Noble liquid element calorimetry

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New technologies for discovery
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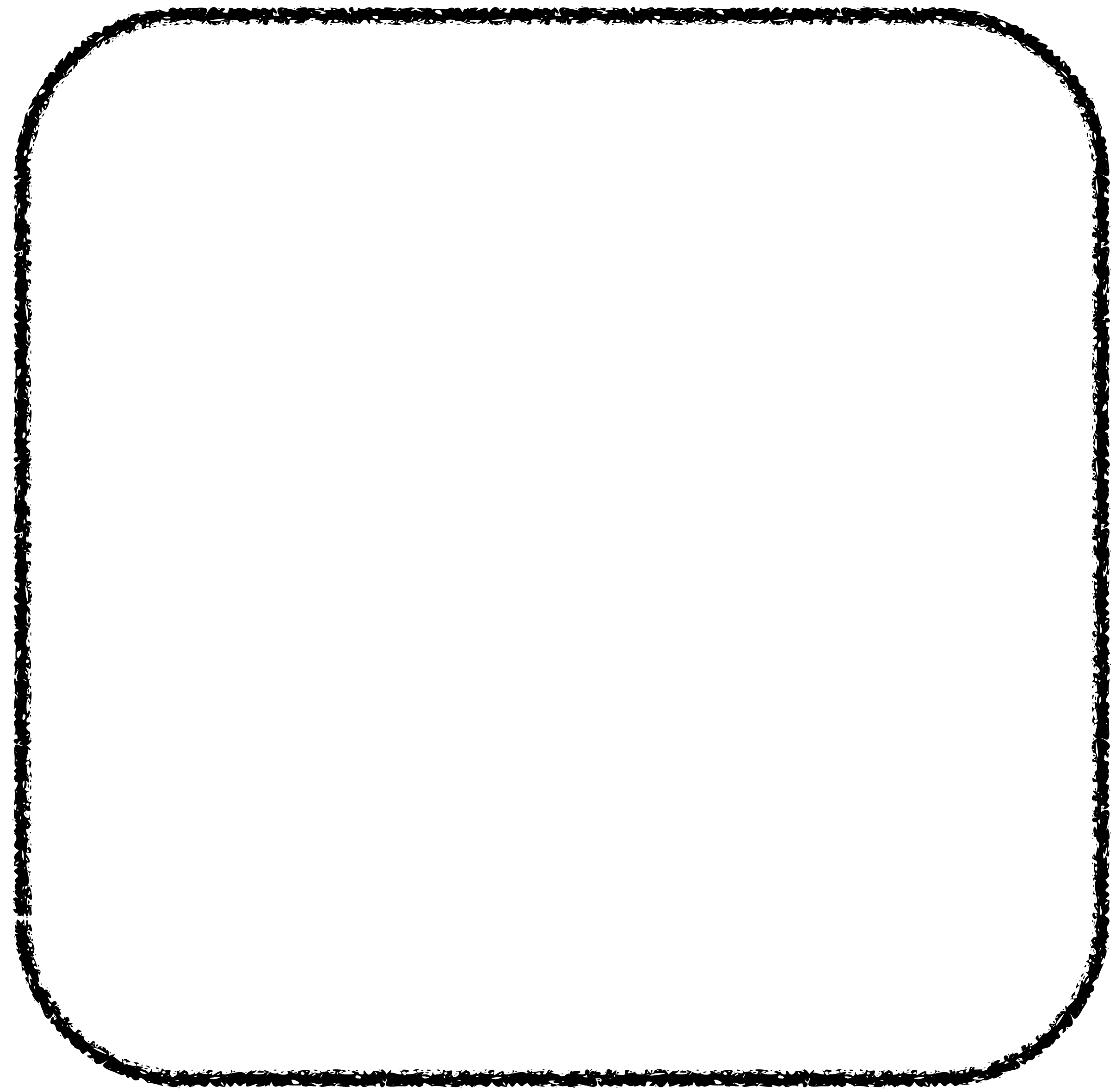
How to make a noble liquid detector

1. Prepare a vacuum chamber

Since it is liquid. Any shape is ok*

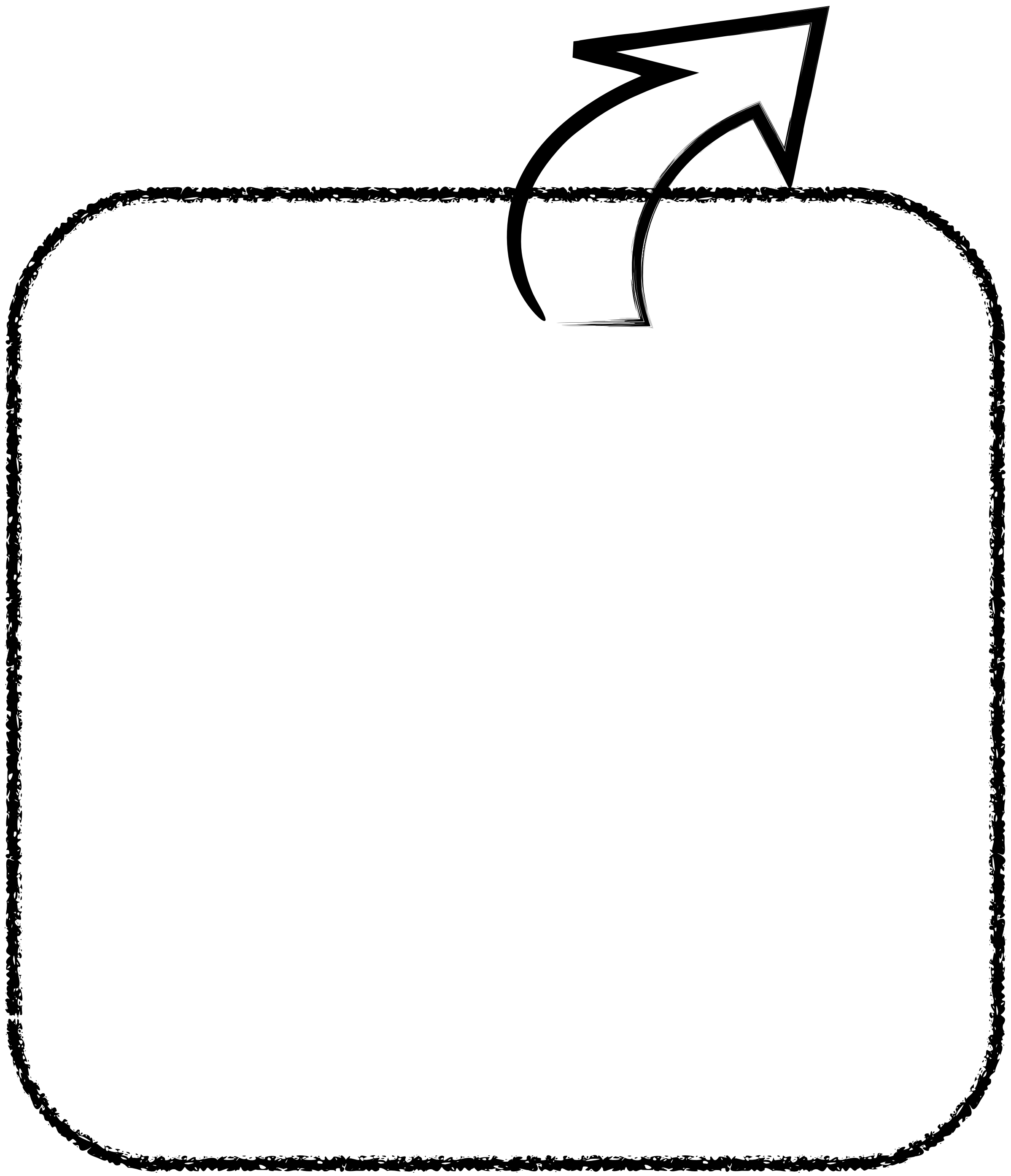


* (as long as your chamber withstand the pressure)

How to make a noble liquid detector

2. Evacuate the chamber

Impurities (water, O_2…) can deteriorate the performance of your detector by trapping electrons, absorbing the scintillation light etc.
Purity of ppb level is needed.

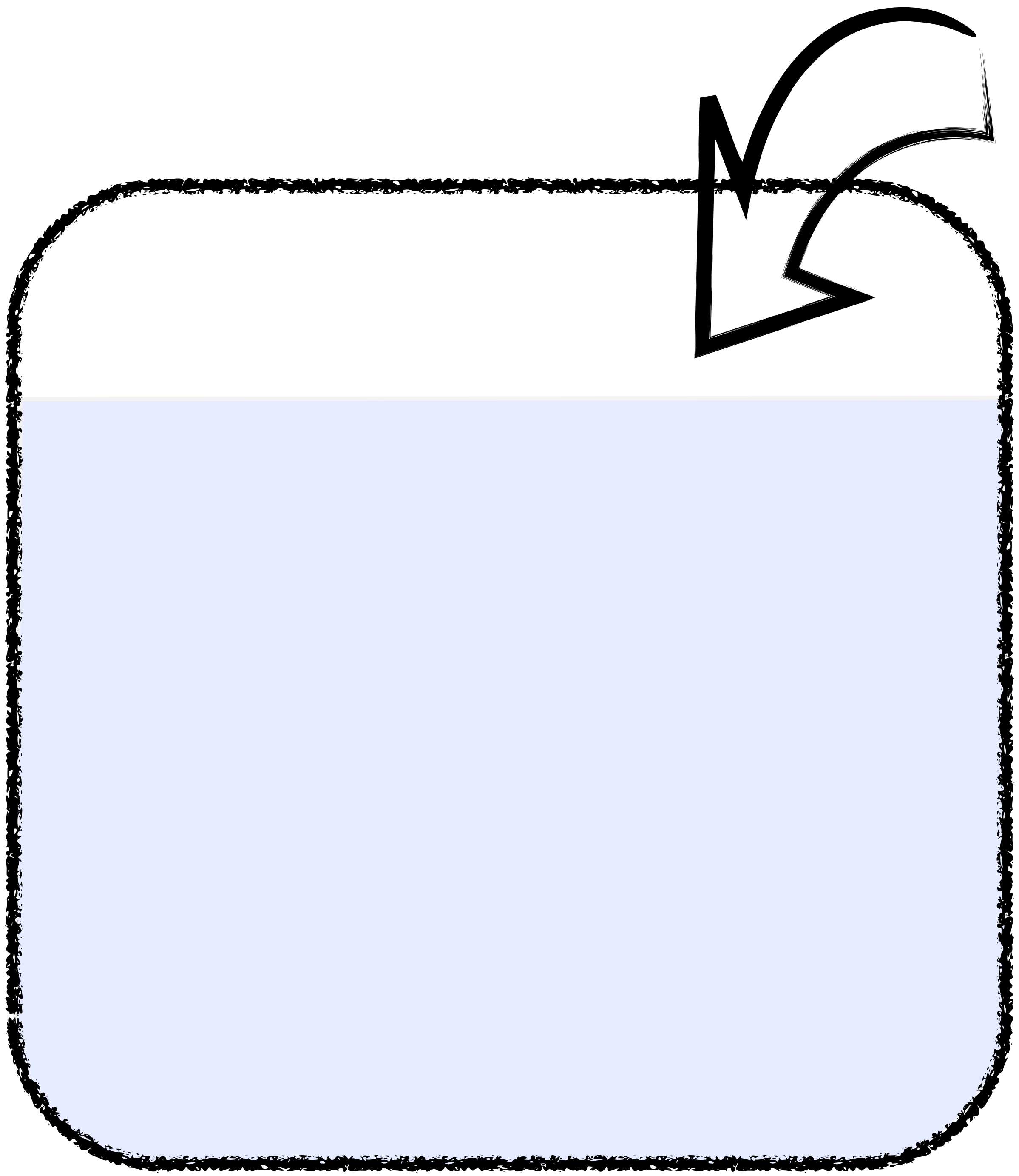


How to make a noble liquid detector

3. Put noble liquid

For keeping the noble liquid,
you need to cool it down.

Element	Boiling point
He	4.2
Ne	27.1
Ar	87.3
Kr	119.9
Xe	165.0

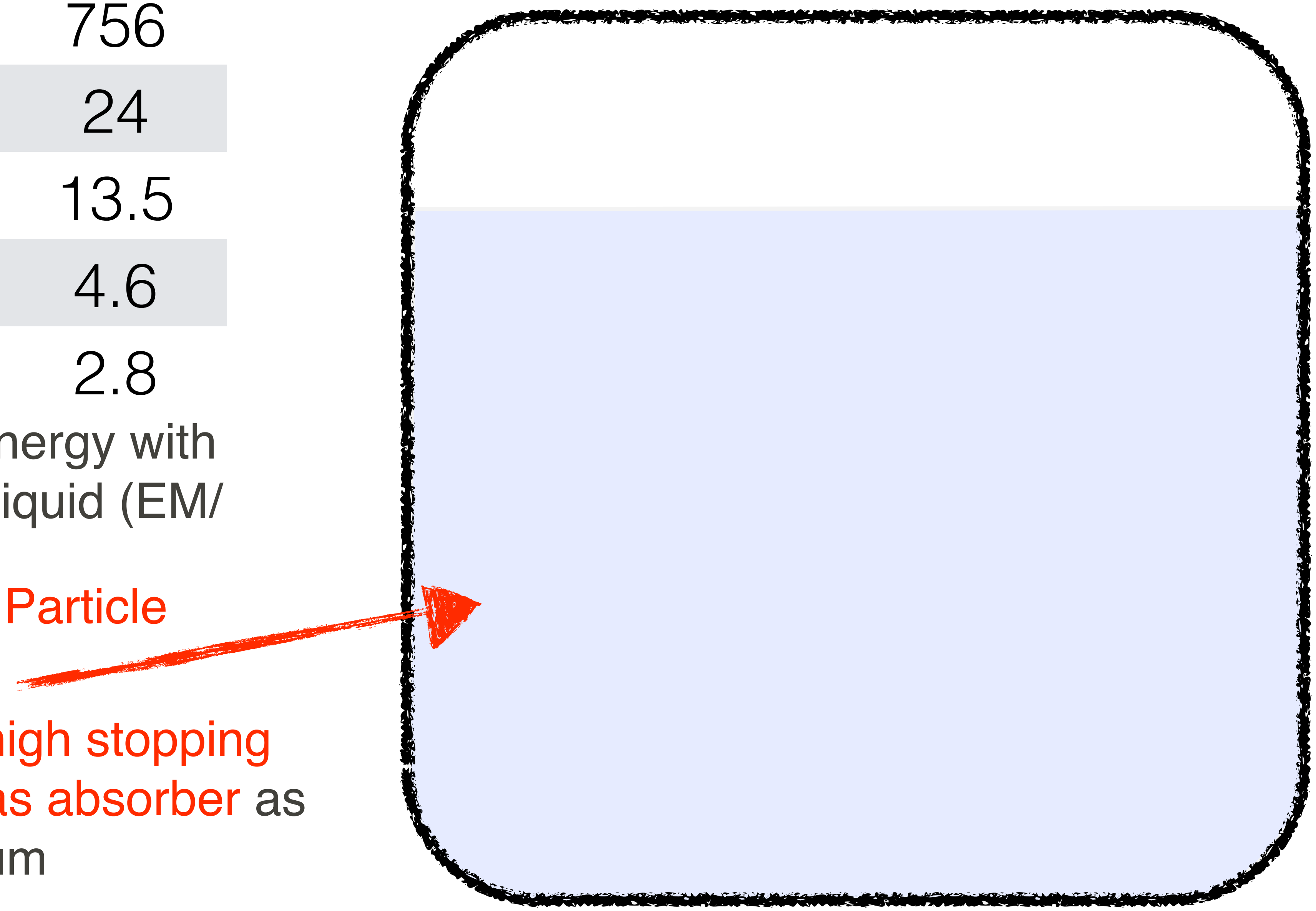


How to make a noble liquid detector

What happens when a particle enters the noble liquids ?

Element	Density	Radiation length (cm)
He	0.13	756
Ne	1.2	24
Ar	1.4	13.5
Kr	2.4	4.6
Xe	3.1	2.8

The particle loses energy with interacting with the liquid (EM/ hadronic shower).



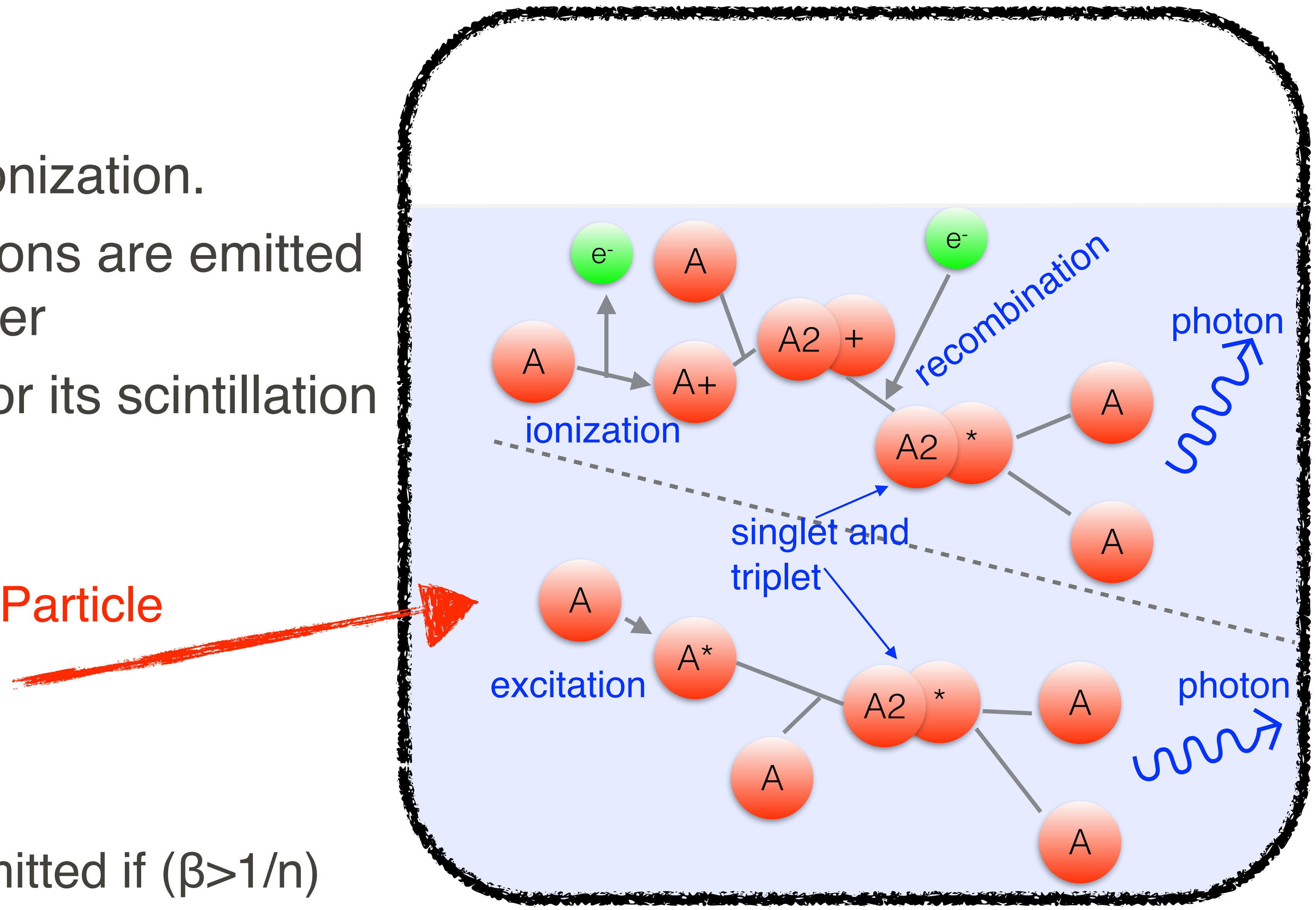
Ar,Kr and Xe have high stopping power. They serve as absorber as well as active medium

You can make totally active calorimeter !

How to make a noble liquid detector

What happens when a particle enters the noble liquids ?

- Electrons from ionization.
- Scintillation photons are emitted from excited dimer
  - →Transparent for its scintillation photons

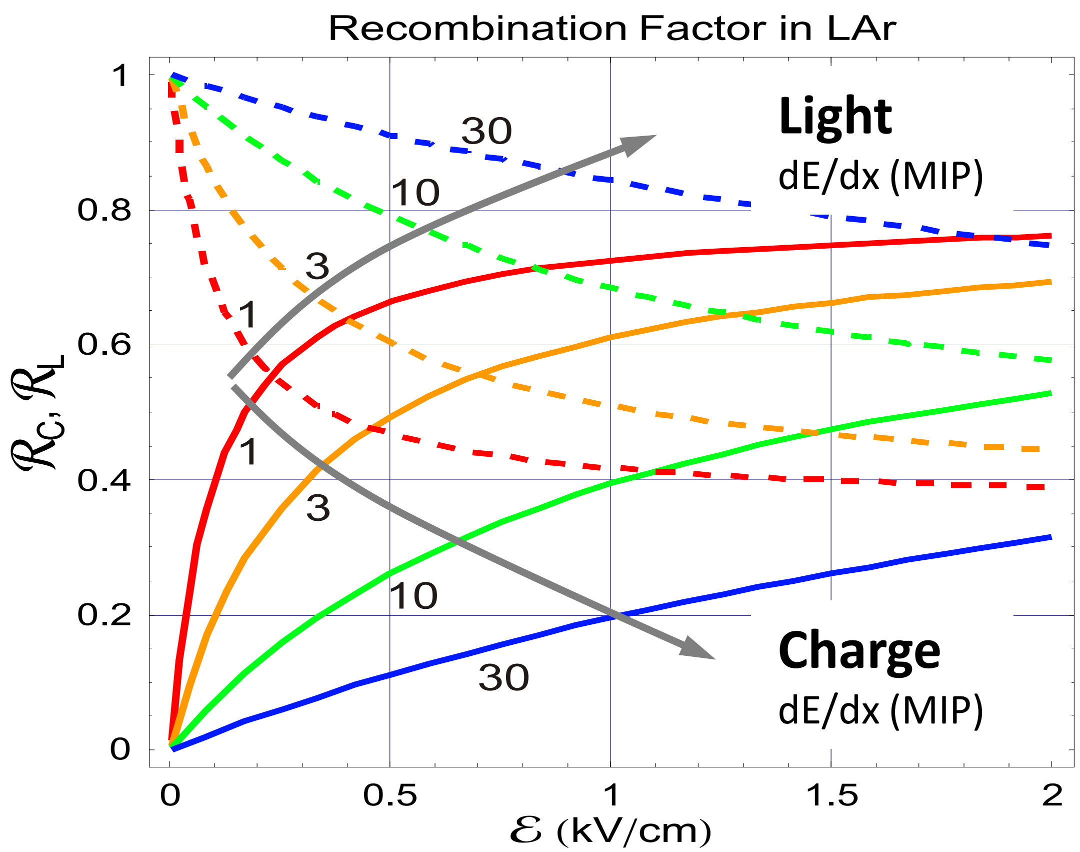


Cerenkov light is emitted if ($\beta>1/n$)

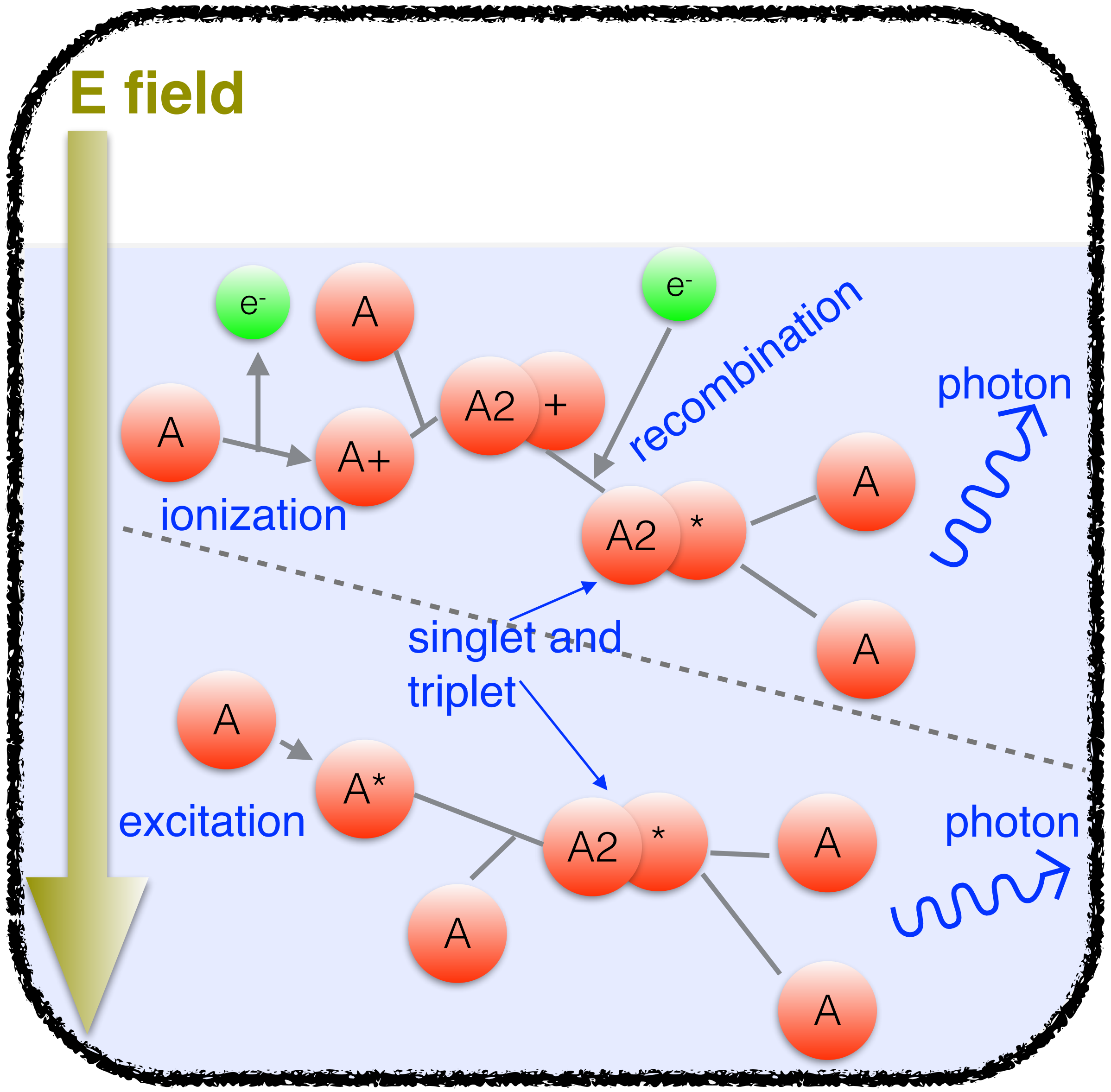
This figure taken from "Particle Detection with Liquid Nobles" by James Nikkel

How to make a noble liquid detector

What happens when you apply an electric field ?



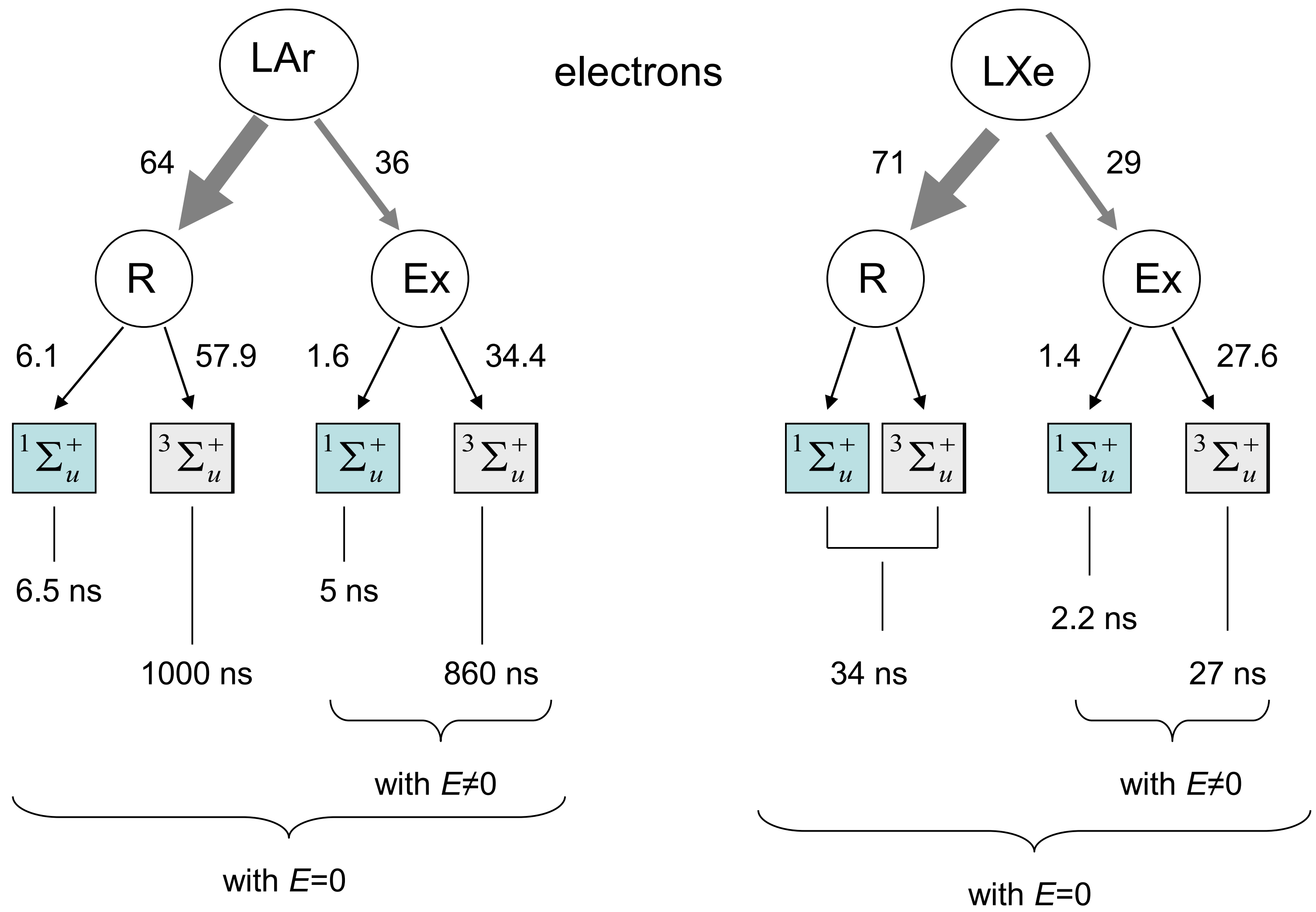
taken from
"Fundamental Properties of Noble Liquids" by Craig Thorn, CPAD, 2013



This figure taken from "Particle Detection with Liquid Nobles" by James Nikkel

Charge/light ratio changes as a function of the E field.

Scintillation signal from noble liquid

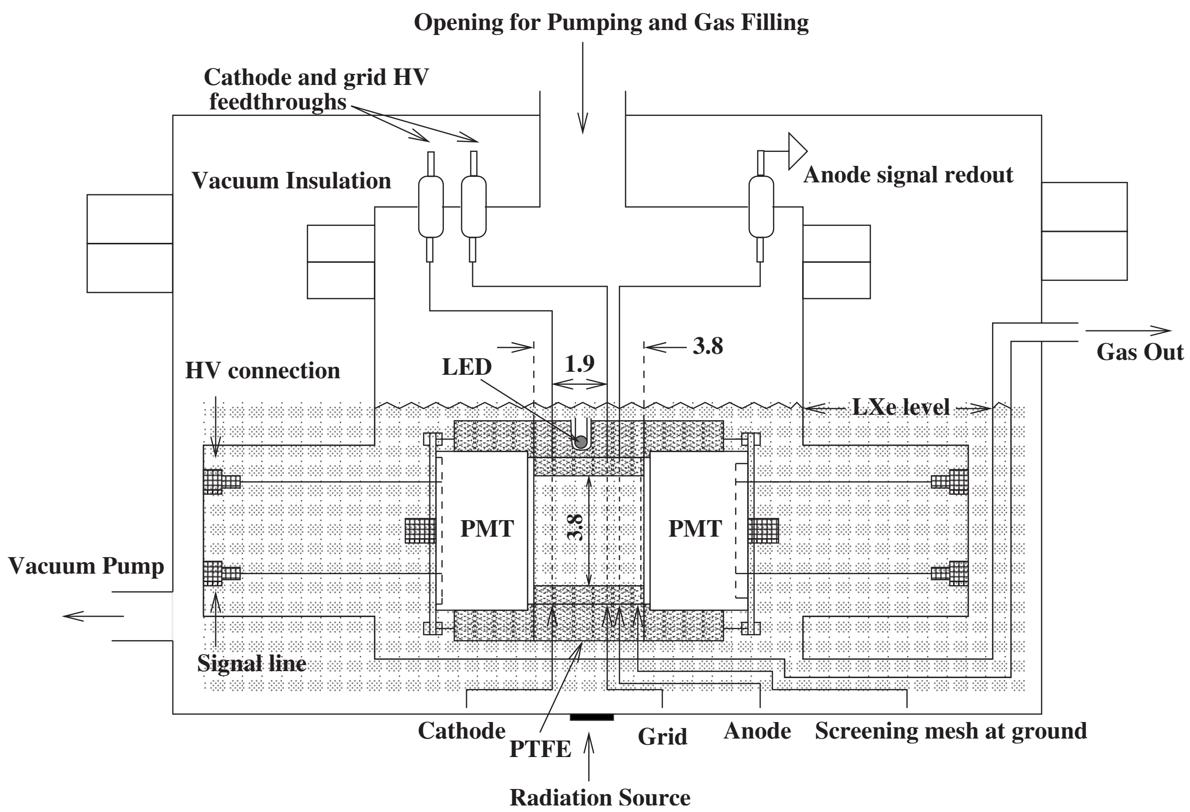


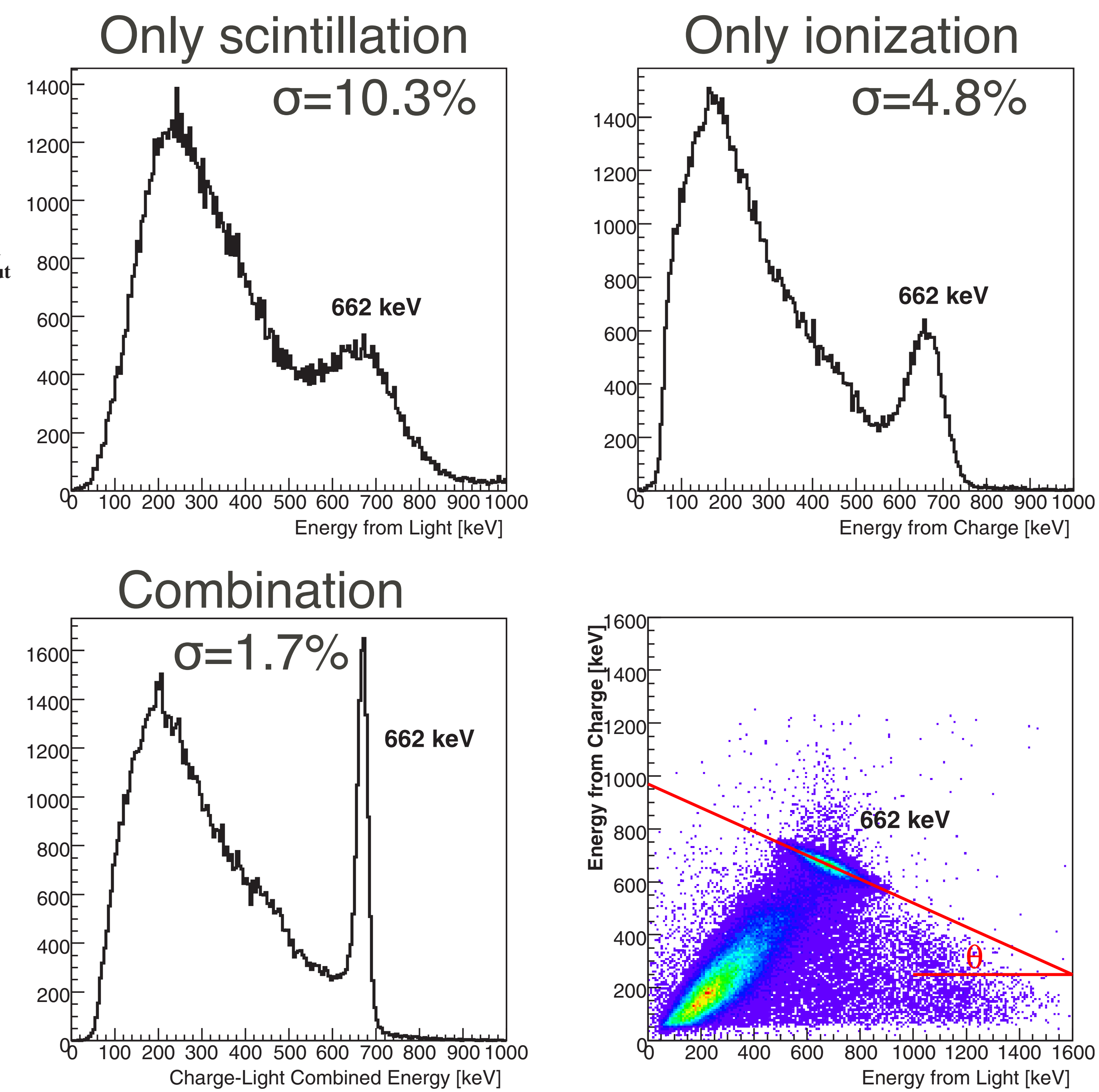
arXiv:1207.2292v3

- The scintillation signal decay time depends on the singlet or triplet.
- The singlet to triplet ratio depends on the linear energy transfer (LET).
  →Particle ID with pulse shape

Anti-correlation of scintillation and ionization

^{137}Cs 662 keV γ

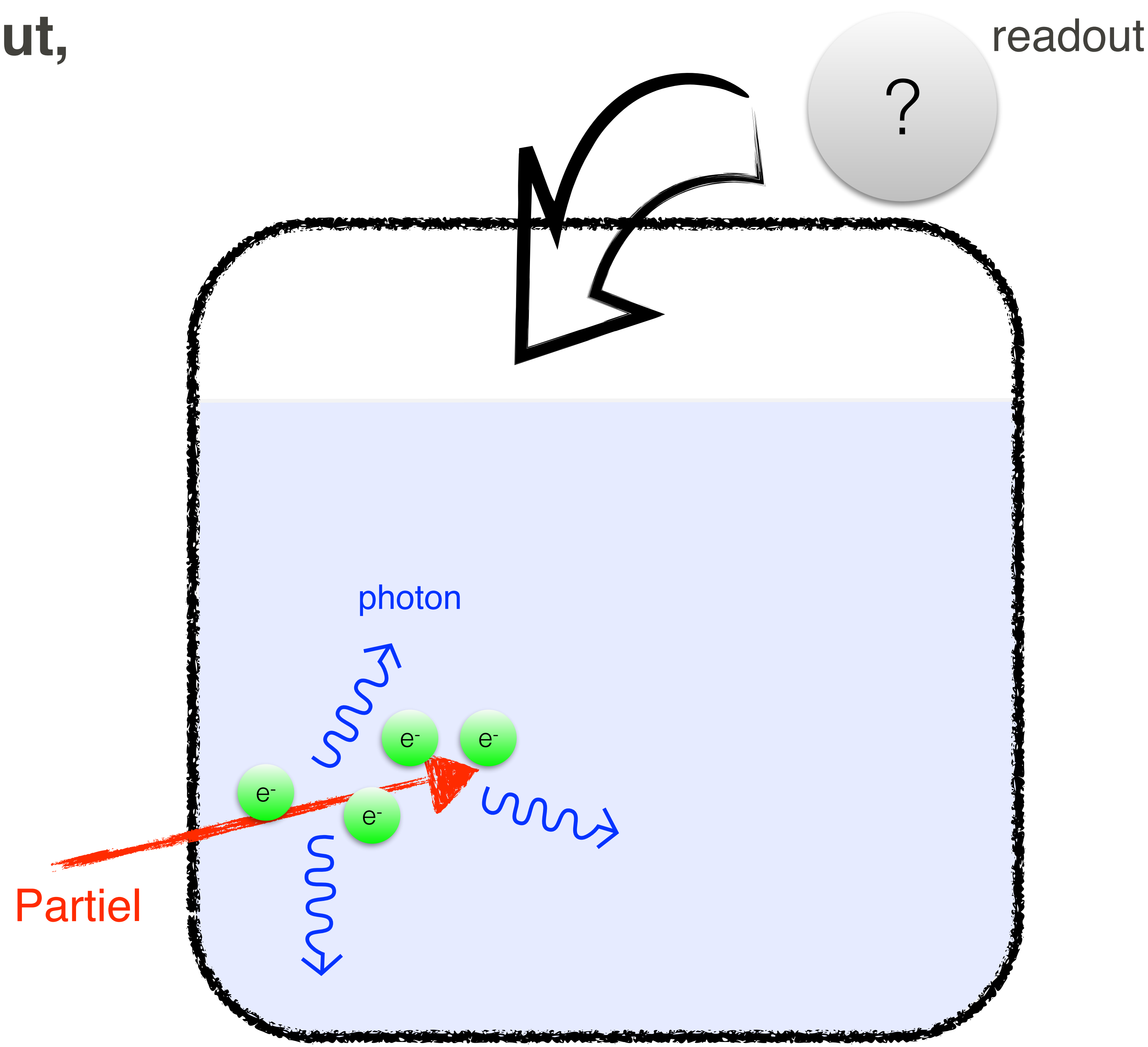




- Ionization and scintillation signals are strongly anti-correlated
- Energy resolution can be very much improved by using both the signals.

How to make a noble liquid detector

3. Put signal readout,



How to make a noble liquid detector

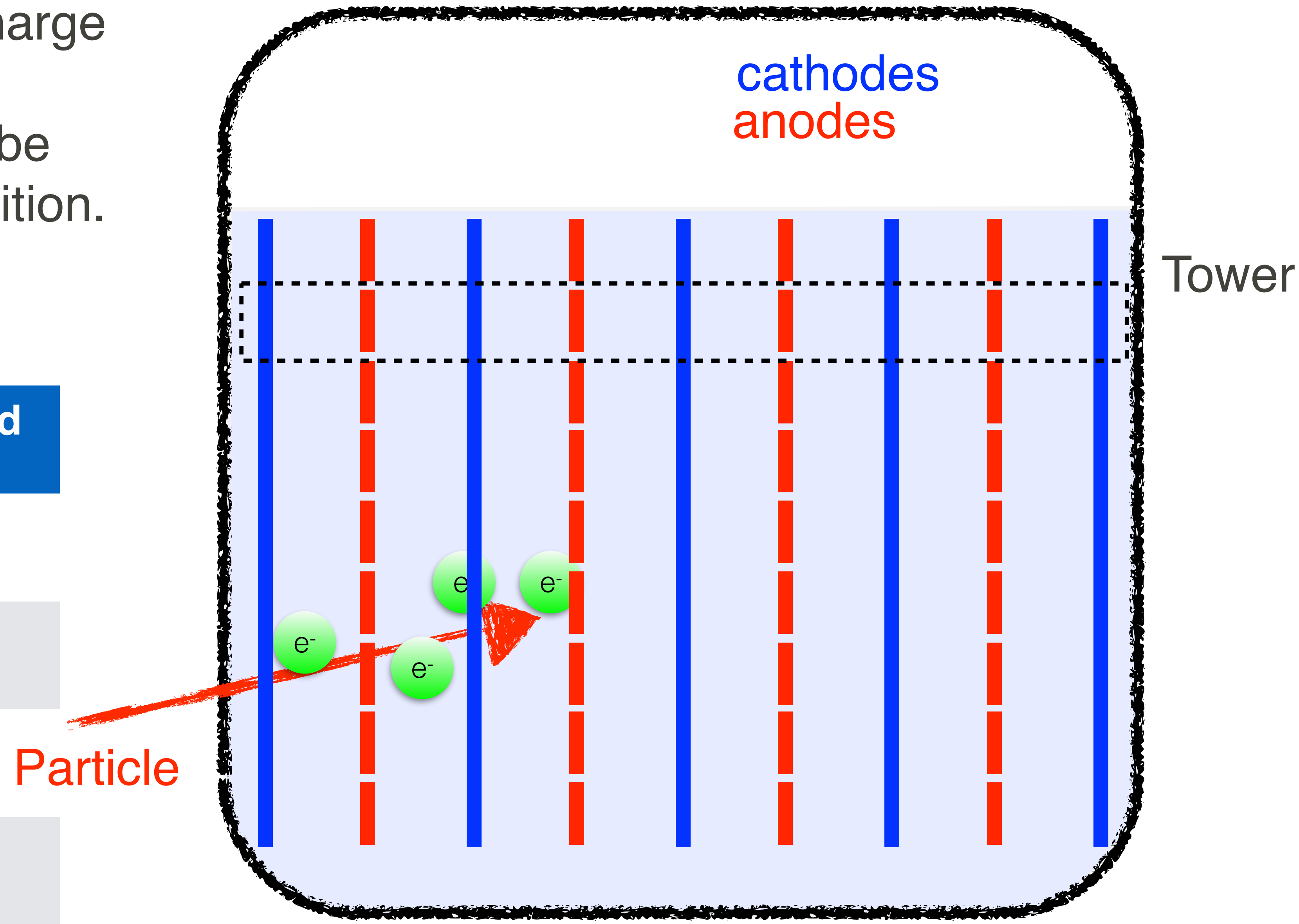
3. Put signal readout,

Homogeneous calorimeter

Anode/Cathode for reading charge

Cathodes and/or anodes can be segmented for measuring position.

Element	Electron yield (e-/keV)
He	39
Ne	46
Ar	42
Kr	49
Xe	64



How to make a noble liquid detector

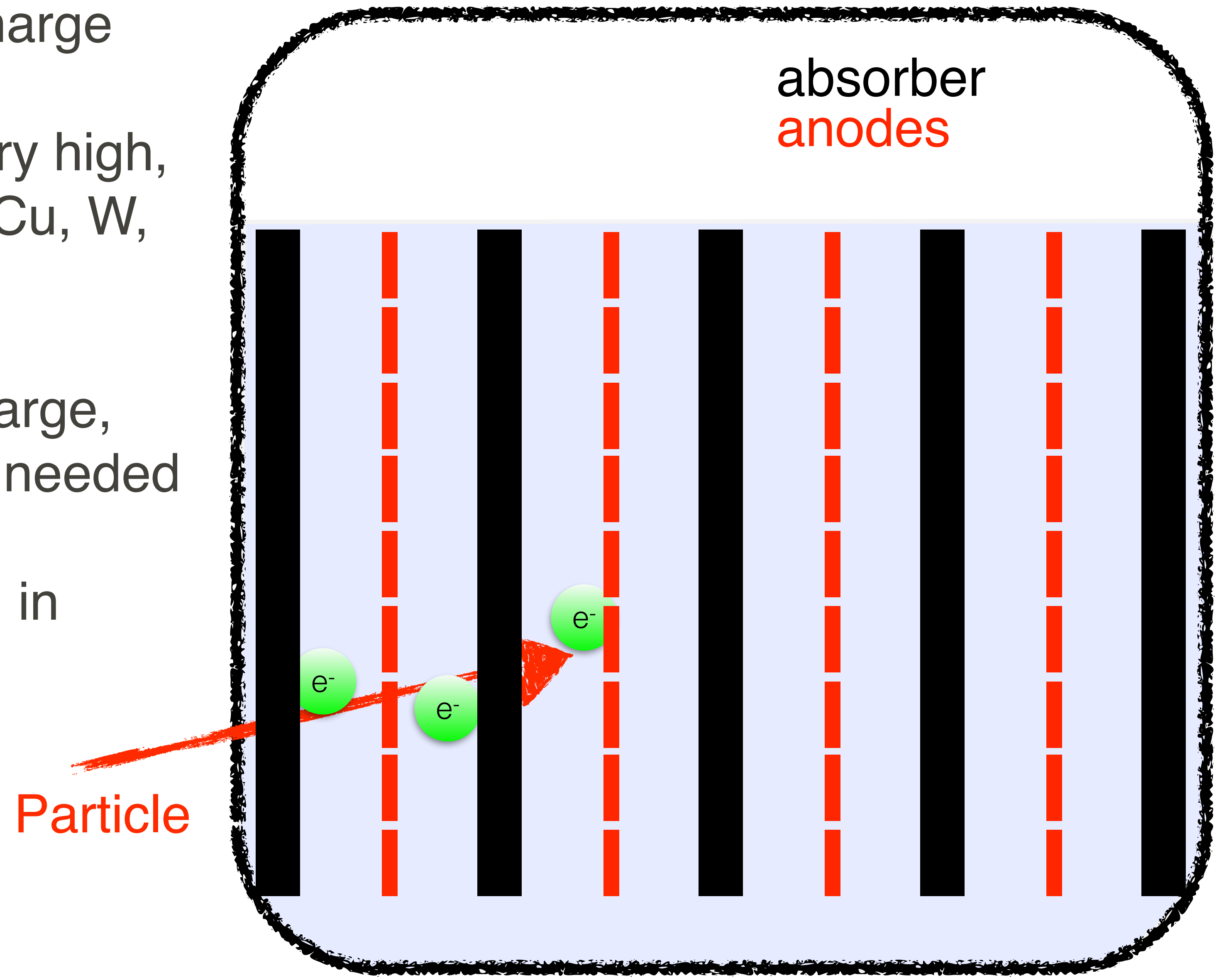
3. Put signal readout,

Sampling calorimeter

Anode/Cathode for reading charge

If the energy of radiation is very high,
You can put heavy absorber (Cu, W, Pb, U etc.)

Since the ionization signal is large, additional multiplication is not needed (not like gas chamber)
→ Signal amplitude is uniform in space and stable in time



How to make a noble liquid detector

3. Put signal readout,

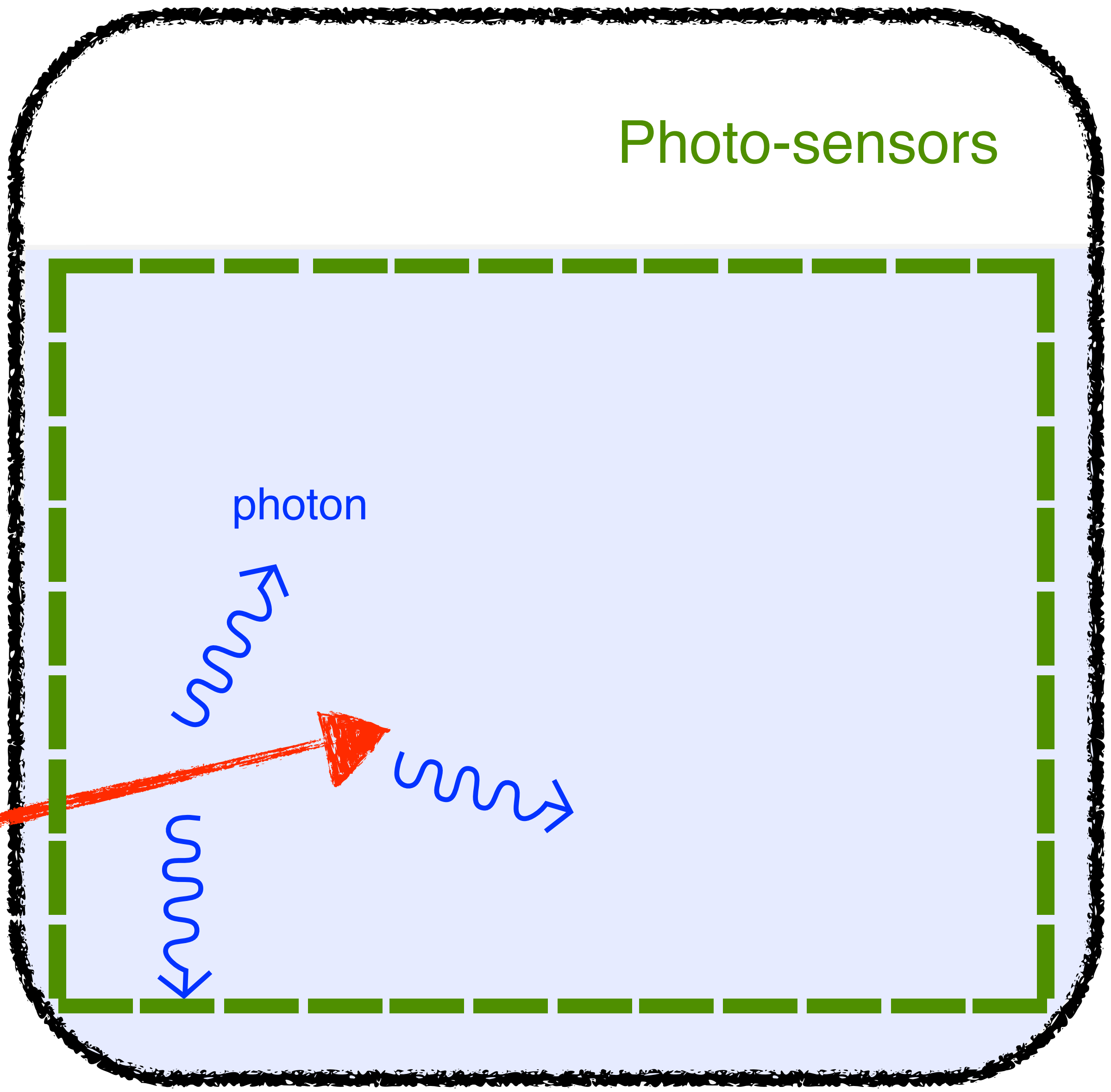
Photo-sensors for reading scintillation

Scintillation calorimeter

Scintillation signal is faster than ionization.
More expensive than reading charge (in general)

Scintillation wavelengh is shorter than other scintillators
→ Special sensors or wavelength-shifter are needed.

Element	Photon yield (photon/keV)	Wavelength (nm)
He	22	80
Ne	32	78
Ar	40	128
Kr	25	148
Xe	42	178



Technologies to detect VUV photons

- VUV sensitive SiPM (e.g. MEG + Hamamatsu)
- Wavelength shifter (WLS, e.g. TPB) deposited on PMT, SiPM or APD
- WLS coated plated in front of photo-sensors
- GEM + photocathode coated with wavelength shifter
- 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), 35% QE for 170—450 nm

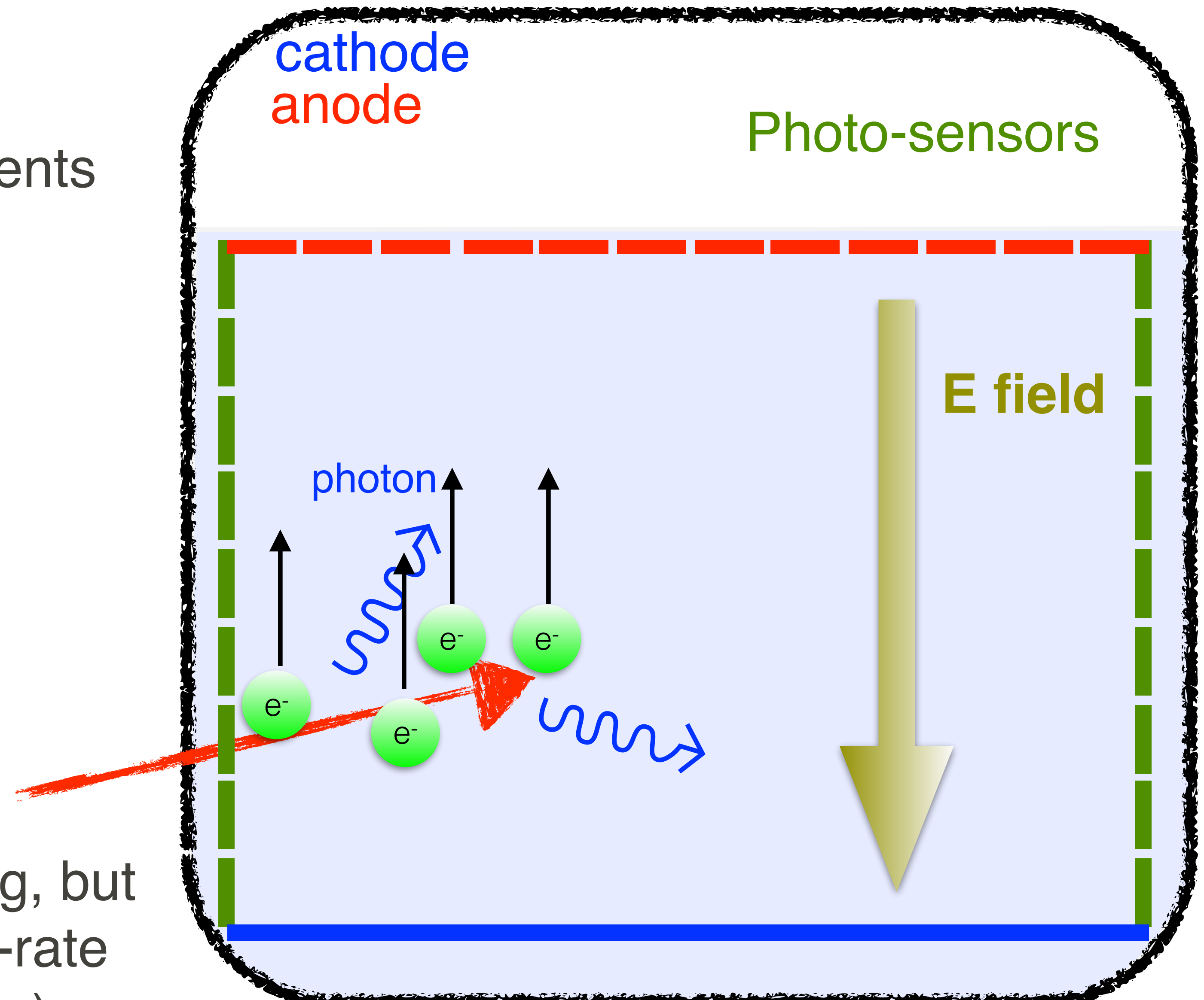
How to make a noble liquid detector

3. Put signal readout,

TPC

Very precise position measurement

Detailed 3D reconstruction of events



This type of readout is interesting, but not used for calorimeter for high-rate experiments. (Drift time O(mm/μs) can be too long if distance is long.)

There are many developments for neutrino detectors, astrophysics, 0ν double beta searches, medical application etc.

Features and advantages of noble liquids

- Flexibility in the design of the detector and readout
- Scalability with uniform response
- Radiation hard
  - Important for the future high luminosity experiments
- Scintillation and/or ionization signals available
  - Ionization suitable for very large scale detectors
  - Large and fast scintillation signal for timing measurement
- Several types of detectors
  - Homogeneous
  - Sampling
  - Scintillation
  - TPC
- Particle-ID with ionization/scintillation ratio and the pulse shape

Noble liquids

He/Ne

- Long radiation length
- Low boiling temperature (< LN_2)
- Short scintillation wavelength (< 90 nm)

Ar

- Low price
- Low radioactivity

→ Sampling calorimeter EM/Hadronic

Kr

- Short radiation length
- High resolution
- Modest price
- High radioactivity

→ Homogeneous calorimeter

Xe

- Very short radiation length
- Very high resolution
- Very expensive (~10 times higher than Kr)

→ Homogeneous/scintillation calorimeter

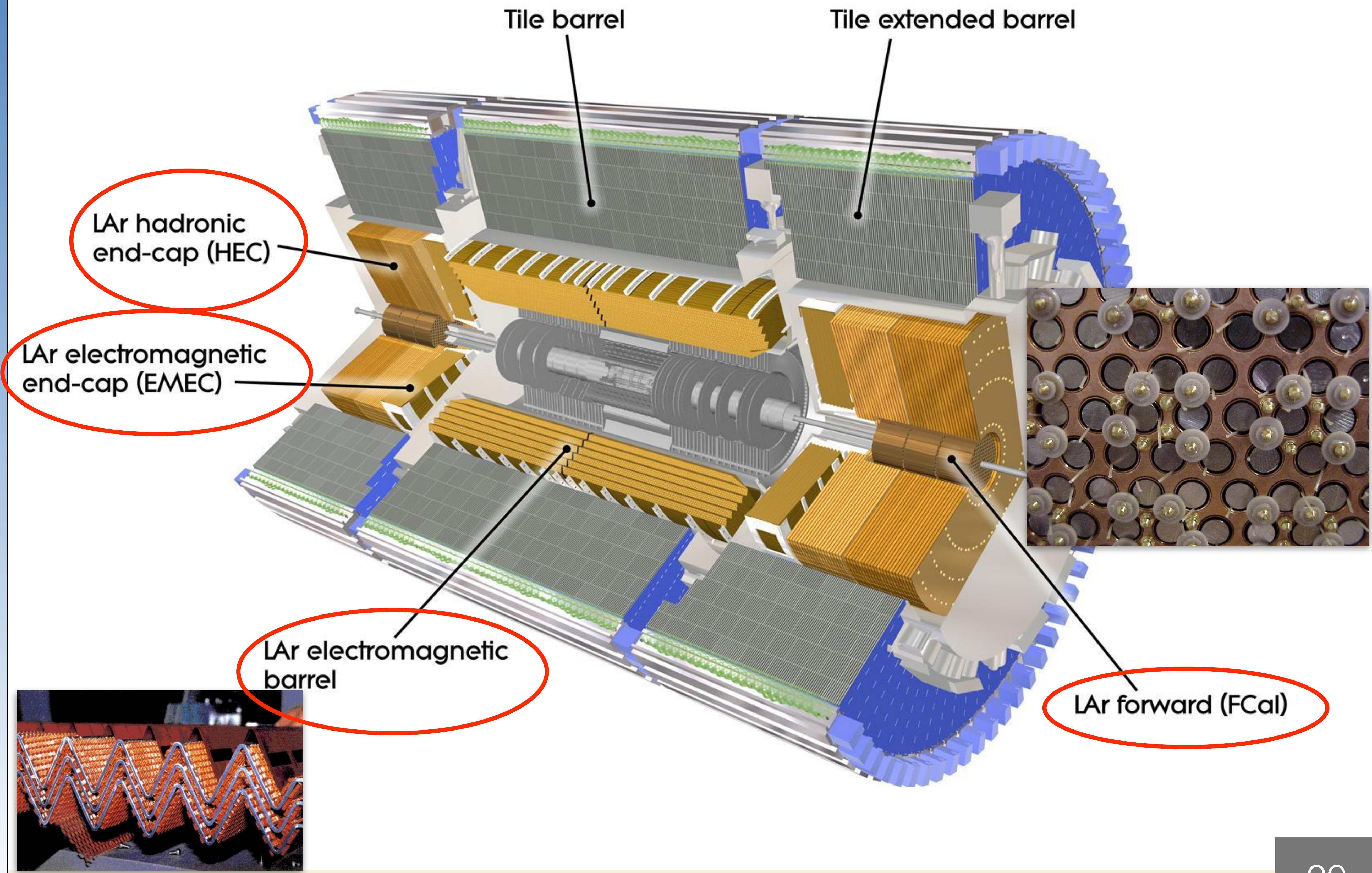
Calorimeters

Experiment	Type	Material	Signal	Resolution (%)
D0	Sampling	LAr	Ionization	$16/\sqrt{E} \oplus 0.3 \oplus 0.3/E$
H1	Sampling	LAr	Ionization	$12/\sqrt{E} \oplus 1$
ATLAS	Sampling	LAr	Ionization	$10/\sqrt{E} \oplus 0.4 \oplus 0.3/E$
NA48/62	Homogeneous	LKr	Ionization	$3.2/\sqrt{E} \oplus 0.42 \oplus 0.09/E$
KEDR	Homogeneous	LKr	Ionization	3 @ 1.8 GeV
CMD-3	Homogeneous	LXe	Ionization	$1.78/\sqrt{E} \oplus 1.86$ combined resolution with CsI
MEG	Homogeneous	LXe	Scintillation	1.7 @ 50 MeV

ATLAS LAr Calorimeter

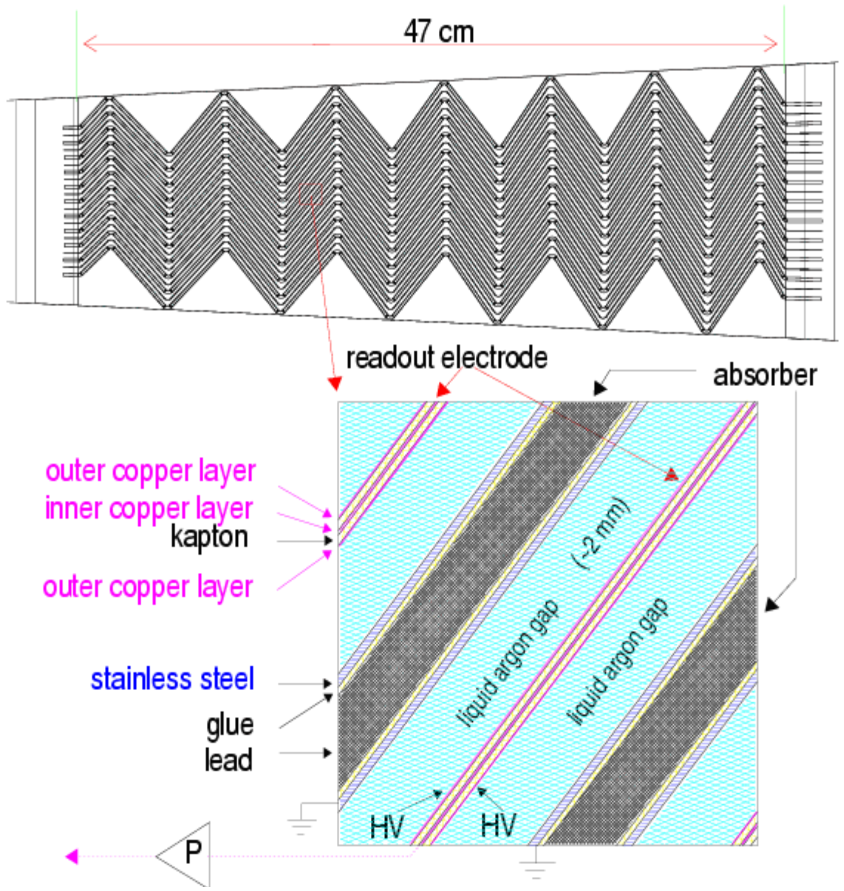
ATLAS calorimeters

LAr chosen for radiation hardness



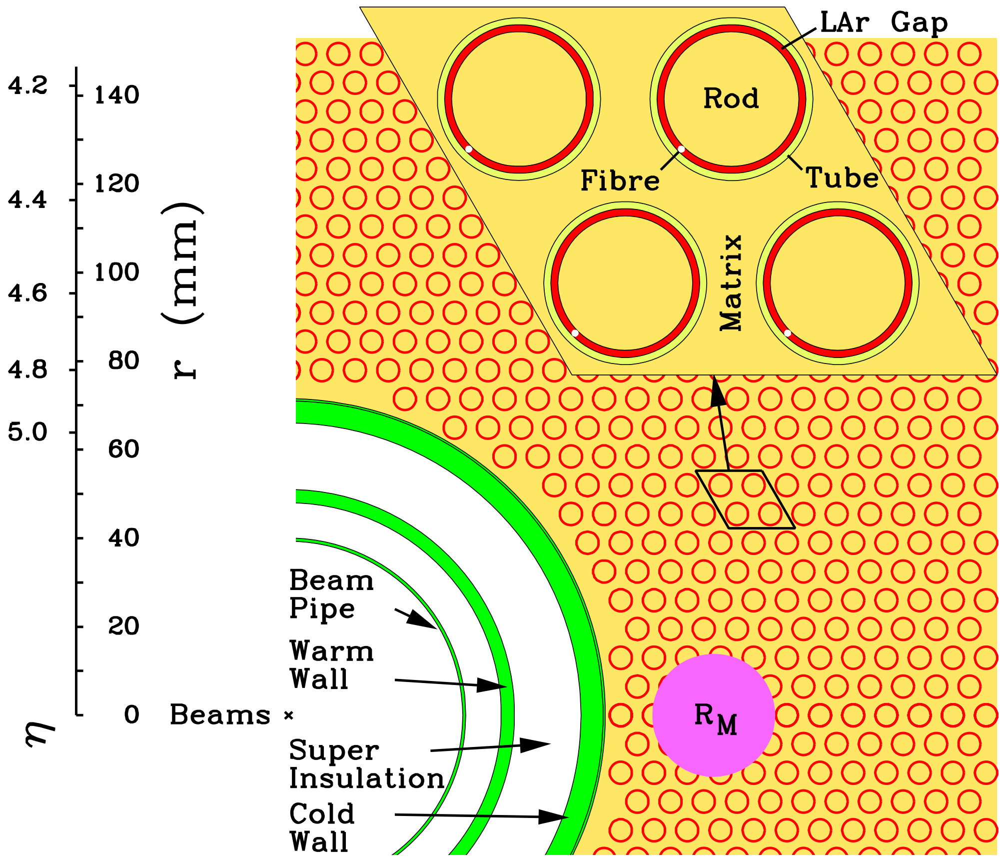
ATLAS LAr

Barrel



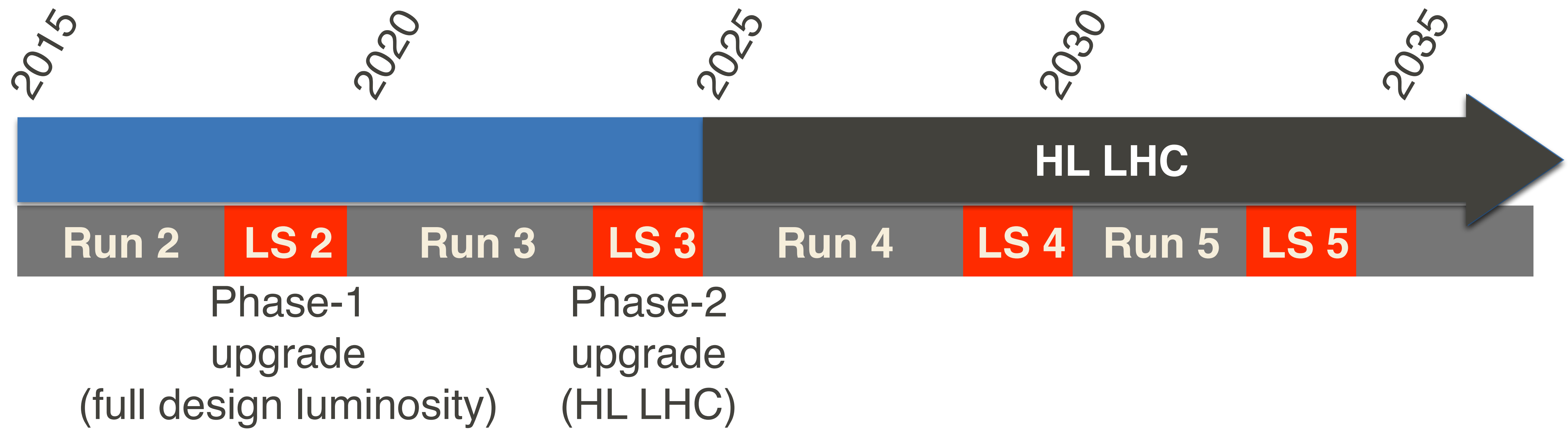
* "Accordion" structure
  * Good hermeticity, azimuthal uniformity
  * Drift in the 2mm LAr gap (drift time 450 — 600 nsec)
  * For the first response, the charge in ~10% of the drift time is read and the pulse is shaped.

Forward



* Copper or Tungsten rods with gaps maintained with PEEK fibers
  * High density (14.5 g/cm^3) with this structure
* Limiting luminosity due to the space-charge efffect is safely high with small LAr gap (0.25, 0.375, 0.5 mm)

ATLAS LAr calorimeter upgrades



- Phase-1
  - Finer granularity readout at the trigger level (super cell)
    - Online reconstruction to discriminate between electrons and jets for rejecting dominant backgrounds such as QCD jets.
- Phase-2
  - Replace the electronics to cope with higher radiation levels
  - Options for modifying the forward calorimeter.

ATLAS LAr for HL LHC

- The performance will NOT be degraded with the integrated luminosity.
- But, it could be impaired at the highest instantaneous luminosity.
  - R&D and upgrade options for avoiding the degradation.

Space charge

Slowly drifting positive ions can distort the electric field

Heat

(worst case) LAr can boil due to the increase energy deposit.

Voltage drop

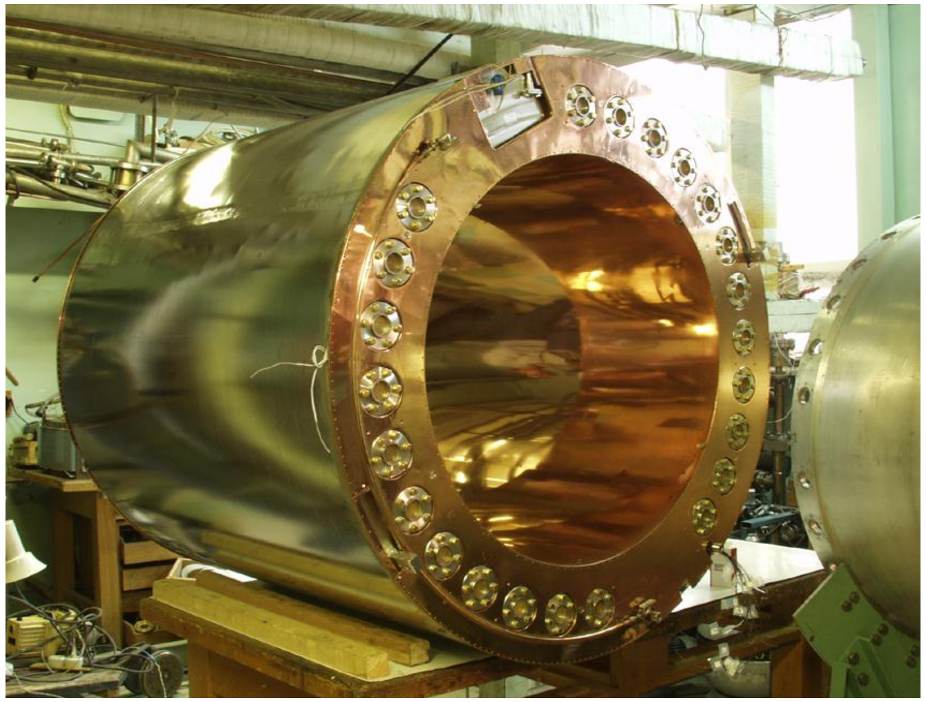
Large HV protection resistance can produce voltage due to high current

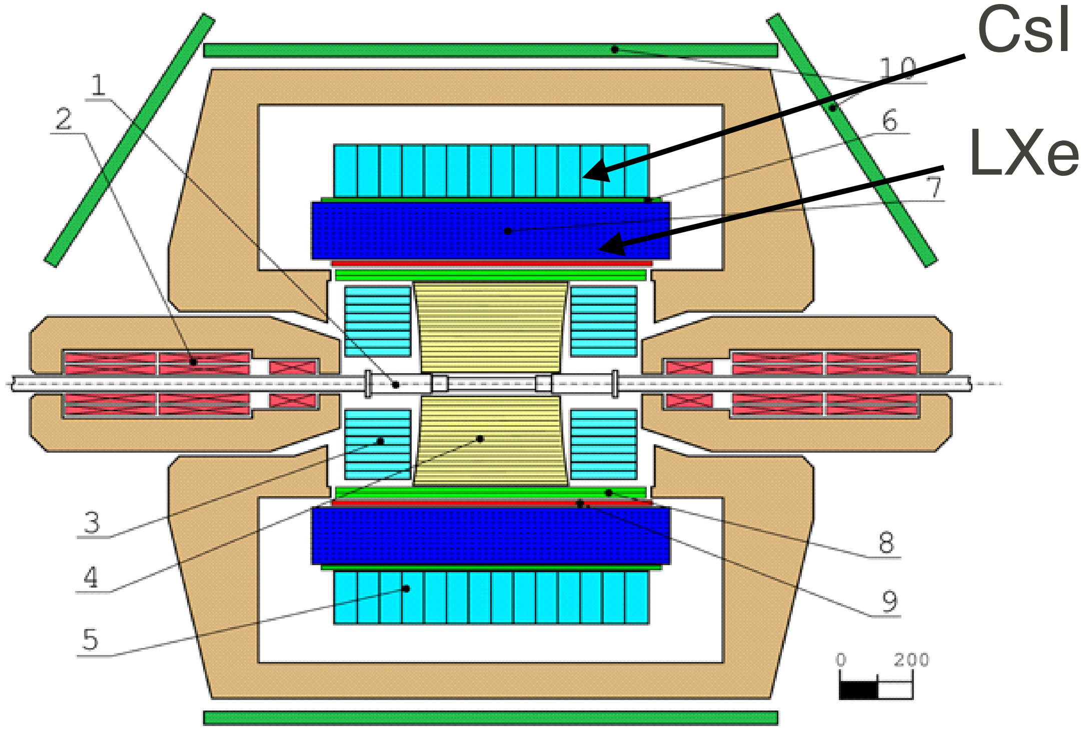
- Two plans for the upgrade of FCal being explored
  - Replace with a new forward calorimeter with smaller LAr gaps ~120 μm (c.f. 250 μm currently)
    - cooling loops to prevent boiling
  - Put additional miniFCal (pCVD diamond)

CMD-3 LXe Calorimeter

CMD-3 LXe calorimeter

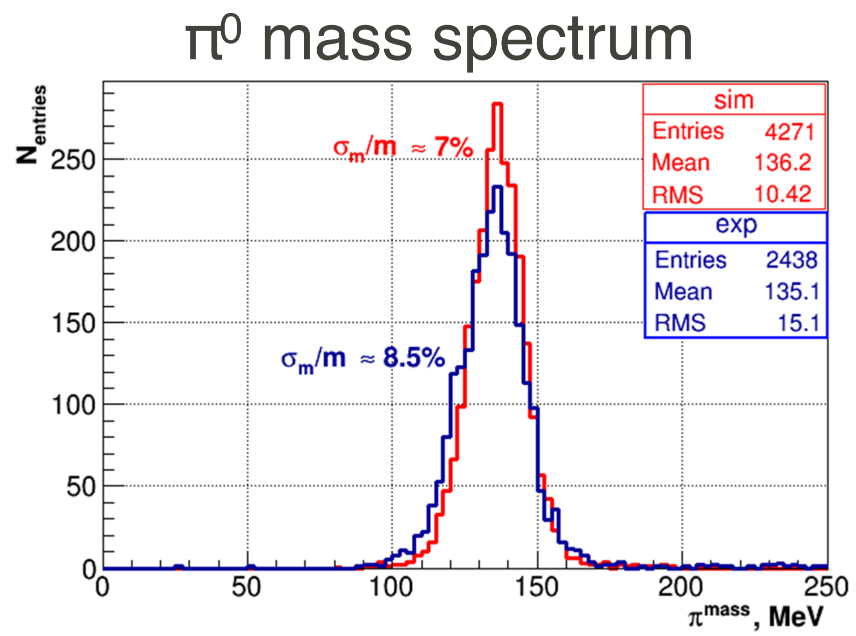
VEPP-2000 e^+e^- collider in Novosibirsk

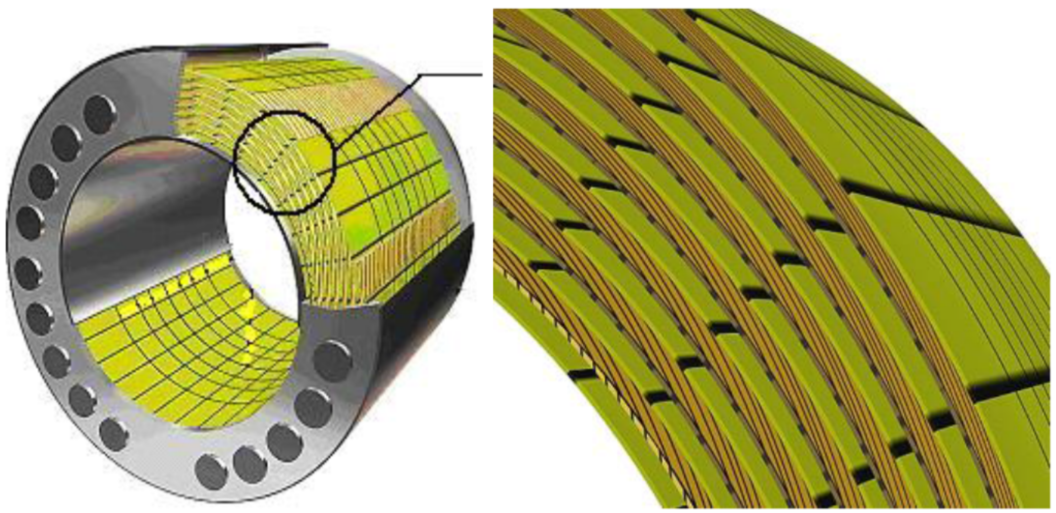


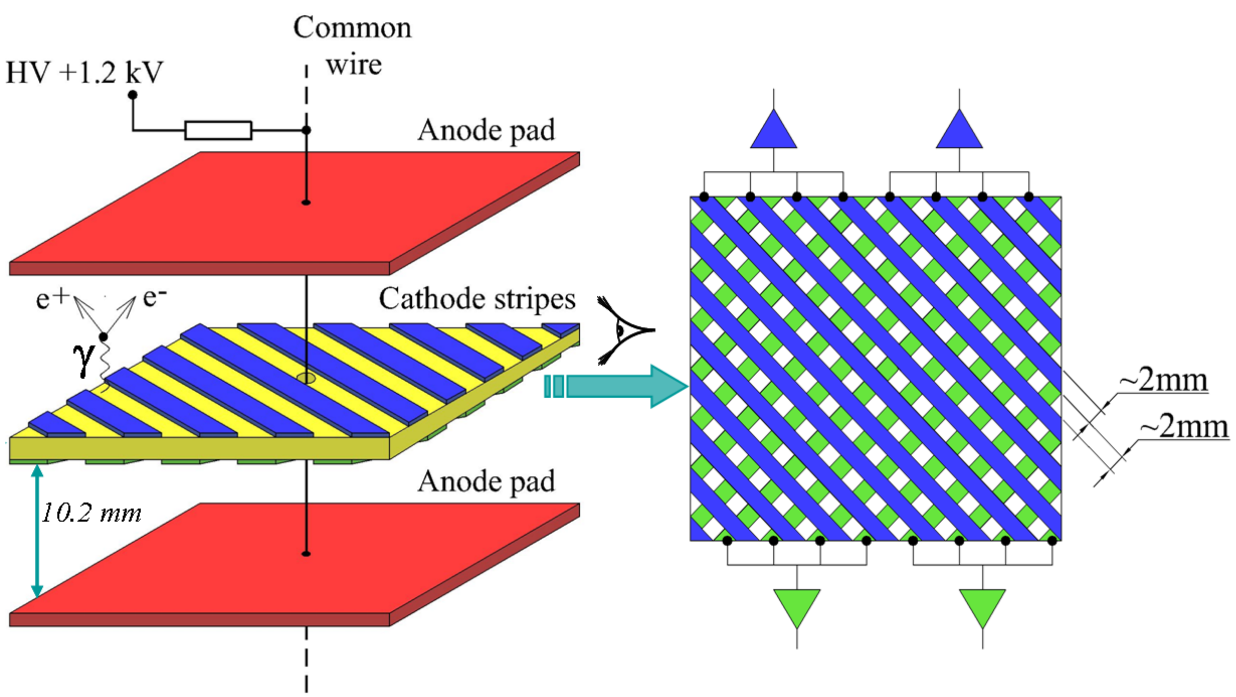


- Combined calorimeter, LXe + CsI
  - 400 l LXe : 5.4 χ_0
  - LXe+CsI : 13.5 χ_0
- Successful operation since 2009
- another 5 — 10 years operation expected.
- Upgrade study of the readout electronics aiming at 1 ns time resolution is ongoing.

CMD-3 LXe cont.



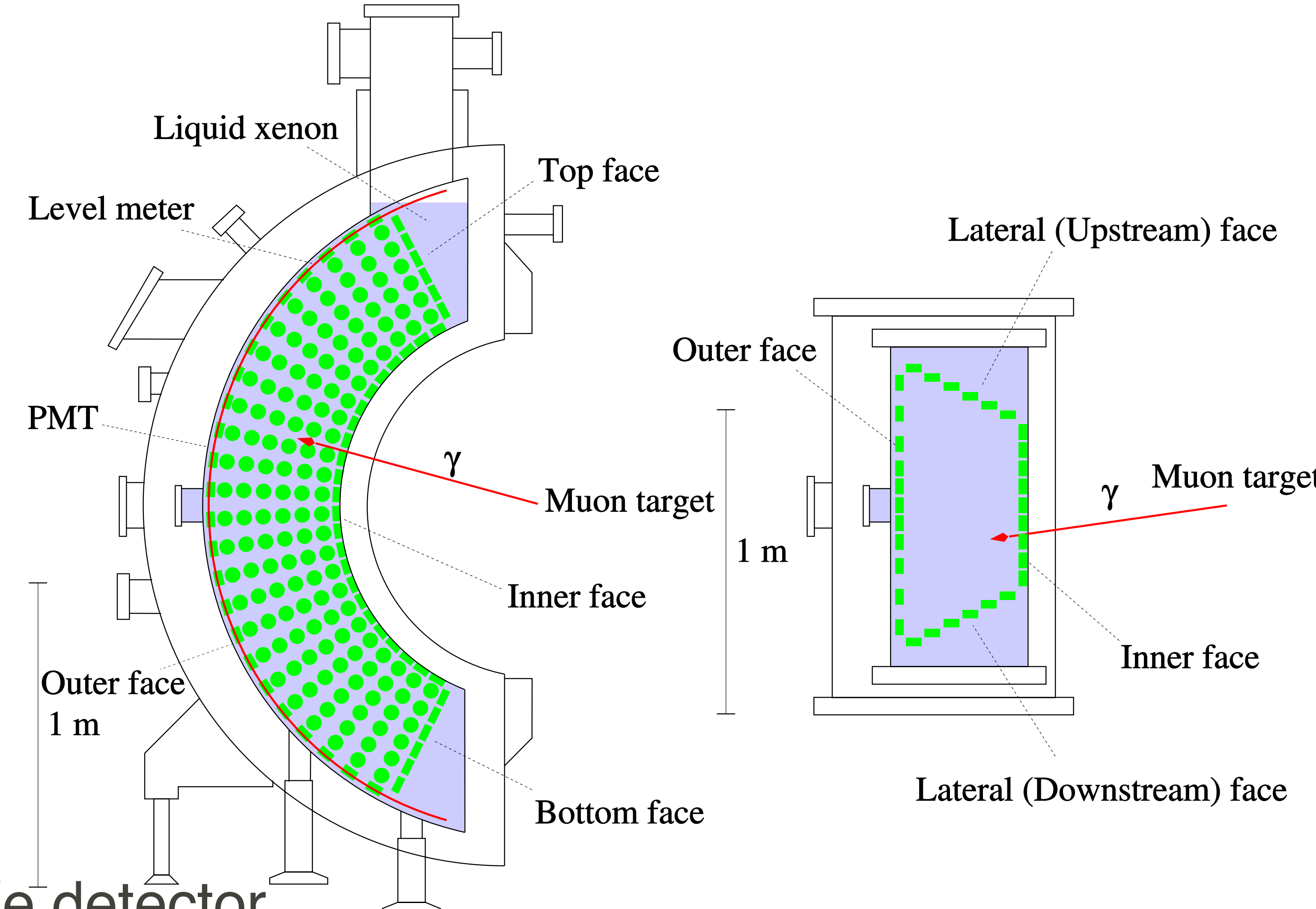




- 7 layers of anode/cathode
  - Maximum drift time : 4.5 µsec
  - Anode segments forms a tower for calorimetry
    - Average "tower" size : 8.5×10×15 cm³
  - Cathode strips to measure position
    - "Semi-Transparent" orthogonal electrodes structure for determining two coordinates.
    - Position resolution 1.6 mm @ 100 MeV

MEG LXe Calorimeter

MEG calorimeter

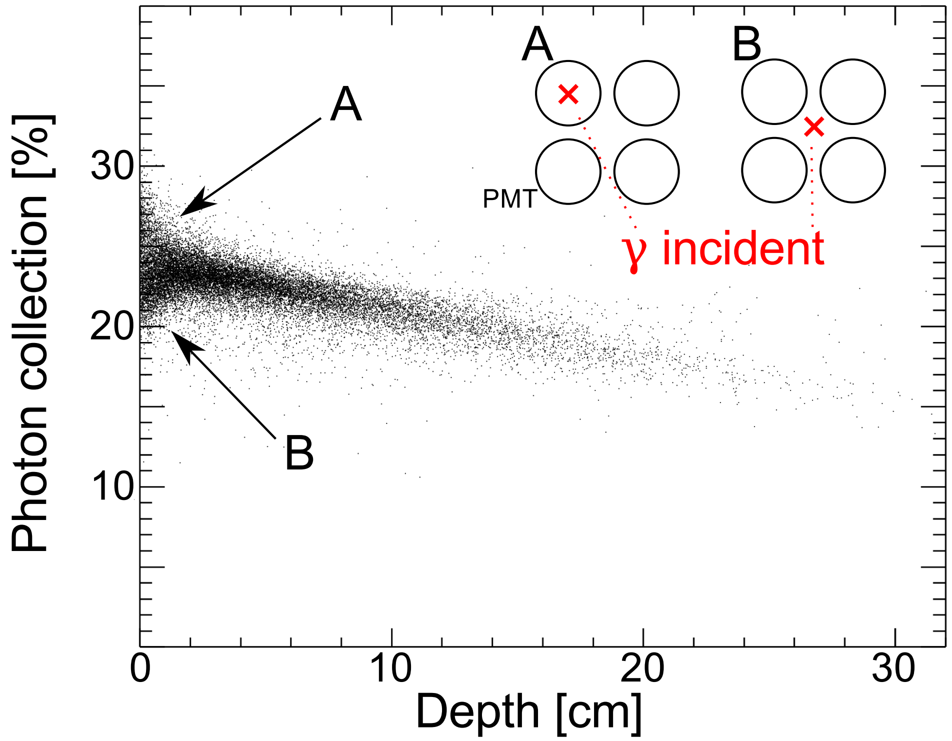


- The largest (**900 litters**) LXe detector
- **846** VUV sensitive PMTs directly detect scintillation photons (Q.E × C.E. ~ **16%** for 178 nm photons)
- Excellent energy, position and time resolutions
- Pileup-identification capable with using waveform and charge distribution

Calorimeter performance limitations

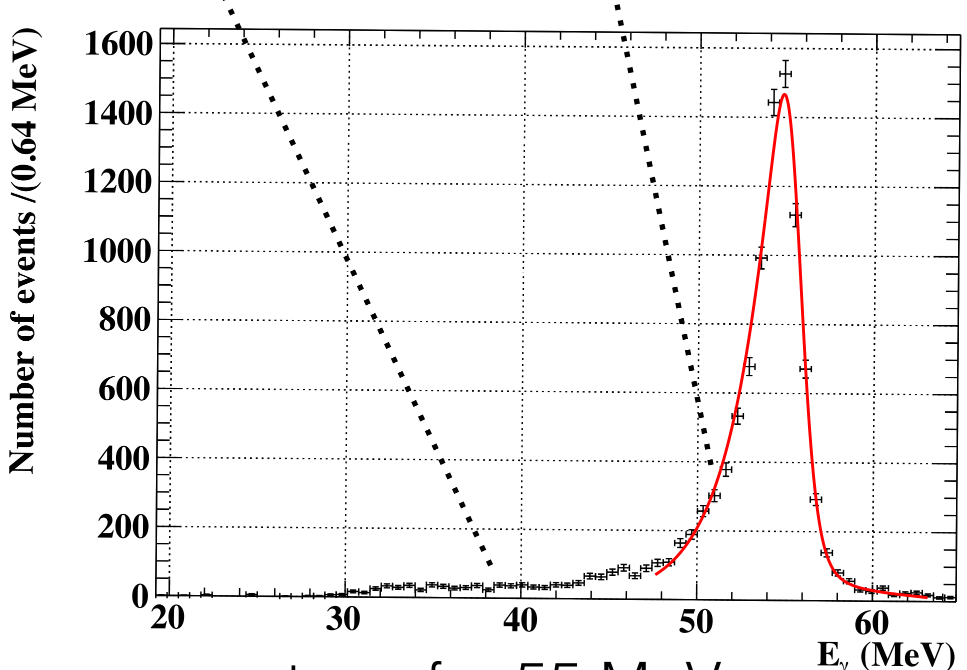
Resolution of shallow events (~40%) is worse because of **large position dependence of photon-collection efficiency**.

Lower energy tail due to **energy loss** of γ rays before entering LXe, and **energy leaks** from the inner or lateral faces.



Energy leaks from LXe

Energy loss before LXe



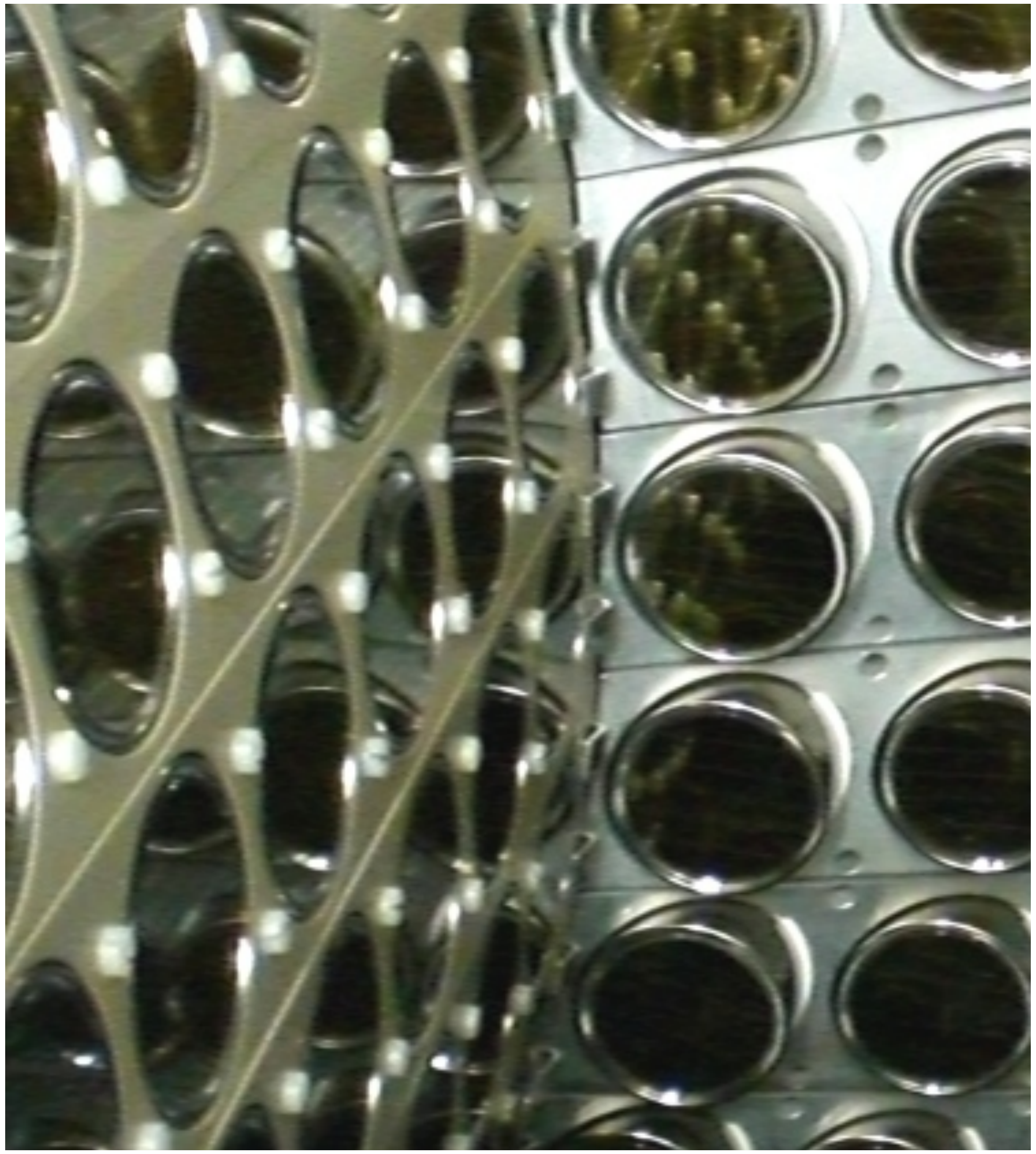
Energy spectrum for 55 MeV γ

shallow events / deep events (d > 2cm)

Energy resolution [%]	2.4 / 1.7
Position resolution [mm]	5
Time resolution [ps]	67
Efficiency	64.7

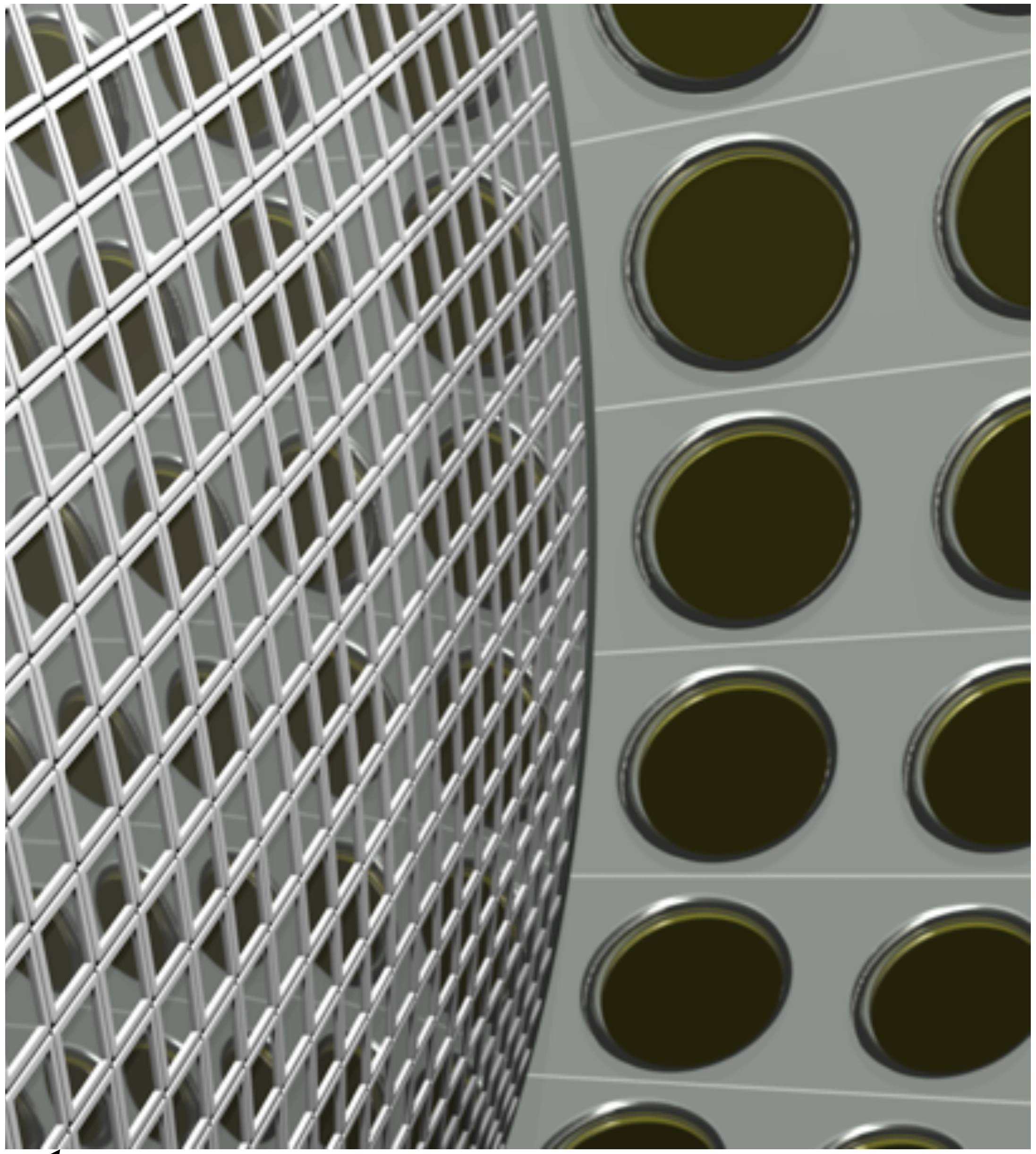
Calorimeter upgrade concept

Present



2 inch PMT
216 ch

Upgraded

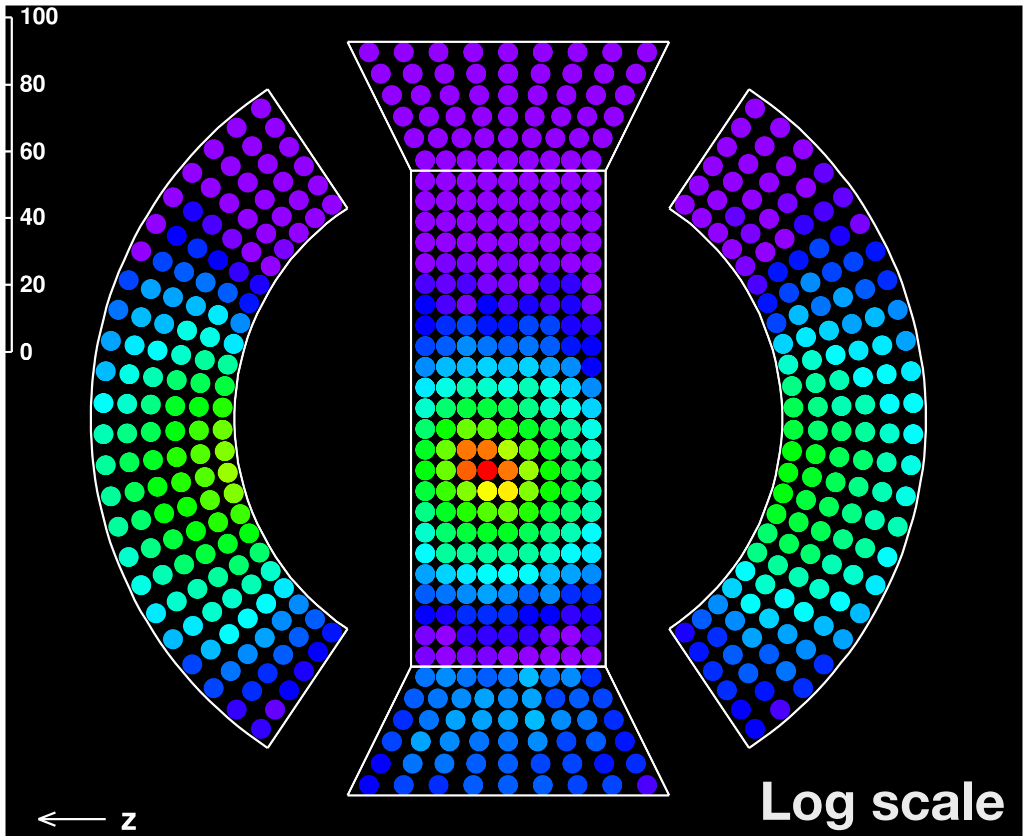


computer graphics

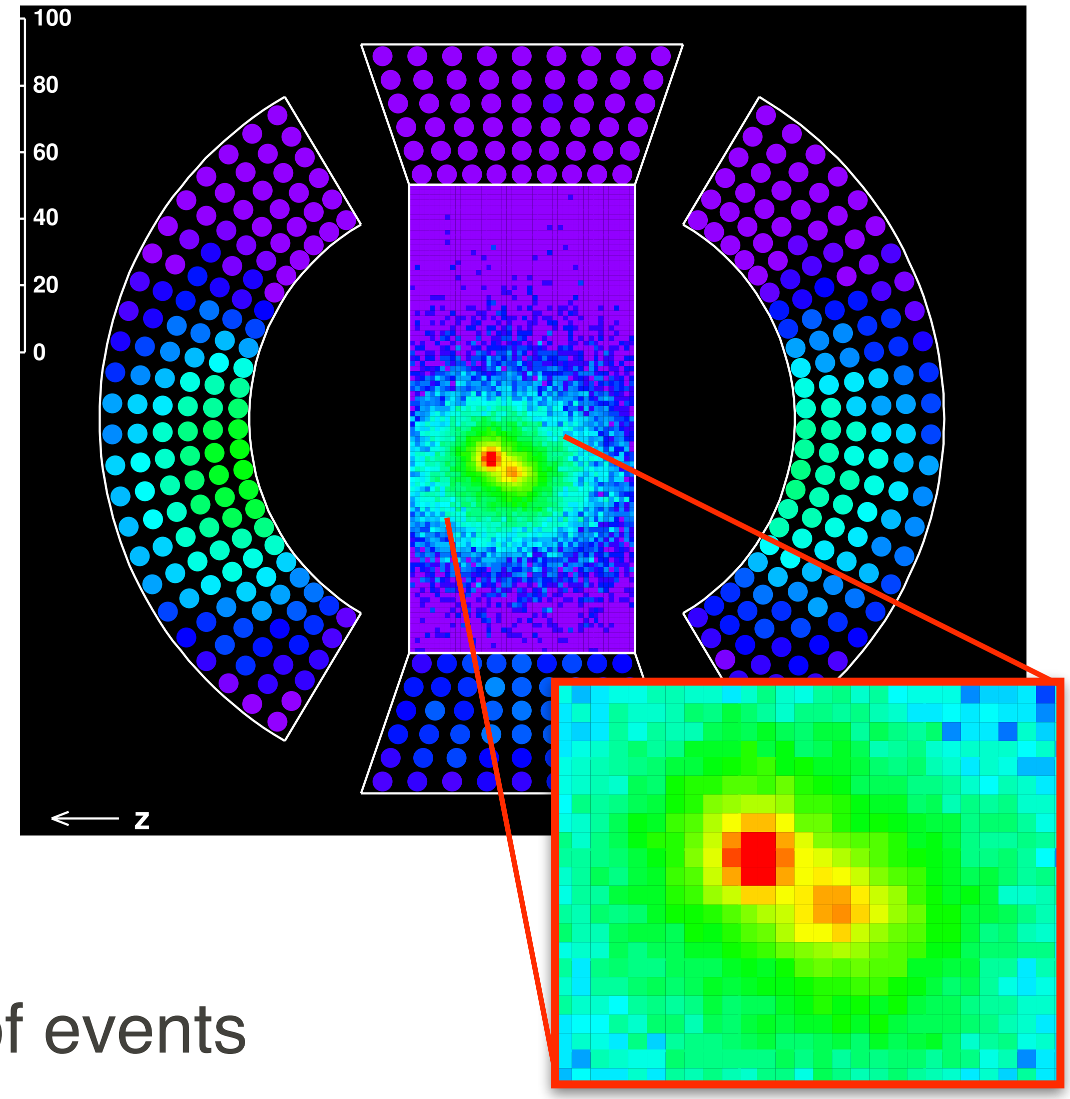
12×12 mm² SiPM
~ 4000 ch

Event display

MEG I



MEG II

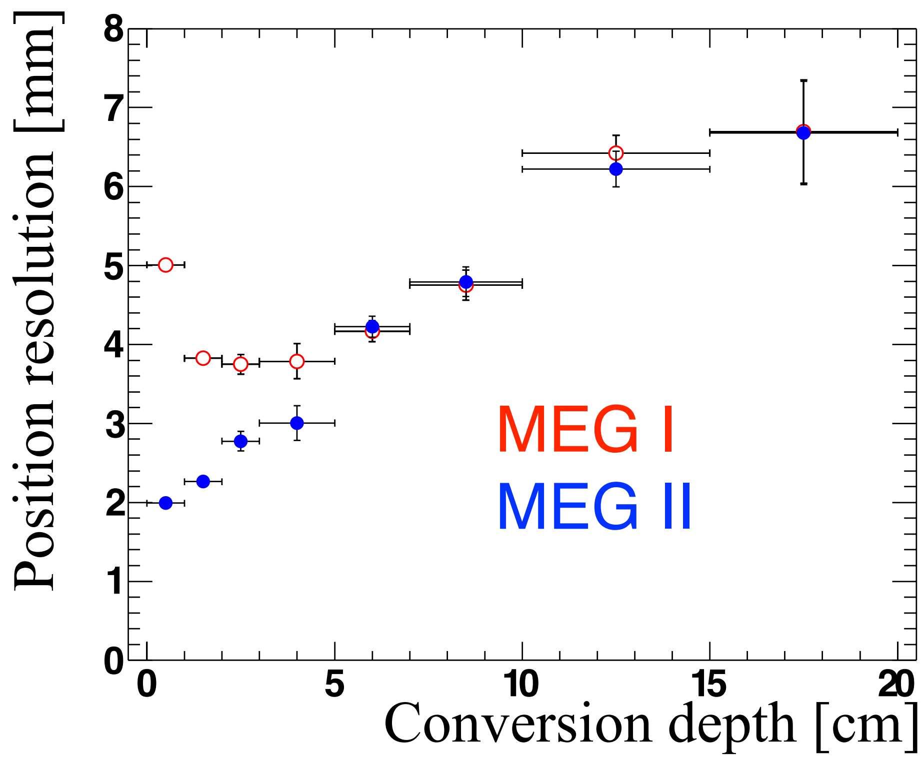


16 times higher 2D “imaging” capability of events

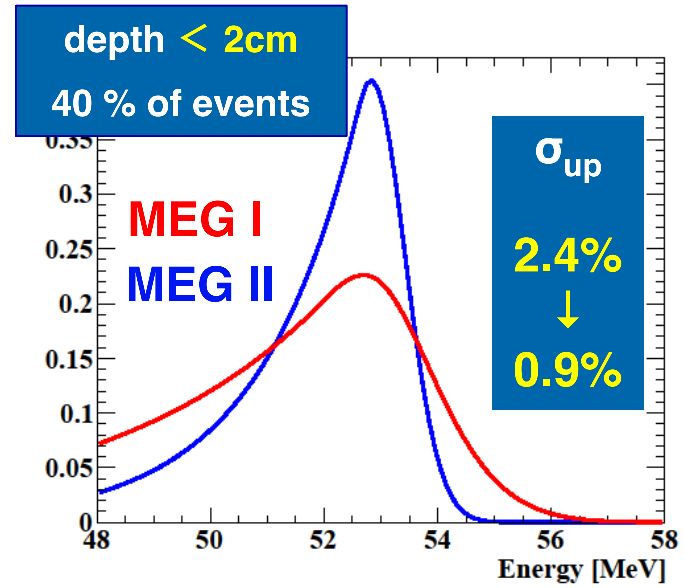
- More uniform energy respose
- Better position resolution with using the shower-shape information
- Pileup identification

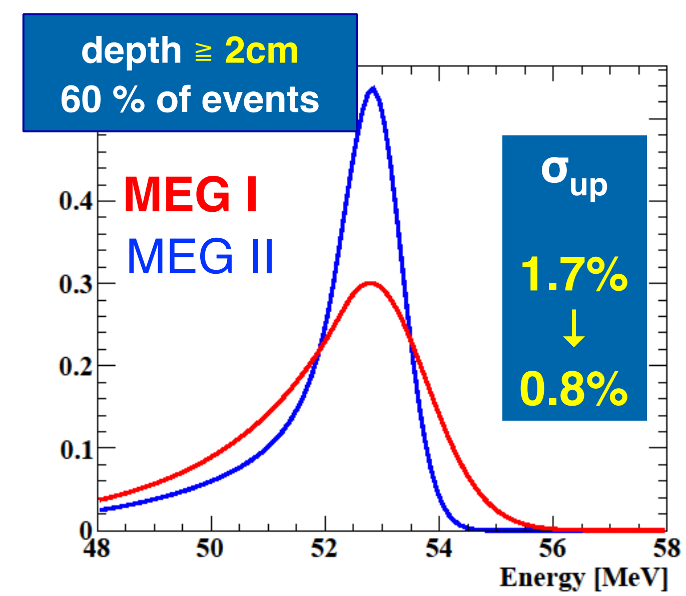
MEG II calorimeter expected resolutions

MC position resolution



Energy spectrum





shallow events

deep events (d > 2cm)

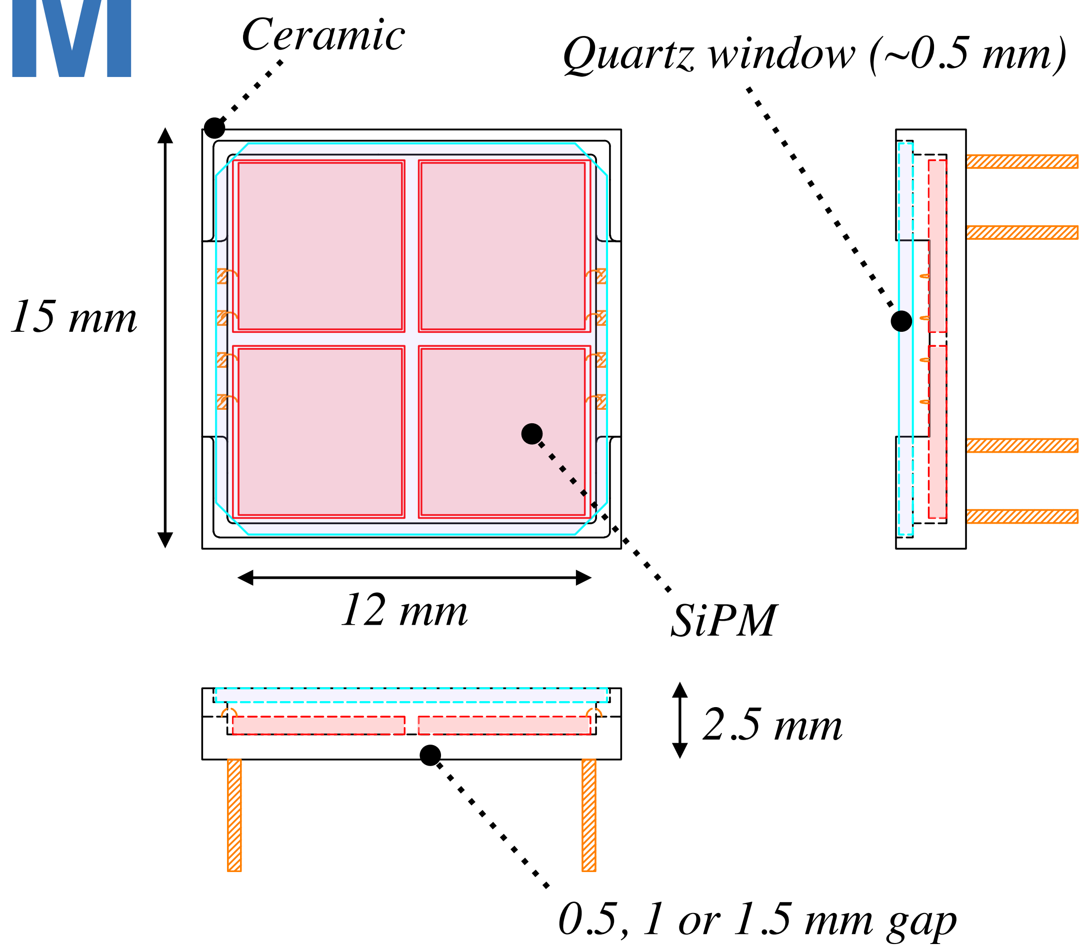
	MEG	MEG II (MC)
Energy resolution [%]	2.4 / 1.7	0.9 / 0.8
Position resolution [mm]	5 / 5	2.2 / 2.0
Time resolution [ps]	67	56
Efficiency	64.7	70.4

horizontal

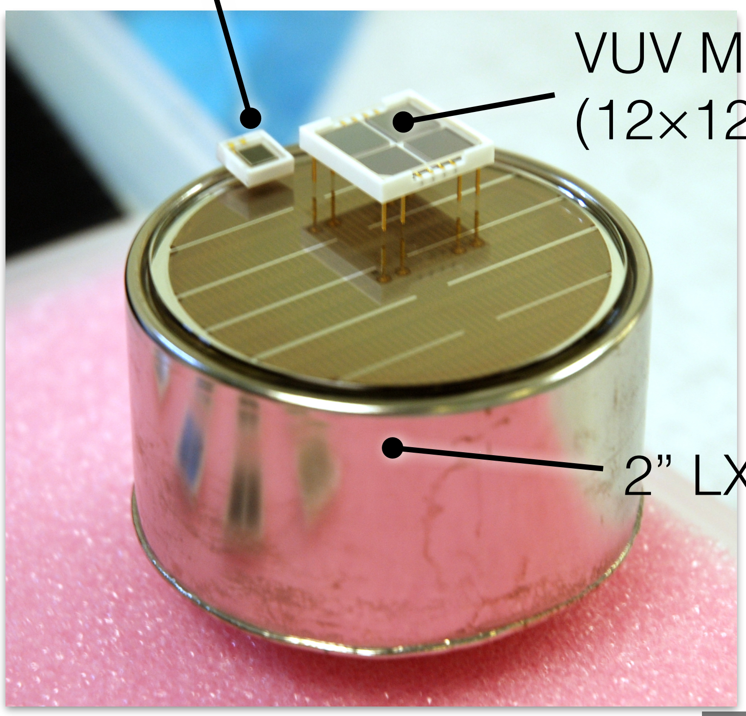
vertical

VUV-sensitive SiPM

We developed **VUV-sensitive MPPC** with Hamamatsu
model : S10943-4186(X)

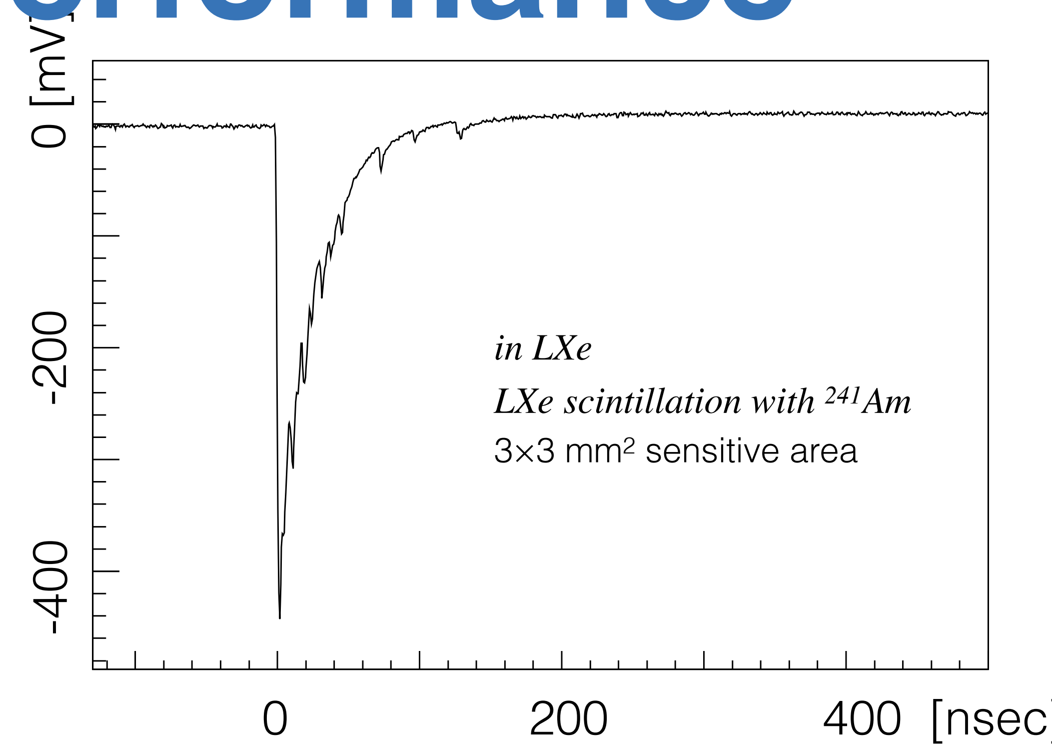


- **Sensitive to LXe scintillation light**, λ~178 nm
  - No protection layer, thinner insensitive layer
  - Optimized optical property of the surface
- **Large sensitive area, 12×12 mm²**
- **50 μm** pixel pitch : **55.7k pixels** in each package
- Metal quench resister suitable for the low temperature use
- **Four segments** in each package
  - Possible to read each segment separately or to connect them outside of the package
- Thin **quartz window** for protection
  - Open space between the window and SiPMs to allow LXe enter the space



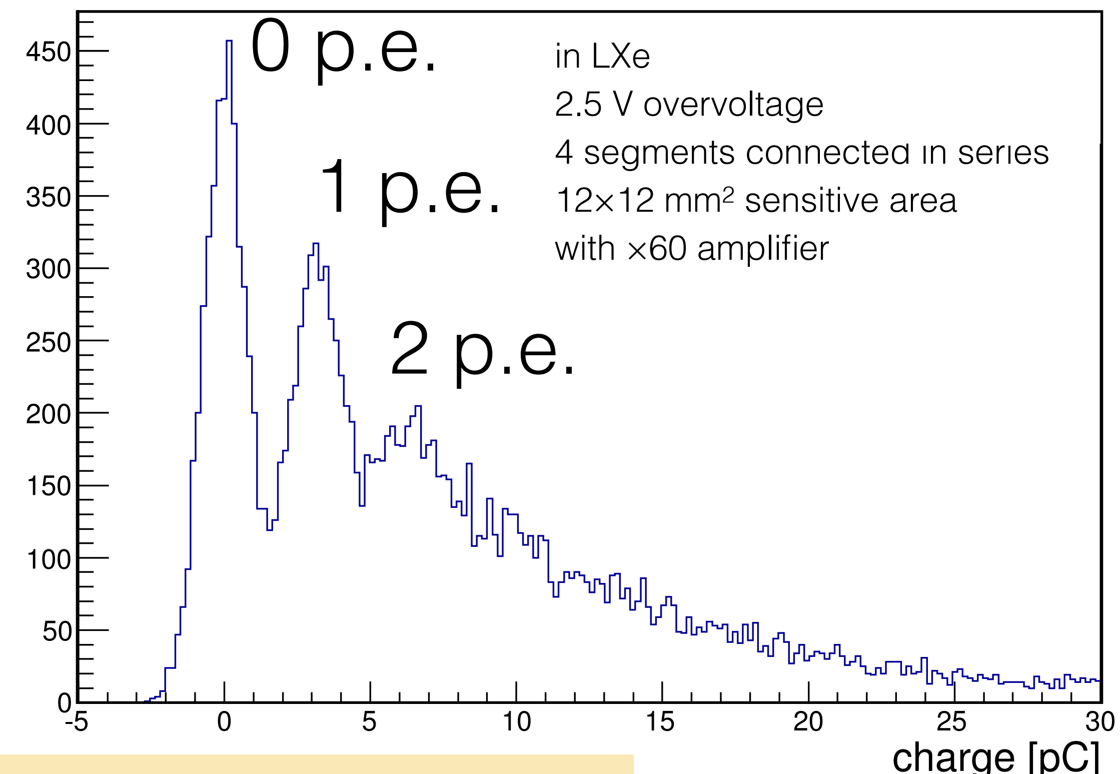
VUV-sensitive SiPM Performance

- Good gain uniformity
  - **Single photo-electron peak is visible**.
- **VUV sensitivity confirmed**
- Dark noise is suppressed in LXe temperature
- Crosstalk/afterpulse suppression technologies
- **Long waveform** due to large sensor-capacitance can be an issue for high-rate measurement (time resolution, pileups).
  - Solved by connecting 4 segments in series (instead of parallel) for smaller combined capacitance.



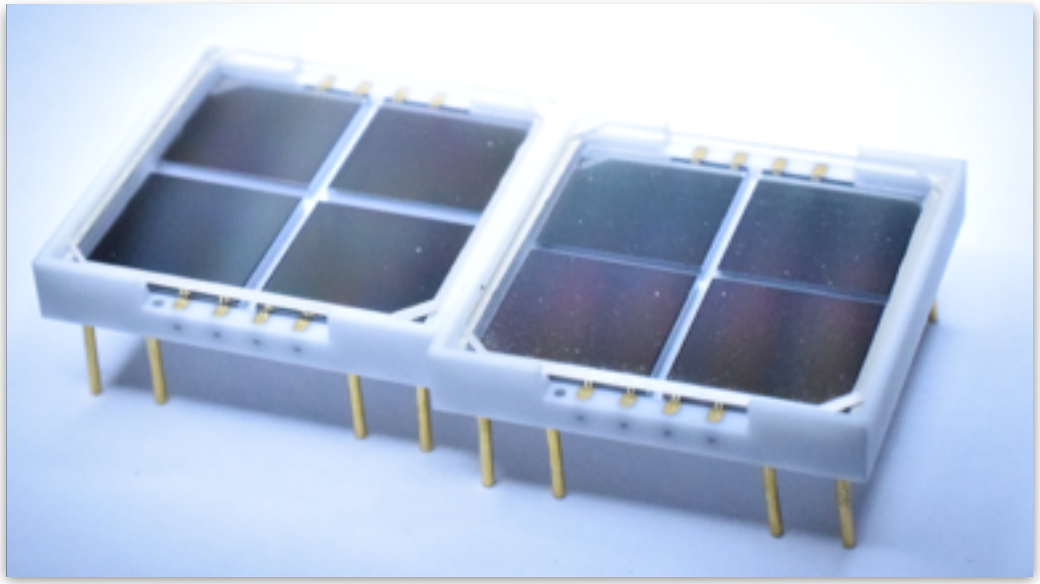
Gain	8×10^5
PDE @ 178nm	17—27%
Dark rate	~ 500 Hz
Crosstalk	15%
Afterpulse	10%
Signal decay time	38 ns

in LXe (~160 K)
with 6.5 V overvoltage
when connected 4 segments in series
12×12 mm² sensitive area



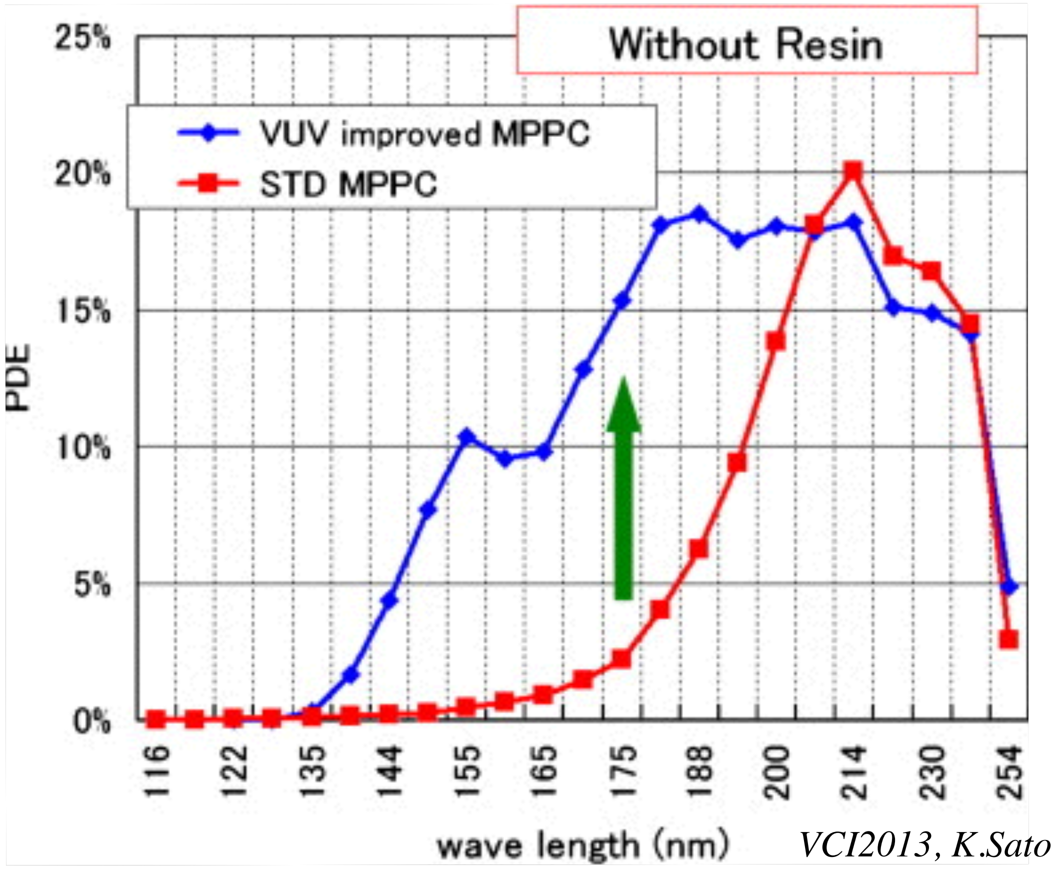
VUV SiPM other applications

- SiPM has many advantages over PMT
  - Good single p.e. resolution
  - Small sensor thickness
    - Flexibility of the detector design
  - Simple sensor structure
  - Lower bias voltage
  - Insensitive to E and B field



- Many other experiments are testing this model.
  - nEXO (LXe)
  - XENON (LXe)
  - mu2e (BaF2, 200nm)
  - ANKOK (LAr, 128nm, PDE~7%)

arXiv:1505.00091v1 [physics.ins-det]

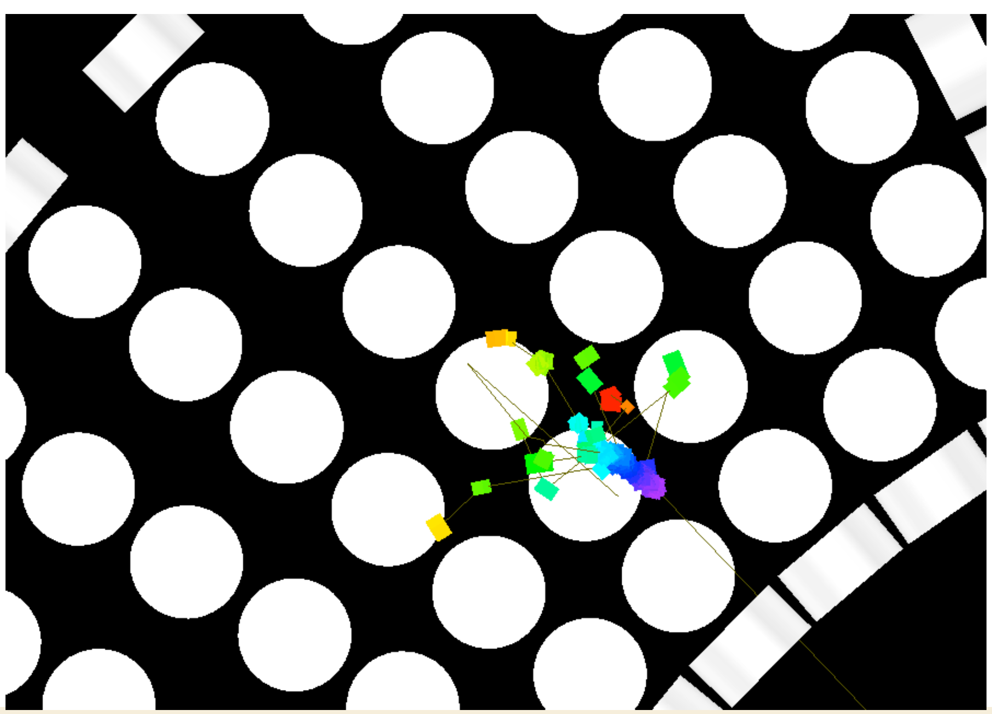


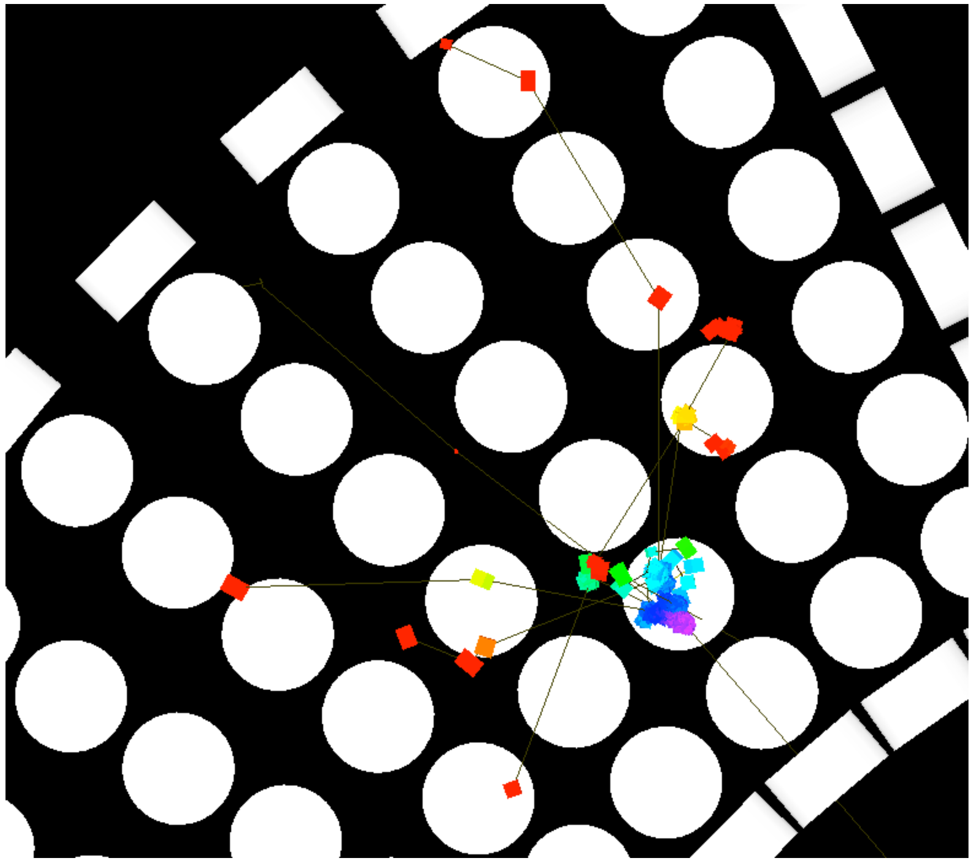
VCI2013, K.Sato

What would limit resolutions in MEG II

- We can observe the projected shower shape
  - The conversion point is reconstructed from the projected image.
  - Energy (photon-collection efficiency) is corrected by the single reconstructed position
- We can not observe 3D shape of the shower.
  - **Resolutions would be limited by the shower-shape fluctuation**

Energy deposit in MEG LXe (MC)



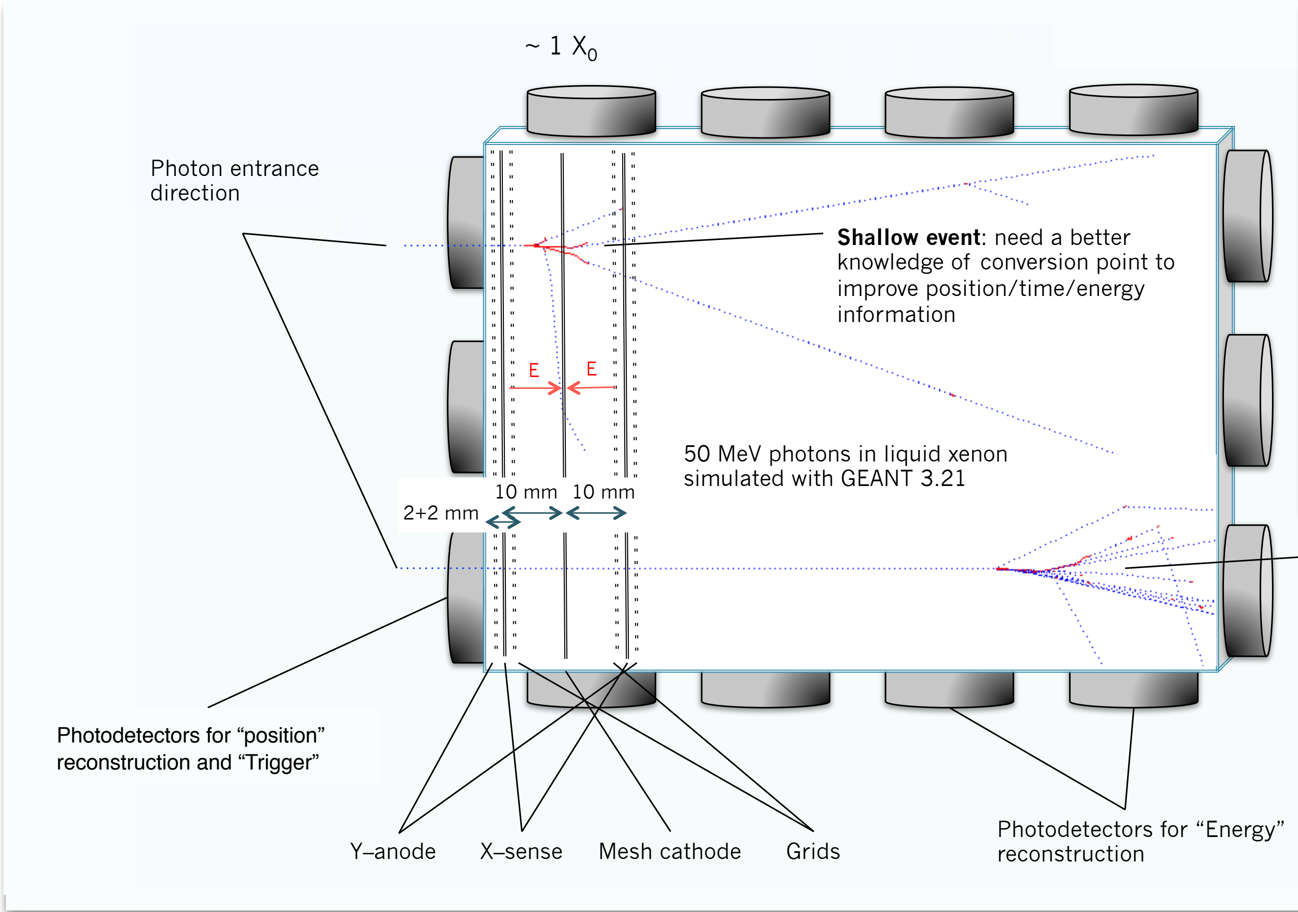


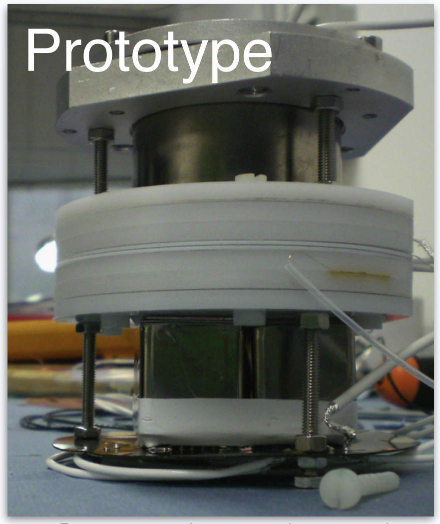
FOXFIRE Feasibility Of liquid Xenon detector with Frontend for Ionization Real-time Extraction

This project aim also neutrino-less double beta searches

This project aims at developing techniques, where the ionization and scintillation signals are both used, towards high-rate, high-energy (tens of MeV) environment.

For using the detector in high-rate environment, the TPC is put at the first 3 cm ~ χ_0, where ~65% of gammas convert.





- Fast collection of charge (<5 µs)
- Precise 3D reconstruction of photon conversion point
- Better timing of the photon
- Less position-dependent energy estimate

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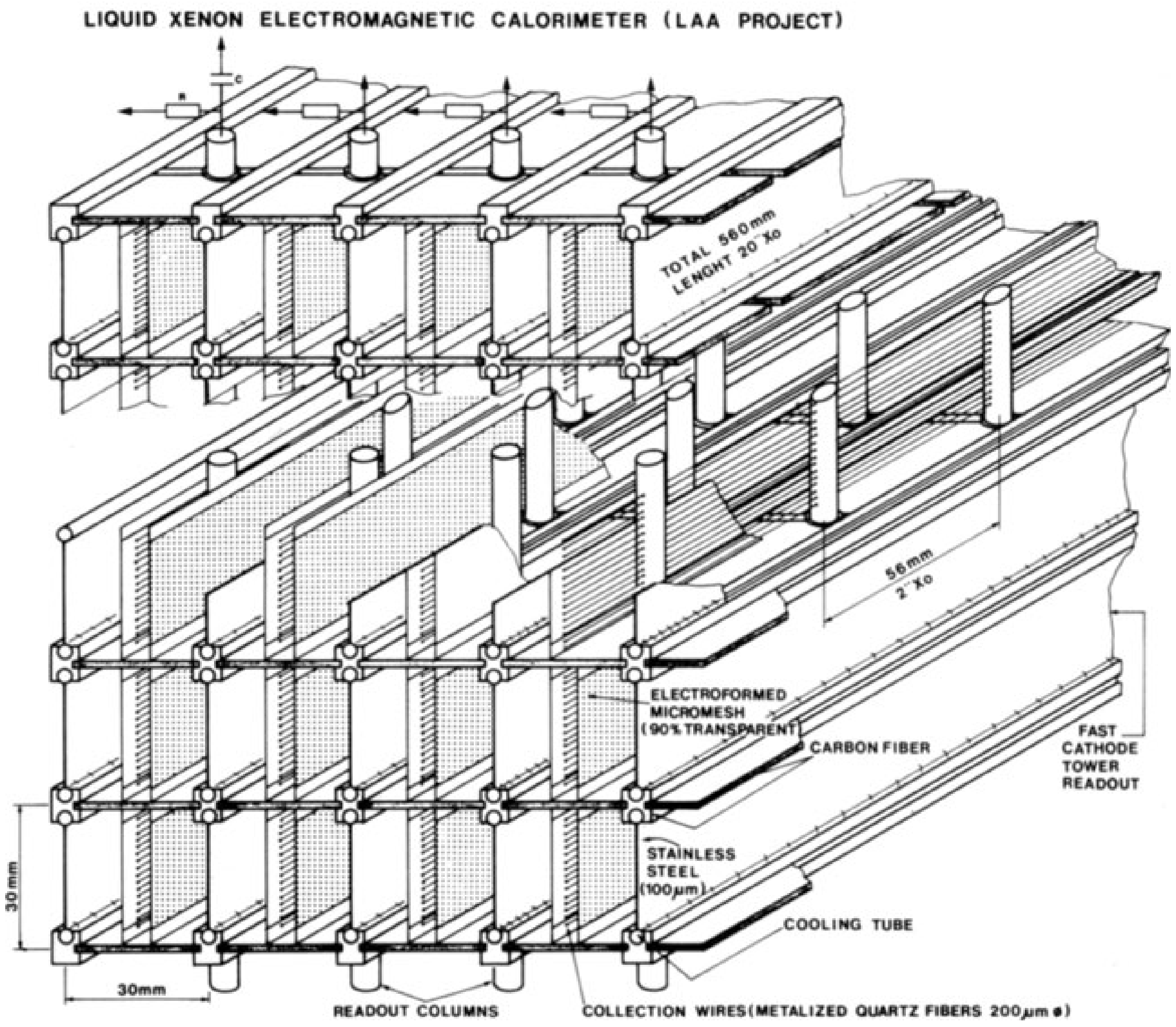
Totally active calorimeter

In 90's, there was an idea of LXe or LKr calorimeter for Higgs searches.

- By reading both the ionization and scintillation signals, excellent resolutions were expected,
  - energy : 1%/√E
  - direction : 1mrad
  - vertex origin : 1mm
- Consists of many drift cells (30×30×56 mm → drift distance < 15mm)
  - (x, y) position reconstruction with the charge-division (y) and drift time (x).
- The slow drift velocity (3 mm/μs in pure xenon) can be improved to 20mm/μs by adding 3% methane.
- A tower consists of 14 cells and a photo-sensor is equipped.
- The final detector would have 60 tons of xenon or 110 tons of krypton.

A photo-sensor equipped at the end of each tower.



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Totally active calorimeter

In 9

ver.

Segmented noble liquid detector with charge/light signals (with short drift distance) can be the future calorimeter technology for high-rate experiments, for example for μ→eγ searches,

Advanced technologies available today

- There are many studies for noble liquid TPC (neutrino, dark matter, 0γ ββ, medical applications…)
- VUV sensitive photon sensors.

- The final detector would have 60 tons of xenon or 110 tons of krypton.

Conclusions

- LAr continue to play a major roll for the hadron collider experiments because of the radiation tolerance.
- LKr and LXe detectors are used kaon, muon and middle-size collider experiments because of their high resolutions.
- Technologies for the future calorimeters
  - Newly developed VUV-sensitive SiPM will be used in MEG II and many other experiments.
  - Simultaneous usage of scintillation and ionization signals (segmented TPC) is an interesting technology for future calorimeters.

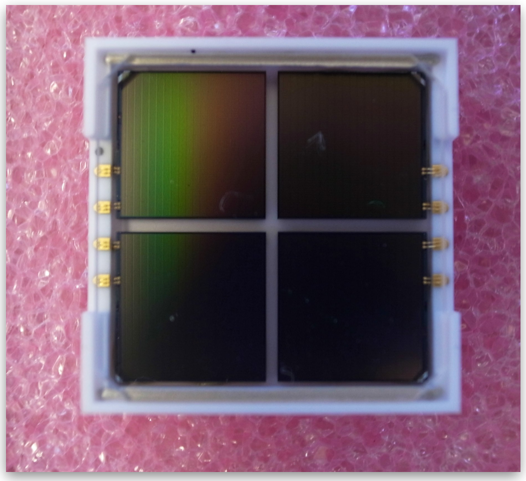
Noble liquids

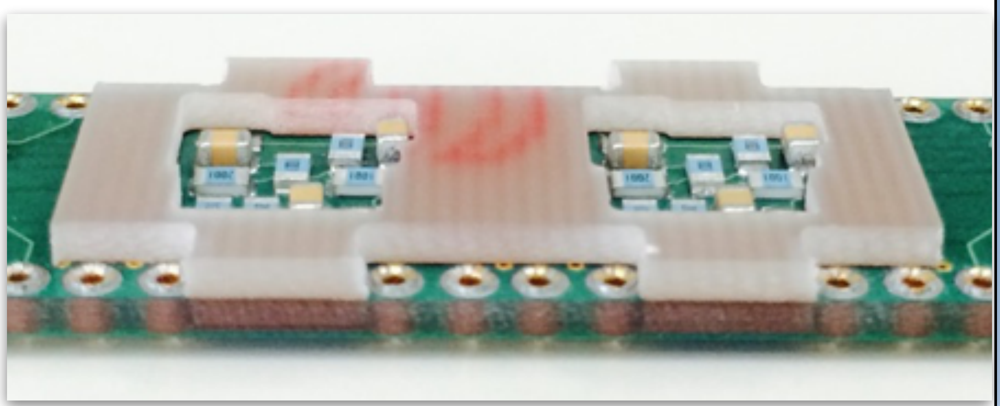
numbers mostly taken from "Particle Detection with Liquid Nobles" by James Nikkel

prices from Shuen-Chen Hwang, Robert D. Lein, Daniel A. Morgan (2005). "Noble Gases". Kirk Othmer Encyclopedia of Chemical Technology. Wiley. pp. 343–383.

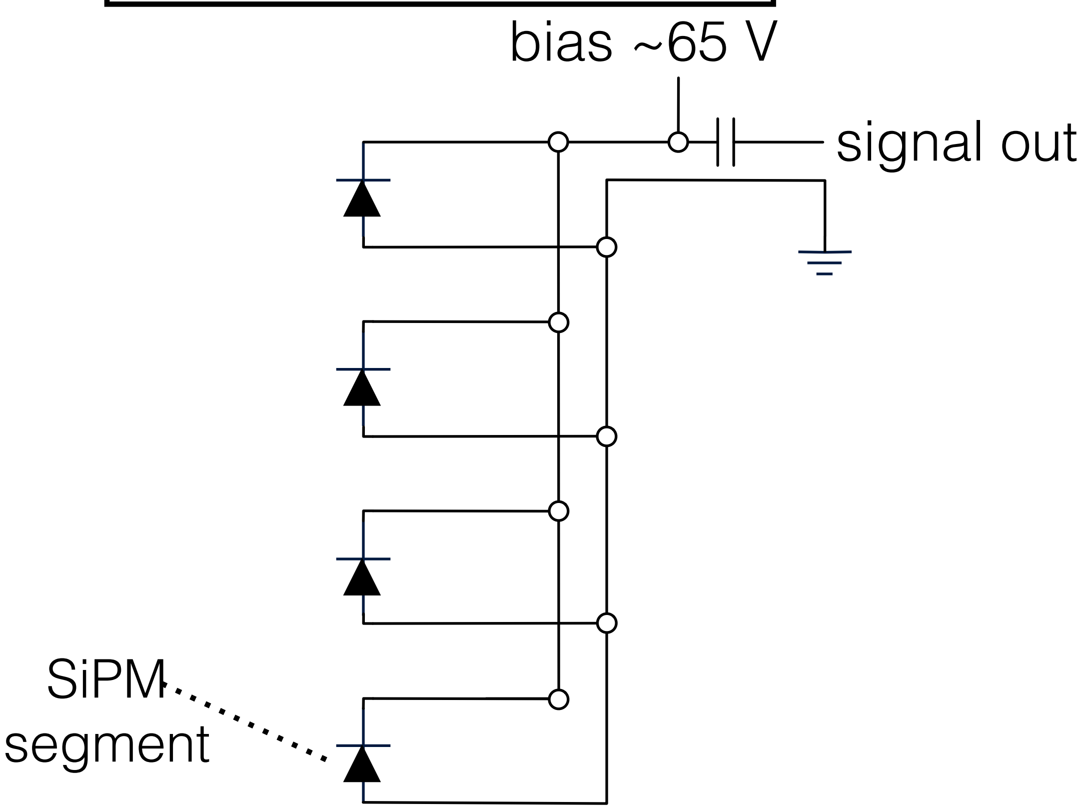
Element	Density	Boiling point	Electron yield (e-/keV)	Photon yield (photon/keV)	Scintillation wavelength (nm)	Radiation length (cm)	Radioactive	Price 2004 US$/$m^3$
He	0.13	4.2	39	22	80	756	0	22—45
Ne	1.2	27.1	46	32	78	24	0	60—120
Ar	1.4	87.3	42	40	128	13.5	1 Bq/kg	2.7—8.5
Kr	2.4	119.9	49	25	148	4.6	1 MBq/kg	400—500
Xe	3.1	165.0	64	42	178	2.8	< 10μq/kg	4000—5000

SiPM connections

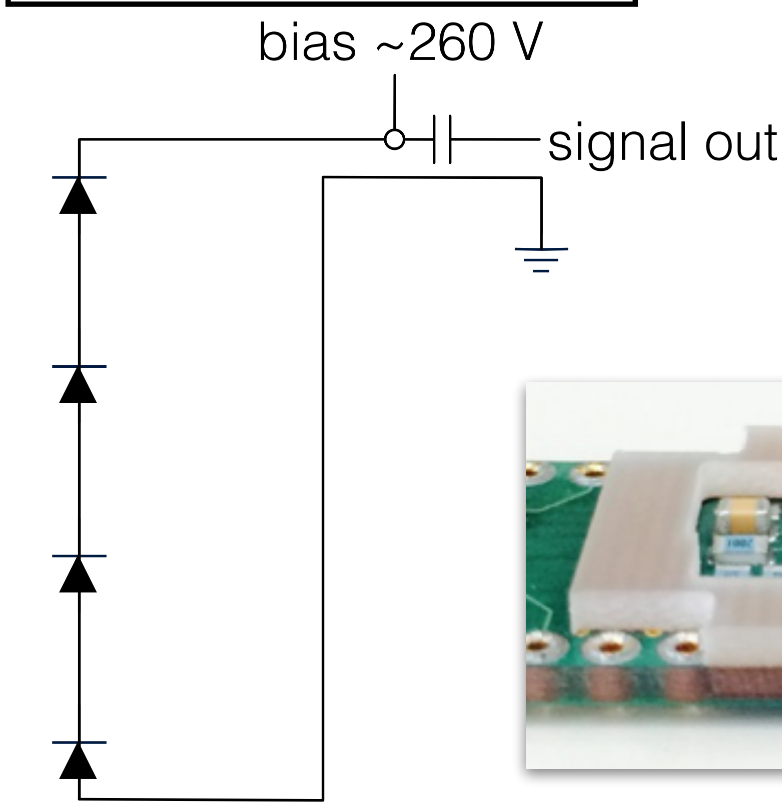




Parallel connection

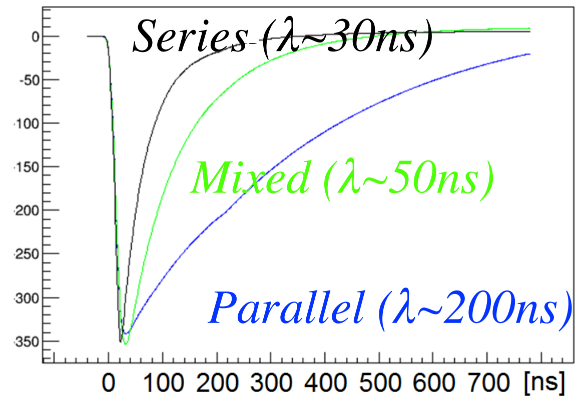


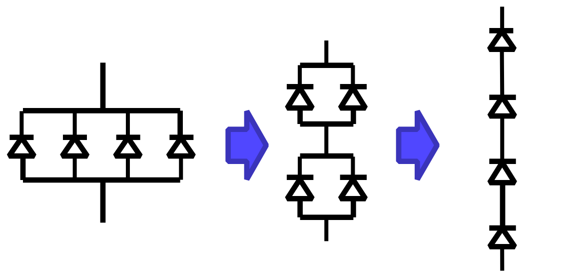
Series connection



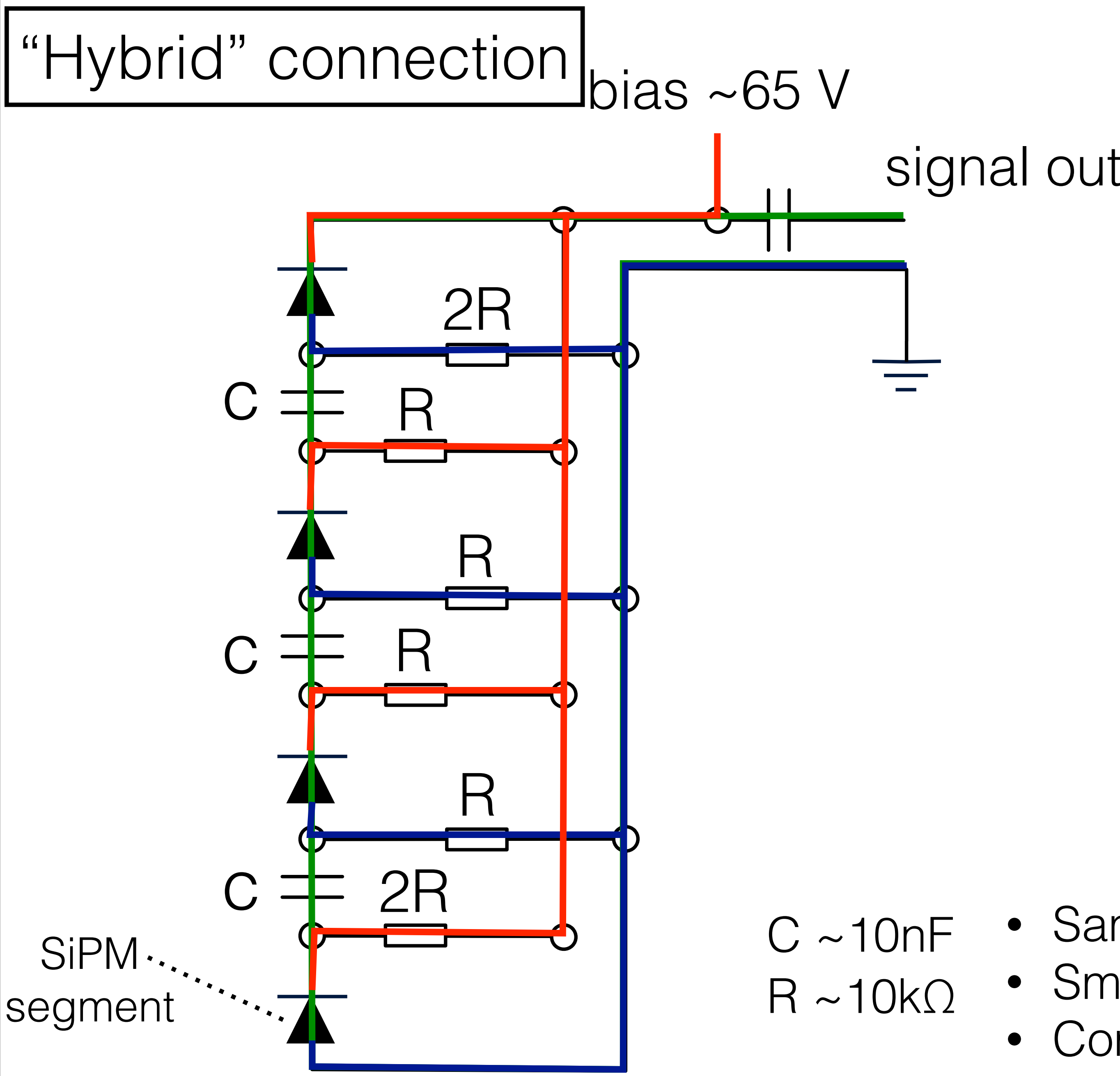
- Equivalent to a single large SiPM
- Common bias voltage (~65 V)
- ☹ Large capacitance → Long waveform

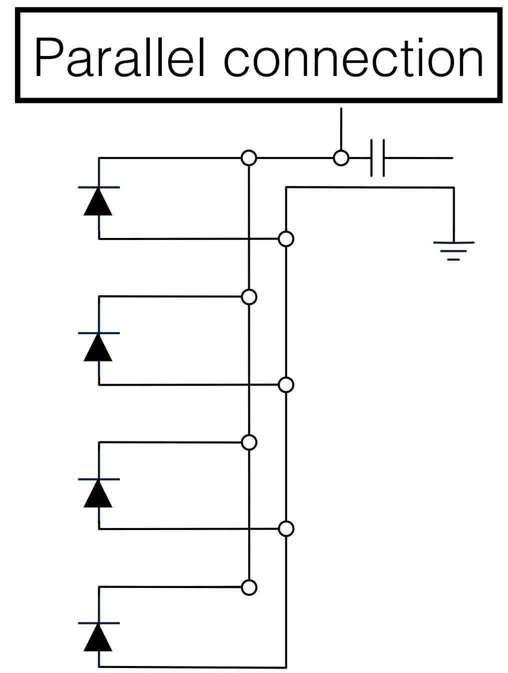
- High bias voltage (~260 V)
- ☹ Different electric potential → possibility of discharge
- Same over-voltage automatically
- Small capacitance → Short waveform

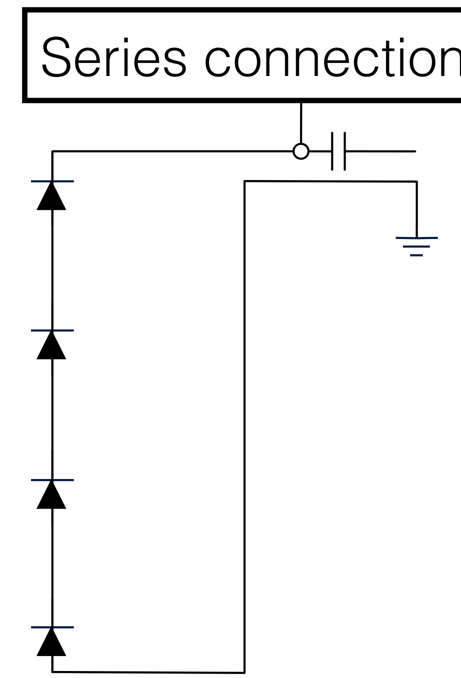




“Hybrid” connection







Fast pulse (**signal**)

Constant voltage (**ground**, **bias**)

C ~10nF
R ~10kΩ

- Same potential on the surface of SiPMs
- Small capacitance → Short waveform
- Common bias voltage (~65 V)