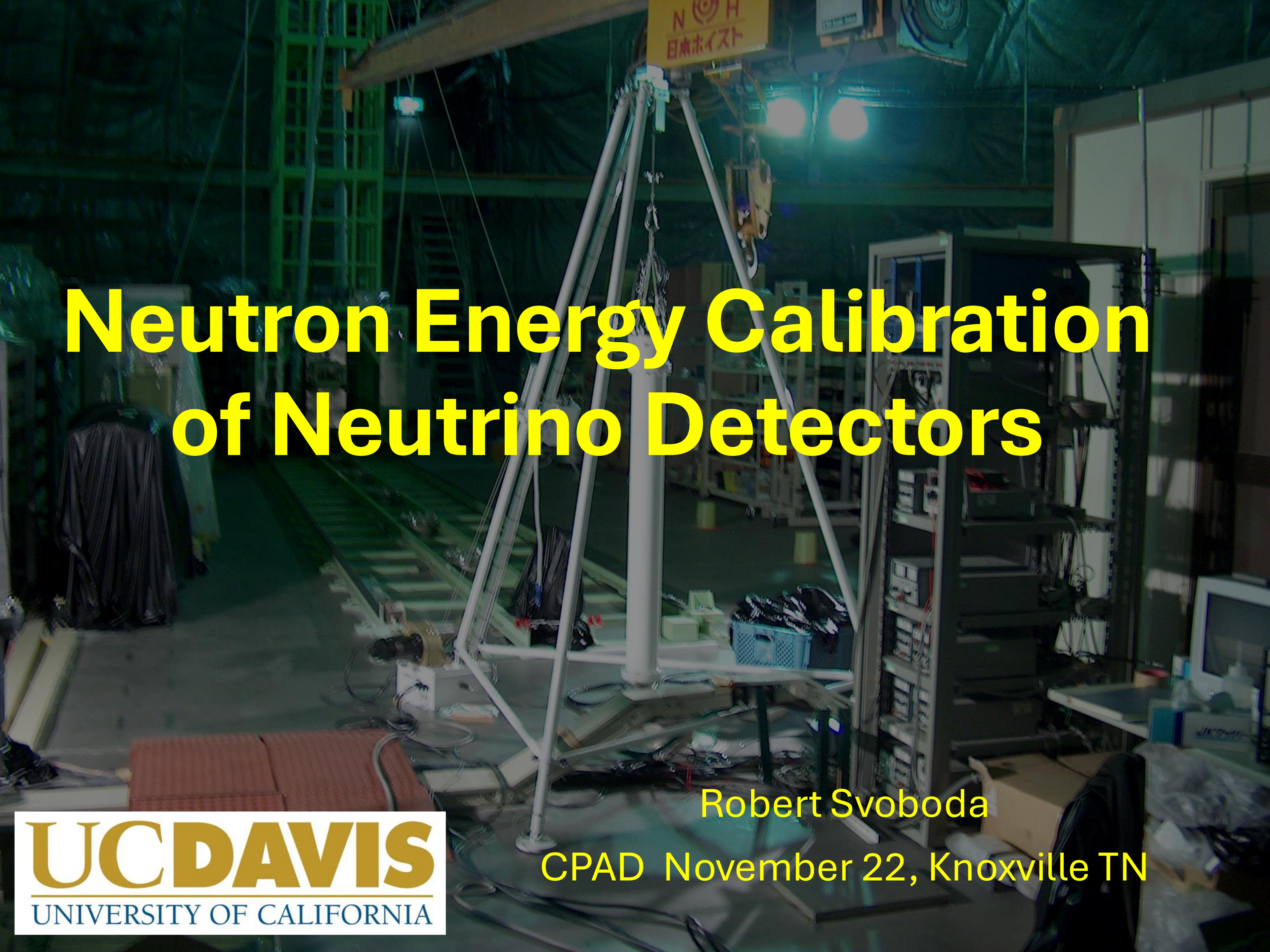

Neutron Energy Calibration of Neutrino Detectors

Robert Svoboda

CPAD November 22, Knoxville TN

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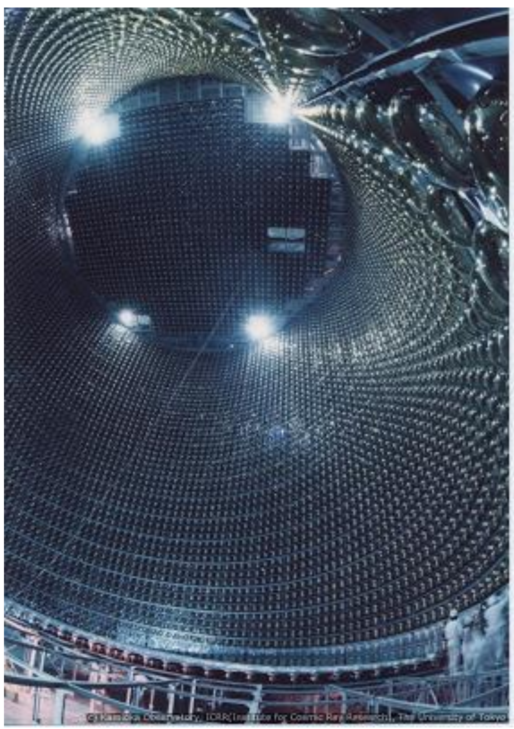
A Tale of Two Detectors

...and two related problems

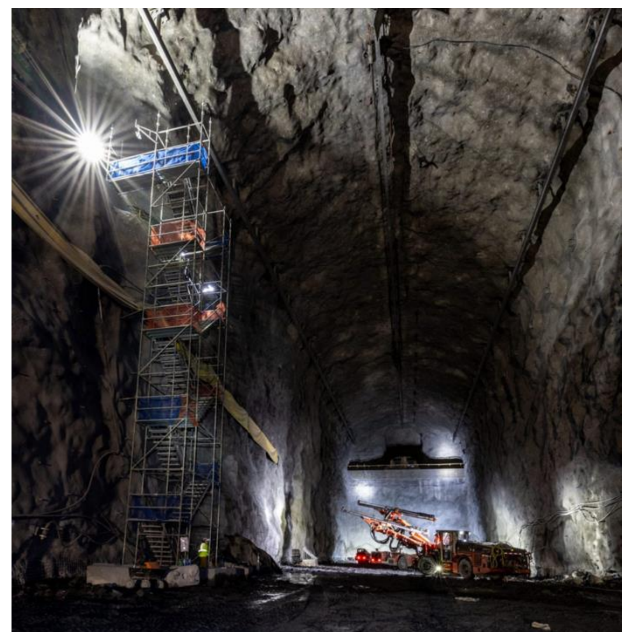
- **Super-Kamiokande**

How to get the absolute energy scale to better than 1% in order to solve the solar neutrino problem?



- **DUNE Far Detector**

How to get the absolute energy scale to better than 2% in order to discover CP violation?



A Tale of Two Detectors

...and two related problems

- **Super-Kamiokande**

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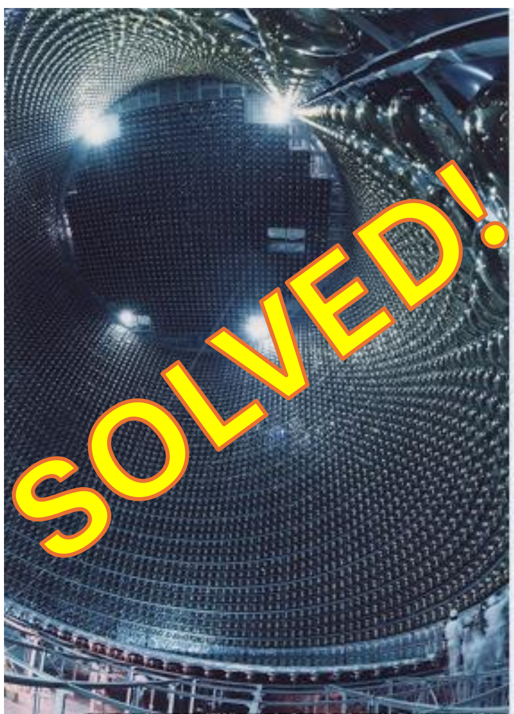
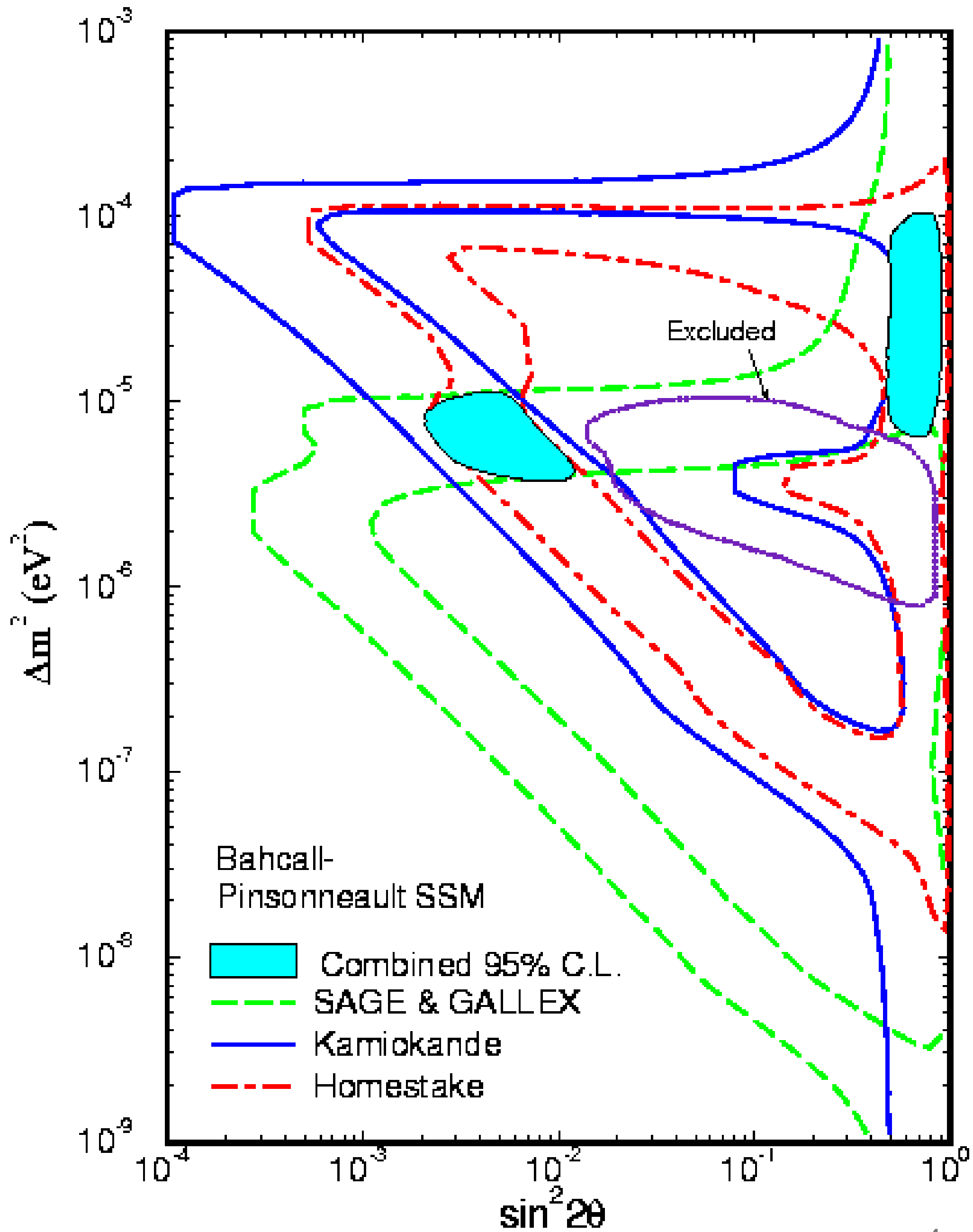


- **DUNE Far Detector**

How to get the absolute energy scale to better than 2% in order to discover CP violation?

Around 1997 when solar neutrino data from the four running experiments was combined there were two regions of oscillation parameters that would solve the “Solar Neutrino Problem”



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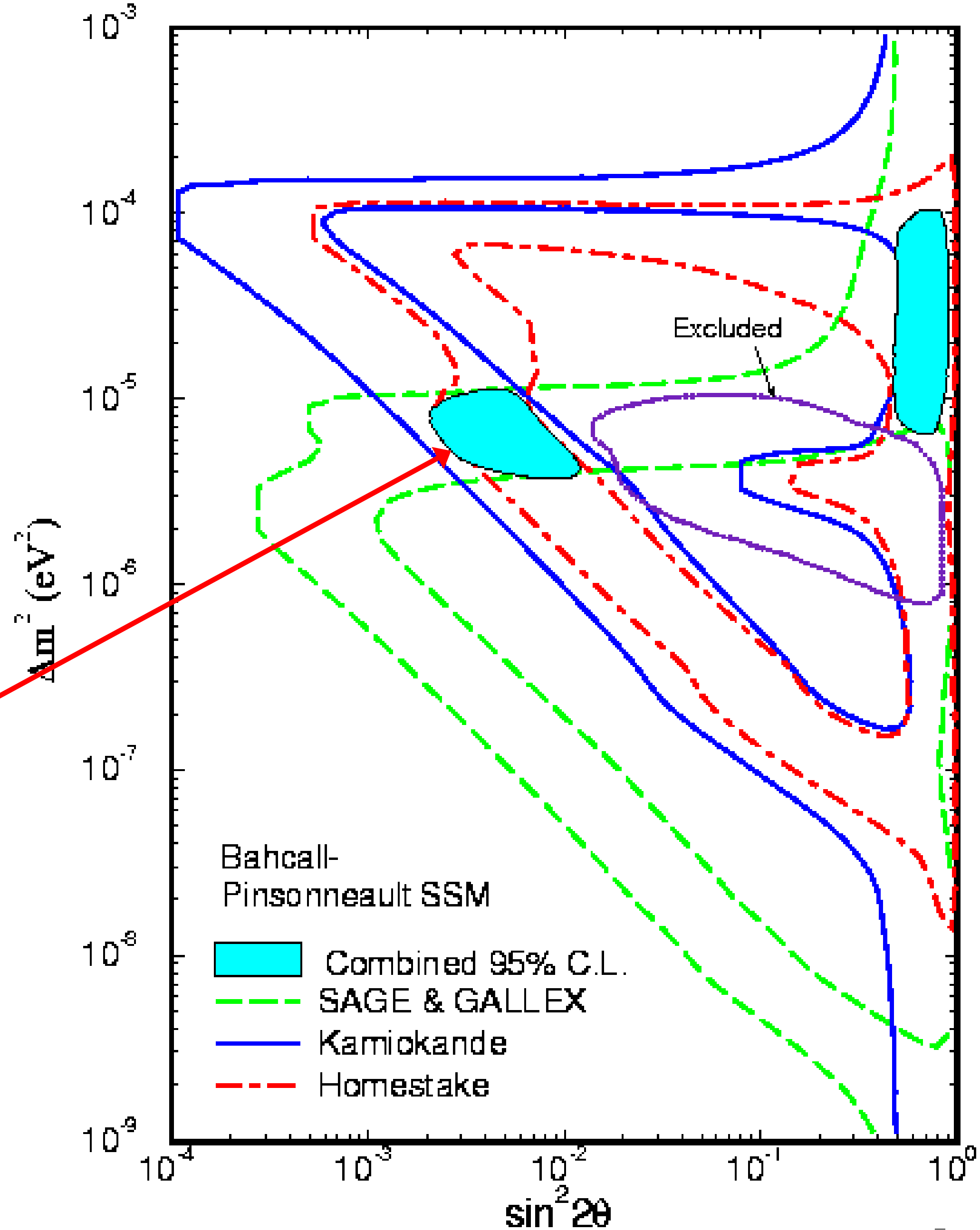
Around 1997 when solar neutrino data from the four running experiments was combined there were two regions of oscillation parameters that would solve the "Solar Neutrino Problem"

"SMA" region



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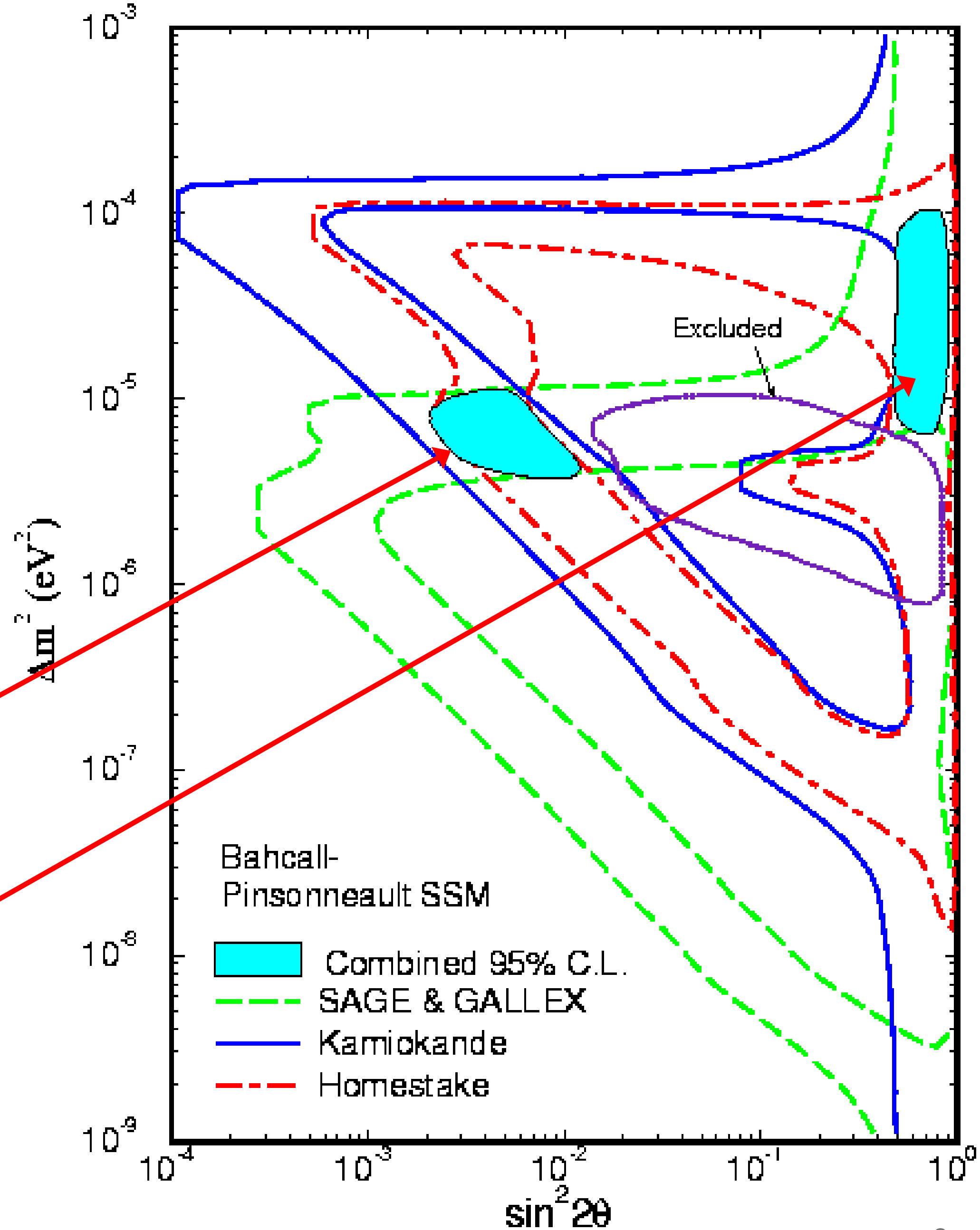
Around 1997 when solar neutrino data from the four running experiments was combined there were two regions of oscillation parameters that would solve the "Solar Neutrino Problem"

"SMA" region

"LMA" region



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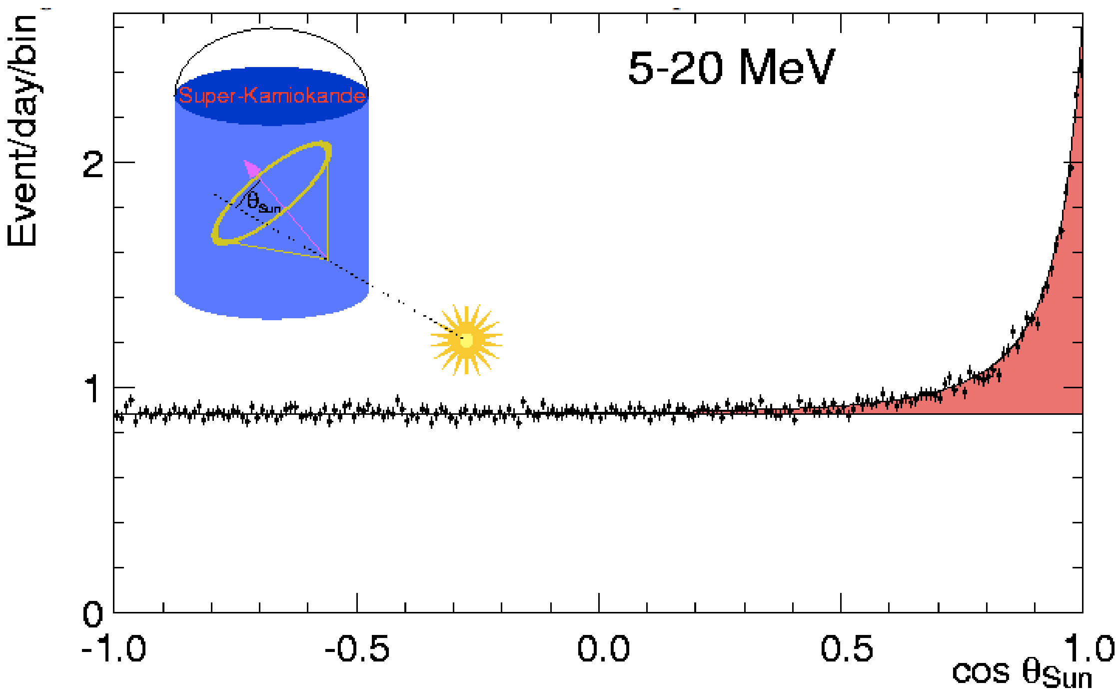
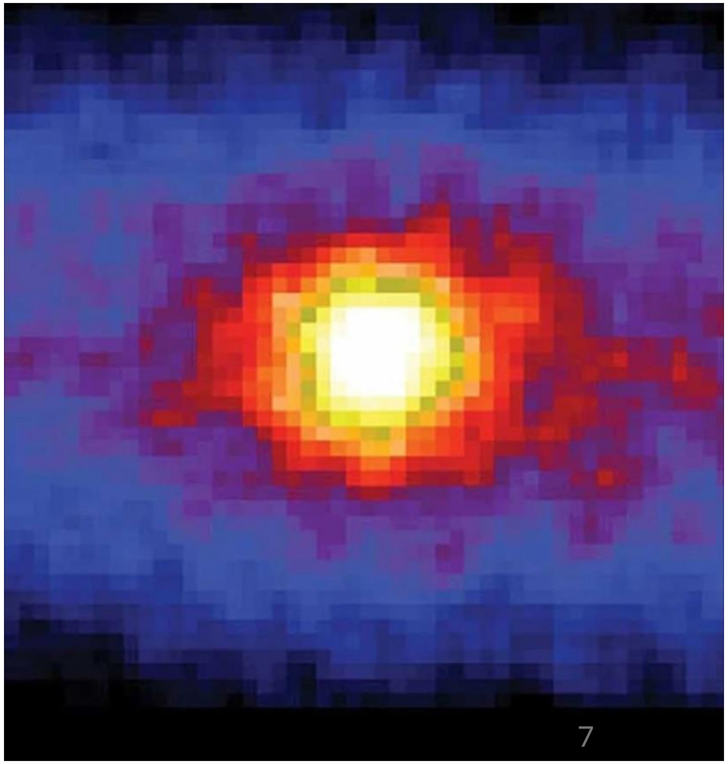
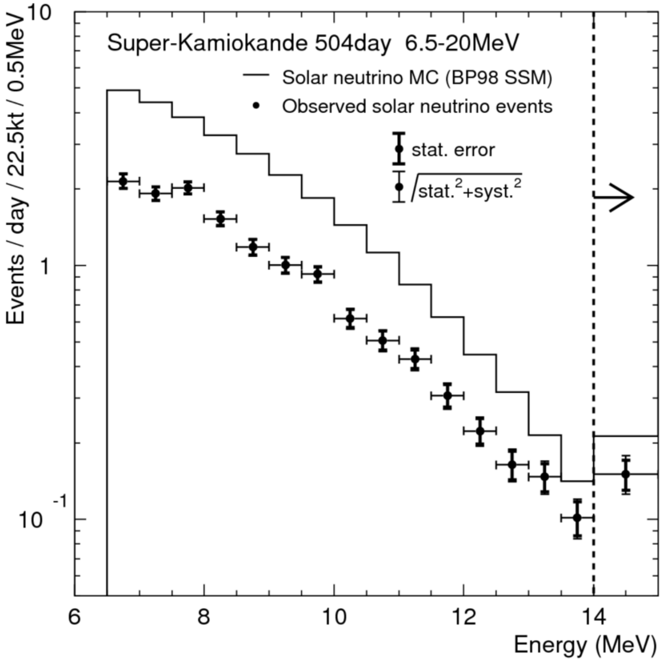
Super-Kamiokande was designed to have unprecedented statistics for solar neutrinos and should be able to choose between these two regions **IF** the energy scale was understood to unprecedent precision





IF the energy scale was understood to unprecedent precision

$$\nu_e e^- \longrightarrow \nu_e e^-$$



Super-Kamiokande uses neutrino electron scattering to detect solar neutrinos.

This cross section has a flat distribution in the energy of the outgoing electron, which tends to wash out energy spectrum measurements.

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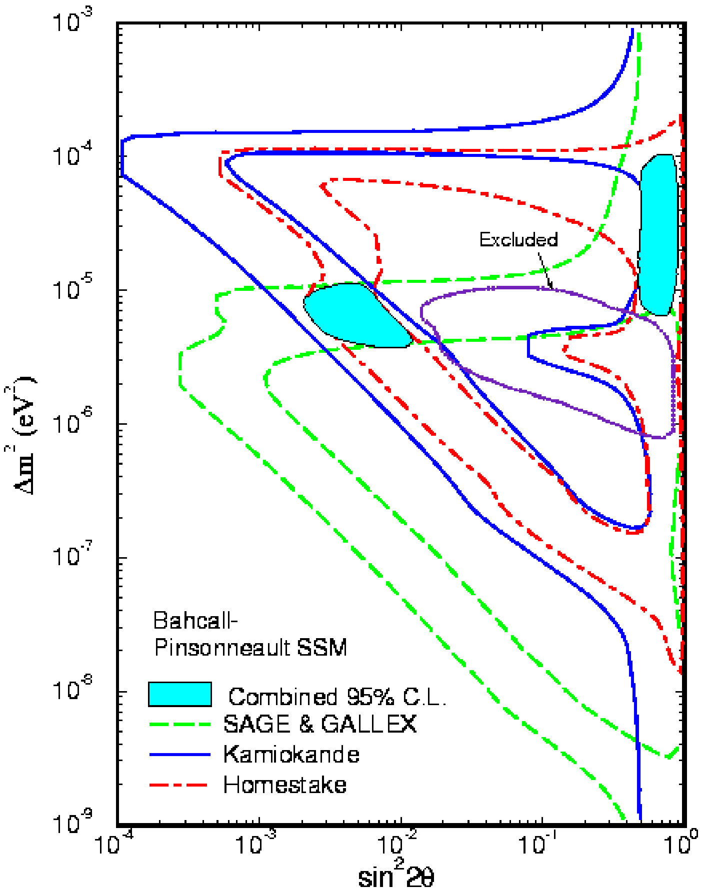
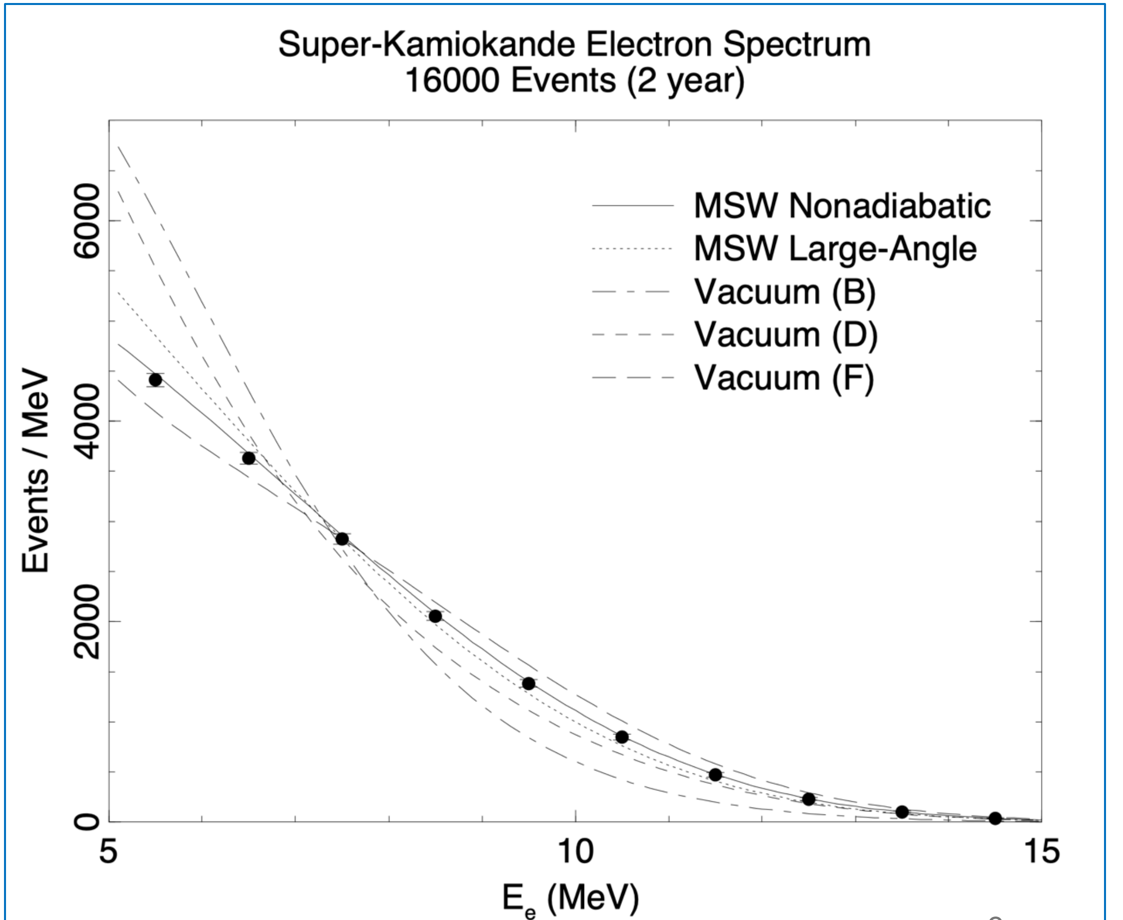
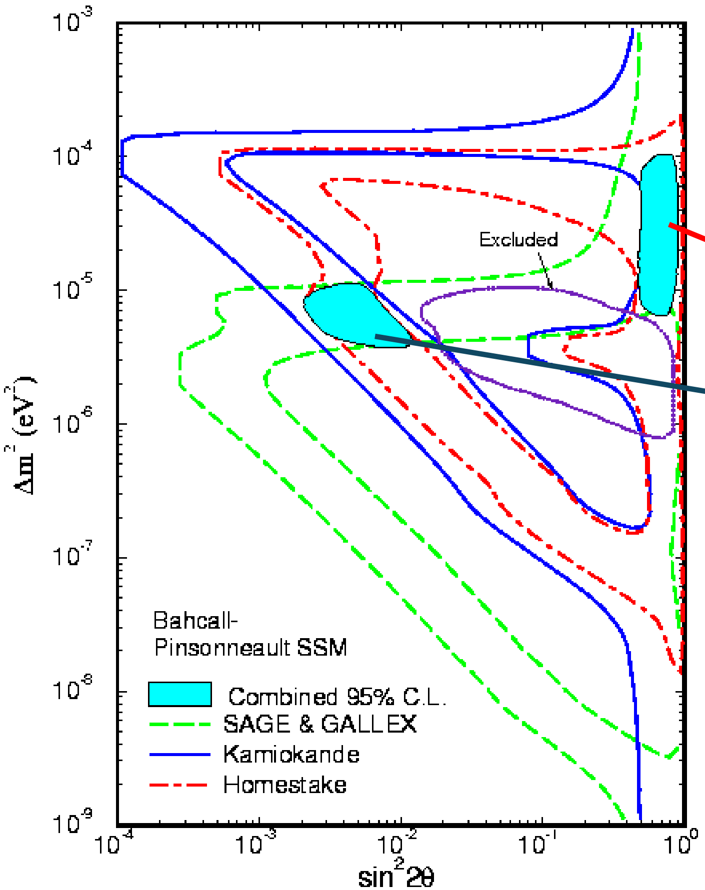
IF the energy scale was understood to unprecedent precision

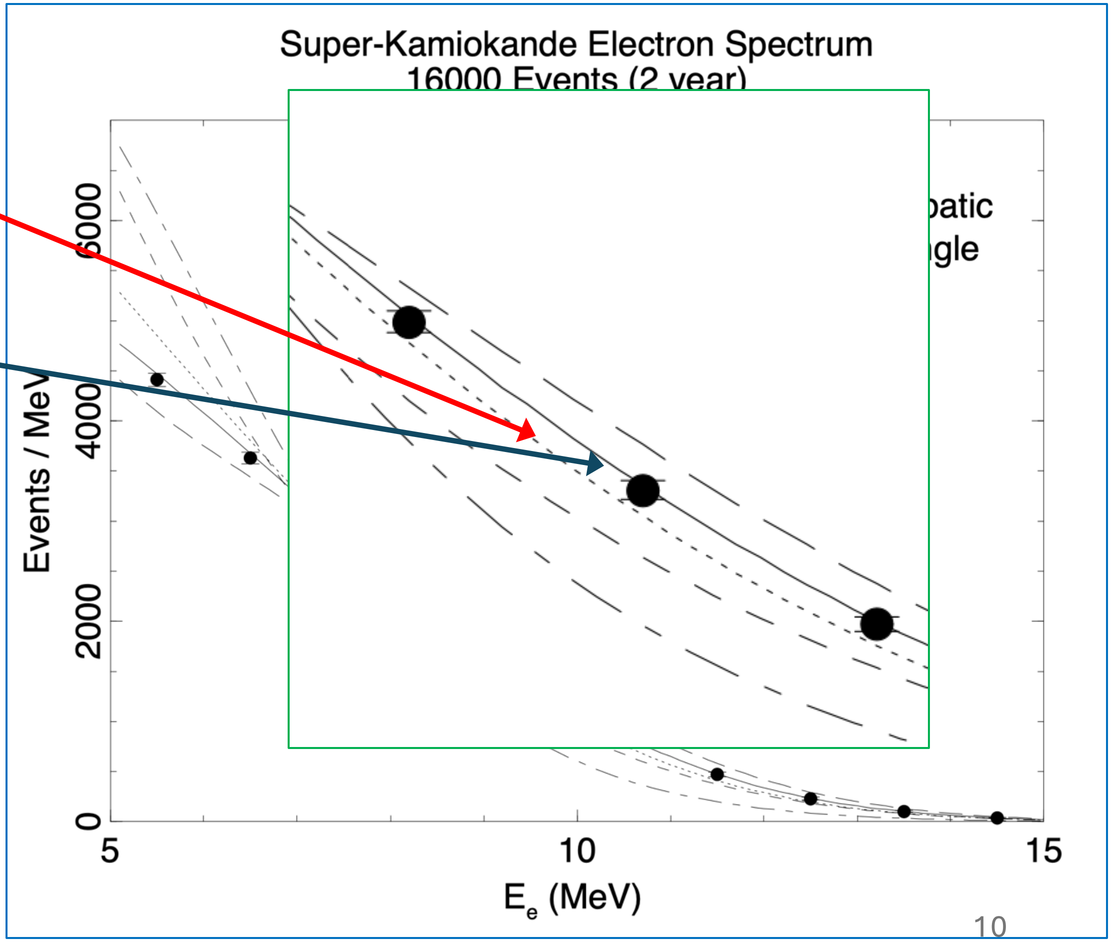




IF the energy scale was understood to unprecedent precision

<1%





Radioactive Source

Ni-Cf source composed of a Californium neutron source surrounded by nickel wire immersed in a water moderator. An ion chamber provideed a trigger signal.

Easy to deploy, but significant systematic uncertainties due to shadowing and gamma attenuation inside the device

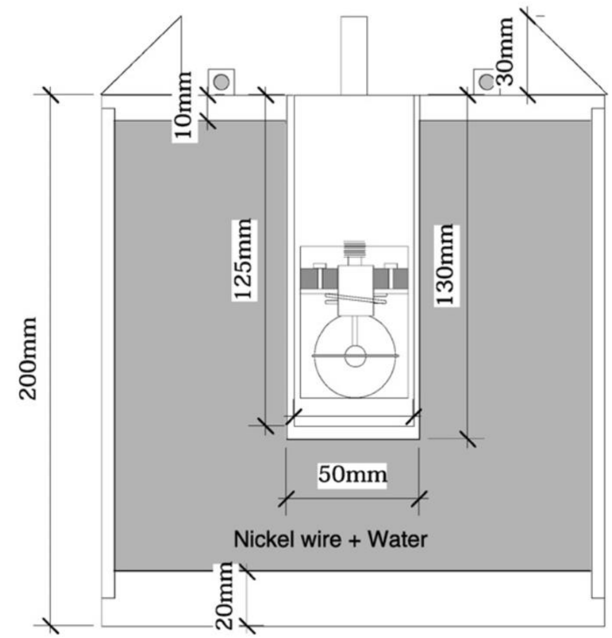


Fig. 43. Configuration of Cf-Ni *gamma*-ray calibration source. The spherical object in the middle of the source is the fission counter.

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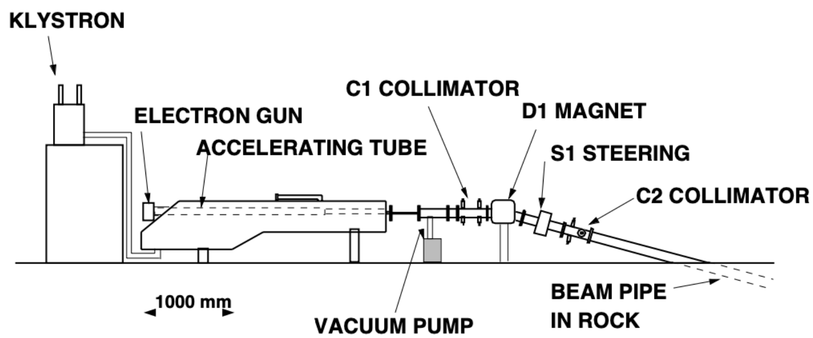
Electron LINAC

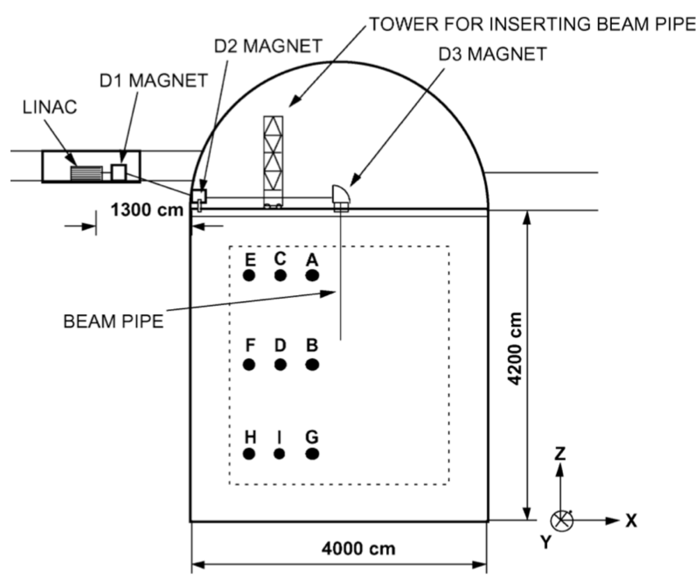
This got 1% energy scale uncertainty for a few positions for electrons in fixed directions

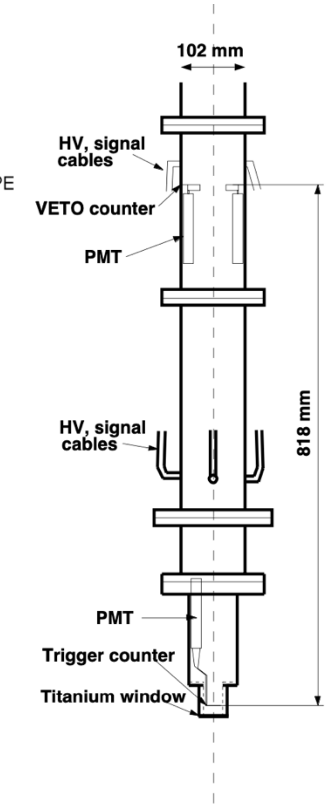
Very restricted in tank locations accessible

Significant corrections for shadowing near the tip of the beam pipe

Getting a few points could take a week or more of downtime







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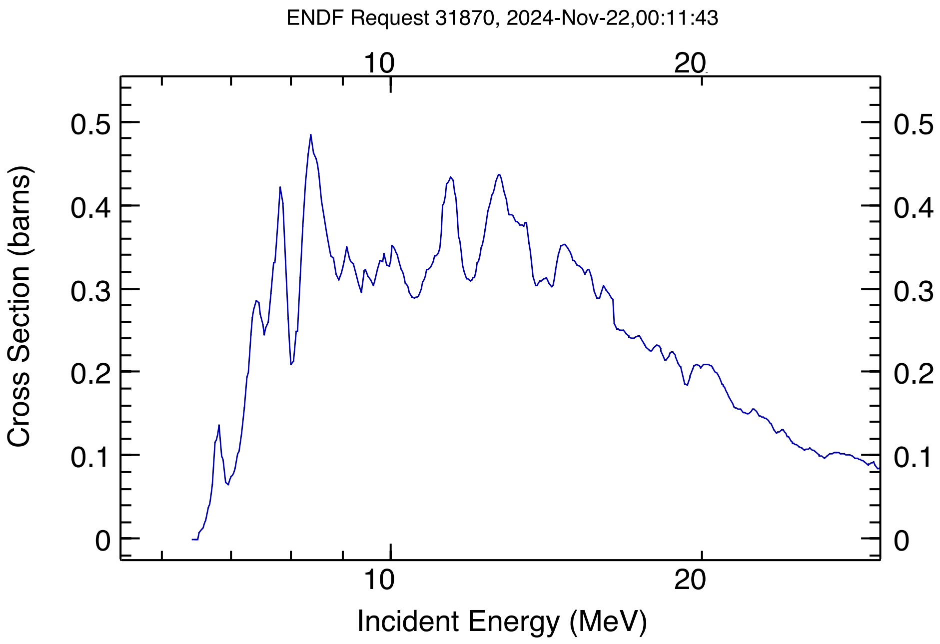
Neutron fusion on Oxygen

$n + {}^{16}O \rightarrow {}^{16}N$ Q=-2.350 MeV endothermic



Requires a neutron above this energy for this to happen

${}^{16}N \rightarrow {}^{16}O + e^{-} + \bar{\nu}_e$ Q=10.419 This is exothermic!

$t_{1/2}$ = 7.13 seconds

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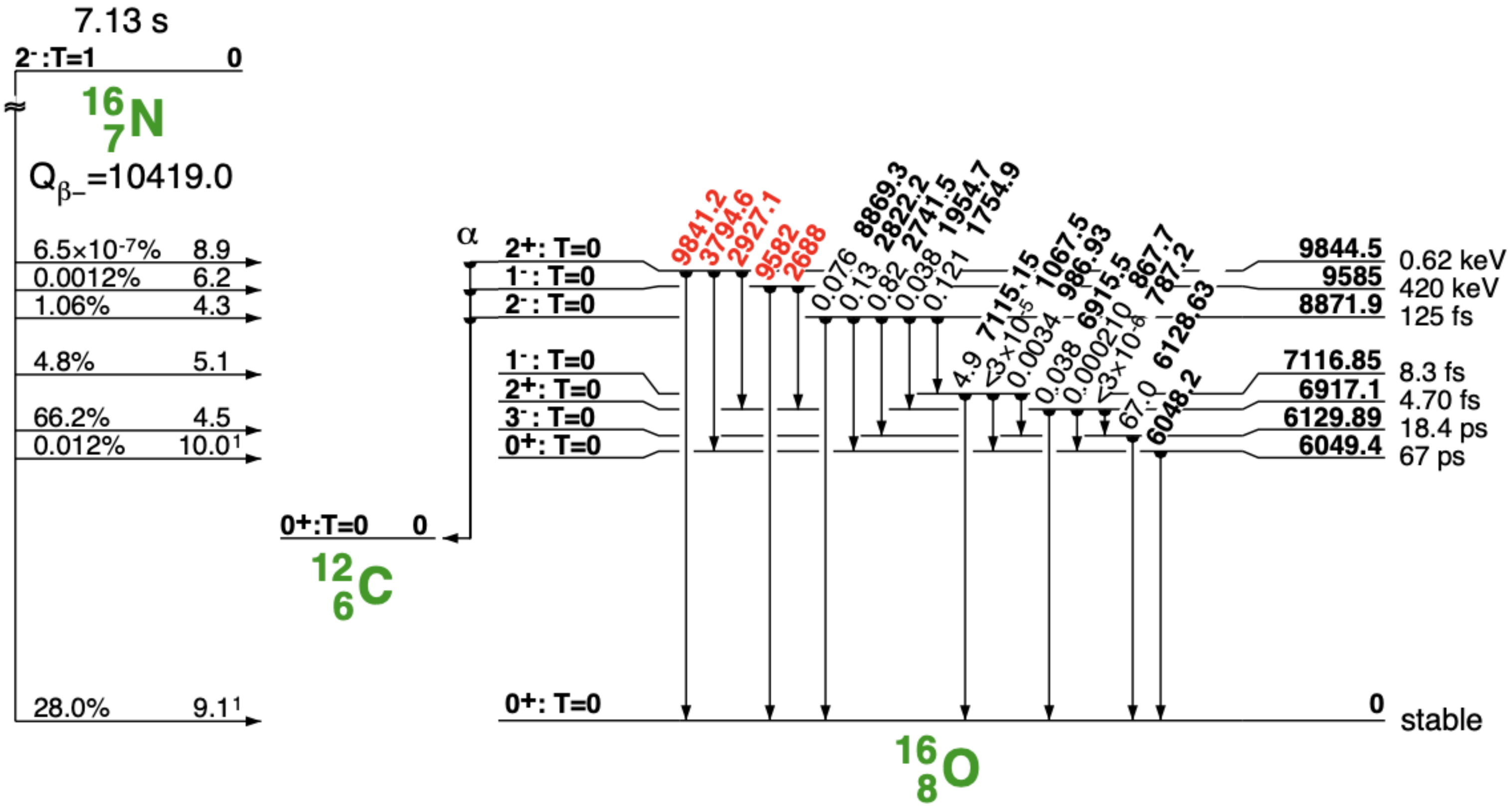
Nitrogen-16 beta decay

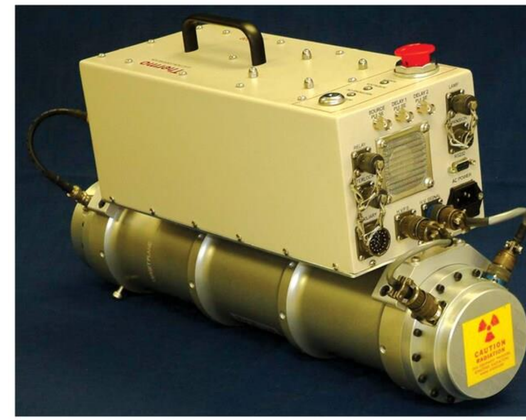


Maybe we could get a small pulsed energetic neutron device to make 16-N then move it out of the way and watch the decays over 15-20 seconds?

- No shadowing systematics
- Huge amount of data quickly
- Can be done frequently
- Can be done in many locations

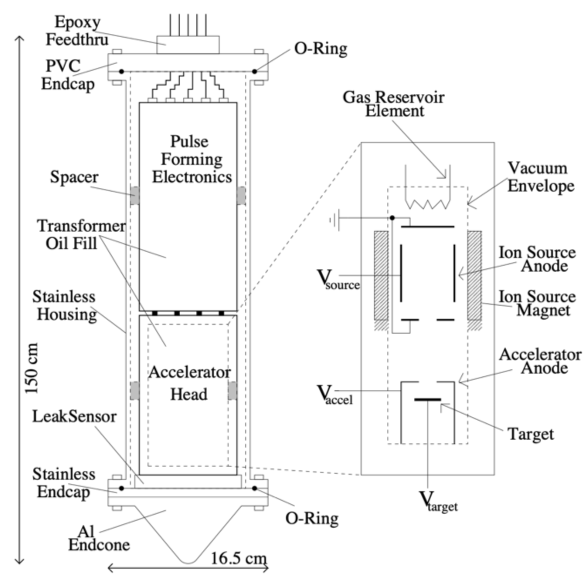
Deuterium-Tritium (DT) generators

$^{2}H + {}^{3}H \rightarrow {}^{4}He + n \qquad E_n = 14.1\ \text{MeV}$

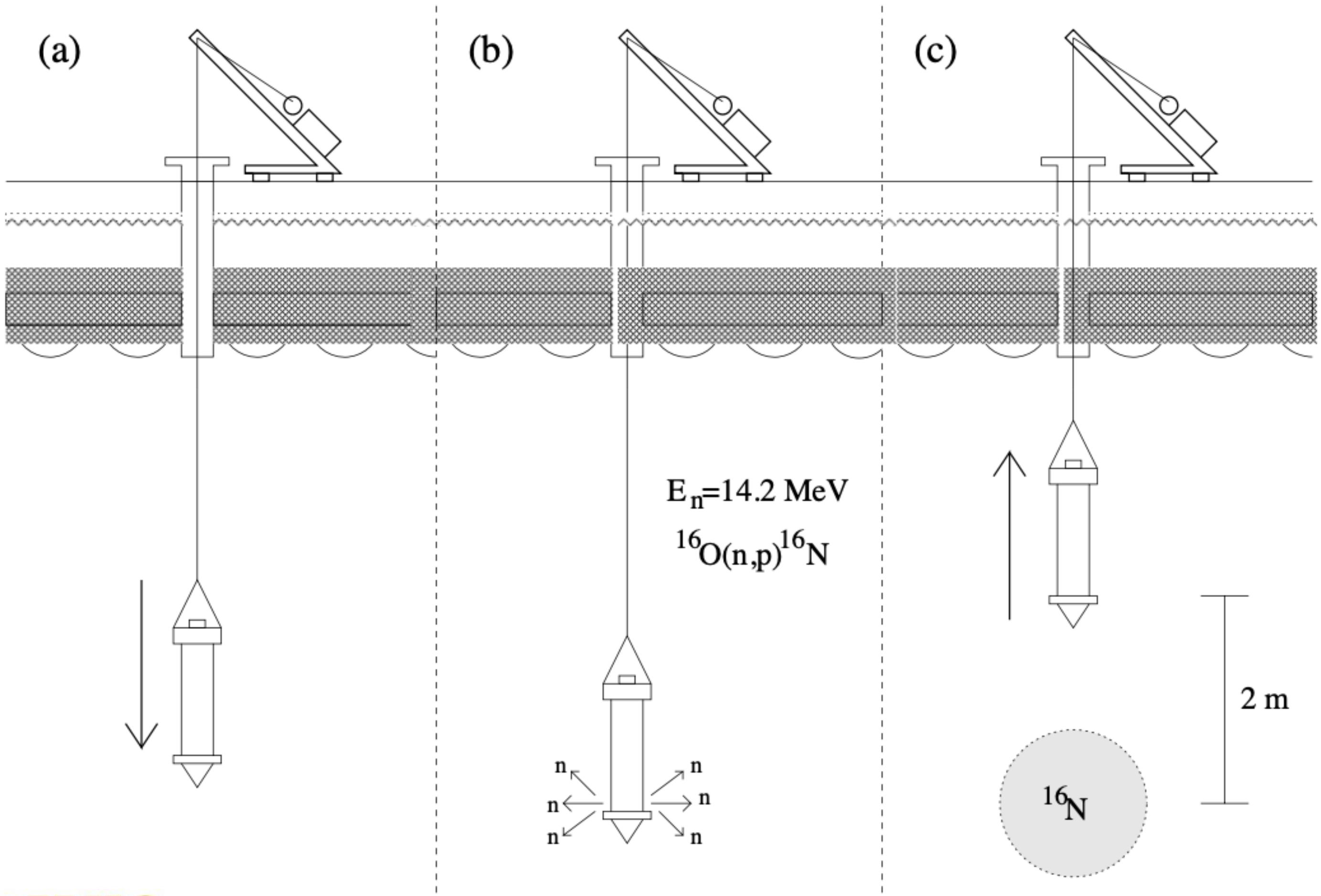


Commercial devices were available to do this!

...just have to make them operate underwater under computer control



Deuterium-Tritium (DT) generators



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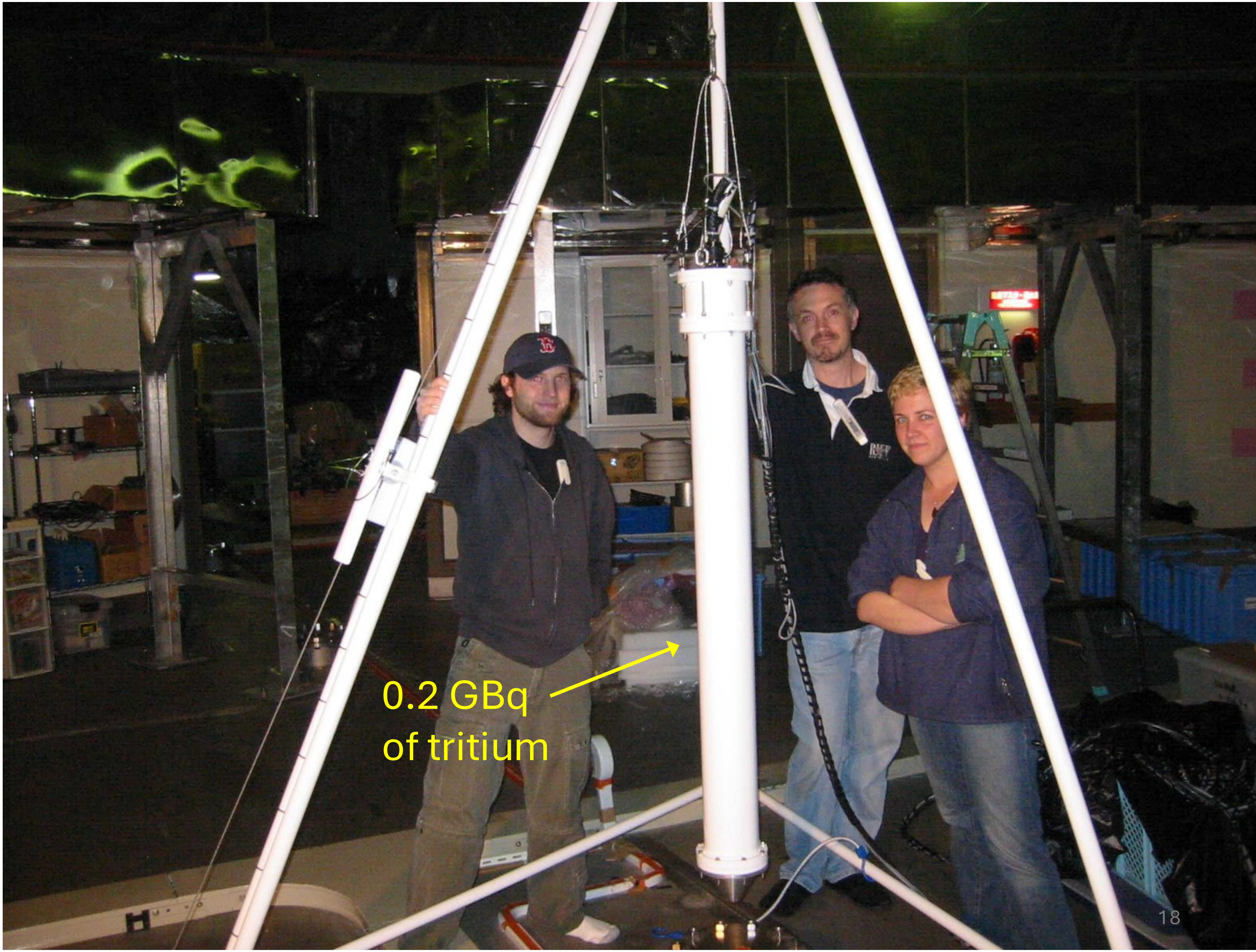
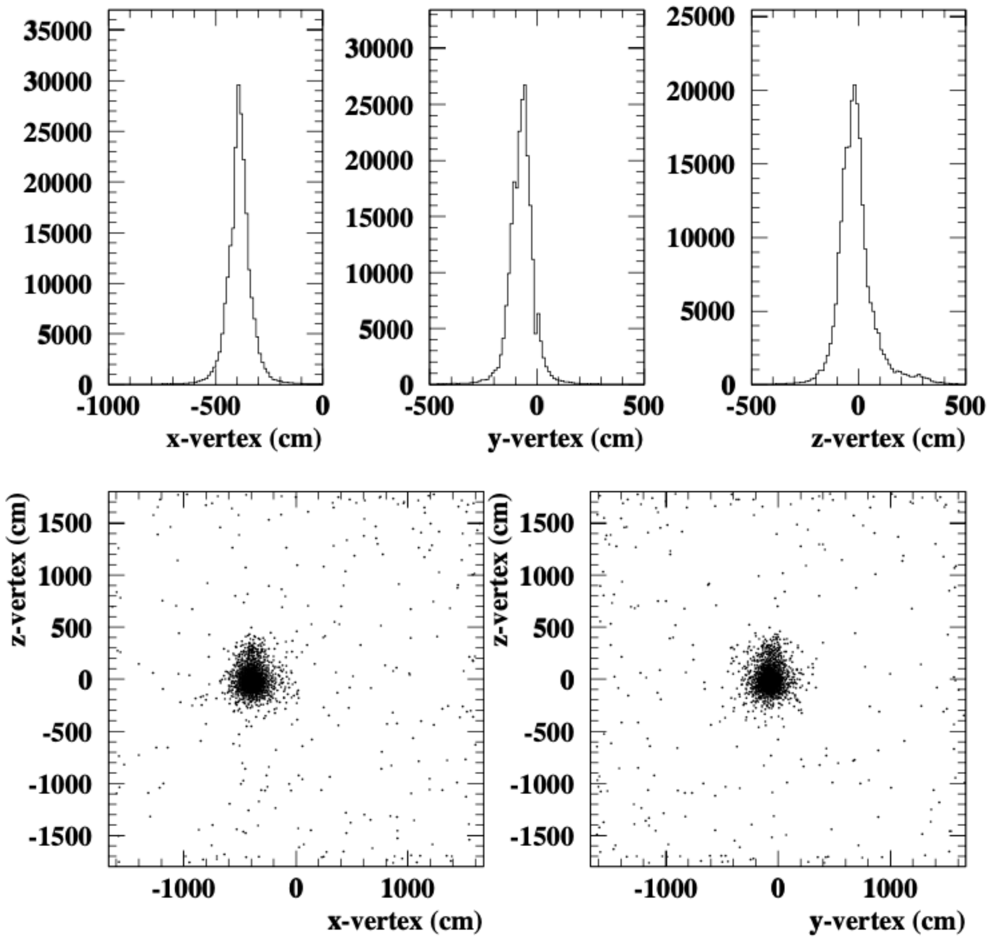

0.2 GBq
of tritium

It worked!

fitted vertex of 16-N events



So much data we can afford to wait 2 half-lives to ensure sample purity

The 16-N half life is measured to better than 1% ENDF value

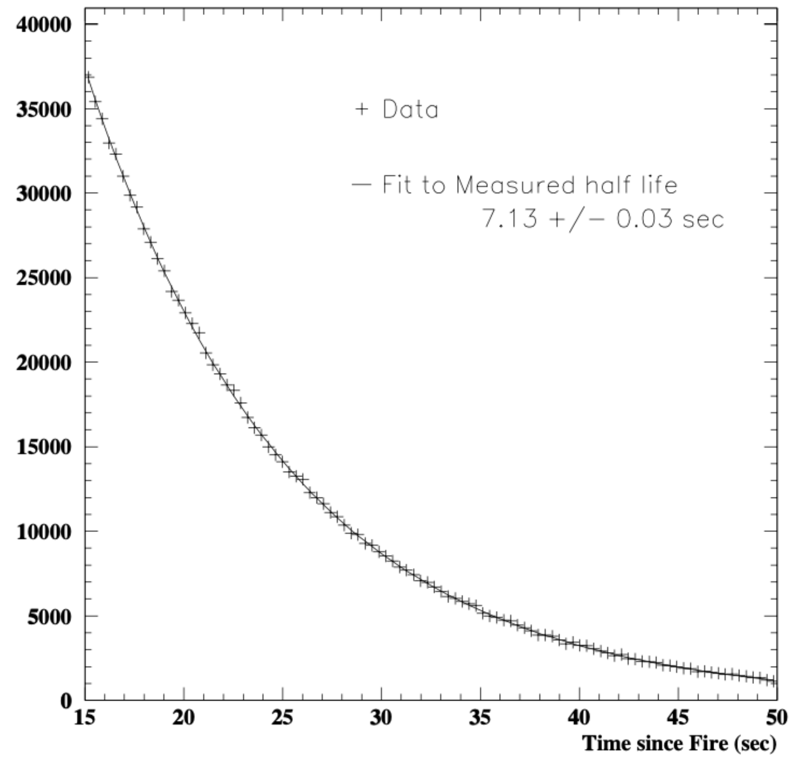
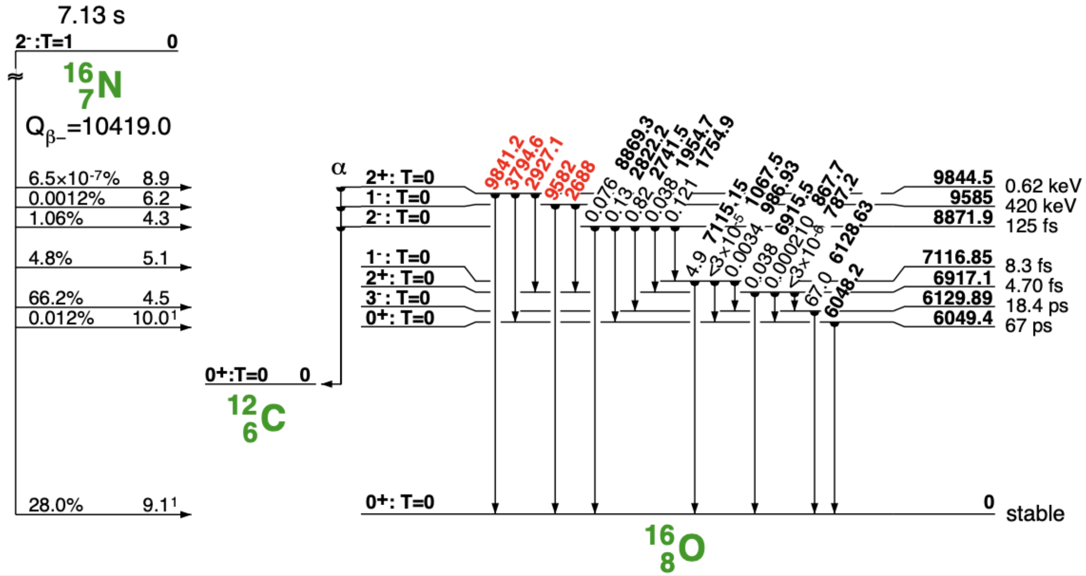
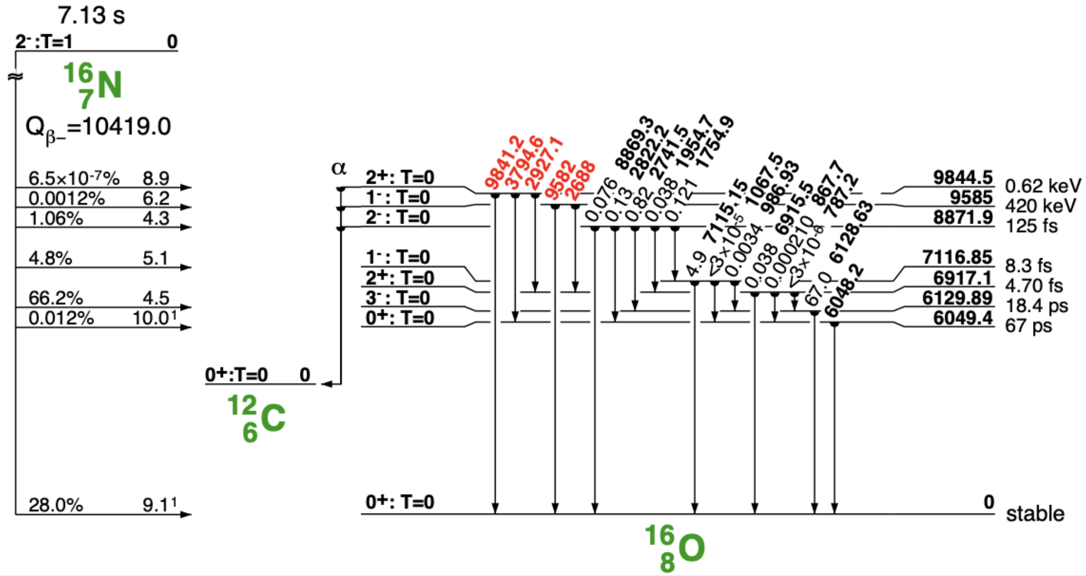
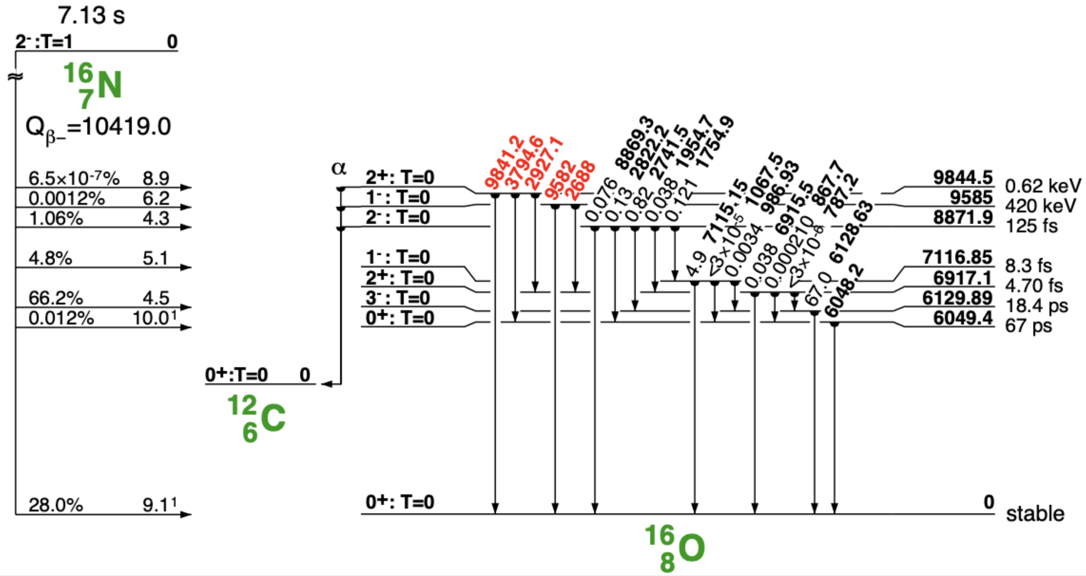


Figure 3.26: Distribution of time since generator fire for several DTG runs. Data with time since fire less than 15 sec are not included to ensure that all data are taken after the crane has been fully withdrawn.


7.13 s
2⁻:T=1 0
16 7 N
Qβ−=10419.0
6.5×10⁻⁷% 8.9
0.0012% 6.2
1.06% 4.3
4.8% 5.1
66.2% 4.5
0.012% 10.0
28.0% 9.1
0+:T=0 0
12 6 C
α
2+: T=0
1⁻: T=0
2⁻: T=0
1⁻: T=0
2+: T=0
3⁻: T=0
0+: T=0
0+: T=0
9844.5 0.62 keV
9585 420 keV
8871.9 125 fs
7116.85 8.3 fs
6917.1 4.70 fs
6129.89 18.4 ps
6049.4 67 ps
0 stable
16 8 O



Fraction	$J_i^p \rightarrow J_f^p$	ΔI	Gamma Energy (MeV)	Type
66.2%	$2^- \rightarrow 3^-$	+1	6.129	GT allowed
28.0%	$2^- \rightarrow 0^+$	-2	none	GT 1st forbidden
4.8%	$2^- \rightarrow 1^-$	+1	7.116	GT allowed
1.06%	$2^- \rightarrow 2^-$	+0	8.872	F+GT allowed
0.012%	$2^- \rightarrow 0^+$	-2	6.049	GT 1st forbidden
0.0012%	$2^- \rightarrow 1^-$	+1	9.585	GT allowed



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0.0012%	$2^- \rightarrow 1^-$	+1	9.585	GT allowed

Correction	Effect on Energy (%)
Forbidden Line Shape	+0.12%
Nuclear Recoil	<0.01%
Nuclear Coulomb Field	-0.08%
Dirac Eqn. Wavefunctions	-0.01%
Nucleon Wavefunctions	<0.01%
Radiative Corrections	-0.17%
Atomic Screening	<0.01%

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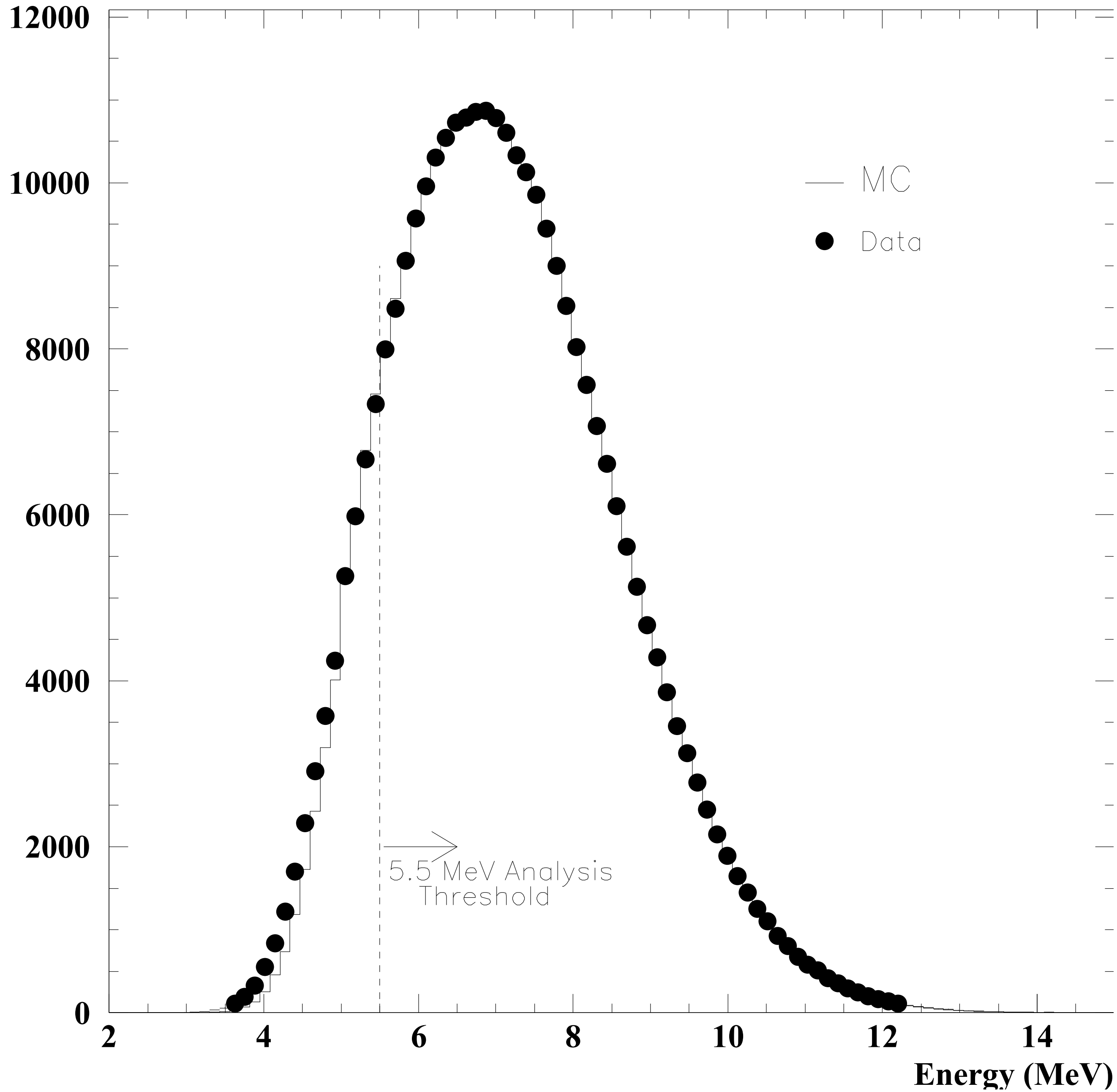
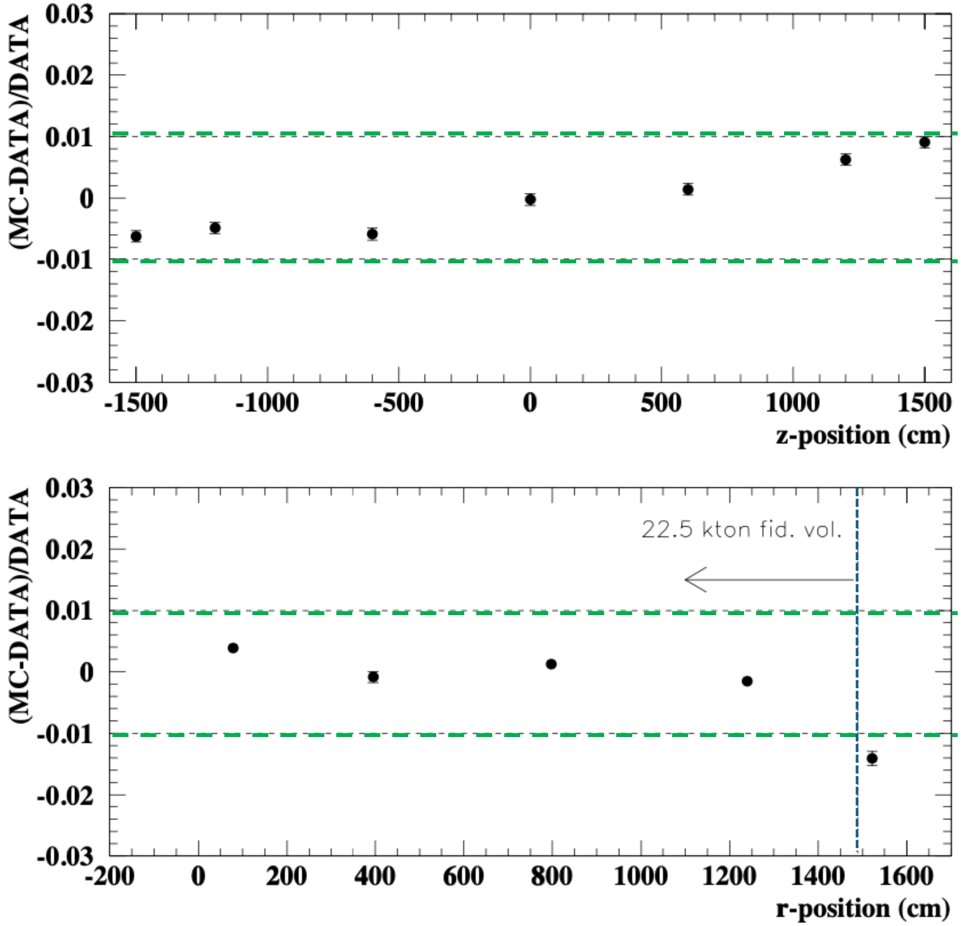


12000
10000
8000
6000
4000
2000
0
2
4
6
8
10
12
14
Energy (MeV)
MC
Data
5.5 MeV Analysis
Threshold

Table 3.3: Summary of systematic errors from the DTG calibration.

Contamination from natural background	$< 0.01\%$
^{16}N MC decay modeling	$\pm 0.1\%$
Unmodeled decay lines	$< 0.01\%$
Shadowing of Cherenkov photons	$\pm 0.1\%$
DTG data selection systematic	$\pm 0.1\%$
DTG related radioactive background	$\pm 0.1\%$
Total Systematic Error	$\pm 0.2\%$

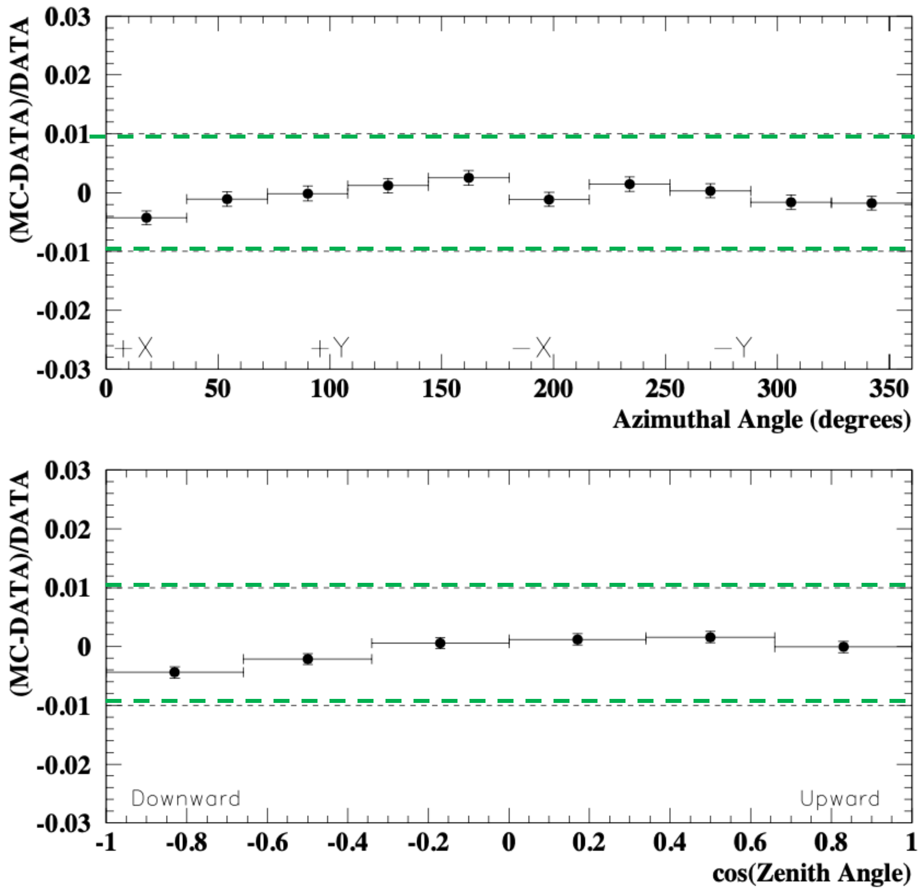


variation of energy scale versus height in the detector

variation of energy scale versus radial distance from centerline

Figure 3.24: Position dependence of the energy scale as measured by DTG data. At each r and z vertex position, a position-weighted average over all z and r positions, respectively, is performed Only statistical errors are shown. Dashed lines indicate deviations of $\pm 1\%$.

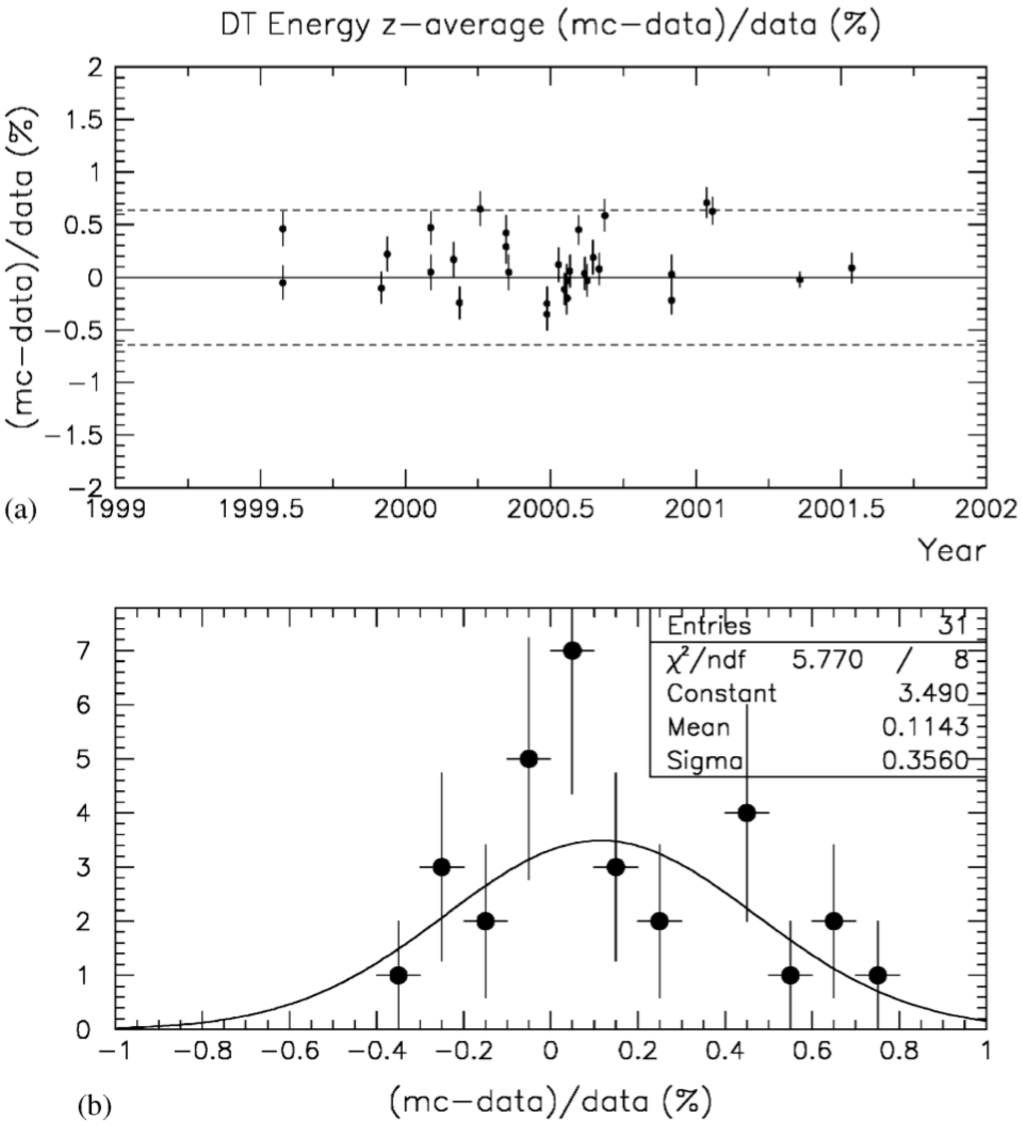
Since negligible shadowing, we were able to show that angular dependence of the energy scale was <1%



Azimuthal angle dependence of energy scale

Zenith angle dependence of energy scale

Figure 3.25: Angular dependence of the energy scale from DTG data. Dashed lines indicate deviations of $\pm 1\%$.



Time-dependence turned out to be the largest systematic

The detector energy scale drifted over several years.

In my experience such effects are common

DUNE take warning!

By 2002 Super-Kamiokande was able to show that the SMA solution was not viable - showing that the first SNO result must be due to LMA parameters

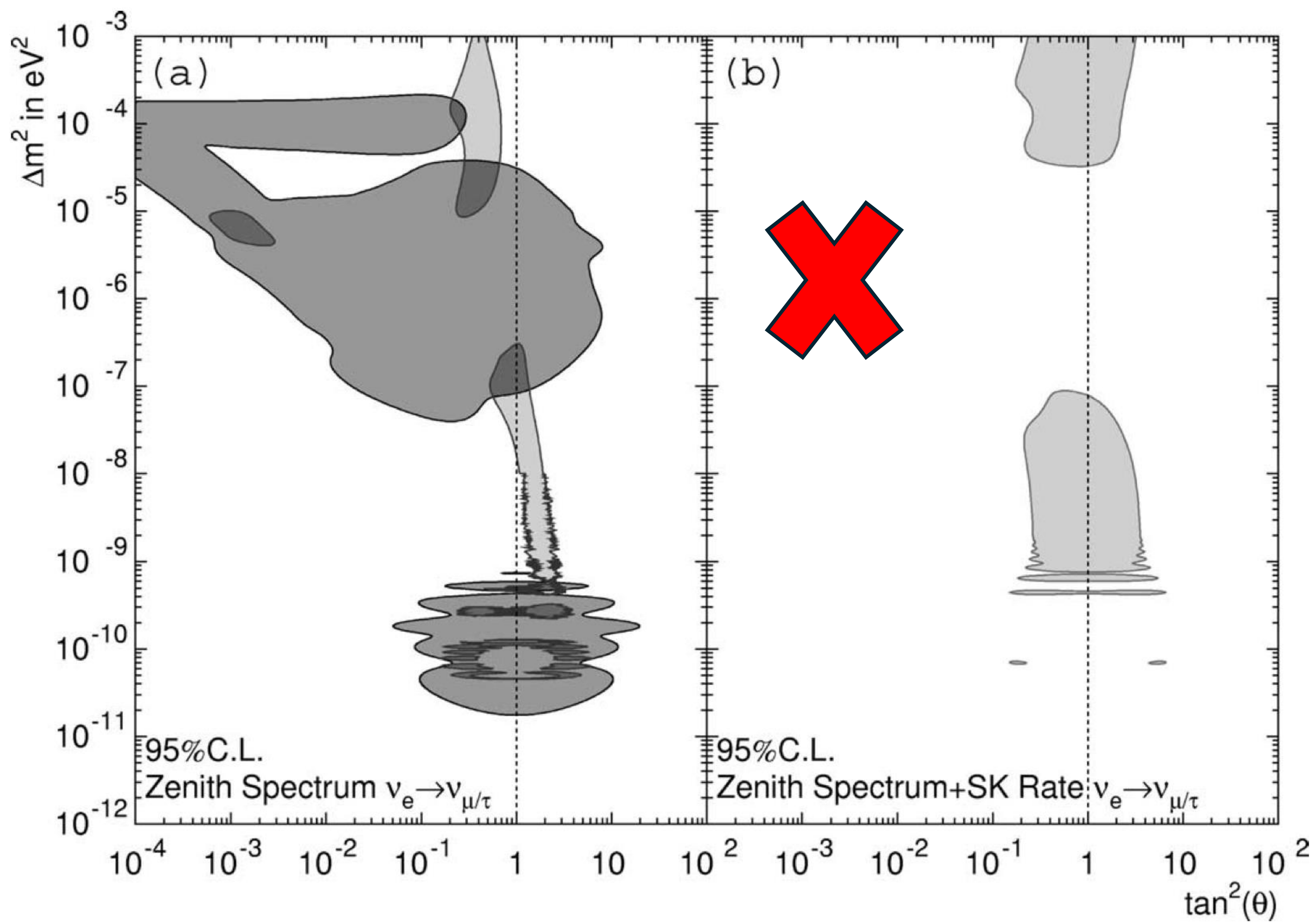
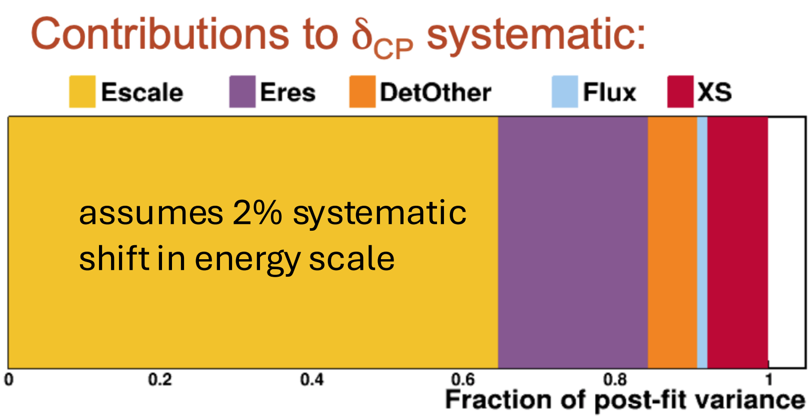


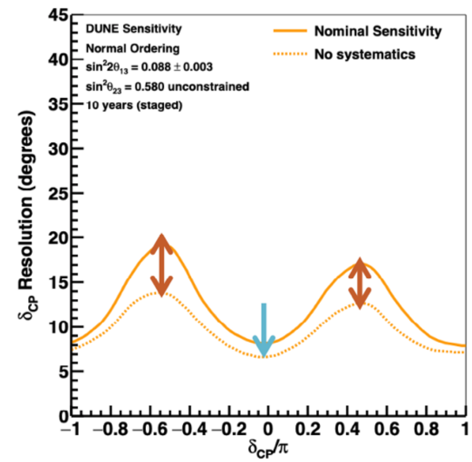
Fig. 2. (a) SSM flux independent excluded areas (gray) using the SK zenith spectrum shape alone overlaid with the allowed regions of Fig. 1(b) in light gray. The overlap of both is shaded dark gray. (b) Allowed areas using only SK data and the SSM ^{8}B neutrino flux prediction. Both allowed regions indicate large neutrino mixing.

Thoughts about DUNE

Systematic uncertainty in δ_{CP} due to the absolute energy scale

This is the major detector uncertainty remaining after ND inputs





Includes full FD simulation and automated reconstruction; parametrized ND samples; detailed treatment of systematics

(E.Worcester, ND Review June 2019)

..of course, this assumes the energy scale shift is constant over a decade years

Systematic uncertainty in δ_{CP} due to the absolute energy scale

- How will we reach 2% energy scale uncertainty?
  - Through-going CR muons
    - dE/dx issues underground
    - coverage and rate
  - Stopping CR muons
    - coverage and rate
  - Low energy sources
    - extrapolation issues

What role can calibration sources at ~10 MeV play in physics at ~1 GeV?

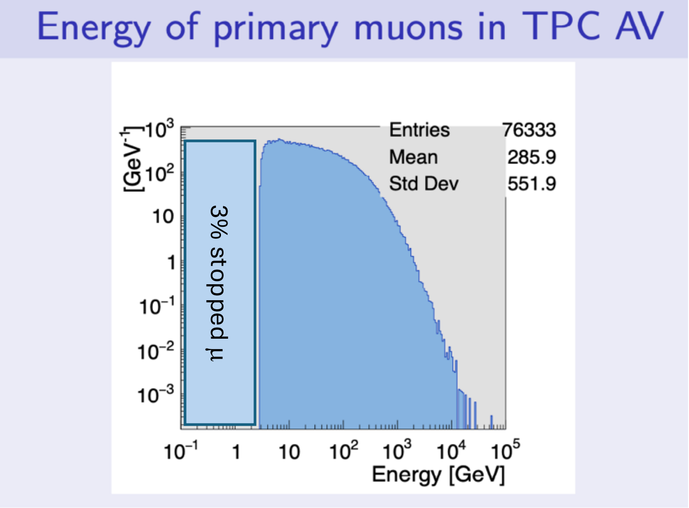
Could the uncertainty be reached with CR muons?

CR Muon Energy Spectrum

TABLE II. Muon flux parameters as calculated with MUSIC/MUSUN.

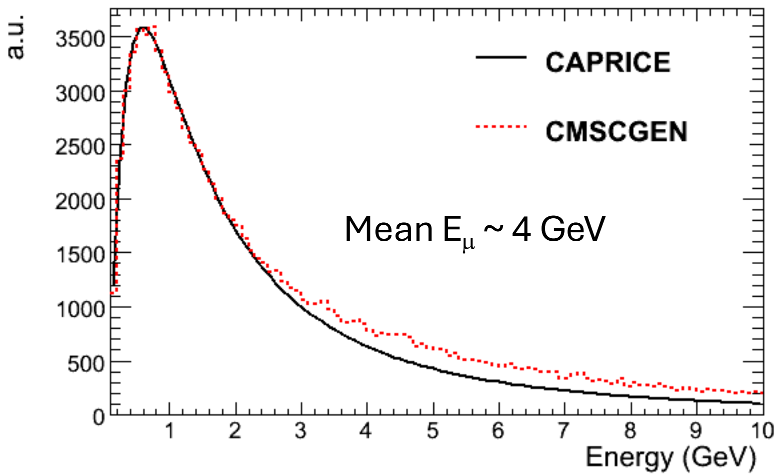
Total flux, $cm^{-2}s^{-1}$	Mean E_μ, GeV	Mean slant depth, m w. e.	Mean θ, deg.
5.66×10^{-9}	283	4532	26

30.6 days of throughgoing CR muons



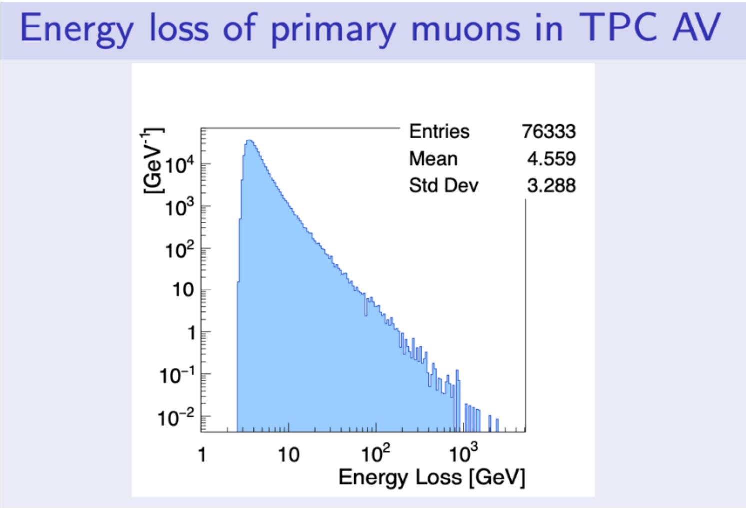
V.Pec Cosmic WG update 20200326

muon energy distribution at sea level

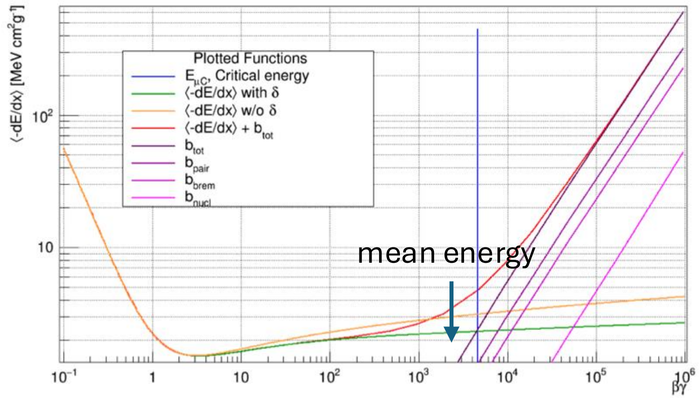


Adam, W. & Bergauer, Thomas & Dragicevic, Marko & Friedl, M. & Frühwirth, Rudolf & Haensel, S. & Hrubec, J & Krammer, M & Oberegger, M. & Pernicka, M. & Schmid, Stefan & Stark, R. & Steininger, H. & Uhl, D. & Waltenberger, Wolfgang & Widl, Edmund & Mechelen, P. & Cardaci, M. & Beaumont, W. & Tsang, K.. (2009). Performance studies of the CMS Strip Tracker before installation. 10.1088/1748-0221/4/06/P06009.

CR Muon Energy Loss



V.Pec Cosmic WG update 20200326



(Ingles, Junk, and Marchionni)

At 280 GeV simulations show a wide spread in dE/dx due to the fact that Bremsstrahlung and direct pair production become increasingly important.

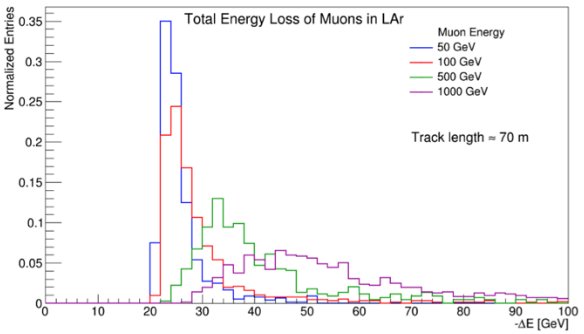


FIGURE 10. Total energy loss in DUNE Far Detector

variation in muon dE/dx for fixed energy muons

Michels from stopped muons are useful, but only about one every 8 minutes/module

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The Super-Kamiokande Experience

- In SK it was not enough just to do a calibration once in a single spot
  - Moveable LINAC that could be placed at many different radii and depths, and a deflecting magnet to change electron direction
  - Portable DT generator that could do a complete calibration at a single port in about a day.
- Needed to make sure that YEAR 1 neutrino energy scale and resolutuon were the same as YEAR 5 energy scale and resolution.

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Energy Scale Variation in DUNE

- We should not expect the DUNE cryostat to be a benign isothermal mass of liquid argon with no currents or variation in drift parameters over a decade
- We should not expect that the energy scale measured in 2029 for neutrinos will be the same in 2039. Need to **prove** it to be credible
- BTW – It would be interesting to look at a systematic energy scale shift between neutrino running and anti-neutrino running, as they occur years apart.
- Some of us are now working to make a neutron source calibration plan for DUNE that is fast, repeatable, and with small systematics

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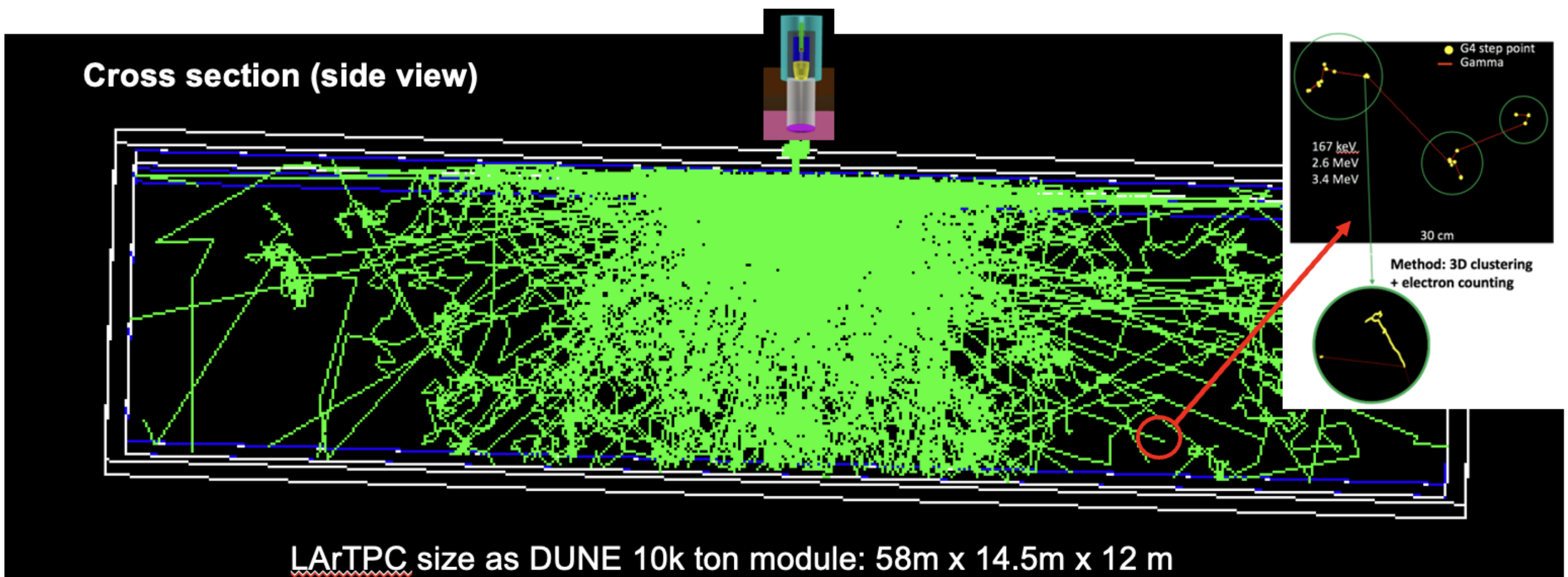
DUNE Pulsed Neutron Source

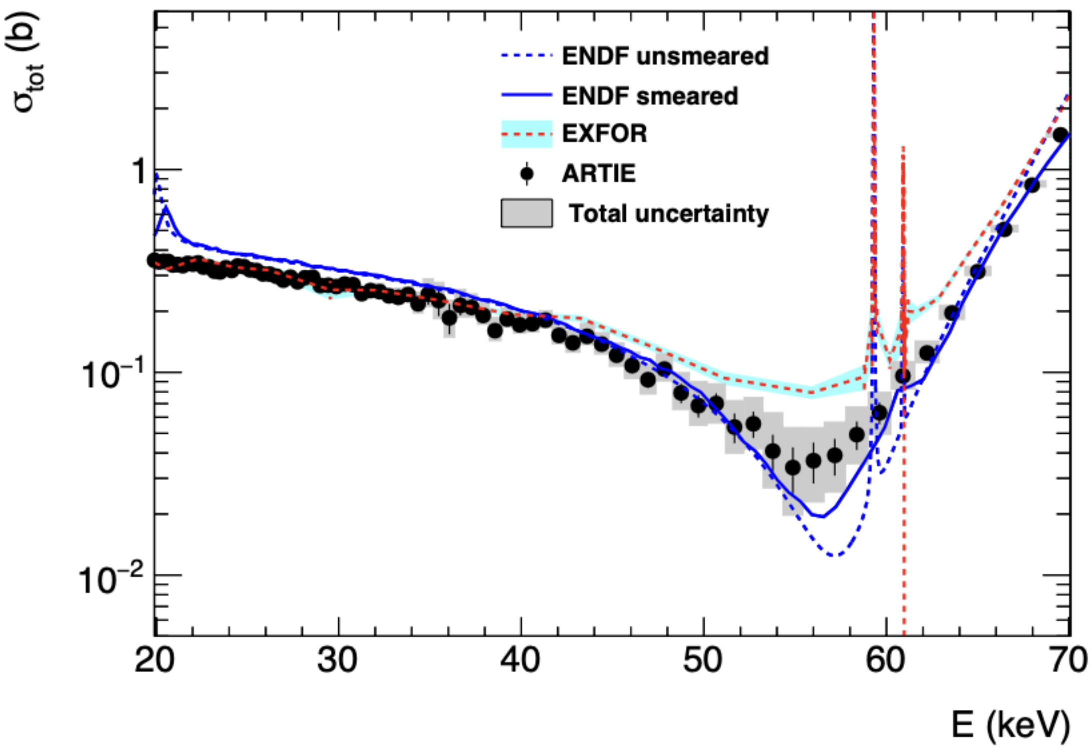
Neutrons can penetrate deep into the DUNE FD even when pulsed from outside the cryostat



Why does this work?

Measurement of the total neutron cross section on argon in the 20 to 70 keV energy range

S. Andringa,[1] Y.Bezawada,[2] T. Erjavec,[2] J. He,[2] J. Huang,[2] P. Koehler,[3] M. Mocko,[3] M. Mulhearn,[2] L. Pagani,[2] E. Pantic,[2] L. Pickard,[2] R. Svoboda,[2] J. Ullmann,[3] and J. Wang[4,5]
(ARTIE Collaboration)
[1] *Laboratório de Instrumentação e Física Experimental de Partículas (LIP), Av. Prof. Gama Pinto, 2, 1649-003, Lisboa, Portugal*
[2] *University of California at Davis, Department of Physics and Astronomy, Davis, CA 95616, U.S.A.*
[3] *Los Alamos National Laboratory, Physics Division, Los Alamos, NM 87545, U.S.A.*
[4] *University of California at Davis, Department of Physics, Davis, CA 95616, U.S.A.*
[5] *South Dakota School of Mines and Technology, Physics Department, Rapid City, SD 57701 USA*
(Dated: December 9, 2022)



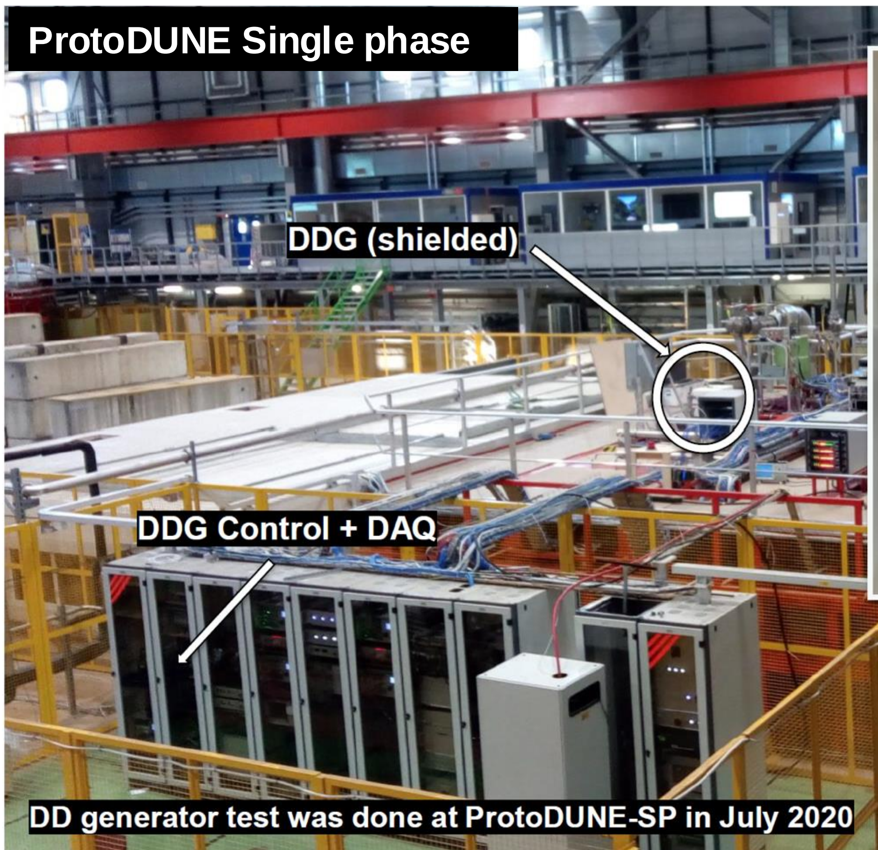
In 2022 we showed that an interference feature exists in the argon-neutron scattering cross section that increases the scattering length for neutrons in this range from ~3 meters to ~30 meters

(see T.Erjavec Thesis for more details beyond the publication)

Argon Resonant Transport Interaction Experiment (ARTIE) at LANSCE

ProtoDUNE-1 test proved that neutrons do indeed penetrate to the depth expected

- A DD generator test was performed in 2020 during ProtoDUNE-1 at CERN



(From left to right) protoDUNE-SP module and the DDG installation location; DDG; DDG inside the shielding; roof feedthrough at which DDG is deployed

(Images from M. Fanì, DUNE Collab. Meeting, Sep 2020)

(see theses of Y.Bezawada and J.Huang)

Upcoming…

- Test of the neutron system at both ProtoDUNE detectors with improved triggering
- Higher precision cross section measurement scheduled for LANSCE in 2025 (ARTIE II)
- Multiple Argon Experiment (MArEx) program at CERN nTOF had a first test run in 2023. Planning a run to extend the energy range of the n-Ar scattering cross-section in 2025
- Efforts to pick out neutron capture events using ML are underway and show great promise…it looks like this can be done.

Thanks to CPAD!

Thanks to all who worked so hard on the Super-K precision energy calibration two decades ago - too bad nature chose the LMA solution!

Thanks to all the people who worked **and are working** on the ARTIE, ACED, ProtoDUNE, and nTOF experiments for DUNE. This work is critical!