Community Report on $0\nu\beta\beta$-decay

Nigel Smith, SNOLAB

Thanks to community for (substantial) input and TAUP presenters, especially Stefan Schönert for contributions

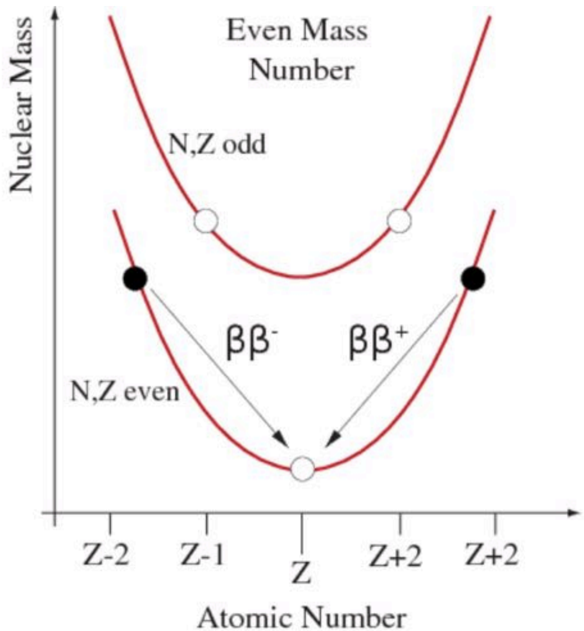
Overview of talk

- Double Beta Decay
  - The physics payload
  - Characteristics of experimental challenges
  - Experimental techniques
  - Current/future experiment updates

- Central messages:
  - Physics payload from $0\nu\beta\beta$ is highly compelling
  - Much progress over last couple of years addressing challenge of scale-up to tonne-scale detectors; next step ready to go
  - Support infrastructure exists within underground labs

Physics of 0νββ

- Neutrino-less double beta decay can occur if
  - Lepton number is not conserved
  - The neutrino is its own anti-particle (Majorana nature)
- A heavy right-handed Majorana neutrino would provide a natural 'see-saw' mechanism for generating light neutrino masses
- The matter - antimatter asymmetry in the Universe may be coupled to the weak sector
  - via CP-violating Majorana phases, $\Delta L \neq 0$ and leptogenesis



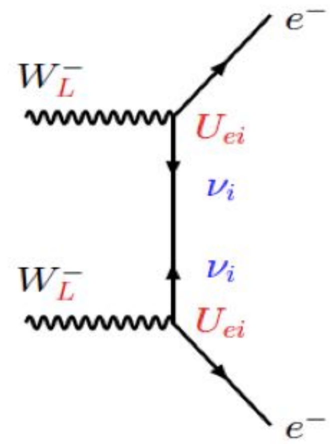
Isotope	Nat ab.	$Q_{\beta\beta}$
^{48}Ca	0.19 %	4262.96(84) keV
^{76}Ge	7.6%	2039.04(16) keV
^{82}Se	8.7%	2997.9(3) keV
^{96}Zr	2.8%	3356.097(86) keV
^{100}Mo	9.6%	3034.40(17) keV
^{116}Cd	7.5%	2813.50(13) keV
^{130}Te	34.5%	2526.97(23) keV
^{136}Xe	8.9%	2457.83(37) keV
^{150}Nd	5.6%	3371.38(20) keV

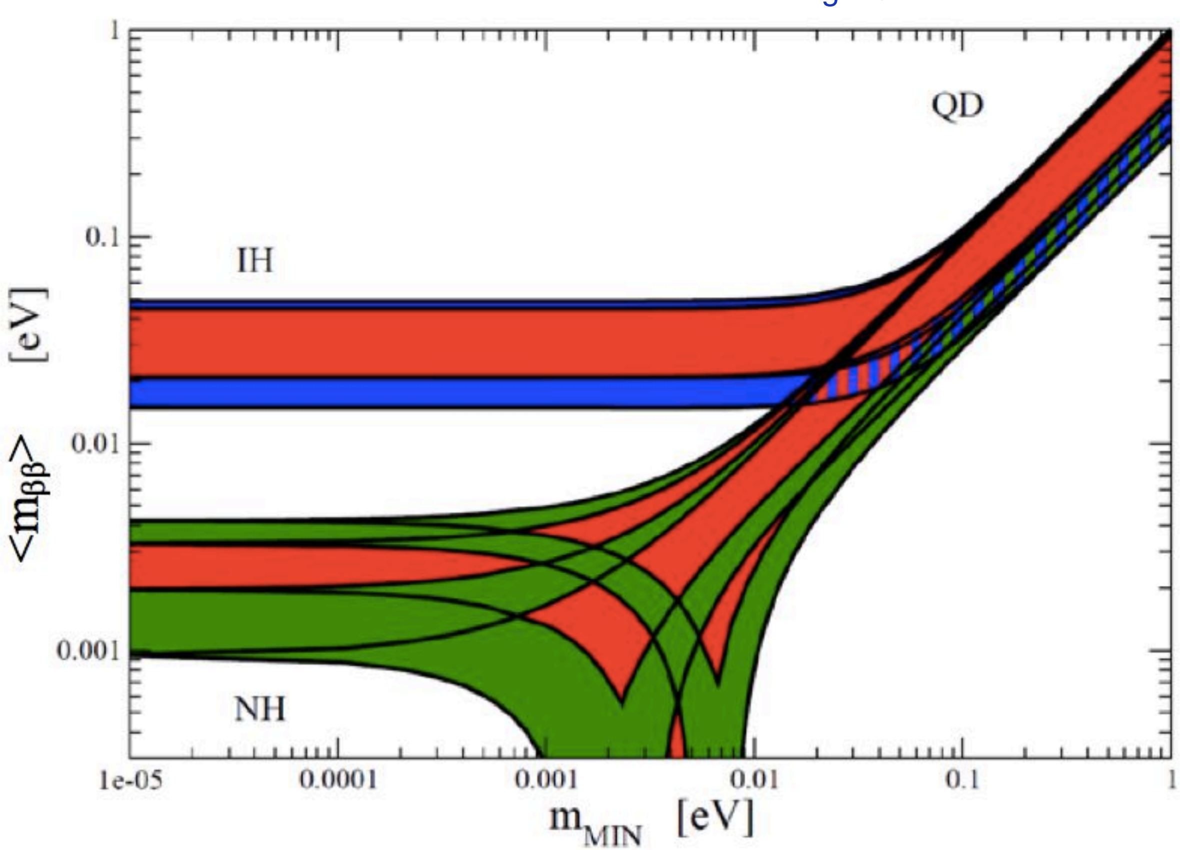
Physics of 0νββ

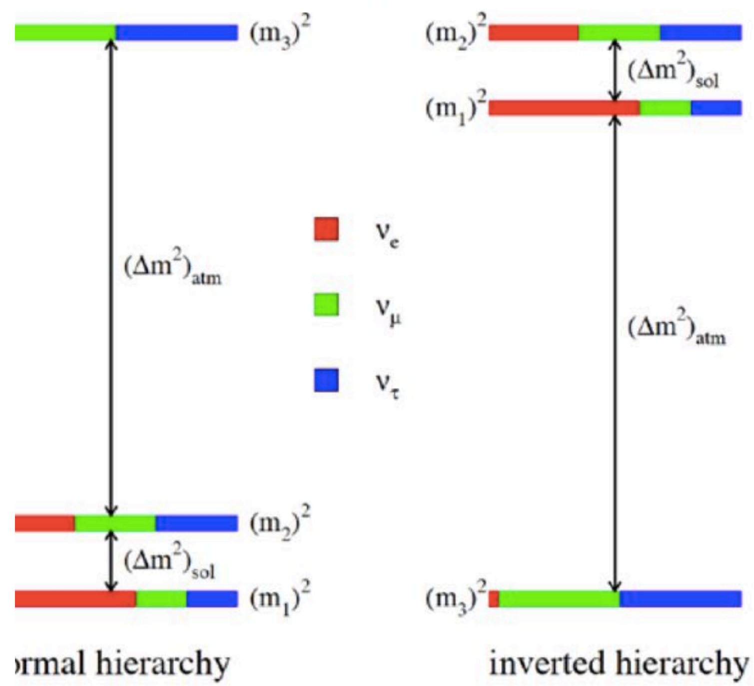
- Provides a mechanism to determine neutrino mass and (potentially) hierarchy

$$\left| \sum_i m_i U_{ei}^2 \right| \equiv \langle m_{\beta\beta} \rangle$$

Mixing matrix

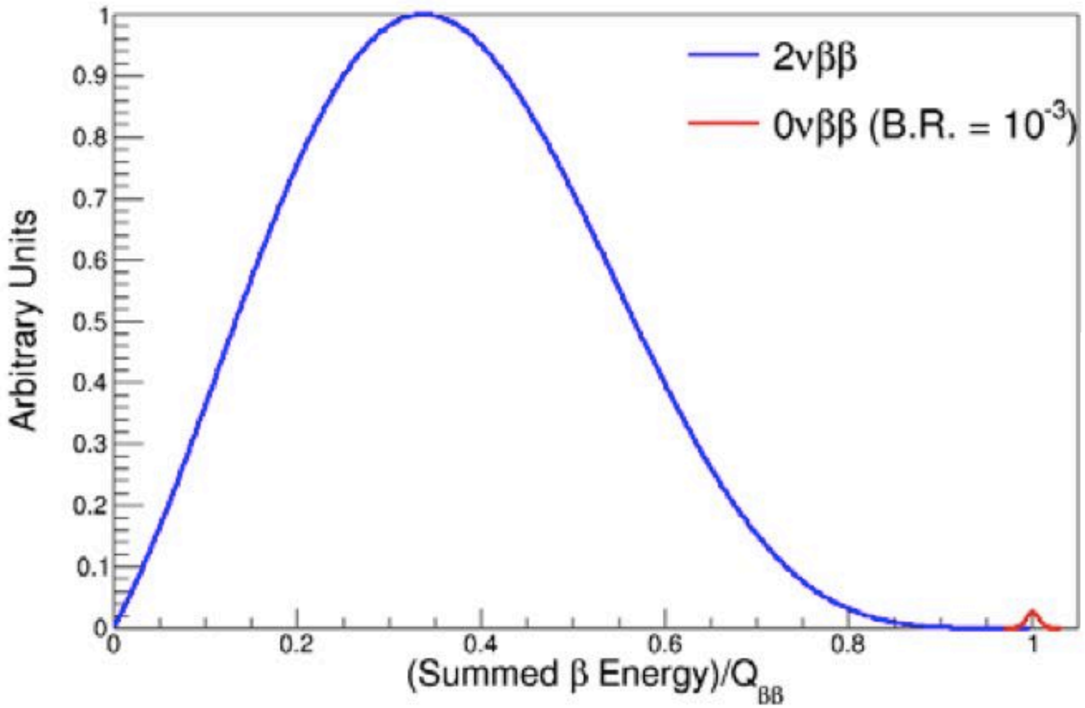


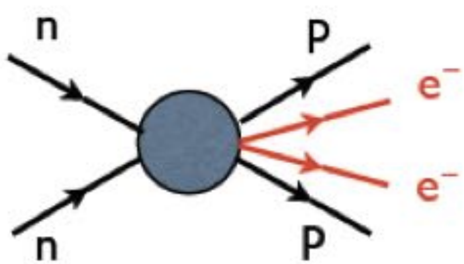




$0\nu\beta\beta$ Experimental challenge

- Looking for full energy peak of electrons at the tail of the (expected and irremovable) two-neutrino beta decay
  - $0\nu\beta\beta$ $T_{1/2}$ ~ 10^{27}- 10^{28} years
  - $2\nu\beta\beta$ $T_{1/2}$ ~ 10^{19} - 10^{21} years
- Tonne scale detectors required to reach higher half-life
- Need to remove/understand all backgrounds contributing to region of interest
  - including cosmogenic activation and c.r. by-products



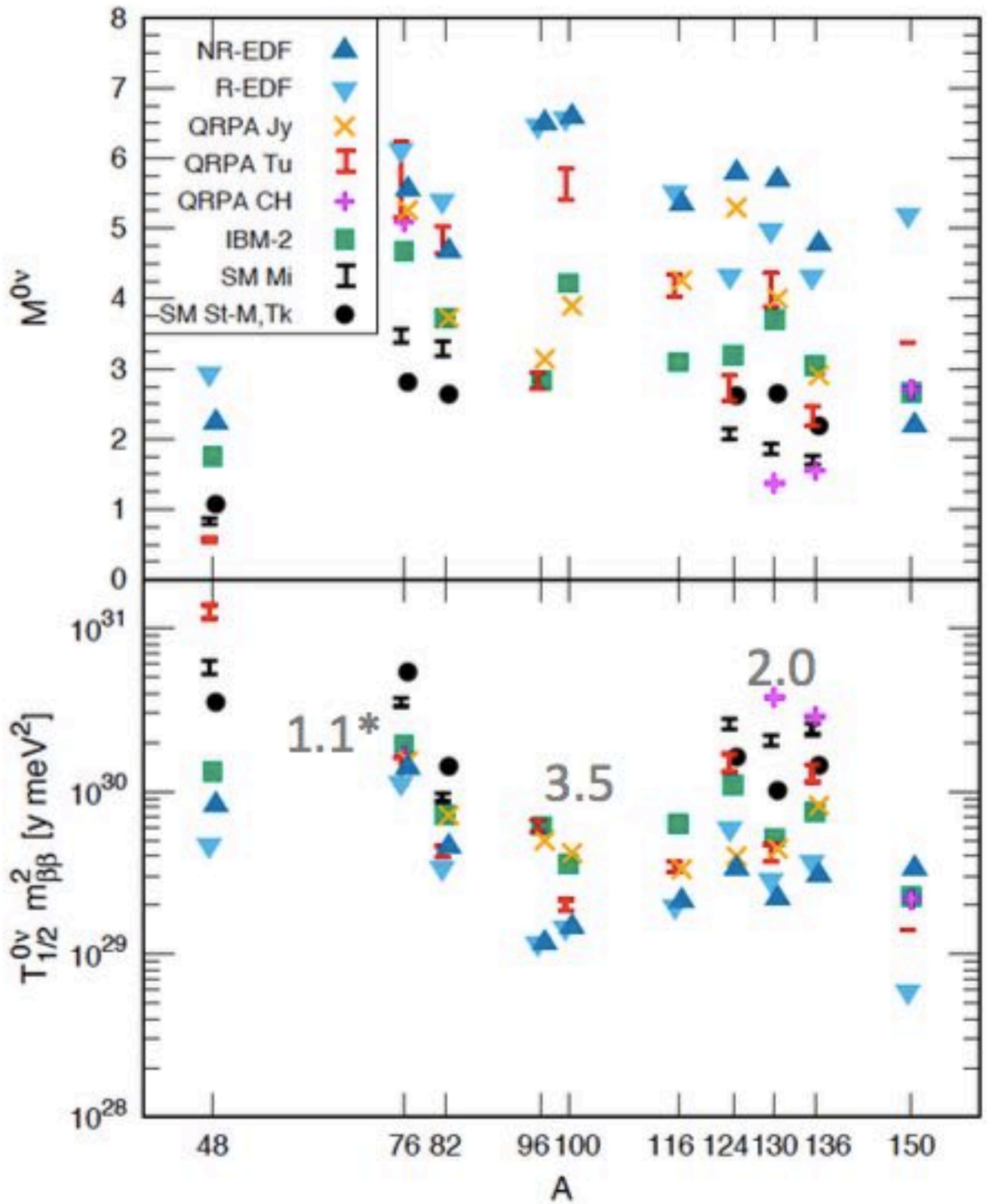


Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral Nuclear matrix element

0νββ Nuclear Matrix Elements



- Signal rate is similar for all isotopes when comparing decay rate/mass.
- Differences exist from experimental perspectives
  - Q-value
  - natural abundance
  - experimental technique

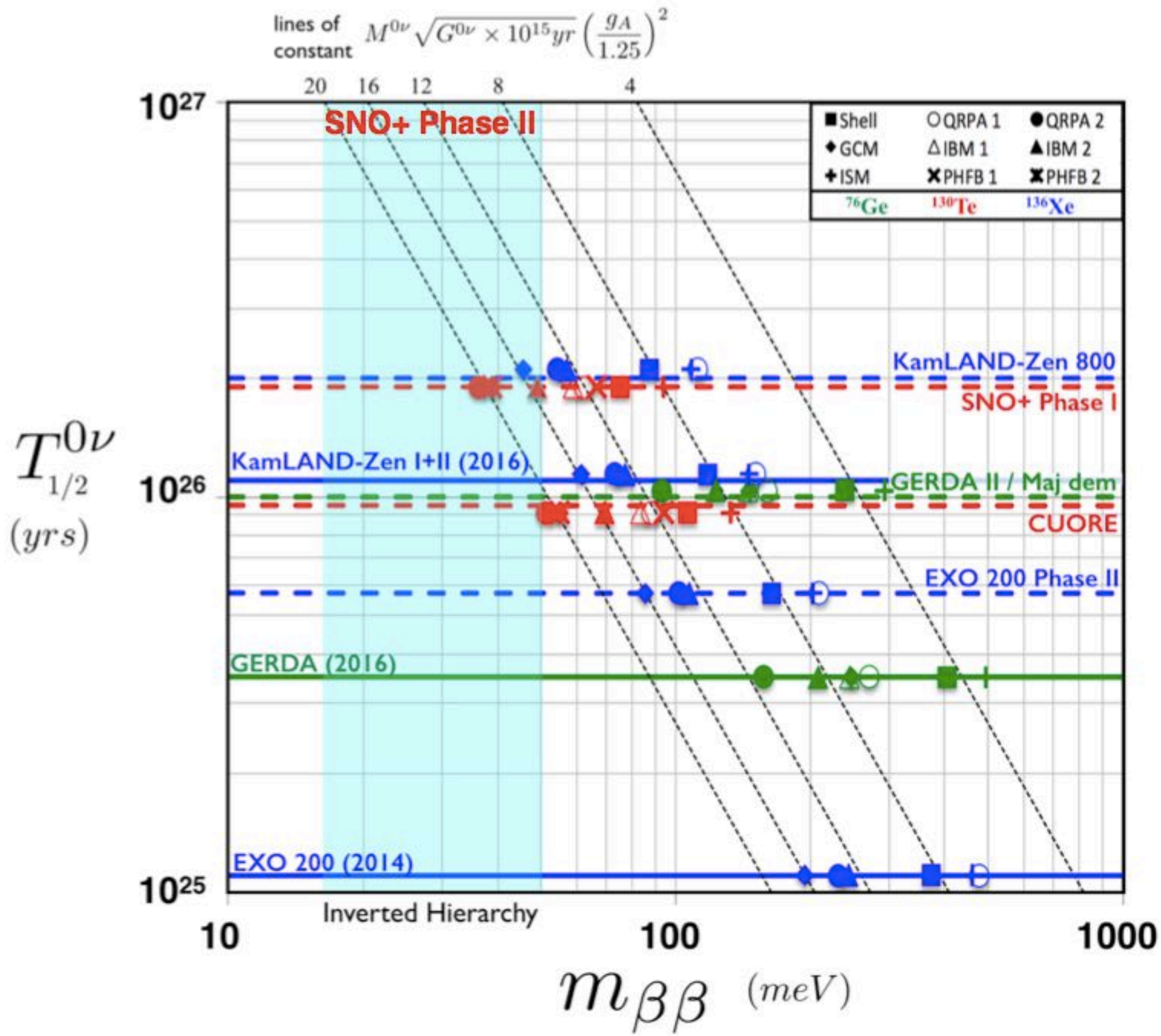
*number = signal rate per 1000 kg yr exposure & for middle of NME values for For $\langle m_{ee} \rangle$ = 17.5 meV ('bottom of IH' for g_A=1.25, $\sin^2\theta_{12}$ = 0.318)

Engel & Menédez arXiv:1610.06548v2

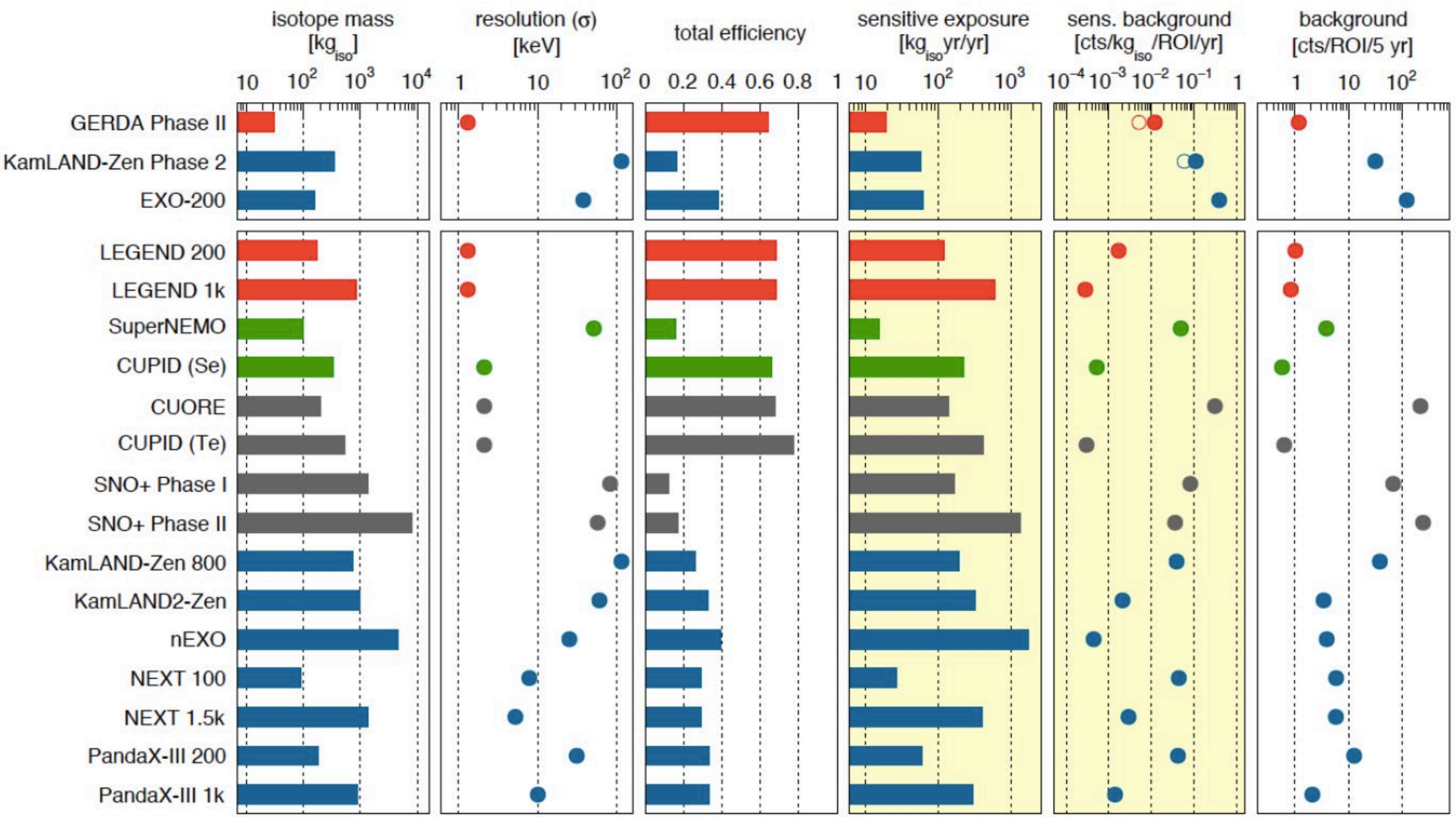
Experimental Techniques

Isotope	Technique	Experiment
^{136}Xe	L(Xe) TPC	EXO-200 / nEXO
	G(Xe) TPC	NEXT / PANDA-X-III
	Xe-loaded Scintillator	Kamland-ZEN
^{130}Te	Te-loaded Scintillator	SNO+
	Te Bolometers	CUORE / CUPID-Te
^{100}Mo	Mo Bolometers	CUPID-Mo / AMORE
^{82}Se	Se Bolometers	CUPID-0
	Se Calorimeter-Tracker	SuperNEMO
^{76}Ge	Ge Semiconductor	GERDA - MJD - LEGEND / CDEX

Search status (pre-TAUP)

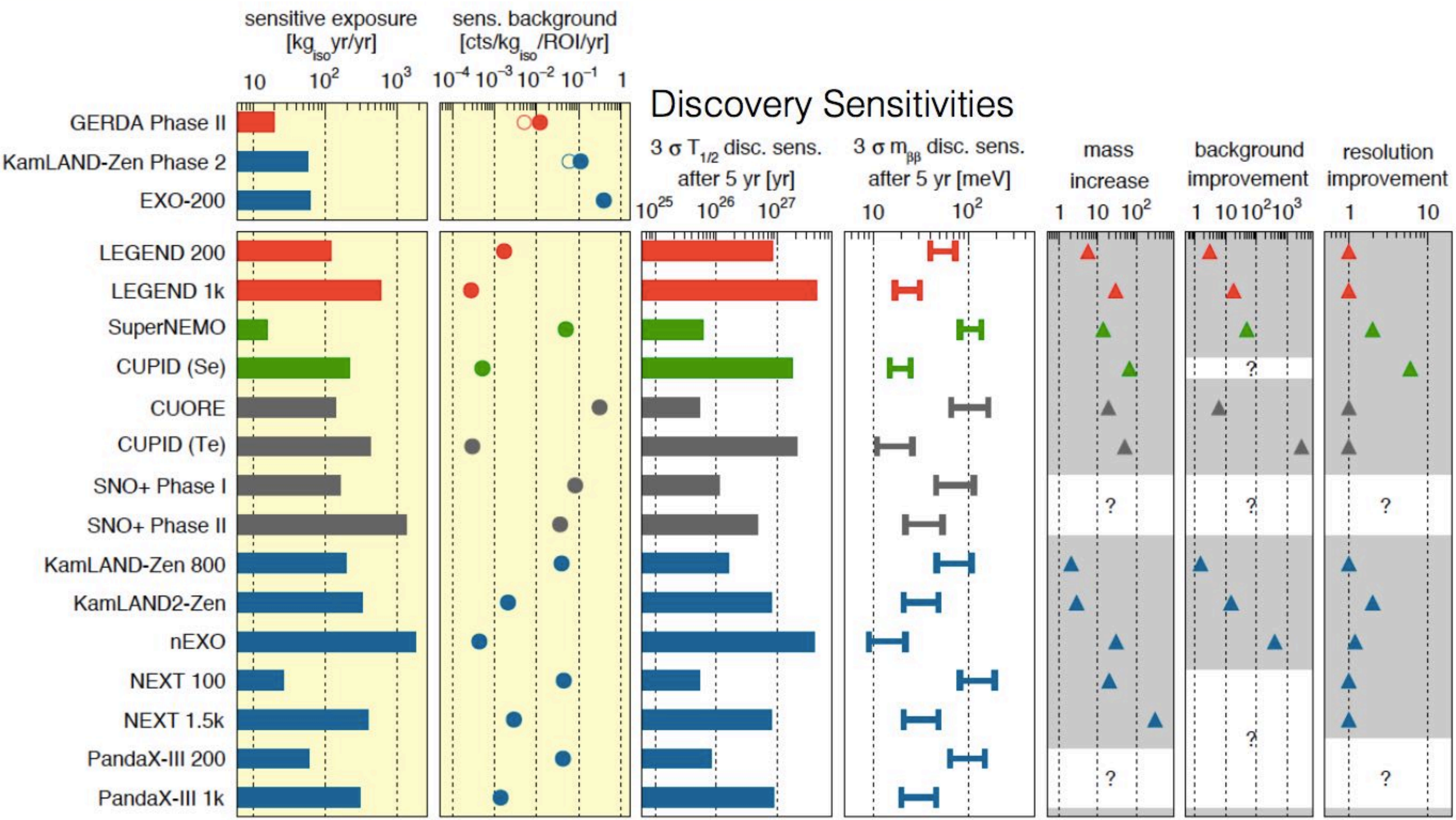


Comparison of Experiments



Adapted by Stefan Schönert from Agostini, Benato, Detwiler arXiv:1705.02996

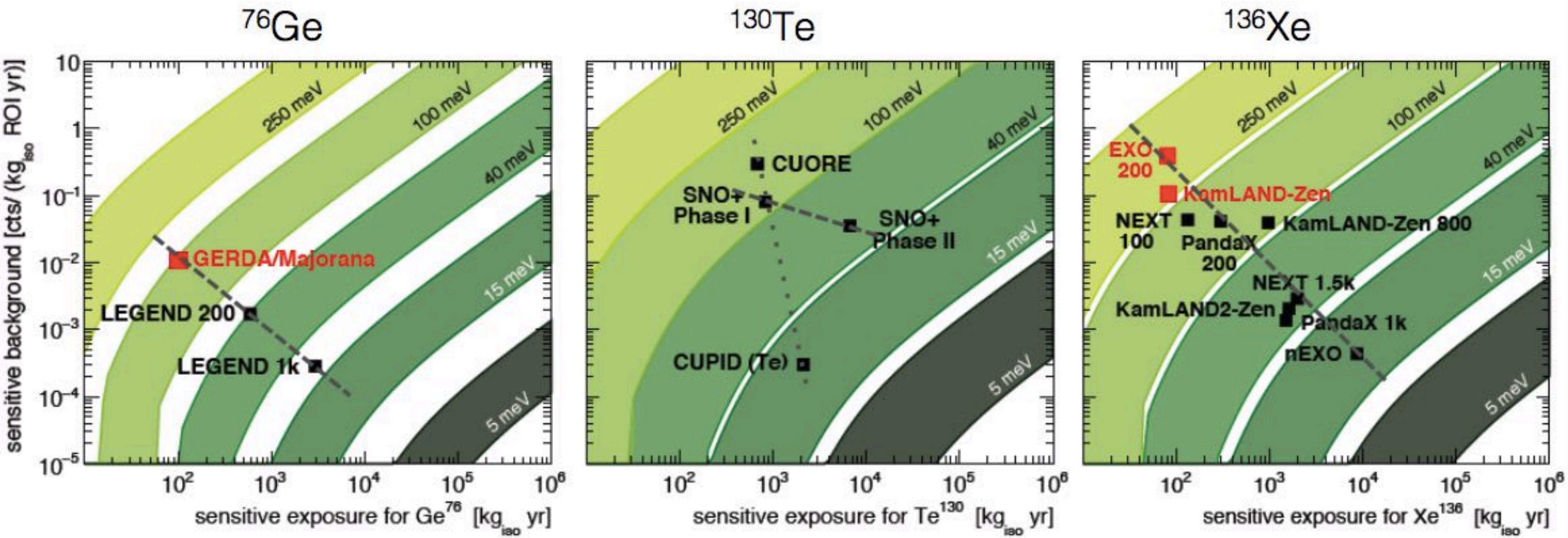
Comparison of Experiments



Adapted by Stefan Schönert from Agostini, Benato, Detwiler arXiv:1705.02996

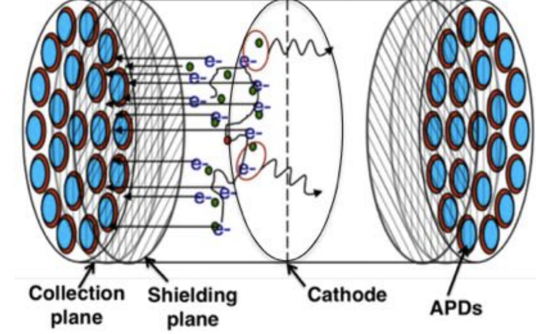
Comparison of Experiments

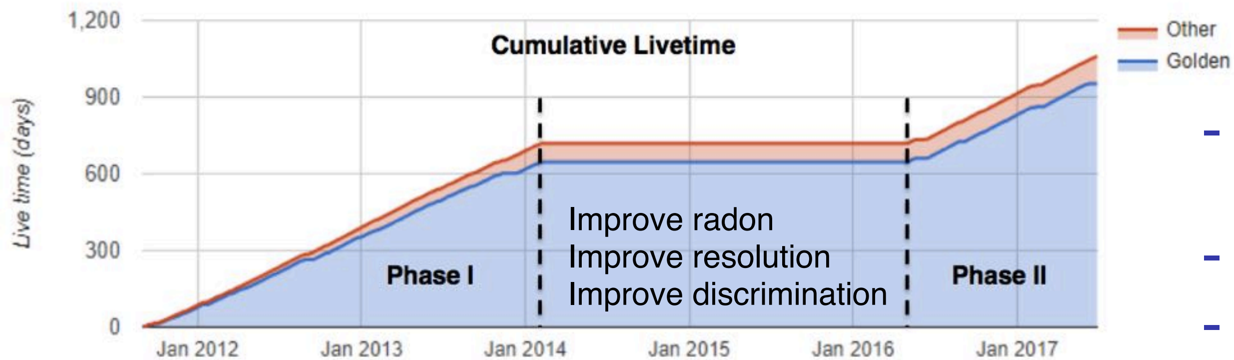
- Discovery potential of experiments
  - Comparison of exposure vs background for various isotopes
  - Correlation to mass scale



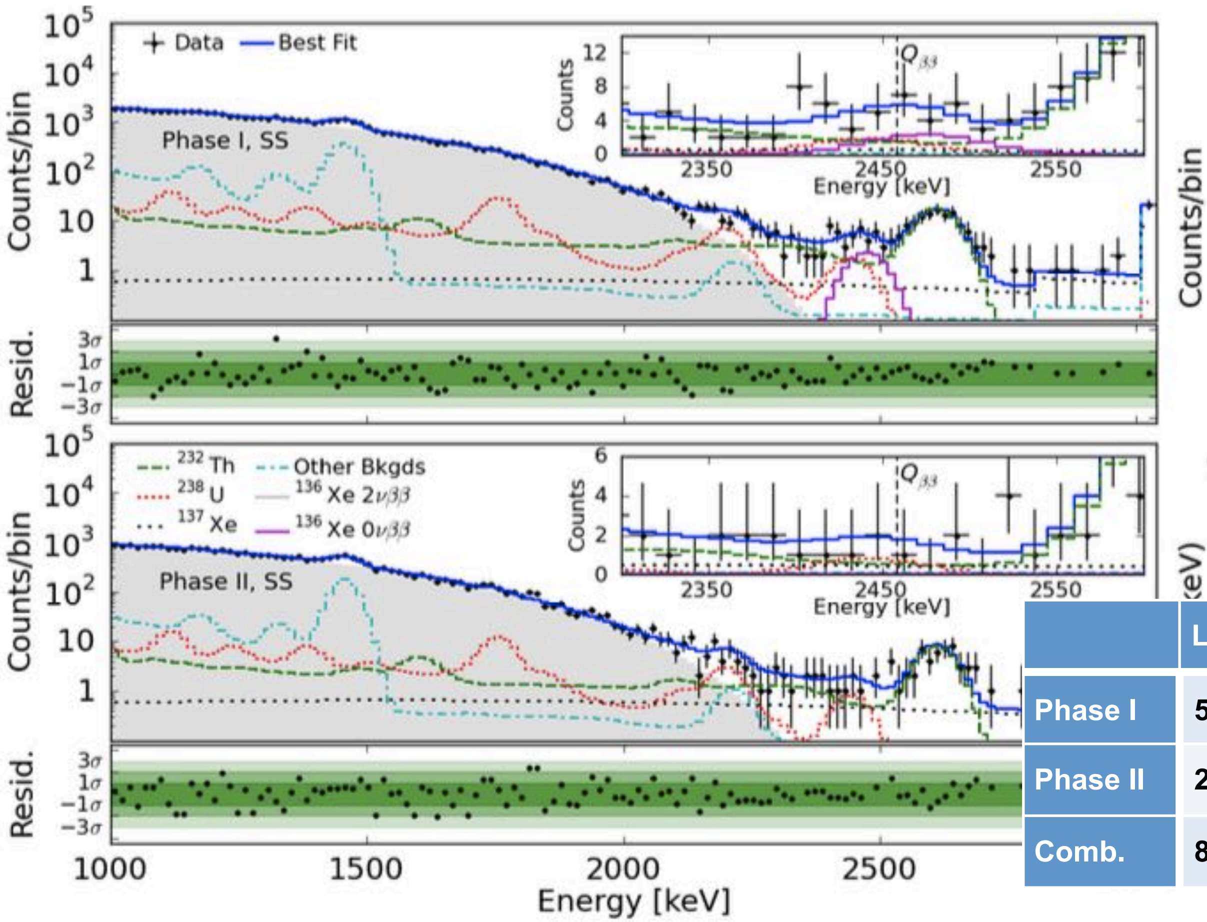
Agostini, Benato, Detwiler arXiv:1705.02996

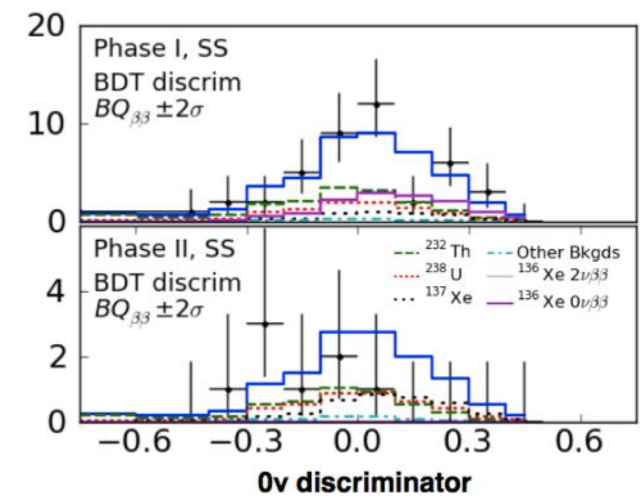
EXO-200





- Enriched xenon TPC, two APD collection planes
- 1.23% resolution at Q-value (2458 keV)
- Discrimination using single/multi-site, spatial distribution & cluster size -> boosted decision tree





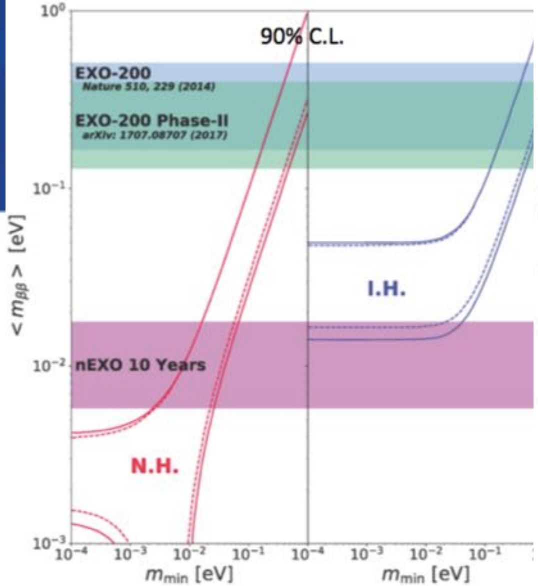
	Lifetime	Exposure	Sensitivity (90% cl)	Limit (90% cl)
Phase I	596.7 d	122.0 kg.yr	$T_{1/2}^{0\nu\beta\beta}$ > 2.9x10^{25} yr	$T_{1/2}^{0\nu\beta\beta}$ > 1.0x10^{25} yr
Phase II	271.8 d	55.6 kg.yr	$T_{1/2}^{0\nu\beta\beta}$ > 1.7x10^{25} yr	$T_{1/2}^{0\nu\beta\beta}$ > 4.4x10^{25} yr
Comb.	868.5 d	177.6 kg.yr	$T_{1/2}^{0\nu\beta\beta}$ > 3.7x10^{25} yr	$T_{1/2}^{0\nu\beta\beta}$ > 1.8x10^{25} yr

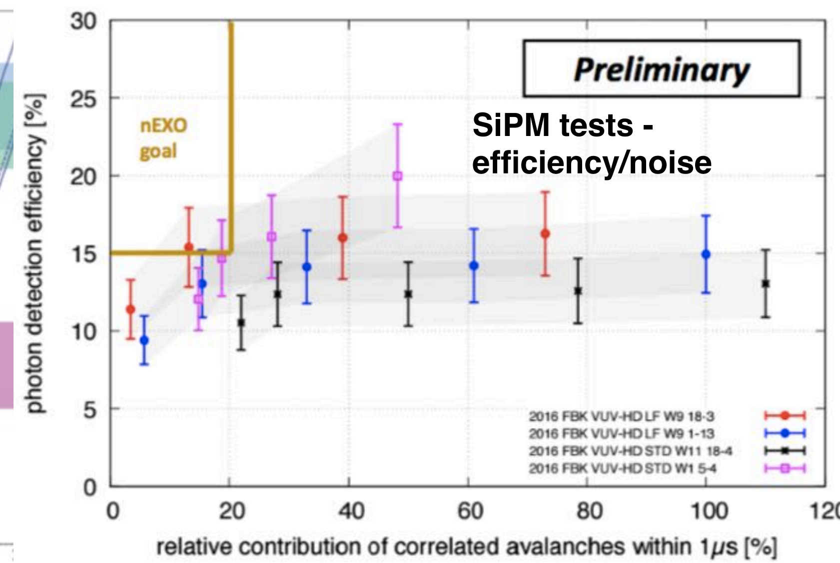
Gratta & Licciardi, TAUP2017

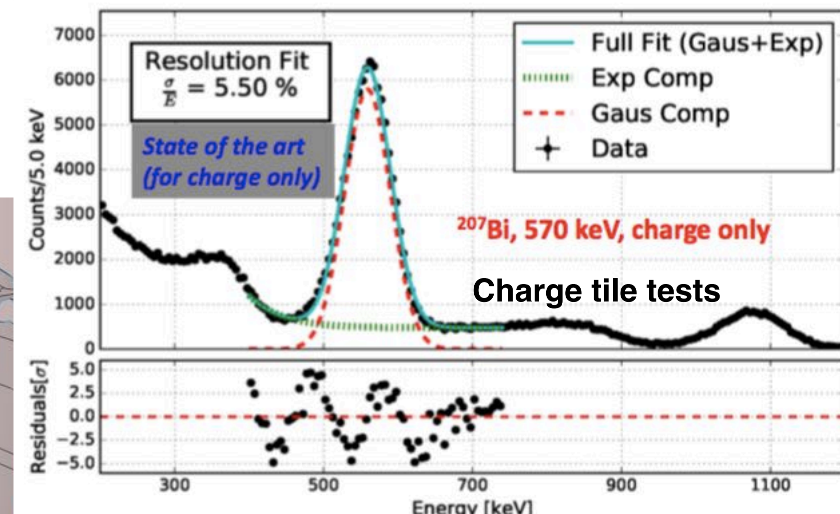
nEXO

- 5 tonne LXe TPC
- Improvements and R&D focussed:
  - Light collection (SiPM)
  - Charge collection (tiles)
  - HV stability
  - Background controls sensitivity
- Improve through:
  - fiducialisation
  - 2x discrimination (SS/MS)
  - Resolution (light/charge)
  - Potential Ba-tagging

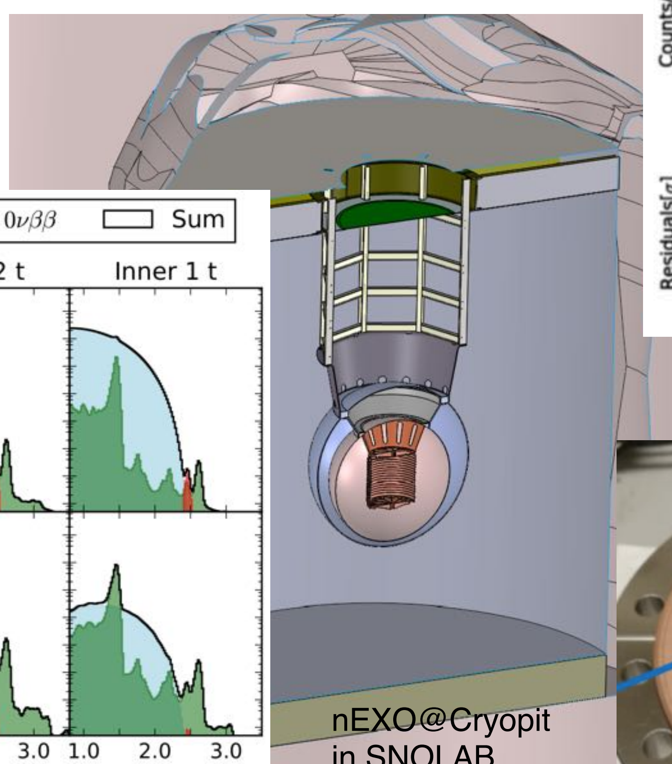
For 10y livetime and $0\nu\beta\beta$ $T_{1/2}$= 5x10^{27}y

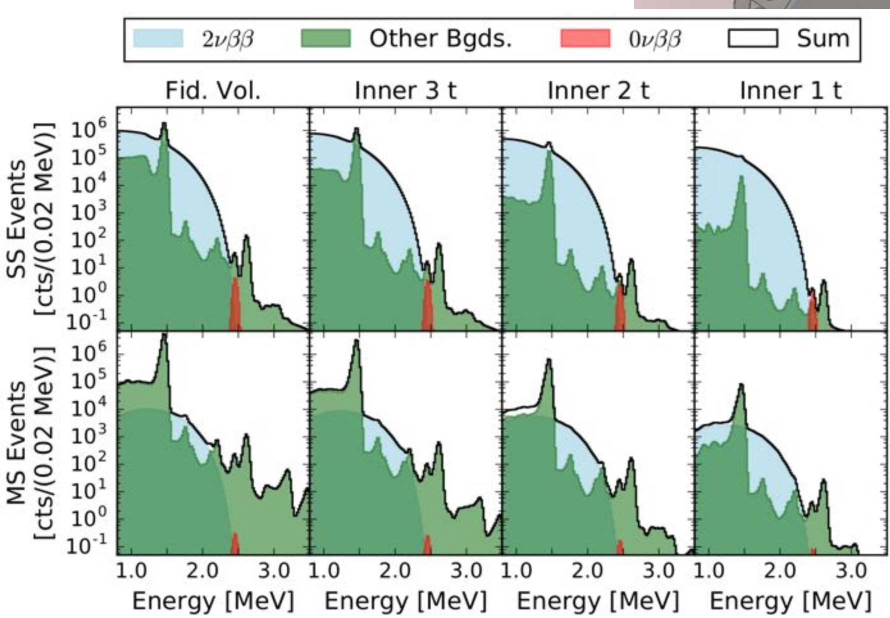




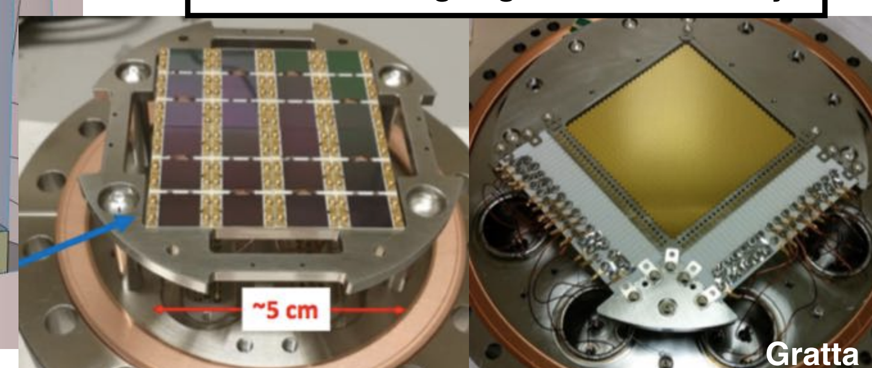


JINST 13 P01006 (2018) arXiv:1710.05109



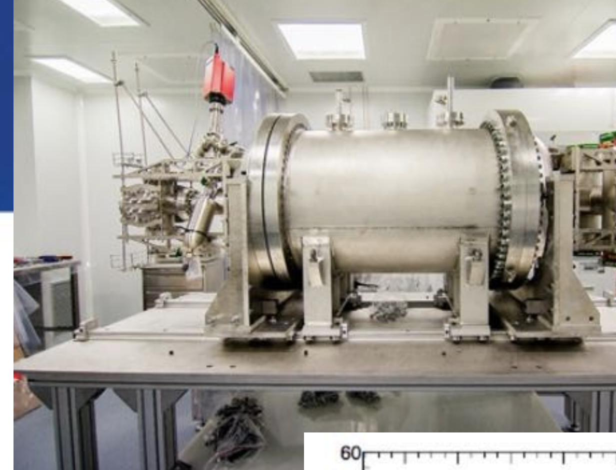


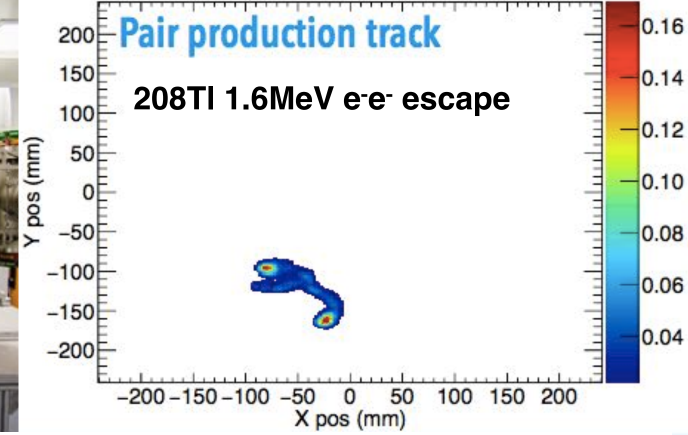
Combined charge/light tests underway

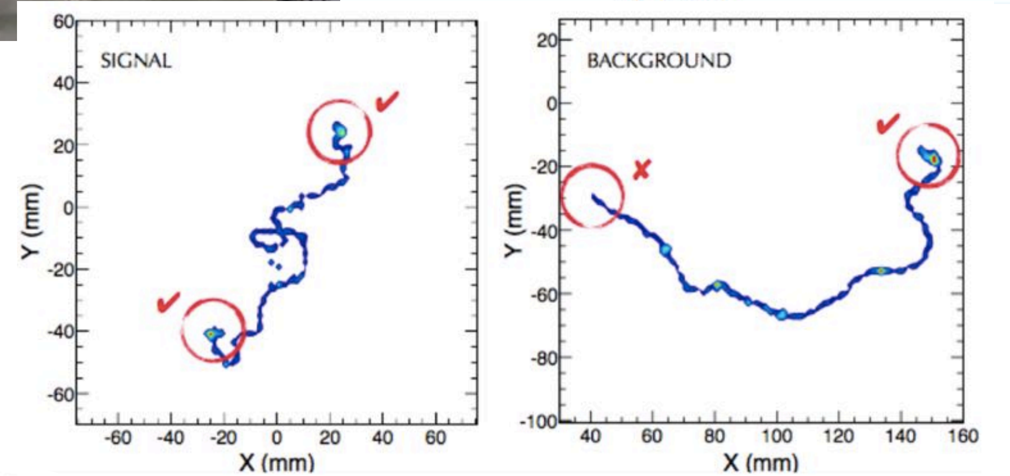


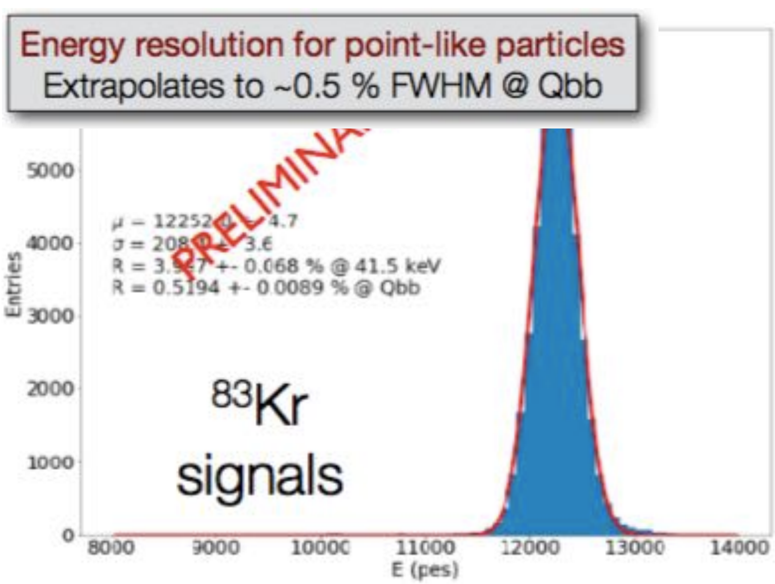
NEXT

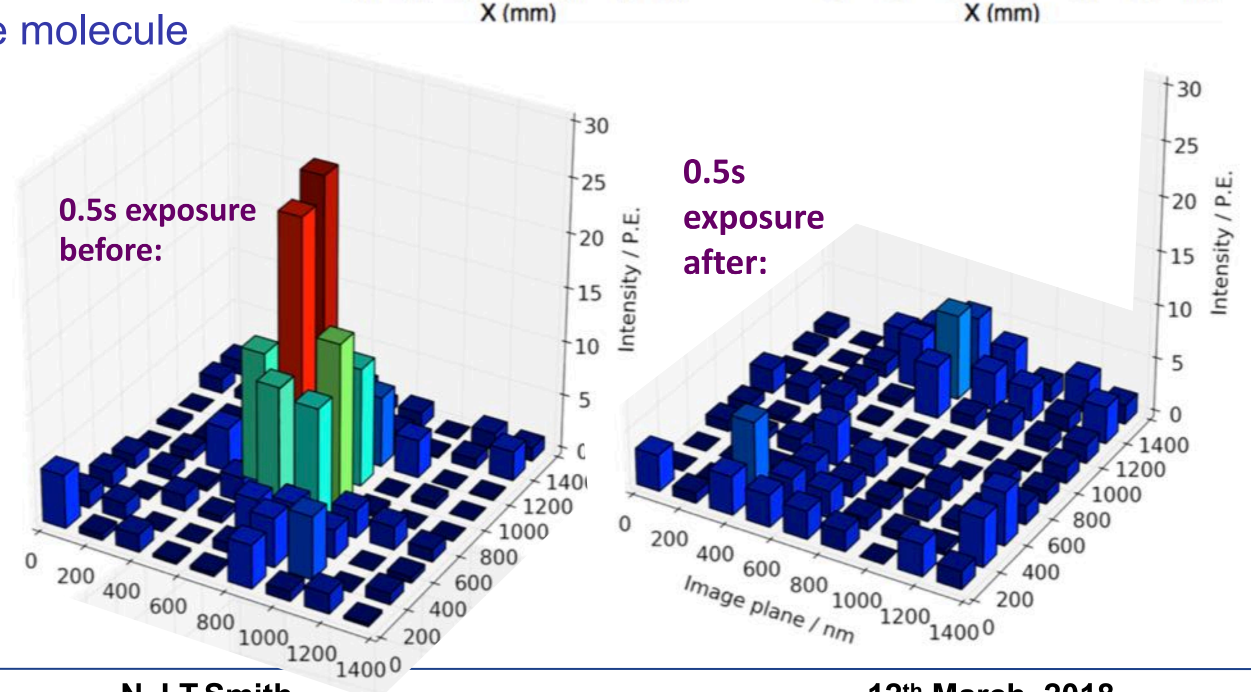
- High pressure Xe gas TPC
    - electroluminescent amplification
    - PMT/SiPM readout
- NEXT-White (NEW)
    - Built underground at Laboratorio Subterráneo de Canfranc (Spanish Pyrenees)
    - 10 kg of xenon gas in active volume. Stable operation since October 2016.
    - Calibration runs ongoing with natural Xe at 7bar.
    - NEXT-100 planned for 2019 (100kg)
- Ultimately aim for Ba-tagging to remove all backgrounds (except $2\nu\beta\beta$) using single molecule fluorescence







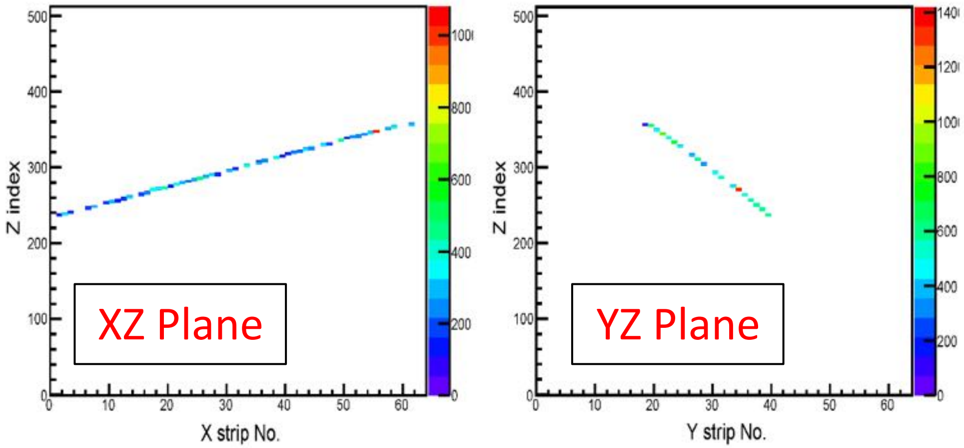




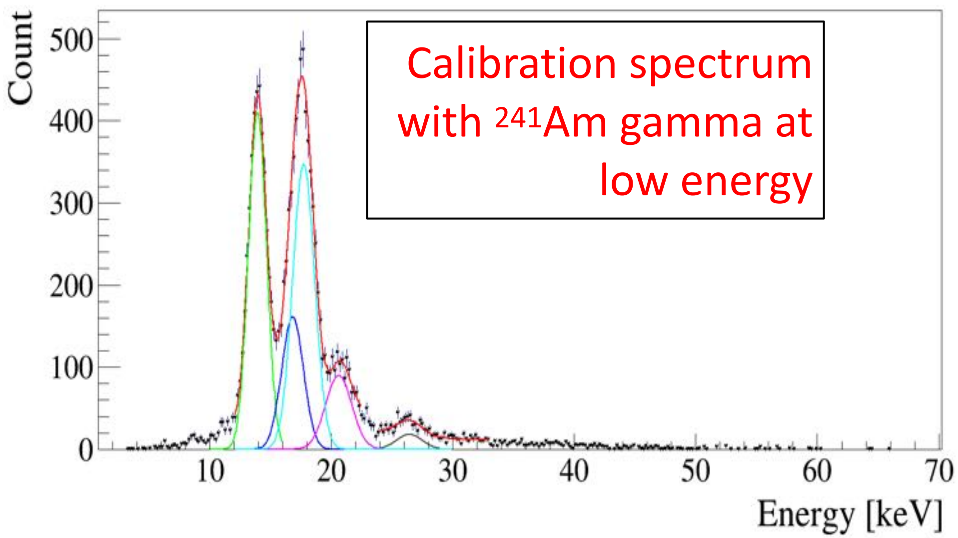
PandaX-III

- Phased approach with multiple 200 kg enriched xenon gas TPC for a ton-scale $0\nu\beta\beta$ experiment [ArXiv:1610.08883]
- HPGas TPC: 4 m^3 inner volume and 10 bar working pressure
- Main design features: good energy resolution and background suppression with tracking [ML: arXiv:1802.03489]
- 16kg prototype under operation
  - 7 Microbulk Micromegas modules for charge readout, 896 channels in total
  - 20×20cm active area, 3 mm pitch size with XY strip readout

TPC during installation

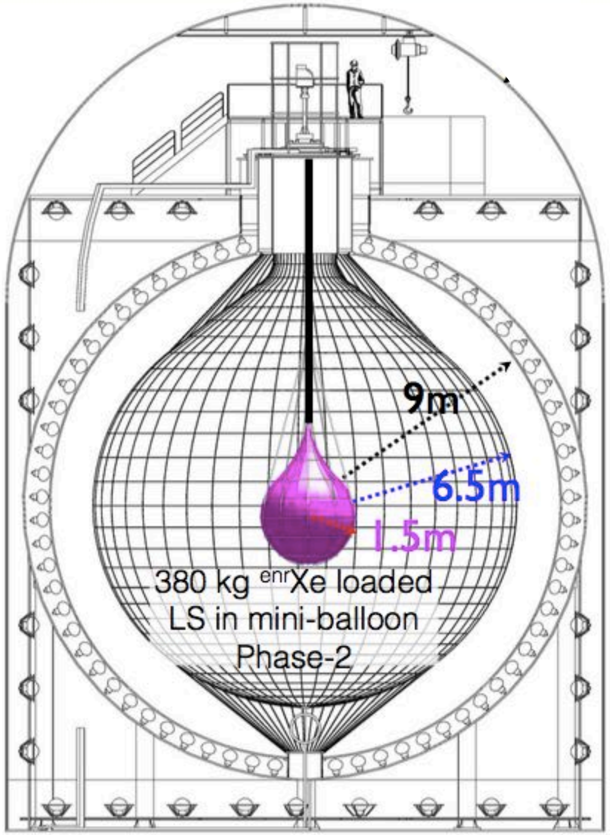


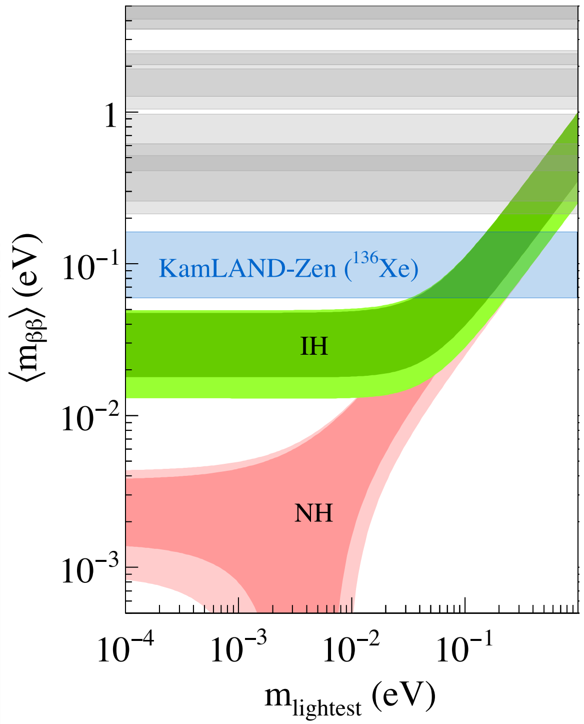
Cosmic muon track in TPC

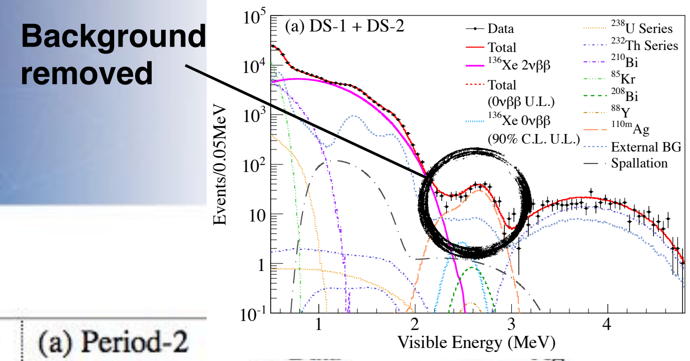


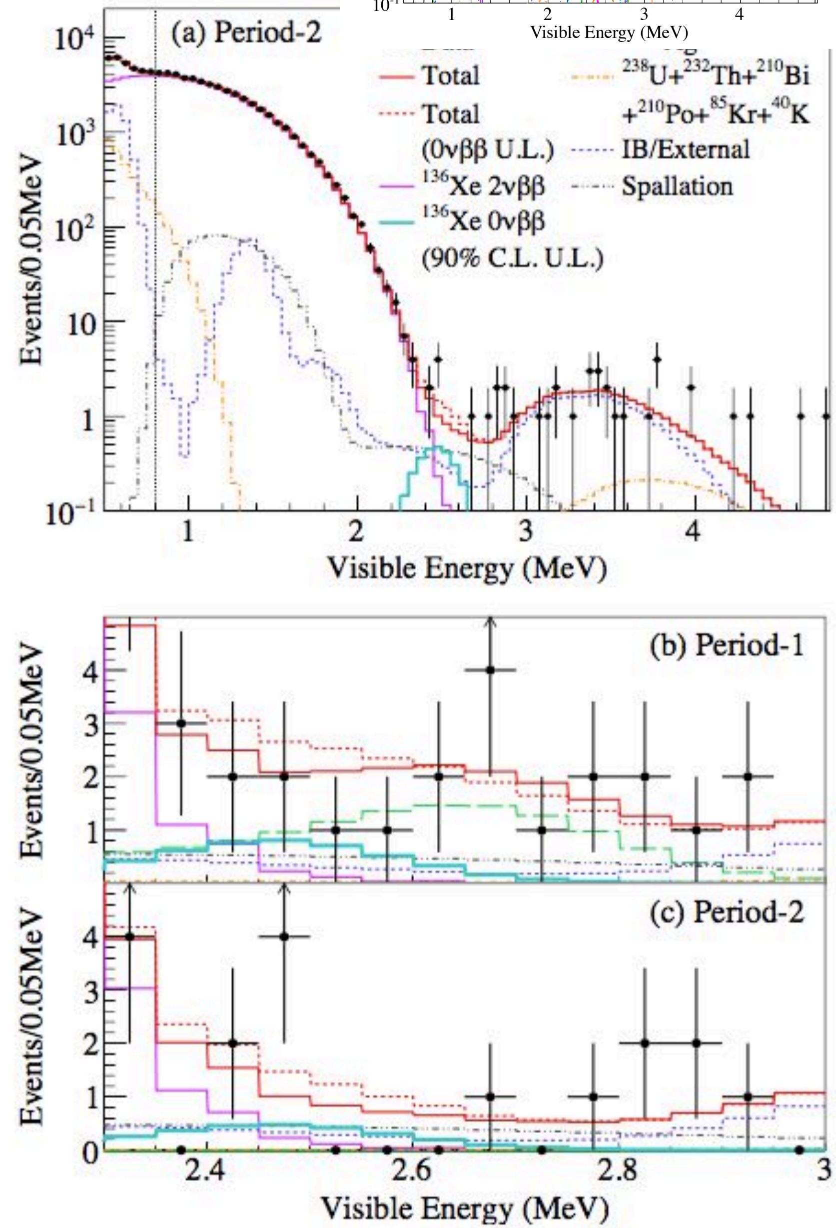
Calibration spectrum with ^{241}Am gamma at low energy

KAMLAND-ZEN







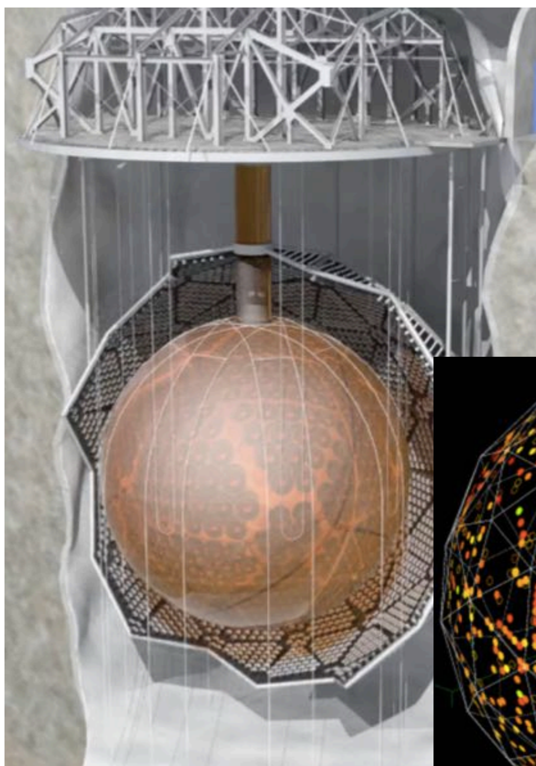


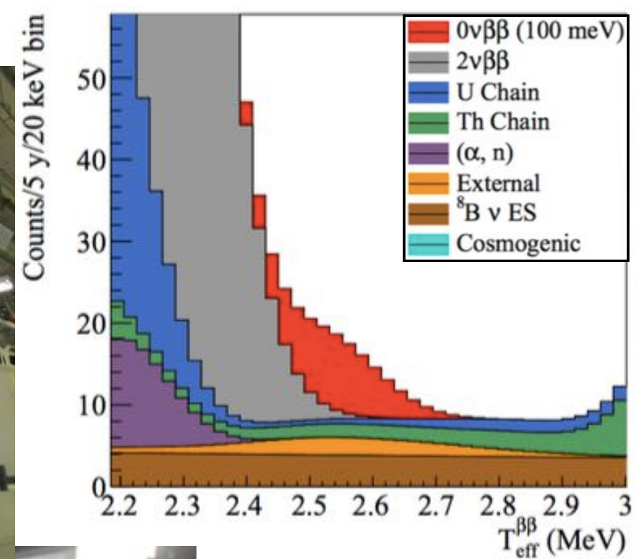
- Xe-doped liquid scintillator
- Phase-II improved background; 534.5 days (504 kg-yr)
  - Sensitivity: > 5.6 10^{25} yr (90% C.L.)
  - Phase I + II: > 1.07 10^{26} yr (90% C.L.)
  - Next phase: data taking 750 kg enriched Xe starting summer 2018 (new balloon to be installed April)
- KamLAND2-Zen with 1000kg+ proposed

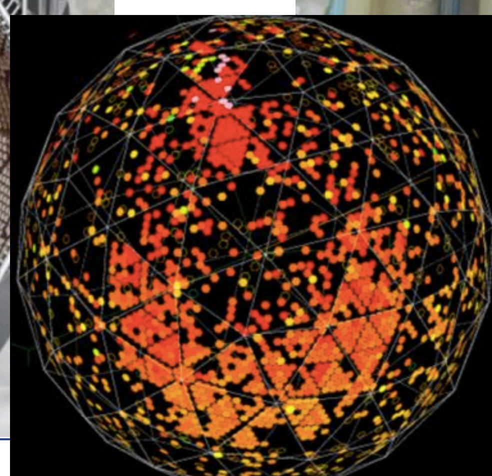
PRL117, 082503 (2016)

SNO+

- ^{130}Te loaded liquid scintillator reusing SNO infrastructure
  - All detector engineering complete: water data taking started May 2017
  - Objective is 780 tonnes linear alkyl benzene (+PPO+Te-ButaneDiol)
  - LAB purification plant in final commissioning, fill expected August 2018
  - 3.8 tonnes TeA underground cooling; 4 tonnes en route from China
  - Te and butane-diol plant in construction, expected loading 2019
- Phase-I: 3.9 t Te @0.5% loading → 1300 kg 130Te; Planned phase-II 3% loading
- Phase-I: $T_{1/2} > 1.96 \times 10^{26}$ yr (90% CL); $m_{\beta\beta} < 36\text{-}90$ meV





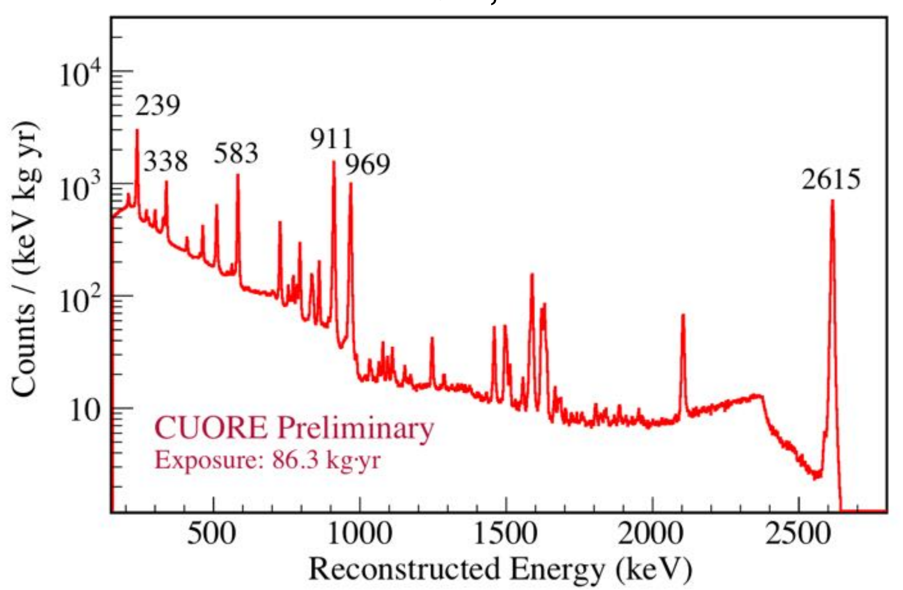


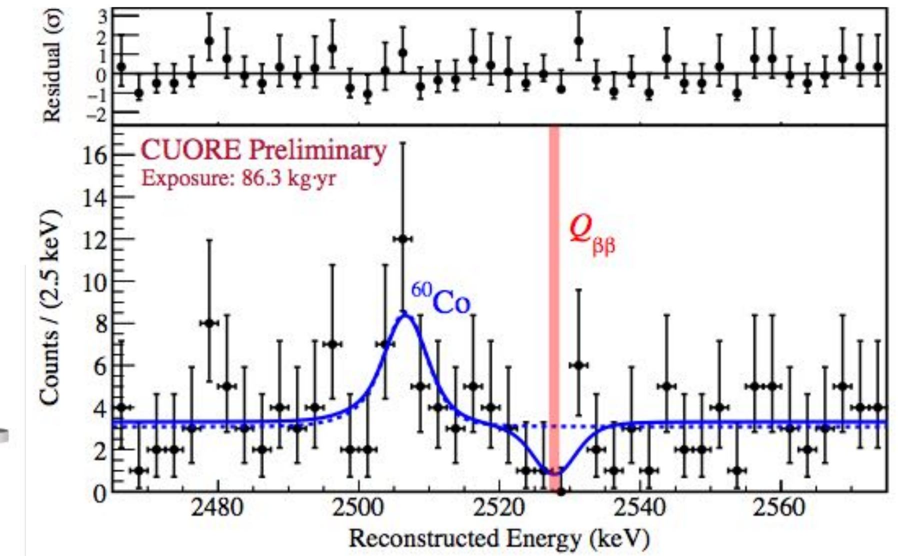
Caden - TAUP2017

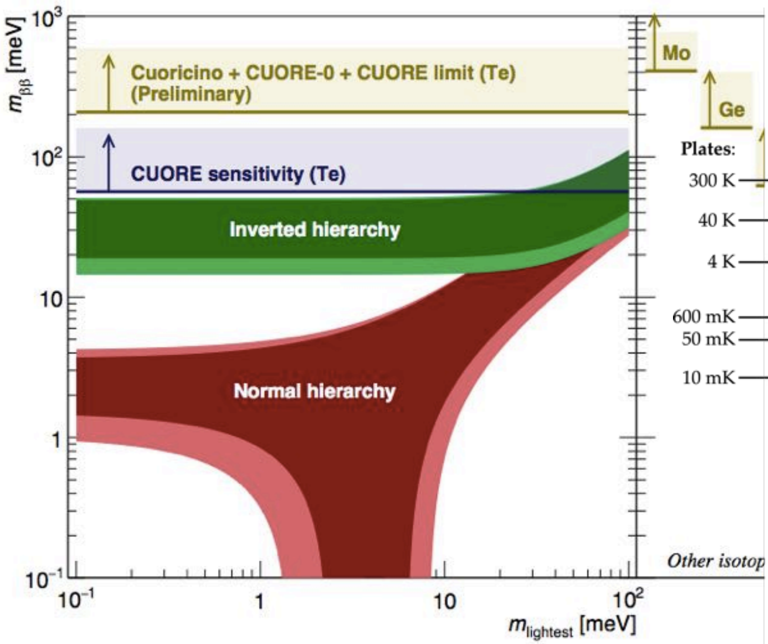
CUORE

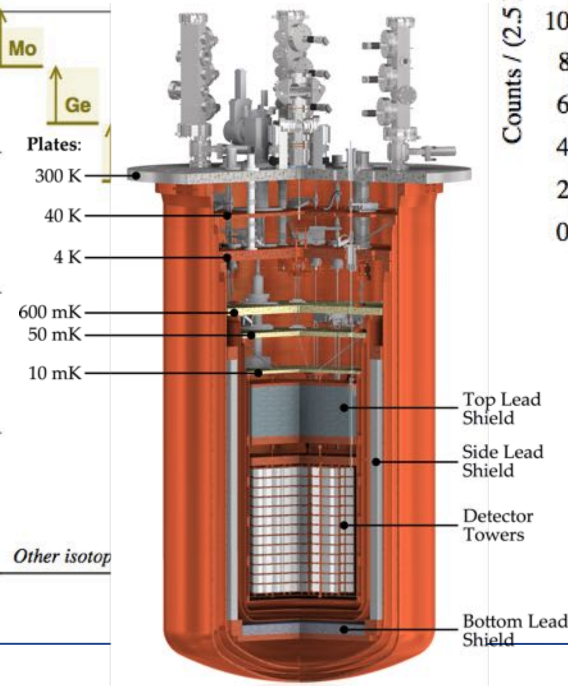
- 988 Te 15 mK cryogenic bolometers; 742kg TeO_2 (206kg ^{130}Te)
- Energy resolution 0.2% - 0.4% (under optimisation)
- Data start April 2017: ^{130}Te exposure of 24 kg.yr
- 155 events in ROI: fit uses ^{60}Co peak, background + $0\nu\beta\beta$
- Best fit decay rate: $(-1.0\pm0.4)\times10^{-24}$ / yr
    - Decay rate limit (90% CL): 0.51×10^{-25} / yr
    - Half-life limit (90% CL): $T_{1/2}^{0\nu\beta\beta} > 1.3\times10^{25}$ yr
- Combined fit with CUORE-0/CUORICINO: $T_{1/2}^{0\nu\beta\beta} > 1.5\times10^{25}$ yr
    - $m_{\beta\beta} < 140 - 400$ meV
- Final sensitivity (Eur. Phys. J. C (2017) 77:532)
    - $T_{1/2}^{0\nu\beta\beta} > 9\times10^{25}$ yr ; $m_{\beta\beta} < 60 - 165$ meV

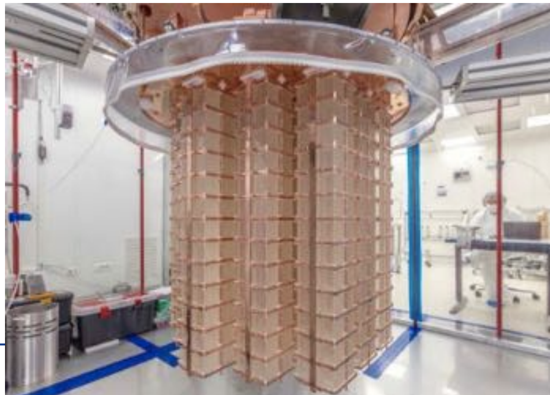
arXiv:1710.07988, submitted to PRL





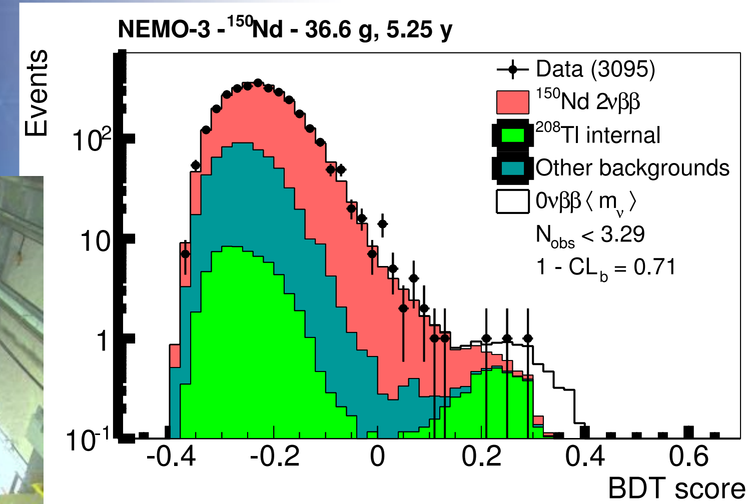


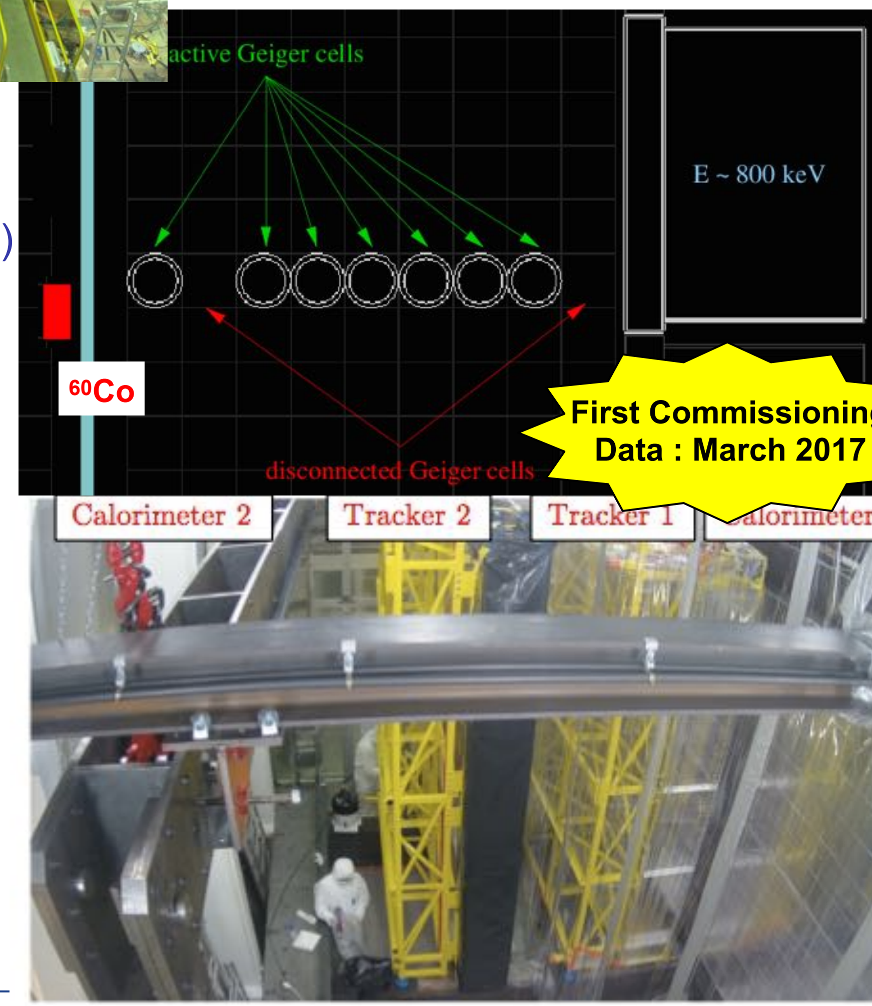




NEMO-III / SuperNEMO

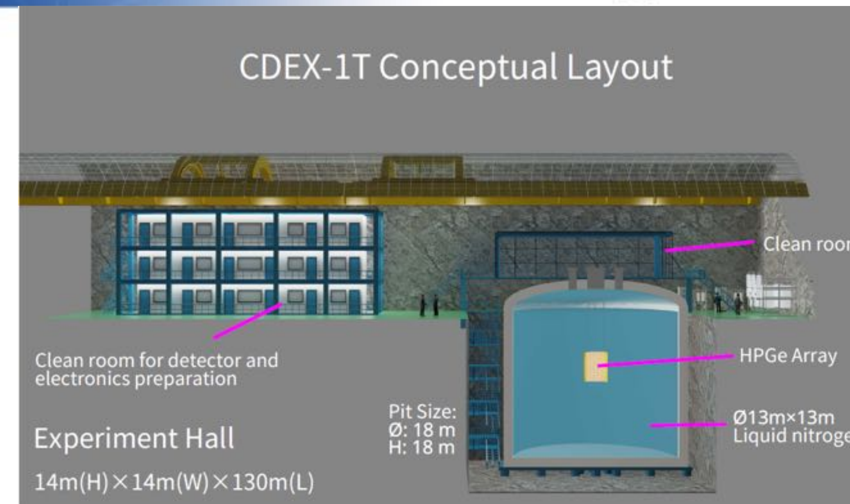
- Source and detector separated
  - Tracker and calorimeter
- Previous result: ^{100}Mo(7kg) m < 0.3 - 0.6 eV
- ^{150}Nd(36.6g) Phys.Rev. D94 (2016), 072003
  - $T_{1/2}^{0\nu\beta\beta}$ > 2.0 x 10^{22} yr (90% cl)
  - $m_{\beta\beta}$ < 1.6 - 5.3 eV
- ^{116}Cd(410g) Phys.Rev. D95 (2017), 012007
  - $T_{1/2}^{0\nu\beta\beta}$ > 1.0 x 10^{23} yr (90% cl)
  - $m_{\beta\beta}$ < 1.4 - 2.5 eV
- ^{150}Nd Neutrinoless quadruple decay limit PRL 119, 041801 (2017)
  - $T_{1/2}^{0\nu4\beta}$ > (1.1-3.2) x 10^{21} yr (90% cl); expected (1.3-3.7) x 10^{21} yr
- SuperNEMO demonstrator in construction
  - 6.3 kg of ^{82}Se (Qββ = 2.998 MeV) in 36 foils
  - Tracker: 2034 drift cells in Geiger mode
  - Polystyrene scintillator energy resolution : 4% FWHM at 3 MeV (^{82}Se Qββ)
  - Half detector constructed, under commissioning
  - Data start in 2018
- Demonstrator objective
  - 17.5 kg×yr initial exposure (2.5 yr):
  - $T_{1/2}^{0\nu\beta\beta}$ > 6.5 x 10^{24} yr
  - $m_{\beta\beta}$ < 0.20 - 0.40eV

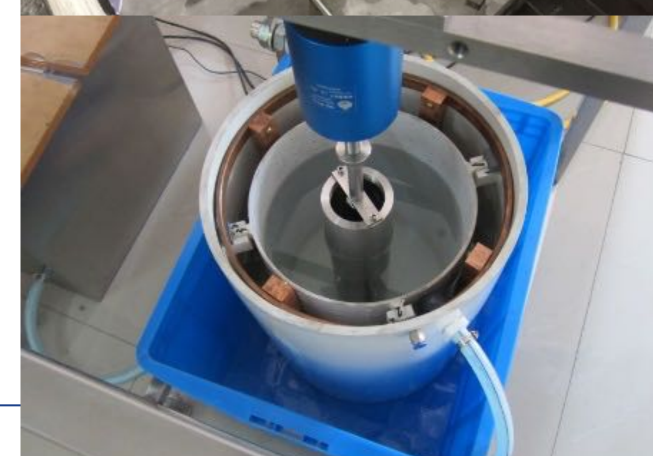


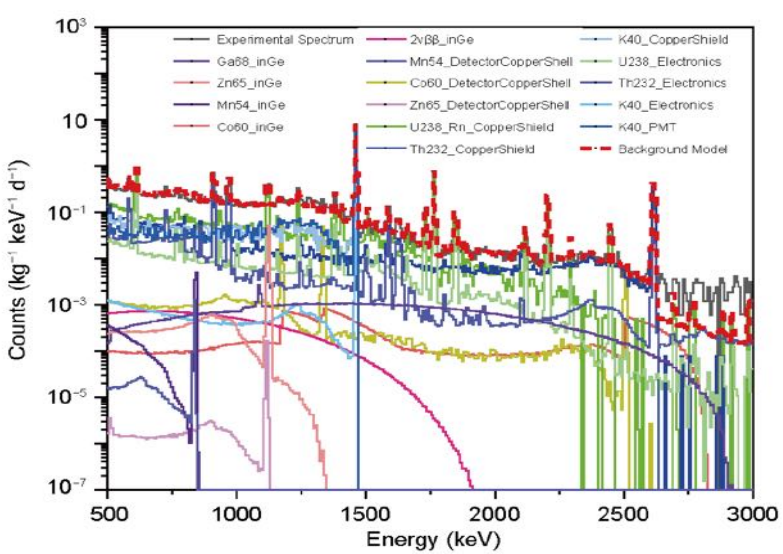


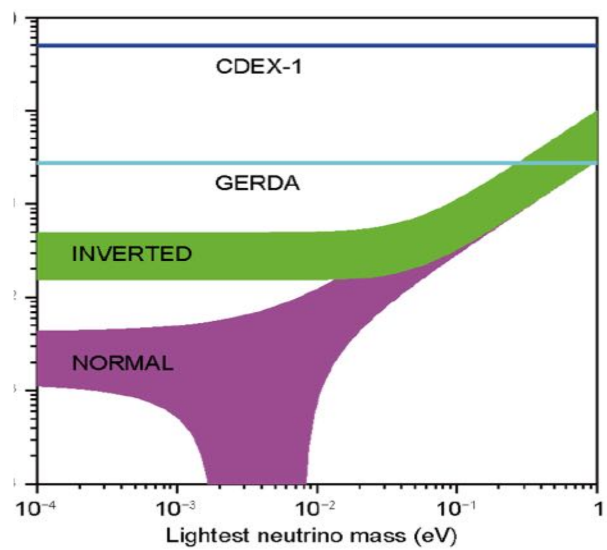
CDEX

- CDEX-1 PPC Ge detector
  - Method developed to estimate the level of cosmogenic events @ 2MeV based on cosmogenic characteristic X-ray peaks <10keV;
  - L. Wang, Q. Yue*, et al. Sci. China Phys. Mech. Astron. (2017) 60: 071011



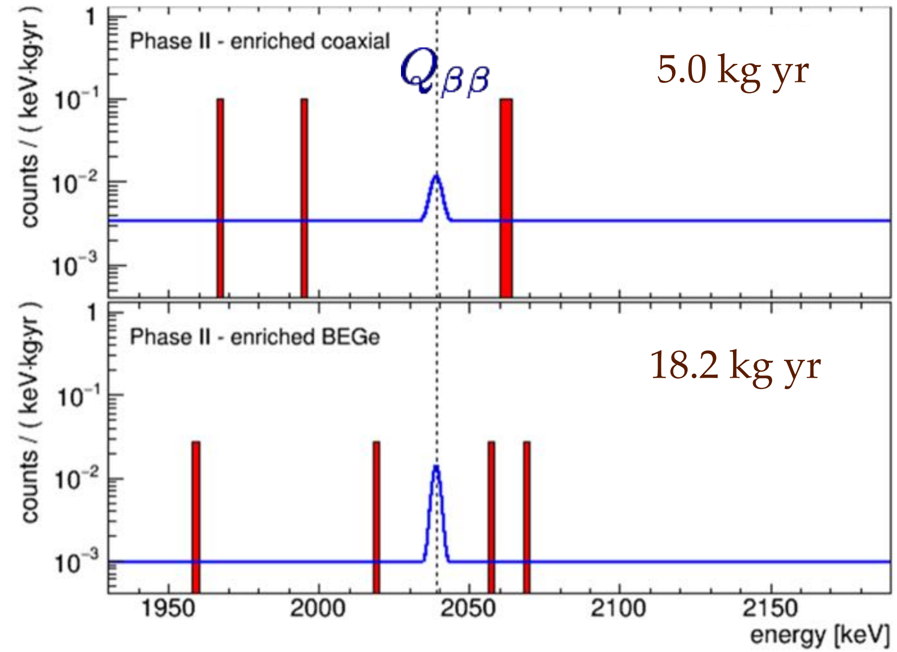


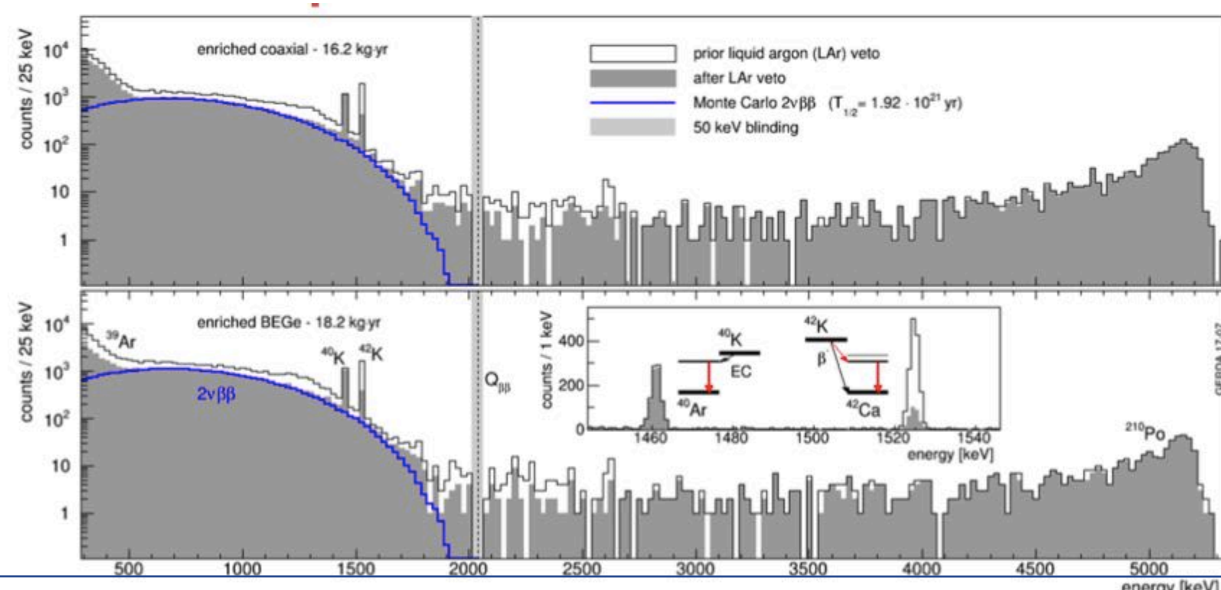


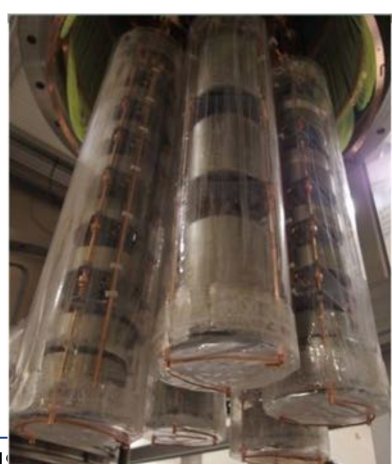


GERDA

- Ge semiconductors in LAr shield
  - Minimal support structures on crystals
  - 35.6 kg of 87% enriched 76Ge crystals
    - 30 BEGe detectors (20.0 kg)
    - 7 coaxial HdM and IGEX (18 kg)
  - 2.9 keV FWHM @ 2039 keV
  - BG goal: 1 cts/(keV.t.yr)
- Recent results (arXiv:1710.07776)
  - BI: $1.0^{+0.6}_{-0.4}$ cts/(keV.t.yr)
  - $T_{1/2}^{0\nu\beta\beta} > 8.0\times10^{25}$ yr (90% C.L.)
  - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 5.8\times10^{25}$ yr

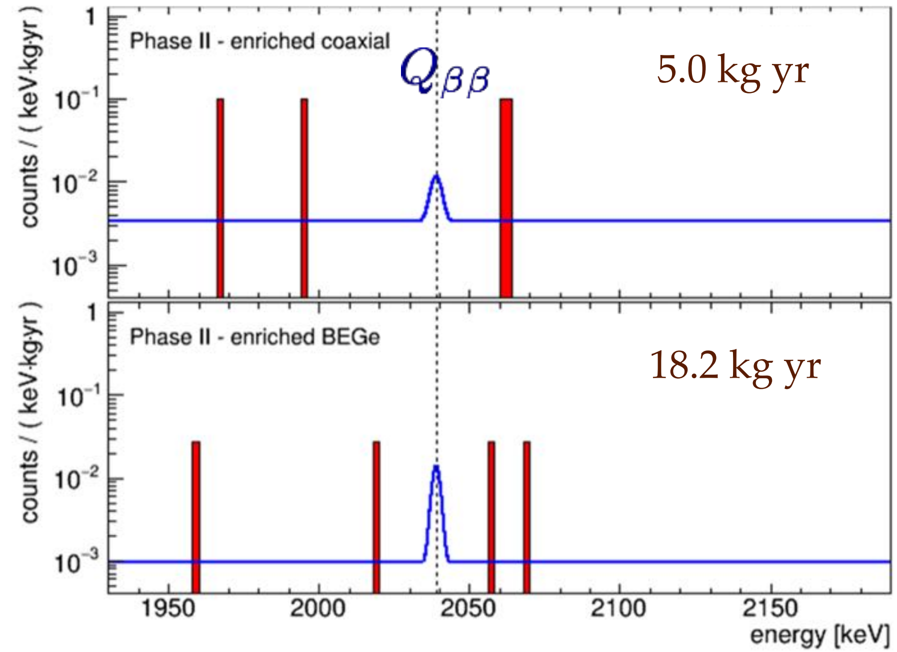


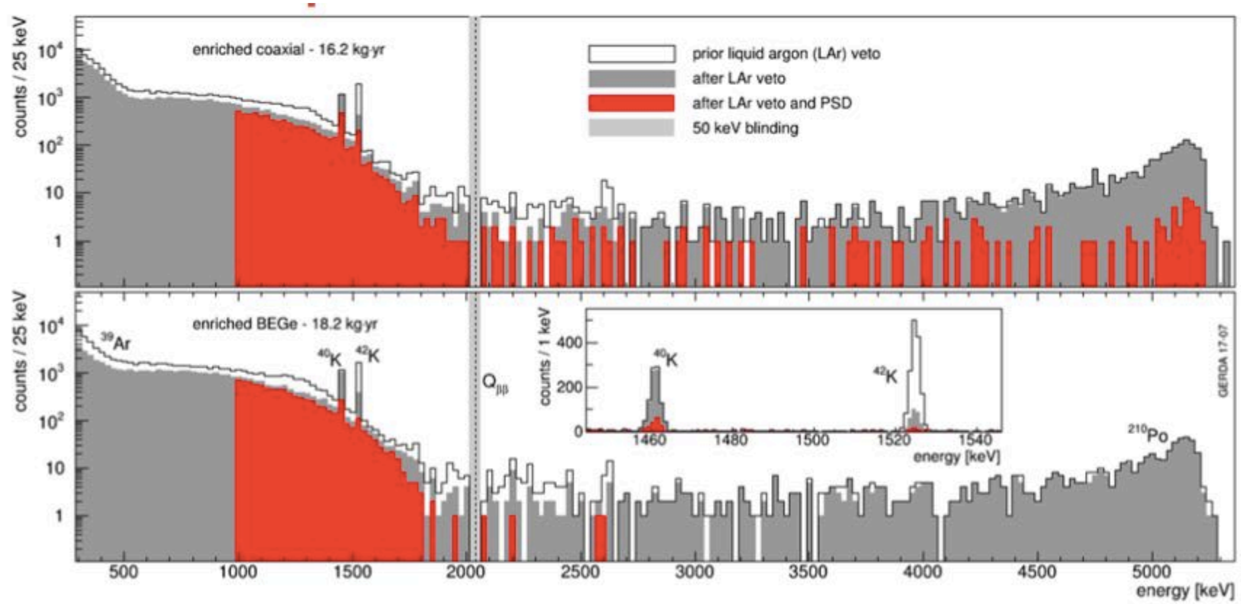


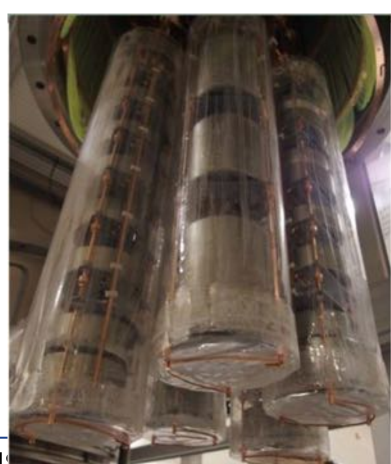


GERDA

- Ge semiconductors in LAr shield
  - Minimal support structures on crystals
  - 35.6 kg of 87% enriched 76Ge crystals
    - 30 BEGe detectors (20.0 kg)
    - 7 coaxial HdM and IGEX (18 kg)
  - 2.9 keV FWHM @ 2039 keV
  - BG goal: 1 cts/(keV.t.yr)
- Recent results (arXiv:1710.07776)
  - BI: $1.0^{+0.6}_{-0.4}$ cts/(keV.t.yr)
  - $T_{1/2}^{0\nu\beta\beta} > 8.0\times10^{25}$ yr (90% C.L.)
  - Sensitivity $T_{1/2}^{0\nu\beta\beta} > 5.8\times10^{25}$ yr

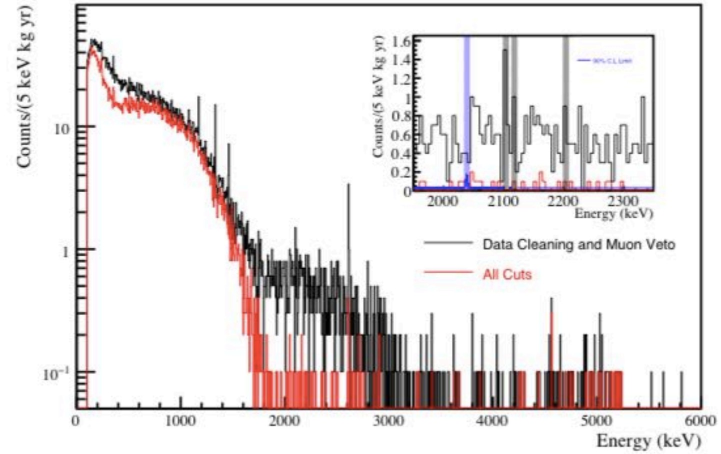


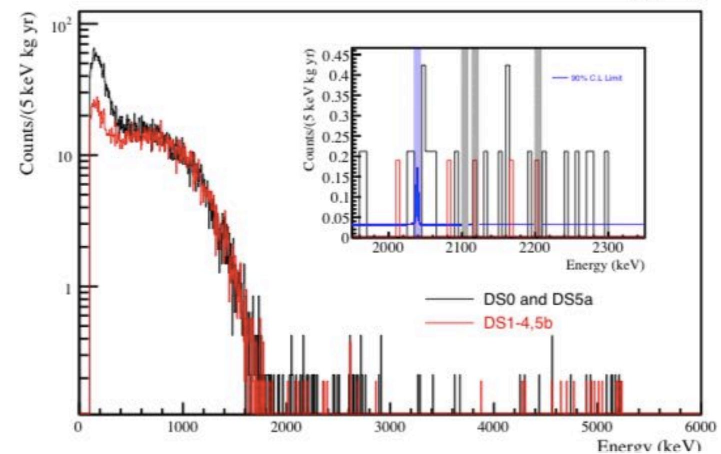


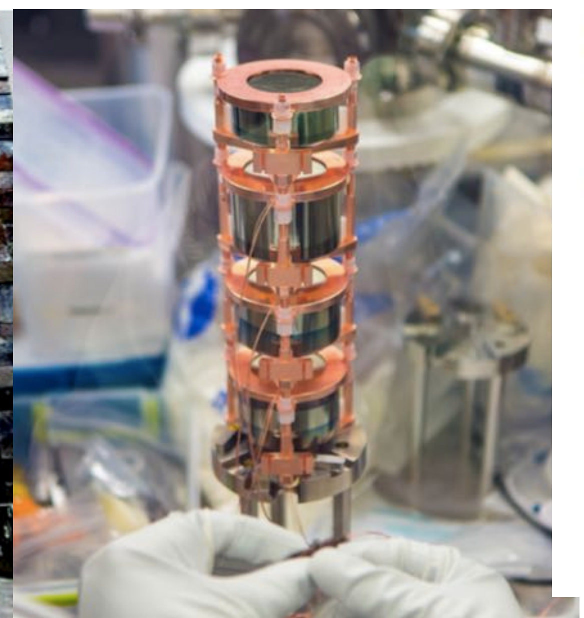


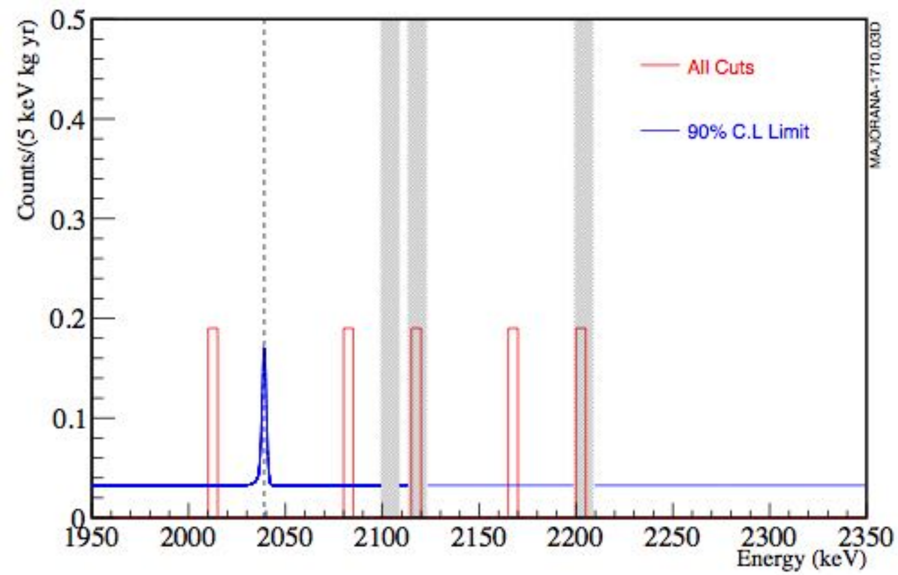
Majorana Demonstrator

- "Traditional" shielding design
- 44.1-kg of P-type, point contact Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals (35 PPC)
  - 14.4 kg of ^{nat}Ge (BEGe)
  - BG goal: 1 cts/(keV.t.yr):
- Copper structures electro-formed underground
  - Average Th decay chain ≤ 0.1 μBq/kg
  - Average U decay chain ≤ 0.1 μBq/kg
- 9.95 kg-yr exposure of enriched detectors (arXiv:1710.11608)
  - 2.4 keV FWHM at 2039 keV
  - $T_{1/2}^{0\nu\beta\beta} > 1.9\times10^{25}$ yr (90% C.L.); sensitivity $T_{1/2}^{0\nu\beta\beta} > 2.1\times10^{25}$ yr
  - Background index of $1.6^{+1.2}_{-1.0}$ cts/(keV.t.yr)









LEGEND Status (arXiv:1709.01980)

- Merging of GERDA and Majorana, 47 institutes, 237 scientists

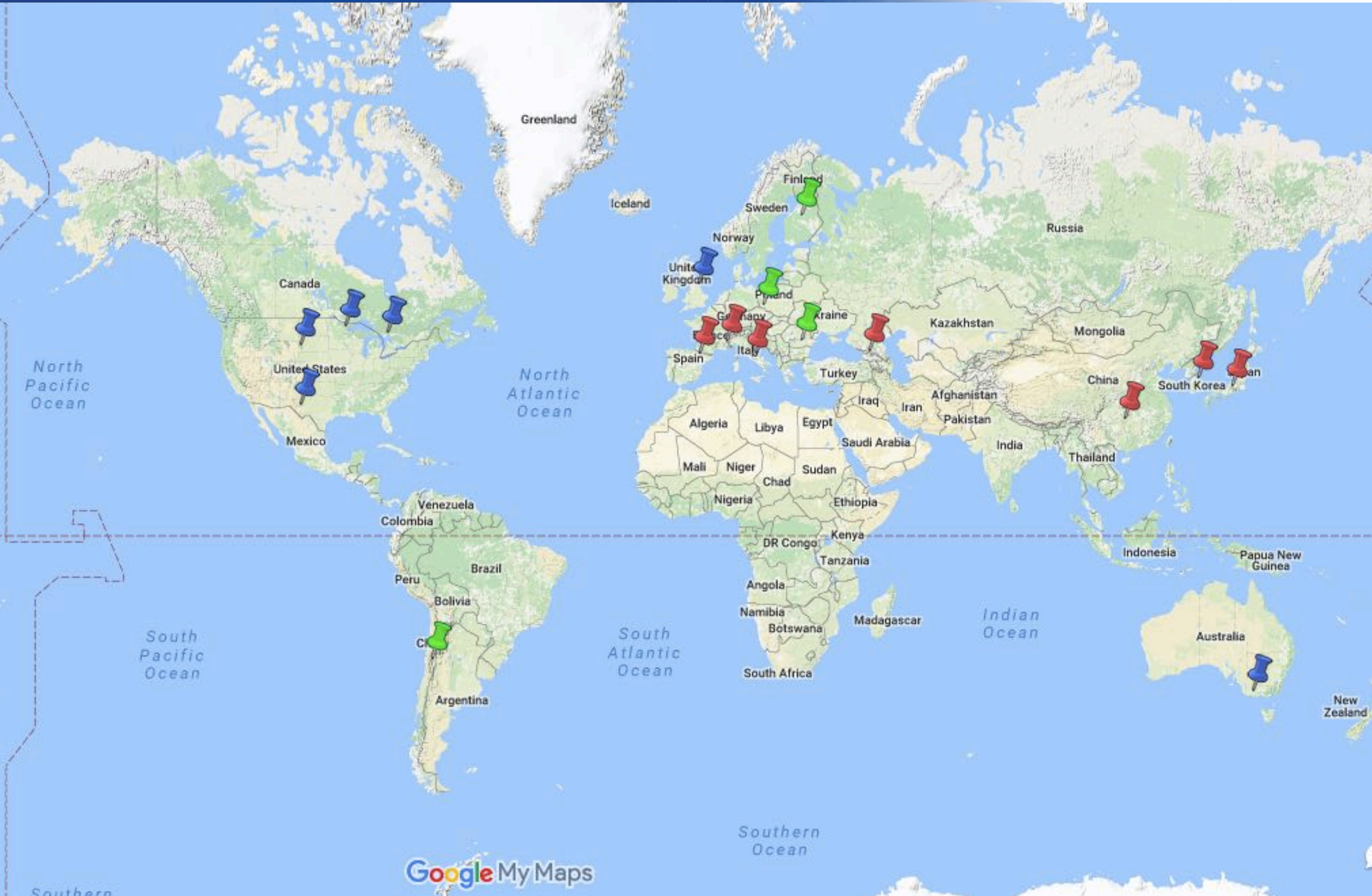
First Stage:
- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal
  0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors

Subsequent Stages:
- 1000 kg ^{76}Ge (staged)
- Timeline coordinated with First Stage
- BG goal
  0.1 cts/(FWHM t yr)
- Location tbd
- Required depth (Ge-77m) under investigation

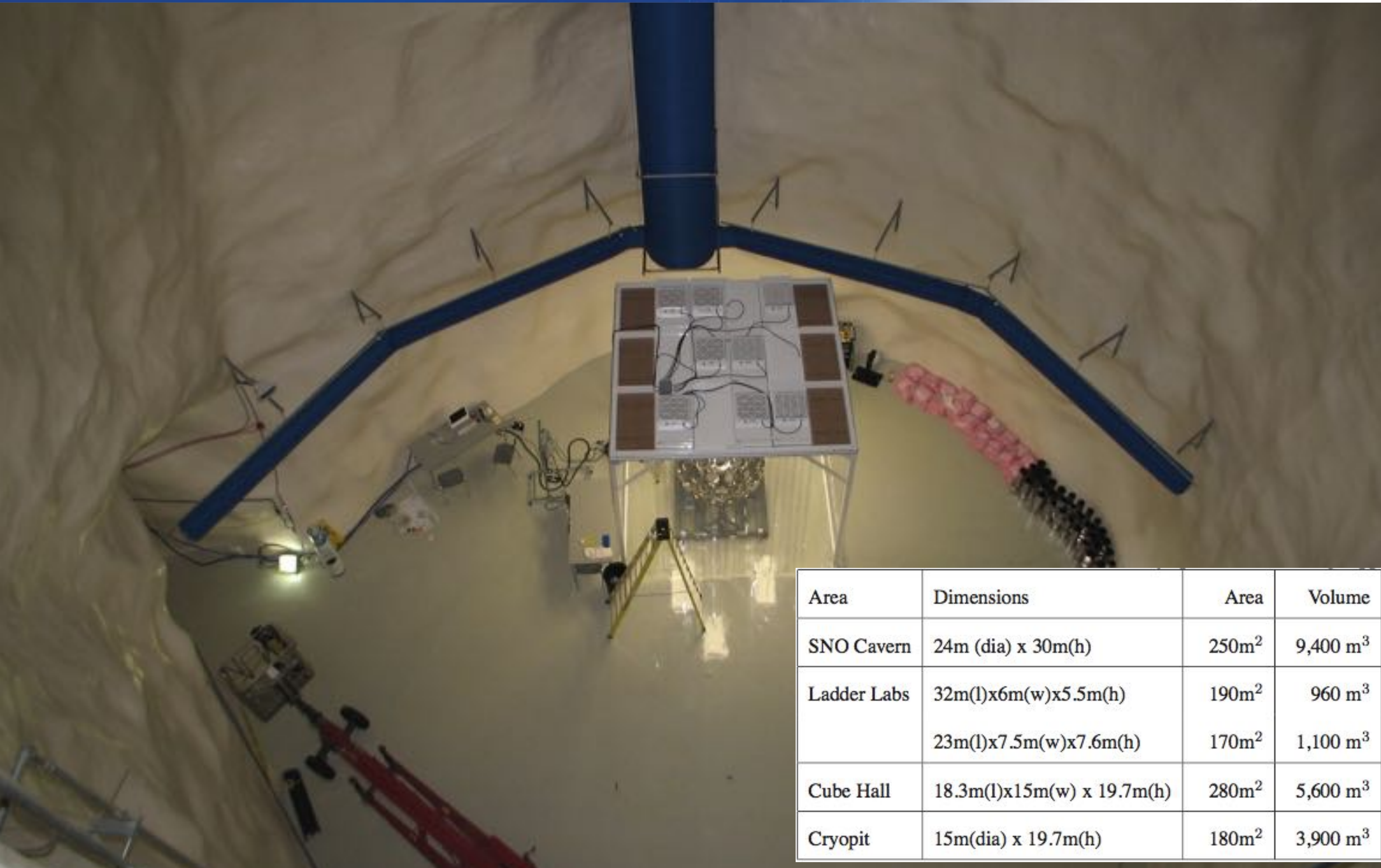
- Have funding for 130 kg from a number of international partners
- Proposal submitted to NSF for 50 kg of detectors and readout electronics for 170 channels
- Proposal will be submitted to LNGS in mid March
- Background goal sufficient for nearly background-free meas.(0.6 cts/(FWHM t yr))
- Discovery Sensitivity >10^{27} yr

- Aiming for excellent discovery potential due to resolution and background
- DOE Funding for key R&D (NSAC-recognised)
- Other R&D development funded by institutional support
- Background goal sufficient for nearly background-free meas. (0.1 cts/(FWHM t yr))
- Discovery Sensitivity >10^{28} yr

Underground Facilities



Cryopit staging area



Area	Dimensions	Area	Volume
SNO Cavern	24m (dia) x 30m(h)	250m^2	9,400 m^3
Ladder Labs	32m(l)x6m(w)x5.5m(h)	190m^2	960 m^3
	23m(l)x7.5m(w)x7.6m(h)	170m^2	1,100 m^3
Cube Hall	18.3m(l)x15m(w) x 19.7m(h)	280m^2	5,600 m^3
Cryopit	15m(dia) x 19.7m(h)	180m^2	3,900 m^3

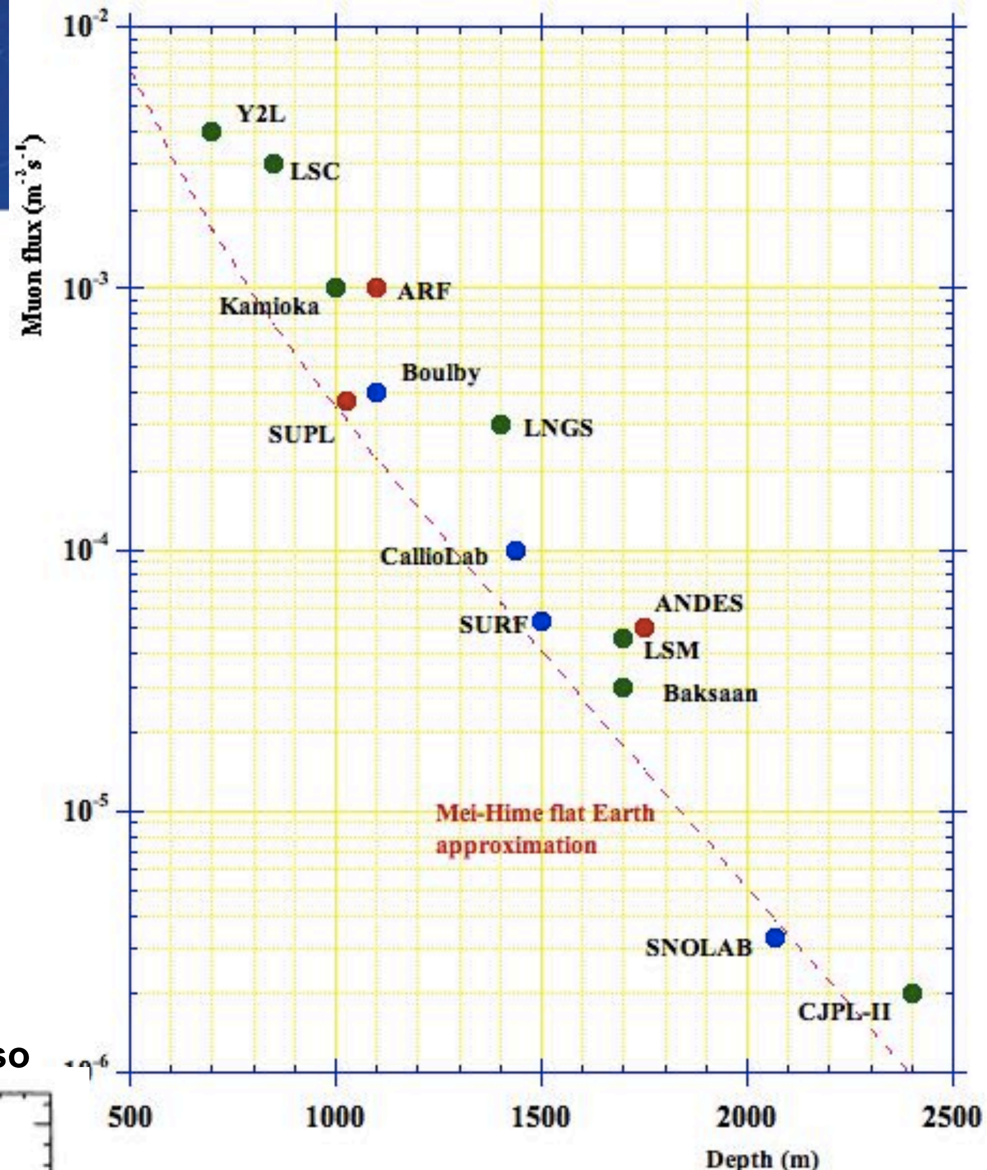
Update on 0νββ

- Physics goals of 0νββ include: lepton number violation; Majorana-nature of neutrino; neutrino effective mass measurement; neutrino hierarchy exploration
- Substantial progress over the last few years:
  - Multiple experiments have attained sensitivities of $T_{1/2} > 10^{25}$ years, now reaching $T_{1/2} \sim 10^{26}$ years.
  - Techniques maturing, developing low background material production / assay, analysis techniques
- Next generation detectors (tonne scale) are being developed by large international collaborations
  - Based on experience gained during the operation of current generation detectors
  - Required R&D well advanced or completed
  - All aim for sensitivity and discovery levels at $T_{1/2} > 10^{27}$ years
  - Internationalisation of double-beta field occurring, both in creation of large scale collaborations, but also inter-collaboration merging
- Required deep underground infrastructure needs to maintain pace as required
  - Coordination between deep underground facilities developing more strongly
  - Infrastructure construction may need preparation time (esp. if new cavities required at great depth)

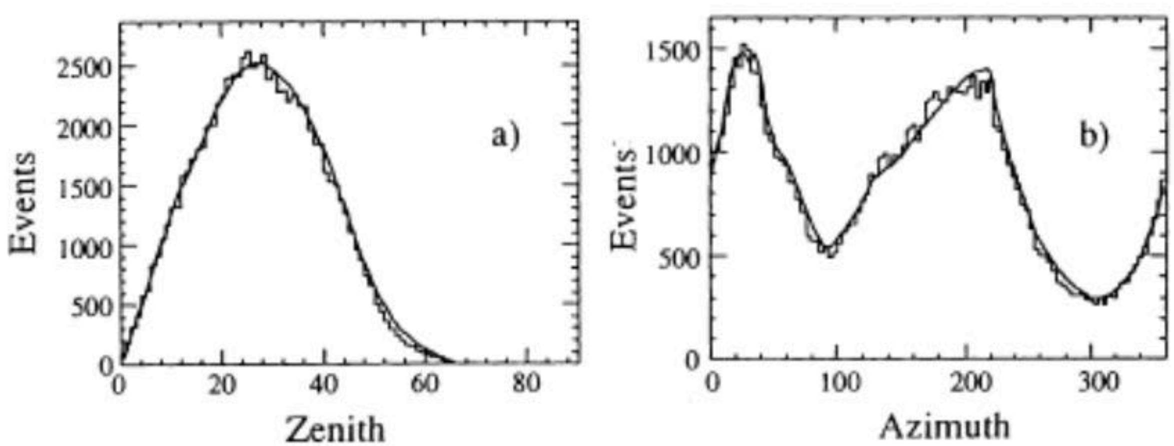
Underground Infrastructure

Effect of over-burden

- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced products
- Muons can be veto'd in anti-coincidence shield; secondary products may be an issue
- Cosmogenics may require underground material production or purification
  - May also contribute to b/grounds (e.g. ^{11}C)
- Muon flux depends on
  - overburden
  - overburden profile
  - seasonal effects

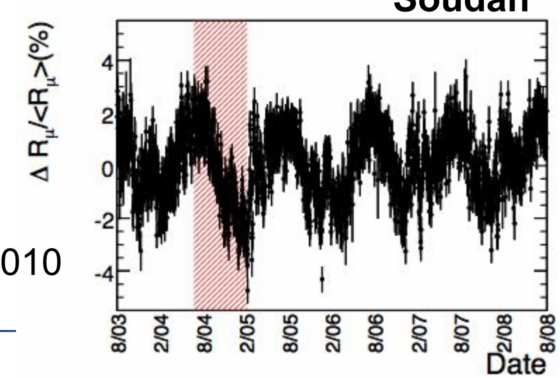


Gran Sasso



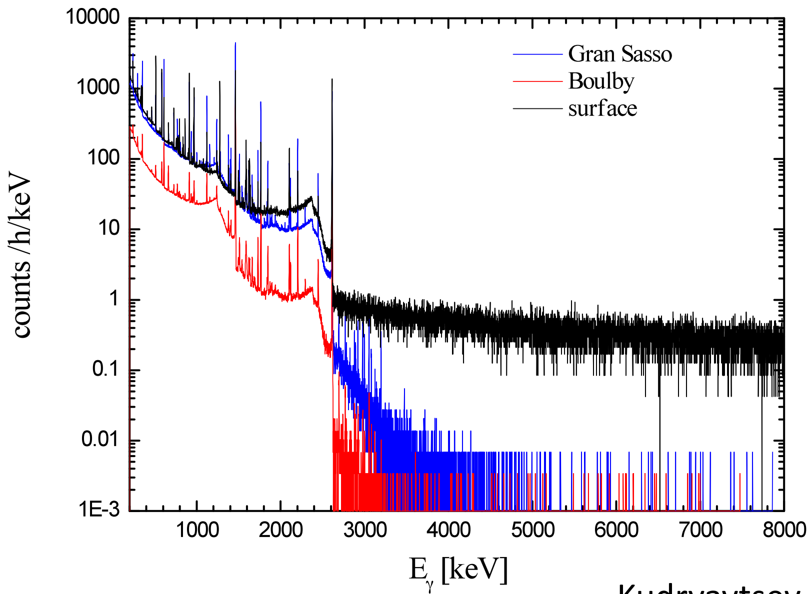
Bellotti 1990

Soudan

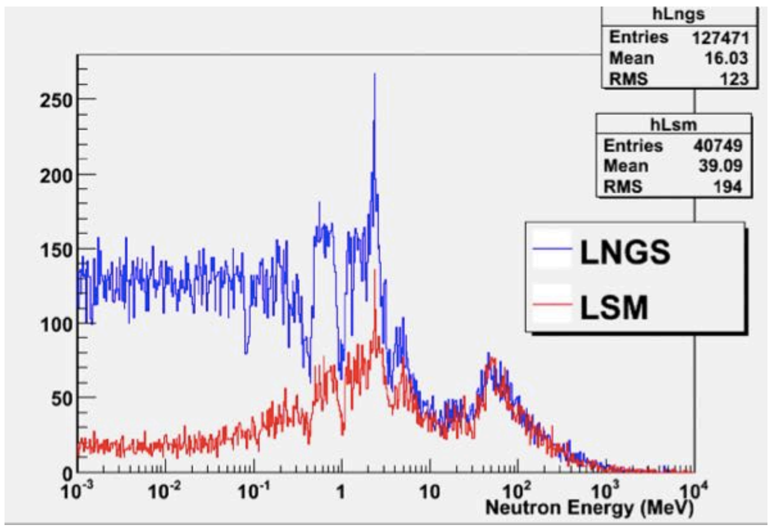


Adamson 2010

Radiogenic Backgrounds



Kudryavtsev



Persiani / Selvi

- Reduction in γ-ray background at higher energies from c.r. and neutron reduction
  - important for nuclear astrophysics dedicated beam experiments, and some 0νββ isotopes
- Below 3.5MeV dependent on local geology and rock material

- Neutron production from c.r. muon spallation, U/Th fission, (α, n) reactions, radon reactions
- Spectrum in laboratory depends on local geology (rock composition)
  - both for fast and thermal neutrons
  - U/Th + moderators
  - muons + moderators
  - small levels of high neutron cross-section contaminants make a big difference

Characteristics

	SNOLab	LNGS	LSC	Boulby	LSM	Callio Lab	Baksan	SURF	CJPL-I/II	Kamioka	Y2L
Date of creation	2003 (1991)	1987	2010	1989	1982	1995	1967	2007 (1967)	2009/ 2014	1983	2003 A6 2014 A5
Personnel	100	106	12	6	12	13	227	125	20	94	4
Surface U/S [m^2]	5350/ 3100	17000/ 95000	1600/ 2550	1700/ 400	400	220	1600/ 10000	1900/ 190	8000	15000/ 3000	300/ 60
Volume [m^3]	30000	**180000**	10000	7200	3500	1000*	23000	7160	4000/ **300000**	150000	5000
Depth [m]	2070	1400	850	1100	1700	1440	1700	1500	2400	1000	700
Access [V or H]	V	H	H	V	H	V / drive in	H	H	H	H	Drive in
Makeup Air [m^3/h]	12000	35000-60000	20000	300	5500	3600	1440	510000	_	6000	3300
Air change/day	10	5-8	48	24	38	7	_	144 (LUX)	_	6	15
Muon flux [$m/m^2/s$]	$3.1\ 10^{-6}$	$3\ 10^{-4}$	$3\ 10^{-3}$	$4\ 10^{-4}$	$4.6\ 10^{-5}$	$1\ 10^{-4}$	$3\ 10^{-5}$	$5.3\ 10^{-5}$	$2\ 10^{-6}$	10^{-3}	$4\ 10^{-3}$
Radon [Bq/m^3]	130	80	100	**<3**	15	70	40	300	40	80	40
Cleanliness	2000 or better	Only in sector	Only in sector	10000	ISO9	Only in sector	Only in sectors	3000	Only in sectors	Only in sectors	Only in sectors

Ianni - TAUP2017

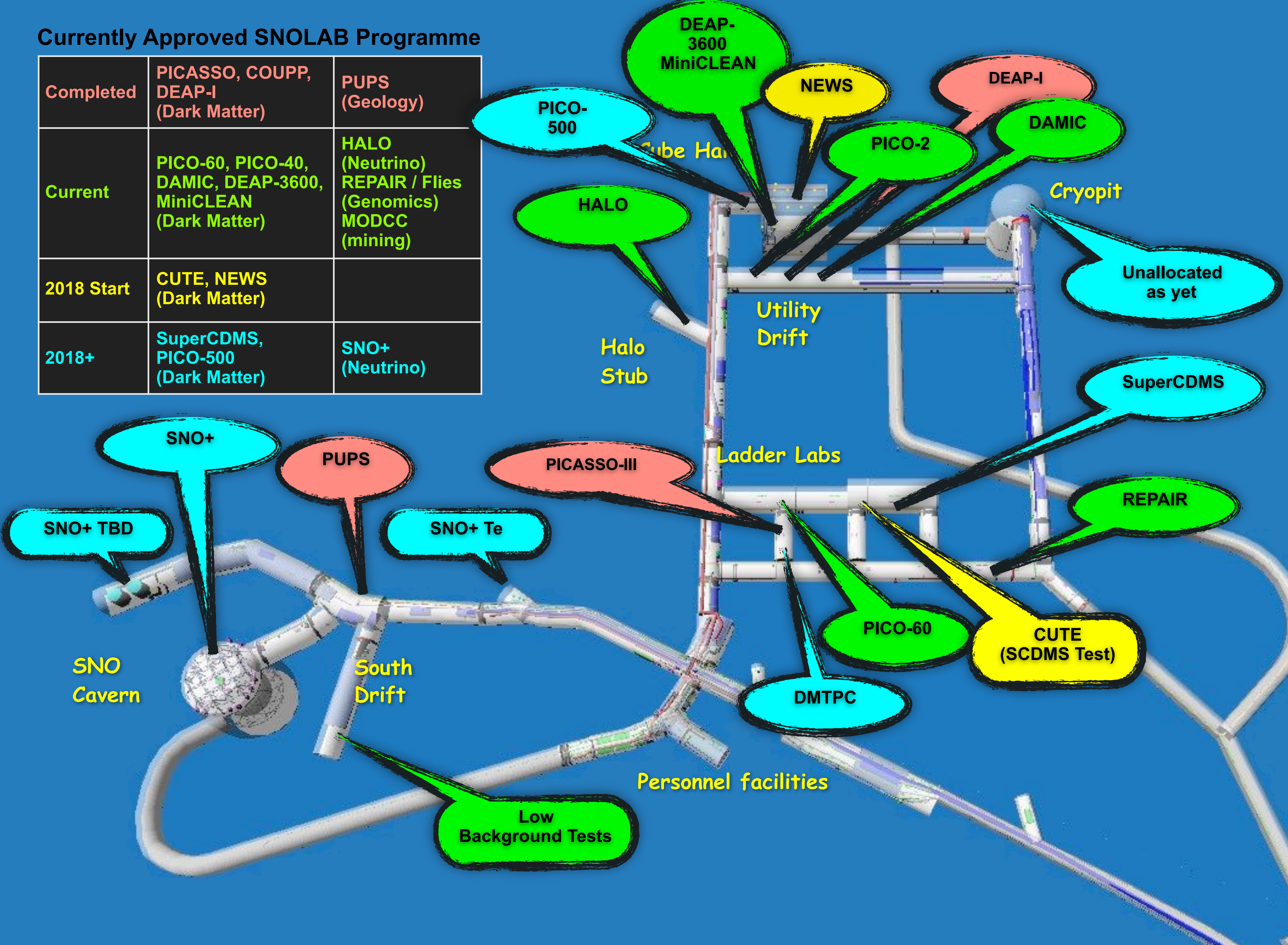
Upcoming facilities

	SUPL	ARF	ANDES
Expected to be in operation	end of 2018	mid-end of 2019	2027
Personnel	3	20	–
Access	Drive in	V / drive in	H
Volume [m^3]	3025	47000	70000
Surface [m^2]	350	2000	2800
Outside surface [m^2]	100	1000	Foreseen building
Depth [m]	1025	1100	1750
Muon Flux [$\mu/m^2/s$]	$3.7\ 10^{-4}$	$\sim 10^{-3}$	$\sim 5\ 10^{-5}$
Makeup air [m^3/h]	From the mine through Rn purification	7840	-
Air change/day	96	6	-
Cleanliness requirement	Yes (SNOLab style)	Only in sectors	–

Ianni - TAUP2017

Currently Approved SNOLAB Programme

Completed	PICASSO, COUPP, DEAP-I (Dark Matter)	PUPS (Geology)
Current	PICO-60, PICO-40, DAMIC, DEAP-3600, MiniCLEAN (Dark Matter)	HALO (Neutrino) REPAIR / Flies (Genomics) MODCC (mining)
2018 Start	CUTE, NEWS (Dark Matter)	
2018+	SuperCDMS, PICO-500 (Dark Matter)	SNO+ (Neutrino)



Lab Co-ordination efforts

- Co-ordination efforts between deep underground facilities are strengthening
  - LNGS/SNOLAB initiated G7 GRO GRI proposal
    - https://www.bmbf.de/files/151109_G7_Broschere.pdf
  - DULIA: attempt for EU coordination (funding) between LNGS, LSC, Boulby, LSM, CallioLab
  - Coordination and links on outreach and comms
    - LNGS/LSC deploying muon counters available to public
  - Sharing of best practice
    - Developing in operational matters, EH&S, expt. management, expt. reviews, governance
    - low background counting/assay (LRT series), shared databases
  - Sharing of work loads
    - 'blitzes' on low background counting
  - Can this extend to science projects?
    - e.g. Cygnus distributed array of detectors for DM
- IUPAP WG9 Neutrino Panel and inclusion of $0\nu\beta\beta$
  - Forms a major part of the drivers for deep underground facilities as **infrastructure** for the delivery of this science field
  - Connecting to ApPIC working group