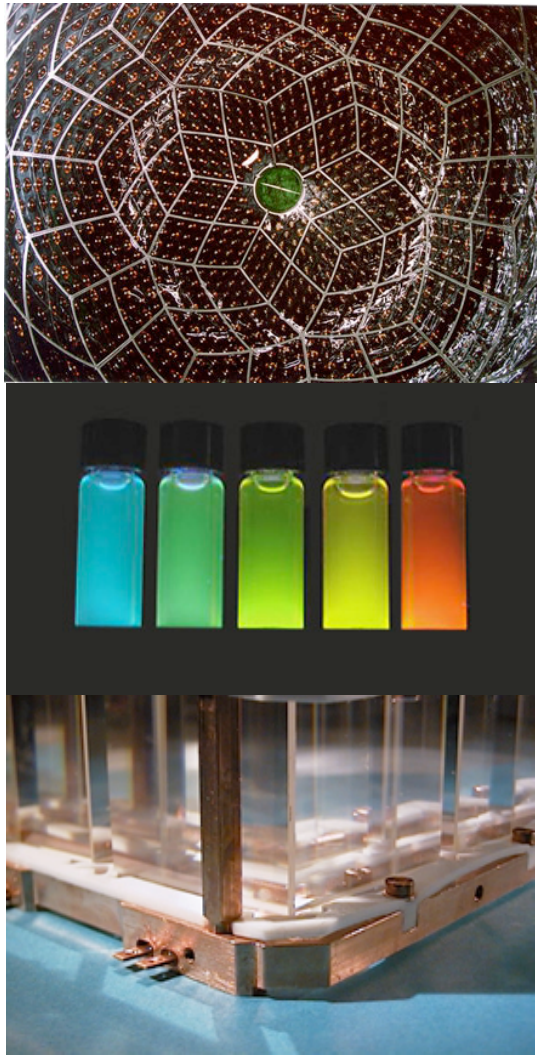
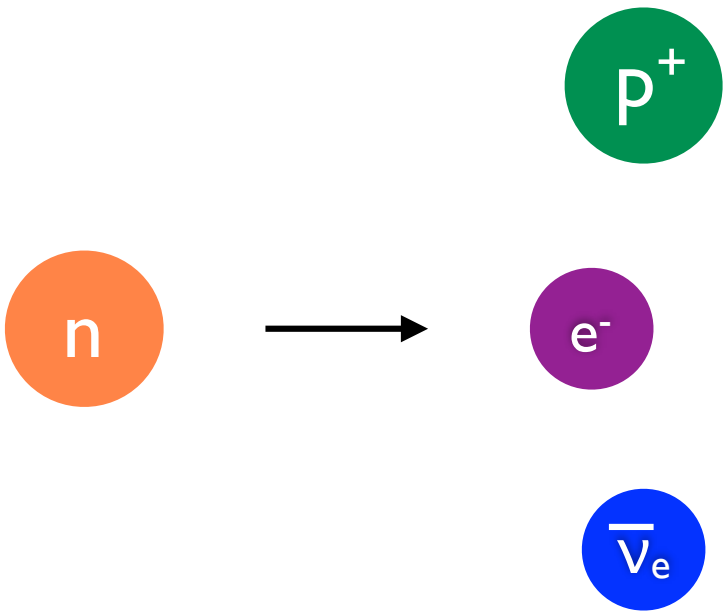


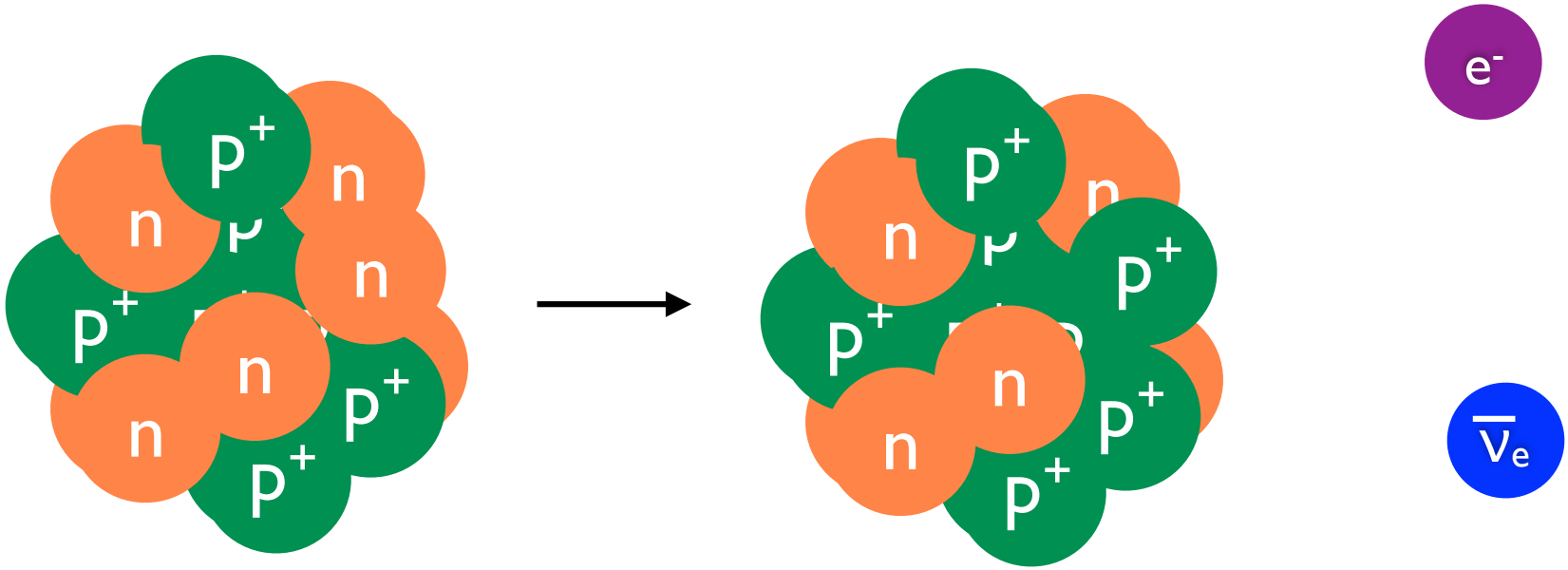
Bigger or Colder: Majorana Neutrinos and the Search for Neutrinoless Double-Beta Decay

Lindley Winslow
Massachusetts Institute of Technology

This is beta decay.



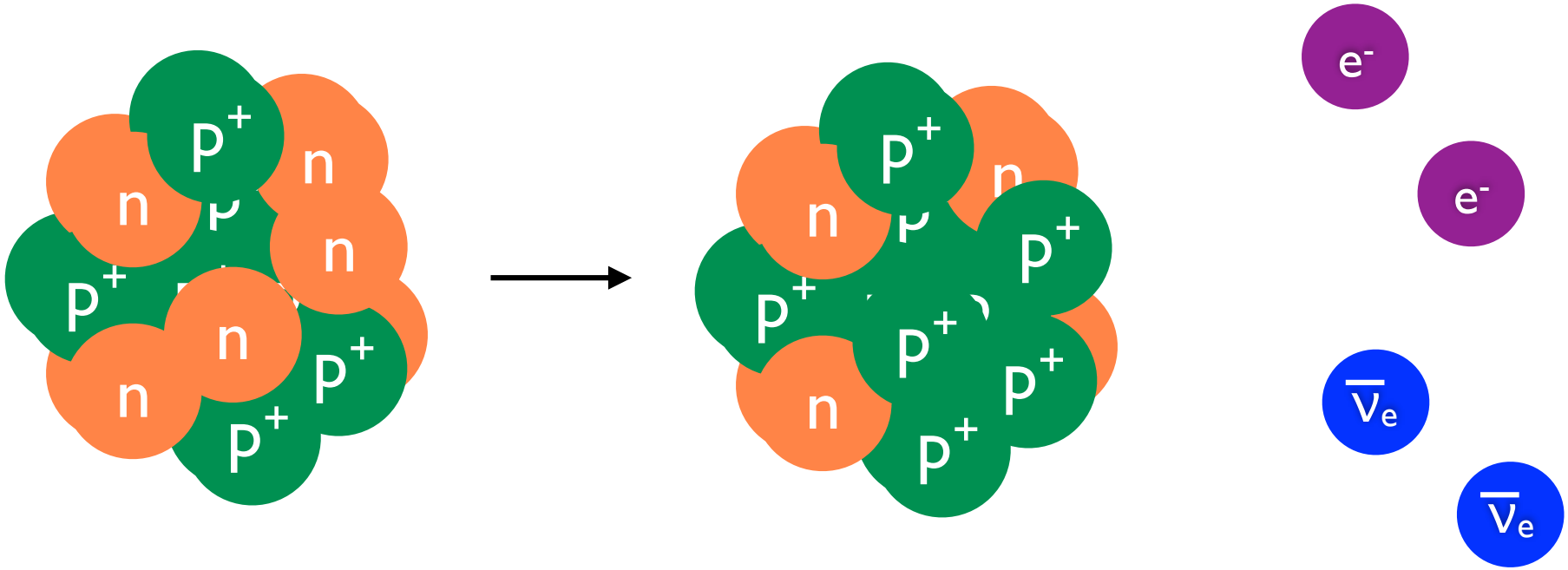
It usually takes place in a nucleus.



Z=number of protons
A=number of neutrons plus protons

Z+1
A=same

This is double-beta decay.

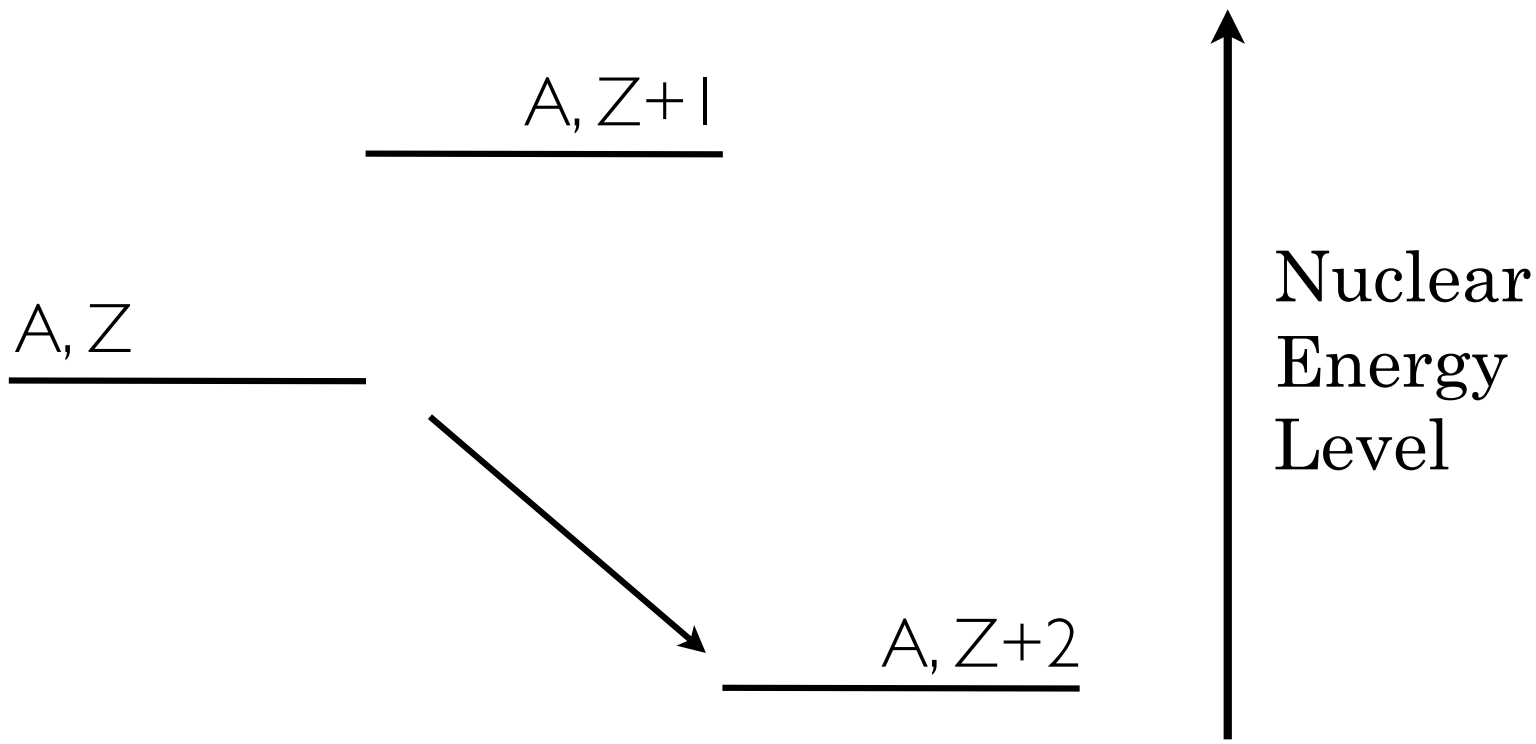


Z+2
A=same

Change in number of leptons is zero.

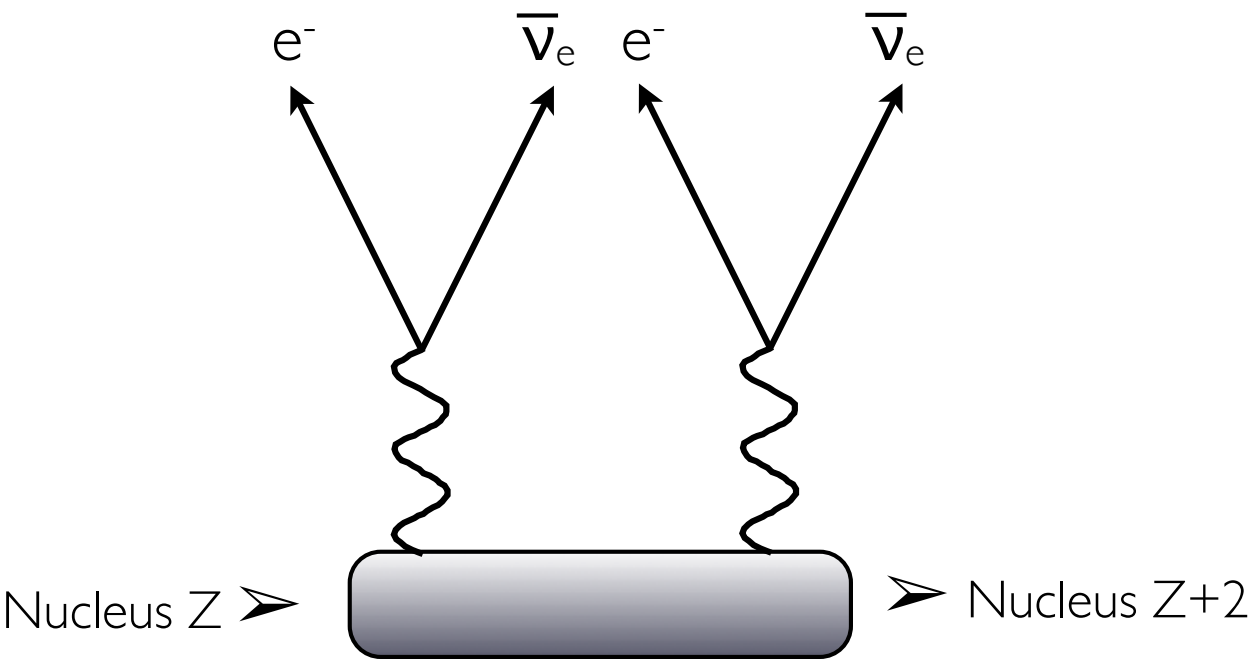
Double Beta Decay

Due to energy conservation some nuclei can't decay to their daughter nucleus, but can skip to their "granddaughter" nucleus.



The Standard Model Process

This process is completely allowed and the rate was first calculated by Maria Goeppert-Mayer in 1935.

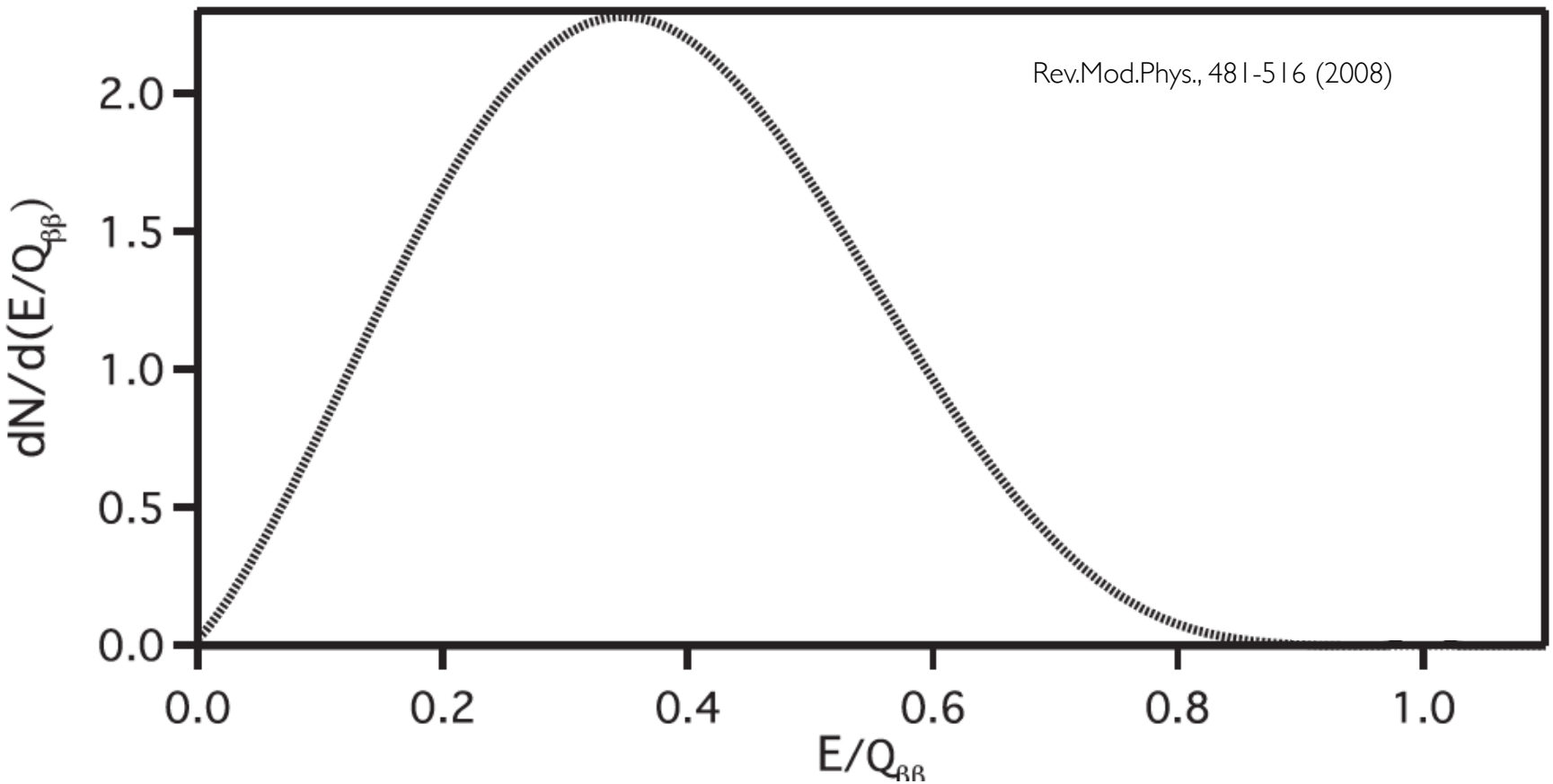


Nuclear Process

Phys. Rev. 48, 512-516 (1935)

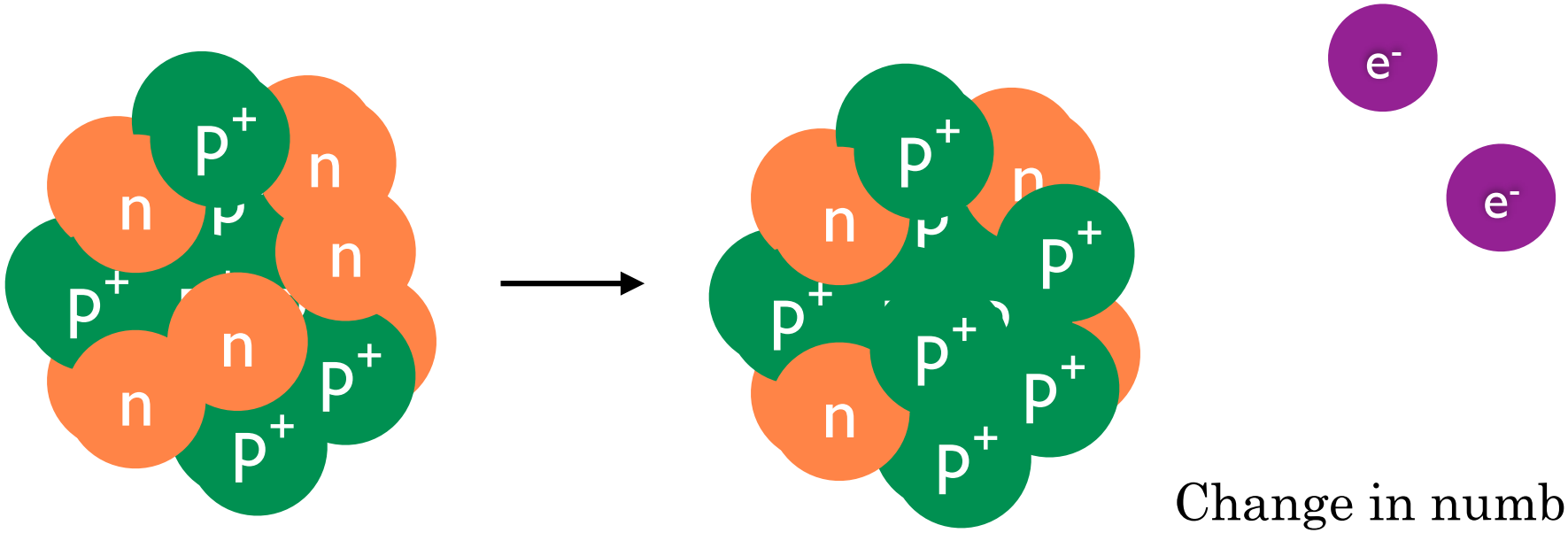
Double Beta Decay

The sum of the electron energies gives a spectrum similar to the standard beta decay spectrum.

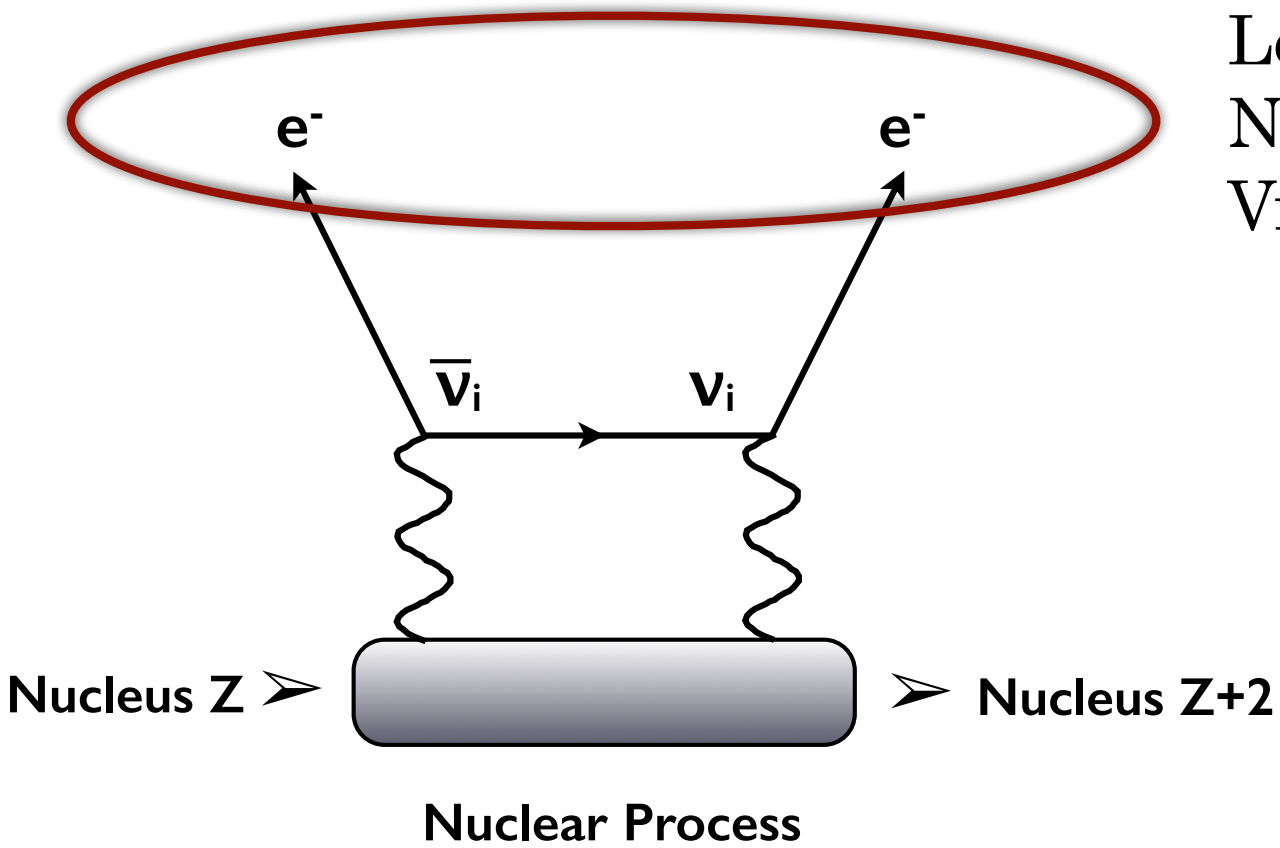


This has been observed in most interesting isotopes.

This is neutrinoless double-beta decay.



Change in number of leptons is plus 2!



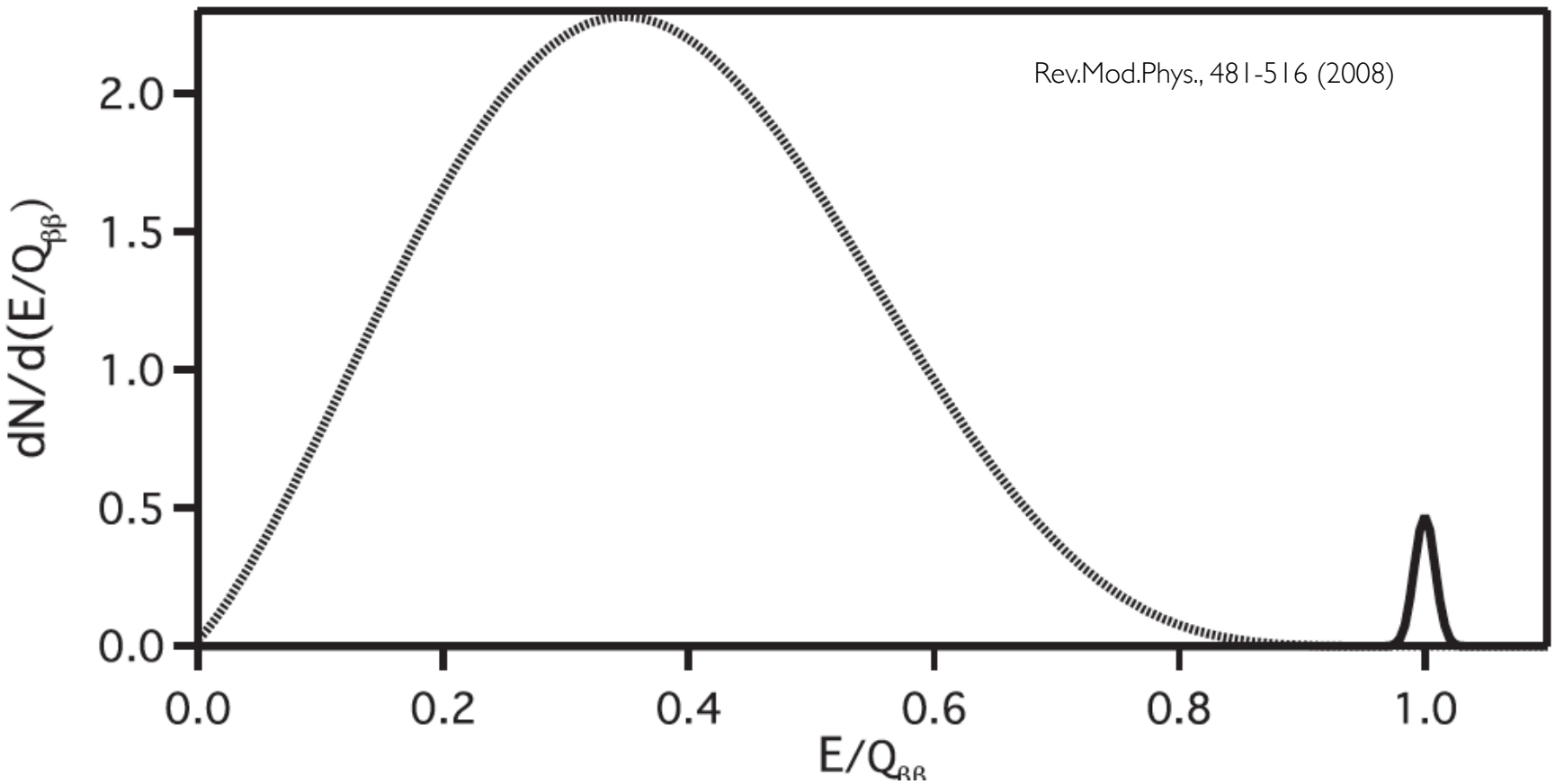
Lepton Number Violation!

Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)

Double Beta Decay

The sum of the electron energies gives a spike at the endpoint of the 2v double beta decay.



What is measured is a half-life...

The half-life of the neutrinoless decay via LMNE:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Phase space factor

- This is a difficult calculation, dependent on the decay mechanism.
- Notice higher endpoint means faster rate.

Common Candidates:

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	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

See ATOMIC DATA AND NUCLEAR DATA TABLES 61, 43-90 (1995) for all 69+19!

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2.$$

Nuclear Matrix Element

This is a VERY difficult calculation with large errors and substantial variation between isotopes...motivates searches with multiple isotopes!

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

Effective Majorana
Mass of the neutrino

Electron Neutrino Mass:

$$m_{\nu_e}^2 = \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Effective Majorana Mass:

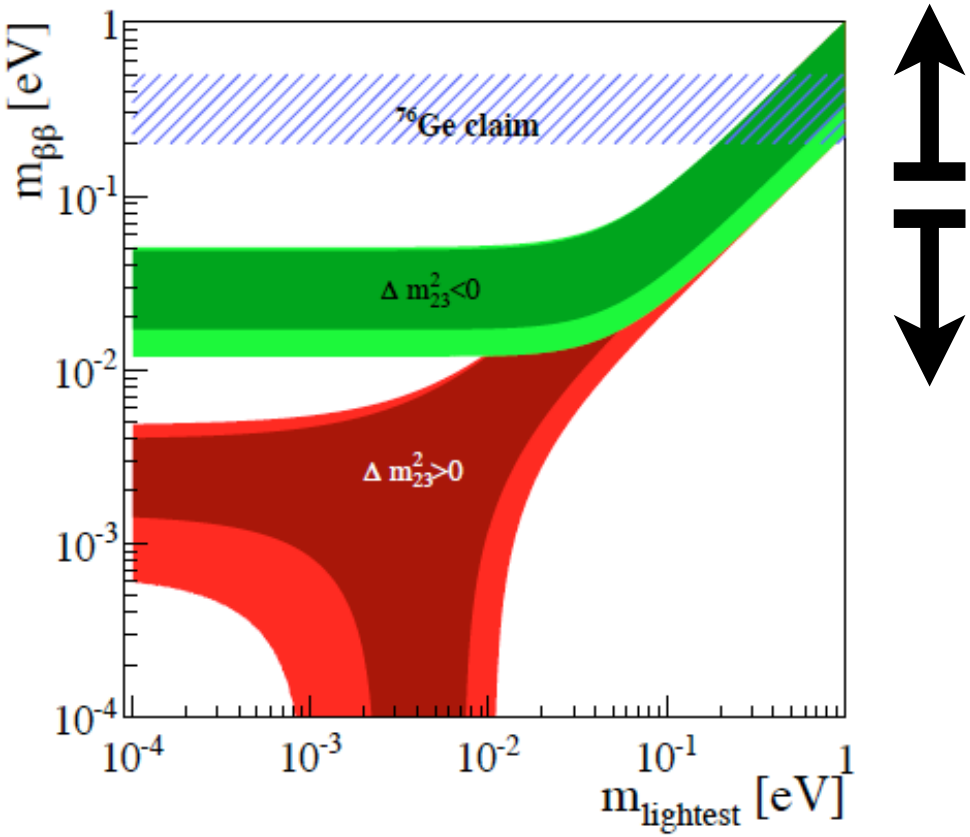
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

Two more phases!

Double Beta Decay Parameter Space:

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$



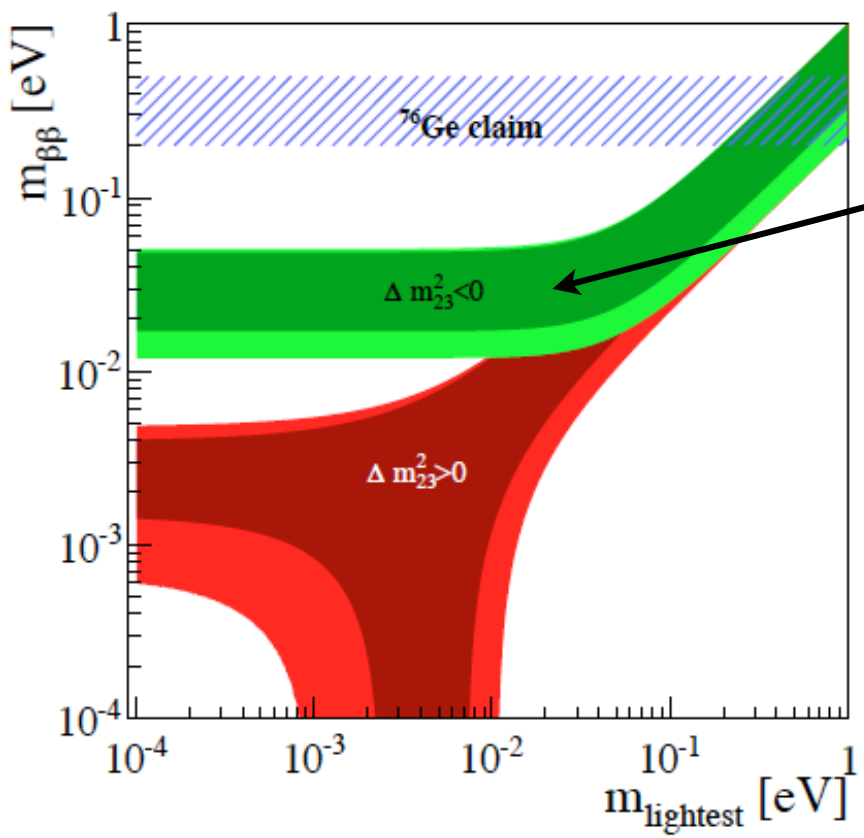
excluded

more sensitive experiments needed

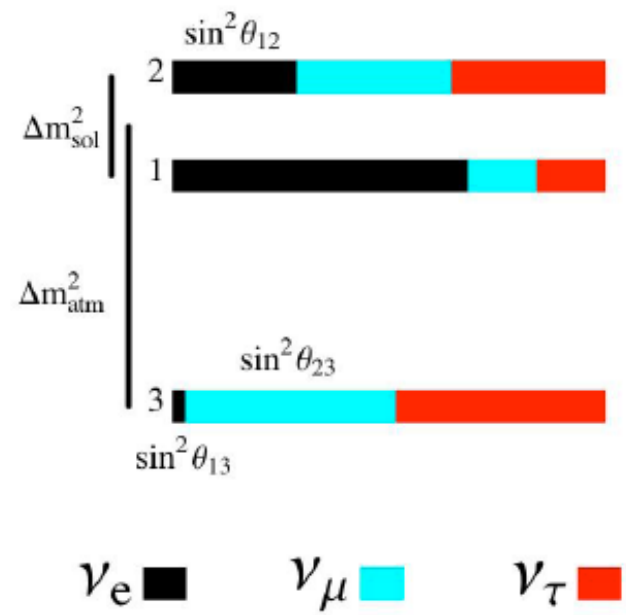
As experiments become more sensitive they push down in this parameter space excluding larger masses.

Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$

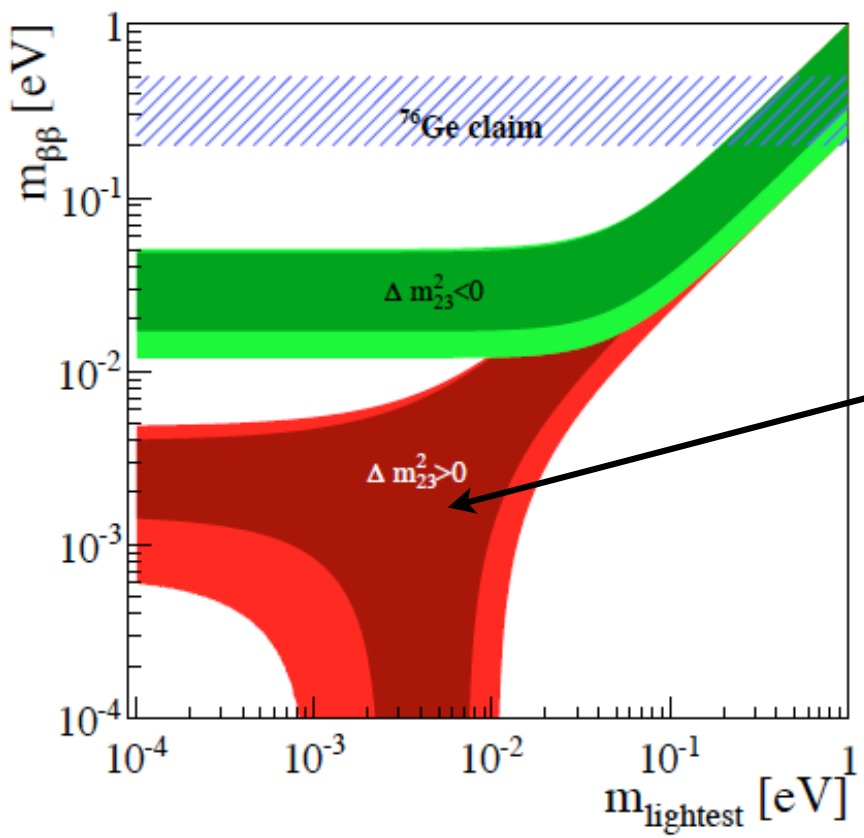


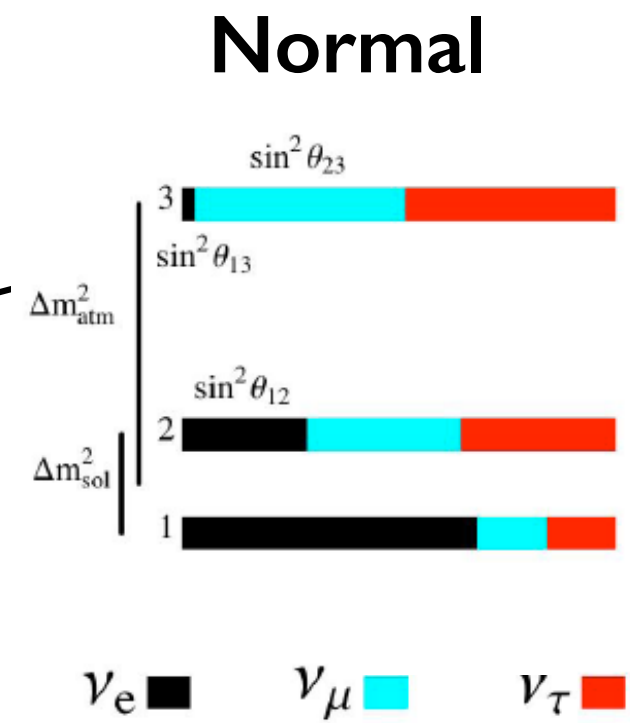
Inverted



Double Beta Decay Visualizing the Equations:

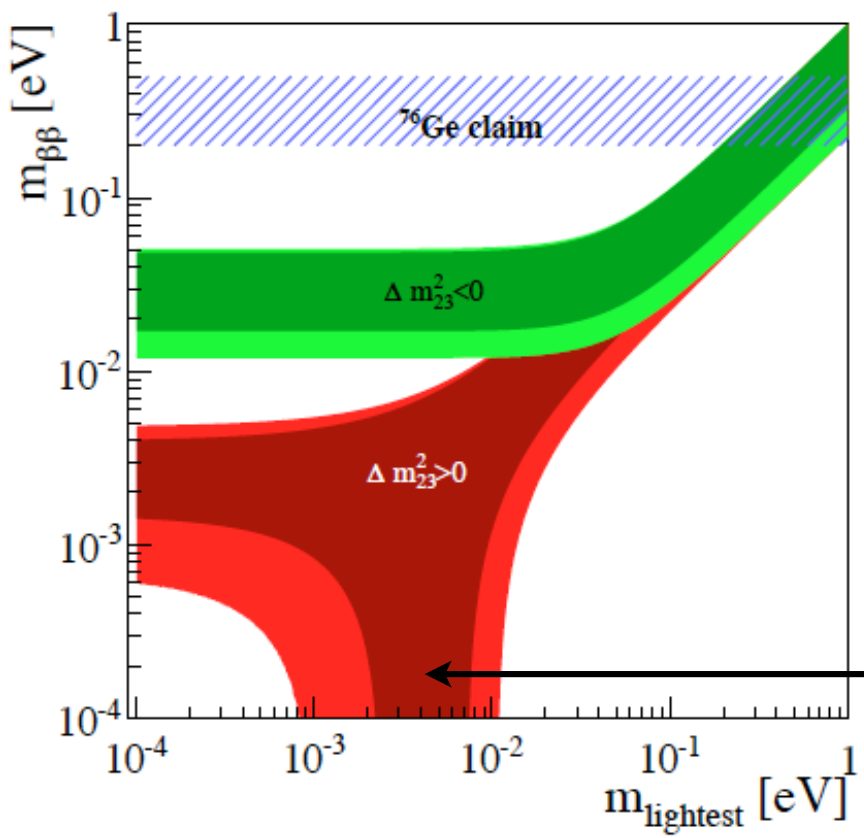
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$





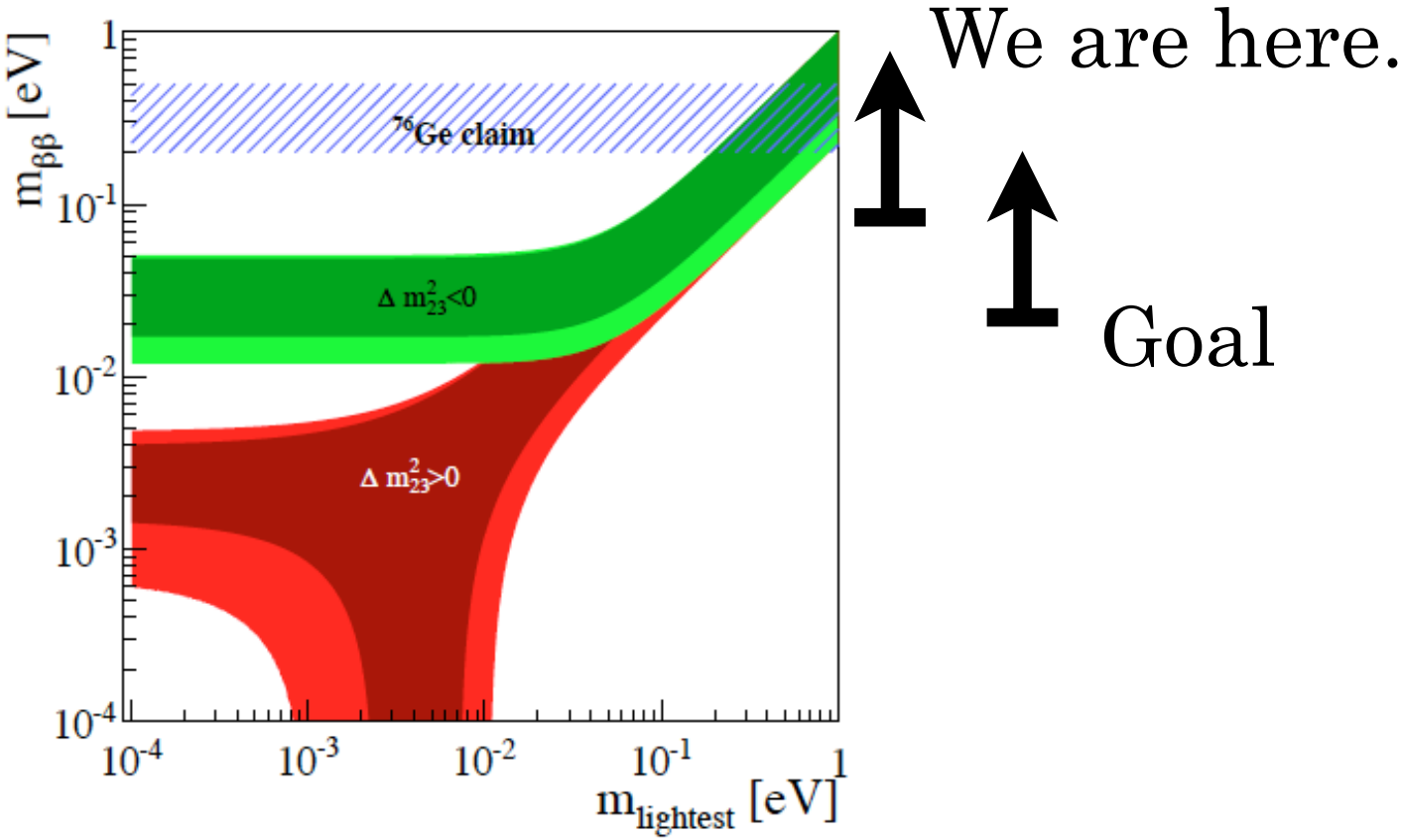
Double Beta Decay Visualizing the Equations:

$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3 \sin^2\theta_{13}$$

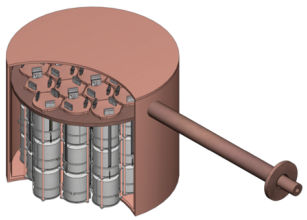


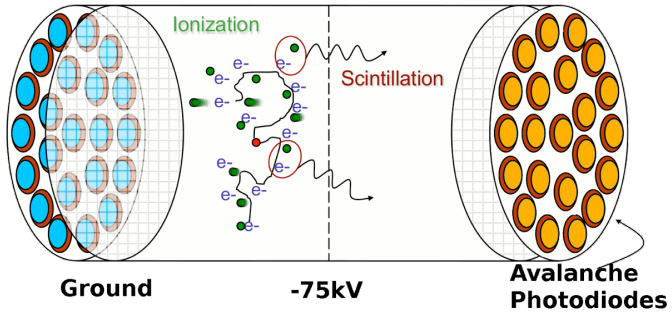
The dark part of the width of these bands is real and if nature is cruel there could be some very nasty interference.

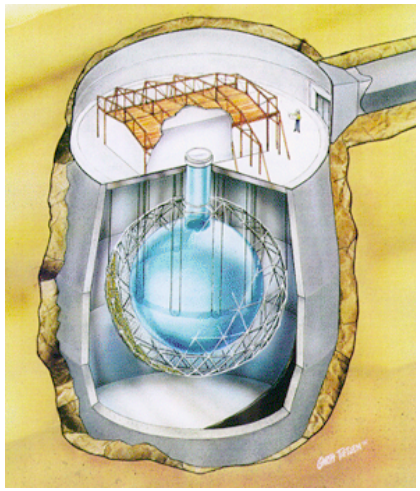
Goal: Definitive search in the Inverted Hierarchy (IH)

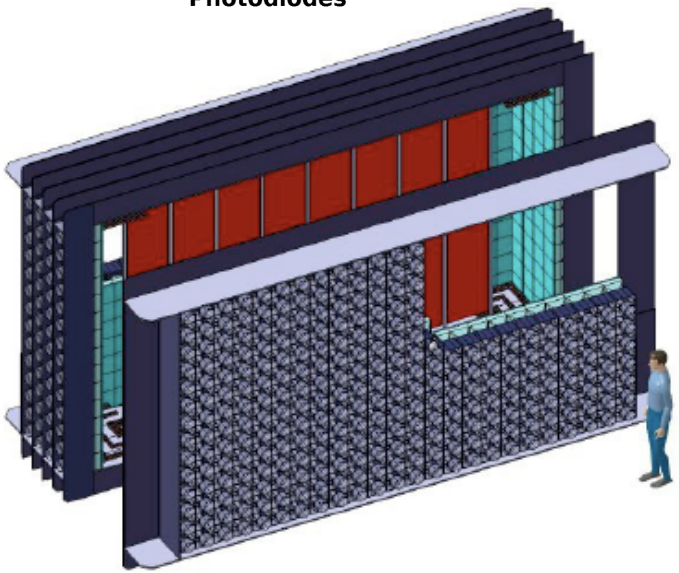


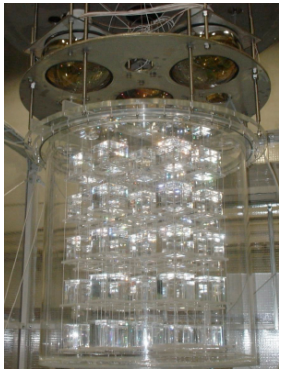
A lot of detector ideas:

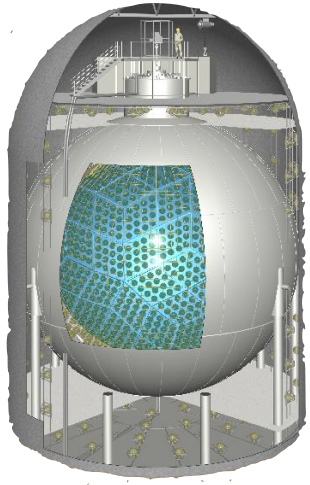


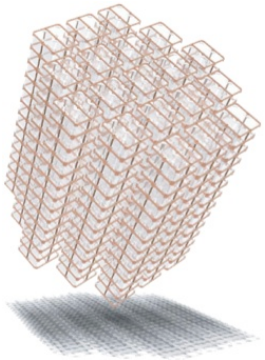


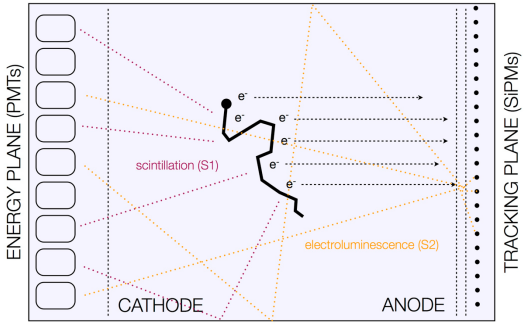




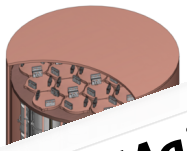




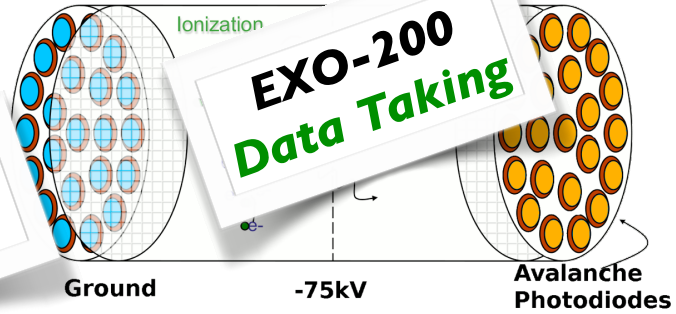




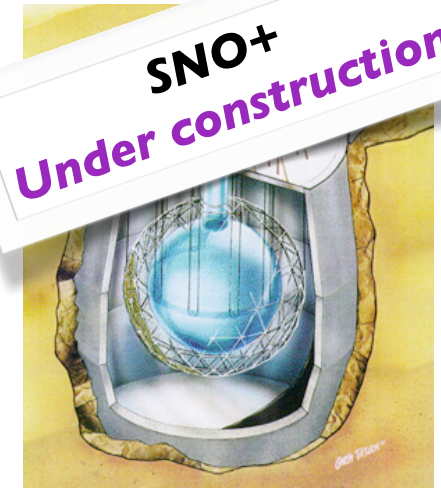
A lot of detector ideas:



Majorana
Data Taking



EXO-200
Data Taking



SNO+
Under construction

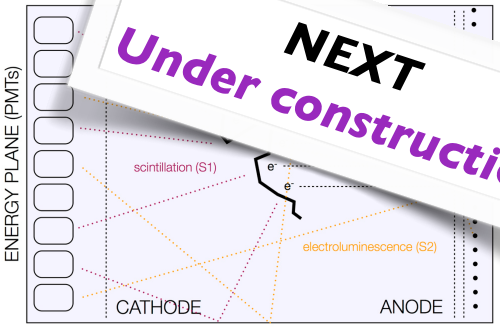
GERDA
Data Taking

SuperNEMO
Under construction

CANDLES
Complete

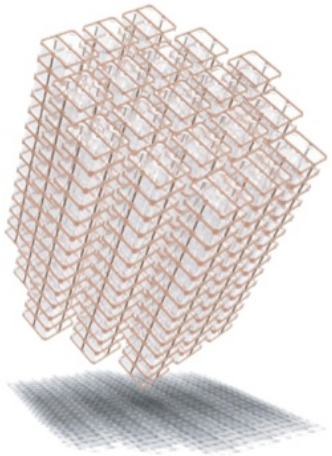
KamLAND-Zen
Data Taking

CUORE
Data Taking



NEXT
Under construction

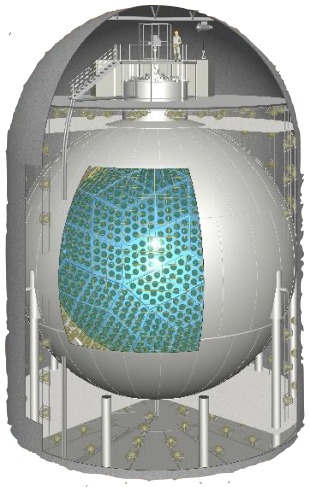
Good
Energy
Resolution



Bolometers

More Difficult
to make big.

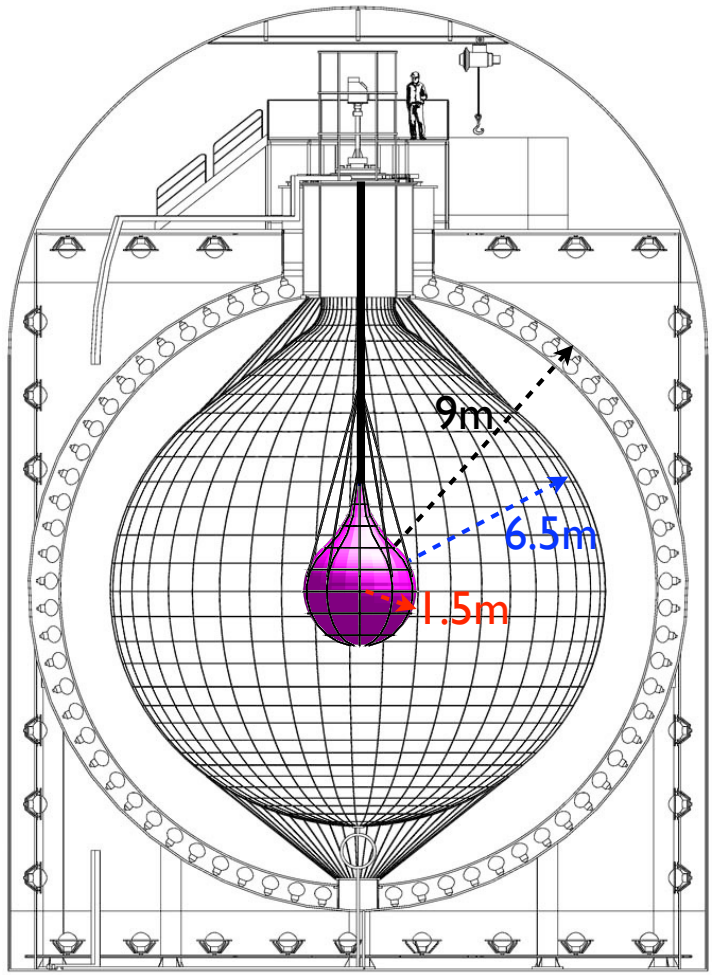
Good
at Size



Scintillator

Bad Energy
Resolution

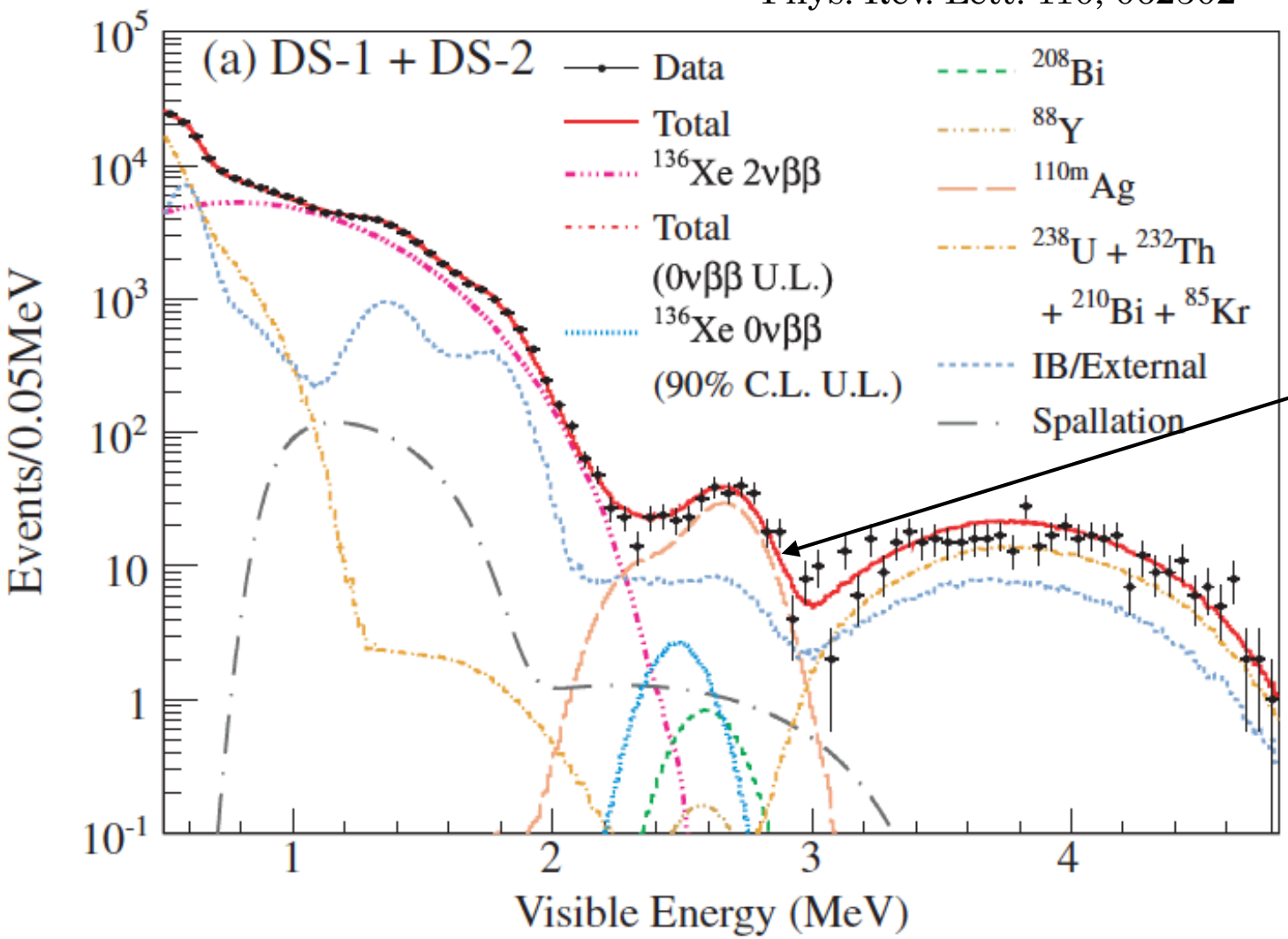
KamLAND-Zen



Phase I: 320 kg 90% enriched ^{136}Xe
Phase II: 380 kg

KamLAND-Zen started in 2011:

Phys. Rev. Lett. 110, 062502

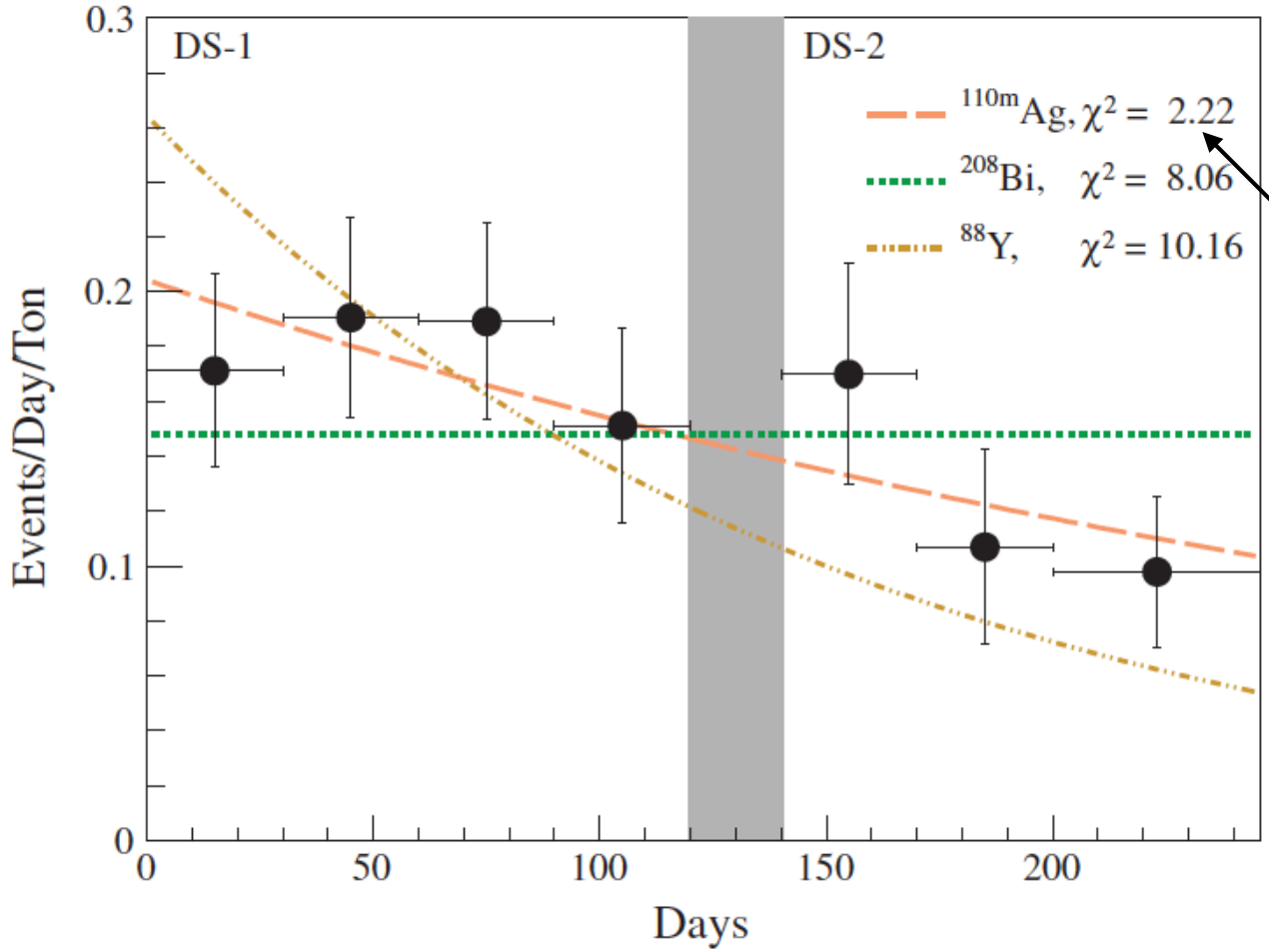


What is this?

Exposure=89.5 kg-years.

KamLAND-Zen started in 2011:

Phys. Rev. Lett. 110, 062502



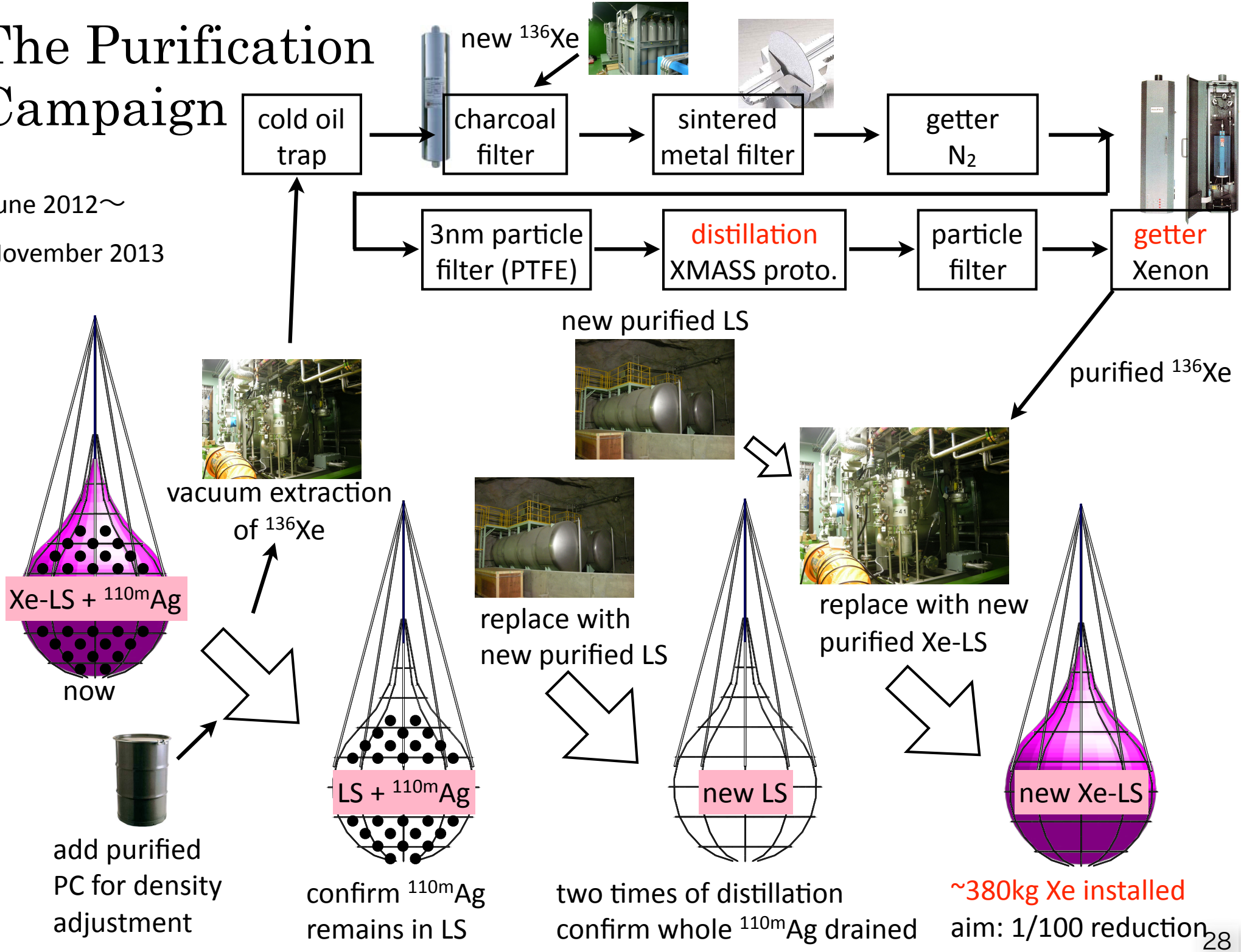
Decay matches a metastable silver isotope which is a common fission product.

Exposure=89.5 kg-years.

The Purification Campaign

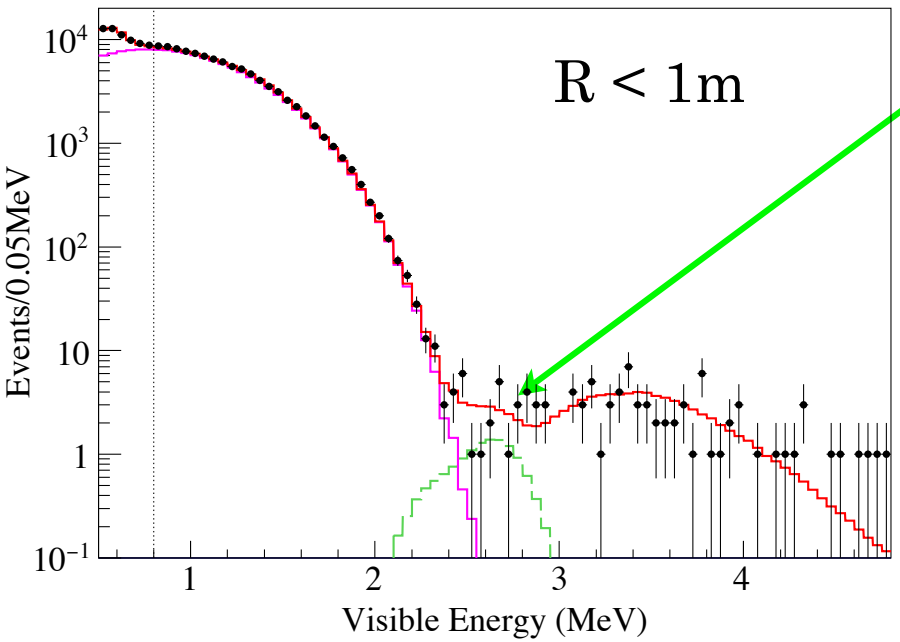
June 2012～

November 2013



KamLAND-Zen Phase 2: Post Purification

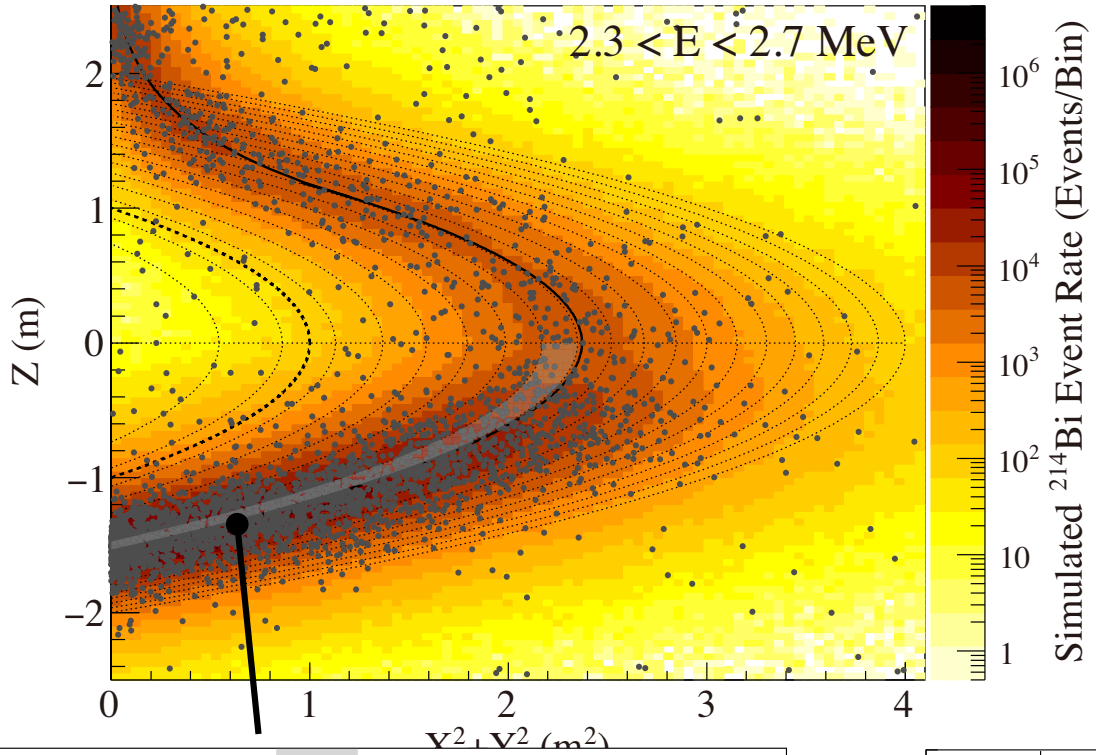
^{110m}Ag still exists?



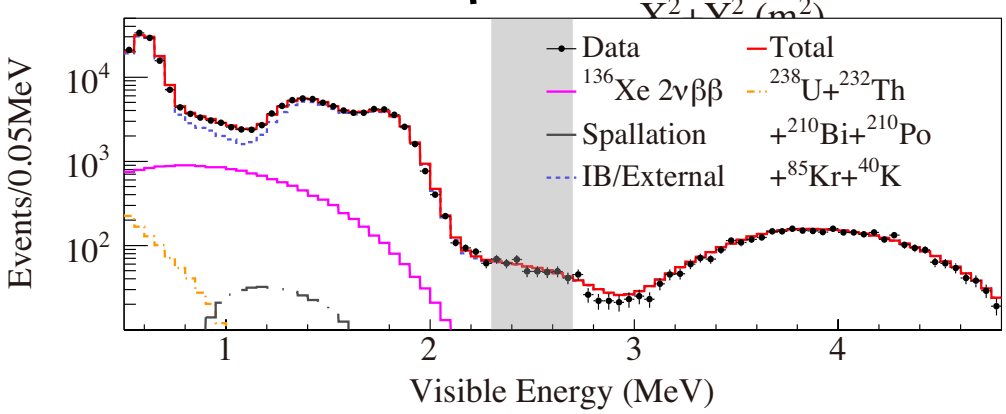
Full phase-2 data-set

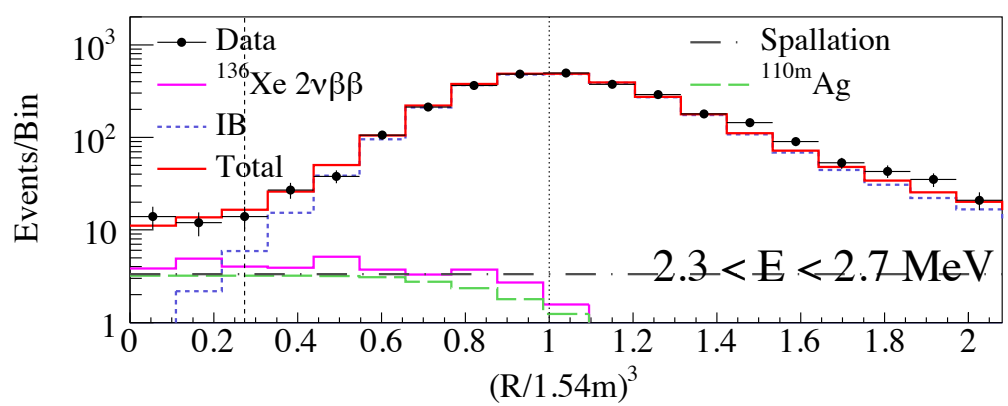
- After Purification
- December 2013 - October 2015
- Livetime 534.5 days, exposure 504 kg-yr
- For Reference: $T_{1/2}(^{110m}Ag)$ = 250 days.

Analysis uses Energy and Position!



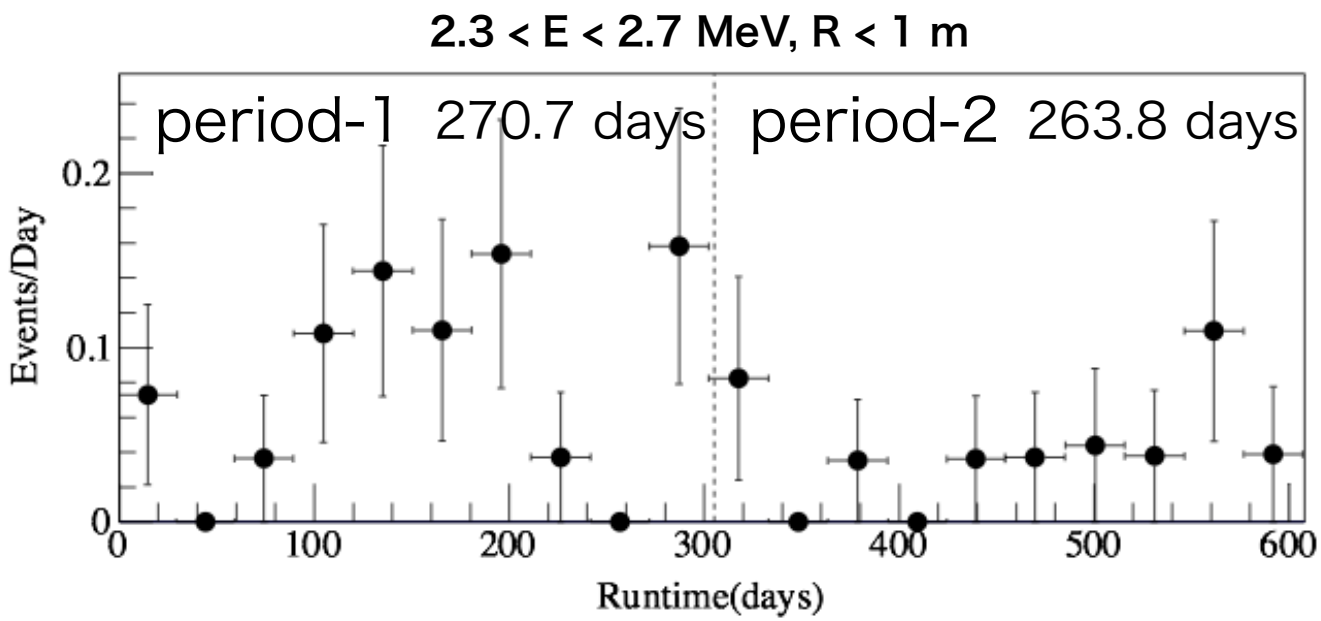
Fit constructed from 40 Equal volume bins.





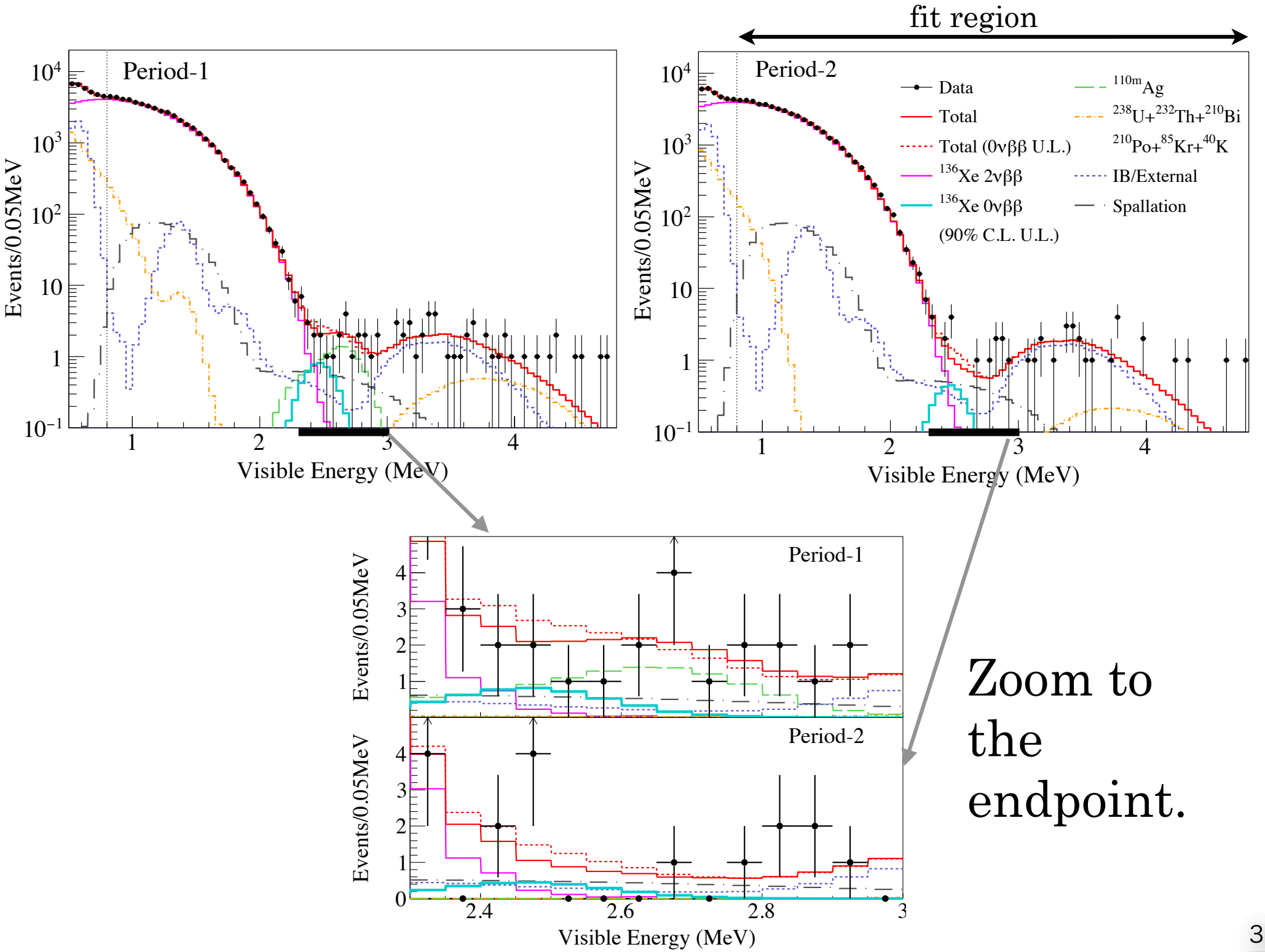
Energy and radial distributions are well-reproduced by known BGs.

Analysis uses two time periods.



22 events 11 events

Hypothesis is that “dust” sank, however also consistent with a simple decay at 2σ.


fit region
Period-1
Period-2
Events/0.05MeV
Visible Energy (MeV)
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
Zoom to the endpoint.

Phase 2 - Results on 0ν2β

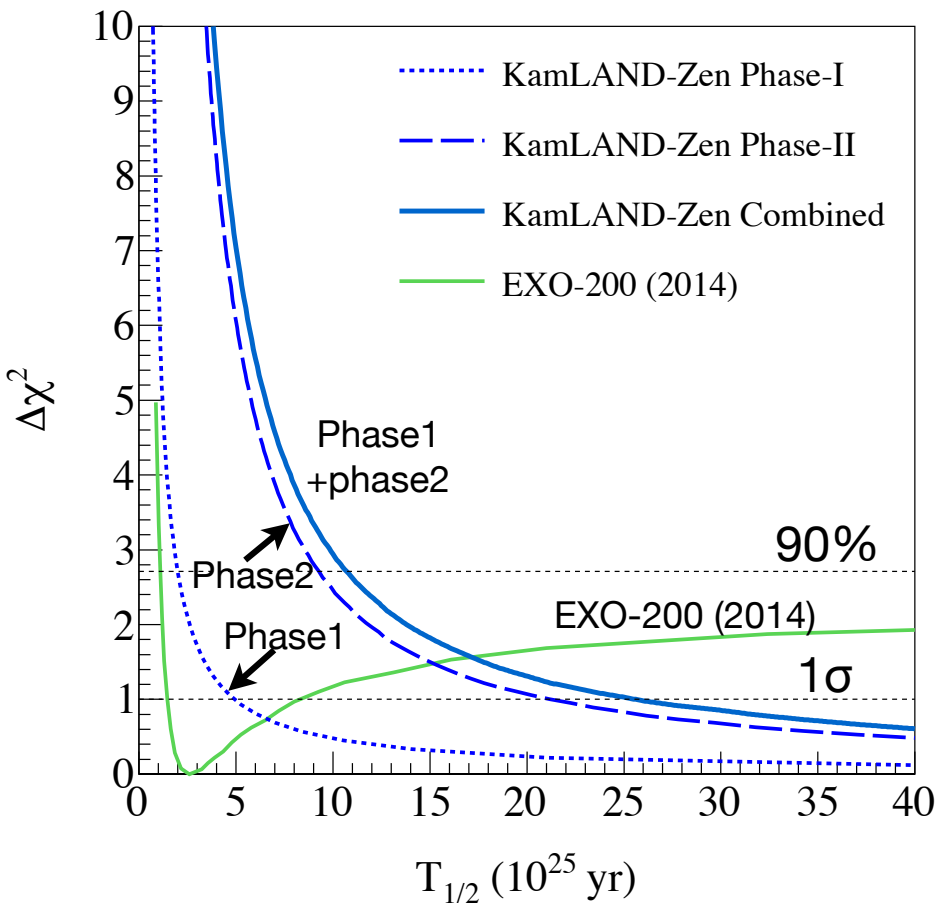
	period-1	period-2
livetime	270.7 days	263.8 days
^{136}Xe 0ν2β decay rate	< 5.5 /kton/day	< 3.5 /kton/day

combined < 2.4 /kton/day (90%C.L.)

^{136}Xe 0ν2β half-life > 9.2×10^{25} yr (90%C.L.)

sensitivity > 4.9×10^{25} yr (11% probability)

^{136}Xe 0νββ Decay Half-life



KamLAND-Zen
Half-life limit (@90%C.L.)

Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

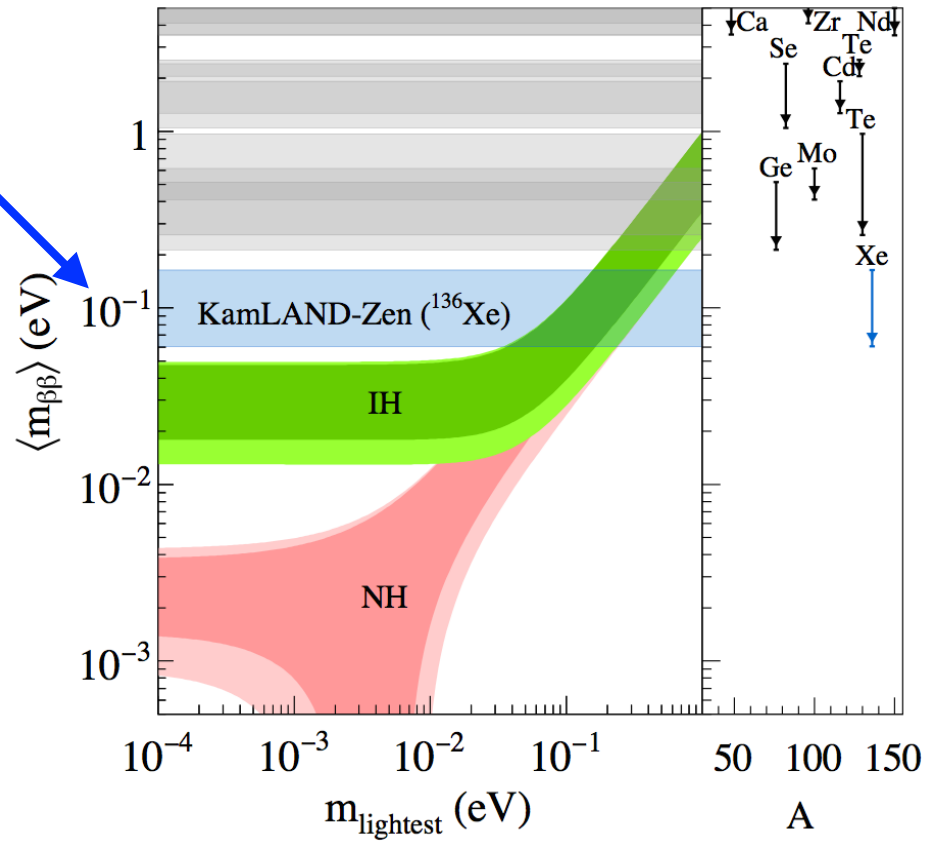
Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

Combined $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

^{136}Xe 0νββ Decay Half-life

$\langle m_{\beta\beta} \rangle$ < (61- 165) meV

90%C.L. upper limits on $\langle m_{\beta\beta} \rangle$



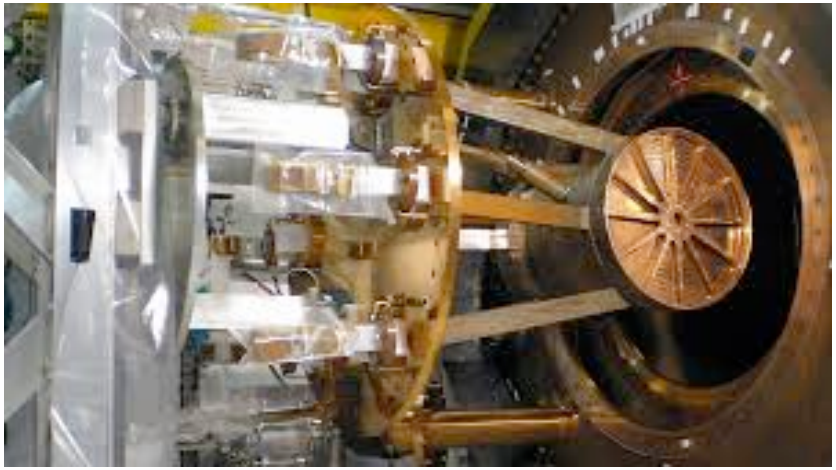
Commonly used NME with g_A~1.27,
Improved phase space calculations.

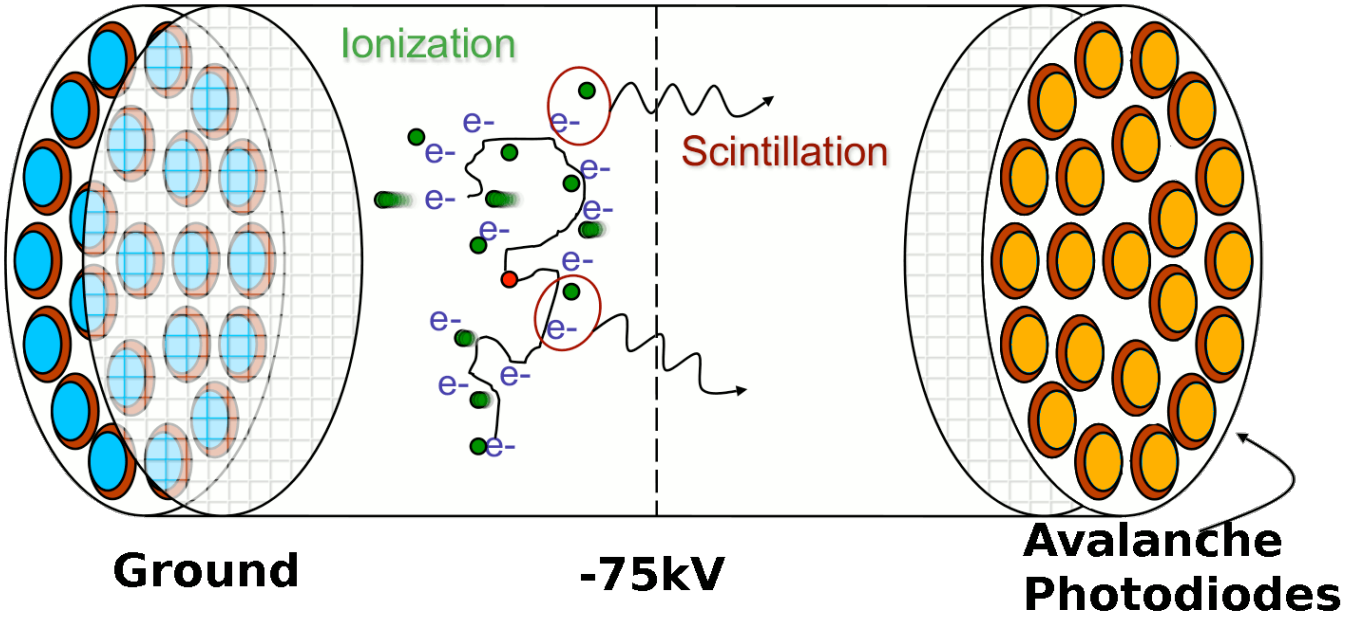
Getting Ready to enter the inverted hierarchy with KamLAND-Zen 800!

Enriched Xenon Observatory

EXO

for double beta decay





EXO-200

- Liquid xenon time projection chamber (~150 kg, enriched to 80% ^{136}Xe)
- Topological discrimination and σ = 1.3% energy resolution
- Taking data since 2011:

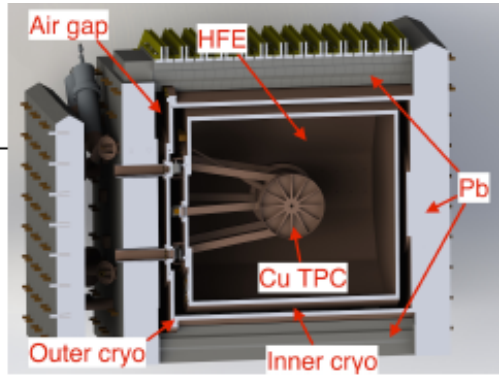
  Phase I: Sept 2011 – Feb 2014
  (~100 kg yr)
  Phase II: May 2016 - present
  (~200 kg yr with upgrades, projected)

- Phase 1 results:

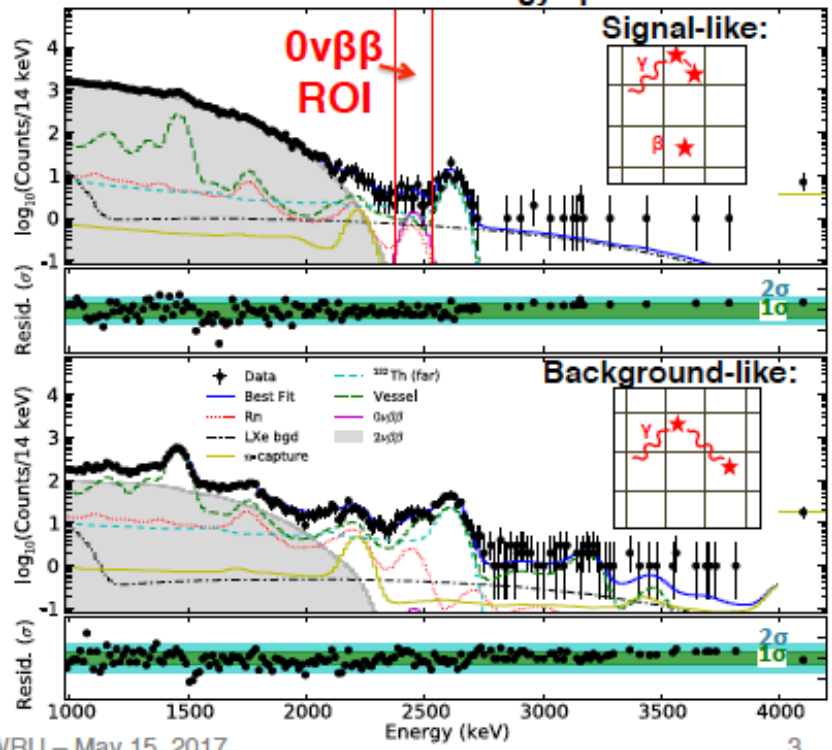
$T_{1/2}^{2\nu\beta\beta}$ = 2.172 ± 0.017 ± 0.060 ·10^{21} yr
(stat.) (syst.)
*Phys. Rev. C **89**, 015502, arXiv:1306.6106 (2013)*

$T_{1/2}^{0\nu\beta\beta}$ > 1.1 ·10^{25} yr
$\langle m_{\beta\beta} \rangle$ < 190 - 450 meV
*Nature **510**, 229, arXiv:1402.6956 (2014)*

- First Phase 2 results in summer 2017



EXO-200 Phase 1 energy spectrum:



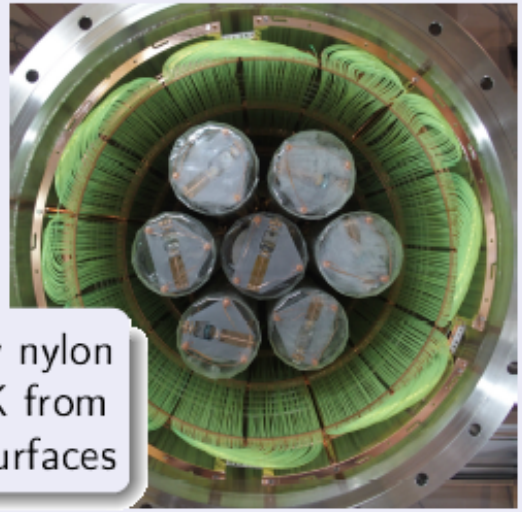
GERDA: A Search in ^{76}Ge

Phase II: Final Integration ... in Dec 2015

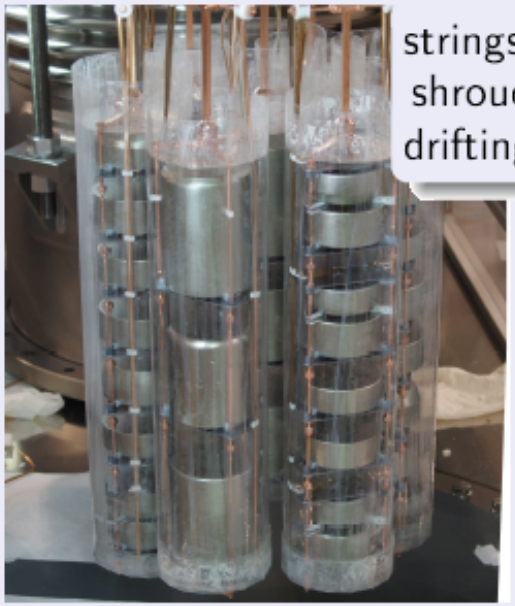
40 detectors (all working) in 7 strings:

1. 30× ^{enr}BEGe (20.0 kg)
2. 7× ^{enr}semi-coaxial (15.8 kg)
3. 3× ^{nat}semi-coaxial (7.6 kg)

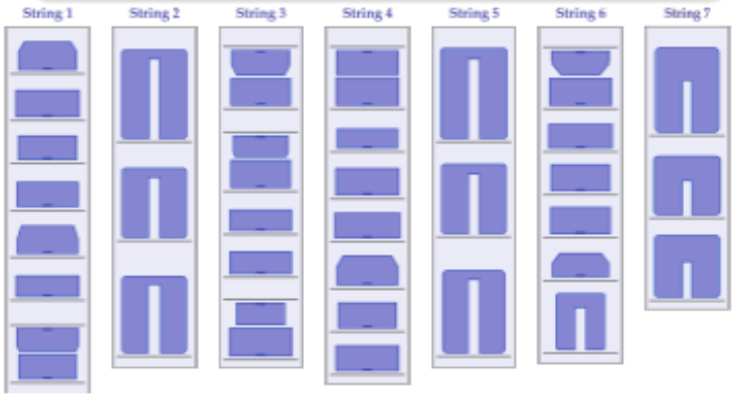
bottom view



side view

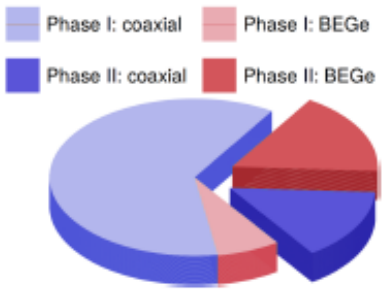


strings surrounded by nylon shroud to reduce ^{42}K from drifting to detector surfaces



First Phase II Result

from Neutrino 2016 data release

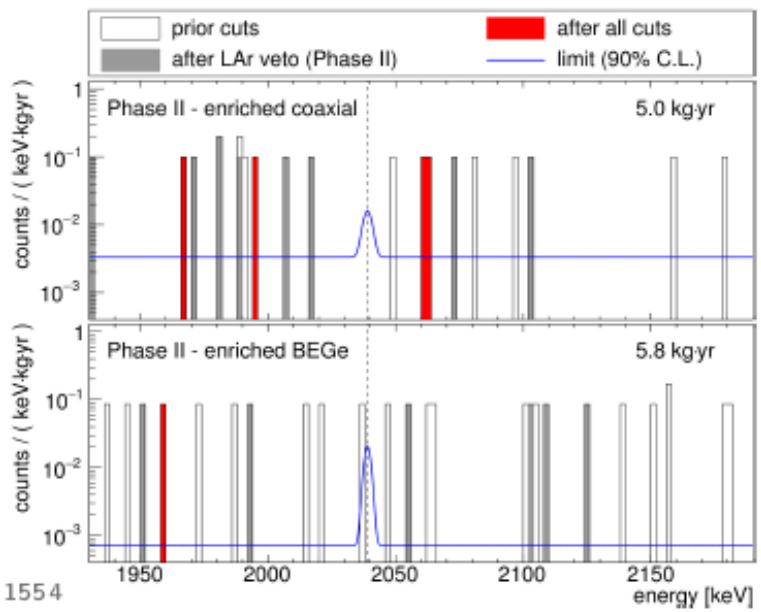


data set	exposure [kg·yr]	$FWHM$ [keV]	efficiency PSD	efficiency total*	BI [$10^{-3}\,\frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}$]
PI golden	17.9	4.3(1)	0.85	0.57(3)	11 ± 2
PI silver	1.3	4.3(1)	0.85	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.92	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.85	0.58(4)	5^{+4}_{-3}
PIIa coaxial	**5.0**	**4.0(2)**	**0.79**	**0.53(5)**	$3.5^{+2.1}_{-1.5}$
PIIa BEGE	**5.8**	**3.0(2)**	**0.87**	**0.60(2)**	$0.7^{+1.1}_{-0.5}$

* including enrichment, active mass, reconstruction efficiencies, dead time

- unbinned profile likelihood:
  6× flat background @ 1930-2190 keV
  1× common Gaussian signal at $Q_{\beta\beta}$

	profile likelihood 2-side test-stat**	Bayesian flat prior
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit [10^{25}yr]	>5.3 (90% CL)	>3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25}yr]	>4.0 (90% CL)	>3.0 (90% CI)



** frequentist test-statisitics & methods EPJC 71 (2011) 1554

Conclusions

- GERDA Phase II is running stable
- 3-4 keV energy resolution @ $Q_{\beta\beta}$
- blind analysis on first 10.8 kg·yr of data
- published in Nature 544 (2017) 47

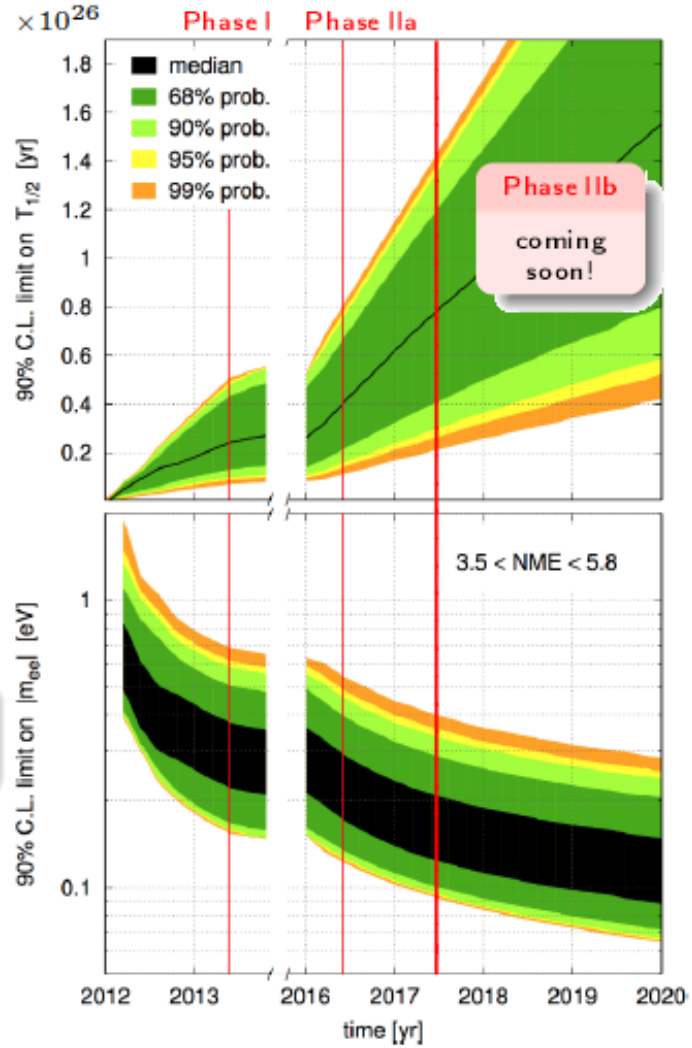
new limit on $0\nu\beta\beta$ decay in ^{76}Ge		
$T^{0\nu}_{1/2}$	$>$	$5.3 \cdot 10^{25}$ yr (90% CL)
$m_{\beta\beta}$	$<$	$(0.15 - 0.33)$ eV (90% CL)

- exposure further increased to 28.5 kg·yr

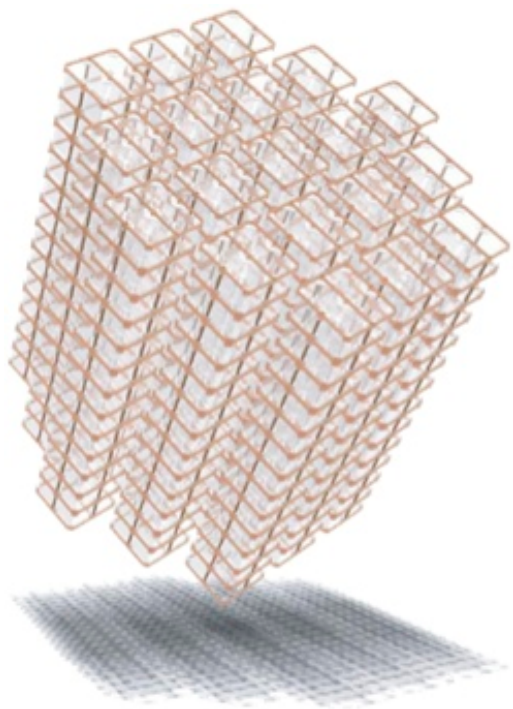
background index @ $Q_{\beta\beta}$	
coaxial	$2.2^{+1.1}_{-0.8} \cdot 10^{-3}$ cts/(keV·kg·yr)
BEGe	$0.6^{+1.1}_{-0.8} \cdot 10^{-3}$ cts/(keV·kg·yr)

GERDA PhaseII is "the" high-resolution and background-free $0\nu\beta\beta$ experiment!

GERDA Phase II goals		
background	$\sim 10^{-3}$ cts/(keV·kg·yr)	✔
exposure	> 100 kg·yr	⏲
sensitivity	$T^{0\nu}_{1/2} > 10^{26}$ yr	⏲

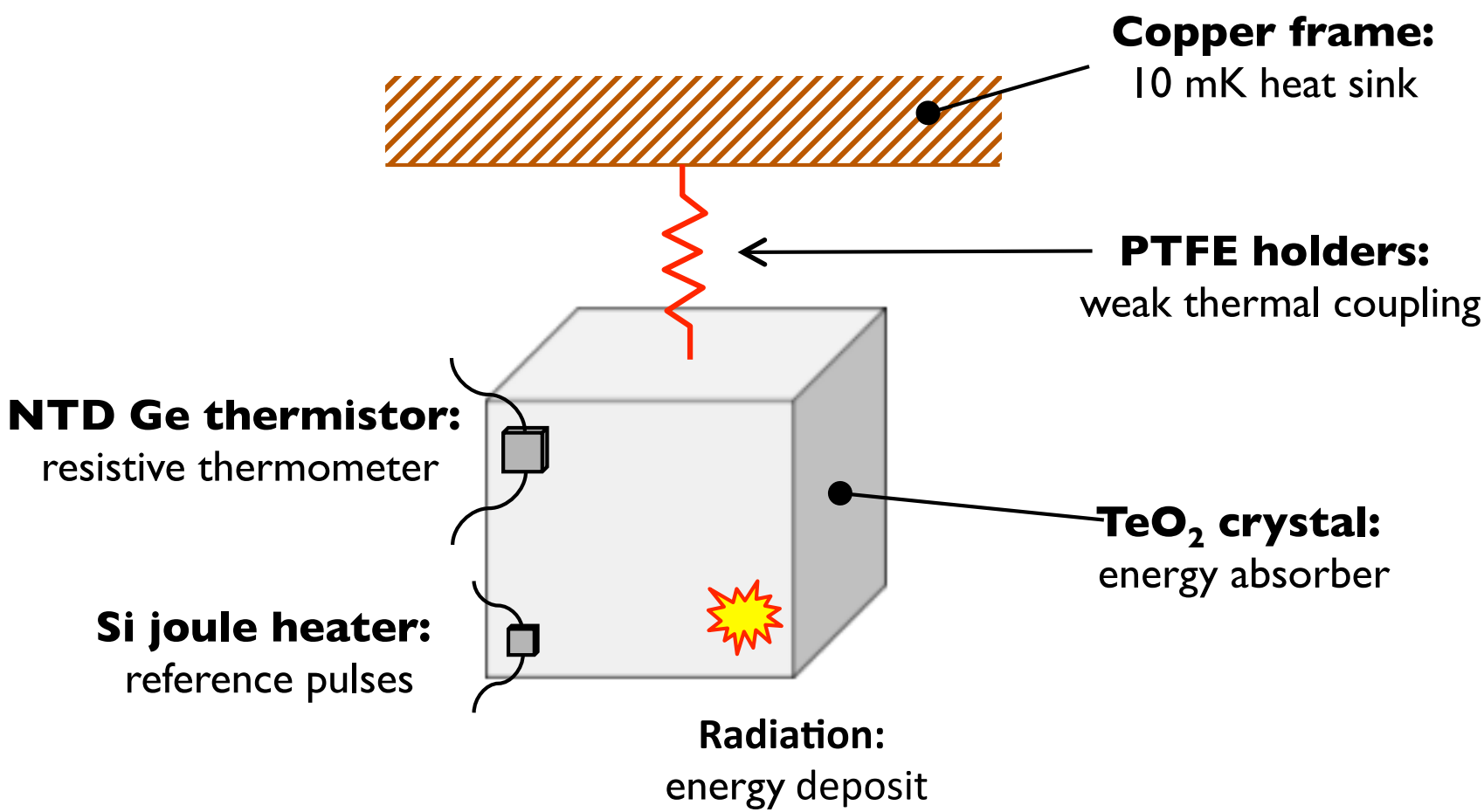


CUORE:
Cryogenic Underground Observatory for Rare Events



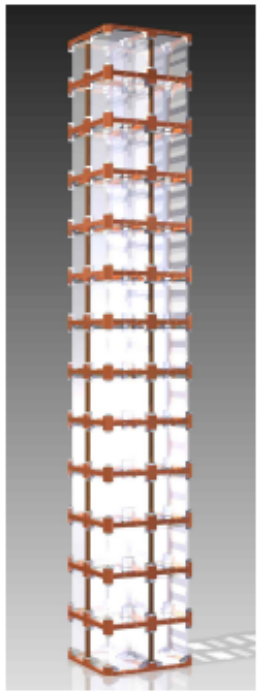
Super Cool

How Bolometers work:

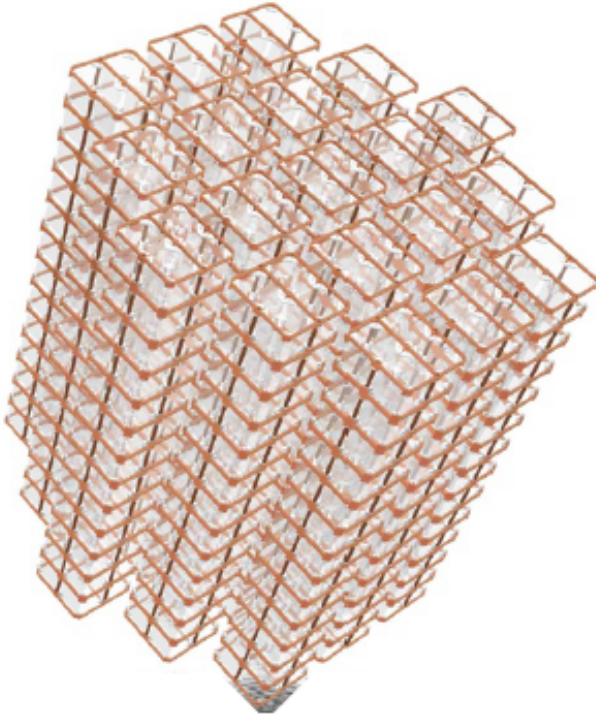


CUORE:
Cryogenic Underground Observatory for Rare Events

CUORICINO
11 kg



CUORE-0
11 kg



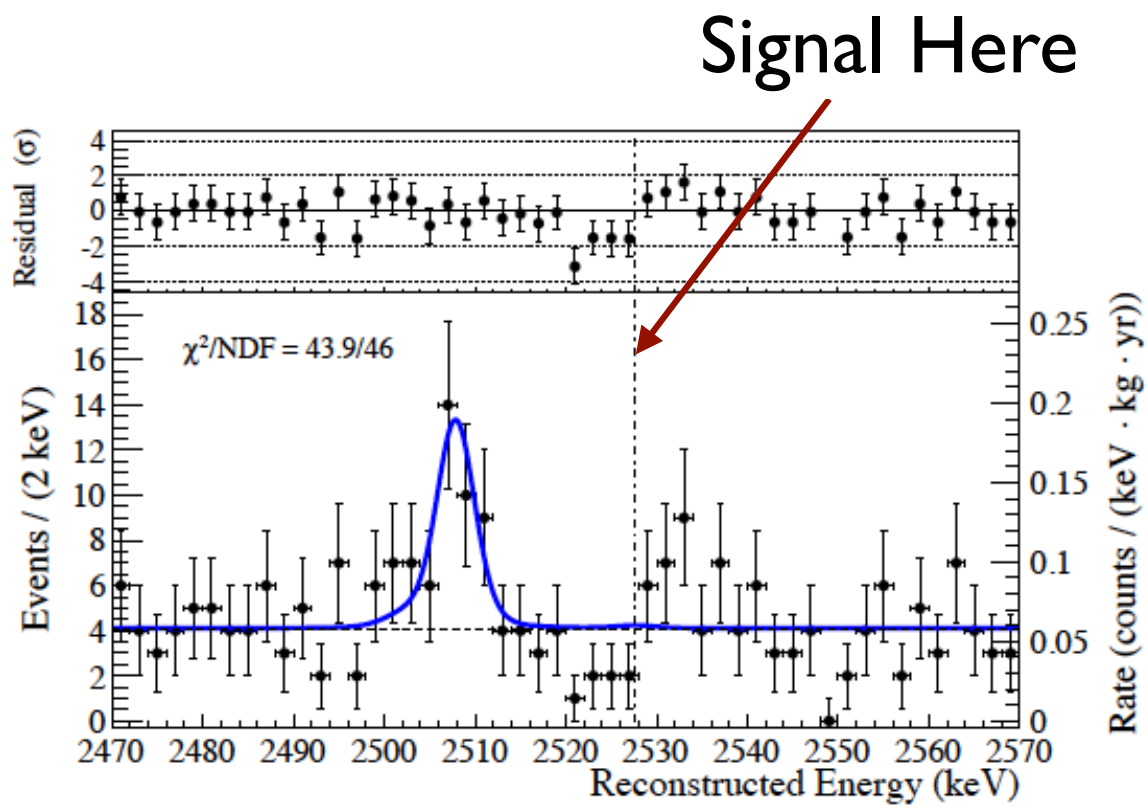
CUORE
206 kg

CUORE:
Cryogenic Underground Observatory for Rare Events

$$T^{0\nu}_{1/2} > 4.0 \times 10^{24}\ \mathrm{yr}$$

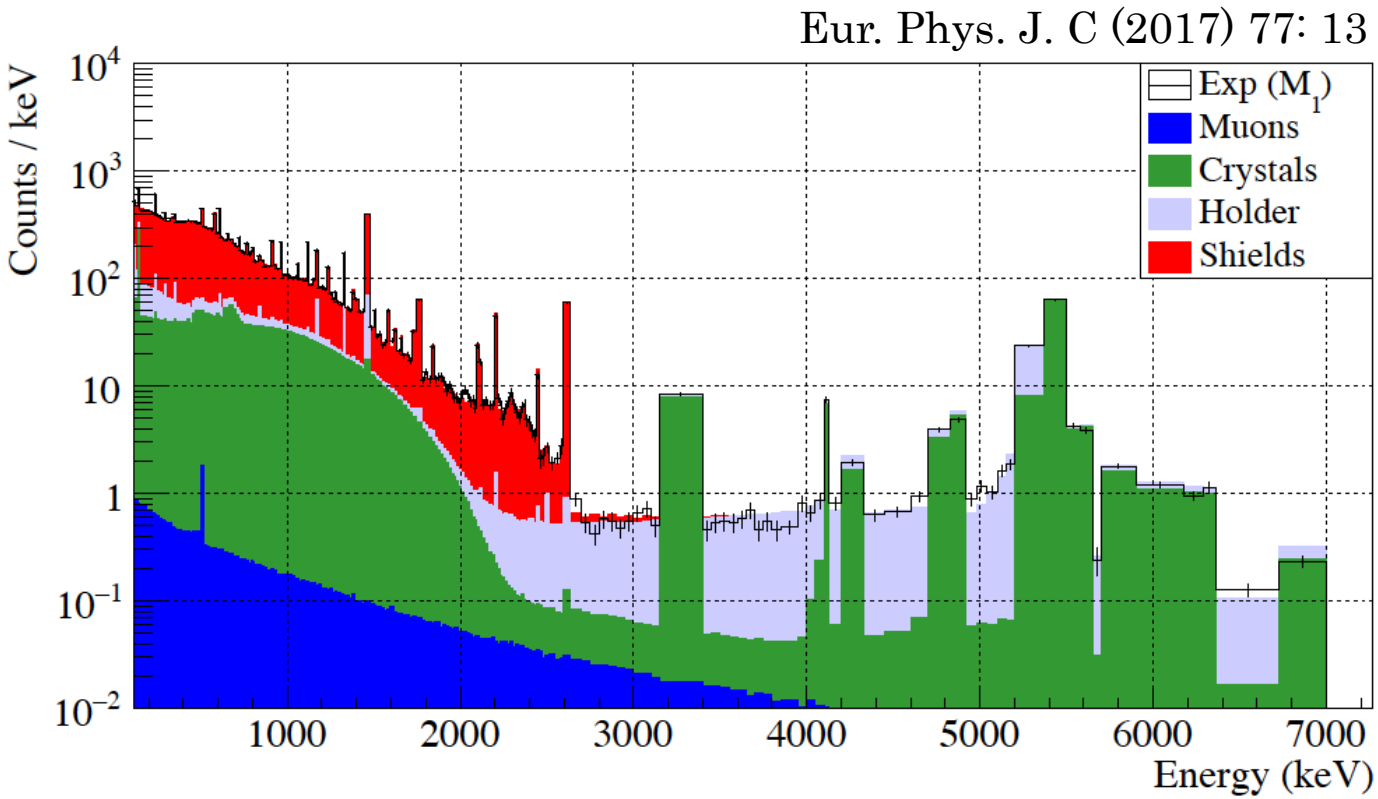
(90% C.L.)

Phys.Rev.Lett. 115 (2015) 10, 102502



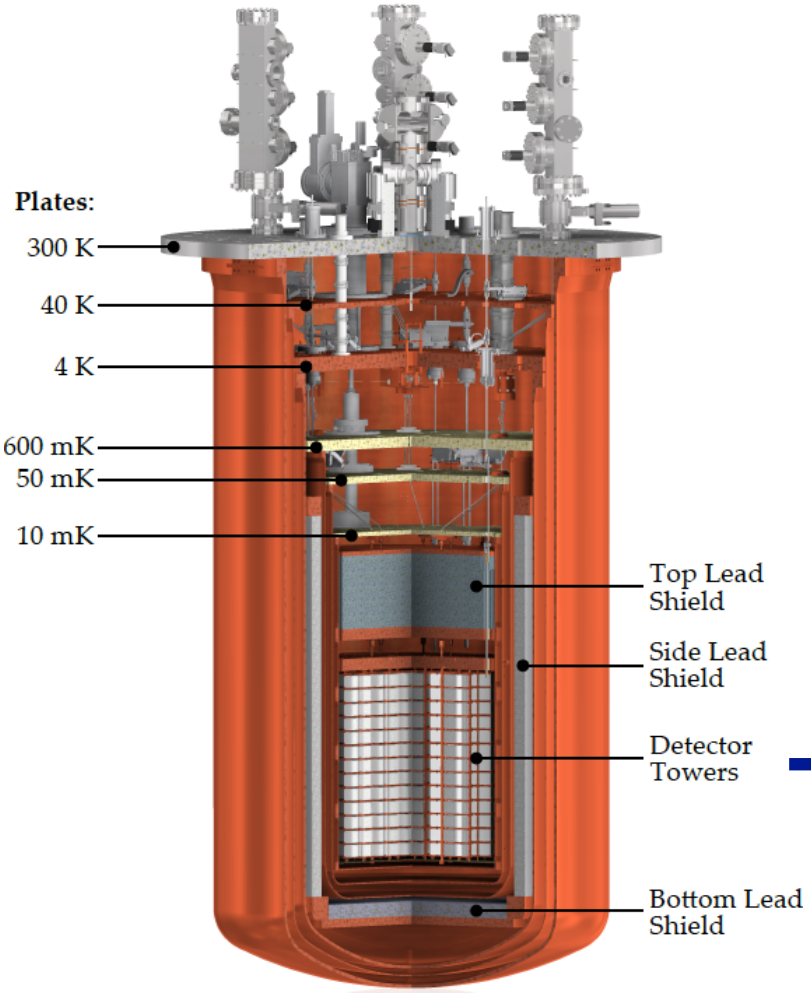
- First results from CUORE-0 (one CUORE-style tower operated in old cryostat).

CUORE:
Cryogenic Underground Observatory for Rare Events

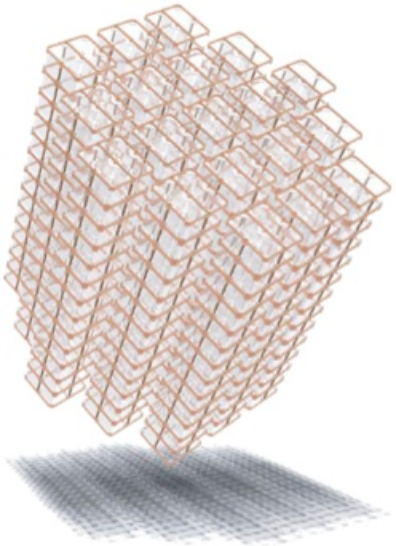


- A detailed study of the backgrounds in CUORE-0 gives us confidence in the background levels in the full CUORE detector.

CUORE:
Cryogenic Underground Observatory for Rare Events

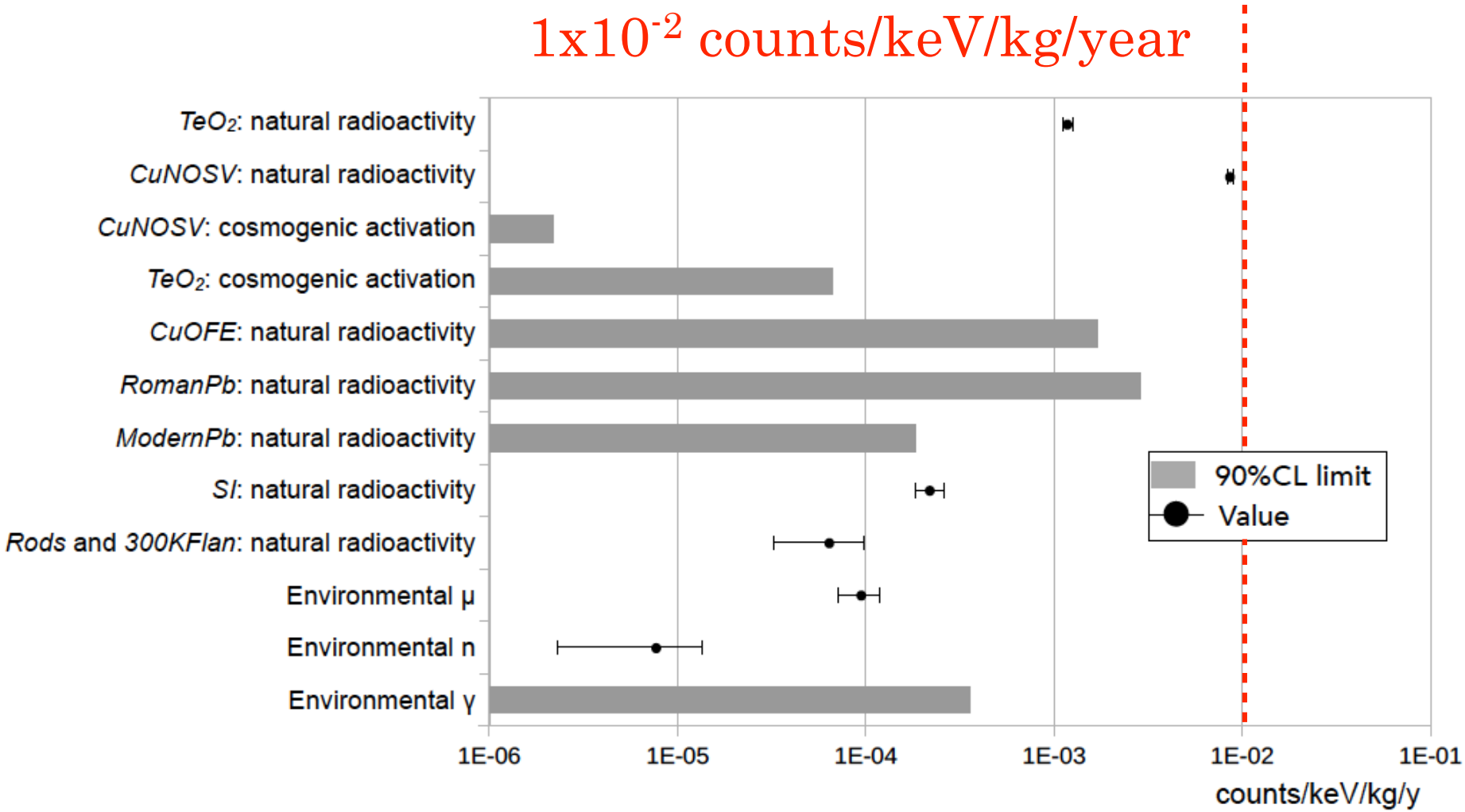


- 19 Towers, 988 TeO_2 crystals operated as bolometers.
- We are the "Coldest cubic meter in the known universe".



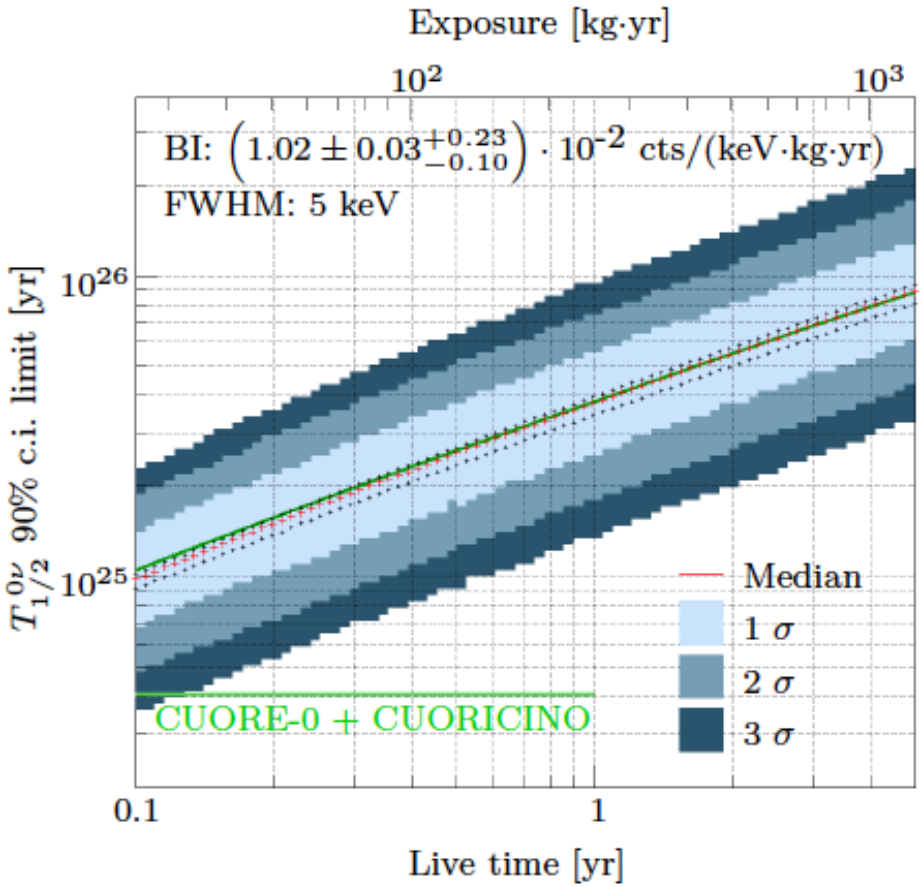
CUORE:
Cryogenic Underground Observatory for Rare Events

Goal:
$1x10^{-2}$ counts/keV/kg/year



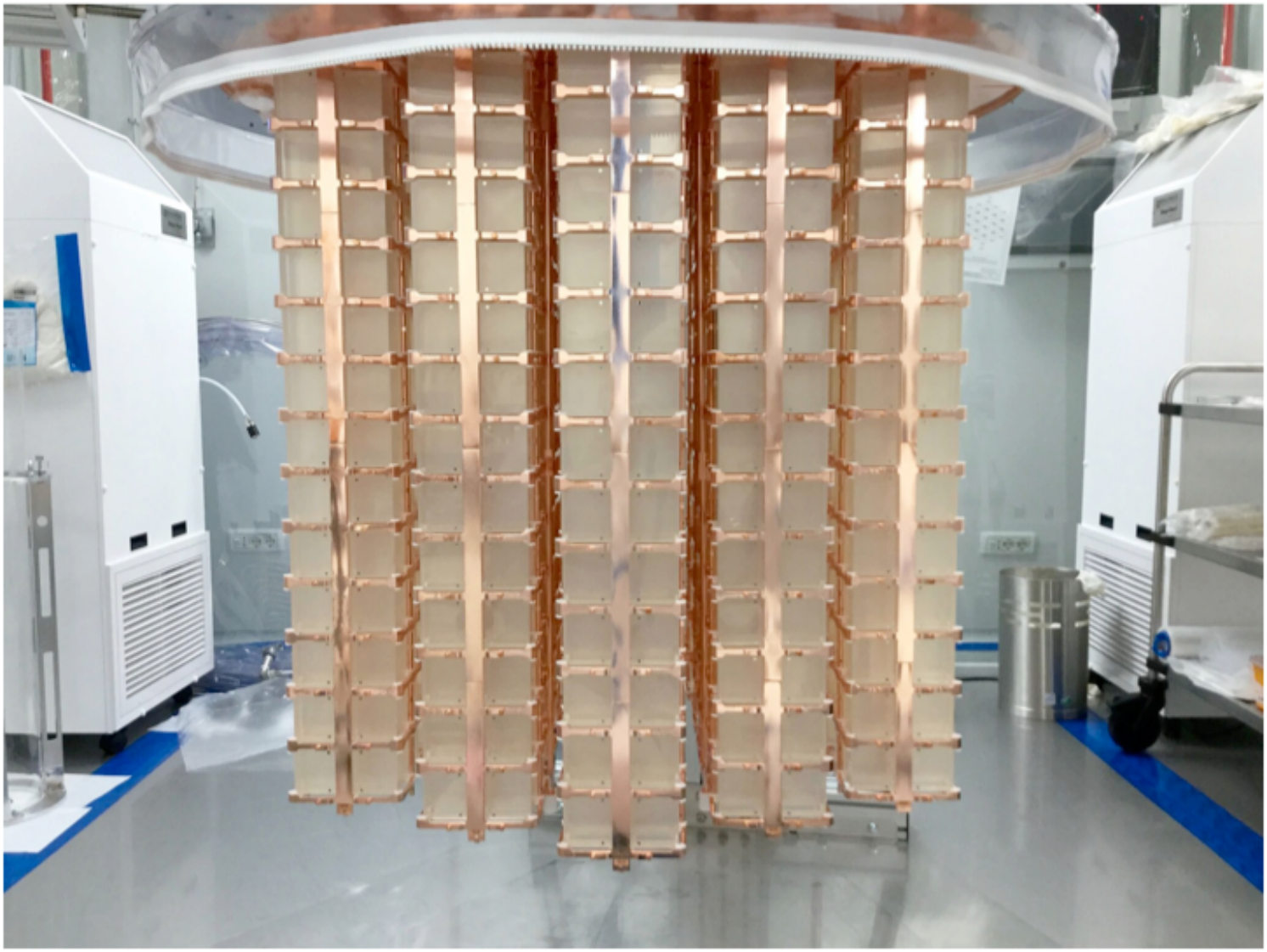
arXiv:1704.08970

CUORE:
Cryogenic Underground Observatory for Rare Events

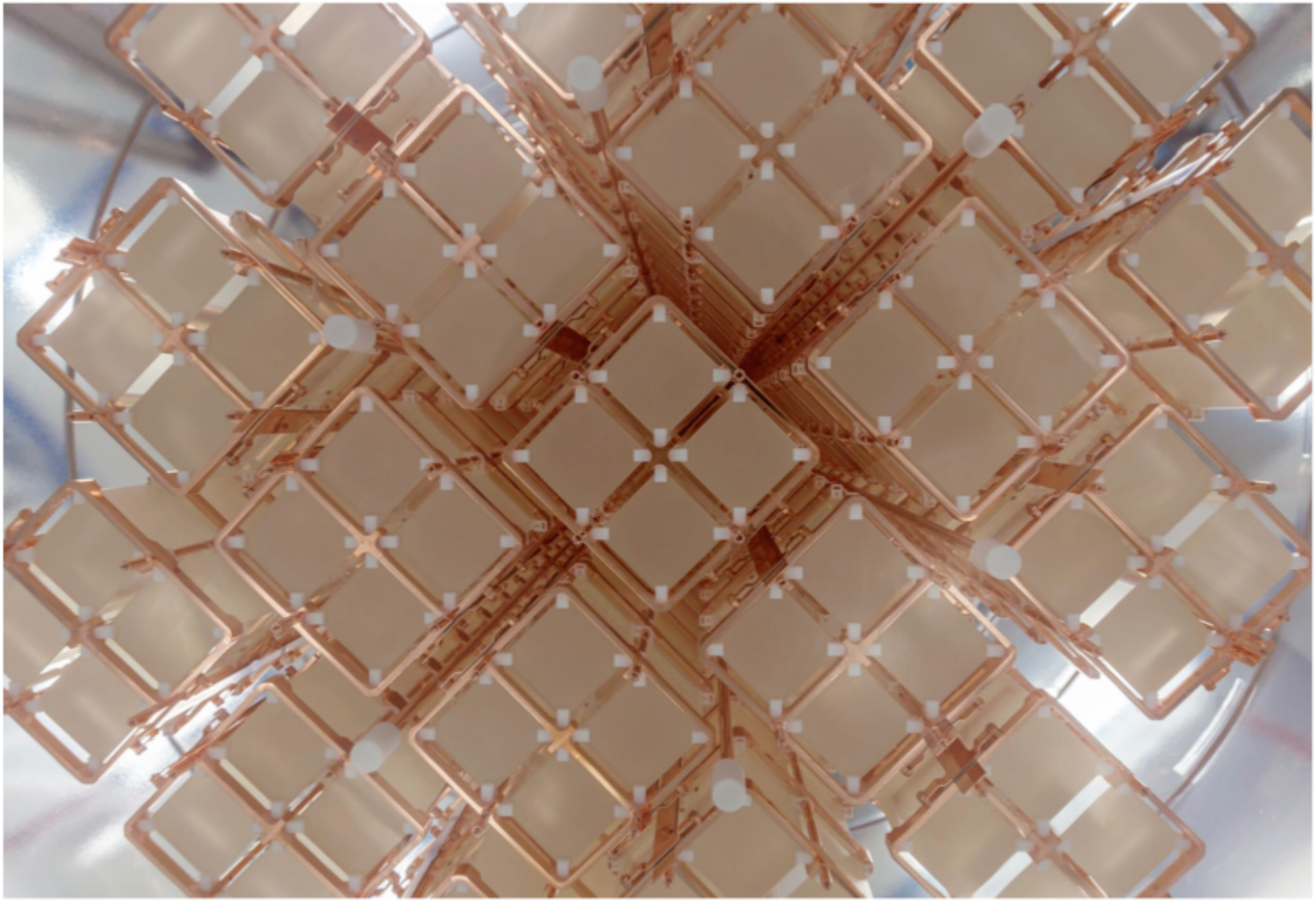


arXiv:1705.10816

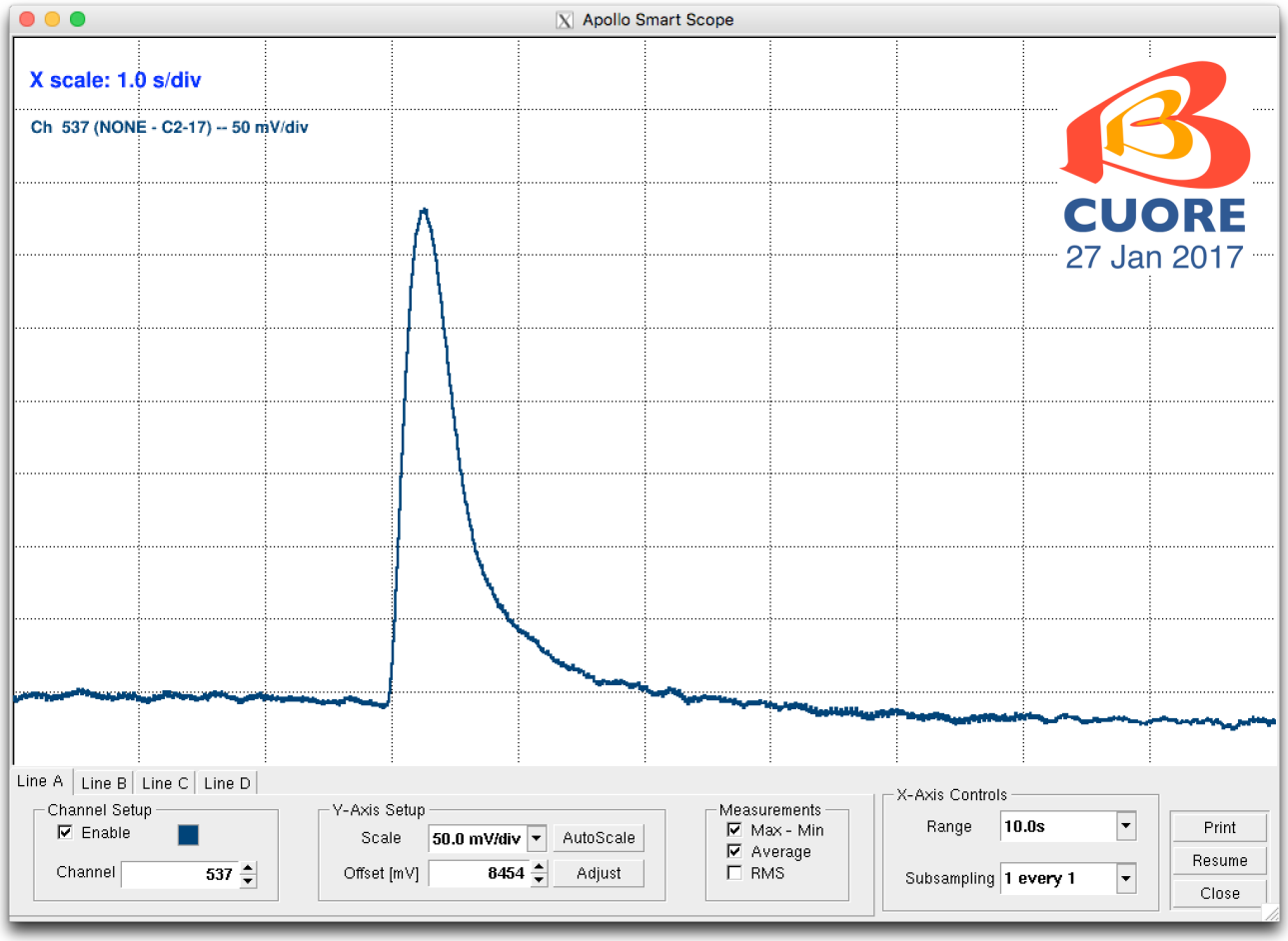
CUORE:
Cryogenic Underground Observatory for Rare Events



CUORE:
Cryogenic Underground Observatory for Rare Events

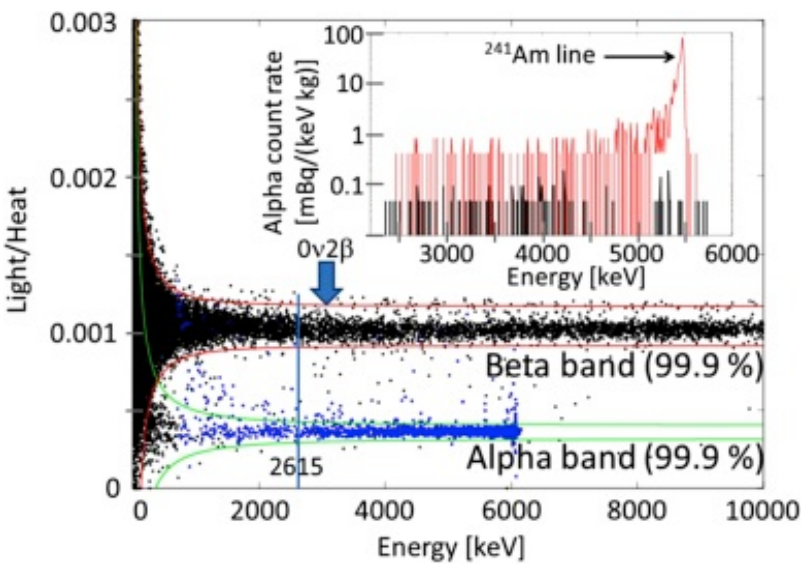


Data Taking has Started!



The commissioning was completed in April 2017.

CUPID:
CUORE with Particle ID

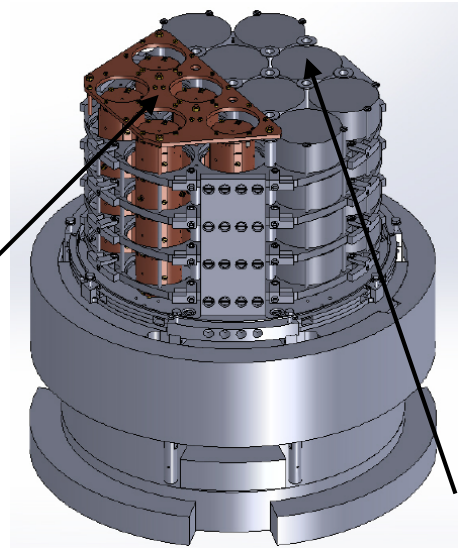


LUMINEU:
Physics Letters B, Volume 710, Issue 2, 2012, Pages 318-323

For ton-scale detector need:

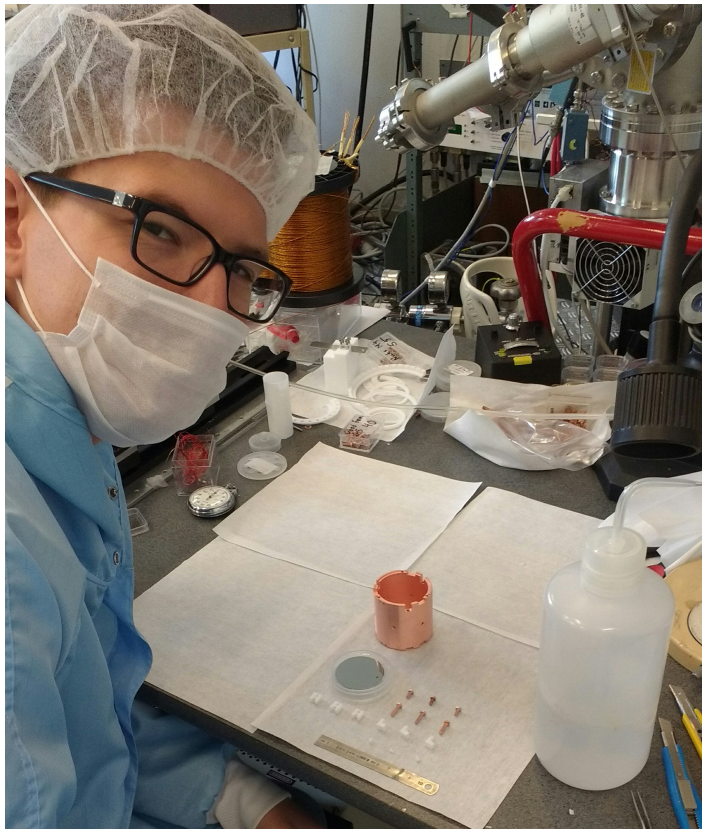
- Enriched crystals with better background rejection.
- Scintillating bolometers are one way to do this. ZnMoO4 is one promising crystal.
- Re-uses CUORE fridge, so this more of an upgrade to an existing detector than a new experiment.
- RMD Inc. has SBIR Phase 2 grant to grow crystals in US.

CUPID-Mo Demonstrator



CUPID-Mo

EDELWEISS



MIT Graduate Student Joe Johnston assembling the CUPID-Mo bolometric test tower, funding through MISTI-France

- We are working closely with the Orsay group both on crystal testing and the realization of a demonstrator experiment.
- The 20 Li_2MoO_4 crystal phase-I demonstrator will start taking data at the end of the year, final bolometric tests being performed now!

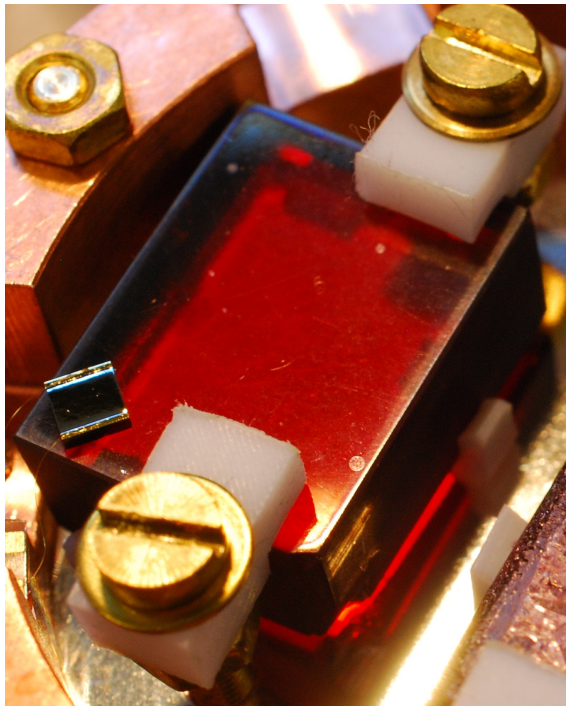
First US Crystals: $LiInSe_2$

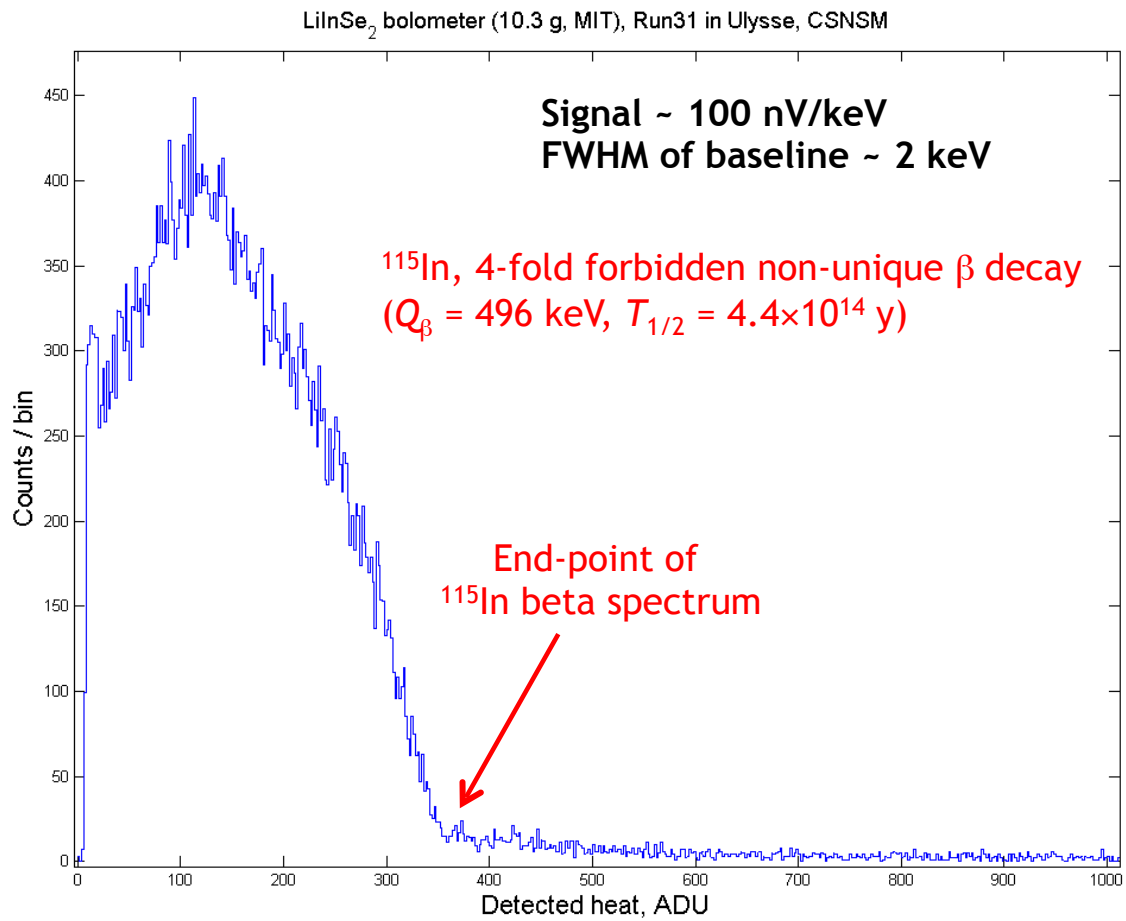
PHYSICAL REVIEW C **93**, 034308 (2016)

Forbidden nonunique β decays and effective values of weak coupling constants

M. Haaranen,[1] P. C. Srivastava,[2] and J. Suhonen[1]
[1]*University of Jyväskylä, Department of Physics, P.O. Box 35 (YFL), FI-40014, University of Jyväskylä, Finland*
[2]*Department of Physics, Indian Institute of Technology, Roorkee 247667, India*
(Received 28 October 2015; revised manuscript received 22 January 2016; published 8 March 2016)

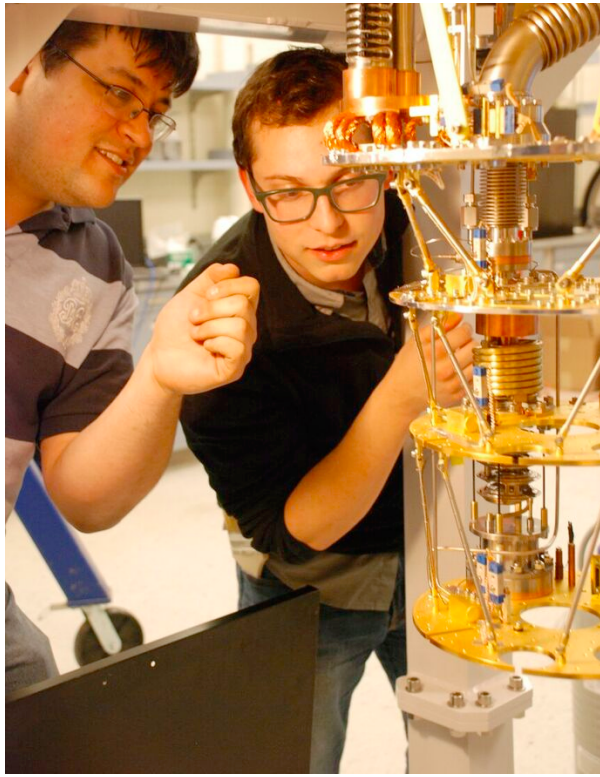
Tests done with Orsay Group:



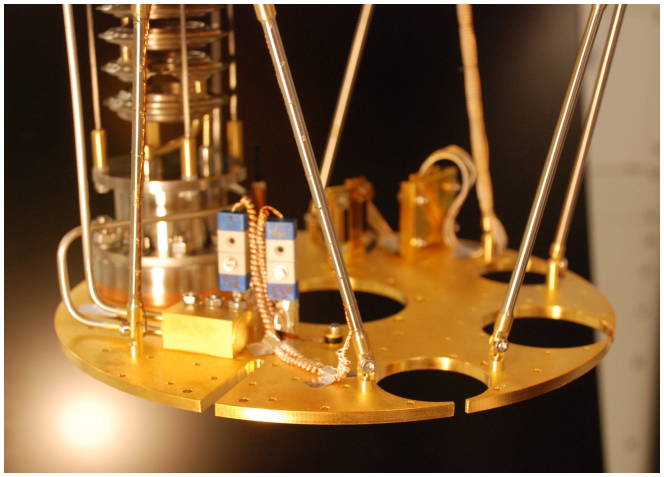


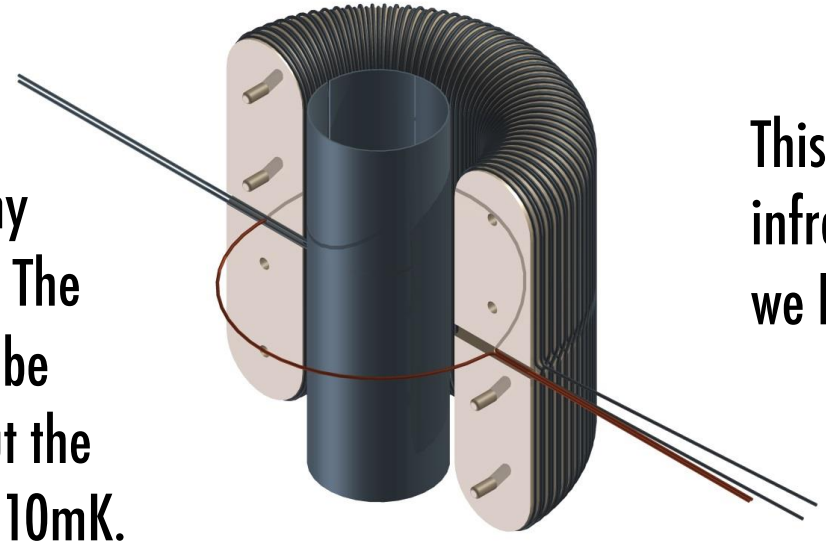
The crystal doesn't work for double-beta experiments because of the In , but can help with theoretical uncertainties in the nuclear physics (quenching of g_A).

Axions: ABRACADABRA-10cm



SQUID readout of the pickup cylinder, therefore the apparatus should be as cold as possible.

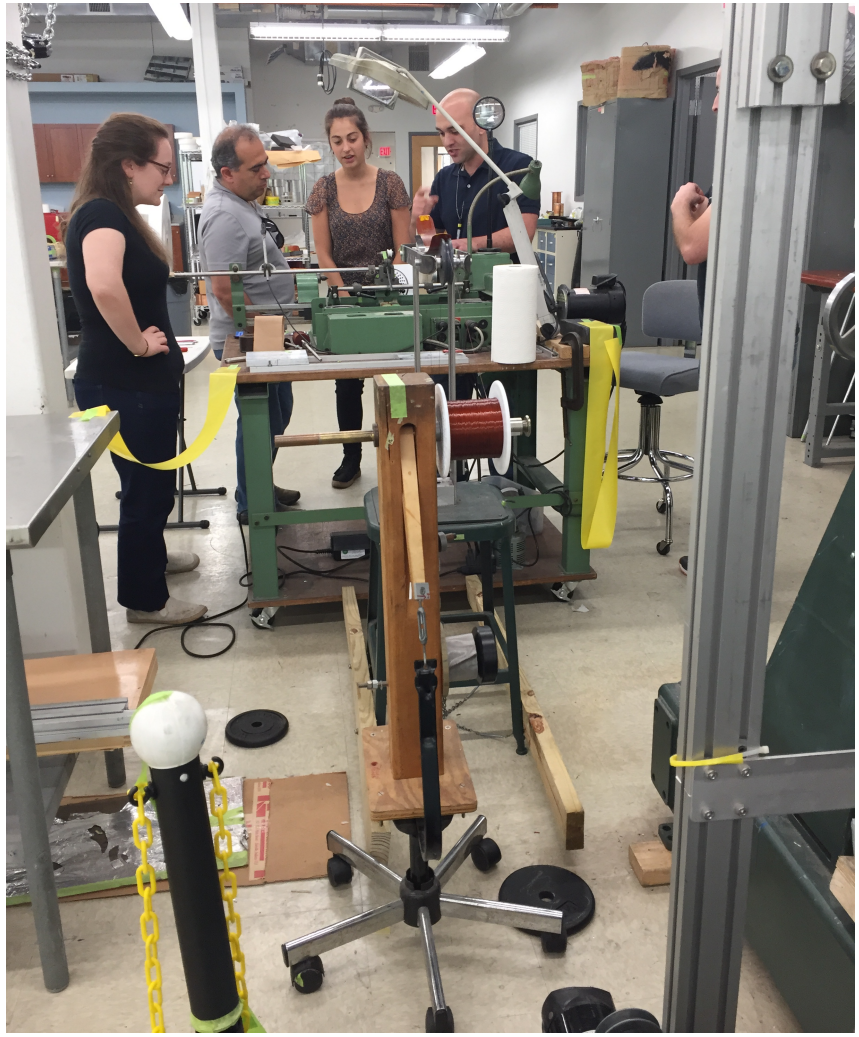


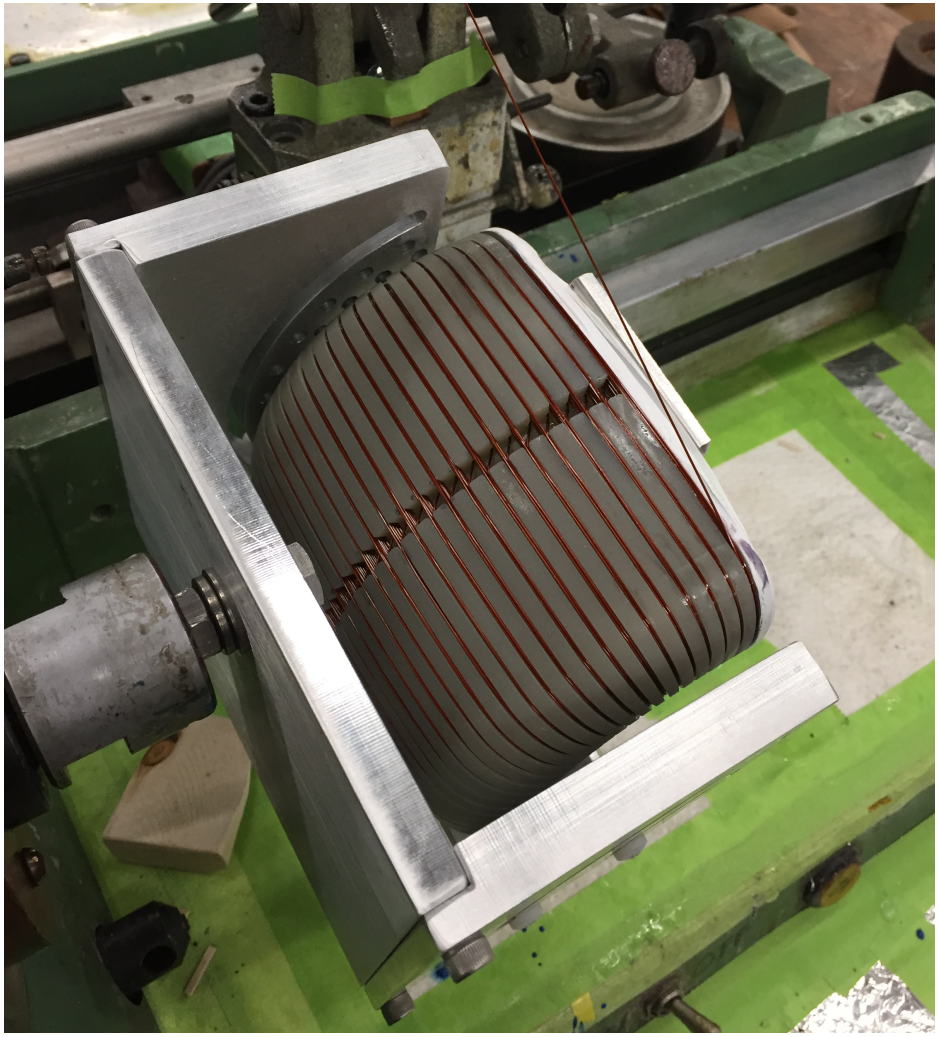


ABRACADABRA will be run in my Triton400 dilution refrigerator. The super conduction magnet may be cooled using warmer stages but the central cylinder needs to be at 10mK.

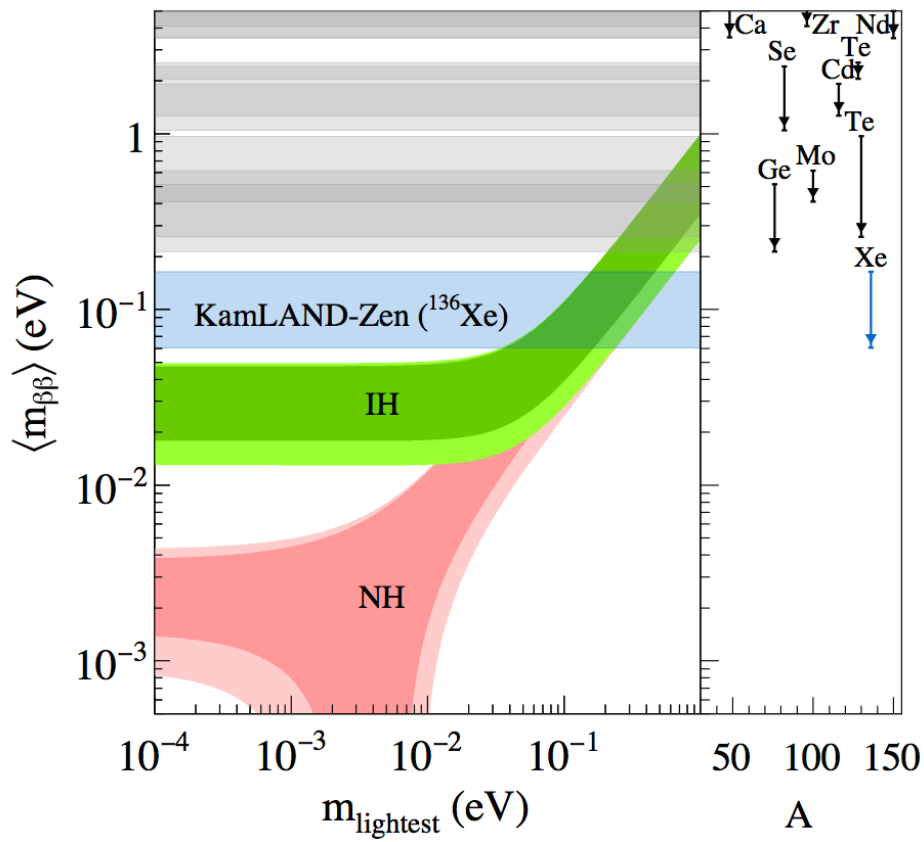
This effort makes use of infrastructure and expertise that we built for the bolometer effort!

Axions:
ABRACADABRA-10cm





Back to Double-Beta Decay

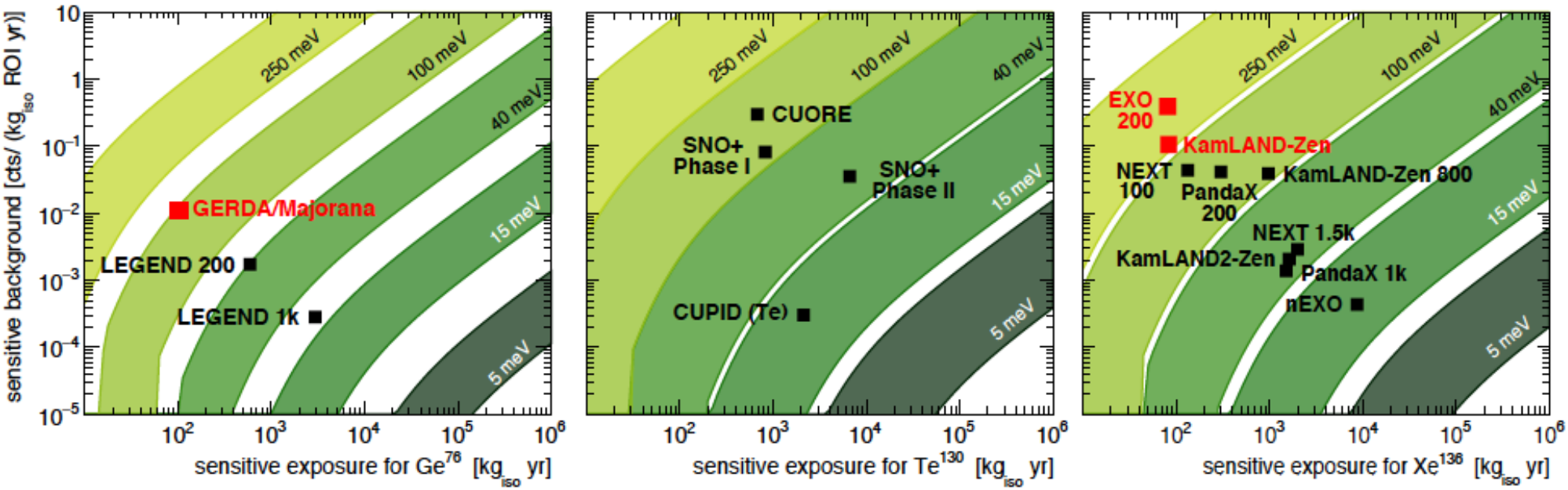


Discovery probability of next-generation neutrinoless double-β decay experiments

Matteo Agostini*
Gran Sasso Science Institute, L'Aquila, Italy

Giovanni Benato†
Department of Physics, University of California, Berkeley, CA 94720 - USA
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 74720 - USA

Jason Detwiler‡
Center for Experimental Nuclear Physics and Astrophysics,
and Department of Physics, University of Washington, Seattle, WA 98115 - USA



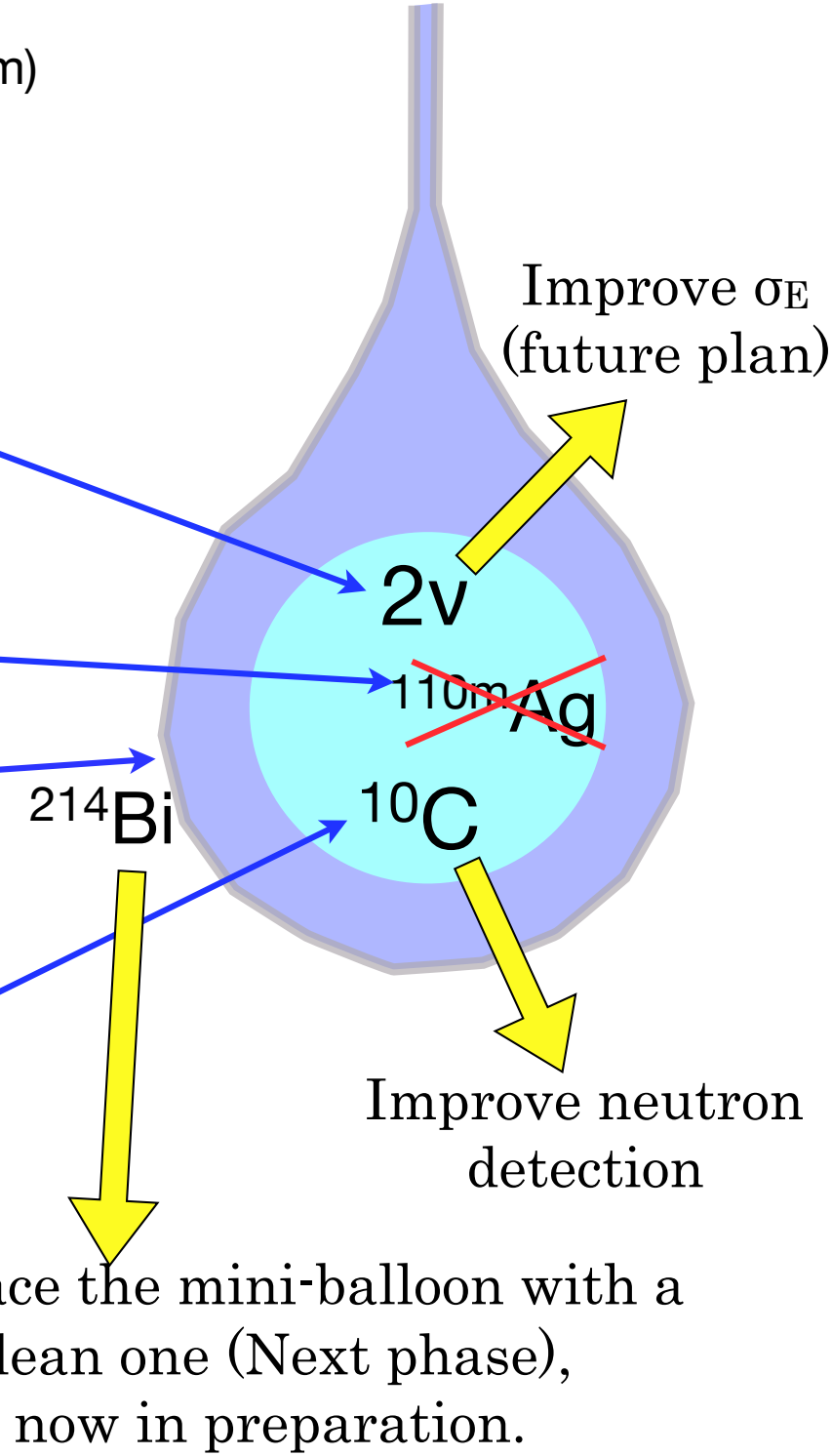
Back to Double-Beta Decay

- The current best limit is 1×10^{26} years from KamLAND-Zen.
- More results expected soon from CUORE, GERDA Phase II, Majorana, SNO+, see Friday from 11:30-1:00.
- World wide effort to design and build the definitive IH experiment.
- I didn't even get to tell you about more ambitious projects.

Summary of the B.G. (2.3<E<2.7MeV, R<1m)

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

* ^{137}Xe production rate was overestimated in the e-print (arXiv:1605.02889v1[hep-ex]10 May 2016). The correct numbers and figures are slightly changed and presented here, and is appeared in arXiv:1605.02889v2..



Outer Detector Refurbishment:

January 2016

New Mini-Balloon Leak Checking and Installation

MIT Undergraduates Hannah Taylor and Andrea Herman

Summer 2016

Current best limit
Neutrinoless Double-Beta Decay

1×10^{26} years

OR

~5 events per year per TON of Isotope