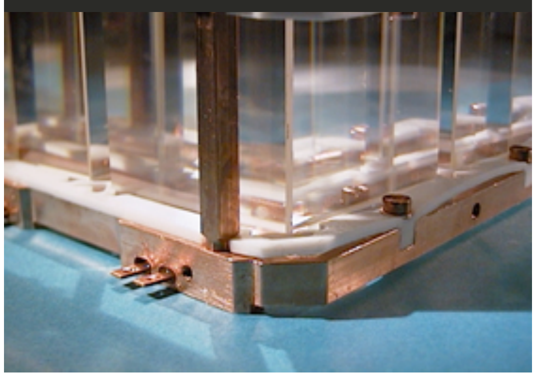
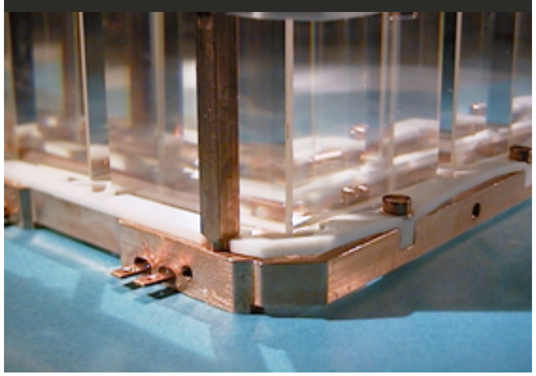




Bigger or Colder: Majorana Neutrinos and the Search for Neutrinoless Double-Beta Decay

Lindley Winslow
Massachusetts Institute of Technology



Double-Beta Decays

Lindley Winslow
Massachusetts Institute of Technology

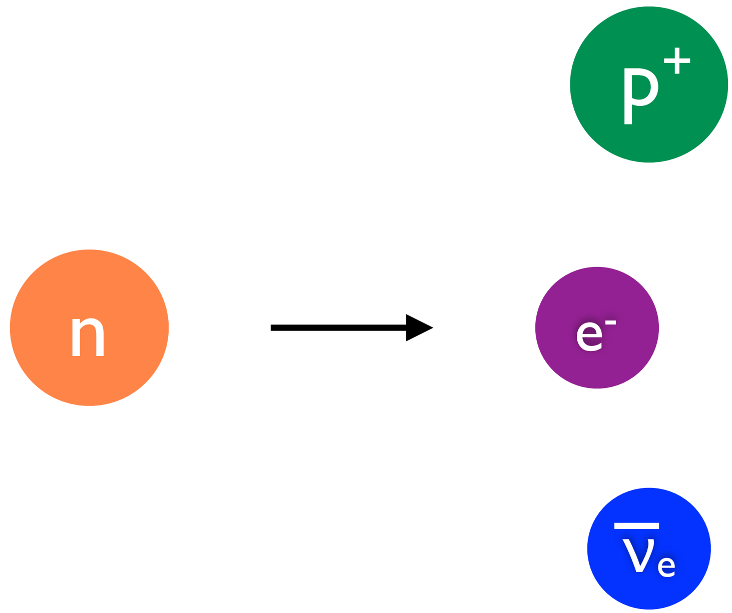
Current best limit
Neutrinoless Double-Beta Decay

1×10^{26} years

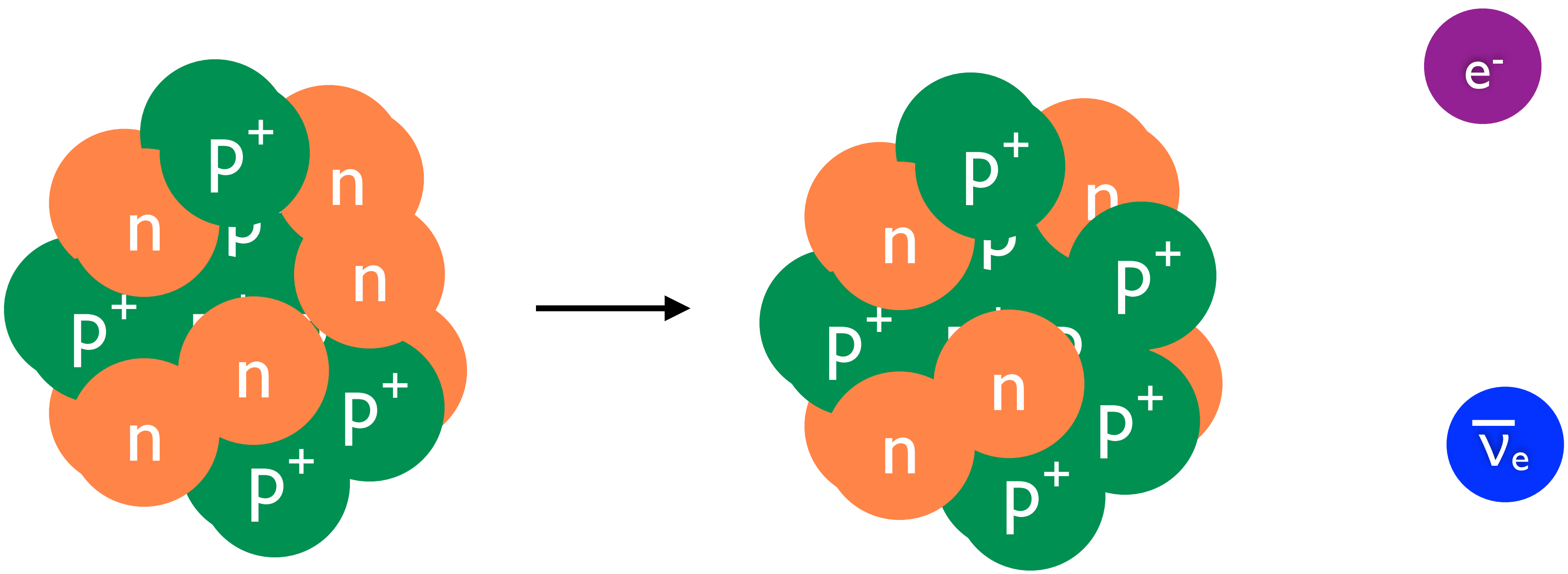
OR

~5 events per year per TON of Isotope

This is beta decay.



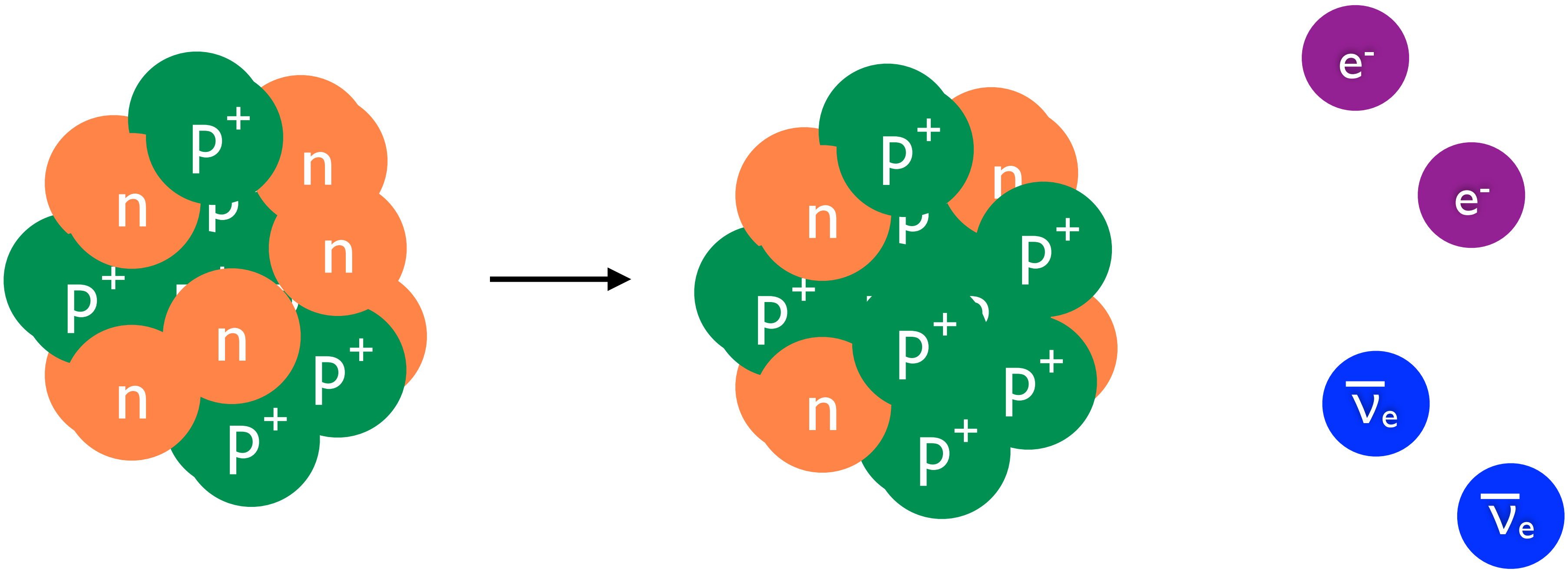
It usually takes place in a nucleus.



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

Z+1
A=same

This is double-beta decay.

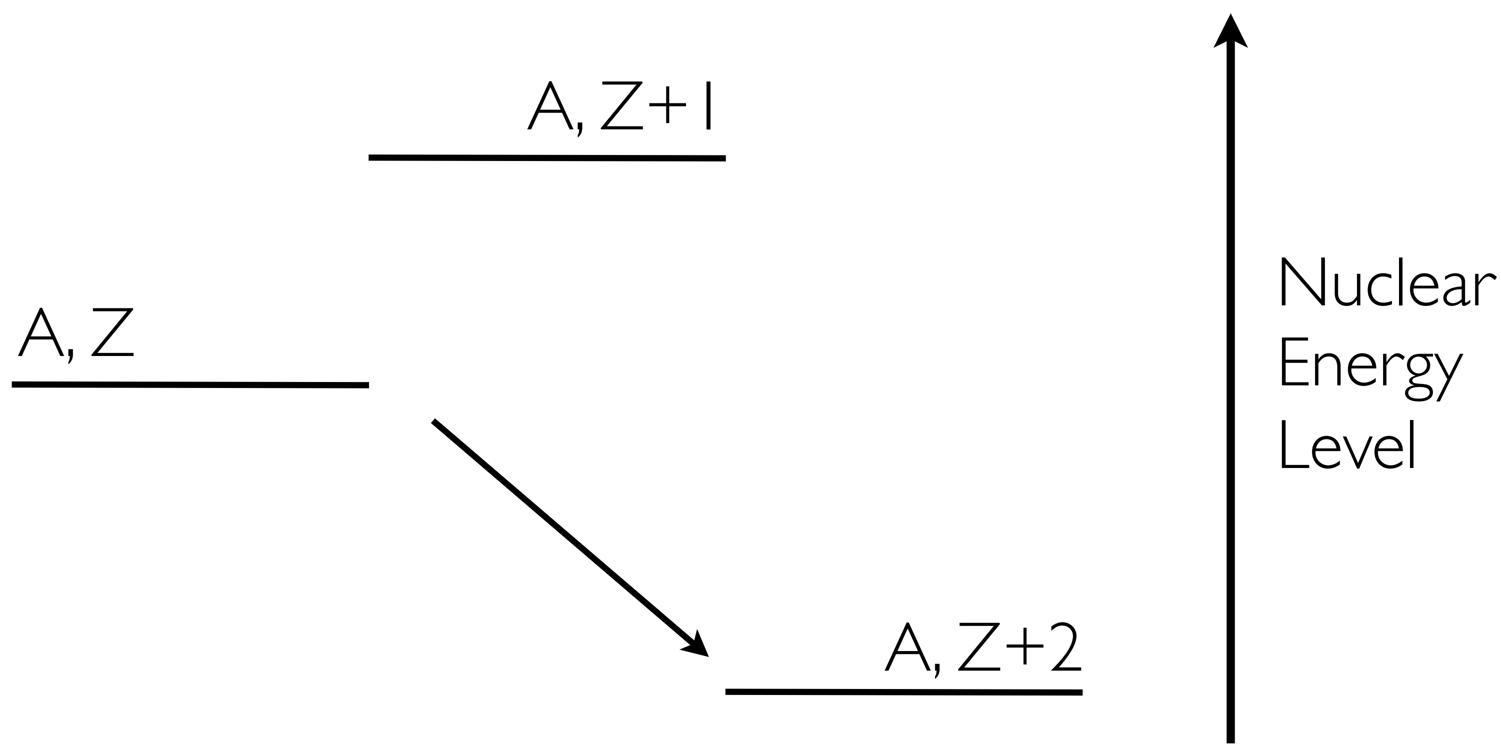


Z+2
A=same

Change in number of leptons is zero.

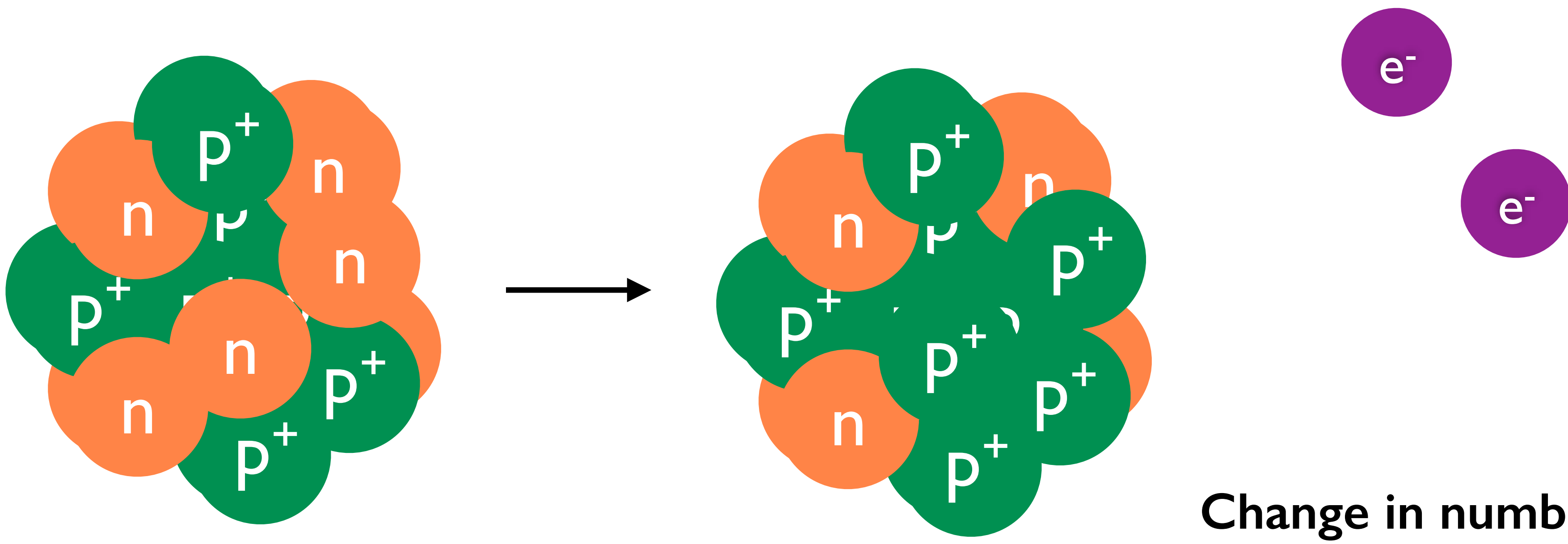
Double Beta Decay

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

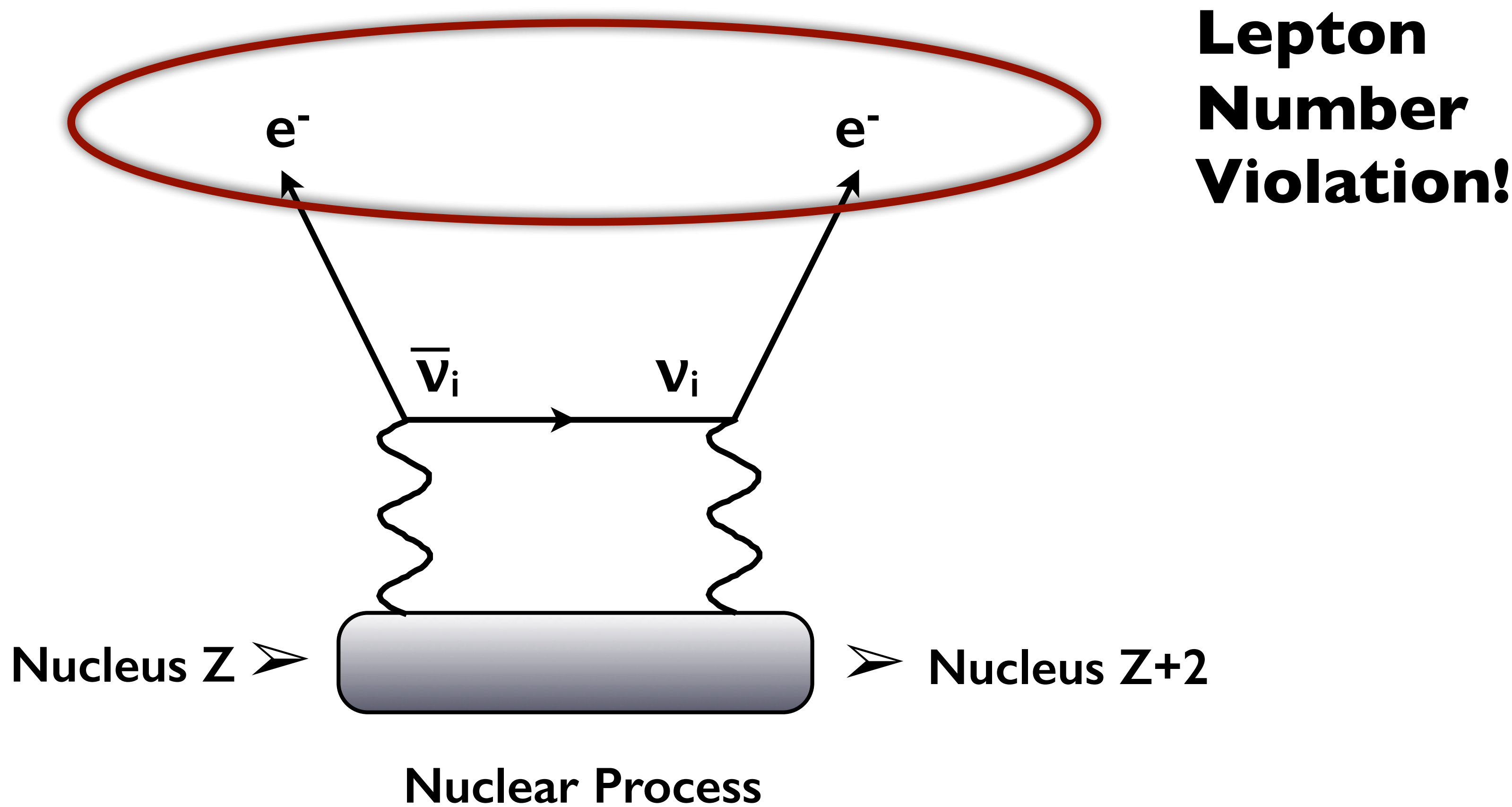


Just a few isotopes!

This is neutrinoless double-beta decay.



Change in number of leptons is plus 2!

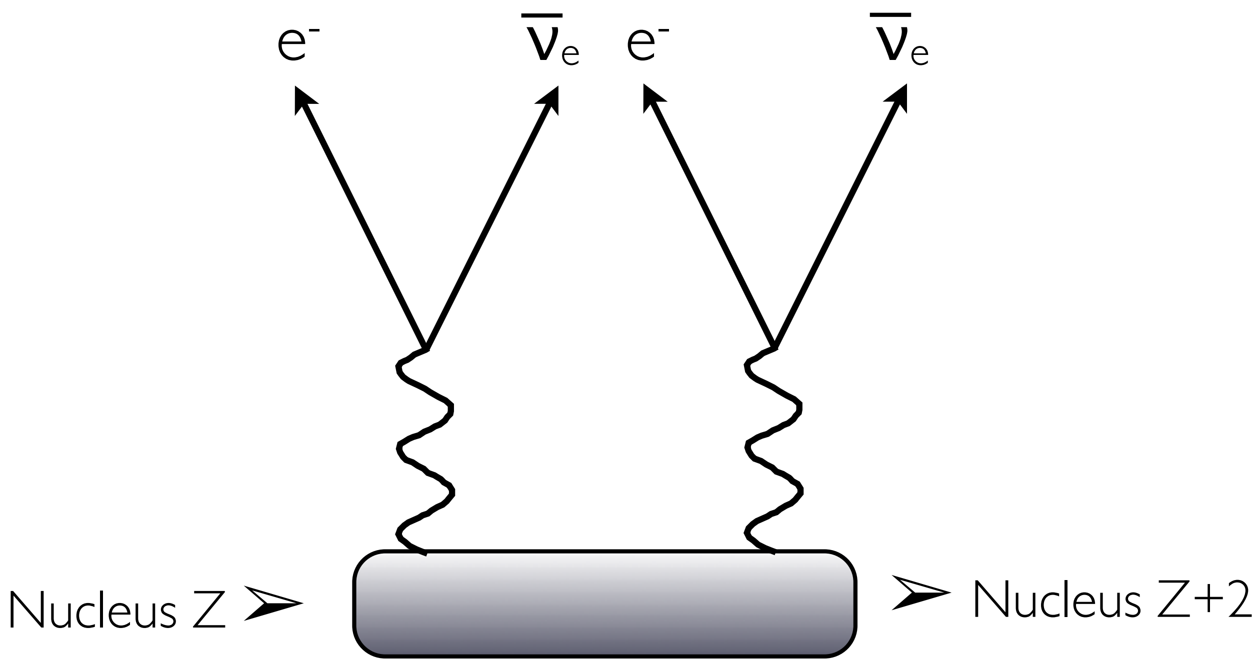


Neutrinoless Double Beta Decay

Light Majorana Neutrino Exchange (LMNE)

The Standard Model Process

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

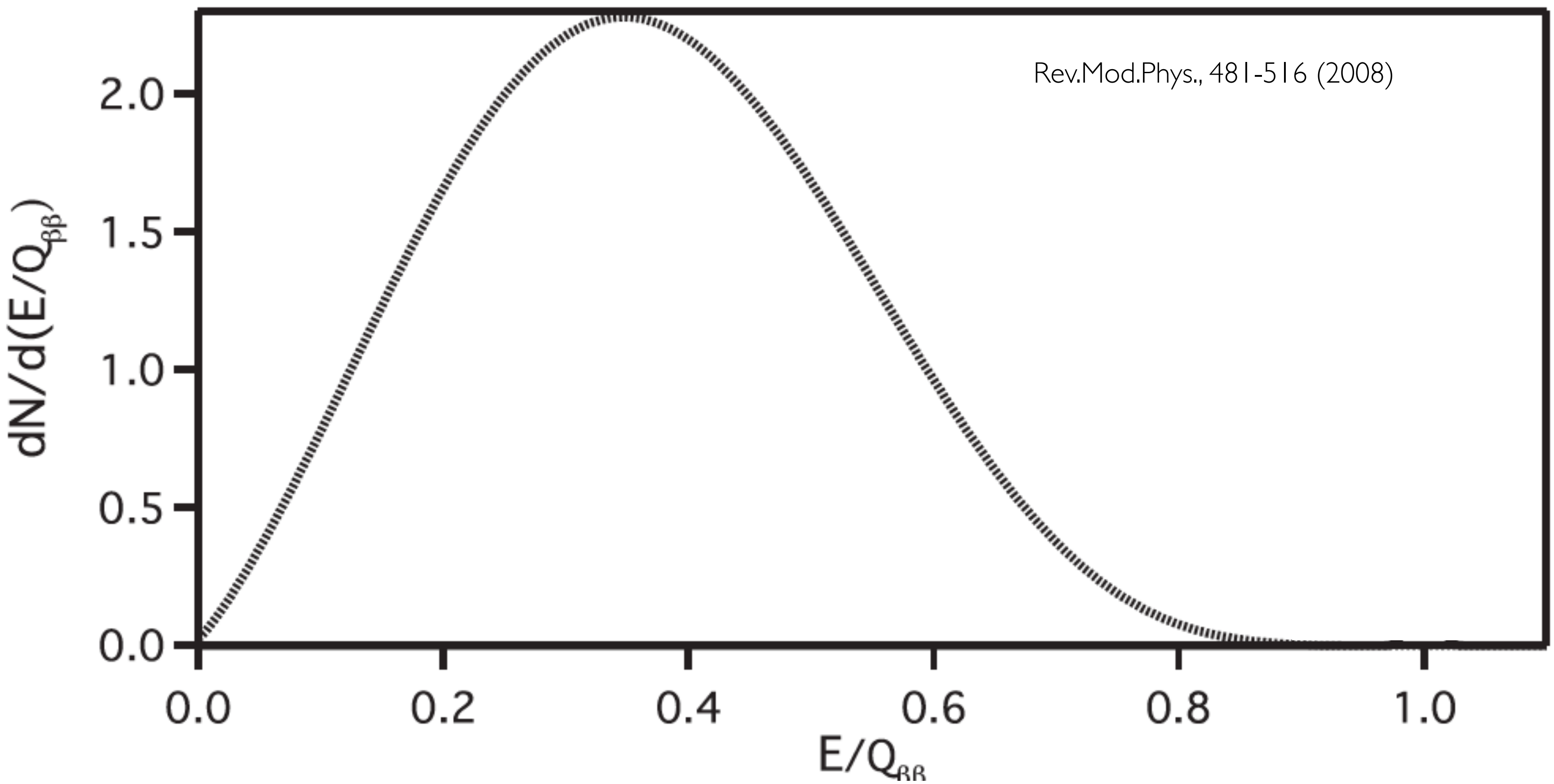


Nuclear Process

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

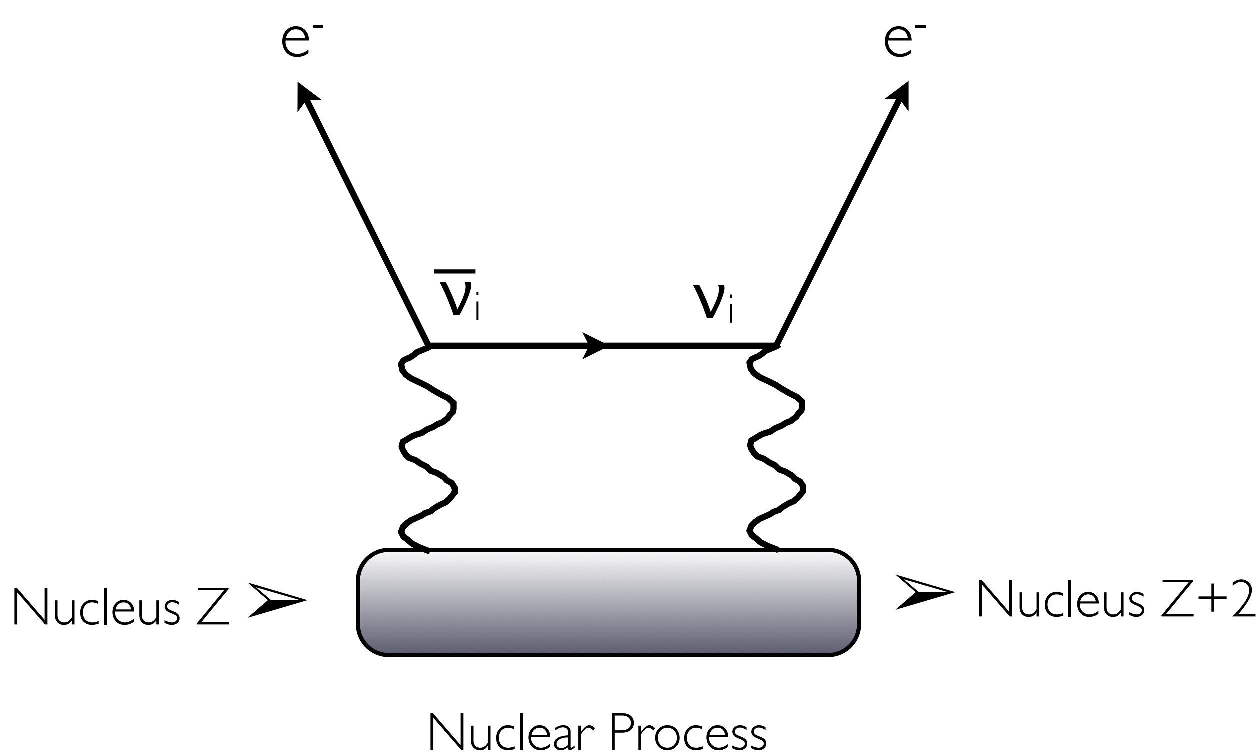
Double Beta Decay

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



This has been observed in isotopes such as ^{130}Te and ^{116}Cd.

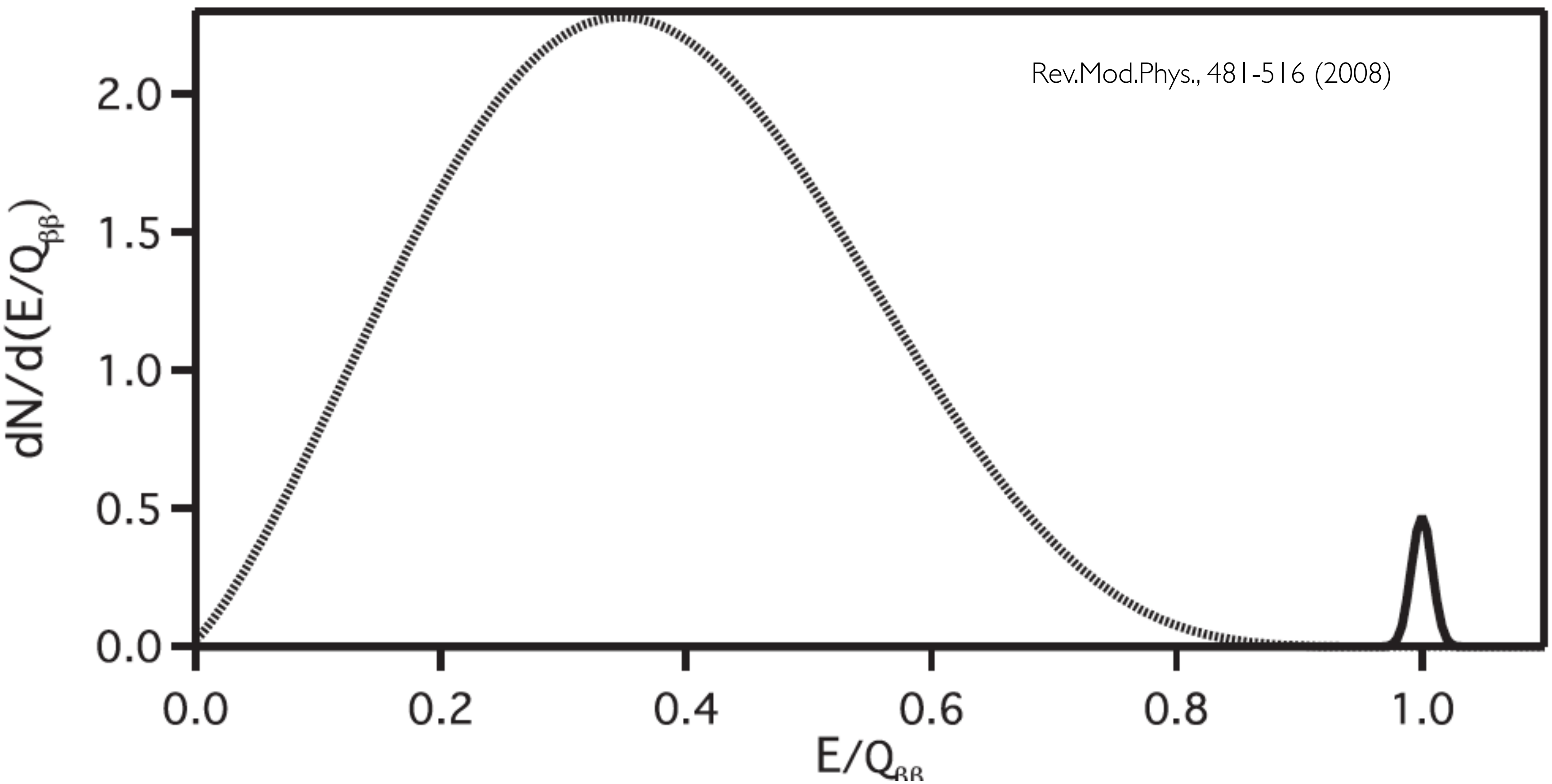
Neutrinoless Double Beta Decay



Light Majorana Neutrino Exchange

Double Beta Decay

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



What is measured is a half-life...

The half-life of the neutrinoless decay via LMNE:

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

Phase space factor
This is a difficult calculation dependent on the decay mechanism.
Notice higher endpoint means faster rate.

What is measured is a half-life:

The half-life of the neutrinoless decay via LMNE:

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

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:

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

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:

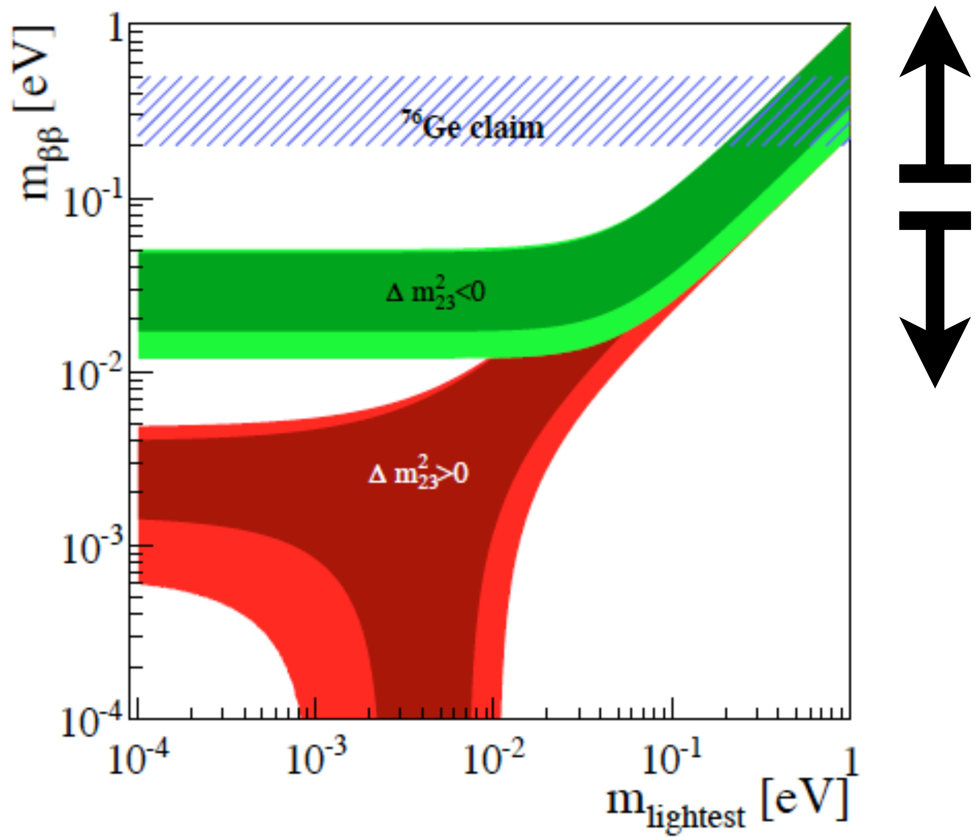
$$m_{\beta\beta} = \sum_i V_{ei}^2 m_i = \cos^2\theta_{13}(m_1 e^{2i\beta}\cos^2\theta_{12} + m_2 e^{2i\alpha} sin^2\theta_{12}) + m_3\sin^2\theta_{13}$$

Two more phases!

Double Beta Decay Parameter Space:

Double Beta Decay Visualizing the Equations:

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



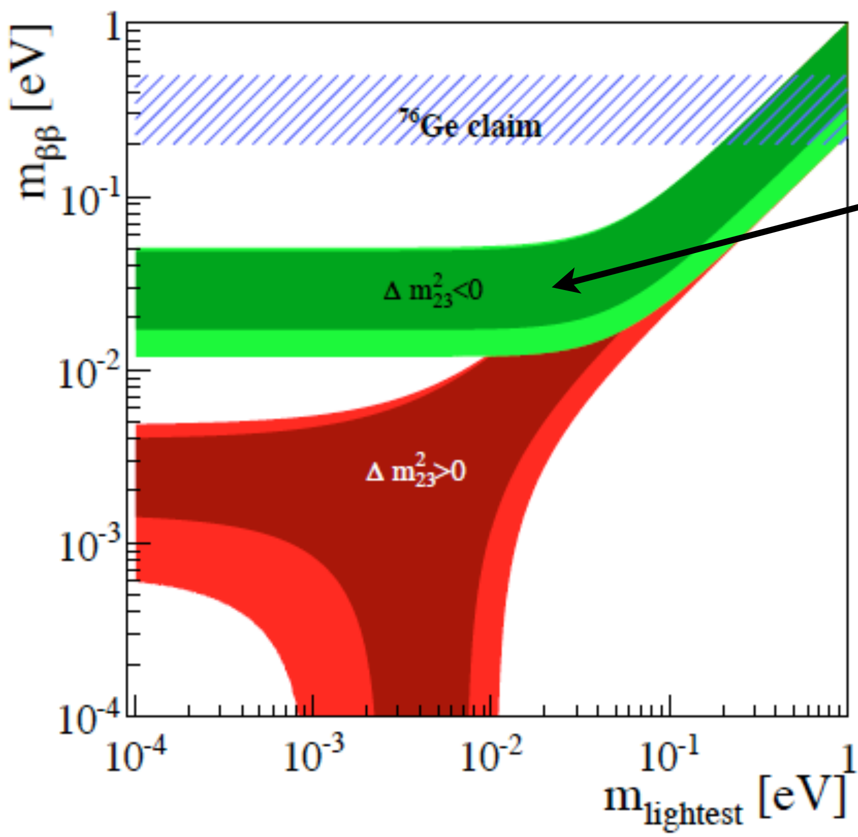
excluded

more sensitive experiments needed

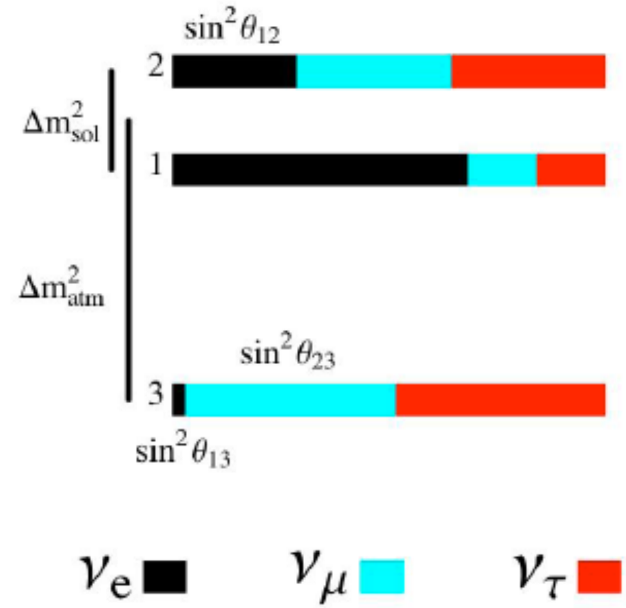
As experiments become more sensitive they push down in this parameter space excluding larger masses.

Double Beta Decay Visualizing the Equations:

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

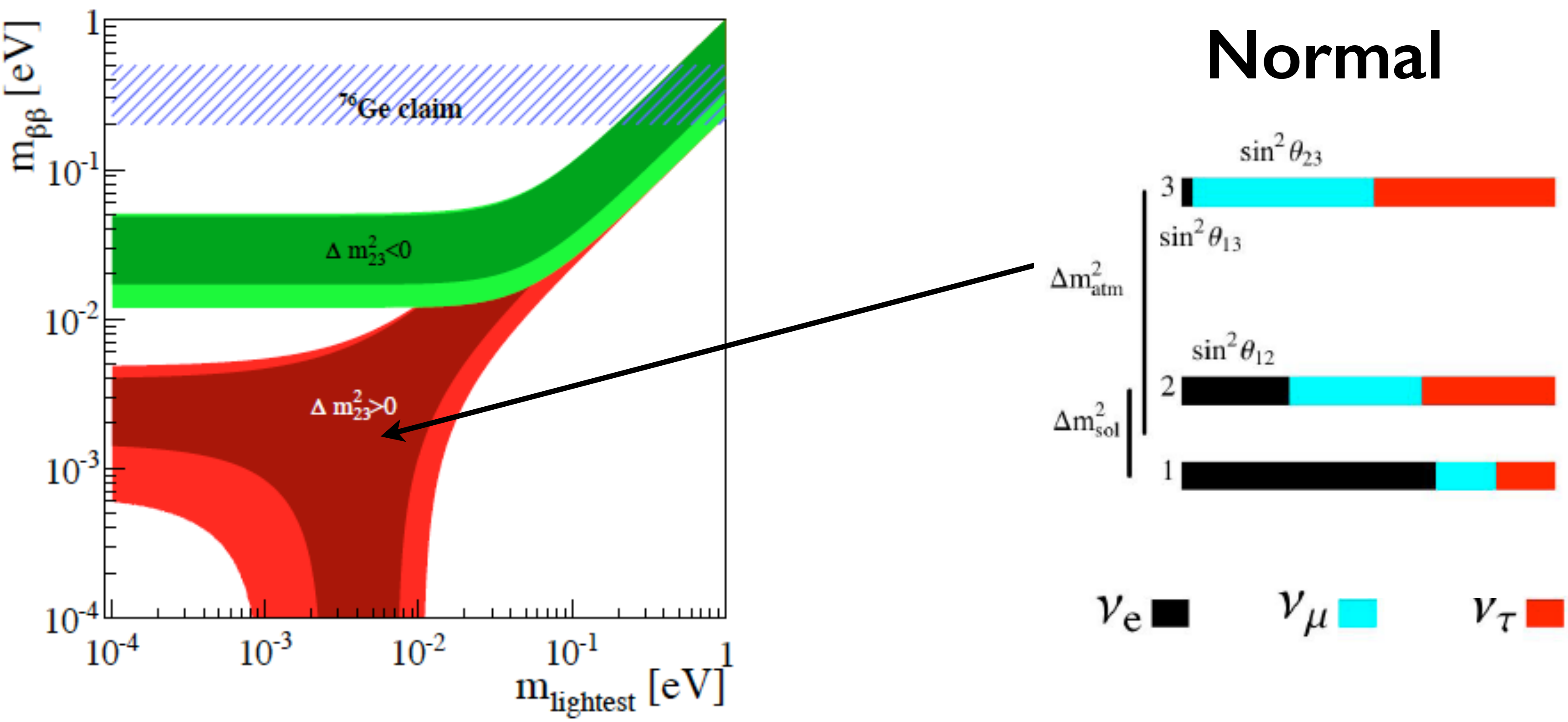


Inverted



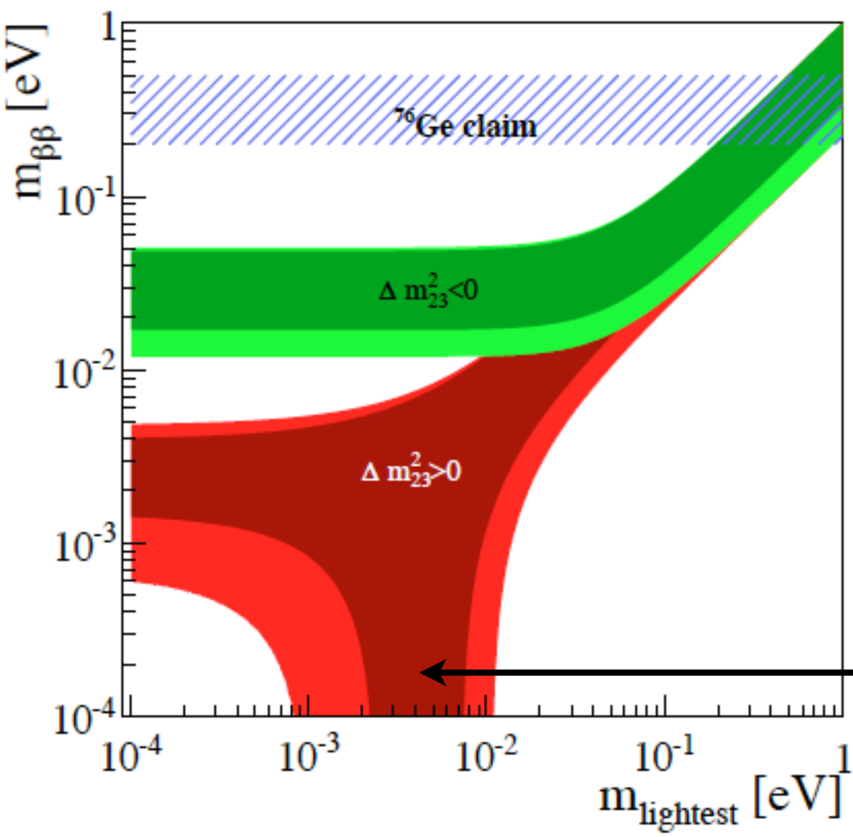
Double Beta Decay Visualizing the Equations:

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



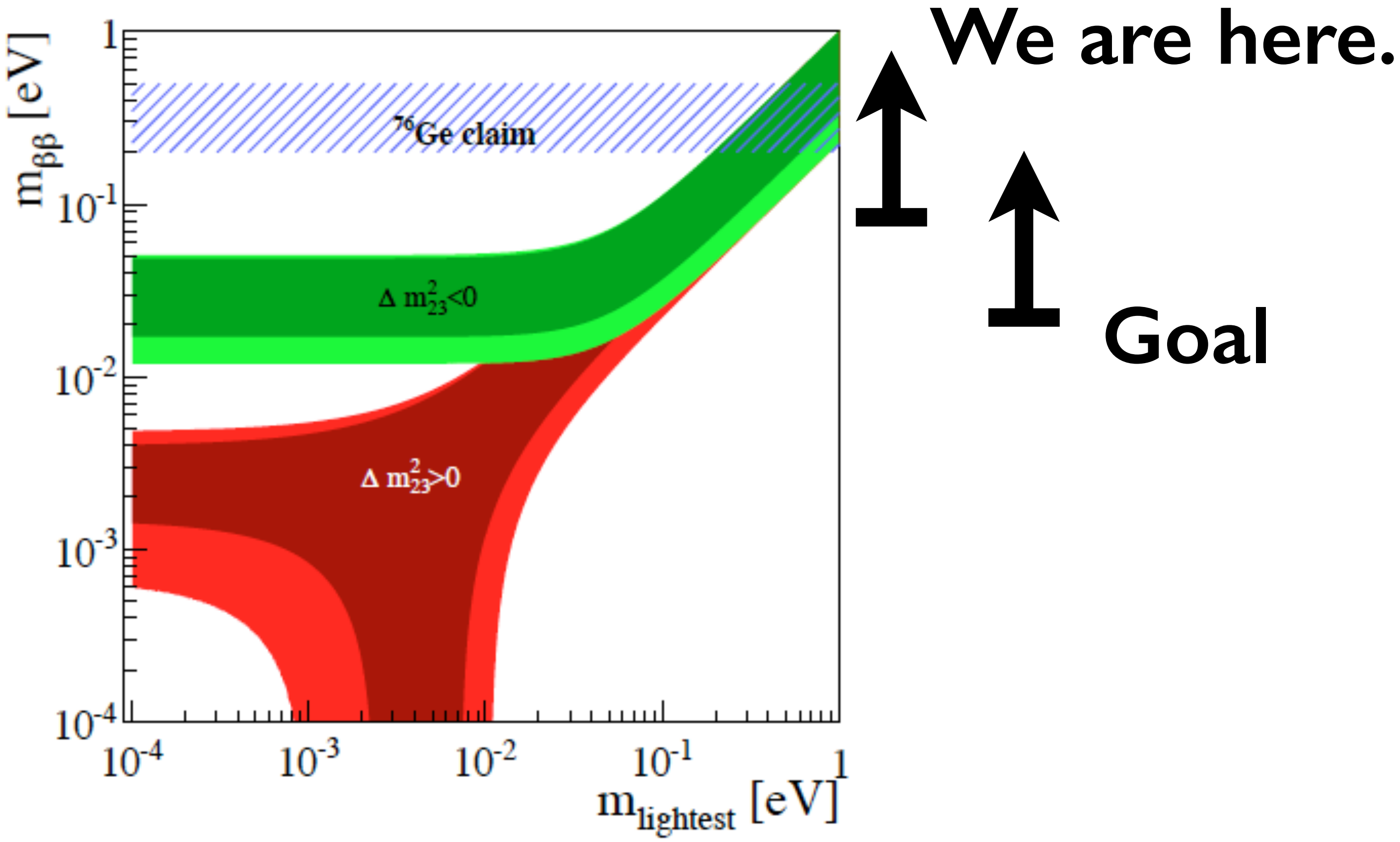
Double Beta Decay Visualizing the Equations:

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

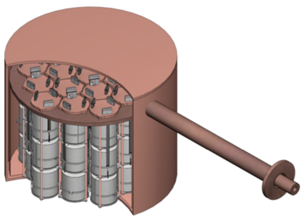


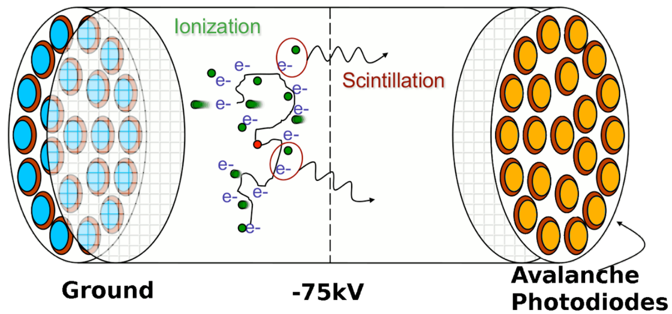
The dark part of the width of these bands is real and if nature is cruel there could be some very nasty interference.

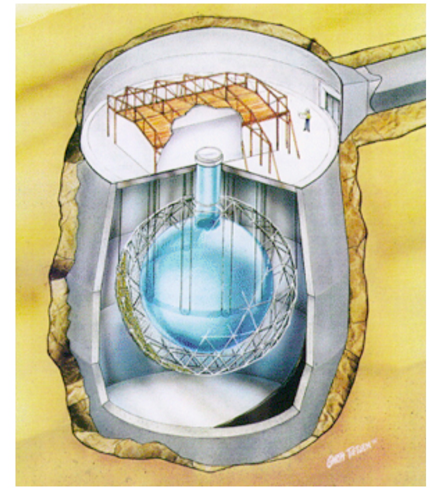
Goal: Definitive search in the Inverted Hierarchy (IH)

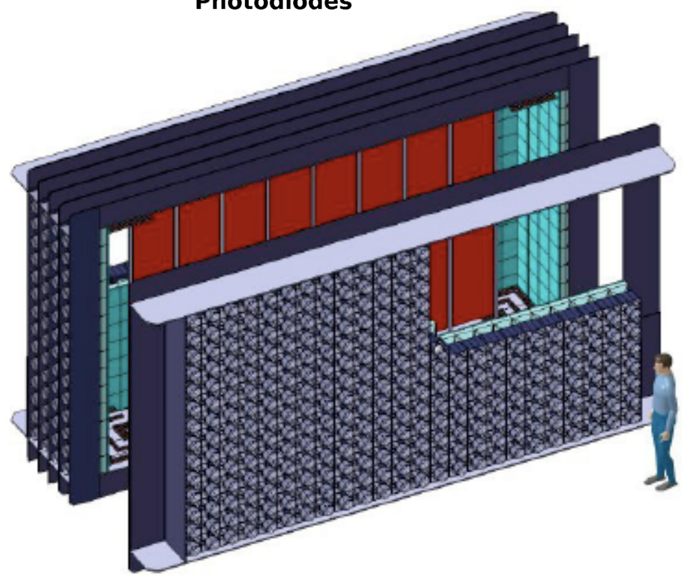


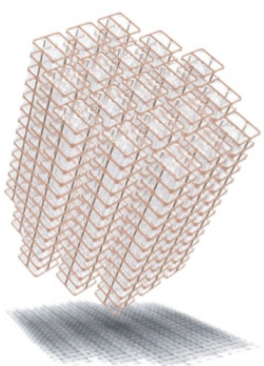
A lot of detector ideas:

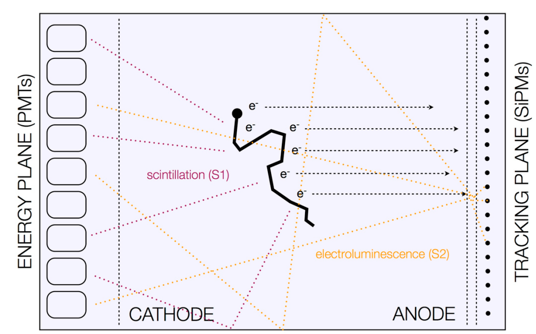


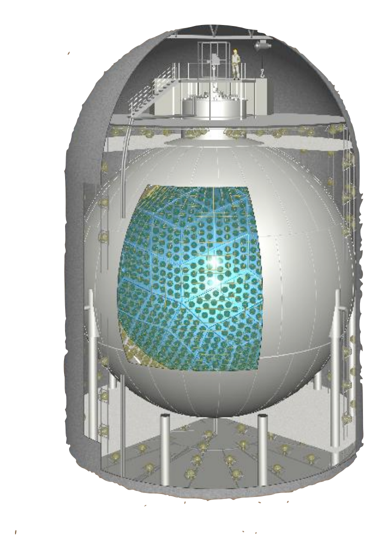




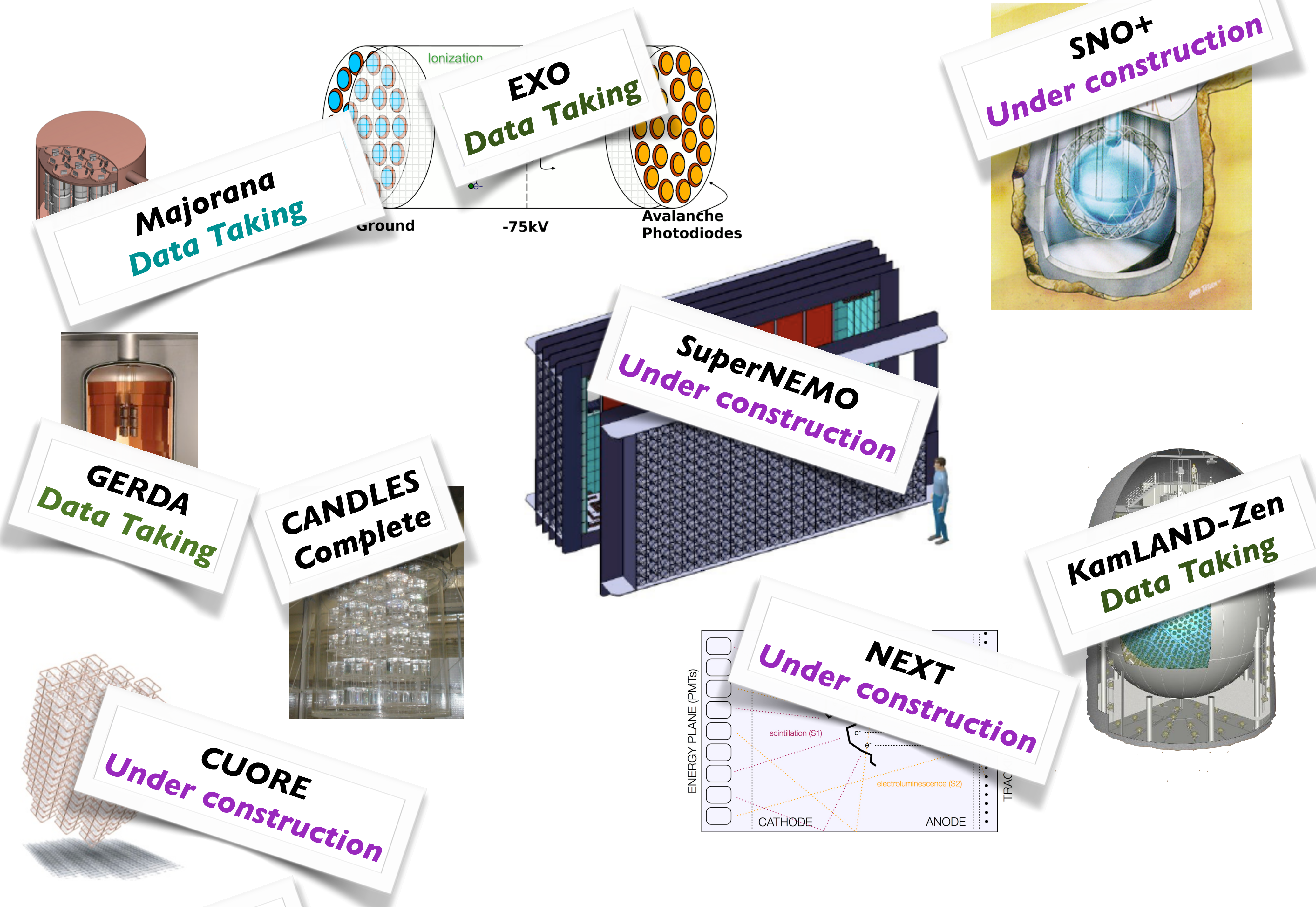




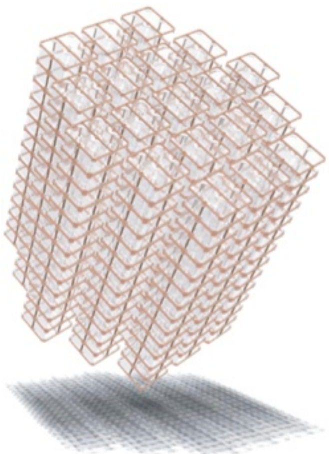




A lot of detector ideas:



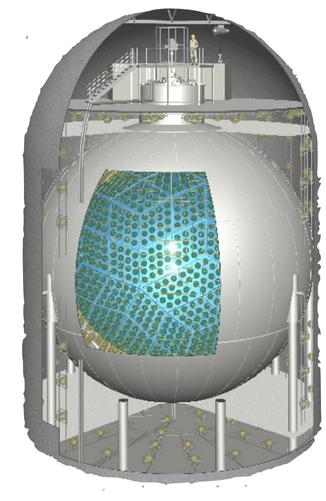
Good
Energy
Resolution



Bolometers

More Difficult
to make big.

Good
at Size

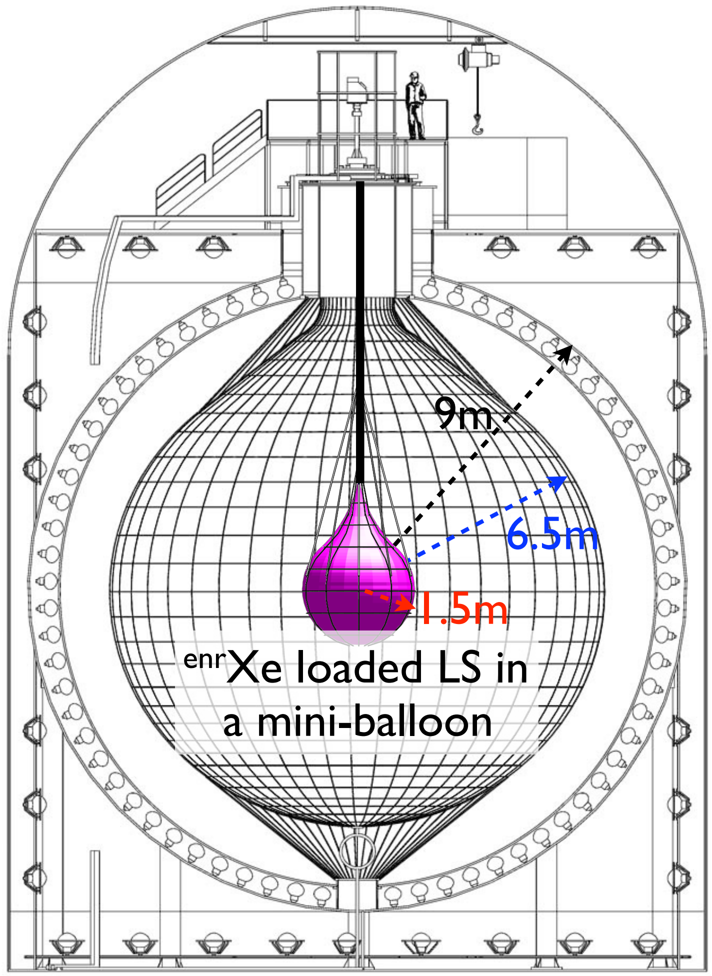


Scintillator

Bad Energy
Resolution

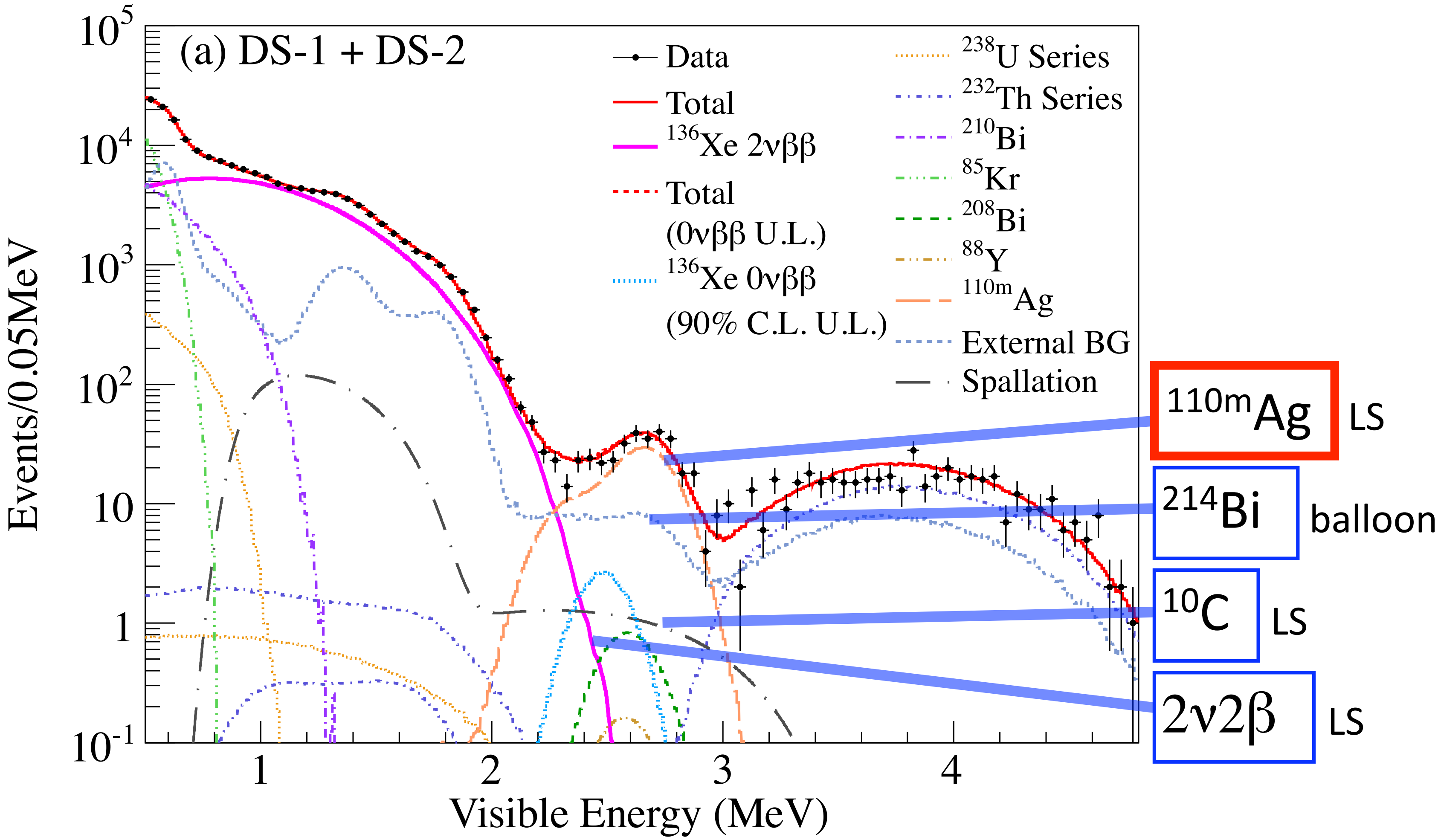
KamLAND-Zen

Zero Neutrino
double beta decay search



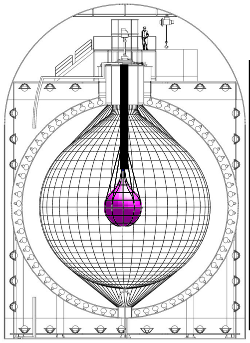
320kg 90% enriched ^{136}Xe installed for phase-1 and 380kg for phase-2

KamLAND-Zen started in 2011:

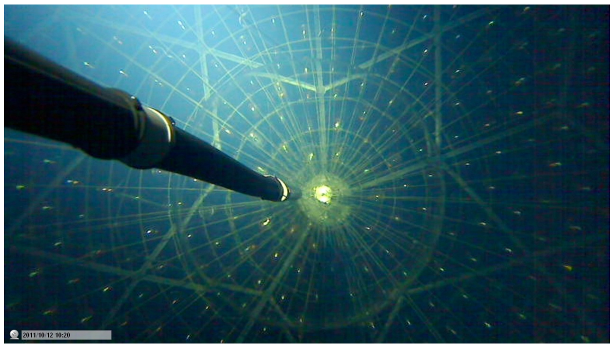


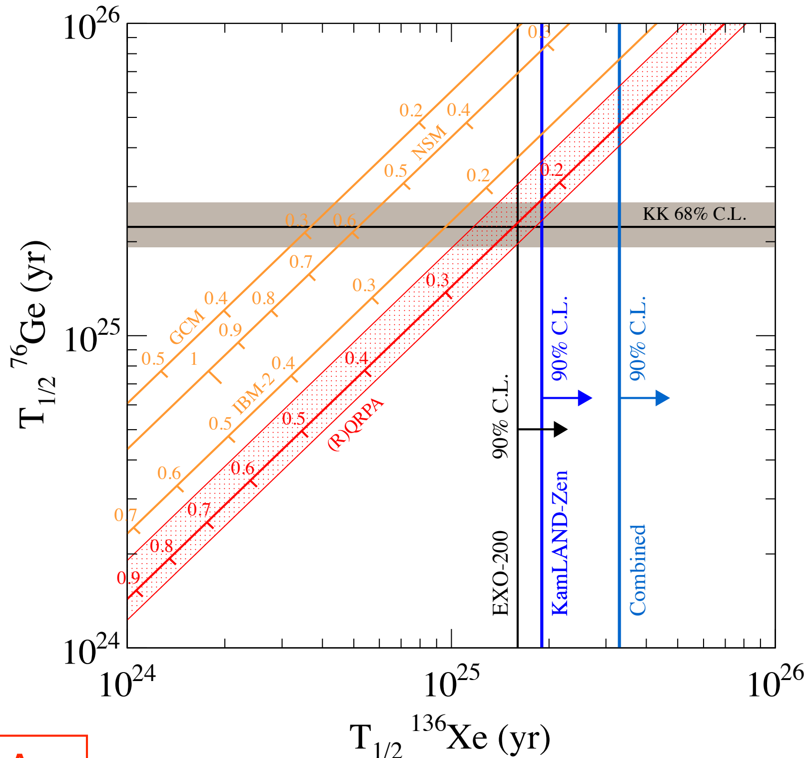
An Unexpected BG was found!

Published result w/ high silver rate (phase-1):



~320kg 90% enriched ^{136}Xe installed initially





Phys.Rev.Lett, 110, 062502 (2013)

so far the world best limit

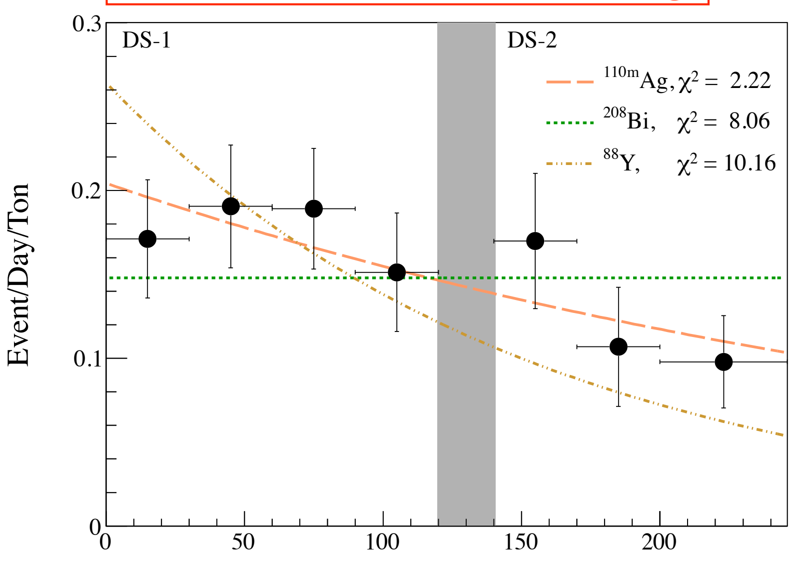
$T_{1/2} > 1.9 \times 10^{25}$ yrs (KL-Zen)

$> 3.4 \times 10^{25}$ yrs (combined)

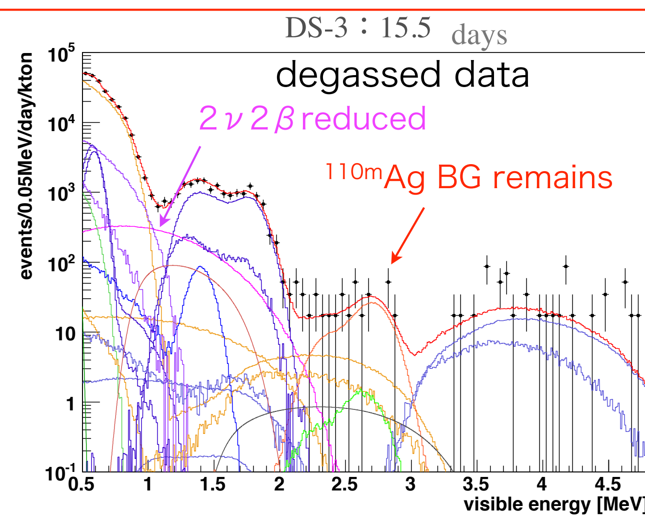
$\langle m_{\beta\beta} \rangle < 120 \sim 250\,\mathrm{meV}$

KK-claim refuted at 97.5% CL

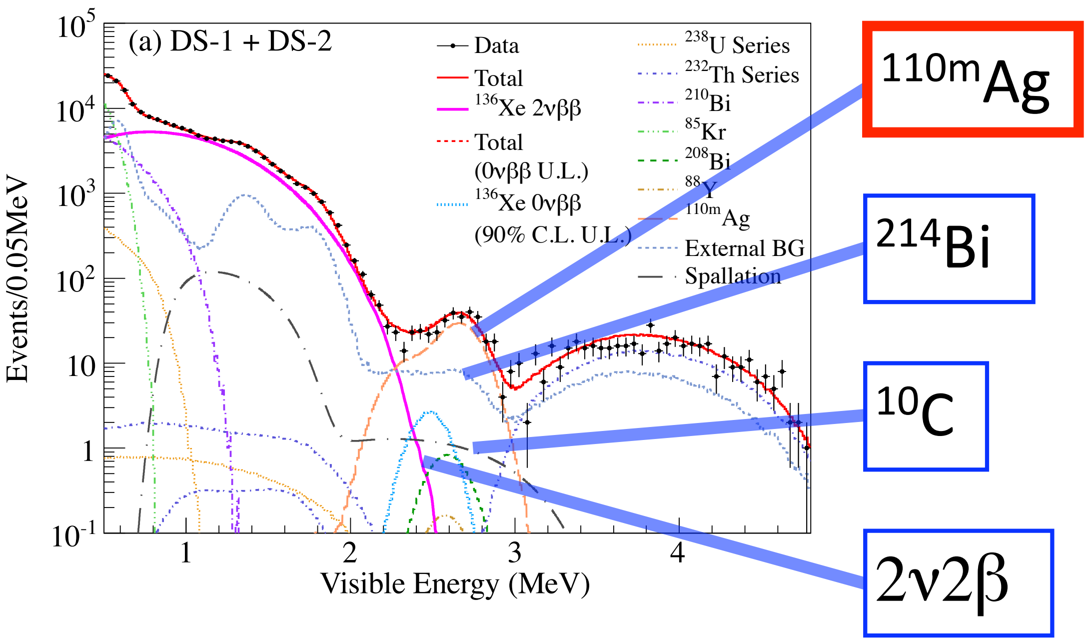
BG identified as ^{110m}Ag



Xe on-off measurement demonstrated



What can be done?



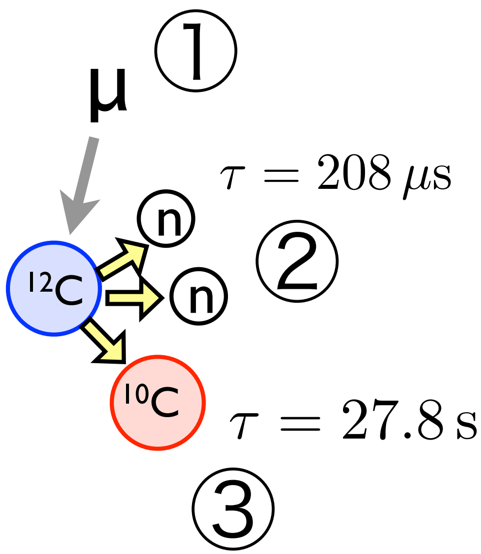
purification !!

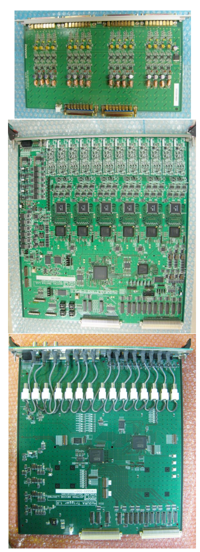
fine binning of volume

triple fold coincidence

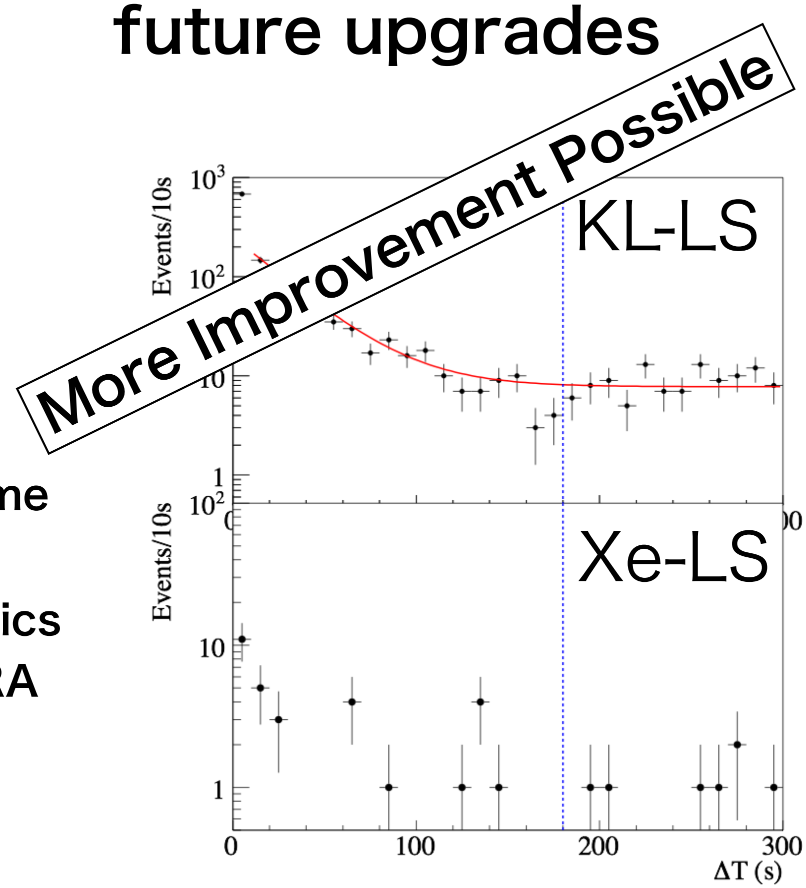
future upgrades

Three-fold coincidence for ^{10}C rejection (64% Efficiency):



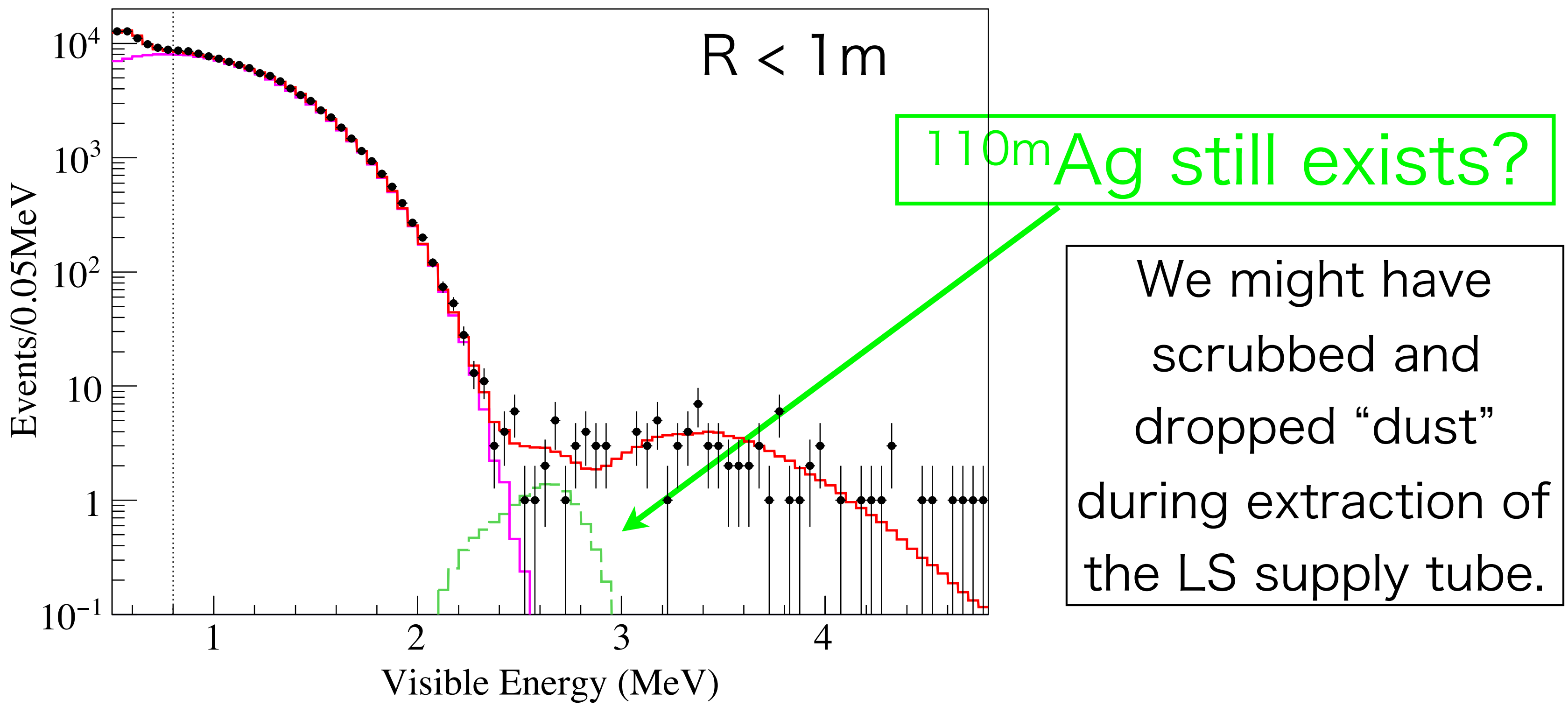


dead time free electronics MoGURA



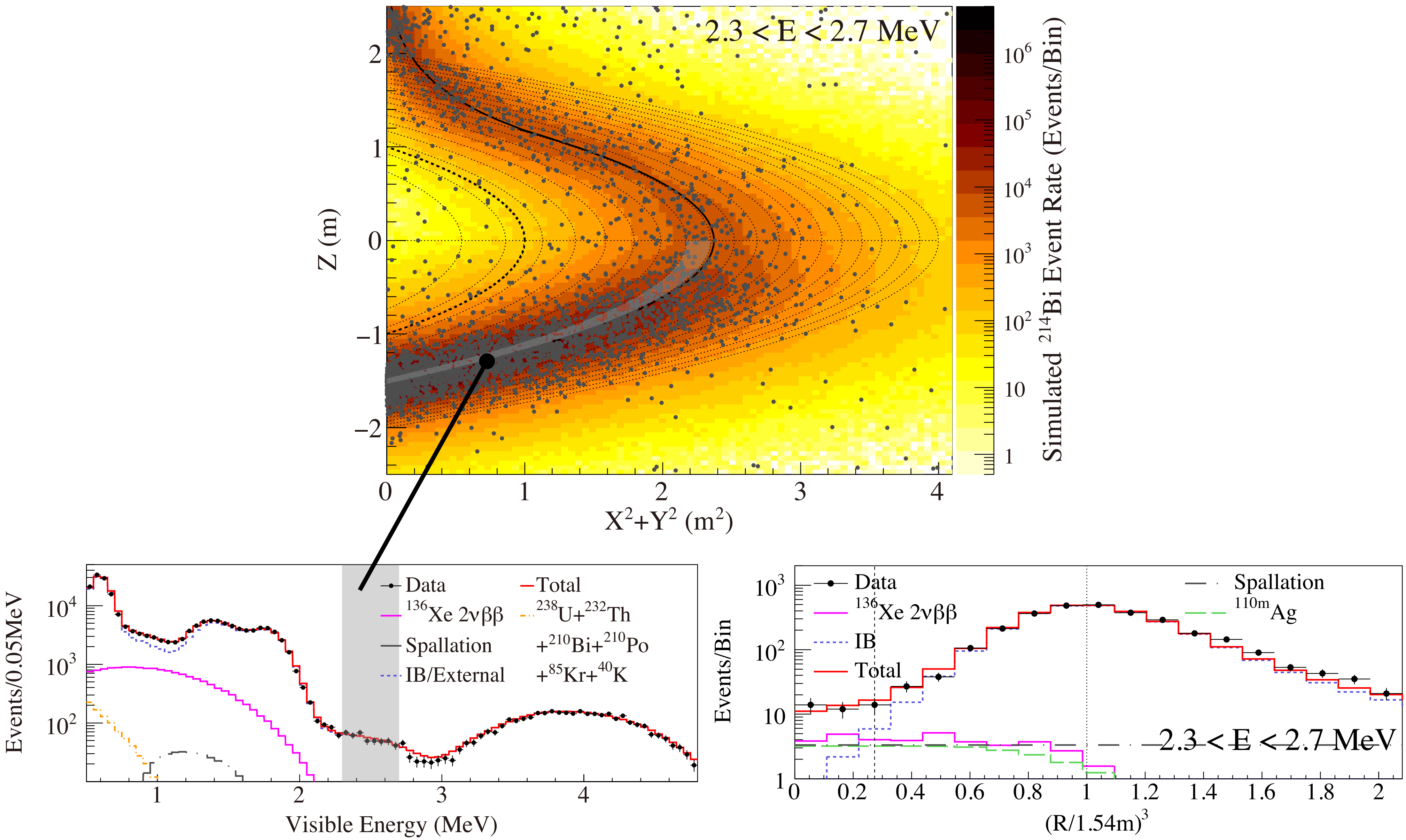
Full phase-2 data-set

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



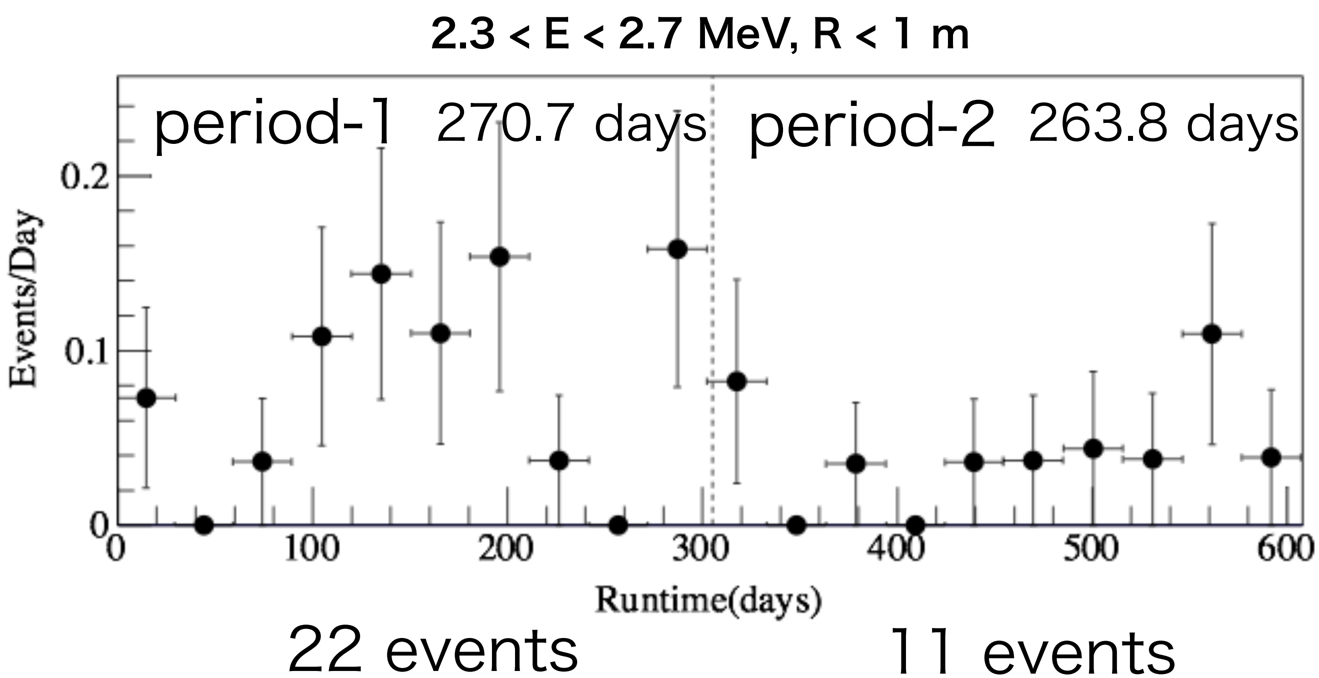
We might have scrubbed and dropped "dust" during extraction of the LS supply tube.

Analysis:
40 equal-volume bins



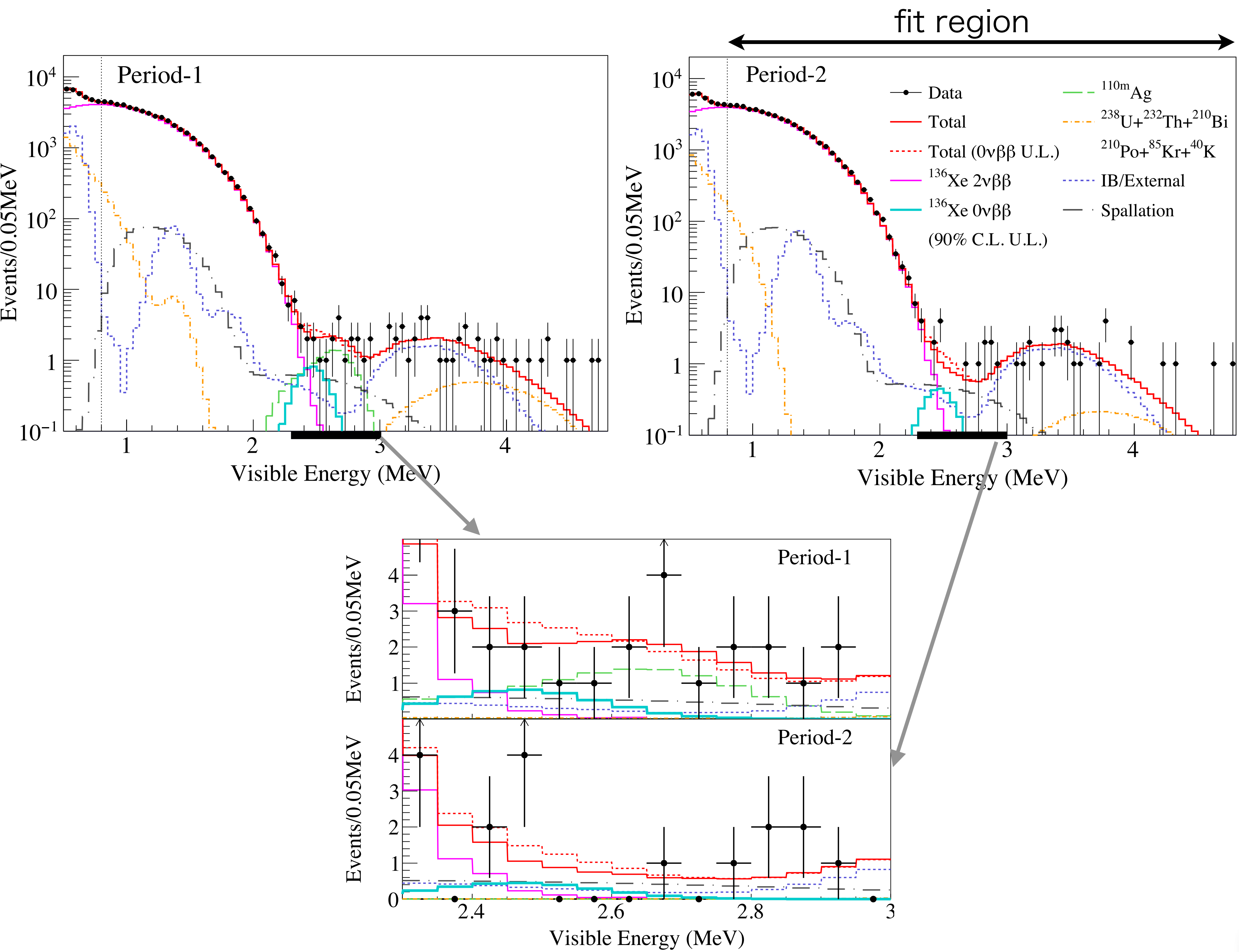
Energy and radial distributions are well-reproduced by known BGs.

Analysis:
2 Time Periods



A hypothesis:
"Dust" sank !?

However, only ~2σ discrepancy from a simple decay



fit region
Period-1
Period-2
Data
Total
Total (0νββ U.L.)
^{136}Xe 2νββ
^{136}Xe 0νββ
(90% C.L. U.L.)
^{110m}Ag
^{238}U+^{232}Th+^{210}Bi
^{210}Po+^{85}Kr+^{40}K
IB/External
Spallation
Events/0.05MeV
Visible Energy (MeV)

Phase 2 - Results on $0\nu 2\beta$

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

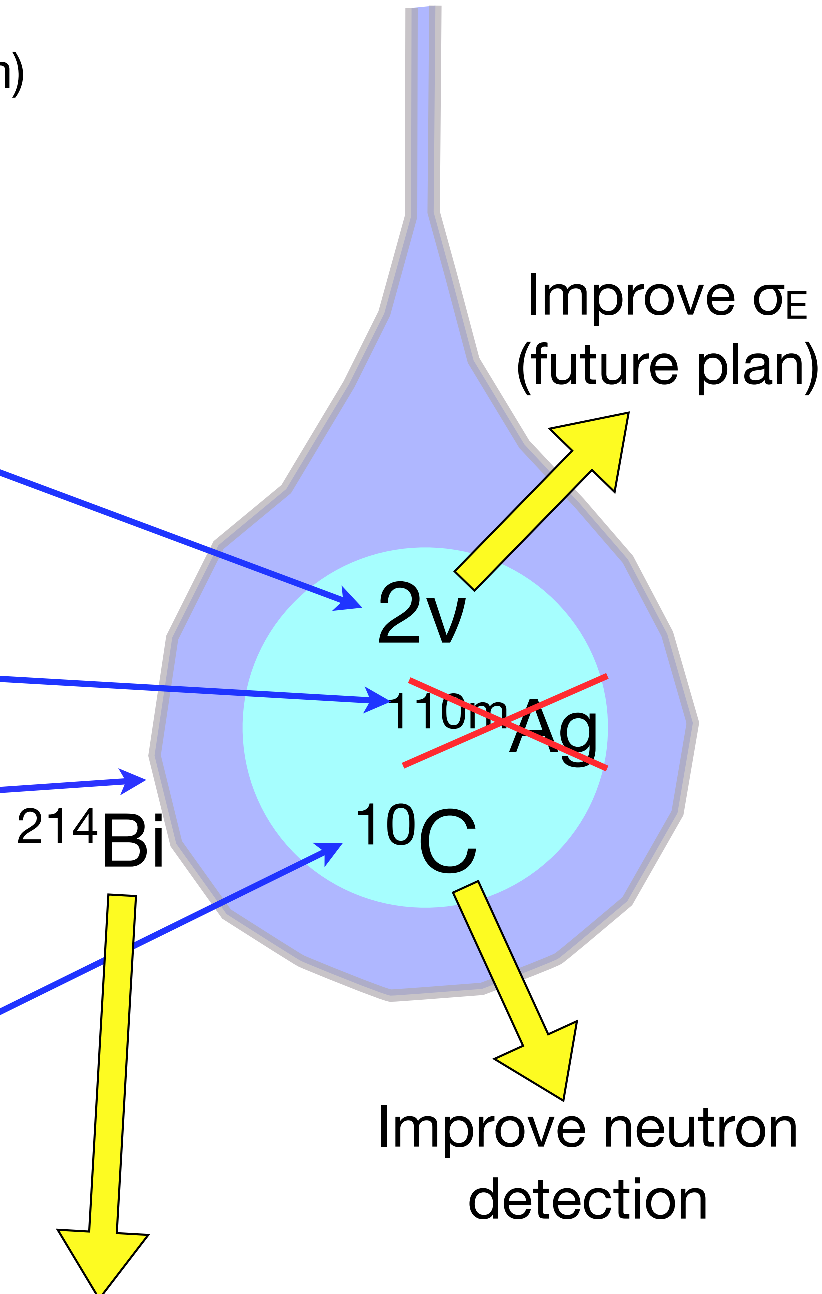
combined < 2.4 /kton/day (90%C.L.)

^{136}Xe $0\nu 2\beta$ half-life > 9.2×10^{25} yr (90%C.L.)

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

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

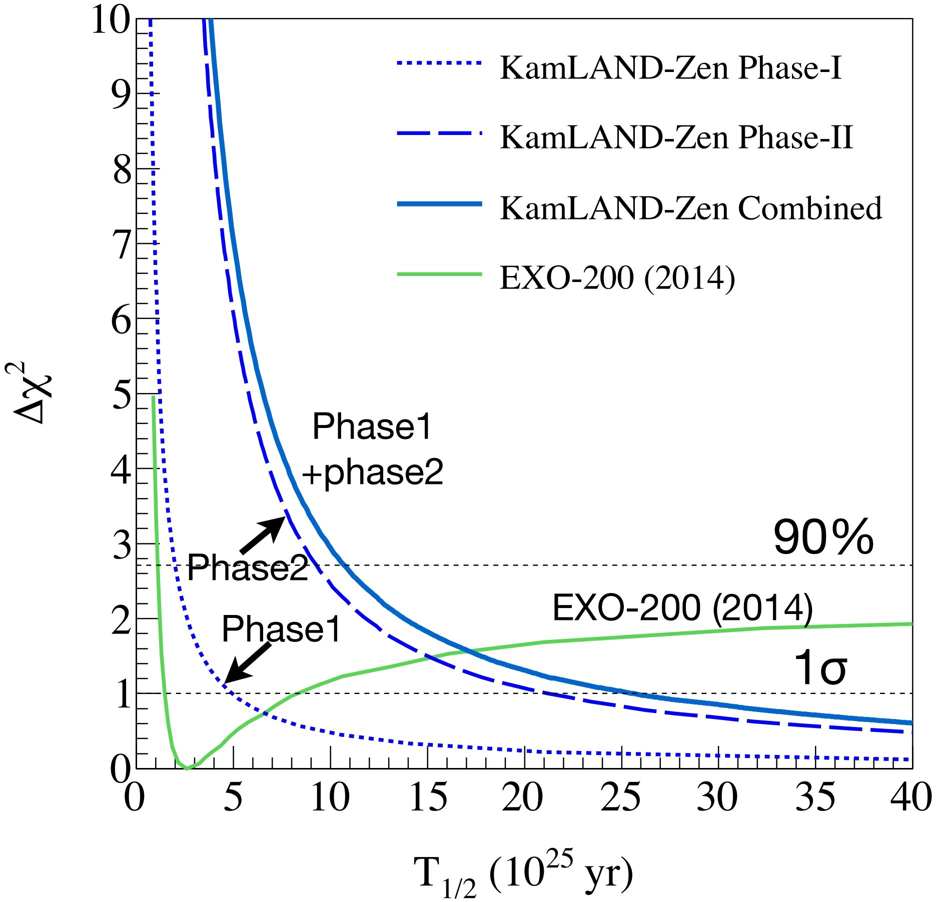
	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
$^{136}Xe\ 2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{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. today.

Replace the mini-balloon with a clean one (Next phase), now in preparation.

^{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 $\mathbf{T^{0\nu}_{1/2} > 1.07\times10^{26}}$ **yr**

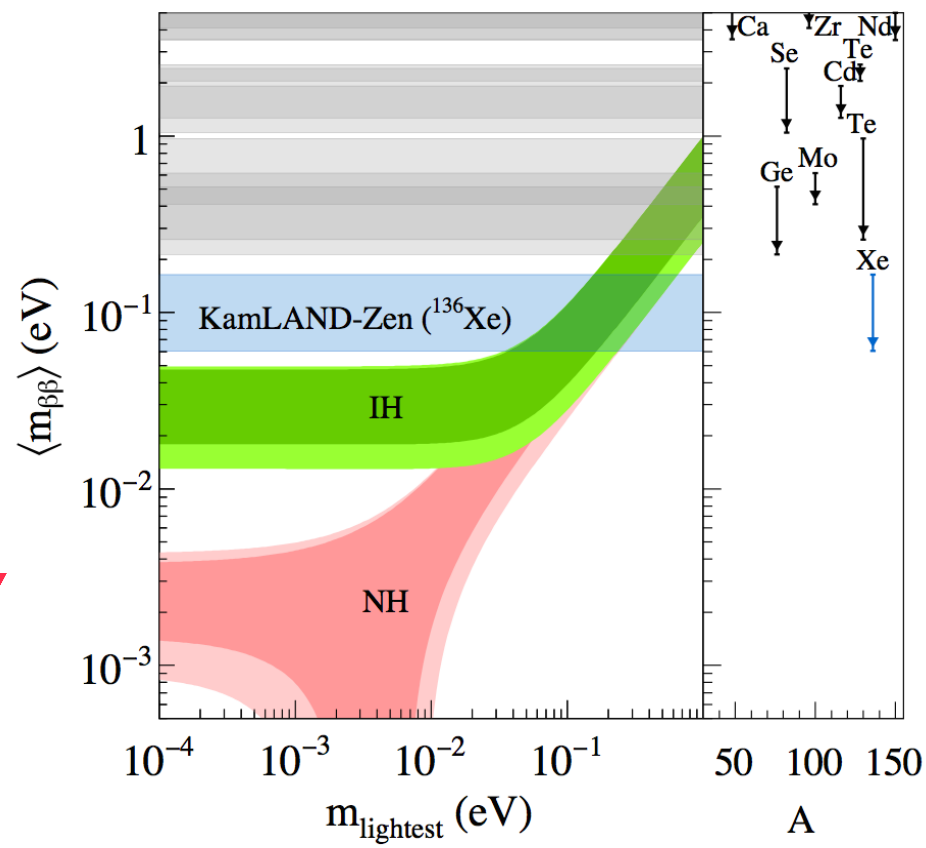
^{136}Xe 0νββ Decay Half-life

⟨$m_{\beta\beta}$⟩ < (61- 165) meV

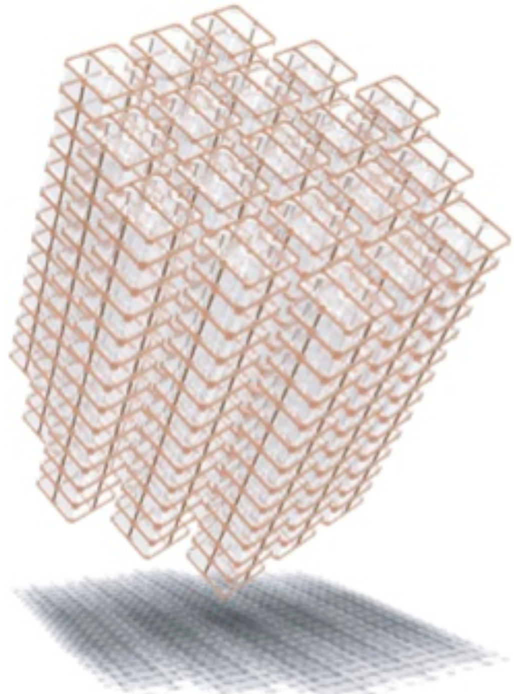
Commonly used NME with g_A~1.27,
Improved phase space calculations.

⟨$m_{\beta\beta}$⟩ limit reaches below 100meV and getting close to the IH region !

90%C.L. upper limits on ⟨$m_{\beta\beta}$⟩

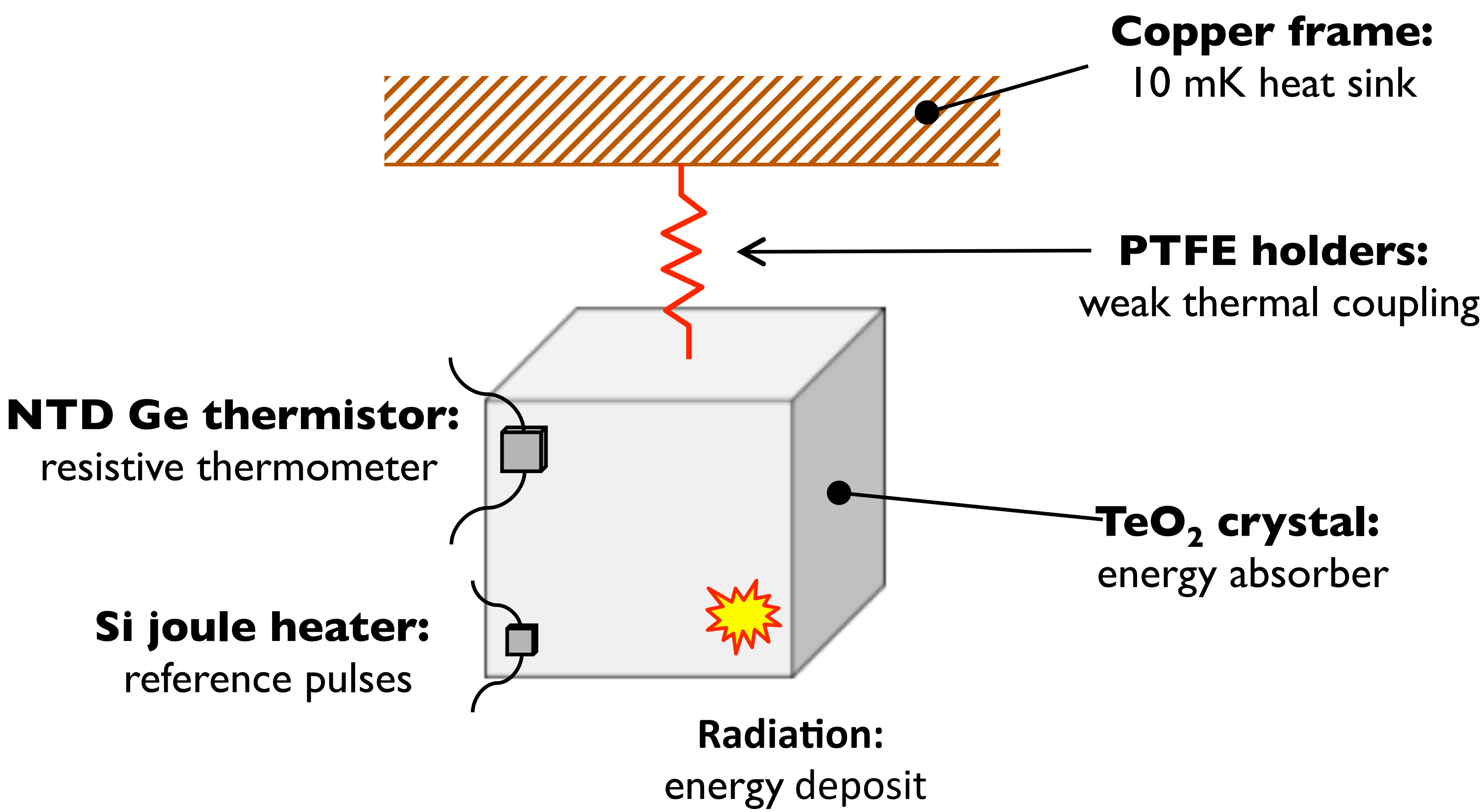


CUORE



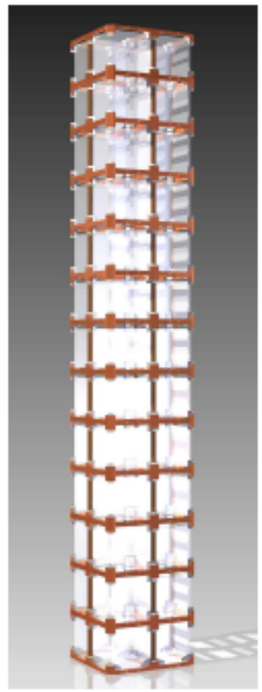
Super Cool

How Bolometers work:

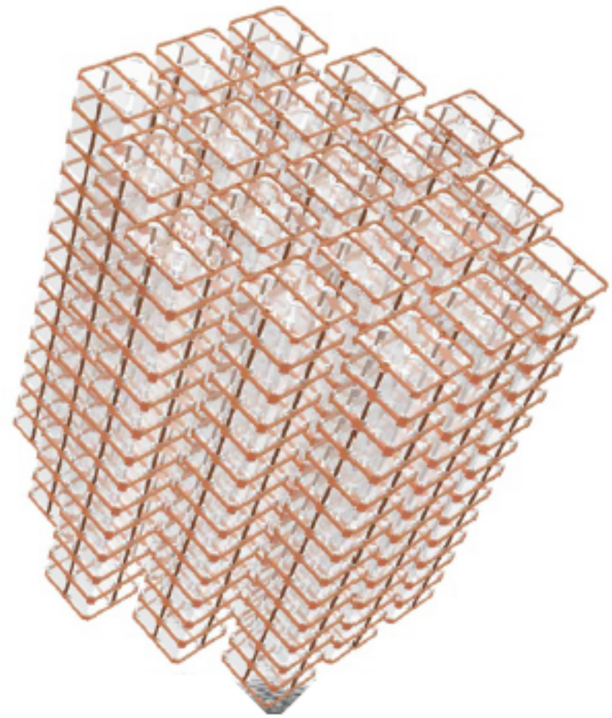


The Next Generation of Bolometer Experiments:

Cuoricino
2003–2008
11 kg ^{130}Te



CUORE-0
2012–2014
11 kg ^{130}Te



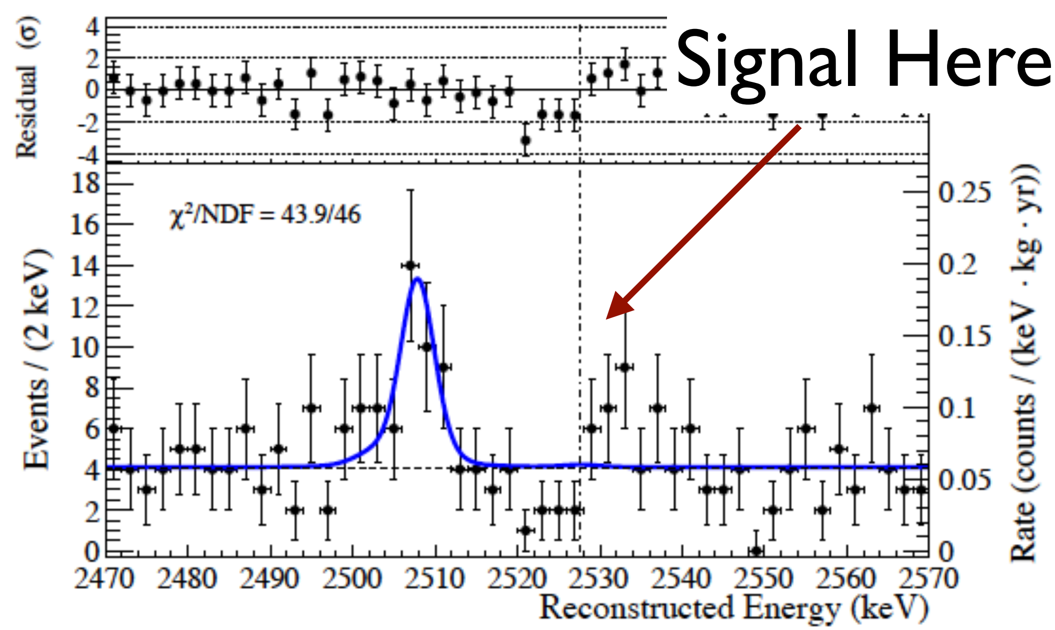
CUORE
2013–2018
206 kg ^{130}Te

CUORE:

Cryogenic Underground Observatory for Rare Events

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

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



- First results from CUORE-0 (one CUORE-style tower operated in old cryostat).
- Shows CUORE will reach cleanliness goals.

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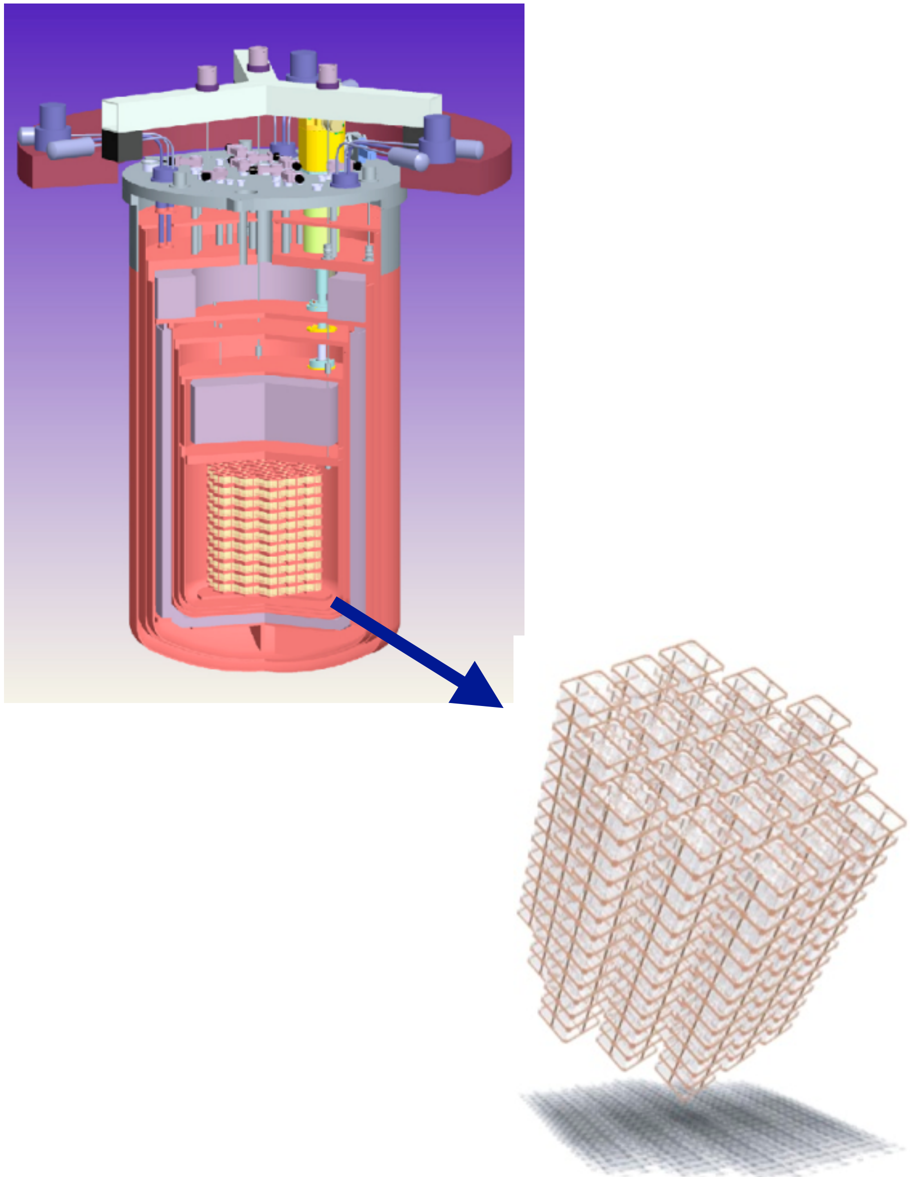
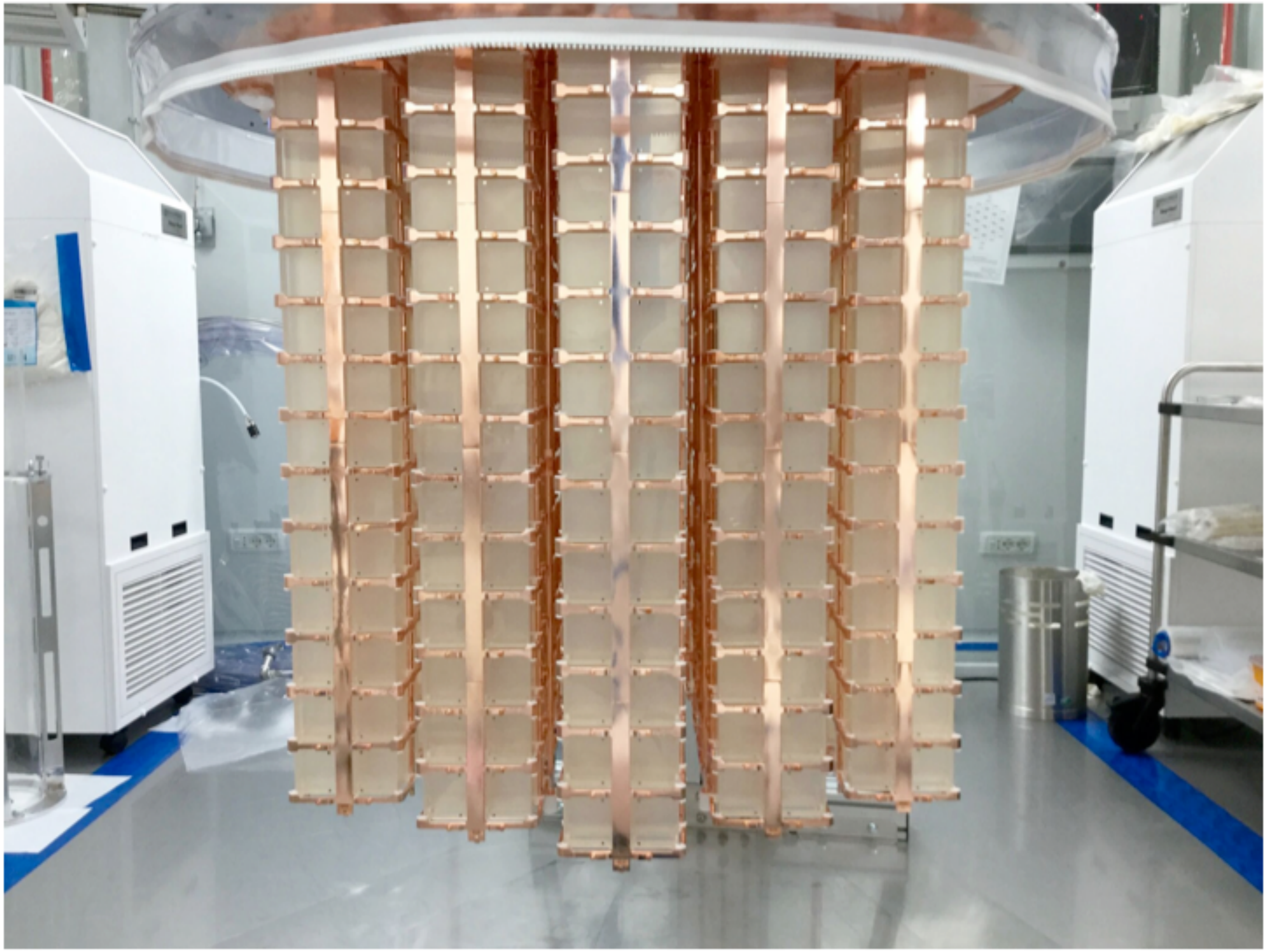
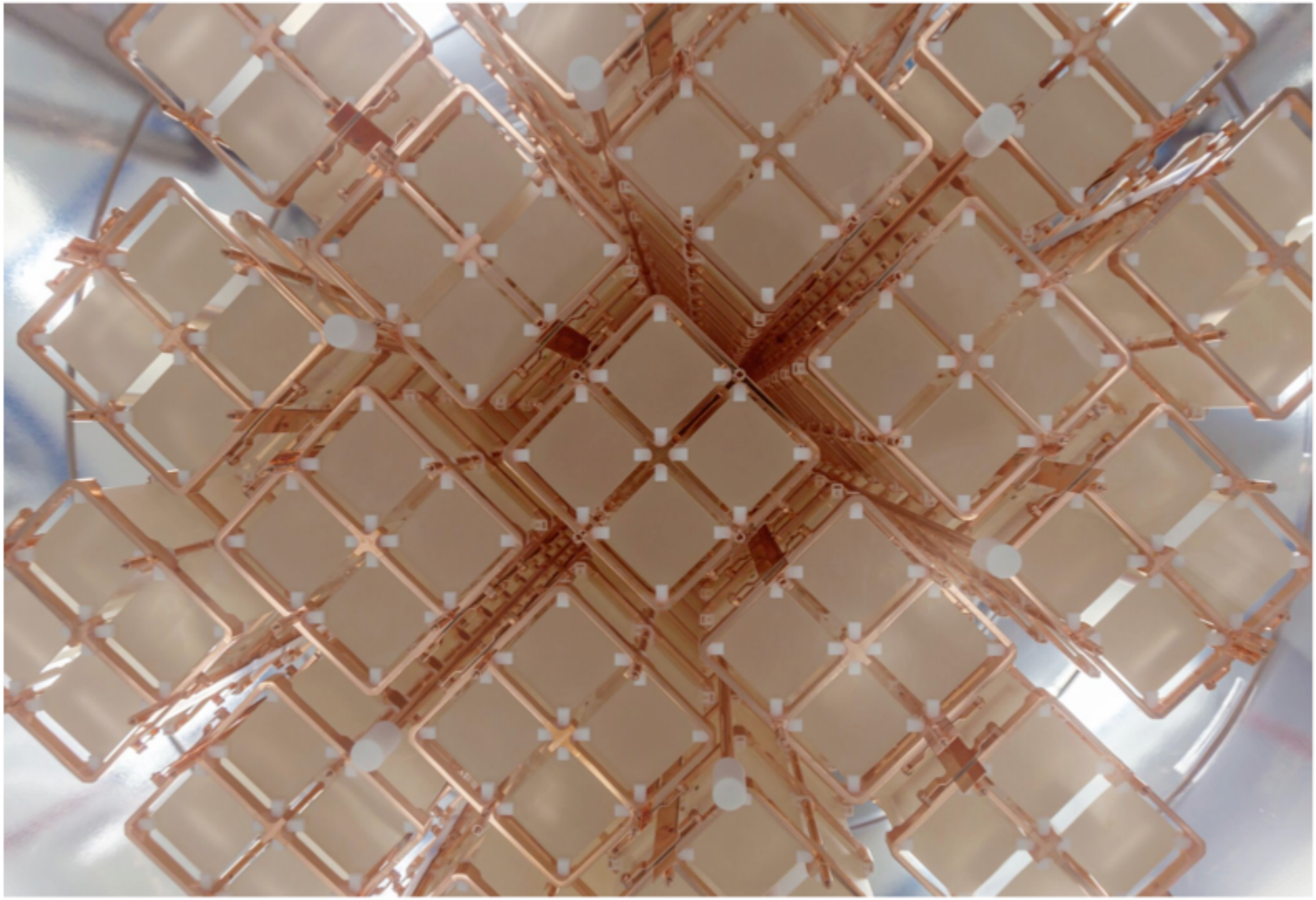


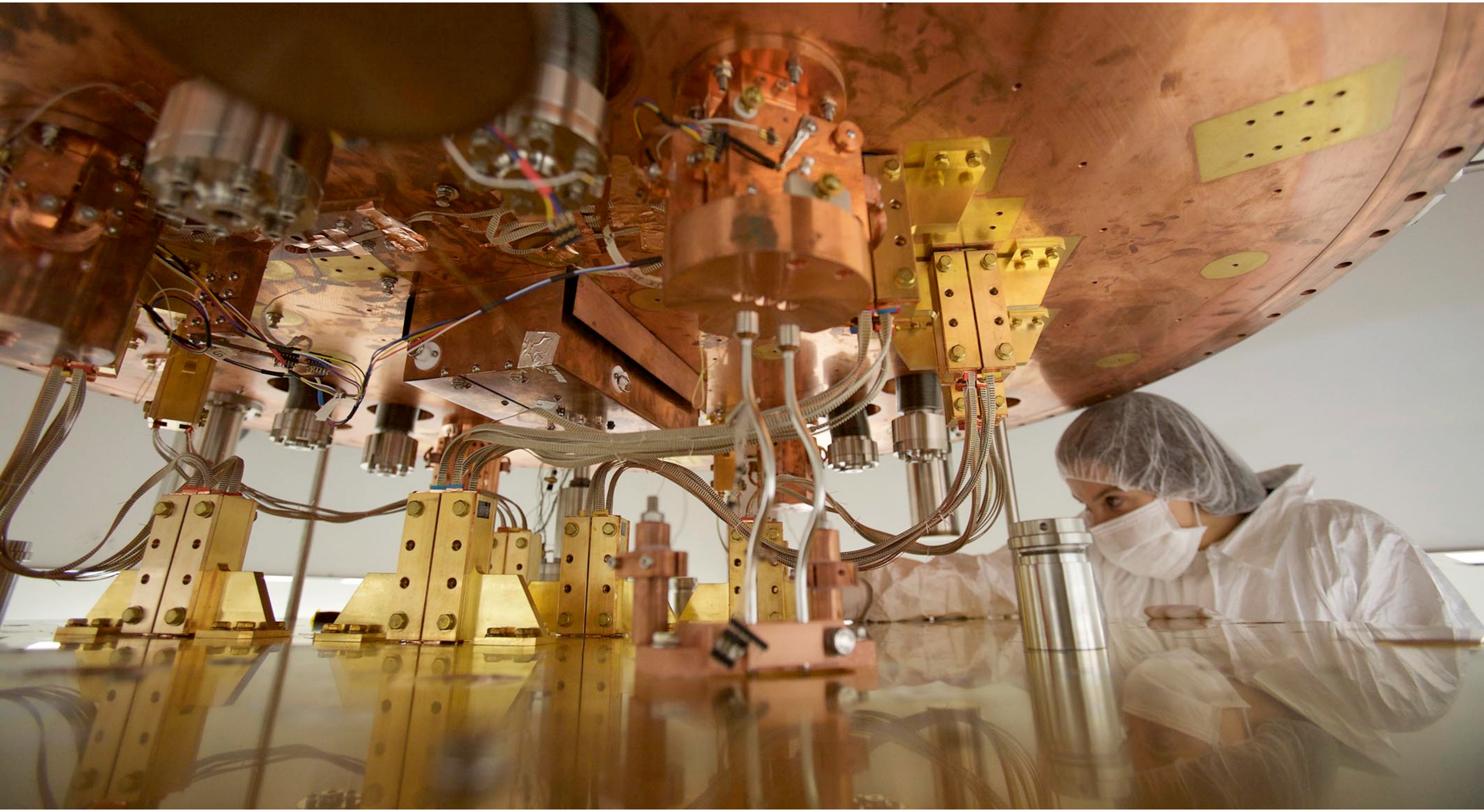
- 19 Towers, 988 TeO2 crystals operated as bolometers.
- We are the “Coldest cubic meter in the known universe”.

In real life…



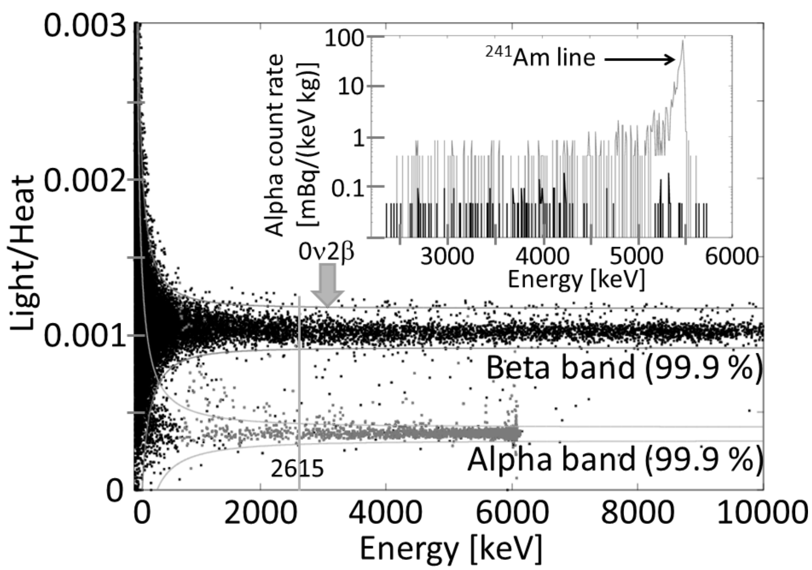


First data in Early 2017!



MIT Postdoc Dr. Lucia Canonica

CUPID:
CUORE with Particle ID



For ton-scale detector need:

- Enriched crystals with better background rejection.
- Scintillating bolometers are one way to do this. ZnMoO4 is the most promising crystal.
- Re-uses CUORE fridge, so this more of an upgrade to an existing detector than a new experiment.

First Crystals: $LiInSe_2$

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Forbidden nonunique β decays and effective values of weak coupling constants

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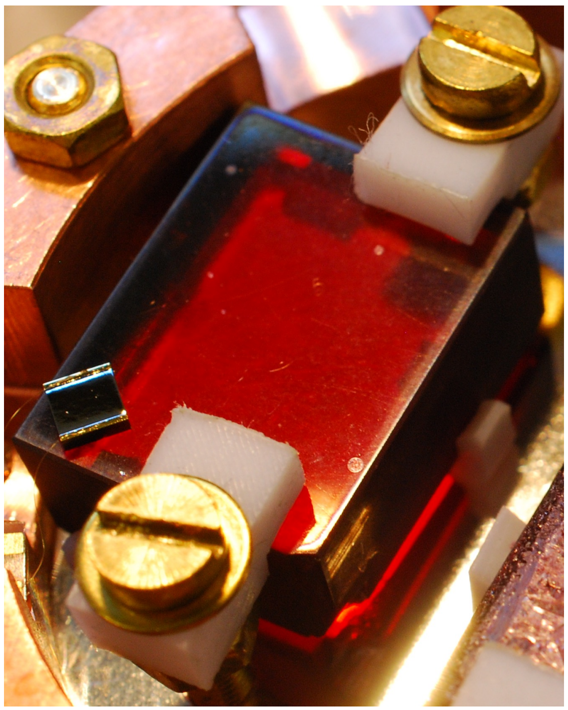
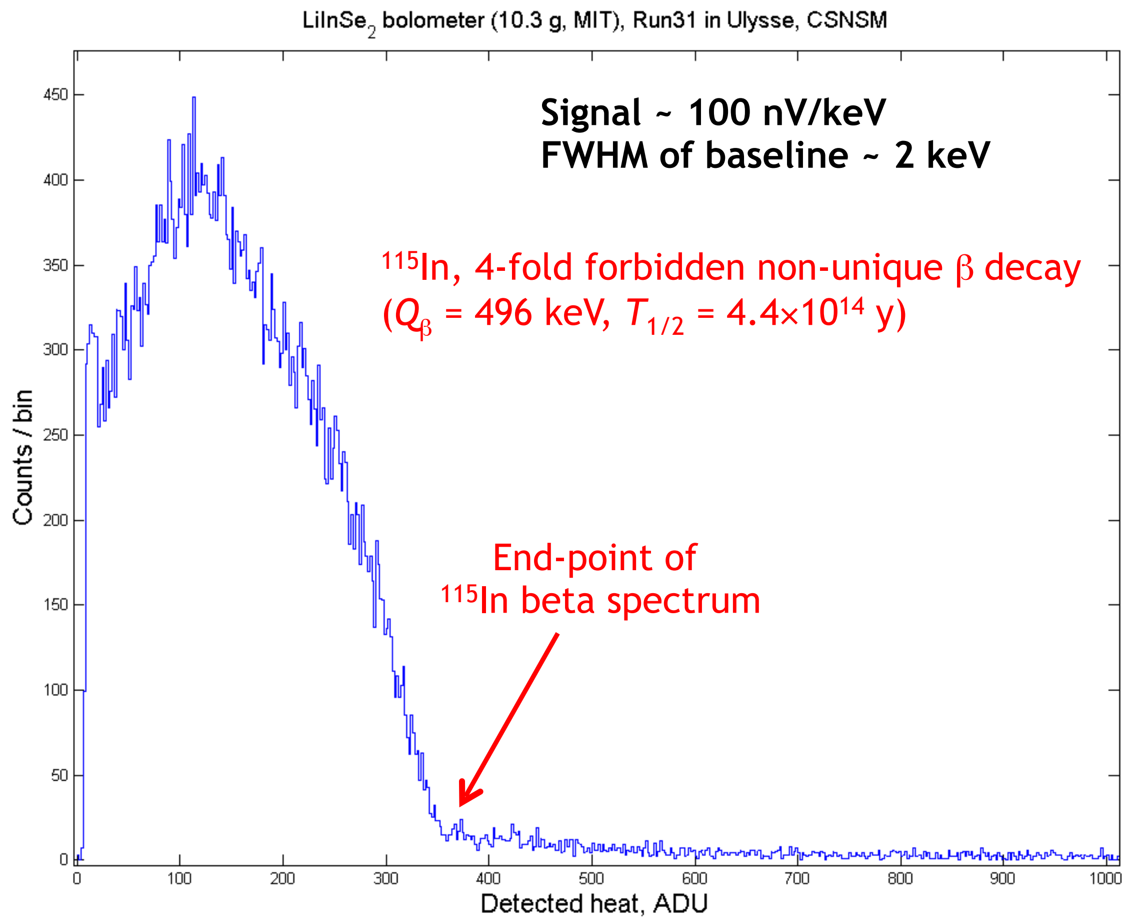
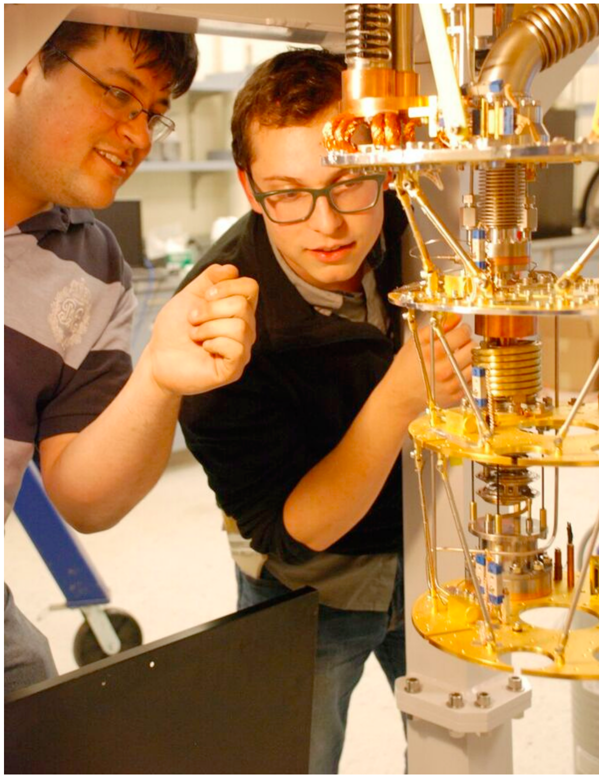


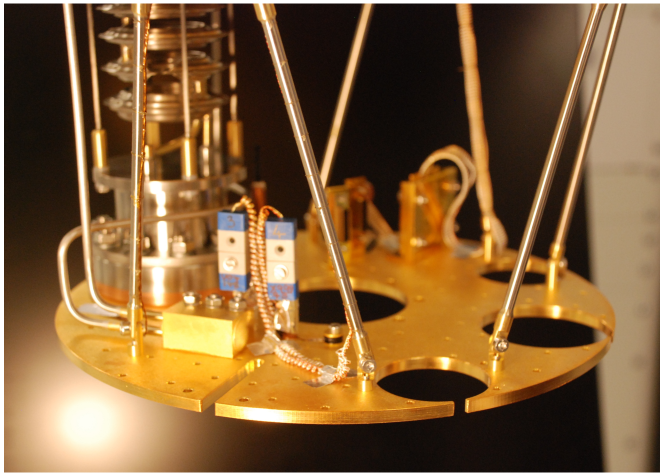


The crystal doesn't work for double-beta experiments because of th
but can help with theoretical uncertainties in the nuclear physics (quenching of g_A). $LiInSe_2$

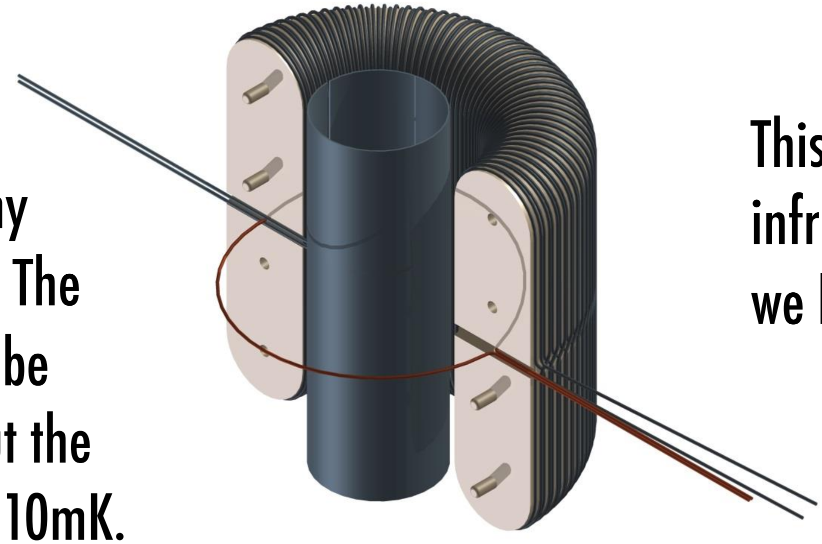
ABRACADABRA-10cm



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

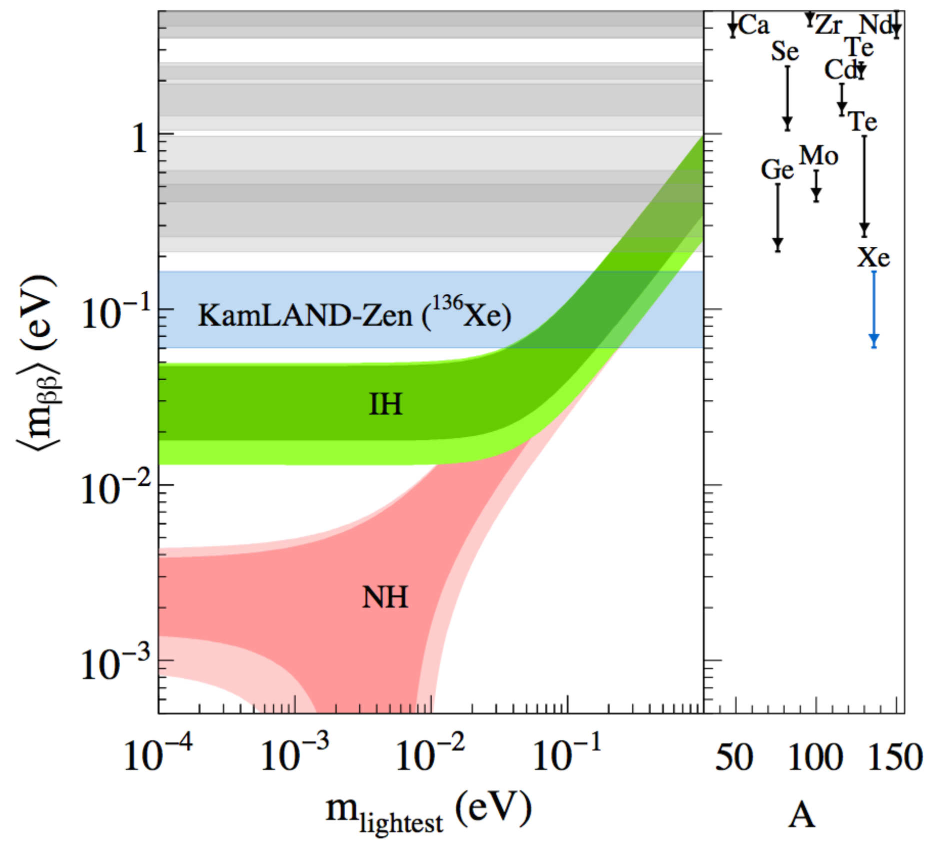


ABRACADABRA will be run in my Triton400 dilution refrigerator. The super conduction magnet may be cooled using warmer stages but the central cylinder needs to be at 10mK.



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

Back to Double-Beta Decay



Back to Double-Beta Decay

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

Outer Detector Refurbishment:

January 2016

New Mini-Balloon Leak Checking and Installation

MIT Undergraduates Hannah Taylor and Andrea Herman

Summer 2016