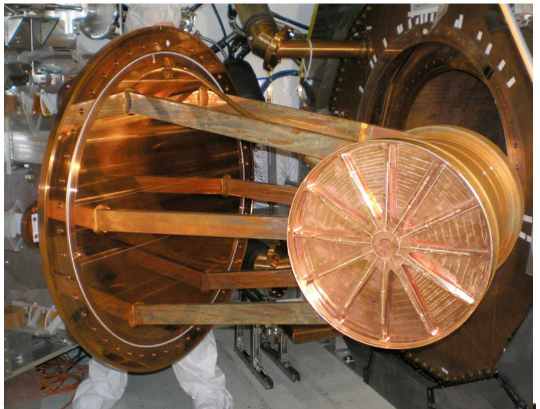
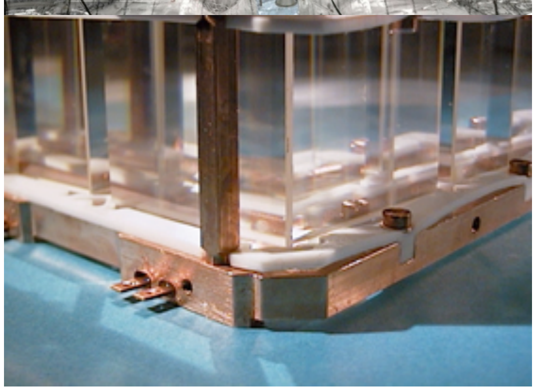
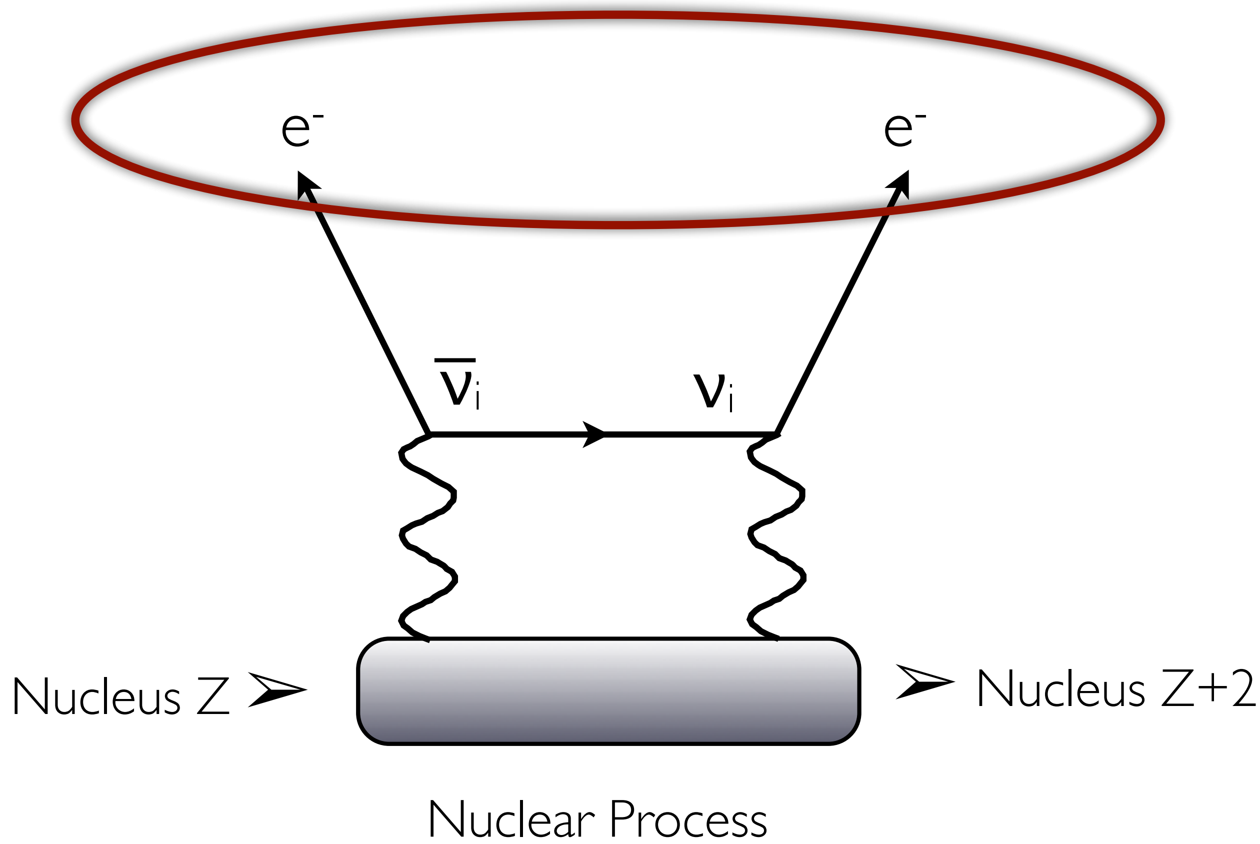


Double-Beta Decay: Part 2
Backgrounds and More Experiments

Lindley Winslow
Massachusetts Institute of Technology



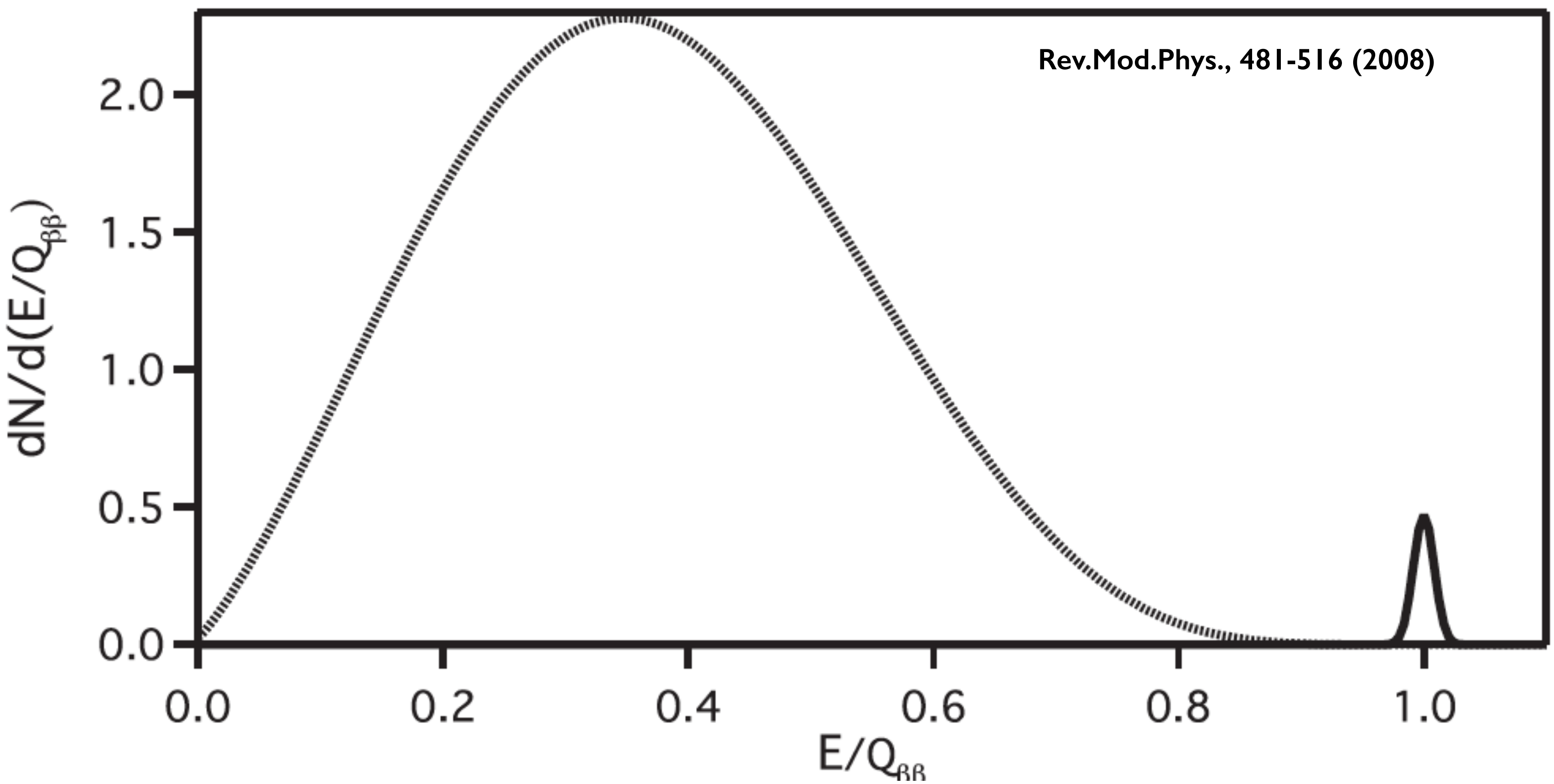
Lepton Number Violation!

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)

Neutrinoless Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the “neutrino-full” double beta decay.



From Last Time:
How do you relate the cosmological measurements?

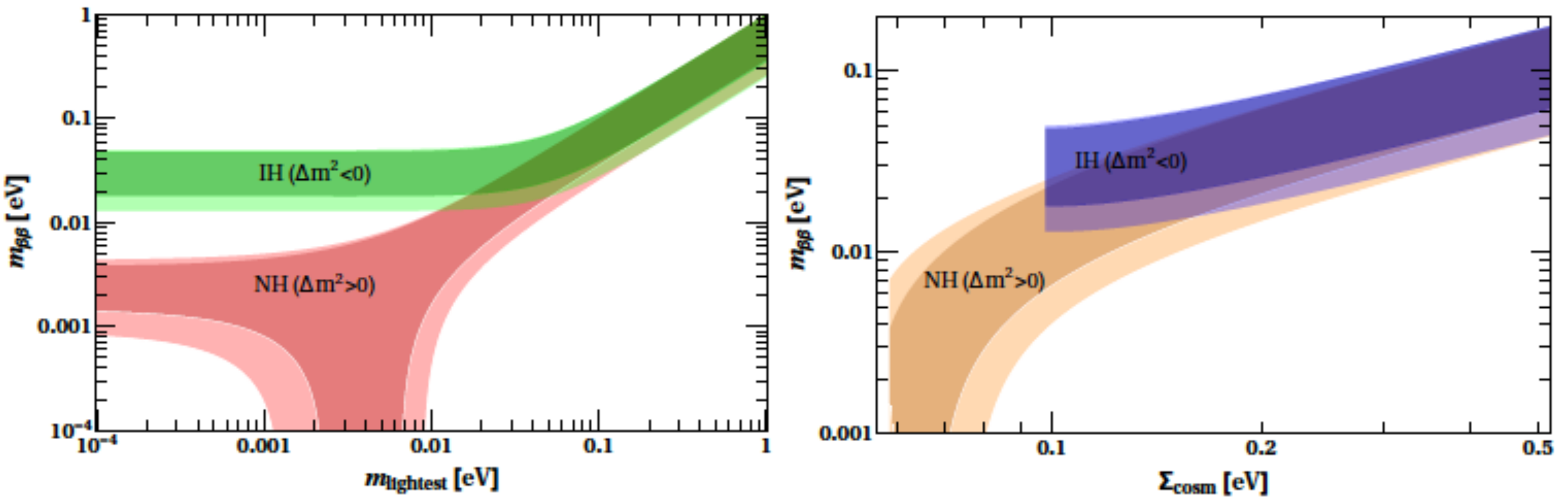
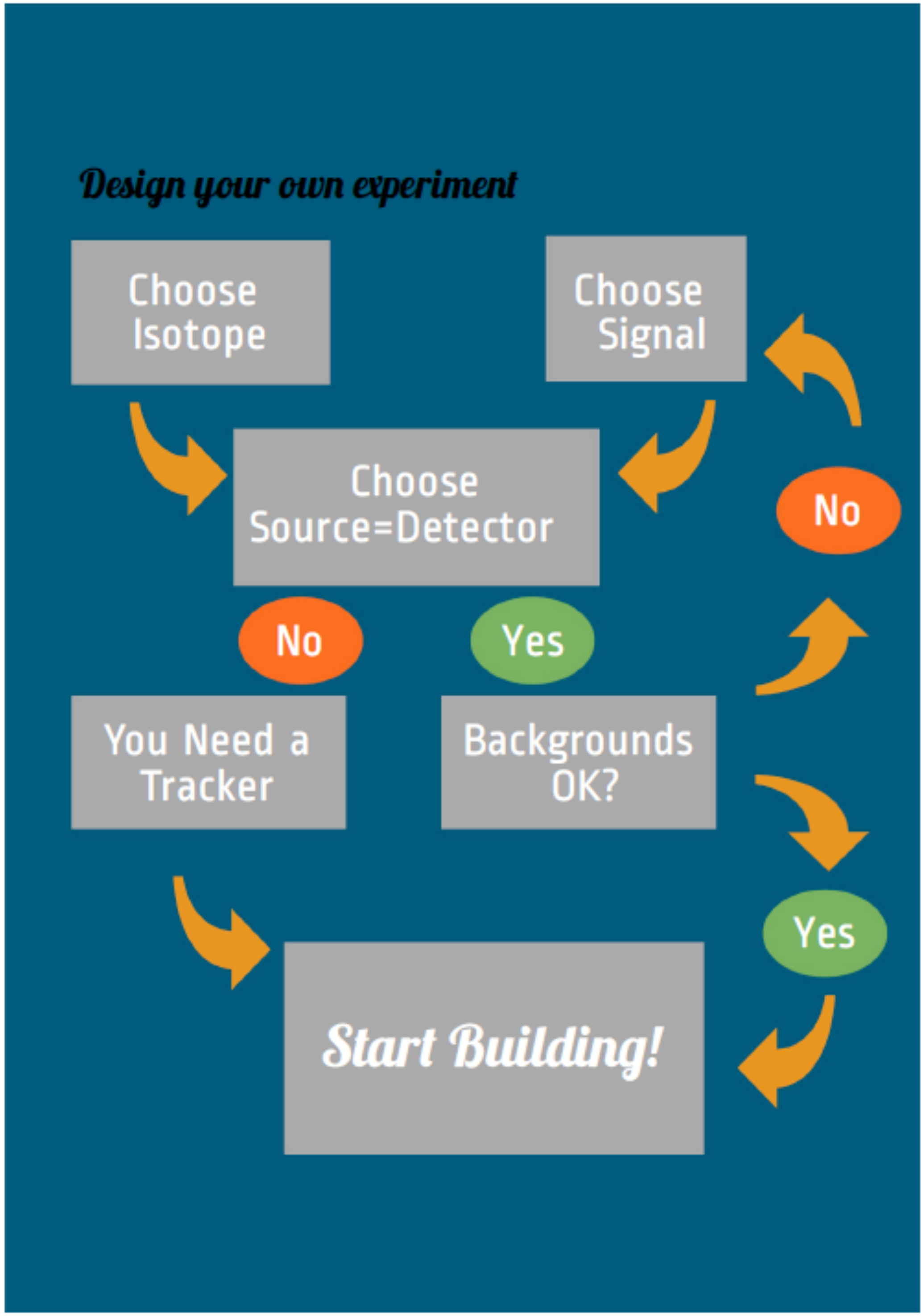


FIG. 6. Updated predictions on $m_{\beta\beta}$ from oscillations as a function of the lightest neutrino mass (left) and of the cosmological mass (right) in the two cases of $\mathcal{NH}$ and $\mathcal{IH}$. The shaded areas correspond to the 3σ regions due to error propagation of the uncertainties on the oscillation parameters. Figure from Ref. [91].

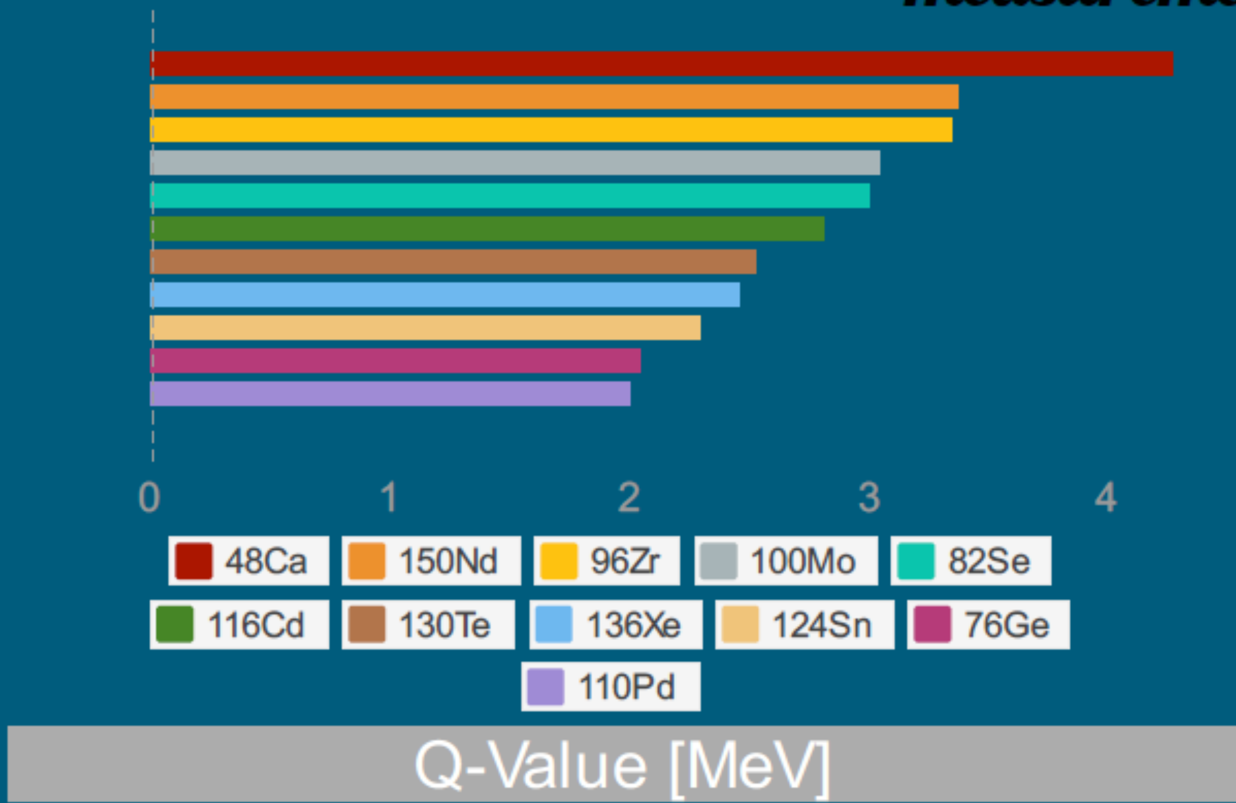
Let's make a detector!

Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.527 MeV	34.5%
^{136}Xe	2.457 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%


Design your own experiment
Choose Isotope
Choose Signal
Choose Source=Detector
No
Yes
No
You Need a Tracker
Backgrounds OK?
Yes
Start Building!

Choose an Isotope

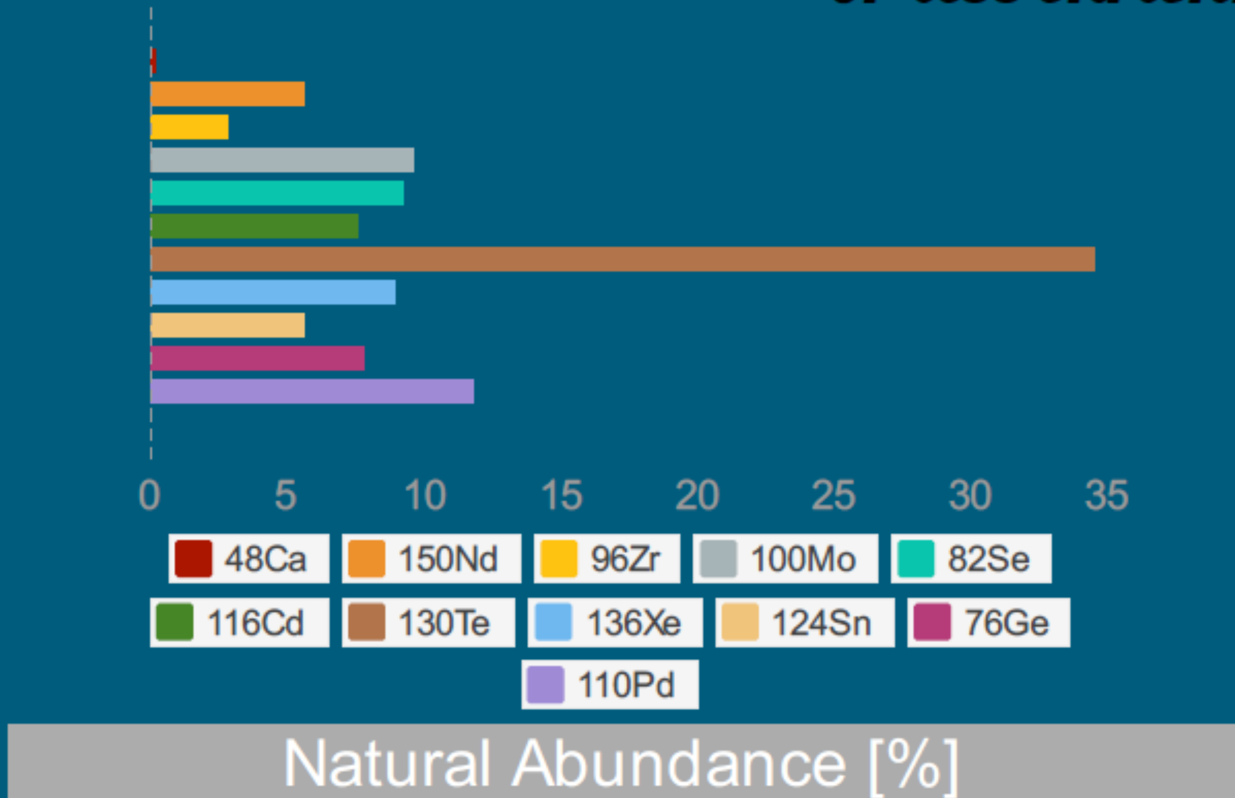
High Q-Value means a higher rate and an easier measurement!



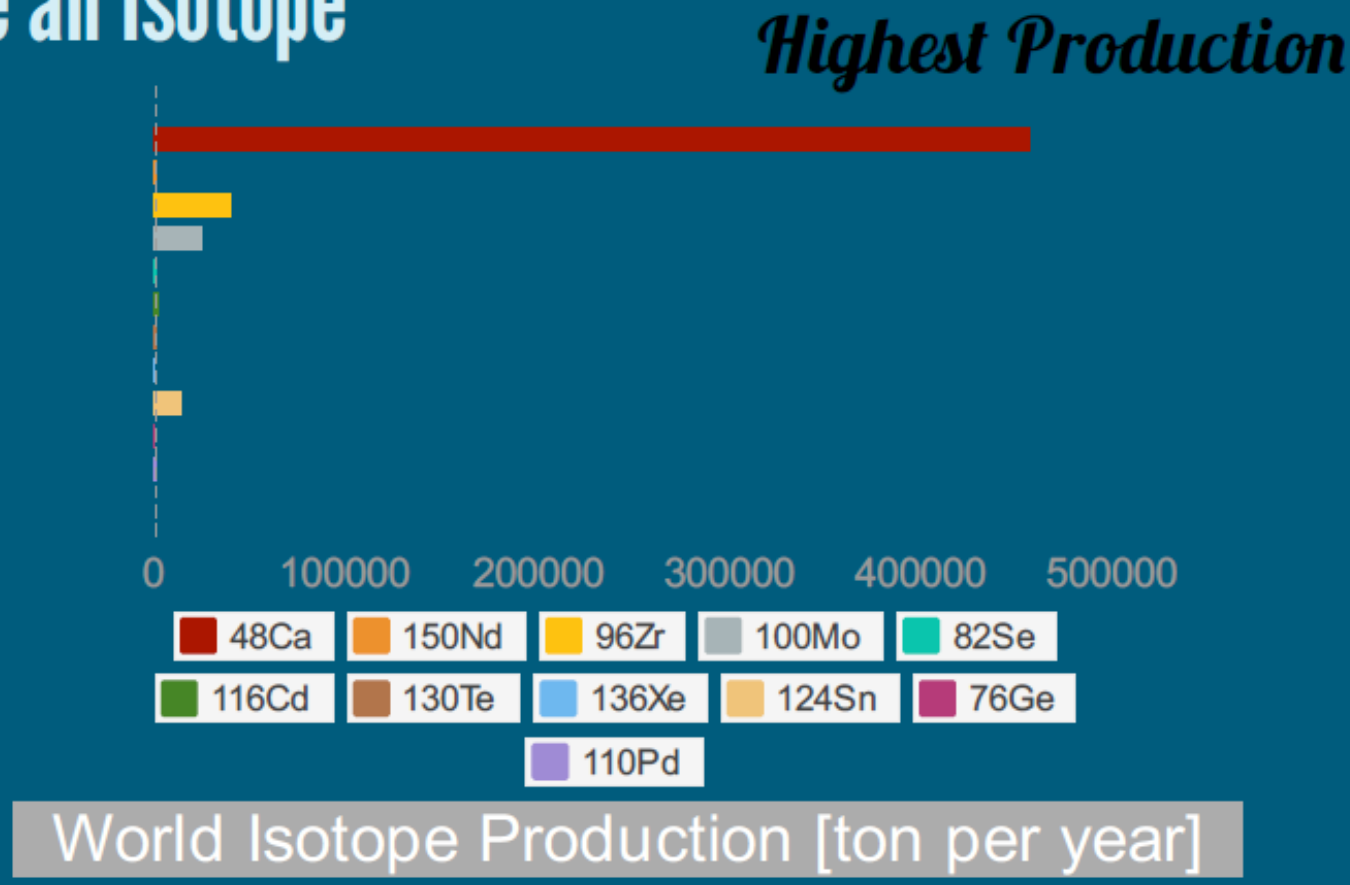
PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

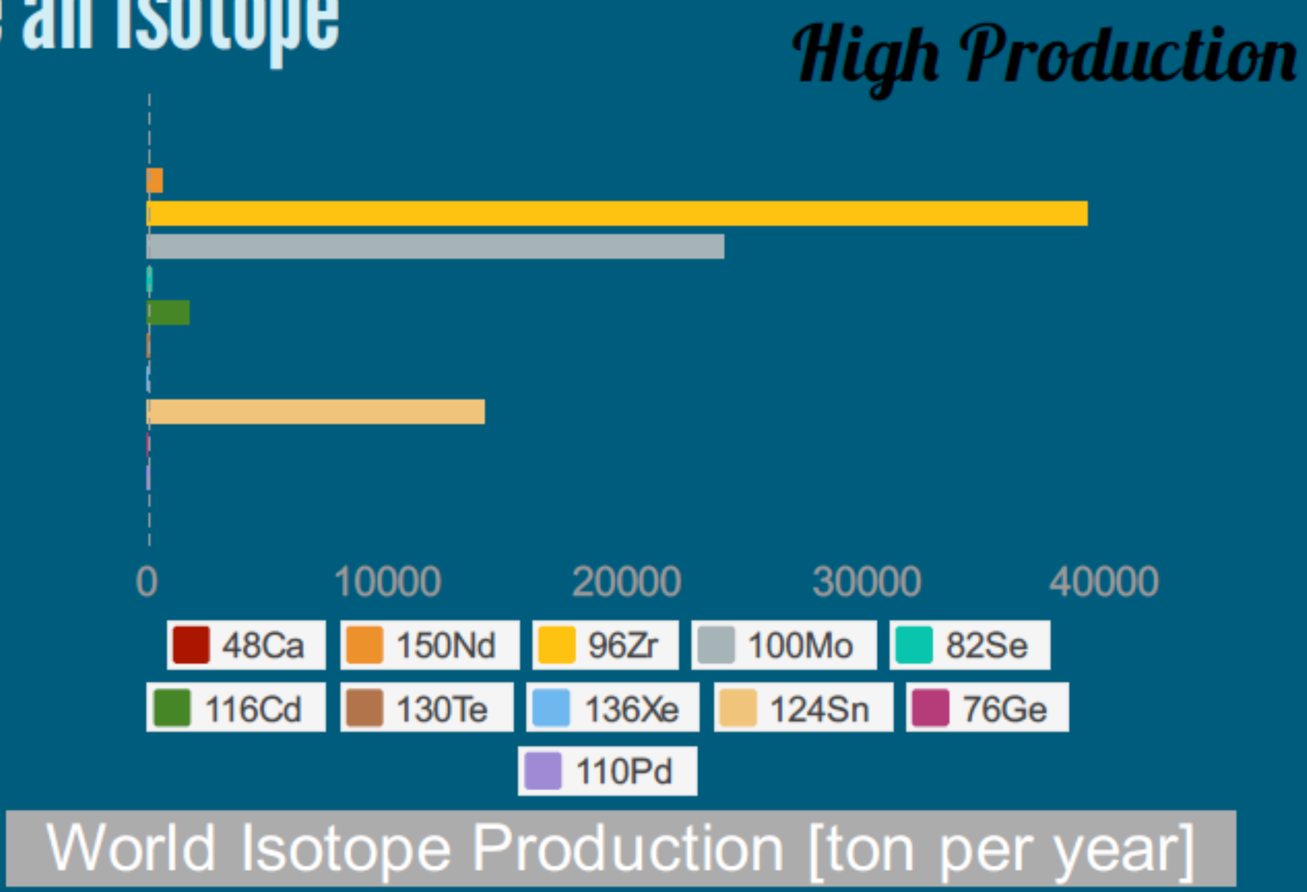
High natural abundance means a smaller detector or less enrichment!



Choose an Isotope



Choose an Isotope



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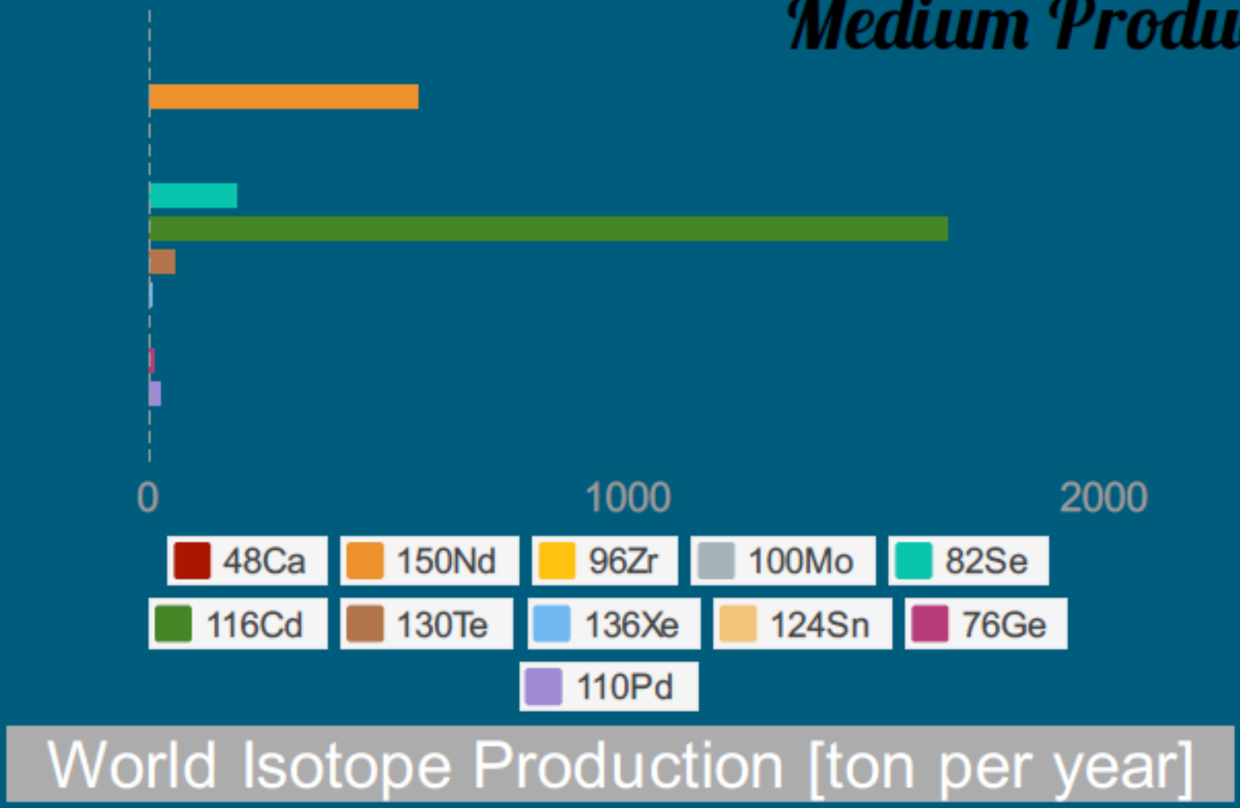
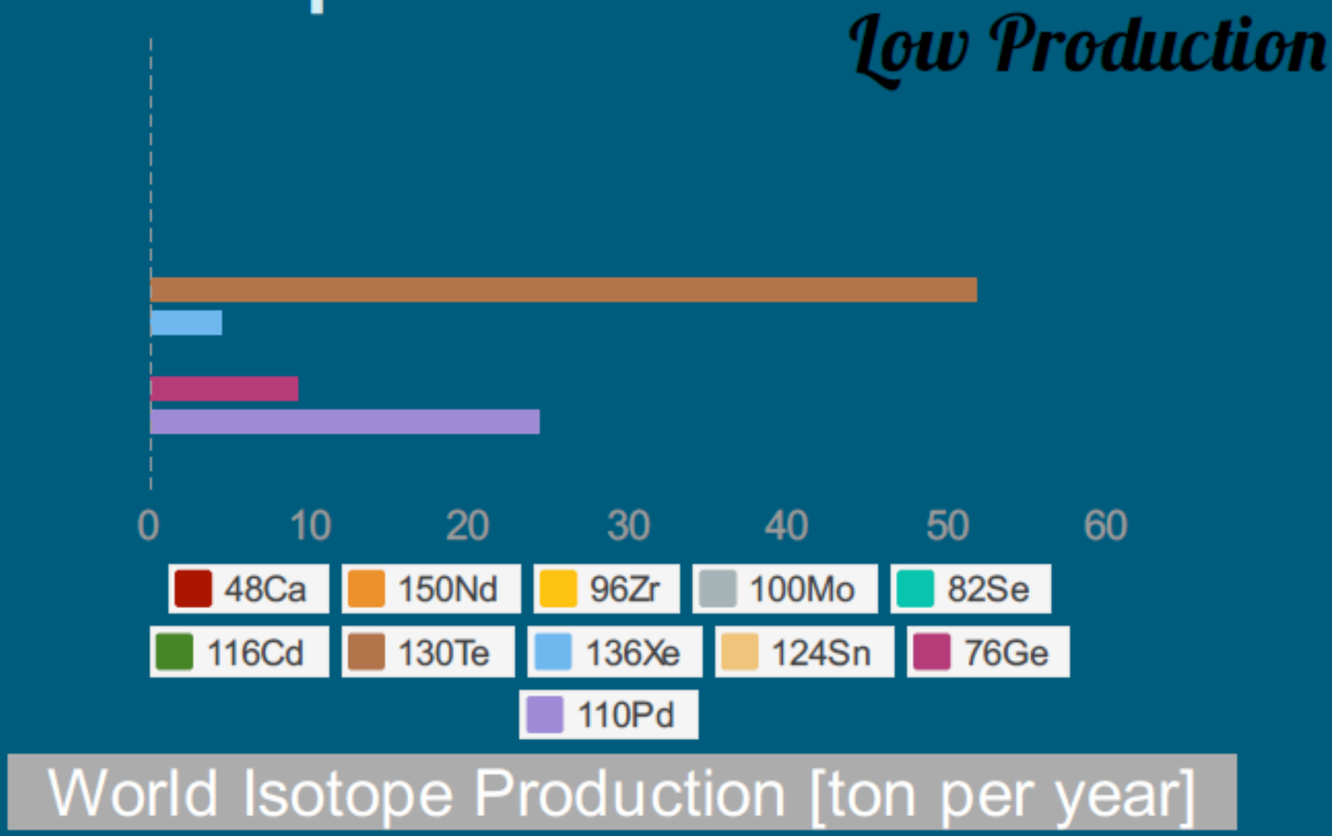
Choose an Isotope

Medium Production

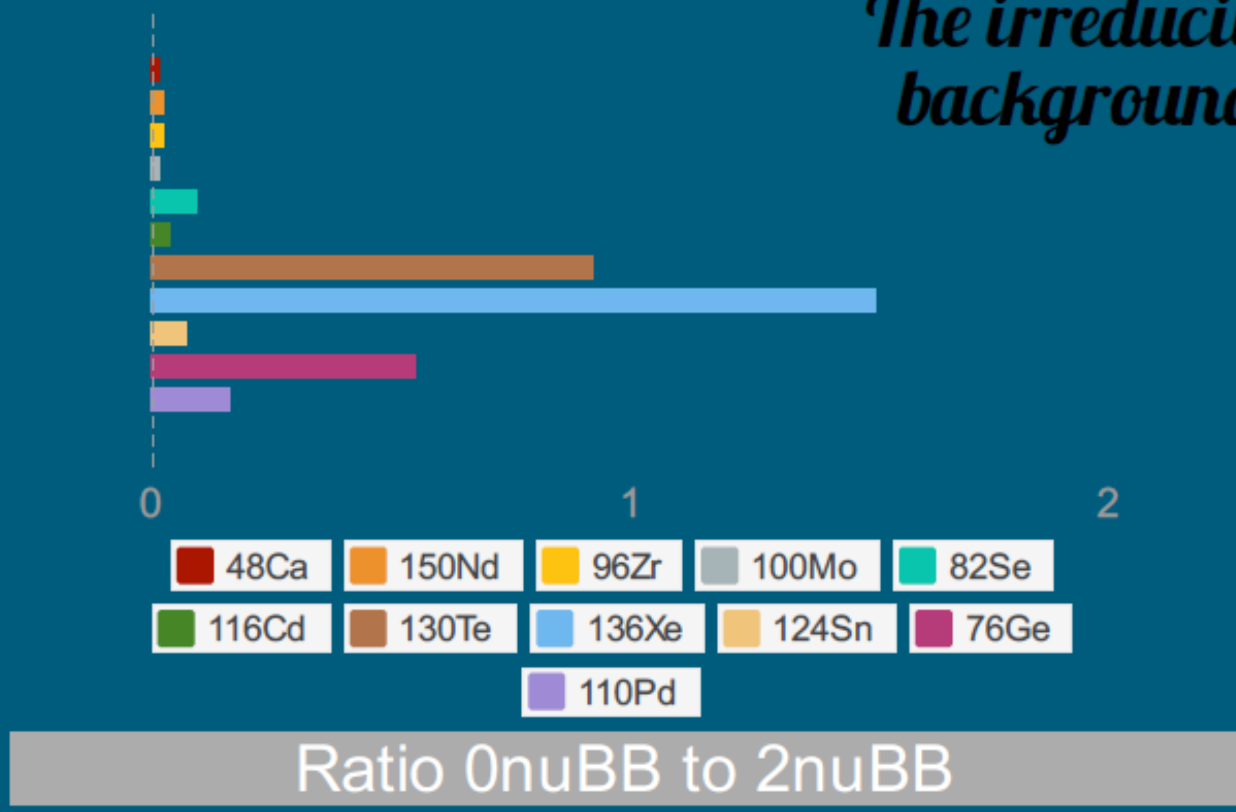


Choose an Isotope

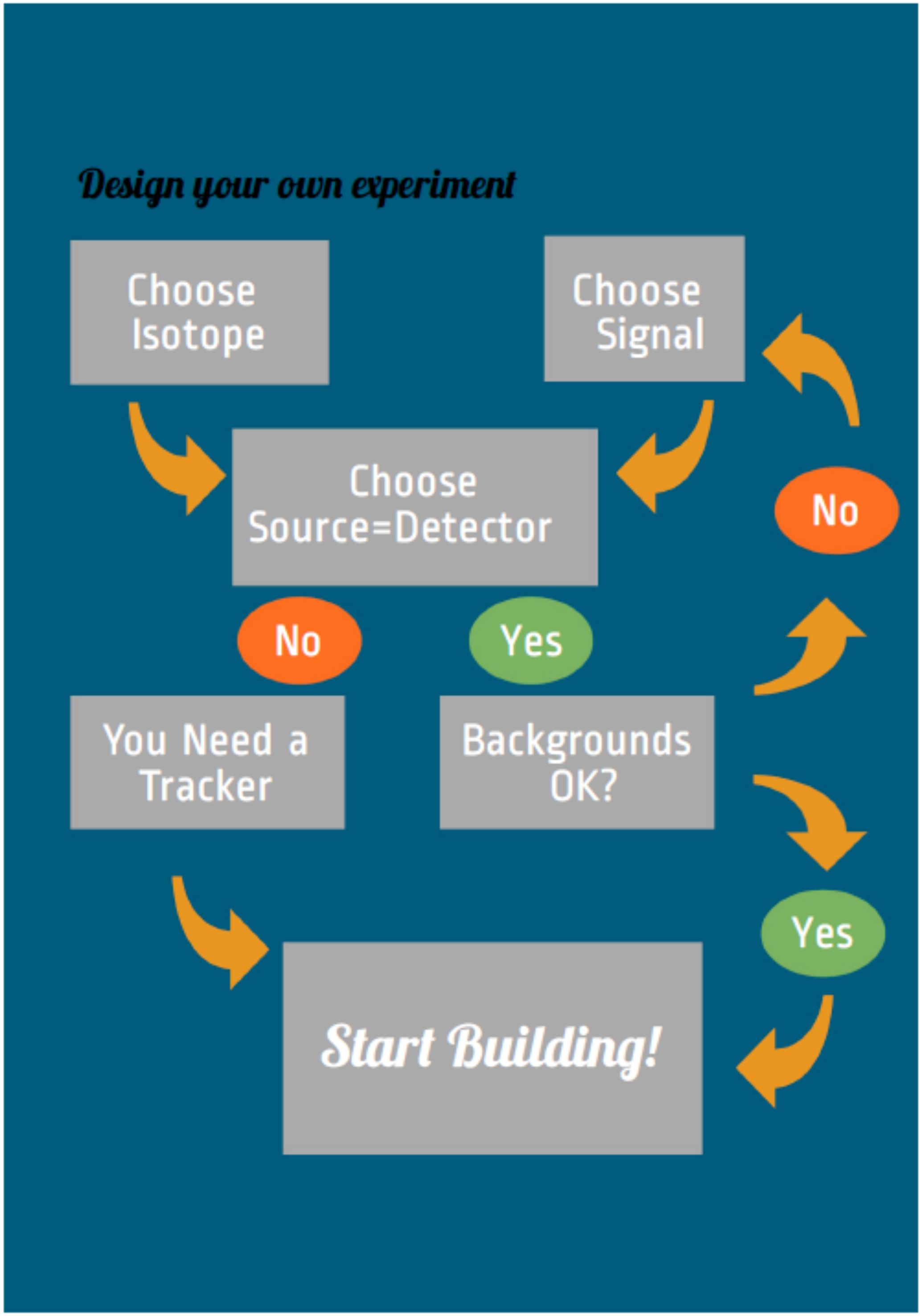


Choose an Isotope

The irreducible background!

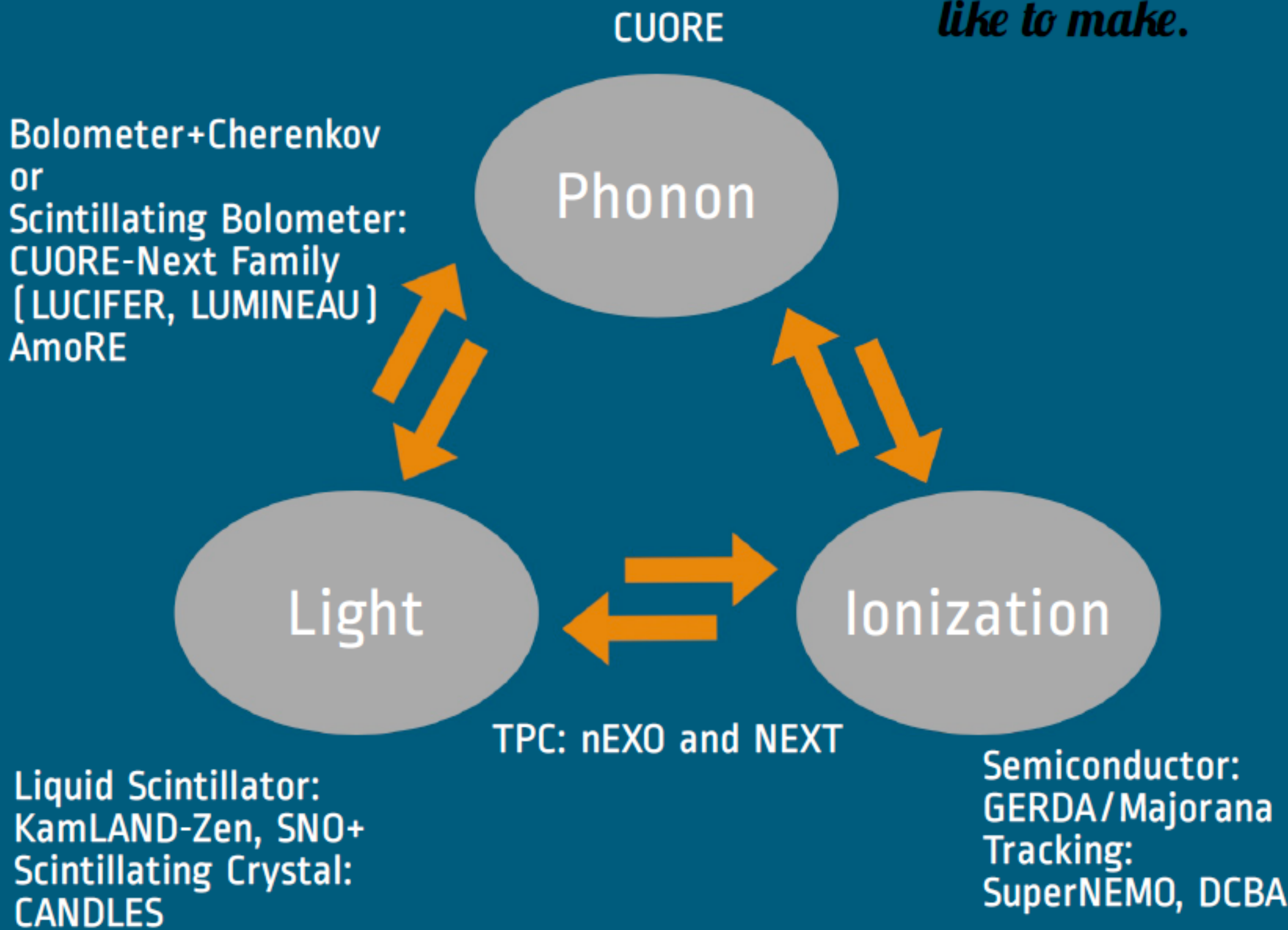


PHYSICAL REVIEW D 87, 071301(R) (2013)

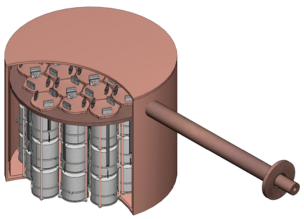

Design your own experiment
Choose Isotope
Choose Signal
Choose Source=Detector
No
No
Yes
You Need a Tracker
Backgrounds OK?
Yes
Start Building!

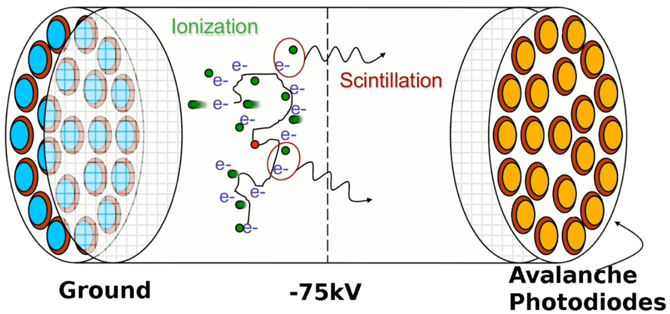
Choose a Signal:

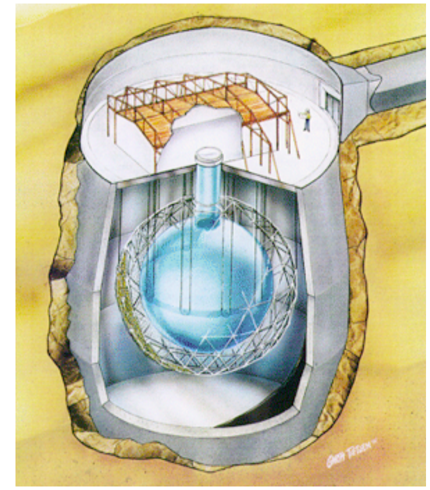
A diagram that the direct dark matter experiments like to make.

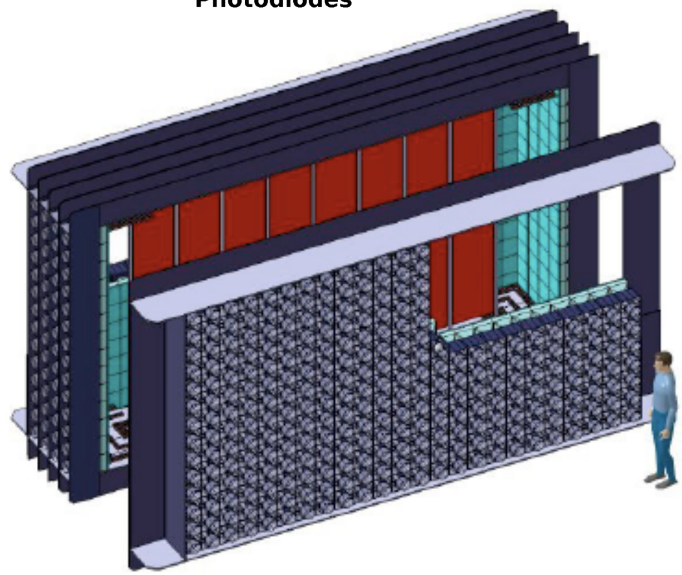


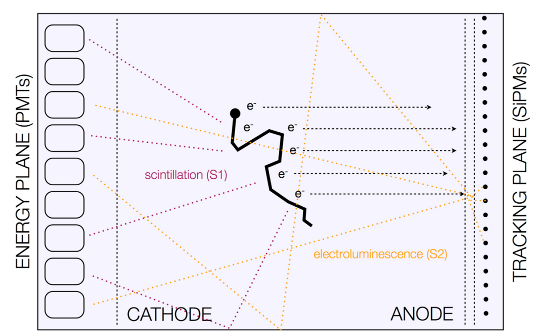
A lot of detector ideas:

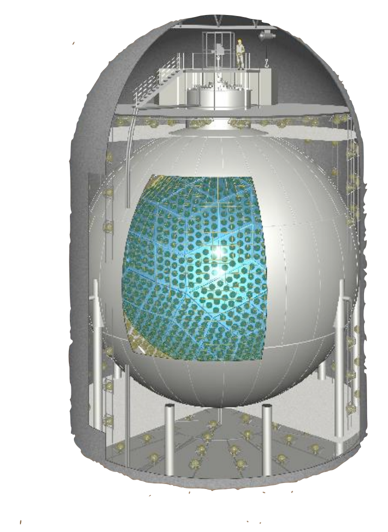


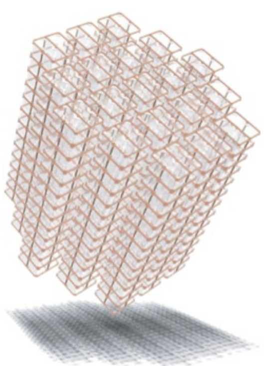




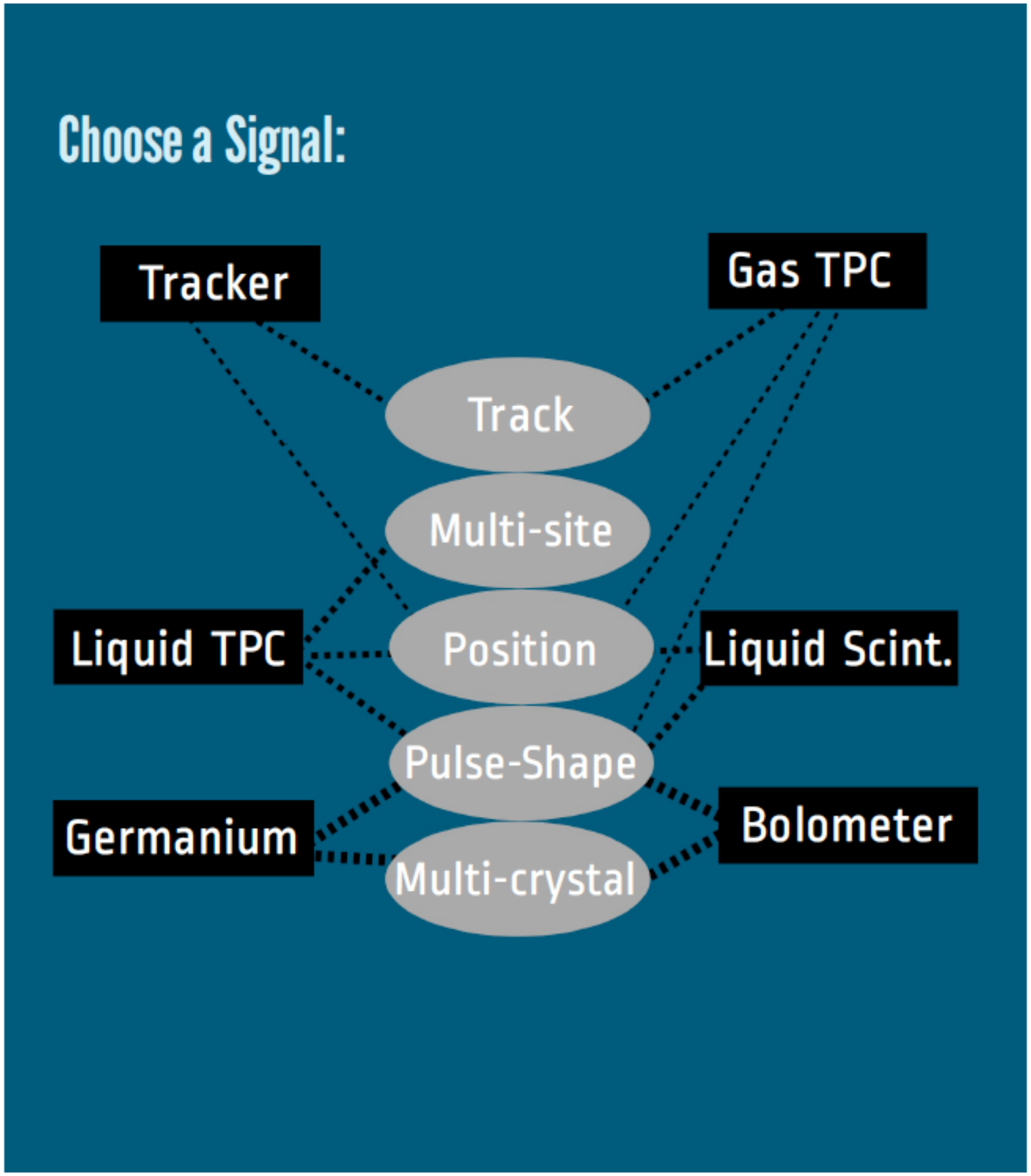




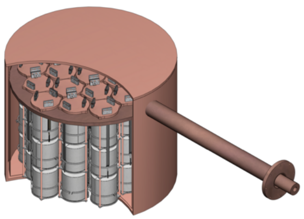


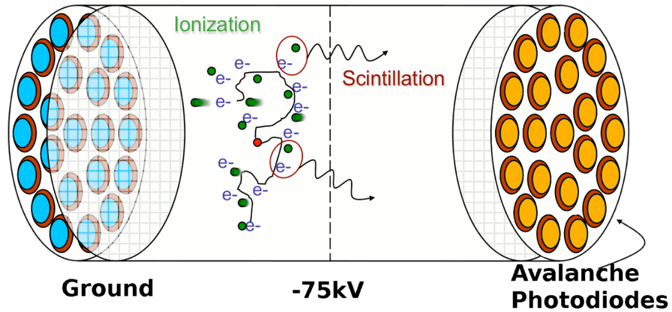


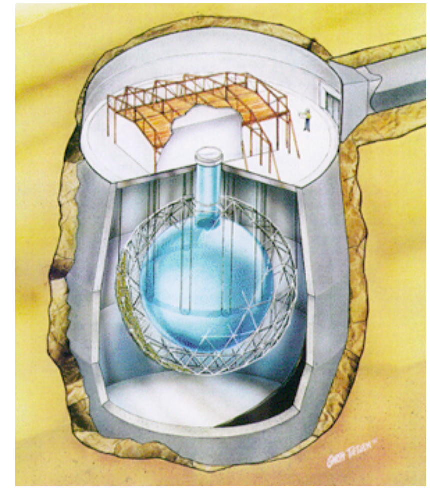
Detector Data:

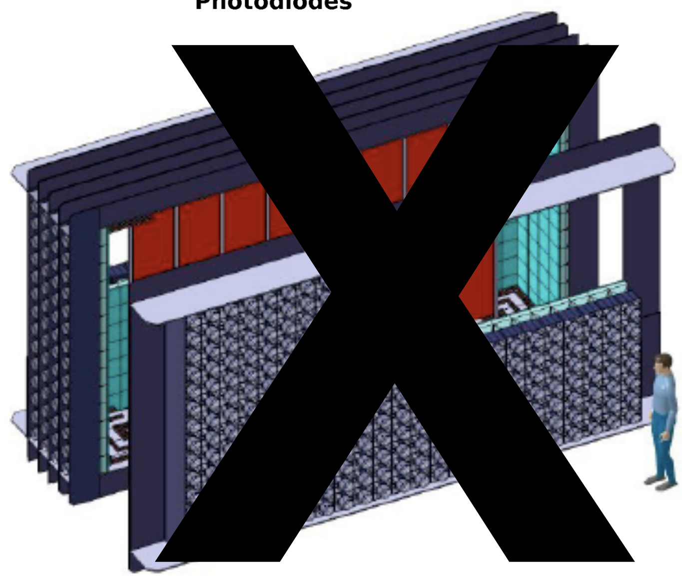


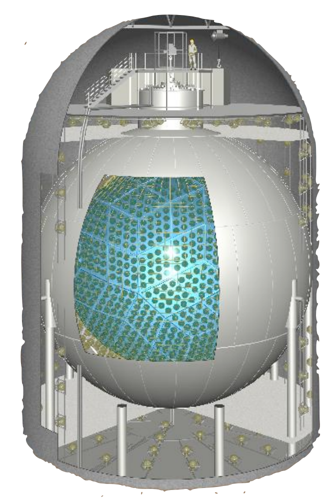
source = detector

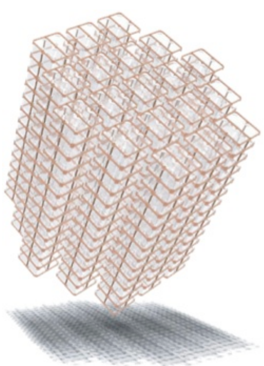


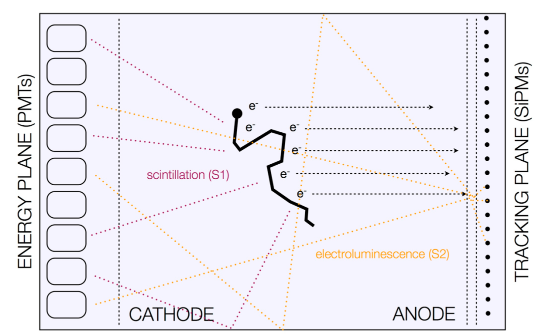




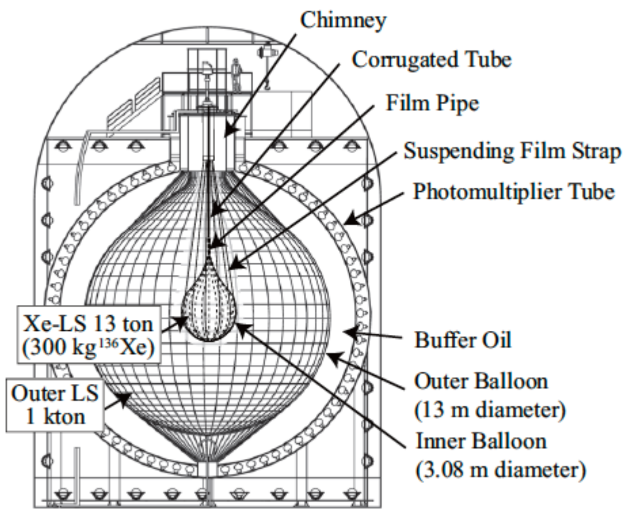






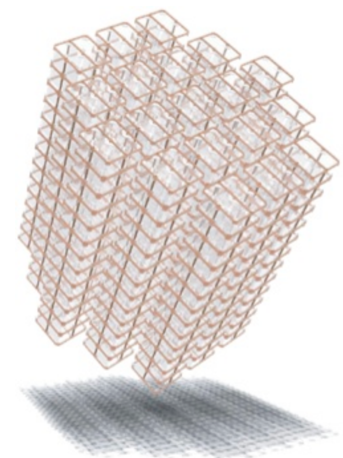


Good at Size

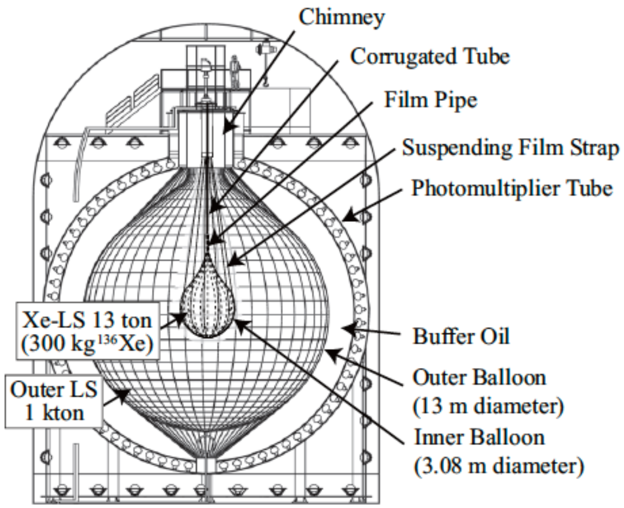


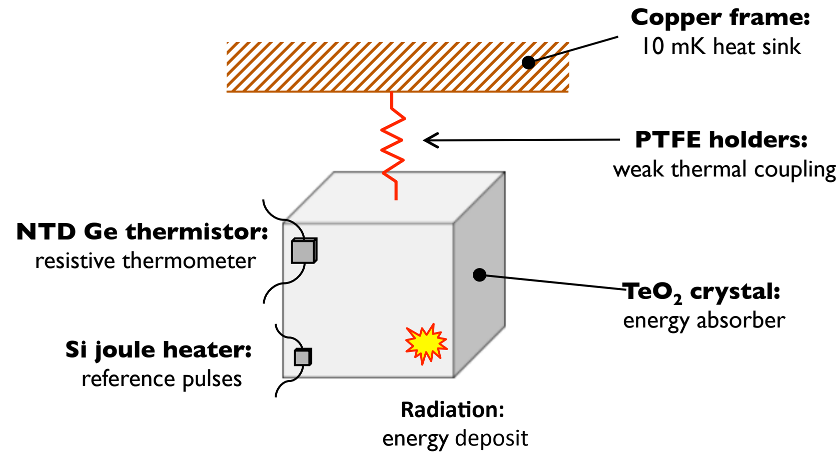
Bad Energy Resolution

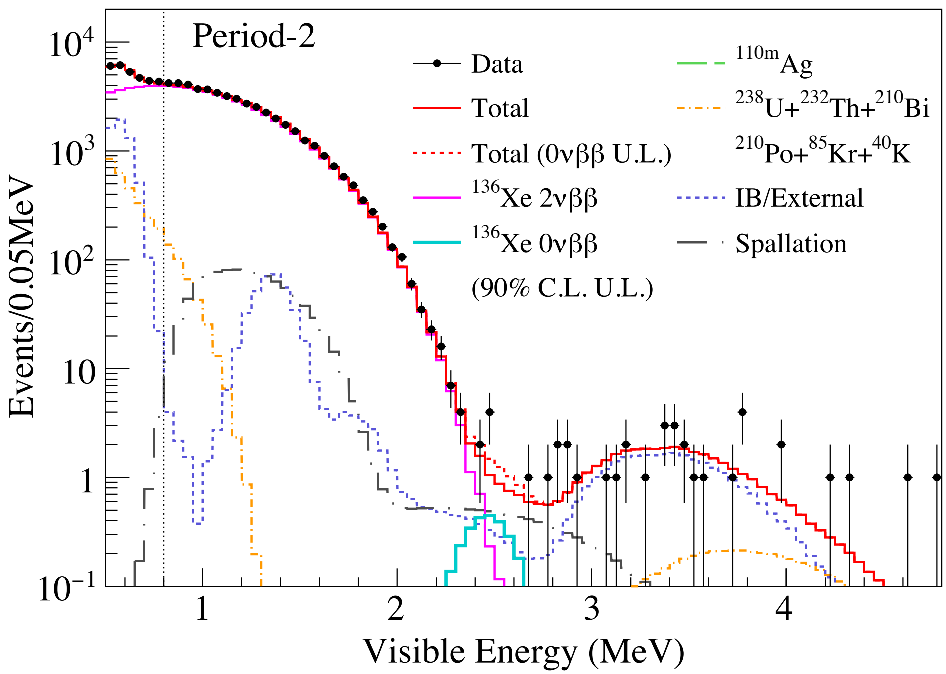
Good Energy Resolution

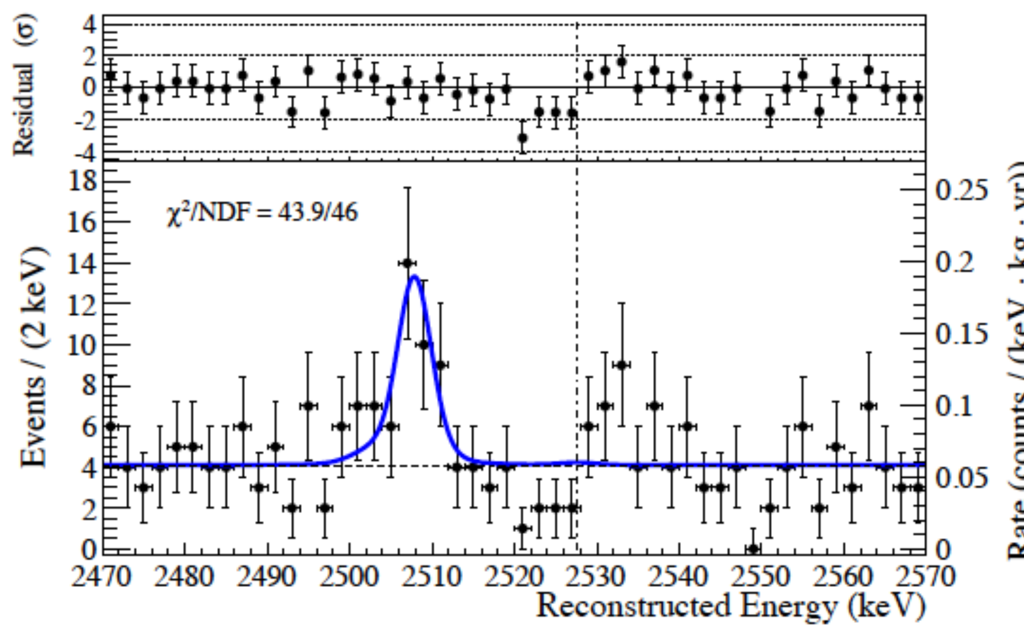


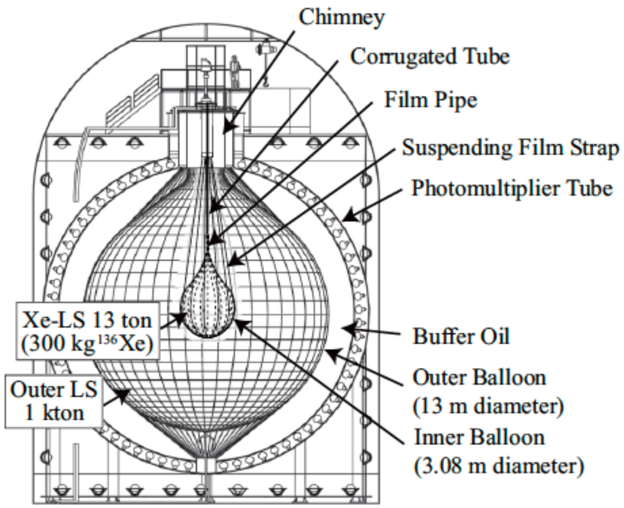
More Difficult to make big.

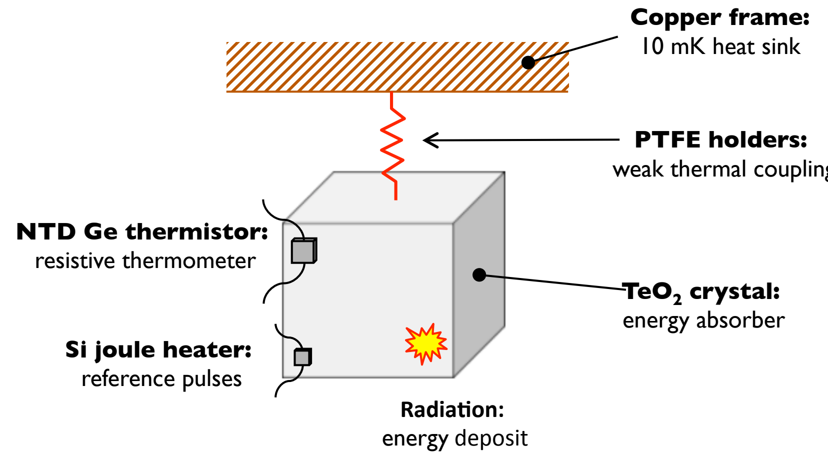

Chimney
Corrugated Tube
Film Pipe
Suspending Film Strap
Photomultiplier Tube
Xe-LS 13 ton
(300 kg 136Xe)
Outer LS
1 kton
Buffer Oil
Outer Balloon
(13 m diameter)
Inner Balloon
(3.08 m diameter)

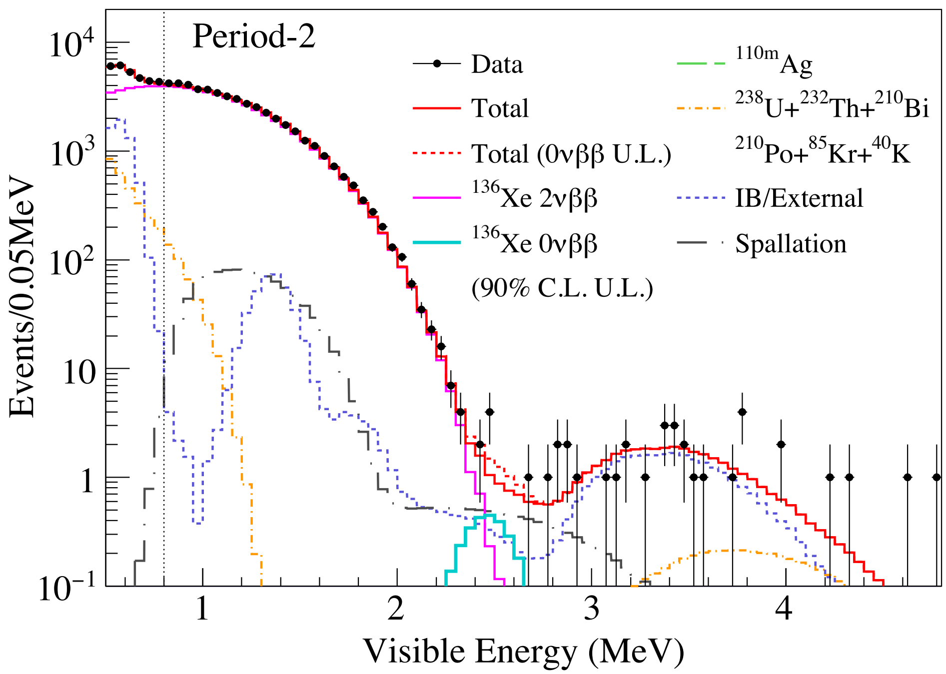

Copper frame:
10 mK heat sink
PTFE holders:
weak thermal coupling
NTD Ge thermistor:
resistive thermometer
TeO2 crystal:
energy absorber
Si joule heater:
reference pulses
Radiation:
energy deposit

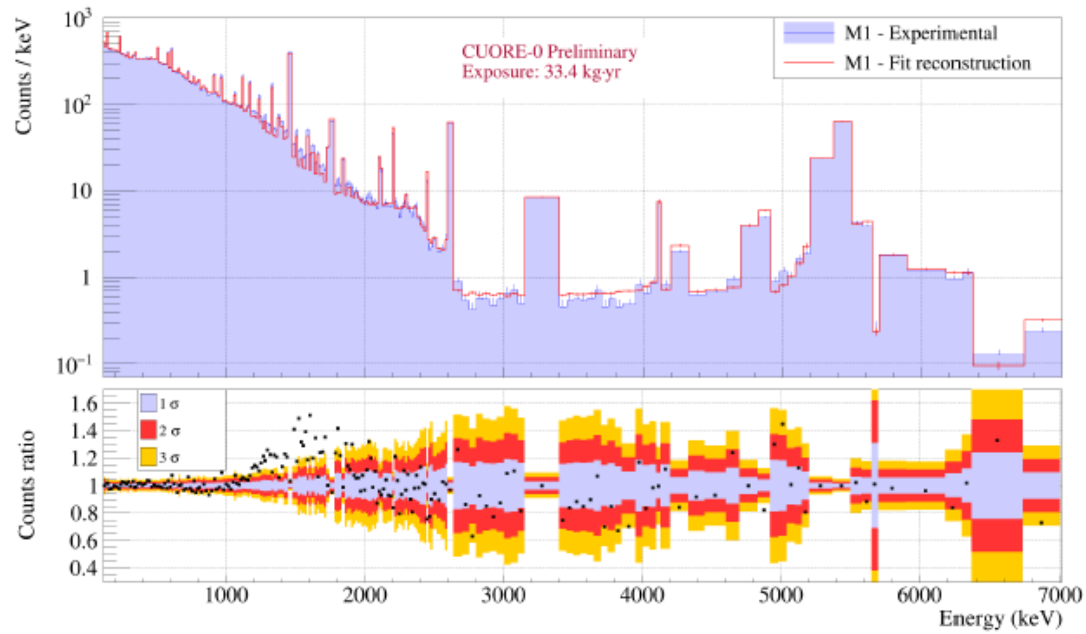

Period-2
Data
Total
Total (0νββ U.L.)
136Xe 2νββ
136Xe 0νββ
(90% C.L. U.L.)
110mAg
238U+232Th+210Bi
210Po+85Kr+40K
IB/External
Spallation
Events/0.05MeV
Visible Energy (MeV)


Residual (σ)
χ²/NDF = 43.9/46
Events / (2 keV)
Reconstructed Energy (keV)







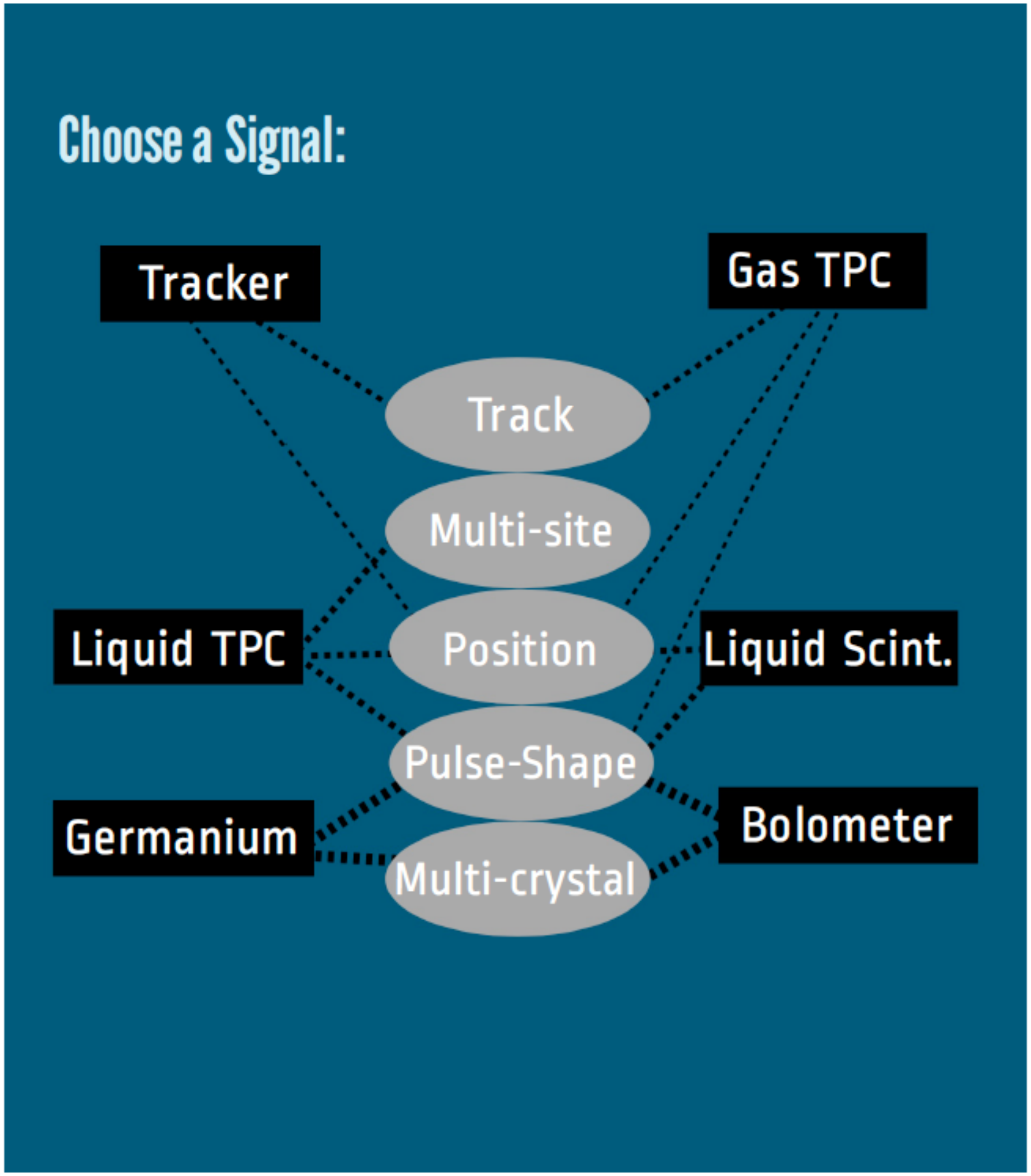


All energy depositions fully contained i.e. no gammas escape.

So Much More detail!
Also, the relative intensity of individual gamma lines tells a lot about the source position.

^{76}Ge - GERDA/Majorana

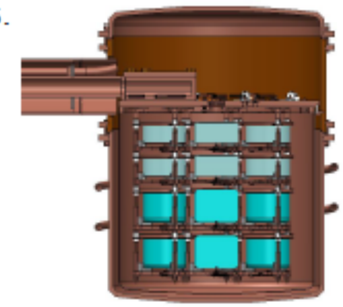
Detector Data:



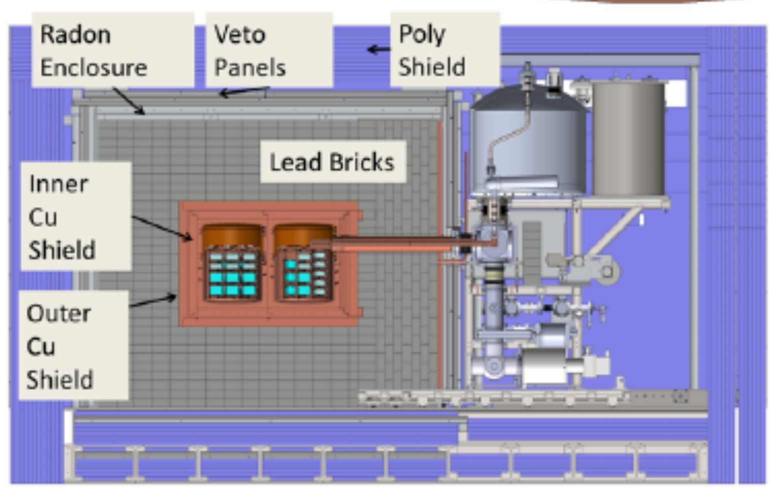
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics with additional contributions from international collaborators.

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 $0\nu\beta\beta$ 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
- 44.8-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 15.1 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



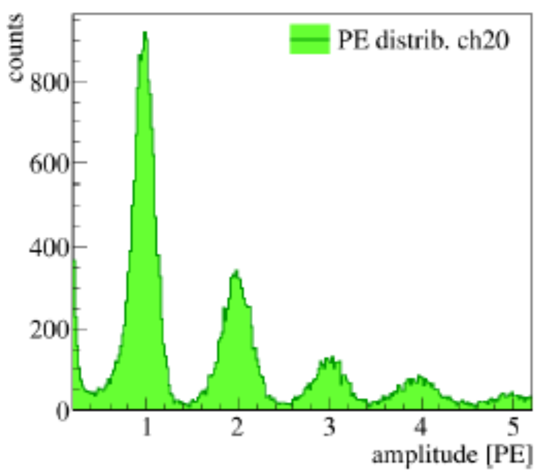
Phase II upgrade: LAr scintillation light veto

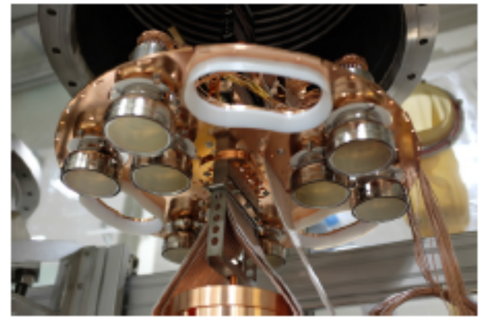
Hybrid veto instrumentation:

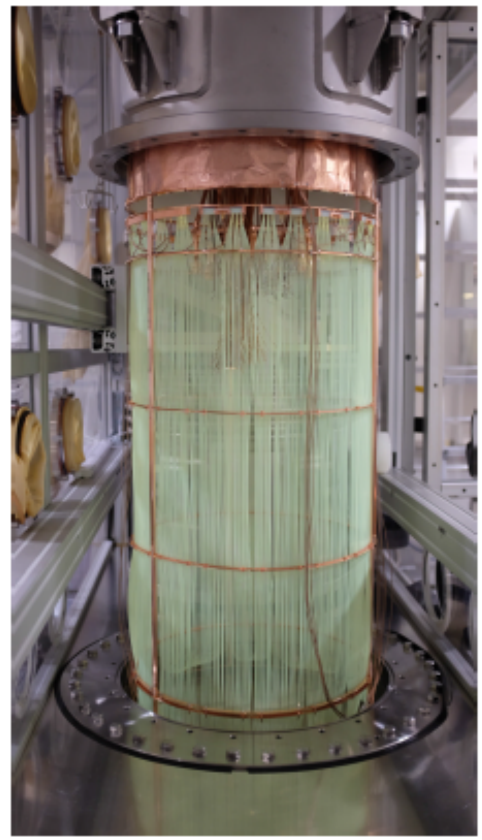
- 16 PMTs (9 top / 7 btm)
- 800 m fibers coated with WLS + 90 SiPMs
- nylon mini-shroud around each string coated with WLS

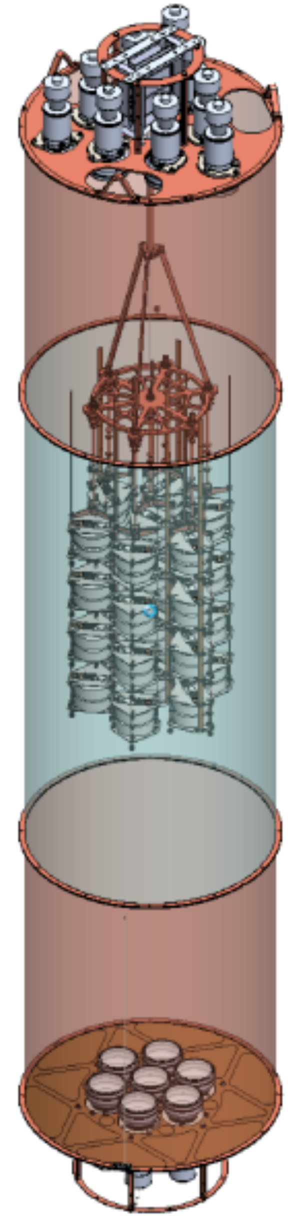
Parameters optimized for each channel:

- ~0.5 PE threshold
- $\sim 5 - 6\,\mu s$ anticoincidence window



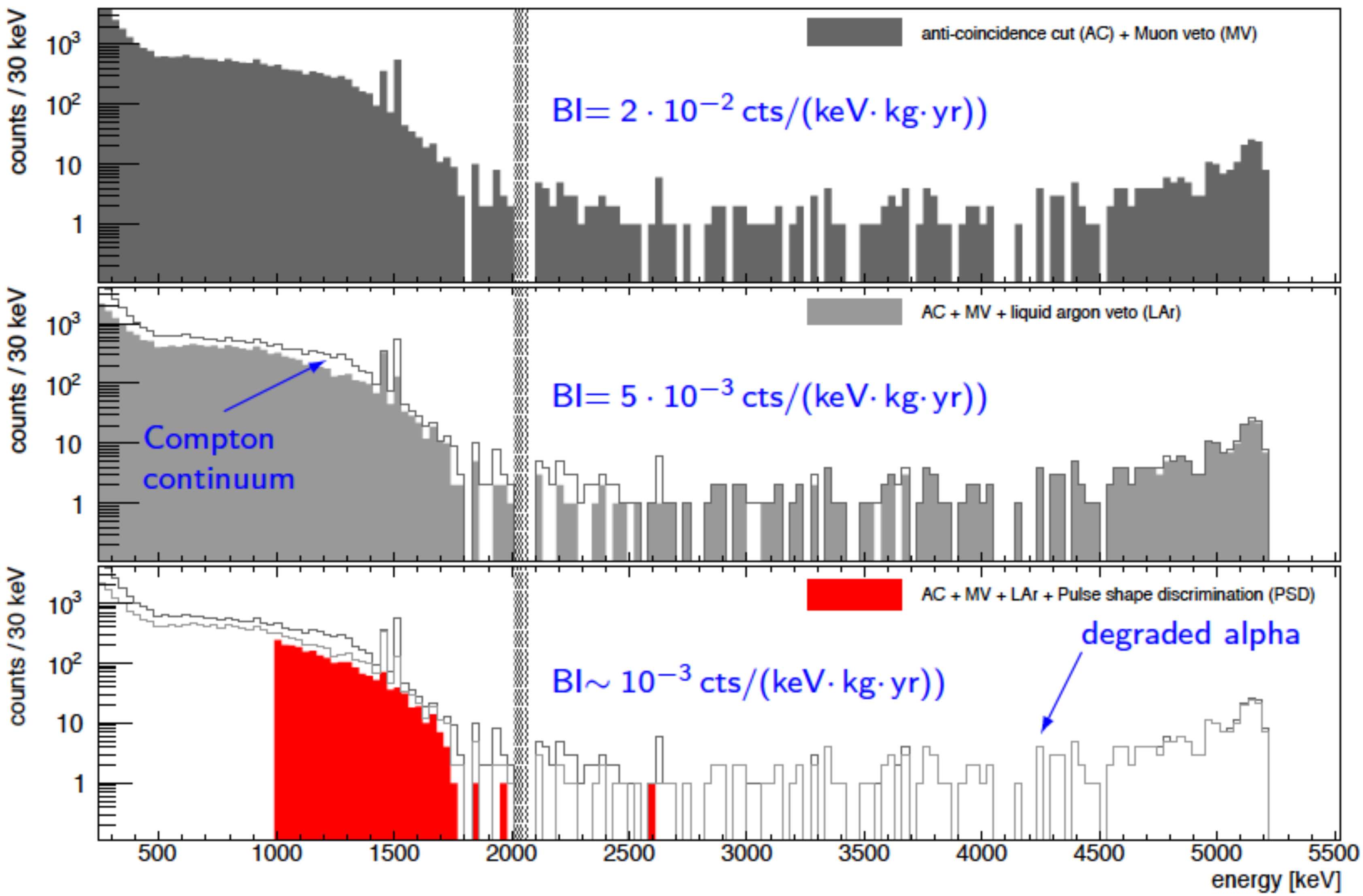




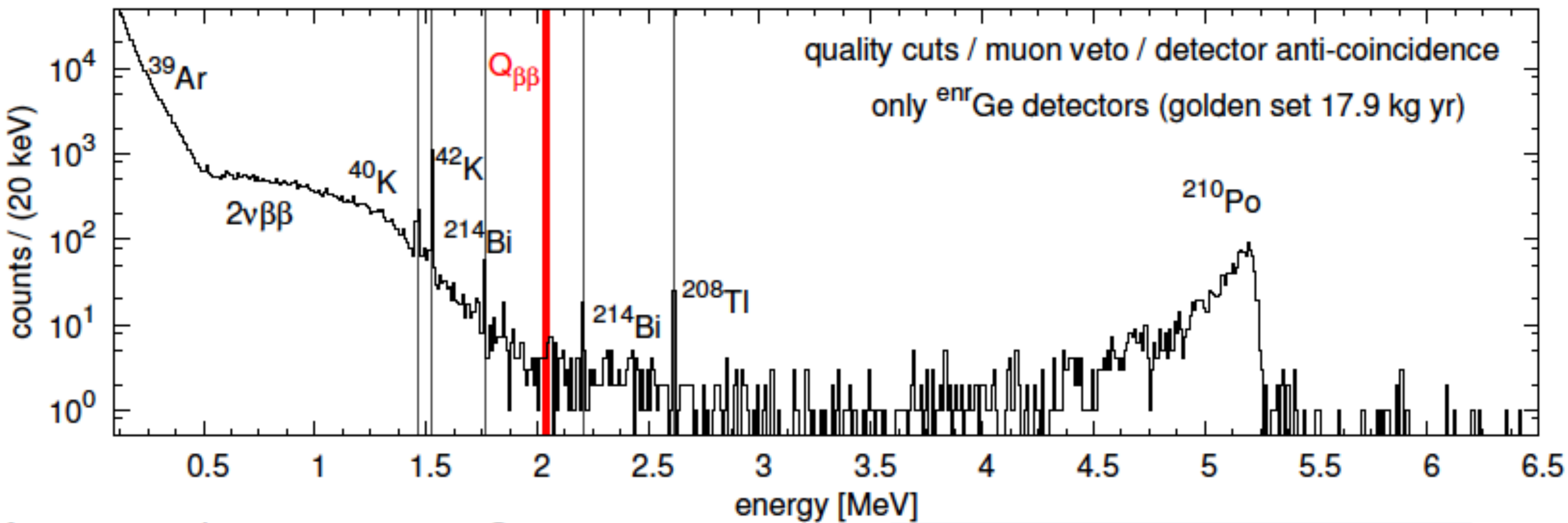


[see poster P4.057]

Background suppression - BEGe



Main spectral components in Phase I

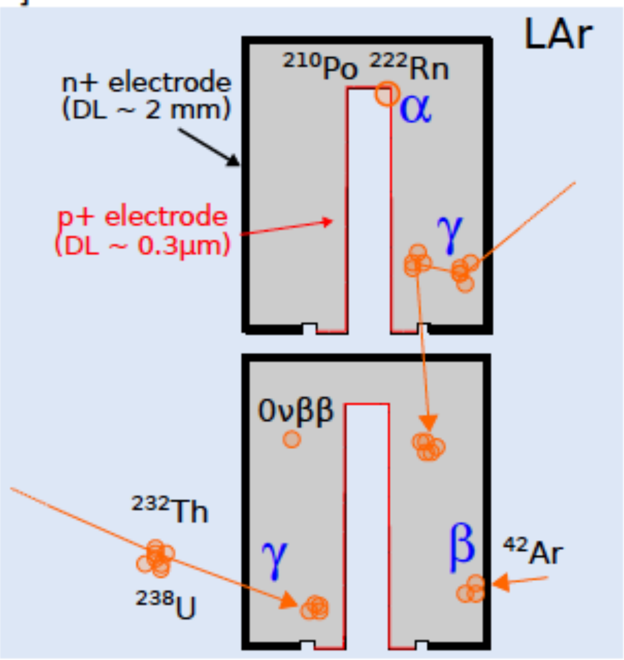


Main spectral components at $Q_{\beta\beta}$:

- γ: ^{208}Tl, ^{214}Bi
- β: ^{42}Ar (cosmogenic)
- α: ^{210}Po surface contamination or ^{222}Rn in LAr

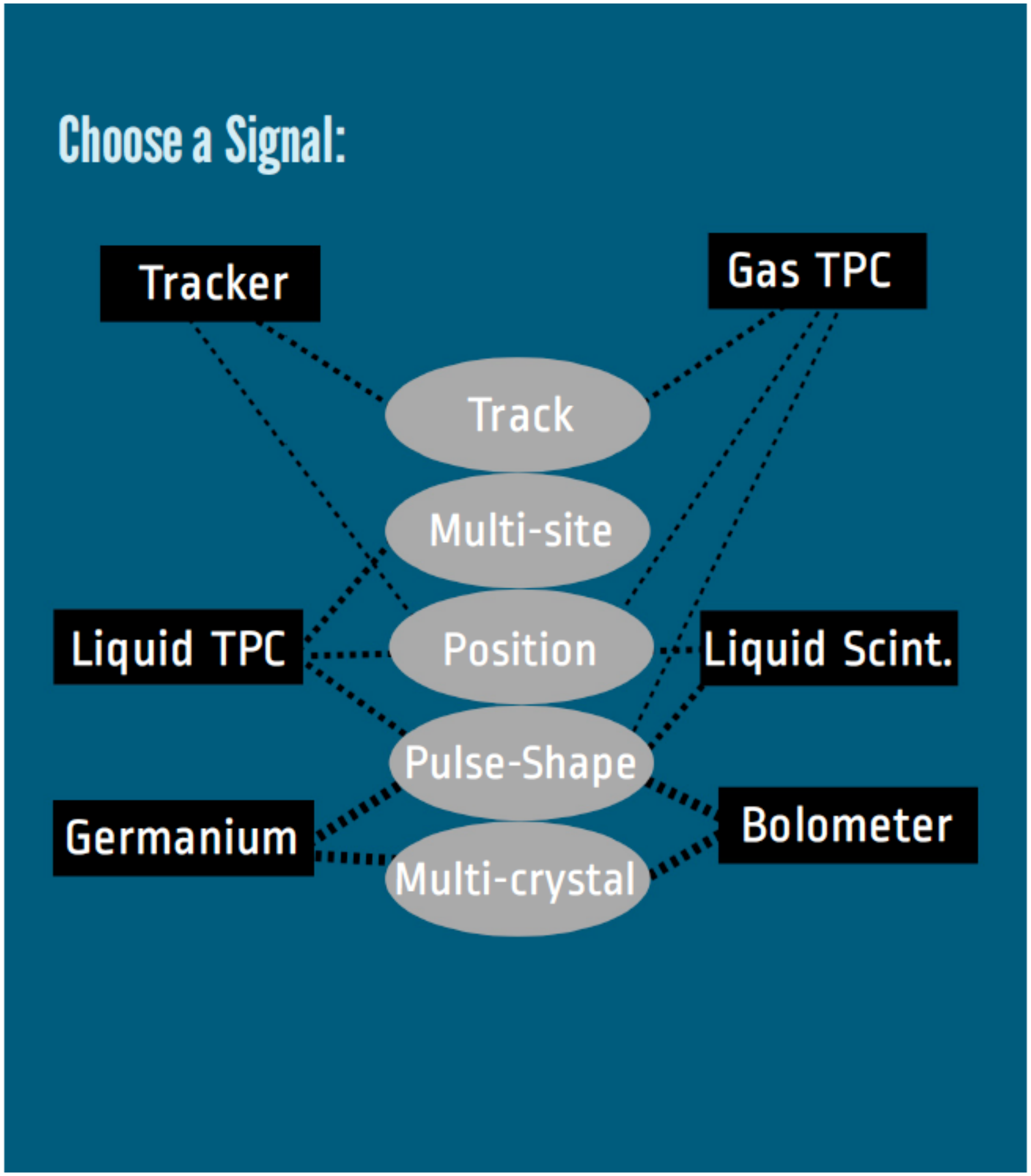
Active suppression techniques:

- AC: detector anti-coincidence
- PSD: pulse shape discrimination
- LAr veto: read-out LAr scintillation light (new in Phase II)



^{136}*Xe - EXO-200/nEXO*

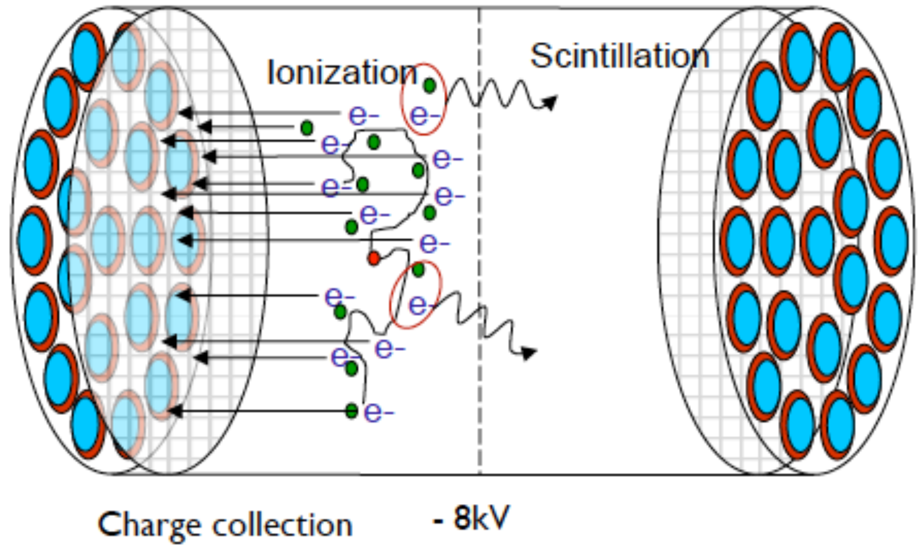
Detector Data:



From Liang Yang

Use Liquid Xenon Time Projection Chambers (TPC) to Search for $0\nu\beta\beta$ Decay

- Xe is used both as the source and detection medium.
- Simultaneous collection of both ionization and scintillation signals.
- Full 3-D reconstruction of all energy depositions in LXe.
- Monolithic detector structure, excellent background rejection capabilities.

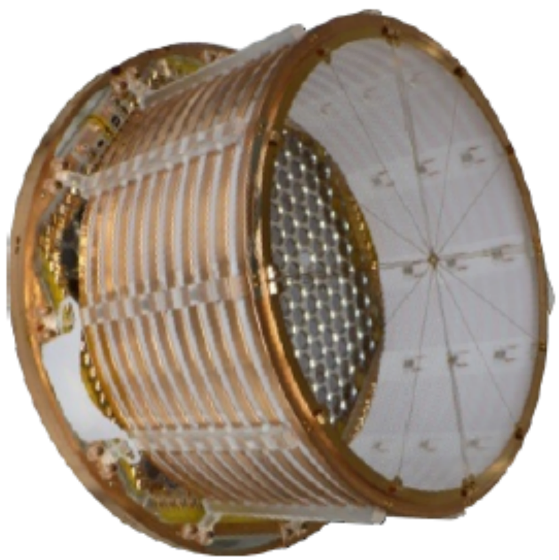


Example of TPC schematics (EXO-200)

EXO-200 is a running LXe detector with ~110 kg active volume. It has demonstrated key performance parameters for $0\nu\beta\beta$ search, and can reach $0\nu\beta\beta$ half-life sensitivity of 5.7 $\times10^{25}$ yrs after Phase-II operation.

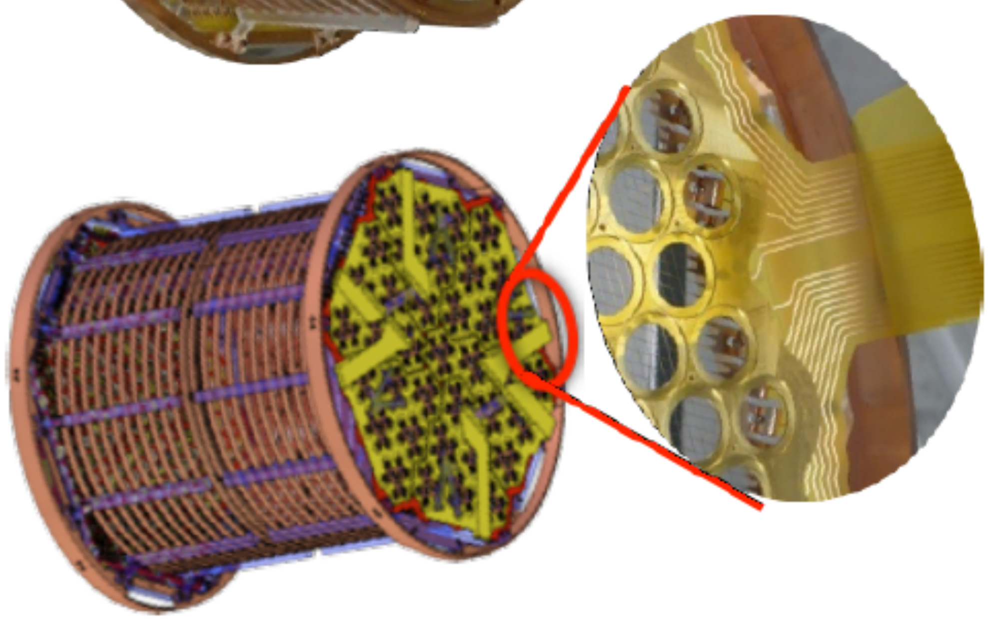
nEXO is a proposed ~ 5 tonne detector. Its design will be optimized to take full advantage of the LXe TPC concept and can reach $0\nu\beta\beta$ half-life sensitivity of ~ 10^{28} yrs

The EXO-200 TPC



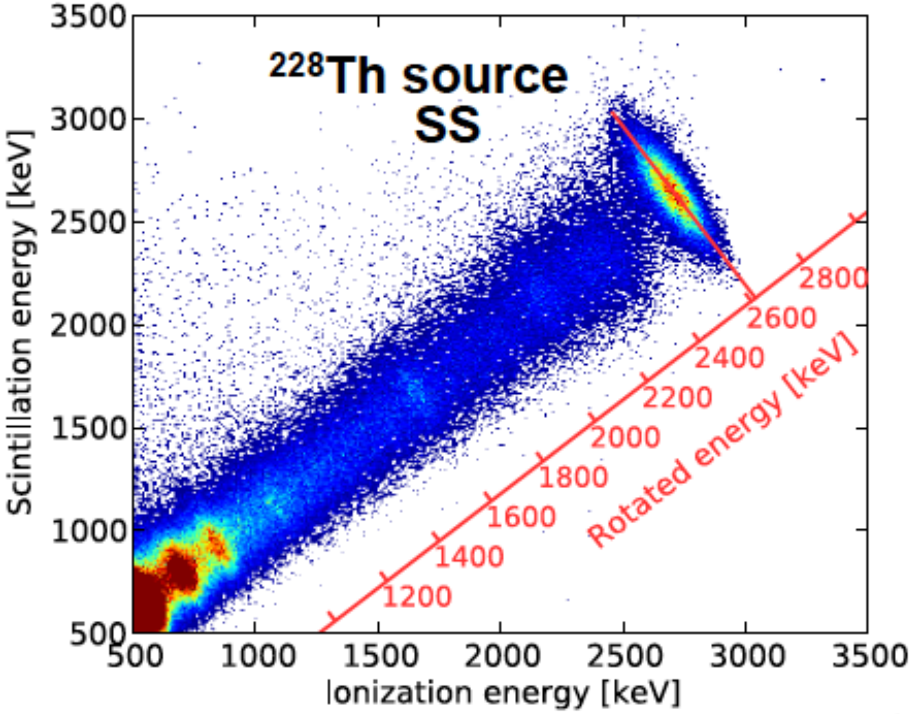
Two almost identical halves reading **ionization** and 178 nm **scintillation**, each with:

- 38 U triplet wire channels (charge)
- 38 V triplet wire channels, crossed at 60º (induction)
- 234 large area avalanche photodiodes (APDs, light in groups of 7)
- All signals digitized at 1 MHz, ±1024 μs around trigger (2 ms total)
- Drift field 376 V/cm
- TPC housed in a copper vessel with 1.37 mm wall thickness



From Liang Yang

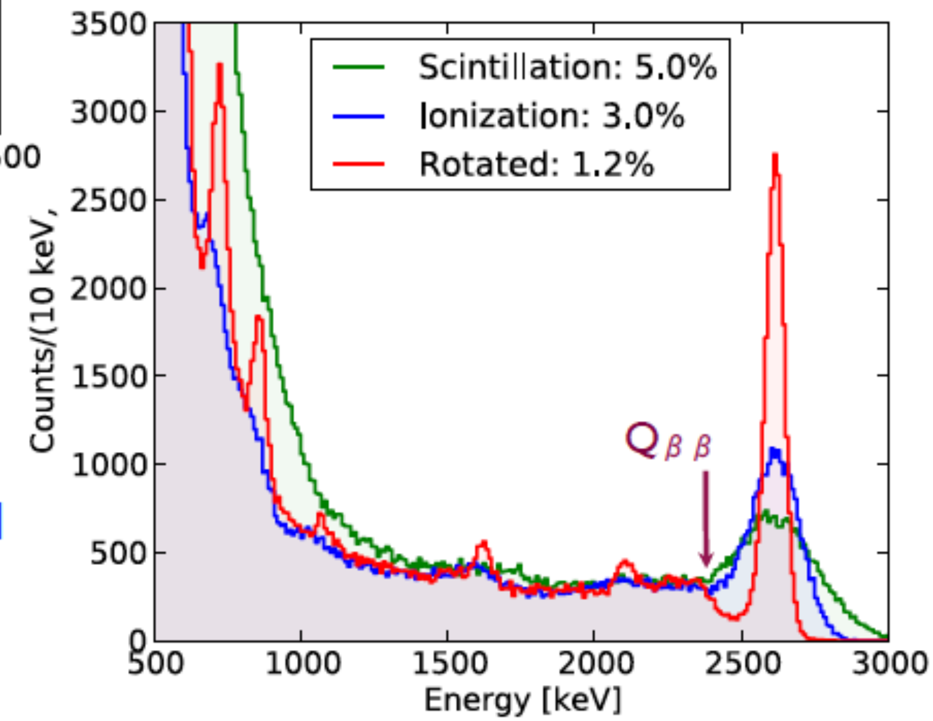
Detector Energy Resolution



Combining Ionization and Scintillation energy to enhance energy resolution

Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

(E.Conti et al. Phys Rev B 68 (2003) 054201)

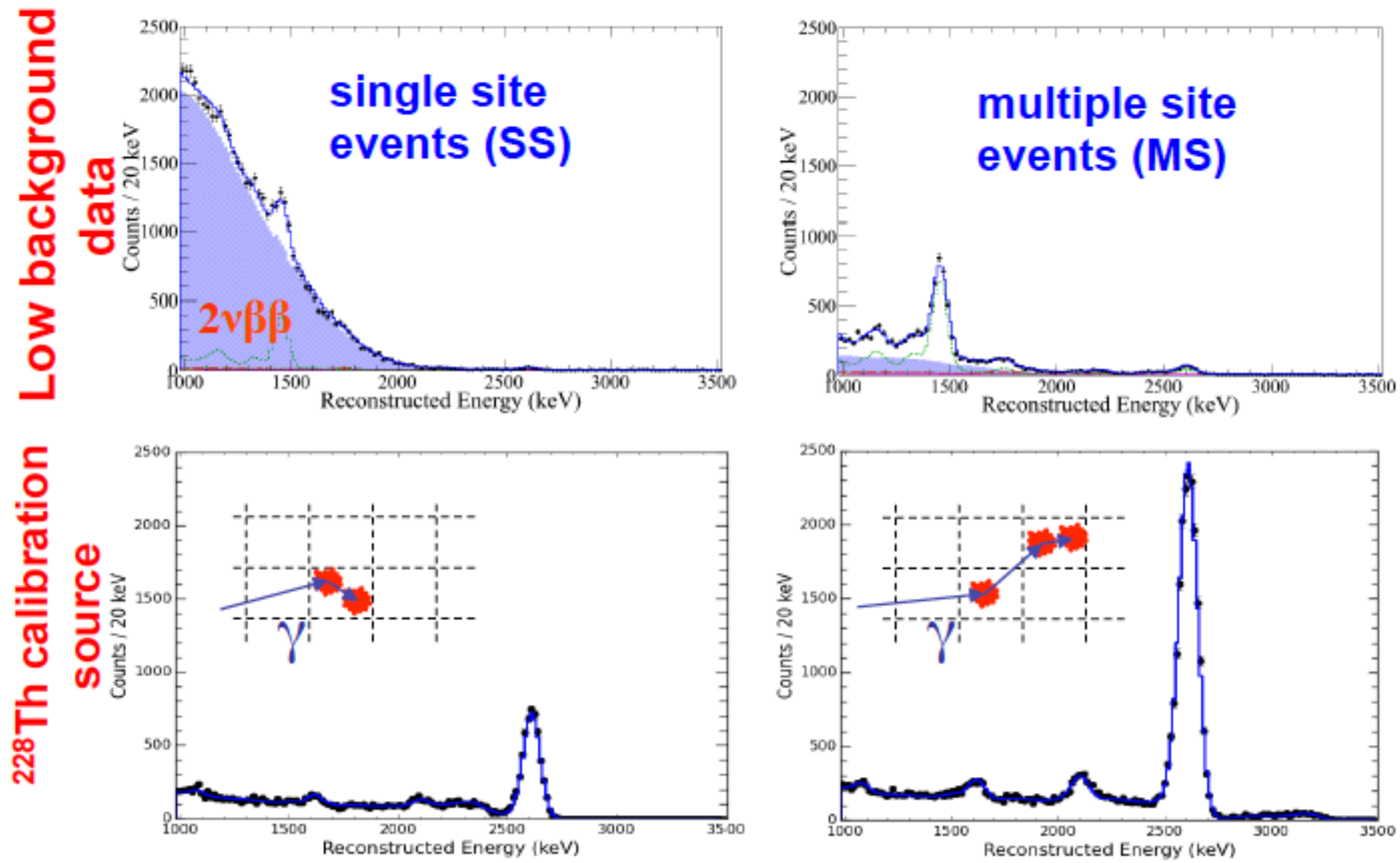


EXO-200 has achieved ~ 1.25% energy resolution at the Q value.

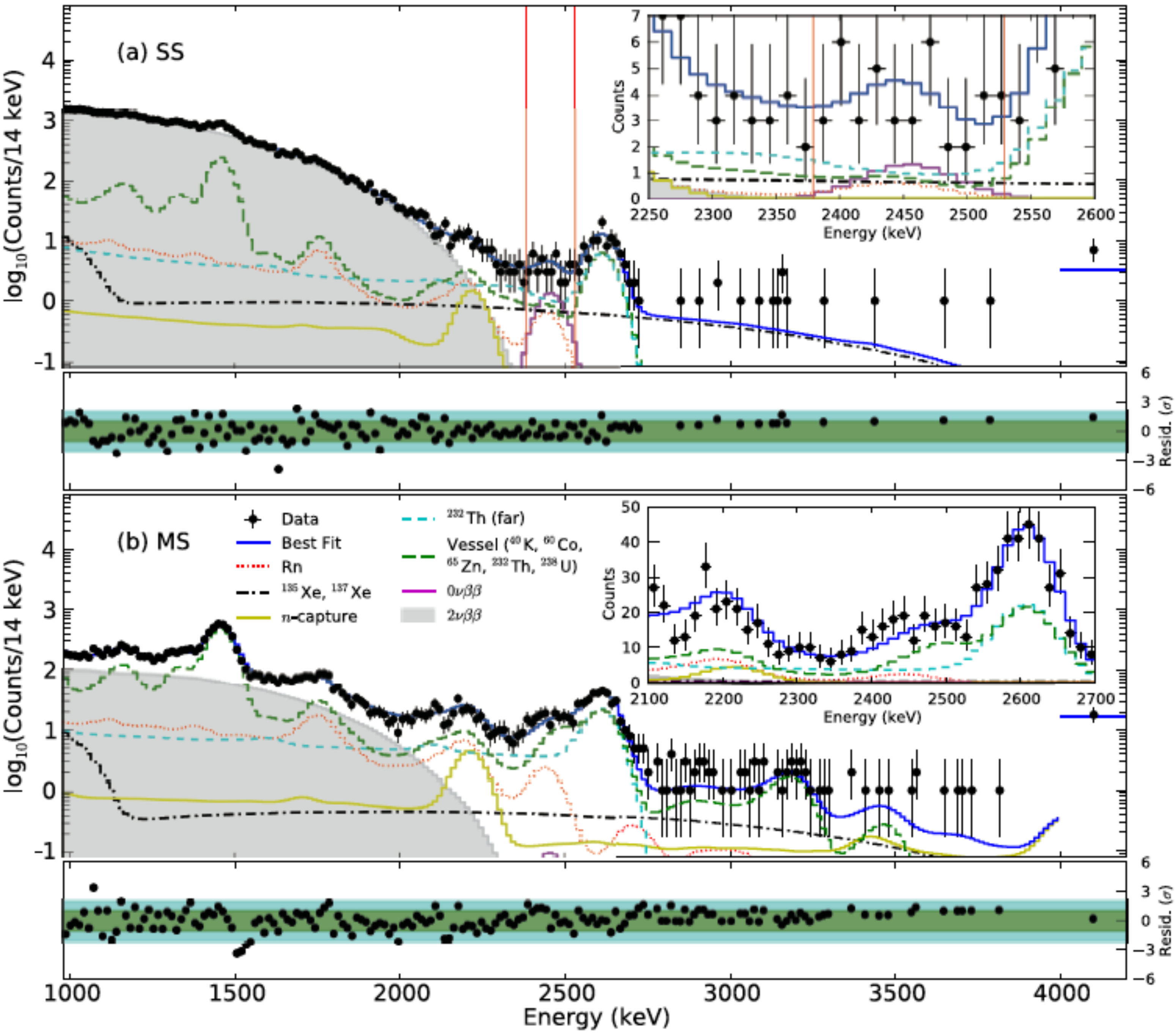
nEXO will reach resolution < 1%, sufficient to suppress background from 2νββ.

From Liang Yang

Topological Event Information



- **TPC allows the rejection of gamma backgrounds because Compton scattering results in multiple energy deposits.**
- **SS/MS discrimination is a powerful tool not only for background rejection, but also for signal discovery.**

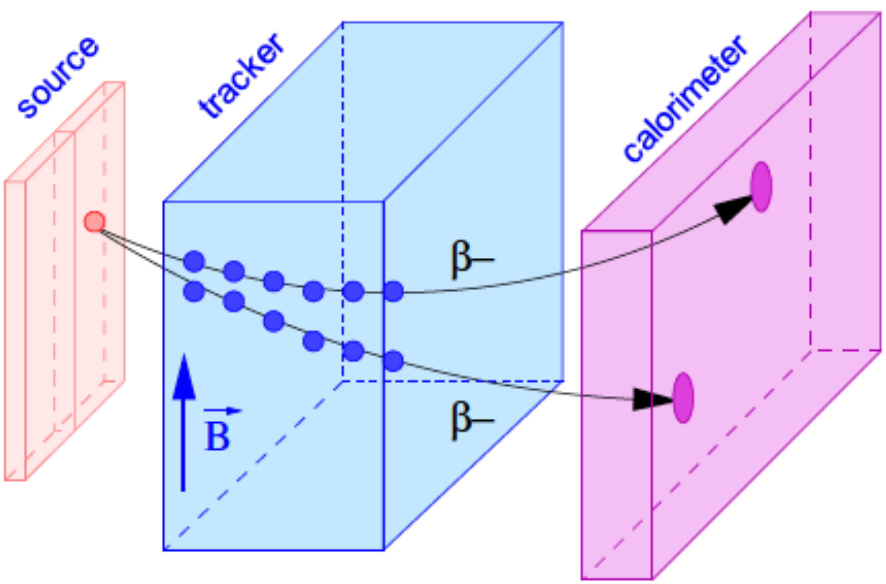


(a) SS
(b) MS
log10(Counts/14 keV)
Resid. (σ)
Energy (keV)
Counts
Data
Best Fit
Rn
135Xe, 137Xe
n-capture
232Th (far)
Vessel (40K, 60Co, 65Zn, 232Th, 238U)
0νββ
2νββ

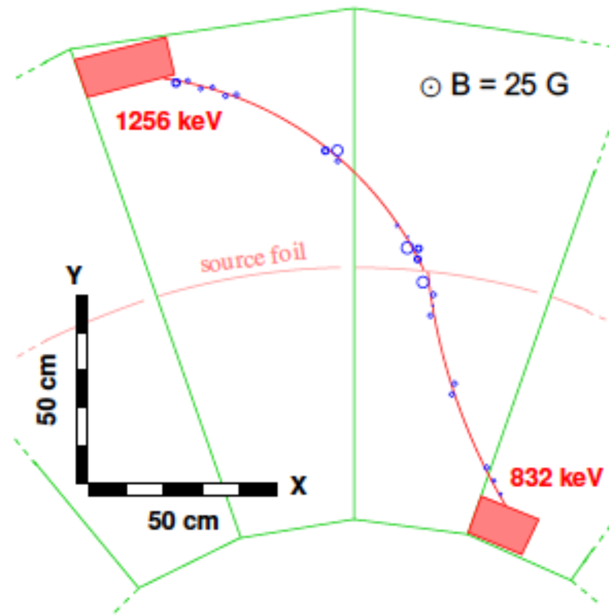
NEMO-2/SuperNEMO - A Tracker

The Tracker-Calorimeter Technique

- Source separated from detector: (almost) any solid isotope can be hosted.
- Generally poorer energy resolution than "homogeneous" detectors such as HPGe and bolometers.
- Full topological event reconstruction including $e^{\pm}$, γ-ray and α-particle identification.

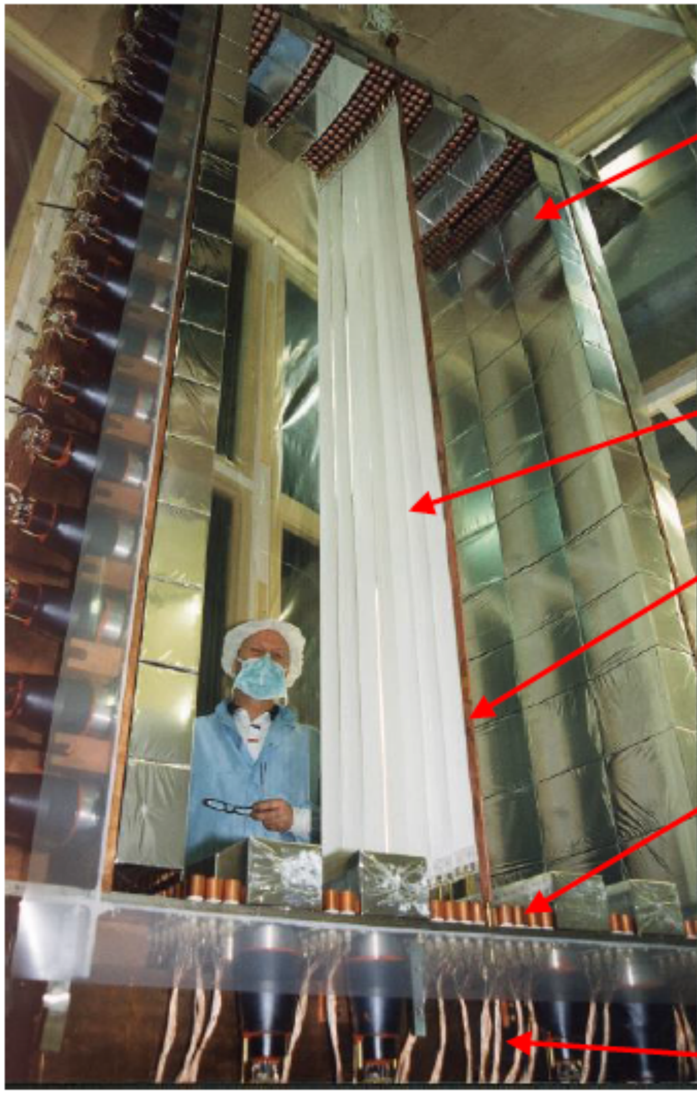


Candidate ^{100}Mo Double-Beta Decay Event in NEMO-3



- Strong background suppression by particle identification, event characterisation & timing.
- Ability to disentangle different mechanisms for $0\nu\beta\beta$, by looking at variables other than ΣE.

The NEMO-3 Experiment



- 5” low activity PMT coupled to PS scintillator blocks.
- Energy resolution :

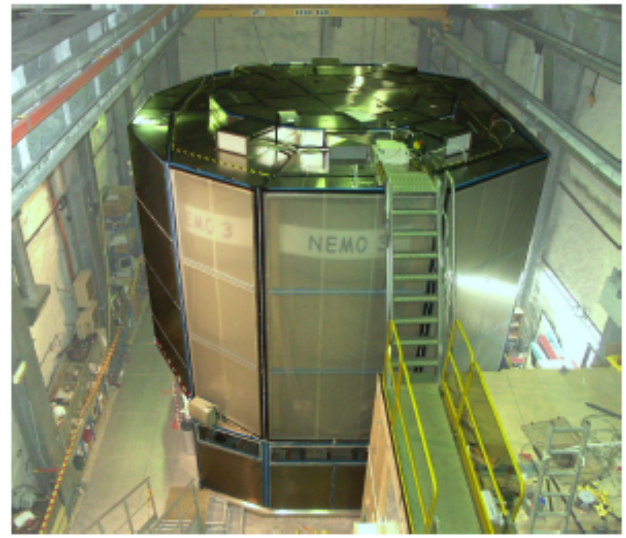
$$\frac{\Delta E(\mathrm{FWHM})}{E} = \frac{14\%}{\sqrt{E(\mathrm{MeV})}}$$

- Source strips.
- Metallic or composite structure.

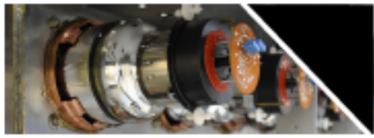
- Calibration tubes.
- Host ^{207}Bi and other sources.

- Cathode rings surrounding each vertical anode wire.
- 3D tracker hits from transverse drift and longitudinal plasma propagation.
- 25 Gauss B-field

- Cu/Fe structure.

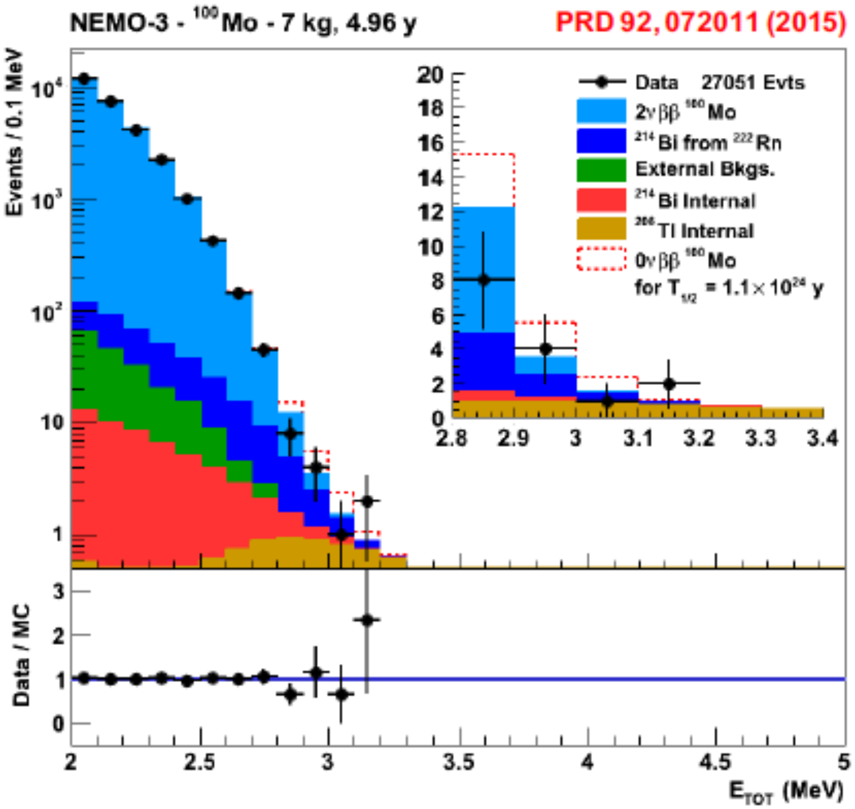


- Ran from 2003 to 2011.
- Surrounded by shielding and anti-radon enclosure.
- Located at 4800 m.w.e. at the Laboratoire Souterrain de Modane (LSM).
- ^{100}Mo (7kg) ; ^{82}Se (1kg)
- ^{116}Cd, ^{150}Nd, ^{48}Ca, ^{96}Zr, ^{130}Te



Search for $0\nu\beta\beta$ in ^{100}Mo

- Backgrounds constrained in these and other control channels.
- Search for a $0\nu\beta\beta$ signal in the region $2.0 < E_{TOT} < 3.2$ MeV distribution (larger than ROI_{FWHM})



- For the hypothesis of light Majorana neutrino exchange :

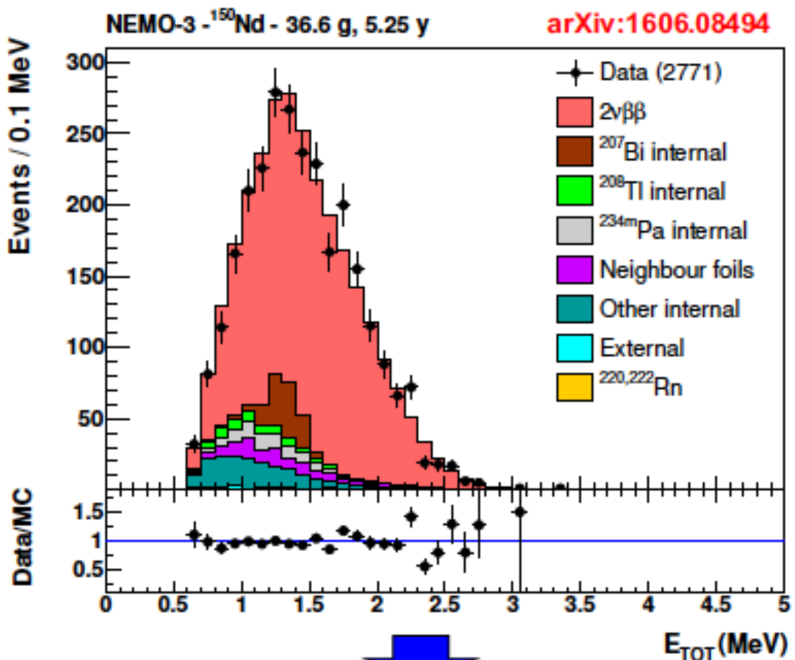
$$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{24} \text{ yr (90\% C.L.)}$$
$$\langle m_\nu \rangle < 0.3 - 0.6 \text{ eV}$$

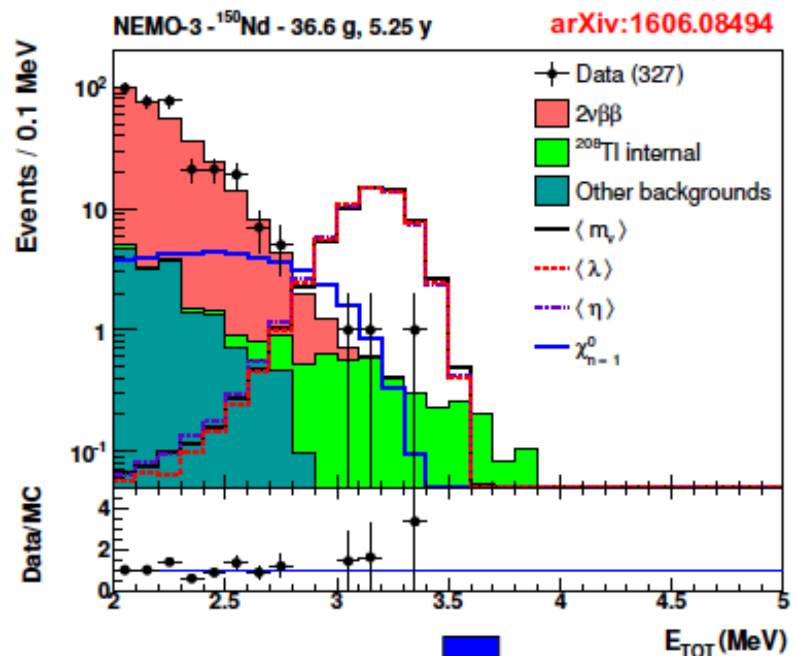
- Close to the best limits from other experiments, with only 7kg of isotope.
- No events in [3.2-10] MeV for 47 kg.yr

- Competitive bounds also placed on :
  - R-parity violating couplings in the case of gluino/neutralino mediated $0\nu\beta\beta$.
  - RHC couplings.
  - Majoron-neutrino couplings.

Double-Beta Decay of ^{150}Nd

- ^{150}Nd : $Q_{\beta\beta}$ = 3.4 MeV and the largest phase space of any isotope.





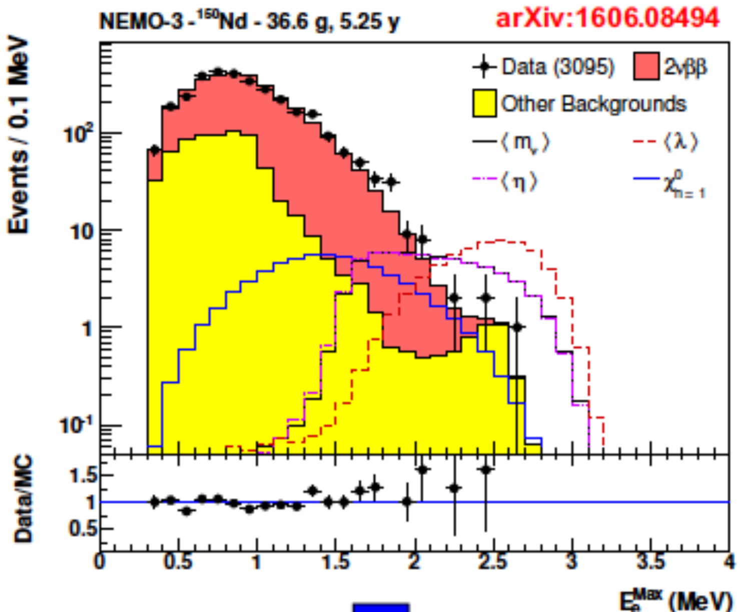
- Most precise measurement of the $2\nu\beta\beta$ rate:

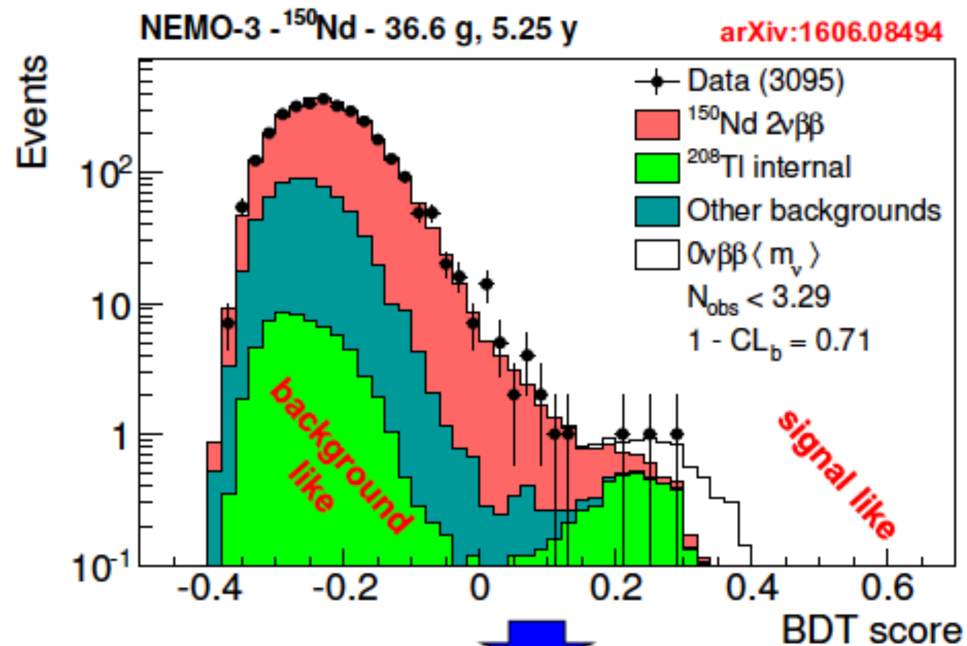
$$T^{2\nu}_{1/2} = [9.34 \pm 0.22\,(\mathrm{stat.})\,^{+0.62}_{-0.60}(\mathrm{syst.})] \times 10^{18}\ \mathrm{yr}$$

- The total energy is the single most sensitive variable in searching for $0\nu\beta\beta$.

Double-Beta Decay of ^{150}Nd

- Rich information provided by full event reconstruction can be exploited through multi-variate analysis techniques such as Boosted Decision Trees.





- Partitioning of energy between the two electrons is particularly sensitive to the mechanism of 0νββ.
- Nine other kinematic and detector variables are fed into the BDT.

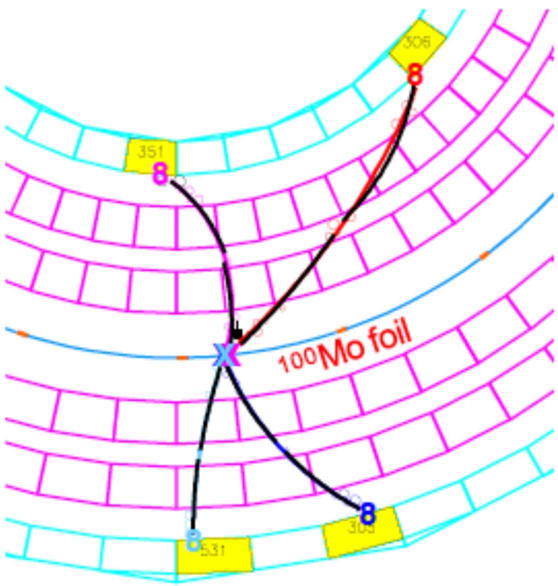
$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{22}\,\mathrm{yr}\;(90\%\;\mathrm{C.L.})$$

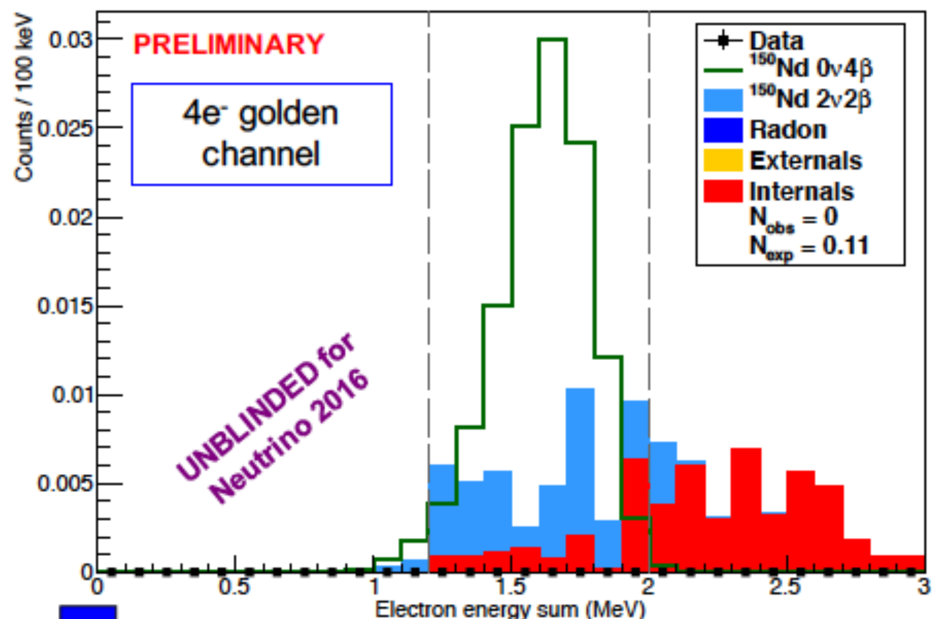
$$\langle m_\nu \rangle < 1.6 - 5.3\ \mathrm{eV}$$

- Expected (observed) half-life limit is 11% (34%) better than using E_{TOT} alone.

Quadruple Beta Decay of ^{150}Nd

- Lepton number violating processes with ΔL=4 are possible with Dirac Neutrinos (Heeck & Rodejohann 2013) Neutrinoless quadruple beta decay ($0\nu4\beta$) is one such process.
- The best candidate is $^{150}\text{Nd} \xrightarrow{2.079\ \text{MeV}} {}^{150}\text{Gd} + 4e^-$
- Unique sensitivity with topological reconstruction capability of NEMO-3.

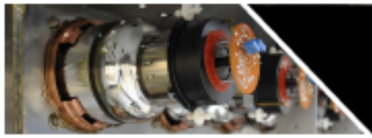




- Combined with other channels :

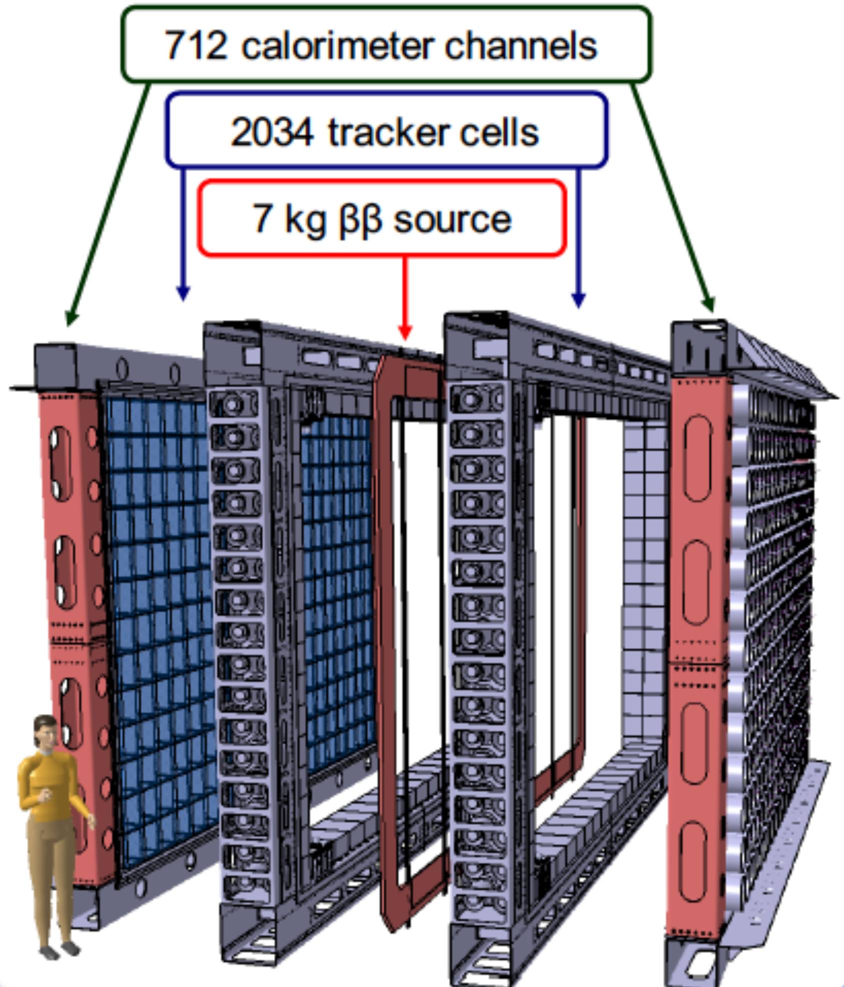
$$T_{1/2}^{0\nu4\beta} > 2.6 \times 10^{21}\ \text{yr (90\% C.L.)} \quad [4.3 \times 10^{21}\ \text{yr expected}]$$

- *World's first limit on this process.*



SuperNEMO Demonstrator Module

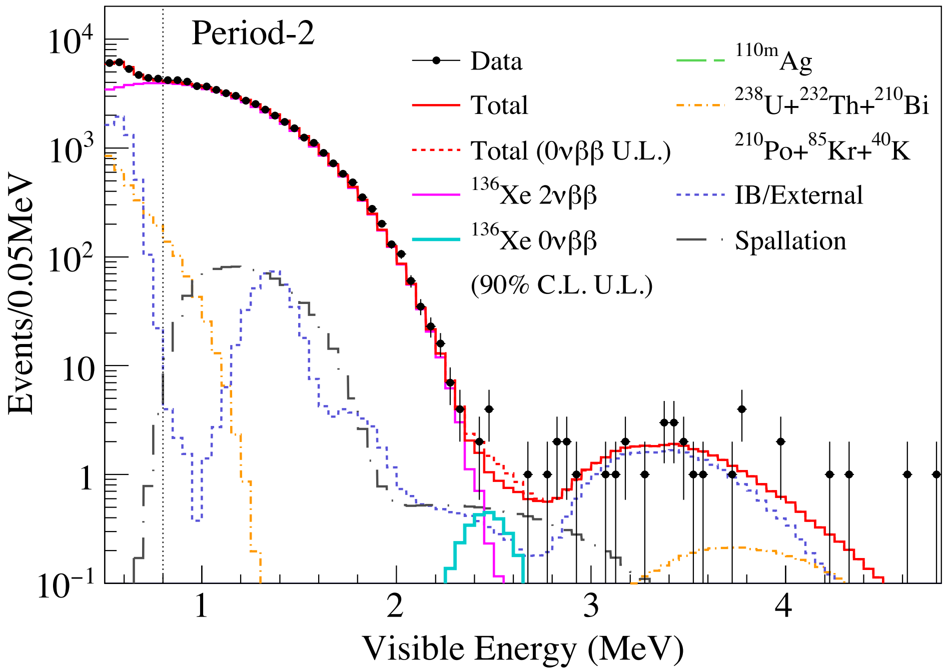
- Change isotope $^{100}Mo \longrightarrow {}^{82}Se$
- New purification & fabrication techniques.
- Possibility of hosting other sources, e.g. ^{150}Nd

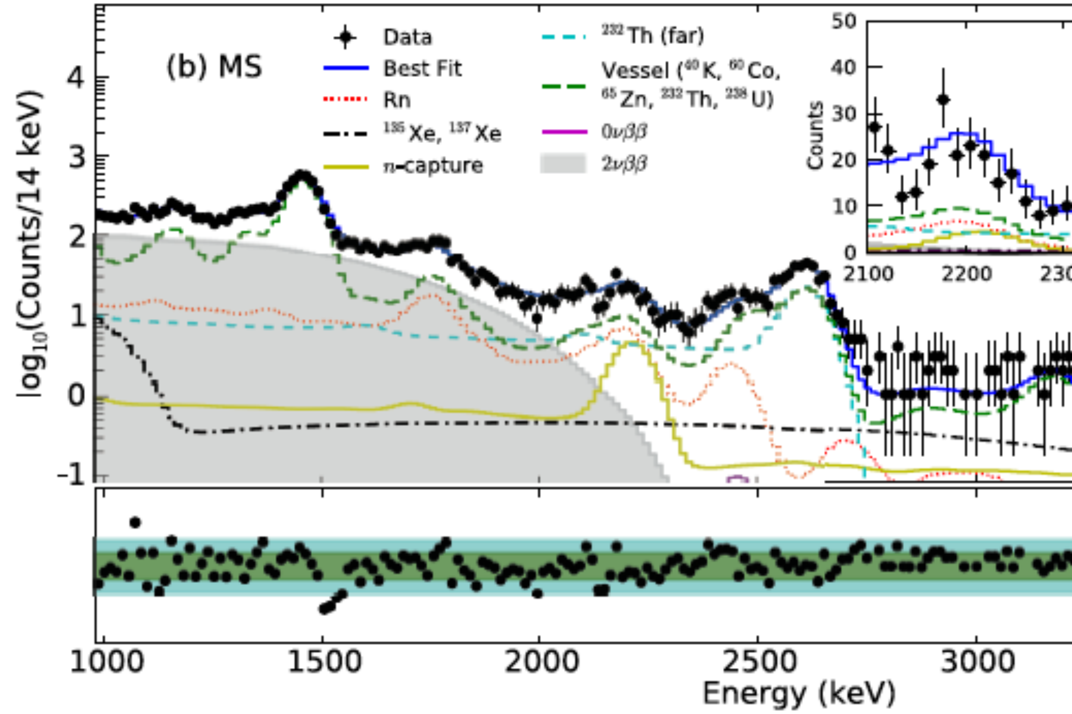


Demonstrator Module

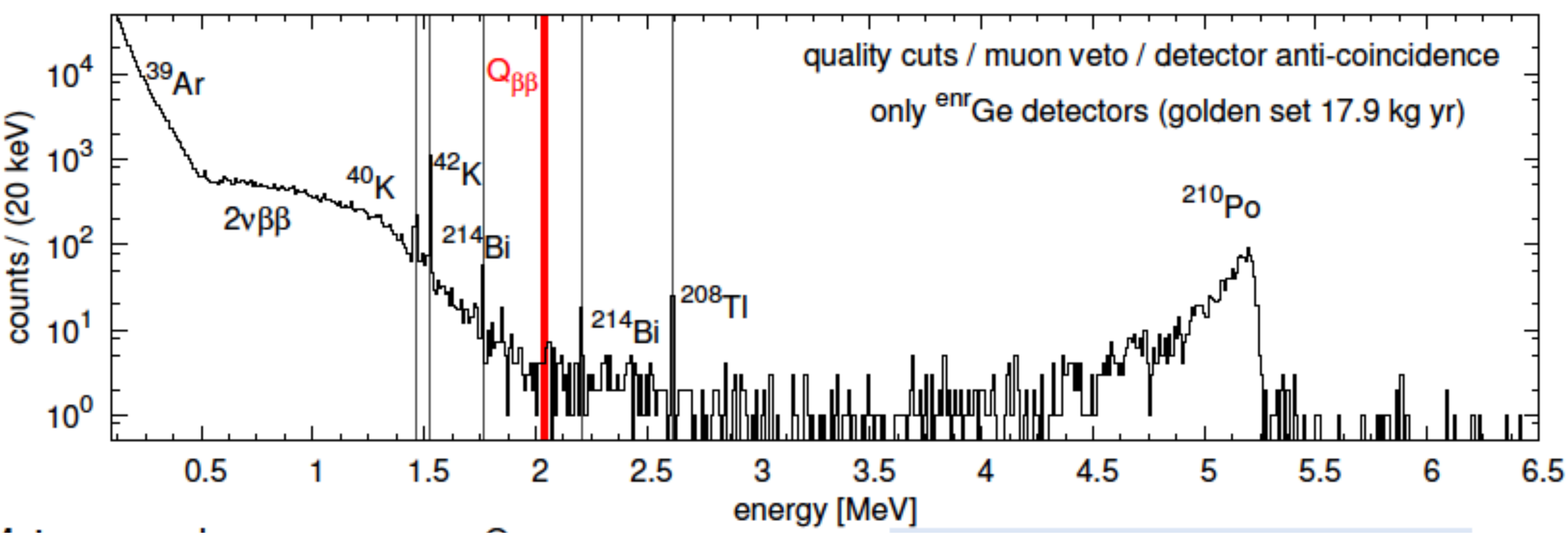
- Reduce radon in gas by factor 30.
- Strict radiopurity control of all materials.
- Improved efficiency, calibration etc.

Backgrounds?





Main spectral components in Phase I



This is a lot of Nuclear Physics!

Some Random Ones

^{110m}Ag

- metastable state of silver
- fission product
- What is its lifetime?
- Why is it so long?

Let’s do some research!

http://www.nndc.bnl.gov/chart/

Some Random Ones

^{40}K

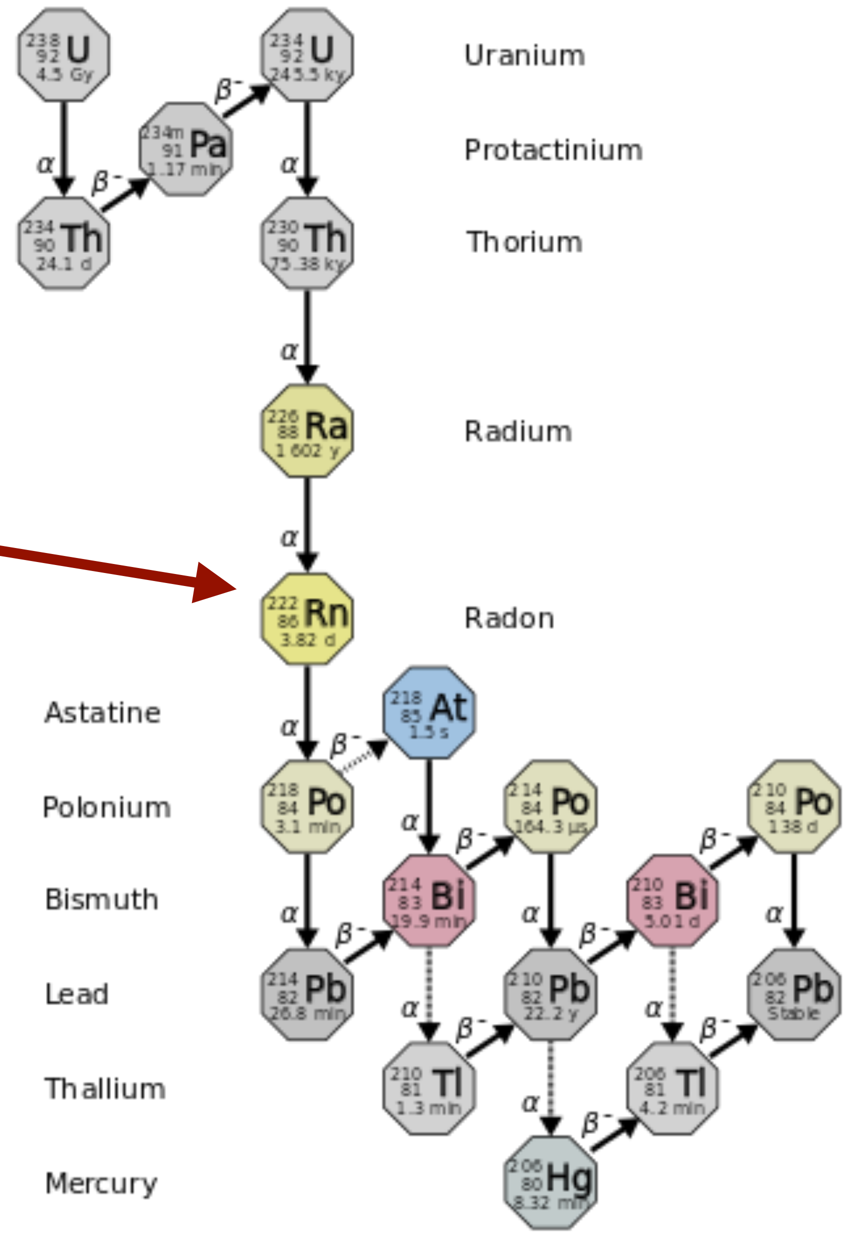
- Long lived
- Naturally occurring
- What is it's characteristic gamma ray?
- Why is it so long-lived?

Uranium Chain

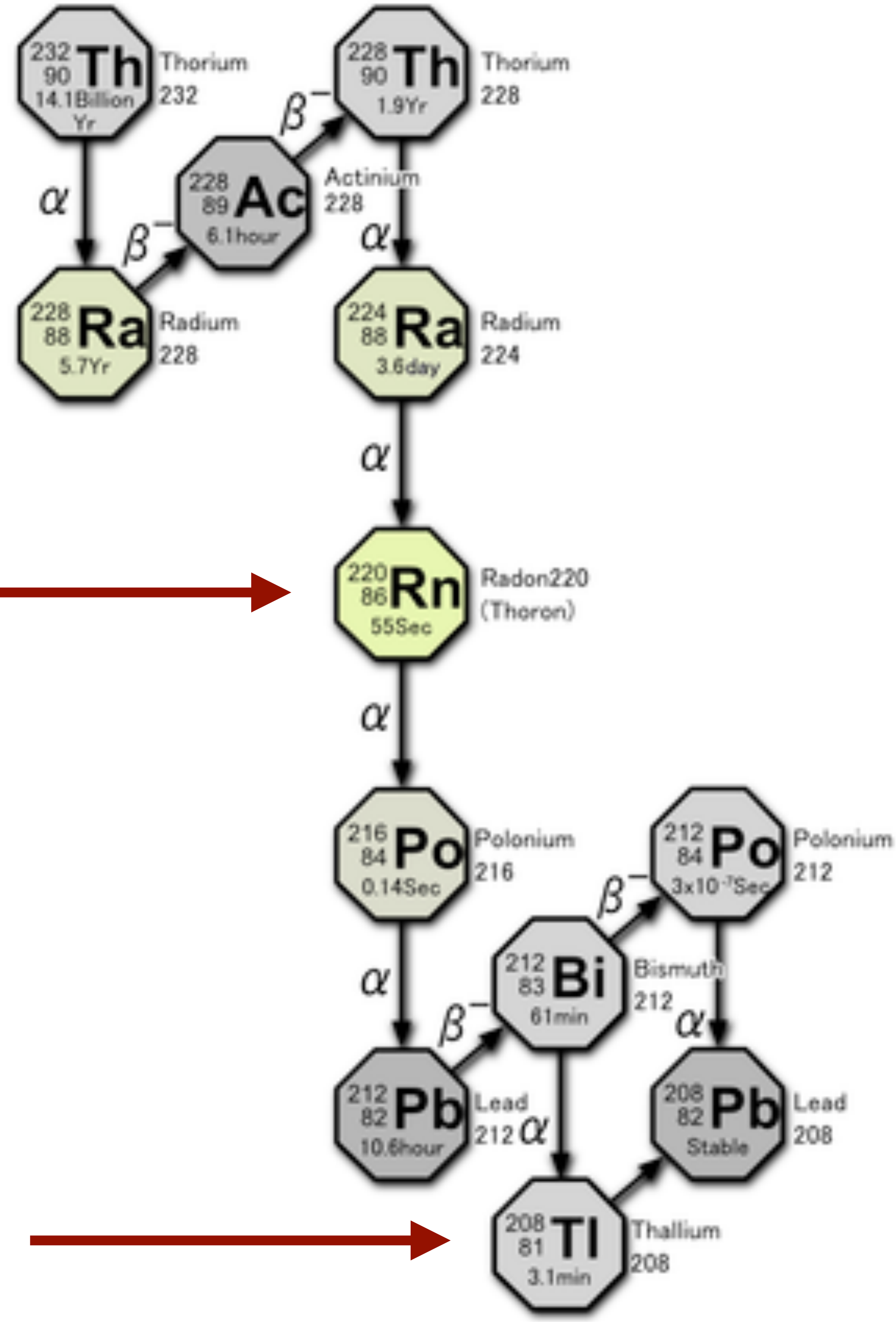
Long Lived

Often times it is radon that is coming into your detector.

Note: mixture of beta and alpha decays, the Bi-Po decays are particularly useful for coincidence analyses.



Thorium Chain



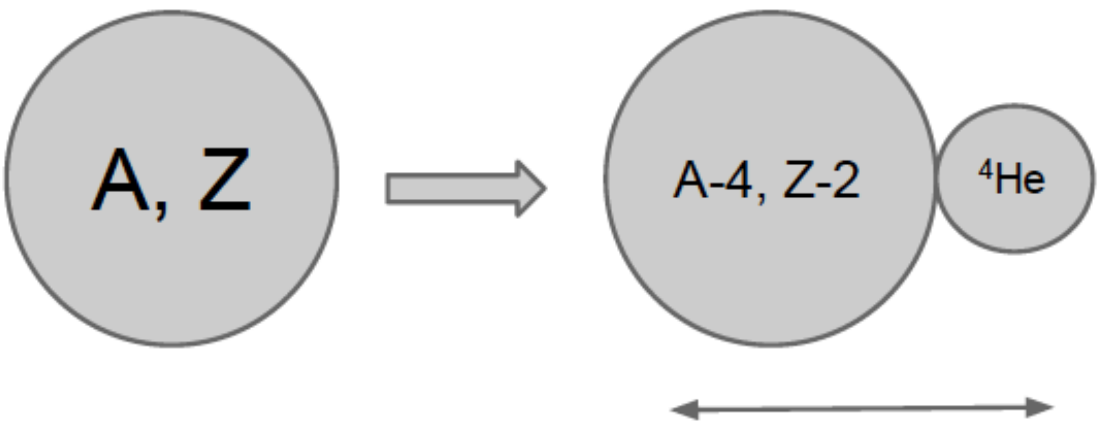
Long Lived

Often times it is radon that is coming into your detector.

Highest energy gamma ray of either U or Th chain.

Alpha Decay Pretty Simple

Picturing Alpha-Decay

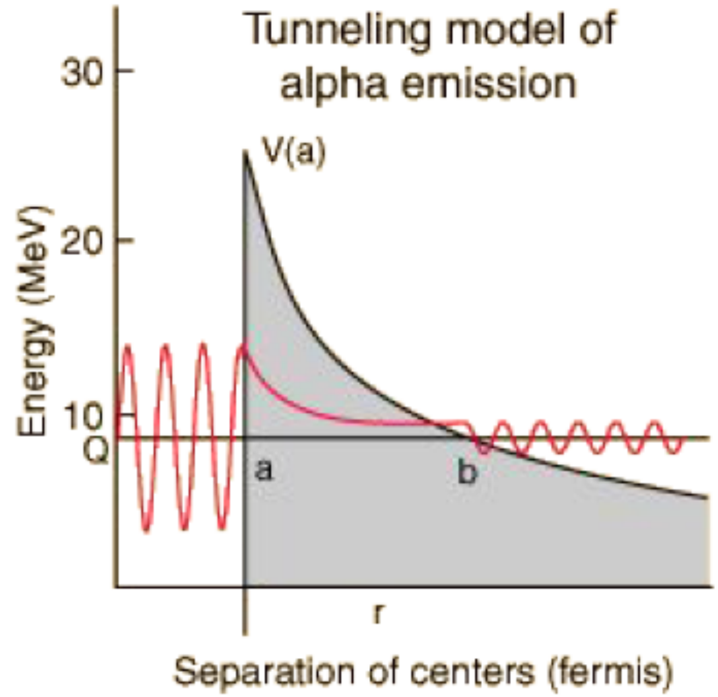


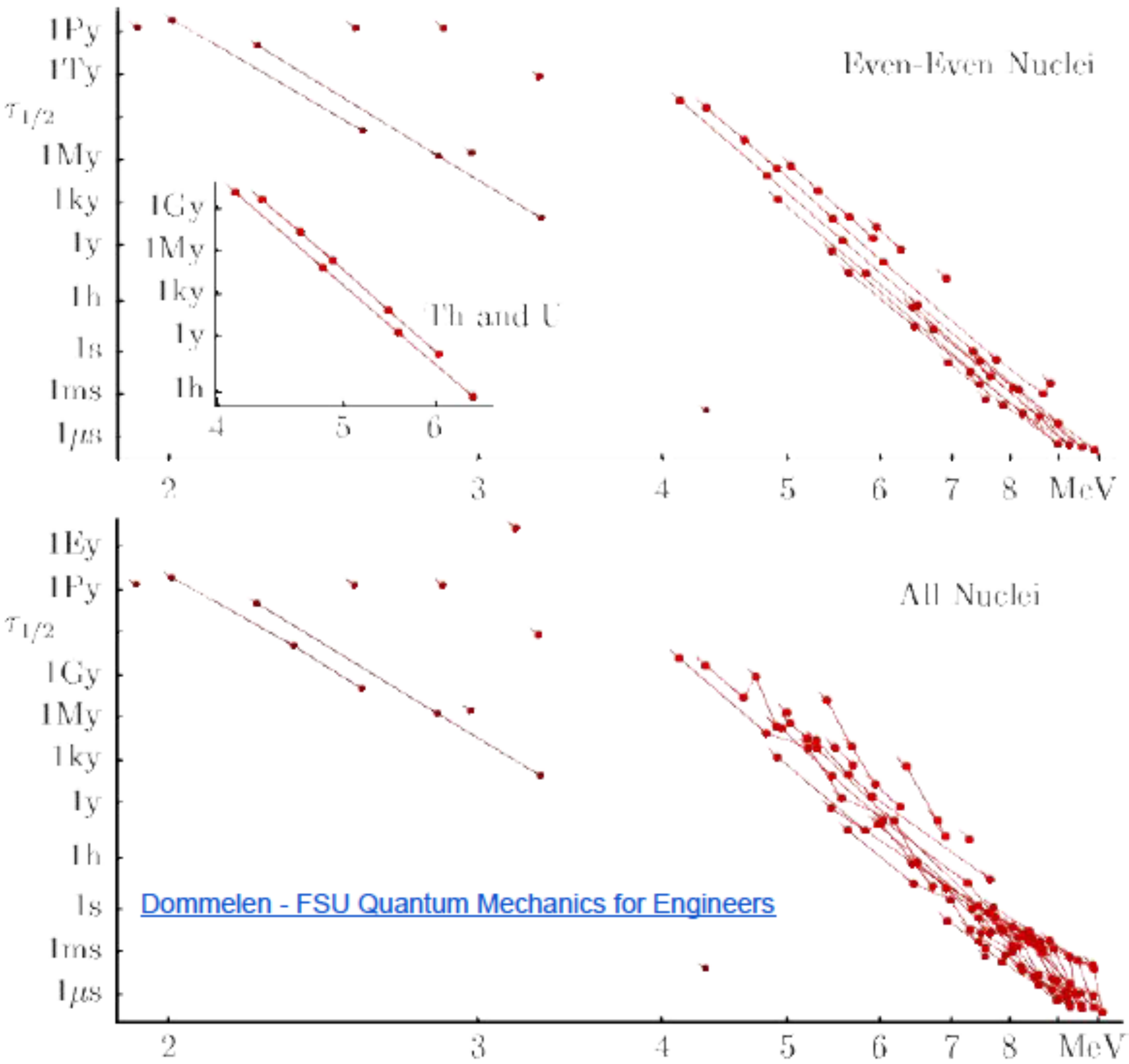
r_s

This is the radius over which the strong force acts.

This is a tunneling phenomenon.

Classically the α particle can’t escape, but quantum mechanically it can tunnel through the barrier.

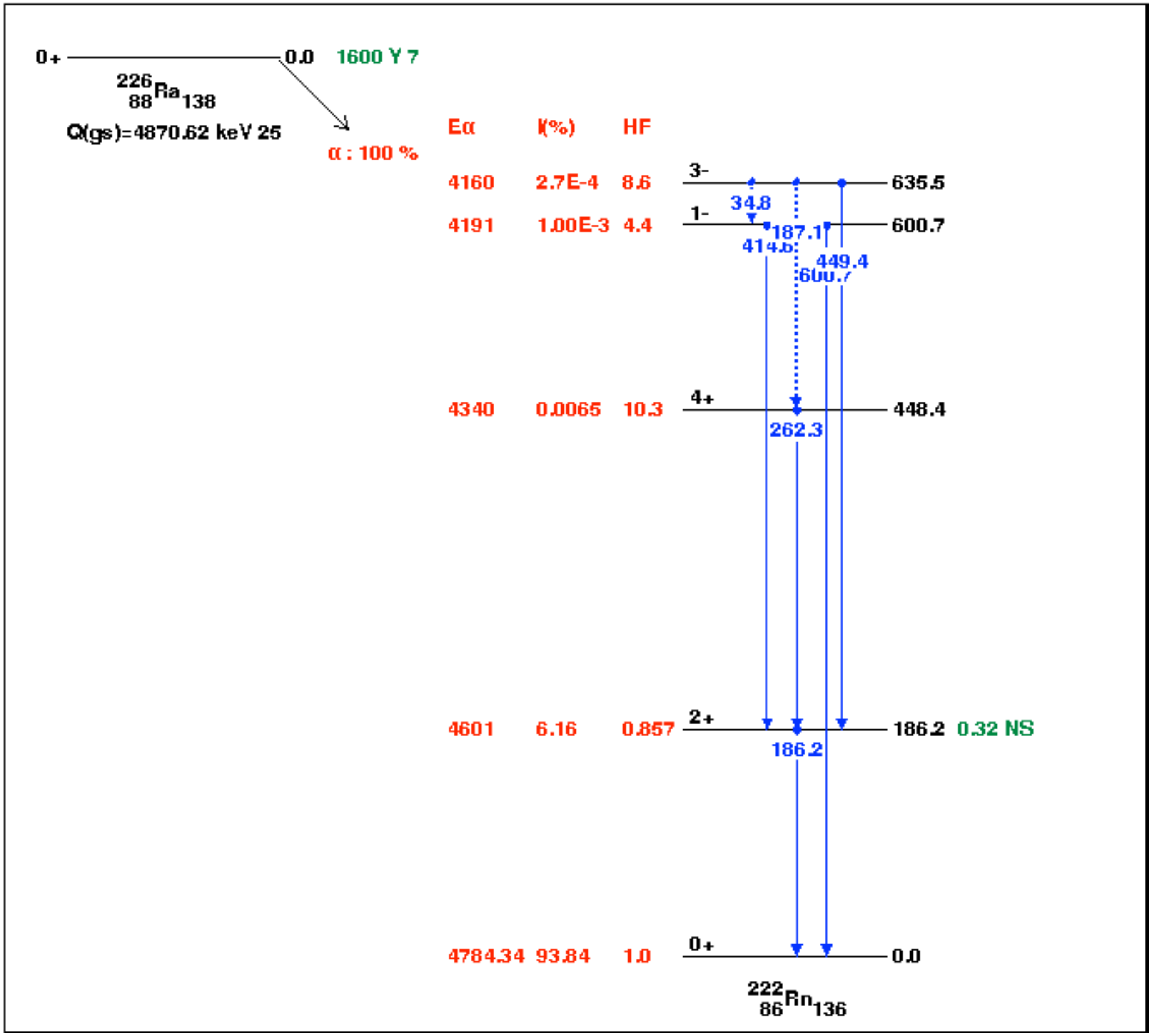




General result half-life inversely proportional to Q-value.

Alpha Decay to Excited States

Q-Value reduced so becomes less probable.



Beta Decay

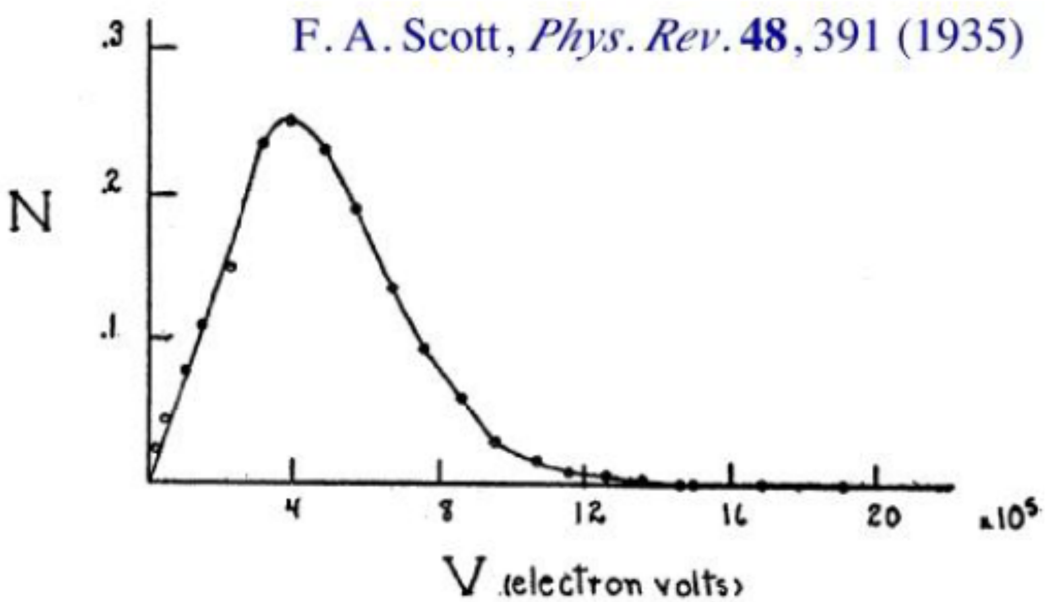
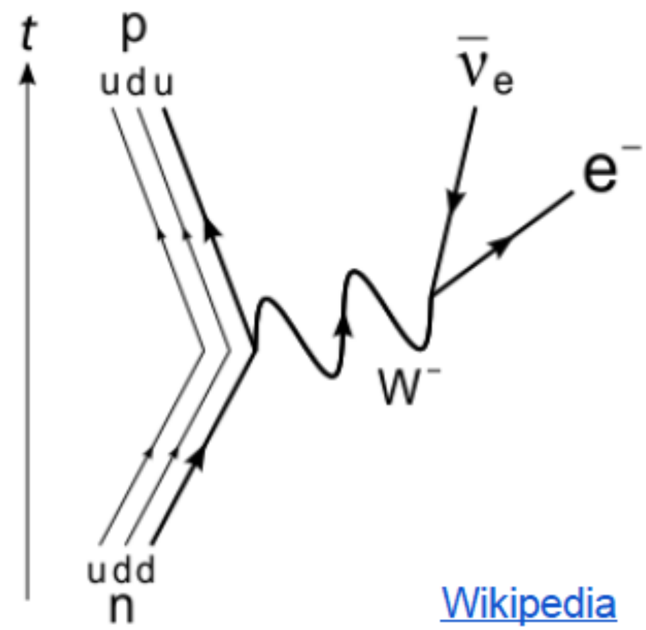


FIG. 5. Energy distribution curve of the beta-rays.



Wikipedia

Fermi's Golden Rule

This is a result from perturbation theory.

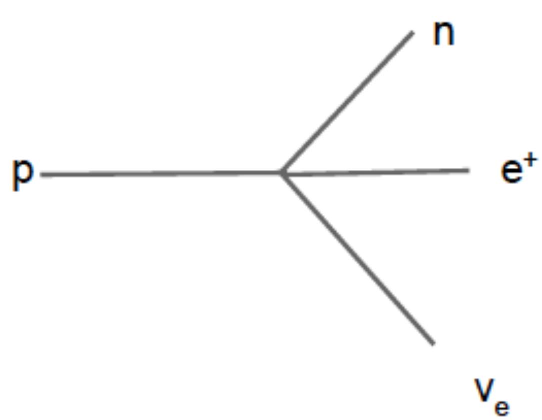
$$R = \frac{2\pi}{\hbar}|H_{fi}|^2 n_f(E_0)$$

Decay rate

Matrix element linking initial and final states.→ How easy is this transition?

Density of states for energy released in this decay E_0. →How many states could do this transition?

Fermi's Theory of Beta Decay



A completely general matrix element:

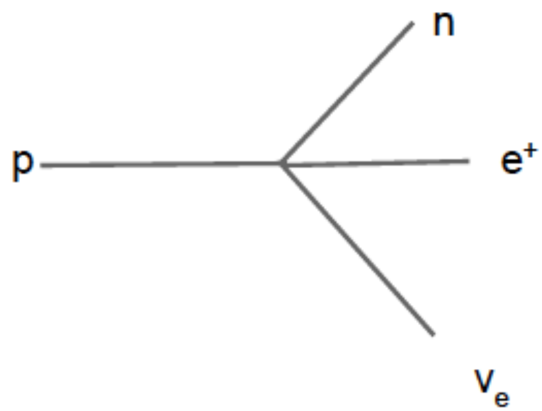
$$H_{fi} = \int \Psi_f^* H \Psi_i d^3\vec{r}_n d^3\vec{r}_p d^3\vec{r}_e d^3\vec{r}_\nu$$

Becomes a simplified matrix element:

$$H_{fi} = G_W \int \psi_n^*(\vec{r})\psi_e^*(\vec{r})\psi_\nu^*(\vec{r})\psi_p(\vec{r}) d^3\vec{r}$$

Point-like interaction justified by heavy W bosons = short interaction range.

Fermi's Theory of Beta Decay



Plane wave is a good assumption for the neutrino:

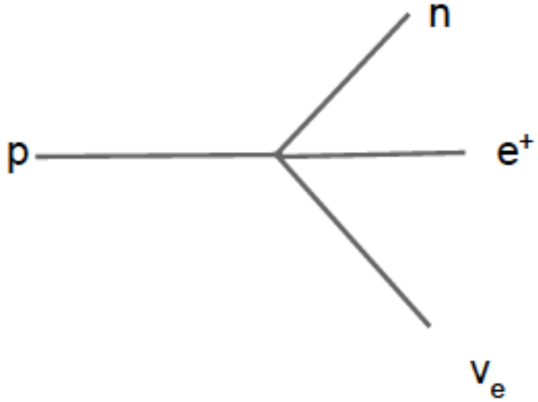
$$\psi_\nu(\vec{r}) = \frac{1}{V^{1/2}} e^{i\vec{k}_\nu \cdot \vec{r}_\nu}$$

For now use a plane wave for the electron too:

$$\psi_e(\vec{r}) = \frac{1}{V^{1/2}} e^{i\vec{k}_e \cdot \vec{r}_e}$$

In principle the electron interacts with the Coulomb potential of the nucleus and at second order the electron cloud (this can get very complicated).

Fermi's Theory of Beta Decay



In the plane wave approximation:

$$H_{fi} = \frac{G_W}{V} \int \psi_n^*(\vec{r})\psi_p(\vec{r})e^{-i(\vec{k}_e+\vec{k}_\nu)}d^3\vec{r}$$

The wave vectors k_e and k_v are small over the range of the nuclear wave-functions, so what do we do?

Fermi's Theory of Beta Decay

An expansion of course:

$$H_{fi} = \frac{G_W}{V}\int \psi_n^*(\vec{r})\psi_p(\vec{r})d^3\vec{r} - \frac{iG_W}{V}(\vec{k}_e + \vec{k}_\nu)\cdot\int \psi_n^*(\vec{r})\psi_p(\vec{r})e^{-i(\vec{k}_e+\vec{k}_\nu)}d^3\vec{r} + \cdots$$

This integral is 0 or ~1.

If the first term is ~1, then this is an allowed decay. If the first term is 0 then it is a forbidden decay (remember nothing is really forbidden in quantum mechanics it just gets less probable.

Forbidden Transitions

These are the selection rules:

$$\Delta J = L-1, L, L+1$$

$$\Delta\pi = (-1)^L$$

Forbiddenness	ΔJ	$\Delta\pi$
Superallowed	$0^+ \rightarrow 0^+$	no
Allowed	$0, 1$	no
First forbidden	$0, 1, 2$	yes
Second forbidden	$1, 2, 3$	no
Third forbidden	$2, 3, 4$	yes

Let's now look at the energy dependence.

$$dR = \frac{2\pi}{\hbar}|H_{fi}|^2 n_\nu(E_0 - E_e) n_e(E_e) dE_e$$

Let's now look at the energy dependence.

$$dR = \frac{2\pi}{\hbar}|H_{fi}|^2 n_\nu(E_0 - E_e) n_e(E_e) dE_e$$

Density of plane wave states:

$$n(E)dE = \frac{V}{(2\pi)^3}\frac{4\pi}{\hbar^3 c^3}(E^2 - m^2c^4)^{\frac{1}{2}} E dE$$

including the rest mass of the particle, note all calculations done with relativistic relation between energy and momentum.

Putting them together:

$$dR = \frac{G_W^2 |M_F|^2}{2\pi^3 \hbar^7 c^6} S_0(E_e) dE_e$$

and all energy dependence comes from the leptons....

$$S_0(E_e) = [(E_0 - E_e)^2 - m_\nu^2 c^4]^{\frac{1}{2}} (E_0 - E_e)(E_e^2 - m_e^2 c^4)^{\frac{1}{2}} E_e$$

this is true for allowed decays some energy dependence can come from angular momentum conservation needs in forbidden decays...this is outside the scope of this discussion.

Doing better...

Let's add the interaction with the Coulomb potential of the daughter nucleus Z_d.

$$F(Z_d, E_e) = \left| \frac{\psi_e(Z_d, 0)}{\psi_e(0, 0)} \right|^2$$

So our energy dependence becomes....

$$S_c(E_e) = F(Z_d, E_e) S_0(E_e)$$

Non-Relativistic Approximation.

$$F(Z, E_e) = \frac{2\pi\eta}{1 - e^{-2\pi\eta}}$$

$$\eta = \pm\frac{Ze^2}{4\pi\epsilon_o \hbar v}$$

+ = electrons
- = positrons

V is the velocity of the electron.

What happens as v→0

$$F(Z, E_e) = 2\pi\eta$$

Electrons have enhanced decay rate at low energies/velocities.

$$F(Z, E_e) = 2\pi|\eta|e^{-2\pi|\eta|}$$

Positrons have to effectively tunnel out at low energies/velocities.

Total Decay Rate

$$\frac{1}{\tau} = \frac{G_W^2 |M_F|^2 m_e^5 c^4}{2\pi^3 \hbar^7} f(Z_d, E_0)$$

$$f(Z, E_0) = \left(\frac{1}{m_e c^2}\right) \int_{mc^2}^{E_0} F(Z, E_e)(E_0 - E_e)^2 (E_e^2 = m_e^2 c^4)^{\frac{1}{2}} E_e dE_e$$

Separates out all electron kinematics/interactions. This formulation let's you substitute in more detailed calculations.

logft - Only the nuclear physics.

$$\frac{1}{\tau} = \frac{G_W^2 |M_F|^2 m_e^5 c^4}{2\pi^3 \hbar^7} f(Z_d, E_0)$$

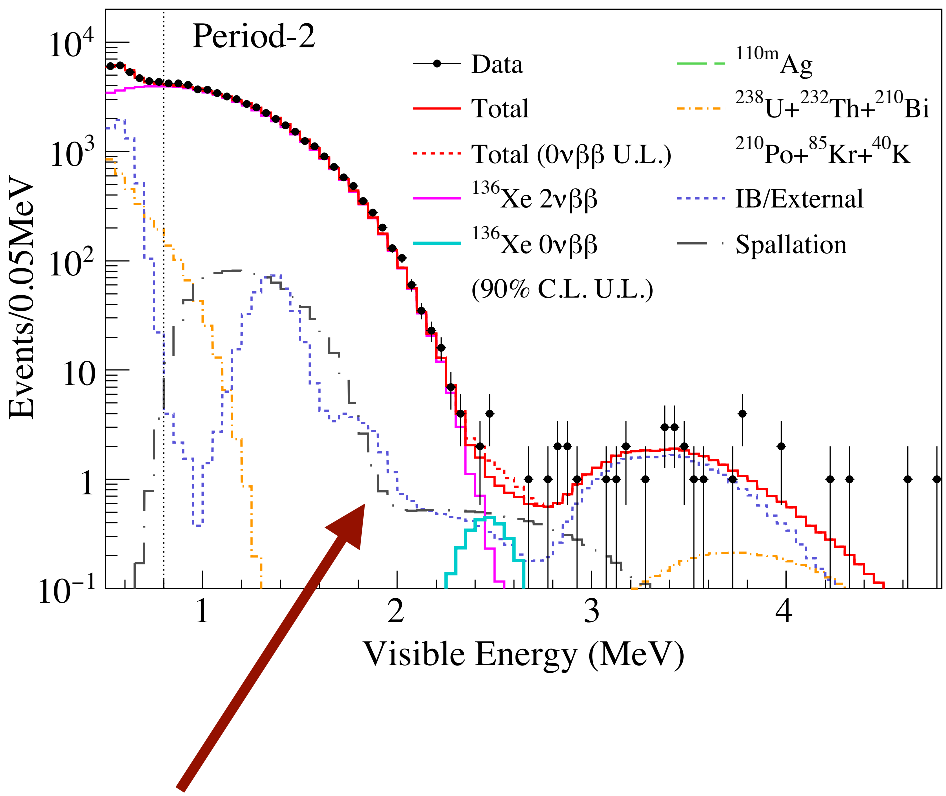
Table 8-2. Classifications of β-decay Transitions

Transition Type	Log ft	L_β	Δπ	Fermi ΔJ	Gamow-Teller ΔJ
Superallowed	2.9 – 3.7	0	No	0	0
Allowed	4.4 – 6.0	0	No	0	0,1
First forbidden	6 – 10	1	Yes	0,1	0,1,2
Second forbidden	10 – 13	2	No	1,2	1,2,3
Third forbidden	> 15	3	Yes	2,3	2,3,4

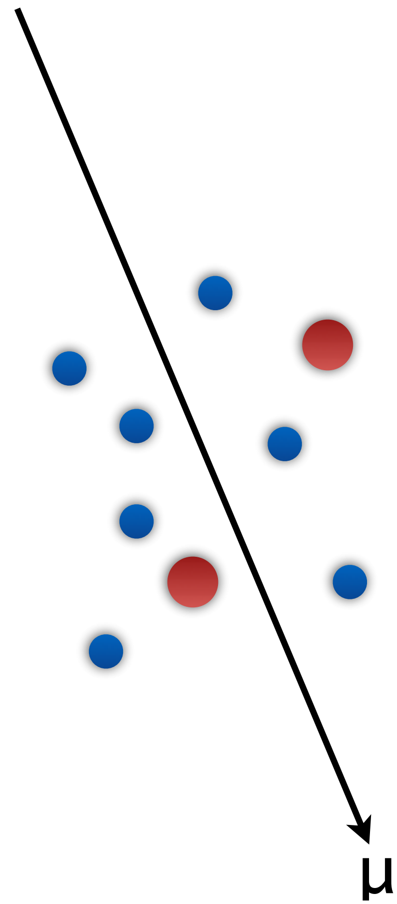
Oregon Course

^{40}K, Why is it so long-lived?

^{208}Tl, What does it look like inside and outside a detector? (contained and not contained)



What is this?



Muon travels through making lots of neutrons and other things including light isotopes.

Neutron Production:

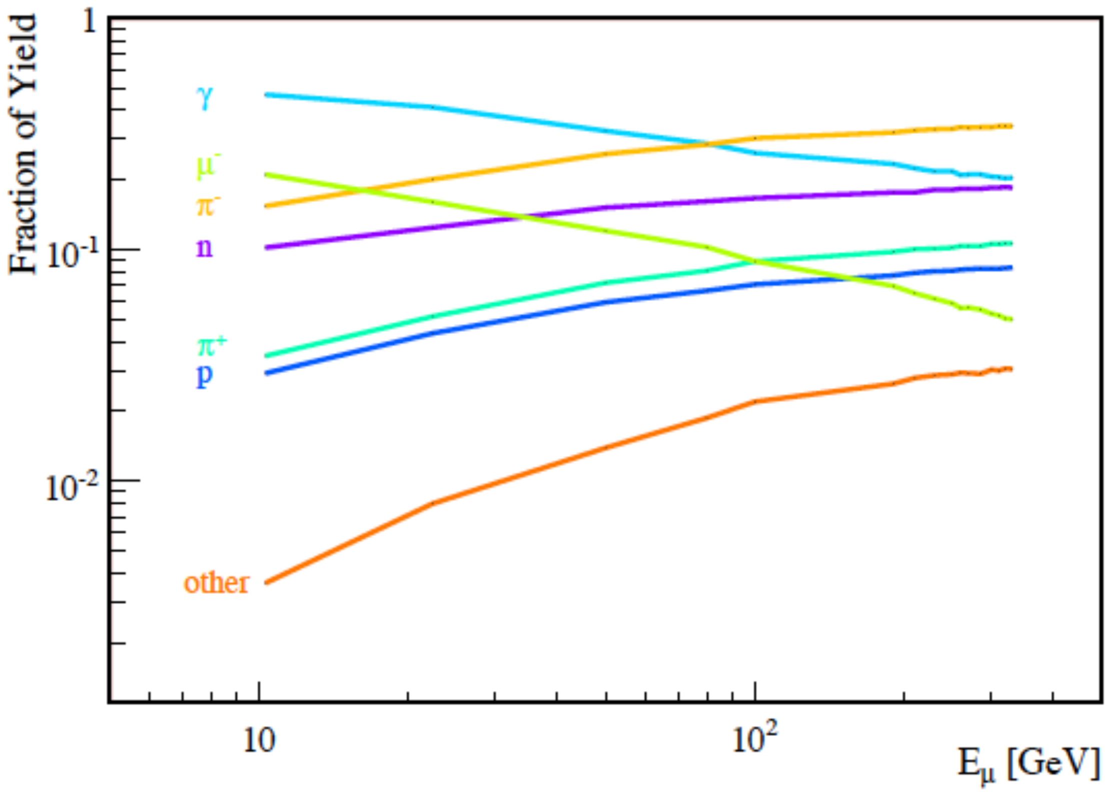


Figure 7.4: Neutron producing process initiator as a function of muon energy as calculated by FLUKA. At low energies most neutrons are produced by (γ, n) reactions. Above 100 GeV pion induced reactions dominate.

Light Isotope Production:

Table 7.3: Light isotope production at $E_\mu = 260$GeV and the exponent of a power law fit to the simulation data.

Isotope	N $\times 10^{-8}$ per μ g/cm^2	Dominant Process	Power Law Exponent
^{11}C	4608.33 ± 17.19	^{12}C(γ, n)	0.703 ± 0.002
^{7}Be	1167.95 ± 8.65	^{12}C(γ, nα)	0.684 ± 0.004
^{10}Be	446.35 ± 5.35	^{12}C(n, ^{3}He)	0.825 ± 0.007
^{12}B	308.53 ± 4.45	^{12}C(n, p)	0.828 ± 0.009
^{8}Li	234.17 ± 3.87	^{12}C(n, pα)	0.821 ± 0.010
^{10}C	211.28 ± 3.68	^{12}C(π^+, np)	0.810 ± 0.010
^{6}He	133.97 ± 2.93	^{12}C(n, 2p^{3}He)	0.818 ± 0.013
^{8}B	63.97 ± 2.03	^{12}C(π^+, ^{2}H^{2}H)	0.804 ± 0.019
^{9}Li	35.06 ± 1.50	^{12}C(π^-, ^{3}He)	0.801 ± 0.026
^{9}C	14.94 ± 0.98	^{12}C(π^+, ^{3}H)	0.772 ± 0.039
^{12}N	8.59 ± 0.74	^{12}C(p, n)	0.921 ± 0.045
^{11}Be	9.36 ± 0.77	^{12}C(n, 2p)	0.753 ± 0.051
^{8}He	3.53 ± 0.48	^{12}C(π^-, ^{3}H)	0.926 ± 0.078
^{13}B	3.14 ± 0.45	^{13}C(n, p)	0.742 ± 0.075
^{15}O	0.51 ± 0.18	^{13}C(p, n)	0.793 ± 0.244
^{13}N	0.64 ± 0.20	^{16}O(γ, n)	1.120 ± 0.220

Where does ^{60}Co come from?

http://www.nndc.bnl.gov/sigma/

or

http://www.nndc.bnl.gov/exfor/exfor.htm

Hint: (n, alpha)