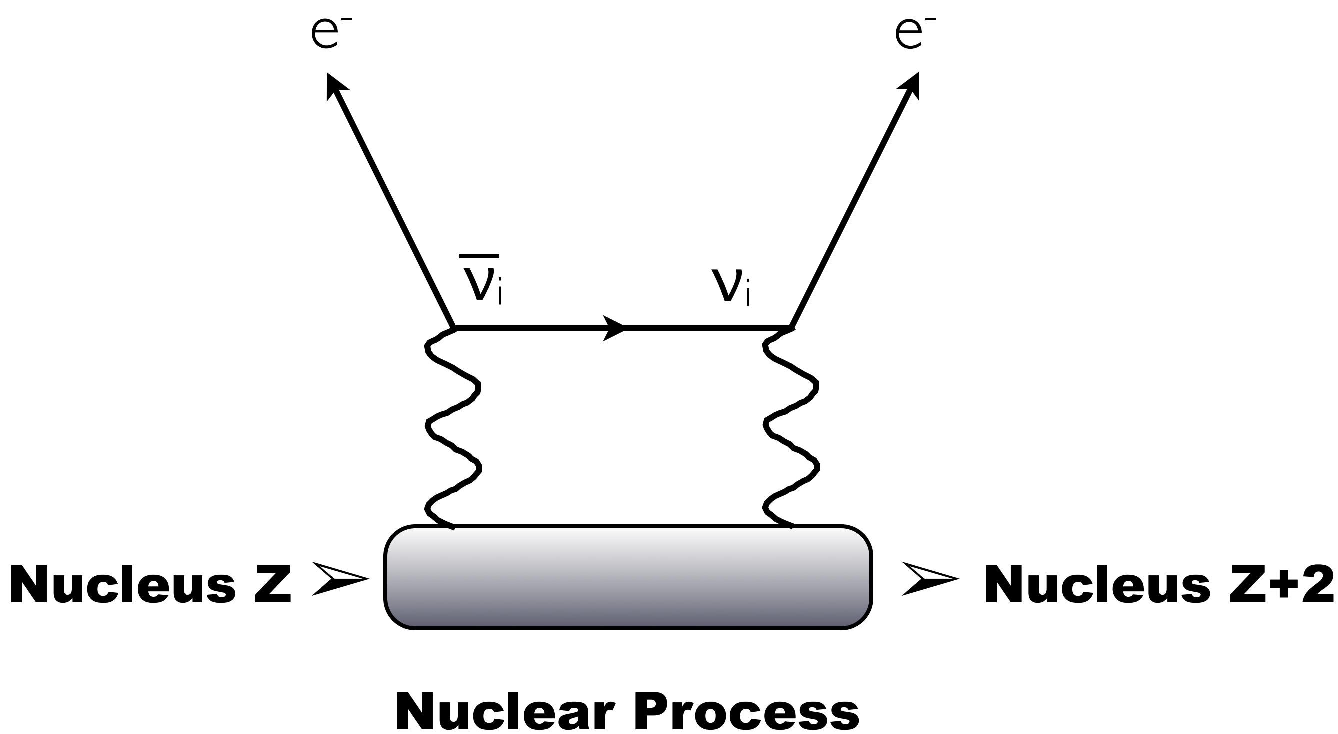
Discovering the Majorana Neutrino

The Next Generation
Of
Experiments

Lindley Winslow
UCLA

At a neutrino conference,
this is the search for nothing.

Neutrinoless Double Beta Decay

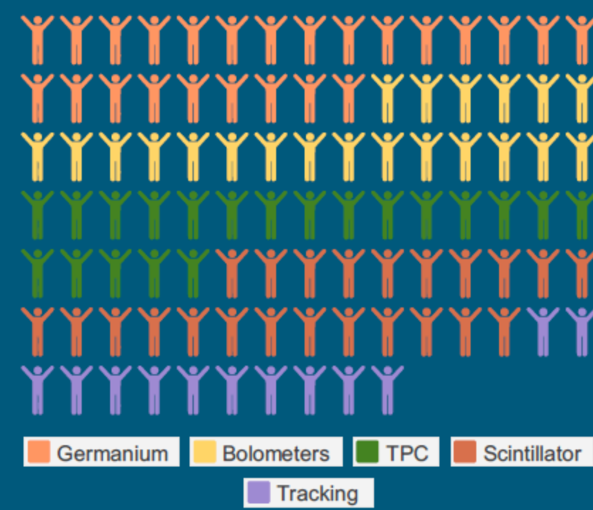


Light Majorana Neutrino Exchange

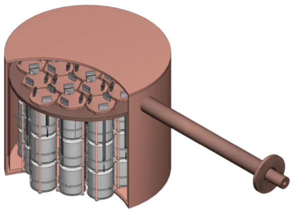
A Worldwide Effort

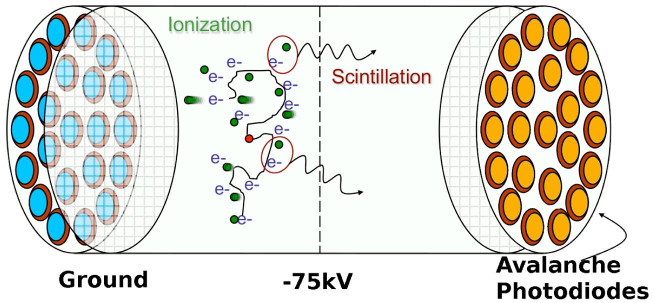
Underground labs around the world!

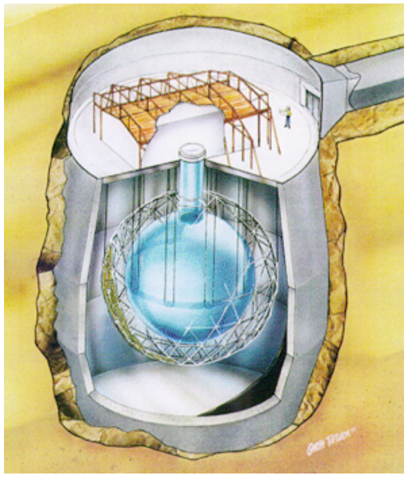
Approximately 840 physicists!

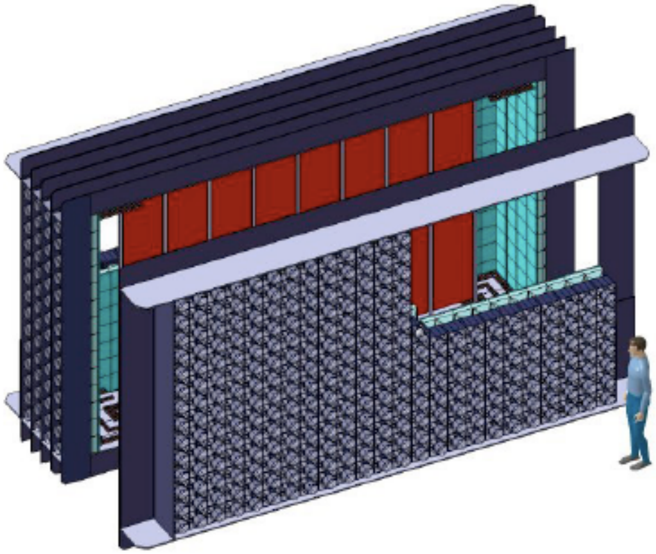


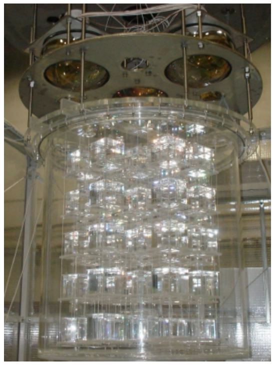
An explosion of technology!

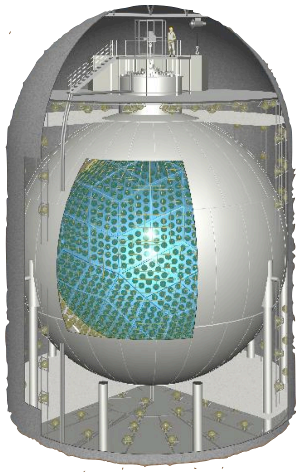


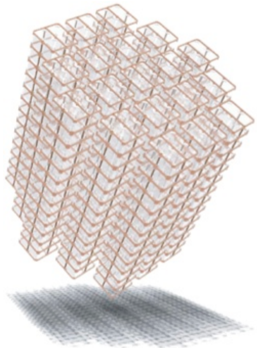


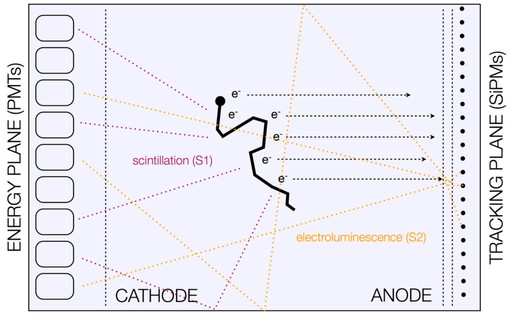




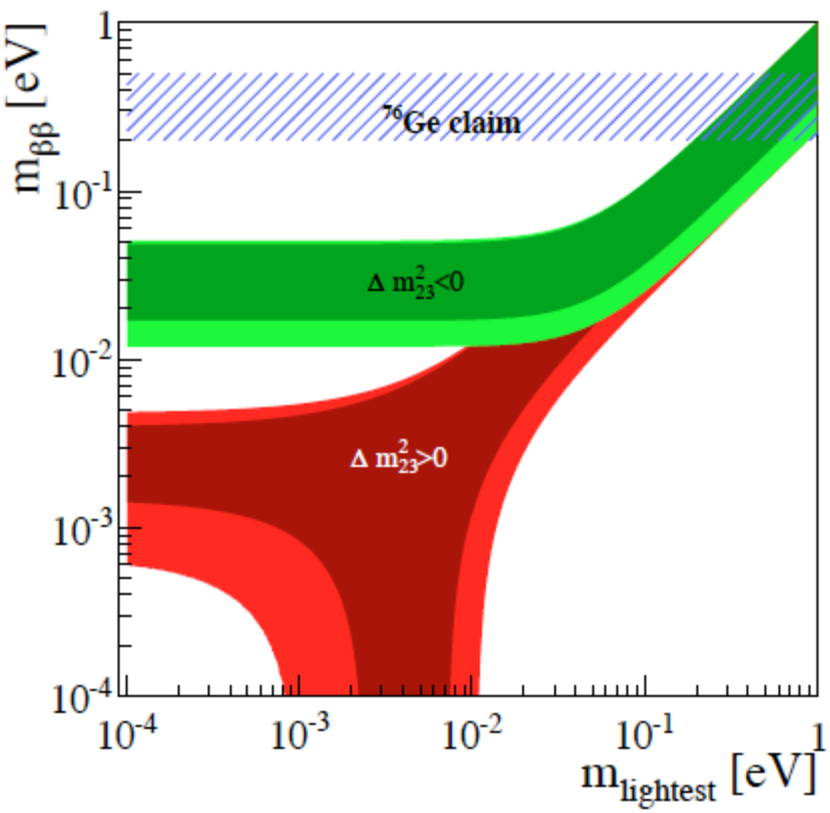




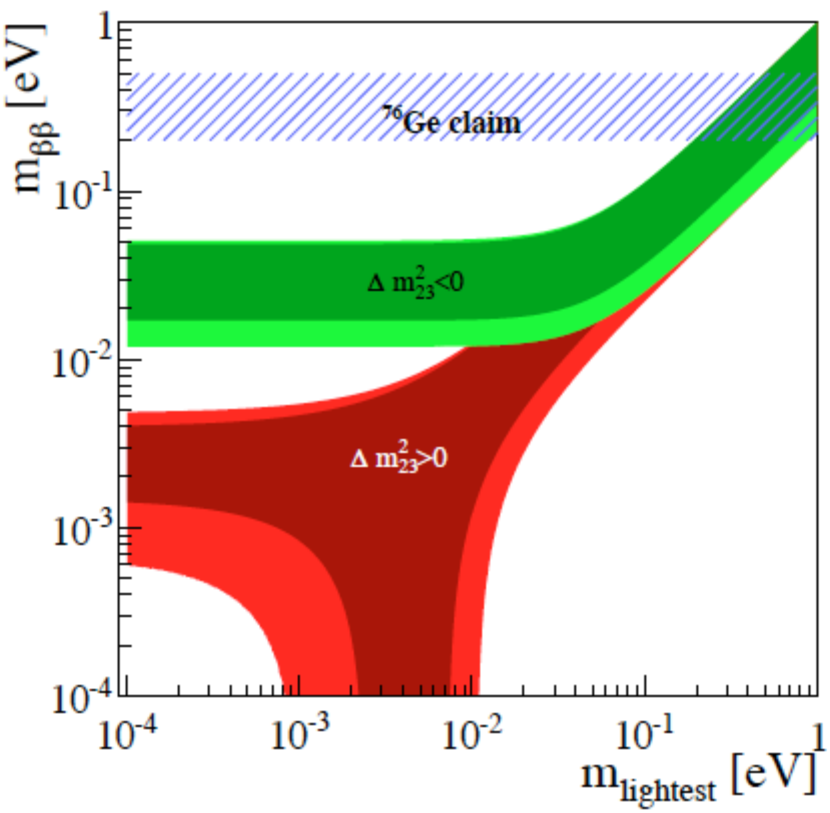




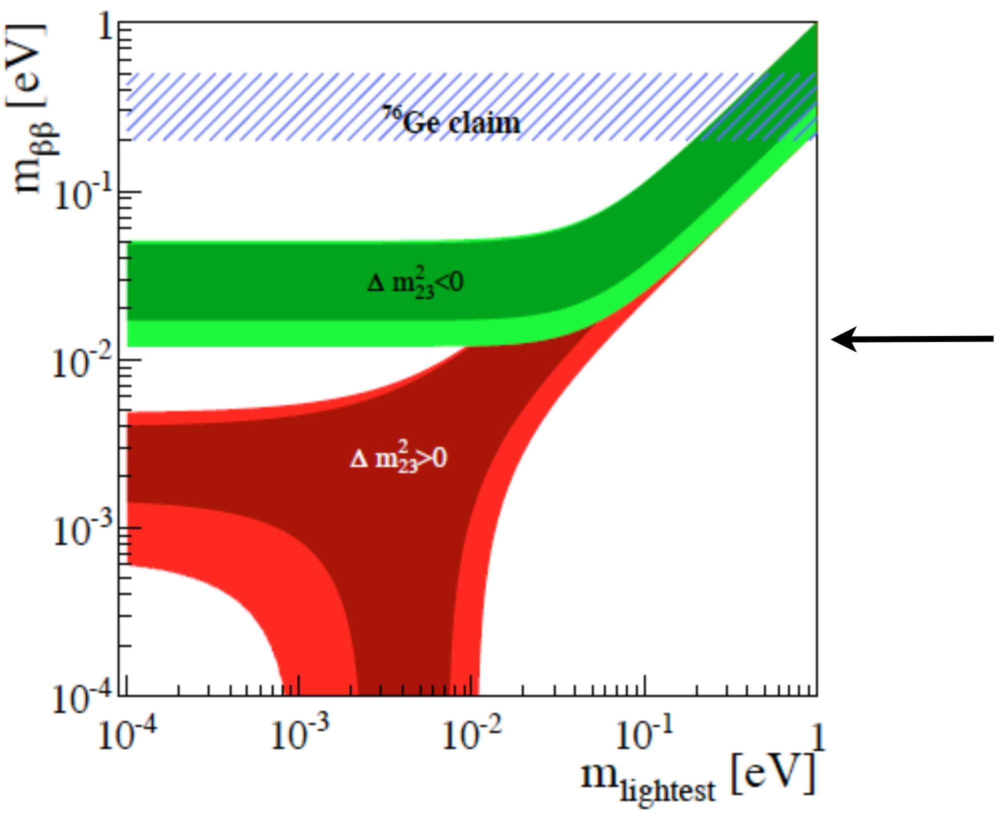
Where are we?


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$m_{\beta\beta}$ [eV]
^{76}Ge claim
$\Delta m^2_{23}<0$
$\Delta m^2_{23}>0$
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$m_{lightest}$ [eV]

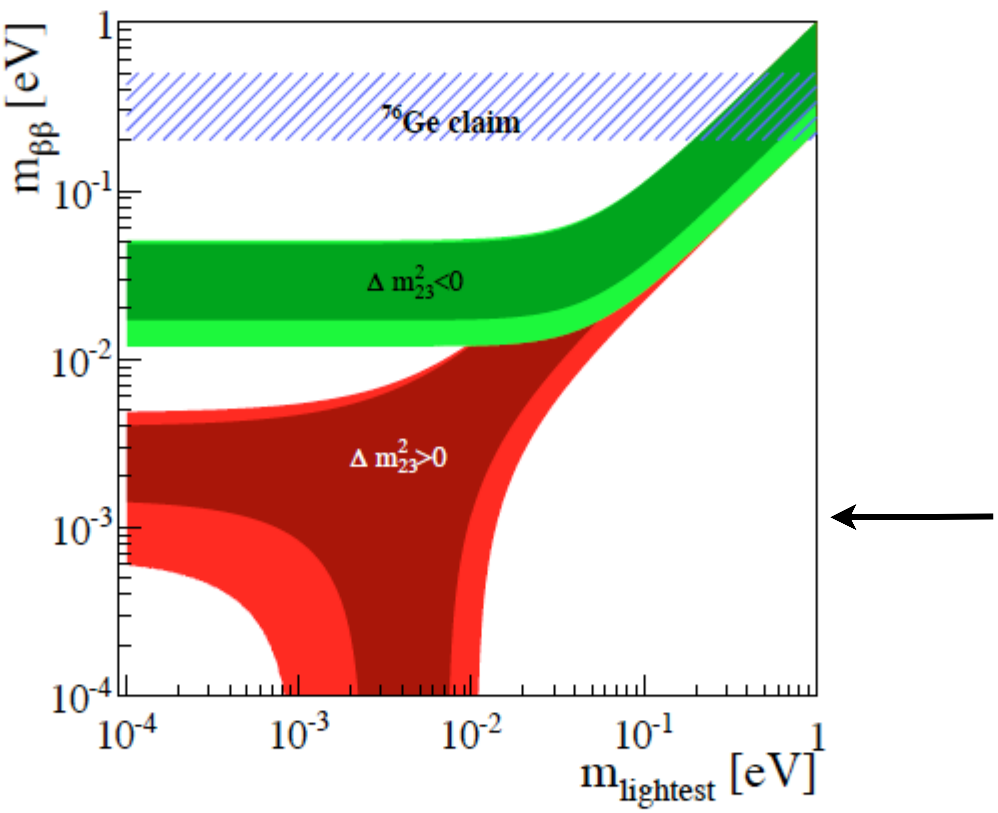
We are here.



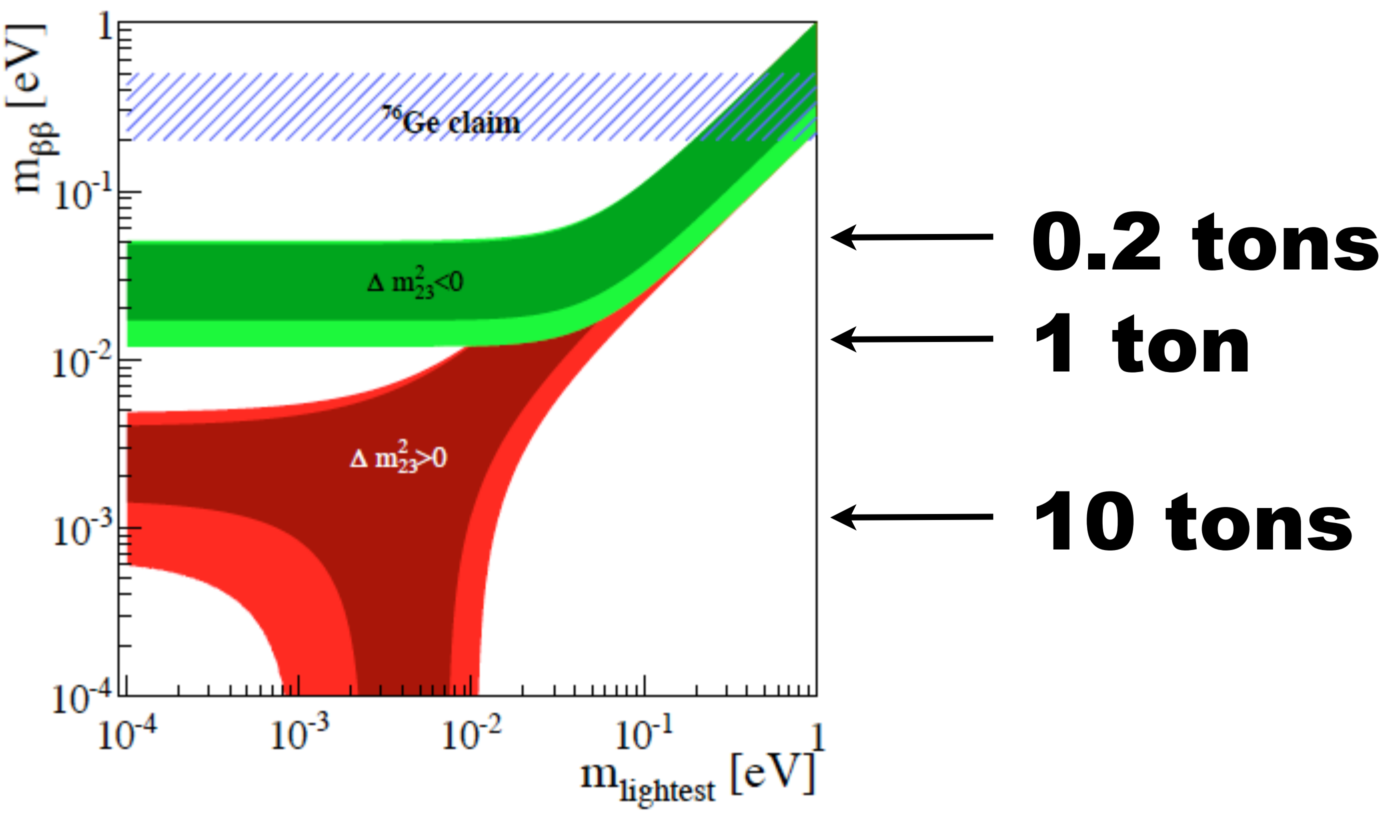
By 2018, we will be close to here with experiments currently under construction.



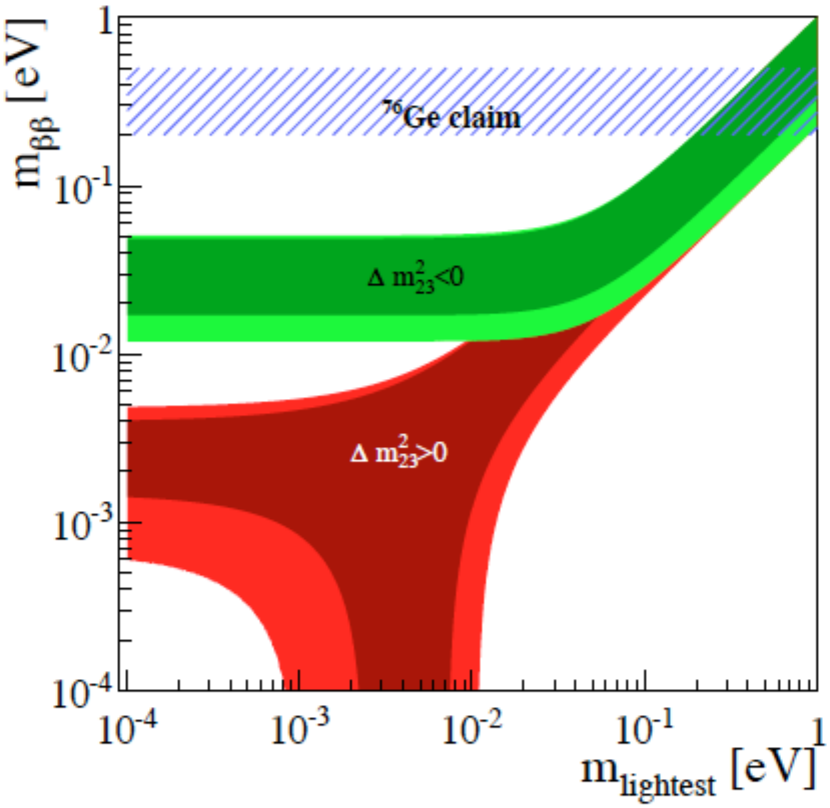
By 2025, we hope to eliminate Majorana neutrinos in the inverted hierarchy.



By 2035, some of us have begun to dream about getting to the normal hierarchy.



Warning: Factors of 5 hanging around.



Gen1	Gen2	Gen3
Now	2018	2025
0.2 ton	1 ton	10 ton
150 meV	15 meV	1.5 meV

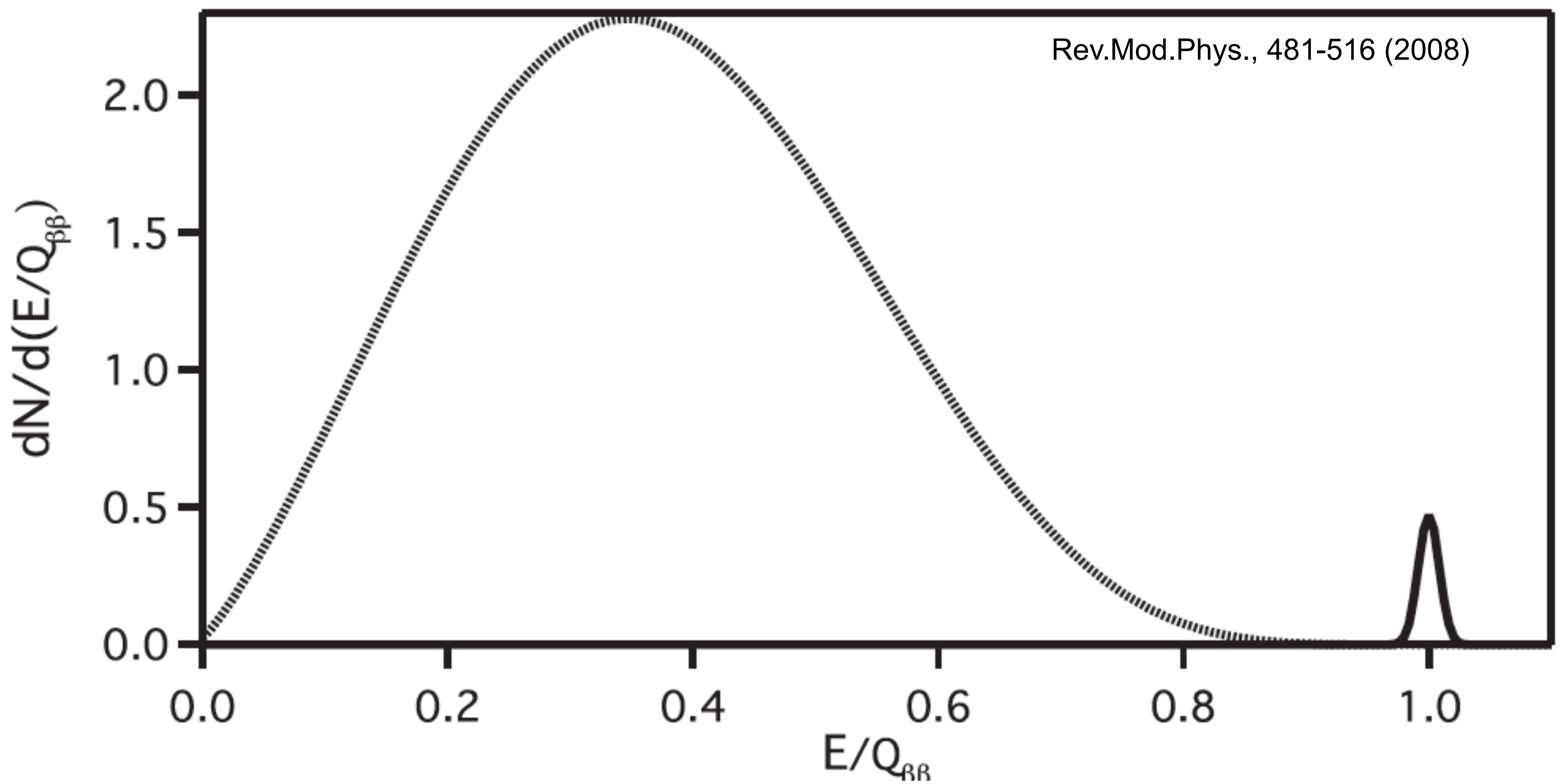
Warning: Factors of 5 hanging around.

Report to the Nuclear Science Advisory Committee

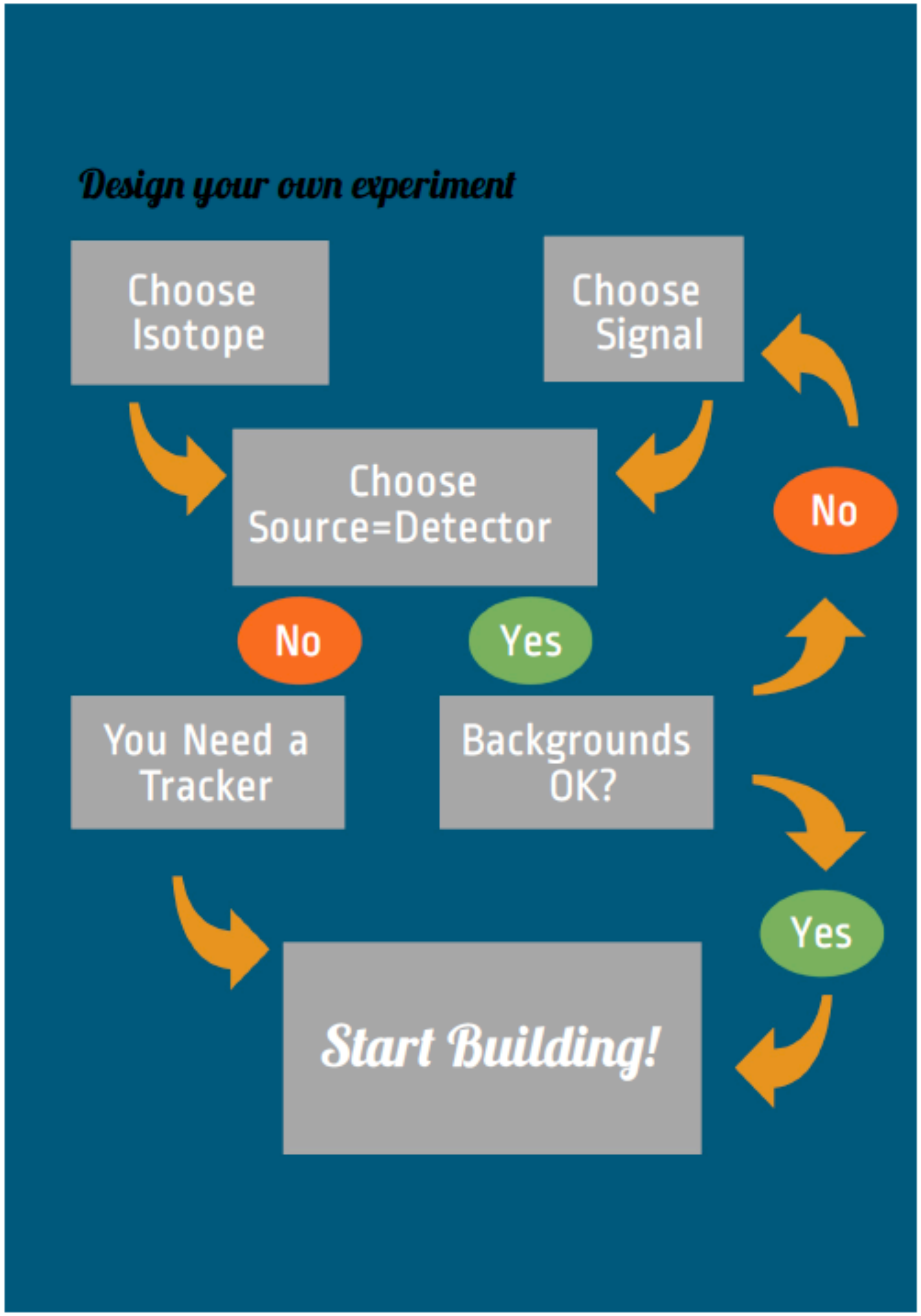
http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf

Each of the current approaches has technical advantages and each has significant remaining challenges to demonstrate sensitivity at a level suitable for covering the inverted neutrino mass hierarchy region. Based on the information provided to us, we judge that in a period of 2-3 years there will be much more information available from the results of these experiments. At that point one could assess the future prospects with much higher reliability than today.

We know exactly where to look.



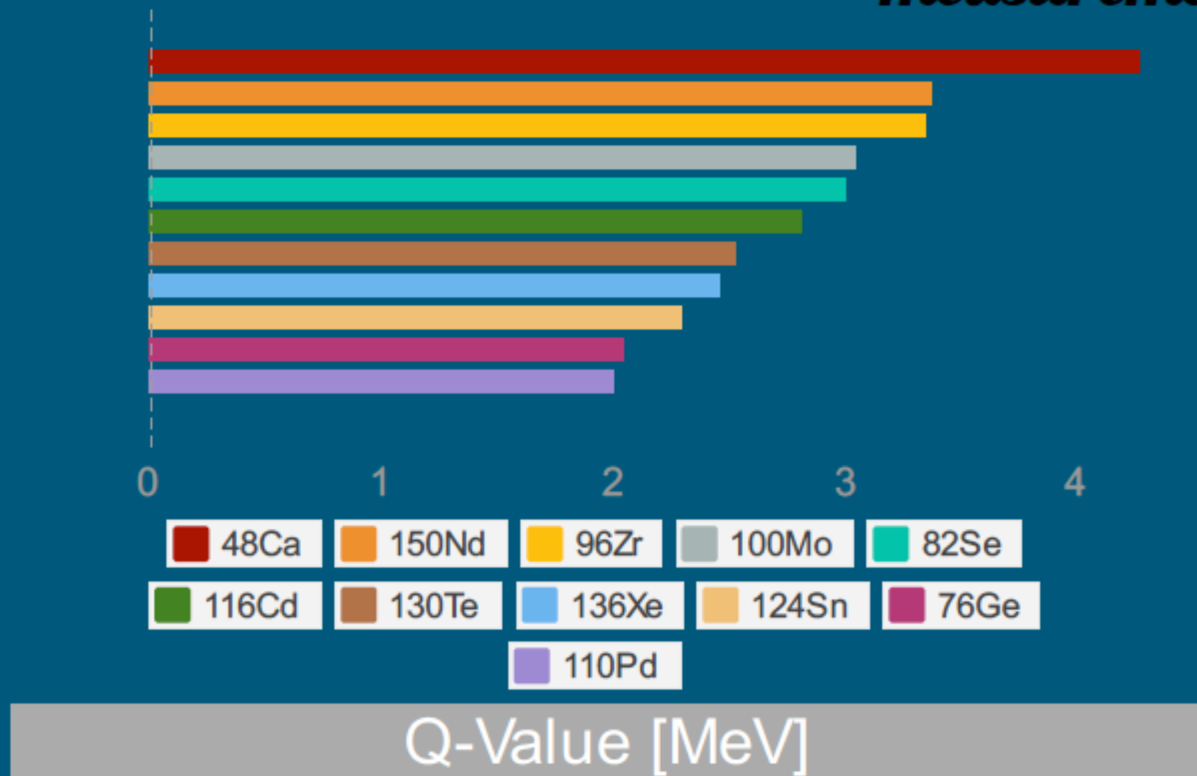
☛ Why is it so hard to figure out what experiment to do next?



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

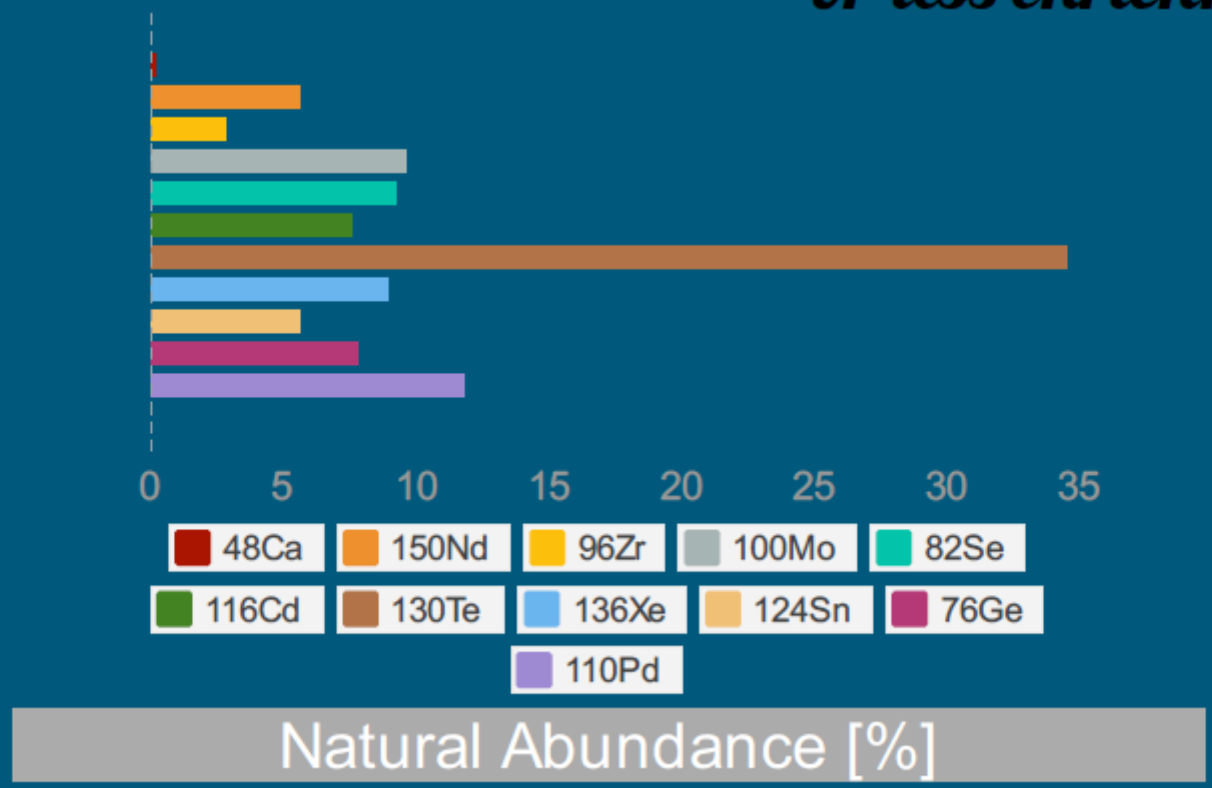
High Q-Value means a higher rate and an easier measurement!



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

Choose an Isotope

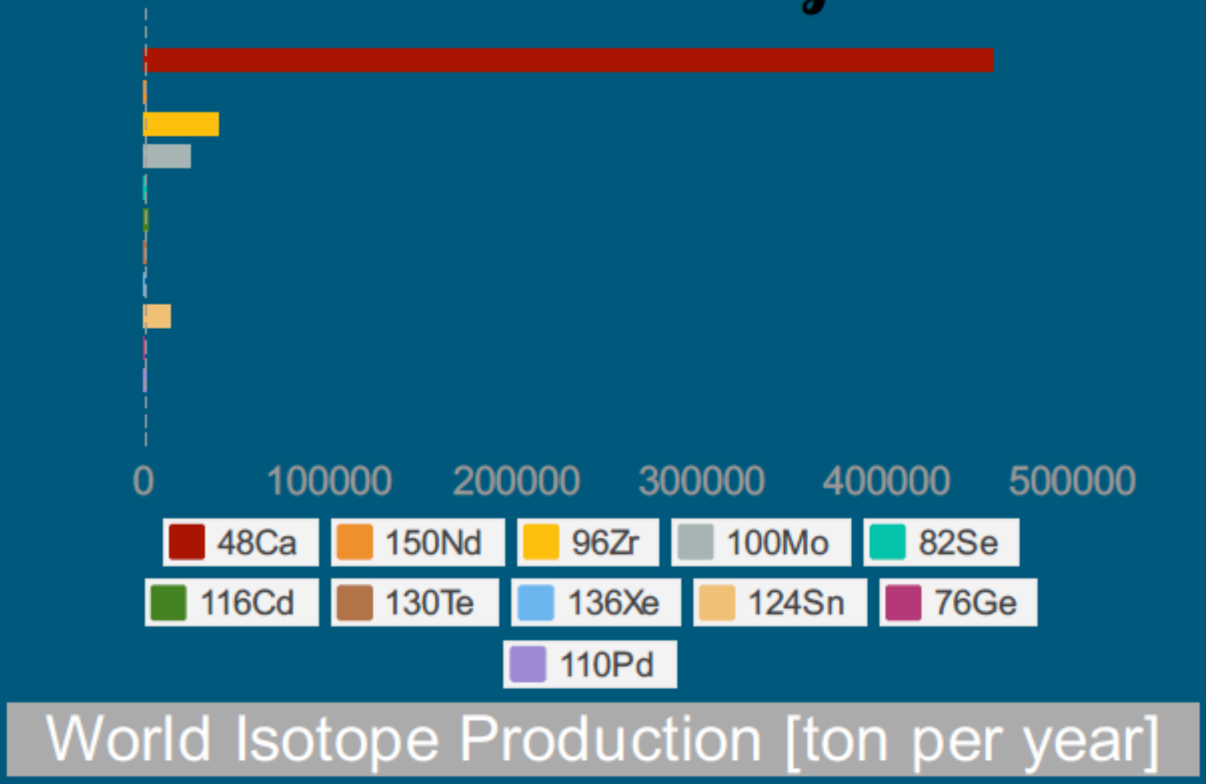
High natural abundance means a smaller detector or less enrichment!



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

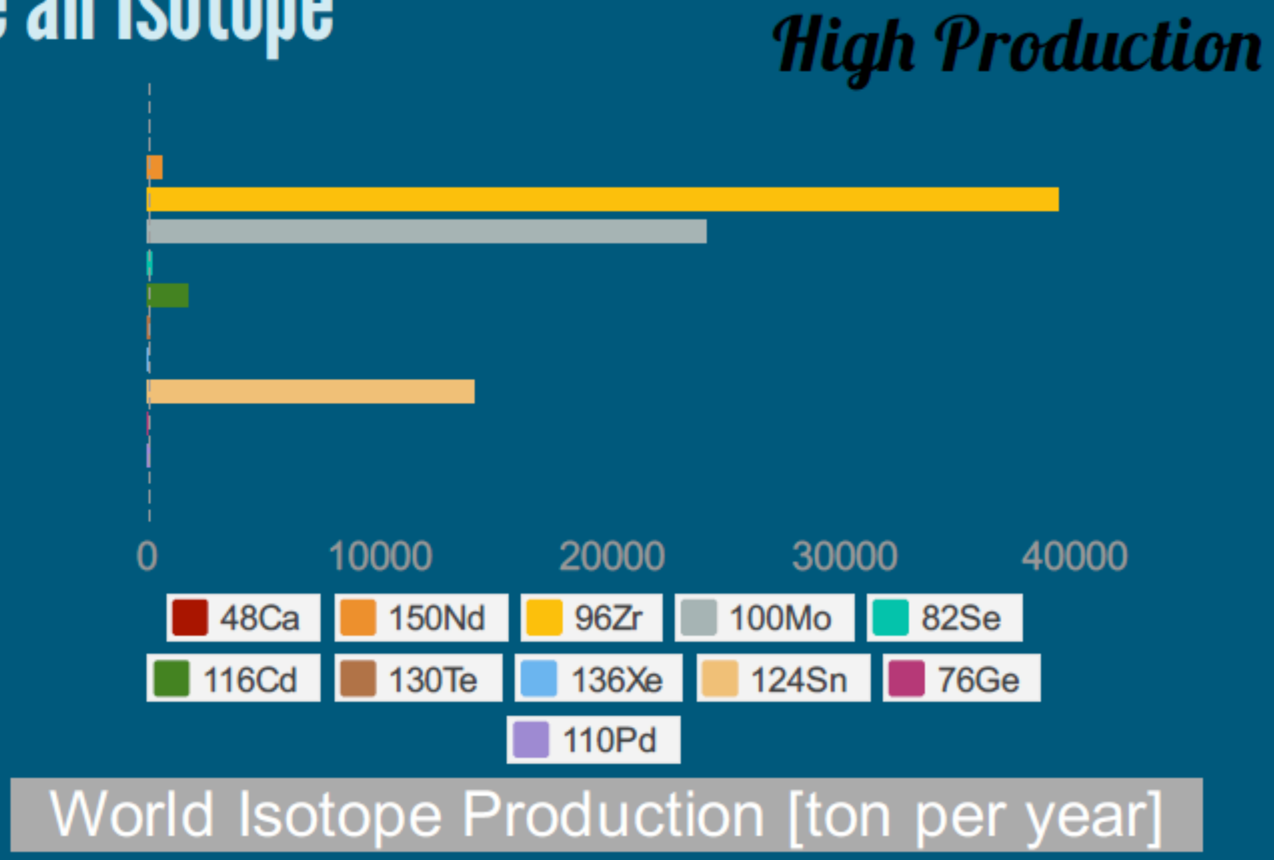
Choose an Isotope

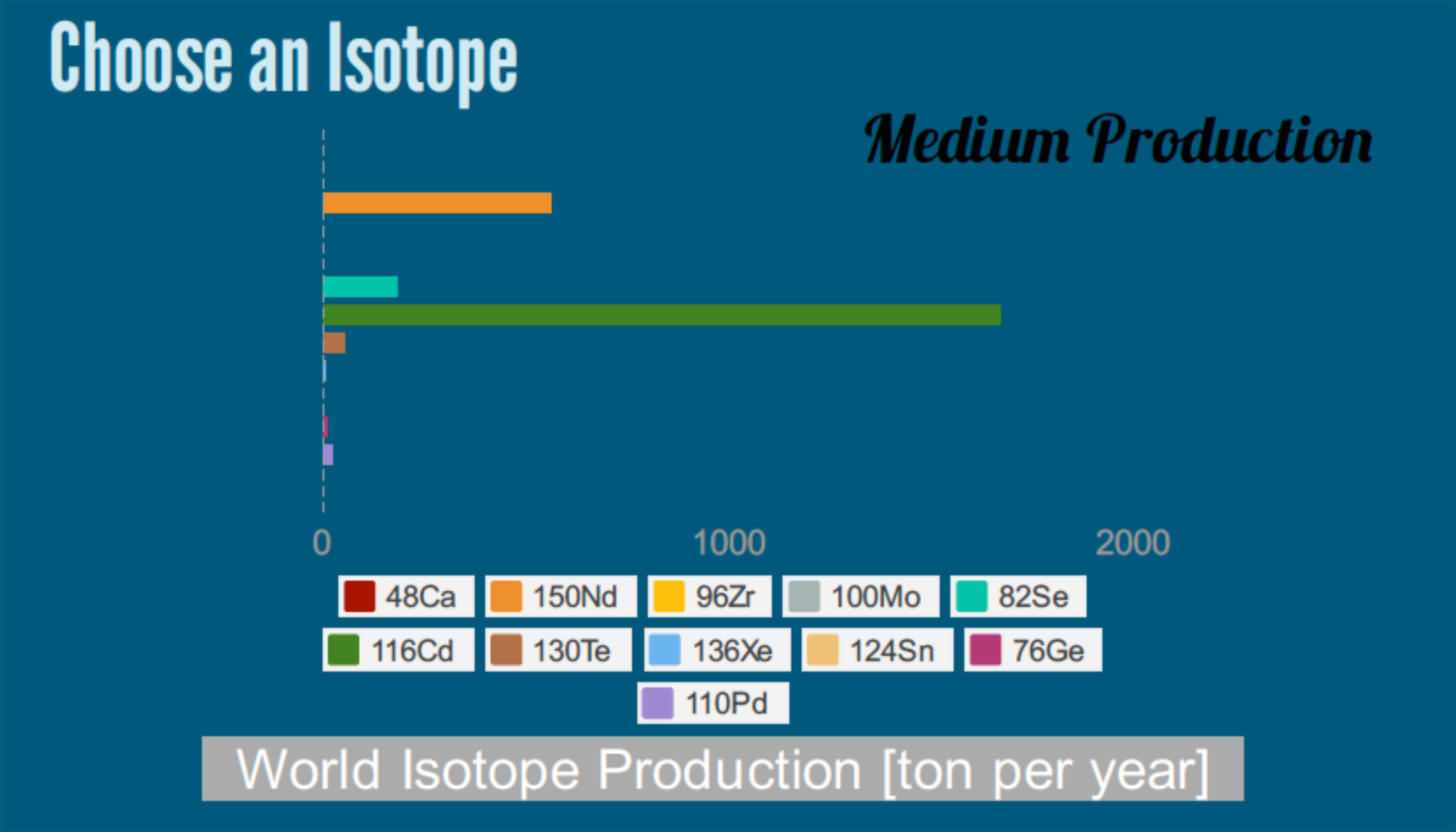
Highest Production



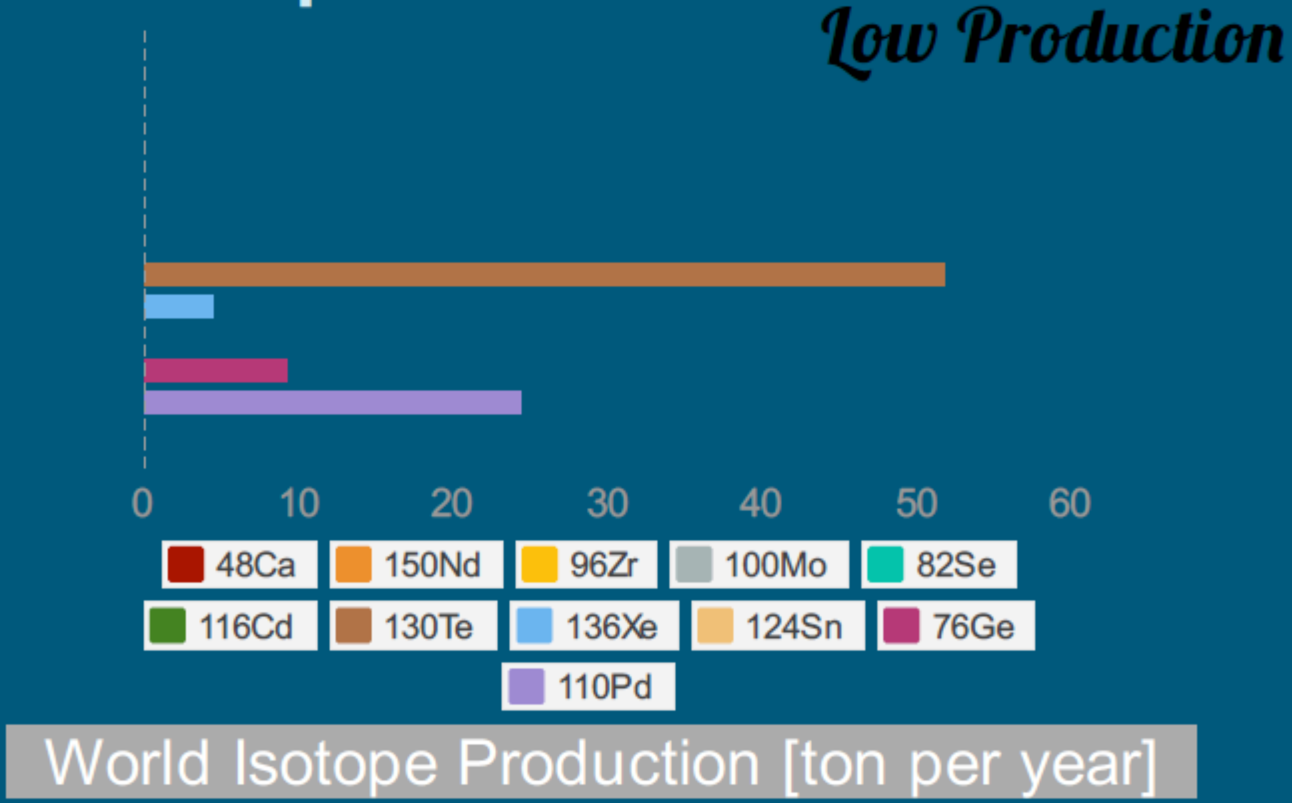
PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope




Choose an Isotope
Medium Production
0
1000
2000
48Ca
150Nd
96Zr
100Mo
82Se
116Cd
130Te
136Xe
124Sn
76Ge
110Pd
World Isotope Production [ton per year]

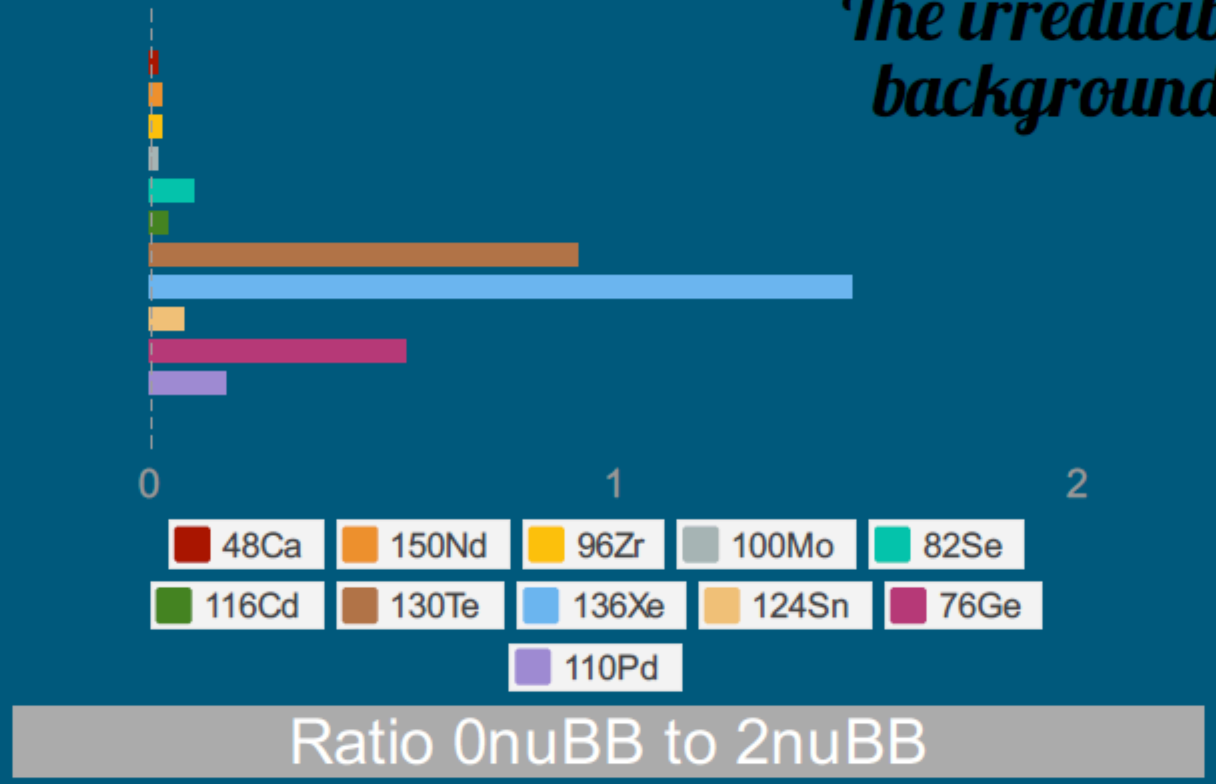
Choose an Isotope



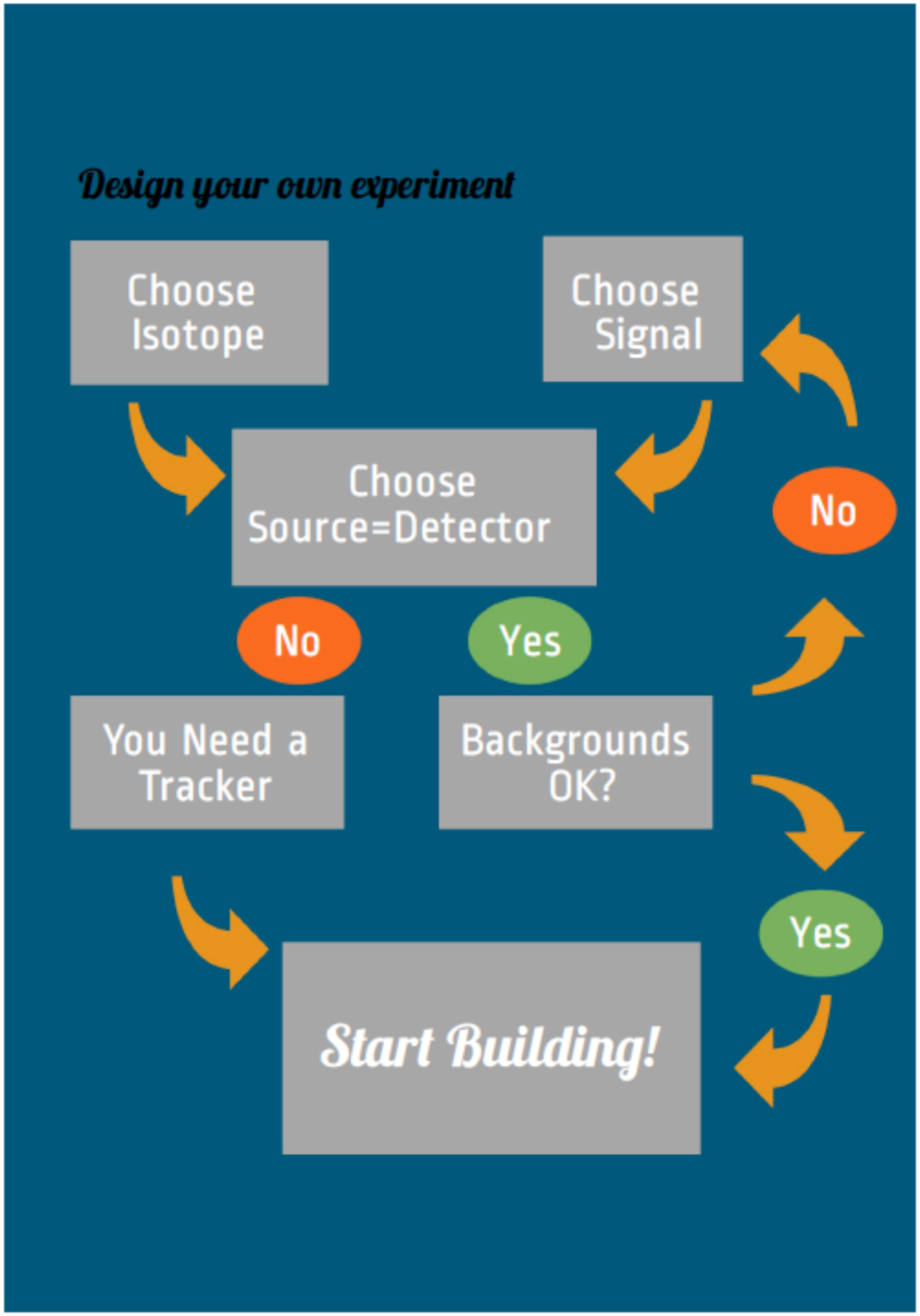
PHYSICAL REVIEW D 87, 071301(R) (2013)

Choose an Isotope

The irreducible background!



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

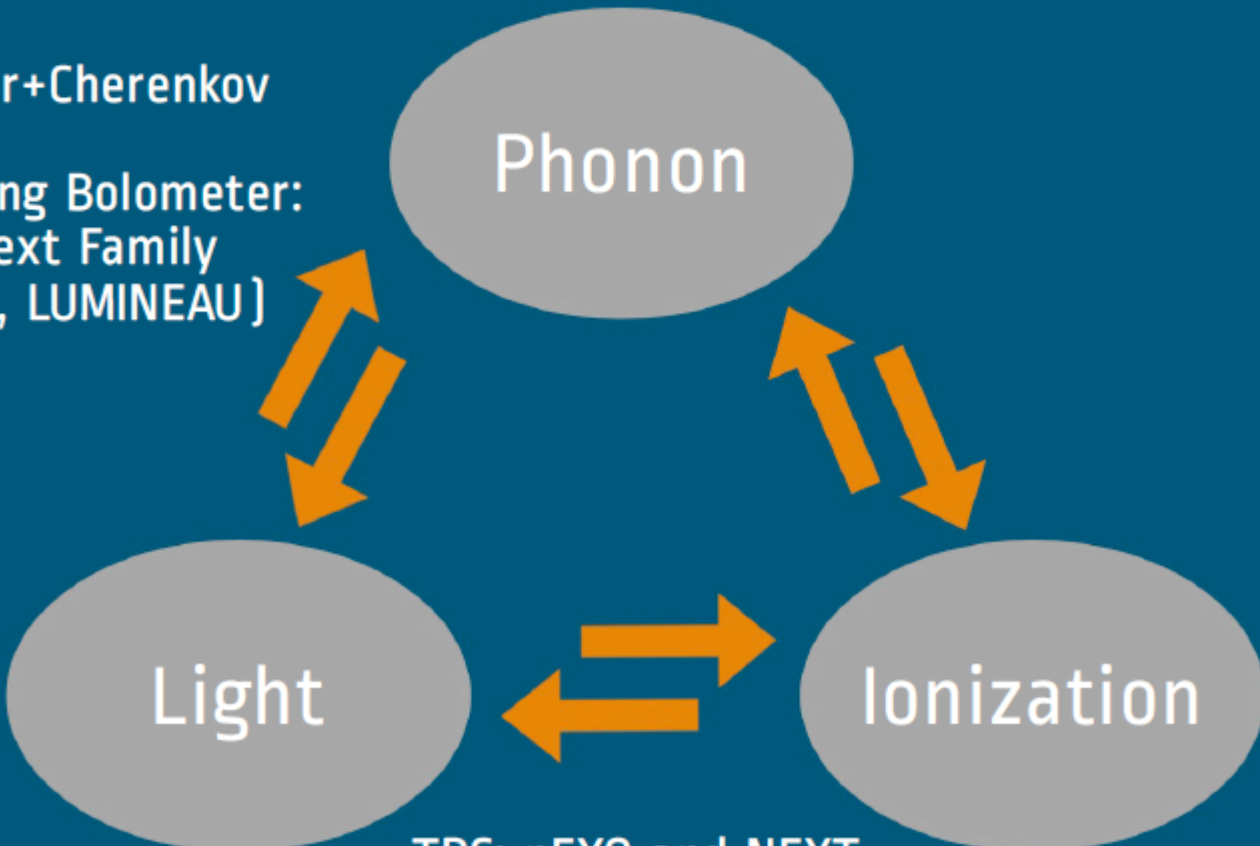

Design your own experiment
Choose Isotope
Choose Signal
Choose Source=Detector
No
Yes
You Need a Tracker
Backgrounds OK?
No
Yes
Start Building!

Choose a Signal:

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

CUORE

Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
(LUCIFER, LUMINEAU)
AmoRE



TPC: nEXO and NEXT

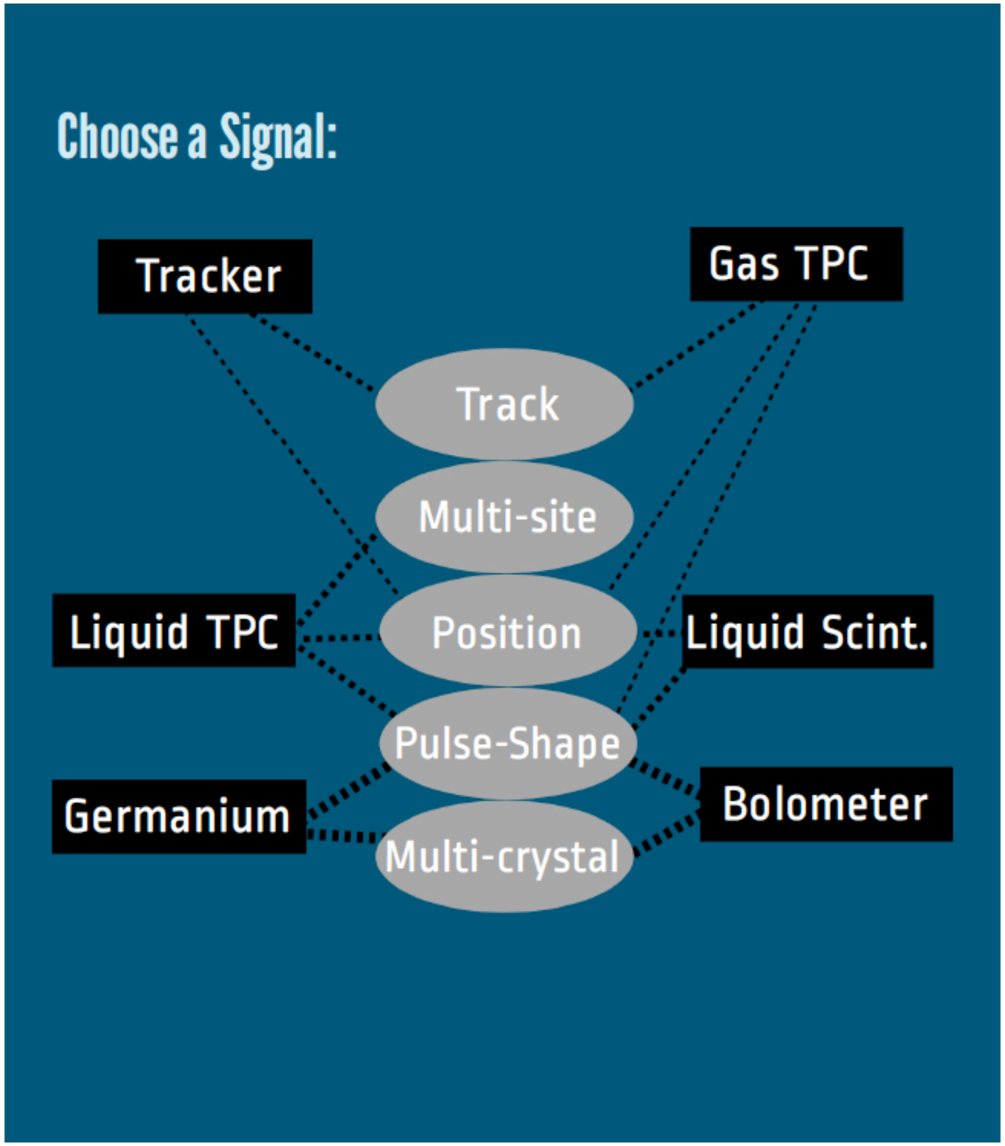
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES

Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

An aside, most of these detectors are perfectly good dark matter detectors just optimized differently.

☛ Does not seem cost effective to combine efforts in Gen2.

My attempt at a better diagram:



The Gen1 experiments are teaching us that these techniques can be powerful…

… and the experiment with the best energy resolution is not necessarily the best route forward.

Discovering the Majorana Neutrino

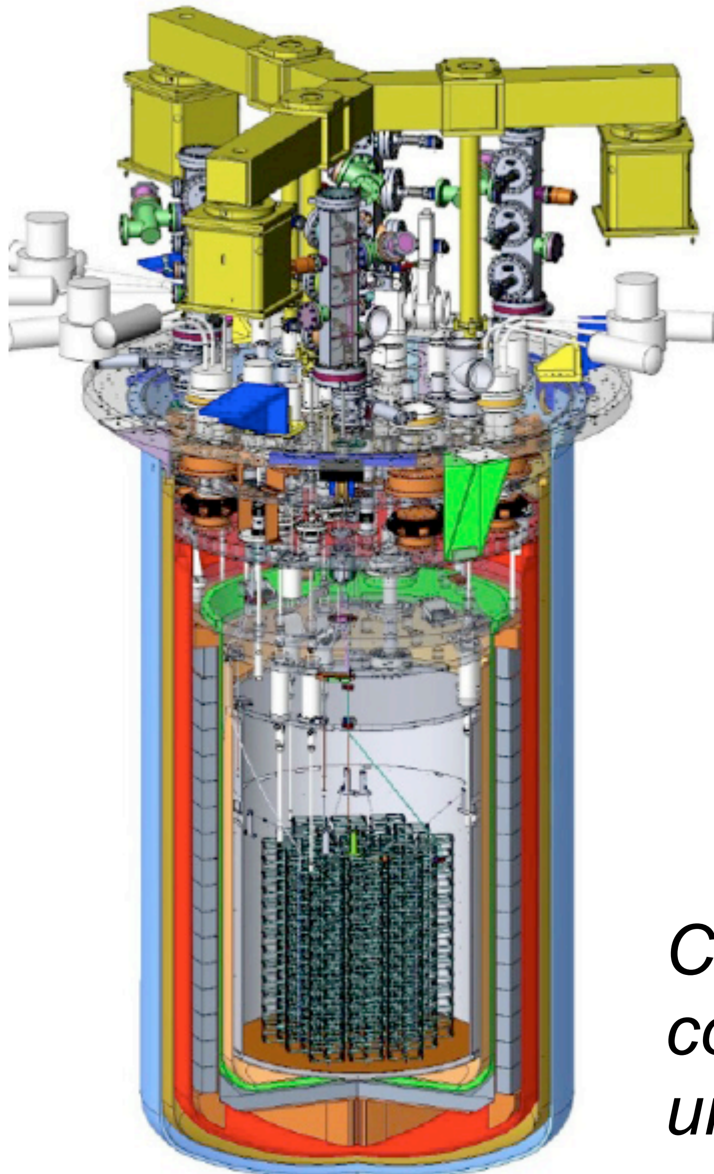
The Experiments

Most Intricate

↓

Simplest

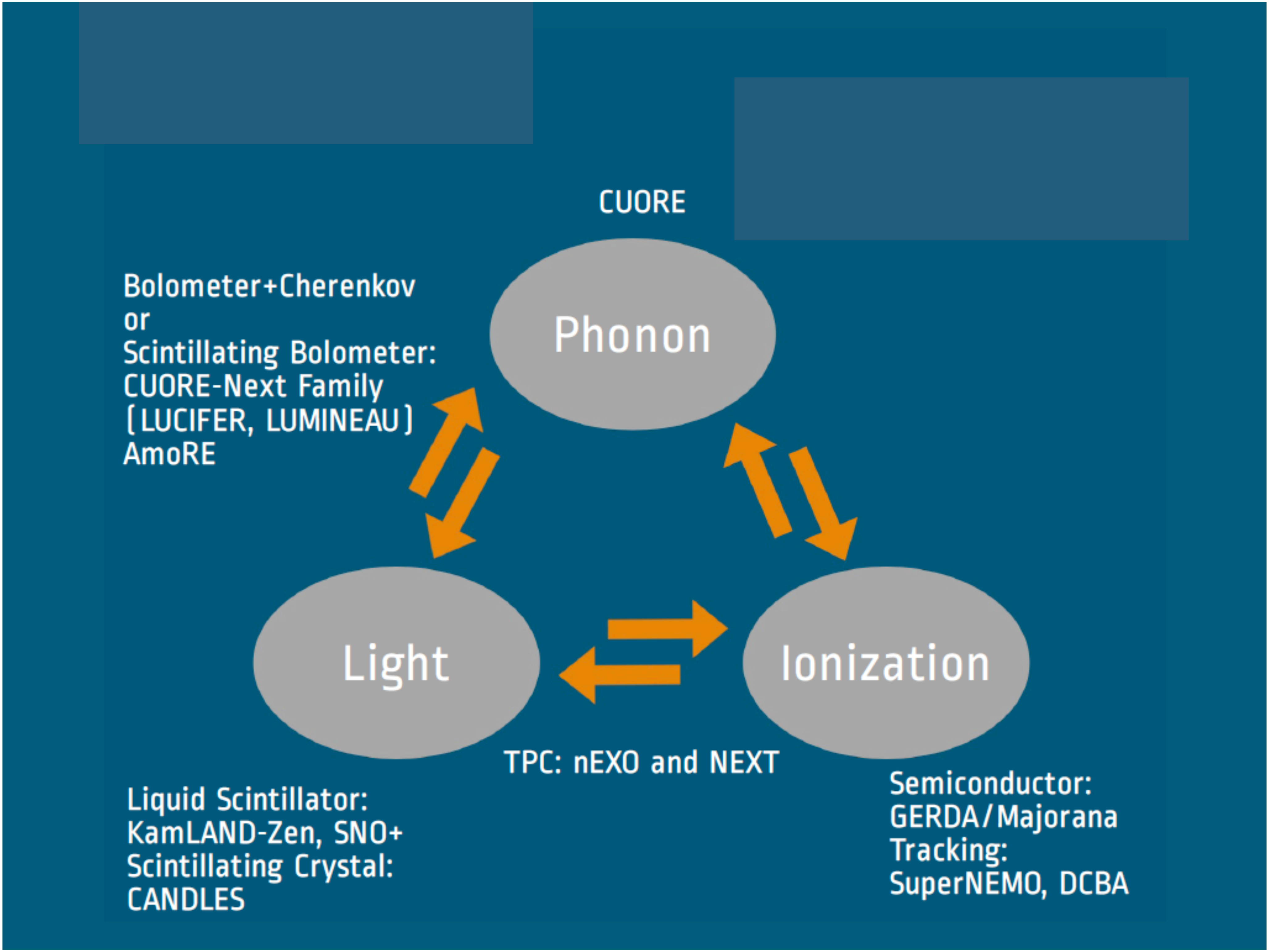
The Bolometers



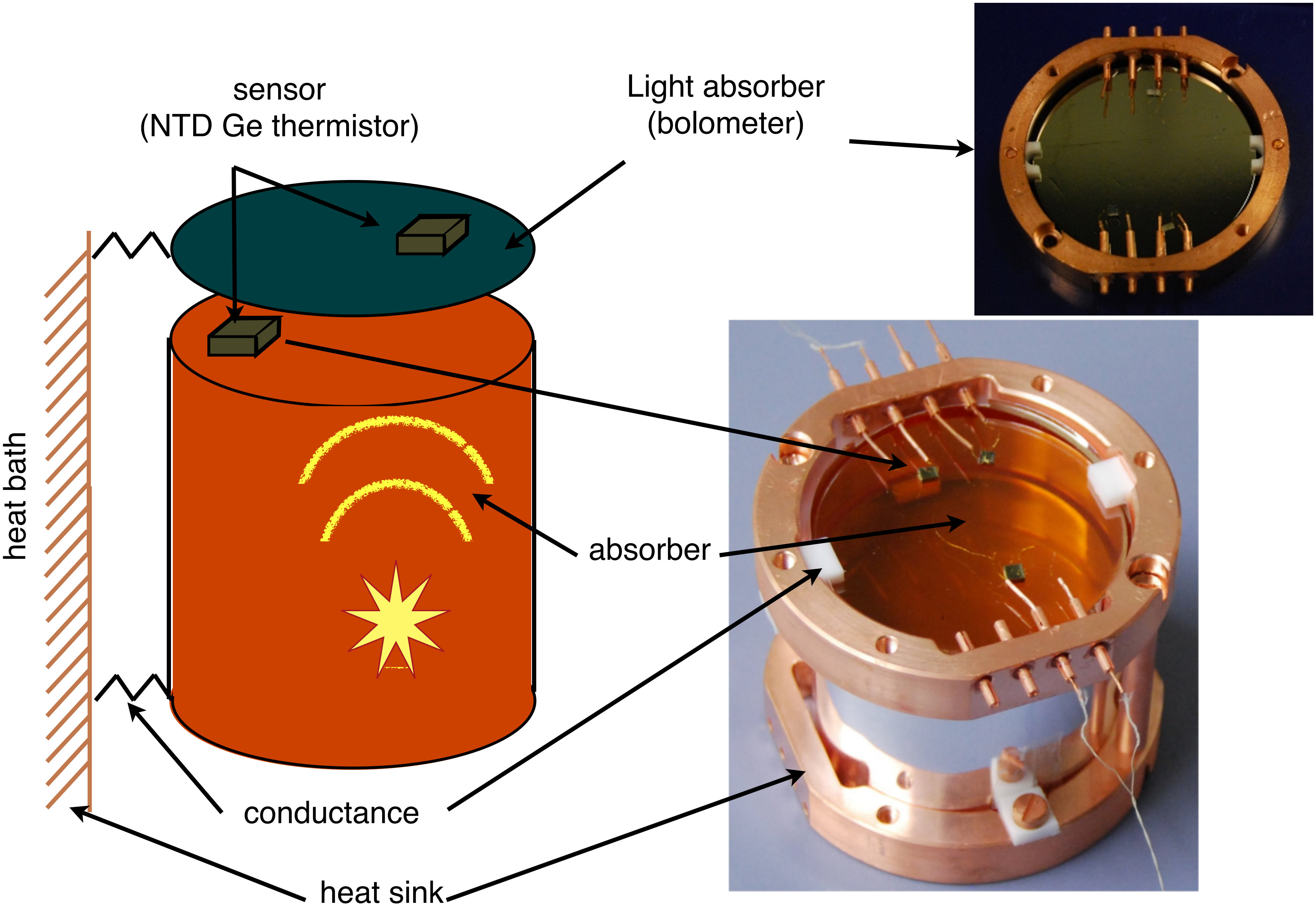
CUORE will be the coldest 1m3 in the universe when its complete.

Pros and Cons of Bolometers

- Pros
  - Source = detector
    - High detection efficiency for $0\nu\beta\beta$
  - High intrinsic energy resolution
    - <0.2% FWHM, comparable to HPGe
  - Possibility to operate with multiple isotopes
  - Opportunities for particle identification with the same readout technique
    - Light detection with bolometers (see L. Cardani's talk)
  - Scalable to ~1000s of detectors
  - Rejection of multi-site events by vetoing coincidence between detectors
- Cons
  - Slow time response: need low backgrounds
  - Limited fiducialization of events
  - Limited self-shielding
  - Costs grow (roughly) linearly with detector mass


CUORE
Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
(LUCIFER, LUMINEAU)
AmoRE
Phonon
Light
Ionization
TPC: nEXO and NEXT
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

Scintillating Bolometers



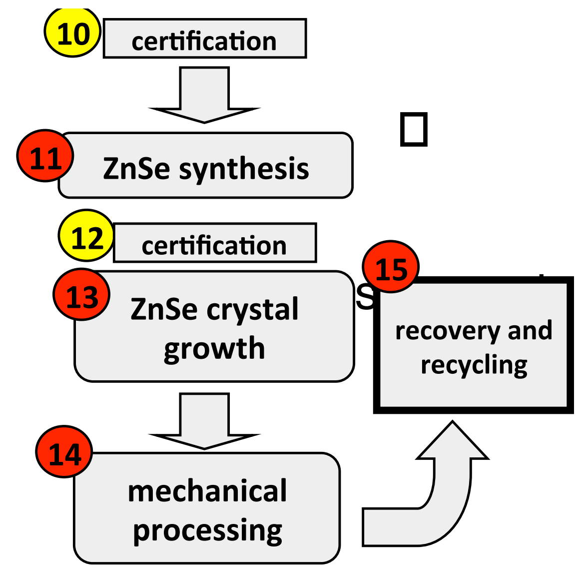
The CUORE-Next Family:
LUCIFER and LUMINEU

LUCIFER

- ERC Advanced Grant n. 247115
  - Budget: 3.2 M€
  - Project duration: 01.03.2010-01.03.2015
- Goal: demonstrator of an experiment with bkg.~1cts/ton/y/keV with sensitivity comparable to next generation experiment.
- Scintillating bolometers technique
  - Alfa background rejection thanks to the scintillation light
- Crystals:
  - Primary choice: ZnSe with enriched Se at 95% in ^{82}Se (Q=2997 keV, i.a.=8.7%)
  - Secondary choice: $ZnMoO_4$ (Q=3034 keV, i.a.=9.6%)

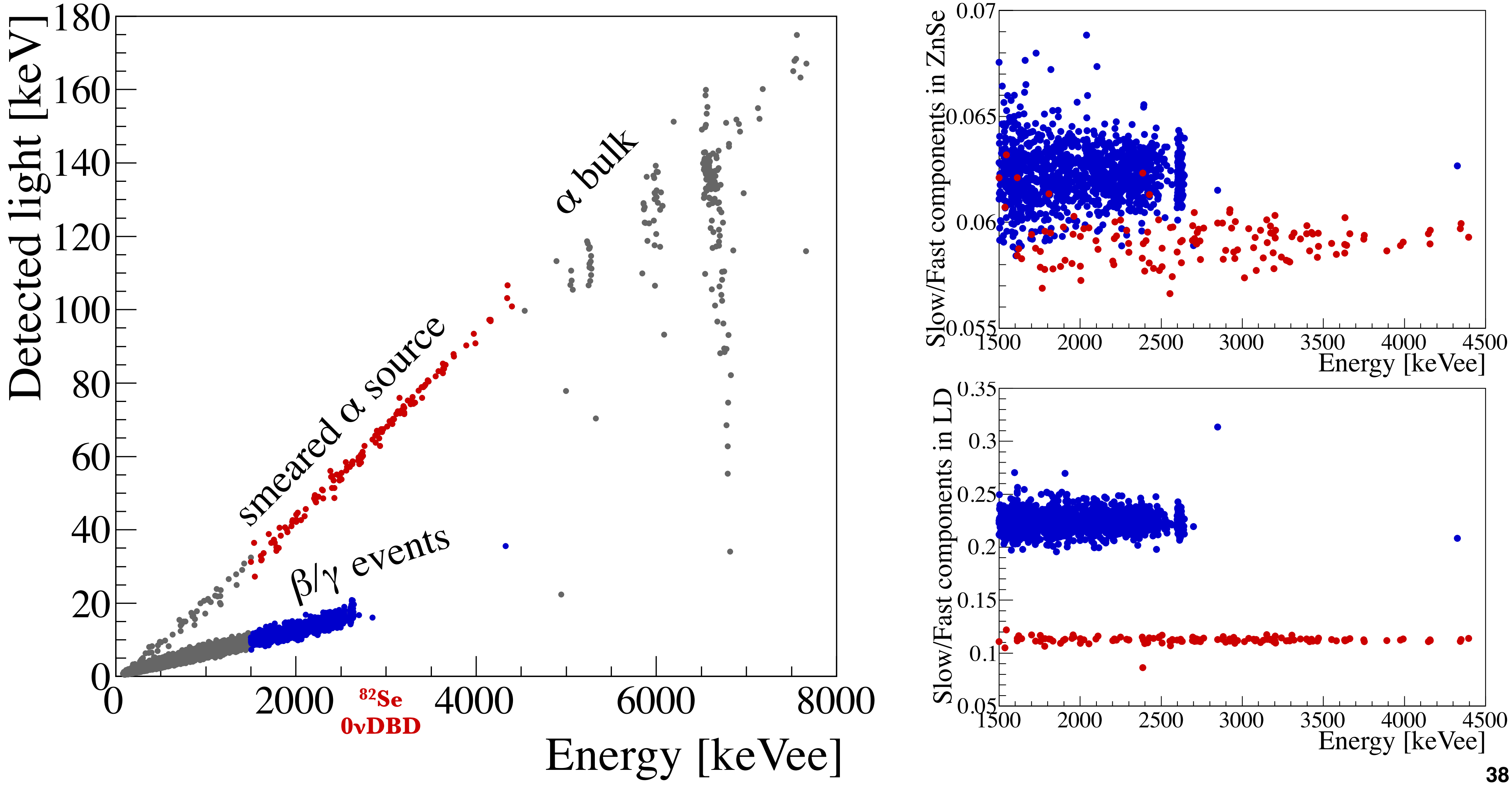
Synthesis & crystal growth

- Crystal dimension fixed: cylinder ∅=45mm, h=55mm, w=460.7g(nat Se),
- SmiLab Ltd(Ukraine): only supplier able to perform synthesis and crystal growth
- Crystals growth is difficult:
  - High melting point(1525°C) & total vapor pressure(~2Bar) deviation from stoichiometry
  - Very difficult control of local temperature defects
- Required efficiency of growth and processing > 65%
- Smilab not able to reach such efficiency: TPY ~22%
- Alternative supplier ISMA Kharkov is being tested.

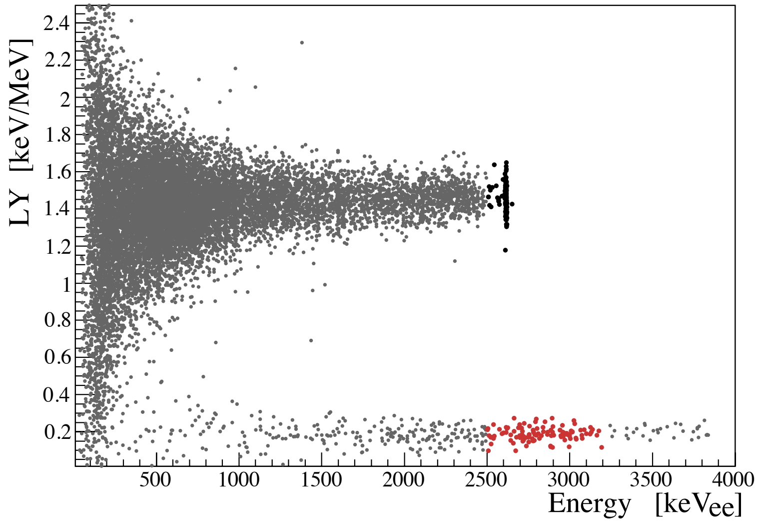


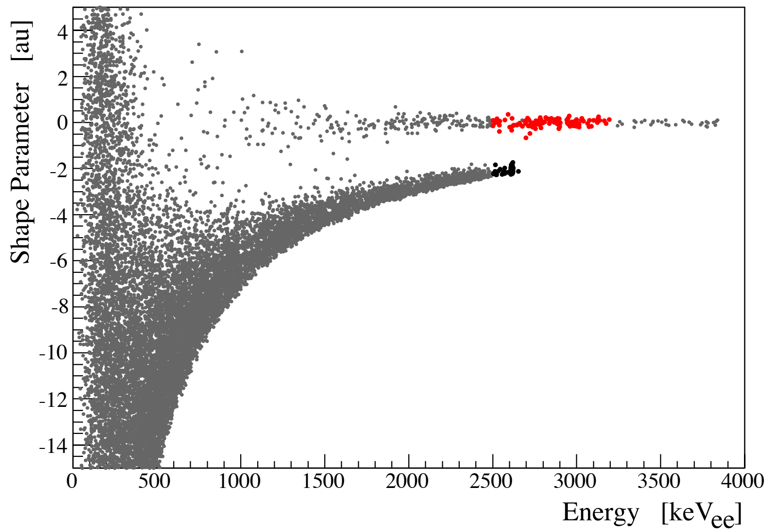
ZnSe

- 430 g ZnSe crystal **JINST 1305 (2013) P05021**
- LY ~6.5 keV/MeV for β/γ, QFα ~4, poor light collection□ pulse shape discrimination on light detector

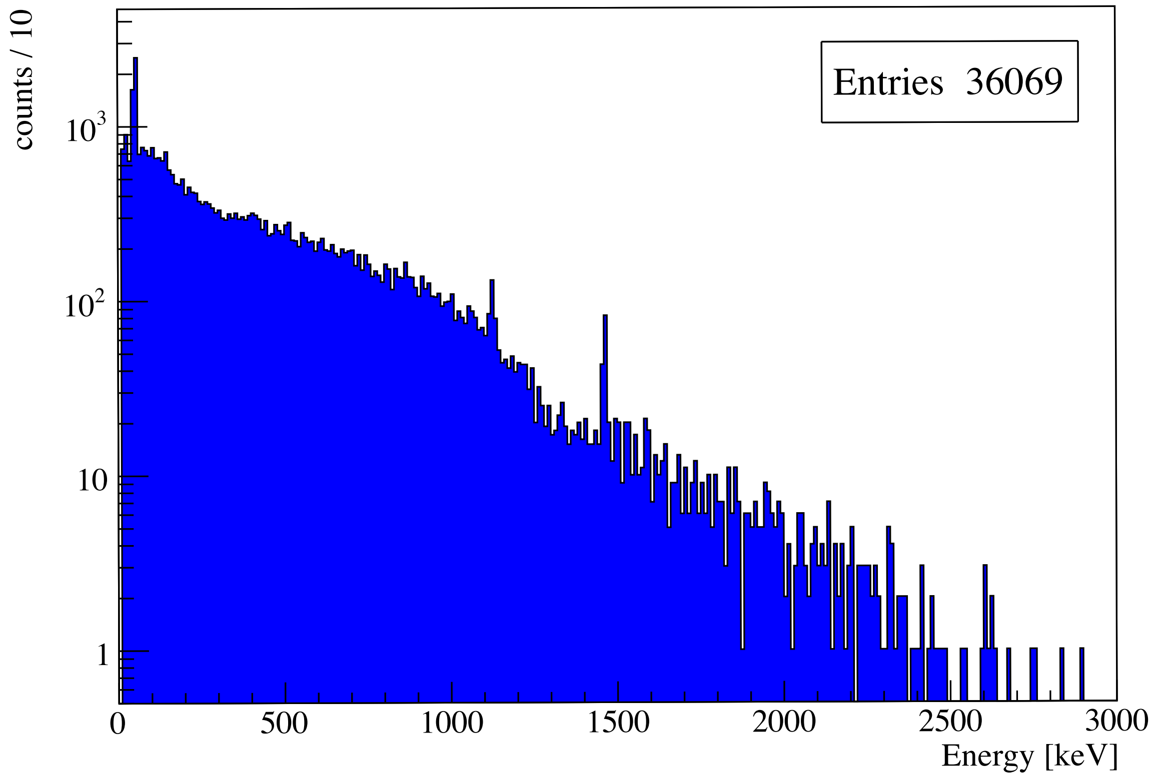


$ZnMoO_4$





m=330 g
FWHM= 6 keV, LY~1.5 keV/MeV,QF~0.17
Ur, Th cont.< 6μBq/kg



- First measurement of 2ν ^{100}Mo decay published *J. Phys. G: Nucl. Part. Phys.* **41** 075204.
- MOU between INFN, IN2P3, ITEP: common interest for an experiment based on ~10 kg of ZnMoO4 with 95% enriched ^{100}Mo.

June 2014

LUMINEU summary

Luminescent **U**nderground **M**olybdenum **I**nvestigation for **NEU**trino mass and nature

Funded by Agence Nationale de la Recherche (France)

Collaboration: **France** (Orsay, Saclay, ICMCB Bordeaux), **Ukraine** (KINR Kiev), **Russia** (NIIC Novosibirsk), **Germany** (Heidelberg) ; about 40 physicists - engineers

Aim: Set the bases for a **next-generation neutrinoless double-beta** decay experiment for the study of the isotope ^{100}**Mo** embedded in **$ZnMoO_4$ scintillating bolometers**

Current activity on new regular-shape natural crystals and enriched crystals

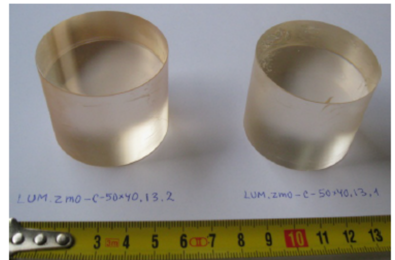
New $ZnMoO_4$ LUMINEU crystals have been grown in NIIC (Russia) by using LTG Cz

• Improved $ZnMoO_4$ (2 × 338 g) were produced. A boule was grown, melted and then crystallized again. Molybdenum was purified by using double recrystallization from solutions [1]

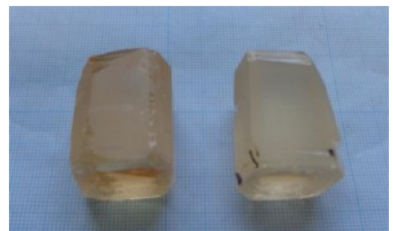
• First $Zn^{100}MoO_4$ boule was developed from deeply purified ^{100}Mo and two samples (64 and 61 g) were produced [2]

New bolometers based on two improved $ZnMoO_4$ and first $Zn^{100}MoO_4$ crystals will be tested soon at the LSM

arXiv:1405.6937v1 [physics.ins-det]

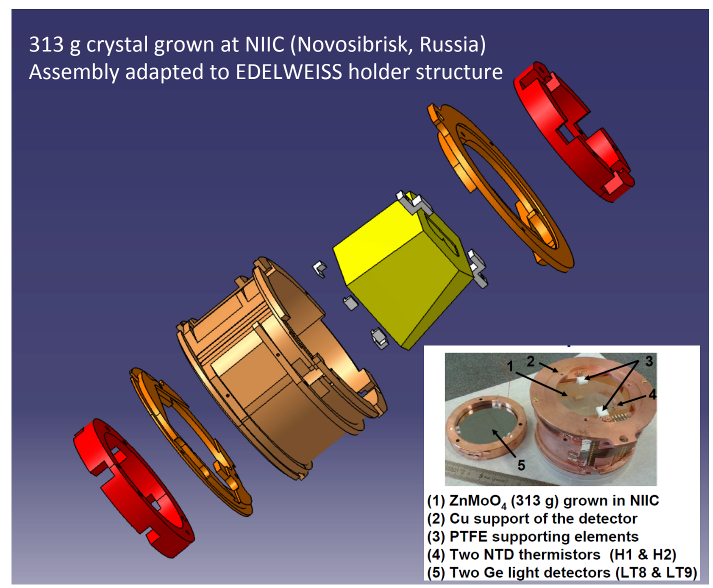


$ZnMoO_4$ ∅50×40 mm



$Zn^{100}MoO_4$ □24×31 mm

Assembly of a 313 g natural ZMO detector



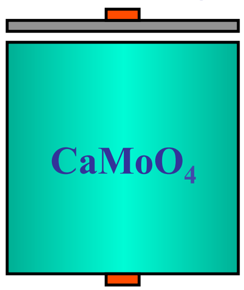
AMoRE-200


YangYang(Y2L) Underground Laboratory
(Upper Dam)
YangYang Pumped
Storage Power Plant
1000m
700m
(Power Plant)
(Lower Dam
Y2L
Seoul
Pyongyang
북한
동해
서해
대한민국
Daejeon
Daegu
Kwangju
Busan
Hiroshima
Fukuoka
양양양수발전소
KIMS (Dark Matter Search)
AMoRE (Double Beta Decay Experiment)
Minimum depth : 700 m / Access to the lab by car (~2km)

AMoRE detector technology

$^{40}Ca^{100}MoO_4$ + MMC

Low Temp. Detector
Source = Detector



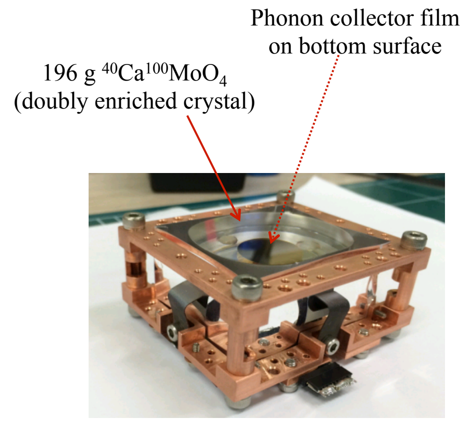
<10-50 mK>

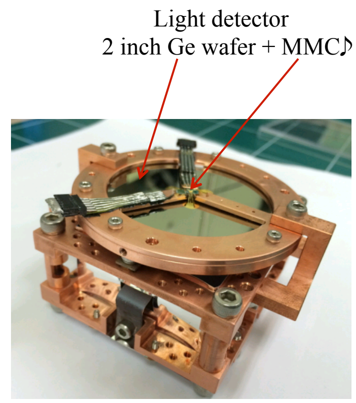
$CaMoO_4$
- Scintillating crystal
- High Debye temperature: T_D = 438 K, $C \sim (T/T_D)^3$
- ^{48}Ca, ^{100}Mo 0νββ candidates
- AMoRE uses $^{40}Ca^{100}MoO_4$ w. enriched ^{100}Mo and depleted ^{48}Ca

MMC (Metallic Magnetic Calorimeter)
- Magnetic temperature sensor (Au:Er) + SQUID
- Sensitive low temperature detector with highest resolution
- Wide operating temperature
- Relatively fast signals
- Adjustable parameters in design and operation stages

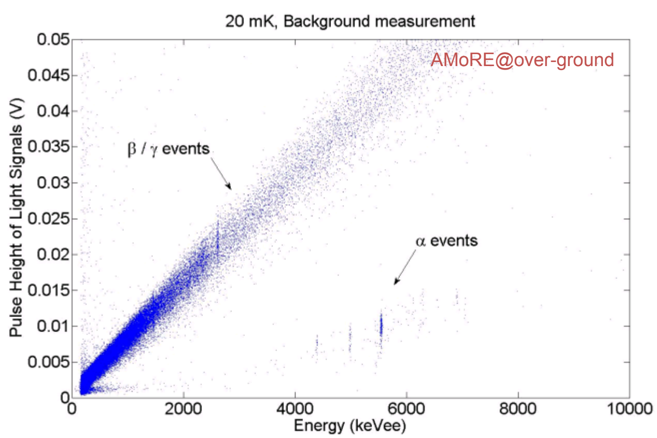
The latest results!

Detector assembly

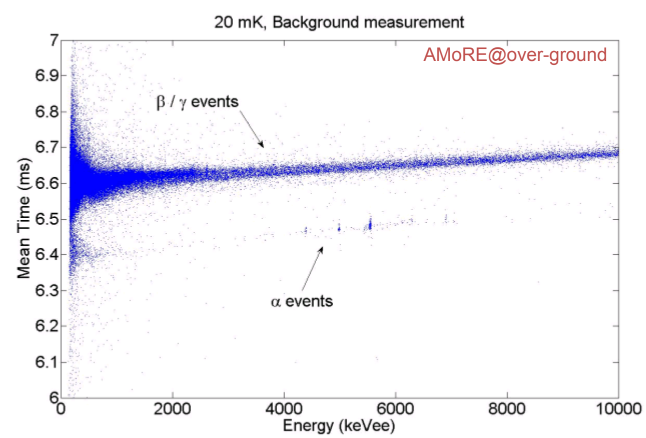


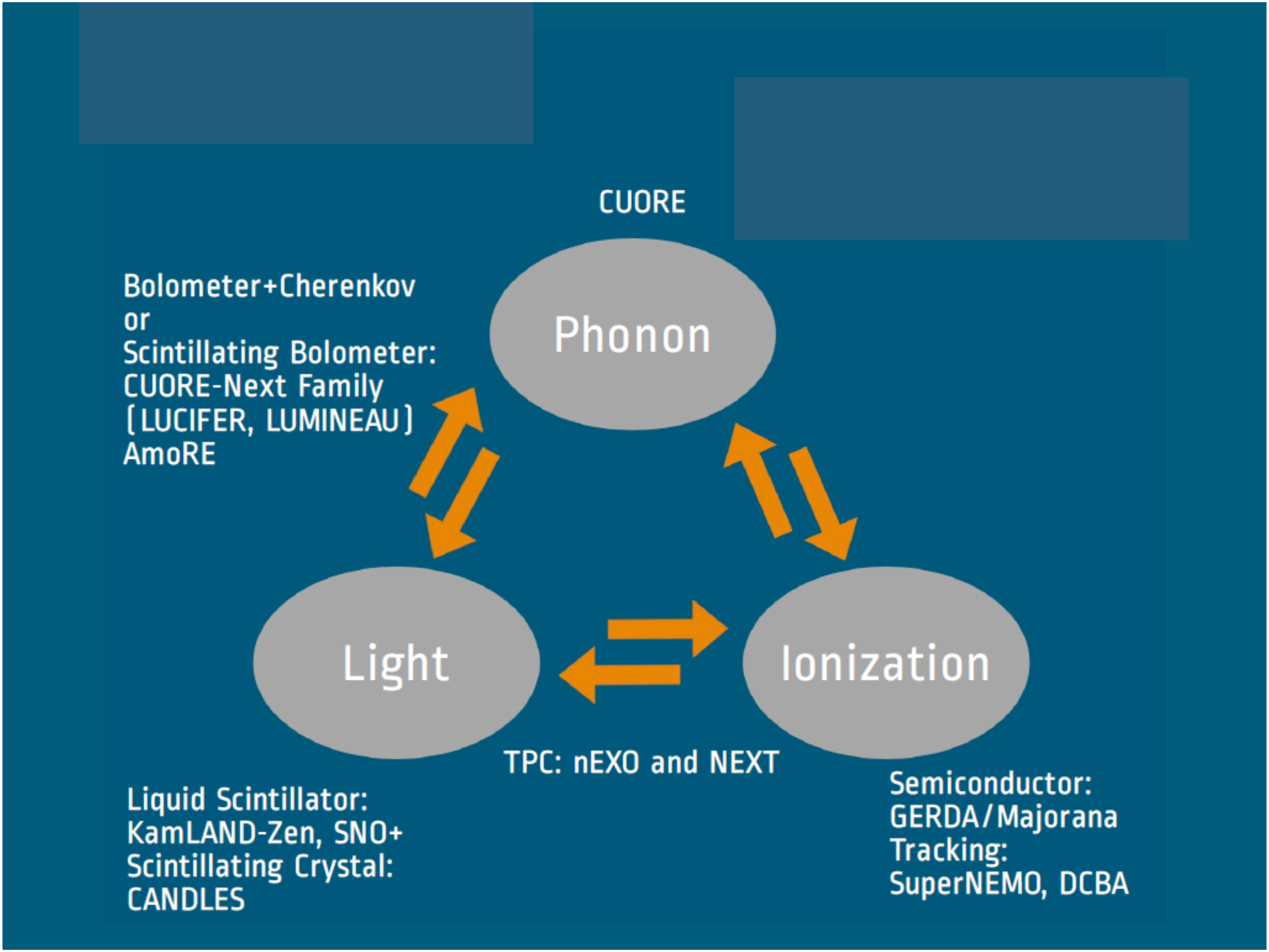


Phonon vs Light



PSD with phonon only




CUORE
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or
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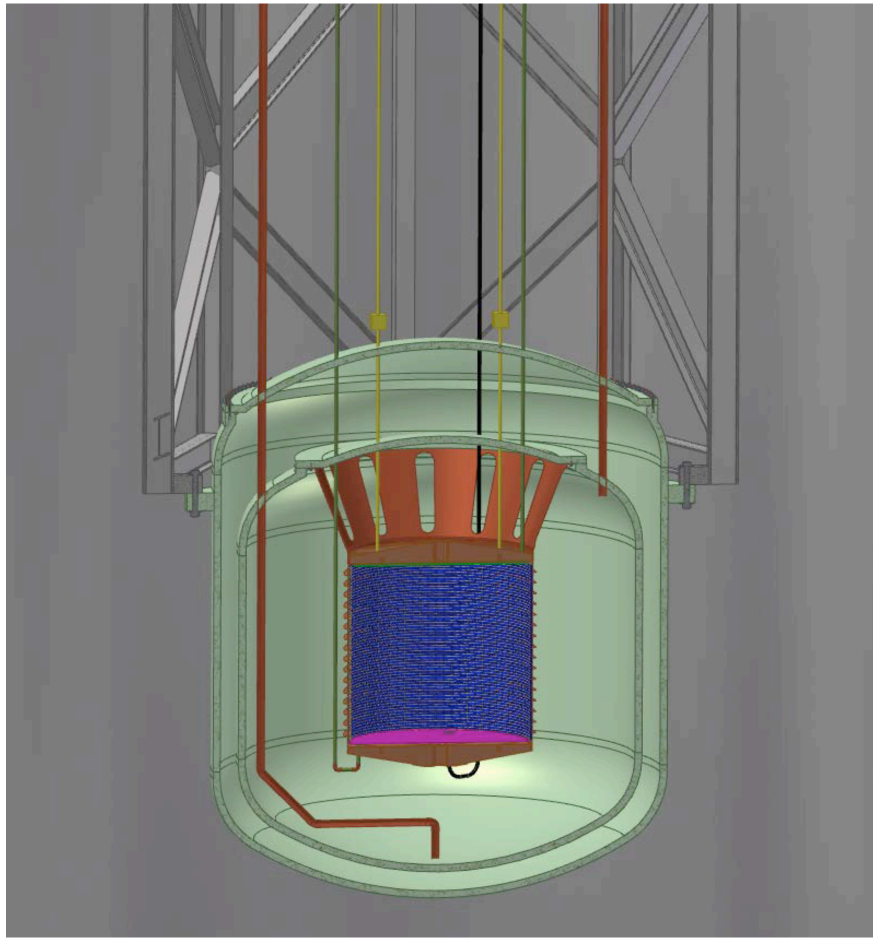
TPC: nEXO and NEXT
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

The Liquid TPC



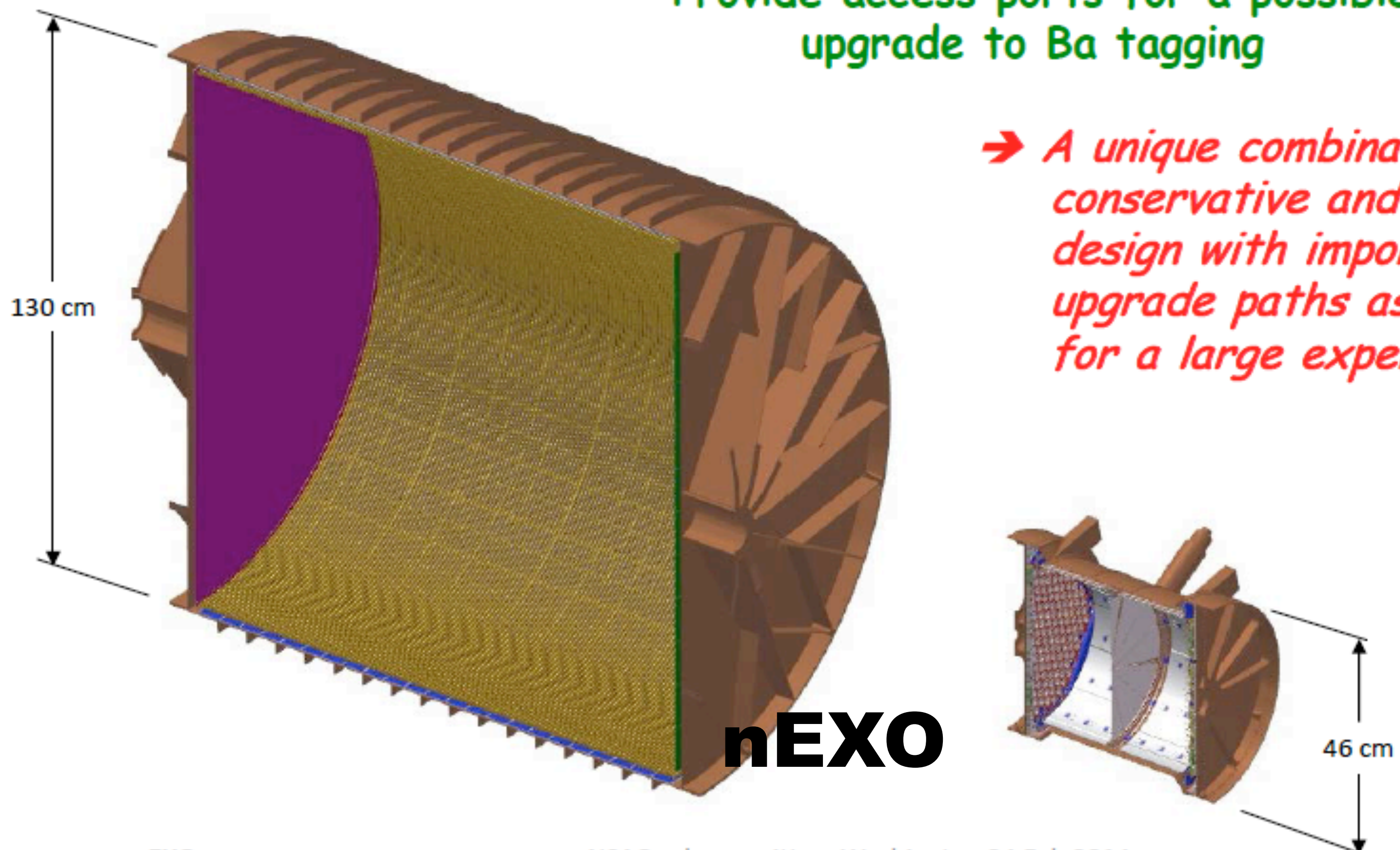
nEXO

nEXO

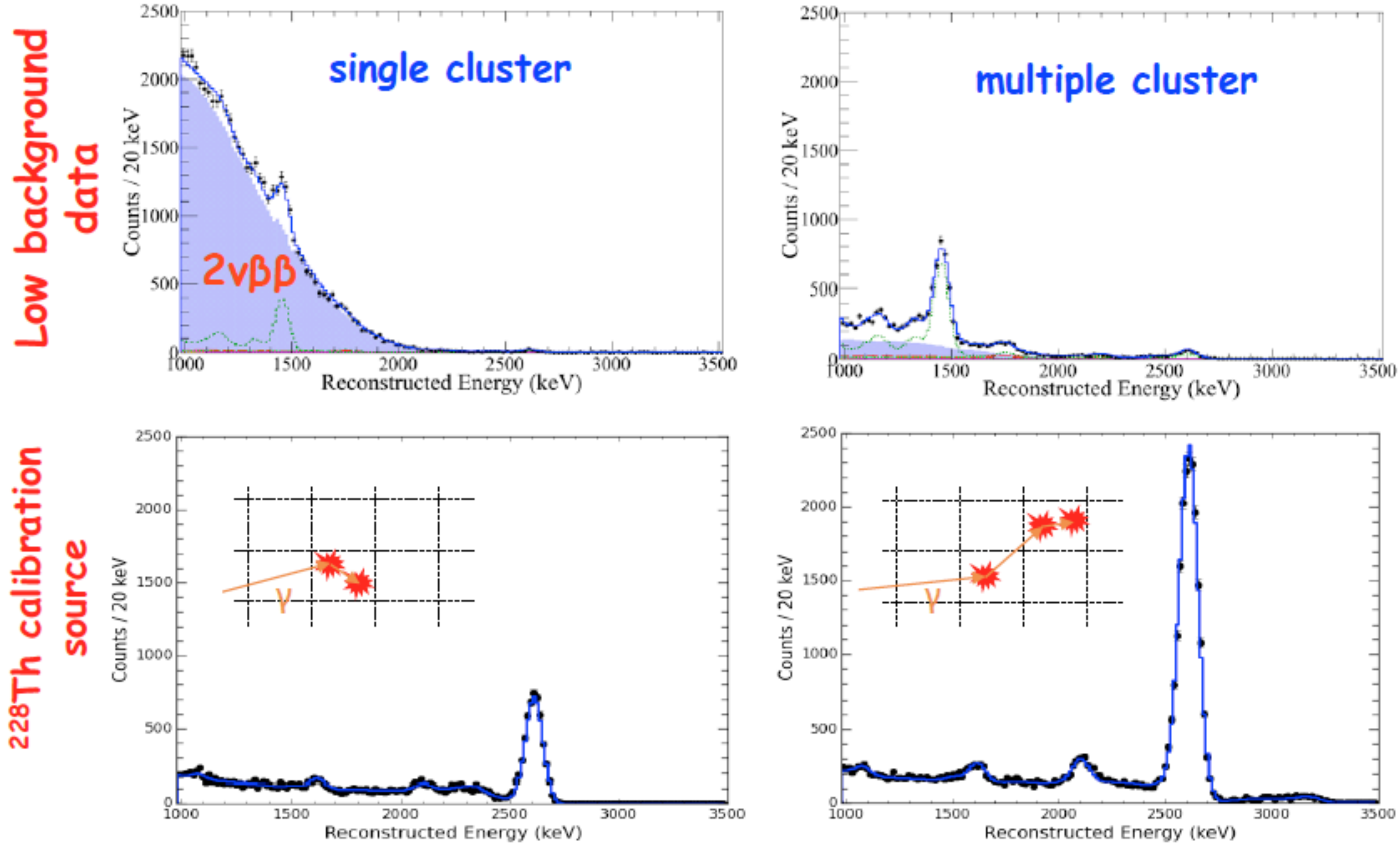
- 5 tonnes of ^{enr}Xe: entirely cover inverted hierarchy *(more later)*

- LXe TPC "as similar to EXO-200 as possible"
- Provide access ports for a possible later upgrade to Ba tagging

➔ *A unique combination of conservative and aggressive design with important upgrade paths as desirable for a large experiment*



Tracking:
an essential tool to identify and suppress backgrounds



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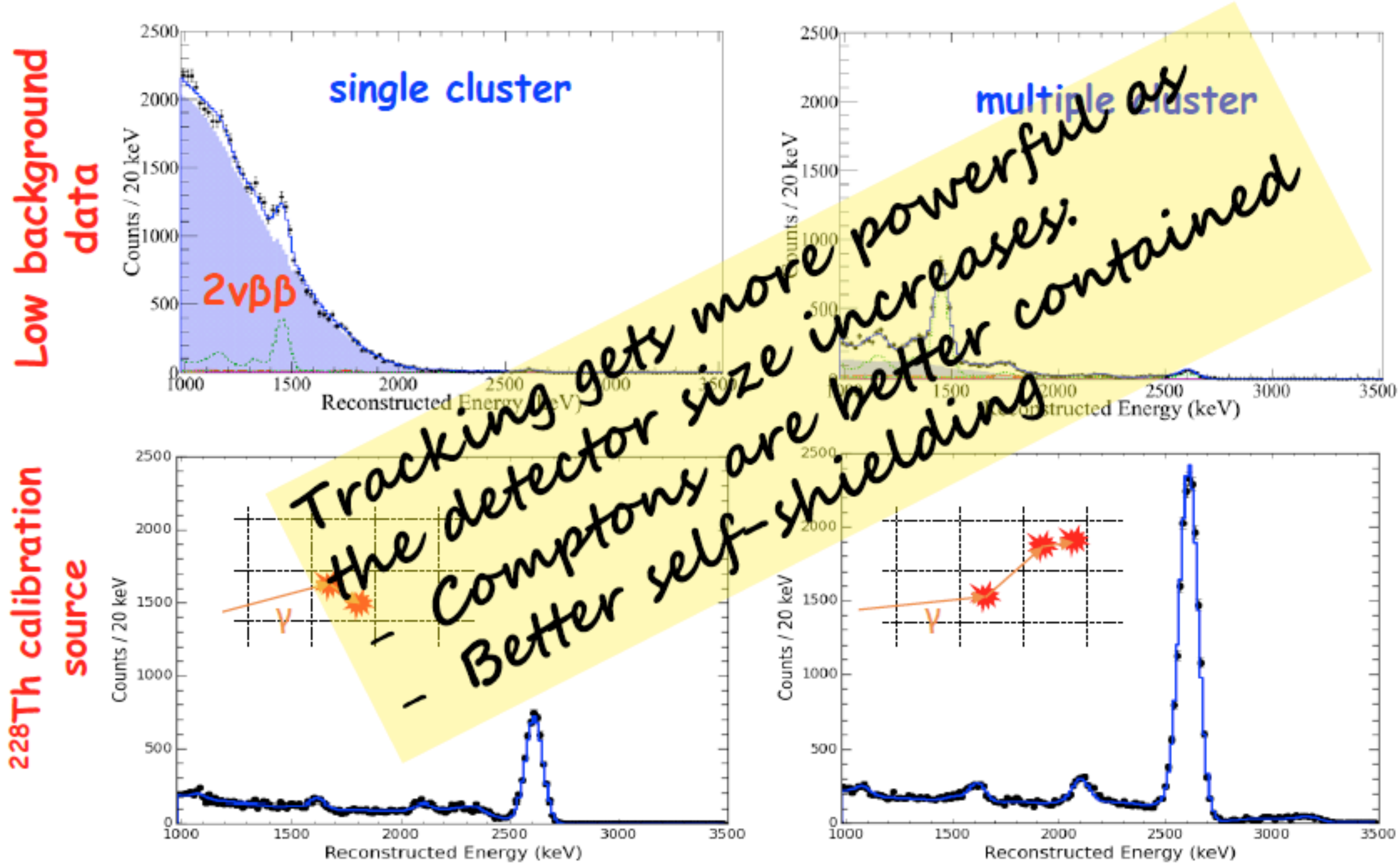
an essential tool to identify and suppress backgrounds

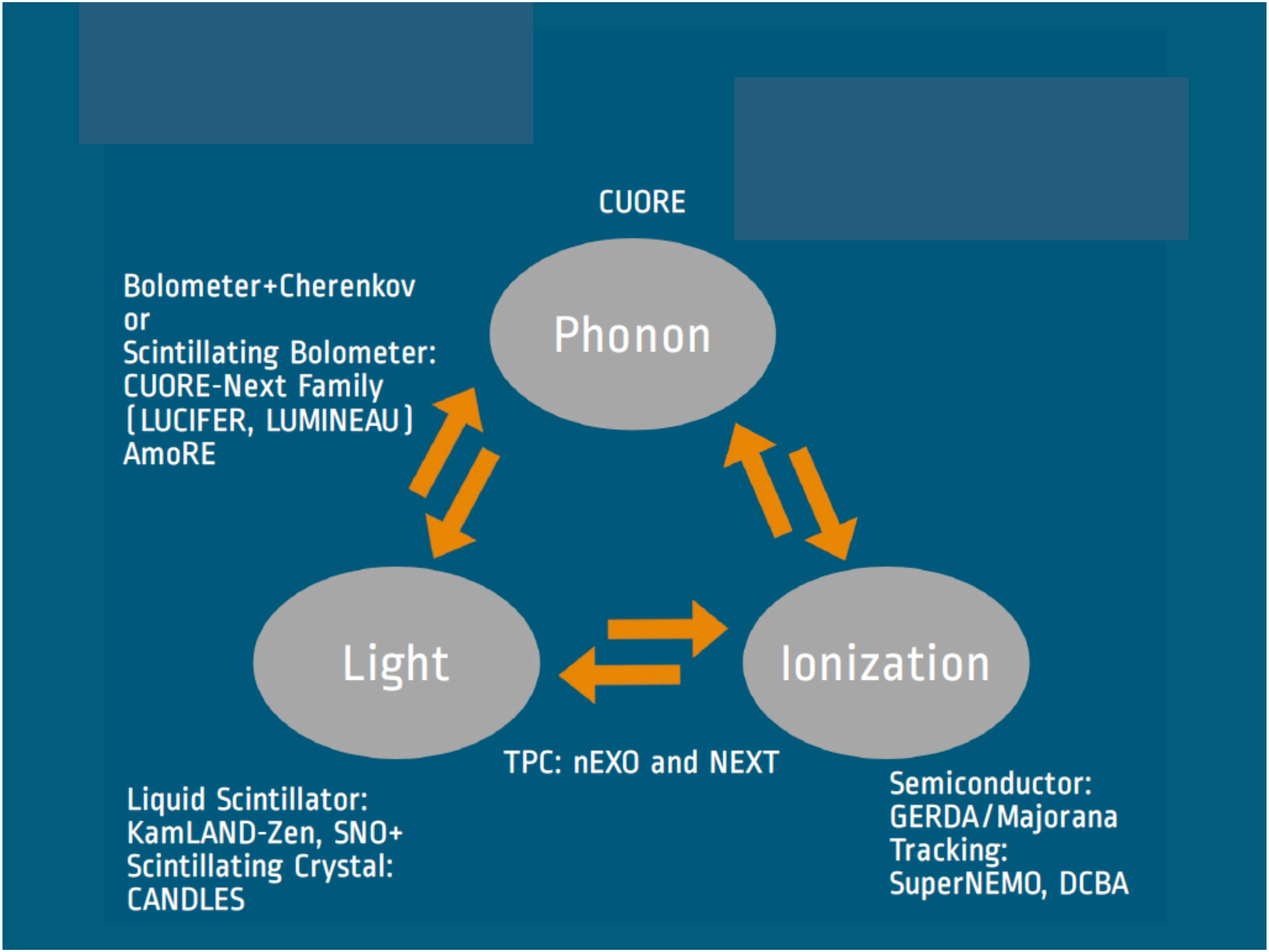


without barium tagging...a straightforward path towards 5 tons.

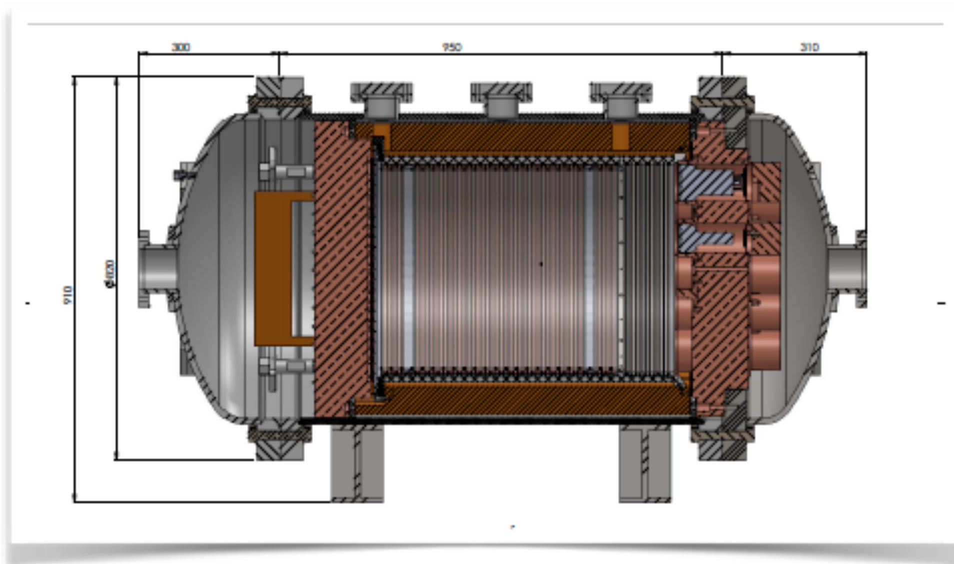
R&D in progress

Item/concept	Reason to change	Cat	Risk
Water shield	More convenient for large size, very standard	2	None
Vertical detector axis	Horizontal for EXO-200 due to site constraint	1	None
Composite cryostat	Too large for conveyance at SNOlab, composite easier to build underground, lighter	2	Low
One drift space	Lowest background in the middle	1	Medium
Internal electronics	Lower outgassing, lower activity, better S/N	2	Low
SiPMs	Better S/N, Lower mass, More common, no HV	1, 2	Medium
No Teflon reflectors	Lower outgassing	1	None
Higher charge readout density	Better background rejection	1	Low
High Voltage Noise	EXO-200 (and other LXe dets) can't reach full HV	1	Medium
Add LXe purity mtr	Longer drift, harder calibration	2	Low
Add prepurif Xe source	No purity loss from feeds, higher live time	1	None

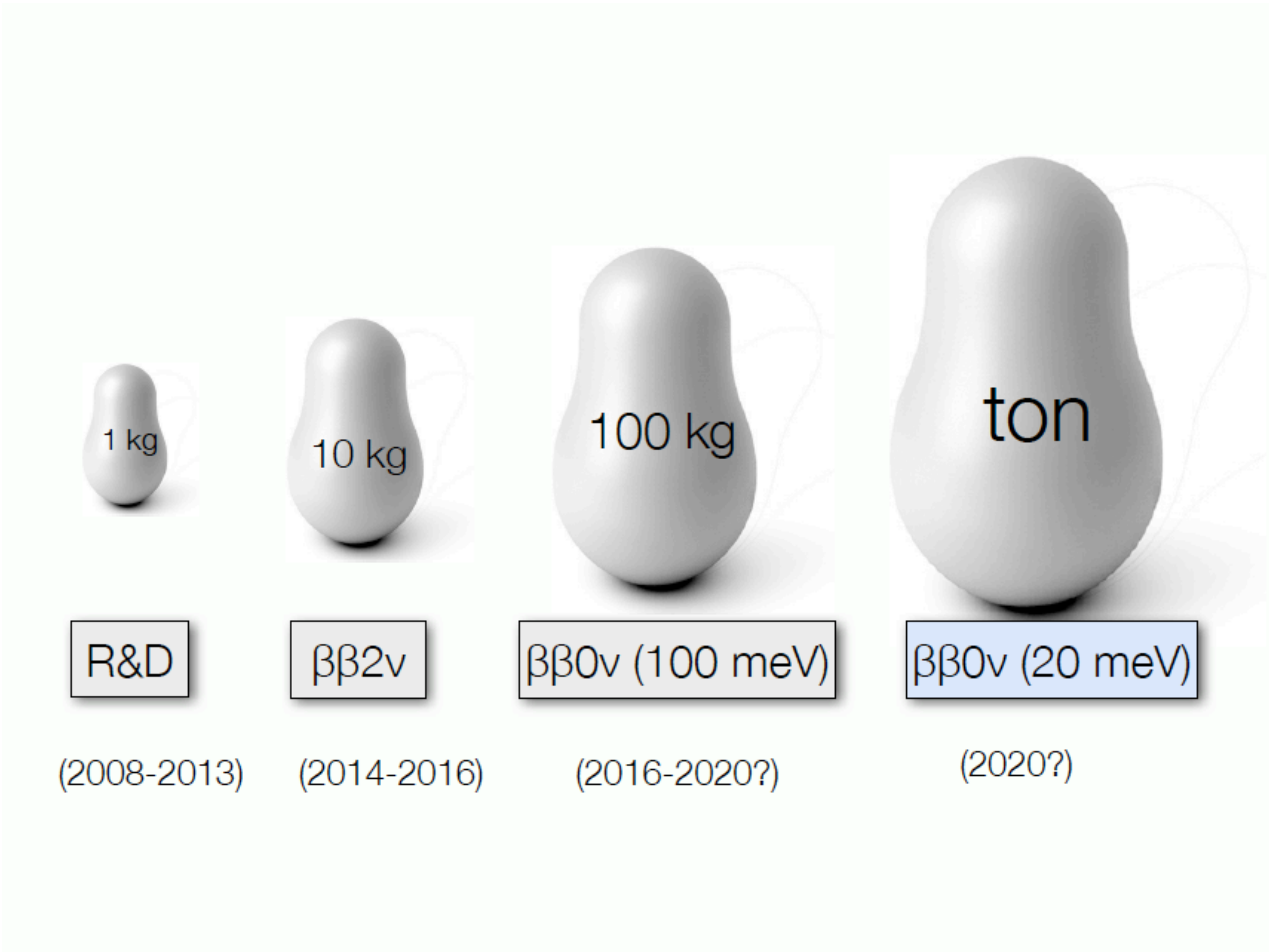
None of these items precludes starting CD1


CUORE
Bolometer+Cherenkov
or
Scintillating Bolometer:
CUORE-Next Family
(LUCIFER, LUMINEAU)
AmoRE
Phonon
Light
Ionization
TPC: nEXO and NEXT
Liquid Scintillator:
KamLAND-Zen, SNO+
Scintillating Crystal:
CANDLES
Semiconductor:
GERDA/Majorana
Tracking:
SuperNEMO, DCBA

High Pressure Gas TPC



NEXT


1 kg
10 kg
100 kg
ton
R&D
ββ2ν
ββ0ν (100 meV)
ββ0ν (20 meV)
(2008-2013)
(2014-2016)
(2016-2020?)
(2020?)

NEXT100 program

Background model and sensitivity:

- Uncertainties in activities of materials due to limited sensitivity translate into uncertainties in sensitivity. Improve radio purity measurement techniques
- Understand all sources of background, including unexpected (e.g. radon sources, cosmogenics). NEW operation.

Energy resolution and topological signal:

- Goal: achieve near-to-Fano resolution (0.5 % FWHM) in the full detector. NEW operation.
- Fully exploit the power of the signal topology. Characterise with $2\beta\beta$ and Tl double escape peak. NEW operation.

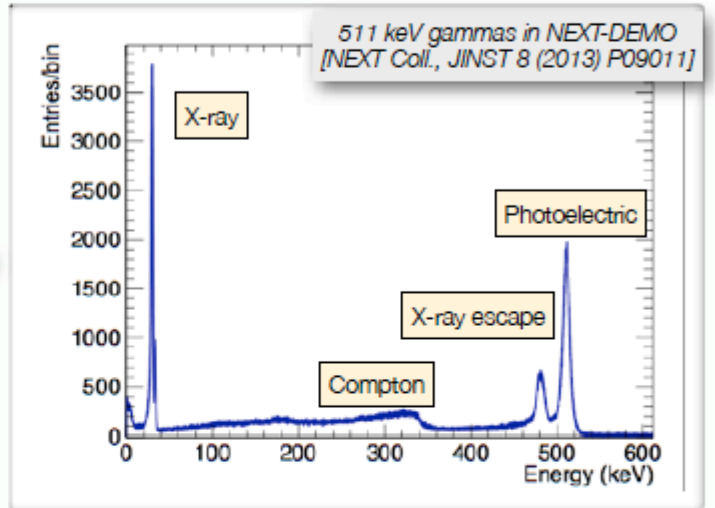
Challenges:

- Grids (size, stored energy, sparks). R&D under way.
- Reduce radioactive budget. KDB circuits without adhesive layers. ultra radio pure copper.
- Understanding TPB (uniformity, stability, glow). DEMO, NEW operation.

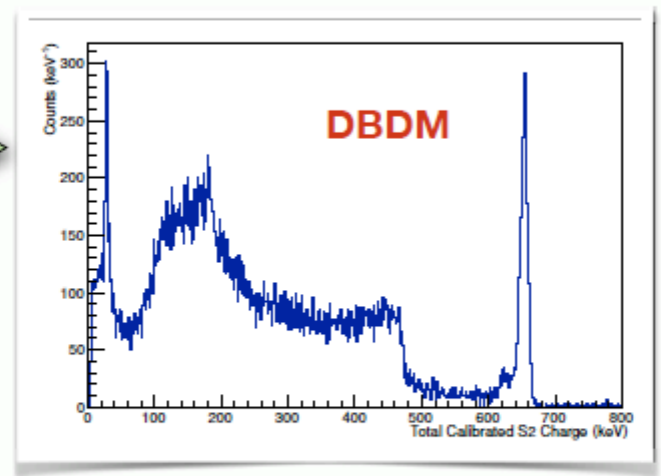
NEXT R&D: detector performance achievements

- 1.8% FWHM energy resolution for 511 keV electrons over large fiducial volume

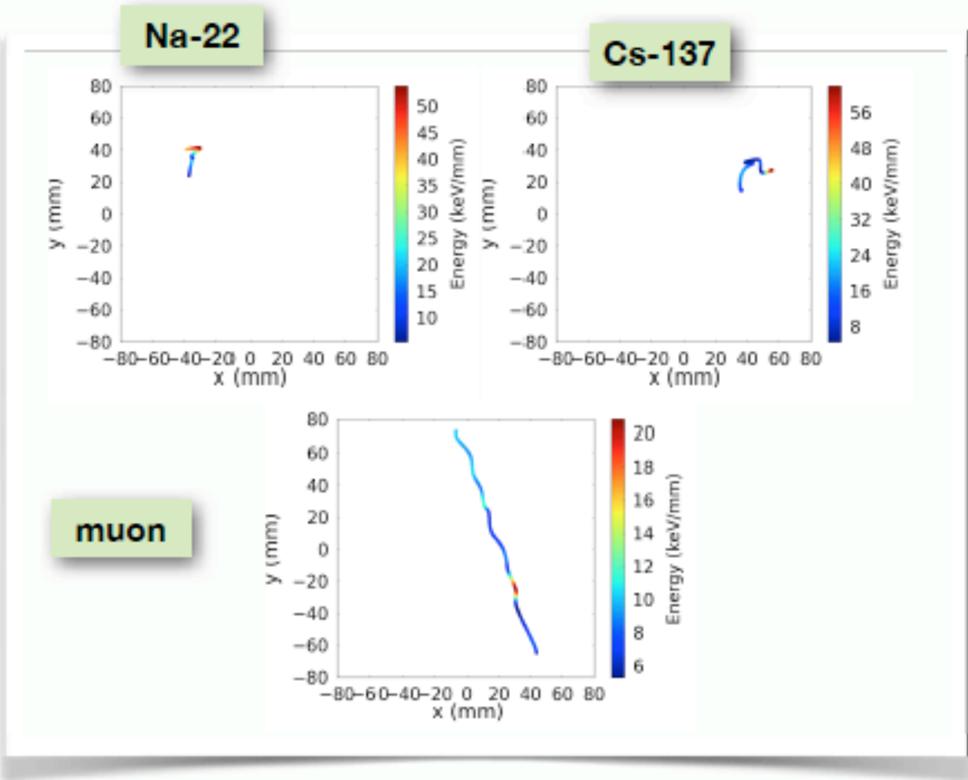
- Extrapolates to 0.75% FWHM at $Q_{\beta\beta}$ energy of 136Xe decay

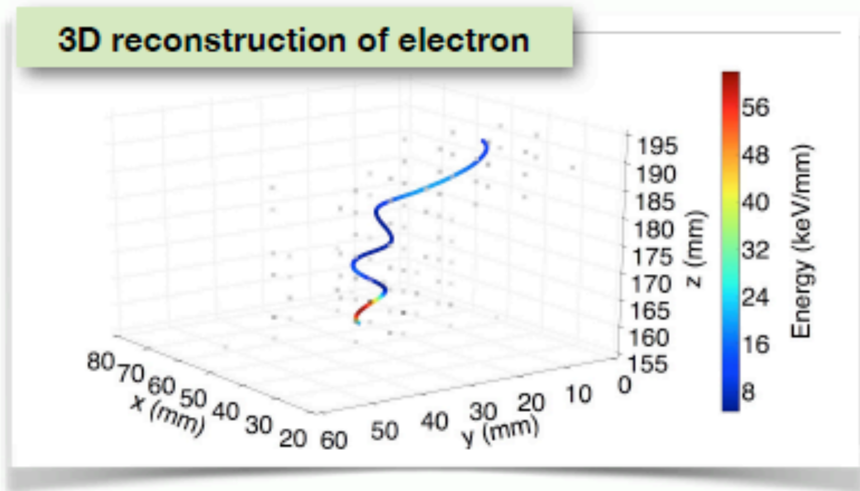


- The DBDM prototype at LBNL extrapolates to **0.5 % FWHM** at $\mathbf{Q_{\beta\beta}}$ using 660 Cs-137 electrons



Topology of the signal in next

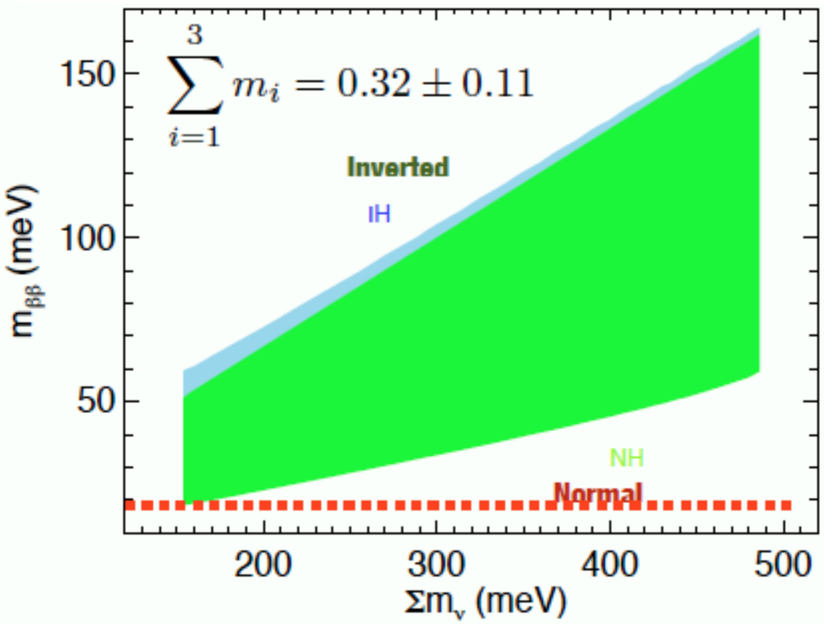




- Higher energy deposition clearly visible at electron track end-point.
- Tracks reconstructed using SiPMs + PMTs

Majorana Gas Instrumented with Xenon

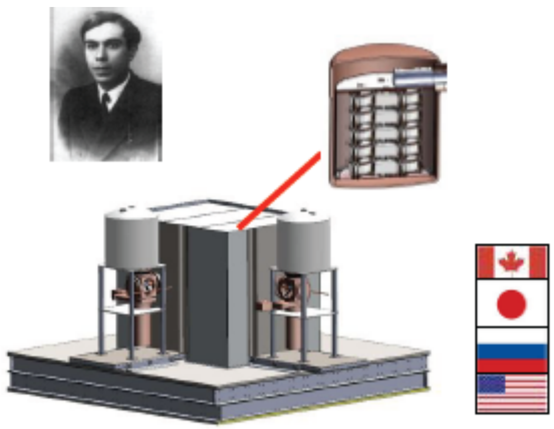
MAGIX

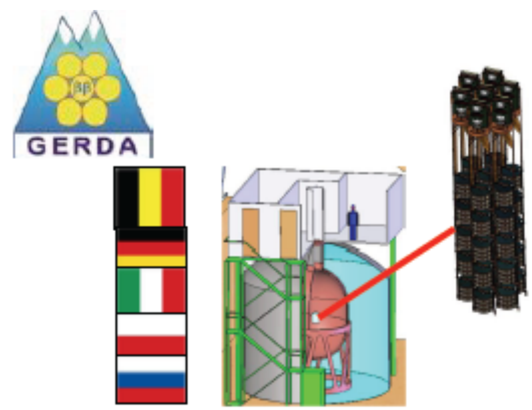


What is MAGIX

- Baseline concept.
- It is a symmetric TPC filled with O(1 ton) of Xenon enriched at 90% in Xe-136 at a pressure of 15 bar.
- The drift length is 2 x 2 m (2 ms drift, DEMO measures lifetimes of > 10 ms)
- The TPC radius is about 1 m.
- The active volume is about 12 m^3 (1 ton at 15 bar)
- The event energy is integrated by wavelength shifting light guides surrounding the gas and read by PMTs located outside the fiducial volume.
- The event topology is reconstructed by two planes of radiopure silicon pixels (MPPCs by default).

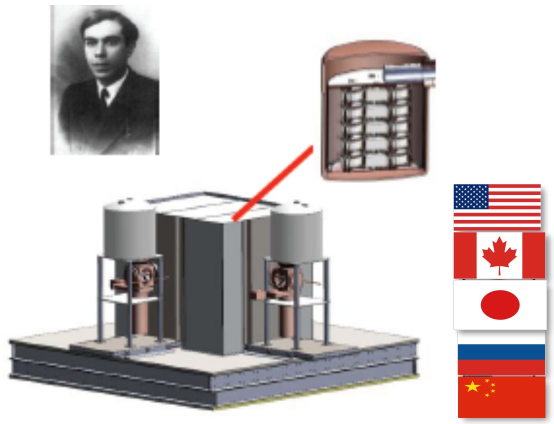
Germanium Detectors

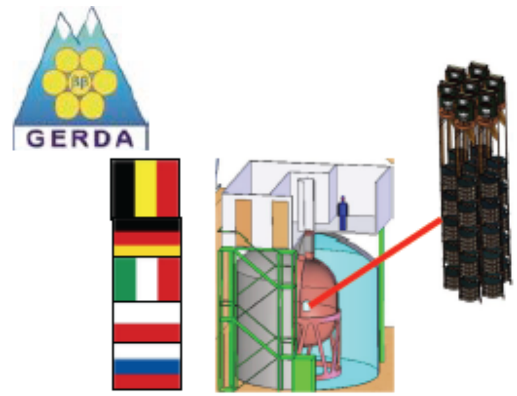




Majorana/GERDA

MAJORANA DEMONSTRATOR and GERDA





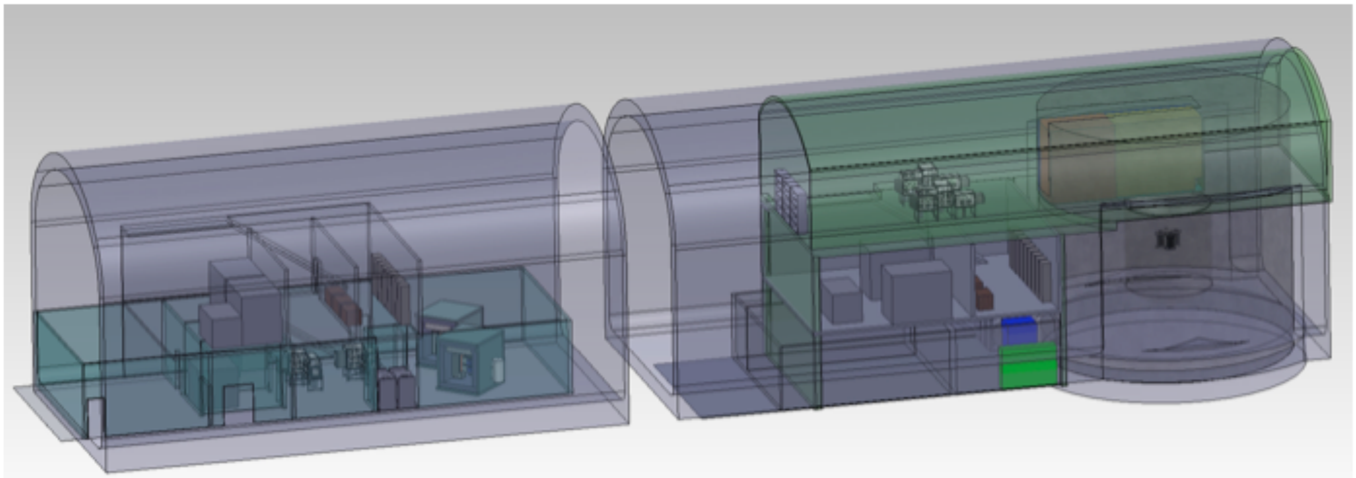
- ^{76}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg ^{76}Ge and 10 kg ^{nat}Ge PPC detectors

- ^{76}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: 18 kg (H-M/IGEX xtals)
- Phase II: +20 kg PPC detectors

Joint Cooperative Agreement:

Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale experiment
Select best techniques developed and tested in GERDA and MAJORANA

Baseline Experimental Configurations



Compact

Two shields, each with 8 EFCu vacuum cryostats

Cryogenic Vessel

Diameter of water tank:

- ~11 m for LAr,
- ~15 m for LN (shown)

Isotope Cost

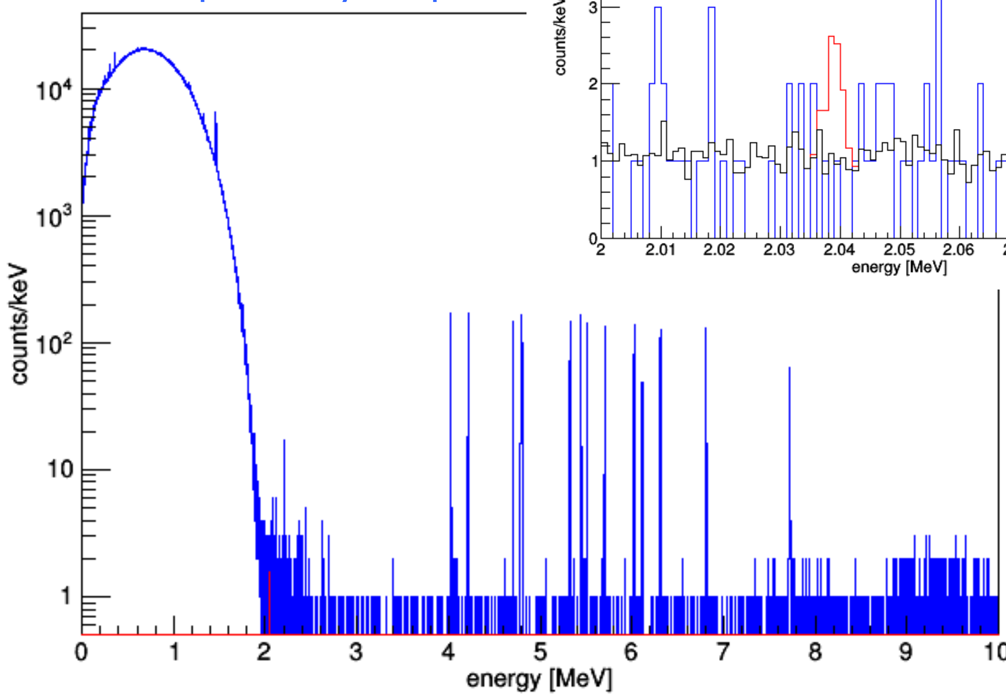
- Enriched Ge (87%) costs about $90/g ($6.8M/kmole)
- But Ge is used efficiently
  - Production losses
    - Reduction/refinement ~0% 1.7% in captured remainders
    - Trimmings recovery ~0% Actual pieces recovered
    - Etch losses (90% recov.) ~1% recent R&D result
    - Sludge (grindings in fluids,70% rec.)~4.5% recent R&D estimate
  - Total loss ~6%
  - Fiducial Volume 94%
- Once purified, Ge does not get contaminated.
- For Ge, to produce 1 t of enriched material requires about 13 t of natural Ge. The Ge prod. per year is about 120 t. Not a huge perturbation on world supply.

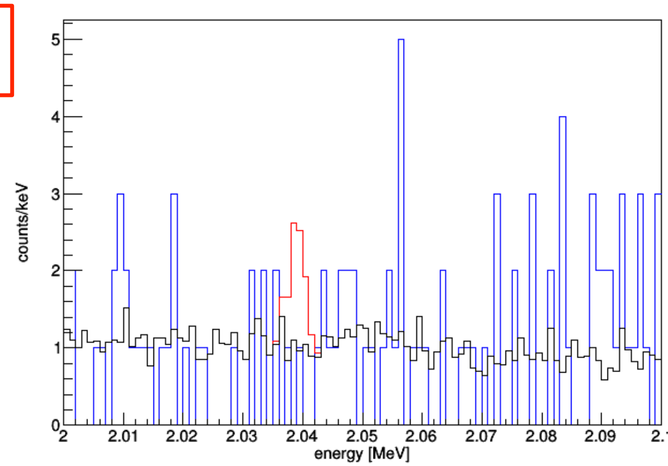
Simulated Spectrum - 5 t-y Exposure

90% UL 3.2×10^{27} y

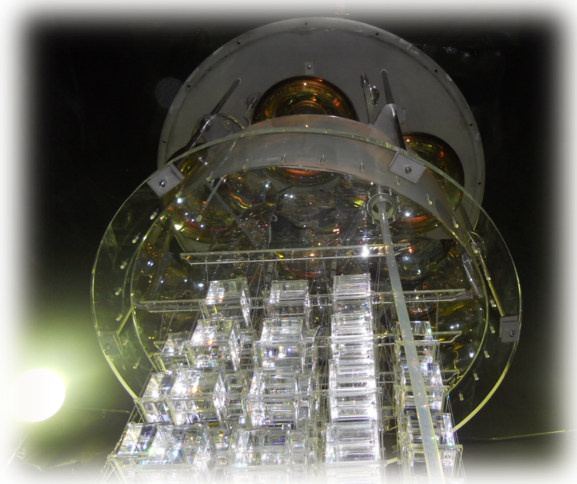
High statistics MC

Specific 5-y sample





Scintillating Crystals



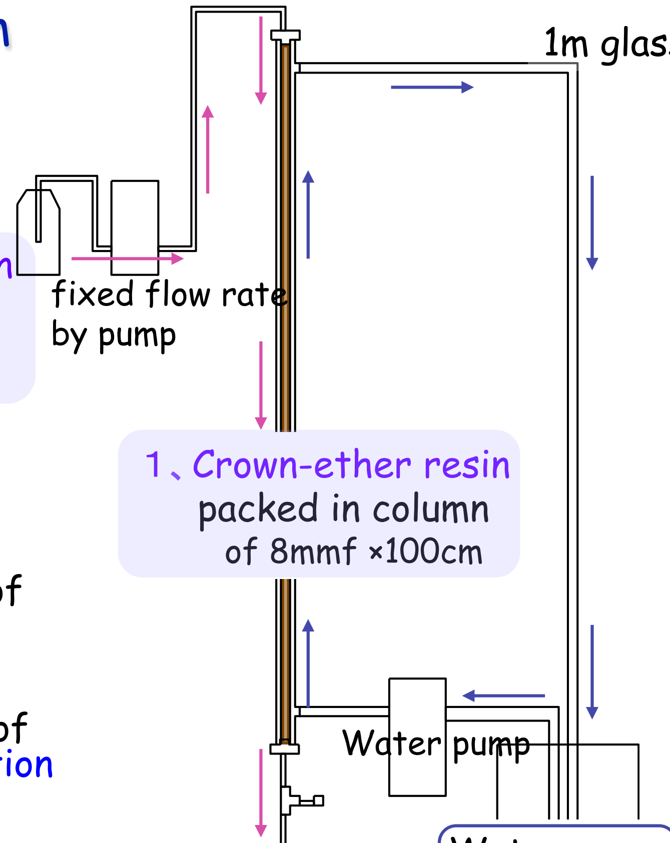
CANDLES

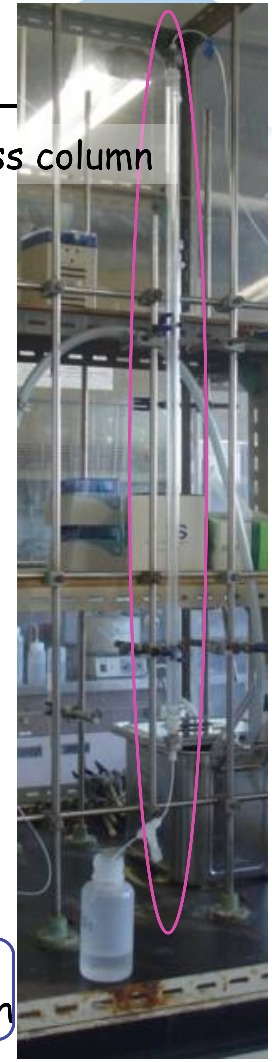
Experimental Setup

Experimental system

Chromatography:
Breakthrough method
= Migration of Ca solution in resin area

2、Ca solution
$CaCl_2$ +Conc. HCl





1、Crown-ether resin packed in column of 8mmf ×100cm

3、Sampling by fraction collector

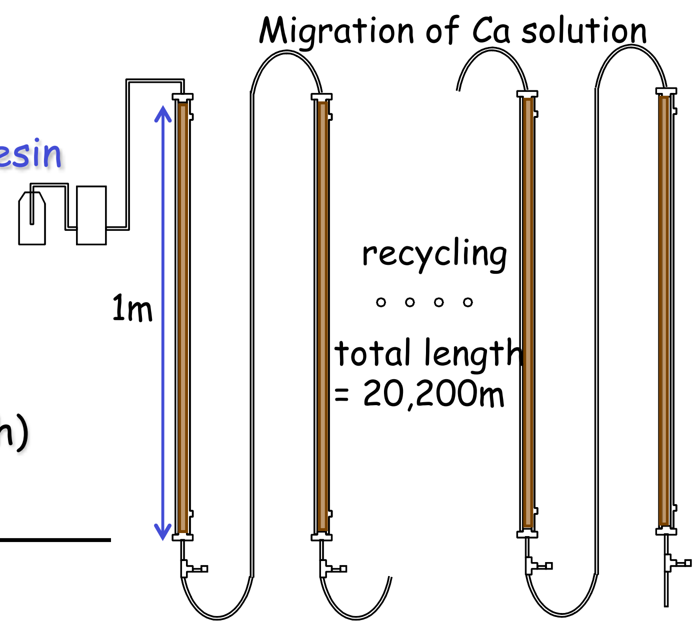
4、Measurement of Ca concentration

5、Measurement of isotopic ratio

Now working towards mass production.

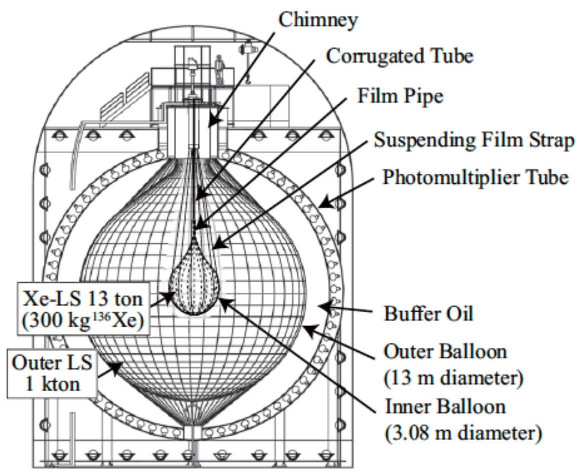
Further Enrichment

- Further Enrichment
  - First Test
    - 1m glass column was applied.
    - Migration Time(length) = ~7hours(1m)
  - Next = long migration test
    - 10 glass columns(10×1m) are applied.
    - Recycling of crown-ether resin after rinsing
    - Total Migration Time(length) = ~70hours(20m), ~250hours(200m)



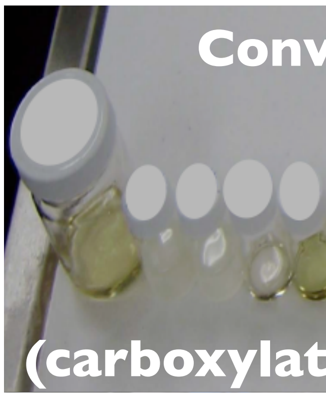
Now working towards mass production.

Liquid Scintillators



KamLAND-Zen and SNO+

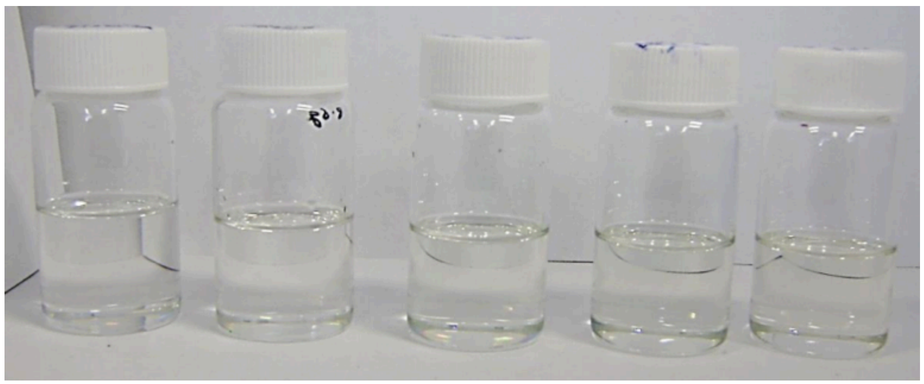
First Attempts at Te-Loaded Scintillator (at BNL)



- …then, breakt eveloped at BNL, works for or

Percent Loading of Tellurium is Feasible

- 0.3%, 0.5%, 1%, 3%, 5% (from left to right)

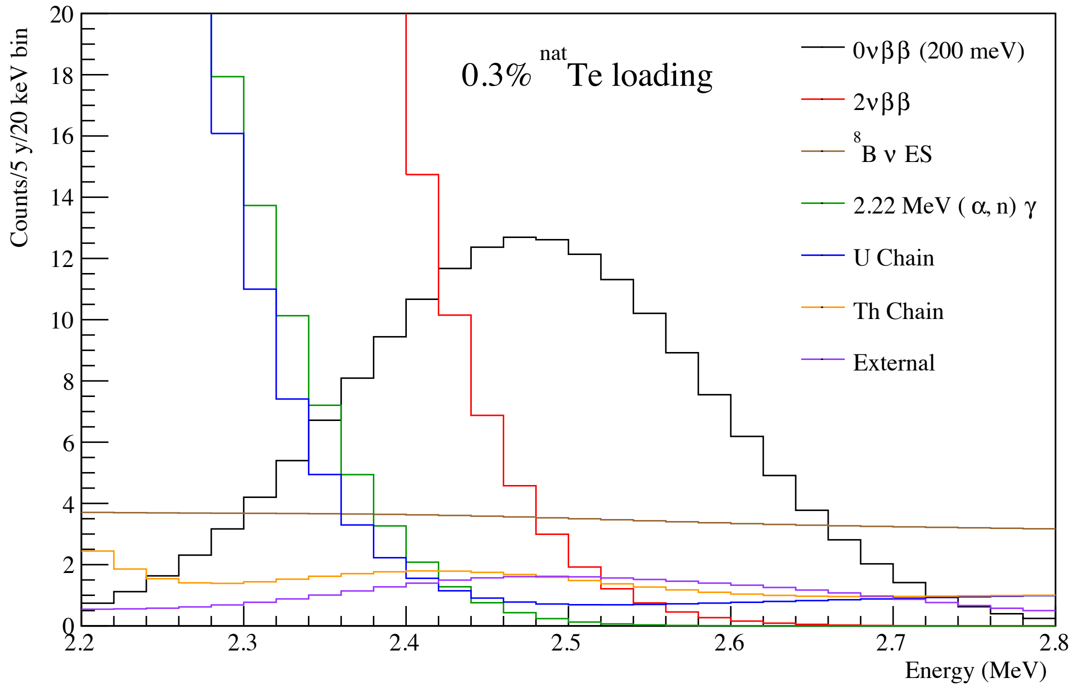


- 3% Te in SNO+ Phase II DBD corresponds to 8 tonnes of ^{130}Te *isotope* (cost for this much tellurium is only ~$15M)

Status

- electronics and DAQ upgrades completed
- now filling the SNO+ detector with water
- water-filled data taking starts in 2014
    - to study external backgrounds and detector optics
- now installing liquid scintillator purification plant
- liquid scintillator fill to start in 2015
- installation of tellurium purification skid and Te purification in late 2015
- addition of Te to SNO+ liquid scintillator and DBD run in 2016

Spectrum Plot (5-yr Simulated)

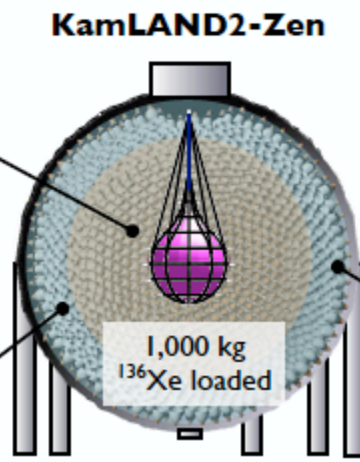


KamLAND2-Zen

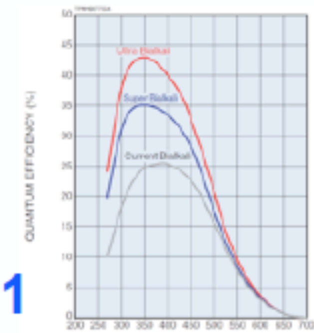
Liquid Scintillator (LS)

× 1.5

Buffer Oil (BO)



× 2.1



High Q.E. PMT

(17 inch → 20 inch)

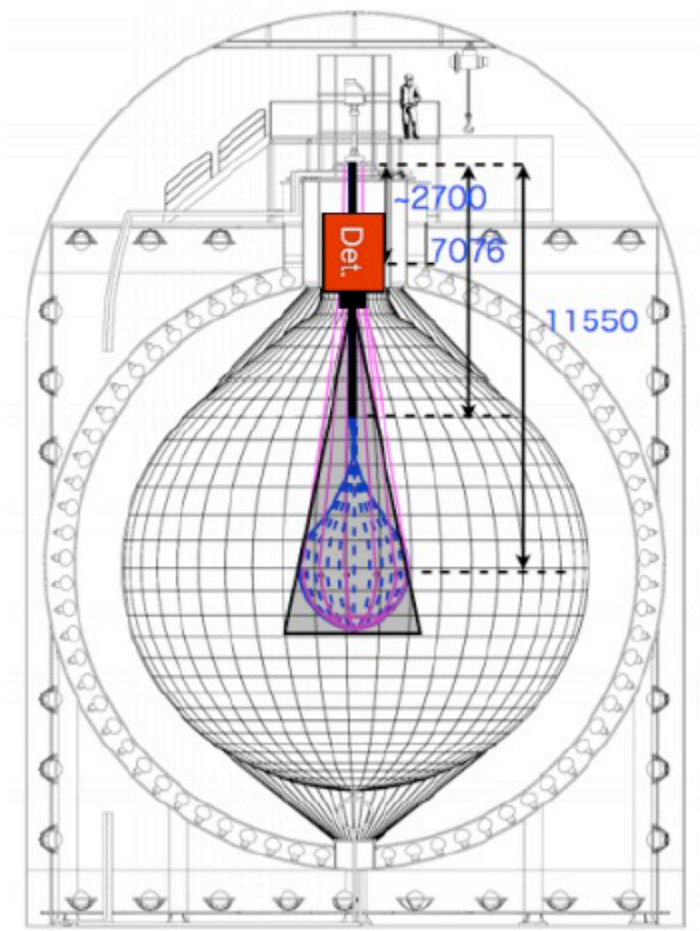
× 1.8

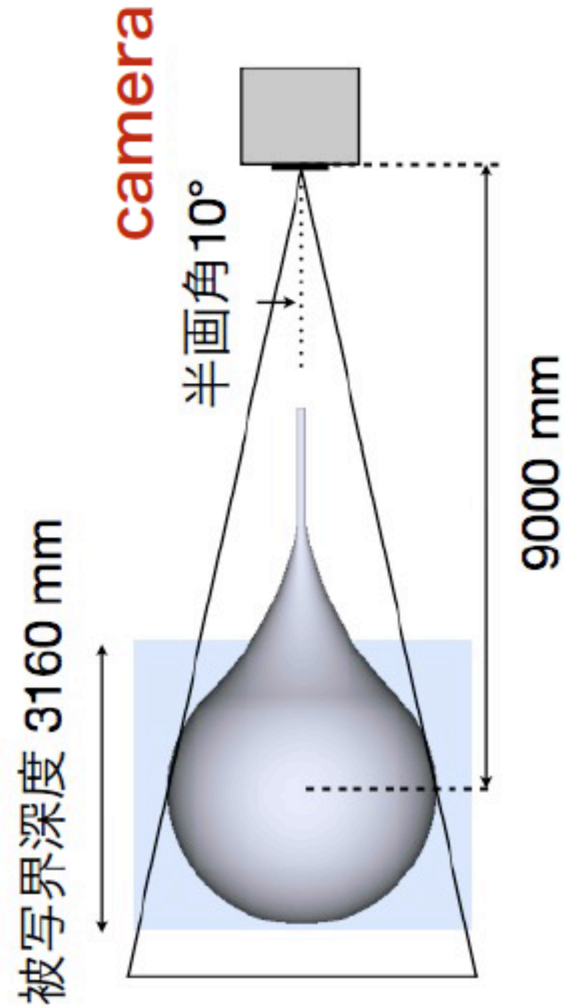
Light Collecting Mirror

energy resolution $\Delta E \sim \times$ **0.42** ⟶ 2ν background < 1 / 100

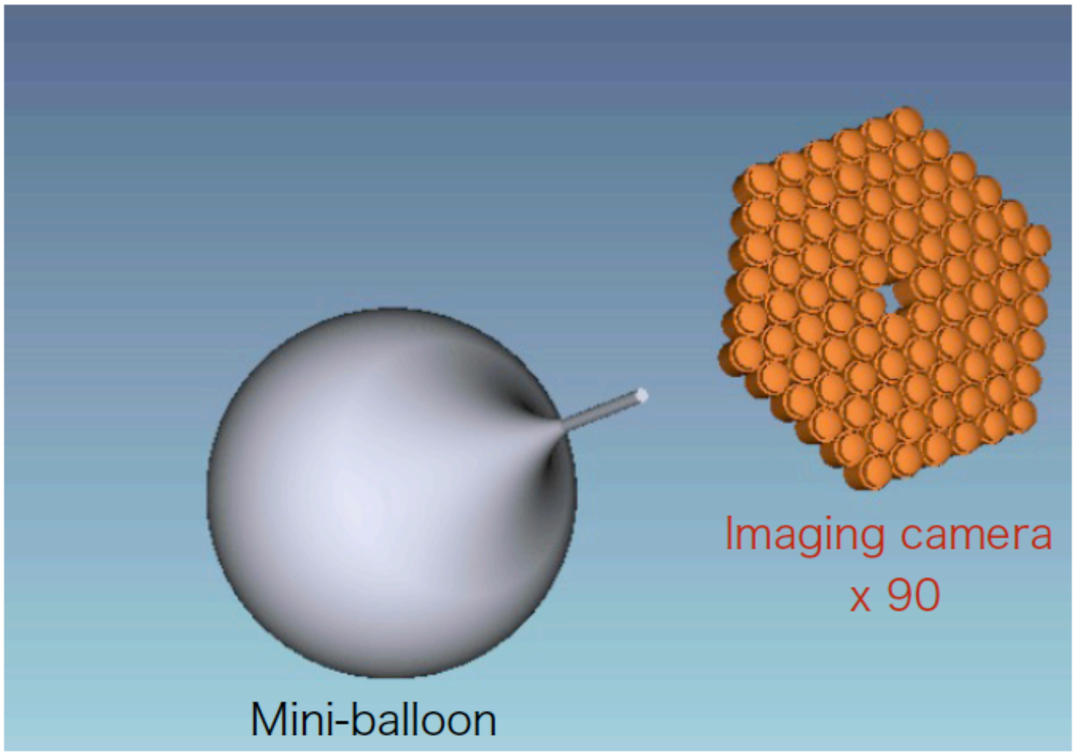
target $\langle m_{\beta\beta} \rangle$ sensitivity ~ 20 meV / 5 years

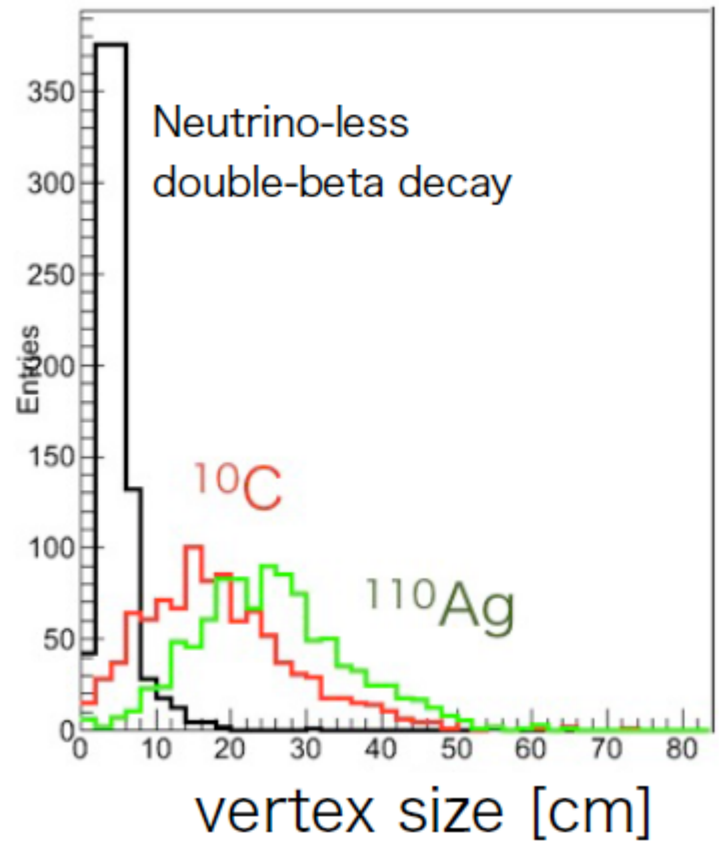
Also working on an imaging camera...



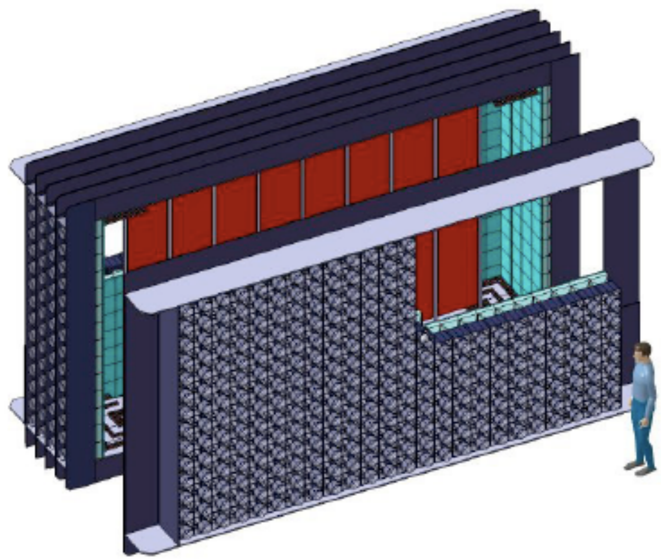


Tagging efficiency > 90%





The Trackers

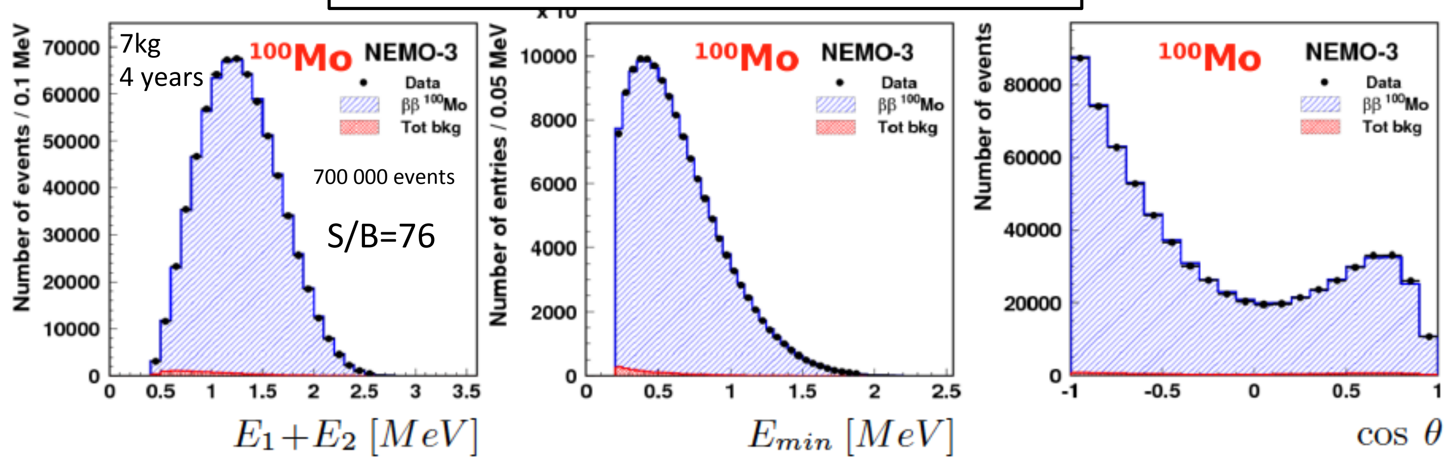


SuperNEMO and DCBA

Avantages of the tracko-calo technique

Accurate measurement of ββ(2ν) observables (NEMO3 results)

$T_{1/2}^{2\nu} = 7.16 \pm 0.01\ (\text{stat}) \pm 0.54\ (\text{syst})\ 10^{18}$ y
[Phys. Rev. Lett. 95, 182302 (2005)]

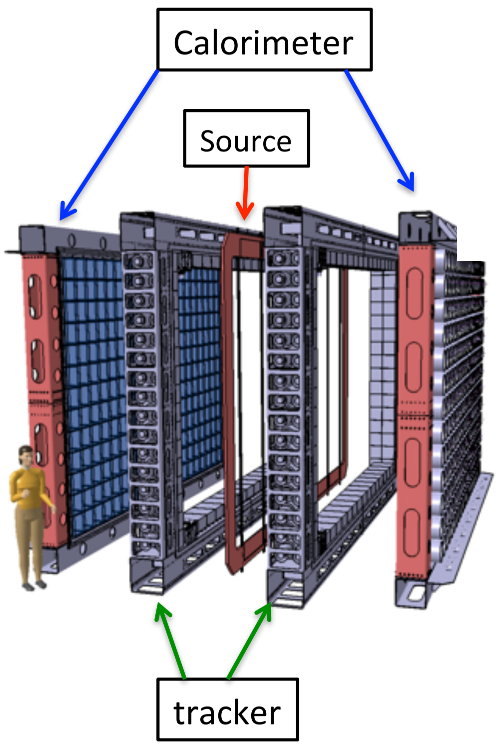


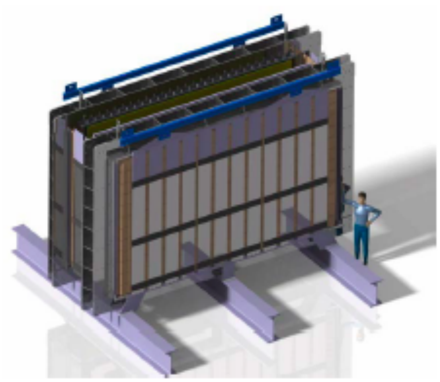
- Nuclear physics (ββ(2ν) half-life to extract N.M.E., HSD vs SSD)
- To look for exotic physics like bosonic neutrinos

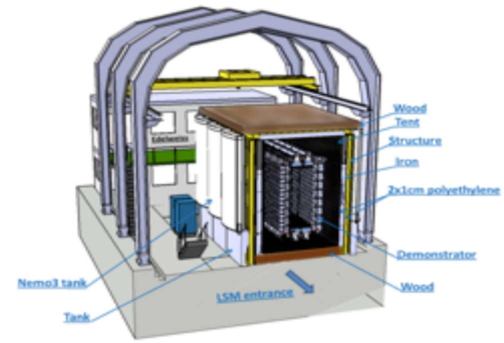
To go to higher mass

	NEMO-3	SuperNEMO
Mass	7 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
	7 isotopes	^{150}Nd, ^{48}Ca
Foil density	60 mg/cm^2	40 mg/cm^2
Energy resolution (σ | FWHM)		
@ 1 MeV	6.3 | 15 %	3.0 | 7 %
@ 3 MeV	3.4 | 8 %	1.7 | 4 %
Radon in tracker		
$\mathcal{A}(^{222}\text{Rn})$	$\sim$ 5.0 mBq/m^3	$\sim$ 0.15 mBq/m^3
Sources contaminations		
$\mathcal{A}(^{208}\text{Tl})$	$\sim$ 100 μBq/kg	$<$ 2 μBq/kg
$\mathcal{A}(^{214}\text{Bi})$	60 - 300 μBq/kg	$<$ 10 μBq/kg
Detector		
tracking cells	6180	20×2034
calo blocks	1940	20×712
Sensitivity (90 % CL)		
$\mathcal{T}^{0\nu}_{1/2}$	$>$ 1.1 10^{24} y	$>$ 1 10^{26} y
$\|m_{\beta\beta}\|$	$<$ 0.3 - 0.8 eV	$<$ 40 - 100 meV

SuperNEMO demonstrator module





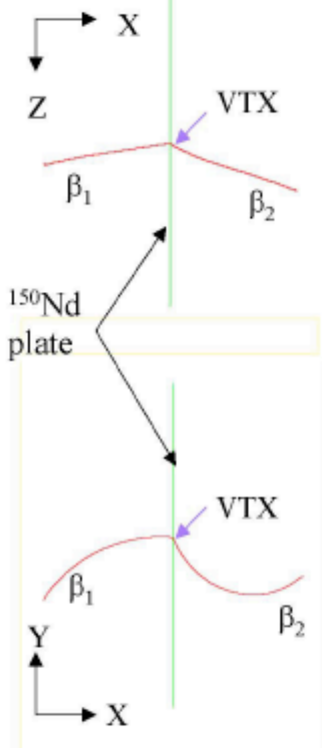


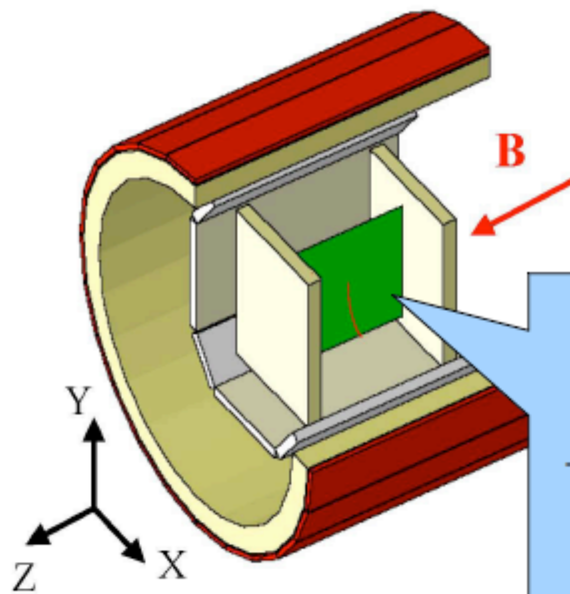
- Ultra low background detector
- Modular detector with 3 main components :
  - Central source foil frame : 7 kg of isotope
  - Tracking : 2 000 drift chambers
  - Calorimeter : 712 scintillators+ PMTs
- Shielded by iron (300 tons) and water
- Construction in progress
- Installation and commissioning at Modane Underground Laboratory 2014 – 2015
- Data taking end 2015

No background expected for 2 years of data. 7 kg ^{82}Se $T_{1/2} > 6.6\ 10^{24}$ y $\langle m_{\nu} \rangle < 0.16 - 0.44$ eV

DCBA: method

- have source plate(s) inside of the tracking volume
  Source plate: ^{100}Mo (^{150}Nd in future)
- emitted two electrons make helical trajectories inside of the tracking volume
- reconstruct momenta of two electrons





Source plate is put parallel to the B-field
→ electrons having large angle to the source plate, travel across the B-field

DCBA-T2.5

2005 DCBA
- charge dividing
- 6 mm pitch wires (xy + xz)

2007 DCBA-T2
- ^{100}Mo source (natural Mo 30g)
- 0.6 - 0.8 kG magnetic field
- Normal conducting magnet: 9h/day operation (Mon.-Fri)

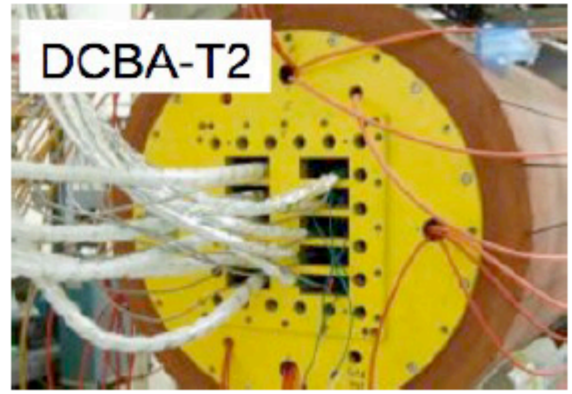
2011 DCBA-T2.5
- 6 mm pitch wires (xy + xz)
- ^{100}Mo source (natural Mo 30g)
- 0.8 kG magnetic field
- super-conducting magnet:

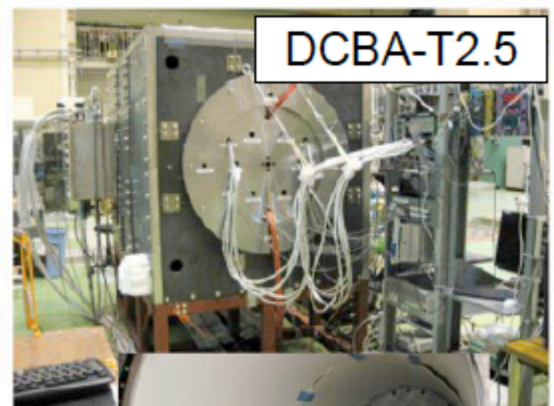
24h nonstop operation

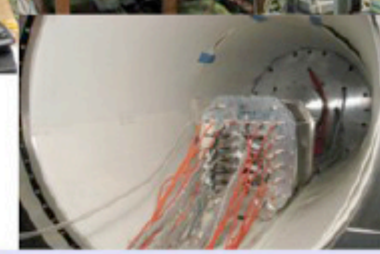
now

2014 DCTA-T3
- 3 mm pitch wires (xy + xz)*8
- ^{150}Nd (5.6% in natural Nd_2O_3)
- B=3 kG at the maximum

2017 MTD (tentative name)
- ^{82}Se ^{150}Nd(enriched) several 10 kg

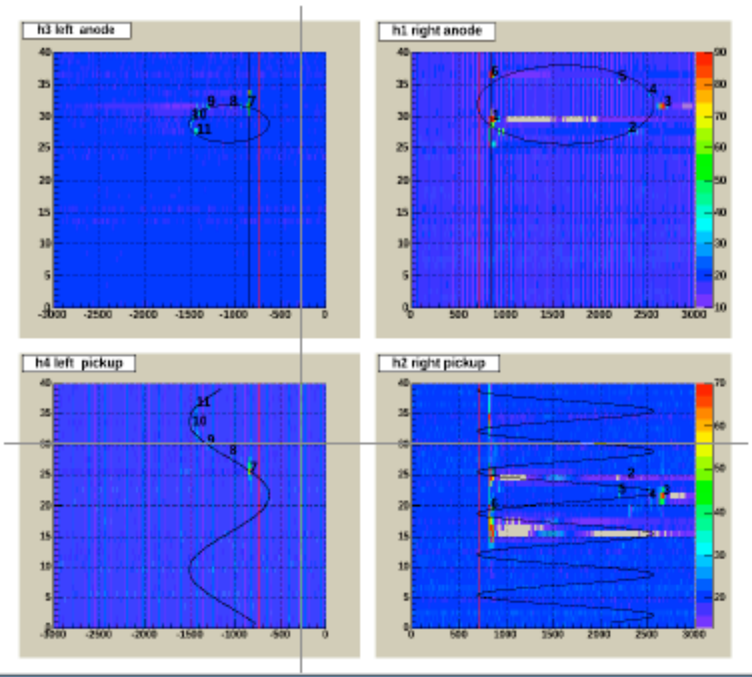


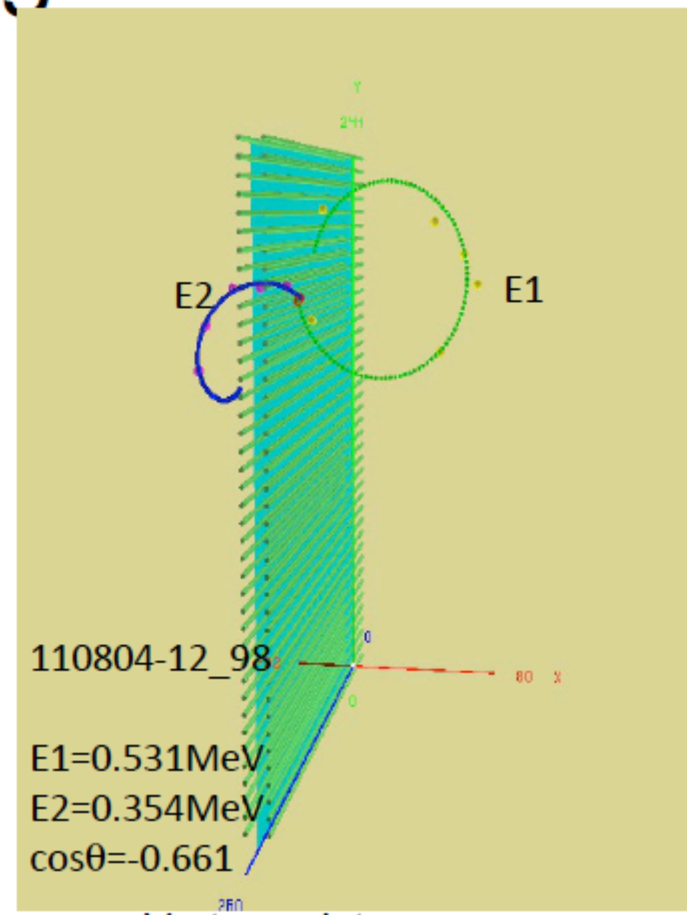




DCBA-T2 Chamber installed into the DCBA-T3 SC-Magnet

Another $2\nu\beta\beta$ signal candidate





Characteristics of
the signal candidate

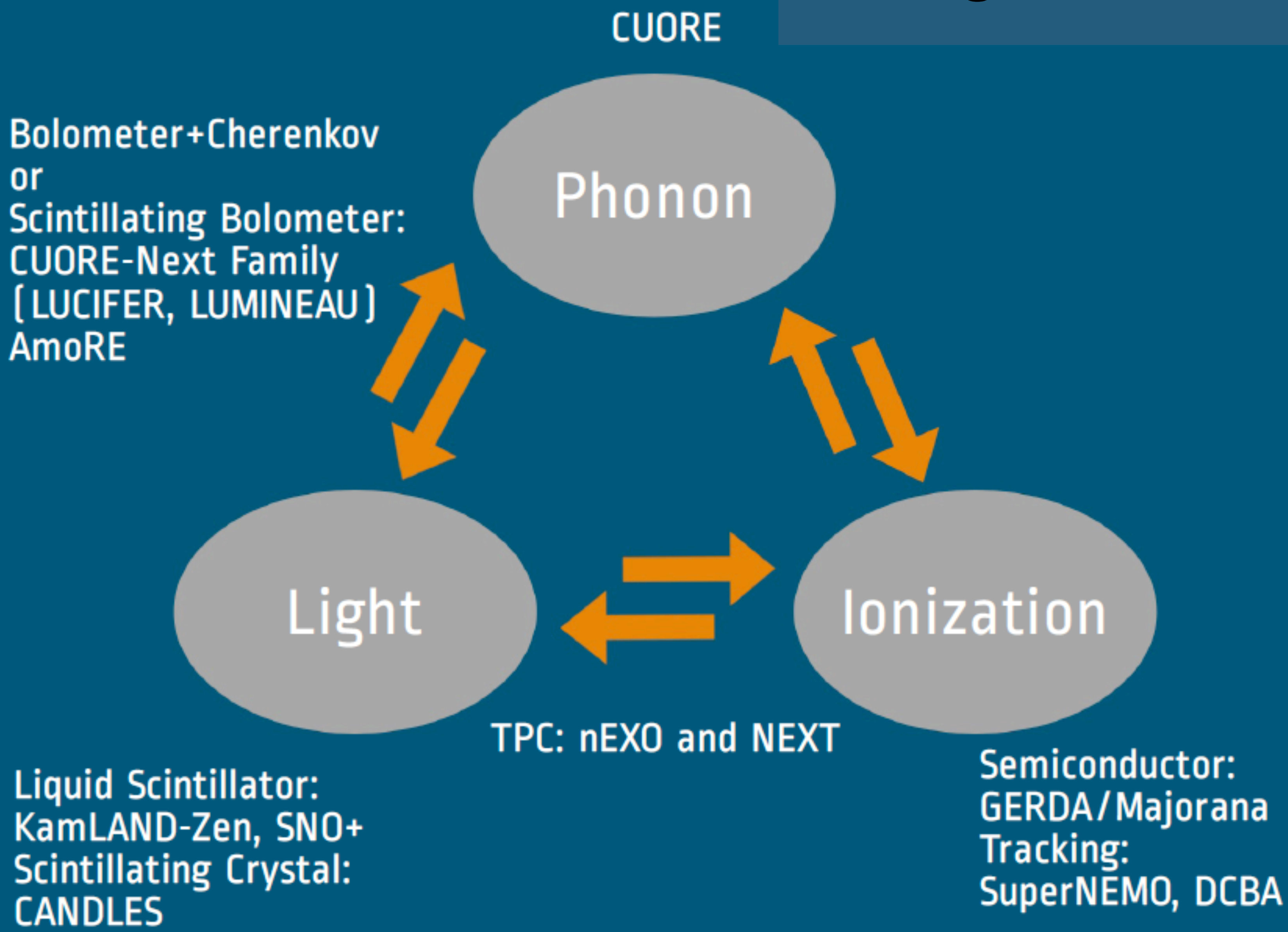
1. trajectory of the two tracks looks like inverse "S" shape
2. vertex points of two tracks are consistent

Vertex point

	E1	E2
Y	183.0mm	183.9mm
Z	151.7mm	146.3mm

That is all of them!

Exciting R&D Ahead!

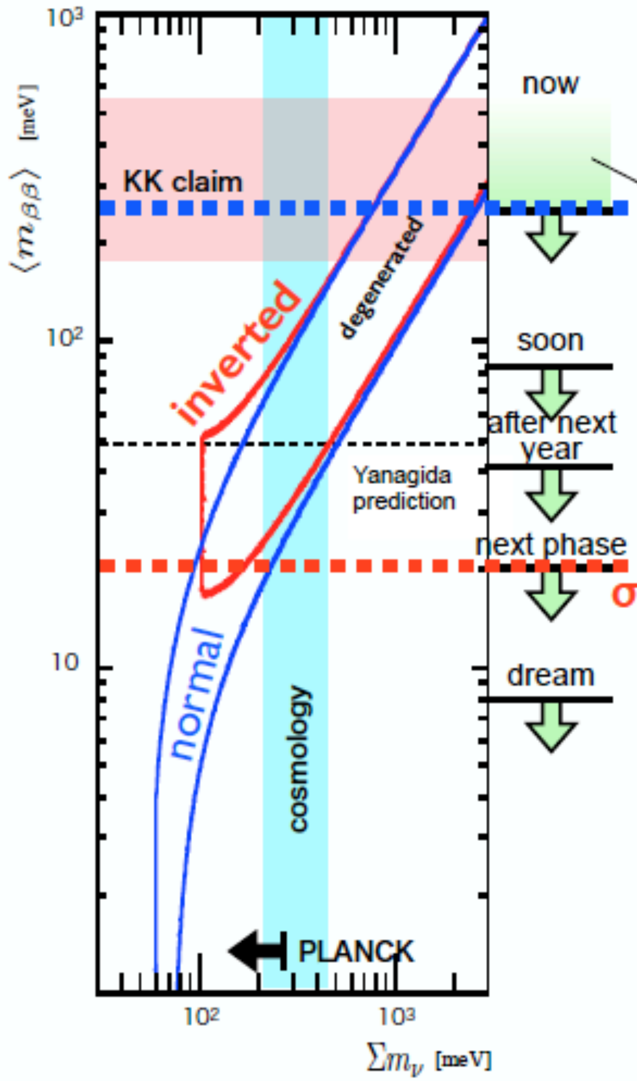


Discovering the Majorana Neutrino

Thinking Ahead

The above hope to get through the inverted hierarchy.

Prospects of KamLAND-Zen



KamLAND-Zen 89.5 kg-yr

$\langle m_{\beta\beta} \rangle$ < 160-330 meV @ 90% C.L.

uncertainty of nuclear matrix element

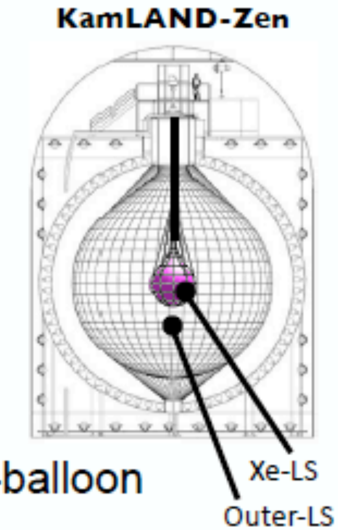
KamLAND-Zen after purification

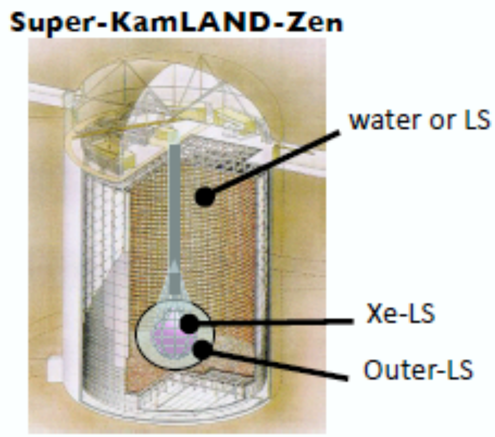
reduction of radioactive backgrounds

KamLAND-Zen 800 kg, high purity mini-balloon

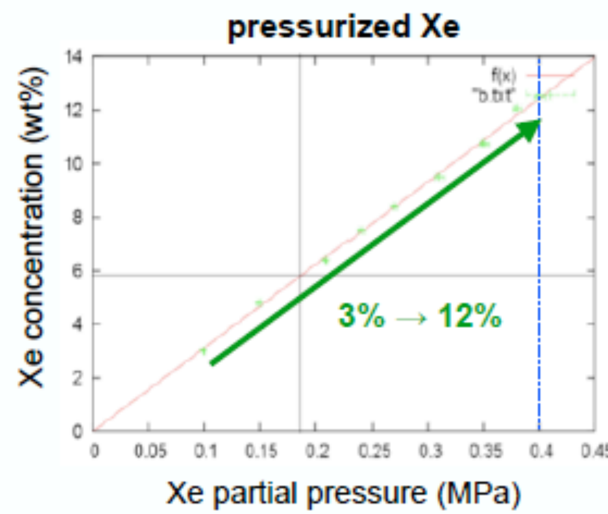
KamLAND2-Zen 1000 kg, high light yield LS

σ_E(2.5MeV) = 4% → 1.8%



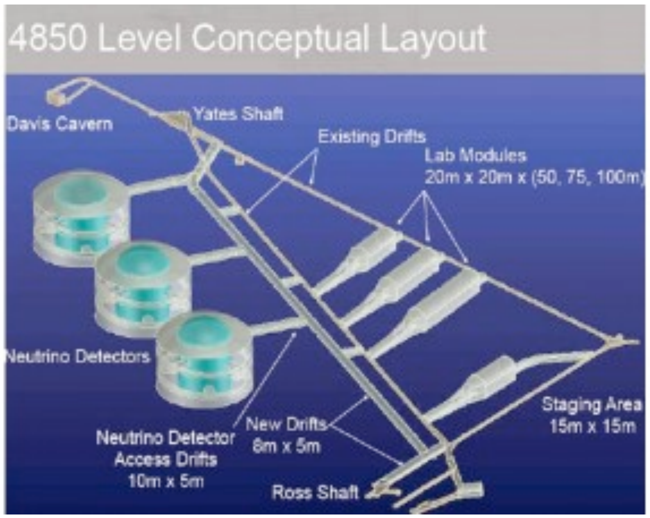


increase decay target nuclei by pressurized Xe

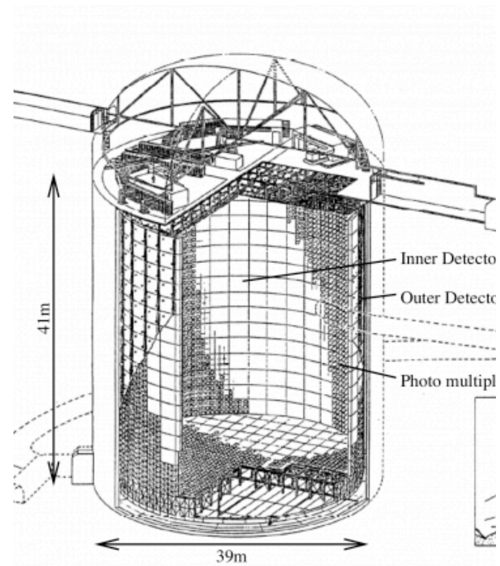


4 times at 30 m depth

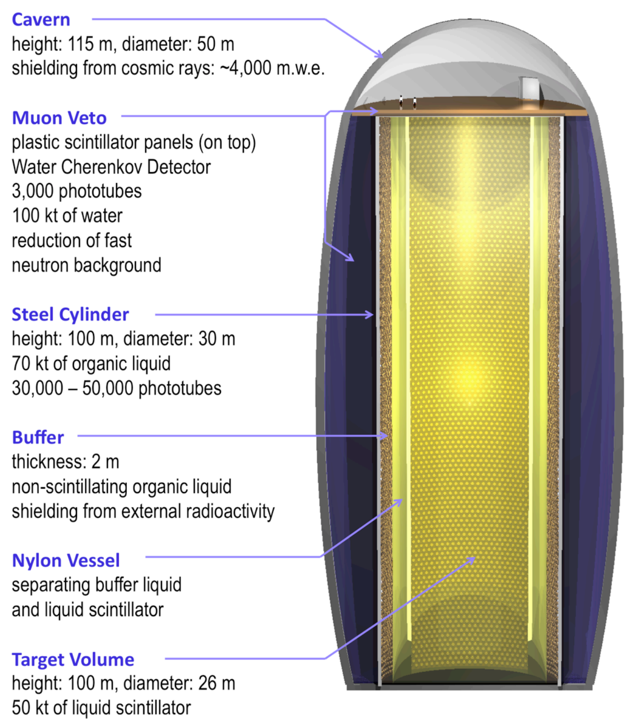
Dream Big!



4850 Level Conceptual Layout
Davis Cavern
Yates Shaft
Existing Drifts
Lab Modules
20m x 20m x (50, 75, 100m)
Neutrino Detectors
Staging Area
15m x 15m
New Drifts
8m x 5m
Neutrino Detector
Access Drifts
10m x 5m
Ross Shaft

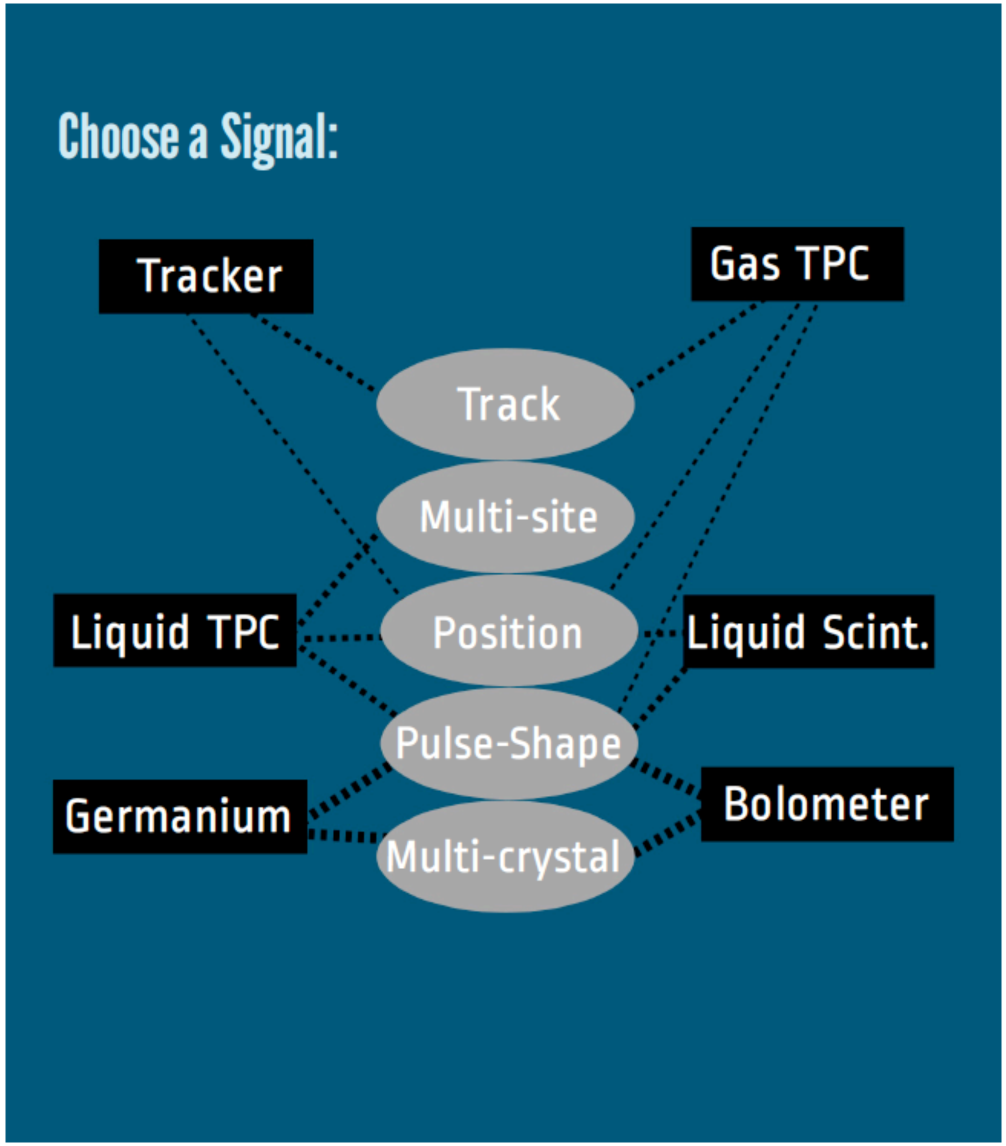


Inner Detecto
Outer Detecto
Photo multipl
41m
39m



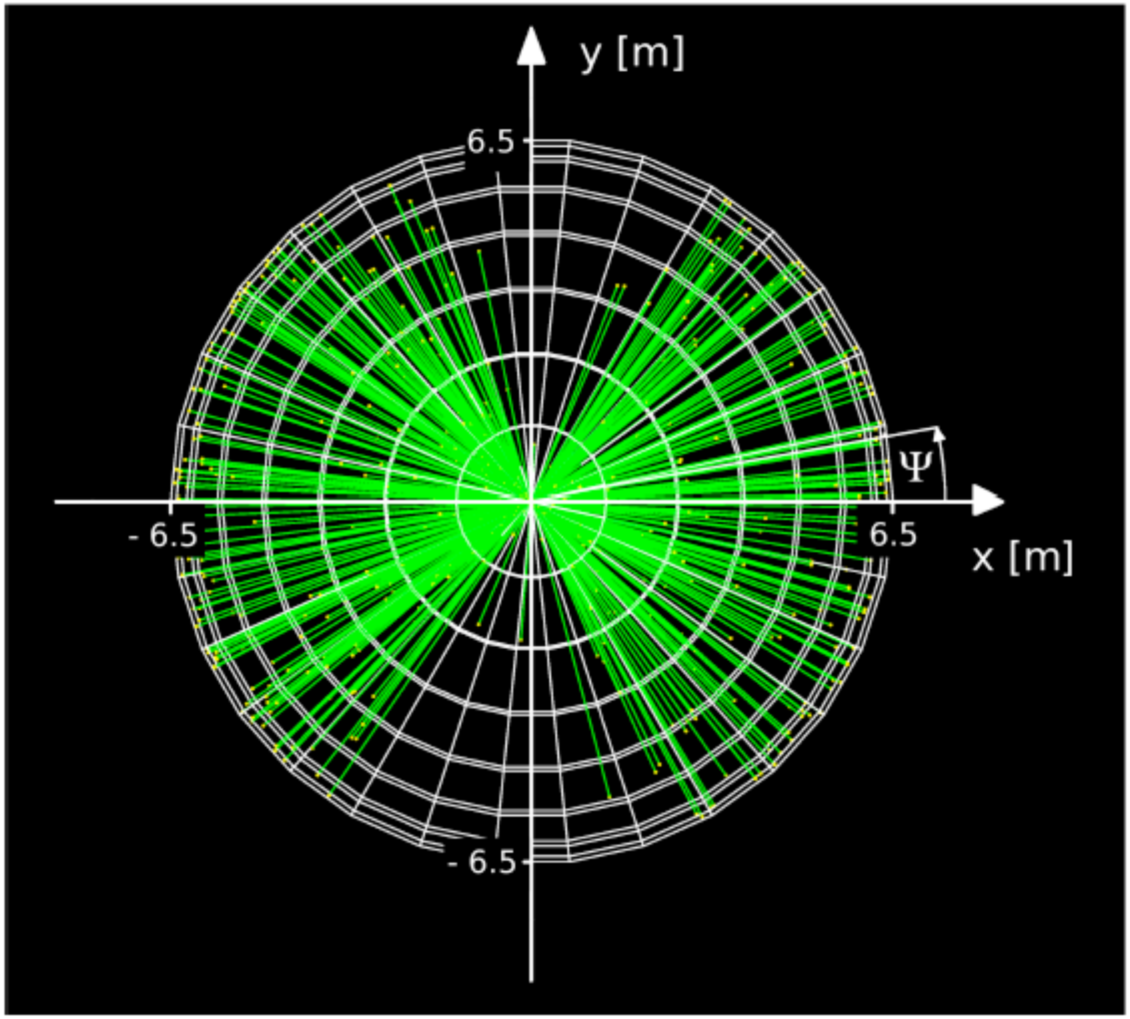
Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w.e.
Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
3,000 phototubes
100 kt of water
reduction of fast
neutron background
Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
30,000 – 50,000 phototubes
Buffer
thickness: 2 m
non-scintillating organic liquid
shielding from external radioactivity
Nylon Vessel
separating buffer liquid
and liquid scintillator
Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

We really need another signal!



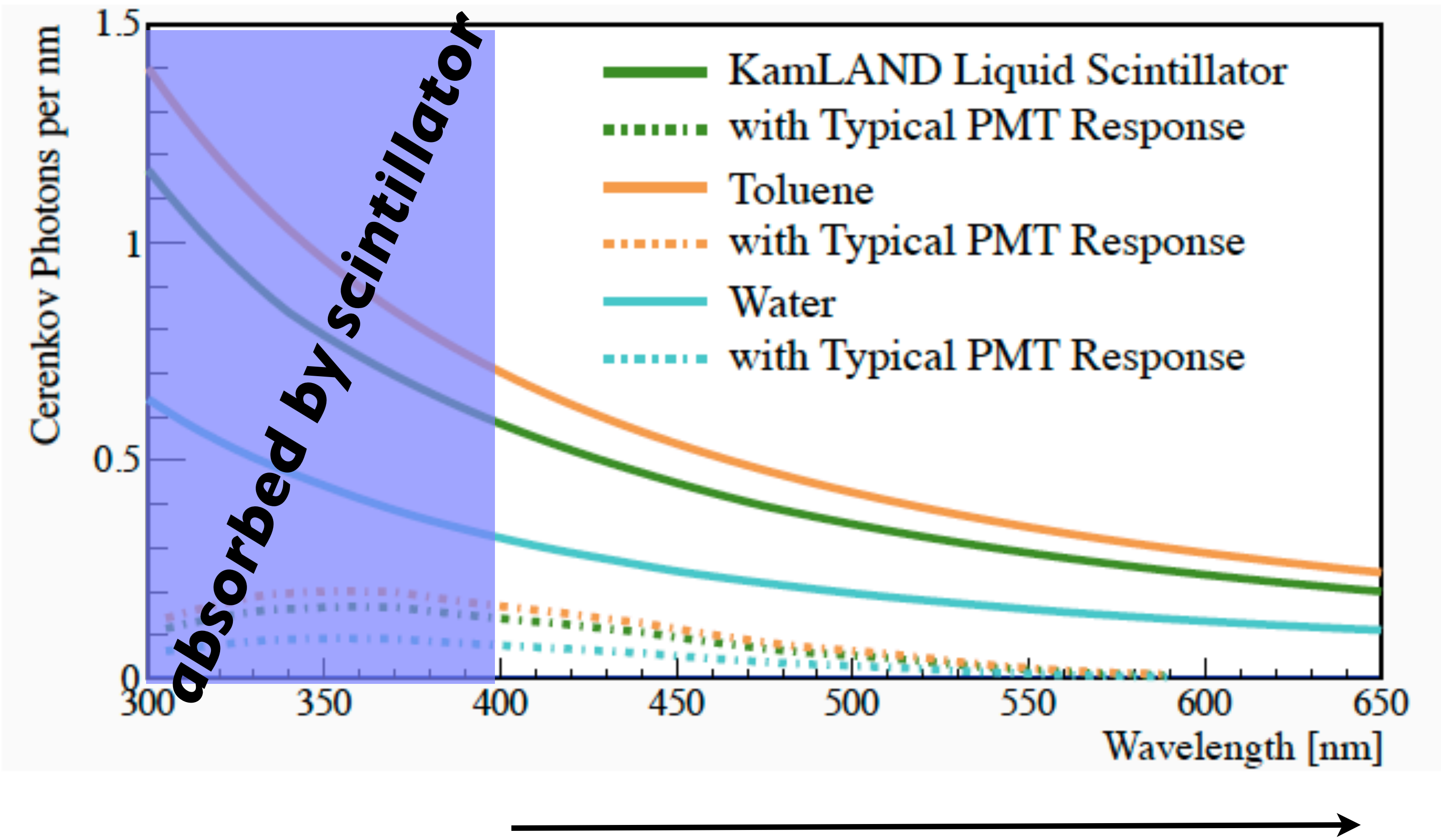
How about tracking?

Neutrinoless Double Beta Decay (Cherenkov Only)



The Cherenkov light is still there...

Number of Cherenkov Photons for a 1MeV e-

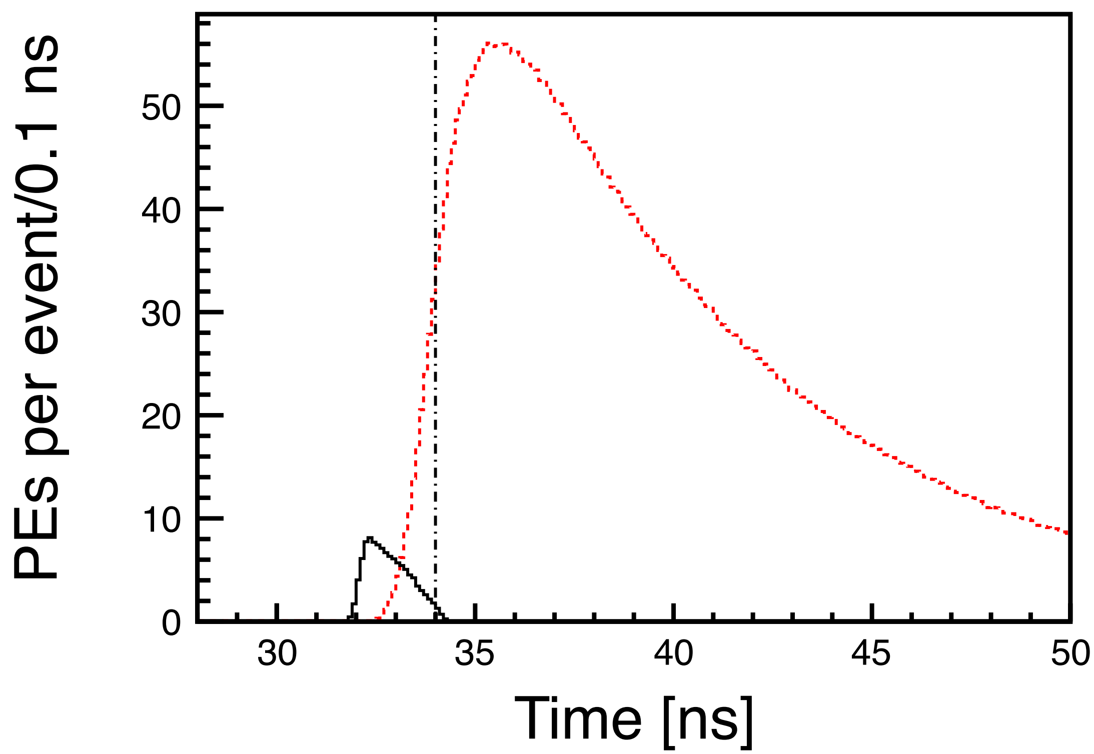


Retains directional information!

Longer wavelengths travel faster and scintillation processes have inherent time constants.

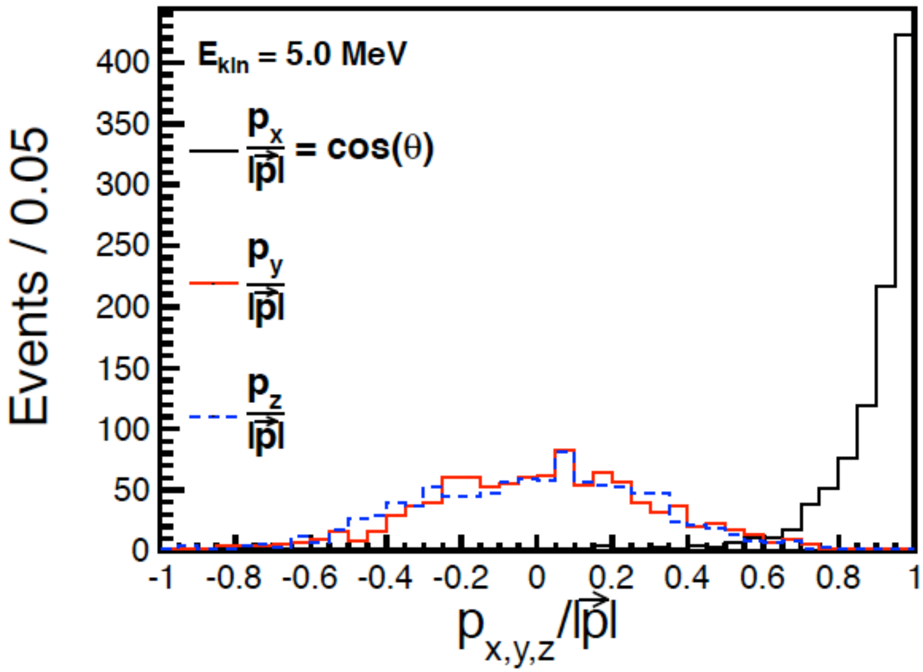
arXiv:1307.5813

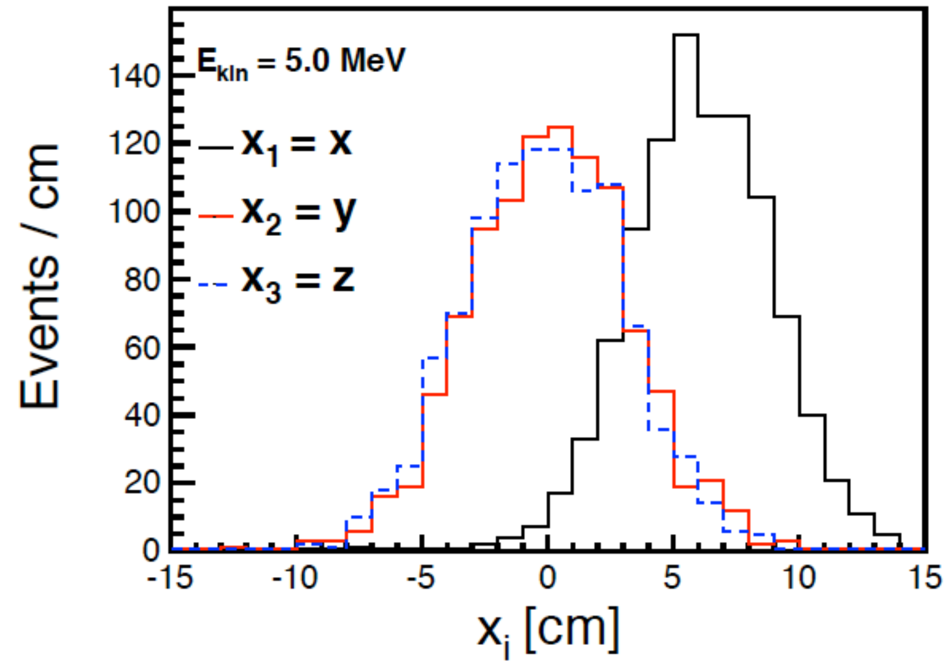
So if you have good enough timing....



you should be able to separate the scarce Cherenkov from the abundant scintillation light.

If we put this timing data into basic reconstruction algorithms (from WCsim)...



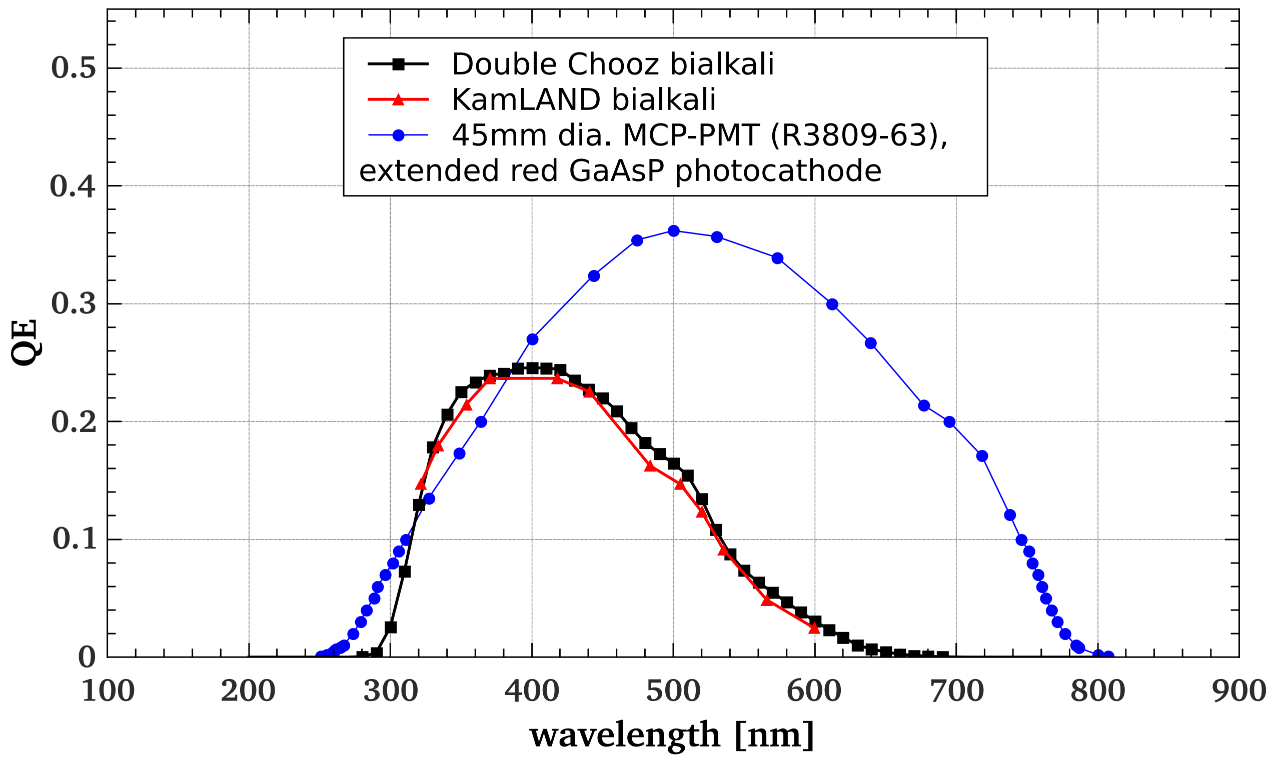


we can reconstruct vertices and **direction** at the center of the detector.

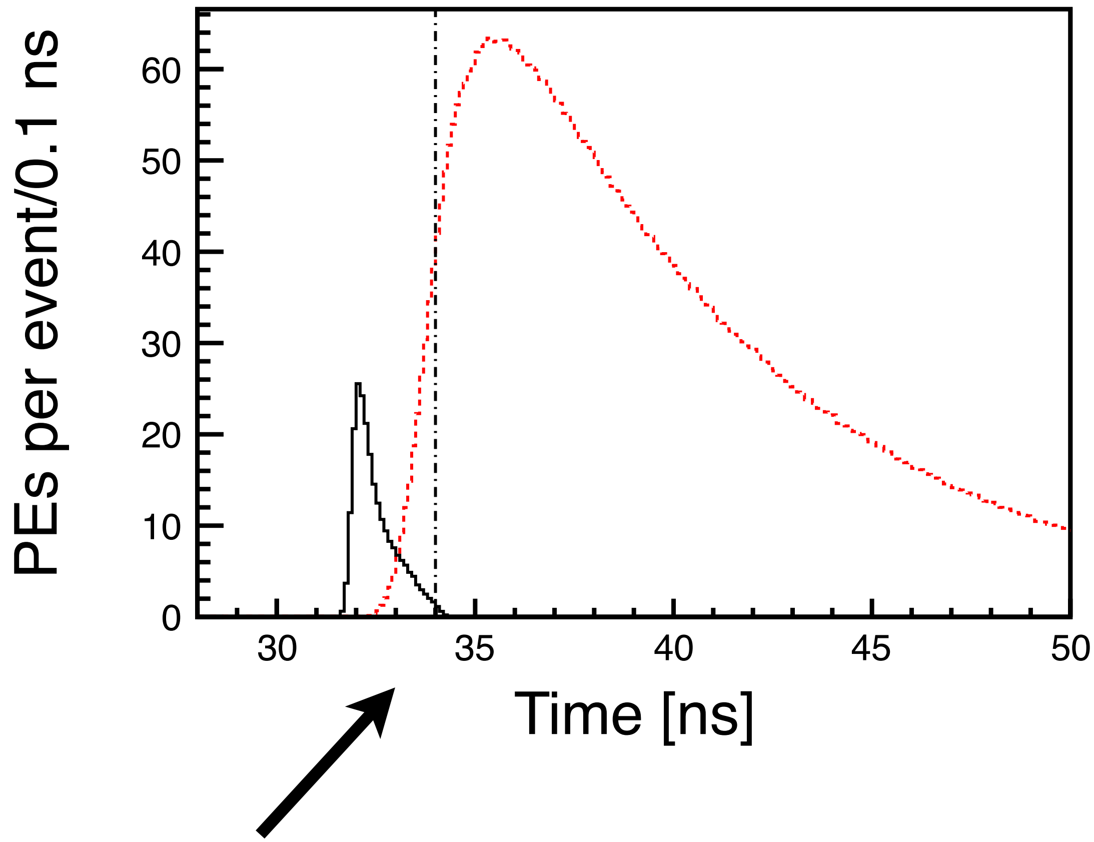
arXiv:1307.5813

The separation needs more red light.

What about a more red sensitive PMT?



This gives beautiful results!

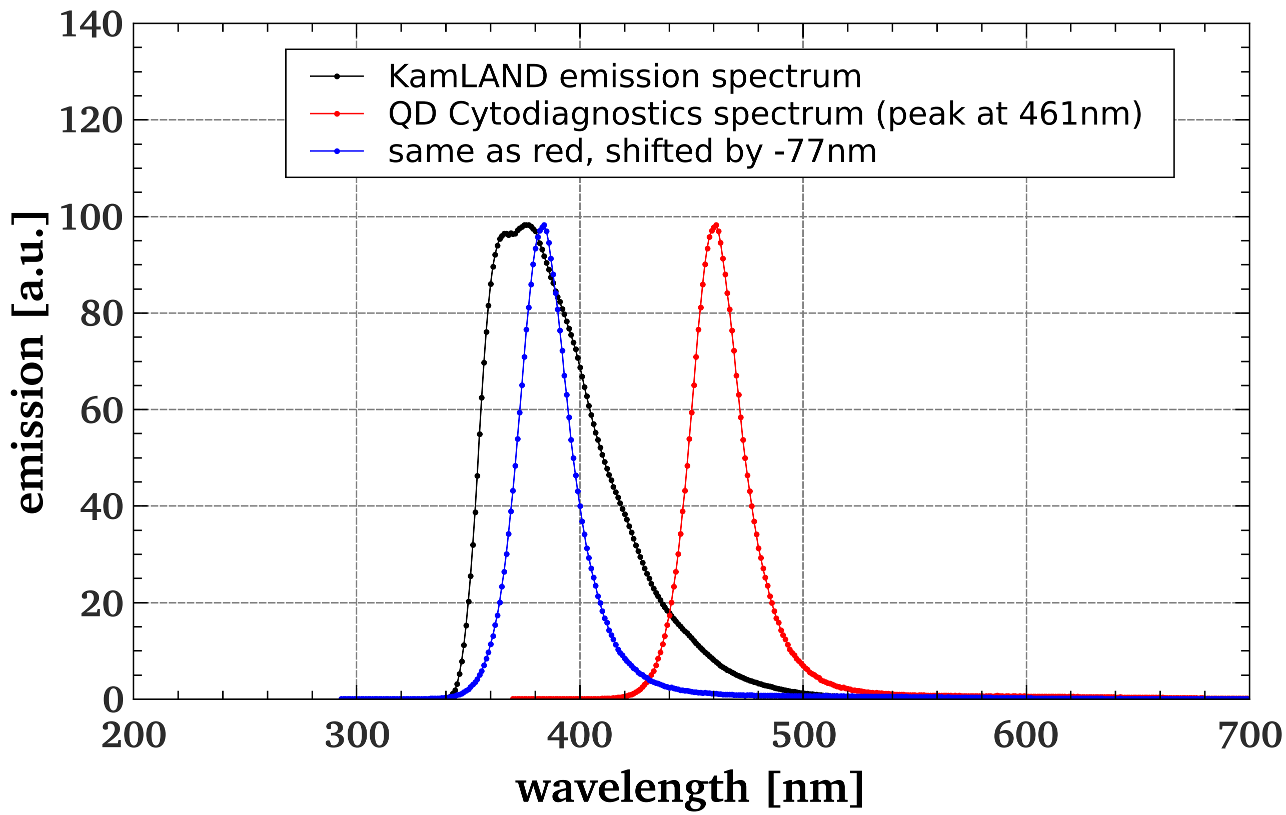


$R_{c/s}$ = 1.01

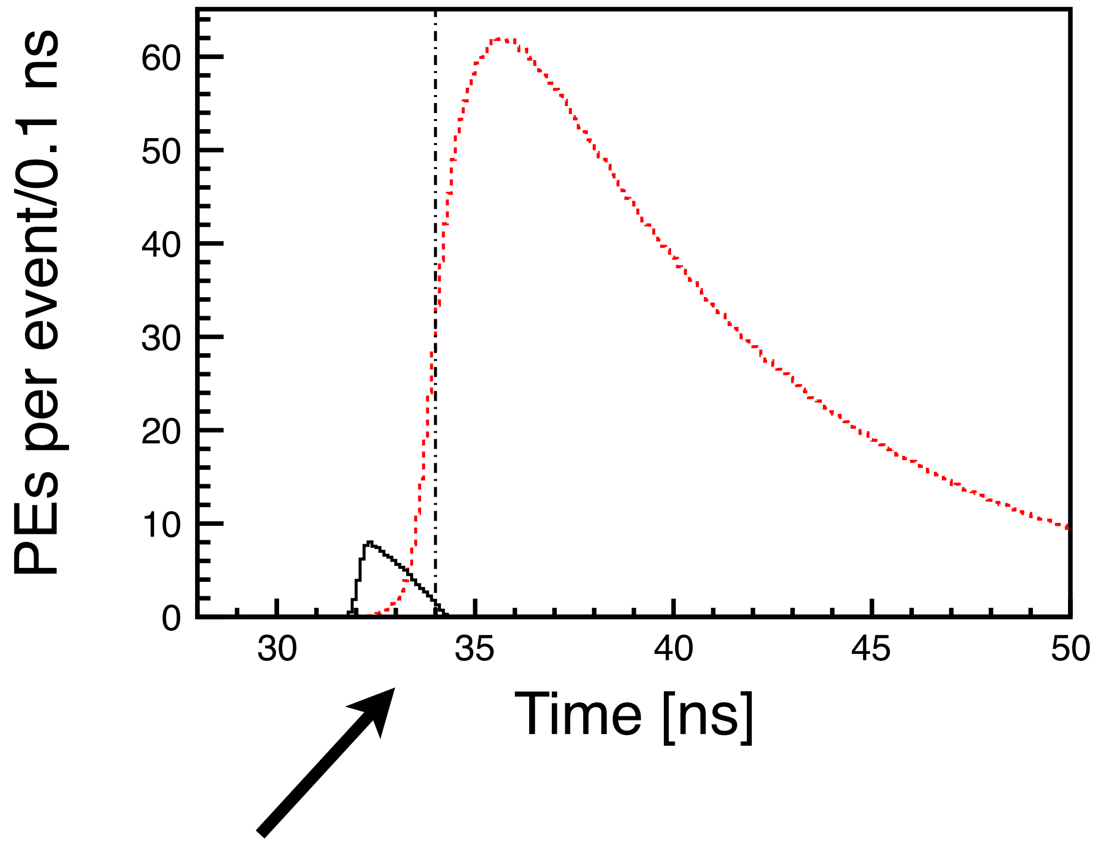
The problem is it is a 1cm diameter PMT...

arXiv:1307.5813

What if I could narrow the emission spectrum?



This is the narrowed emission spectrum with traditional PMTs and 0.1ns timing.



$R_{c/s}$ = 0.86

This is the quantum-dot-doped liquid scintillator.

What are Quantum Dots?

Quantum Dots are semiconducting nanocrystals.

A shell of organic molecules is used to suspend them in an organic solvent (toluene) or water.

Common materials are CdS, CdSe, CdTe...

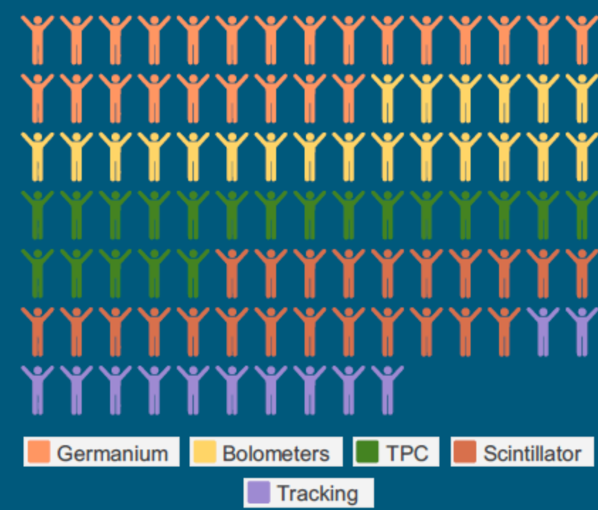
Quantum Dot Materials Overlap with Candidate Isotopes!

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%

More scintillator R&D underway from nanocrystals and quantum dots to water based scintillators with amazing attenuation lengths.

A Worldwide Effort

Approximately 840 physicists!



Underground labs around the world!

The next few years are going to be very exciting as we wait for the first results from several of the Gen1 experiments and R&D for Gen2 ramps up.

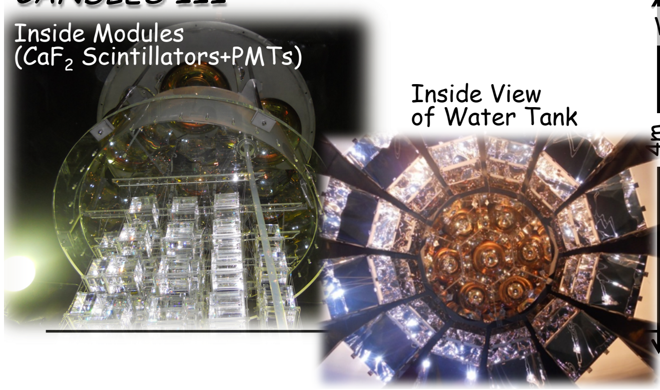
Discovering the Majorana Neutrino

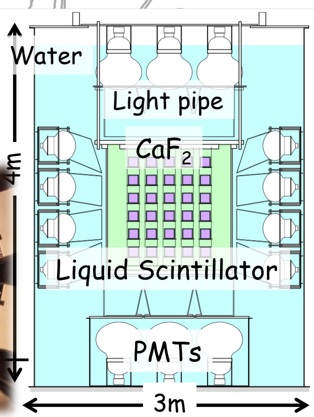
The End

Current Status

- CANDLES III at Kamioka Lab.
  - 96 CaF_2(305kg,0.187%^{48}Ca) + liquid scintillator
  - Installation of light-pipe(light concentration) system in 2012.
  - Upgrade of DAQ system in 2013.

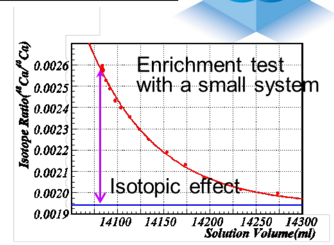
CANDLES III





Future Experiment

- ^{48}Ca enrichment
  - R&D for next CANDLES system
  - Under development
    for a large amount of ^{48}Ca



- CANDLES IV ~
  - ^{48}Ca enrichment
  - Cooling system(~3°C)
    for good energy resolution
- Schedule

	2014	2015	2016	
CANDLES III	Test of Cooling System			Measurement at Kamioka Lab. sensitivity 0.5eV
Next CANDLES				^{48}Ca enrichment Construction of detector . . . not funded yet