Astrophysics relevance of neutrino cross sections (and SNS)

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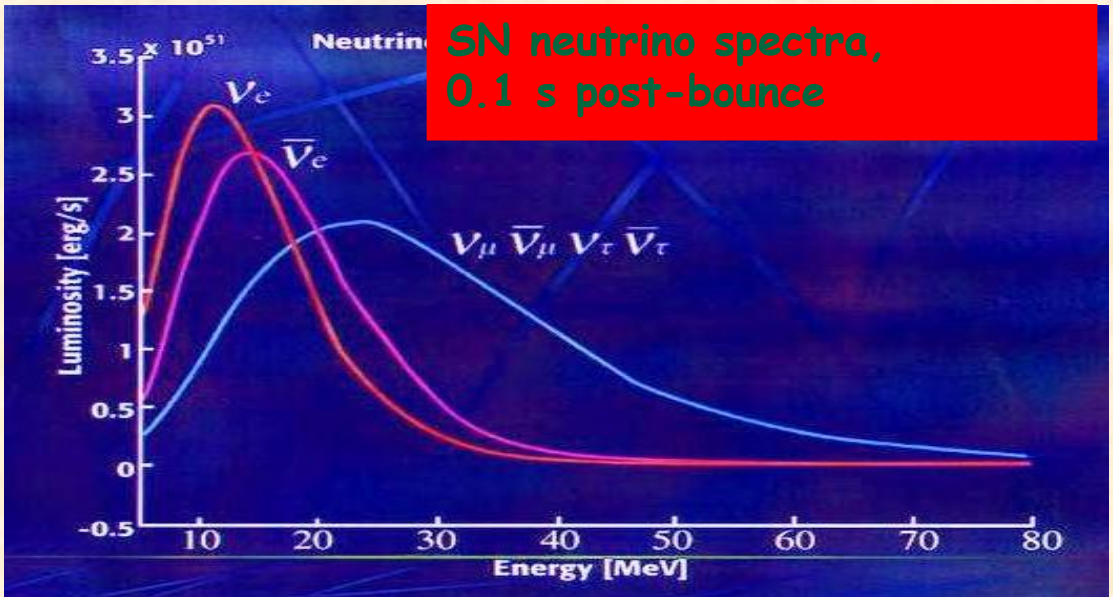
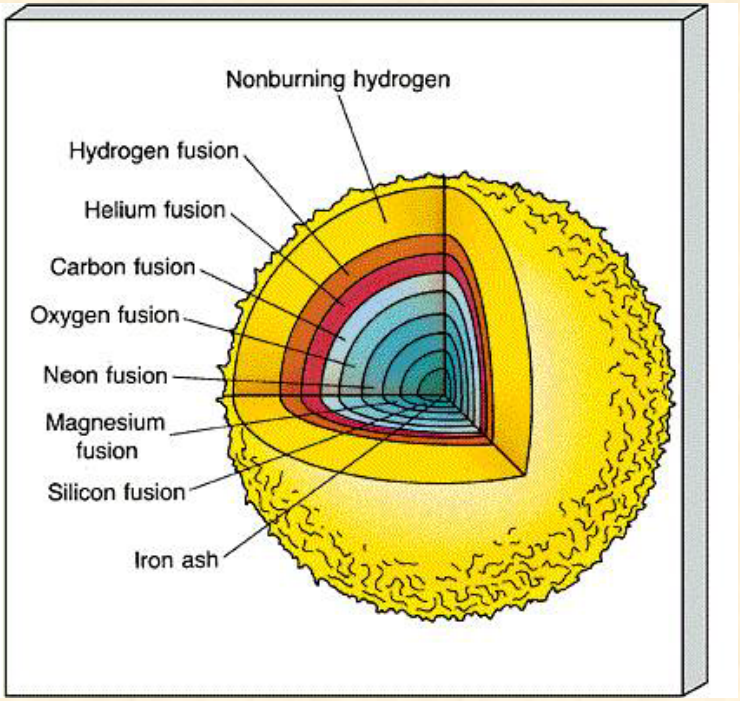
SLAC

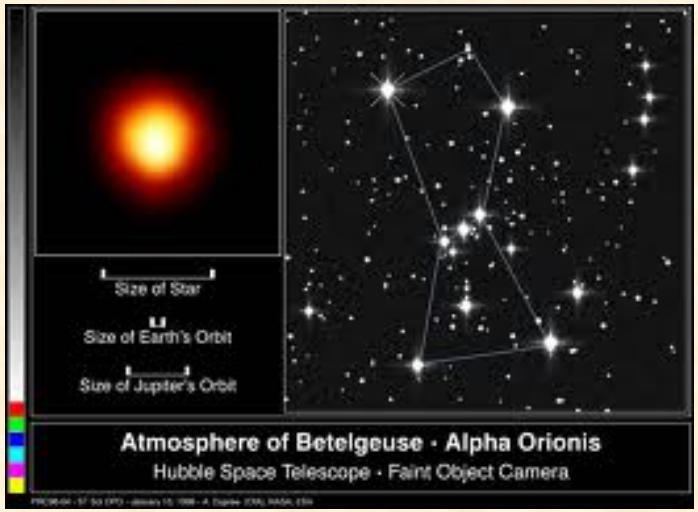
Core-collapse supernovae

- **Destruction of massive star initiated by the Fe core collapse**
  10^{53} ergs of energy released
  99% carried by neutrinos
- **A few should happens 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 details of explosion and it is not completely understood**



Pre Supernovae

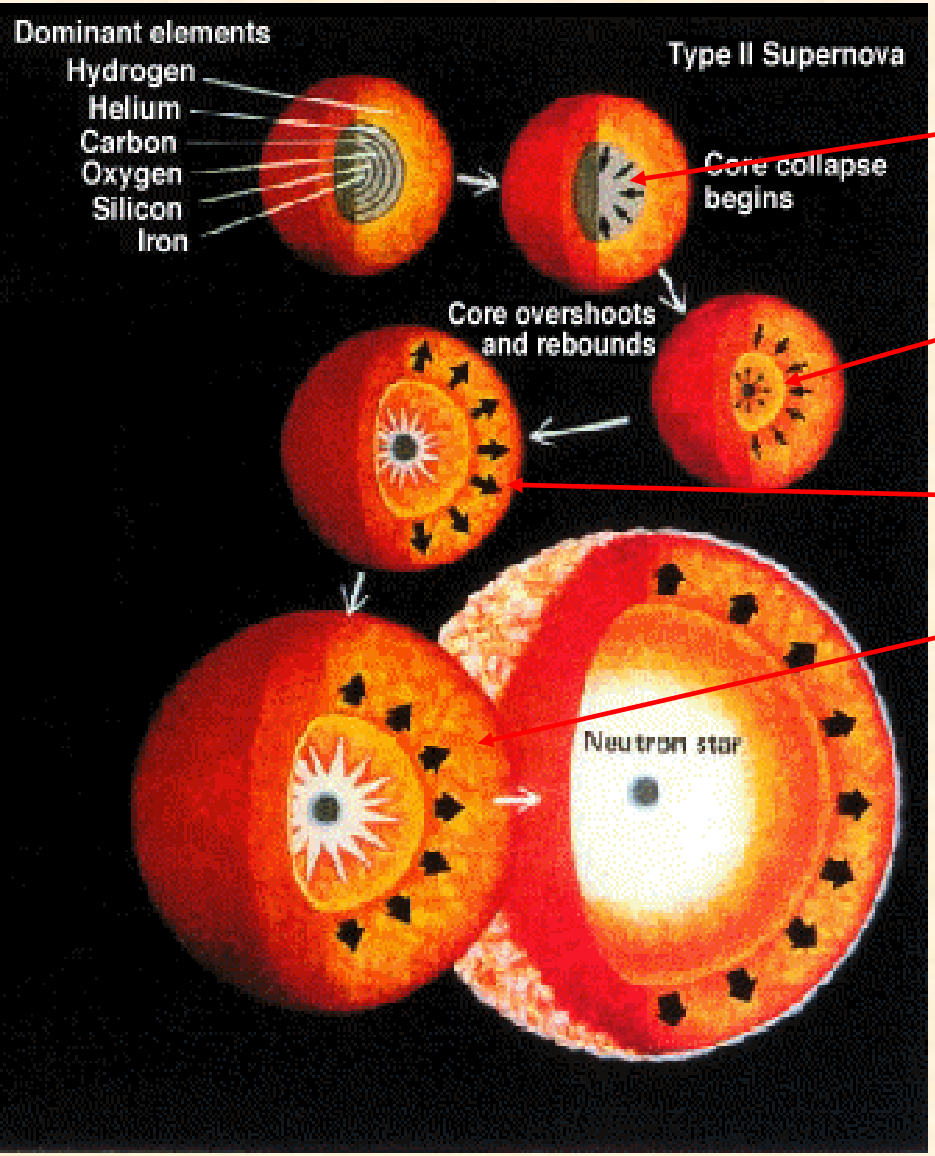




Evolutionary stages of a 25 MSUN star:

Stage	Temperature (K)	Duration of stage
Hydrogen burning	4×10^7	7×10^6 years
Helium burning	2×10^8	5×10^5years
Carbon burning	6×10^8	600 years
Neon burning	1.2×10^9	1 year
Oxygen burning	1.5×10^9	6 months
Silicon burning	2.7×10^9	1 day
Core collapse	5.4×10^9	1/4 second
Core bounce	2.3×10^{10}	milliseconds
Explosion	about 10^9	10 seconds

Neutrinos in SN



Strong neutrino pulse generated as a result of core deleptonisation via electron capture on heavy nuclei

Neutrino trapped in the core but eventually ~10% of core rest mass radiated by neutrinos of all flavors

Energy transfer to the stalled shock

Neutrino wind affect nucleosynthesis

Neutrino – nuclei interactions are playing major role in SN dynamics !!!!

Neutrinos and Core Collapse SN

Electron capture and core collapse

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

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

- New calculations using a hybrid model of SMMC and RPA predict significantly higher rates for N>40
- Supernovae models w/ new rates:

  shock starts deeper and weaker **but** less impedance

ν opacities

- 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
  - νA coherent scattering
  - ν_e-e scattering
  - $\nu\nu$ scattering
  - ν–ν annihilation

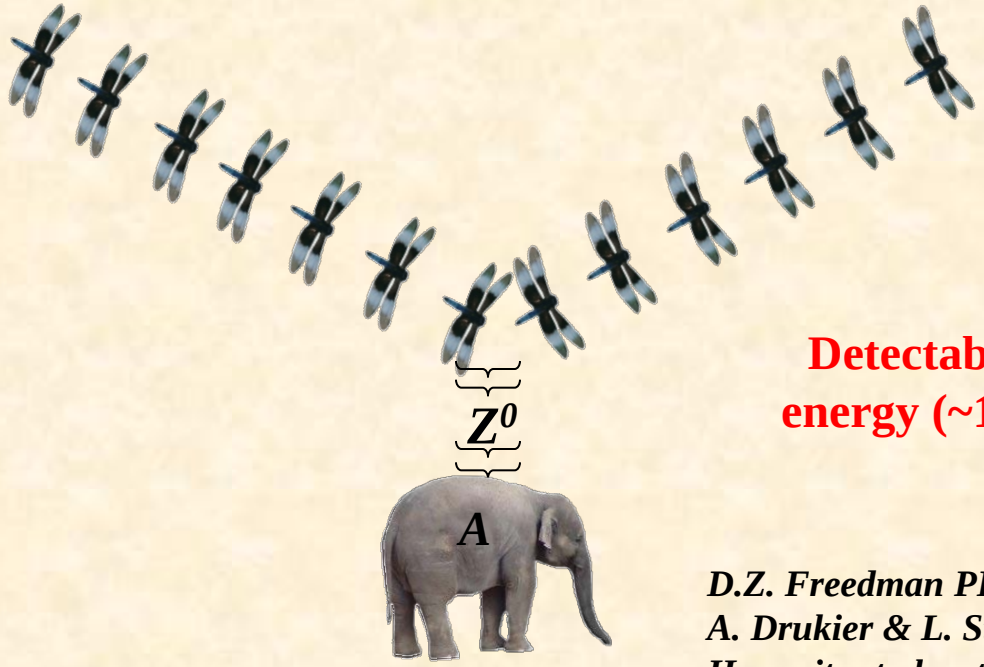
ν reactions and nucleosynthesis

- Neutrino reactions with nuclei ahead of the shock may alter the entropy & composition of in fall [Bruenn & Haxton (1991)].
- 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)].

The weak interaction plays a crucial role in supernova !

We need good understanding of neutrino interactions !

Neutrino Coherent Scattering



Detectable only via very low energy (~10keV) nuclear recoil

D.Z. Freedman PRD 9 (1974)
A. Drukier & L. Stodolsky, PRD 30, 2295 (1984)
Horowitz et al. astro-ph/0302071

Straight-forward to calculate

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

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

Never observed
Important for supernova dynamics (neutrino opacity)

What New Physics Could be Learned From Neutrino Coherent Scattering?

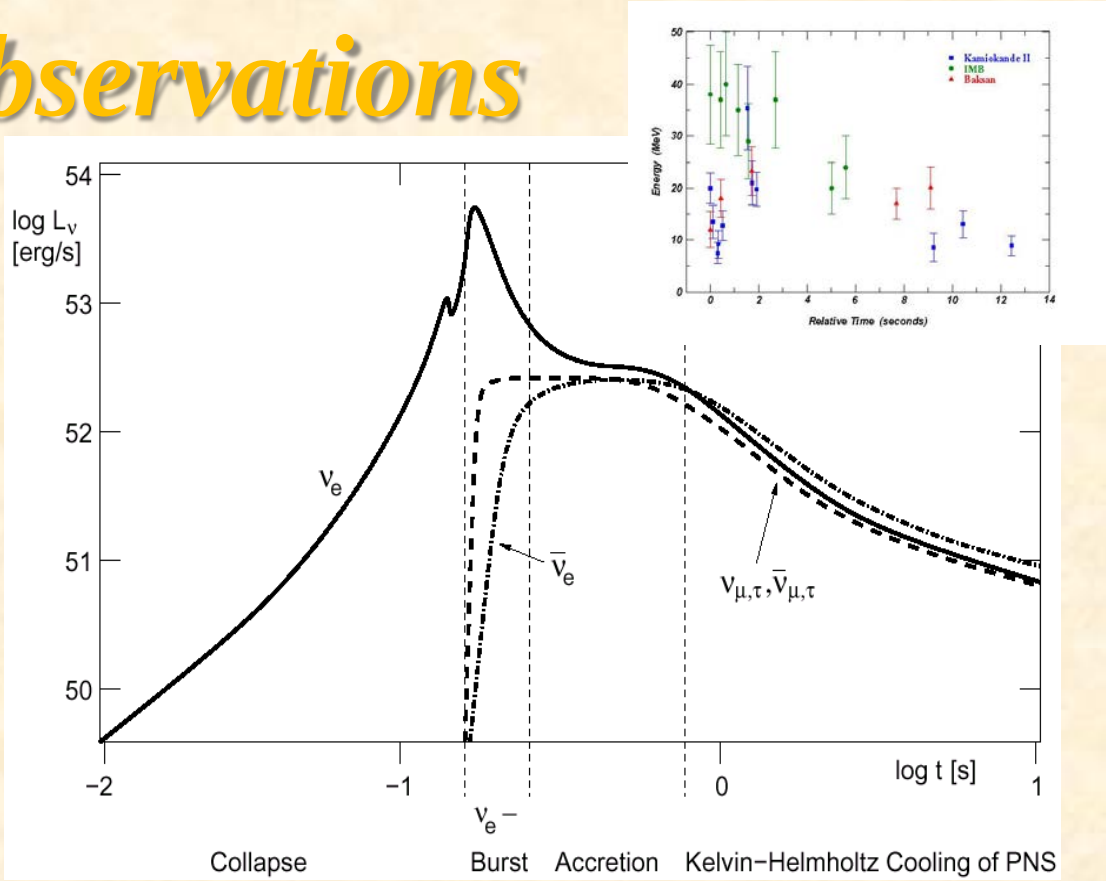
K. Scholberg, Phys. Rev D 73 (2006) 033005

Basically, any deviation from SM is interesting...

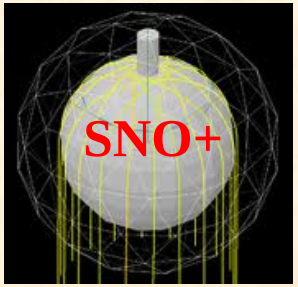
- Weak mixing angle:
  could measure to ~few % (new channel)
- Non Standard Interactions (NSI) of neutrinos:
  could significantly improve constraints

It is difficult to study it on Nuclear Reactors because of the continues flux and very low recoil energies

Supernova ν observations



Measurement of the neutrino energy spectra and time distribution from a Galactic supernova would provide a wealth of information on the conditions in supernovae, neutrino oscillations, etc.



- **An accurate understanding of neutrino cross sections is important for interpretation of neutrino signals from supernovae.**
- **Nuclei of interest: ^{2}H, C, O, Fe, Pb**

Neutrinos Nuclei Interactions at 10-50 MeV range are:

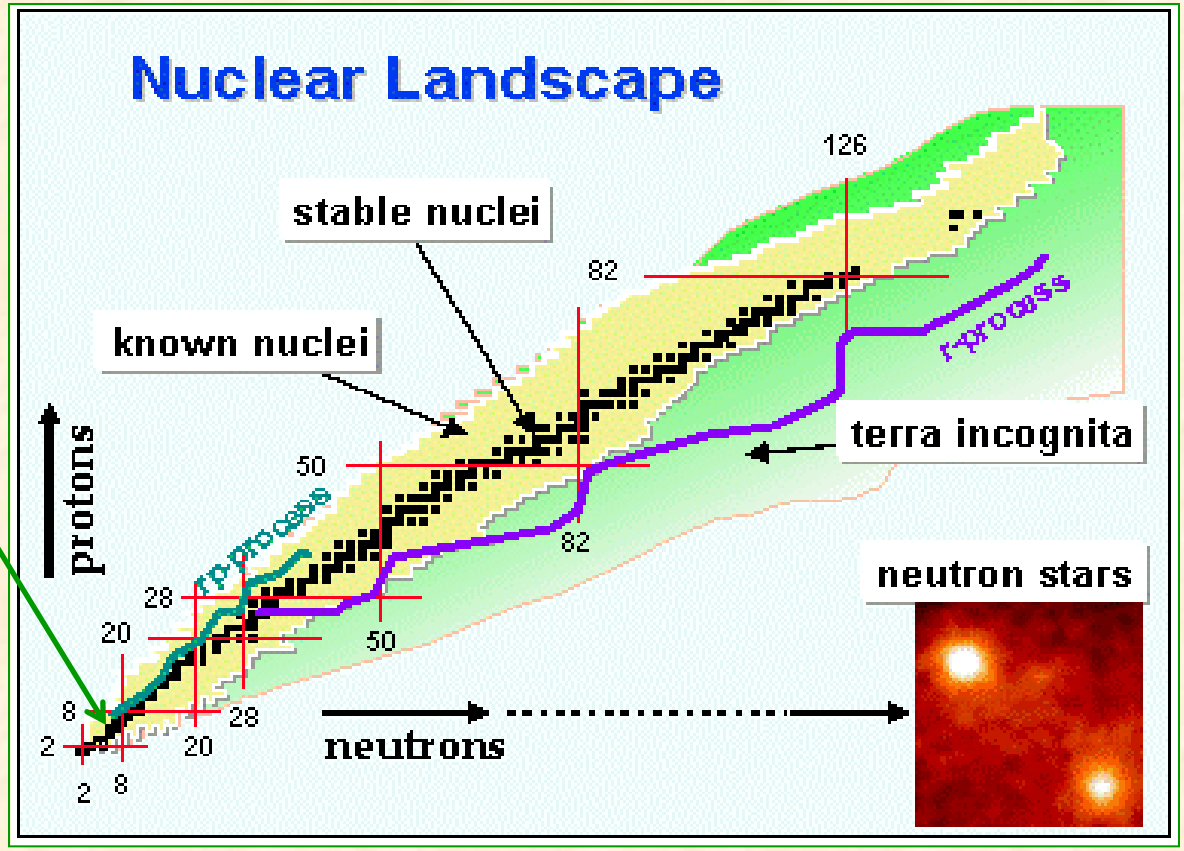
Important for understanding of supernovae mechanism

Important for neutrino detection from SN

Have a general interest for the nuclear theory

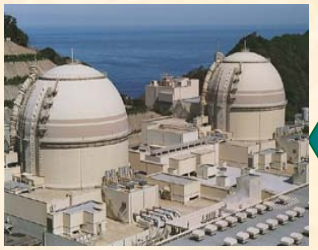
So far it is a green field. Only ν-C interactions have been accurately studied experimentally.
There are ~ 40% accurate data for d,Fe,I

ν-d is well understood theoretically and indirectly has been measured by SNO



It is important to provide accurate ν-A measurements for wide range of isotopes

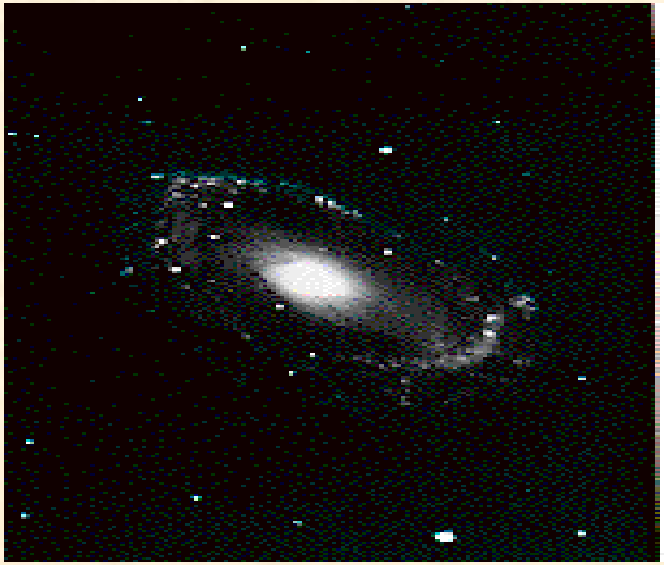
Man Made Neutrino Sources

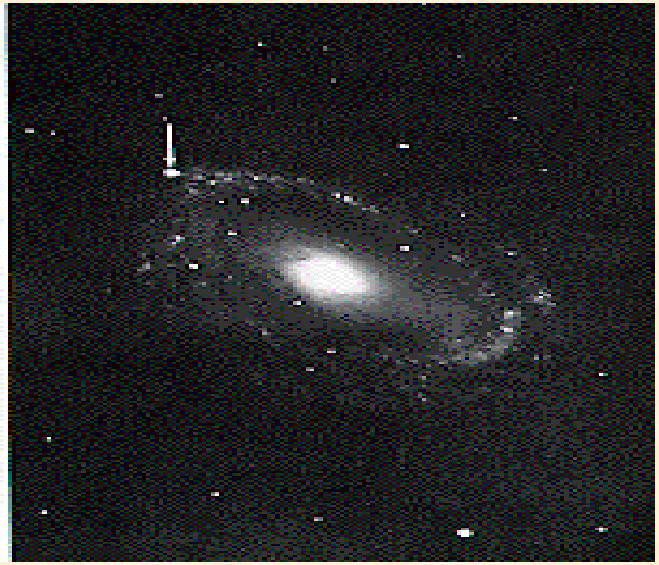


Nuclear reactors
E_ν<7 MeV

Stop Pion Facilities
$7<E_\nu<53$ MeV
This resion is nicely coincides with neutrino energies produced during the
Super Novae Explosion

H.E. "accelerators"
E_ν >100 MeV





In E-M
$L_{SN} \sim L_{galaxy}$

In Neutrinos
$L_{SN} \sim 3000\ L_{galaxy}$

SNS- Spallation Neutrino Source

SNS layout

1.3 GeV proton linear accelerator

Accumulator ring

Main target

SNS Parameters

Proton beam energy – 0.9 - 1.3 GeV

Intensity - 9.6 · 10^{15} protons/sec

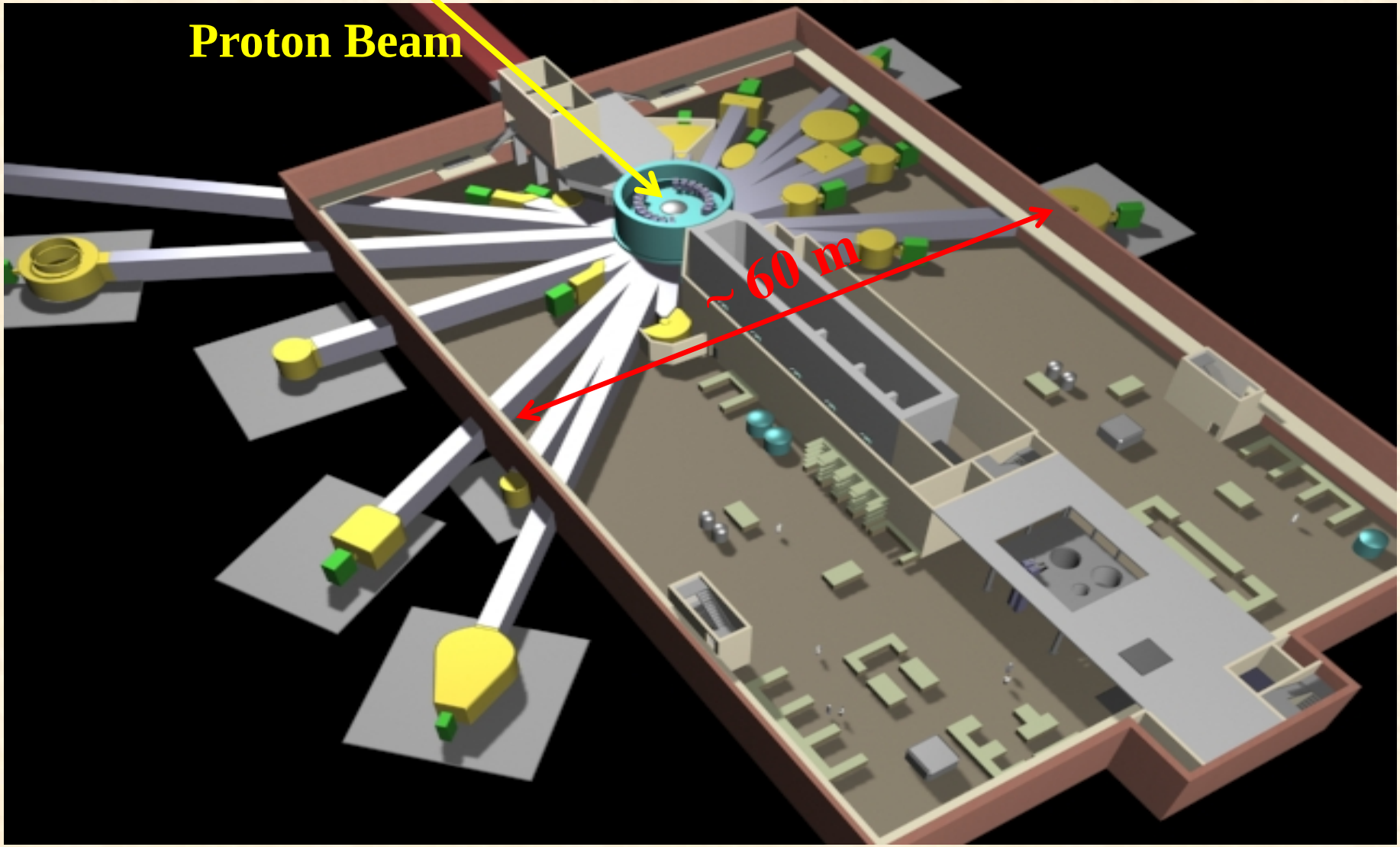
Pulse duration - 380ns(FWHM)

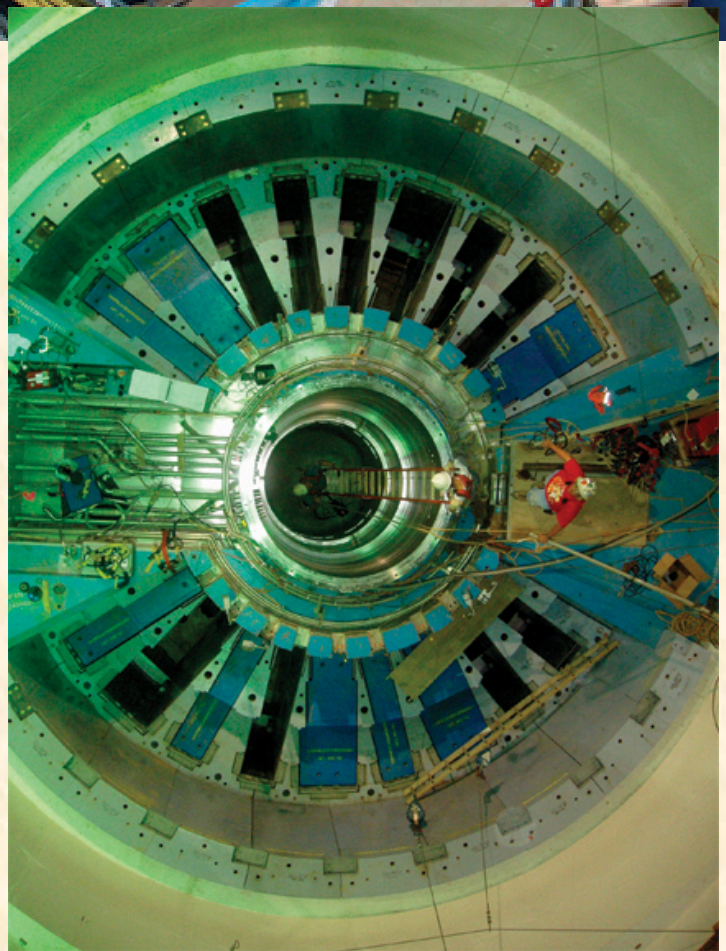
Repetition rate - 60Hz

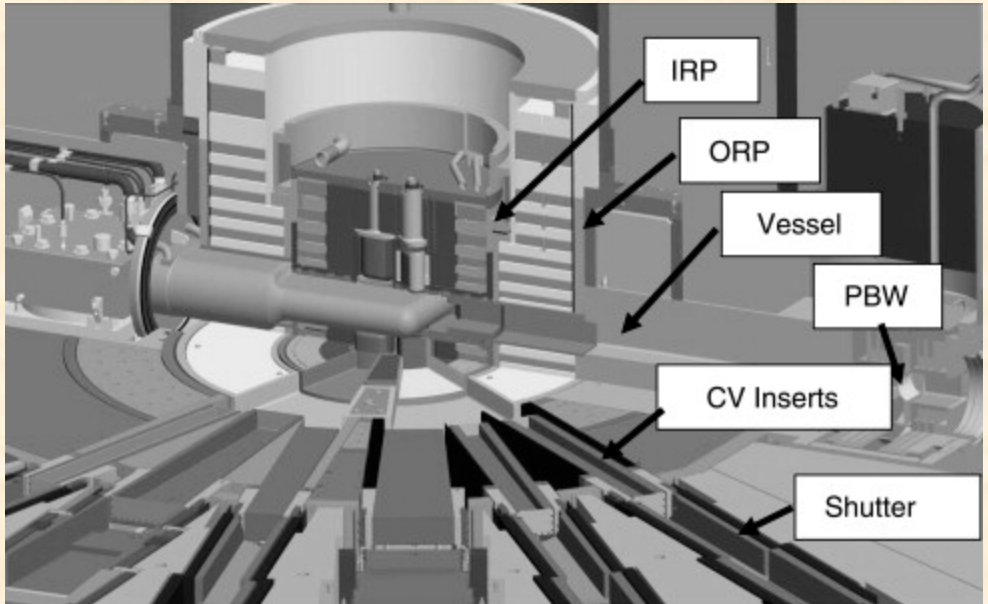
Total power – 0.9 – 1.3 MW

Liquid Mercury target

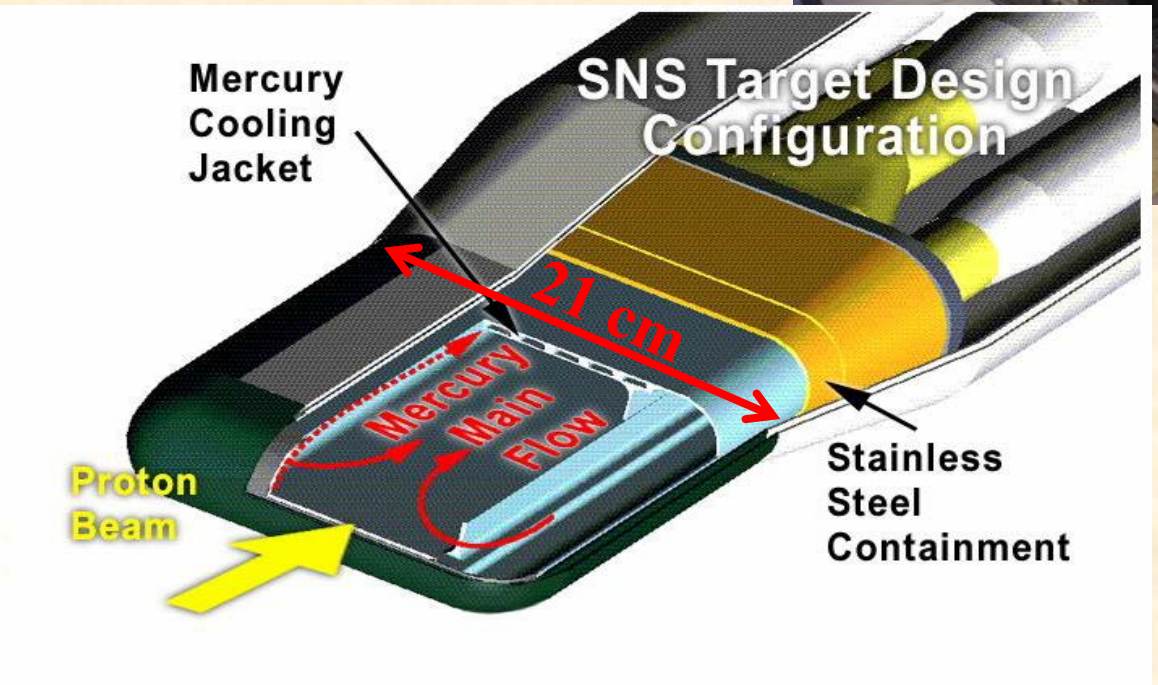
Target building






IRP
ORP
Vessel
PBW
CV Inserts
Shutter

Mercury target

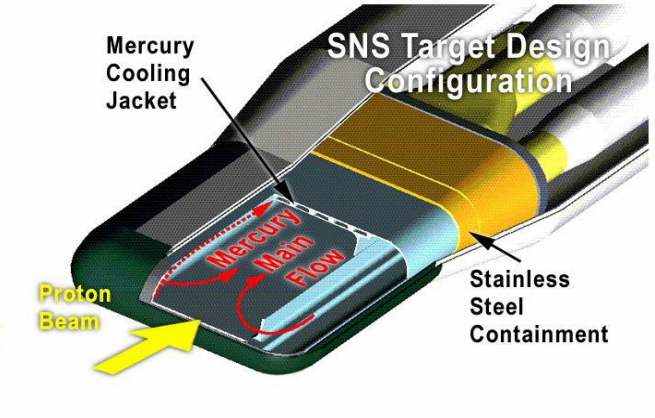


Mercury Inventory – 20 t
Flow rate 340 kg/sec
V_{max} 3.5 m/sec
T_{in} 60^0C
T_{out} 90^0C

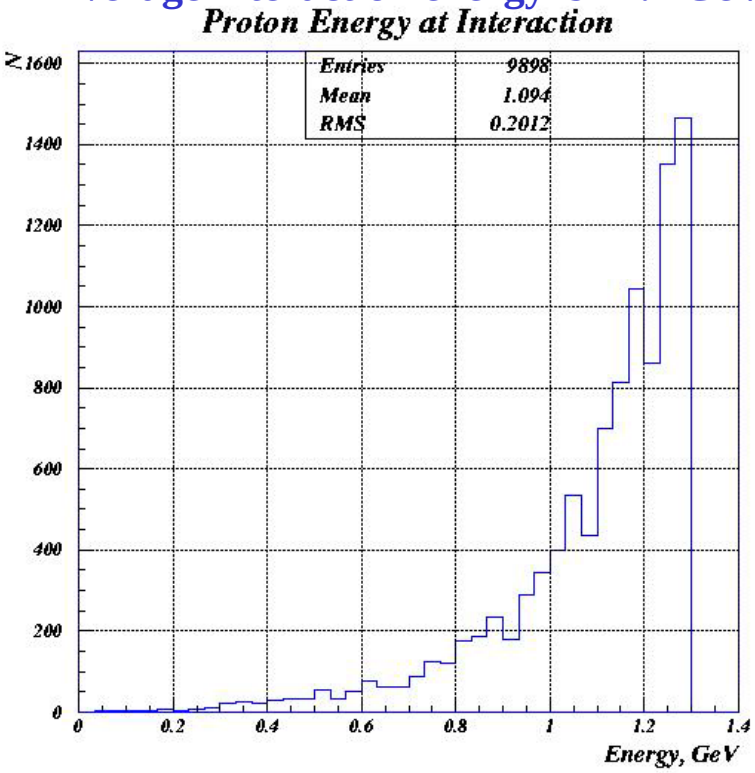
Mercury lasts the entire 40 year lifetime of SNS no change is required

Stainless steel vessel should be replaced periodically

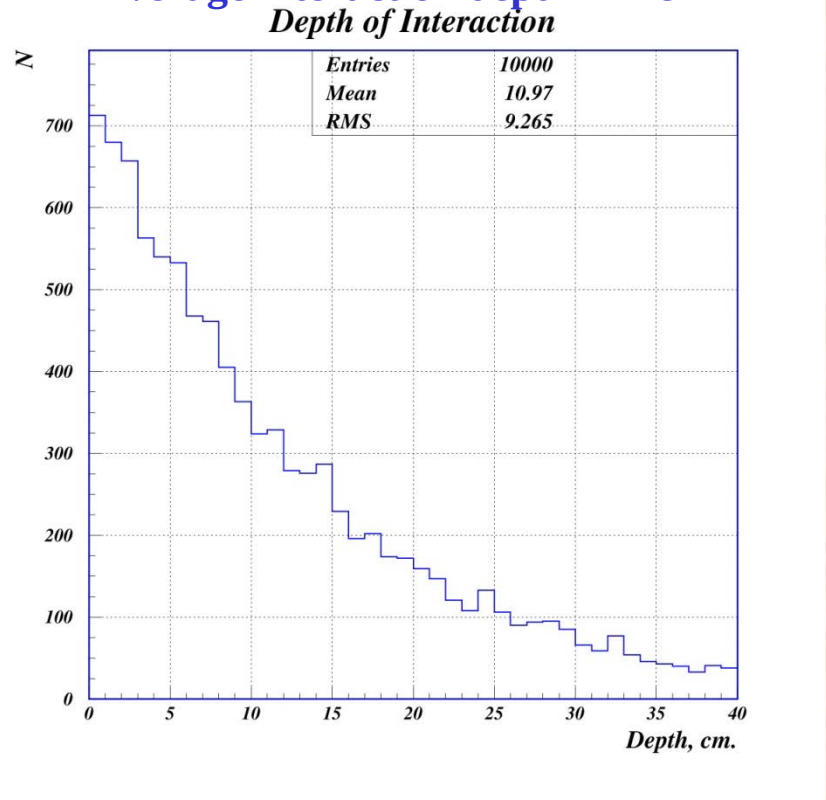
Some Details of Interaction in the Target



Average interaction energy is ~1.1 GeV



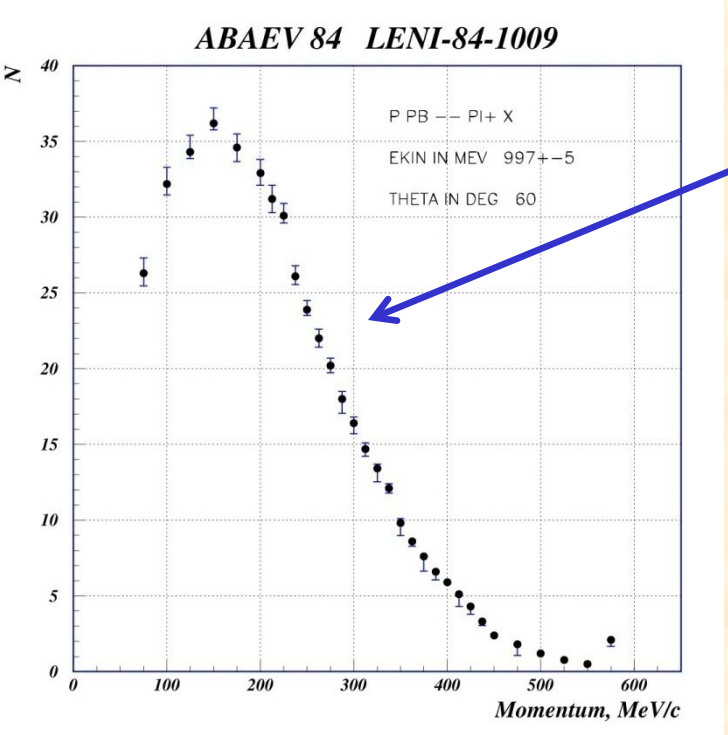
Average interaction depth ~11 cm



Proton interacts near the front part of the target

DIF vs. DAR

Pion Spectra

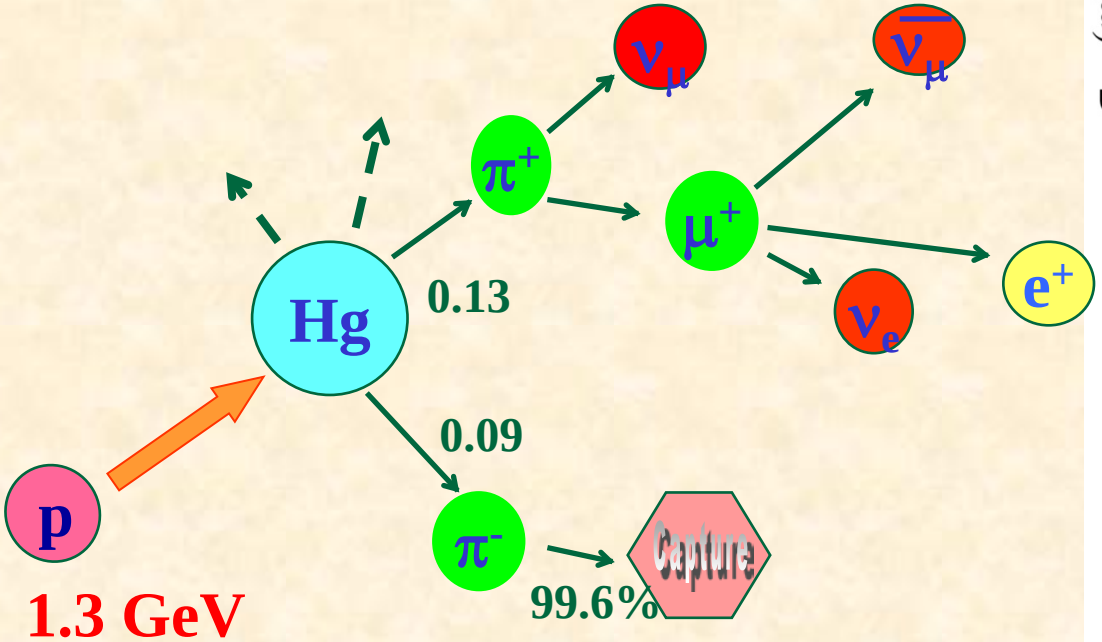


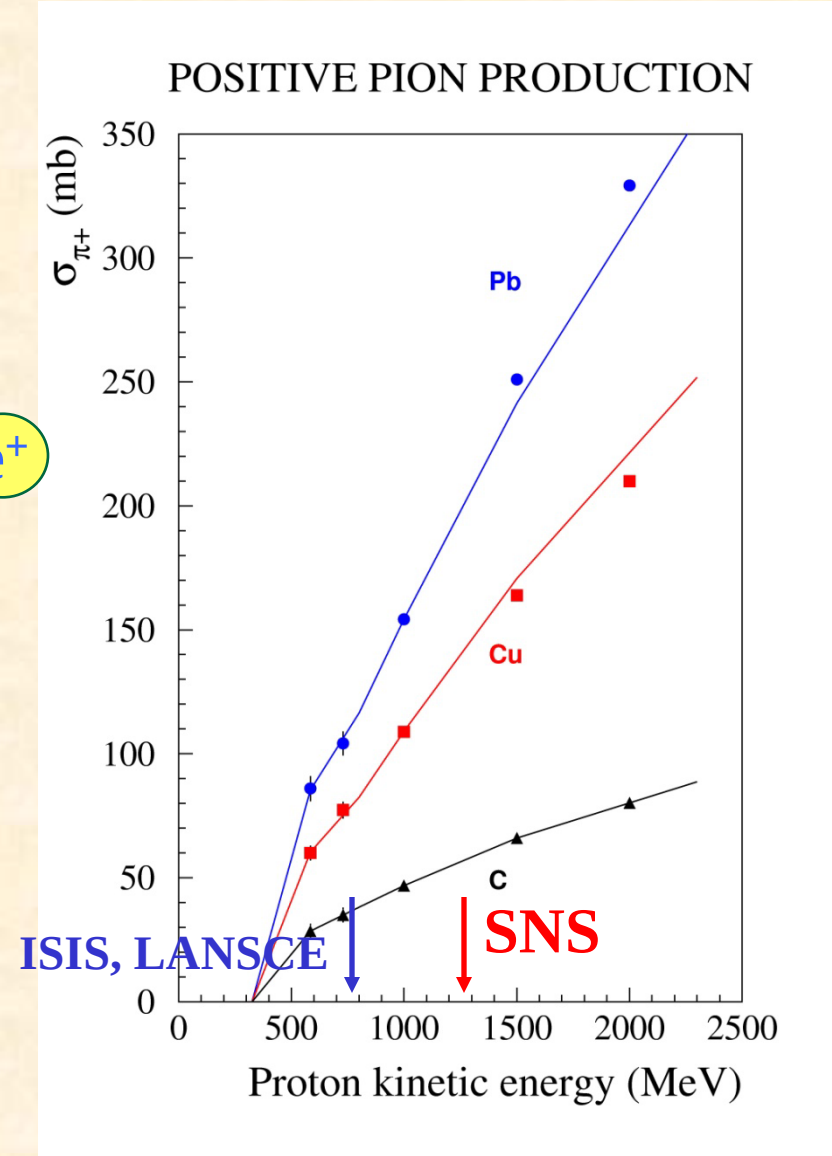
200 MeV/c pions range in mercury is ~ 5 cm

Very few pions have a chance to decay before coming to the rest, or escape from the traget

Because of the bulk Mercury target, SNS is a Decay At Rest facility !!

Neutrino Production



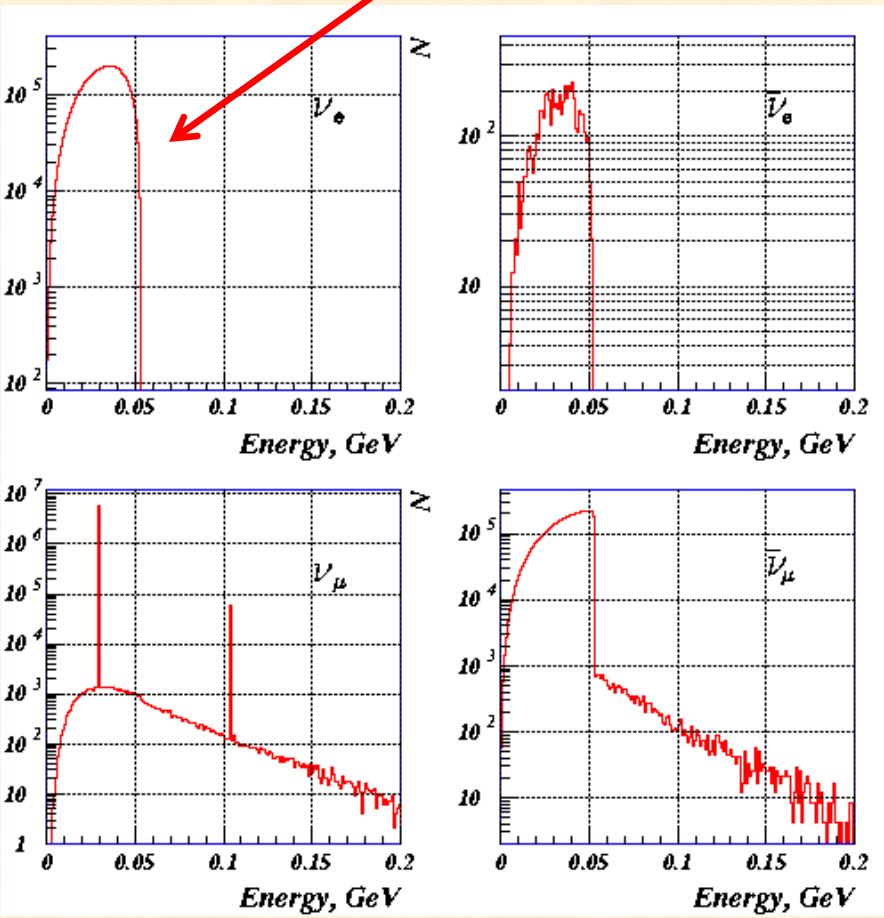


At the first approximation:

π^+/proton = 0.14*E(GeV)-0.05
For E~0.8-1.5 GeV

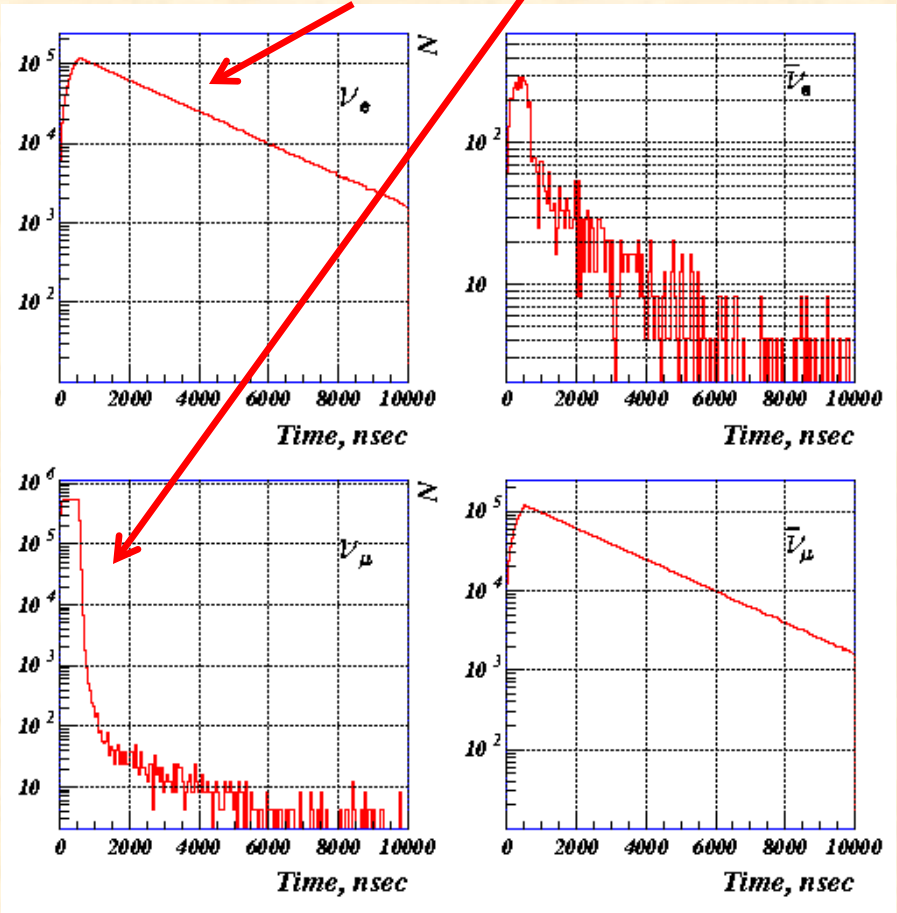
Calculated spectra of neutrinos from SNS

Neutrino spectra well defined



Energy

ν_e, ν_μ-bar and ν_μ are in the different time intervals



Time

Neutrino Rates

Number of protons on the target for 1.1 mA at 1.3 GeV is $0.687 \cdot 10^{16}$ sec^{-1}

Number of each flavor neutrino produced by one proton is 0.13

SNS live time is 2/3 of the year

Number of each flavor of neutrinos produced at SNS is $1.9 \cdot 10^{22}$ $year^{-1}$

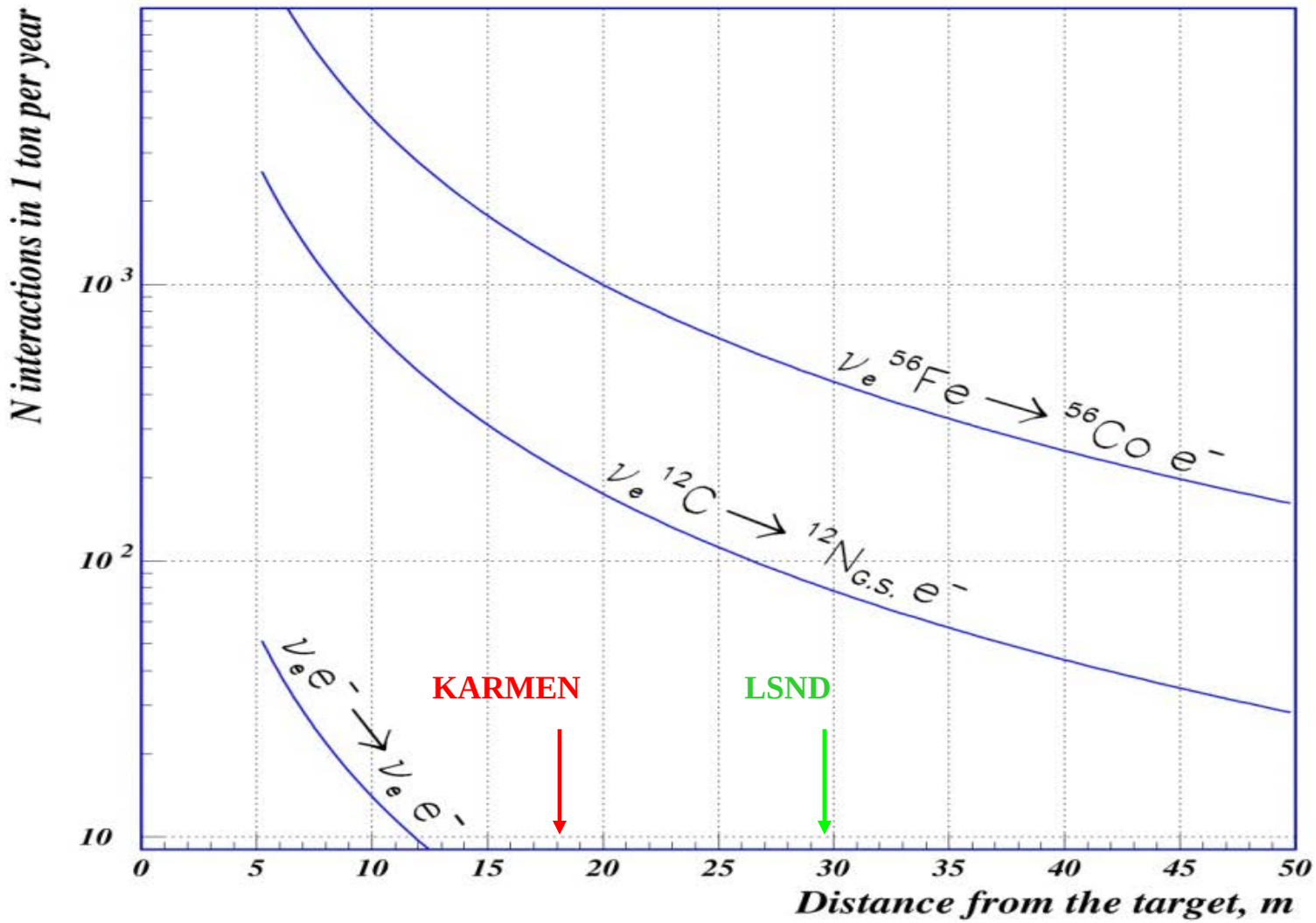
Caveat:
There is larger flux of antineutrinos from decay of radioactivity in the target
However, heir energy is a few MeV and almost continues in time.

Cross Sections Integrated over SNS spectra.

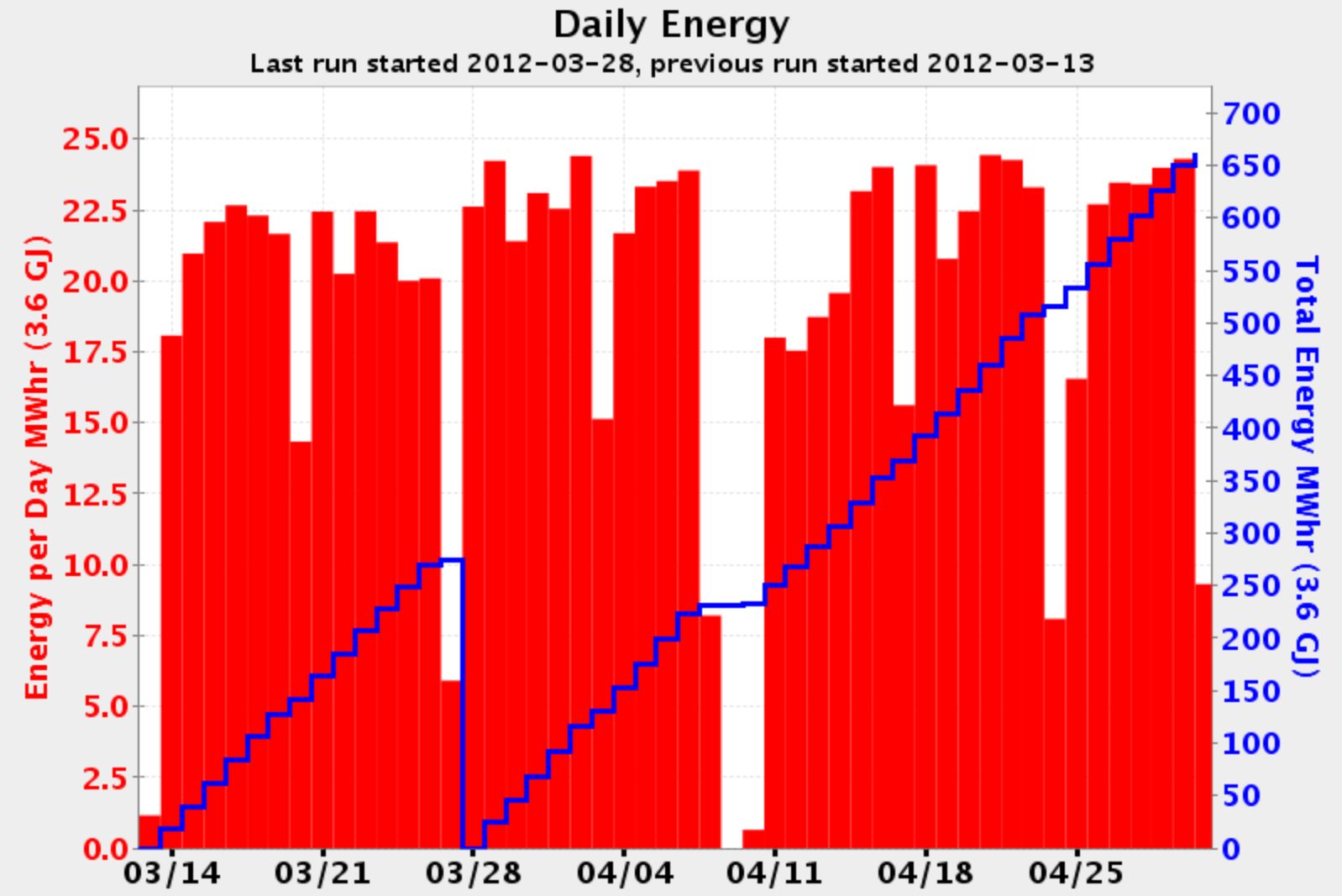
Reaction	Integrated Cross Section
$\nu_e e^- \rightarrow \nu_e e^-$	$0.297 \cdot 10^{-43}$ cm^2
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	$0.050 \cdot 10^{-43}$ cm^2
$\nu_e {}^{12}C \rightarrow {}^{12}N_{gs}\ e^-$	$0.92 \cdot 10^{-41}$ cm^2
$\nu_e {}^{12}C \rightarrow \nu_e\ {}^{12}C^*$	$0.45 \cdot 10^{-41}$ cm^2
$\nu_\mu {}^{12}C \rightarrow \nu_\mu {}^{12}C^*$	$0.27 \cdot 10^{-41}$ cm^2
$\nu_e {}^{56}Fe \rightarrow {}^{56}Co\ e^-$	$\sim 2.5 \cdot 10^{-40}$ cm^2

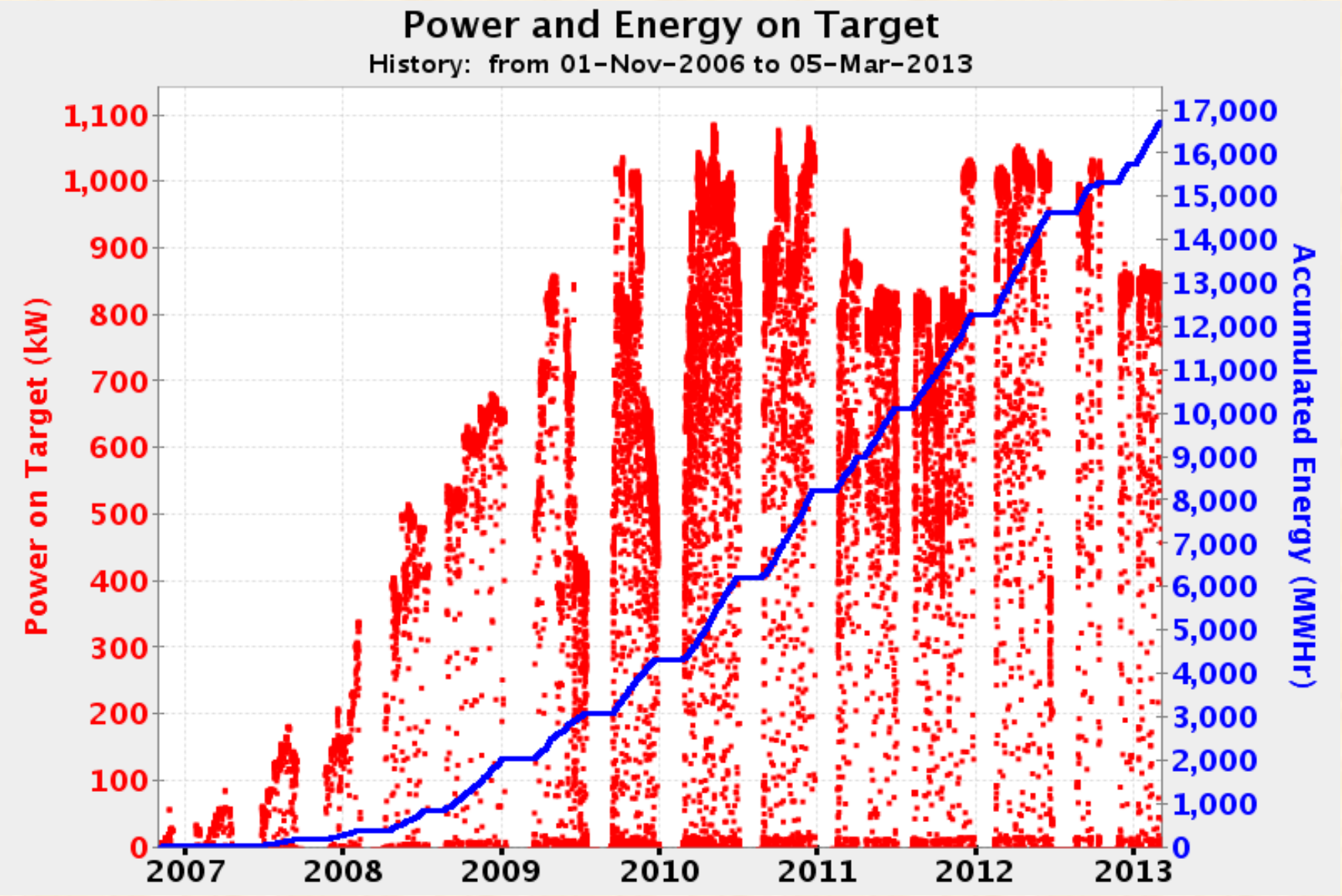
SNS delivers ~ $1.9 \cdot 10^{22}$ neutrinos per year

Detector mass and interaction rates

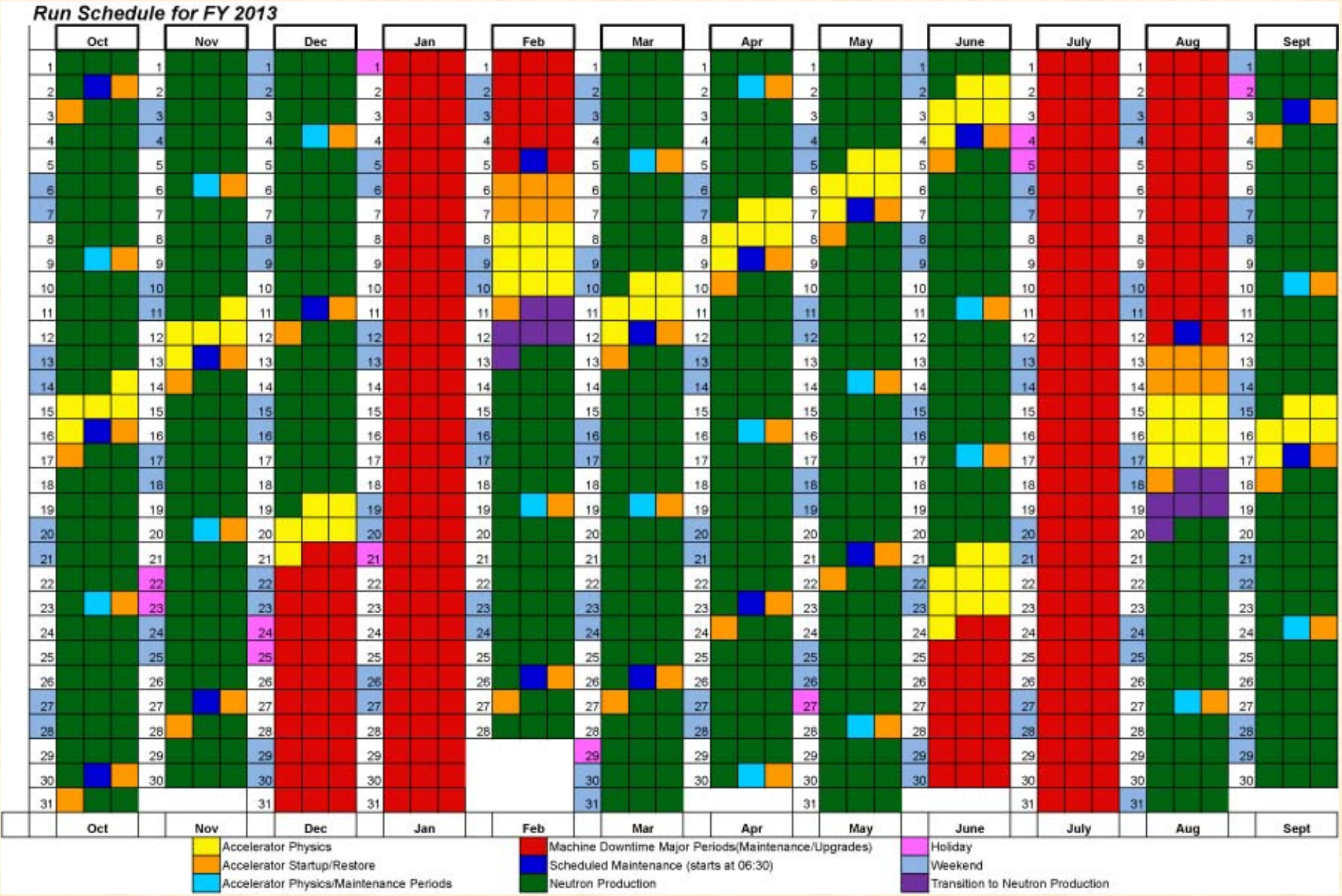


SNS is Is in Stable Operations



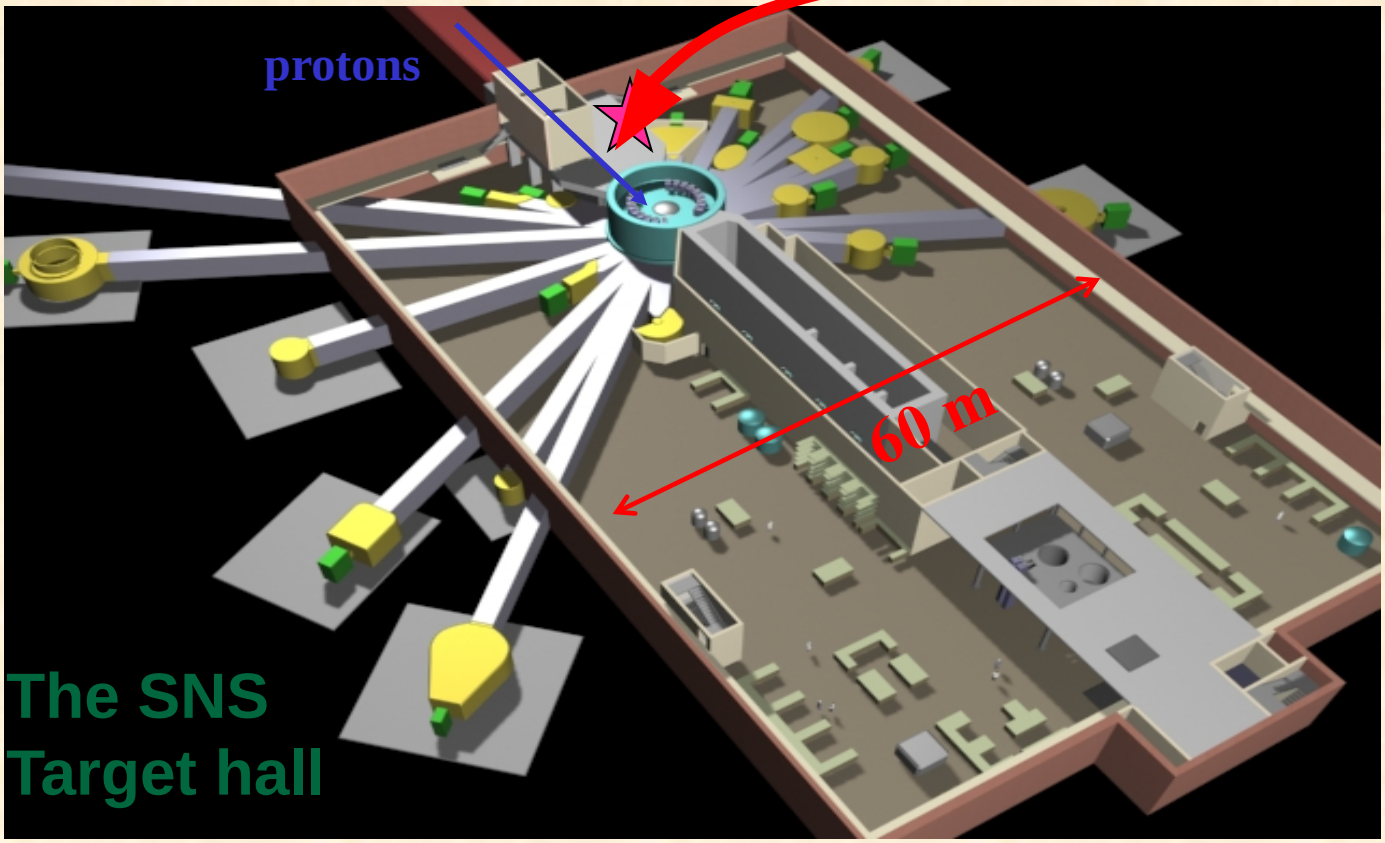

Power and Energy on Target
History: from 01-Nov-2006 to 05-Mar-2013
Power on Target (kW)
1,100
1,000
900
800
700
600
500
400
300
200
100
0
Accumulated Energy (MWHr)
17,000
16,000
15,000
14,000
13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
2007
2008
2009
2010
2011
2012
2013

SNS Calendar



Potential Locations for Neutrino Experiments at the Spallation Neutron Source

site inside target building



20 m^2 x 6.5 m (high)

Close to target ~ 20 m
$\rightarrow$ 2×10^7 $\nu/cm^2/s$

θ=165° to protons
$\rightarrow$ lower backgrounds

There are multiple sites available outside of the target building, distances ~40-60 m

SNS induced BG

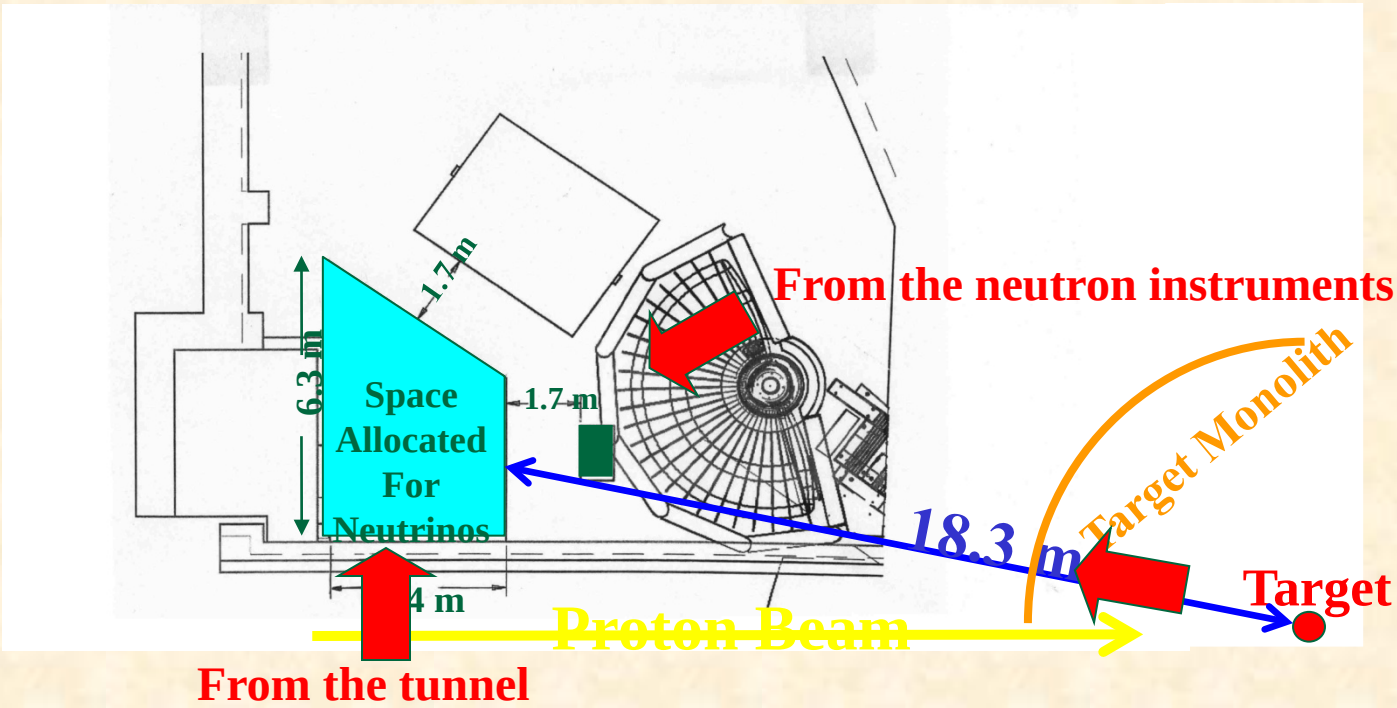
Most dangerous B.G. is from SNS neutrons

Analysis is complicated because many uncertainties still exist.

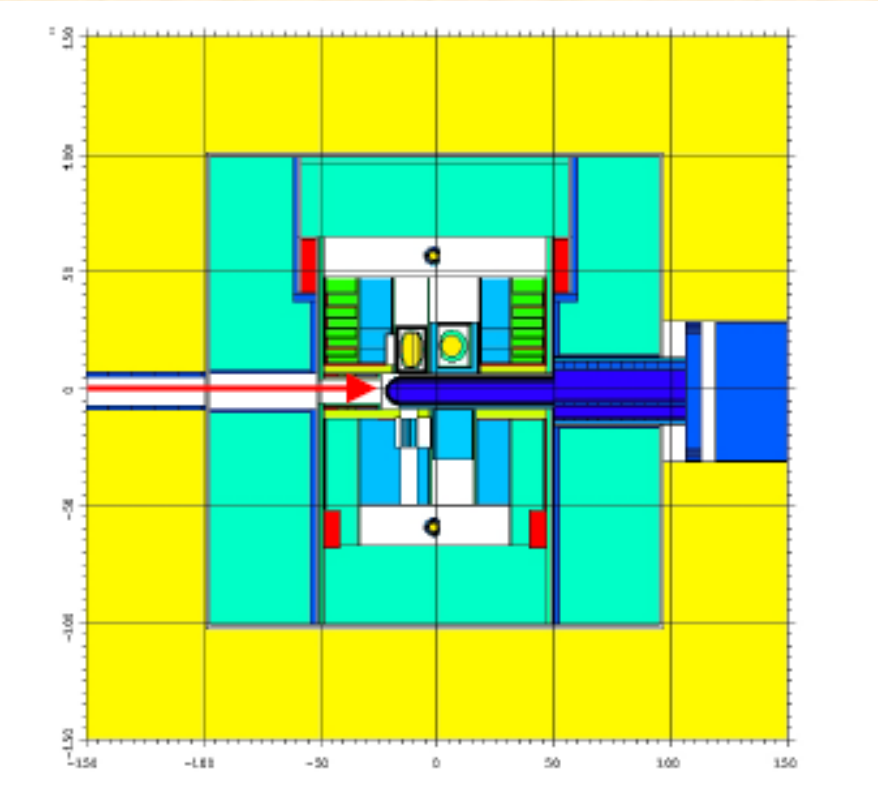
We know for sure that environment is OK for humans.

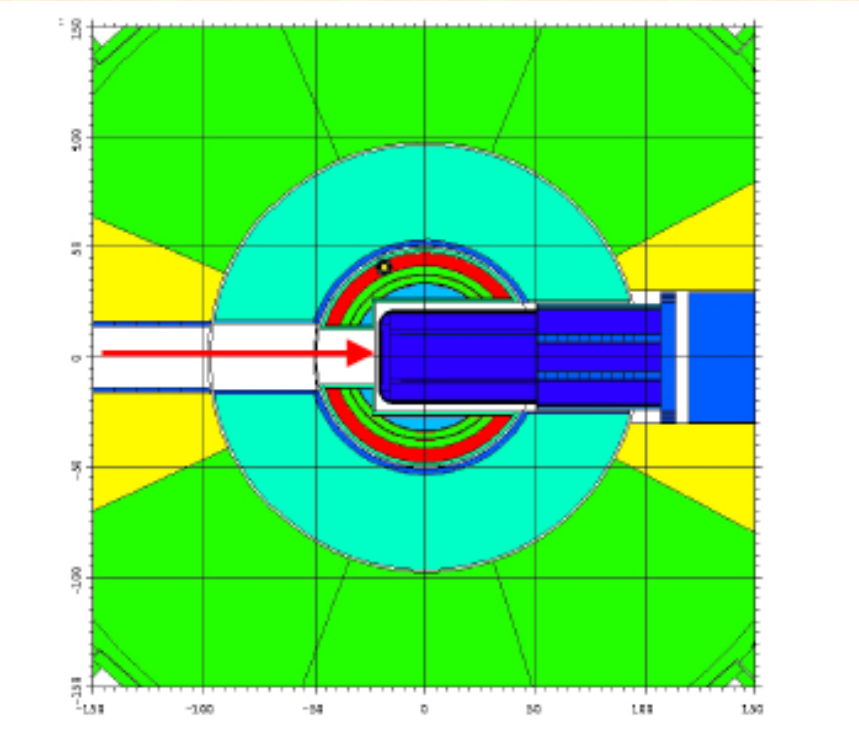
However neutrinos detectors are much more sensitive then humans!

We considered three major sources:



Target Neutrons



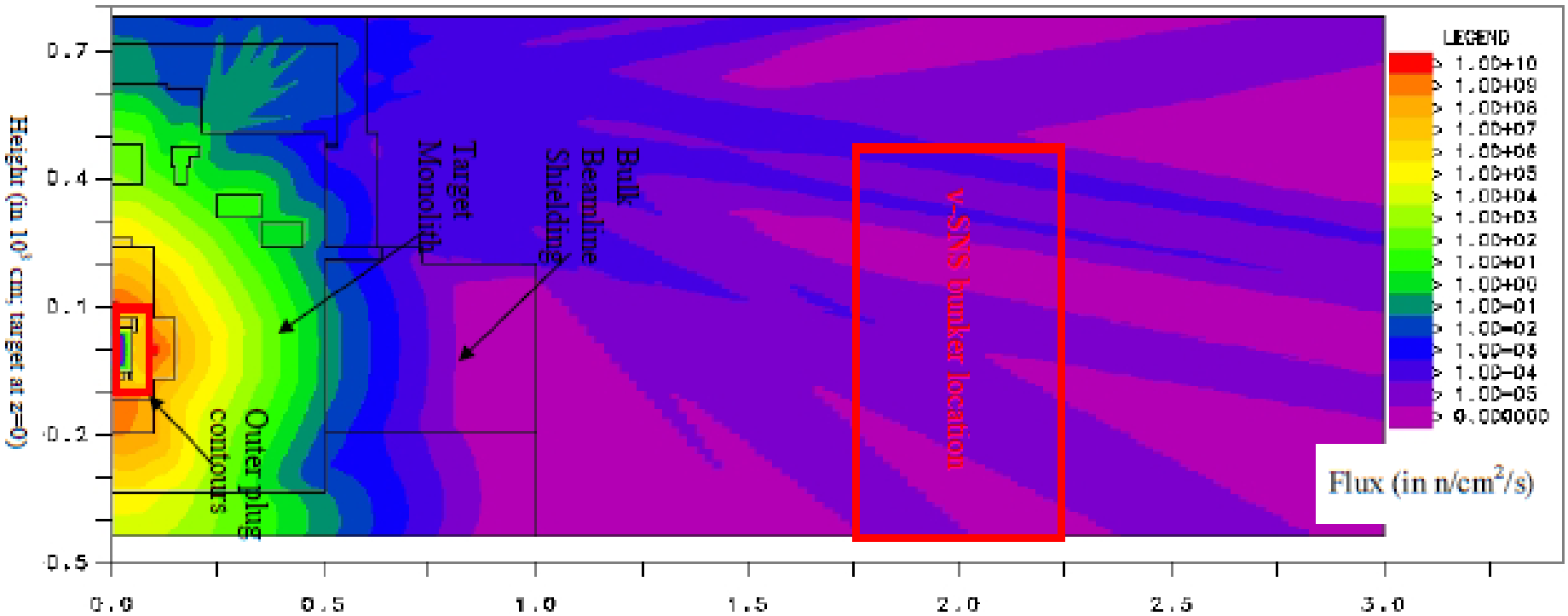


Full 3D MSNPX calculations were performed till ~2 m

Coupling tool MTD was used to couple to 2D DORT code to propagate further.

Instrumental floor was modeled up to distance of 30 m

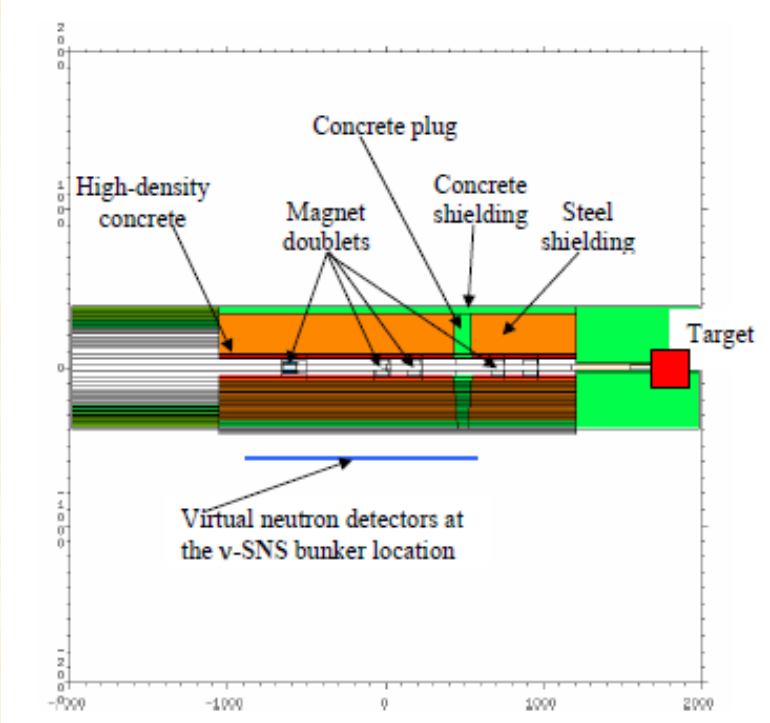
Neutrons from the Target

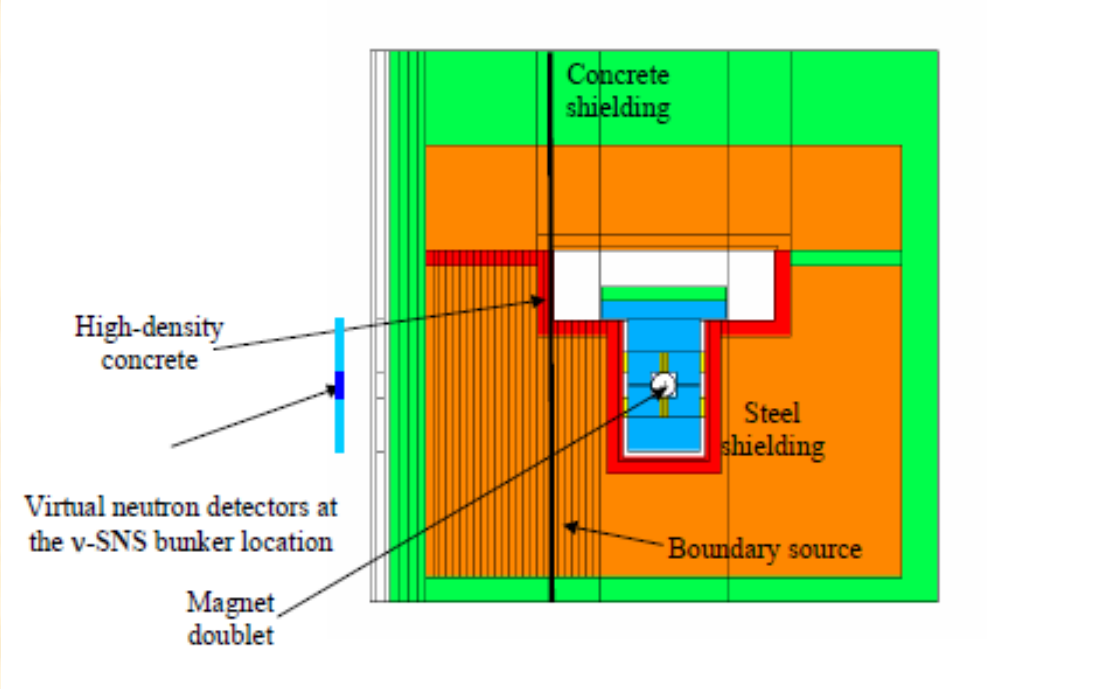


Neutrons from the Tunnel

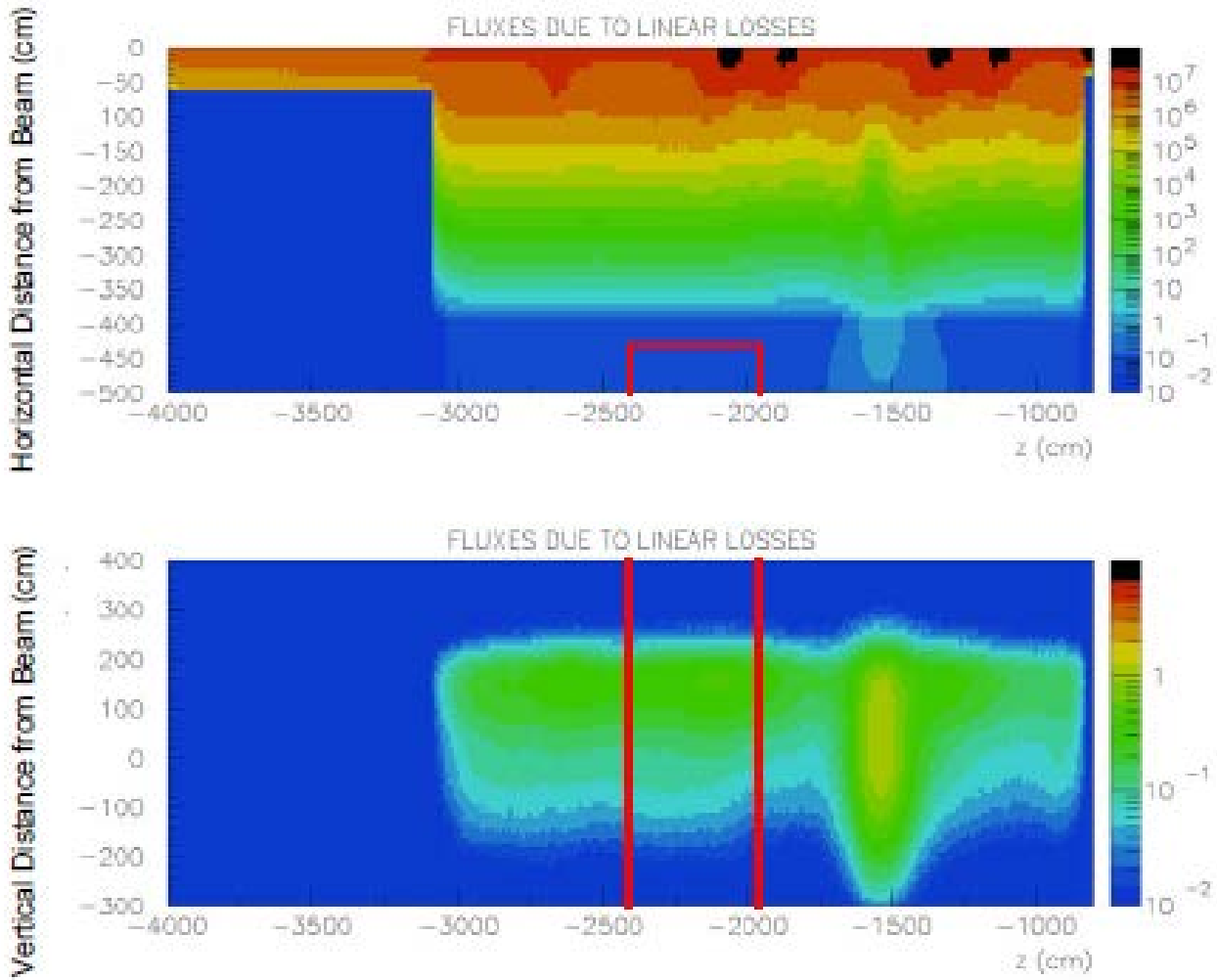
Similar Calculations were done taking into account beam losses

Beam losses ~ 1W/m (Linear source)

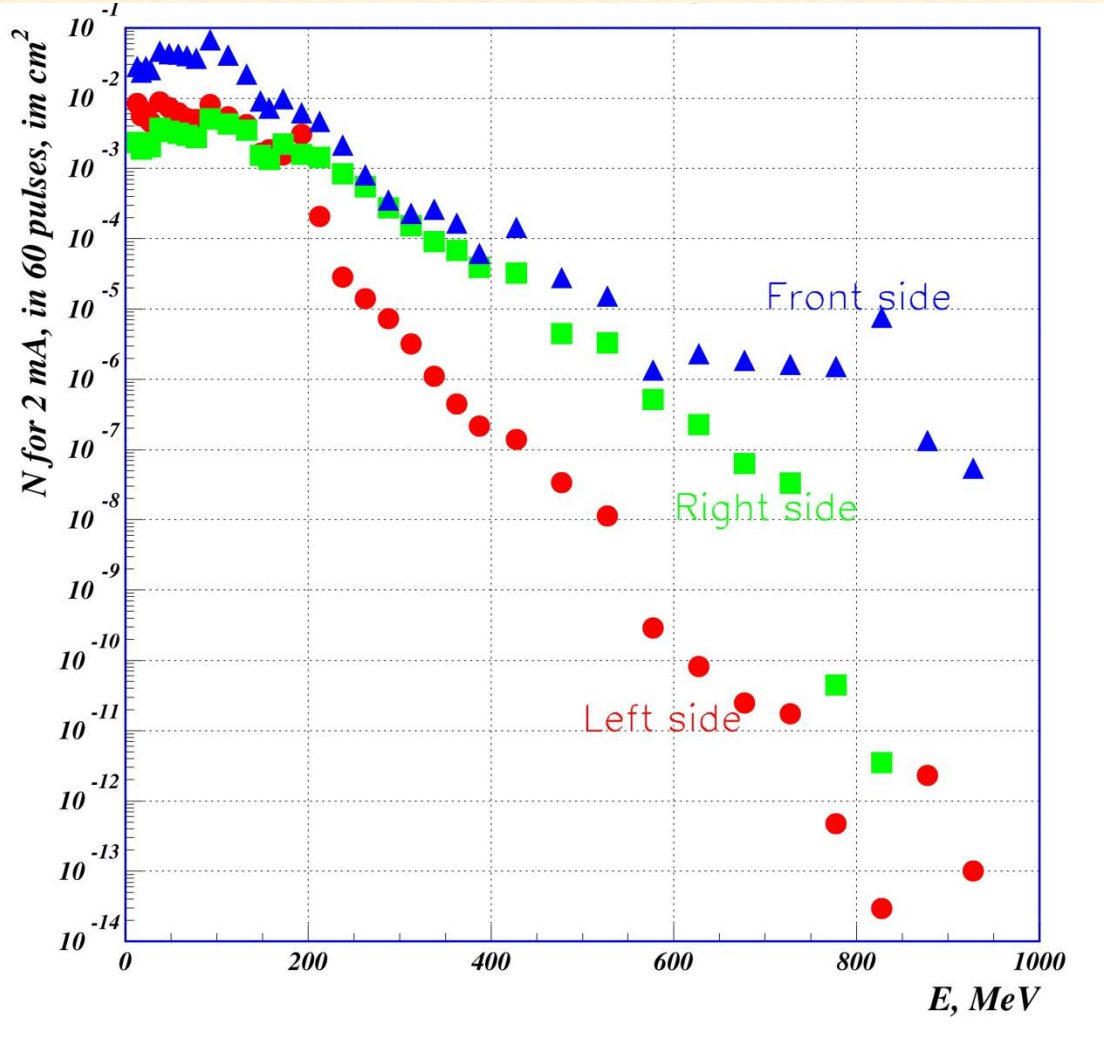




Neutrons from the Tunnel



SNS induced neutron flux at 20 meters



High energy neutrons can be eliminated using time cut

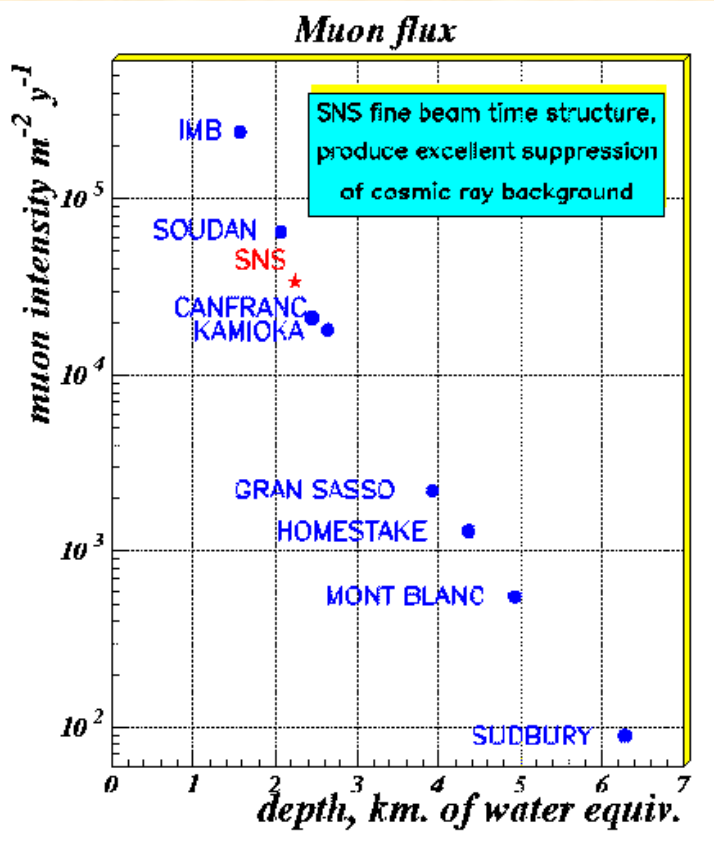
To reduce low energy neutrons (neutron gas), extra shielding and neutron absorbers are required

Just moving out without erecting extra shielding:

- **Front side (target) $1/R^2$**
- **Right side (instruments)** ***required detailed study***
- **Left side (tunnel) 1/R**

Cosmic rays BG estimation

Lets assume shielded bunker with area of 25 m^2 on the surface



SNS duty factor is $4 \cdot 10^{-4}$

This effectively reduce flux to 10^5 muons and ~600 neutrons per day entering enclosure

We need one meter of steel overburden to reduce hadronic component of atmospheric showers and hermetic veto with efficiency of 99%

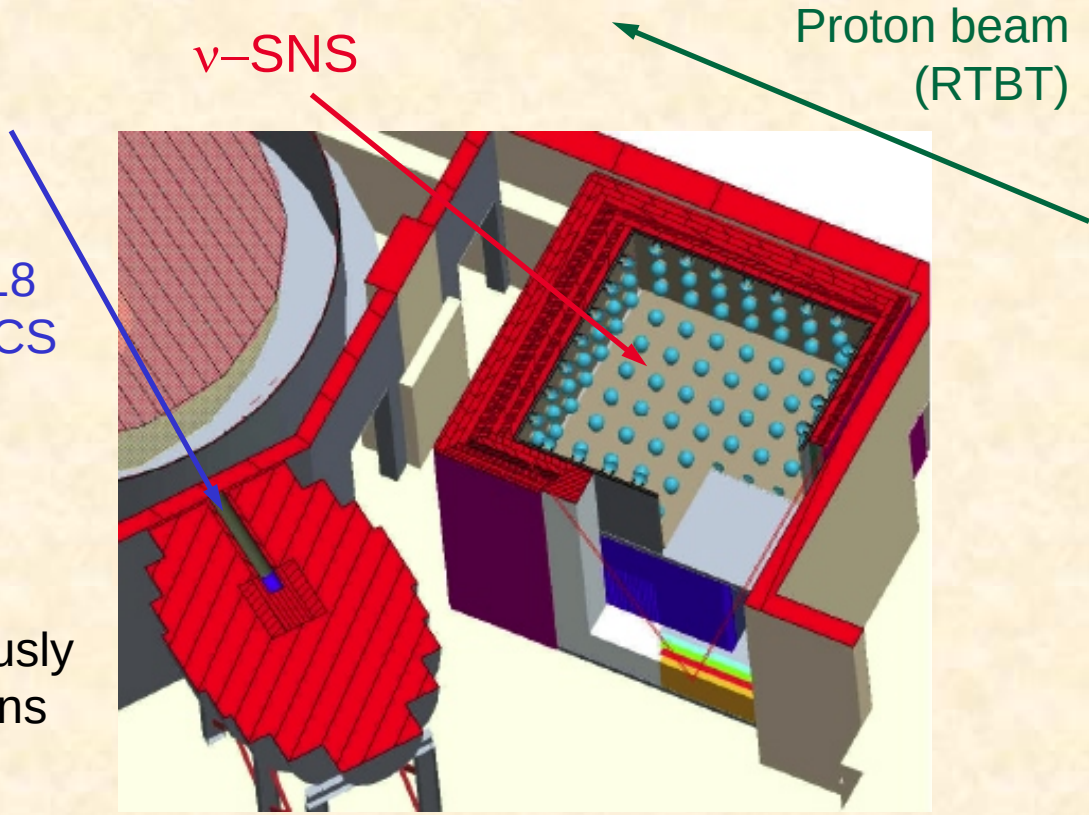
Simulations shows that expected number of untagged neutrons events in the detector is a few per day.

This is below expected neutrino event rates

Extra factor can be expected from PID in detectors.

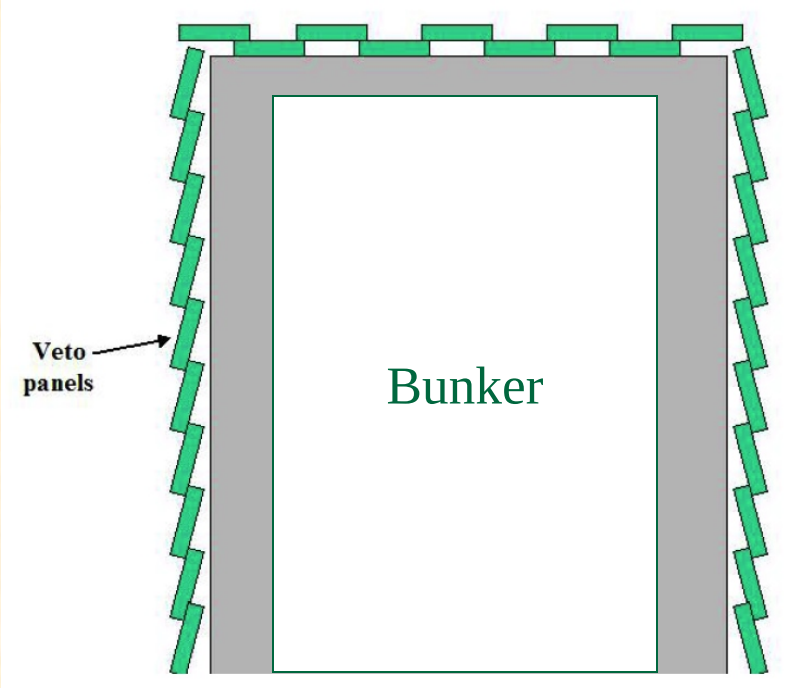
Possible Concept of Shielded Enclosure for Neutrino Experiments

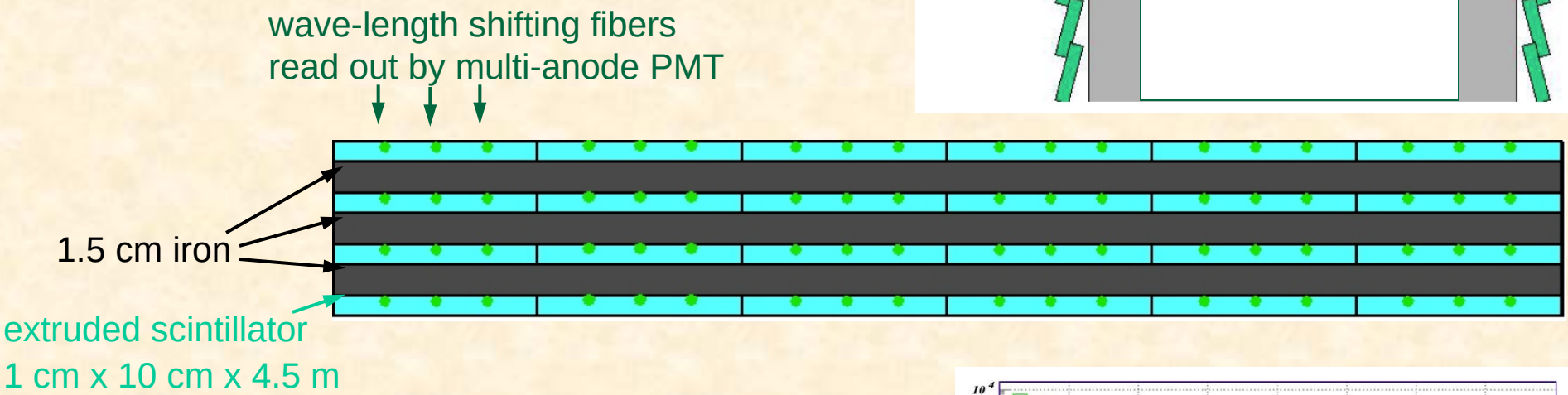
- Total volume = 130 m^3
  4.5m x 4.5m x 6.5m (high)
- Heavily-shielded
- 60 m^3 steel ~ 470 tons
  1 m thick on top
  0.5 m thick on sides
- Active veto
- ~70 m^3 instrumentable
- Configured to allow 2 simultaneously operating detectors of up to 40 tons
  νA coherent scattering
  43 m^3 liquid detector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



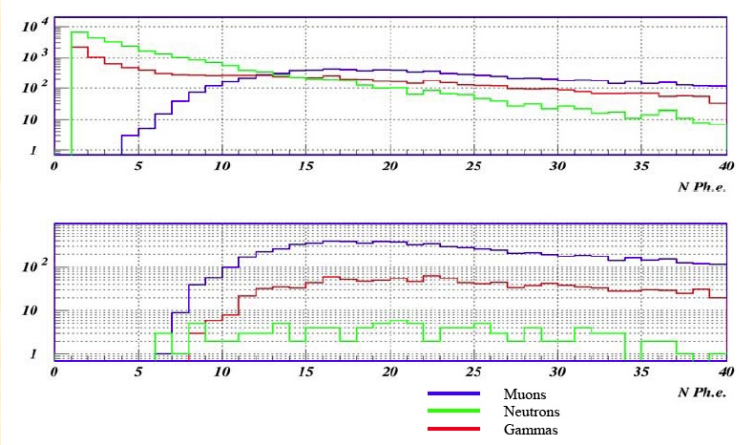
Cosmic Ray Veto

Sensitive to cosmic muons
Blind for gammas from
(n , gamma) capture





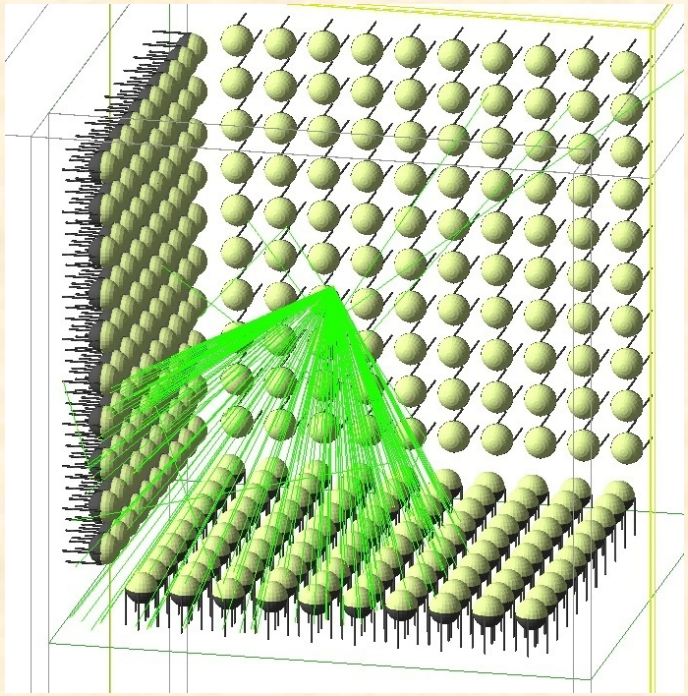
- Efficiencies
  - muons ~99% muons
  - 7.6 MeV gamma = 0.005%
  - neutron =0.07%



Homogeneous Experiment

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

- $\delta E/E \sim 6\%$
- $\delta x \sim$ 15-20 cm
- $\delta\theta \sim 5° - 7°$



First 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)

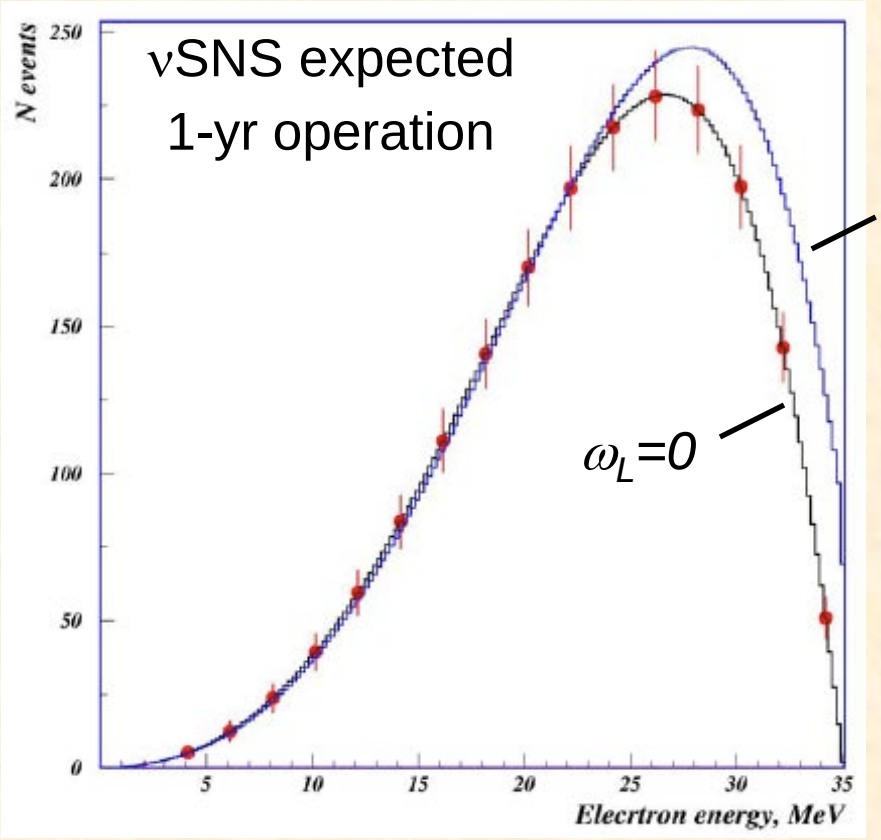
Standard Model Tests

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

$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N_{g.s.}$

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

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

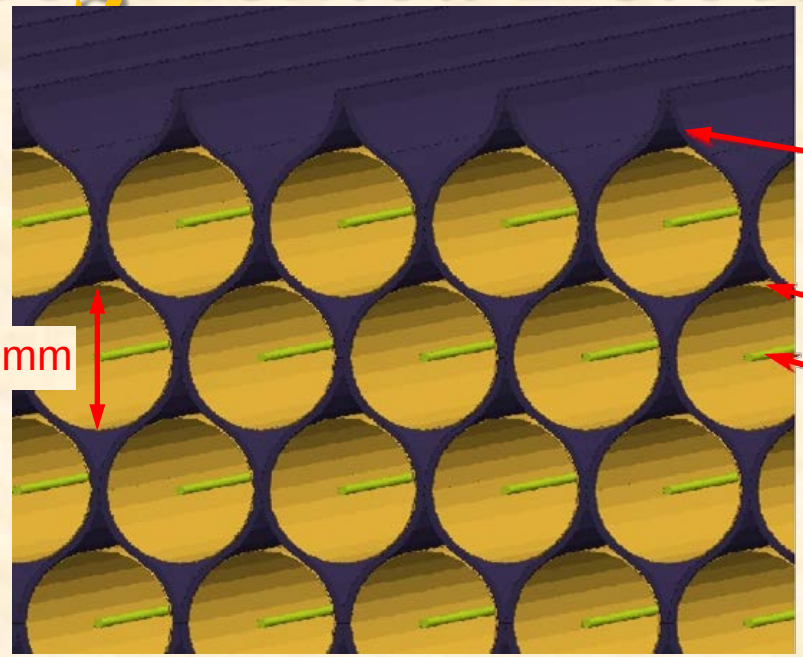


ω_L=0.11 KARMEN upper limit

Armbruster *et al.*, PRL81 (1998)

- ~20 ton detector could substantially improve the limit on ω_L with only 1 year of data taking

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

- **1.4×10^4 gas proportional counters (straw tube)**
- **3m long x 16mm diameter**

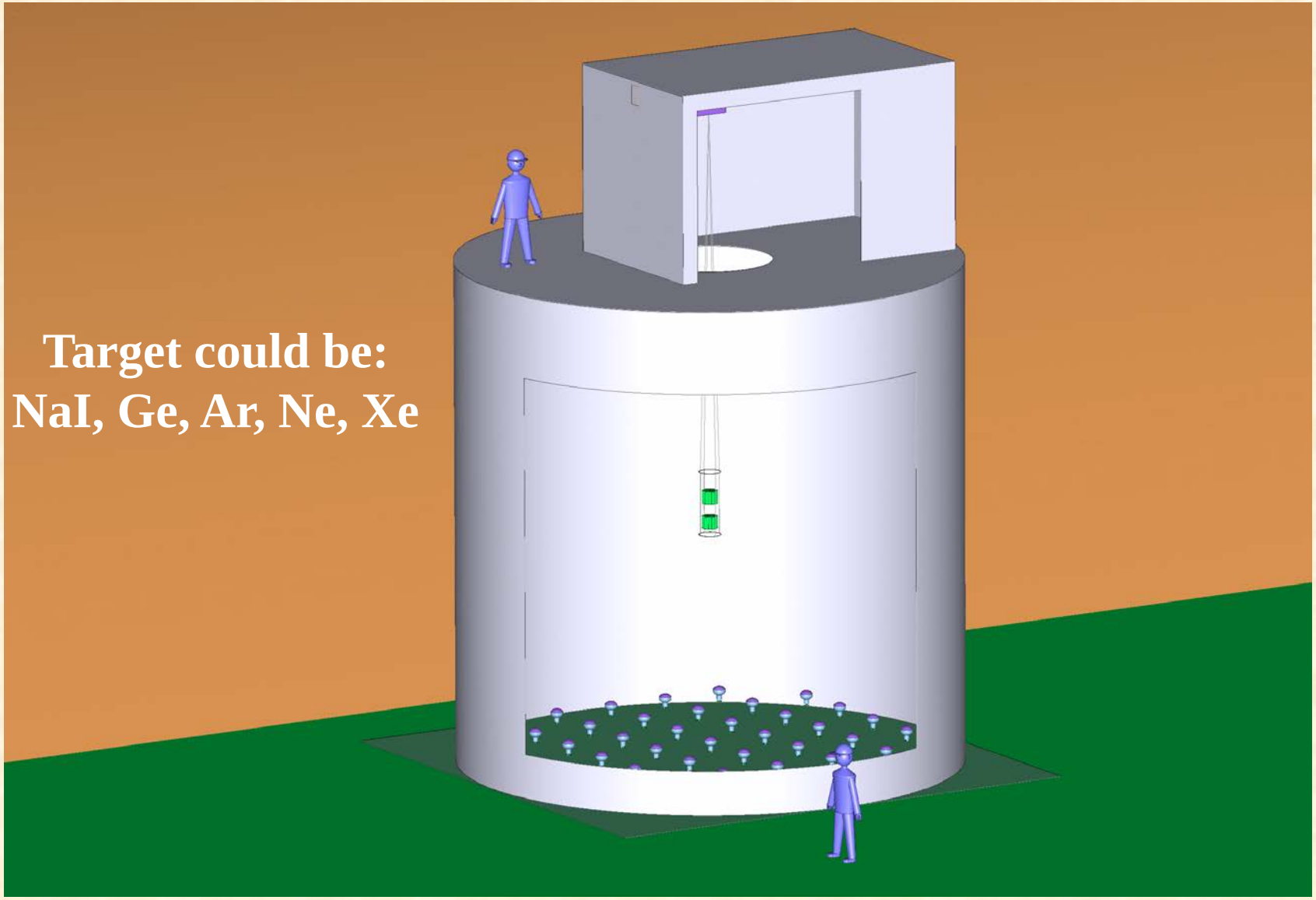
3D position by Cell ID & charge division

PID and Energy by track reconstruction

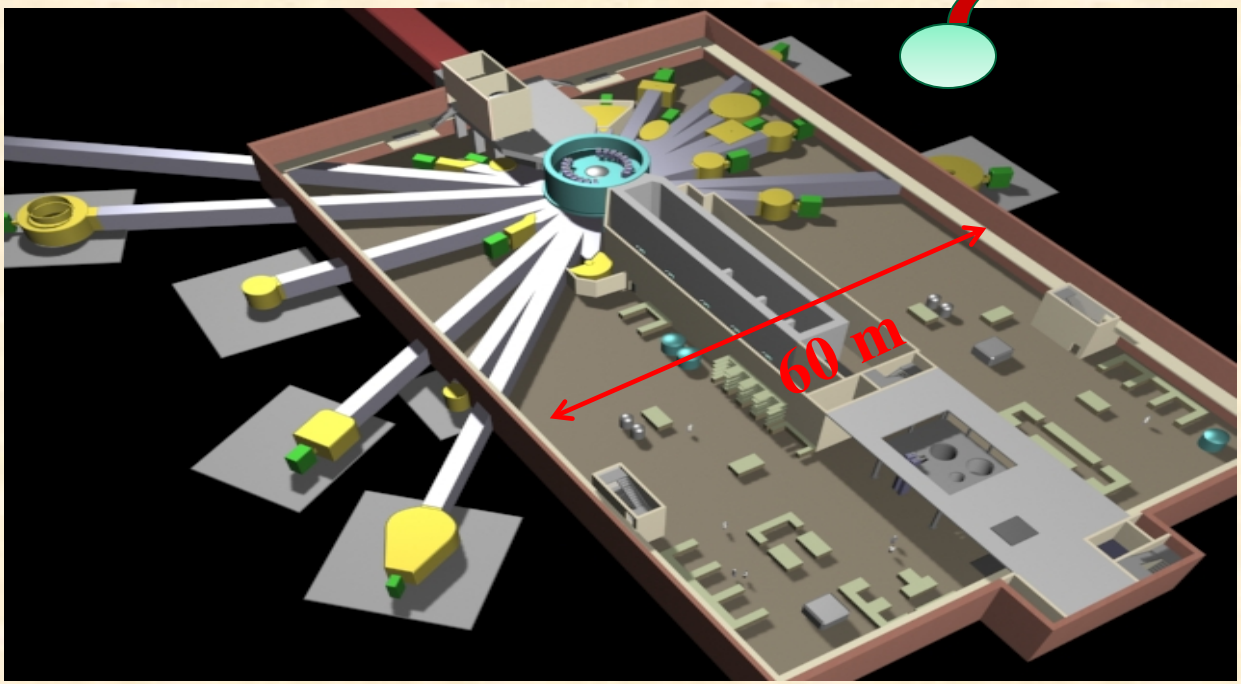
Expected Statistic

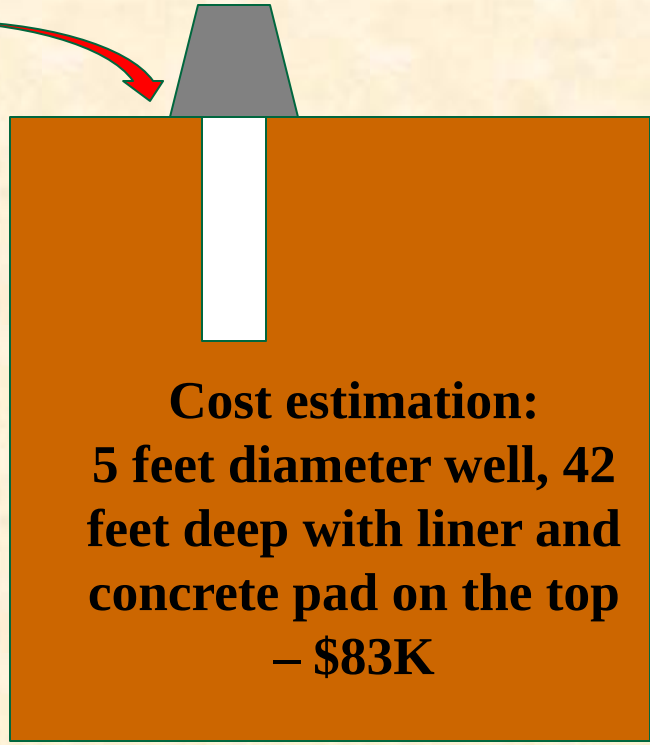
- **1100 events/yr $\nu_e + Fe \rightarrow Co + e^-$**
- **1100 events/yr $\nu_e + Al \rightarrow Si + e^-$**
- **4900 events/yr $\nu_e + Pb \rightarrow Bi + e^-$**

The CLEAR (Coherent Low Energy A Recoils) Experiment



Potential Underground Location for a Compact detector

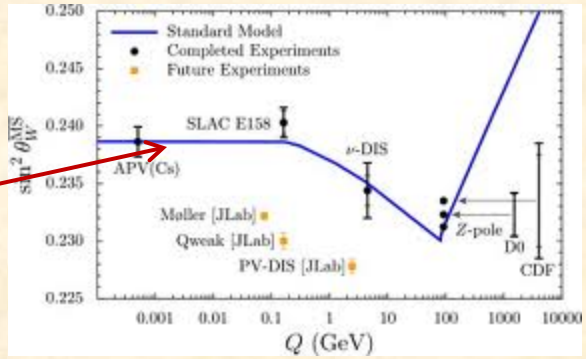




Multiple locations are possible

Large $\nu + e^- \rightarrow \nu + e^-$ statistics.

If to build large enough detector (water Cherenkov) there is interesting possibility to measure $\sin^2\theta_W$ with high precision at low Q^2



$$\frac{\partial\sigma(\nu_\mu e)}{\partial T} = \frac{2G_F^2 m_e}{\pi}\left[(s-1)^2 + s^2\left(1-\frac{T}{E_\nu}\right)^2 - s(s-1)\frac{m_e T}{E_\nu^2}\right]$$

Where: $s = 2\sin^2\theta_W$ **For $\nu_e e$ s-1 → to s+1, and for $\bar{\nu}_\mu e$ s-1 → s**

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e)+\sigma(\bar{\nu}_\mu e)} = \frac{3}{4}\frac{1-2s+4/3s^2}{1+s+2s^2}$$

For $\sin^2\theta_W$ =0.23 → R=0.13
If $\sin^2\theta_W$ changes by 1%,
R changes by ~2%

Number of ν_μ produced at stop pion facility is the same as sum of $\nu_e + \bar{\nu}_\mu$, so flux normalization disappears

Summary & Outlook

- Understanding of neutrino interactions are important for:
  - Physics of Supernova
  - Calculation of response of Large Neutrino Detectors to Milky Way Supernova

- The combination of high flux and favorable time structure at the SNS is very attractive for diverse program of neutrino studies. Such a program can include:

1. cross section measurements
2. search for a neutral current coherent scattering
3. short baseline oscillations
4. neutrino magnetic moment
5. measurement of $\sin^2\theta_w$