PandaX III for the Search of Neutrinoless Double Beta Decay

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Physics beyond the Standard Model

The discovery that neutrinos have a mass is the first evidence for physics beyond the Standard Model.

There are other phenomena predicted by various theories of new physics. Some of these effects are heavily searched for, e.g.

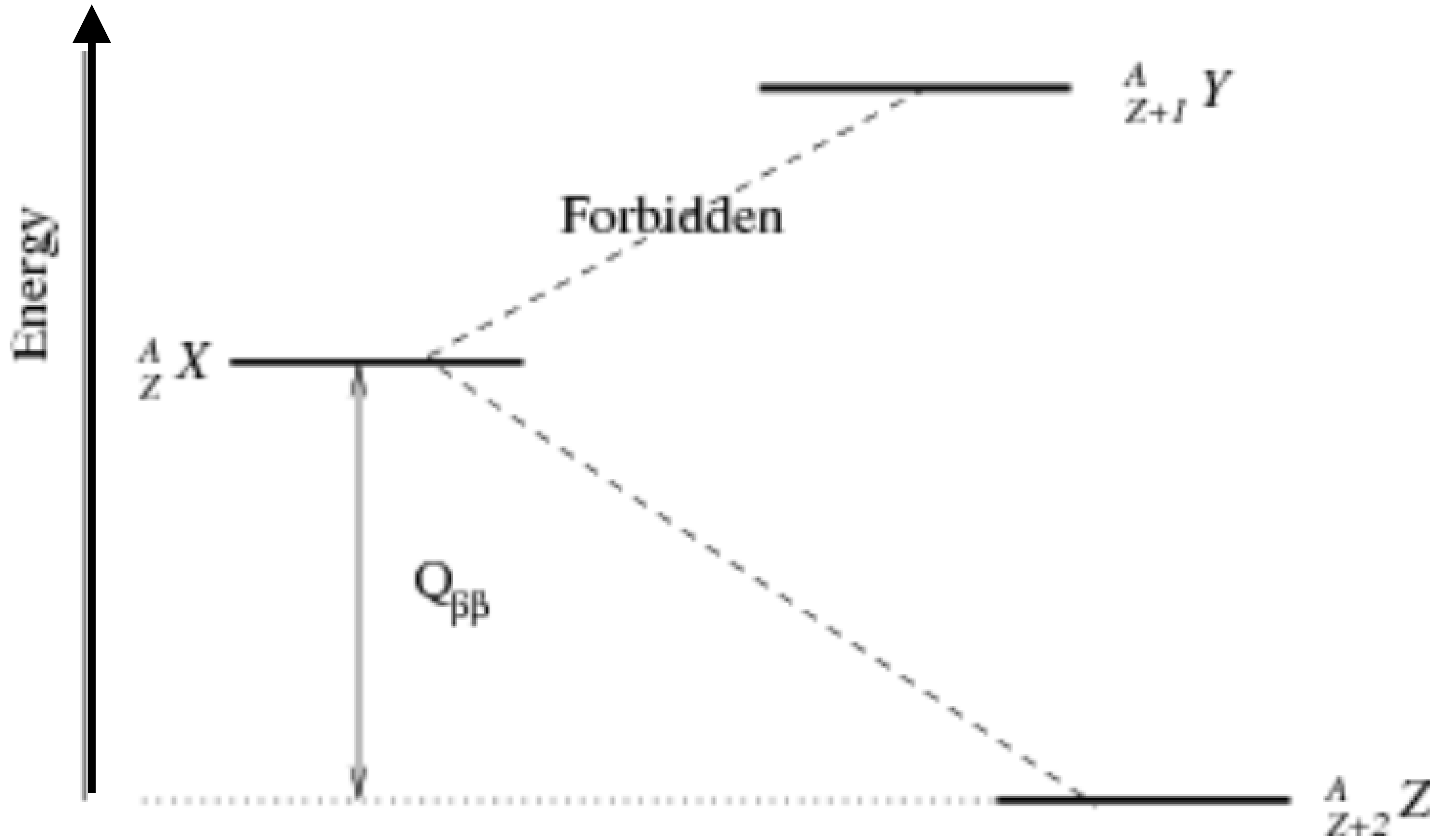
1. Dark Matter
2. Neutrinoless Double Beta Decay

For Dark Matter there is indirect proof of existence from astronomical observations. Most of the searches were for Weakly Interacting Massive Particles (WIMP). Positive results claimed by some experiments contradicted each other and and were finally ruled out

Double Beta Decay

Beta Decay is the conversion of a neutron into a proton in a nucleus with emission of an electron and an (anti)-neutrino

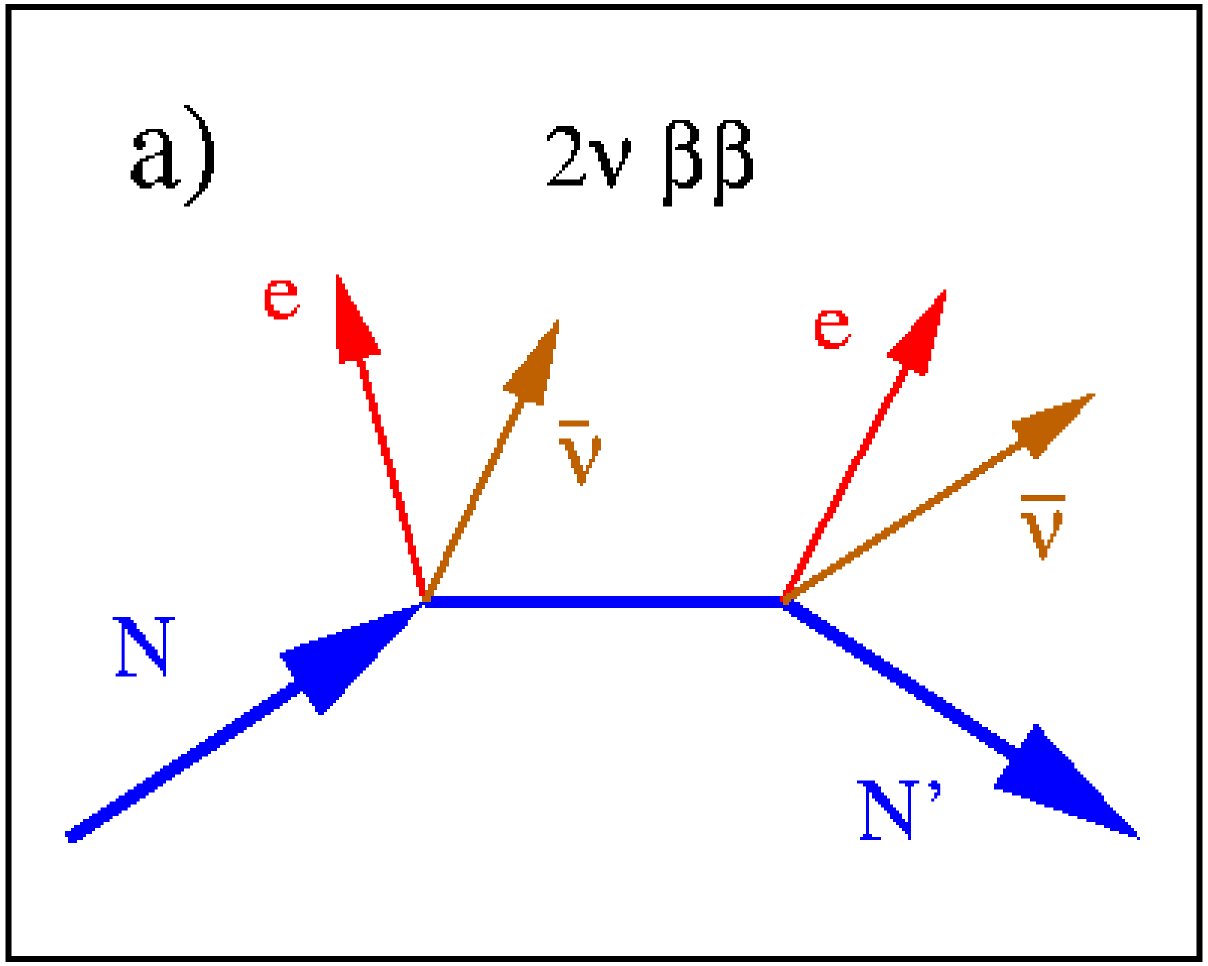
In some cases Beta Decay is **forbidden** by energy conservation, i.e. the energy of the decay product is higher than the original nucleus. The simultaneous decay of 2 neutrons into 2 protons, however, might be possible. This is a **standard second order process**.

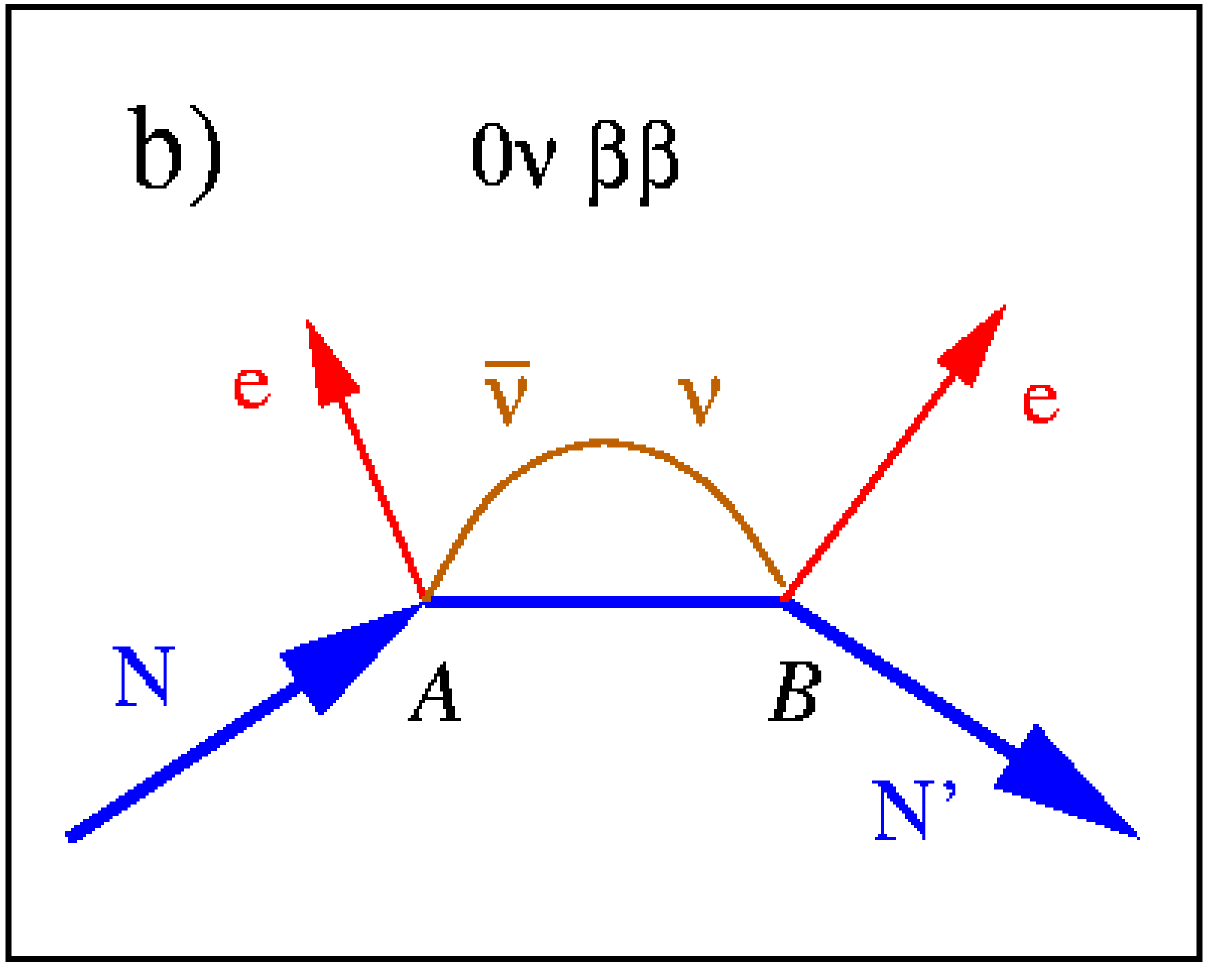


Ettore Majorana showed in 1937 that the physics of the Beta Decay remains unchanged if the neutrinos are their own anti-particles. In this case they would be called **Majorana particles** instead of **Dirac particles**.

Wendell Furry concluded it 1939 that if the neutrinos are Majorana particles then one should observe the **Double Beta Decay without any neutrinos**.

Two Types of Double Beta Decay





2νββ Mode:

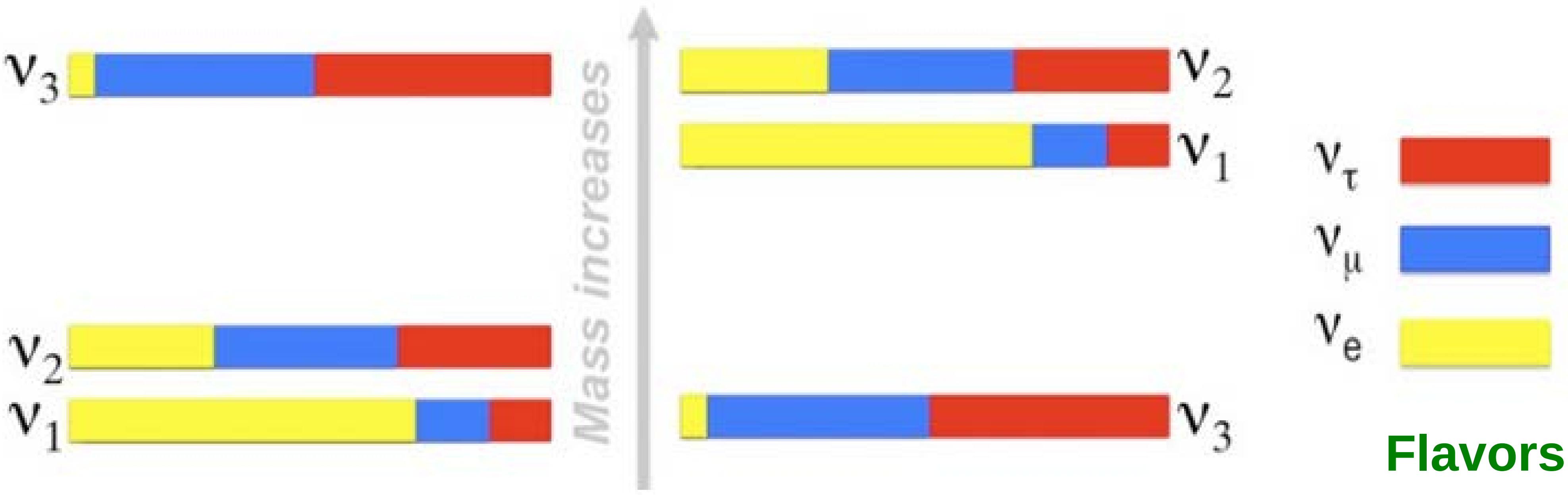
a conventional 2nd order process in Standard Model

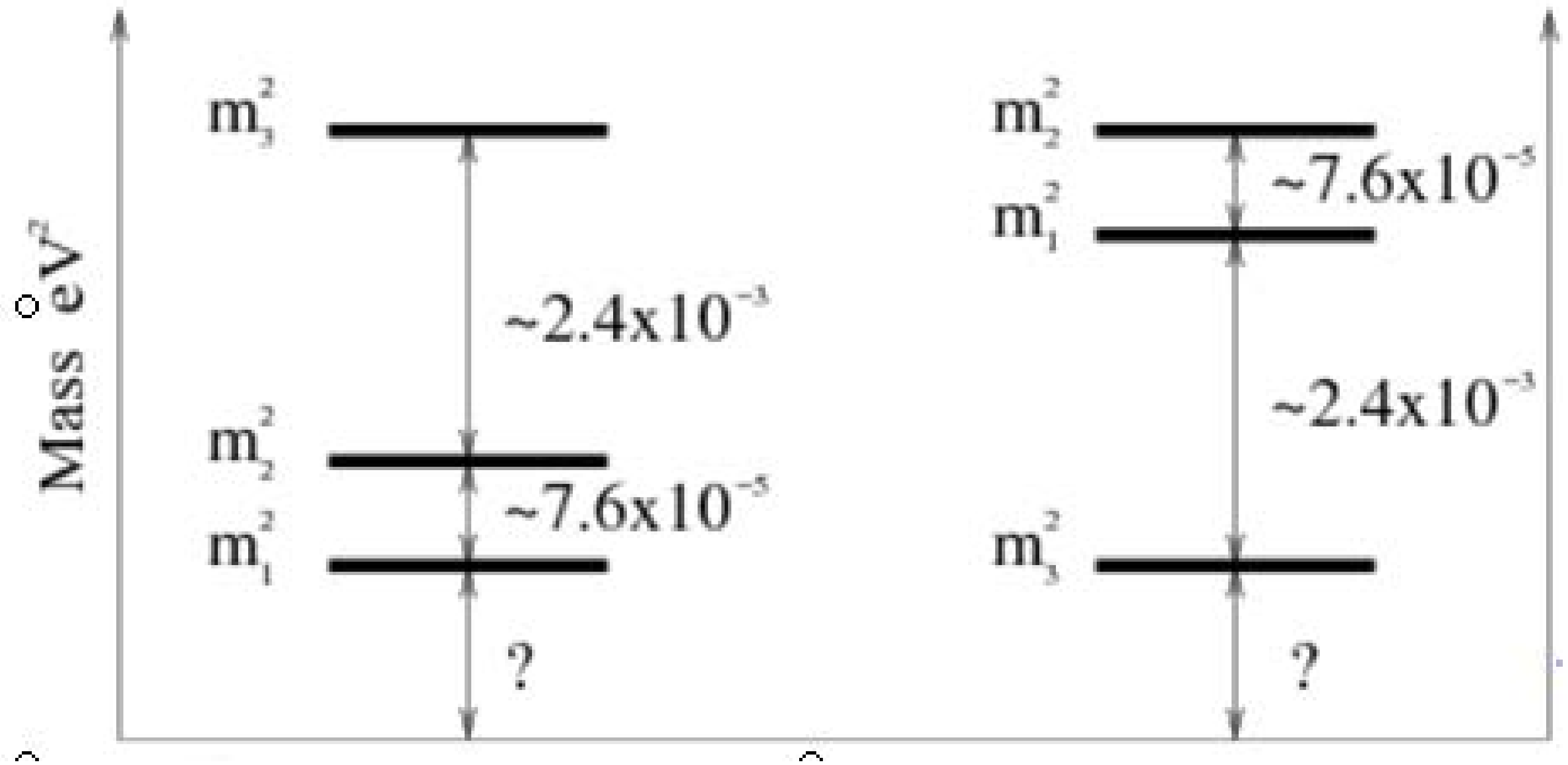
0νββ Mode:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation
- Neutrino Hierachy

Flavor Content of Neutrino States

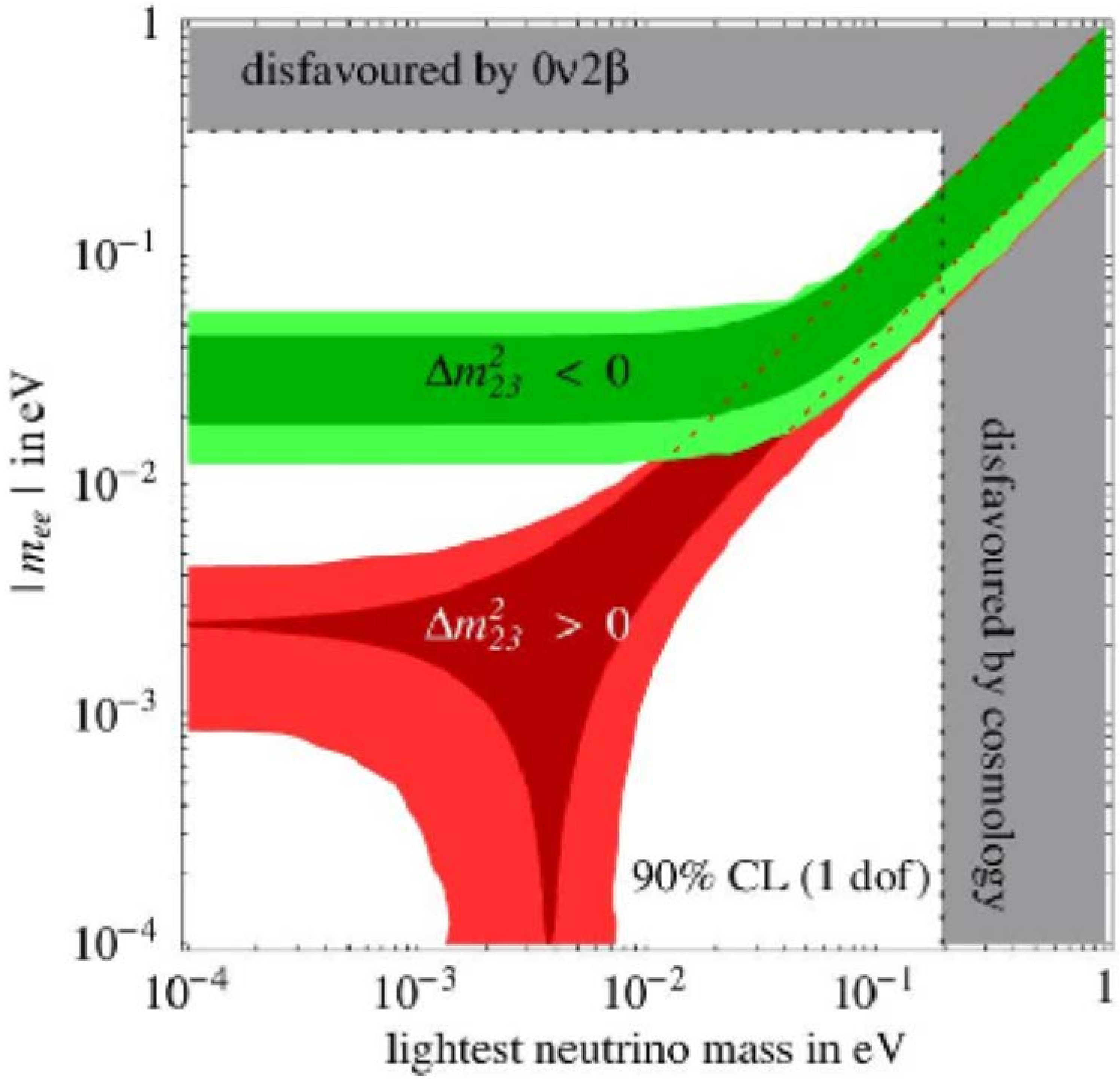
Normal Hierarchy   Inverted Hierarchy





Neutrino Mass Scale

Effective Mass versus Lightest Neutrino Mass



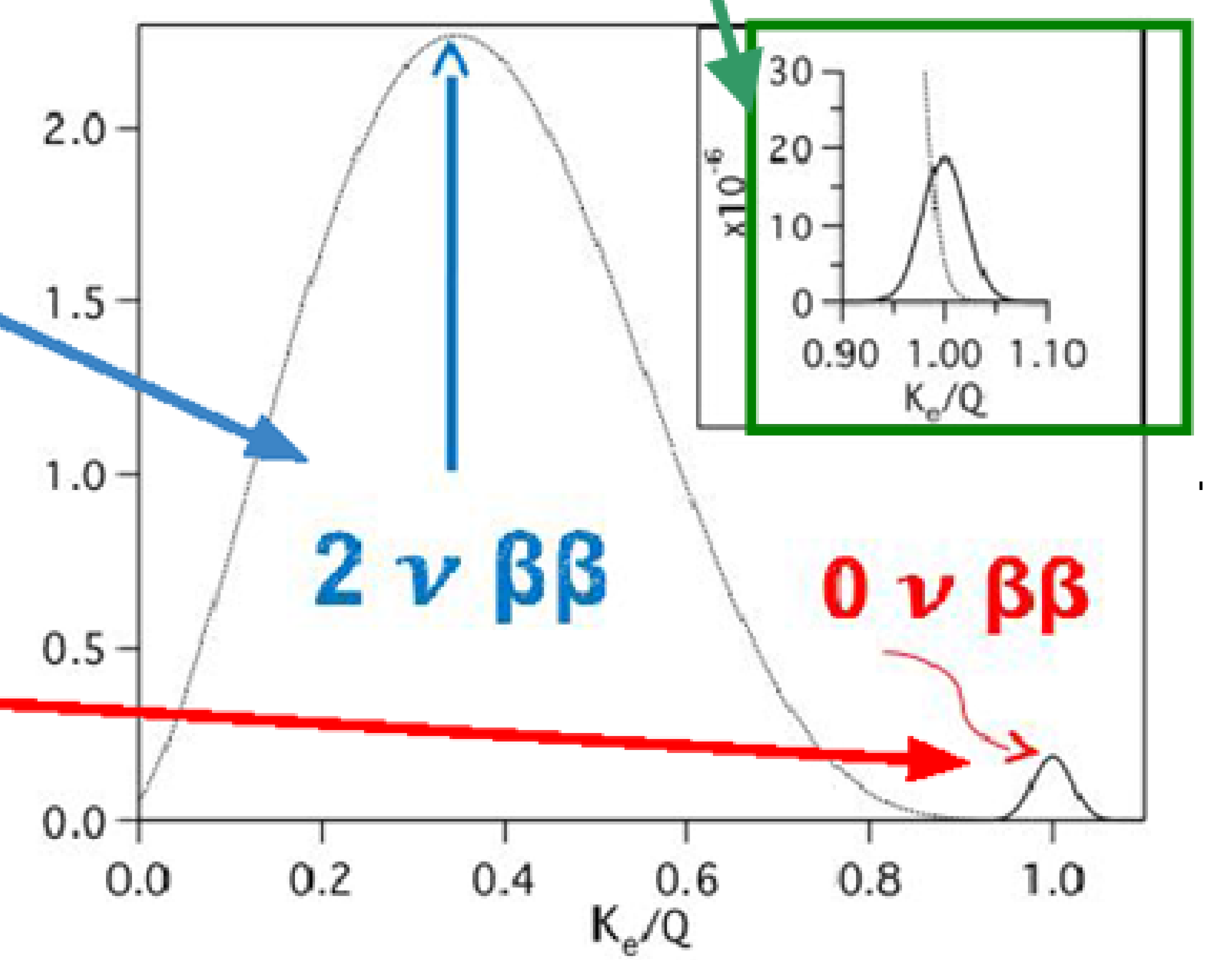
Dark Colored Areas
Assume no Error Bars

Observable Energy Spectra

The 0 neutrino decay is much more rare.
Note the **different scale (10^{-6}).**

Energy Spectrum for:
$(A,Z) \longrightarrow (A,Z+2)+2e^{-}+2\nu_e$

Energy Spectrum for:
$(A,Z) \longrightarrow (A,Z+2)+2e^{-}$



The energy scale is given by the **Q-value** of the interaction.

Overview of the DBD Experiments

Ton scale is needed to settle the nature of neutrinos
(**Majorana versus Dirac)**
when the neutrino masses have the **inverted hierarchy.**

Second Generation (G2) experiment must be scalable to ton scale

More than 20 experiments in the world. None of them has proven scalability to ton level for various reasons.

Scaling a detector to ton scale is easier with liquid/gas detector.

Natural xenon can be enriched ^{136}Xe

Xenon has high Q-value

Key Requirements for Discovering 0νDBD

1. Deep underground lab.	JingPin Lab>2400 m)
2. Water shield	(sufficient for 5 modules 1T)
3. Good energy resolution	(1 – 3 %)
4. Good position resolution	(2 – 3 mm)
5. Large mass	(200 kg of ^{136}Xe / module)
6. Scalable to 1 ton	(with 5 modules)
7. Charge read out	(AGET chip)
8. Good granularity of read out	Reconstruction of e Tracks)
9. Good control of radioactivity	(Ge Counting station)
10. Manage Rn concentration	(Rn reduced air and water)

DBD Detectors (Difference to DM)

Since we need a large mass of Xe in a shield, deep underground

why not use DM detectors with Liquid Xenon?

Dark Matter and Double Beta Decay are entirely different optimization of a xenon TPC

Background rejection:

For DM we look for **Nuclear Recoils (NR)**

For DBD we look for **Electron Recoils (ER)**

Most background coming from γ-rays.
This means for DBD:

No background rejection with **S2/S1**

No background rejection with **PSD**

DBD Detectors

Only selection criterion: Energy

0ν DBD gives a line spectrum

2ν DBD gives spectrum up to the maximum energy

Good background discrimination is essential

Required:

Lower ER background

Better energy resolution

Additional background discrimination

Change Liquid to HP Gas

What do we gain with gaseous detector?

Intrinsic energy resolution up to 60 bar with charge only.

Tracking capability. (20 cm long tracks at 10 bar)

Scalable Detector

Lower background. (No PMTs or bases)

With charge only: No PMTs, No Reflectors

No cryogenics

Do we need t_o ?

Detector is much larger for same mass

Very high voltages in gas (of order 100 kV)

Pressure Vessel (10 – 15 bar)

Change Liquid to HP Gas

- Possibly excellent energy resolution. Intrinsic: 0.3% FWHM
- Read out with charge only. No PMTs, no reflectors
- Low-background, may be as low as 10^{-3} cnt/keV/kg/yr
- Tracking capability (20 cm tracks for 2 MeV)
- No cryogenics
- Scalability (there is already 1 ton ^{136}Xe in the world, $30M)
- Use of TMA for photo-ionization. Stronger signal, reduced longitudinal diffusion, more stable operation

- Disadvantage : Pressure Vessel

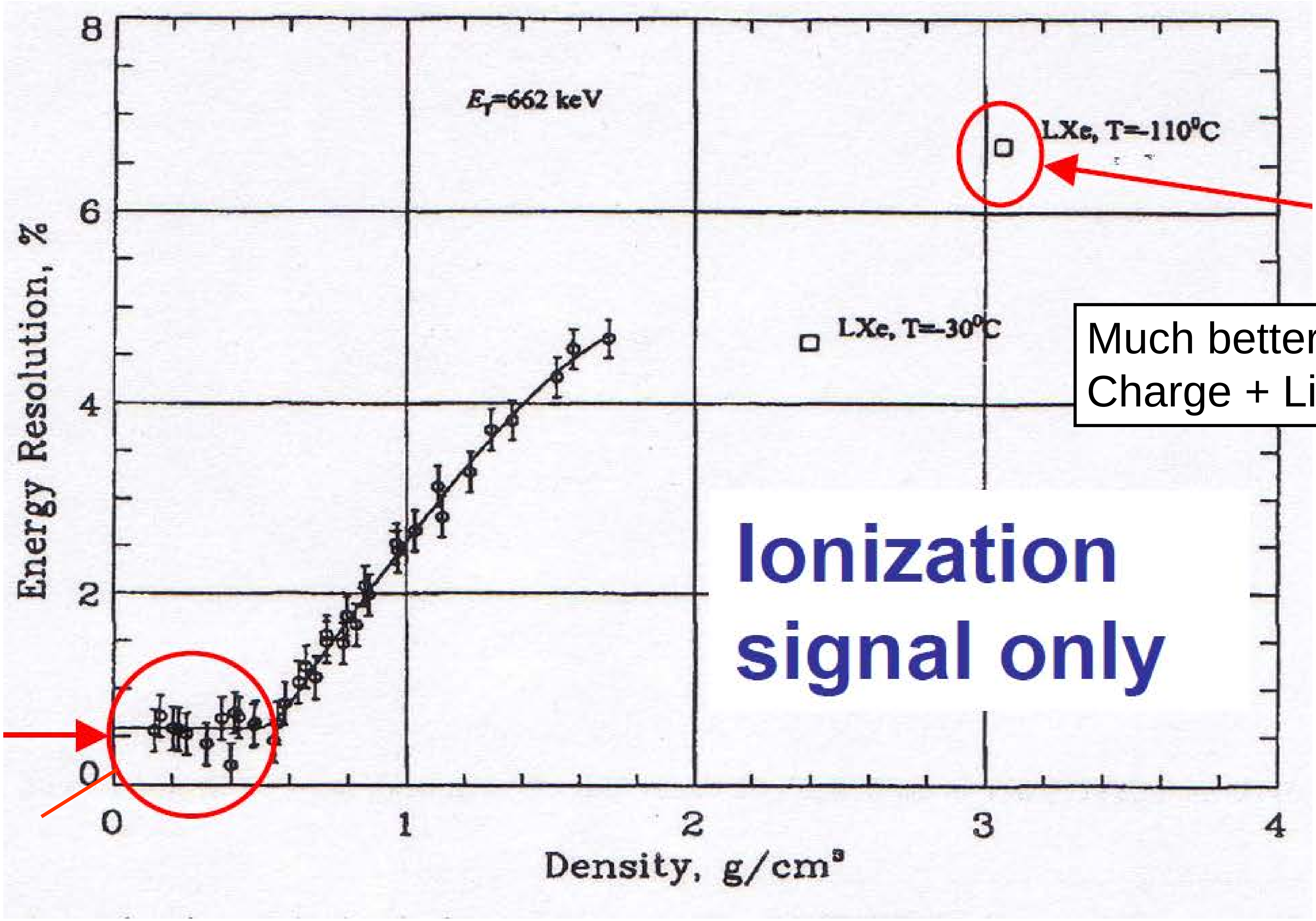
Dark Matter and Double Beta Decay are entirely different optimization of a xenon TPC

PandaX III Concept

Our goal: Develop a detector with:

- Good energy resolution (< 1 % FWHM at 2.50 MeV)
- Low background (< 10^{-3} cts/keV/kg/yr)
- Large size (3 - 4 m^3)
- High pressure gas (10 - 15 bar)
- Enriched xenon (> 80 % of ^{136}Xe)
- Tracking capability
- Operation in the new JingPin Lab
- Scalable to 1 ton (modular?)

Enhanced Energy Resolution



Much better with Charge + Light

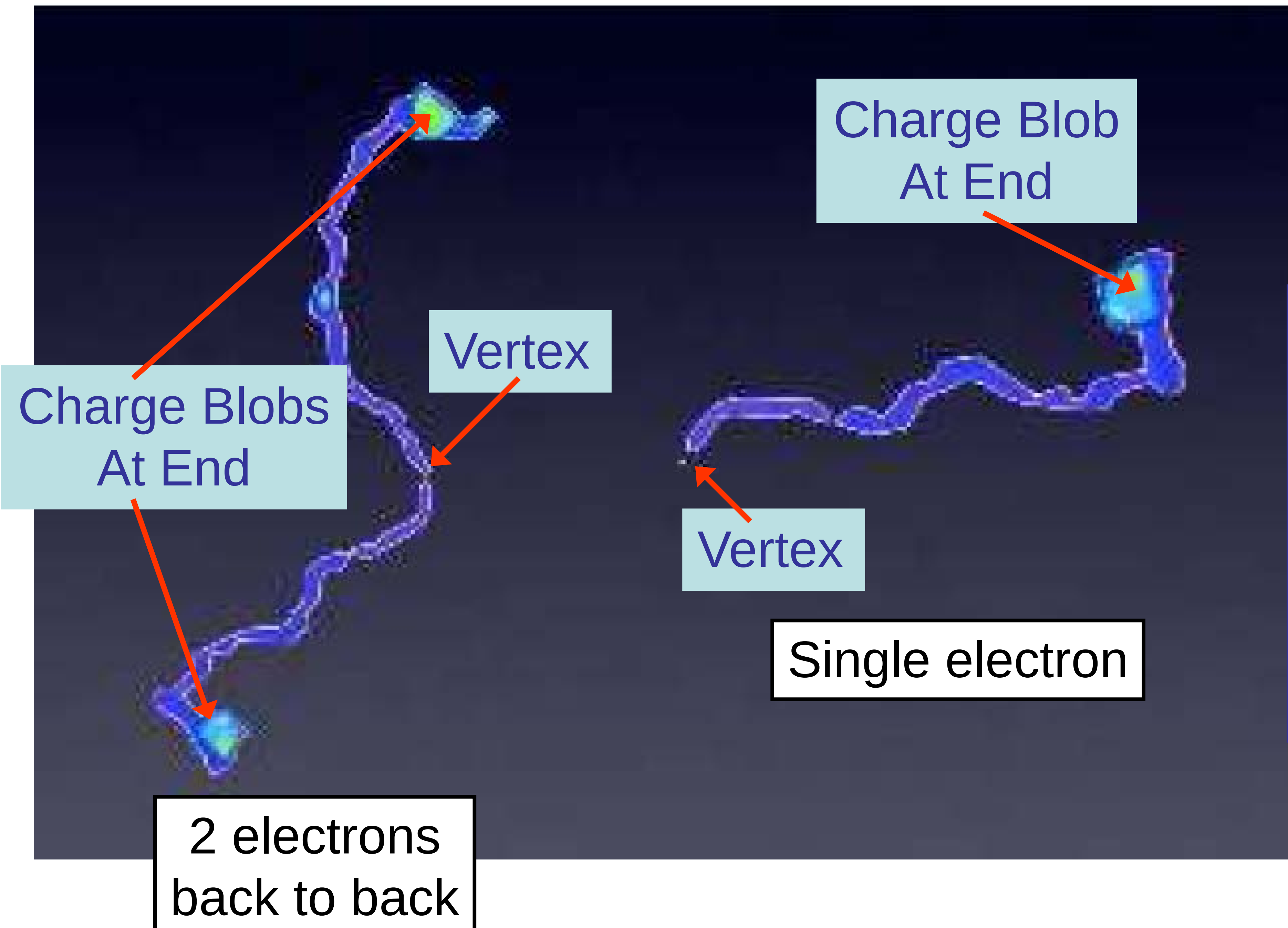
Ionization signal only

Very good up to 0.55 g/^{3} (60 bar)

Advantages of High Pressure Xe Gas

Tracking capability in 10 bar Xe

Track length for 2 MeV about 20 cm



Tracks are not Straight due to scattering!

Clear difference between **one track of 2 MeV** and **two tracks of 1 MeV** from the same vertex

^{136}Xe $0\nu\beta\beta$ Event Topology

DBD events will show **two electrons** of (2.458 / 2) MeV each

The **back to back** electrons come from **one vertex**

The electrons scatter a lot. Tracks will not be straight.

Track length is **10 – 15 cm** in 10 bar Xe for each electron

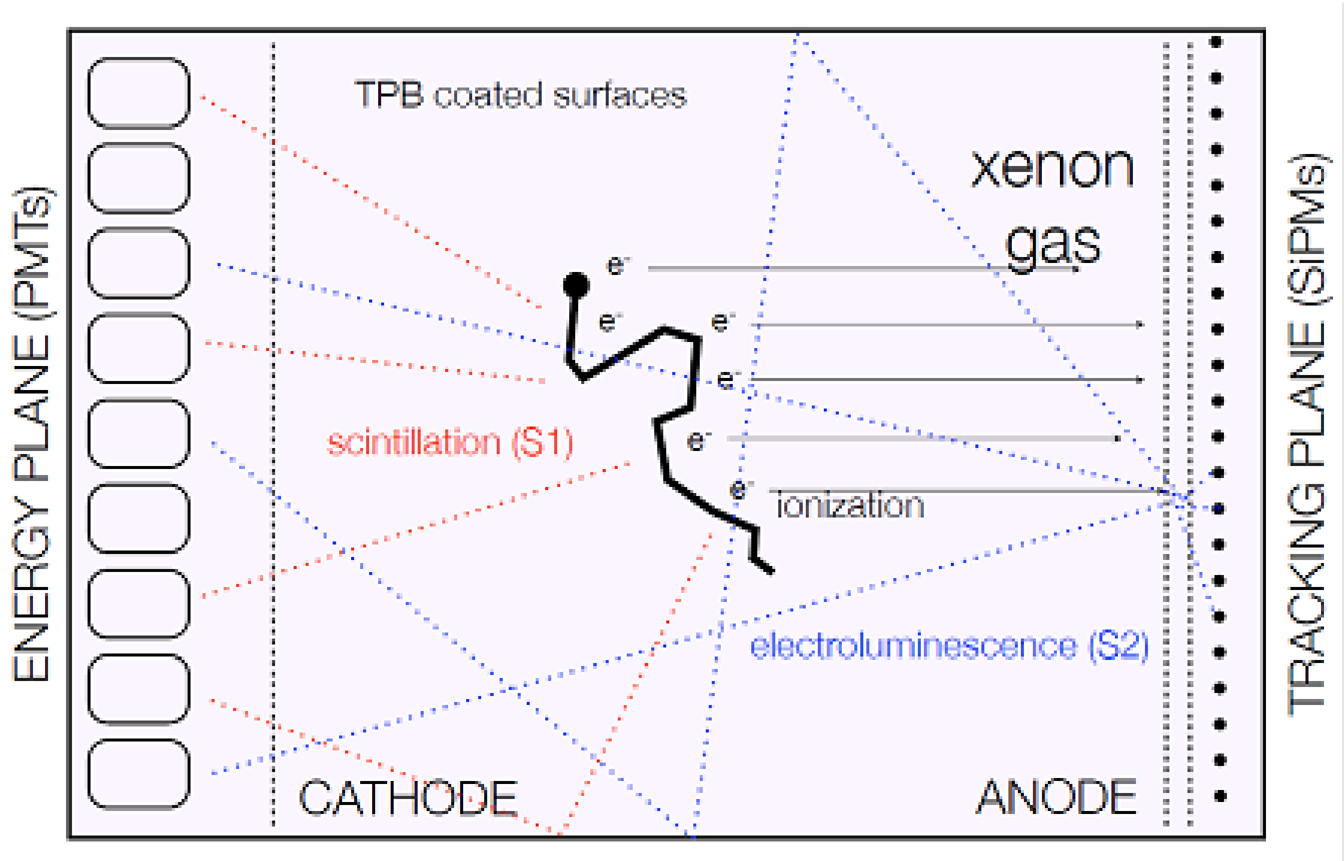
Ionization density will increase at the end of the tracks

The two tracks will produce about **100k ionization electrons**

A 2.4 MeV background γ-ray has only one charge blob at one end. Also, the first half of the track is much more straight.

The Competition: The NEXT Experiment

NEXT is a 100 kg gaseous xenon (^{136}Xe) detector foreseen for the Camfranc Laboratory in Spain.
It will be operated at 15 bar.
The read out is optical using electro-luminescence. Surfaces are coated with TPB as wavelength shifter. The photosensors are MPPC (Si-PM).
The position resolution is supposedly sufficient for tracking the electron at 2 x 1 MeV.



Asymmetric design. The cathode (HV) is situated next to the photo-Sensors (ground). Some dead space.

Disadvantages of the NEXT Approach

- Stretching wires on a large diameter is challenging
- In the homogeneous field any displacement of wires will limit the energy resolution
- Position resolution might be sufficient, but in gas an event has more than one point. Tracking?
- Energy integrated with PMT signals only. Losses of light? TPB homogeneity? Energy resolution? 1% FWHM?
- MPPC cost? Effectiveness?
- PMT’s under 15 bar?
- Background? Vessel? Muon background? PMT and bases?

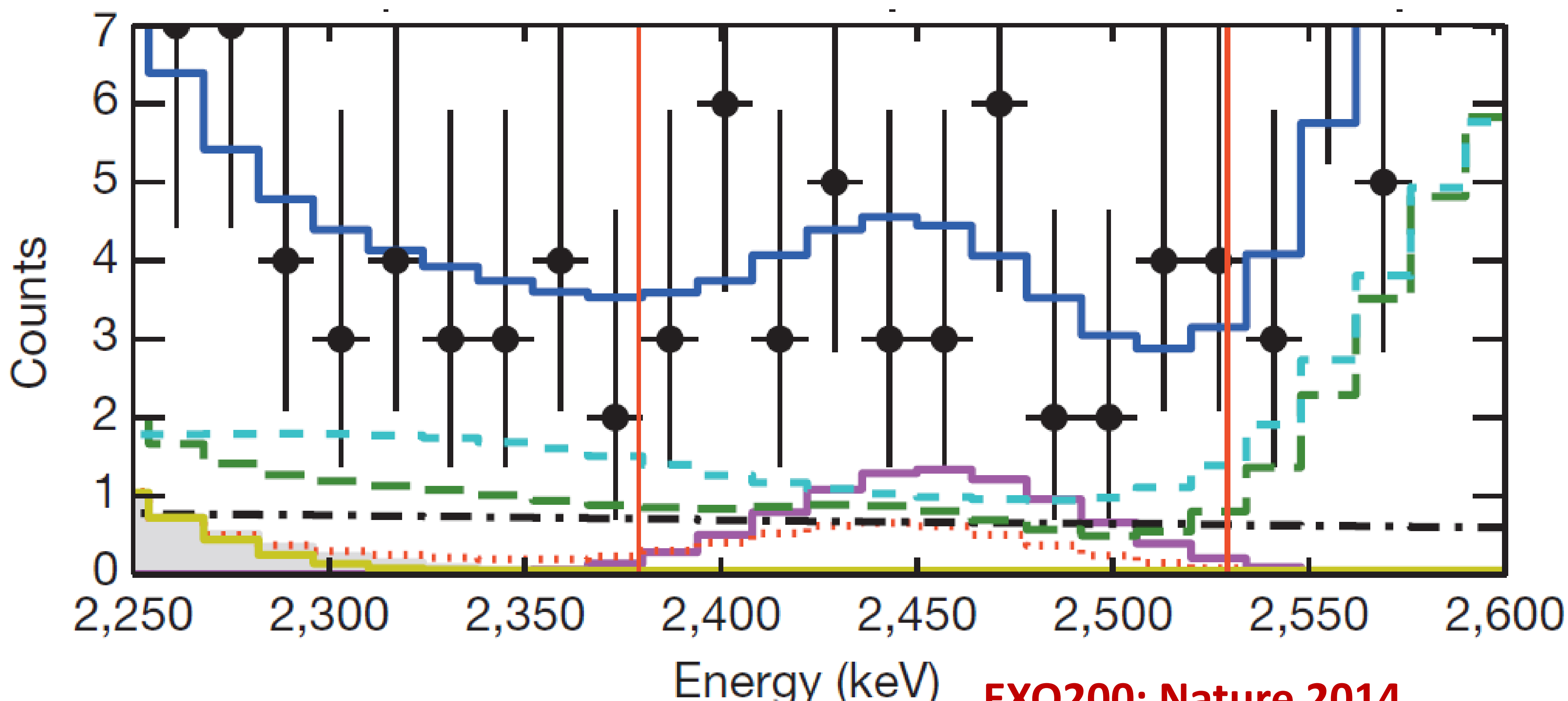
Most recent results with ^{136}Xe: EXO200

- •200 kg Liquid Xenon TPC
- •2 years of run time
- •Good control of radioactivity
- •Good energy resolution (3%)

Within 2 σ :

Observed Events: **39**

Expected Background: **31**



EXO200: Nature 2014

Detection Capability of a HP ^{136}Xe Detector

If $0\nu\beta\beta$ Decay exists, the events must statistically hide in the EXO200 results

Assume the following detector:

Same mass : 200 kg of ^{136}Xe
Same radiopurity
Same energy resolution
Same run time: 2 yrs
But: **Tracking capability**

If the tracking capability allows rejection of 99 % of the background, The 31 expected background events of EXO200 are reduced to **0.3 events**. The measurement is **nearly background free**.

PandaX-III Main Differences

- Alternative realization of read out: symmetric charge readout
  - Stage1:MircoMegas, energy resolution 2-3% FWHM
  - Stage2:TopMetal (modified CMOS), energy resolution 0.5%

- Light readout? (optional, required?)

- New type HP vessel

- 200 kg modules for scalability to 1 ton

- Deepest underground lab (CJPL)

PandaX-III Physics Goals

Prove superiority of technology for $0\nu\beta\beta$

Competitive mass (**200 kg**) and modular design

Easy upgrade to **1 ton** (5 modules)

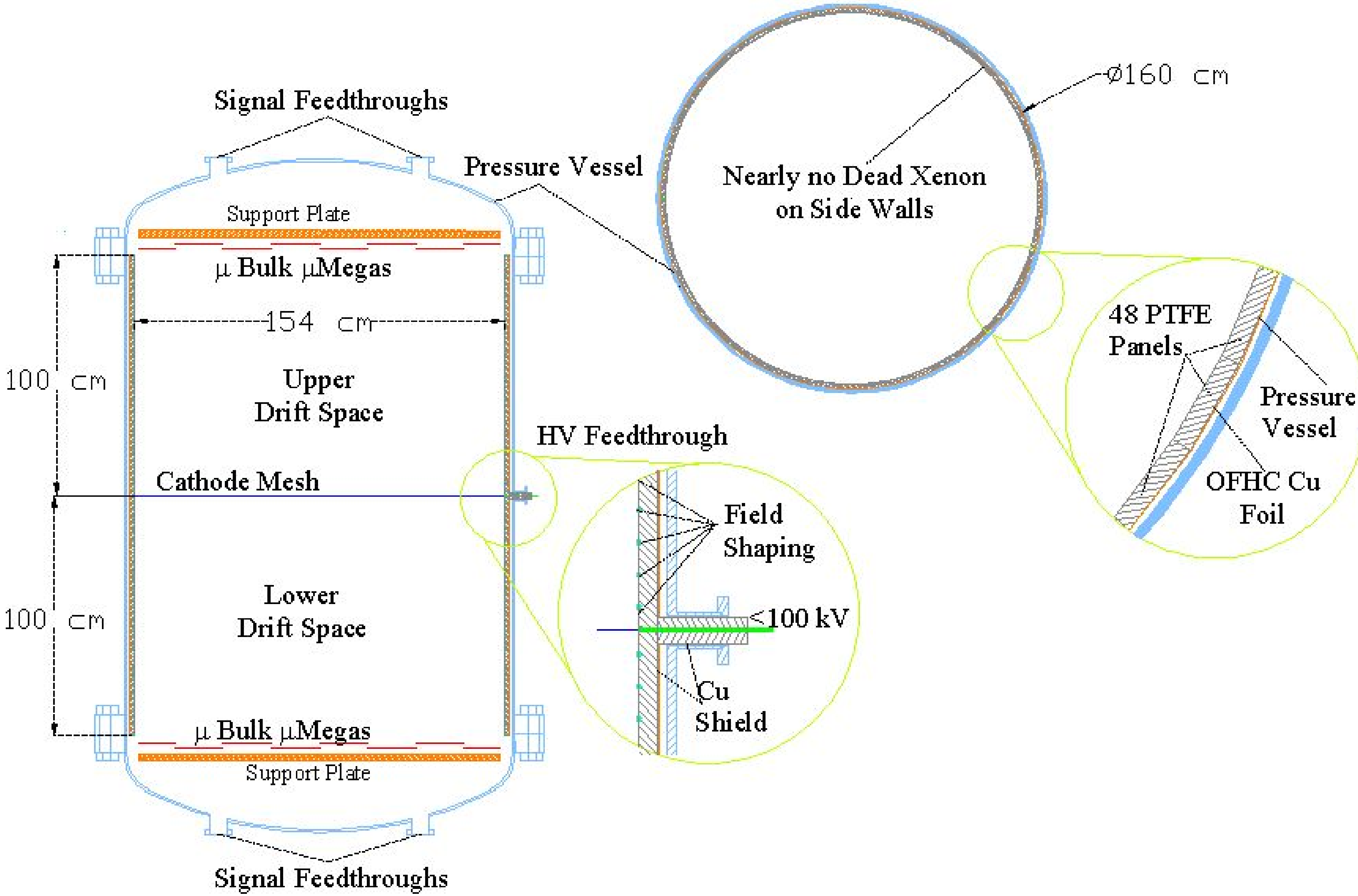
Discovery potential

In time for next generation neutrino physics

PandaX III Technical Specifications

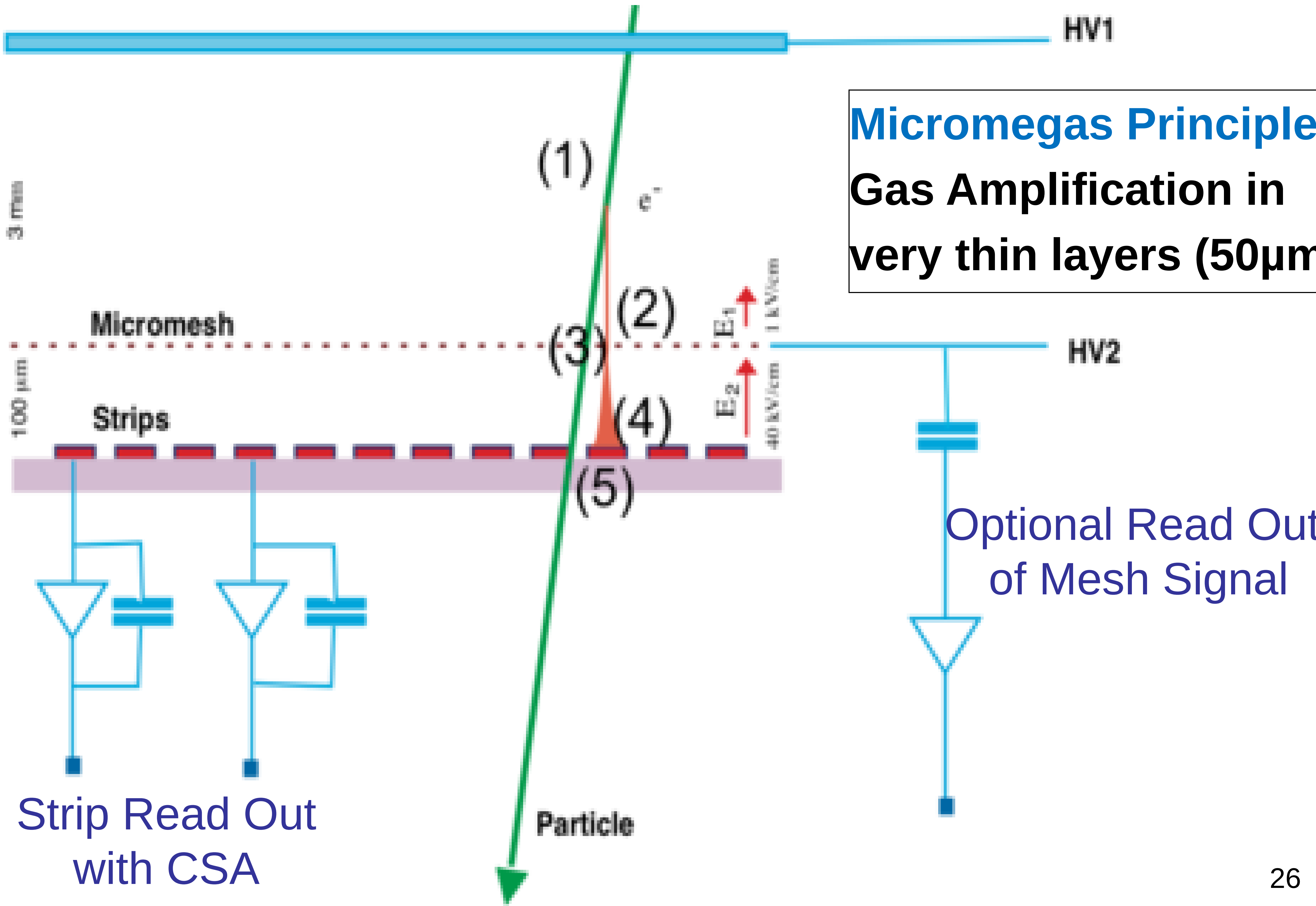
- Size: 1.5 m inner diameter
- 2 m long cylinder
- Split into 2 Drift Regions
- Cathode (with HV) in the center
- MicroBulk microMegas as read out on both ends
- Low radioactivity (either Cu, or reinforced Kevlar vessel)

Schematic of PandaX III



Read Out of TPC with μMegas

Micromegas Principle:
Gas Amplification in very thin layers (50μm)



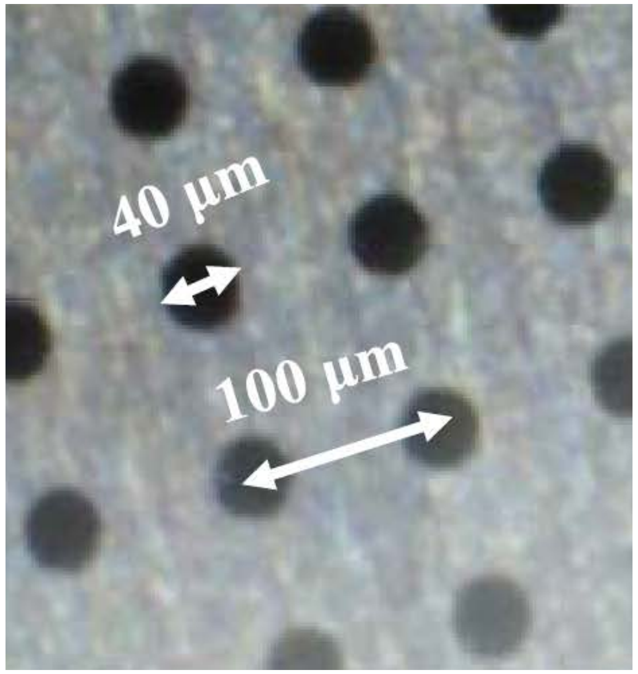
MicroMegas Read Out

μBulk μMegas

MicroBulk technology is using lithography
Superb quality

Main constituents: Kapton and Copper

→ **Potentially very Radiopure**

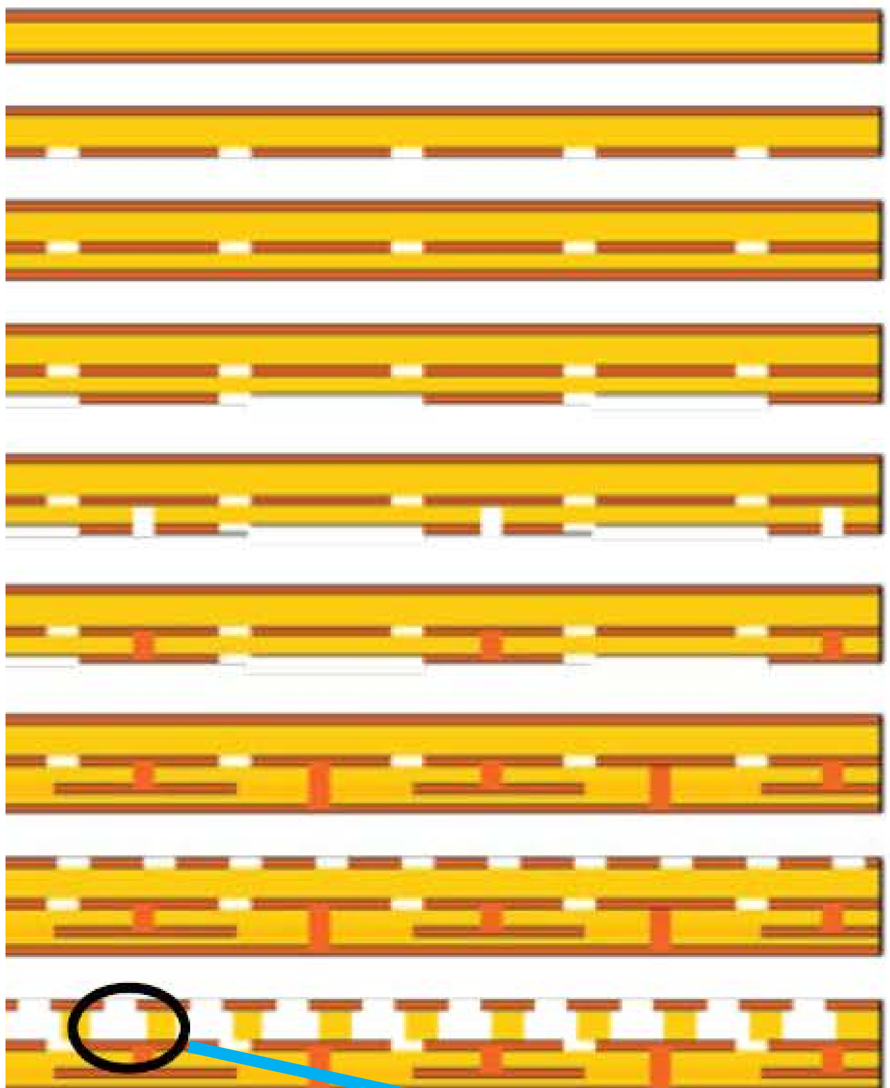


High Gap Homogeneity

→ **Good Energy Resolution**

Fabricated at the CERN PCB Workshop
(Rui de Oliveira et al.)
JINST 5(2010) P12001

Manufacturing of μBulk μMegas



Double side Cu-coated (5 μm) Kapton foil (50 μm),

Construction of readout strips/pads (photolithography)

Attachment of a single-side Cu-coated kapton foil (25/5 μm)

Construction of readout lines

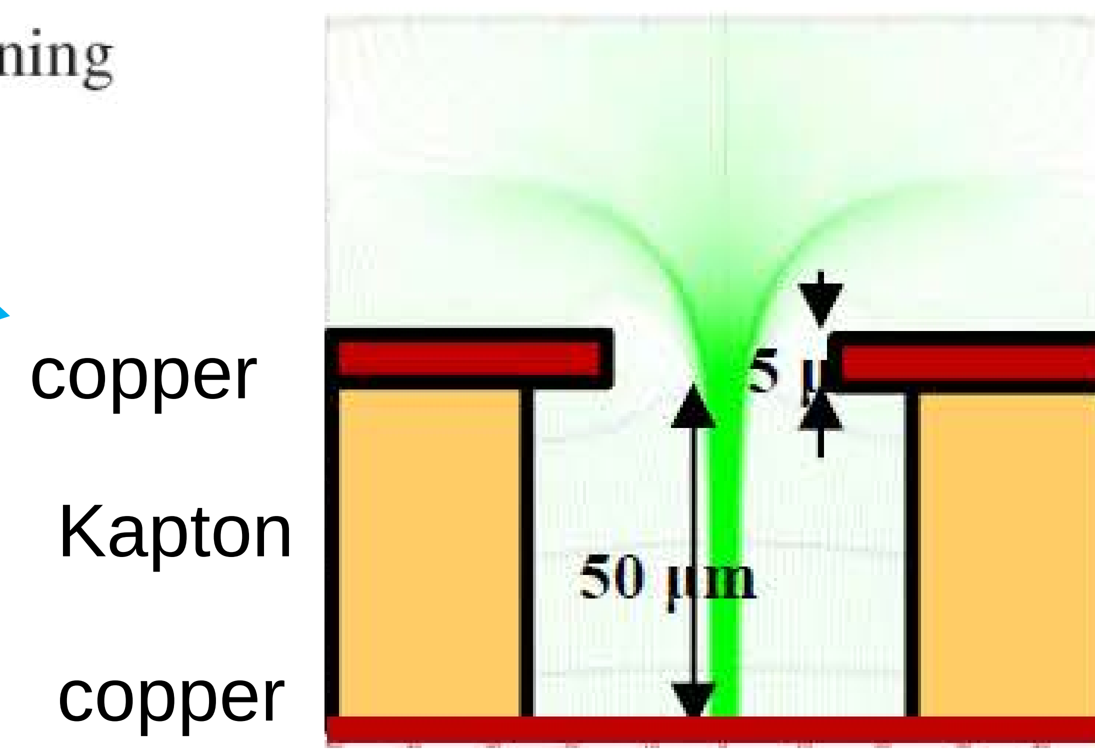
Etching of kapton

Vias construction

2^{nd} Layer of Cu-coated kapton

Photochemical production of mesh holes

Kapton etching / Cleaning



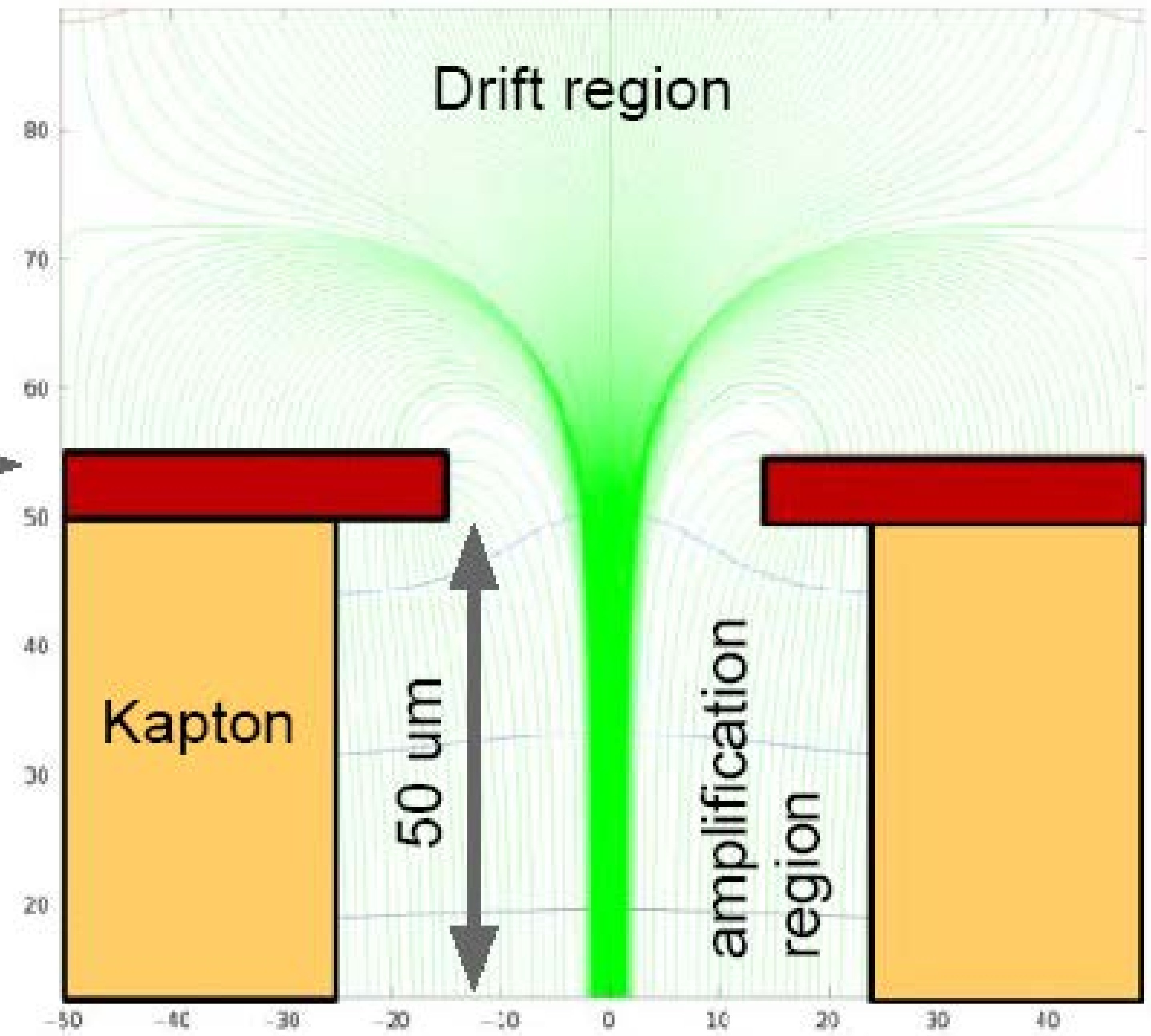
Single Amplification Cell

Fabrication of μBulk μMegas

The Kapton layer is 50 μm thick.

The copper layer is only 5 μm thick.

Copper



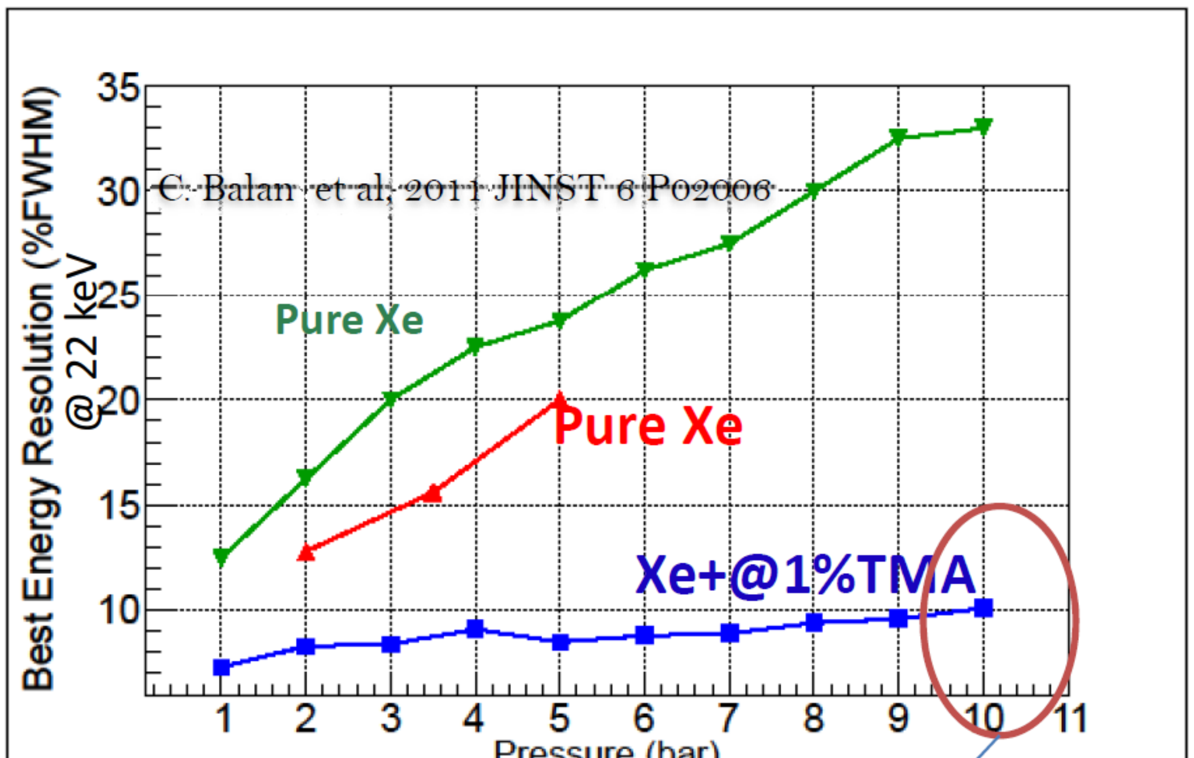
Single Amplification Cell

Microbulk Technology provides detector read out with **small mass** budget and uses very **radiopure** materials (Copper and Kapton)

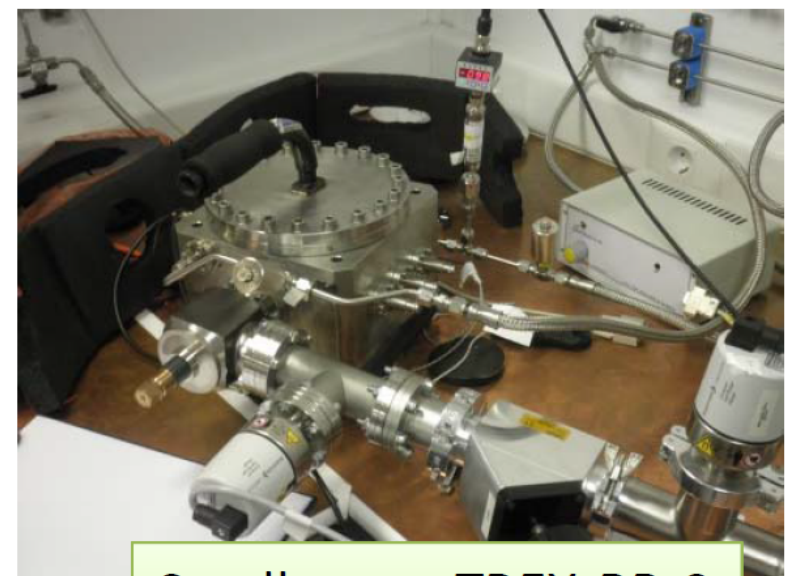
Photo Ionization with TMA

The ionization potential of TMA is so low that the scintillation light of xenon ionizes the TMA molecules.

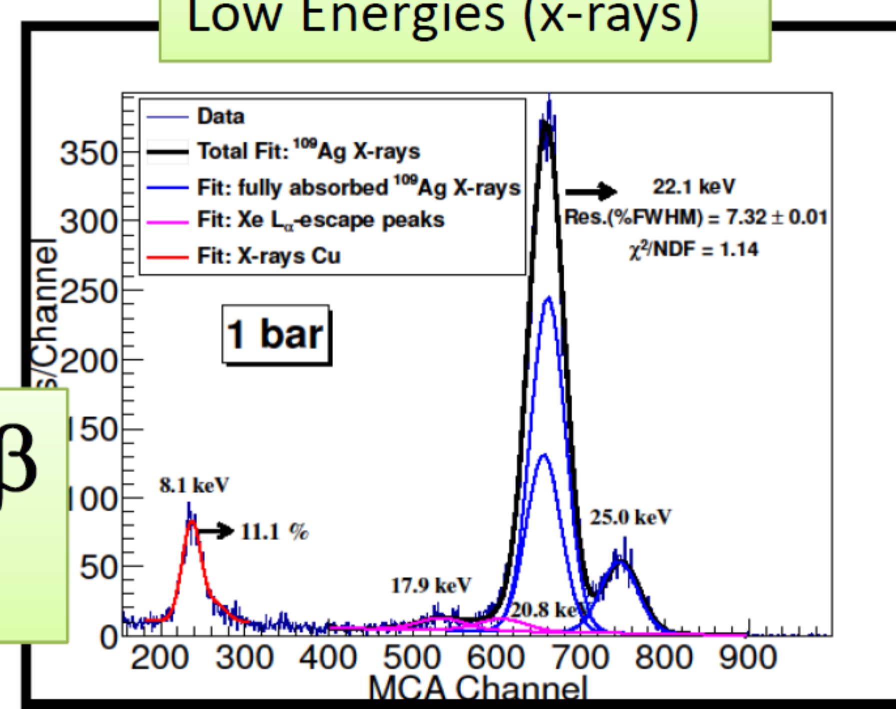
- Addition of TMA to Xe: perfect combination!
- higher gains, better E res, more stable operation



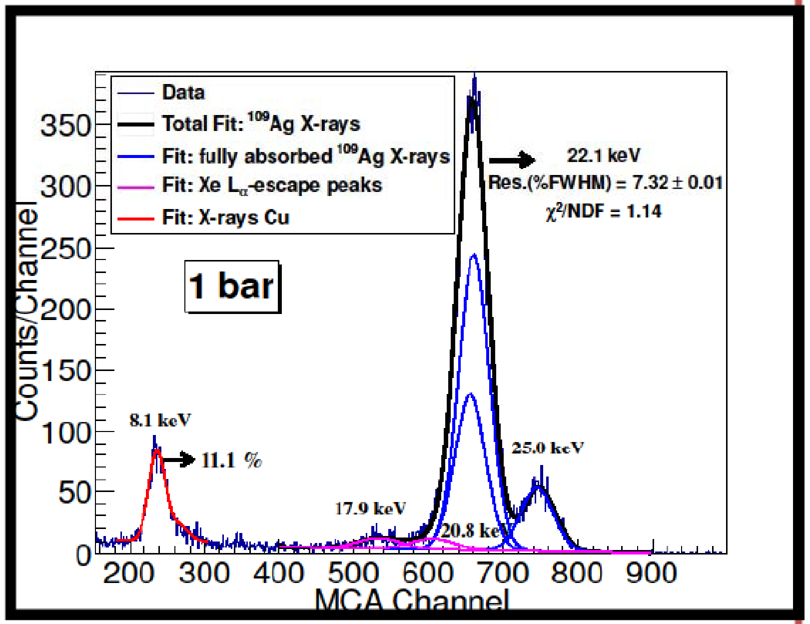
0.9% FWHM @ Qββ
10 bar



Small setup TREX-BB-0
Low Energies (x-rays)

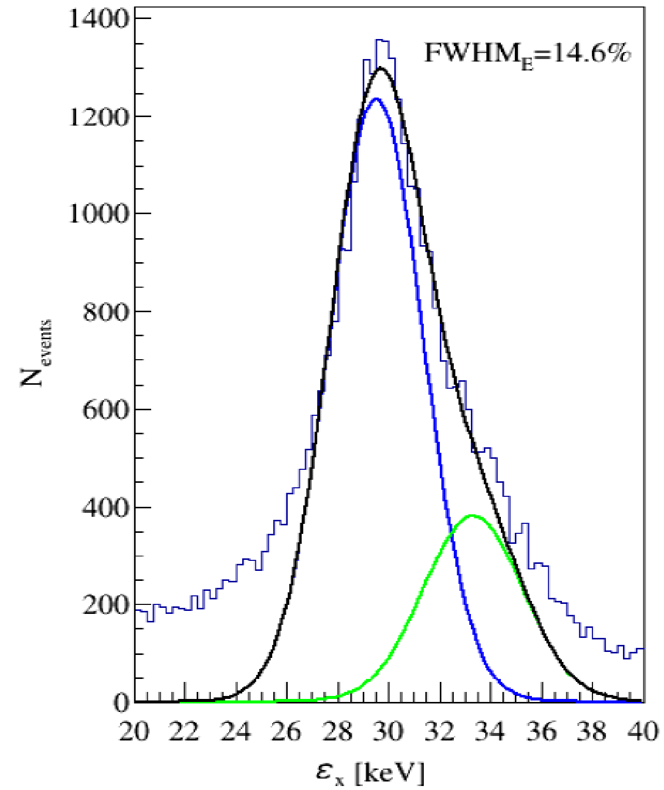


Energy Resolution of Real Data



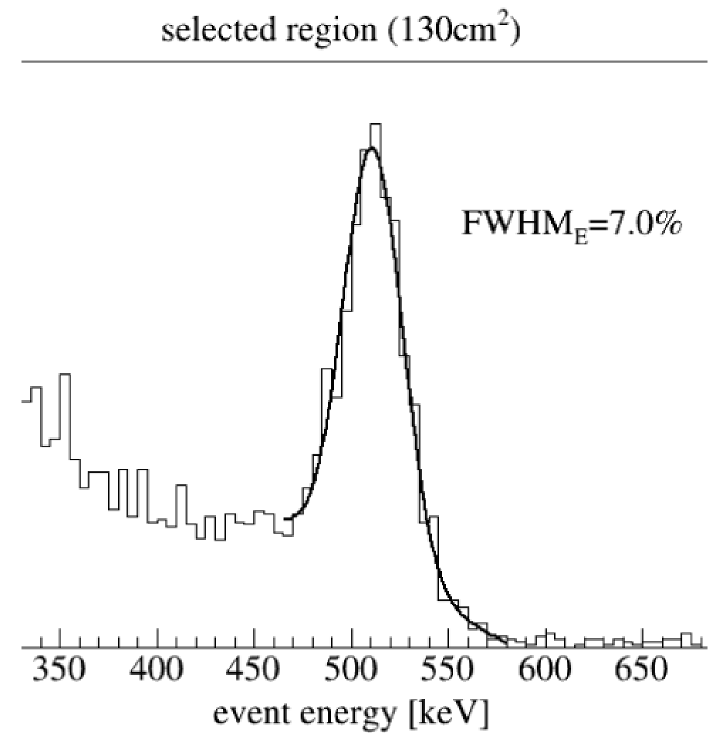
Small setup TREX-BB-0
Low Energies (x-rays)
~10% FWHM @ 22 keV

0.9% FWHM @ Qββ 10 bar



Large setup NEXT-MM
Low Energies
(isolated x-rays)
~15% FWHM @ 22 keV

1.4% FWHM @ Qββ 10 bar

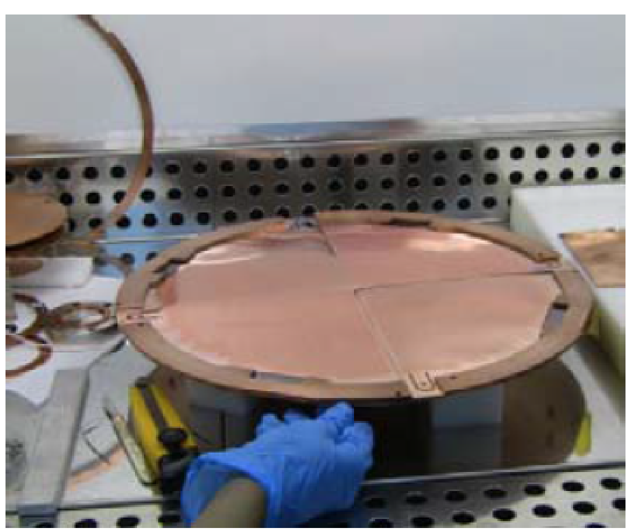


Large setup NEXT-MM
High energies (511 keV)
~7% FWHM @ 511 keV

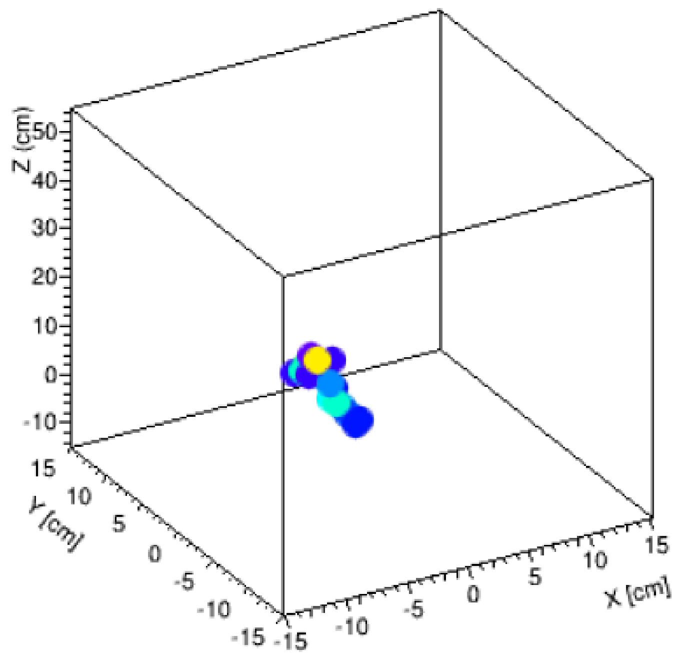
3.1% FWHM @ Qββ 10 bar

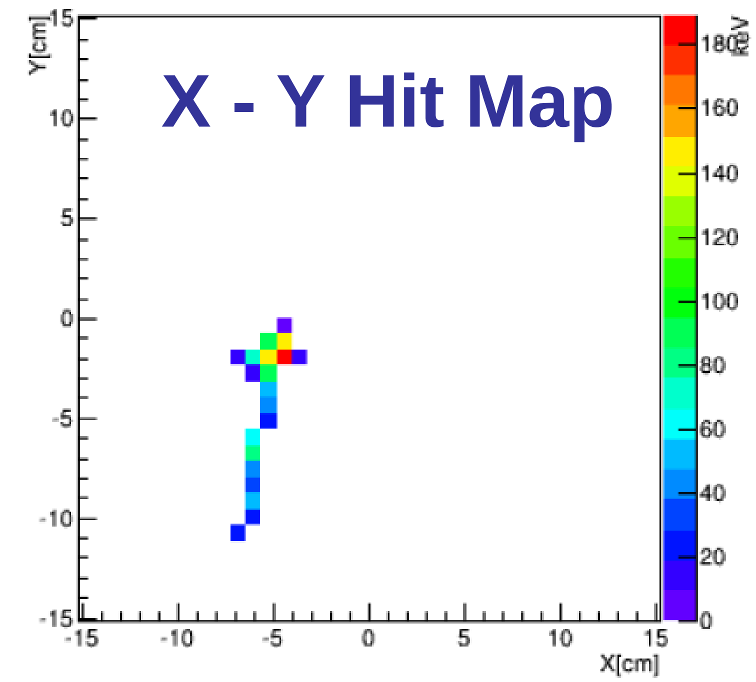
Real Track Images

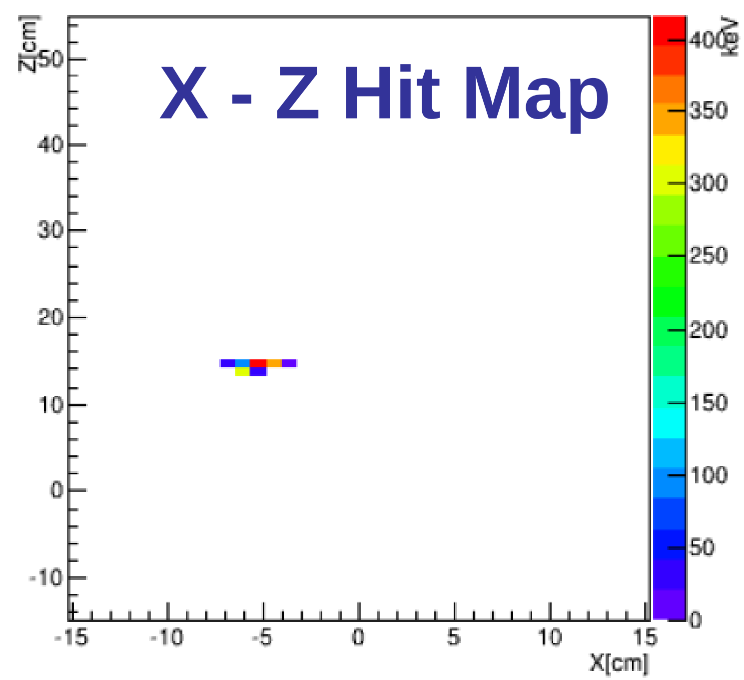
^{22}Na events (1274 keV) in "NEXT-MM" Detector in Zaragoza

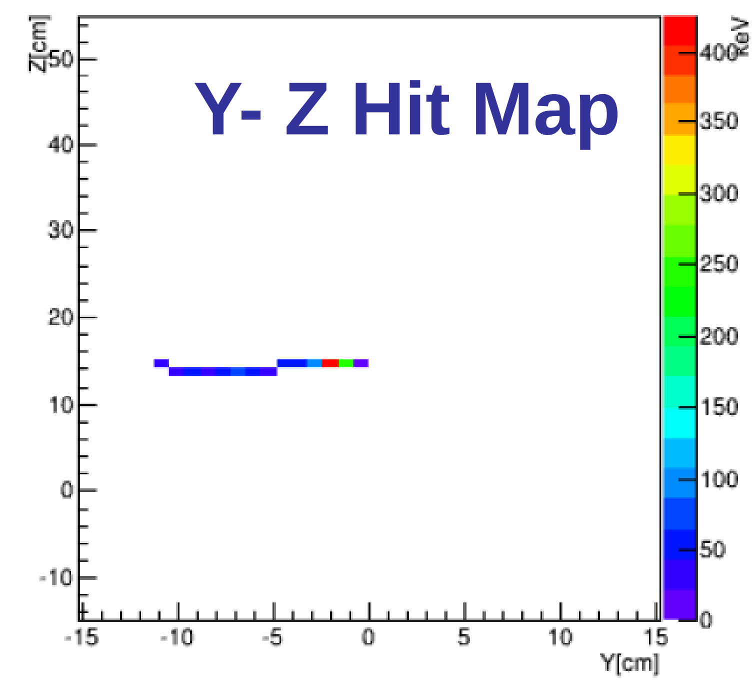


3D Hit Map









"½" of $0\nu\beta\beta$ Events

Read Out Electronics

Charge read out only, **no light**,
(no PMTs, no reflectors, no sensors on perimeter)

Avalanche formation does introduce additional fluctuations.
What is the best combination of **gas and electronics gain**?

The two end plates will be instrumented.
The Cathode (HV) is in the Center.

Area of one End Plate (70 cm diam.) : 1.5 m^2

Pixel size **7 x 7 mm^2**
Area 0.5 cm^2
Pixels/plate 30,000

Total : **60,000 channels**

Strip Length* : 20 cm
Strip Pitch : **5 mm**
Strips(x and y)/plate : 3,000

Total : **6,000 channels**

* Strip length is limited by max. capacitance.

AGET Chip

ASIC chips, mature technology

AGET chip selected. Developed at Saclay for TPC read out

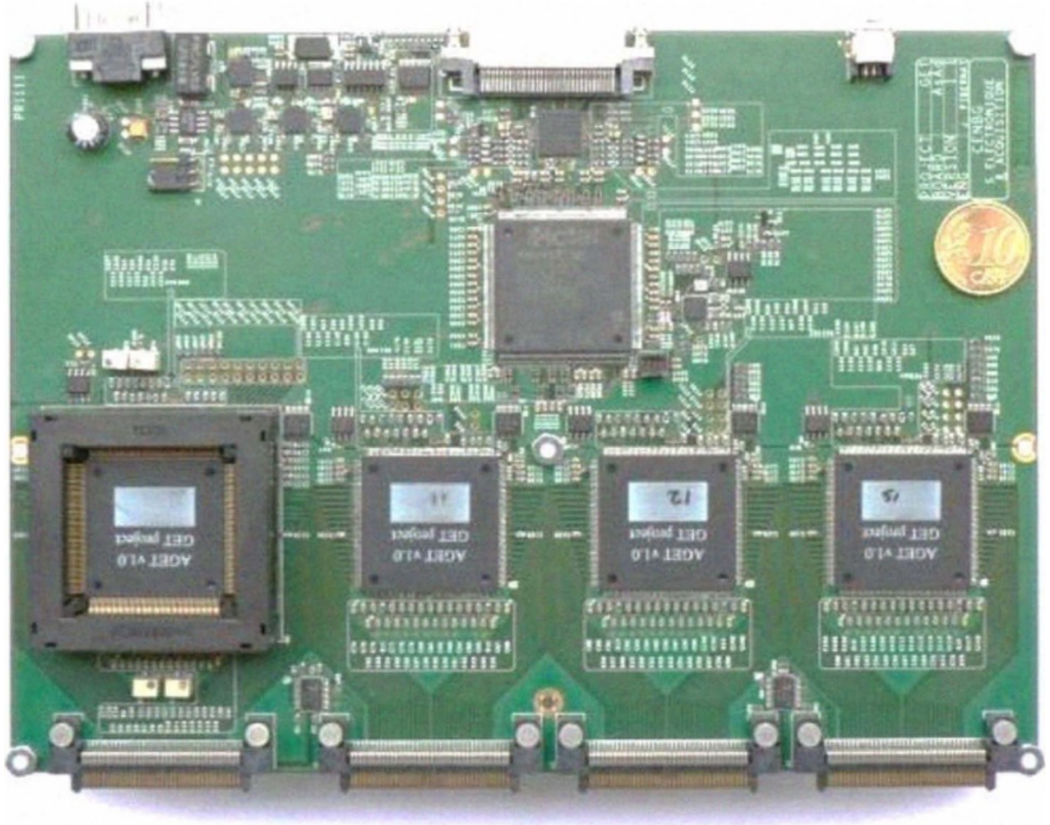
AGET is a new development of AFTER chip

Groups have already experience with the use of AFTER chip

64 channels per chip

Self trigger capability

Front end card with ADC and protection circuit available



Requirement for FEE

To be mounted where? **Inside TPC**? **Outside**?
Outside of shield is impossible (> 5 m long cables!)

Inside TPC:

1. Radioactivity
2. High Pressure
3. Heat production
4. Purity for xenon
5. Connectors

Outside TPC:

1. Within water!
2. Cu shielding to TPC
3. Feed throughs
4. Capacitance of lines
5. Awkward to install

Outside seems easier at present

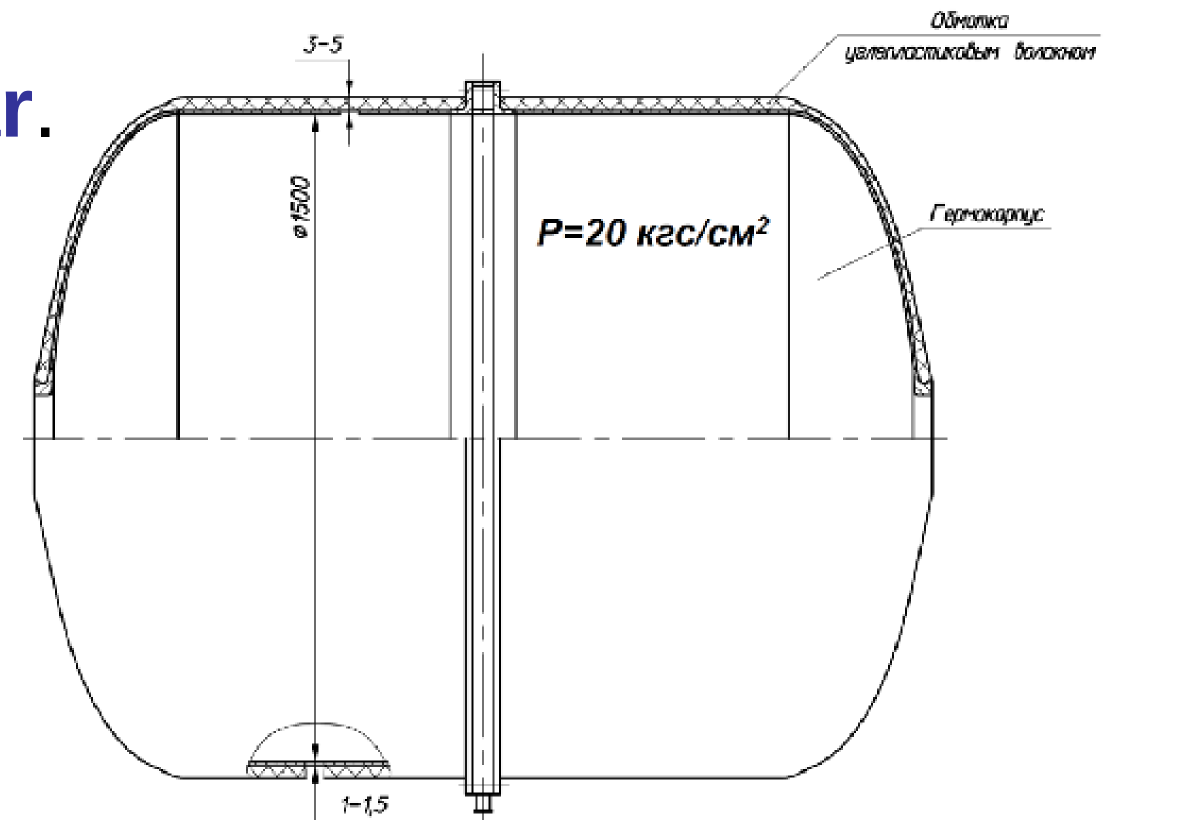
Development of connectors and feedthroughs required

High Pressure Vessel

Detector Vessel is right next to sensitive volume.
No ‘self shielding’ like in LXe DM experiments

Possible solutions:

1. Standard **SS Vessel**. Radioactivity probably too high even with special steel.
2. **OFHC Copper Vessel**. Several cm thick. Very heavy (8 tons). Cosmogenics during manufacturing and transport?
3. **Carbon Fiber reinforced Kevlar**. Russian aerospace design (MEPhI) with OFHC liner (1- 2 mm thick)



Xenon Gas

Only ^{136}**Xe** can be used to study Double Beta Decay

Natural abundance of ^{136}Xe : **8.9%**

We need **90 % enrichment**. Then we have 80 % of ^{136}Xe

Only known vendor: JSC “PA ECP”

Price: about **30 k$ / kg**

For 200 kg of enriched ^{136}Xe we have to provide
2.4 ton of natural xenon

Scaling up to 1 ton

Easiest solution make 5 modules with 200 kg each.

Water shield in JinPing Lab is sufficiently large!

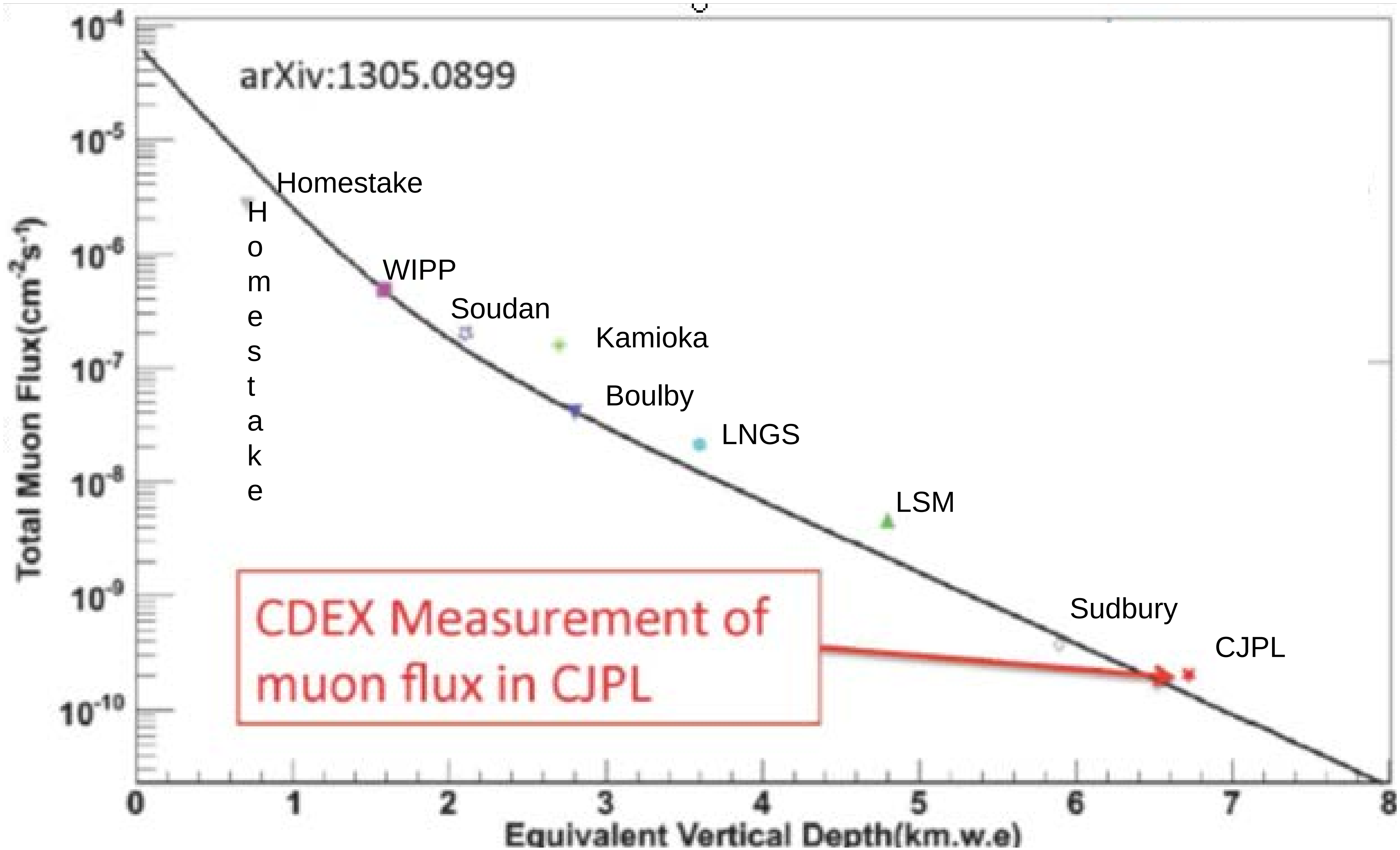
Future modules can be improved. Background, Read Out, HV Design, higher pressure, etc.

Advantage: If one module has problems, data taking can continue during repairs.

Disadvantage: Some xenon lost in additional fiducial cuts

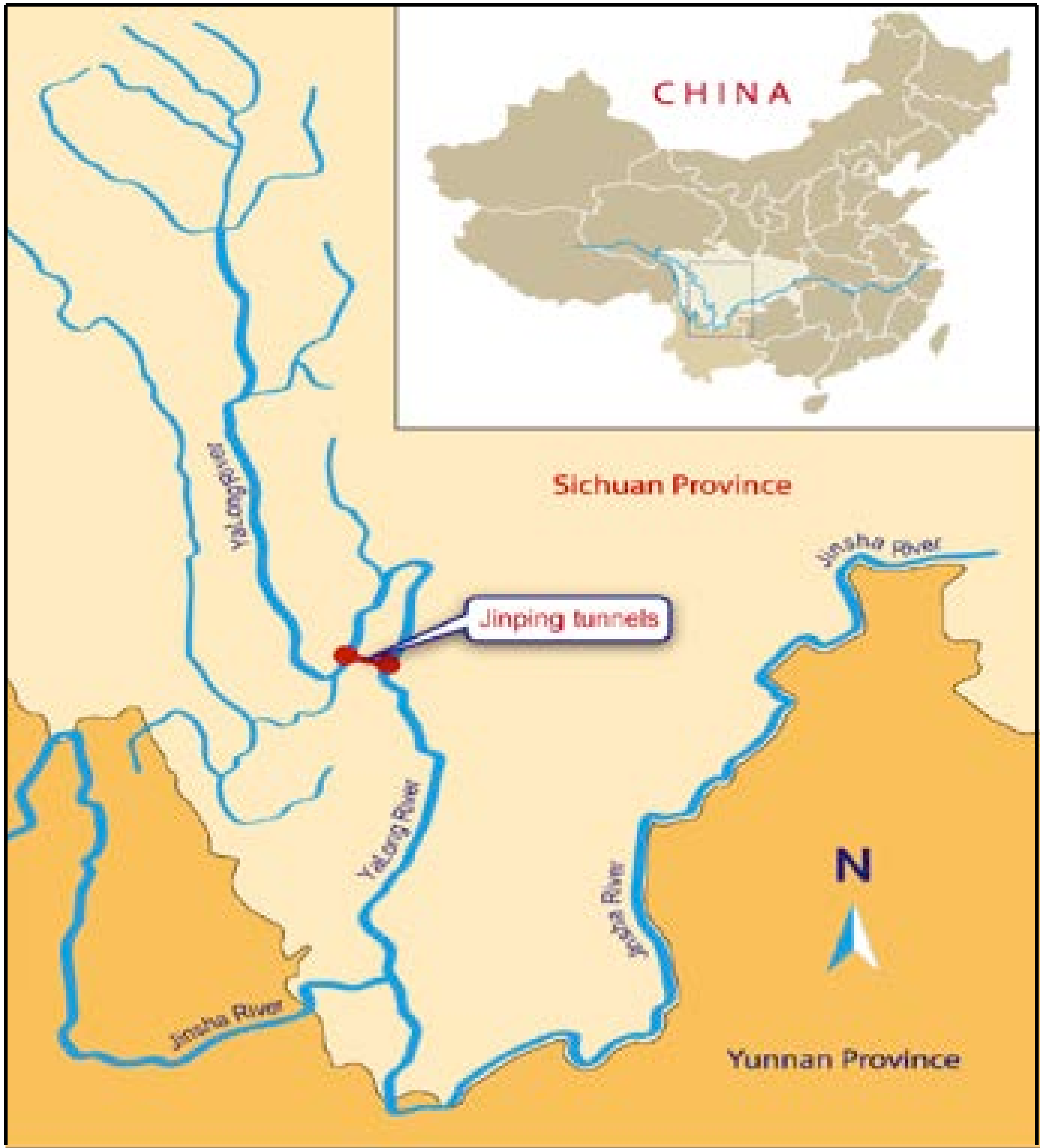
With more experience may be a single larger detector will be preferable.

Muon Flux at CJPL



Muon Veto shield will not be necessary

The CJPL Laboratory



~**2400 m** overburden

Deepest underground lab in operation

6720 mwe ~57 muon/yr/m^2

New much larger lab under construction

Low radioactivity marble rock

Easy access – located in the middle of a 18 km tunnel, not a public road

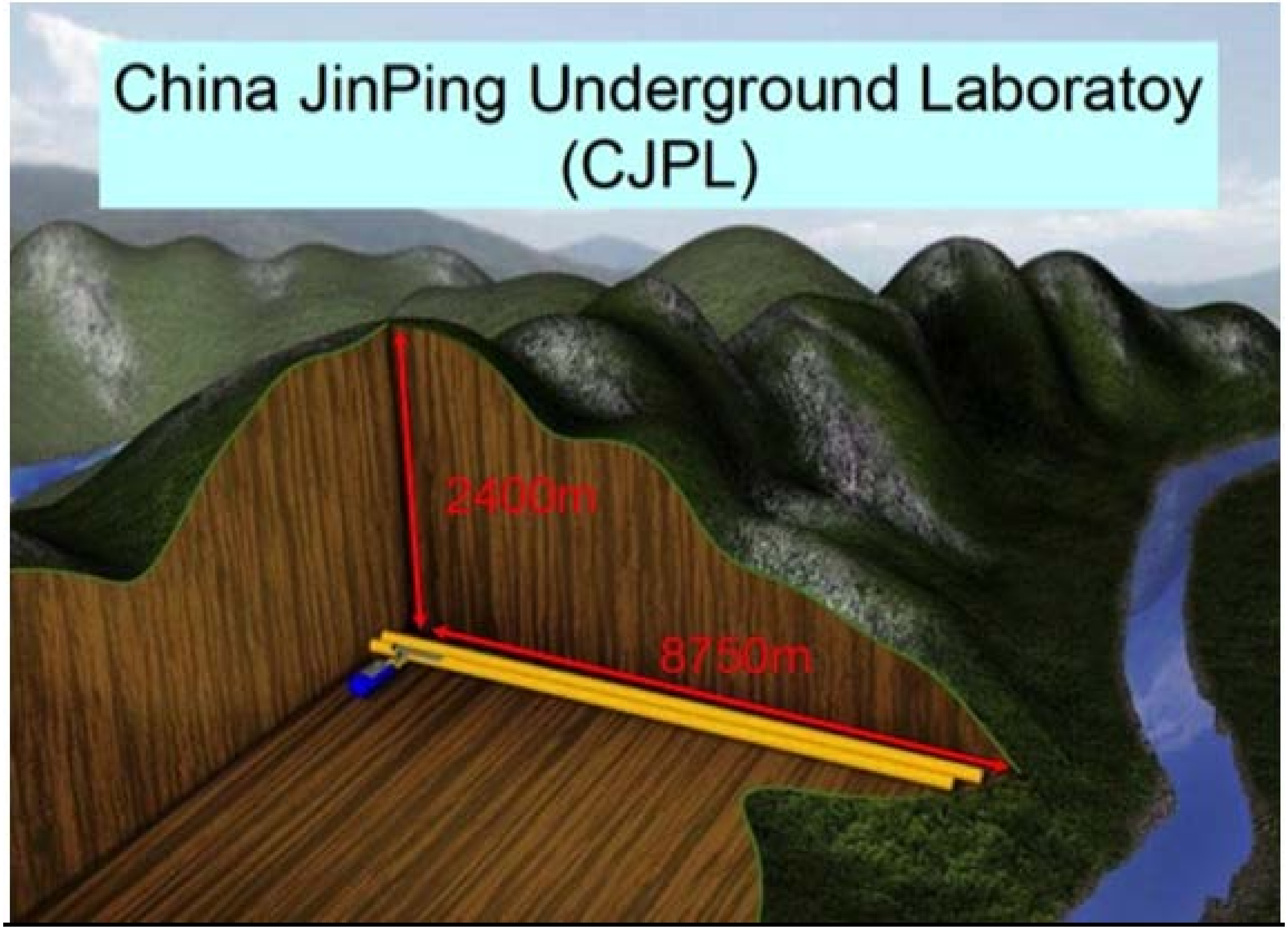
The CJPL Laboratory

Depth and
Rock QUaliy

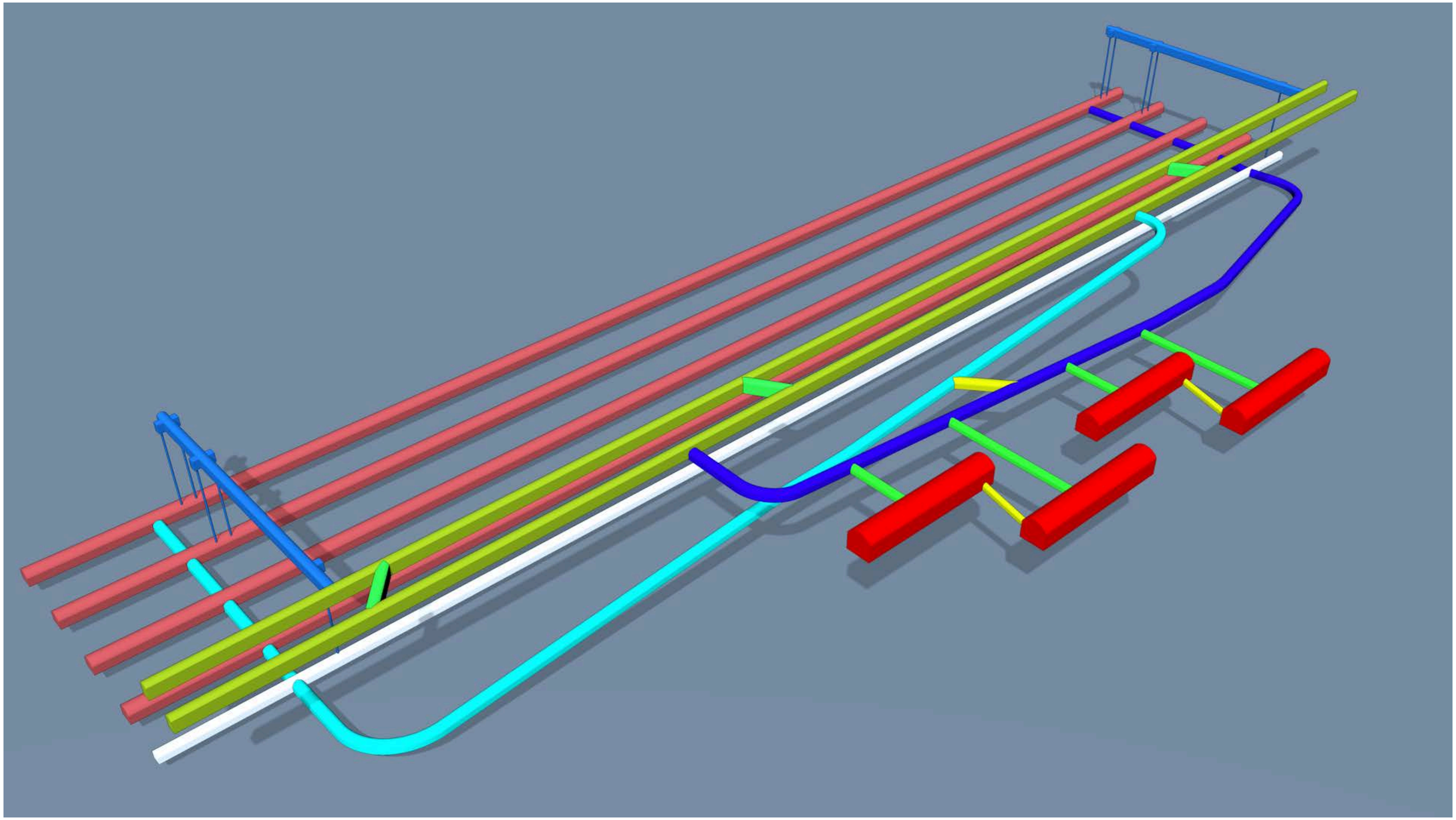
facility	depth [mwe]	μ flux [events/m^2/yr]	rock	^{238}U [Bq/kg]	^{232}Th [Bq/kg]	^{40}K [Bq/kg]
Jinping (PandaX)	6,800	60	marble	1.8 ± 0.2	< 0.27	< 1.1
Homestake (LUX)	4,300	950	rhyolite	100	45	900
Grand Sasso – Hall B (XENON)	3,500	8,030	dolomite	5.2	0.25	4.9

The CJPL Laboratory

The CJPL Laboratory



Preliminary Design of CJPL-II



	CJPL-I	CJPL-II
Rock Work	4000 m^3	131000m^3
Electric Power	70 kVA	1000 kVA
Fresh Air	2400 m^3/h	40000 m^3/h

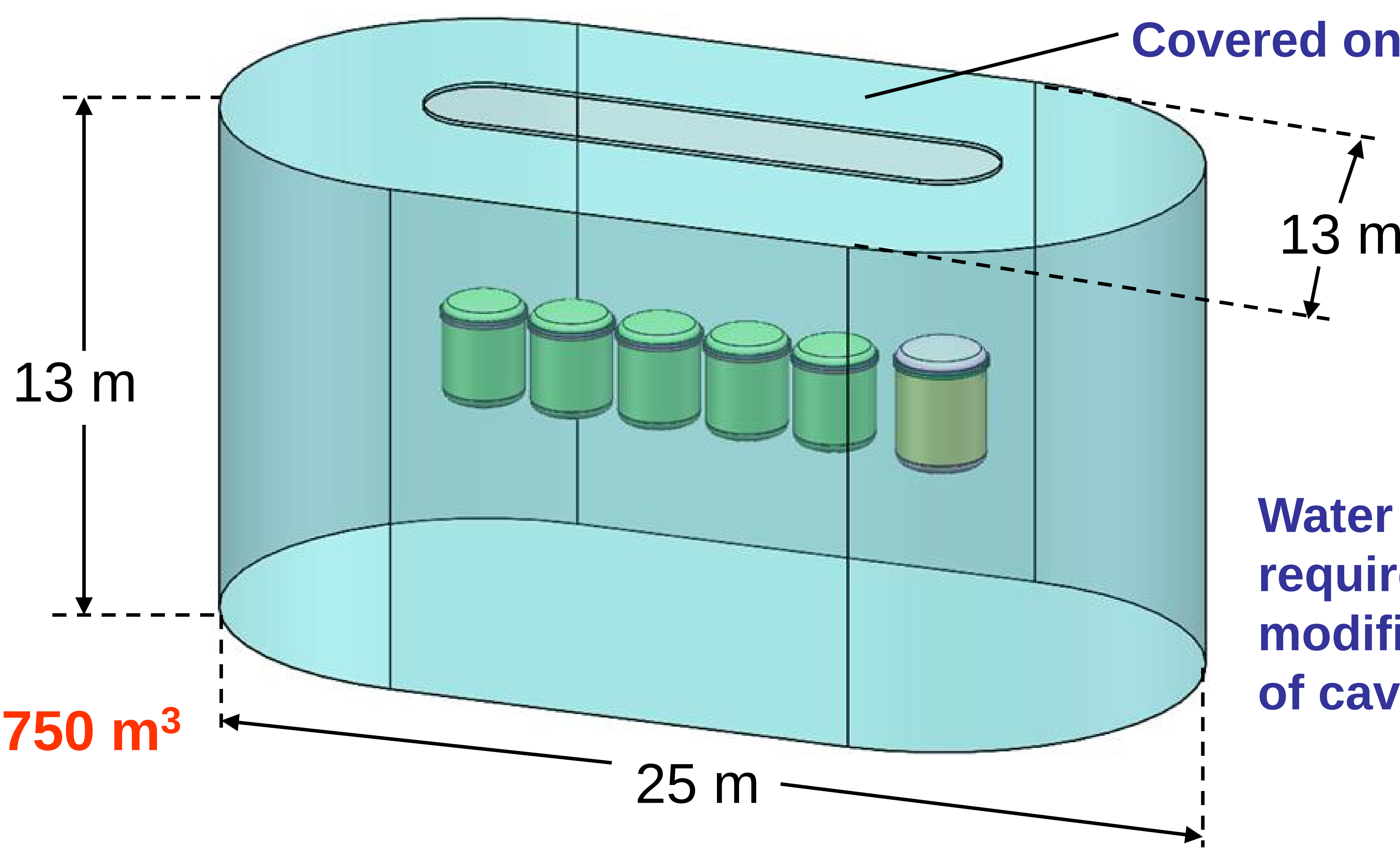
Experimental Hall

Water Shield for PandaX III

Water Shield located in ground, like swimming pool

Size sufficient for 5 modules of PandaX III. (+DM detector?)

Water cleaned and (U / Th) removed. **> 5 m water** on all sides



3750 m^3

Water shield required modification of cavern

Schedule

Aggressive schedule to be competitive
with next generation DBD experiments

Development and tests continuing
Design later in 2016
Simulation study continuing
Laboratory Construction to be finished end 2016
digging of water shield progressing
Installation starting in late 2016
Commissioning during 2017

Present Collaborators

China :	SJTU	Gas System, TPC
	USTC	Electronics, MicroMegas
	PKU	Background Counting
	ZSU	Background Counting, Simulation
	CCNU	Alternative Electronics
US :	Maryland	
	LBL	Alternative Electronics, Vessel
	Princeton	Radioactivity
Russia :	MEPHI	Xe136, Vessel
Spain :	Zaragoza	Micromegas
France :	CEA	Electronics

Collaboration not yet fully set up.
We are looking for additional help.