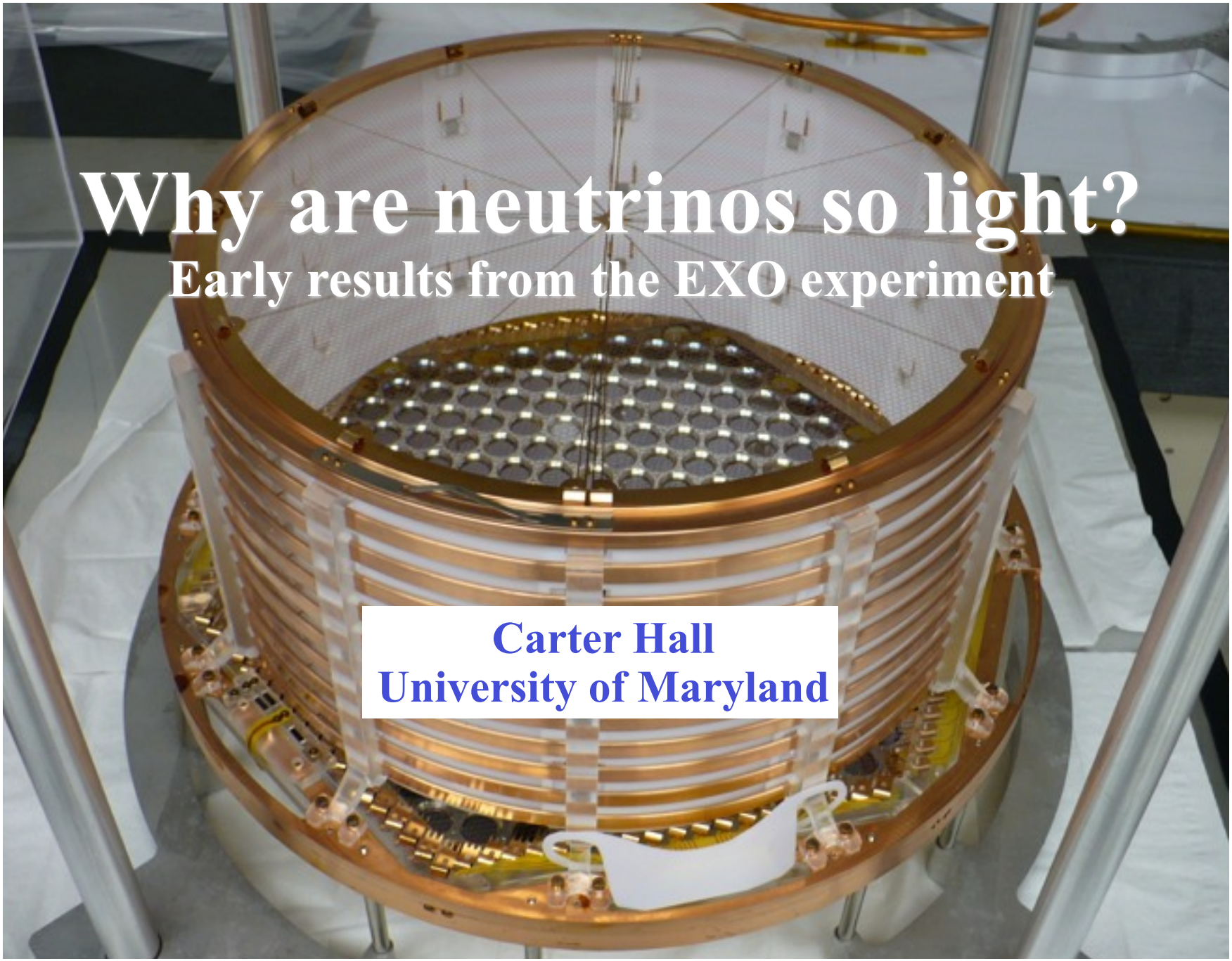
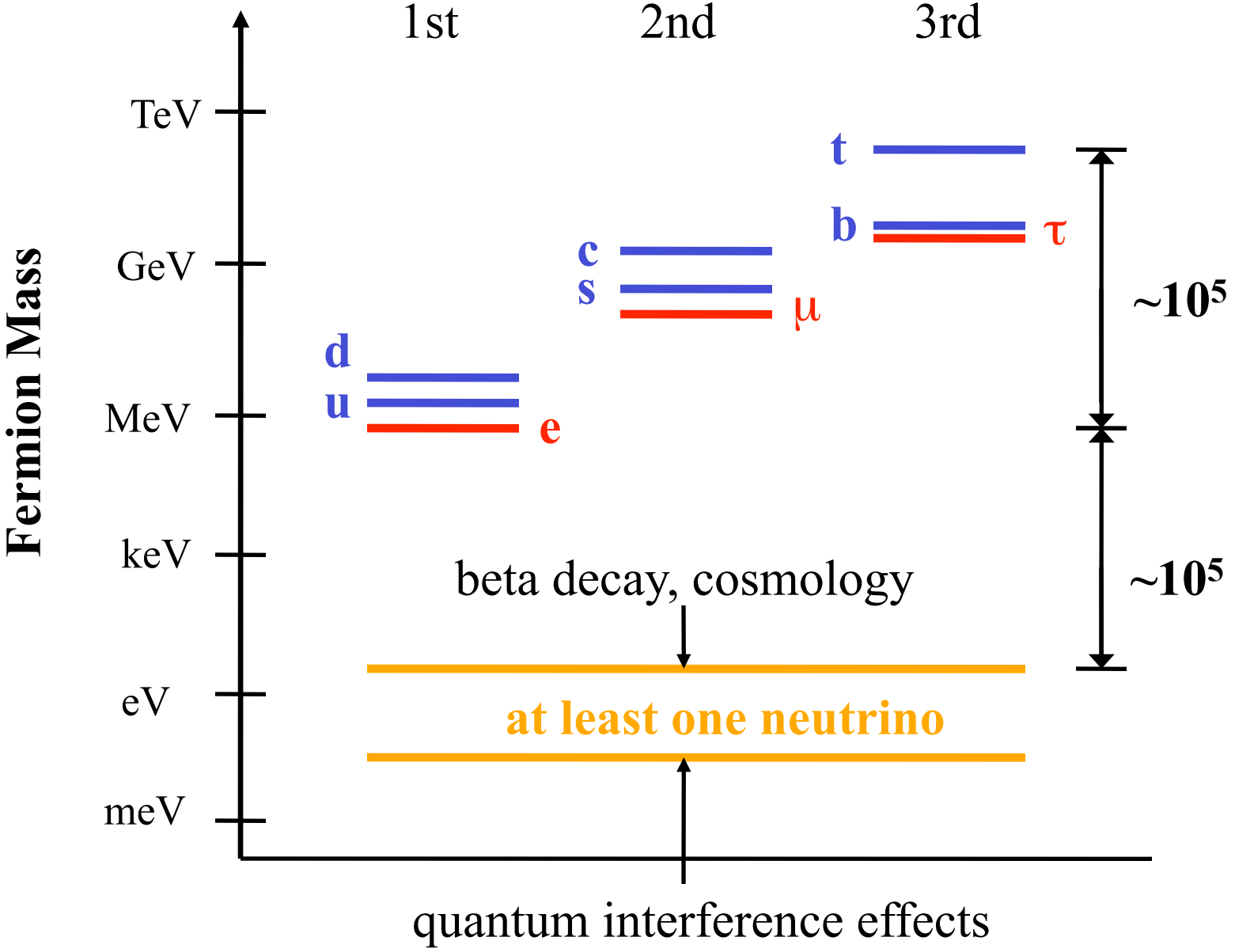


Why are neutrinos so light?

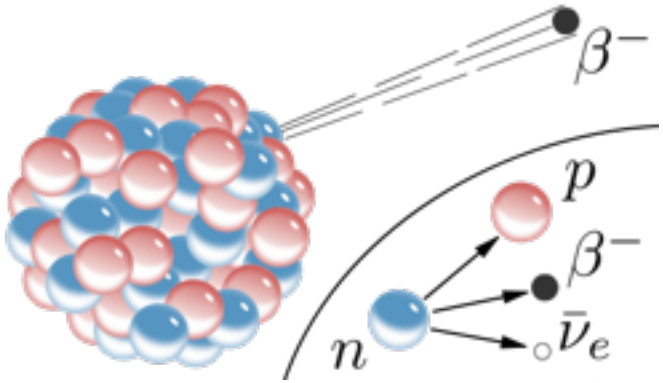
Early results from the EXO experiment

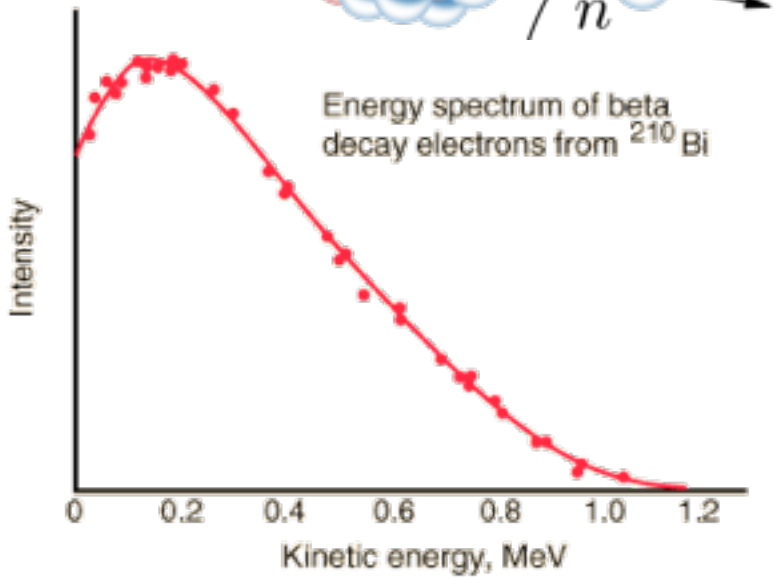
Carter Hall
University of Maryland

Spin 1/2 mass spectrum



Neutrino mass from beta decay (1932)





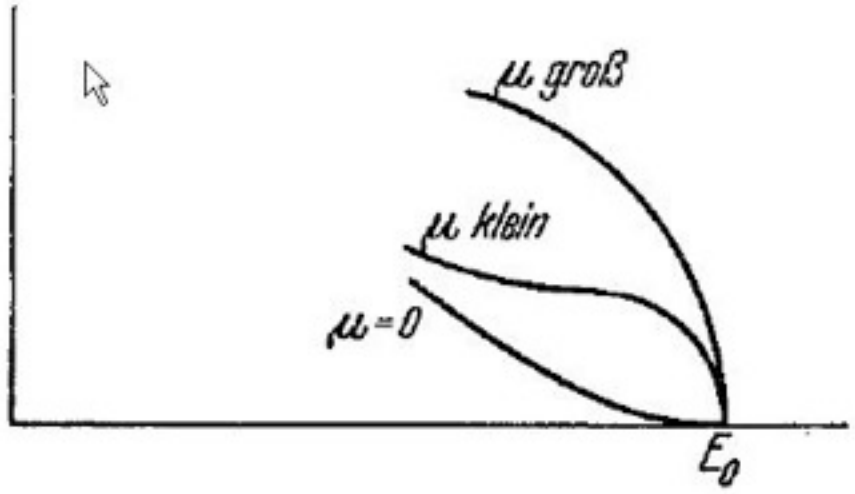
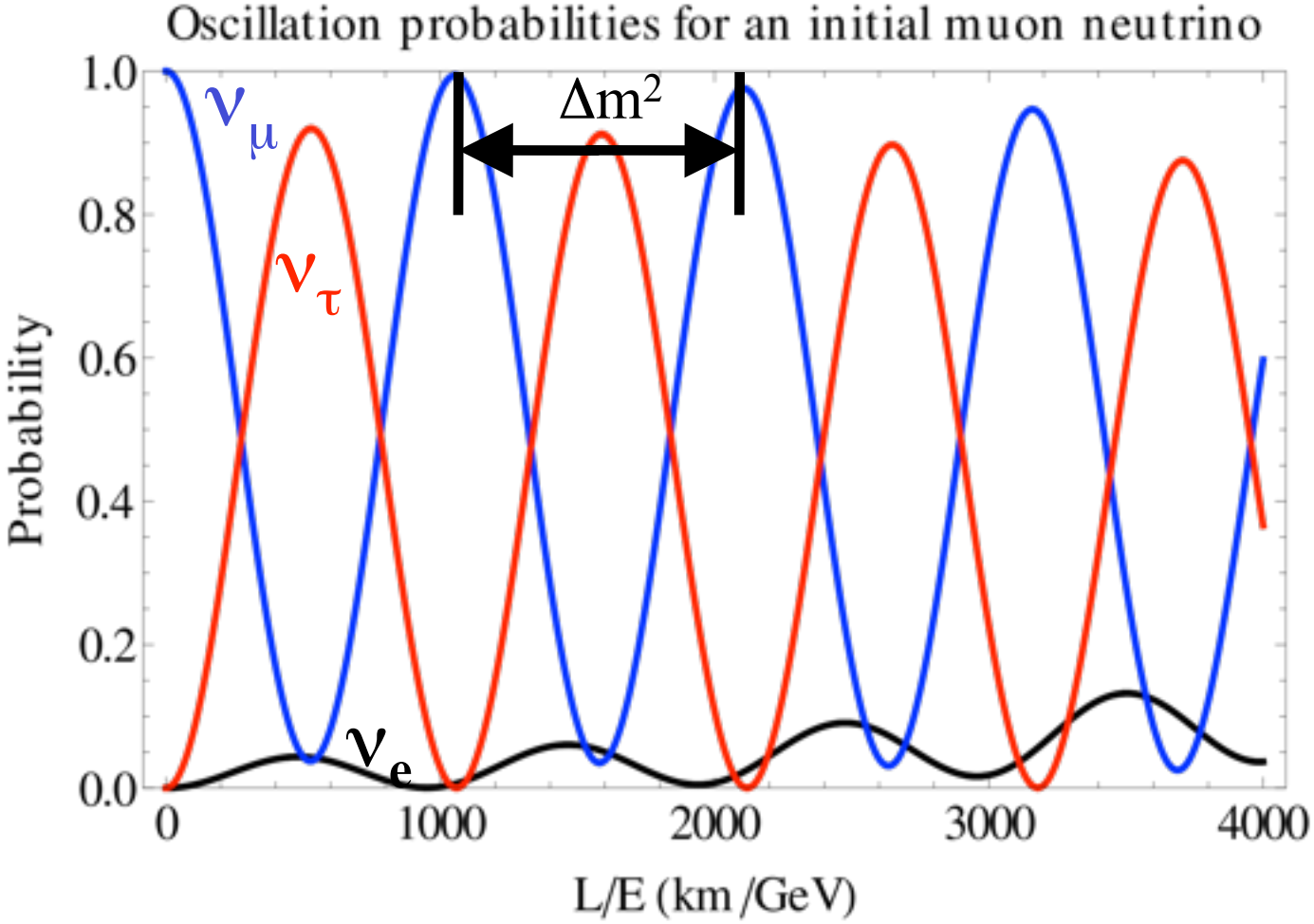


Fig. 1.

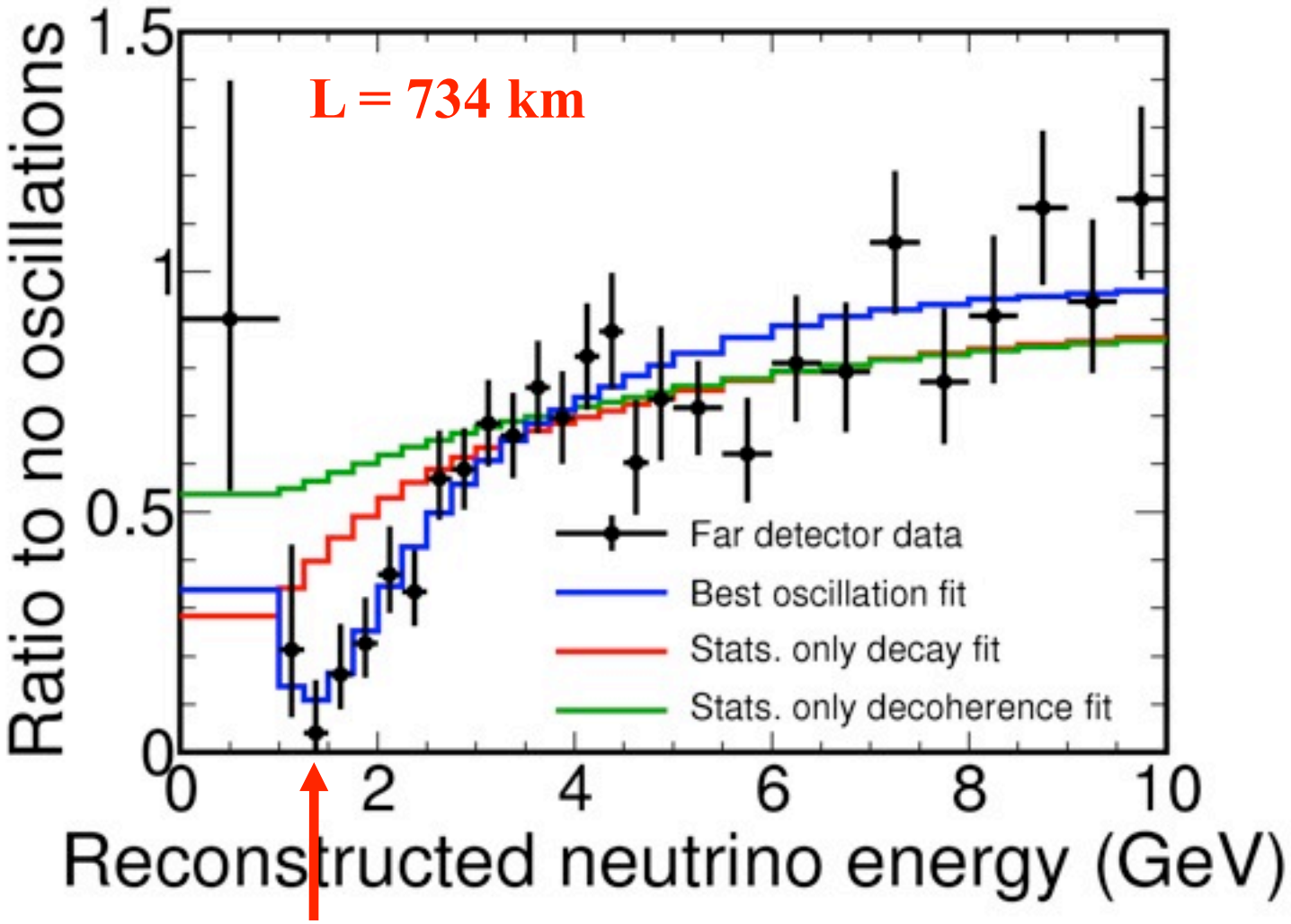
"The greatest similarity to the empirical curve is given by the theoretical curve for m = 0. Hence we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

A quantum mechanical 3-state system

$$\left|\nu_{\mu}(t)\right\rangle = U_{\mu 1}\left|1\right\rangle e^{-i(m_1^2 L/2E)} + U_{\mu 2}\left|2\right\rangle e^{-i(m_2^2 L/2E)} + U_{\mu 3}\left|3\right\rangle e^{-i(m_3^2 L/2E)}$$



MINOS experiment – Fermilab - Minnesota

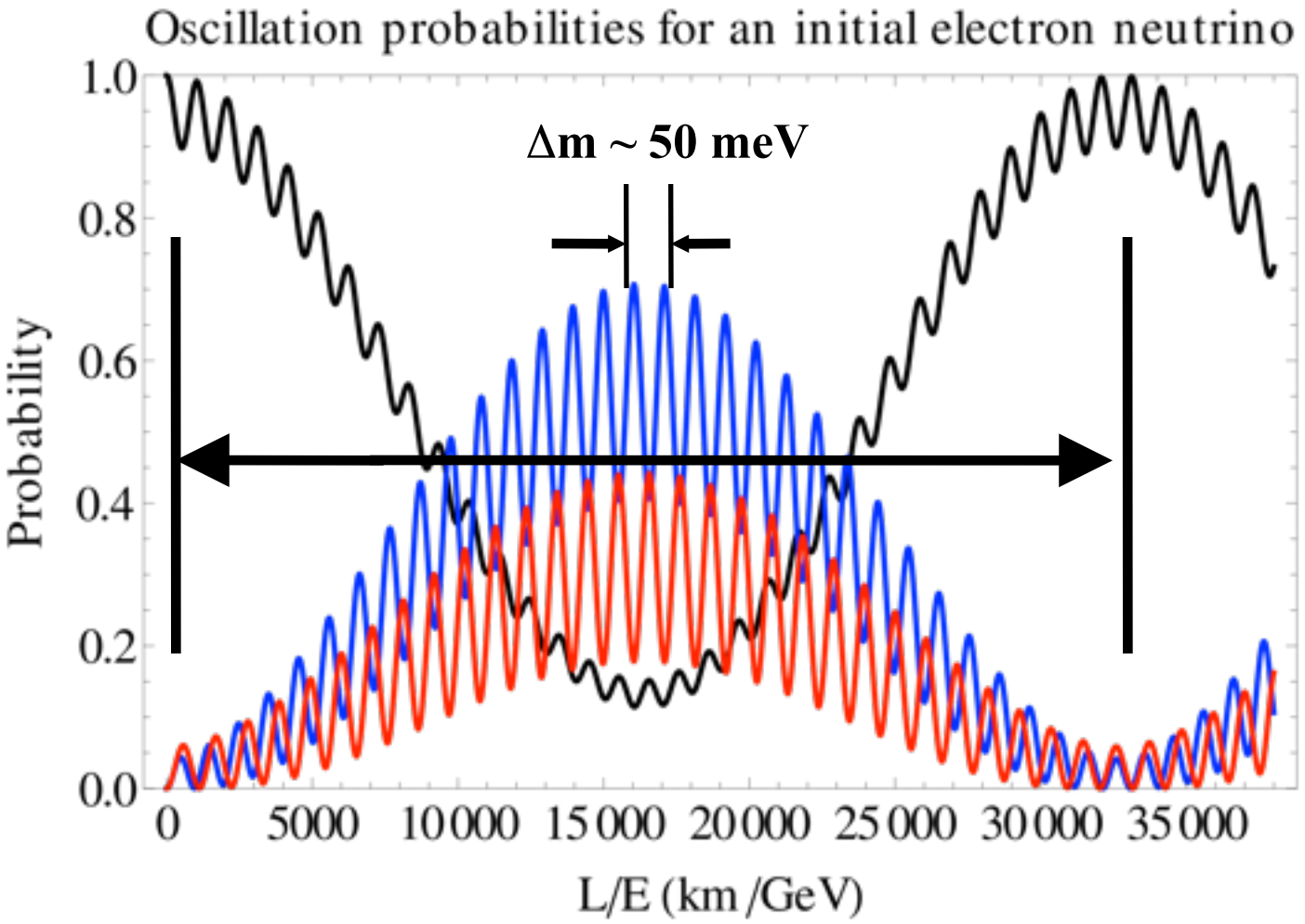


L/E of 1st oscillation minimum measures $\Delta m^2 \sim (50\ \text{meV})^2$

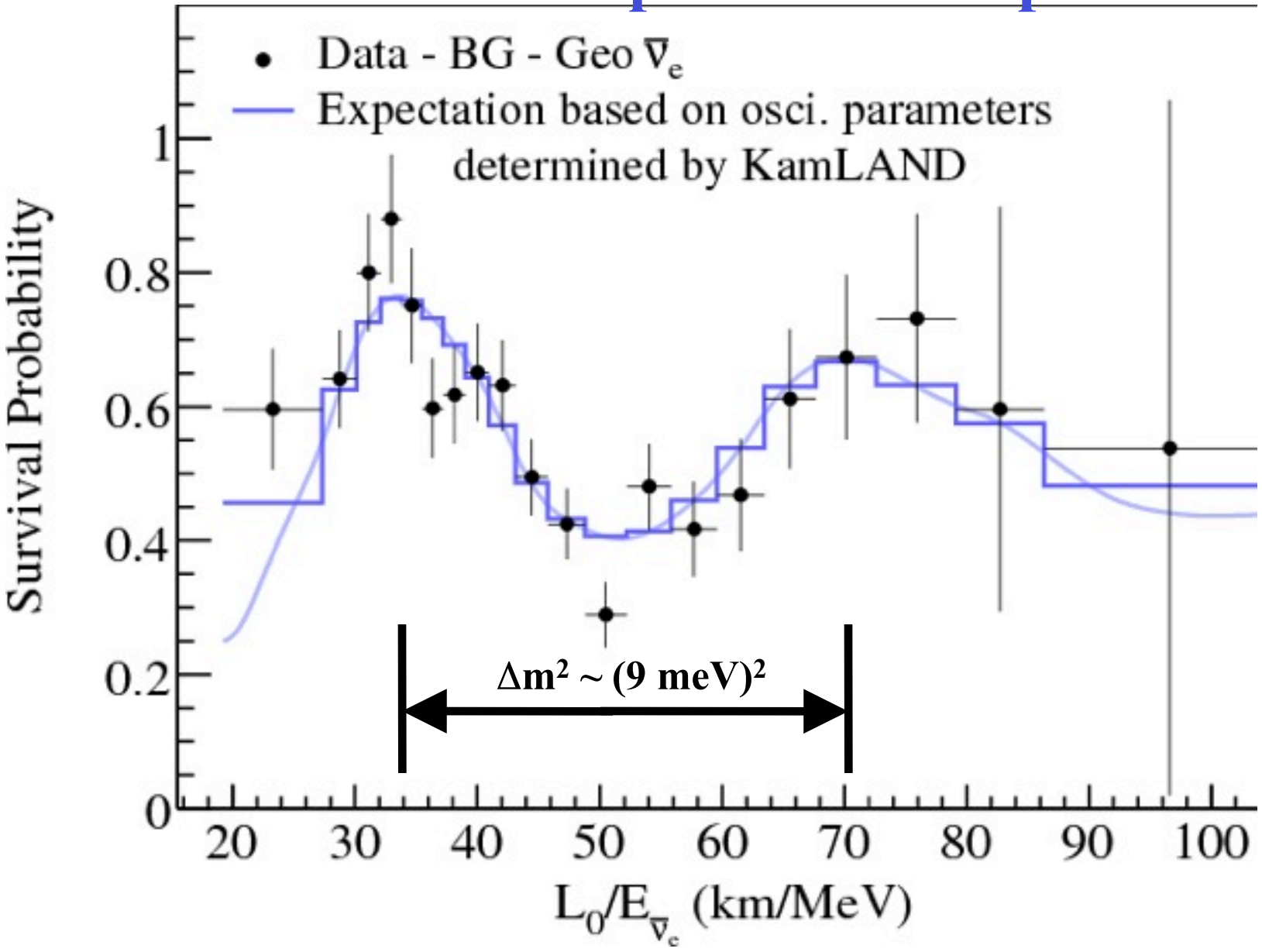
One neutrino mass eigenstate must have at least m ~ 50 meV.

A quantum mechanical 3-state system

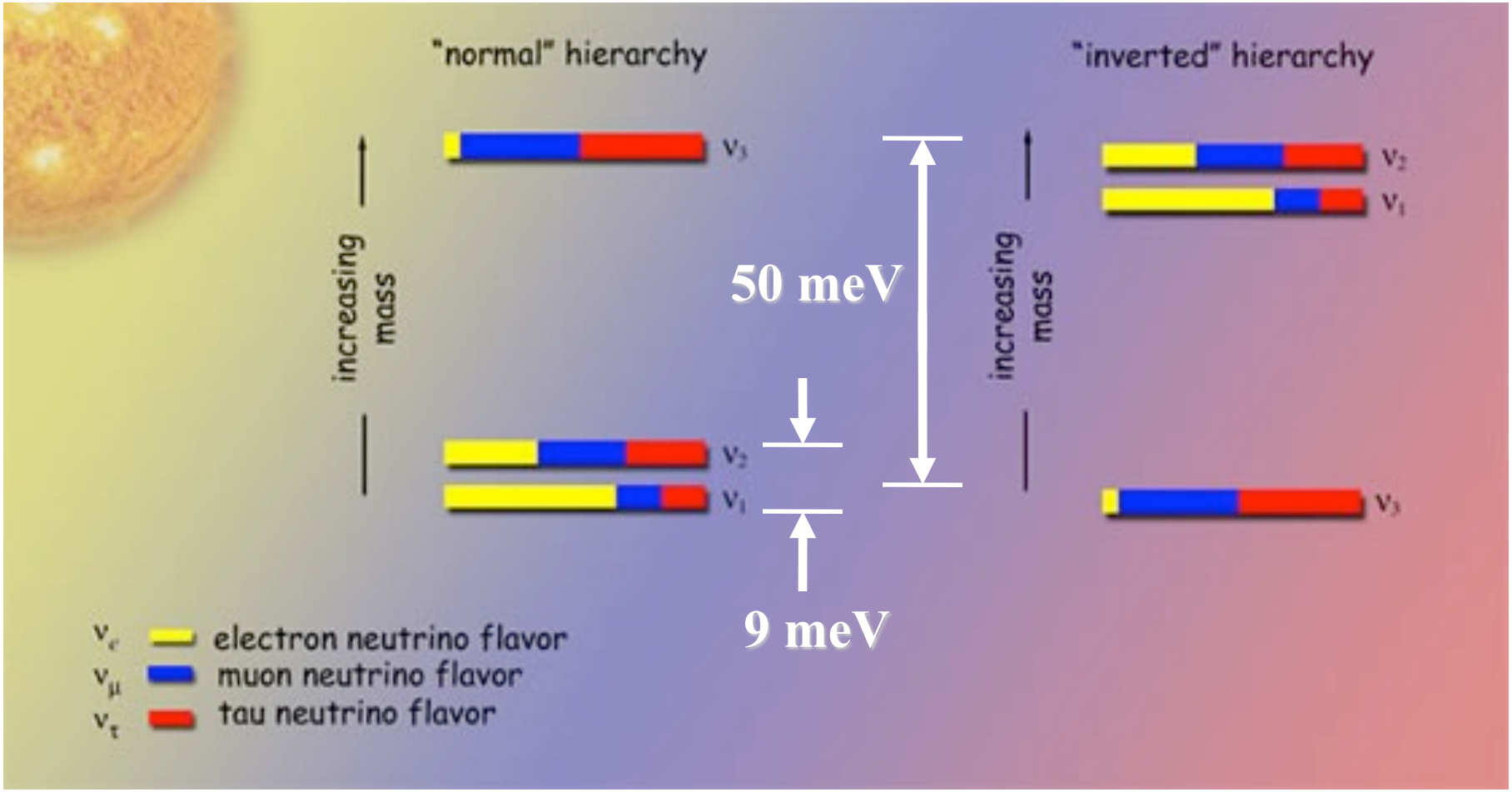
$$\left|\nu_e(t)\right\rangle = U_{e1}\left|1\right\rangle e^{-i(m_1^2 L/2E)} + U_{e2}\left|2\right\rangle e^{-i(m_2^2 L/2E)} + U_{e3}\left|3\right\rangle e^{-i(m_3^2 L/2E)}$$



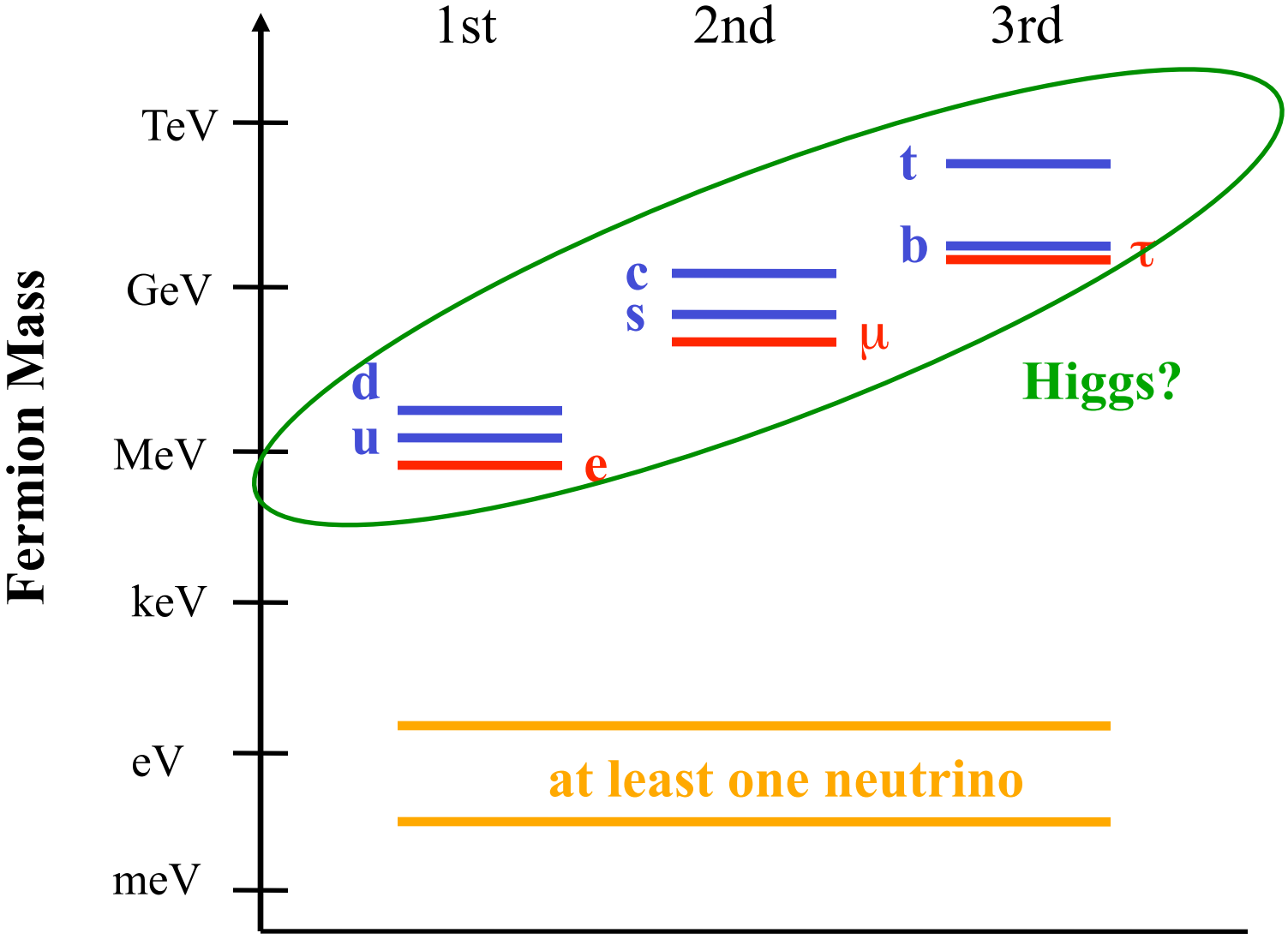
KamLAND experiment – Japan



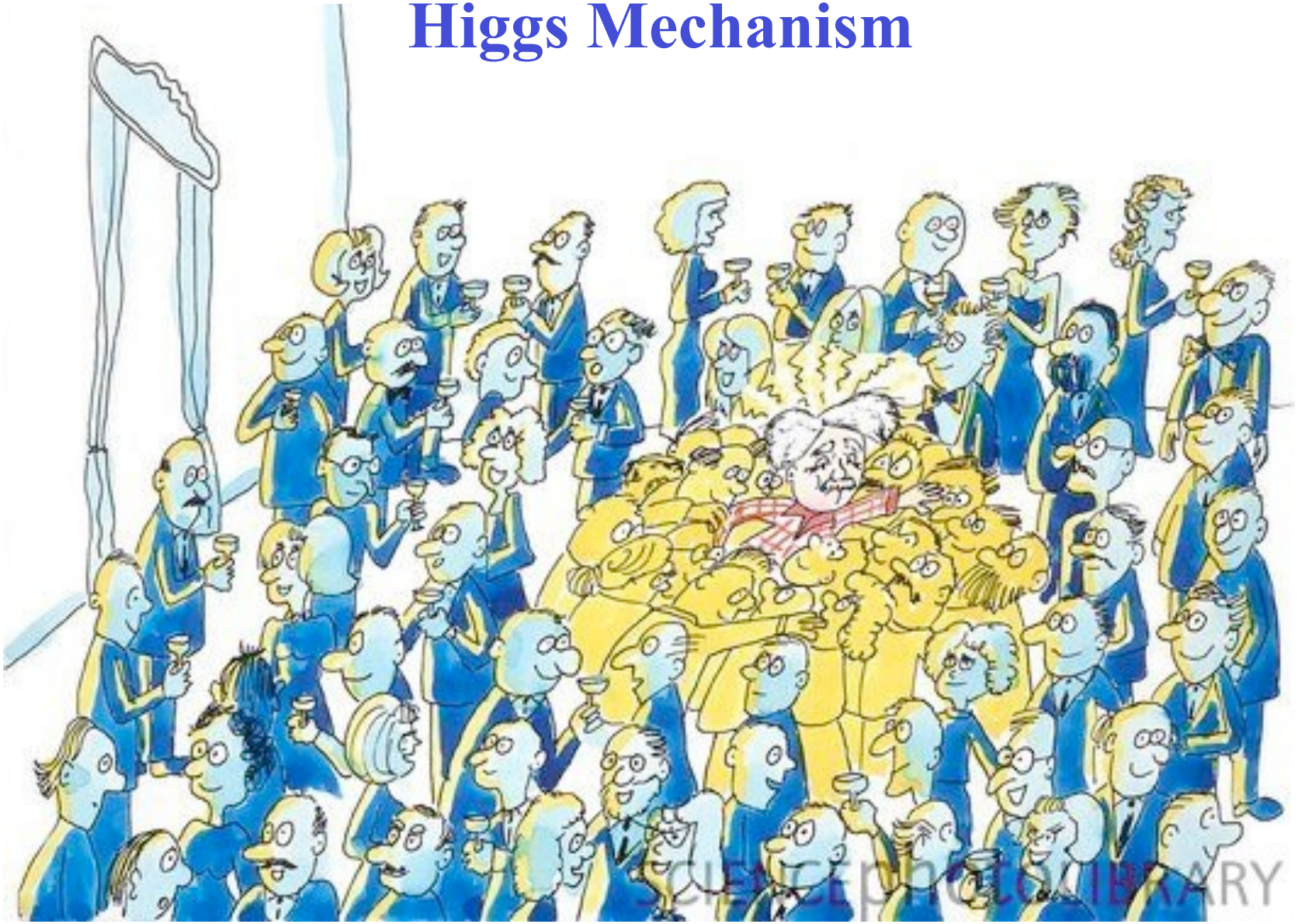
Neutrino mass hierarchy



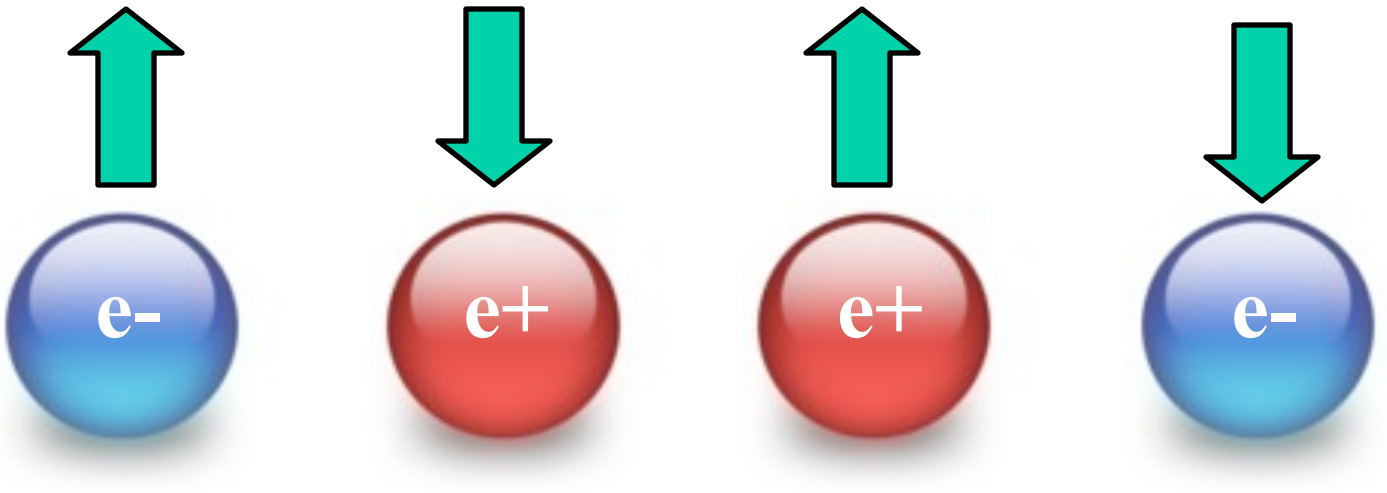
Spin 1/2 mass spectrum



Higgs Mechanism



Spin ½ Fermions



spin-up electron

spin-down positron

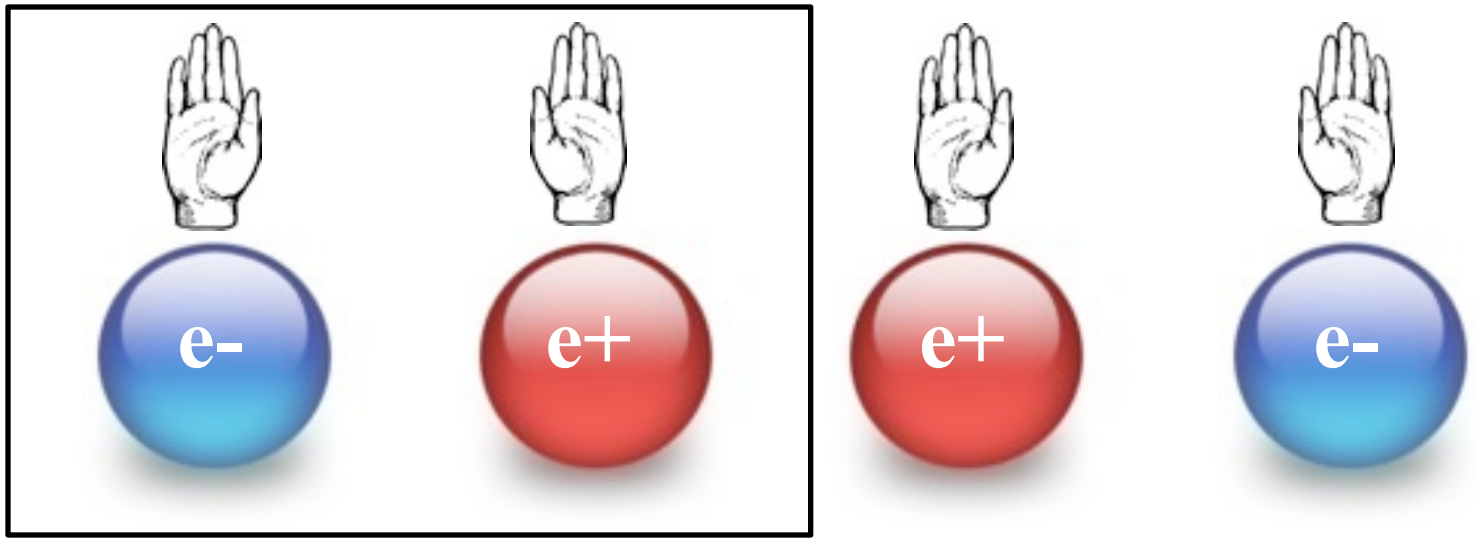
spin-up positron

spin-down electron

Dirac: Four degrees of freedom to describe a spin ½ particle

Spin ½ Fermions

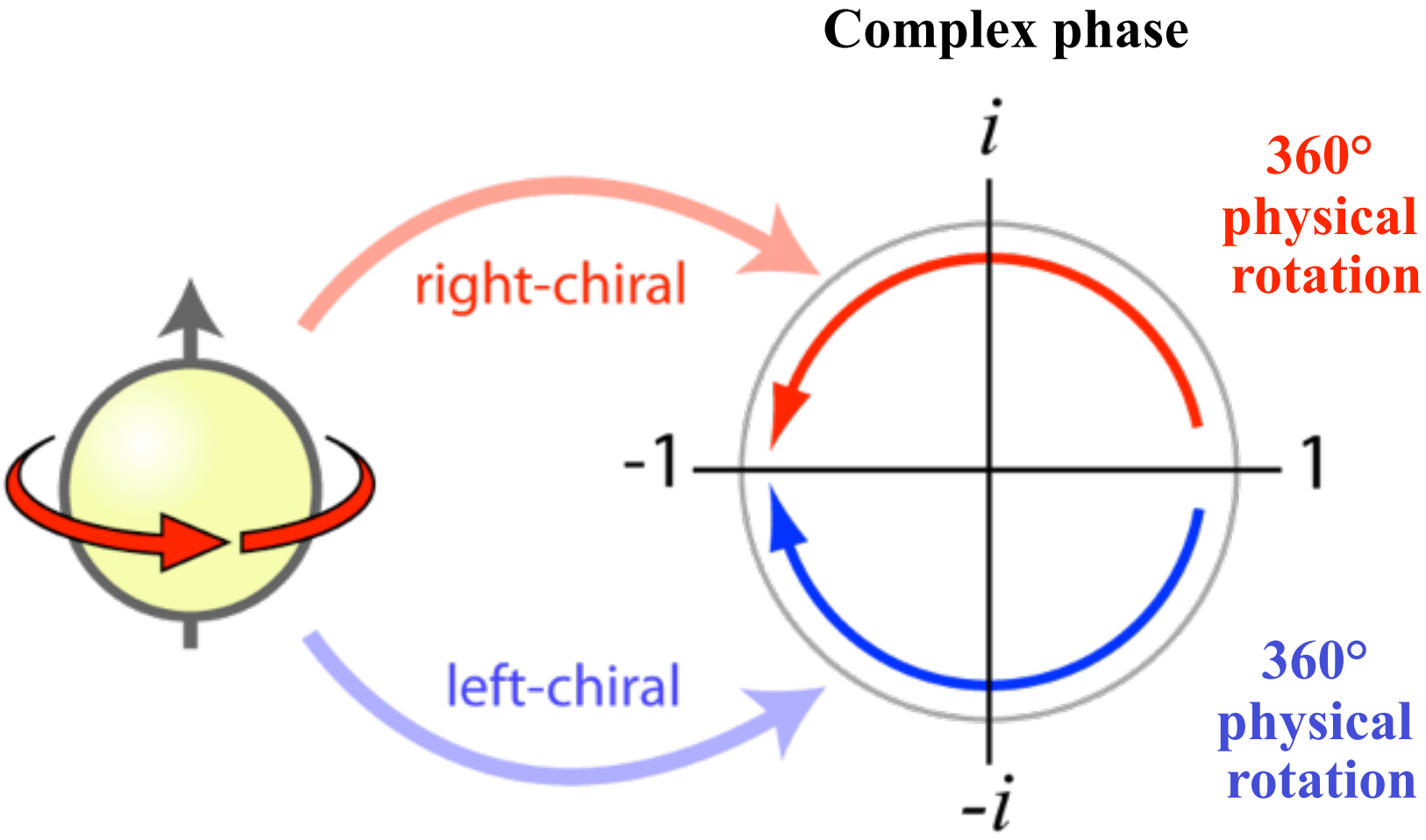
No weak interactions



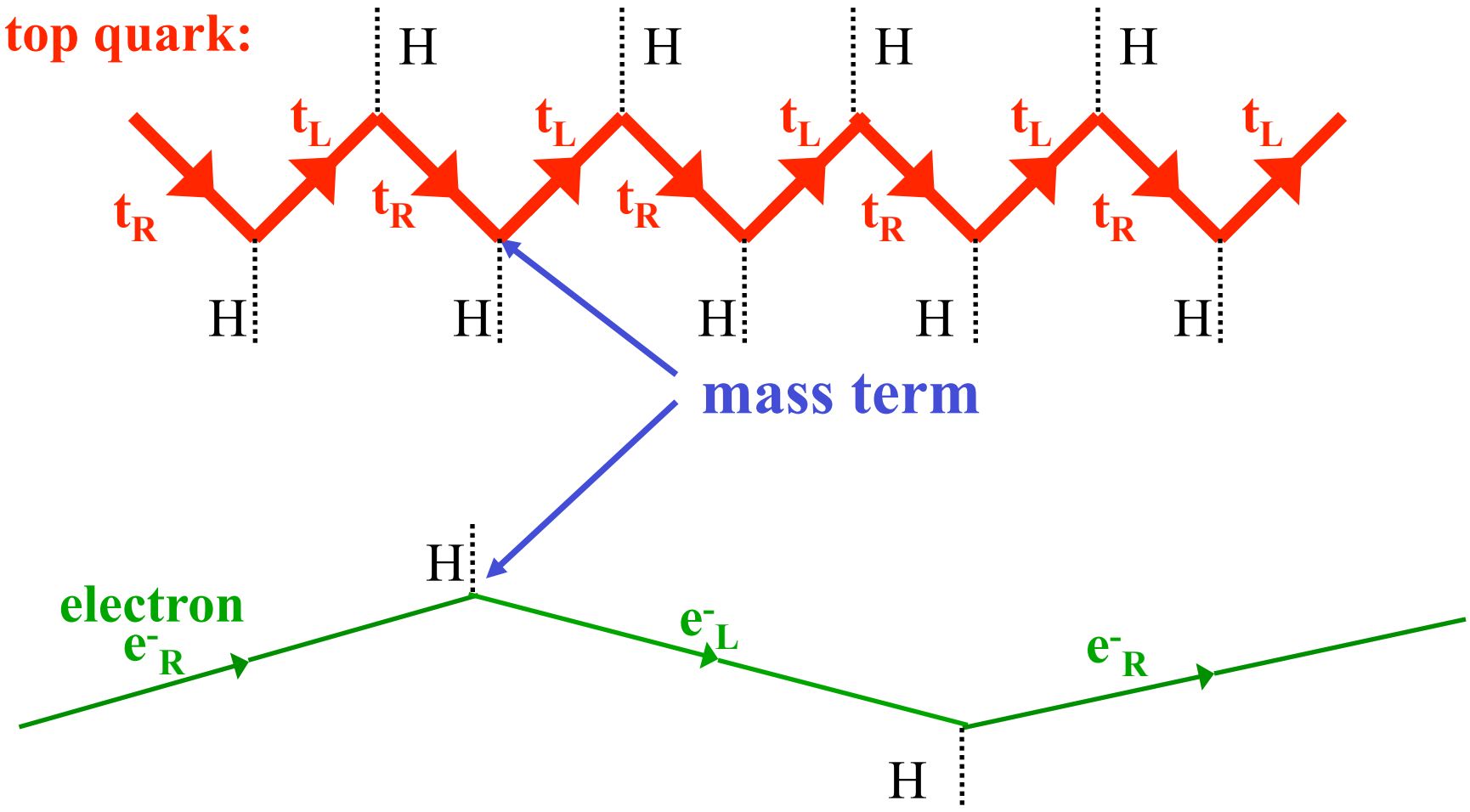
right handed electron | left-handed positron | right handed positron | left-handed electron

Dirac: Four degrees of freedom to describe a spin ½ particle

Spin ½ Fermion - Handedness



Fermion mass terms connect left-handed and right-handed states

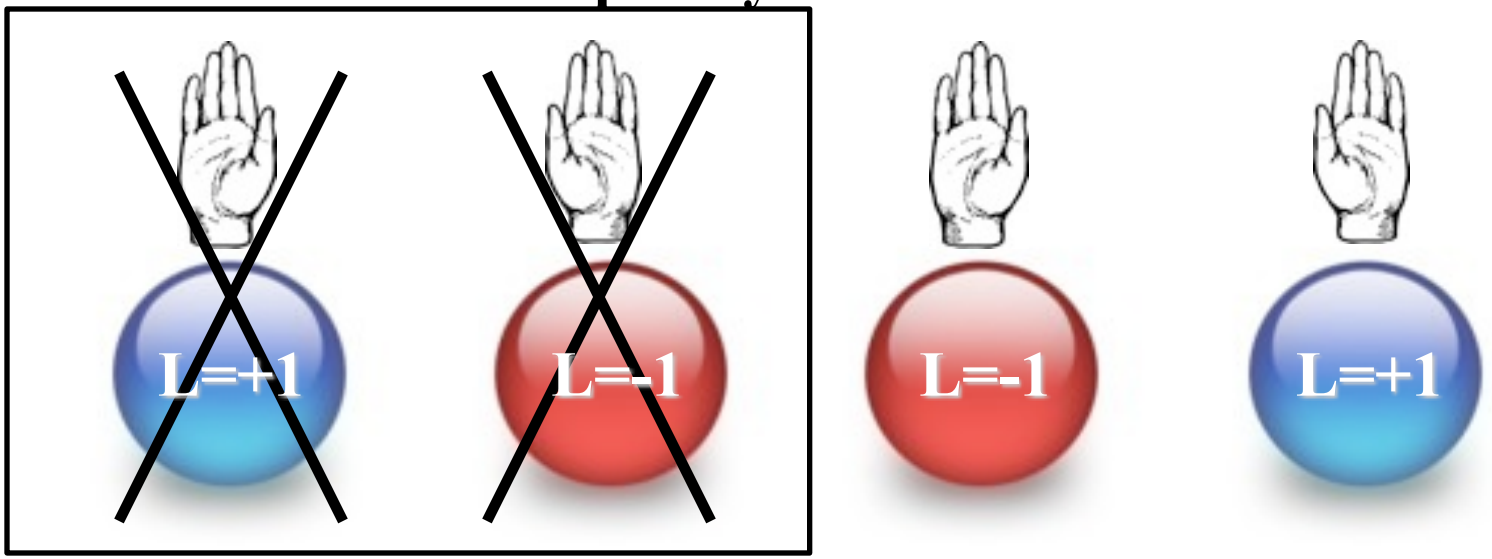


Dirac mass term: conserves charge ($e^- \rightarrow e^-$)

What about a massless neutrino?

No weak interactions.....

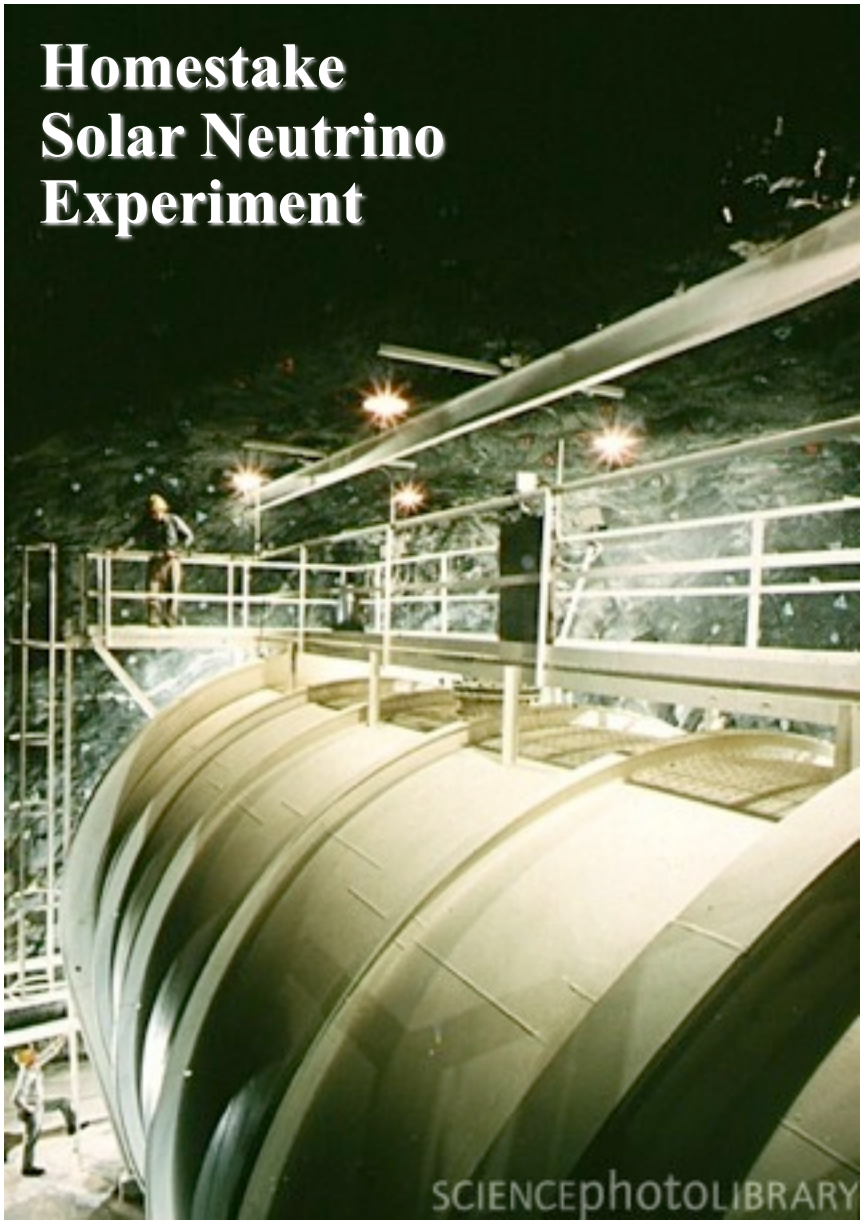
no interactions at all – completely sterile!

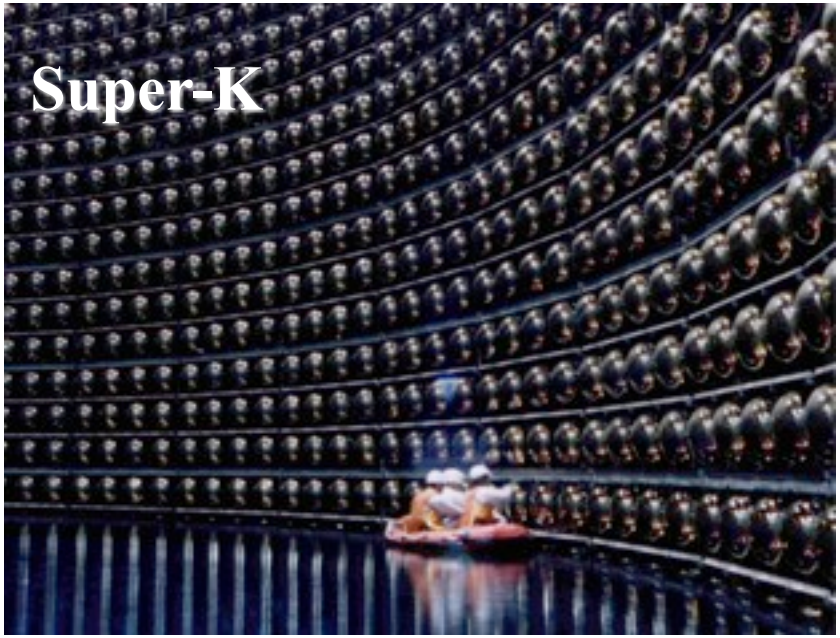


right handed neutrino | left-handed anti-neutrino | right handed anti-neutrino | left-handed neutrino

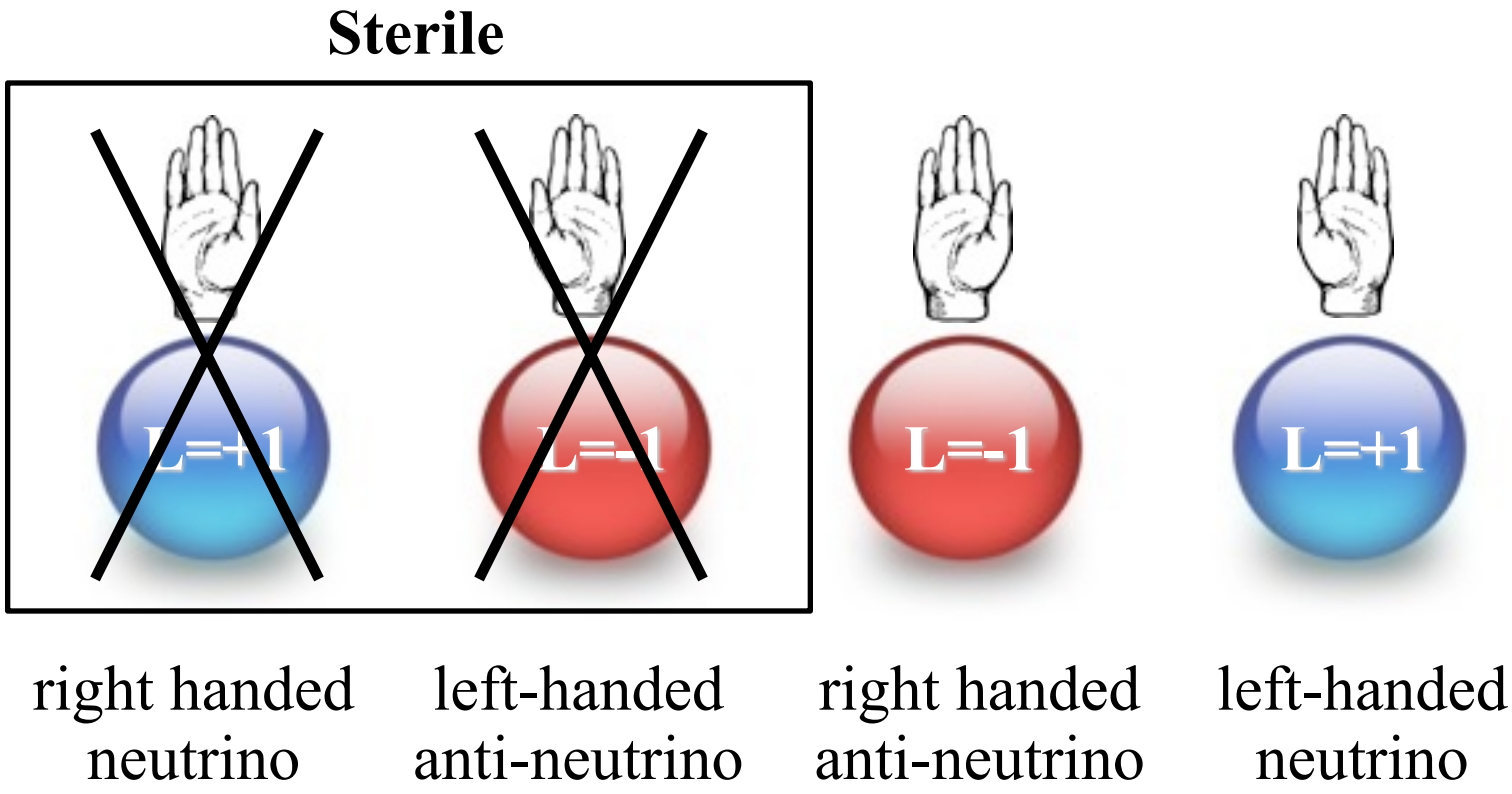
The old standard model "explanation" for massless neutrinos:
Nature "had no use" for sterile states, so they are left out.
This prevents the Higgs from giving neutrinos a Dirac mass.

But neutrinos do have mass.





No problem..... just put the sterile states back.

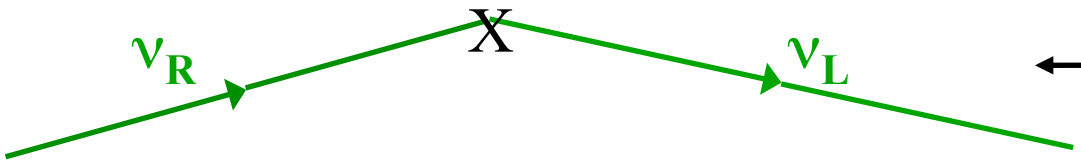


Dirac neutrino: carries a conserved charge (lepton number)

Types of Neutrino mass terms

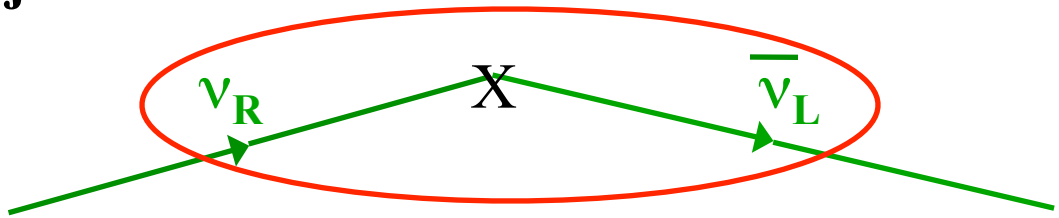
Dirac Neutrino Mass

Conserves lepton number



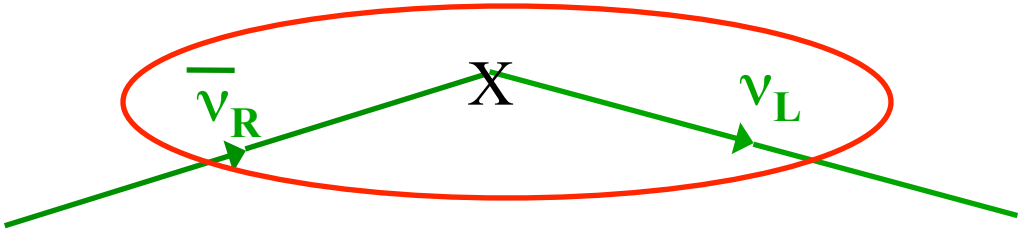
Standard model Higgs can create only a Dirac mass

Majorana Mass 1



violates conservation of lepton number

Majorana Mass 2



Neutrinos may have all three types of mass terms

See-saw mechanism

generated by the Higgs

Suppose $m_{Dirac} \sim 100$ GeV, like the top quark

and $m_{Majorana} \sim 10^{15}$ GeV

generated by some type of new physics at the Grand Unification energy scale

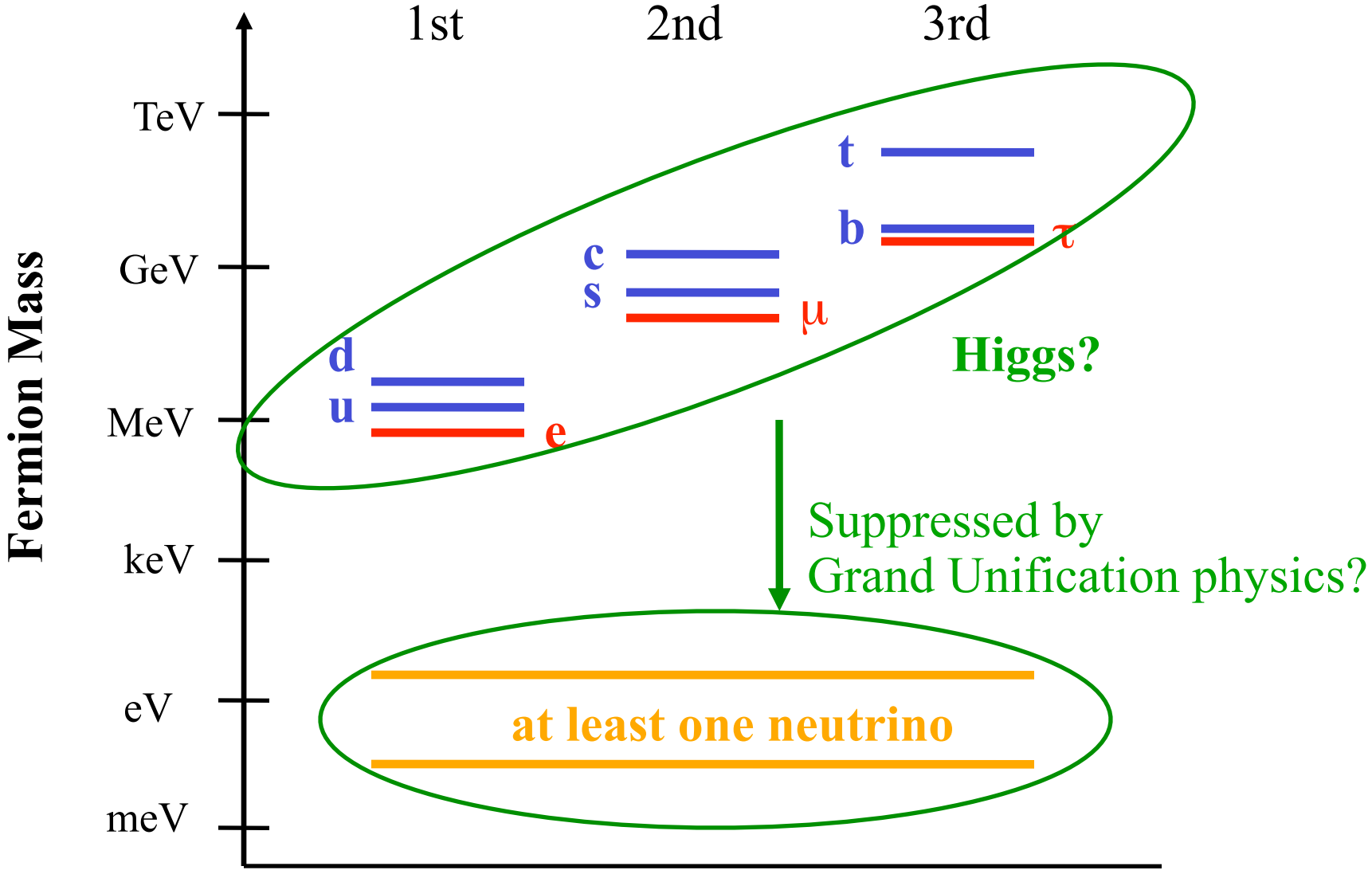
Then we would observe two **Majorana** neutrinos,

with $m_1 \approx \frac{m_D^2}{M_{GUT}} \approx 10^{-2}$ eV like atmospheric ν oscillations

$m_2 \approx M_{GUT}$ too large to be seen directly

M.Gellman, R.Slanksy, P.Ramond, R.Mohapatra, G.Senjanovic

Spin 1/2 mass spectrum



Dirac and Majorana neutrinos

Dirac fermion: particle is charged, so $f \neq \bar{f}$ (e-, μ-, τ-, quarks).
A Dirac neutrino carries lepton number:

$$\nu : L = +1, \bar{\nu} : L = -1$$

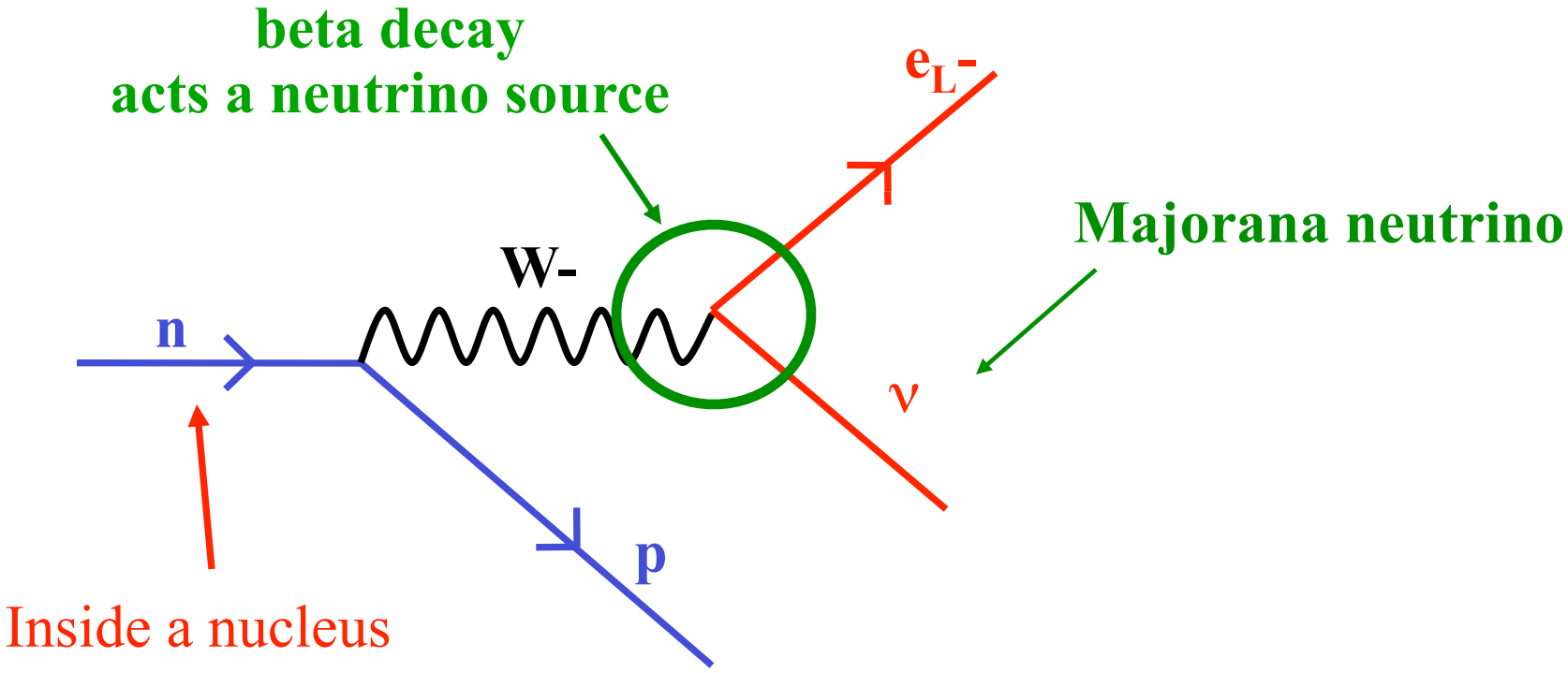
Majorana fermion: particle carries no charge, so $f = \bar{f}$

A Majorana neutrino cannot carry lepton number.

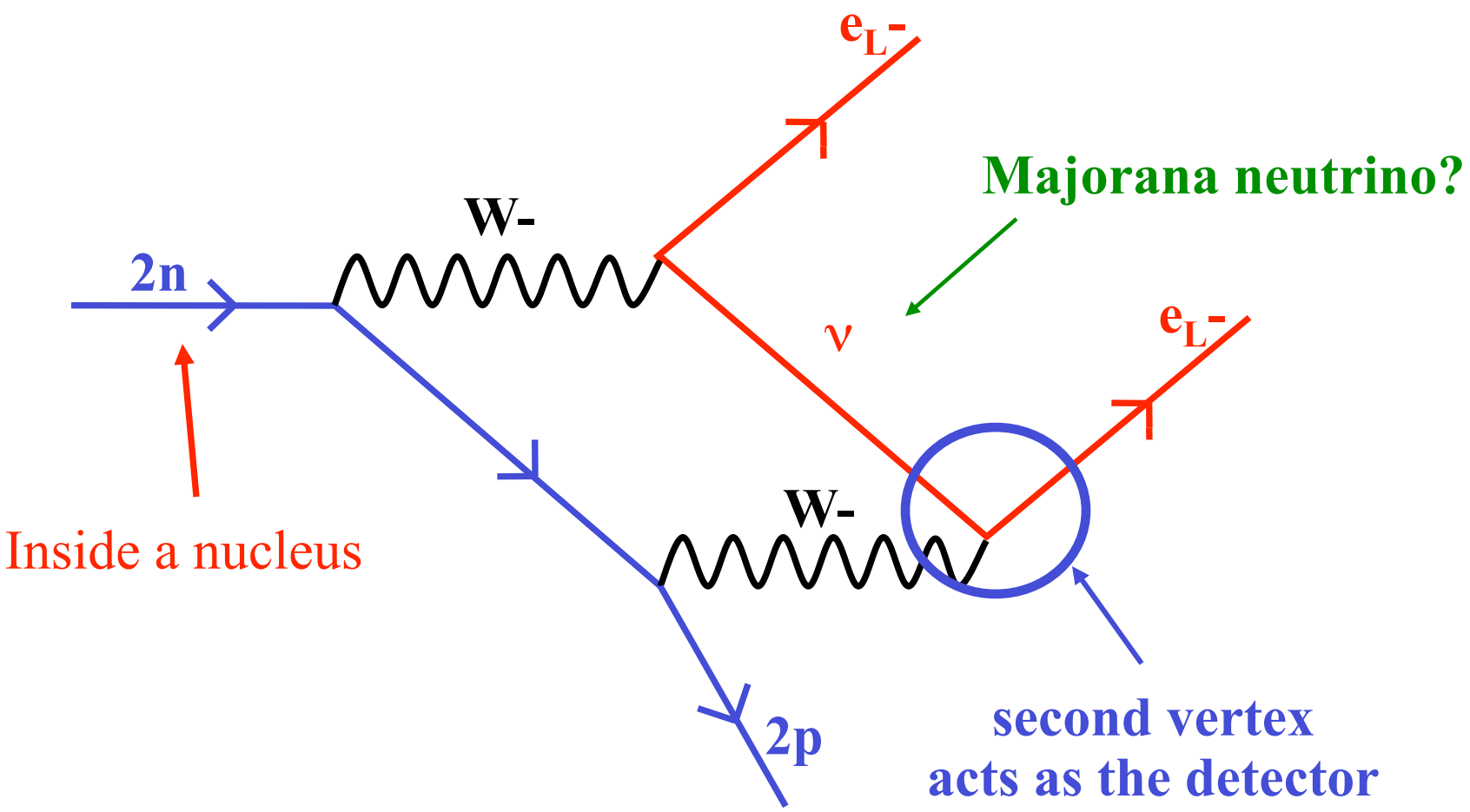
Does the neutrino carry lepton number?

Is the neutrino its own antiparticle?

Use nuclear physics to test neutrino charge properties:

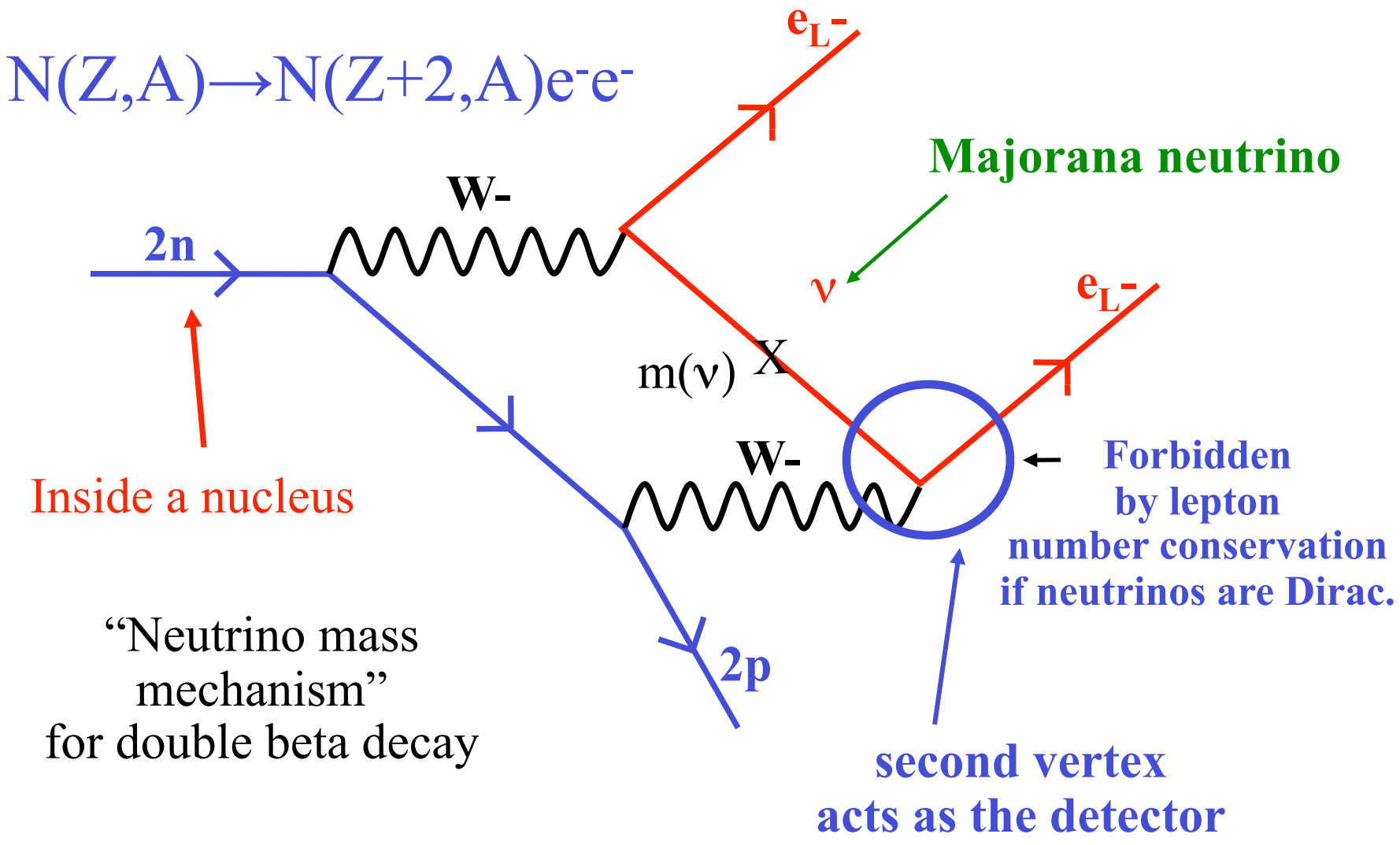


Use nuclear physics to test neutrino charge properties:



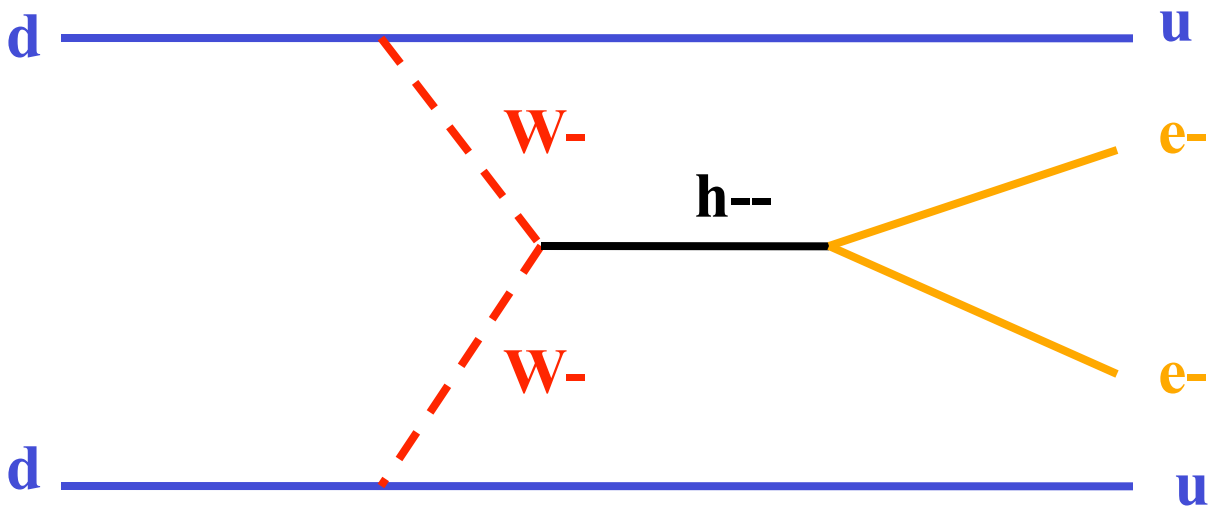
Neutrinoless Double Beta Decay ($\beta\beta0\nu$)

Forbidden if neutrino mass is Dirac only



Many types of new physics lead to ββ0ν

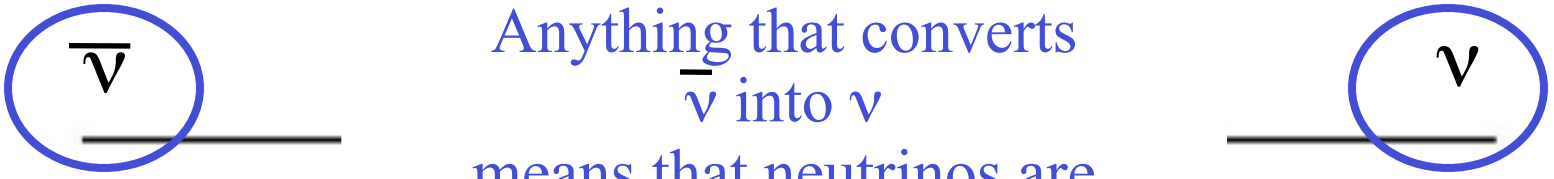
Right handed weak currents, leptoquarks,
supersymmetry, ect.,



"Doubly charged Higgs mechanism"
for double beta decay

Does this spoil neutrino physics interpretations of ββ0ν ?

Black Box Theorem

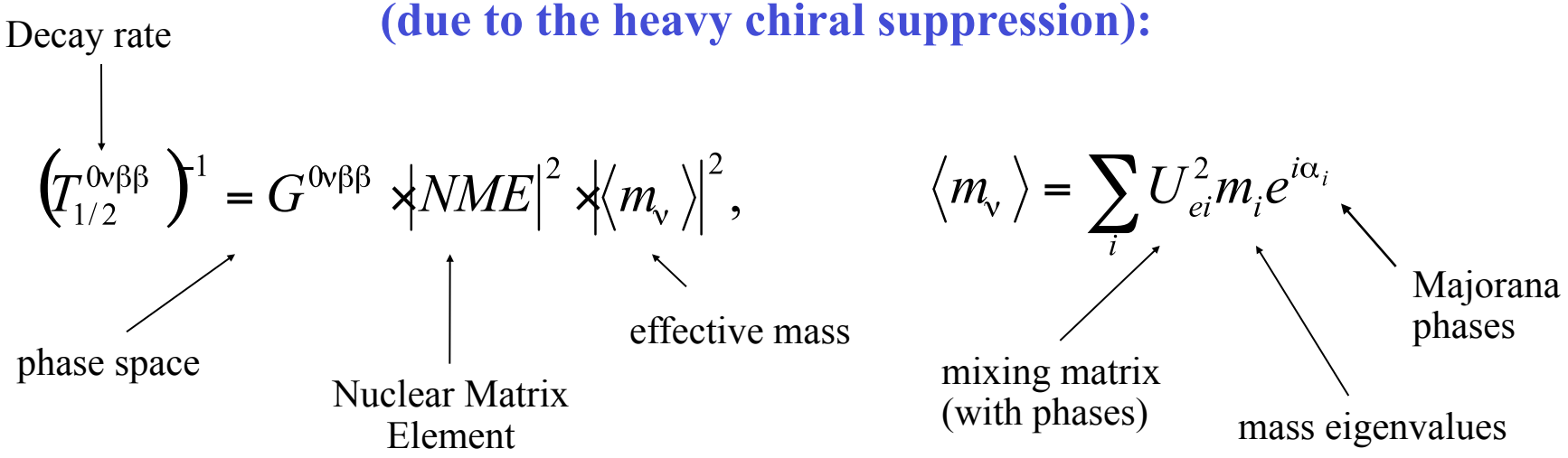


Anything that converts $\bar{\nu}$ into ν
means that neutrinos are Majorana

If we see $\beta\beta0\nu$, we know that Majorana neutrinos exist!

The ββ0ν half-life depends DIRECTLY on the absolute neutrino masses

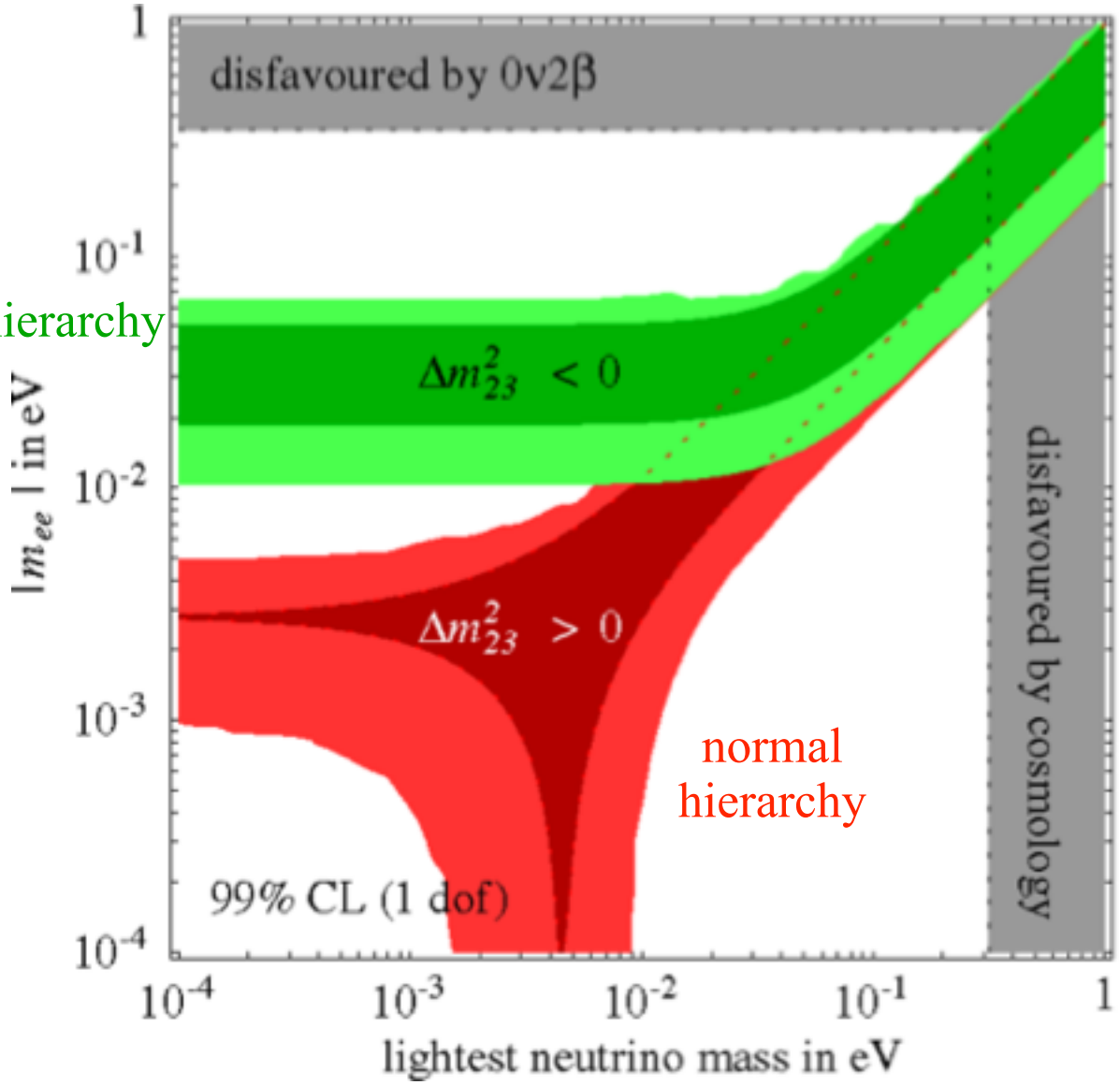
(due to the heavy chiral suppression):



We can use the ββ0ν decay rate to measure the absolute neutrino mass if:

1) neutrinos are Majorana
2) we have a reliable calculation of the nuclear matrix element
3) the neutrino mass mechanism dominates the decay

What ββ0ν can tell us about the neutrino mass scale

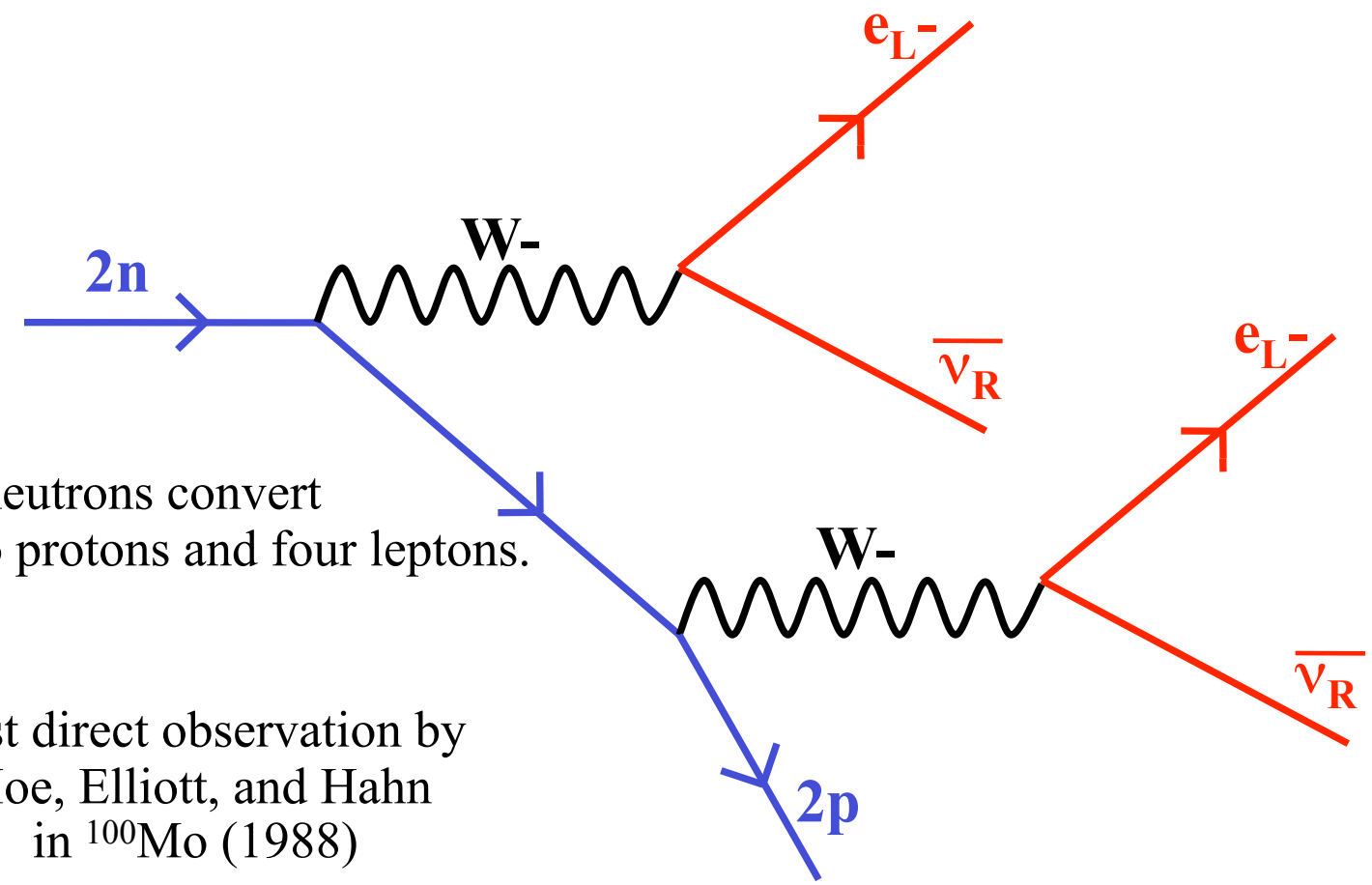


inverted hierarchy

pseudo-degenerate

Figure from Strumia & Vissani, Nucl. Phys. B **726** 294 (2005)

Two-Neutrino Double Beta Decay:

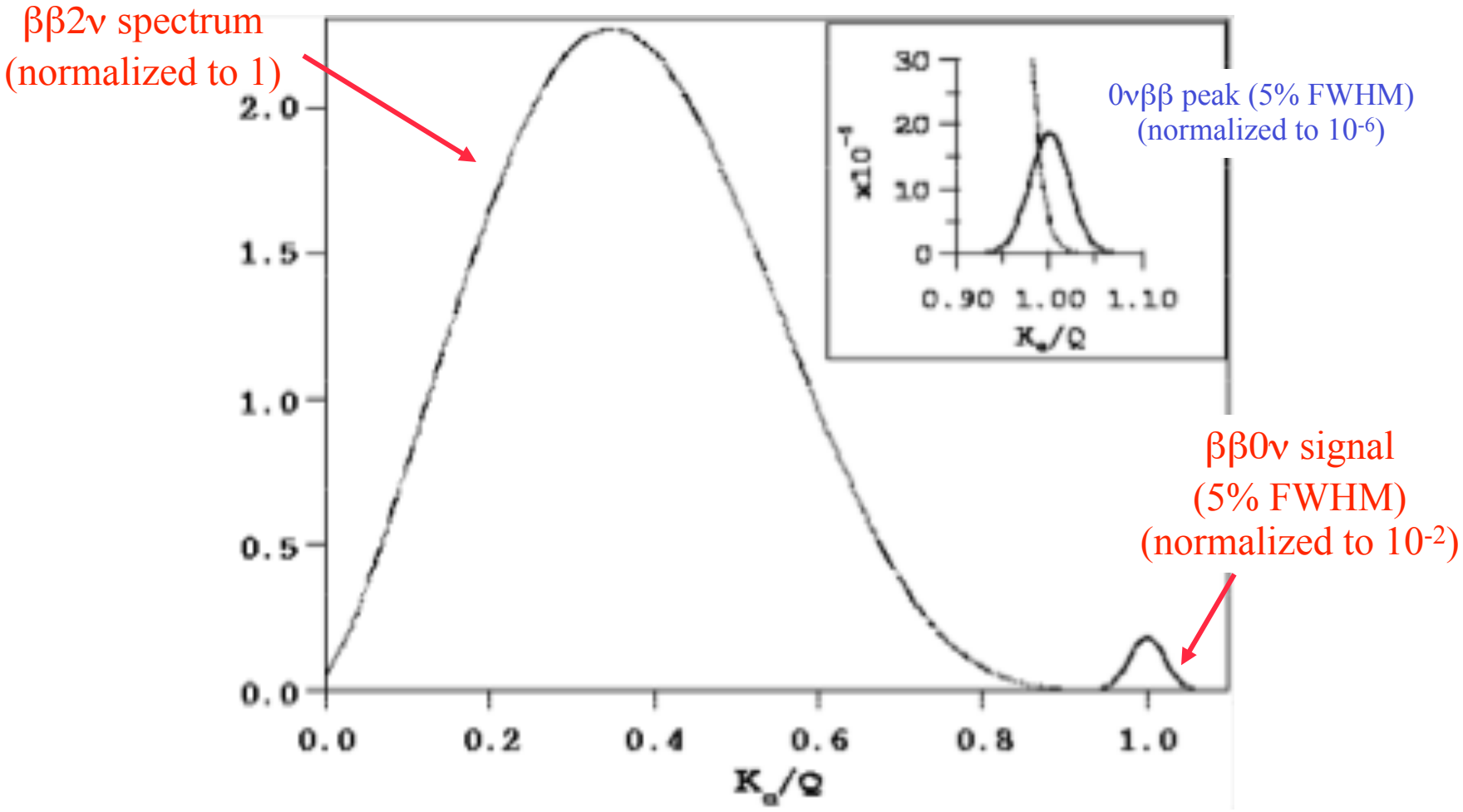


Two neutrons convert
to two protons and four leptons.

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

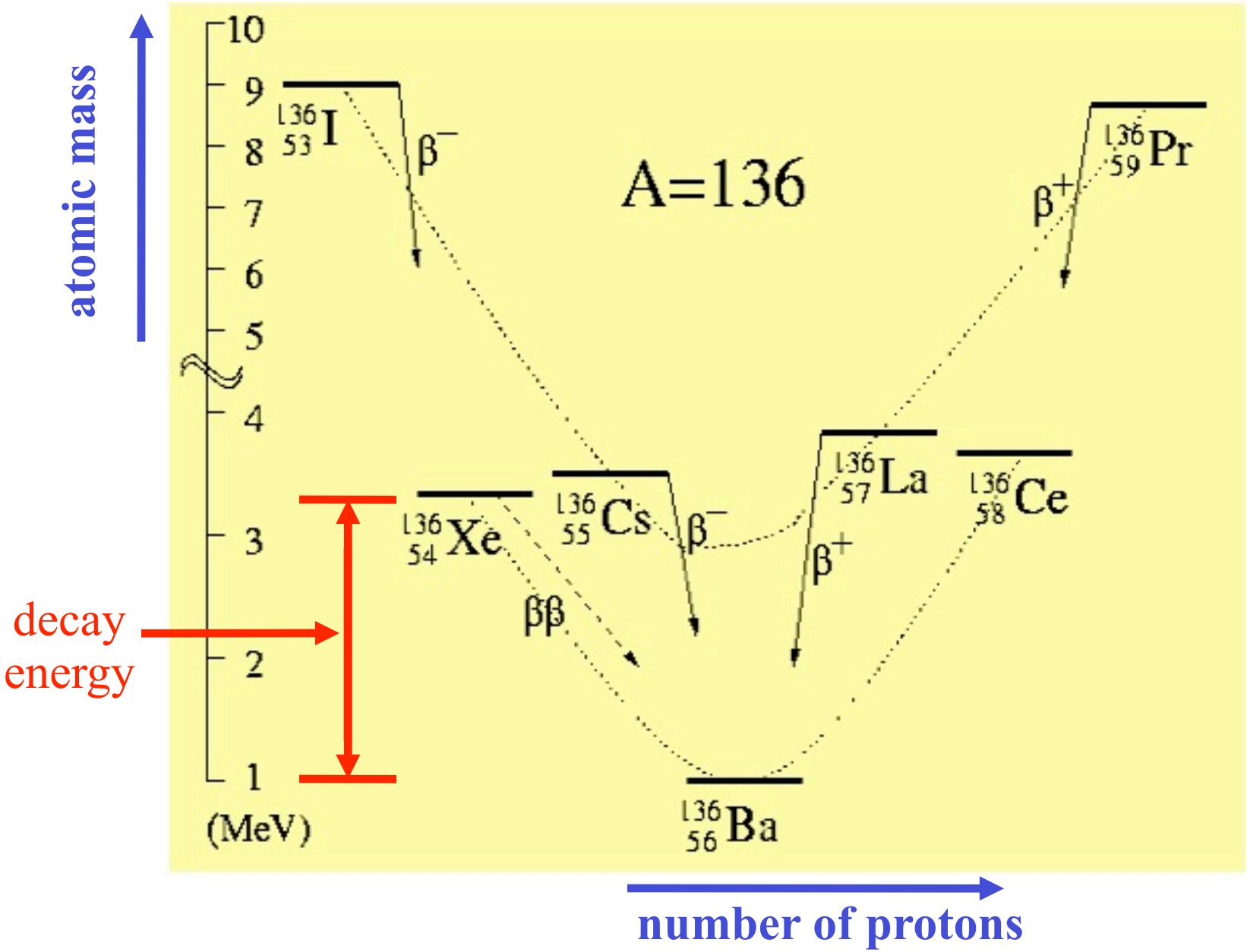
**No direct implications for neutrino mass,
but useful for constraining and testing
the nuclear matrix element calculations**

ββ0ν signature: a peak in the ββ energy spectrum



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

What nuclei are ββ candidates?

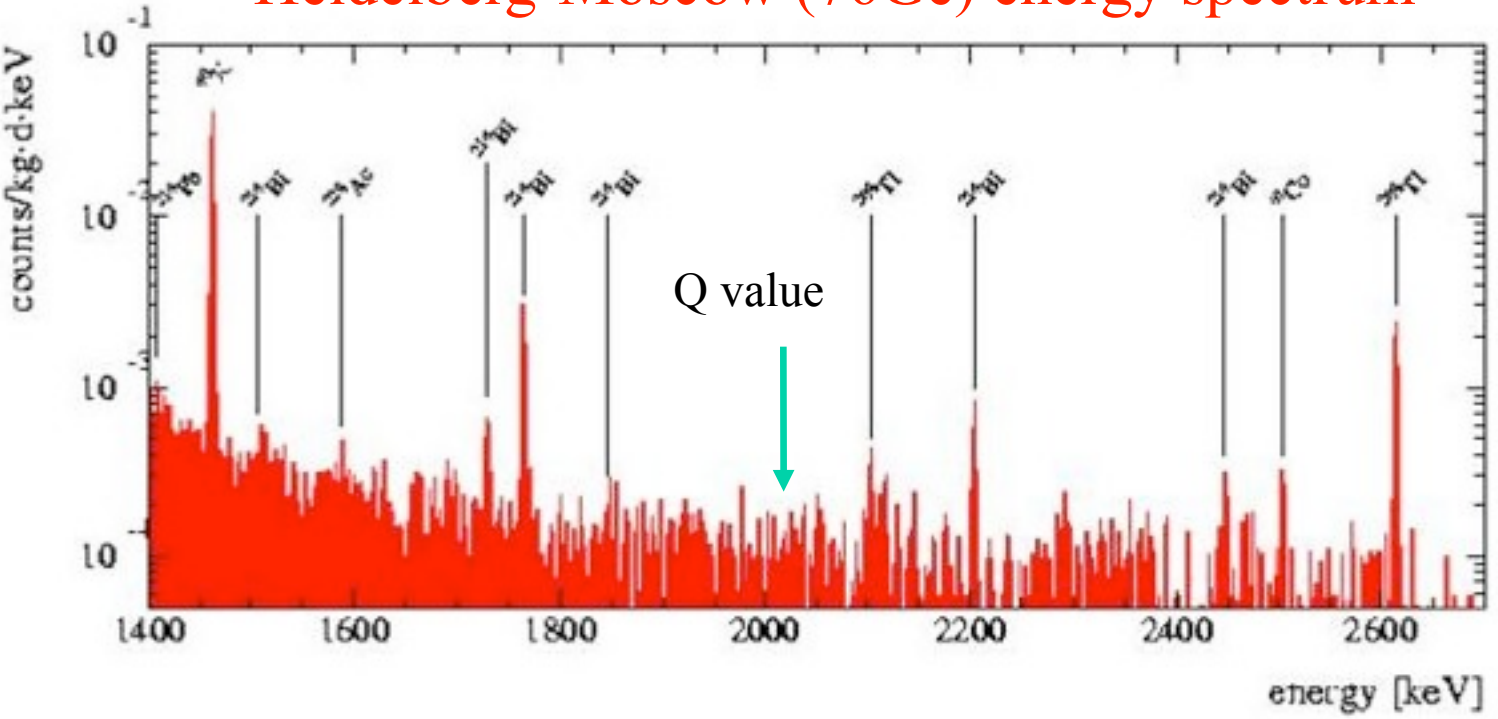


Choose a ββ source isotope:

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

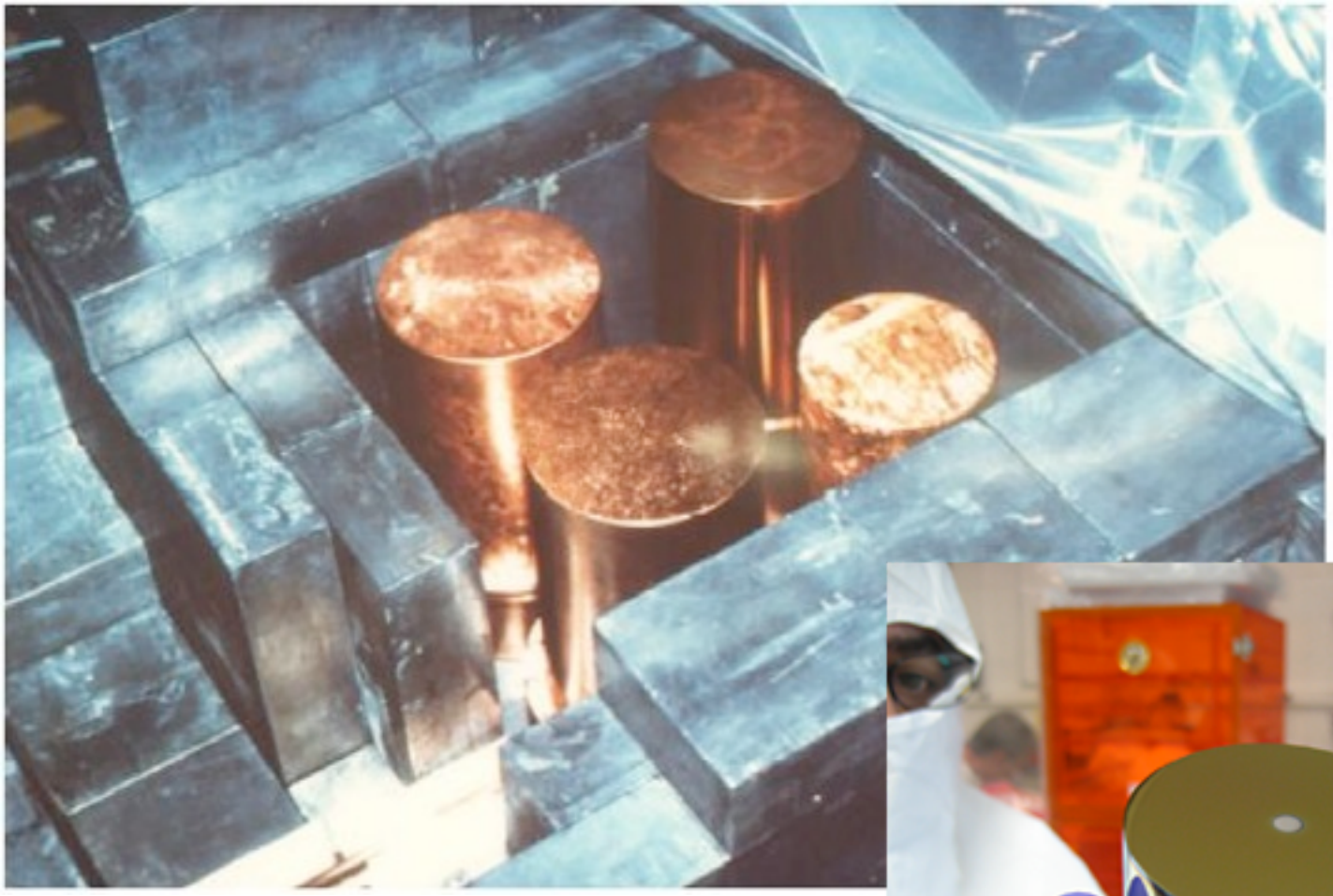
The most sensitive double beta decay experiments to date are based on 76-Germanium.

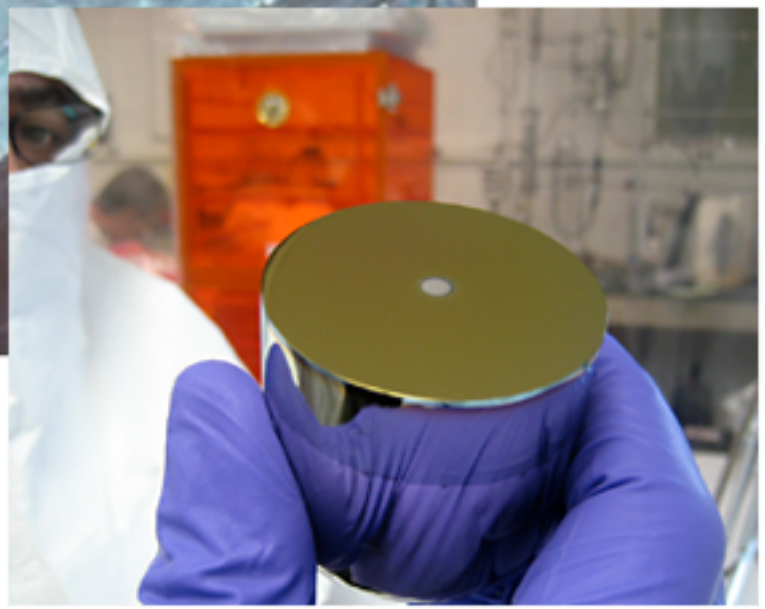
Heidelberg-Moscow (76Ge) energy spectrum



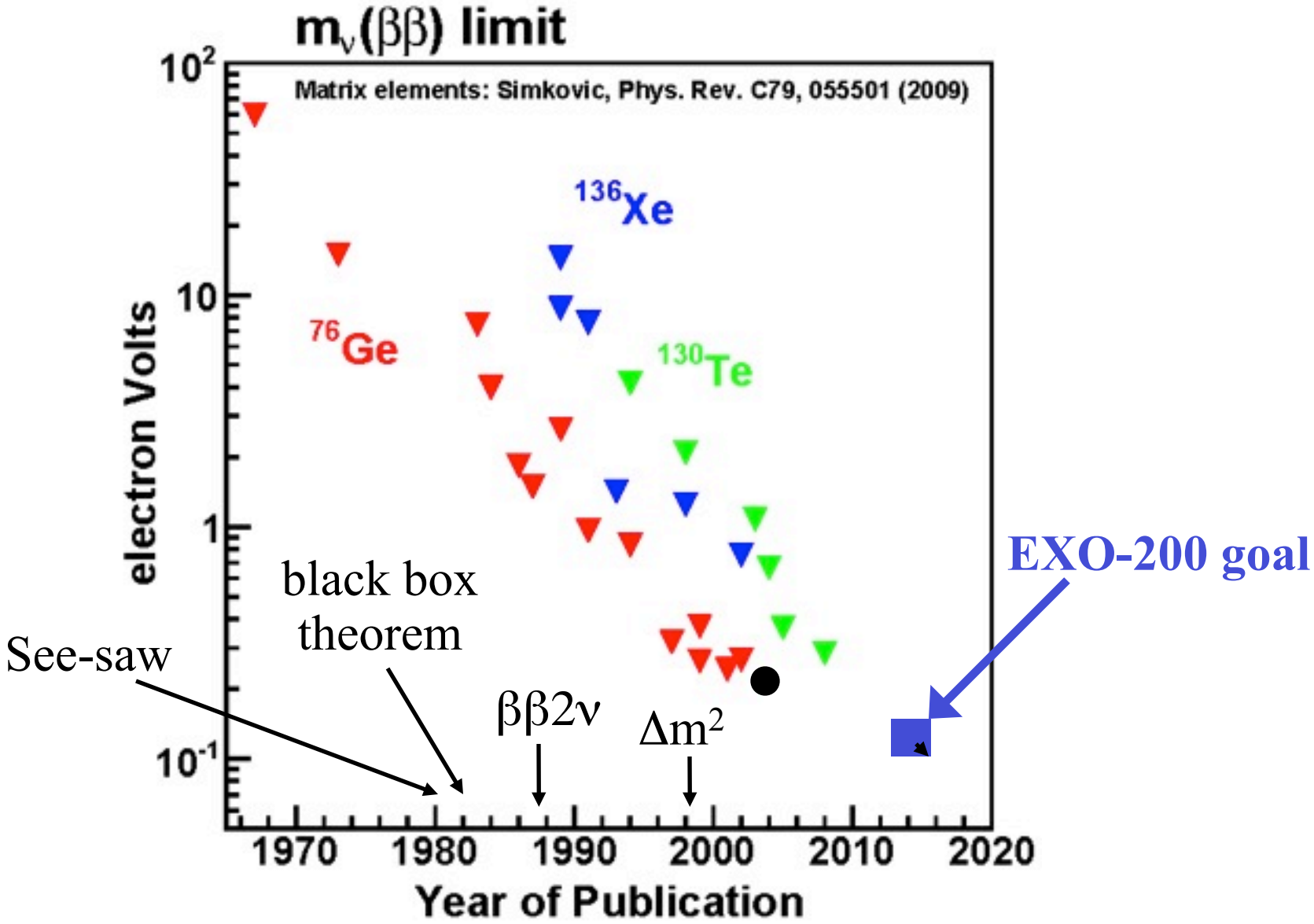
Half-life limit: 1.9 x 10^{25} years (H-M and IGEX)
Majorana neutrinos ruled out for masses greater than ~0.35-1.0 eV

Germanium diode experiments – Heidelberg-Moscow - 2001

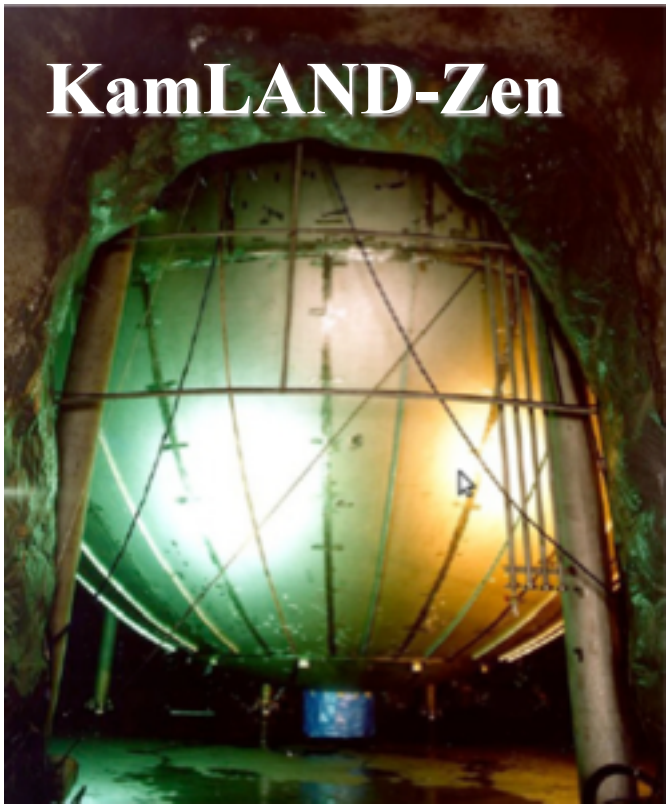




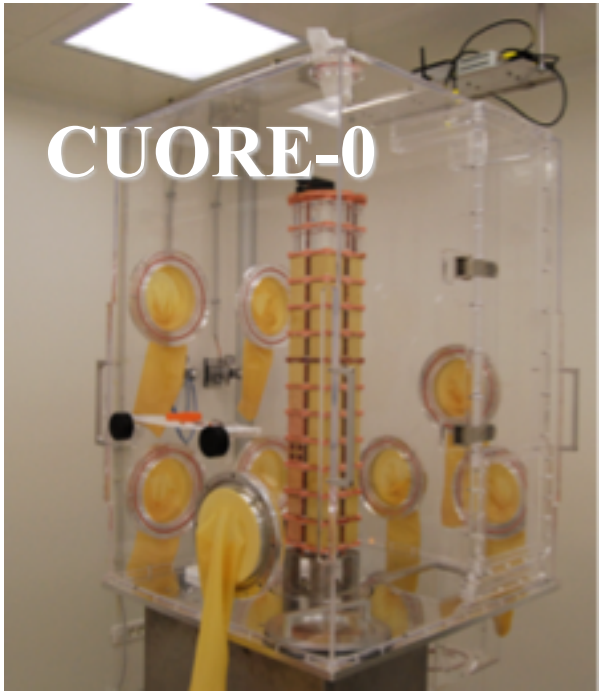
Moore's Law for ββ0ν

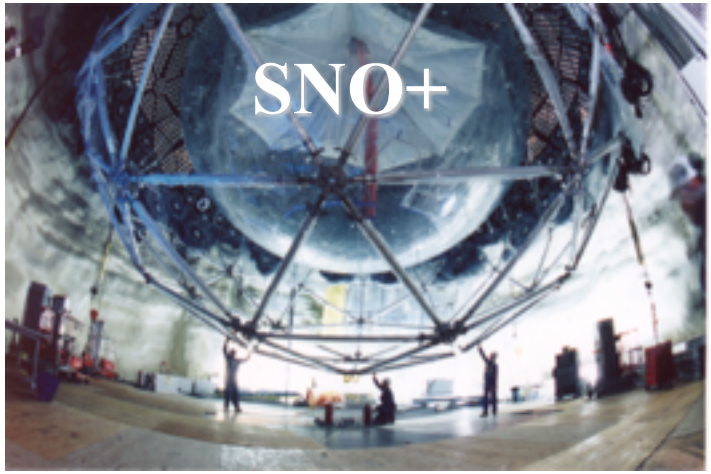


GERDA


KamLAND-Zen

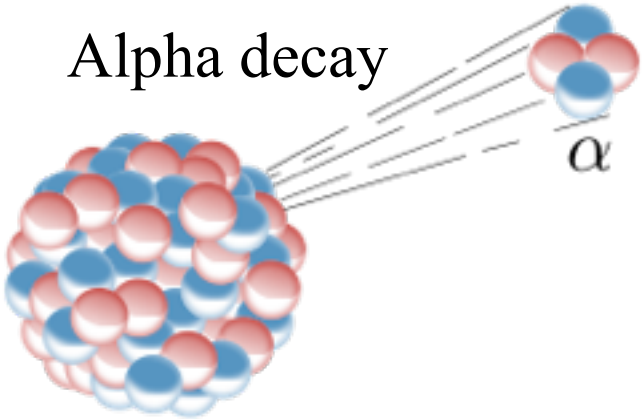
Majorana


CUORE-0

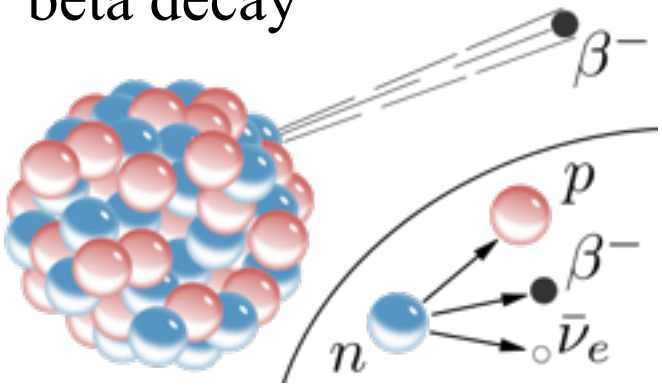

SNO+

Backgrounds: all ordinary radioactive decay

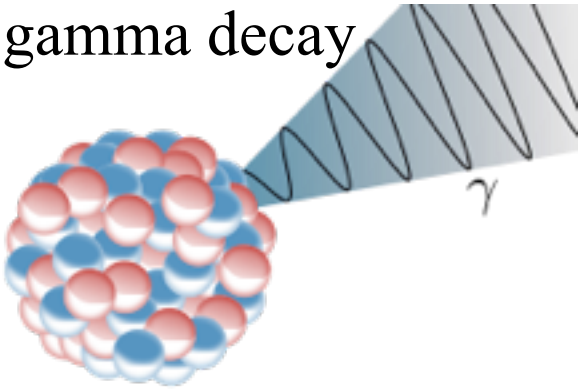
Alpha decay

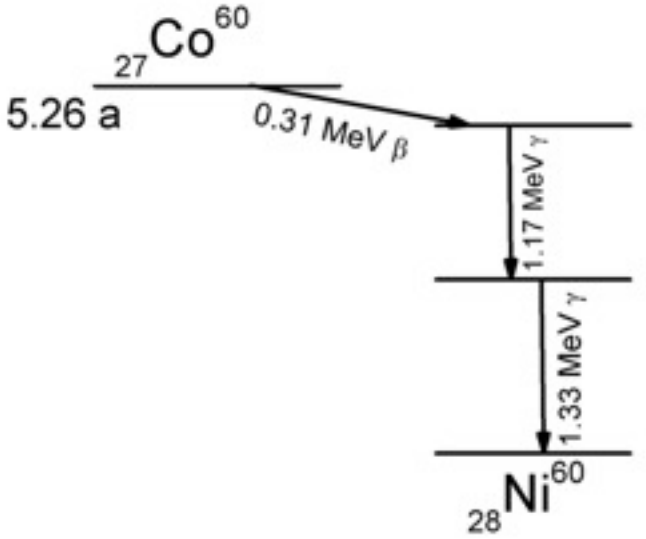


beta decay

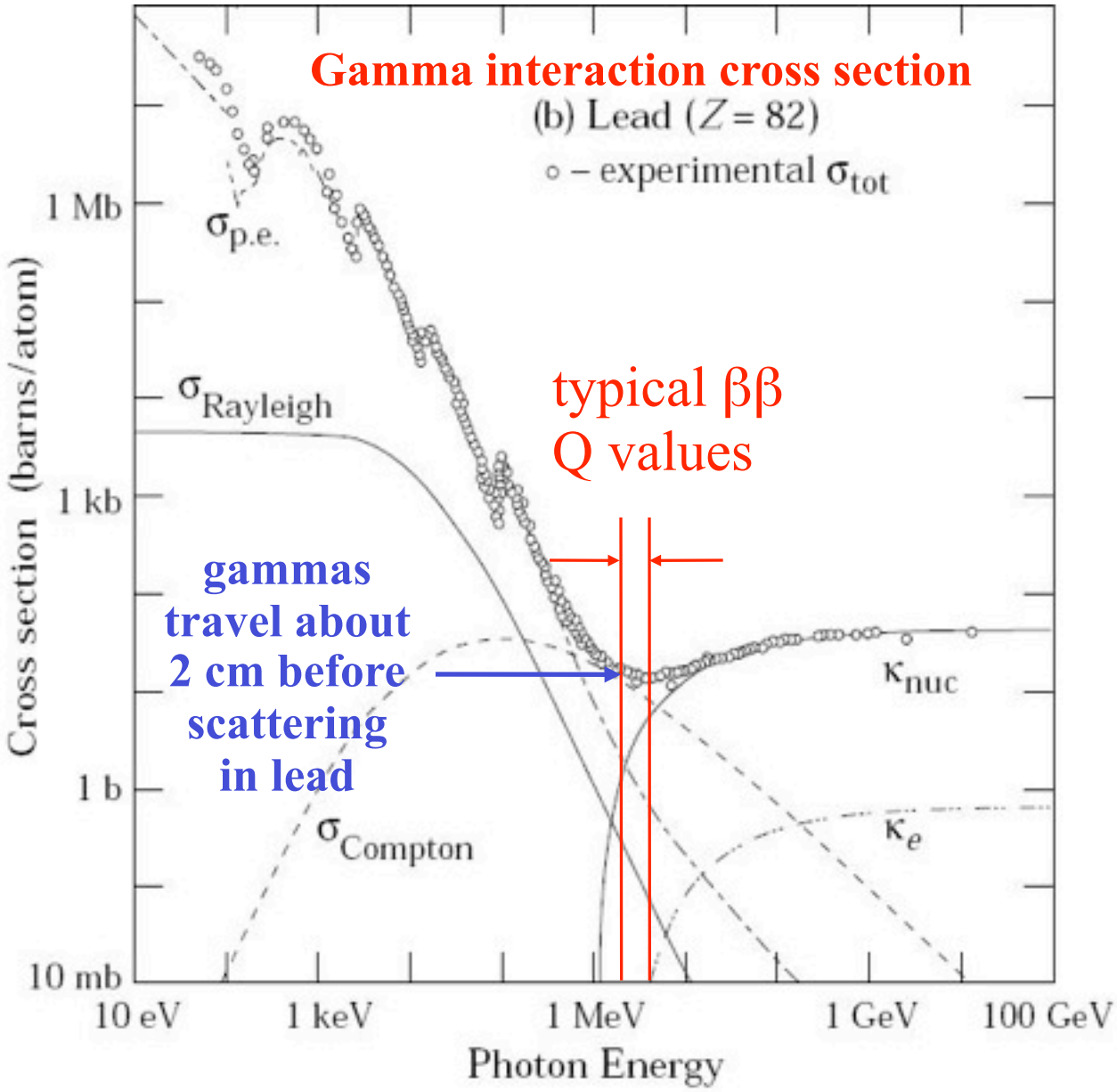


gamma decay

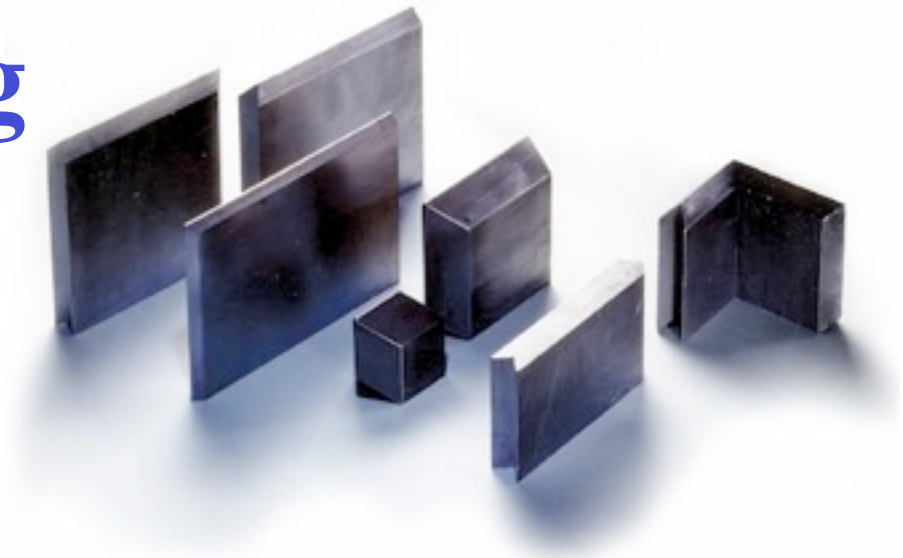




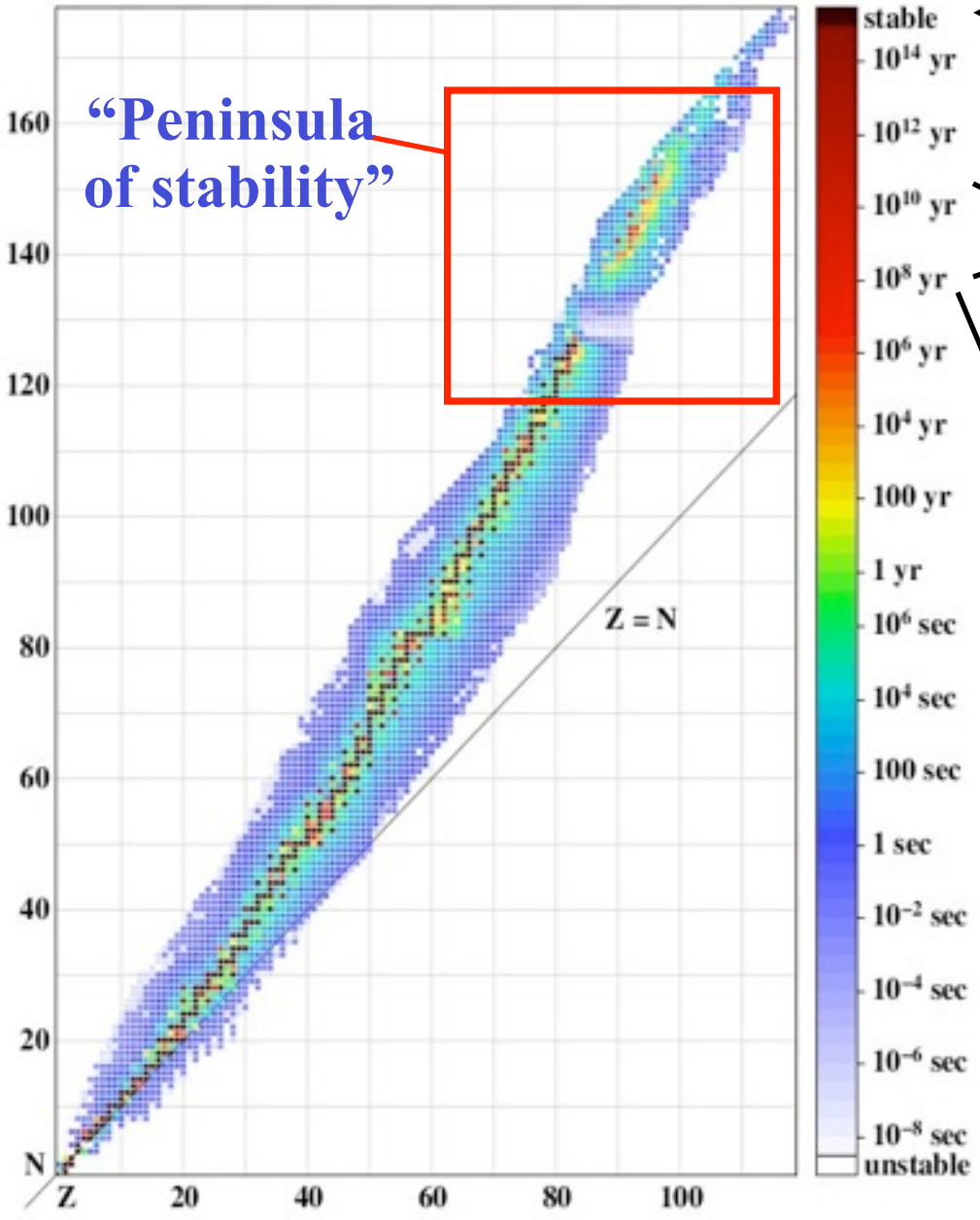
Shielding gammas is difficult!



Lead shielding



Nuclide half lives

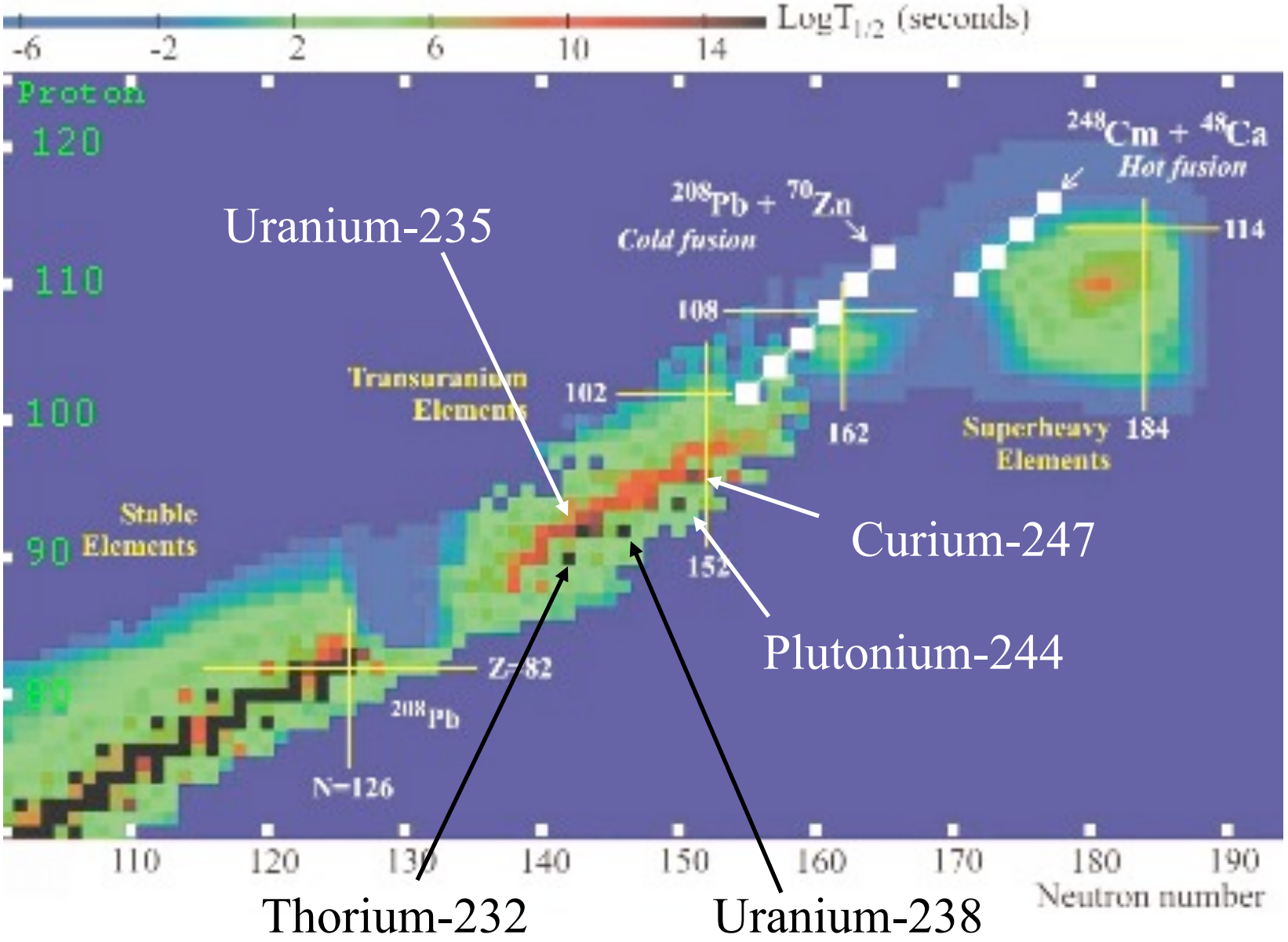


← "Stable": ~10^{15} years
ββ0ν halflife is 10^{10} times longer (at least)

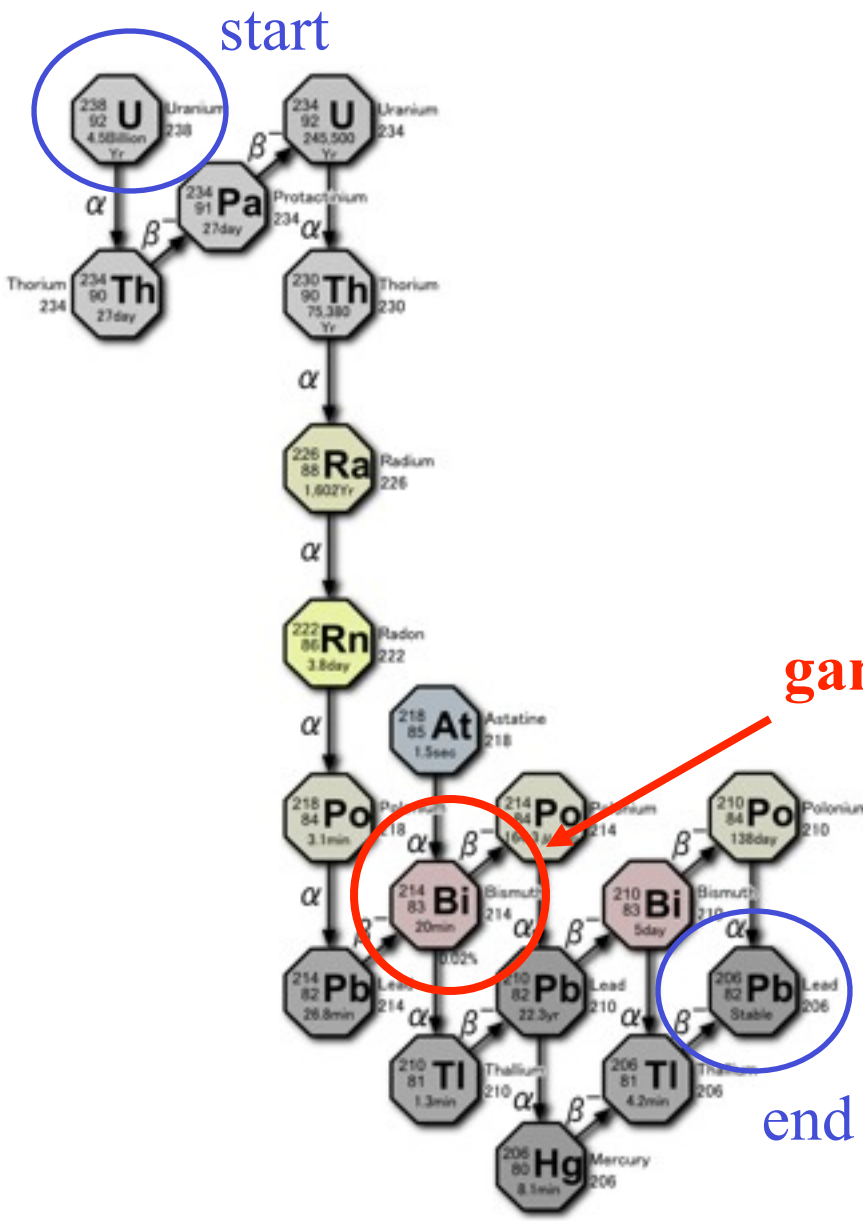
half-life comparable to age of the earth

half-life short compared to age of the earth

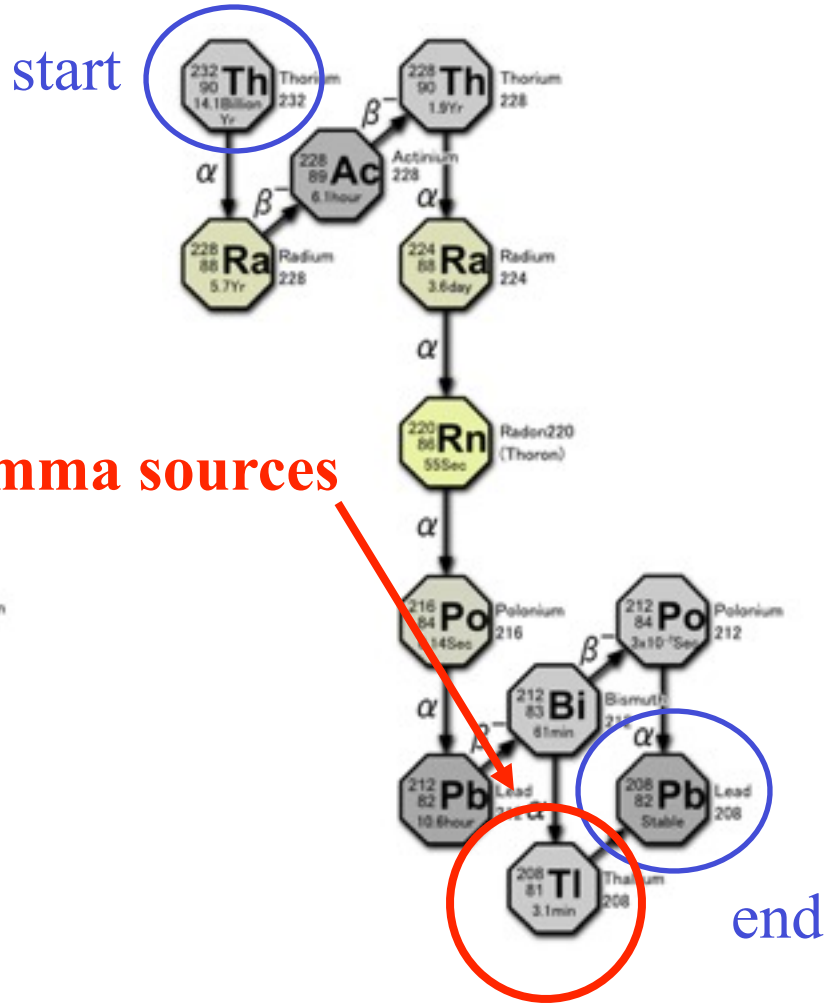
Peninsula of Stability



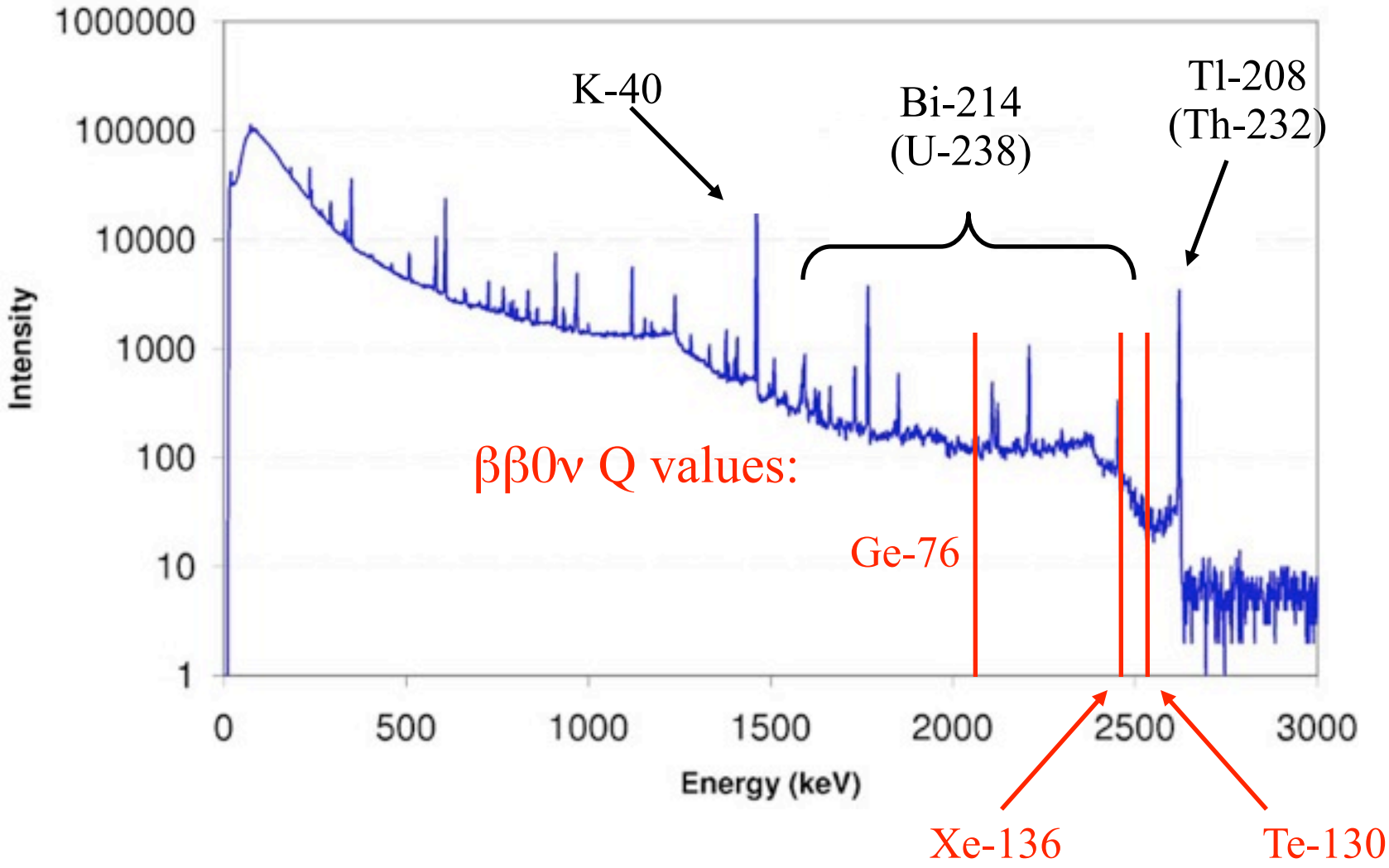
Uranium-238 decay chain



Thorium-232 decay chain



Ordinary radioactive decay here on earth



Get smarter: Single Ba^+ ion detection

$^{136}Xe \rightarrow {}^{136}Ba^{++}\ e^-e^-$

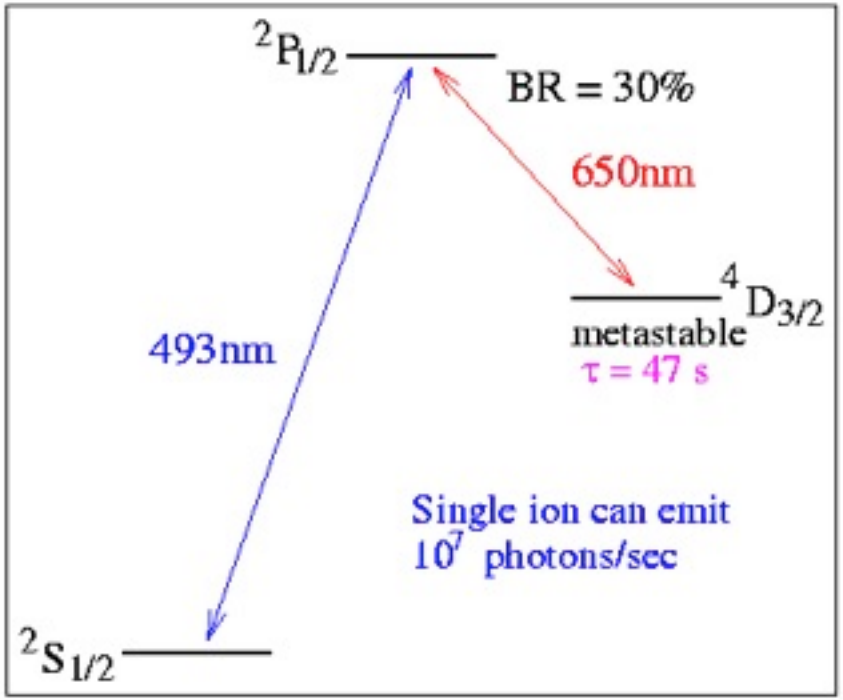
Daughter identified by optical spectroscopy of Ba^+, well studied in ion traps for more than 25 years

[Neuhauser, Hohenstatt, Toshek, Dehmelt, Phys. Rev. A 22 (1980) 1137]

- very specific signature ("Λ" shelving)

- cycling 493/650 nm transitions gives a fluorescence rate of ~10^8 Hz (in vacuum)

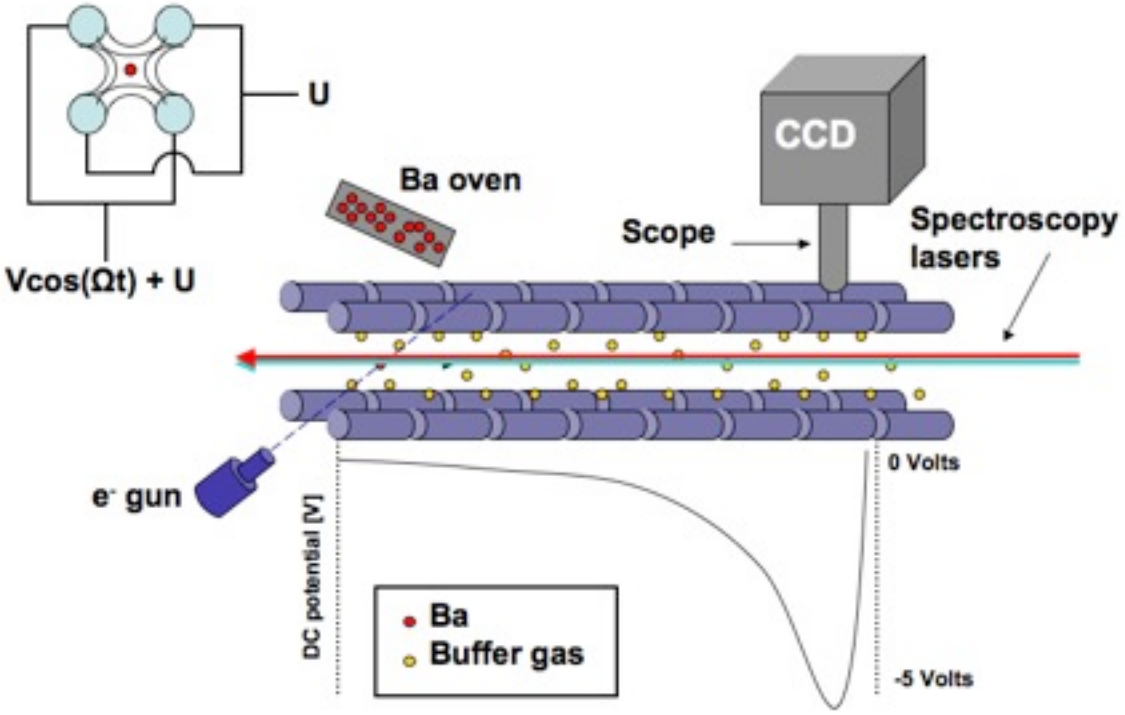
plenty of light!

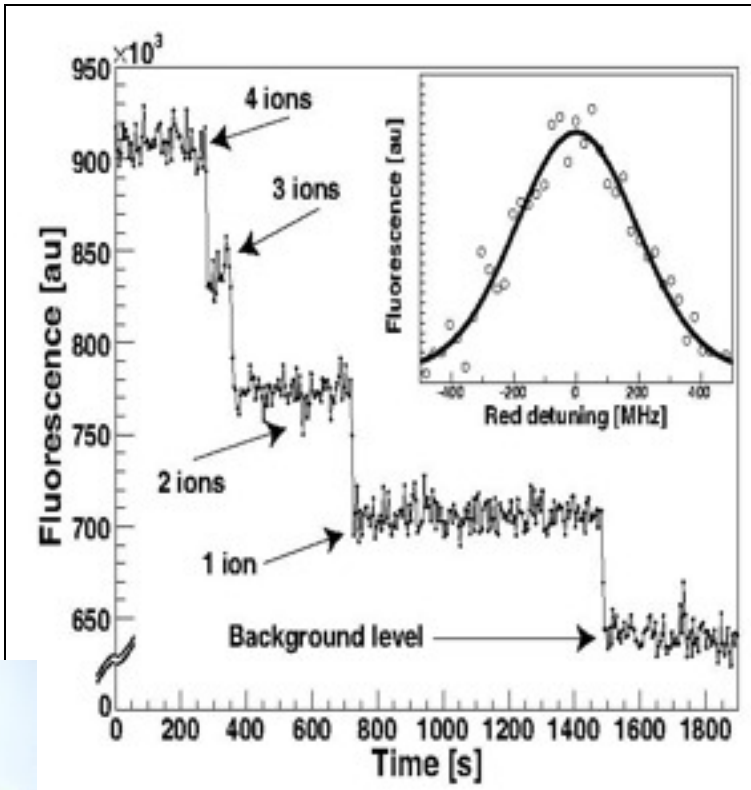


Level structure for Ba^+

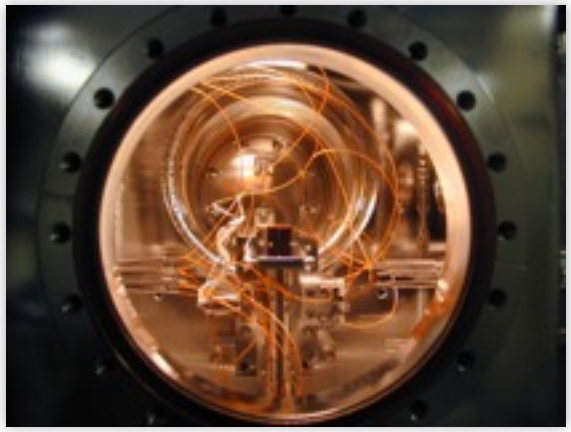
Ba+ Tagging: Ion Trap + fluorescence

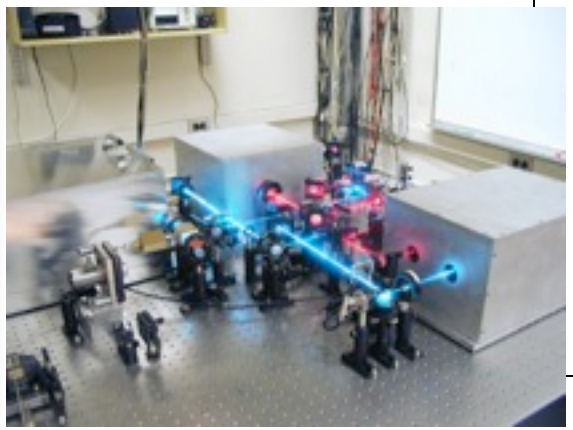
QuickTime™ and a decompressor are needed to see this picture.





~9σ discrimination in 5s integration



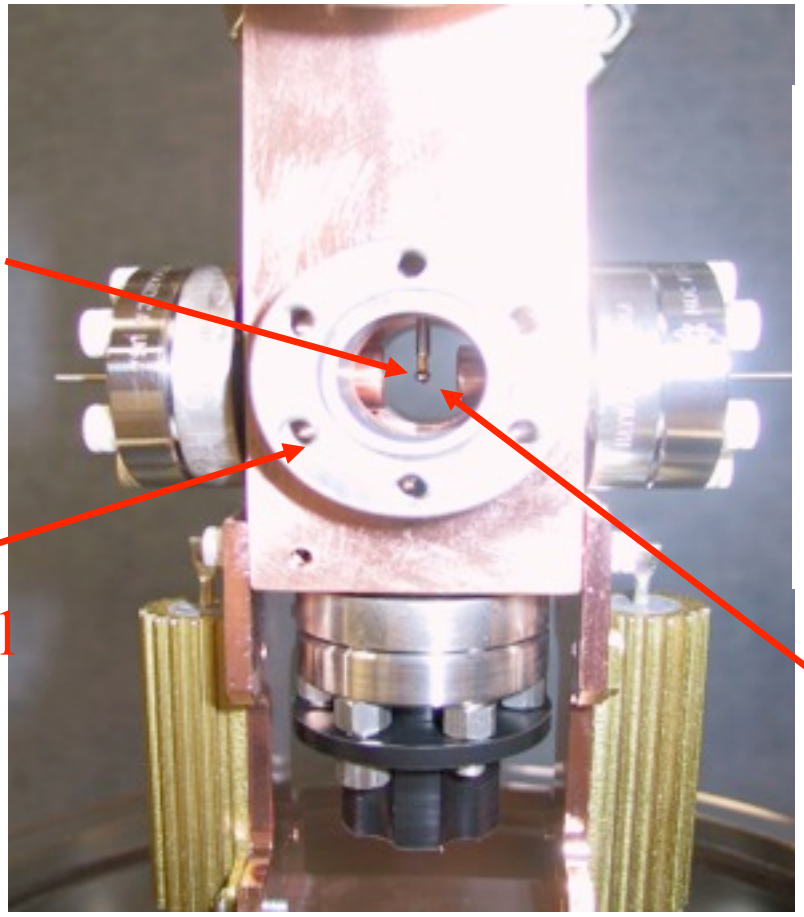


M.Green et al., *Phys Rev* A**76** (2007) 023404
B.Flatt et al., *NIM* A**578** (2007) 409

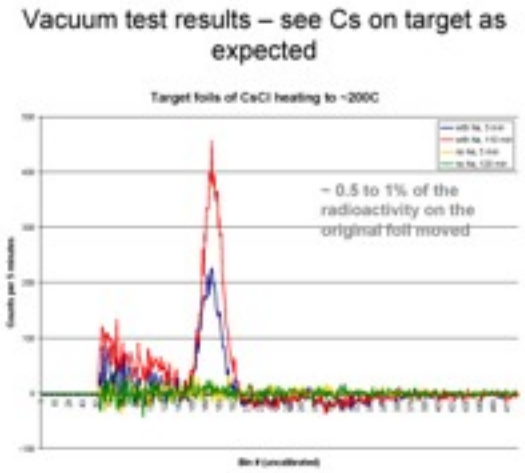
Prototype electrostatic probe to study ion grabbing and release

Probe tip

Liquid xenon cell

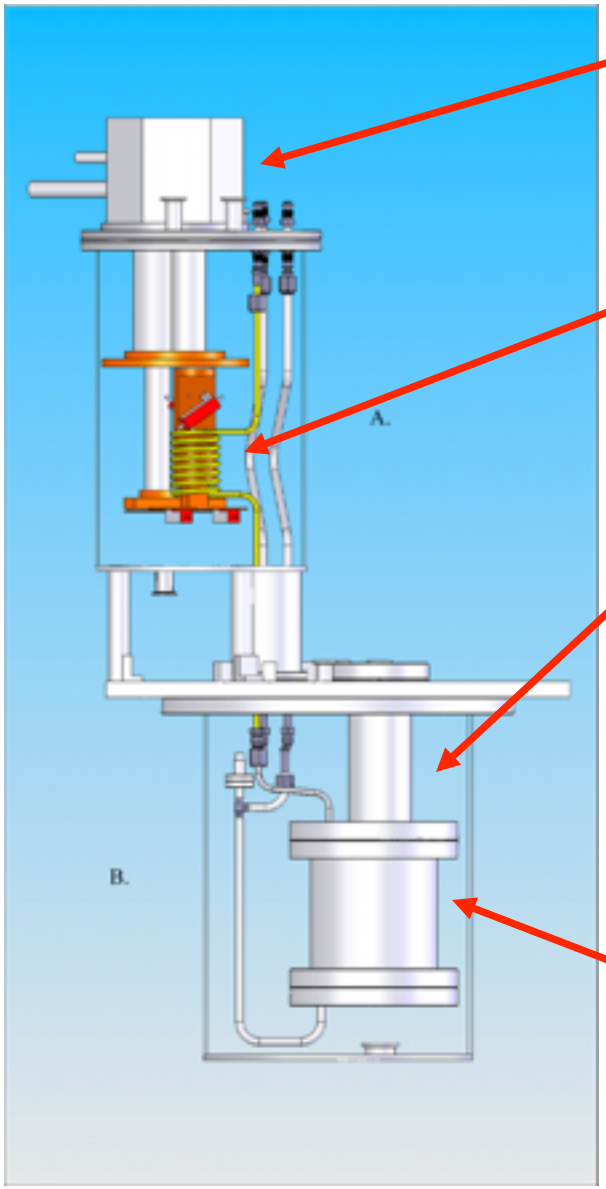


Th+ source



Prototype probe collects Th+ in liquid xenon,
then we observe them with an α counter above the liquid surface.

Grabbing ions from liquid xenon

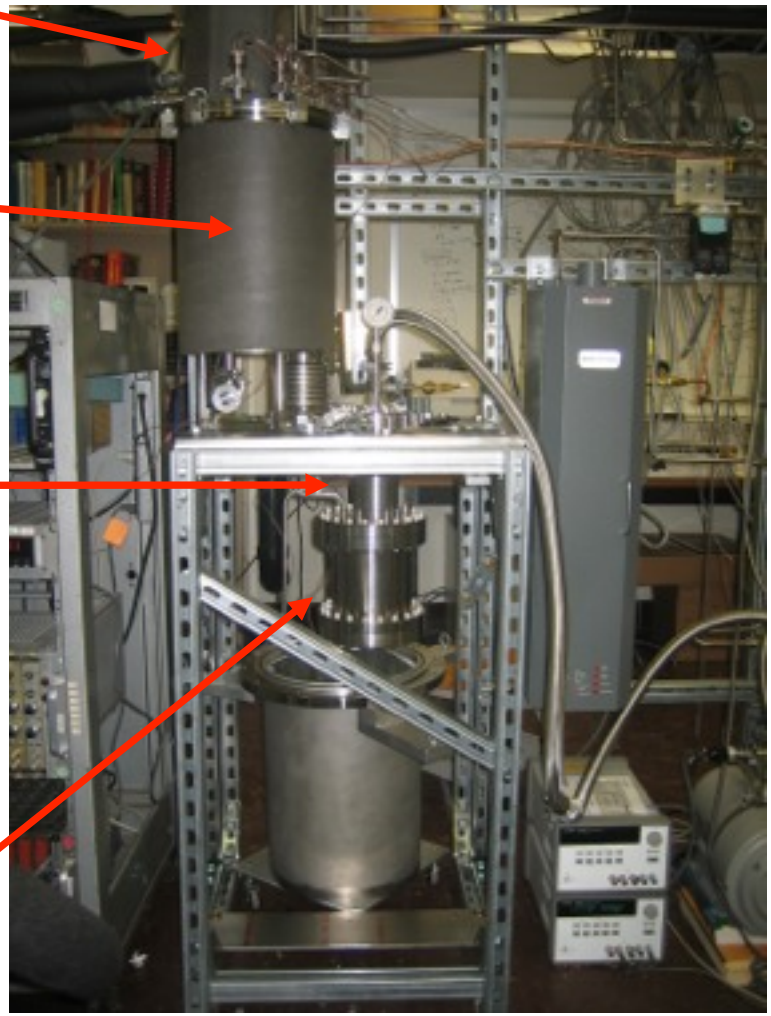


refrigerator cold head

xenon condenser

3” diameter access port

3-liter (10 kg) liquid xenon storage vessel



ITEP

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UNIVERSITY OF
MARYLAND

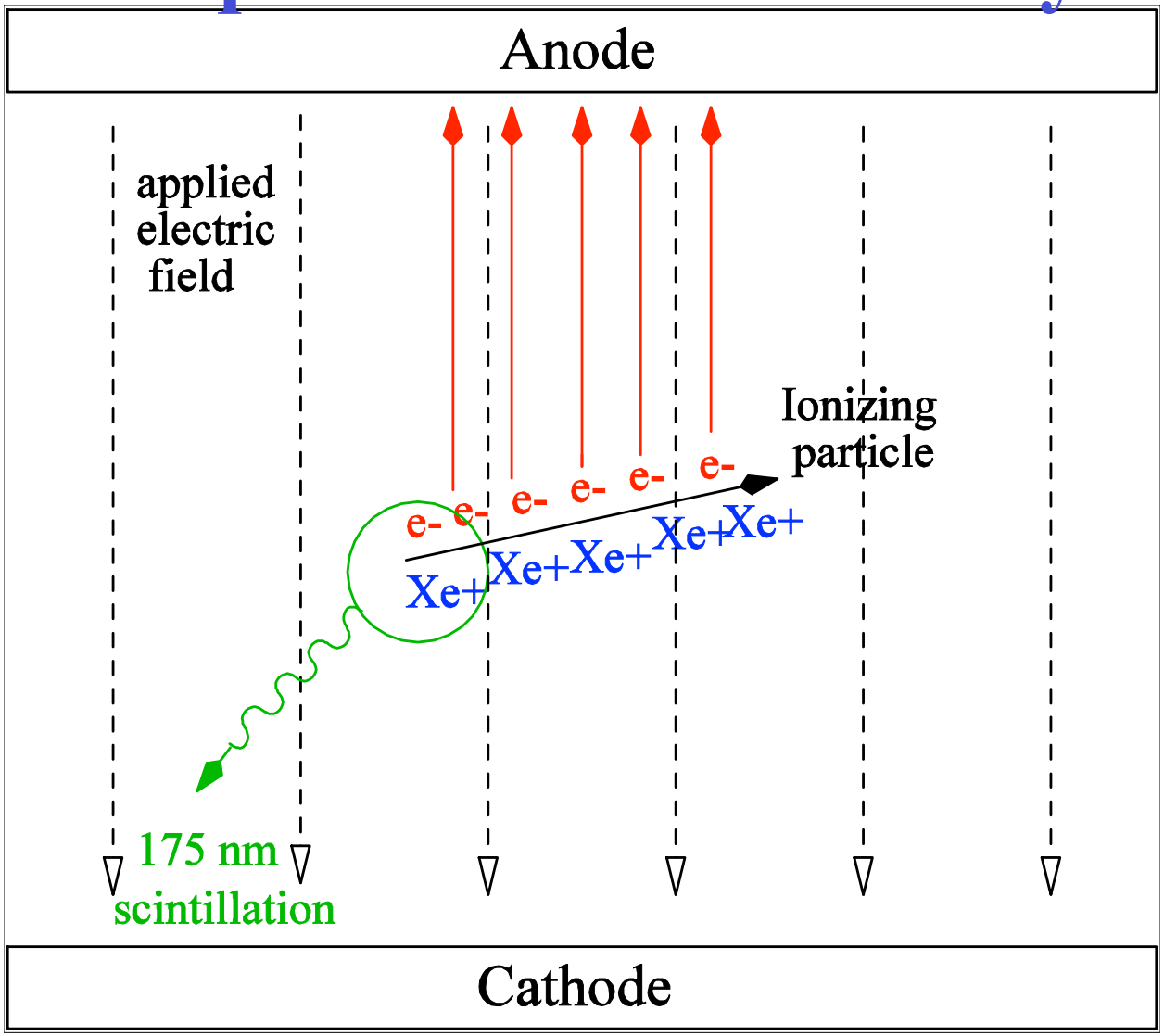
LaurentianUniversity
UniversitéLaurentienne

Colorado State University
Knowledge to Go Places

The EXO-200 experiment

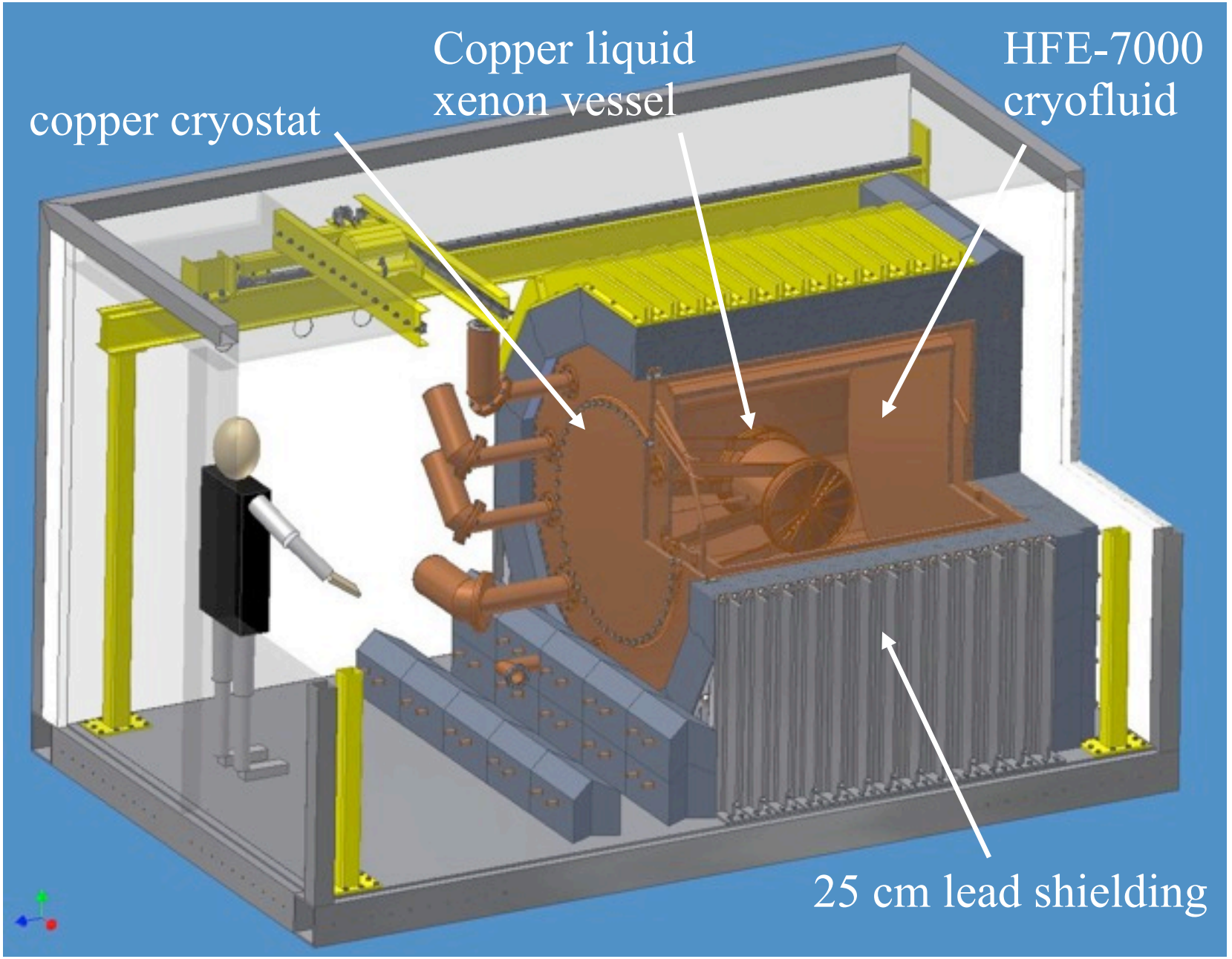
200 kg of xenon enriched to 80% in ^{136}Xe:

Liquid xenon calorimetry

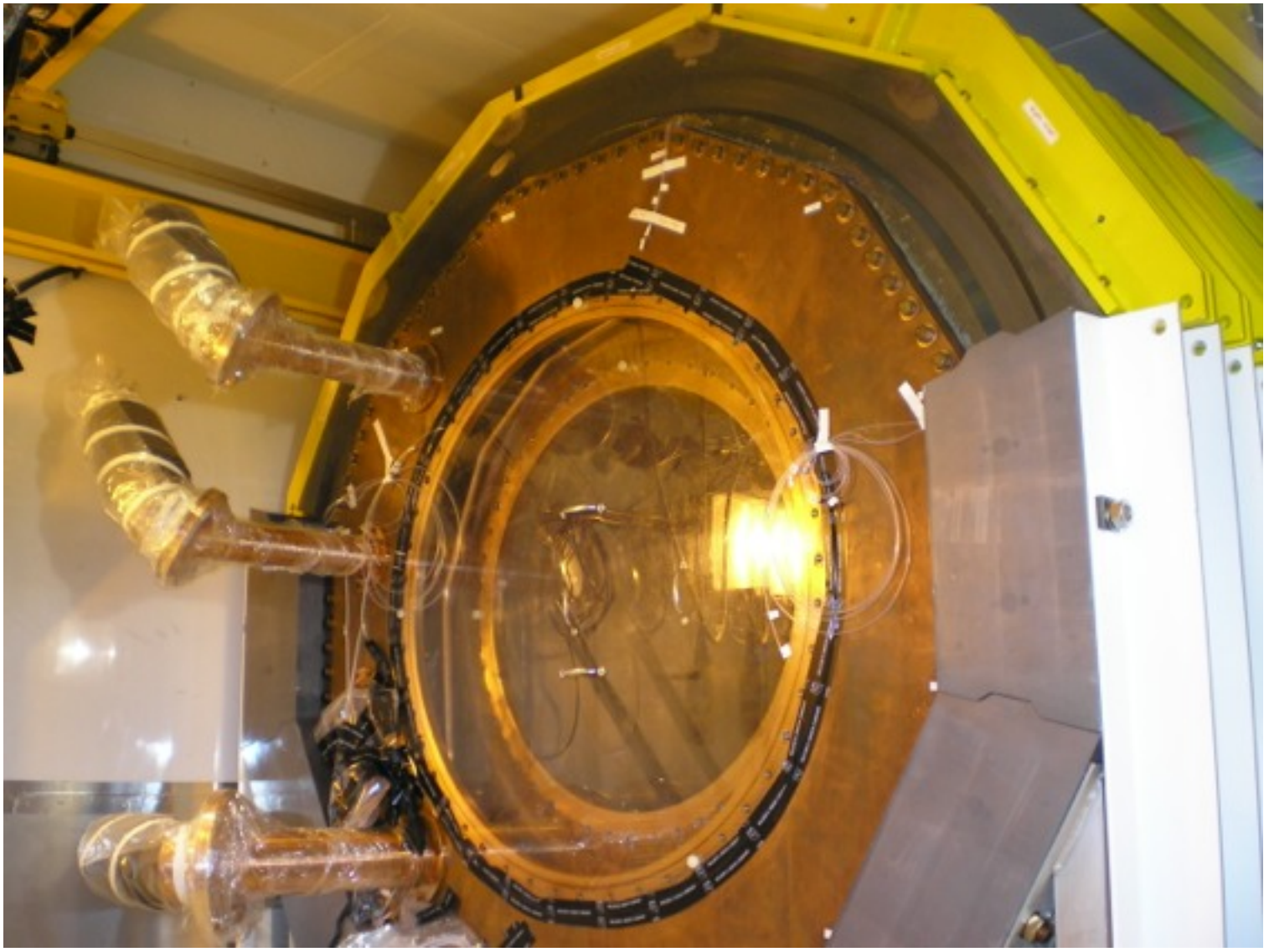


Measure the event energy by collecting the ionization on the anode and/or observing the scintillation.

EXO-200: the first 200 kg ββ0ν experiment

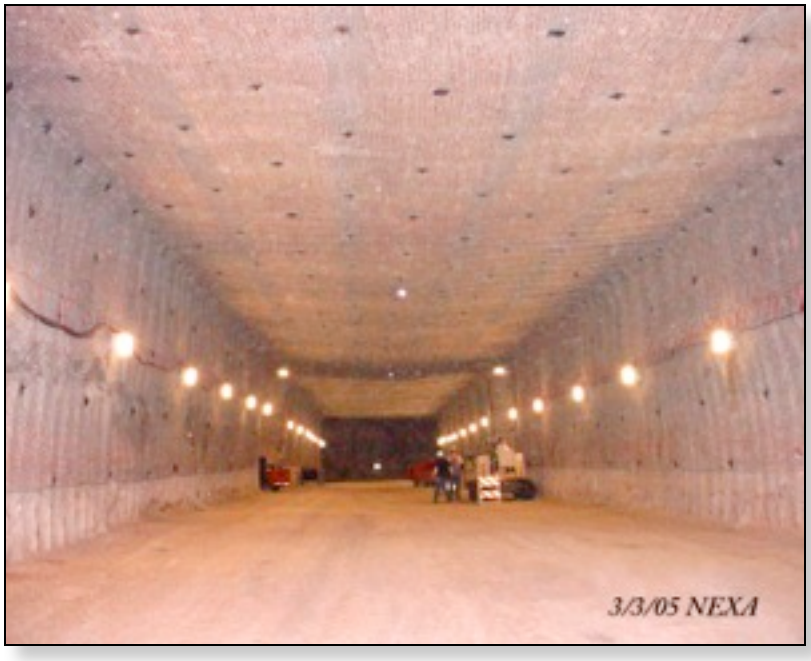


EXO-200 cryostat & lead



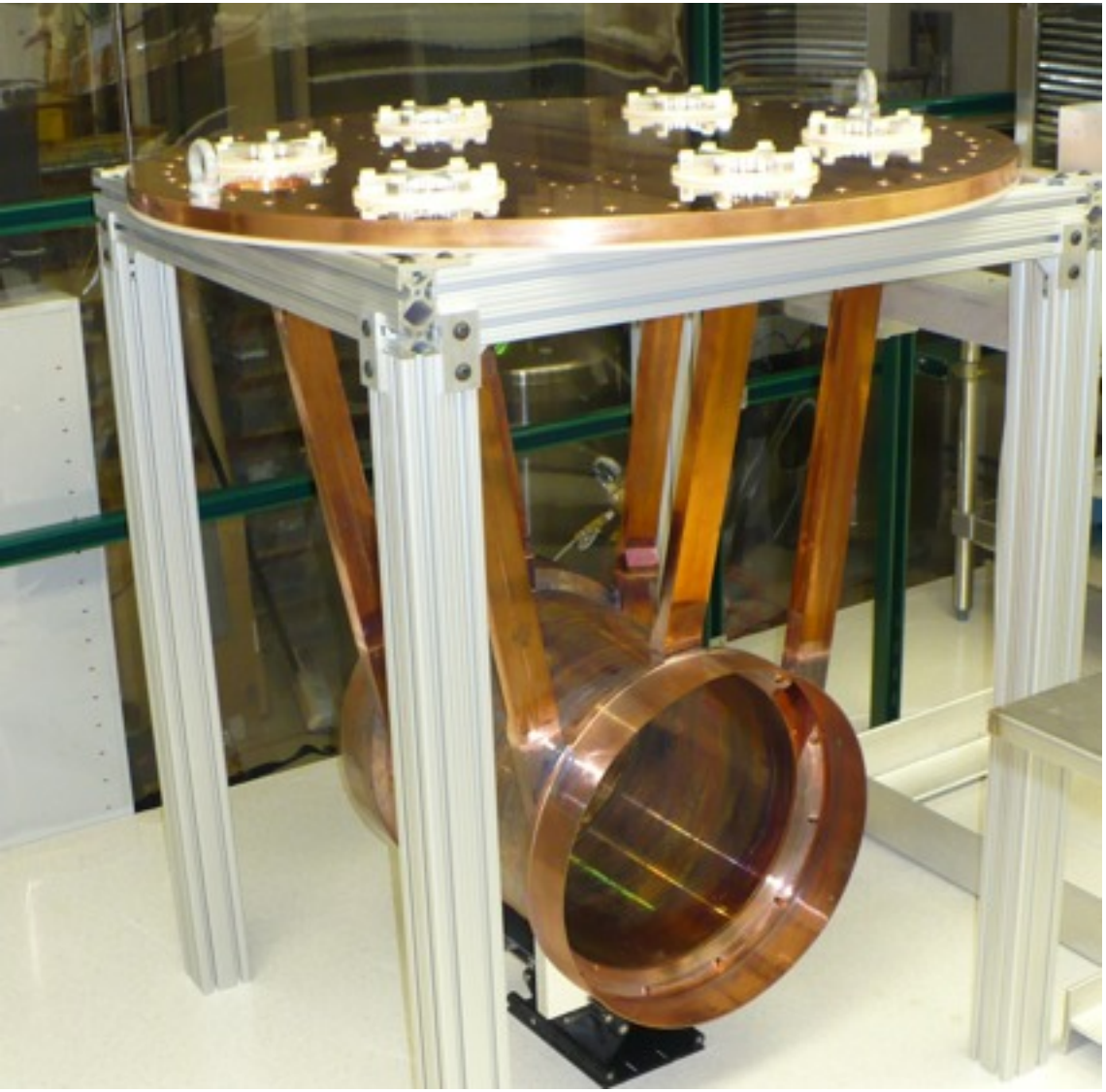
2150 feet underground
at the WIPP facility in Carlsbad, NM

Before EXO



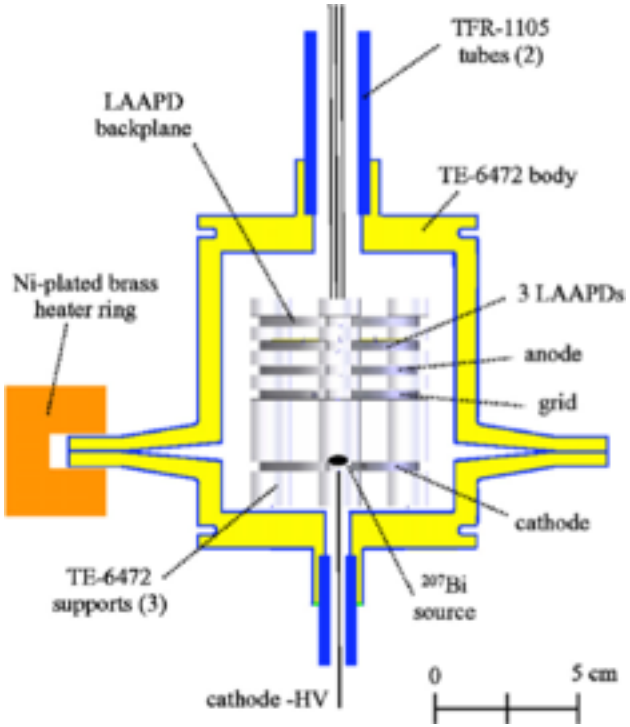
With EXO

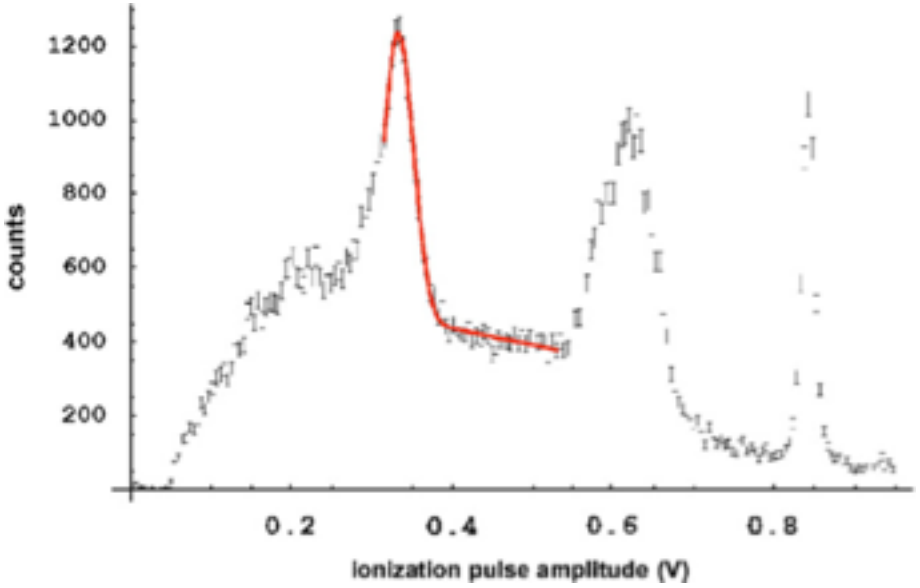
EXO-200 liquid xenon vessel: a thin copper balloon



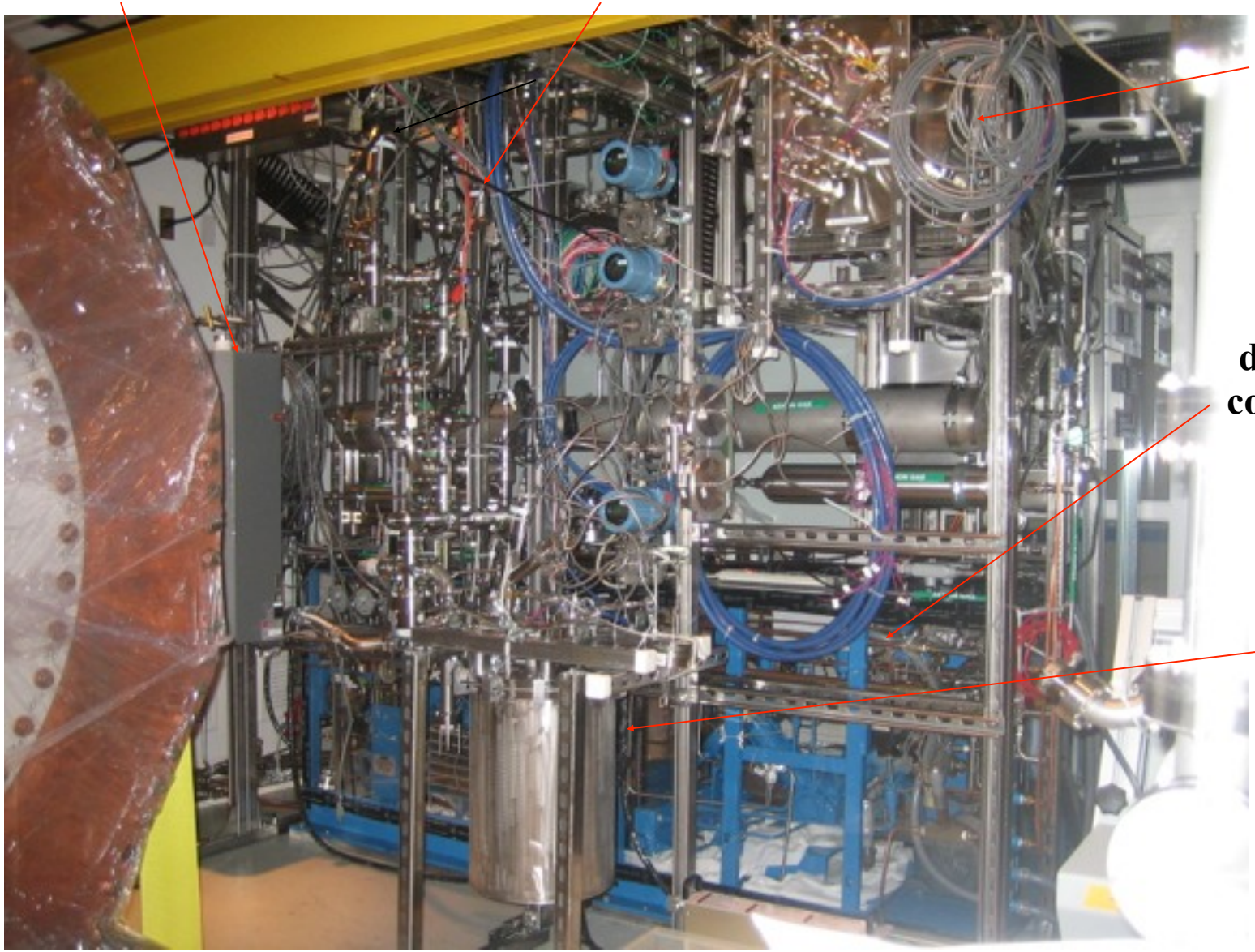
- Very light (wall thickness 1.5 mm, total weight 15 kg), to minimize material.
- All parts machined under 7 ft of concrete shielding to reduce activation by cosmic rays.
- Different parts are e-beam welded together at Applied Fusion.
- End caps are TIG welded.

A liquid xenon vessel made of teflon(!)



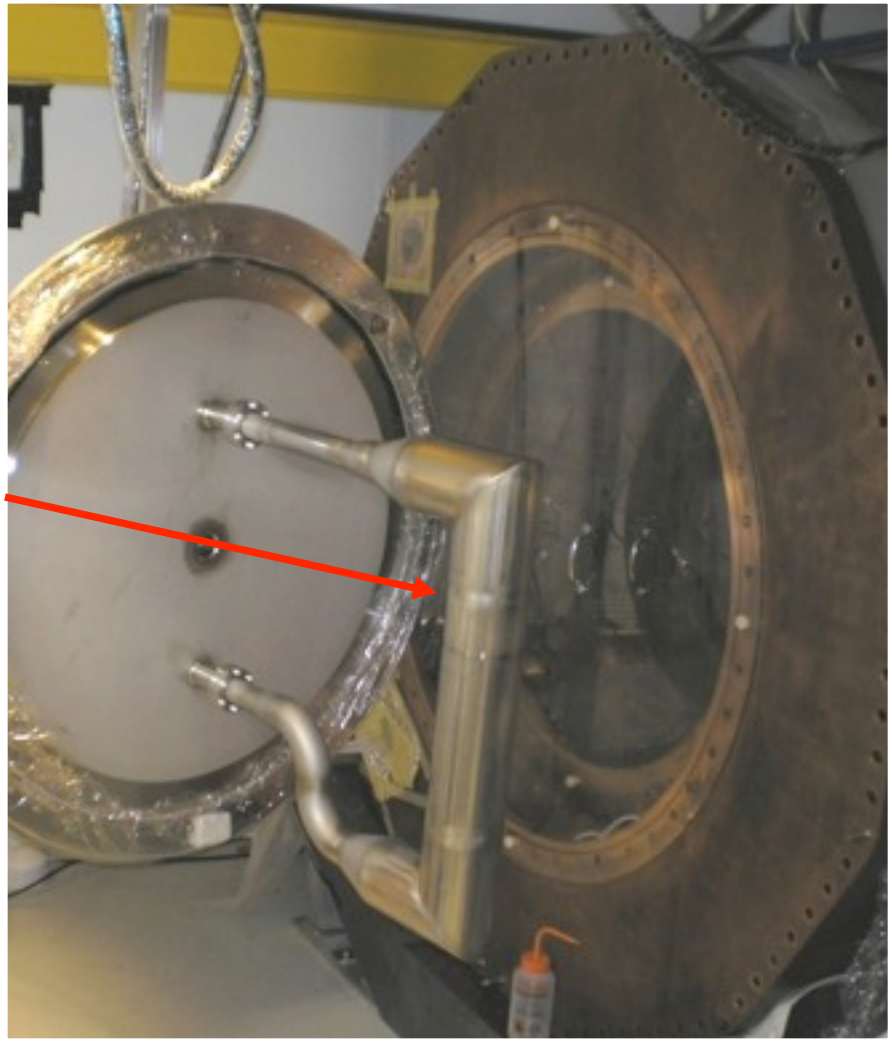


EXO xenon handling &purification system

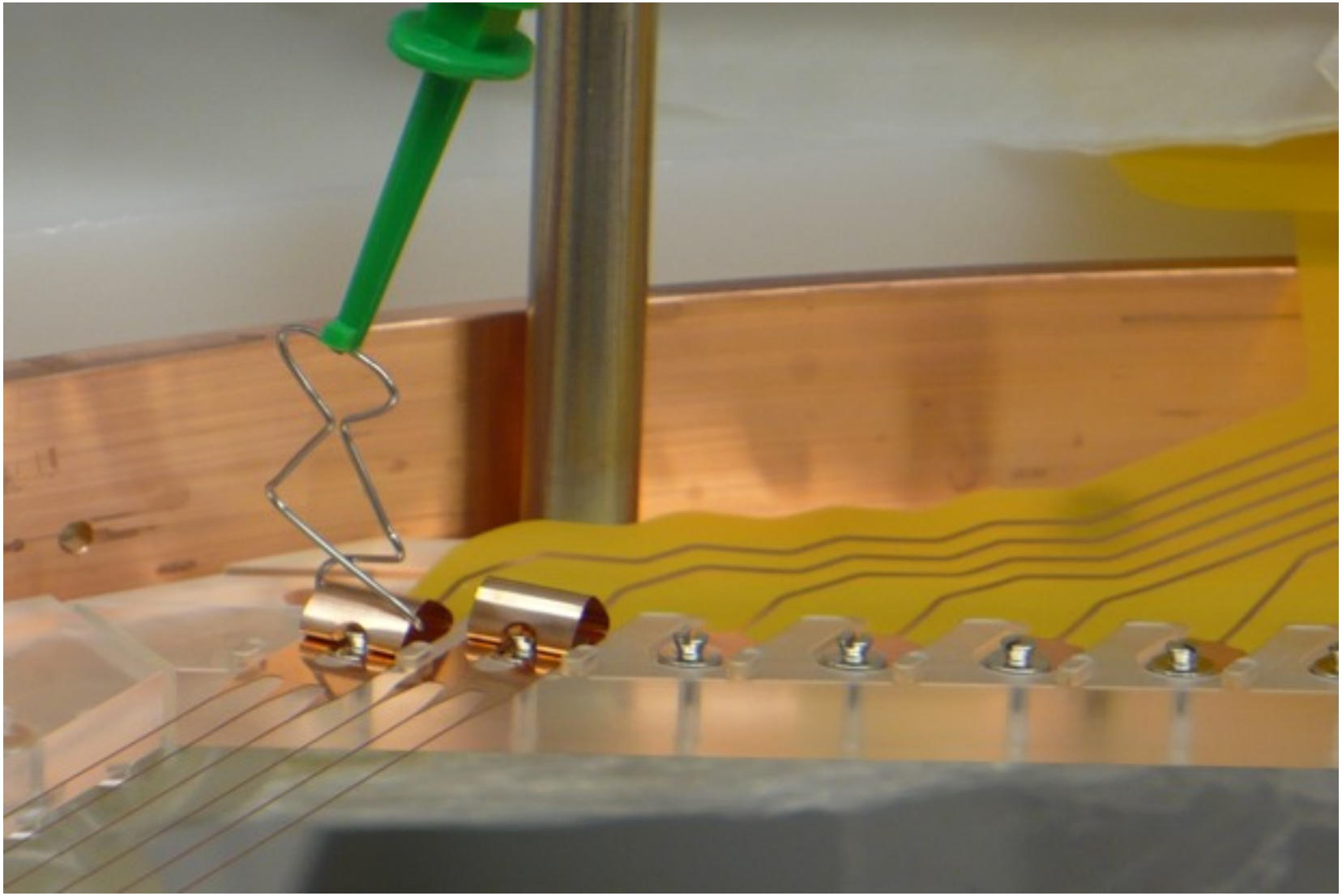


Commissioning of cryogenics and fluid handling – 2007-2009

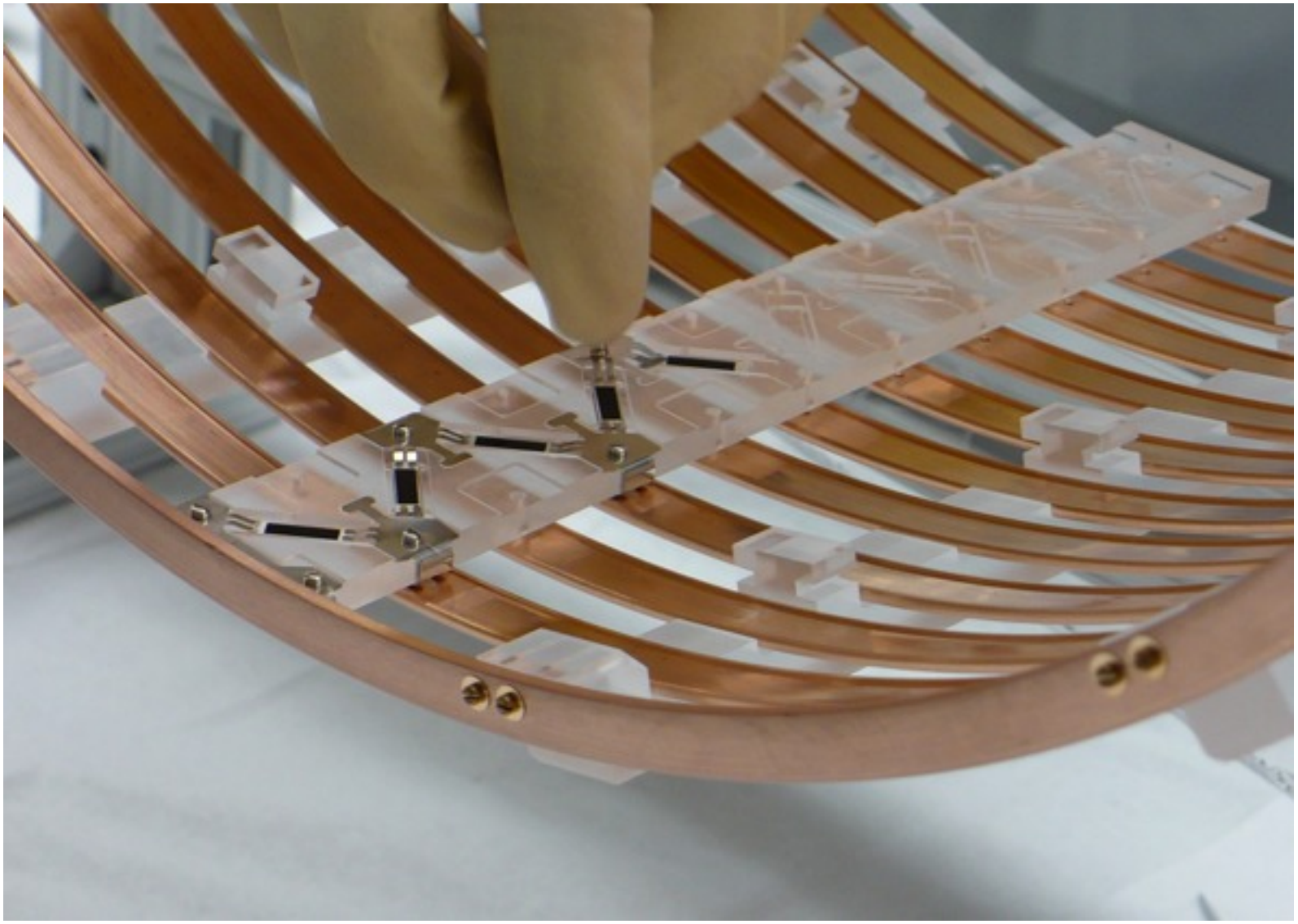
Dummy LXe vessel (stainless steel)



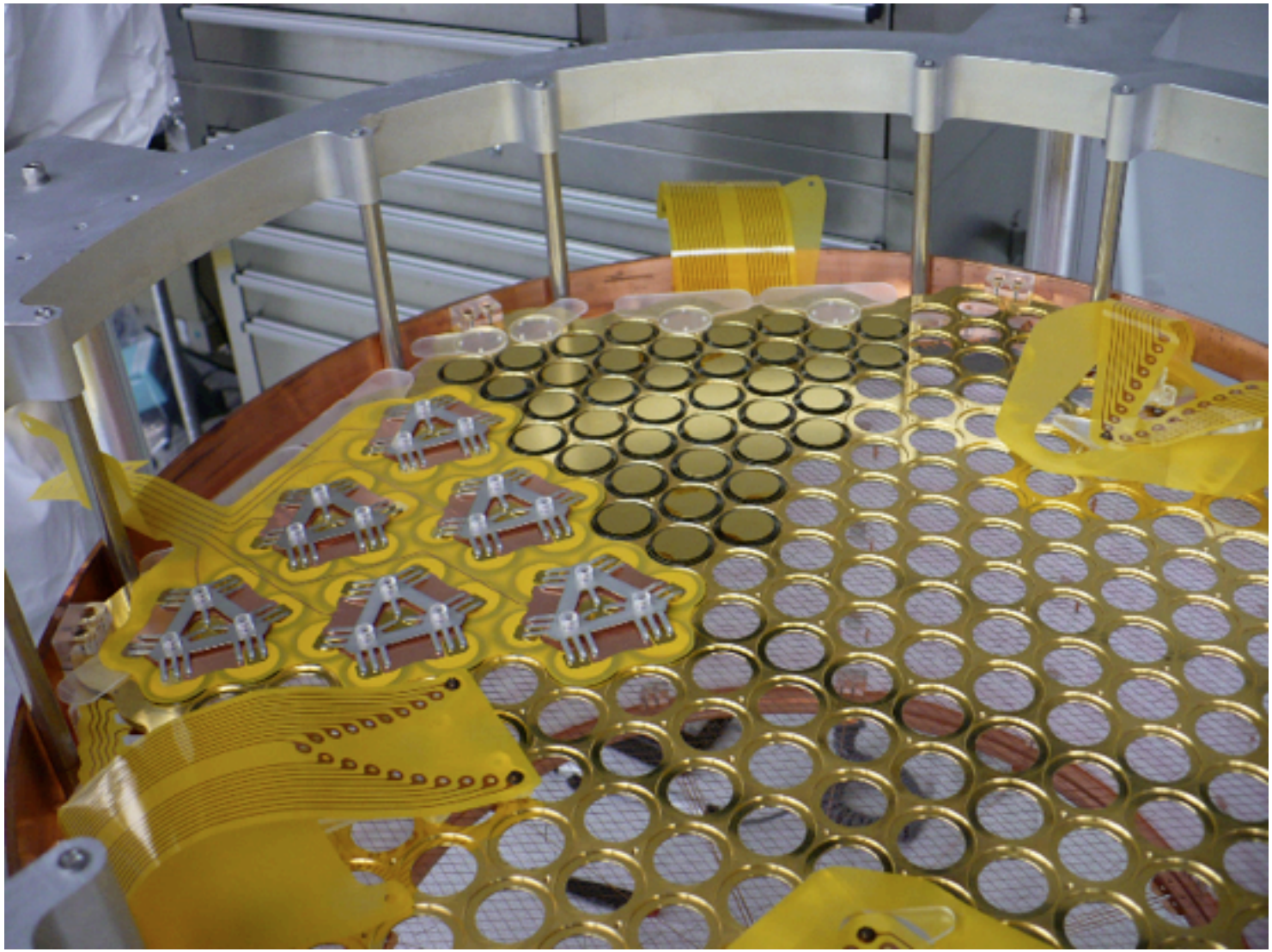
EXO-200 TPC Construction



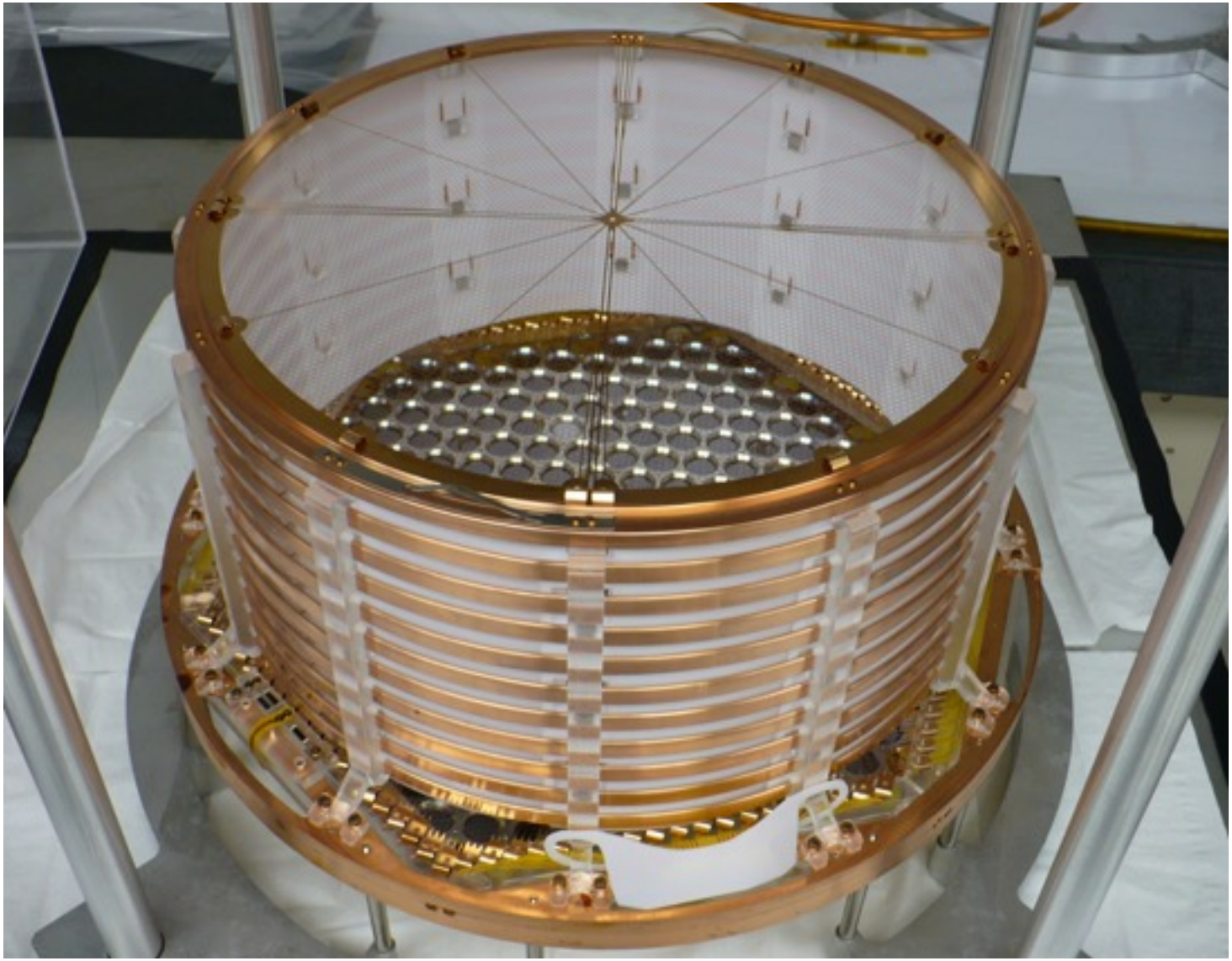
EXO-200 TPC Construction



EXO-200 TPC Construction



A fully instrumented half-detector



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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Systematic study of trace radioactive impurities in candidate construction materials for EXO-200

D.S. Leonard[a,*], P. Grinberg[b], P. Weber[c,1], E. Baussan[c,2], Z. Djurcic[a,3], G. Keefer[a], A. Piepke[a], A. Pocar[d], J.-L. Vuilleumier[c], J.-M. Vuilleumier[c], D. Akimov[e], A. Bellerive[f], M. Bowcock[f], M. Breidenbach[g], A. Burenkov[e], R. Conley[g], W. Craddock[g], M. Danilov[e], R. DeVoe[d], M. Dixit[f], A. Dolgolenko[e], I. Ekchtout[f], W. Fairbank Jr.[h], J. Farine[i], P. Fierlinger[d], B. Flatt[d], G. Gratta[d], M. Green[d], C. Hall[j], K. Hall[h], D. Hallman[i], C. Hargrove[f], R. Herbst[g], J. Hodgson[g], S. Jeng[h], S. Kolkowitz[d], A. Kovalenko[e], D. Kovalenko[e], F. LePort[d], D. Mackay[g], M. Moe[k], M. Montero Díez[d], R. Neilson[d], A. Odian[g], K. O'Sullivan[d], L. Ounalli[c], C.Y. Prescott[g], P.C. Rowson[g], D. Schenker[c], D. Sinclair[f], K. Skarpaas[g], G. Smirnov[e], V. Stekhanov[e], V. Strickland[f], C. Virtue[i], K. Wamba[g], J. Wodin[d,4]

[a]*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL, USA*
[b]*Institute for National Measurements Standards, National Research Council Canada, Ottawa, ON, Canada*
[c]*Institut de Physique, Université de Neuchatel, Neuchatel, Switzerland*
[d]*Physics Department, Stanford University, Stanford, CA, USA*
[e]*ITEP, Moscow, Russia*
[f]*Physics Department, Carleton University, Ottawa, ON, Canada*
[g]*Stanford Linear Accelerator Center, Menlo Park, CA, USA*
[h]*Physics Department, Colorado State University, Fort Collins, CO, USA*
[i]*Department of Physics, Laurentian University, Sudbury, ON, Canada*
[j]*Department of Physics, University of Maryland, College Park, MD, USA*
[k]*Physics Department, University of California, Irvine, CA, USA*

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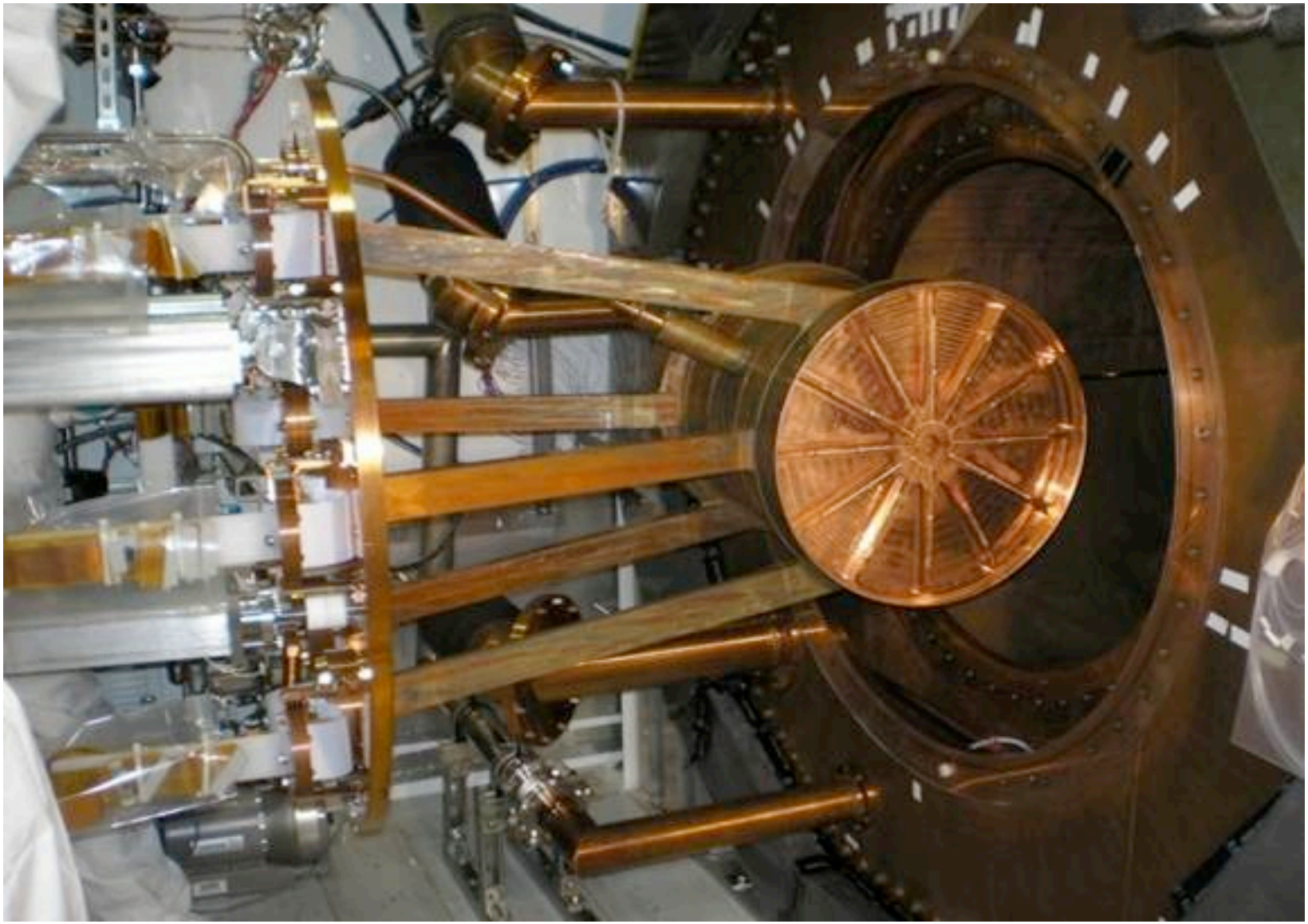
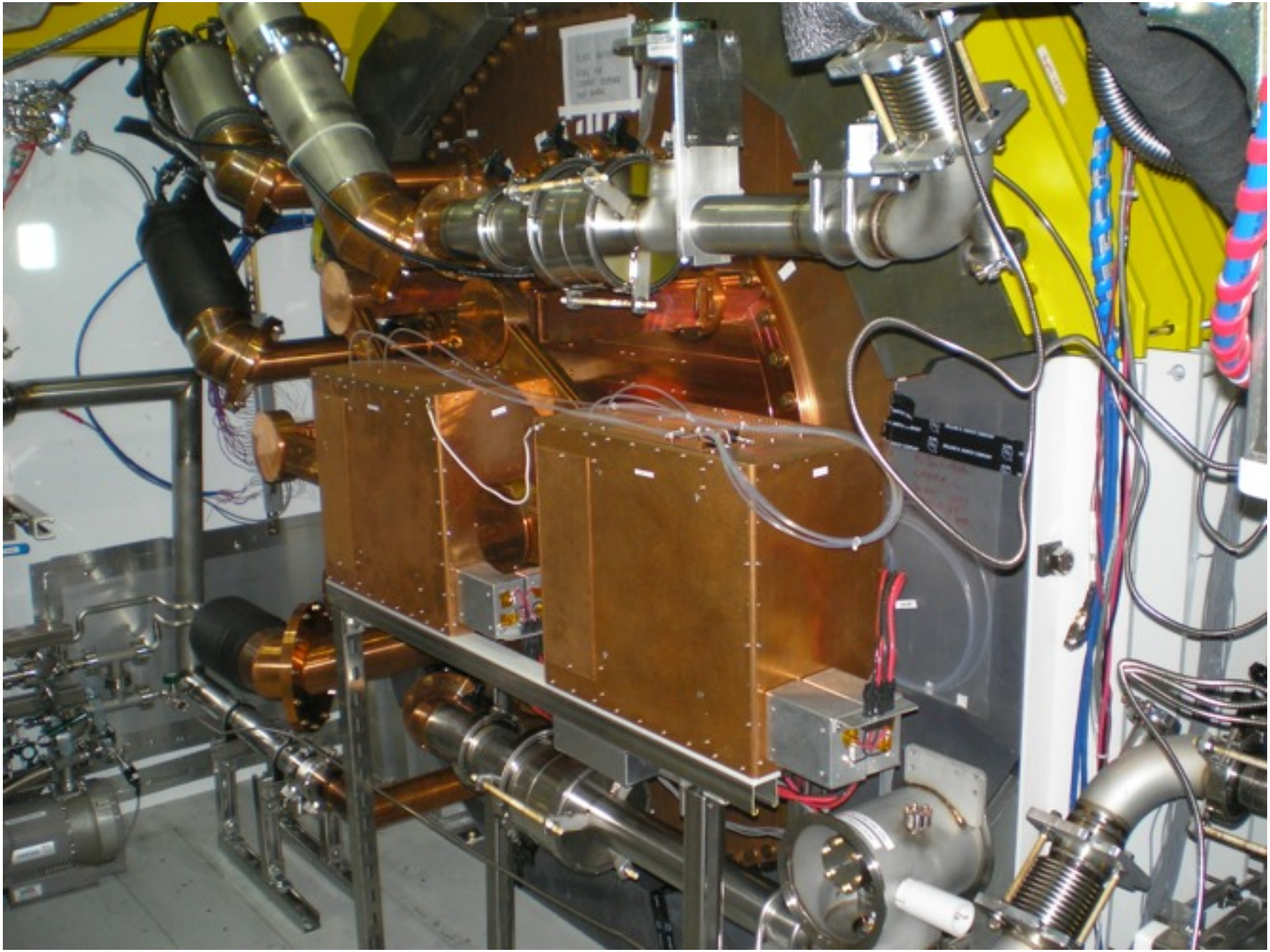
Table 3 (*continued*)

#	Material	Method	K conc. (10^{-9} g/g)	Th conc. (10^{-12} g/g)	U conc. (10^{-12} g/g)
85	Cleaned photo-etched phosphor-bronze APD spiders from Newcut Inc. Base material is entry 80	ICP-MS	<60	65 ± 5	1700 ± 10
86	Undeanal photo-etched phosphor-bronze APD spiders from Vaga Industries. Base material is entry 80	ICP-MS	<60	9 ± 1	113 ± 1
87	Cleaned photo-etched phosphor-bronze APD spider contacts from Vaga Industries. Base material is entry 80	ICP-MS	<70	8 ± 1	71 ± 3
88	Undeanal photo-etched phosphor-bronze APD spider contacts from Vaga Industries using selected chemicals. Base material is entry 80	ICP-MS	–	23 ± 3	317 ± 25
89	Cleaned photo-etched phosphor-bronze APD spider contacts from Vaga Industries using selected chemicals. Base material is entry 80	ICP-MS	–	10.6 ± 2.0	12.4 ± 2.1
90	RD Chemical Company RD38, Vaga Industries photo-etch chemical	A.G. Ge	<124000	<74000	–
91	DI water for Vaga Industries photo-etch	A.G. Ge	<57000	<27000	<9200
92	Solid soda ash from Hill Brothers Inc., Vaga Industries photo-etch chemical	A.G. Ge	<13200	<52000	39300 ± 11300
93	Used ferric chloride from Phibro Tech Inc., Vaga Industries photo-etch chemical	A.G. Ge	26100 ± 7300	63200 ± 7900	20300 ± 2700
94	Fresh ferric chloride from Phibro Tech Inc., Vaga Industries photo-etch chemical	A.G. Ge	<29000	<12300	<3300
95	RD Chemical Company RD87, Vaga Industries photo-etch chemical	A.G. Ge	<54000	<89000	–
96	Alcohol, Vaga Industries photo-etch chemical	A.G. Ge	<49000	<34000	<10100
97	California Fine Wire, 20 mil phosphor–bronze wire, annealed. Lot #24987	GD-MS	<23	<20	<20
98	California Fine Wire, 20 mil Copper wire, annealed CFW-100-156 Lot #25477. ^{60}Co: <0.28 mBq/kg	Ge	<180	<86	101 ± 35
99	California Fine Wire, 20 mil annealed Cu wire, CFW-100-156, Lot #25477	Shiva Inc., GD-MS	<0.5	<10	<10
100	California Fine Wire, 20 mil annealed Cu–Be wire, alloy 25, CFW-100-034	Shiva Inc., GD-MS	<0.5	370000	1800000
	Photo-etching: Cu on polyimide substrate				
101	Cu coating Nippon Steel Chemical Co., Espanex flat cable MC18-50-00CEM. Polyimide thickness: 50 μm, Cu thickness: 18 μm	ICP-MS	–	<3 (<0.05 pg/cm^2)	19 ± 2 (0.30 ± 0.03 pg/cm^2)
102	Polyimide substrate Nippon Steel Chemical Co., Espanex flat cable MC18-25-00 CEM, lot 65605-11R1. Polyimide thickness: 25 μm, Cu thickness: 18 μm	NAA[a]	<299	<1600	<1500

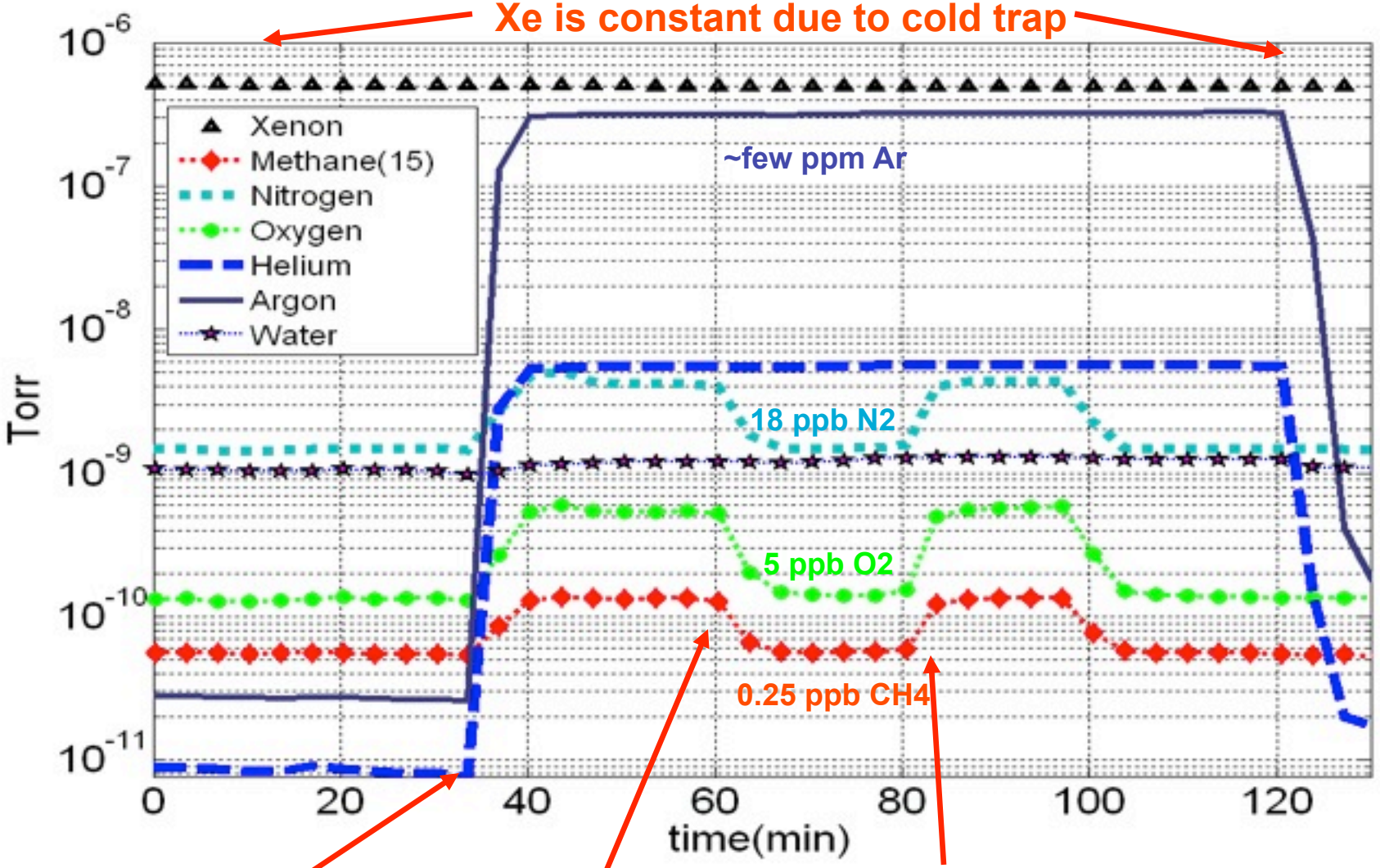
Final TPC installation - January 2010





Screen the xenon for impurities with mass spectrometry

Sensitivity : 0.1 ppb O2
1.0 ppb N2
0.06 ppb CH4
0.5 ppt Kr

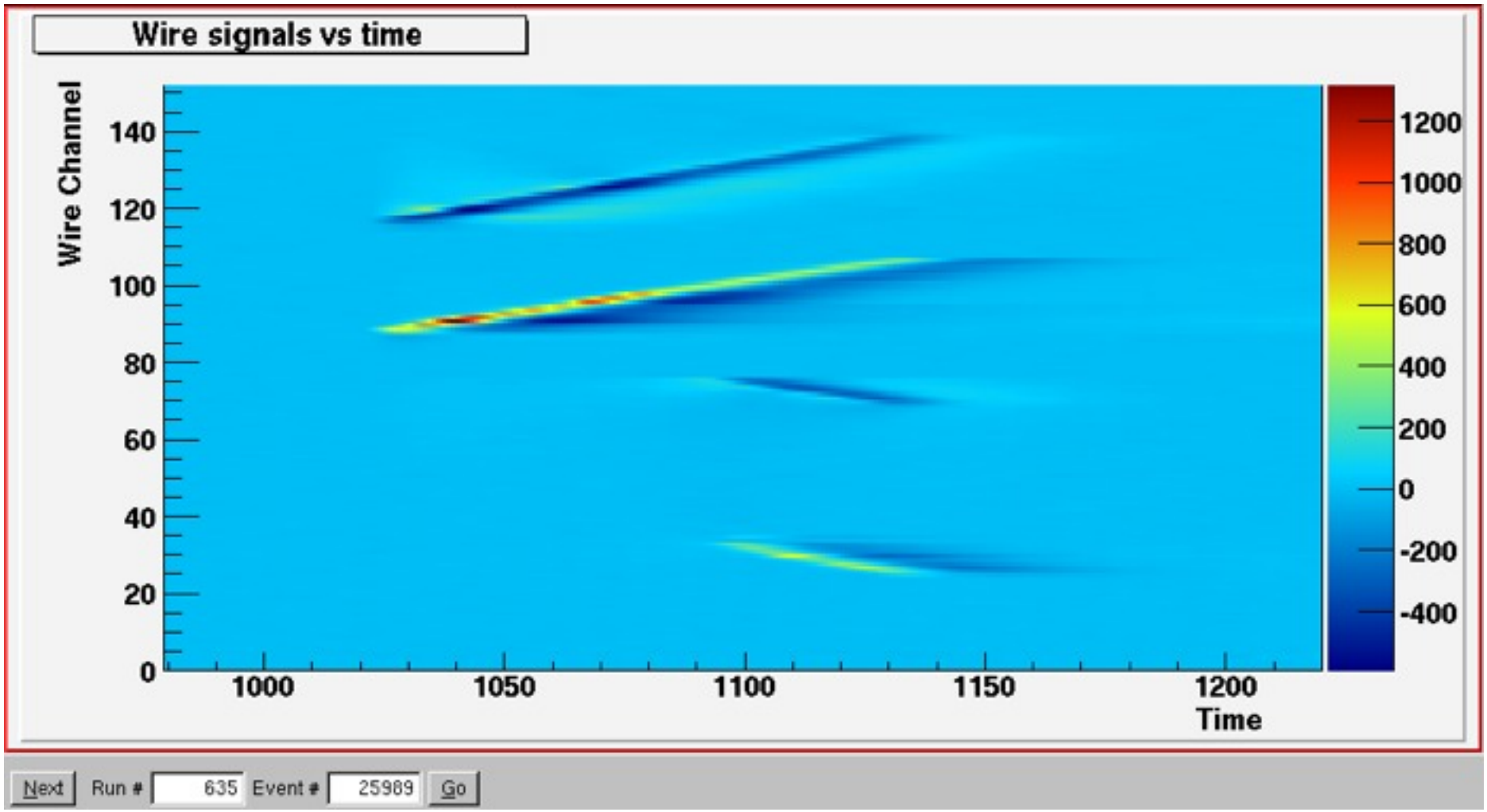


open leak valve, bypass gas purifier

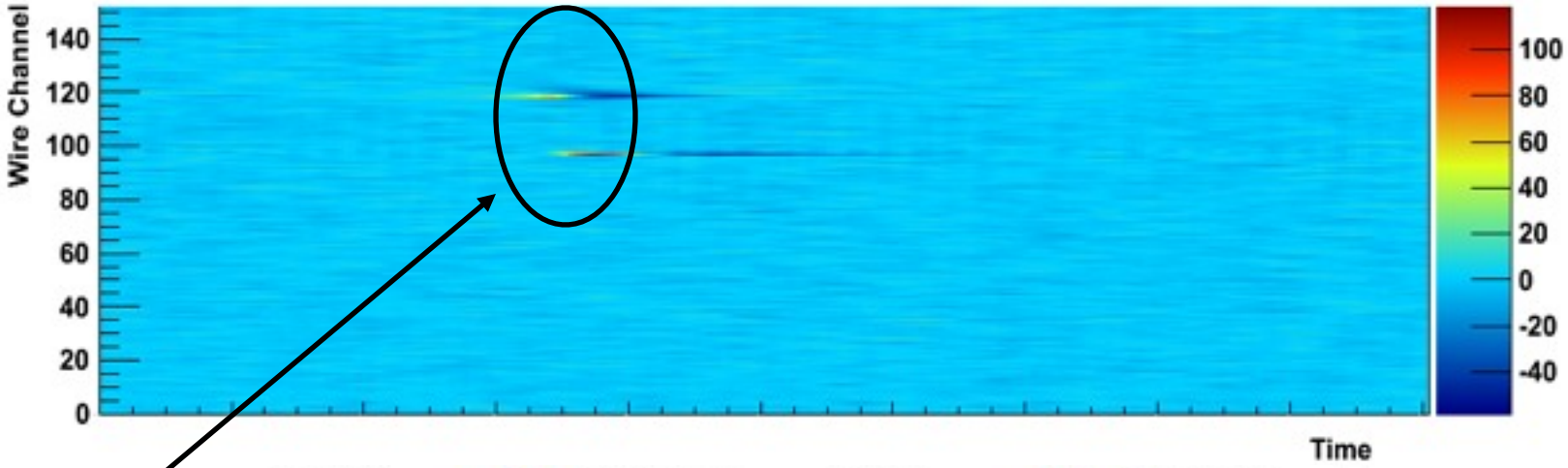
flow through gas purifier

bypass gas purifier

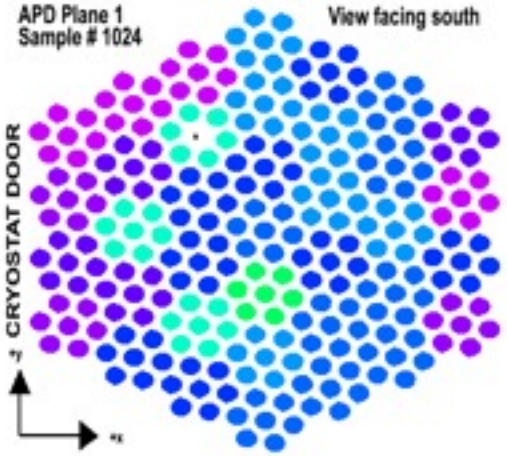
A cosmic ray muon in the EXO liquid xenon TPC

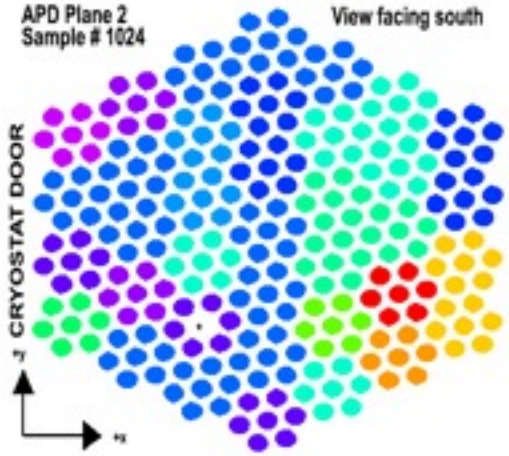


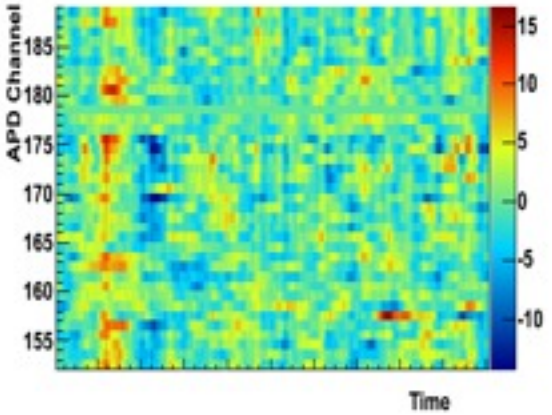
Four views of the same muon track: 2 TPCs x X&Y views

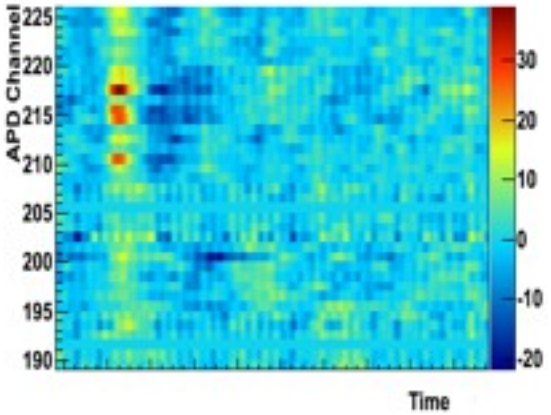


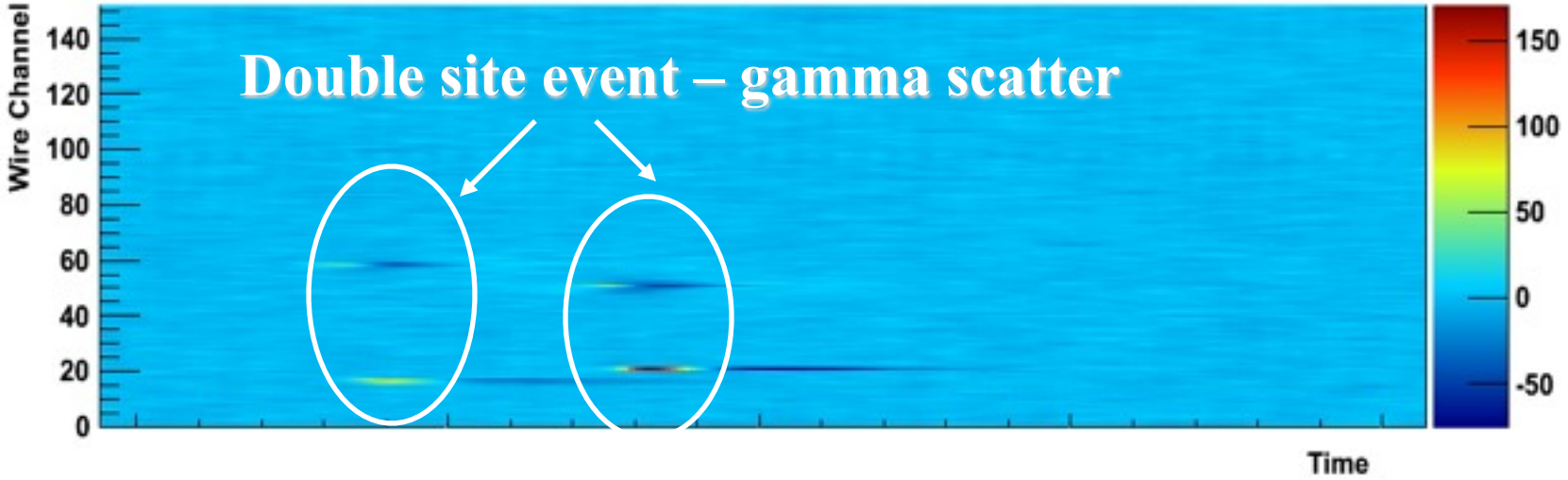
Single-Site Event

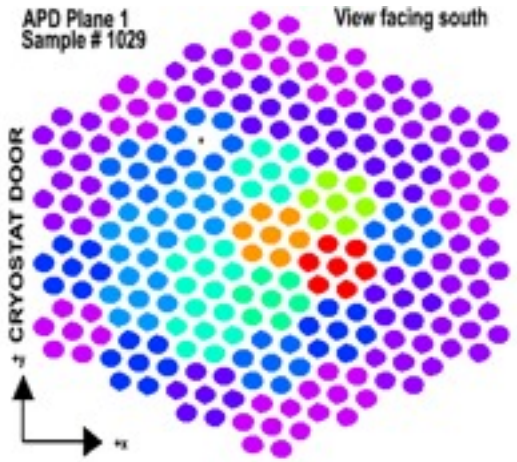


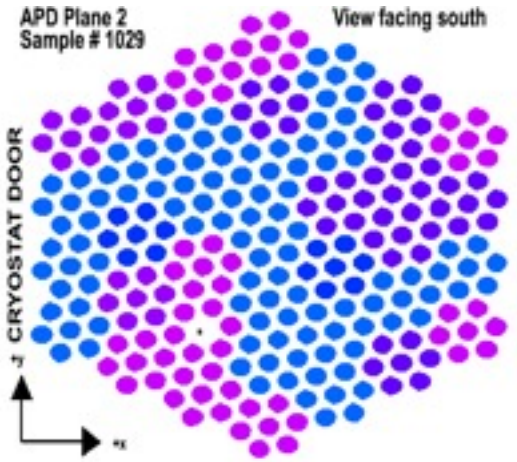


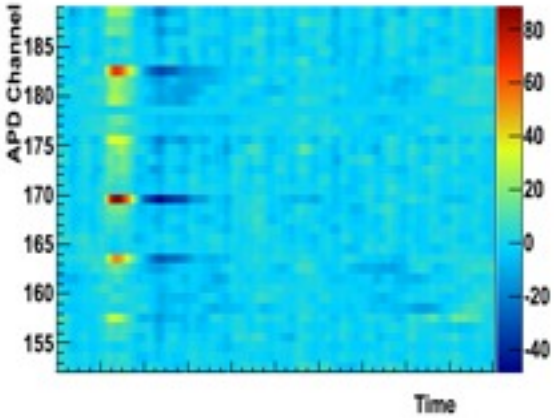


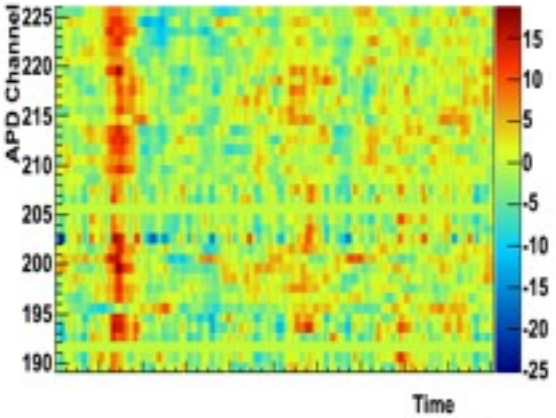



Double site event – gamma scatter
Wire Channel
Time

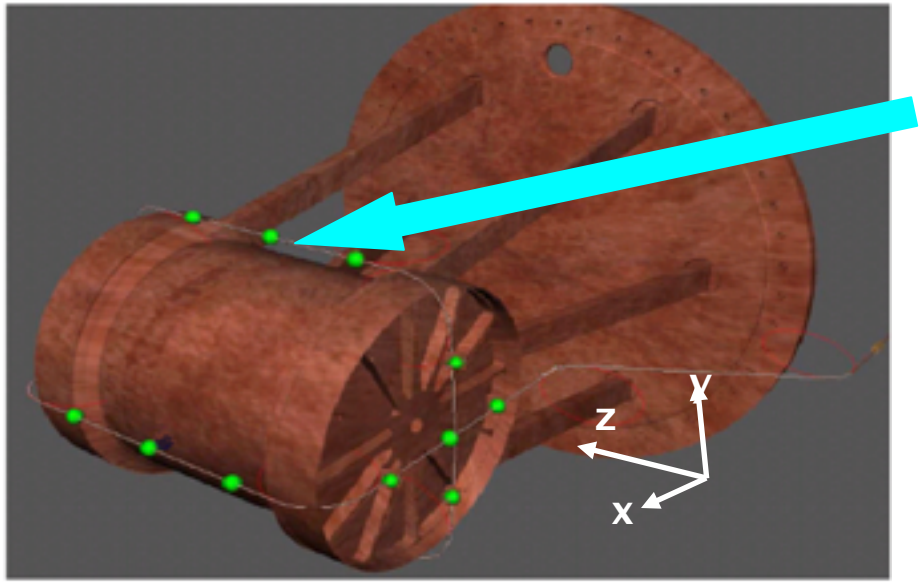

APD Plane 1
Sample # 1029
View facing south
CRYOSTAT DOOR

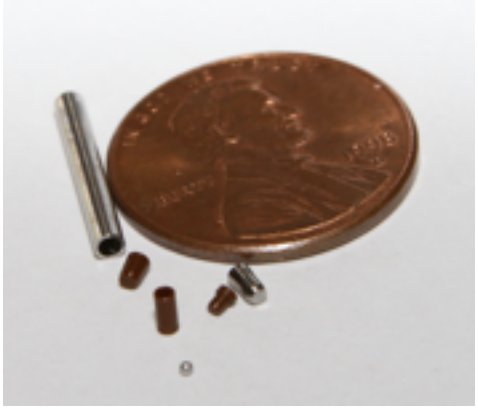

APD Plane 2
Sample # 1029
View facing south
CRYOSTAT DOOR


APD Channel
Time


APD Channel
Time

Calibration Source Run



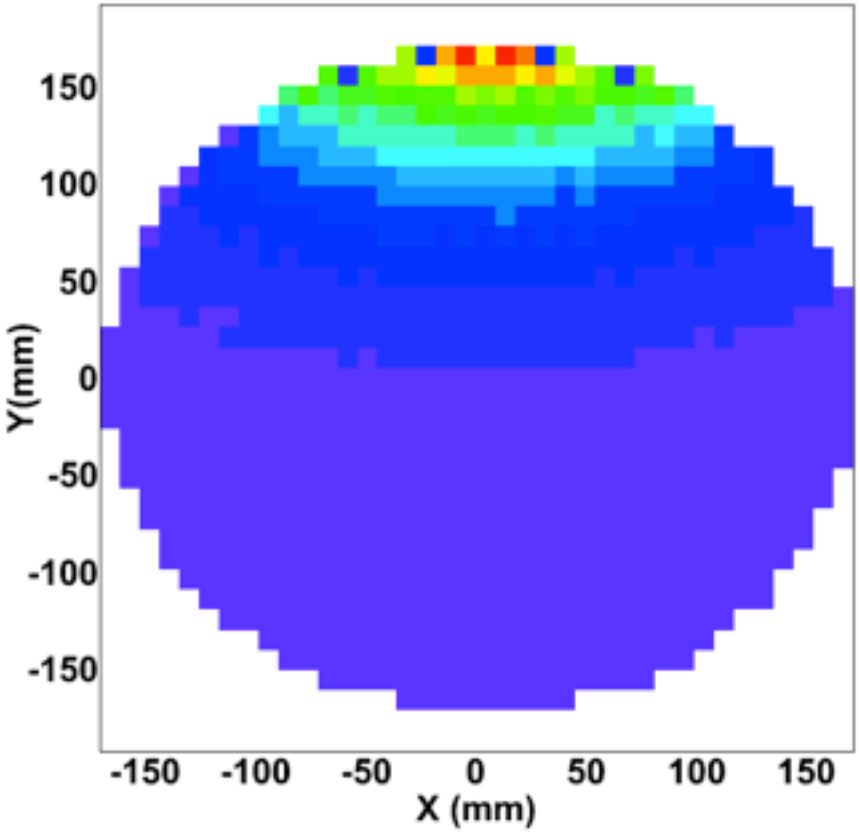


Sources:

^{137}Cs, ^{60}Co, ^{228}Th

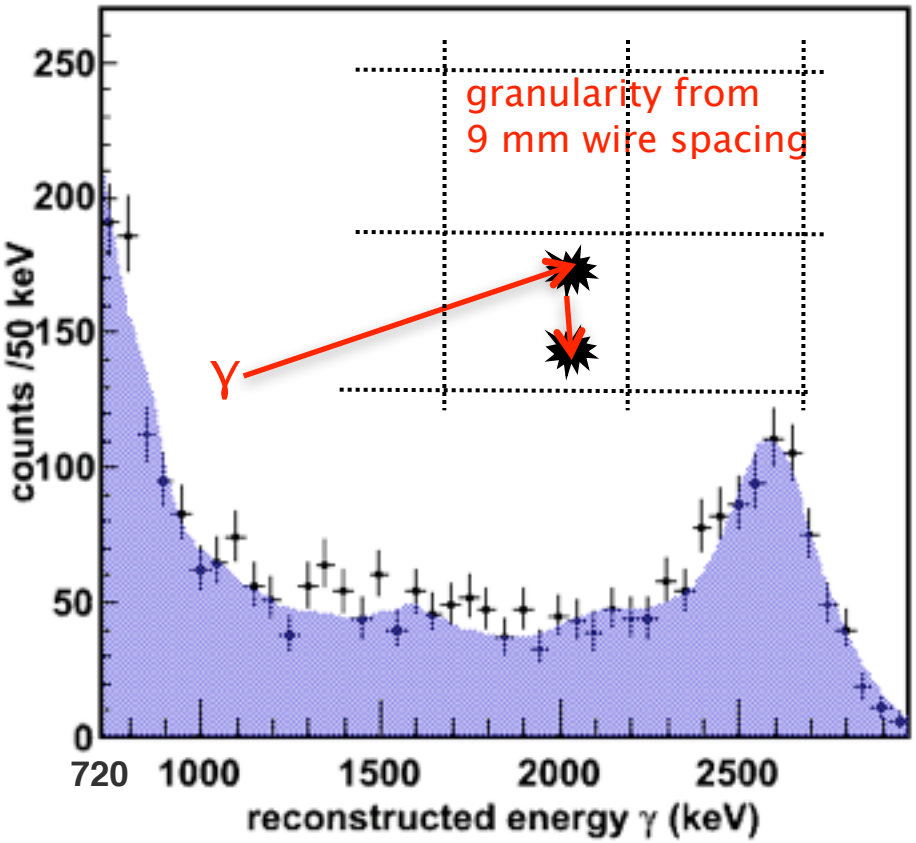
Various calibration sources can be brought to several positions just outside the detector

x-y distribution of events clearly shows excess near the source location

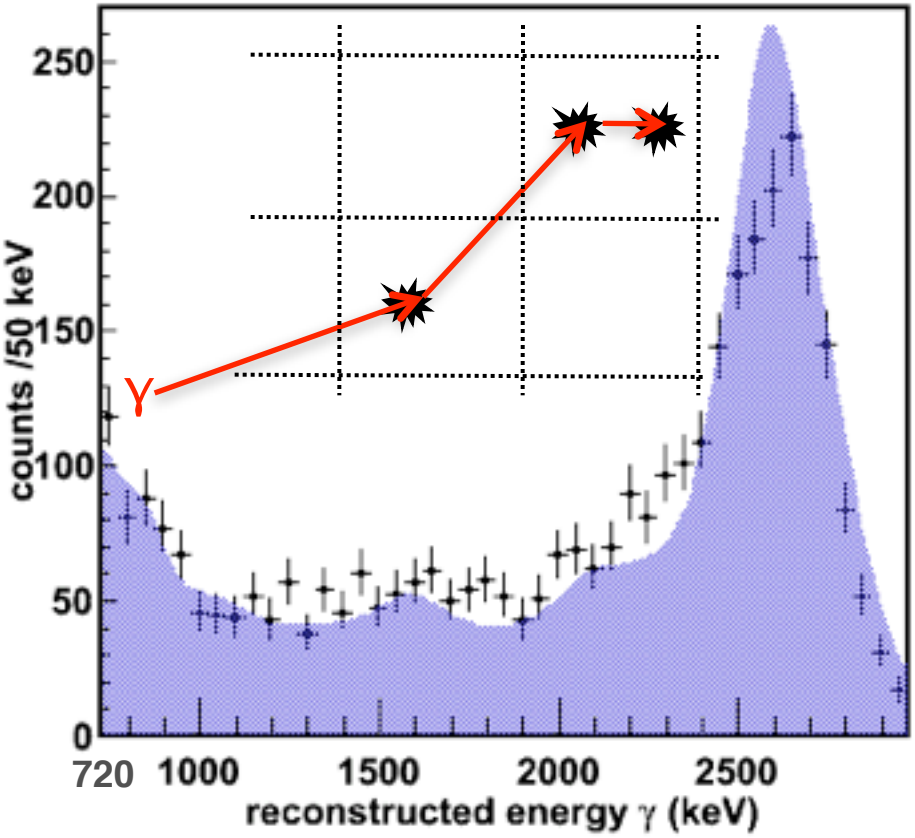


Radioactive Source Calibration Run

single – cluster



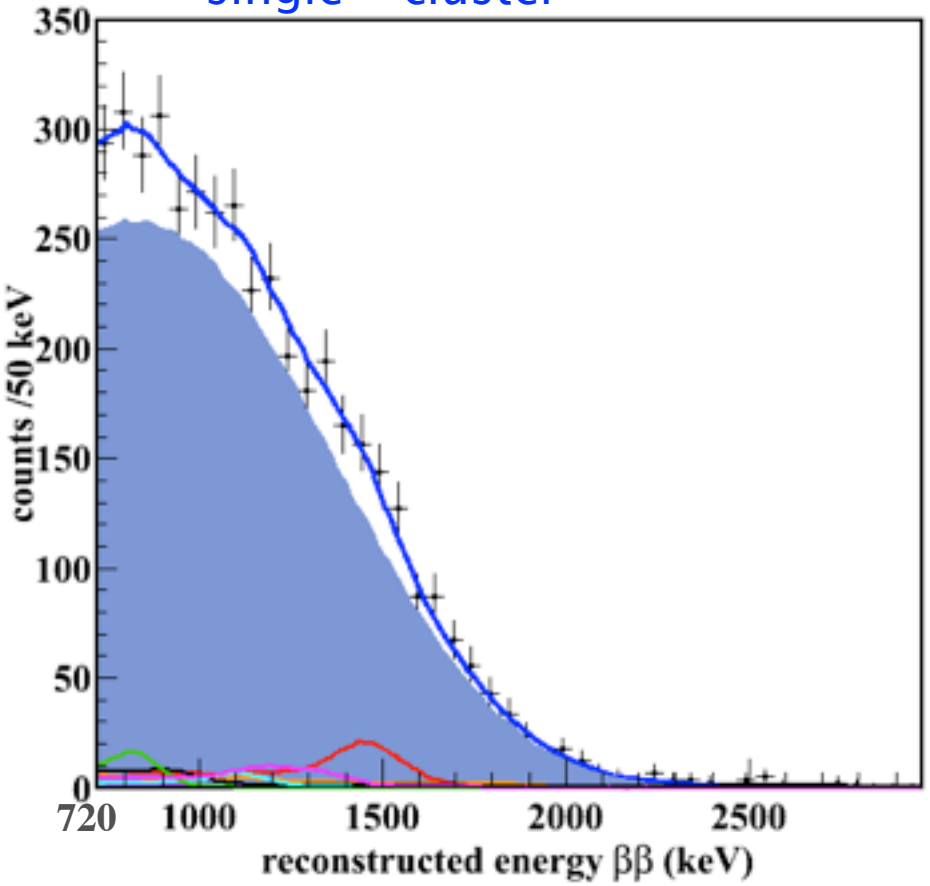
multiple – cluster



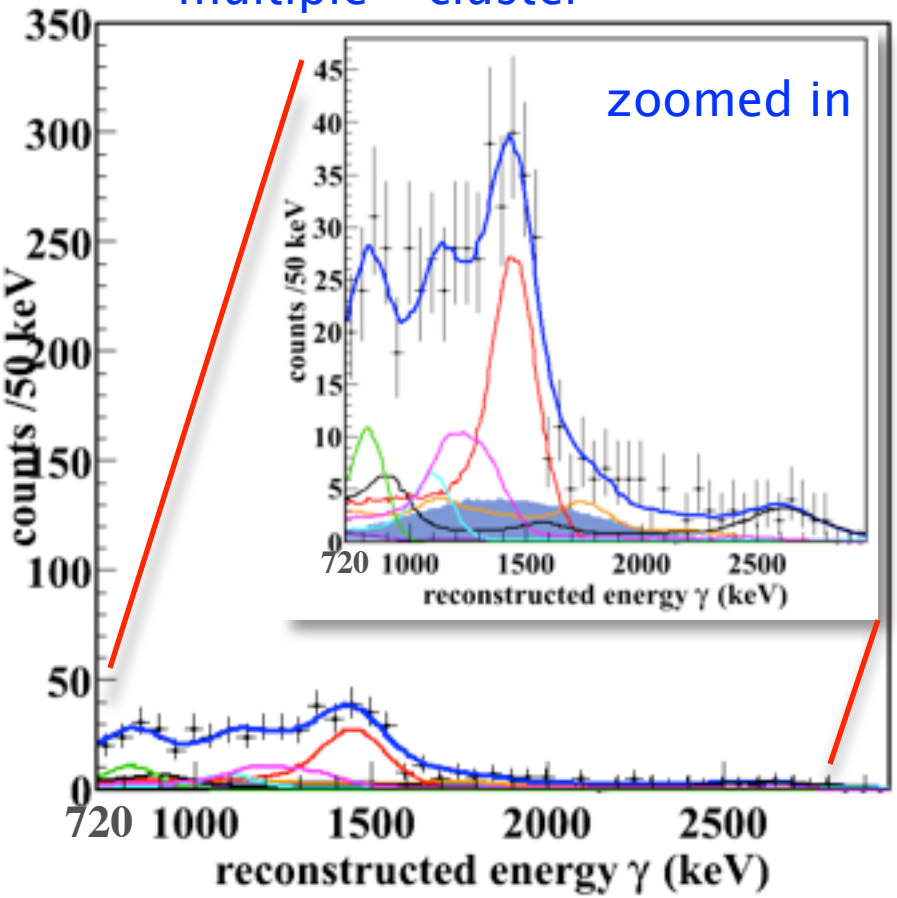
- Calibration runs compared to simulation
  - -There are no free parameters for these comparisons (worst agreement is +8%)

Physics Data – June/July 2011

single – cluster

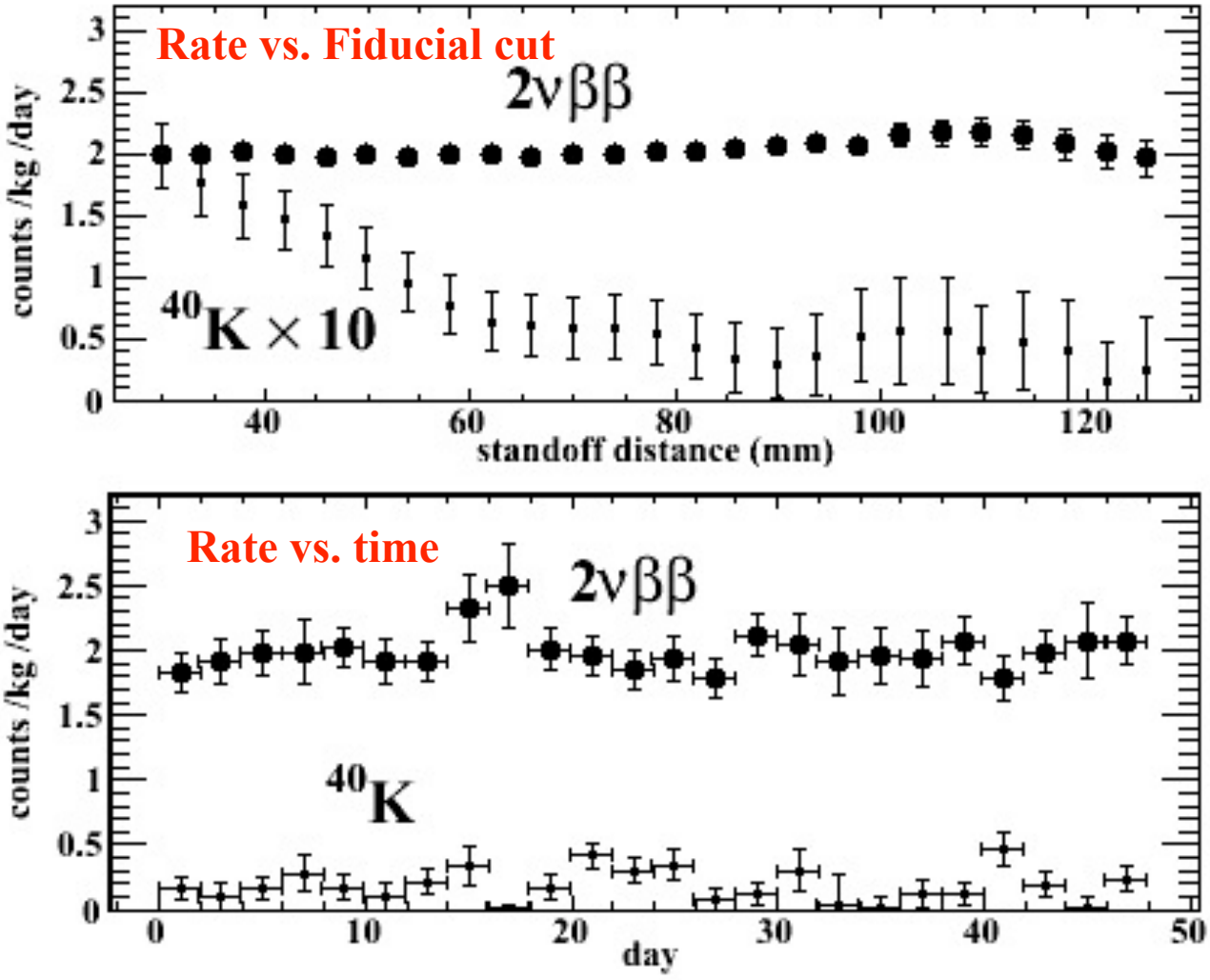


multiple – cluster



- 31 live-days of data
- 63 kg active mass
- Signal / Background ratio 10:1
  - as good as 40:1 for some extreme fiducial volume cuts

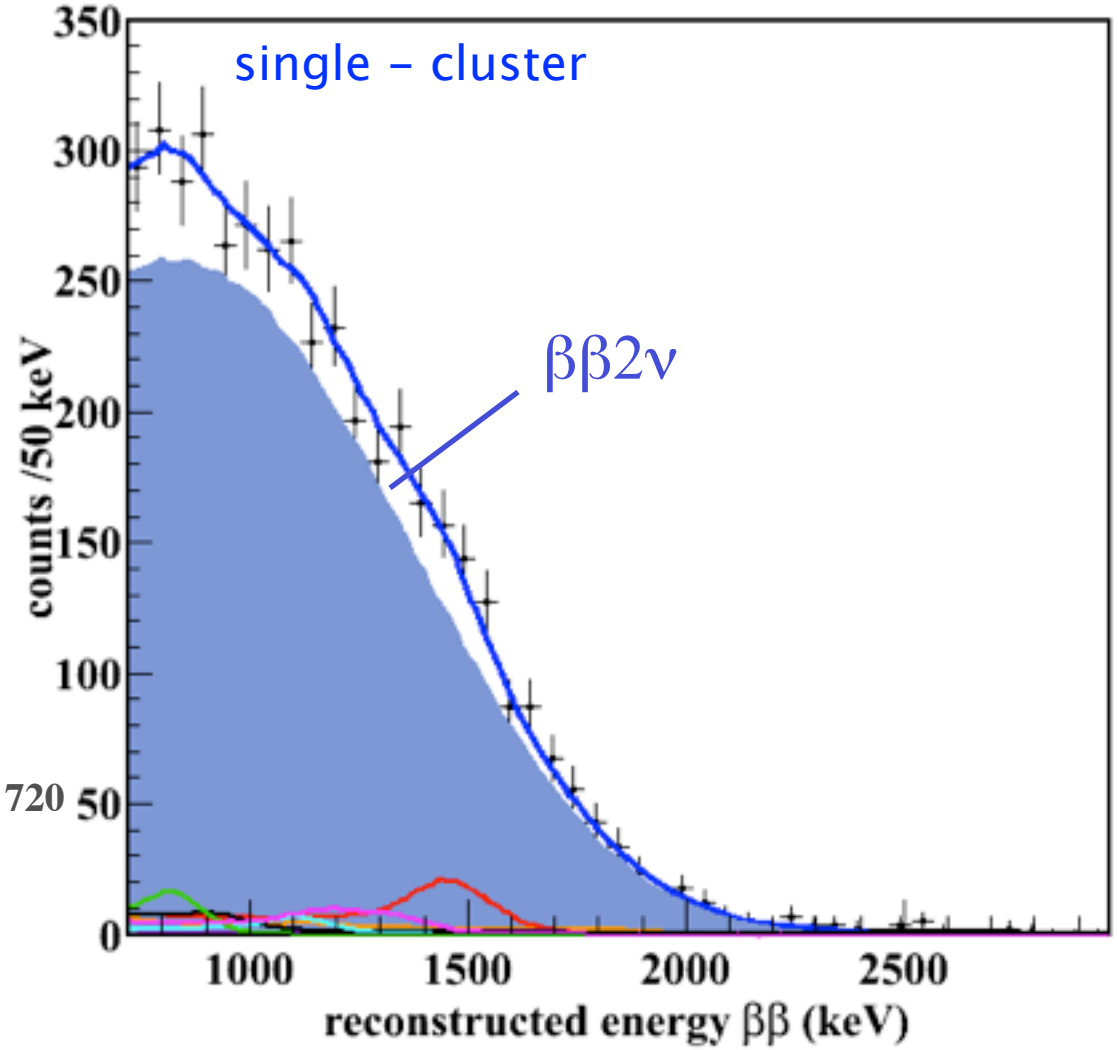
Physics Data – June/July 2011



- ββ2ν signal is uniformly distributed in the xenon, while backgrounds are near the edges.

- ββ2ν rate is constant in time, as expected.

First Observation of bb2n in ^{136}Xe



^{136}Xe→^{136}Ba ββ2ν
First observation
of ββ2ν in this isotope

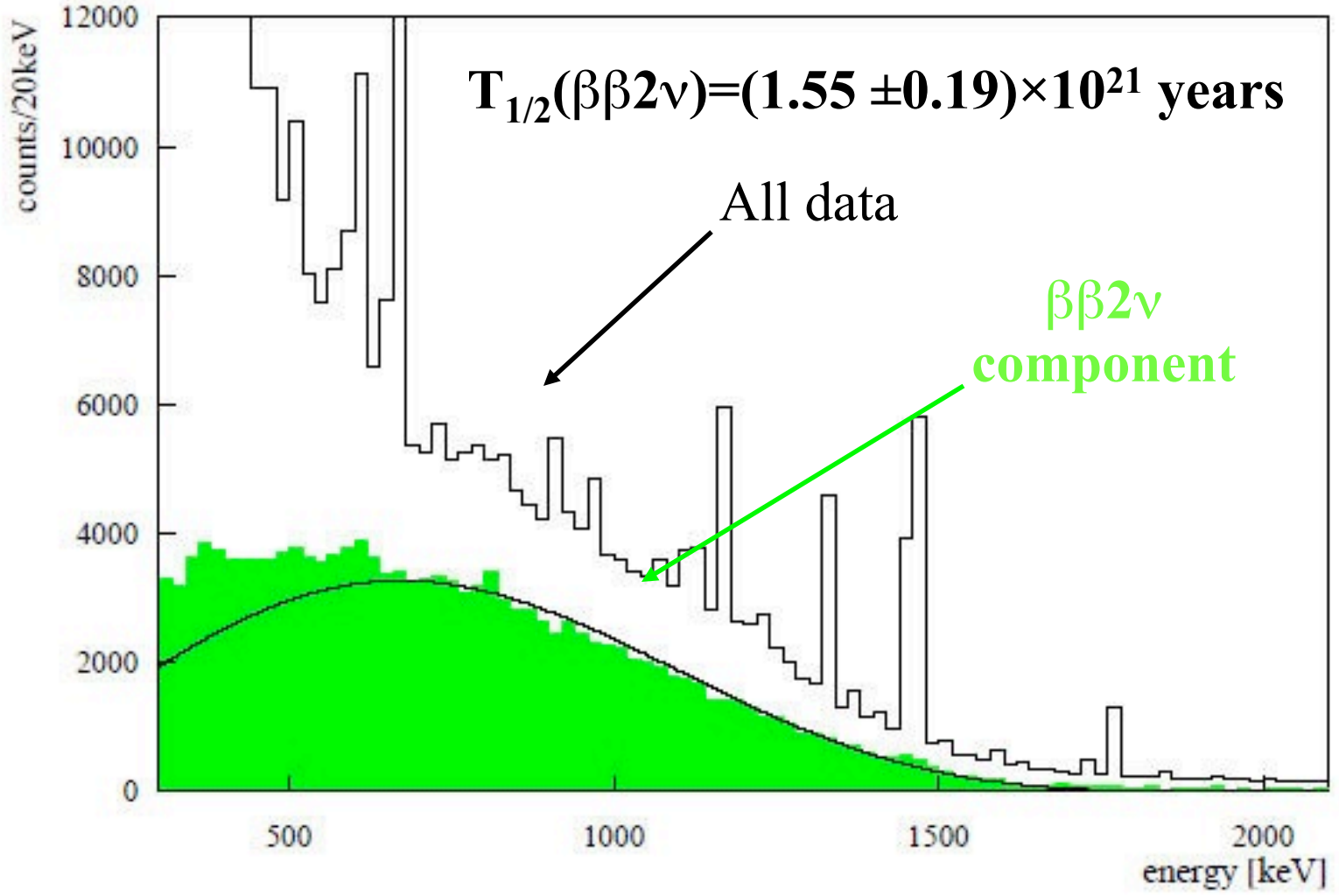
Longest half-life ever
directly observed.

Only 31 days of data.

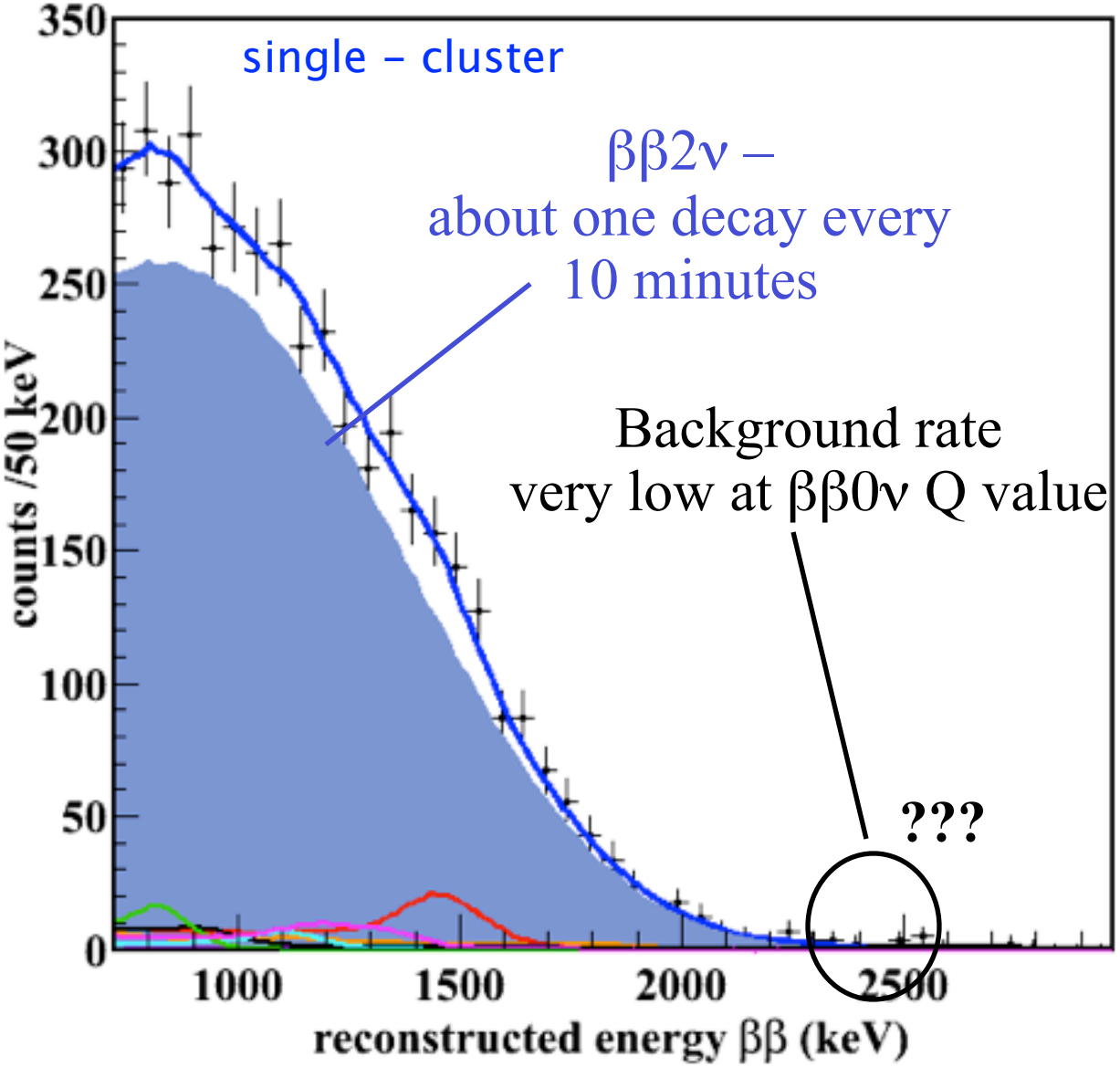
Signal-to-background
ratio 10:1

$T_{1/2} = 2.11 \cdot 10^{21}$ yr (± 0.04 stat) yr (± 0.21 sys) **[arXiv: 1108.4193],**
to appear in PRL

ββ2ν observed in 76Ge – Heidelberg-Moscow experiment - 2001



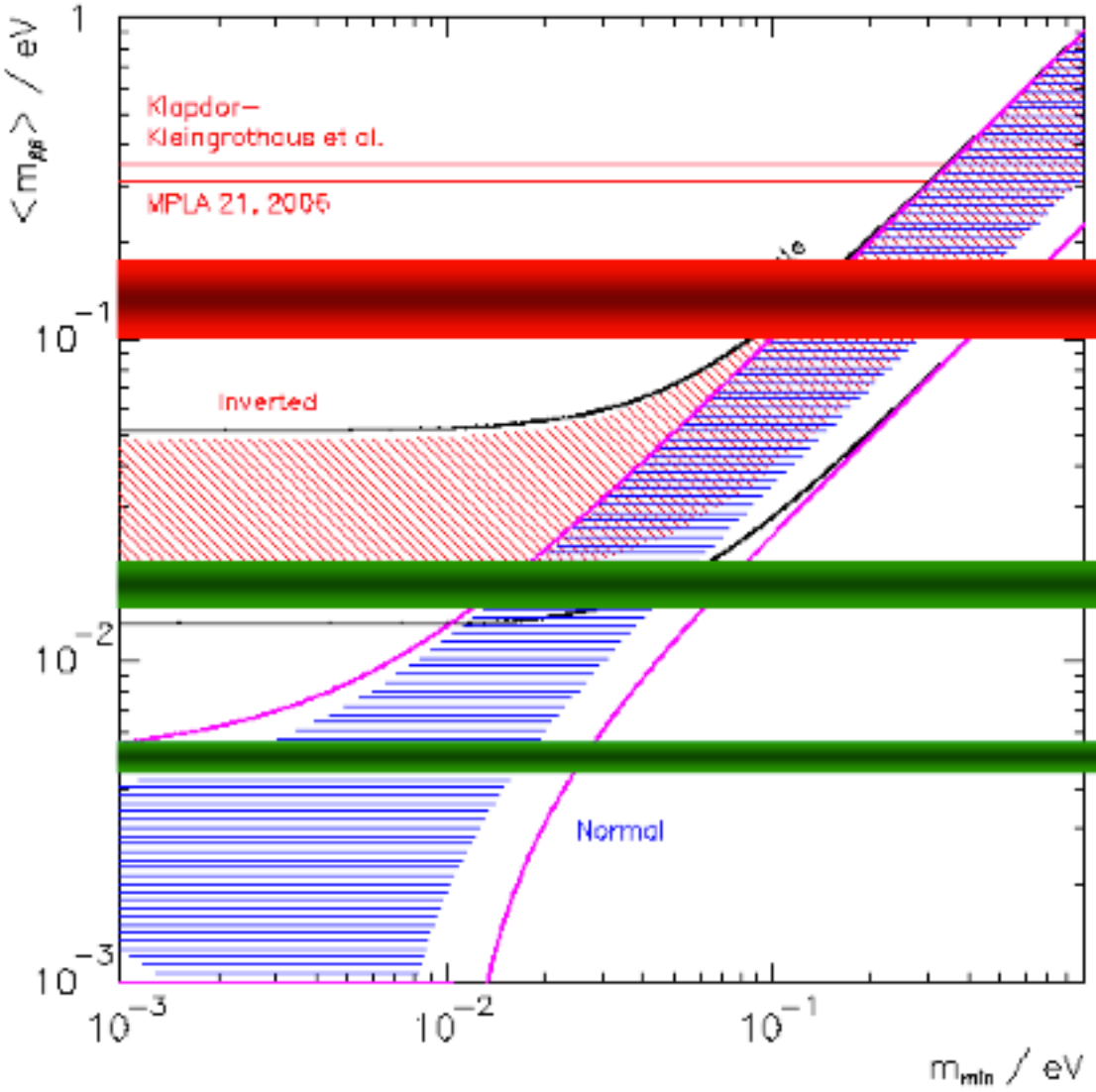
Search for ββ0ν in ^{136}Xe



This month:

- Completed upgrade to front end electronics optimize energy resolution.
- Finish installation of radon tent.
- Finish final construction of lead wall.
- Begin long-term physics run to search for ββ0ν.

EXO Sensitivity



EXO-200

~100 meV sensit.

2 ton, 5yr, ~18 meV

Full-EXO sensitivity

10 ton, 10yr, ~5 meV

The EXO Collaboration

D. Auty, M. Hughes, R. MacLellan, A. Piepke, K. Pushkin, M. Volk

University of Alabama, Tuscaloosa AL

P. Vogel

California Institute of Technology, Pasadena CA

A. Coppens, M. Dunford, K. Graham, P. Gravelle, C. Hagemann, C. Hargrove, F. Leonard, K. McFarlane, C. Oullet, E. Rollin, D. Sinclair, V. Strickland

Carleton University, Ottawa ON, Canada

L.Kaufman

Indiana University

M. Moe

University of California, Irvine, Irvine CA

C. Benitez-Medina, S. Cook, W. Fairbank, Jr., K. Hall, N. Kaufold,
B. Mong, T. Walton

Colorado State University, Fort Collins CO

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

ITEP Moscow, Russia

B. Beauchamp, D. Chauhan, B. Clevel
Johnson, U. Wichoski, M. Wilson

Laurentian University, Sudbury ON, Canada

C. Davis, A. Dobi, C. Hall, S. Slutsky, Y-R. Yen

University of Maryland, College Park MD

J. Cook, T. Daniels, K. Kumar, P. Morgan, A. Pocar, B. Schmoll, C. Sterpka, D. Wright

University of Massachusetts Amherst, Amherst MA

D.Leonard

University of Seoul, Republic of Korea

M. Auger, D. Franco, G. Giroux, R. Gornea, M. Weber, J-L. Vuilleumier

Laboratory for High Energy Physics, Bern, Switzerland

W. Feldmeier, P.Fierlinger, M. Marino

Technical University of Munich, Garching, Germany

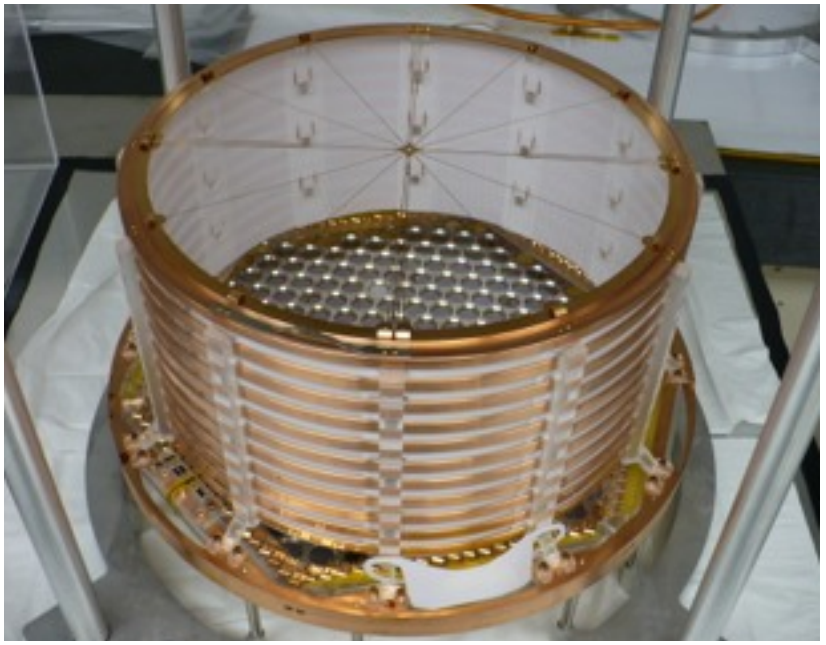
N. Ackerman, M. Breidenbach, R. Conley, W. Craddock, S. Herrin, J. Hodgson, D. Mackay, A. Odian, C. Prescott, P. Rowson, K. Skarpaas, M. Swift, J. Wodin, L. Yang, S. Zalog

Stanford Linear Accelerator Center (SLAC), Menlo Park CA

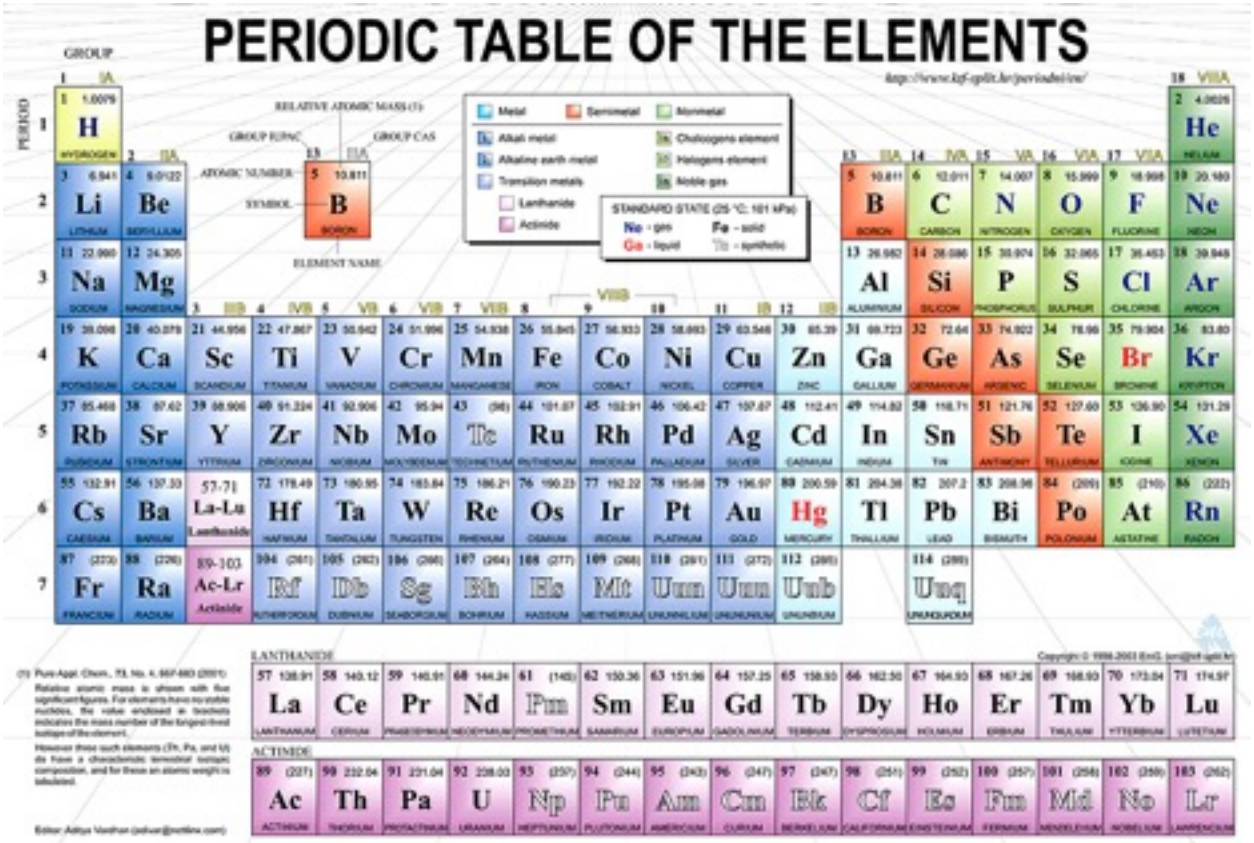
J.
.R.
urov, D.

We need this:

But we also need this:



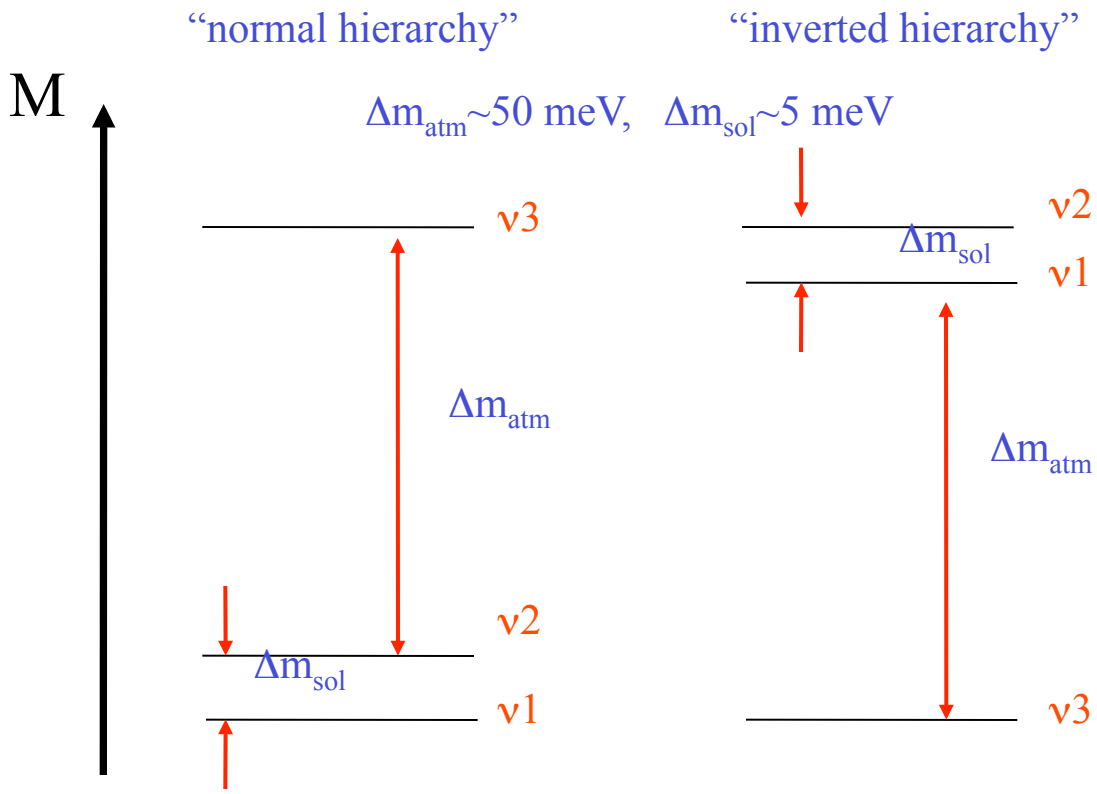
What's in a BNC connector?



ν_e is a mixture of several mass states:

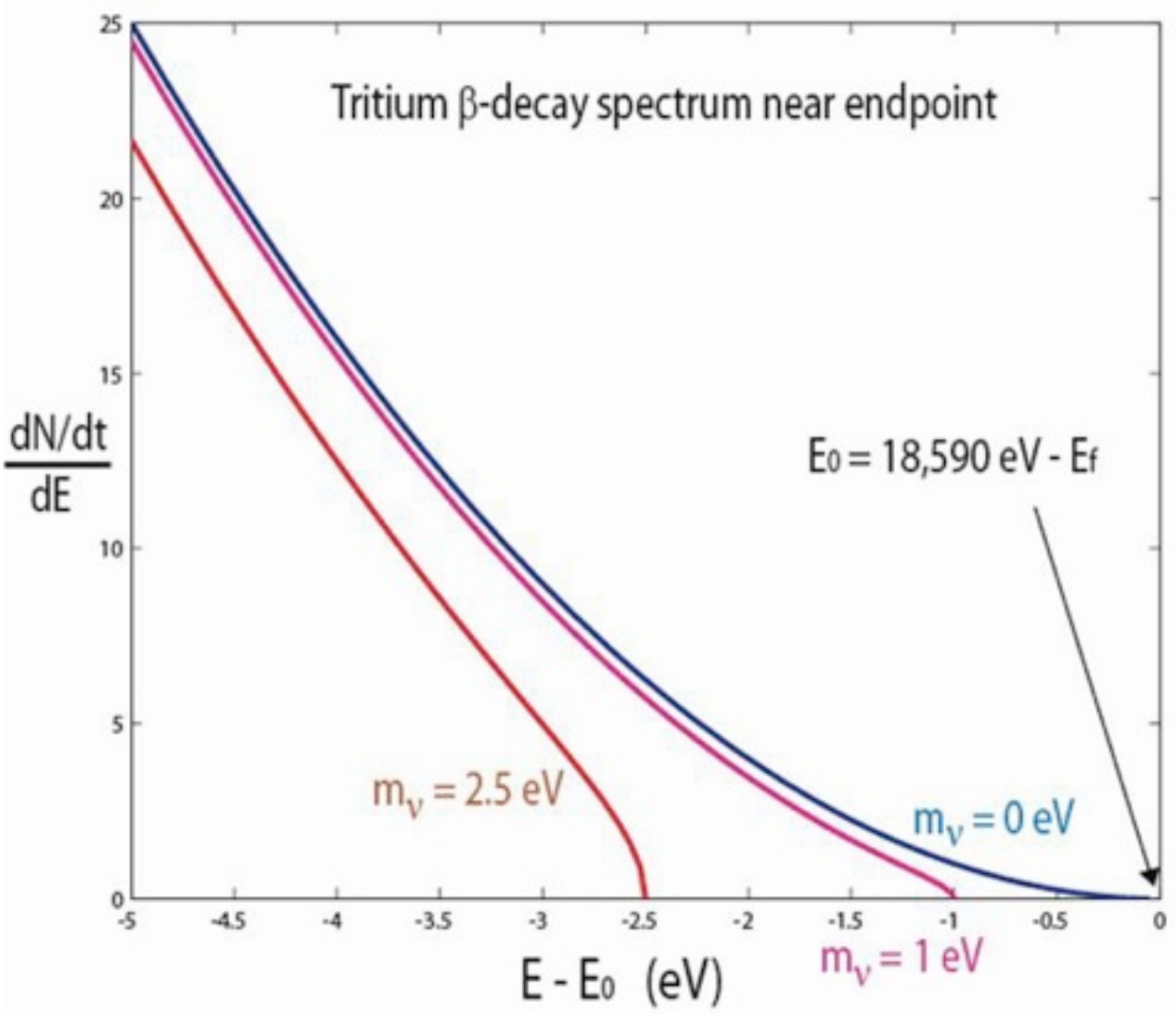
$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

small



Neutrino oscillation experiments measure the Δm's, but not the absolute masses

Neutrino mass from tritium beta decay



$m(\nu_e) < 2.2$ eV from Mainz experiment (1998)

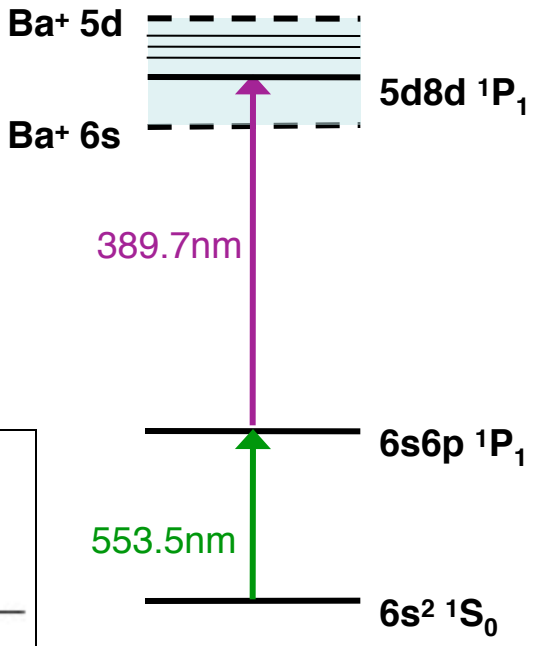
KATRIN beta spectrometer moving through Leopoldshafen, Germany

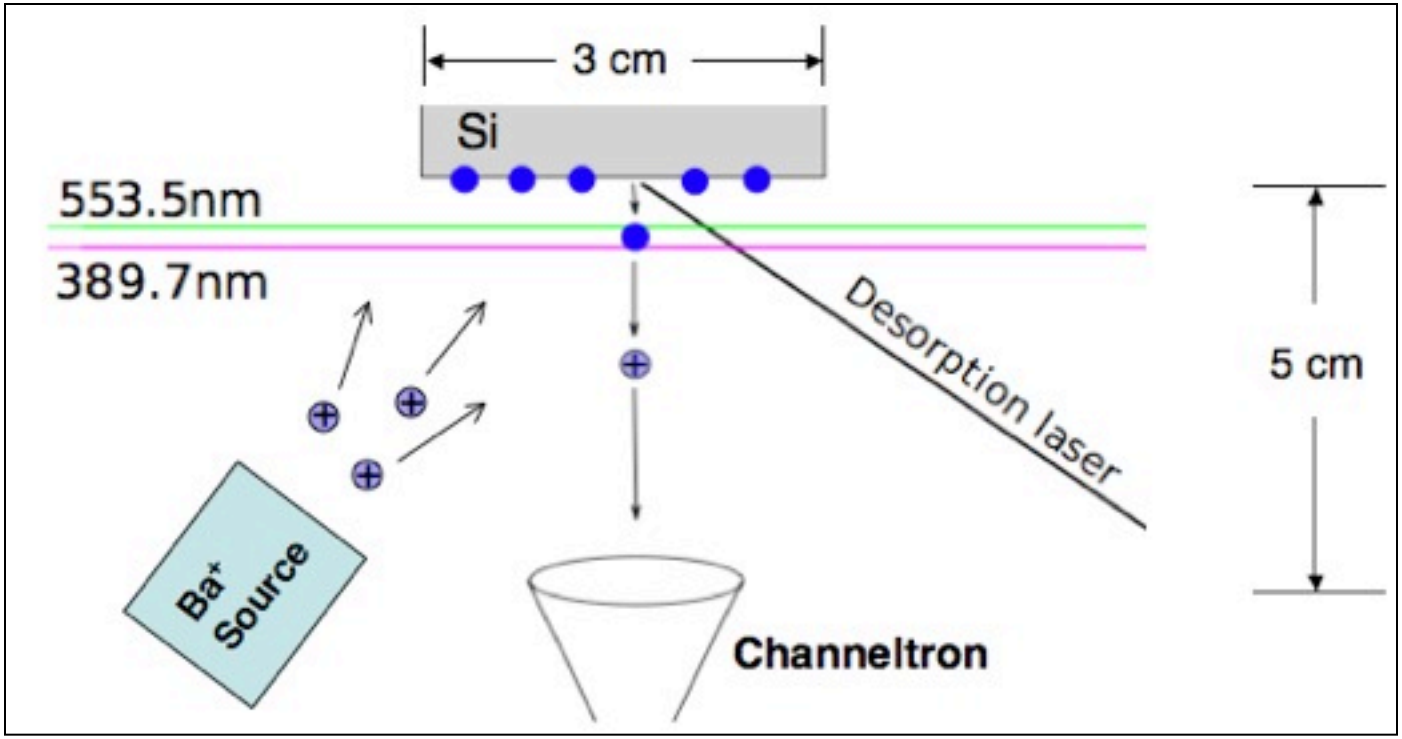
First data in 2012. Expected sensitivity: $m(\nu_e) \sim 0.2$ eV

Ba+ Tagging: RIS

QuickTime™ and a decompressor are needed to see this picture.

- **Resonant Ionization Spectroscopy** uses lasers tuned to atomic resonances to first *excite* and then *ionize* specific atoms.
- We use pulsed dye lasers at 553.5 nm and 389.7 nm.
- Autoionization: The 5d8d $^1P_1$ state decays to a lower energy ionized state, allowing use of the high cross section of the resonance to achieve ionization.





Ba+ Tagging: RIS

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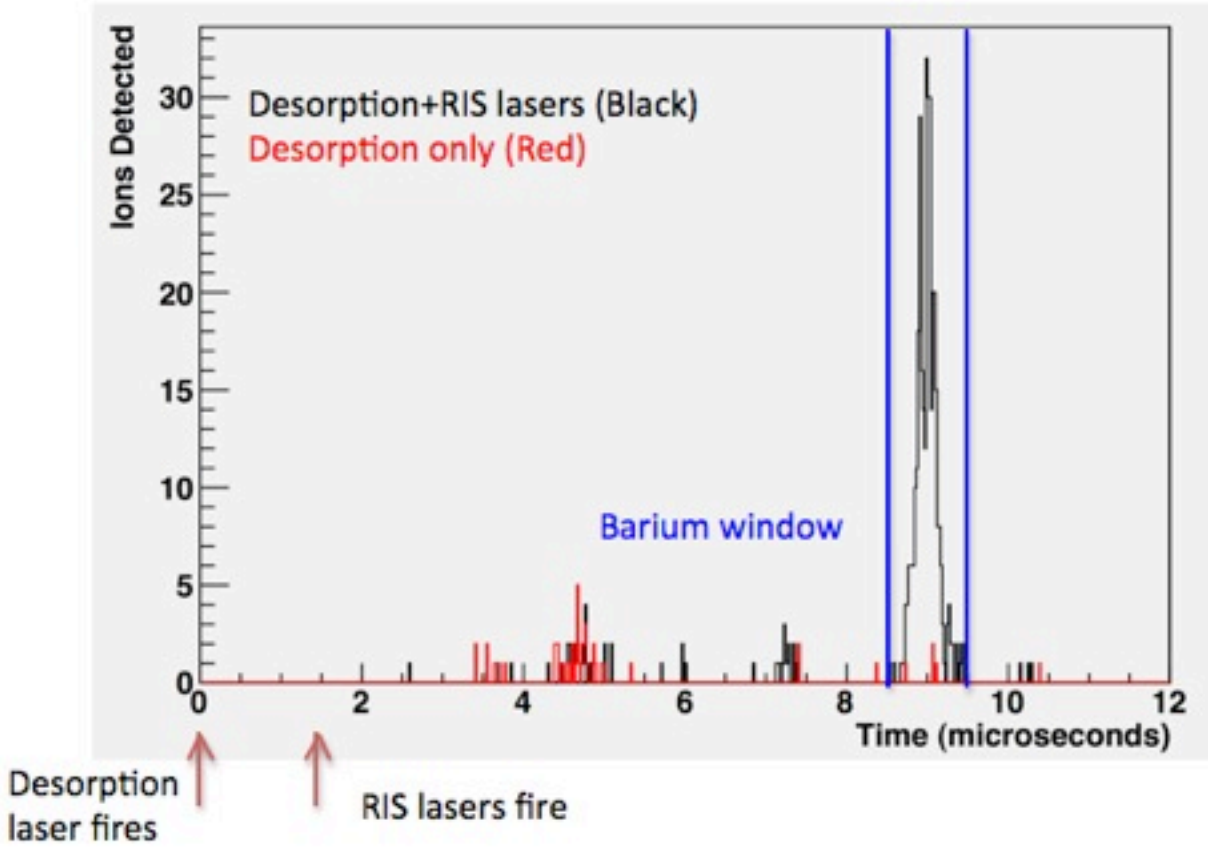
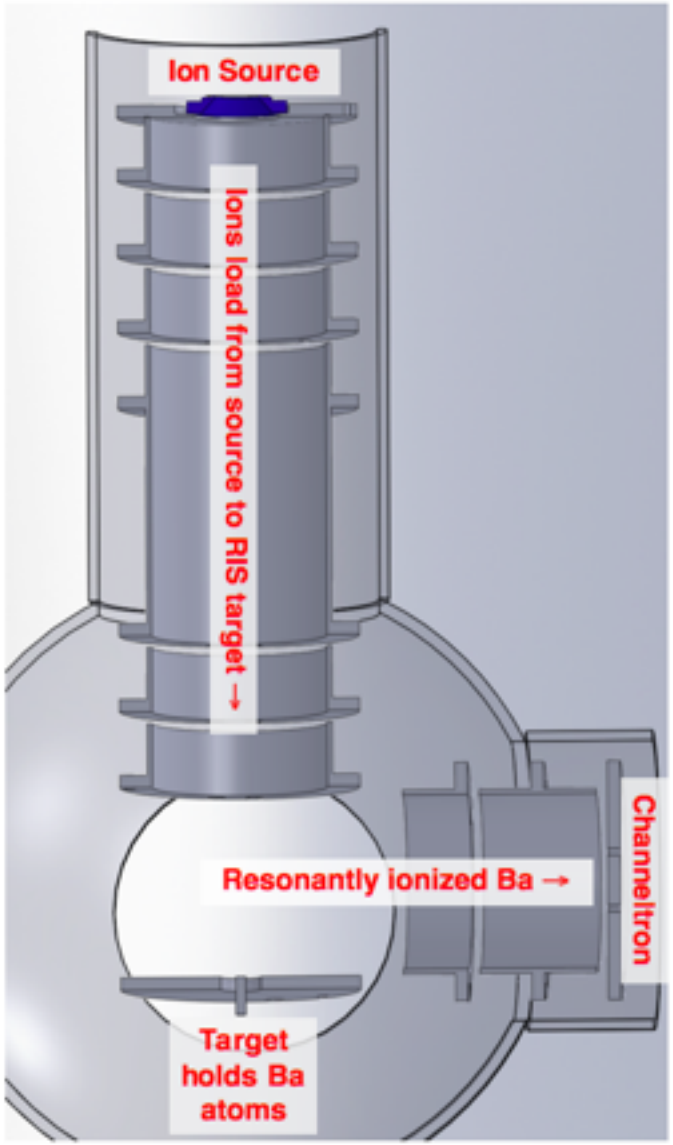
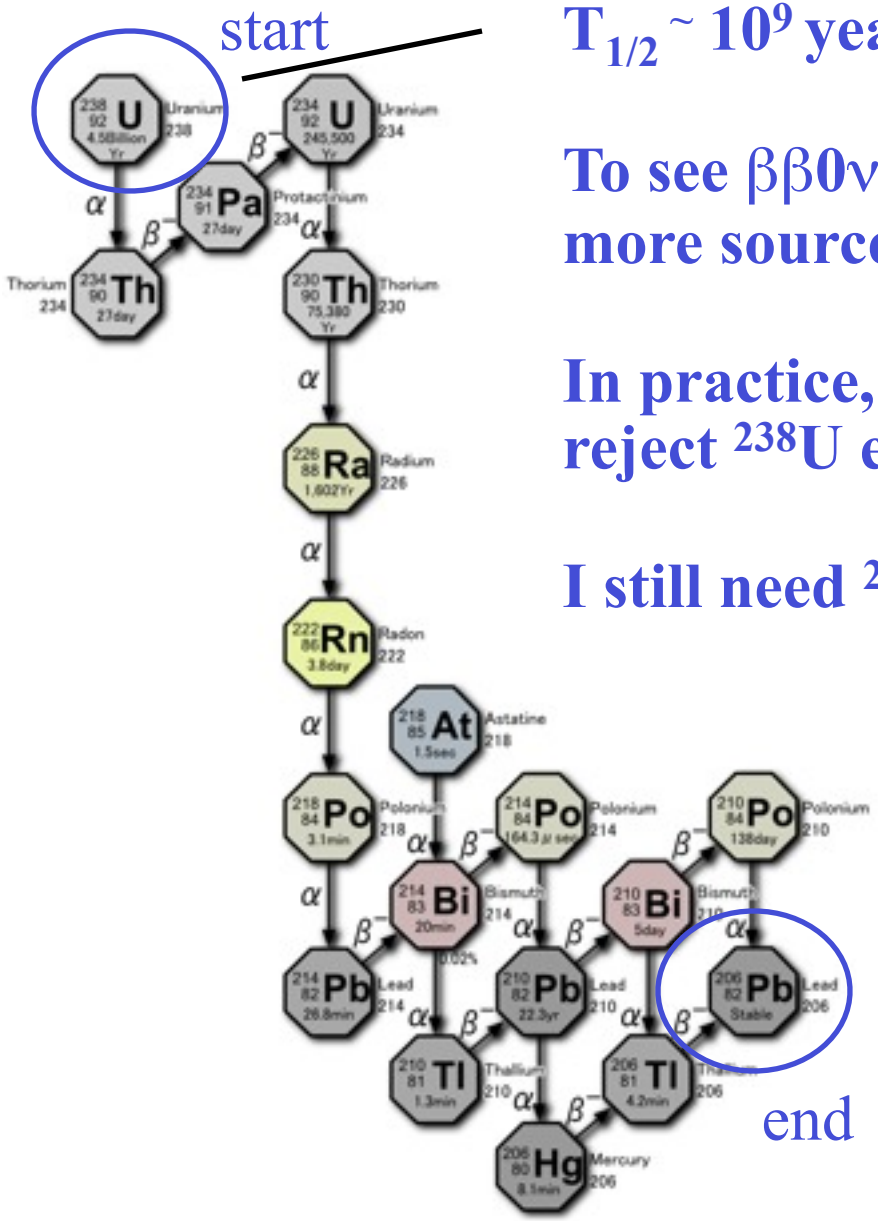




Efficiency of ~10^{-3} in "bulk mode" setup. New "single ion mode" setup about to start taking data.

Uranium-238 decay chain



$T_{1/2} \sim 10^9$ years.... ~10^{16} times faster than $\beta\beta0\nu$

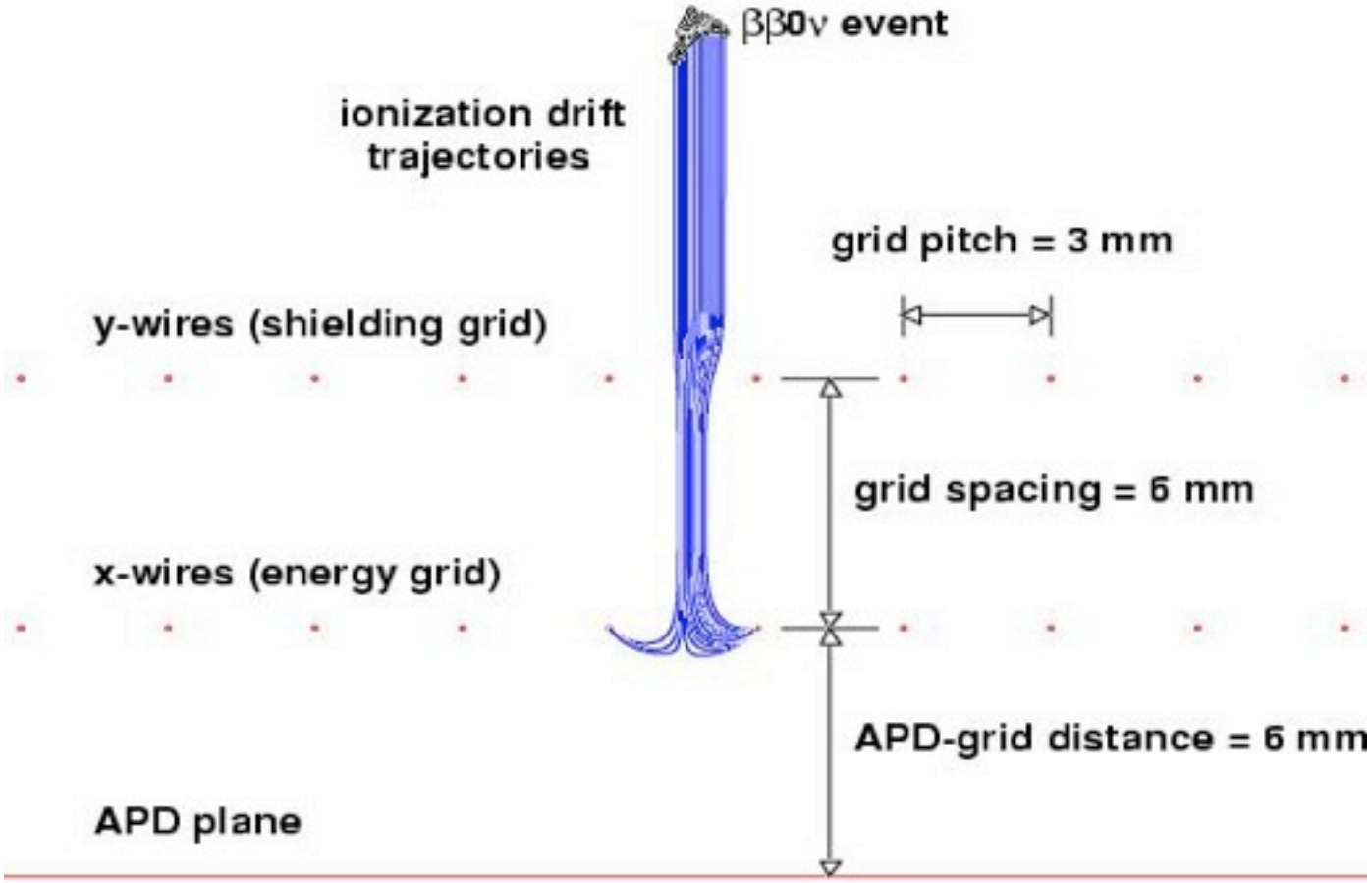
To see $\beta\beta0\nu$, my detector must have 10^{16} times more source isotope than ^{238}U.

In practice, my detector is smart enough to reject ^{238}U events 99.9% of the time.

I still need $^{238}U/(source) \sim 10^{-13}$.

With 100 kg of source,
I'm allowed 10 nanograms ^{238}U.

Crossed wire planes and APD array measure event energy and position



y-position given by induction signal on shielding grid.
x-position and energy given by charge collection grid.
APD array observes prompt scintillation to measure drift time.