The Quest for Neutrino-less Double Beta Decay

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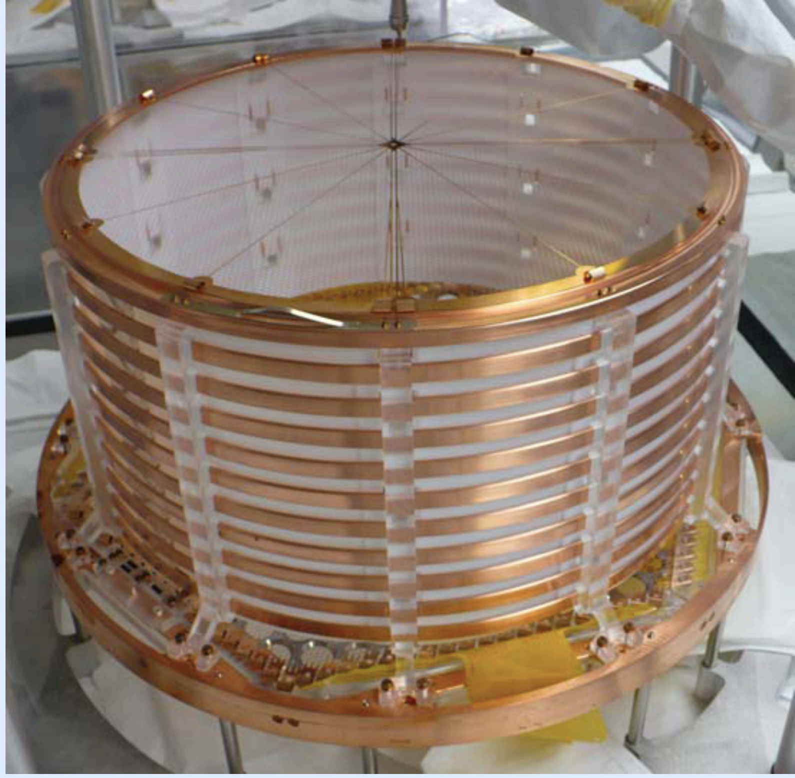
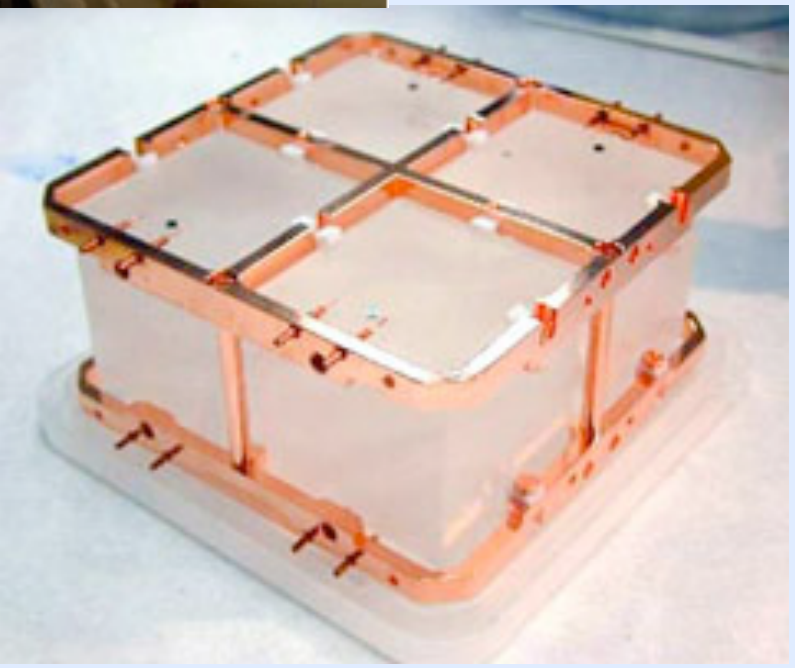
TIPP 2011
2nd International Conference on Technology and Instrumentation in Particle Physics
Chicago, 9-14 June 2011

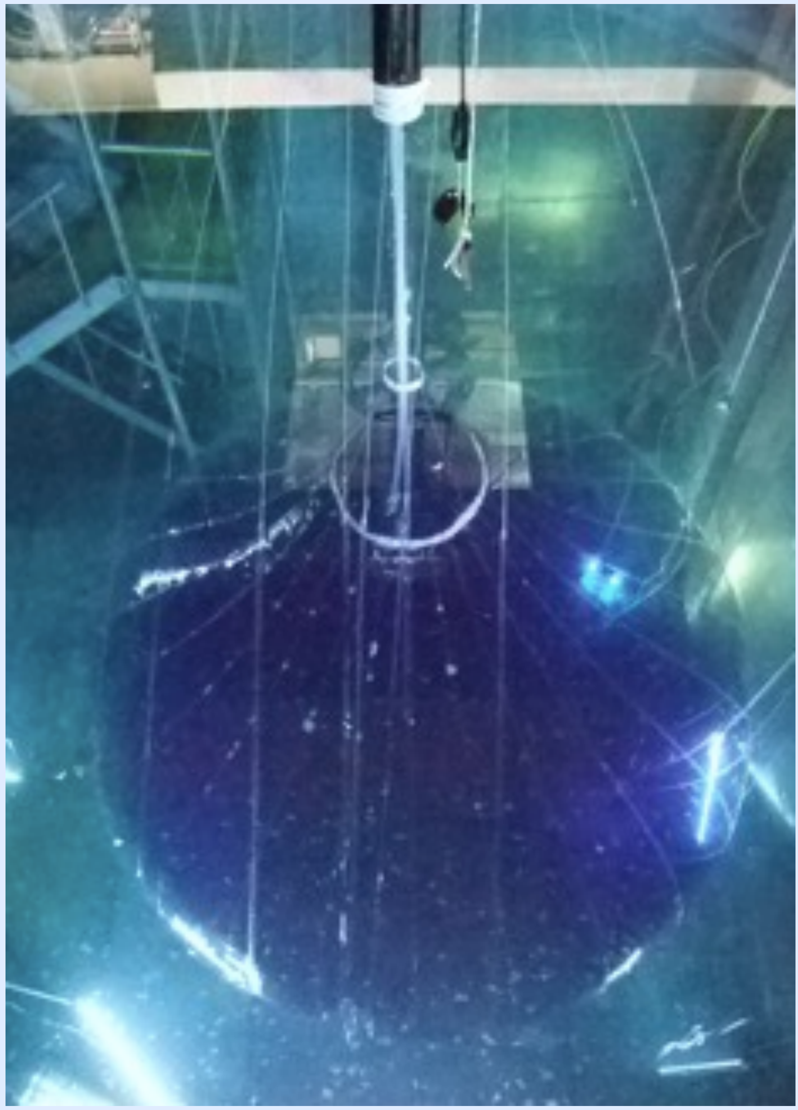


outline

- ***neutrinoless double beta decay***
  - theoretical interest
  - 2ν ββ decay: measured lifetimes
  - experimental status of 0ν ββ decay
  - scientific motivation and goals

- ***detection techniques***
  - common threads and challenges
  - specific experimental approaches

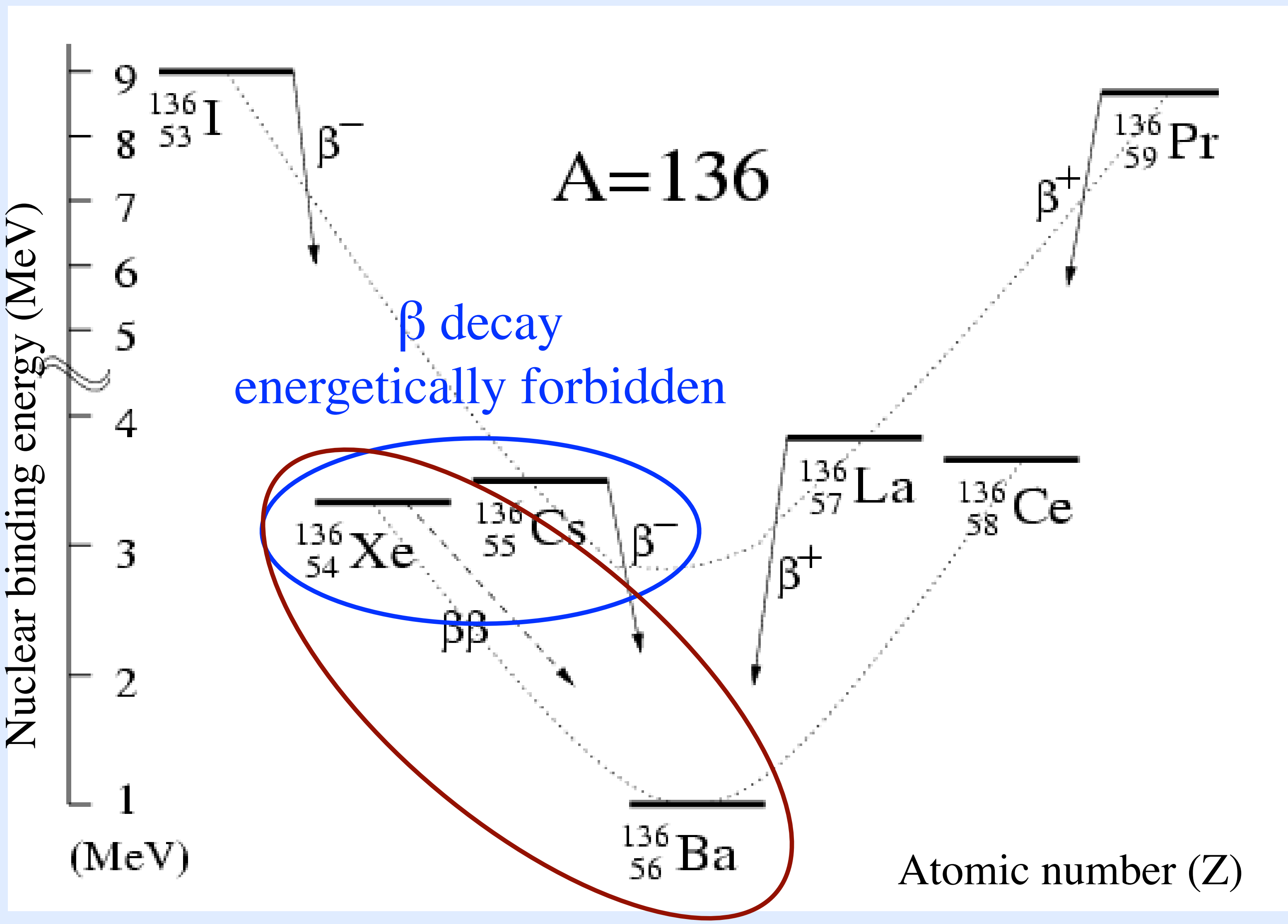


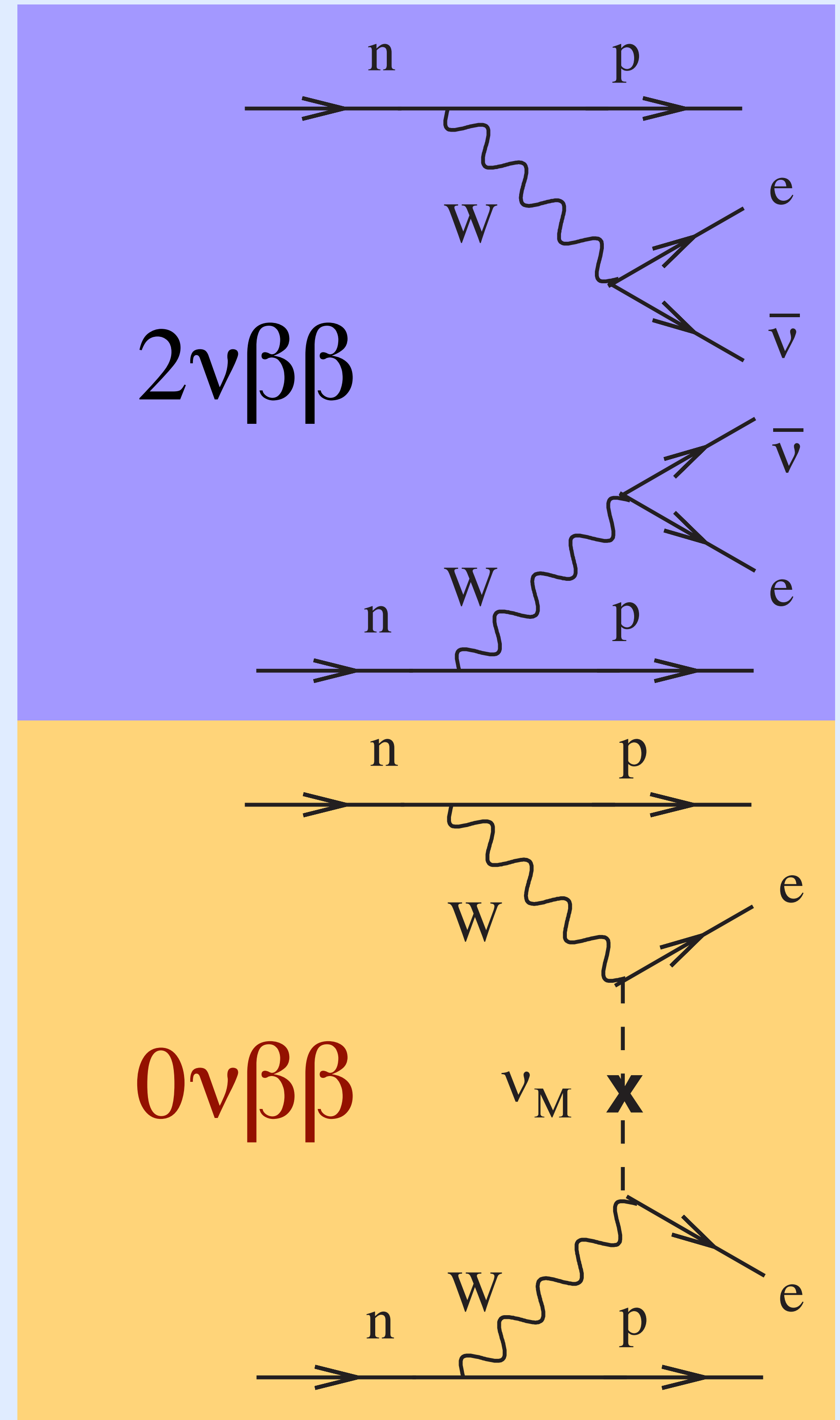


- ***experiments***
  (broad-brush and personal overview)
  - current status
  - near and far future

double beta decay

- second order weak process
- predicted in 1935 by Göppert-Meyer after Wigner's suggestion (~10^{17} years!)





possibility of non-standard 0νββ process

measured quantity: decay rate

nuclear matrix element
(calculated within particular nuclear models)

directly measured quantity

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

calculable phase space factor

(in case of a light neutrino exchange)

Majorana neutrino mass (coherent superposition, can be zero with unlucky cancellations)

$$\langle m_{\beta\beta}\rangle^2 = \left|\sum_i^N |U_{ei}|^2 e^{i\alpha_i} m_i\right|^2 \quad (\text{all } m_i \geqslant 0)$$

In kinematic searches of neutrino mass in β-decay:

$$\langle m_\beta\rangle^2 = \Sigma_i |U_{ei}|^2 m_i^2 > 0$$

(a positive definite quantity)

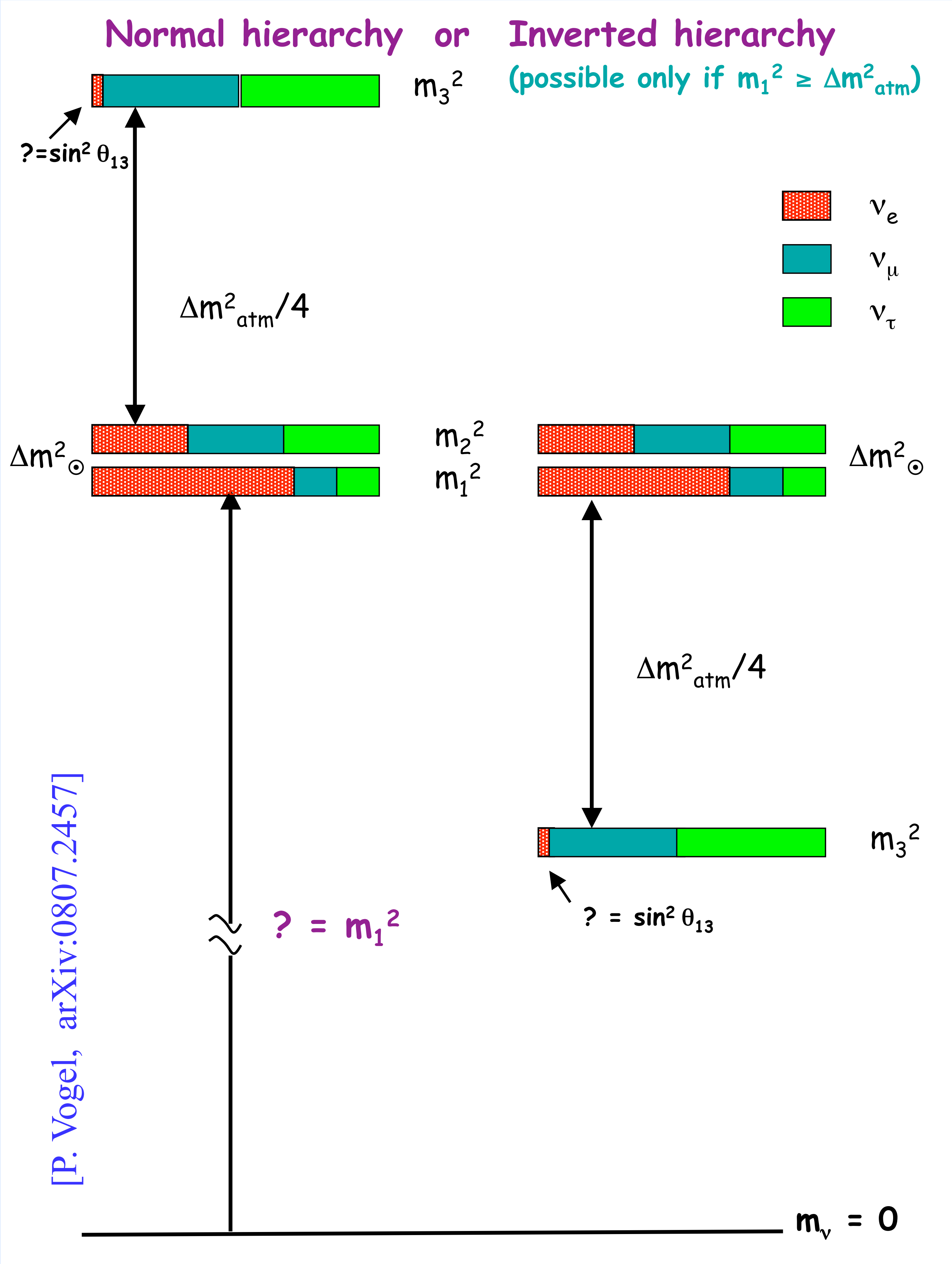
neutrino masses

from oscillation experiments:

- solar neutrinos + KamLAND (LMA-MSW): $\Delta m^2_{12} \sim 8\times10^{-5}$ eV^2, $\tan^2\theta_{12} \sim 0.4$
- atmospheric neutrinos + K2K/MINOS: $\Delta m^2_{23} \sim 3\times10^{-3}$ eV^2, $\sin^2 2\theta_{23} > 0.9$
- Chooz / Palo Verde: $\sin^2 2\theta_{13} < 0.2$

- only mass differences are measured

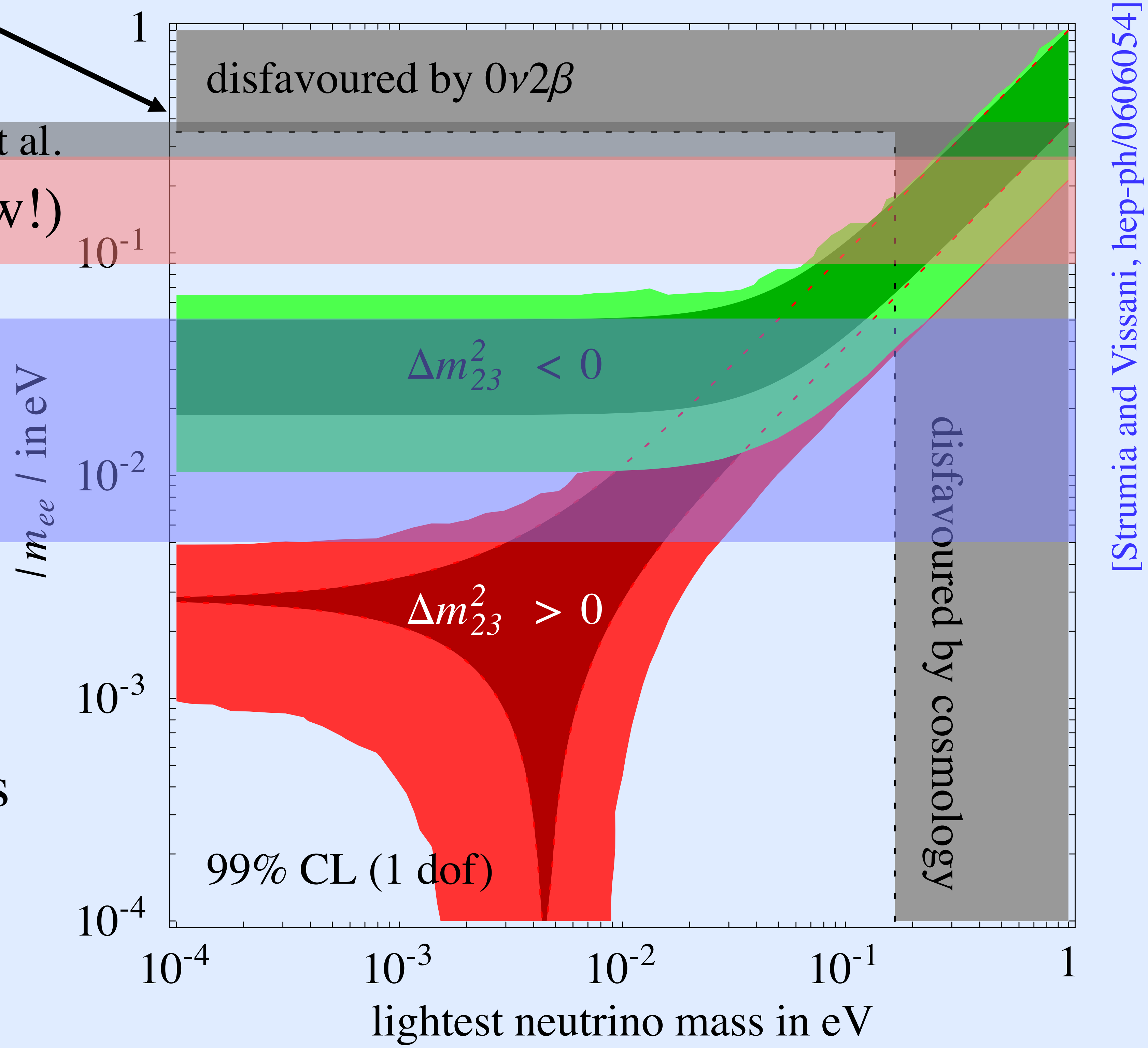
- at least one neutrino has a mass of ~50 meV



0νββ and neutrino masses

~ 10 kg experiments

from neutrino oscillations:



~ 100 kg experiments (now!)

~ ton experiments

m_{eff} ~ 50 meV: ~ 10^{27} years

(10^{27} nuclei ~ 10^3 moles ~ 100 kg)

so, why study 0νββ decay?

its observation is directly associated with the discovery of:

- lepton number violation
- Majorana particles (neutrinos)

and enables us to:

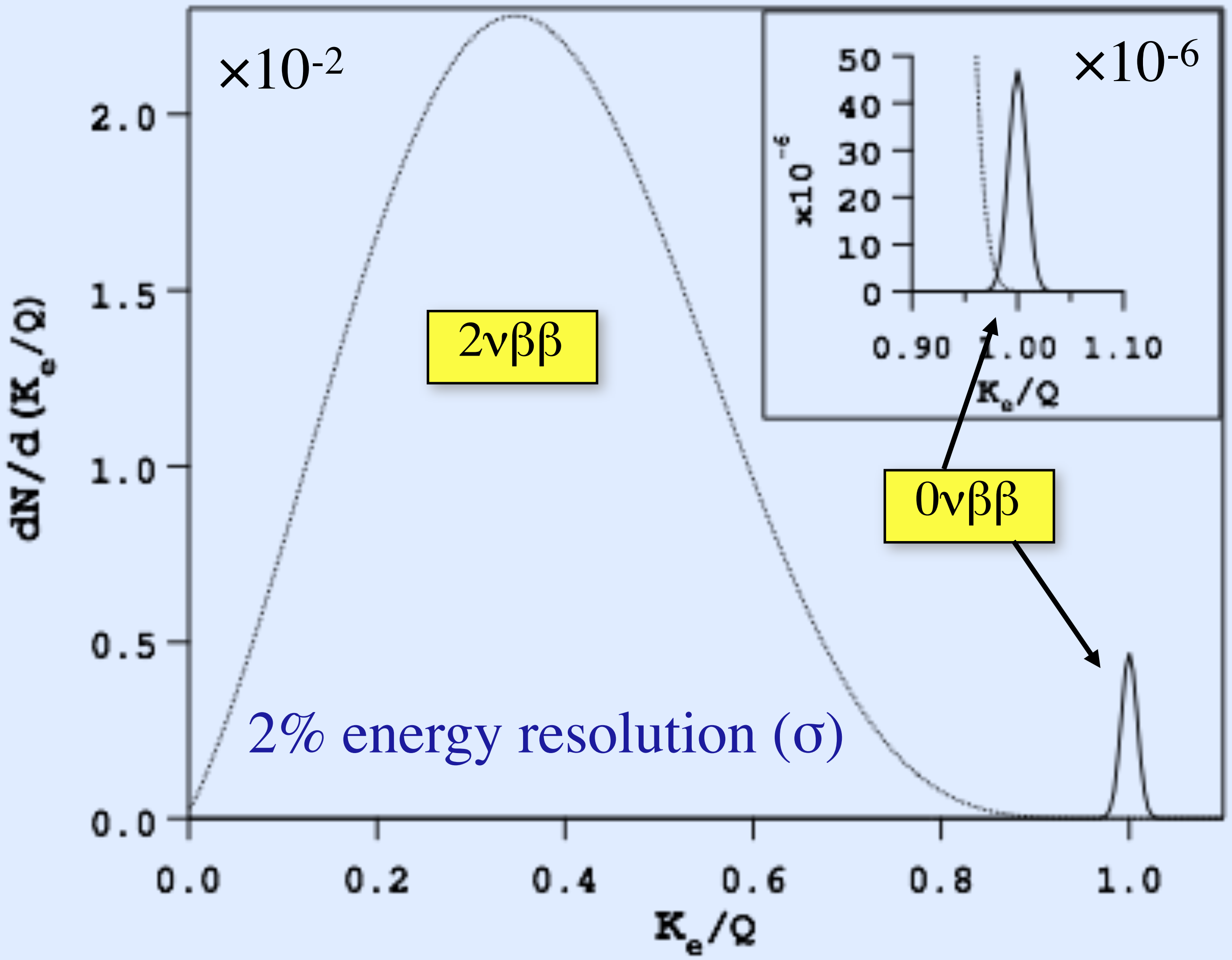
- measure the absolute mass scale of neutrinos
- shed light on the matter/antimatter asymmetry (?)

how is 0νββ measured in the laboratory?

- very rare events: need to suppress non-ββ background with low radioactivity detectors (γ's in particular)

- large mass: large source, isotope enrichment

- energy resolution: separate 0νββ mono-energetic peak in the 2-electron energy spectrum and fewer non-ββ background events in the peak



[P. Vogel, arXiv:hep-ph/0611243]

- tracking: identify individual electron tracks to discriminate between single- and 2-electron events (discrimination of β and γ background radiation)

- multi-isotope: measure different isotopes with the same detector to cross-check results and reduce systematic and theoretical uncertainties

- decay product identification: unambiguously from ββ events

ββ decay candidate isotopes

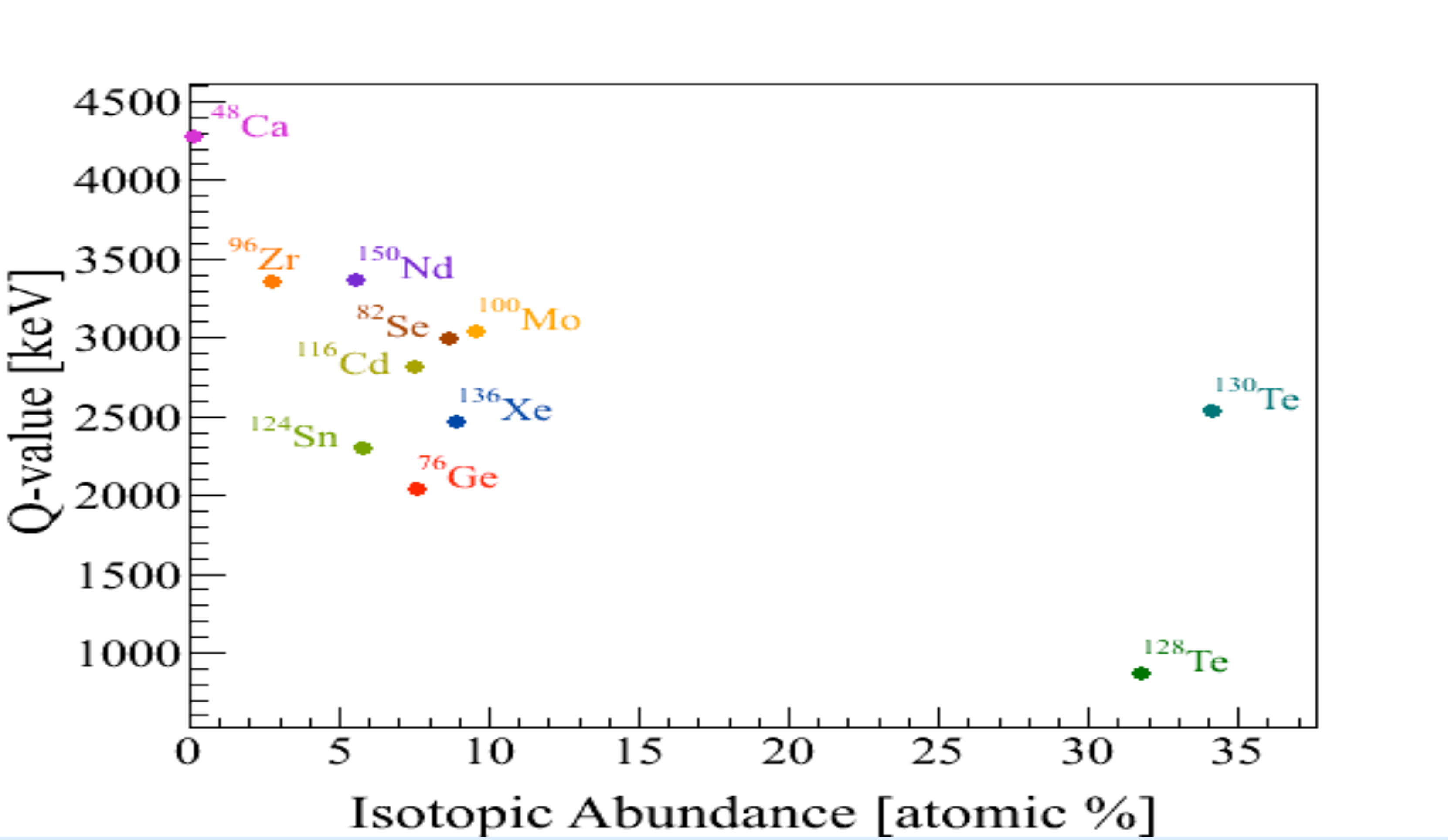
Candidate	Q (MeV)	Isot. ab. (%)	$T_{1/2}^{2\nu}$ (10^{21} y)	$T_{1/2}^{0\nu}$ (10^{21} y)	$\langle m_\nu \rangle$ (eV)	Detection technique (active exposure to date)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.19	0.043	> 14	< 7.2-44.7	Ge counting / crystal scintillator
$^{76}Ge \rightarrow ^{76}Se$	2.039	7.8	1.74	> 19000 ★	< 0.33-1.35	enriched HPGe (72 kg y)
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2	0.96	> 210	< 1.2-3.2	plastic scintillator, foil source (1 kg y)
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8	0.21	> 1.0		plastic scintillator, foil source
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6	0.07	> 580	< 0.6-2.7	plastic scintillator, foil source (7 kg y)
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5	0.29	> 170	< 1.7	crystal scintillator
$^{128}Te \rightarrow ^{128}Xe$	0.868	31.7		> 7700	< 1.1-1.5	geochemical
$^{130}Te \rightarrow ^{130}Xe$	2.529	33.8	0.61	> 3000	< 0.41-0.98	bolometers, crystals (11 kg y)
$^{134}Xe \rightarrow ^{134}Ba$	0.838	10.4		> 58		LXe scintillator (1.1 kg y)
$^{136}Xe \rightarrow ^{136}Ba$	2.458	8.9	> 10	> 450	< 0.8-5.6	LXe scintillator (4.5 kg y)
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6	0.0097	> 18	< 4.0-6.3	plastic scintillator, foil source
$^{160}Gd \rightarrow ^{160}Dy$	0.858	21.9		> 1.3		crystal scintillator

[Avignone, Elliott, Engel, Rev. Mod. Phys. 80 (2008) 481; arXiv:0810.0248; PDG 2006, J. Phys. G, 33 (2006) 1, Table of isotopes, http://ie.lbl.gov]

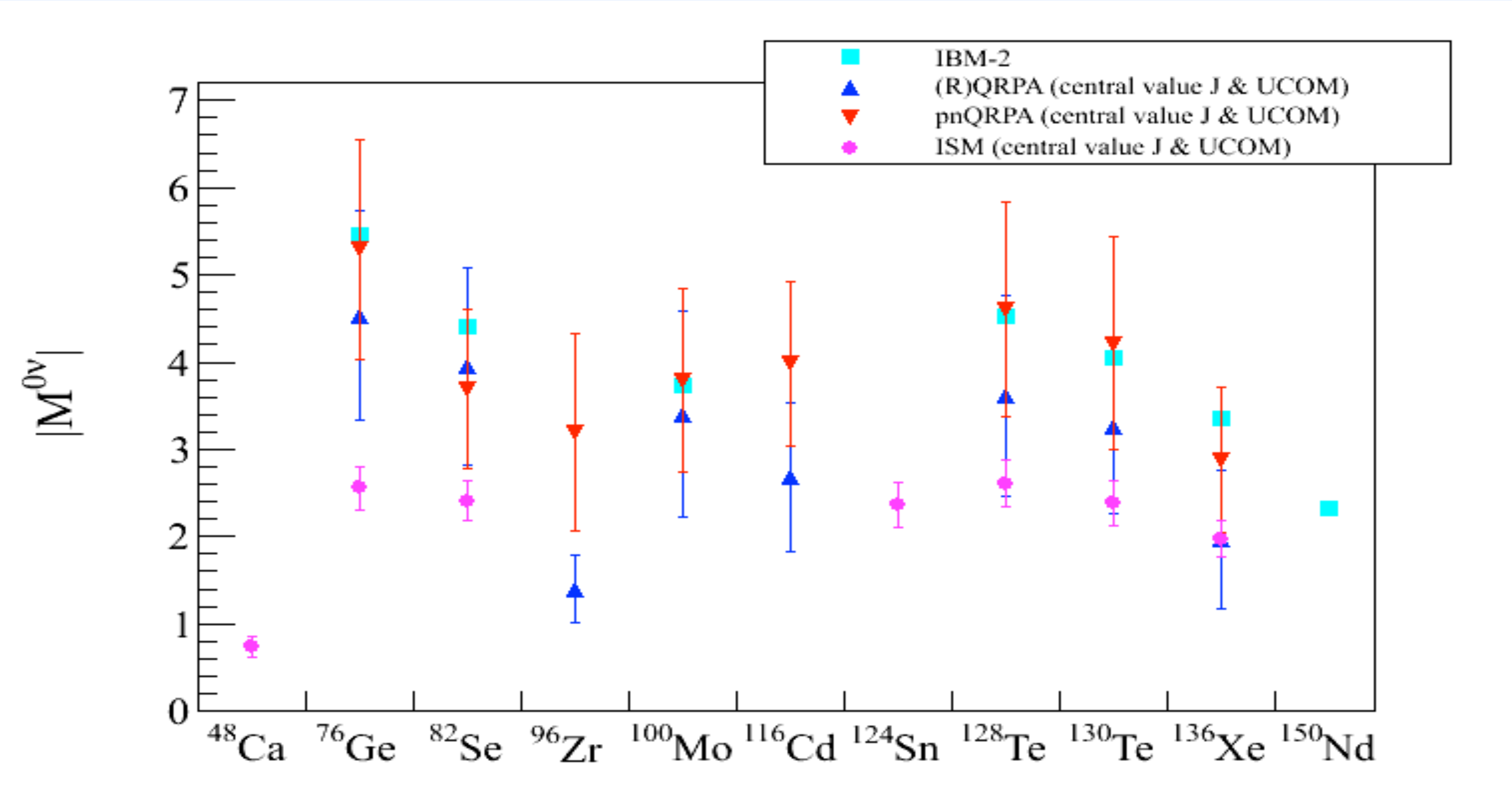
★ positive claim for 0νββ detection [Phys. Lett. B, 586(2004)198]

possibility of looking for decays to excited states and double positron/capture decays

ββ isotope shopping



1. isotopic abundance



2. magnitude of nuclear matrix element

discovery of 0νββ?

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

[Mod. Phys. Lett. A27(2001)2409]

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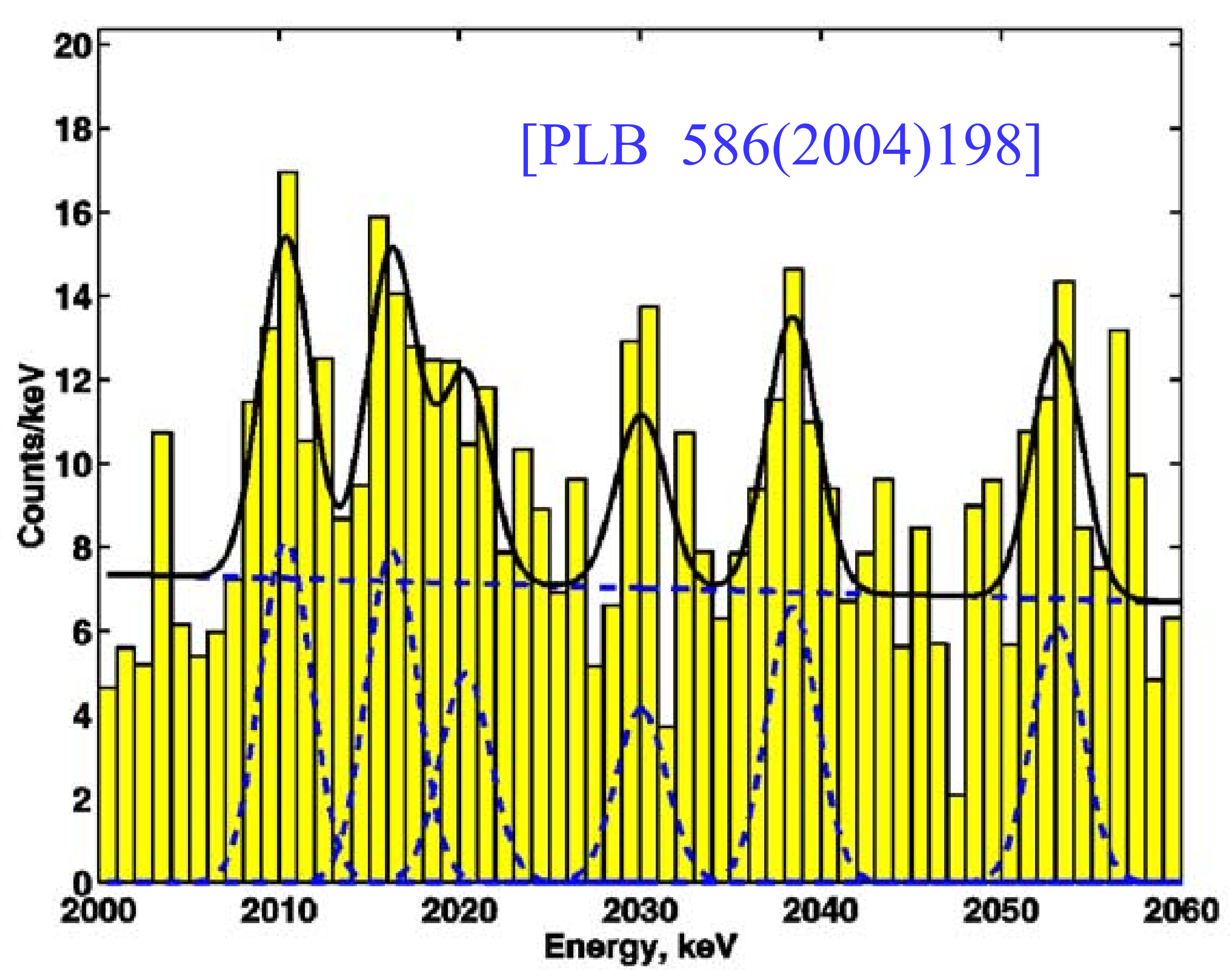
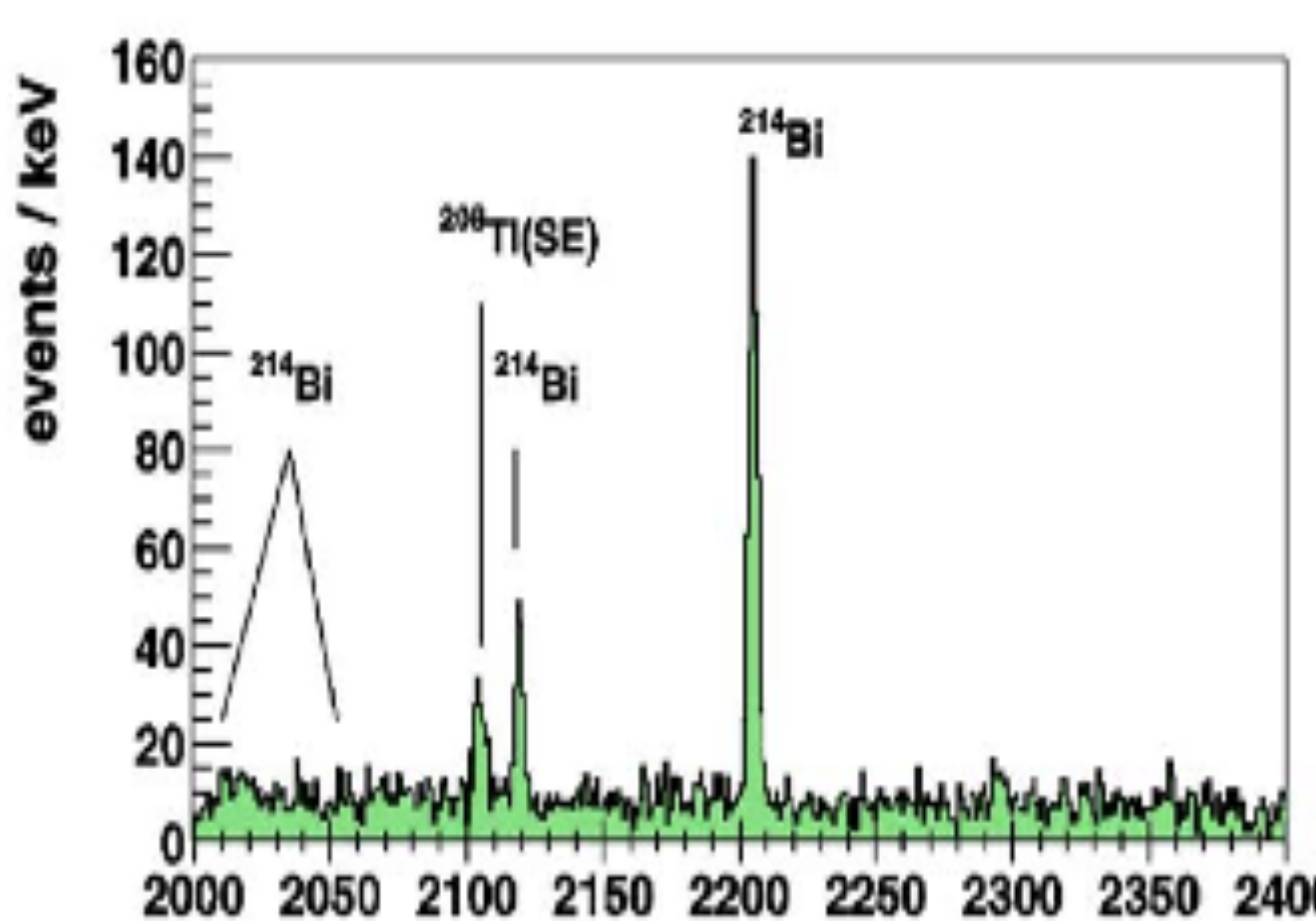


$T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31}\ 10^{25}$ years

$m_\nu^{eff} = 0.32 \pm 0.03$ eV

- enriched (86%) ^{76}Ge crystals
- excellent energy resolution
- if limit: $T_{1/2} > 1.9 \times 10^{25}$ y



controversial issue:

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
H.V.Klapdor-Kleingrouthaus et al. Mod. Phys. Lett. 21 (2006) 1547

current/future experiments (personal view)

Isotope	Experiment	Main principle	Fid mass	Lab
^{76}Ge	Majorana†	E_{res}, 2 site tag ultra low bg Cu shield	30+30kg	Homestake
	Gerda†	E_{res}, 2 site tag LAr shield/veto	18→40 kg	Gran Sasso
	MaGe/GeMa	see above	~1ton	Homestake? Gran Sasso?
^{150}Nd	SNO+	size+shielding	56 kg	SNOlab
^{150}Nd or ^{82}Se	SuperNEMO‡	Tracking	100-200 kg	Canfranc Frejus
^{130}Te*	CUORE	E Res.	204 kg	Gran Sasso
^{136}Xe	EXO NEXT KamLAND-Zen	tracking / size+shielding	150 kg	WIPP/ Canfranc/ Kamioka
		Ba tag, tracking	1-10ton	Homestake/ SnoLab?

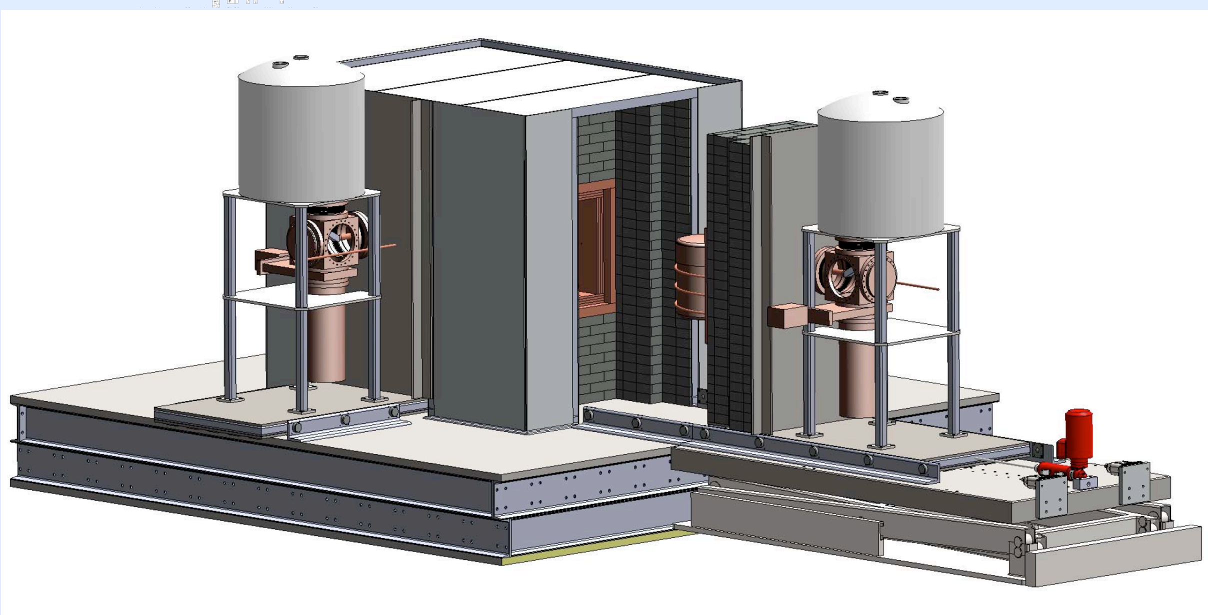
Many other ideas for the future are omitted in the interest of time
* No isotopic enrichment in baseline design
† Plan to merge efforts for ton-scale experiment
‡ Non-homogeneous detector

germanium crystals

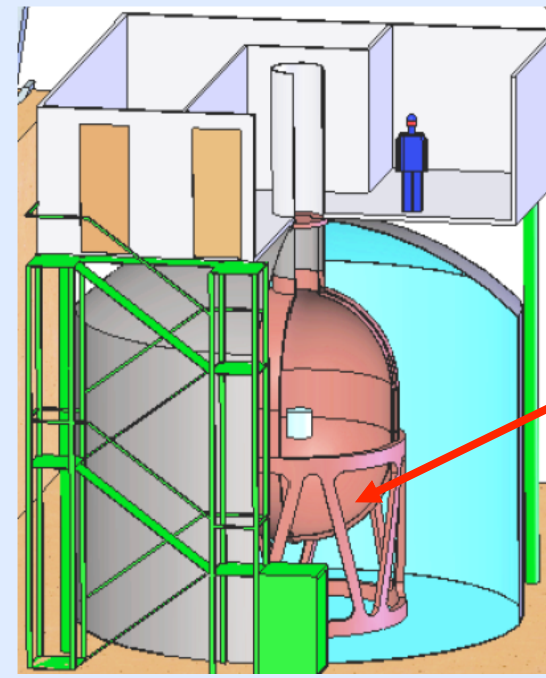
- ✓ proven technology (currently holds best sensitivity)
- ✓ know how to purify (0.1-0.2 counts/kg/y/keV so far)
- ✓ fantastic energy resolution (FWHM ~0.1-0.2%)
- ✓ possibly relatively compact
- ✓ source = detector, high detection efficiency
- ✴ expensive to enrich (but proven)
- ✴ suffers from cosmogenic activation (timing is critical in all stages of crystal production, testing and deployment)
- ✴ few reliable manufacturers worldwide

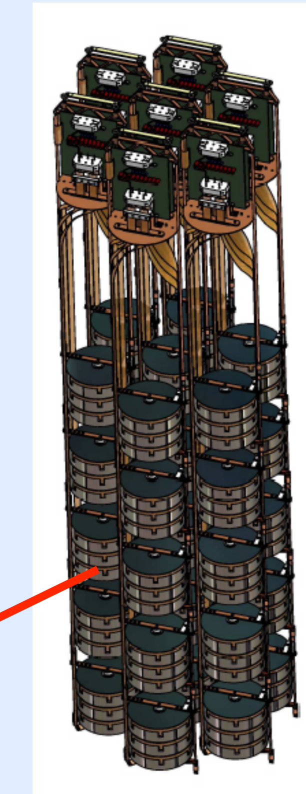
ton-scale germanium experiments

MAJORANA



GERDA





- **Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat**
- **Shield: electroformed copper / lead**
- **Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.)**

- **'Bare' ^{enr}Ge array in liquid argon**
- **Shield: high-purity liquid Argon / H_2O**
- **Phase I (2011): ~18 kg (HdM/IGEX diodes)**
- **Phase II (2012): add ~20 kg new detectors - Total ~40 kg**

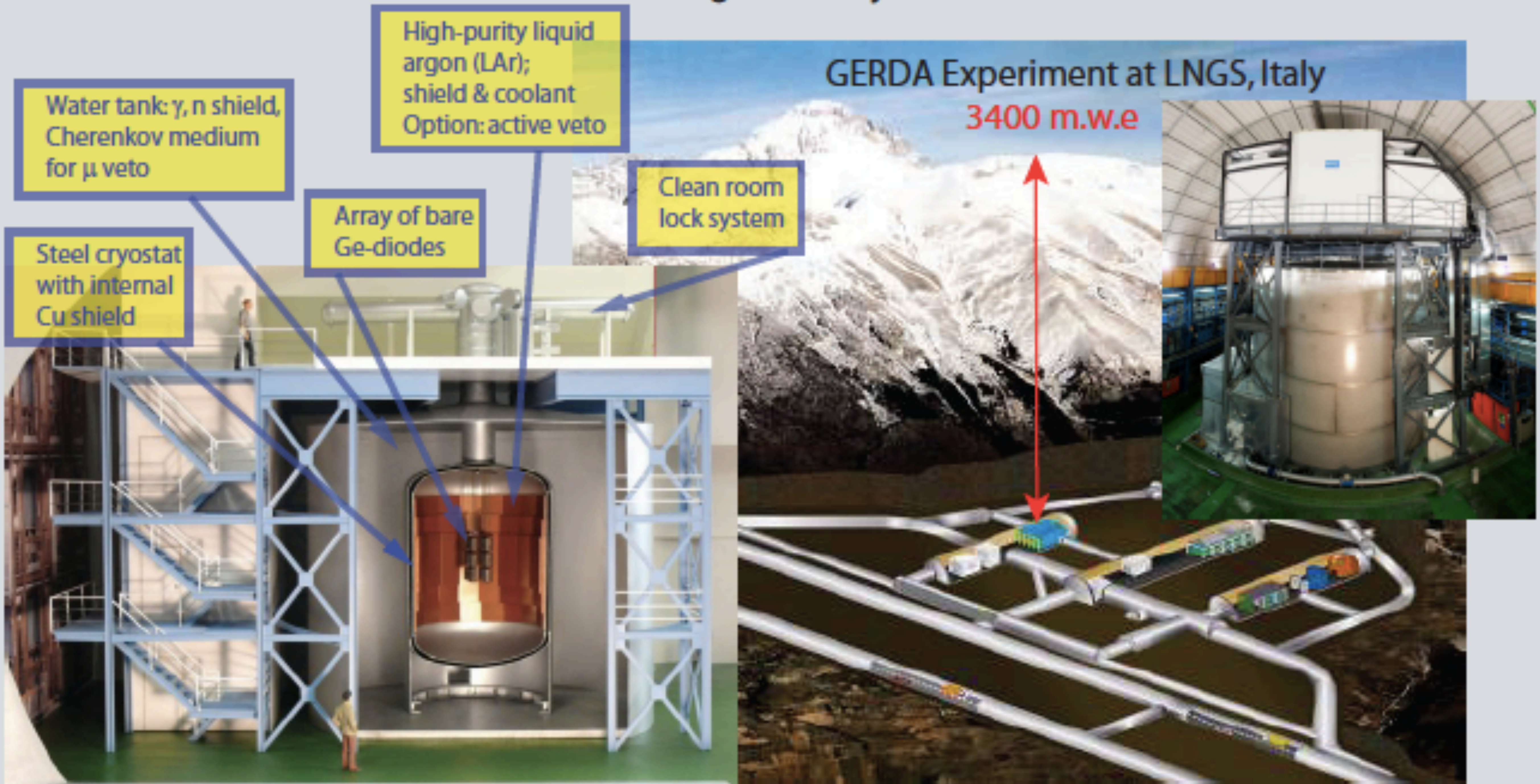
Joint Cooperative Agreement:

- **Open exchange of knowledge & technologies (e.g. MaGe, R&D)**
- **Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA**

courtesy of Steve Elliott

GERmanium Detector Array - GERDA

Deep underground site for suppression of cosmic ray muons
Graded shielding against ambient radiation
Rigorous material selection
Signal Analysis



from Chris O'Shaughnessy @ SLAC 2011

GERDA @ Gran Sasso

- **Nov/Dec.'09**: Liquid argon fill
- **Jan '10:** Commissioning of cryogenic system
- **Apr/Mai '10:** emergency drainage tests of water tank
- **Apr/Mai '10:** Installation c-lock
- **May '10:** 1st deployment of FE&detector mock-up (27 pF) - pulser resolution 1.4 keV (FWHM); first deployment of non-enriched detector
- **June '10:** Start of commissioning run with ^{nat}Ge detector string
- **Soon**: start of Phase I physics data taking

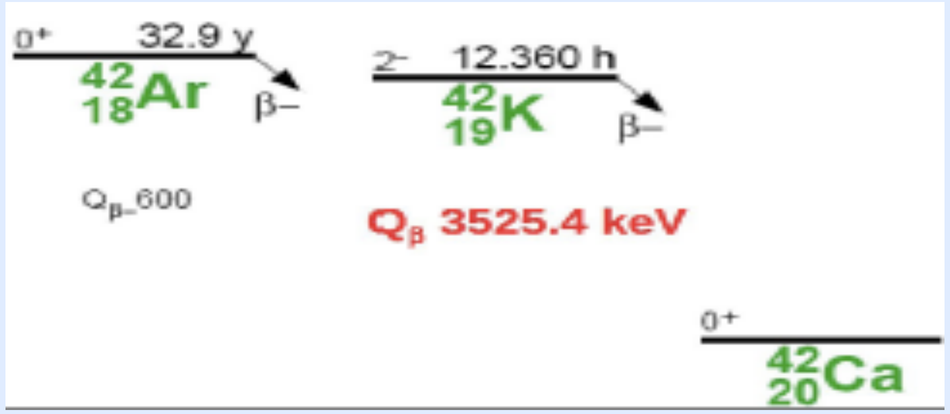
nat-Ge crystals from Genius test facility

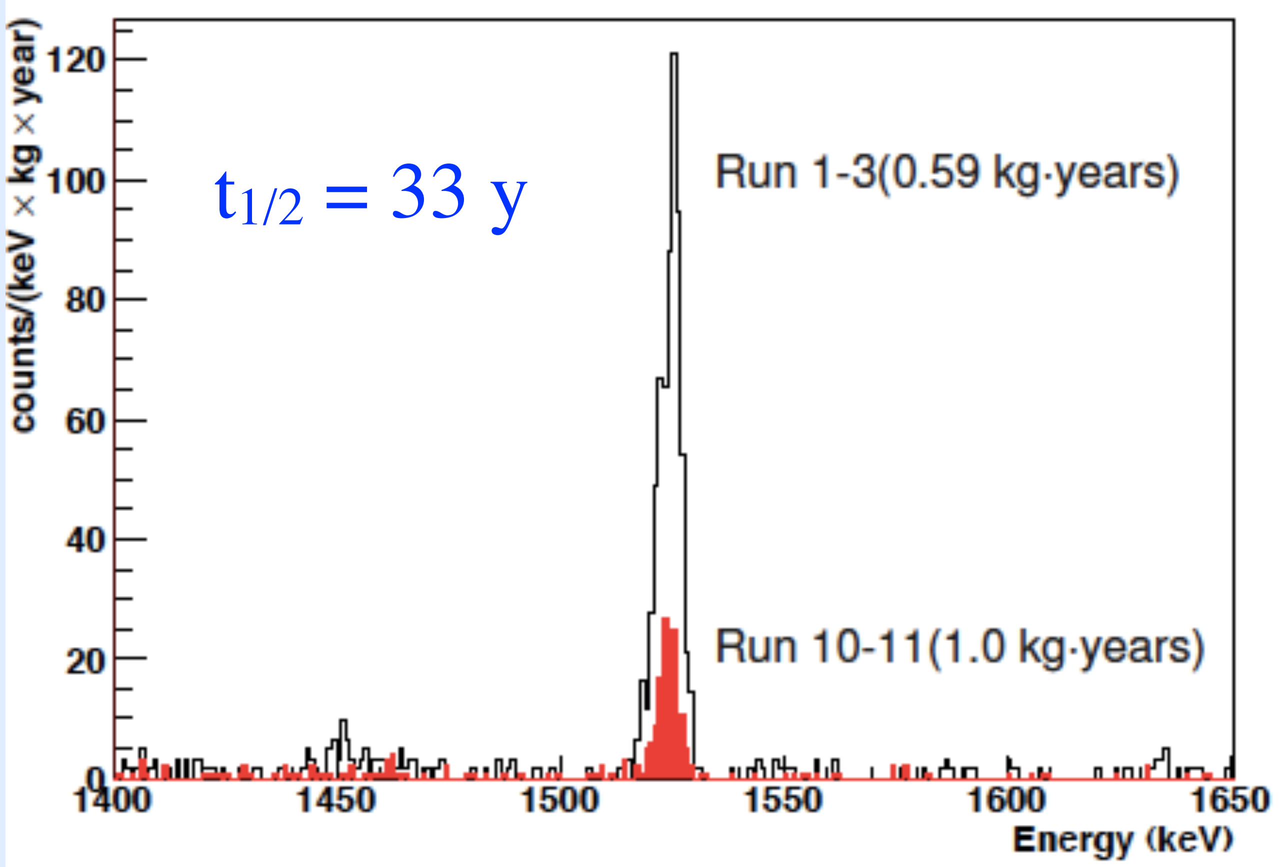
from Chris O'Shaughnessy @ SLAC 2011

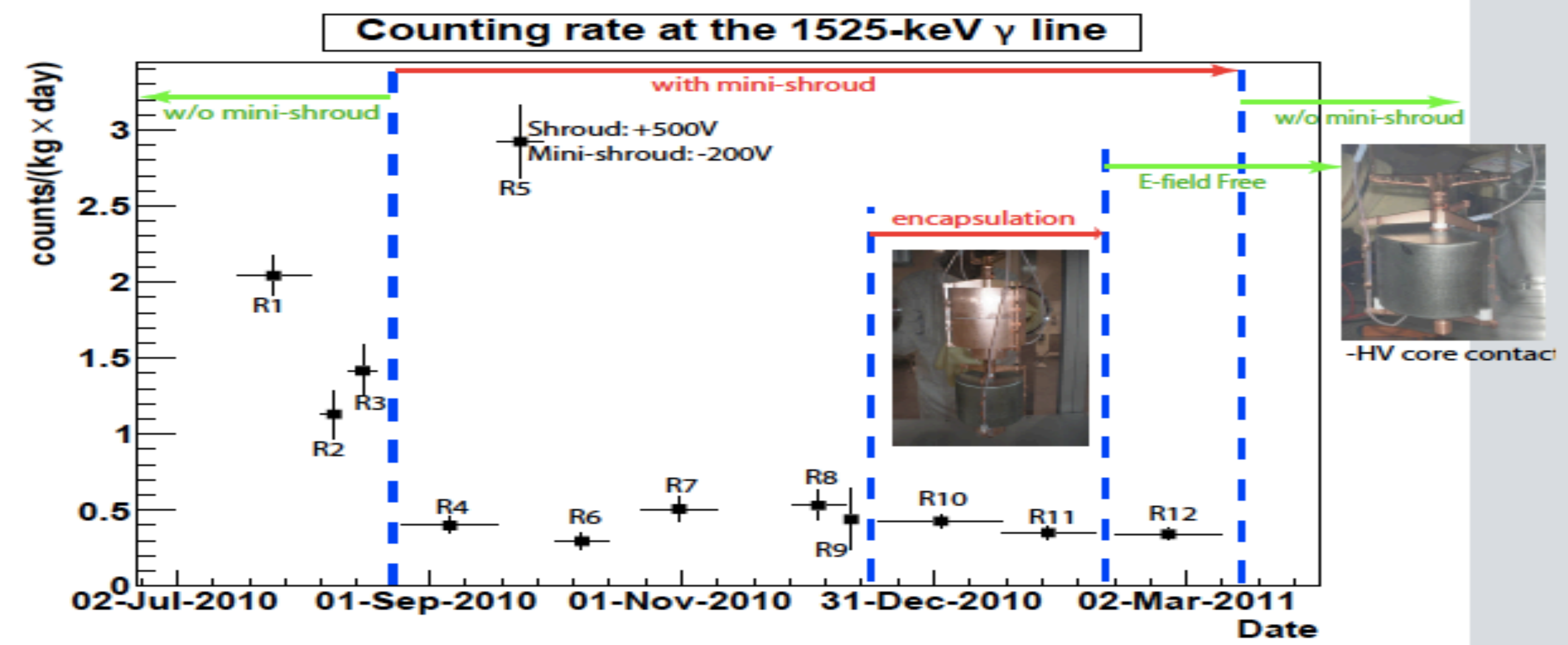
GERDA @ Gran Sasso

from Chris O'Shaughnessy @ SLAC 2011

an unexpected background: ^{42}Ar

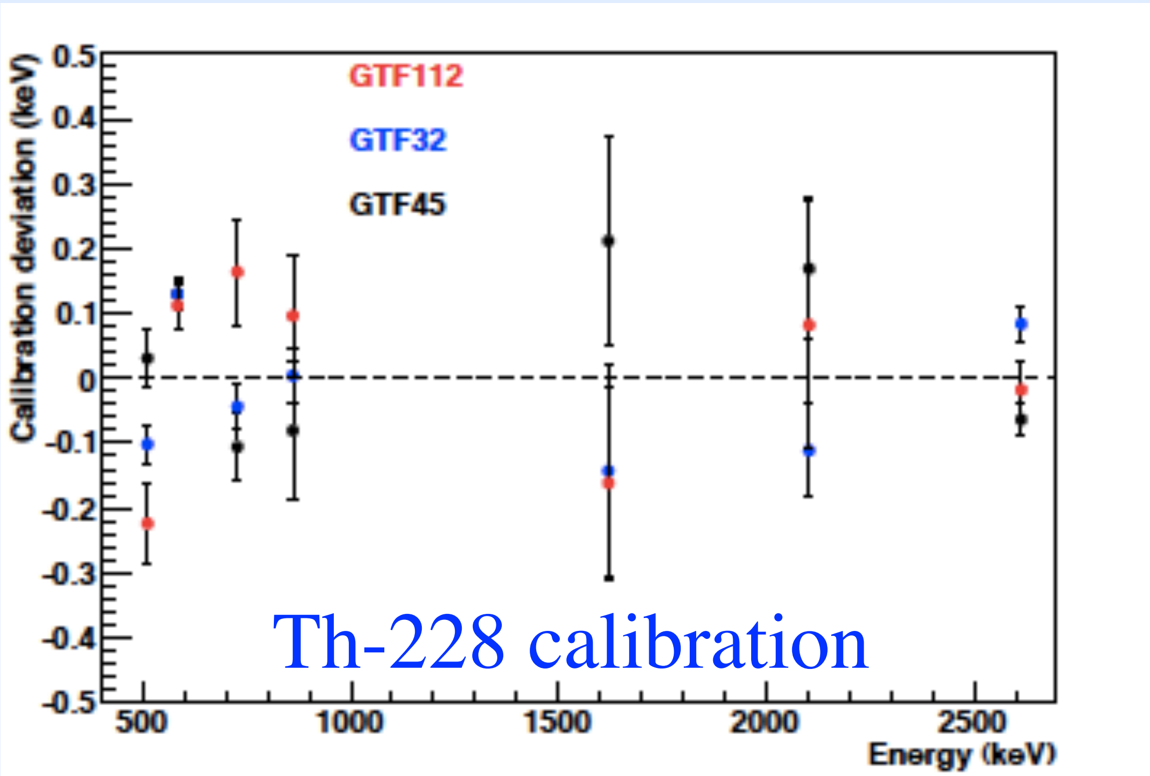


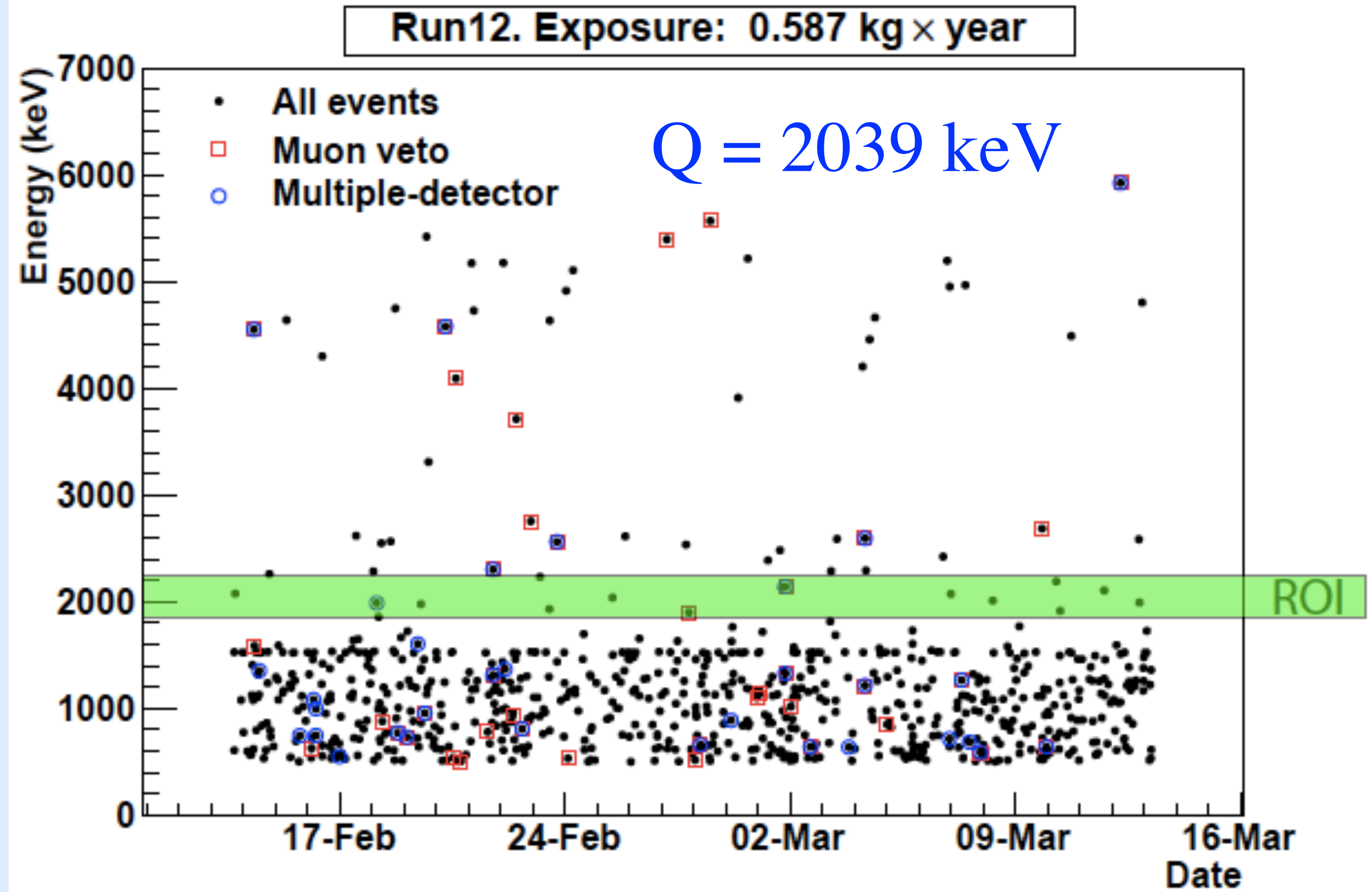


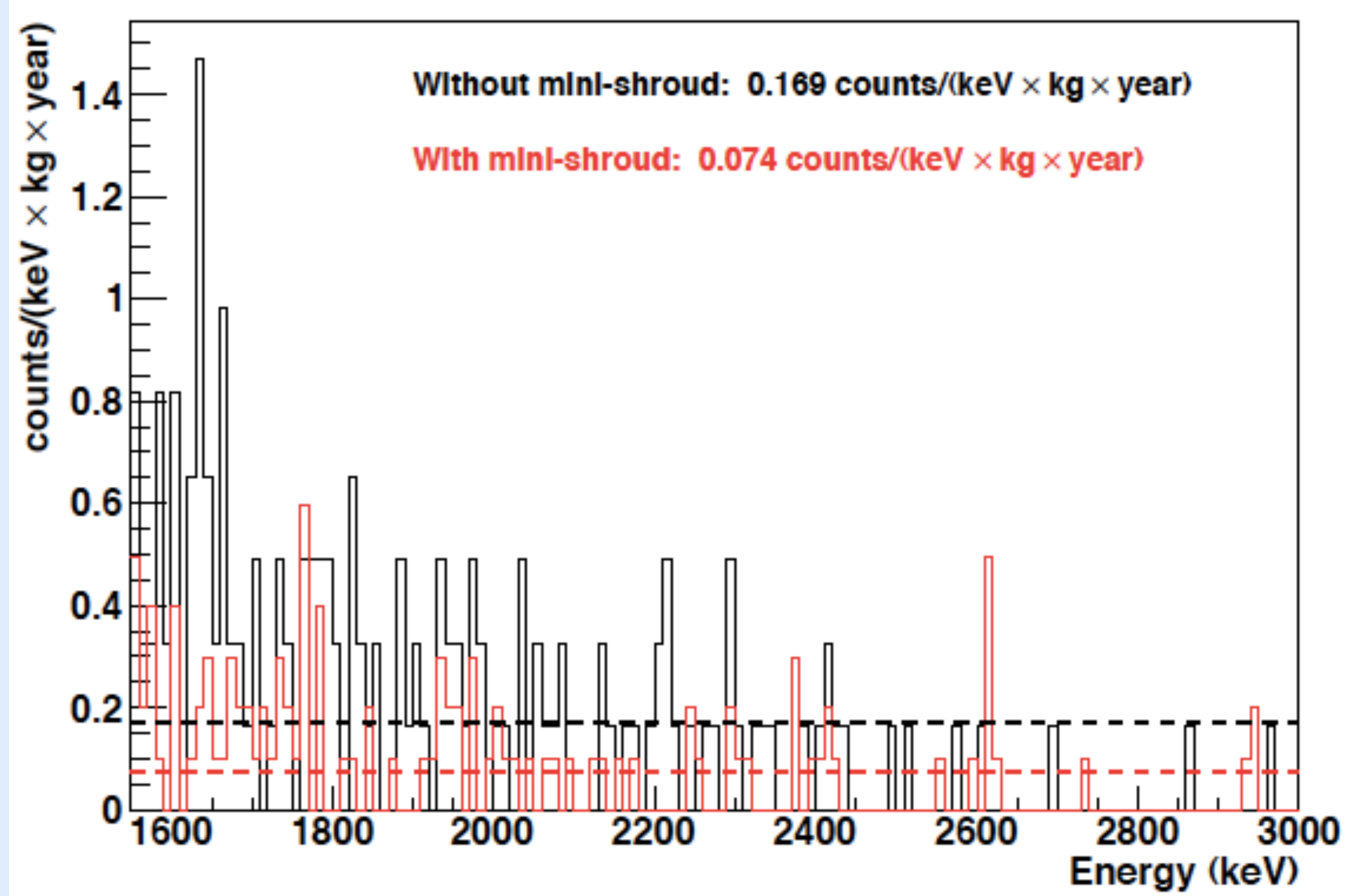


from Chris O'Shaughnessy @ SLAC 2011

performance



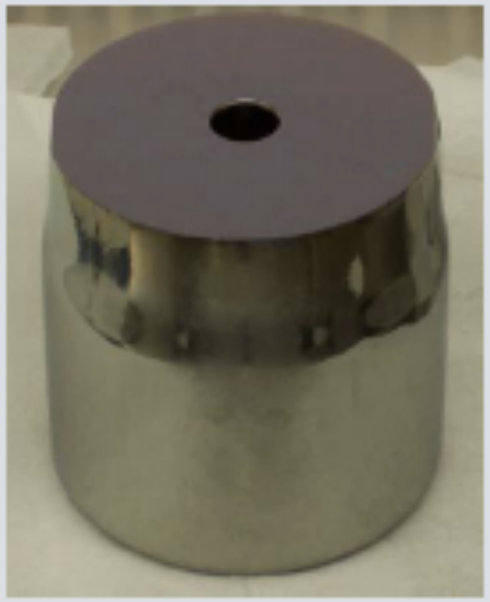




- Bgd rate significantly lower than previous experiments (HdMo, IGEX), but still higher than Phase I bgd goal (0.01 cnts/(kg · yr · keV))
- Possible cosmogenic bgd contribution due to exposure history of diodes
- Run 13: "Field-free" (n+ outer contact @0V) & removal of mini-shroud
- Deployment of 3 enriched detectors with known low activation history

from Chris O'Shaughnessy @ SLAC 2011

GERDA sensitivity




Phase I

- 3 IGEX & 5 HdMo Detectors 17.9 kg
- (6 non-enriched Genius-TF for reference)

Phase II

- 35 kg 6N enriched Ge Metal
- 18 kg Detector slices expected for BEGe diode production
- IKZ Crystal pulling R&D for n-type segmented detectors

✓ pulse shape analysis for background ID

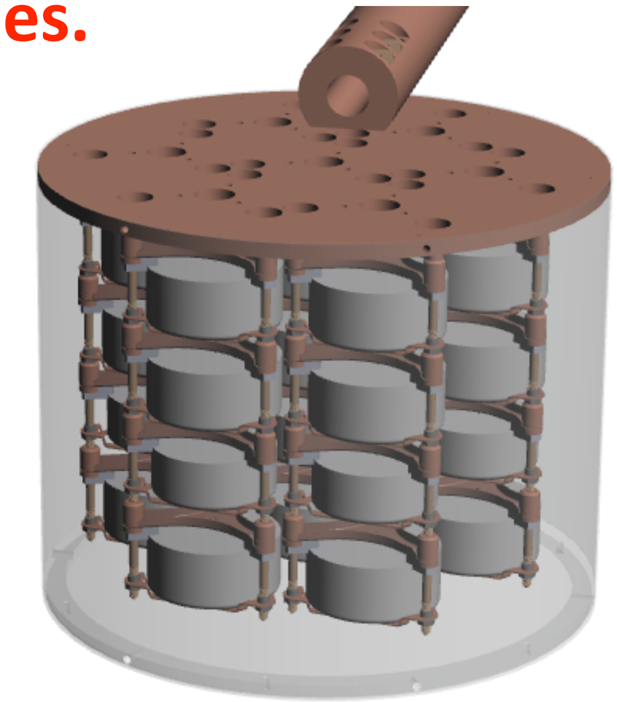
Phase	I	II
Exposure [kg·yr]	15	100
Bg [counts/kg·yr·keV]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$[eV]	0.23-0.39	0.09-0.15

from Chris O'Shaughnessy @ SLAC 2011

The MAJORANA DEMONSTRATOR Module

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- 40-kg of Ge detectors
  - Up to 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
  - Examine detector technology options focus on point-contact detectors for DEMONSTRATOR

- Technical goal: Demonstrate background low enough to justify building a tonne scale Ge experiment.
- Science goal: build a prototype module to test the recent claim of an observation of $0\nu\beta\beta$. This goal is a litmus test of any proposed technology.

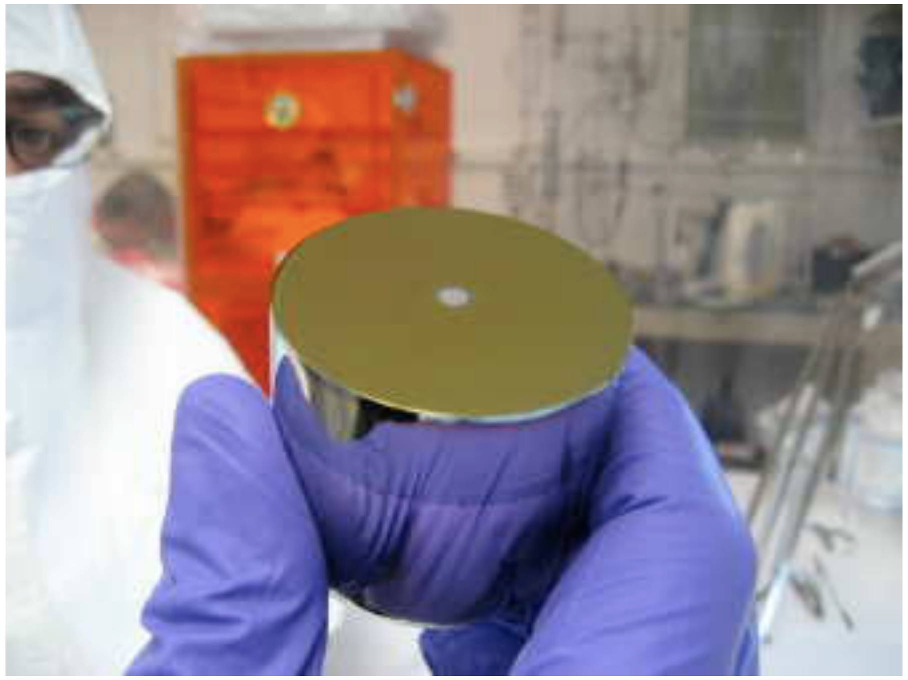
- Agreement to locate at 4850' level at Sanford Lab
- Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)

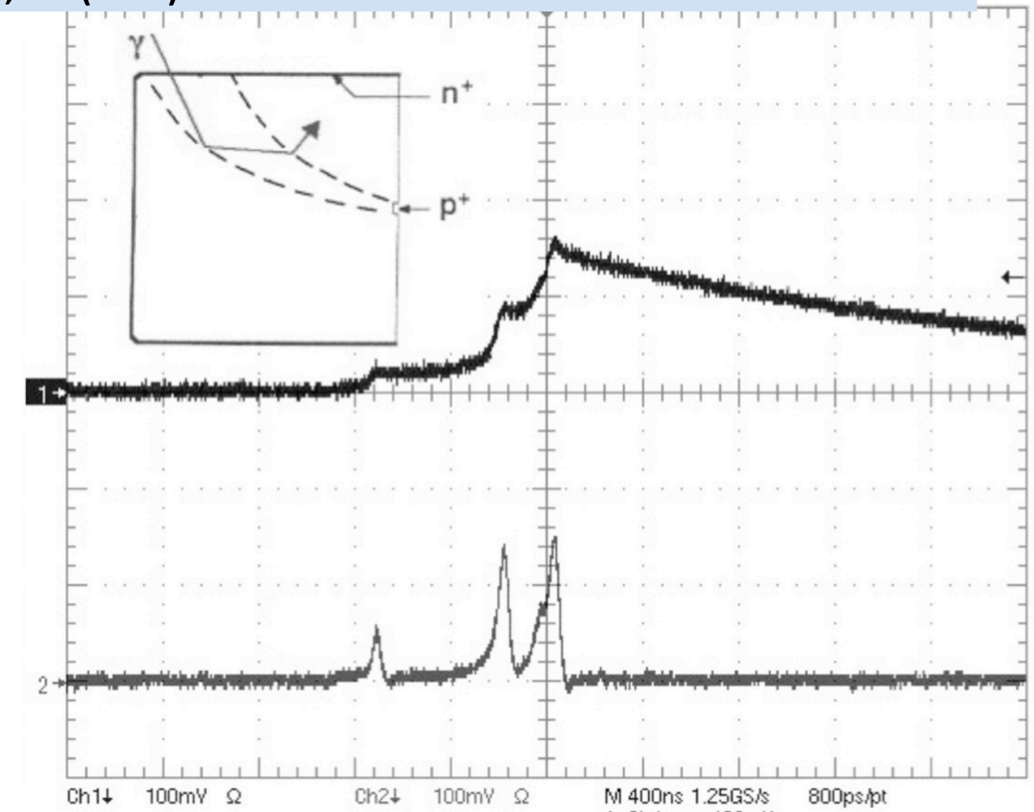
~ 4 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

courtesy of Steve Elliott

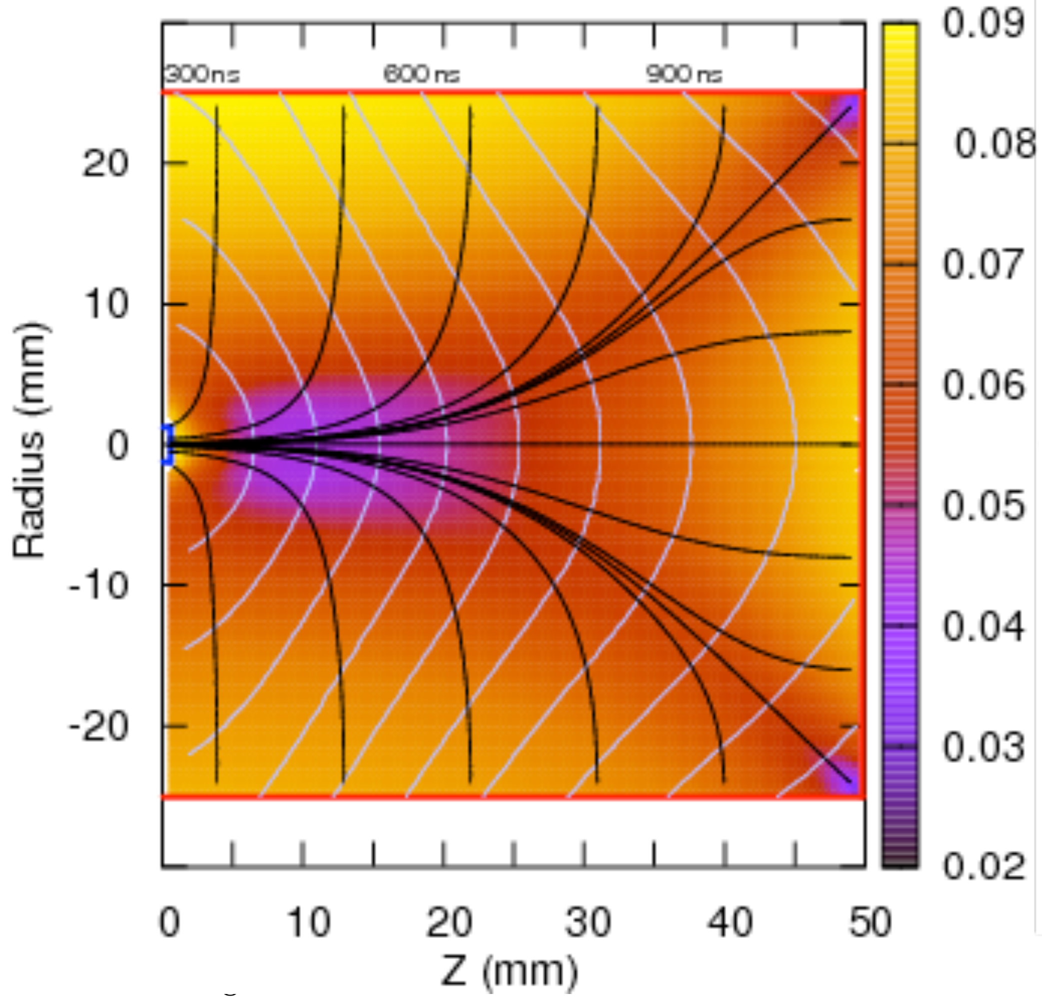
Point Contact Detectors

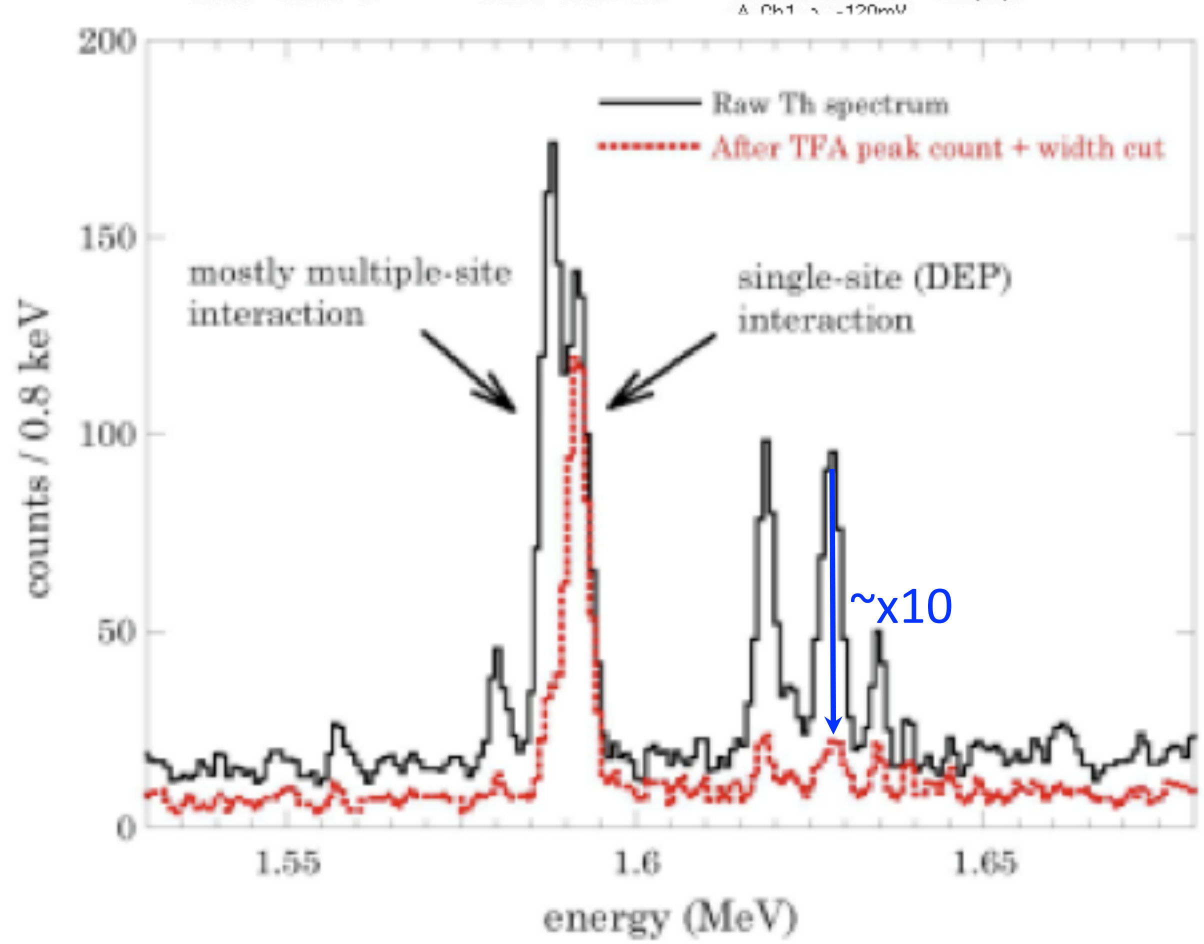
Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989).





Hole v_{drift} (mm/ns) w/ paths, isochrones

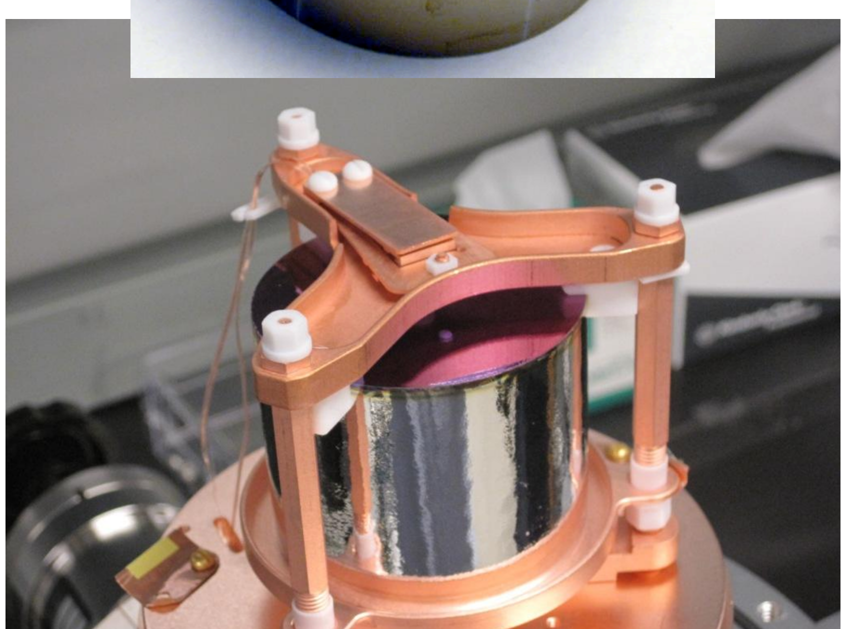


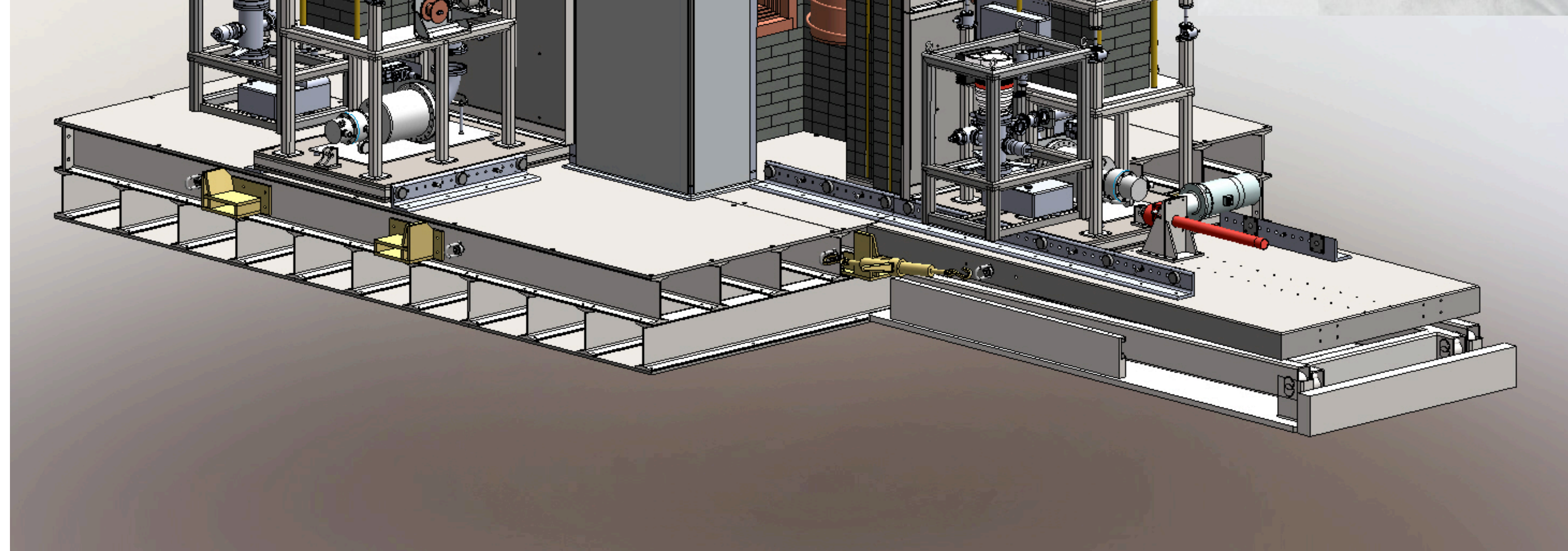


courtesy of Steve Elliott

MJD Implementation

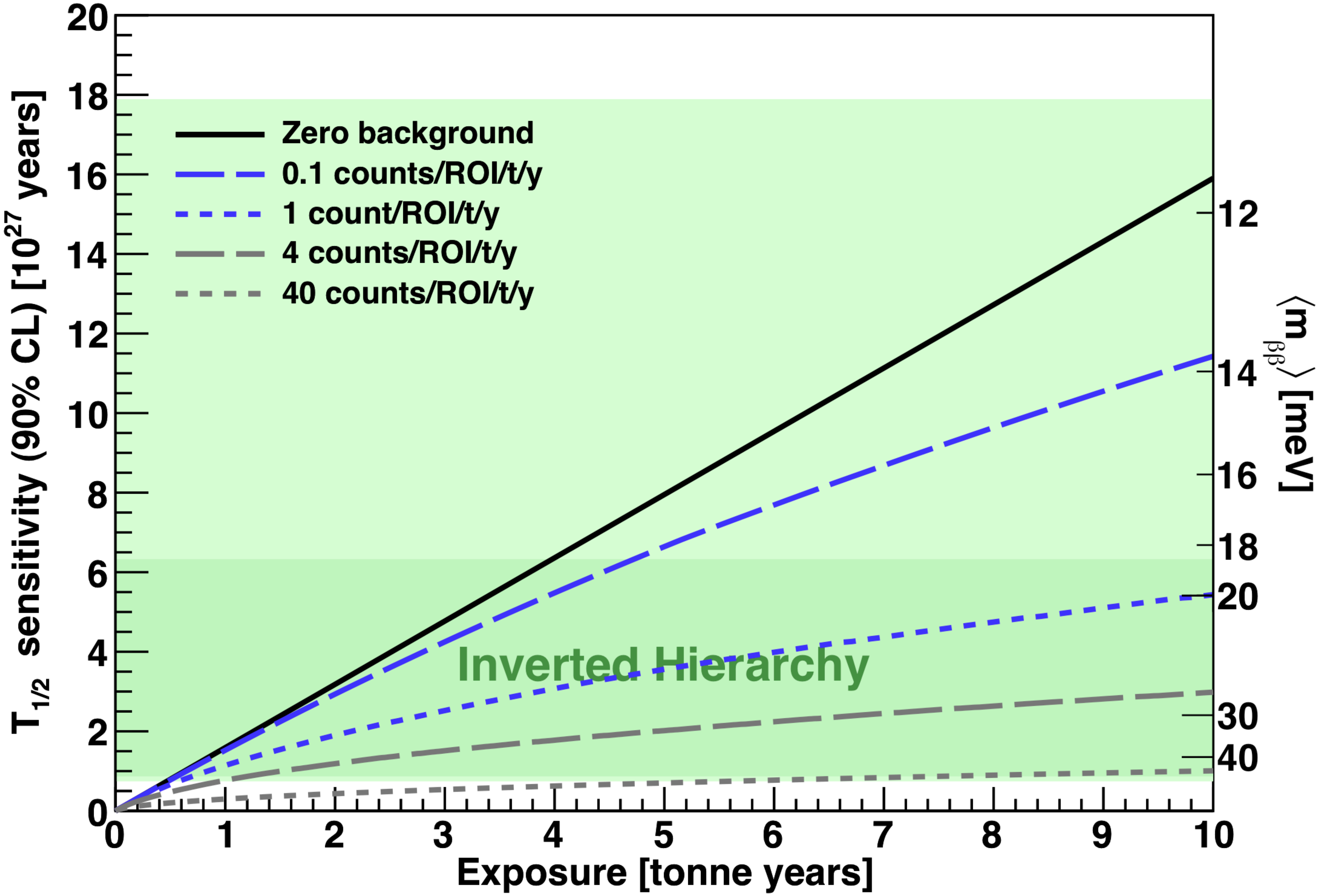
- Three Phases
  - Prototype cryostat (3 strings, ^{nat}Ge) (Oct. 2012)
  - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) (Mar. 2013)
  - Cryostat 2 (up to 7 strings ^{enr}Ge) (Sept. 2014)





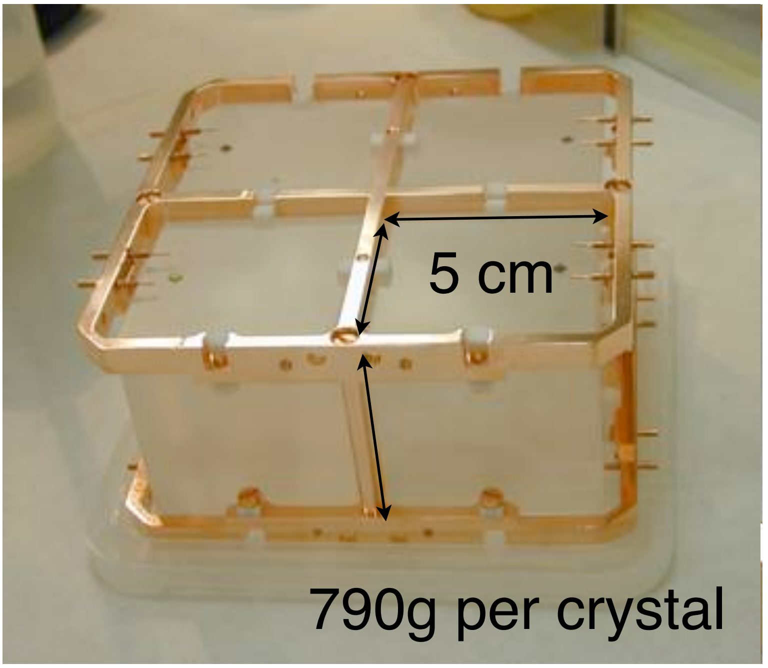
courtesy of Steve Elliott

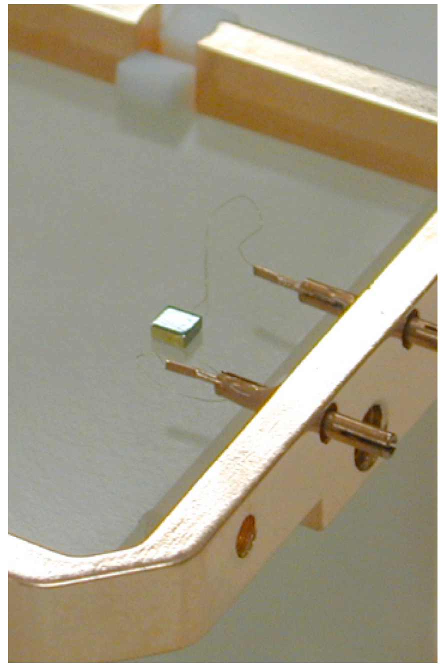
Ma-Ge: the tonne-scale

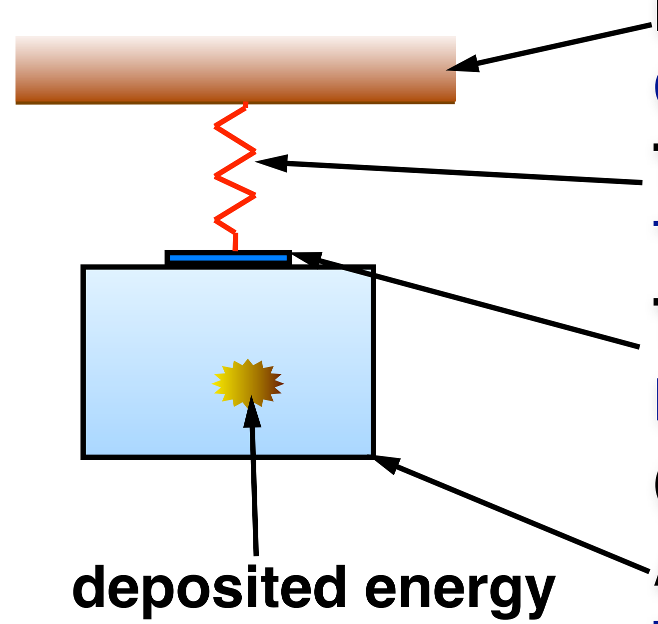


courtesy of Steve Elliott

TeO_2 Bolometers







Heat sink:
Cu structure (8-10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor
(dR/dT ≅ 100 kΩ/μK)
Absorber:
TeO_2 crystal

TeO_2 Bolometer: Source = Detector

For E = 1 MeV: $\Delta T = E/C \cong 0.1$ mK
Signal size: 1 mV

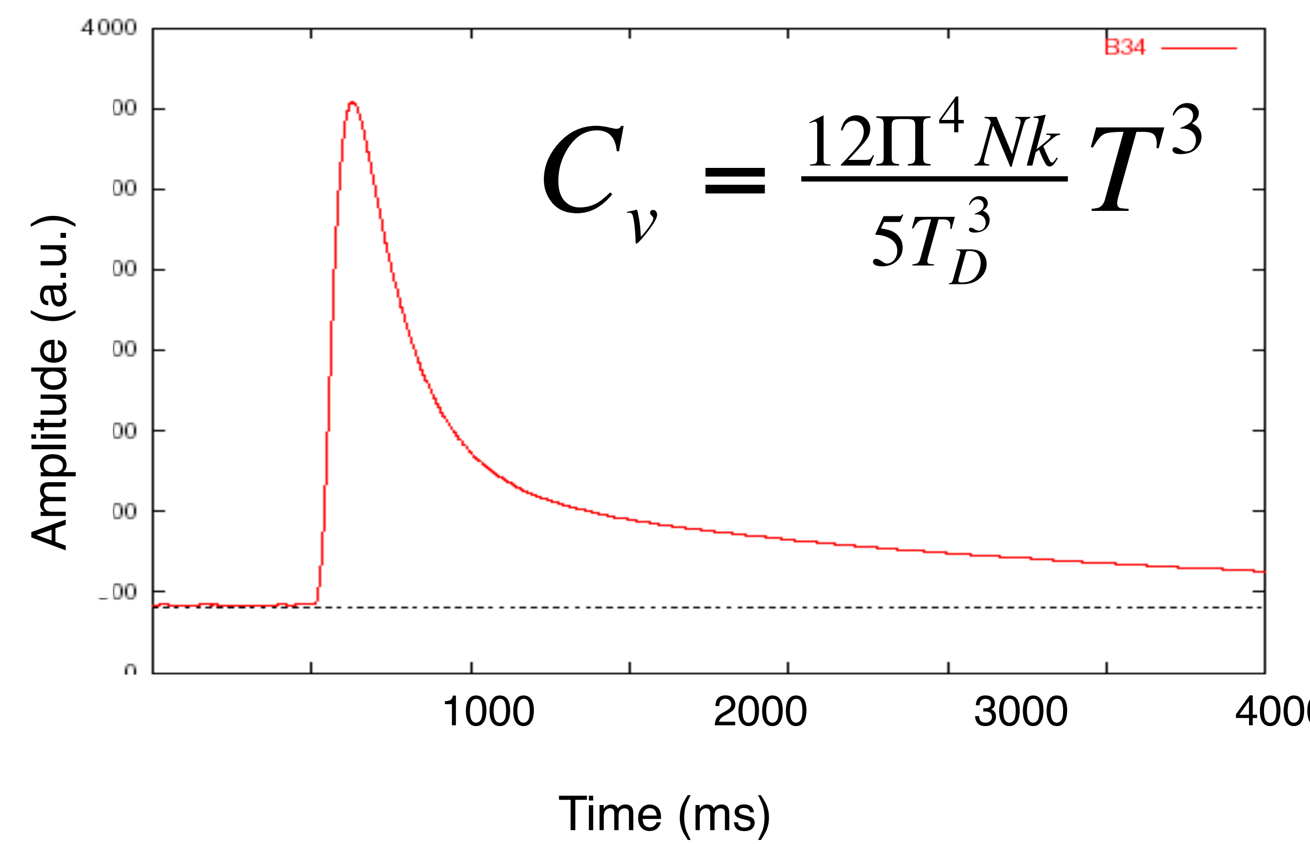
voltage signal ∝ energy deposited

Time constant: $\tau = C/G = 0.5$ s
Energy resolution: ~ 5-10 keV at 2.5 MeV

✓ excellent energy resolution

✳ no particle ID

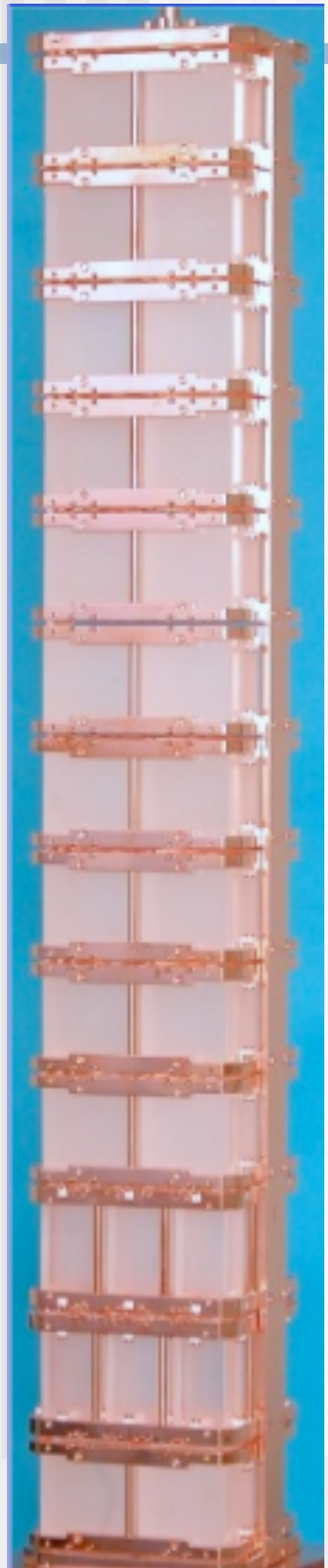
Single pulse example

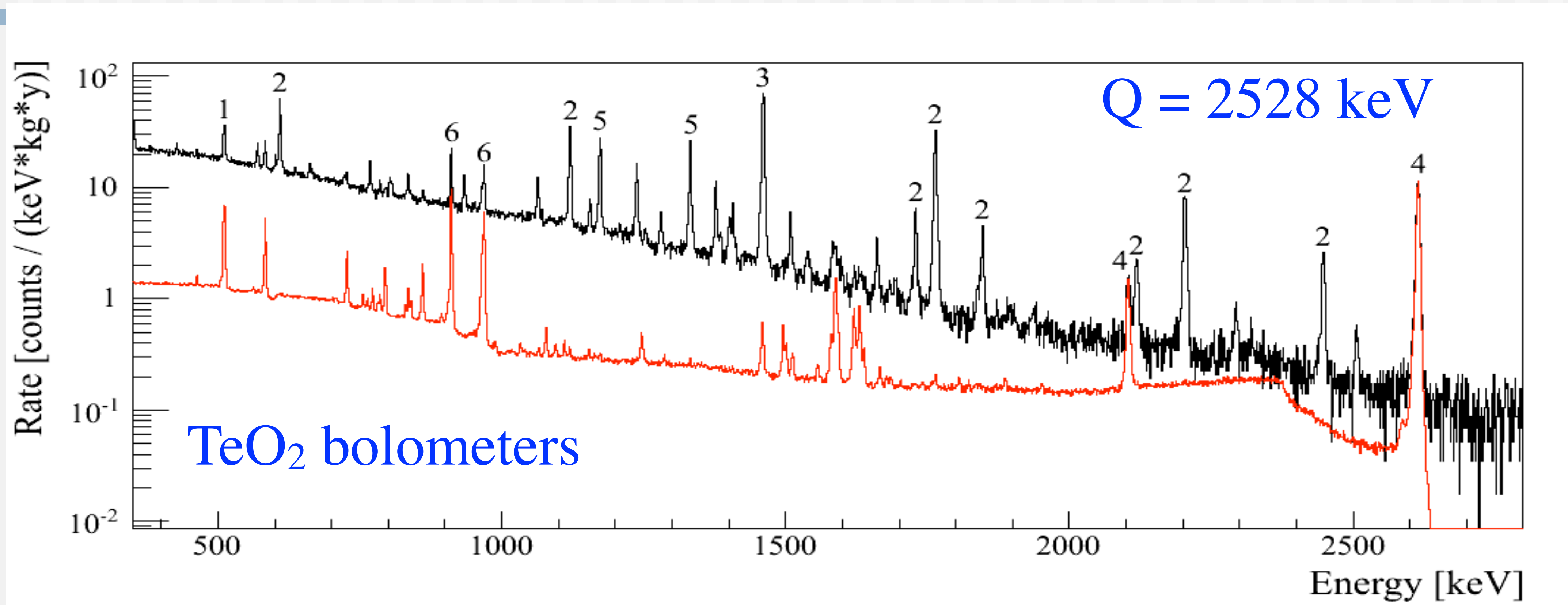


$$C_v = \frac{12\Pi^4 Nk}{5T_D^3} T^3$$

courtesy of Karsten Heeger

CUORICINO @ LNGS



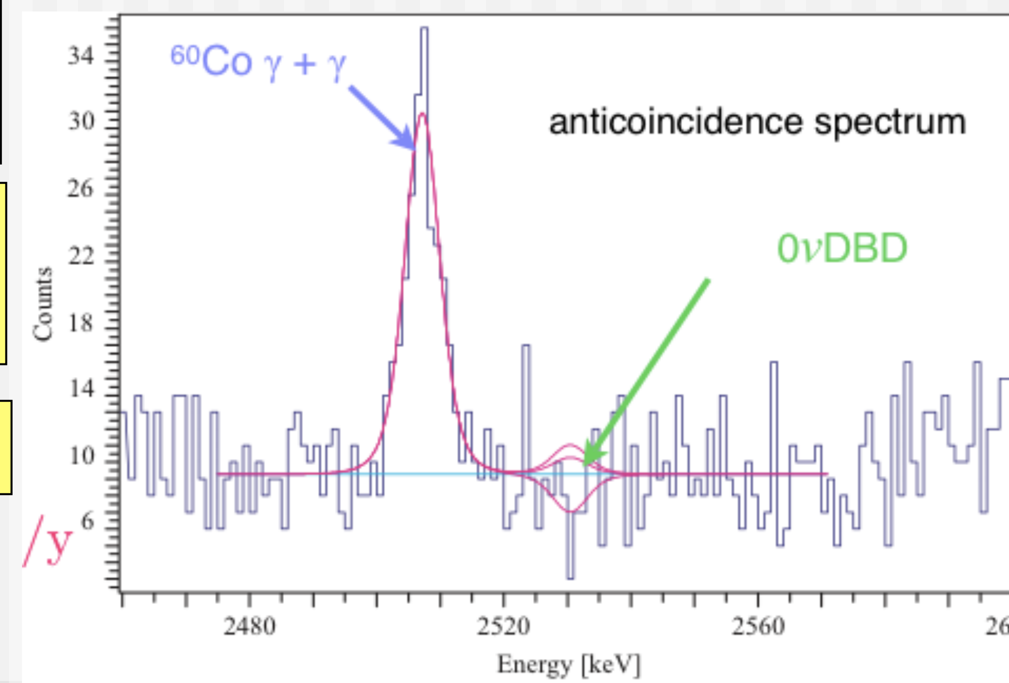


BKG@ROI = 0.169 ± 0.005 cts / (keV kg yr)
19.75 kg (^{130}Te) yrs of exposure

2v mode: $T_{1/2}(2v)$ ~= 0.9 ± 0.15 · 10^{21} yr

A. S. Barabash, Czech. J. Phys. 52, 567-573 (2002)

0v mode: T1/2(0v) > 2.8 · 10^{24} yr @ 90% C.L.

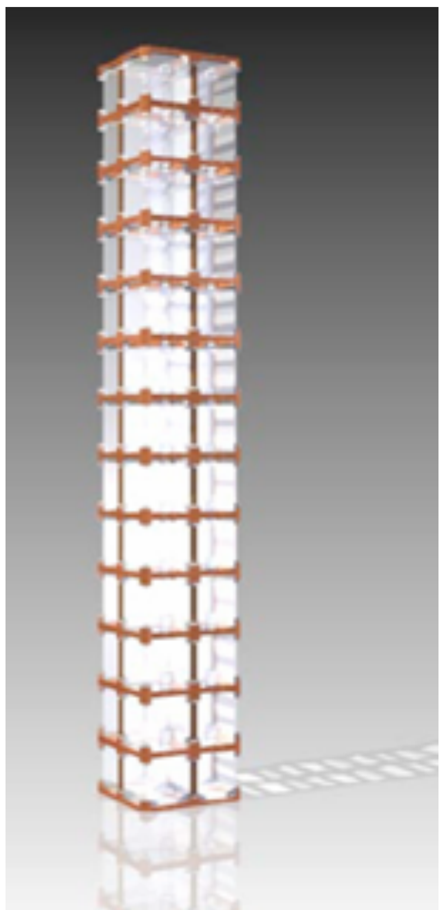


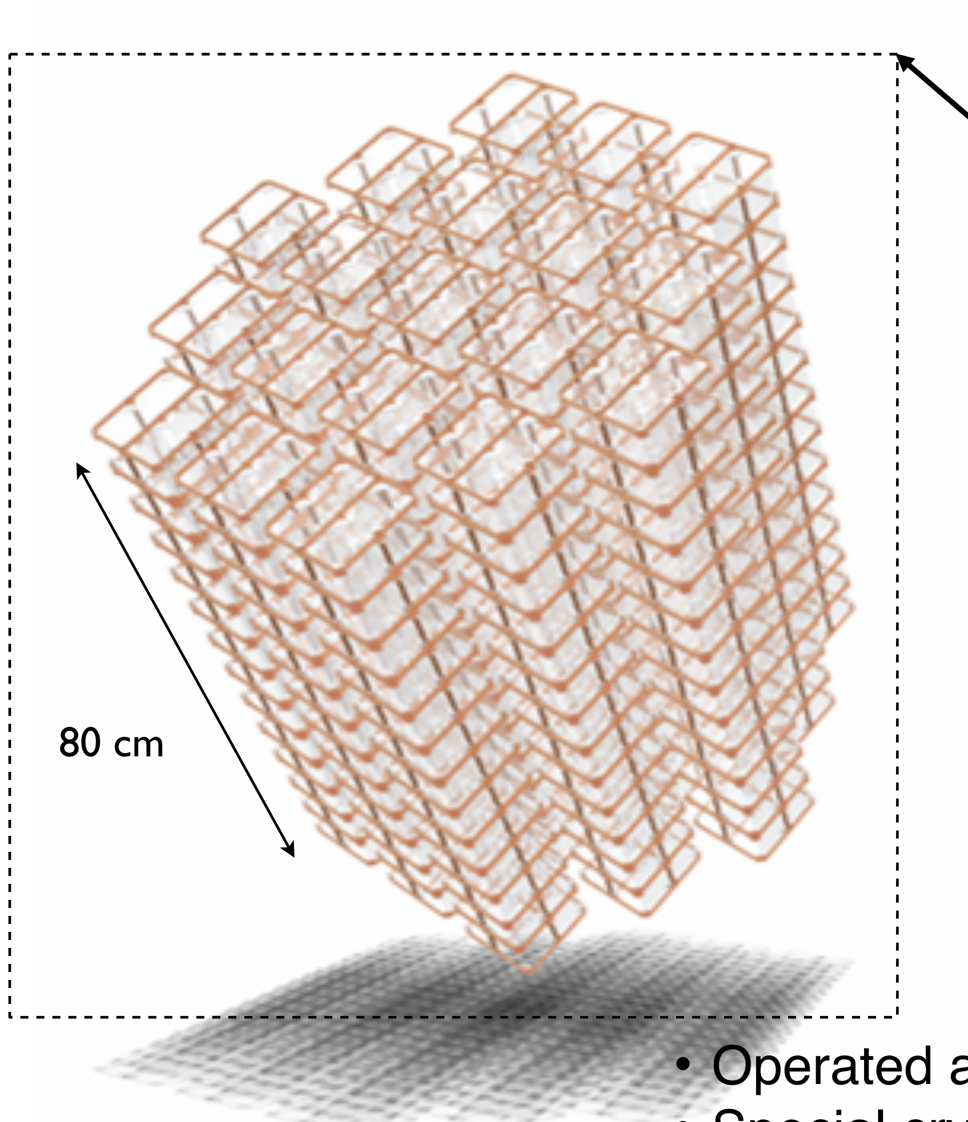
✓ ^{130}Te is >34% abundant

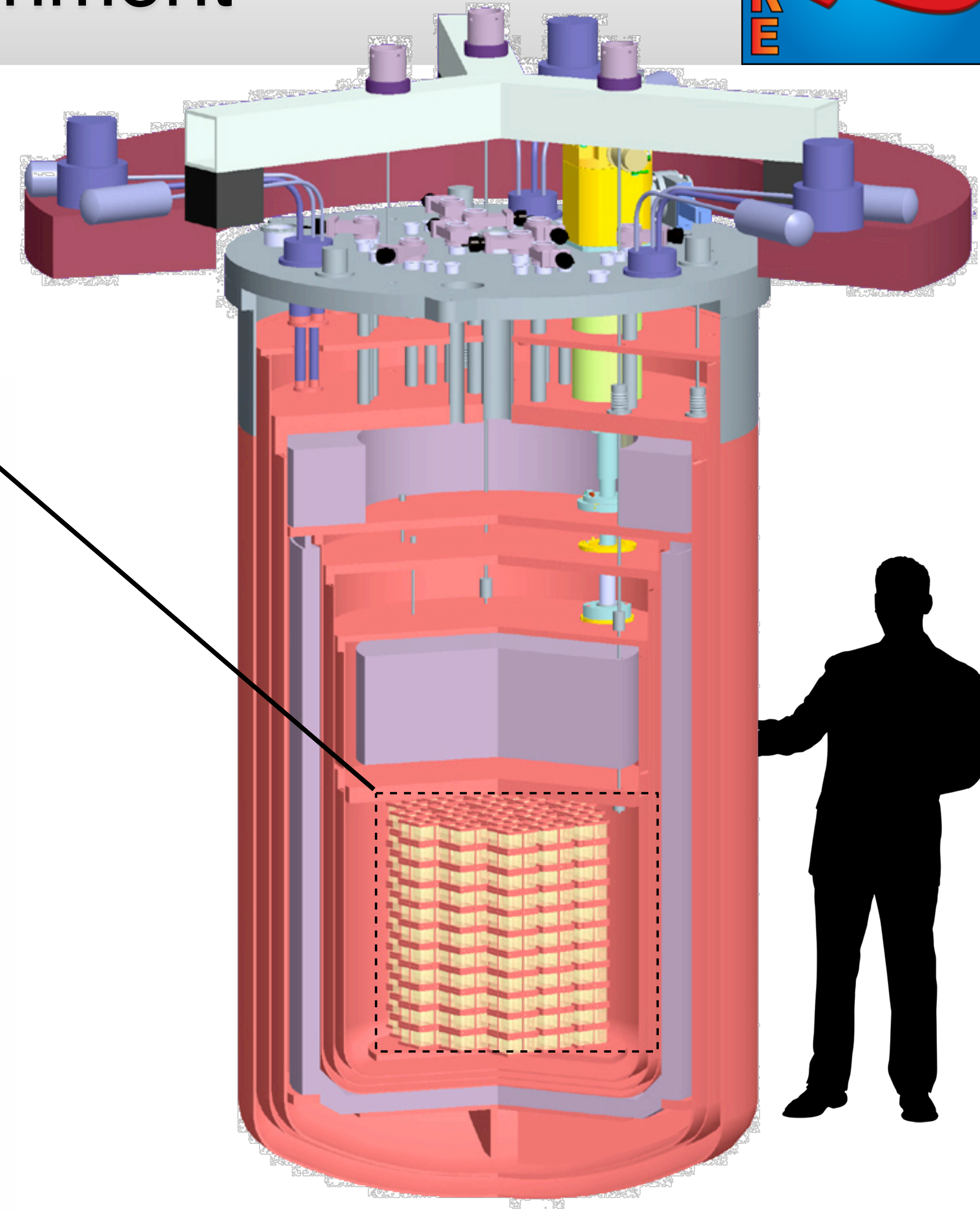
adapted from Tom Bloxham @ PHENO 2011

CUORE Double Beta Decay Experiment

CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers with mass of ~ 200 kg of ^{130}Te





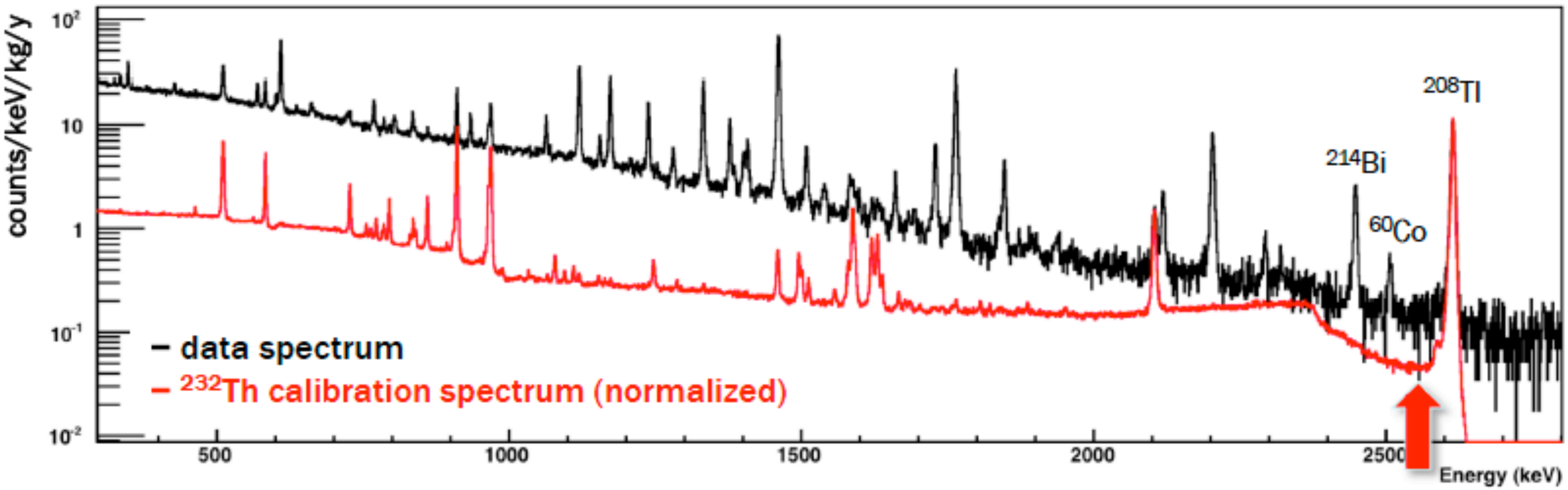


19 Cuoricino-like towers with 13 planes of 4 crystals each

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

courtesy of Karsten Heeger

CUORE Backgrounds

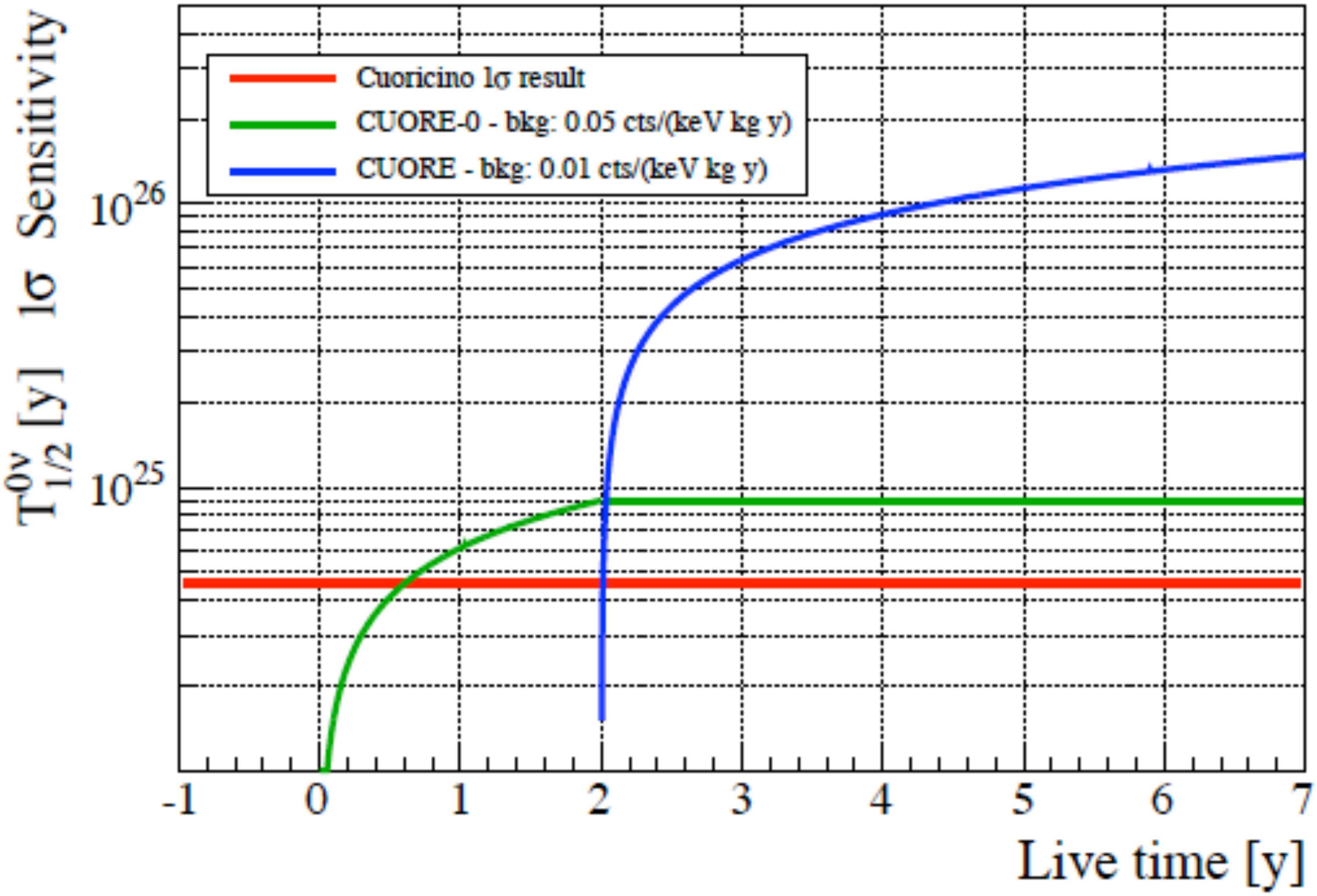


- There are three main sources of background in the region of interest (2430–2630 keV):
  - (~40%) Compton events from 2615 keV peak of ^{208}Tl, from ^{232}Th cryostat contamination
  - (~50%) Degraded alphas from ^{238}U and ^{232}Th on copper surfaces
  - (~10%) Degraded alphas from ^{238}U and ^{232}Th on crystal surfaces
- The 2506 keV ^{60}Co peak is likely due to cosmic-ray activation of the copper

- expected backgrounds in the ROI of $10^{-2} \sim 10^{-3}$ counts/kg keV (×20 better thn Cuoricino)

courtesy of Karsten Heeger

CUORE Sensitivity



CUORE-0

- is the first tower of CUORE. It will be constructed with the tools being build to construct CUORE
- as a stand alone experiment is very competitive with the present generation of 0νββ experiments.

2012 start of CUORE-0

$\langle m_{\beta\beta}\rangle$ < 170-350 me (1σ)

2014 start of CUORE

$\langle m_{\beta\beta}\rangle$ < 47-87 meV (1σ)

courtesy of Karsten Heeger

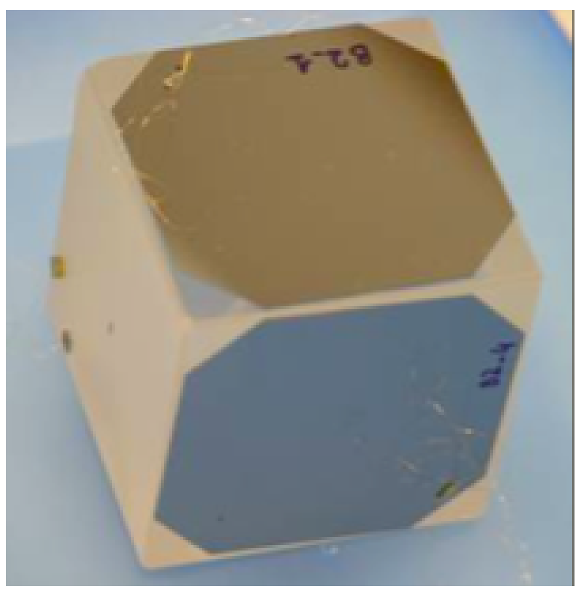
Beyond CUORE - Future Opportunities

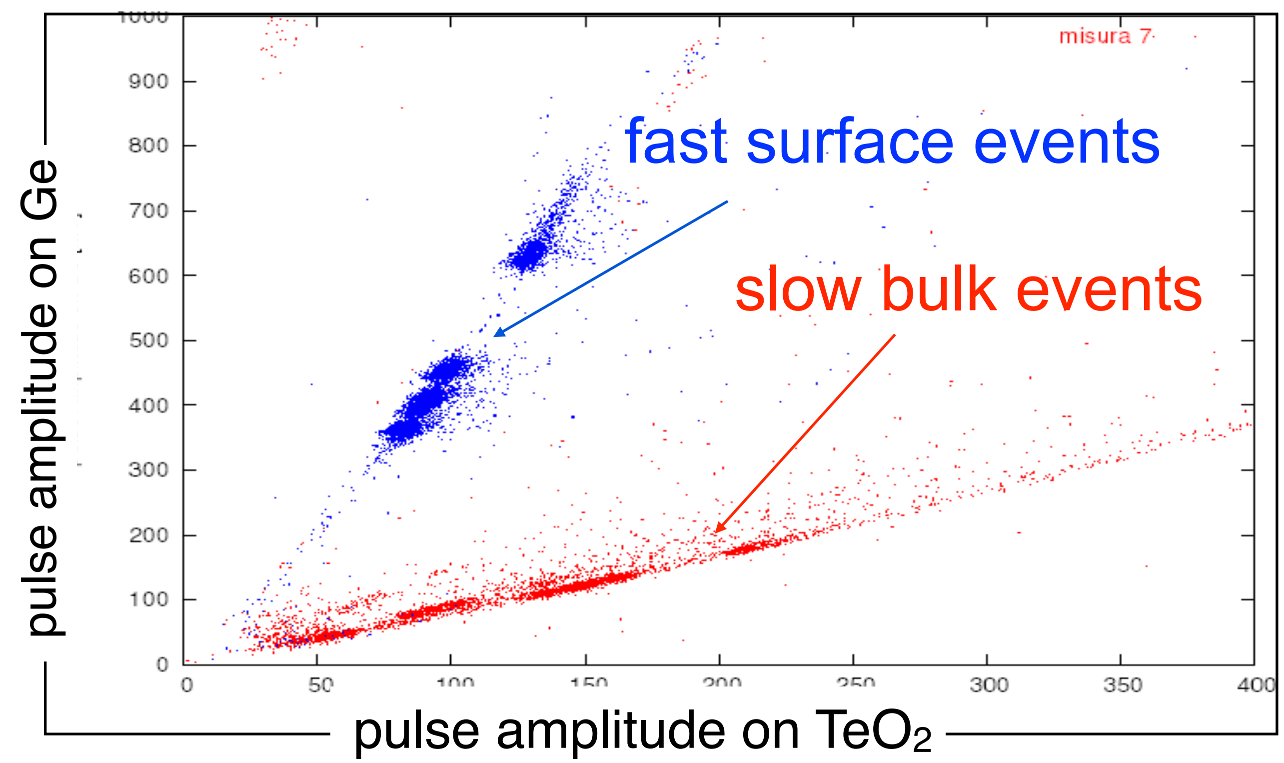
Advanced Bolometers

- active background rejection (surface sensitive detector or scintillating bolometers)
- enriched bolometric detectors
- other isotopes

Isotope
^{48}Ca
^{76}Ge
^{82}Se
^{96}Zr
^{100}Mo
^{116}Cd
^{128}Te
^{130}Te
^{136}Xe
^{150}Nd

surface sensitive bolometers





other isotopes

Tested bolometrically,
as good as TeO_2

CaF_2, Ge, $PbMoO_4$, $CdWO_4$

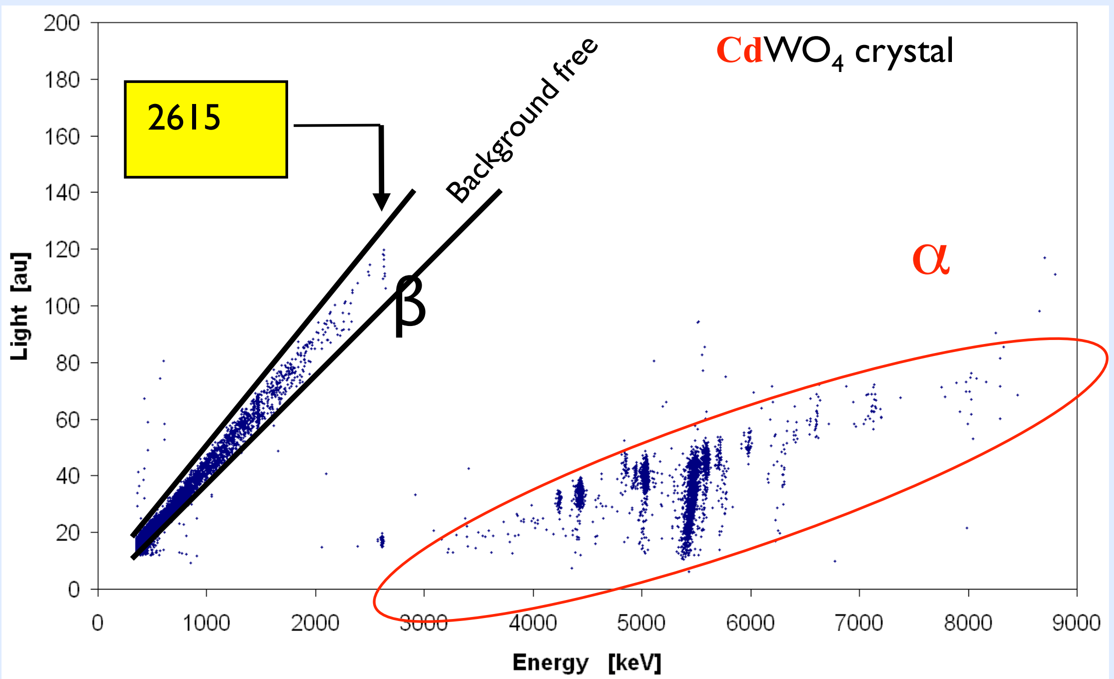
isotopic enrichment of ^{130}Te

- up to 3x more sensitive
- no change to CUORE cryostat

courtesy of Karsten Heeger

scintillating bolometers

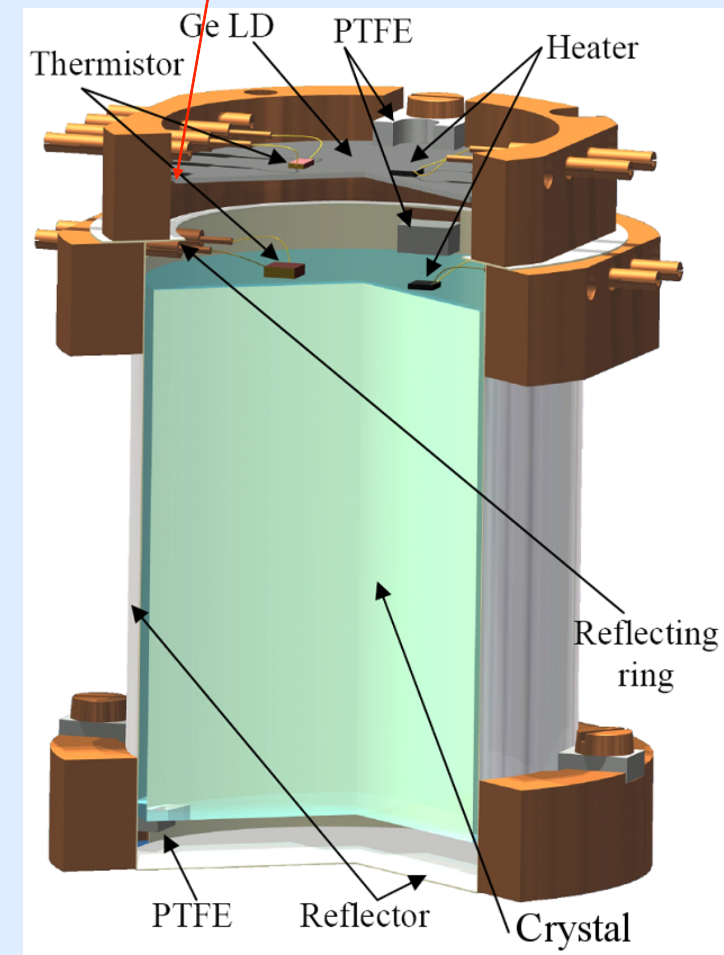
Thanks to the simultaneous detection of Heat signal and Light signal α particles can be discriminated

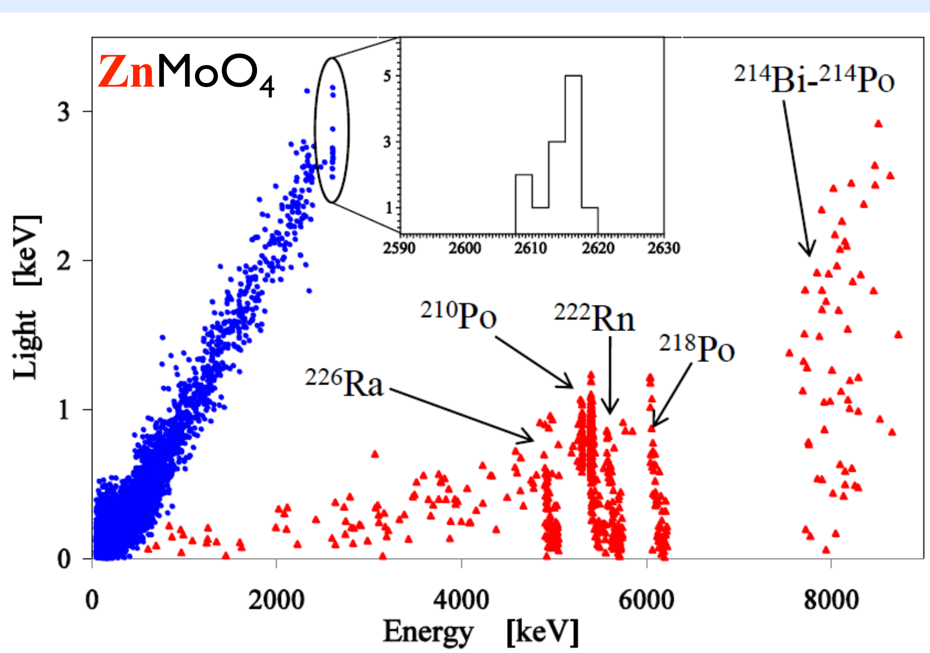


C. Arnaboldi et al., Astropart. Phys. 34 (2010) 143.

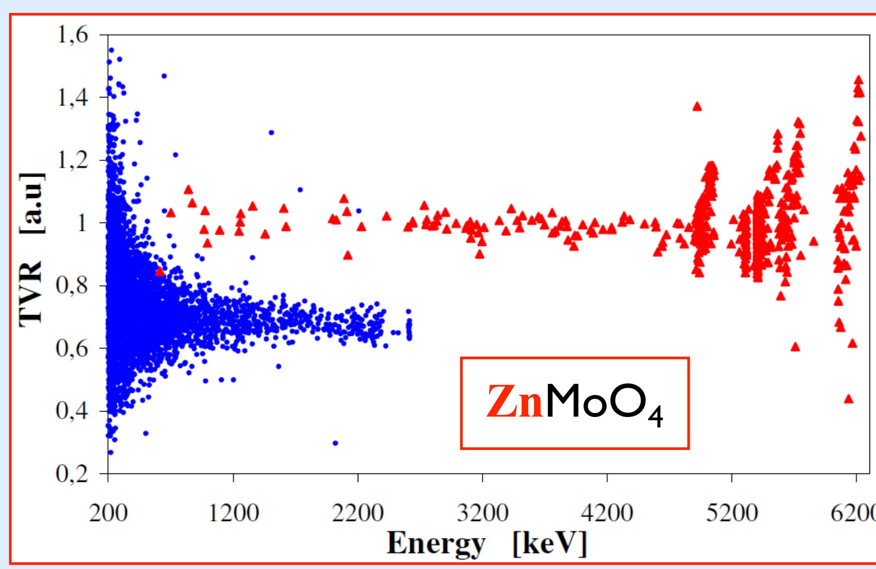
- α particles produce a background continuum in ββ energy range
- no particle ID

The light detector is very sensitive "dark" bolometer





L. Gironi et al., 2010 JINST 5 P11007



Particle identification WITHOUT Light detection

Some scintillating Mo and Se based bolometers permit α discrimination due to different thermal pulse development, without Light detection
C. Arnaboldi et al., Astropart. Phys. 34 (2011) 797

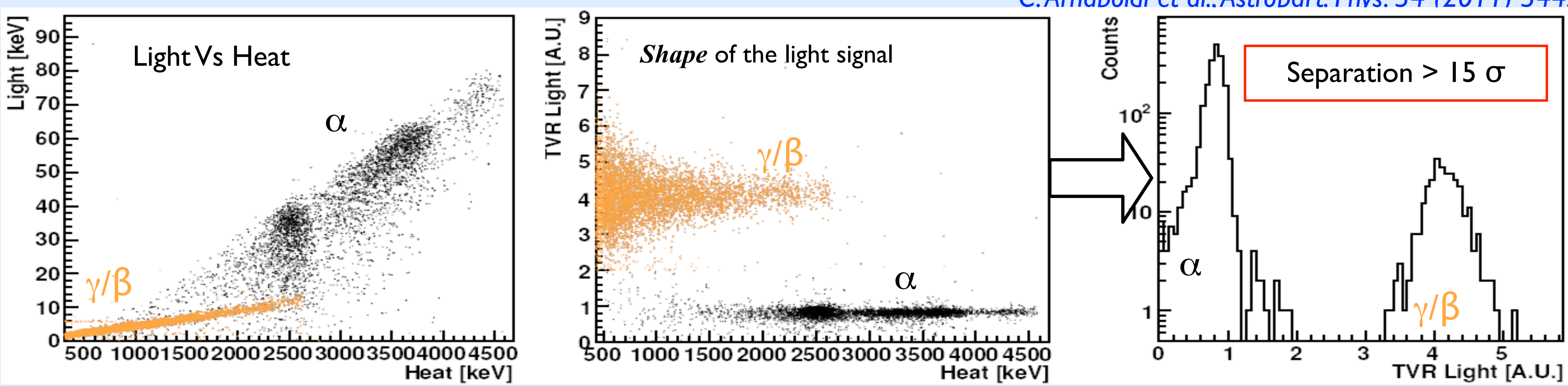
courtesy of Stefano Pirro

the Lucifer project

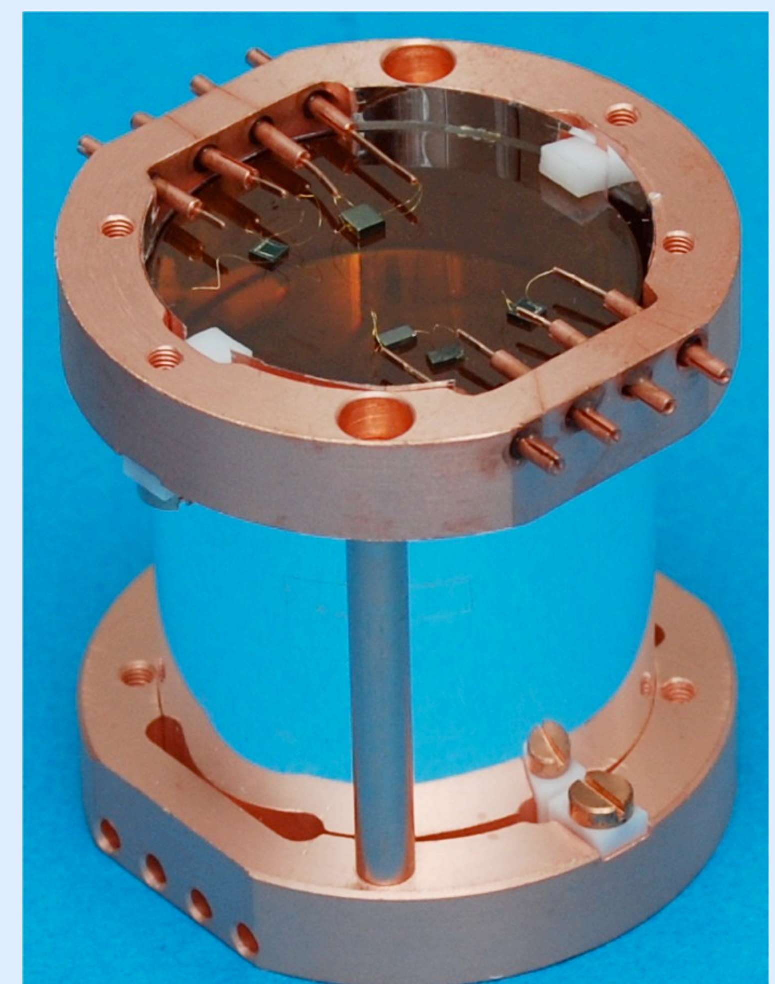
The Lucifer Project is an EU Advanced Grant aiming to the construction of a Scintillating bolometer experiment.

European Research Council erc

C. Arnaboldi et al., Astropart. Phys. 34 (2011) 344.



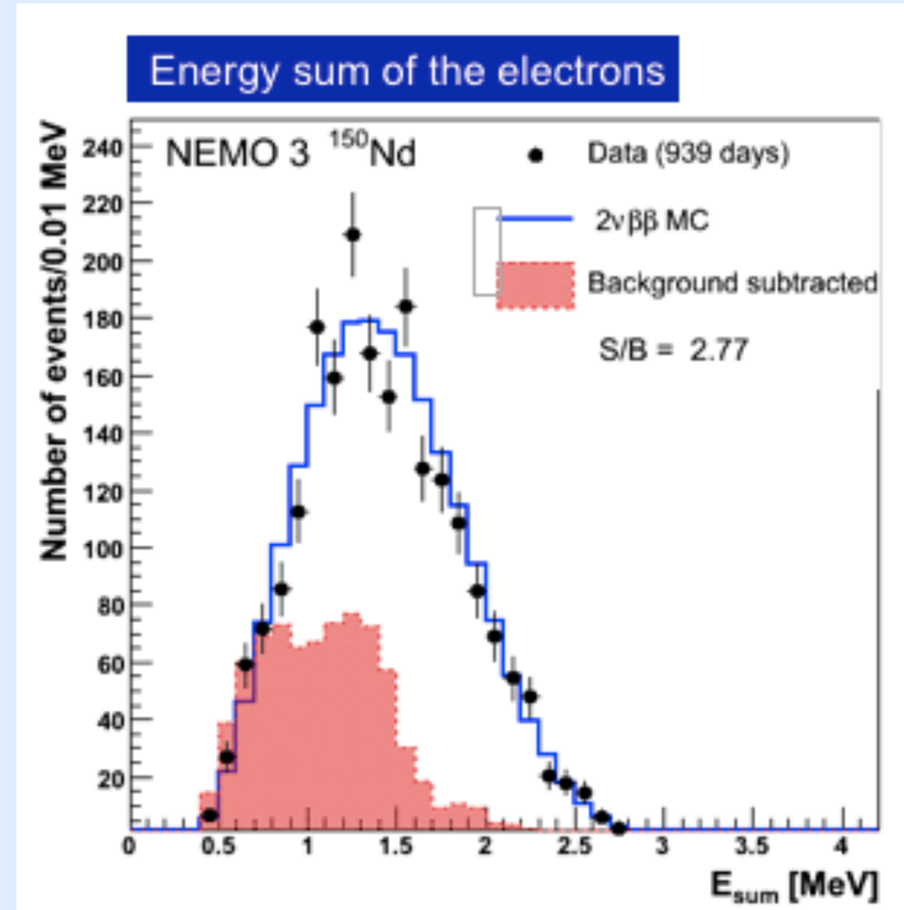
- Lucifer will consist of an array of enriched ZnSe crystals with a total ^{82}Se mass of ~ 10 kg
- ZnSe is a "puzzling" promising scintillating crystal, being the only scintillator with an "inverse" Scintillating QF (≈4)
- The enriched ^{82}Se production (Urenco) is starting and the delivery of the 10 kg is foreseen for end 2013
- The expected background in the ROI (2995 keV) dominated by environmental ^{214}Bi is expected to be ≤ **0.006 c/keV/kg/y**
- Lucifer will be hosted in the CUORICINO cryostat (LNGS), once the CUORE-0 tower will finish data taking (2014-2015)



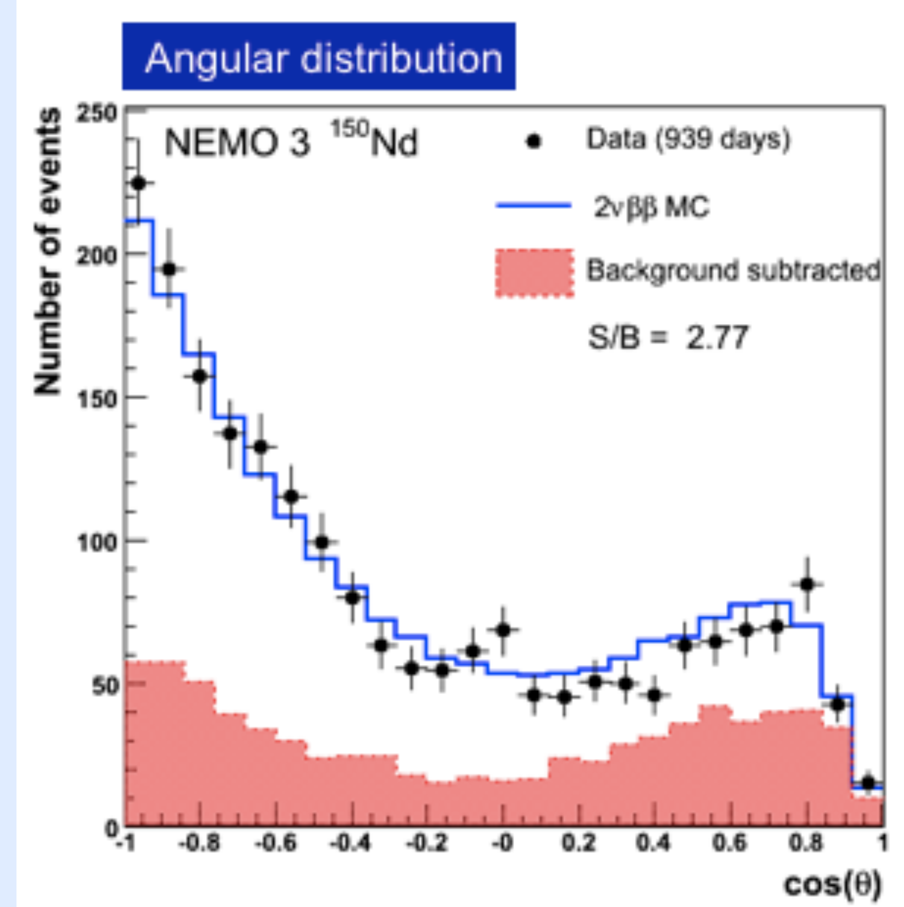
courtesy of Stefano Pirro

tracking: NEMO3

- ✳ thin ββ foils inside gas tracker + calorimeter
- ✳ magnetic field
- ✳ measured 2νββ lifetimes with excellent S/B ratio (Nd-150, Se-82, Te-130, ...)



- ✓ tracking: excellent 1 vs 2 electron discrimination
- ✓ multiple isotopes at once (all solid ones, in principle)
- ✳ relatively poor energy resolution
- ✳ small amounts of isotope (~kg) , large detector



From NEMO 3 to SuperNEMO

NEMO 3		SuperNEMO
^{100}Mo	isotope	^{150}Nd or ^{82}Se
7 kg	isotope mass M	100 – 200 kg
8 %	efficiency ε	~ 30 %
A(^{208}Tl): < 20 μBq/kg A(^{214}Bi): < 300 μBq/kg	internal contamination ^{208}Tl and ^{214}Bi in the ββ foil	A(^{208}Tl) < 2 μBq/kg ***if ^{82}Se***: A(^{214}Bi) < 10 μBq/kg
8% @ 3 MeV	energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{24}$ y $\langle m_\nu \rangle < (0.3 – 0.6)$ eV		$T_{1/2}(0\nu\beta\beta) > 2 \times 10^{26}$ y $\langle m_\nu \rangle < (50 – 100)$ meV

liquid scintillators

- dissolve DBD isotope in a large, unsegmented volume (100-1000 tonnes) of liquid scintillator
- relatively old idea from Raju Raghavan, then CAMEO

✓ isotope can be dissolved at ~2-3% (100's of kg!)

✓ possibility of switching isotope
(but some isotopes are hard to dissolve)

✓ wonderful radiation shielding

✓ proven purification from radioactivity

✳ relatively poor energy resolution, but high statistics

SNO+ Double Beta Decay

- SNO+ with Nd-loaded liquid scintillator
- 0.1% Nd in 1000 tons of scintillator
  - with natural Nd corresponds to 56 kg of ^{150}Nd isotope
- sensitivity below 100 meV with natural Nd
- meters of ultra-low background self-shielding against gammas and neutrons
  - leads to well-defined background model
- liquid detector allows for additional *in-situ* purification
- (possibility to enrich Nd)

slides from Mark Chen

SNO+

1000 t D_2O will be replaced by Nd loaded LS

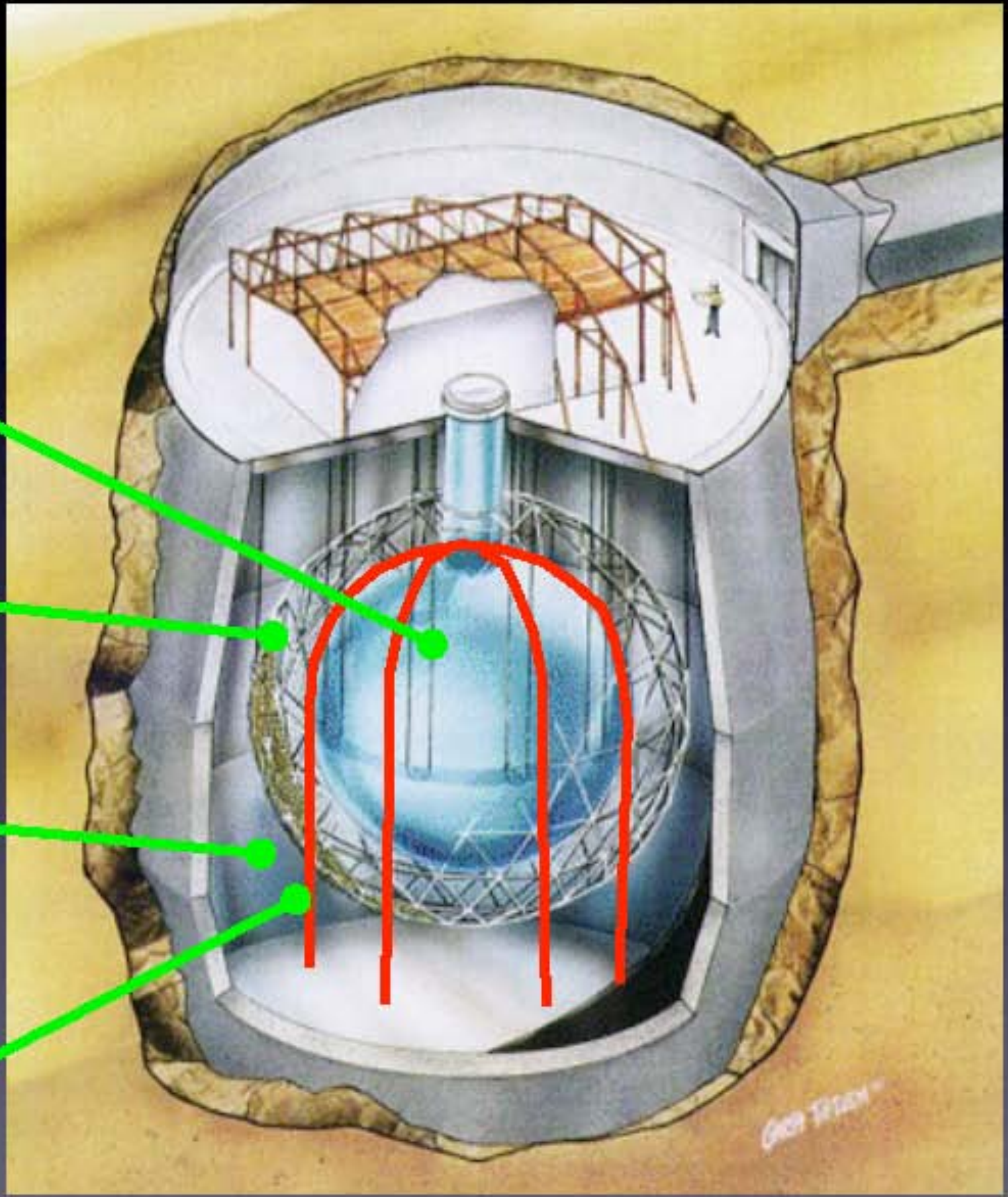
0.1 wt% = 780 kg Nd(natural)
= 44 kg Nd-150

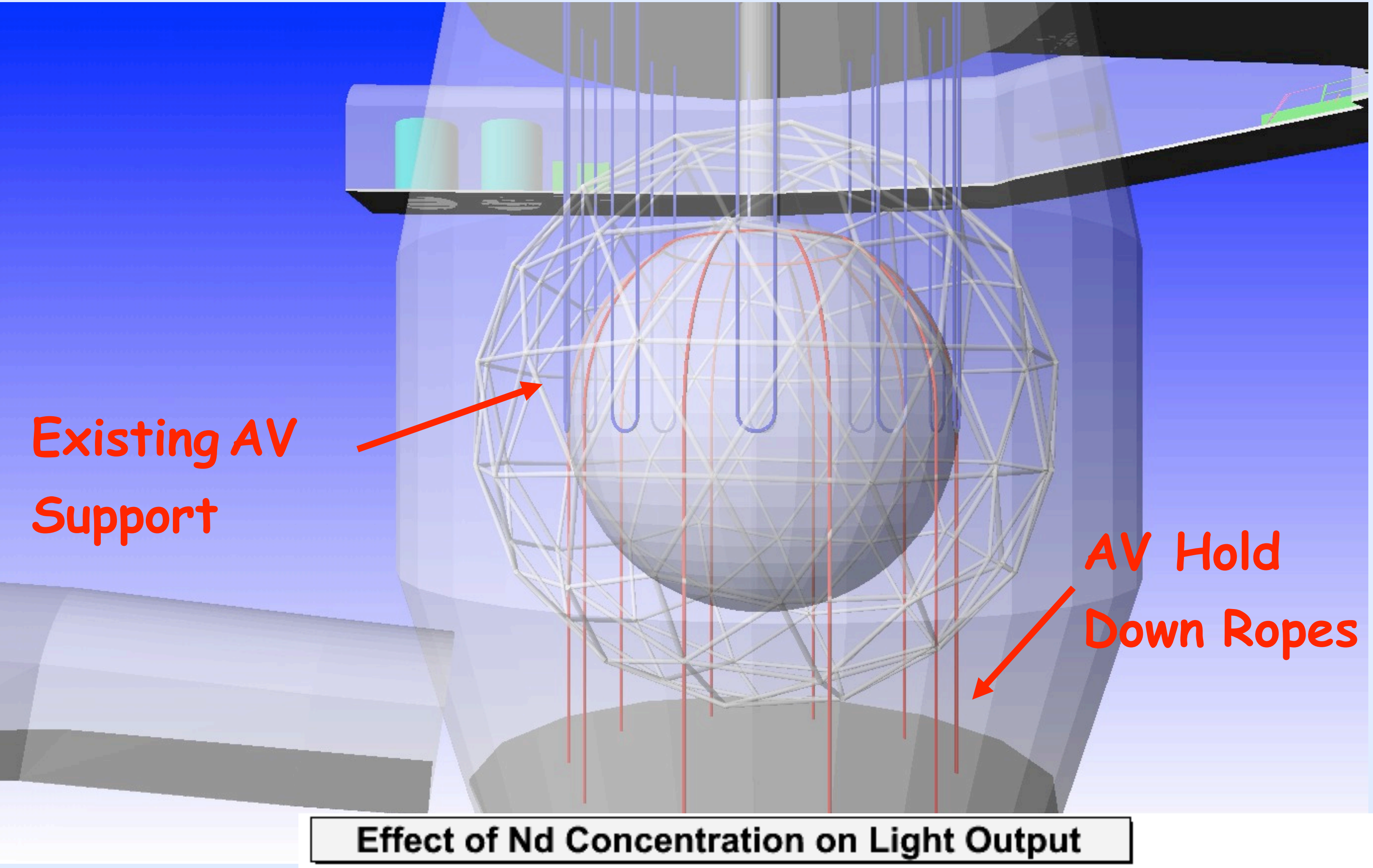
9500 PMTs

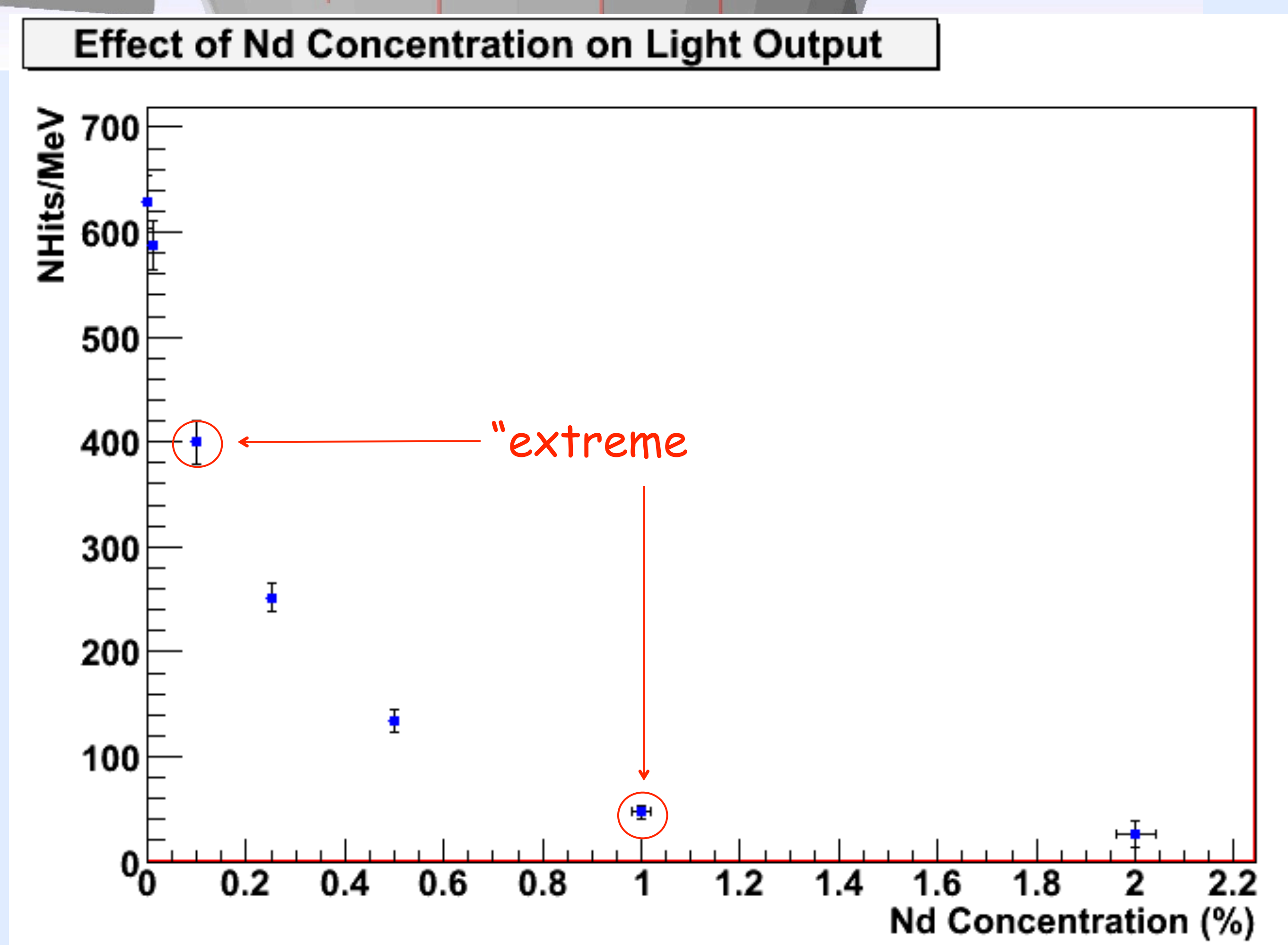
Energy res = 5 %@1 MeV

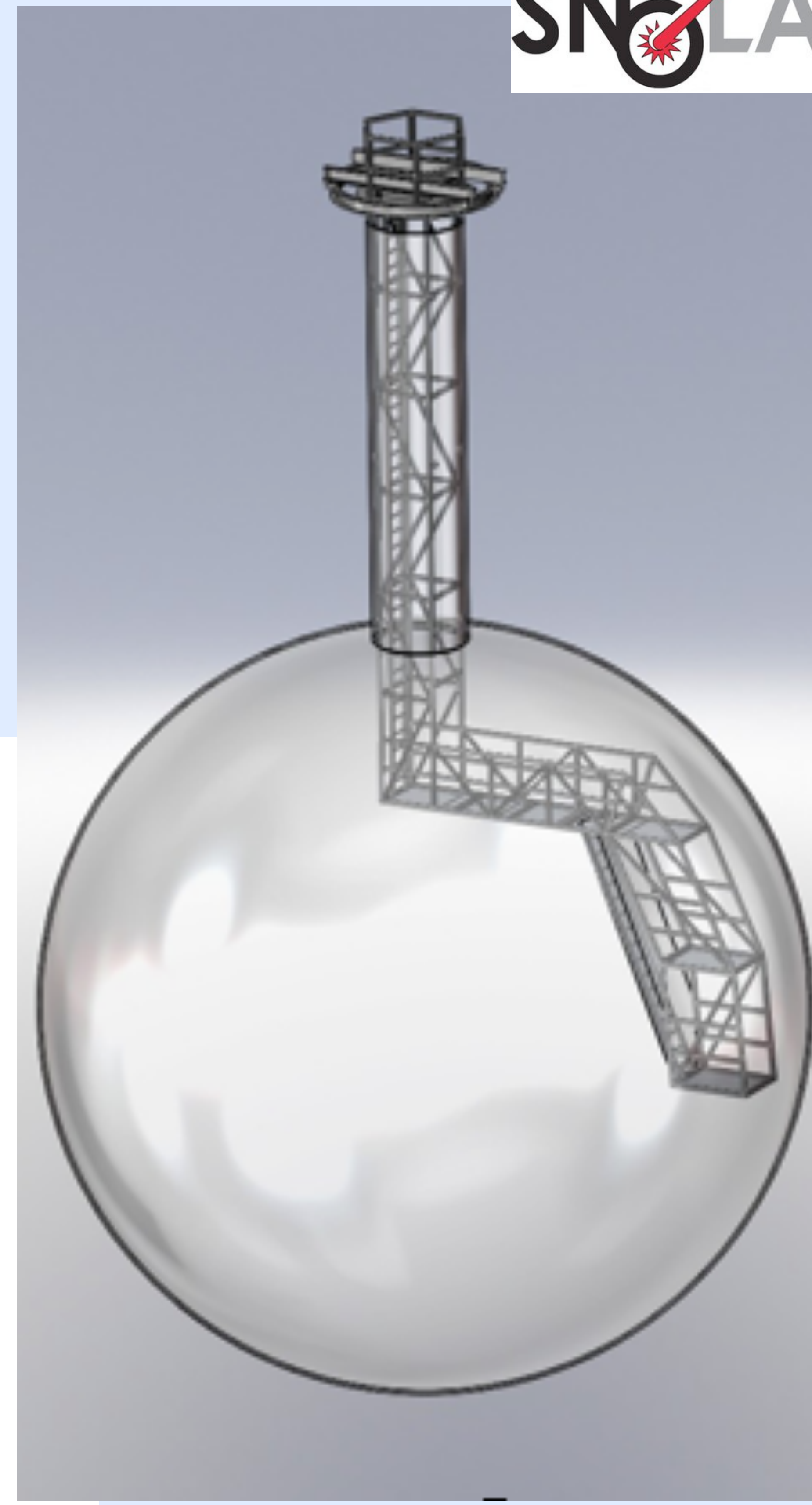
7000 t pure water shield

Hold down ropes will be installed

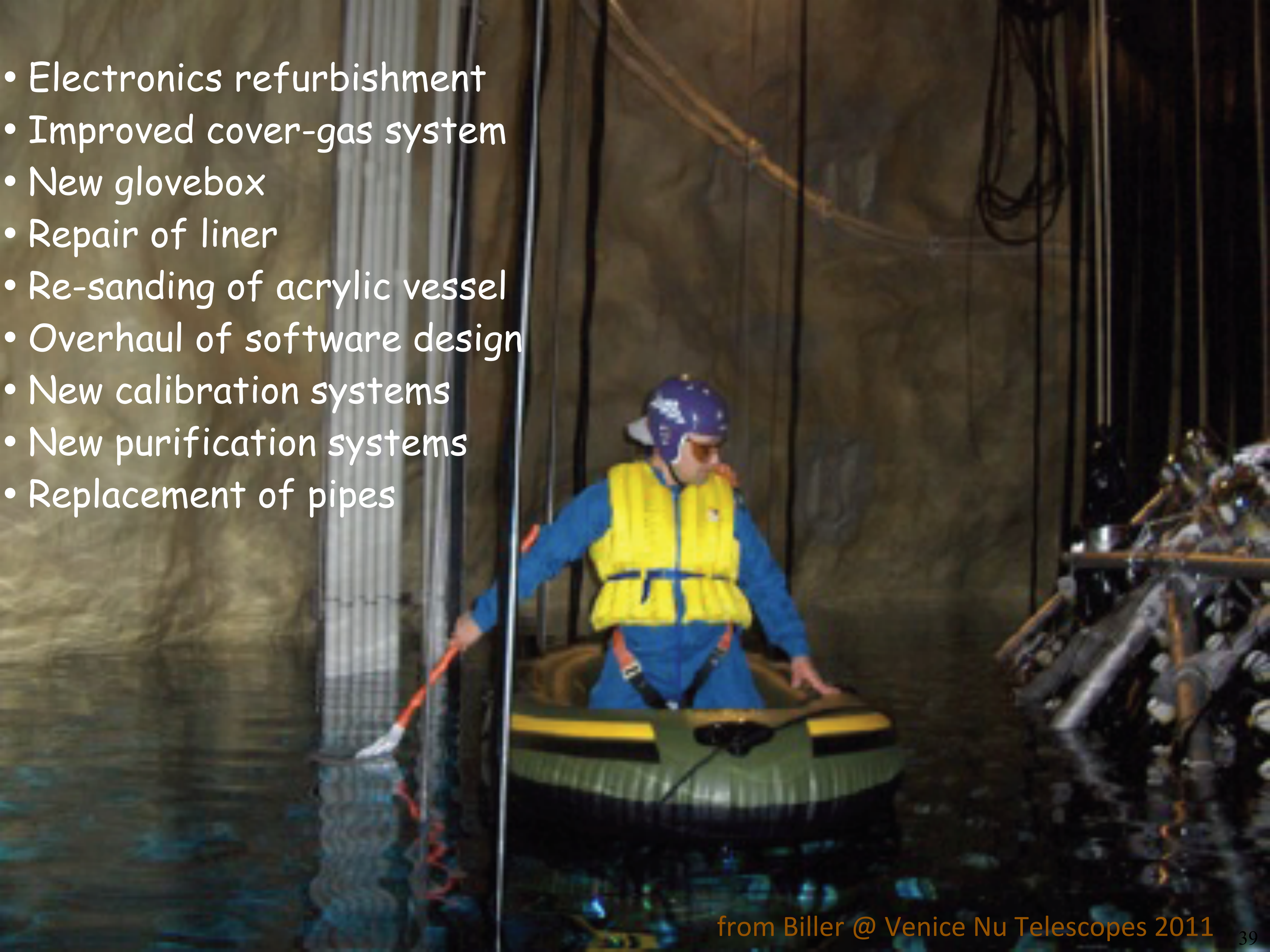






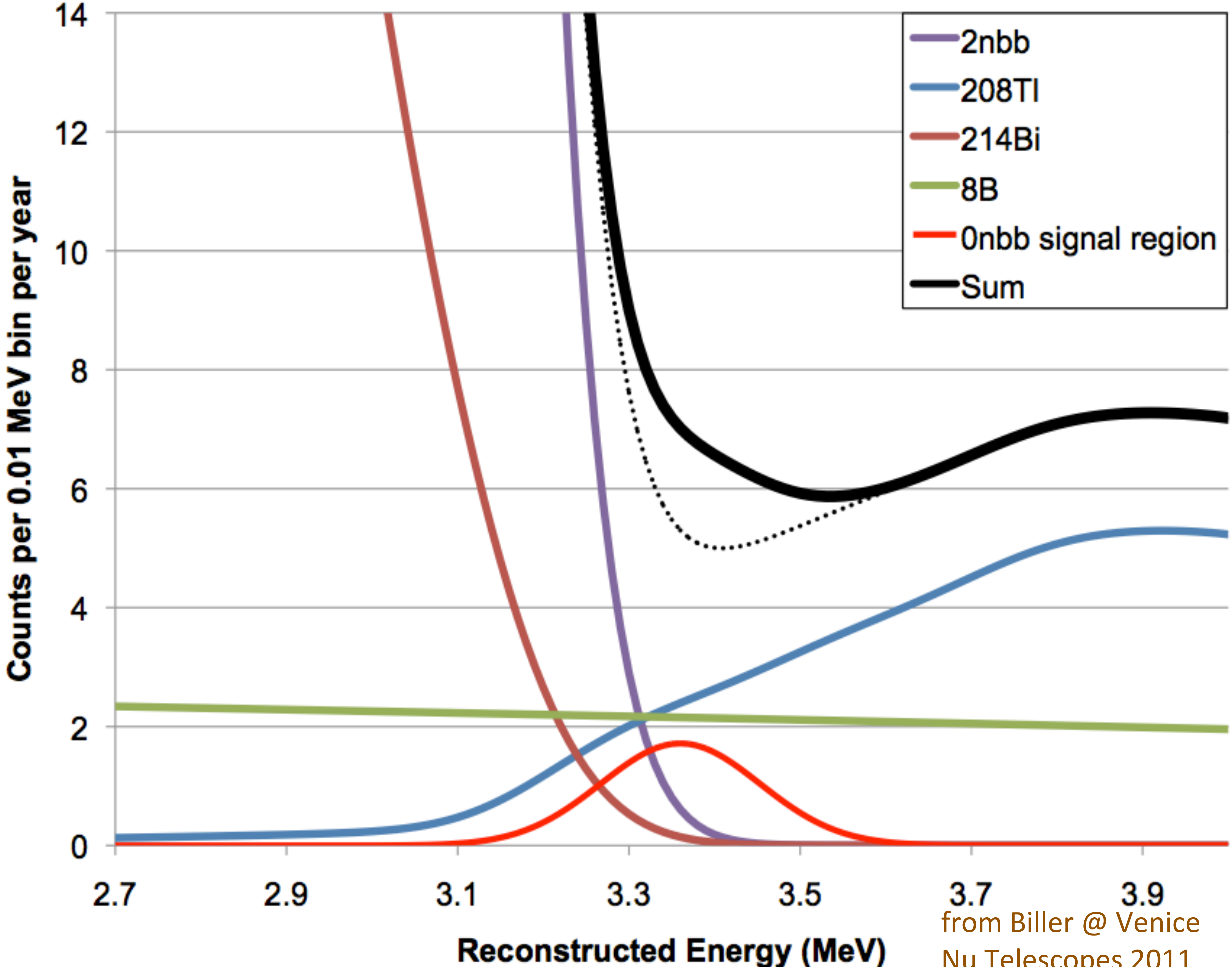


from Biller @ Venice Nu Telescopes 2011



- Electronics refurbishment
- Improved cover-gas system
- New glovebox
- Repair of liner
- Re-sanding of acrylic vessel
- Overhaul of software design
- New calibration systems
- New purification systems
- Replacement of pipes

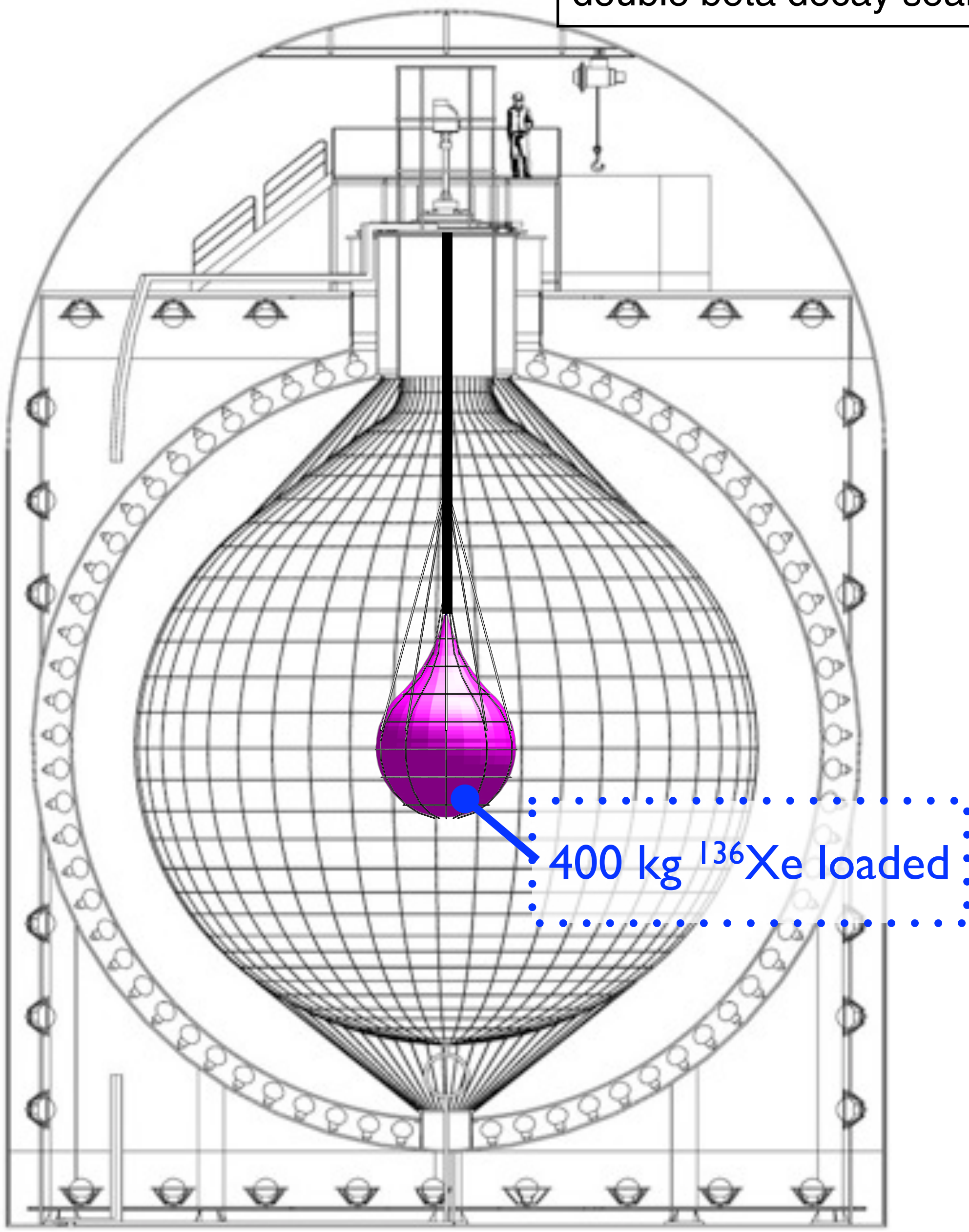
from Biller @ Venice Nu Telescopes 2011



from Biller @ Venice
Nu Telescopes 2011

KamLAND-Zen

Zero Neutrino
double beta decay search



Merit of using Xe

- isotopic enrichment, purification established
- soluble to LS more than 3 wt%, easily extracted
- slow $2\nu2\beta$ ($T_{1/2}>10^{22}$ years) requires modest energy resolution

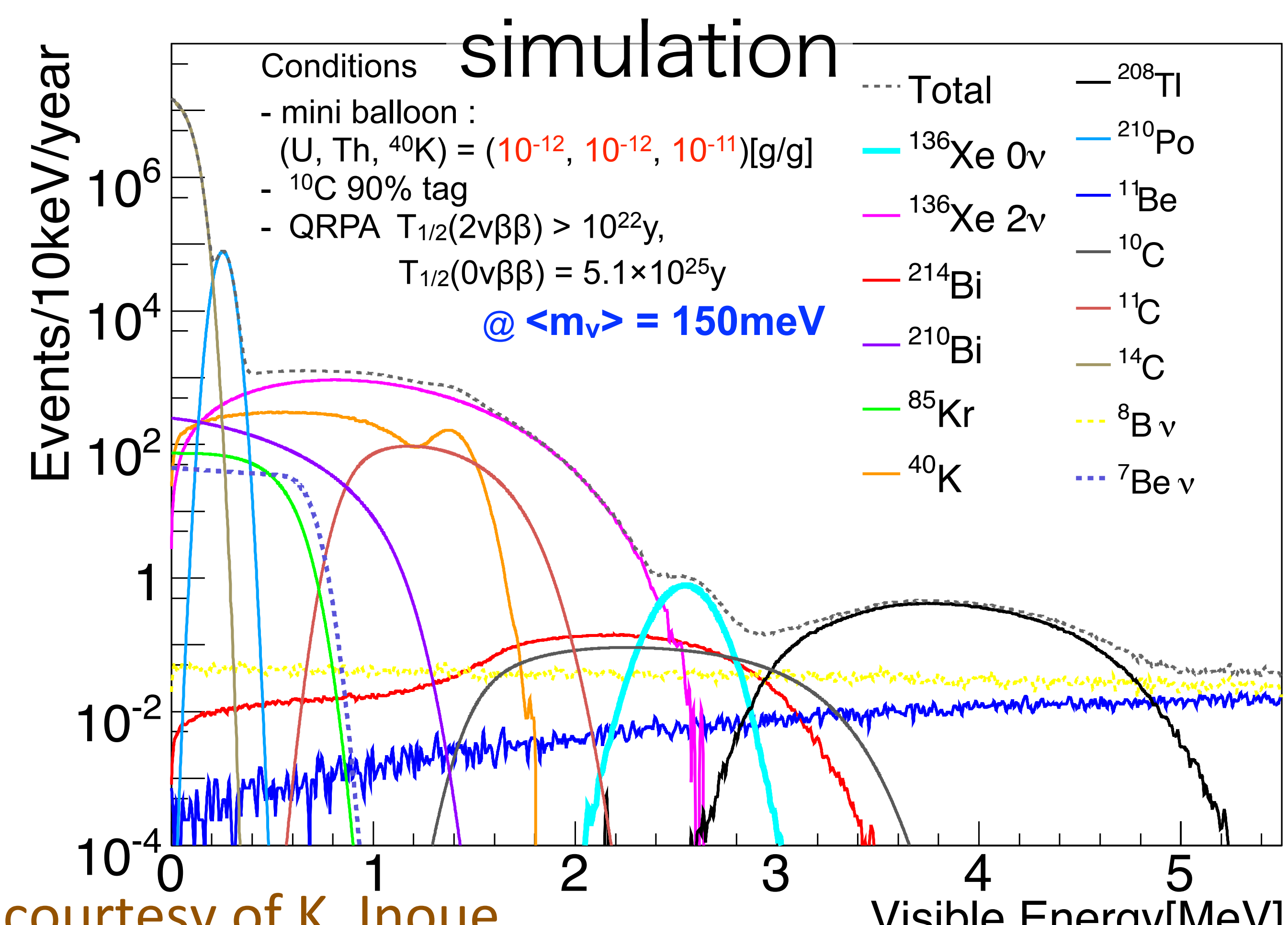
Merit of using KamLAND

- ultra low radioactivity environment based on ultra pure LS and 9m radius active shield
  U: $<3.5\times10^{-18}$ g/g, Th: $<5.2\times10^{-17}$ g/g
- no modification to the detector is necessary
- high sensitivity with low cost (1st phase budget secured, 290 kg in hand, 130kg to be delivered in June)

~60 meV in 2 years

- reactor and geo- antineutrino observations continue
- high scalability (2nd phase)
  1000 kg ^{136}Xe, improvement of energy resolution with light concentrators and brighter LS (~30M$)

~20 meV in 5 years



courtesy of K. Inoue

Preparation Status

- Xenon loaded LS with the same density, luminosity, transparency

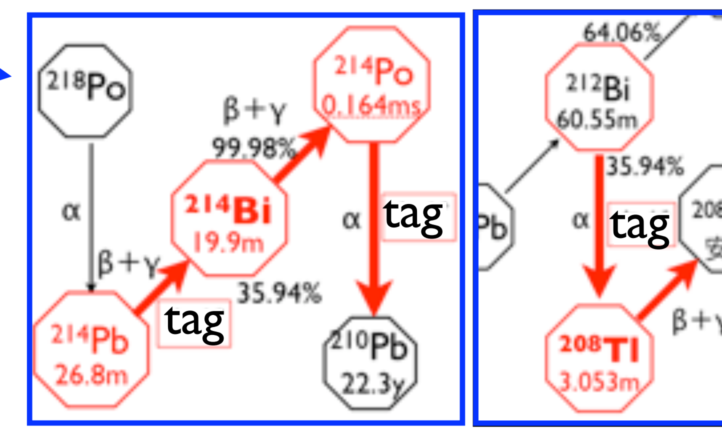
done

KamLAND LS	
dodecane	80%
pseudo-cumene	20%
PPO	1.36 g/liter

Xenon loaded LS	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
Xenon	3 wt%

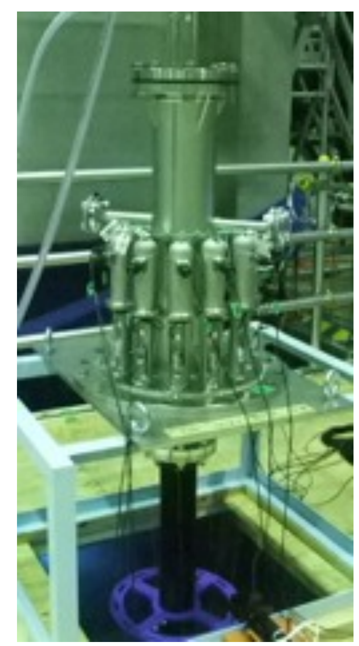
- 3.16 m ϕ Mini-balloon (target: thin, 25μm, and low radioactivity, 10^{-12} g/g U/Th)

make these possible

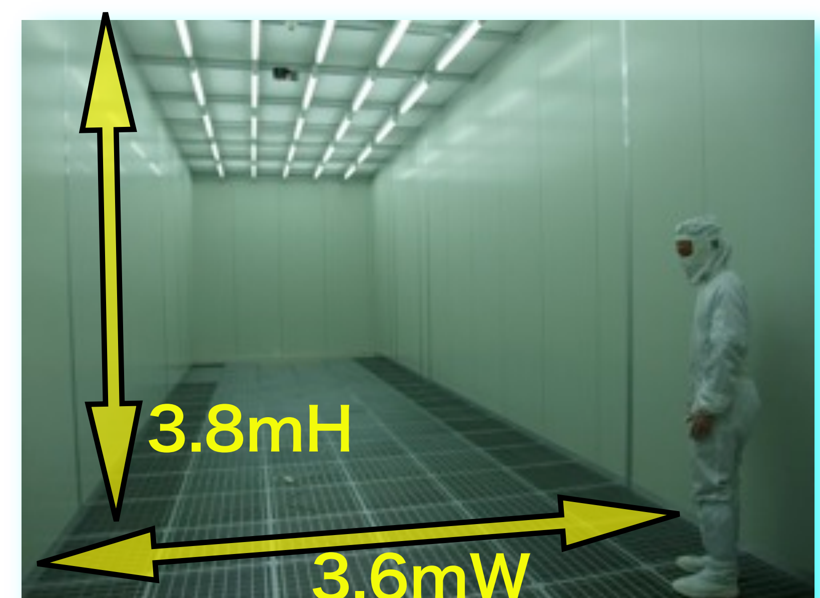


Mini-balloon fabrication with 25μm Nylon film

Rehearsal of the deployment and inflation



Mini-balloon suspension structure



Class 1 super clean room for the mini-balloon fabrication to start in May

courtesy of K. Inoue

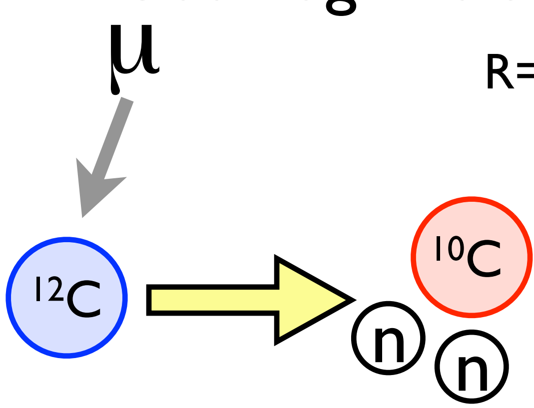
- Xenon handling system (mixing, extraction) etc

installed, starting up

Xe mixing line

Xe extraction and storage line

- Cosmogenic background rejection with dead-time free electronics



R=21.1 /kton-day

1.74~3.65 MeV

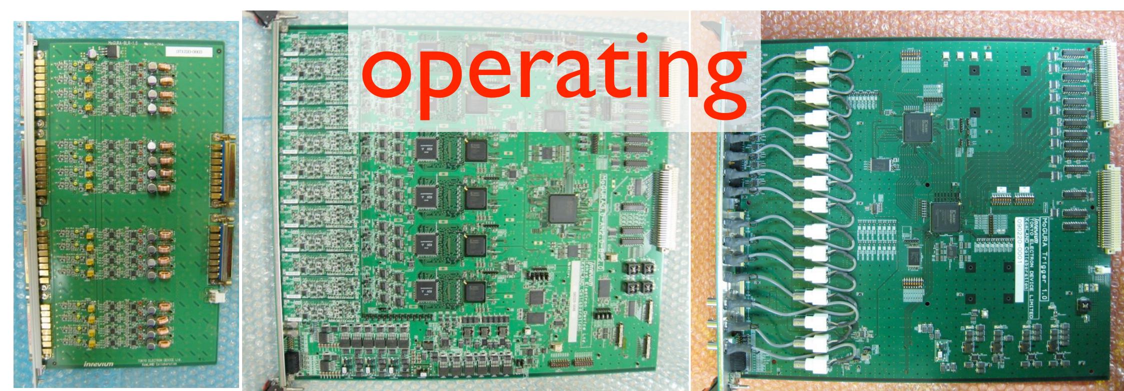
(cf. $Q_{\beta\beta}$=2.48 MeV)

τ=27.8 sec

τ=207 μsec

factor 20 reduction with neutron tagging

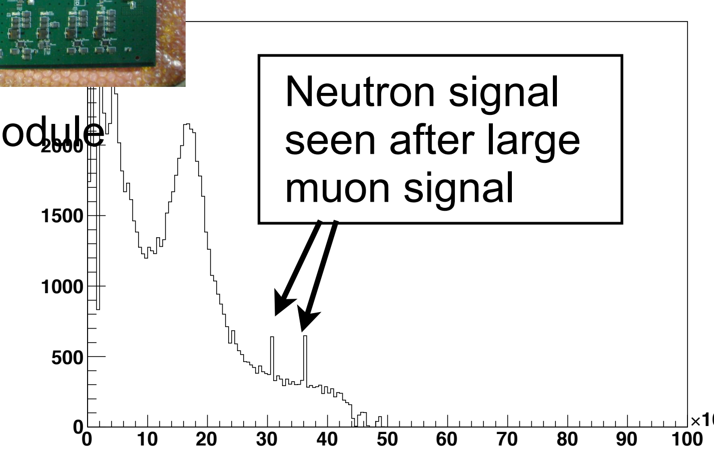
operating



Baseline restorer and signal splitter

1GHz FADC +
3 range 200 MHz FADC
for each channel

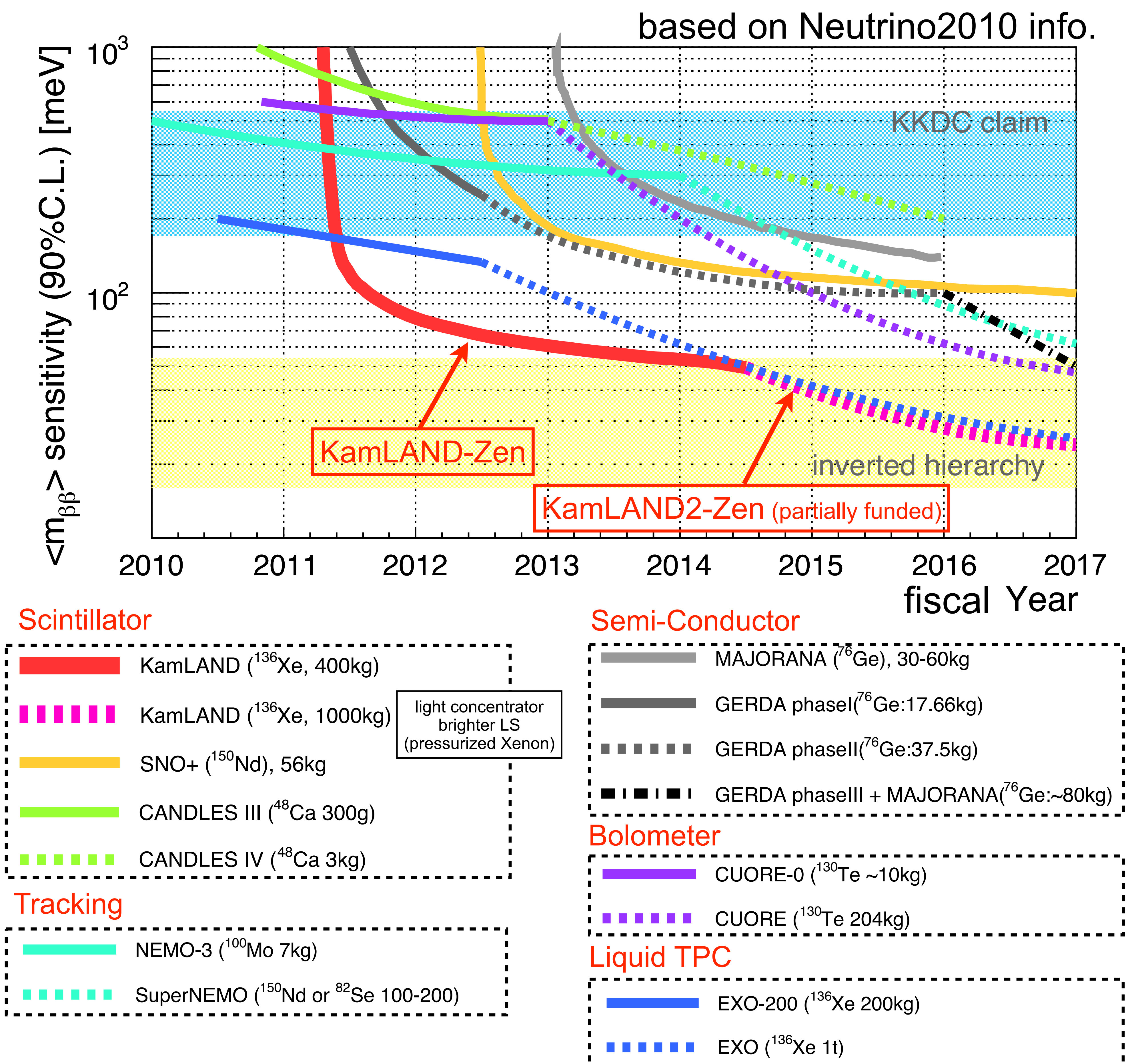
Trigger module

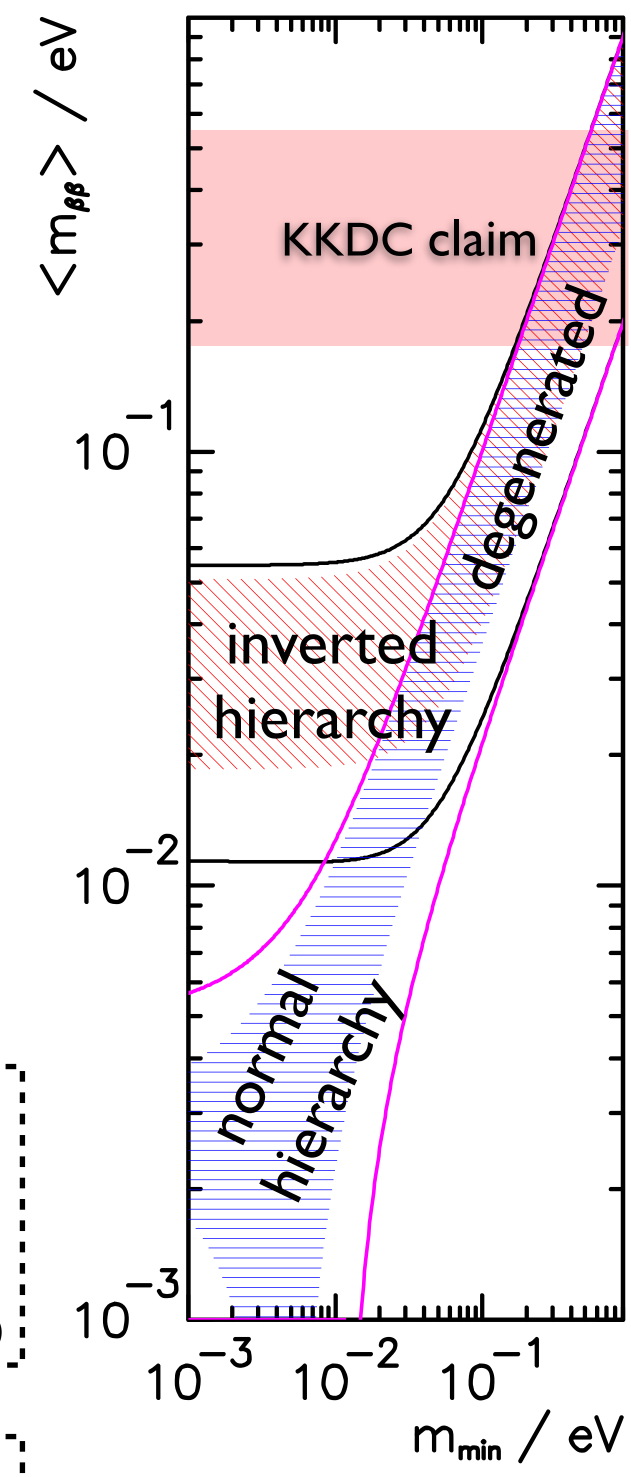


KamLAND-Zen planned to start in August

courtesy of K. Inoue

Expected sensitivity of KamLAND-Zen





courtesy of K. Inoue

xenon experiments

✓ known purification technology (both pure or in scintillator)

✓ can be re-purified and transferred between detectors

✓ simplest enrichment (proven at the 100's kg scale)

✓ scalable technology (dark matter experiments help!)

✓ source = detector, high detection efficiency

✓ allows for particle ID

✓ standard $2\nu\beta\beta$ mode not observed yet

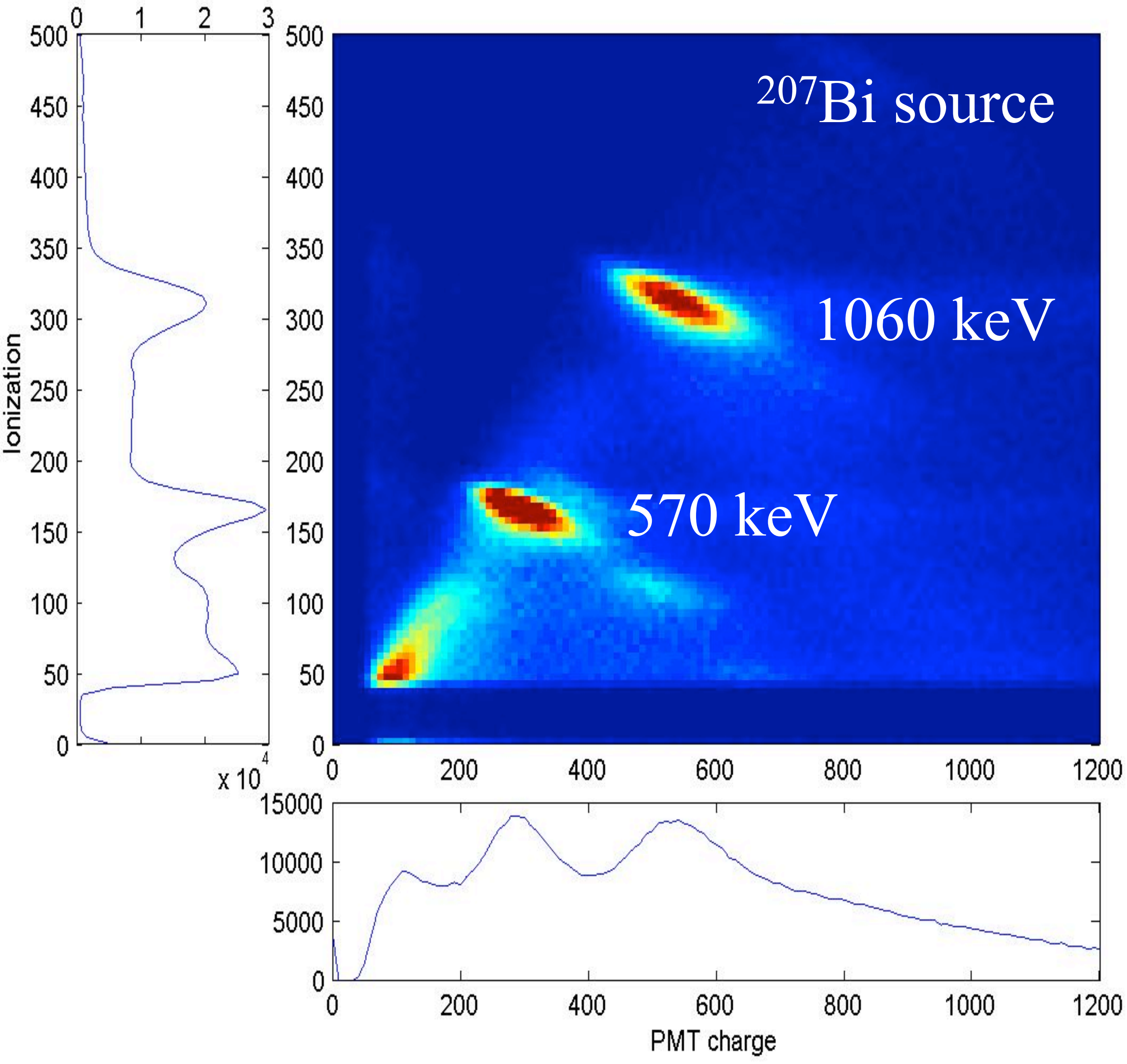
(current limit: $T^{0\nu}_{1/2} > 1 \times 10^{22}$ y) [R. Bernabei et al., Phys. Lett. B 546 (2002) 23]

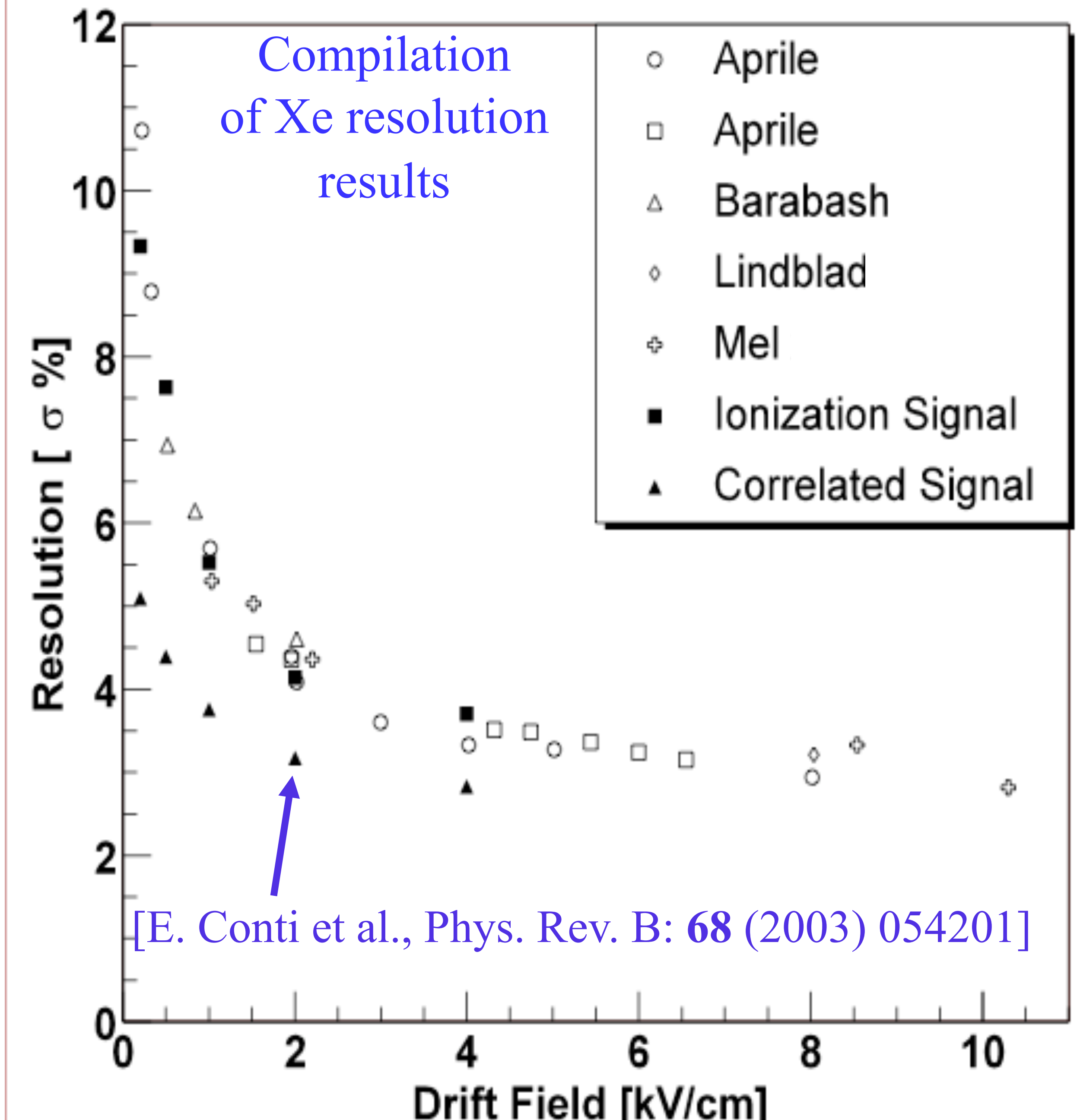
✴ energy resolution: GXe > LXe > scintillator

Anti-correlated ionization and scintillation improves the energy resolution in LXe

Ionization alone:
σ(E)/E = 3.8% @ 570 keV
or 1.8% @ $Q_{\beta\beta}$

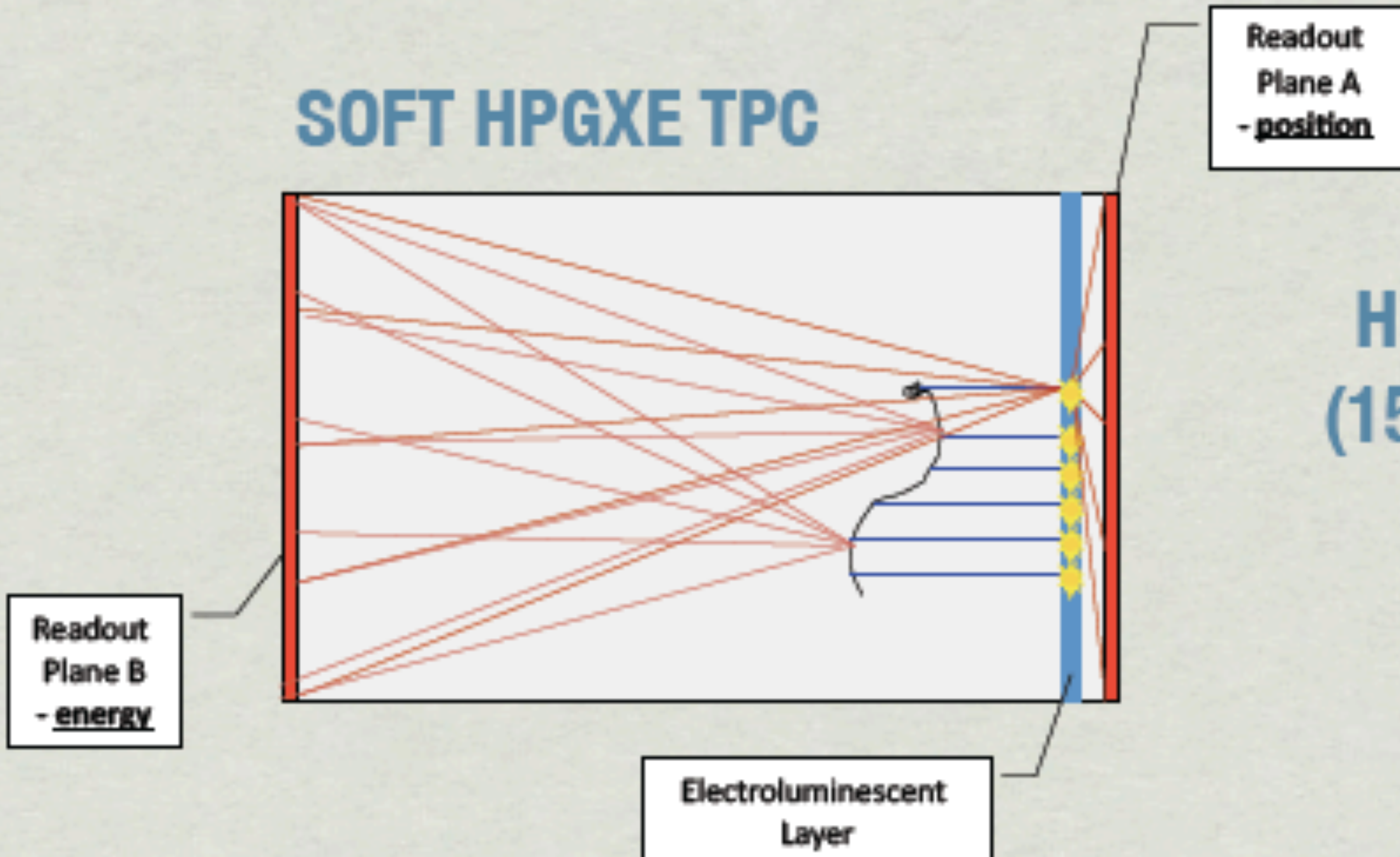
Ionization + Scintillation:
σ(E)/E = 3.0% @ 570 keV
or 1.4% @ $Q_{\beta\beta}$





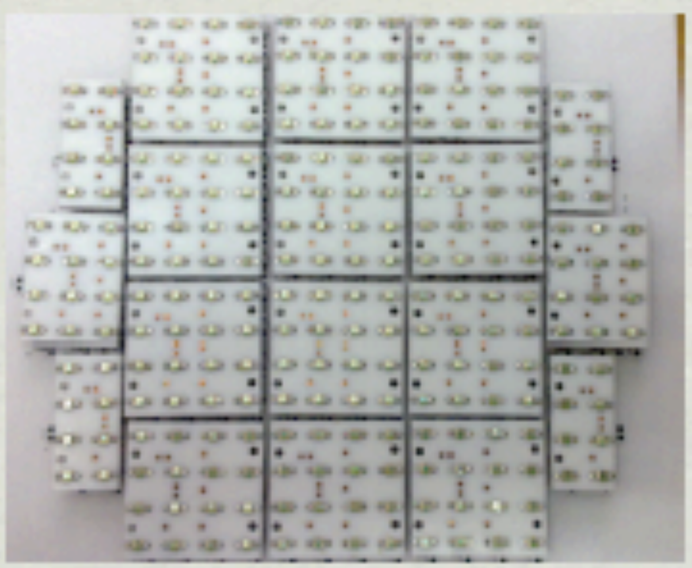
NEXT TECHNOLOGY

SOFT HPGXE TPC

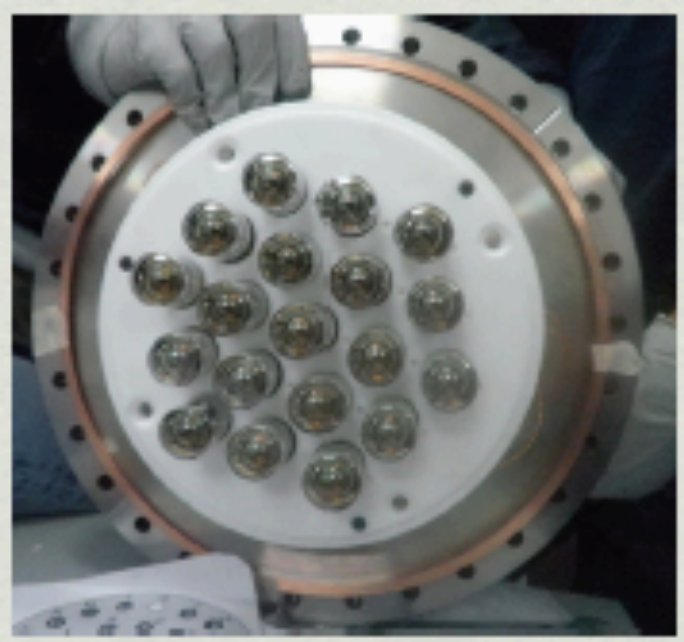


HPGXE
(15 BAR)

TRACKING PLANE (SIPMS)



SIPMS COATED WITH TPB

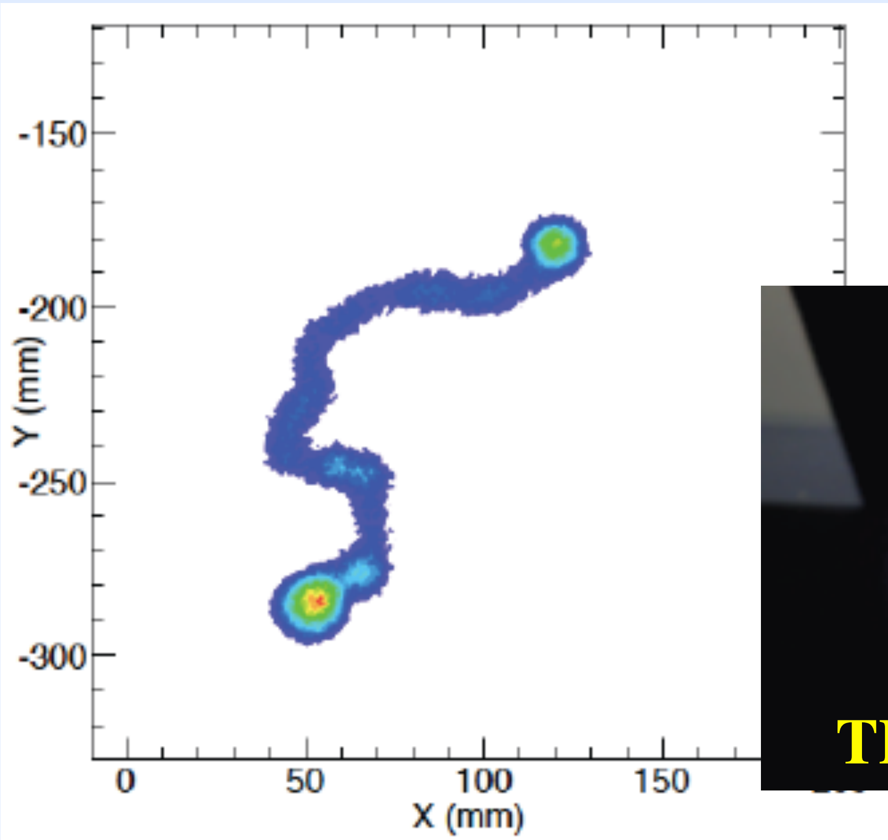


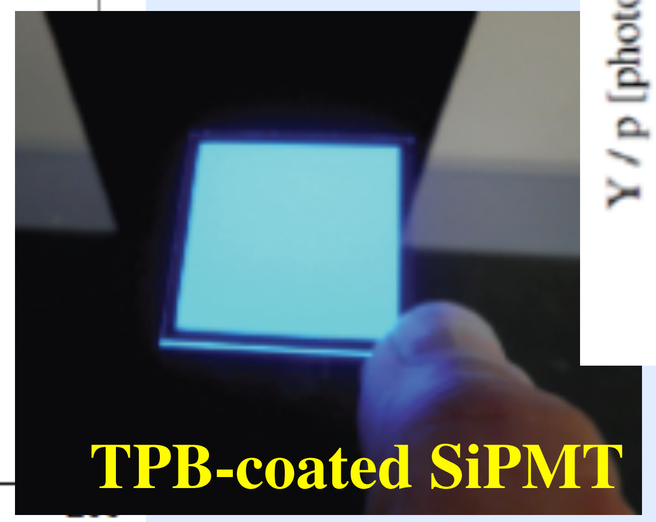
ENERGY PLANE (PMTS)

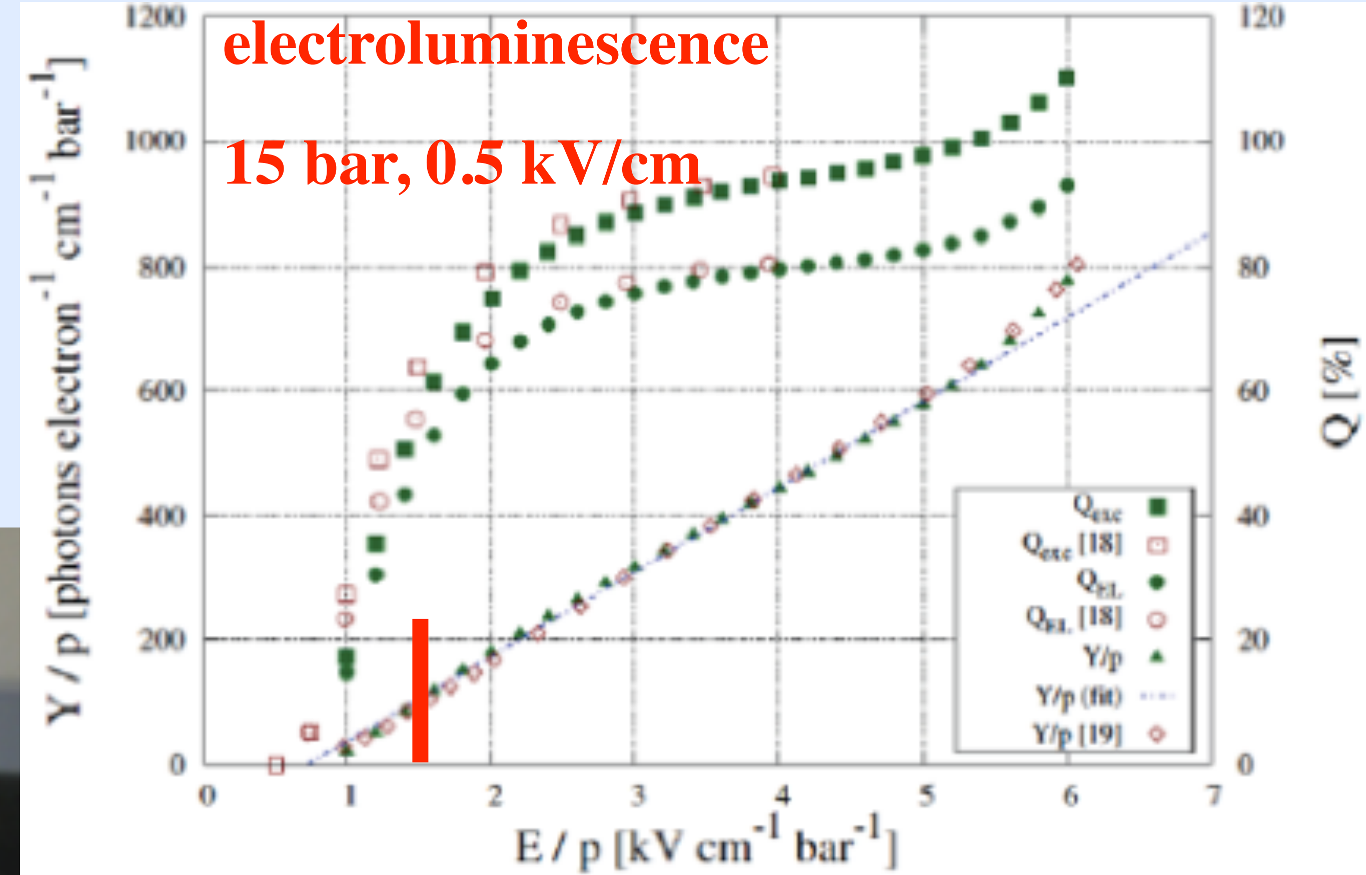
ENRICHED XENON AT LSC

courtesy of JJ Gomez Cadenas

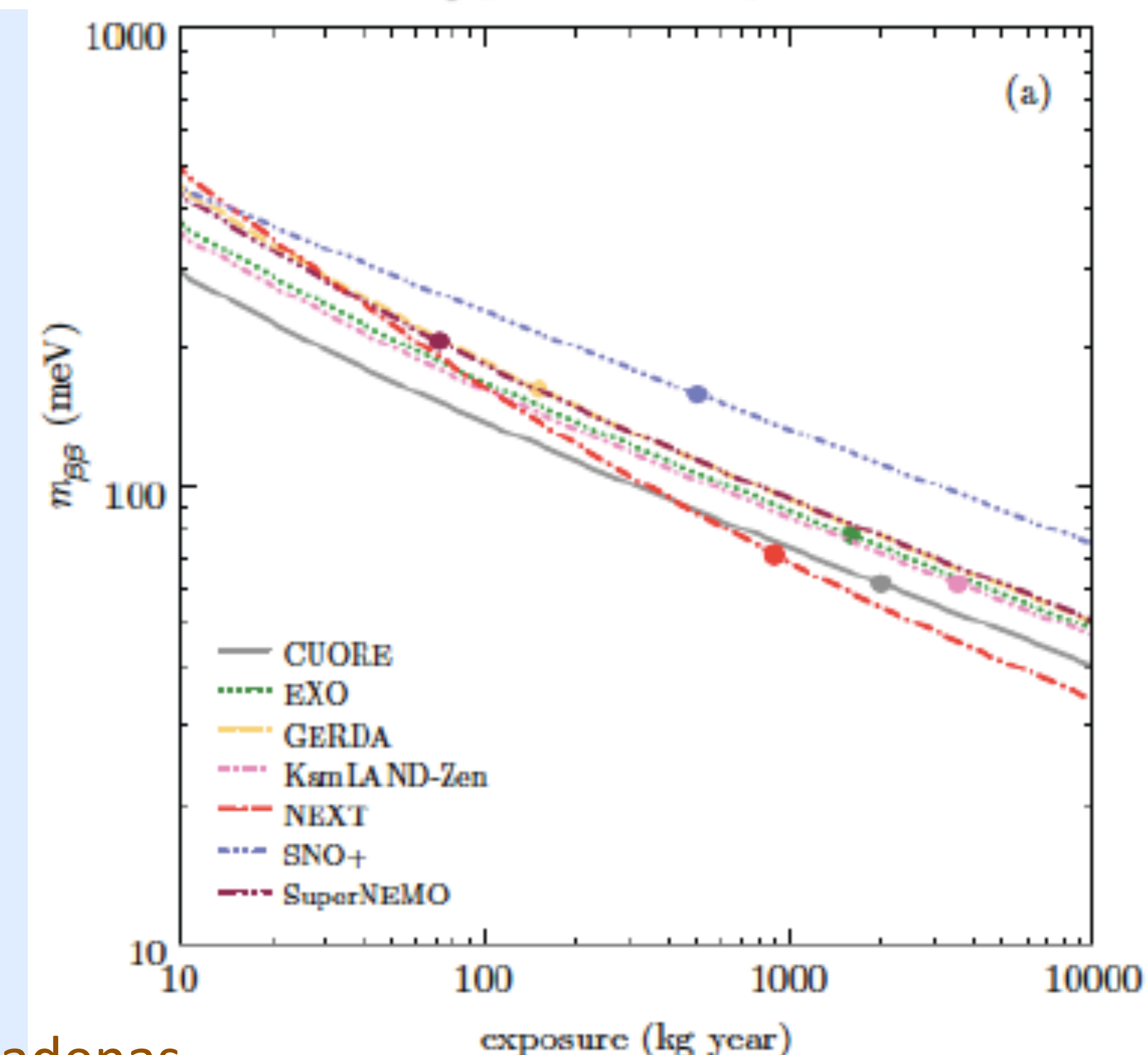
NEXT-100 @ LSC







- ✓ 1 vs 2 electrons!
- ✓ good energy resolution
- ✓ $2{\times}10^7$ bg rejection
- ✓ $2{\times}10^{-4}$ cts/keV/y/kg



- Depleted Xenon run in 2014

courtesy of JJ Gomez Cadenas

the EXO program

"EXO is a program aimed at building a xenon double beta decay experiment with a one or more ton ^{136}Xe source, with the particular ability to detect the two electrons emitted in the decay in coincidence with the positive identification of the ^{136}Ba daughter via optical spectroscopy for unprecedentedly low background"

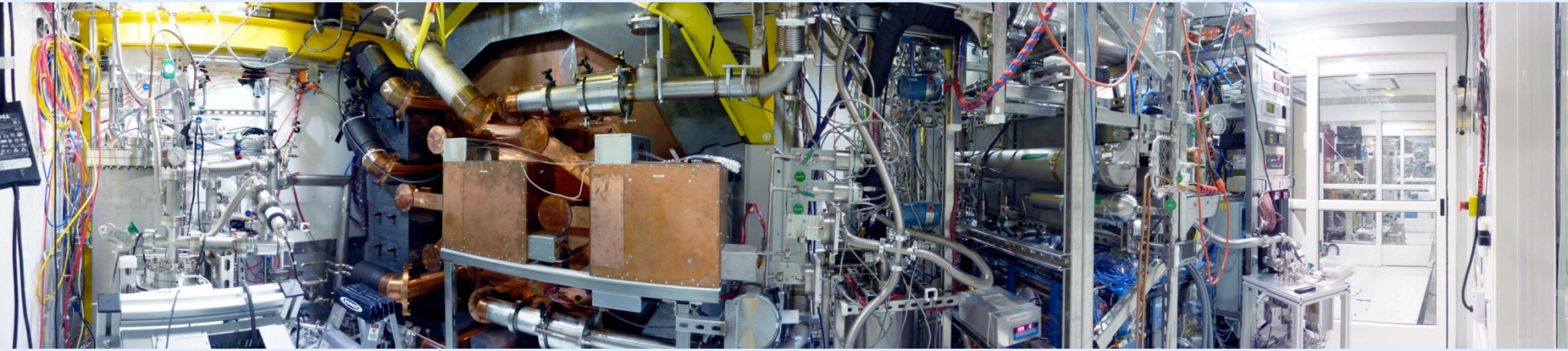
EXO-200

EXO-200 is a large LXe TPC with scintillation light readout. It uses a source of 200 kg of enriched xenon (80% ^{136}Xe).

$\rightarrow$ EXO-200 has no $^{136}Ba^{+}$ identification $\leftarrow$

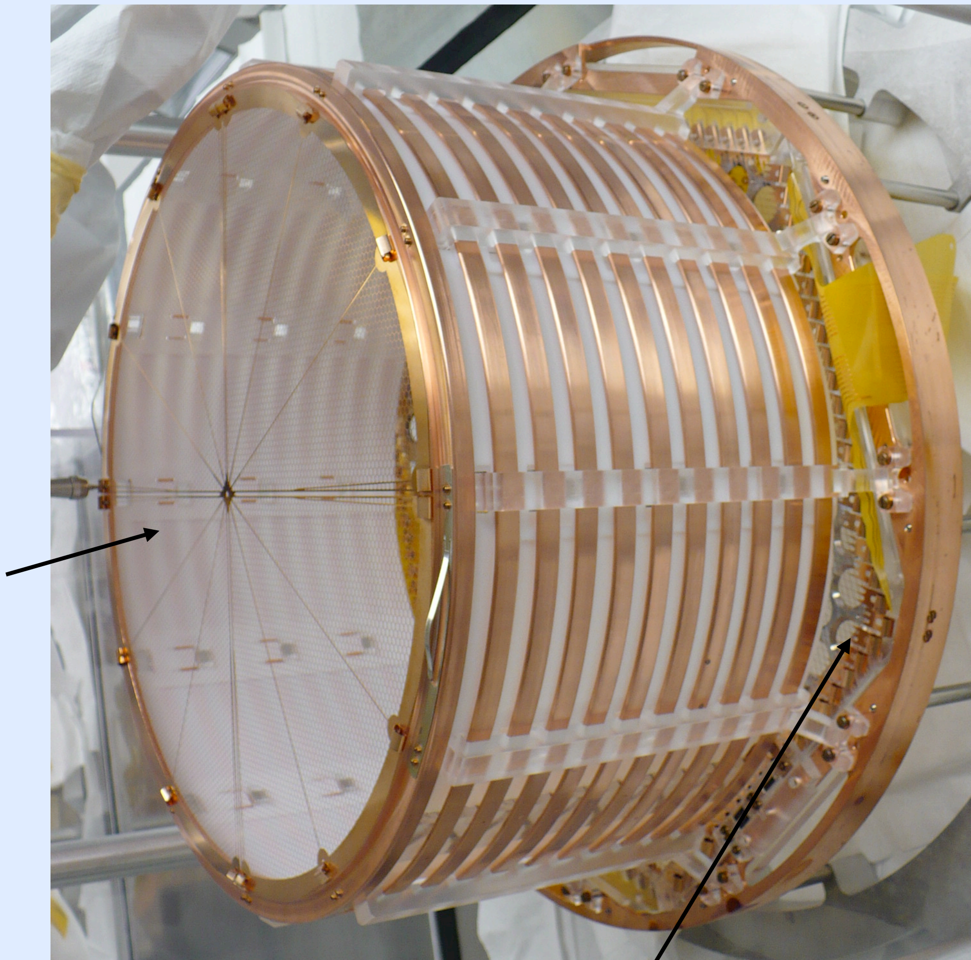
- look for $0\nu\beta\beta$ decay of ^{136}Xe with competitive sensitivity (current limit: $T^{0\nu}_{1/2} > 1.2 \times 10^{24}$ y)
  [R. Bernabei et al., Phys. Lett. B 546 (2002) 23]
- measure the standard $2\nu\beta\beta$ decay of ^{136}Xe
- test backgrounds of large LXe detector at ~2000 m.w.e. depth
- test LXe technology and enrichment on a large scale
- test TPC components, light readout (~500 LAAPDs), and radioactivity of materials, xenon handling and purification, energy resolution

EXO-200 @ WIPP

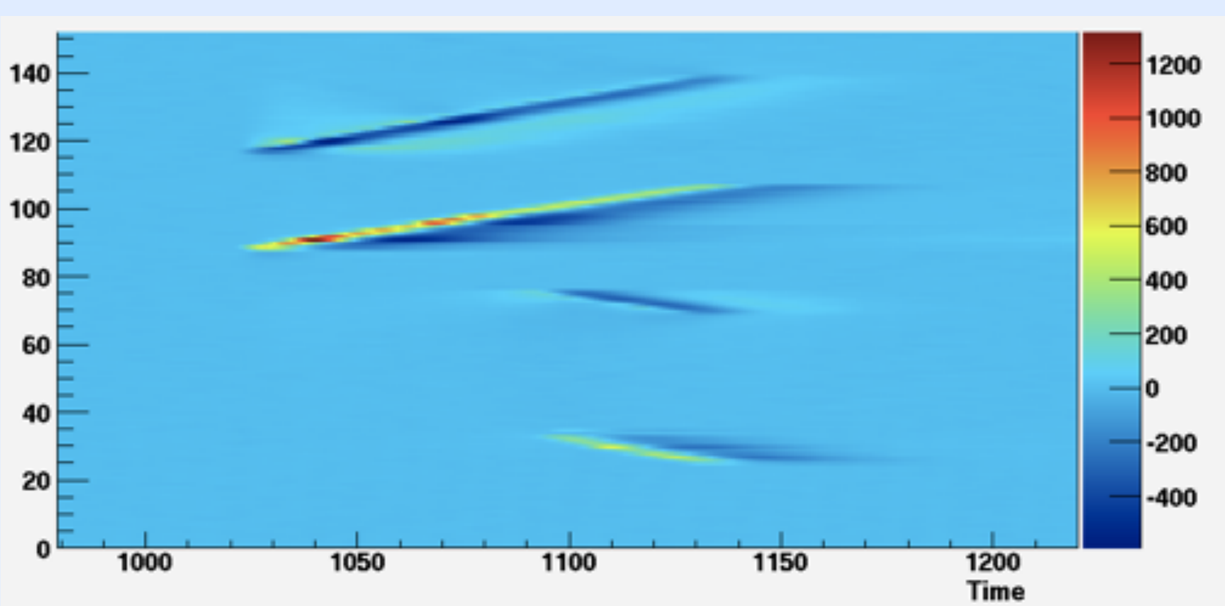


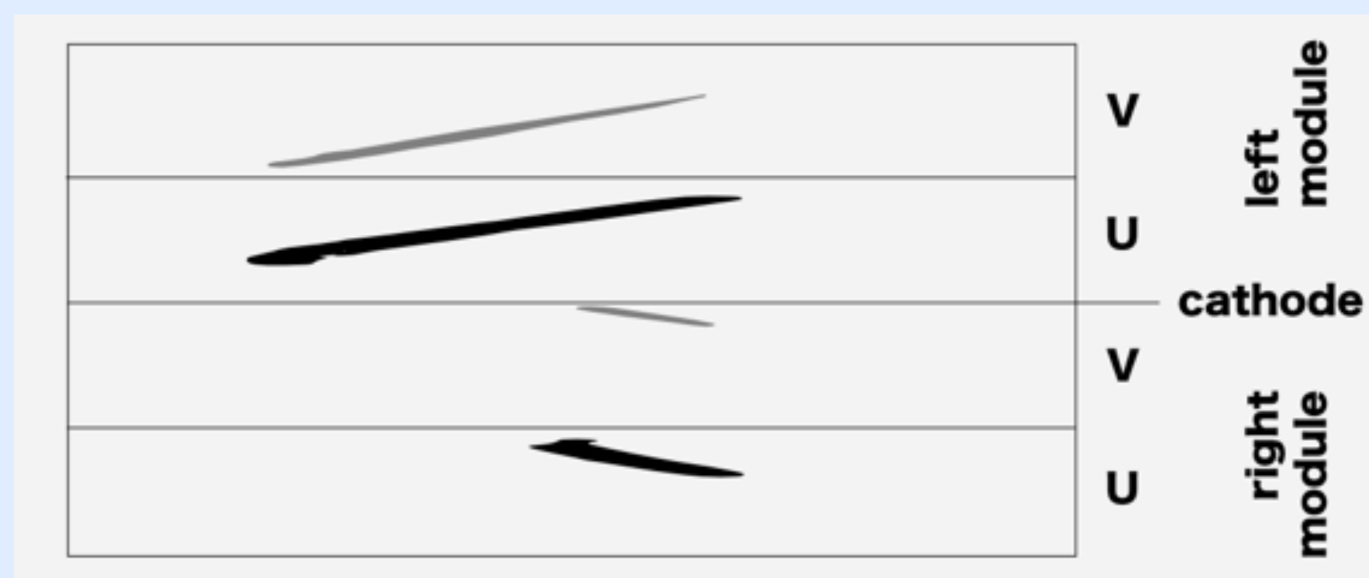
EXO-200 engineering run (Dec 2010)

- ✓ natural xenon
- ✓ test stability of LXe/GXe systems
- ✓ measure Xe purity
- ✓ generally test detector performance
- ✓ test source calibration system
- ✓ test Xe emergency recovery
- ✳ no front Pb shield
- ✳ no Rn-suppressed enclosure
- ✳ no Rn trap in Xe system
- ✳ no muon veto

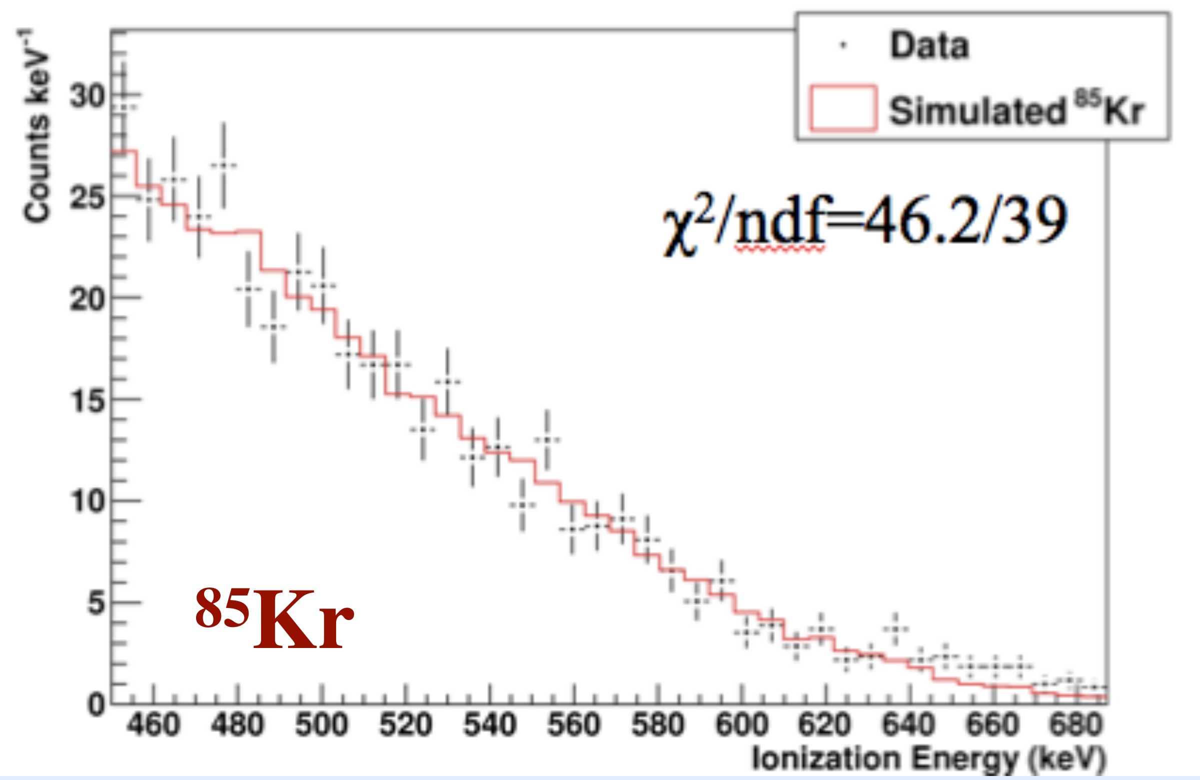


a muon event:





some known offenders (in ^{nat}Xe)

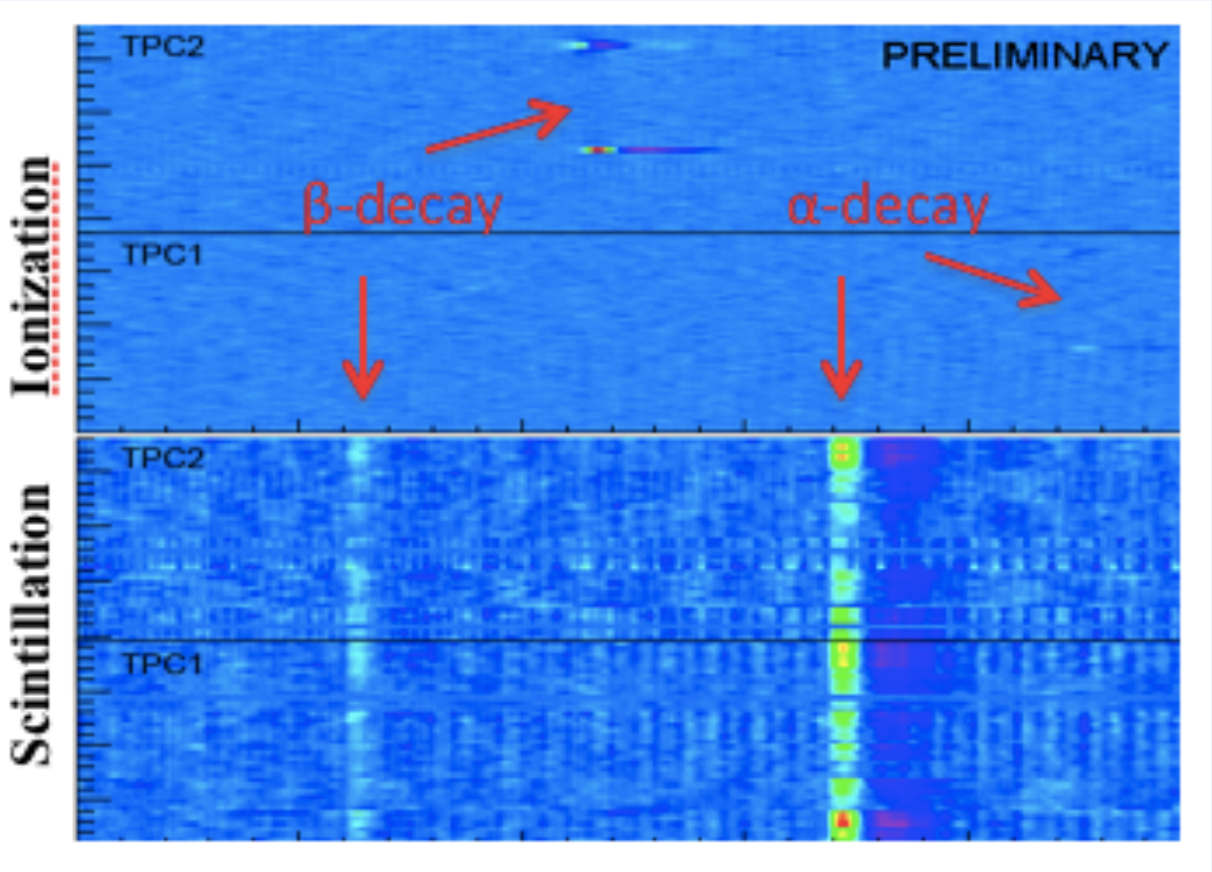


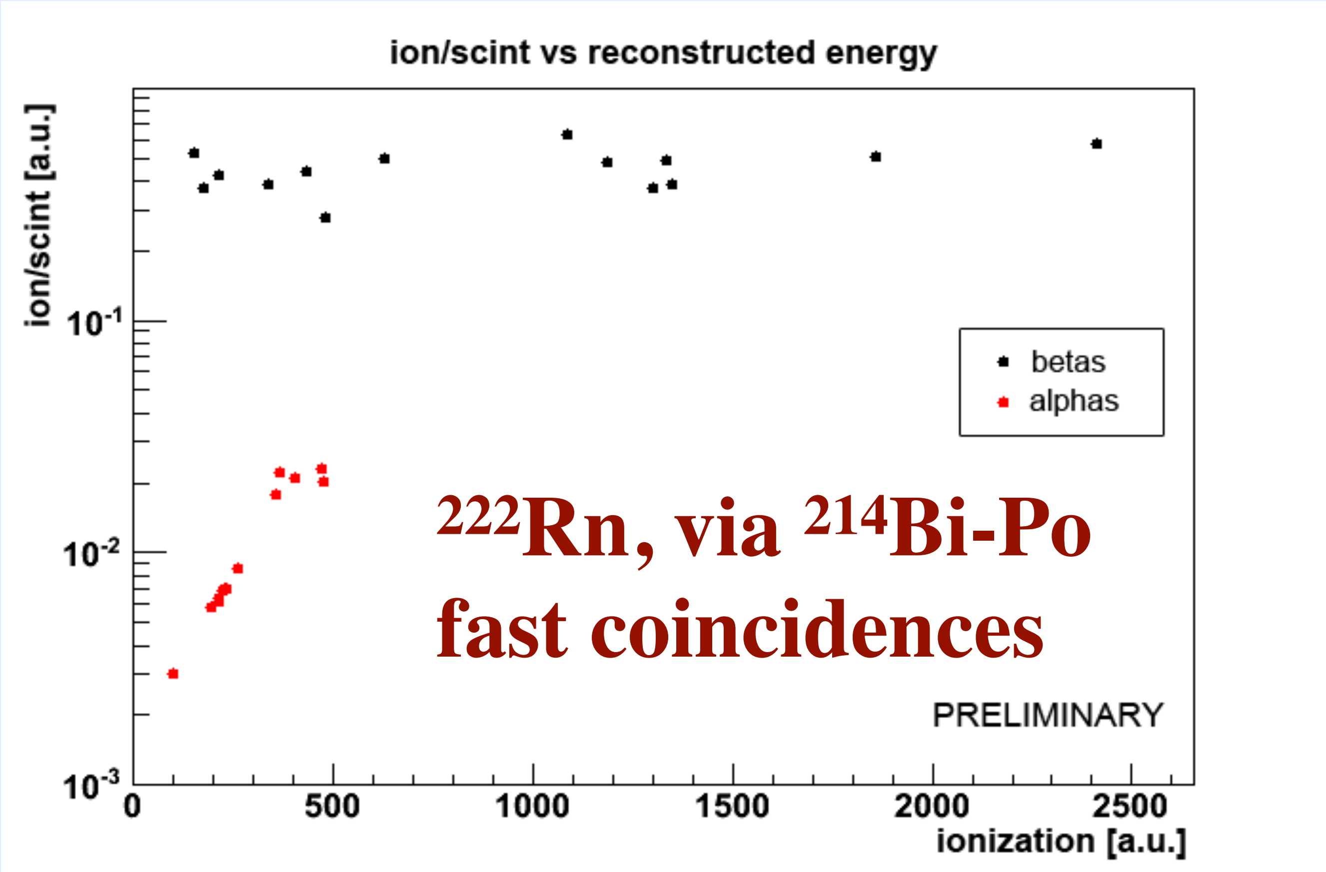
the total Kr concentration in the ^{nat}Xe was measured to be, using a special technique involving mass-spectroscopic analysis in the gas phase,

$$(42.6 \pm 5.7)\cdot 10^{-9} \text{ g/g}$$

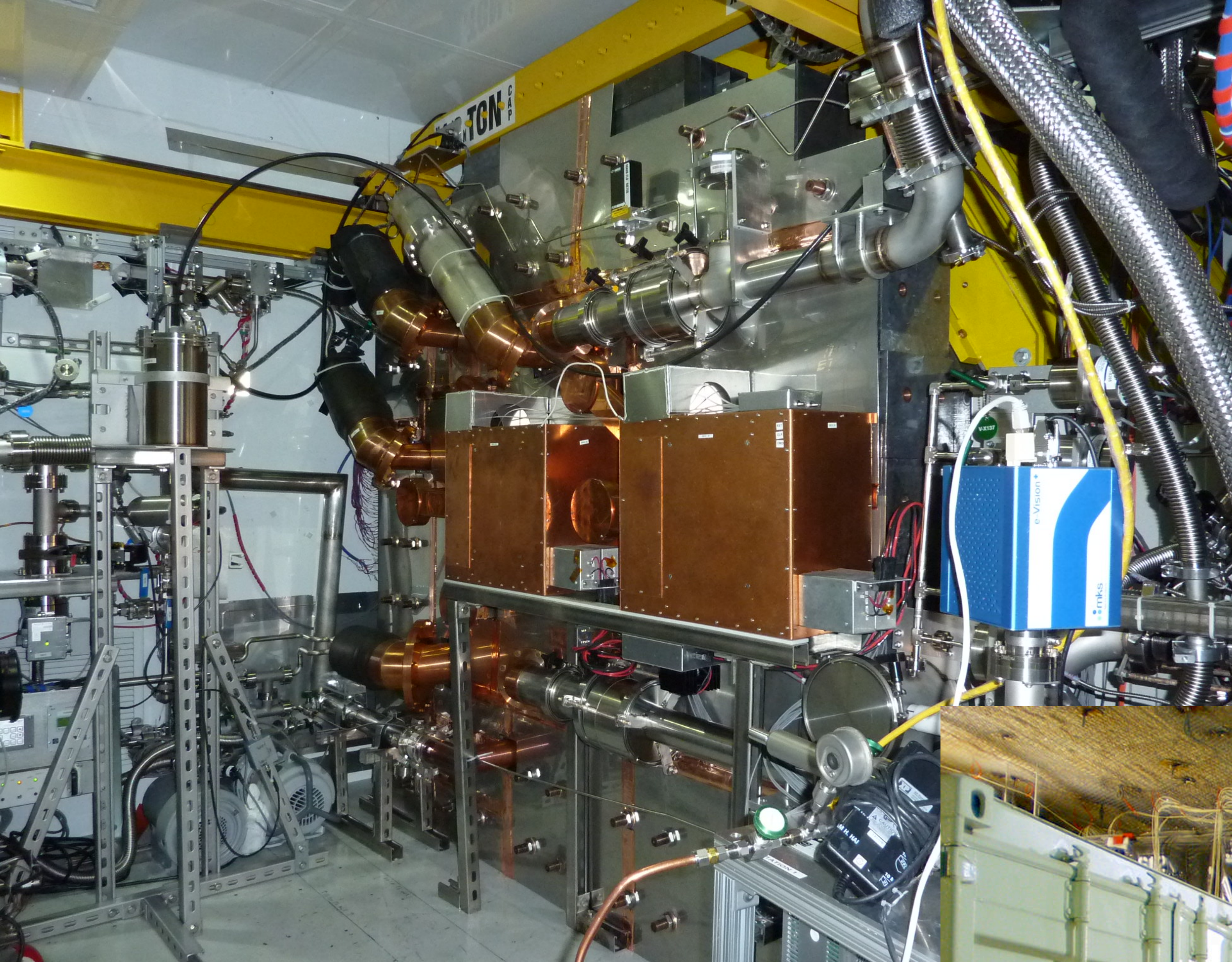
[A. Dobi et al., arXiv:1103.2714v1]

→ consistent with Mass Spec result assuming standard ^{85}Kr/Kr concentration of ~10^{-11}





status of EXO-200



Front shield
& Rn enclosure

Veto counter installed
and commissioned

now running with
enriched xenon!

refer to Russell Neilson's talk for more details

EXO-200 sensitivity

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (meV) QRPA[1]	NSM[2]
EXO-200	0.2	70	2	1.6*	40	6.4×10^{25}	109	135

** σ(E)/E = 1.4% obtained in EXO R&D, Conti et al., Phys. Rev. B 68 (2003) 054201*

[1] Simkovic et al. Phys. Rev. C79, 055501(2009) [use RQRPA and g_A= 1.25]

[2] Menendez et al., Nucl. Phys. A818, 139(2009), use UCOM results

improves sensitivity for ^{136}Xe $0\nu\beta\beta$ by one order of magnitude

should detect $2\nu\beta\beta$ of ^{136}Xe (~50 events/day at current limit)

(reference: 10^{25} years lifetime => 440 events/year/ton of ^{136}Xe)

discovery claim in ^{76}Ge: $T_{1/2} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ y

46/170 (QRPA/NSM) events above 40 bg: confirm or rule out at 5/11.7 σ

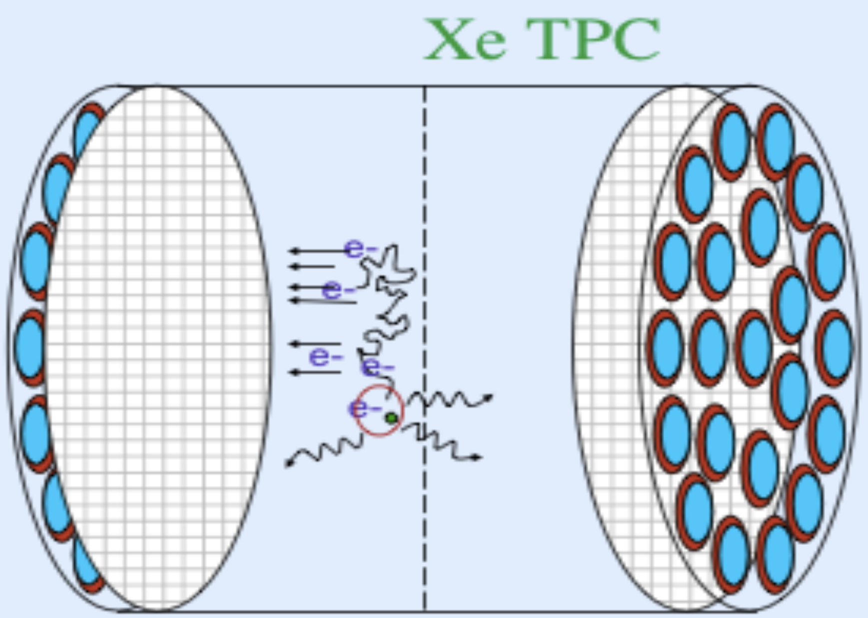
a ton-scale EXO

xenon admits a novel coincidence technique:

drastic background reduction by Ba daughter tagging!

detect the 2 electrons
(ionization + scintillation in xenon detector)

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^{-} \ (+\ 2\nu_e)$$



[M. Moe, Phys. Rev. C 44 (1991) R931]

a ton-scale EXO

xenon admits a novel coincidence technique:

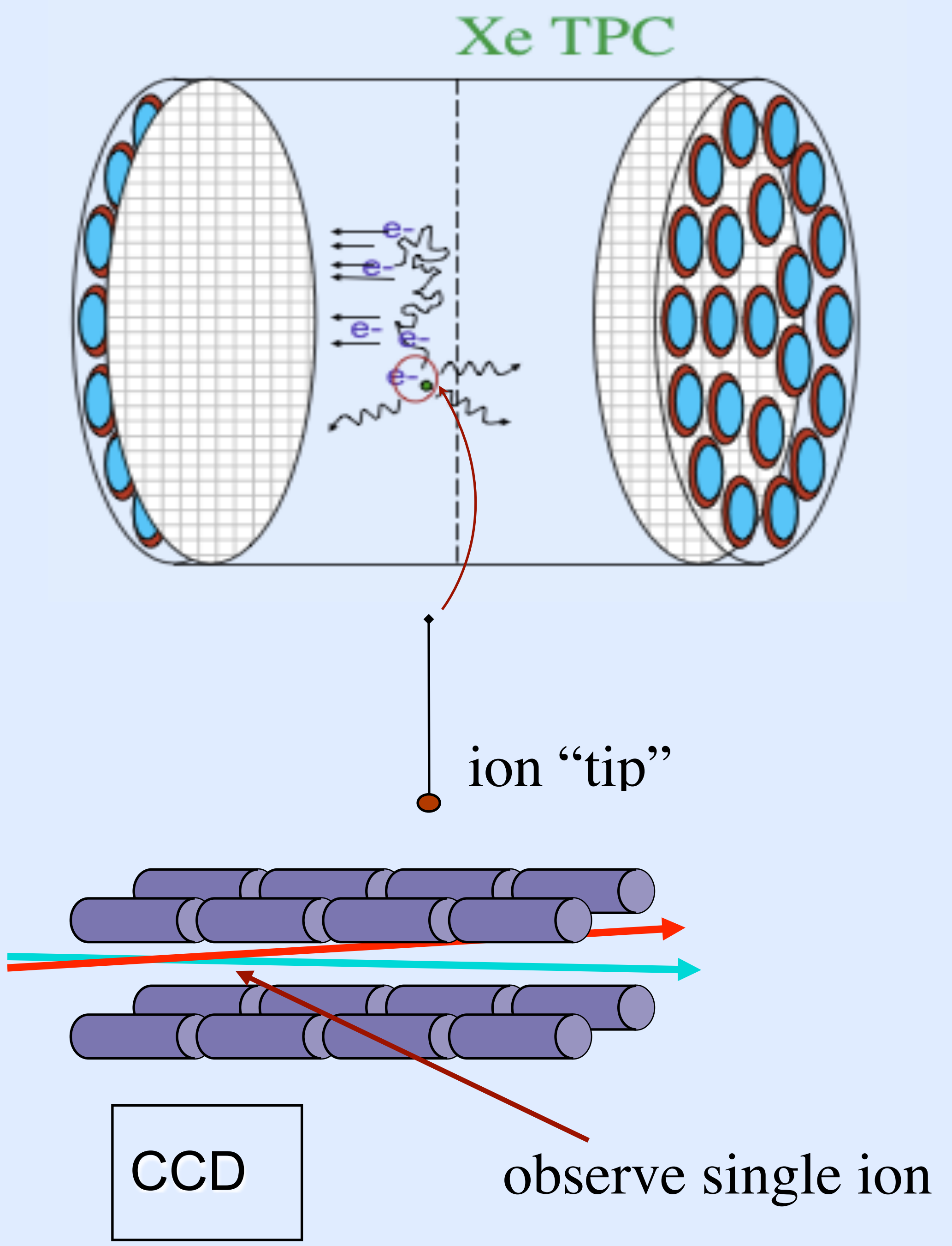
drastic background reduction by Ba daughter tagging!

detect the 2 electrons
(ionization + scintillation in xenon detector)

$$^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}^{++} + 2e^{-} \; (+\, 2\nu_e)$$

positively identify daughter via
optical spectroscopy of Ba^{+}

other Ba^{+} identification strategies are being
investigated within the EXO collaboration

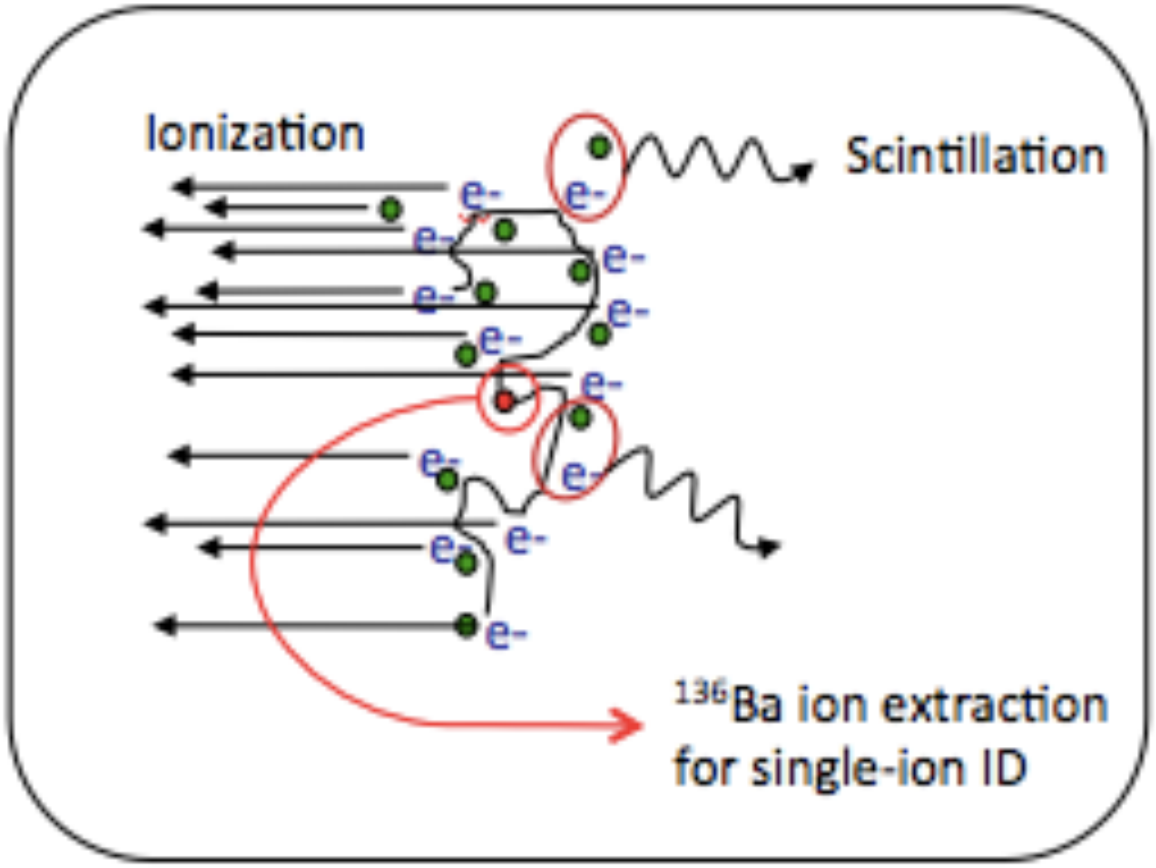


[M. Moe, Phys. Rev. C 44 (1991) R931]

'full' EXO R&D

- Full EXO ~ ton scale gas or liquid TPC
- "Tagging" of *0νββ* daughter nucleus ^{136}Ba ion for background rejection – R&D underway
  - Ion extraction from a TPC
  - Ion trapping
  - Ion identification with
    - Laser Induced Fluorescence (LIF)
    - Resonant ionization spectroscopy (RIS)
  - Single ion RIS
  - Others…
- GXe TPC R&D underway
  - 10 bar GXe TPC under construction
  - Test tracking, ionization+scintillation readout, ΔE/E, Ba tagging interface, etc.

Full EXO *0νββ* detection



"Tagging" ^{136}Ba ion in real time may allow for rejection of all backgrounds except 2νββ.

(see Karl Twelker's talk for more details)

sensitivity of ton-scale EXO with barium tagging

Assumptions:

1. 80% enrichment in 136
2. Intrinsic low background + Ba tagging eliminate all radioactive background
3. Energy resolution only used to separate the 0ν from 2ν modes:
4. Select 0ν events in a ±2σ interval centered around the 2.458 MeV endpoint
5. Use for $2\nu\beta\beta$ $T_{1/2} > 1\cdot10^{22}$yr (Bernabei et al.)

Case	Mass (ton)	Eff. (%)	Run Time (y)	σ_E/E @ 2.5MeV (%)	$2\nu\beta\beta$ Background (events)	$T_{1/2}^{0\nu}$ (y) (90% CL)	Majorana mass (meV) QRPA[1]	NSM[2]
large	1	70	5	1.6*	0.5 (use 1)	$2*10^{27}$	19	24
very large	10	70	10	1†	0.7 (use 1)	$4.1*10^{28}$	4.3	5.3

* σ(E)/E = 1.6% obtained in EXO R&D, Conti et al Phys Rev B68 (2003) 054201

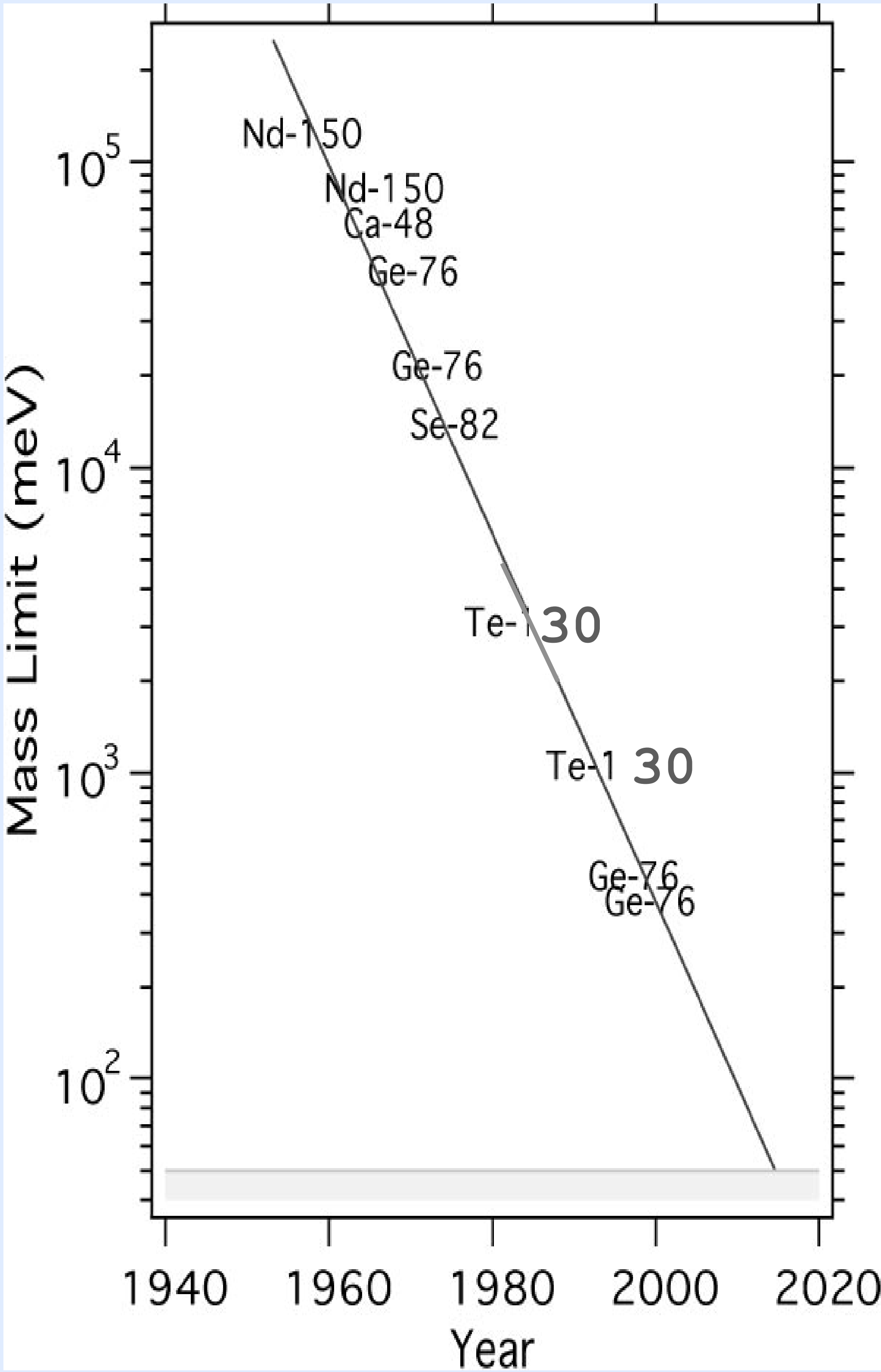
† σ(E)/E = 1.0% considered as an aggressive but realistic guess with large light collection area

1 Šimkovic et al., Phys. Rev. C79 055501 (2009) [use RQRPA with g_A=1.25]

2 Menendez et al., Nucl. Phys. A818 139 (2009) [use UCOM results]

outlook

- ✓ the quest for for neutrino-less double beta decay (0νββ), started half a century ago, should reach the inverted neutrino mass hierarchy in the next 5-10 years
- ✓ 0νββ would represent new physics and decree neutrinos as Majorana fermions, possibly indicating the way towards understanding the origin of neutrino mass and the matter/antimatter asymmetry
- ✓ the required rare-event detector technology is now entering the phase of 0νββ experiments at the 100's kg scale, sensitive to neutrino masses of ~100 meV or less



- ✓ many competing efforts are under way; a firm detection of this process will require its observation in more than one isotope in order to validate the theoretical understanding of the fundamental nuclear process

choose wisely, and ...


4

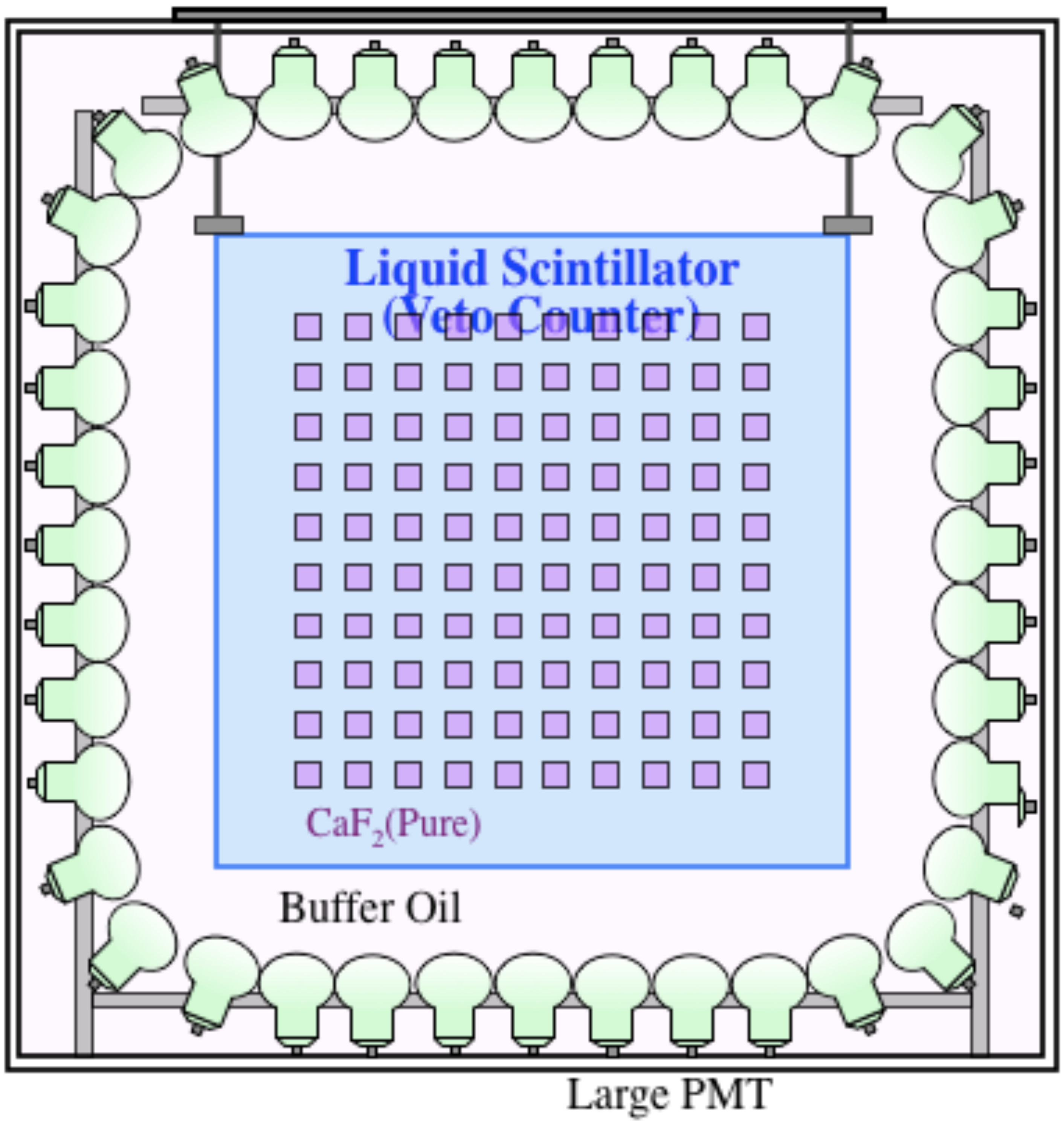

… if it’s a rose, it will bloom


4


4
thank you!

CANDLES

CAlcium fluoride for studies of Neutrino and Dark matrters by Low Energy Spectrometer



- **CaF_2(Pure)**

  200kg, 300kg, 3t,30t(2%)

  ^{48}Ca (200g, 300g, 3kg, 300kg)
- **Liquid Scintillator**

  Wave Length Shifter

  4 π Active Shield

  Passive shield
- **Photomultiplier**

  energy resolution

✓ ^{48}Ca has highest Q = 4.3 MeV

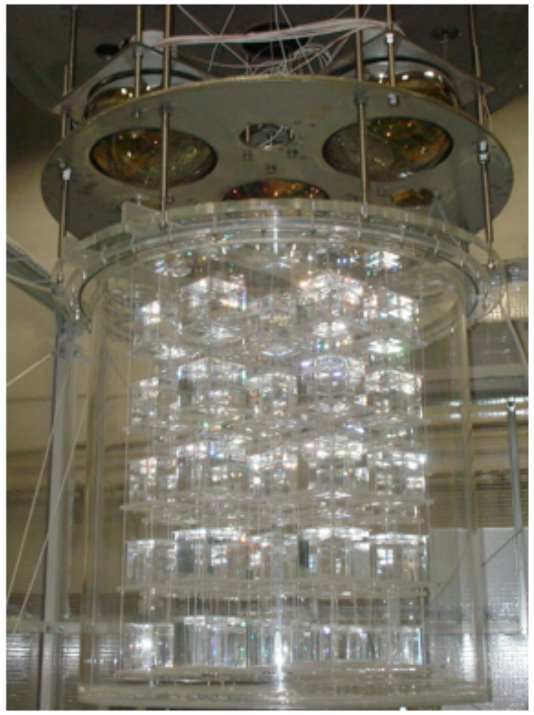
✳ 0.2% isotopic abundance

✳ difficult enrichment

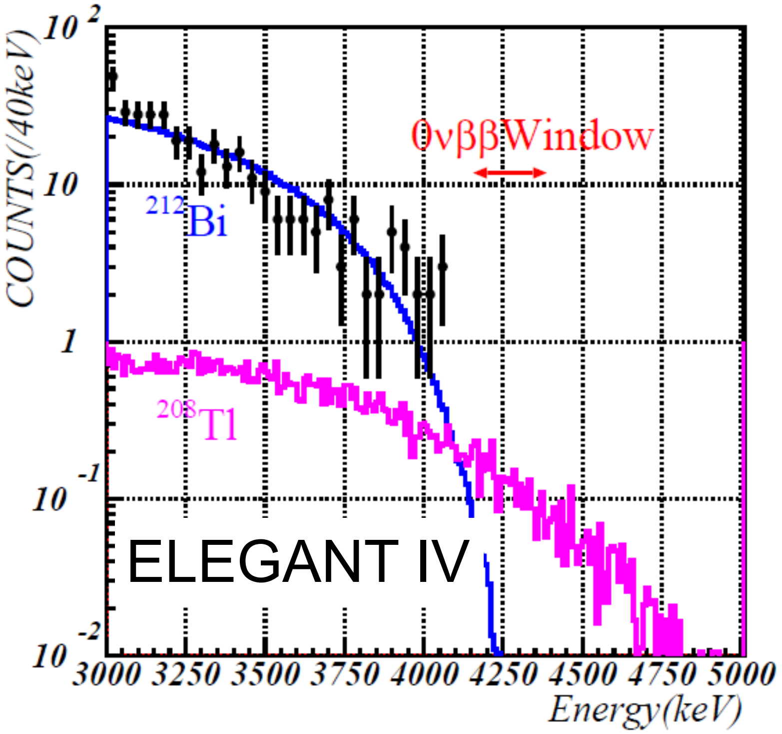
from T. Kishimoto

Milestones

- ELEGANT VI
  - running with new BG rejection (2ν)
- CANDLES I, II
- CANDLES III
  - $10cm^3$ cube (100 crystals) ~0.5 eV
  - BG of CaF_2 ~30 μBq/kg (<100 μBq/kg)



$10cm^3$ x 56 CaF_2



$$\langle m_\nu \rangle < 3.5 \sim 21.7 \text{ eV} \ \ (90\% \ \text{C.L.})$$

Achieved (Osaka)

- CANDLES III(UG)
- CANDLES IV
  - $10cm^3$ cube (1000 crystals) 3.2t
  - BG of CaF_2 ~10 μBq/kg for 0.2 eV
  - Kamioka
  - CANDLES V to sense ~10 meV region
  - ~30 ton CaF_2 and 2% enrichment

Kamioka

from T. Kishimoto