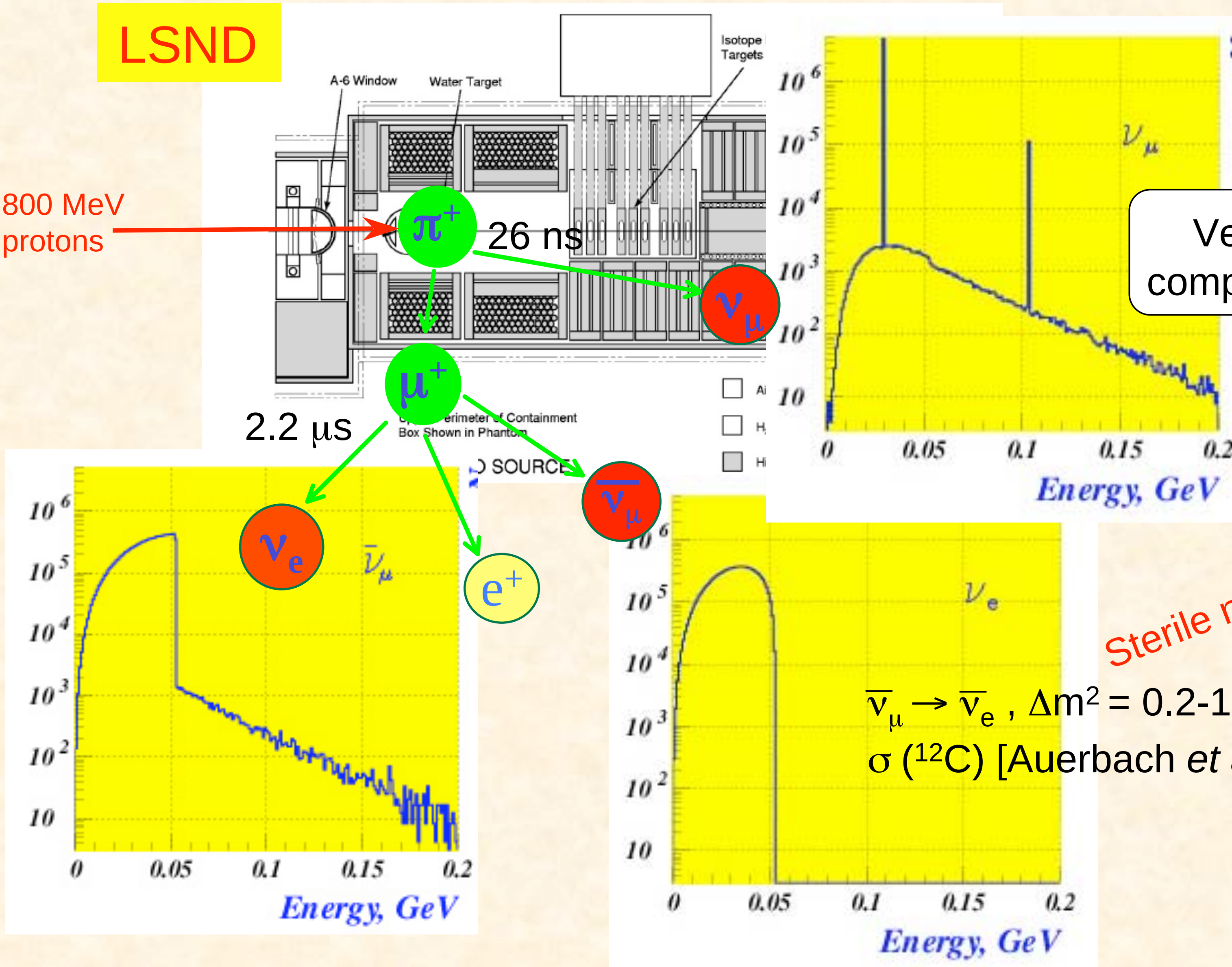
Opportunities with stopped-pion neutrinos at the SNS

J. C. Blackmon, Physics Division, ORNL

on behalf of the νSNS collaboration

1. Stopped-pion neutrinos
2. Supernovae and neutrinos
3. νSNS overview
4. Potential instruments & physics
   - νA coherent scattering
   - ν reaction cross sections I: liquids
   - Other standard model physics
   - ν reaction cross sections II: solids
   - Prototype testing
5. Backgrounds
6. Outlook

LSND at LANSCE (LANL)

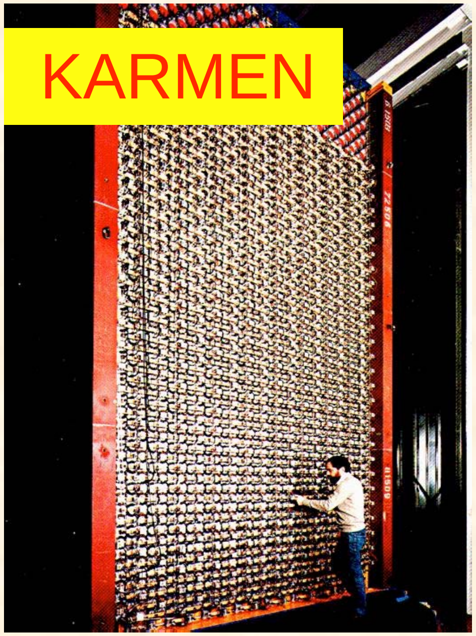


Very small $\bar{\nu}_e$ component ($\sim 10^{-4}$)

Sterile neutrinos ?

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\Delta m^2 = 0.2\text{-}10\ eV^2$

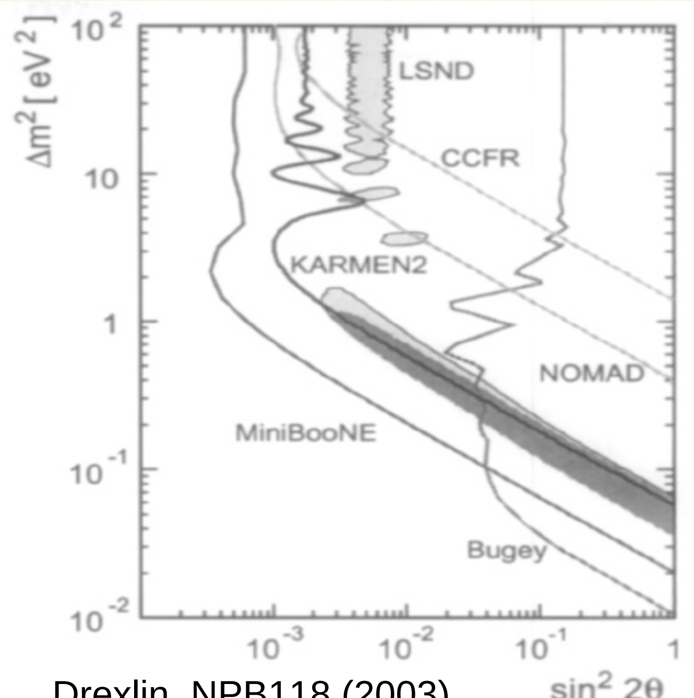
σ (^{12}C) [Auerbach *et al*. (2001)]



KARMEN at ISIS (RAL)

- KARMEN and LSND used similar techniques
  - Liquid scintillator
  - $\overline{\nu}_e + p \rightarrow n + e^+$
  - Prompt signal ⊗ correlated neutron capture

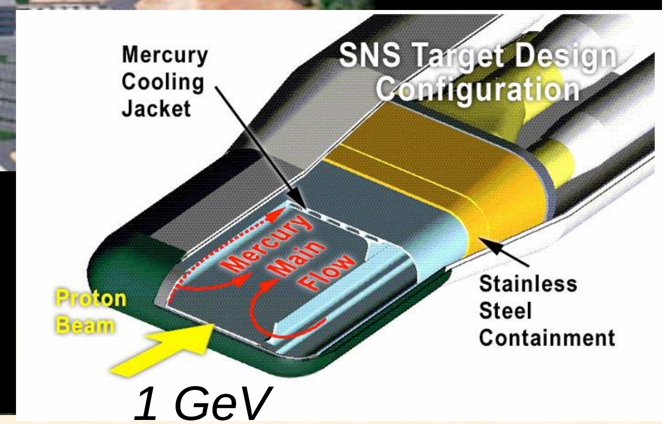
	LSND	***KARMEN***
# protons	28.9 C	9.4 C
Pulse width	600 μs	0.5 μs
In-flight	3%	Very low
baseline	30 m	18 m
events	32±9	< 5 (90%)
fraction (10^{-3})	2.64±0.67±0.45	< 0.85



Drexlin, NPB118 (2003)

- $\sigma_{cc}(^{12}C) = (8 \pm 1) \times 10^{-42}$ cm^2
  [Bodmann *et al*. (1992)]
- Also ν+Fe (~40%) [Maschuw (1998)]

Spallation Neutron Source



Similar pulse structure to ISIS → greatly suppressed backgrounds

Currently operating at low power
100kW in FY07

Eventual operation > 1 MW (~FY09)

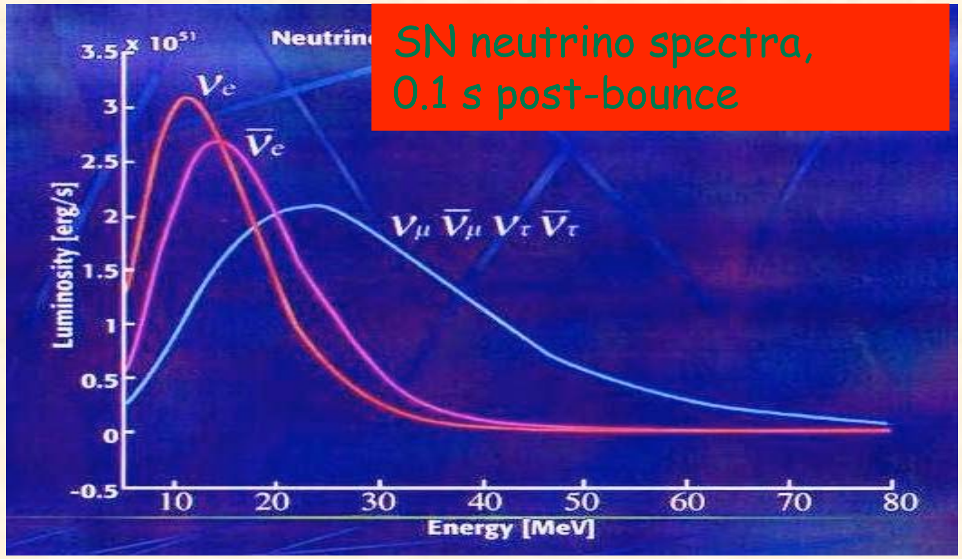
→ ~7x10^{12} π / spill
(~10x ISIS)

OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

SNS

SN 1987a
Anglo-Australian Observatory

Core-collapse supernovae



- Destruction of massive star initiated by the Fe core collapse

  10^{53} ergs of energy released

  99% carried by neutrinos with energies close to that from μ decay

- A few happen every century in our Galaxy, but the last one observed was over 300 years ago

- Dominant contributor to Galactic nucleosynthesis

- Neutrinos and the weak interaction play a crucial role in the mechanism, which is not not well understood

Electron capture and core collapse

- Electron capture and the charged-current ν_e reaction are governed by the same nuclear matrix element:

  ν_e + A(Z,N) ↔ A(Z+1,N-1) + e^-

- What are the rates?

  Gamow-teller strength distributions

  First-forbidden contribution

  g_A/g_V modifications by nuclear medium

- New calculations using a hybrid model of SMMC and RPA predict significantly higher rates for N>40

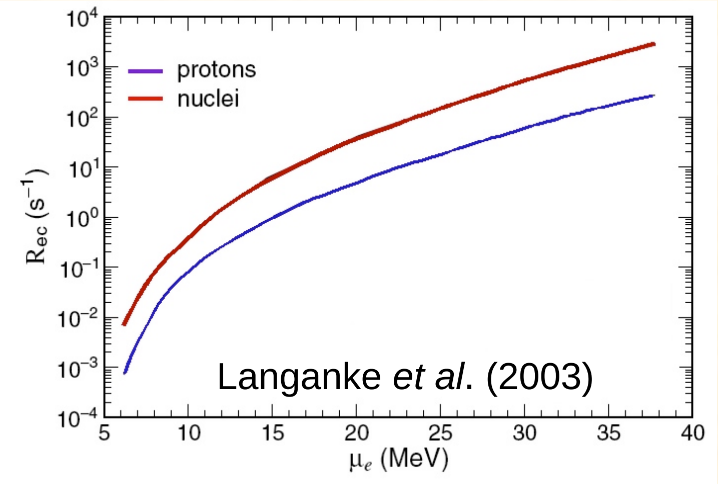
  mixing and temperature unblock $f_{5/2}$

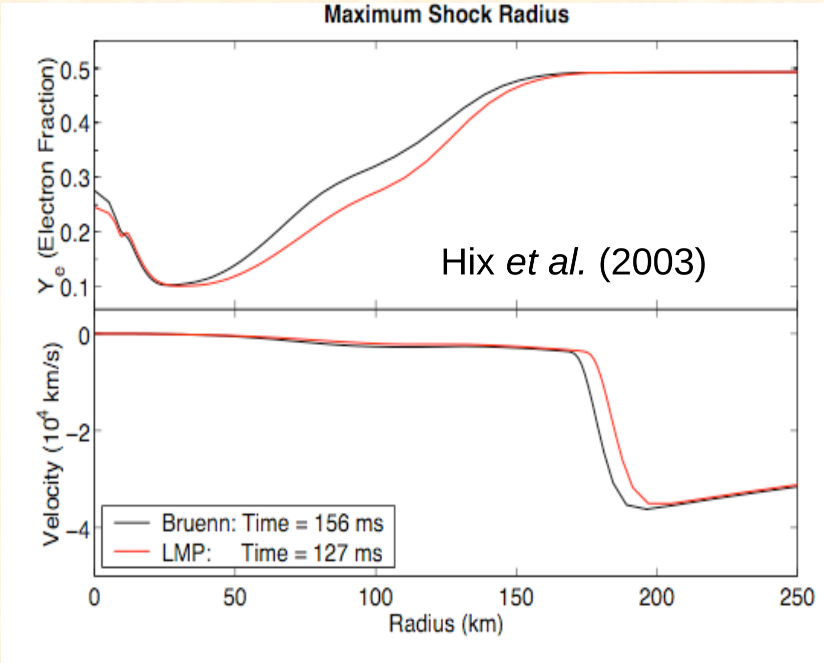
Hix, Messer, Mezzacappa, et al

- Supernovae models w/ new rates:

  shock starts deeper and weaker

  but less impedance





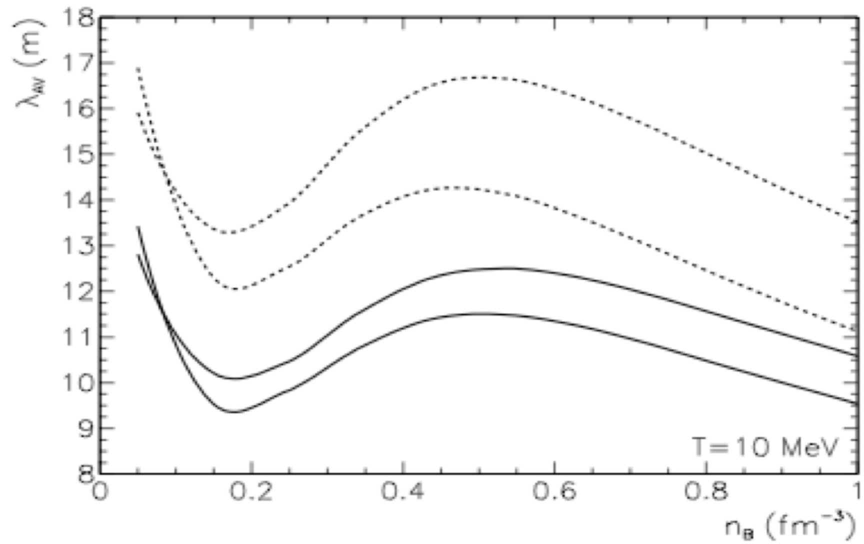
➡ The weak interaction plays a crucial role in establishing the dynamics of the supernova shock wave

ν opacities

- Prompt supernova mechanism fails
- Neutrinos interactions are believed to be crucial in the delayed mechanism
- Realistic treatment of ν opacities is required for supernova models

- Many ingredients
  - Charged-current reactions on free nucleons (and nuclei)
  - Neutral-current scattering
  - ν_e-e scattering
  - Inelastic processes
  - $\nu\nu$ scattering
  - $\nu-\nu$ annihilation

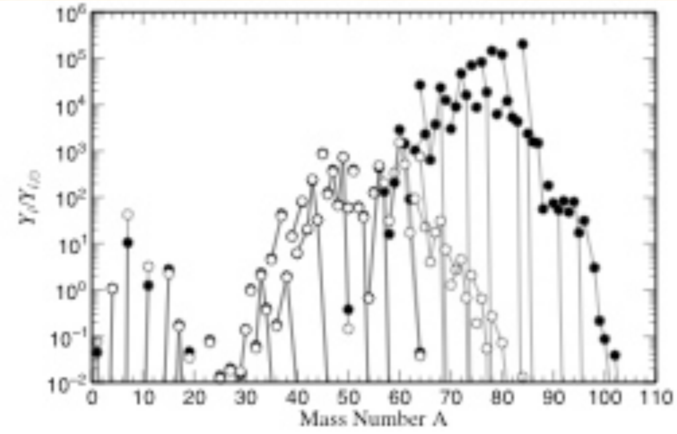
Horowitz and Pérez-García PRC 68 (2003)



Neutrino reactions and nucleosynthesis

- Neutrino reactions with nuclei ahead of the shock may alter the entropy & composition of infall → less resistance [Bruenn & Haxton (1991)].

- Neutrino reactions will alter distribution of iron peak elements. Cross sections are important for interpreting observations in metal-poor stars [Fröhlich *et al*., astro-ph/0410208 (2005)].

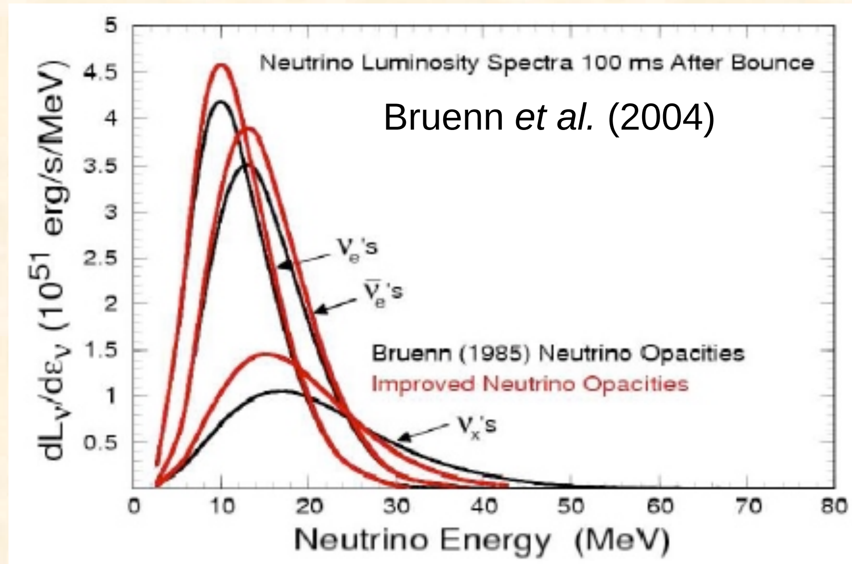


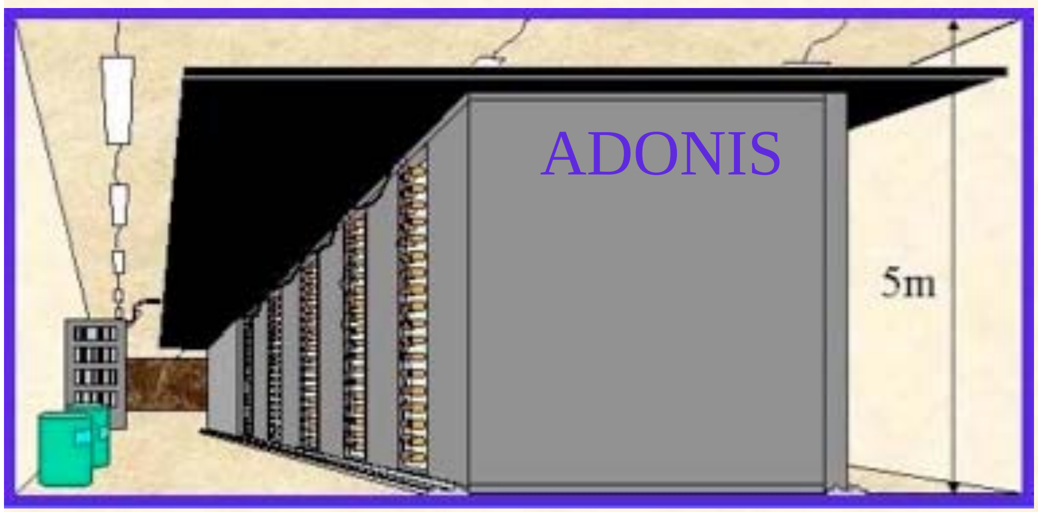
- In the outer layers, neutrino reactions may be the dominant source for boron & fluorine [Woosley *et al.* (1990)] and rare isotopes like ^{138}La and ^{180}Ta [Heger *et al.* (2005)]. Observed abundances may provide constraints on supernovae.
- Neutrino reactions may have an important influence on nucleosynthesis in the r process: setting the neutron-to-proton ratio and altering the abundance pattern [Haxton *et al.* (1997)]. Light p-process nuclei [Meyer *et al*. (2003)]?

ν-nucleus cross sections are important for understanding the supernova explosion mechanism and nucleosynthesis

Supernova ν observations

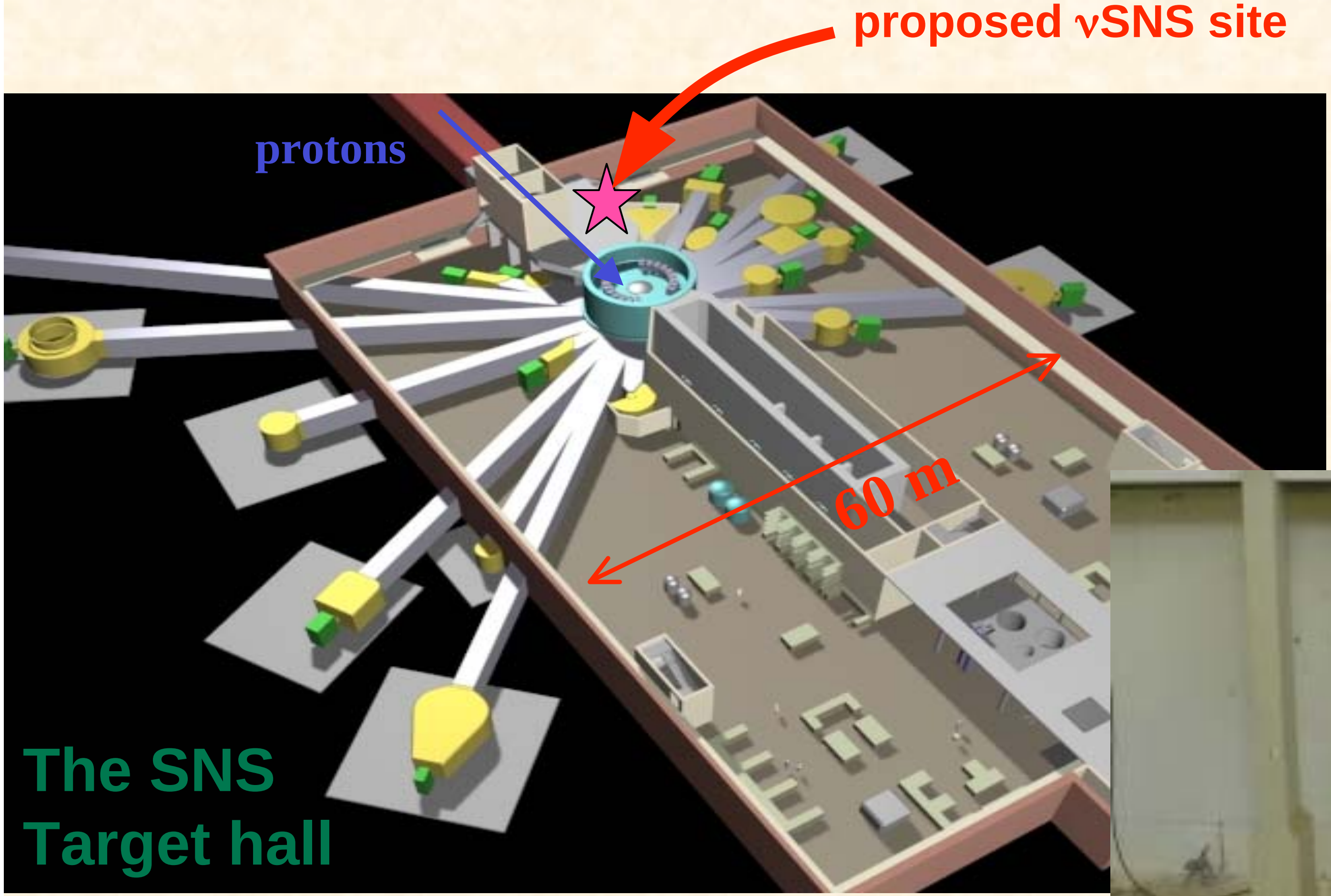
- Observations of supernova neutrinos provide us with a window into the conditions deeper within the explosion, i.e. below the photosphere.
- Measurement of the neutrino energy spectra from a Galactic supernova would provide a wealth of information on the conditions in supernovae, neutrino oscillations, etc.
- Nuclei of interest: ^{2}H, C, O, Pb





- An accurate understanding of neutrino cross sections is important for designing and interpreting measurements of neutrinos from supernovae.

A neutrino facility at the Spallation Neutron Source



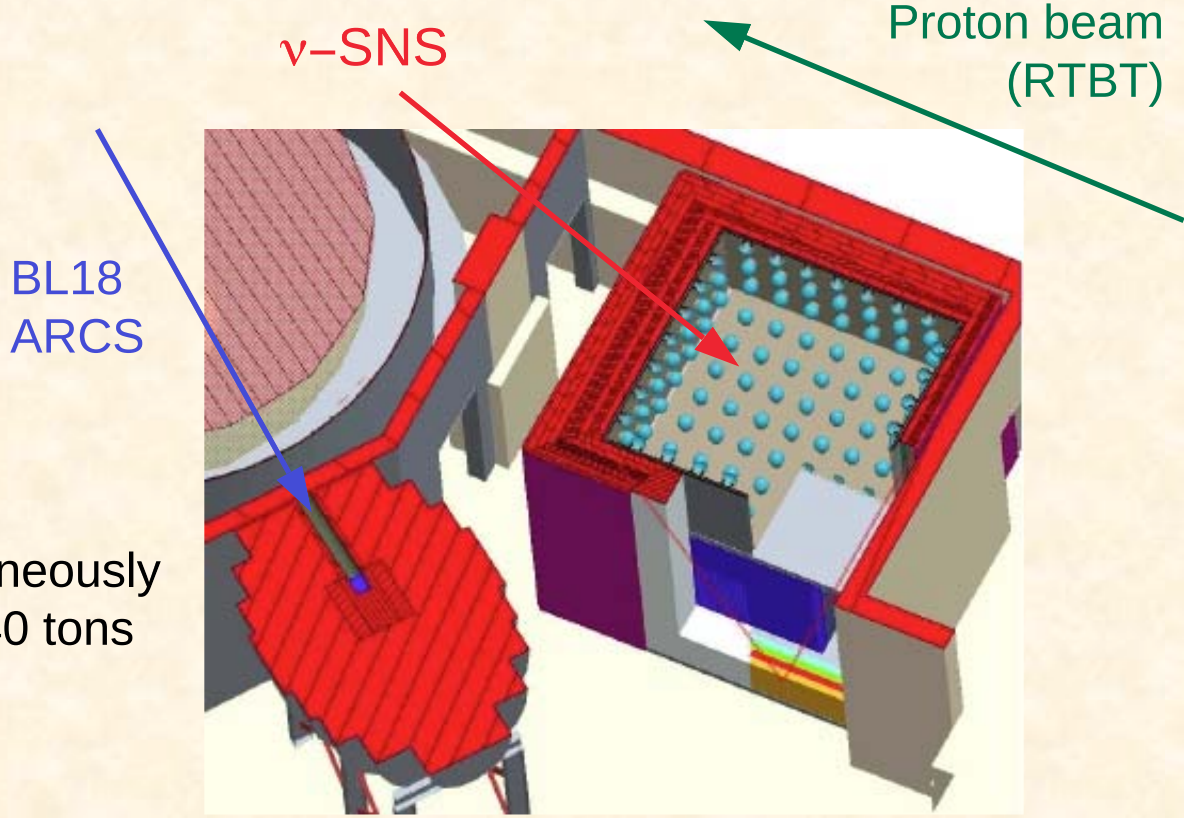
20 m² x 6.5 m (high)

Close to target ~ 20 m
→ 2×10^7 ν/cm²/s

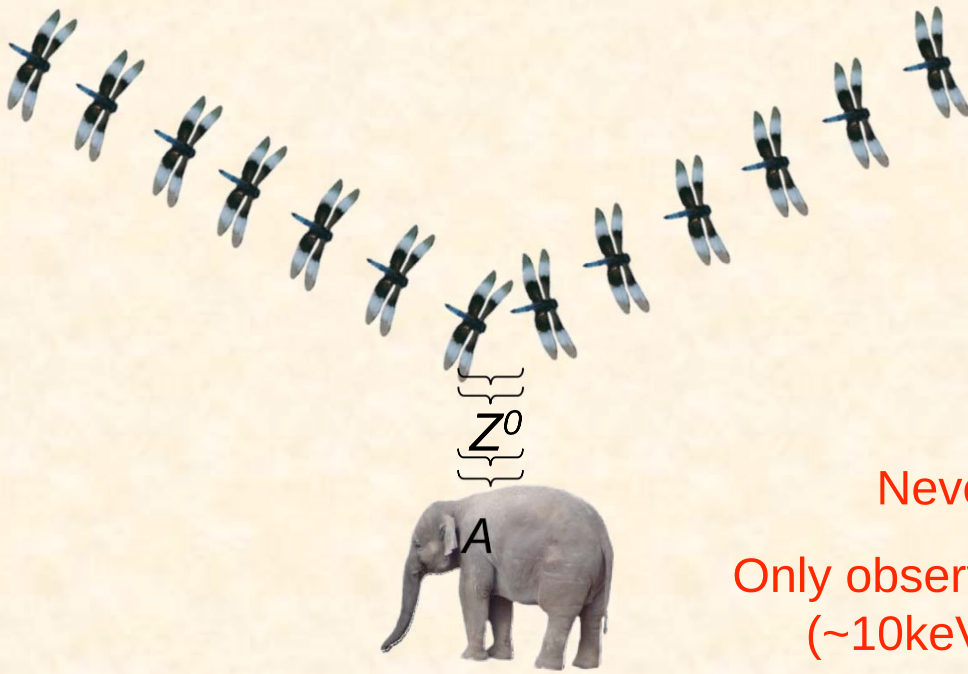
θ=165° to protons
→ lower backgrounds

ν–SNS facility overview

- Total volume = 130 m^3
  - 4.5m x 4.5m x 6.5m (high)
- Heavily-shielded
- 60 m^3 steel ~ 470 tons
  - 1 m thick on top
  - 0.5 m thick on sides
- Active veto
- ~70 m^3 instrumentable
- Configured to allow 2 simultaneously operating detectors of up to 40 tons
  - νA coherent scattering
  - 43 m^3 liquid detector
  - Segmented detector for solids
  - Prototypes



Coherent Scattering



Never measured

Only observable is low energy (~10keV) nuclear recoil

D.Z. Freedman PRD 9 (1974)

Straight-forward to calculate

Huge cross section > 10^{-39} cm^2

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

Important for supernova dynamics (neutrino opacity)

CLEAN

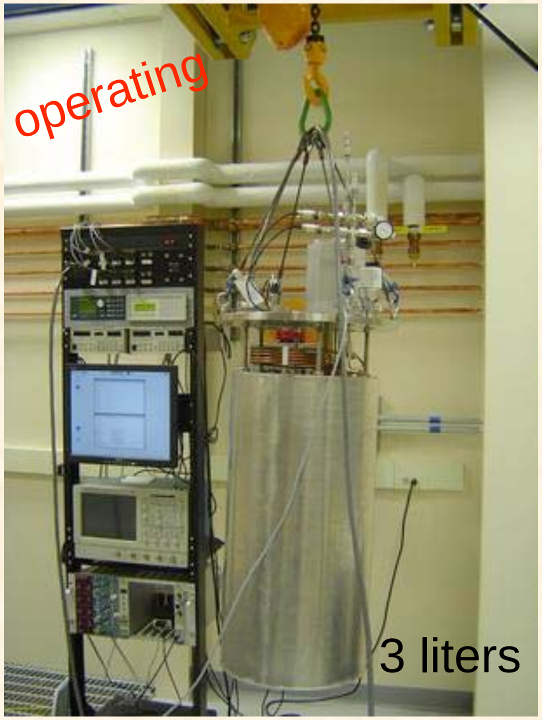
McKinsey et al.

Very high purity liquid Ne or Ar (scintillators)

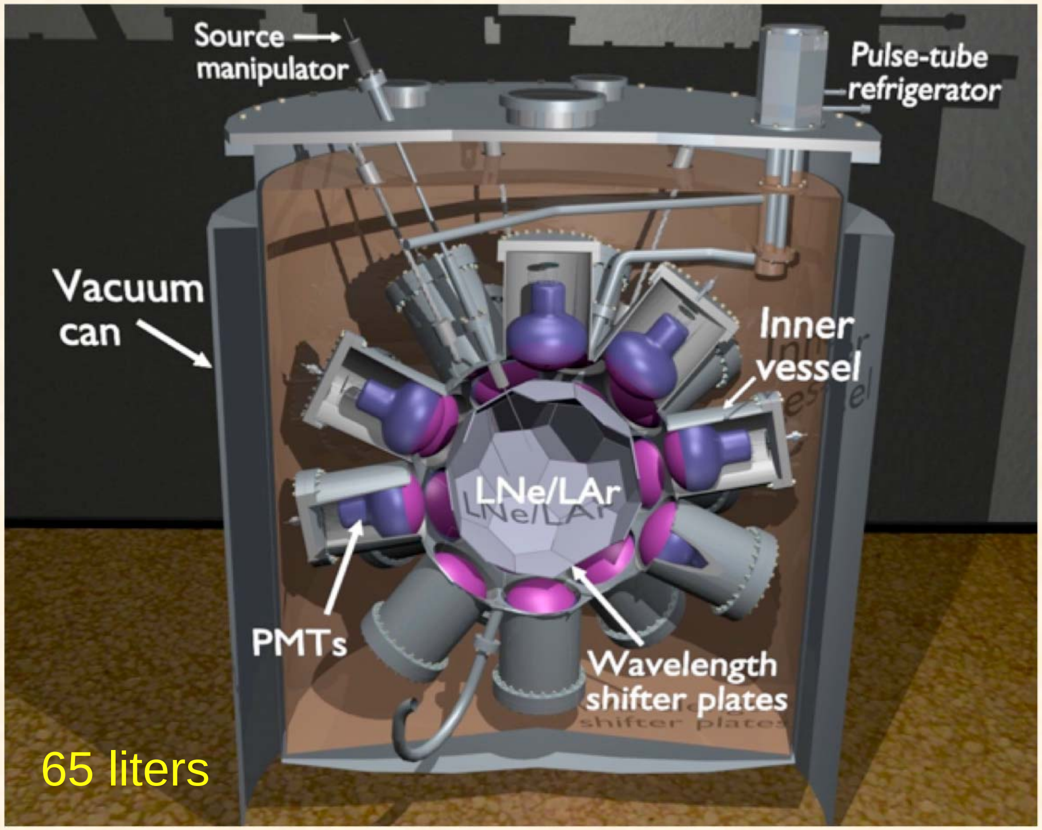
Good recoil/electron discrimination

100 ton device under development (SNO-Lab or DUSEL)

Micro-CLEAN

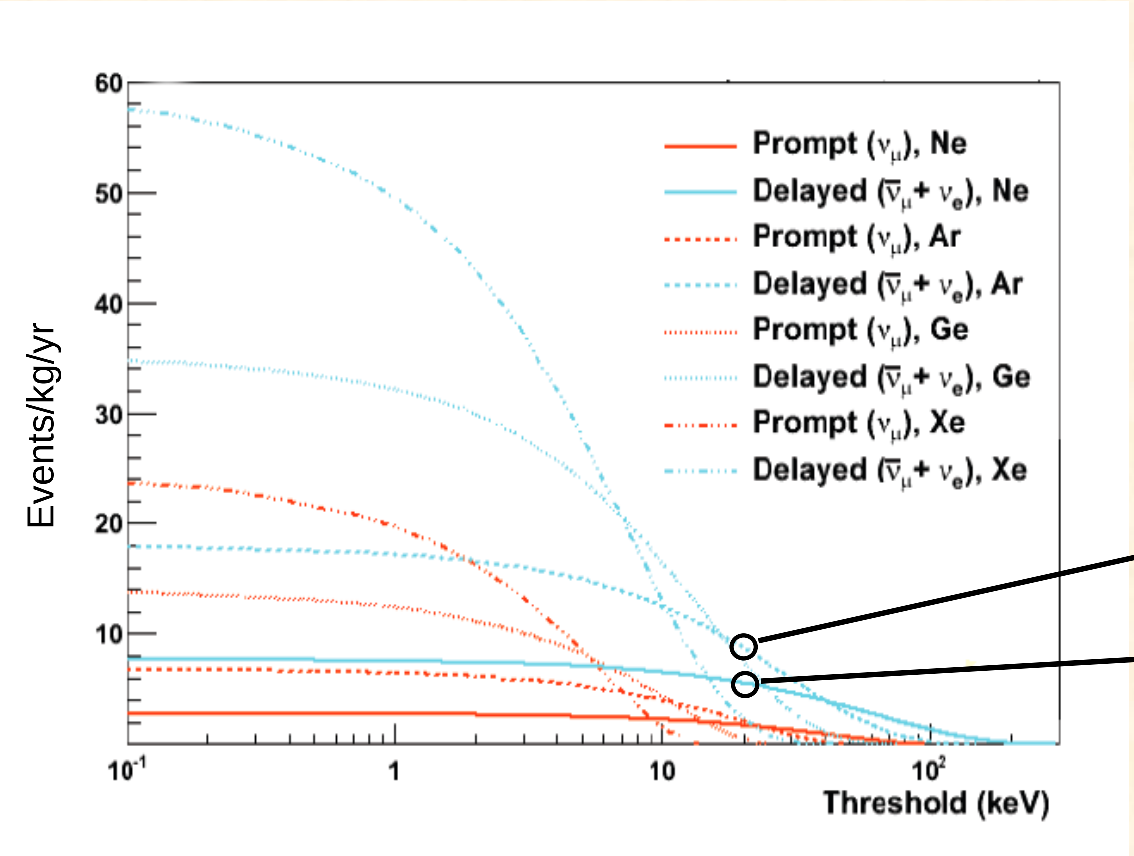


Mini-CLEAN under construction



νA scattering using mini-CLEAN at νSNS

Scholberg et al.



Mini-CLEAN event rate above 20 keV threshold

900 /yr in Ar

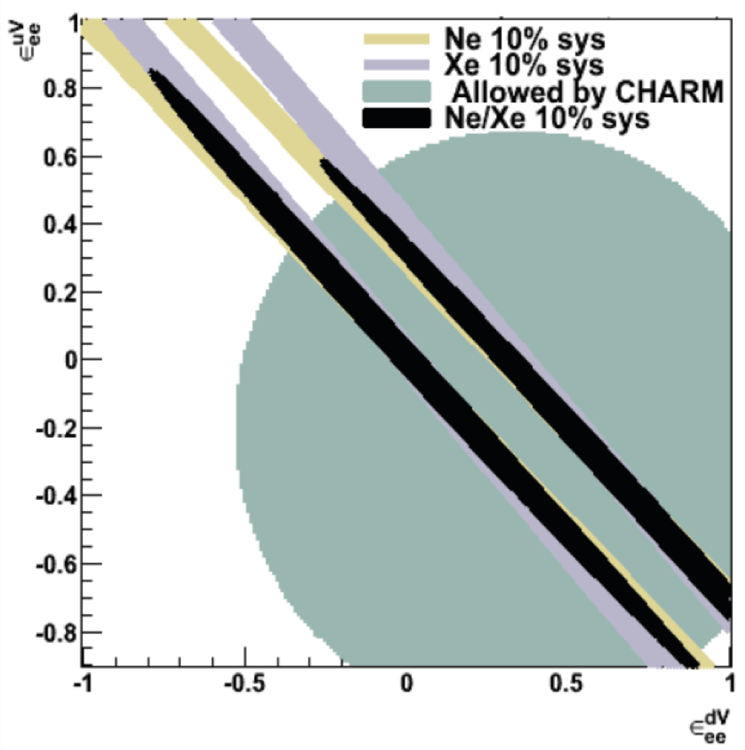
400 /yr in Ne

Background rates at E~10 keV at the SNS?

Testing the standard model σ

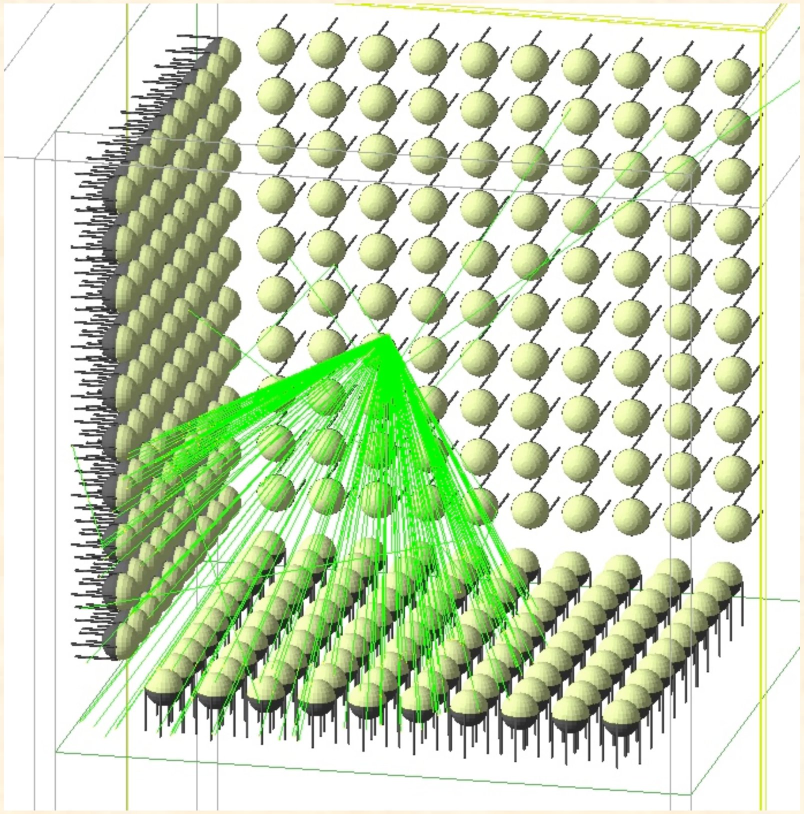
$$L^{NSI}_{\nu\, hadron} = \frac{-G_F}{\sqrt{2}} \sum_{q=u,d;\alpha,\beta=e,\mu,\tau} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5) \nu_\beta] \times (\epsilon^{qL}_{\alpha\beta} [\bar{q} \gamma^\mu (1-\gamma^5) q] + \epsilon^{qR}_{\alpha\beta} [\bar{q} \gamma^\mu (1+\gamma^5) q])$$

Substantial improvements in the limits on certain nonstandard interactions can be obtained with 10% measurements of the the coherent scattering cross section



Homogeneous detector

- 3.5m x 3.5m x 3.5m steel vessel (43 m^3)
- 600 PMT's (8" Hamamatsu R5912)
  - → Fiducial volume 15.5 m^3 w/ 41% coverage
- Robust well-understood design
  - LSND
  - MiniBoone



- Potential experiments
  - – 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)

Performance

Geant4 Monte Carlo simulations ongoing

- $\delta E/E \sim 6\%$

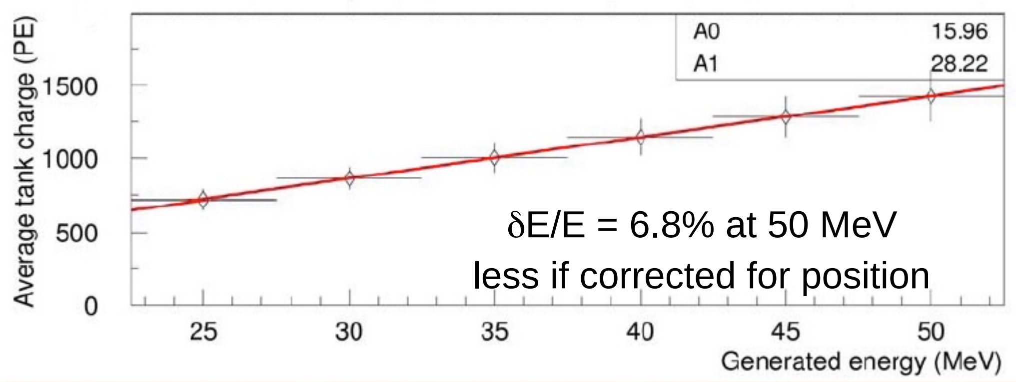
- $\delta x \sim$ 15-20 cm

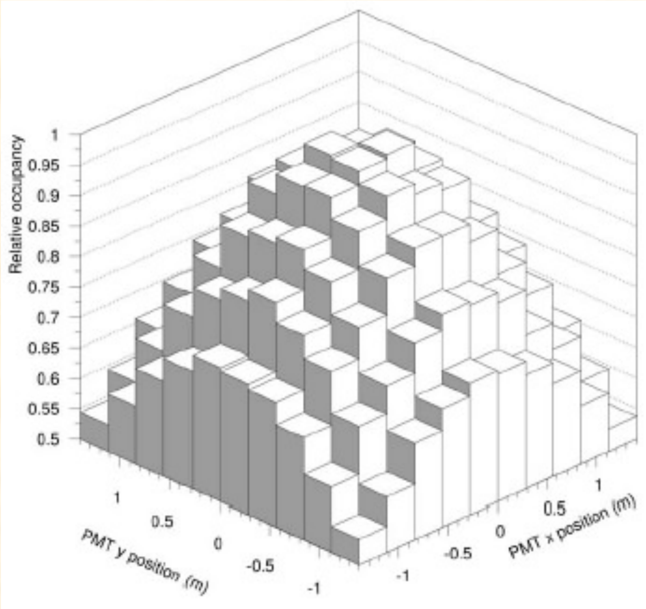
- $\delta\theta \sim 5° - 7°$

- Neutron discrimination?

- Layout and coverage

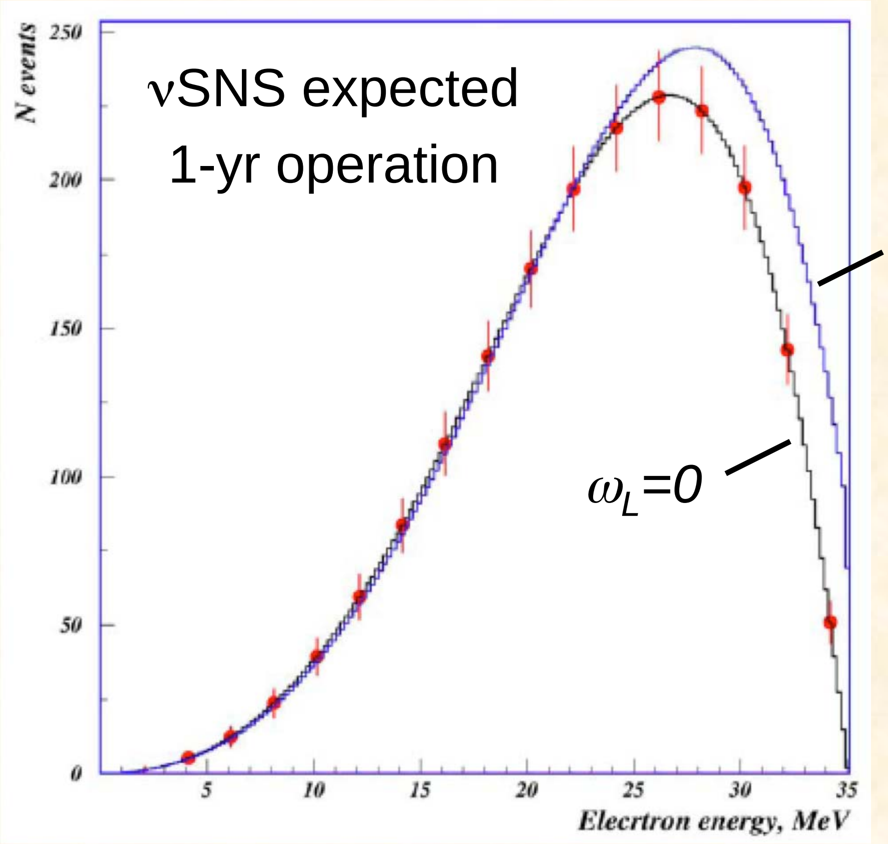
- More compact photosensors
  60% of mass lost to fiducial cut





Other standard model tests

- Shape of the ν_e spectrum from μ decay is sensitive to scalar and tensor components of the weak interaction



$$dN_{\nu_e}/dx = \frac{G_F^2 m_\mu^5}{16\pi^3} Q_L^\nu (G_{0(x)} + G_1(x) + \omega_L G_2(x))$$

ω_L=*0.11* KARMEN upper limit

Armbruster *et al*., PRL81 (1998)

- We should substantially improve the limit on ω_L with only 1 year of data

Other standard model tests

- Some models predict muon decay branches that violate lepton flavor-number conservation at the levels of up to 10^{-4}

$$\mu^+ \rightarrow e^+ + \overline{\nu}_e + \nu_\mu$$

- Such decays could account for a fraction of the LSND signal.

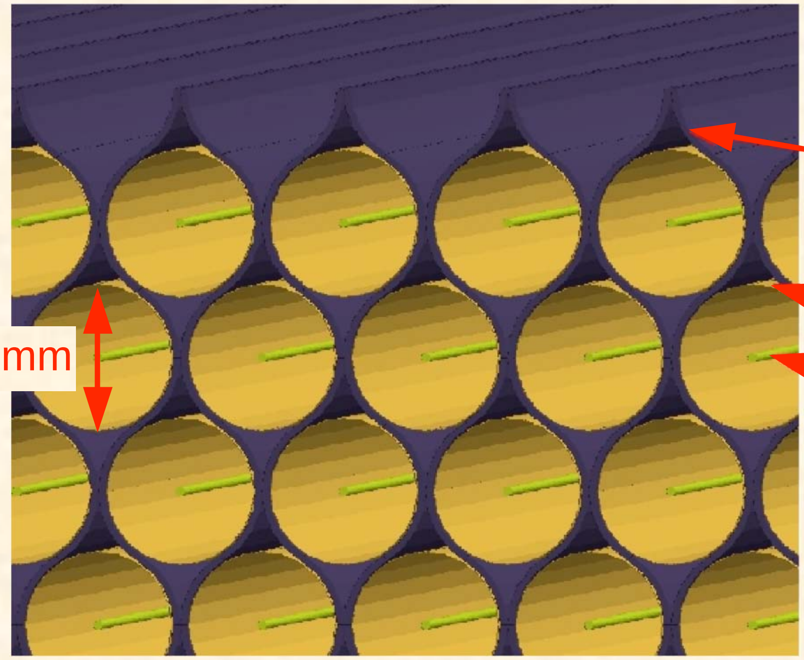
$\overline{\nu}_e$ branching ratio (10^{-3})	
LSND	2.65 ± 0.67 ± 0.45
KARMEN	< 0.85

Simulated νSNS rate with b.r.=1

Target material:	Mineral oil	Water
$\bar{\nu}_e$ events/year	31400	32300
with fiducial cut	12900	13200
and combined efficiency	3200	3300

- Simulations indicate the background rate at the SNS may be substantially lower than at KARMEN
  - $^{12}C(\nu_e,e)^{12}N$ eliminated with H_2O
  - $\overline{\nu}_e$ background reduced ~2x.
- Expect branching ratio limit to be reduced by ~2x in 2 years

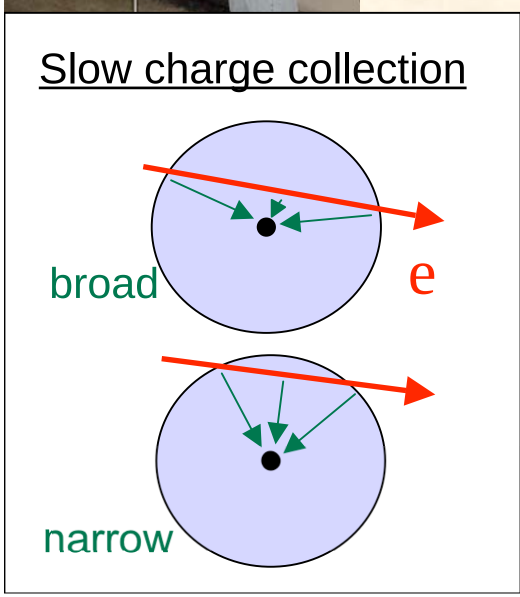
Segmented detector

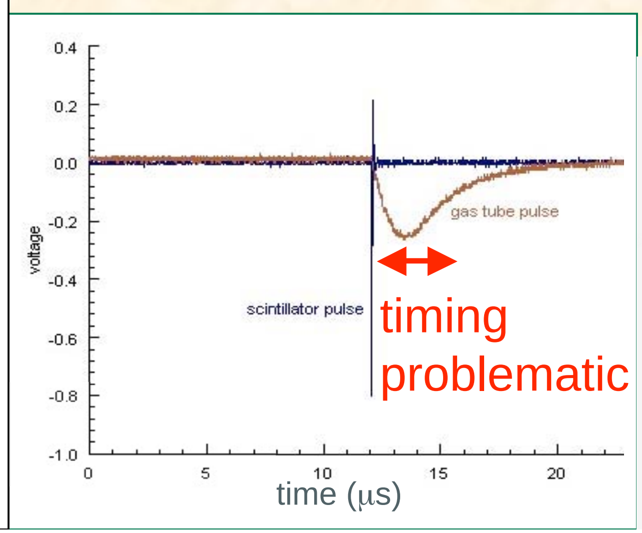


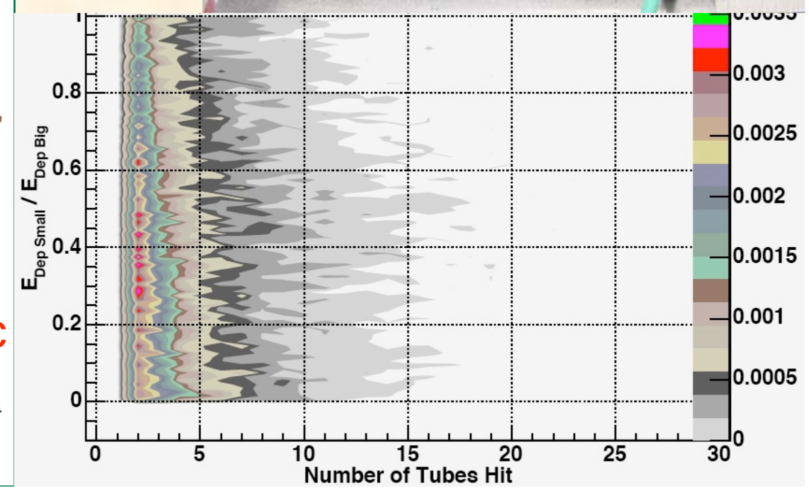
- Target - thin corrugated metal sheet (e.g. 0.75 mm-thick iron)
  - Total mass ~14 tons, 10 tons fiducial
  - Other good metal targets: Al, Ta, Pb
- Detector
  - $1.4x10^4$ gas proportional counters (strawtube)
  - 3m long x 16mm diameter
- 3D position by Cell ID & charge division
- PID and Energy by track reconstruction
- Expected Precision
  - 1100 events/yr ν_e+Fe→Co+e^-
  - 1100 events/yr ν_e+Al→Si+e^-
  - 4900 events/yr ν_e+Pb →Bi+e^-

Strawtube R&D

- Currently testing prototypes
  - Diameters between 10-16 mm
  - Lengths ranging up to 2 m
  - Gases (Ar-CO_2, Isobutane, CF_4)
- Measure resolution with cosmic muons
  - Energy, position, time
- How much can time resolution be improved using pulse shape information?
- Simulations to improve the fast neutron discrimination.







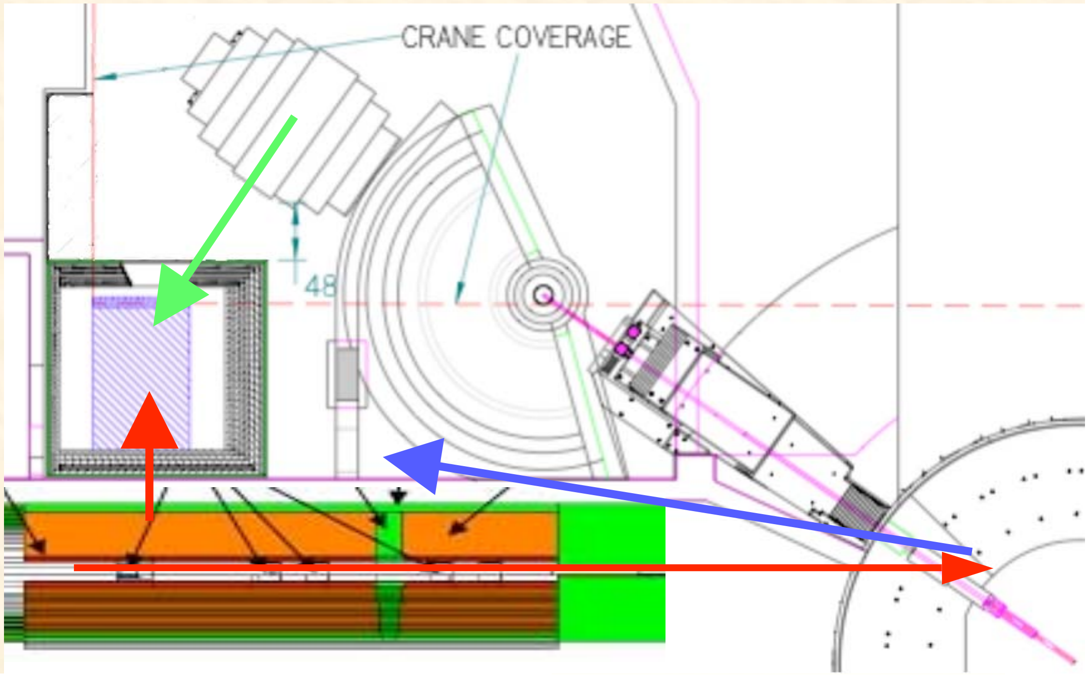
Backgrounds

- Uncorrelated
  - Cosmic rays
    - Muons → neutrons
    - Neutrons
  - Cosmogenic activity
  - SNS activation
  - Natural radioactivity

Reduced by ~ 6×10^{-4}

(60 Hz * 10 μs)

- Correlated prompt
  - Beam loses in RTBT
  - From the SNS target
  - Neighboring instruments
- Multiply-scattered neutrons



Cosmic rays

- Problem: μ + Fe → n + X

  2900 μ/s * 6×10^{-4} → 1.7 Hz coincident

  99% efficient veto → 3% of beam spills vetoed

  Untagged muons:

  63 untagged muons/hour in coincidence

  ~2% produce fast neutrons traversing detector

  30 fast neutrons /day (11000 /year)

  Must be further reduced by detector signatures

  Can be very accurately characterized

Need high efficiency veto

- Cosmic ray neutrons

  ~ 60 n/s * 6x10-4 → 3100 /day coincident

  Only reduced by shielding → sets scale for bunker

  1-m-thick steel ceiling reduces flux by 10^2

  → 30 fast neutrons/day

  leaves ~ 40 m^3 of shielding for sides

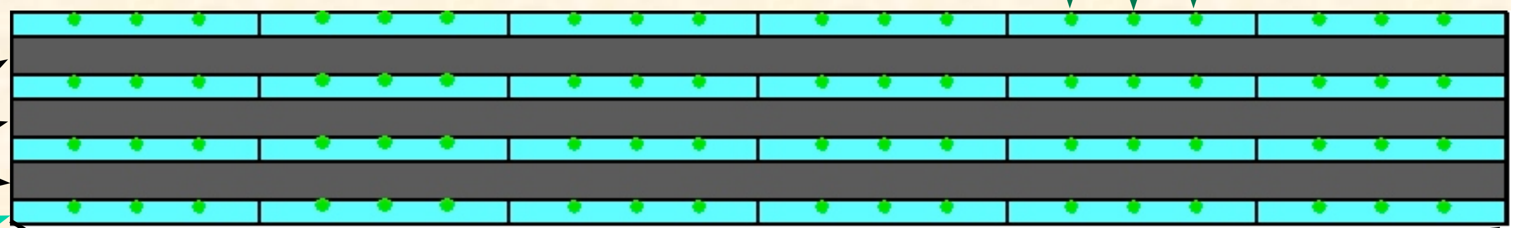
  → 0.5-m-thick walls on average

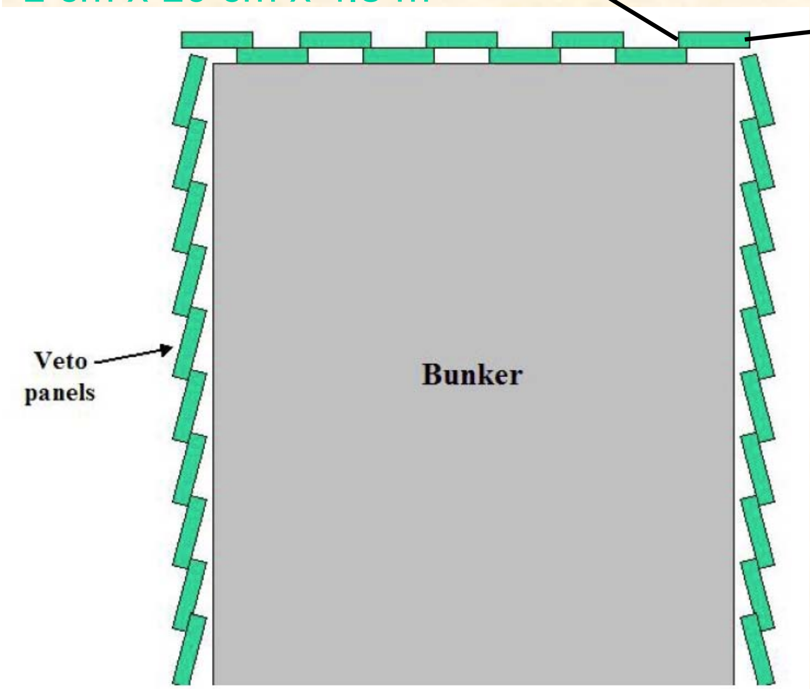
Cosmic ray veto

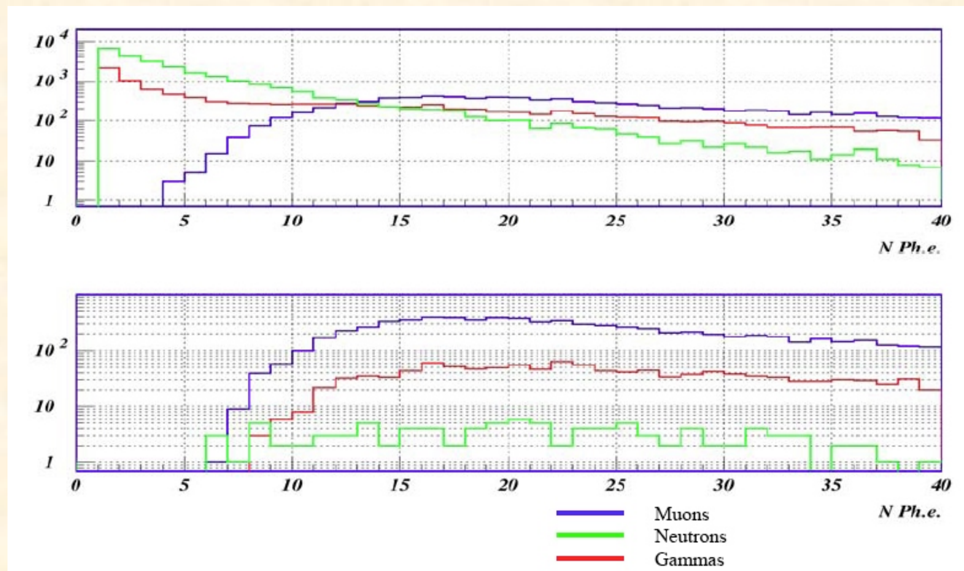
wave-length shifting fibers
read out by multi-anode PMT

1.5 cm iron

extruded scintillator
1 cm x 10 cm x 4.5 m





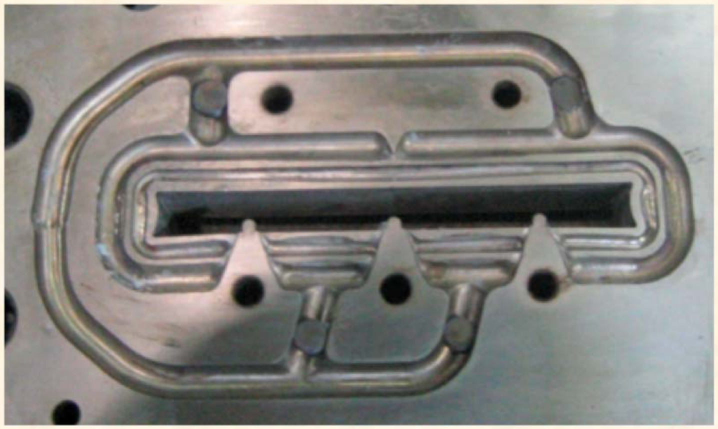


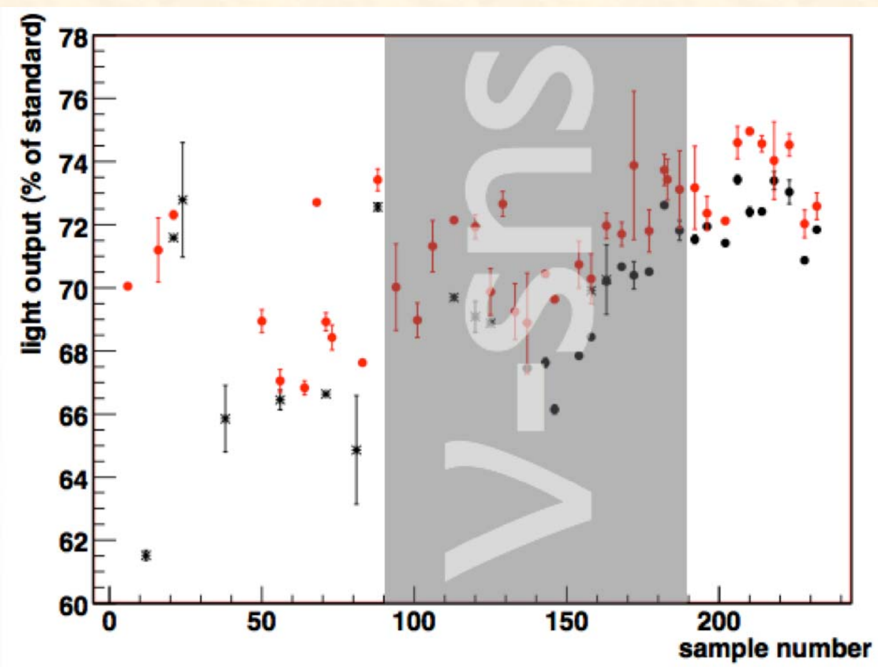
- Efficiencies
  - muons ~99% muons
  - gamma = 0.005%
  - neutron =0.07%

November 2005 production

- In collaboration with MECO

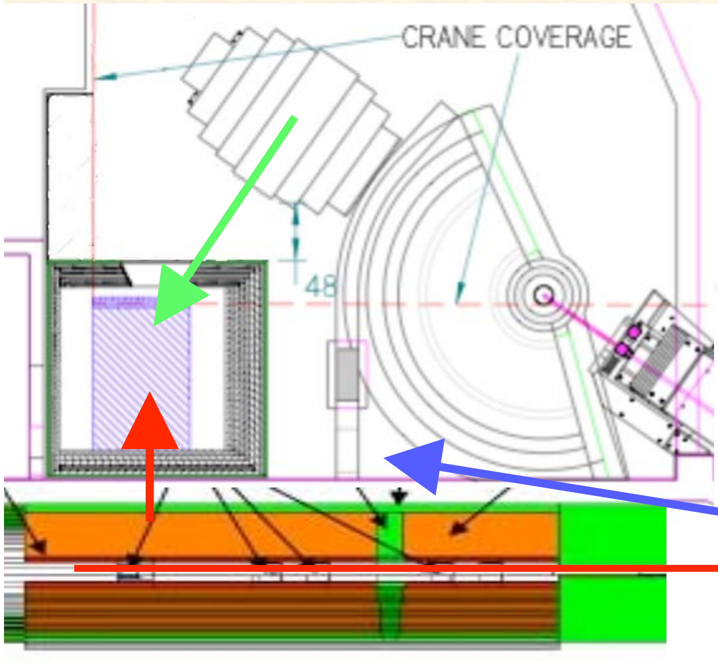
  100 x 4.5-m planks extruded for νSNS

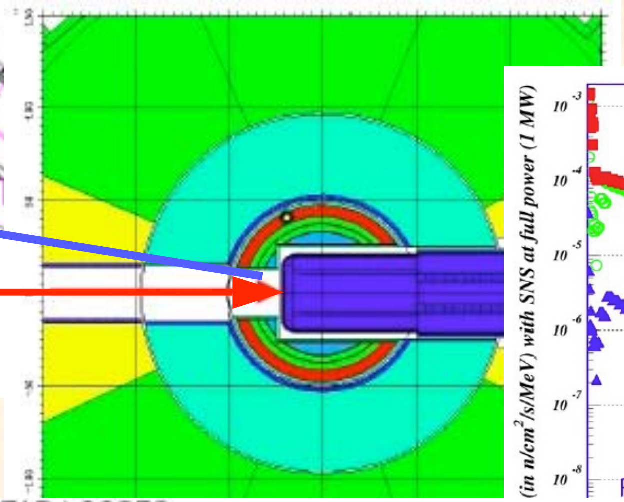


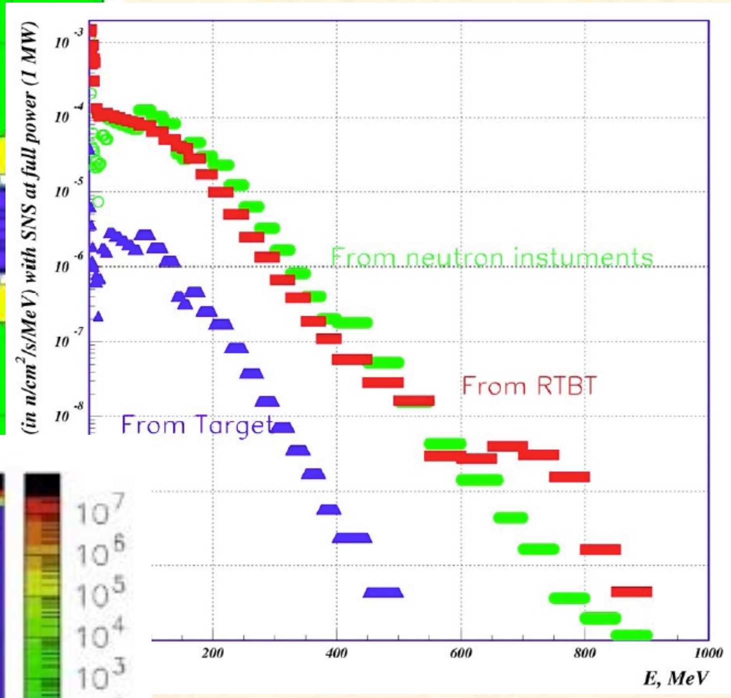


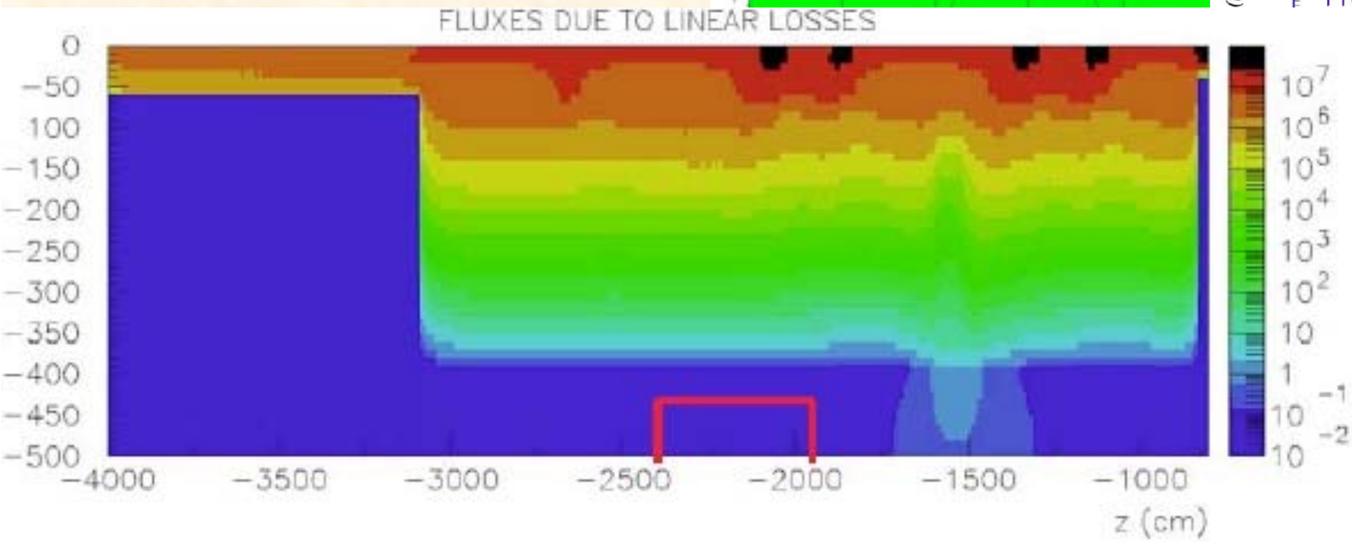
SNS Neutrons

- Three sources considered:
  - Direct neutrons from SNS target
  - Scattered neutrons from BL17/18
  - Neutrons from beam losses in the RTBT

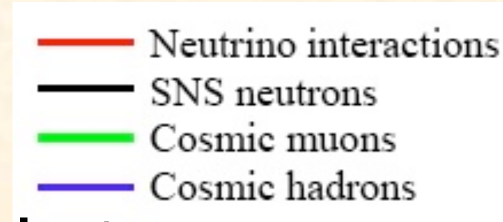


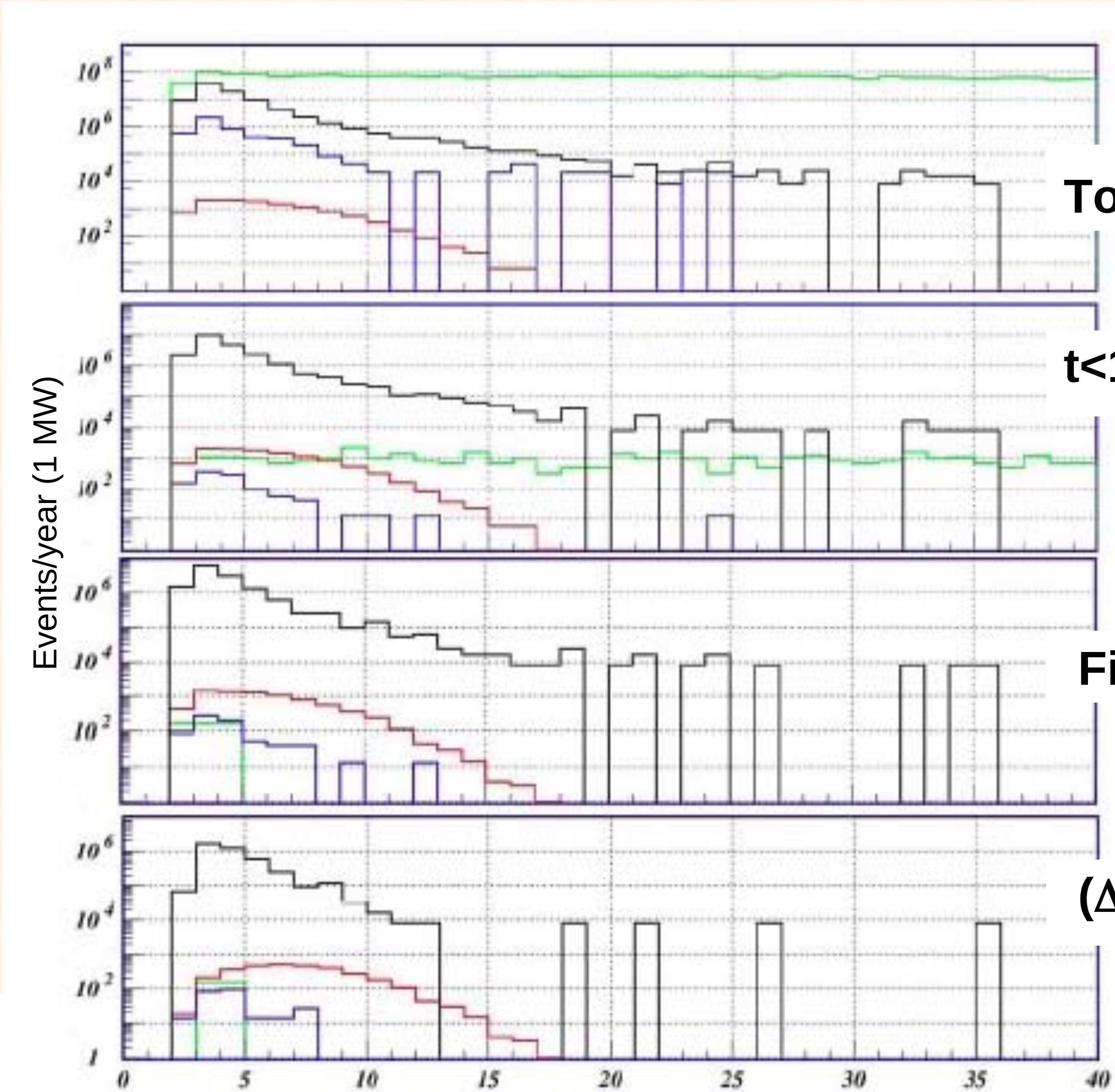






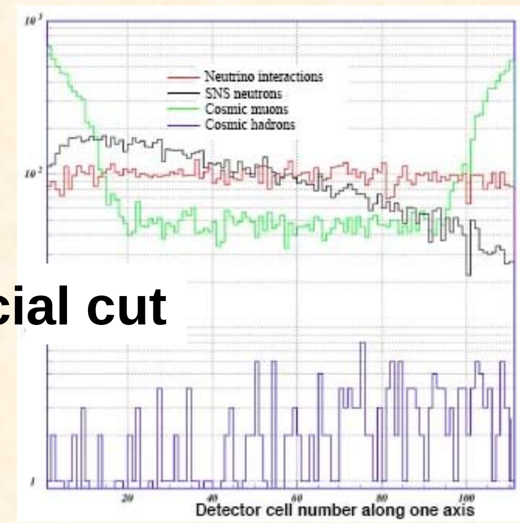
Segmented Performance: $\nu_e + Fe \rightarrow Co + e^-$





Total rate

t<10μs & no veto (98%)



Fiducial cut

$(\Delta E/\text{cell})_{ave}$ < 10 keV

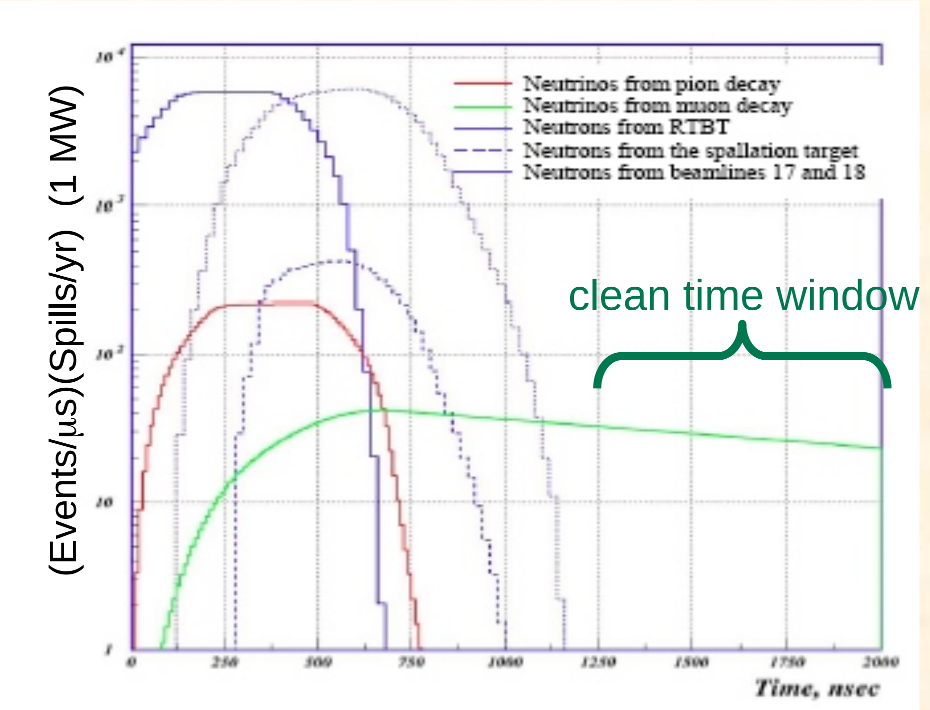
57% ν efficiency

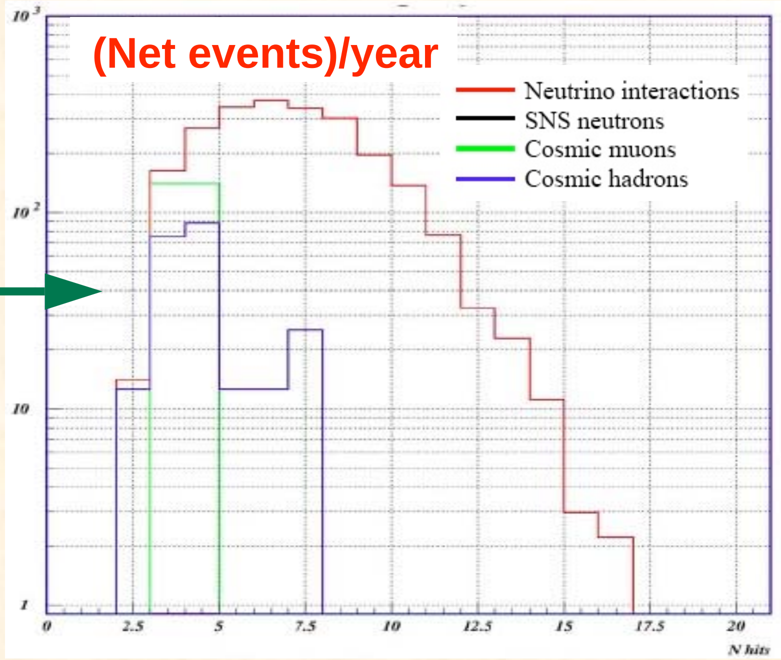
cosmics eliminated

Neutrons little reduced

Time cut

- Negligible fast neutron background expected after ~ 1 μs

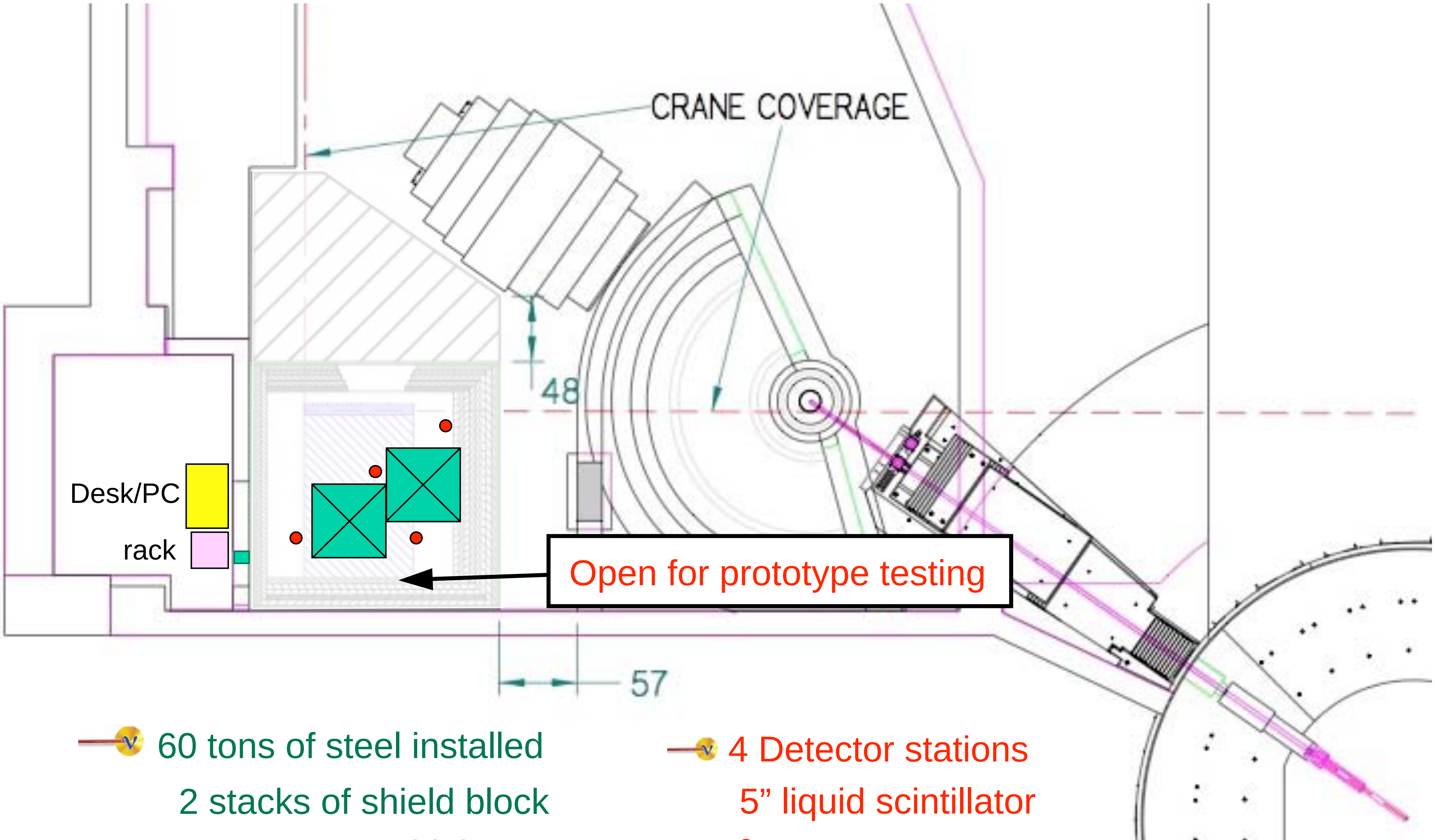




Crucial to understand neutron background, especially for t=1-10μs

Time cut (μs)	ν efficiency (%)
1.2-10.0	43
1.5-10.0	37
1.8-10.0	34
2.0-10.0	30

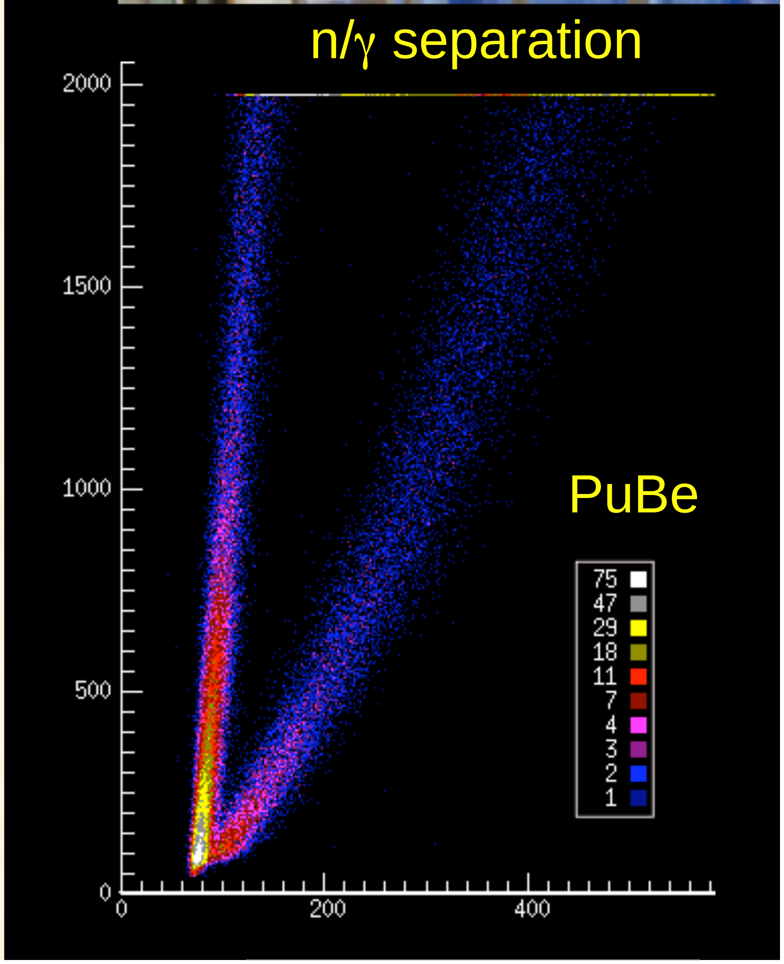
Background Studies Layout



- 60 tons of steel installed
  - 2 stacks of shield block
  - 52"x 52" x 60" high
- 4 Detector stations
  - 5" liquid scintillator
  - ^{3}He counters

Installation

- Block installation complete
- Detectors and data acquisition system now being installed
- Expect to be ready for SNS run cycle in October 2006

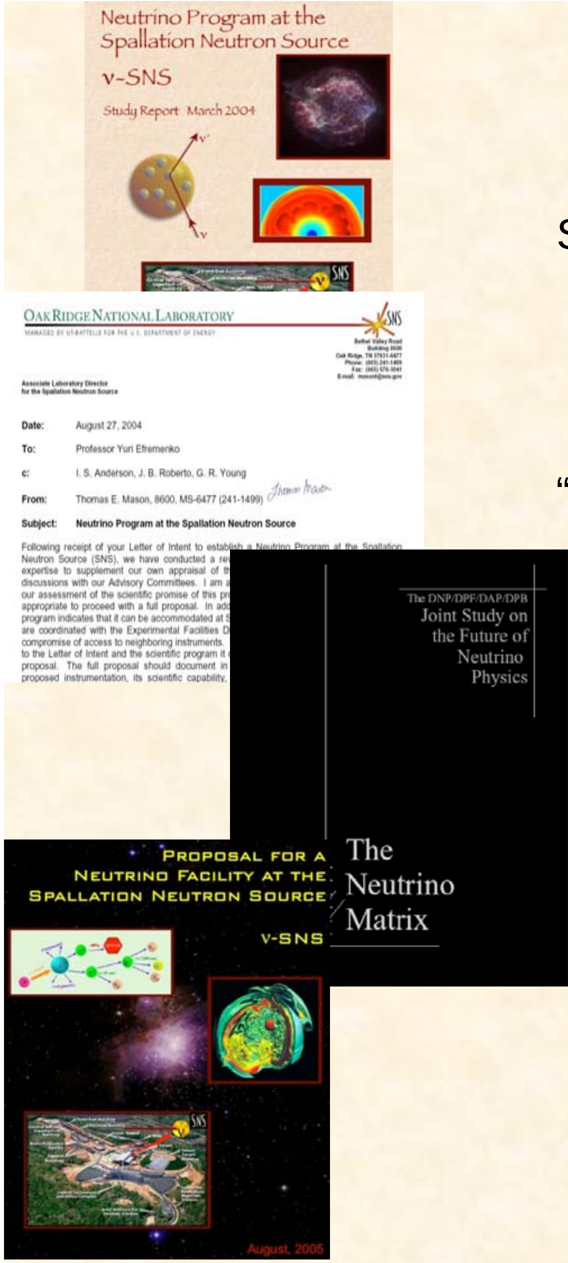


ν–SNS Collaboration

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

- Active, diverse collaboration
  - 20 institutions

System	*Lead*
Project manager	Efremenko (Tenn)
Bunker	Cianciolo (ORNL)
Segmented Detector	Hungerford (Houston)
Homogeneous Detector	Stancu (Alabama)
νA Scattering	Scholberg (Duke)
Veto	Greife (Mines)
SNS & Backgrounds	Blackmon (ORNL)
Theory	McLaughlin (NCSU) Hix (ORNL)



Timeline

March 2004
Study report completed
Letter of Intent to SNS

August 2004
"Green light" from SNS

October 2004
Neutrino Matrix

August 2005
Proposal submitted
Likely withdrawn

FY07
NSAC LRP

FY 2010-FY2011
Construction

Project Cost

Item	***$M***
Bunker	2.3
Veto	1.1
Segmented Detector	1.2
Homogeneous Detector	1.2
Mini-CLEAN	0.5
Cont. & Escl. (FY06$)	+50%

2. The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena, such as the existence of a neutrino magnetic dipole moment. Interpretation of atmospheric and long-baseline accelerator-based neutrino experiments, understanding the role of neutrinos in supernova explosions, and predicting the abundances of the elements produced in those explosions all require knowledge of neutrino cross sections. New facilities, such as the Spallation Neutron Source, and existing neutrino beams can be used to meet this essential need.

Summary & Outlook

- Neutrino scattering and reactions are important for understanding supernovae
  - Influence core collapse
  - Affect shock dynamics
  - Modify the distribution of iron-peak elements
  - May be the dominant source of B, F, ^{138}La, ^{180}Ta
  - Affect r process nucleosynthesis
- The combination of high flux and favorable time structure at the SNS can allow a diverse program of measurements
  - High statistics in less than 1 year of operation
- We have a strong collaboration of experimentalists and theorists
- We welcome new ideas and participation
- νSNS must figure into the NSAC Long-Range Plan if we are to capitalize on this opportunity
- See **http://www.phy.ornl.gov/nusns**