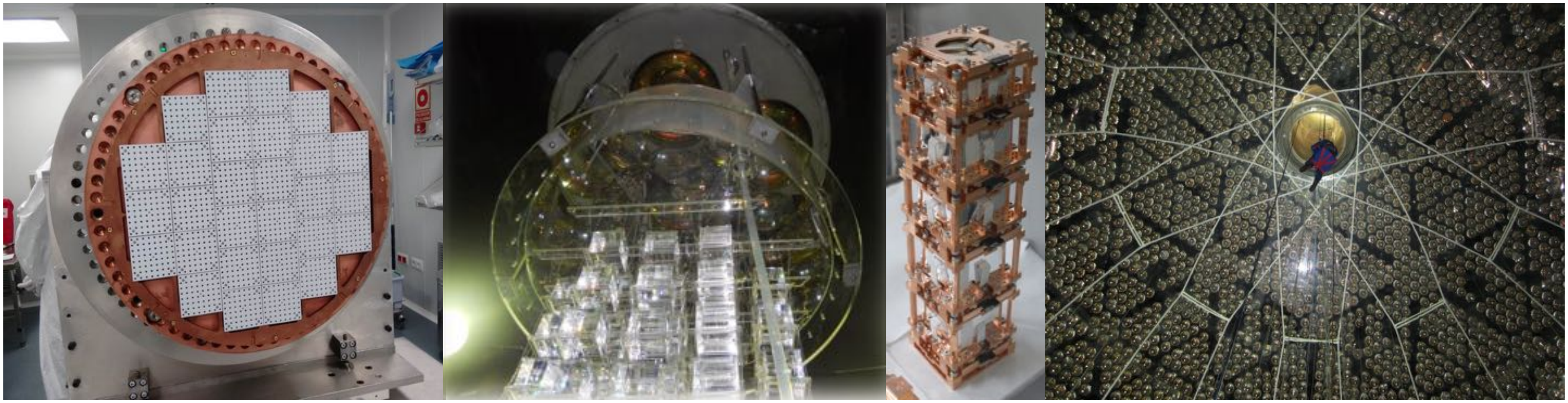

Future Neutinoless Double Beta Decay Search Experiments

Alex Wright
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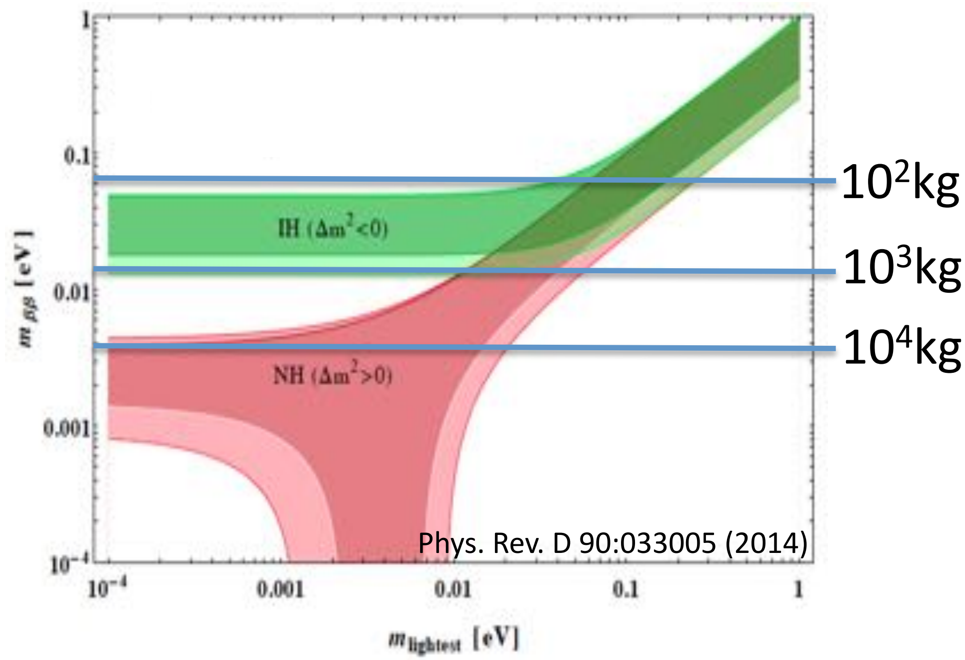
Neutrino 2016, University College London

With thanks to all who provided material:
Juan Jose Gomez Cadenas, Michel Sorel & Paola Ferrario; Mark Chen & Steve Biller; Nobuhiru Ishihara; Yeongduk Kim & Hyon-Suk Jo; Tadafumi Kishimoto & Saori Umehara; Stefan Schönert; Xiangdong Xi & Han Ke; Qian Yue; Kai Zuber & Stefan Zatschler

Introduction

- Global neutrinoless double beta decay search program includes many experiments using different isotopes and technologies.
- Key detector parameters
  - Mass
  - Energy Resolution
  - Background Control
- The sensitivity of neutrinoless double beta decay experiments is rapidly improving
  - Currently approaching the top of the inverted hierarchy region
  - Next-generation experiments will explore the inverted hierarchy region
- New developments are needed to probe the normal hierarchy region

Rough isotope mass requirements to reach different sensitivities.



Current experiments and R&D Programs

Experiment	Isotope	Technique	Location
Majorana Demonstrator	^{76}Ge	Point contact Ge	Sanford
GERDA II	^{76}Ge	Semicoax/BE Ge + veto	LNGS
CDEX	^{76}Ge	Point contact Ge	CJPL
NG-Ge76	^{76}Ge	Point contact Ge	
COBRA	^{116}Cd, etc	CdZnTe	LNGS
CANDLES	^{48}Ca	CaF_2 scintillator + veto	Kamioka
AMoRE	^{100}Mo	Low-T MMC	Y2L
DCBA/MTD	^{100}Mo	Foils + tracker	KEK
MOON	^{100}Mo	Foils + scintillator	
EXO200	^{136}Xe	LXe TPC	WIPP
nEXO	^{136}Xe	LXe TPC	SNOLAB
NEXT	^{136}Xe	High-P TPC	LSC
PandaX III	^{136}Xe	High-P TPC	CJPL
KamLAND-Zen	^{136}Xe	Liquid scintillator	Kamioka
SuperNEMO	^{82}Se	Foils + tracker	
CUPID	^{130}Te, ^{82}Se, ^{100}Mo, ^{116}Cd	Hybrid bolometers	
CUORE/CUORE-0	^{130}Te	TeO_2 bolometers	LNGS
SNO+	^{130}Te	Liquid scintillator	SNOLAB

I am to focus on those that have not yet presented:

Experiment	Isotope	Technique	Location
COBRA	^{116}Cd, etc	CdZnTe	LNGS
CANDLES	^{48}Ca	CaF_2 scintillator + veto	Kamioka
AMoRE	^{100}Mo	Low-T MMC	Y2L
DCBA/MTD	^{100}Mo	Foils + tracker	KEK
NEXT	^{136}Xe	High-P TPC	LSC
PandaX III	^{136}Xe	High-P TPC	CJPL
SNO+	^{130}Te	Liquid scintillator	SNOLAB

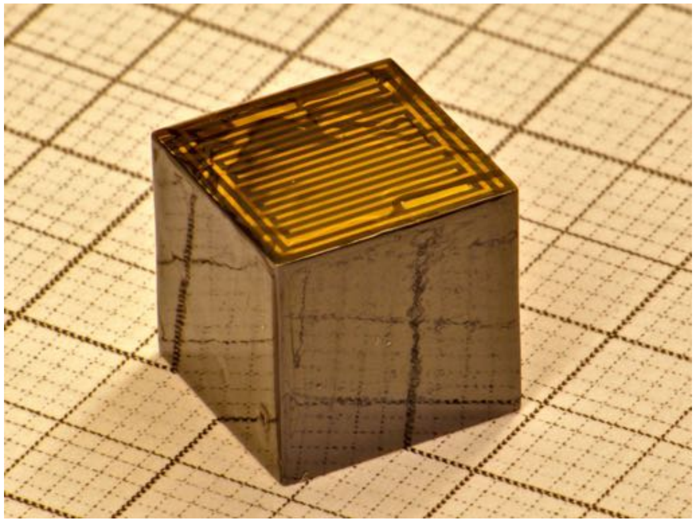
Presentation will be high-level, for details see posters:

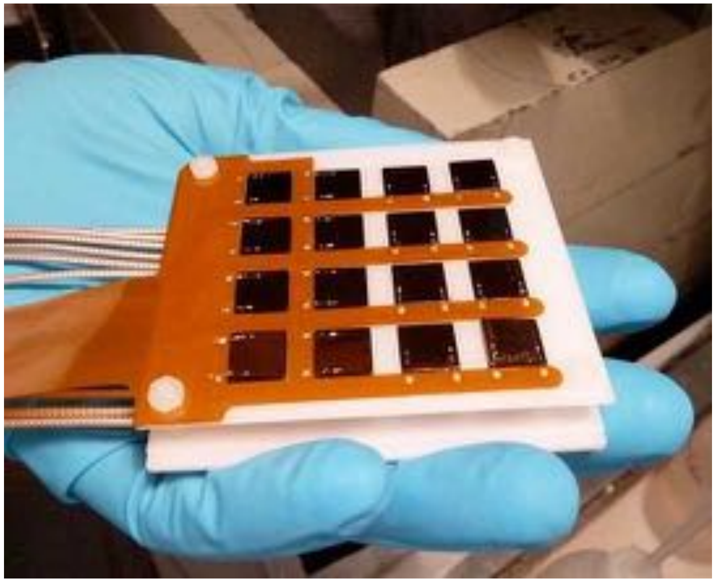
COBRA	P1.061 - Pulse shape discrimination techniques for the COBRA experiment
CANDLES	P1.060 - Development of scintillating bolometer for 48Ca neutrinoless double beta decay search
AMoRE	P4.049 - Status of the AMoRE experiment
NEXT	P4.064 - Topological signature in the NEXT high pressure xenon TPC
	P4.065 - Sensitivity of the NEXT100 detector to neutrinoless double beta decay
	P4.066 - The NEW detector: construction, commissioning and first results
SNO+	P1.015 - Scattering length monitoring at the SNO+ detector
	P1.072 - Commissioning the SNO+ Detector
	P1.073 - Pulse shape analysis techniques in liquid scintillator for the identification and suppression of radioactive backgrounds to neutrinoless double beta decay
	P1.074 - A new technique to load 130Te in liquid scintillator for neutrinoless double beta decay experiments
	P4.067 - Physics capabilities of the SNO+ experiment
	P4.068 - Background analysis for the SNO+ experiment
	P4.069 - Calibration of the SNO+ experiment

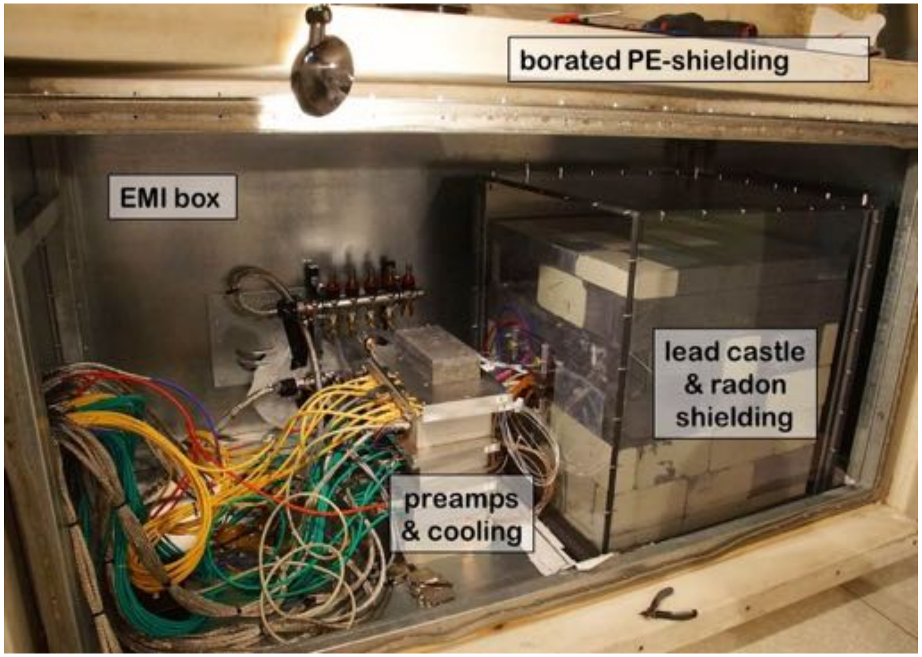
COBRA

(**C**dZnTe **0**ν Double **B**eta **R**esearch **A**pparatus)

- CdZnTe: an intrinsic semiconductor at room temperature
  - Contains 5 double beta isotopes
- COBRA Demonstrator, 4x4x4 array of 1cm^3 (6g) detectors operated at LNGS
  - 216 kg-d exposure







NIM A **807**:114 (2016)
arXiv:1509:04113

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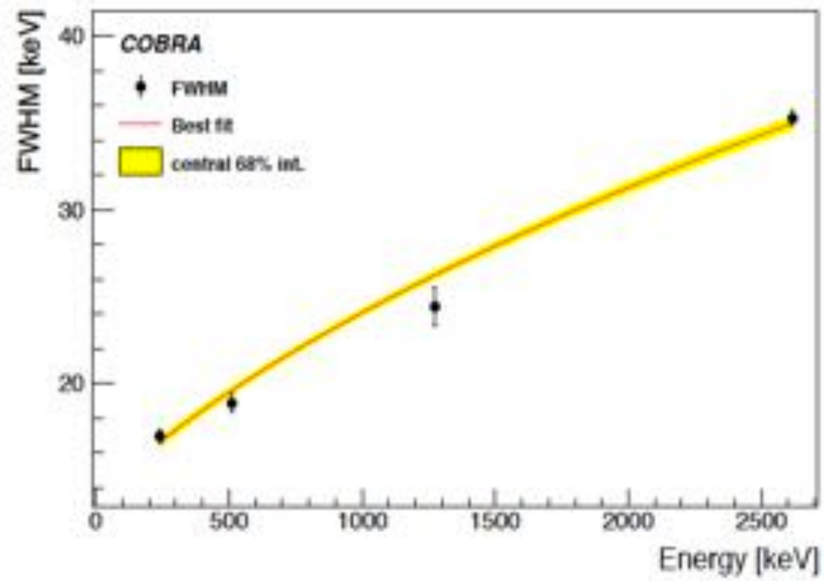
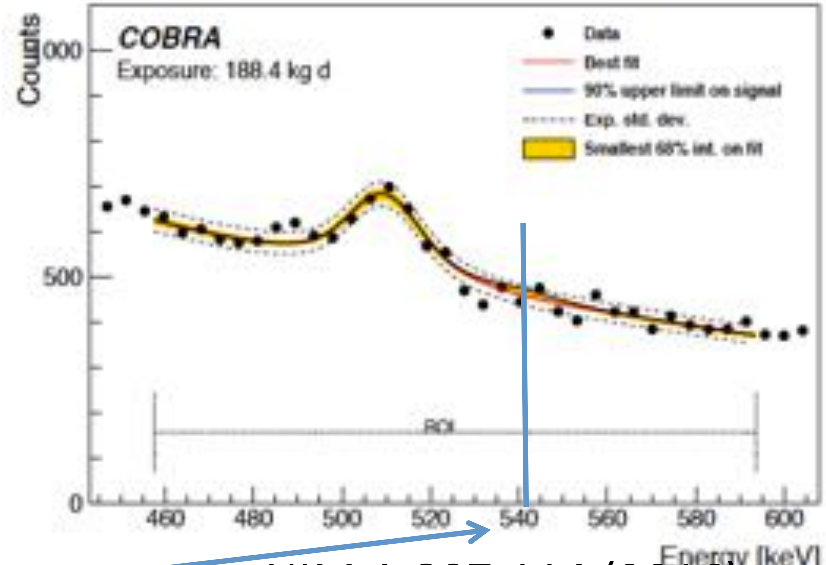


Isotope	BI [cts/(keV kg yr)]	90% Cred. limit
^{114}Cd	$213.9^{+1.0}_{-1.7}$	1.8×10^{21} yr
^{128}Te	$65.5^{+0.5}_{-1.6}$	2.0×10^{21} yr
^{70}Zn	$45.1^{+0.6}_{-1.0}$	7.4×10^{18} yr
^{130}Te	$3.6^{+0.1}_{-0.3}$	6.7×10^{21} yr
^{116}Cd	$2.7^{+0.1}_{-0.2}$	1.2×10^{21} yr



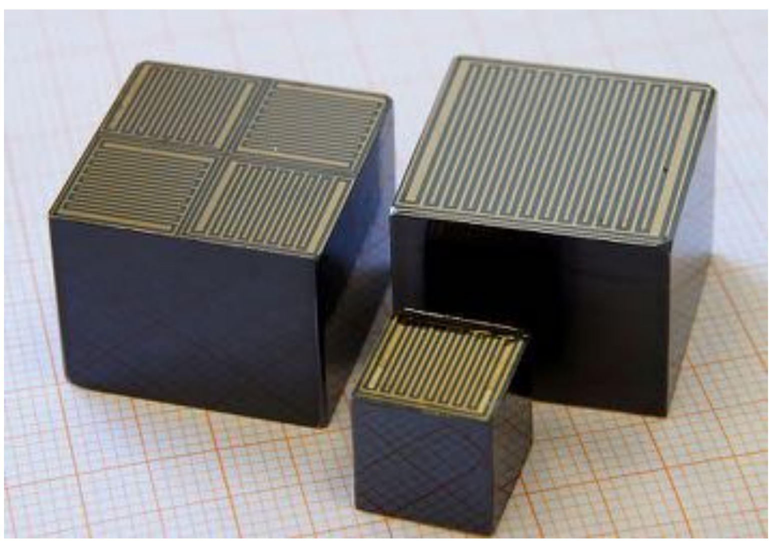
^{114}**Cd $Q_{\beta\beta}$**

NIM A **807**:114 (2016)
arXiv:1509:04113

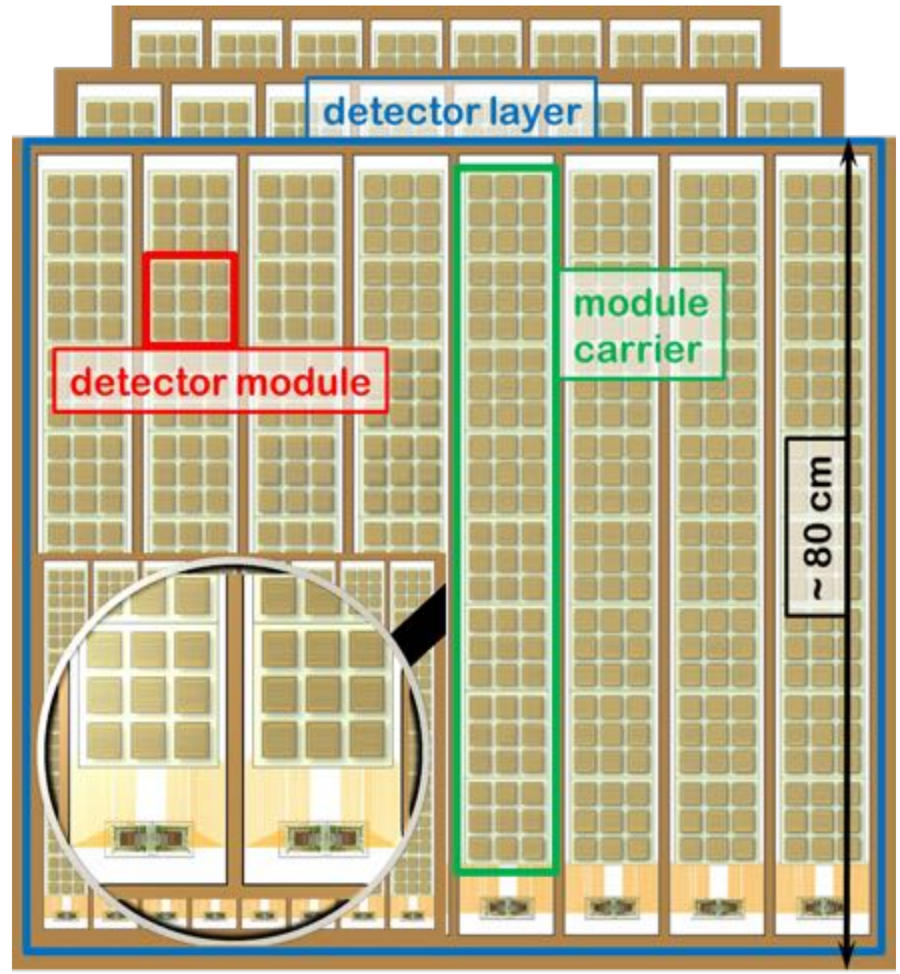
COBRA

(**C**dZnTe **0**ν Double **B**eta **R**esearch **A**pparatus)

- Moving towards a 415kg array
  - Modular 20 layer design
  - Larger 2x2x1.5cm (36g) crystals with segmented readout
- Funding for a 3x3x3 test array of new crystals with improved readout



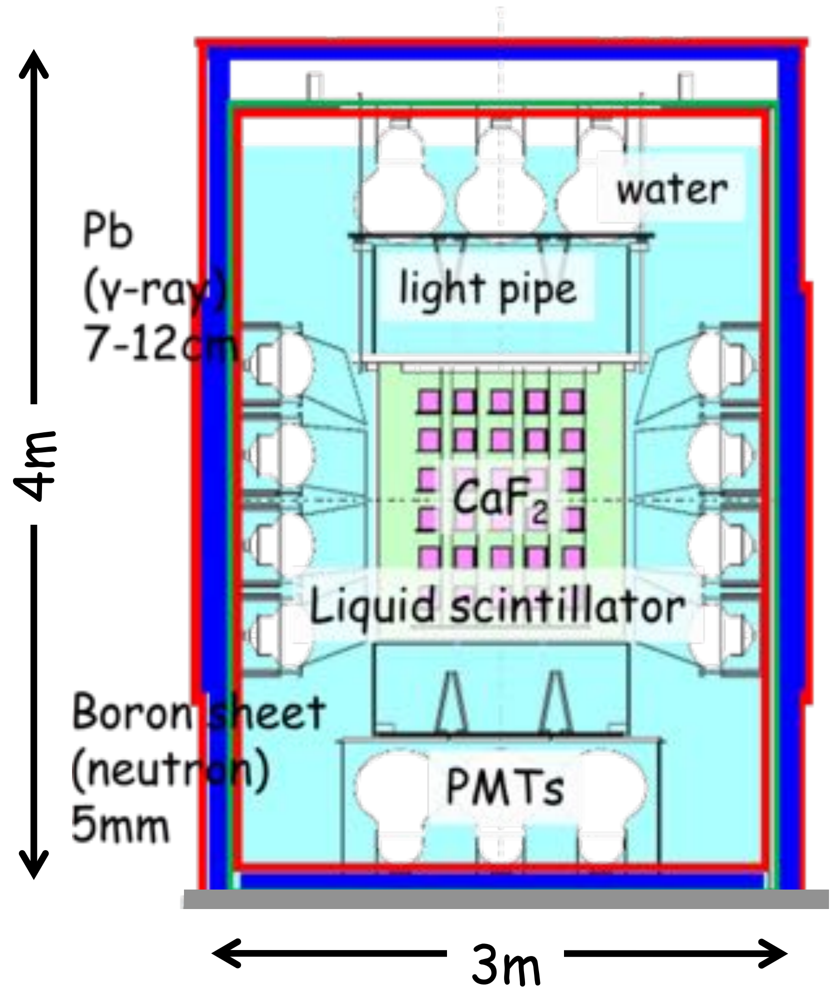
NIM A **806**:159 (2016)



CANDLES

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

- CANDLES System
  - for $^{48}Ca(Q_{\beta\beta}4.3MeV, 0.187\%)$
  - CaF_2 detector
  - 4π active shield
- Current detector system : CANDLES III
  - ($305kg, 0.187\% ^{48}Ca$) + 2T liquid scintillator
  - Improvement : Installation of the shielding system (Pb, B)
    - To reduce γ-ray backgrounds from neutron capture
  - Expected sensitivity $\langle m_\nu \rangle = 0.5eV$



CANDLES

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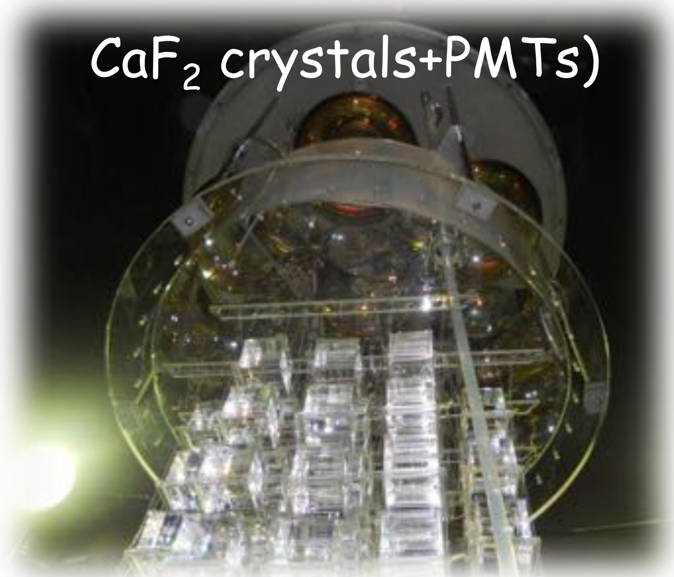
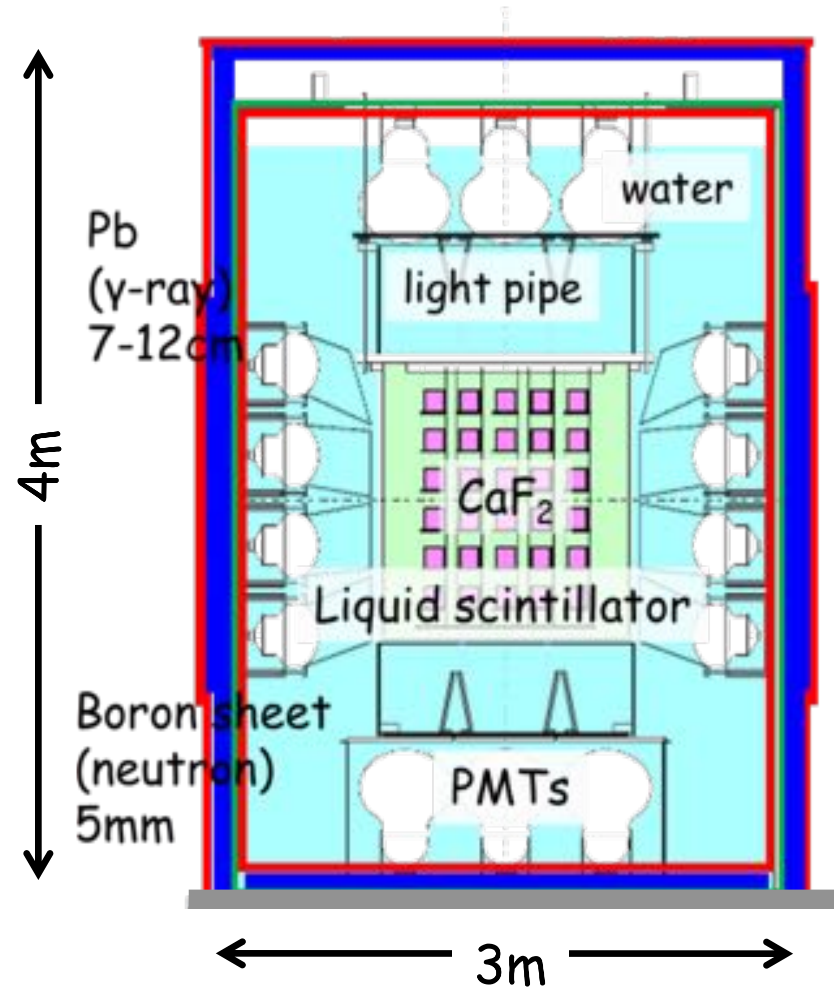
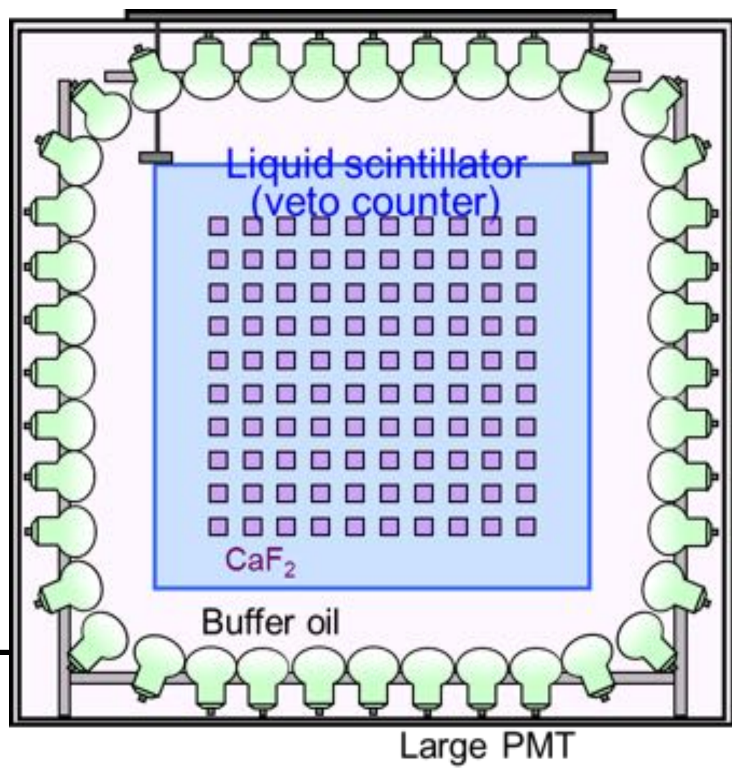


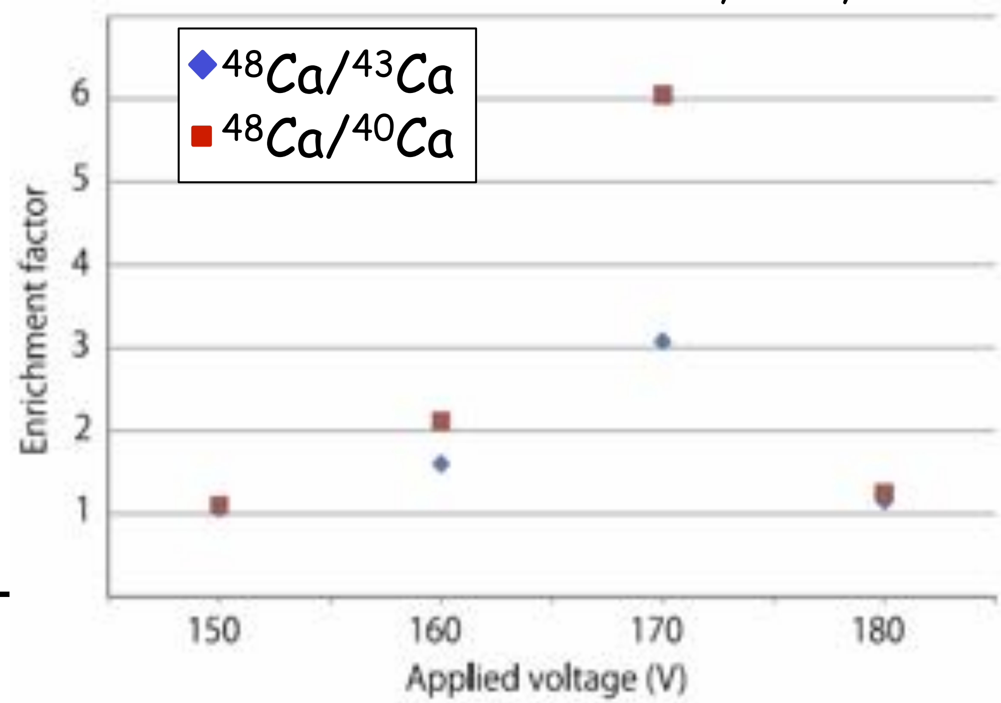


CANDLES

- R&D
  - Enrichment of ^{48}Ca by electrophoresis demonstrated
  - Scintillating $^{48}CaF_2$ bolometers under investigation
- Sensitivity by next CANDLES system
  - $\langle m_\nu \rangle \sim 0.1eV$: CaF_2 scintillator system
  - $\langle m_\nu \rangle \sim 0.01eV$: $^{48}CaF_2$ bolometer system



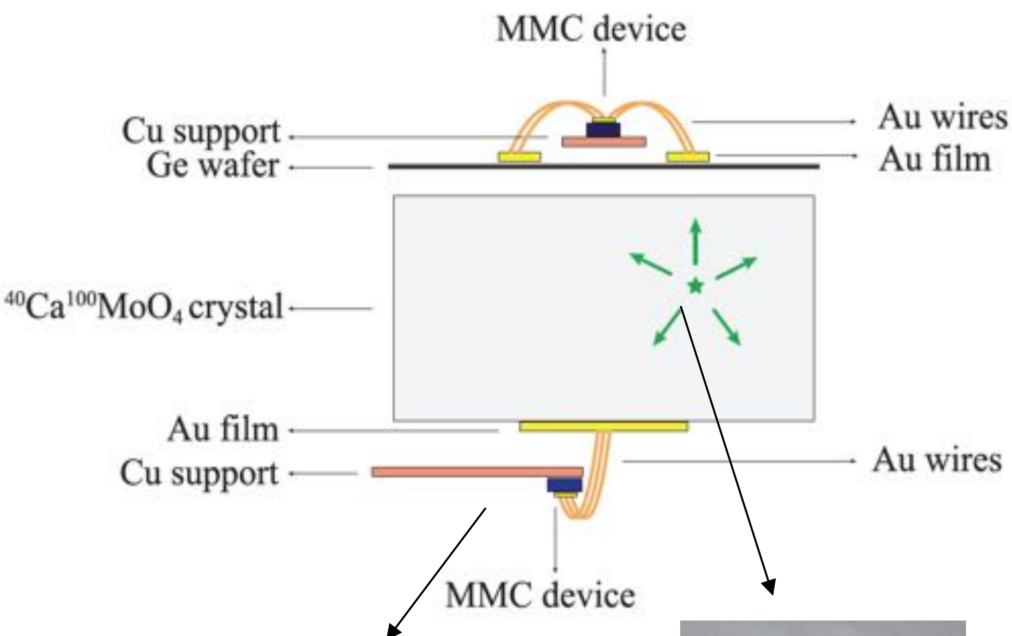
PTEP, 2015, 033D03

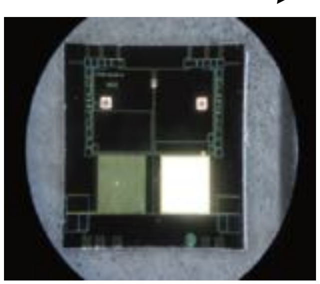


AMoRE

AMoRE (Advanced Mo-based Rare process Experiment) is a project searching for neutrinoless double beta decay (0νββ) of ^{100}Mo using Mo-based crystals and metallic magnetic calorimeters (MMCs) at low temperatures

Simultaneous measurement of heat and light by MMCs

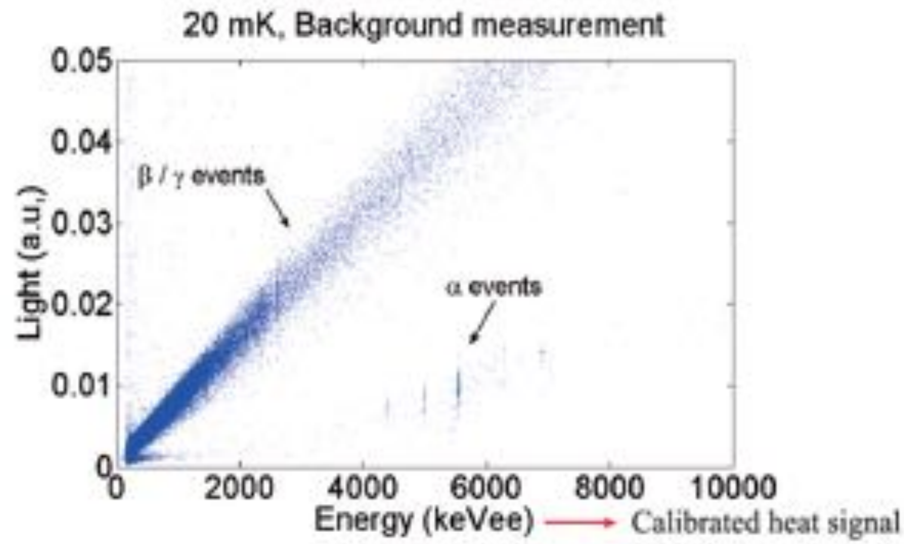




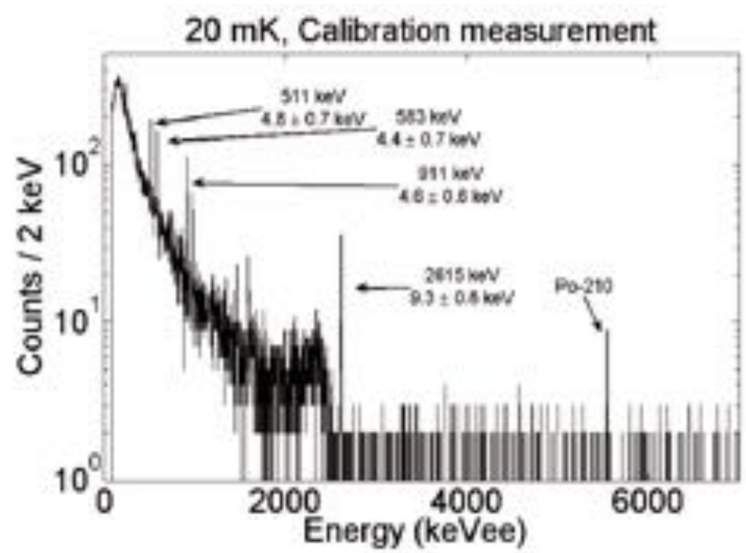
metallic magnetic calorimeter

$^{40}Ca^{100}MoO_4$ crystal
^{100}Mo is a source of 0νββ

Above-ground measurements



Heat/light simultaneous measurement : separation of α and β/γ



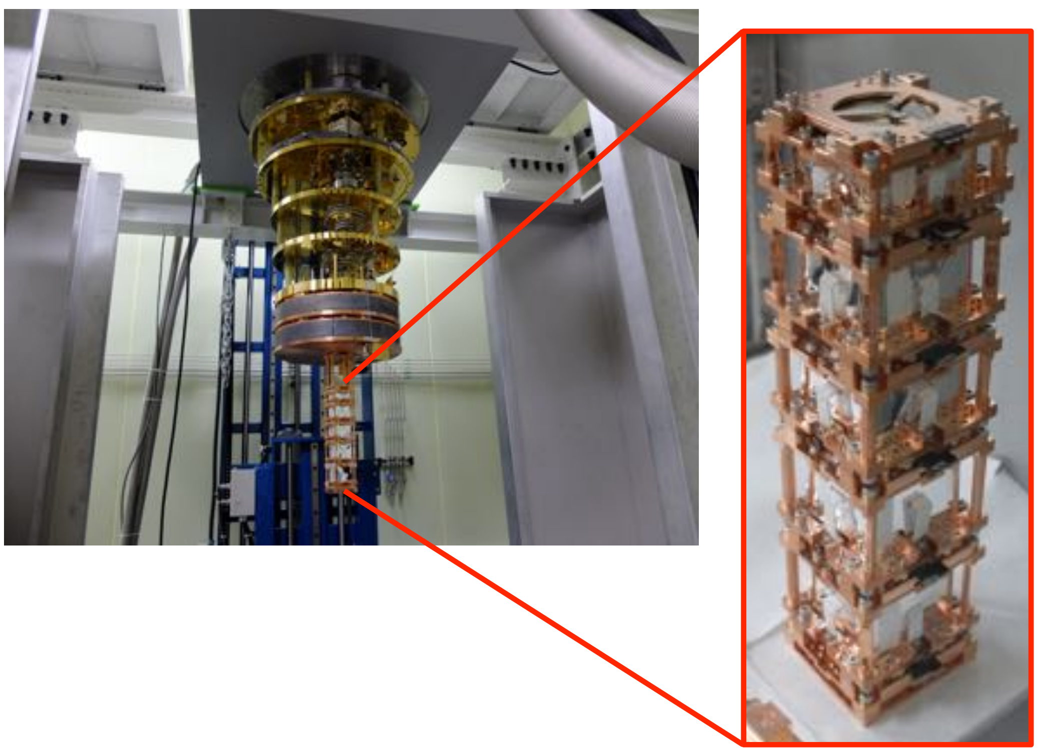
Energy spectrum obtained with a ^{232}Th external source
$\Delta E_{FWHM} \approx 9$ keV @ 2.6 MeV

AMoRE-pilot experiment at Yangyang underground laboratory (Y2L)

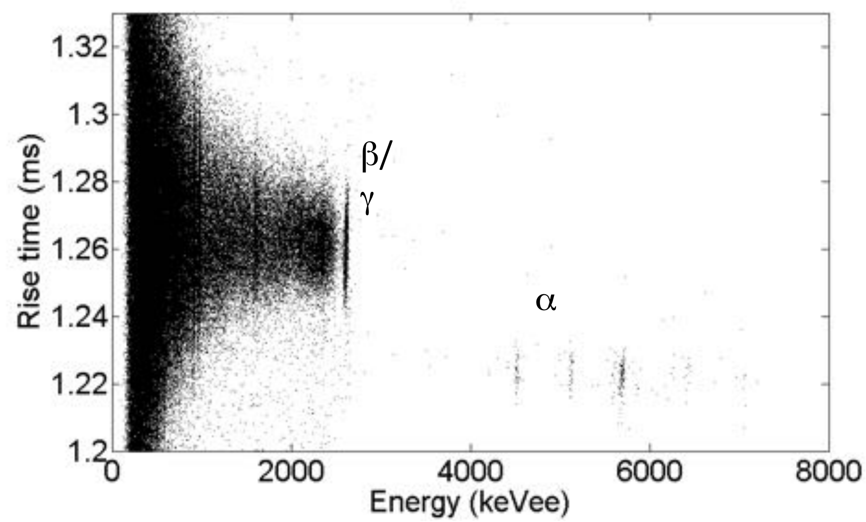
YangYang Underground Laboratory (Y2L, South Korea) :

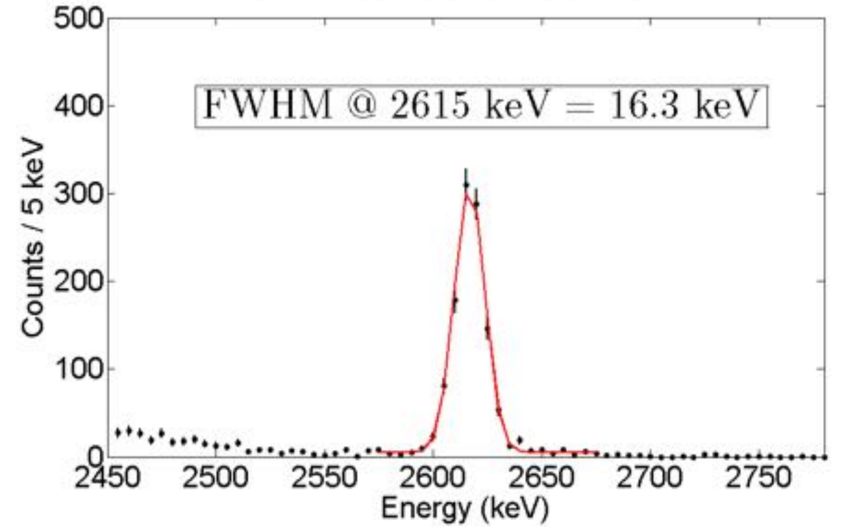
- Located in a tunnel of the Yangyang pumped storage power plant
- Minimum vertical depth : 700 m

AMoRE-pilot: five $^{40}Ca^{100}MoO_4$ crystals (1.5 kg)
5 phonon detectors + 6 photon detectors



Underground measurements





Energy resolution to be improved after vibration reduction

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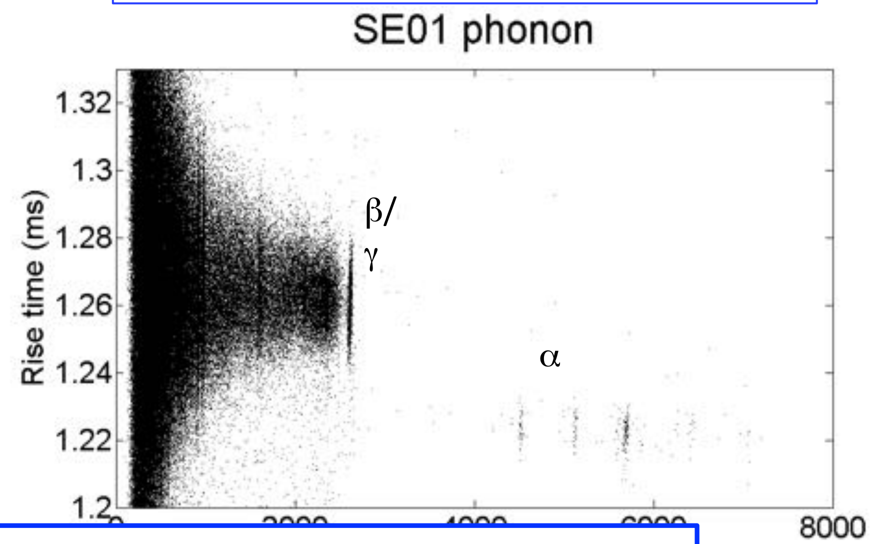


Future AMoRE Program

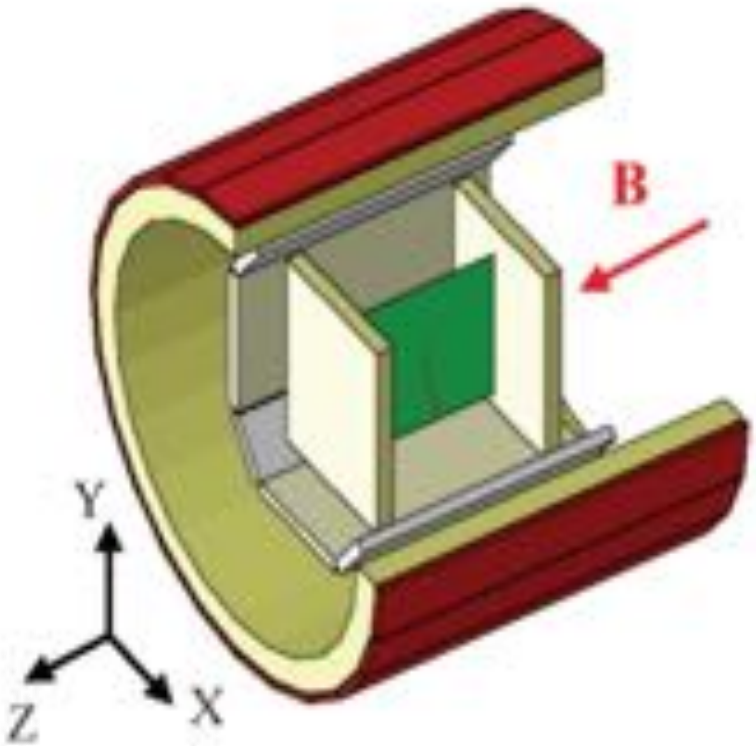
	$^{40}Ca^{100}MoO_4$ Mass (kg)	Projected $\langle m_{\beta\beta} \rangle$ Sensitivity (meV)
Amore Pilot (Current)	1.5	210 - 400
Amore I (~2016)	5.0	70 - 140
Amore II (2018+)	200	12 - 22

arXiv:1512.05957

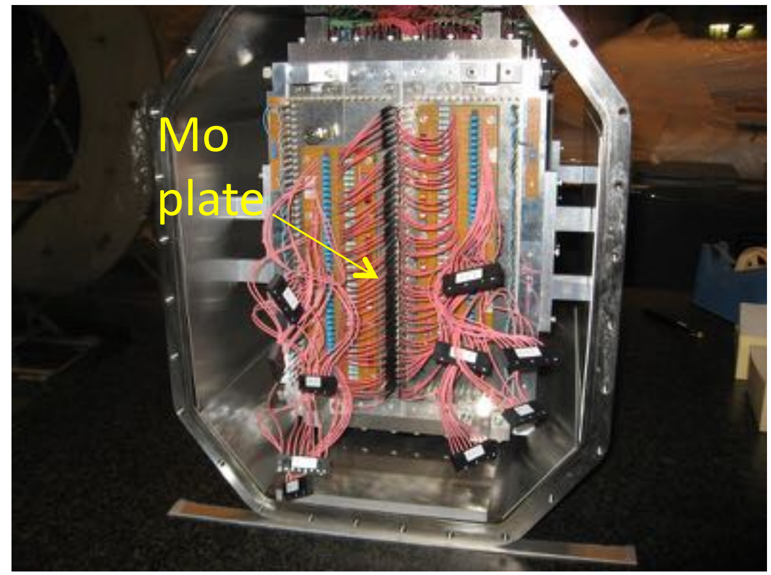
Present & future of DCBA and MTD

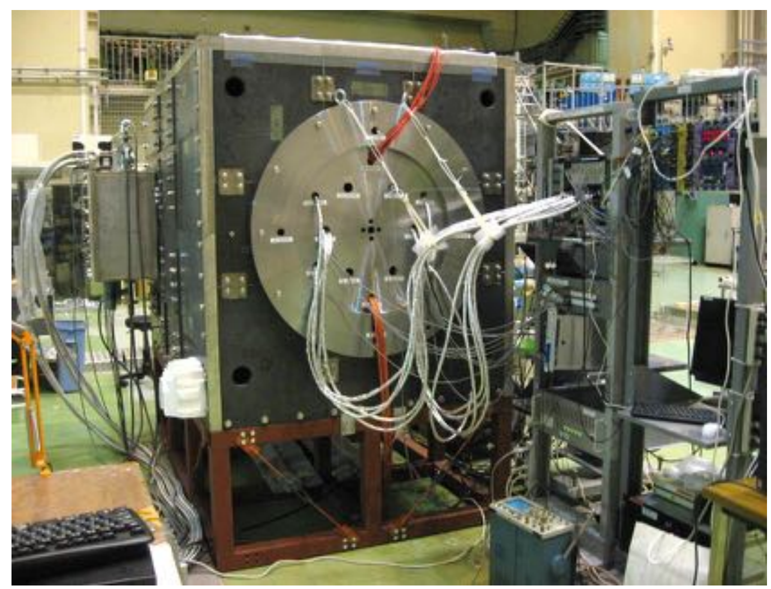
(Drift Chamber Beta-ray Analyzer and Magnetic Tracking Detector)

A tracking detector with source foils in the tracking volume.



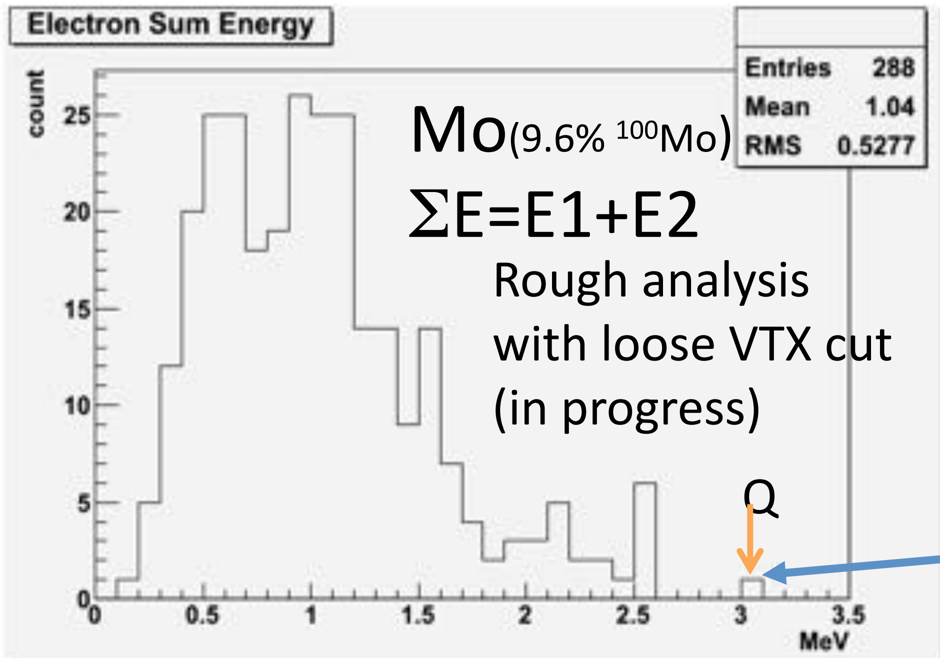
DCBA-T2.5 (30g ^{nat}Mo, 0.8kG) has been running at KEK surface exp. room

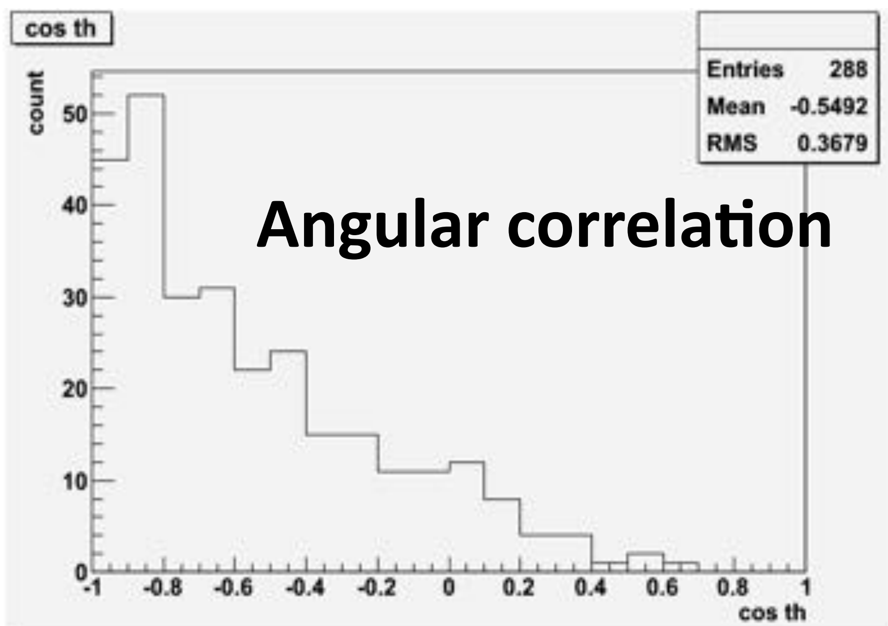




Two electron events taken by DCBA-T2.5 (T2 chamber + T3 magnet)

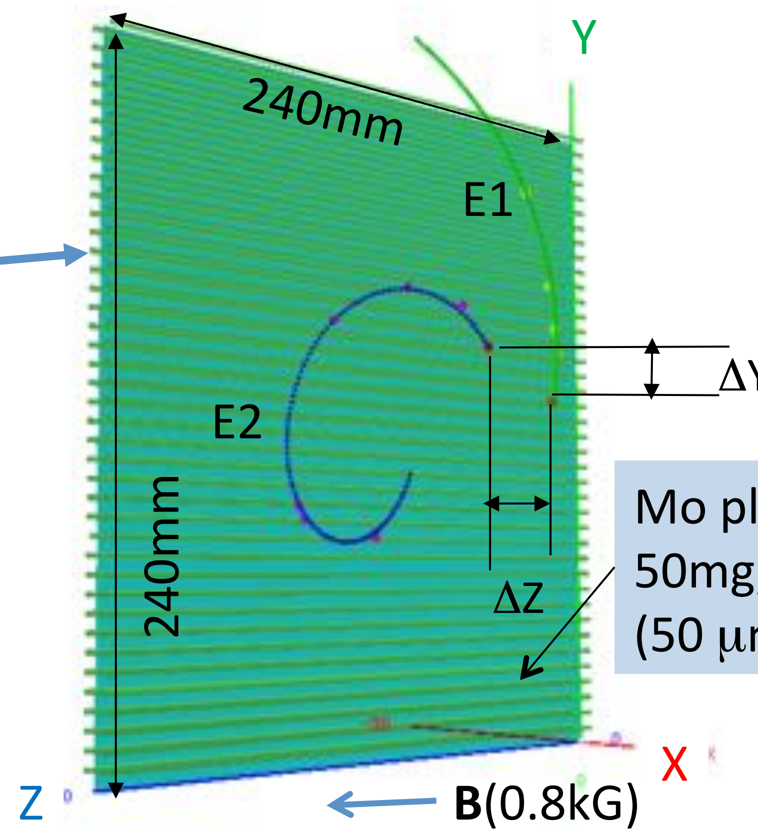
(after eliminating cosmic-rays with track shape separation, but still including backgrounds)





Event-111117-126_38

E1=2.23 MeV E2=0.81 MeV
ΔY=19 mm ΔZ=54 mm

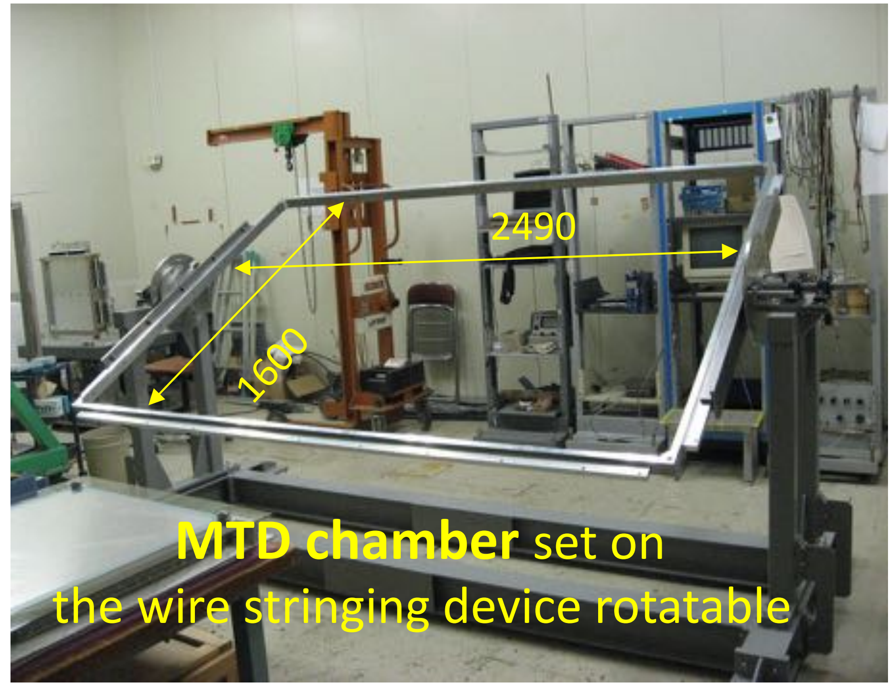


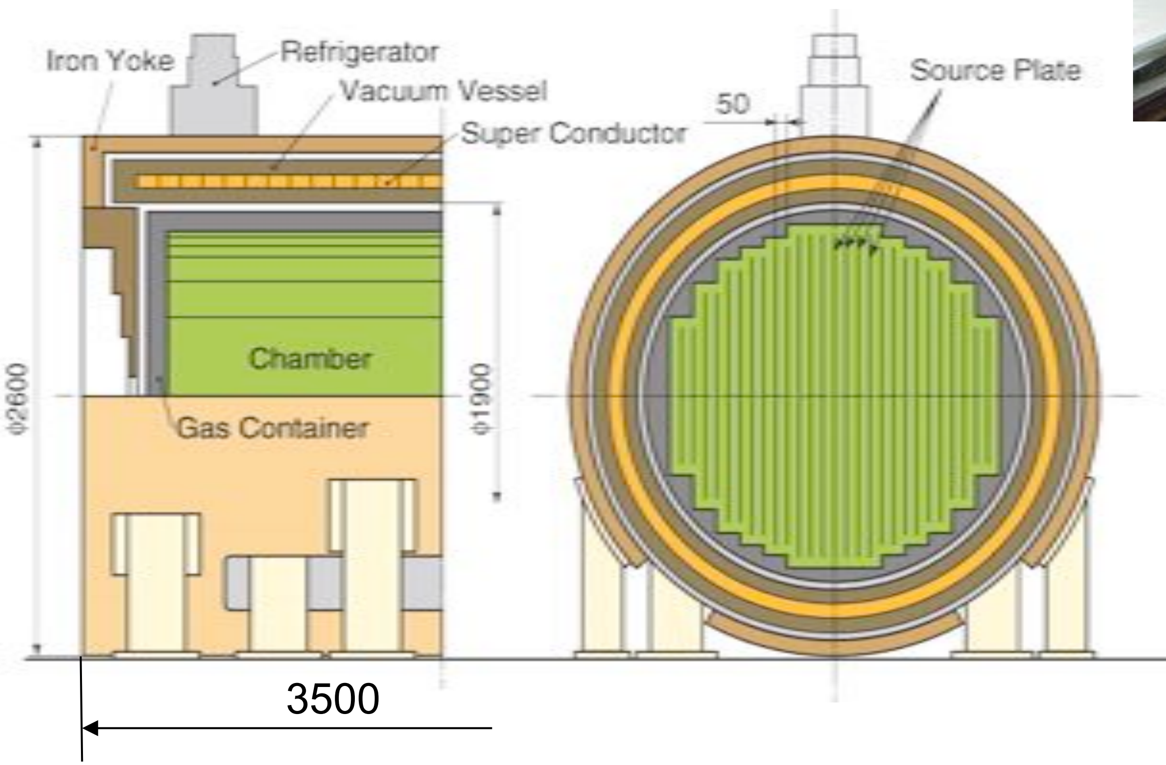
Mo plate
50mg/cm^2
(50 μm)

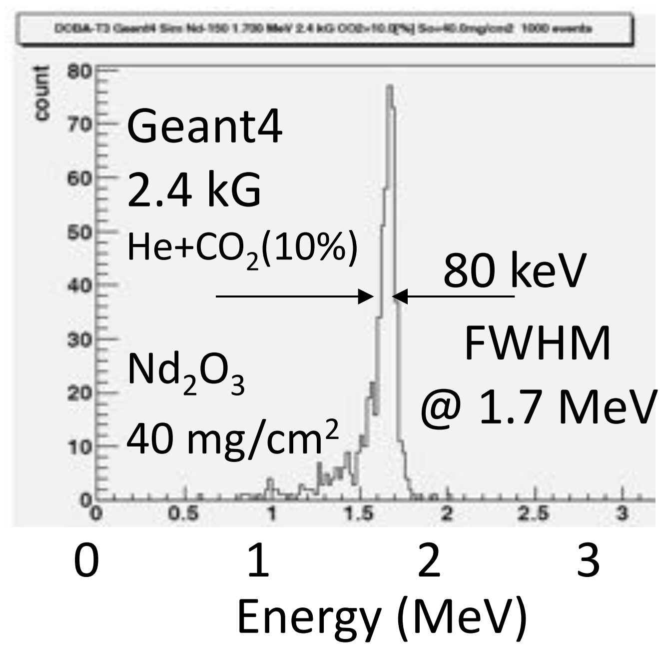
Background event (double Compton probably), because vertex differences (ΔY, ΔZ) are large.

MTD

Chamber cell : the same as DCBA-T3,
Source plate: 80 m^2/module
Thickness: 40 mg/cm^2,
Source weight: 32kg/module







Expected Energy Resolution $\frac{\mathrm{FWHM}(E_{sum}) = \sqrt{2}\times 80\mathrm{keV}}{Q_{\mathrm{Nd\text{-}150}}(3370\mathrm{keV})} \approx 3.4\%$

NEXT Experiment

(Neutrino Experiment with a Xenon TPC)

- Search for the neutrinoless double beta decay of ^{136}Xe at the Laboratorio Subterraneo de Canfranc with a TPC filled with 100 kg of high-pressure xenon gas

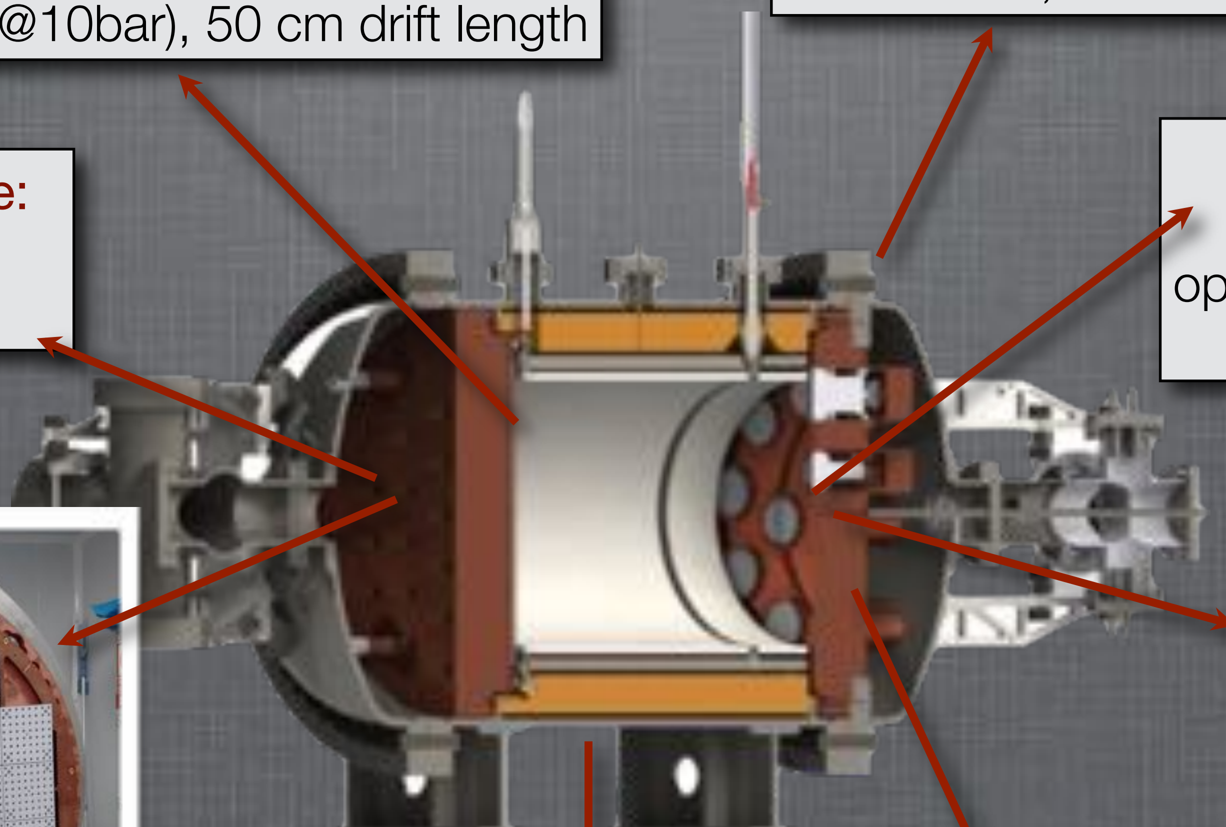
(2010-2014) Demonstration of detector concept	(2015-2018) Underground and radio-pure operations, background, ββ2ν	(2018-2021) Neutrinoless double beta decay search

NEW (NEXT-WHITE) at glance

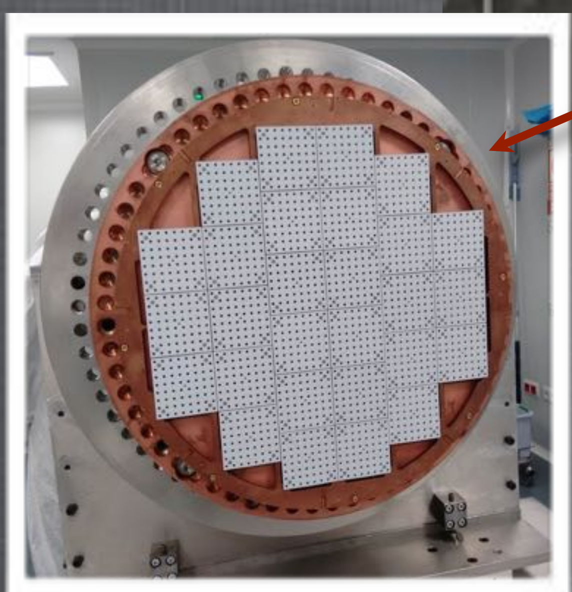
Time Projection Chamber:
10 kg active region(@10bar), 50 cm drift length

Pressure vessel:
316-Ti steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch



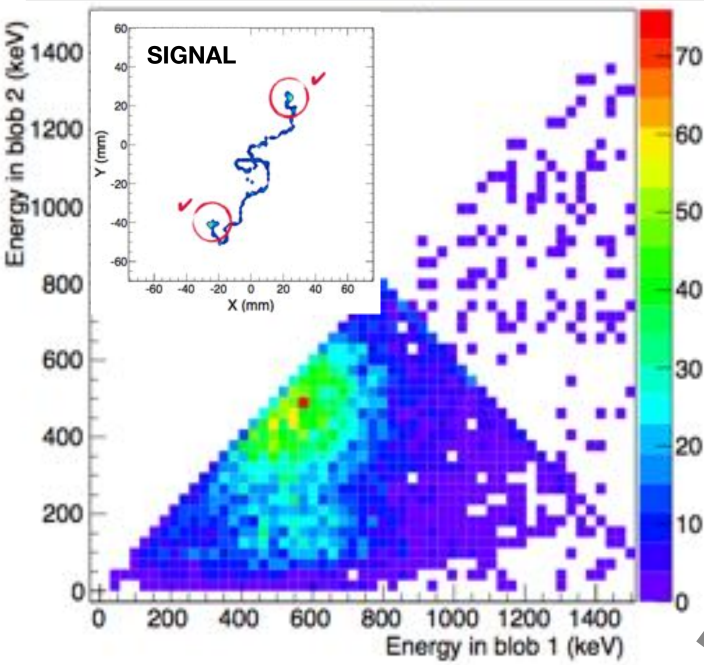
Energy plane:
12 PMTs,
operating at vacuum.
30% coverage

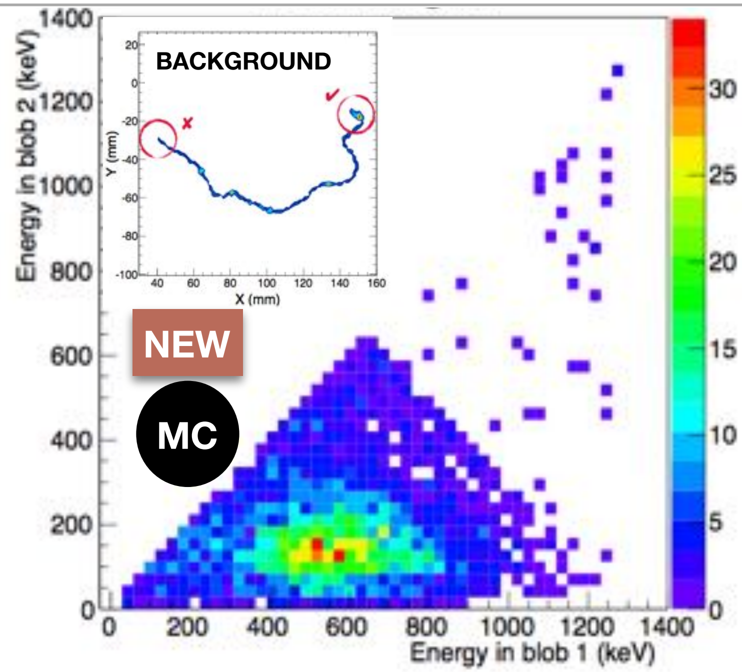


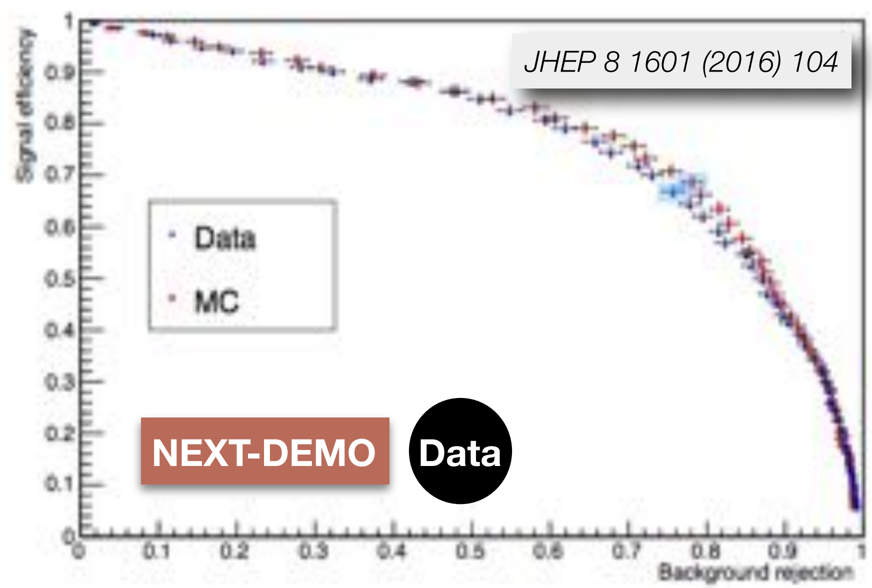
Inner shield:
copper, 6 cm thick

Mother can:
12 cm copper plate that
separates pressure from
vacuum and adds shielding.

NEXT Topological Rejection

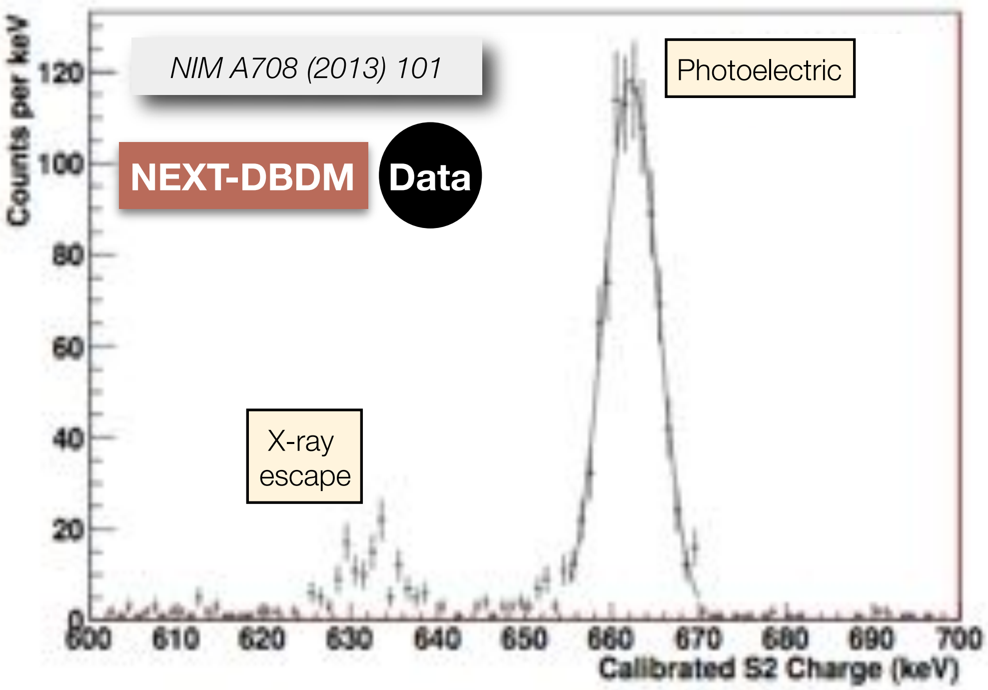




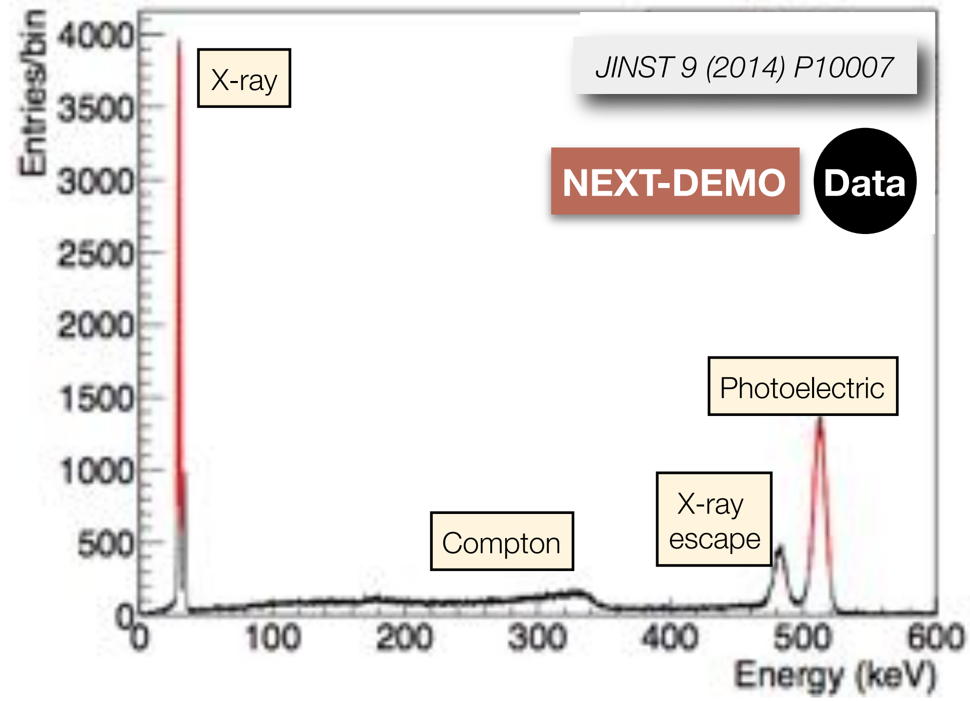


- Require identification of two Bragg peaks for ββ candidate events
- Validated with calibration data

NEXT Energy Resolution



- 1.1% FWHM resolution for 662 keV electrons

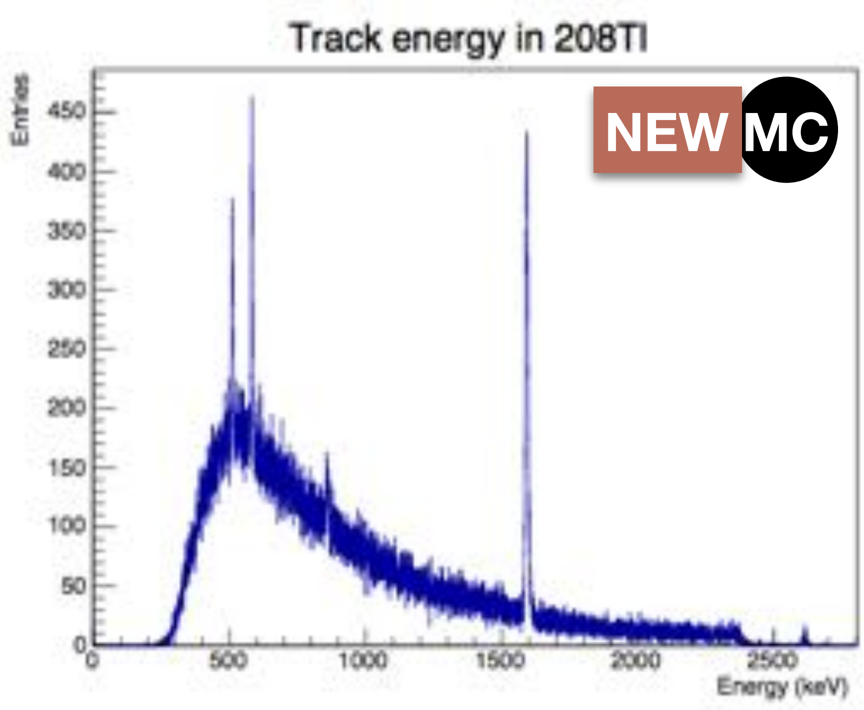


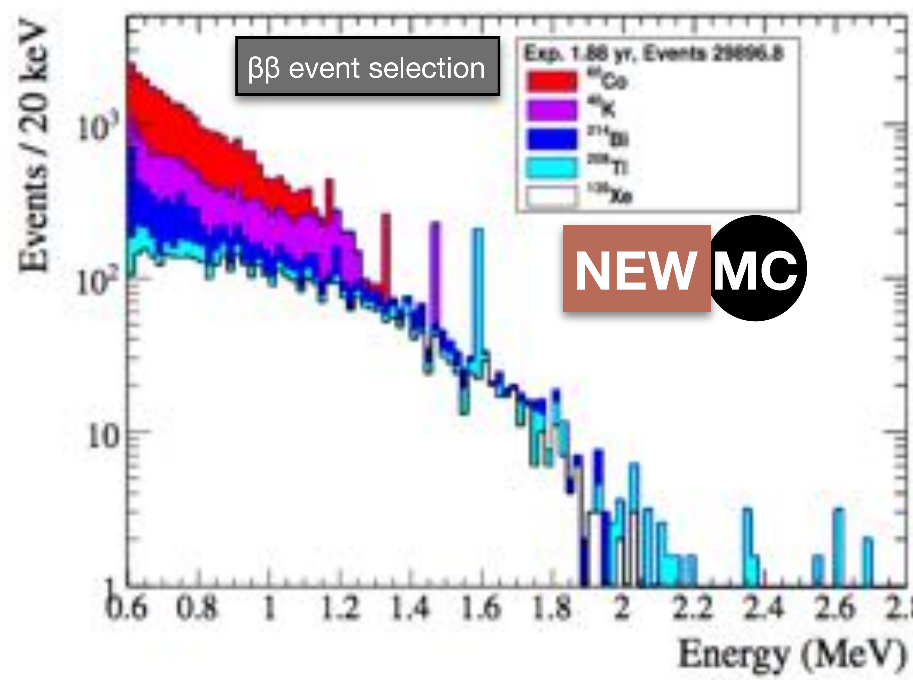
- 1.6% FWHM resolution for 511 keV electrons

NEXT measurements extrapolate to 0.5-0.7% FWHM energy resolution at $Q_{\beta\beta}$

NEXT-White (NEW) Science Goals

Period	Configuration	Goals
2016 (2nd half)	Depleted Xe	Calibration, energy resolution, topological rejection
2017 (1st half)	Depleted Xe	Background rate and energy spectrum
2017 (2nd half)	Enriched Xe	ββ2ν rate



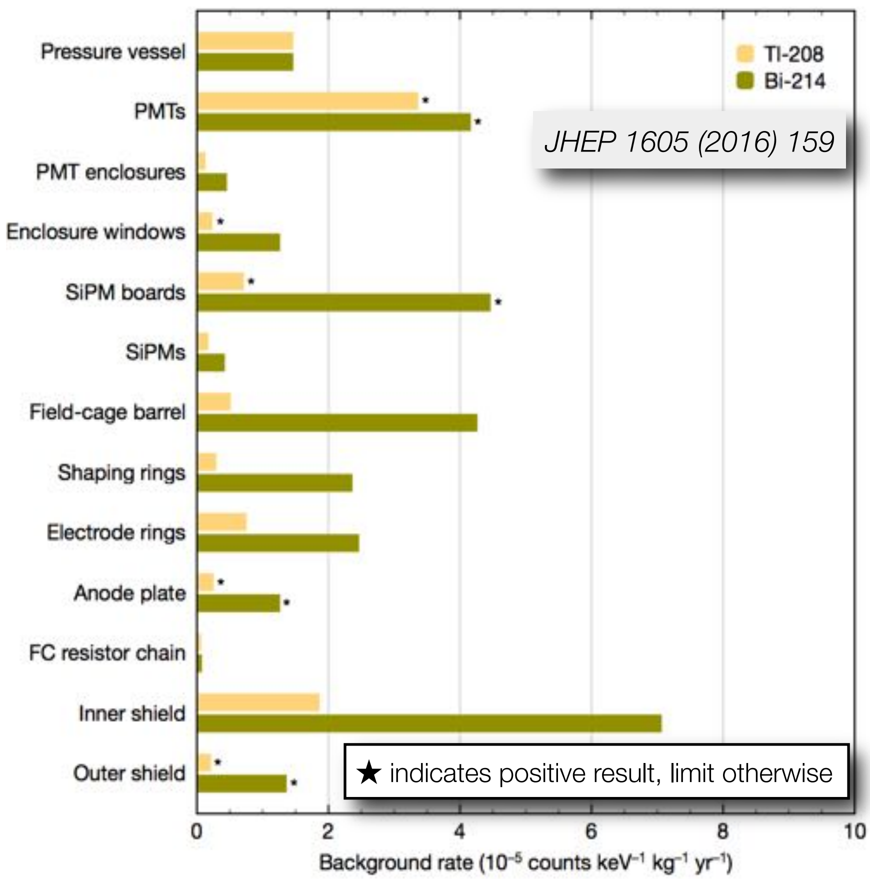


- 0.58% FWHM resolution at $Q_{\beta\beta}$ expected
- 10% (stat.) accuracy after 200 days for ββ2ν

NEXT-100 Sensitivity to ββ0ν

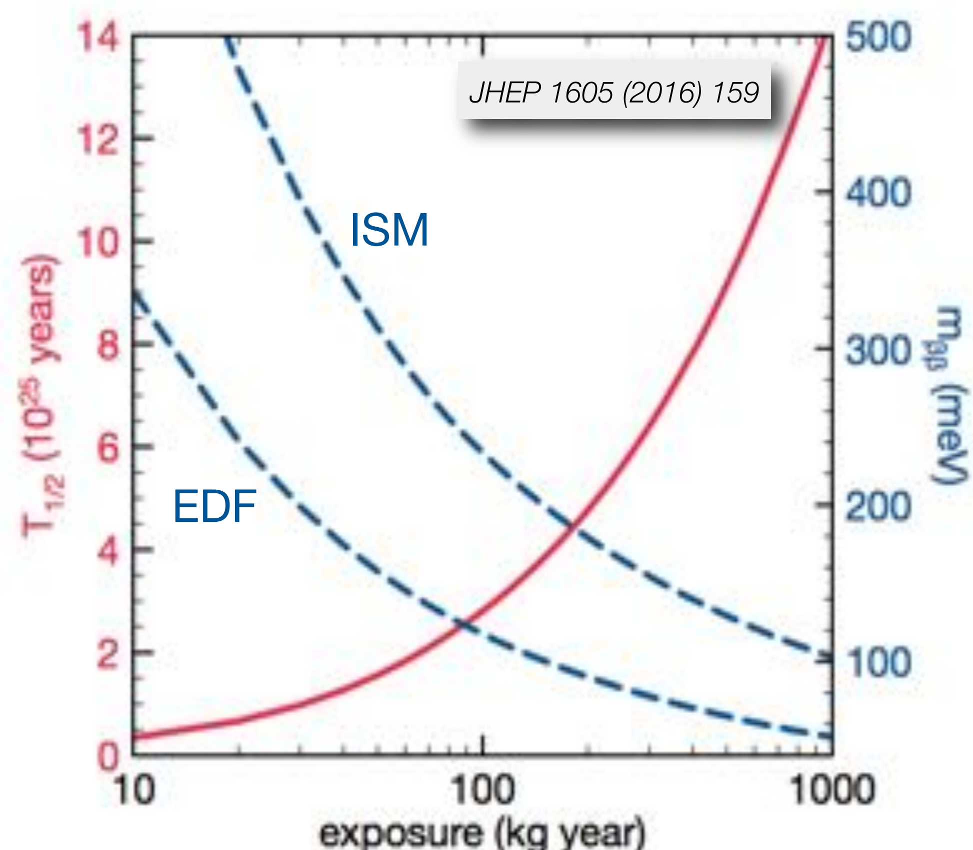
Backgrounds

- $< 4\times10^{-4}$ counts keV^{-1} kg^{-1} yr^{-1} overall background rate in ROI expected



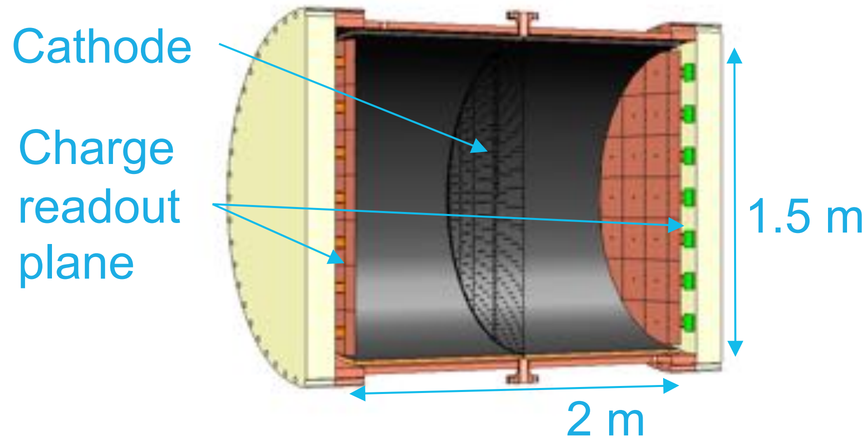
ββ0ν

- $T_{1/2} = 6\times10^{25}$ yr sensitivity expected in 3 yr (90% CL)

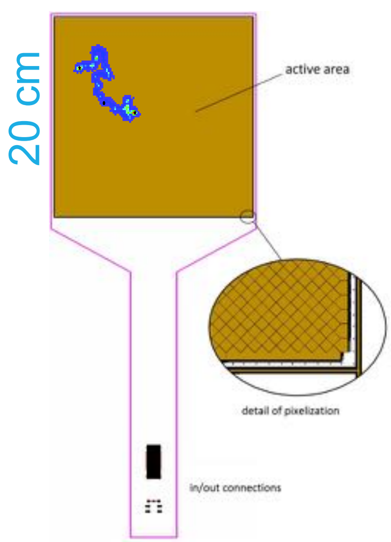


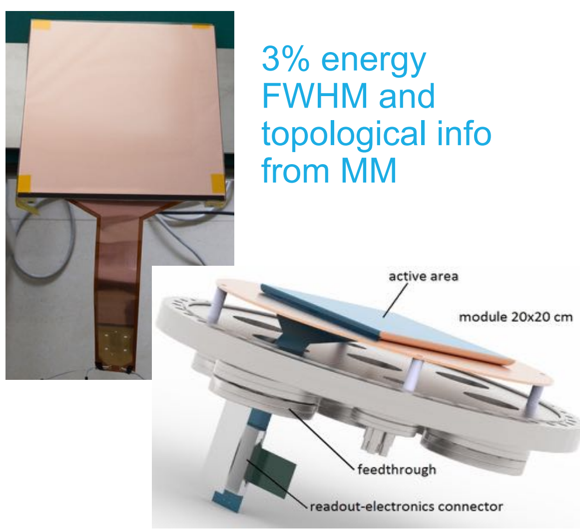
PandaX-III: high pressure gas TPC for neutrinoless double beta decay of ^{136}Xe

TPC: 200 kg scale, symmetric, double-ended charge readout with cathode in the middle

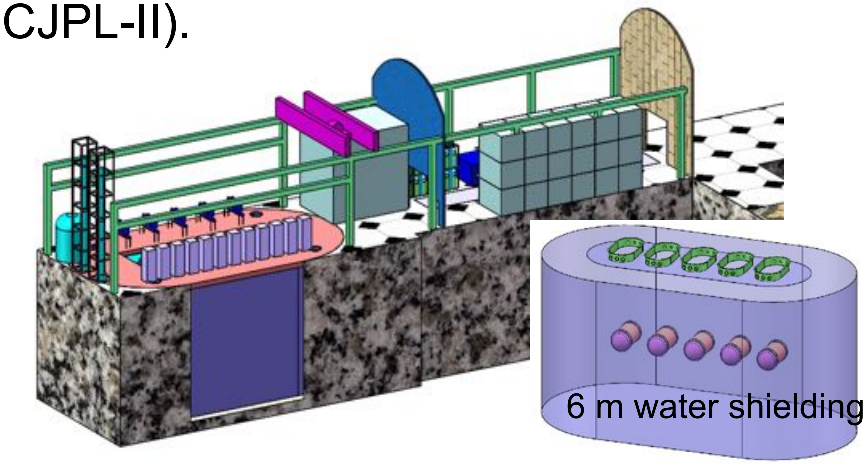


Charge readout plane: tiles of square microbulk Micromegas (MM) modules with X, Y strips





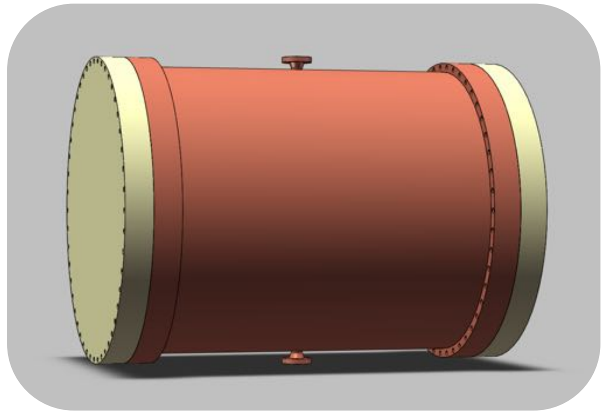
PandaX-III will be located at Hall #B4 at China Jin Ping underground Laboratory (CJPL-II).



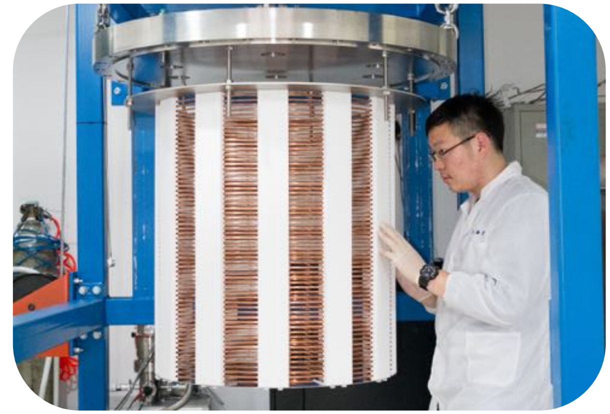
- 200 kg enriched ^{136}Xe purchased
- Prototype TPC commissioned at SJTU
- First module will be installed in 2017
- Four more upgraded modules for a ton scale experiment (projected in 2022)
- Expected half-life sensitivity at 10^{26} year (3yr, 90% CL) with background rate of 10^{-4} c/keV/kg/yr in the ROI

Status

150 kg of 90% enriched ^{136}Xe purchased

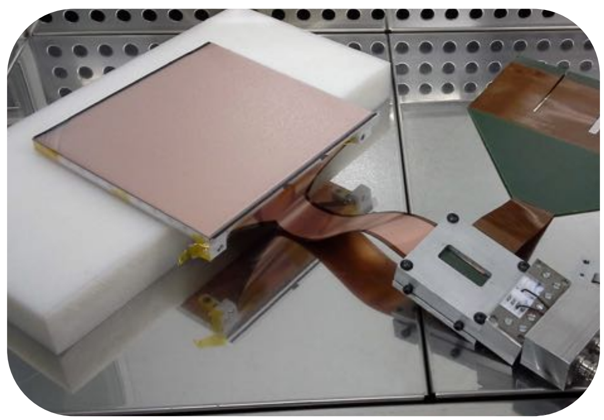


High pressure vessel made of OFHC copper designed



20 kg scale prototype TPC made and taking data with MicroMegas

Front end electronics are being designed and tested



First batch of 20 cm square MicroMegas modules made and commissioned

Excavation of water pit finished. Finalizing the layout of Hall B4 at CJPL-II

SNO+

- Refill the SNO detector with 780 tonnes of linear alkylbenzene liquid scintillator
- Broad physics program:
  - Solar neutrinos
  - Reactor neutrinos
  - Geo-neutrinos
  - Supernova neutrinos
  - Neutrinoless double beta decay

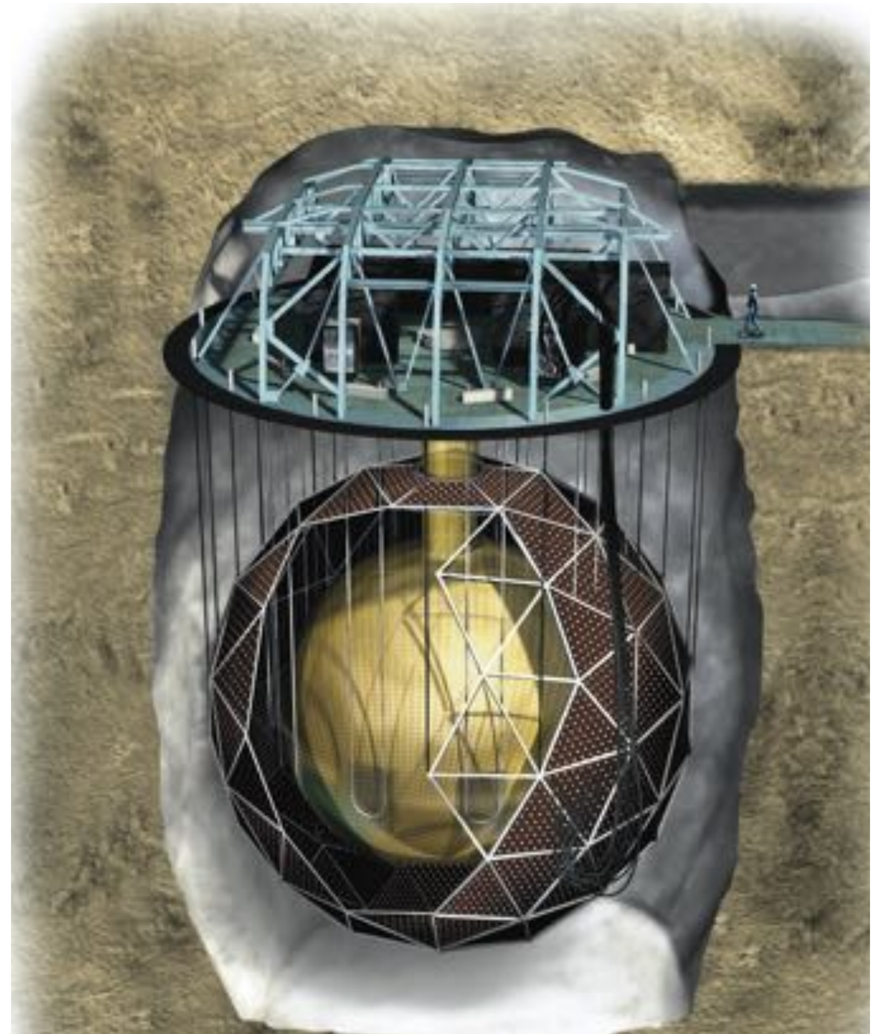
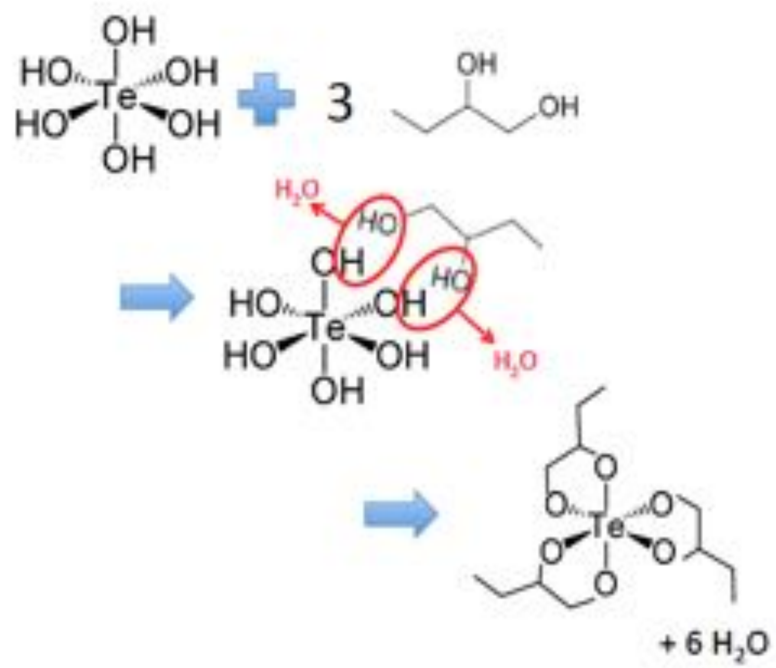


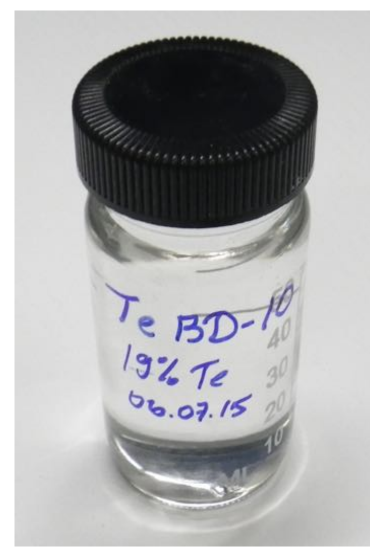
Image courtesy National Geographic

See AHEP 2016:6194250 (2016) for a recent review.

Load Tellurium into the SNO+ Scintillator

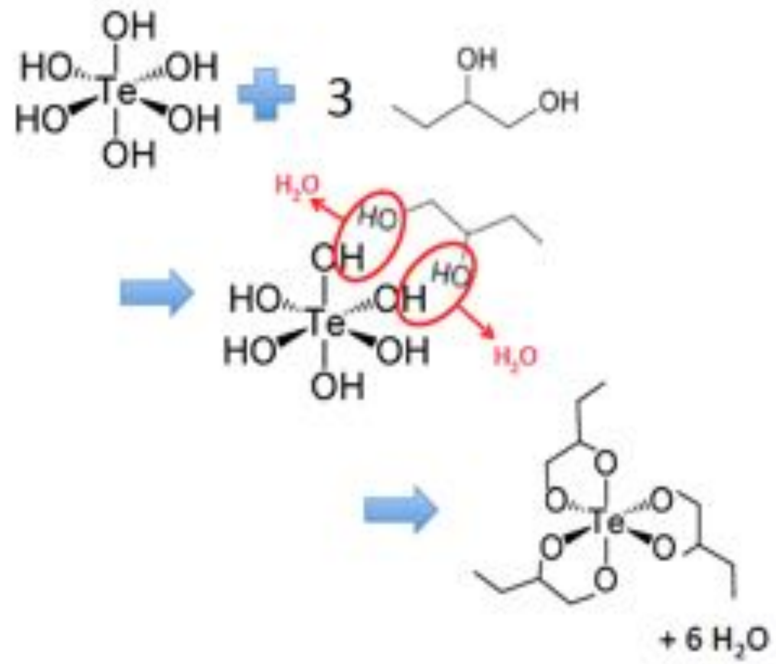
- 780 tonne detector and high ^{130}Te isotopic abundance gives large isotope mass
  - 0.5% (w/w) Te in SNO+ Phase I is 3.9 tonnes of Te or 1333 kg of ^{130}Te (260kg fiducial)
  - Could increase to percent-level loading in future phases
- Tellurium can be dissolved into LAB scintillator as an organometallic complex
  - Tellurium-butanediol complex is very transparent, shows some quenching

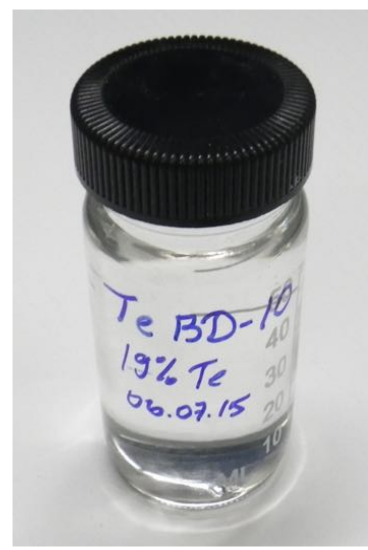




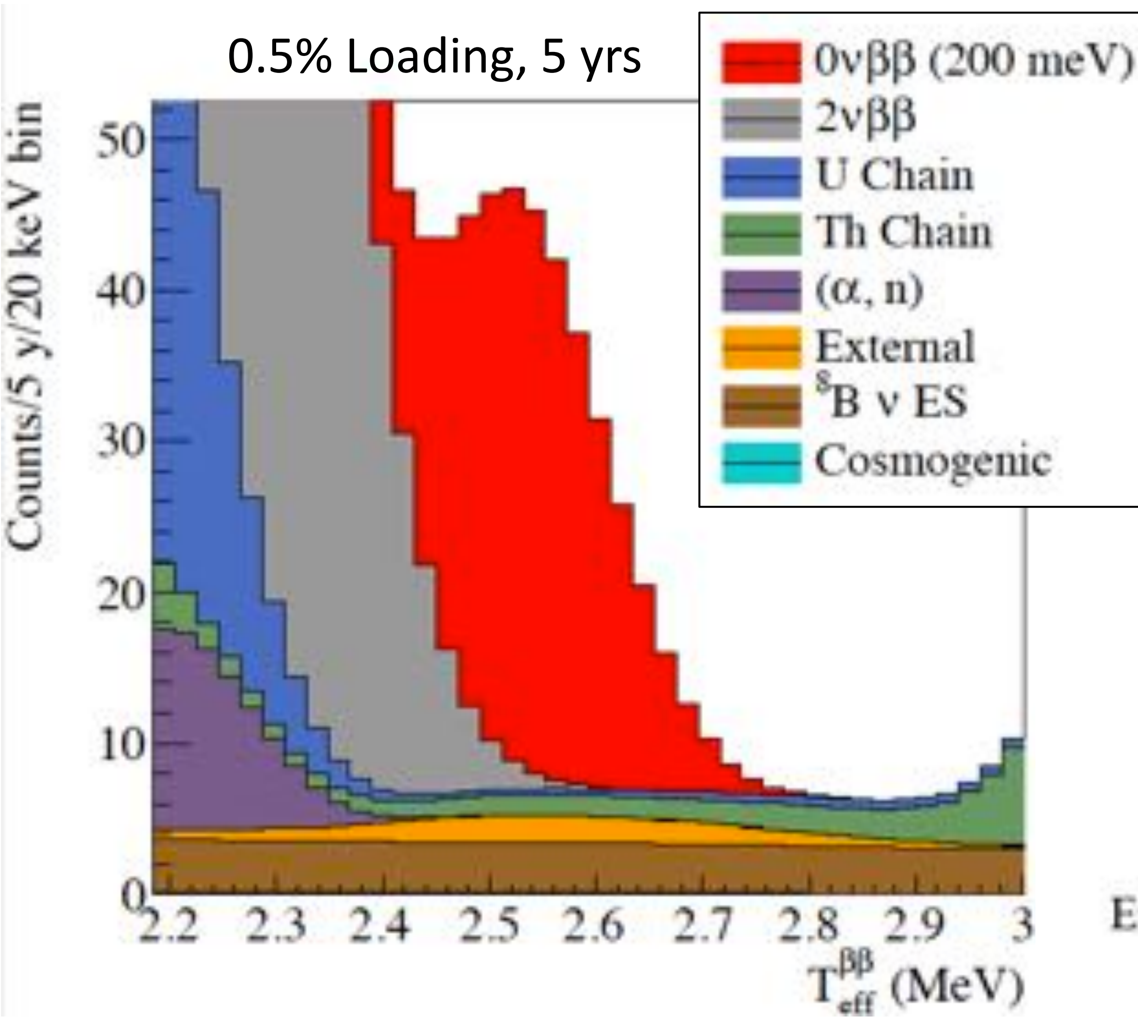
Load Tellurium into the SNO+ Scintillator

- Expect ~400 p.e./MeV in SNO+ at 0.5% Te loading
  - 2% loading workable with current quenching & upgraded PMTs & reflectors; work to reduce quenching ongoing
- Very low backgrounds are achievable
  - Scintillator backgrounds low
  - Te can be purified underground via recrystallization (NIM A 795:132 (2015))
  - Butanediol can be distilled
  - Fiducialization, delayed co-incidence rejection, and PSD further reduce backgrounds

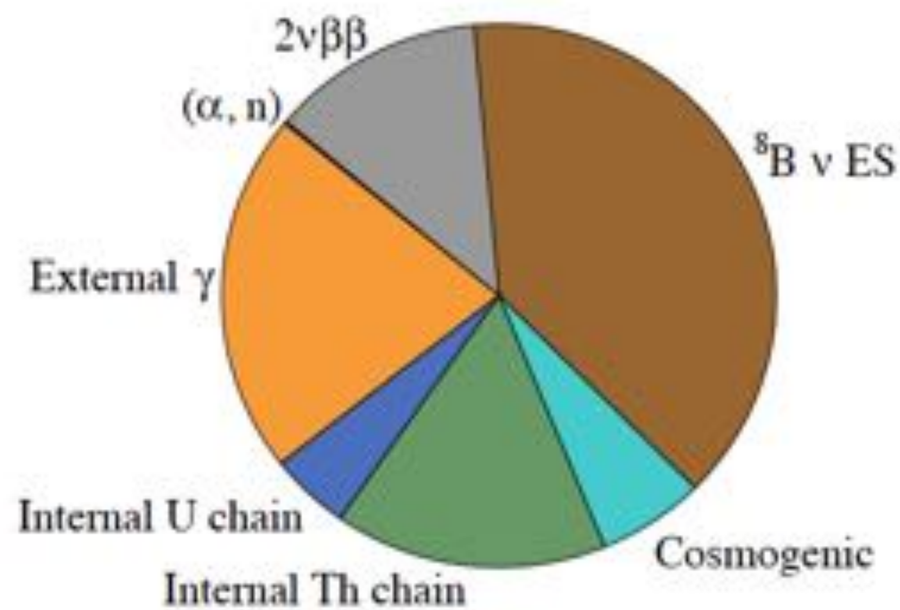




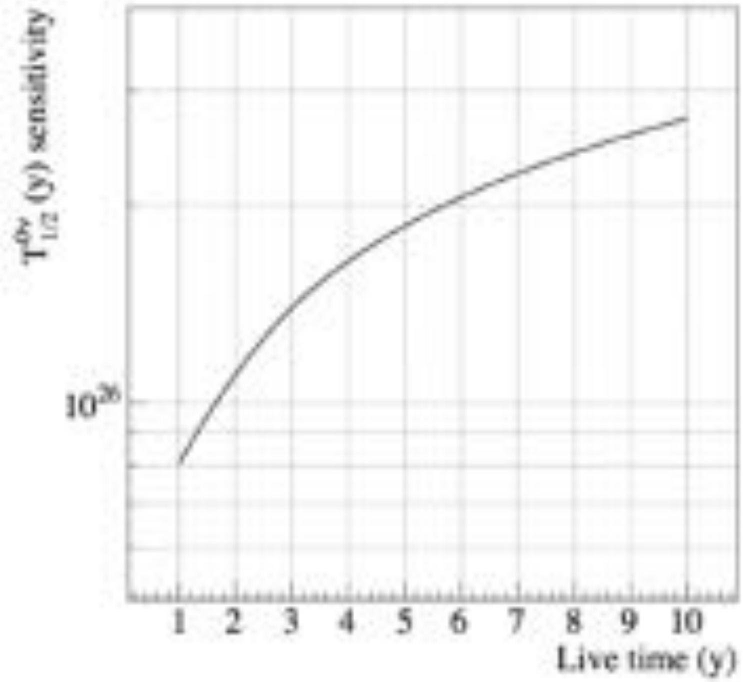
Expected Backgrounds & Spectrum



Expected Backgrounds Total:
13.4 counts/year in ROI (Year 1)

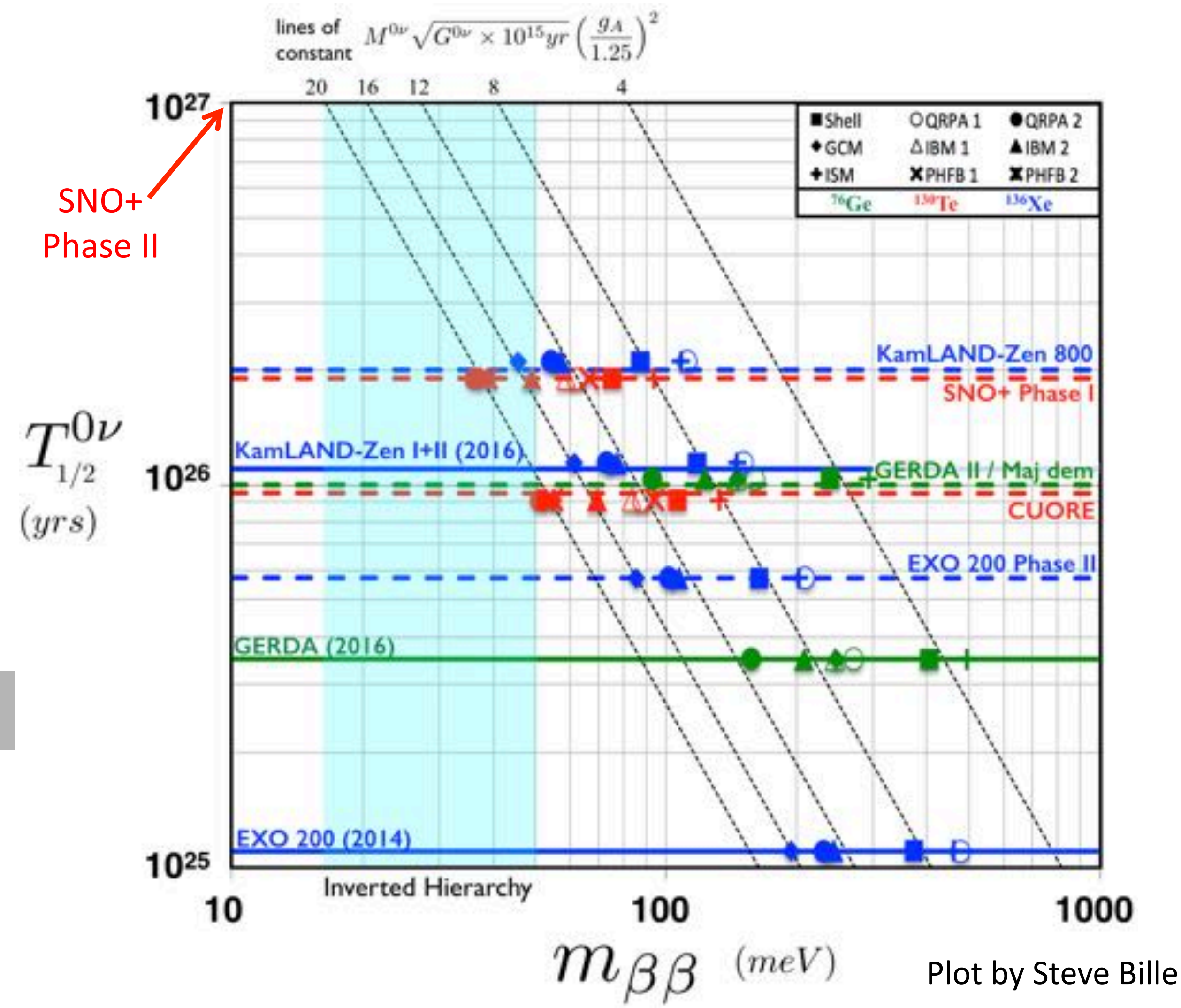


SNO+ Expected Sensitivity



$T_{1/2} \geq 1.96 \times 10^{26}$ yr (90% CL, 5 yr)

Comparison with Other Experiments



Plot by Steve Biller

SNO+ Status

- Scintillator purification plant installed, commissioning under way
  - First LAB on site in a few months
  - Scintillator fill beginning spring 2017
- In the process of re-filling the detector with ultra-pure water
  - A few leaks in the cavity liner identified and repaired
  - New hold-down system for the acrylic vessel installed and fully tested
  - Making PMT repairs along the way
- Tellurium purification, installation underground beginning later this year
  - Loading system to follow in 2017
  - 1.8 T telluric acid (=1 T Te) stored underground for ~1 year now, 2.0 T telluric acid currently being shipped from supplier
- Tellurium loading early in 2018

Conclusion

- There is a rich program of upcoming double beta decay experiments and R&D projects
- Experiments currently in construction/ commissioning should reach the top of the inverted hierarchy region
- Next generation experiments should substantially probe the inverted hierarchy

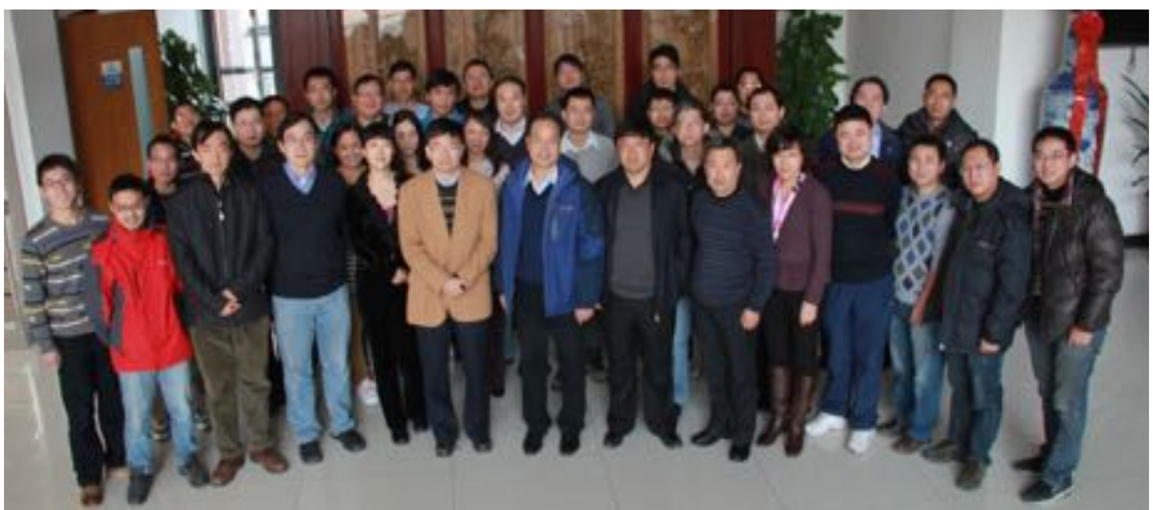
Presentation will be high-level, for details see posters:

COBRA	P1.061 - Pulse shape discrimination techniques for the COBRA experiment
CANDLES	P1.060 - Development of scintillating bolometer for 48Ca neutrinoless double beta decay search
AMoRE	P4.049 - Status of the AMoRE experiment
NEXT	P4.064 - Topological signature in the NEXT high pressure xenon TPC
	P4.065 - Sensitivity of the NEXT100 detector to neutrinoless double beta decay
	P4.066 - The NEW detector: construction, commissioning and first results
SNO+	P1.015 - Scattering length monitoring at the SNO+ detector
	P1.072 - Commissioning the SNO+ Detector
	P1.073 - Pulse shape analysis techniques in liquid scintillator for the identification and suppression of radioactive backgrounds to neutrinoless double beta decay
	P1.074 - A new technique to load 130Te in liquid scintillator for neutrinoless double beta decay experiments
	P4.067 - Physics capabilities of the SNO+ experiment
	P4.068 - Background analysis for the SNO+ experiment
	P4.069 - Calibration of the SNO+ experiment

CDEX

(China Dark Matter Experiment)

- Developing low background Ge detector capabilities through a staged detector program
  - Ge enrichment
  - Crystal growth
  - PCGe fabrication
  - Electroformed copper
- 10kg PC^{nat}Ge currently operating in LAr veto
- Envision a 1T double beta decay & dark matter experiment at CJPL



- Large Pit (Φ18m×18m) in CJPL now available
- LN_2 tank (Φ13m×13m) for cooling and shielding
- Tens of Kg HPGE array will begin to be deployed in several years

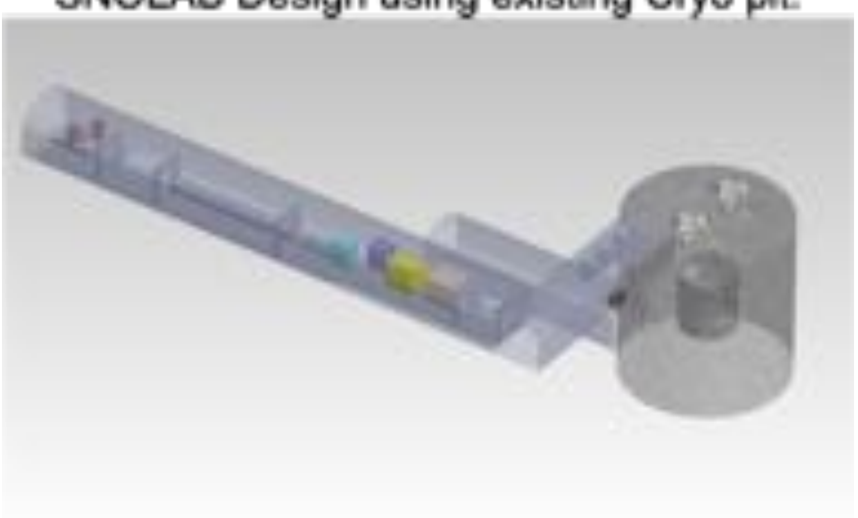
CJPL

NG-Ge76

(Next Generation Ge76)

- New collaboration forming to move towards a single tonne-scale Ge project
  - Select best technologies from existing experiments
  - Envision a phased implementation
    - Perhaps 200→500→1000 kg
  - Target >6×10^{27}yr sensitivity (5 yr 90% CL), with background ~0.1 c/ROI-T-yr

SNOLAB Design using existing Cryo pit.



Generic Design using Jinping style cavity