(Liquified) Noble gas calorimetry and the MEG II LXe calorimeter

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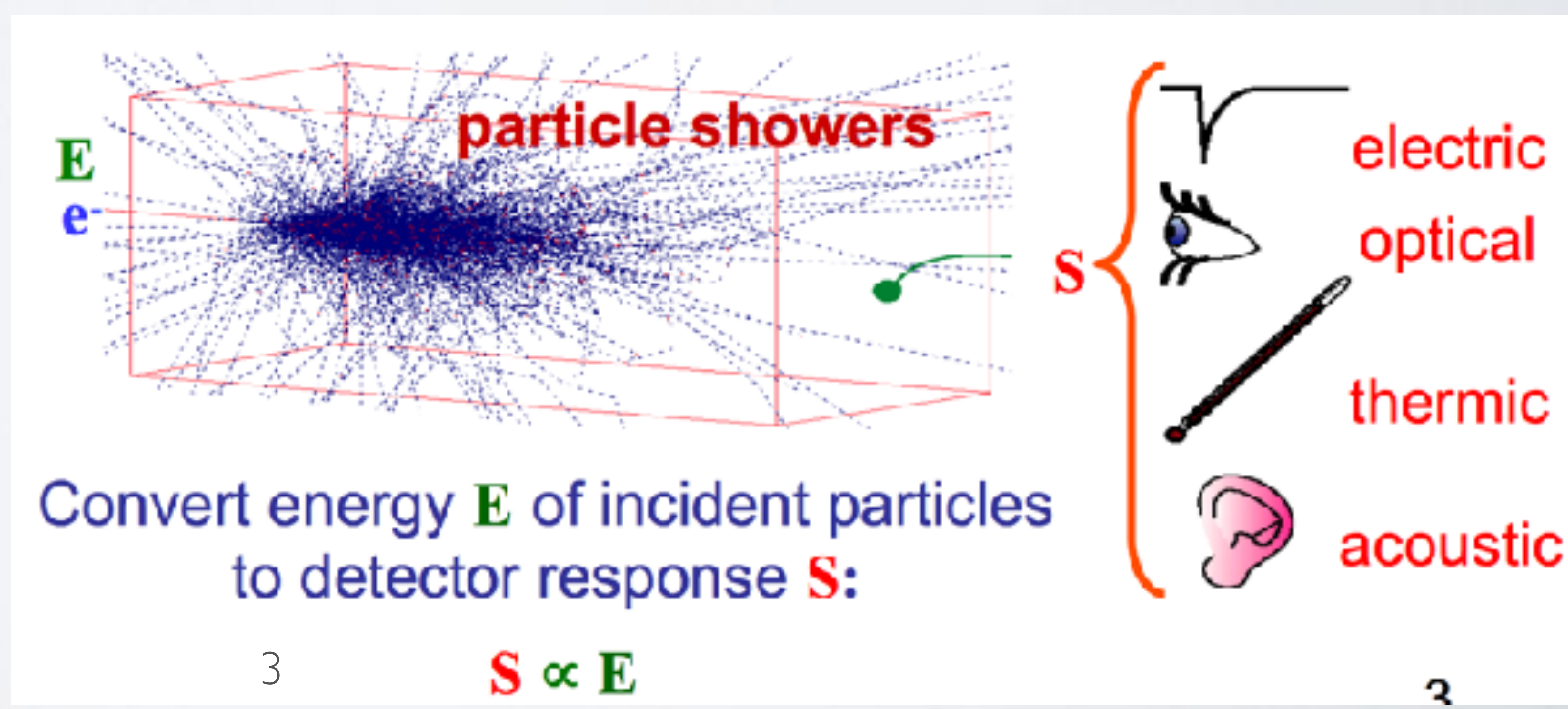
Outline

- Introduction
  - Calorimetry
  - (Liquefied) Noble gas / Liquid xenon
- MEG II liquid xenon detector
- Other applications

Calorimetry

- Calorimetry is a widespread technique in particle physics
  - Detection of particles, measurements of their properties, through total absorption in a block of matter, the calorimeter
  - In the absorption, almost all particle’s energy is eventually converted to heat, hence the term calorimeter
  - instrumented targets (neutrino experiments/proton decay /cosmic ray detectors), shower counters, 4π detectors for collider experiments
- Calorimetry makes use of various detection mechanisms
  - Scintillation
  - Cherenkov radiation
  - Ionization
  - Cryogenic phenomena



Calorimetry

- Measure charged + neutral particles
- Performance of calorimeters improves with energy and is constant over 4π

Calorimeter: $\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}$
[see below]

Gas detector: $\frac{\sigma_p}{p} \sim p$
[see above]

- Obtain information fast (<100ns feasible)
  - recognize and select interesting events in real time (trigger)

Electromagnetic shower

- Dominant processes at high energies (E>few MeV) :
  - Photons : Pair production

$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\,\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right)$$
$$= \frac{7}{9}\frac{A}{N_A X_0}$$

[X_0: radiation length] [in cm or g/cm²]

Absorption coefficient:

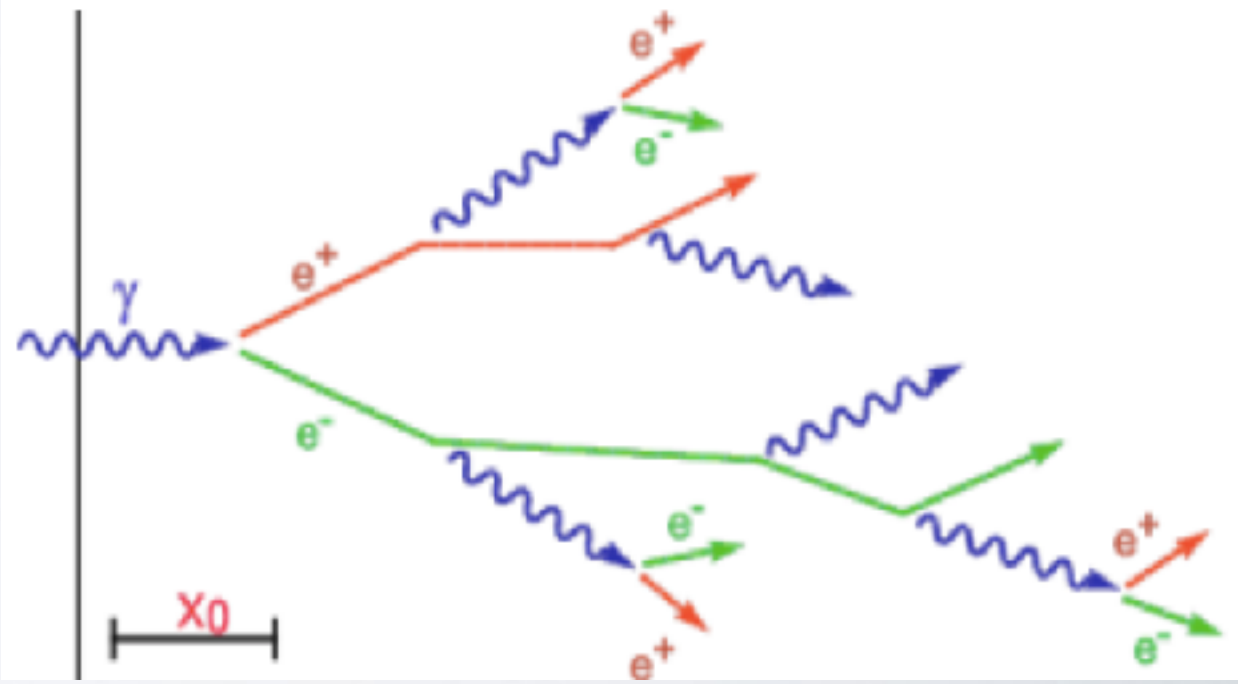
$$\mu = n\sigma = \rho\frac{N_A}{A}\cdot\sigma_{\text{pair}} = \frac{7}{9}\frac{\rho}{X_0}$$

Mean free path l = 1/μ

- Electrons : Bremsstrahlung

$$\frac{dE}{dx} = 4\alpha N_A\,\frac{Z^2}{A}r_e^2\cdot E\,\ln\frac{183}{Z^{\frac{1}{3}}} = \frac{E}{X_0}$$

$$\rightarrow E = E_0 e^{-x/X_0}$$



Liquefied noble gas / Liquid xenon

Basic Properties of Liquified Noble Gases

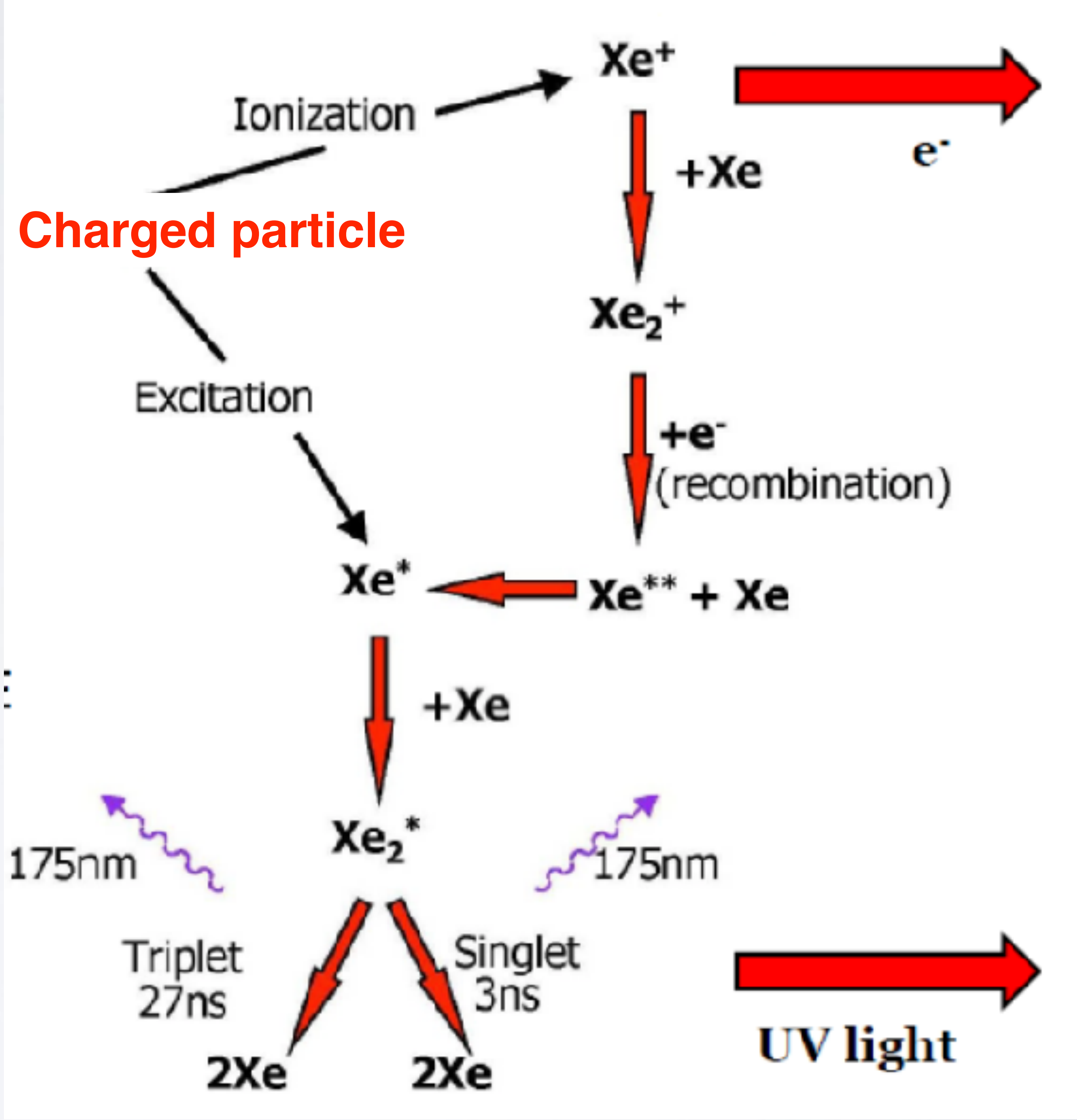
- Dense and homogeneous : good for large detectors
- Do not attach electrons, heavier noble gases give high electron mobility (ionization signal)
- Easy to purify
- Inert, not flammable, very good dielectric
- High scintillation yields

- LXe
  - High density (3g/cm³), short radiation length
  - Easy cryogenics (165K)
  - Short scintillation wavelength (175nm)
  - Very high resolution
  - Fast (~ns) response
  - Expensive (~10 times higher than Kr)

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Scintillation and Ionization

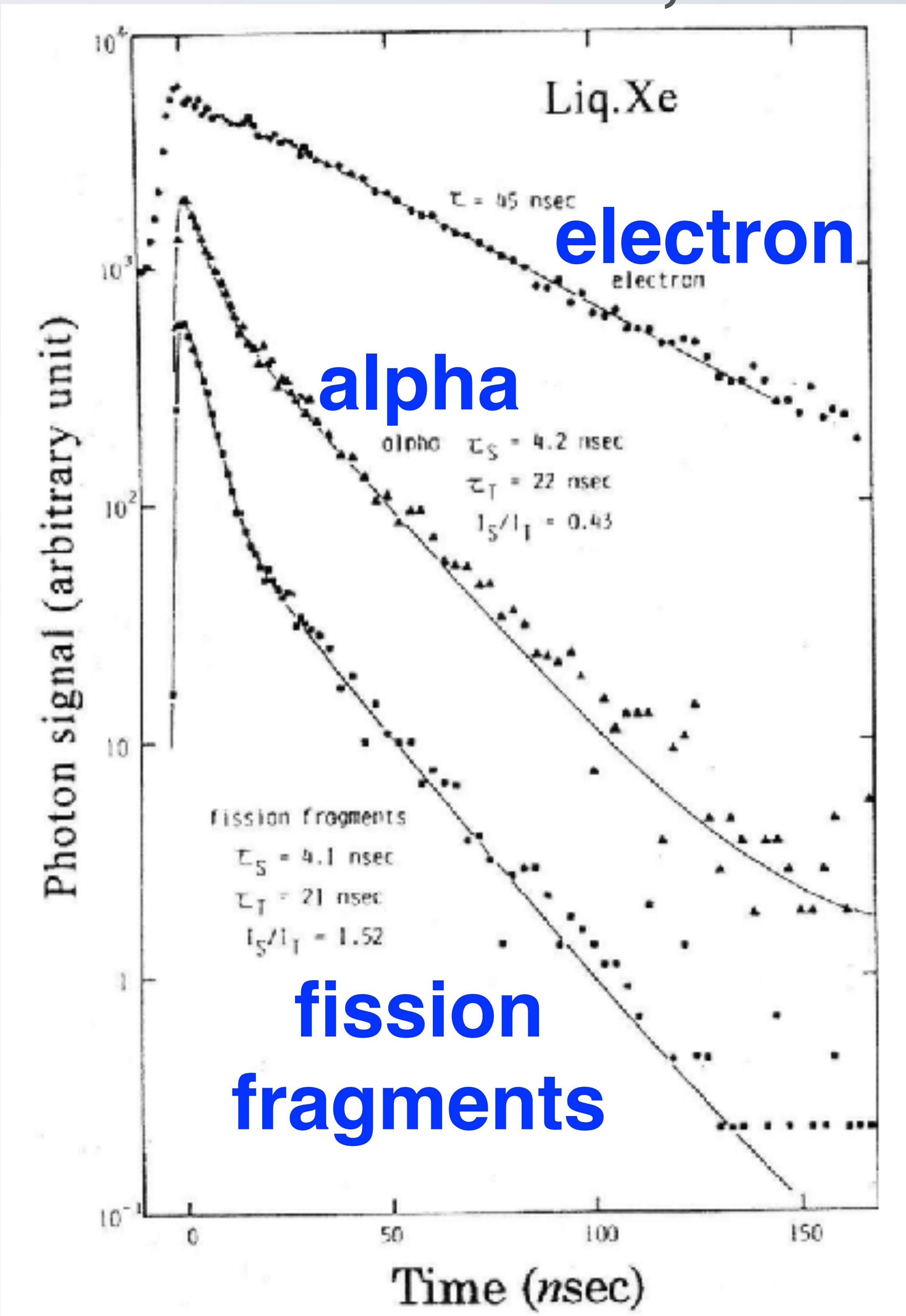
- Charged particle produces both atomic excitations and ionization
- Atomic excitations react with surrounding liquid to form excimers, which fluoresce
    - Transparent for its scintillation photons (no self absorption)
- Recombining charge also produces excimers, which fluoresce
- Excitation/Ionization ratio depends on the incident particles
- VsUV light detected by photo sensors, ionization by TPC etc.



Scintillation Pulse Shape

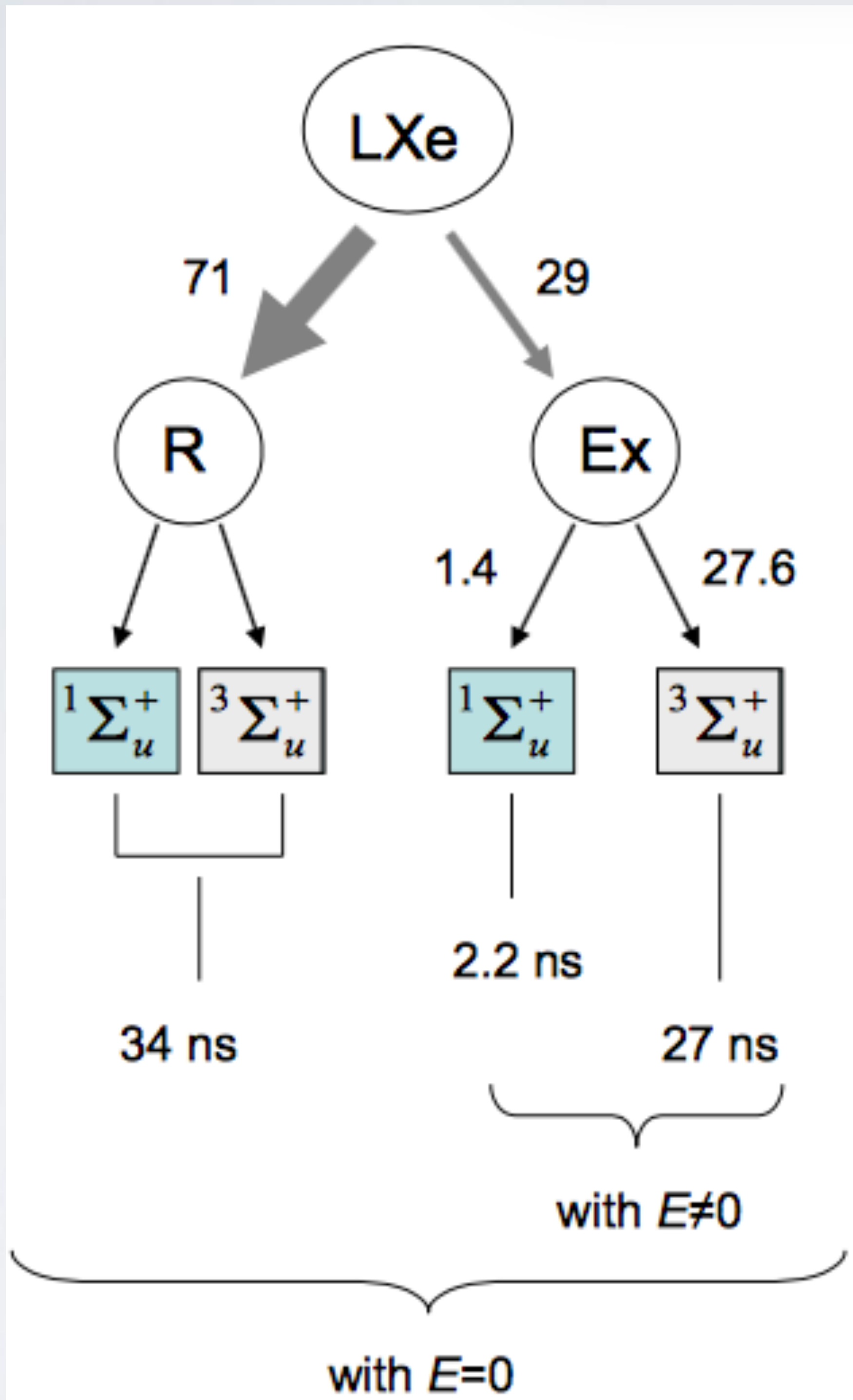
- Two decay components from de-excitation of singlet and triplet states of dimers
- Recombination speed depends on dE/dx (very fast by alpha)
- LXe: fastest of all noble liquid scintillators
    - 4ns/22ns for alpha
    - 45ns for e/γ (recombination)

Hitachi, 1983

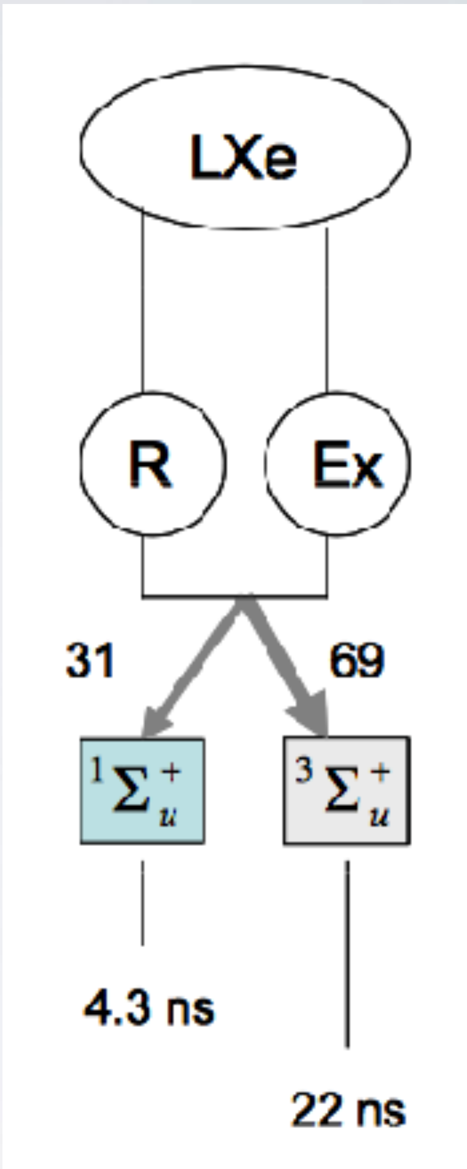


Scintillation signal

electrons



alpha-
particles



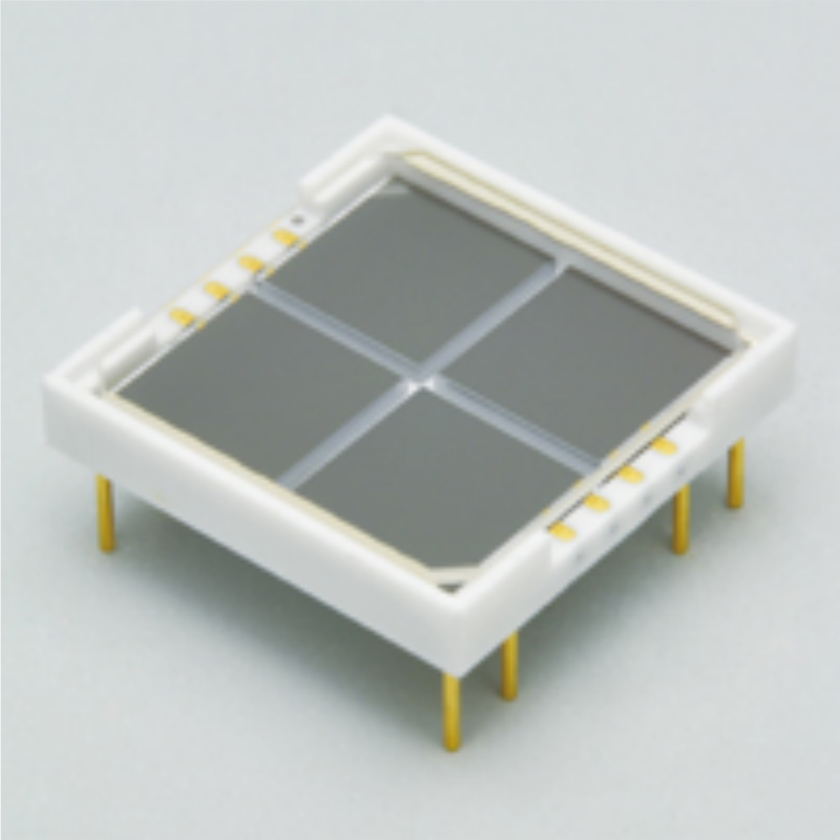
arXiv:1207.2292

- Particle ID possible by pulse shape

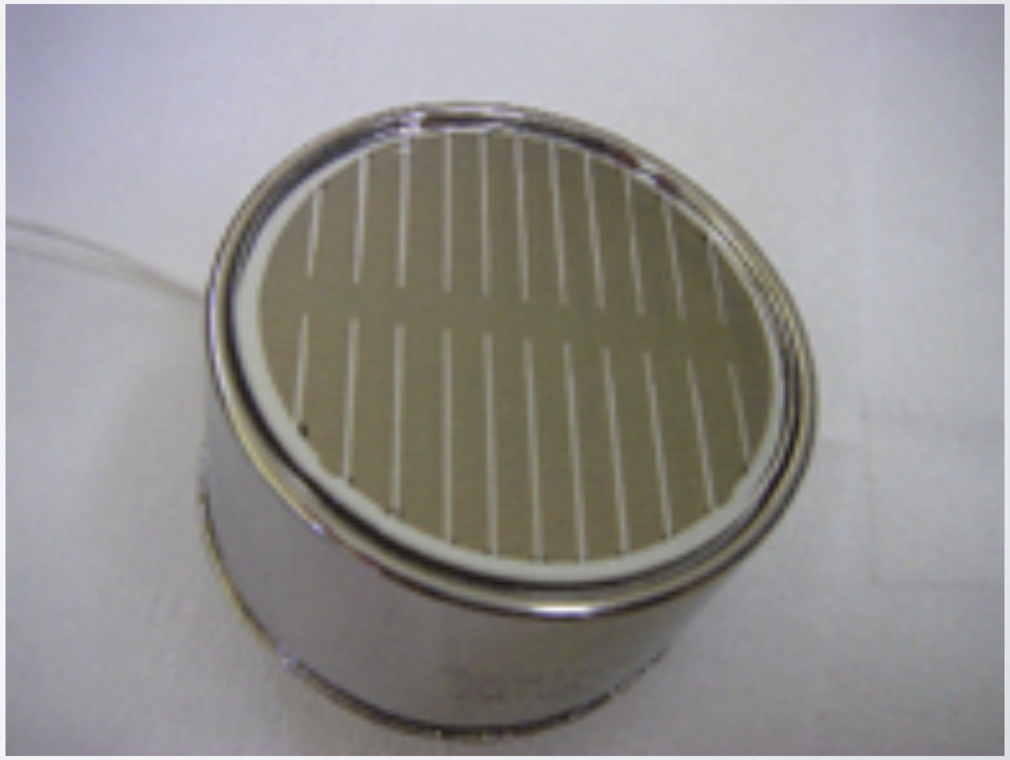
Scintillation calorimeter

- Photo-sensors for reading scintillation
  - Scintillation signal is faster than ionization
  - More expensive than reading charge (in general)
- Scintillation wavelength is shorter than other scintillators
  - Special sensors or wavelength shifter are needed

Light Collection in Liquid Xenon



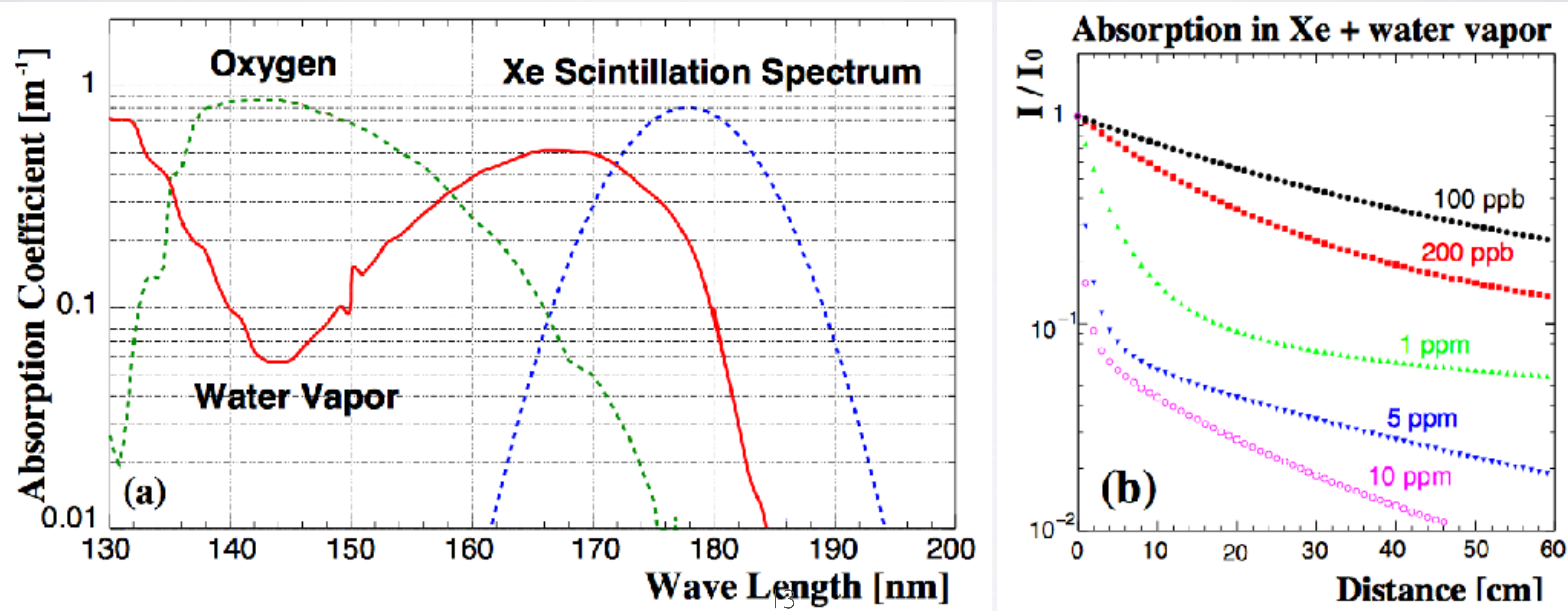
- VUV sensitive SiPMs (MEG + Hamamatsu)
- Cryogenic PMTs with fused silica windows
- Wavelength shifter (TPB etc.) deposited on PMT, SiPM or APD
- WLS coated plated in front of photo-sensors
- WLS coated on reflective detector wall
- Light guide (Acrylic bar coated with WLS) coupled to SiPM
- Large area picosecond photo-detector (LAPPD)
- Quartz photon intensifying detector (QUPID)



Light attenuation by impurities

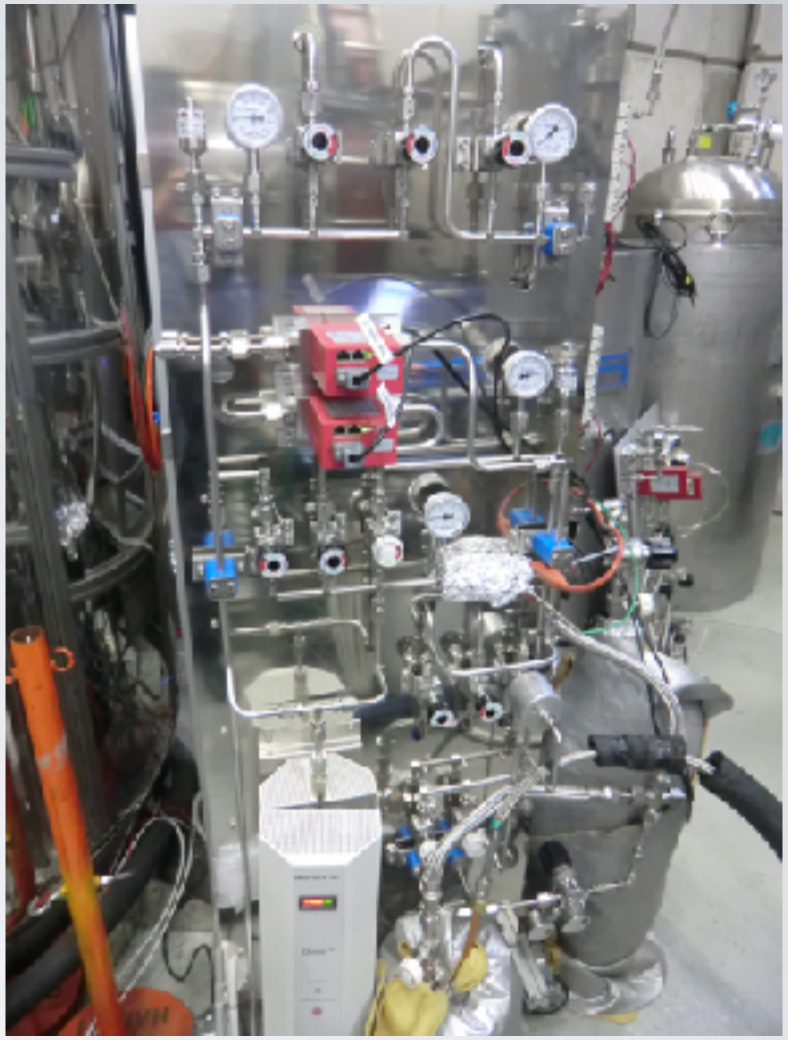
- Impurities (water, O_2, …) dissolved in the liquid absorb UV photons, reducing the light

Ozone, 2005



How to remove impurities?

- Evacuation of the cryostat
  - If there are PMTs etc. we can not bake it.
- Gaseous purification
  - Heated Metal Getter Purifier
    - Zirconium metal forms irreversible chemical bonds
    - Almost all impurities (except inert gases) can be removed!
    - Slow (~4L/h)
- Liquid purification
  - Molecular sieves (Zeolites)
    - Very small holes can absorb mainly water
    - fast (~40L/h)

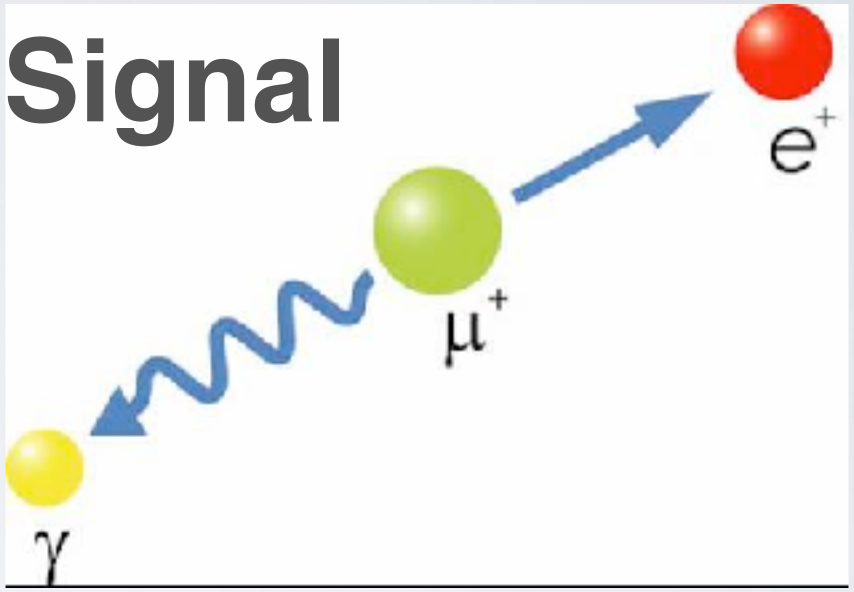


MEG II Liquid Xenon Detector

MEG experiment

- Lepton flavour violating muon decay ($\mu^+ \rightarrow e^+\gamma$) search experiment
- $3\times10^7 \mu^+/s$ beam rate at PSI
- Upper limit of the branching ratio of $\mu^+ \rightarrow e^+\gamma$ 4.2×10^{-13} (2016)

Signal



Back-to back
Coincident
$E_e = E_\gamma = 52.8\text{MeV}$

Background

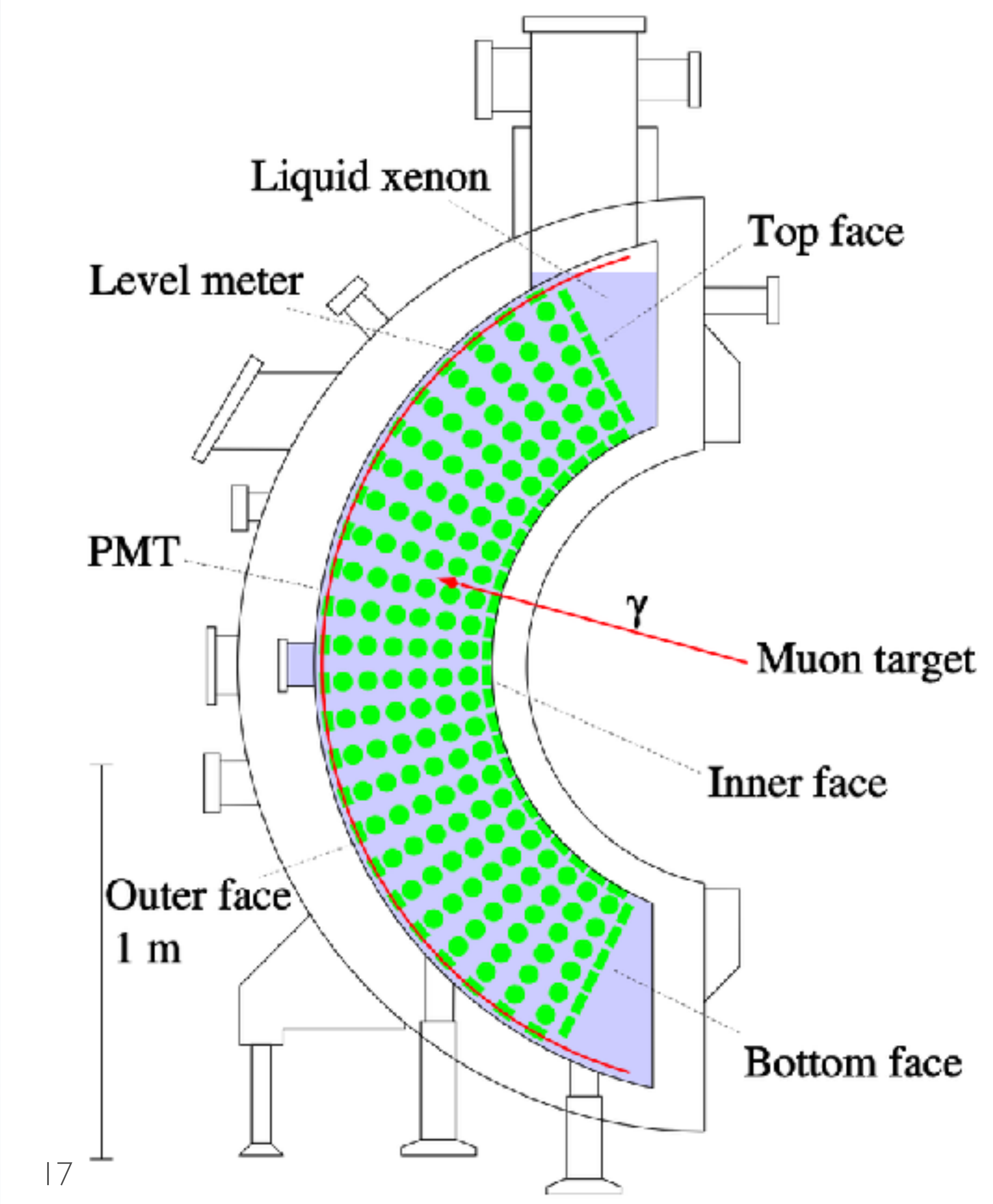
Accidental e^+ and γ, RMD

$$N_{acc} \propto (R_\mu)^2 \times T \times (\Delta E_\gamma)^2 \times \Delta E_e \times (\Delta\Theta_{e\gamma})^2 \times \Delta t_{e\gamma}$$

All the detector resolutions important to reduce the accidental background

MEG LXe detector

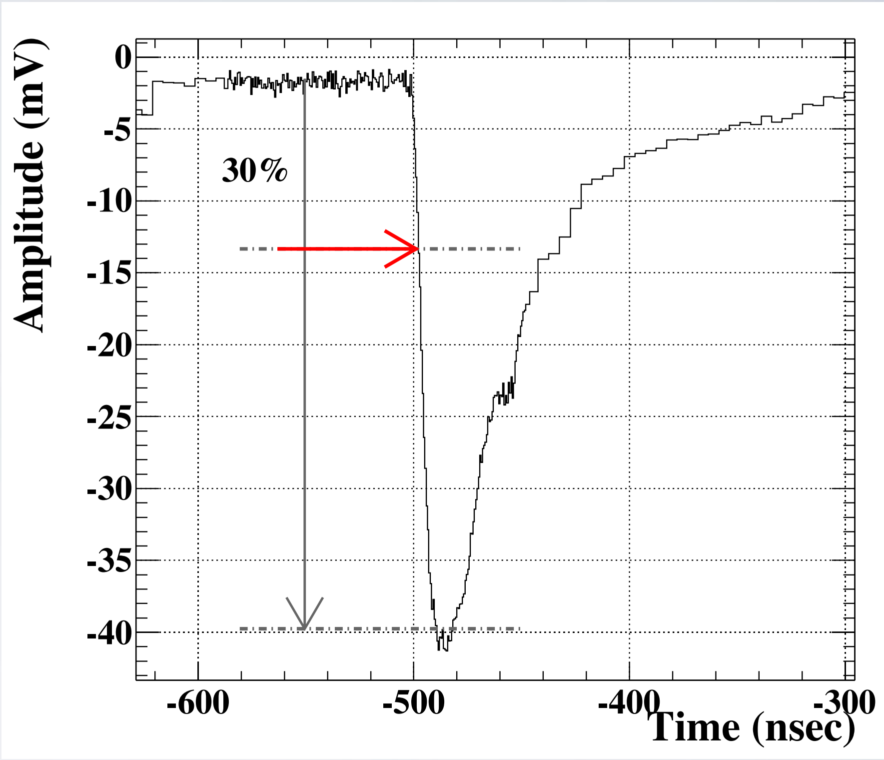
- The largest (900 liters) LXe detector (at least in 2008)
  - Pioneer experiment for large liquid xenon detectors
- 846 VUV sensitive PMTs directly detect scintillation photons (QExCE~16% for 175nm photons)
- Excellent energy, position and time resolutions
- Pileup-identification capable by using waveform and charge distribution



Reconstruction

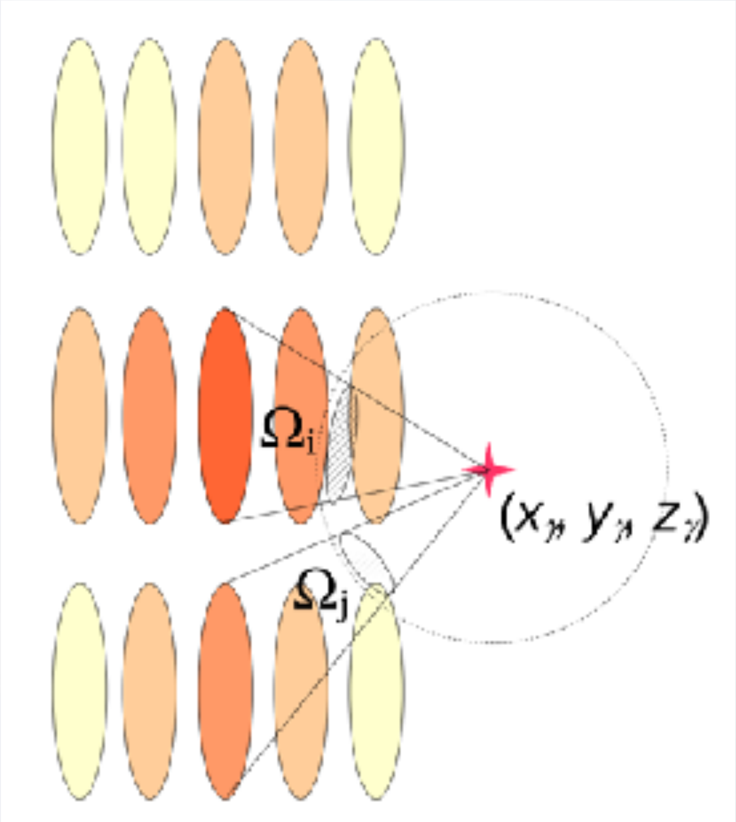
- Position
  - light distribution on gamma incident face

$$\chi^2_{\mathrm{pos}} = \sum_i \frac{N_{pho,i} - c \times \Omega_i(x_\gamma, y_\gamma, z_\gamma)}{\sigma_{pho,i}(N_{pho,i})}$$



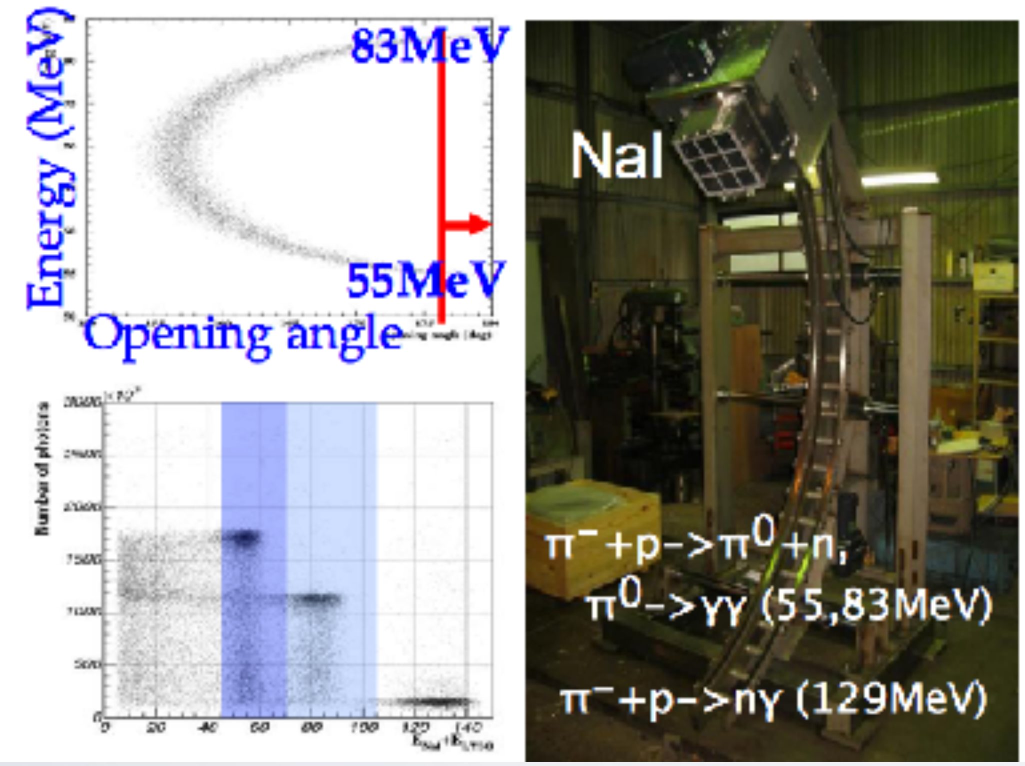
- Energy
  - Charge sum of all photo sensors
- Timing
  - Arrival time of scintillation light more than 50 photoelectrons

$$\chi^2_{\mathrm{time}} = \sum_i \frac{(t_{hit,i} - t_{LXe})^2}{\sigma_{t,i}(N_{pe})^2}$$

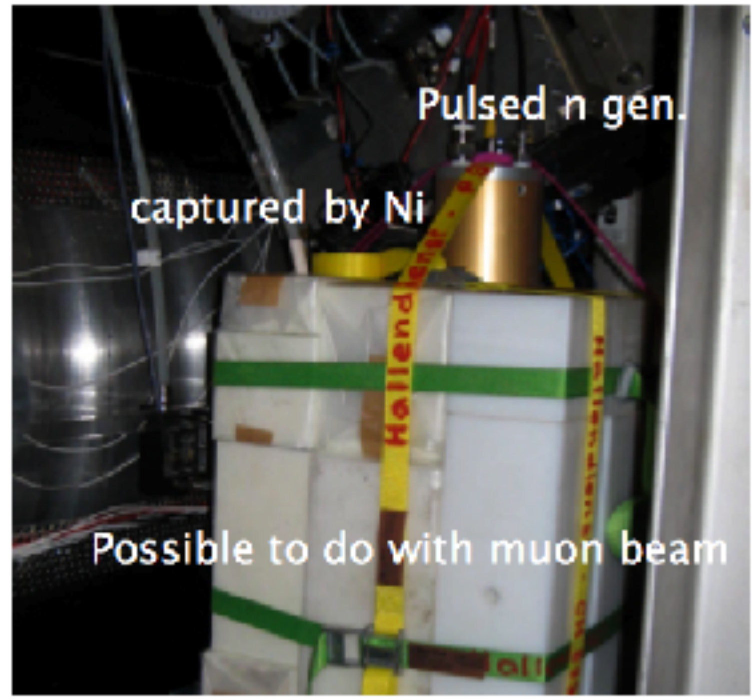


Calibration

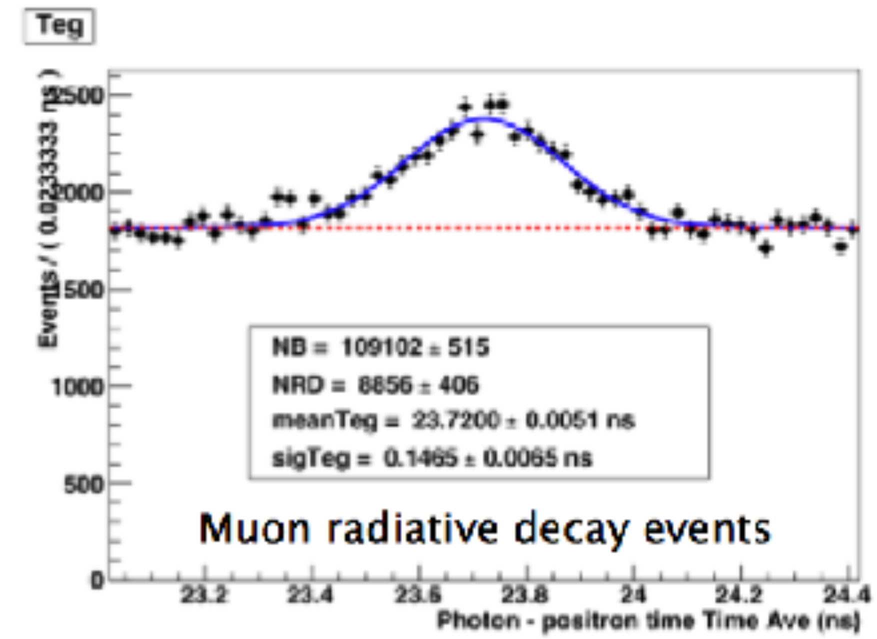
55MeV γ



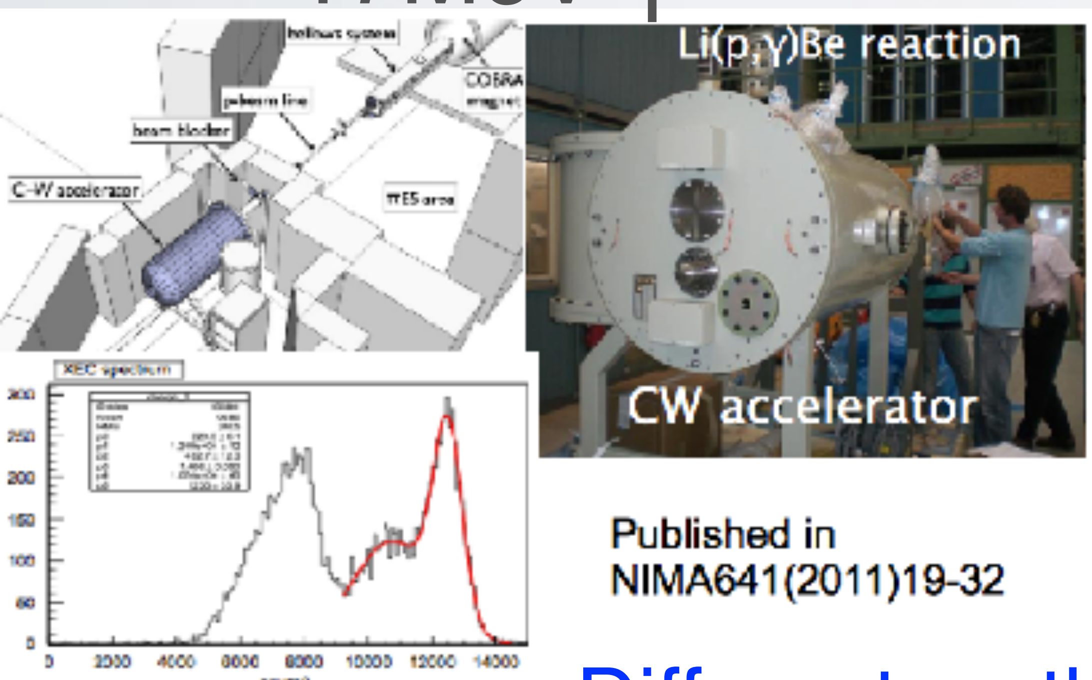
9MeV γ



Timing resolution



17MeV γ



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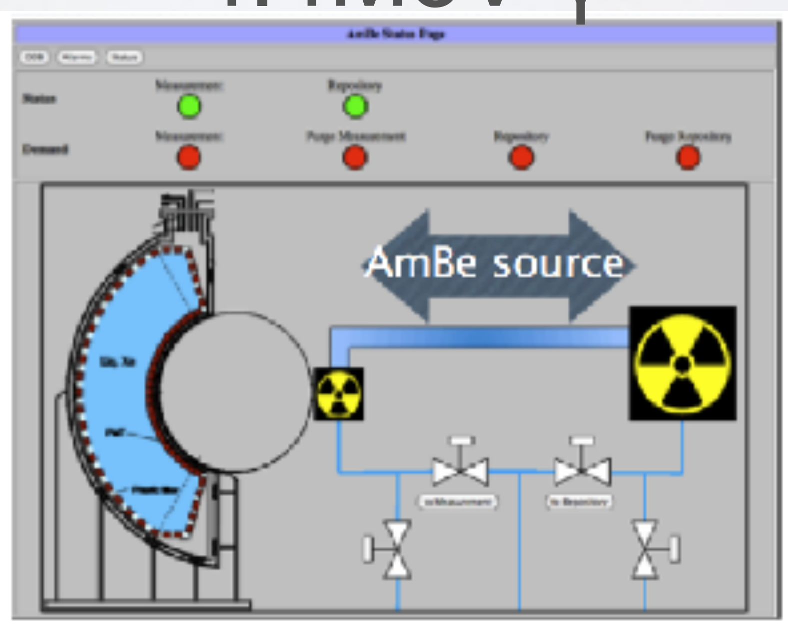
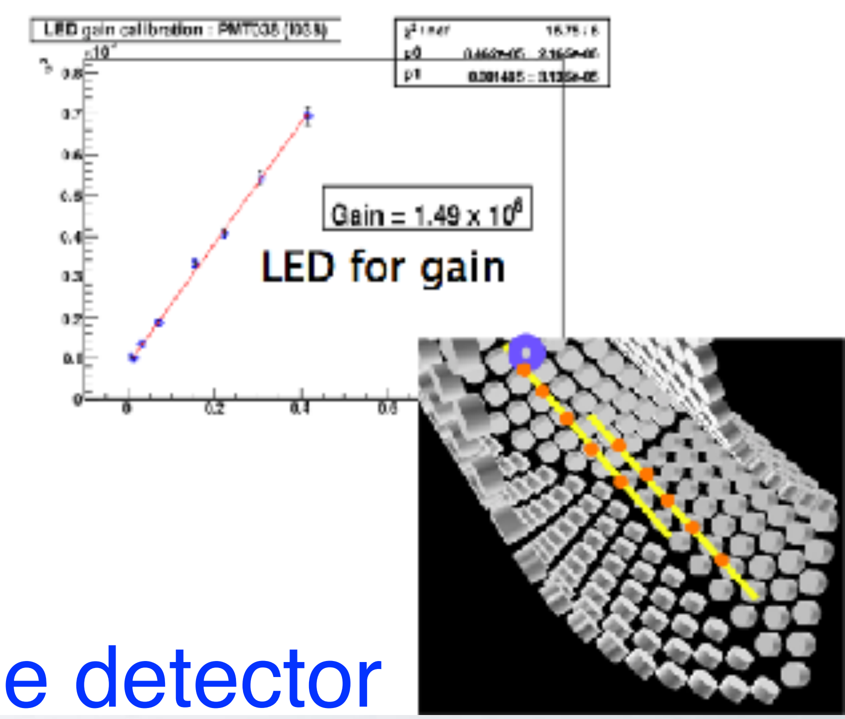
4.4MeV γ



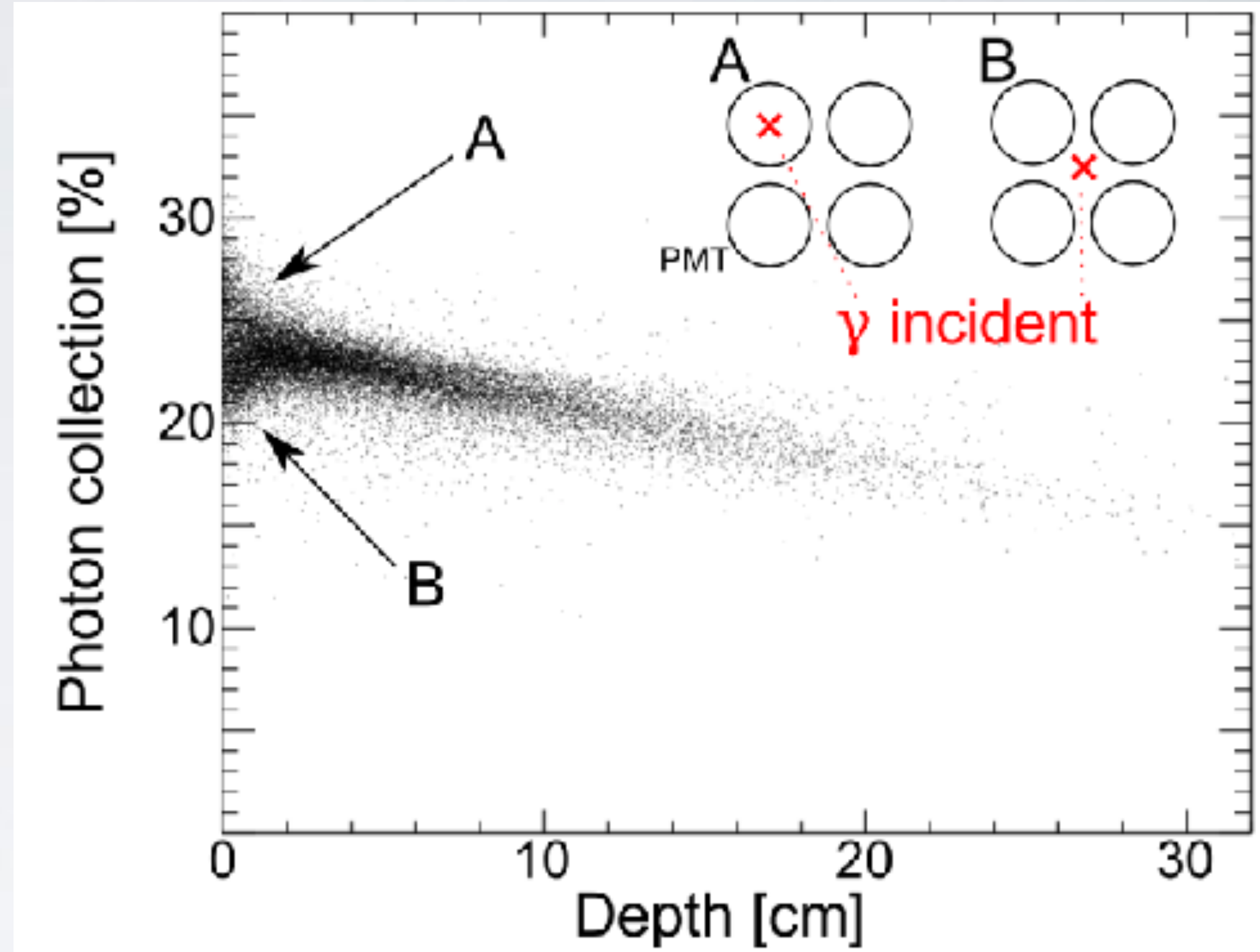
LED, α

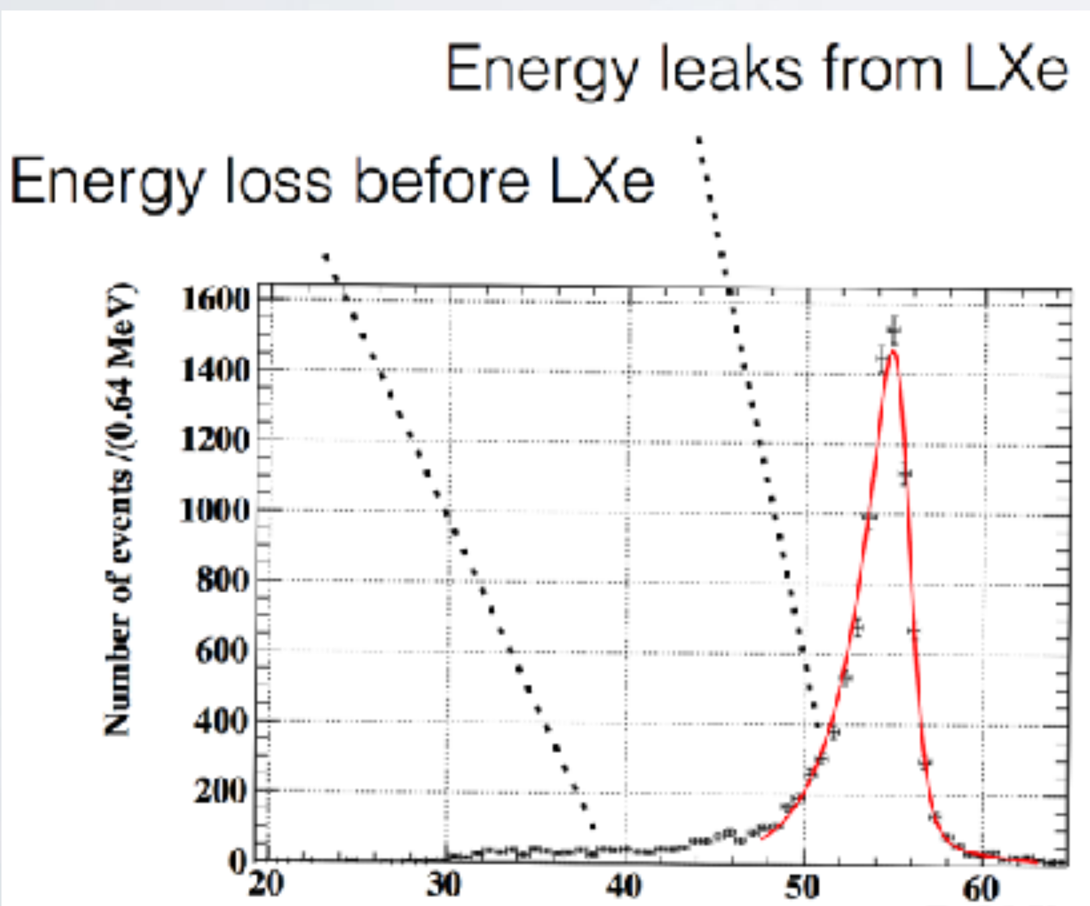


Different methods to understand the detector

Calorimeter performance limitation

- Resolution of shallow events (~40%) is worse because of large position dependence of photon-collection efficiency
- Lower energy tail due to energy loss of γ before entering LXe and energy leaks from the inner or lateral faces

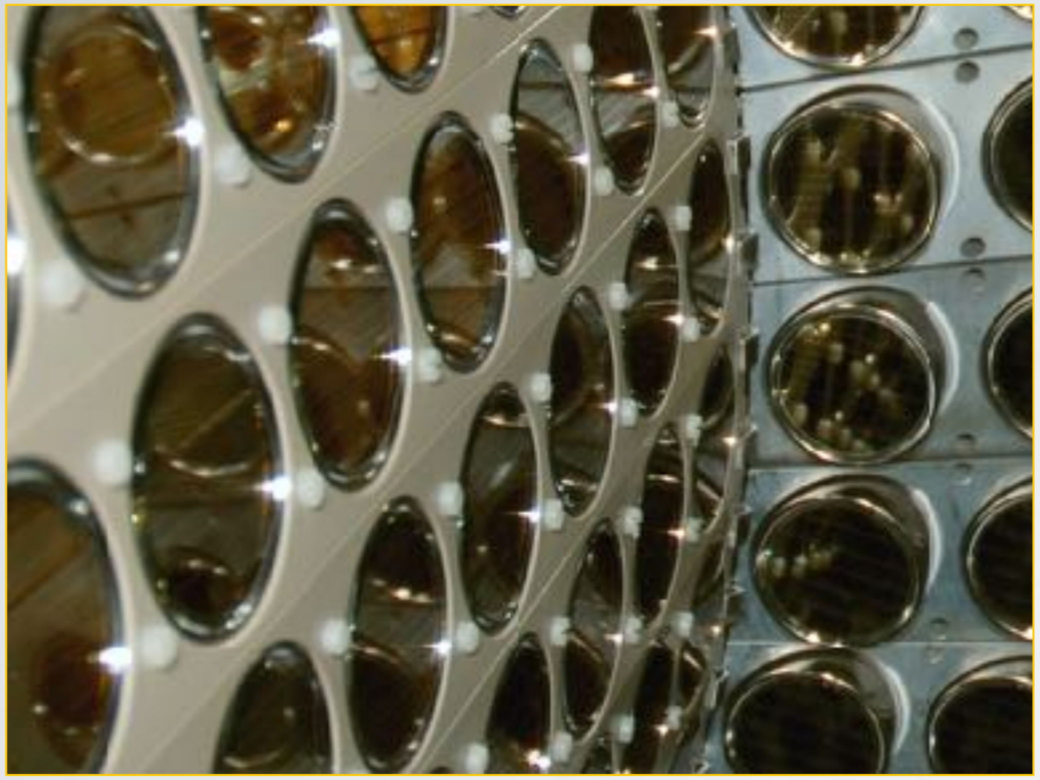




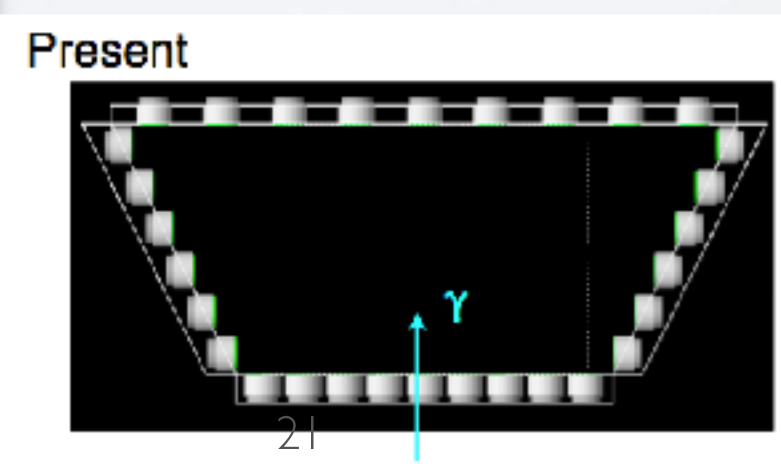
Energy spectrum for 55 MeV γ

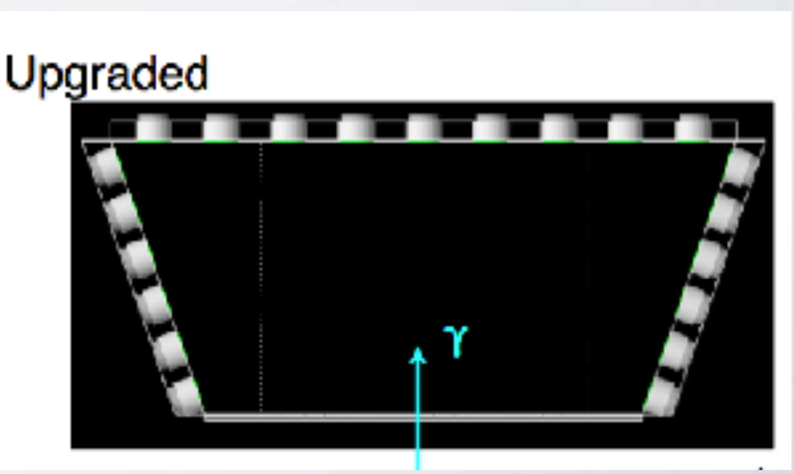
	shallow events / deep events (d > 2cm)
Energy resolution [%]	2.4 / 1.7
Position resolution [mm]	5
Time resolution [ps]	67
Efficiency	64.7

MEG II LXe detector

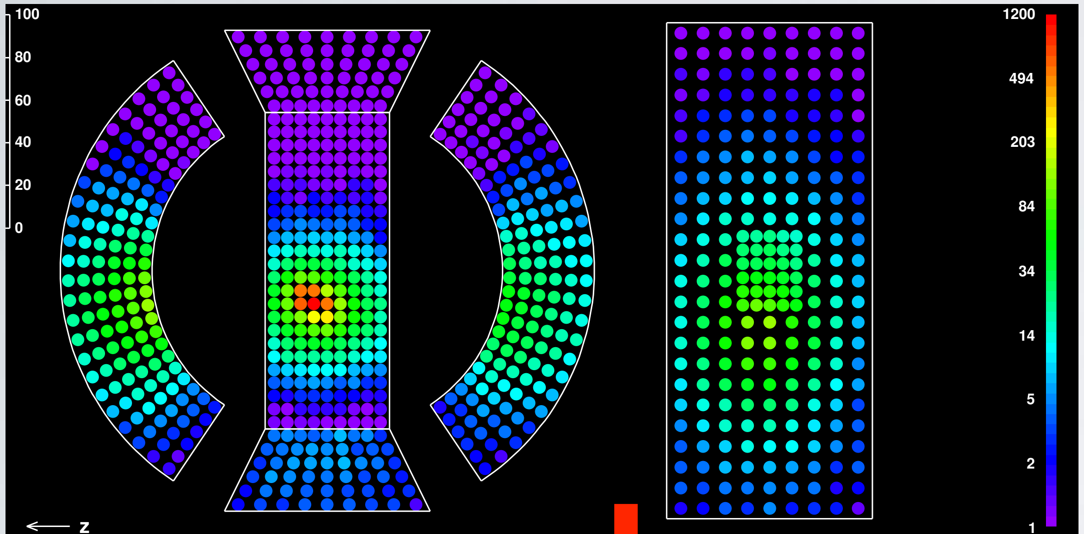


- 900L LXe (cryostat reused)
- Finer granularity for γ incident face
  - 216 2” diameter PMT
    → 4092 12x12mm² MPPCs
- 668 PMTs for top/bottom/lateral faces
- Wider incident face
- Lateral PMT slant angle

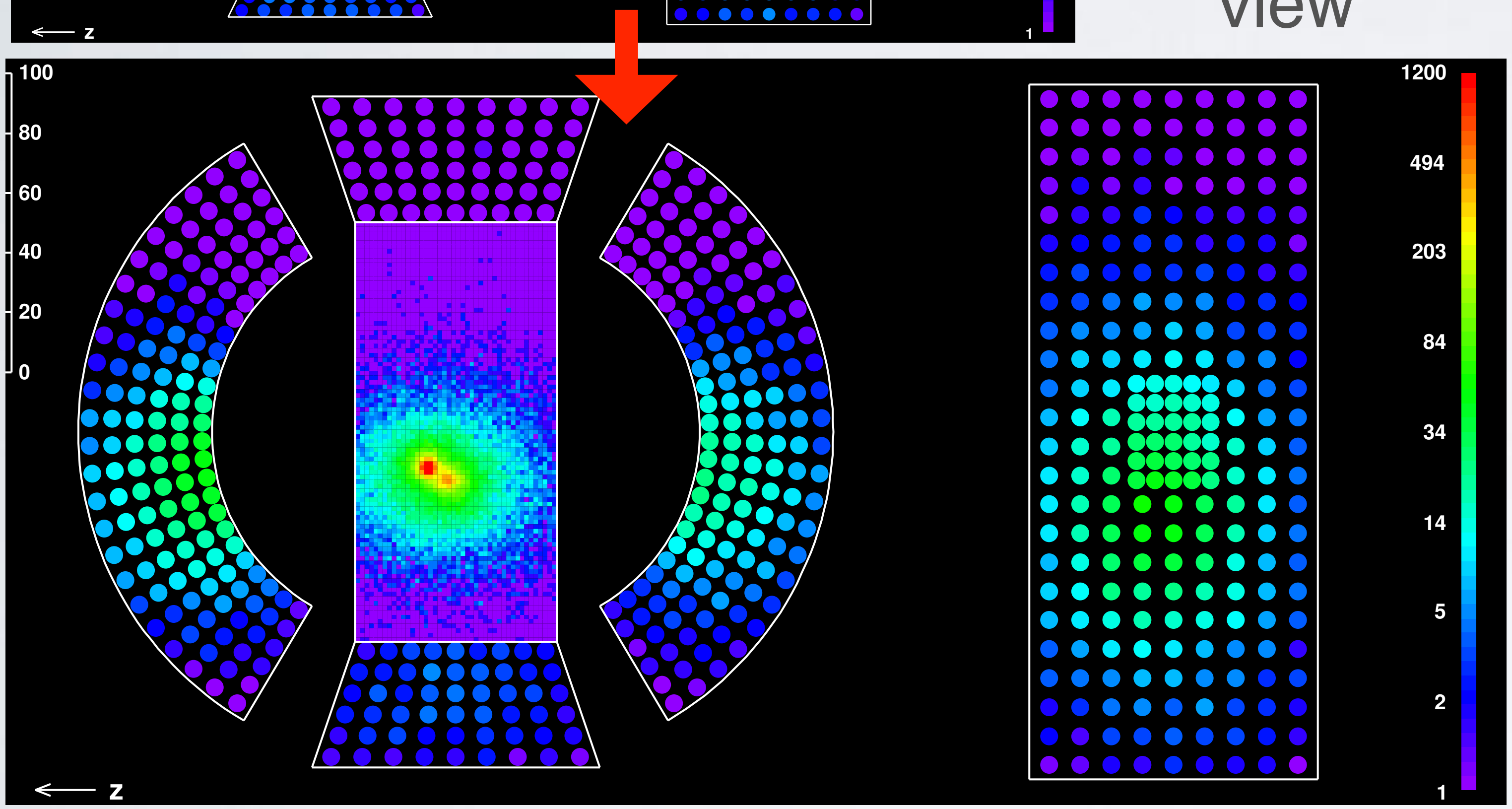


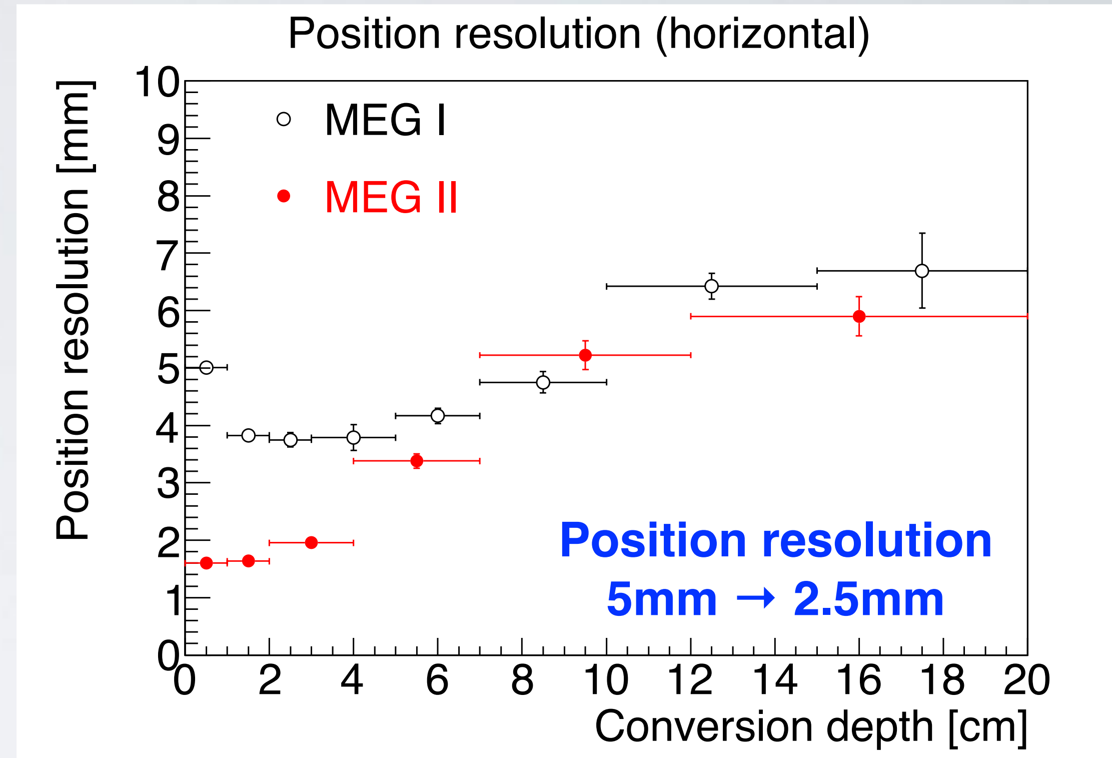


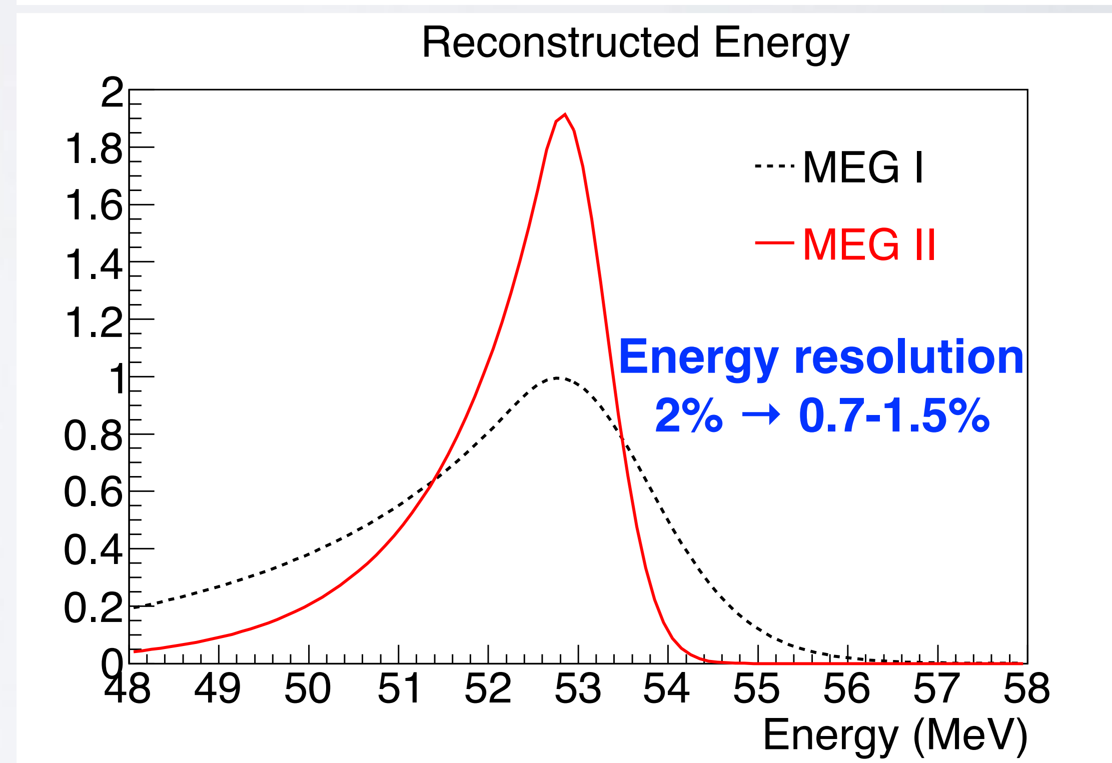
Expected performance



Development view



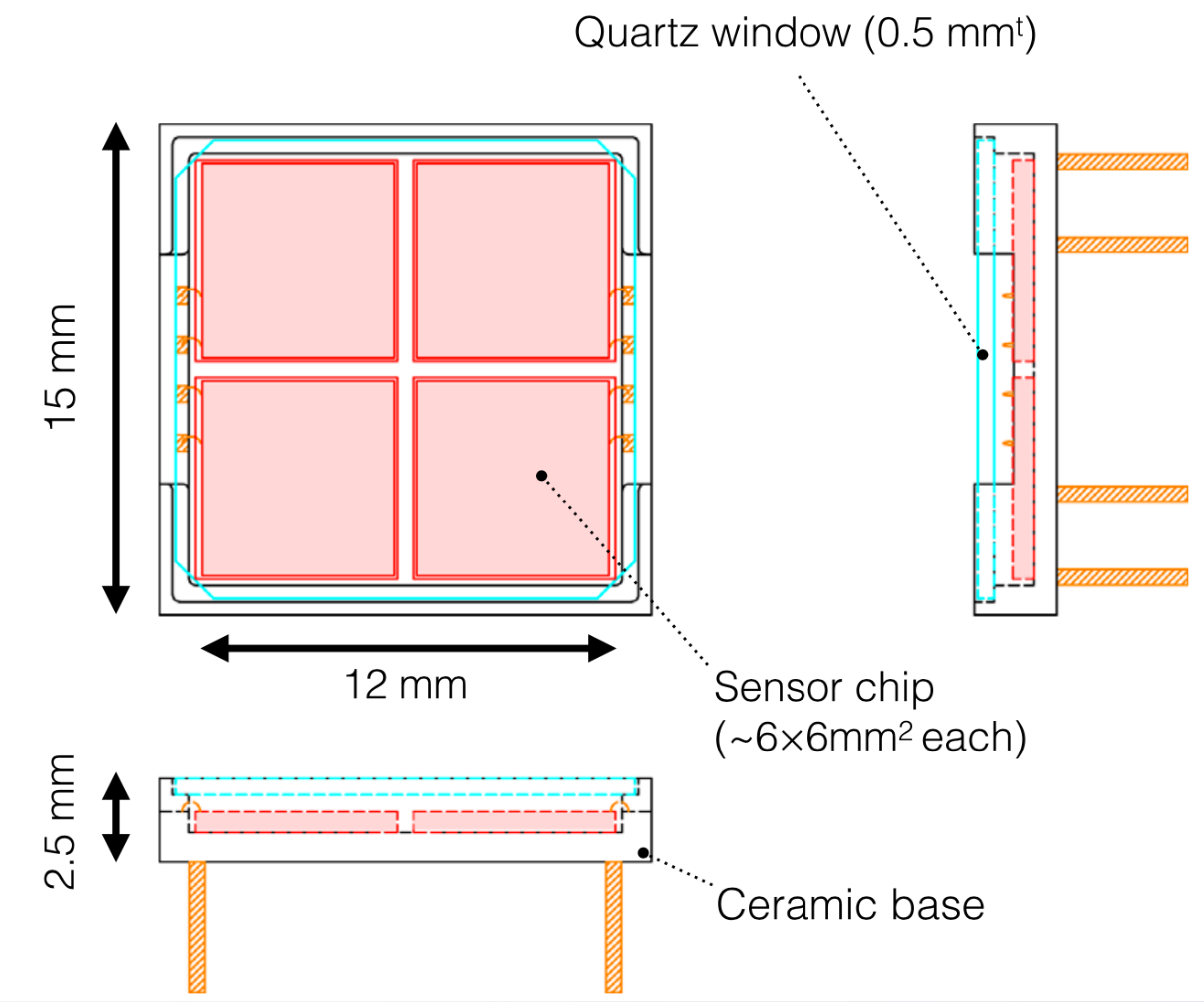


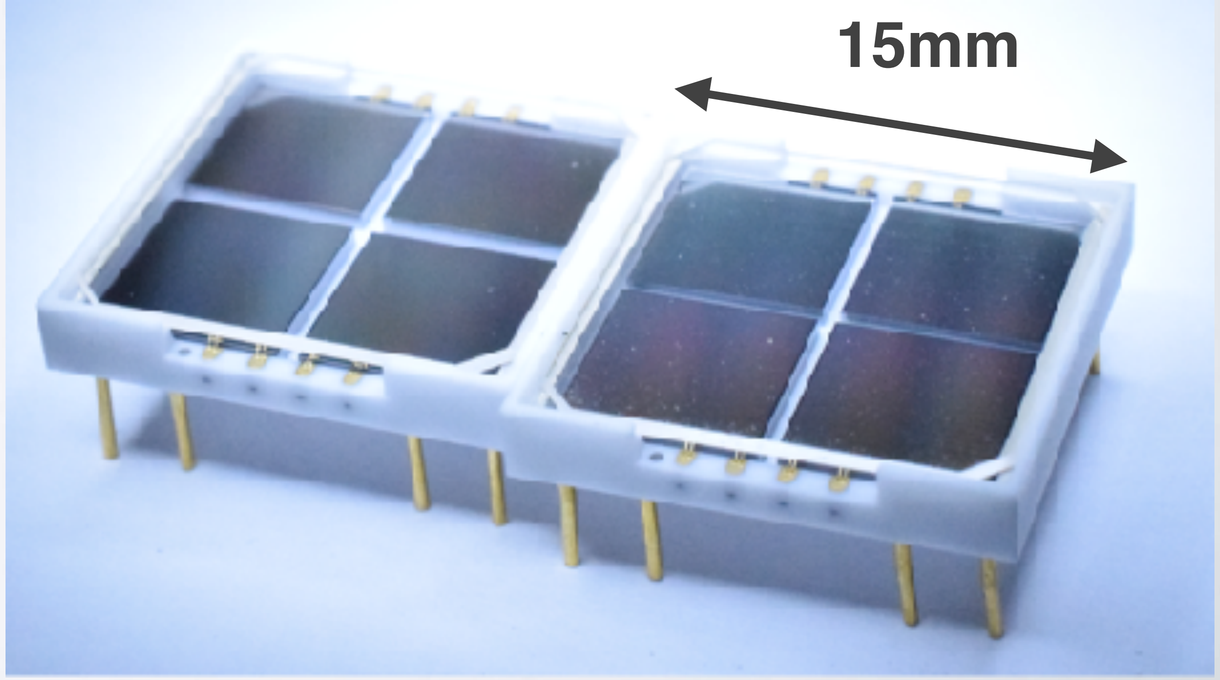


- Finer granularity, better uniformity, less shower leakage
- Less material budget (detection efficiency 65% → 70%)
- Timing resolution 67ps → 50-70ps

New SiPM development

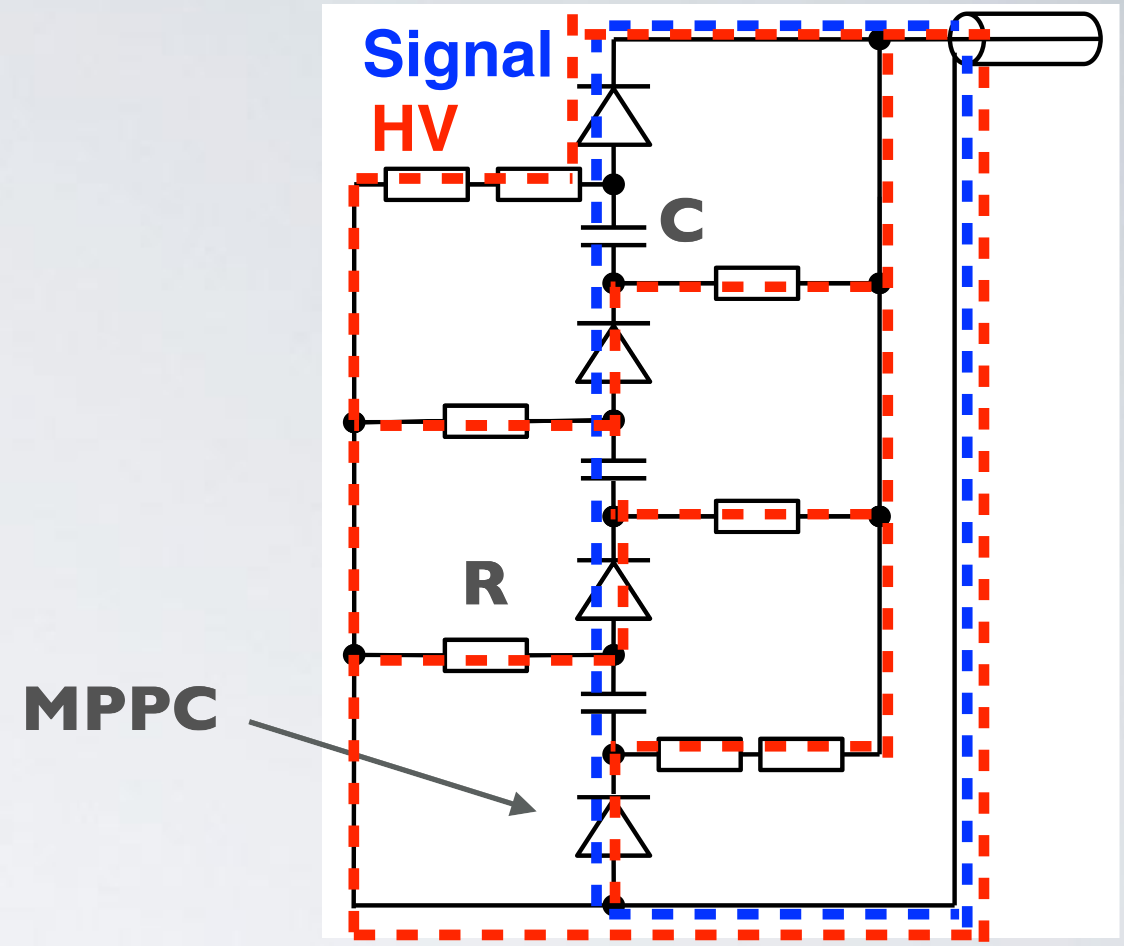
- 2” diameter PMT (Hamamatsu, R9869)
  - working in LXe, developed for MEG in collaboration with Hamamatsu. QE ~ 15%
- SiPM is a good candidate to replace PMT
  - 1p.e. peak resolution, insensitive to magnetic field, thin, lower bias voltage etc.
- MPPC for MEG II (Hamamatsu, S10943-4372)
  - MPPC is a kind of SiPM, produced by Hamamatsu
  - Four 6x6 mm^2 chips, ceramic package, 50μm pixel pitch, VUV-sensitive, quartz window in front of SiPM, metal quench resistor

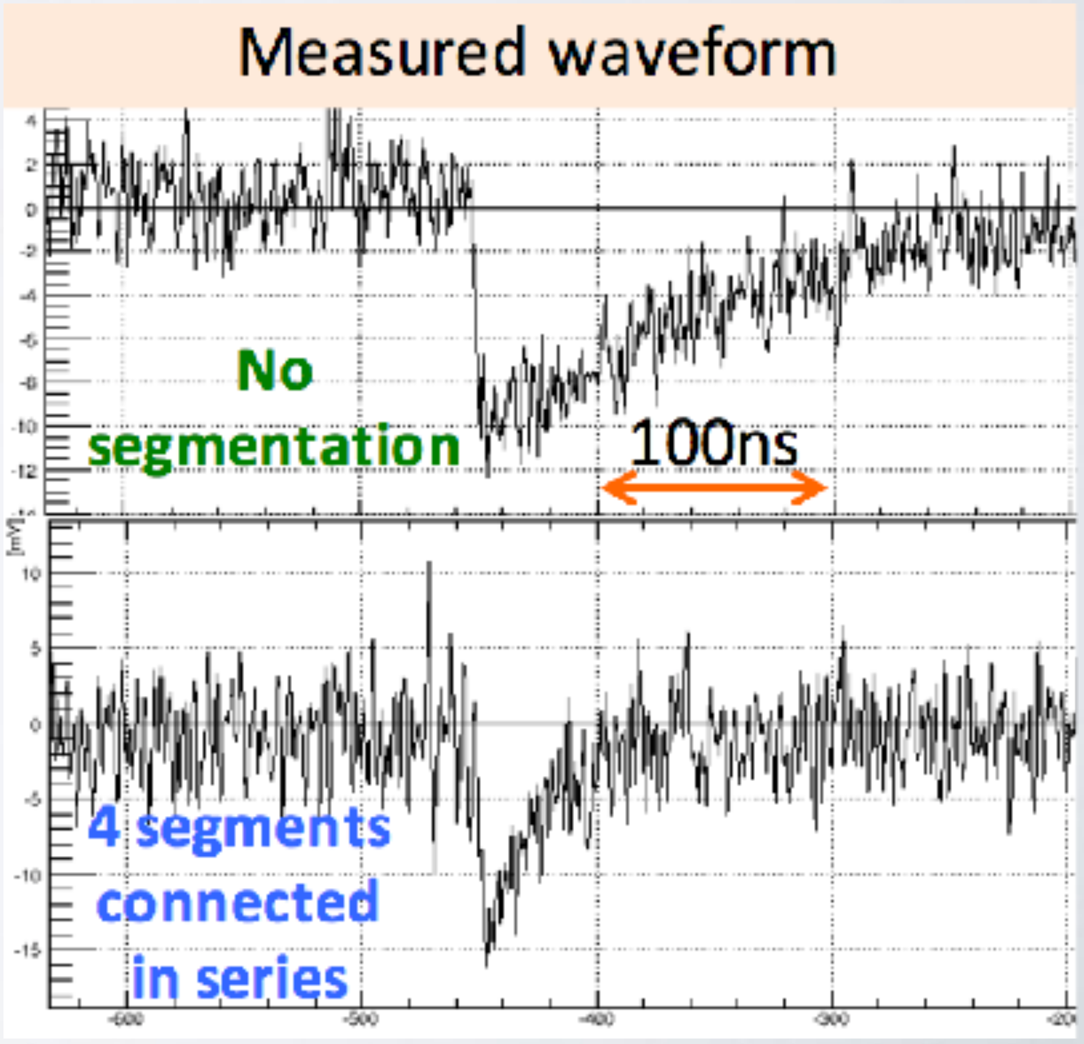




Large Area SiPM

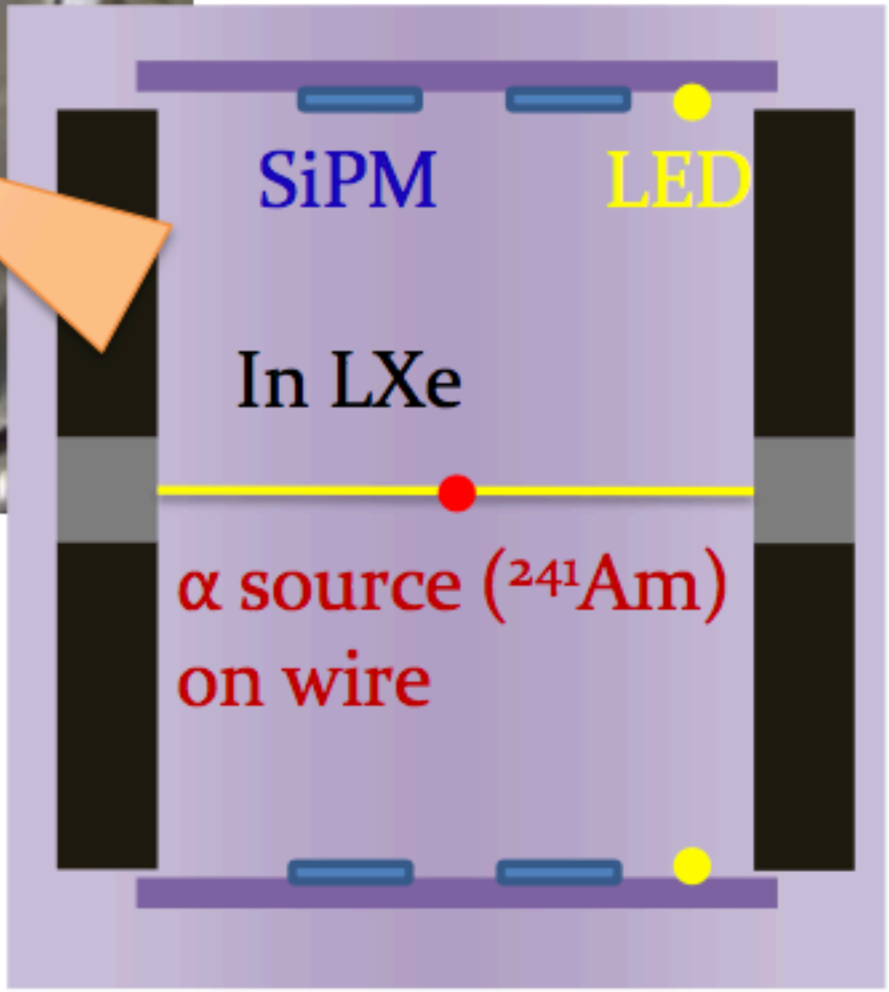
- Large area SiPM in general has
  - large capacitance, long signal tail
  - large dark rate
- Our solution (to make a single ch. 12x12mm^2 MPPC)
  - Segmented into 4 chips, which are connected in series for signal readout line, in parallel for voltage supply line
    - Avoid large capacitance, manageable signal tail is realized (<50ns)
    - Common bias voltage (~65V)
  - Dark noise suppressed at low temperature
  - Single photoelectron peak can be resolved





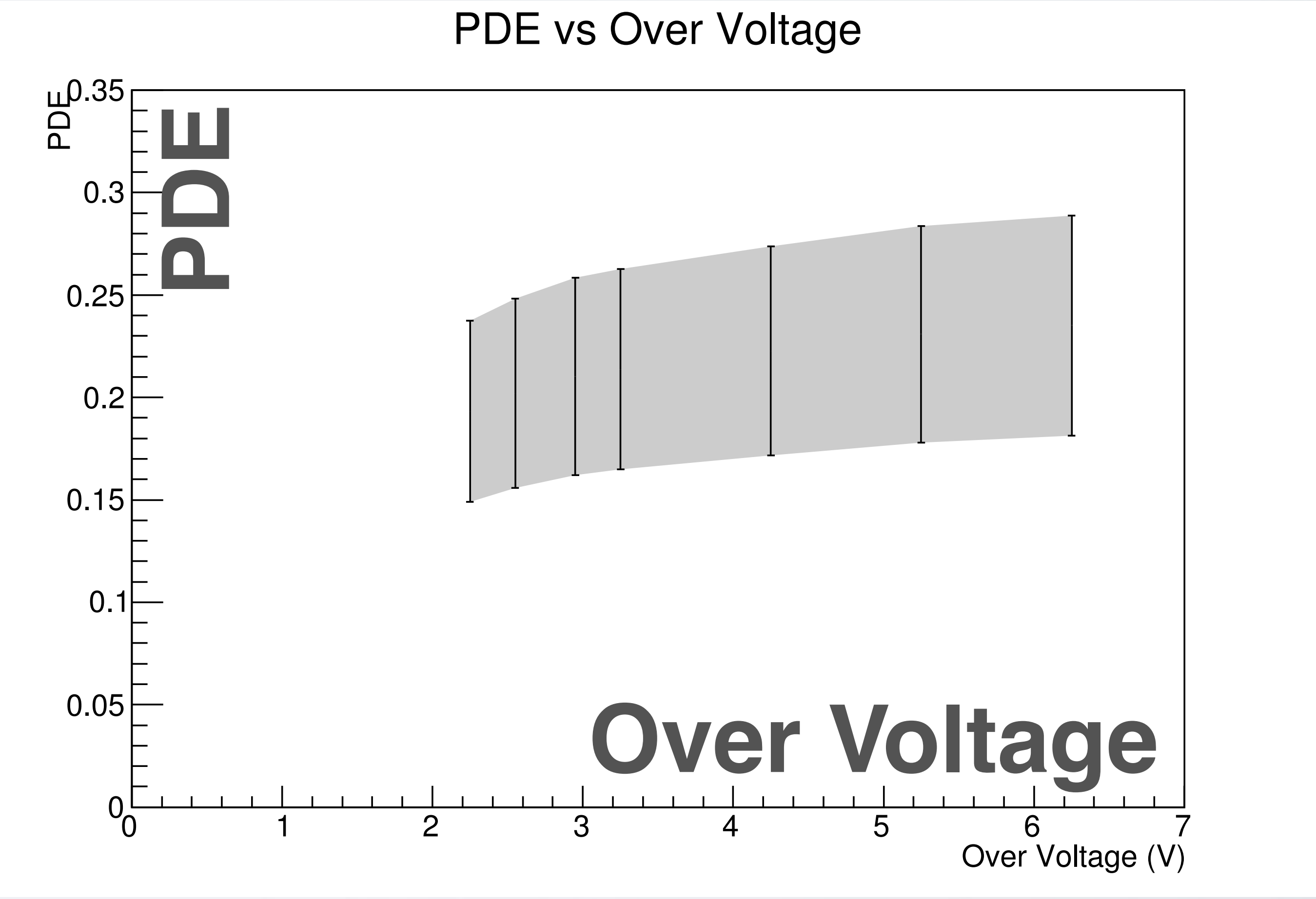
Setup for R&D

- 2L LXe test chamber at Paul Scherrer Institute (PSI) in Switzerland
  - Small setup to develop new SiPM quickly
- Basic properties of SiPM
  - PDE measured with alpha source ^{241}Am with non-reflective coating
  - Single photoelectron peak
  - LED light for gain, cross-talk, after-pulse

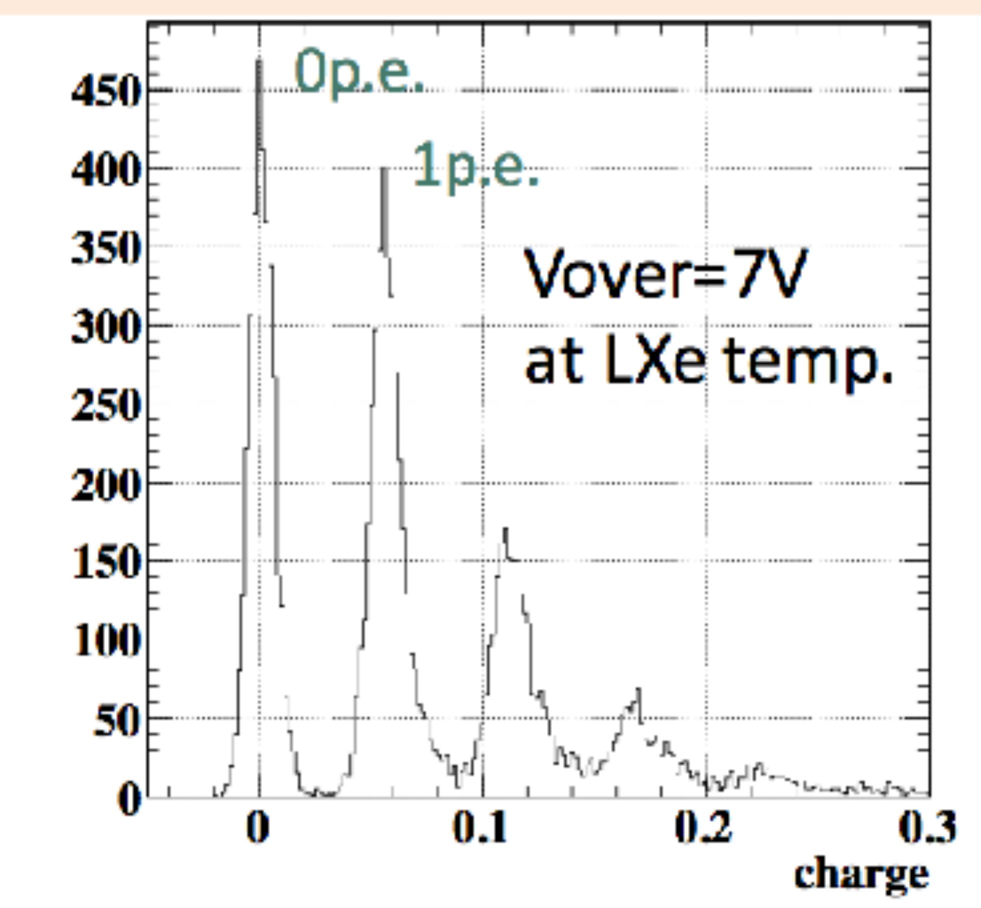


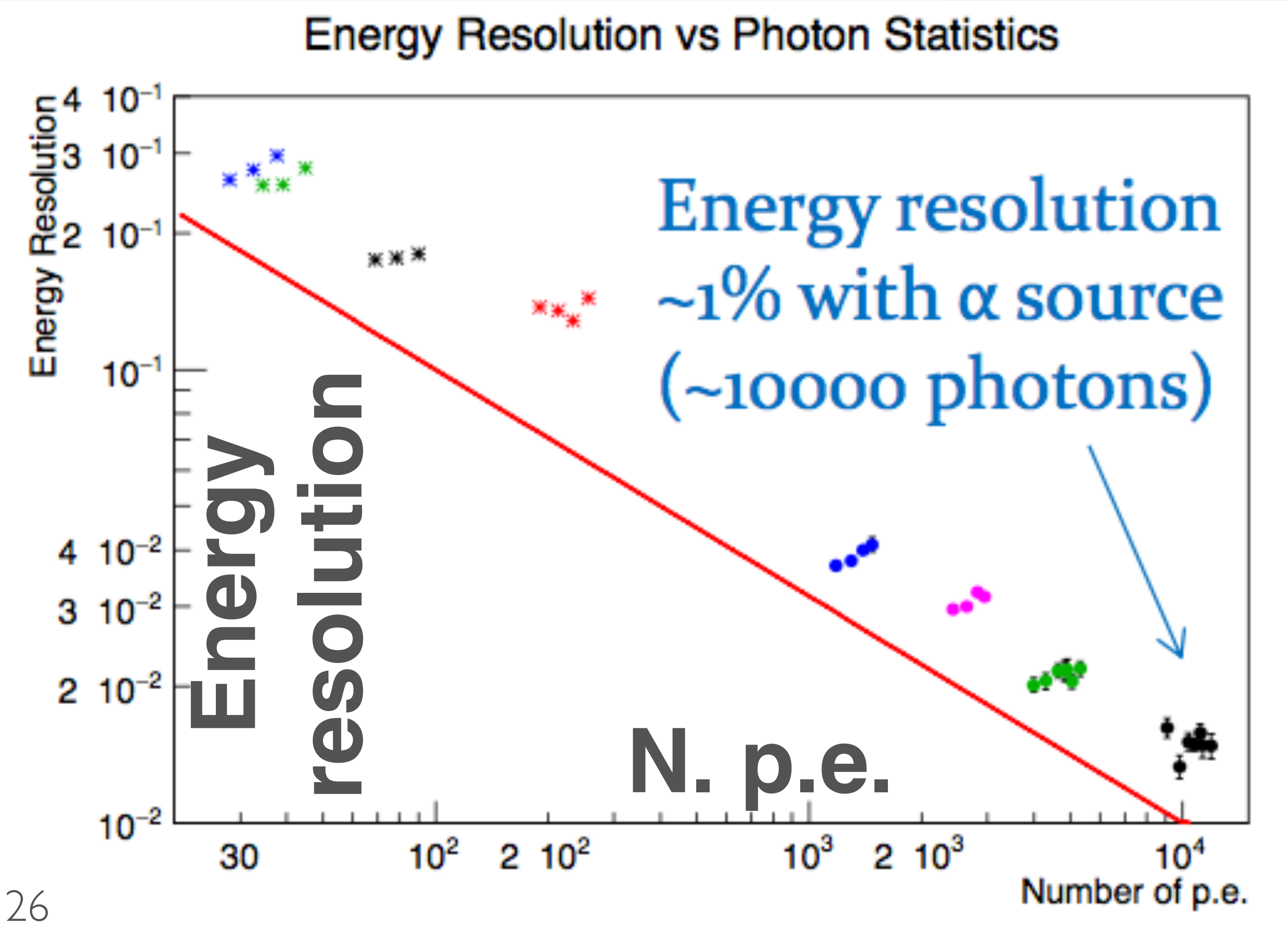
Performance

- Vover ~ 7V, w/ series connection
- Single photoelectron peak resolved
- Gain: 8x10^5, PDE>~15%, Signal decay time: 30ns
- Energy resolution still improves at large number photoelectron region



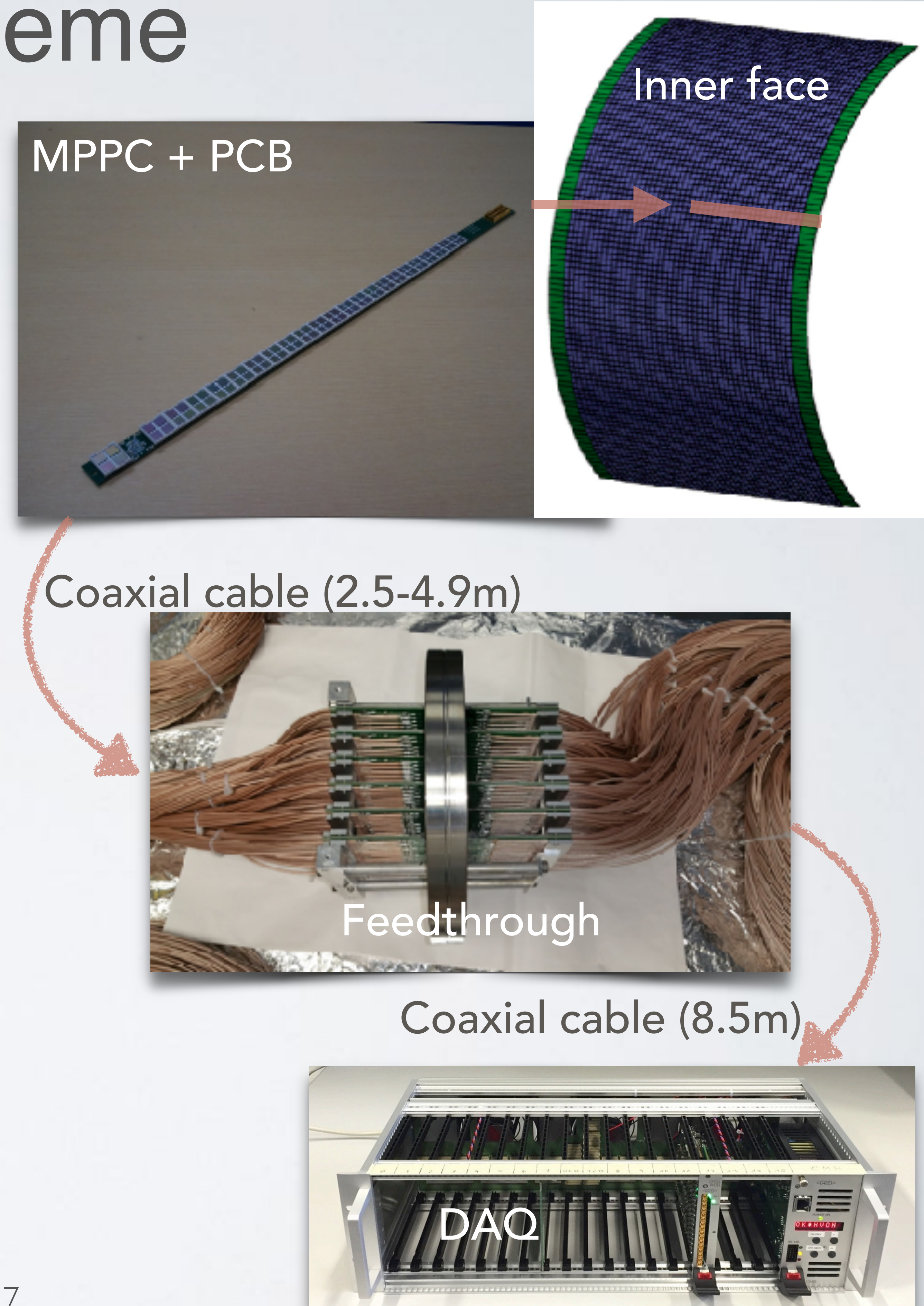
Charge distribution using LED





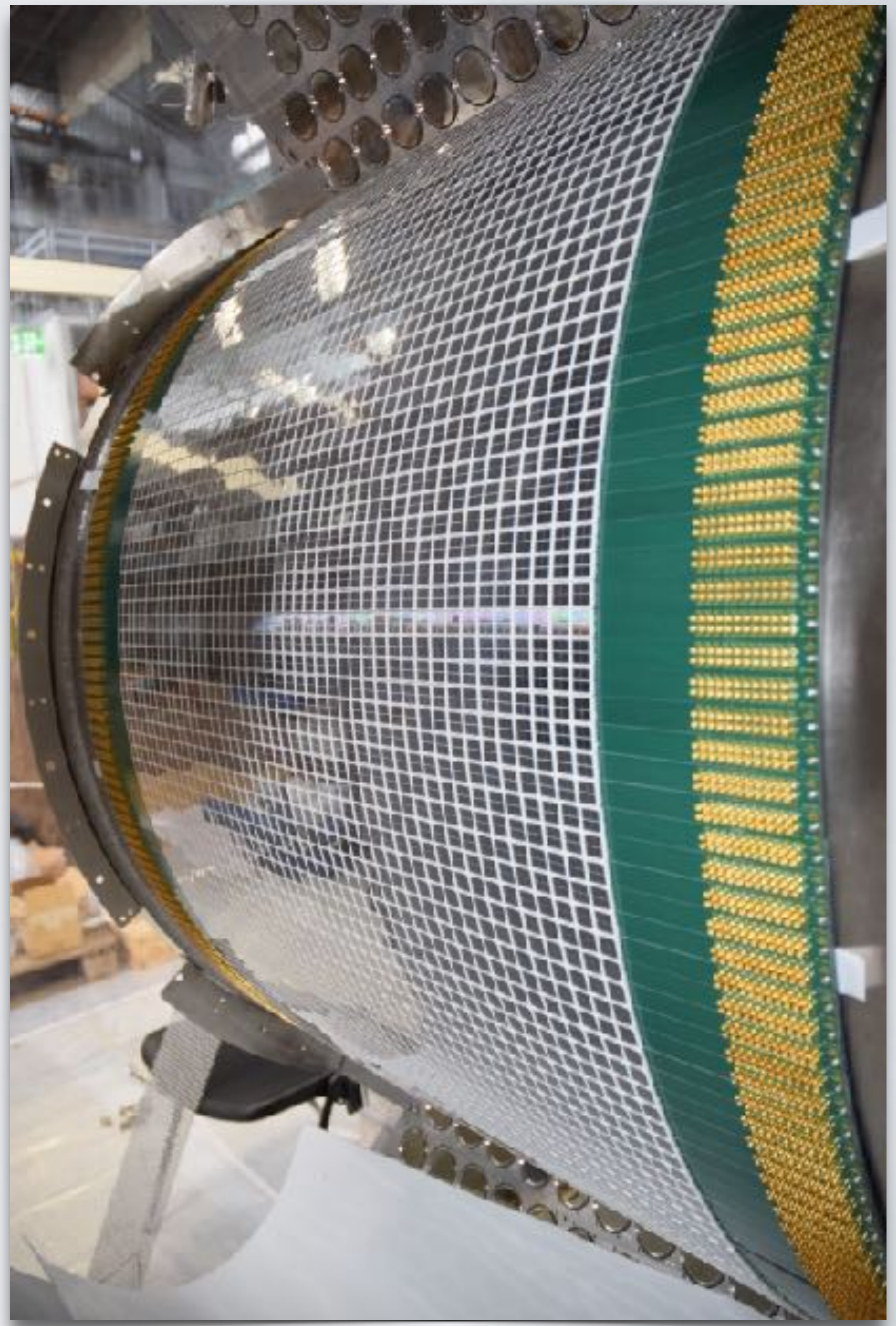
Signal readout scheme

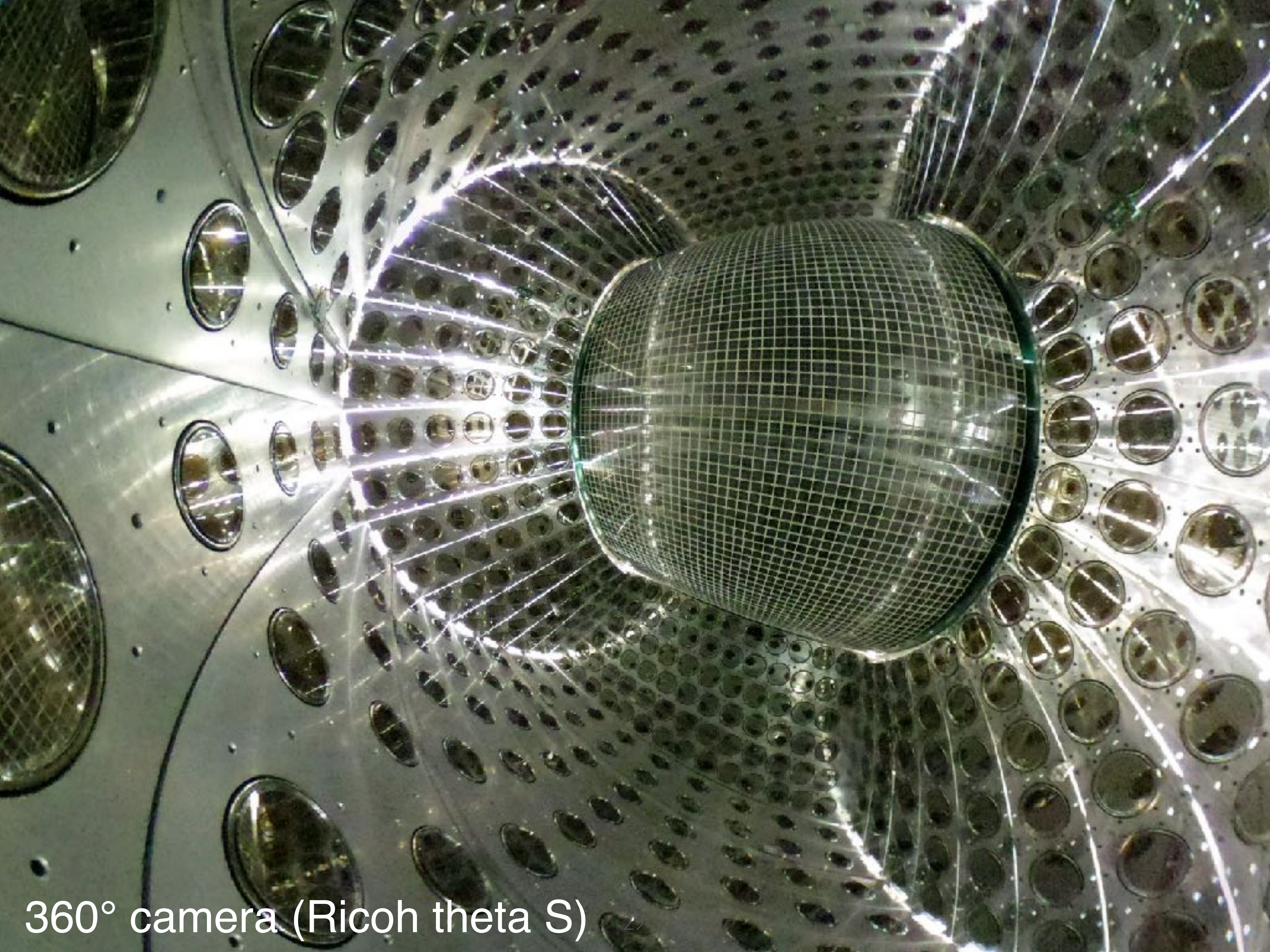
- MPPCs plugged on assembly PCB
    - Series connection for four chips on PCB
- MPPC signal transmitted over long cable (11-13.4m) w/o amplifier
- High density PCB-based feedthrough
    - PCB with coaxial-like signal line, 50Ω impedance, high noise immunity
    - High density 72ch x 6 PCB x 10 flanges
- Waveform digitizer
    - Fully integrated DAQ board including bias supply for SiPM, waveform digitizer, FPGA-based trigger (WaveDREAM)



Detector construction

- All assembly PCB + MPPCs installed into the LXe detector
- MPPC position is measured by 3D Faro arm scanner
- SiPM current with LED light is checked by each row when cable connection is carried out
- PMTs are re-used. Top/bottom/lateral PMT holders are modified for better uniformity.

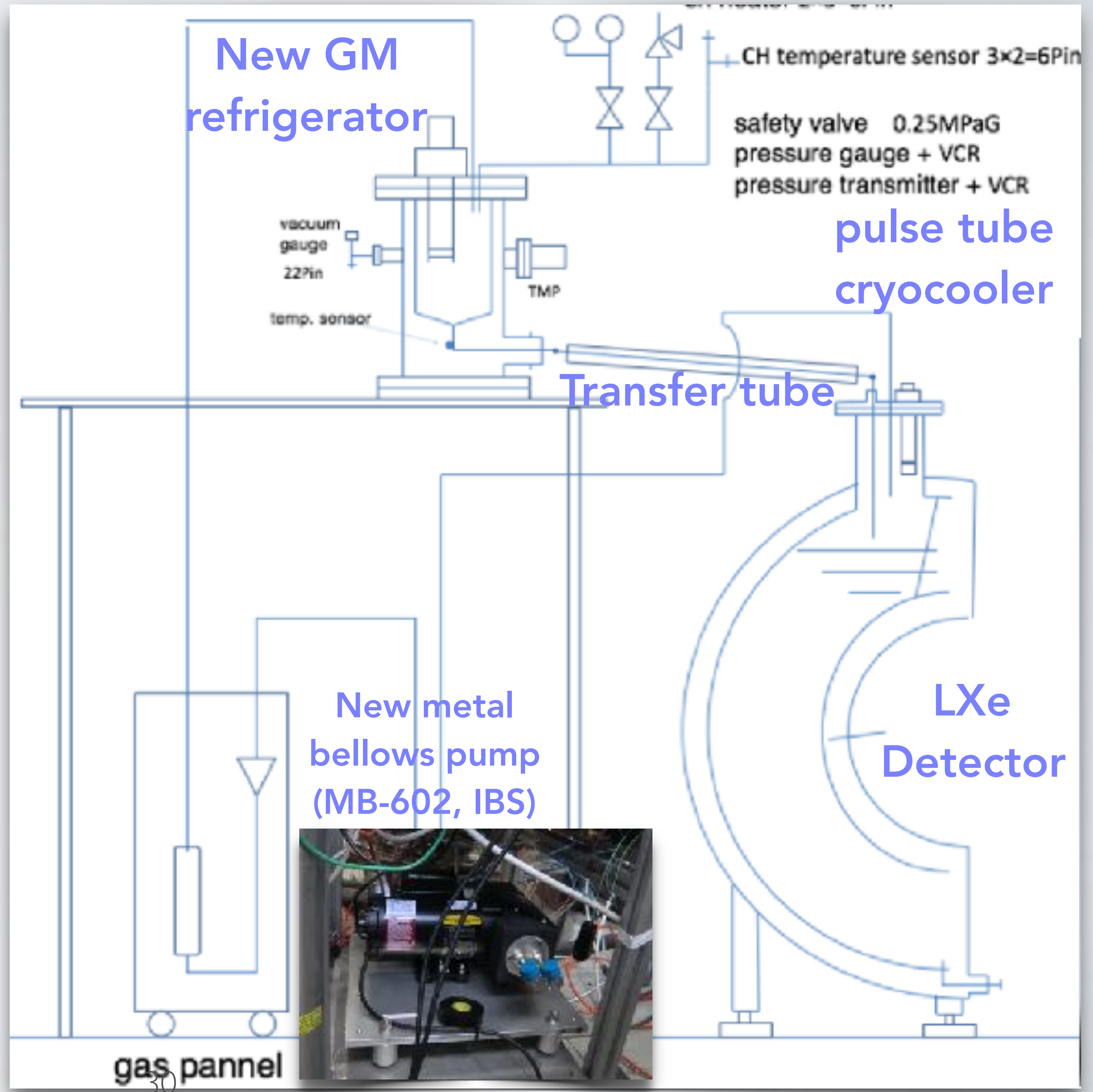




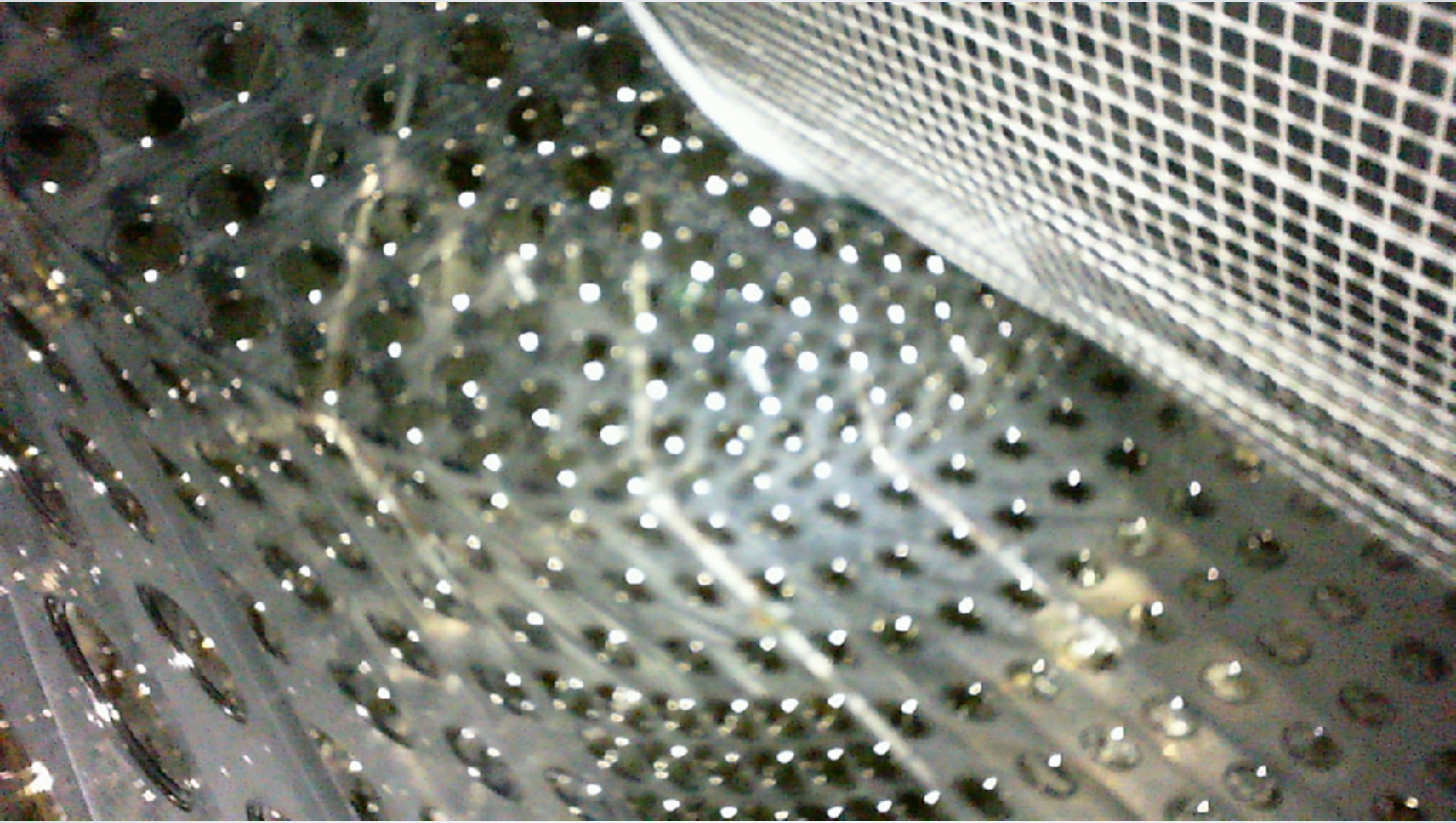
360° camera (Ricoh theta S)

Cryogenics

- Increase cooling power
  - GM refrigerator (AL300, CRYOMECH, 430W@165K) connected to the detector via thermal insulated transfer tube
  - pulse tube cryocooler reused (200W)
- The system is working already in detector pre-cooling with gaseous xenon
- Then, we started liquid xenon transfer from 1000L liquid storage tank to the LXe detector

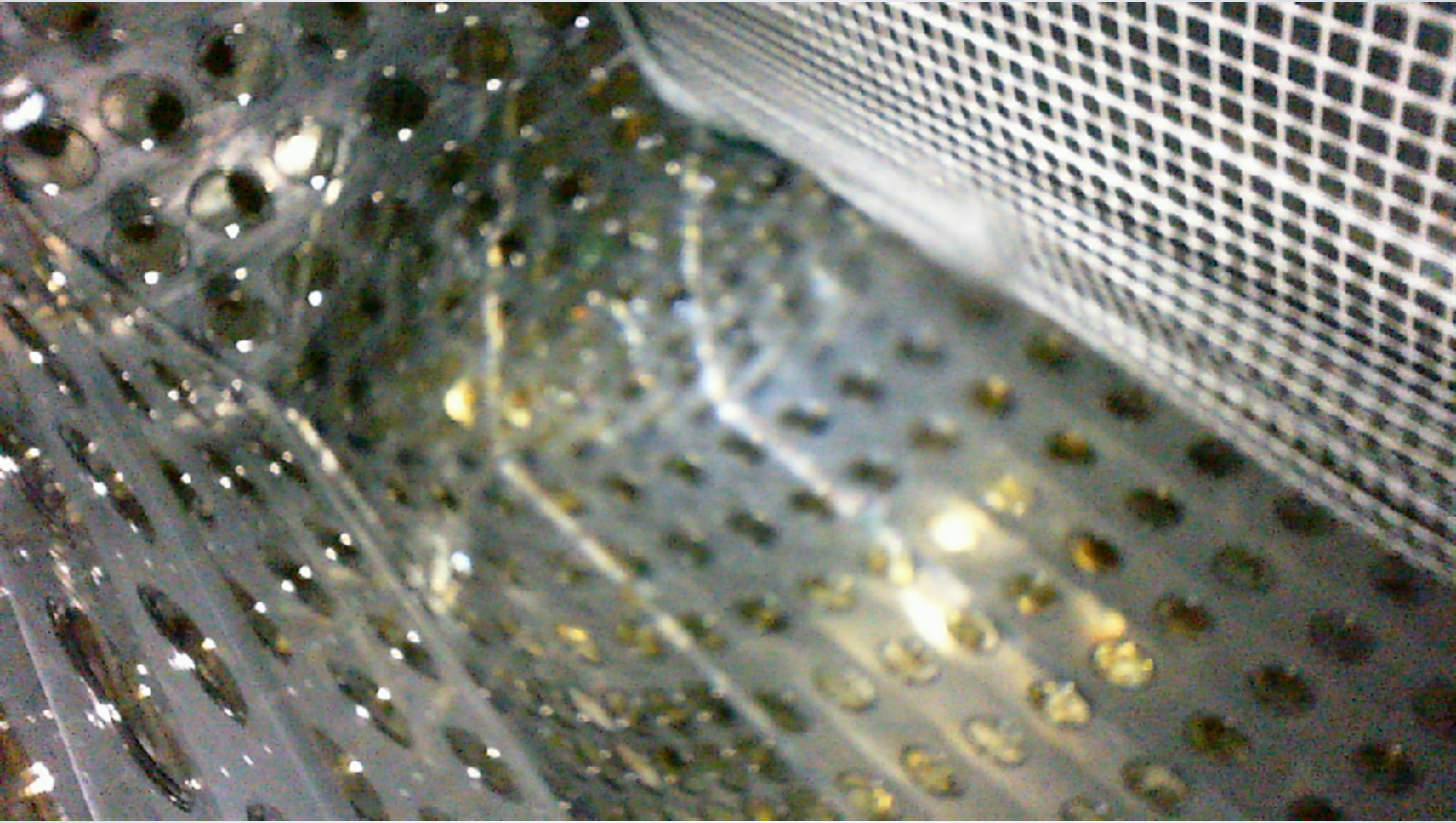


Liquid transfer



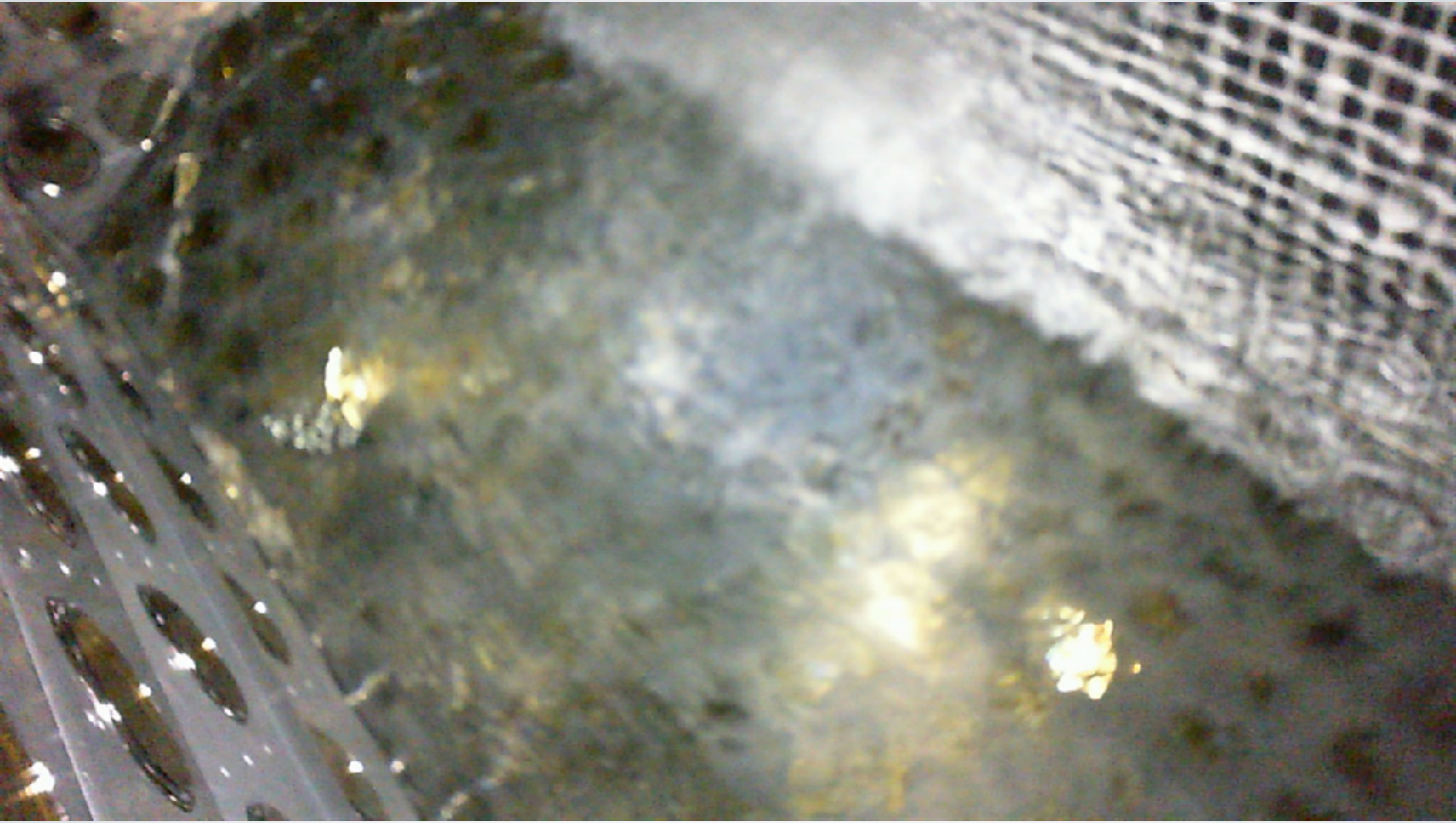
Viewed by USB camera : LifeCam HD-5000

Liquid transfer



- Liquid level is around half

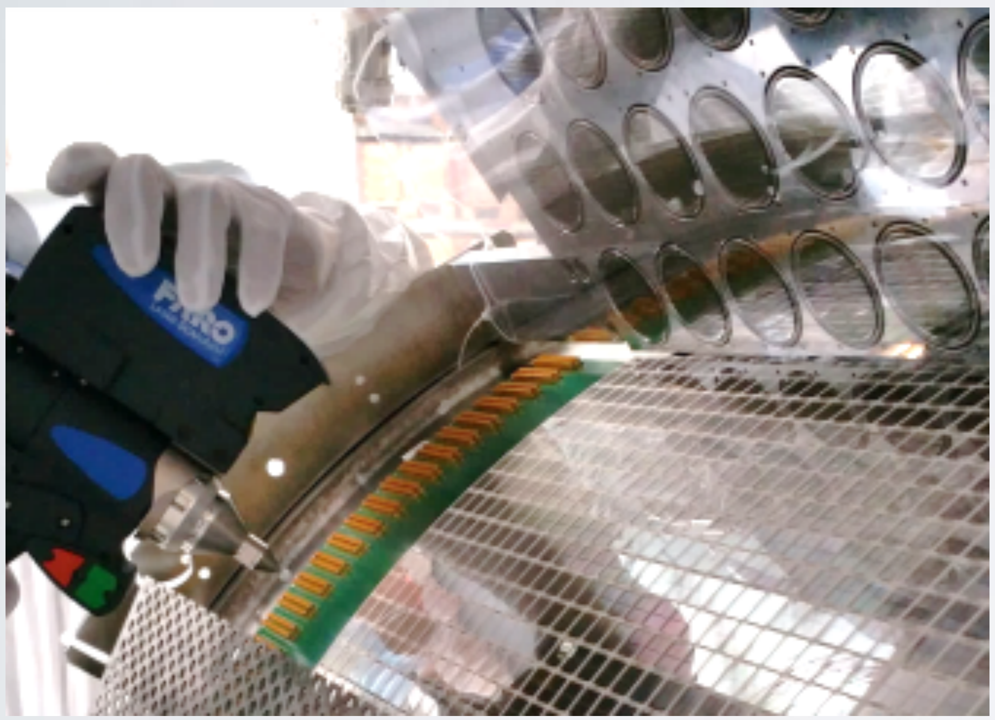
Liquid transfer



- Liquid level is close to the USB camera

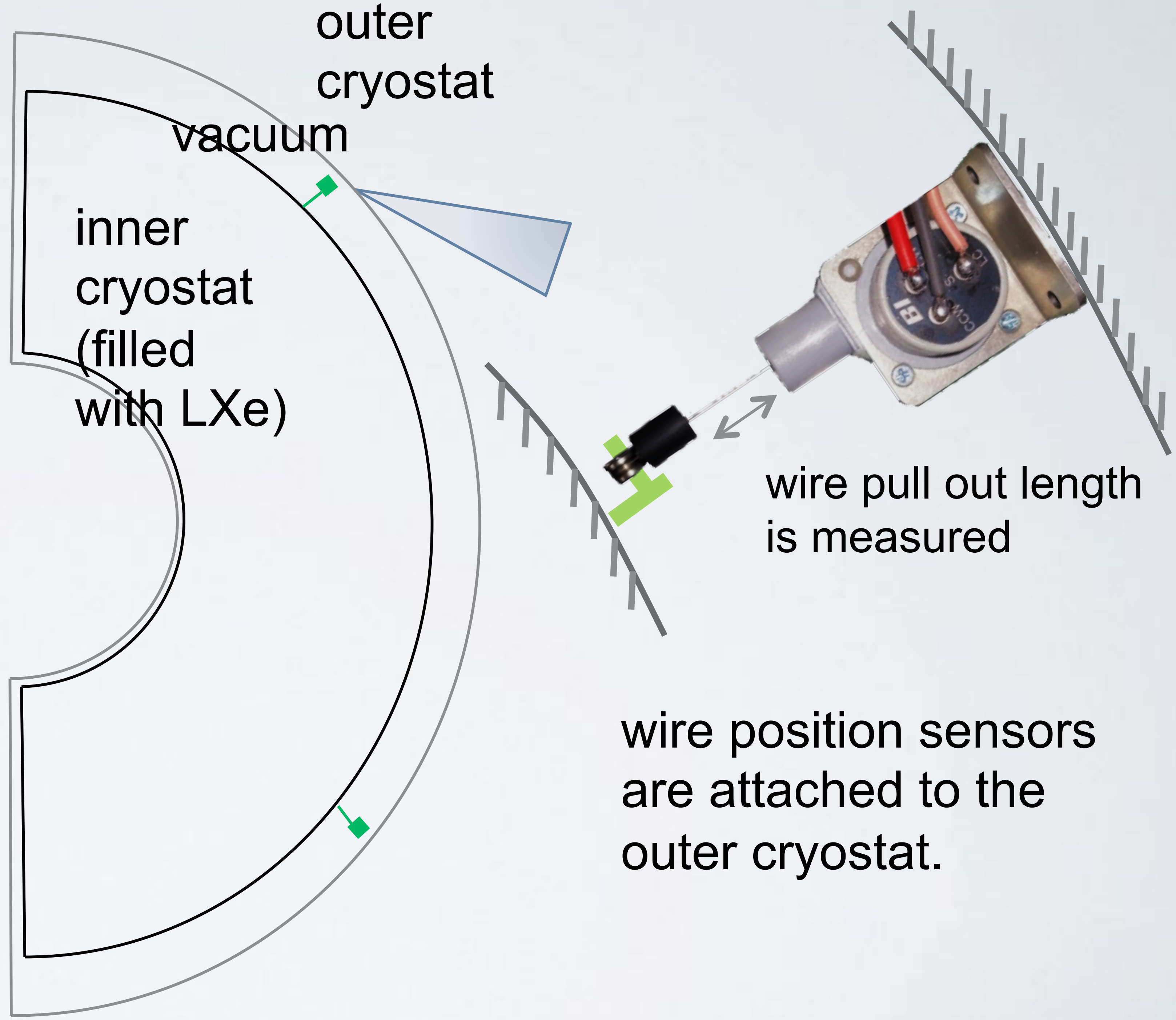
Position monitoring

MPPC position was scanned with laser after installation ↓



However, inner cryostat deforms by heat shrink and LXe load.

→ Monitor the movement by position sensors

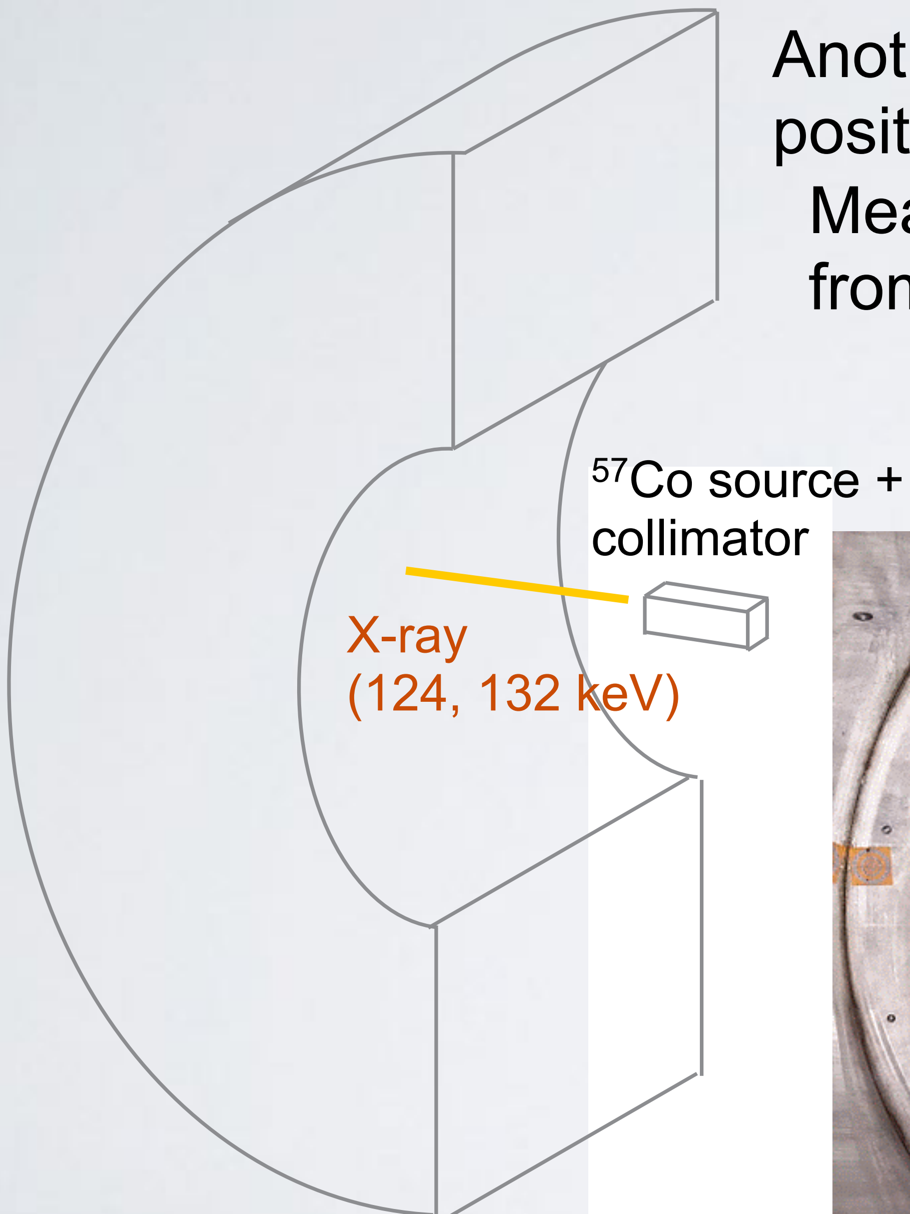


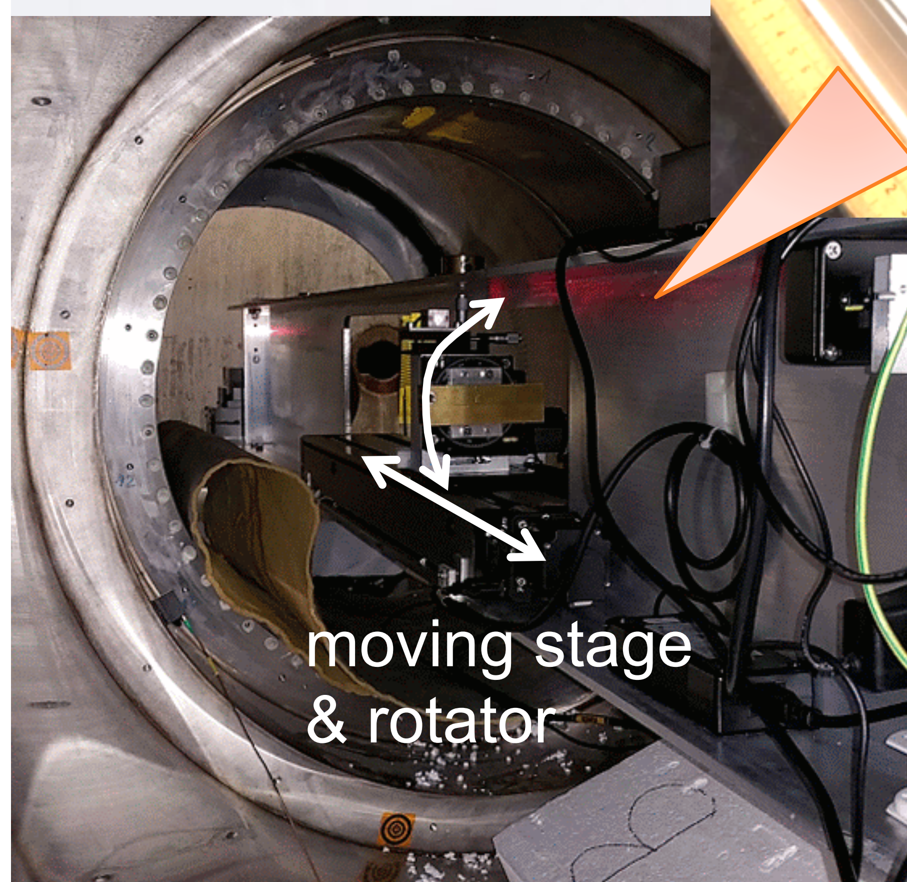
wire position sensors are attached to the outer cryostat.

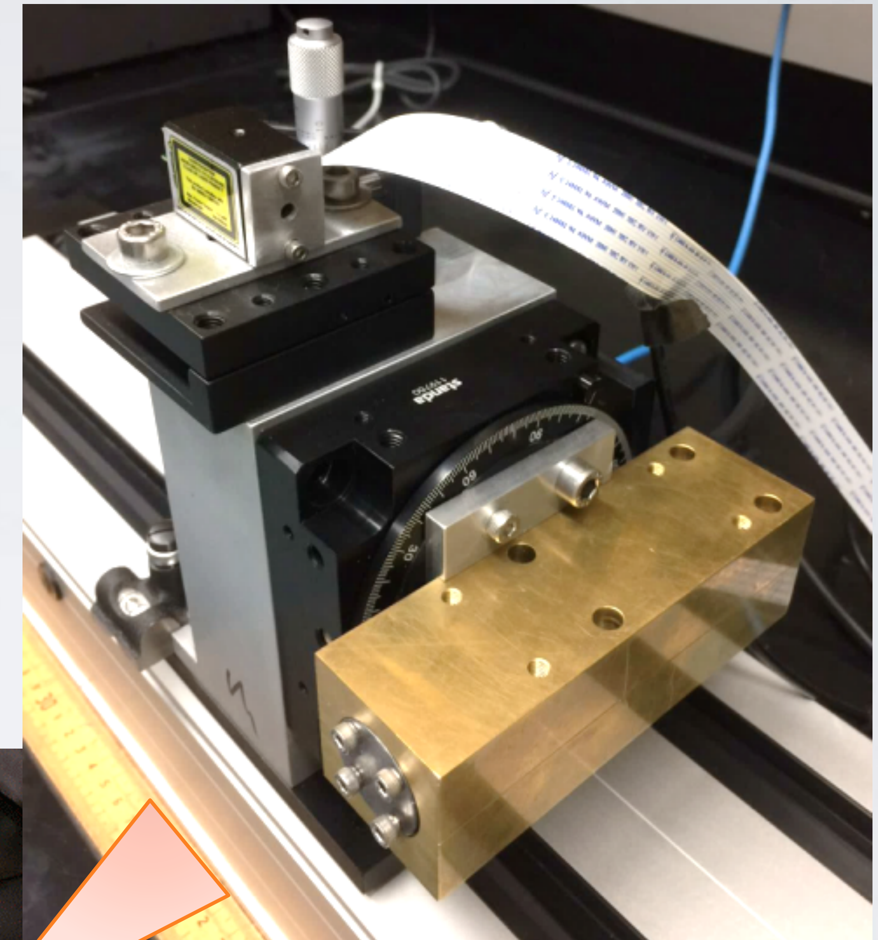
X-ray survey

Another method for position check:

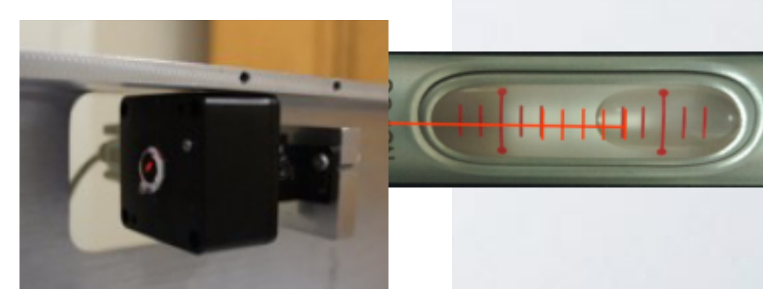
Measure MPPC signal from the X-rays.



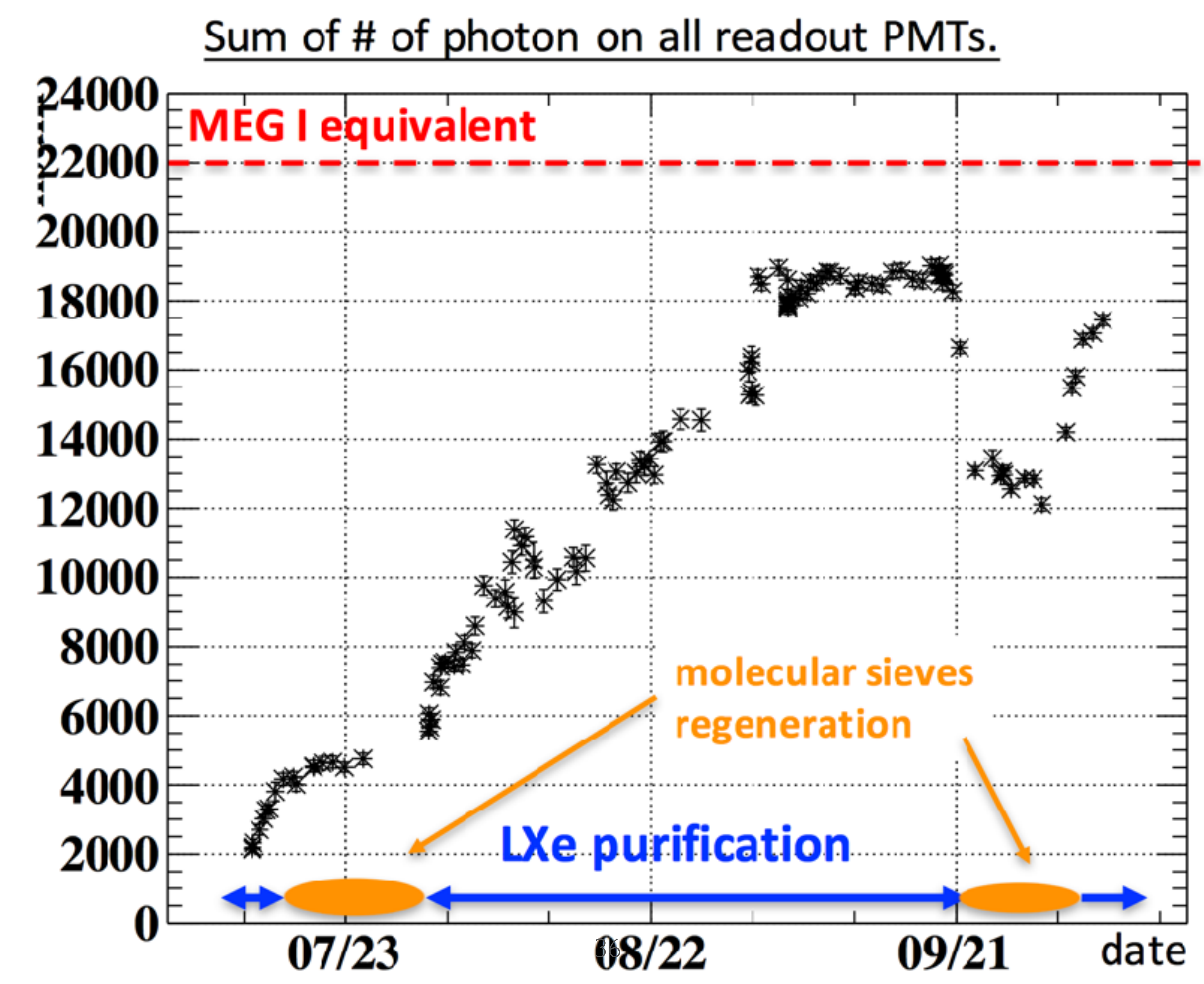




Position of the stage is measured by laser and monitored by laser and bubble level + camera.



Purification

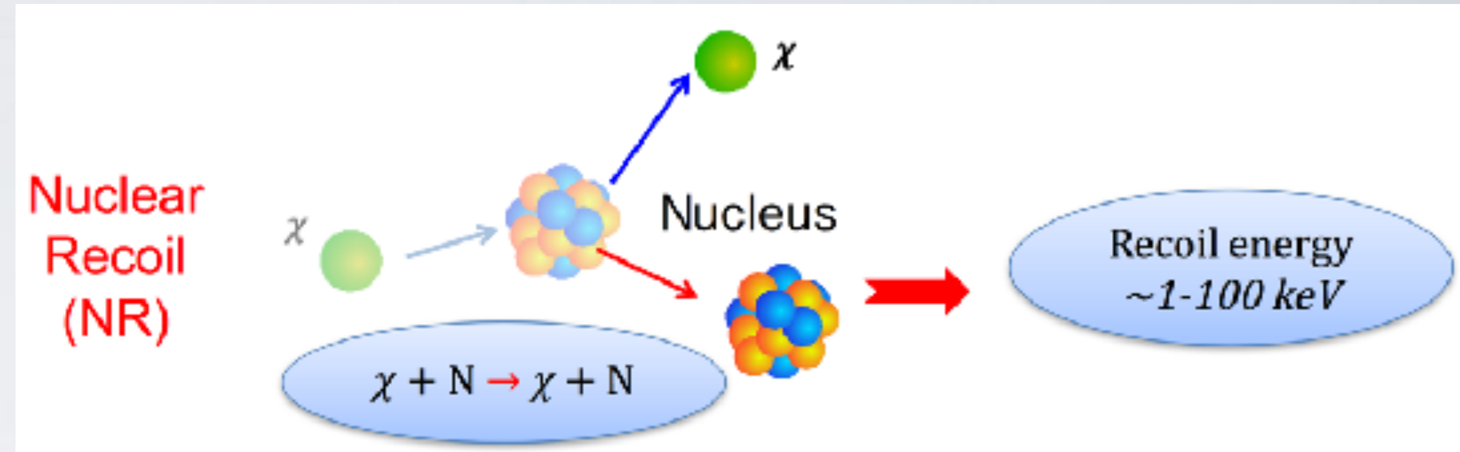


Prospects

- November: 17.6MeV γ with CW
- December: Muon beam with TC, RDC
- 2018 Engineering run + physics run

Other experiments

- LXe
  - Dark matter experiment
    - High stopping power, active volume is self-shielding



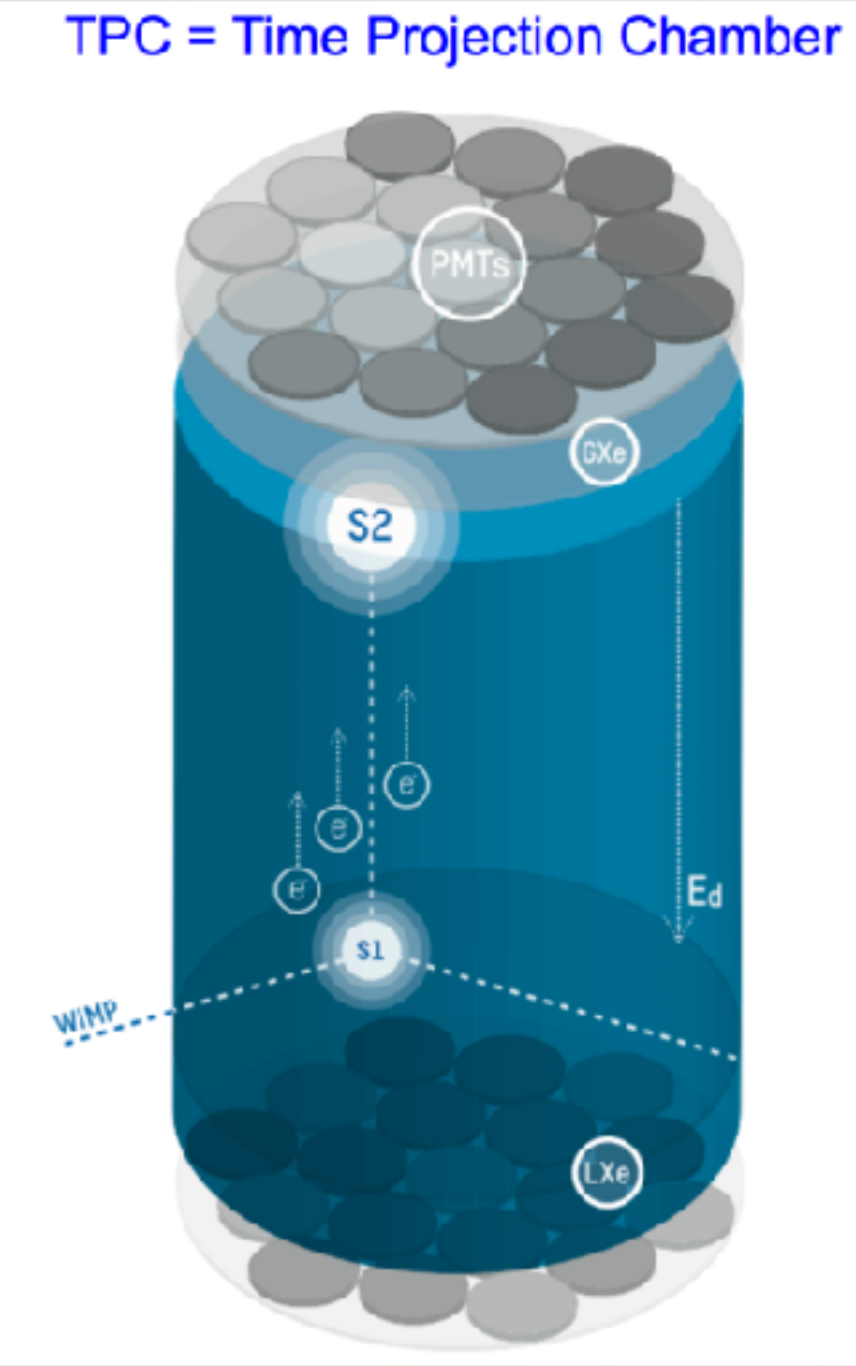
    - Electronic recoil discrimination with simultaneous measurement of scintillation and ionization
    - Dual-phase (liquid/gaseous) detector uses both scintillation/ionization
    - XENON100, LUX, PANDAX-II, Xenon1t (next generation experiments: XENONnT, LZ, DARWIN)
  - Double beta decay experiment
    - EXO

0νββ in ^{136}Xe

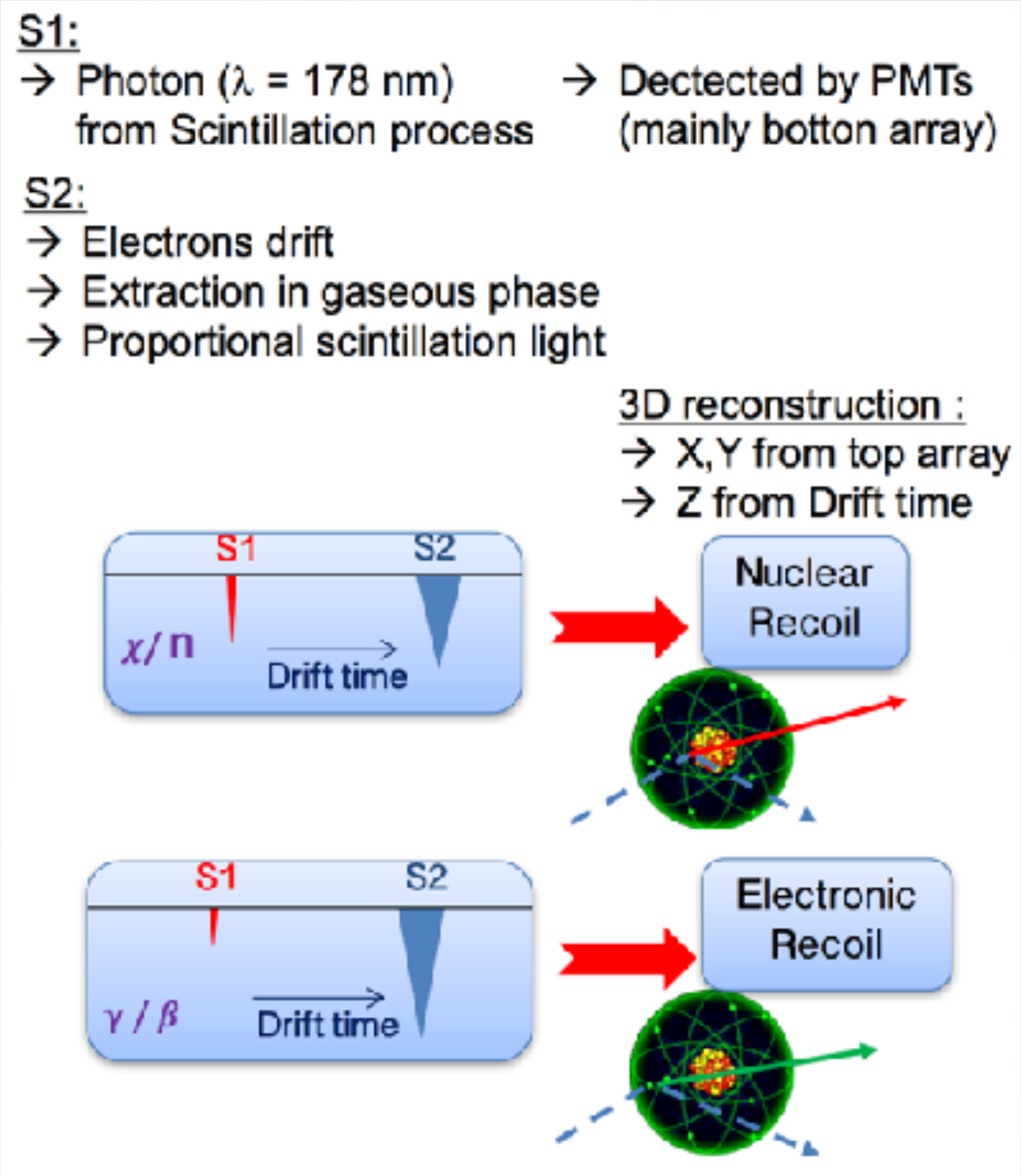
- $^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^-$, Q-value 2457.83±0.37 keV

  - Medical application
    - Single photon emission computed tomography (SPECT) / Positron emission tomography (PED)

Dark matter application



Dual-phase liquid xenon detector

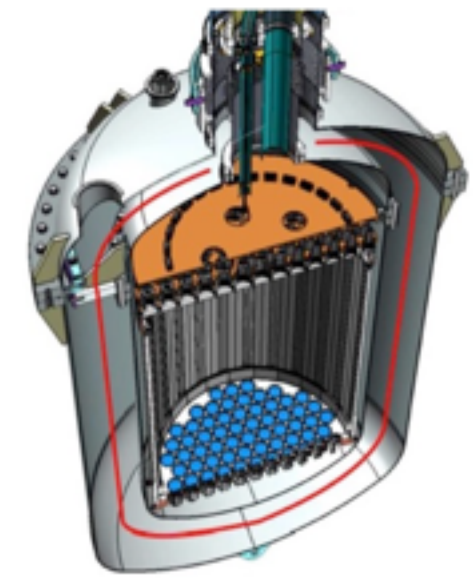


S2/S1 ratio depends on particles, used for background rejection

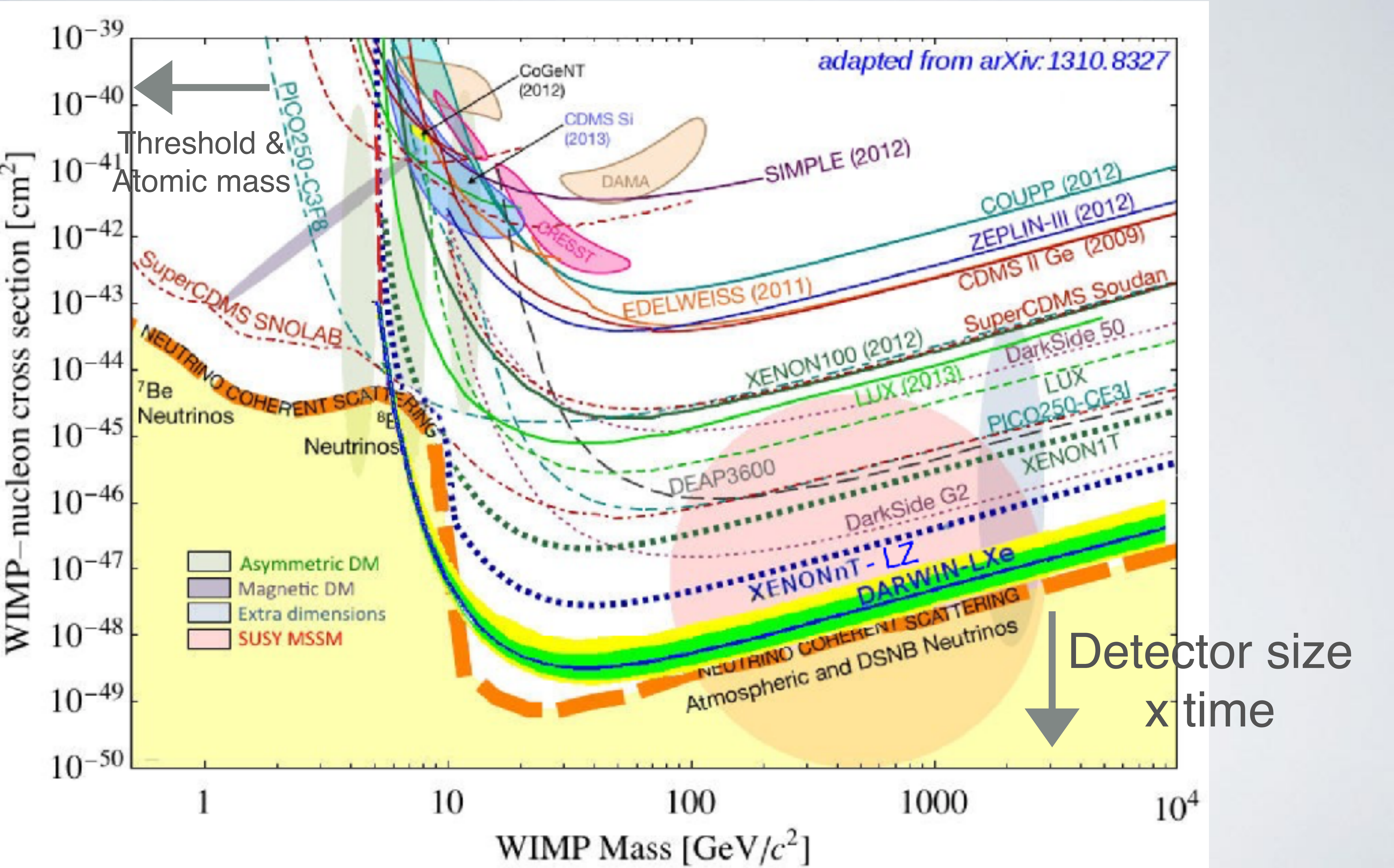
This type of readout can not be used for calorimeter for high-rate experiments (Drift time O(mm/μs) can be too long if the detector is large)

The XENON-Program @ LNGS

Gran Sasso, Italy (3600 mwe)

	XENON10	XENON100	XENON1T	XENONnT
				
Period	2005-2007	2008-2016	2012-2018	2019-2023
Total mass	25 kg	161 kg	3200 kg	~8000 kg
Drift length	15 cm	30 cm	100 cm	144 cm
Status	Completed (2007)	Completed (2016)	Running	Construction
σ_{SI} limit (@50 GeV/c^2)	8.8×10^{-44} cm^2	1.1×10^{-45} cm^2	1.6×10^{-47} cm^2 (2018)	1.6×10^{-48} cm^2 (2023)

Dark matter search



Most results are from LXe experiments

Summary

- Calorimetry is widespread technique in particle physics
- Liquefied noble gases have many good features to get good energy/timing/position resolutions
- MEG II liquid xenon detector uses large area VUV-sensitive SiPM on the γ incident face. The detector operation is started.
- Next year, MEG II experiment will start engineering run and physics run.

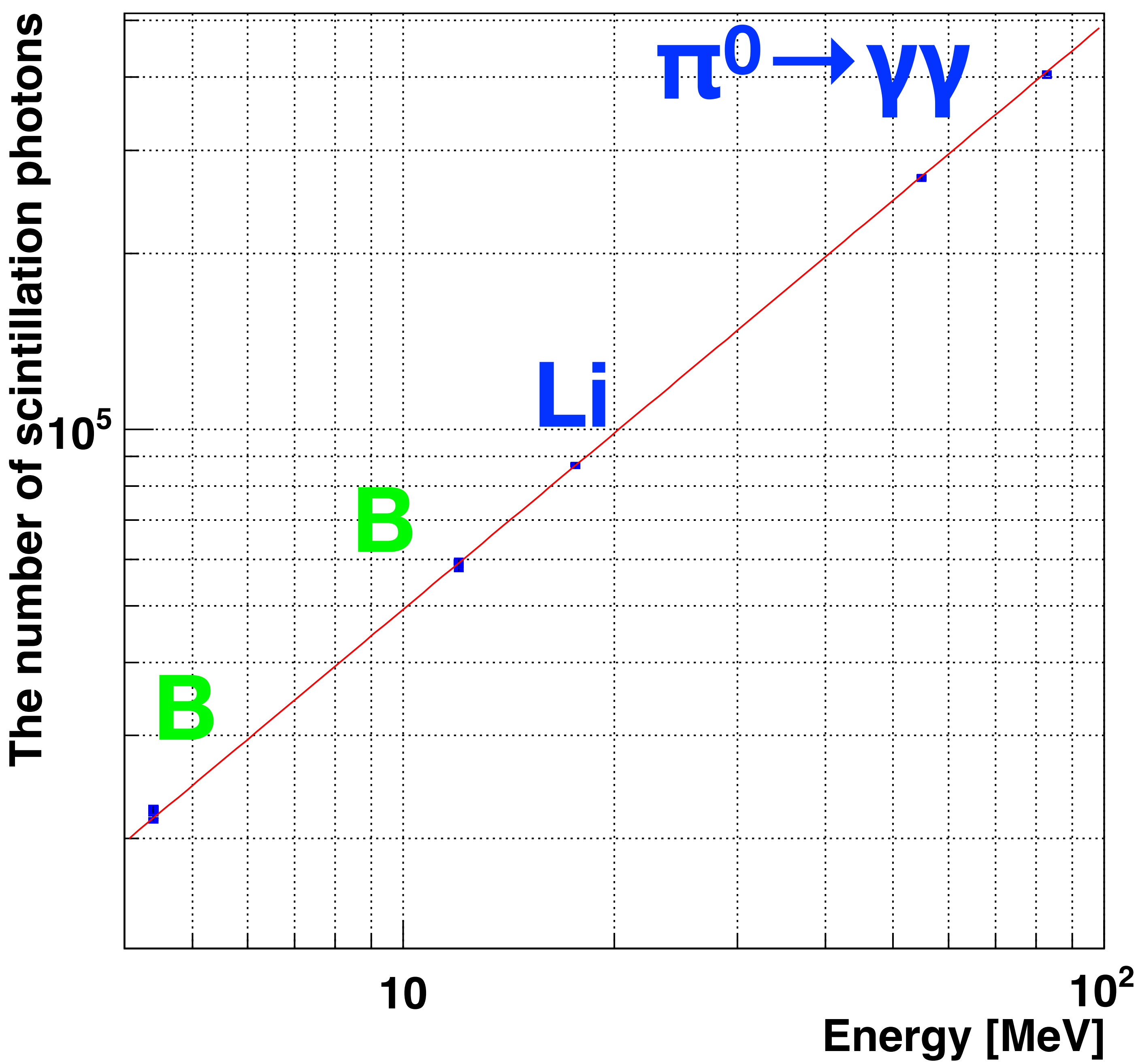
Backup

Table 1. Energy expended per scintillation photon for different particles.

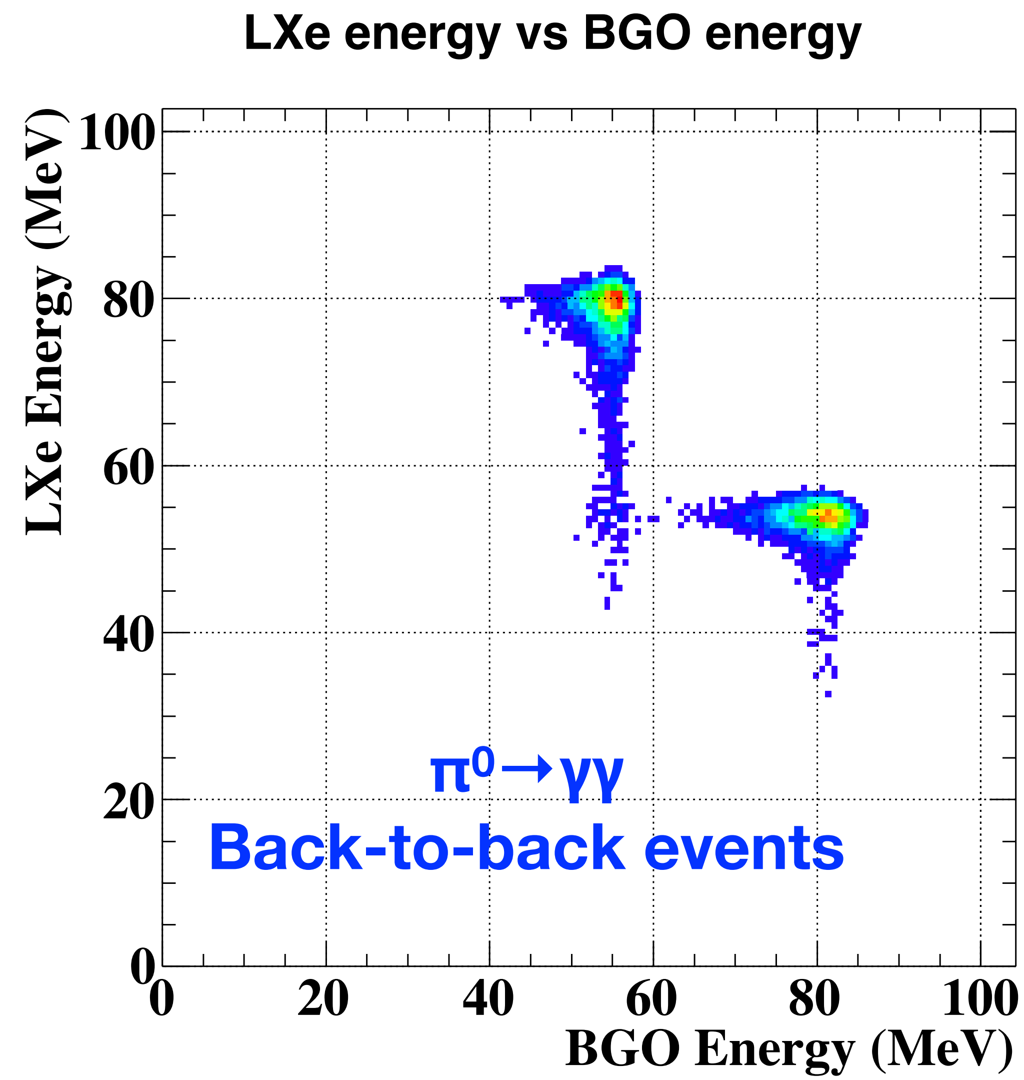
Particle	Energy	LET, MeV/(g·cm^2)	W_s, eV (LAr)	W_s, eV (LXe)
No quenching; W_s^{min}	–	–	19.5 ± 1.0 [a] 19.8 [b] 18.4 [b]	13.8 ± 0.9 [a] 13.0 [b] 14.7 ± 1.5 [c] 13.45 ± 0.29 [d] 13.7 ± 0.2 [e]
Relativistic electrons	1 MeV	≈ 1	25.1 ± 2.5 [c] 24.4 [a]	23.7 ± 2.4 [c] 21.6 [a] 22.5 ± 2.5 [f] < 35 [g] 42 ± 6 [h] 67 ± 22 [i]
Low energy electrons	20 – 100 keV	~7 to 2	–	18.3 ± 1.5 [f] 14.2 [j] 12.7 ± 1.3 [k] 29.6 ± 1.8 [l]
α-particles	≈ 5 MeV	$\sim 4 \times 10^2$	27.1 [a] 27.5 ± 2.8 [c]	17.9 [a] 19.6 ± 2.0 [c] 16.3 ± 0.3 [m] 17.1 ± 1.4 [f] 39.2 [n]
Relativistic heavy ions	~ 1 GeV/amu	$\sim 10^2$ to 10^3	19.4 ± 2.05 [c]	14.7 ± 1.5 [c]
Nuclear recoils*	60 keV	$2.9/4.0 \times 10^3$	~ 100 [p] (exp) ~ 90 [q] (theor)	95 ± 20 [r] (exp) ~ 77 [s] (theor)
	20 keV	$2.6/2.7 \times 10^3$	~ 100 [p] (exp) ~ 105 [q] (theor)	110 ± 20 [r] (exp) ~ 86 [s] (theor)
	5 keV	$1.9/1.5 \times 10^3$	~ 100 [p] (exp) ~ 140 [q] (theor)	160 ± 40 [r] (exp) –
Fission fragments	~ 1 MeV/amu	$\sim 10^4$	110 [t]	60 [u]

arXiv:1207.2293

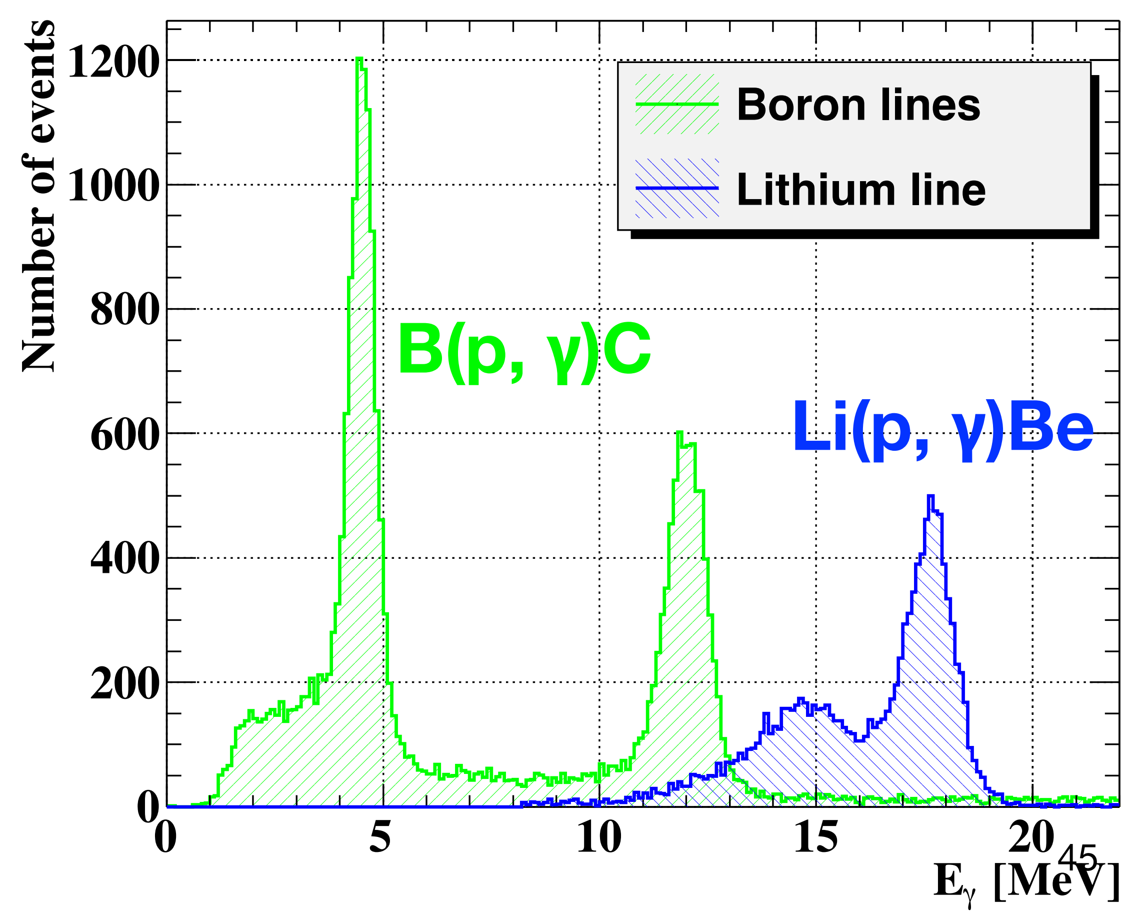
Linearity



The number of scintillation photons
10^5
10
10^2
Energy [MeV]
B
B
Li
$\pi^0 \rightarrow \gamma\gamma$

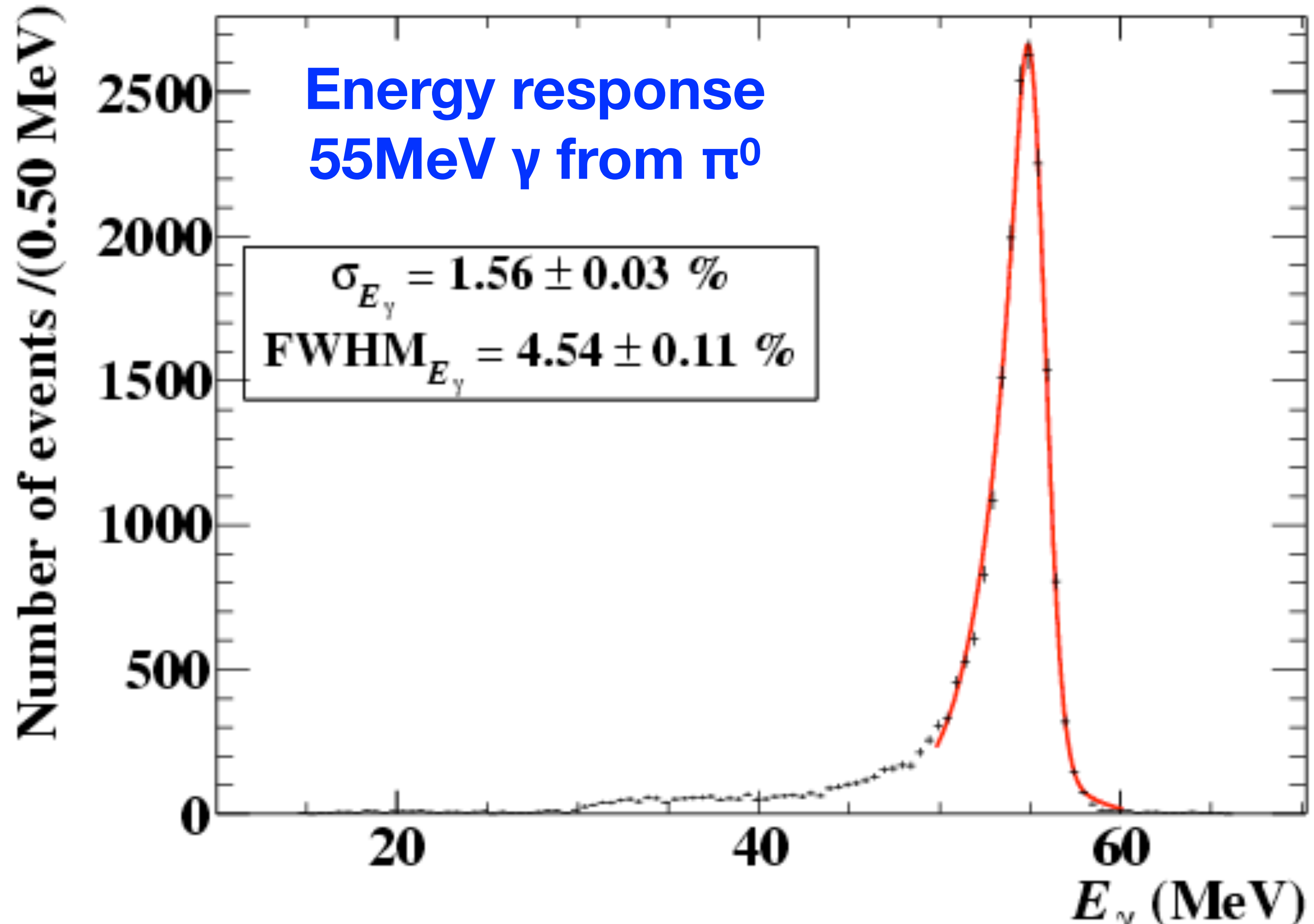


LXe energy vs BGO energy
LXe Energy (MeV)
BGO Energy (MeV)
0
20
40
60
80
100
$\pi^0 \rightarrow \gamma\gamma$
Back-to-back events

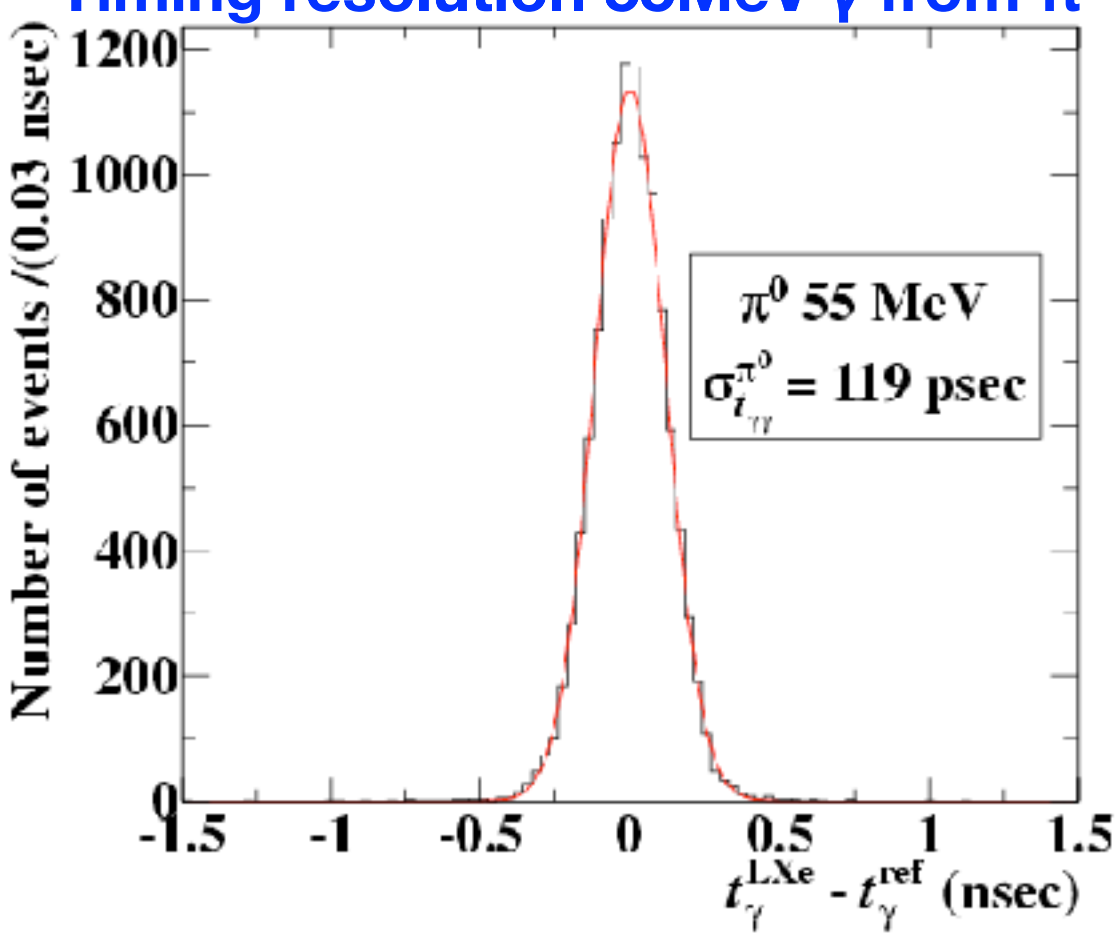


Number of events
E_γ [MeV]
0
200
400
600
800
1000
1200
0
5
10
15
20
Boron lines
Lithium line
B(p, γ)C
Li(p, γ)Be

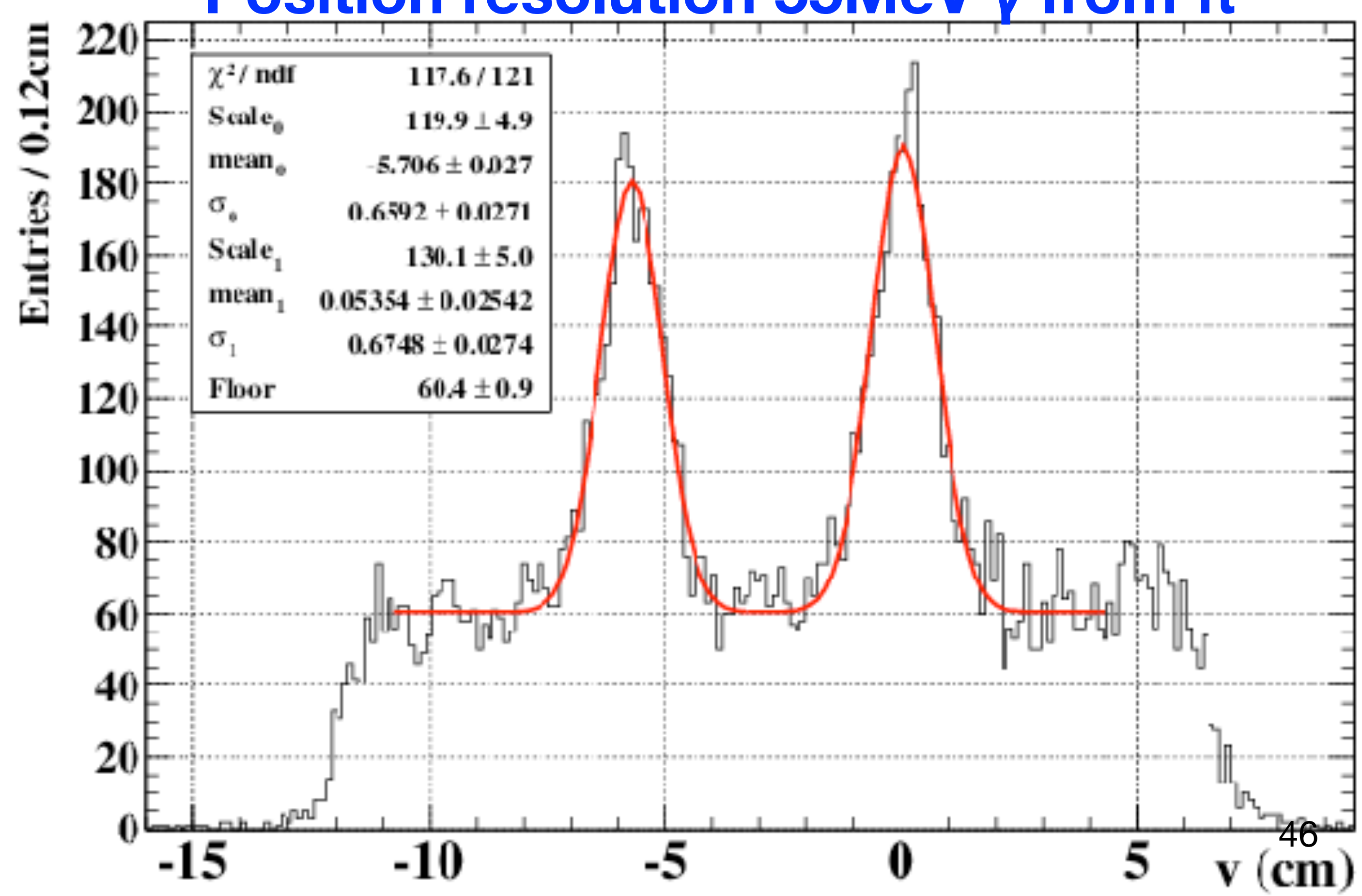
Performance



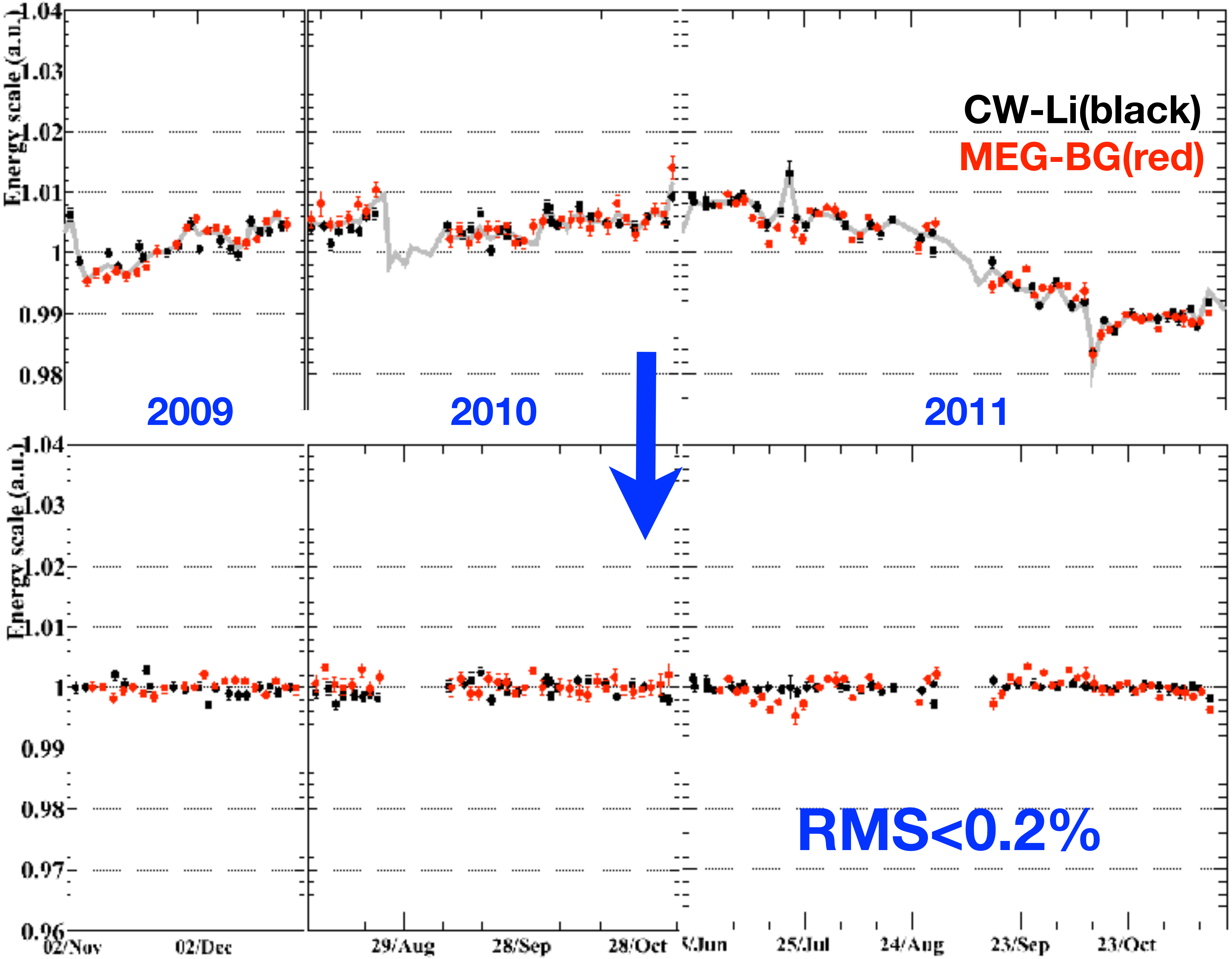
Timing resolution 55MeV γ from π⁰



Position resolution 55MeV γ from π⁰

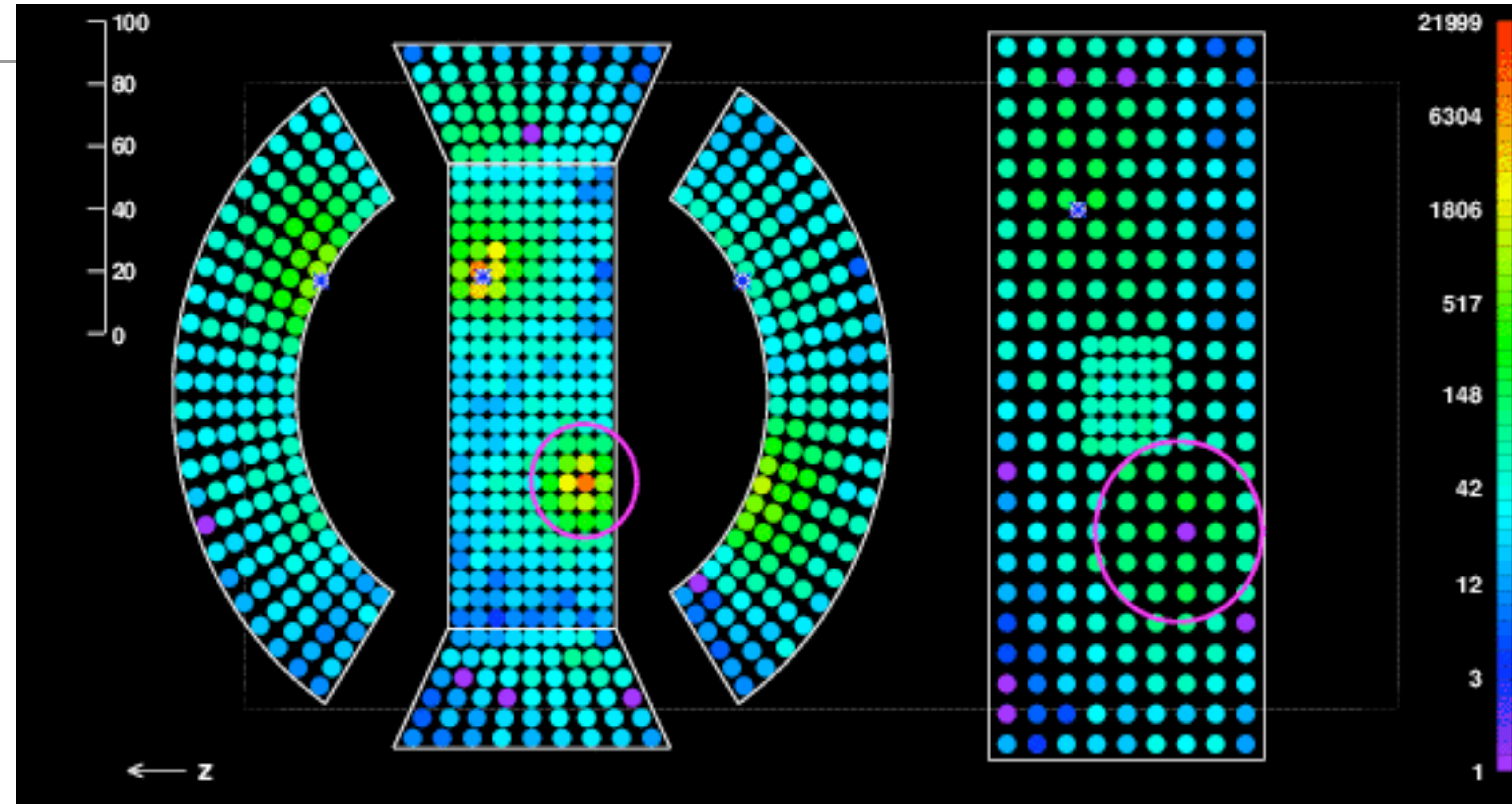


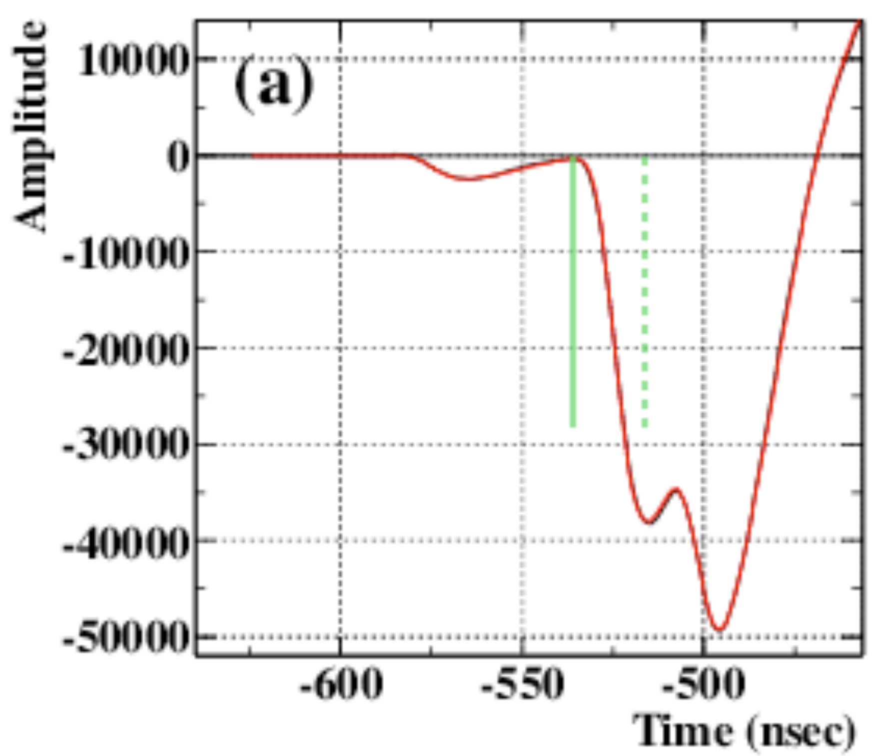
Energy scale uncertainty

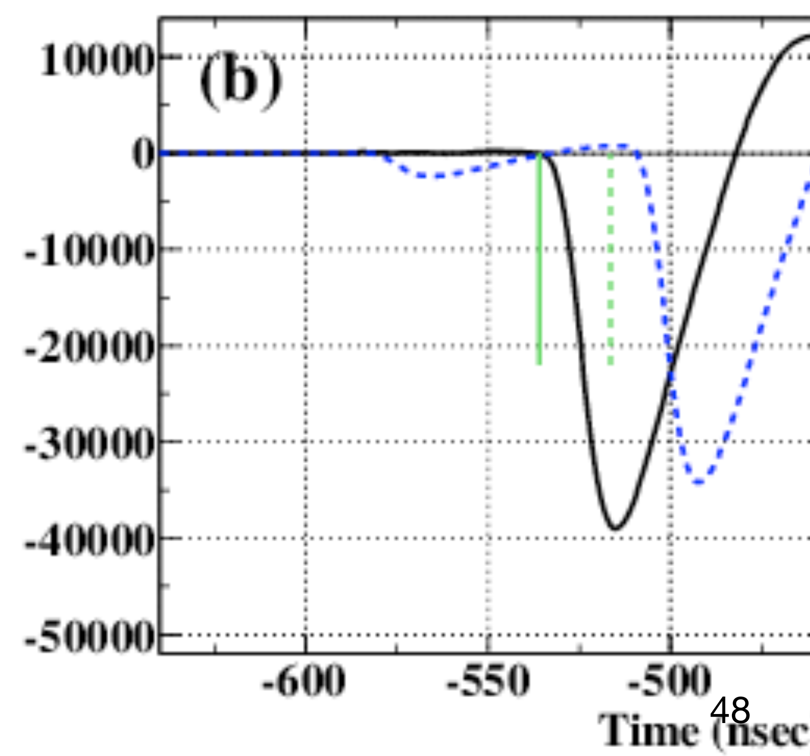


Pileup

- At $3\times10^7 \mu^+$/s beam rate, 15% of triggered events suffer from pile-up.
- Light distribution
- Waveform peak search
- χ^2/NDF distribution in time reconstruction
- Only pile-up γs are subtracted, and the main γ is used not to lose signal efficiency
- Analysis efficiency : 98%

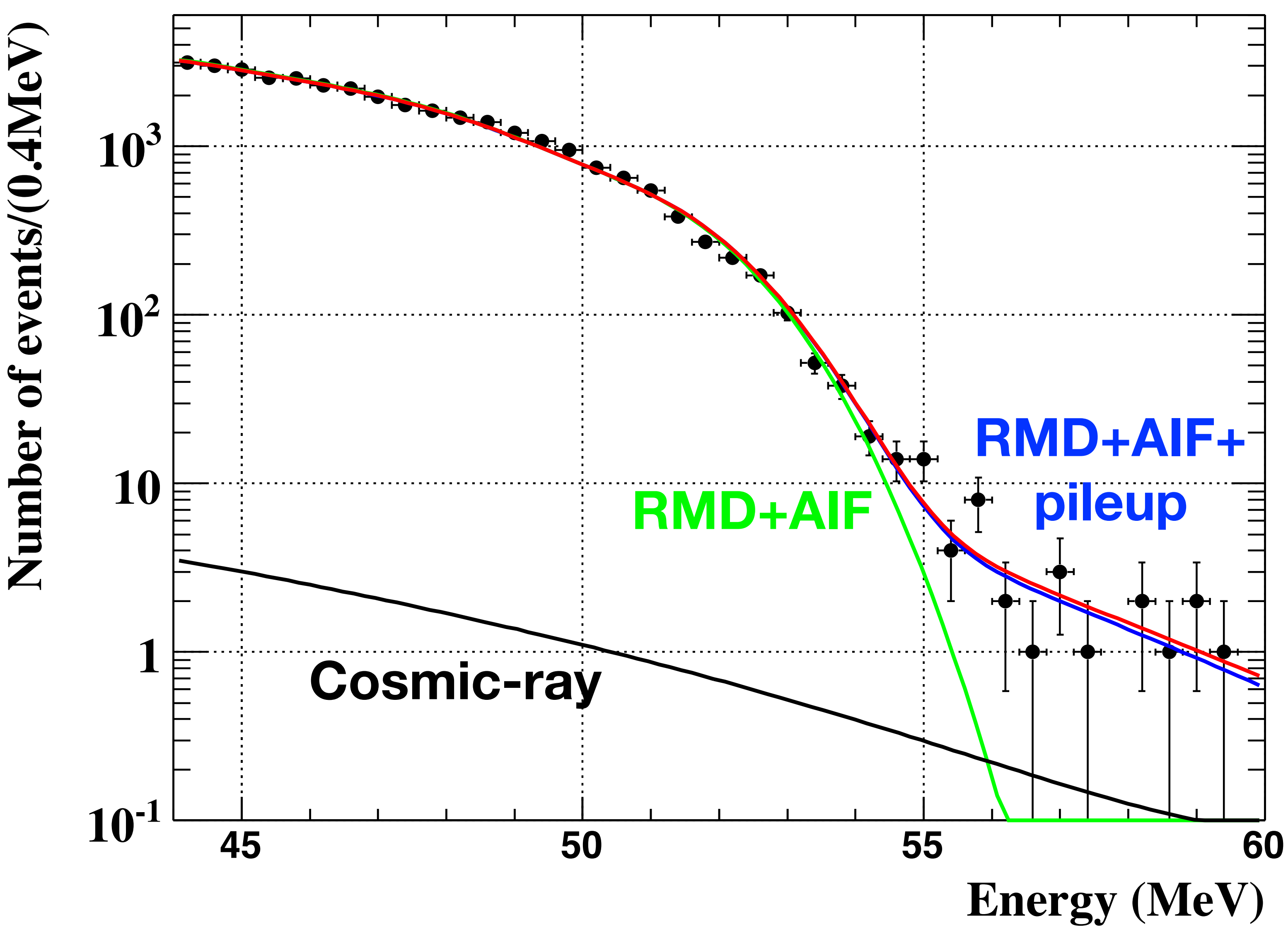






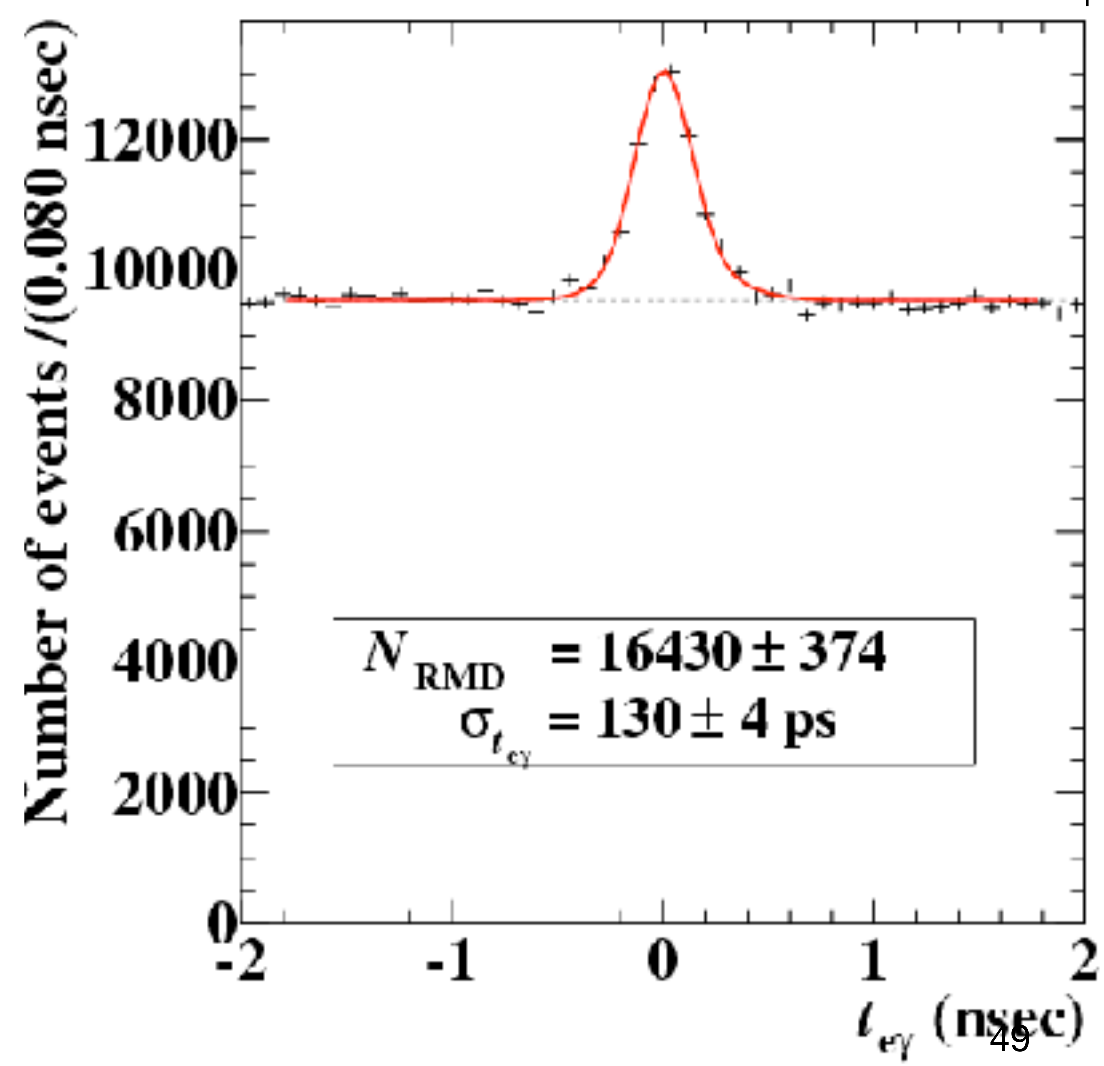
In physics run

- time sideband data in physics run are used to study γ-ray background spectra



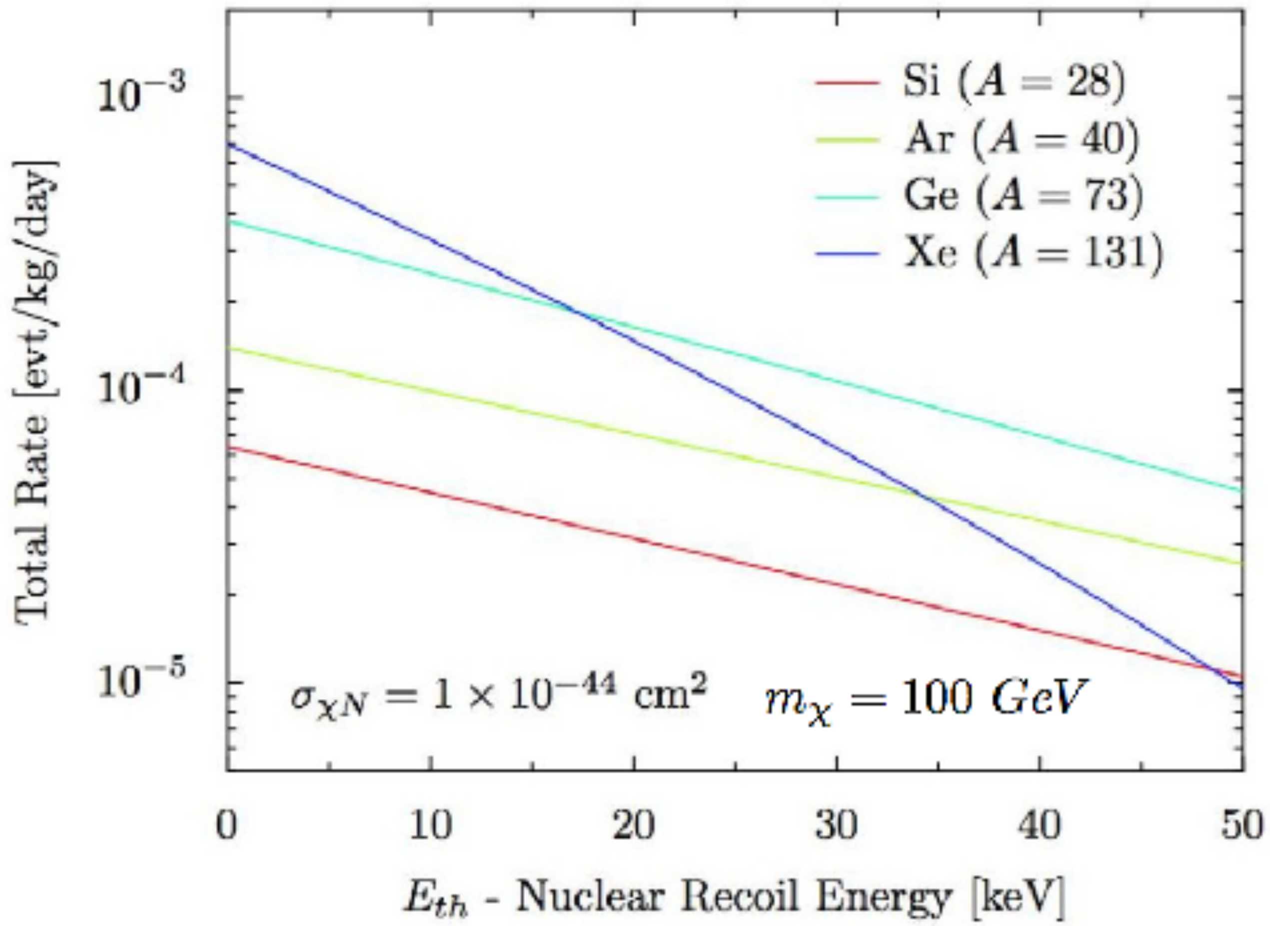
- Radiative muon decay events $\mu \to e\nu\nu\gamma$ are used to study timing resolution

Time difference between T_e and T_γ



Xenon for dark matter

- Large mass number A (131) (Interaction cross section $\propto A^2$)
- 50% odd isotopes (^{129}Xe, ^{131}Xe) for Spin-Dependent interactions
- Kr can be reduced to ppt levels
- High stopping power, i.e. active volume is self-shielding
- Efficient scintillator (178 nm)
- Scalable to large target masses
- Electronic recoil discrimination with simultaneous measurement of scintillation and ionization



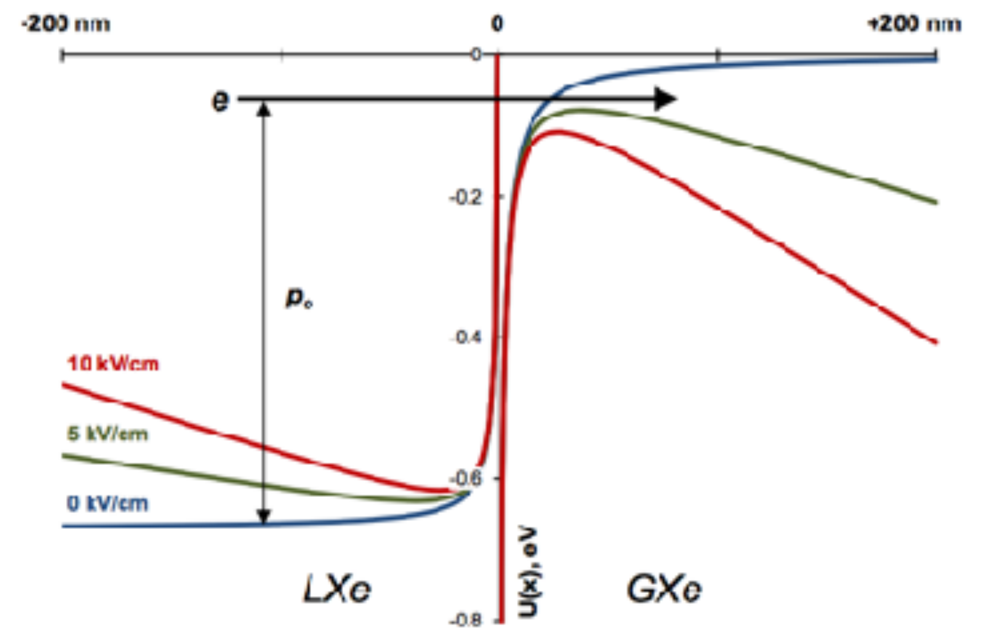


Figure 17. Illustration of the electron emission process in double-phase xenon; the figure shows the potential energy of excess electrons near the liquid-gas interface calculated from the model in [206], with different electric field strengths indicated for the liquid.

- Electron emitted from liquid to gas by electric field

- Electroluminescence in the gas phase

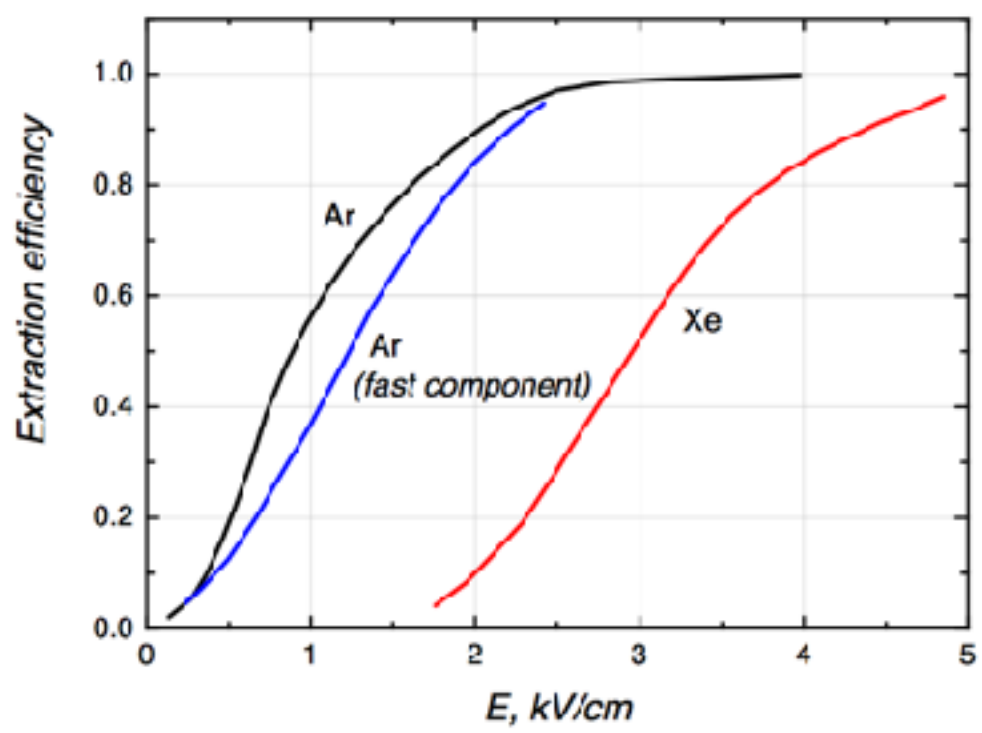
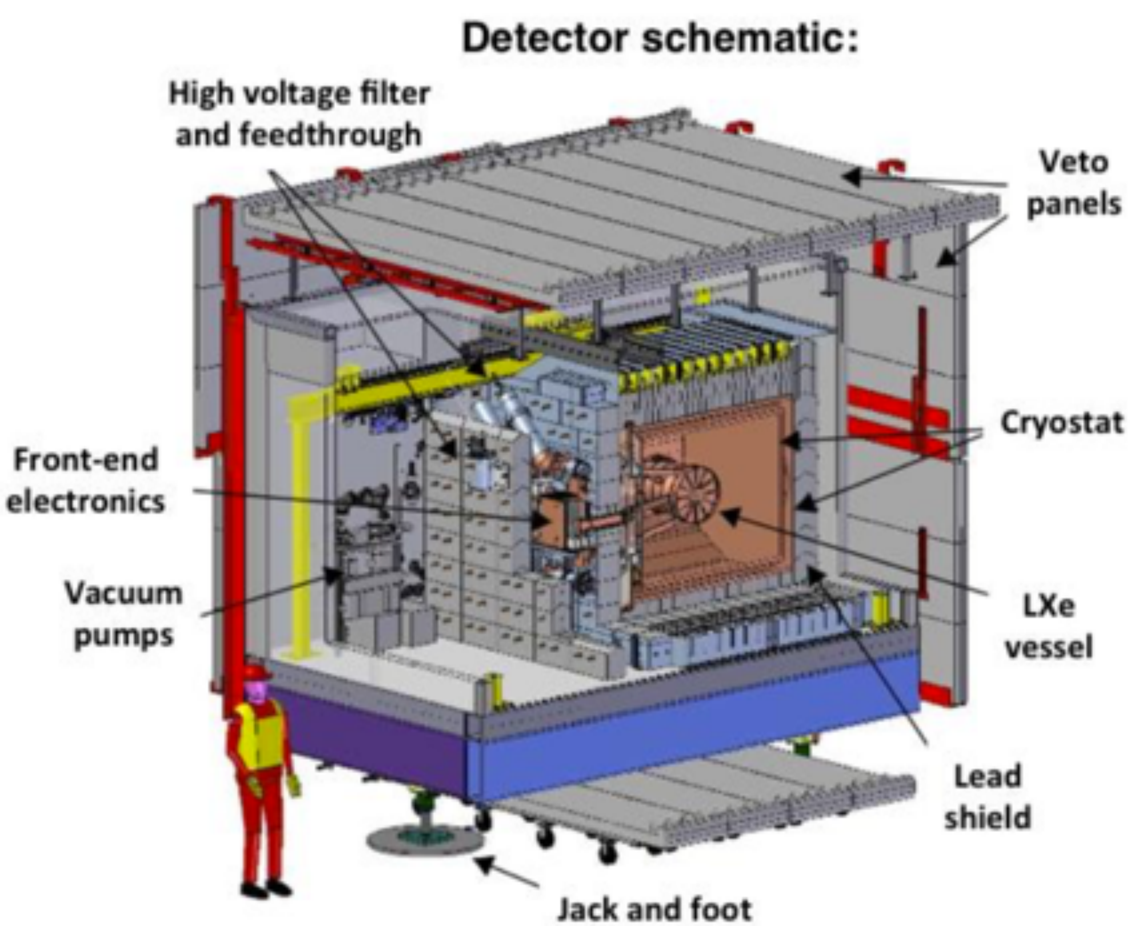
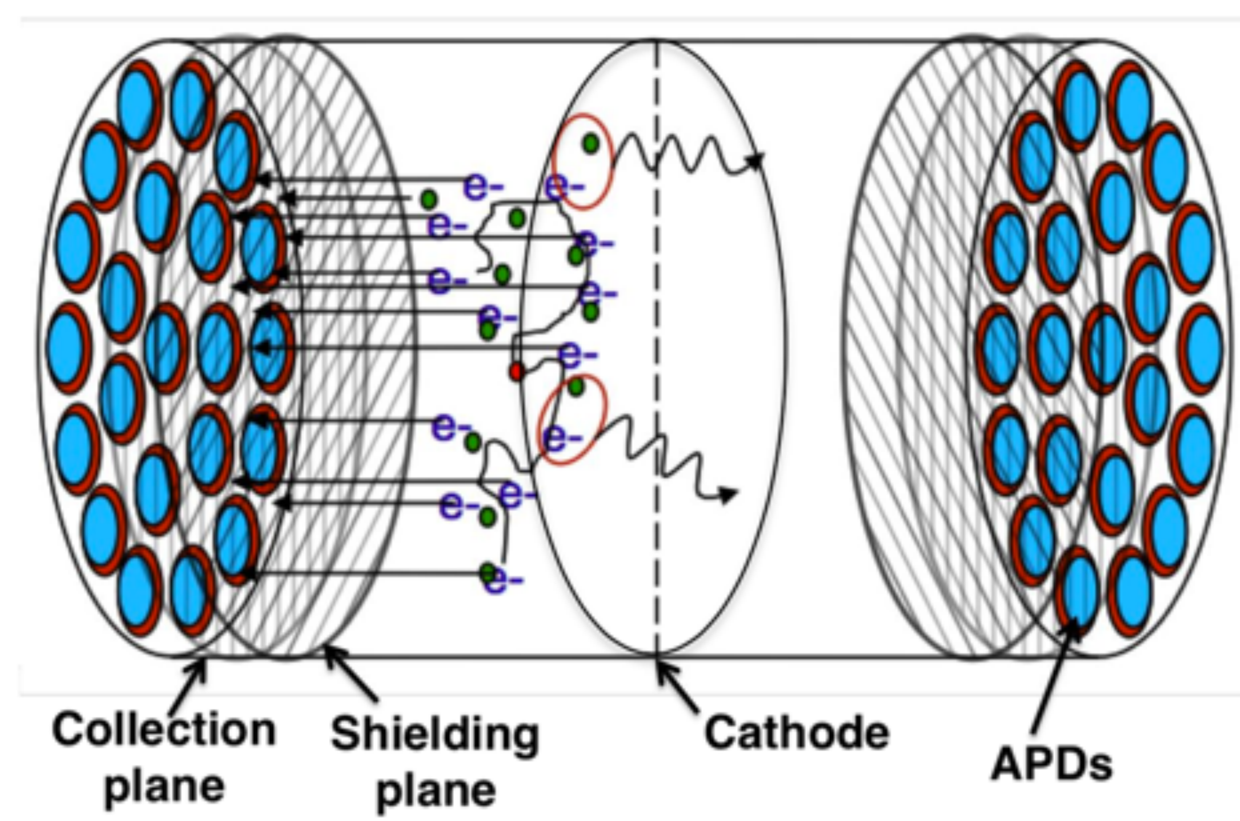


Figure 18. Probability of electron emission from liquid to gas as a function of electric field. Re-drawn from data in [207].

TPC

- EXO-200 consists of a radiopure TPC filled with enriched LXe (80.6%)
- Located at Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA
- High-voltage applied between cathode and anodes (opposite ends)
- Two measurements of energy deposited in event
  - Scintillation light (178 nm), by large avalanche photo-diodes (APDs)
  - Ionization charge, by 2 wire grids (induction and collection)



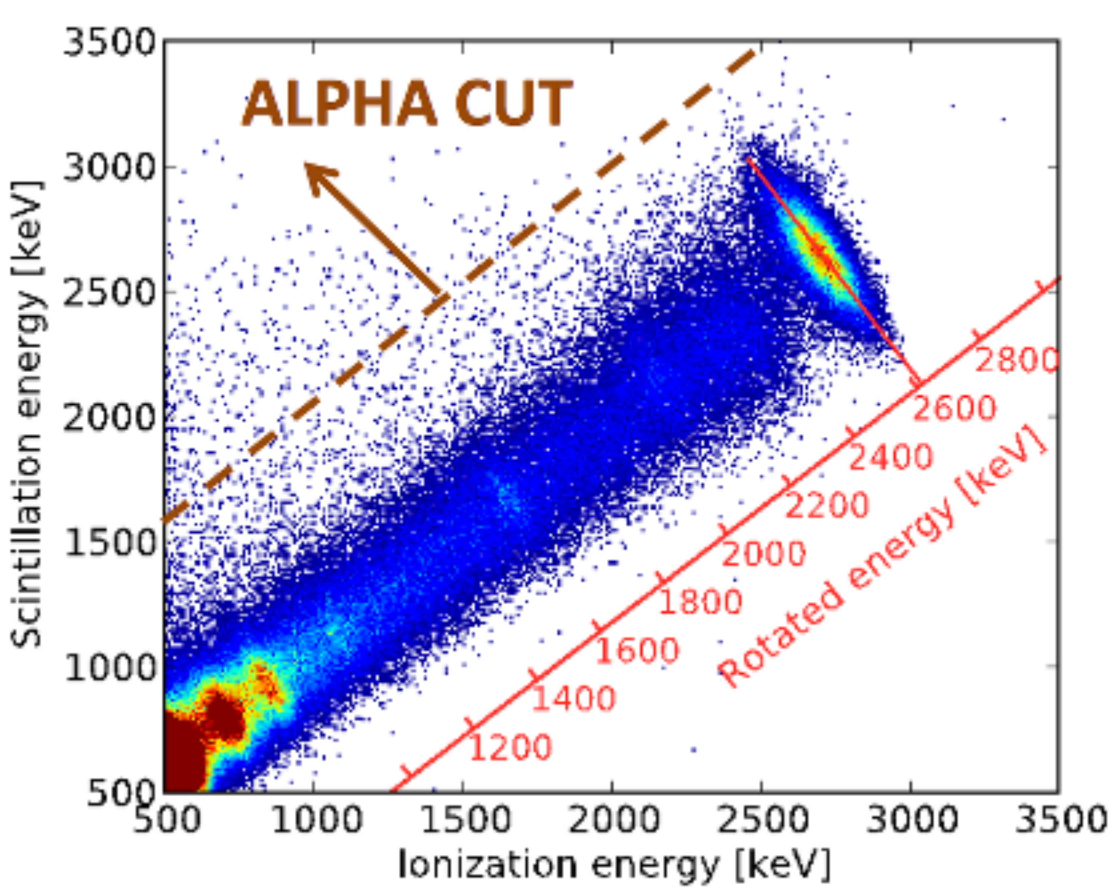


Energy

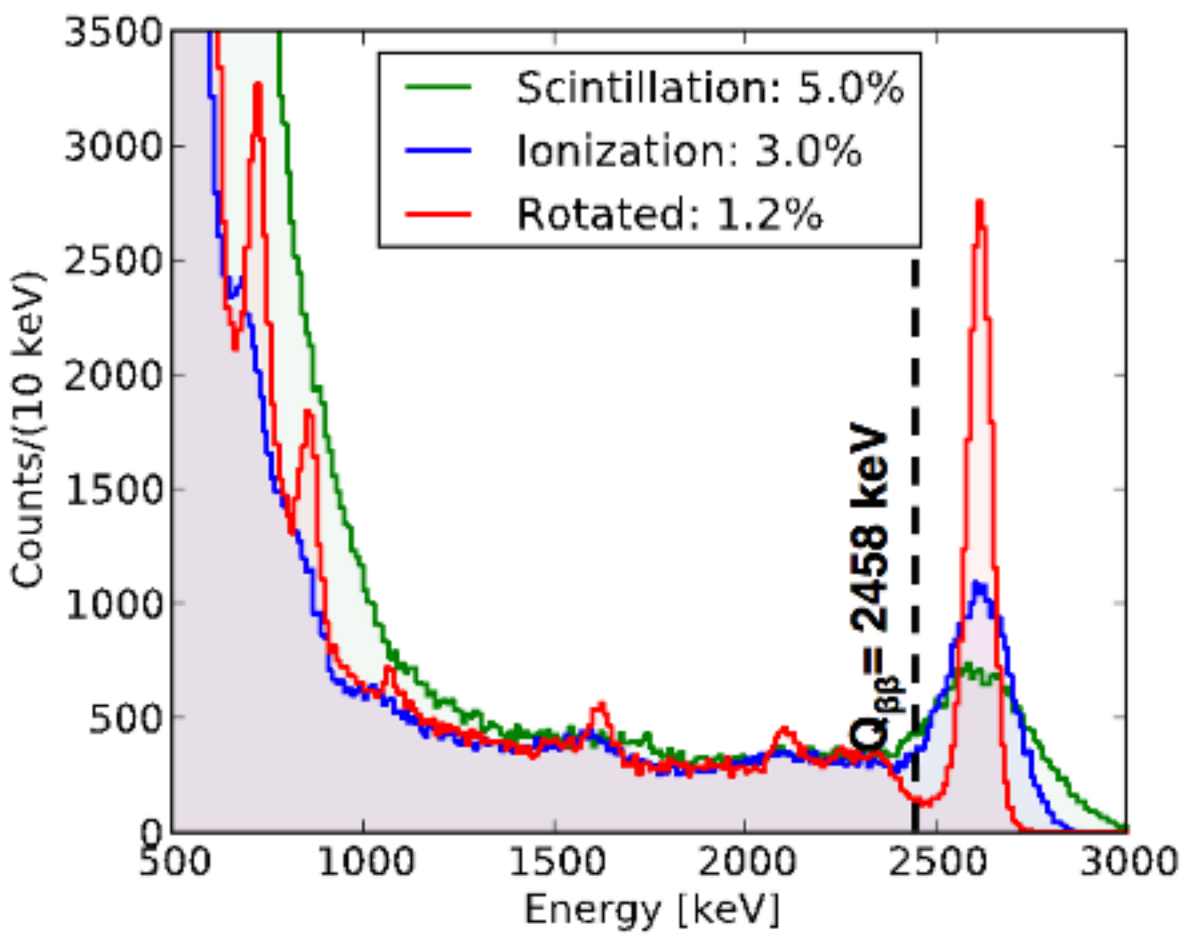
- Rejection of α particles (vs β/γ) using light/charge ratio

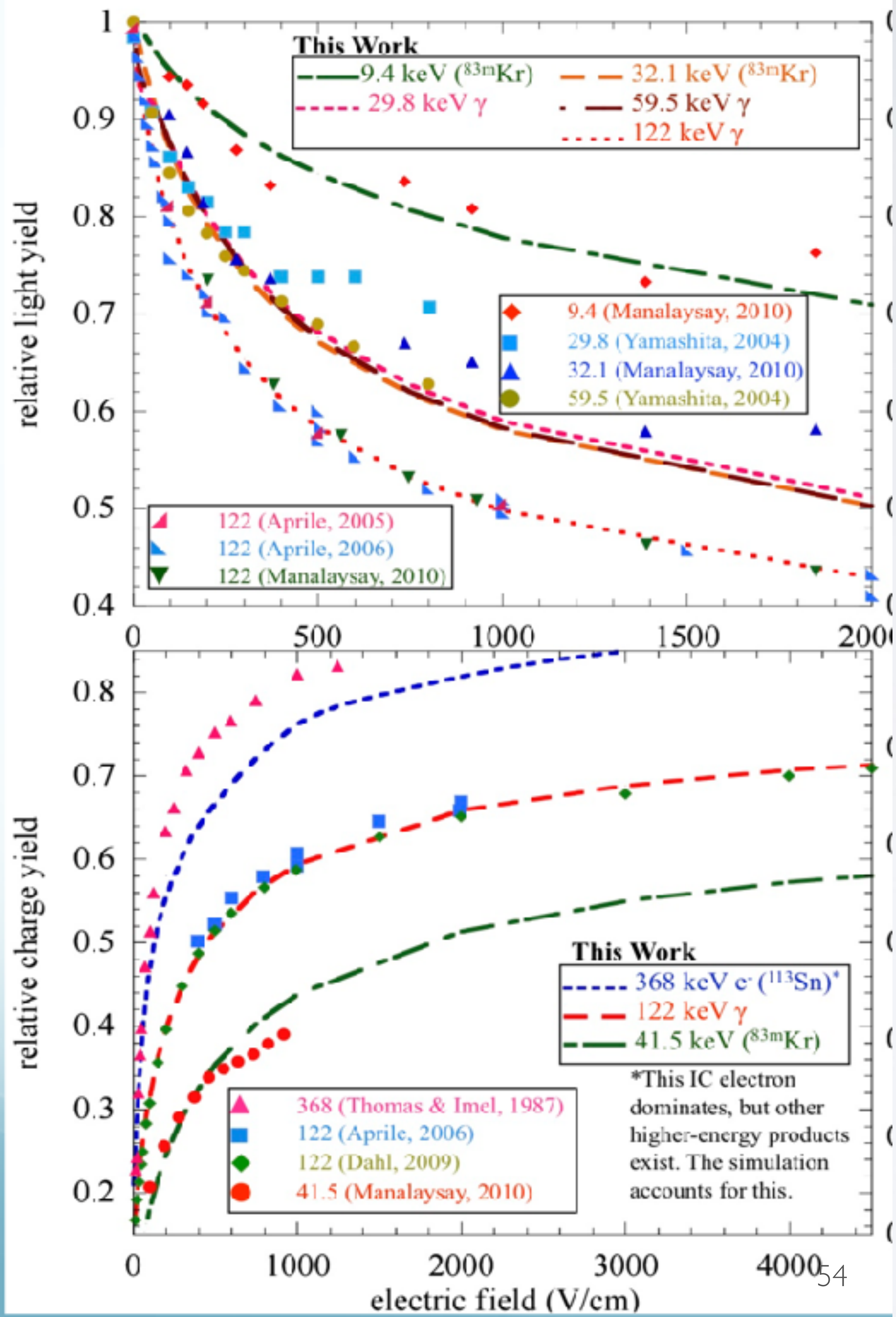
- Using anti-correlation between charge and scintillation response
  - "Rotated" energy provides optimal resolution in the energy of interest

Scintillation vs. ionization, ^{228}Th calibration:



Reconstructed energy, ^{228}Th calibration:

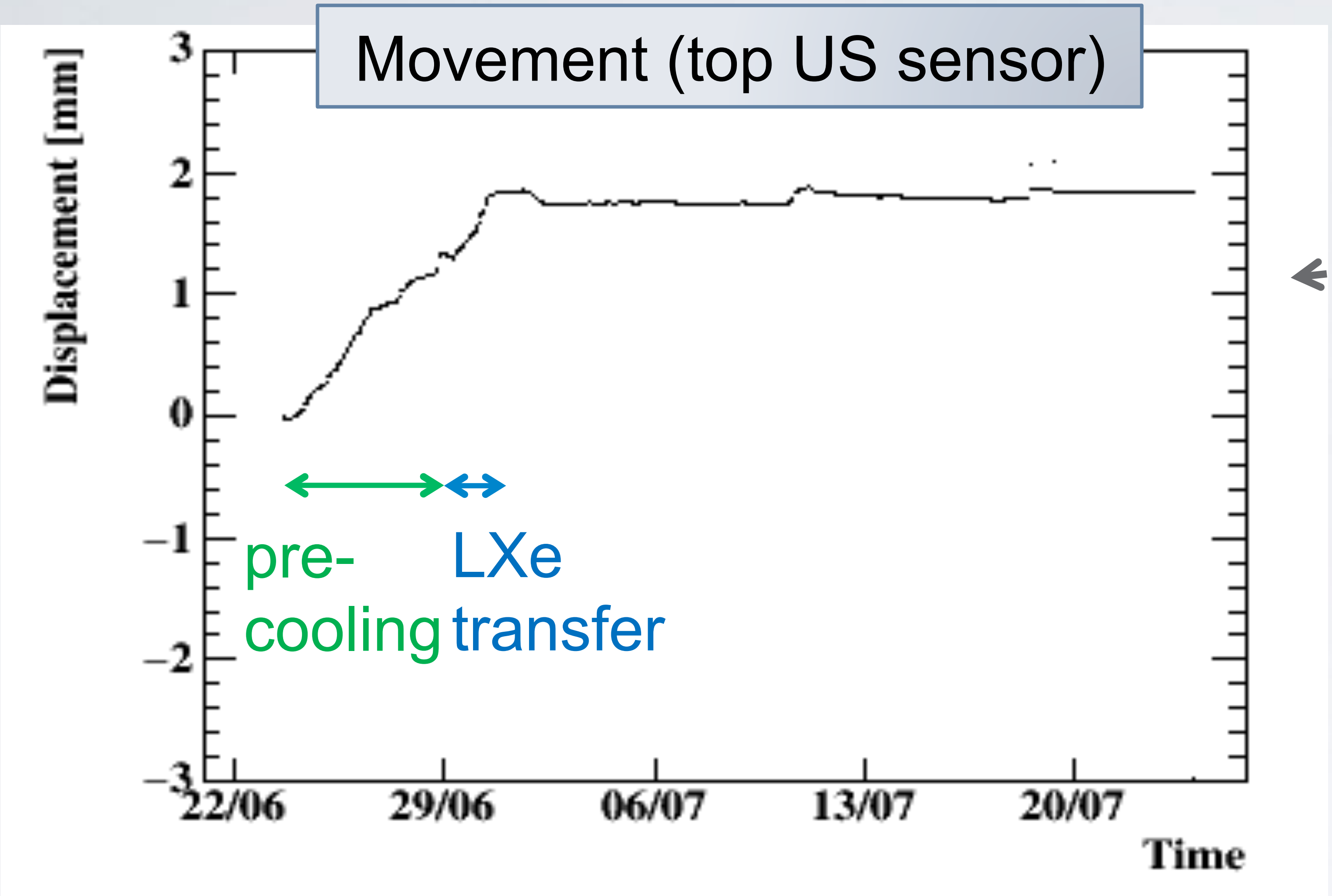


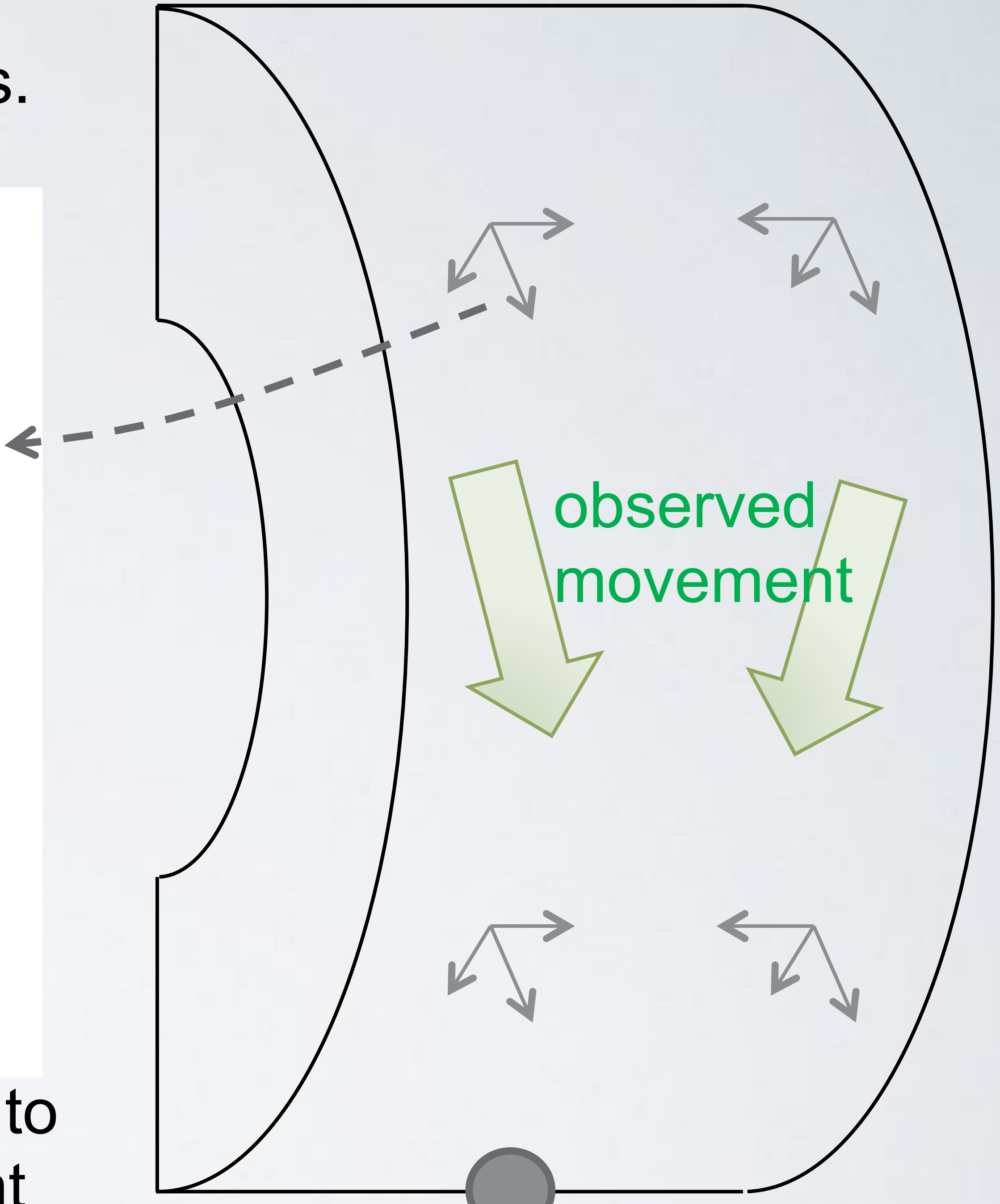


- Light/charge ratio depends on electric field

Position monitoring

3 sensors are installed at 4 different places.



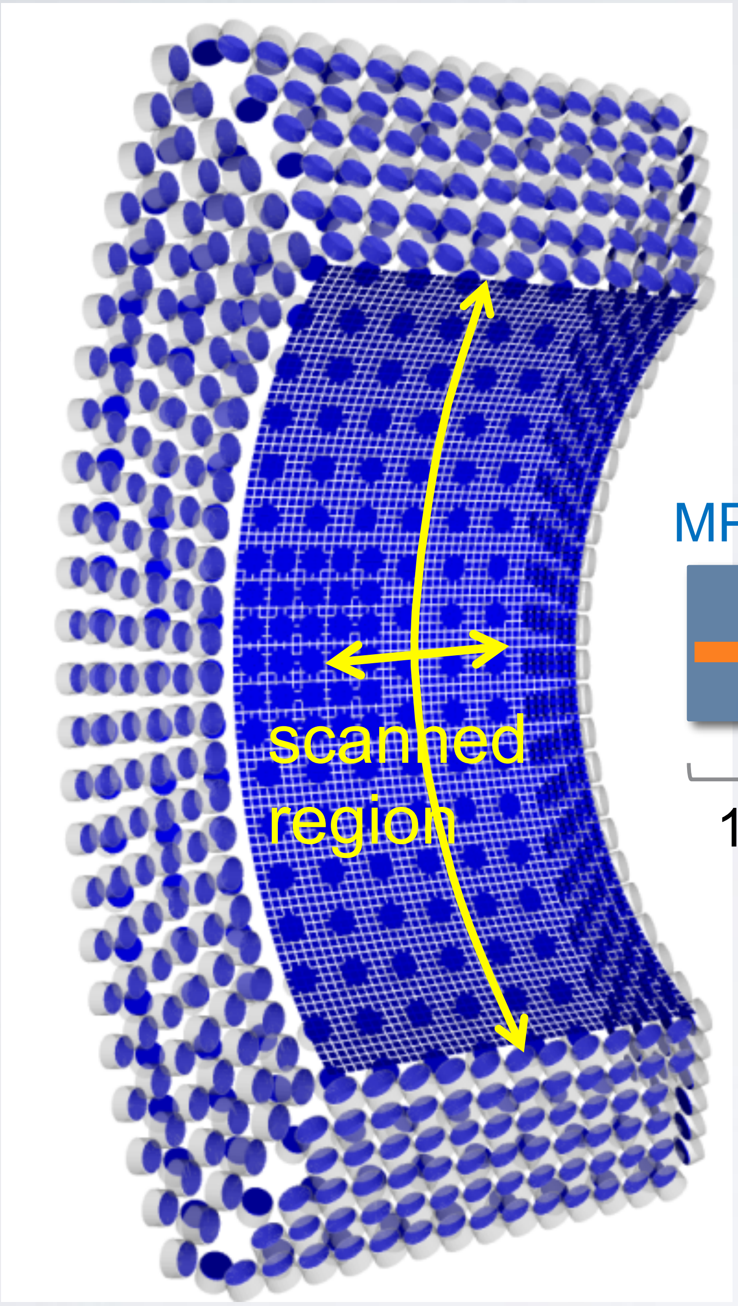


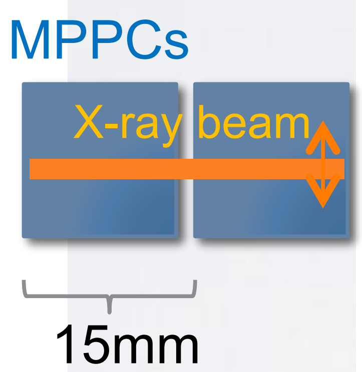
Moved mostly during the pre-cooling due to heat shrink. Result was roughly consistent with what we expect (~1.6×10^{-3}mm/m/K heat shrink to bottom direction)

Cryostat is fixed at the bottom middle.

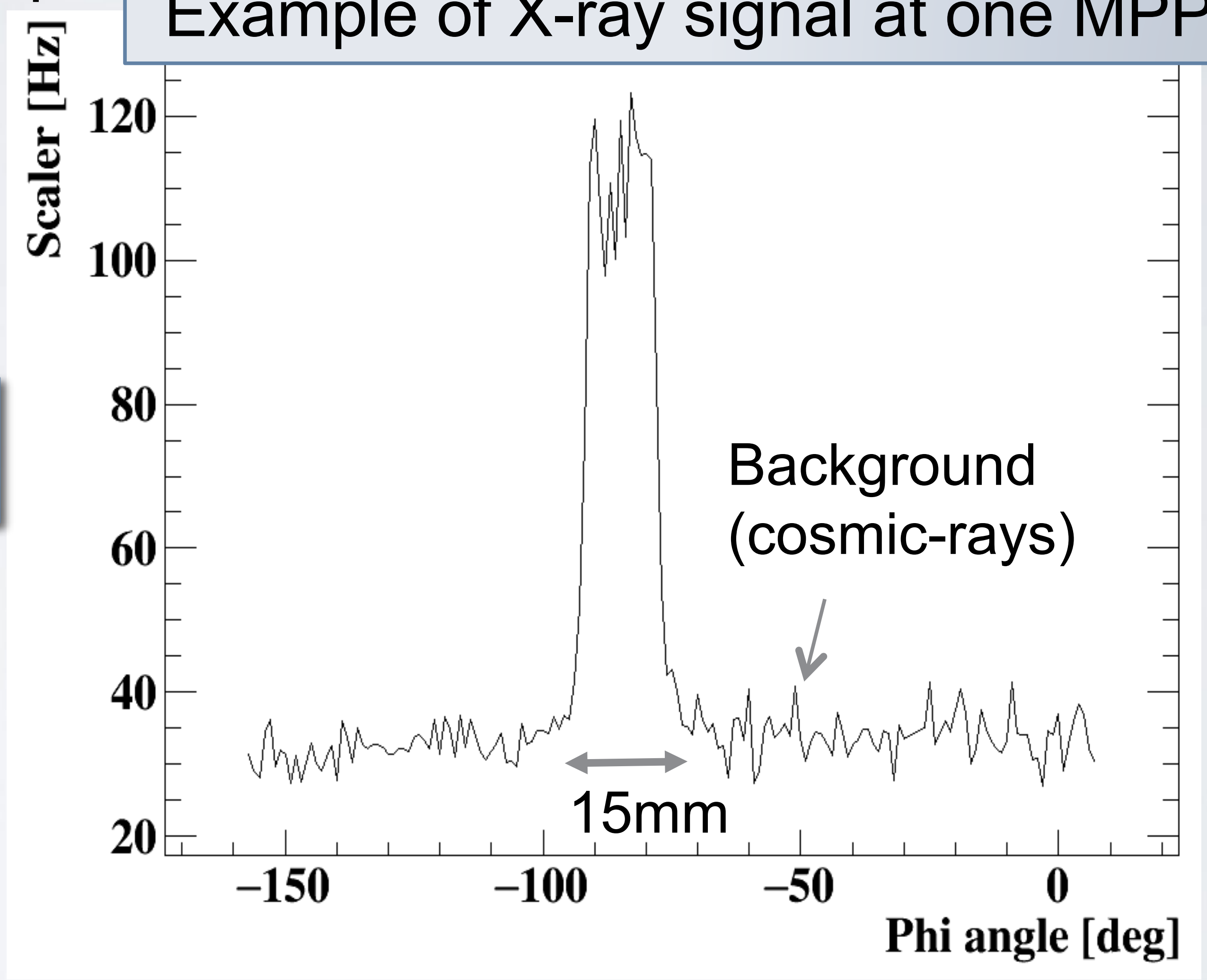
X-ray survey

Scan was performed in two directions in 1mm step.
X-ray spot size ~ 2 mm x 30 mm





Example of X-ray signal at one MPPC



Event rate increase was successfully observed around X-ray irradiated region.
Analysis is ongoing.