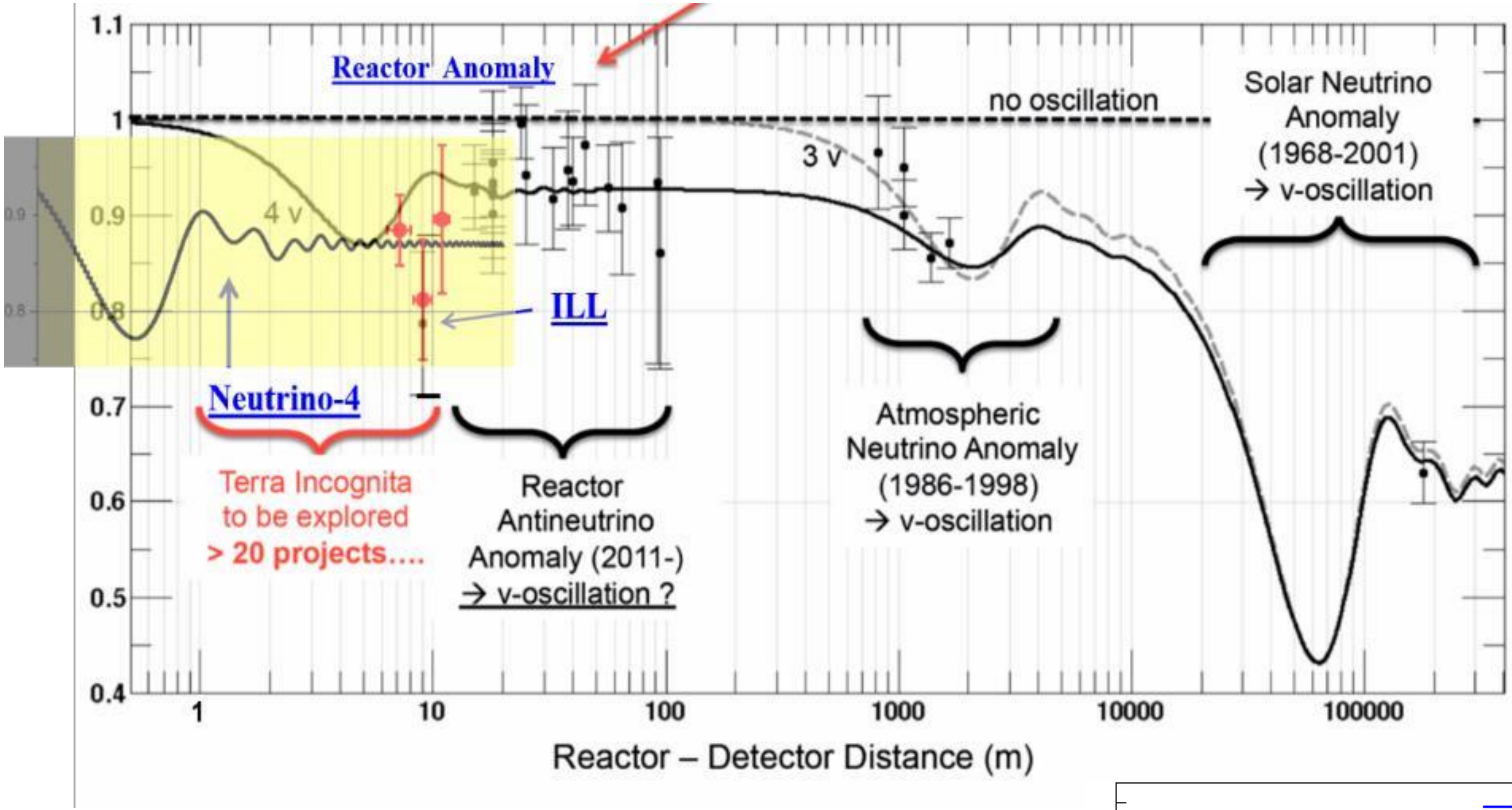
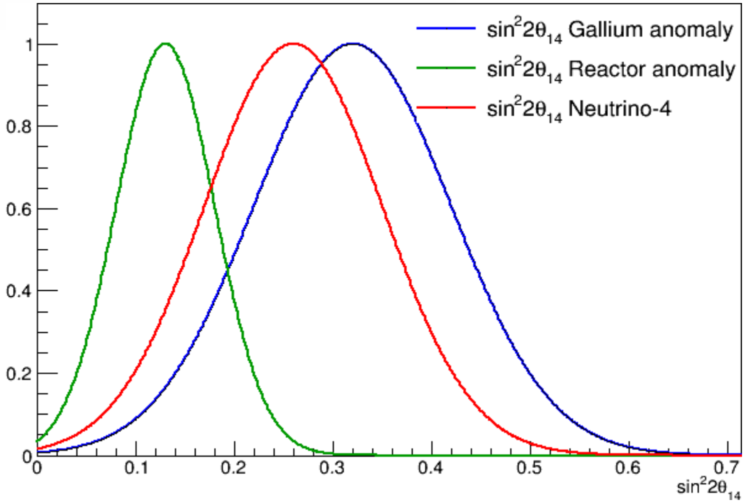
Reactor antineutrino anomaly

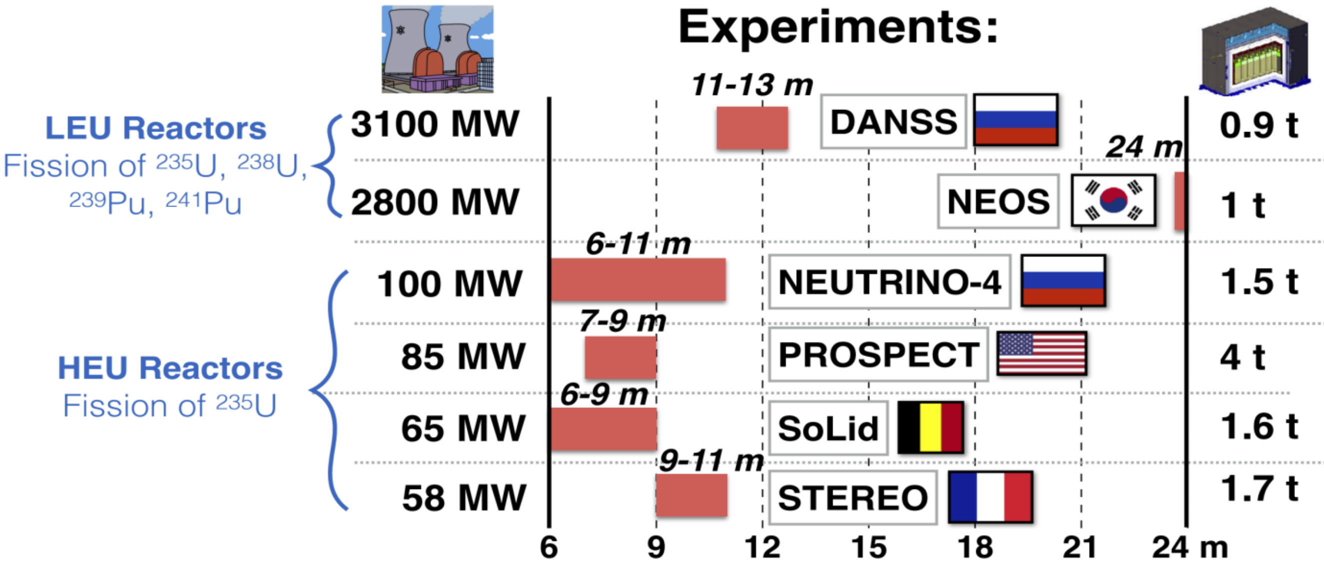


Observed/predicted averaged event ratio :
R=0.938 ± 0.23 (2.7σ)

- **Value of $sin^2(2\theta_{14})$**
  - **Neutrino-4 : 0.26 ± 0.09 (2.9σ)**
  - **Gallium : 0.32 ± 0.10 (3.2σ)**
  - **Reactor : 0.14 ± 0.05 (2.6σ)**
  - **Combined : 0.19 ± 0.04 (4.6σ)**



SBL Reactor Neutrino Experiments



(chart courtesy of B. Roskovec)

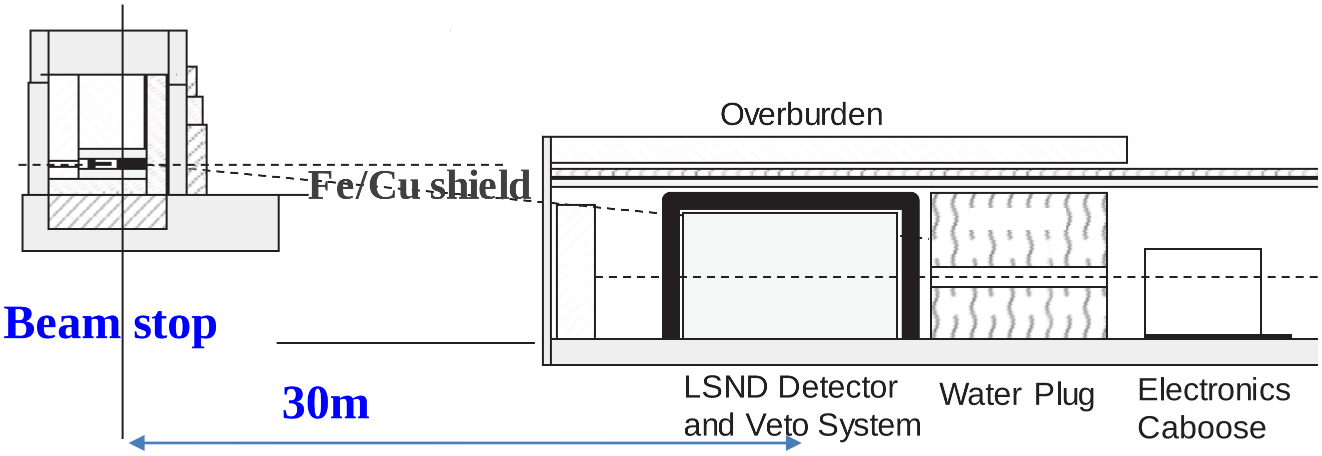
+ (mini-)CHANDLER, NuLAT

- **Search for sterile neutrino, L~O(10 m) sensitive to large Δm^2**
- **Reactor Antineutrino Anomaly**

Experiment	Solid	Neutrino-4	PROSPECT (II)	STEREO	DANSS	NEOS	JUNO-TAO
Power [MW]	80	100	85	58	3,100	2,800	4,600
Baseline [m]	6 – 9	6 – 12	7 – 9	9 – 11	10 – 13	24	~44
Detector mass [t]	1.6	1.5	4	1.7	0.9	1	2.8
Detector technology	Seg. ^{6}Li-PS	Seg. Gd-LS	Seg. ^{6}Li-LS	Seg. Gd-LS	Seg. Gd-PS	Unseg. Gd-LS	Unseg. Gd-LS
Energy resolution	14%	25%	4.5%	7%	34%	5%	< 2%
Overburden [mwe]	8	3.5	0.5	15	50	20	10
S/B	1/3	0.54	1.4	1.1	58	>20	10

Liquid Scintillator Neutrino Detector (LSND) : $\bar{\nu}_{\mu} \to \bar{\nu}_{e}$

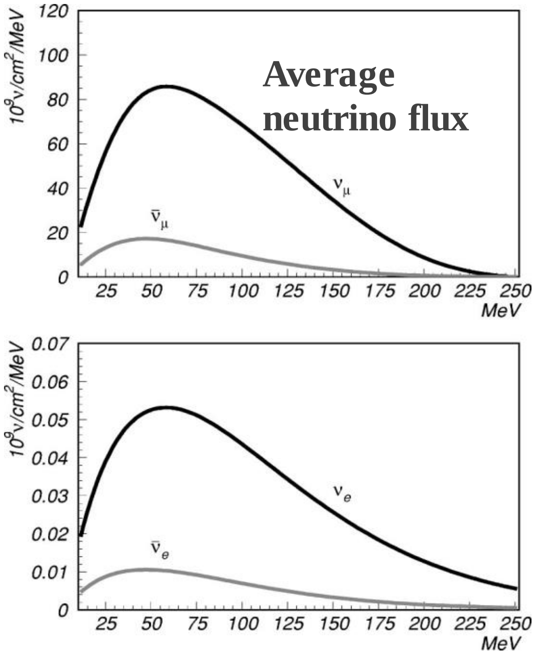
798 MeV proton beam (~1mA)+30cm H_2O/Low-Z target → many $\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
$\bar{\nu}_\mu$ oscillate to $\bar{\nu}_e$ and reaction $\bar{\nu}_e p \to e^+ n$
(Q = – 1.804 MeV)



- **cylindrical tank 8.3 m long by 5.7 m in diameter.**
- **1220 8-inch Hamamatsu PMTs covered 25% of the area with photocathode.**
- **Filled with 167 metric tons of liquid scintillator consisting of mineral oil and 0.031 g/l of b-PBD.**
- **This low scintillator concentration allows the detection of both Cherenkov light and scintillation light and yields an attenuation length of more than 20 m for wavelengths greater than 400 nm.**
- **A typical 45 MeV electron → produced a total of ~1500 photoelectrons, of which ~280 photoelectrons were in the Cherenkov cone.**
- **Signal : both the e^+ and the 2.2 MeV γ from the reaction $np \to d\gamma$.**
- **PMT time and pulse-height signals → σ_{pos} ~14 cm, σ_{pos} ~12°, σ_E ~7% at the Michel endpoint of 52.8 MeV.**
- **Cosmic veto → reduce rate 10kHz to 50Hz**
- **the visible energy was required to be greater than 15 MeV in order to eliminate ^{12}B β decays from cosmic ray μ^- that stop and capture in the oil.**

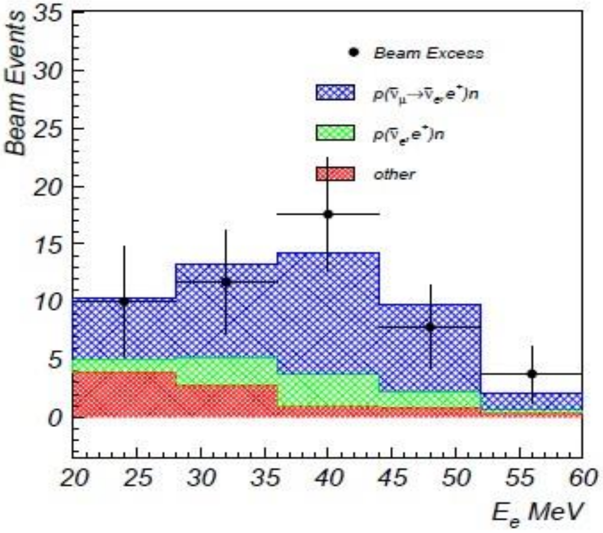
Accelerator based neutrino physics : LSND anomaly

Total data : 28896C of protons on the production target



[PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

$\bar{\nu}_\mu \to \bar{\nu}_e$ $L \simeq 30\,\text{m}$ $20\,\text{MeV} \le E \le 60\,\text{MeV}$



- Well known source of $\bar{\nu}_\mu$:

  $$\mu^+ \text{ at rest} \to e^+ + \nu_e + \bar{\nu}_\mu$$

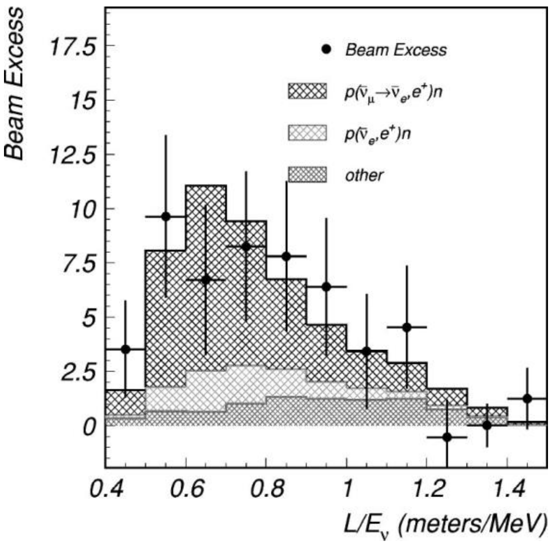
- $\bar{\nu}_\mu \xrightarrow[L \simeq 30\,\text{m}]{} \bar{\nu}_e$
- Well known detection process of $\bar{\nu}_e$:

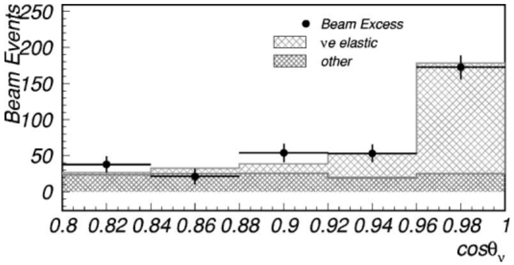
  $$\bar{\nu}_e + p \to n + e^+$$

- But signal not seen by KARMEN with same method at $L \simeq 18\,\text{m}$

[PRD 65 (2002) 112001]

Nominal $\approx 3.8\sigma$ excess $\Delta m^2 \gtrsim 0.2\,\text{eV}^2$ $(\gg \Delta m^2_{\text{A}} \gg \Delta m^2_{\text{S}})$





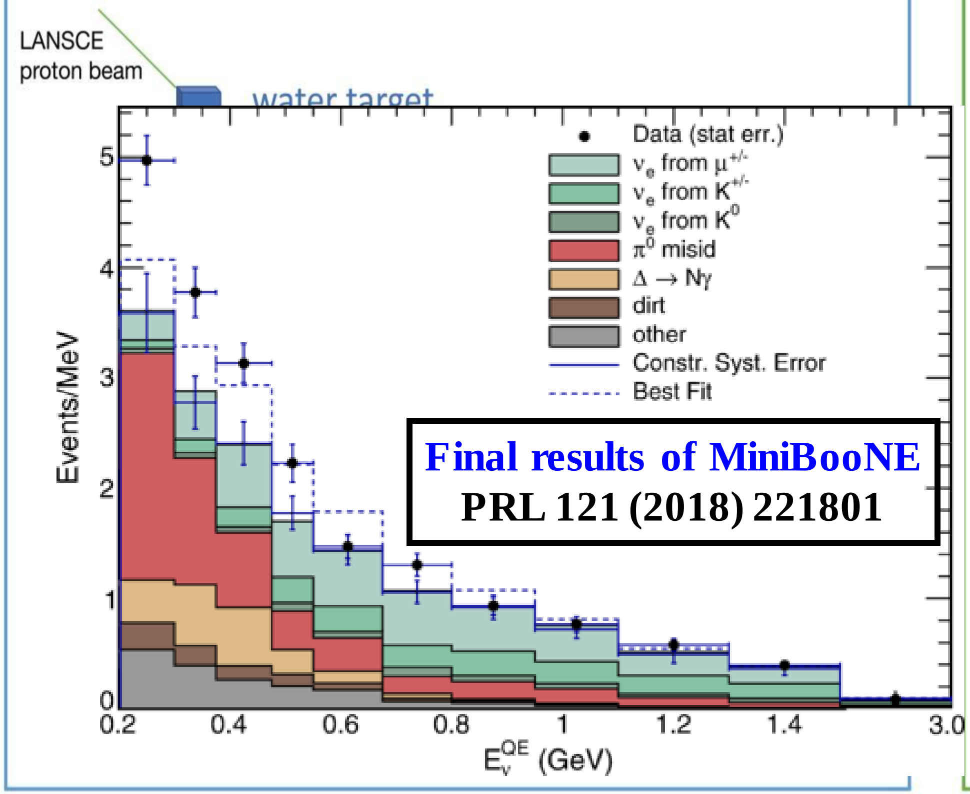
Best fit point $\left(sin^2(2\theta), \Delta\text{m}^2\right) = \left(0.003, 1.2\ \text{eV}^2\right)$:
expect 89 events and observation $87.9 \pm 22.4 \pm 6.0$

MiniBooNE to verify LSND result

LSND (1993-1998)

0.8 GeV proton beam

Decay At Rest neutrino flux

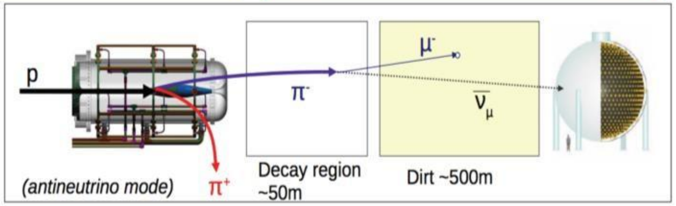


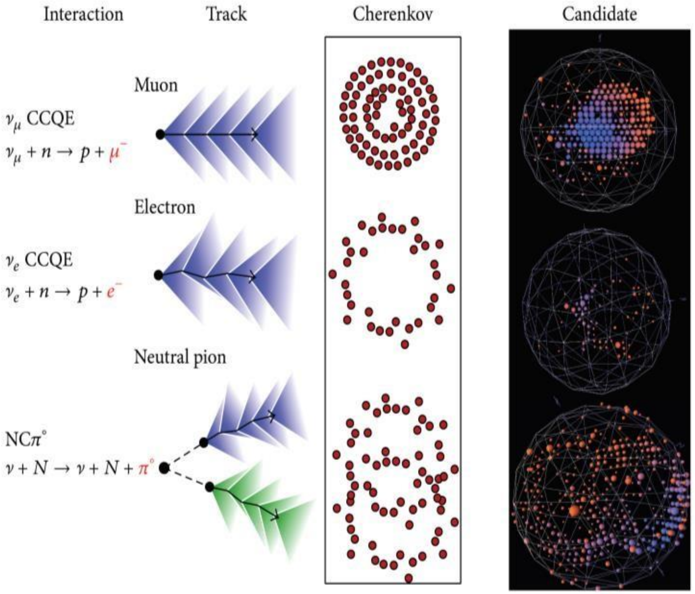
Final results of MiniBooNE
PRL 121 (2018) 221801

MiniBooNE (2002-2019)

8 GeV proton beam

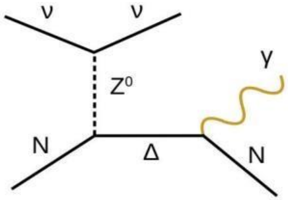
Decay In Flight beam

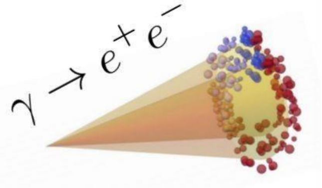




Different systematics. Same L/E baseline.

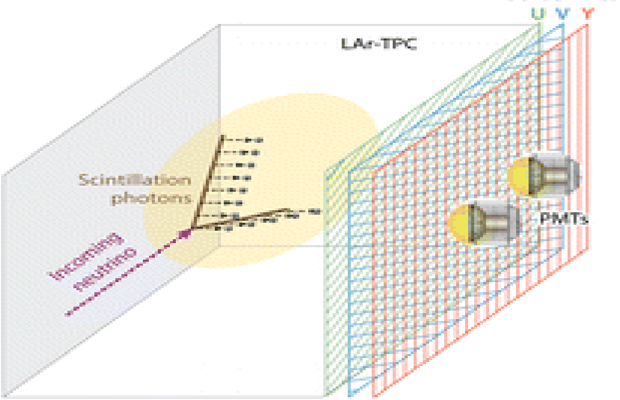
MiniBooNE support LSND result, but others do not → dedicated short baseline experiment at FNAL with three detector

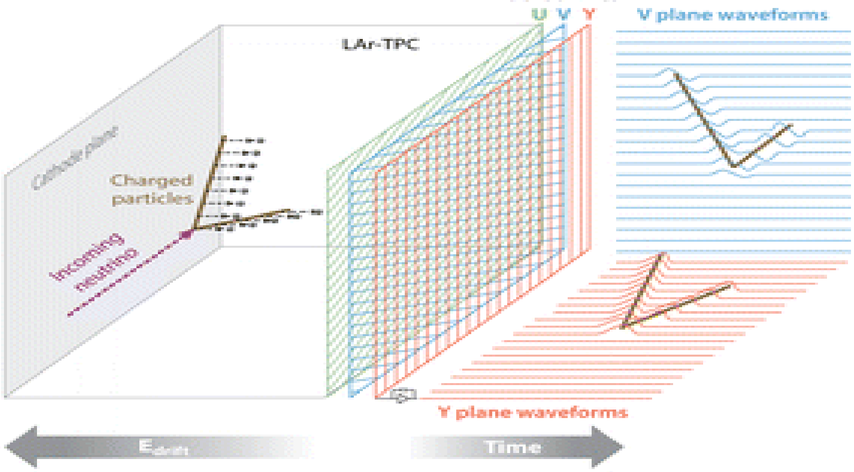




LAr technology

- First proposed by Prof. C. Rubbia in 1977 just after the concept of TPC by Dave Nygren in 1970.
- MiniBooNE/LSNB anomaly is from electron signal, which is indistinguishable from photon backgrounds of different sources,
  - misidentification of π^0 as an electron-like event,
  - ν_e from kaon and muon decays in the beamline,
  - single-photon production via the resonant process $\Delta \rightarrow N\gamma$, and
  - single-photon events from neutrino interactions in the dirt and material surrounding the detector.
- $\Delta \rightarrow N\gamma$ has attracted particular interest because it does not come directly from measurements but rather is based on nonperturbative theoretical calculations
- e-γ discrimination capability in LArTPC is important to understand the signal/background nature of the ν_e-like event excess observed by MiniBooNE
  - Identification in the gap between photon conversion vertex and the neutrino interaction vertex
  - Measuring the dE/dx in the first few cm of electron of photon EM shower

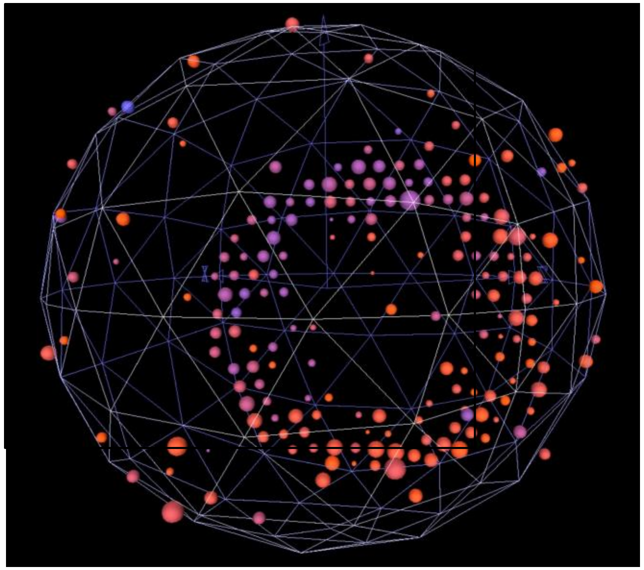


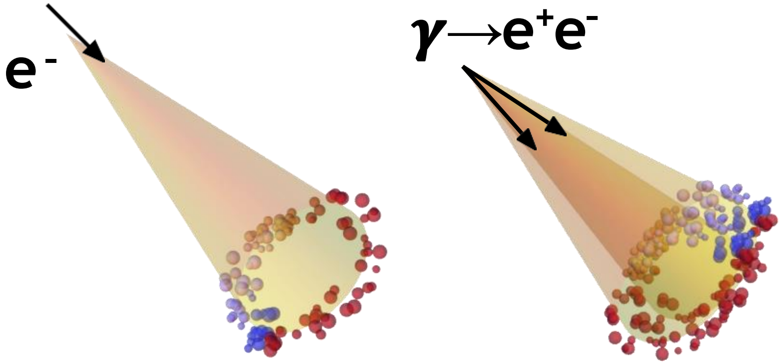


What can LArTPCs do that MiniBooNE couldn’t?

Electrons or Photons?

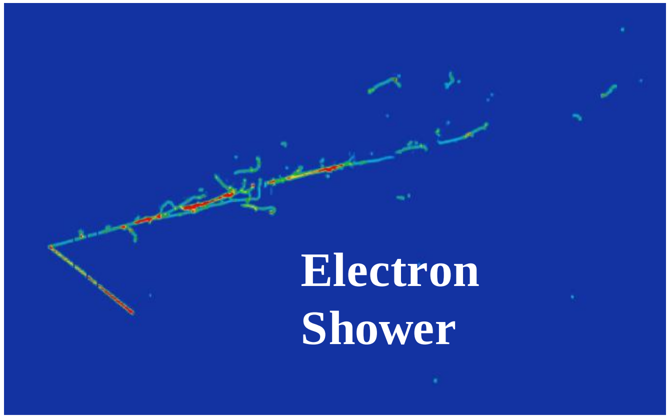
Electron Cherenkov ring event in MiniBooNE

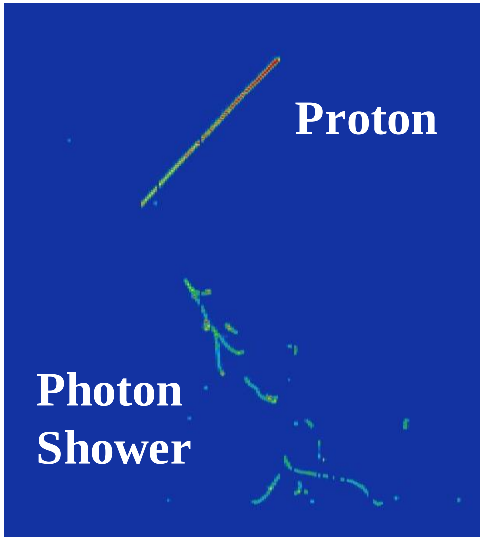




LArTPC’s give us **fully active calorimeter** alongside **high-resolution tracking**

CC ν_e + 1 proton candidate data event

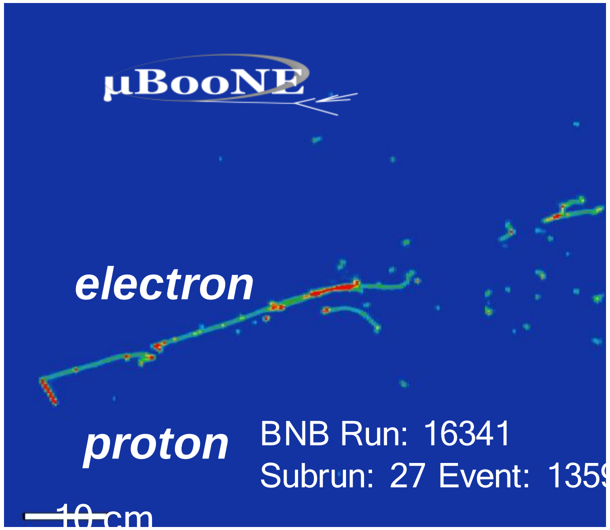




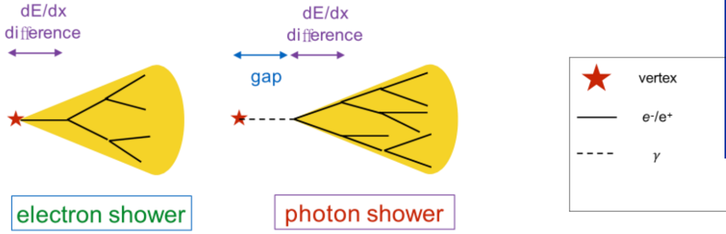
NC single photon + 1 proton candidate data event

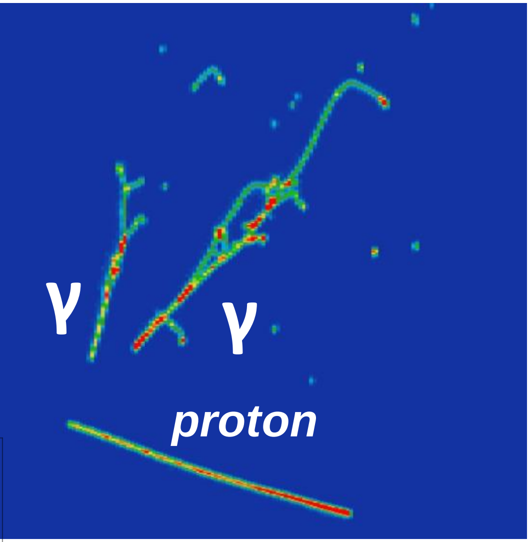
Allows for strong photon ↔ electron separation and particle identification across whole SBN program!

e/γ separation in LAr detector

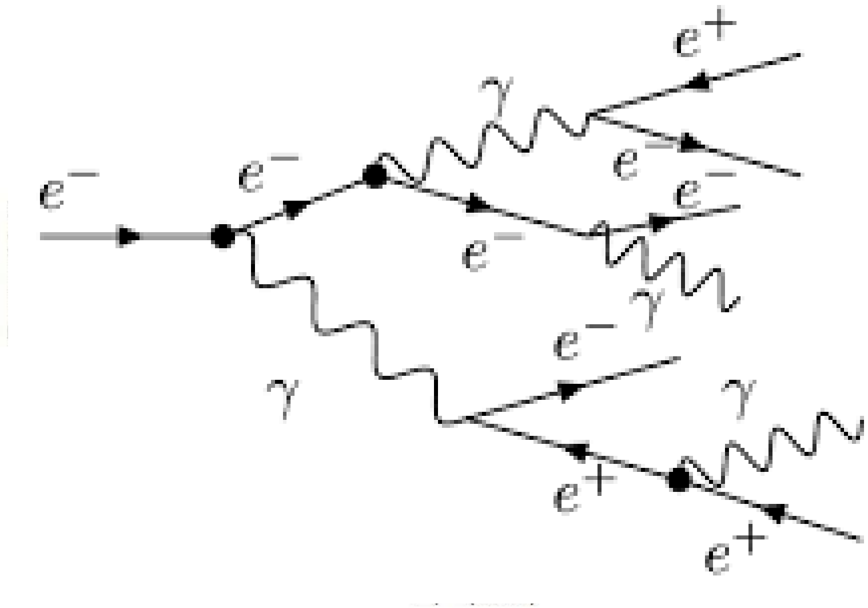


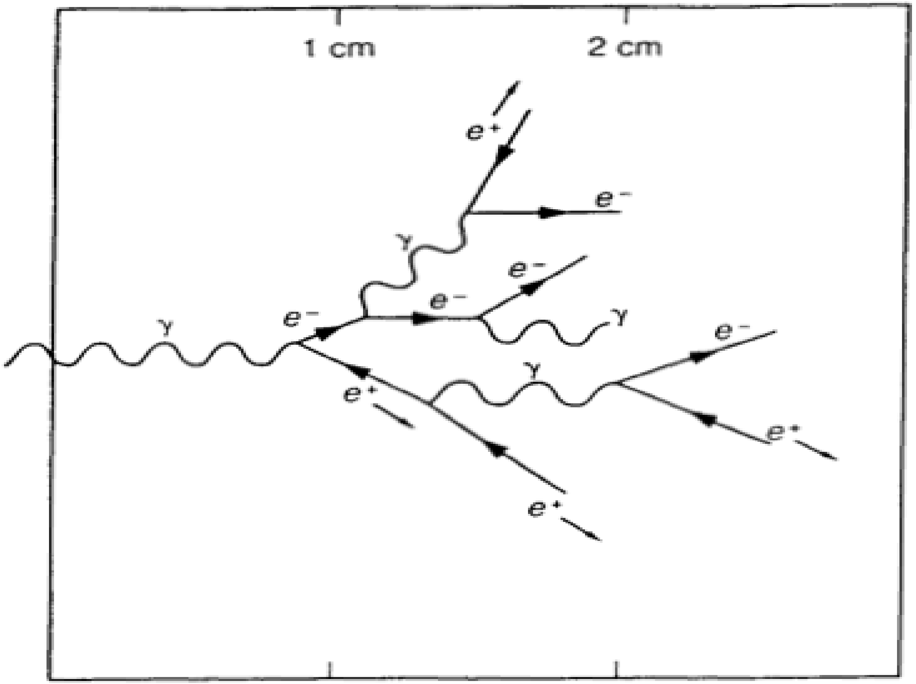
- **Gap between primary interaction of trajectory of gamma signal**
- **In the first radiation length of the observed trajectory, the average signal for γ is double than electrons.**



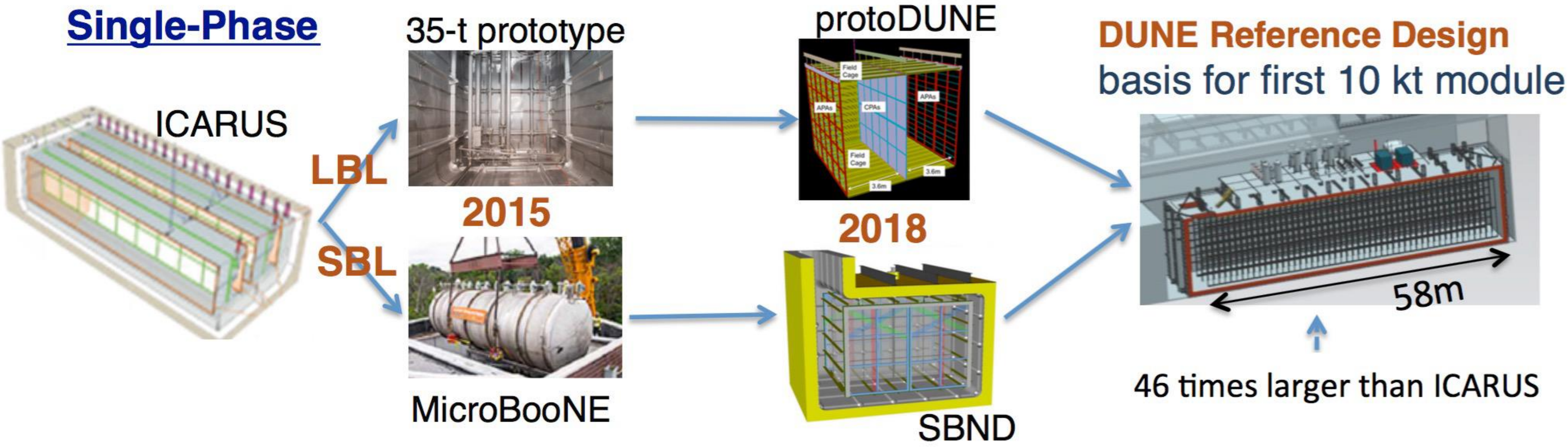


MiniBooNE, PRL 121, 221801 (2018)





Development of LArTPC for Neutrino Experiments

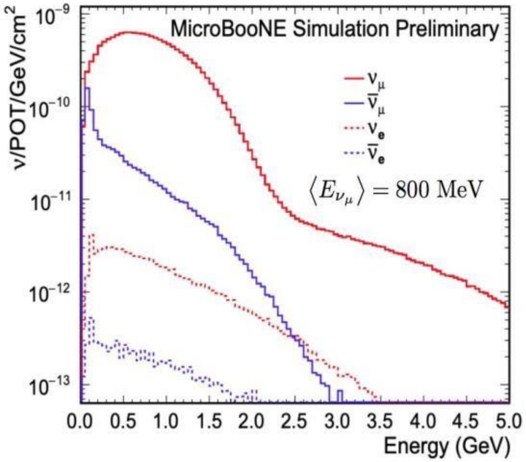


Warm readout → Cold Analog → Cold Digitisation and Multiplexing

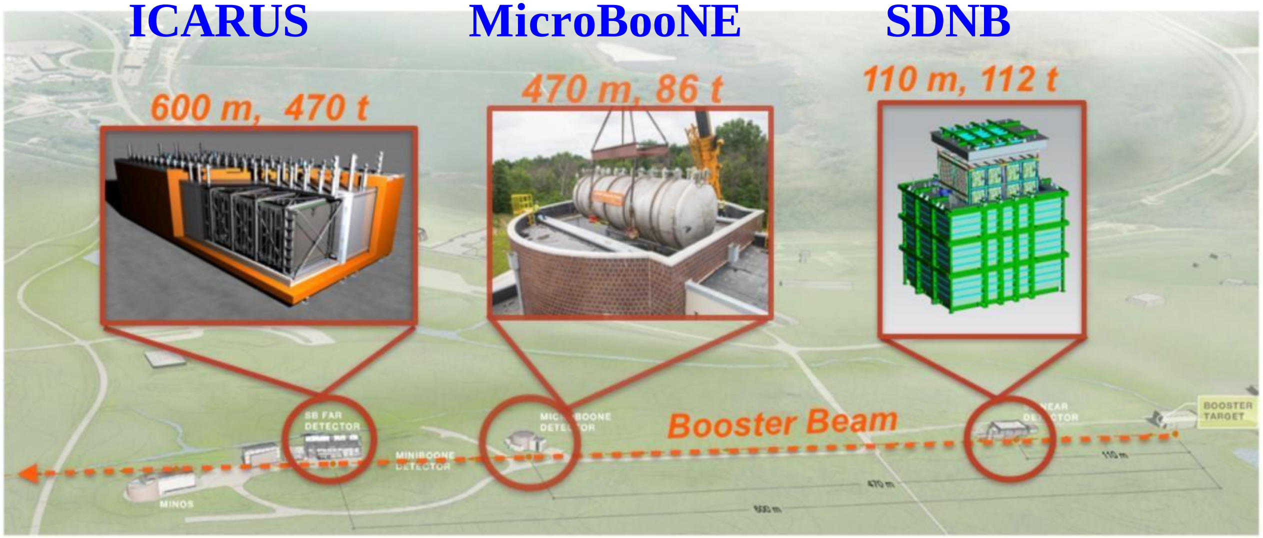
- **Cold Electronics is the key technology for Large LArTPC**
  - **"The cold electronics that it remains an optimal solution for very large TPC"**
    - **Cited from Veljko Radeka, et al. Cold Electronics for "Giant" Liquid Argon Time Projection Chambers. 1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (GLA2010)**
  - **Tremendous effort of many institutes in the DUNE collaboration towards LArTPC instrumented with cold electronics**

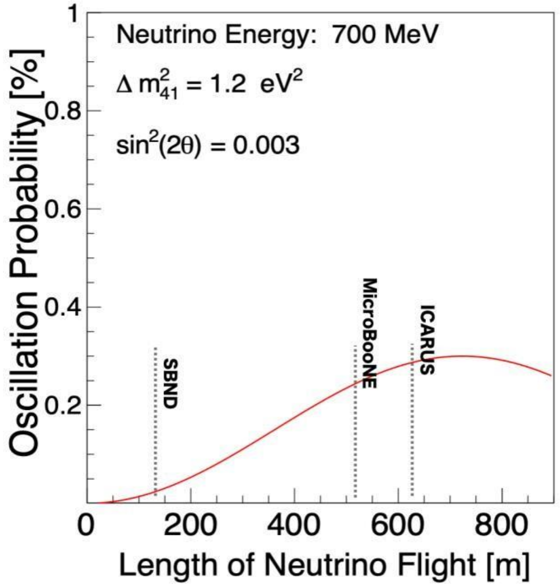
FNAL Short Baseline Program (SBN)

- LArTPC detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations measuring both appearance and disappearance channels with three detectors
- Measure neutrino cross sections on liquid argon
- Same detector technology and neutrino beamline: reducing sys
to the % level
  - A detection technique providing an excellent neutrino identi
backgrounds
  - 3m concrete overburden to absorb >99% photon/hadron fro
  - Program aimed at definitely solving the “sterile neutrino puzzle” by exploiting: the well characterized Final States

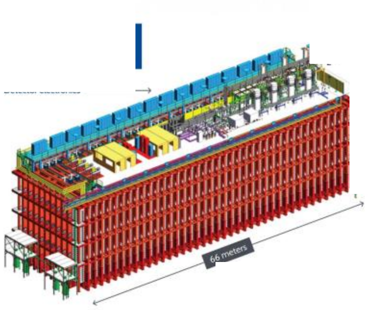


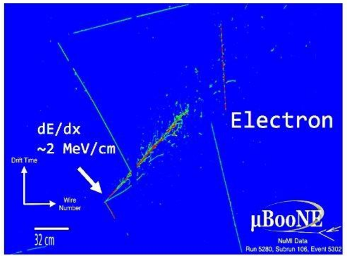
ICARUS **MicroBooNE** **SDNB**





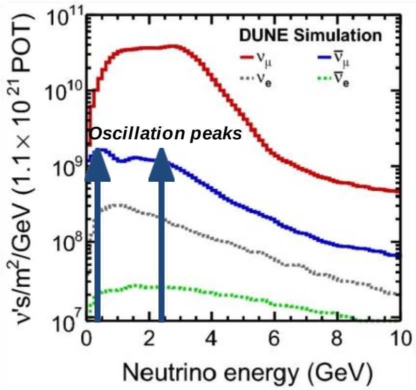
One-slide DUNE



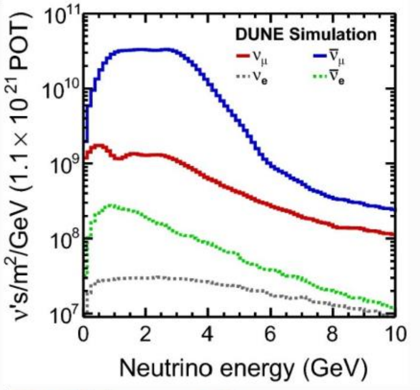


Broad band neutrino and antineutrino beam

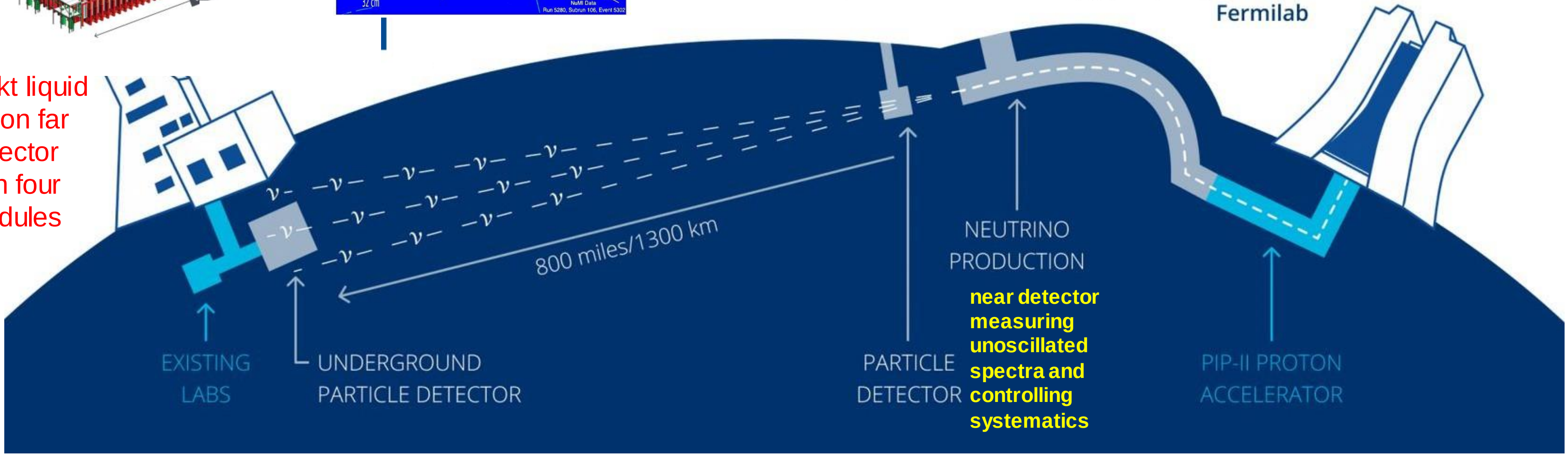
Neutrino mode



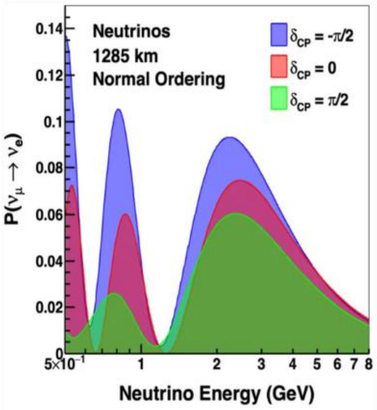
Antineutrino mode

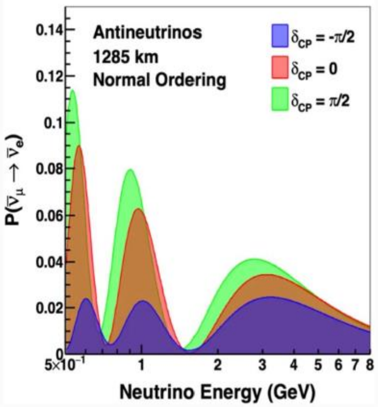


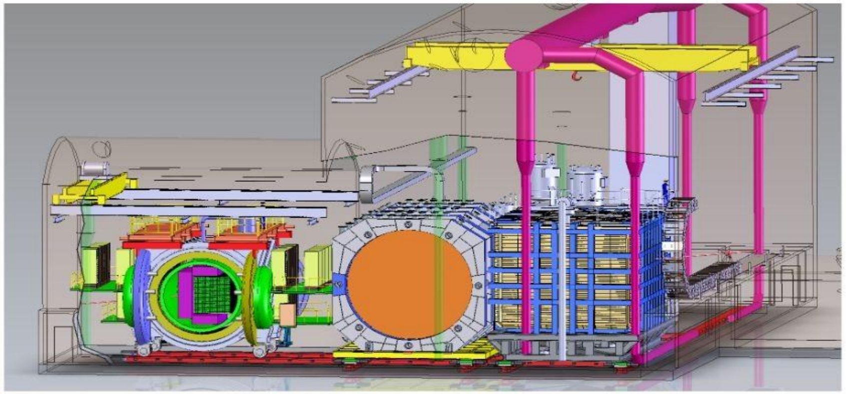
70 kt liquid argon far detector with four modules



near detector measuring unoscillated spectra and controlling systematics

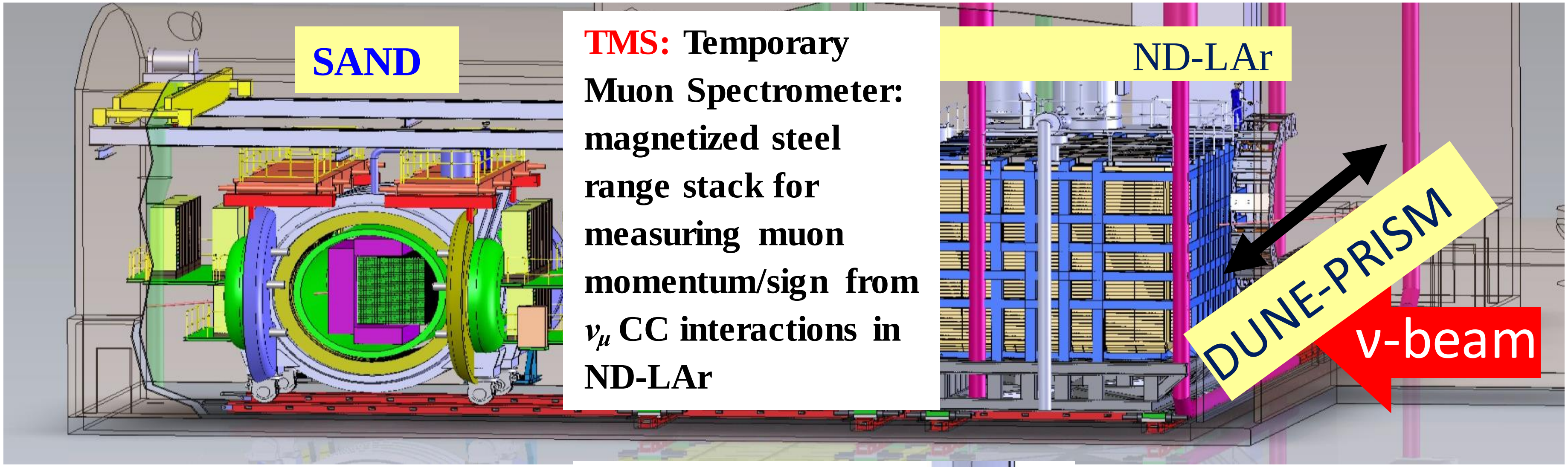




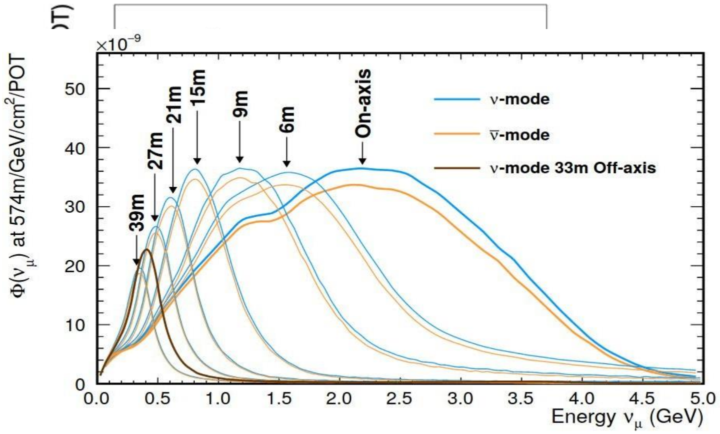


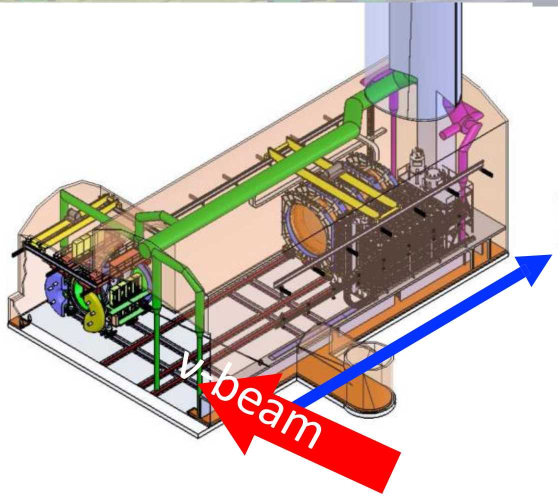
DUNE Near detectors

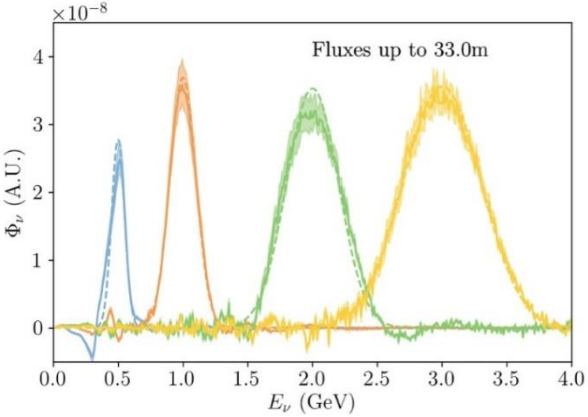
- 3 components: 2 of which (ND-LAr, ND-GAr) move off-axis giving different flux
  - ND-LAr: Liquid Argon TPC with optically isolated modular pixelated readout (50t)
  - ND-GAr: High Pressure gas TPC (1t) + ECAL + magnet
  - SAND: 3D plastic scintillator target (8t) + trackers + ECAL + magnets



TMS: Temporary Muon Spectrometer: magnetized steel range stack for measuring muon momentum/sign from ν_μ CC interactions in ND-LAr

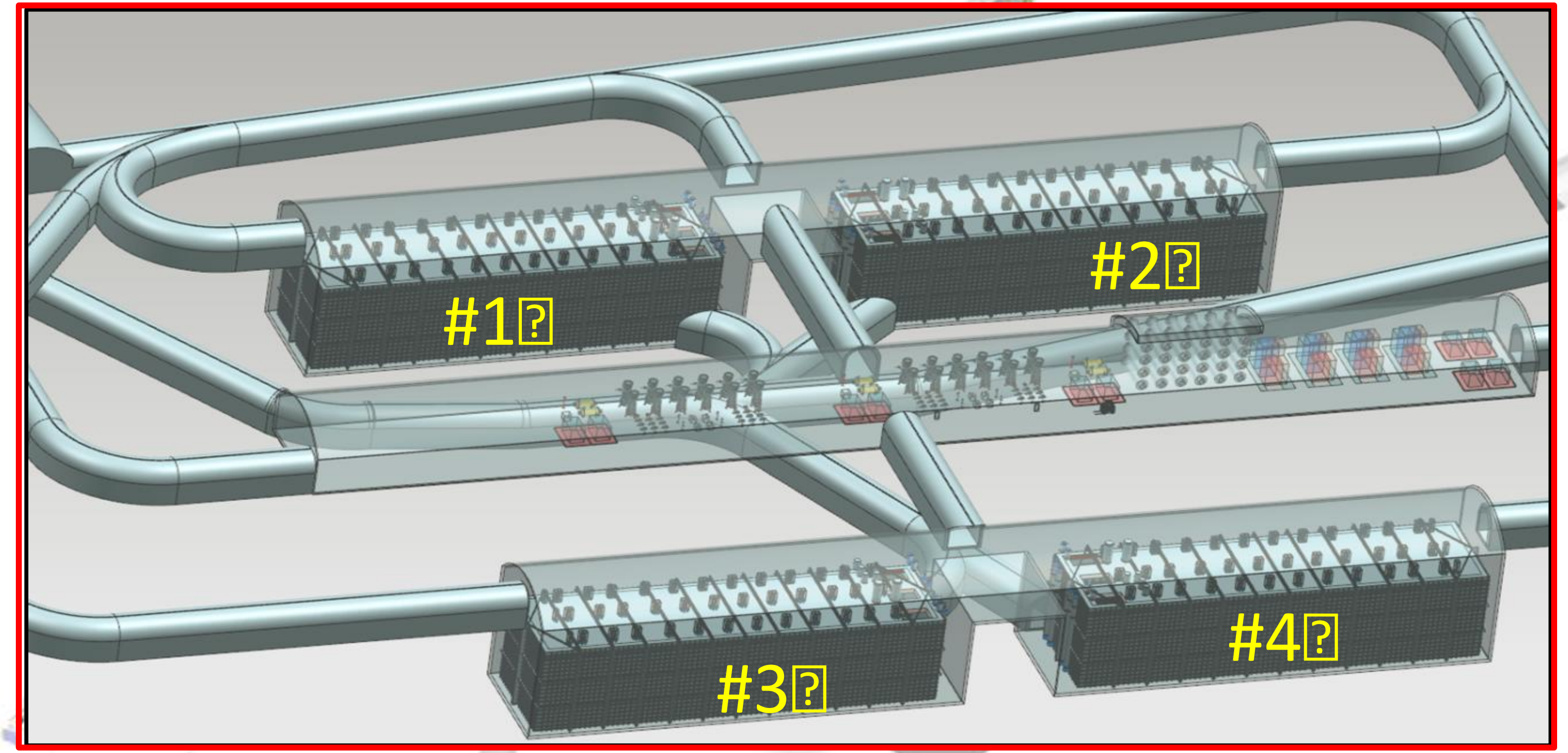






TDR Far Detector Strategy

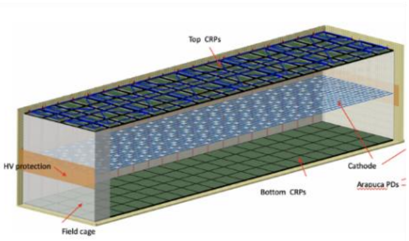
- TDR describes 4 identically sized cryostats: 2 single phase (SP) + 1 dual phase (DP) + 1 “module of opportunity”, each about 17 kt
- The full experiment, including Near Detector and 2.4 MW beam will be needed to reach the P5 physics goal.

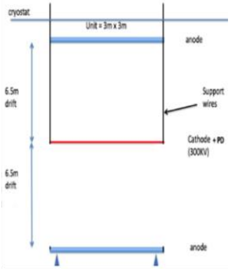


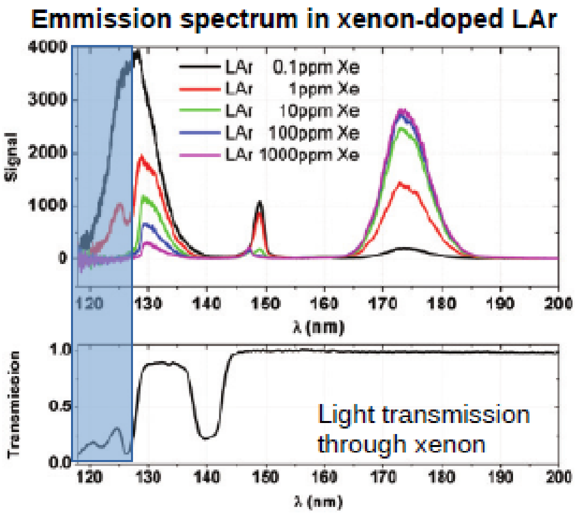
- 40 kT LAr TPC:
  - Modular approach: 4 caverns, 4 independent 10 kT (fiducial) modules
  - Approach allows: Staged build & Flexibility to exploit advancements in LAr TPC technique

Xe doped LAr to enhance λ_{att}

- **In the large scale LAr detector (neutrino experiment), scintillating photon moves more than 5-6m, whereas λ_{att} in pure LAr is only ~1m.**

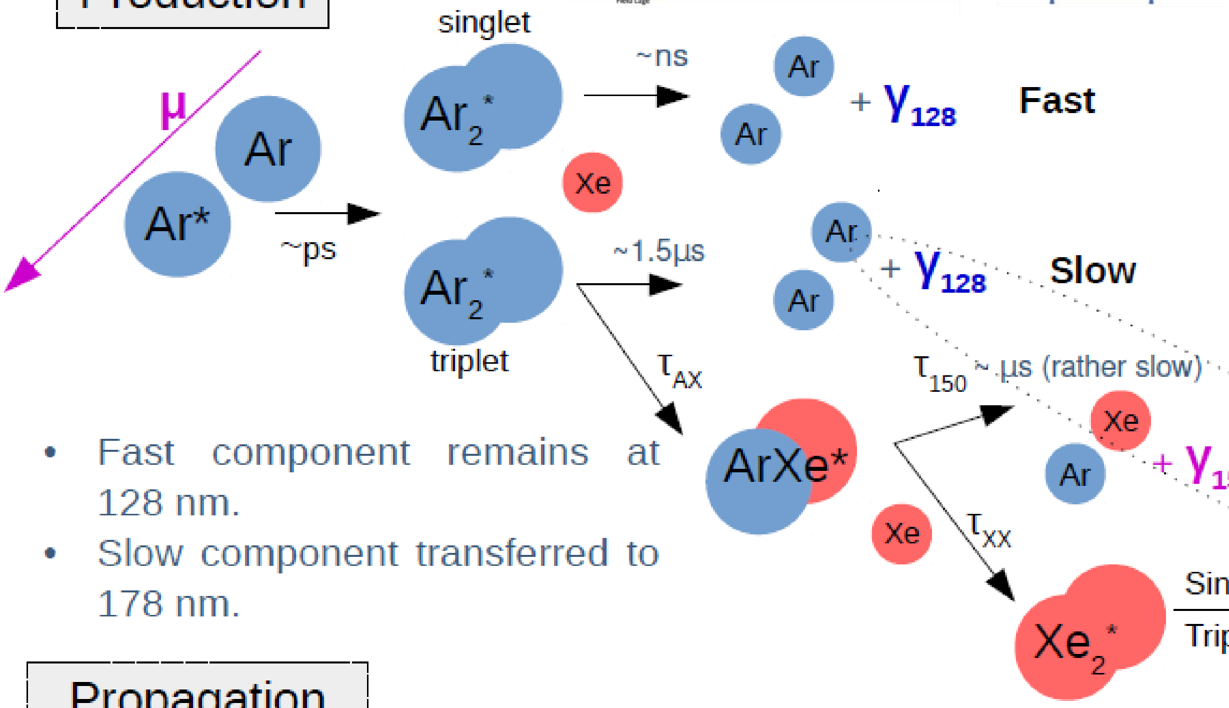






[3] A. Neumeier et al 2015 EPL 109 12001

Production



+ γ_{150} (at low ppm)

Xe
Xe
+ γ_{178}

- Fast component remains at 128 nm.
- Slow component transferred to 178 nm.

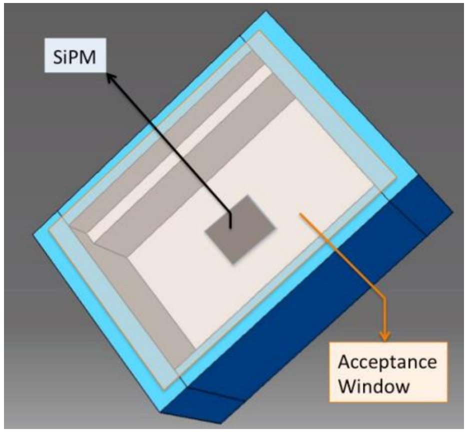
Propagation

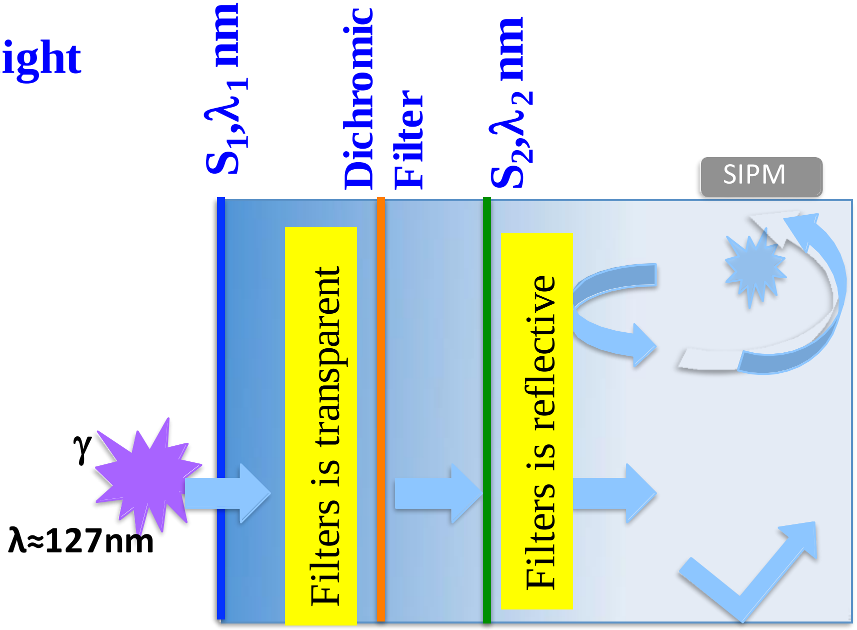
- Xenon absorbes the 128 nm photons during propagation, no absorption at 178 nm and 150 nm photons [3].
- Larger Rayleigh scattering length for 178 nm photons (~9m vs 1m for 128 nm photons) → More collection at large distances [4].

[4] M. Babicz et al 2020 JINST 15 P09009

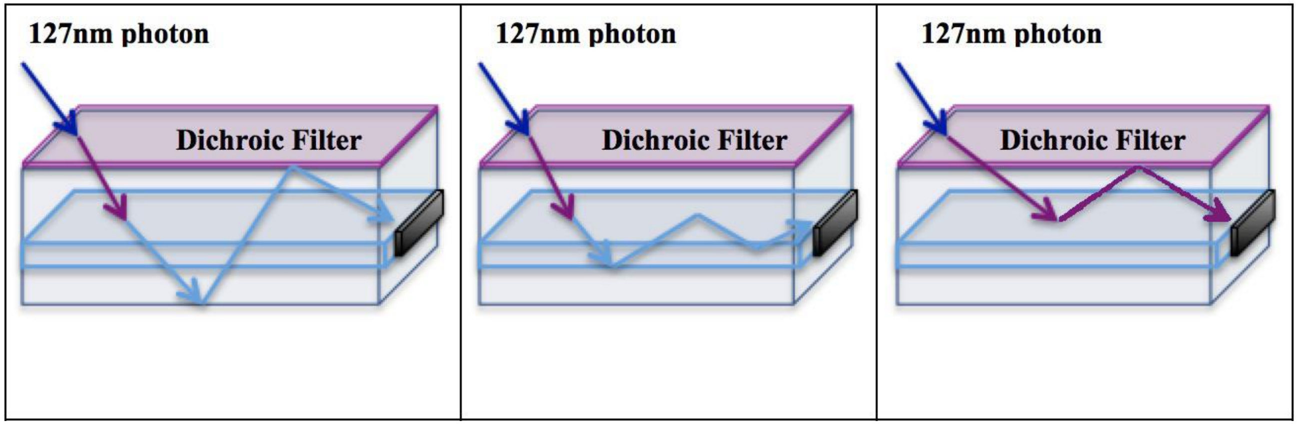
Argon R&D Advanced Program at UniCAmp (ARAPUCA)

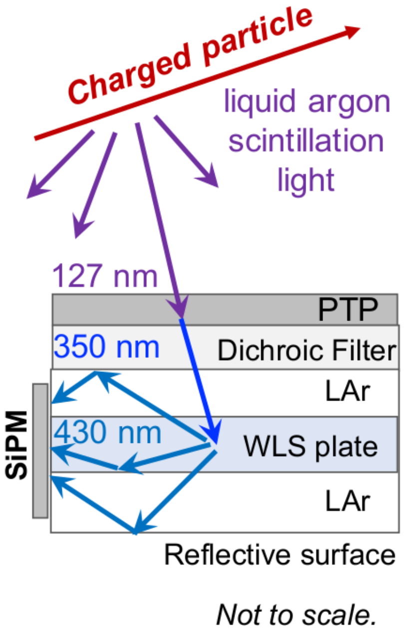
- **A New device for liquid argon scintillator light detection**



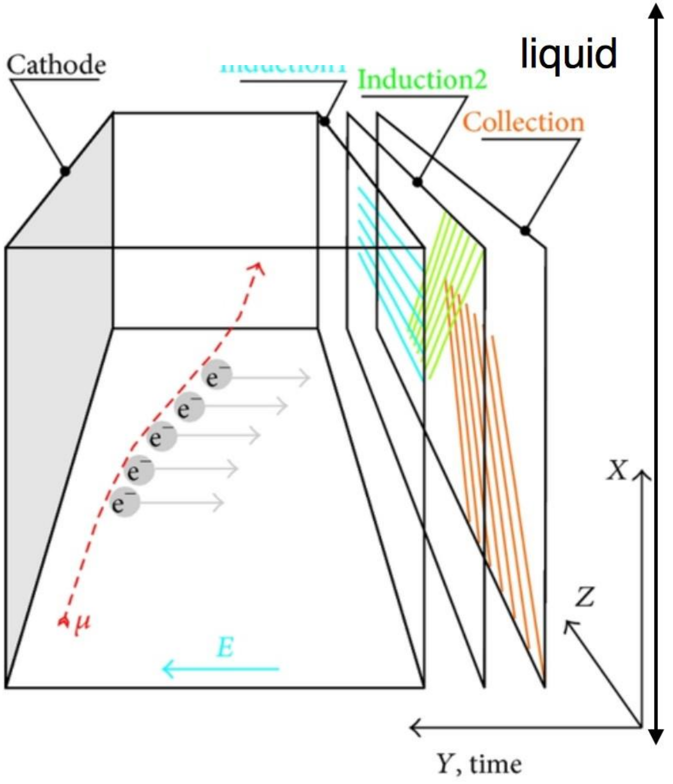


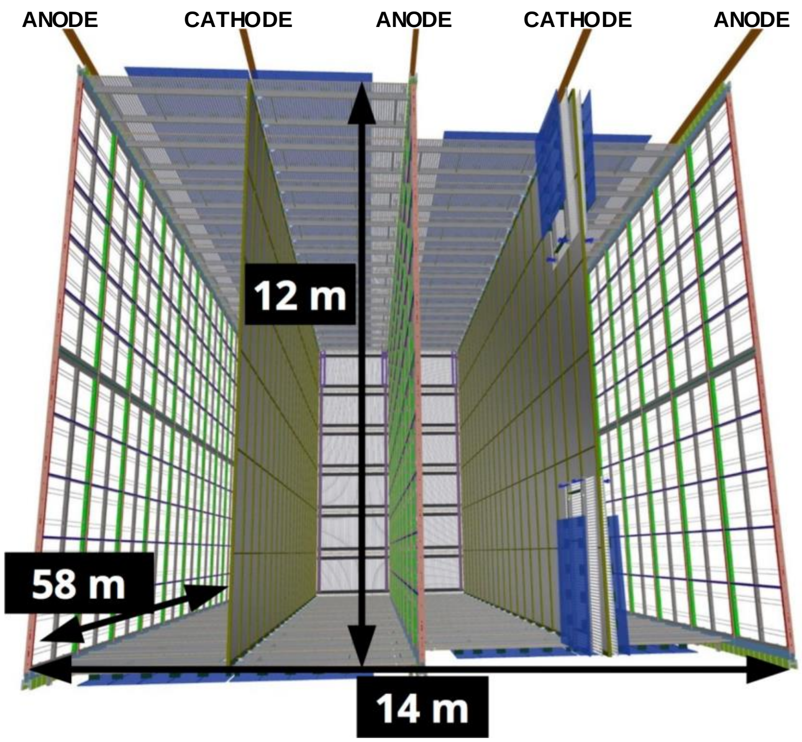
- **X-ARAPUCA : A hybrid solution between an ARAPUCA and a light guide**
- **A short pass dichroic filter with a cut-off wavelength at 400nm coated with para-TerPhenyl (pTP) on the external side ($\lambda_{emission} \approx 350$nm) and TetraPhenylButadiene (TPB) ($\lambda_{emission} \approx 430$nm)**





FD#1: Horizontal Drift LArTPC

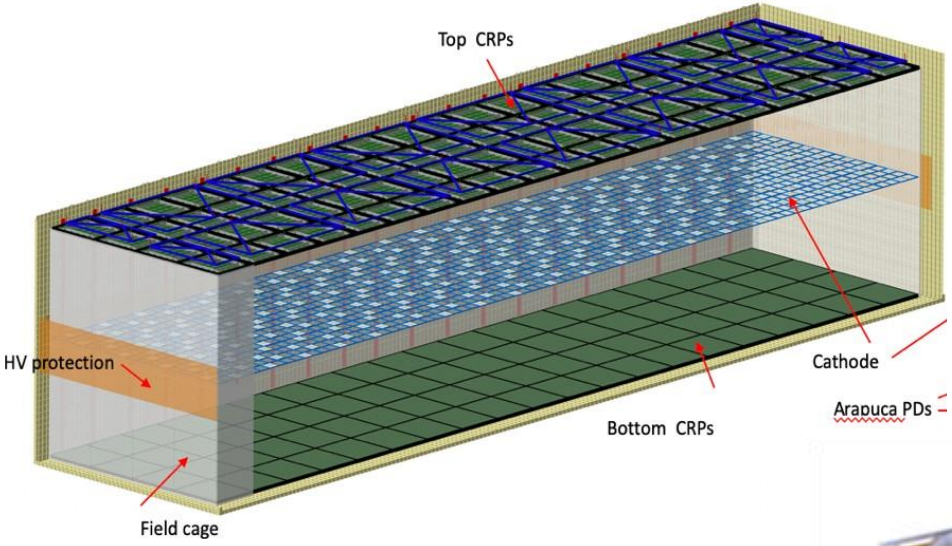




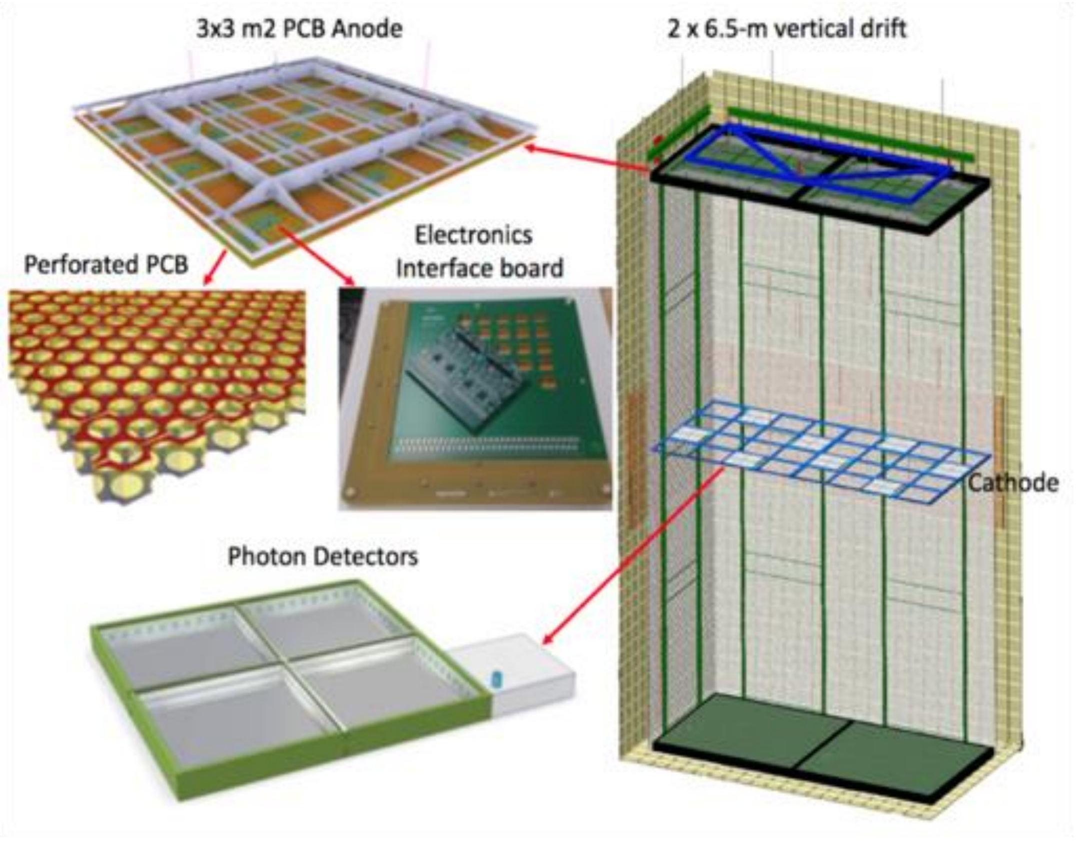
JINST 15 T08010 (2020)

- **12 m × 14 m × 58 m active volume**
- **Each Anode-Cathode chamber has 3.5 m drift**
- **Cathode at –180 kV**
- **150 Anode Plane Assemblies (APAs) with 384,000 readout wires**
- **Anode planes have wrapped wires (readout on both sides)**
- **6000 photon detection system (PDS) channels for light readout**

FD#2: Vertical Drift LArTPC



- VD technology evolved from extensive R&D from single and dual phase LArTPCs
- Designed to maximize active volume
- Perforated PCBs with segmented electrodes (strips) as readout units



- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- –300kV on cathode; 450 V/cm field

(Neutrino less) Double beta decay experiments

${}_{Z}A \rightarrow {}_{Z+2}A + 2\beta^{-} + 2\nu_e$ Normal lepton#-conserving DBD

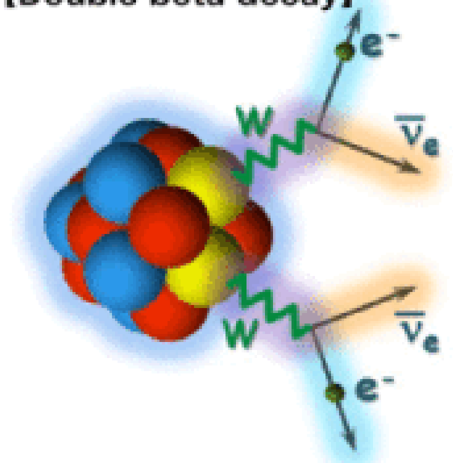
${}_{Z}A \rightarrow {}_{Z+2}A + 2\beta^{-}$ Lepton#-violating DBD

$\Gamma_{2\beta 0\nu} \propto$ [phase-space] × [Nuclear ME] × $\langle m_\nu{}^2 \rangle$

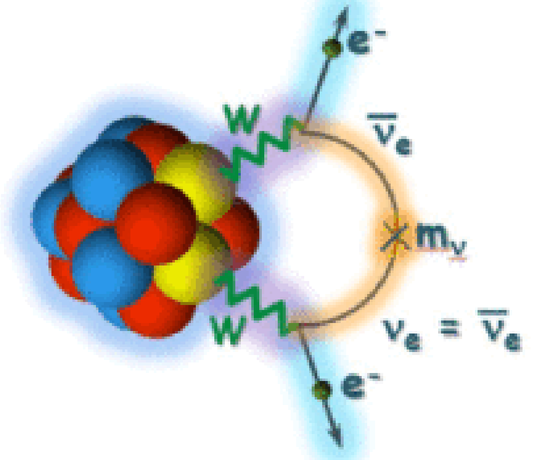
$\Gamma_{2\nu} \propto Q^9$, $\Gamma_{0\nu} \propto Q^5$

High $Q_{2\beta}$ desirable for background from radioactivity

[Double beta decay]

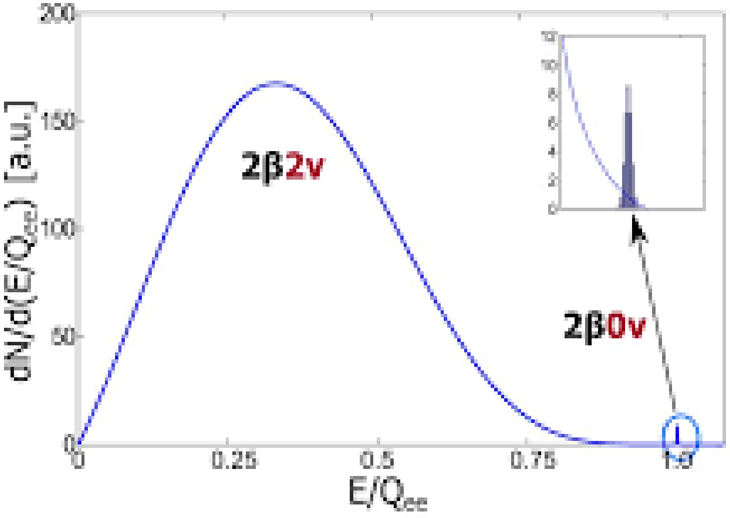


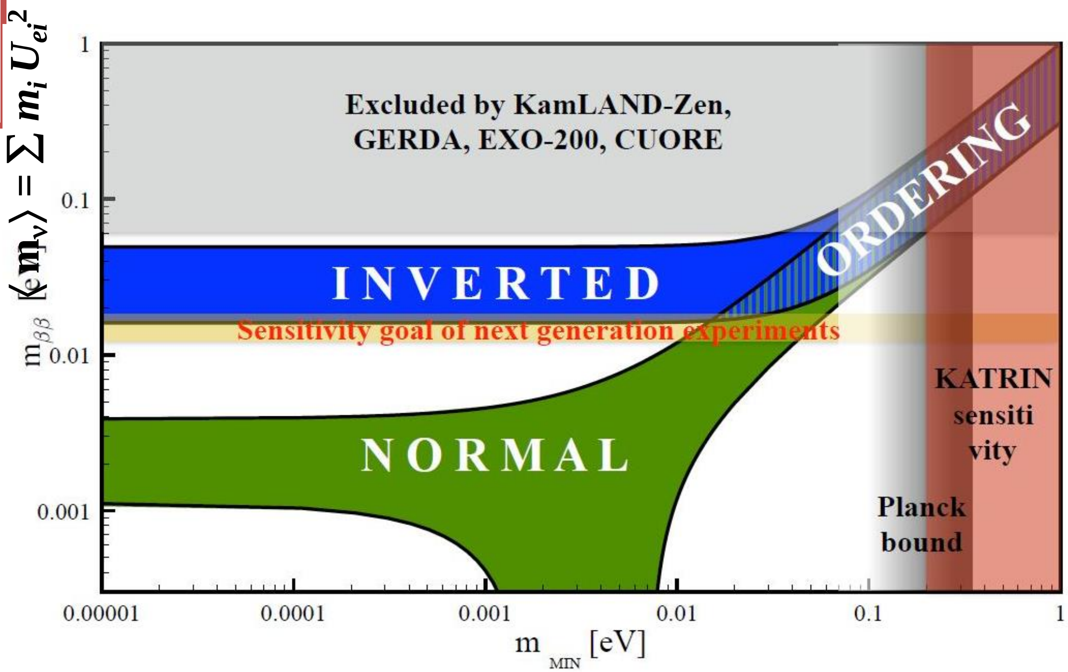
Double beta decay which emits anti-neutrinos



Neutrinoless double beta decay

E.g. ^{76}Ge Q_{ee} = 2039 k





0ν2β decay candidates

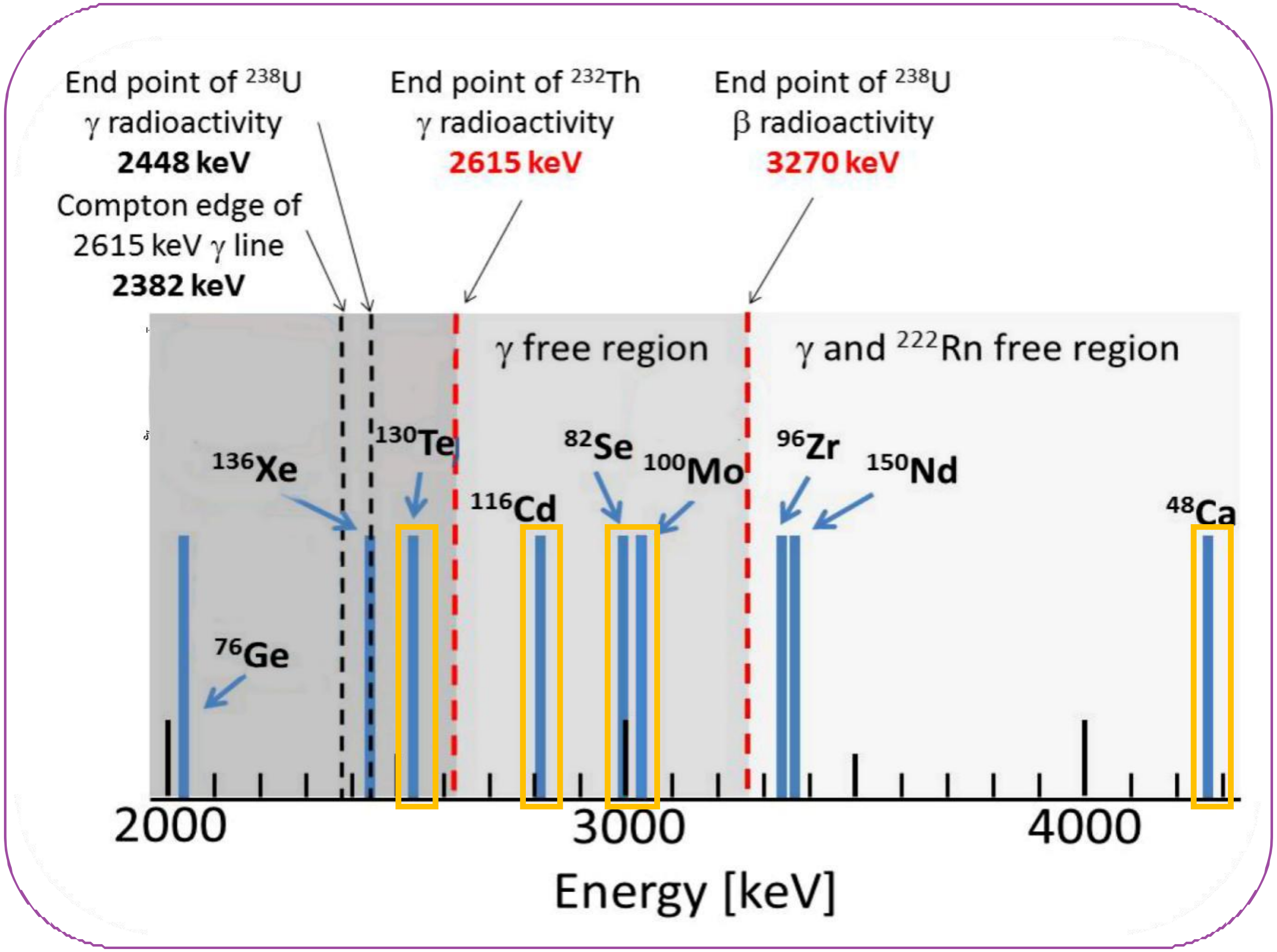
Experimental requirements:

- **Isotopic abundance and/or large scale enrichment**
- **High $Q_{\beta\beta}$ → lower background level in ROI and higher 0ν2β decay rate**

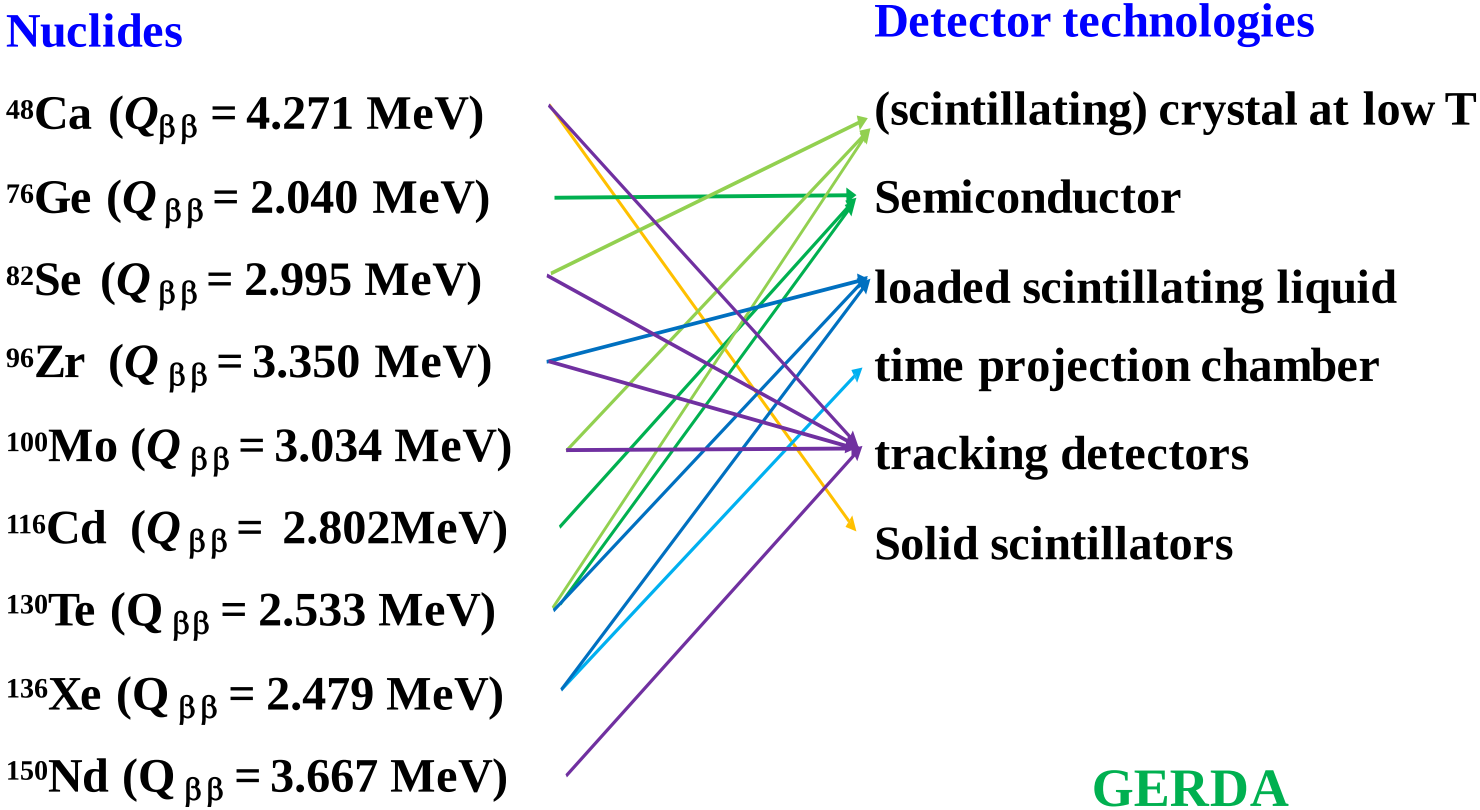
Minimum two isotopes should be measured: for observation and confirmation

$$T_{1/2}^{0\nu2\beta} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Bolometric detectors technology applicable for most of candidates!



Neutrinoless double beta decay



Nuclides

^{48}Ca ($Q_{\beta\beta} = 4.271$ MeV)

^{76}Ge ($Q_{\beta\beta} = 2.040$ MeV)

^{82}Se ($Q_{\beta\beta} = 2.995$ MeV)

^{96}Zr ($Q_{\beta\beta} = 3.350$ MeV)

^{100}Mo ($Q_{\beta\beta} = 3.034$ MeV)

^{116}Cd ($Q_{\beta\beta} = 2.802$MeV)

^{130}Te ($Q_{\beta\beta} = 2.533$ MeV)

^{136}Xe ($Q_{\beta\beta} = 2.479$ MeV)

^{150}Nd ($Q_{\beta\beta} = 3.667$ MeV)

Detector technologies

(scintillating) crystal at low T

Semiconductor

loaded scintillating liquid

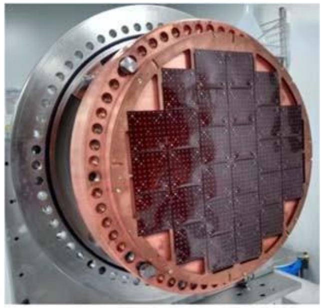
time projection chamber

tracking detectors

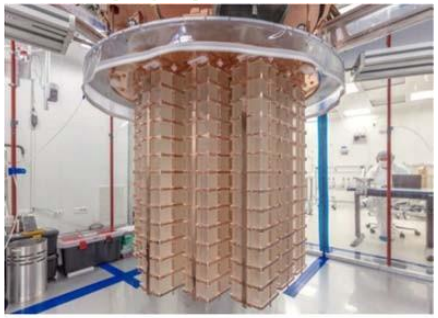
Solid scintillators

Experiments

ELEGANT
CANDLES-III
CUORE
AMoRE
CUPID
GERDA/Majorana/LEGEND
COBRA
nEXO
NEXT (HPXe)
PANDA-X (HPXe)
XENONnT/DARWIN
SNO+
KamLAND-ZEN
ZICOS
(Super)NEMO



NEXT



CUORE

GERDA

Classification by experimental technique

Bolometers

CUORE (^{130}Te)
CUPID (^{82}Se|^{100} Mo|^{130} Te)
AMORE ^{100} Mo

Semiconductors

GERDA (^{76}Ge)
Majorana Demonstrator (^{76}Ge)
LEGEND (^{76}Ge)

Scintillators

KamLAND-Zen (^{136}Xe)
SNO+ (^{130} Te)

Time –Projection Chambers

EXO-200 (^{136}Xe)
nEXO (^{136}Xe)
NEXT (^{136}Xe)

Tracking Calorimeters

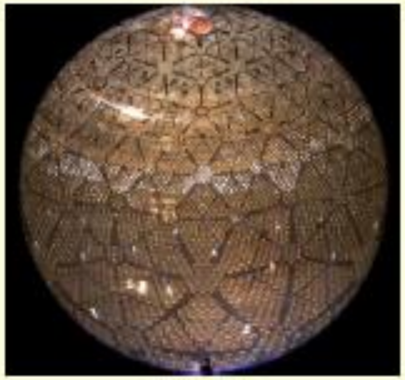
NEMO -3 (^{100}Mo)
SuperNEMO (^{82}Se)

Not exhaustive list of experiments

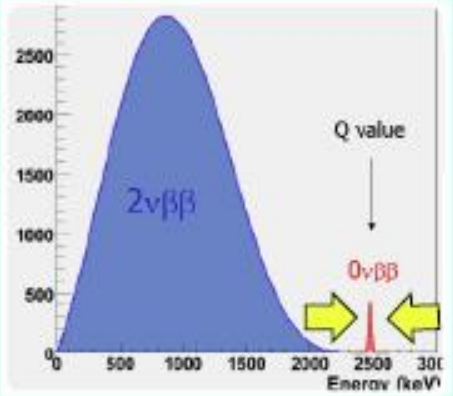
General NDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

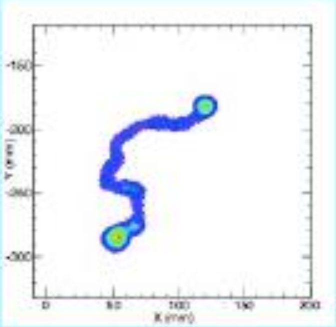
The “Brute Force” Approach

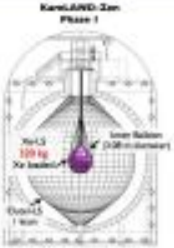


The “Peak-Squeezer” Approach

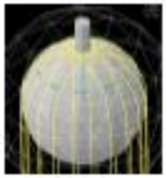


The “Final-State Judgement” Approach





KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)

+more future ideas...

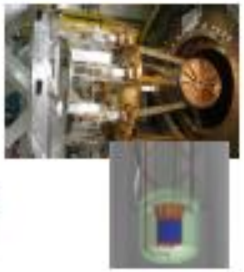
CUORICINO/ CUORE (^{130}Te)

CUPID (^{82}Se)

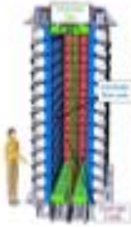
MAJORANA (^{76}Ge)

GERDA (^{76}Ge)

LEGEND (^{76}Ge)



EXO/nEXO (^{136}Xe)



NEMO/ SuperNEMO (various/^{82}Se)

NEXT (^{136}Xe)

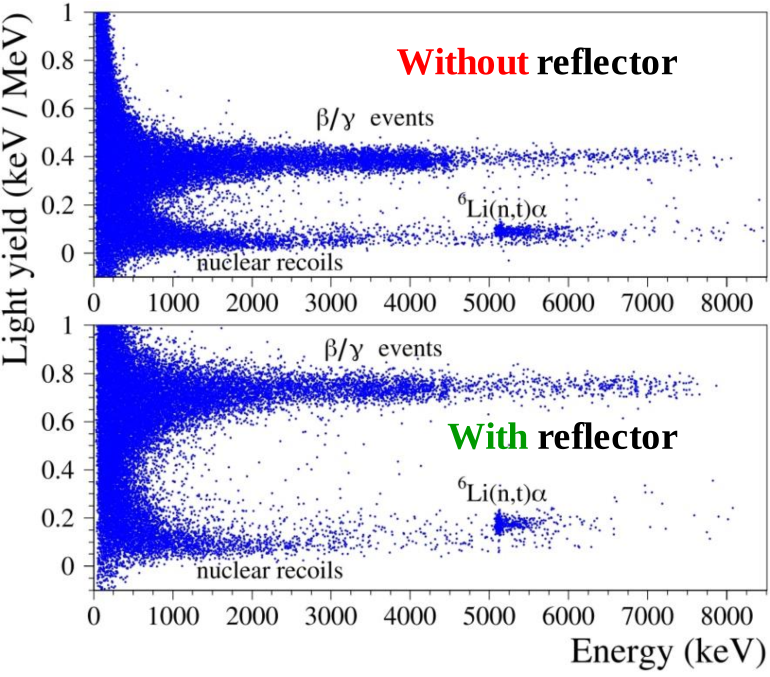
CUPID: CUORE Upgrade With Particle IDentification

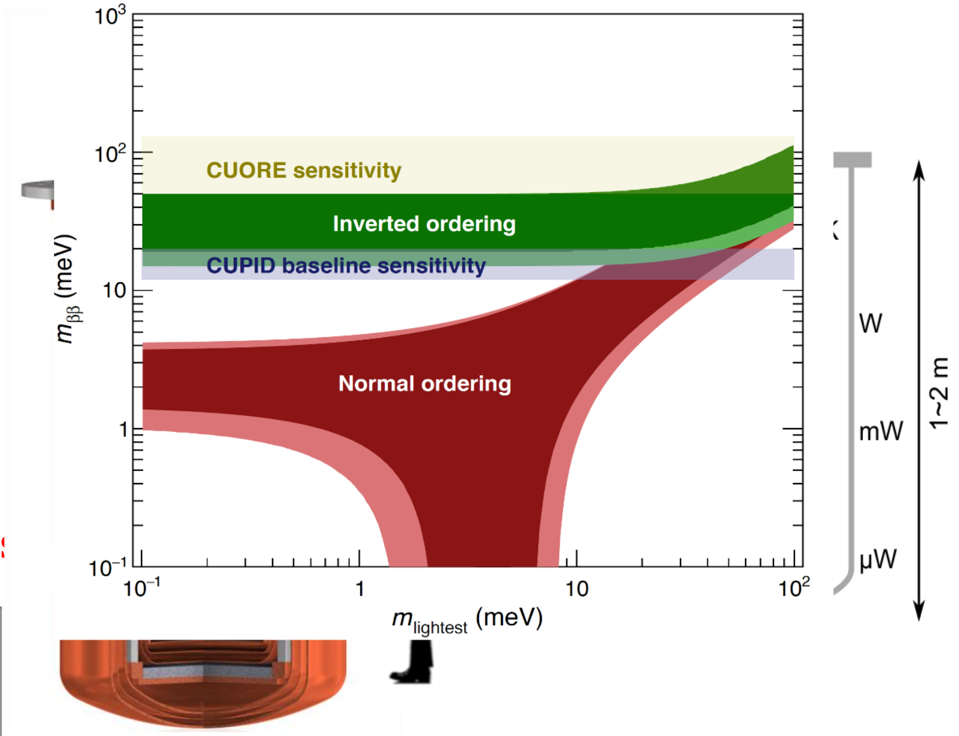
- **Next generation decay 0νββ: replace the CUORE TeO_2 detector with 1596 Li_2MoO_4 scintillating bolometers:**
- **450 kg of $Li_2{}^{100}MoO_4$ (high Q 240 kg of ^{100}Mo)**
- **57 towers of 28 crystals ($45\times45\times45$ mm^3 & mass ~280 gm), each instrumented with a Light Detector**

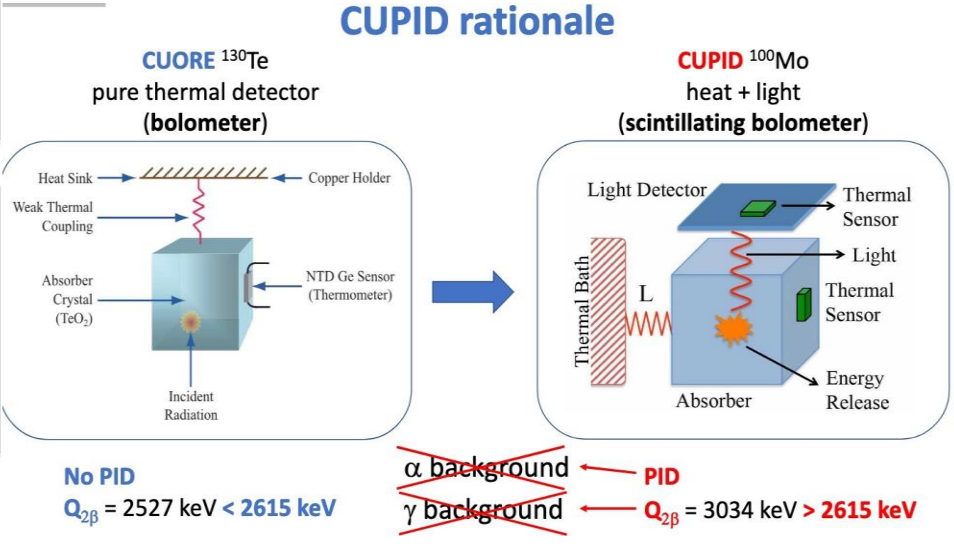
Scintillating bolometer technology : enable

PID

- **Goa**
  Hie
  $m_{\beta\beta}$
  ene
  bac
  cou
- **→e**
  10^2
- **→e**
  meV

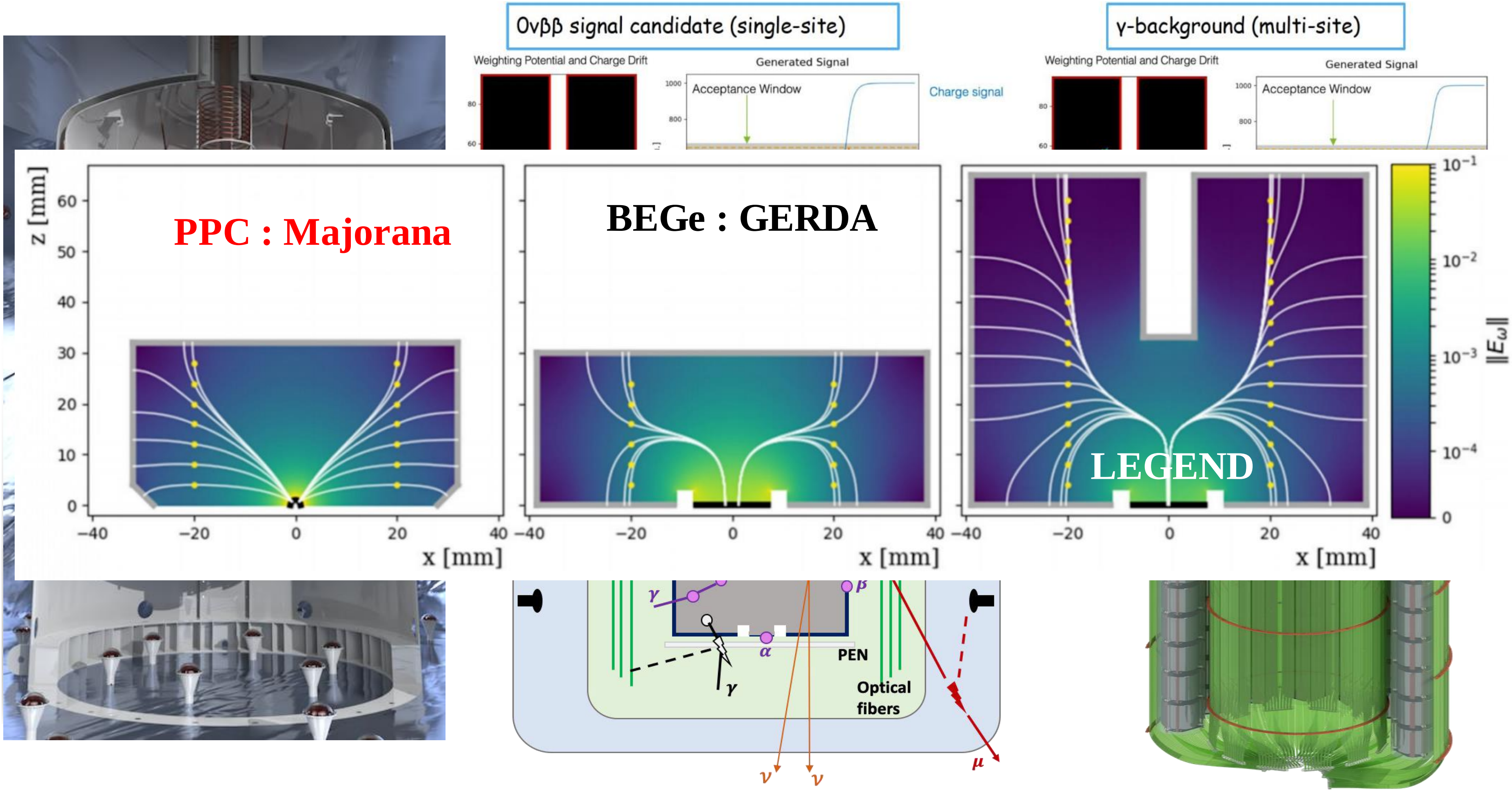






LEGEND-200 at LNGS (2107.11462)

- Based on Majorana + GERDA technologies
- Enriched ^{76}Ge, P-type Point Contact /Broad Energy Ge /Inverted Coaxial Point Contact detectors (➞event topology) & active veto
- LEGEND-200: commissioning & start data taking with 10 strings in 2022
- (≈ 150 kg), goal: 12 strings, goals: $B = 1.0 \times 10^{-4}$ cts/(keV kg yr), $T^{0\nu}_{1/2}$ sens.: 10^{27} yr

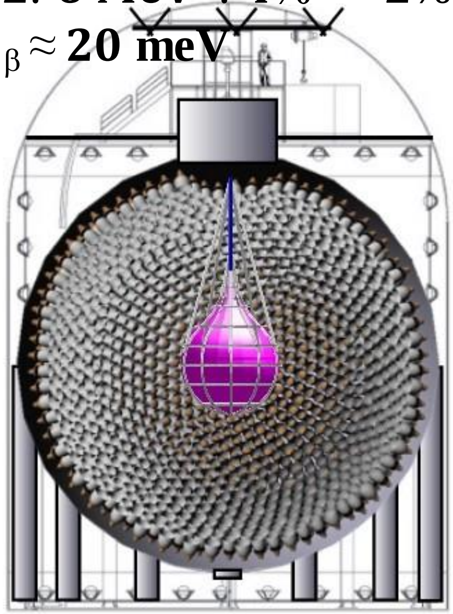


KamLAND-ZEN

- **Liquid scintillator detector KamLAND (1kTon) in Kamioka with a nylon balloon with LS and DBD isotope ^{136}Xe**
- **Q-value 2.458 MeV, dissolved into LS ~3% by weight, enrichment ~90%**

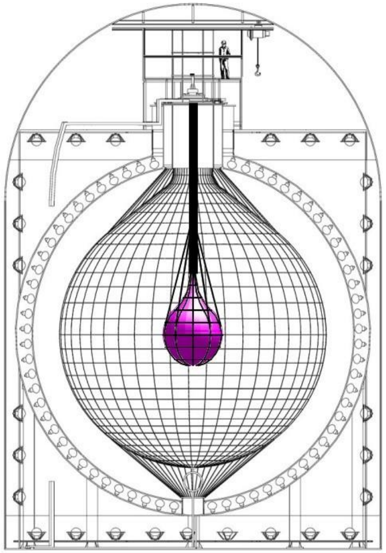
KamLAND2-Zen: future

1 t of Xe
Better energy resolution
Goal: σ 2. 6 MeV : 4% → 2%
$m_{\beta\beta} \approx 20$ meV



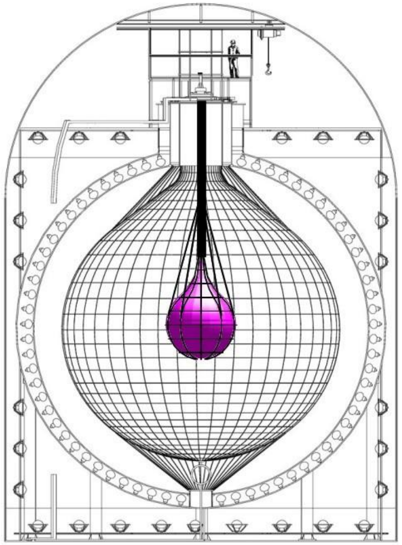
KamLAND-Zen 400: past

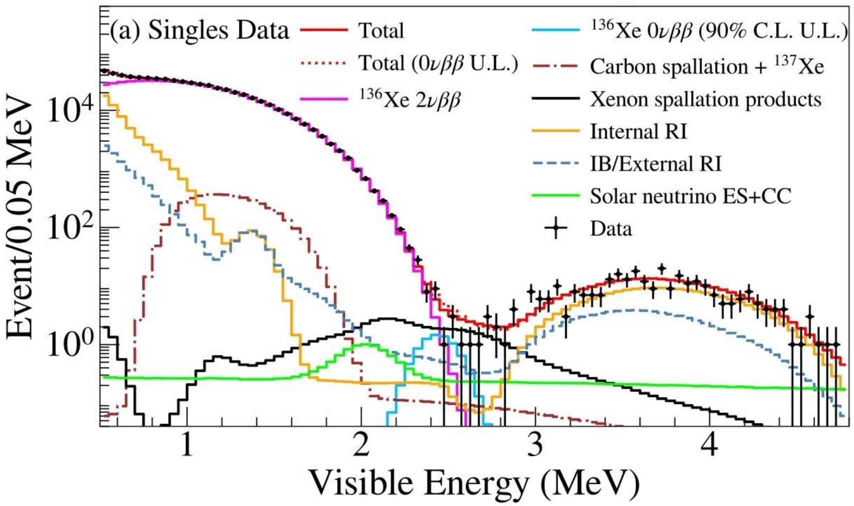
320-380 kg of Xe
Data taking 2011-2015



KamLAND-Zen 800: present

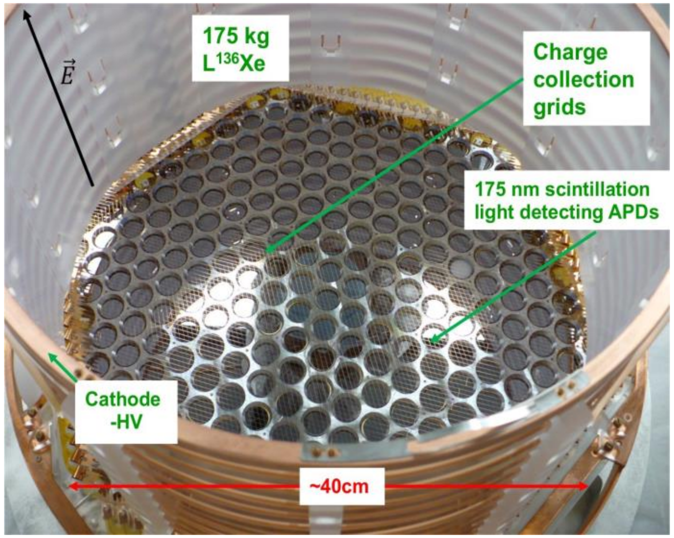
750 kg of Xe, cleaner
DAQ started in 2019



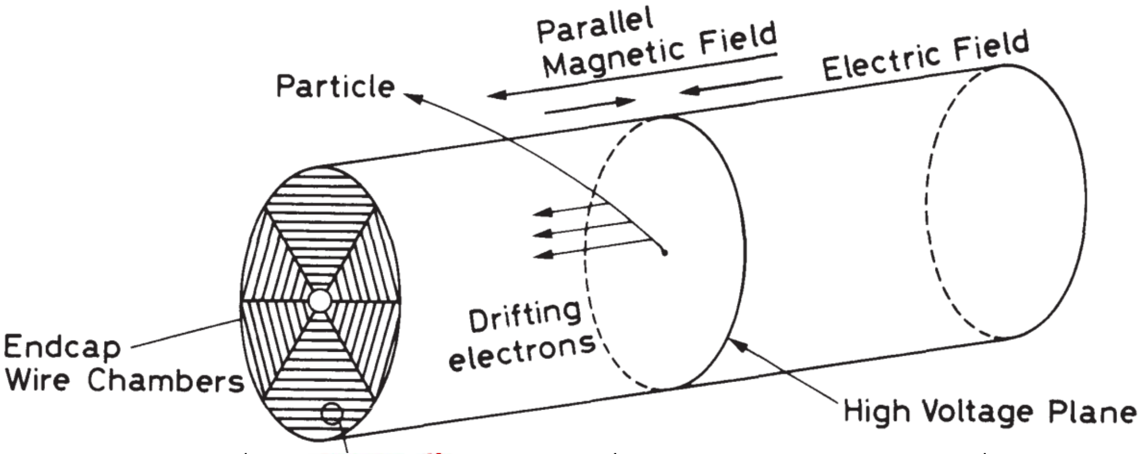


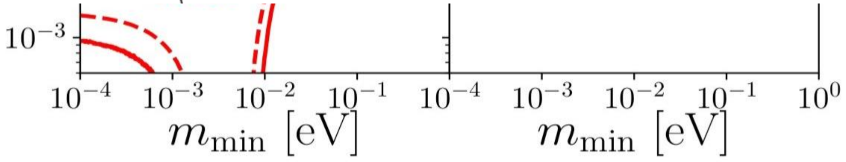
$T^{0\nu}_{1/2} > 2.3 \times 10^{26}$ yr
$m_{\beta\beta} < 36 - 158$ meV

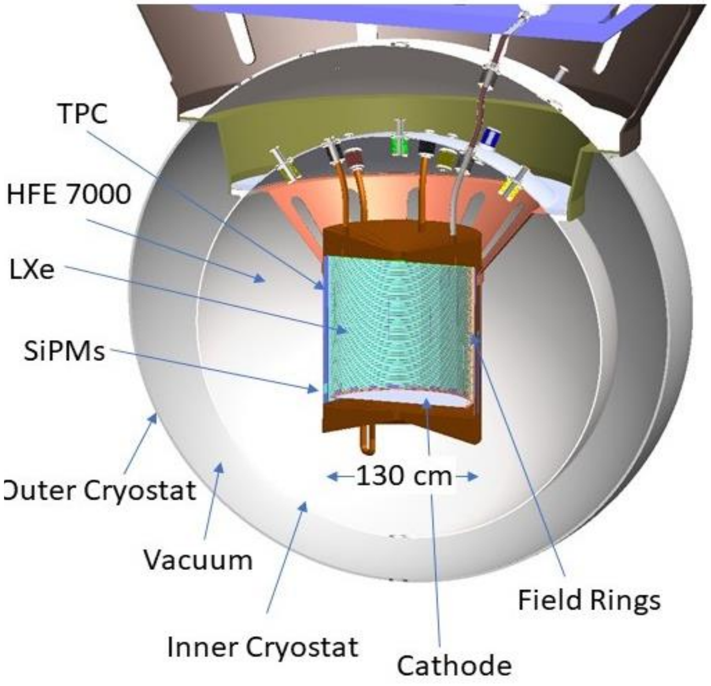
nEXO: a single phase ^{136}Xe-enriched LXe TPC



- nEXO: LXe TPC
- Both the scintillation light and **drifting ionization** signals to obtain 3D images of the energy depositions.
- enriched 136Xe: 5 t
- energy resolution: ≈ 46 keV (FWHM)
- background index: B = 7) 10,; counts/(FWHM kg yr)
- ➞expected sensitivity (10 yr): $T^{0\nu}_{1/2} > 1.35 \times 10^{28}$ yr (90% C.L.)
- ➞expected sensitivity (10 yr): $m_{\beta\beta} < 5$ - 20 meV
- C [illegible]





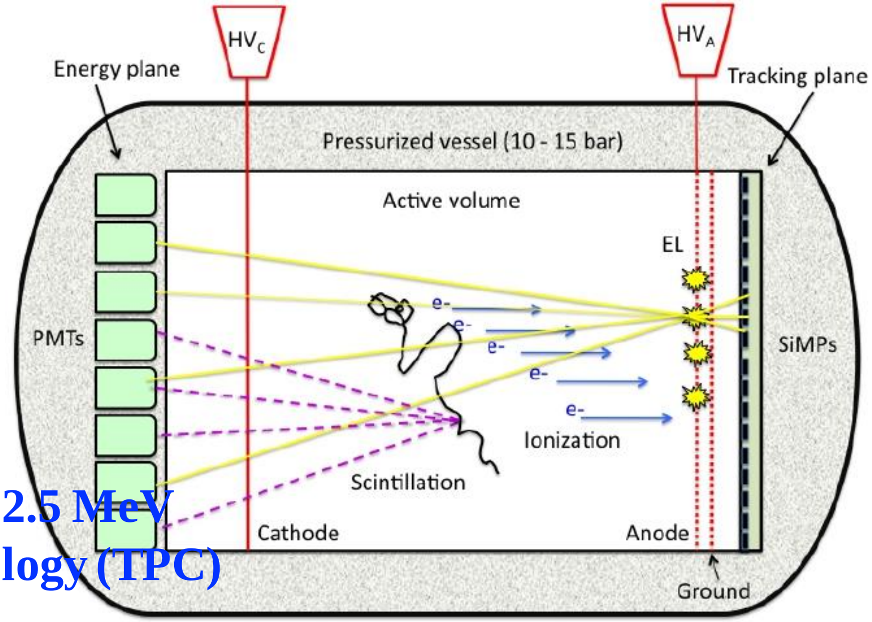


The @next detector concept

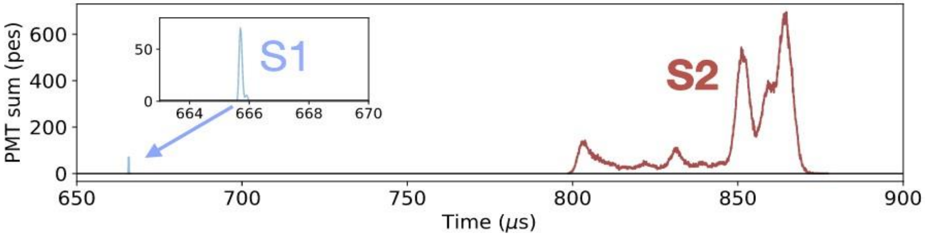
High Pressure Gaseous Xenon Time Projection Chamber with Electroluminescent Amplification

More isotope in the same volume

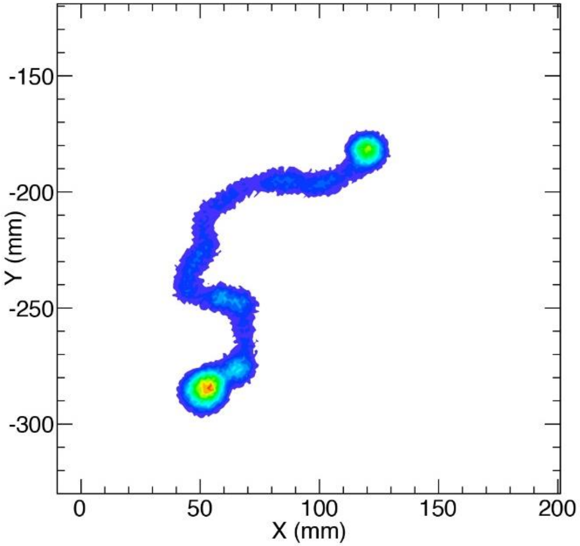
Fully active and homogenous detector → source = detector Great intrinsic energy resolution in gas



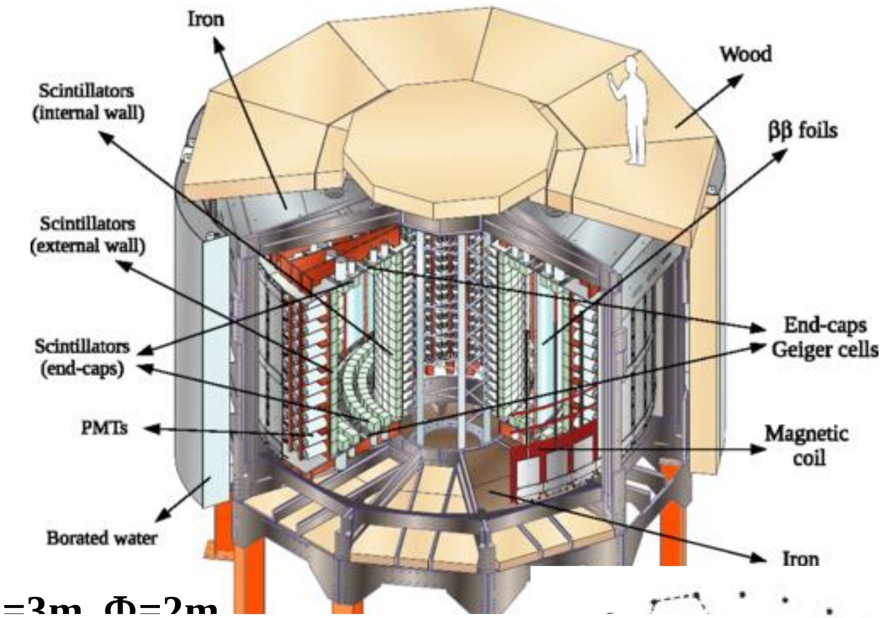
- ^{136}Xe Isotope: High enough abundance $Q_{\beta\beta} = 2.5$ MeV
- Noble gas → ideally suited to detection technology (TPC)



- TPC allows 3D event reconstruction
  - improvement signal over background
- Search for 0νββ requires:
  - Great energy resolution
  - Extremely low background
  - Scalability

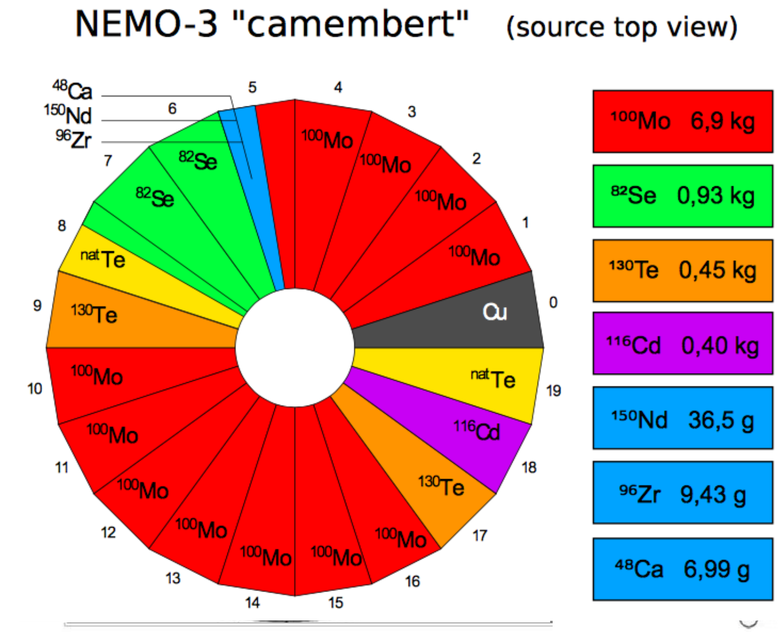


NEMO [Neutrino Ettore Majorana Observatory, PRD 92 (2015) 072011]

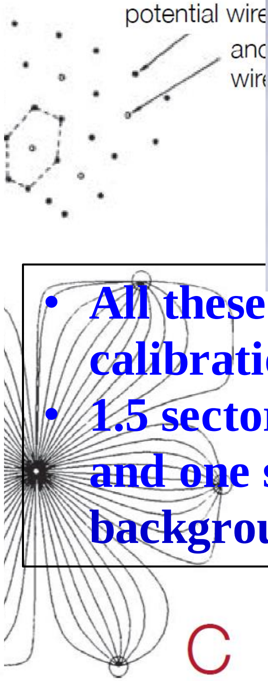


- **Sources :** 58mm/cm^2 foils, 6.9kg of ^{100}Mo
- **Tracker :** 6180 open drift cell cells (anode+ 8 cathode wire), readout on both side, σ_{xy}=3mm, σ_z=10mm
- **Calorimeter :** 1940 polystyrene scintillator (20×20×10cm^3)
  - Internal+end : 3” PMT (σ_E/E 7.2%/√E)
  - Outer : 5” PMT (σ_E/E 5.8%/√E)
  - Time measurement, σ_t ~250ps

L=3m, Φ=2m

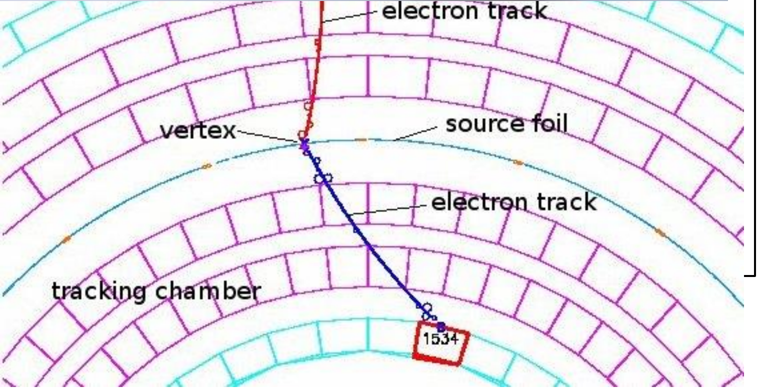


^{100}Mo	6,9 kg
^{82}Se	0,93 kg
^{130}Te	0,45 kg
^{116}Cd	0,40 kg
^{150}Nd	36,5 g
^{96}Zr	9,43 g
^{48}Ca	6,99 g




Not in proportion

- All these *ν*
  calibration
- 1.5 sector
  and one se
  backgroun



Electron neutrino mass measurements

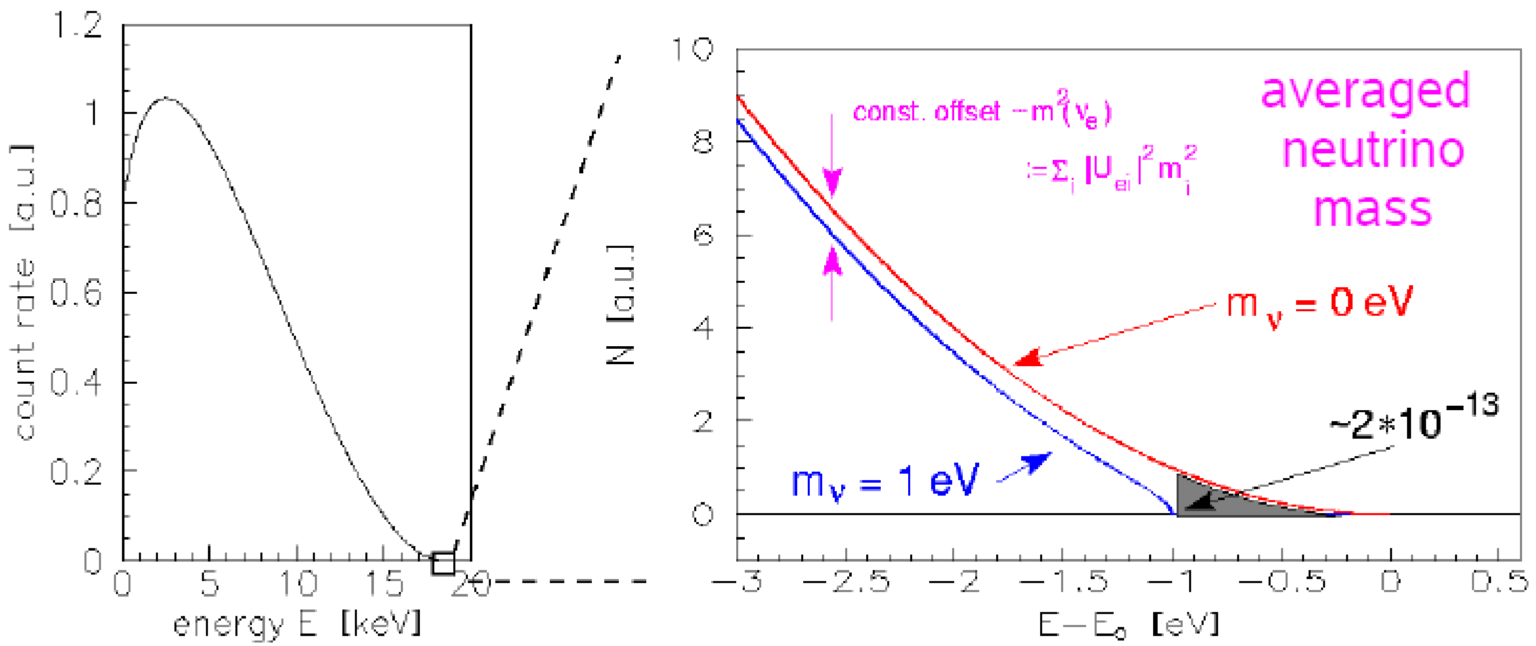
$$dN/dE = K\, F(E_e,Z)\, p\, E_e\, (Q-E_e)\, \Sigma_i |U_{ei}|^2 [(Q-E_e)^2 - m^2(\nu_i)]^{1/2}$$

where $F(E_e,Z)$ is the Fermi function (Coulomb distortion of electron wave-function in final state)

Q = max. energy of electron for $m_\nu = 0$

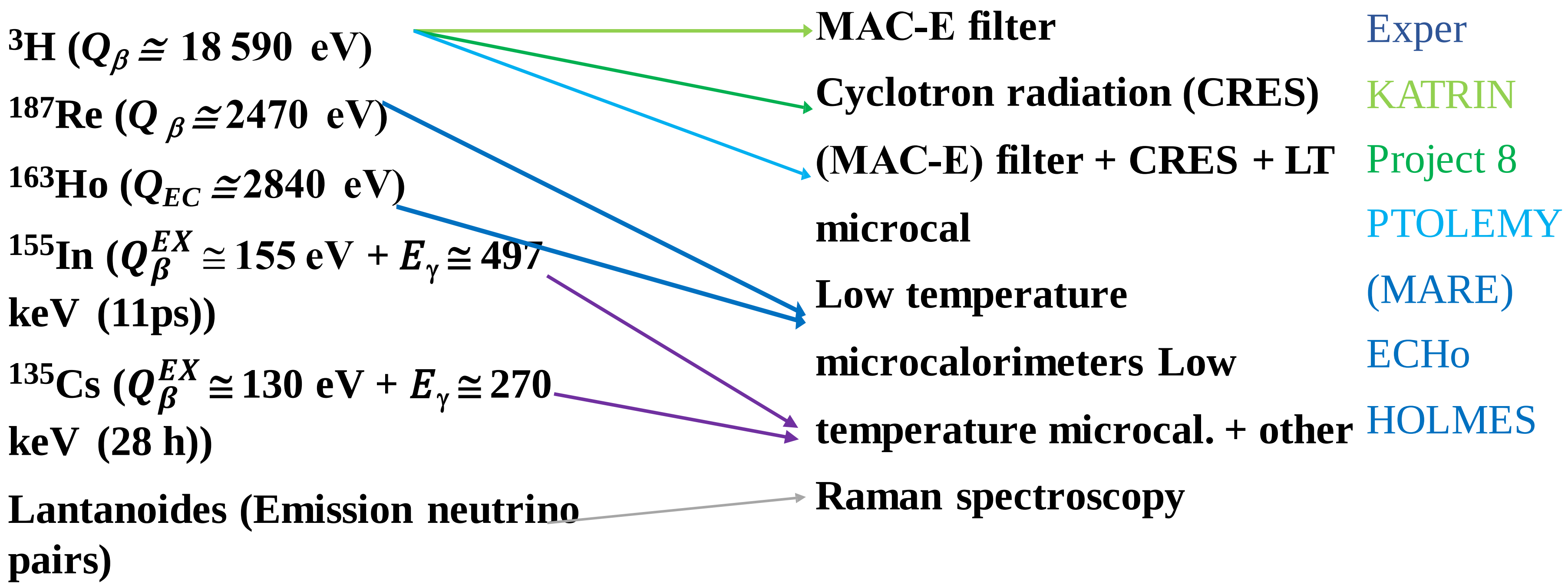
U_{ei} is amplitude for ν_e to be in i^{th} mass eigenstate

$m(\nu_i)$ is the i^{th} neutrino mass eigenstate



Much more details in Michelle Doniski's presentation in next week

Direct ν mass determination



Nuclides

^{3}H ($Q_\beta \cong 18\,590$ eV)

^{187}Re ($Q_\beta \cong 2470$ eV)

^{163}Ho ($Q_{EC} \cong 2840$ eV)

^{155}In ($Q_\beta^{EX} \cong 155$ eV + $E_\gamma \cong 497$ keV (11ps))

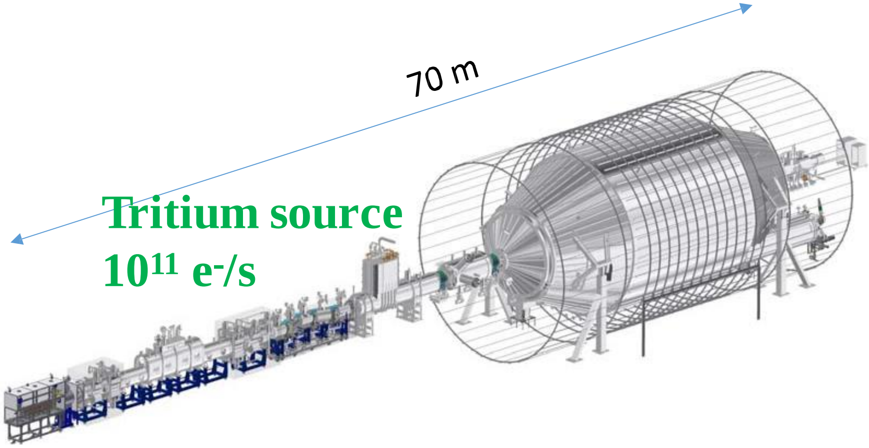
^{135}Cs ($Q_\beta^{EX} \cong 130$ eV + $E_\gamma \cong 270$ keV (28 h))

Lantanoides (Emission neutrino pairs)

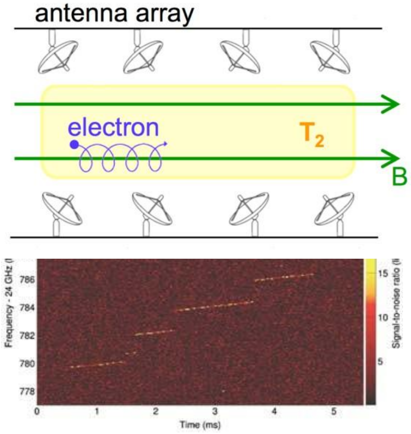
Detector technologies

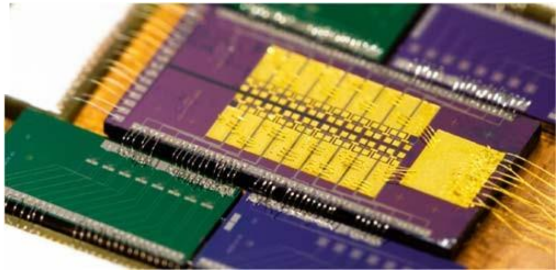
MAC-E filter
Cyclotron radiation (CRES)
(MAC-E) filter + CRES + LT
microcal
Low temperature
microcalorimeters Low
temperature microcal. + other
Raman spectroscopy

Exper
KATRIN
Project 8
PTOLEMY
(MARE)
ECHo
HOLMES

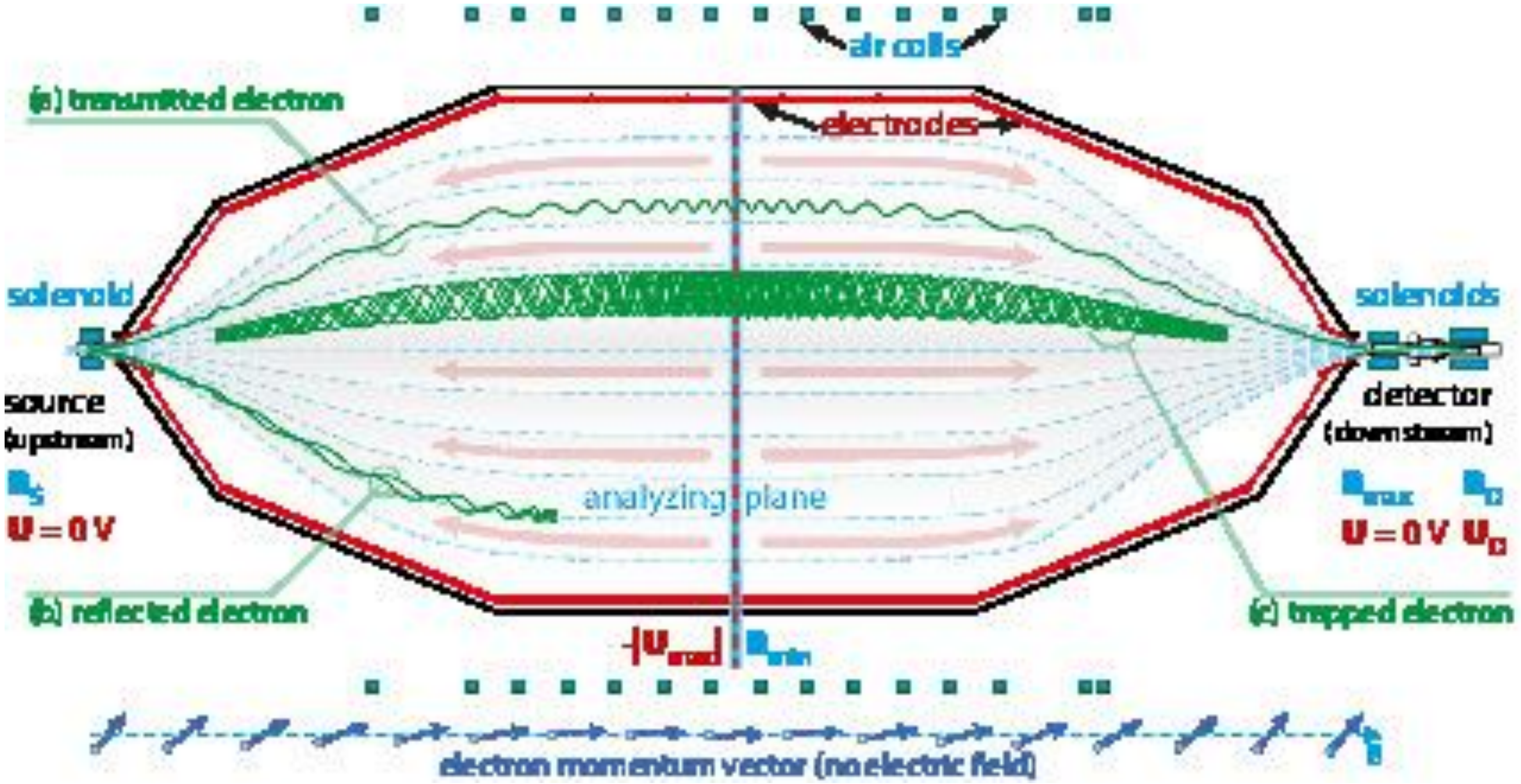


Tritium source
10^{11} e$^-$/s





KATRIN

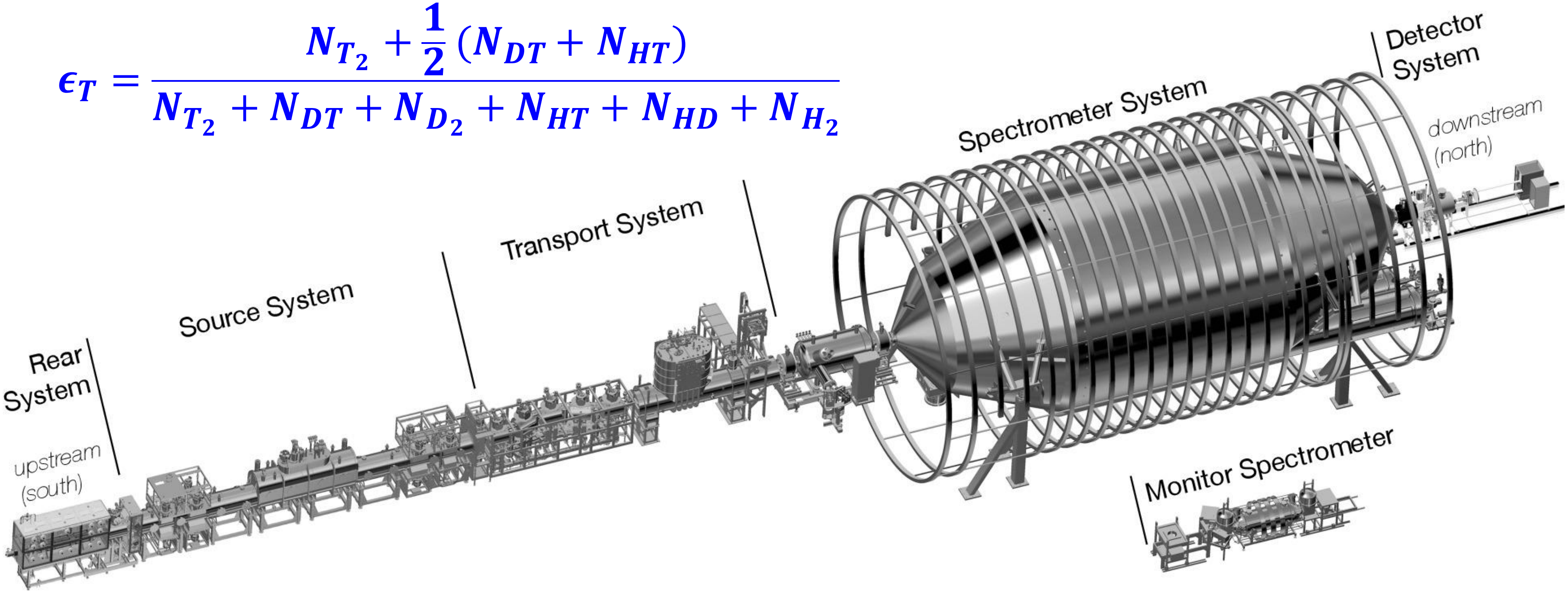


- **Main backgrounds**
  - **Electron from spectrometer wall**
  - **Decay of Radon atom in the column**
  - **Magnetic trapping conditions**
  - **Ionisation of Rydberg atoms (dominant one due to residual gas predominantly H_2)**
- **Main Spectrometer : 23.23m long & φ=9.8m**

KATRIN : 2103.04755

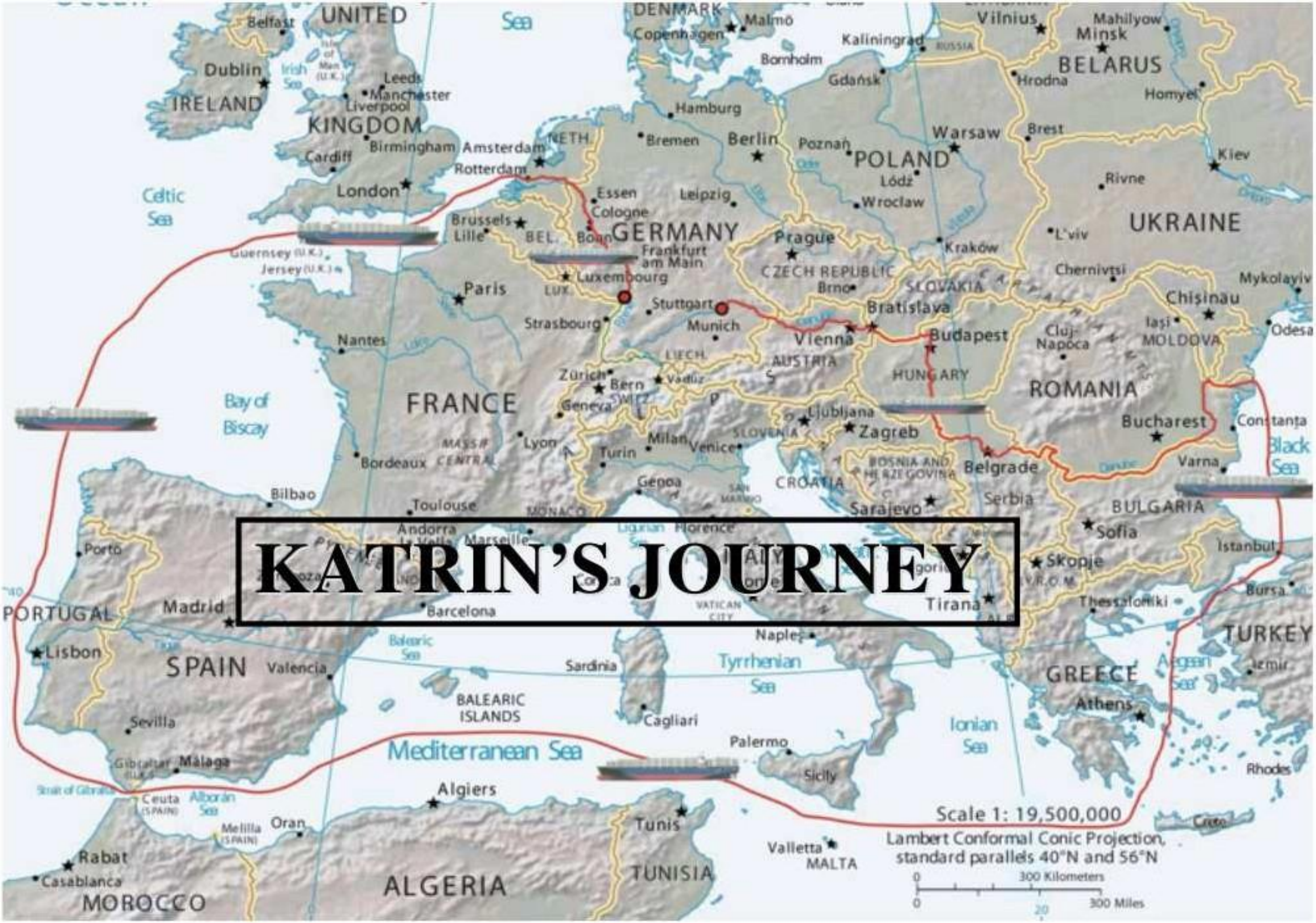
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e + 18.57\ KeV$ Half-life 12.32 year

$$\epsilon_T = \frac{N_{T_2} + \frac{1}{2}(N_{DT} + N_{HT})}{N_{T_2} + N_{DT} + N_{D_2} + N_{HT} + N_{HD} + N_{H_2}}$$



- Goal to have neutrino mass sensitivity upto 0.2 eV
- Key requirements
  - – Vacuum quality (<10^{-11}mbar)
  - – High voltage (ppm (10^{-6}) range for voltage range of down to −35kV
  - – magnetic field stability
  - – Optimal electron transport from source to detector
  - – Main Spectrometer : 23.23m long & φ=9.8m

KATRIN project



KATRIN'S JOURNEY

KARlsruhe TRItium Neutrino experimentKATRIN Experiment

Improved β energy resolution requires a ***BIG*** β spectrometer.