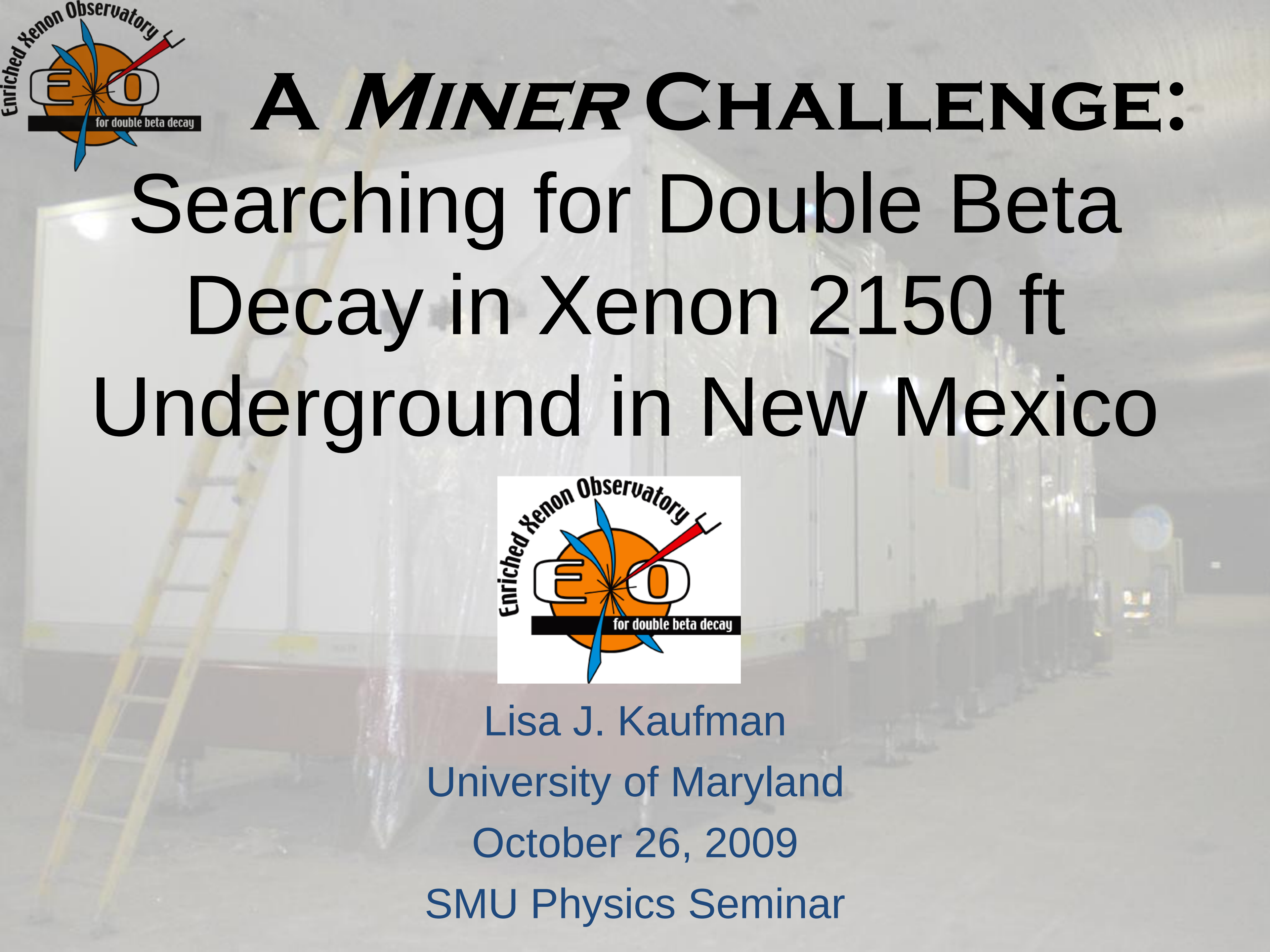


A *Miner* Challenge: Searching for Double Beta Decay in Xenon 2150 ft Underground in New Mexico

Lisa J. Kaufman

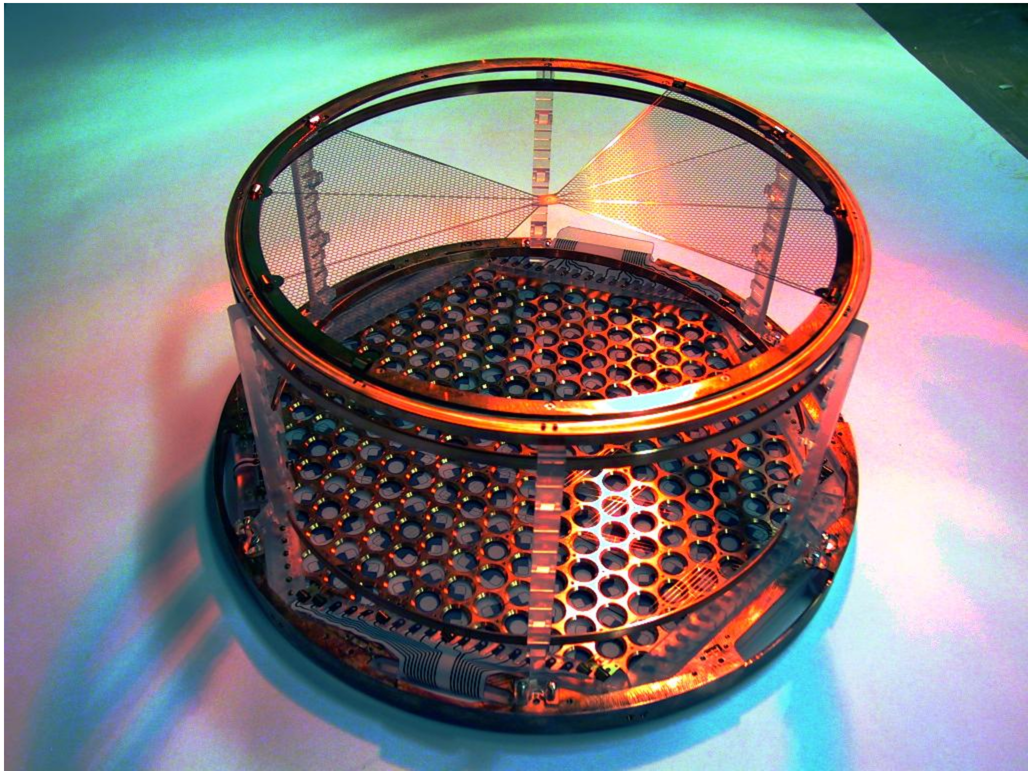
University of Maryland

October 26, 2009

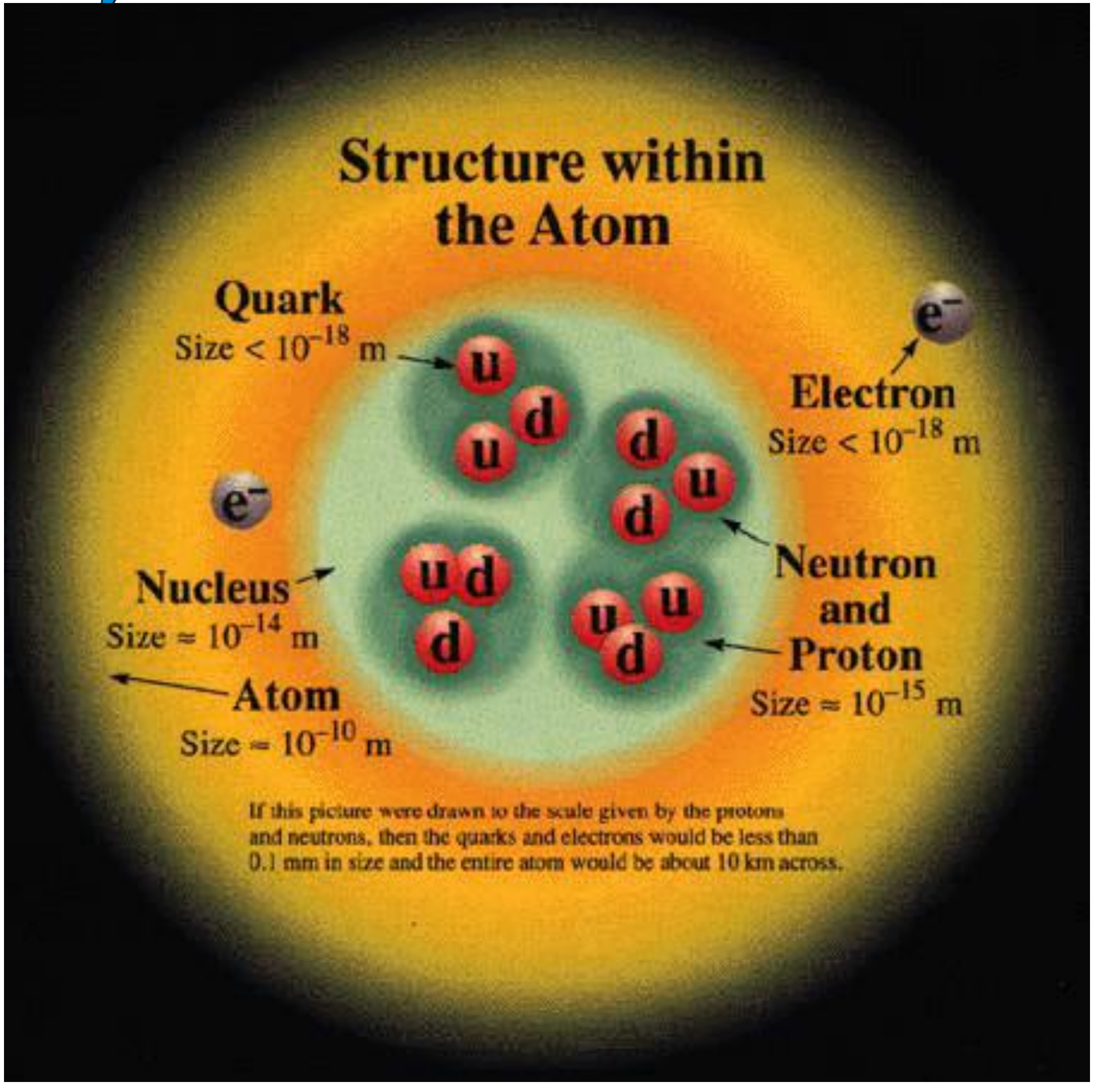
SMU Physics Seminar

Outline

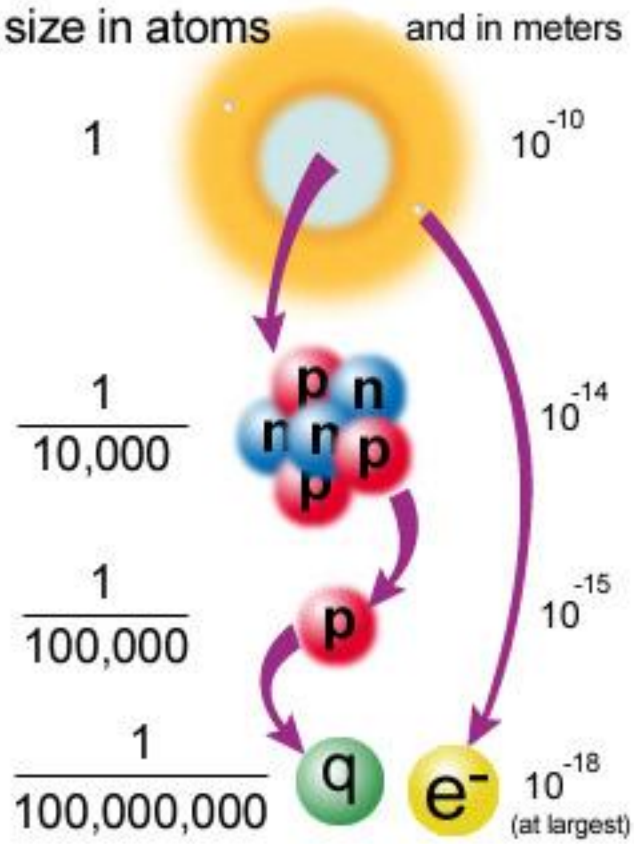
- Beta decay and the neutrino
- Neutrino mass
- Double beta decay
- Overview of EXO purpose and design
- TPC construction
- EXO-200 at WIPP
- Timeline
- Future plans



A little bit of particle physics…



If this picture were drawn to the scale given by the protons and neutrons, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



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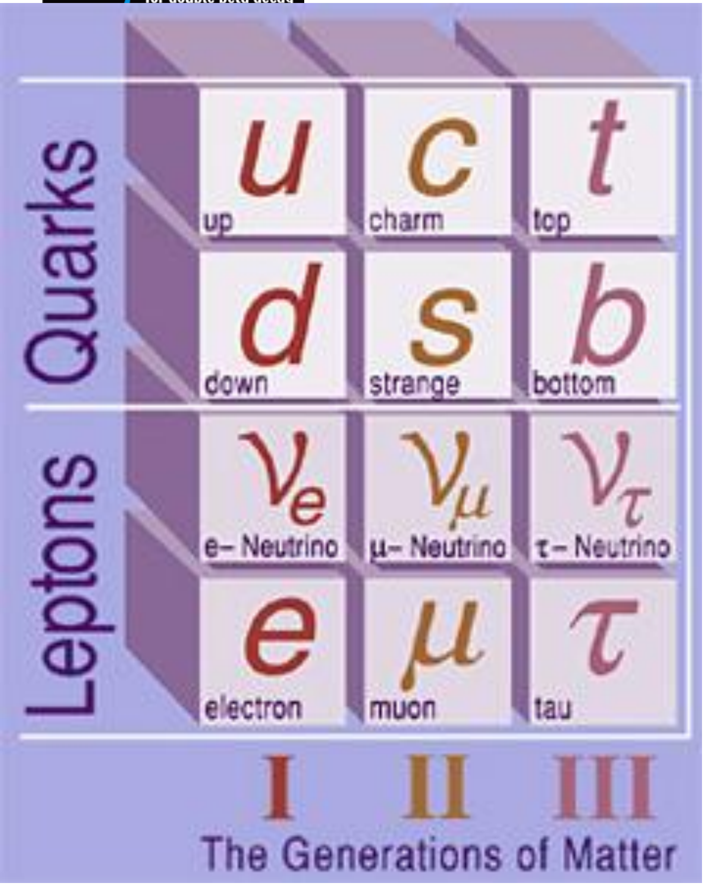
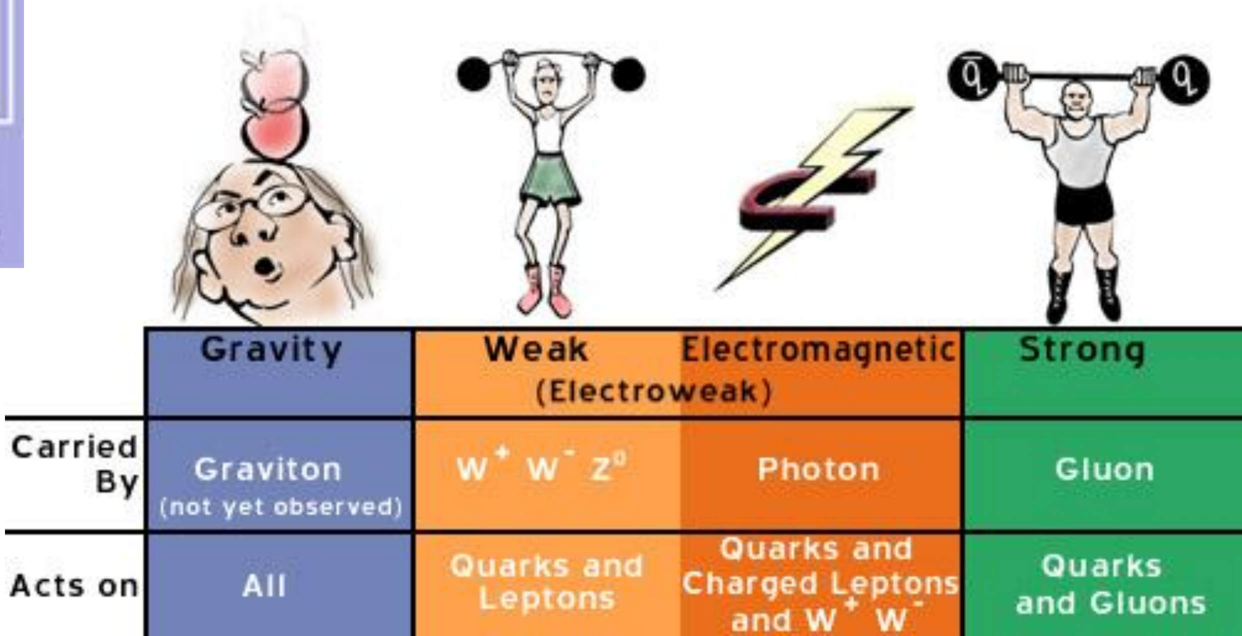


	I	II	III
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e– Neutrino	ν_μ μ– Neutrino	ν_τ τ– Neutrino
	e electron	μ muon	τ tau

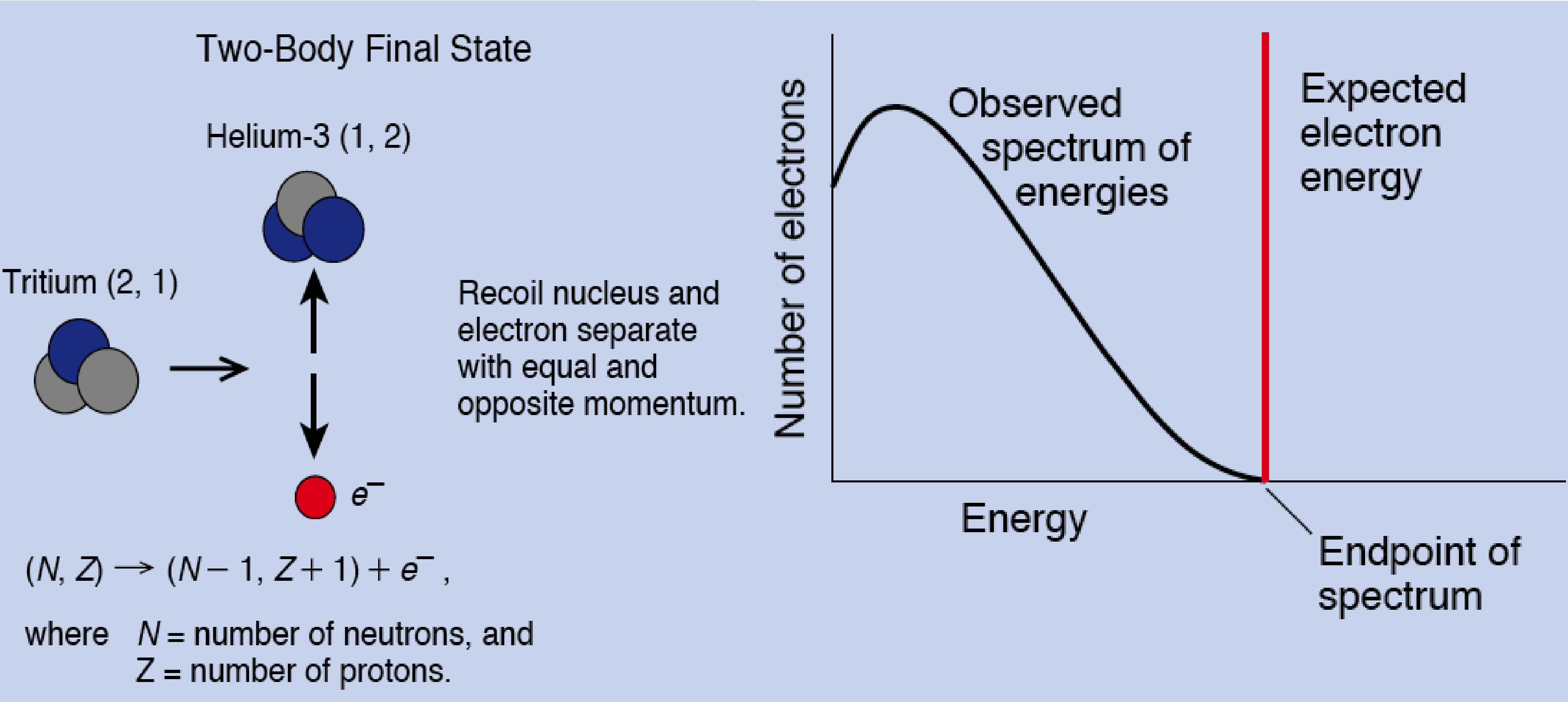
The Generations of Matter

- Three generations of matter
- Three flavors of leptons - e, μ, τ
- The neutral leptons are called neutrinos - ν_e, ν_μ, ν_τ
- Neutrinos only interact via the weak force



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Beta (β) decay, at the beginning



Two-Body Final State

Recoil nucleus and electron separate with equal and opposite momentum.

$$(N, Z) \longrightarrow (N-1, Z+1) + e^-,$$

where N = number of neutrons, and
Z = number of protons.

The beginning…

"I am at present trying to write up the subject of beta rays for my new edition, and I find it the most difficult task in the book…"

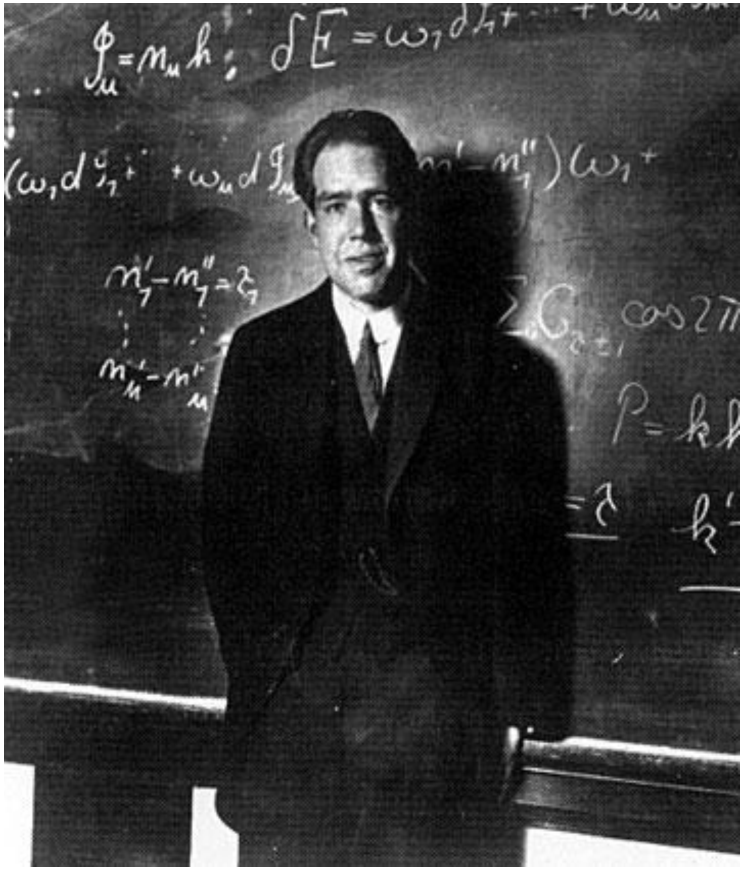
Ernest Rutherford to Otto Hahn (1911)

"…there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin ½ and satisfy the exclusion principle… The continuous beta-spectrum would then become understandable…"

Wolfgang Pauli (1929)

"At the present stage of atomic theory, however, we may say that we have no argument… for upholding the energy principle in the case of beta-ray disintegrations, and are even led to the complications and difficulties in trying to do so."

N. Bohr (1930)



Fermi puts it together

W. Pauli

A lightweight neutral particle is emitted along with the e^- in beta-decay

W. Heisenberg

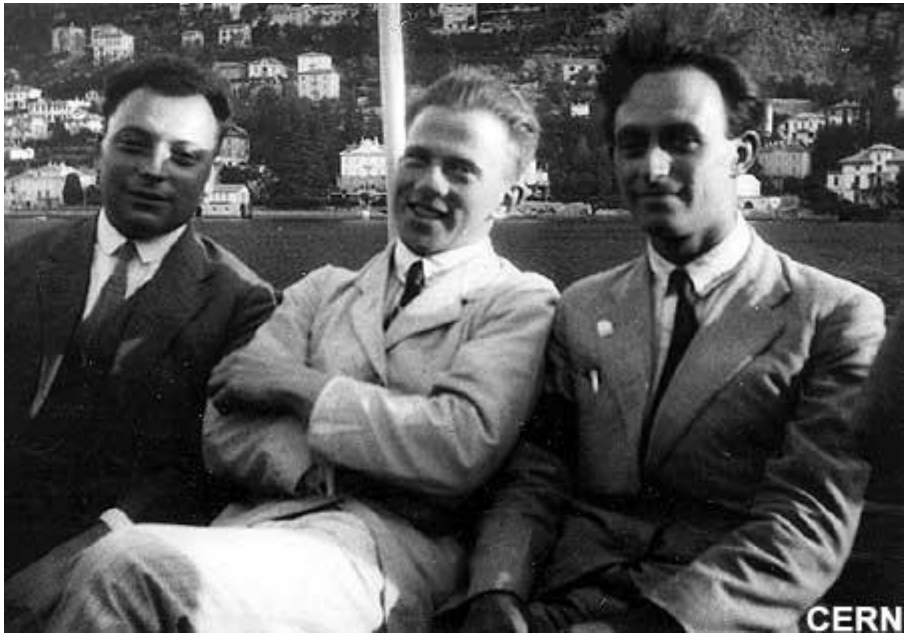
The nucleus consists only of protons and neutrons

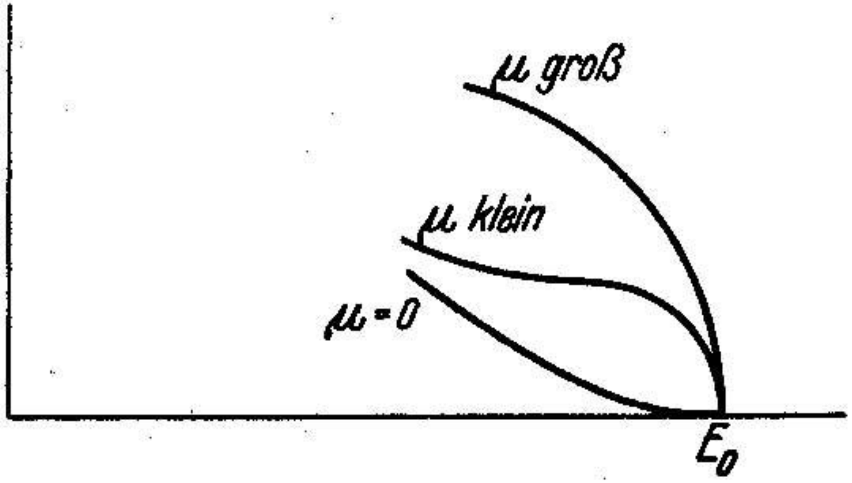
E. Fermi

"… to every transition from neutron to proton is correlated the creation of an electron and a neutrino."

W. Pauli

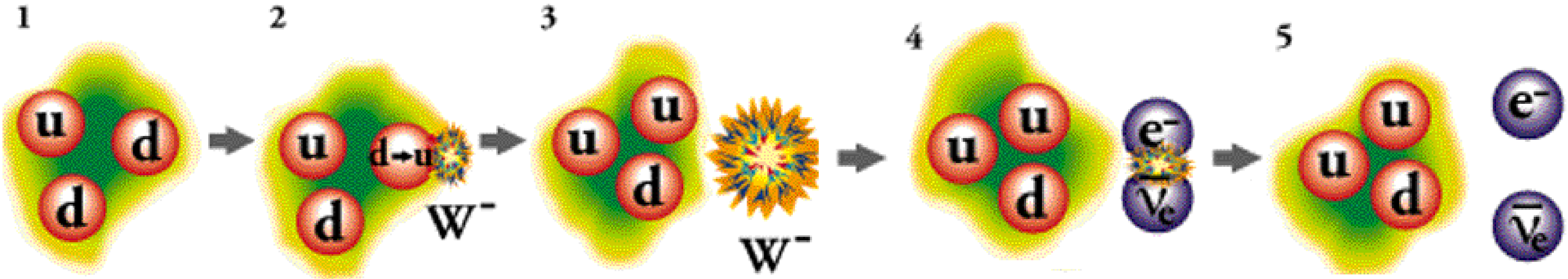
"I have done a terrible thing, I have postulated a particle that cannot be detected."

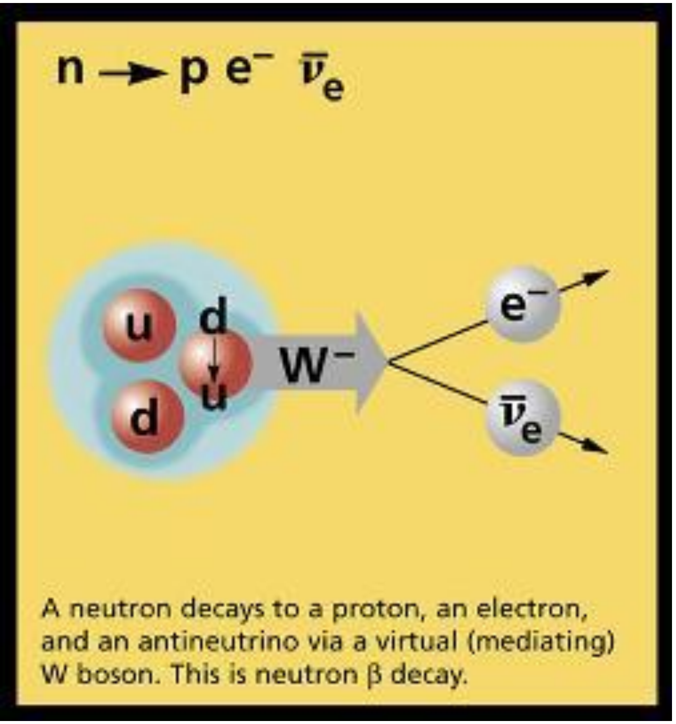




E. Fermi, Z. Phys. 88 (1934) 161

Nuclear Beta (β) Decay: The Solution

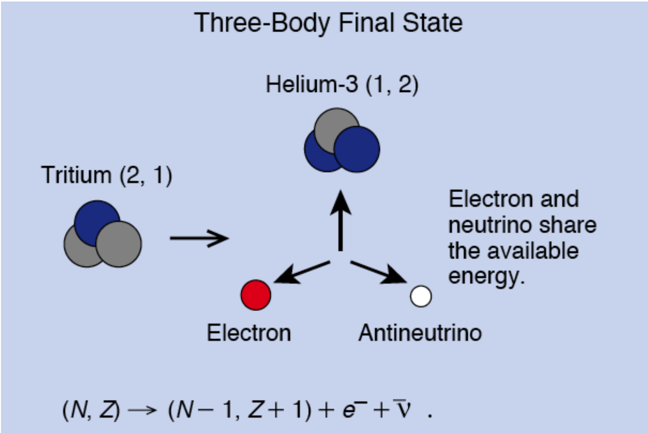



$n \rightarrow p\, e^- \,\overline{\nu}_e$

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

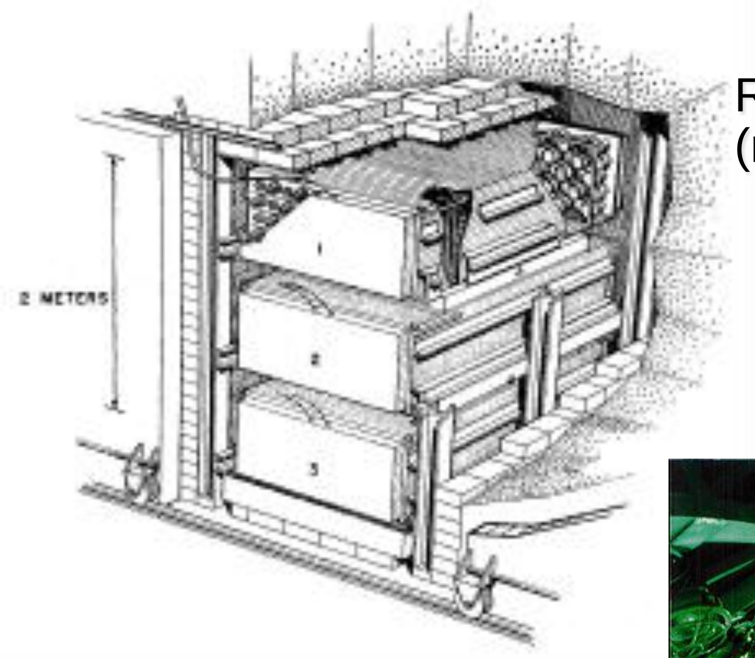
1. Free neutron or neutron in an unstable nucleus is converted to a proton via the weak force

2. To conserve energy, an electron and antineutrino are produced in the process

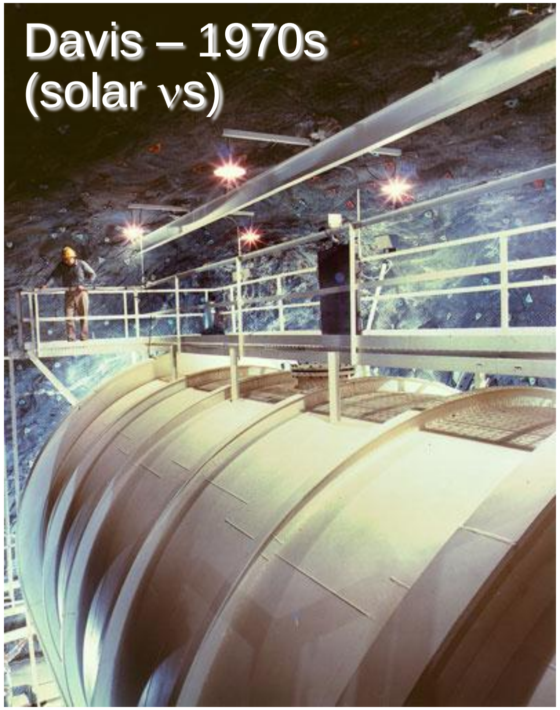


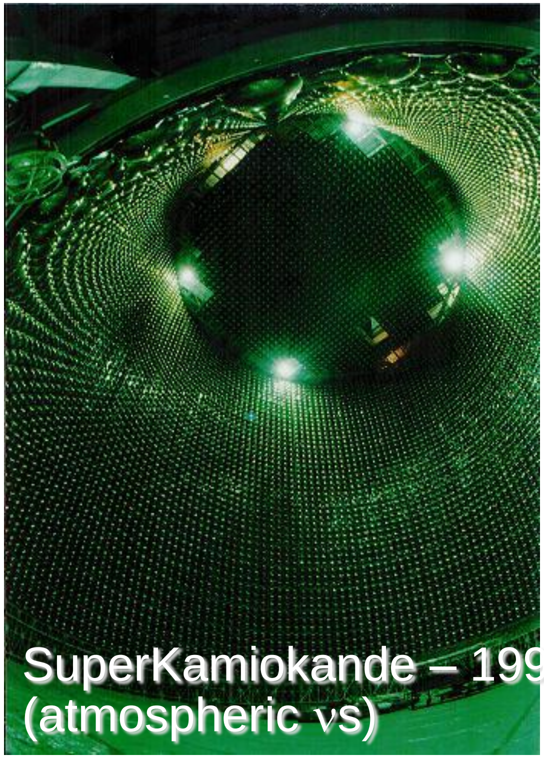
$(N, Z) \longrightarrow (N-1, Z+1) + e^- + \overline{\nu}$.

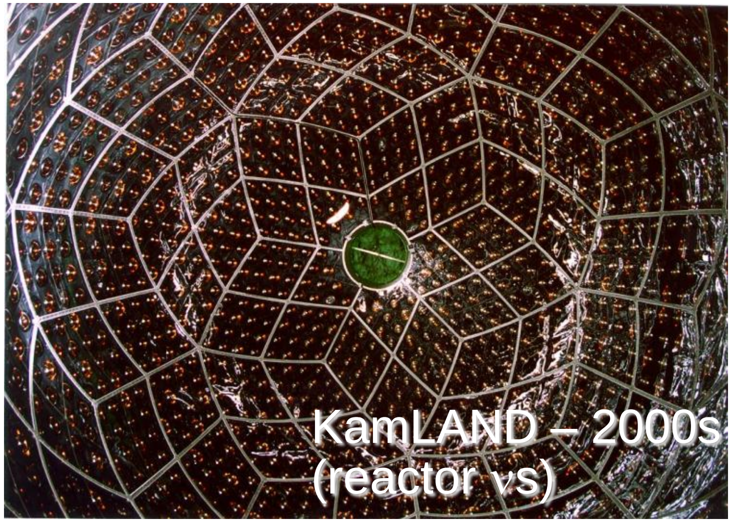
Evidence of Neutrinos



Reines - 1956
(reactor νs)

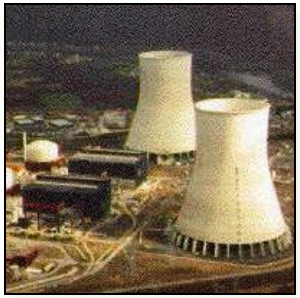

Davis – 1970s
(solar νs)

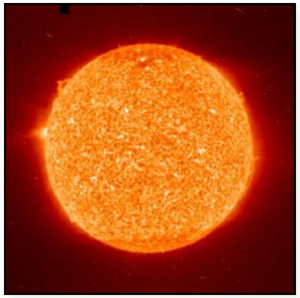

SuperKamiokande – 1990s
(atmospheric νs)


KamLAND – 2000s
(reactor νs)

Sources of neutrinos: artificial and natural

Nuclear Reactors
(power stations, ships)



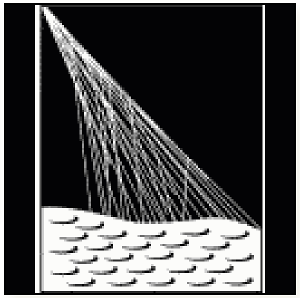


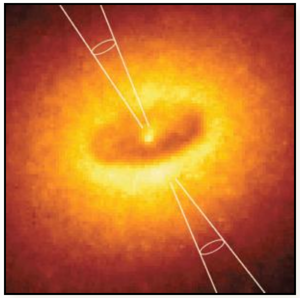
Sun ($\sim 6\text{x}10^{14}$ m^{-2} s^{-1})

Particle Accelerators

Supernovae
(star collapse $\sim 10^{57}$ νs)

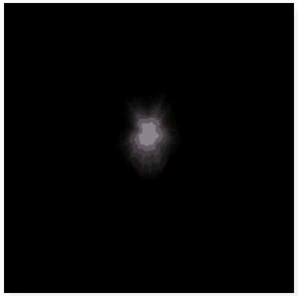
Earth's Atmosphere
(Cosmic Rays)





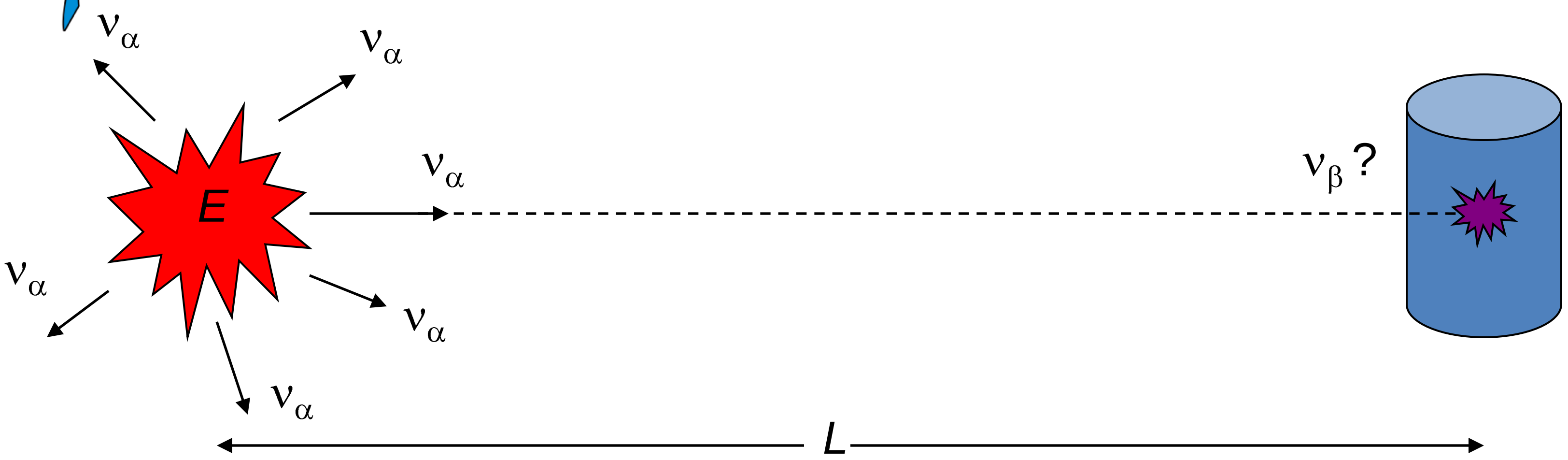
Astrophysical
Accelerators

Earth's Crust
(Natural Radioactivity)



Big Bang
(~ 330 ν/cm^3 locally)

Neutrino oscillations



Neutrino source

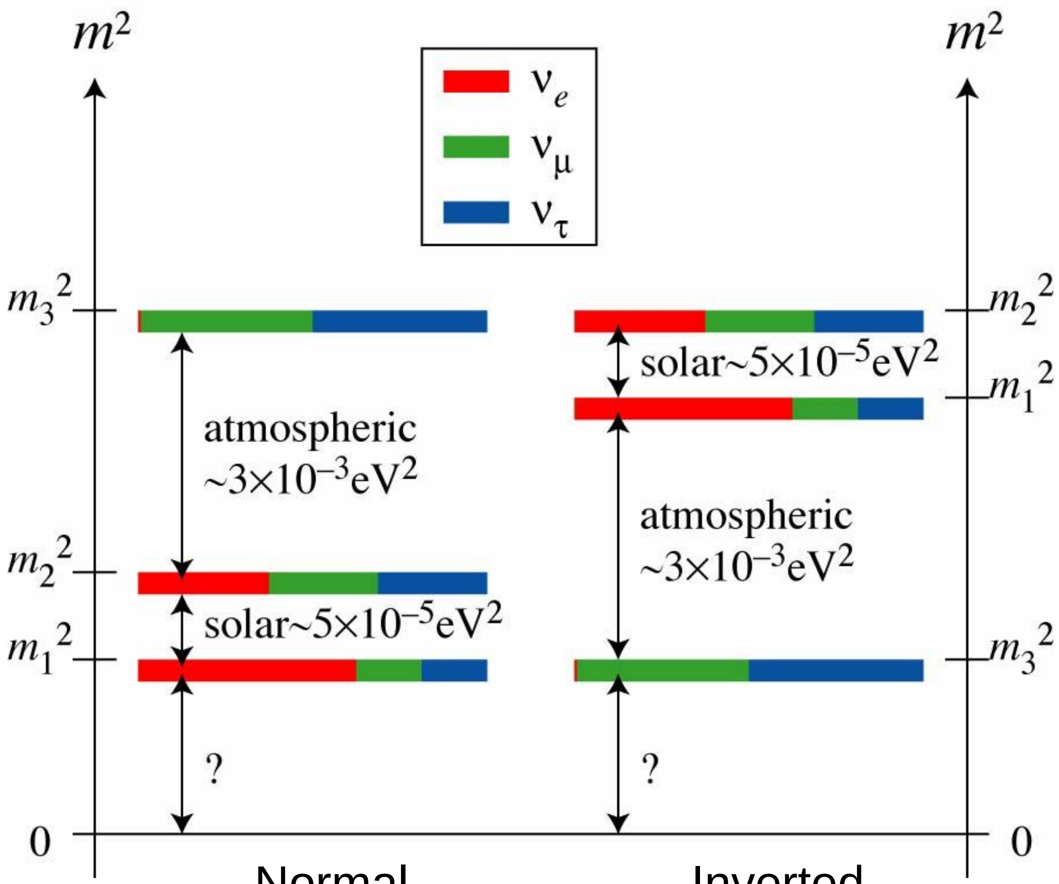
Neutrino detector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Lepton mixing matrix

$$P_{\alpha\rightarrow\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{\alpha\beta} L}{4E}\right)$$

Neutrinos have mass!



Normal
hierarchy

Inverted
hierarchy

Oscillation experiments measure Δm^2's,
but not the absolute masses!

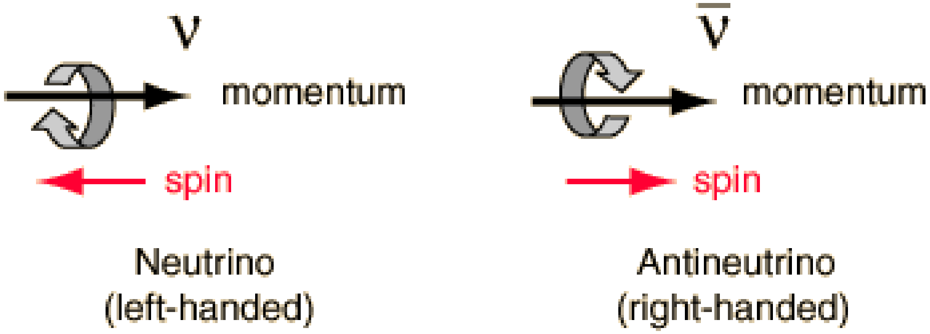
Dirac and Majorana Neutrinos

	Dirac	**Majorana**
Fermion	Particles have charge $\boxed{f \neq \bar{f}}$ (e-, μ-, τ-, quarks)	Particles carry no charge $\boxed{f = \bar{f}}$
Neutrino	Carries lepton number $\nu : L = +1, \bar{\nu} : L = -1$	Cannot carry lepton number

Is the neutrino its own antiparticle?

Helicity

- Helicity is the projection of the particle spin on the direction of the particle’s motion
- Right-handed ➔ motion and spin are along the same direction
- Left-handed ➔ motion and spin are in opposite directions



Dirac and Majorana Neutrinos

Don’t we already know that $\nu \neq \bar{\nu}$?

Typical neutrino scattering experiment:

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu^R \quad \longrightarrow \quad \bar{\nu}_\mu^R N \rightarrow \mu^+ X$$

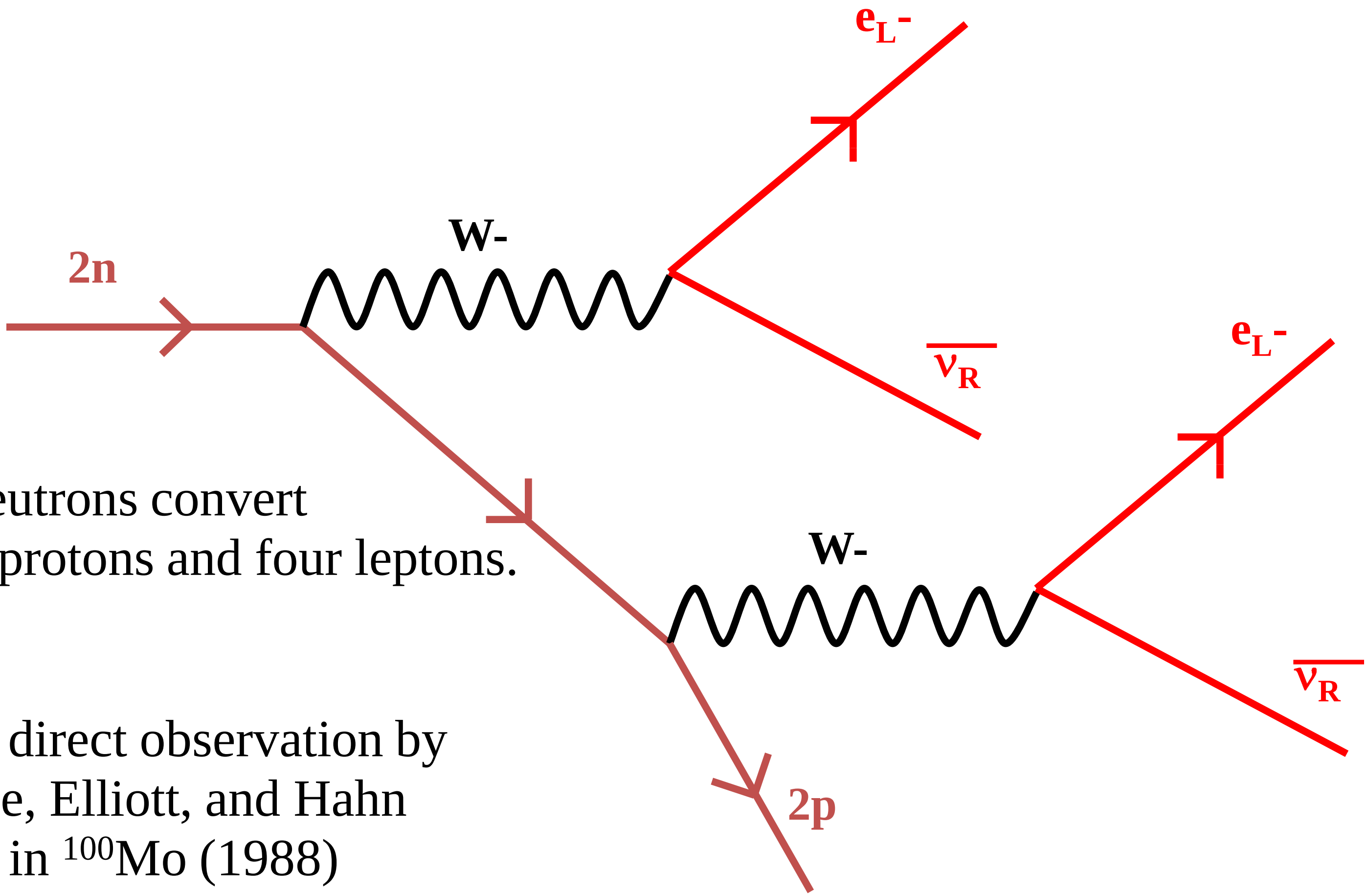
charges always opposite

For Dirac neutrinos, the charge of the μ^+ is determined by Lepton number conservation and the neutrino helicity (weak interaction is 100% left handed).

For Majorana neutrinos, the charge of the μ^+ is determined solely by neutrino helicity.

No experiment has been able to tell us which view is correct.

Two-Neutrino Double Beta Decay gives us a second weak vertex:

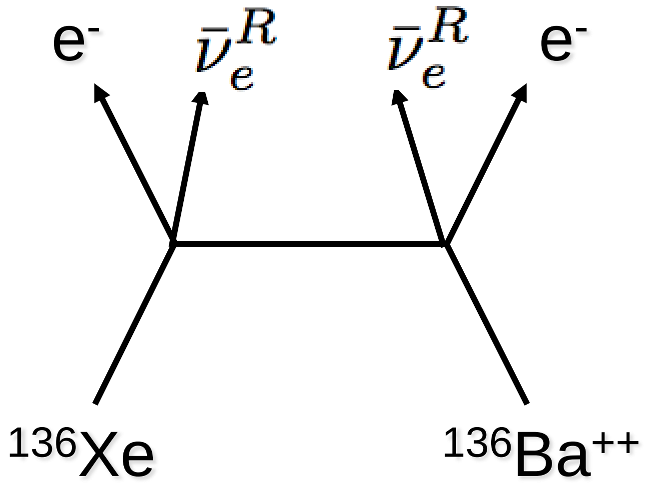


Two neutrons convert
to two protons and four leptons.

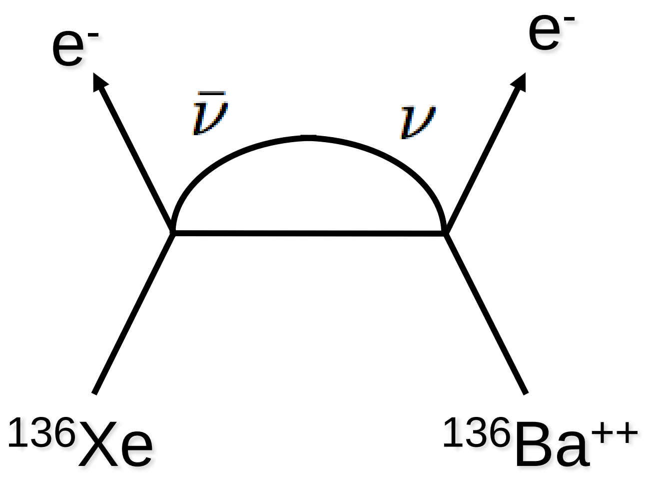
First direct observation by
Moe, Elliott, and Hahn
in ^{100}Mo (1988)

Double Beta Decay

2νββ
ΔL = 0



0νββ
ΔL = 2

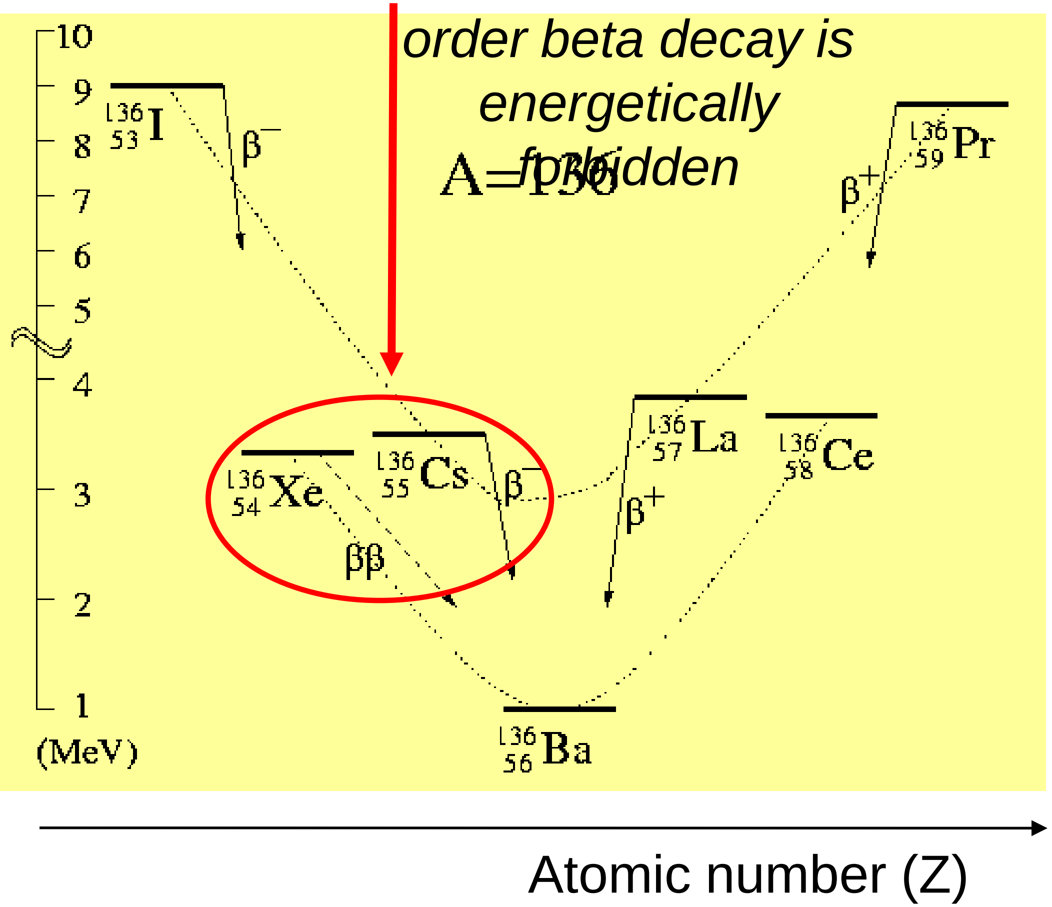


2ν mode:
a conventional
2nd order process
in Standard Model

0ν mode:
a hypothetical process
can happen only if:
$M_\nu \neq 0$, $\nu = \bar{\nu}$ (non-zero Majorana mass)

Double Beta Decay

a second-order process only detectable if first order beta decay is energetically forbidden



Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}\text{Ca}\rightarrow{}^{48}\text{Ti}$	4.271	0.187
$^{76}\text{Ge}\rightarrow{}^{76}\text{Se}$	2.040	7.8
$^{82}\text{Se}\rightarrow{}^{82}\text{Kr}$	2.995	9.2
$^{96}\text{Zr}\rightarrow{}^{96}\text{Mo}$	3.350	2.8
$^{100}\text{Mo}\rightarrow{}^{100}\text{Ru}$	3.034	9.6
$^{110}\text{Pd}\rightarrow{}^{110}\text{Cd}$	2.013	11.8
$^{116}\text{Cd}\rightarrow{}^{116}\text{Sn}$	2.802	7.5
$^{124}\text{Sn}\rightarrow{}^{124}\text{Te}$	2.228	5.64
$^{130}\text{Te}\rightarrow{}^{130}\text{Xe}$	2.533	34.5
$^{136}\text{Xe}\rightarrow{}^{136}\text{Ba}$	2.479	8.9
$^{150}\text{Nd}\rightarrow{}^{150}\text{Sm}$	3.367	5.6

If $0\nu\beta\beta$ is due to light, Majorana neutrinos

$$\langle m_{\beta\beta}\rangle = \left(T_{1/2}^{0\nu\beta\beta} G^{0\nu\beta\beta}(Q,Z)\left|M_{\text{nucl}}\right|^2\right)^{-1}$$

M_{nucl}	can be calculated within particular nuclear models
$G^{0\nu\beta\beta}(Q,Z)$	a known phase space factor
$T_{1/2}^{0\nu\beta\beta}$	is the measured quantity [Hz]

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i e^{i\alpha_i}\right|$$

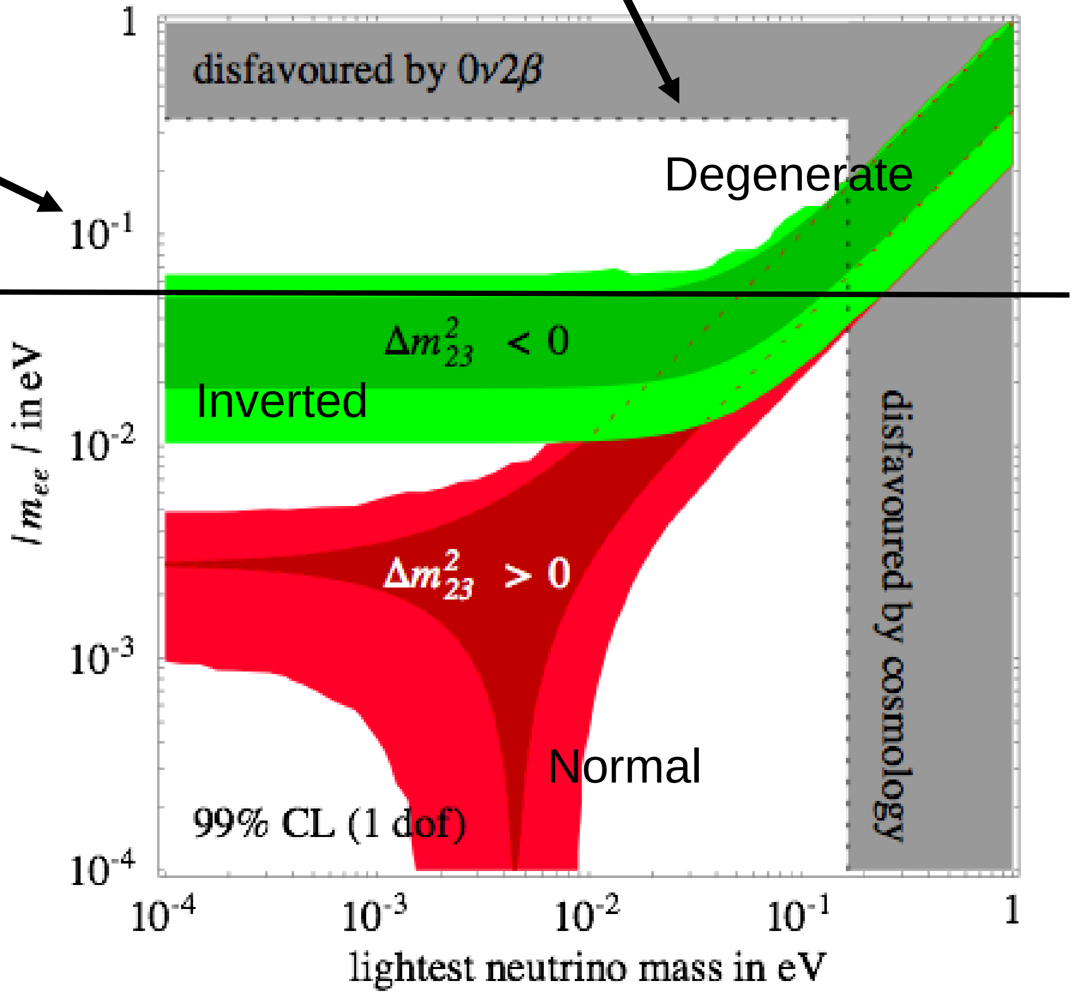
effective Majorana ν mass

$0\nu\beta\beta$ effective neutrino mass

current $0\nu\beta\beta$ sensitivity

from neutrino oscillations:

50 meV



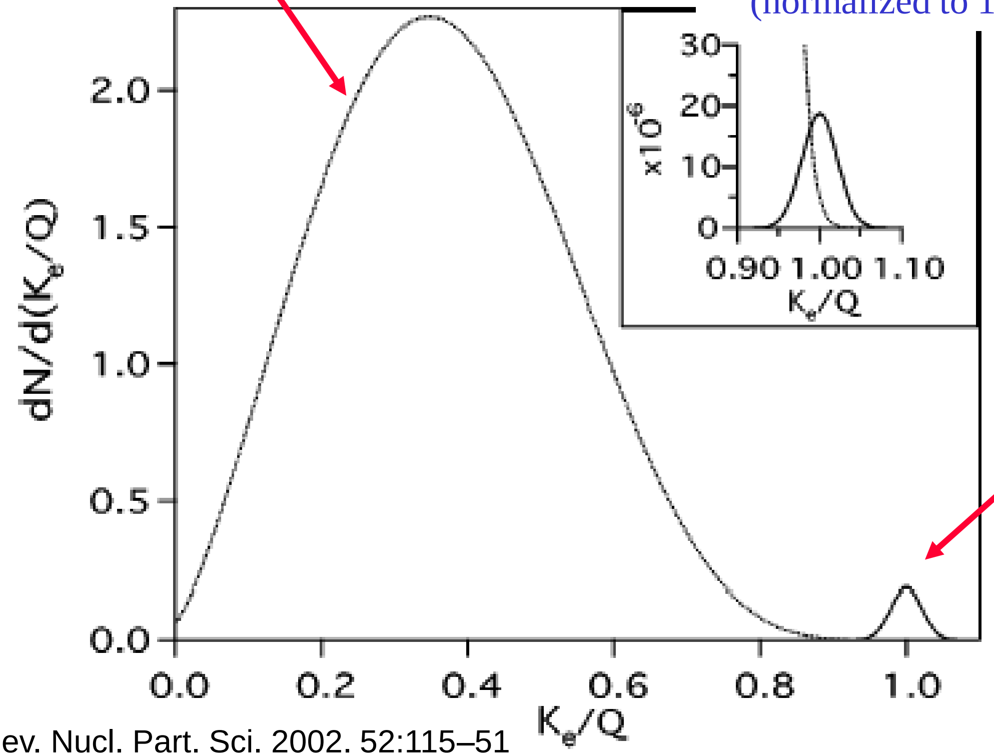
^{76}Ge	(2.1 - 2.6) × 10^{27} y
^{82}Se	(6.0 - 8.7) × 10^{26} y
^{100}Mo	(1.1 - 1.7) × 10^{27} y
^{130}Te	(0.7 - 1.7) × 10^{27} y
^{136}Xe	(1.5 - 5.6) × 10^{27} Y

[Strumia and Vissani, hep-ph/0606054]

ββ0ν strategy: search for a peak in the summed electron energy spectrum at the known Q value

ββ2ν spectrum
(normalized to 1)

0νββ peak (5% FWHM)
(normalized to 10^{-6})



ββ0ν signal
(5% FWHM)
(normalized to 10^{-2})

Elliot, S. et al., Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51

Summed electron energy in units of the kinematic endpoint (Q)

Sensitivity

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A}\left[\frac{MT}{B\Gamma}\right]^{1/2}$$

ε is efficiency
a is isotopic abundance
A is atomic mass
M is source mass
T is time
B is background
Γ is resolution

To maximize sensitivity:

- Large mass
- Low background
- High detection efficiency
- Good energy resolution

In addition, identification of the daughter isotope would reject most sources of background and confirm double beta decay.

Overview

“EXO is a program aimed at building an enriched xenon double beta decay experiment with a one or more ton ^{136}Xe source, with the particular ability to detect the two electrons emitted in the decay in coincidence with the positive identification of the ^{136}Ba daughter via optical spectroscopy”

- The EXO phased approach
  - The EXO-200 detector
  - Ba ion identification

The EXO Collaboration

K. Barry, E. Niner, A. Piepke

University of Alabama, Tuscaloosa AL

P. Vogel

California Institute of Technology, Pasadena CA

M. Dixit, K. Graham, C. Green, C. Hagemann, C. Hargrove, E. Rollin, D. Sinclair, V. Strickland

Carleton University, Ottawa ON, Canada

M. Moe

University of California, Irvine, Irvine CA

C. Benitez-Medina, S. Cook, W. Fairbank, Jr., K. Hall, B. Mong

Colorado State University, Fort Collins CO

D. Akimov, I. Alexandrov, A. Burenkov, M. Danilov, A. Dolgolenko, A. Karelin, A. Kovalenko, A. Kuchenkov, V. Stekhanov, O. Zeldovich

ITEP Moscow, Russia

B. Aharmim, K. Donato, J. Farine, D. Hallman, U. Wichoski

Laurentian University, Sudbury ON, Canada

H. Breuer, C. Hall, L.J. Kaufman, D. Leonard, S. Slutsky, Y-R. Yen

University of Maryland, College Park MD

K. Kumar, A. Pocar

University of Massachusetts Amherst, Amherst MA

M. Auger, G. Giroux, R. Gornea, F. Juget, G. Lutter, J-L. Vuilleumier, J-M. Vuilleumier

Laboratory for High Energy Physics, Bern, Switzerland

N. Ackerman, M. Breidenbach, R. Conley, W. Craddock, J. Hodgson, D. Mackay, A. Odian, C. Prescott, P. Rowson, K. Skarpaas, J. Wodin, L. Yang, S. Zalog

Stanford Linear Accelerator Center (SLAC), Menlo Park CA

L. Bartoszek, R. Cooper, R. DeVoe, M. Dolinski, B. Flatt, G. Gratta, M. Green, F. LePort, M. Montero-Diez, R. Neilson, A. Reimer-Muller, A. Rivas, K. O'Sullivan, K. Twelker

Stanford University, Stanford CA

EXO-200

EXO-200 is a large LXe TPC with scintillation light readout. It uses a source of 200 kg of enriched xenon (80% ^{136}Xe).

→ EXO-200 has no ^{136}Ba^{+} identification ←

Goals:

- Look for 0νββ decay of ^{136}Xe with competitive sensitivity
($T^{0\nu}_{1/2} > 6 \times 10^{25}$ y, current limit: $T^{0\nu}_{1/2} > 1.2 \times 10^{24}$ y)

- Measure the standard 2νββ decay of ^{136}Xe ($Q = 2457.8 \pm 0.4$ keV) and measure its lifetime (best upper limit to date: $T^{2\nu}_{1/2} > 1 \times 10^{22}$ y

[R. Bernabei et al., Phys. Lett. B 546 (2002) 23]

- Test backgrounds of large LXe detector at ~2000 m.w.e. depth
- Test LXe technology and enrichment on a large scale
- Test TPC components, light readout (518 LAAPDs), and radioactivity

Why Xenon?

Xenon isotopic enrichment is easier: Xe is a gas and ^{136}Xe is the heaviest isotope.

Xenon is “reusable”: can be re-purified and recycled into new detector (no crystal growth).

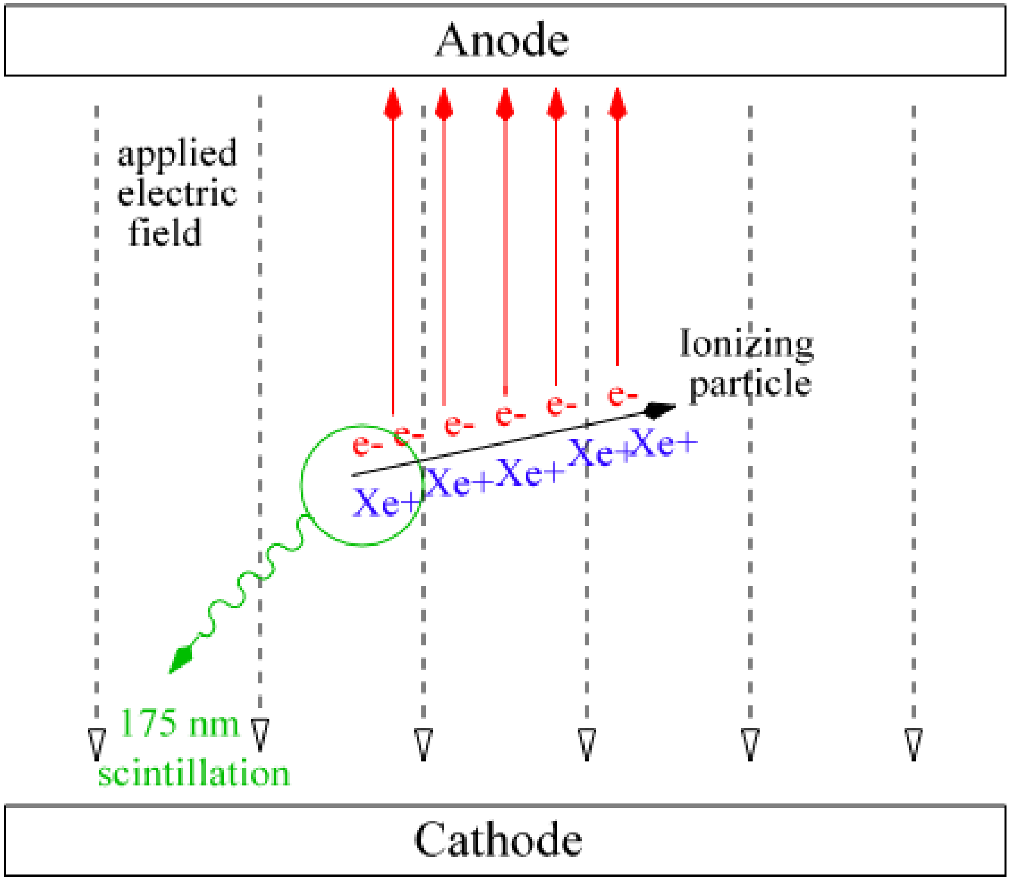
Monolithic detector: LXe is self shielding, surface contamination minimized.

Minimal cosmogenic activation: no long lived radioactive isotopes of Xe.

Energy resolution in LXe can be improved: scintillation light + ionization anti-correlation.

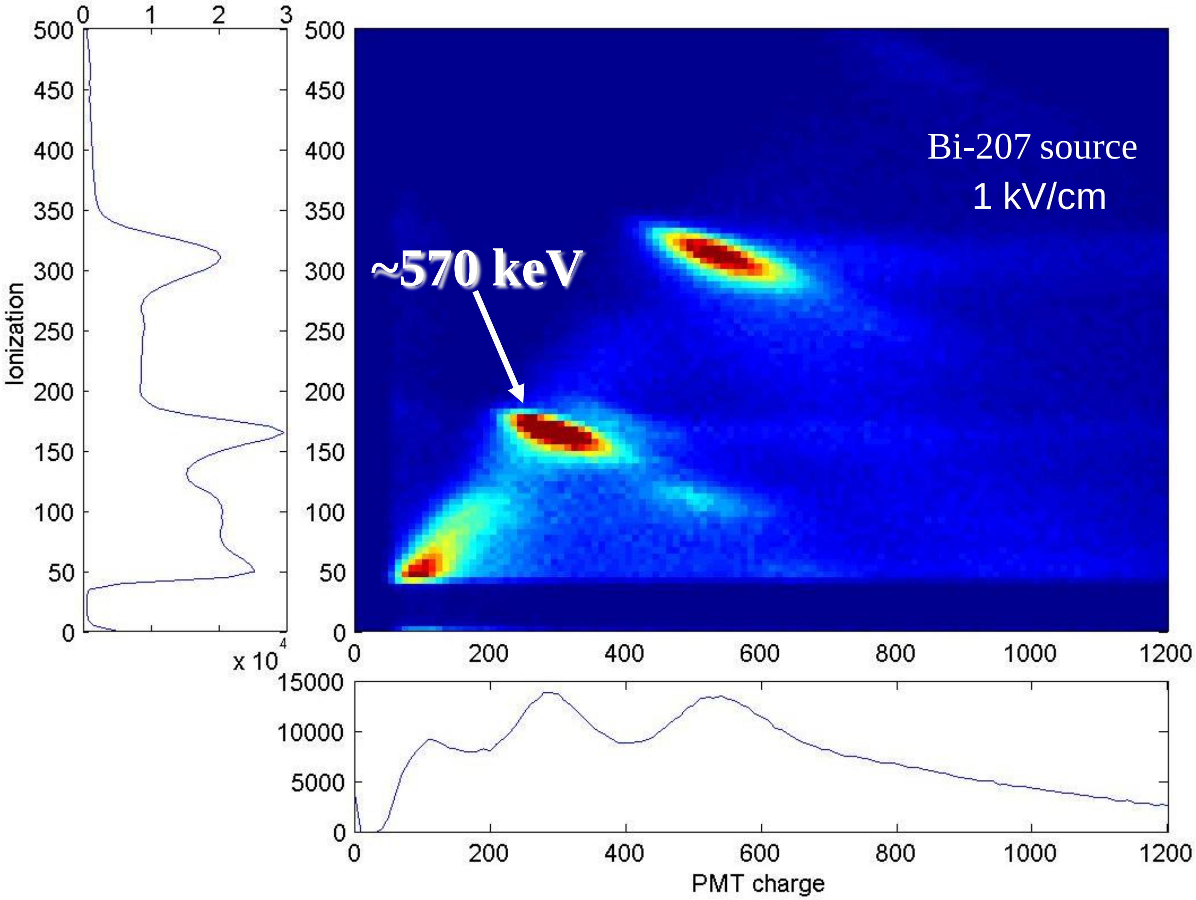
… admits a novel coincidence technique: background reduction by Ba daughter tagging.

EXO-200 Detection Scheme



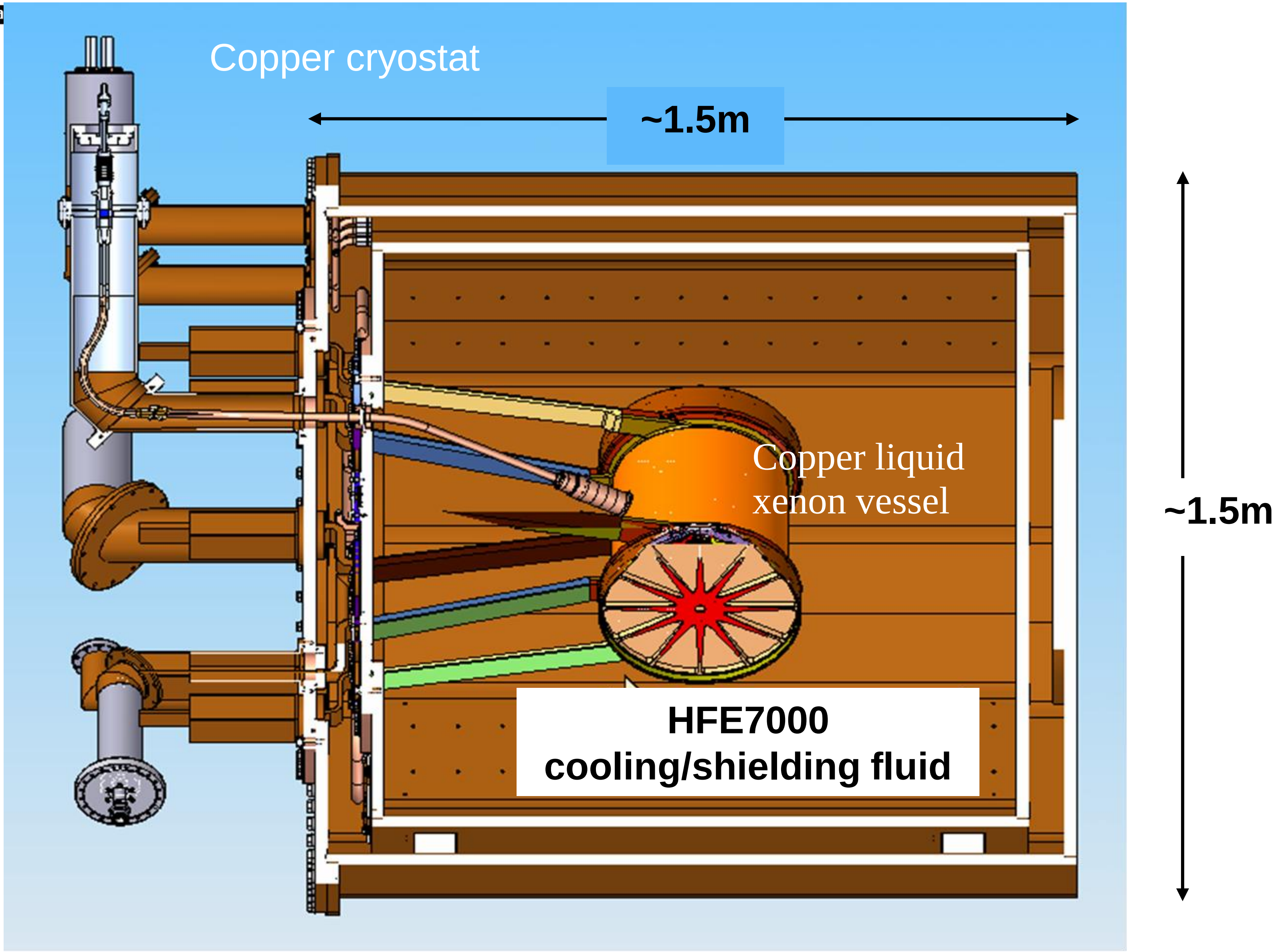
- Timing of the event:
  Scintillation light gives t = 0 for drift time (z)
- Position of the event:
  Crossed wires at the anode (x-y) collect charge at t=z
- Event energy:
  Ionization + scintillation light

LXe Data Show Anticorrelation between Scintillation and Ionization



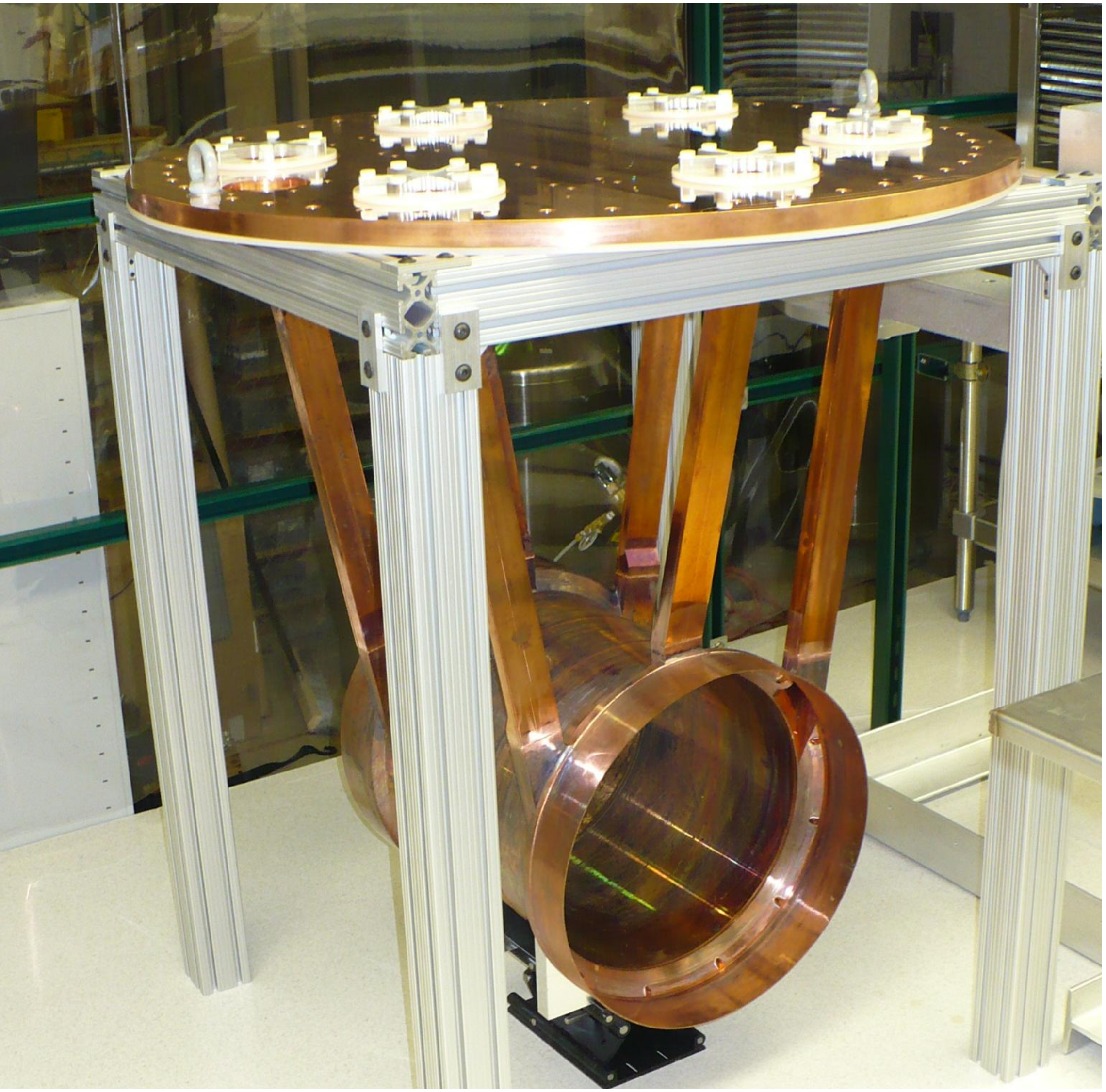
Energy resolution: 3.0% @ 570 keV or 1.6% @ Q(ββ)

EXO-200



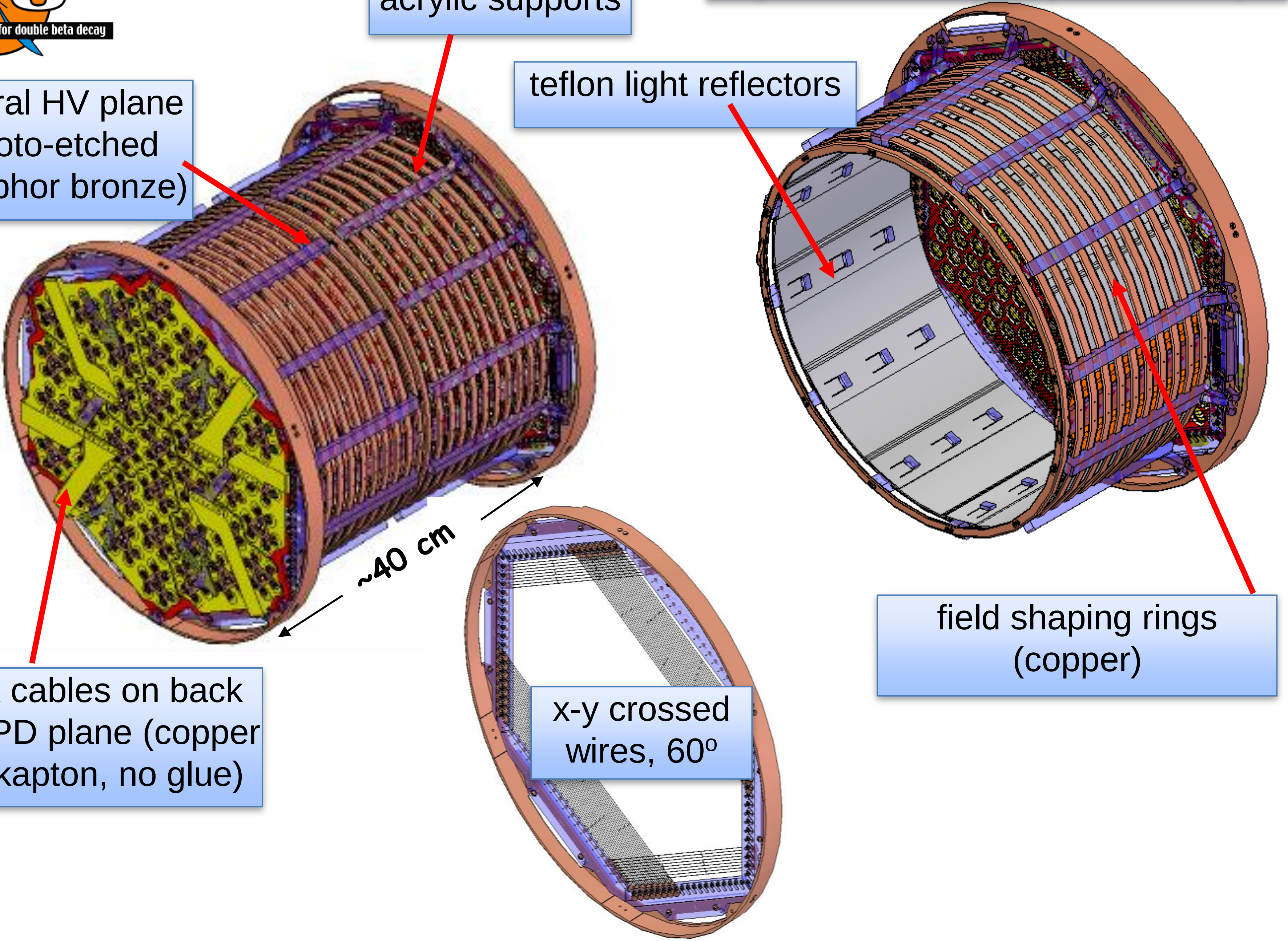
Surrounded by 25 cm Pb shield

Copper Xe Vessel



- Very light (wall thickness 1.5 mm, total weight 15 kg), to minimize material.
- All parts machined under 7 ft of concrete shielding to reduce activation by cosmic rays.
- Different parts are e-beam welded together at Applied Fusion. Construction of the vessel with 55 welds has been completed.
- End caps are TIG welded.

TPC Design



acrylic supports

LAAPD plane (copper) and x-y wires (photo-etched phosphor bronze)

Central HV plane (photo-etched phosphor bronze)

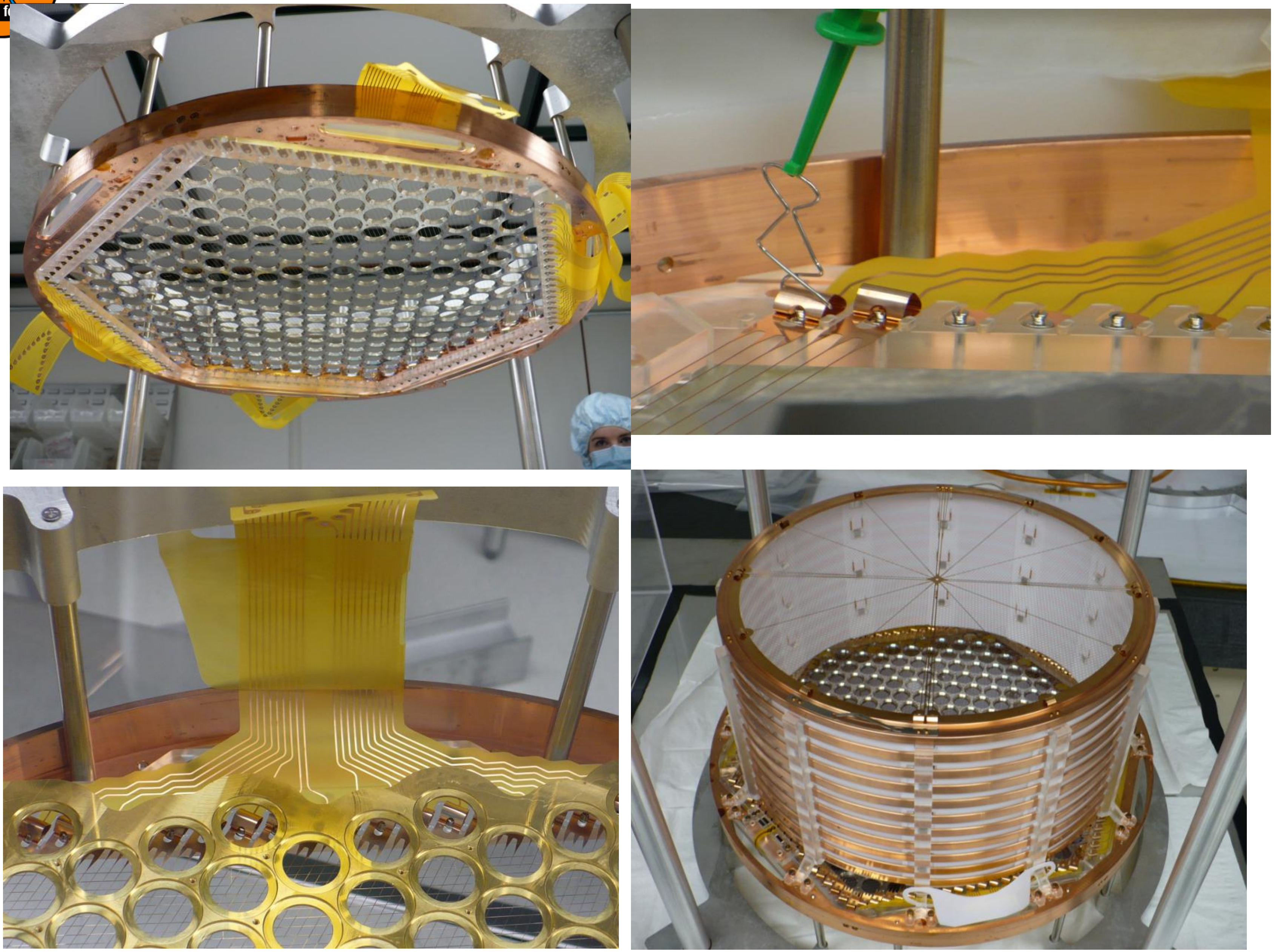
teflon light reflectors

field shaping rings (copper)

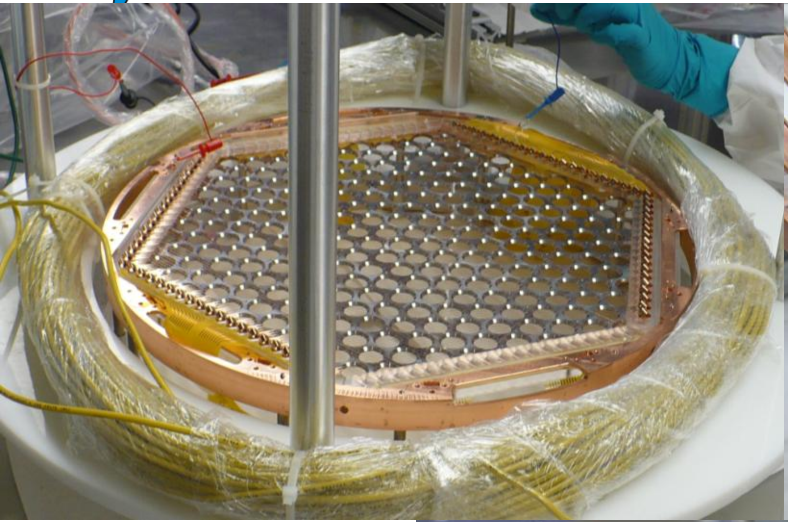
flex cables on back of APD plane (copper on kapton, no glue)

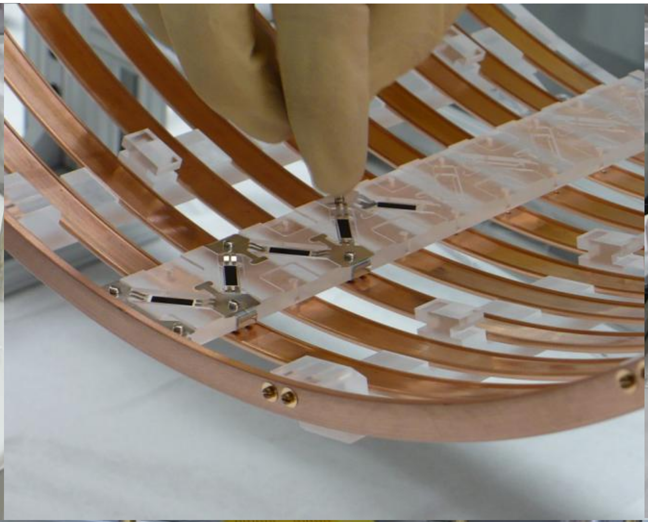
x-y crossed wires, 60º

EXO-200 TPC Construction

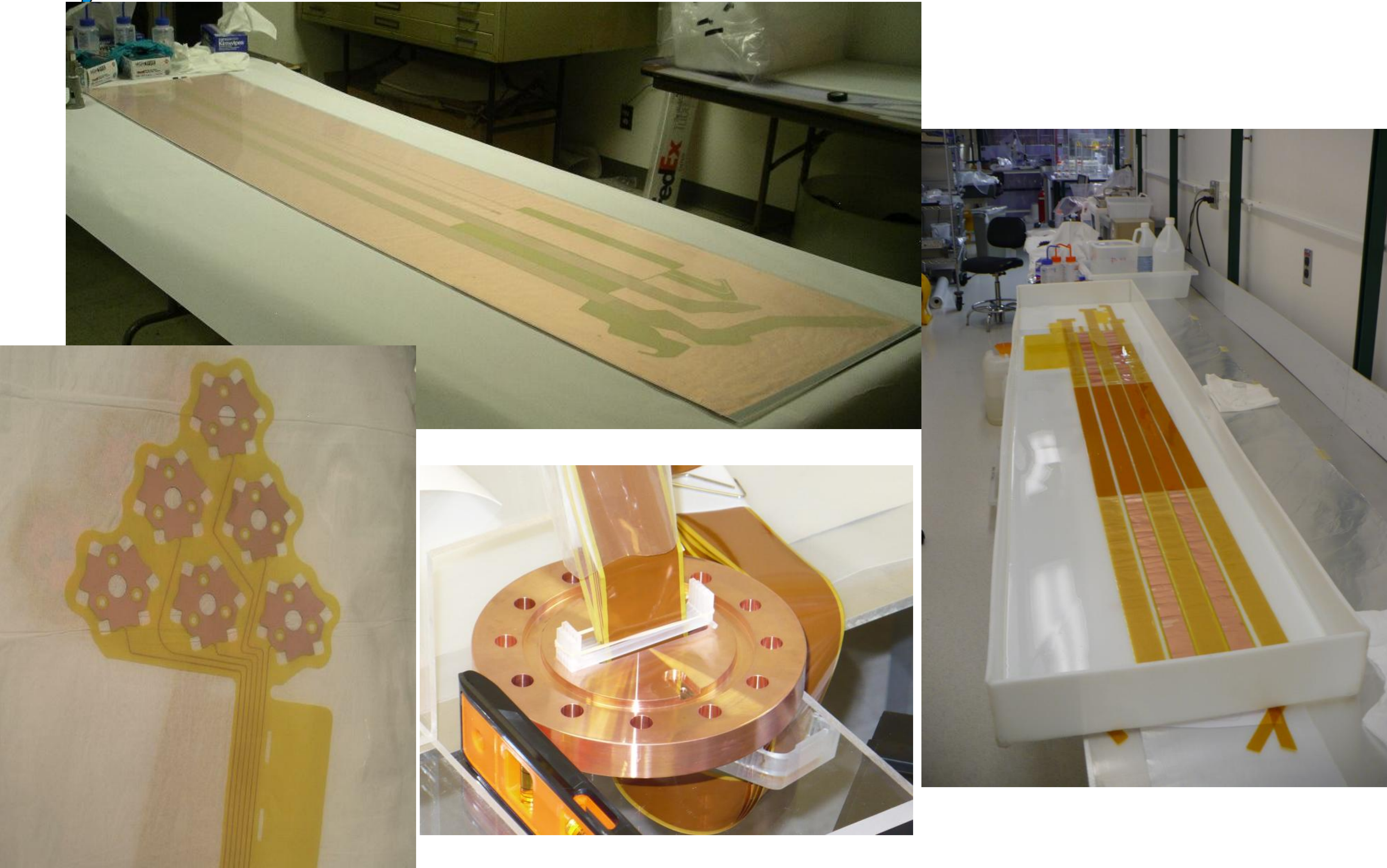


EXO-200 TPC Construction

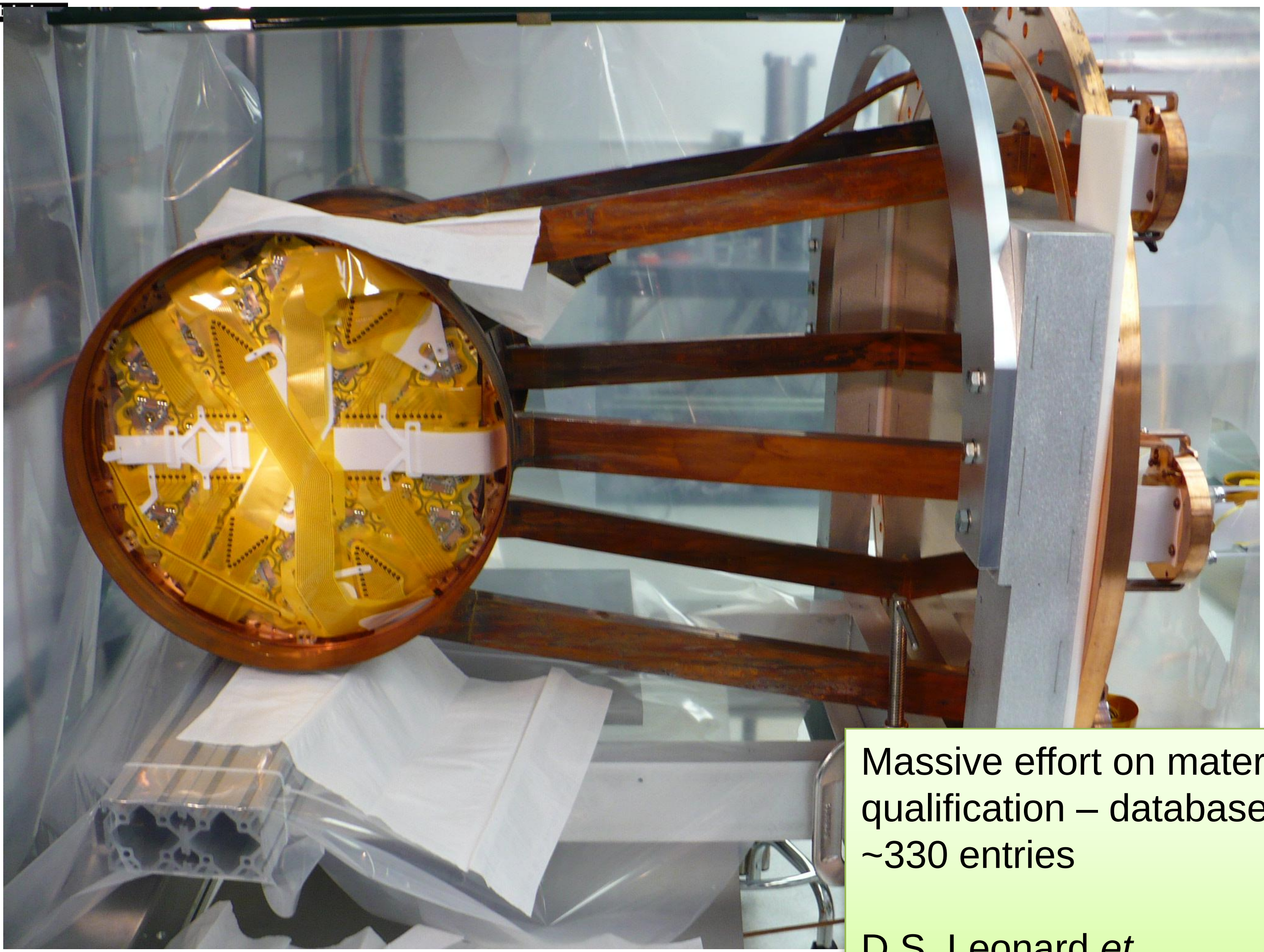




Flex cable etched, cut, and potted!



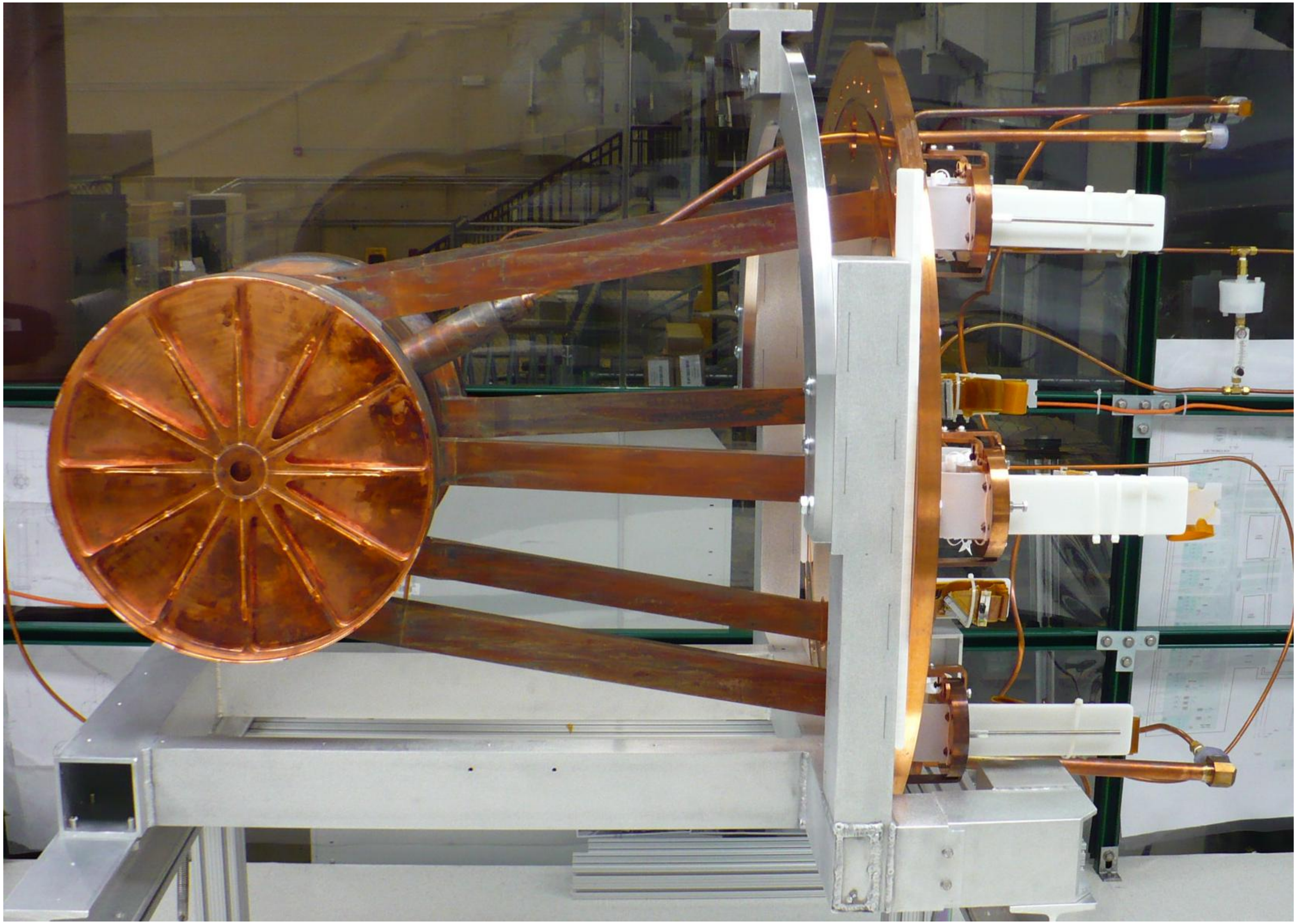
EXO-200 TPC Assembled



Massive effort on materials qualification – database of ~330 entries

D.S. Leonard *et al.*,arXiv:0709.4524 (NIMA)

EXO-200 TPC Completed and Ready to Ship Underground



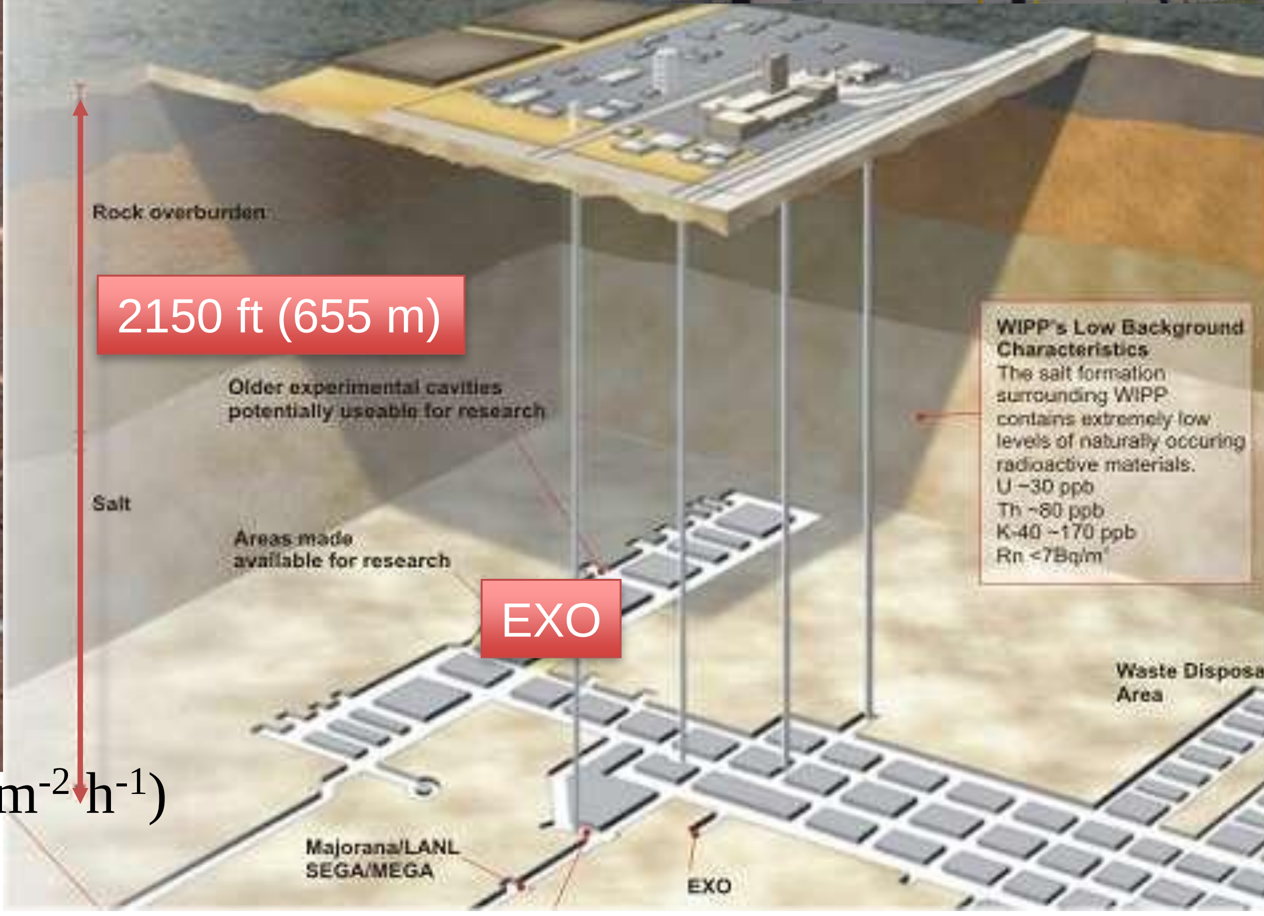
Underground Facility for EXO in Carlsbad, NM


Carlsbad, NM
WIPP/EXO

SMU

Underground Facility
Waste Isolation Pilot Plant (WIPP)
Carlsbad, NM

Aerial View of the WIPP site



2150 ft (655 m)

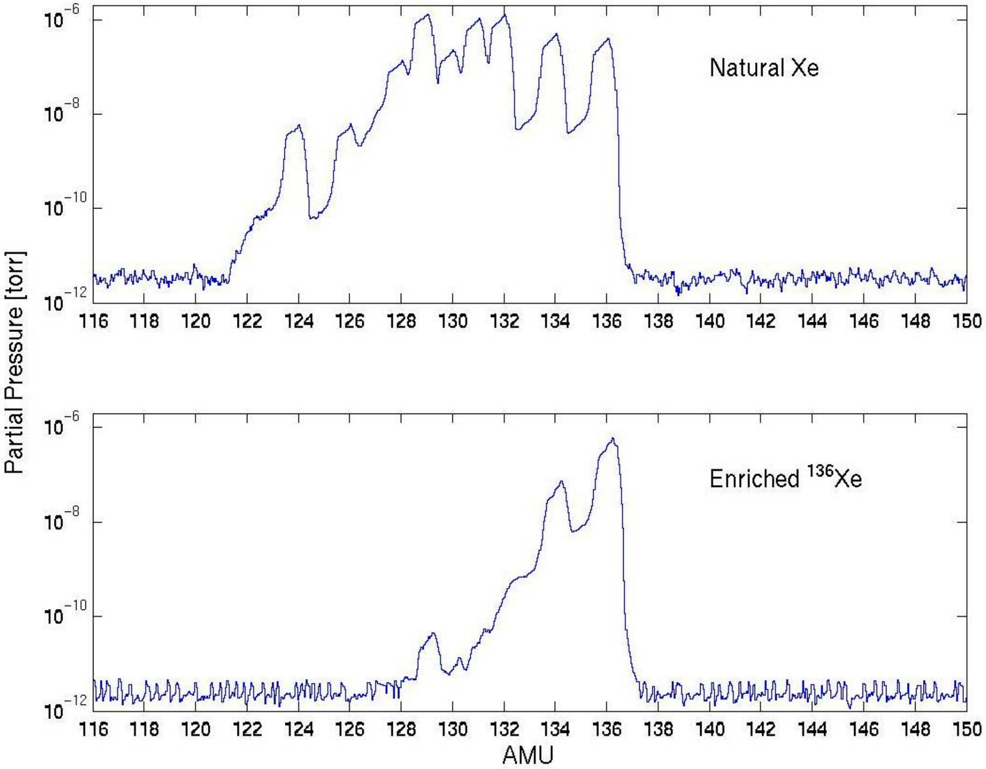
EXO

muon flux at WIPP
(~ 1600 m.w.e.):

$4.77\times10_{-3}$ m$_{-2}$ s$_{-1}$
(3.10×10^{-3} m^{-2} s^{-1}sr^{-1}, ~15 m^{-2}h^{-1})

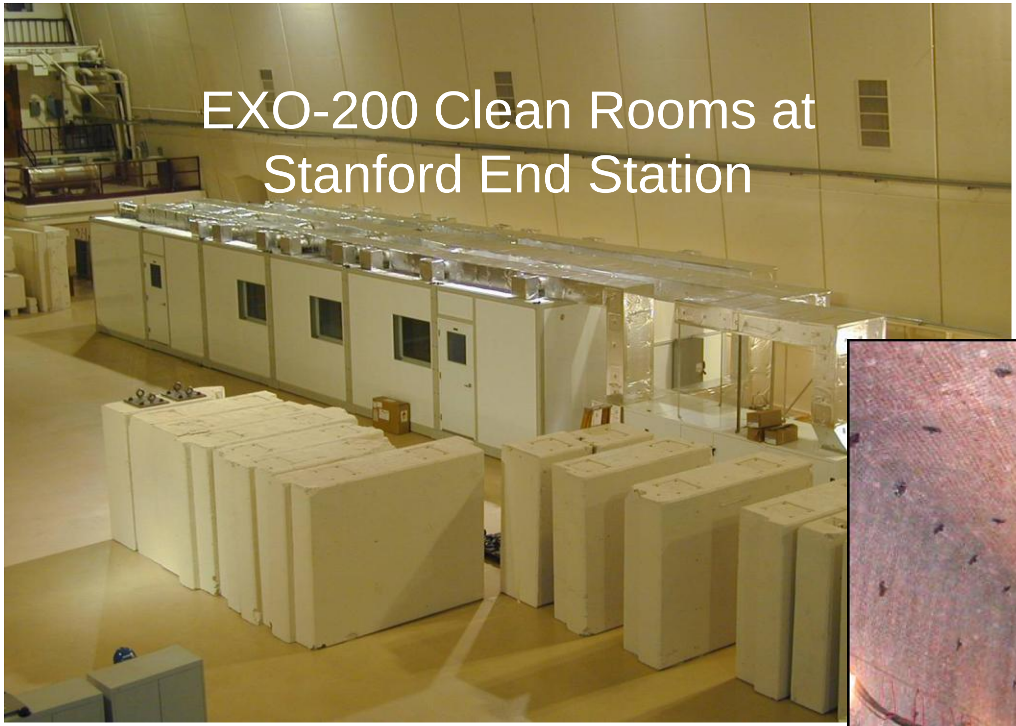
[Esch et al., NIM A 538 (2005) 516]

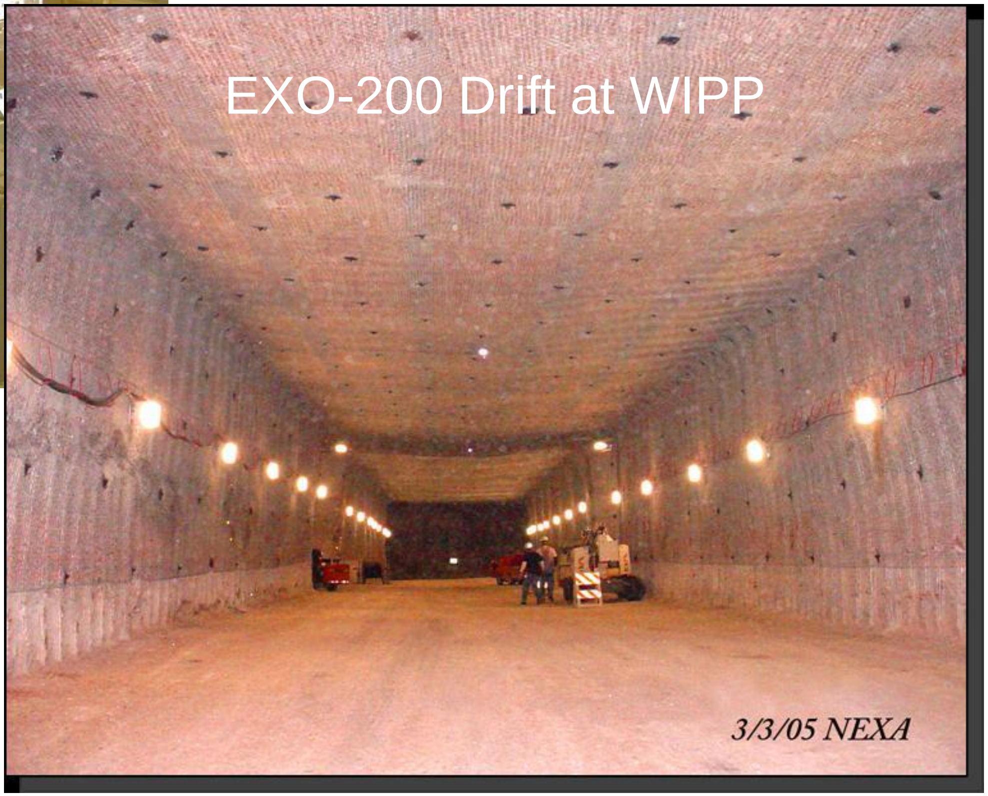
The Crown Jewels of EXO-200



200 kg of xenon enriched to 80% = 160 kg of ^{136}Xe:
The most isotope in possession by any ββ0ν collaboration

EXO-200 Status 2006


EXO-200 Clean Rooms at Stanford End Station


EXO-200 Drift at WIPP

3/3/05 NEXA

Shipping Clean Rooms to WIPP – June 2007

Shipping Clean Rooms to WIPP – June 2007

Fitting the cleanroom into the "waste hoist" – one ½" to spare on each side!

Underground Summer 2007

Clean room modules installed on jacks because the salt creeps over time

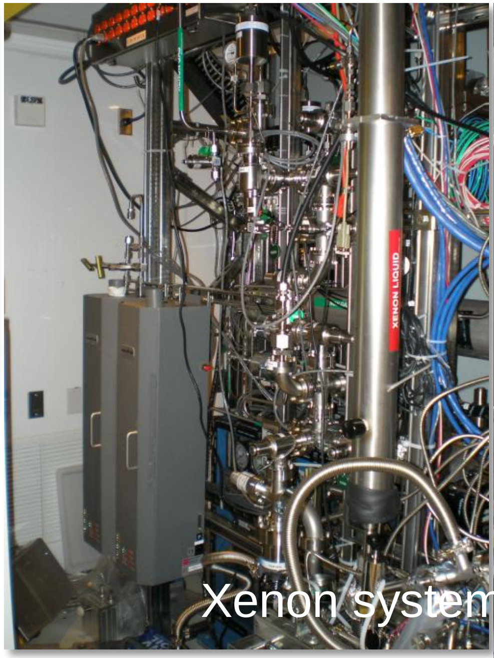
Module Installation @ WIPP

- Modules transported through the mine using the 20-ton and 41-ton forklifts at WIPP
- Module 1 was 30 tons when transported and will weigh 80 tons when all shielding is in place
- Mod 1 had special subfloor
- All other modules were placed and leveled with respect to Mod 1
- All modules were placed on jack stands with special hydraulic jacks installed for Mod 1. This allows us to keep the clean rooms level even though the salt will move over time.

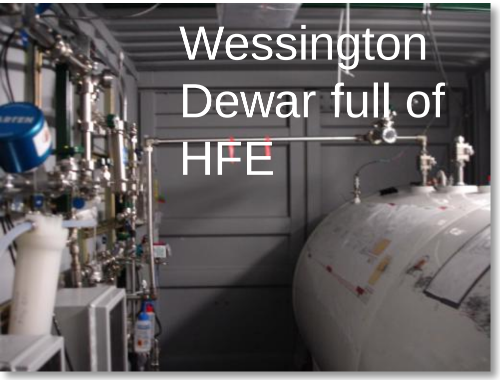
Enriched Xenon Observatory for double beta decay

EXO-200 Installation @WIPP


Machine shop


Xenon system


Electrical hook-u


Wessington Dewar full of HFE


Networking


Chillers

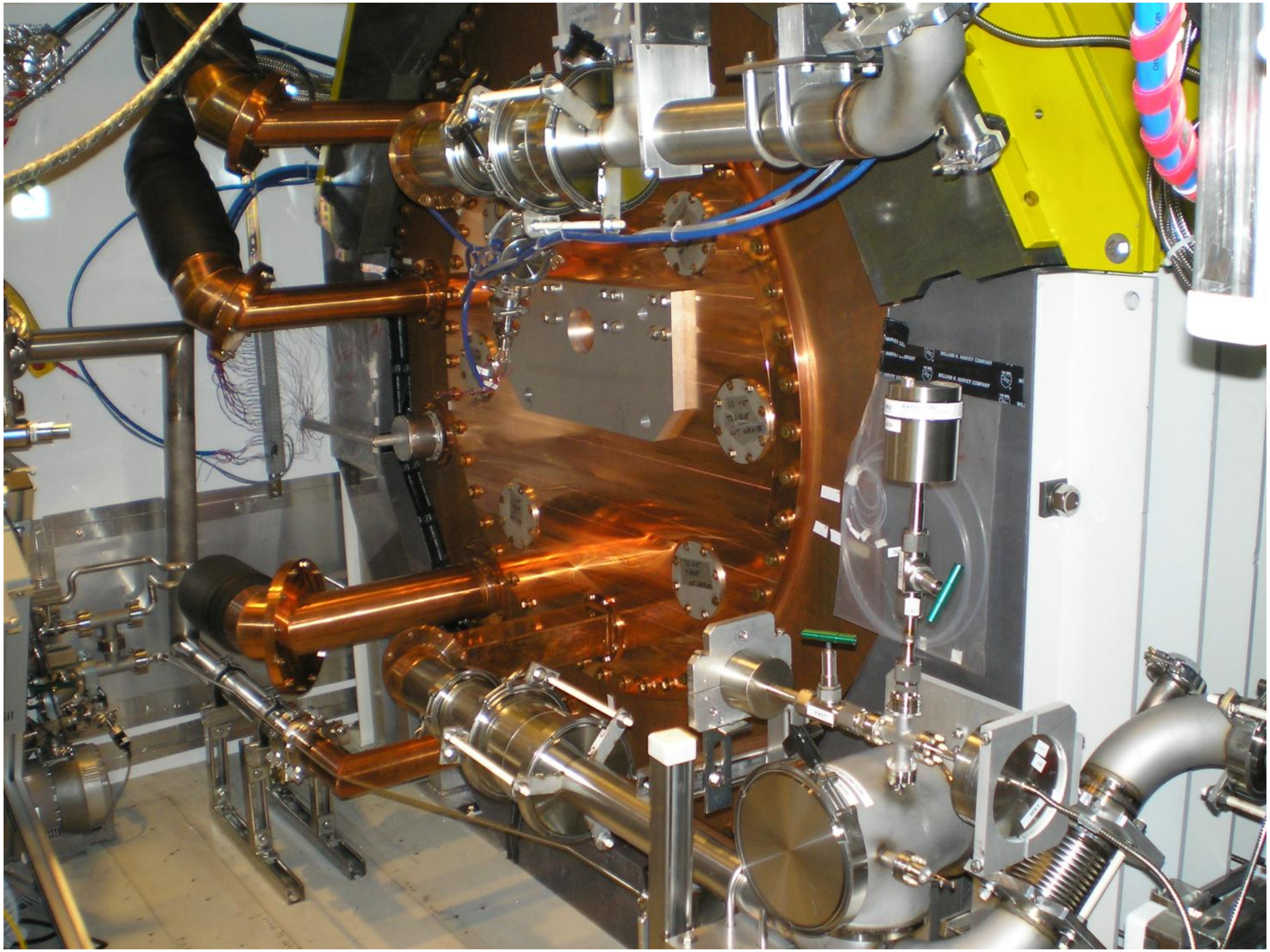

UPS, shop, Xe


HFE storage and transfer

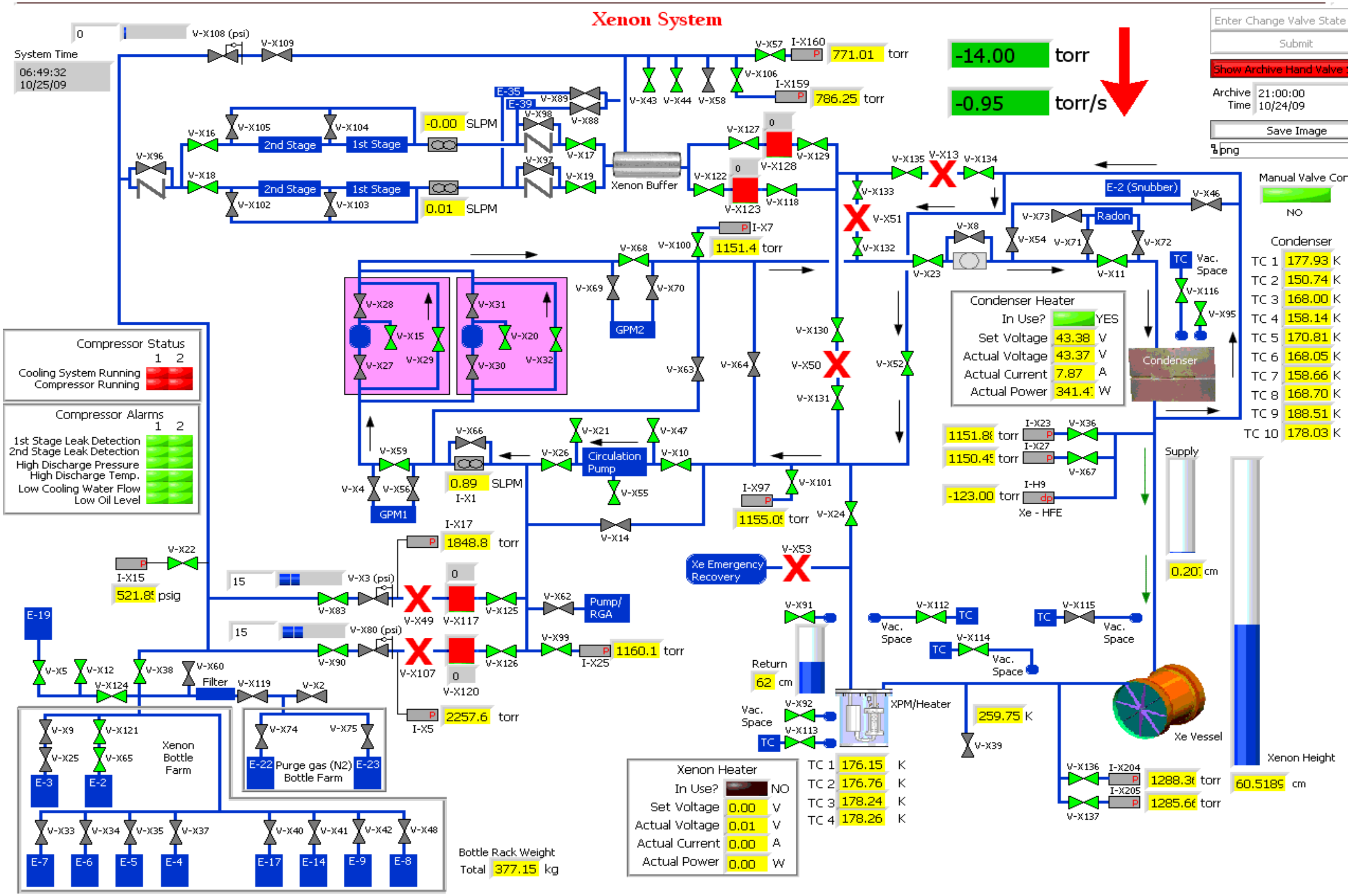

HFE transfer

Cryogenics Systems

Cryogenics systems commissioning underway at WIPP



Xenon System with Full LXe Vessel



Xenon System

System Time
06:49:32
10/25/09

0 V-X108 (psi)

I-X160 771.01 torr

I-X159 786.25 torr

-14.00 torr

-0.95 torr/s

Enter Change Valve State

Submit

Show Archive Hand Valve

Archive Time 21:00:00 10/24/09

Save Image

png

Manual Valve Con

NO

-0.00 SLPM

0.01 SLPM

I-X7 1151.4 torr

Compressor Status

	1	2
Cooling System Running	🟥	🟥
Compressor Running	🟥	🟥

Compressor Alarms

	1	2
1st Stage Leak Detection	🟩	🟩
2nd Stage Leak Detection	🟩	🟩
High Discharge Pressure	🟩	🟩
High Discharge Temp.	🟩	🟩
Low Cooling Water Flow	🟩	🟩
Low Oil Level	🟩	🟩

Condenser Heater

In Use?	🟩	YES
Set Voltage	43.38	V
Actual Voltage	43.37	V
Actual Current	7.87	A
Actual Power	341.4	W

Condenser

TC 1	177.93	K
TC 2	150.74	K
TC 3	168.00	K
TC 4	158.14	K
TC 5	170.81	K
TC 6	168.05	K
TC 7	158.66	K
TC 8	168.70	K
TC 9	188.51	K
TC 10	178.03	K

I-X23 1151.8 torr

I-X27 1150.4 torr

I-H9 -123.00 torr Xe - HFE

I-X1 0.89 SLPM

I-X97 1155.0 torr

I-X17 1848.8 torr

I-X15 521.8 psig

15 V-X3 (psi)

0

15 V-X80 (psi)

0

I-X25 1160.1 torr

I-X5 2257.6 torr

Supply 0.20 cm

Return 62 cm

XPM/Heater

TC 1	176.15	K
TC 2	176.76	K
TC 3	178.24	K
TC 4	178.26	K

259.75 K

Xenon Heater

In Use?	■	NO
Set Voltage	0.00	V
Actual Voltage	0.01	V
Actual Current	0.00	A
Actual Power	0.00	W

I-X204 1288.3 torr

I-X205 1285.6 torr

Xenon Height 60.518 cm

Bottle Rack Weight
Total 377.15 kg

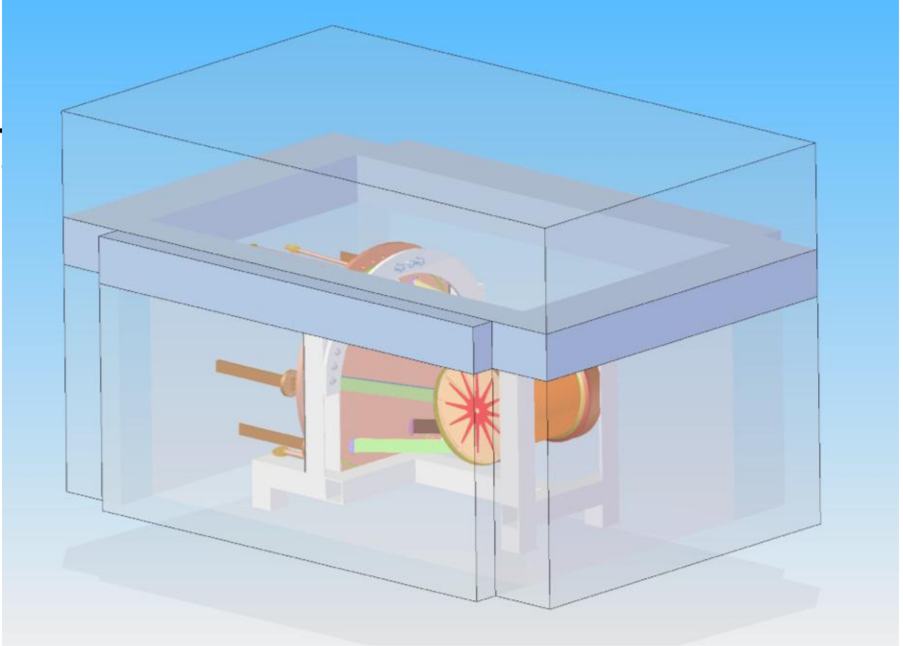
EXO-200 Active Scintillation Muon Veto

- Geometrical placement was optimized by Monte Carlo.

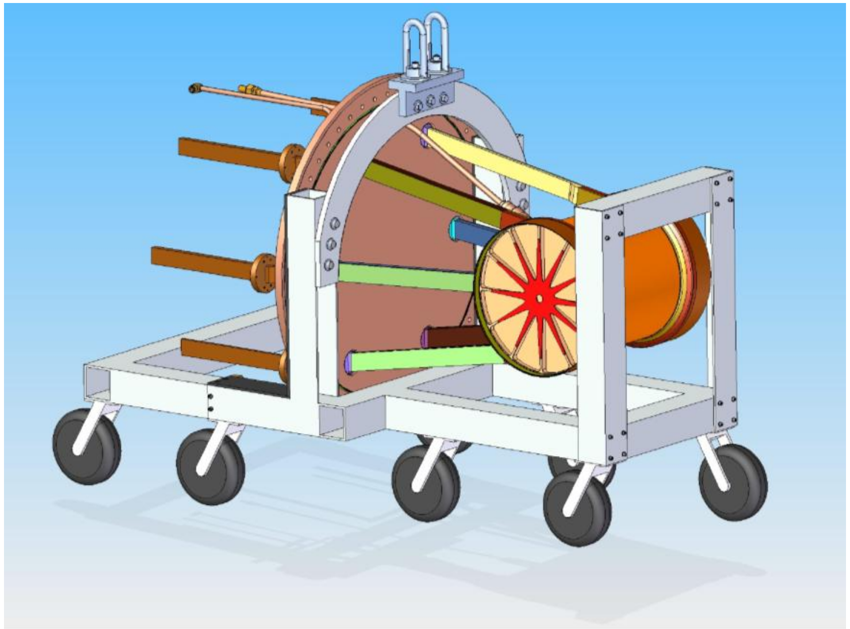
- About 96% muon background rejection is achievable with panel arrangement.

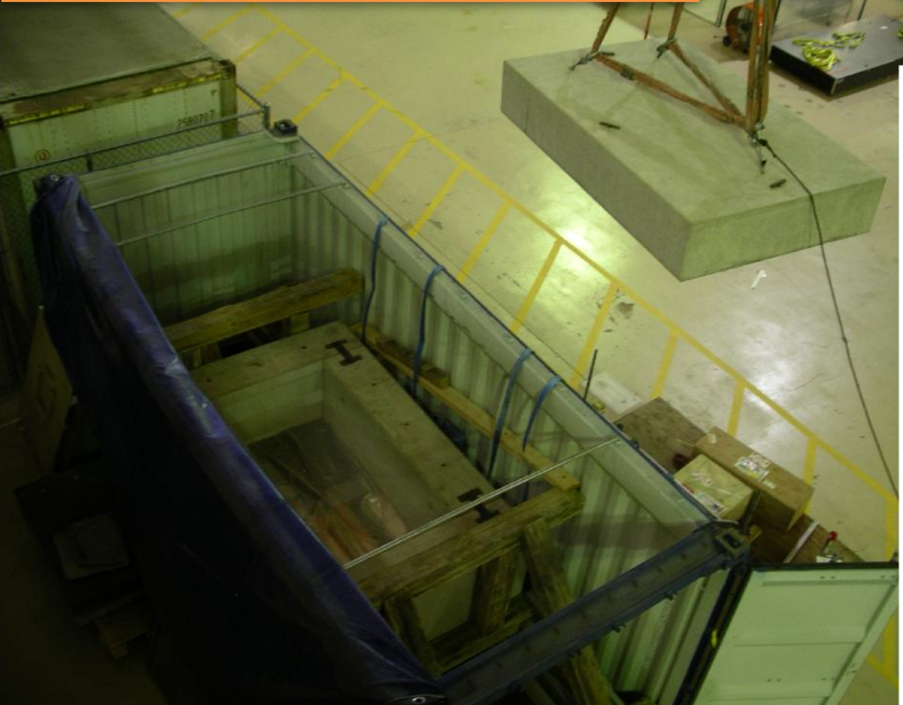
- To stay within background budget we only need 90% efficiency.

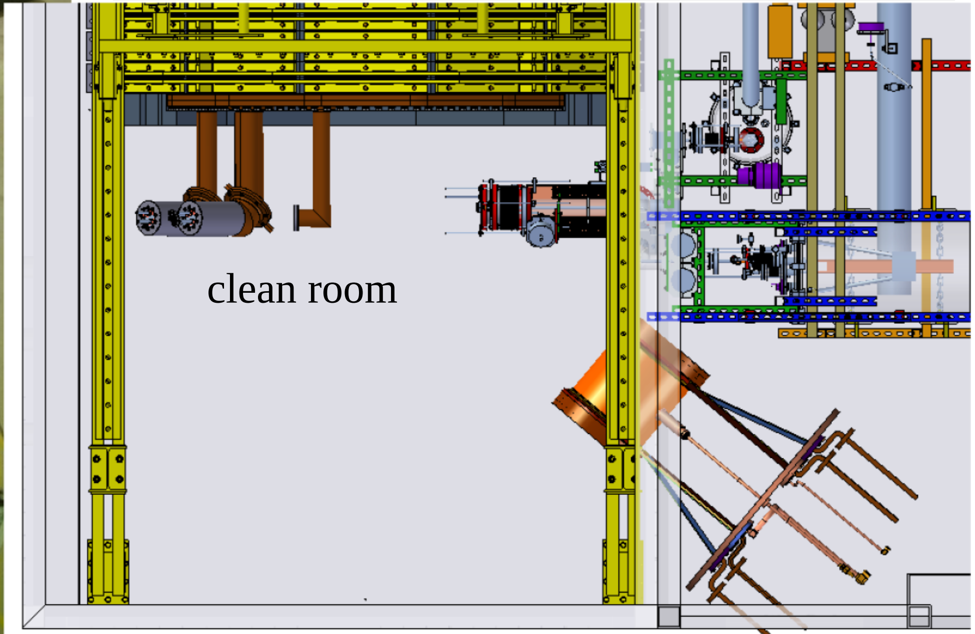
TPC Shipment to WIPP November 2009



concrete-shielded container



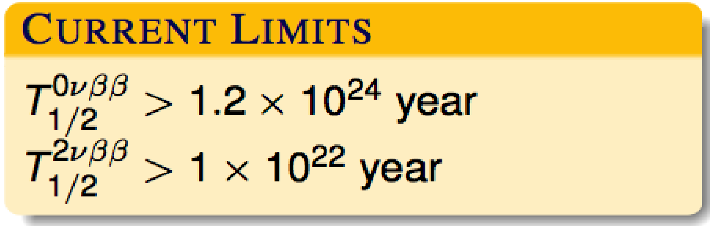




EXO-200 Sensitivity

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV)	
							QRPA	NSM
EXO-200	**0.2**	**70**	**2**	**1.6**	**40**	**6.4 x 10^{25}**	**0.133**[1]	**0.186**[2]

1) Rodin, *et. al.*, Nucl. Phys. A **793** (2007) 213-215
2) Caurier, *et. al.*, arXiv:0709.2137v1



CURRENT LIMITS

$$T_{1/2}^{0\nu\beta\beta} > 1.2 \times 10^{24} \text{ year}$$
$$T_{1/2}^{2\nu\beta\beta} > 1 \times 10^{22} \text{ year}$$

Improves on previous ^{136}Xe experiments by one order of magnitude and competitive with the best ββ0v experiments in the world.

•EXO-200 will also make the first observation of ββ2v in Xe-136.

•If Heidelberg observation claim is correct, EXO-200 will see between 46 and 170 events, on a background of 40 events (5.0 σ to 11.7 σ effect).

Sensitivity to 2ν mode

2νββ of ^{136}Xe has never been observed.

	$T_{1/2}$ (yr)	evts/year in EXO-200 (no efficiency applied)
Experimental limit		
Leuscher et al	$>3.6\cdot10^{20}$	<1.3 M
Gavriljuk et al	$>8.1\cdot10^{20}$	<0.6 M
Bernabei et al	$>1.0\cdot10^{22}$	<48 k
Theoretical prediction [$T_{1/2}^{max}$]		
QRPA (Staudt et al)	$=2.1\cdot10^{22}$	=23 k
QRPA (Vogel et al)	$=8.4\cdot10^{20}$	=0.58 M
NSM (Caurier et al)	$(=2.1\cdot10^{21})$	(=0.23 M)

Excellent prospects for detection of the 2ν decay mode in EXO-200.

EXO-200 Schedule

- Currently clean rooms, support facilities (UPS, machine shop, Xe , etc) are located underground at WIPP
- Cryogenic liquid and gas systems and controls are being commissioned at WIPP in progress
- ESIII clean room at Stanford: TPC assembly, installation in the Cu Xe vessel, mechanical and electrical testing completed
- Muon Veto tested at Alabama shipped to WIPP in Nov 2008 and installation completed summer 2009
- Detector shipment to WIPP November 2009
- Cooldown and installation in Early 2010
- Engineering run (natural Xe) followed by Physics Run

EXO Sensitivities

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @2.5MeV (%)	$2\nu\beta\beta$ BG (events)	$T^{0\nu}_{1/2}$ (yr) 90%CL	Majorana Mass (meV)	
							QRPA[1]	NSM[2]
Conservative	1	70	5	1.6	0.5 (use 1)	2×10^{27}	24	33
Aggressive	10	70	10	1	0.7 (use 1)	4.1×10^{28}	5.3	7.3

1) Rodin, et. al., Nucl. Phys. A 793 (2007) 213-215

2) Caurier, et. al., arXiv:0709.2137v1