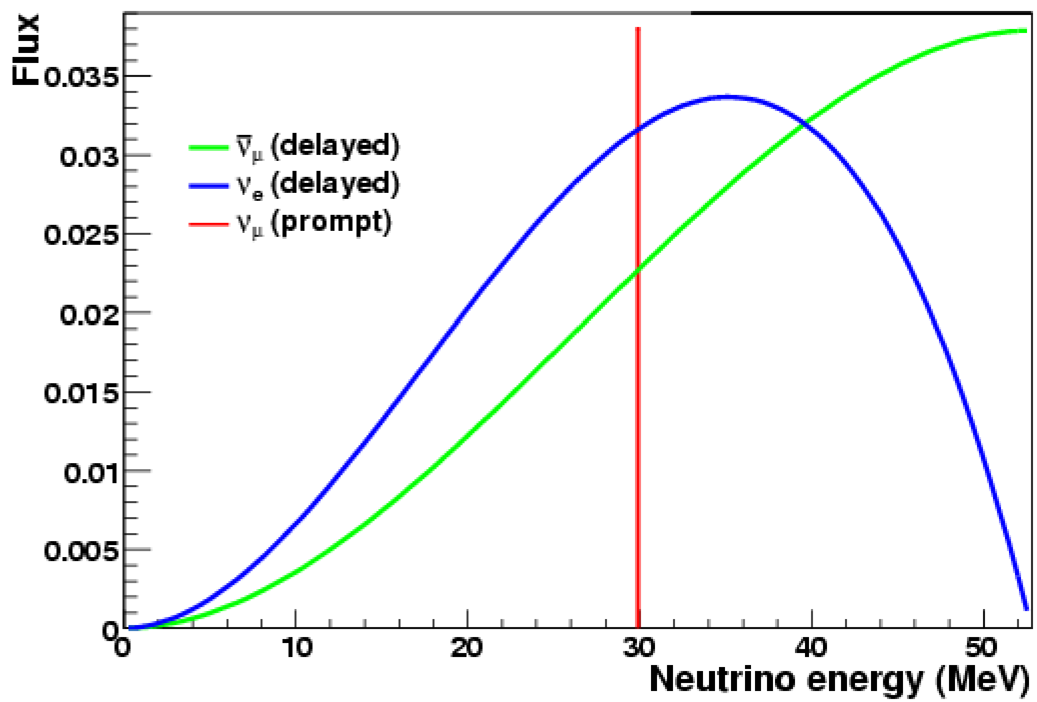

**From J. Galambos, A. Aleksandrov, Y. Efremenko**

# 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




$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

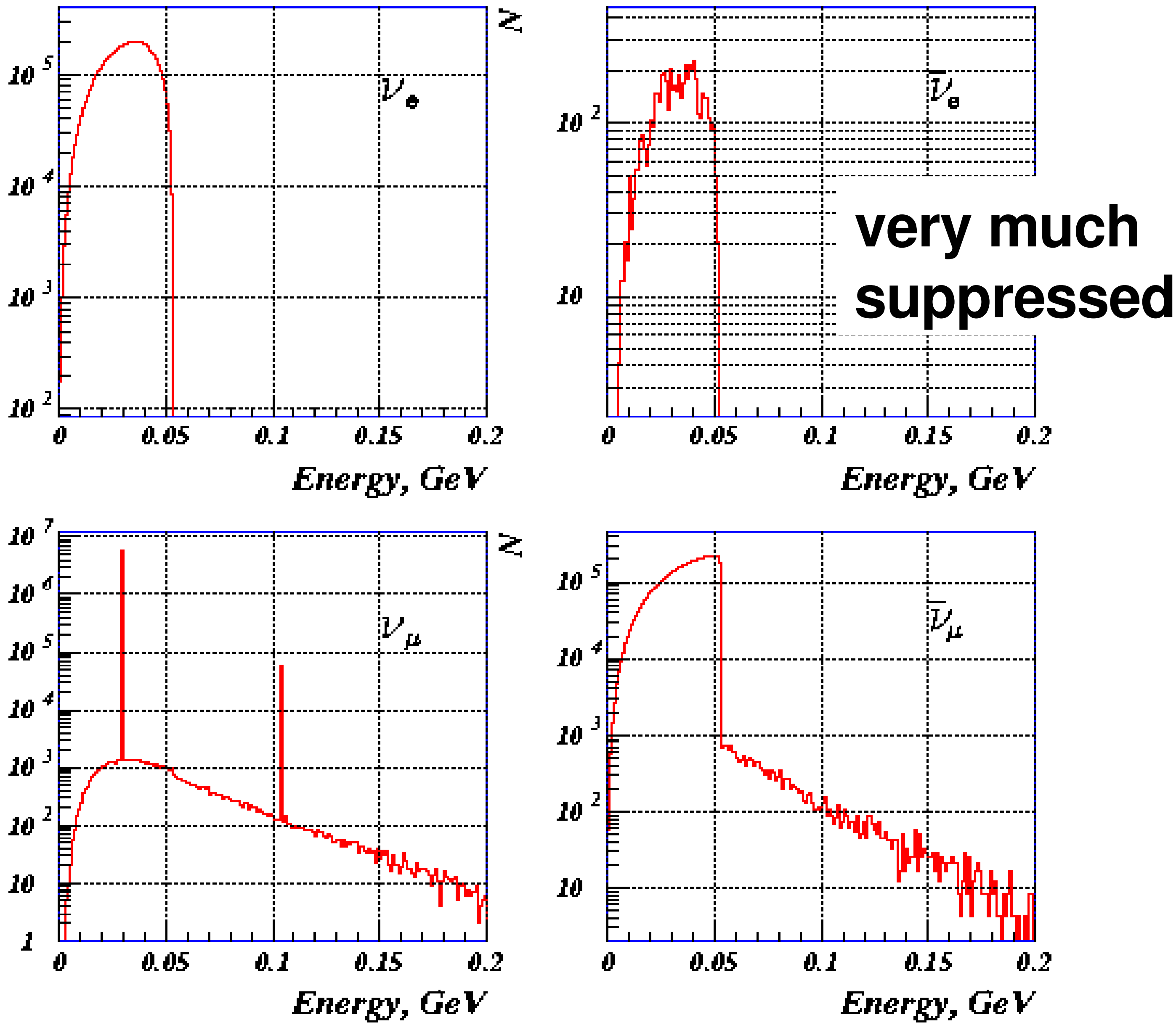
2-body decay: monochromatic 29.9 MeV $\nu_\mu$
PROMPT

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

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

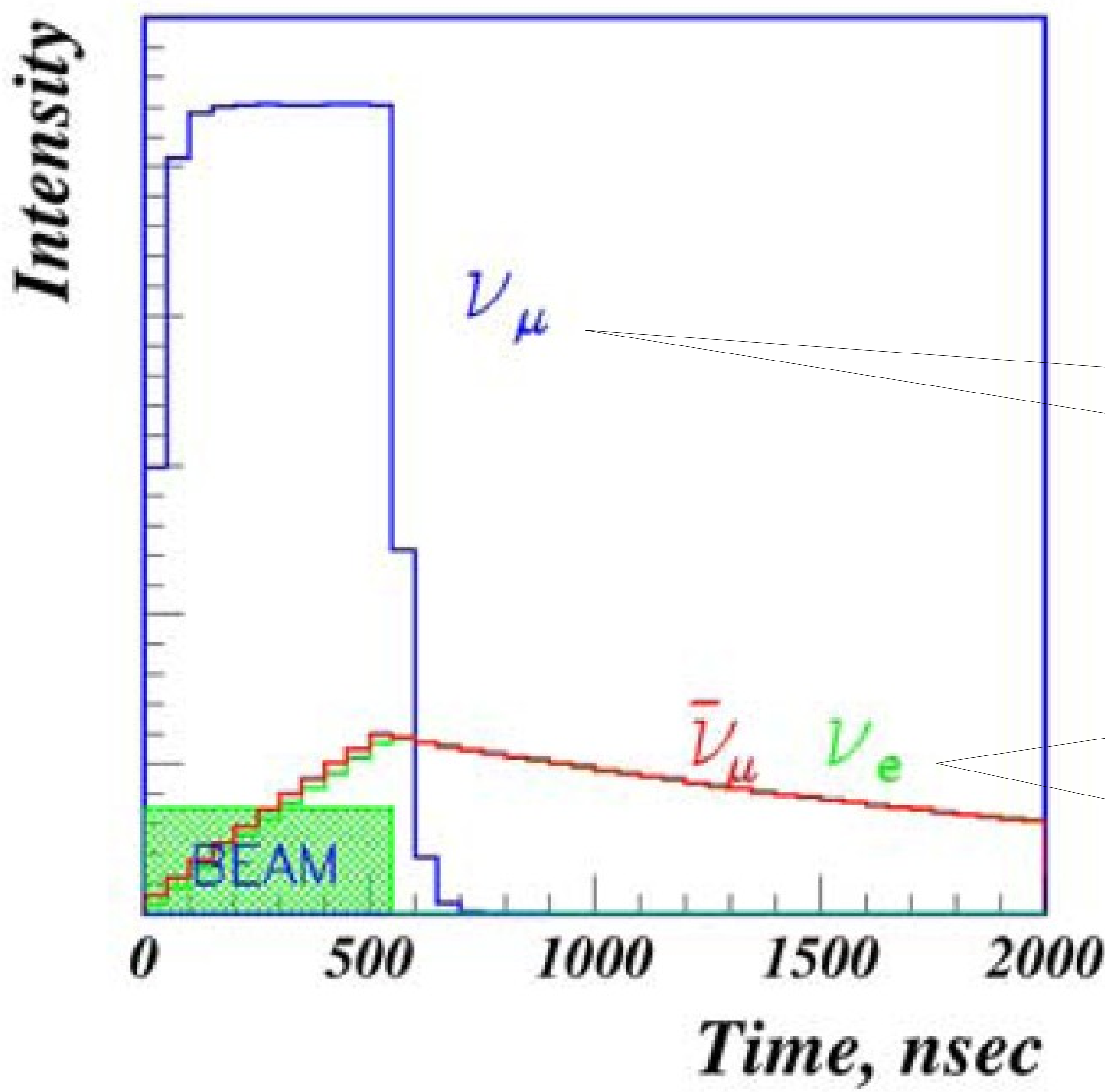
# More detailed calculation of the spectra

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




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

# Time structure of the source




60 Hz *pulsed* source

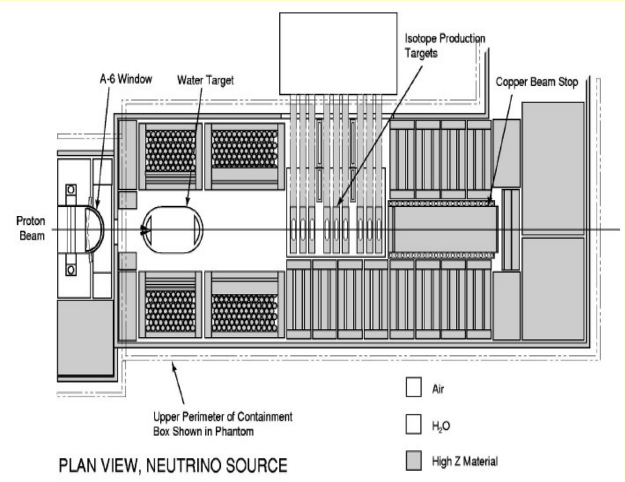
in time with beam

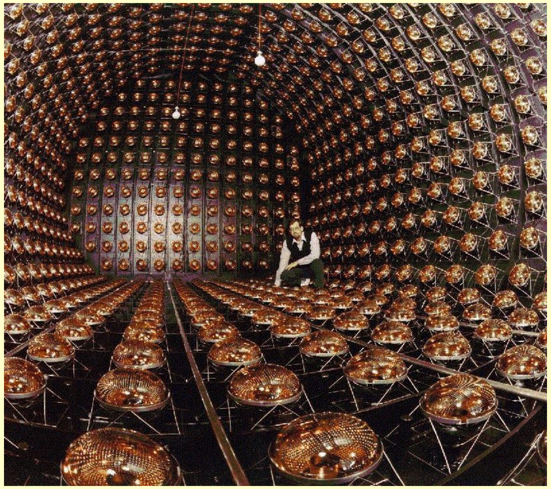
delayed on μ decay timescale (2.2 μs)

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

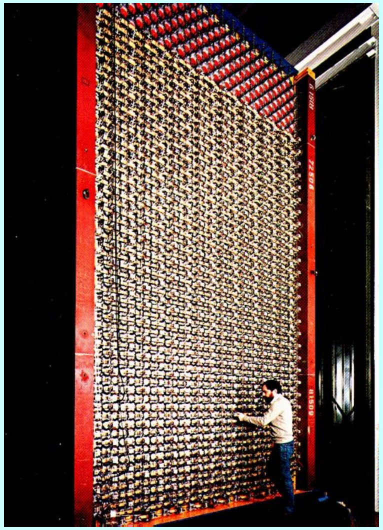
# Previous neutrino experiments at stopped-pion neutrino sources

**LSND at LANSCE (LANL)**



**KARMEN at ISIS (RAL)**

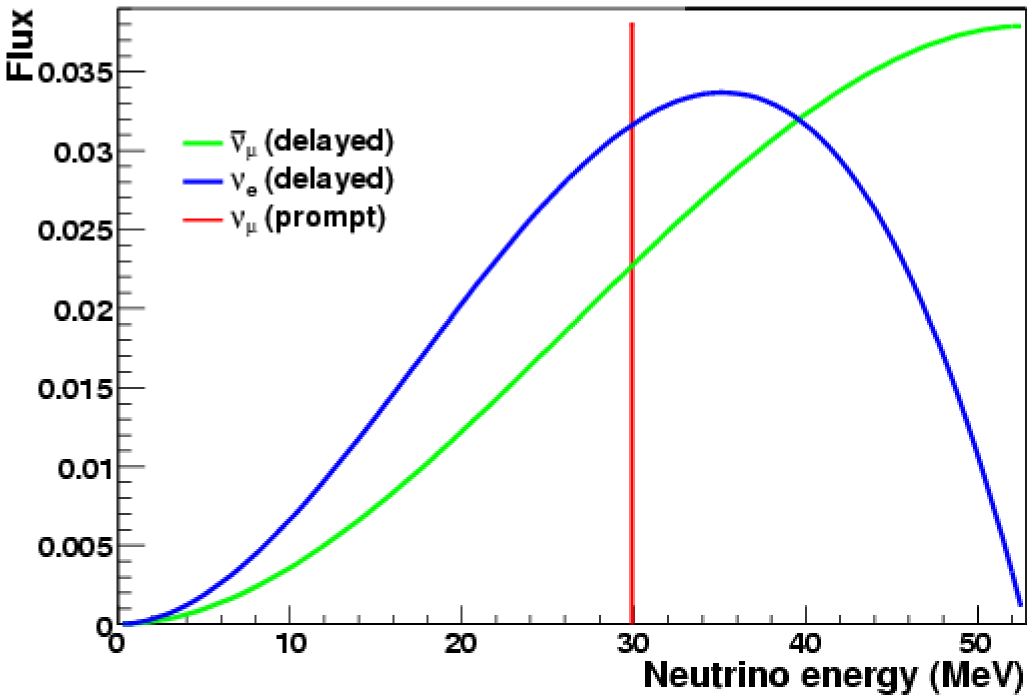


# Comparison of stopped-pion neutrino sources

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

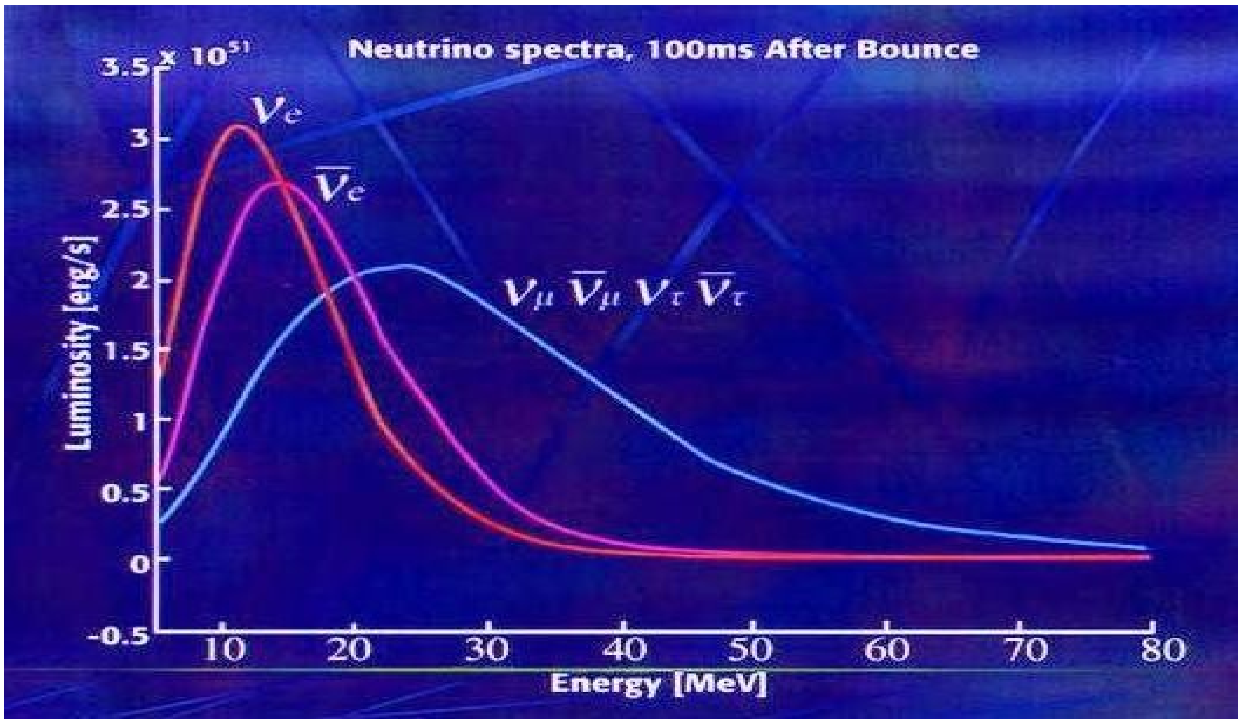
- -very high intensity ν's
- -~below K threshold
- -very little DIF
- -narrow pulses

# 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**

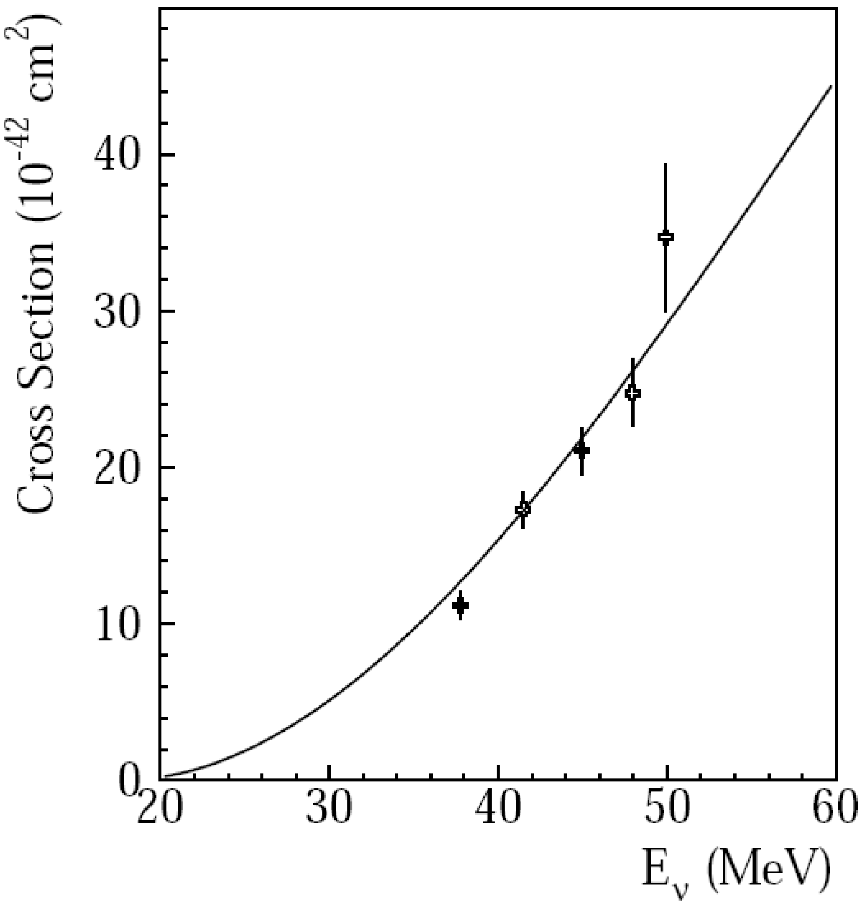
1. Understanding of *core-collapse SN processes*, nucleosynthesis
2. Understanding of *SN $\nu$ detection* processes

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

**e.g.**

## LSND

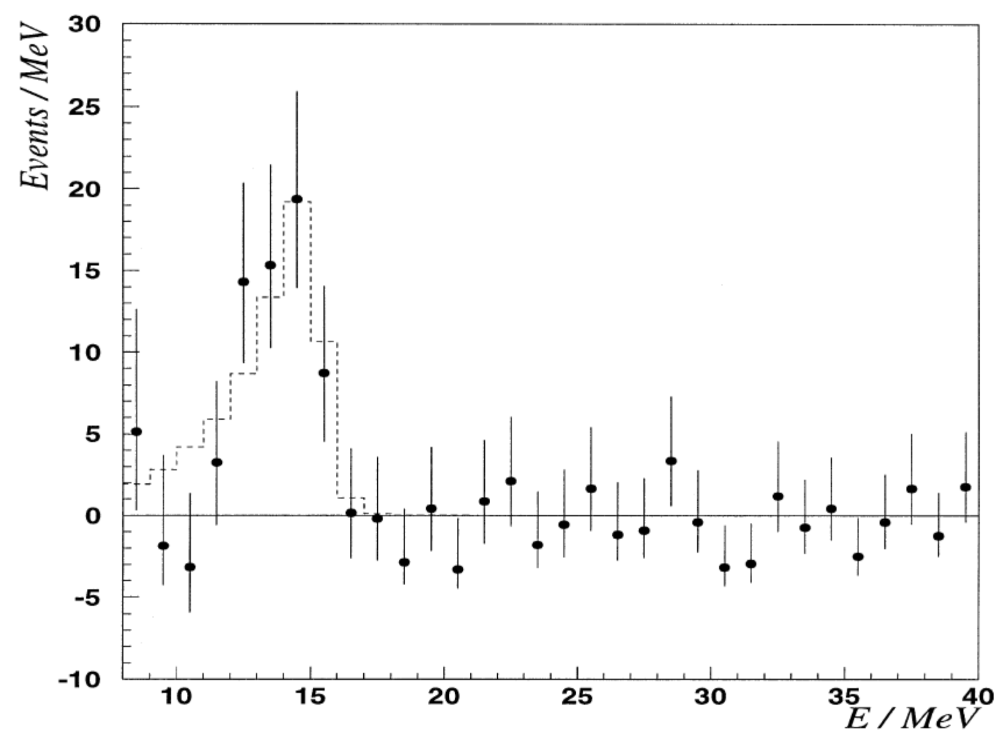
**Phys. Rev. C 66 (2002) 015501**




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

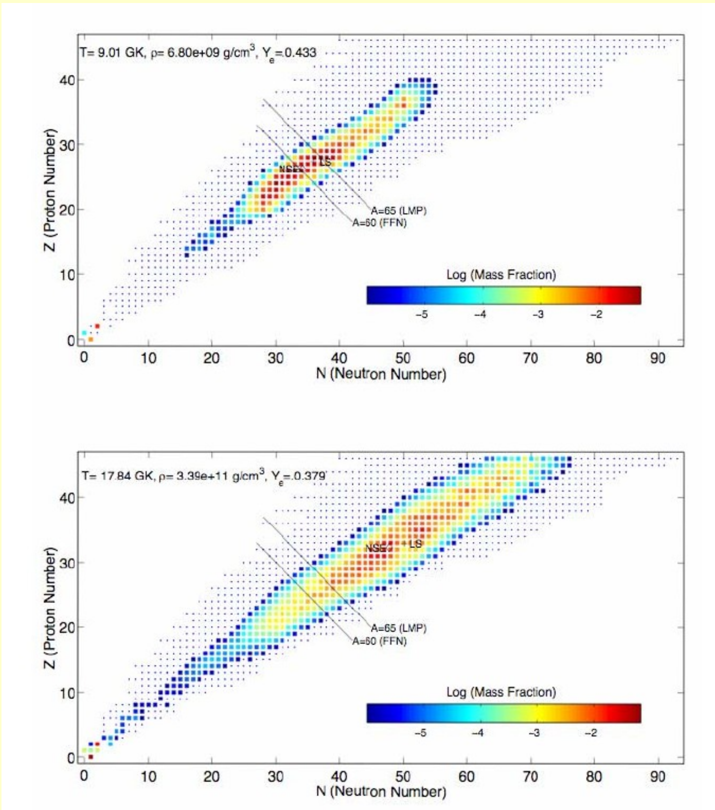
## Karmen

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




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

# Core collapse dynamics




Liebendorfer *et al.*, 2001

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

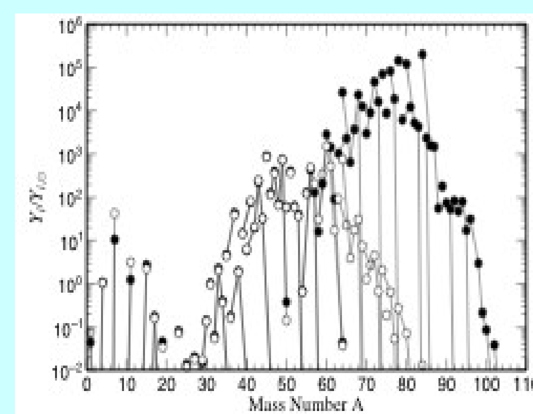
$$\nu_e + A(Z,N) \leftrightarrow A(Z+1,N-1) + e^-$$

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

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

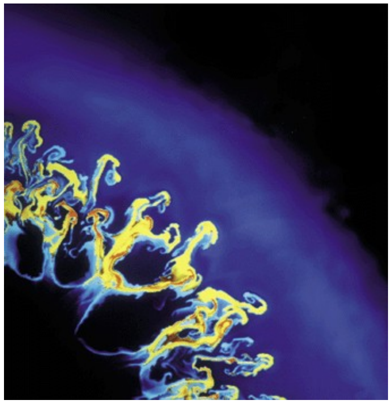
# Supernova nucleosynthesis

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

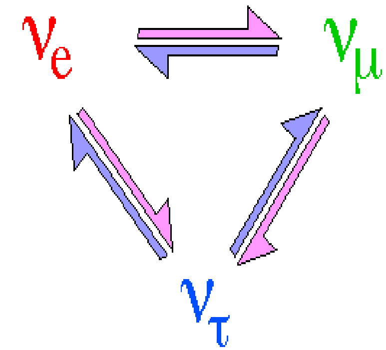



Fröhlich *et al.*, Astrophys. J. 637 (2006) 415-426

# 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-scn; some tagging, poor pointing

**Elastic scattering:** few % of invβdk, 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

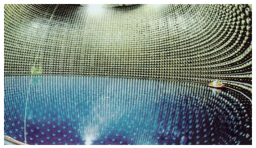
$$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$$

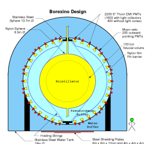
$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

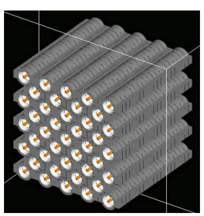
$$\hookrightarrow (A,Z) + \gamma$$

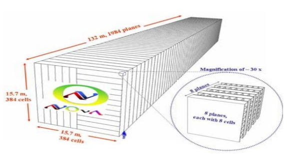
?

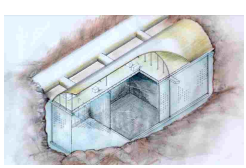
# Supernova neutrino detectors, current & future

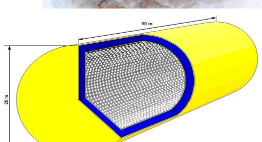




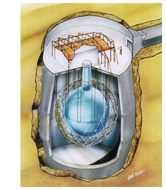


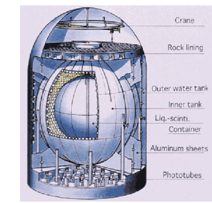


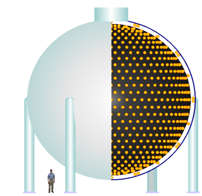


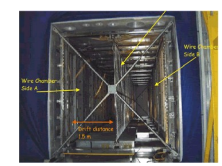


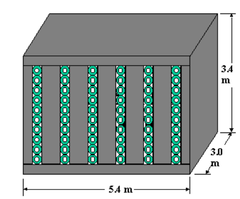
| *Detector* | *Type* | *Mass (kton)* | *Location* | *Events at 8.5 kpc* | *Status* |
|---|---|---|---|---|---|
| Super-K | Water | 32 | Japan | 7000 | Running as SK III |
| SNO | Heavy water | 1($D_2O$)<br>1.4($H_2O$) | Canada | 400<br>450 | Running until end of 2006 |
| LVD | Scintillator | 1 | Italy | 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/ 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 | $^{100}$Mo | 0.03 | ? | 20 | proposed |
| NOνA | Scintillator | 20 | USA | 4000 | proposed |
| OMNIS | Pb | 2-3 | USA? | >1000 | proposed |
| LANNDD | 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 |

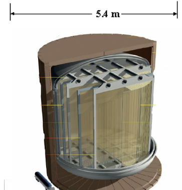


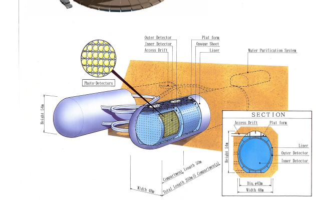








**Most urgently needed supernova neutrino CC and NC cross-section measurements: (total and differential)**

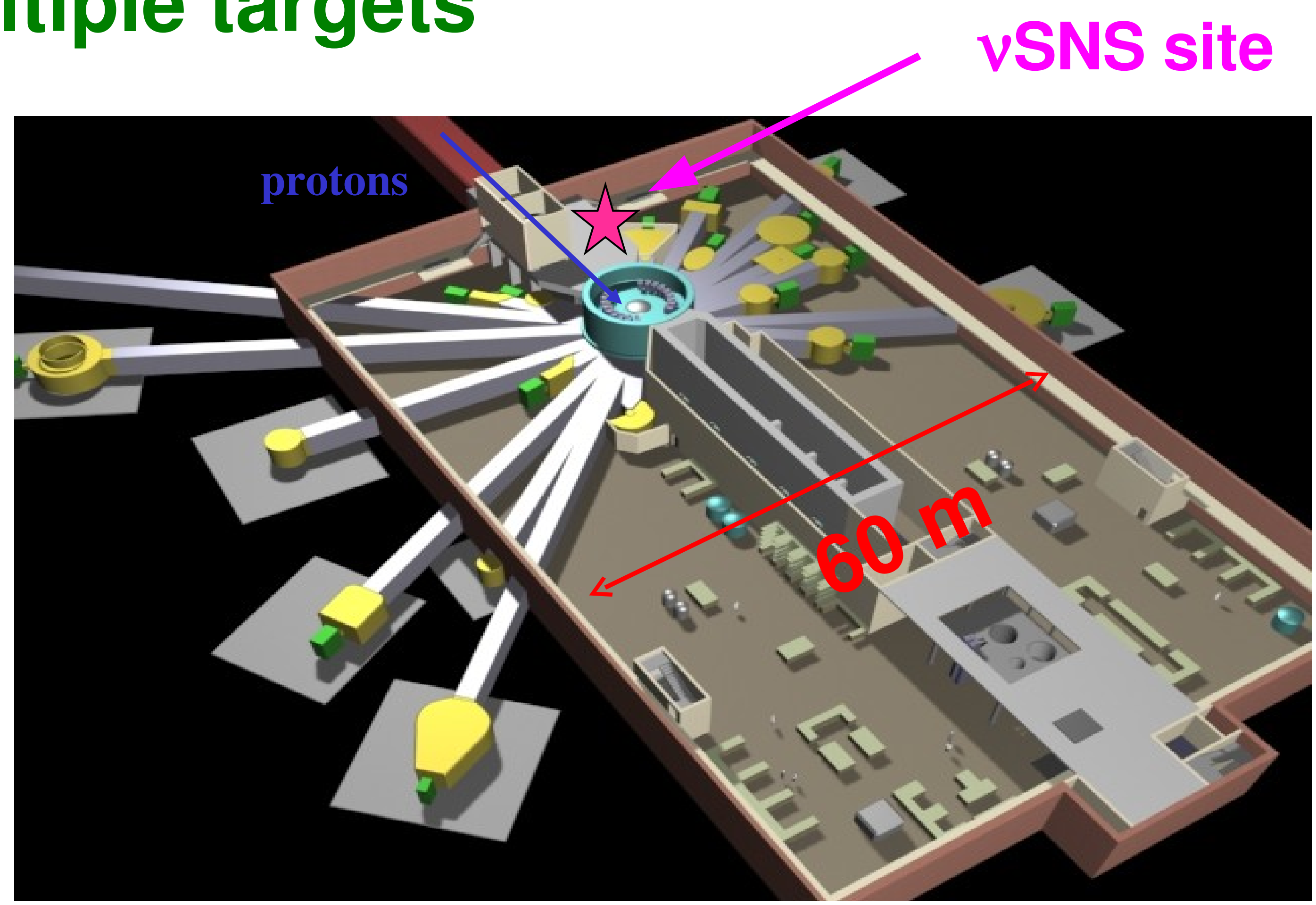
**oxygen, argon, lead,**

**iron, (carbon)**

## So, how can we address these needs?

# NuSNS (Neutrinos at the SNS)

**A neutrino facility with capability to measure multiple targets**

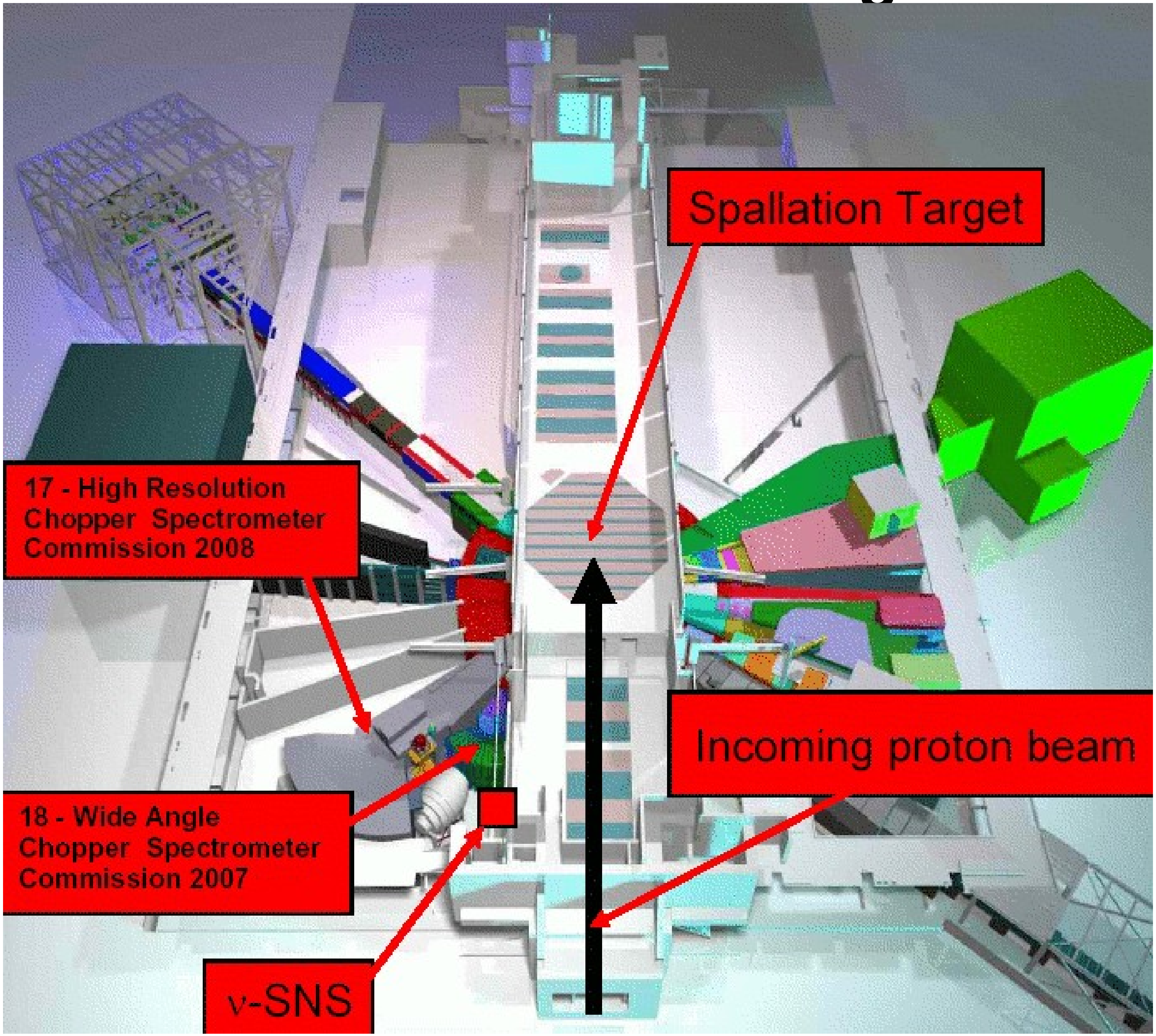


# NuSNS collaboration:  20 US institutions


| *System* | *Lead* |
|---|---|
| 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**

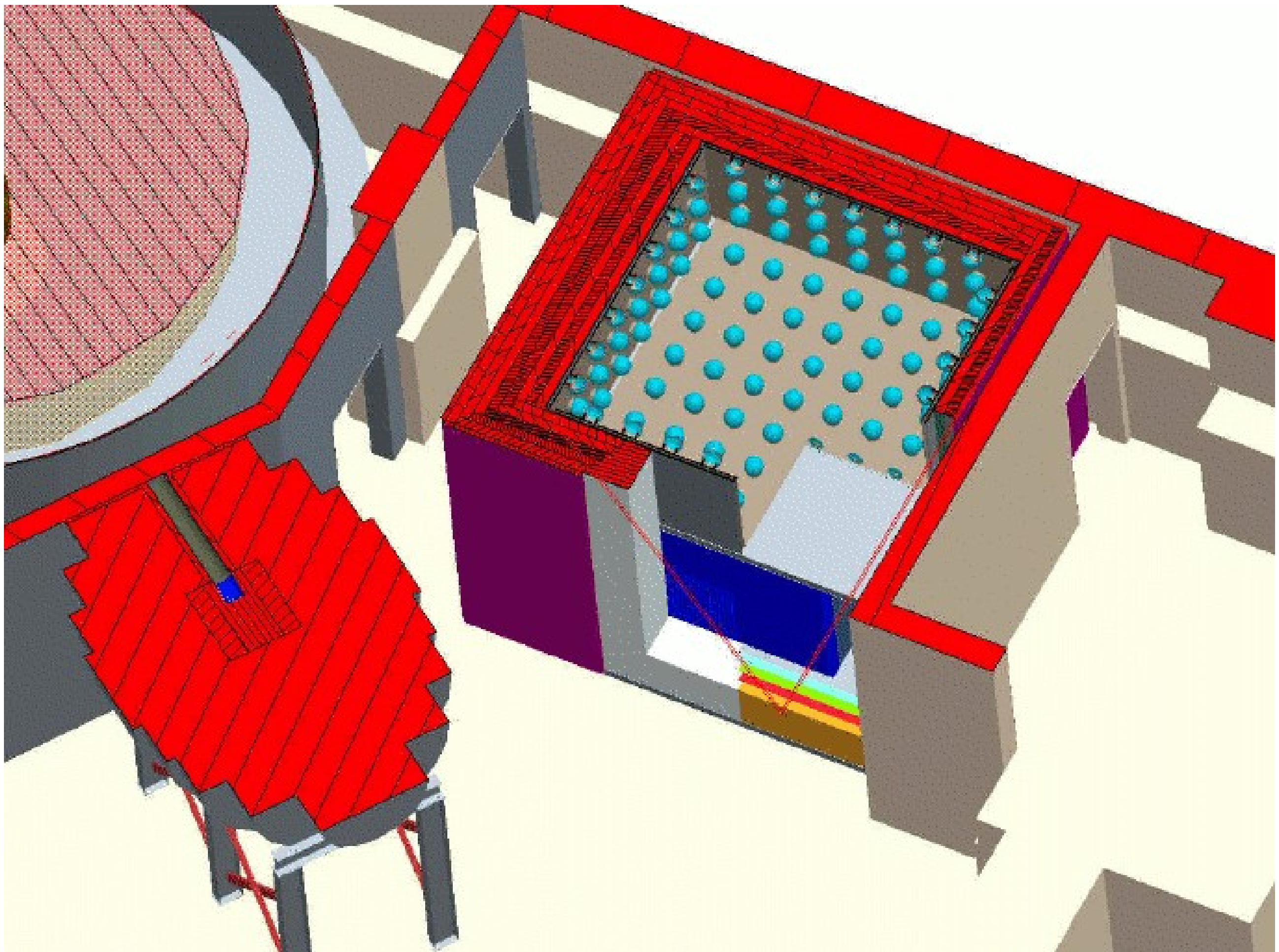
# Spot identified 20 m from the target



Conventional ~10 ton detectors w/ few MeV thresholds:

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

} changeable targets



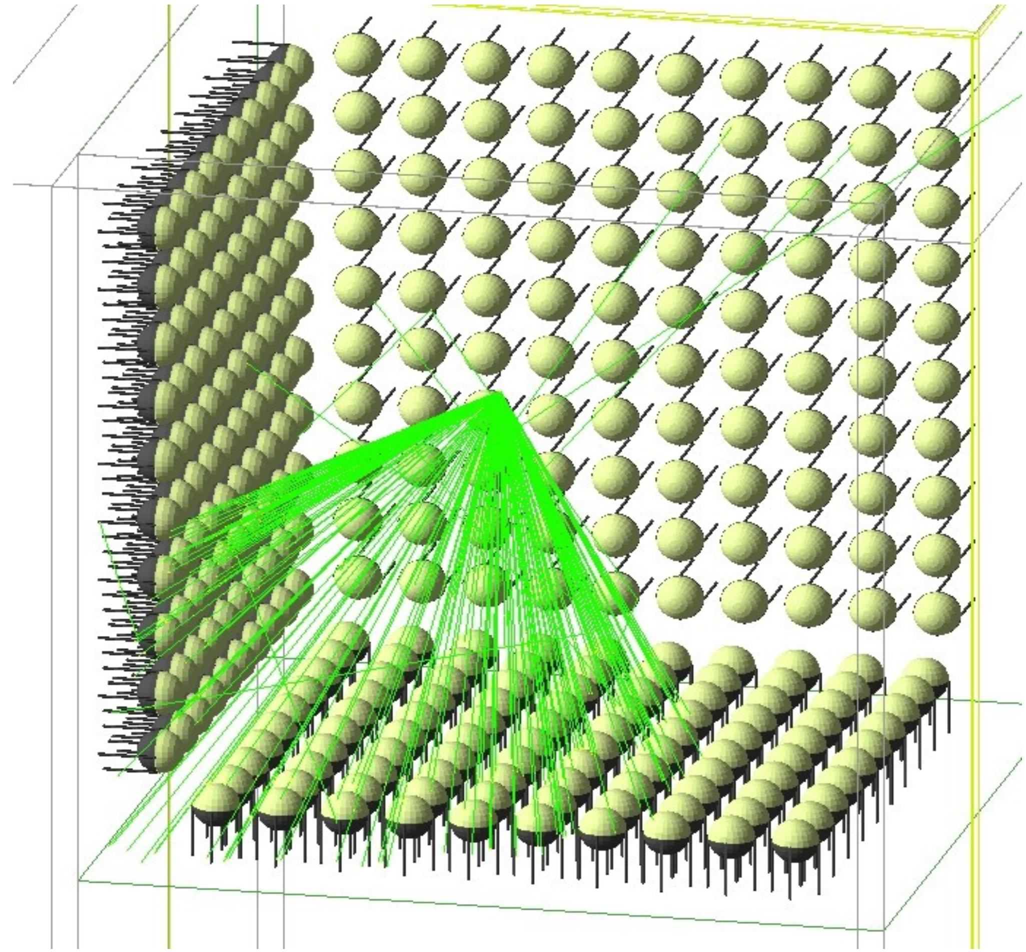
Concrete + steel bunker, 1 m ceiling, 0.5 m walls; inner $4.5 \times 4.5 \times 6.5\ m^3$ volume

Aims to be 'user facility'

# The Homogeneous Detector: liquid targets

3.5m x 3.5m x 3.5m
steel vessel
(43 $m^3$, 15.5 $m^3$
fiducial volume)
600 8" PMTs

(41% coverage)



Well known technology!

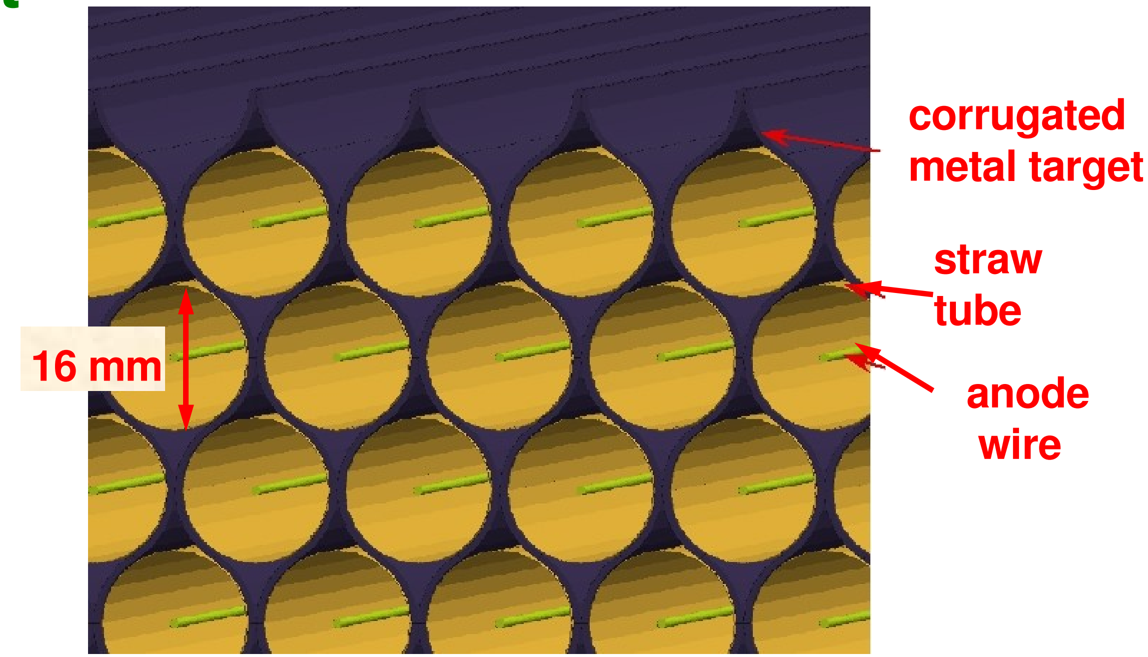
## Potential targets

- 1300 events/yr $\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$ (mineral oil)
- 450 events/yr $\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$ (water)
- 1000 events/yr $\nu_x + {}^{2}H \rightarrow p + n + \nu_x$ (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: $1.4\times10^{4}$ gas proportional counters (straw tube),
3m long x 16mm diameter

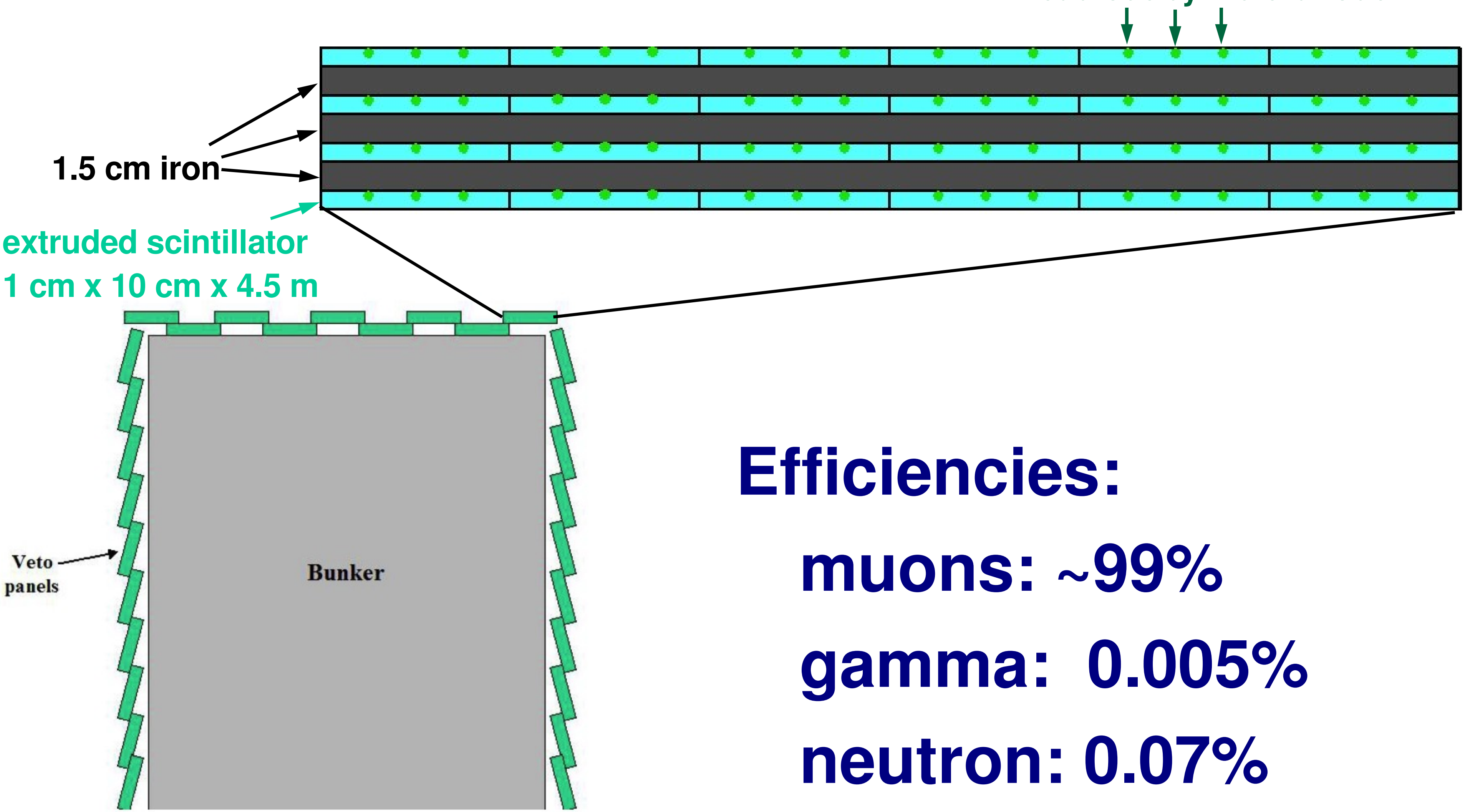



- 3D position by cell ID & charge division
- PID and energy by track reconstruction

<u>Potential targets</u>

- 1100 events/yr $\nu_e + Fe \rightarrow Co + e^-$
- 1100 events/yr $\nu_e + Al \rightarrow Si + e^-$
- 4900 events/yr $\nu_e + Pb \rightarrow Bi + e^-$

# Cosmic ray veto




**Efficiencies:**

- muons: ~99%
- gamma: 0.005%
- neutron: 0.07%

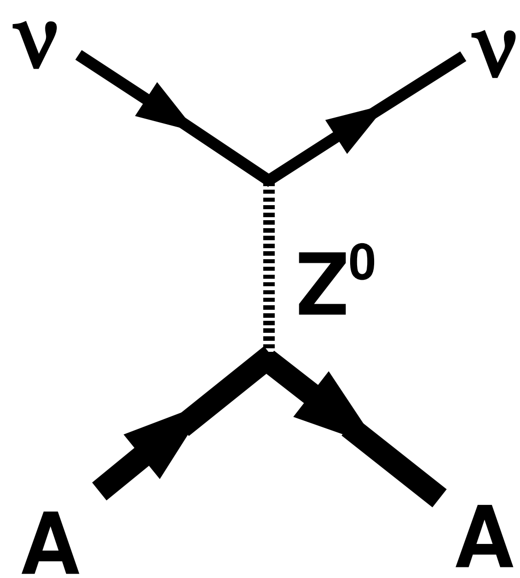
**Geant4 simulation & prototype studies underway for all subdetectors**

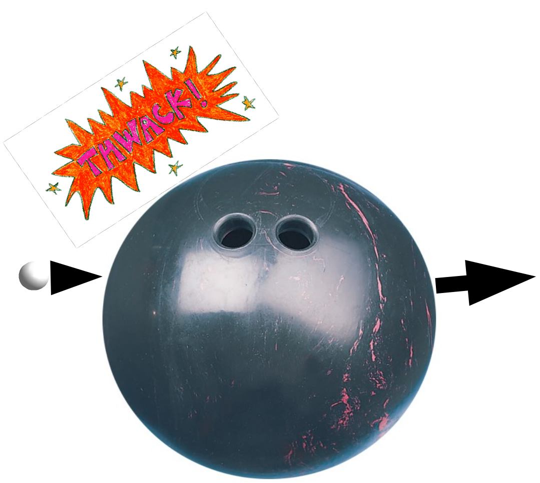
Another physics topic requiring a
different detector technology:

## 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

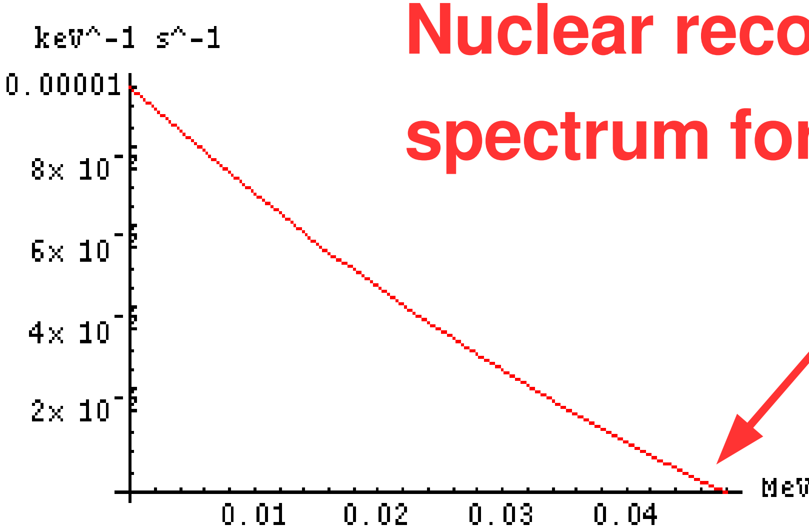
# This process has a cross-section easily calculable in the Standard Model:

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 β dk in few-50 MeV range**



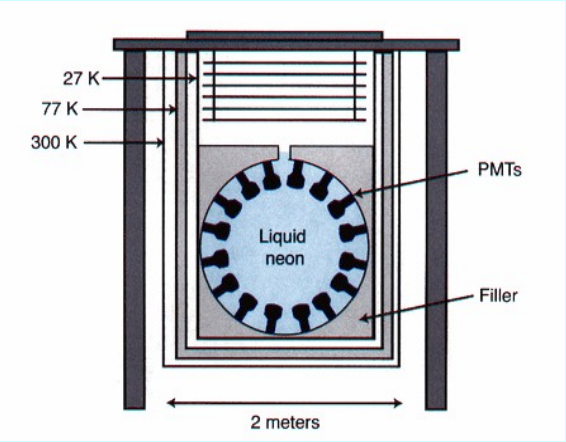

**Nuclear recoil energy spectrum for 30 MeV ν**

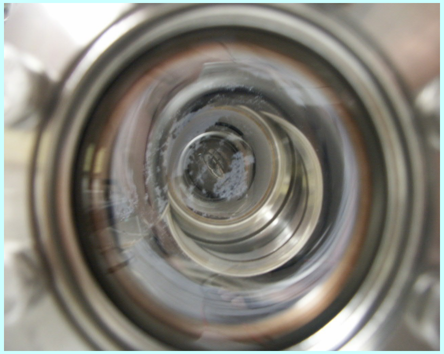
**Max recoil energy is $2E_\nu^2/M$ (48 keV for Ar)**

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

# Detector technologies that might work: (WIMPs)

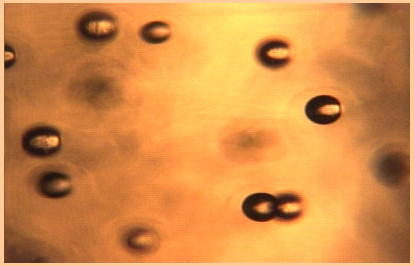
## Noble gas/liquid, single or dual-phase (Ne, Ar, Xe)



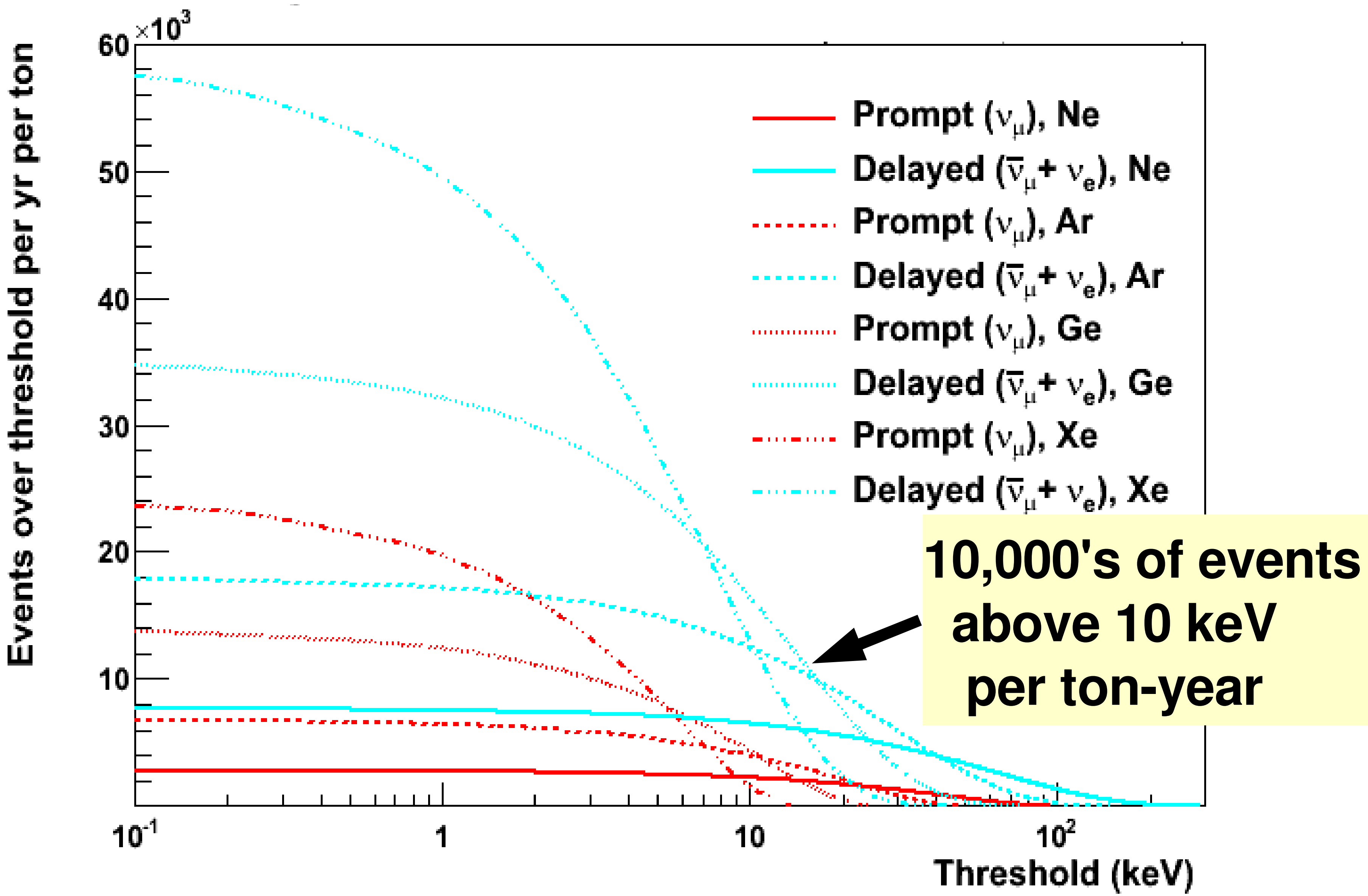
## Germanium

## 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 ⇒ 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-scn is interesting...

- Weak mixing angle:

  could measure to ~5%

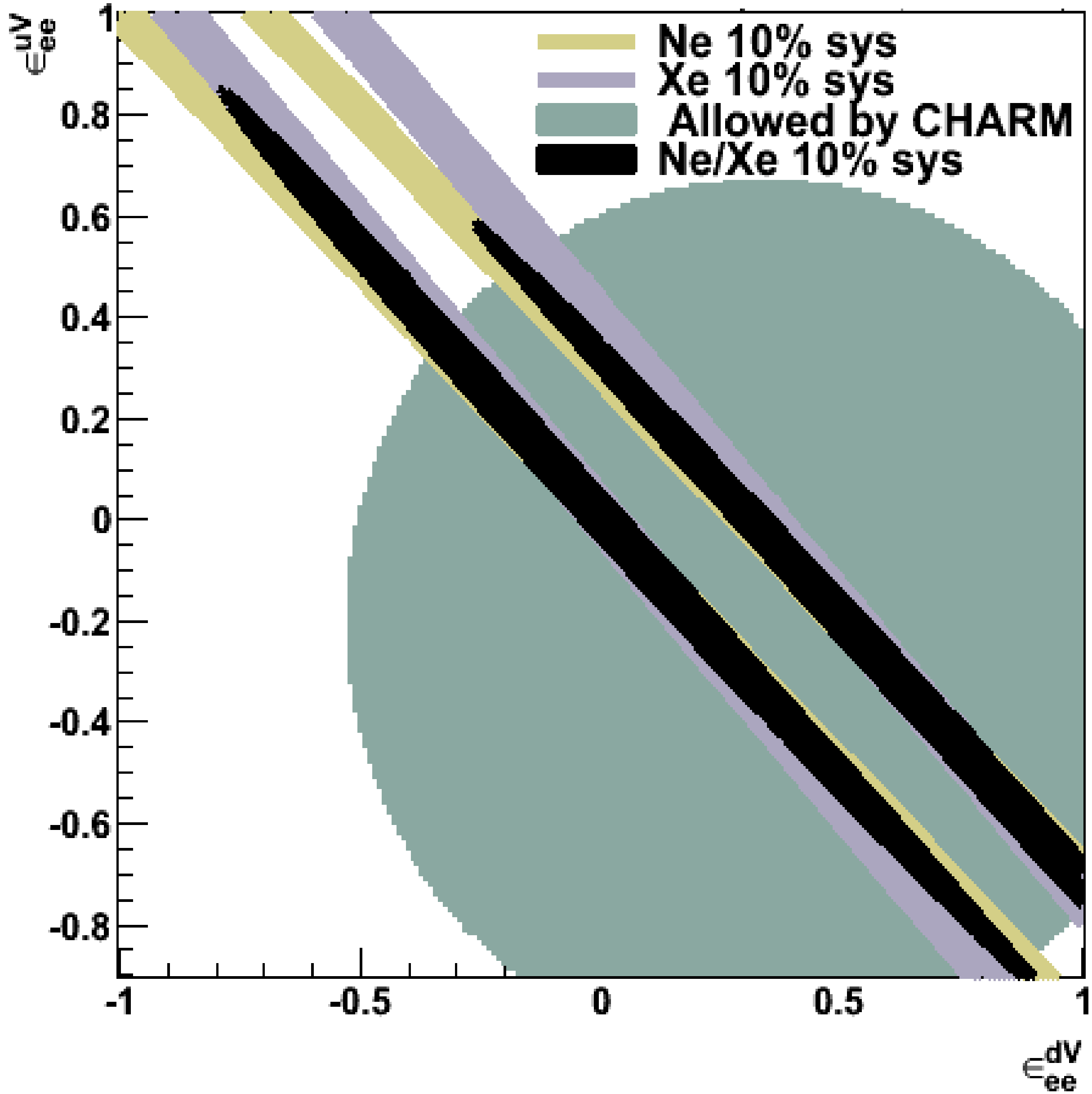
- Non Standard Interactions (NSI) of neutrinos:

  could significantly improve constraints

- Neutrino magnetic moment:

  hard, but maybe doable

# Example: sensitivity to NSI parameters




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

**So, for all these physics topics, detectors are feasible, interaction rates good;**

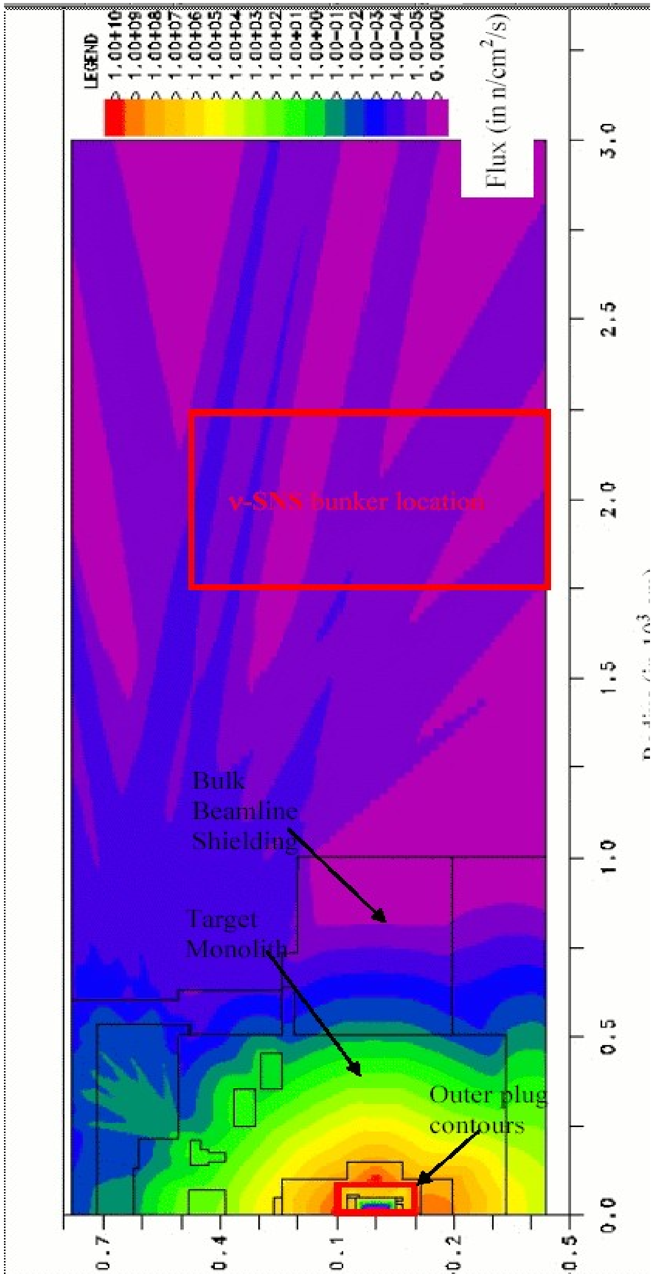
**we still need to fully understand background:**

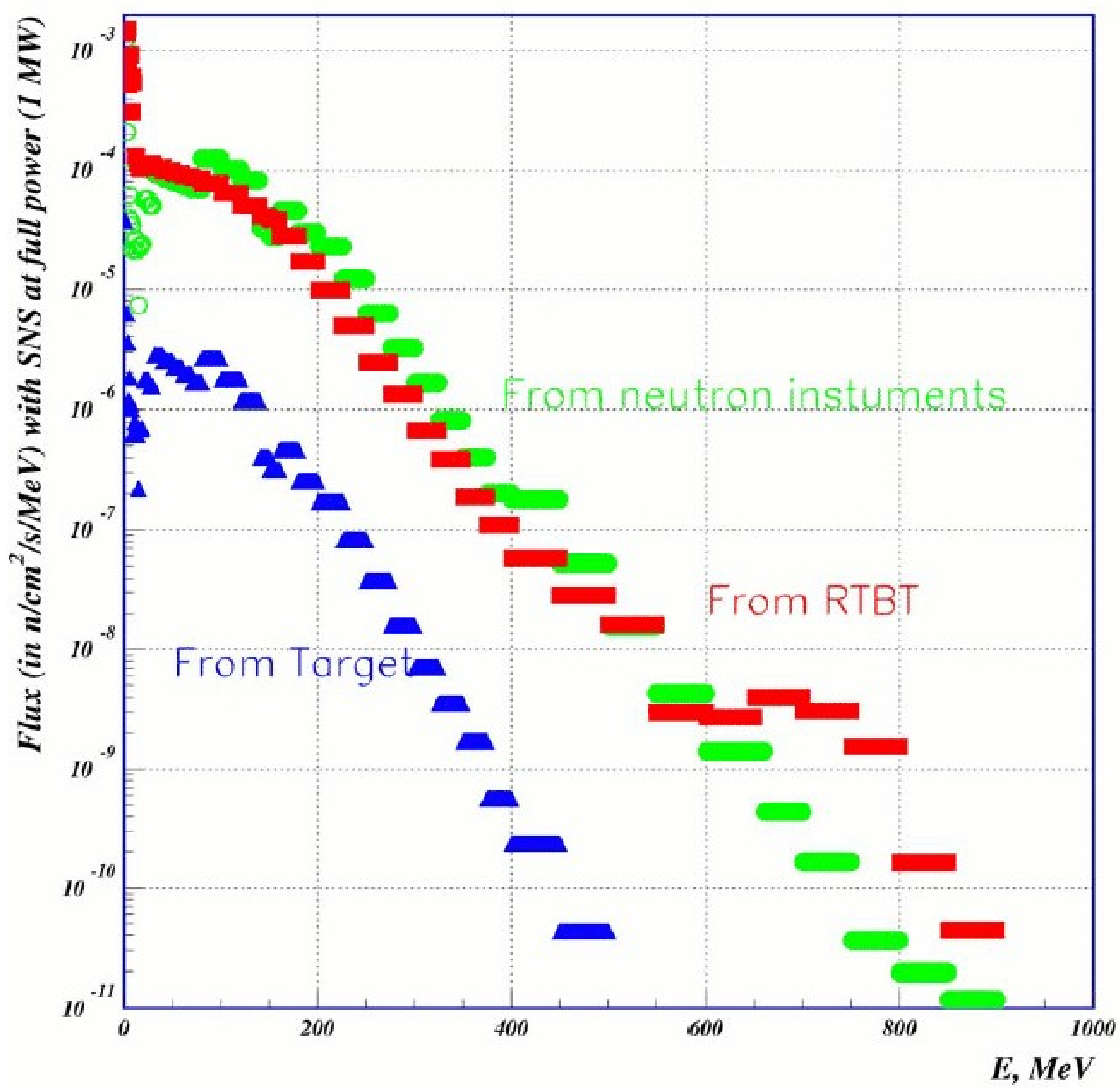
**n's, e's, $\gamma$'s, instrumental...**

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

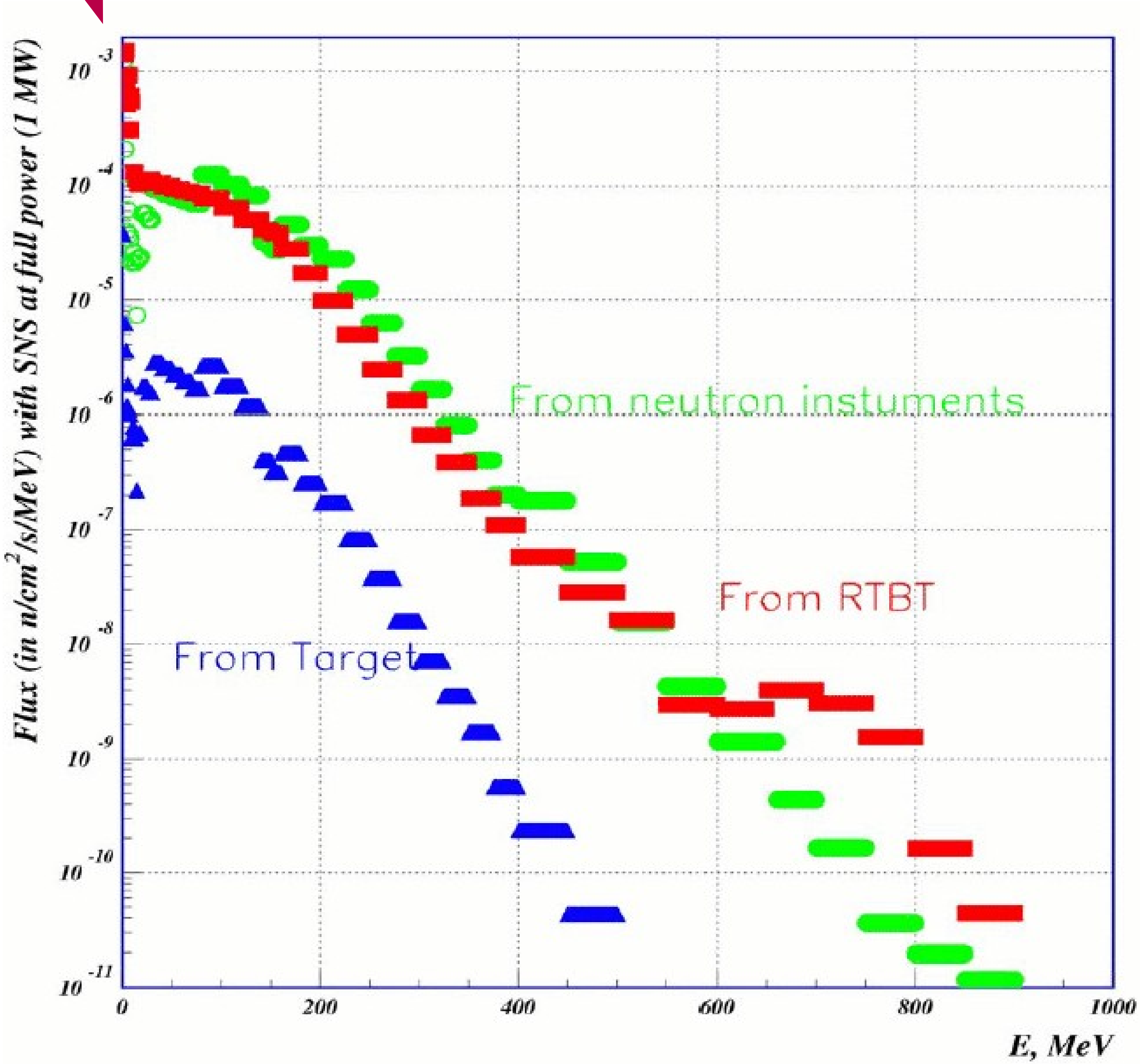
**subject to pulsed beam rejection factor ($10^{-4}$-$10^{-3}$)**

# Background neutron simulations by SNS neutronics group

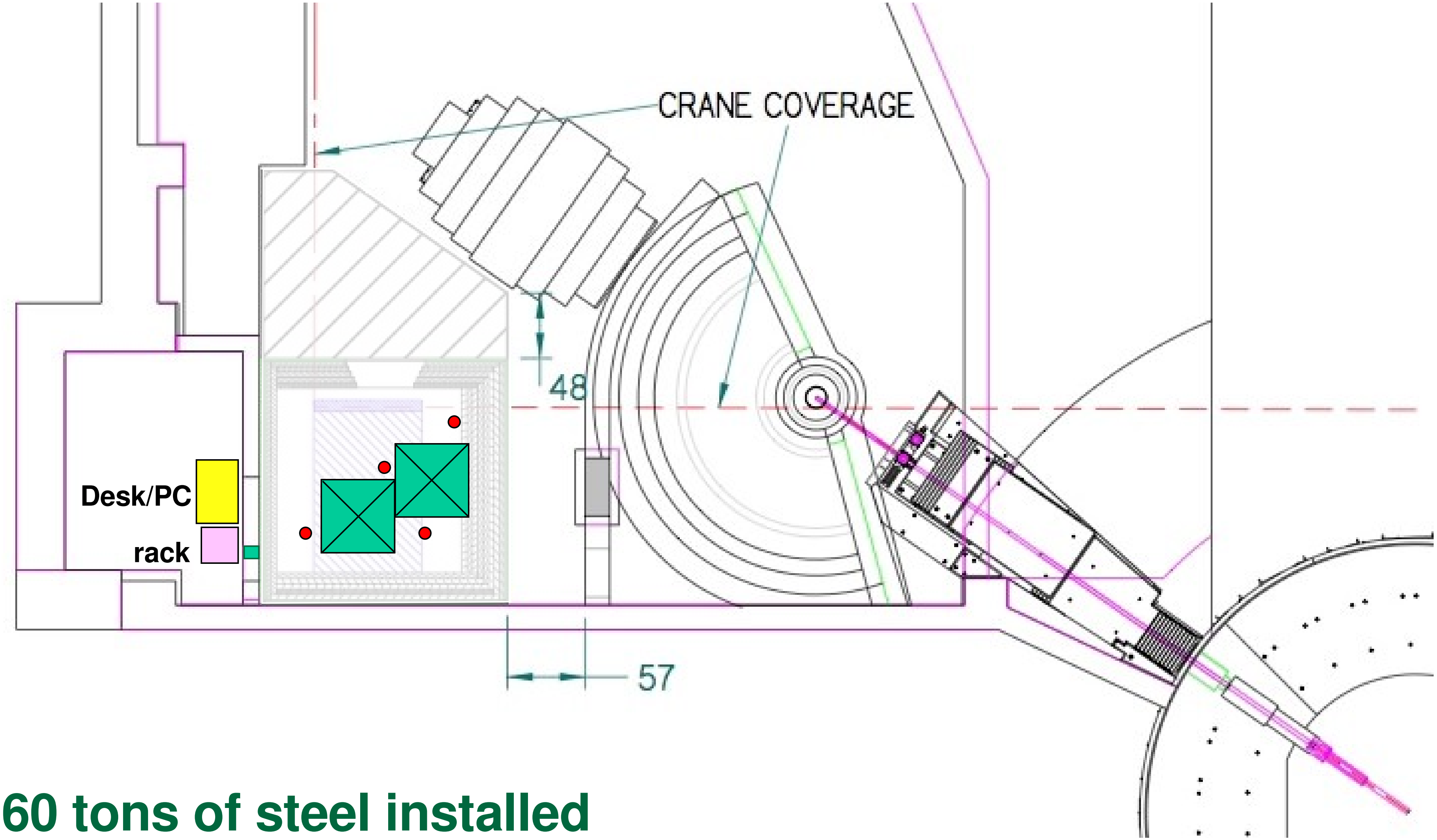


# For coherent NC scattering: need neutron flux in few MeV range, both energy & time dependence



# 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 will continue as beam power ramps up**

# 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