PHYS 575A/B/C

Autumn 2015

Radiation and Radiation Detectors

Course home page:

http://depts.washington.edu/physcert/radcert/575website/

9: Case studies: Non-Cherenkov neutrino detectors; neutron detectors; accelerators

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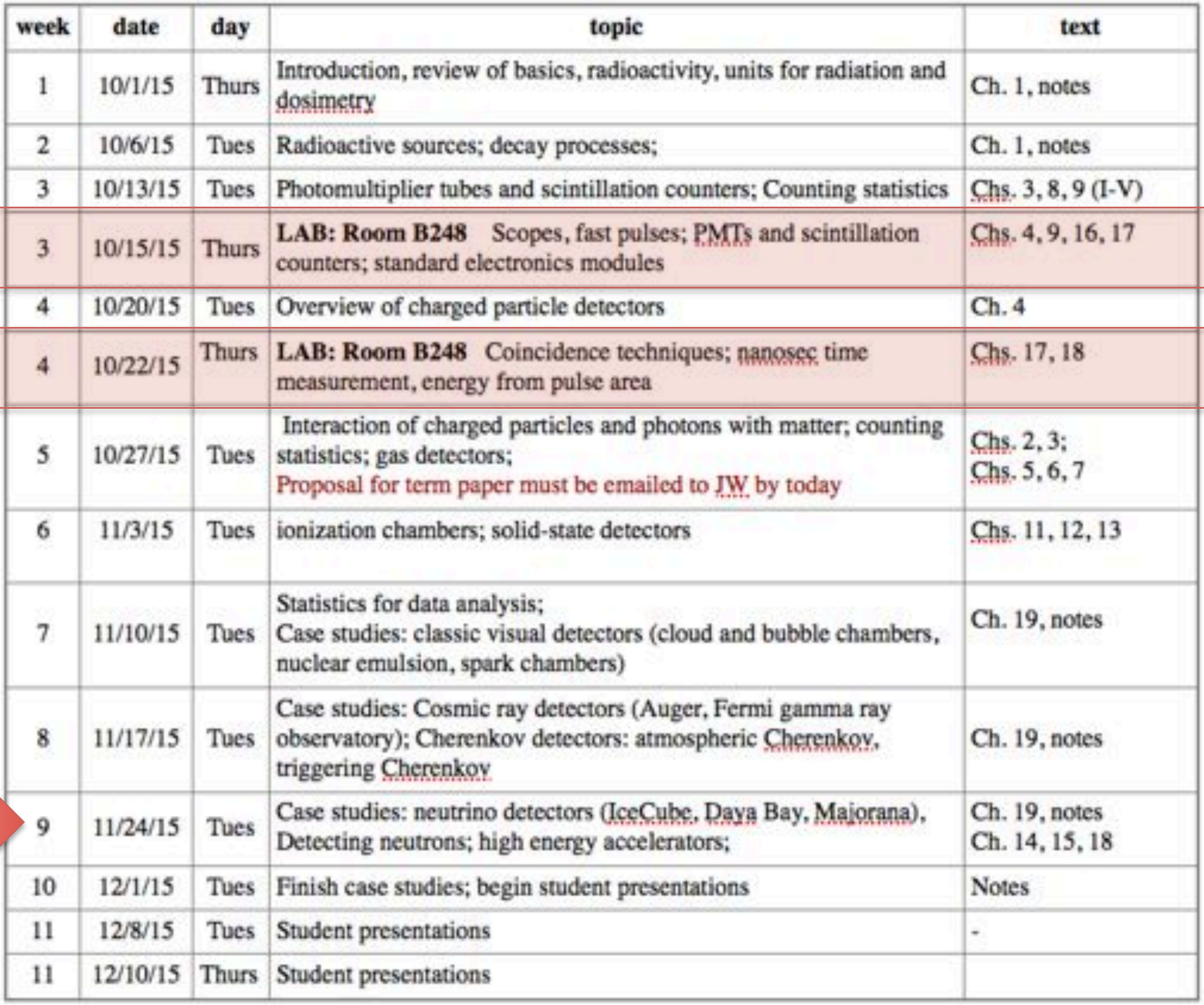
Course calendar (revised)

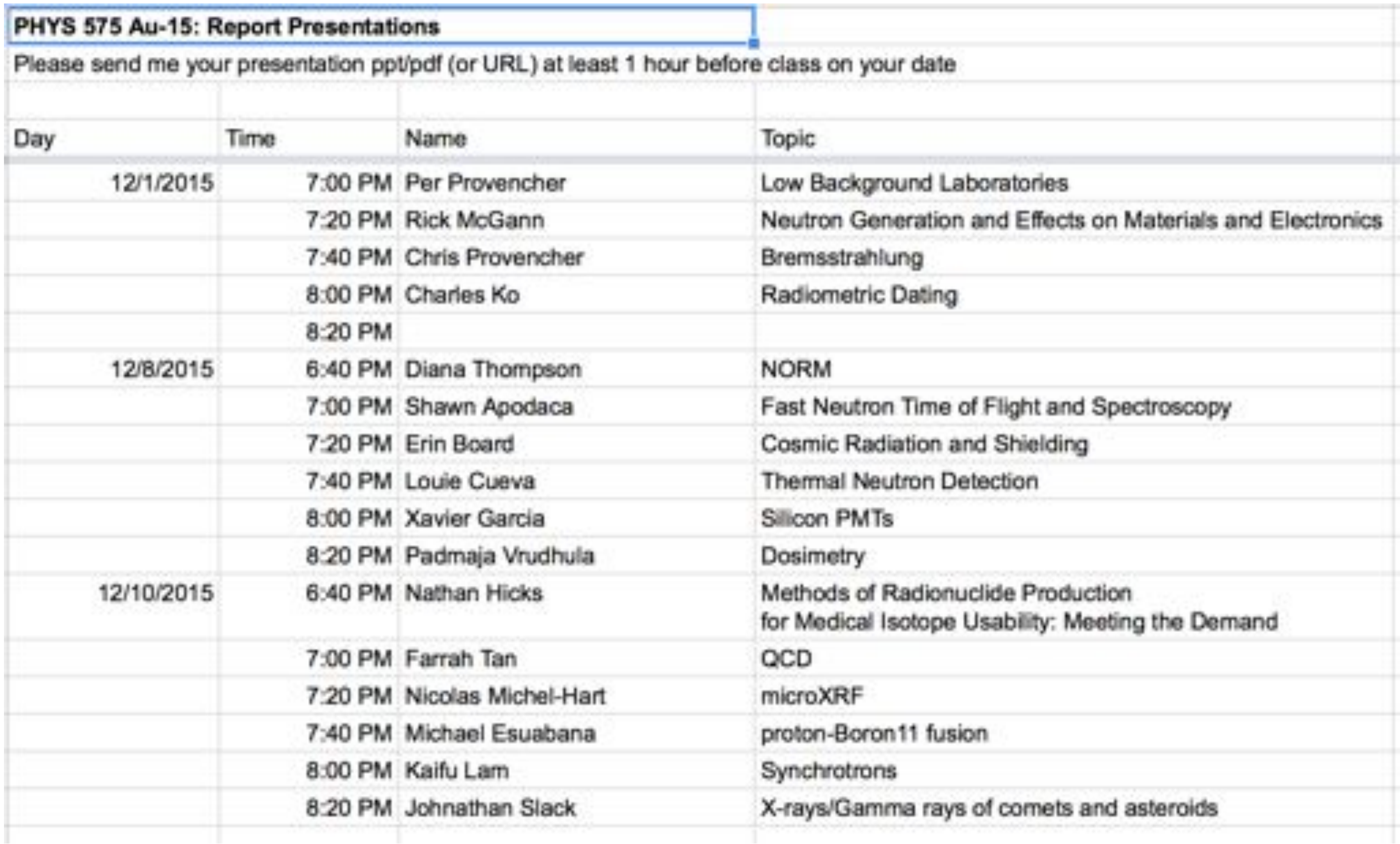


week	date	day	topic	text
1	10/1/15	Thurs	Introduction, review of basics, radioactivity, units for radiation and dosimetry	Ch. 1, notes
2	10/6/15	Tues	Radioactive sources; decay processes;	Ch. 1, notes
3	10/13/15	Tues	Photomultiplier tubes and scintillation counters; Counting statistics	Chs. 3, 8, 9 (I-V)
3	10/15/15	Thurs	**LAB: Room B248** Scopes, fast pulses; PMTs and scintillation counters; standard electronics modules	Chs. 4, 9, 16, 17
4	10/20/15	Tues	Overview of charged particle detectors	Ch. 4
4	10/22/15	Thurs	**LAB: Room B248** Coincidence techniques; nanosec time measurement, energy from pulse area	Chs. 17, 18
5	10/27/15	Tues	Interaction of charged particles and photons with matter; counting statistics; gas detectors; Proposal for term paper must be emailed to JW by today	Chs. 2, 3; Chs. 5, 6, 7
6	11/3/15	Tues	ionization chambers; solid-state detectors	Chs. 11, 12, 13
7	11/10/15	Tues	Statistics for data analysis; Case studies: classic visual detectors (cloud and bubble chambers, nuclear emulsion, spark chambers)	Ch. 19, notes
8	11/17/15	Tues	Case studies: Cosmic ray detectors (Auger, Fermi gamma ray observatory); Cherenkov detectors: atmospheric Cherenkov, triggering Cherenkov	Ch. 19, notes
9	11/24/15	Tues	Case studies: neutrino detectors (IceCube, Daya Bay, Majorana), Detecting neutrons; high energy accelerators;	Ch. 19, notes Ch. 14, 15, 18
10	12/1/15	Tues	Finish case studies; begin student presentations	Notes
11	12/8/15	Tues	Student presentations	-
11	12/10/15	Thurs	Student presentations	

Tonight

Announcements

- Presentation dates: Tues Dec 1, Tues Dec 8, and Thurs Dec 10
  - You MUST send me your presentation (pdf or ppt) no later than 5:30 pm on the day of your talk
  - I will upload all slides for each session so online attendance is possible



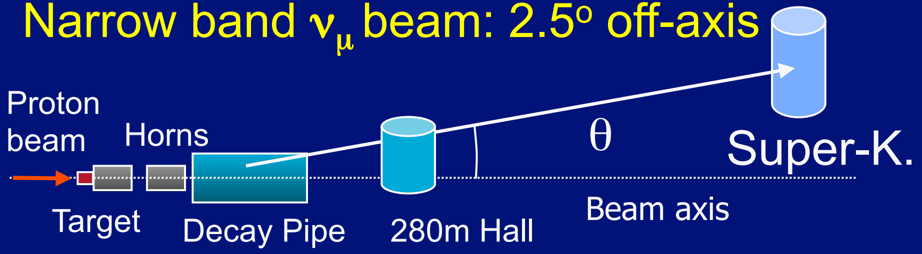
PHYS 575 Au-15: Report Presentations

Please send me your presentation ppt/pdf (or URL) at least 1 hour before class on your date

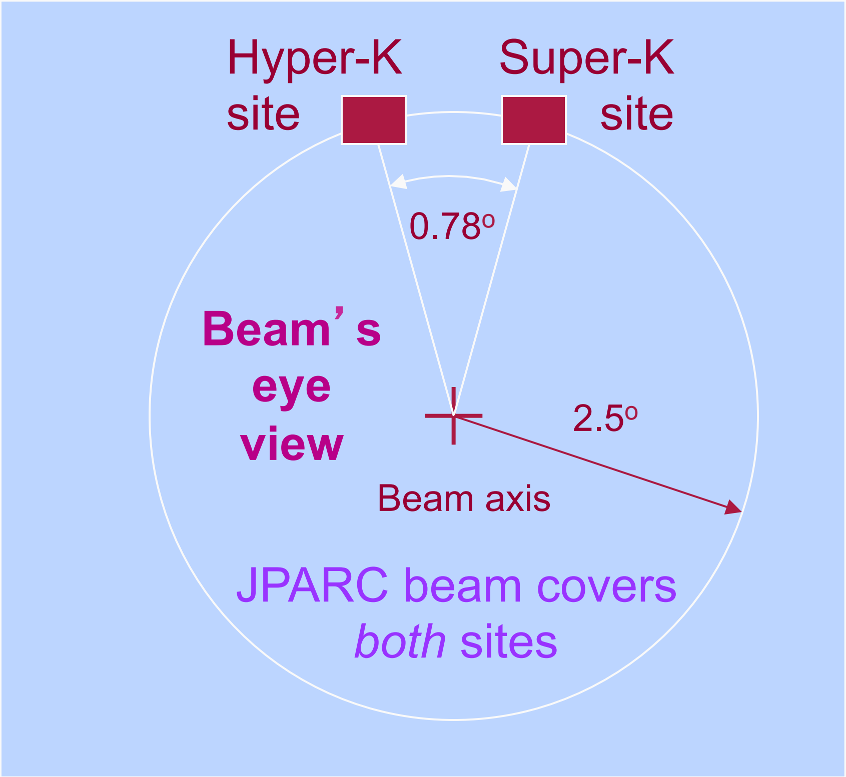
Day	Time	Name	Topic
12/1/2015	7:00 PM	Per Provencher	Low Background Laboratories
	7:20 PM	Rick McGann	Neutron Generation and Effects on Materials and Electronics
	7:40 PM	Chris Provencher	Bremsstrahlung
	8:00 PM	Charles Ko	Radiometric Dating
	8:20 PM		
12/8/2015	6:40 PM	Diana Thompson	NORM
	7:00 PM	Shawn Apodaca	Fast Neutron Time of Flight and Spectroscopy
	7:20 PM	Erin Board	Cosmic Radiation and Shielding
	7:40 PM	Louie Cueva	Thermal Neutron Detection
	8:00 PM	Xavier Garcia	Silicon PMTs
	8:20 PM	Padmaja Vrudhula	Dosimetry
12/10/2015	6:40 PM	Nathan Hicks	Methods of Radionuclide Production for Medical Isotope Usability: Meeting the Demand
	7:00 PM	Farrah Tan	QCD
	7:20 PM	Nicolas Michel-Hart	microXRF
	7:40 PM	Michael Esuabana	proton-Boron11 fusion
	8:00 PM	Kaifu Lam	Synchrotrons
	8:20 PM	Johnathan Slack	X-rays/Gamma rays of comets and asteroids

JPARC neutrino beam uses “off-axis” technique

Narrow band ν_μ beam: 2.5° off-axis



To get anti-neutrinos: reverse horn current

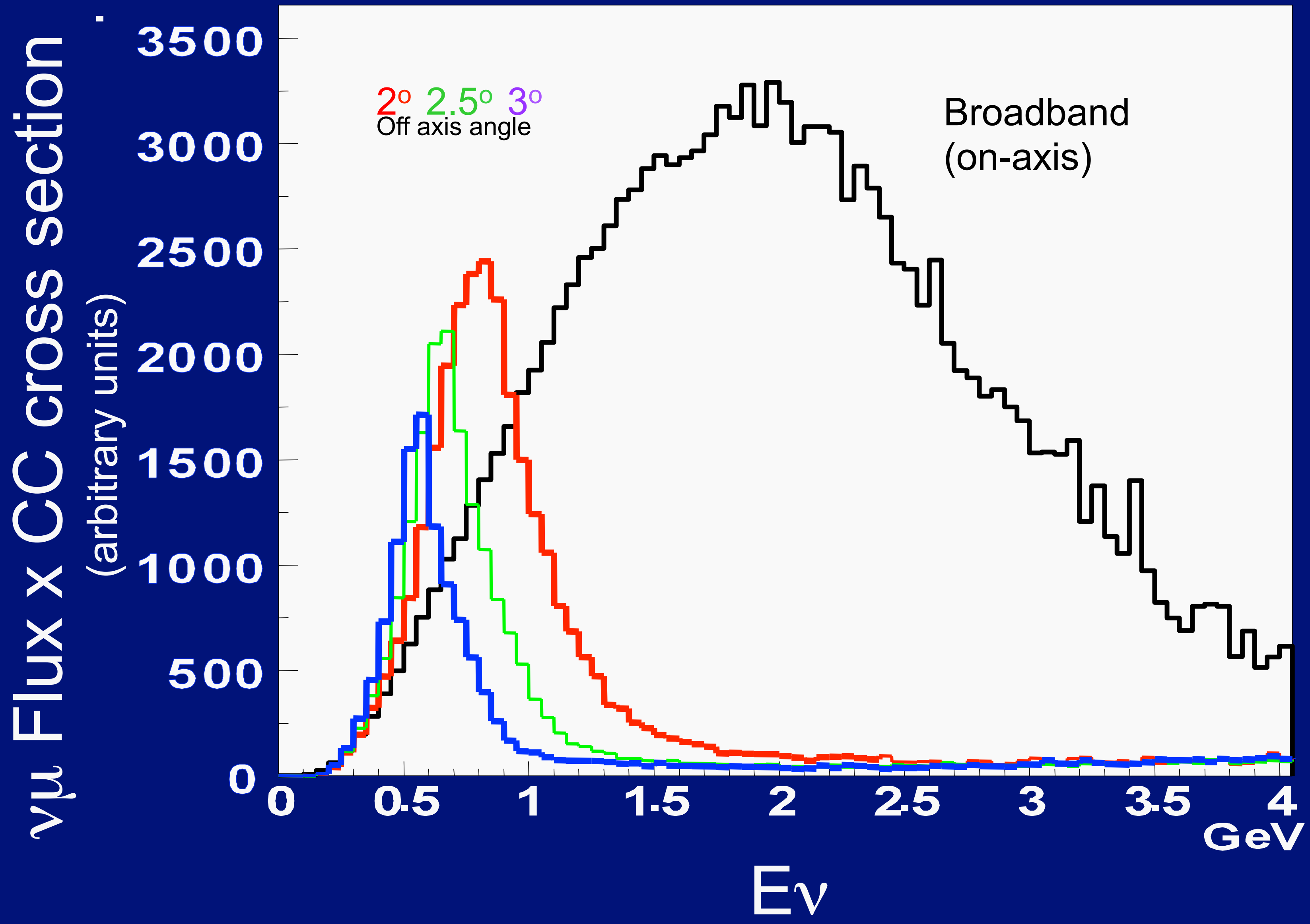


T2K-I event statistics at SK:
(Off axis-2.5 deg, 22.5 kt, per year)

- 2200 total ν_μ events
- 1600 ν_μ CC
- ν_e ~ 0.4% at ν_μ peak E

Target/Horn magnet – test setup
Must handle pulses of 100s of kA

T2K Neutrino E spectra: broadband vs off-axis



Low-energy (reactor) neutrino oscillation experiments

- Nuclear reactors provide high fluxes of electron antineutrinos
  - Flux directly related to power output of nuclear plant
  - Baseline L can be shorter since energy is few MeV (recall: L/E ~ proper time for neutrino)
- Pure water detectors are not optimal – small cross-section*
- Use liquid scintillator (fluors in mineral oil) or Cd compounds

* But: Doping water with gadolinium produces huge cross sections

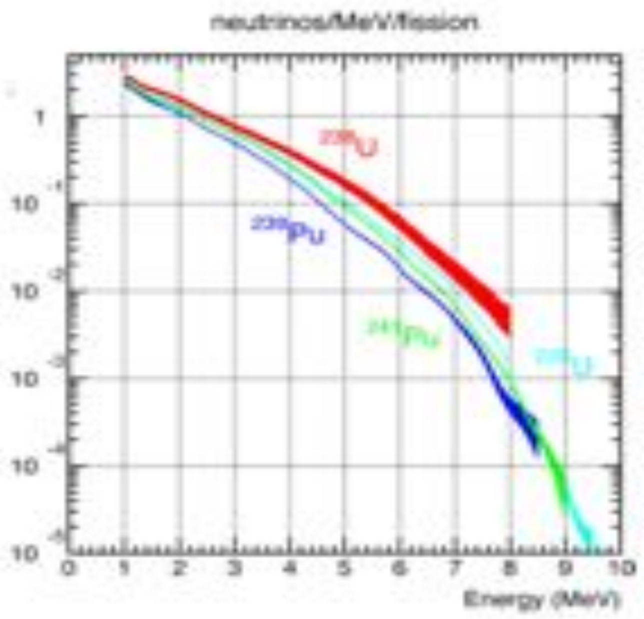
- GADZOOKS = plan to turn Super-K into a Gd detector for antinu
  - Neutrons captured by Gd, 90% capture efficiency for 1% Gd in water
  - Gd → Big fat 8 MeV gamma signal when it decays, easy to detect and identify

Illustrations in this section from presentations by
K. Heeger, U. Wisc
Y. Wang and J. Cao, ICHEP Beijing

Reactor Antineutrinos

Source

$\bar{\nu}_e$ from β-decays
of n-rich fission products

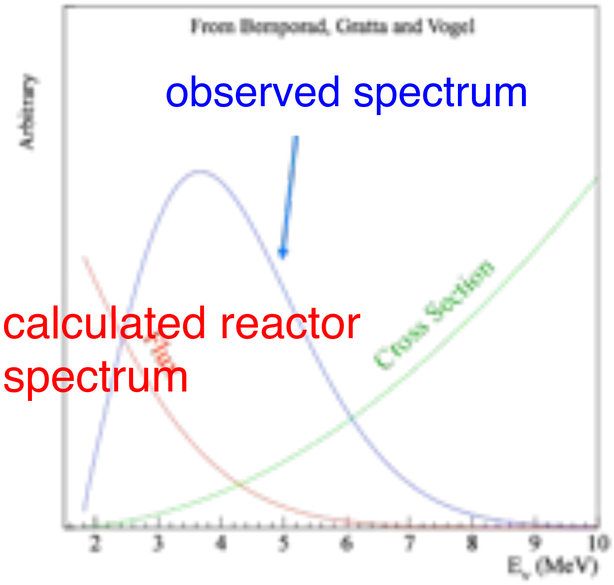


pure $\bar{\nu}_e$ source

> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Detection

inverse beta decay
$\bar{\nu}_e + p \rightarrow e^+ + n$



observed spectrum

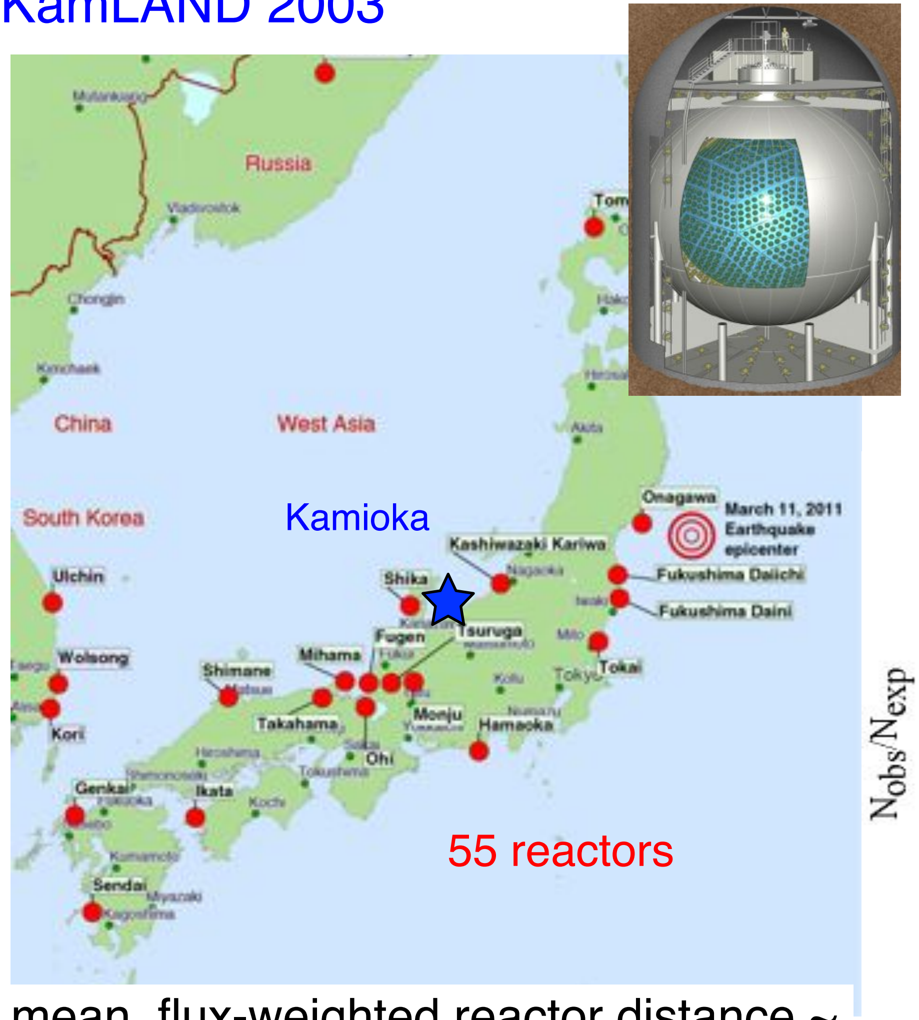
calculated reactor spectrum

mean energy of $\bar{\nu}_e$: 3.6 MeV

only disappearance experiments possible

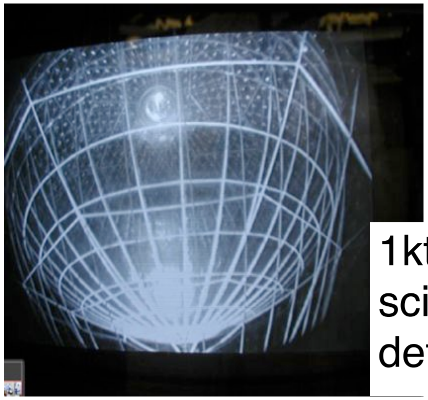
Observation of Reactor $\bar{\nu}_e$ Disappearance

KamLAND 2003



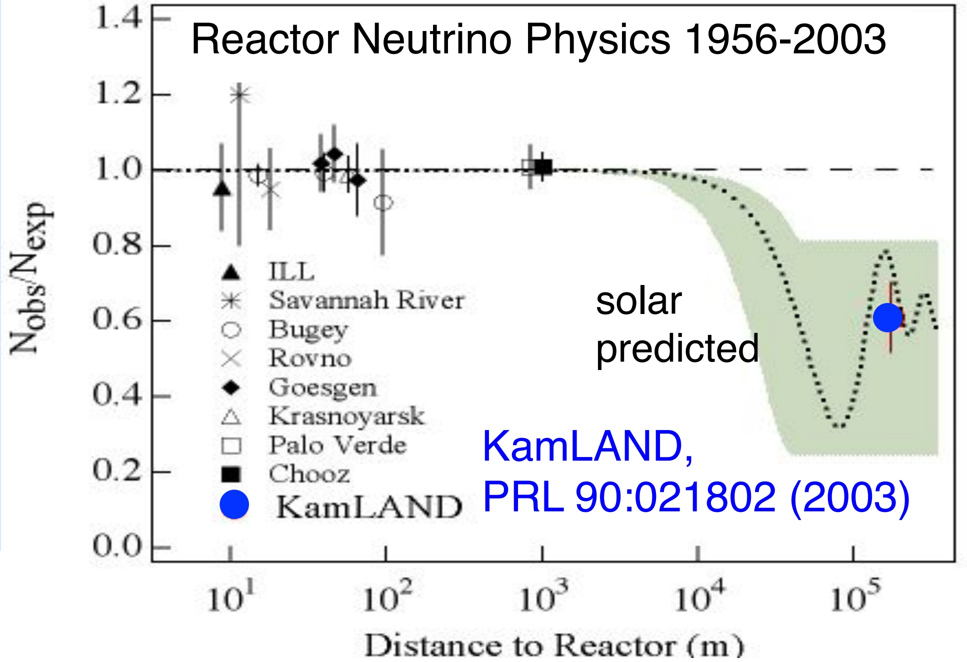
Kamioka

55 reactors



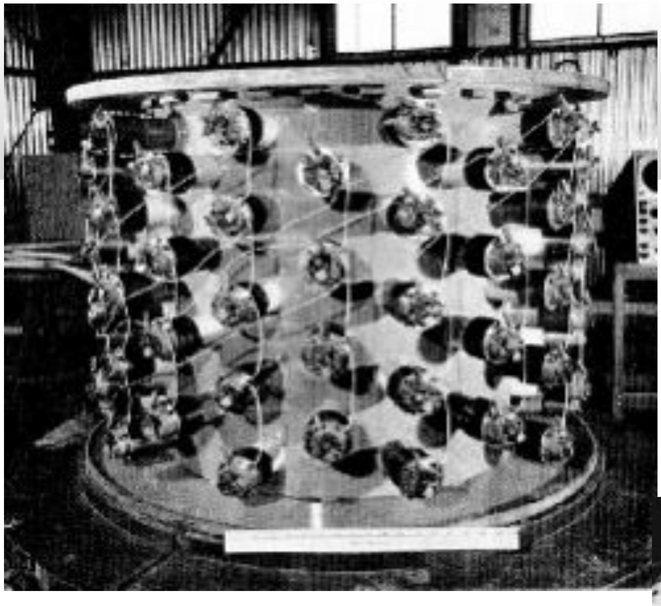
1kt liquid scintillator detector

mean, flux-weighted reactor distance ~ 180km


Reactor Neutrino Physics 1956-2003

solar predicted

KamLAND, PRL 90:021802 (2003)



Long history: Hanford Experiment

(1953) F. Reines, C. Cowan

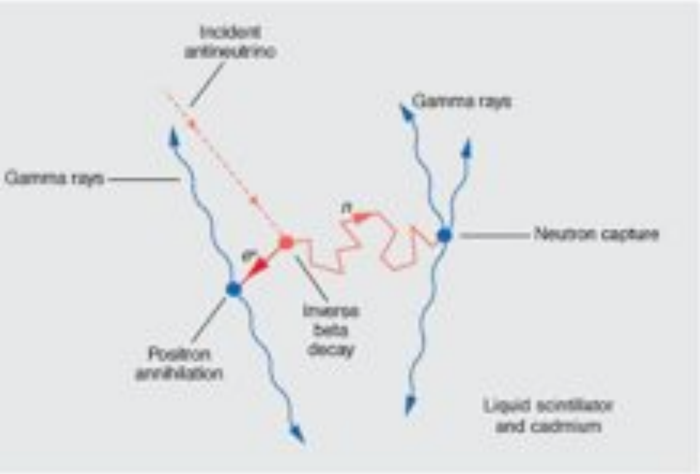
inverse beta decay

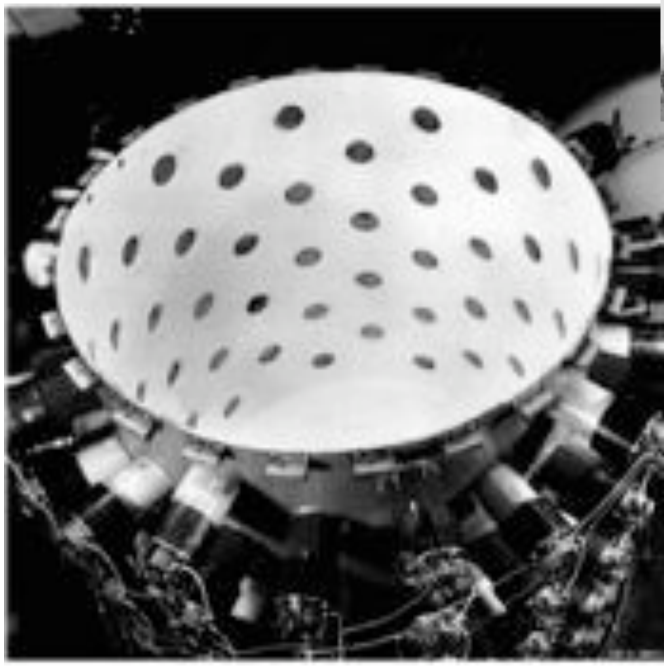
$\nu_e + p \rightarrow n + \;\; e^+ \searrow$ annihilates promptly

$\swarrow$

$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109m}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma$

300 liters of liquid scintillator loaded with cadmium





signal: delayed coincidence between positron and neutron capture on cadmium

0.41+/- 0.20 events/minute

high background (S/N ~ 1/20) made the Hanford experiment inconclusive

The Savannah River (version 2 of Reines) Detector

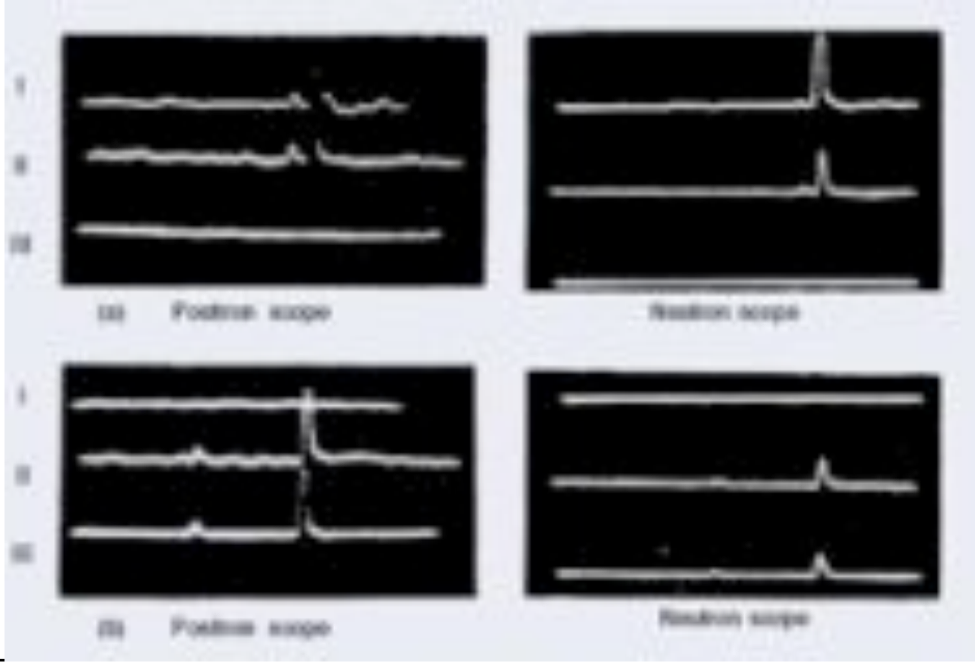
Improved design (1956), bigger reactor

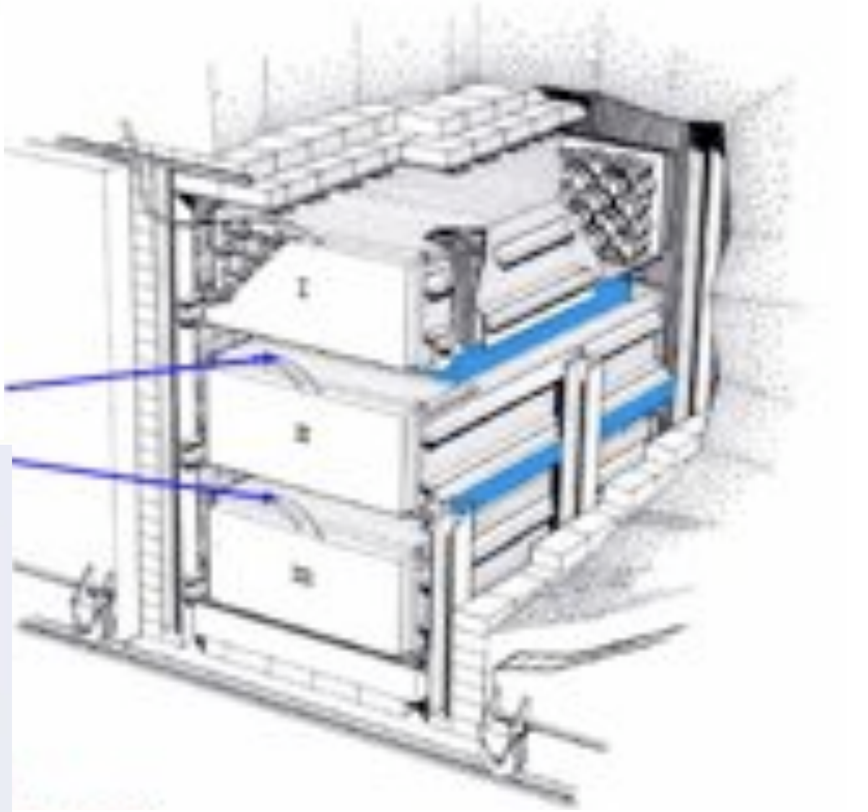
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

target tanks (blue) were filled with water+cadmium chloride

inverse beta decay

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





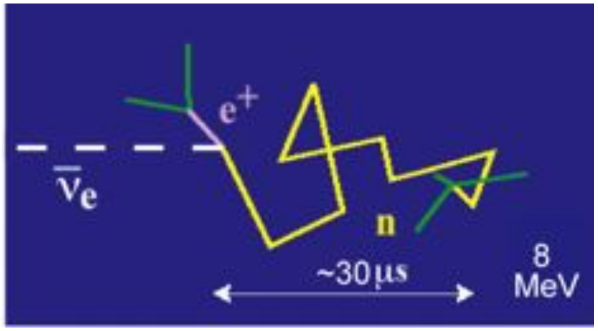
inverse beta decay would produce prompt and delayed signal in neighboring tanks

low E anti-neutrino detection: Inverse-β reaction in liquid scintillator

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

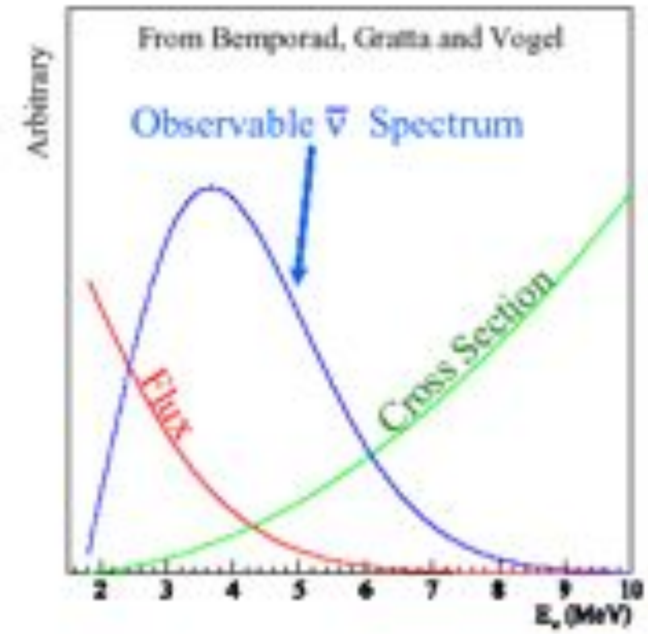
Illustrations in this section from presentations by
Y. Wang, and J. Cao, ICHEP Beijing
K. Heeger, U. Wisconsin

$\tau \approx 180$ or $28\ \mu$s(0.1% Gd)



$$n + p \rightarrow d + \gamma\ (2.2\ \mathrm{MeV})$$
$$n + Gd \rightarrow Gd^* + \gamma\text{'s}\ (8\ \mathrm{MeV})$$

Neutrino Event: coincidence in time, space and energy



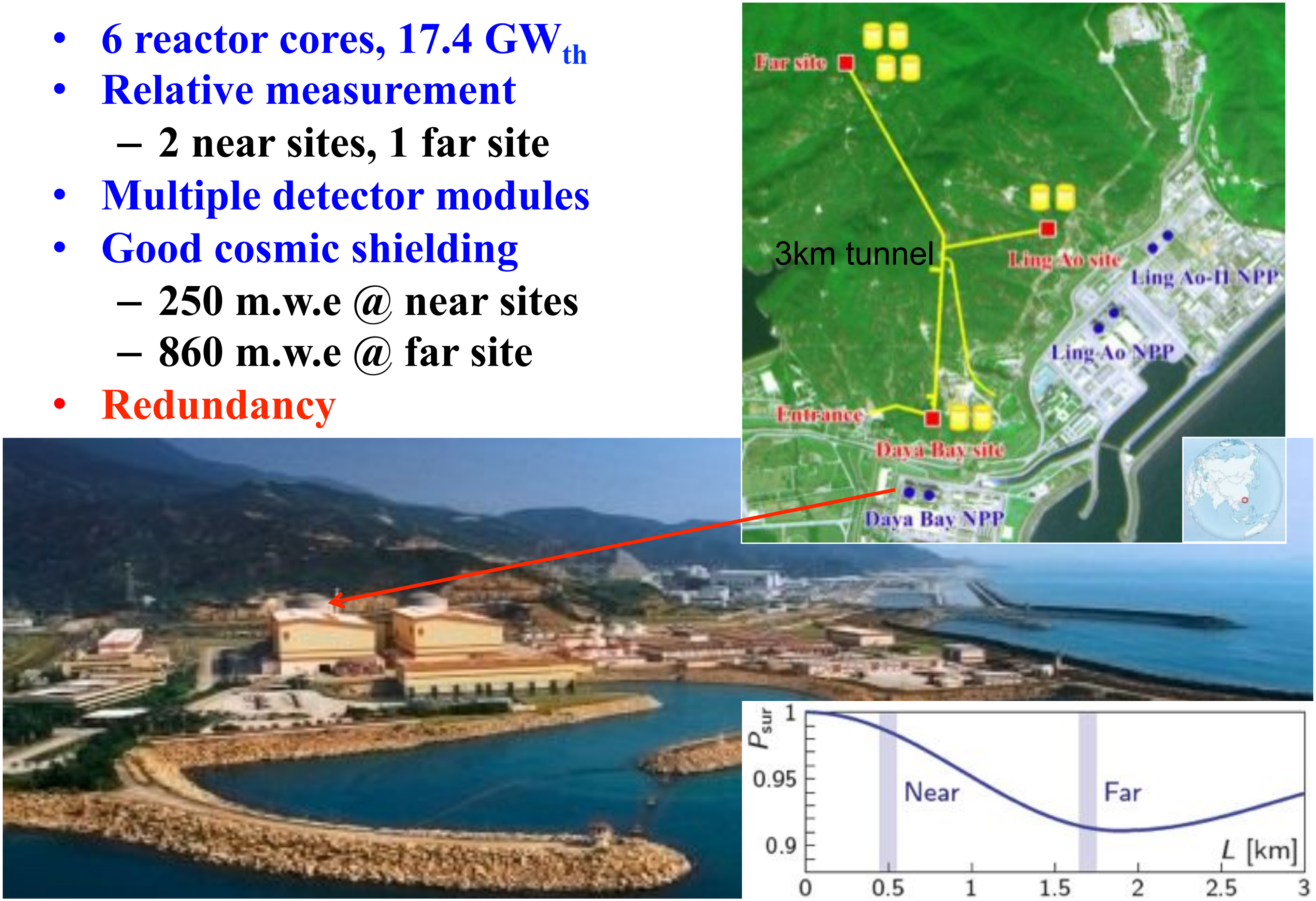
Neutrino energy:

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{–}40\ \mathrm{keV}} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV:\ \text{Threshold}}$$

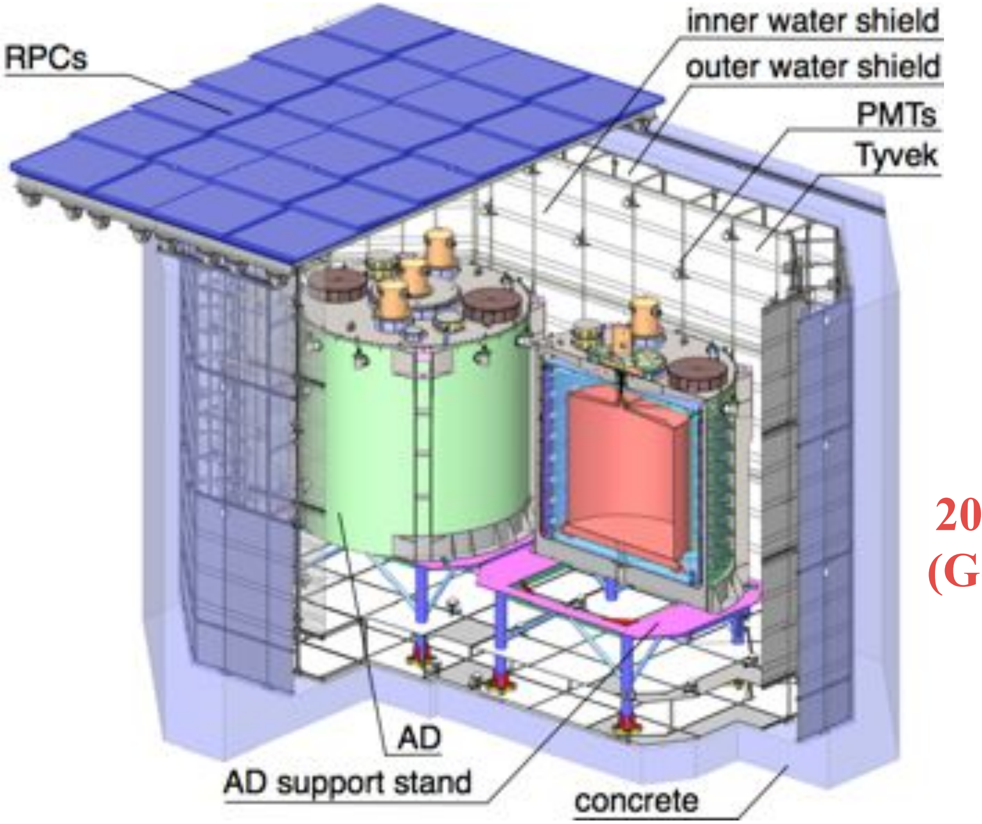
Y. Wang, ICHEP Beijing

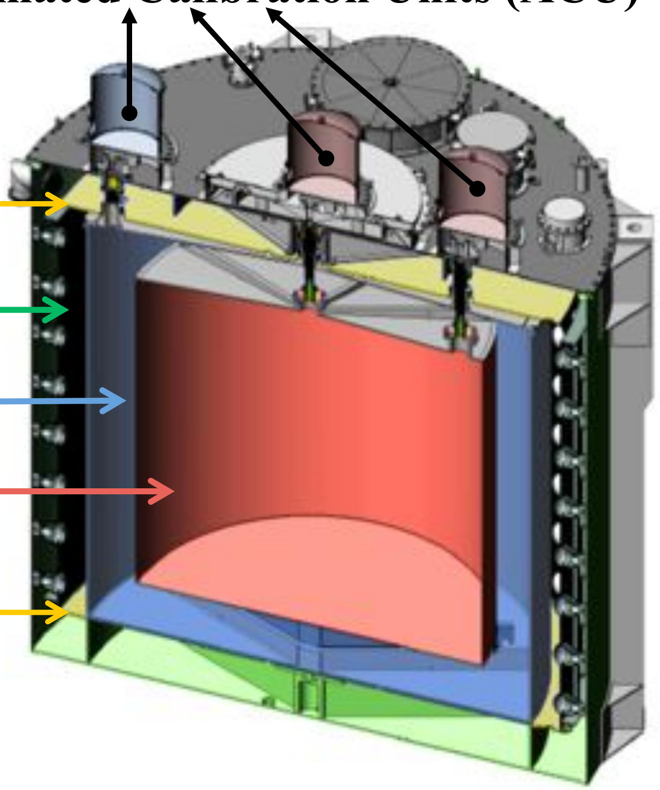
The Daya Bay Experiment

- 6 reactor cores, 17.4 GW_{th}
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ near sites
  - 860 m.w.e @ far site
- Redundancy



The Daya Bay Detectors




Automated Calibration Units (ACU)

reflector

40 t
mineral oil

20 t LS

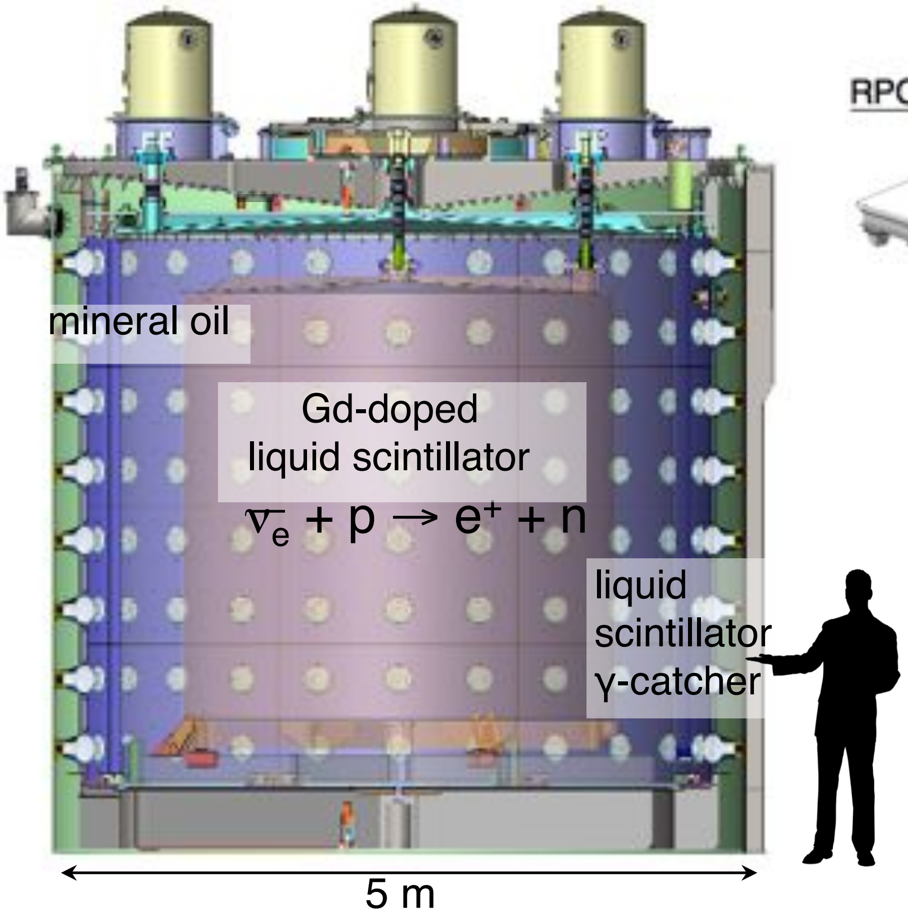
20 t Target
(Gd doped)

reflector

- Multiple AD modules at each site to check uncorr. syst. err.
  - Far: 4 modules，near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

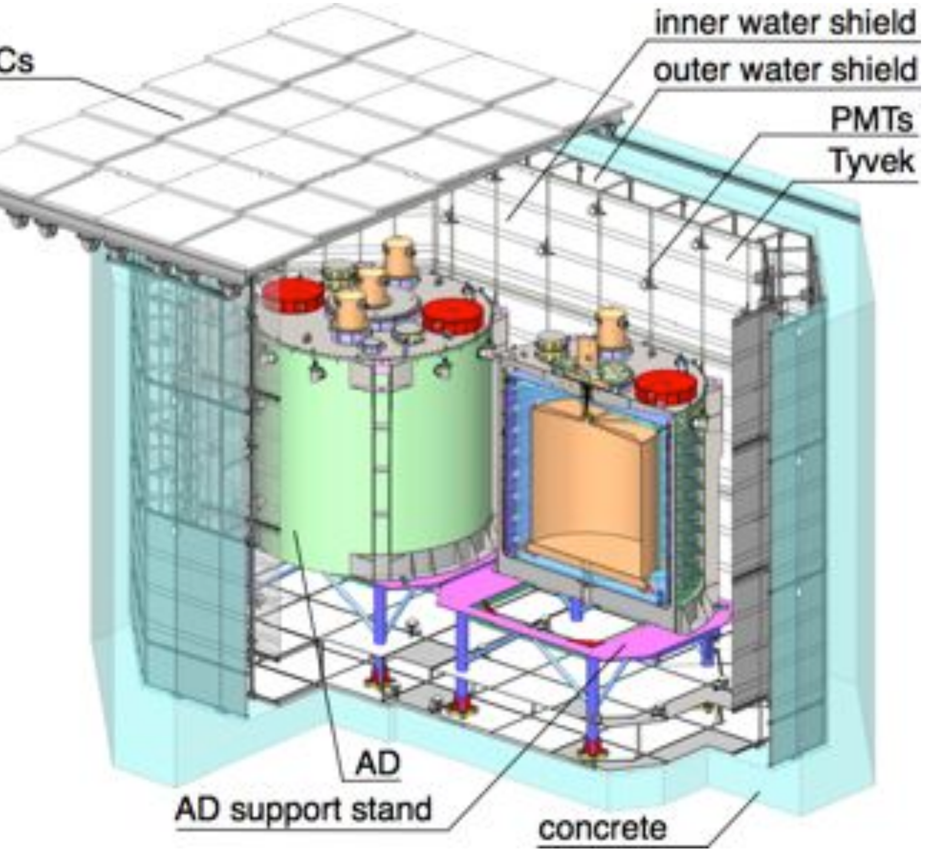
Daya Bay Detectors

6 “functionally identical” detectors
Gd-LS defines target volume, no position cut



target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

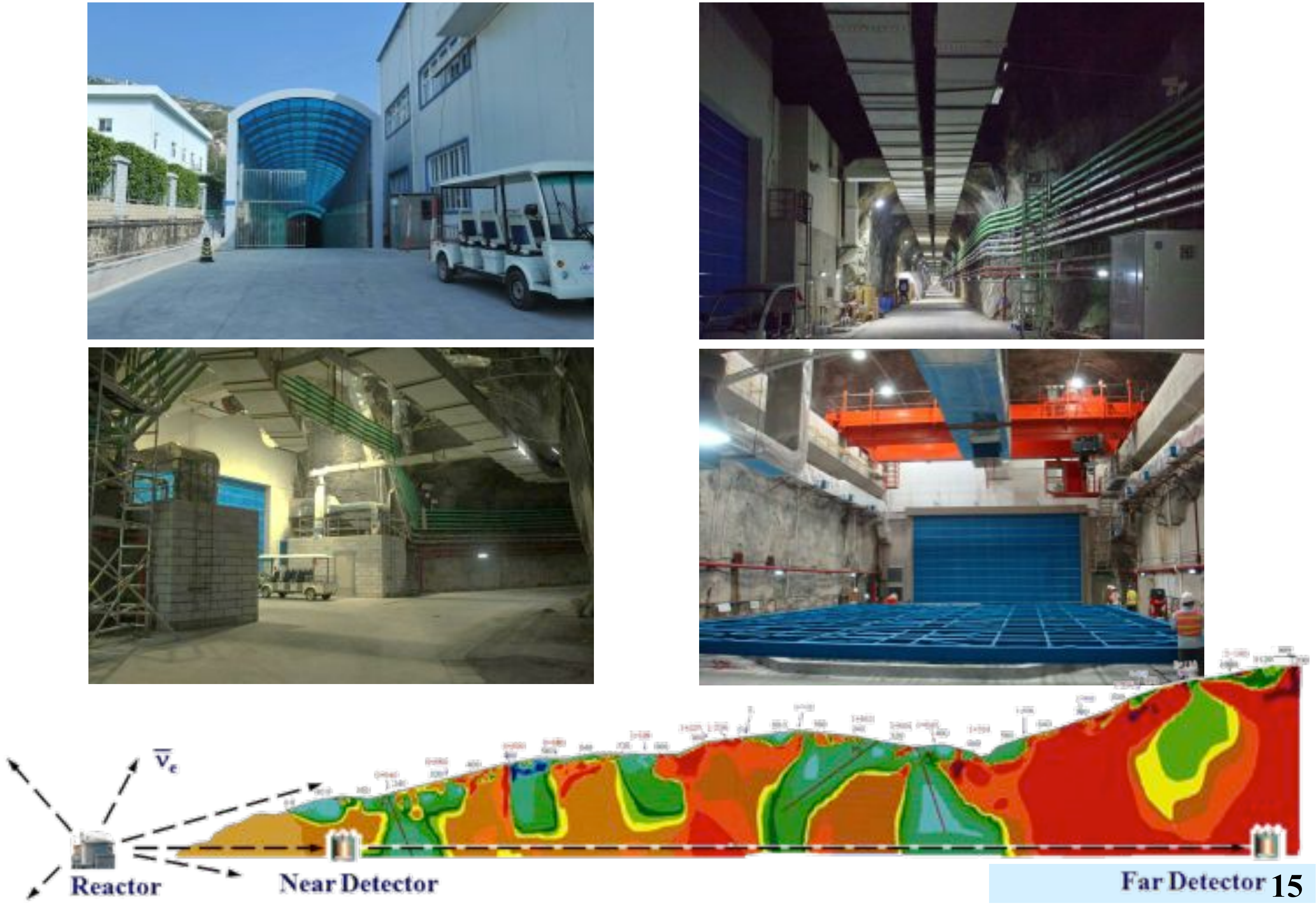
Dual tagging systems: 2.5 meter water shield and RPCs



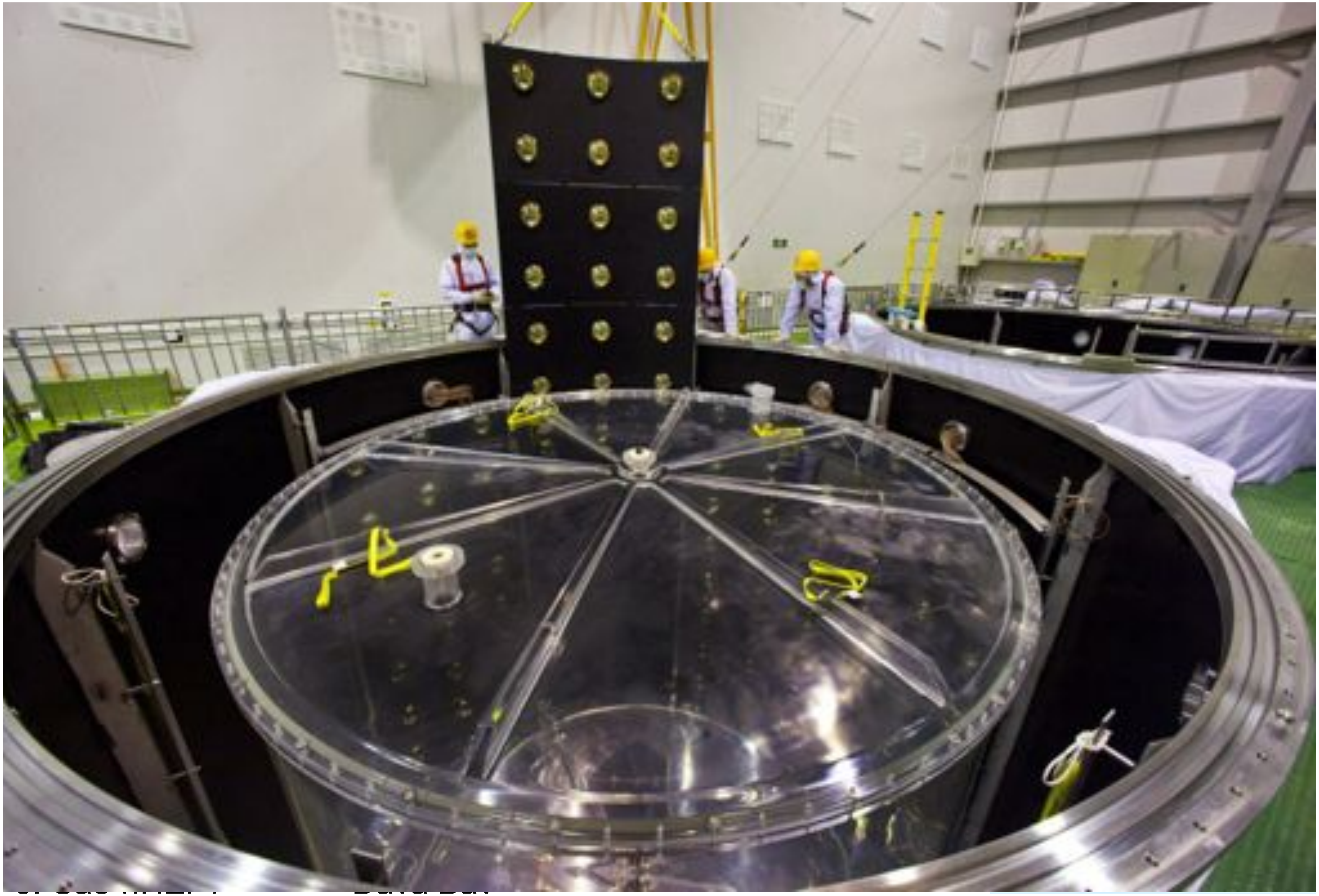
Two-zone ultrapure water Cherenkov detector

multiple detectors allow comparison and cross-checks

Tunnel and Underground Lab.

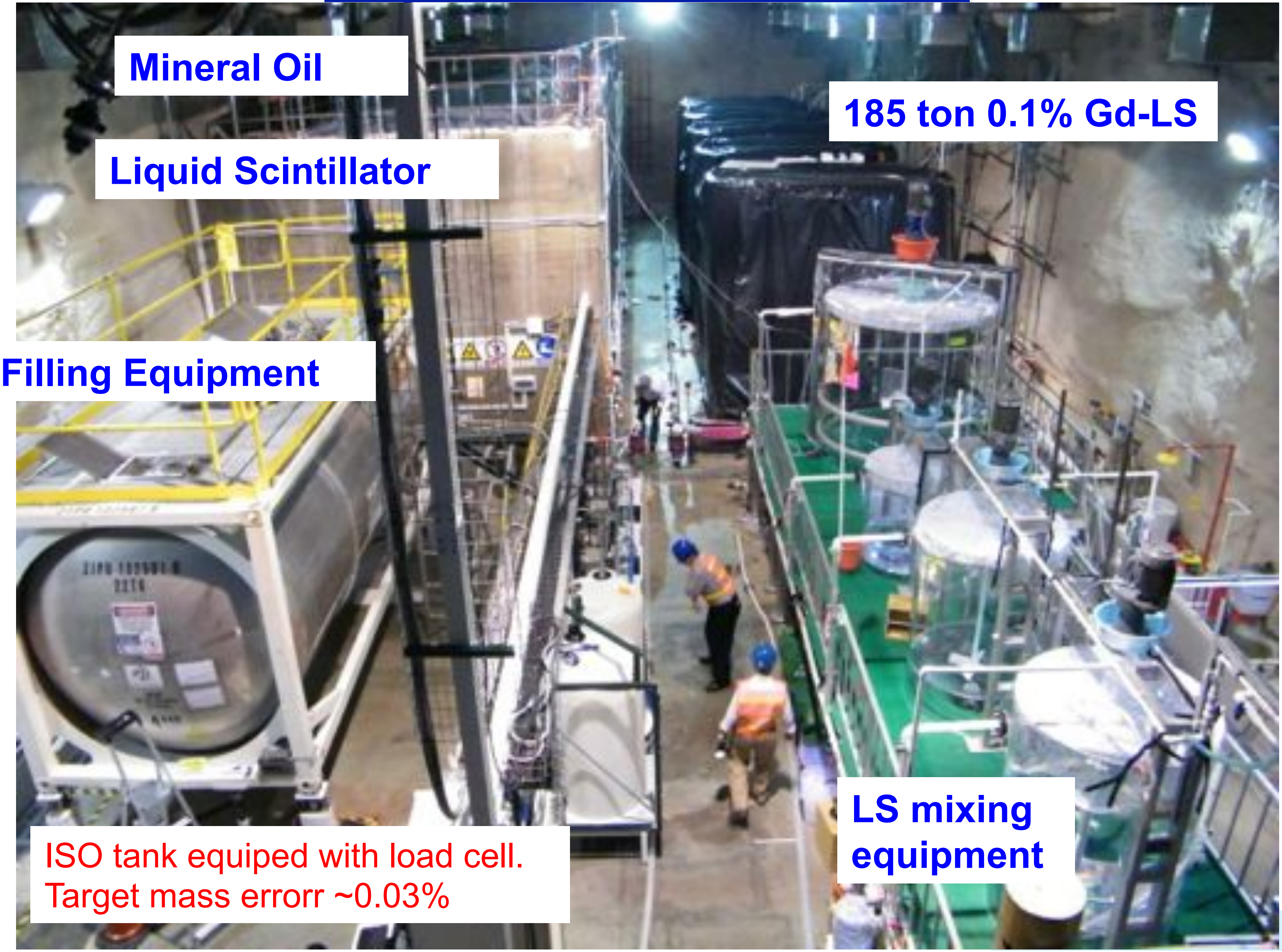


Antineutrino Detector



Muon System Installation

Liquid Scintillator Hall



Mineral Oil

Liquid Scintillator

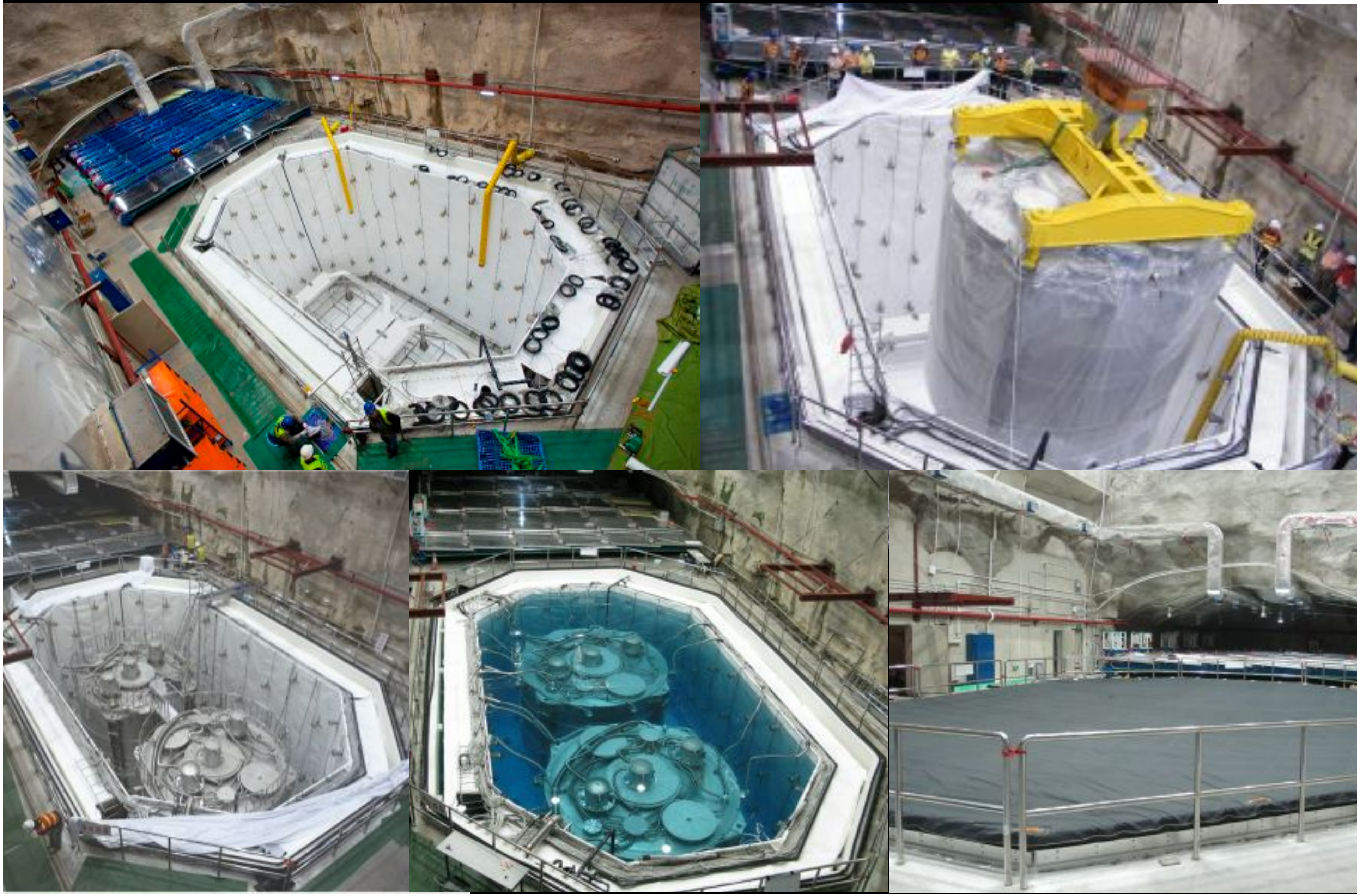
185 ton 0.1% Gd-LS

Filling Equipment

LS mixing equipment

ISO tank equiped with load cell.
Target mass errorr ~0.03%

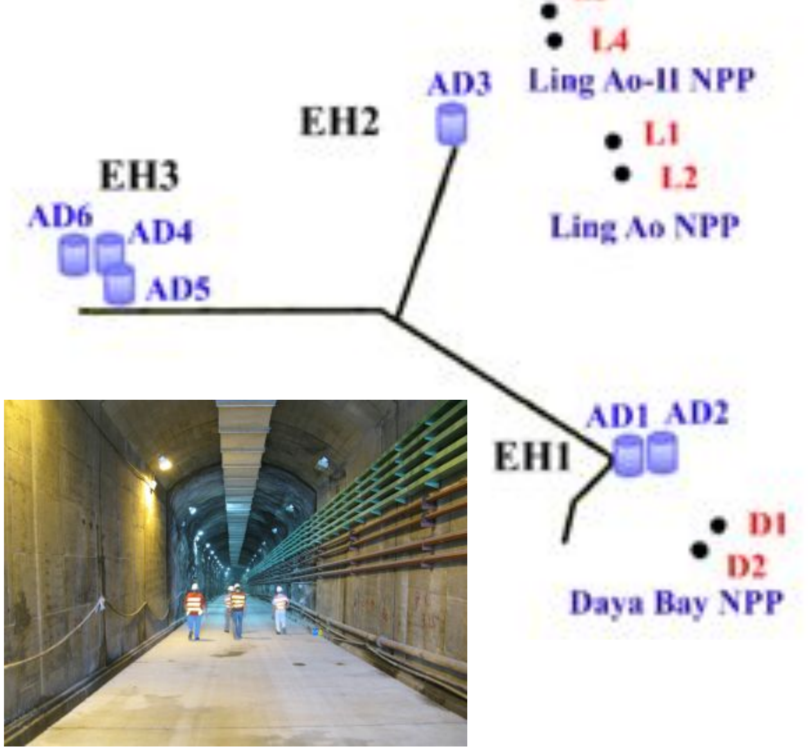
Antineutrino Detector Installation - Near Hall

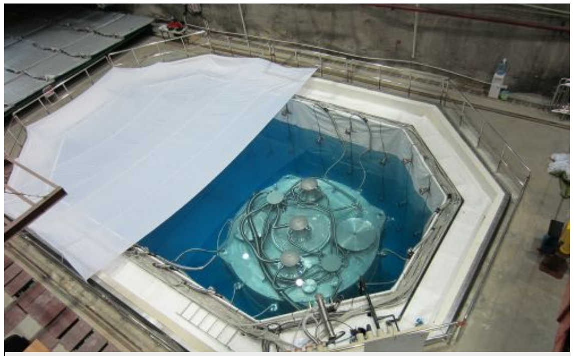


Daya Bay Experiment

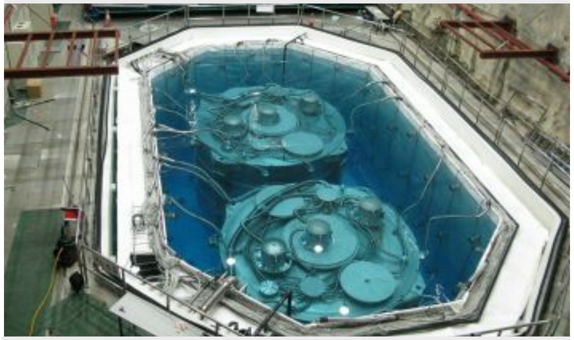
Three Underground Experiment Halls

Hall 3: began 3 AD operation on Dec. 24, 2011





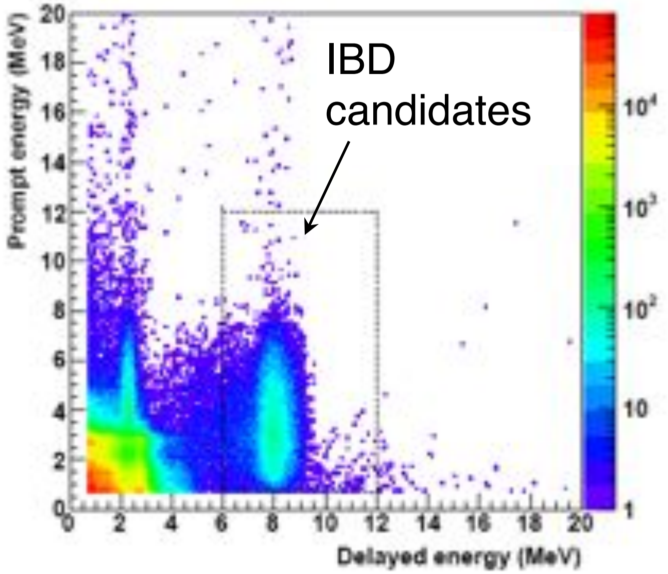
Hall 2: began 1 AD operation on Nov. 5, 2011



Hall 1: began 2 AD operation on Sep. 23, 2011

Antineutrino Candidates (Inverse Beta Decay)

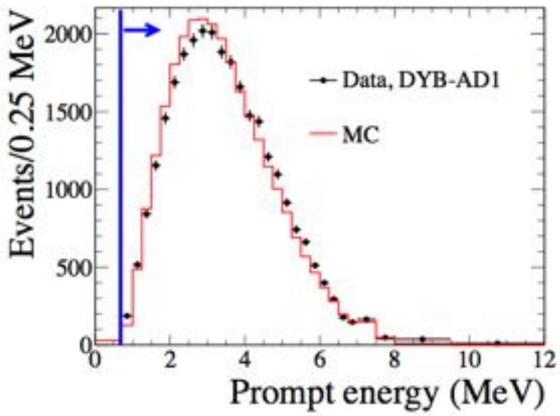
Prompt + Delayed Selection



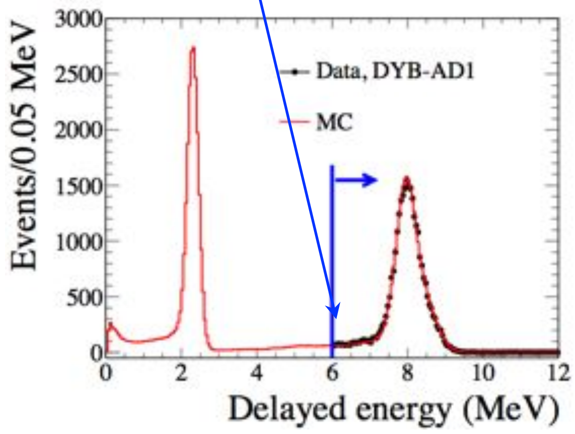
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Uncertainty in relative E_d efficiency (0.12%) between detectors is largest systematic.

Prompt Energy Signal

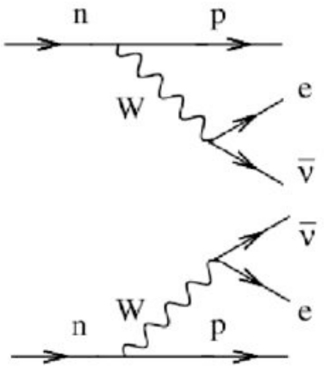


Delayed Energy Signal

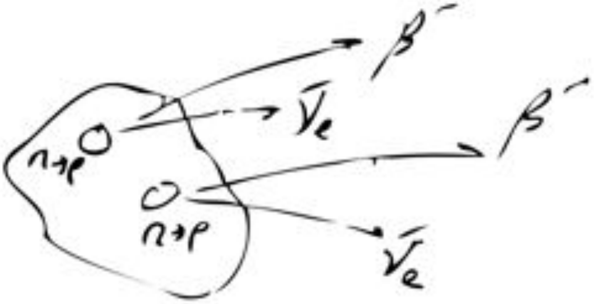


Double-beta decay, with and without neutrinos

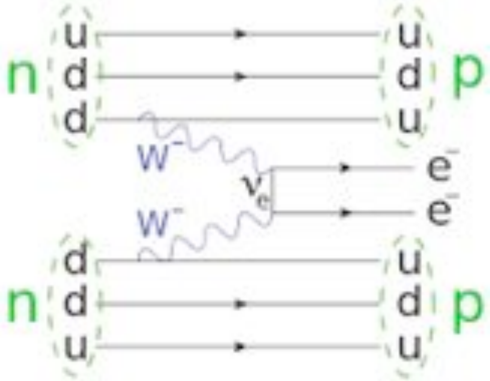
- Ordinary double-beta decay:
  - Simultaneous decays of 2 neutrons in a nucleus



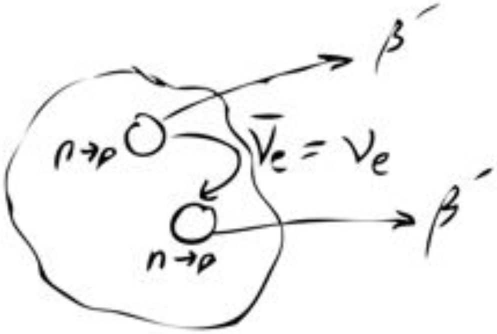
$2\nu\beta\beta$ — $(A,Z) \rightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$
SM Allowed and observed in select even-even isotopes



- *Neutrinoless* double-beta decay:
  - Antineutrinos annihilate **(requires antinu=nu !)**



$0\nu\beta\beta$ — $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$
$\Delta L = 2$



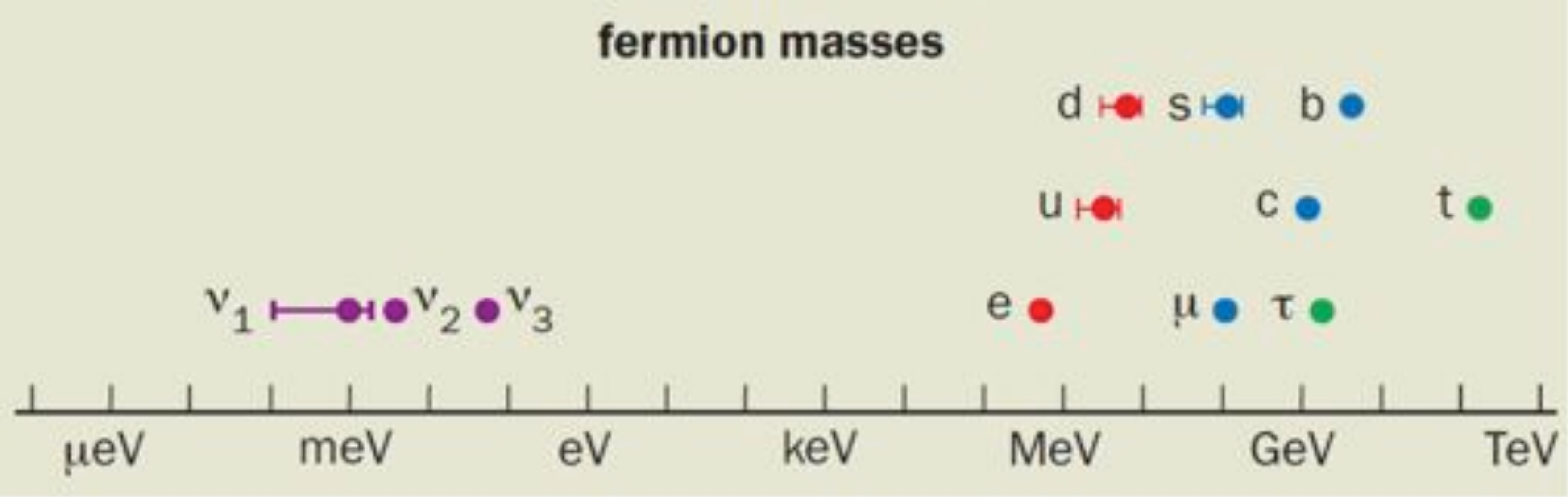
Illustrations in this section from presentations by
J. Detwiler, UW
C. M. O'Shaughnessy,U.N.Carolina, June 2015
S. Elliott, LBNL

Majorana neutrinos

- 1937: Ettore Majorana proposed possibility of spin-1/2 particles (fermions) could be their own antiparticles
  - Neutral spin-1/2 particles are described by a real wave equation (Majorana equation)
  - So, identical to their antiparticle: wave functions of particle and antiparticle are complex conjugates
    - Creation and annihilation operators are identical
  - Standard Model assumes fermions are Dirac particles, with wavefunctions and creation/annihilation operators distinct
- All Standard-Model fermions except neutrinos are known to have distinct antiparticles
  - BUT: non-zero neutrino mass is non-SM
  - Hypothesized "sterile" neutrinos (not observed because they do not display weak interactions, only gravity) could be Majorana
  - In supersymmetry models, neutralinos (superpartners of gauge bosons and Higgs bosons) are Majorana.

Ettore Majorana
1906—1938 (?)
Majorana disappeared from a ferryboat in 1938. Friends presumed suicide. Conspiracy theorists believe he may have hidden in Argentina or Italy and lived until 1959.

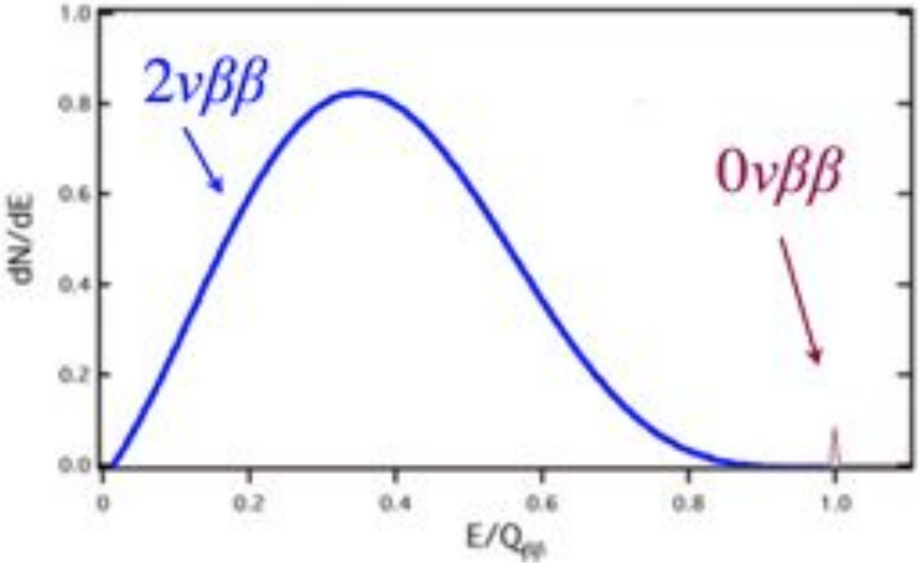
Why are neutrino masses so much smaller than everybody else?



- Do they relate to Supersymmetry?
- Are they Majorana fermions?
- Could this be connected to matter/antimatter asymmetry in the Universe (do neutrinos exhibit CP violation) ?

0νββ Discovery Considerations

- Need large, highly efficient source mass
- Desire extremely low (near-zero) backgrounds in the 0νββ peak region
  - ➡ Signal background 1:1 or better
  - ➡ Best possible resolution, ΔE, to minimize region of interest
- Want best possible energy resolution and/or kinematical method to discriminate 0νββ from 2νββ



Tonne scale experiments require backgrounds of ≤1 cts / ROI-t-y

Need independent observations from different isotopes

One approach: Use ultra-pure Germanium detectors

Source = Detector

Intrinsically high purity, elemental Ge

Demonstrated ability to enrich to 86% ^{76}Ge

0.16% energy resolution at 2039 keV

Well-understood technologies

- Commercial Ge diodes

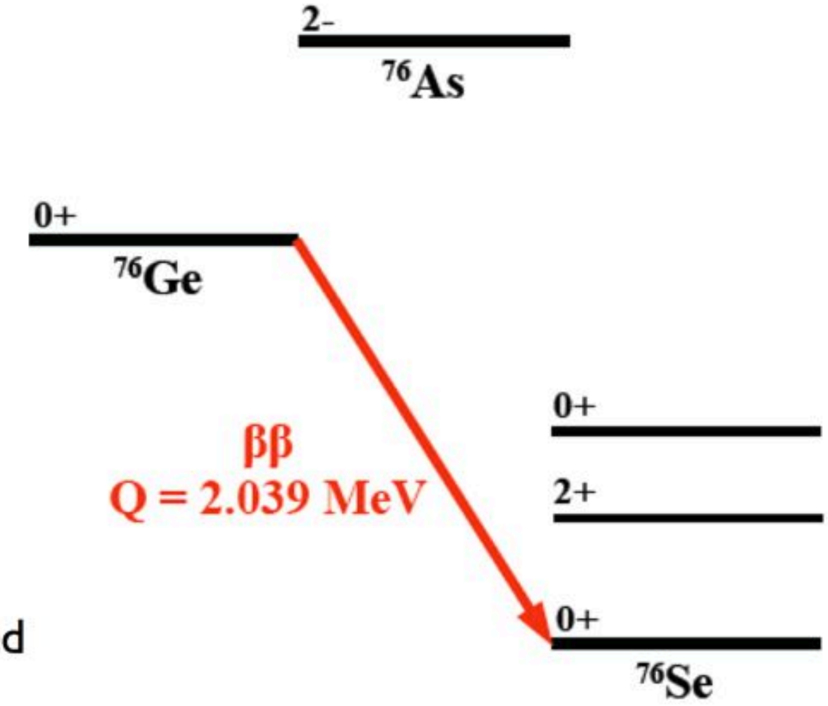
Majorana Experiment design:

Modules of 57 close-packed, 1.1 kg, segmented n-type HPGe detectors enriched to 86% ^{76}Ge

Independent cryostats made of ultra-clean electroformed Cu

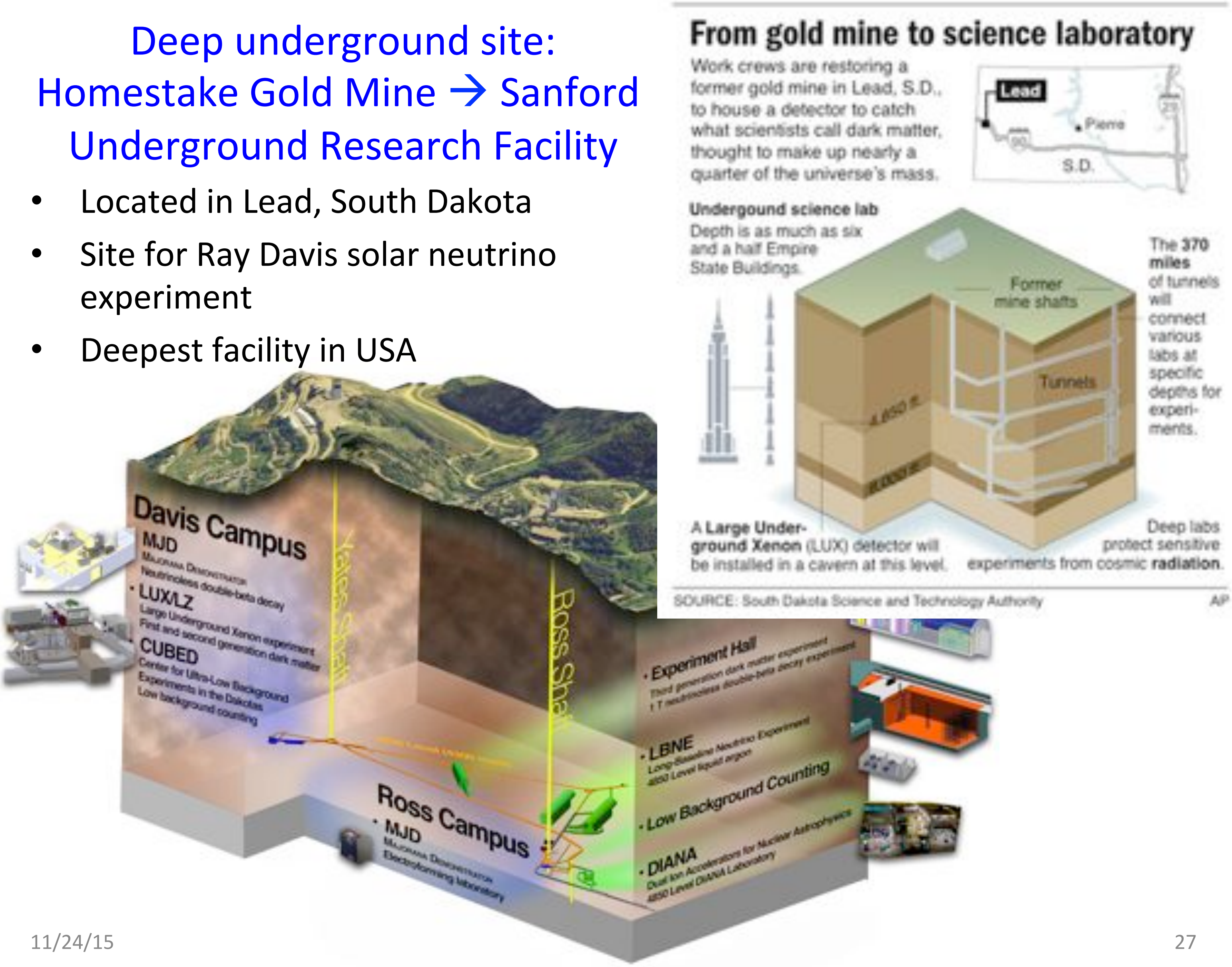
Low background passive lead + electroformed Cu shield and 4π active veto

Located deep underground (4500-6000 mwe)



Deep underground site: Homestake Gold Mine → Sanford Underground Research Facility

- Located in Lead, South Dakota
- Site for Ray Davis solar neutrino experiment
- Deepest facility in USA



From gold mine to science laboratory

Work crews are restoring a former gold mine in Lead, S.D., to house a detector to catch what scientists call dark matter, thought to make up nearly a quarter of the universe's mass.

Undergound science lab

Depth is as much as six and a half Empire State Buildings.

The **370 miles** of tunnels will connect various labs at specific depths for experiments.

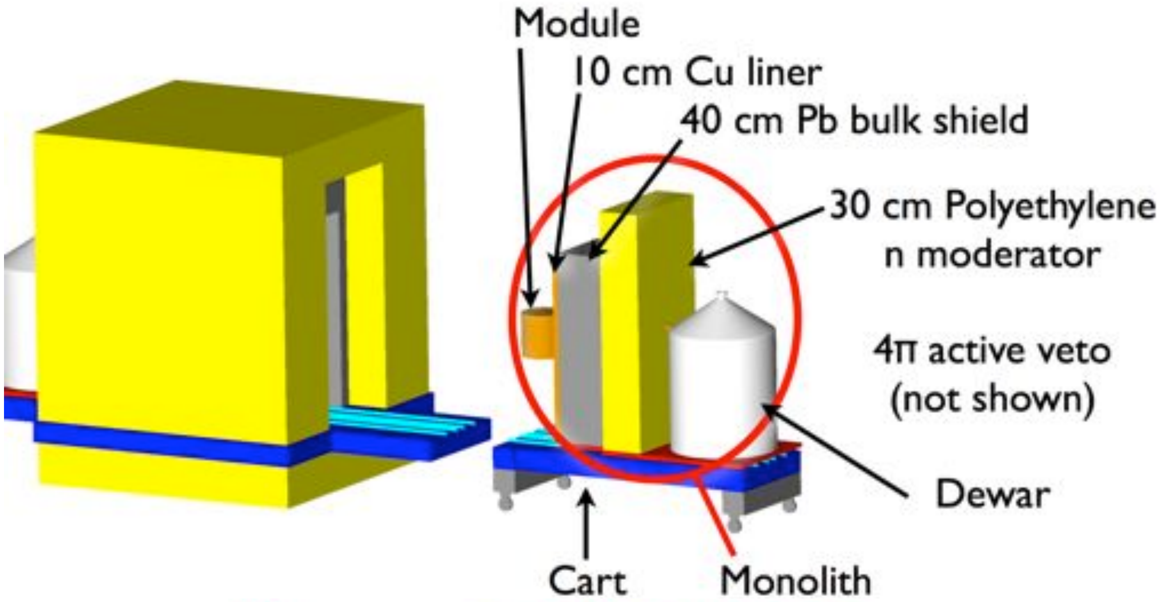
A **Large Underground Xenon** (LUX) detector will be installed in a cavern at this level.

Deep labs protect sensitive experiments from cosmic **radiation**.

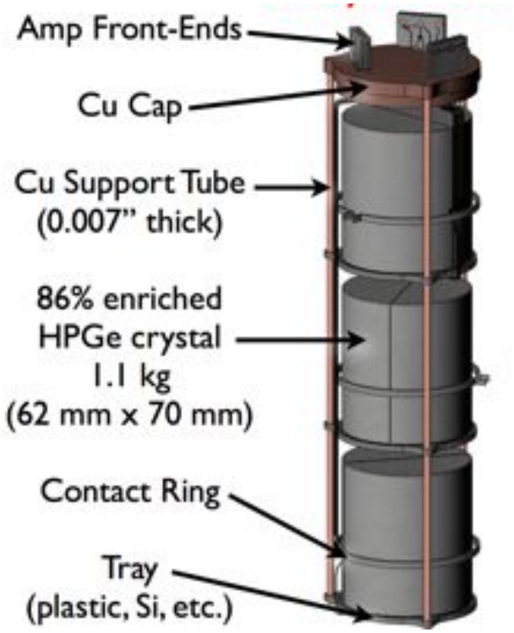
SOURCE: South Dakota Science and Technology Authority — AP

Majorana Experiment (US-Canada-Russia-Japan)

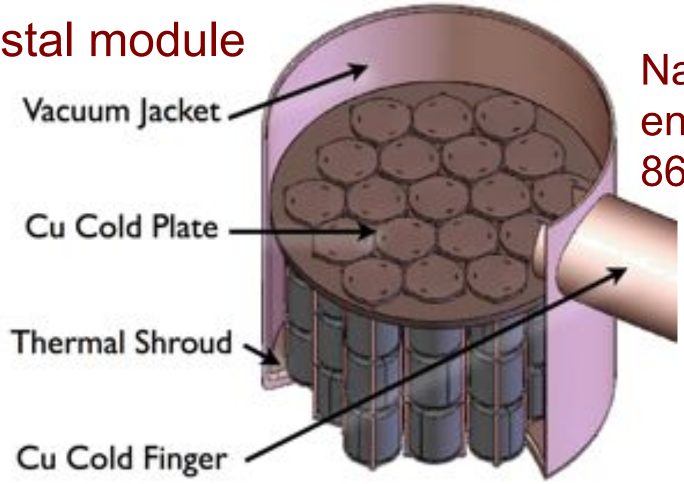
- Ge detectors in super-low BG site (Davis campus in SURF, 4850 ft deep)



3-module string



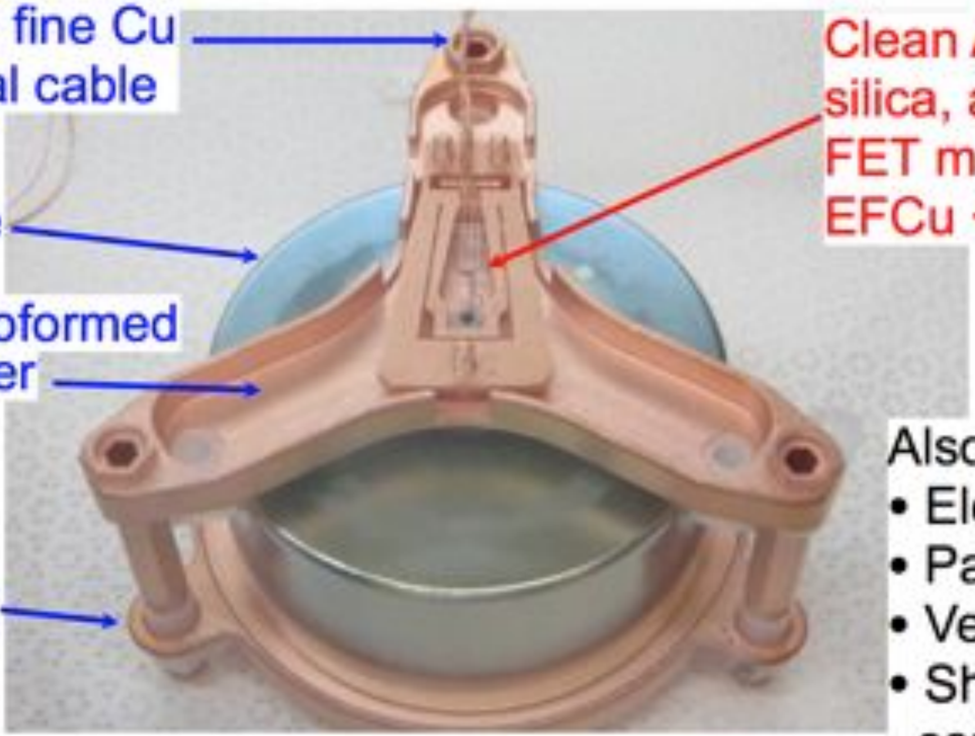
57-crystal module



Natural Ge enriched to 86% ^{76}Ge

Modular – expand to 1 ton total Ge

Individual Ge crystal in Cu mounting



Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn contact pin

Also:
- Electroformed Cryostats
- Parylene coating / seals
- Vespel, PEEK supports (other plastics)
- Shields: Low-BG commercial Cu and Pb


Electroforming Baths in TCR

Inspection of EF copper on mandrels

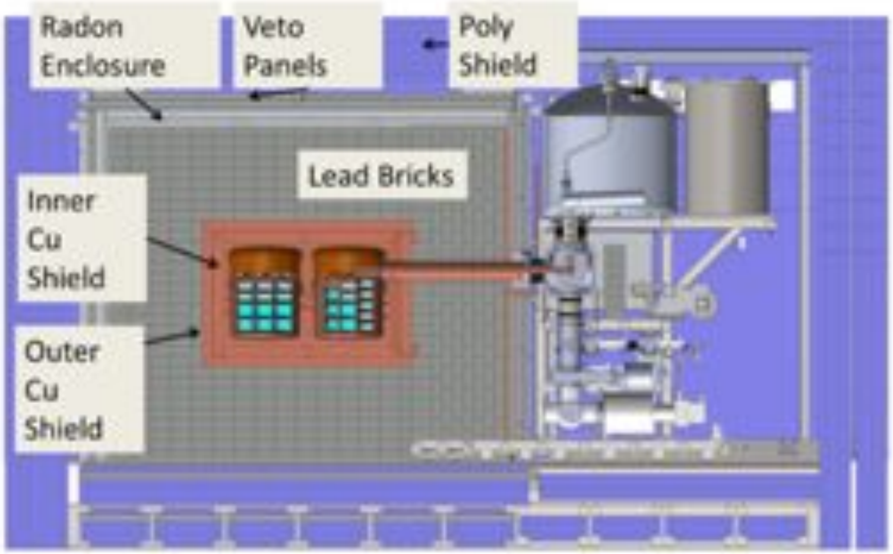
EF copper after machining

- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg

For now: demonstrator project with 44 kg Ge

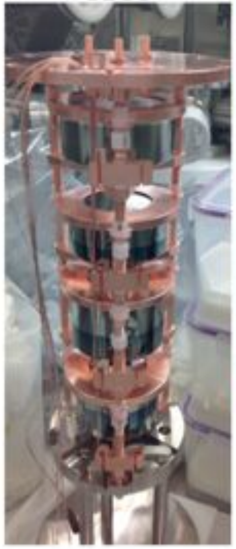
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

- **Located underground at 4850' Sanford Underground Research Facility**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  3 counts/ROI/t/y (after analysis cuts) **Assay U.L. currently ≤ 3.5**
  scales to 1 count/ROI/t/y for a tonne experiment
- **44 kg of Ge detectors**
  - 29 kg of 87% enriched ^{76}Ge crystals
  - 15 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- **Compact Shield**
  - low-background passive Cu and Pb shield with active muon veto

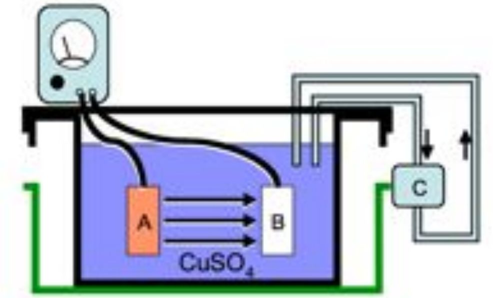


Ultra-low-BG high-purity electroformed Cu mountings for Ge crystals

String with
3 ^{Enr}Ge PPCs
and 1 ^{Nat}Ge
BEGe



- Up to 5 detectors are mounted in 'strings'

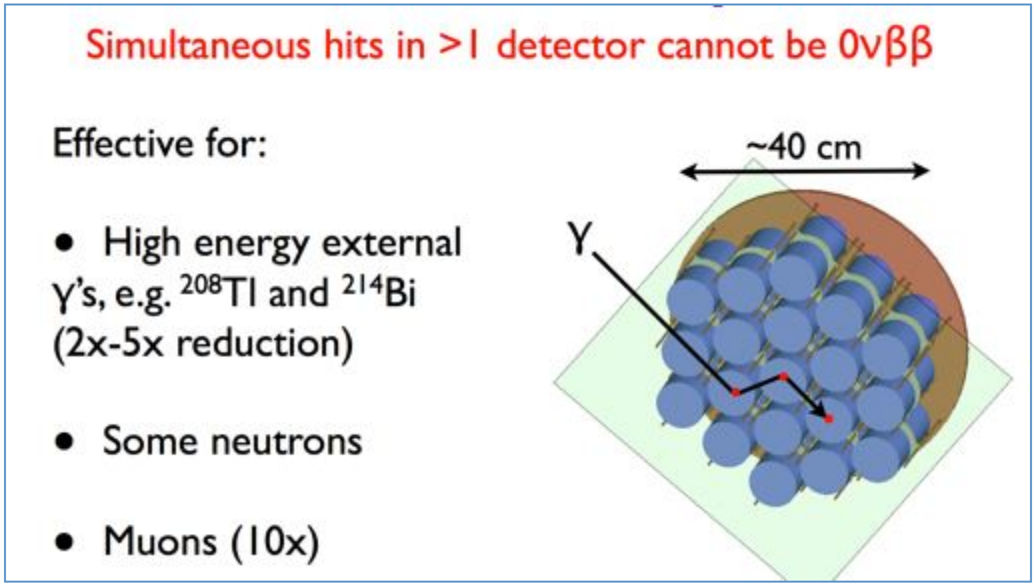


- Semiconductor-grade acids, recrystallized $CuSO_4$, high-purity copper stock
- Baths circulated with microfiltration, barium scavenge; cover gas
- Active plating manipulation, surface machining, cleaning, and passivation

- ^{232}Th < 1 μBq/kg
- Recently improved bath chemistry: requires less surface finishing
- Improved starting stock quality and handling

Event selection for background rejection

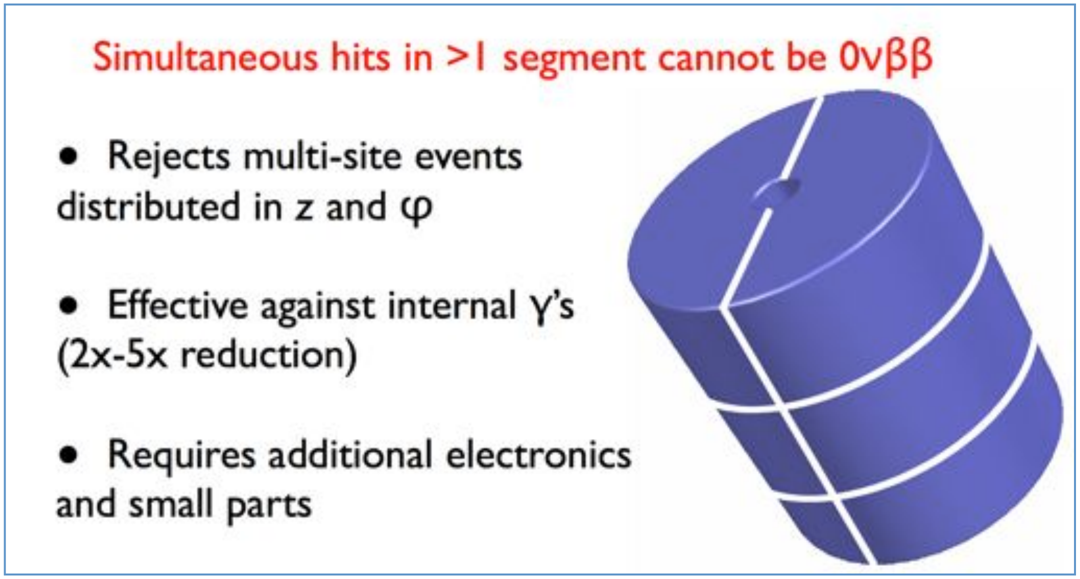
- Main BGs:
  - High energy gammas
  - Neutrinos
  - Muon interactions
    - Spallation products



Simultaneous hits in >1 detector cannot be 0νββ

Effective for:

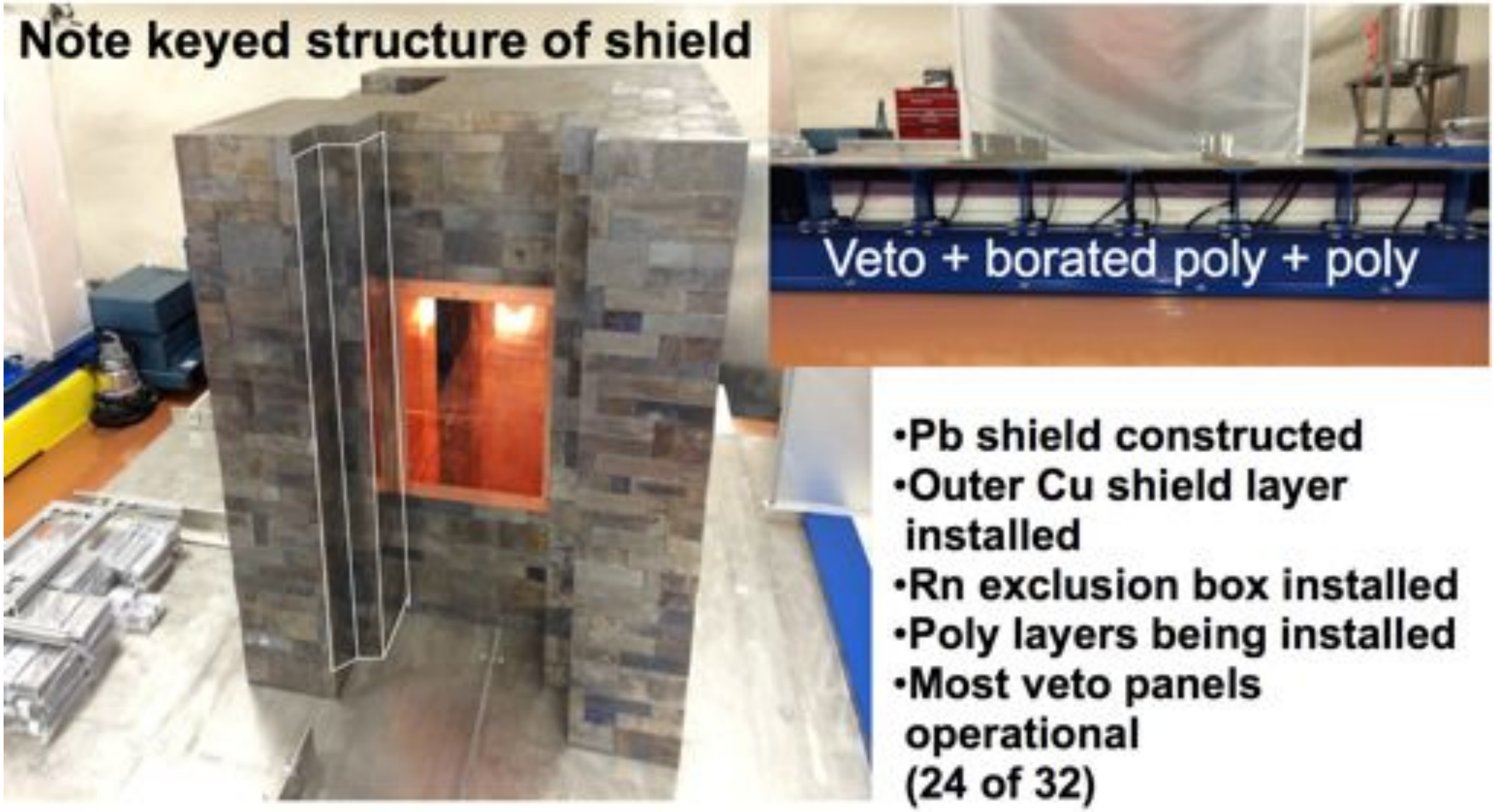
- High energy external γ's, e.g. ^{208}Tl and ^{214}Bi (2x-5x reduction)
- Some neutrons
- Muons (10x)



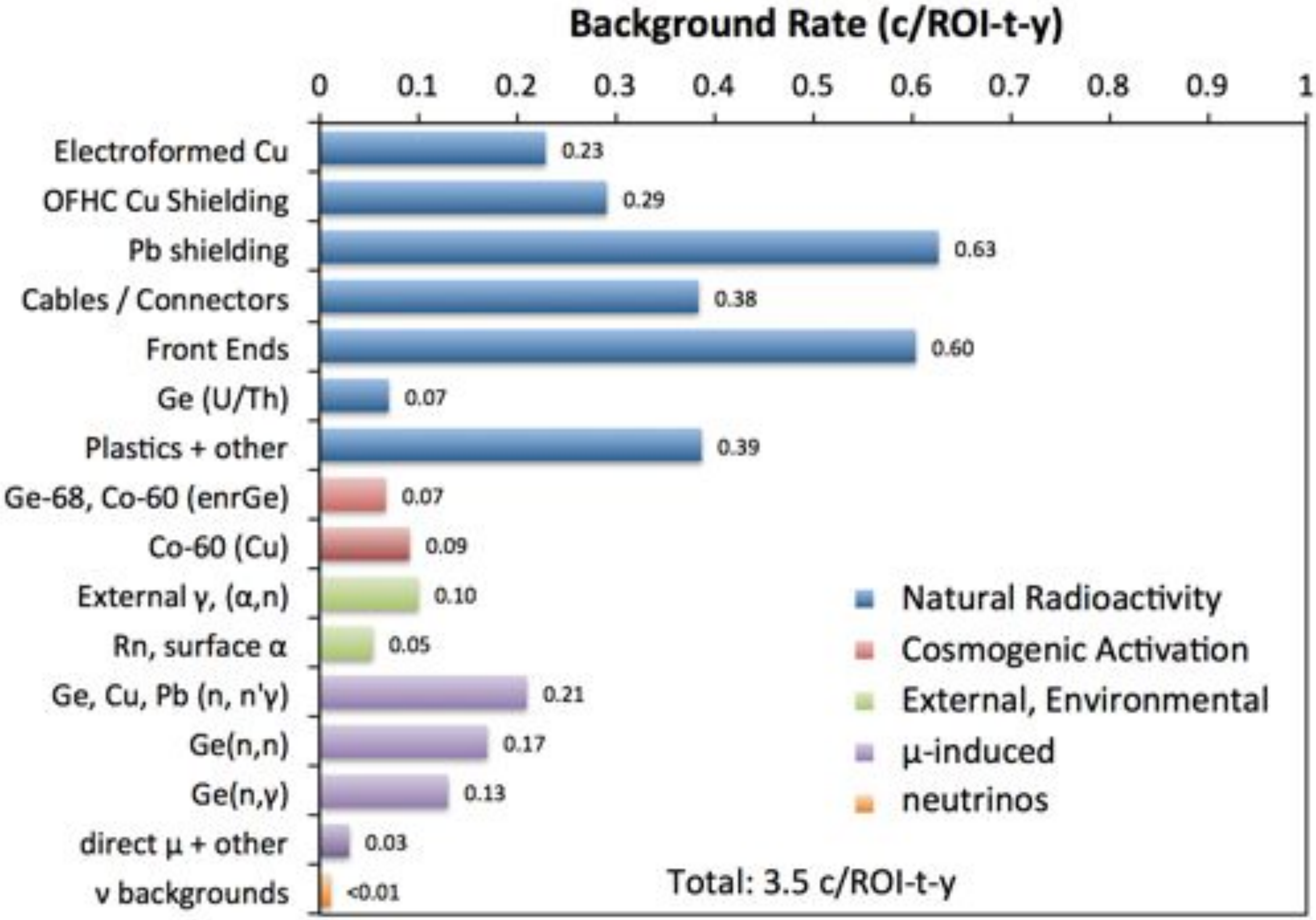
Simultaneous hits in >1 segment cannot be 0νββ

- Rejects multi-site events distributed in z and φ
- Effective against internal γ's (2x-5x reduction)
- Requires additional electronics and small parts

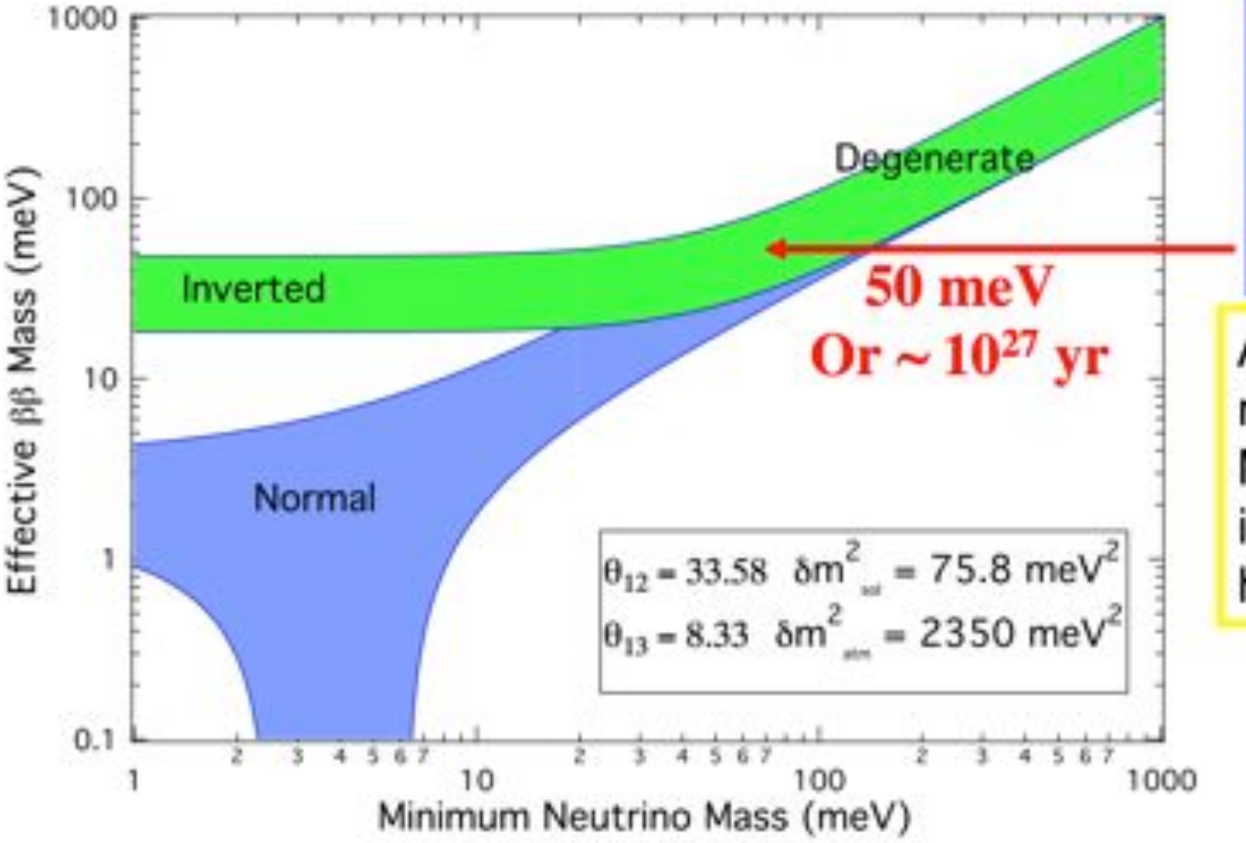
Shielding against neutrons and gammas



- Pb shield constructed
- Outer Cu shield layer installed
- Rn exclusion box installed
- Poly layers being installed
- Most veto panels operational (24 of 32)


Background Rate (c/ROI-t-y)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Electroformed Cu
0.23
OFHC Cu Shielding
0.29
Pb shielding
0.63
Cables / Connectors
0.38
Front Ends
0.60
Ge (U/Th)
0.07
Plastics + other
0.39
Ge-68, Co-60 (enrGe)
0.07
Co-60 (Cu)
0.09
External γ, (α,n)
0.10
Rn, surface α
0.05
Ge, Cu, Pb (n, n'γ)
0.21
Ge(n,n)
0.17
Ge(n,γ)
0.13
direct μ + other
0.03
ν backgrounds
<0.01
Natural Radioactivity
Cosmogenic Activation
External, Environmental
μ-induced
neutrinos
Total: 3.5 c/ROI-t-y

Majorana goals: milli-eV neutrino mass determination, as well as Majorana/Dirac determination



50 meV

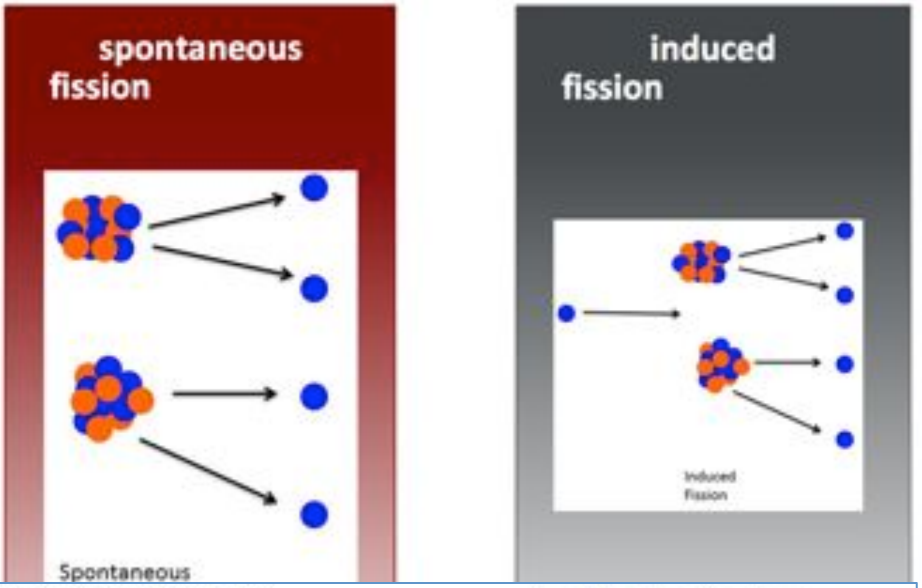
Or ~10^{27} yr

Even a null result will constrain the possible mass spectrum possibilities!

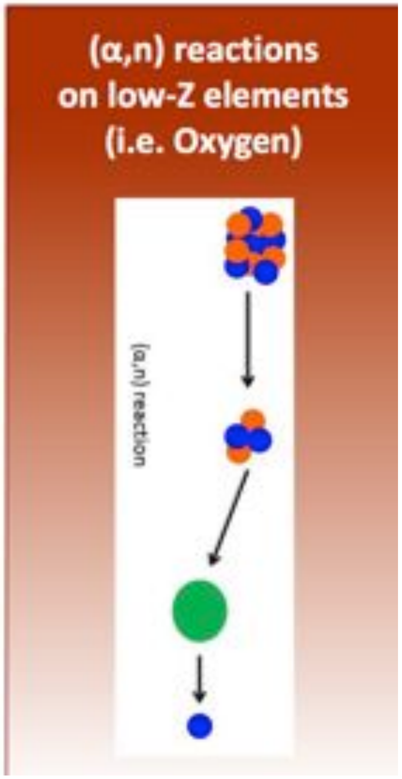
A $m_{\beta\beta}$ limit of ~15 meV would disfavor Majorana neutrinos in an inverted hierarchy.

Neutron detectors

Nuclear materials emit neutrons from 3 different processes:


spontaneous fission

induced fission


(α,n) reactions on low-Z elements (i.e. Oxygen)

Neutron Fission Spectrum

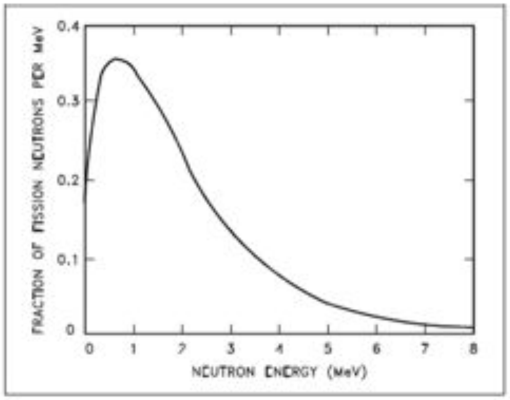
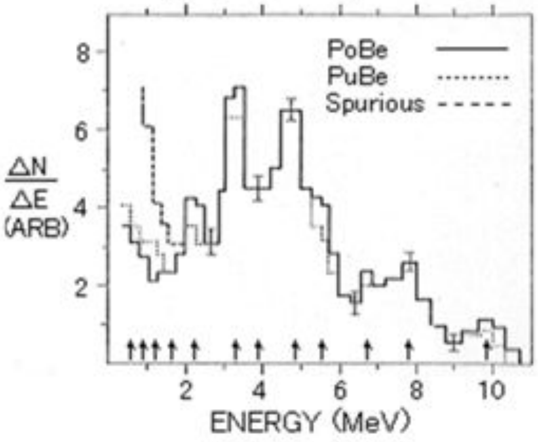


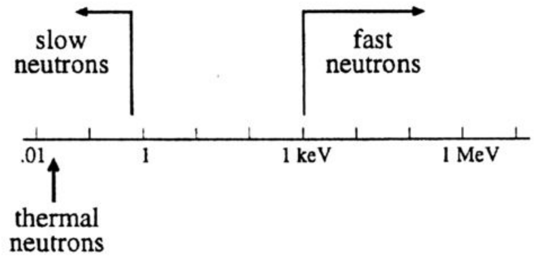
Figure 2 Prompt Fission Neutron Energy Spectrum for Thermal Fission of Uranium-235

Source : DOE Fundamentals Handbook, Nuclear Physics and Reactor Theory DOE-HDBK-1019/1-93

(α,n) Neutron Spectrum



Source : Cember, 4th ed.



Illustrations in this section from: Neutron Detection Systems, Robert Runkle, PNNL Radiation Detection for Nuclear Security Summer School 2014

Neutron detectors

- Neutron detectors use nuclides that capture n and emit charged particles
- Reactions used include (σ's below are for thermal n's)
  - 10B(n,α) [σ ~4000 b] → 2.31 and 2.79 MeV Q values → ~1.5 MeV alphas
  - 6Li(n,α) [σ ~1000 b] → 4.78 MeV Q → ~ 2 MeV alphas
  - 3He(n,p) [σ ~5000 b] → 0.76 MeV Q → ~ 0.6 MeV protons
  - 157Gd (many reactions, to gammas and e's) [σ ~250,000 b !]
- Boron (BF_3 gas, or B-coated) proportional tubes
  - Inner surface of ionization chamber is covered with a thin coat of boron, or BF3 gas is used to fill the PC
  - Neutron is captured by a boron atom and an energetic alpha particle is emitted

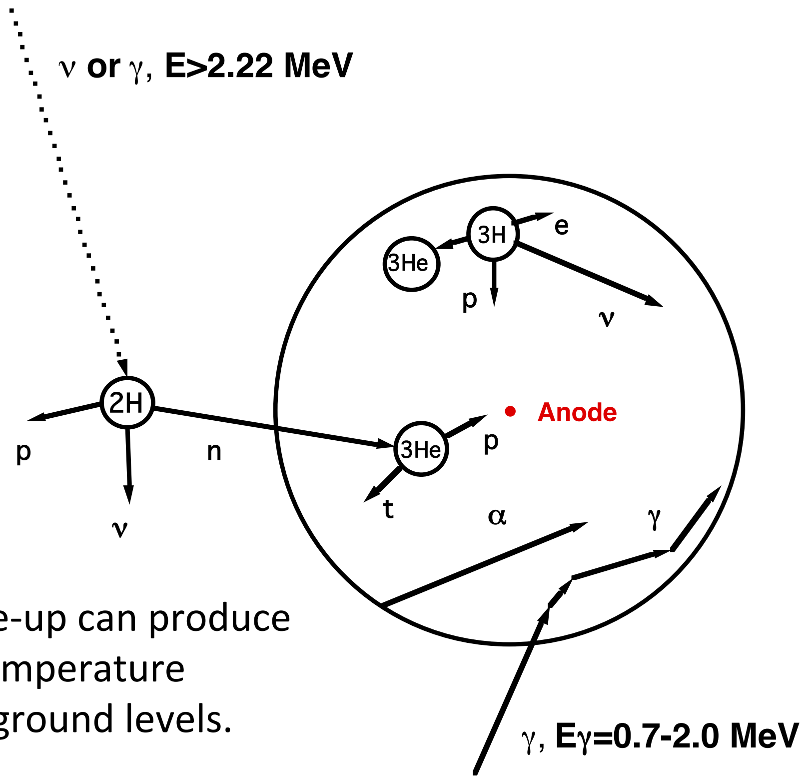
$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li^{+++} + ^{4}_{2}He^{++} + 5e^{-}$$

  - Alpha particle and e's cause ionization within the chamber


www.centronic.co.uk

Neutron detectors

- ^{3}He proportional tubes
  - Example: SNO neutrino detector
    - Neutrino Signal: Neutron from NC interaction
    - Neutrons capture via 3He(n,p)3H in the NCD and produce 573 keV p + 191 keV tritium ionization tracks.



www.sno.phy.queensu.ca/

Distinguishable Backgrounds:

- Tritium in 3He

3H decays deposit on average 6 keV in the gas but pile-up can produce proportional counter signals above threshold. Low-temperature purification of the 3He has resulted in negligible background levels.

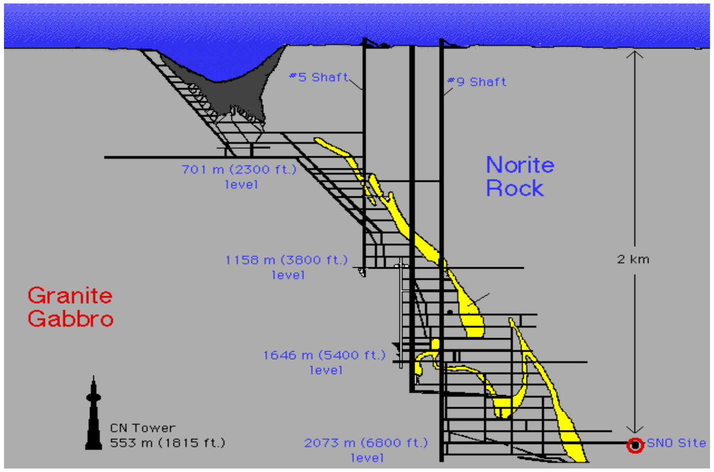
- Surface and Bulk Alpha Activity

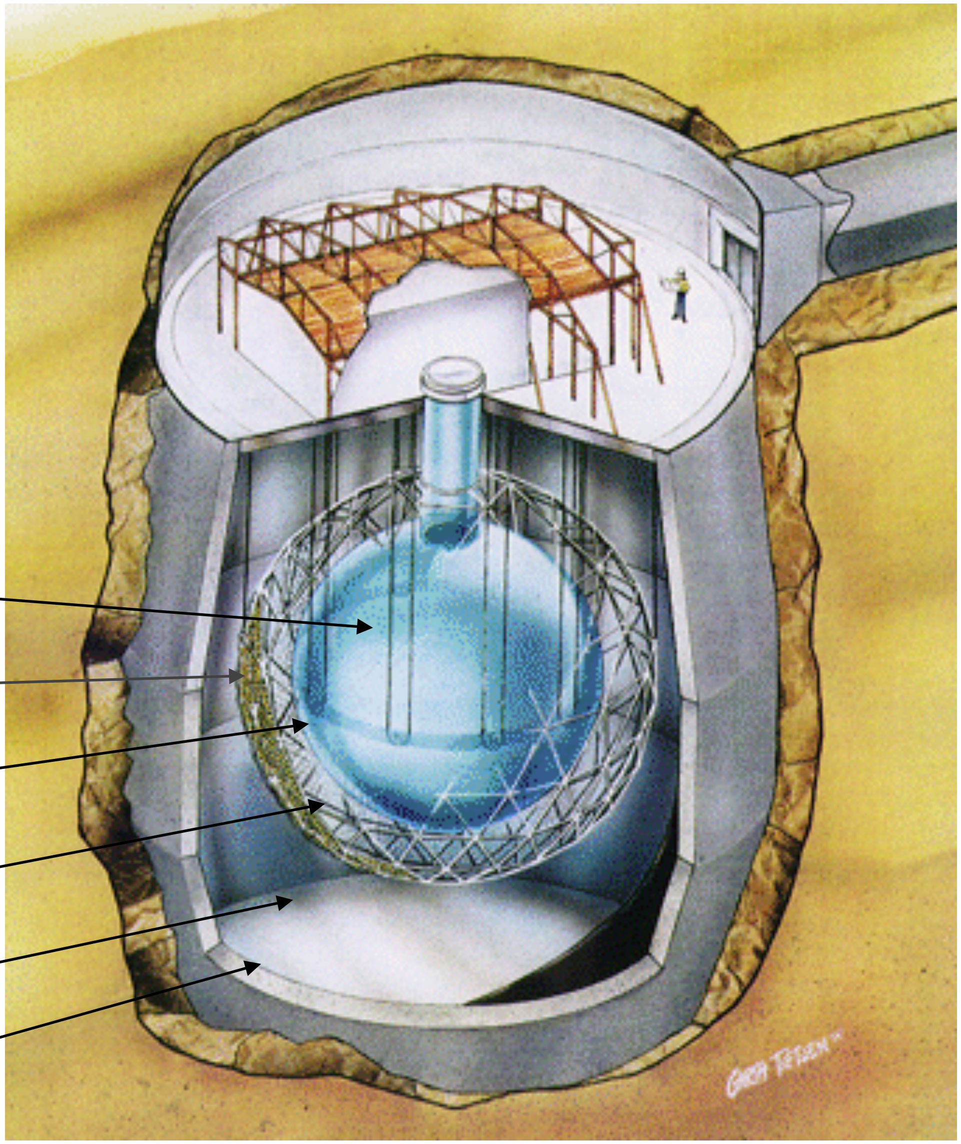
232Th and 238U chains in the NCD walls, along with 210Po surface activity, produce α's that underlie the neutron capture peak. These events can be rejected by event by event analysis of digitized pulses.
(see "Event Identification by Pulse Shape Analysis")

- Electrons and Gammas

betas and gammas from the 232Th and 238U chains only deposit 764 keV through extensive multiple scattering. Less than 2x10-4 fall into the neutron window.

Sudbury Neutrino Observatory





1000 tonnes D_2O

Support Structure for 9500 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

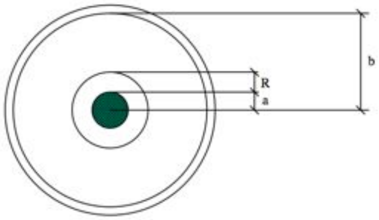
Urylon Liner and Radon Seal

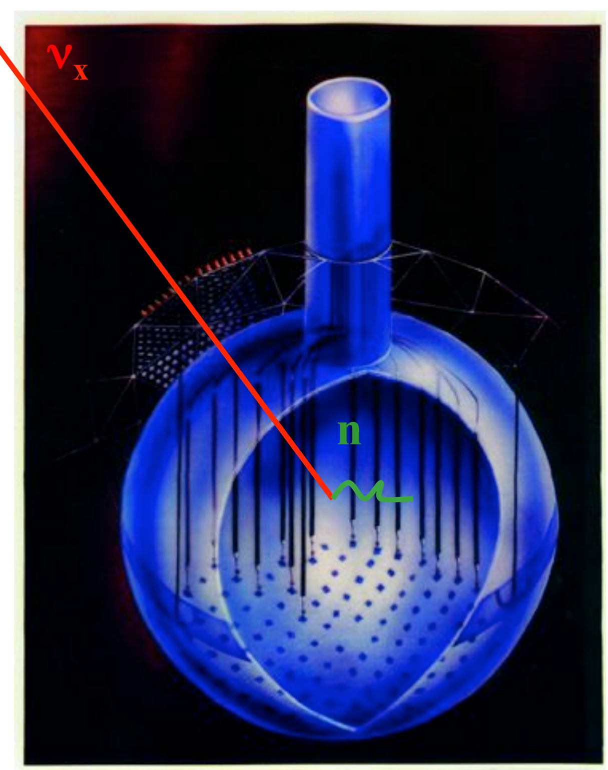
SNO Neutral Current Detection Array

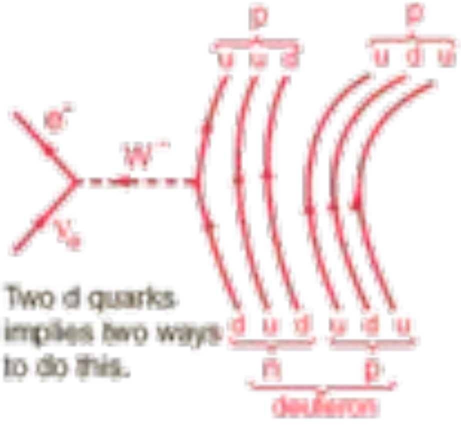
NCD Array:

^{3}He proportional counters detect the neutrons liberated from deuterium by neutrinos.

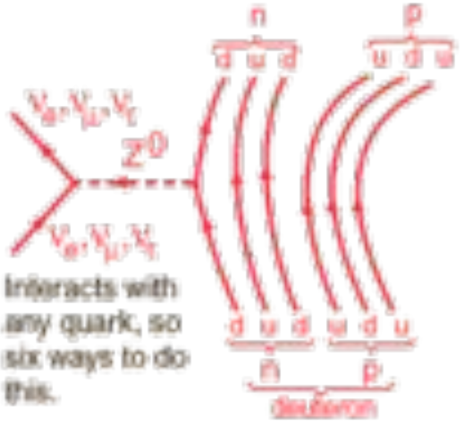
Total Length:	398 m
Vertical Strings:	40
n capture efficiency:	ε_n~21%







Charged current reaction, electron neutrinos only.



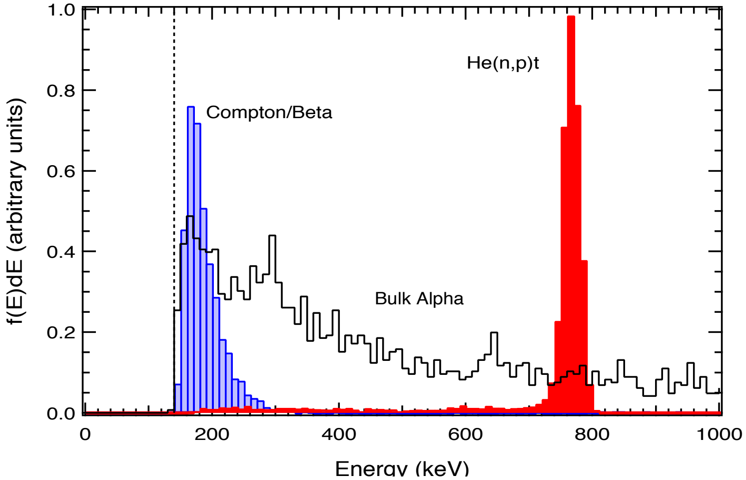
Neutral current reaction, all neutrinos.

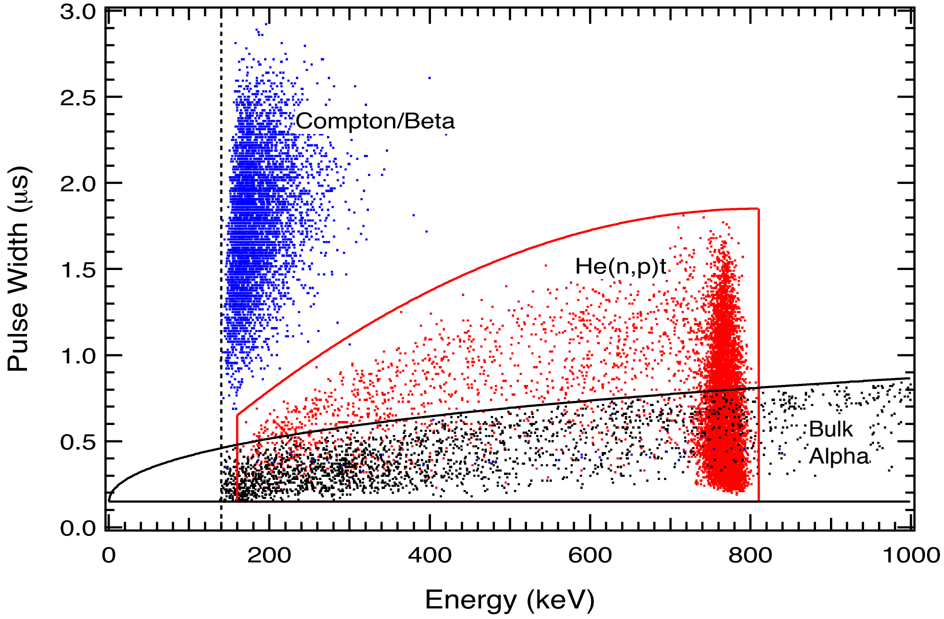
Elastic scattering with any neutrino.

Neutral-current process (Z^0 boson) is equally sensitive to all flavors of nu

SNO NC detectors

- Correlated E and pulse width identifies NC events from BG



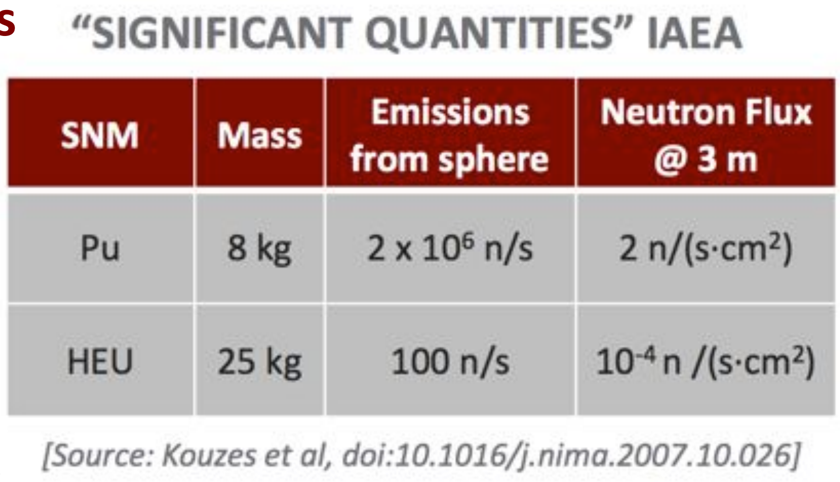


Neutron detectors

Neutron Detectors for Security Monitors

“Significant Nuclear Material (SNM)” = Plutonium and highly enriched Uranium

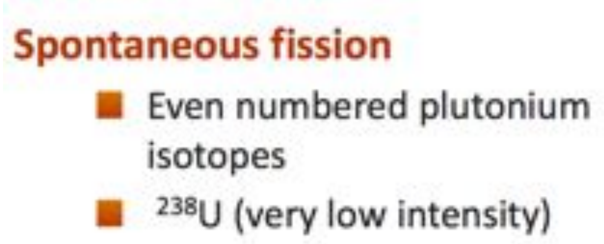
Neutrons are not emitted with significant intensity from natural sources



“SIGNIFICANT QUANTITIES” IAEA

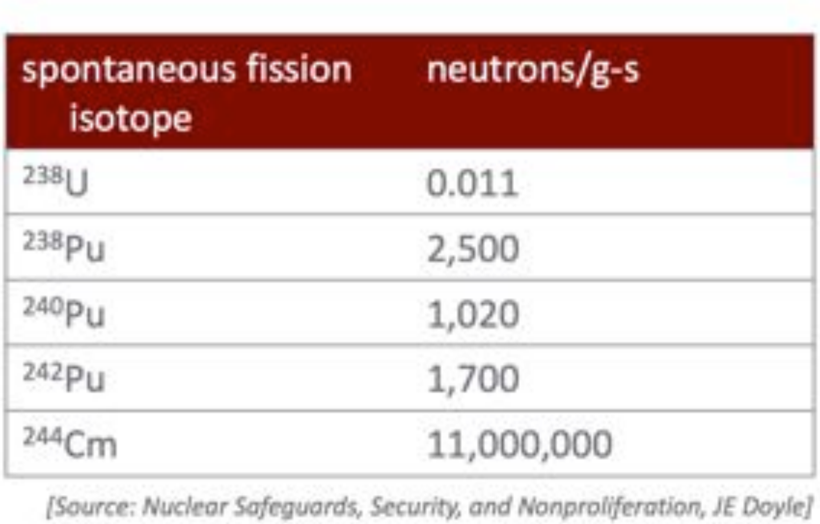
SNM	Mass	Emissions from sphere	Neutron Flux @ 3 m
Pu	8 kg	2×10^6 n/s	2 n/(s·cm^2)
HEU	25 kg	100 n/s	10^{-4} n /(s·cm^2)

[Source: Kouzes et al, doi:10.1016/j.nima.2007.10.026]



Spontaneous fission

- Even numbered plutonium isotopes
- ^{238}U (very low intensity)

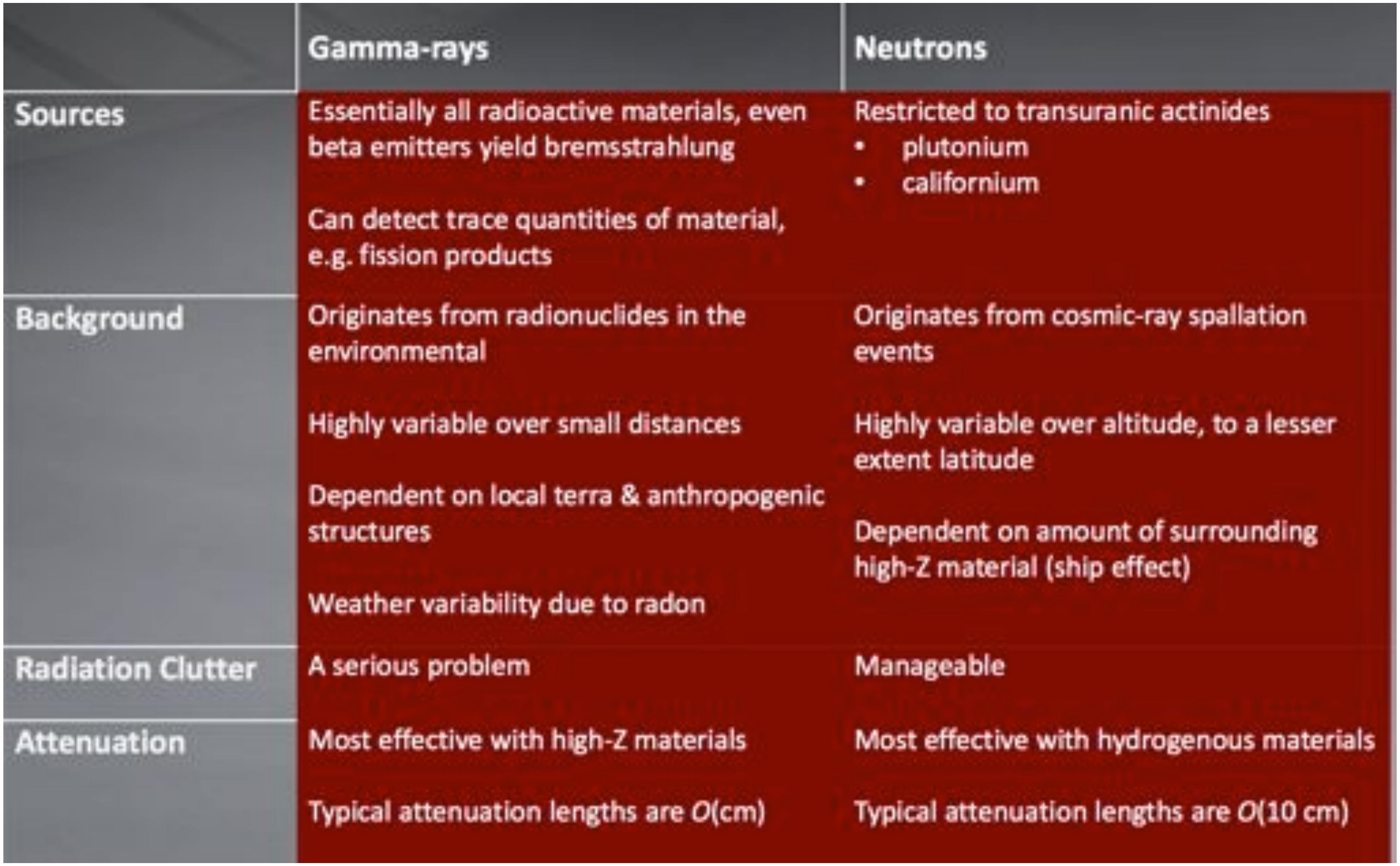


spontaneous fission isotope	neutrons/g-s
^{238}U	0.011
^{238}Pu	2,500
^{240}Pu	1,020
^{242}Pu	1,700
^{244}Cm	11,000,000

[Source: Nuclear Safeguards, Security, and Nonproliferation, JE Doyle]

Neutron detectors

- Why not use widely available, highly efficient gamma-ray detectors?

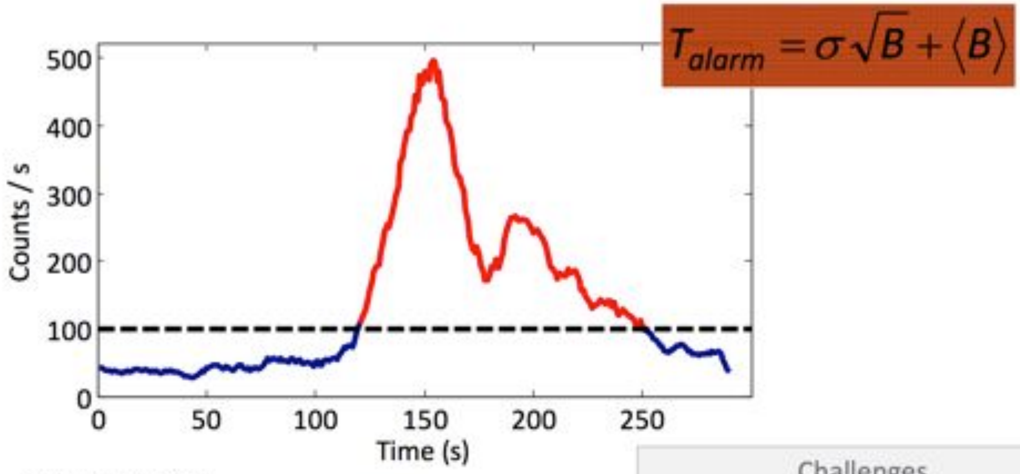


	Gamma-rays	Neutrons
Sources	Essentially all radioactive materials, even beta emitters yield bremsstrahlung Can detect trace quantities of material, e.g. fission products	Restricted to transuranic actinides • plutonium • californium
Background	Originates from radionuclides in the environmental Highly variable over small distances Dependent on local terra & anthropogenic structures Weather variability due to radon	Originates from cosmic-ray spallation events Highly variable over altitude, to a lesser extent latitude Dependent on amount of surrounding high-Z material (ship effect)
Radiation Clutter	A serious problem	Manageable
Attenuation	Most effective with high-Z materials Typical attenuation lengths are *O*(cm)	Most effective with hydrogenous materials Typical attenuation lengths are *O*(10 cm)

Neutron detectors

- Gamma spectroscopy (counting + precise energy spectrum) is useful when
  - Isotopic composition is measurement desired, or
  - Broad range of materials may be of interest, or
  - Source may be shielded by water or hydrogenous materials
- Neutron detectors (counting) are better when
  - Material mass is quantity of interest
  - Plutonium is source
  - Source may be shielded by high-Z materials

Goal: detect presence of a elevated neutron emissions with respect to background



$$T_{alarm} = \sigma\sqrt{B} + \langle B \rangle$$

[Source: J. Ely, PNNL]

Challenges

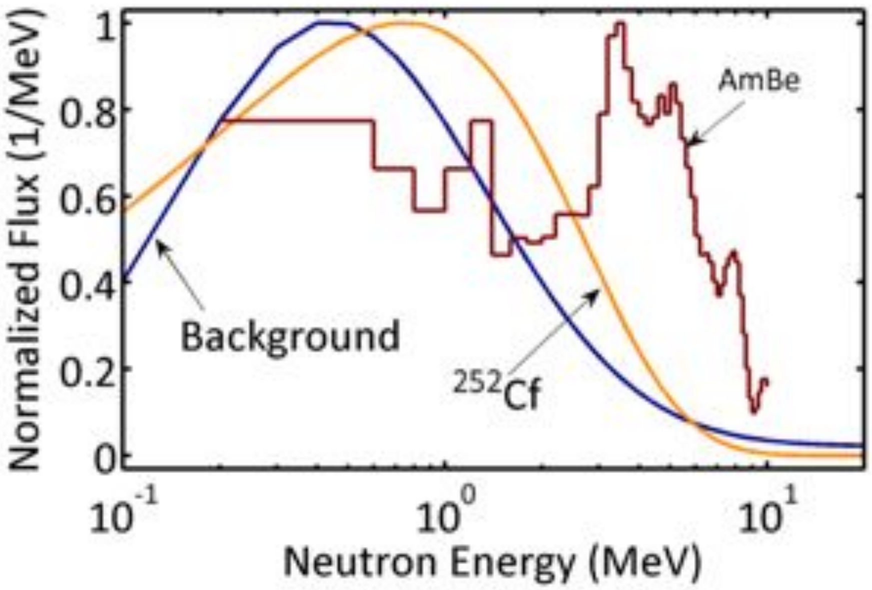
- Short acquisition times O(s)
- Unknown attenuation

Neutron detectors

- Neutron Detectors for Security Monitors

It sounds easy but …

- acquisition times are limited
  - what constitutes an alarm?
- backgrounds change during continuous acquisition
- some gamma-ray sources are huge
- innocent sources exist in commerce, albeit rarely



Neutron detectors

- 3He Neutron Detectors for Homeland Security Radiation Portal Monitors

Contemporary counters rely on ^{3}He for thermal neutron detection

- hydrogenous moderator surrounds sample
- tubes embedded in moderator

[Source: M. Smith, LANL]

[Source: www.canberra.com]

[Source: www.iki.kfki.hu]

Current demands for ^{3}He are greater than supply

- only current source from tritium decay
- tritium stocks dwindling
- recent supply has been ~60 kL/year from stockpile

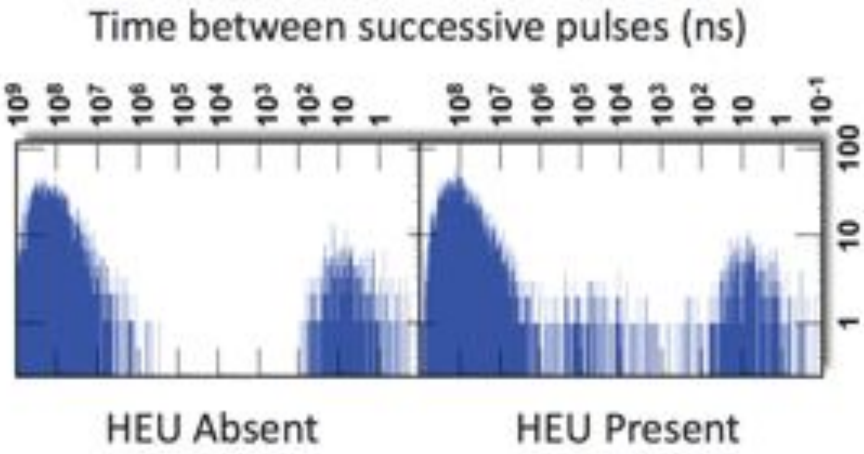
National security demand (was) rising

- GE-Reuter Stokes projects ~65 kL/year

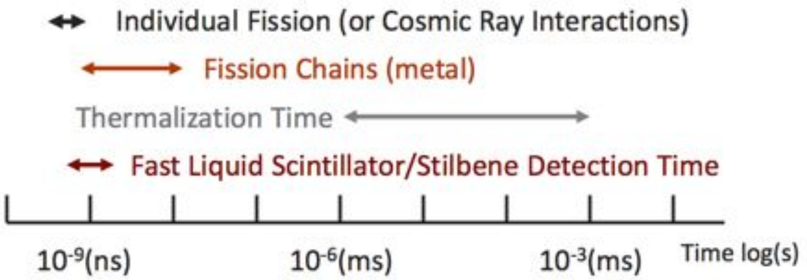
Neutron detectors

- Liquid scintillator detectors have much faster response but low efficiency compared to 3He
  - For high-intensity sources (>10^4 n/sec not a problem
  - Can use correlations (multi-neutron emission) to identify fission sources: n counts are not Poisson-distributed: larger variance

[Source: L. Nakae, LLNL]



[Source: R. Wurtz/N. Snyderman, LLNL]



IAEA and Nuclear Non-Proliferation

- IAEA Interest:
  - Improved knowledge of input plutonium mass at reprocessing facility or repository – currently no better than 5-10%
  - Research reactor power monitoring – currently uses intrusive tech.
  - Verification of bilateral agreements – maybe future role for agency
  - Detection with minimal overburden – allows widespread deployment

IAEA
International Atomic Energy Agency
Atoms for Peace

Final Report:
Focused Workshop on Antineutrino Detection for Safeguards Applications

28-30 October 2008
IAEA Headquarters, Vienna

AAP
2011

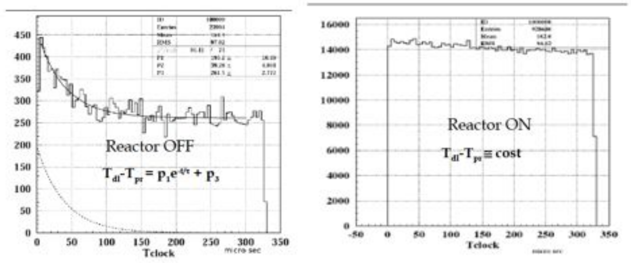
IAEA
International Atomic Energy Agency
Atoms for Peace

AGENDA

Ad Hoc Working Group on Safeguards Applications of Antineutrino Detectors, 14 September 2011, Vienna, Austria

Examples of monitoring detectors under development

CORMORAD: Gd/Plastic segments, no shield/veto



Rnd. Bkg x10^2 Rx On/Off
Exp. signal/Obs.bkg ~1/100

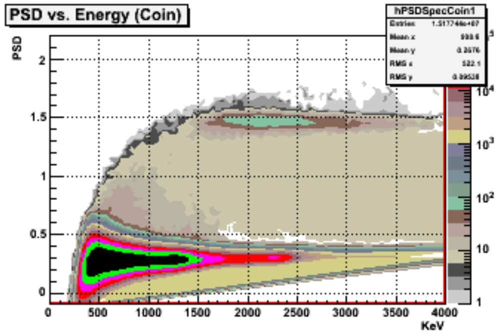
LLNL/SNL: Gd-Water Cerenkov, poly shield/veto

Exp.signal/Obs.bkg ~1/100

PANDA36: Gd/Plastic segments, no shield/veto

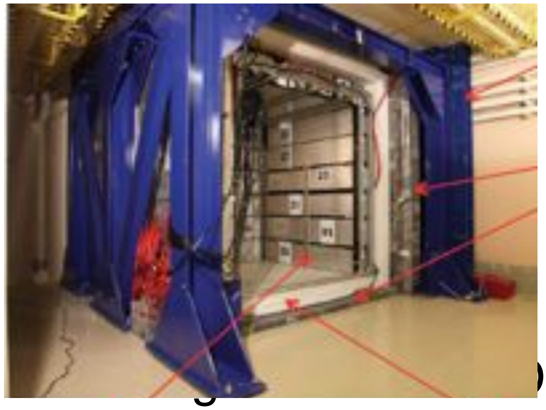
1/50

SNL/LLNL: LiZnS/Plastic, poly shield/veto



Neutron capture PSD gives >10^2 bkg rejection

Nucifer: GdLS, lead/poly/ veto, 7m from RR



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Careful assessment of cosmogenic and reactor background required

Detectors with high selectivity of e+ and/or neutron capture required

Ref: Bowden, LLNL