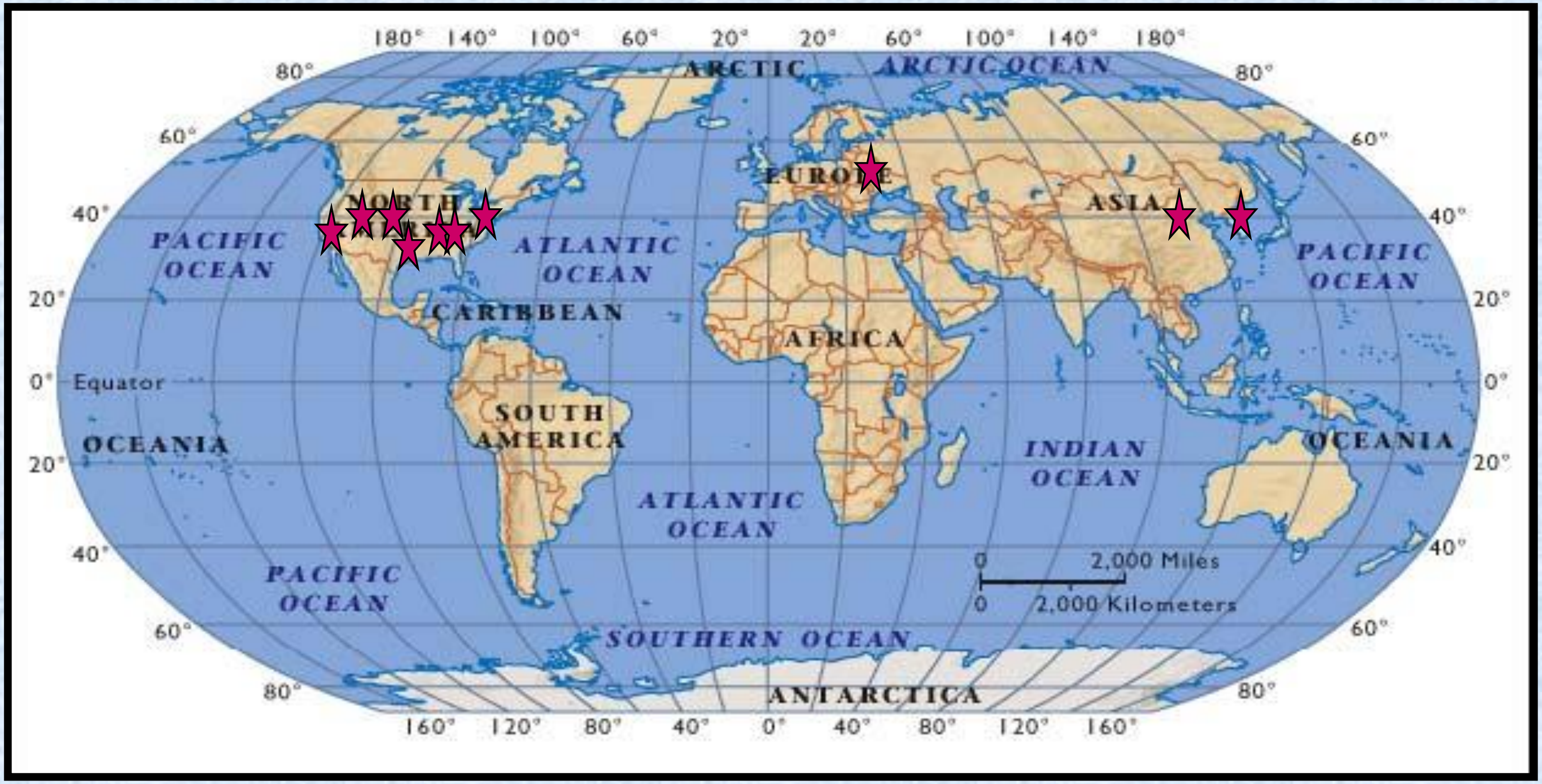
Neutrinos at the Spallation Neutron Source

Ed Hungerford
University of Houston

Collaborating Institutions



University of Alabama, Argonne National Laboratory, California Institute of Technology, ado School of Mines, University of Houston, JINR-Dubna, Los Alamos National Laboratory, North Carolina Central University, Oak Ridge National Laboratory, University of South Carolina, University of Tennessee, Triangle Nuclear Laboratory, University of Wisconsin, Yale University

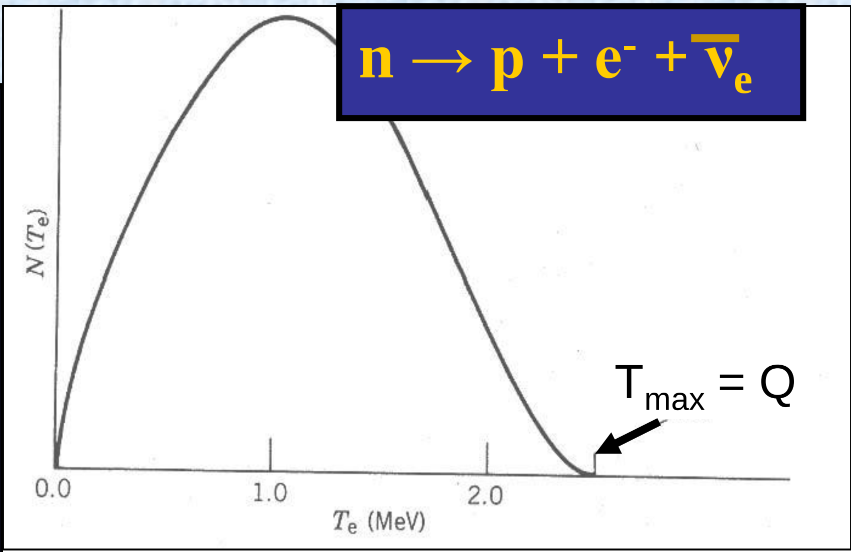
The Neutrino

The electrons from beta decay were observed to have a continuous spectrum

Pauli in 1930 proposed that to conserve Energy and Momentum another particle, with little or no interaction was required – The neutrino

$$n \rightarrow p + e + \nu_e$$

"I am embarrassed that I have proposed a particle that can never be seen"



$$n \rightarrow p + e^- + \bar{\nu}_e$$

- Neutrinos have VERY small masses
- Only left handed neutrinos interact -- very weakly
- 3-generations of neutrinos – Lepton number is conserved

What about the Neutrino?

- Neutrinos – Dirac, Majorana?
- What are the neutrino masses ?
- What is the neutrino mass hierarchy ?
- Is CP violated in the neutrino sector ?
- Are there additional neutrino types, e.g. sterile and non-SM neutrinos?
- What are the mixing angles (in particular θ_{13})?

- How do neutrinos affect the evolution of our universe?

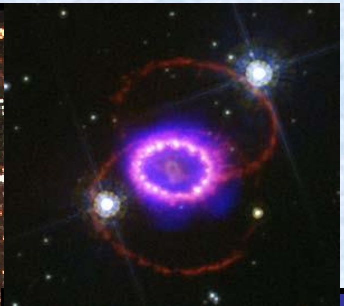
How do neutrinos affect the evolution of our universe?

In Contradiction to Newton’s Concept of the “Fixed Stars” our Universe has, and now is, EVOLVING

Neutrinos and the weak interaction are believed to be crucial in the Core-collapse Type II Supernovae – How does this happen?

SUPERNOVA

- Dominant contributor to Galactic nucleosynthesis
- Occurs in the collapse of the iron core of a massive star - 8-10 Solar mass
- Extremely energetic explosion
  - 10^{53} ergs of energy released
  - 99% in neutrino emission
- A few per century in our Galaxy (last SN 400 yrs ago)



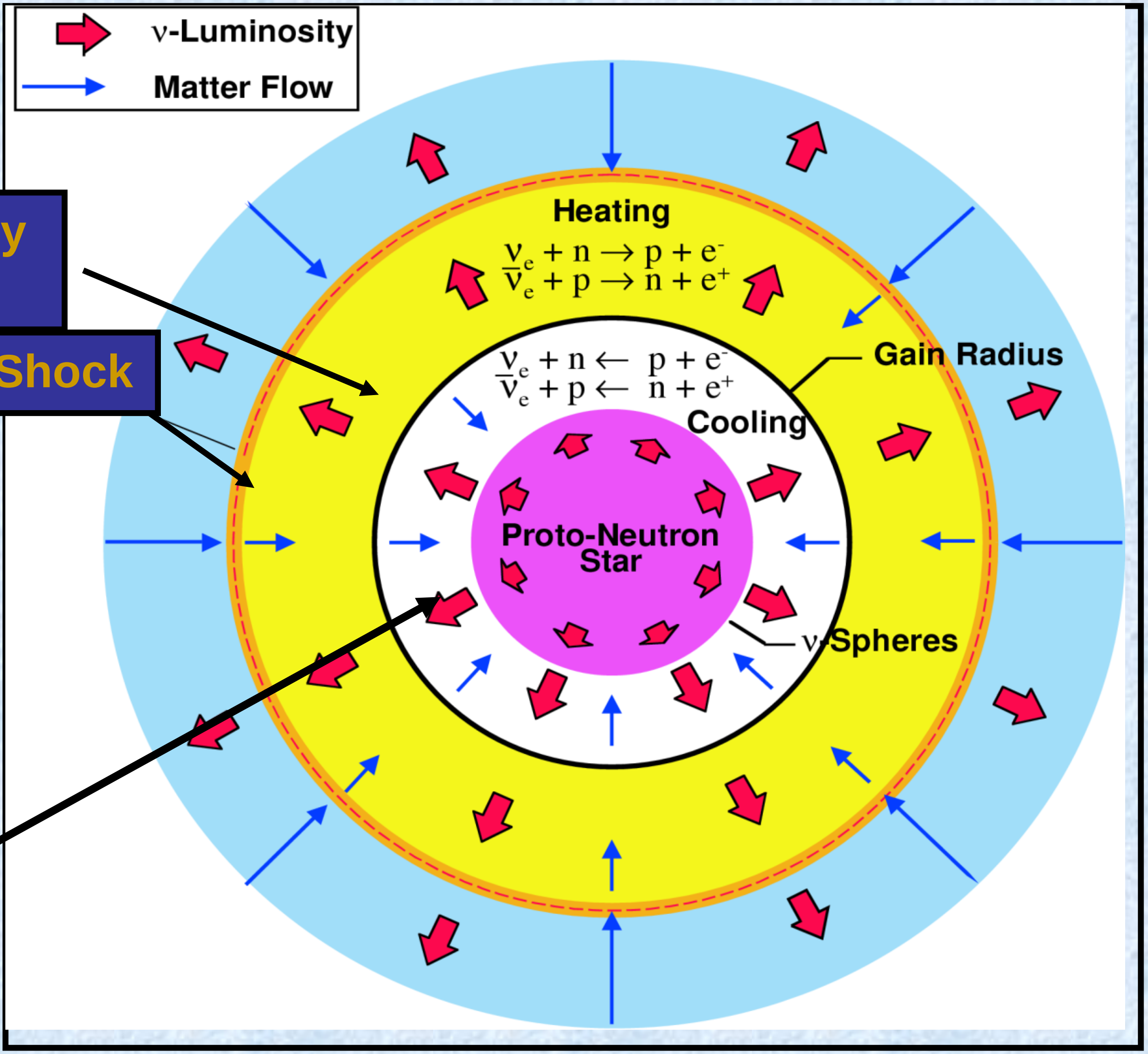
SN 1987A

Brightest SN in

400 yrs

160,000 LY away

Neutrino Emission from Supernovae

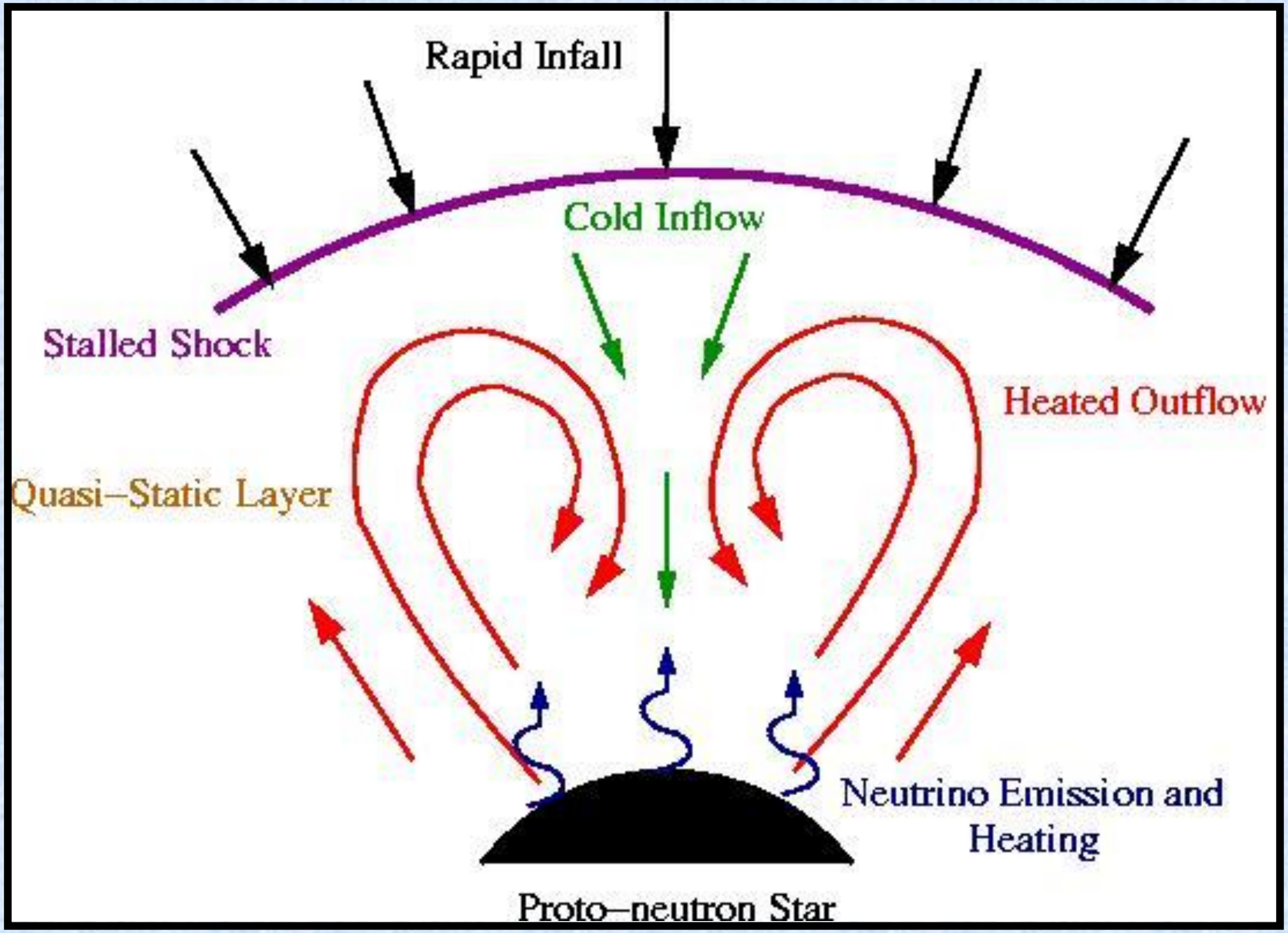


Matter Gains Energy From Neutrinos

Shock

Matter Loses Gravitational Energy to Neutrinos

Convective Model and Neutrino Heating

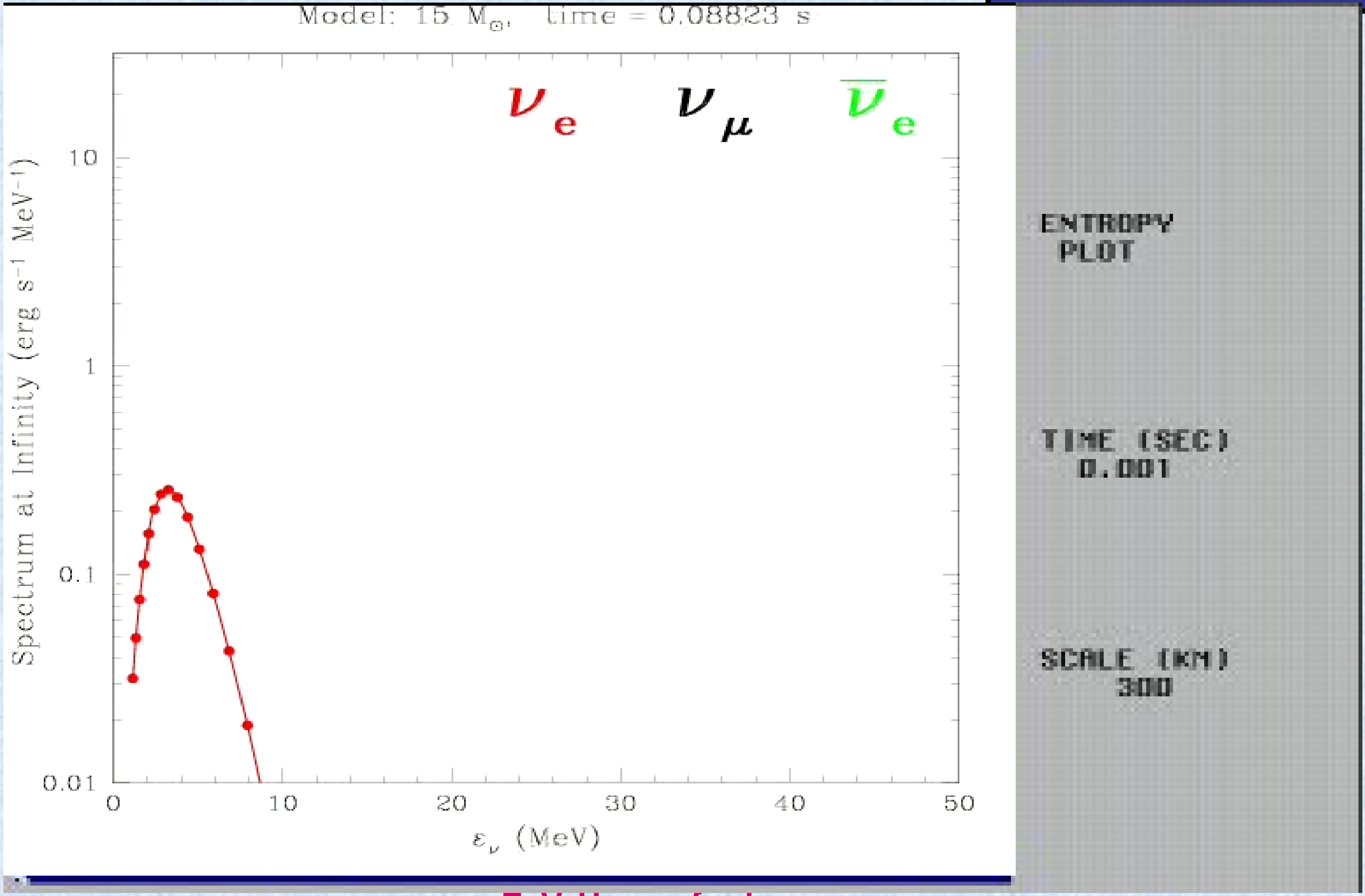


2-D Model of Core Collapse

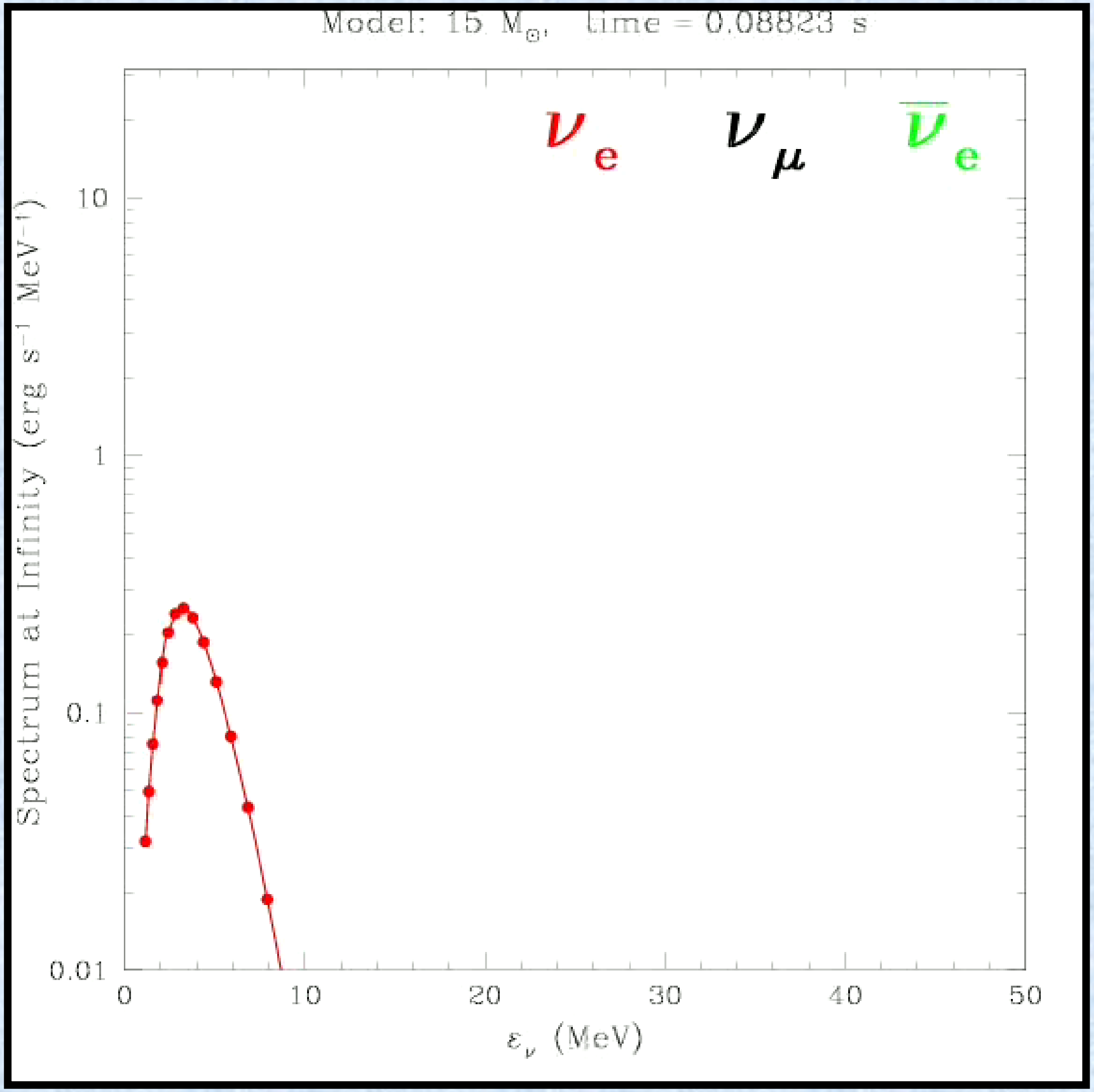
From: Adam Burrows
www.astro.princeton.edu~/burrows

15 Solar Masses

- $0.0 < t < 0.318$s



Neutrino Emission



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15 Solar Masses

- 0.0 < t < 0.318s

Neutrino reactions and nucleosynthesis

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

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

- Neutrino reactions alter the elemental distribution in the ejected material - Cross sections are important for interpreting observations in metal-poor stars [Fröhlich et al., astro-ph/0410208 (2005)].

- Neutrino energy transport reheats the shock. The model has a hot dense core of neutrons surrounded by a shell of alpha and neutrons surrounded by a shell of Fe and Ni, surrounded by consecutive shells of lighter elements. Explosion ejects outer shells.[Ann Rev 27(77)167]

Electron capture and Core collapse

- Electron capture and the charged-current υ_e reaction are governed by the same nuclear matrix element. Electron capture changes protons into neutrons

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

- To Calculate rates we need
  - Gamow-Teller strength distributions
  - First-forbidden contribution
  - g_A/g_V modifications by nuclear medium, etc
- New calculations using a hybrid model of Shell Model Monte Carlo (SMMC) and RPA predict significantly higher rates for N>40 and supernovae shock starts deeper and weaker

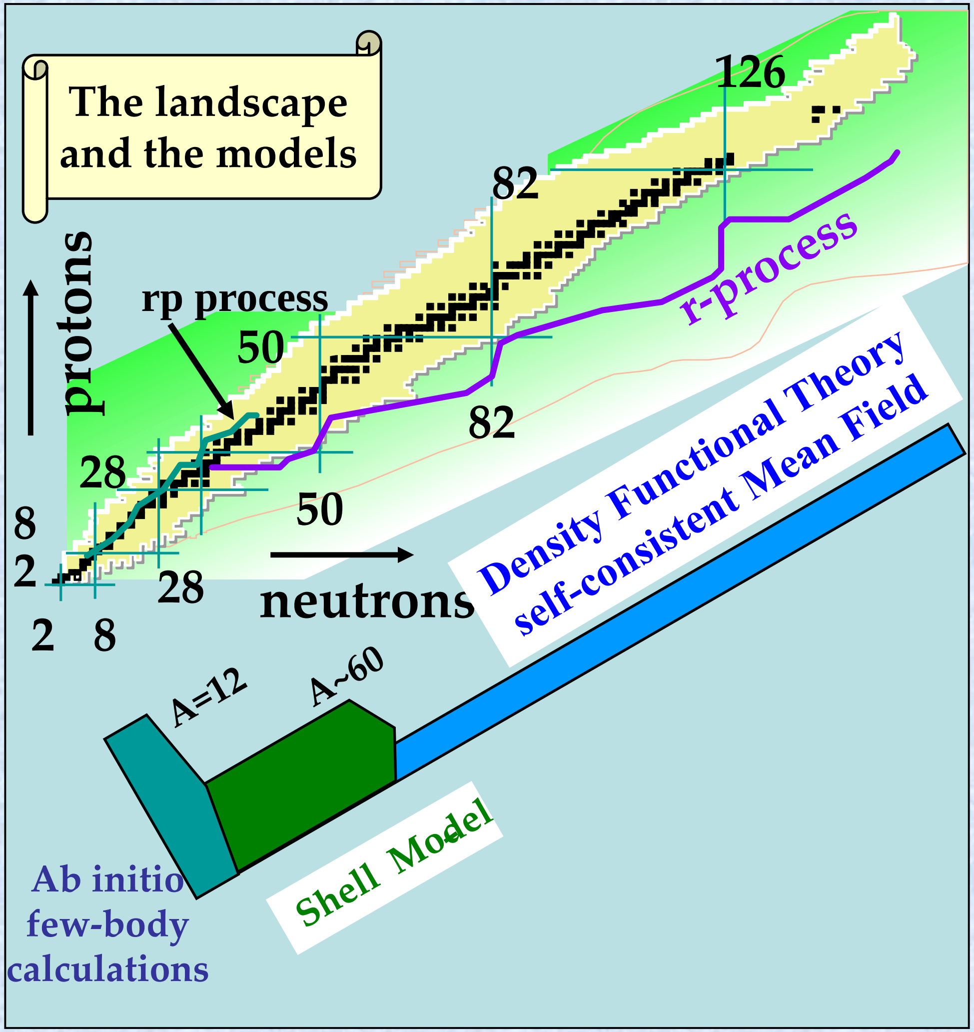
The weak interaction plays a crucial role in establishing the dynamics of the supernova shock wave

Iron core mass and neutronization depend on e^- capture and beta decay rates for A<65

Electron capture producing υ_e on heavy nuclei remains important throughout collapse.

Neutrino Transports energy from the core to the outer shell

Supernovae and Nucleosynthesis



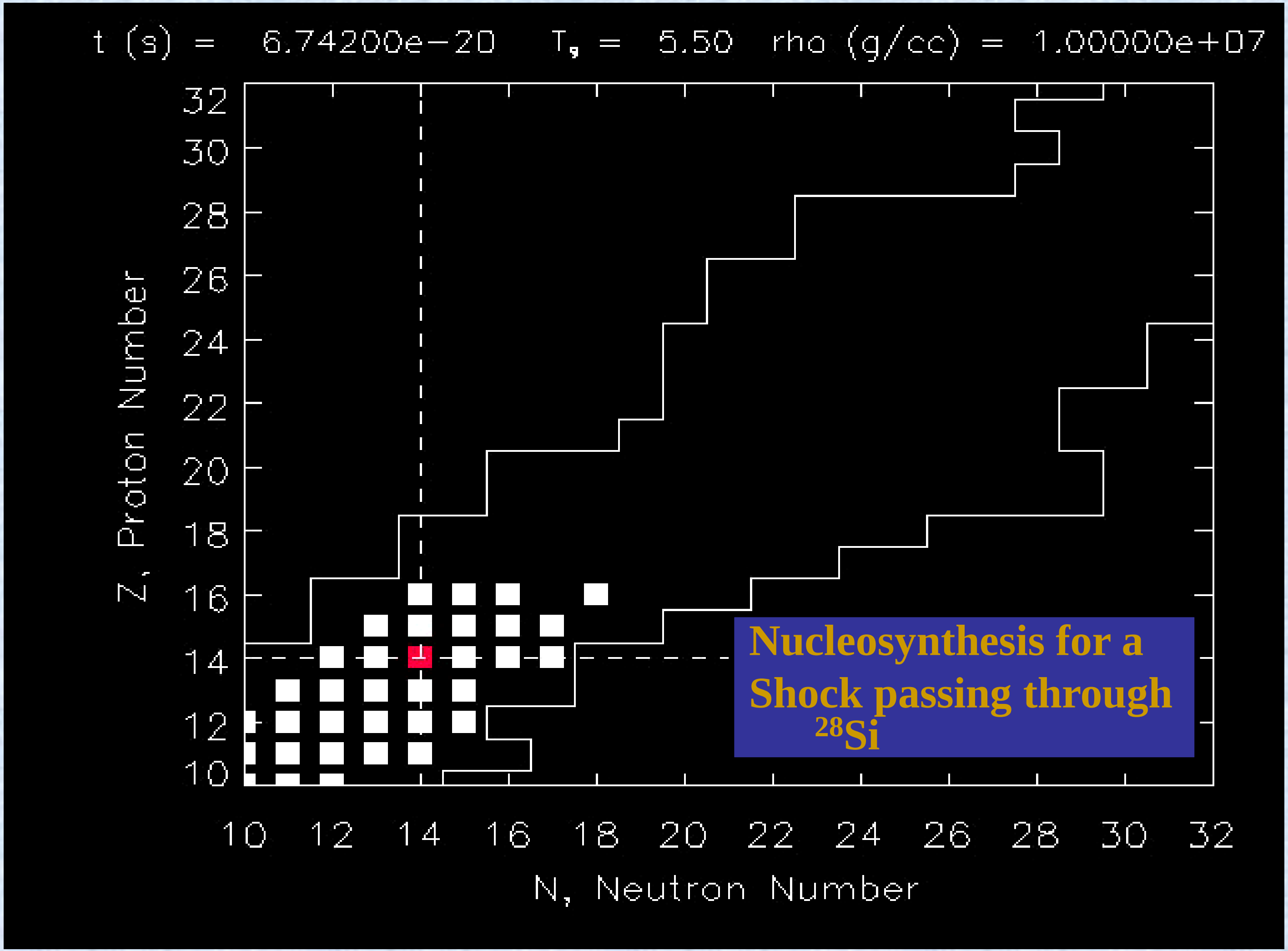
Input

- masses
- weak decay properties
- neutrino interactions
- thermal properties

A convolution of nuclear structure, nuclear astrophysics, weak interactions

A Simulation of Neutrino Nucleosynthesis

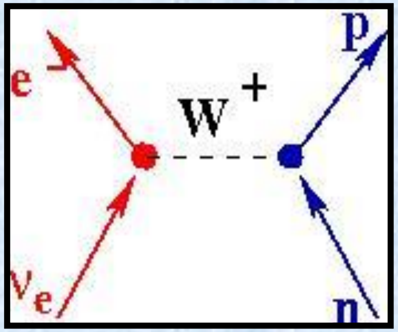
B. S. Mayer
www.astro.princeton.edu/~burrows

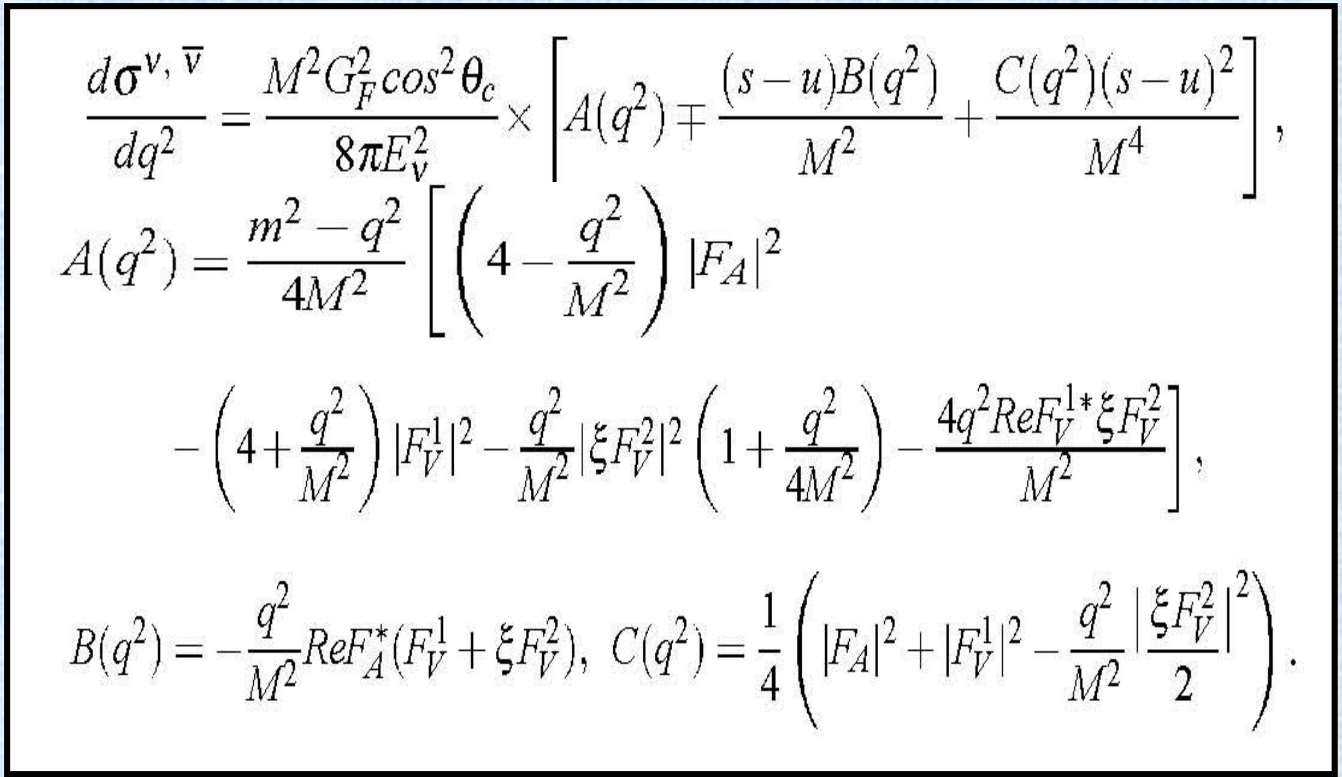


Nucleosynthesis for a Shock passing through ^{28}Si

Neutrino-nuclear cross-sections

Charged Current





$$\frac{d\sigma^{\nu,\,\bar{\nu}}}{dq^2} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2} \times \left[A(q^2) \mp \frac{(s-u)B(q^2)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4} \right],$$

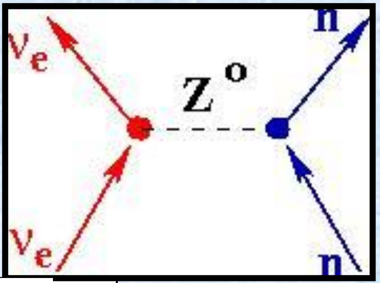
$$A(q^2) = \frac{m^2 - q^2}{4M^2}\left[\left(4 - \frac{q^2}{M^2}\right)|F_A|^2\right.$$

$$\left. - \left(4 + \frac{q^2}{M^2}\right)|F_V^1|^2 - \frac{q^2}{M^2}|\xi F_V^2|^2\left(1 + \frac{q^2}{4M^2}\right) - \frac{4q^2 ReF_V^{1*}\xi F_V^2}{M^2}\right],$$

$$B(q^2) = -\frac{q^2}{M^2} ReF_A^*(F_V^1 + \xi F_V^2),\ \ C(q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 - \frac{q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2\right).$$

Neutrino-nuclear cross-sections

Neutral Current



$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2).$$

$$F(Q^2) = \frac{1}{Q_W}\int [\rho_n(r) - (1-4\sin^2\theta_W)\rho_p(r)] \frac{\sin(Qr)}{Qr} r^2 dr.$$

Coherent (Elastic)

$$\frac{d\sigma}{dT} = \frac{\pi\alpha^2}{m_e^2}\left(\frac{\mu_\nu}{\mu_B}\right)^2 \left[\frac{1 - T/E_\nu}{T}\right] Z^2$$

$$T = \frac{2E_\nu^2}{M_T} cos^2(\theta);$$

Magnetic Moment

Neutrino-nuclear cross-sections

- Both cross sections are needed for supernova modeling - a few % accuracy is required
- Radiative corrections and in-mediun effects (rescaling g_a/g_v, correlations, etc) are required for CC
- Only the CC cross section in C is reasonably well-measured (10%).
- Coherent NC-nuclear has not been observed
- Needed for the calibration of astrophysical neutrino detectors (Low Energy)

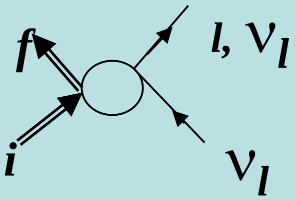
Basic Interaction

Charged current:

$$\begin{pmatrix}\nu\\ \bar{\nu}\end{pmatrix}+(Z,A)\rightarrow\begin{pmatrix}Z+1, A\\ Z-1, A\end{pmatrix}+\begin{pmatrix}l^{-}\\ l^{+}\end{pmatrix}$$

Neutral current:

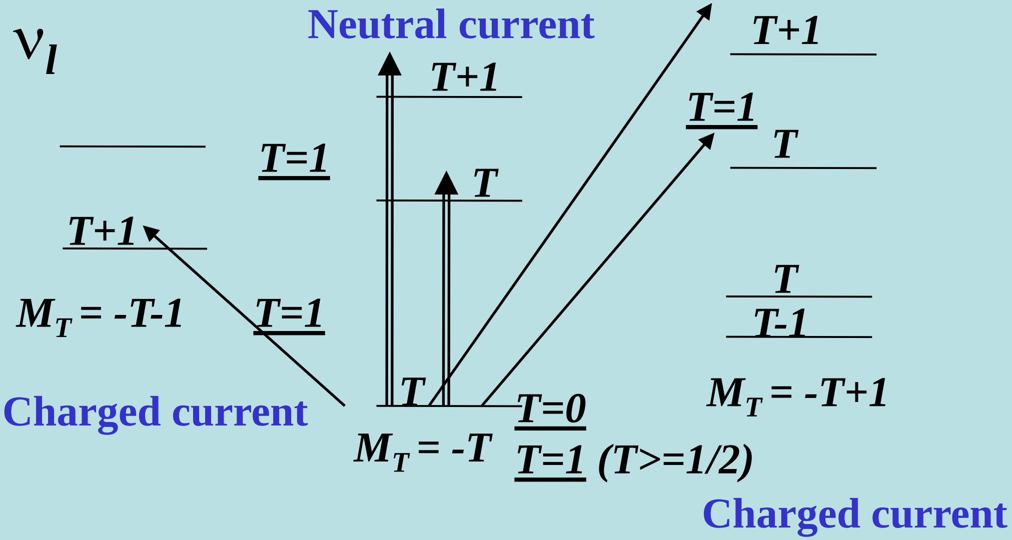
$$\nu+(Z,A)\rightarrow(Z,A^{*})+\nu$$



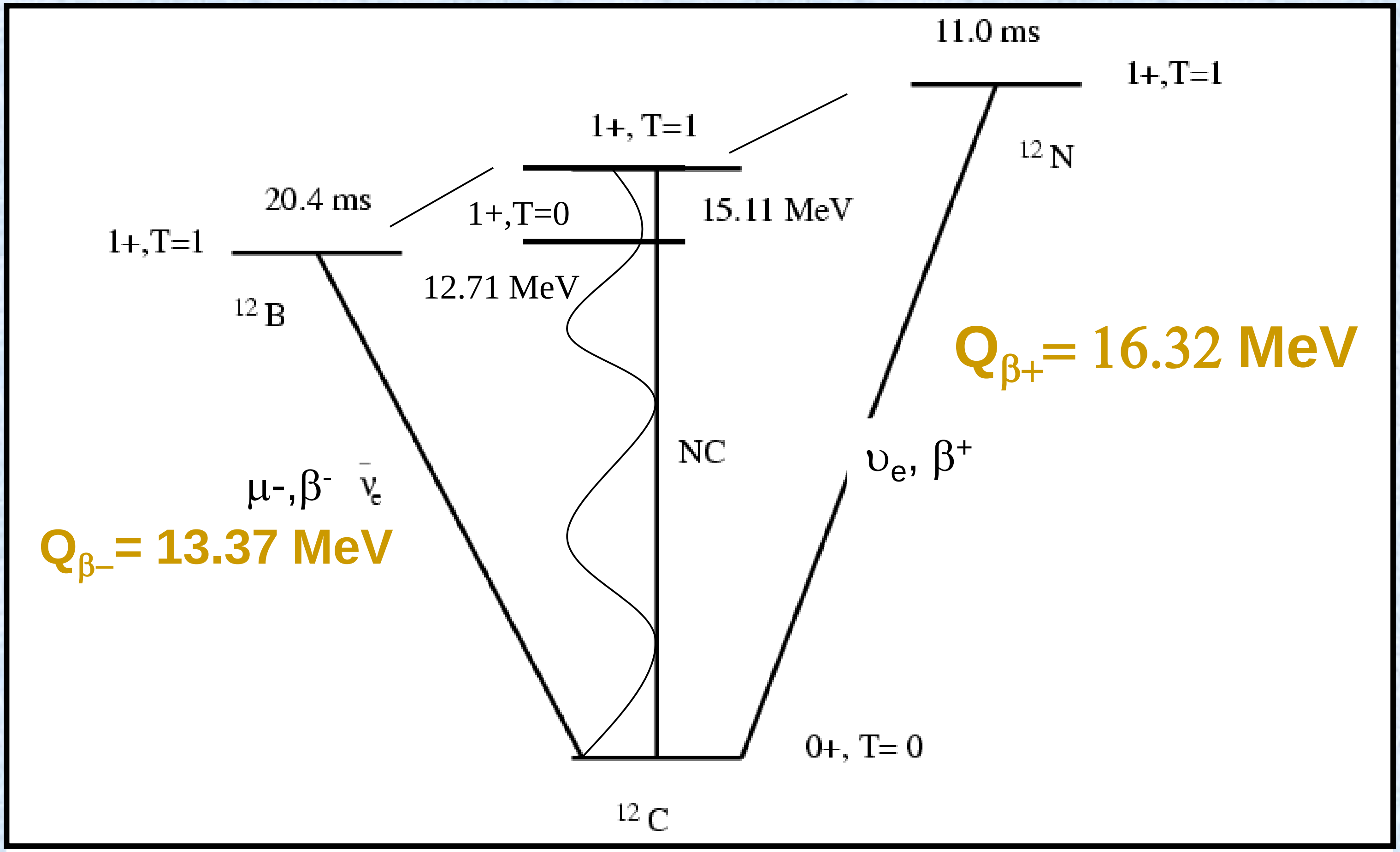
All reactions are possible as long as they obey selection rules

$$T=\frac{|N-Z|}{2}$$

$$M_T=\frac{N-Z}{2}$$



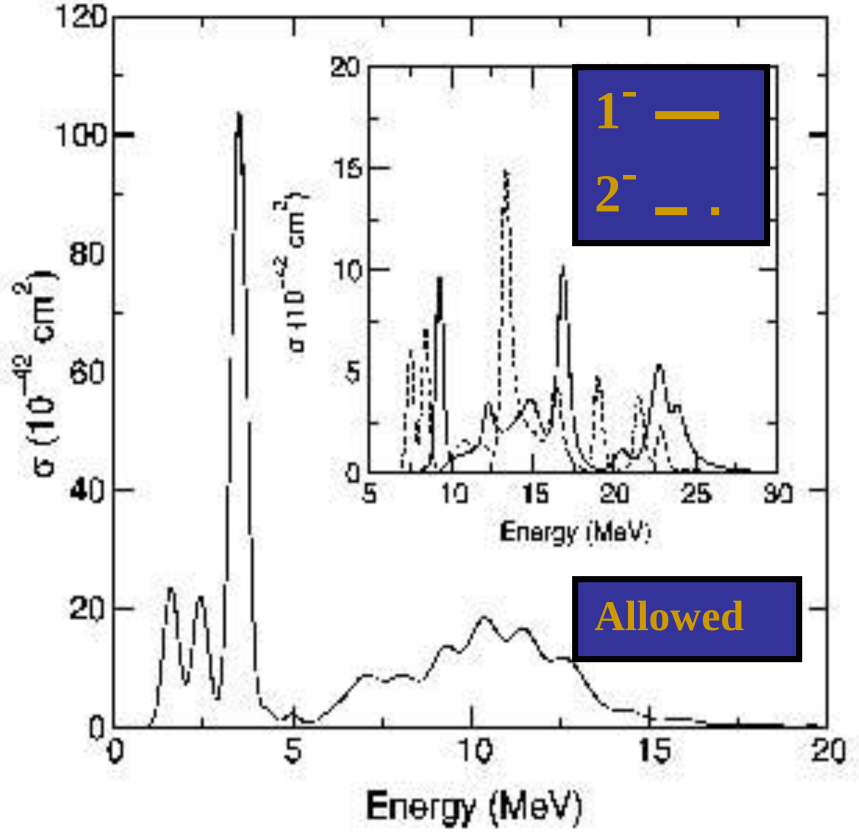
^{12}C Example

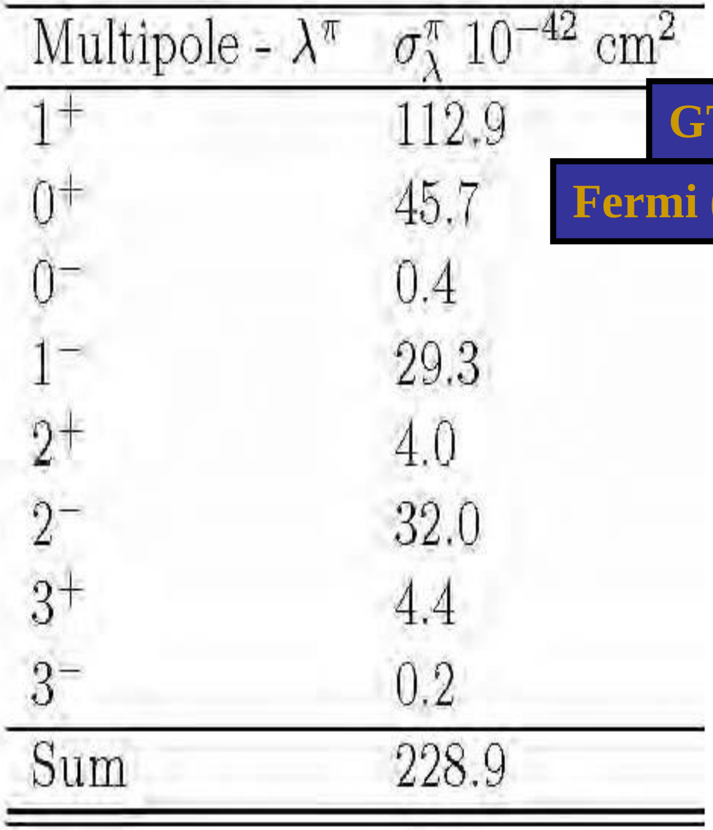


$Q_{\beta+} = 16.32$ MeV

$Q_{\beta-} = 13.37$ MeV

Neutrino-Fe CC Cross section



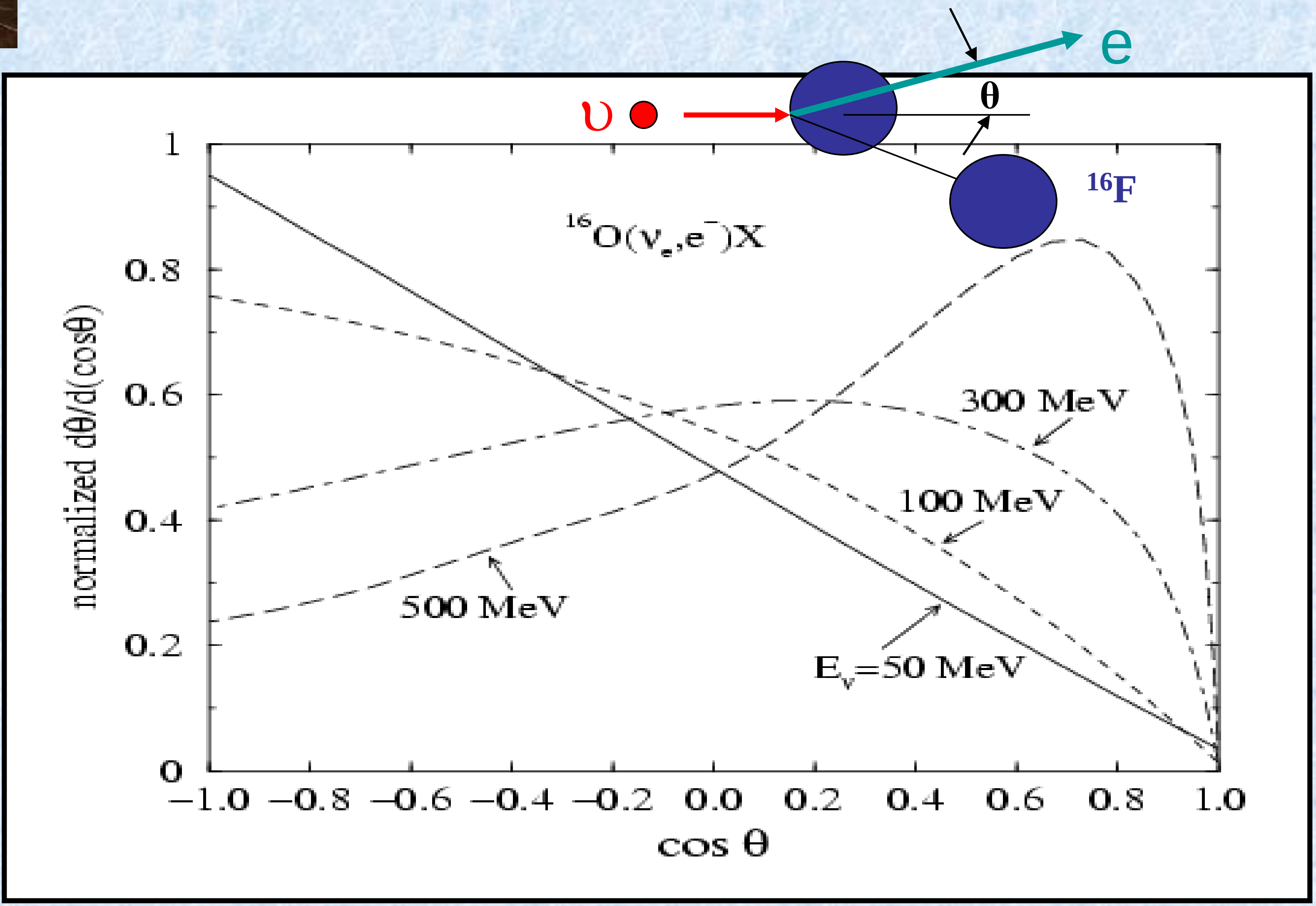


Multipole - λ^π	σ_λ^π 10^{-42} cm^2
1^+	112.9
0^+	45.7
0^-	0.4
1^-	29.3
2^+	4.0
2^-	32.0
3^+	4.4
3^-	0.2
Sum	228.9

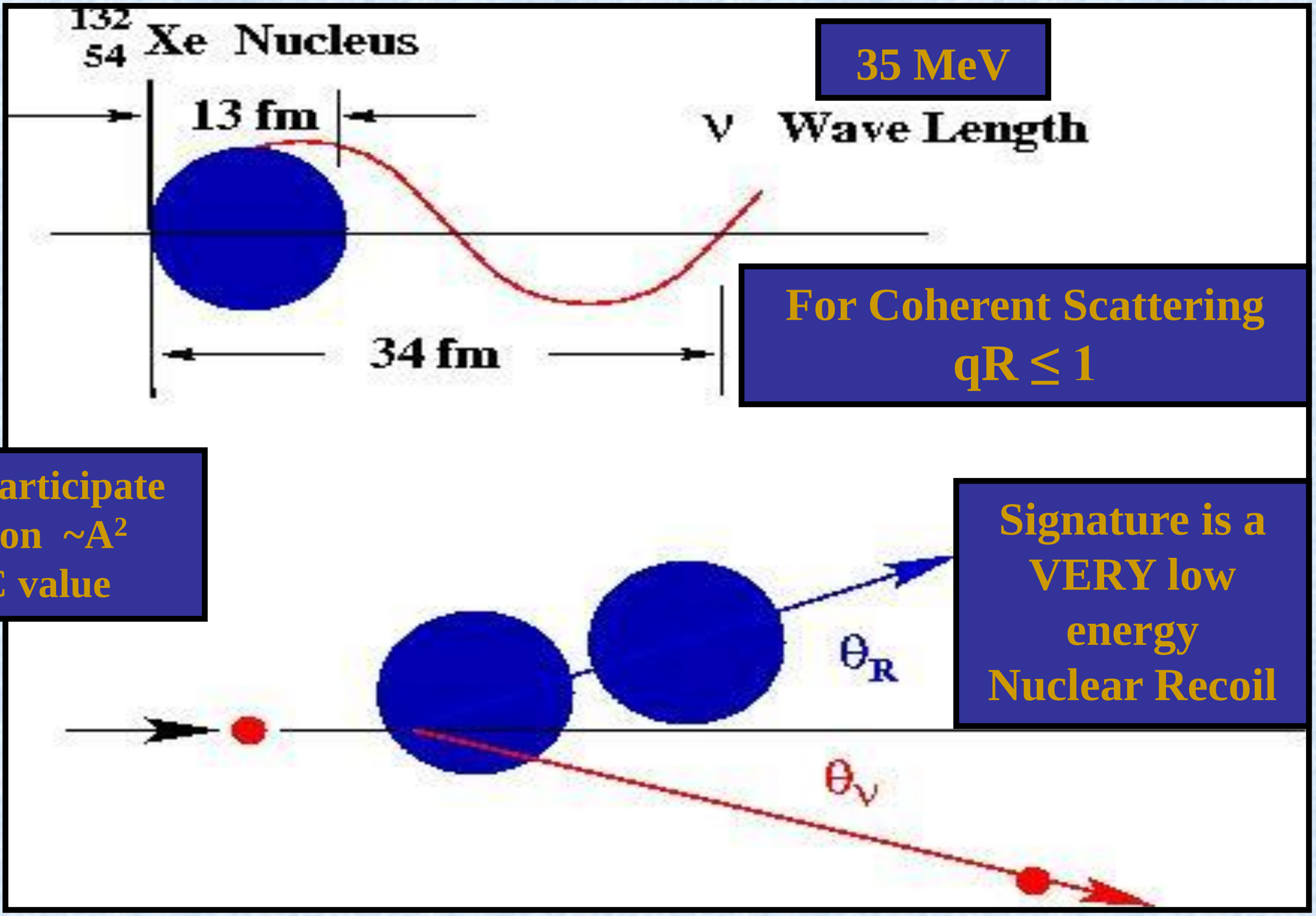
GT

Fermi (IA)

CRPA angular distribution



Neutral Current Reactions
Coherent Scattering from Nuclei



35 MeV

For Coherent Scattering
$qR \leq 1$

All Flavors Participate
Cross Section ~A^2
x 10 of CC value

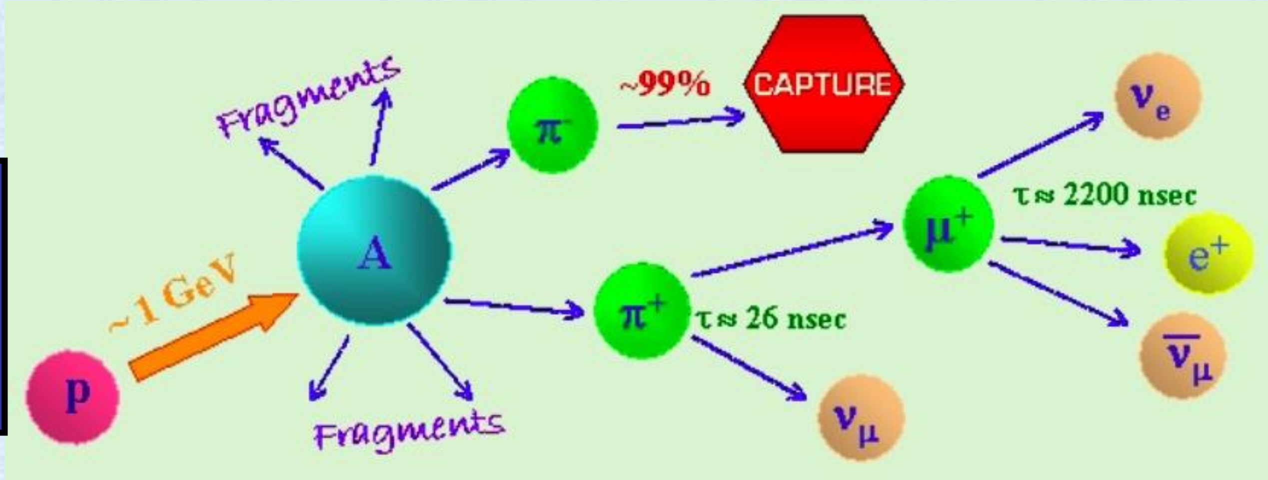
Signature is a
VERY low
energy
Nuclear Recoil

The Oak Ridge Spallation Neutron Source

SNS Parameters

- Primary proton beam energy - 1.3 GeV
- Intensity - 9.6 · 10^{15} protons/sec
- Number of protons on the target 0.687x10^{16} s^{-1} (1.1 ma)
- Pulse duration - 380ns(FWHM)
- Repetition rate - 60Hz
- Total power – 1.4 MW
- Liquid Mercury target
- 0.13 neutrinos of each flavor produced by one proton (9 x 10^{14} s^{-1})
- Number of neutrinos produced ~ 1.9·10^{22}/year
- There is a larger flux of ~MeV anti-neutrinos from radioactive decay from the target

Stopped pion decay



Produces υs with the same energy range as supernovae

KARMEN at ISIS (RAL)

65 tons of liquid Scintillator

100 events/year

υ + C, σ = (8±1) x 10^{-42} cm^2

υ+Fe (~40%)

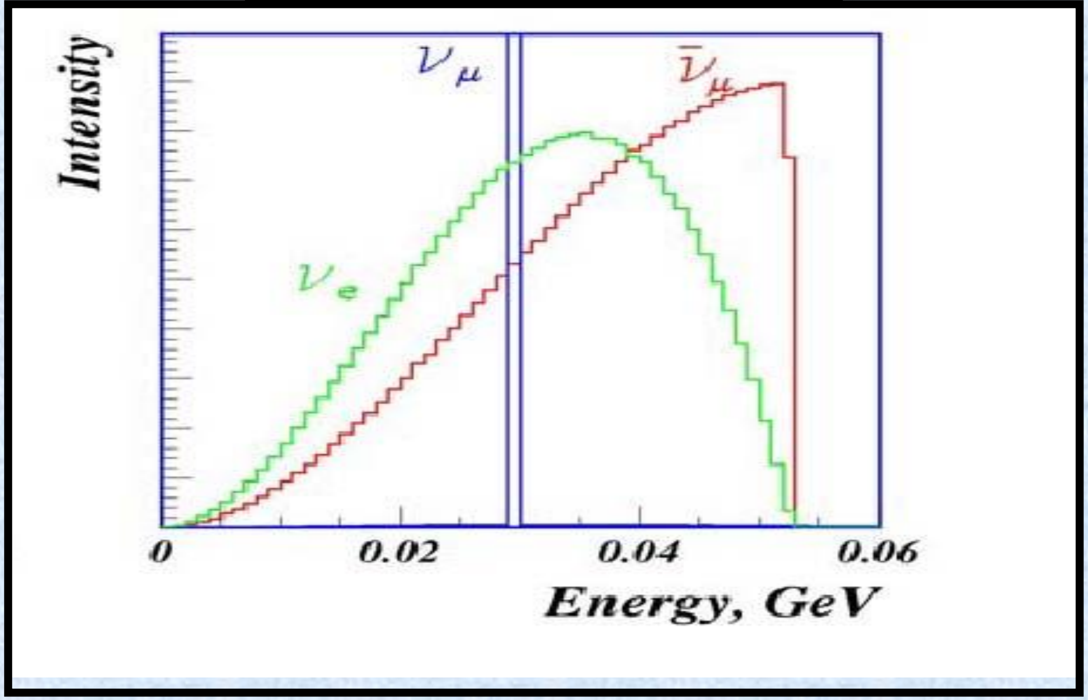
LSND at Los Alamos

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

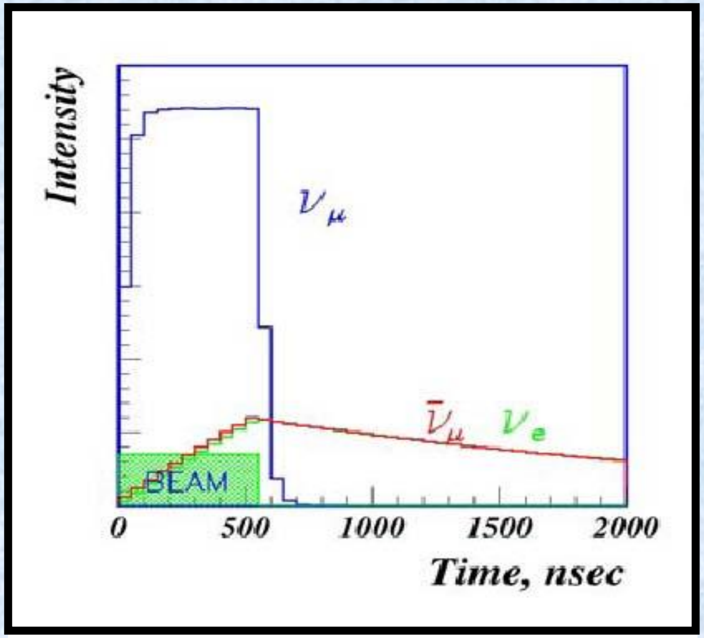
υ+Iodine (40%) [Distel et al. (2003)]

Neutrinos from Stopped π and μ decay

Neutrinos from Stopped Pion Facilities

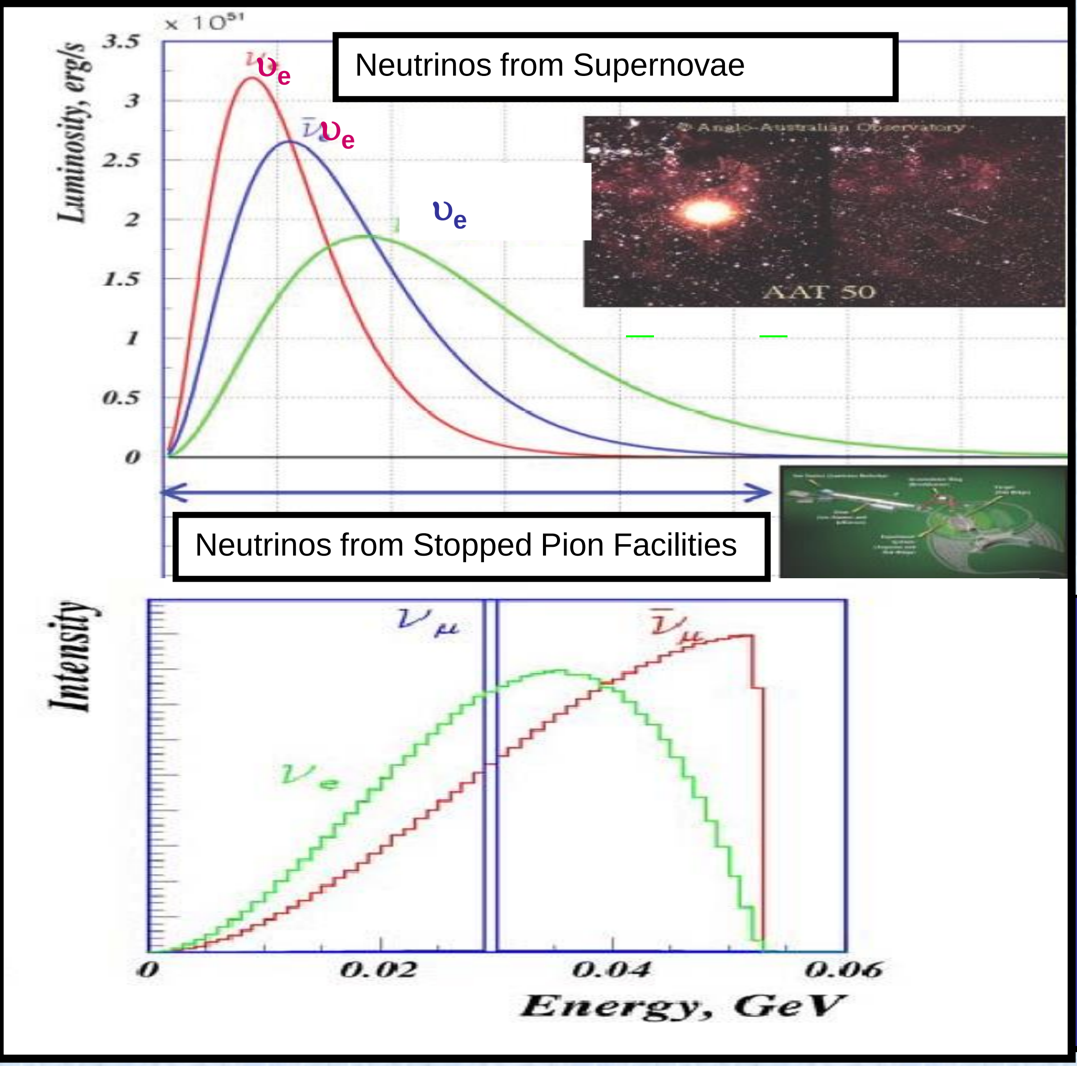


Time Structure of neutrinos From the SNS



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

Motivation for υ-SNS



Important Energy Window

- Just right for supernovae studies
- High Neutrino Flux
- SN detector calibration

- Almost no data

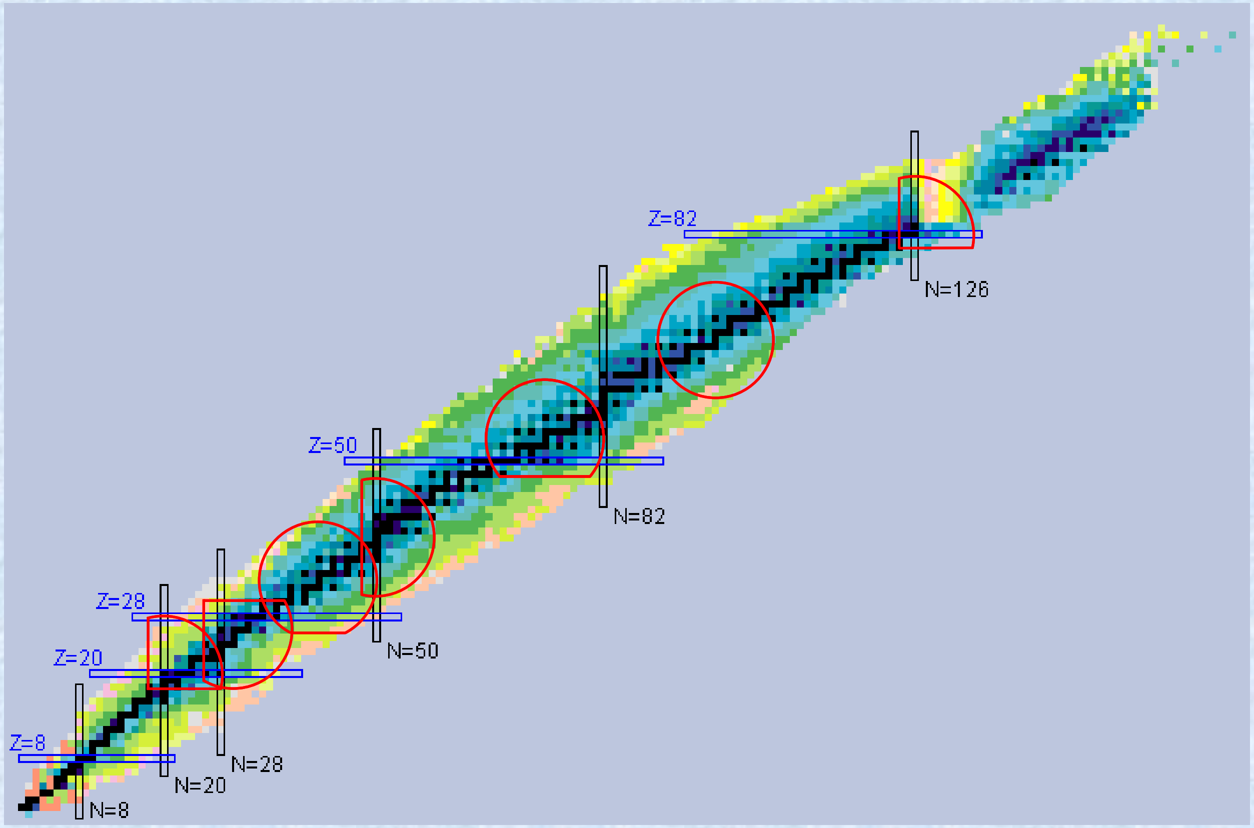
Extremely high neutrino flux

- Potential for precision measurements
- Can address a number of new physics issues
- Nuclear Physics processes
- Can begin with small detectors

Comparison of SNS with other stopped pion facilities

Facility	LANSCE	ISIS	SNS	SNS Advantage
Beam energy	0.8 GeV	0.8 GeV	1.3 GeV	1.7
Beam current	1.0 mA (0.8MW)	0.2 mA (0.16MW)	1.1 mA (1.4 MW)	1.75
Coulomb delivered per year to the target	6500 (LSND)	2370 (KARMEN)	22000	3
Beam structure	Continuous	Two 200 nsec bunches separated by 300 nsec repetition rate - 50 Hz	380 nsec FWHM pulses at 60 Hz	Separation ν_μ from ν_e, better BG suppression
Target	Various	Water cooled Tantalum	Mercury	Source compactness

υ-SNS Coverage of the (N,Z) Plane



Possible targets

^{12}C, ^{16}O, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{75}As, ^{89}Y, ^{127}I, ^{165}Ho, ^{208}Pb

Neutrino Proposals at the SNS Require 2 Detector types

Charged Current Neutrino-Nucleus Reactions

υ-SNS

Coherent Neutrino-Nucleus Scattering (CLEAR – Coherent Low Energy Atomic Recoil)

As an example;

$$\nu_e + {}^{56}\mathrm{Fe} \rightarrow e + {}^{56}\mathrm{Co}$$

Uncertainty in this cross section is due to distribution of the nuclear strength and renormalization of the axial-vector coupling

(GT limit when q →0)

υ + C, σ = (8±1) x 10-42 cm2

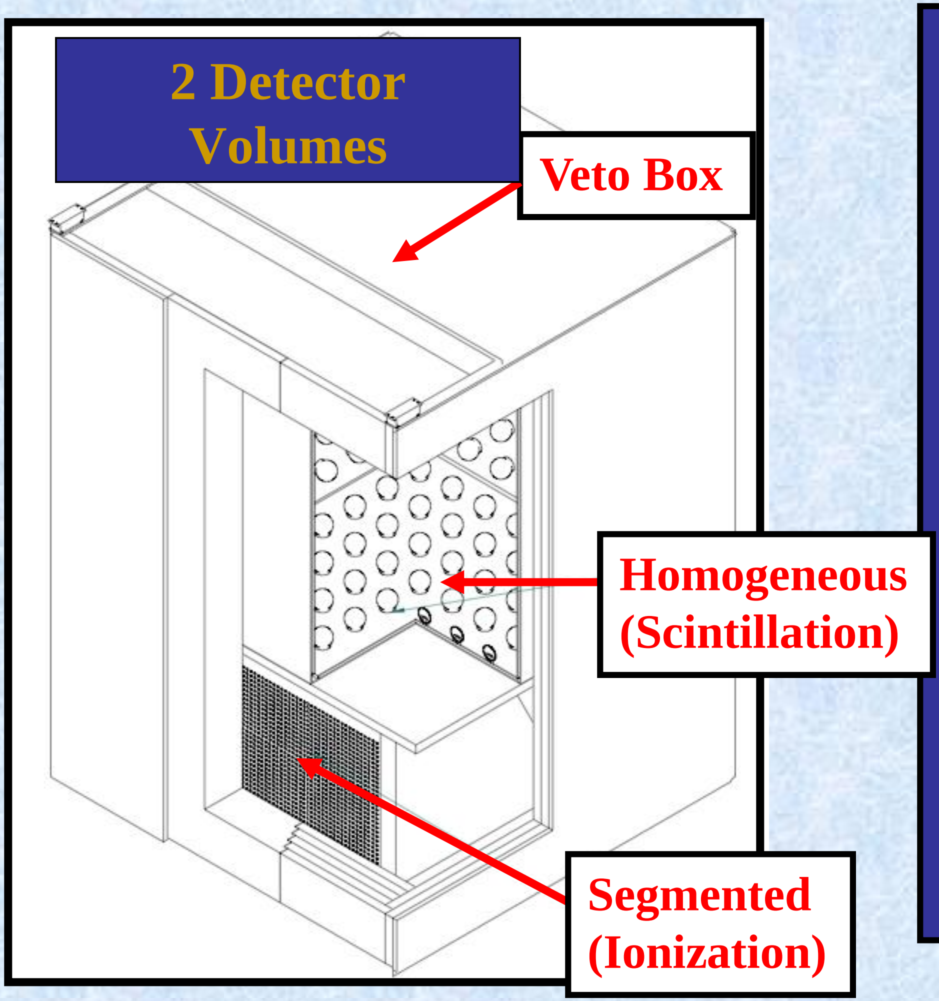
υ+Fe (~40%)

Cross section about 10 times higher and all flavors participate. In principle cross section can be calculated in SM

No previous observation

Important for energy transport in SN

Charged Current Reactions



Target mass ~ 20 t each (1000 (υ_e,e) events/year)

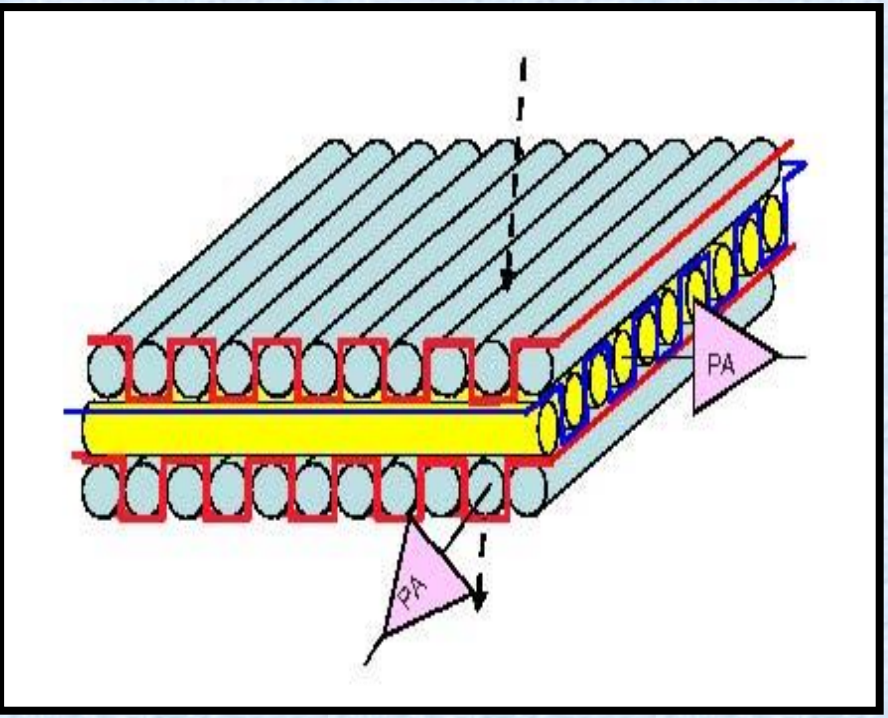
1. Scintillation / Cerenkov

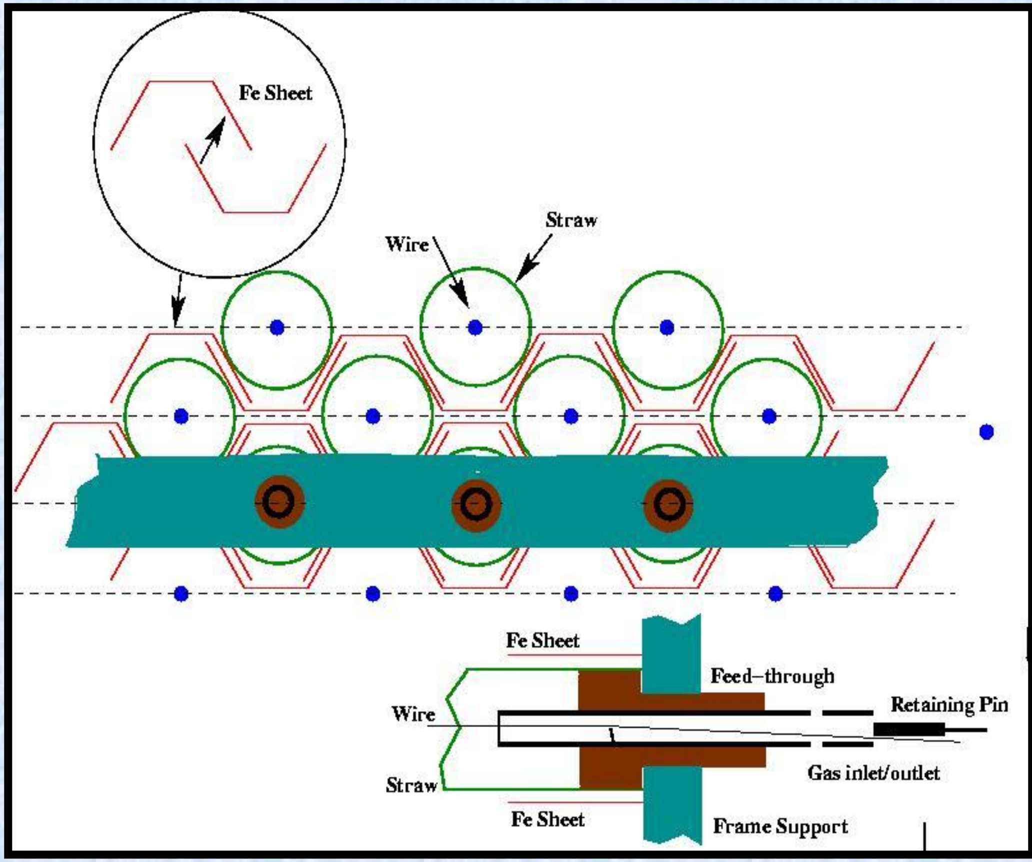
   mineral oil, H_2O, D_2O, ^{127}I (salt)

2. Solid (segmented)

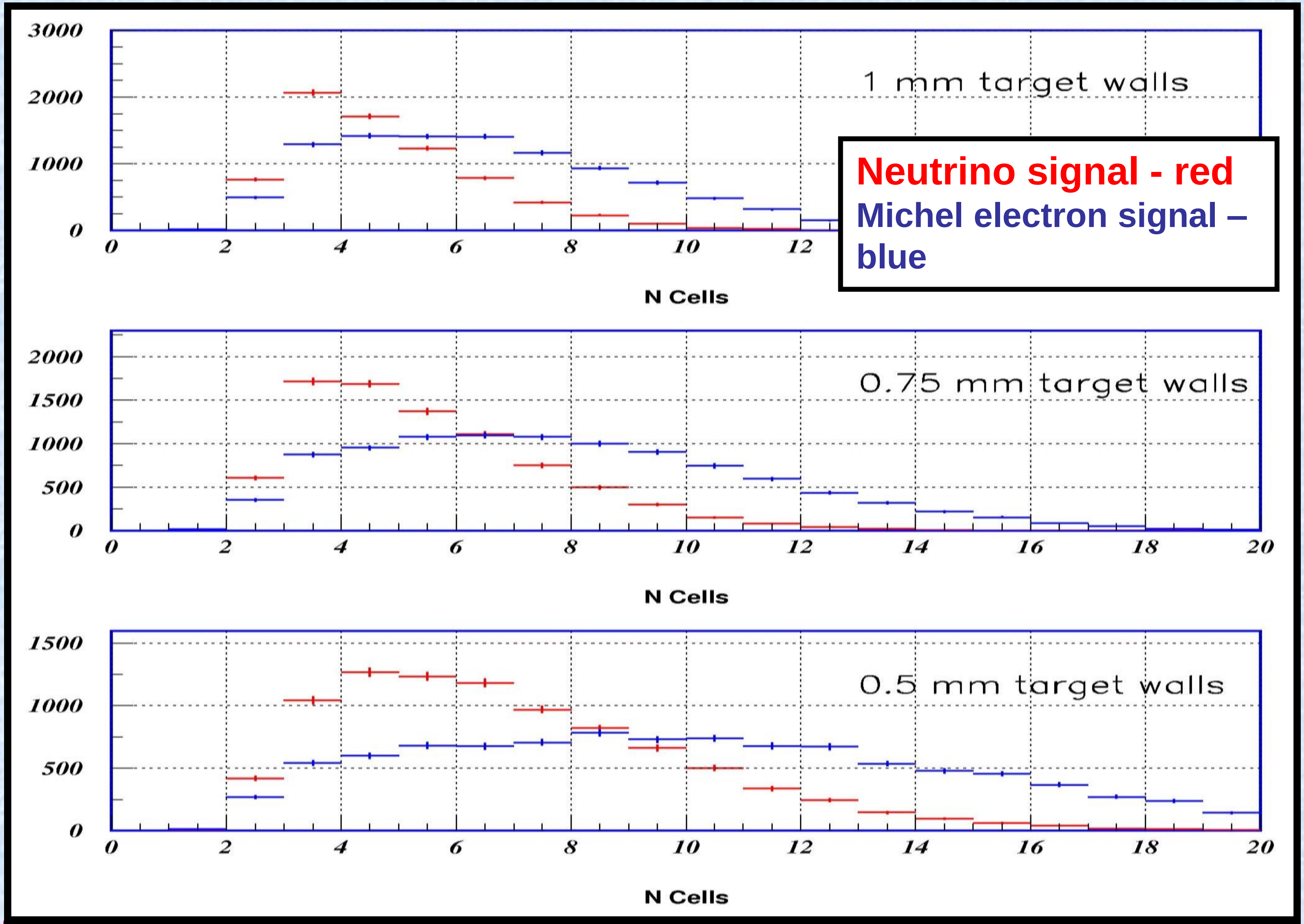
   e.g. Al, Fe, Ta, Bi
   Straw tube technology

Segmented Detector Element





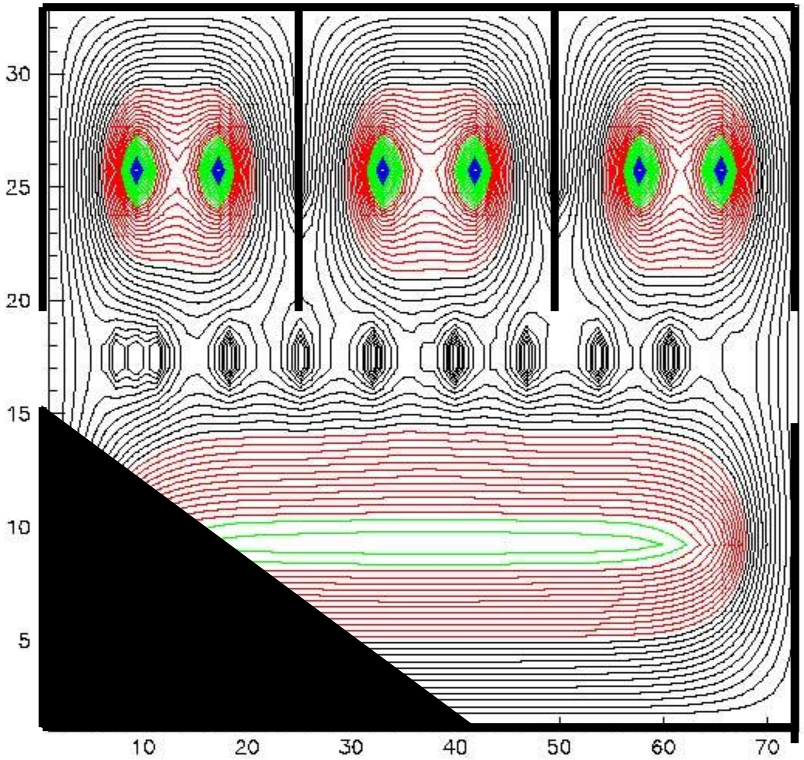
Number of straw cells hit for a Segmented Fe Target

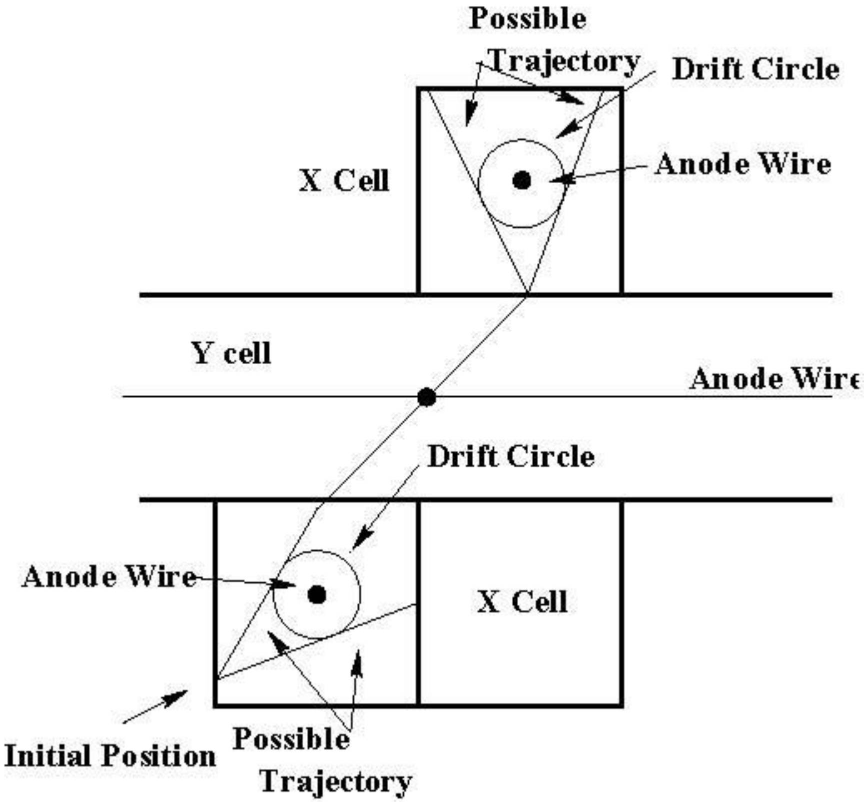


Neutrino signal - red

Michel electron signal – blue

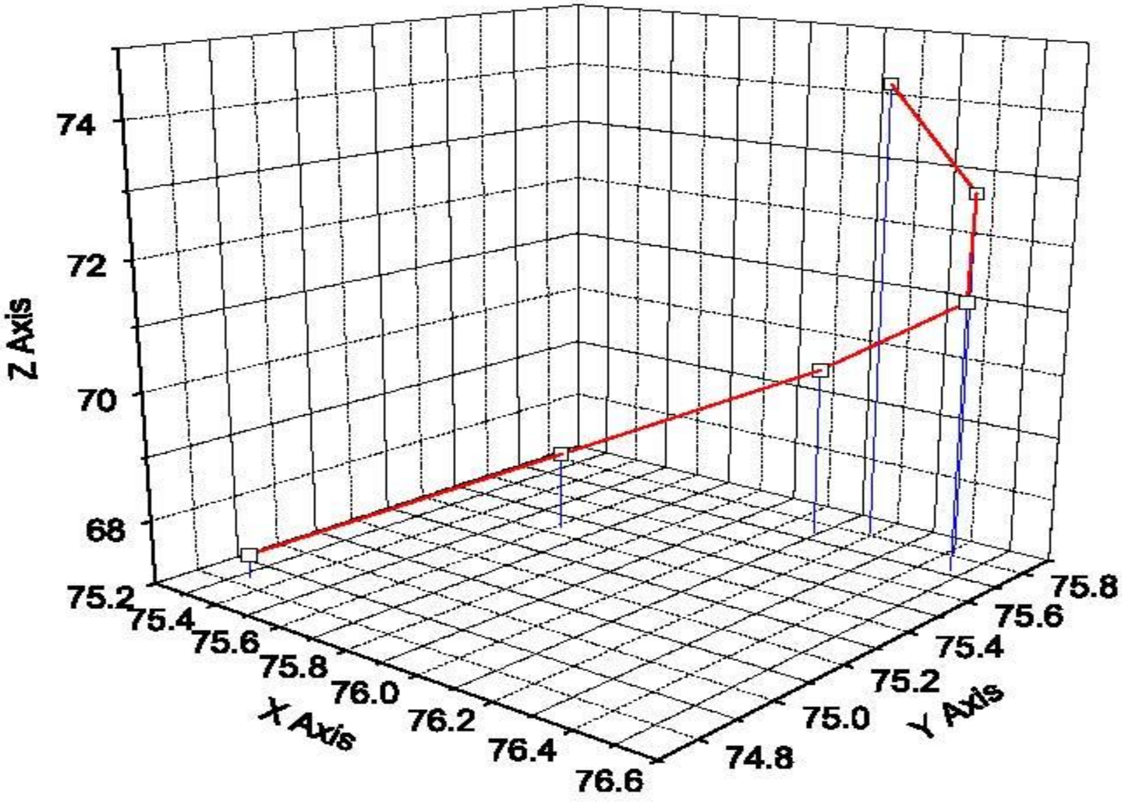
A Revised Detector Geometry



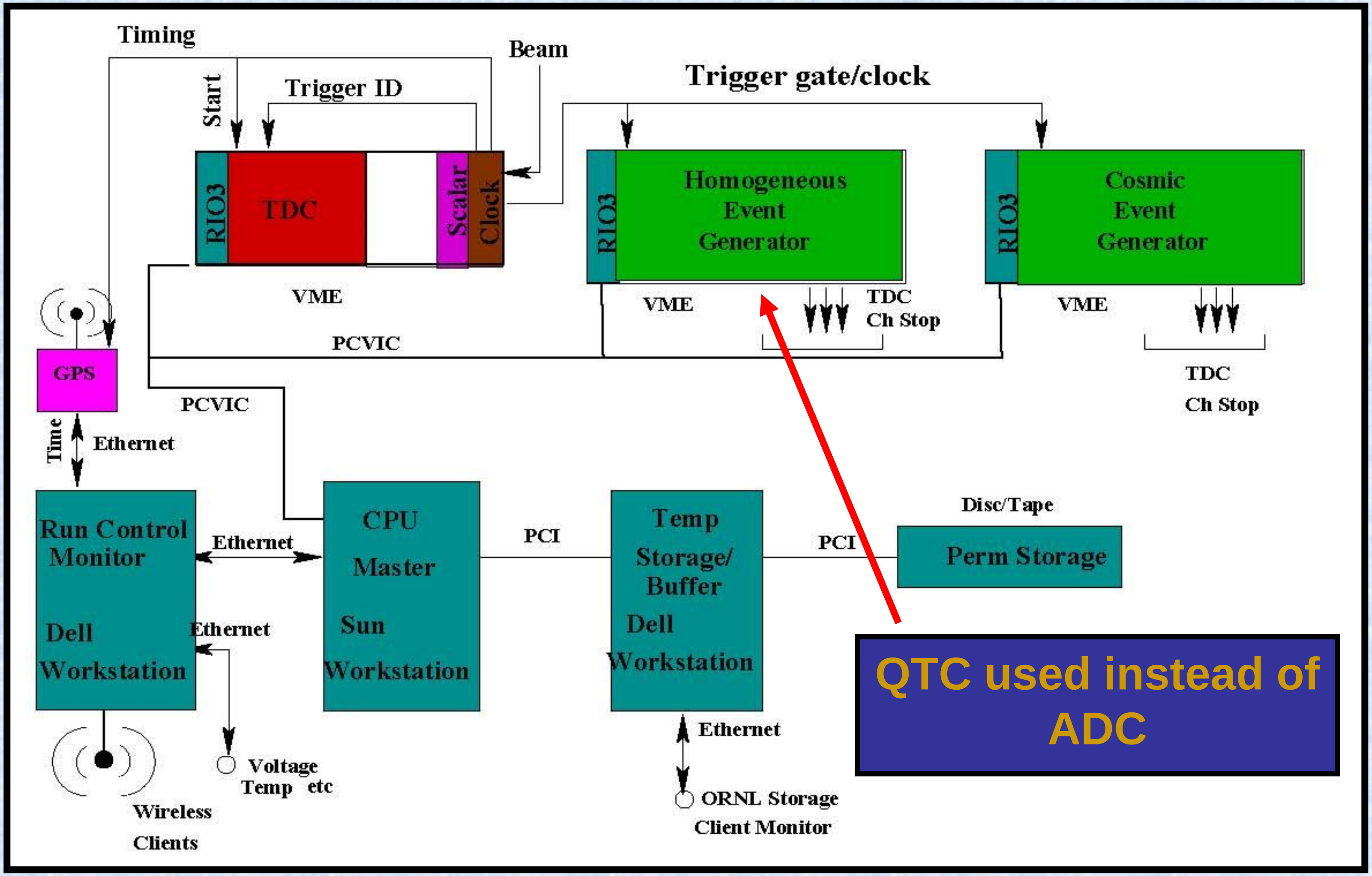


An Example of Tracking a Problem

$\upsilon + {}^{56}\mathrm{Fe} \rightarrow e + {}^{56}\mathrm{Co}^*$



A Schematic Data Acquisition System



QTC used instead of ADC

Expected Total Cross Sections

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 will deliver ~ $1.9 \cdot 10^{22}$ neutrinos per year

Properties of Liquid Noble Gases

Element	Density (g/cc)	Boiling Pt (K)	Mobility (cm2/Vs)	Scint. (nm)	Photon #/MeV	Isotopes	Lifetime Triplet (us)
LHe 2/4	0.145	4.2	(low)	80	19k	2	13 x10^6
LNe 10/20	1.2	27.1	(low)	78	30k	3	15
LAr 18/40	1.4	87.3	400	125	40k	3	1.6
LKr 36/84	2.4	120	1200	150	25k	6	0.09
LXe 54/132	3.0	165	2200	175	42k	9	0.03

2-Phase LXe Detector

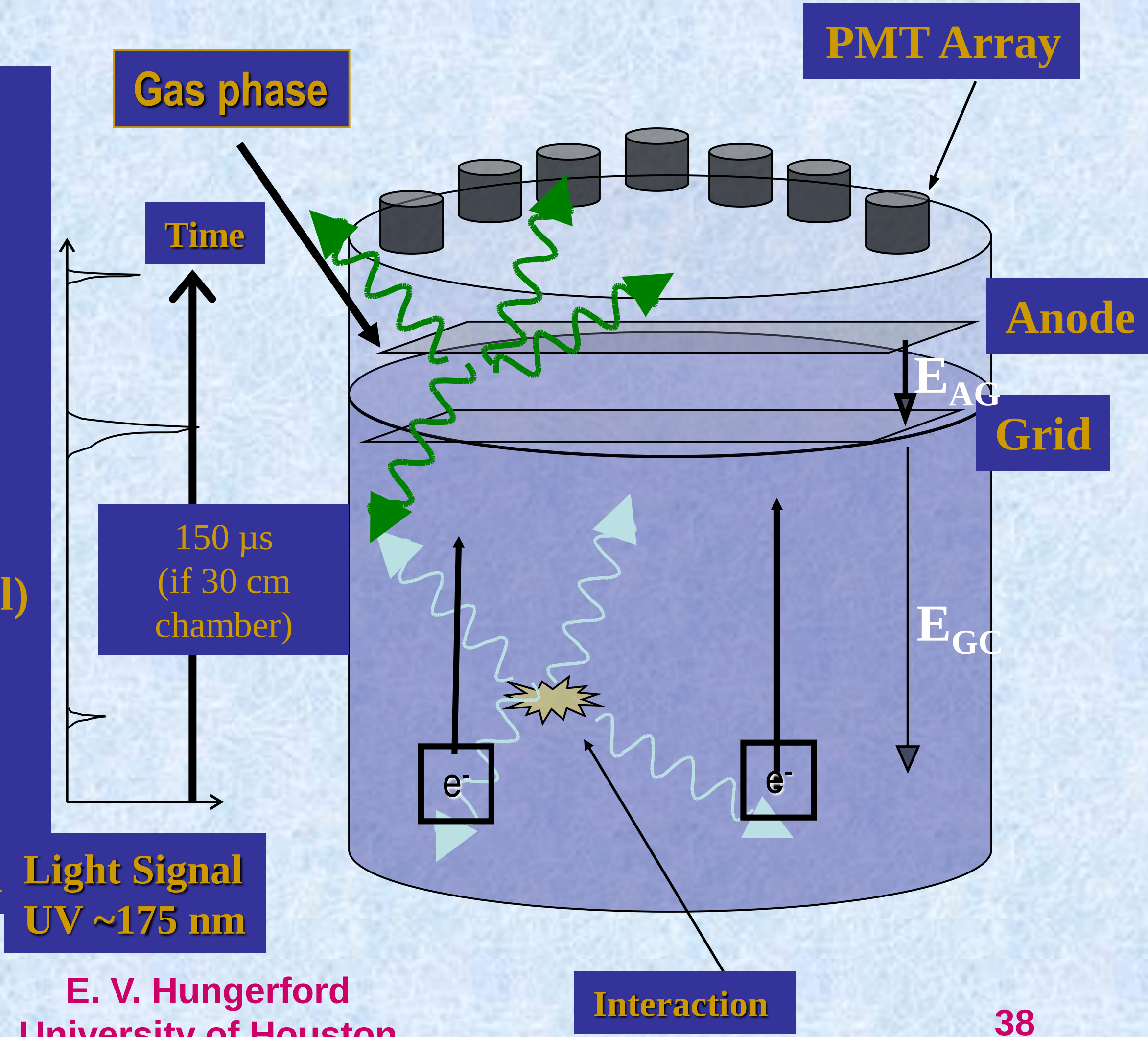
Takes Advantage of high e mobility to produce 2 signals S1 and S2

—

- (S1) - 16 keV nuclear recoil: ≈ 200 photons (quenched)
- (S2) - ionization signal ≈ 7-20 electrons (proportional) (assumes high field 8 kV/cm)

—

Also provides 2-D (3-D with timing) position information



Gas phase

PMT Array

Time

150 μs (if 30 cm chamber)

Anode

E_{AG}

Grid

E_{GC}

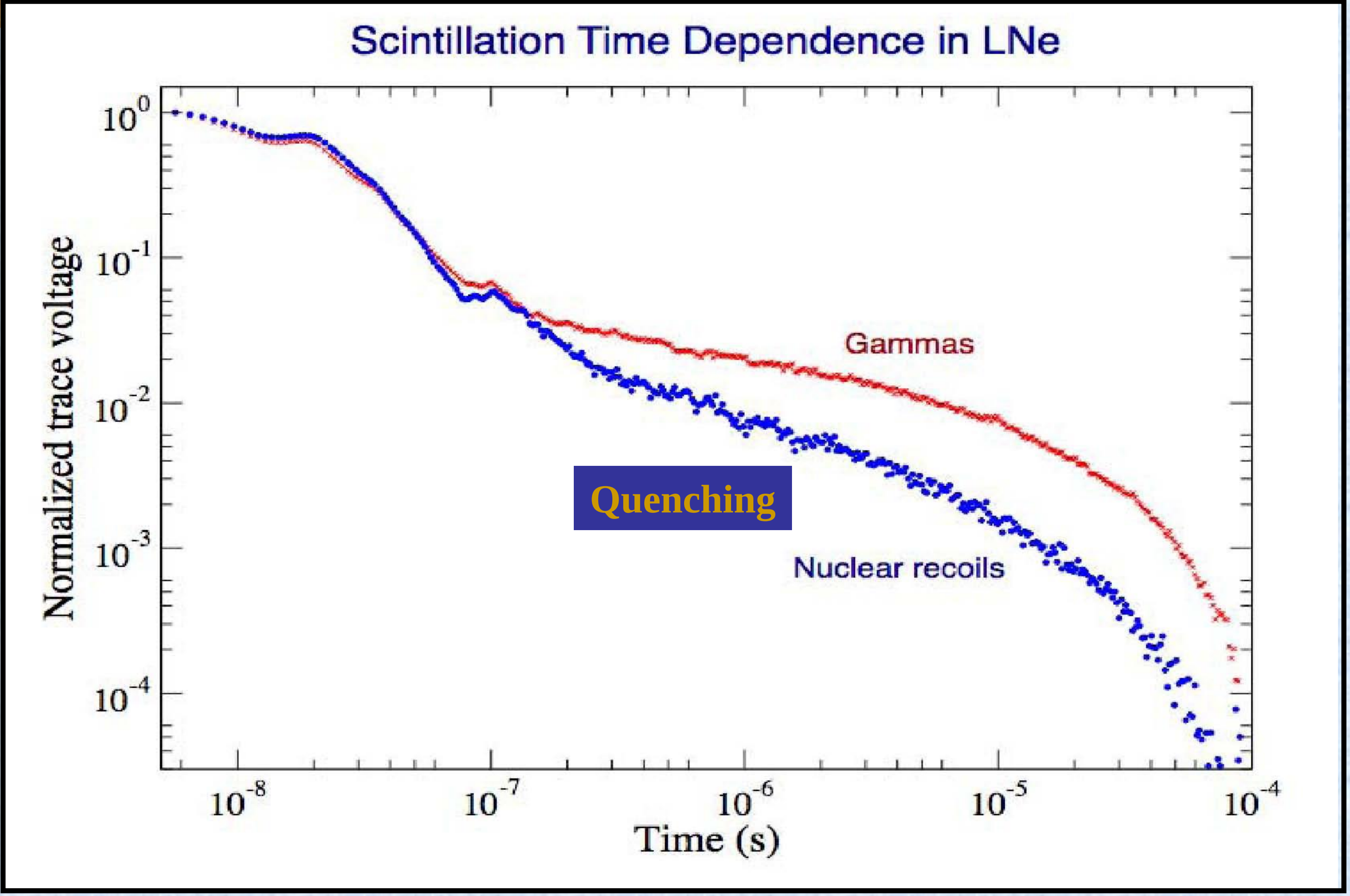
e^-

e^-

Light Signal UV ~175 nm

Interaction

Response of LNe to Nuclear and Gamma Ionization



Quenching

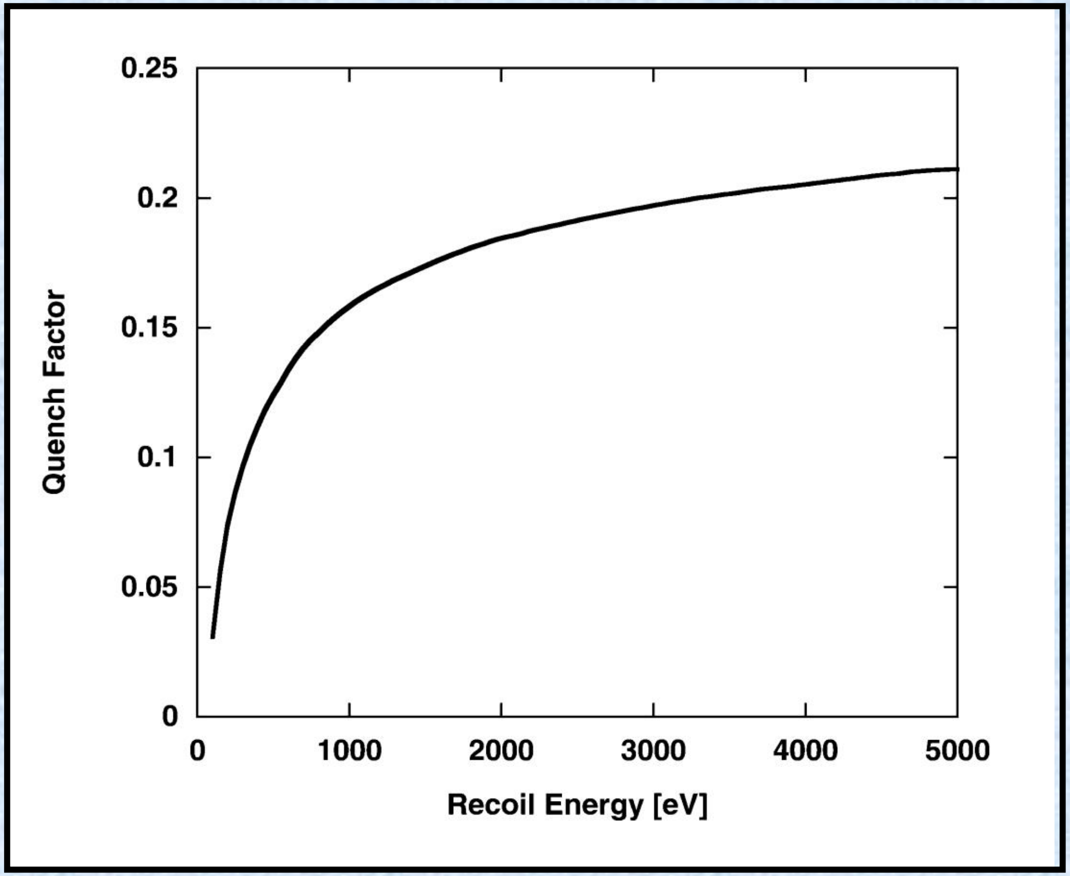
Quenching of Ionization from Nuclear Recoil

Quenching

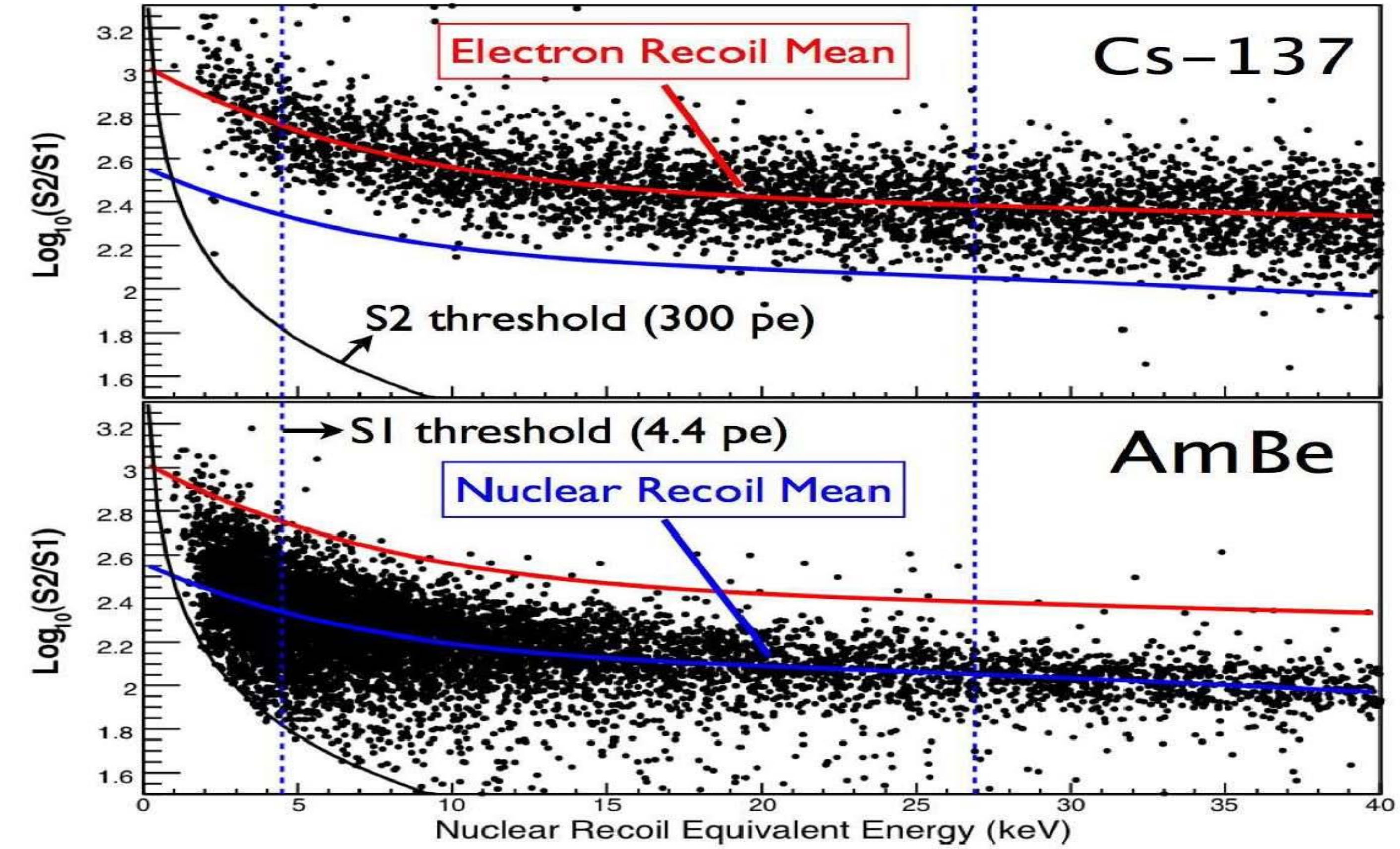
$$q(E) \equiv \frac{N_{\text{ion}}^{\text{nucl}}(E) + N_{\text{exc}}^{\text{nucl}}(E)}{N_{\text{ion}}^{\text{elec}}(E) + N_{\text{exc}}^{\text{elec}}(E)}$$

E Mobility LXe

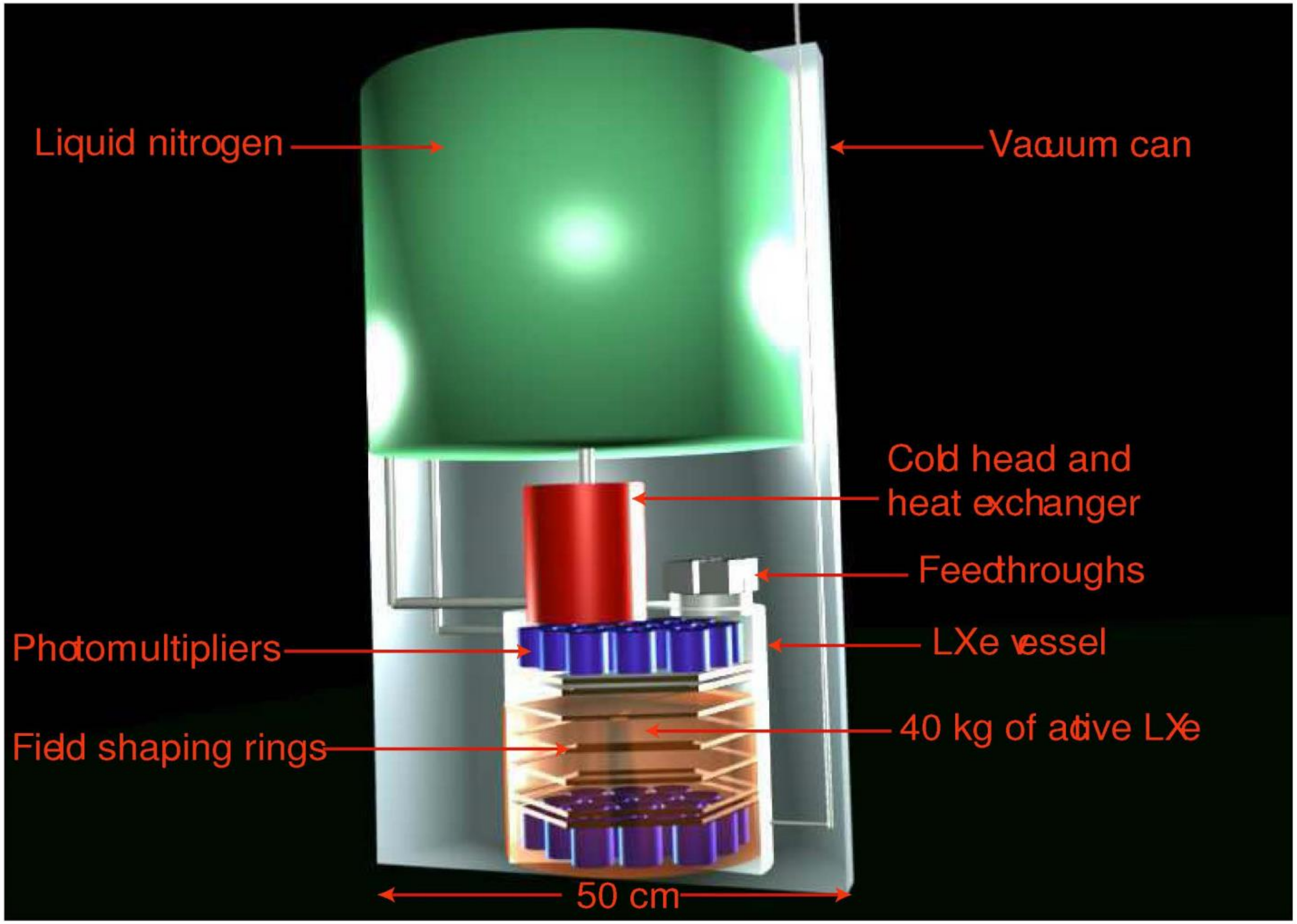
2200 cm^2/Vs



Recoil - Electron/gamma Discrimination

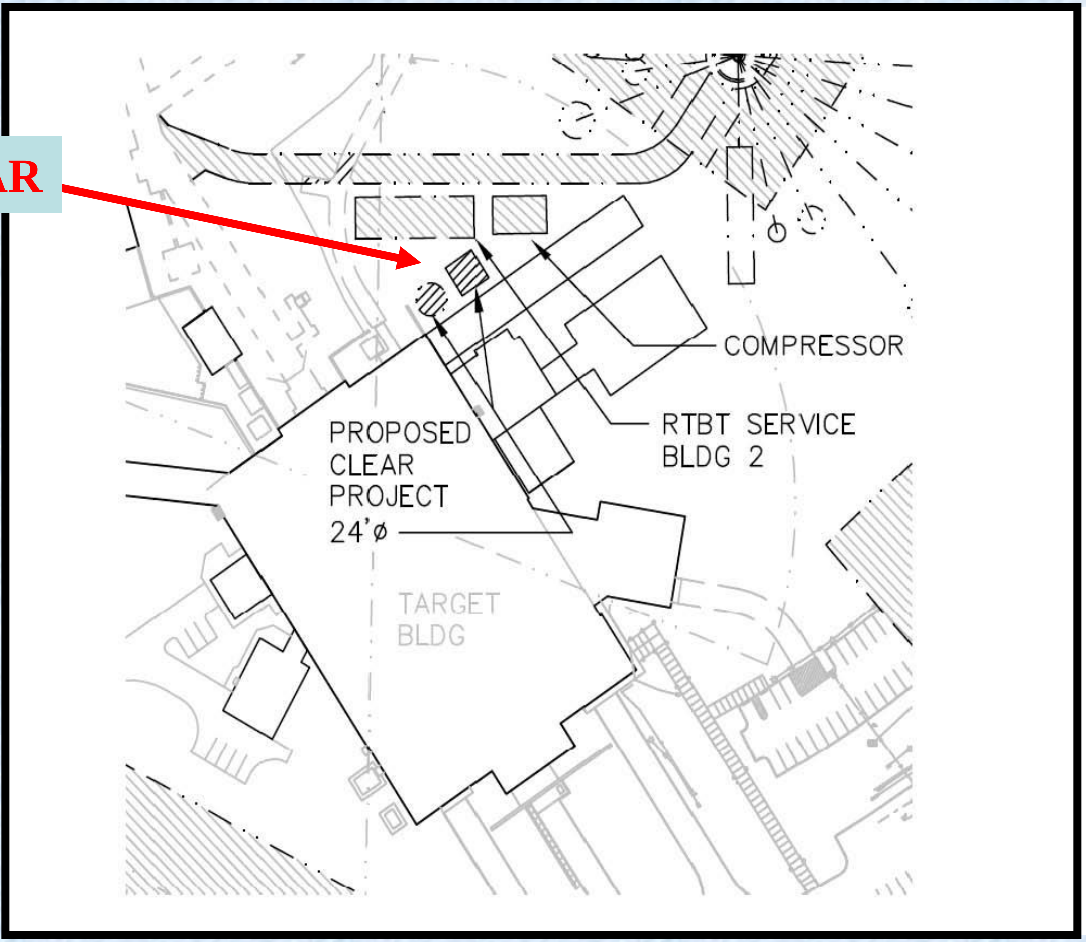


The LXe Detector Flask



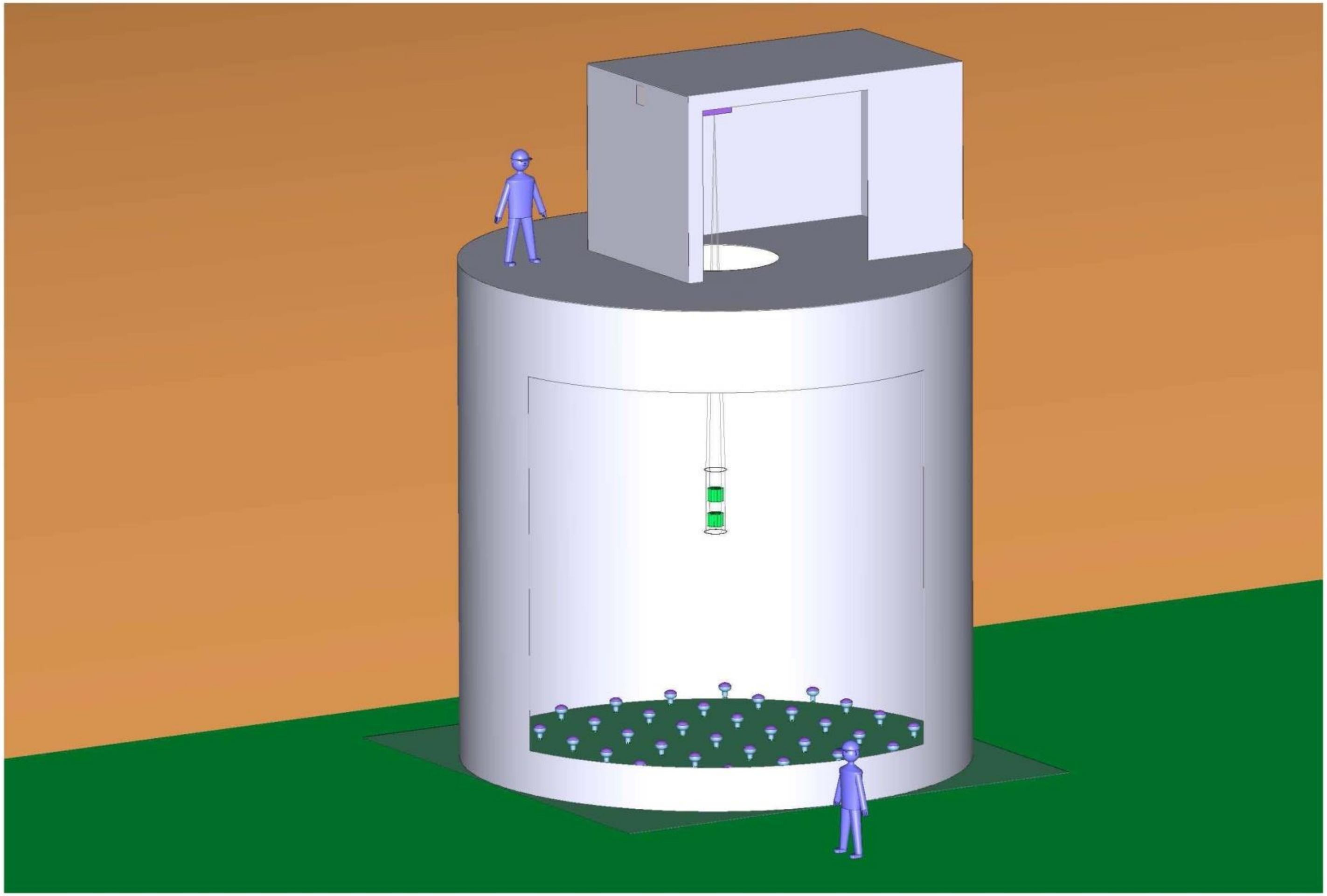
Location of the CLEAR Detector

CLEAR

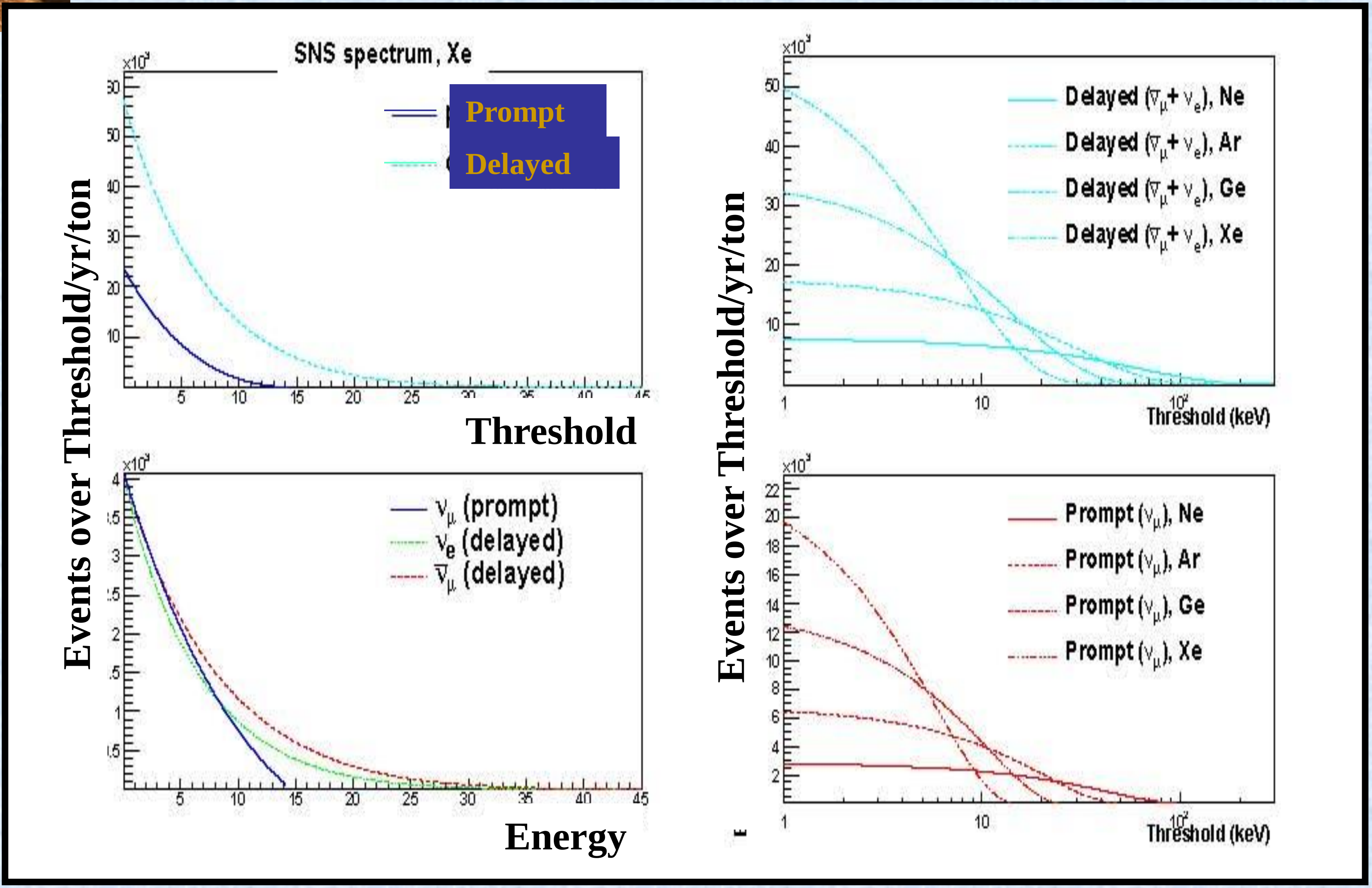


UHMEP

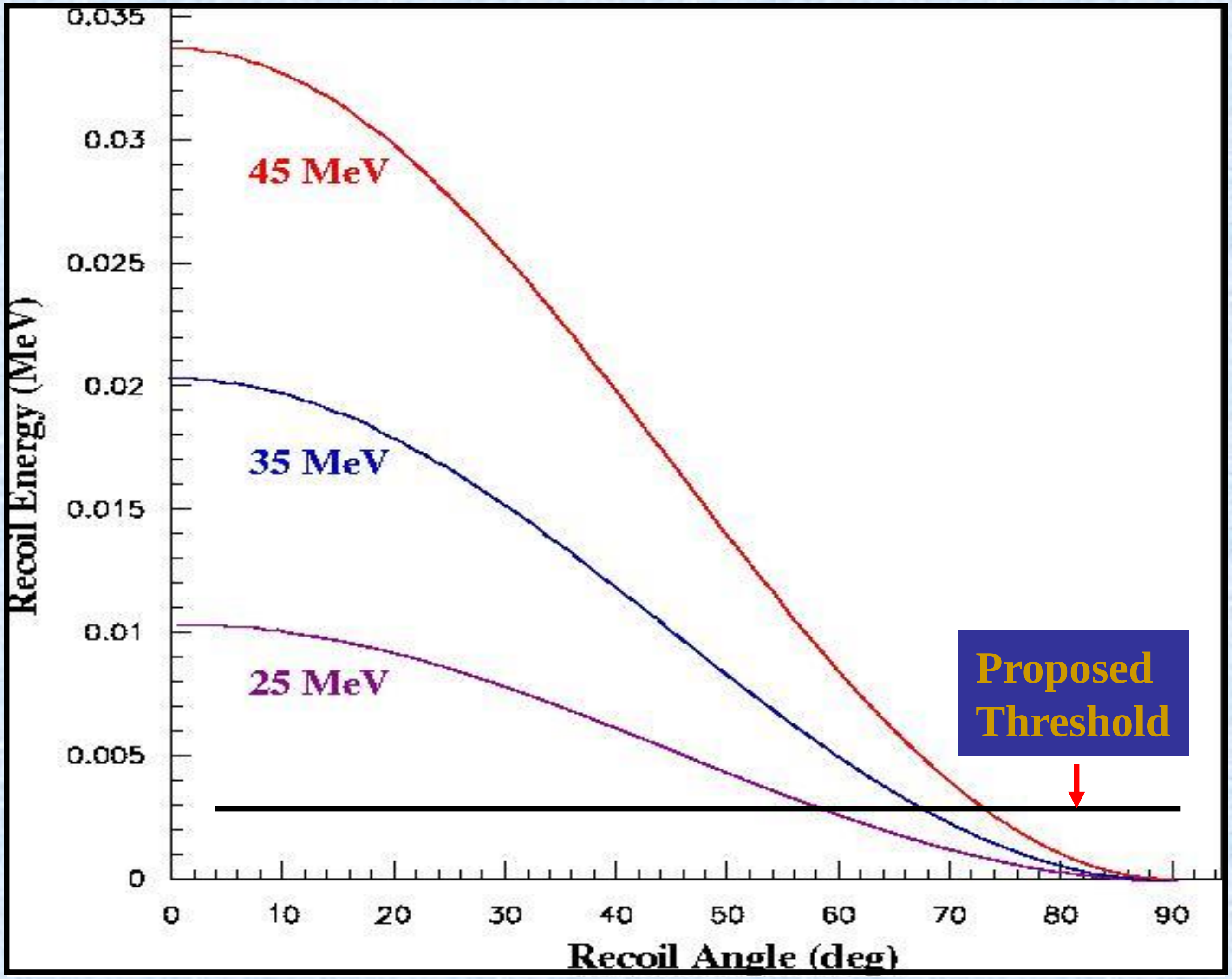
Water Tank Shield



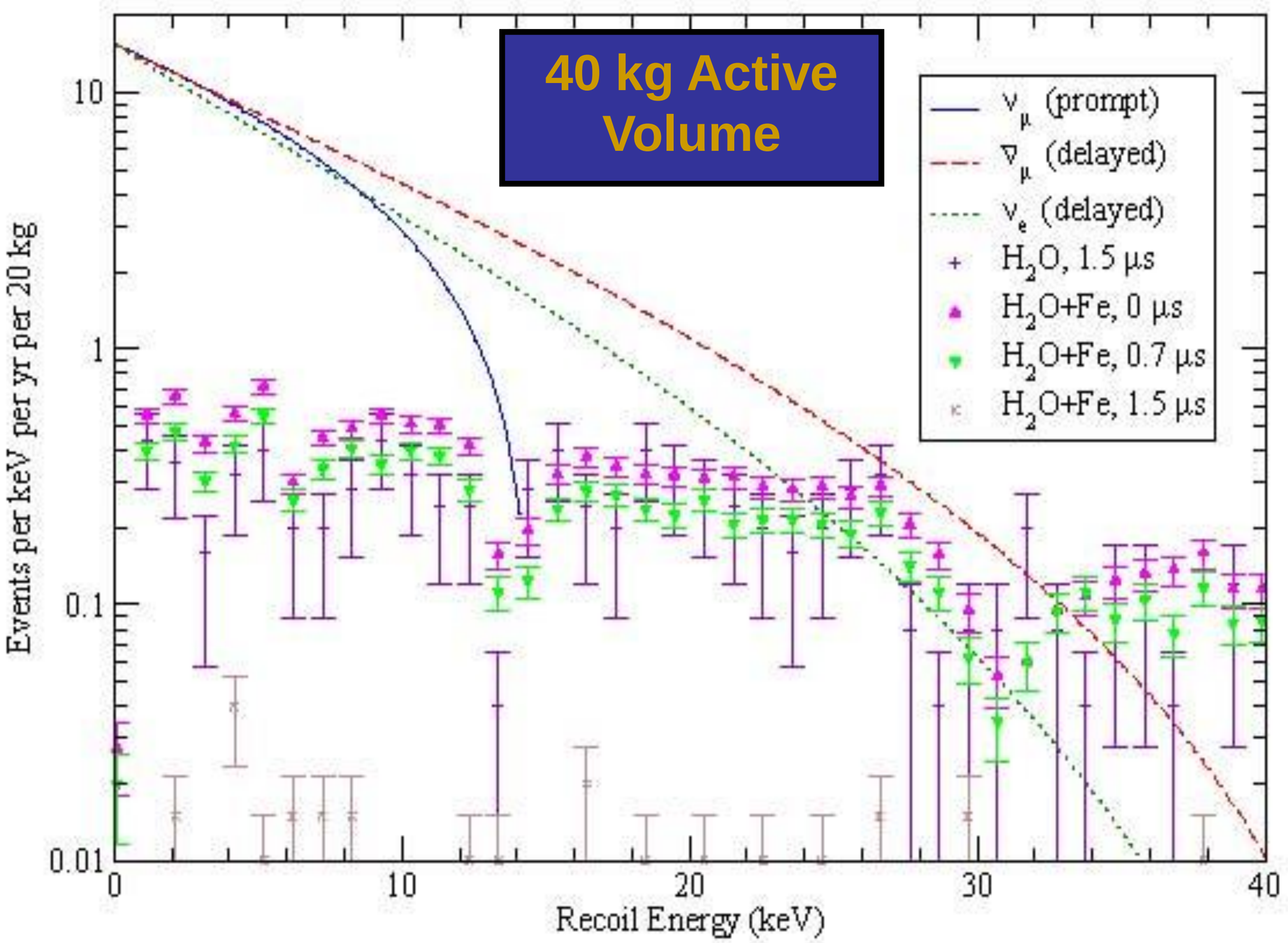
Xe Recoil for Coherent Scattering by SNS Neutrinos



Recoil Energy for Various Incident Neutrino Energies

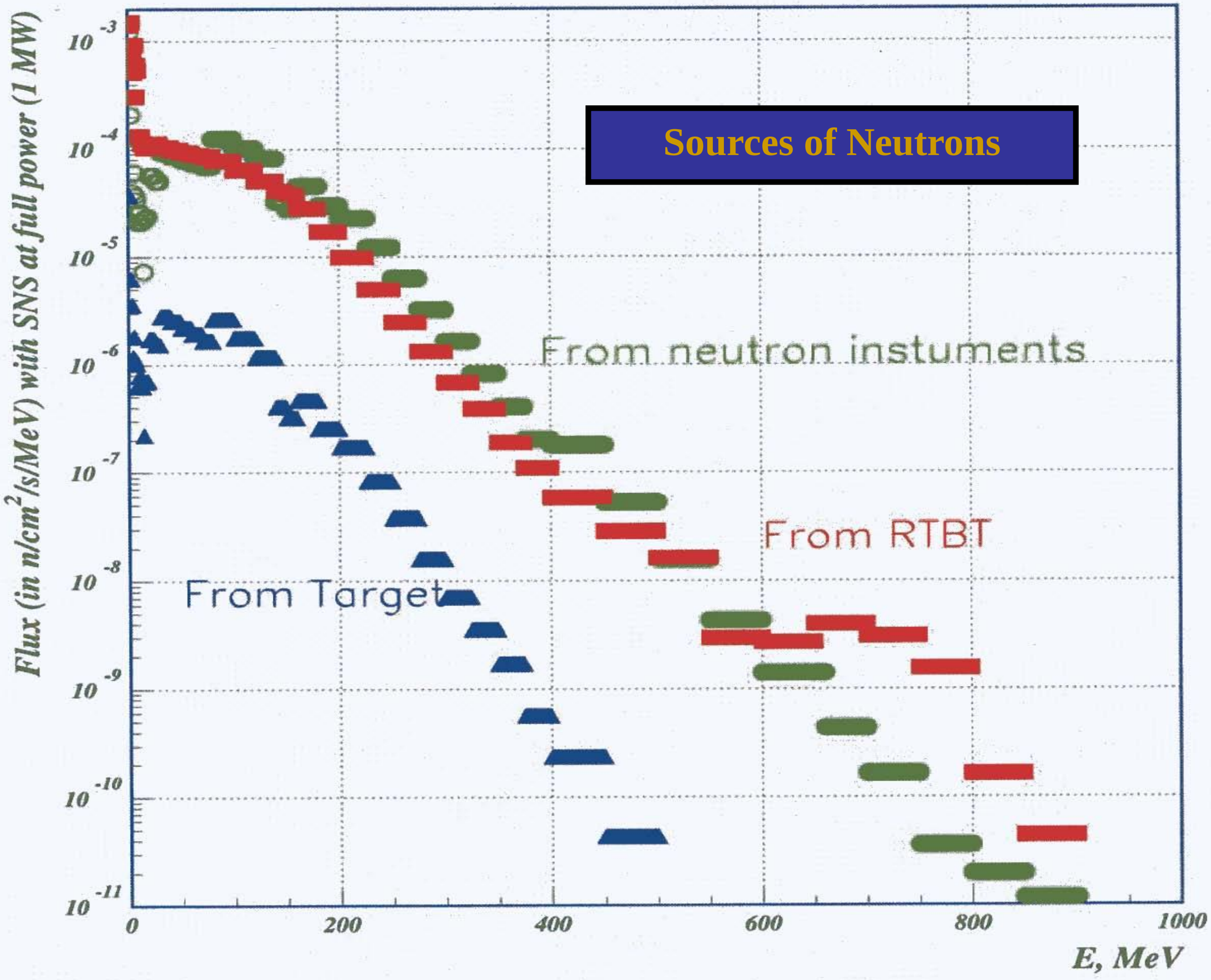


Signal vs Background



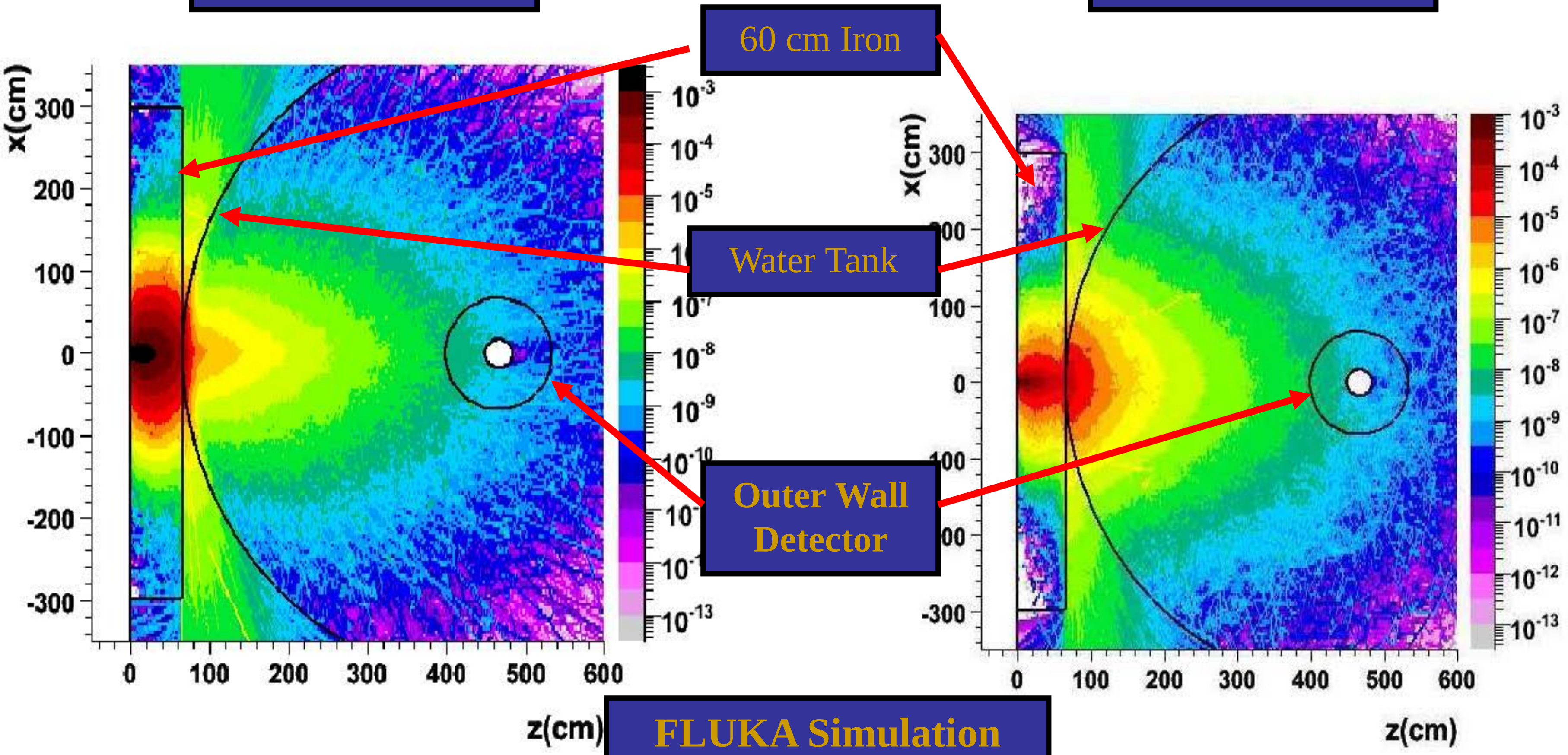
40 kg Active Volume

Neutron Background



Fgure 4.9 Flux (n/s/cm^2/MeV) from SNS sources of high-energy neutrons.

Neutron and Gamma Background



Neutrons

Gammas

60 cm Iron

Water Tank

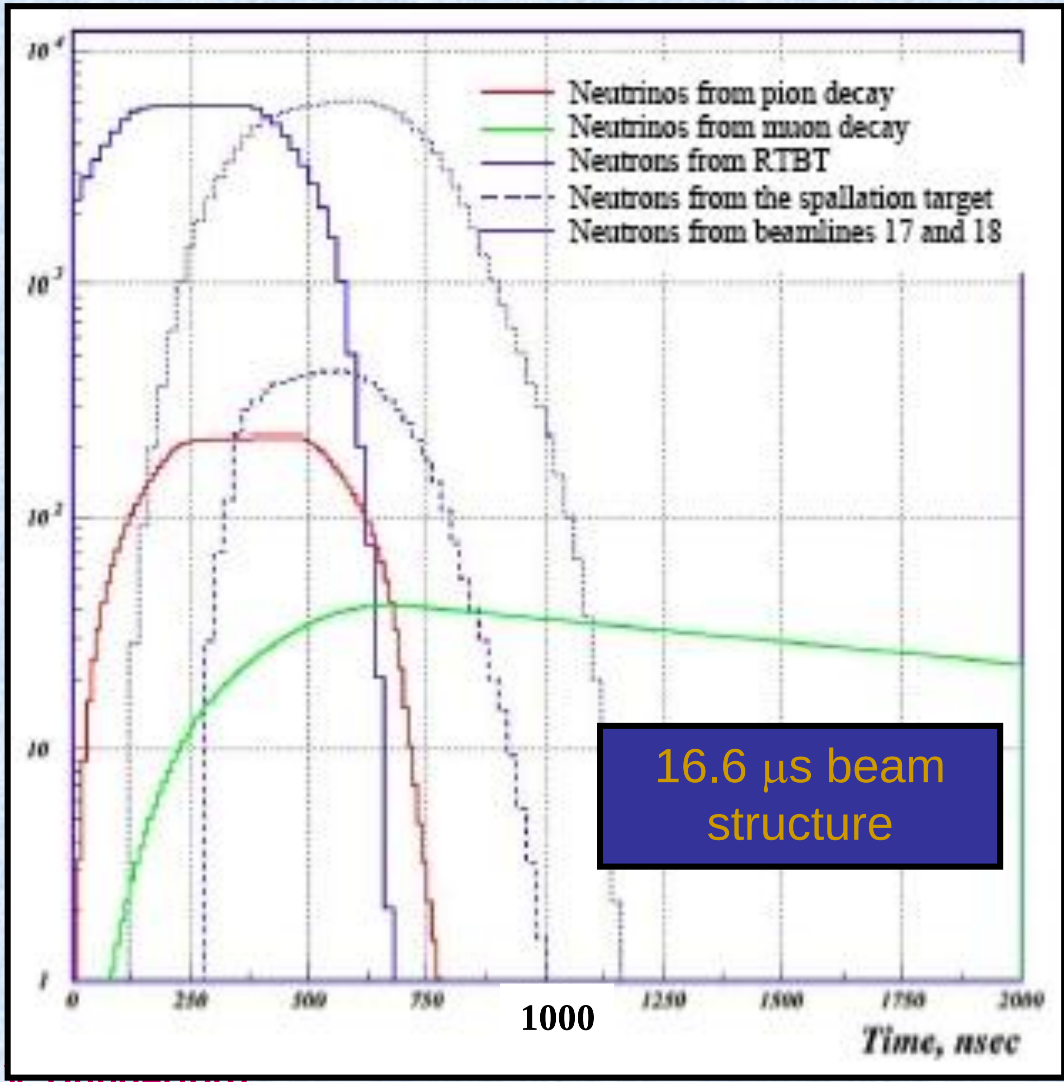
Outer Wall Detector

FLUKA Simulation
60 cm Fe
400 cm of H_2O

Timing

- Time structure crucial
- t > 1 µs cuts most neutron background
- δt > 1µs → lose ν_μ but retains most ν_e

Time cut (µs)	ν efficiency (%)
2-10.0	43
1.5-10.0	37
1.8-10.0	34
2.0-10.0	30



16.6 µs beam structure

Cosmic ray background

- SNS duty factor is $4 \cdot 10^{-4}$ → reduces flux to 10^5 muons and ~600 neutrons per day entering enclosure
- One meter of steel overburden reduces hadronic component of Atmospheric showers → 3×10^3 neutrons/day
- Hermetic veto efficiency of 99% → 30 fast neutrons/day
- Expected number of untagged neutron events is a few per day
- Extra discrimination is expected from detector PID

Cosmic Veto

- CC Detection

  4 layers of plastic scintillator

  Cosmic muons not an issue

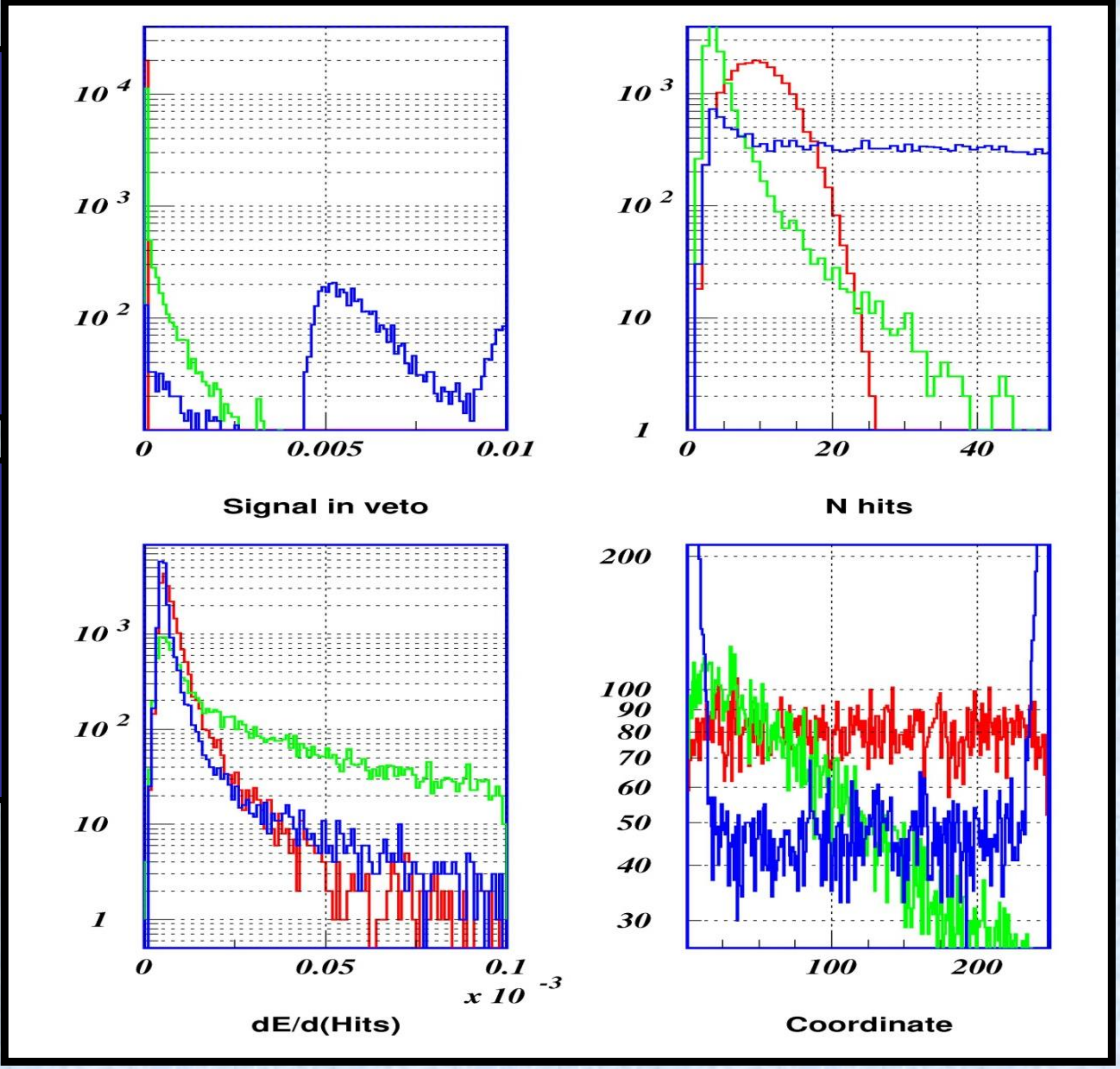
  Neutrons are difficult 10^6 suppression required

- Neutral Current Detection

  Water Cerenkov in the water tank

  Not studied in detail but appears not to present a problem

neutrinos, neutrons, muons



Feb 25, 2008

E. V. Hungerford
University of Houston

Estimated 1 year Yield CC Reaction

Target	Assumed Cross Section (10^{-40} cm^2)	# Target Nuclei	Raw Counts	Assumed Efficiency	Statistical Significance
Segmented Detector (10 ton fiducial mass)					
Iron	2.5 [17]	1.1×10^{29}	3,200	35%	3.0%
Lead	41.0 [20]	2.9×10^{28}	14,000	35%	<1.4%
Aluminum	1.12 [21]	2.2×10^{29}	3,100	35%	3.0%
Homogeneous Detector (15.5 m^3 fiducial volume)					
Carbon	0.144 [17]	5.6×10^{29}	1,000	40%	5.0%
Oxygen	0.08 [22]	4.6×10^{29}	450	40%	7.4%

Estimated 1 year Yield NC Coherent

NC Coherent events/Yr from LXe --- 200

Measurement of Neutrino Magnetic Moment --- 10^{-10} nm

Given the SM extraction of the neutron form factor will not be sufficiently precise to model sensitive

Provides a factor of 10 improvement in the discrimination of Non-standard Interactions

Provides a measure of Q^2_w at Q = 0.04 GeV/c in a different channel ($\delta\sin^2(\theta_W) \approx 5\%$)

Concluding Remarks

- nN reactions are important for supernovae
  - Influence core collapse
  - Affect shock dynamics
  - Modify the distribution of A>56 elements
  - Affects r process - nucleosynthesis
  - May be the dominant source of B, F, ^{138}La, ^{180}T
- nN cross sections are interesting nuclear phy
  - Sensitive to nuclear structure
  - In medium modifications of we ng constants
- Only CC cross sections on C h measured (10%)
- The SNS provides a uniq tunity to measure nN cross sections at energies most rele supernovae and nuclear structure
- CC Cross sectio ements on 2 targets to < 10% accuracy in 1 year!
- We have a ng collaboration of experimentalists and theorists but there is room for additional collaborators
- First measurement of a Coherent NC cross section

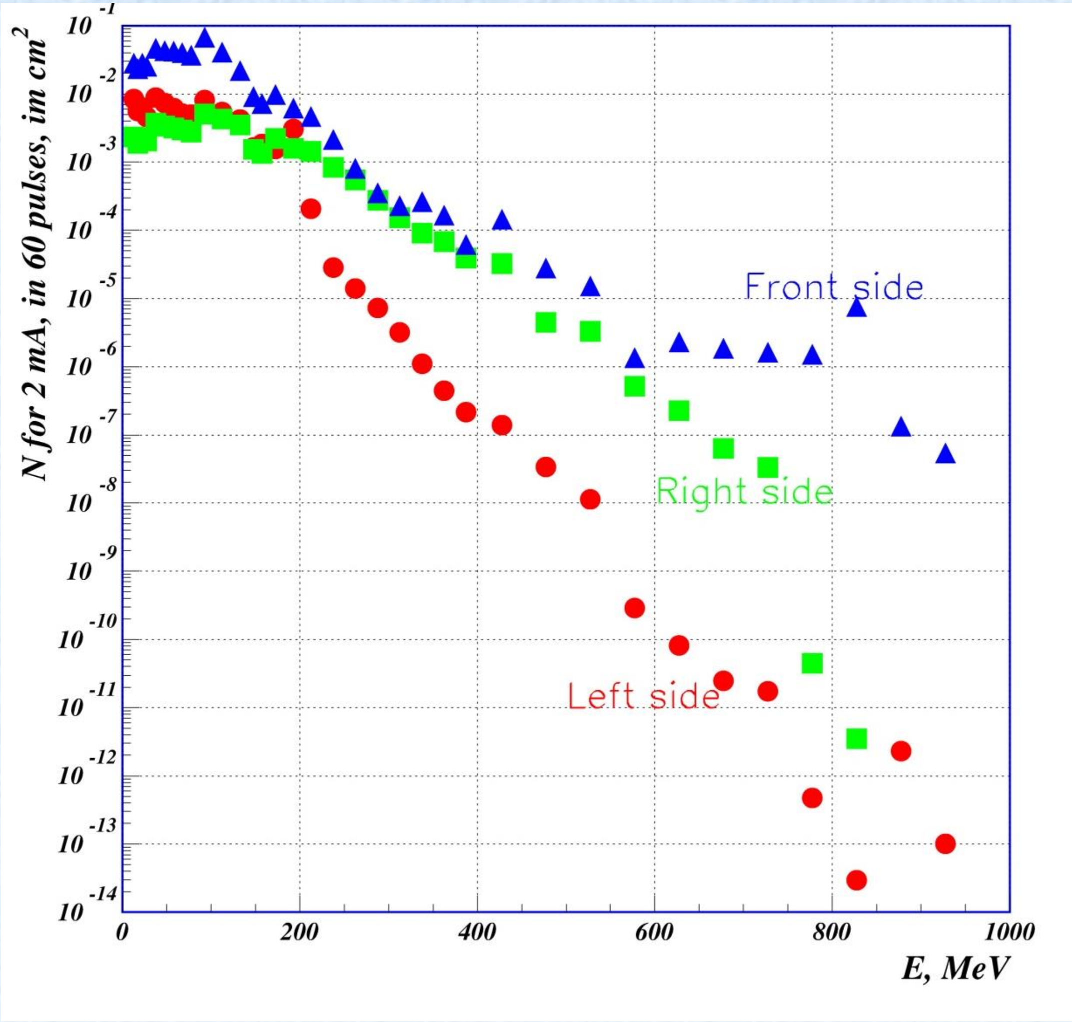
See http://www.phy.ornl.gov/nusns

Neutrino Astrophysics is Awesome

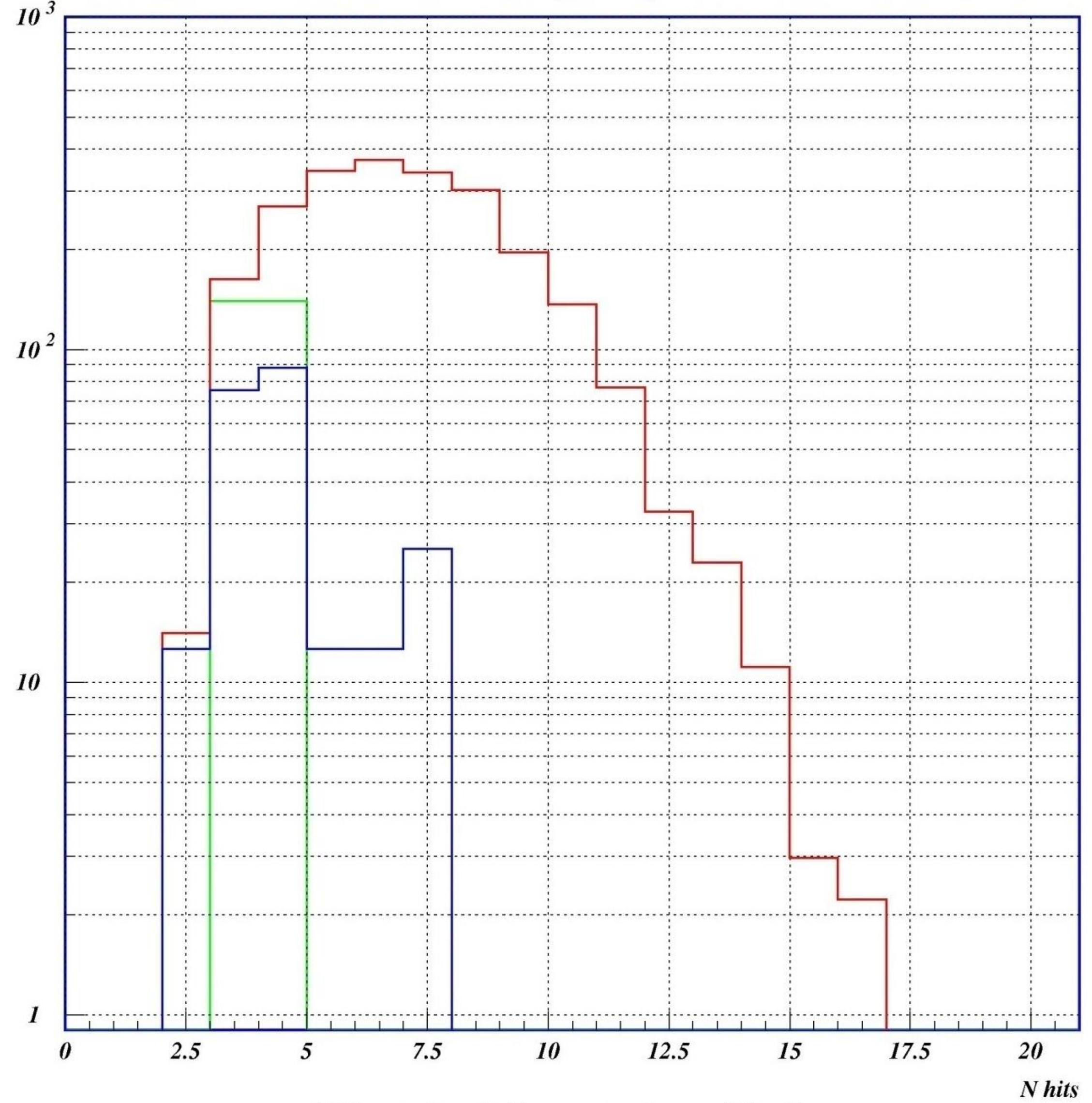
The END

Additional Slides

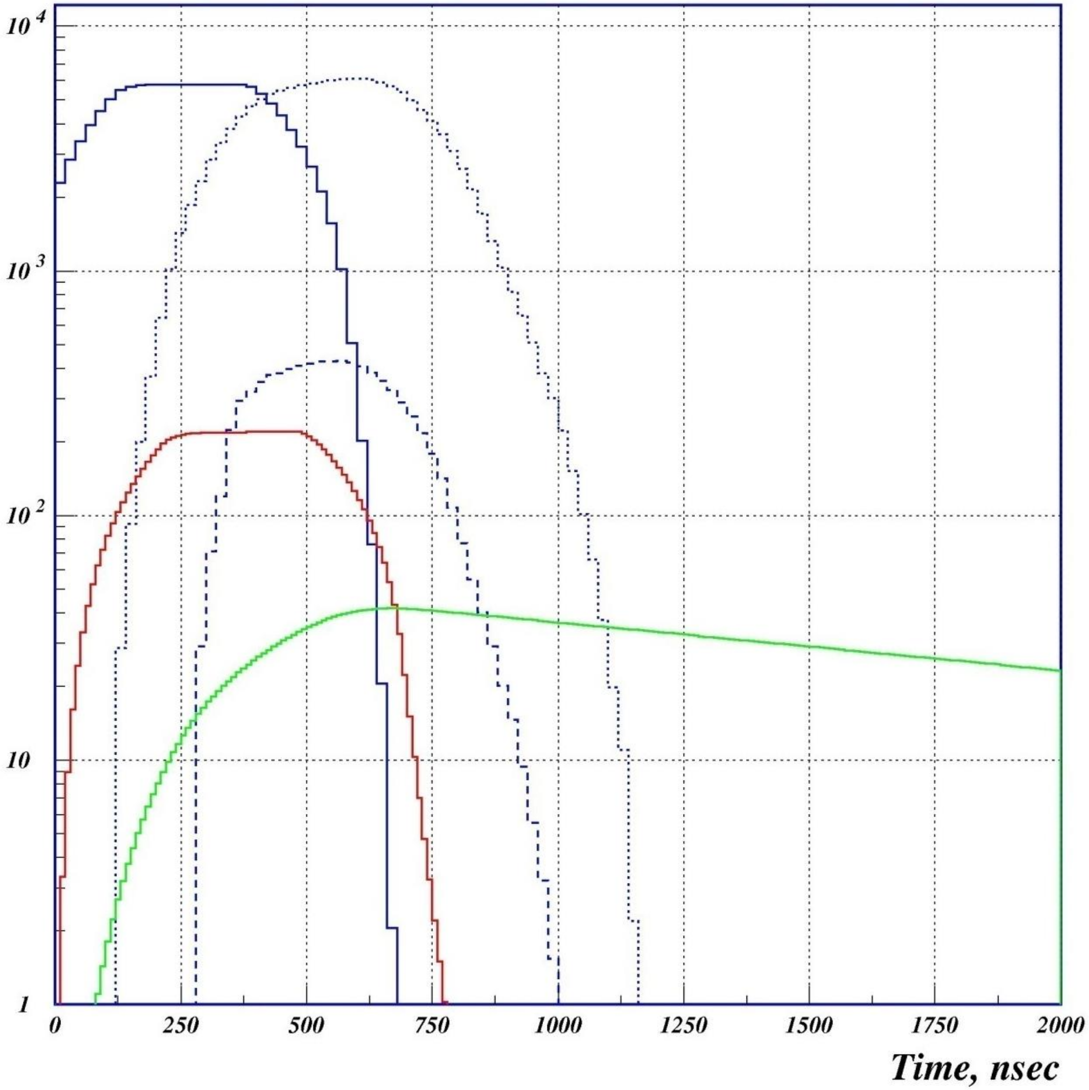
SNS induced neutron flux

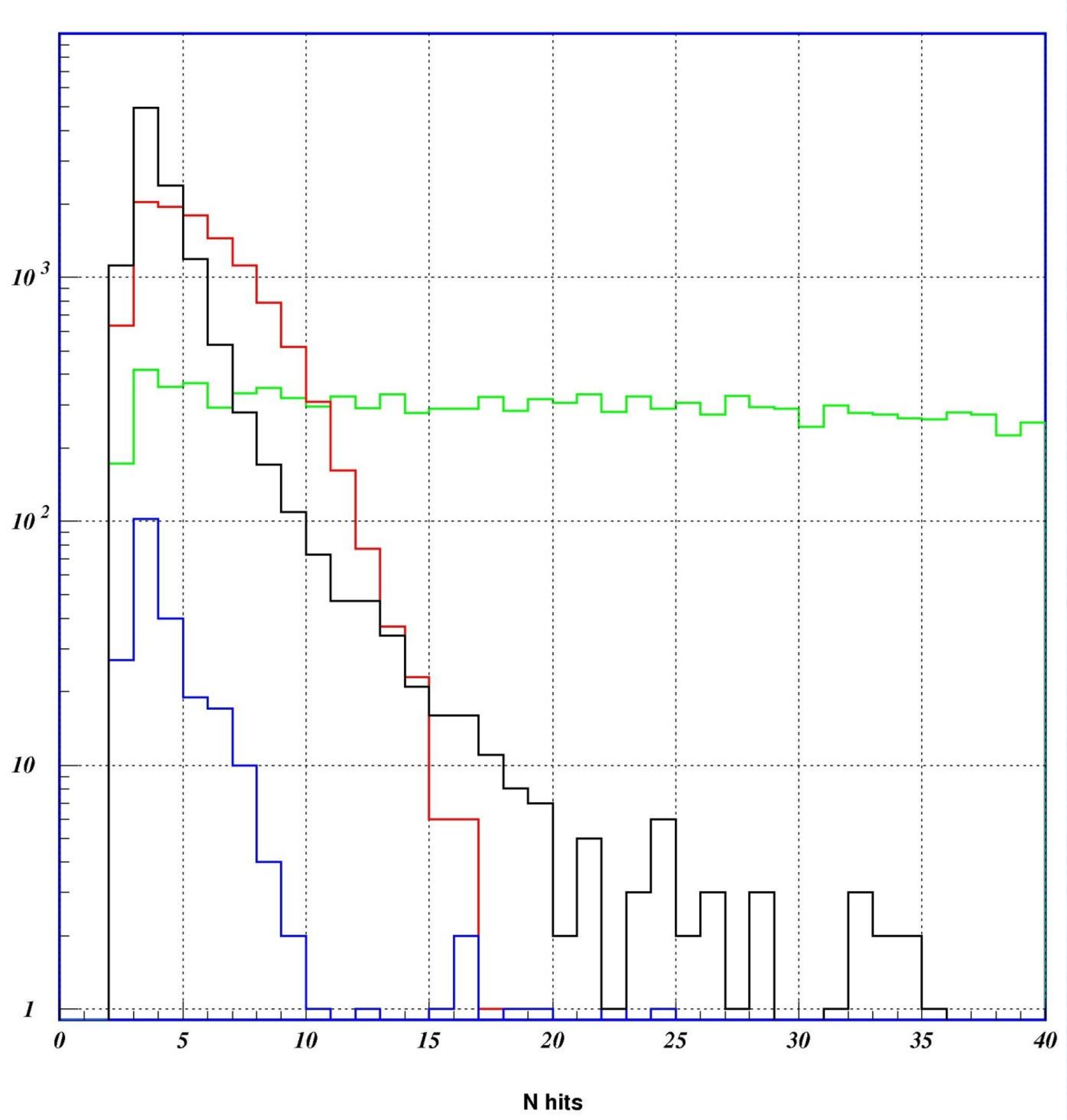


- **High energy neutrons can be eliminated using time cut**
- **Low energy neutrons need shielding and neutron absorbers**
- **PID in detectors is also available**



N hits, + veto + de/dx + compactness + fidu +time


10⁴
10³
10²
10
1
0
250
500
750
1000
1250
1500
1750
2000
Time, nsec


10^3
10^2
10
1
0
5
10
15
20
25
30
35
40
N hits

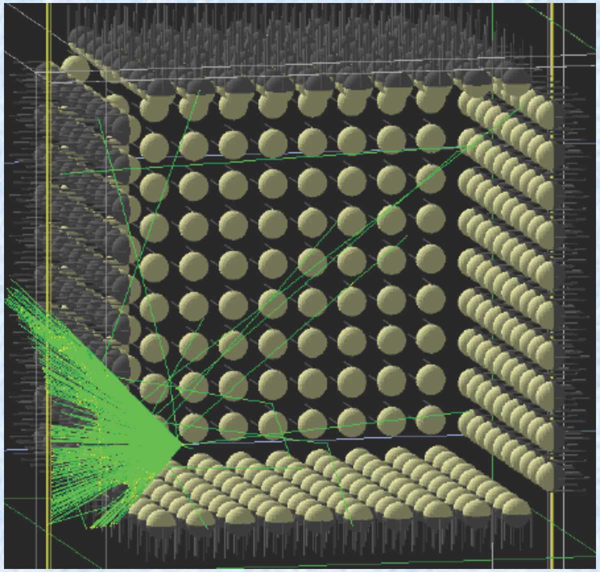
Cross Sections

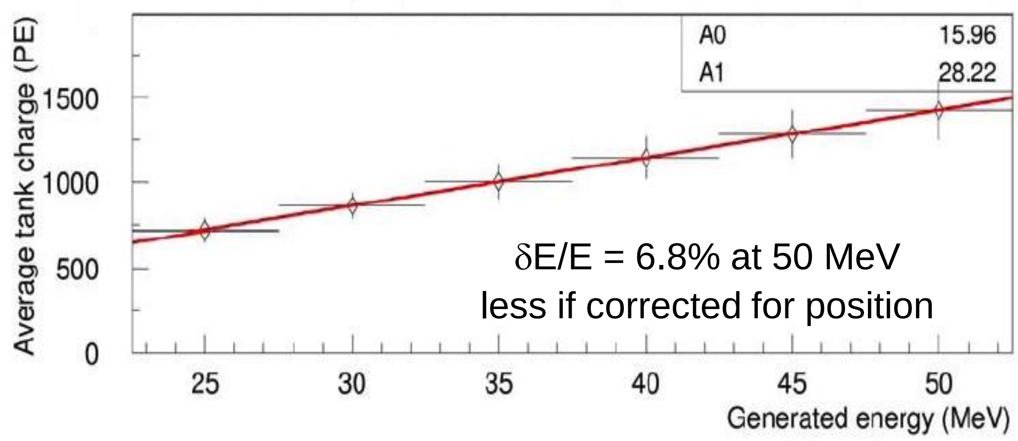
Reaction	Integrated Cross Section
$\nu_e e^- \rightarrow \nu_e e^-$	$0.297 \cdot 10^{-43}$ cm^2
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	$0.050 \cdot 10^{-43}$ cm^2
$\nu_e\,{}^{12}C \rightarrow {}^{12}N_{gs}\, e^-$	$0.92 \cdot 10^{-41}$ cm^2
$\nu_e\,{}^{12}C \rightarrow \nu_e\,{}^{12}C^*$	$0.45 \cdot 10^{-41}$ 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 will deliver ~ $1.9 \cdot 10^{22}$ neutrinos per year

Homogeneous detector

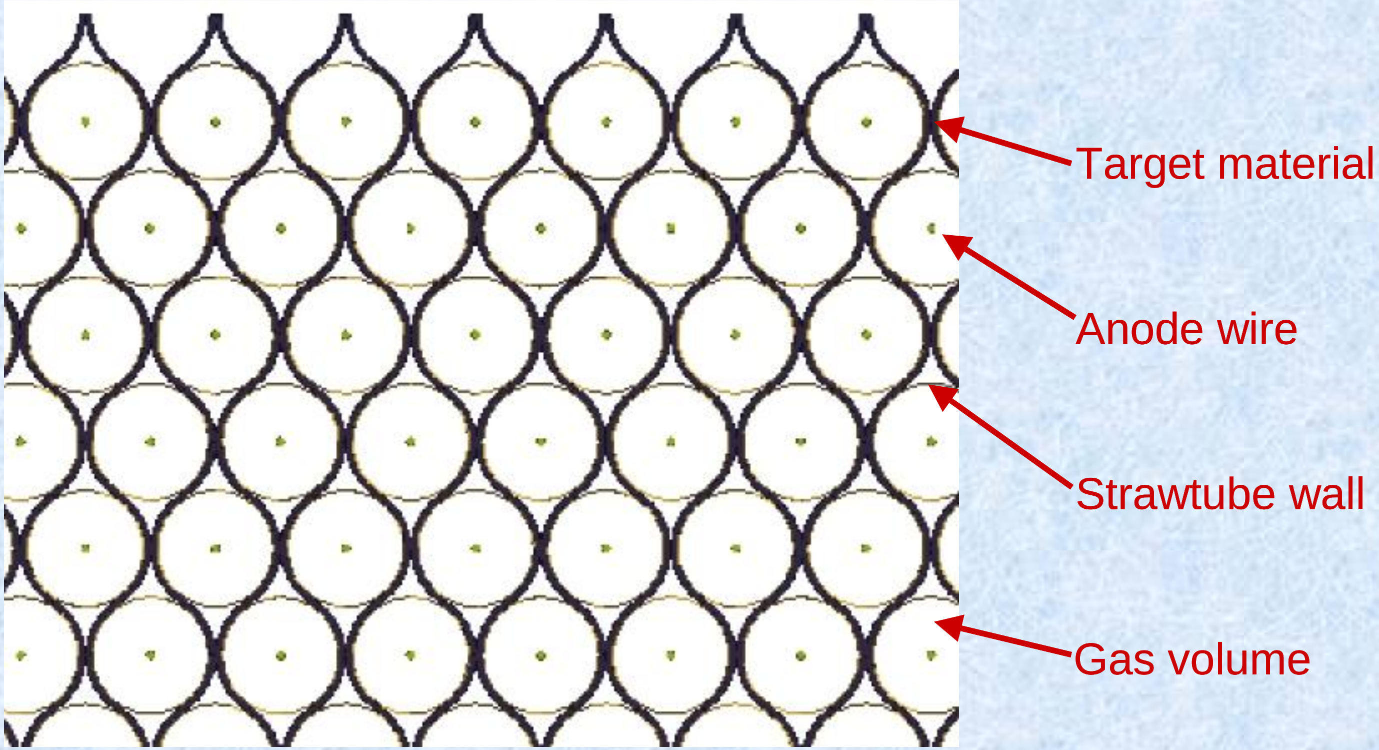
- 3.5m x 3.5m x 3.5m steel tank (43 m^3)
- 600 PMT's (8" Hamamatsu R5912)
  - → Fiducial volume 15.5 m^3 w/ 41% coverage
- 1260 events/yr $\upsilon_e + {}^{12}C \rightarrow {}^{12}N + e^-$ (mineral oil)
- ~450 events/yr $\upsilon_e + {}^{16}O \rightarrow {}^{16}F + e^-$ (water)
- Geant4 simulations
  - dE/E ~ 6%; dx ~ 15-20 cm;
  - dθ ~ 5° - 7°
- Current R&D
  - PMT arrangement
  - Neutron discrimination
  - Compact photosensors



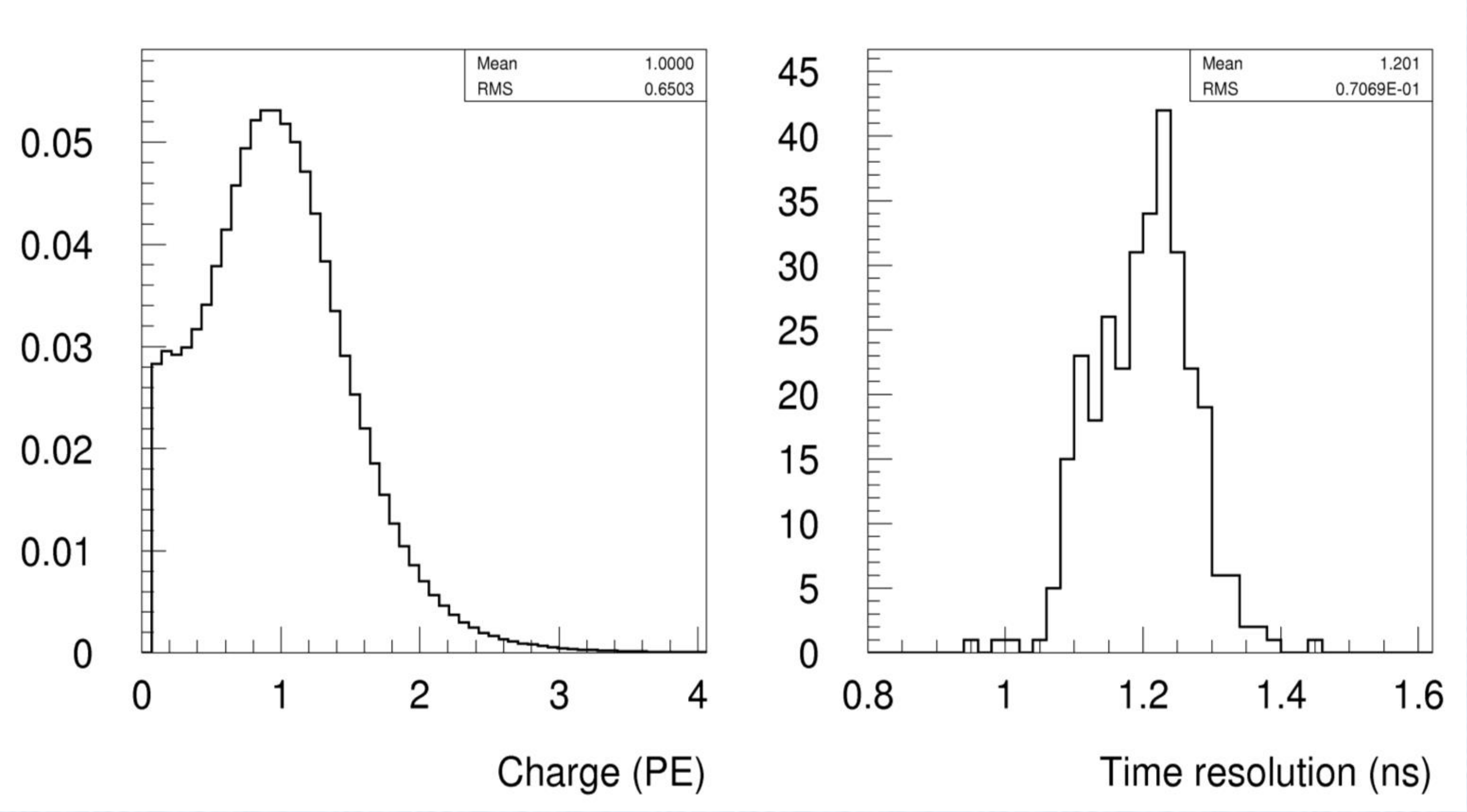


δE/E = 6.8% at 50 MeV
less if corrected for position

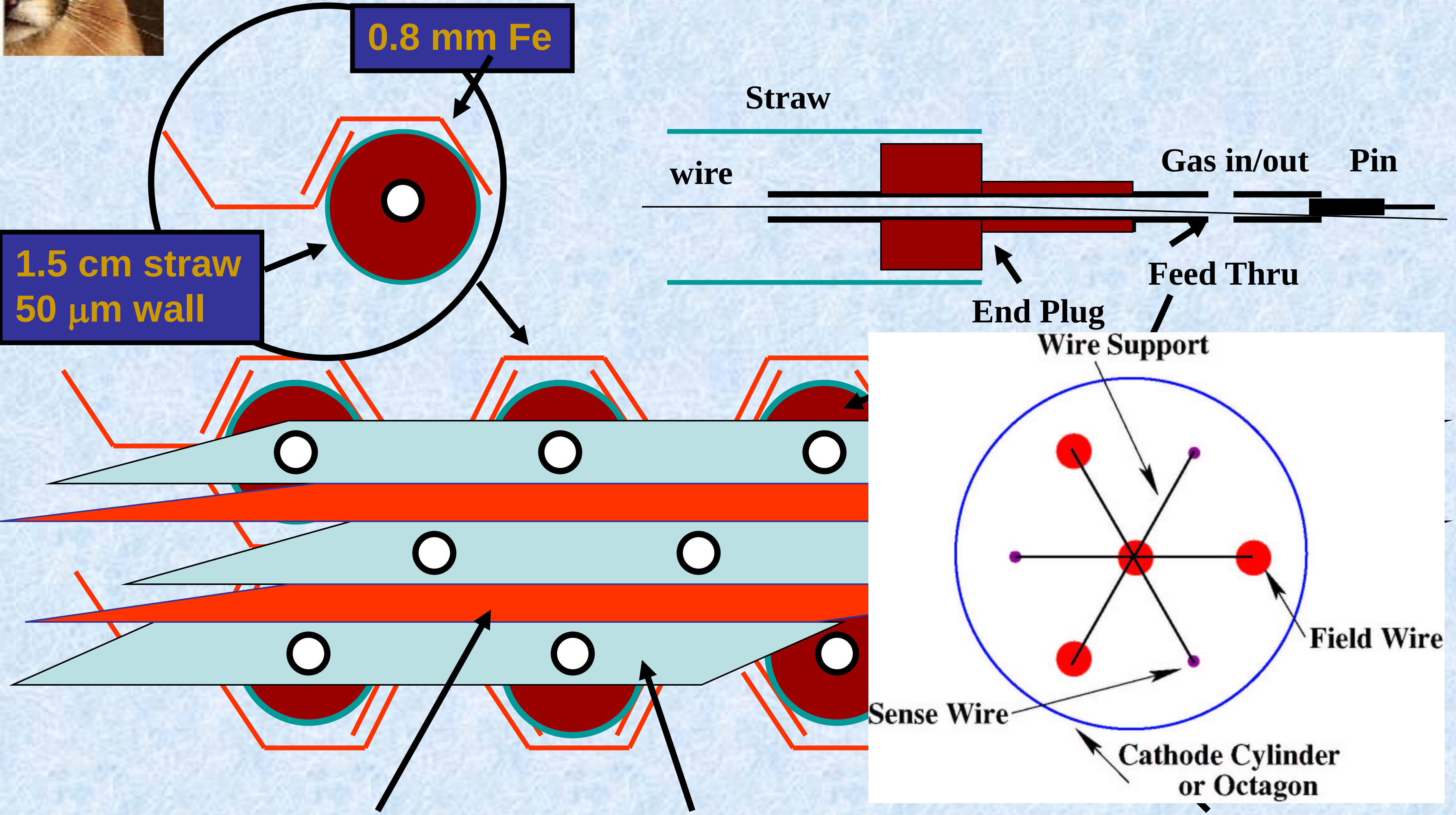
Cross Section of the Segmented Detector



PM Performance



Segmented Detector Section



0.8 mm Fe

1.5 cm straw
50 μm wall

Straw

wire

Gas in/out

Pin

Feed Thru

End Plug

Target Support

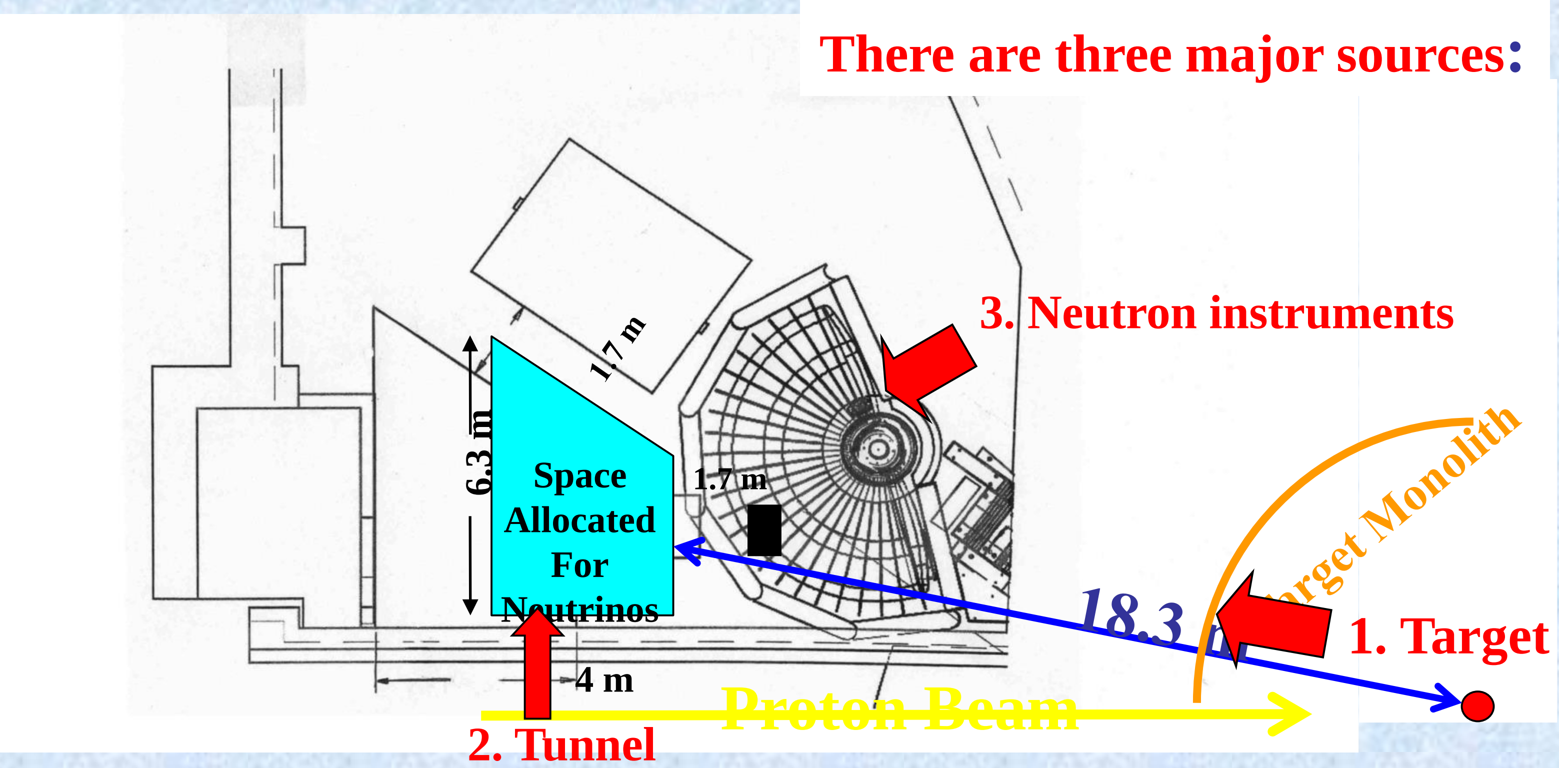
Straw Support

Corrugated Target

Straw

SNS Neutrons

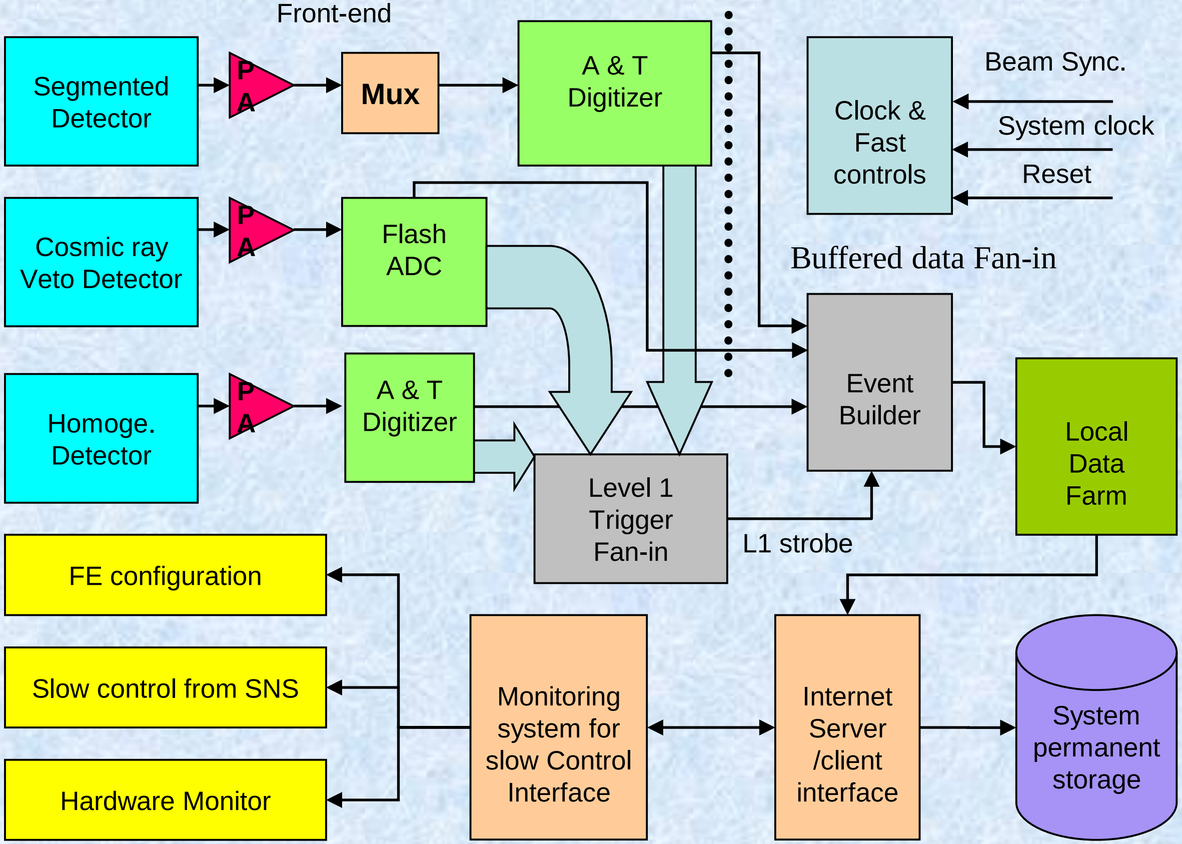
- Most dangerous B.G. is from SNS neutrons
- Analysis is complicated because of many uncertainties
- We know that neutron flux in the hall is small



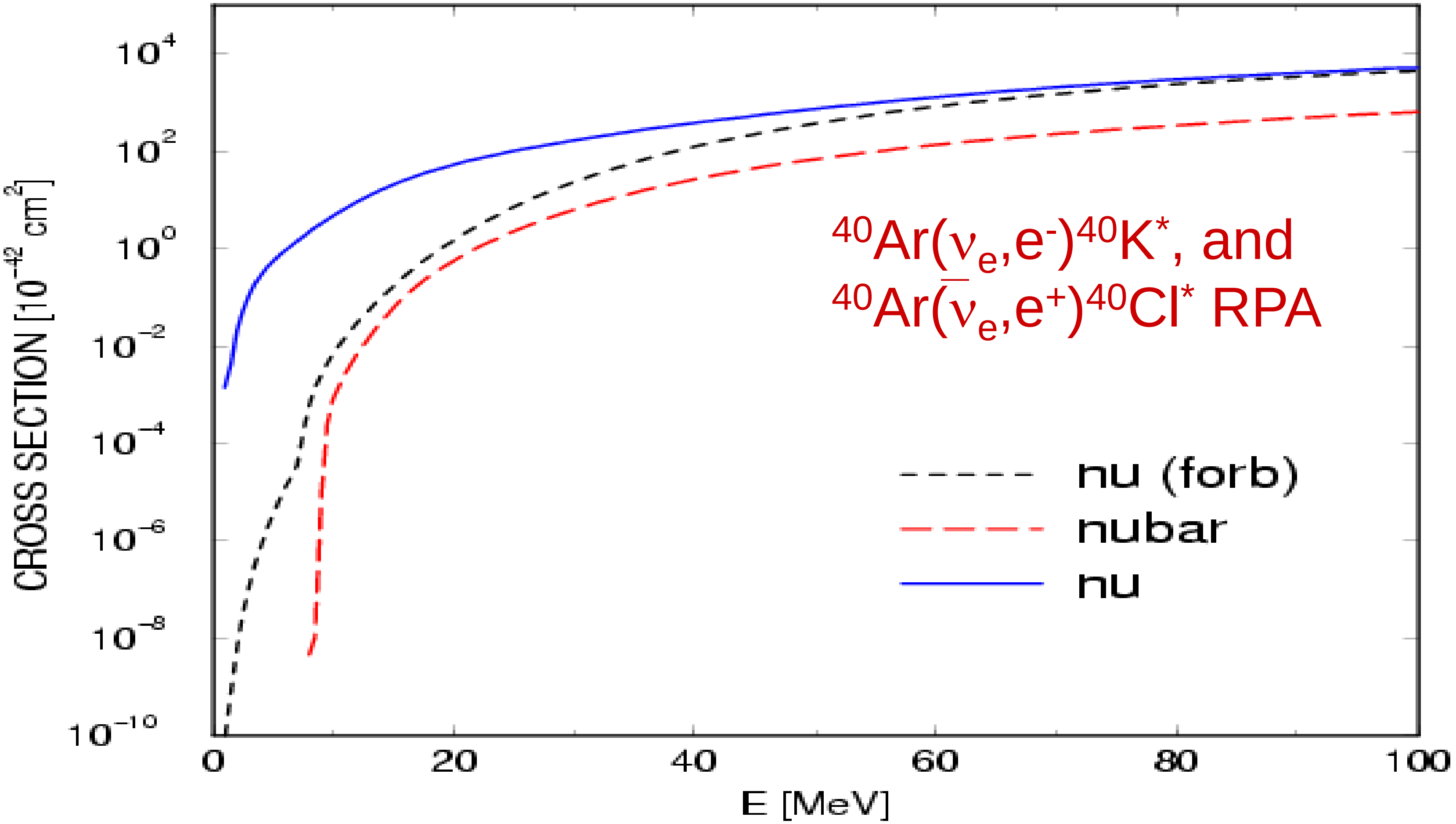
There are three major sources:

Block Diagram of Readout Electronics

- ~30,000 Straw Anodes
- Charge Division
- Multiplexed
- Amplitude and Time



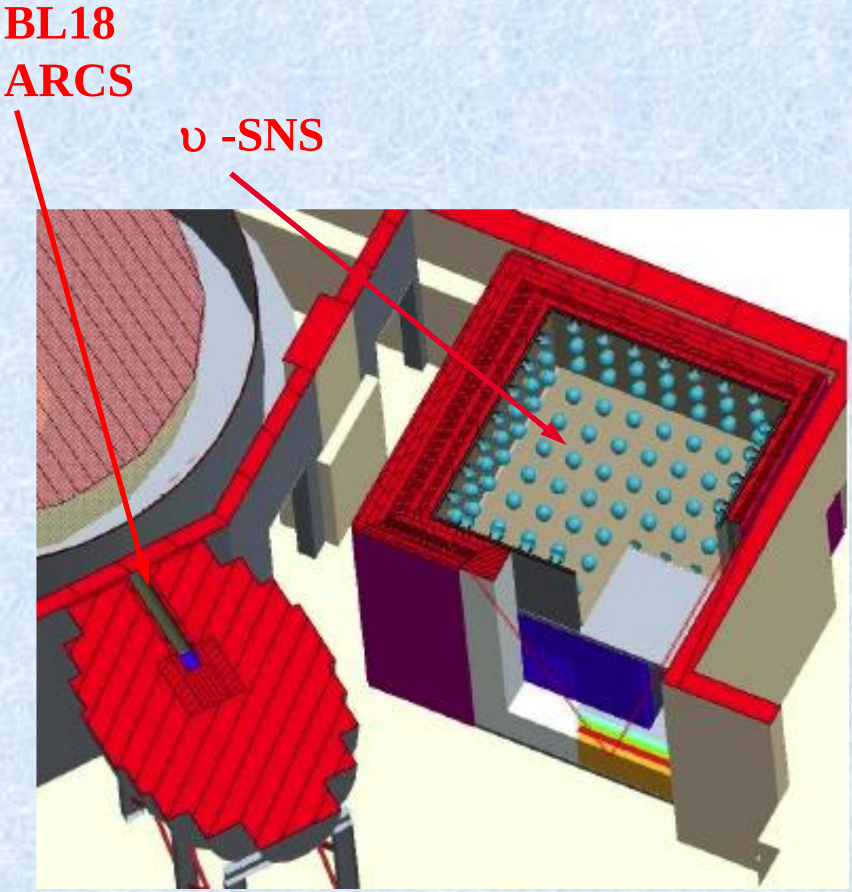
Let me now show some calculated σ for several cases of practical interest (ICARUS). These could be, therefore, used as <u>both</u> tests of calculations and basis for detector design etc.



$^{40}Ar(\nu_e,e^-)^{40}K^*$, and
$^{40}Ar(\bar{\nu}_e,e^+)^{40}Cl^*$ RPA

υ -SNS facility overview

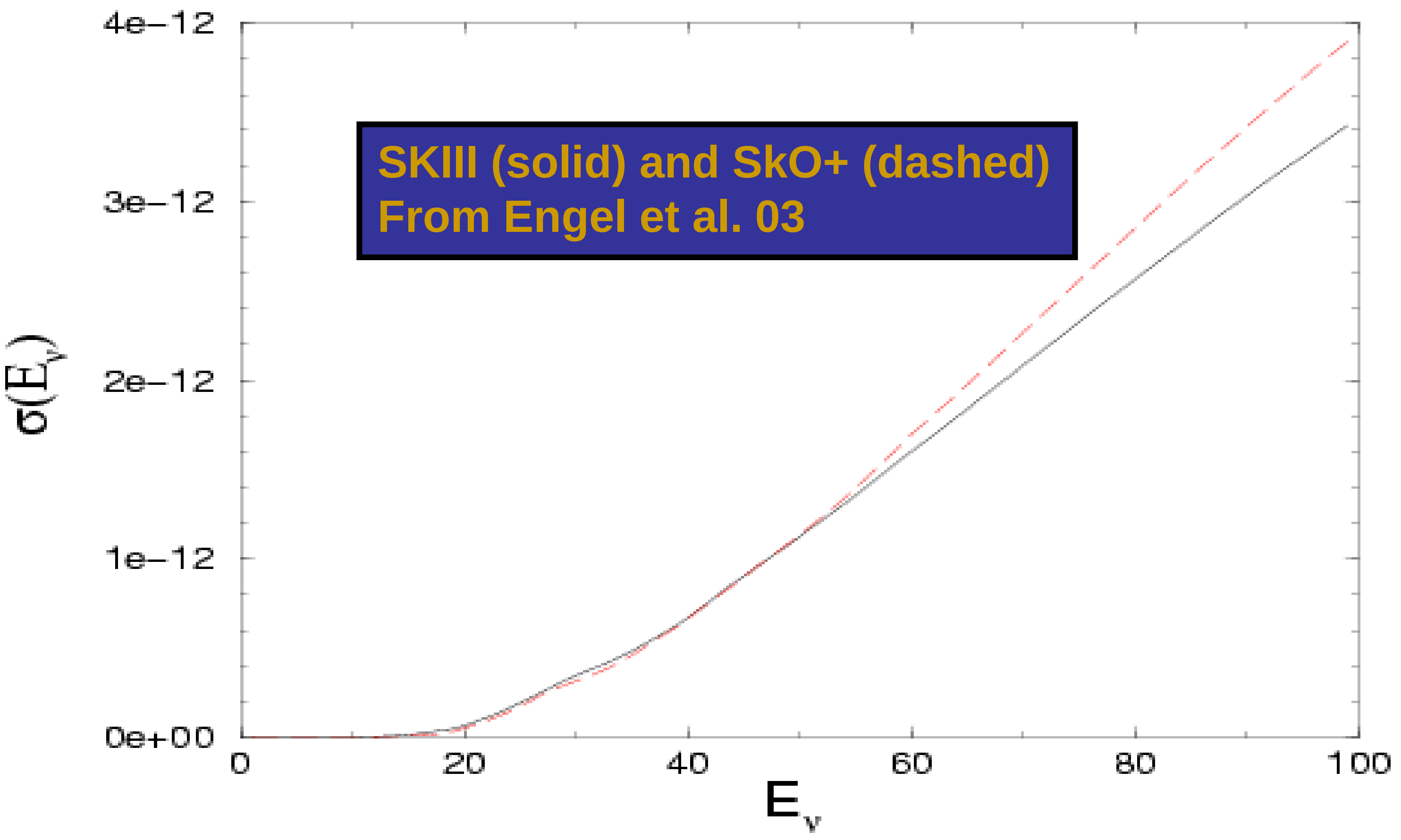
- Total volume = 130 m^3
  - 4.5m x 4.5m x 6.5m (high)
- heavily shielded facility (fast neutrons)
  - 60 m^3 steel ~ 470 tons
  - 1 m thick on top
  - 0.5 m thick on sides
- Active veto detector for cosmic rays
- ~70 m^3 Active
- Configured to allow 2 simultaneously operating detectors



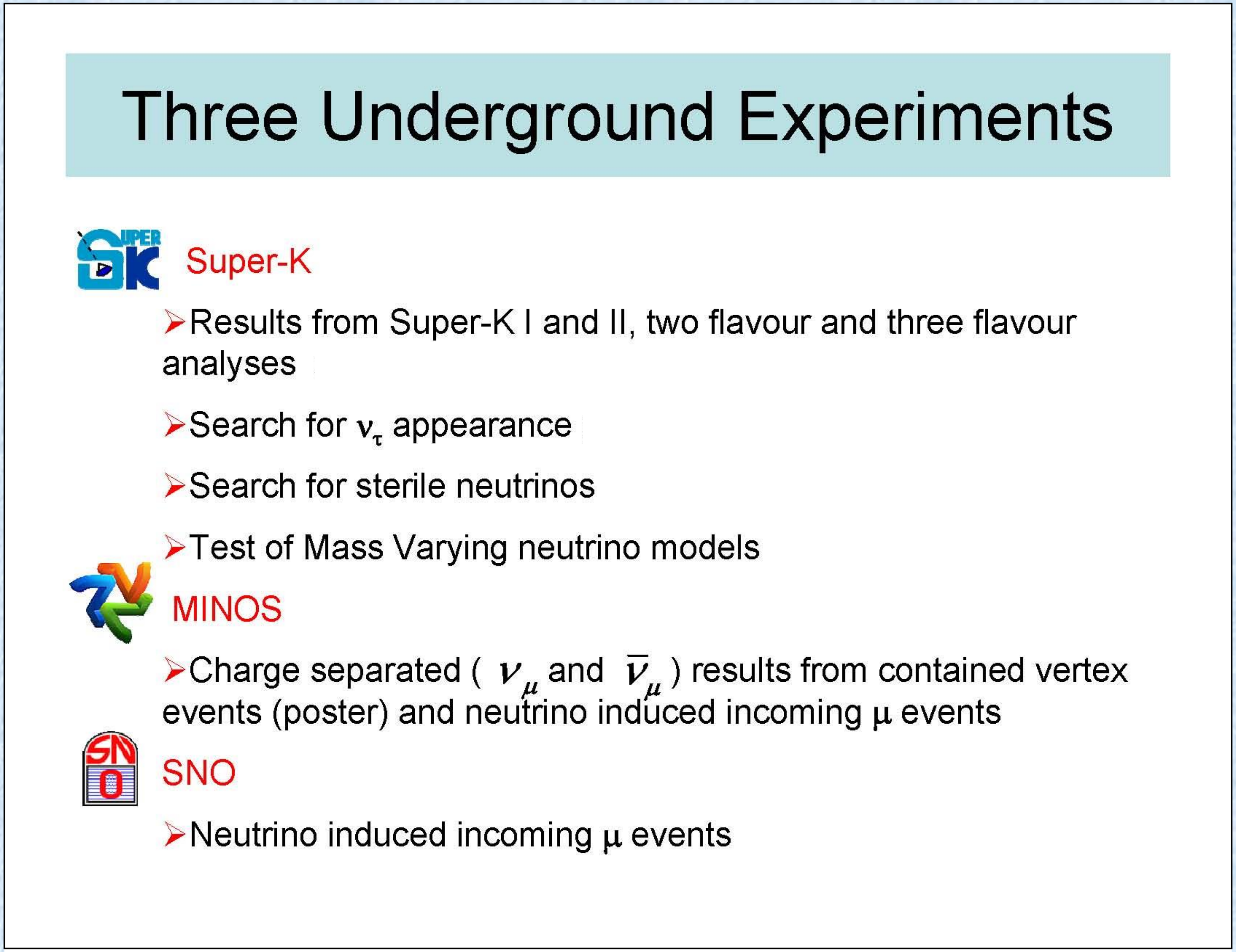
Additional Assumptions

- Monte Carlo Inputs (stated here for the record, won't discuss in detail)
  - Assume threshold for full discrimination 16 keVr
  - Liquid Xe (3 regions)
    - LXe Fiducial (after any x-y-z position cuts) majority of inner Xe / LXe Inner (surrounded by Teflon wall - low Kr content) / LXe Veto (Xe outer layer, 5 cm simulated)
  - Nuclear/Electron Recoil Quenching Factor Primary Light ($QF_{primary}$)
    - Zero Field (Conservative) $QF_p = 20\%$
    - High Field (5 keV/cm) $QF_p = 50\%$
      - Electron recoil primary light yield reduced to 38-36%@ 1-5 kV/cm, (vs zero field) due to ionization component no longer recombining
      - Nuclear recoil primary light yield ~90%@5 kV/cm (vs zero field)
  - Background Discrimination
    - Electron Recoil assumed 99.5% (1 in 200) above threshold of 8 keVee/16 keVr
    - Monte Carlo results focus on rates for region 8-16 keVee (16-32 keVr)
    - External 5 cm LXe veto (Assumed 50 keVee threshold)

CC Cross Section for ^{208}Pb


SKIII (solid) and SkO+ (dashed)
From Engel et al. 03

Examples of Modern Neutrino Experiments



Three Underground Experiments

Super-K

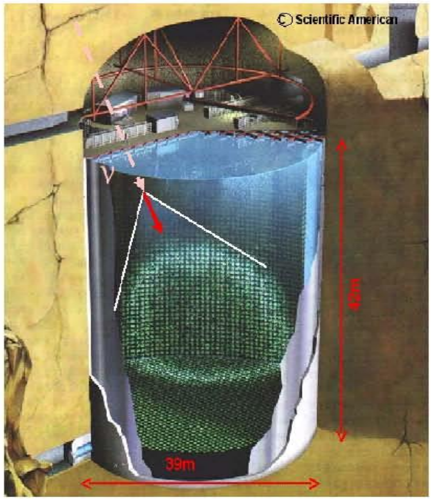
- Results from Super-K I and II, two flavour and three flavour analyses
- Search for ν_τ appearance
- Search for sterile neutrinos
- Test of Mass Varying neutrino models

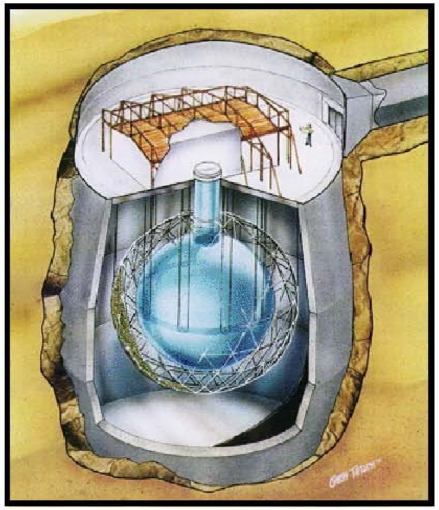
MINOS

- Charge separated (ν_μ and $\bar{\nu}_\mu$) results from contained vertex events (poster) and neutrino induced incoming μ events

SNO

- Neutrino induced incoming μ events





Super K

MINOS

SNO

Experiment and Theory for CC Total Cross section agree for ^{12}C

Exp.results (in $10^{-42}cm^2$):

9.4 ± 0.4 ± 0.8 (KARMEN ν_e, 98, DAR)

8.9 ± 0.3 ± 0.9 (LSND ν_e, 01, DAR)

56. ± 8 ± 10 (LSND ν_μ, 02, DIF)

10.8 ± 0.9 ± 0.8 (KARMEN, NC, DAR)

Calculations:

9.3 , 63, 10.5 (CRPA 96)

8.8 , 60.4, 9.8 (shell model, 78)

9.2 , 62.9, 9.9 (EPT , 88)

CC cross section on Pb

- Lead based detectors are one of the υ-SNS Targets
- No experimental data → detector design relies on calculated cross sections.
- Shell model treatment is not possible so various forms of RPA and other approximations are used

$(10^{-40}\ \text{cm}^2)$

For DAR: Kolbe & Langanke, [01] 36

Suzuki & Sagawa, [03] 32

For FD:

T=6 MeV	8 MeV	10 MeV	
14	25	35	Volpe [02]
11	25	45	Kolbe [01]