NuSNS:

Neutrino Cross-Sections at the Spallation Neutron Source

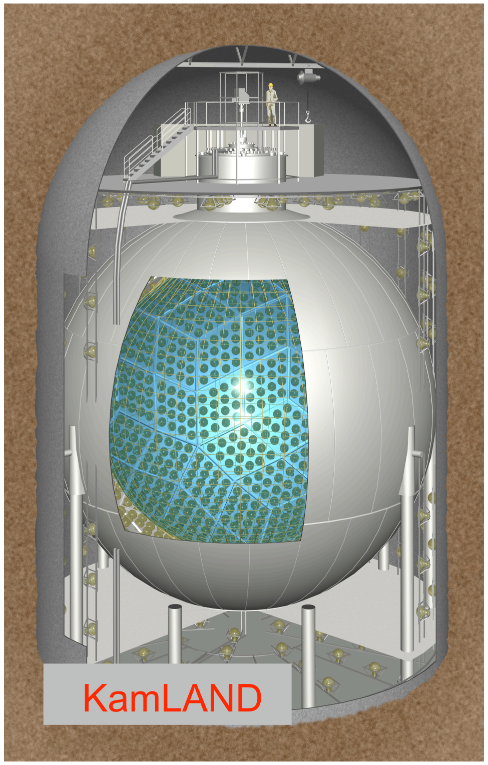
Ion Stancu
University of Alabama

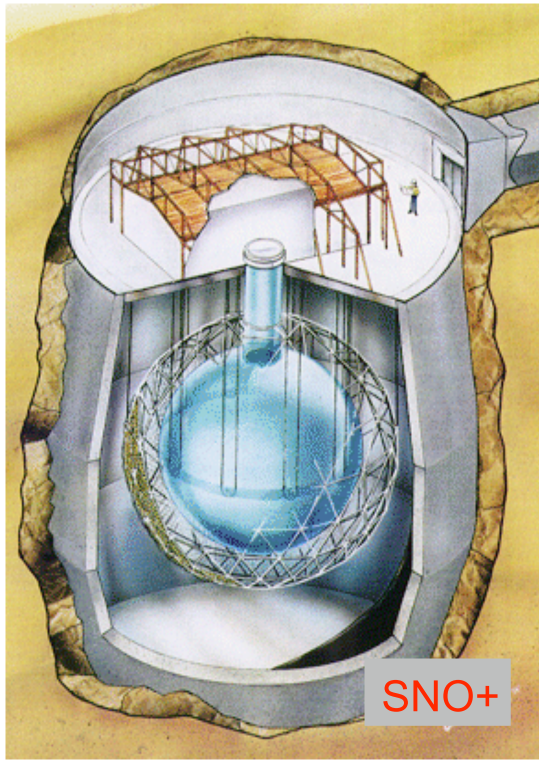
45th Karpacz Winter School/Workshop
Neutrino Interactions: from Theory to MC Simulations
Ladek-Zdroj, Poland (09-Feb-2009)

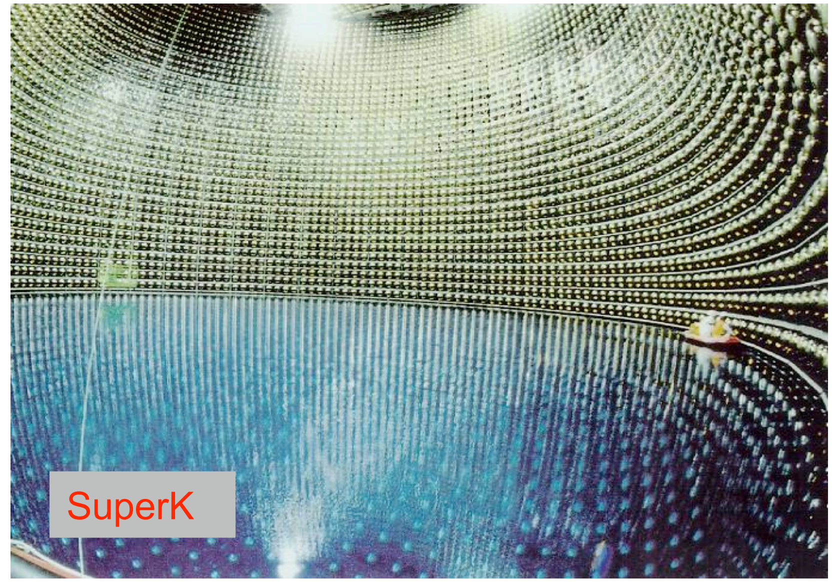
Core-collapse Supernovae

- Among the most energetic explosions in the Universe:
  - 1e+46 J of energy released
  - 99% carried by neutrinos
- A few happen every century in our galaxy, but last one observed over 300 years ago
- Dominant contributor to galactic nucleosynthesis
- Driven by the collapse of the iron core of a massive star, but the explosion mechanism is still not well understood
- Neutrino/electron capture on heavy nuclei plays an important role in all aspects of the core-collapse supernova problem:
  - explosion dynamics
  - nucleosynthesis
  - neutrino detection

SN Neutrino Observatories



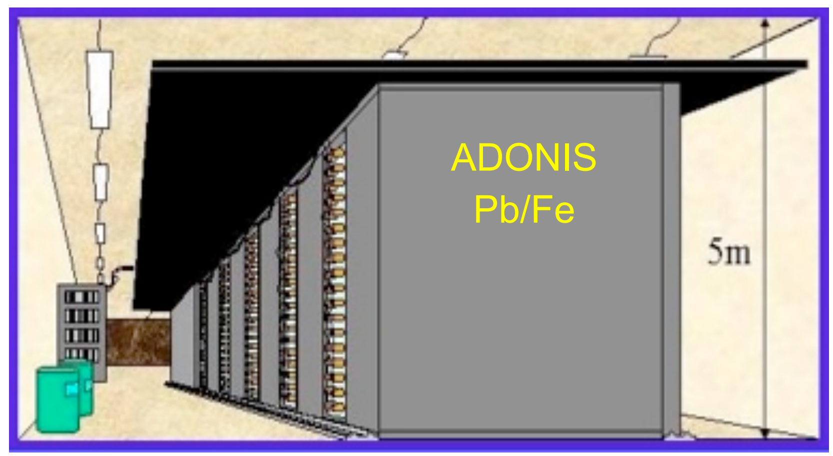




- Measurement of the ν energy spectra, timing, flavour from a galactic SN will provide a wealth of information on the conditions in SNe, neutrino oscillations, etc.

- When the next galactic SN occurs we will likely observe it with several detectors & nuclei.

- Accurate understanding of the neutrino X-sections is important for designing SN neutrino detectors and interpreting the results.



Many proposed experiments...

SN Neutrino Detection Channels

- Inverse β-decay reaction:
  - dominates for detectors with lots of free protons (water, scintillators);
  - only sensitive to $\bar{\nu}_e$;
  - good energy resolution, well-known XS, almost no directionality.

- Elastic scattering:
  - few % of the inverse β-decay, good directionality;
  - no flavour tagging, but well-known XS.

- CC interactions with nuclei:

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

  - probes only one flavour; XS not well known!

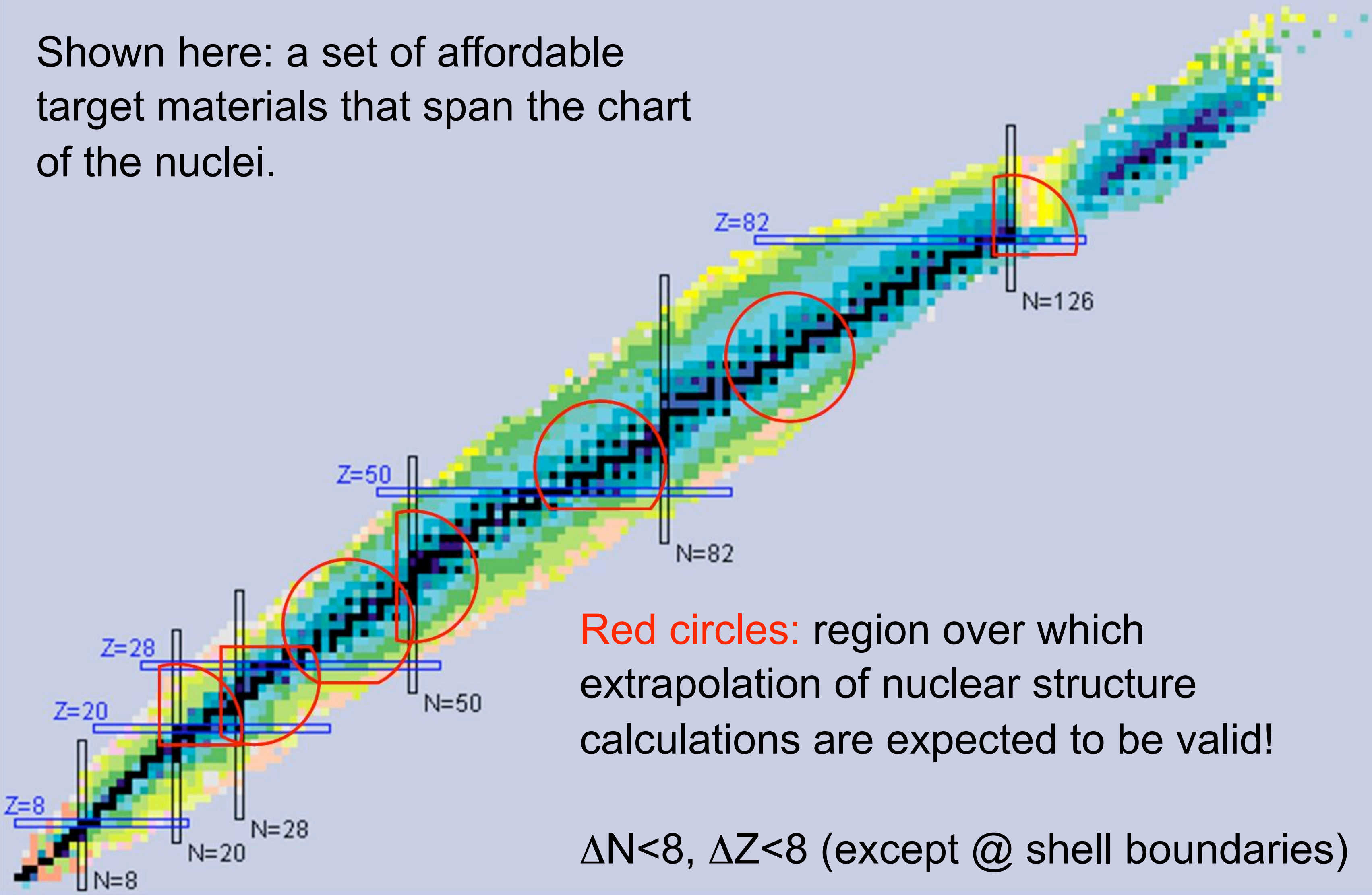
- NC interactions with nuclei:

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

  - probes all flavours; XS not well known!

Which Elements Are Needed?

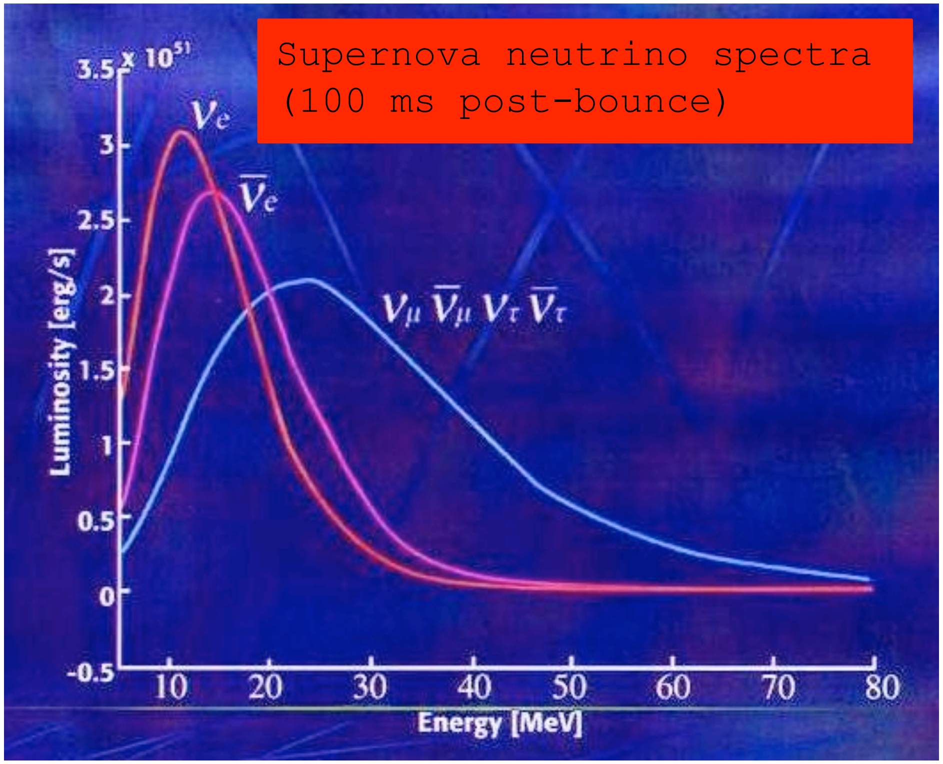
Shown here: a set of affordable target materials that span the chart of the nuclei.



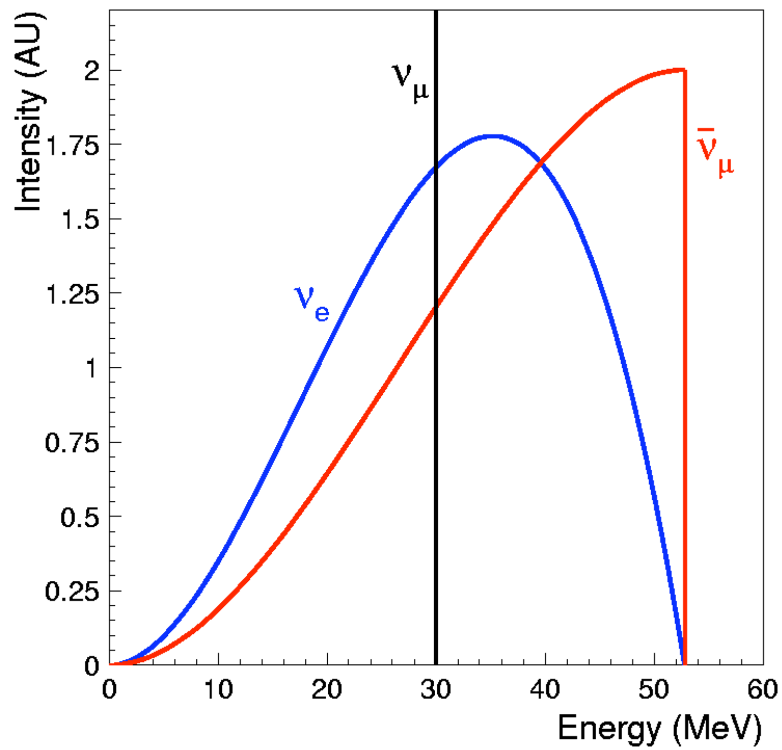
Red circles: region over which extrapolation of nuclear structure calculations are expected to be valid!

$\Delta N<8$, $\Delta Z<8$ (except @ shell boundaries)

Energy Spectra



SPF neutrino spectra

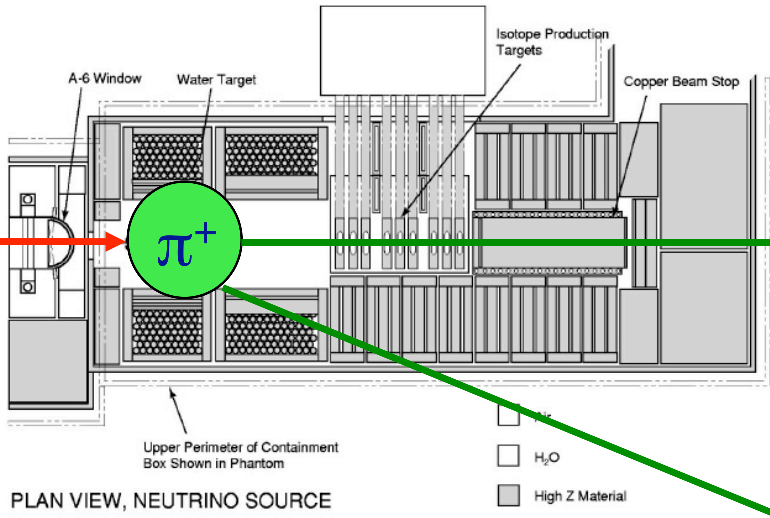


- Neutrino spectra at stopped pion facilities are well-defined and well-understood.
- They have significant overlap with the spectra of neutrinos generated in a SN explosion.

LSND @ LANSCE/LANL

Essentially all negative pions absorbed!

800 MeV protons

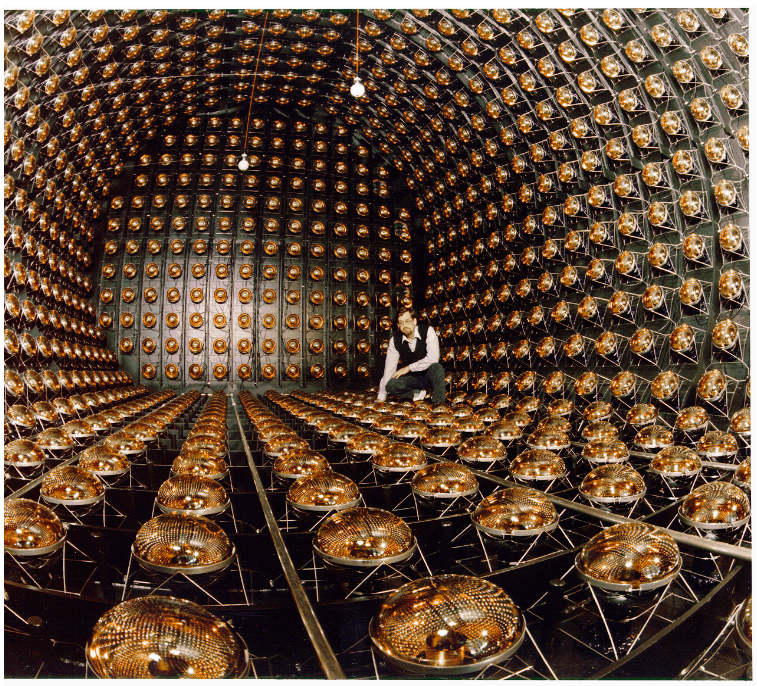


π^+ → ν_μ (τ = 26 ns)

μ^+ → $\bar{\nu}_\mu$ (τ = 2.2 μs)

ν_e

e^+



ν_e C → e^- X

σ = 13.2 ± 0.5 ± 1.3

units: 10^{-42} cm^2

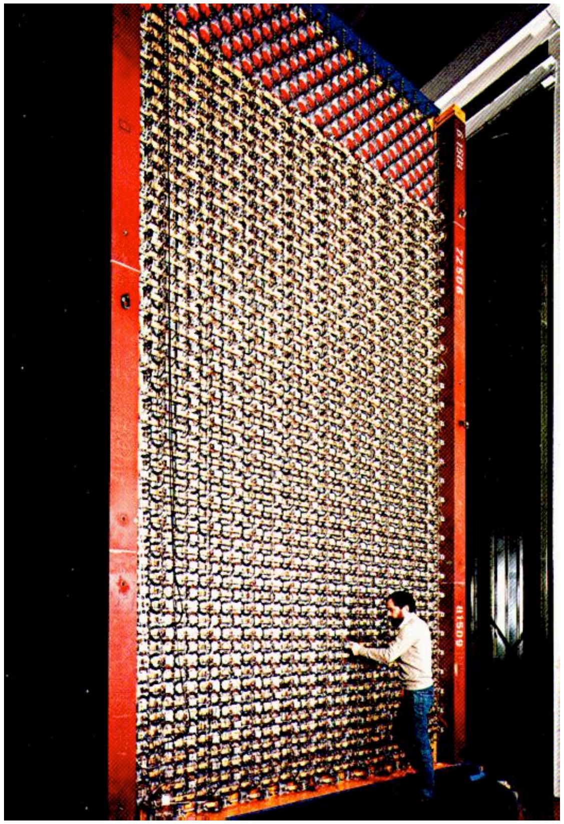
Similar to KARMEN at ISIS

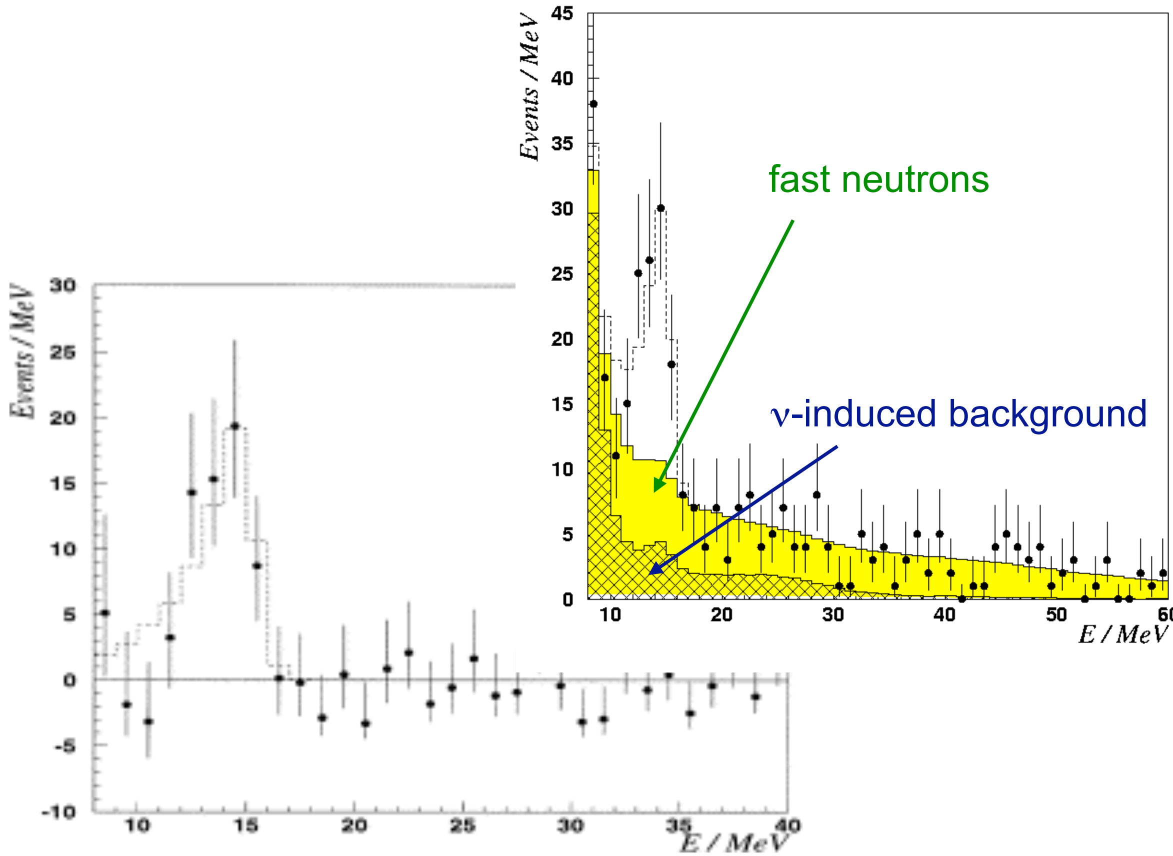
better timing

lower intensity

(also Fe at 40%)

KARMEN ν_μC NC Measurement





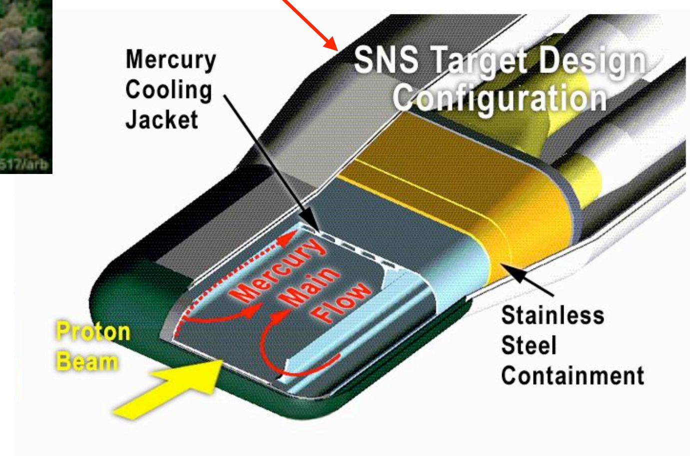
$\sigma_{NC} = (3.2 \pm 0.5 \pm 0.4) \times 10^{-42}\ cm^2$ B. Armbruster et al., Phys. Lett. B423 (1998) 15.

$\sigma_{NC} \sim 2.8 \times 10^{-42}\ cm^2$ Kolbe, Langanke & Vogel, Nucl. Phys. A652 (1999) 91.

The Spallation Neutron Source

The SNS is a $1.4B facility funded and operated by the DOE Basic Energy Sciences

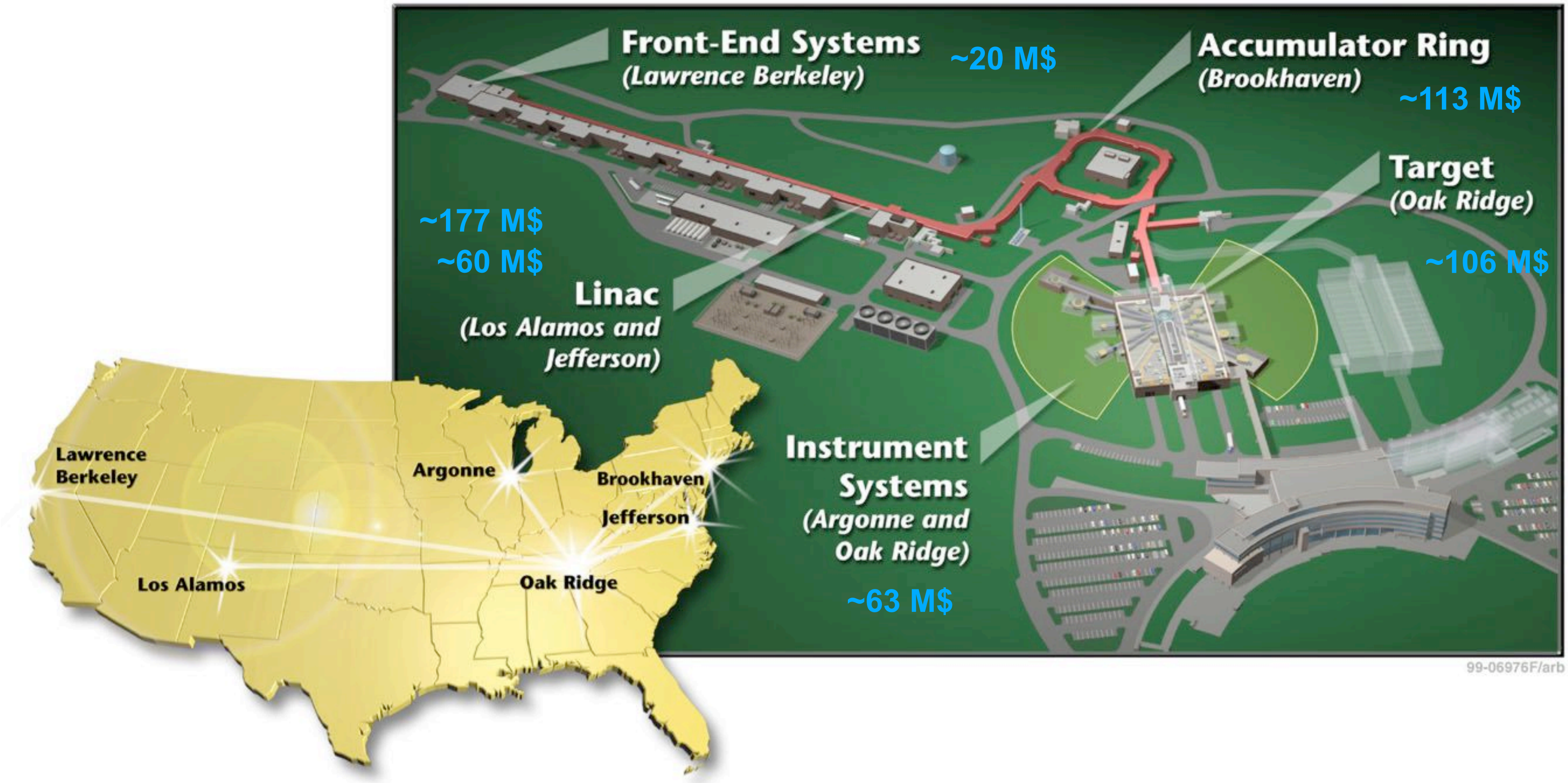
- 16 tons Hg; 360 gallons/min
- High-Z (lots of p&n)
- No radiation damage
- Good at dissipating heat



1 GeV proton LINAC: running!
Will reach 1.4 MW by 2010!

Full power: 1.5e+14 protons on target per pulse
($24\ \mu C$ in 700 ns @ 60 Hz)

Unique Collaboration between 6 National Laboratories

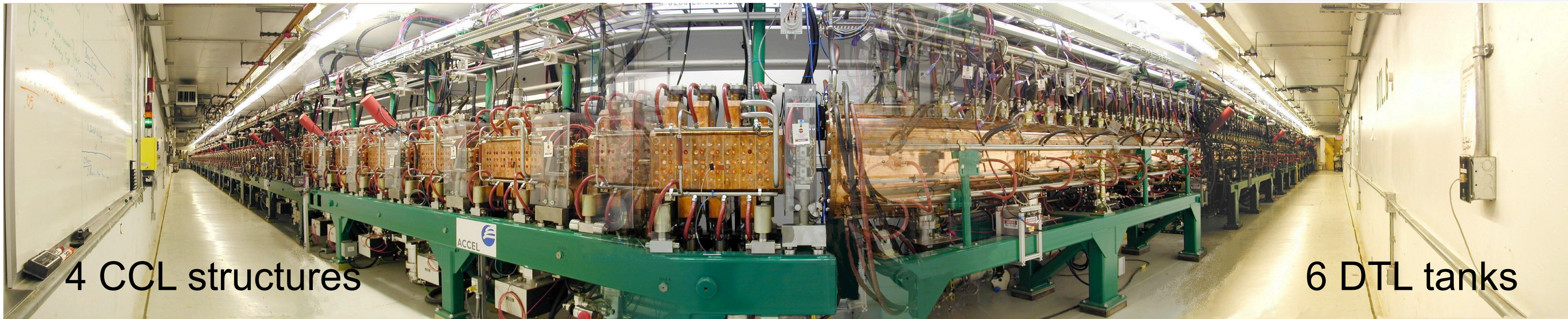


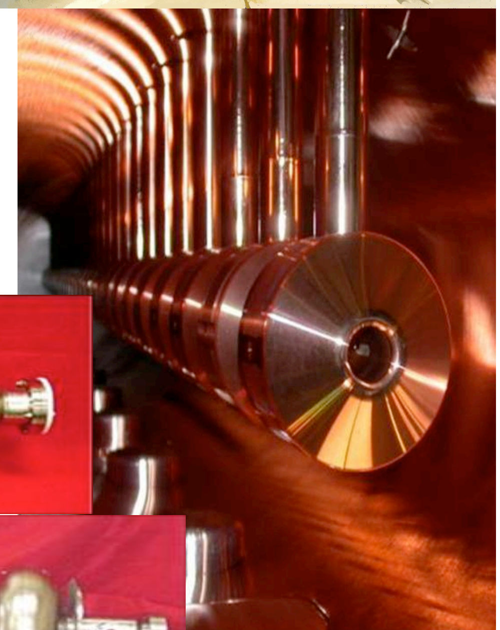
- Nov-1999: Start construction approved (CD-3)
- 28-Apr-2006: SNS commissioning run!
- May-2006: Project work completed (CD-4)

The Finished SNS

The 331-m LINAC

warm

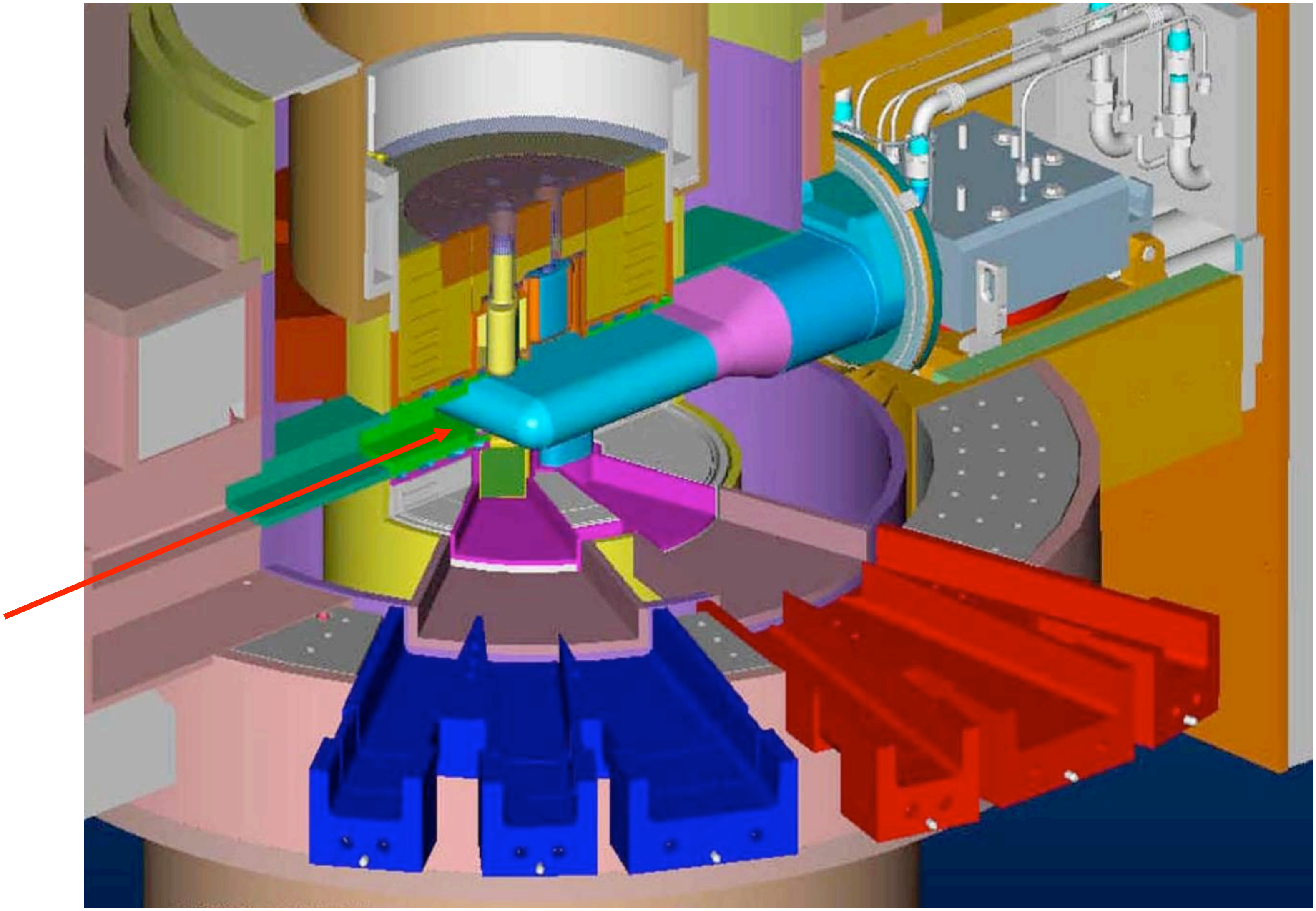




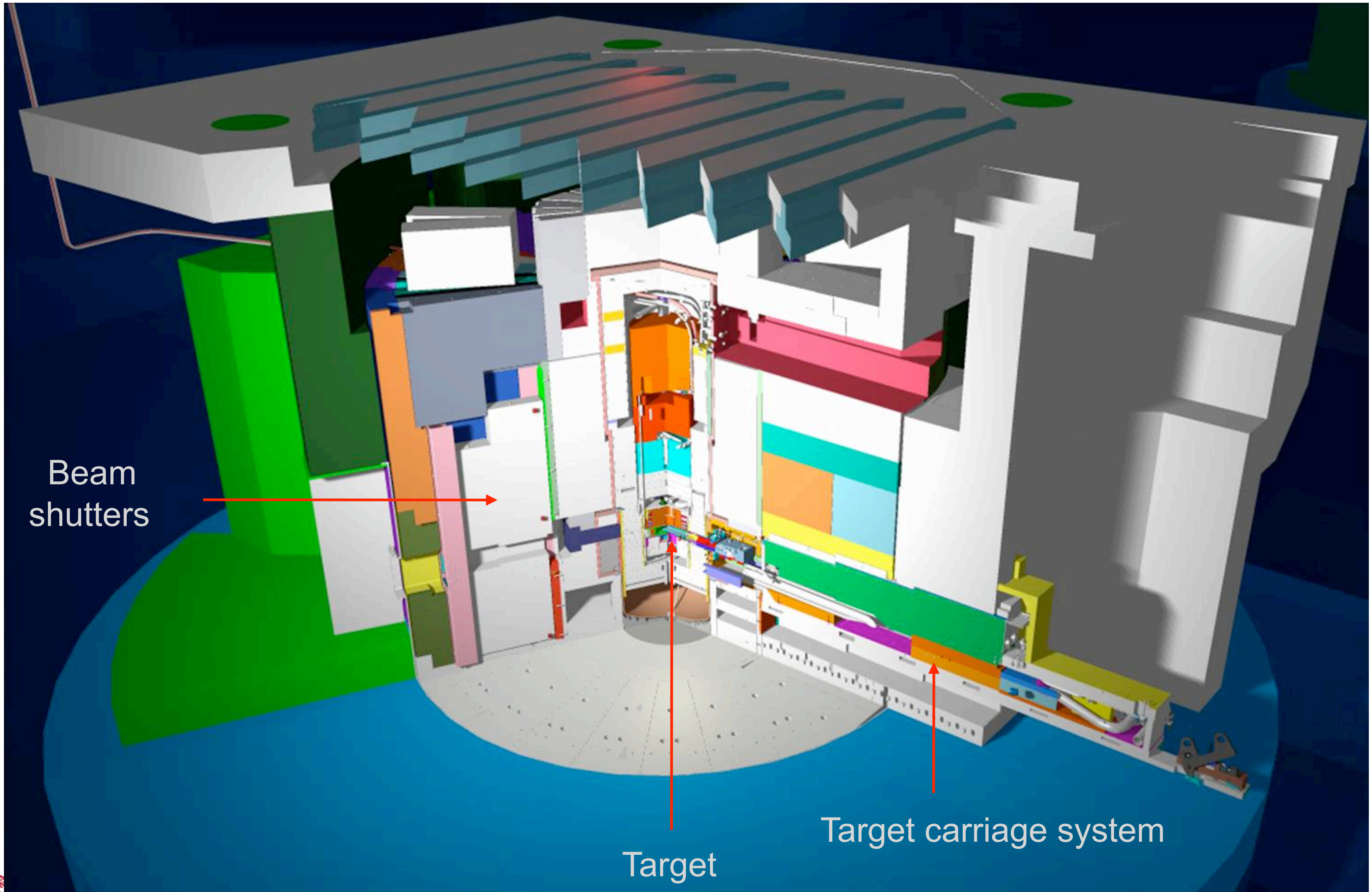
cold (2K): 11+12 (medium+high)-beta cryomodules

Niobium cavities

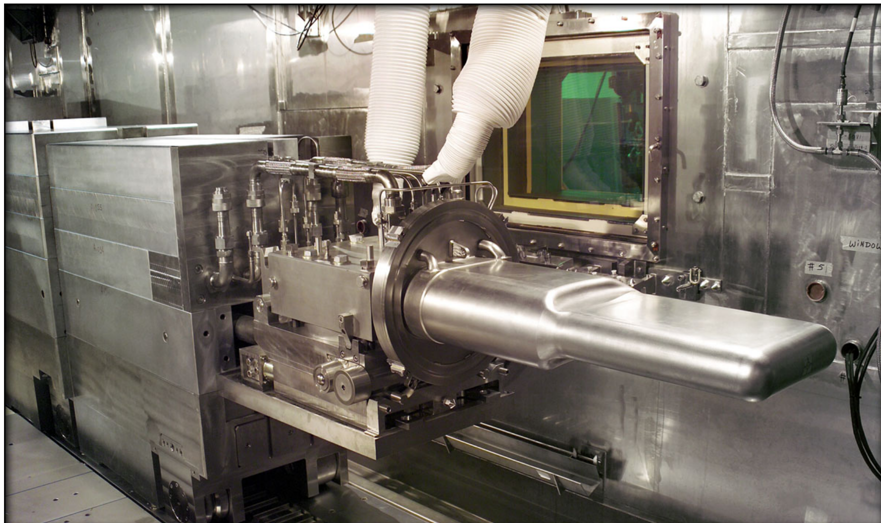
The Target, Moderators & Beamlines

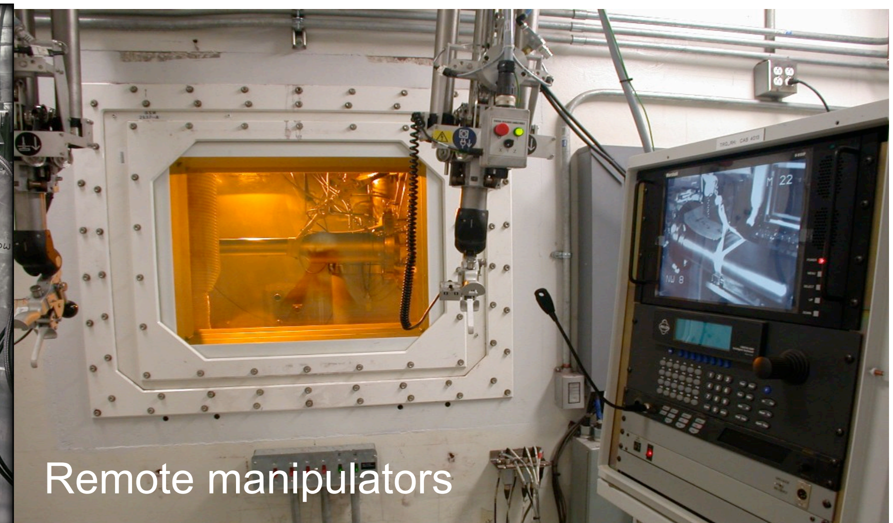


The Target Monolith



Servicing the Target Module



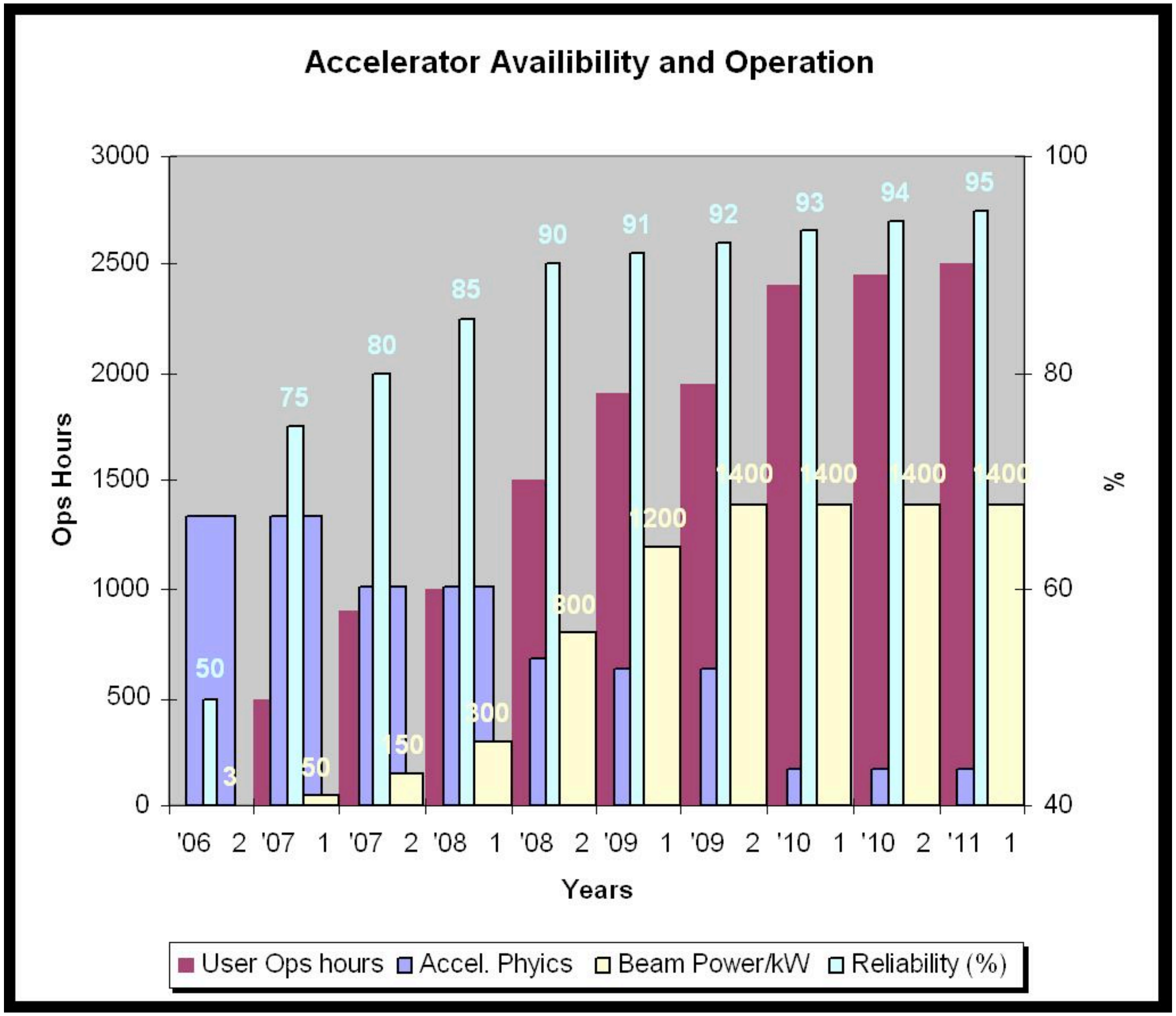


Remote manipulators

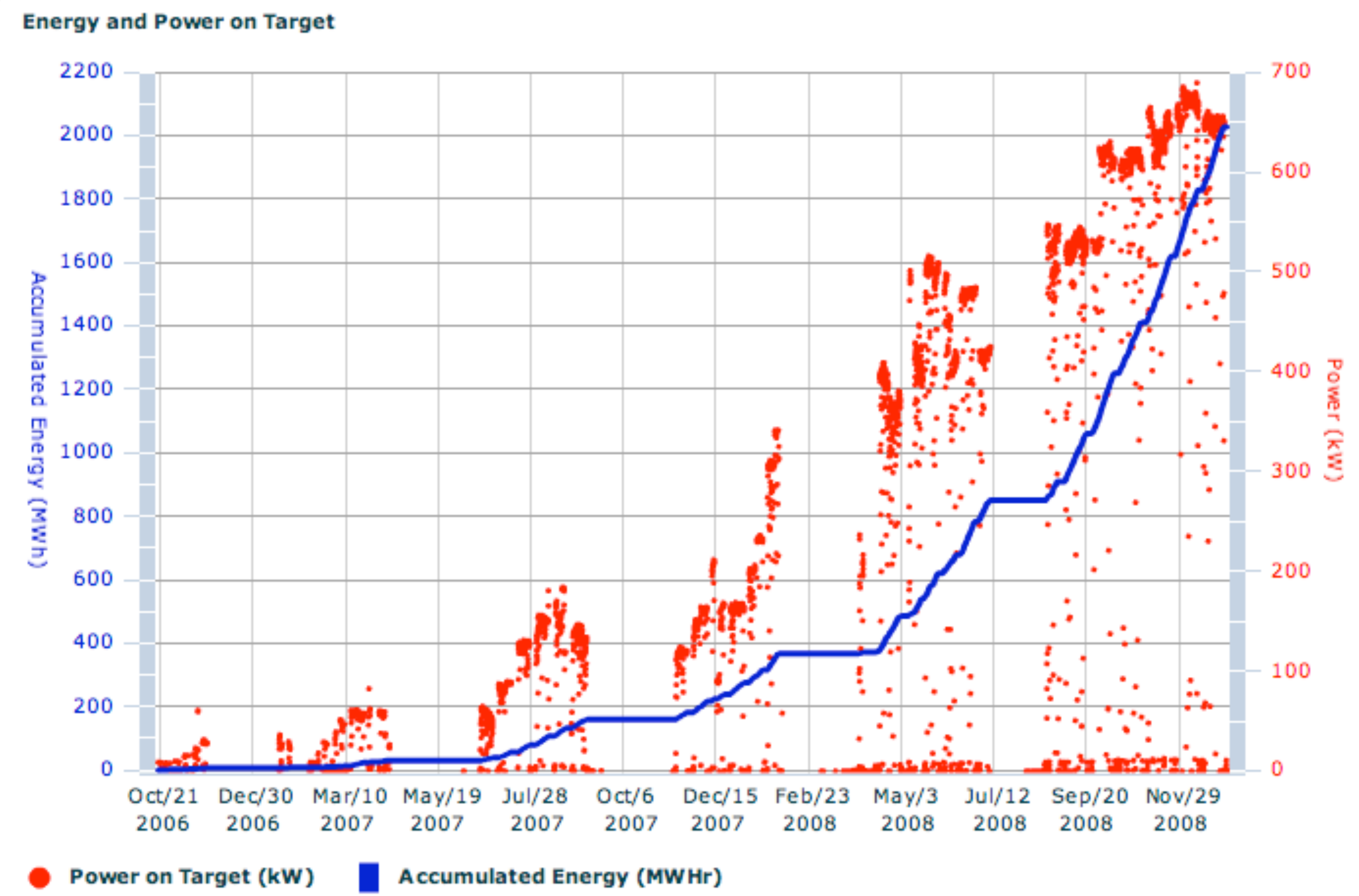
Target service bay

Post-CD4 Intensity Ramp-up: Theory

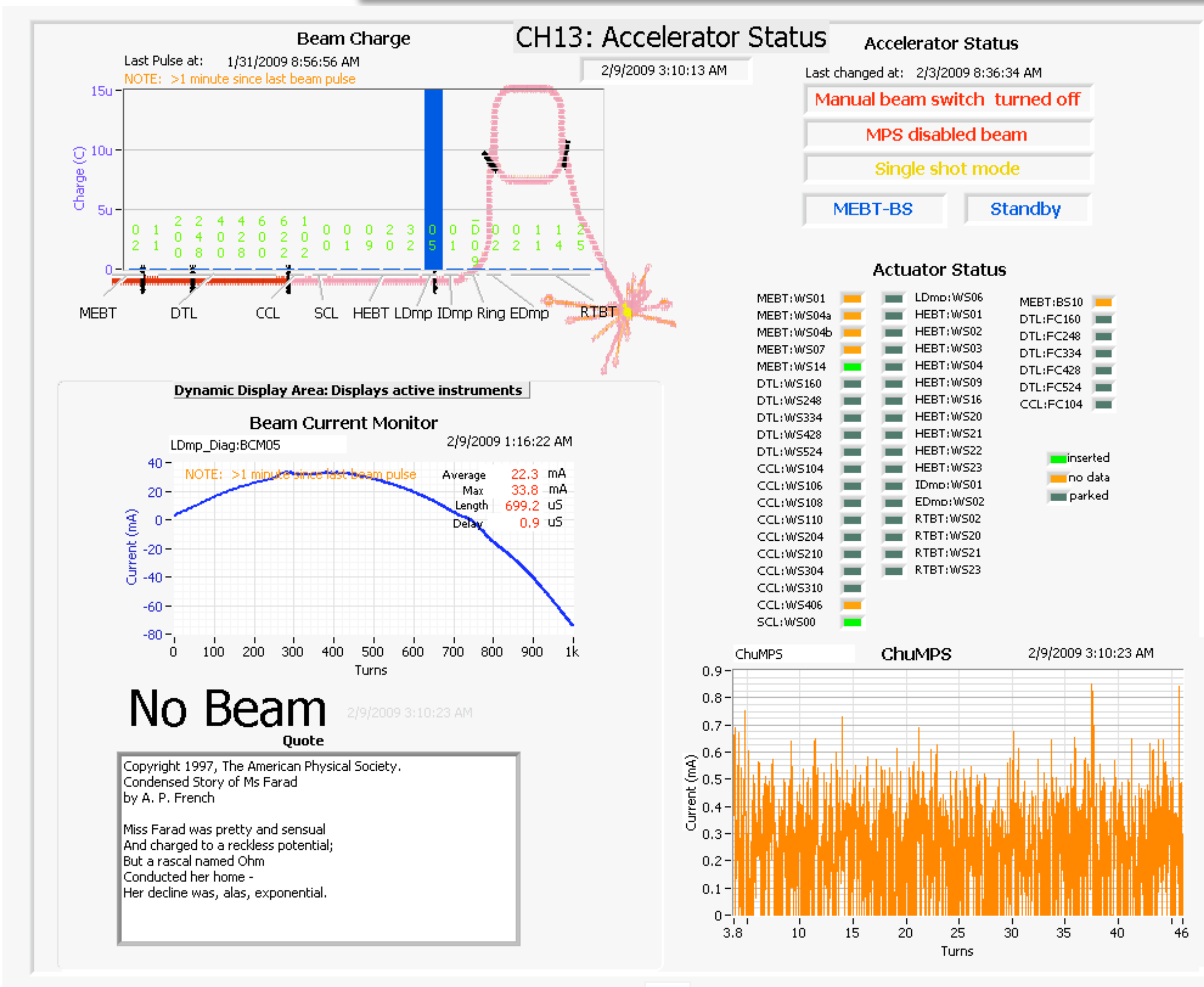
- Commission the beam with low intensity, ~2×10^{13} ppp (10mA, few Hz);
- Ramp up beam power gradually;
- Should reach 1.4 MW by 2010.
- Plans for second target station in ~2010.



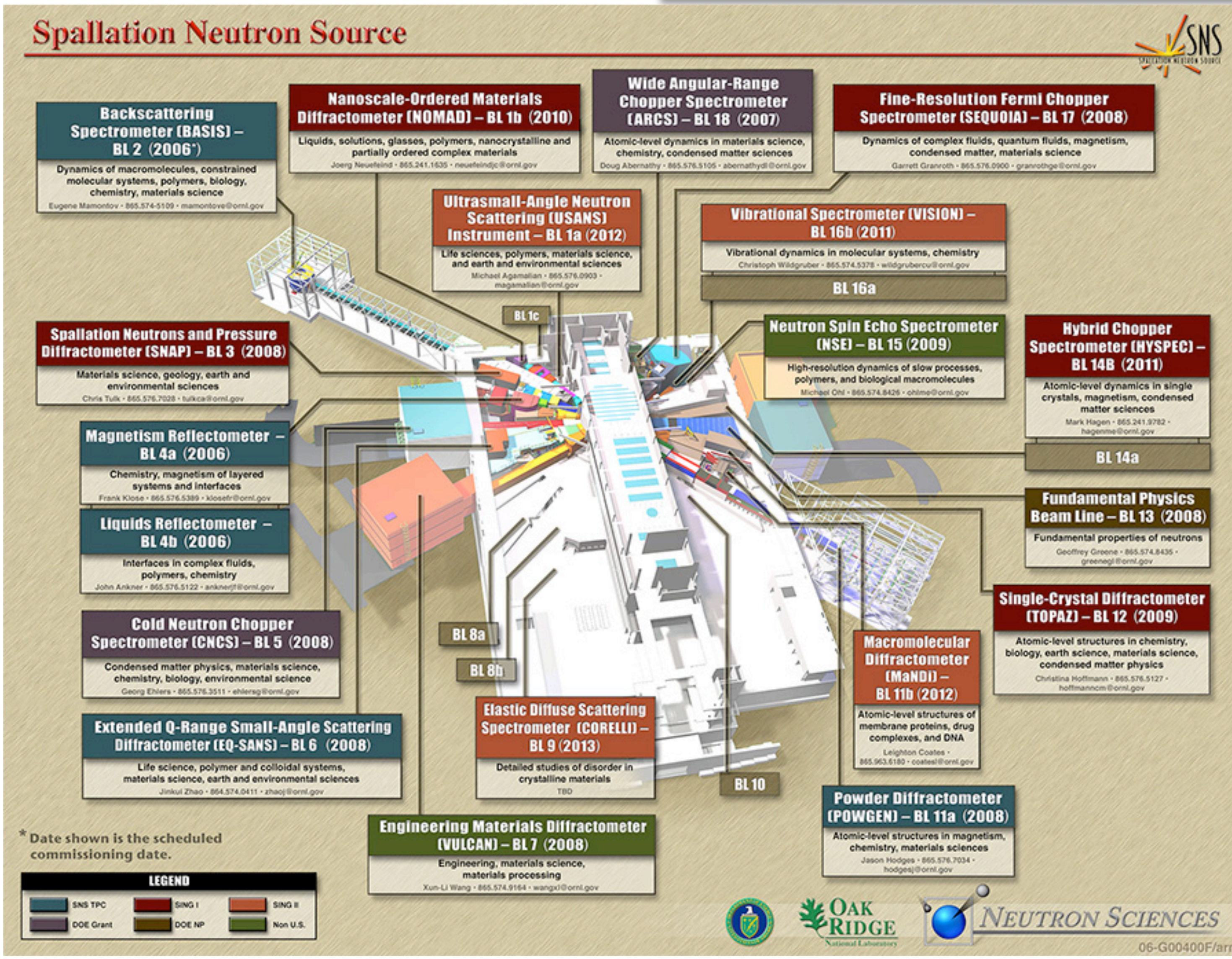
Post-CD4 Intensity Ramp-up: Reality



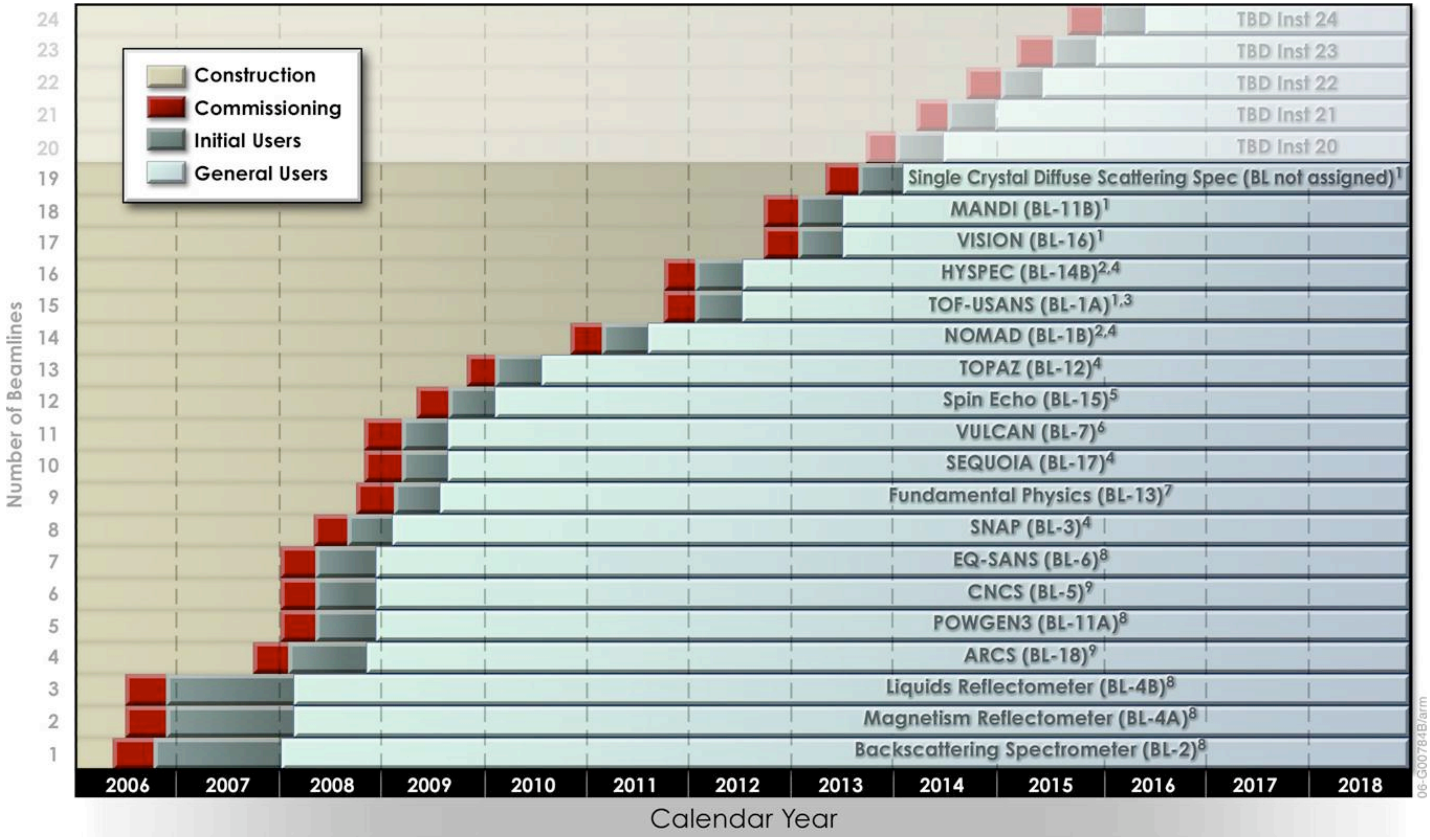
SNS Status: neutrons.ornl.gov/diagnostics



The SNS Experimenal Hall

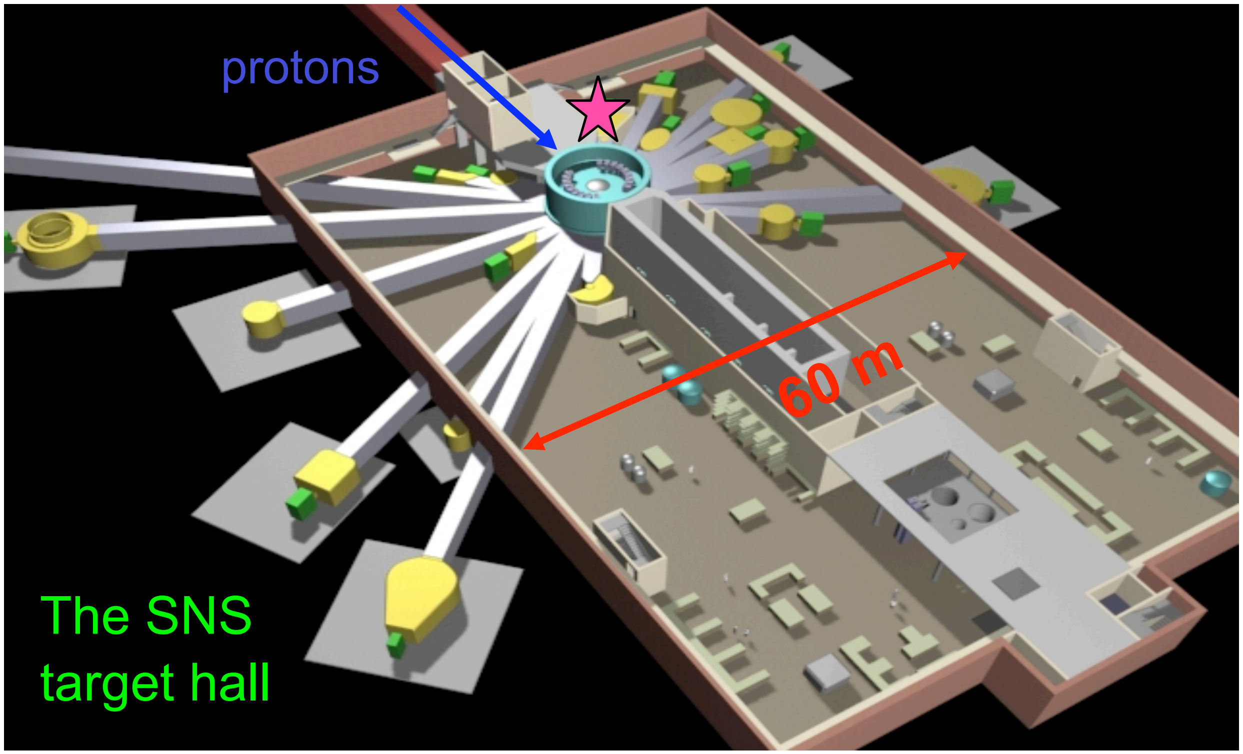


Instrument Commissioning Schedule



The NuSNS Location

proposed NuSNS site



- Close to target

  (prime real estate)

- 20 $m^2 \times 6.5$ m (high)
- 165^0 wrt protons

  (lower backgrounds)

- High floor loading

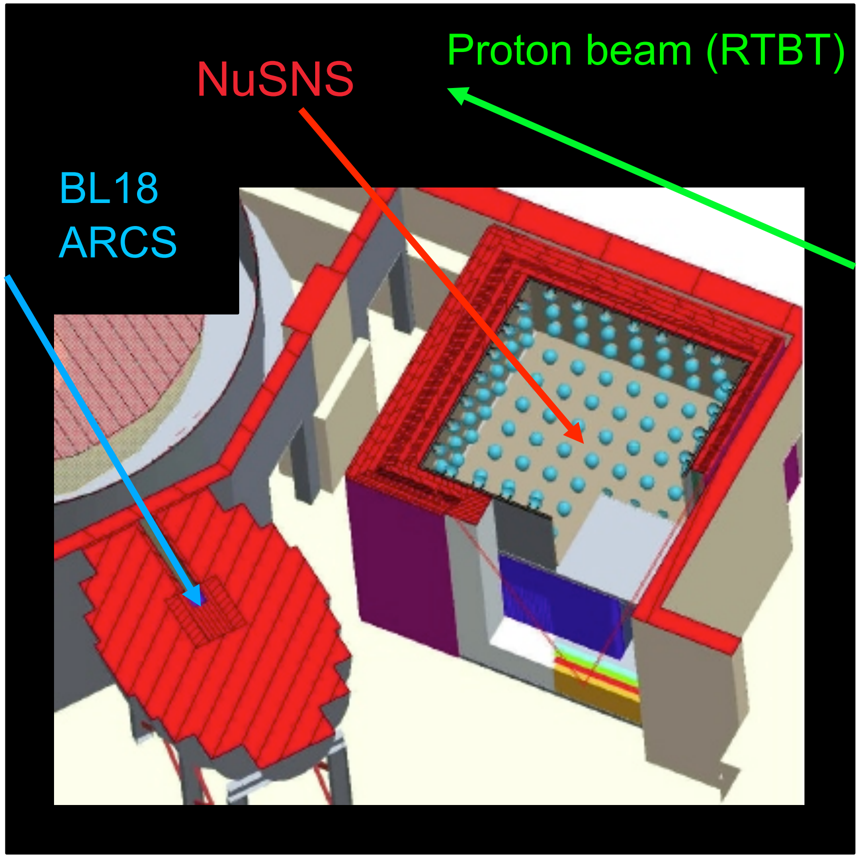
  (about 500 tons)

SNS is the world's most intense neutrino source:

2×10^7 $\nu/cm^2/s$ (each flavour) at 20 m (assuming 1 MW)

NuSNS Facility Overview

- Total volume = 130 m^3
- Heavily shielded (fast neutrons)
- 60 m^3 steel (about 470 tons)
  - 1 m thick on top
  - 0.5 m thick on the sides
- Active veto shield
- About 70 m^3 instrumentable
- Configured to allow operation of two simultaneous (independent) target/detectors:
  - homogeneous – liquids (C, O, d, …)
  - segmented – solid (Fe, Pb, Al, ...)
- Detector active elements will be reusable!



NC coherent also goes here!

Backgrounds: Sources & Strategies

- Uncorrelated:
  - cosmic rays (neutrons, muons neutrons)
  - cosmogenic activity
  - SNS activation
  - Natural radioactivity

  → Reduced by ~6×10^{-4}
  60 Hz $\times$ 10 μs

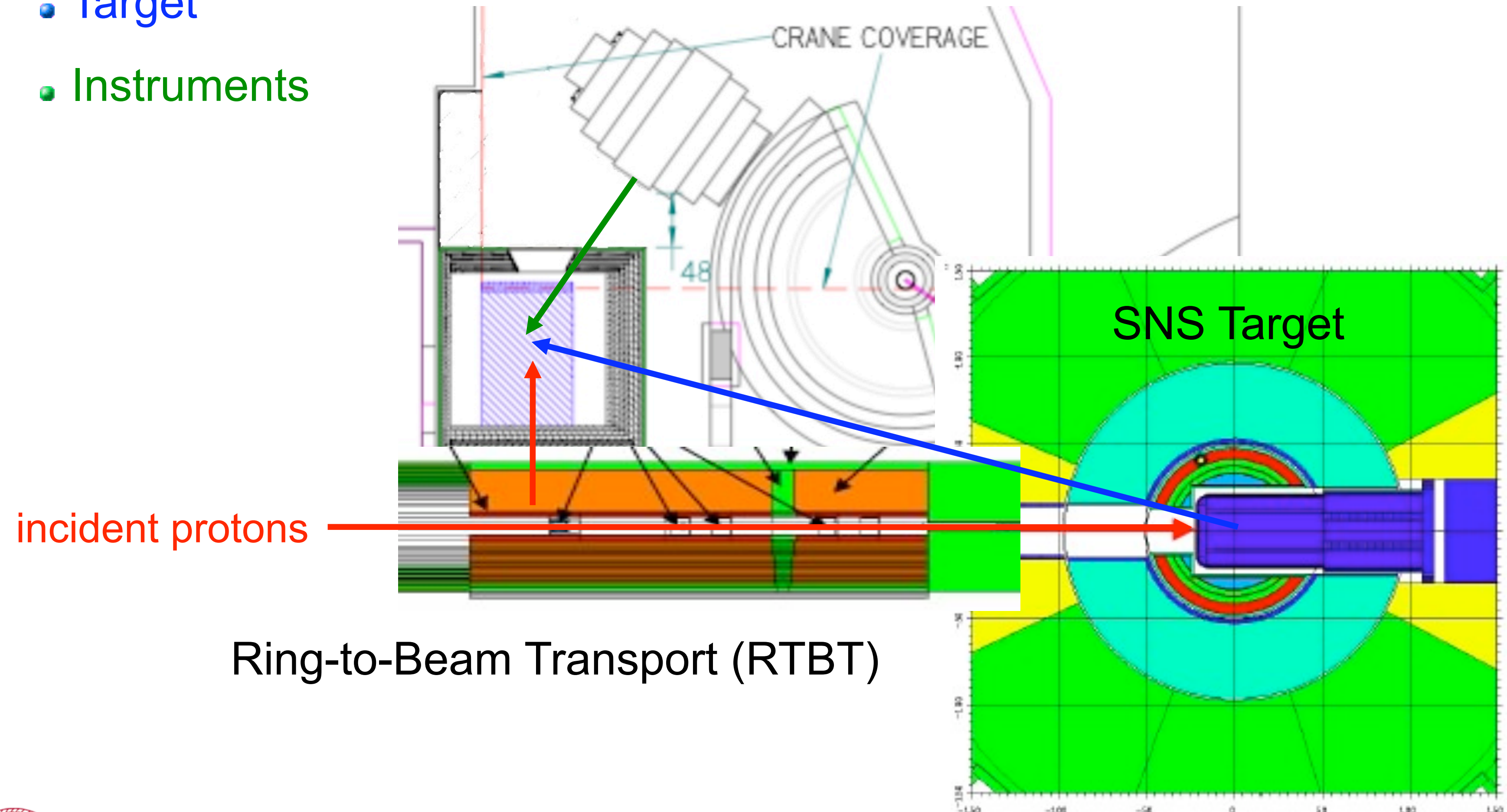
- Correlated prompt (beamline, target, instruments)
- Multiply-scattered neutrons

	Time cut	Shielding	Veto	Particle ID	Beam-off measure & subtract
Cosmic muons	✔		✔	✔	✔
Cosmic neutrons	✔	✔		✔	✔
Long-lived spallation products	✔	✔			✔
SNS neutrons	✔	✔		✔	

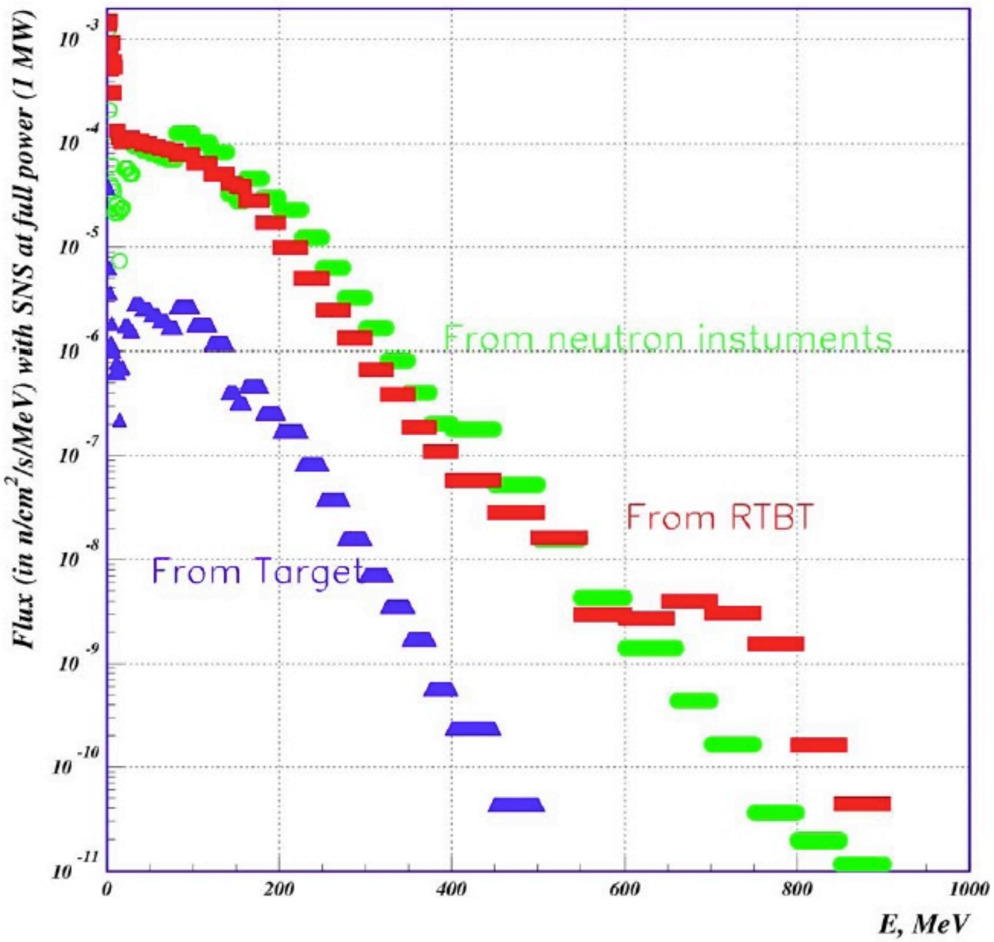
The SNS Neutrons

Possible sources:

- Beam line (RTBT)
- Target
- Instruments



The SNS Neutrons



MC simulations:

- Beamline comparable to neutron instruments
- Target background is 2 orders of magnitude lower

The Cosmic Rays

- Problem: $\mu + Fe \rightarrow n + X$

  2,900 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 the detector

  30 fast neutrons/day (11,000 per year)

  Can be very accurately characterized

Need high efficiency veto!

- Cosmic-ray neutrons:

  ~60 n/s * 6×10^{-4} → 3,100 n/day coincident

  Only reduced by shielding → sets scale for bunker

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

  → 30 fast neutrons/day

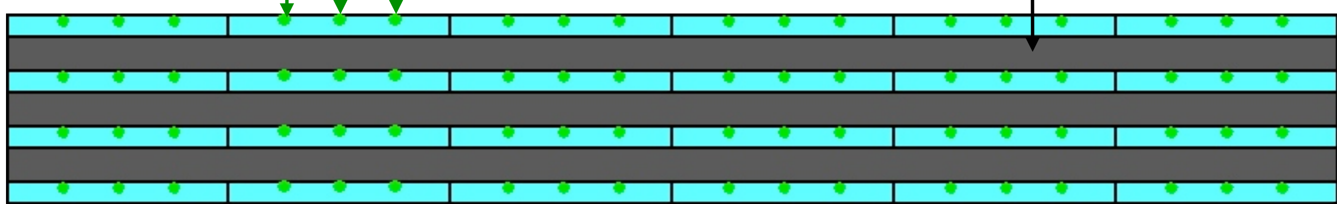
  leaves ~40 m^3 of shielding for sides

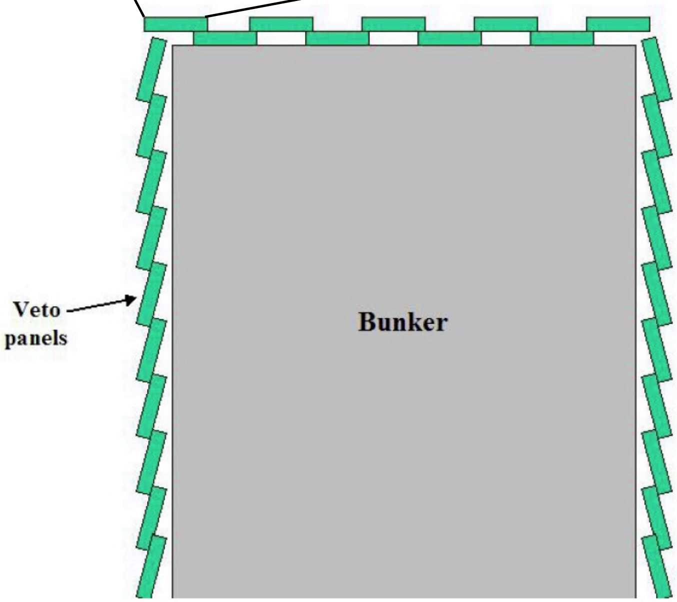
The Active Veto

Wavelength shifting fibers
Readout by multianode PMTs

1.5 cm Fe

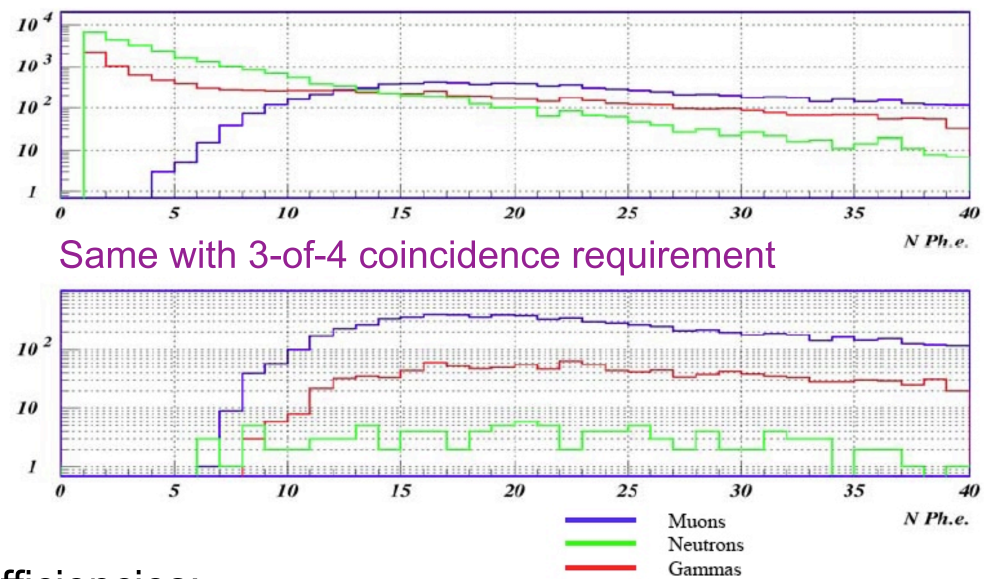
Extruded scintillator
1 cm x 10 cm x 4.5 m





Total #PE for all 4 layers

Same with 3-of-4 coincidence requirement



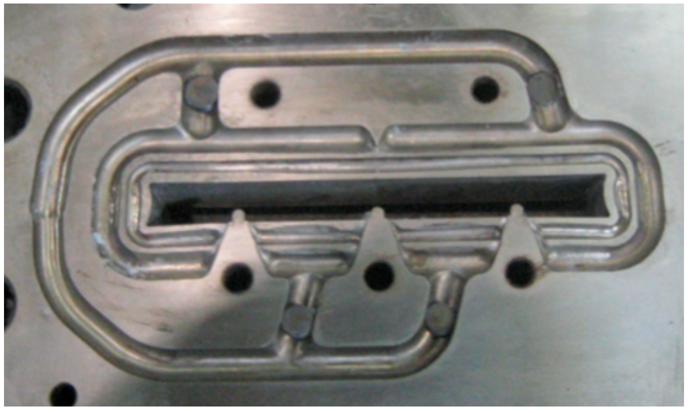
Efficiencies:

muons: 99%

gammas: 0.005%

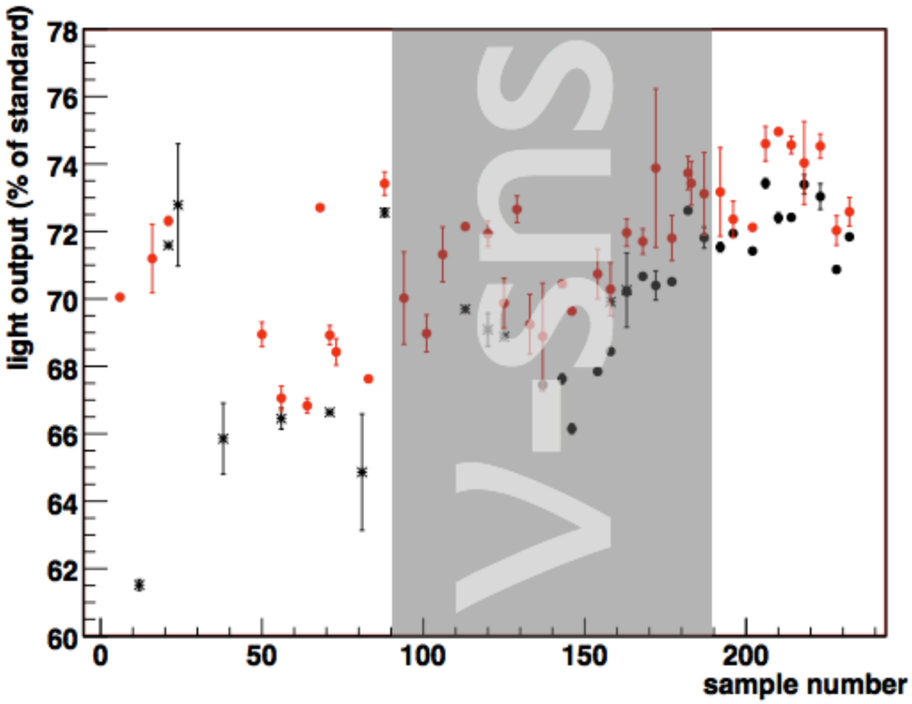
neutrons: 0.07%

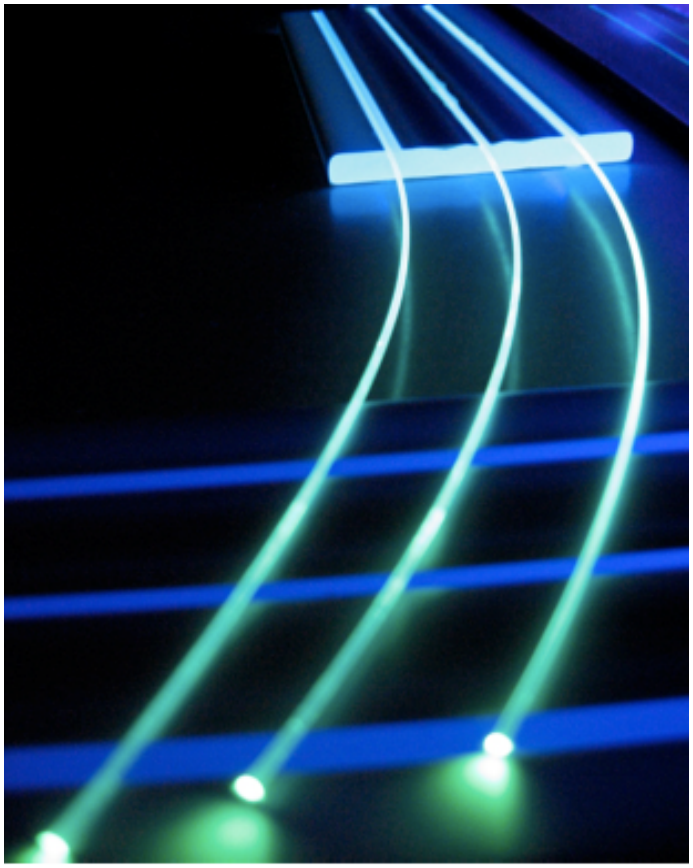
Veto Production



In collaboration with MECO:

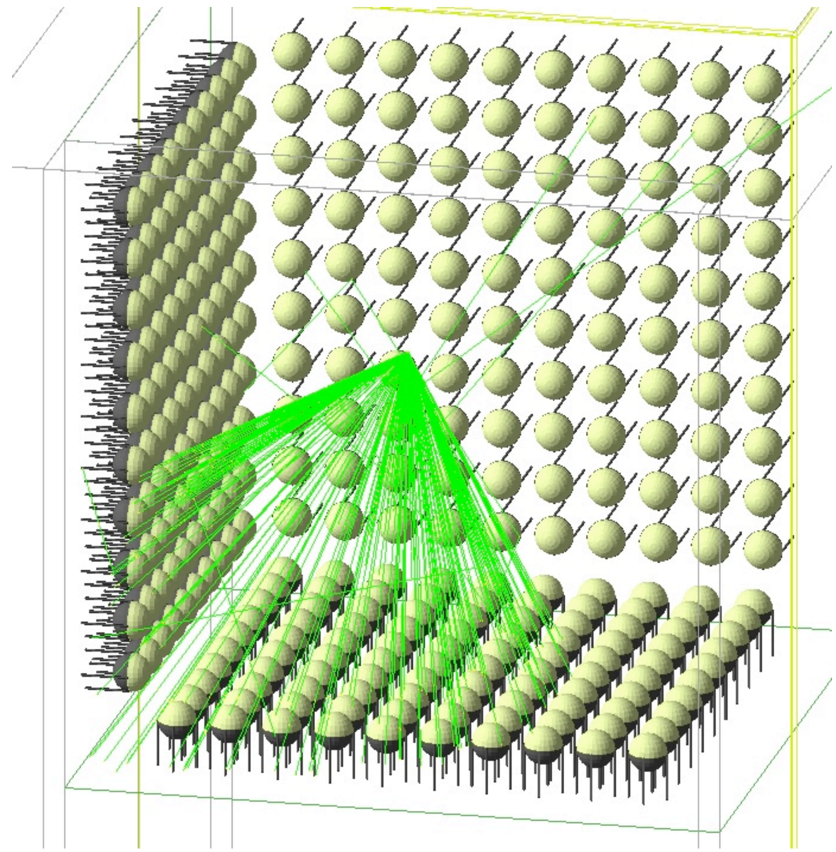
100 4.5-m planks extruded for NuSNS





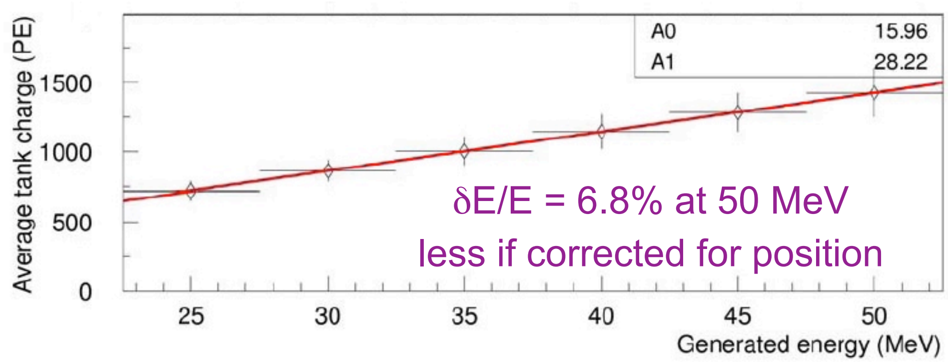
Homogeneous Detector

- 3.5 m x 3.5 m x 3.5 m steel vessel (43 m^3)
- 600 PMTs (8-inch Hamamatsu R5912)
  - Fiducial volume: 16 m^3
  - 41% photocathode coverage
- Robust & well-understood design
  - LSND, MiniBooNE
- Potential experiments:
  - 1,300 events / year mineral oil (C)
  - 450 events / year water (O)
  - 1,000 events / year heavy water (d)

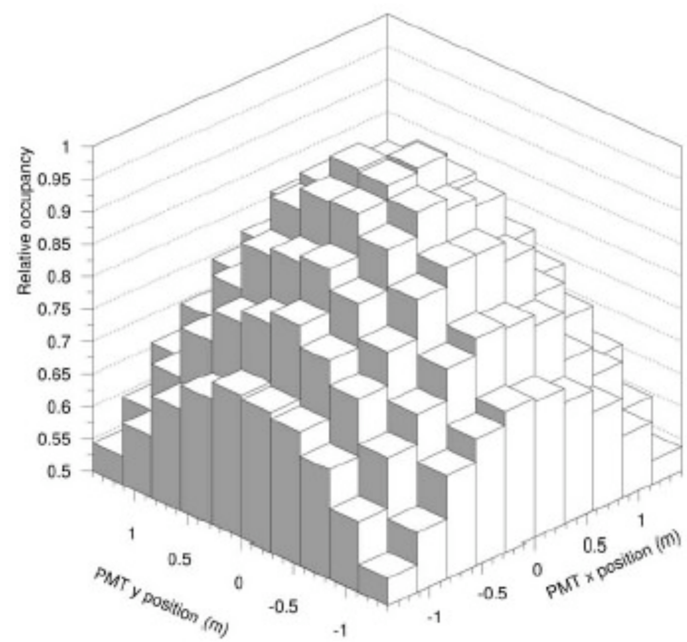


HD Performance

GEANT4 MC simulations ongoing



- Energy resolution: ~6%
- Position resolution: ~15-20 cm
- Direction resolution: ~5-7^0
- Neutron discrimination?
- Layout and coverage?
- Compact photosensors?
  60% of mass lost to
  fiducial volume cut!



SM Tests

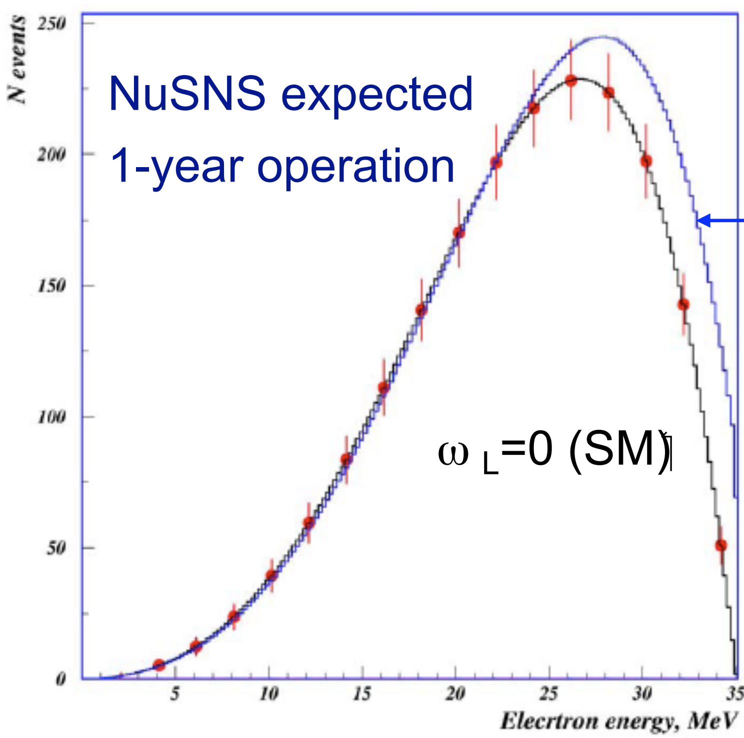
Shape of ν_e spectrum from μ decay is sensitive to scalar and tensor components of the weak interaction.

N_{GS} transition, Q-value=17.3 MeV

radiative corrections

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

scalar+tensor components

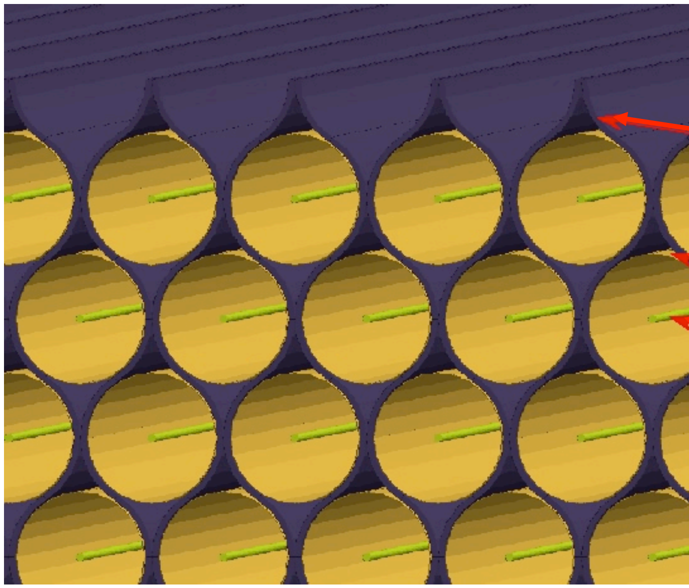


ω_L=0.11 KARMEN upper limit

Armbruster et al., PRL 81 (1998) 520

NuSNS should substantially improve the limit on ω_L within only one year of operation!

Segmented Detector



1,100 events/year $\nu_e + Fe \rightarrow Co + e^-$

Corrugated metal target

Strawtube

Anode wire

1,100 events/year $\nu_e + Al \rightarrow Si + e^-$

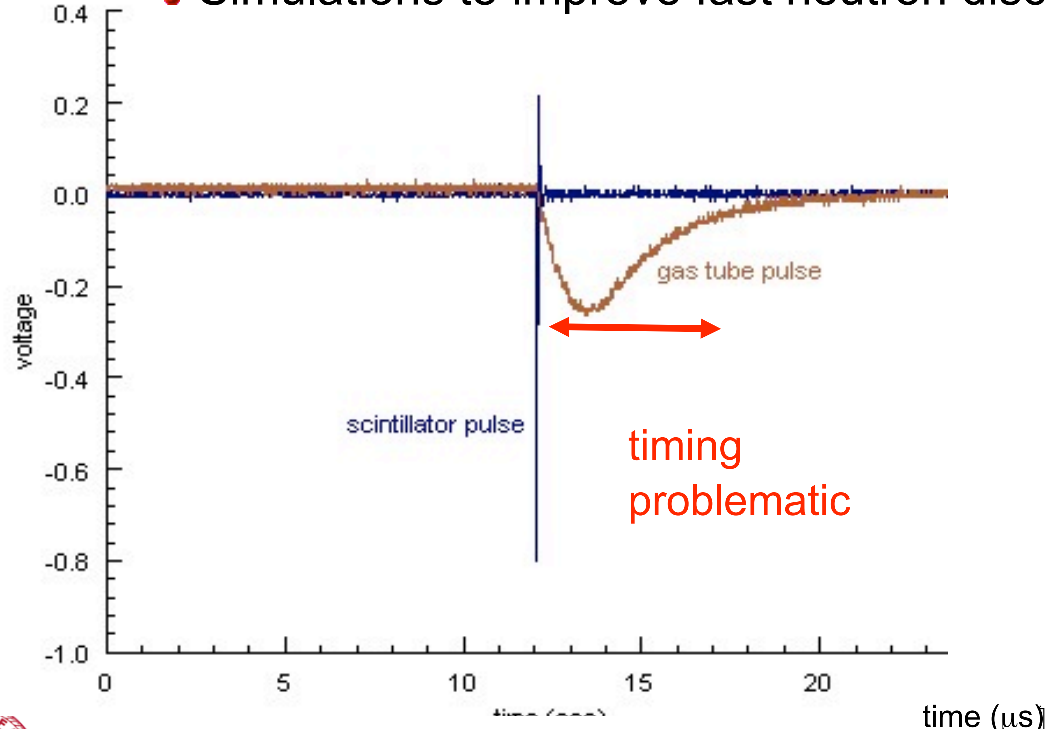
4,900 events/year $\nu_e + Pb \rightarrow Bi + e^-$

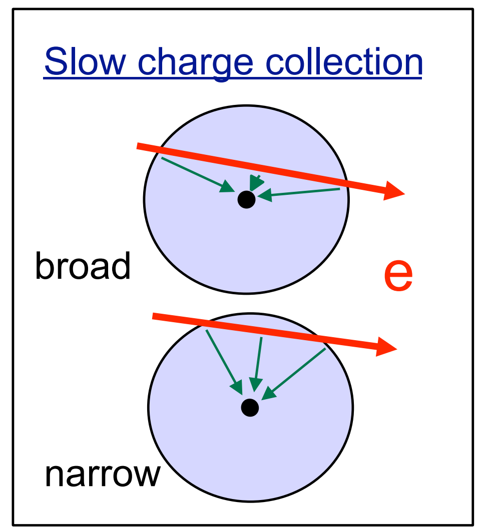
- Target: thin corrugated metal sheet (e.g. 0.75-mm-thick iron)
  - Total mass: ~14 tons, fiducial mass ~10 tons
  - Other good metal targets: Al, Ta, Pb
- Detector: 14,000 gas proportional counters (strawtube):
  - 3m long x 16 mm diameter
- 3D position: cell ID and charge division
- PID and energy: track reconstruction

Strawtube R&D

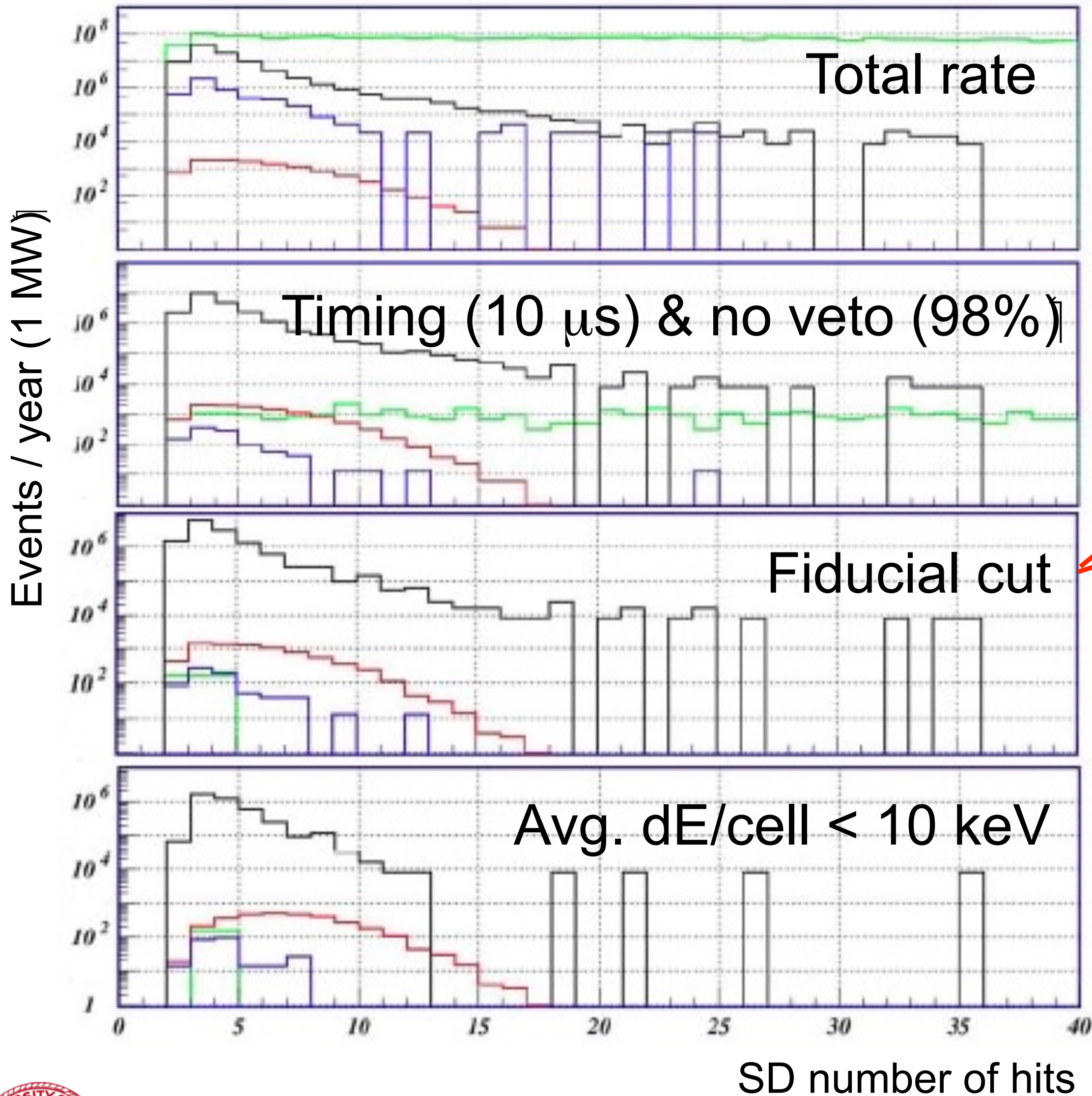
- Currently testing prototypes:

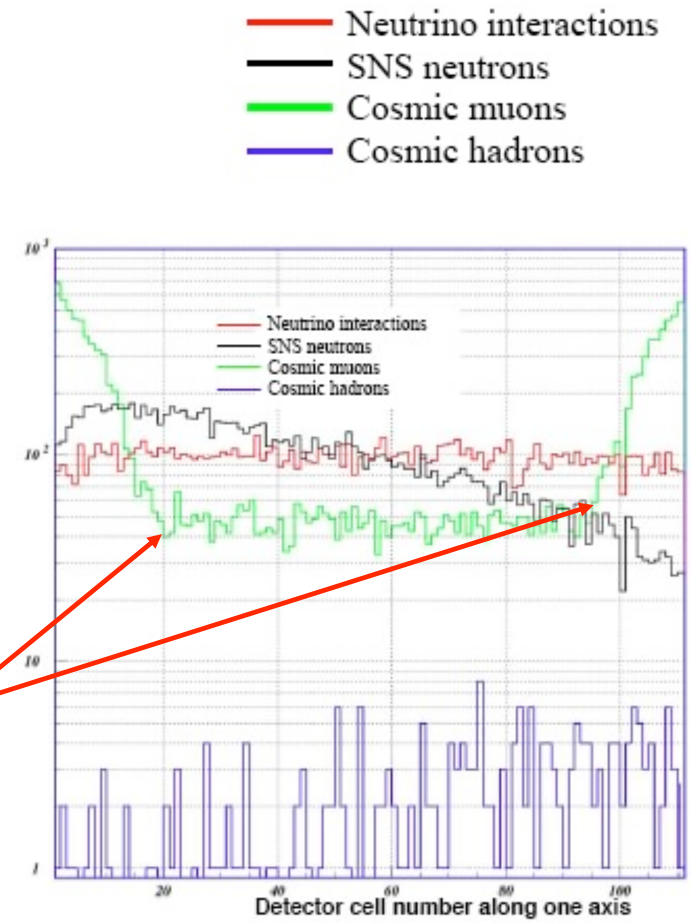
  diameters: 10-16 mm, lengths < 2 m, gases: Ar-CO_2, isobutane, CF_4
- Measure resolution with cosmic-ray muons: energy, position, timing
- Improve timing resolution using pulse shape information?
- Simulations to improve fast neutron discrimination





SD Performance





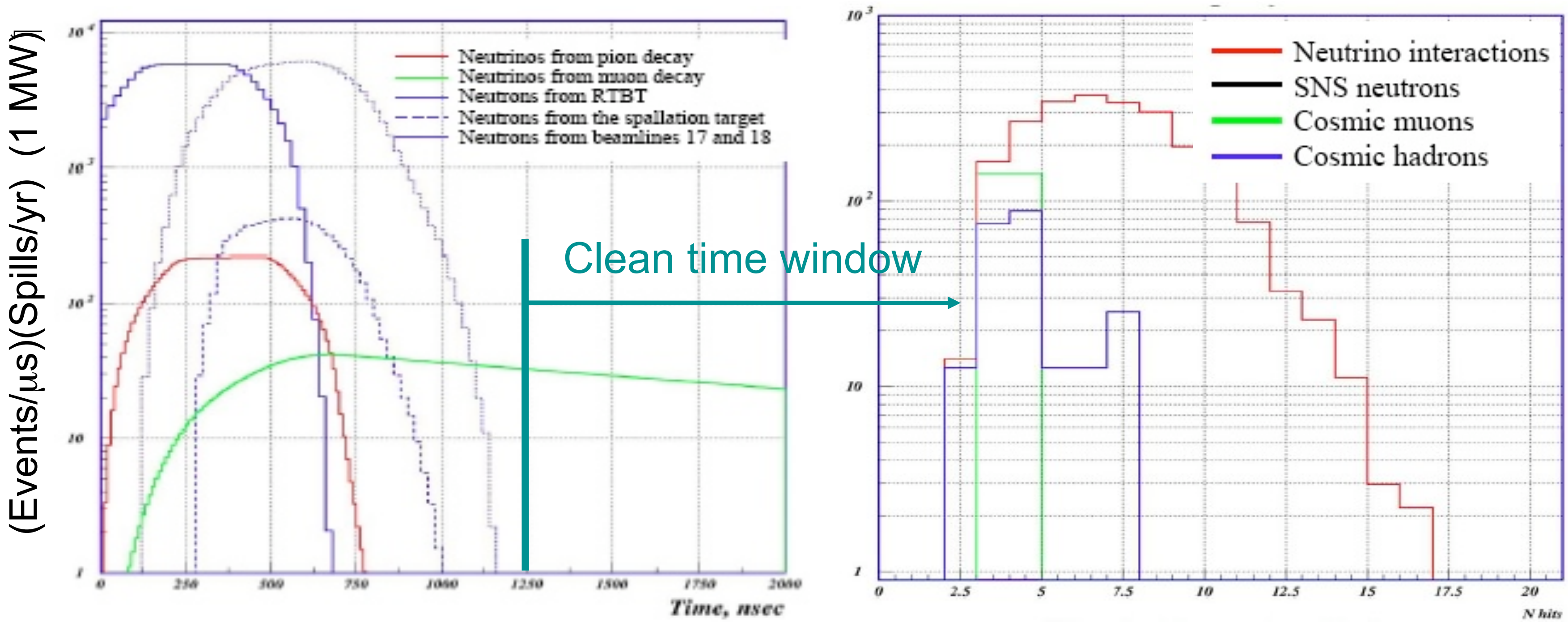
Neutrino efficiency: 57%

Cosmics eliminated!

Neutrons: small reduction!

Timing Cut

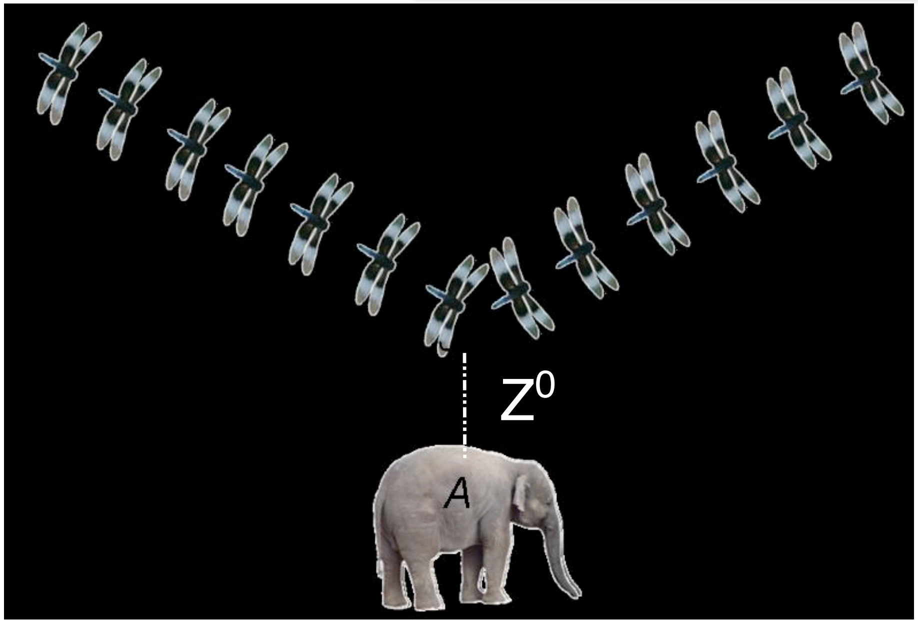
Negligible fast neutron background expected after 1 μs

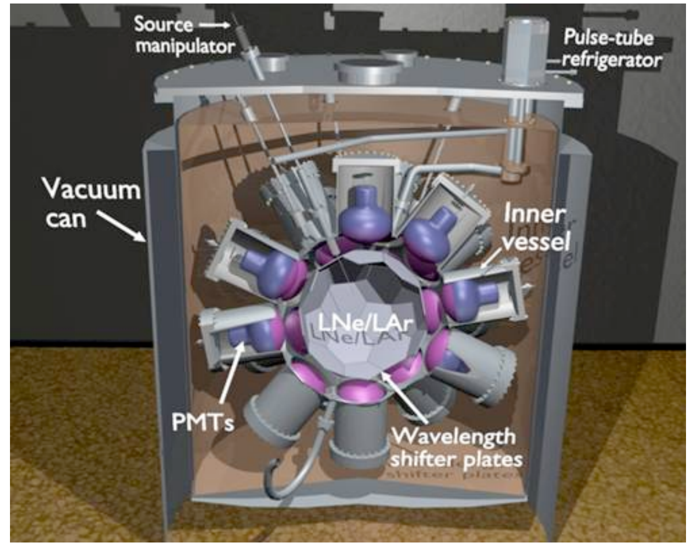


Essential to understand the neutron background, especially for t = 1-10 μs

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

Coherent NC Neutrino-Nucleus Elastic Scattering





XS can be easily computed in the Standard Model

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

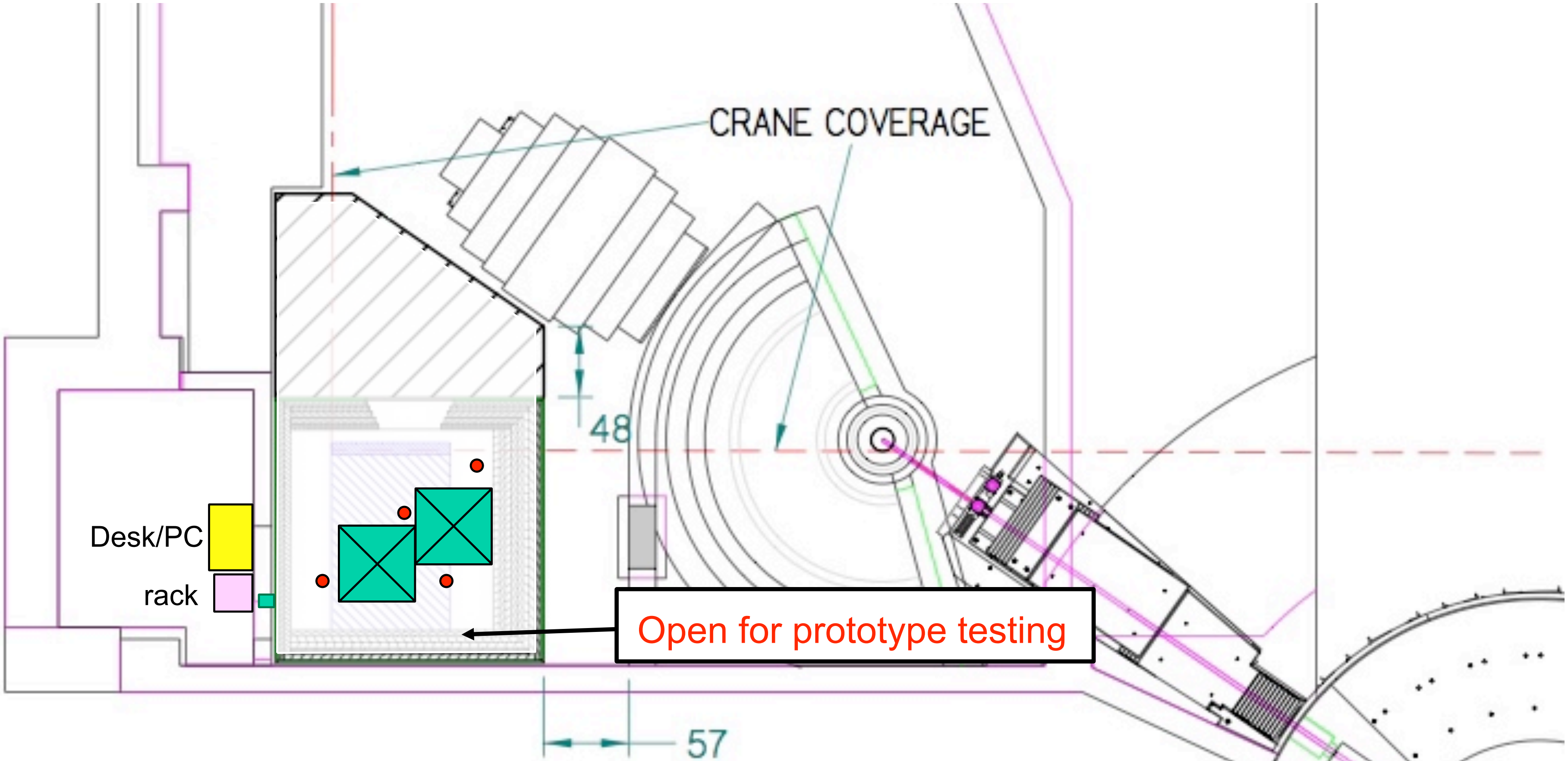
XS is huge (> 10^{-39} cm^2), but recoil energies are low (~10 keV);

Can be detected with Dark Matter search techniques;

Backgrounds are very important!

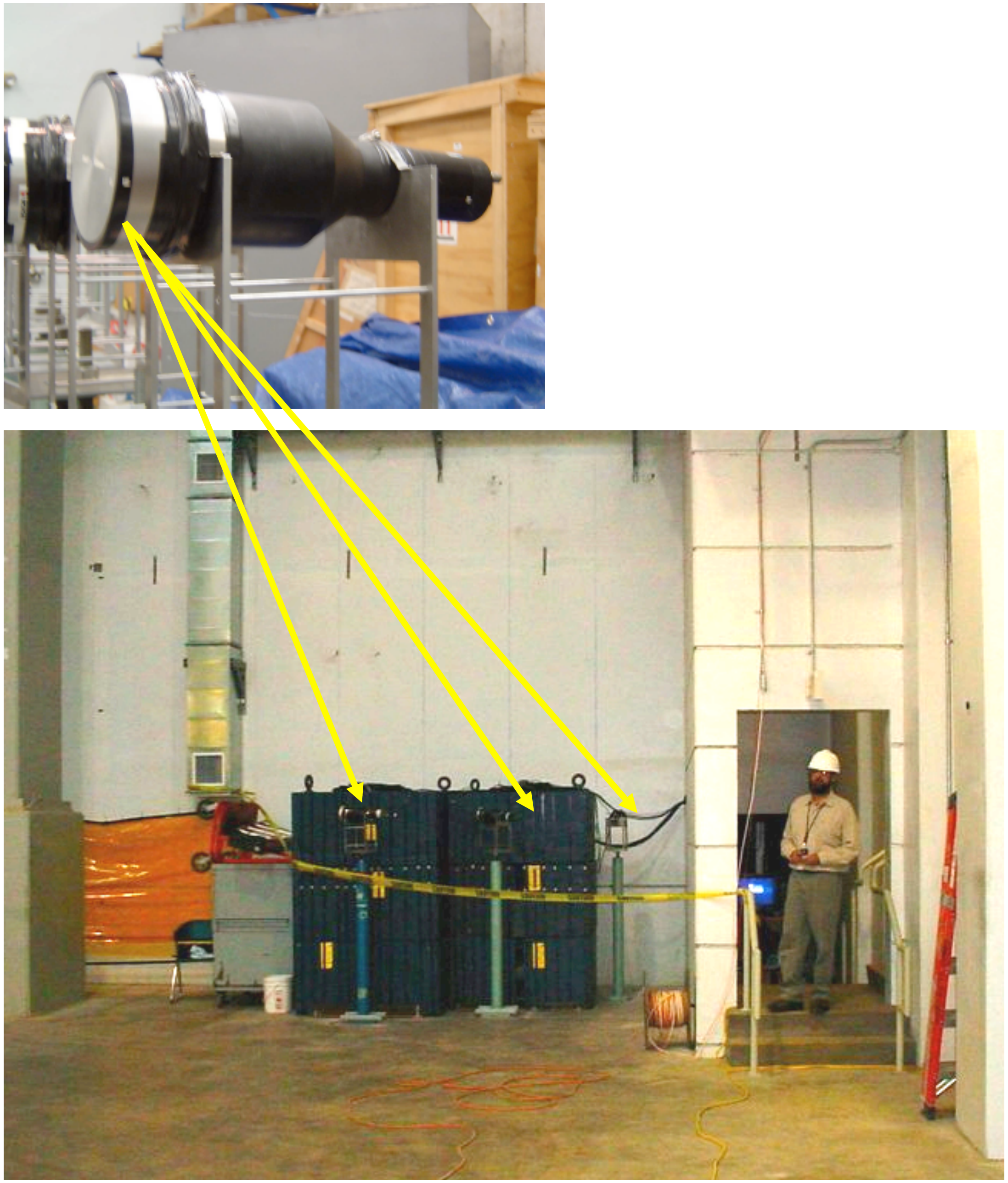
Details: K. Scholberg, PRD 73 (2006) 033005

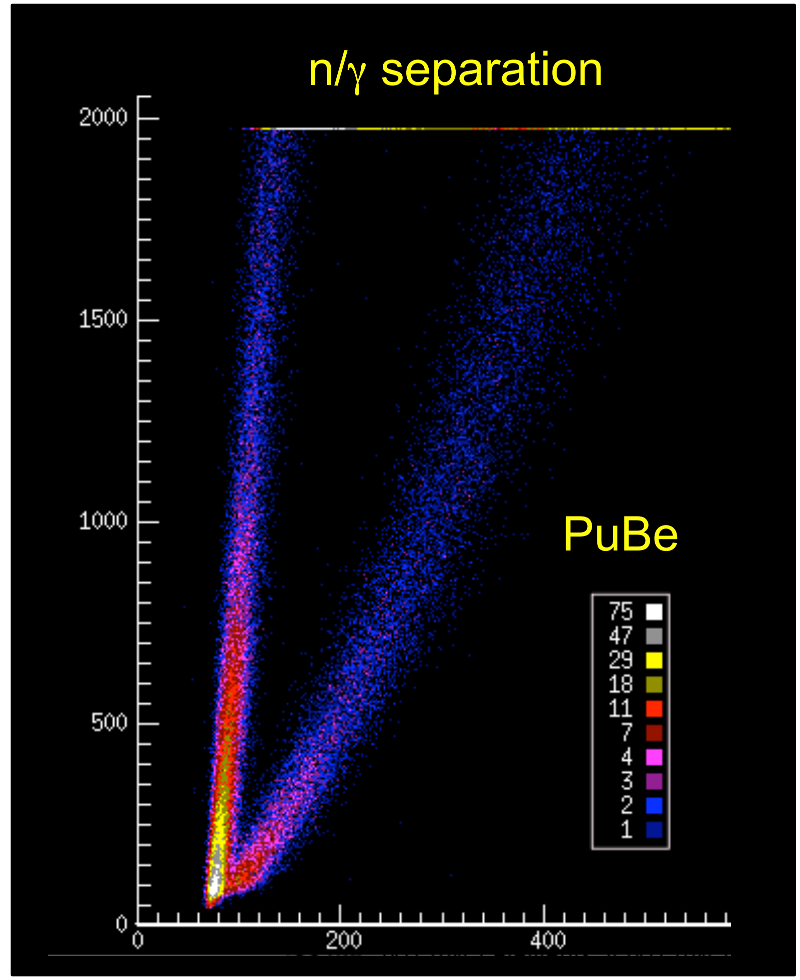
Background Studies



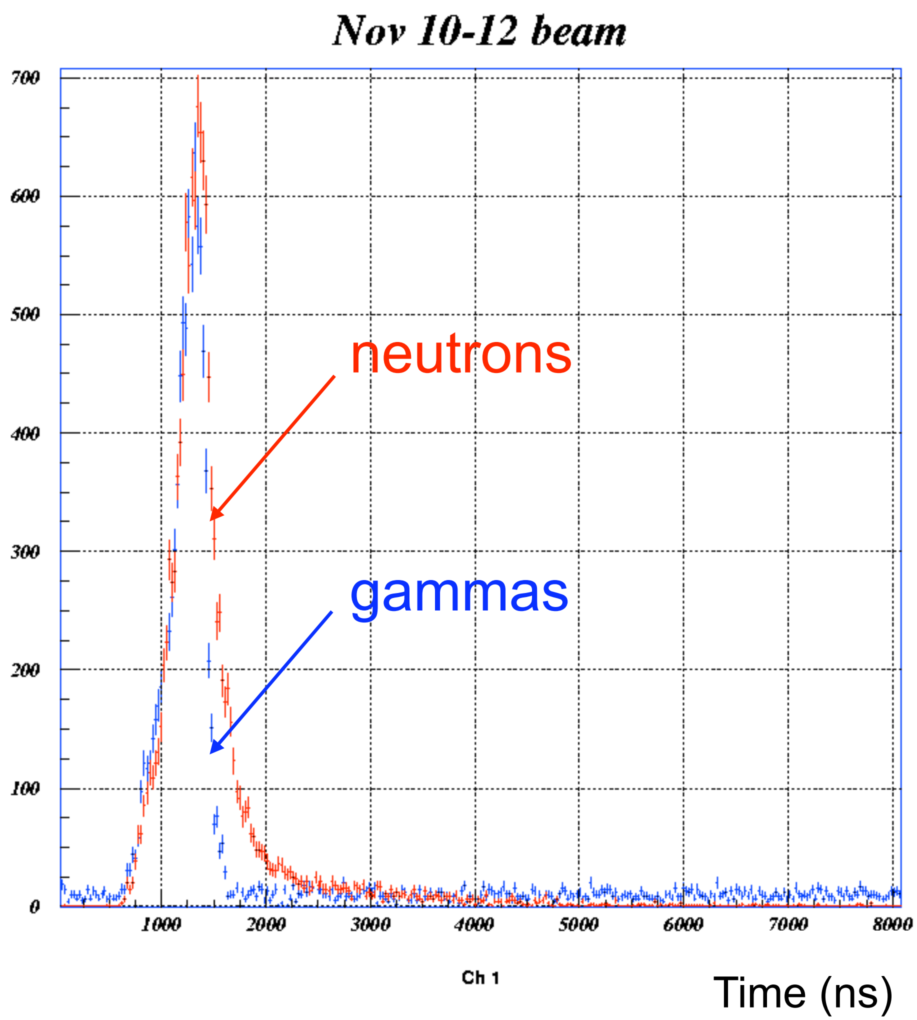
- 60 tons of steel installed
  - 2 stacks of shield block
  - 52”x 52” x 60” high
- 4 Detector stations
  - 5” liquid scintillator
  - ^{3}He counters

Installation





The Results



No neutrons before beam pulse!

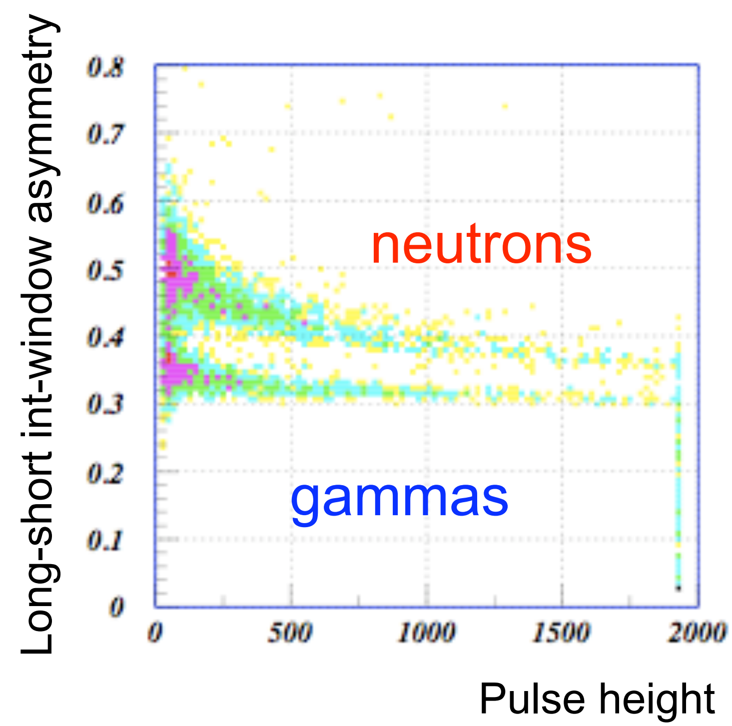
No significant late neutrons!

Flux consistent w. expectations

(for current beam power)

Scaling w. SNS power?

Continue measurements...

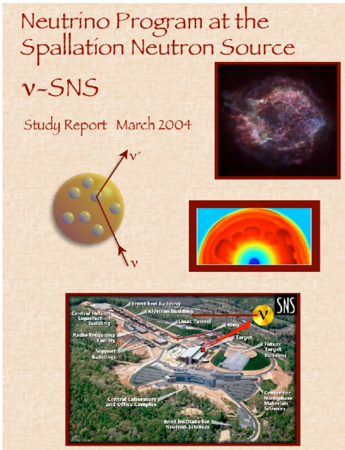


The NuSNS Collaboration

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)
NuA Scattering	Scholberg (Duke)
Veto	Greife (Mines)
SNS & Backgrounds	Blackmon (ORNL)
Theory	McLaughlin (NCSU) Hix (ORNL)



SNS
Bethel Valley Road
Building 8600
Oak Ridge, TN 37831-6477
Phone: (865) 241-1499
Fax: (865) 576-3041
E-mail: masont@sns.gov

Date: August 27, 2004

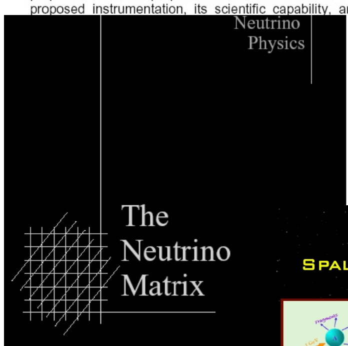
To: Professor Yuri Efremenko

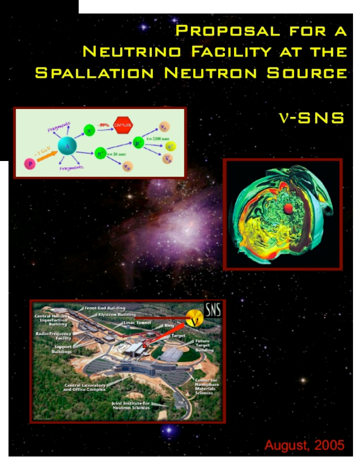
c: I. S. Anderson, J. B. Roberto, G. R. Young

From: Thomas E. Mason, 8600, MS-6477 (241-1499)

Subject: Neutrino Program at the Spallation Neutron Source

Following receipt of your Letter of Intent to establish a Neutrino Program at the Spallation Neutron Source (SNS), we have conducted a review of the submission, enlisting external expertise to supplement our own appraisal of the feasibility of this proposal as well as discussions with our Advisory Committees. I am attaching two referee reports that informed our assessment of the scientific promise of this proposal. Both referees felt that it would be appropriate to proceed with a full proposal. In addition, our own review of the program indicates that it can be accommodated at SNS provided the footprint and floor loading are coordinated with the Experimental Facilities Division to insure there is no unacceptable compromise of access to neighboring instruments. Based on this input there is sufficient merit to the Letter of Intent and the scientific program it describes to warrant proceeding with a full proposal. The full proposal should document in a more detailed way the design of the proposed instrumentation, its scientific capability, and how its makes effective use of the





March 2004
Study report completed
Letter of Intent to SNS

August 2004
"Green light" from SNS

October 2004
Neutrino Matrix

August 2005
Proposal submitted

Replace with
updated version

FY07
NSAC LRP

FY 2010 - FY 2011
Construction

The Timeline

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

derground detector facilities emerges. A successful neutrino program depends on the availability of such underground space.

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.

Conclusions

- Combination of high flux and favorable time structure at the SNS allows for a diverse program of measurements
- High statistics in less than one year of operation
- Near detector for OscSNS (?)
- Strong collaboration of experimentalists and theorists
- We welcome new ideas and participation
- Eagerly awaiting DoE funding decision

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