Liquid Xe Detectors

田内利明、平成18年7月12日
測定器開発室勉強会、素核研、KEK

General Property of Liquid Xenon

http://www.pd.infn.it/~conti/LXe.html

Rich detection media : Scintillation and Ionization

Scintillation	Ionization
energy	position
photomultipliers	ionization chamber with low noise amp. 300e
GEM/photocathod	GEM in 2 phase Xe
Avalanche Photodiodes	

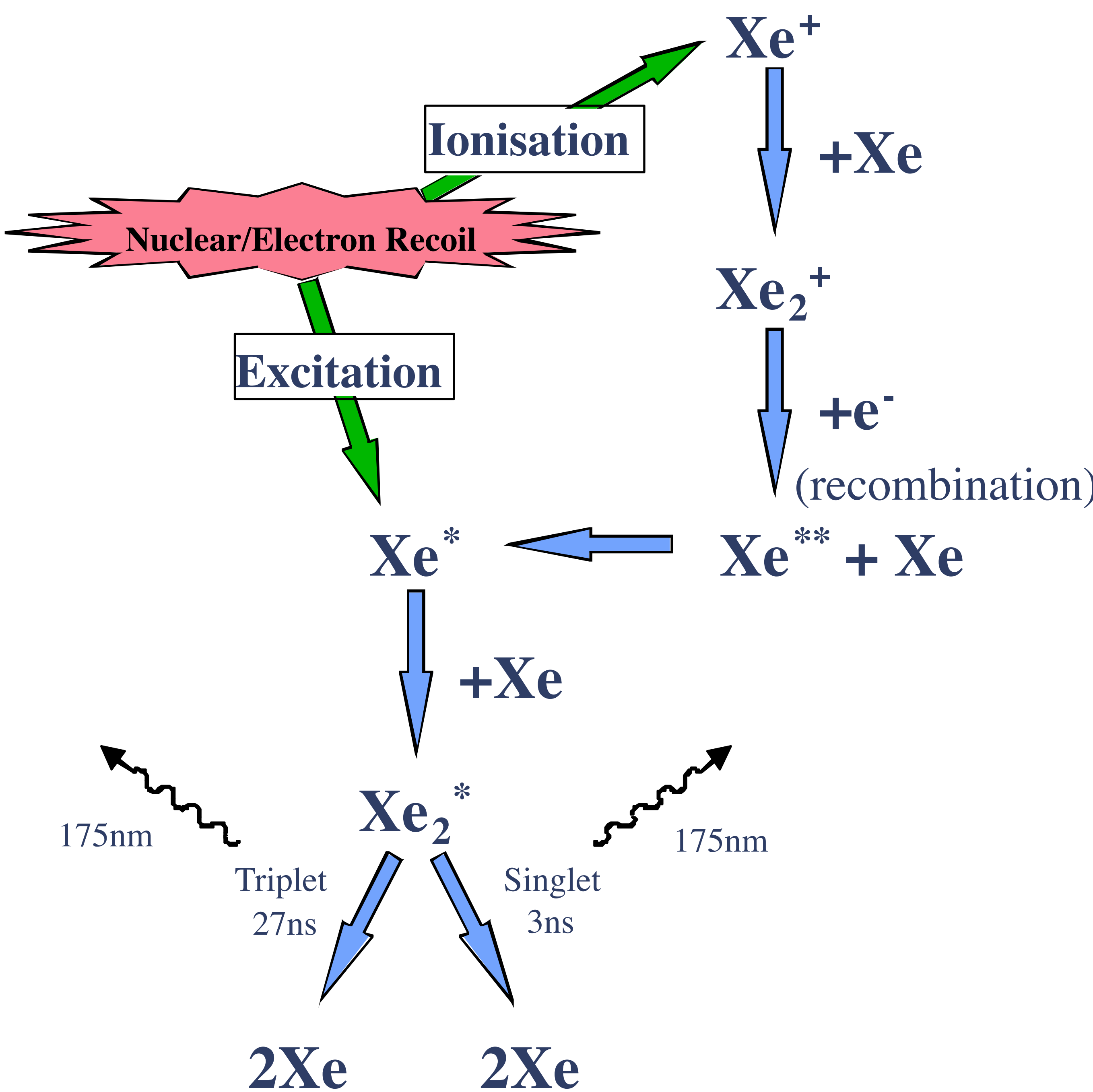
22,000 VUV photons/511KeV with 3ns, 27ns and 45ns

30,000 electron-ion pairs/511KeV
electron drift at 2.3mm/us with 2kV/cm

At 511 keV, 22% photoelectric, 78% Compton with xenon
half a mm for 511 keV photoelectron

Primary ionization signal is weak: of the order of 1, 10, 100 and 500 keV for coherent neutrino, dark matter, solar neutrino and PET respectively.

XENON (PSD and Scint/Ion)

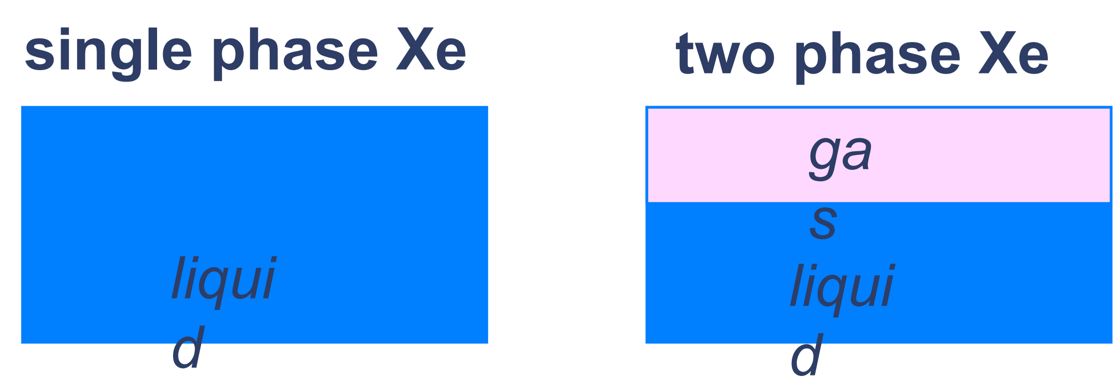


three discrimination techniques

(1) scintillation pulse shape

(2) ionisation-scintillation
- low field-

(3) ionisation-scintillation
- high field, low threshold -



World expertise

• ICARUS-UCLA • Doke group (Japan) • DAMA • Columbia • UKDMC • ITEP

1 Phase

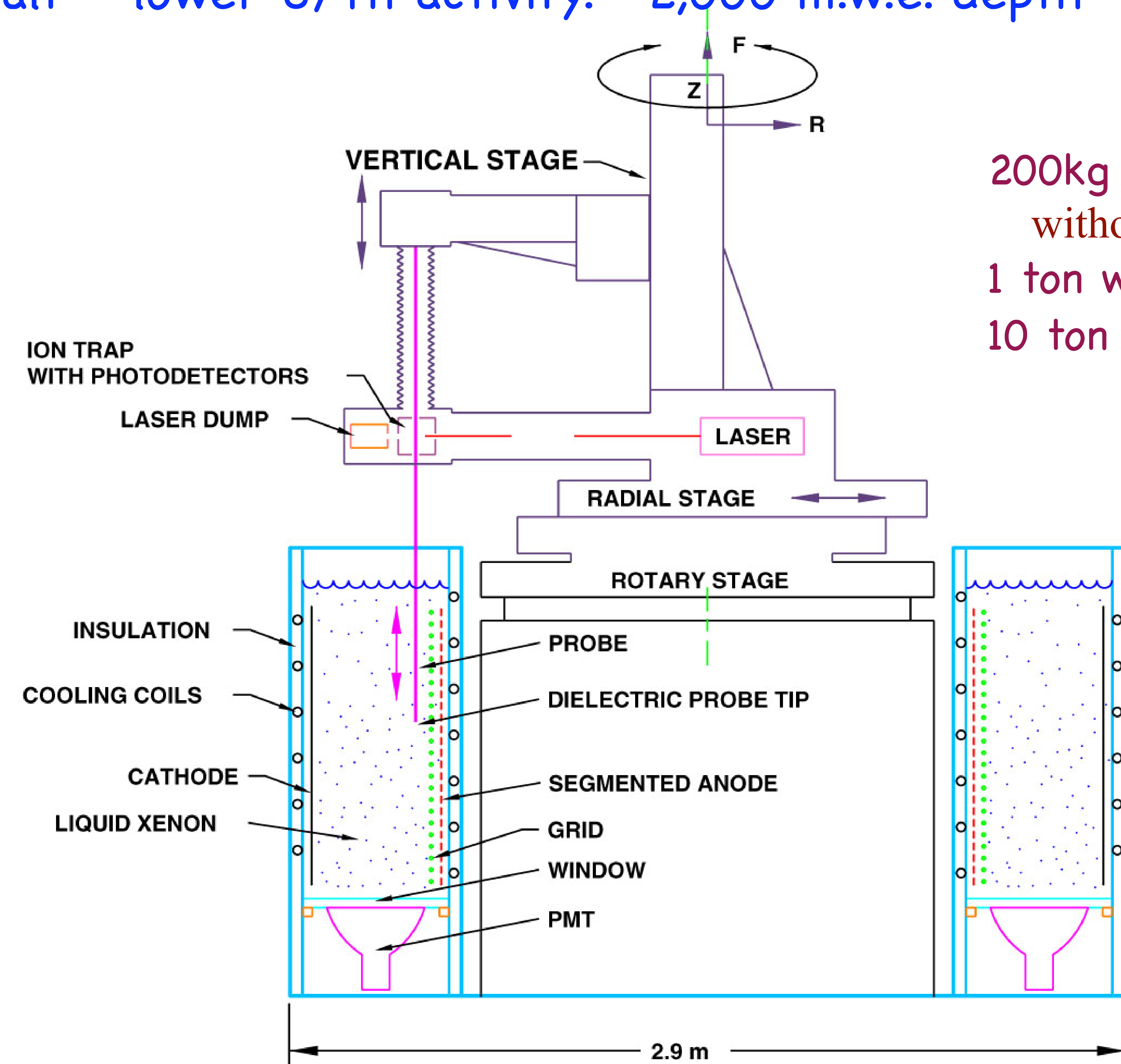
EXO TPC ; 1 phase

2006

http://www-project.slac.stanford.edu/exo/ ; Double β Decay

liqXe-TPC, grid and segmented anode and PMT, 10ton ($3m^3$)

WIPP : Waste Isolation Pilot Plant Carlsbad NM, Excavated in underground salt – lower U/Th activity. ~2,000 m.w.e. depth



200kg (63l), enriched ^{136}Xe (80%) 2006
without Ba tagging for 2 years
1 ton with Ba tagging for 5 years
10 ton with Ba tagging for 10 years

$$^{136}Xe \rightarrow {}^{136}Ba^{++} + e^- + e^-$$

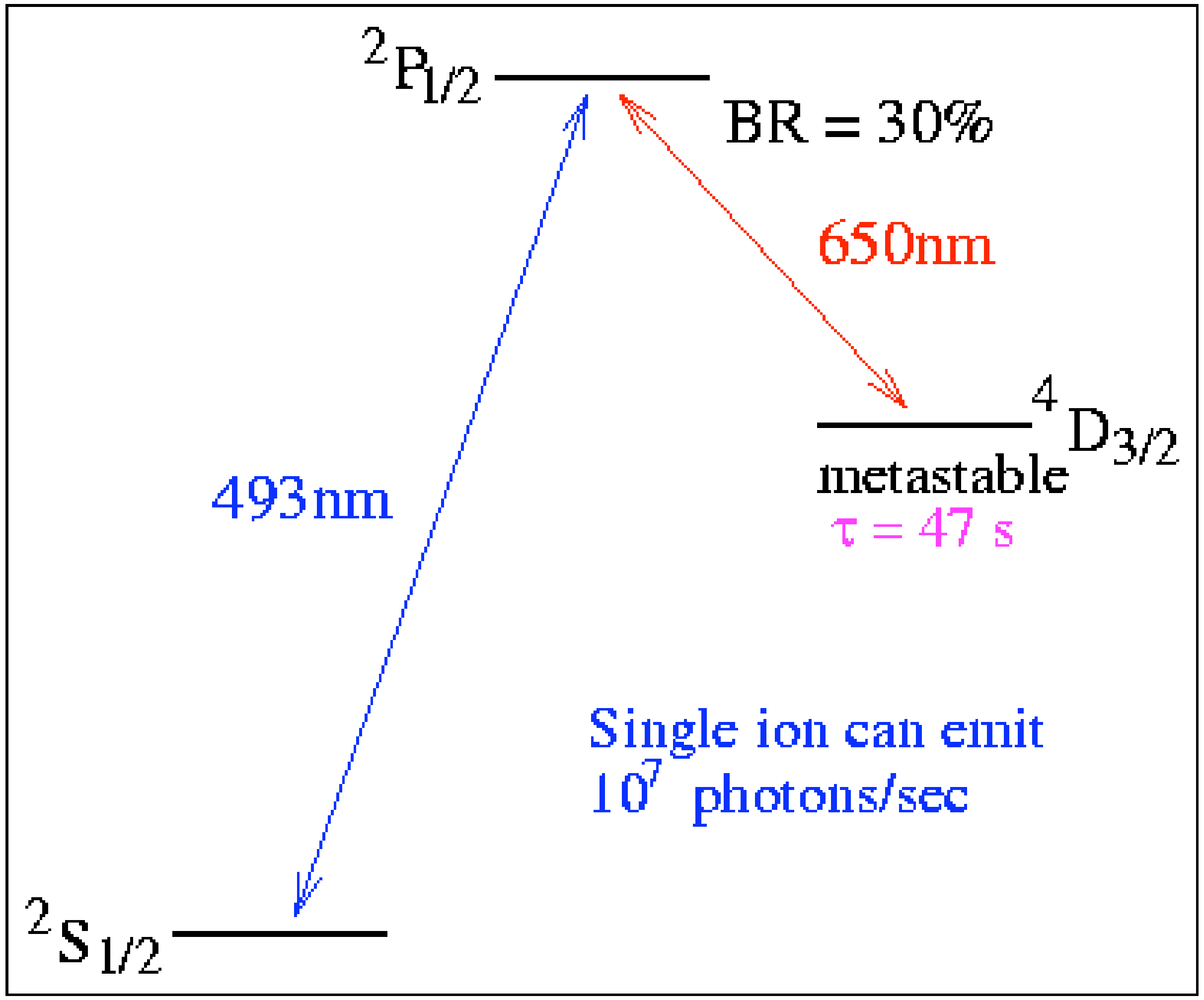
- Extract the Barium ion from the event location (electrostatic probe)
- Deliver the Barium to a laser system for Ba^{136} identification.

Xe offers a new tool to reduce background:

$^{136}Xe \rightarrow {}^{136}Ba^{++}$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba^{+} system best studied (Neuhauser, Hohenstatt, Toshek, Dehmelt 1980)
Very specific signature
"shelving"
Single ions can be detected from a photon rate of 10^7/s

Barium tagging would eliminate all radioactive backgrounds, leaving only $2\nu\beta\beta$.



Level structure for Ba^{+}

It's just crazy enough to work

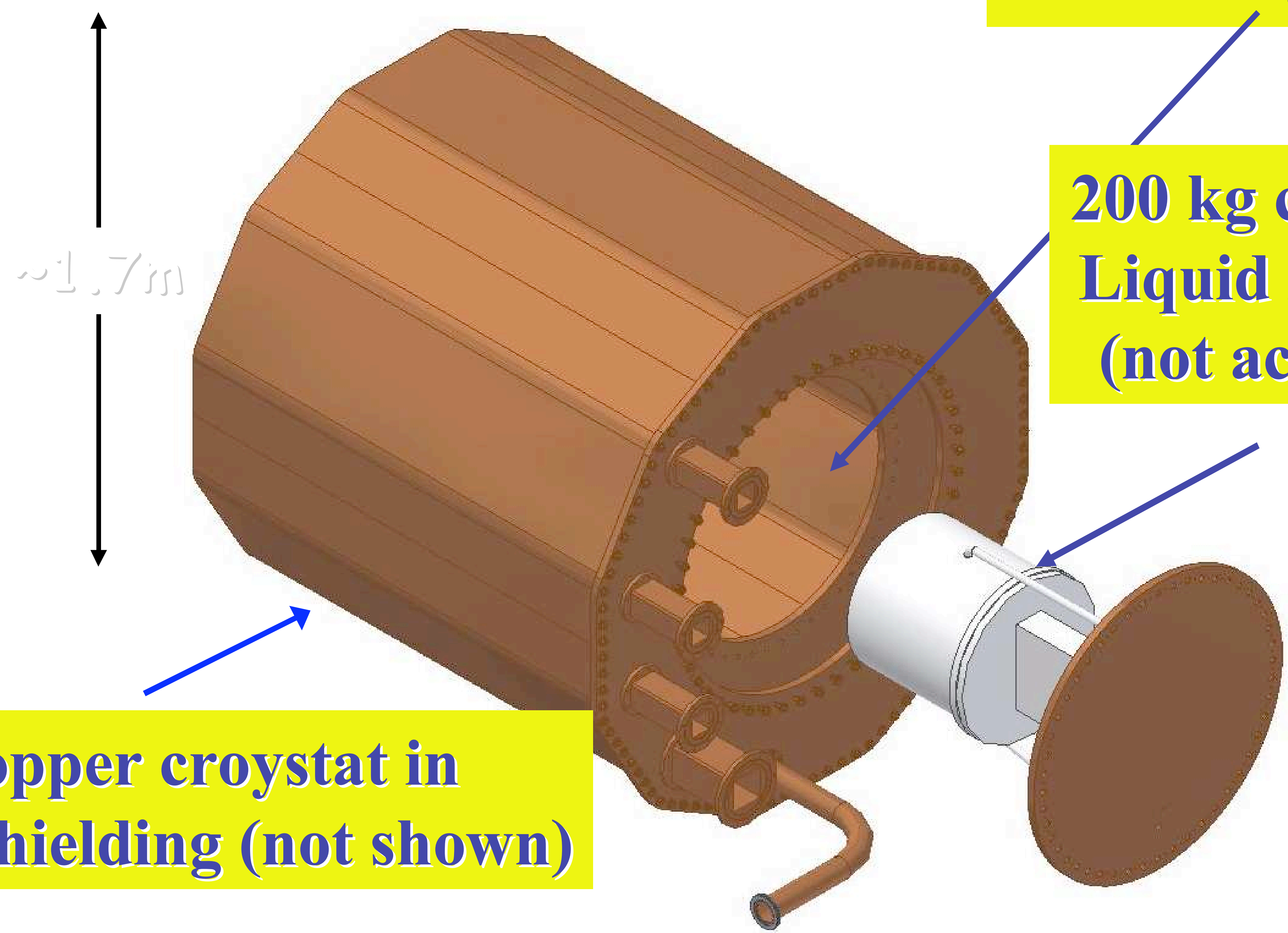
Assuming that the Xe chamber + Ba tagging reduce to 0 all radioactive background...

Isotope	Det mass (kg)	Enrich. (%)	Eff. (%)	Measur. time (yr)	Background	$T_{1/2}^{0\nu\beta\beta}$ (yr)	$<m_n>$ QRPA	(eV) NSM
$^{136}Xe^{*}$	1000	80	70	5	0 + 1.8 events	$8.3*10^{26}$	0.051	0.14
$^{136}Xe^{**}$	10000	80	70	10	0 + 5.5 events	$1.3*10^{28}$	0.013	0.037

* $\sigma(E)/E = 2.8\%$ R.Luescher et al. Phys. Lett. B434 (1998) 407
** $\sigma(E)/E = 2.0\%$ Modest improvement on the above.

The meV region is within reach.

The EXO-200 is an ultra-low background cryogenic apparatus

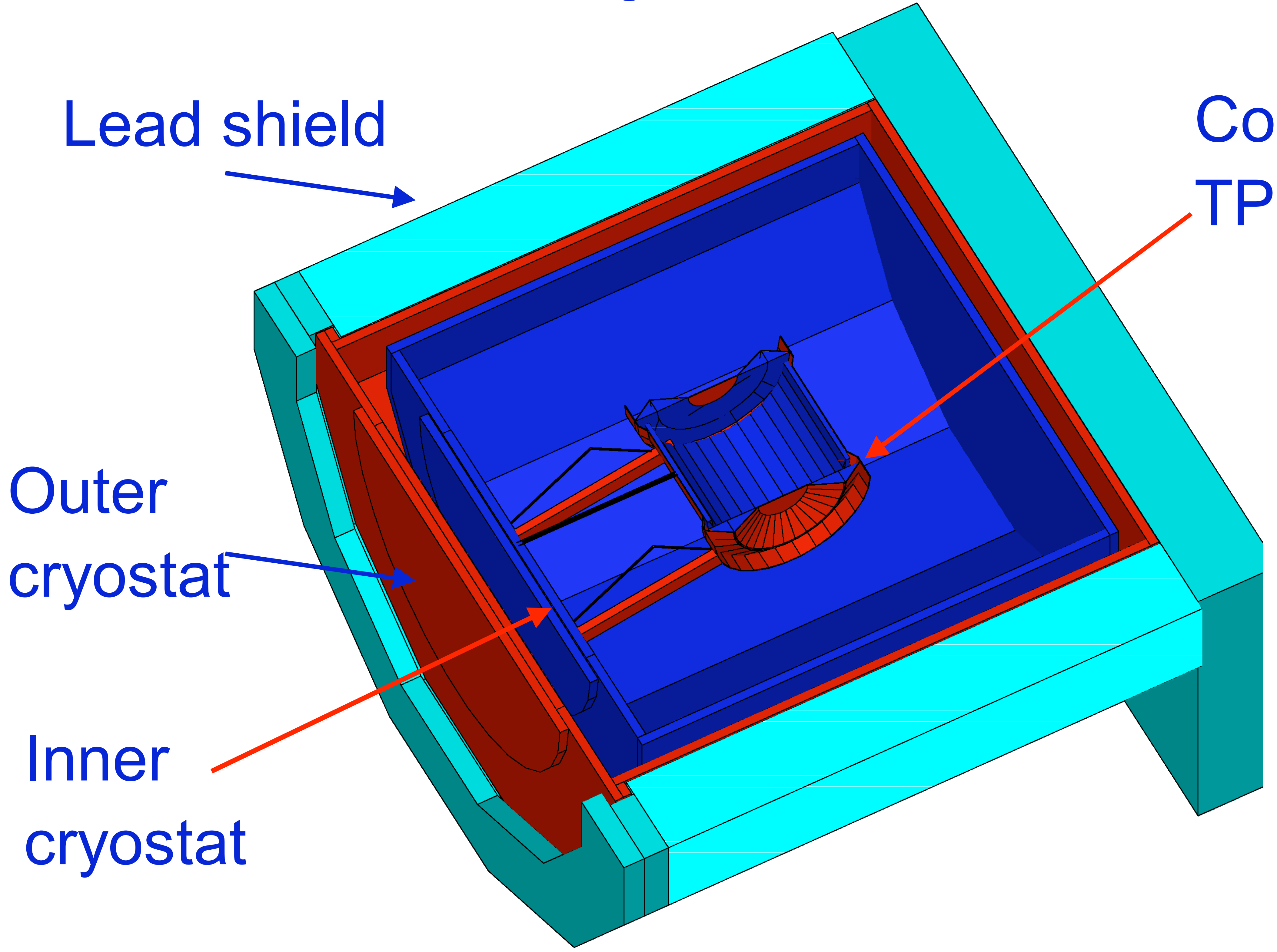


Heat exchange/shielding fluid

200 kg copper chamber
Liquid Xenon at 165 K
(not actual geometry)

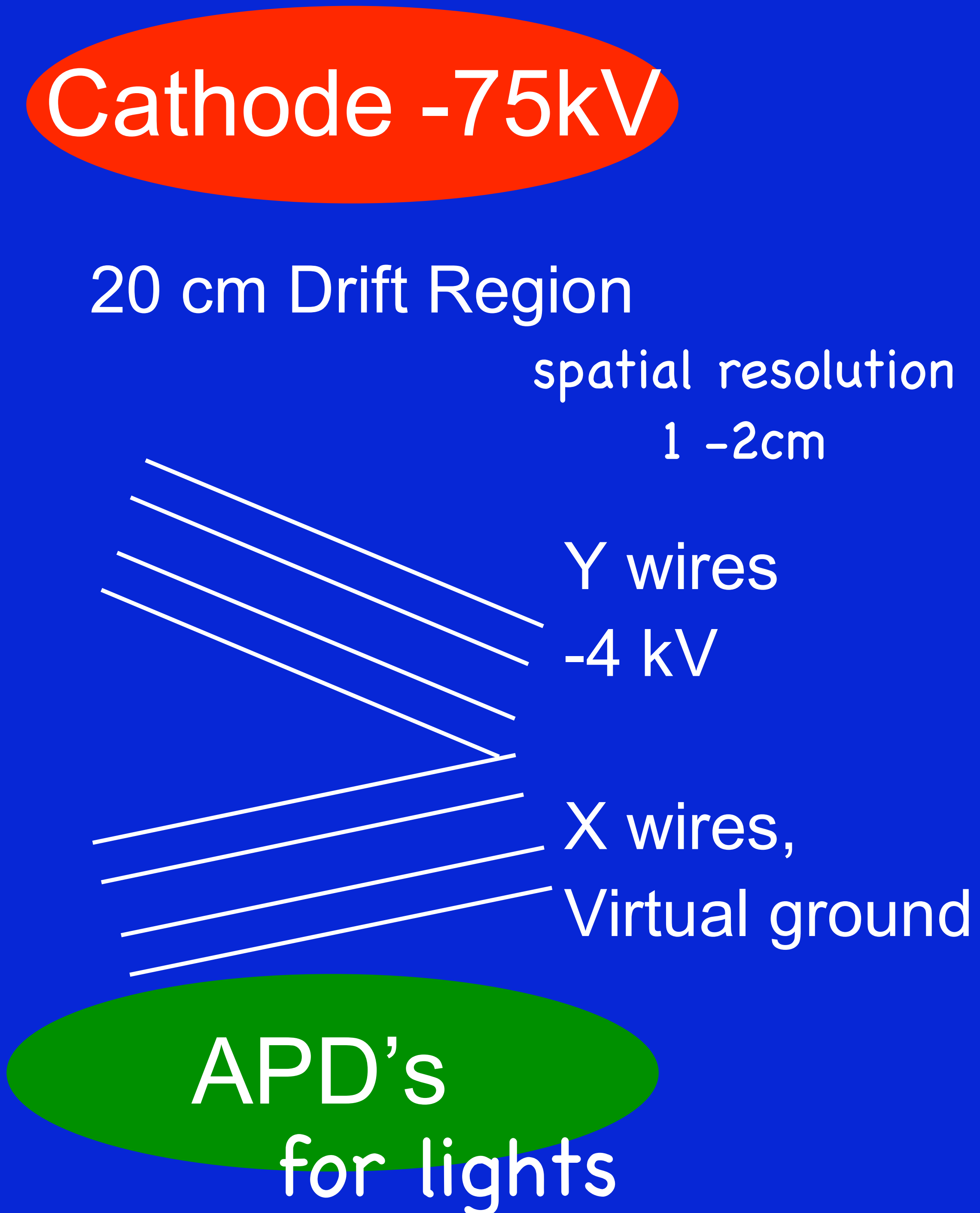
Copper croystat in lead shielding (not shown)

Realistic Monte Carlo Geometry for Background Studies.



Charge Detection

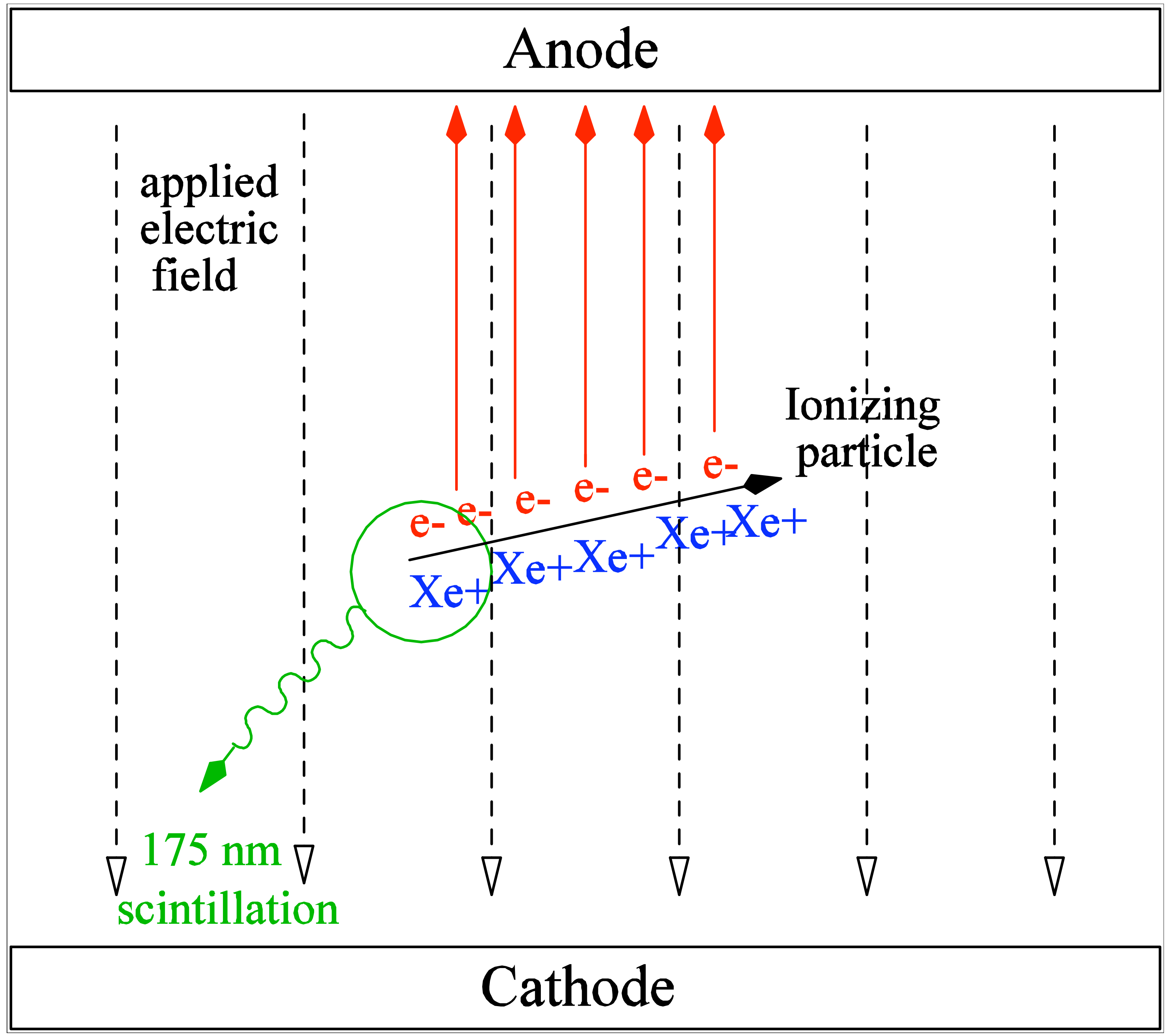
- Double-ended TPC chamber with ~20 cm drift regions
- Mid-plane cathode biased at -75 kV
- 38 Inductive “Y” wires per side at -4 kV, 100% charge transparent.
- 38 “X” wires at virtual ground to collect the charge.
- LXE electron mobility ~2000 $cm^2/(Vs)$
- Saturation velocity ~ 0.28*cm/μs
- Electron lifetime goal of 3ms
  => 2.4% loss at 20 cm.



Xenon calorimetry

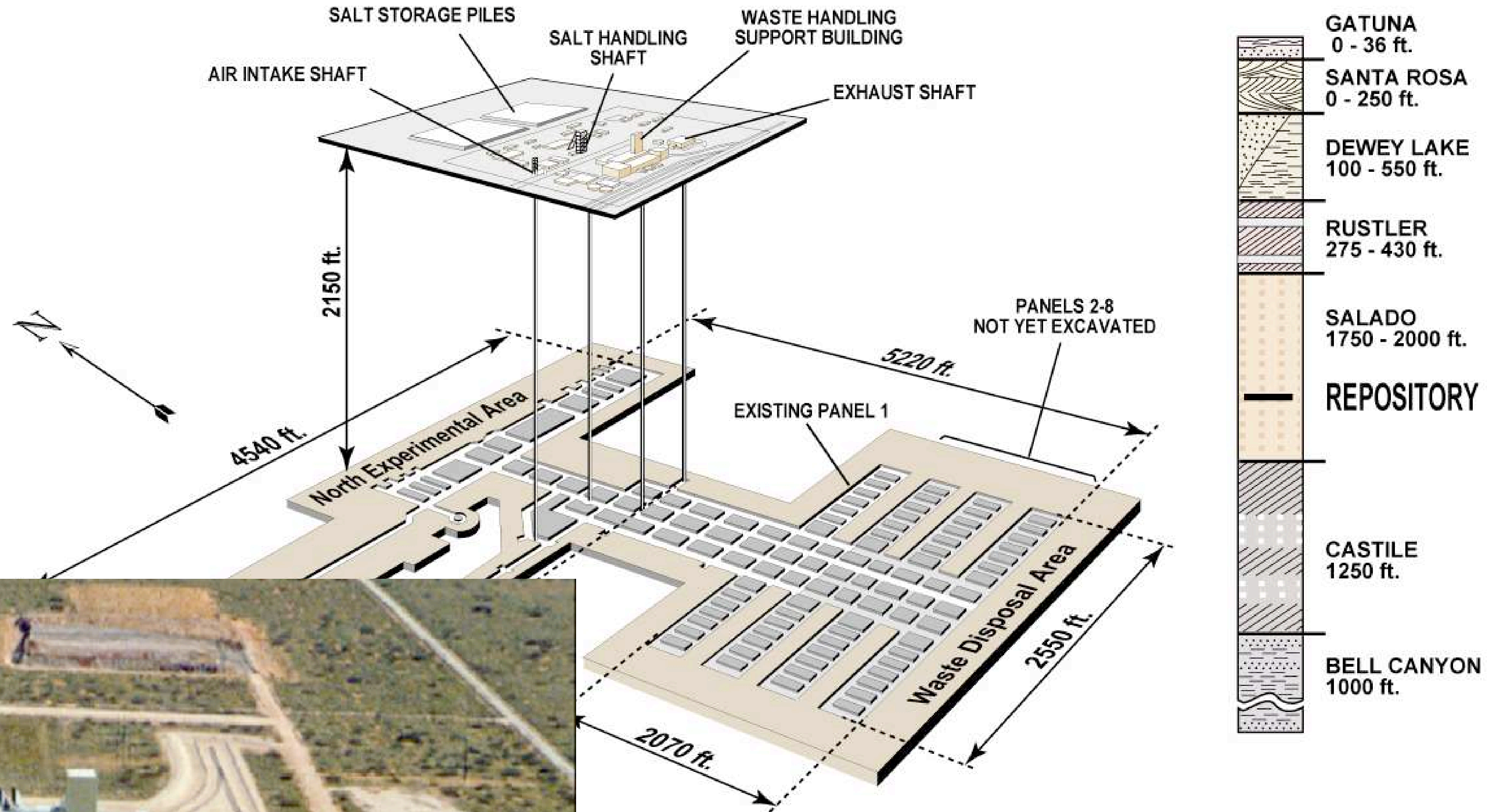
We measure the event energy by collecting the ionization on the anode and/ or observing the scintillation.

As the electric field is increased, the collected ionization increases and the scintillation decreases.



200 kg prototype to be installed at DoE's WIPP, NM

shielding depth
~2.5 km w.e.



A salt mine to store the military radioactive waste…

…and perform low background physics experiments

An experimental facility for EXO

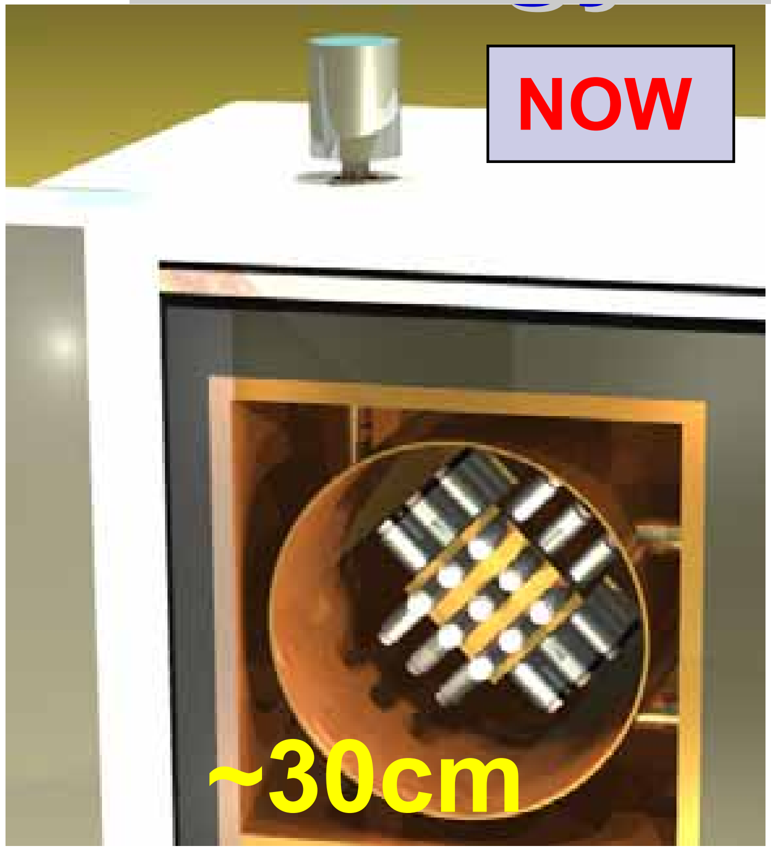
WIPP : Waste Isolation Pilot Plant
Carlsbad NM

Excavated in underground salt – lower U/Th activity.
~2,000 m.w.e. depth

http://www-sk.icrr.u-tokyo.ac.jp/xmass/ ;for Solar ν, 2β, DM

2004

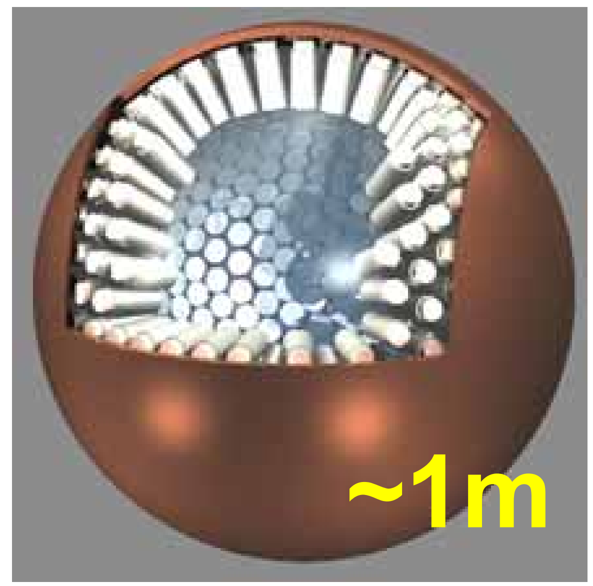
Strategy of the XMASS project ; 1 phase



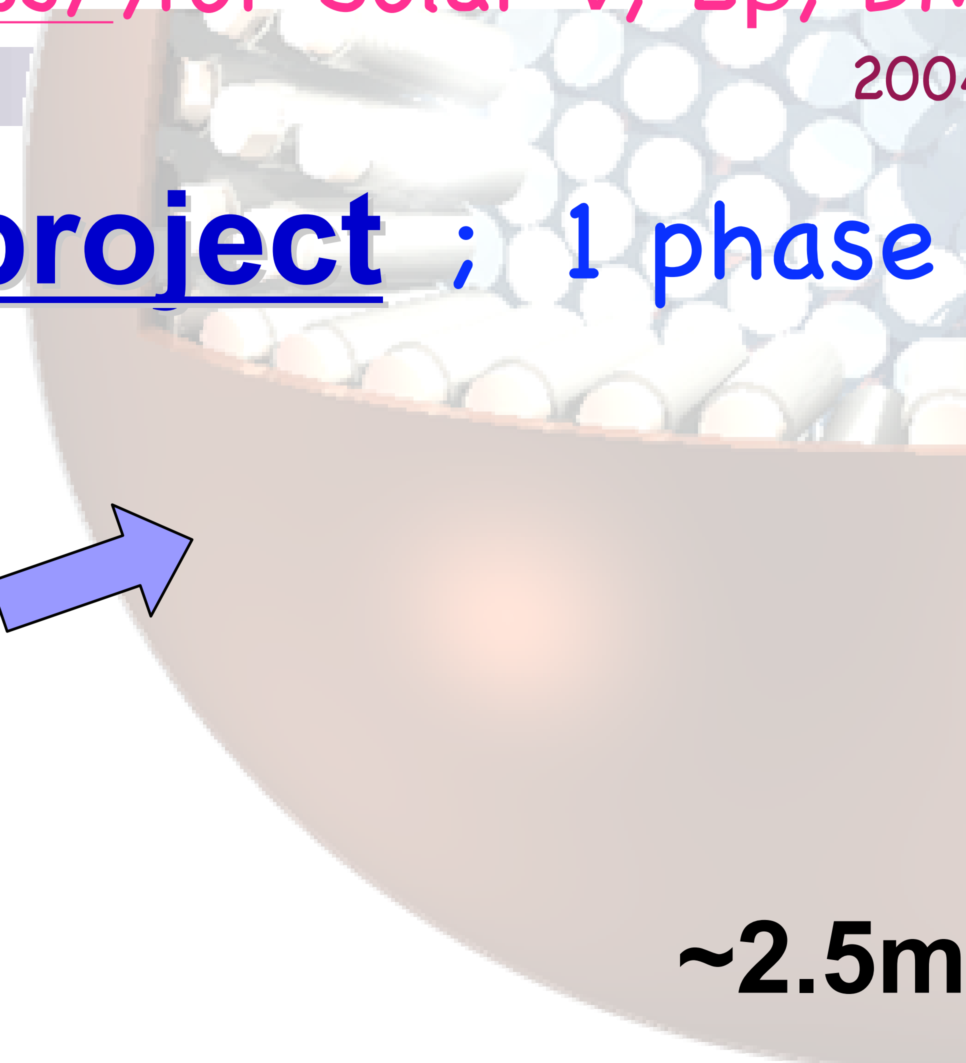
Prototype detector
(FV 3kg) R&D 100kg

Confirmation of feasibilities of the ~1 ton detector

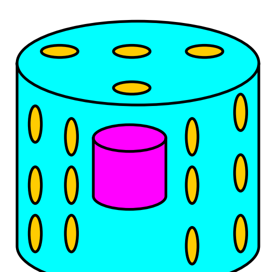
Analysis techniques
Self shielding performance
Low background properties
Purification techniques



~1 ton detector
(FV 100kg)
Dark matter search



~20 ton detector
(FV 10ton)
Solar neutrinos
Dark matter search



Dedicated detector for
Double beta decay search

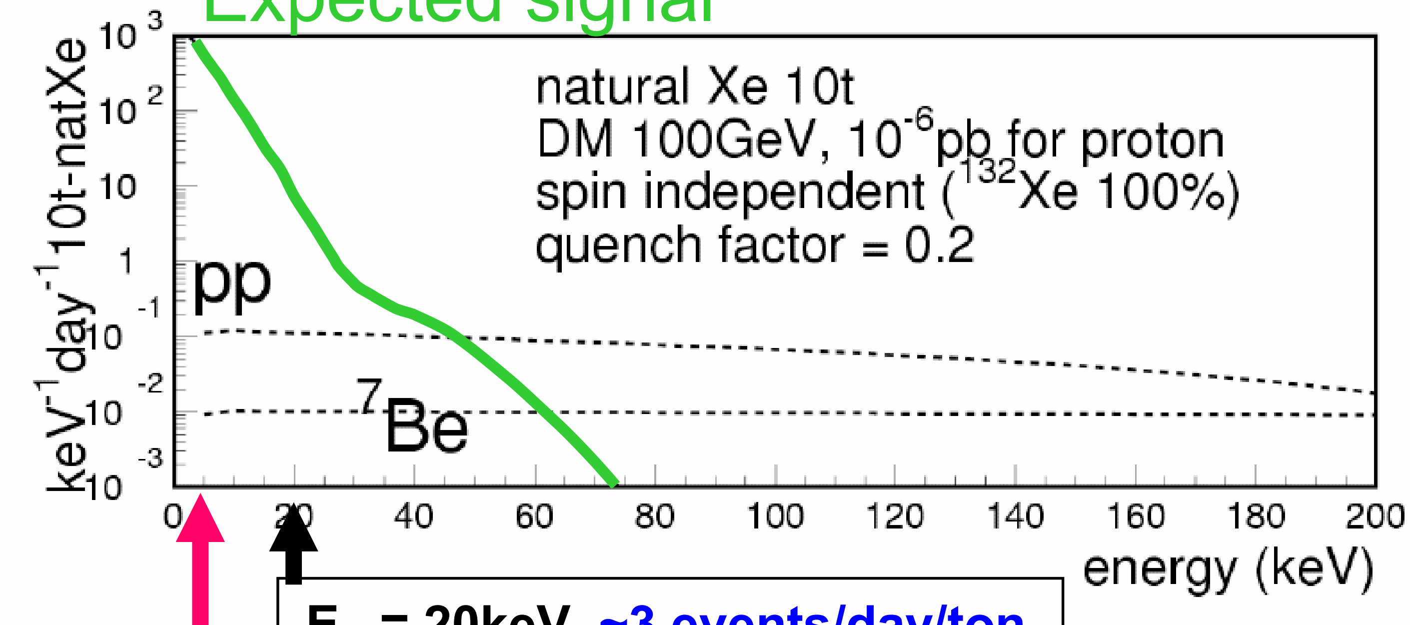
August 18, 2004

Physics goals at XMASS

XMASS FV 0.5ton year
E_{th}=5keV, 3σ discovery

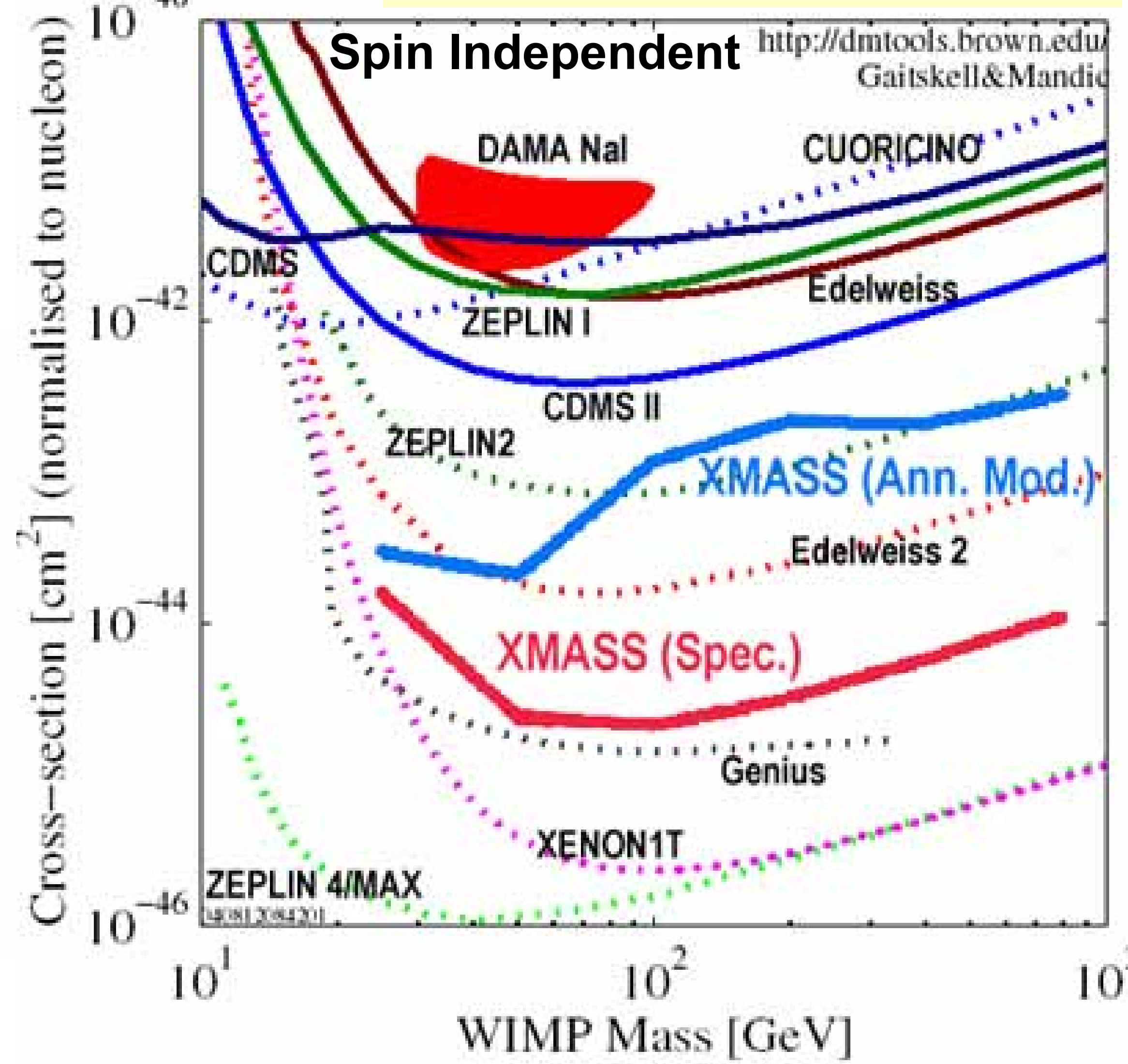
Direct search via nuclear elastic scattering

Expected signal



E_{th} = 20keV ~3 events/day/ton

E_{th} = 5keV ~200 events/day/ton

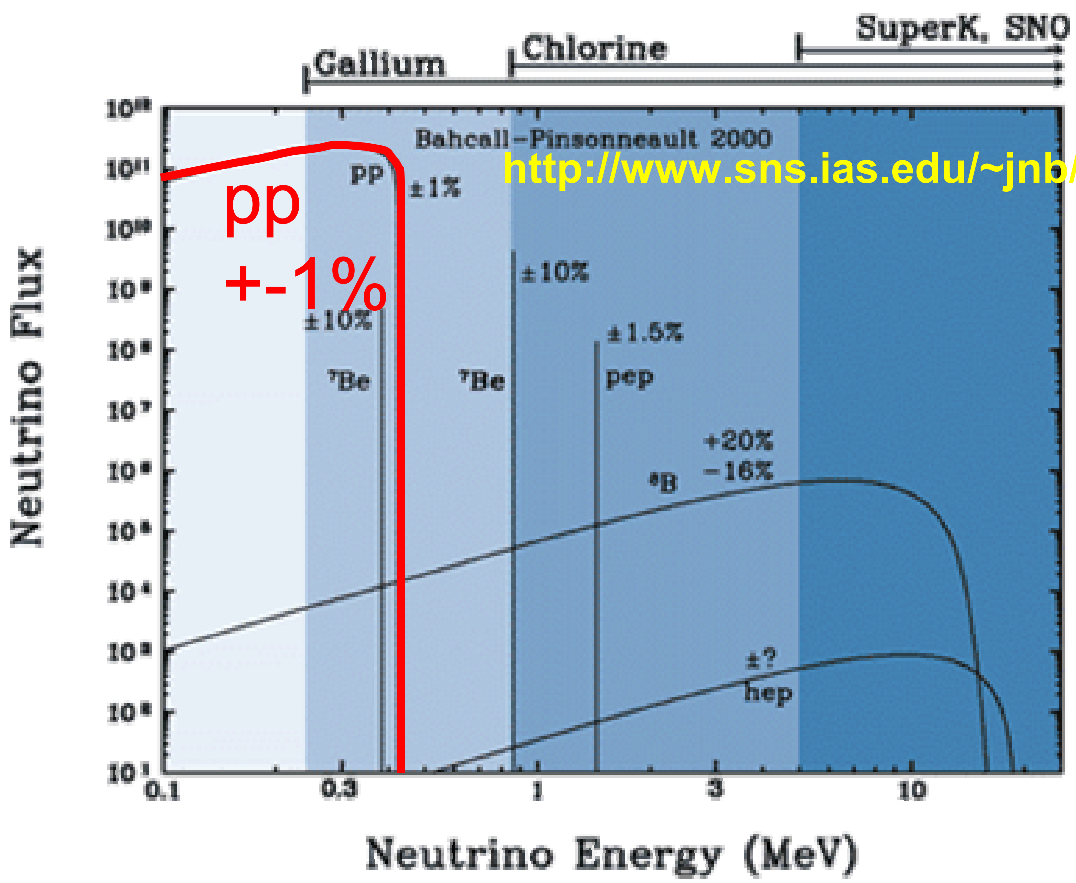


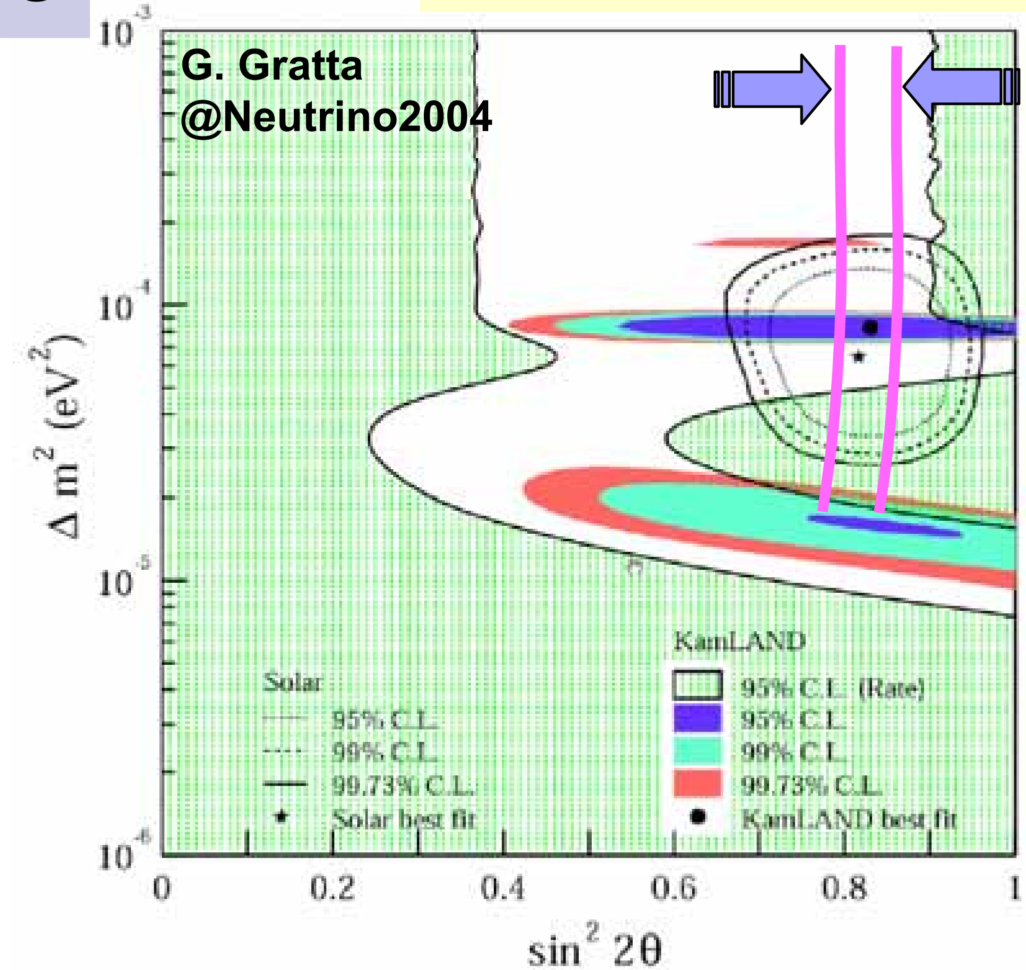
- Xenon MASSive Detector for Solar Neutrinos (pp/^{7}Be)
- Xenon Detector for Weakly Interacting MASSive Particles (Dark Matter Search)
- Xenon Neutrino MASS Detector (Double Beta Decay)

Physics goals at XMASS

Measure pp ν via ν + e → ν + e

XMASS FV 50 ton year (90%CL)





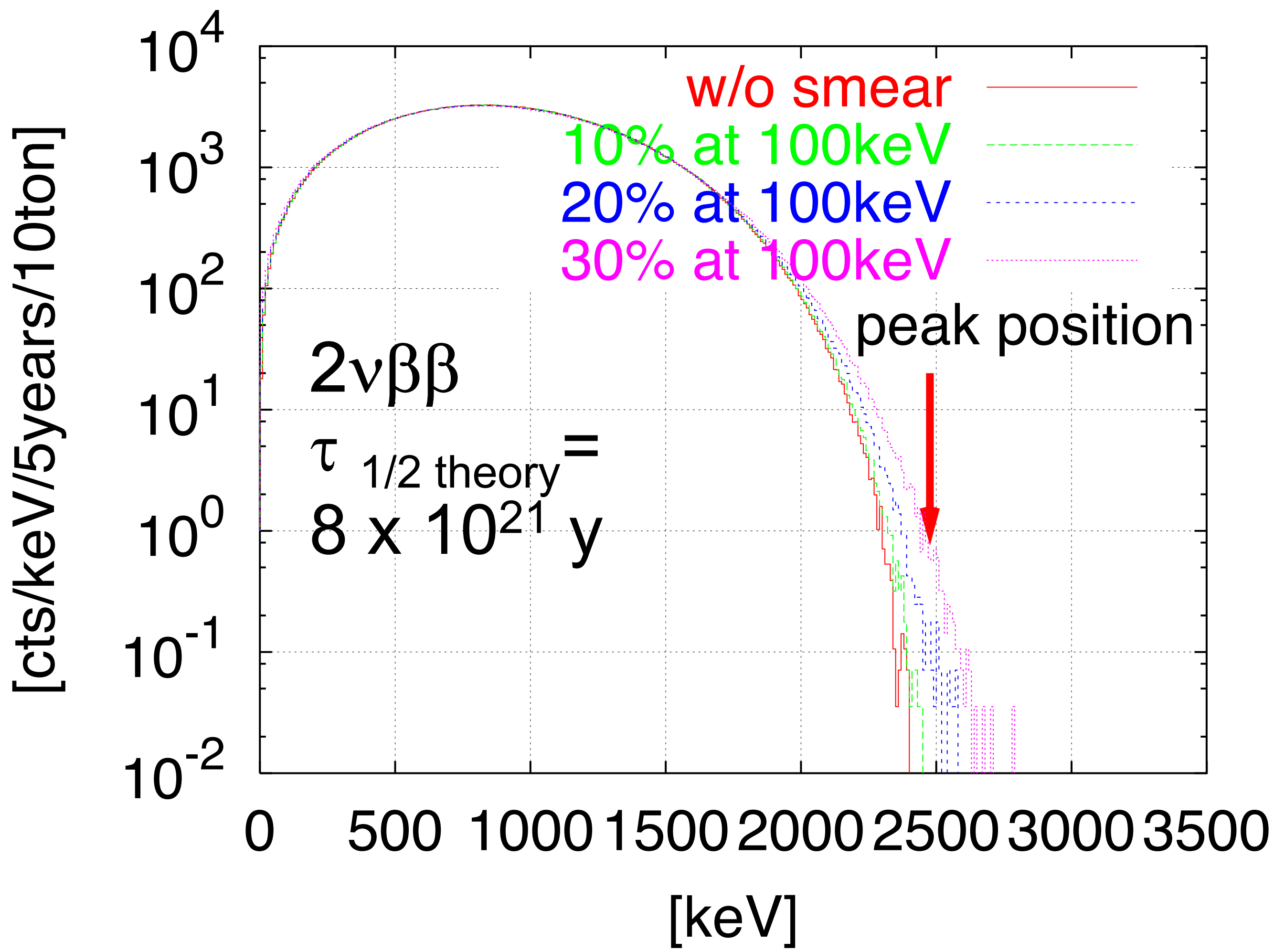
- Xenon MASSive Detector for Solar Neutrinos (pp/^{7}Be)
- Xenon Detector for Weakly Interacting MASSive Particles (Dark Matter Search)
- Xenon Neutrino MASS Detector (Double Beta Decay)

2νββ life time should be measured
Isotope separation would be needed

Physics goals at XMASS

$^{136}Xe \rightarrow {}^{136}Ba + e^- + e^-$

Q-Value: 2.48 MeV

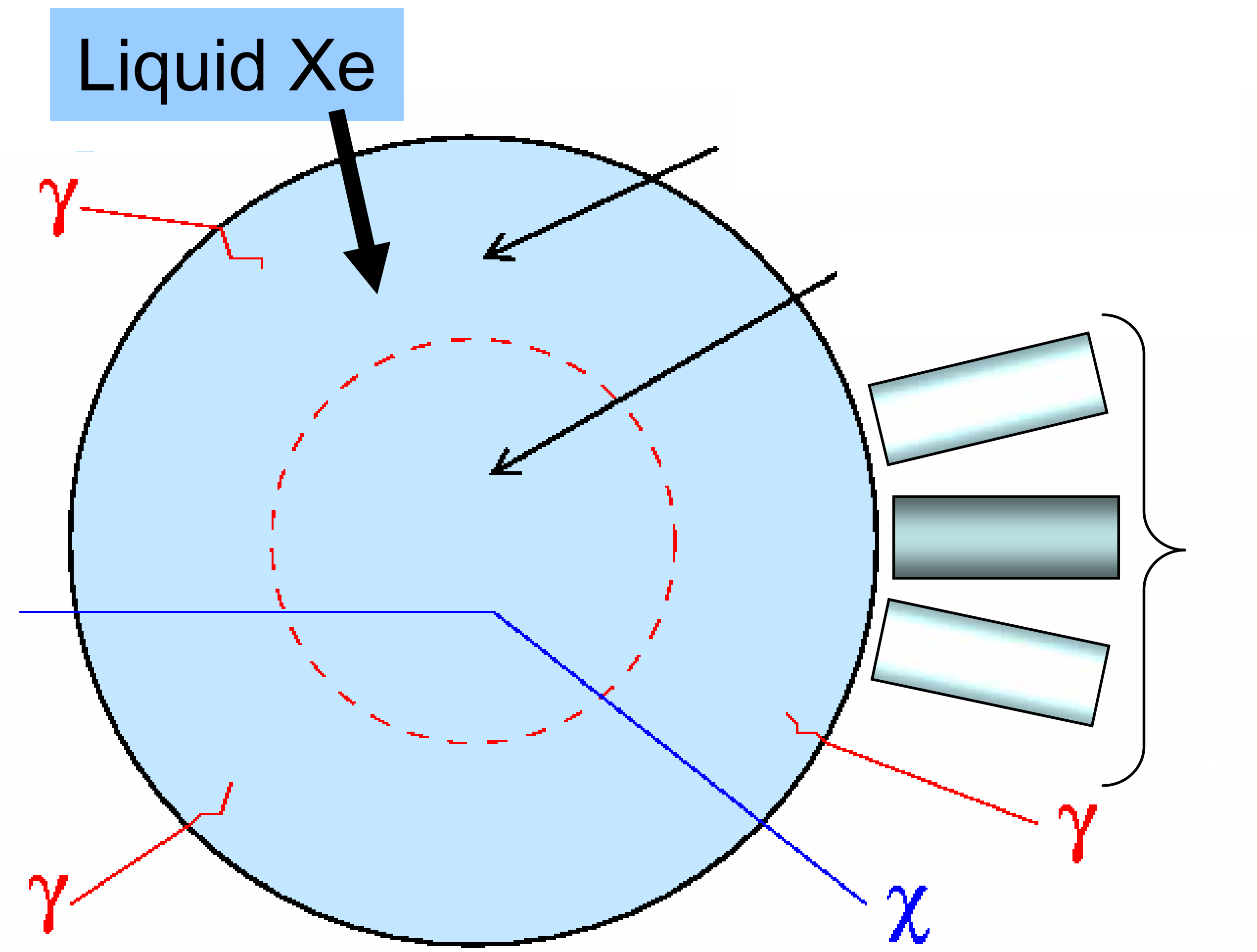


- Search for 0νββ (2νββ) decay of ^{136}Xe (na 8.87%)
- High purity and enriched Xe can be used.
- Energy region is different from solar ν / DM.
- PMTs should not be placed near the detector.

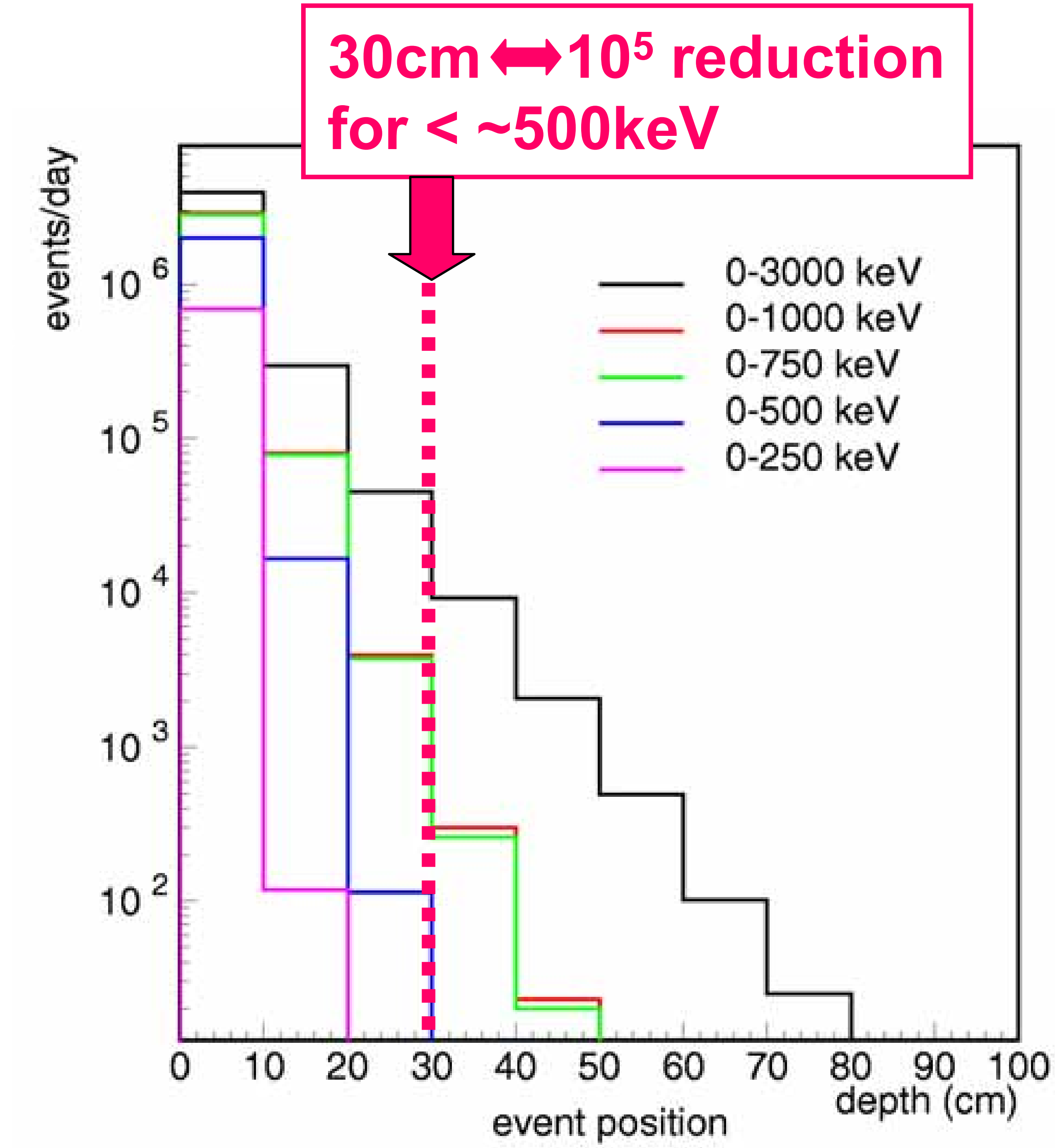
➡ **Need another design of the detector!**
(low priority, at moment…)

- …r Solar Neutrinos (pp/^{7}Be)
- Xenon Detector for Weakly Interacting MASSive Particles (Dark Matter Search)
- Xenon Neutrino MASS Detector (Double Beta Decay)

Self shielding



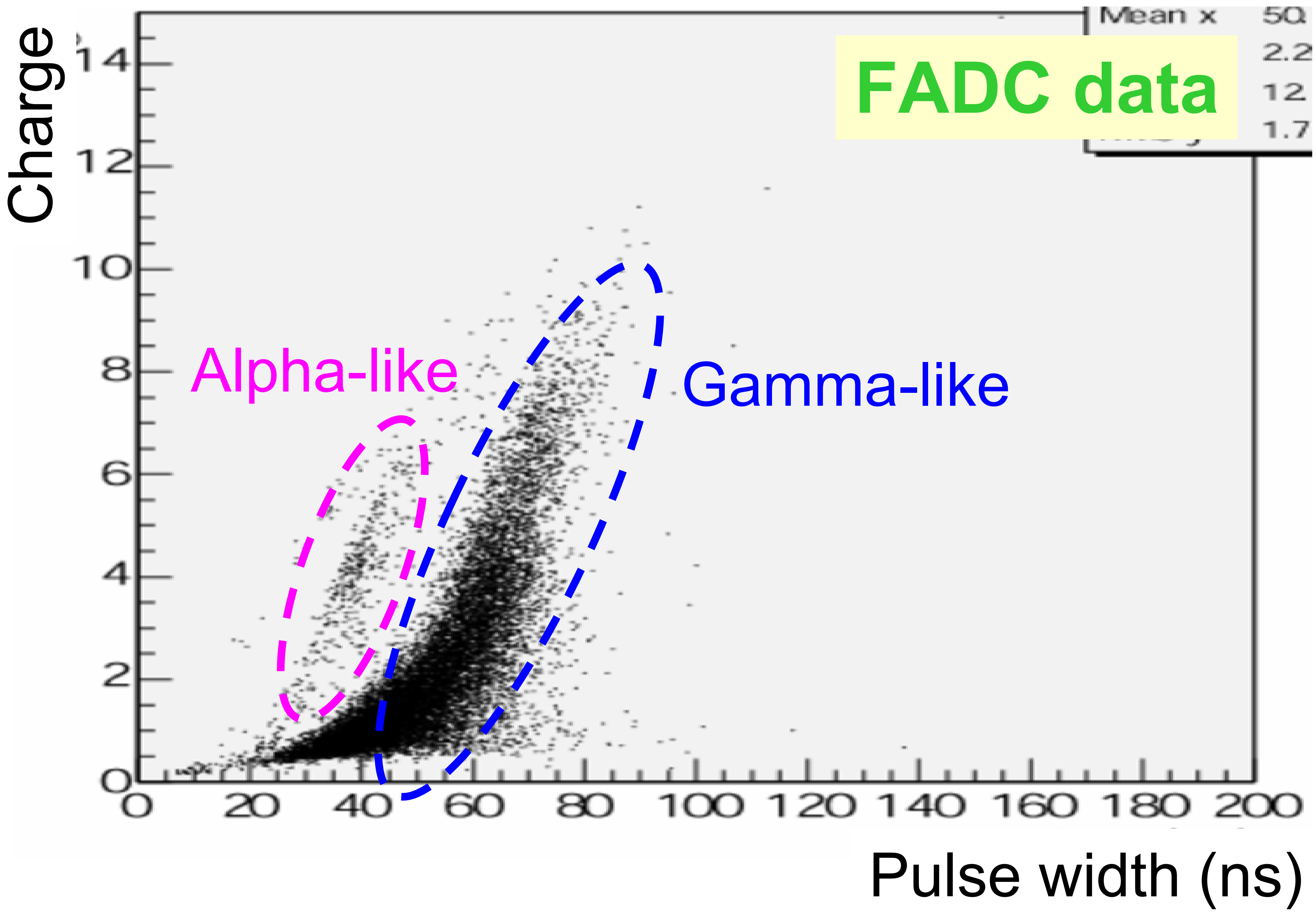
Reconstruct the vertex and energy based on PMTs information (light pattern)



- **Quite effective for the events below ~500 keV (pp ν & DM)**
- **Not effective for double beta decay experiment**

Alpha vs Gamma separation

Aug.04 run
Preliminary

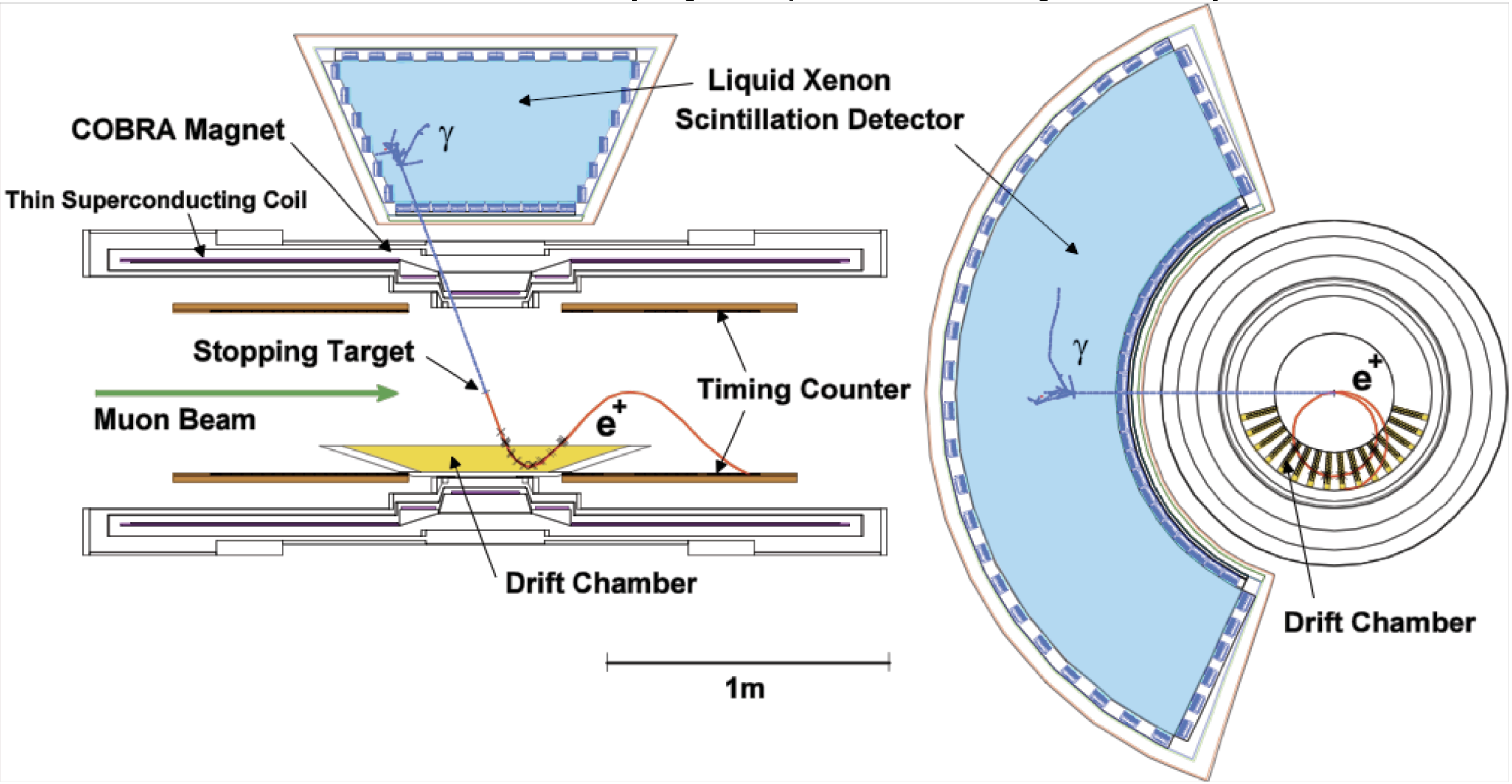


Alpha-gamma separation by using FADC wave form would be possible (under further investigation)

MEG Detector ; 1 phase

http://meg.web.psi.ch/

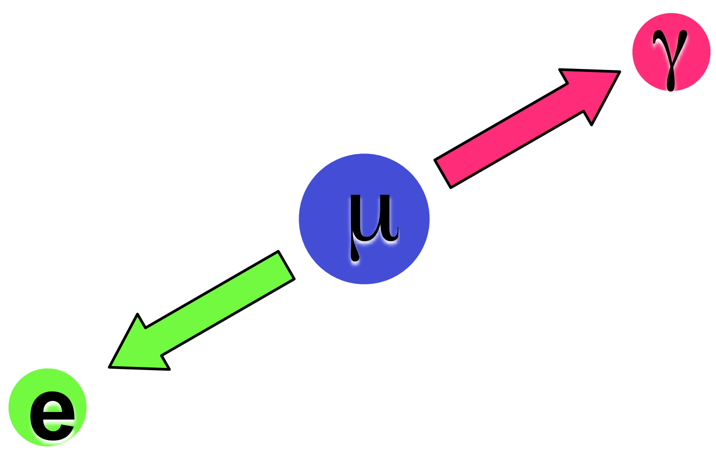
search for muons decaying into positrons and gamma rays



- 800~900 l liquid xenon
- 846 PMTs immersed in the liquid
- No segmentation

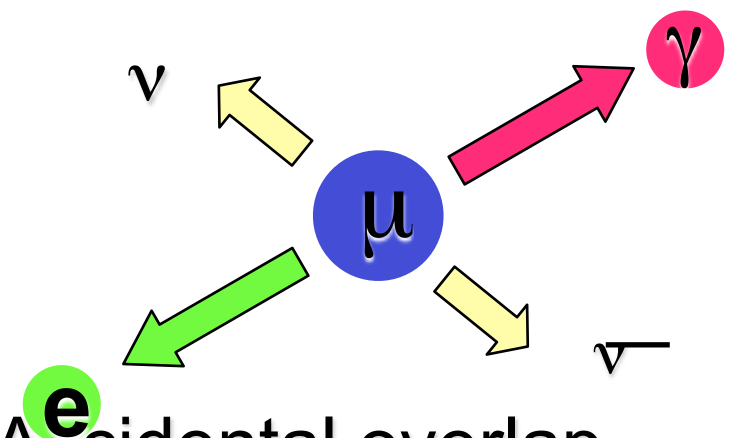
Signal and Background

- Signal

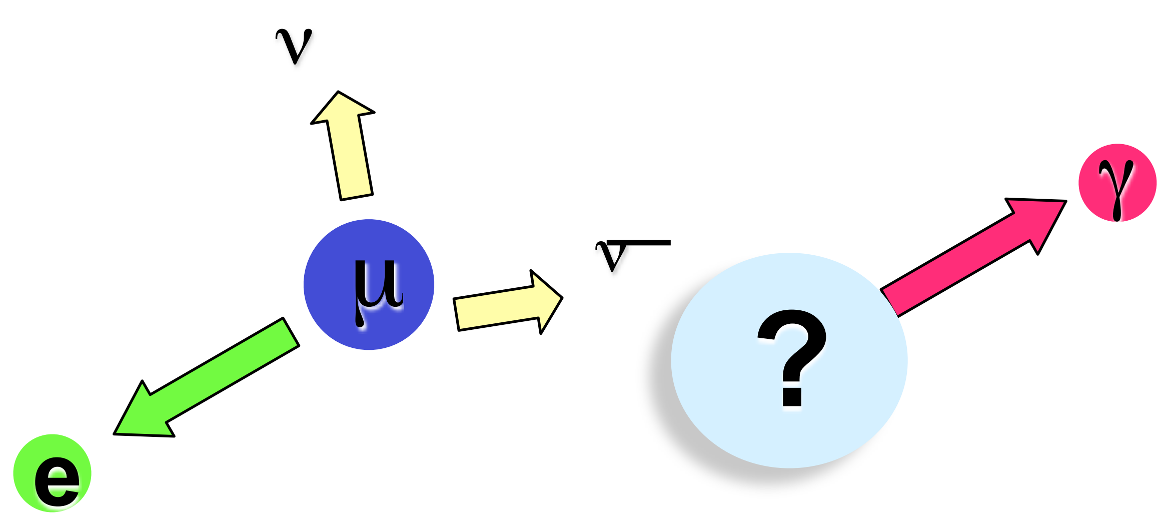


- $E_\gamma = m_\mu/2 =$ 52.8MeV
- $E_e = m_\mu/2 =$ 52.8MeV
- $\theta = 180^o$
- Time coincidence

- Background
  - Radiative μ decay

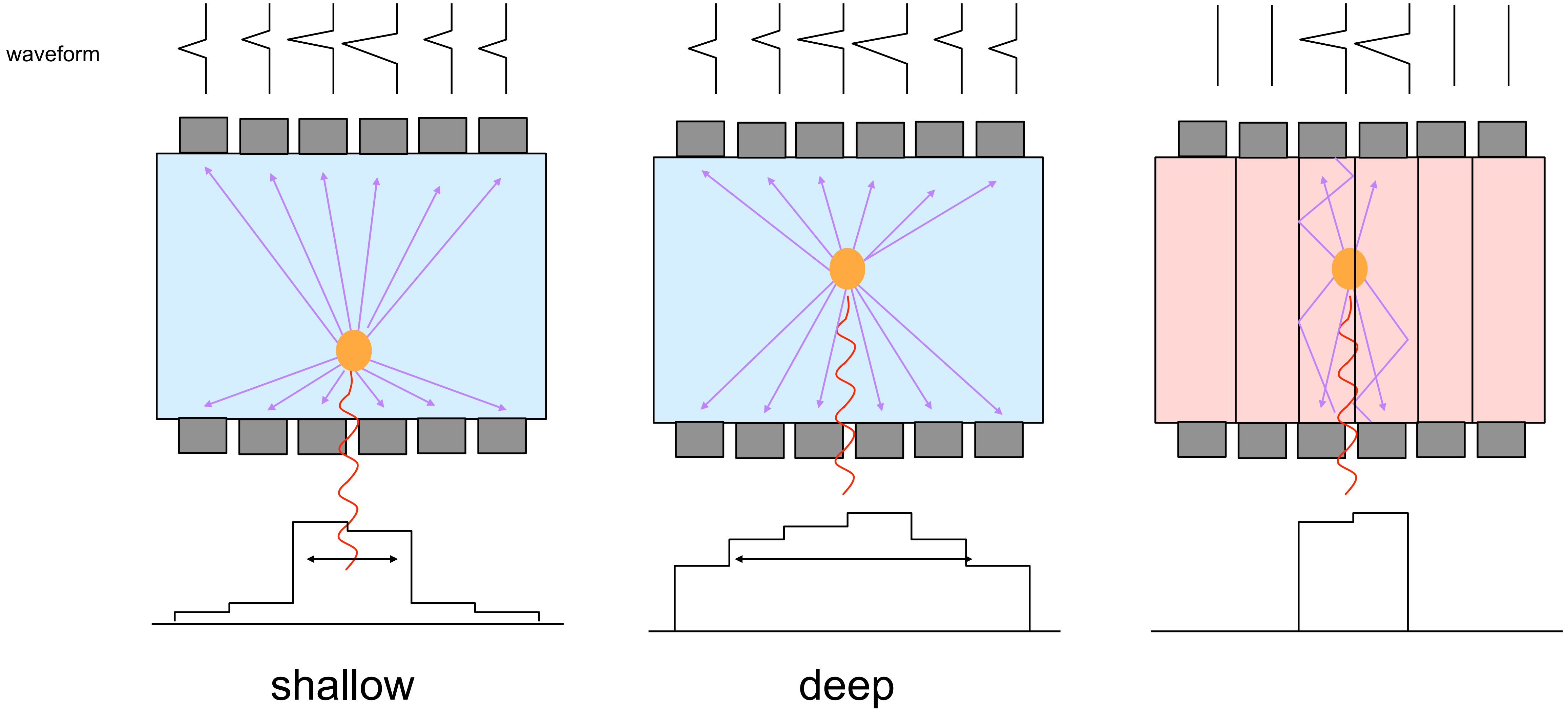


  - Accidental overlap



Depth Reconstruction

- Broadness of light distribution at the entrance side



an active volume of about 70l surrounded by 228 PMTs

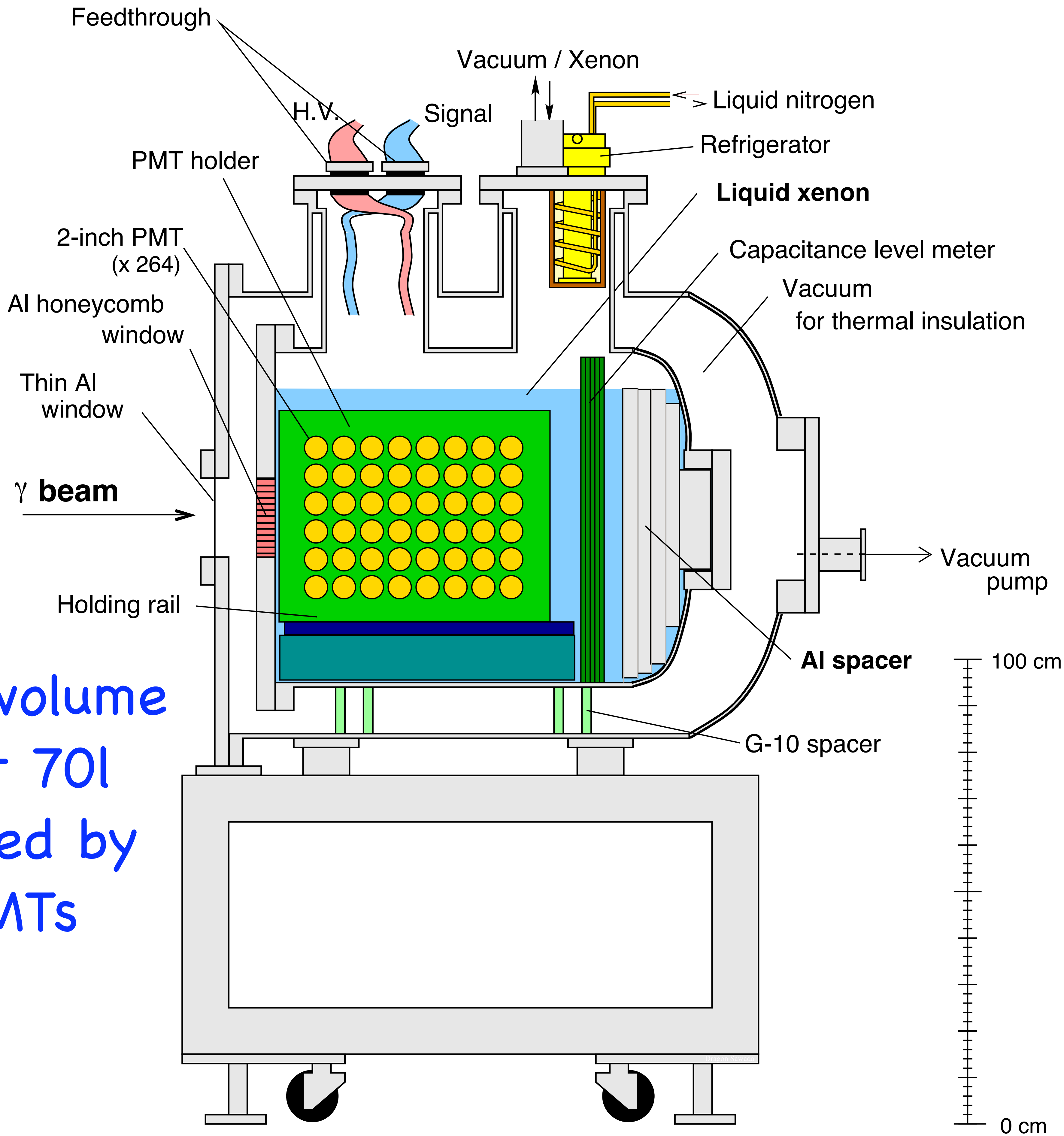


Fig. 1. Schematic view of the large prototype.

LXe-GRIT ; 1 phase

2004

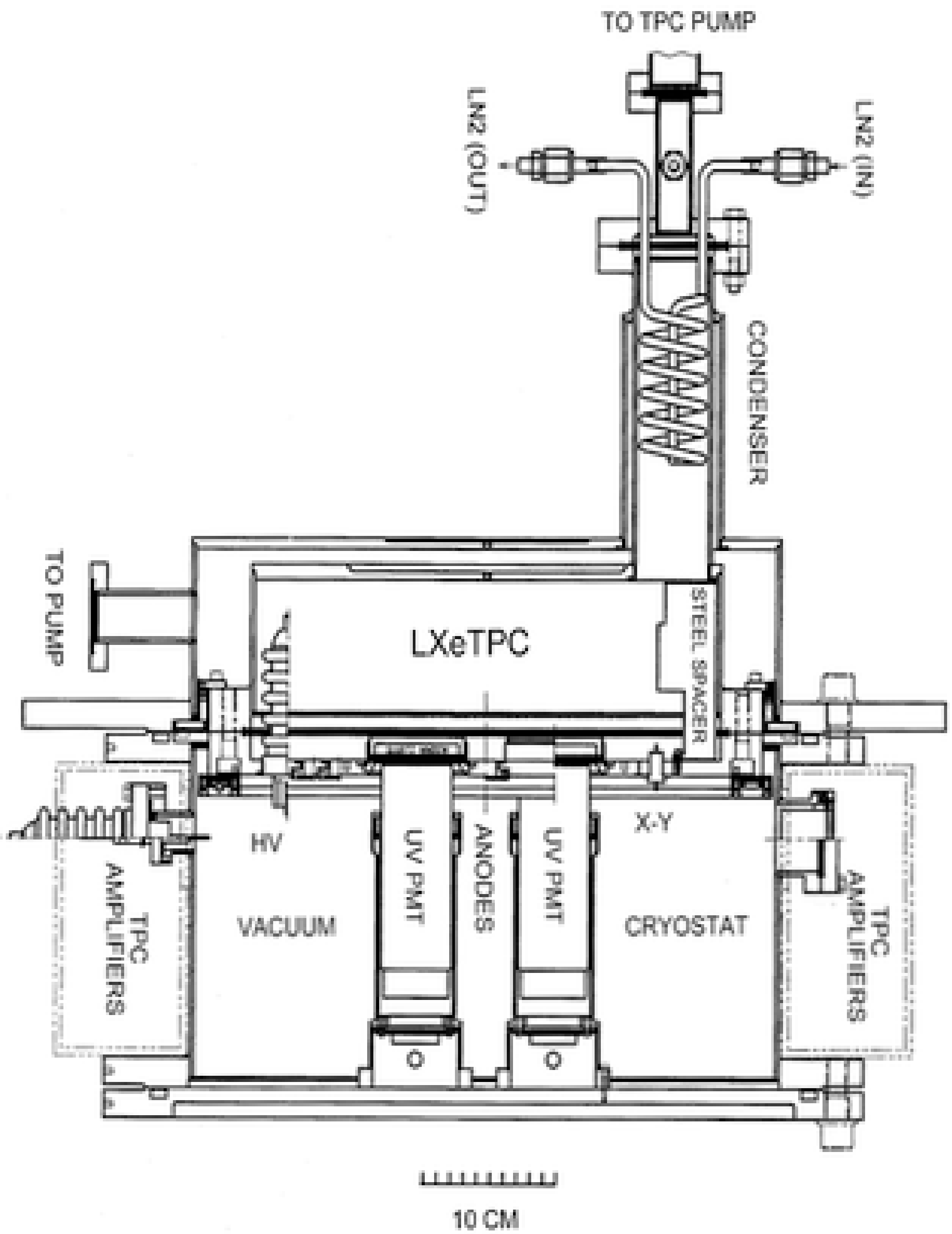
Columbia university - XENON collaboration

baloon flights(1997-2000) of the Liquid Xenon Gamma-Ray Imaging Telescope

γ energy range = 0.511 - 70MeV (e^+ - π^0)

LXeTPC (prototype of Compton telescope) with 7cm long drift

-direction of incident γ can be estimated by sequence of Compton scattering



LXeTPC : 18.6x18.6x7cm^3 (2.4 l)

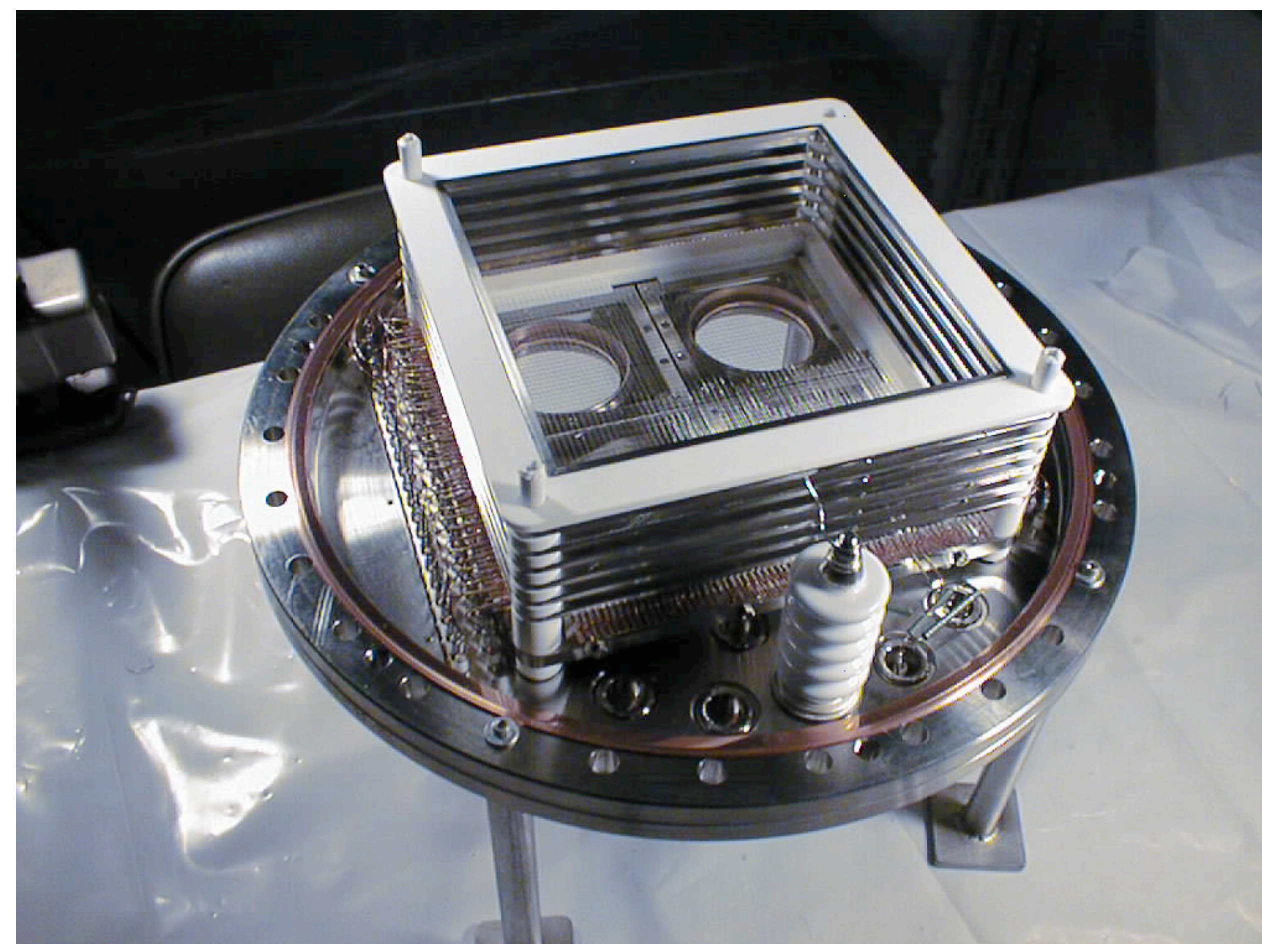
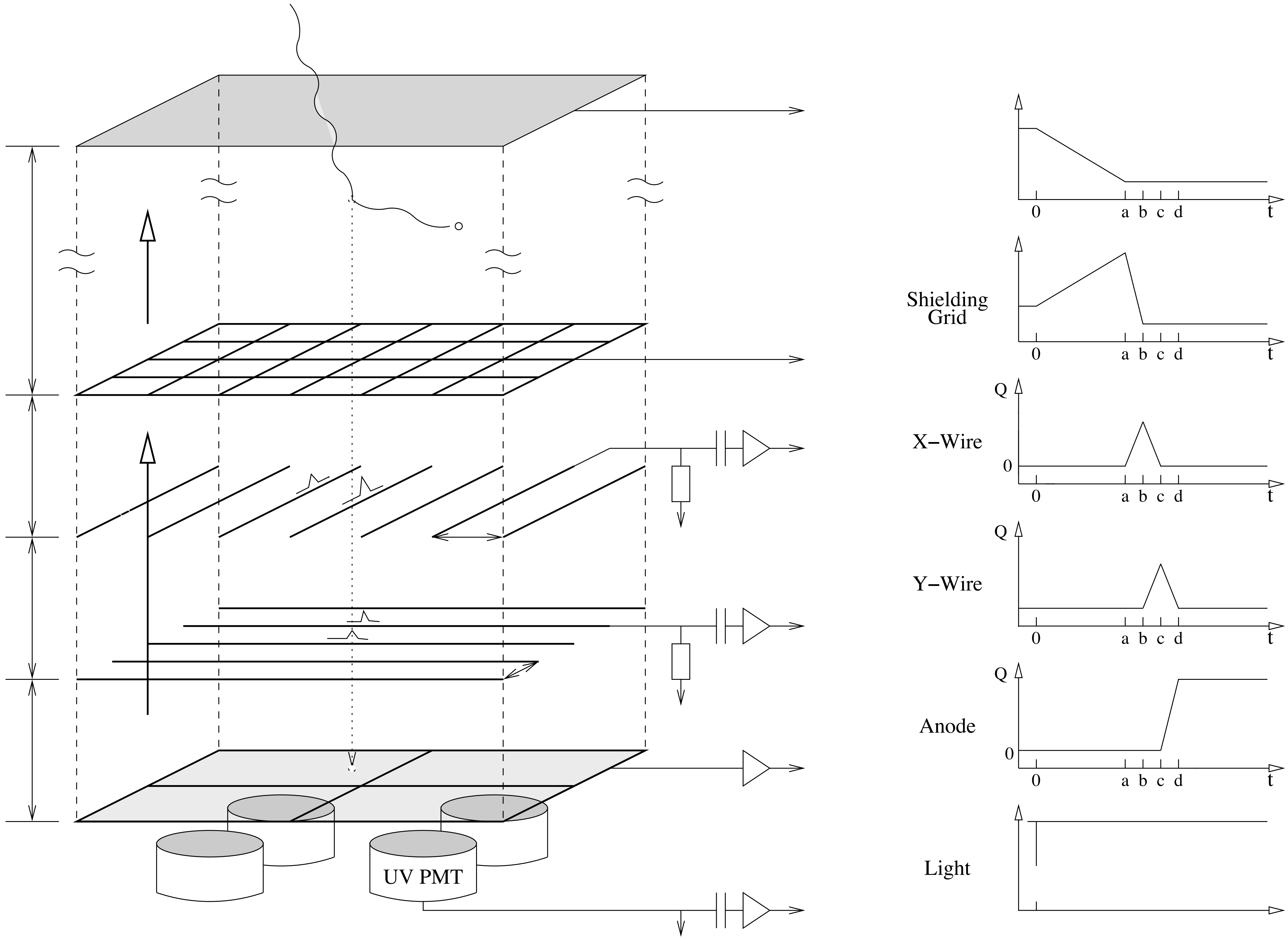
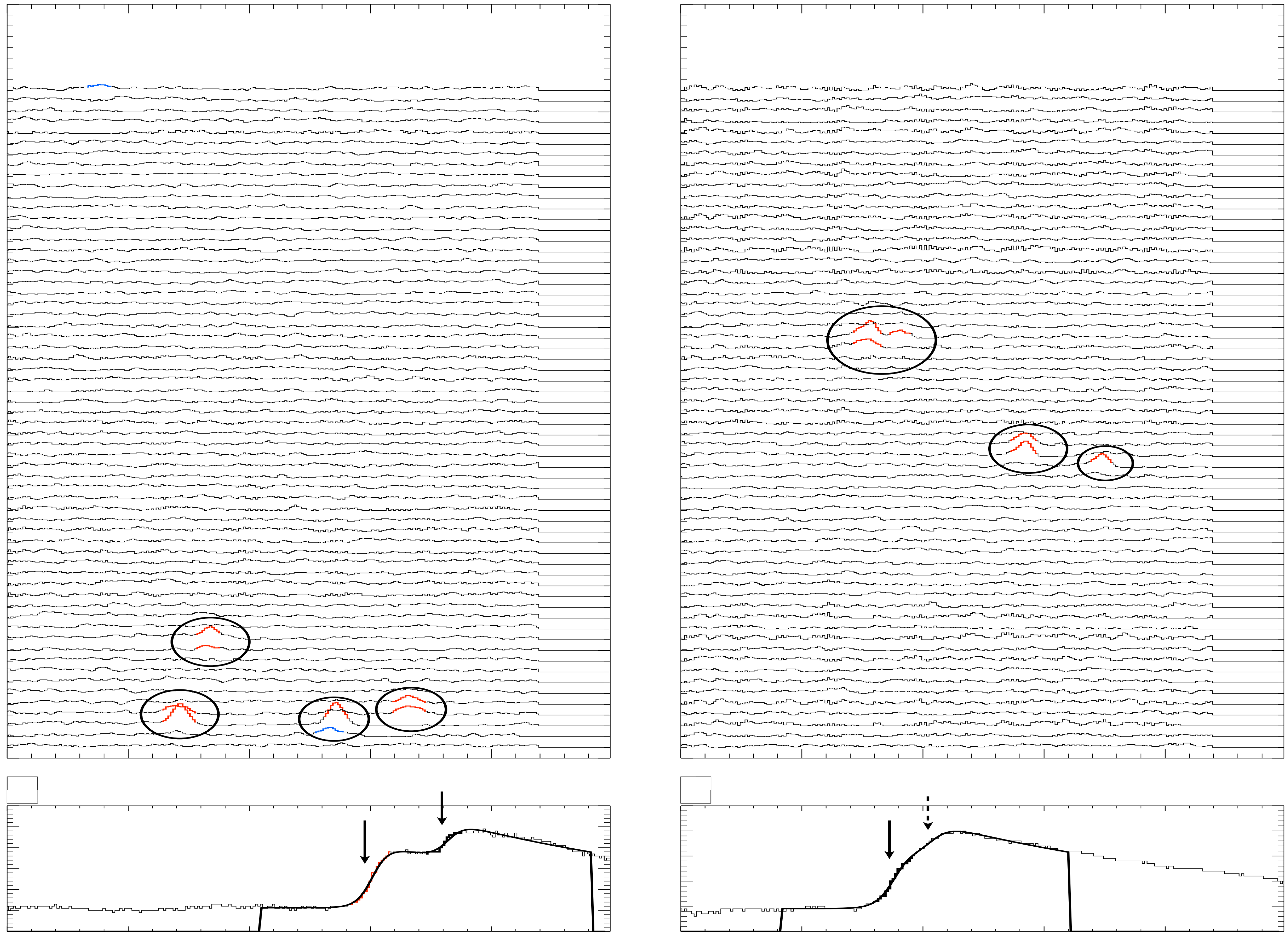
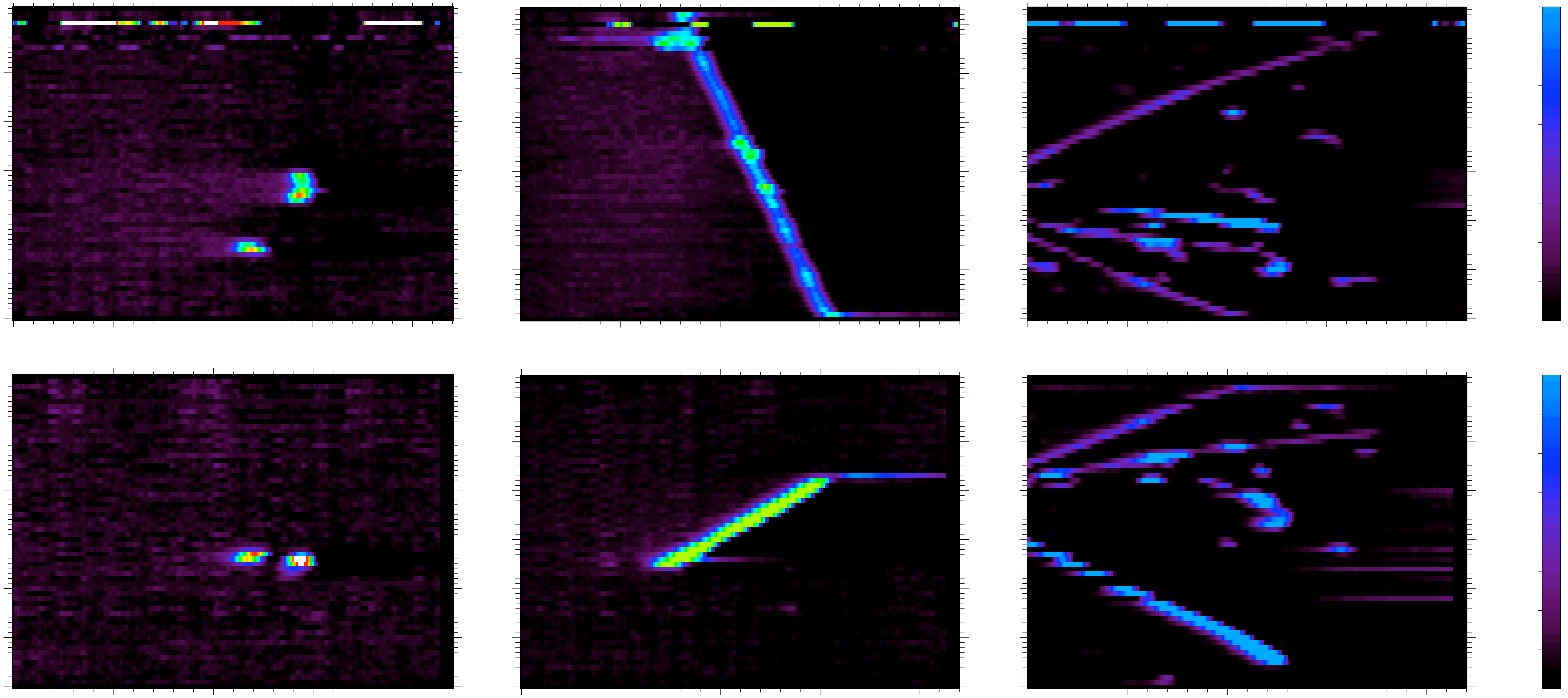


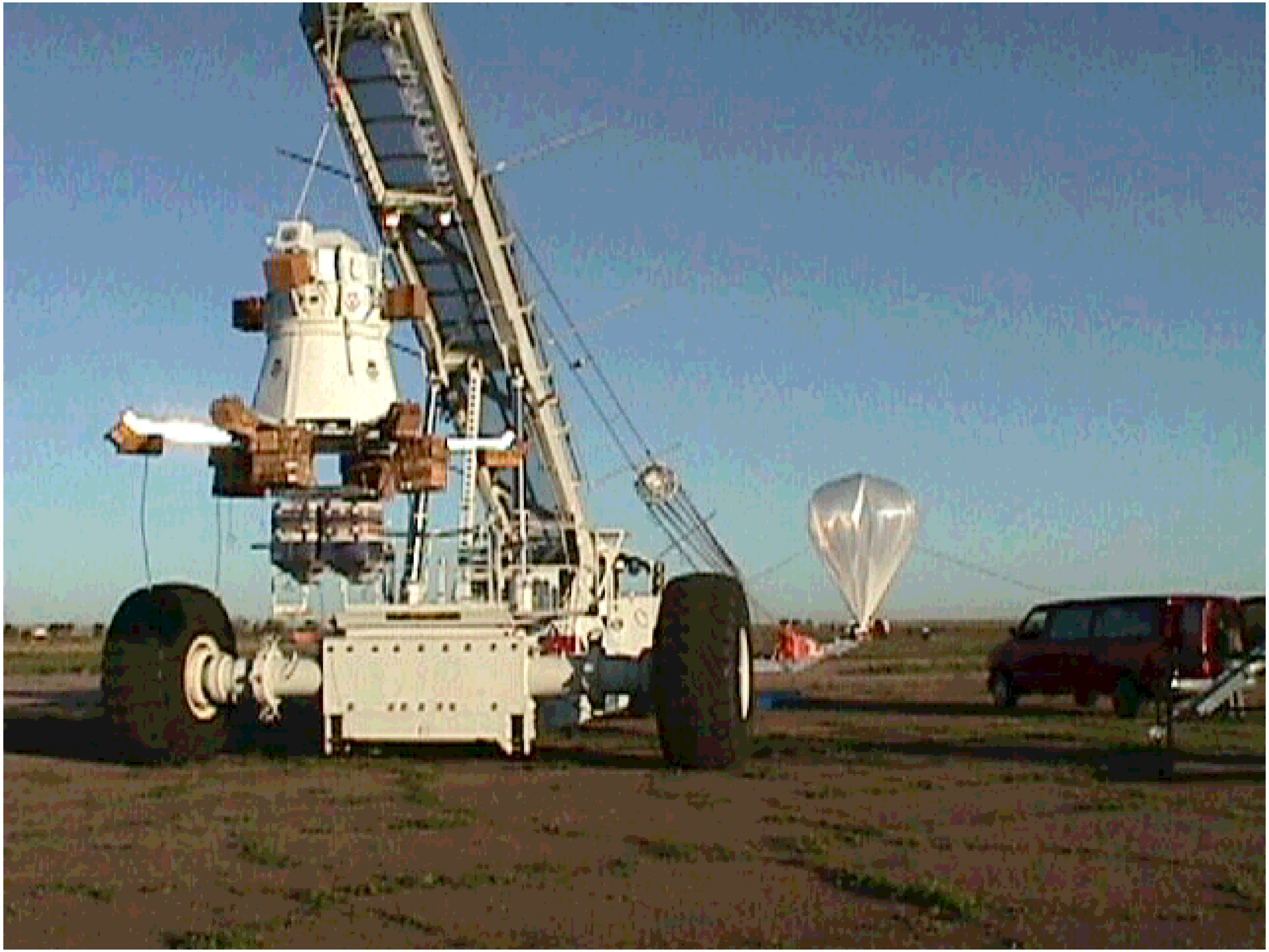
Figure 2.3: Top view of the LXeTPC with the field-shaping rings. The ceramic HV feedthrough is visible in the lower part of the picture.



Shielding Grid
X−Wire
Y−Wire
Anode
Light
UV PMT
Q
0
a b c d
t







LXe TPC PET ; 1 phase

2005

Subatech, Ecole des Mines de Nantes, IN2P3- CNRS and Université de Nantes, France 1 Service de médecine nucléaire, Hôpital de Nantes, France

$1 \times 1 \times 9$ cm^3 cell ; a module of $24 \times 60 \times 9$cm^3 9cm drift
24×60cm^3 anode place segmented by 0.5×0.5mm^2 pads

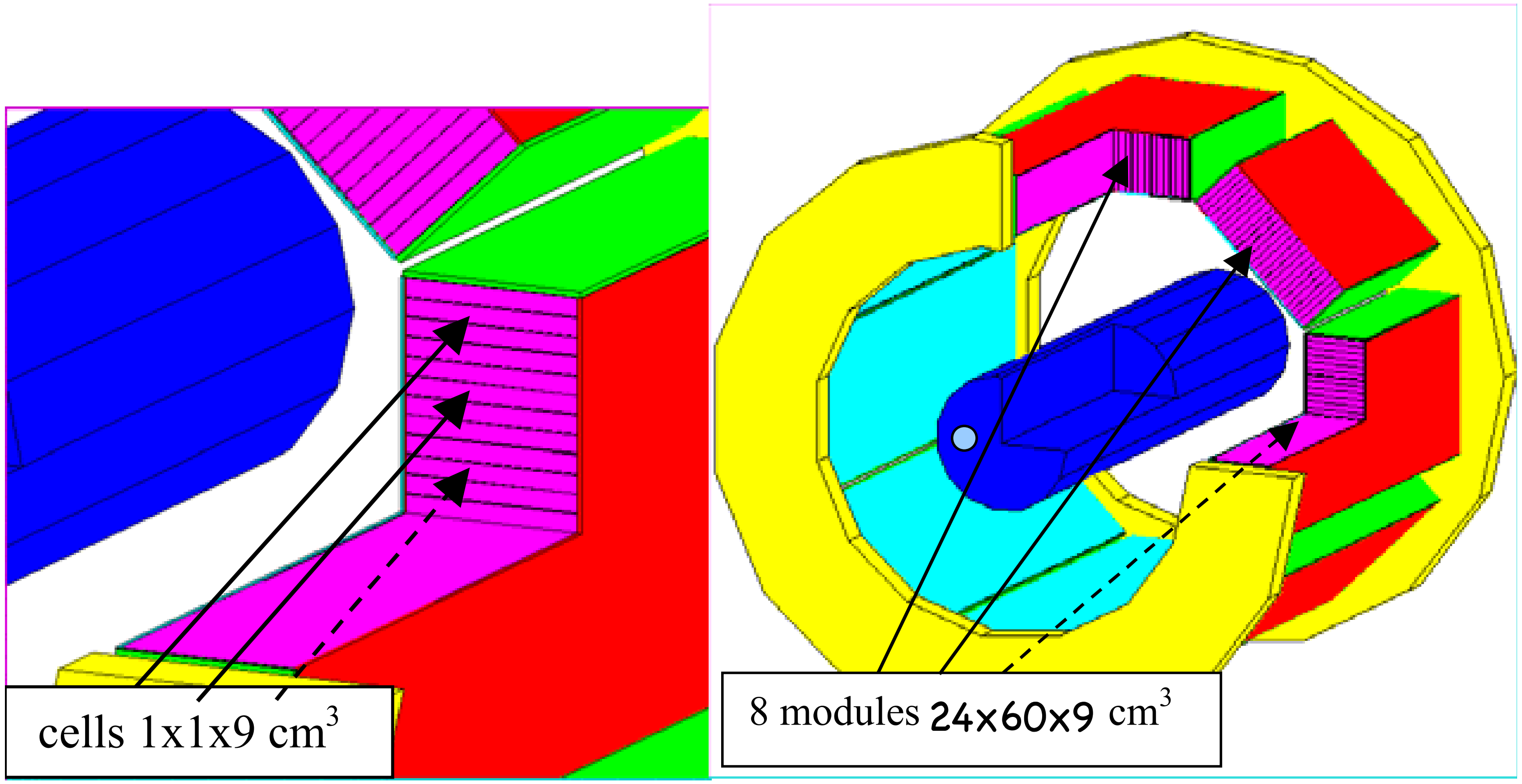


Fig. 1. GEANT3 simulation of a LXe PET camera with a NEMA NU 2-2001 phantom (right) and zoom on individual cells (left). The ^{18}F source is homogeneously distributed in a 3 mm diameter and 70 cm length cylinder positioned at (x=4.5 cm, y=0 cm) in the transverse field of view.

250, 250 and 140 µm (FWHM) for x, y and z coordinates for γ-conversion point

PET camera	Activity (kBq/ml)	Sensitivity – Net Trues (cps/Bq/ml)	Spatial cut (spatial resolution FWHM) (mm)	Energy resolution (FWHM)
BGO	3	30	10 (~7)	26.7
LXe	0.4	190	3 (~1.7)	13.8

Table 1: Performances of the proposed LXe-TPC PET compared to a standard BGO PET camera.

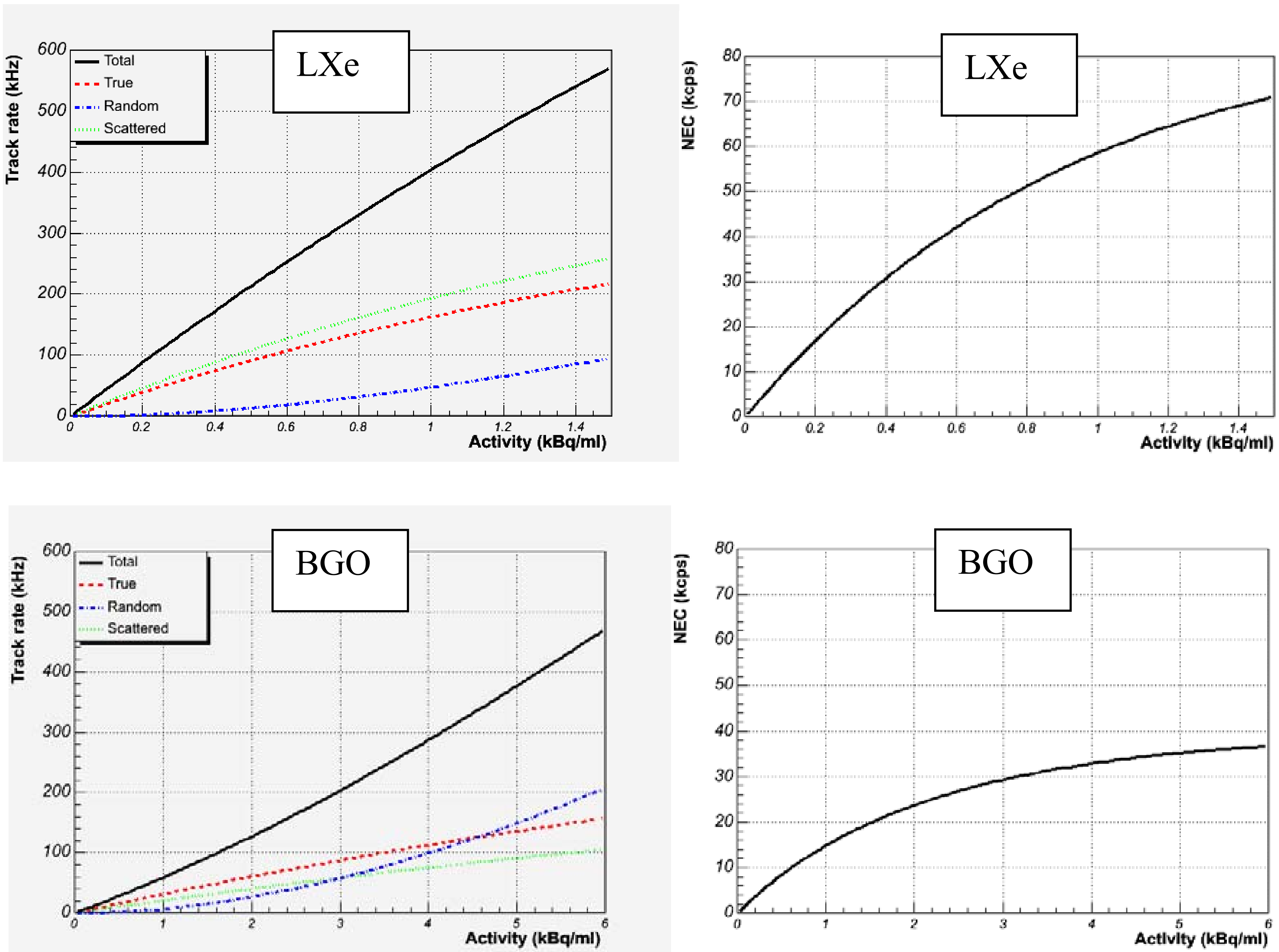


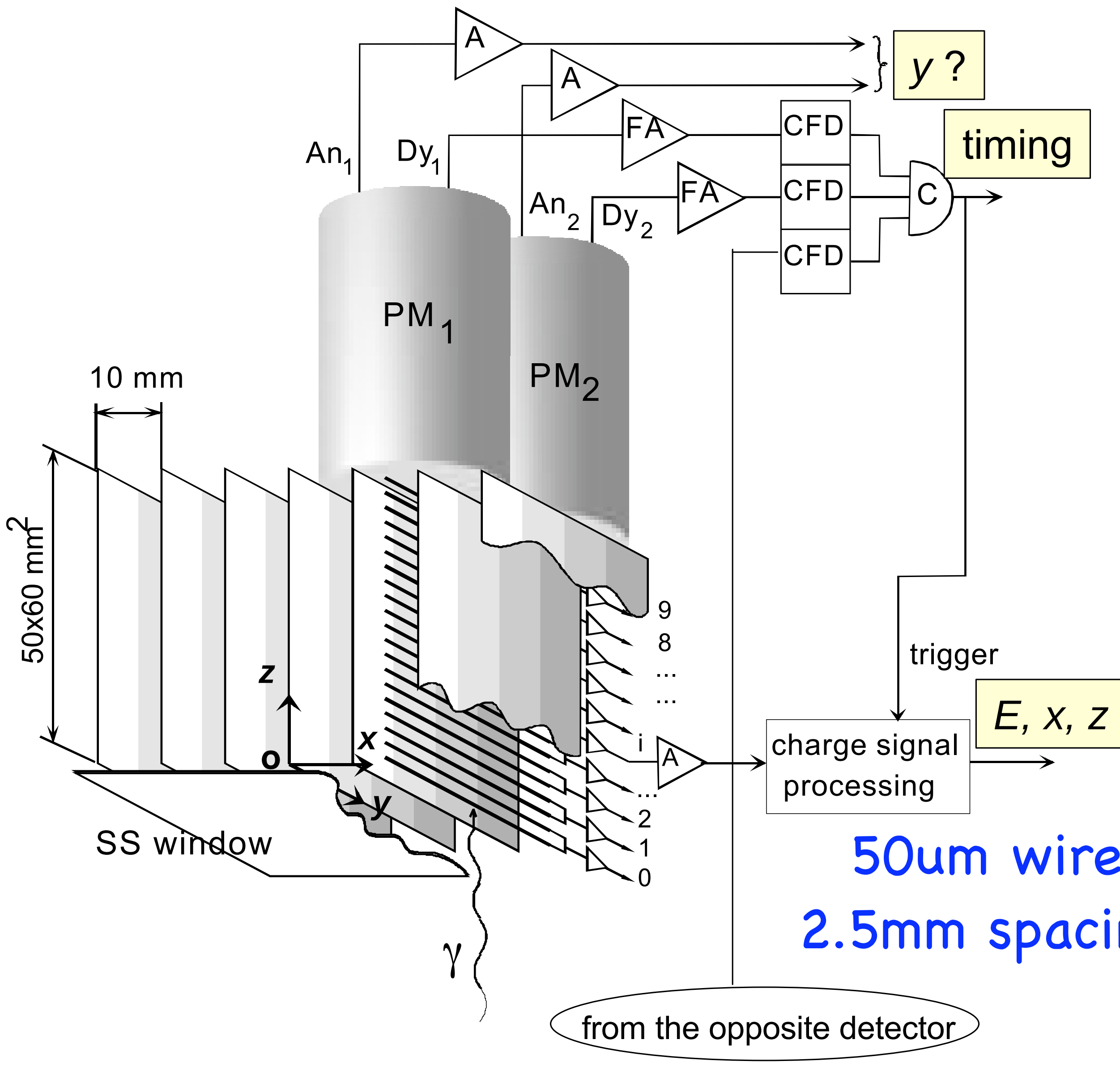
Fig. 5. Track rate for true, scattered and random events (left) and NEC (right) as a function of the activity concentration for the proposed LXe-TPC PET (top) and the standard BGO camera (bottom).

PETYA ; 1 phase

2002

LIP-Coimbra and Department of Physics of the University of Coimbra, 3004-516 Coimbra,Portugal

segmented drift chamber with PMT 1x5x6cm^3 cell (LXe 6cm long)



2.2μs max. collection time
5mm drift

50um wire
2.5mm spacing

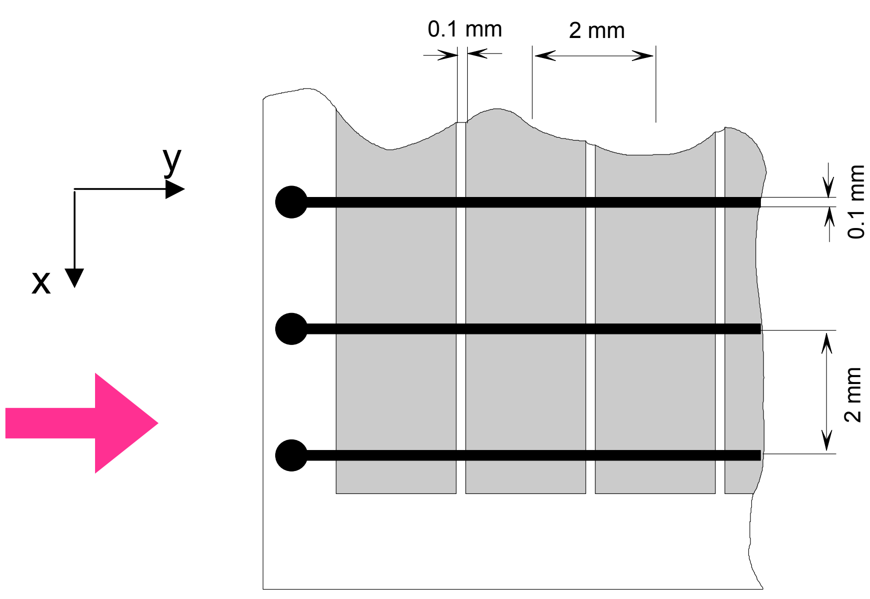


Figure 4. The mini-strip plate.

Figure 2. A schematic of the liquid xenon module for PET and its readout system.

800μm, 800μm, 2mm (FWHM) for x, y, z coordinates

Compare to the crystal, the reconstruction of the event topology is possible so that the first interaction in the detector can be found and its position used in the image reconstruction.

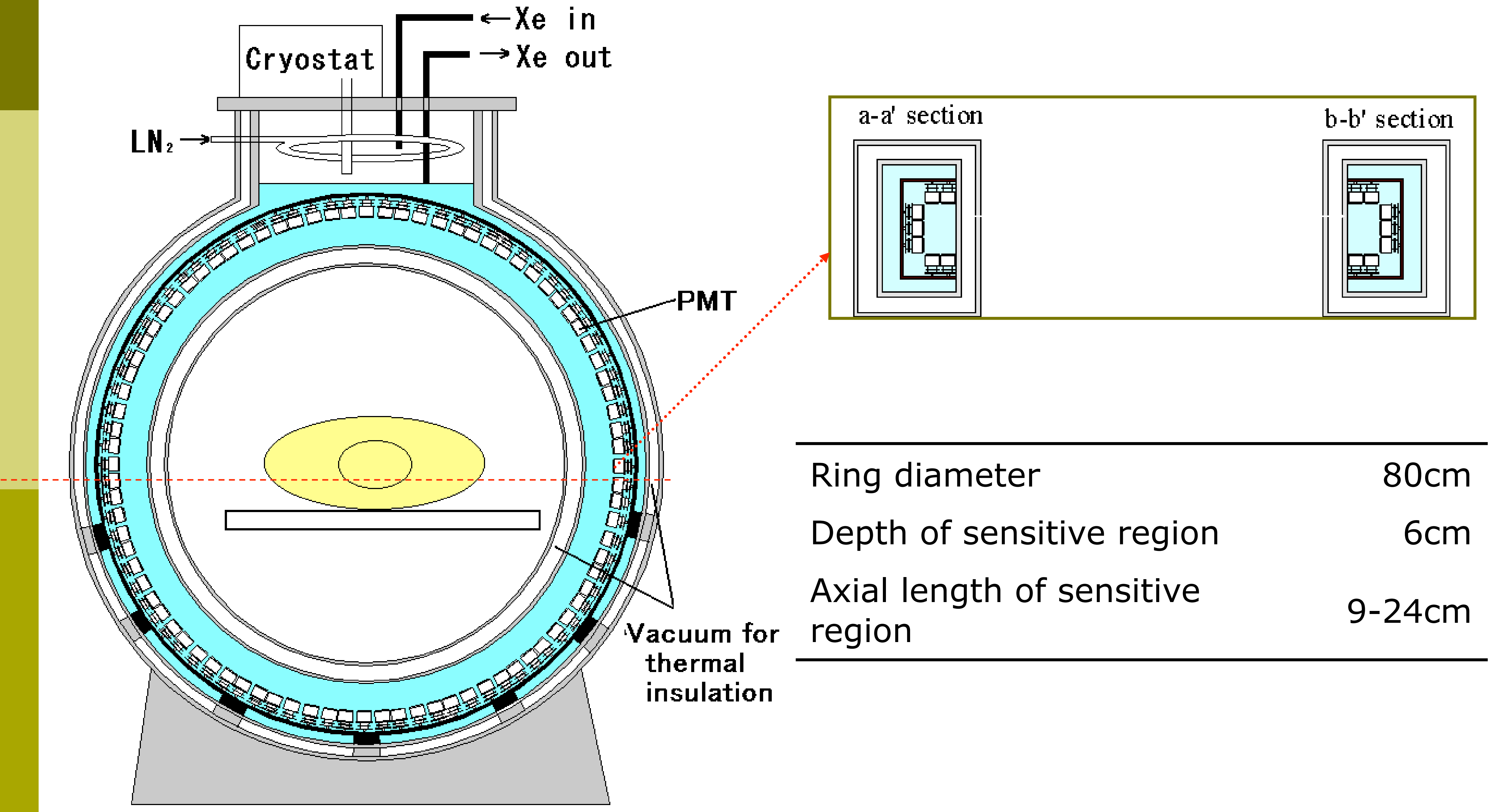
Table 1. Comparison of the liquid xenon detector with scintillation crystal systems

	PETYA	BGO block detector [20]	LSO block detector (CTI) [21]
Time resolution	1.3 ns	2 ns	1.5 ns
Position resolution	$0.8\times0.8\ mm^2$(*)	$5\times5\ mm^2$	$2\times2\ mm^2$
Interaction depth resolution	2 to 5 mm	None	7.5 mm
Energy resolution	15% to 17%	20%	14% to 20% (**)
Efficiency	60%	80%	not quoted
Dead time	$50\ \mu s\cdot cm^2$	$25\ \mu s\cdot cm^2$	not quoted

* $\Delta x\times\Delta y$; Δx - from the drift time measurement; Δy – obtained with the center of gravity method with the mini-strip plate (extrapolated from the measurements with α-source and convoluted with the photoelectron range)
** for a single crystal

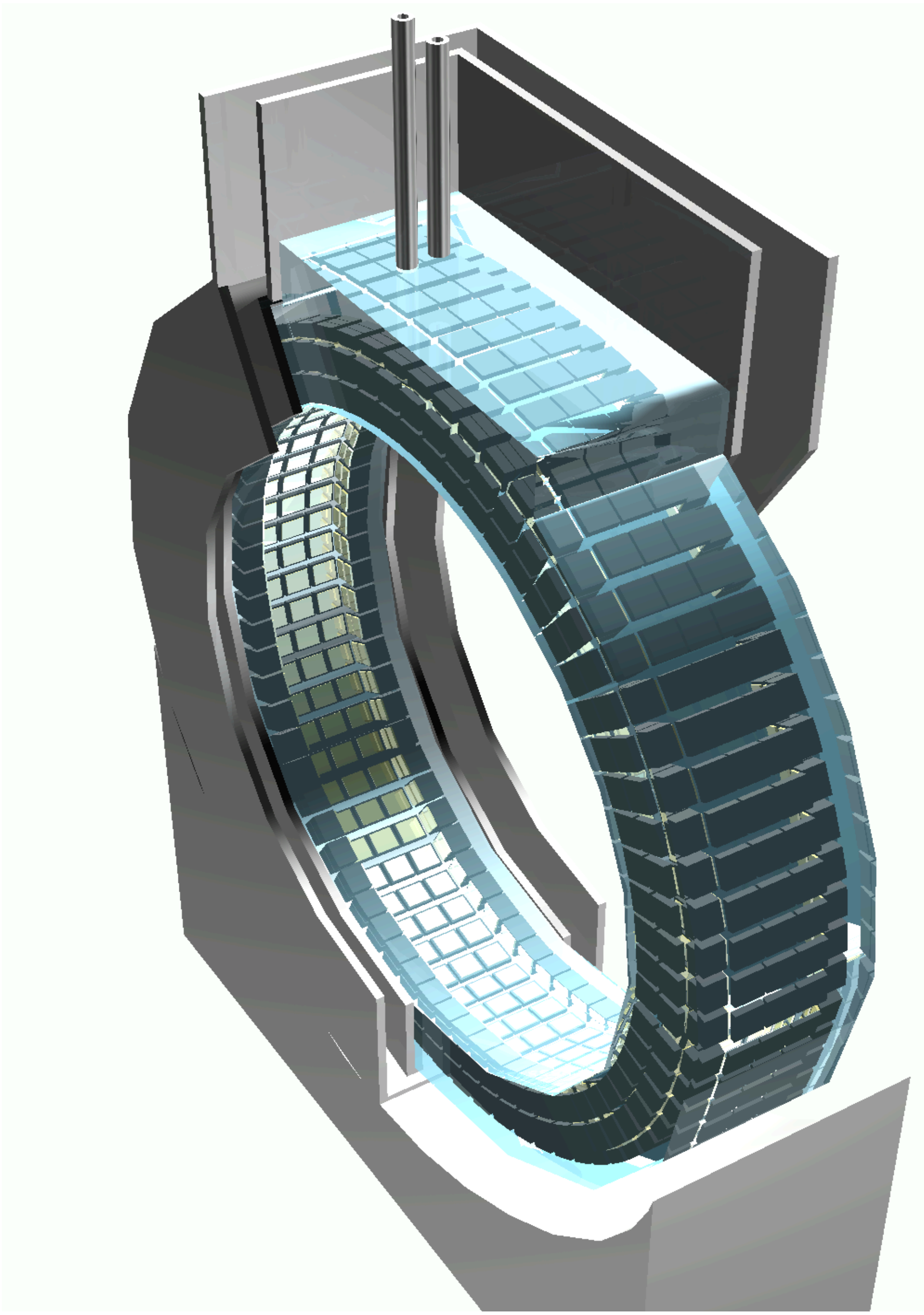
放射線医学総合研究所, 分子イメージングセンター, 先端生体計測グループ,
錦戸文彦 2006

液体キセノンTOF-PET装置



Ring diameter	80cm
Depth of sensitive region	6cm
Axial length of sensitive region	9-24cm

再構成画像による評価

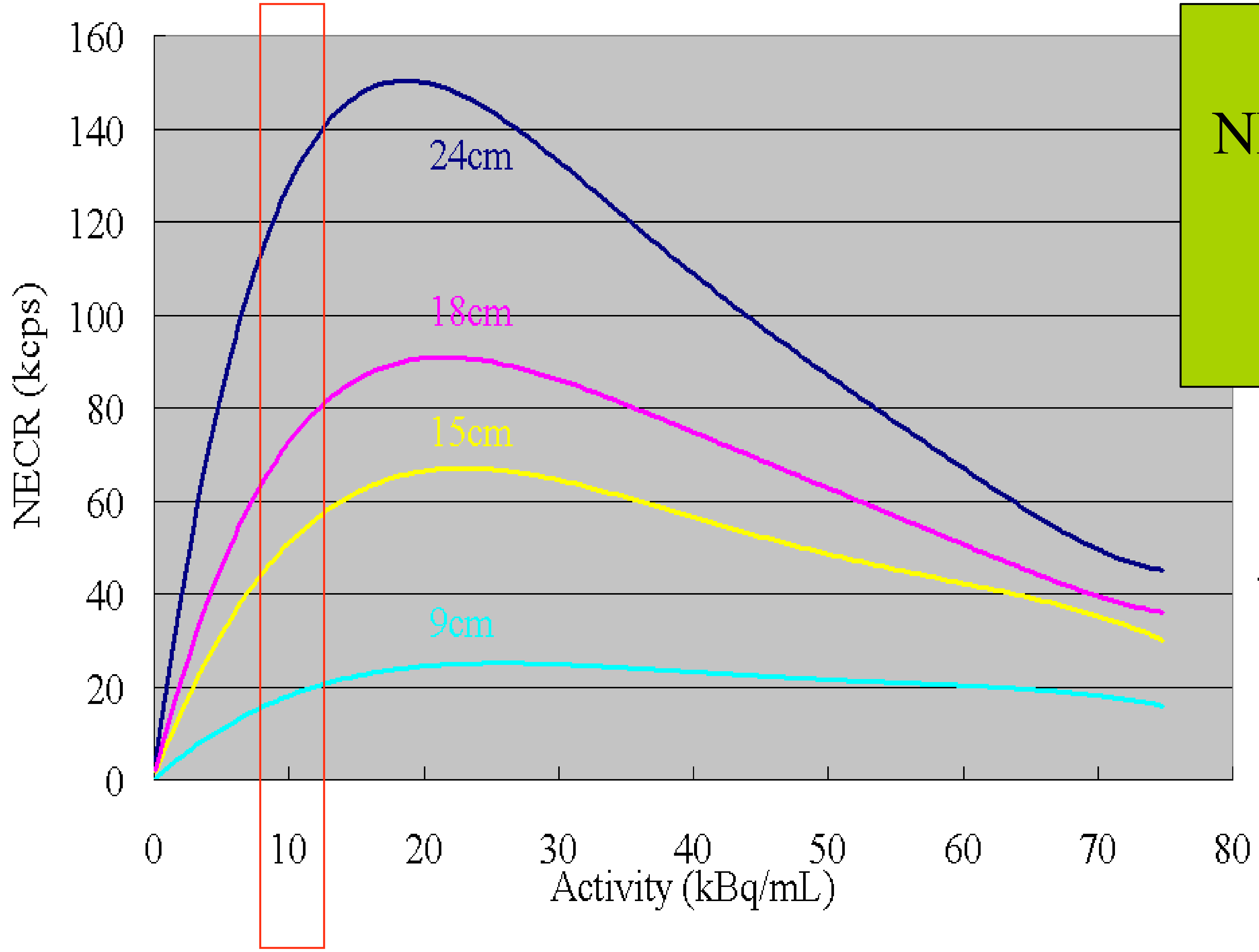


実機を想定したリング型の検出器を仮定してシミュレーションを行い、現段階のプロトタイプ実験で得られている基本特性で、画像を再構成した場合に液体**XePET**がどの程度の性能を発揮するのかを評価する。

- ポイントソースを使った分解能評価。
- **TOF**を使った再構成画像と通常の再構成を行った場合の比較評価。

全身用液体**XePET**イメージ図

NECR



$$\mathrm{NECR} = \frac{T^2}{T+S+R}$$

T：真の同時計数イベント
S：散乱同時計数イベント
R：偶発同時計数イベント

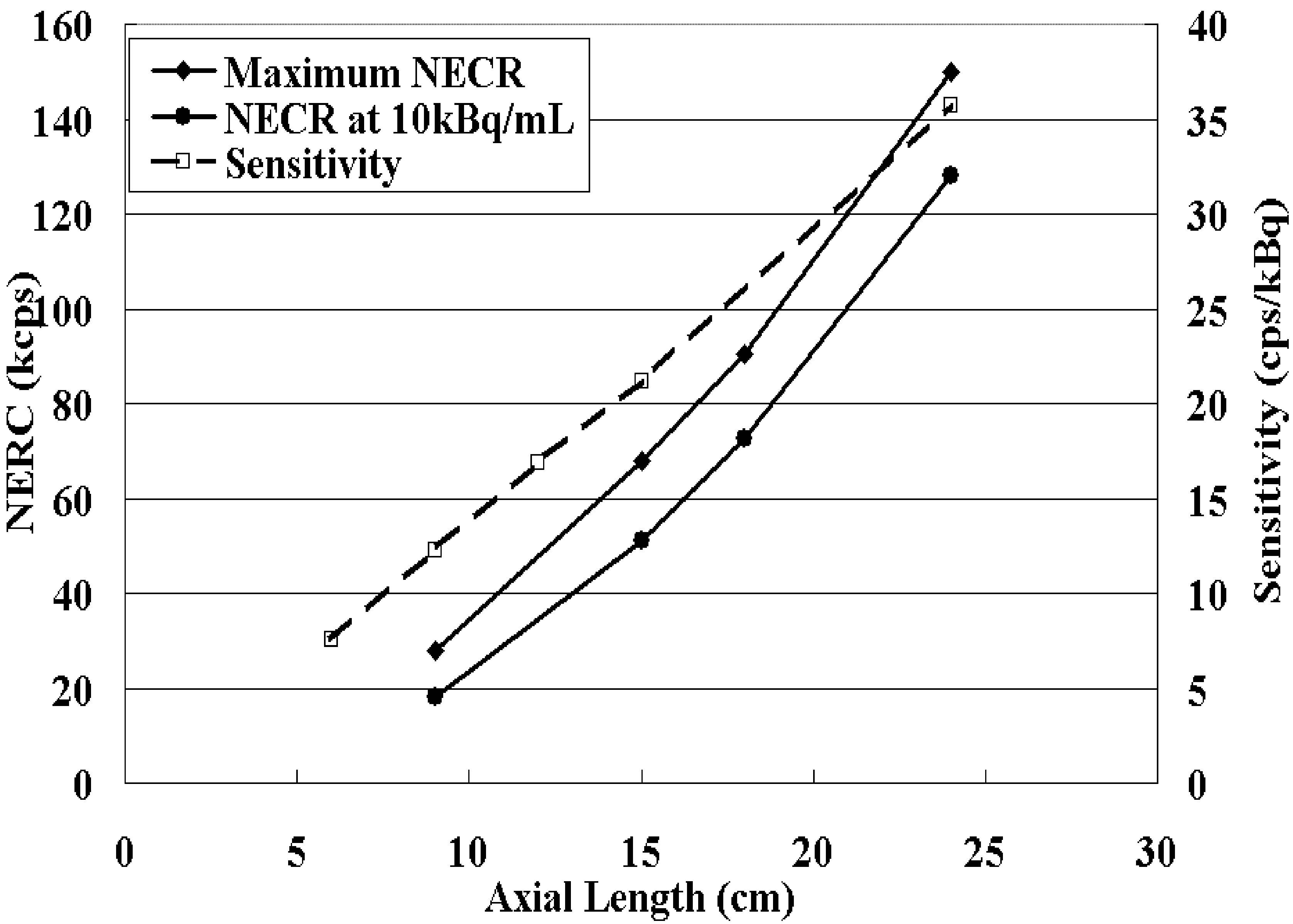
<u>NEC simulation</u>

System dead time:200ns

Coincidence window:4ns

Energy window:450-550keV

装置感度



Sensitivity simulation

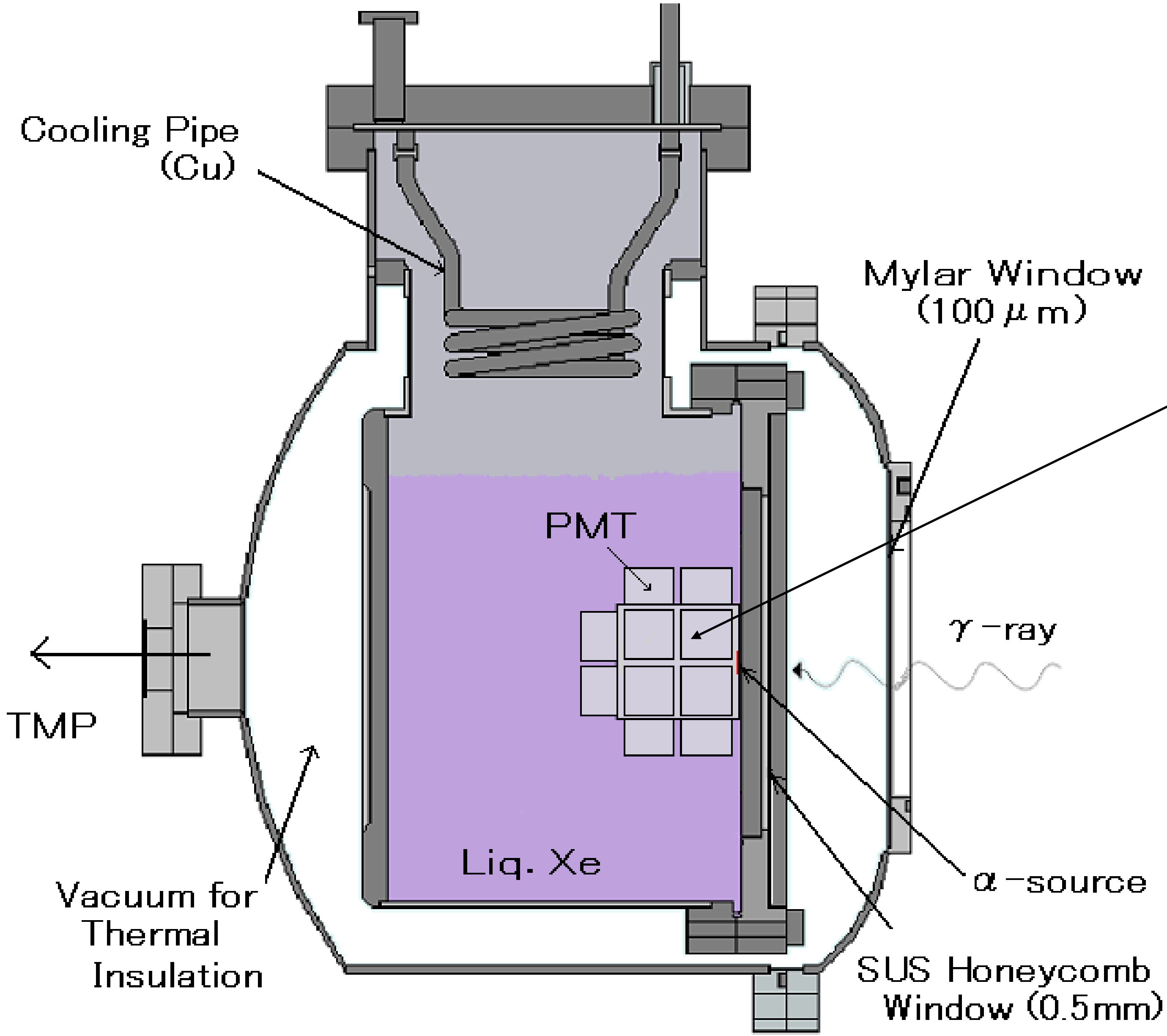
NEMA2001 rod phantom

System dead time:200ns

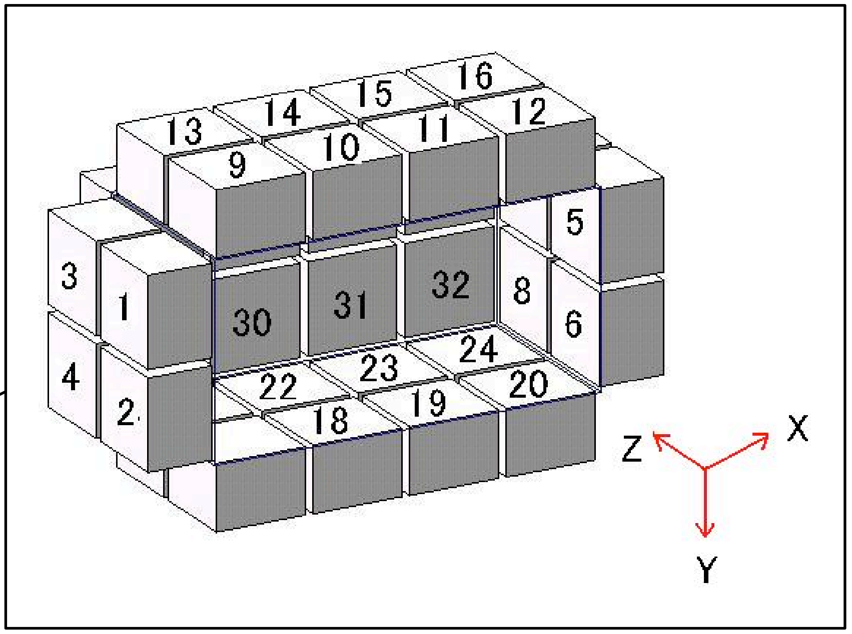
Coincidence window:4ns

Energy window:450-550keV

試作型液体キセノンPET検出器



試作型液体キセノンPET検出器



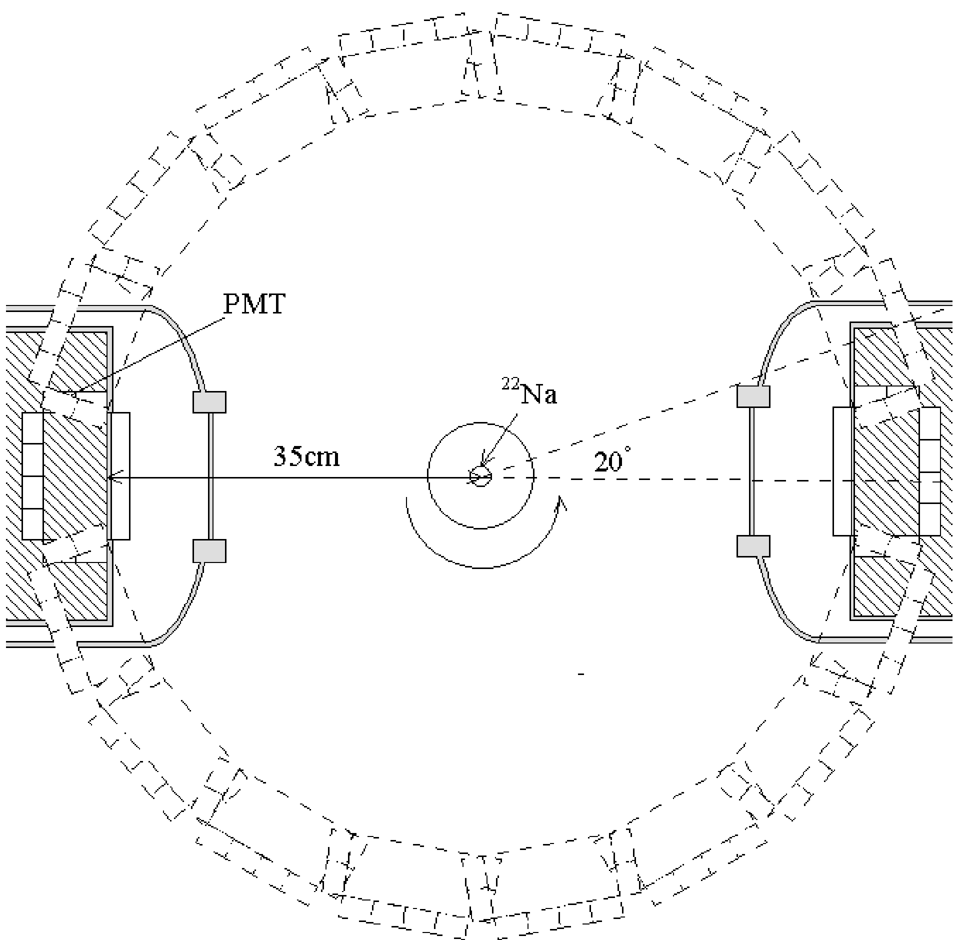
温度	**-110**℃
圧力	**1～2atm**
有感領域	**12×6×6cm³**
到達真空度	10**$^{-6}$Torr**

32PMT

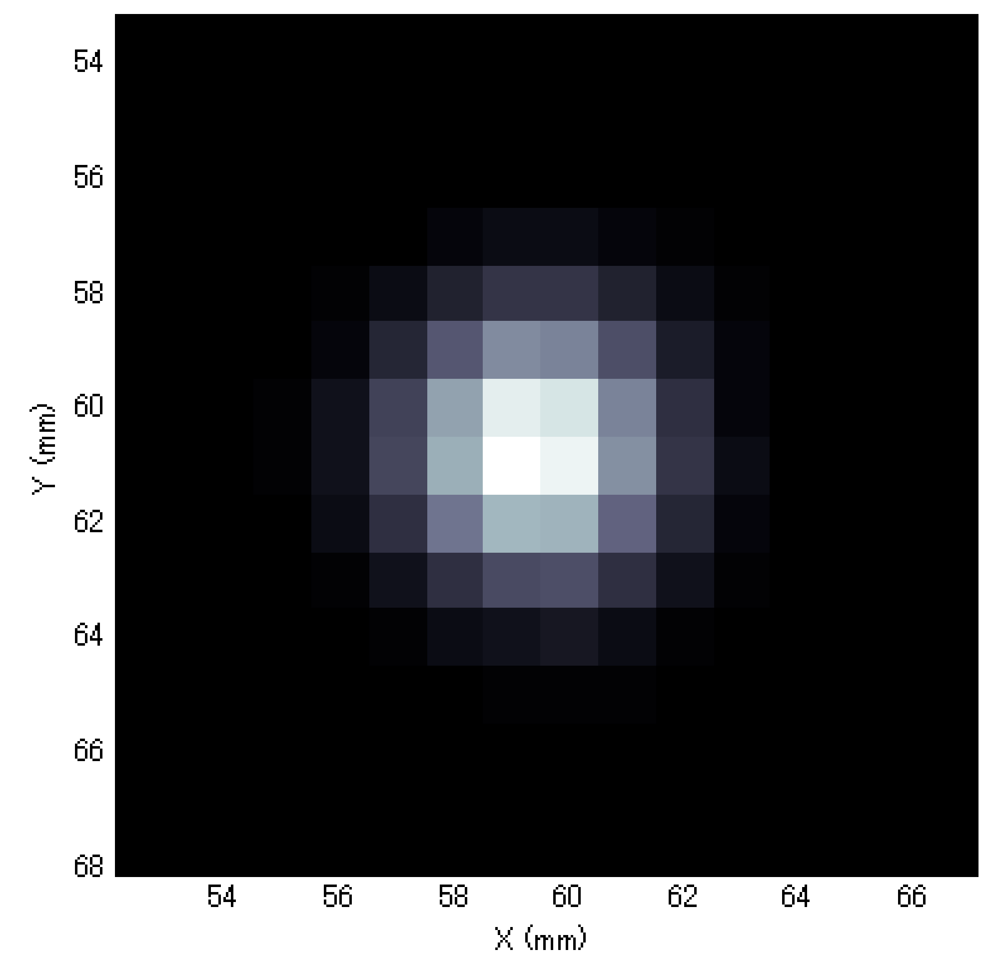
R5900-06MOD×32

liquid Xe 12L

画像再構成



^{22}Na点線源の再構成画像



空間分解能:3.3mm(FWHM)

再構成条件

ML-EM法

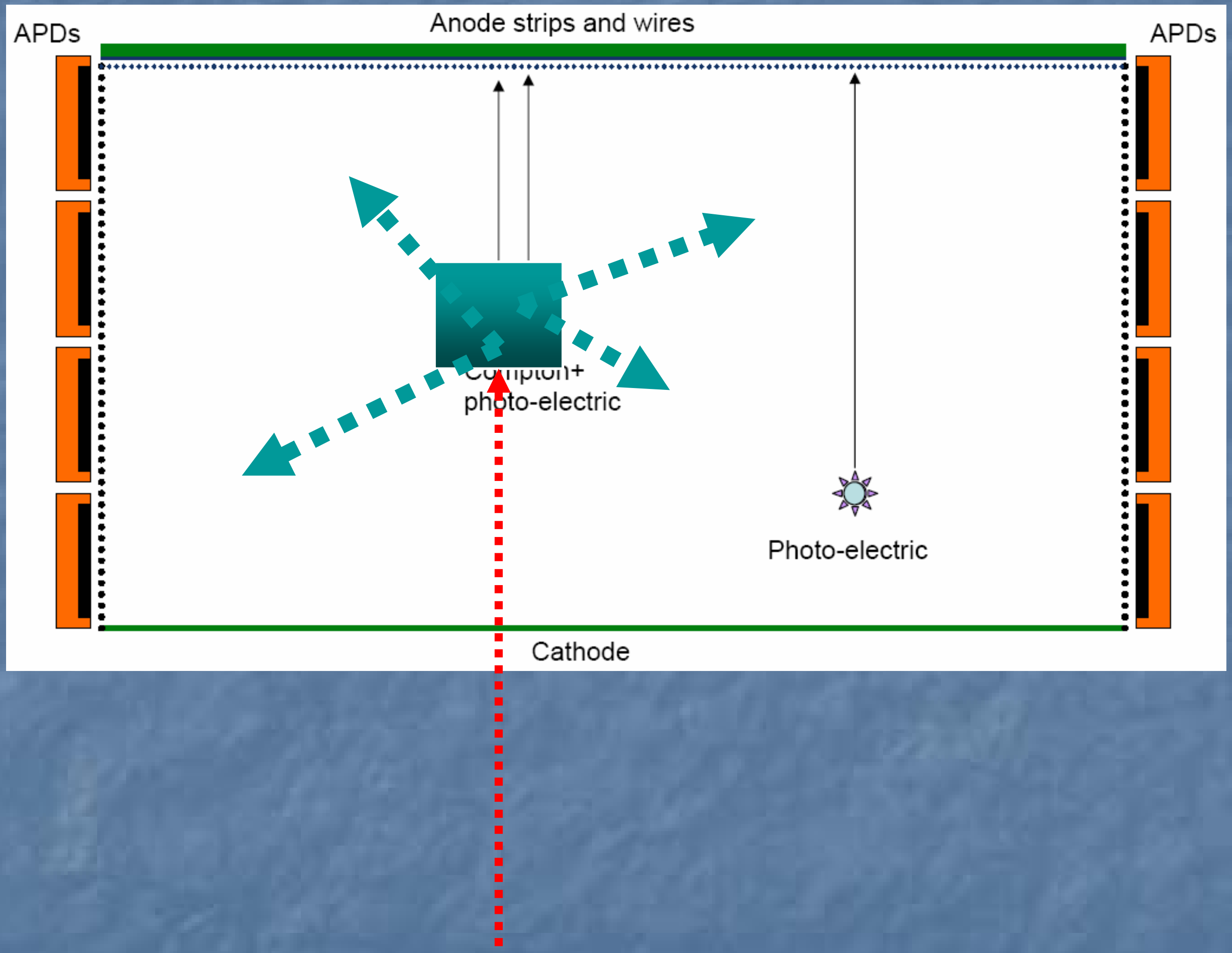
反復回数100回

-5<Y<5の範囲を用いる　→2Dモードを仮定

TRIUMF XEPET

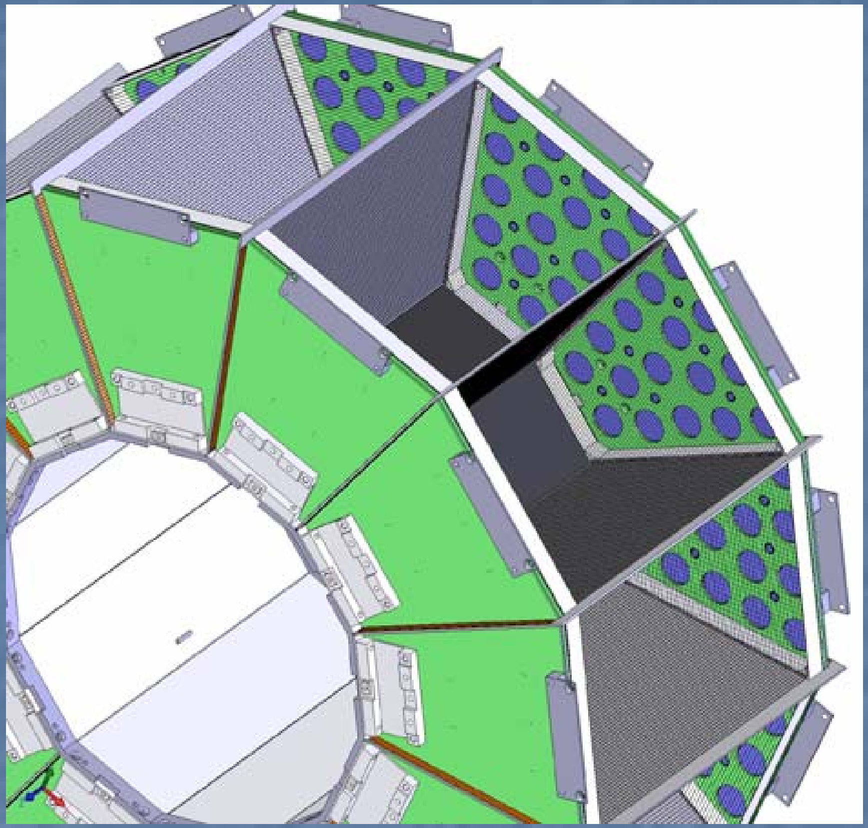
Liquid xenon TPC with distributed light collection.

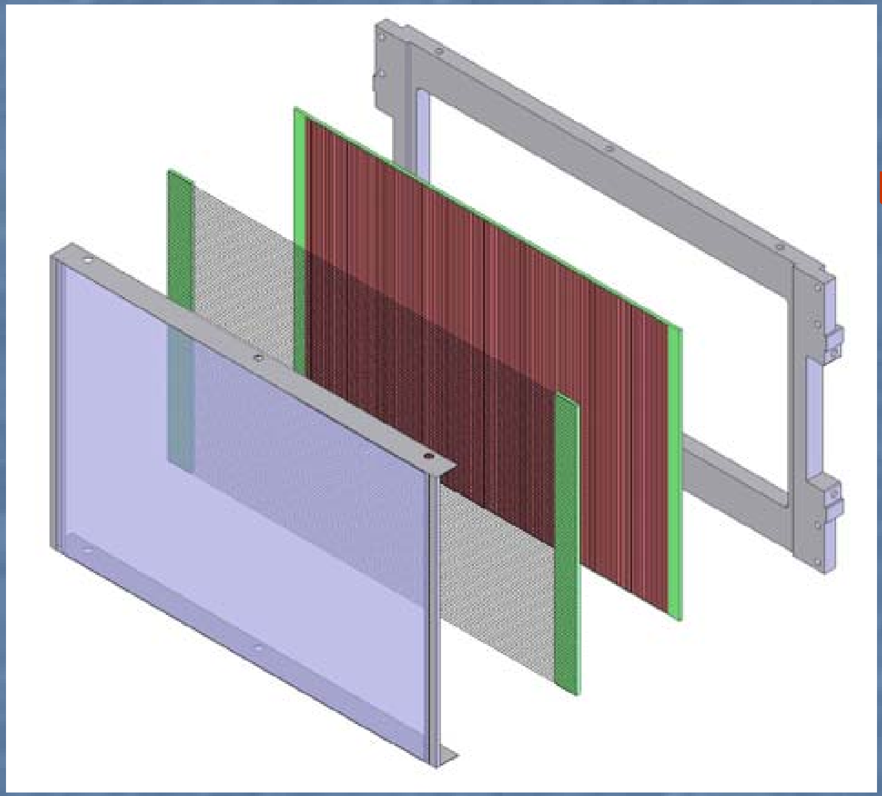
- Scintillation light and ionization signals both used for position and for energy reconstruction
- Find region of interaction from fast light distribution (minimize pileup)
- Reconstruct drift coordinate from drift time; get the other two coordinates with anode electrodes (induction wires perpendicular to anode strips)
- 3-D Position resolution: <1 mm (fwhm)
- Energy resolution: <9% (FWHM); suppresses scatter/random image noise
- Compton reconstruction further suppresses scatter and random backgrounds.



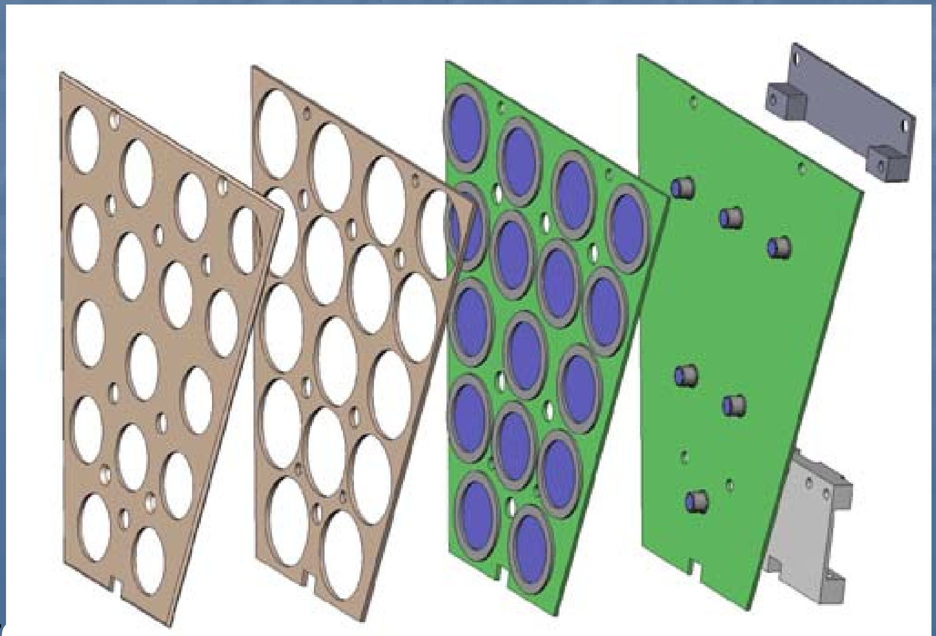
TRIUMF XEPET

- 12 sectors.
  - Field cage formed with strips (between sectors) and wires (ends)
  - Cathode: resistive kapton on ceramic plates





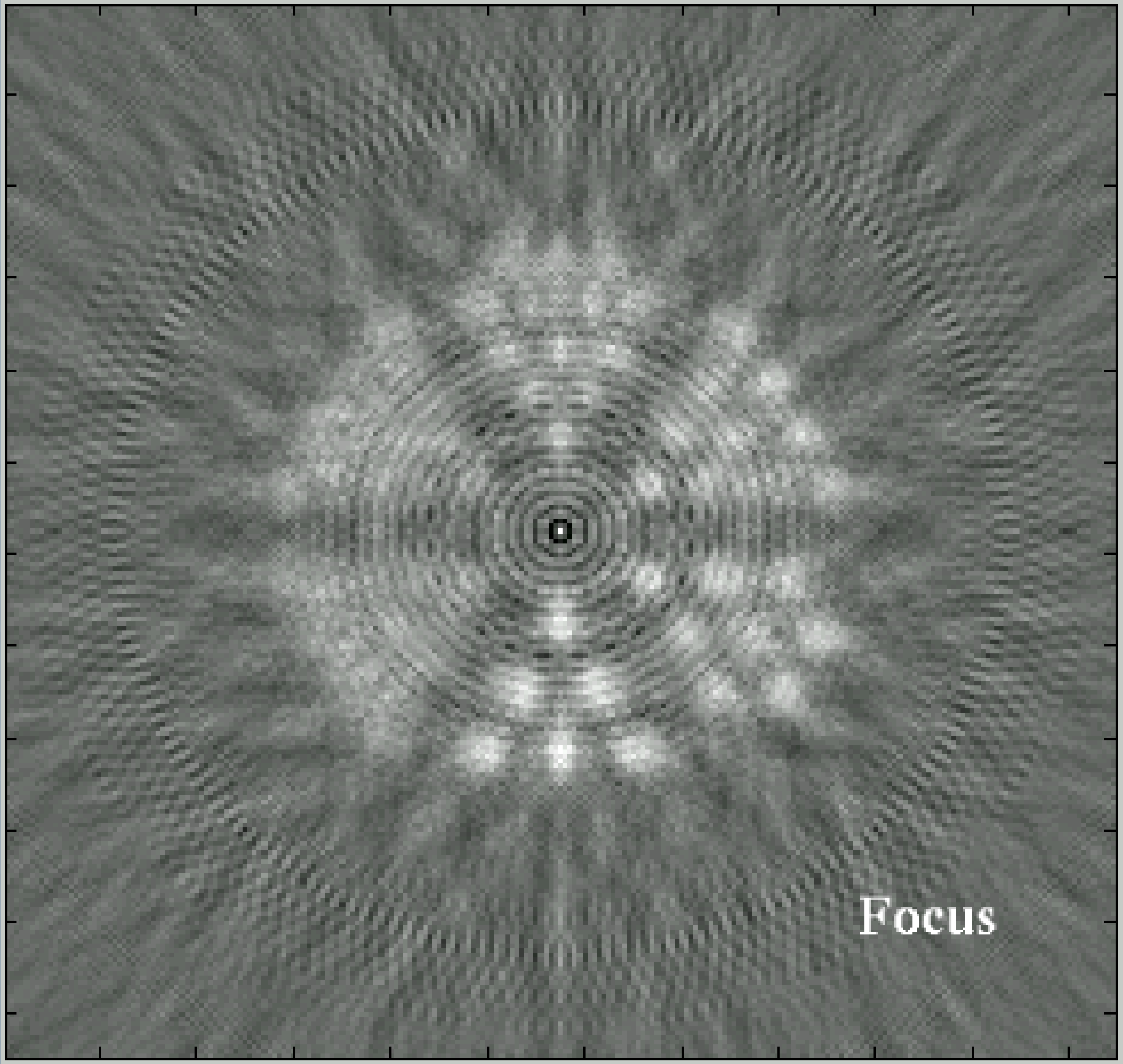
- Anode Charge module
  - 96 wires, 96 strips
  - SS and kapton PCBs
  - AC decoupling with kapton?



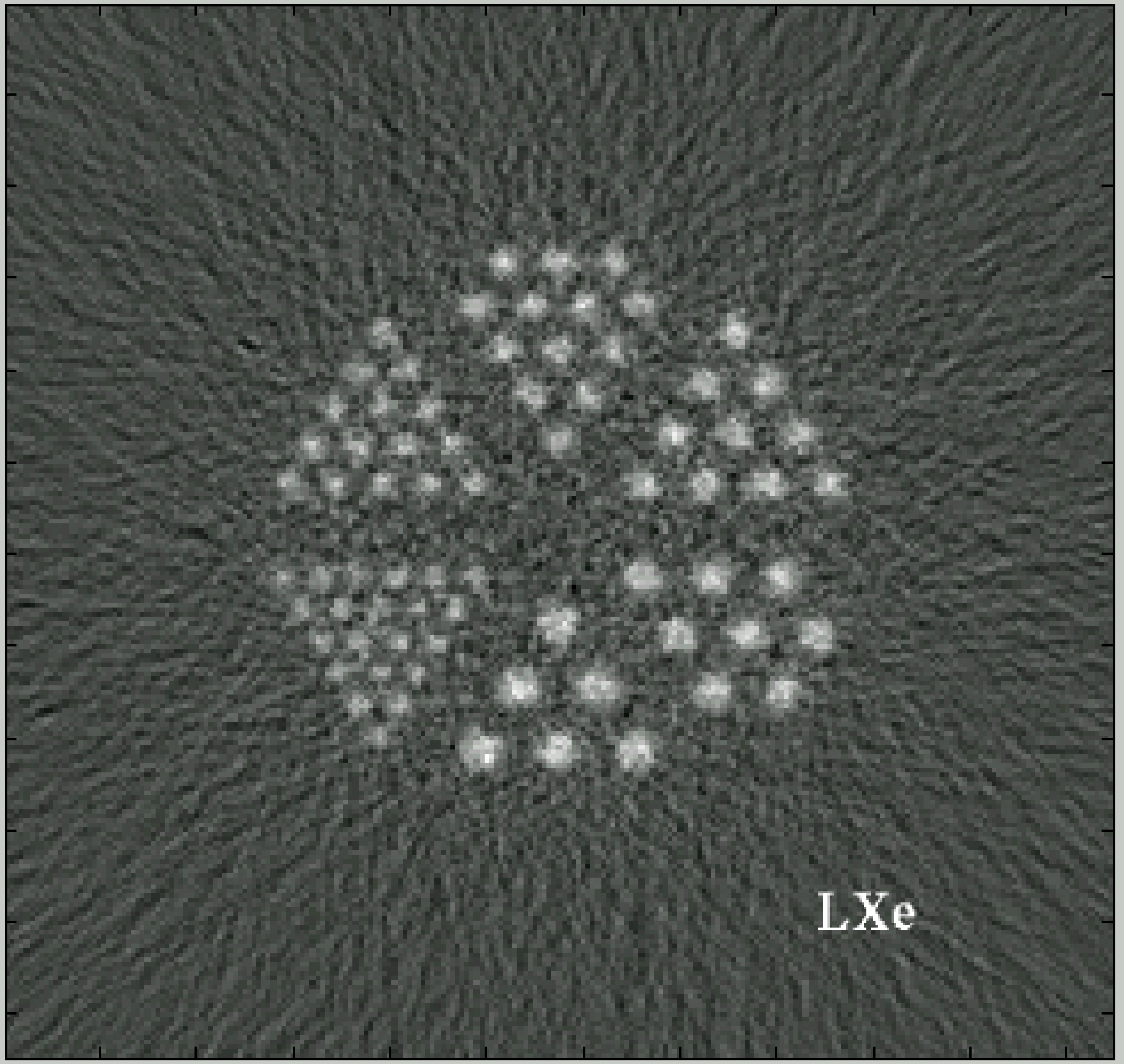
- APD module for light collection
  - 16 APDs and 6 LEDs for monitoring
  - 1 HV line and 16 LV lines (HV tuning)

Comparison of PET Image Simulations

Conventional PET "FOCUS"



TRIUMF XEPET



UBC student Philip Lu

Derenzo Phantom in water:
1mm dia. Minimum feature size.

2 Phase

LXeComp (TPC) β+γ ; 2 phase

2006

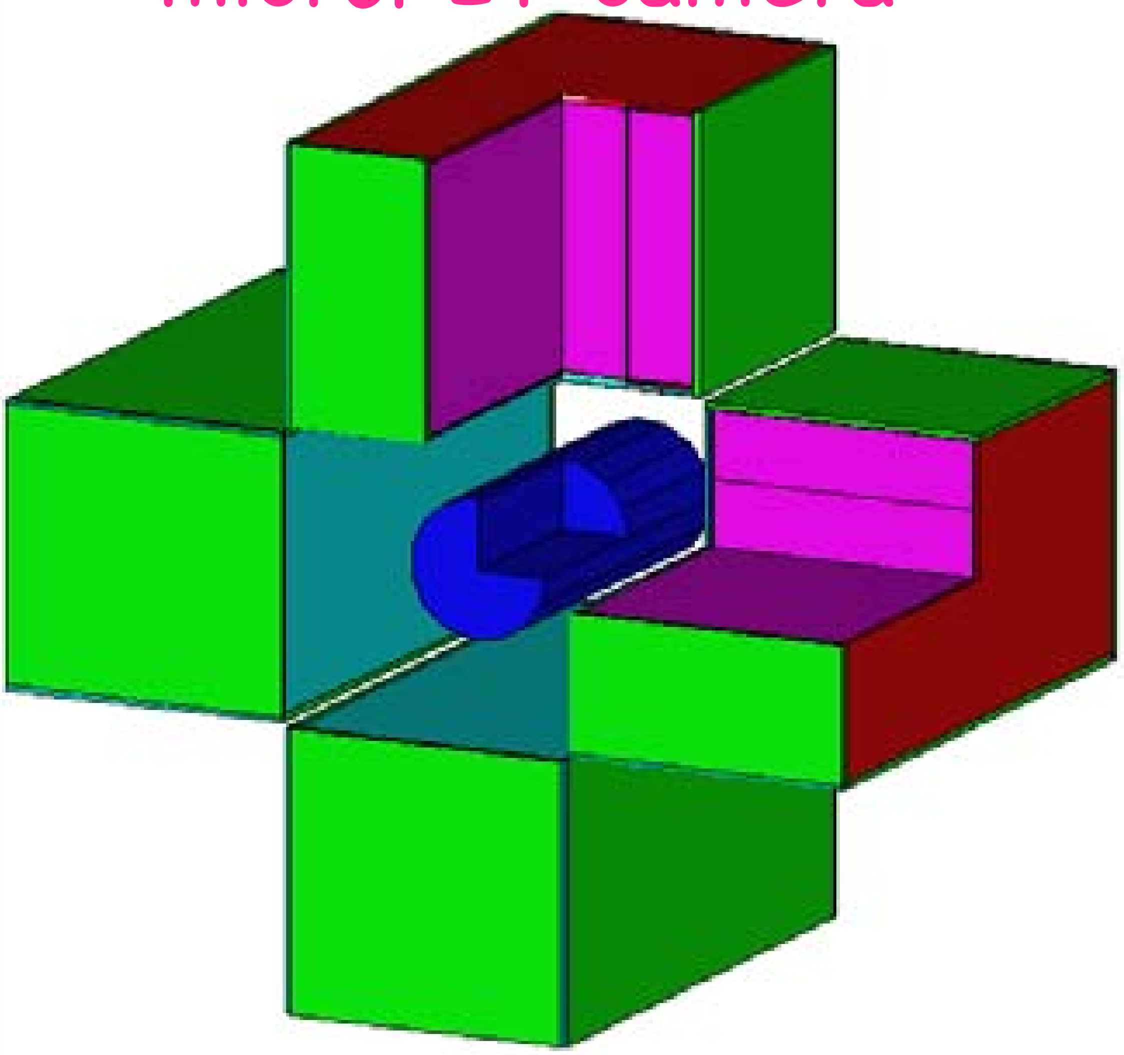
Subatech, Ecole des Mines de Nantes, IN2P3- CNRS and Université de Nantes,

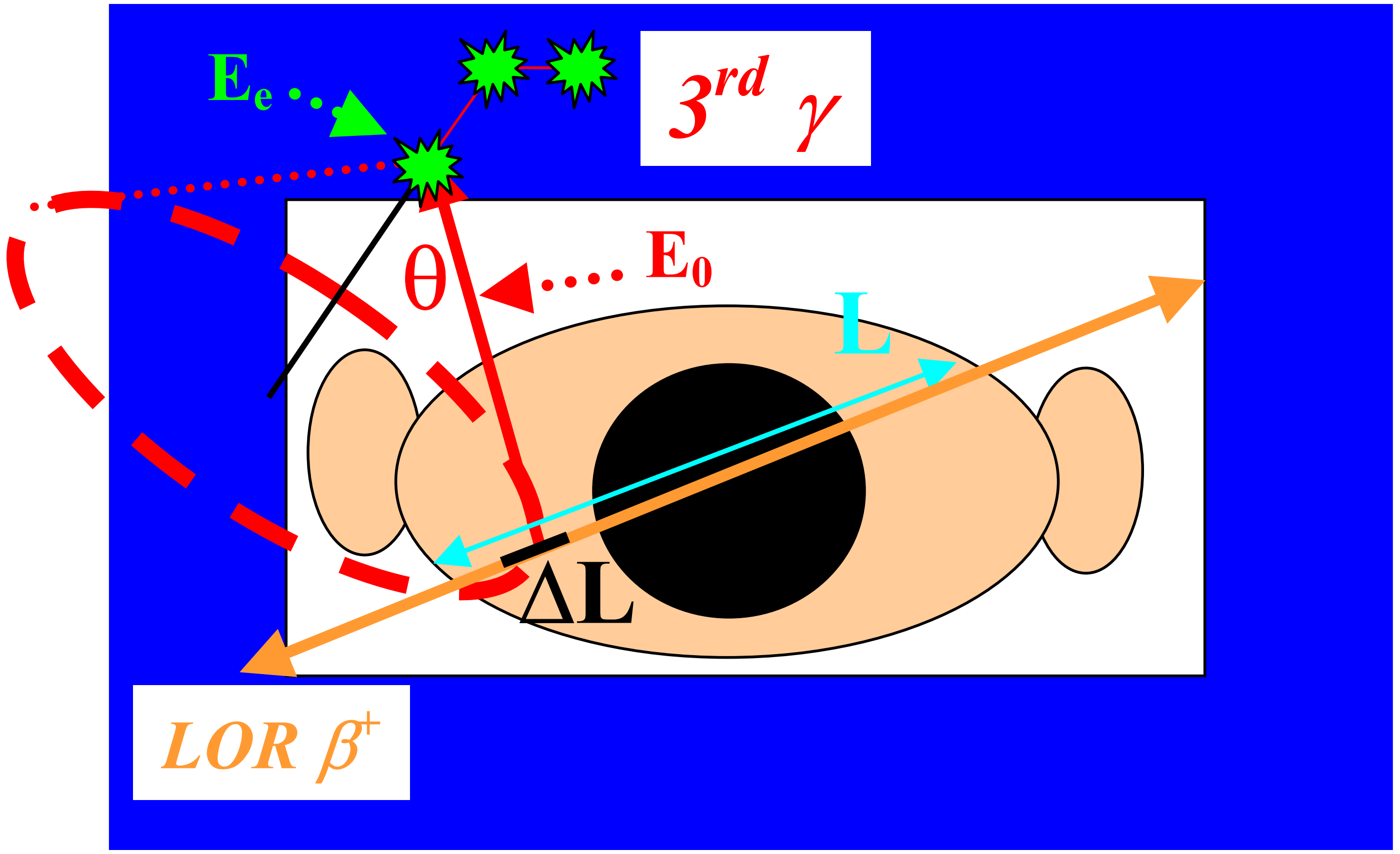
Liquid Xenon (LXe) based detector coupled to large-area fast gas-avalanche imaging photomultipliers (GPM), the UV photons resulting from Xe scintillation are detected in the GPM (Gas Photon Multiplication)

^{44}Sc : a good β+γ yield (94.3%) with only one γ-ray of 1.157 MeV

3x3x12cm^3 cell in 24x12x12cm^3 ; 12cm long liq.Xe for 1.156MeV gamma

microPET camera





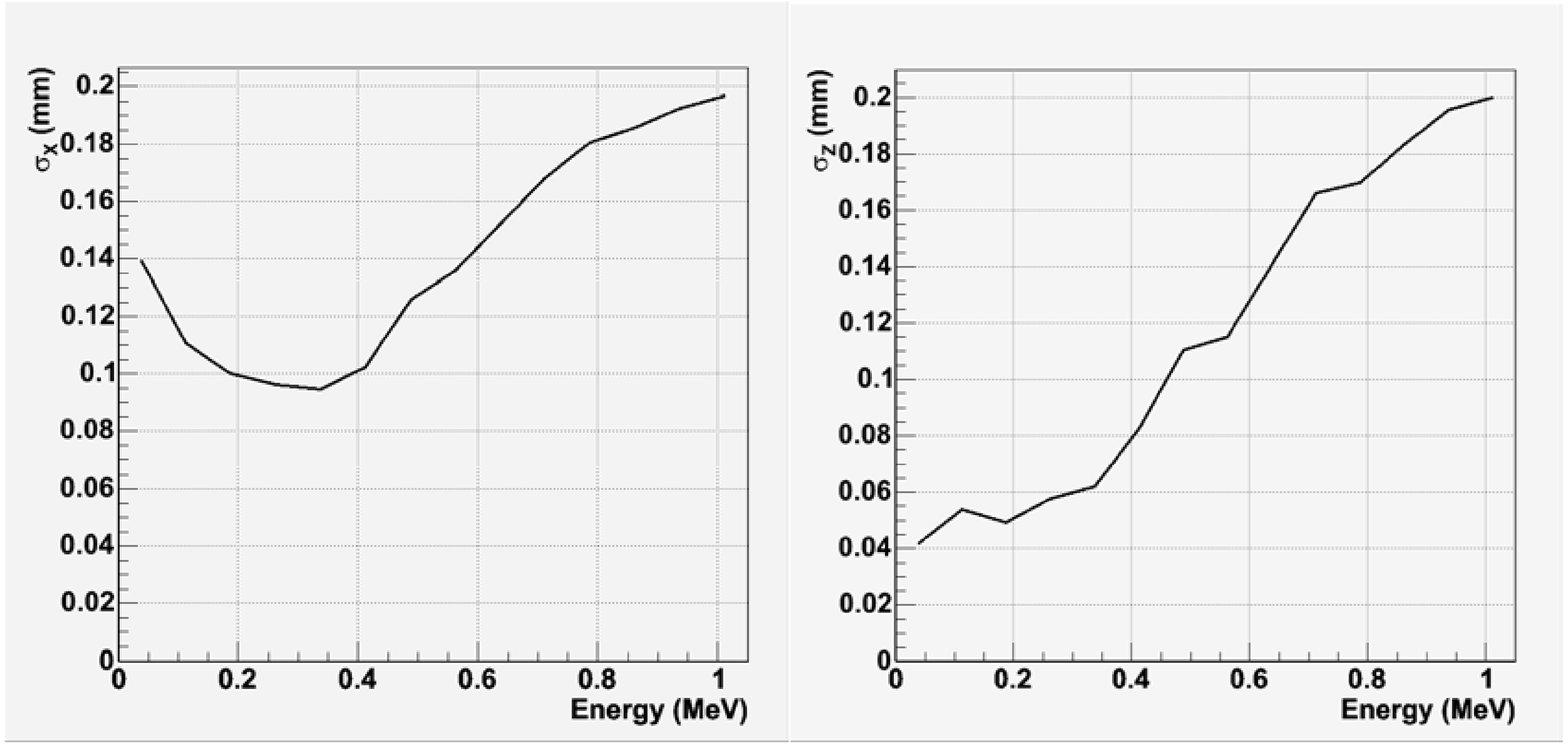


Figure 11: Spatial resolution as a function of the energy deposited by electrons in liquid xenon obtained from simulation, in the anode plane (left) and along the drift direction (right).

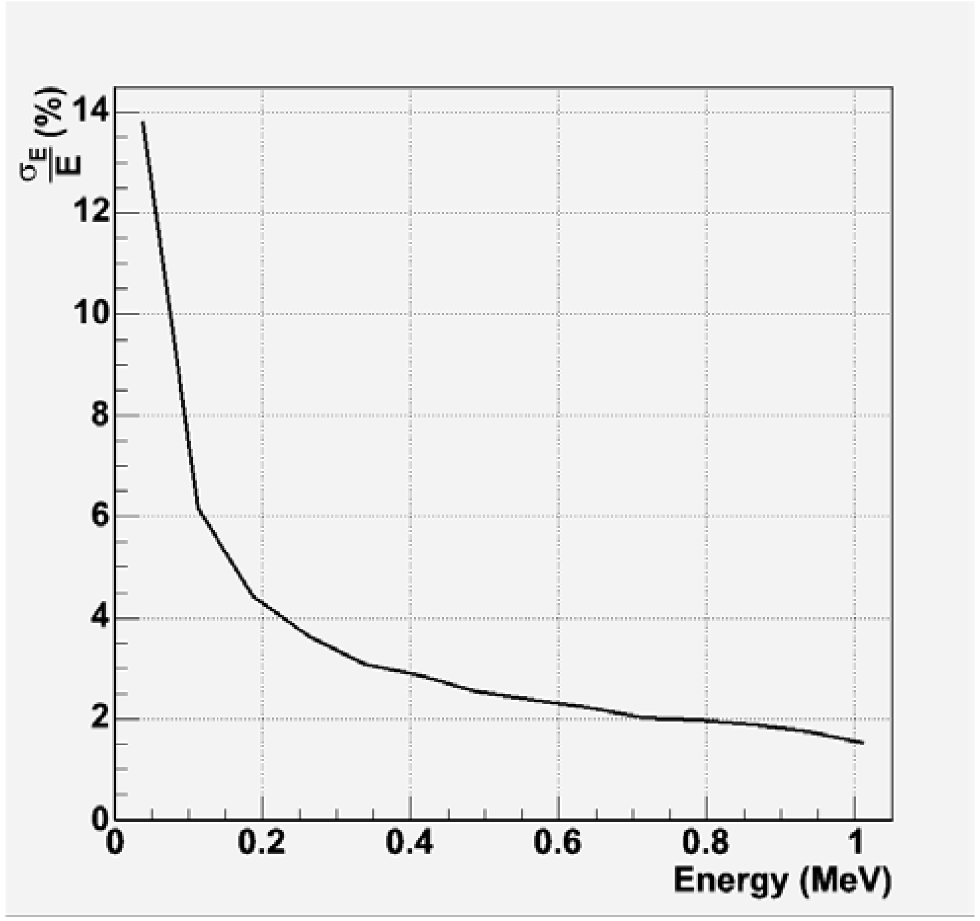


Figure 12: Energy resolution as a function of the energy deposited by electrons in liquid xenon obtained from simulation.

The position of each $\beta^+\gamma$ correlated events has been reconstructed according to the algorithm presented on paragraph 4.1. The obtained image is shown on figure 17. The spatial resolution deduced from the projection of the transverse image slice on a single coordinate is 2.3 mm.

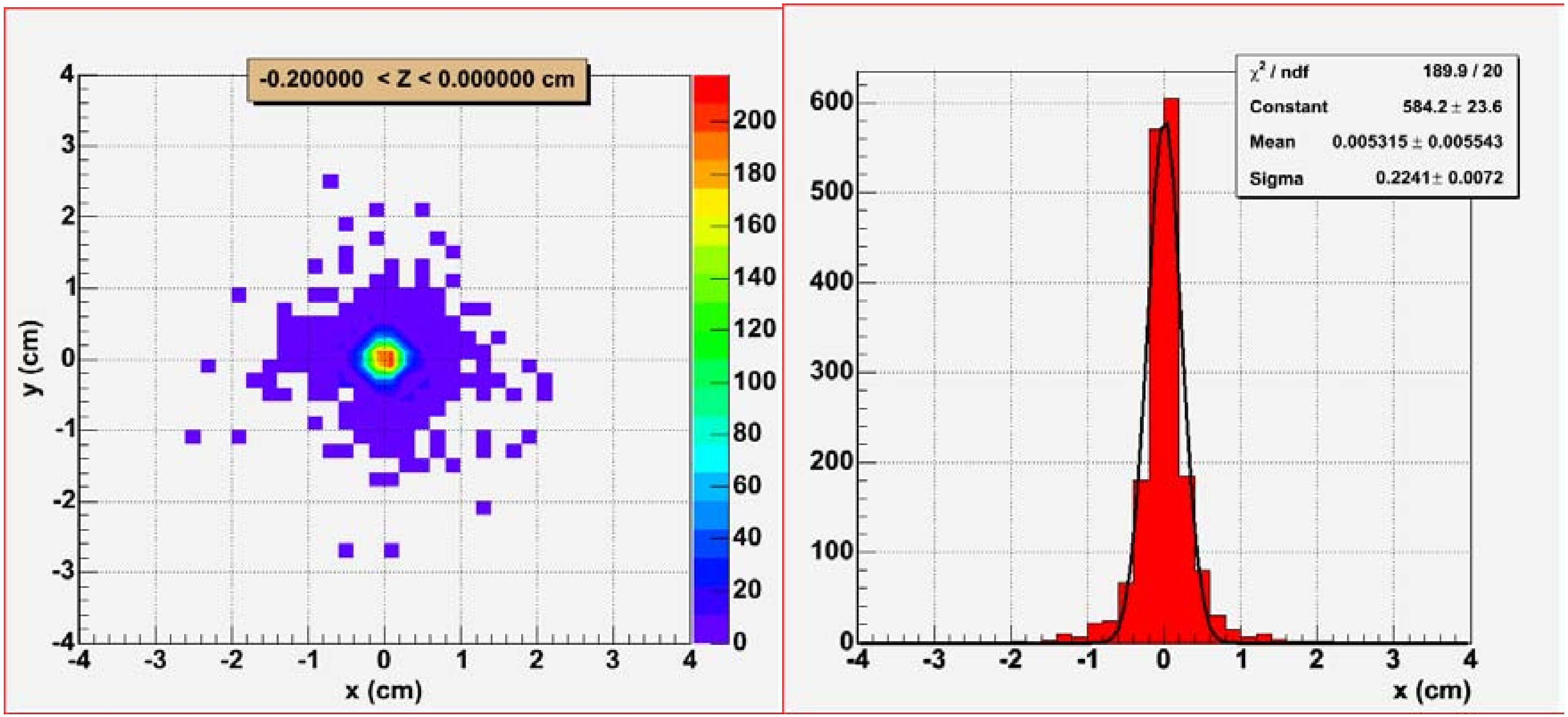


Figure 17: Transverse slice of the reconstructed image of a point source with a voxel size of 2x2x2 mm³ (left) and its projection on one x axis (right). Results have been obtained with 0.5 millions of generated ^{44}Sc decays.

The overall reconstruction efficiency for the events is 1.3%

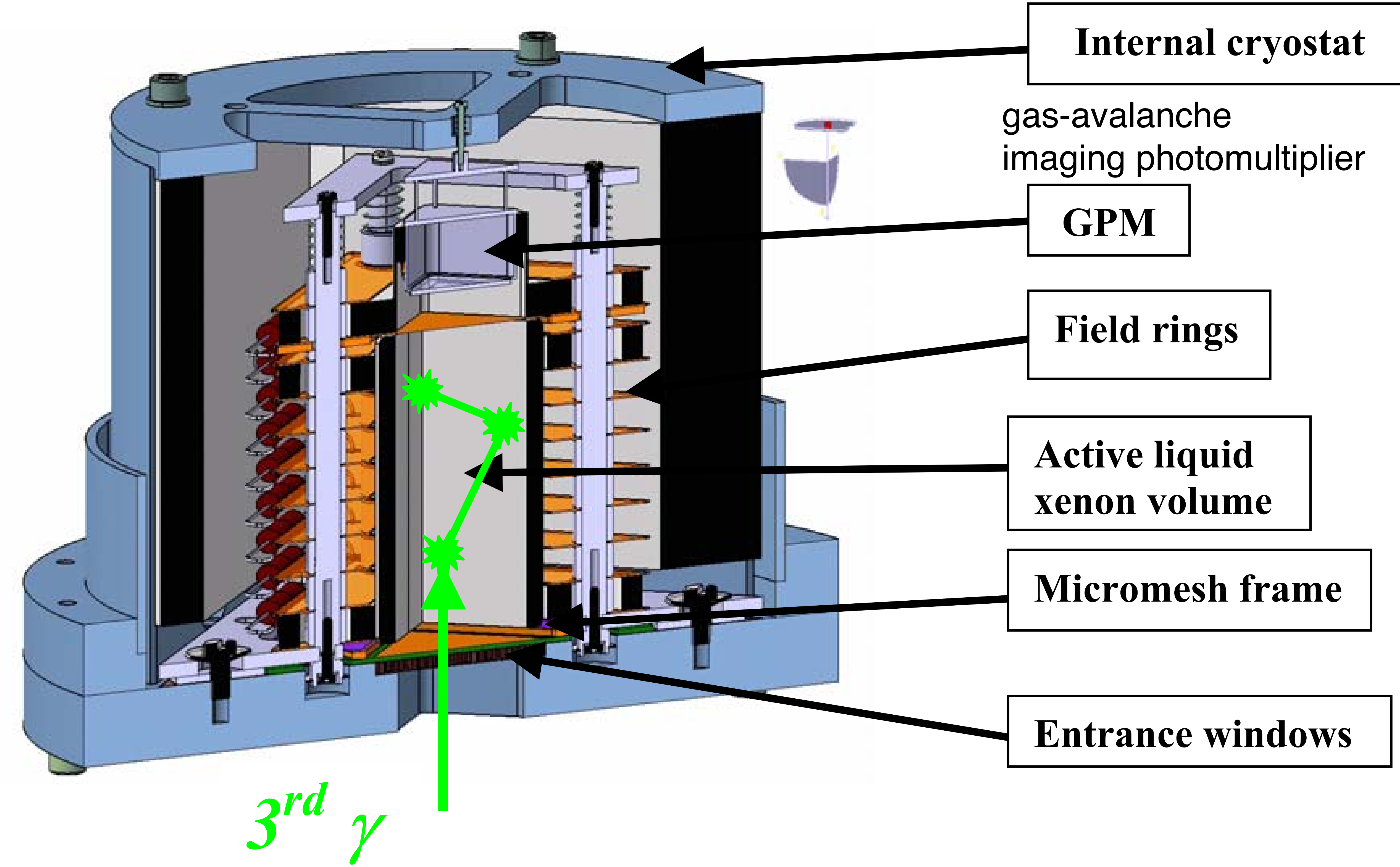
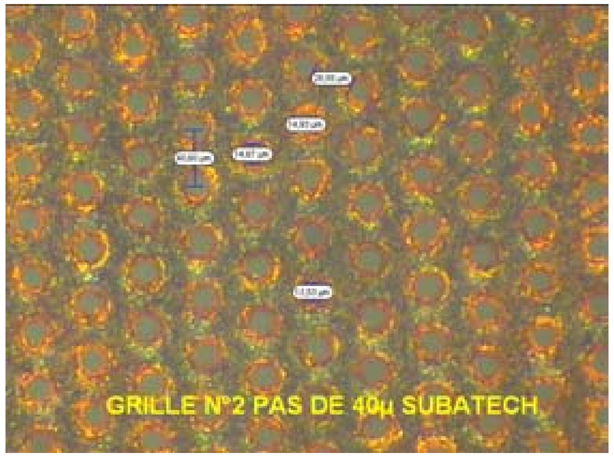


Figure 6: Active volume of the liquid xenon Compton prototype in construction

The ionization signal (~60000 e-/MeV) is collected by a segmented anode of 3x3 cm^2 in the (x,y) plane, after crossing a micromesh "Frish-Grid". This micromesh is a copper grid of 3 μm thickness and 50 μm pitch placed 50 μm above the anode (0.5x0.5 mm^2 pads), readout with no-amplification,

GPM PIM (Parallel Ionization Multiplier)



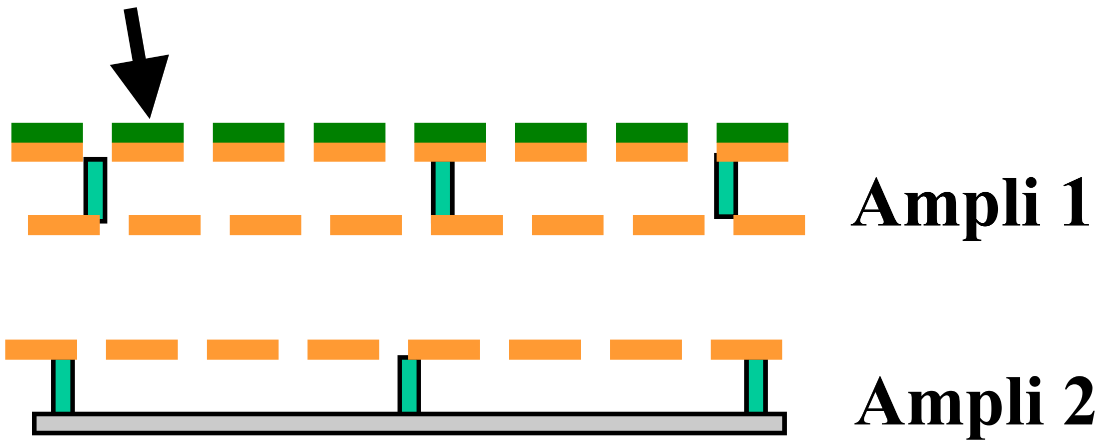
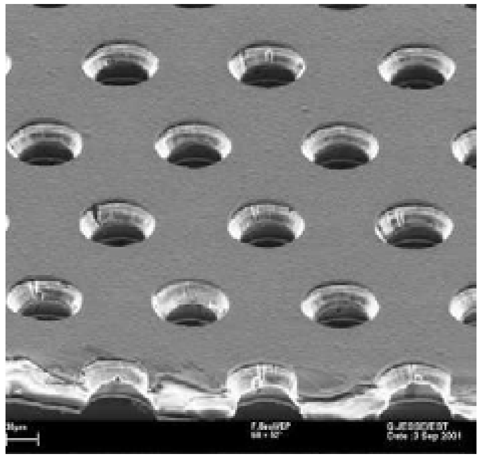
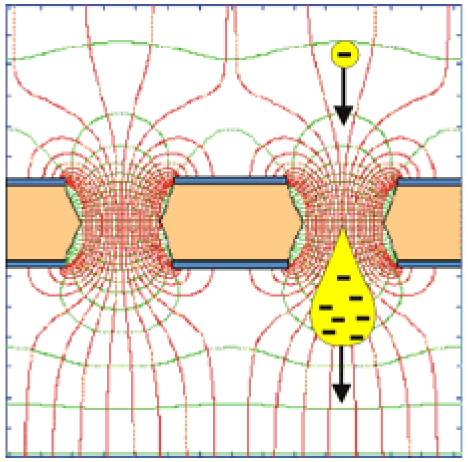


Figure 8. A microscope view of a copper micromesh produced by laser machining: holes are 14 µm diameter with a pitch of 40 µm. The concept of a PIM photon detector with a reflective photocathode.

GEM (Gas Electron Multiplier)





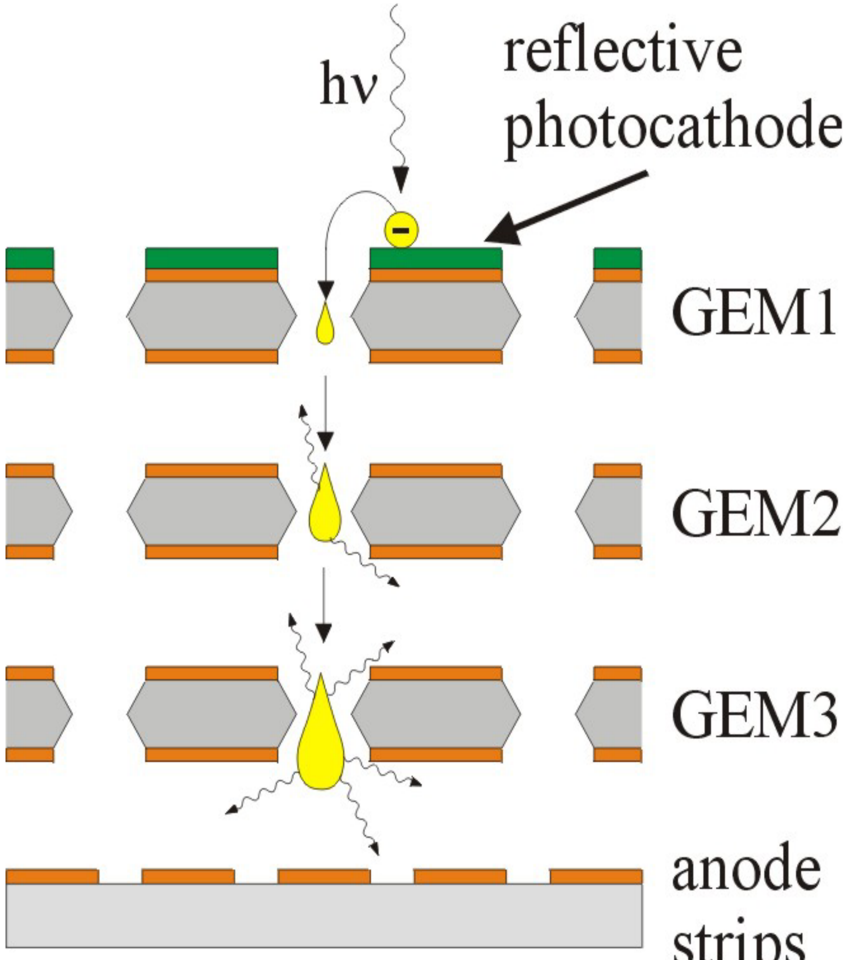


Figure 9. A microscope view of a Gas Electron Multiplier (GEM), produced of 50 micron Cu-cladded Kapton, perforated with 80 micron diameter holes; equi-potentials, electric fields and avalanche multiplication scheme occurring when the GEM is polarized by a few hundred volts; The concept of a multi-GEM photon detector, with a reflective photocathode.

Second Prototype

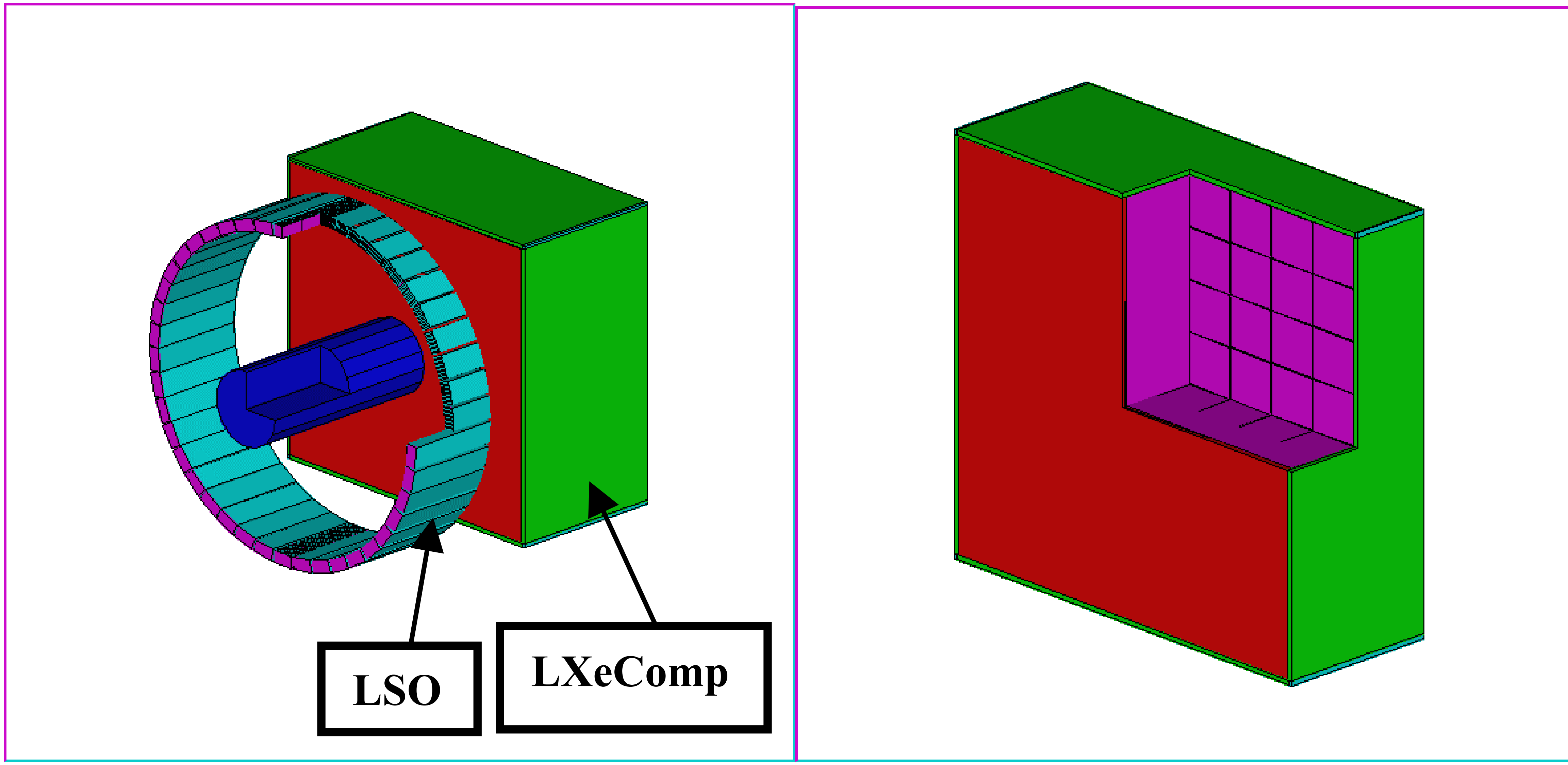
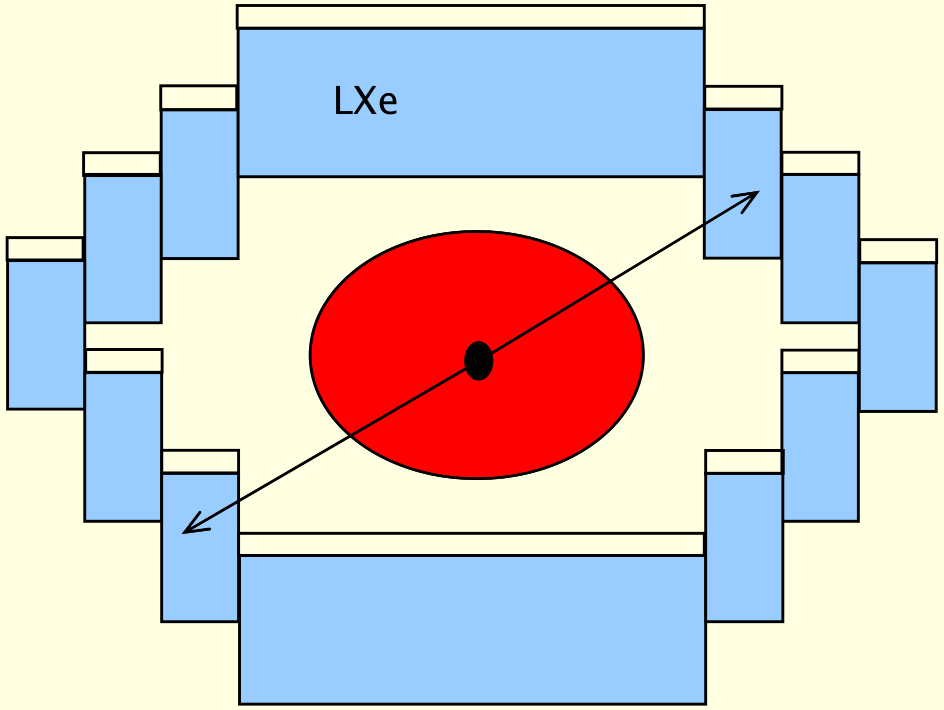


Figure 13: Liquid xenon module associated to LSO microPET camera (left). The module (24x24x12 cm^3) is made of individual cells of 3x3x12 cm^3 separated by 500µm thick PTFE walls (right). The rat phantom is a water cylinder of 6 cm diameter and 15 cm length.

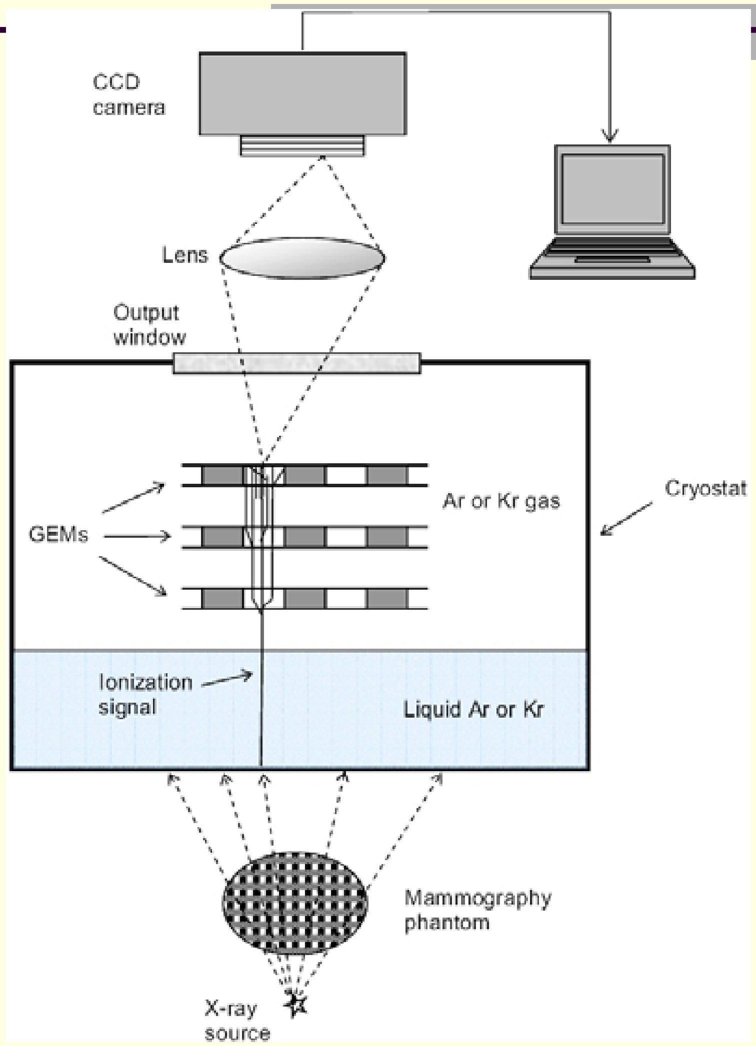
Motivation: cryogenic two-phase detectors for medical applications



GEM-based two-phase Xe or Kr avalanche detector for PET

- Solving parallax problem
- Superior spatial resolution if to use GEM readout

Budker Institute: CRDF grant RP1-2550 (2003)



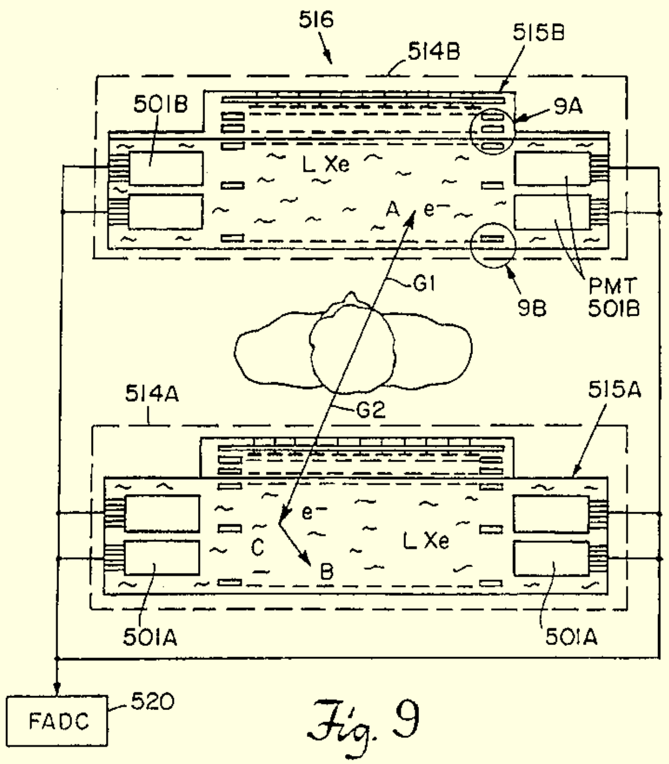


Fig. 9

Two-phase Xe detector for PET

Chen & Bolozdynya, US patent 5665971 (1997)

GEM-based two-phase Ar or Kr avalanche detector for digital radiography with CCD readout

- Robust and cheap readout
- Thin (few mm) liquid layer is enough to absorb X-rays
- Primary scintillation detection is not needed

Budker Institute: INTAS grant 04-78-6744 (2005)

XENON (TPC) ; 2 phase : DM

2006

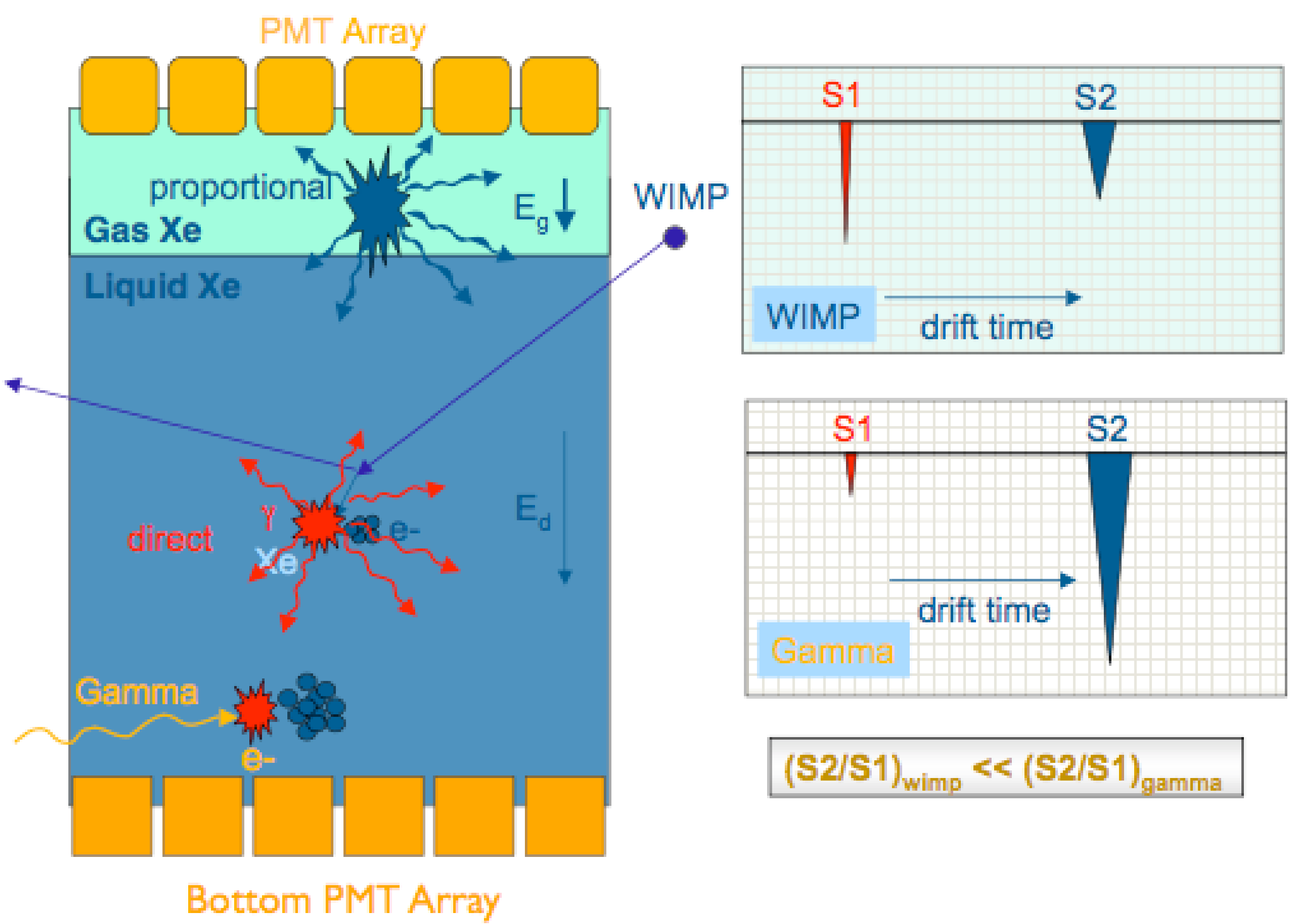
http://www.astro.columbia.edu/~lxe/XENON/

Gran Sasso underground lab, Italy

10kg (XENON-10) -> 1 ton with visible energy threshold of 4keV

1 ton LXeTPC consists of 10 TPCs (100kg): 38cmΦ, 30cm hight cylinder

Under a high electric field, a nuclear recoil will yield a very small charge signal and a much larger light signal, compared to an electron recoil of the same energy. The distinct charge/light ratio is the basis for nuclear recoil discrimination in a LXe (2 phase) detector.



Roadmap:

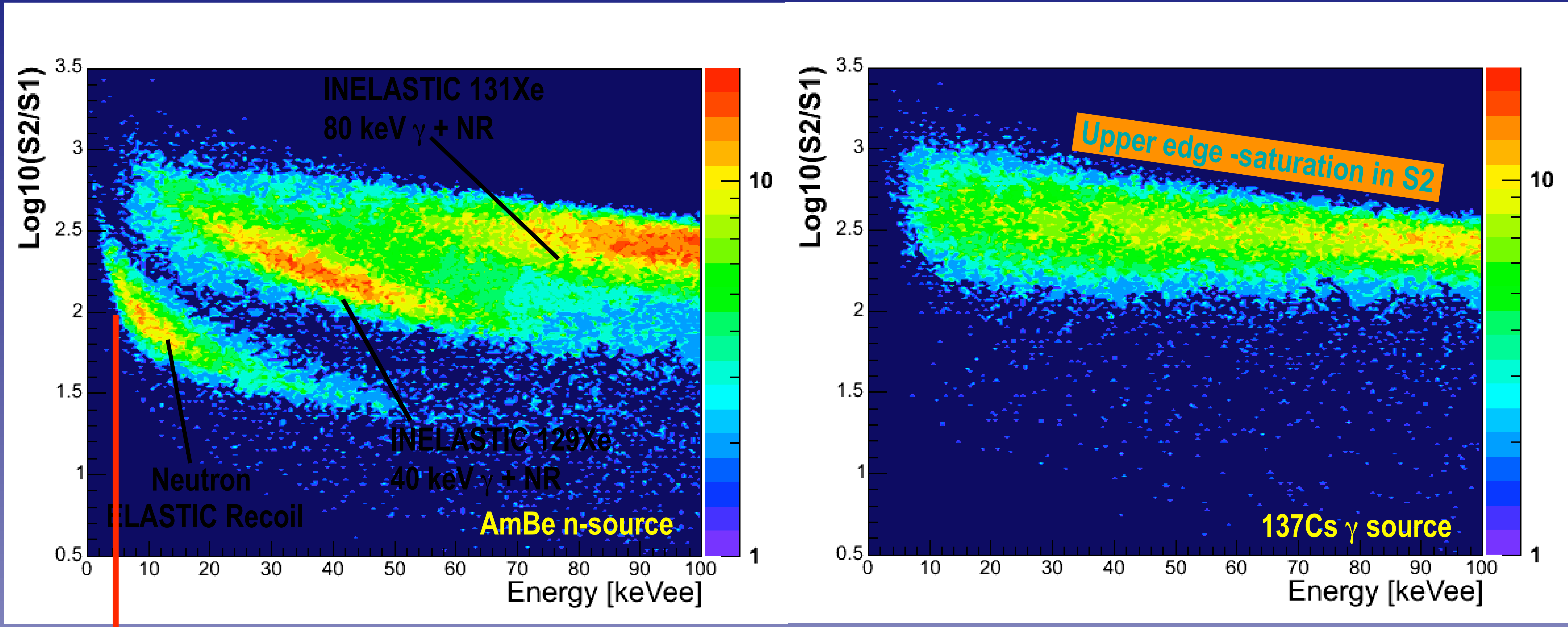
→R&D started 2001

→XENON-3 lab. prototype 2005

→XENON-10 first DM detector now

→XENON-100 design later in 2006

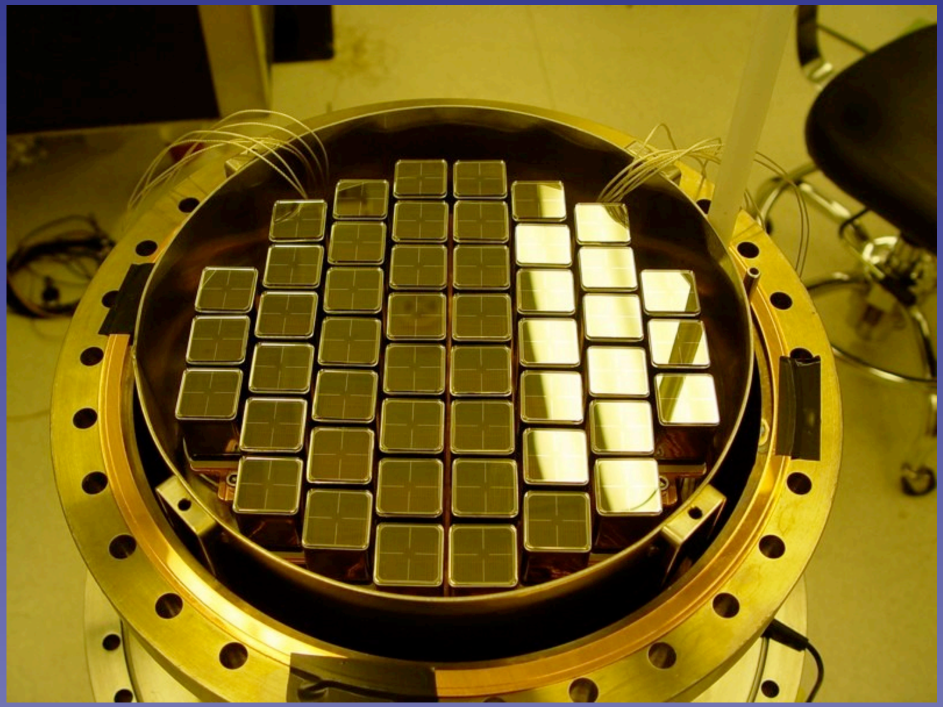
Background Discrimination Capability

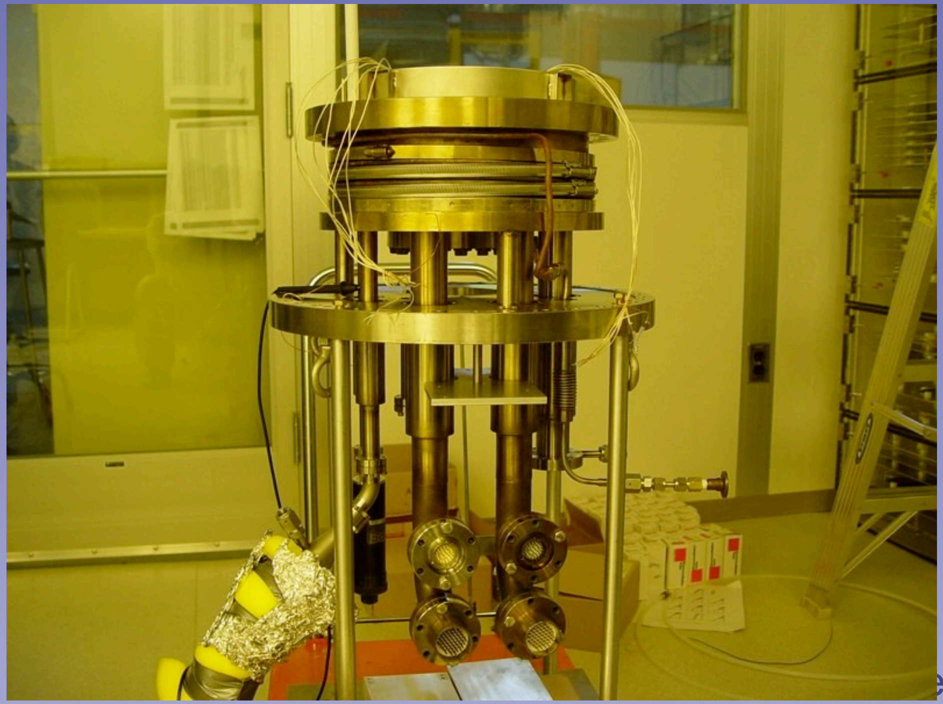


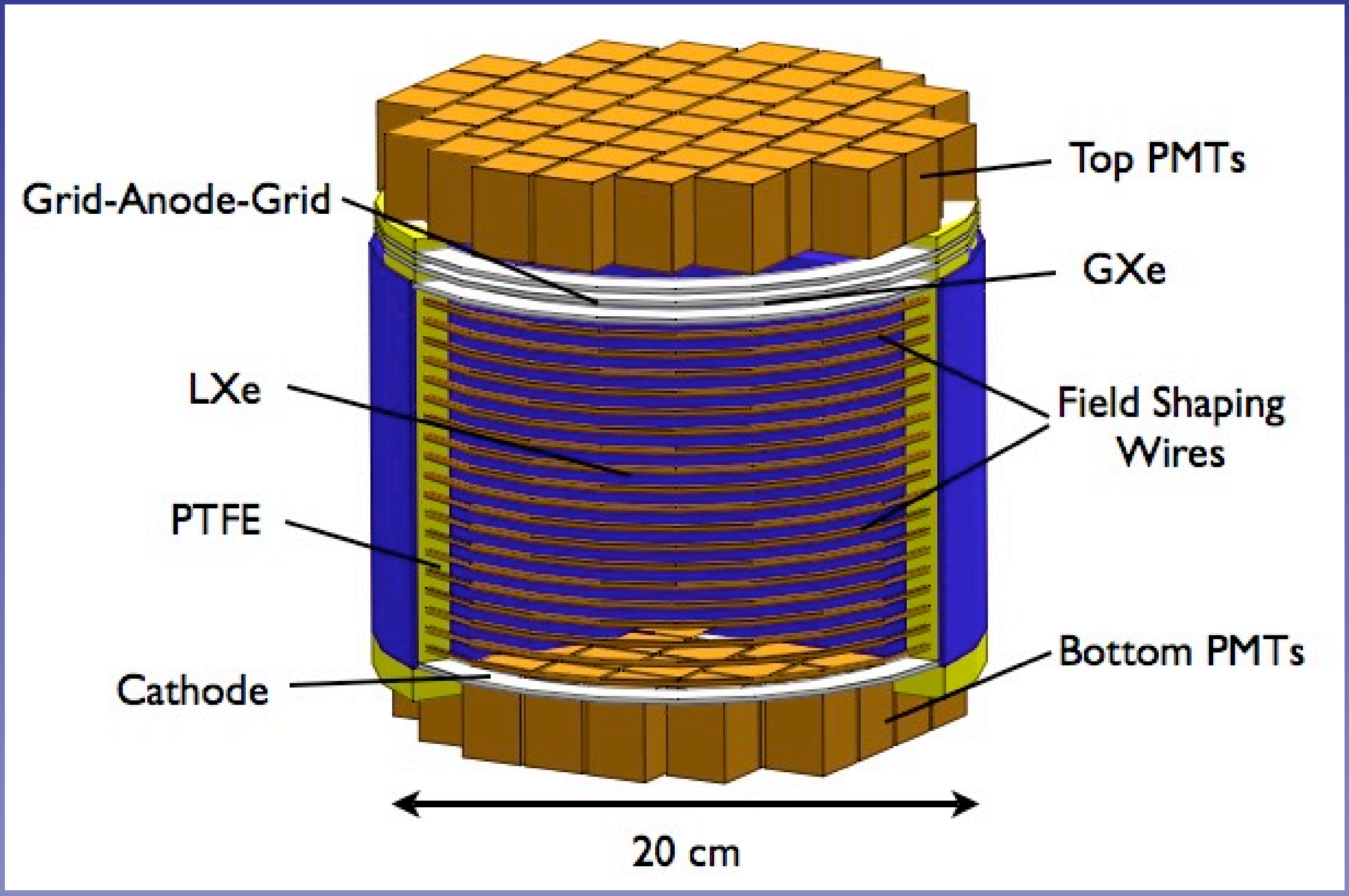
5 keVee energy threshold = 10 keV nuclear recoil

XENON-10 Detector Now at LNGS

- XENON10 now installed and being tested at LNGS (Underground laboratory Gran Sasso, Italy)
- Expect first DM search run June – August 2006







- 48 PMTs on top, 41 on bottom inside LXe
- 20 cm diameter, 15 cm drift length
- 14 kg LXe

Summary & Outlook

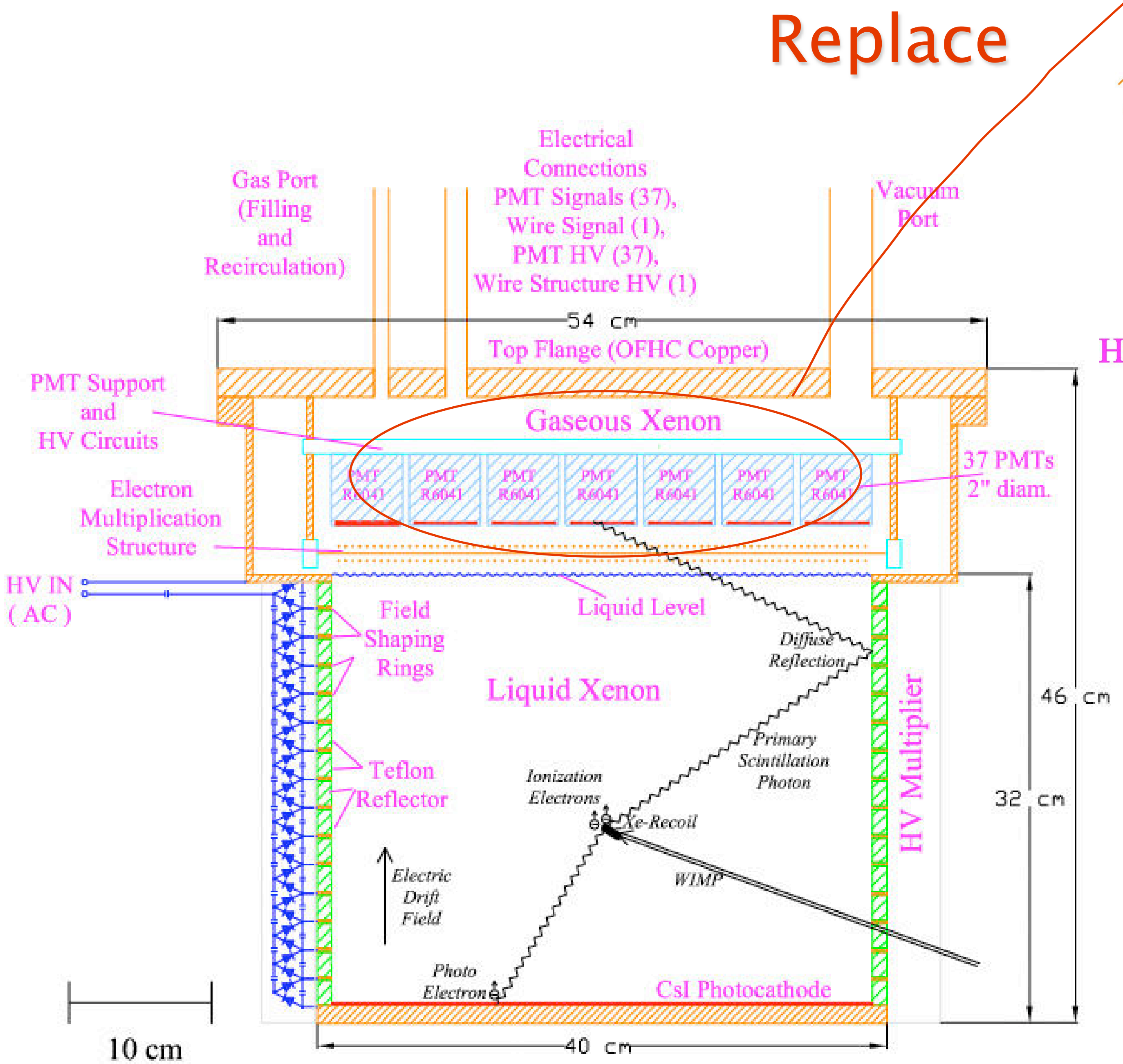
- Dual phase Xenon-TPC's have been developed and tested in the lab, and are expected to start first DM search runs soon.
- Currently, both charge and light readout are based on PMT readout of primary and secondary scintillation light.
- PMT internal radioactivity has been greatly reduced but will become a limiting factor as sensitivities continue to improve.
- Can we profit from higher X/Y spatial resolution?

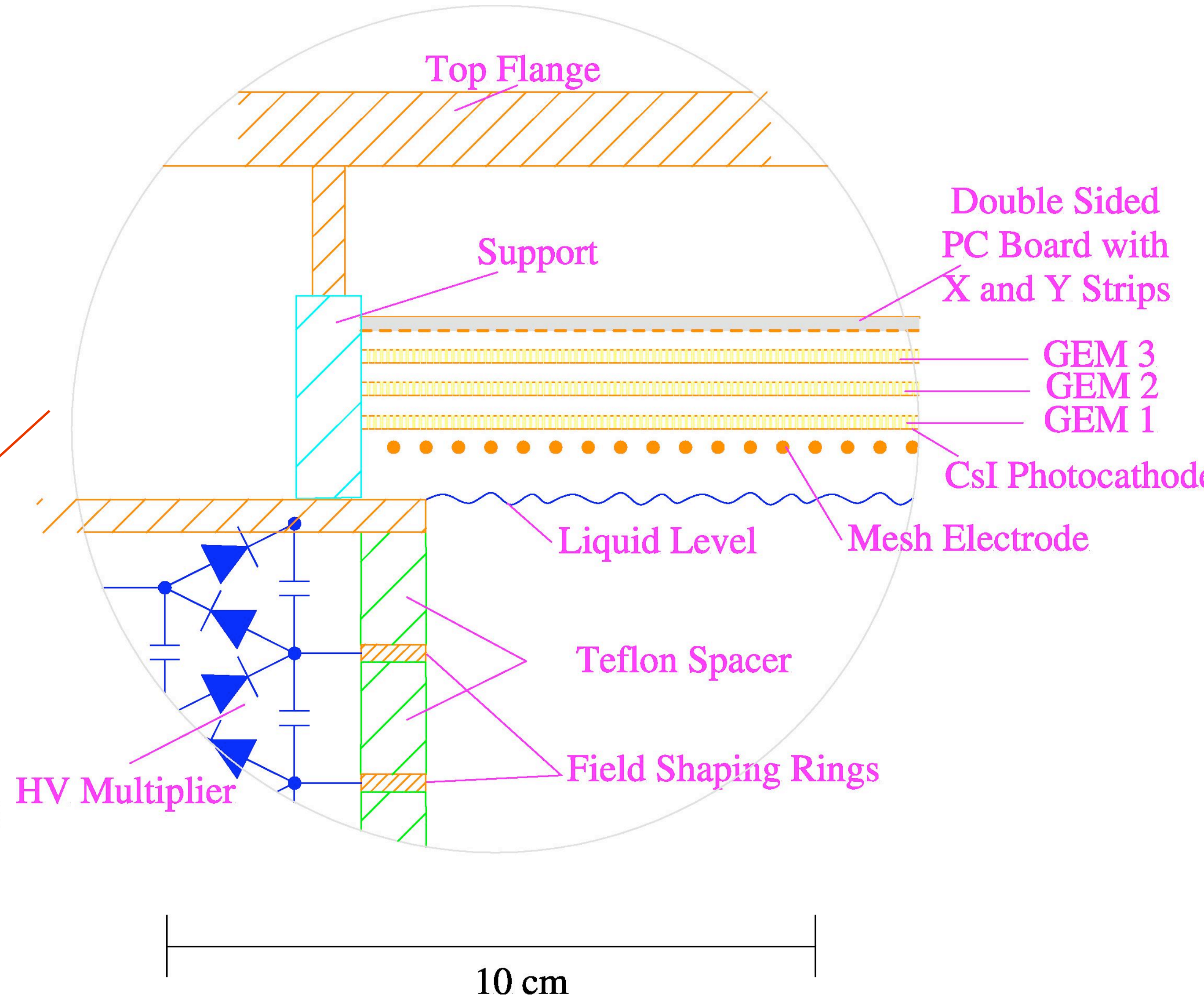
Other readouts?

- Charge readout with GEM's/THGEM's/MicroMegas?
  So far tested: GEM's - difficulties in Xe vapor phase.
- Light readout with sealed gaseous PMT's? Some requirements similar to RICH detectors.
- Semiconductor photosensors?

GEM Implementation in the XENON Detector

Triple-GEM structure with CsI coating. Mesh stearing electrode to tune field for optimum charge transmission and photoelectron extraction from the CsI.





Double-sided PC board with X/Y strips for fine spatial resolution.

Low-noise electronics for optimum thresholds.

ZEPLIN (TPC) ; 2 phase : DM

2001

http://hepwww.rl.ac.uk/ukdmc/ukdmc.html

- -II UKDMC collaboration with US and Italy, 30kg
- -III UKDMC collaboration with US and Russia, 6kg
- -IV UKDMC collaboration with UCLA 1 ton from ZEPLIN II

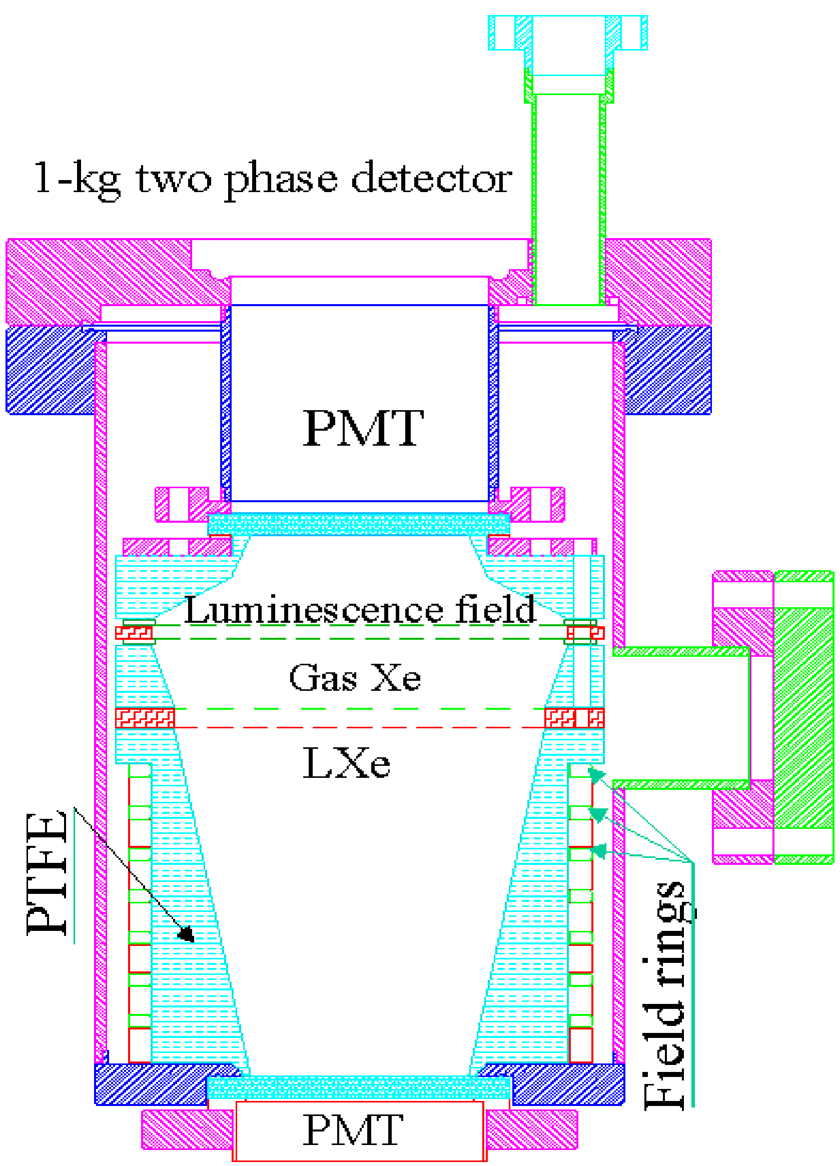


Figure 3. ZEPLIN II: Electroluminescence in gas (principle of a two-phase, 1-kg detector, developed by UCLA-CERN-Torino.

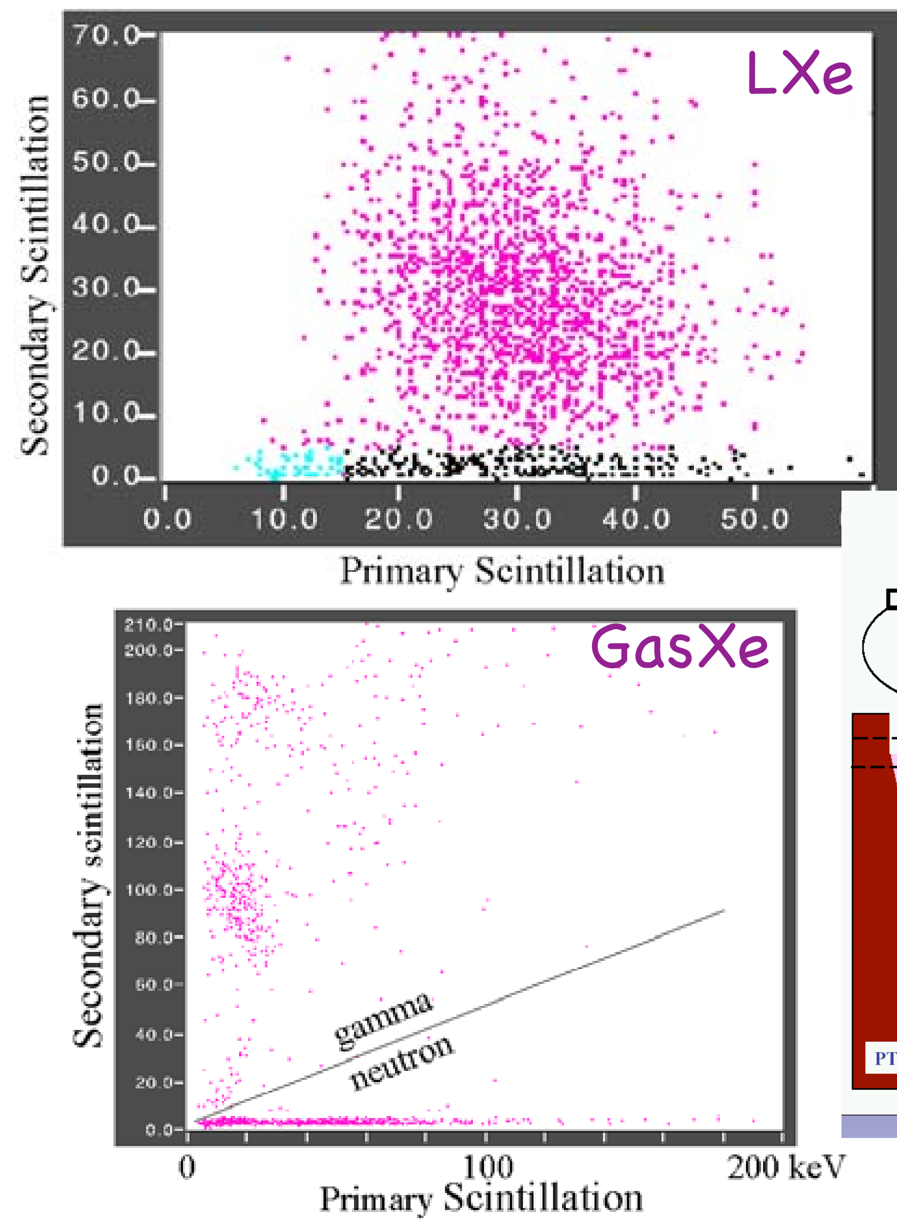
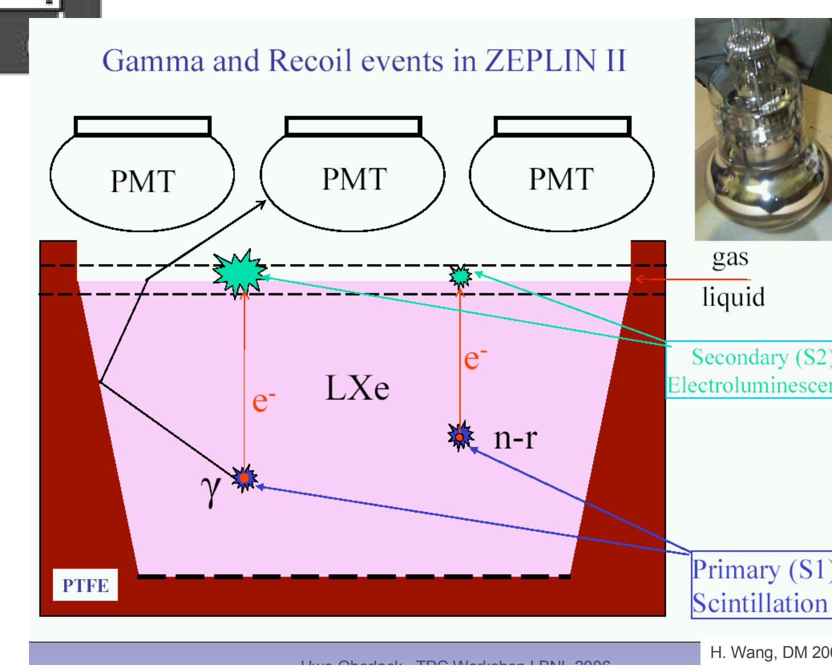


Figure 4. Secondary vs. primary scintillation plot in pure liquid Xe with mixed gamma-ray and neutron sources. The secondary scintillation are produced by proportional scintillation process in liquid Xe (top) and electroluminescent process in gaseous Xe (bottom).

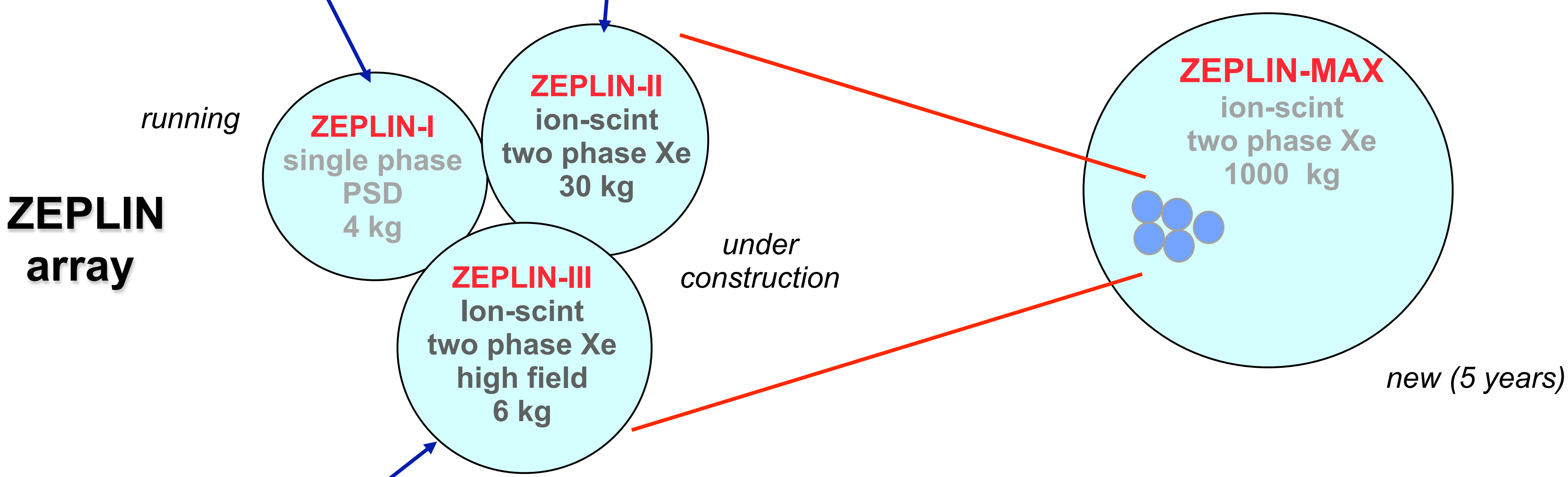


Boulby Collaboration Strategy

demonstrate basic discrimination with PSD - set first limits

basic ionisation-scintillation and high target mass - improve by x10 - UCLA concept

A multinational programme



ionisation-scintillation and high field - ultimate discrimination, low threshold -

Involved in programmes: UCLA, CERN/Padova, Torino, ITEP, Coimbra, Columbia, RAL, ICSTM, Sheffield

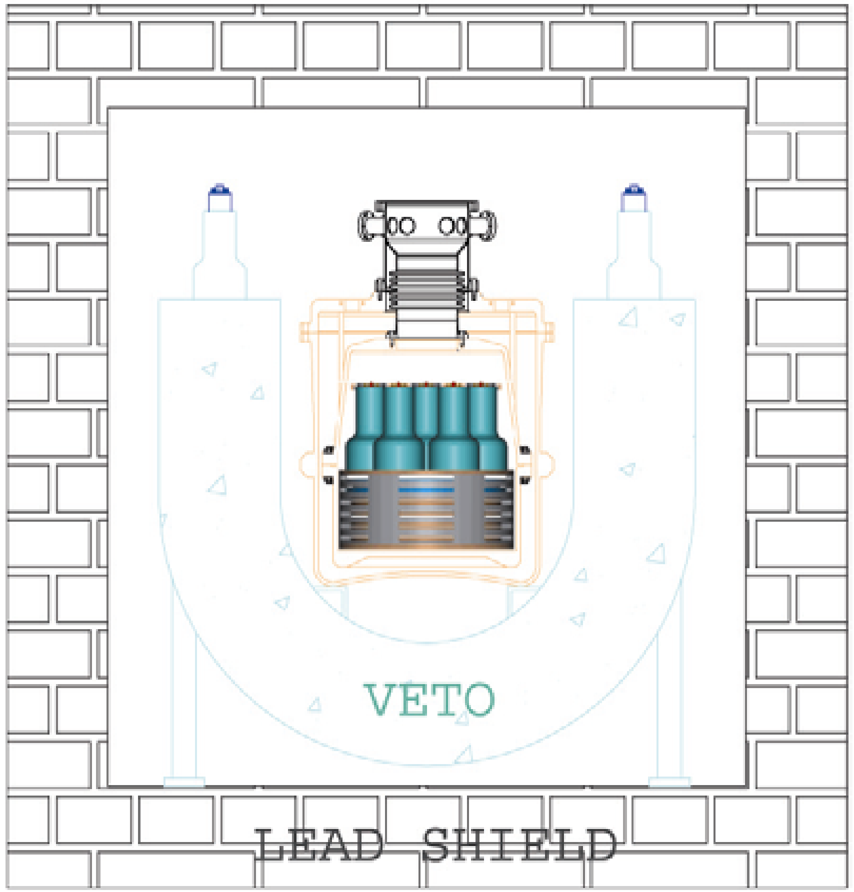


Figure 5a. System setup for Xe target (40 kg total): overall set up.

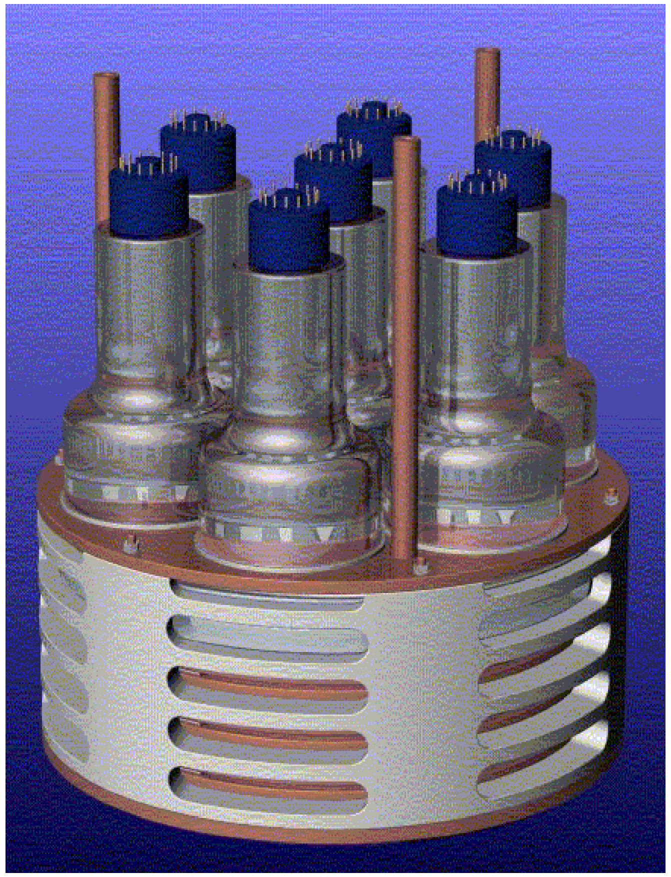


Figure 5b. ZEPLIN II central detector.

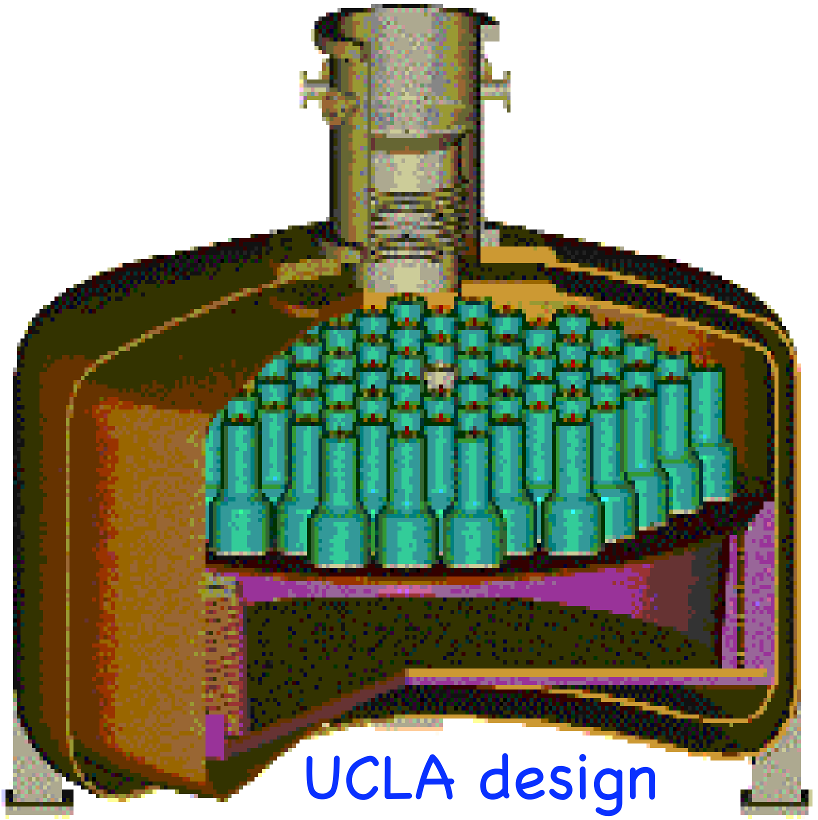


Figure 6. 1-ton scaled up (ZEPLIN IV) detector.

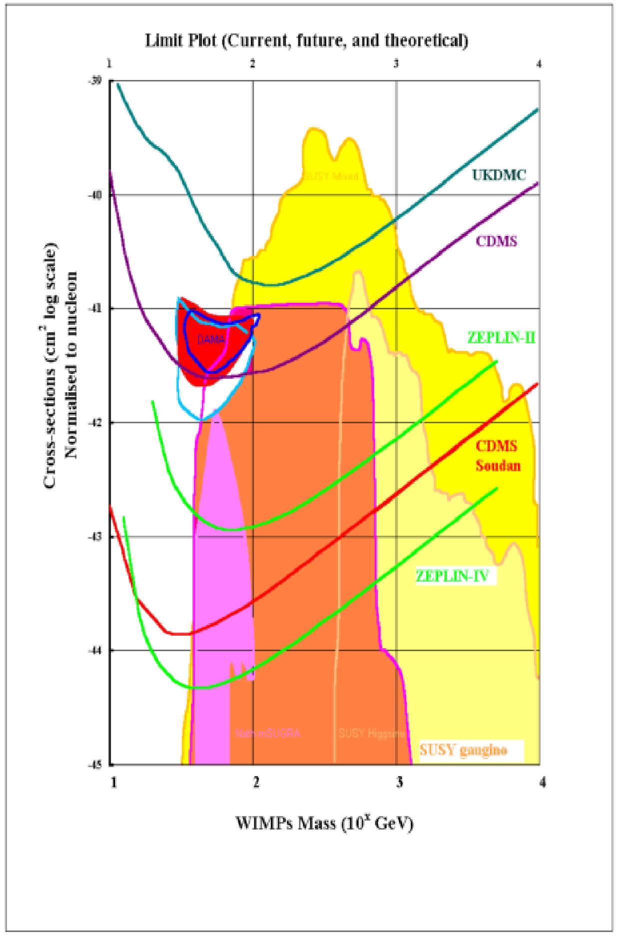
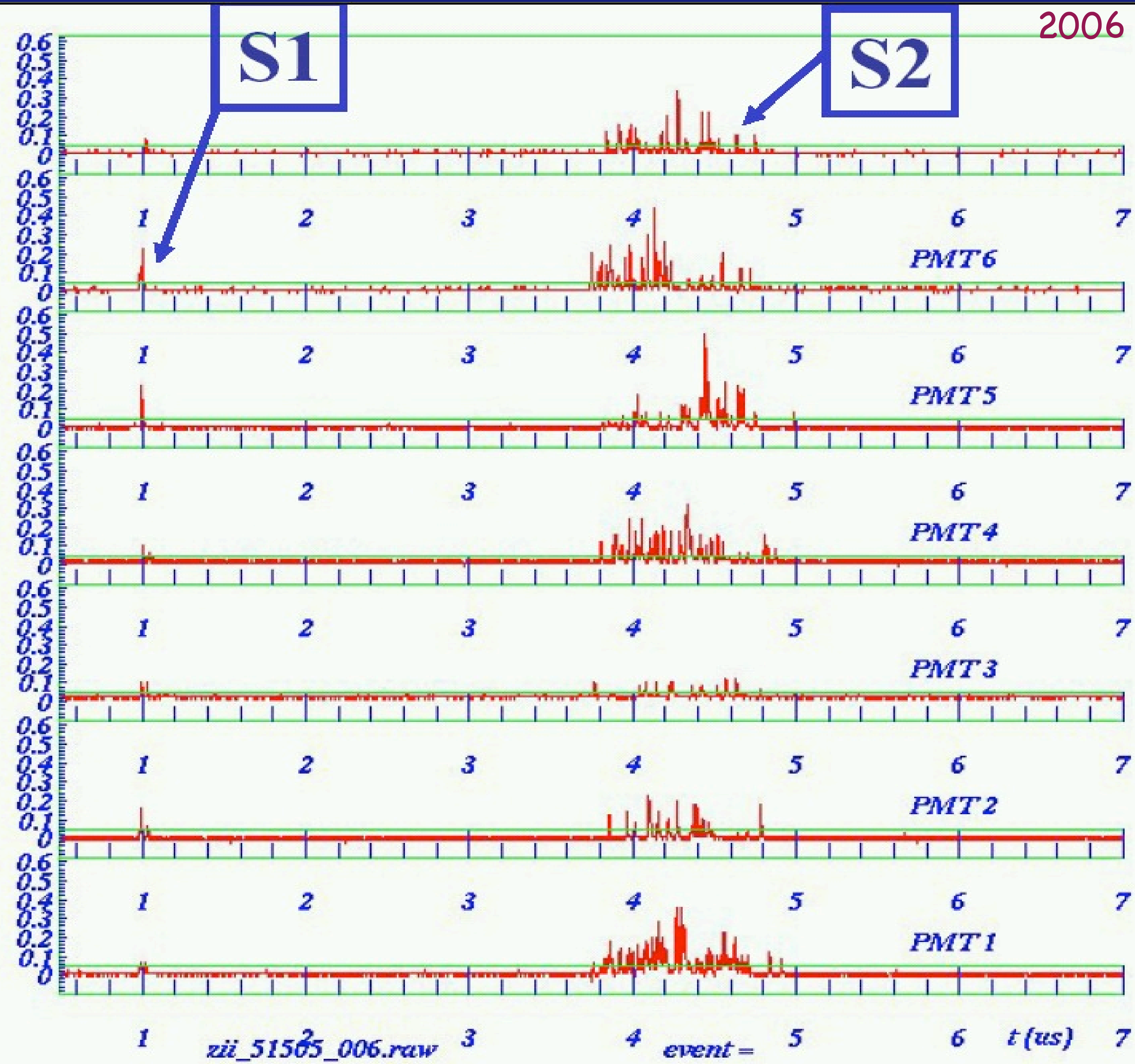


Figure 7. Limit plot (current, future and theoretical).

ZEPLIN II

2006

Recoil Event



H. Wang, DM 2006

ZEPLIN III

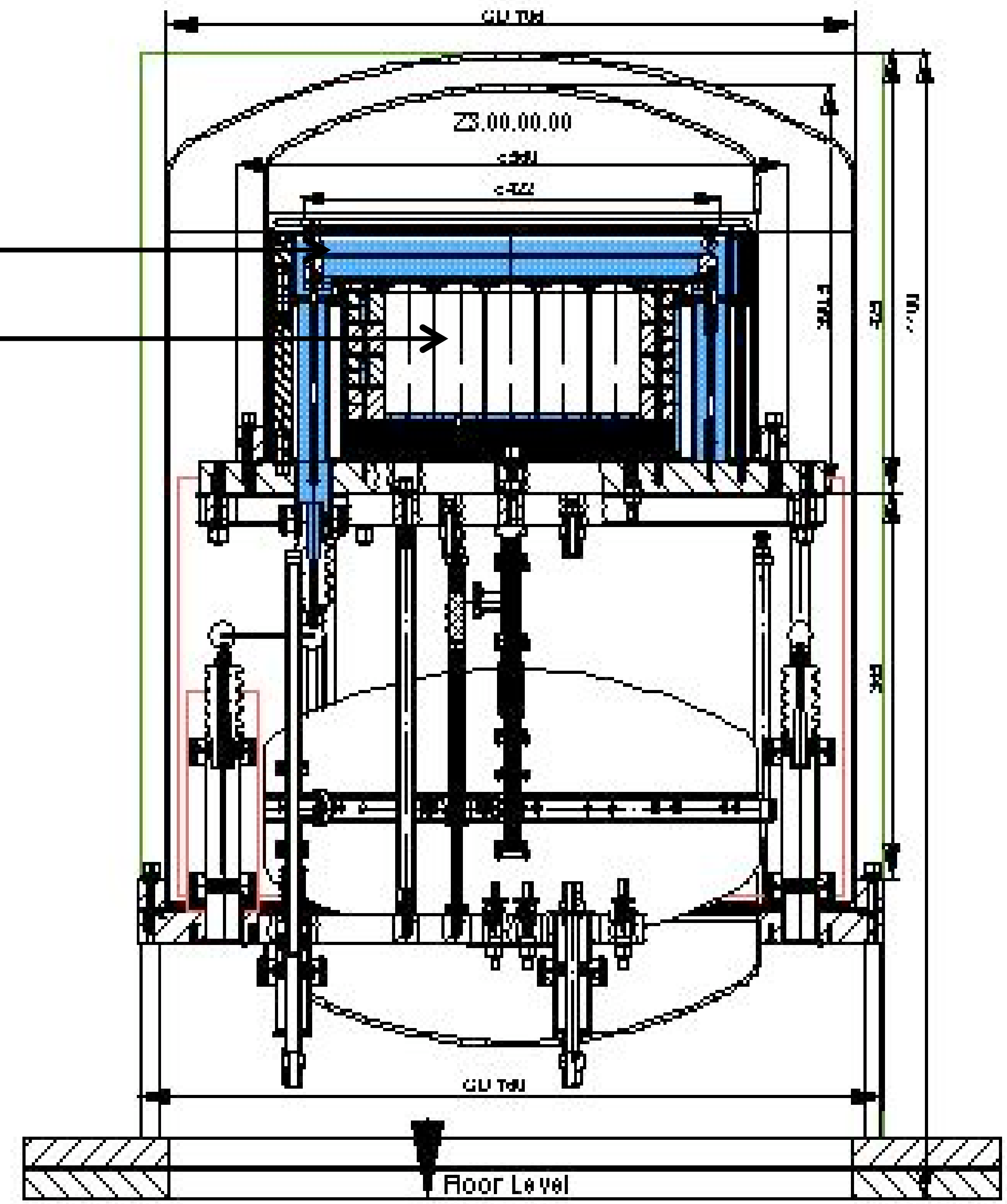
(UKDMC collaboration with US and Russia)

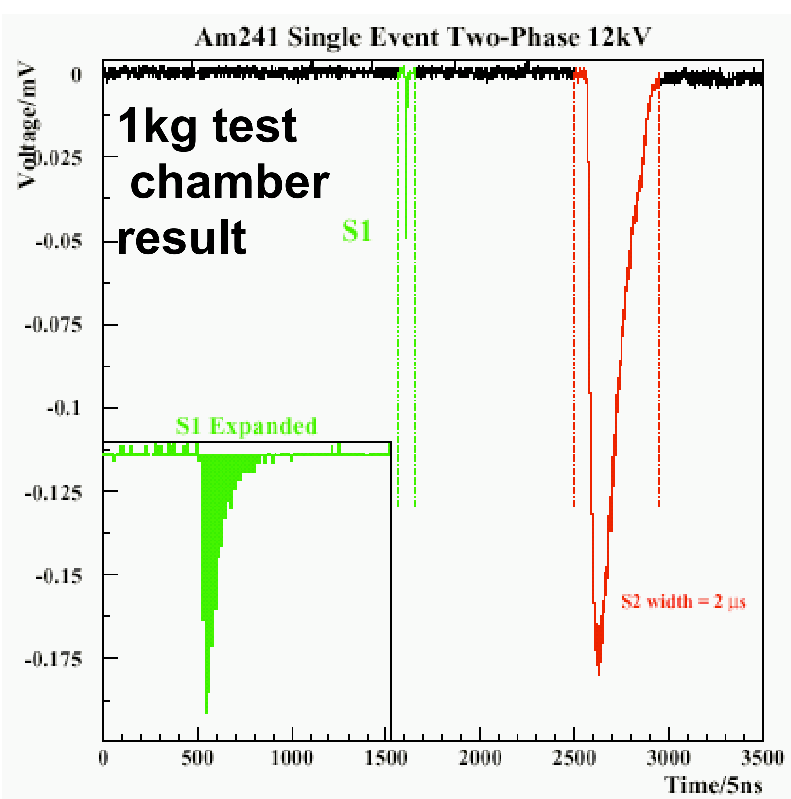
ionisation-scintillation - low threshold

- 6 kg liquid Xe
- High field (20 kV) operation for better discrimination

Xe

31 two-inch photomultipliers

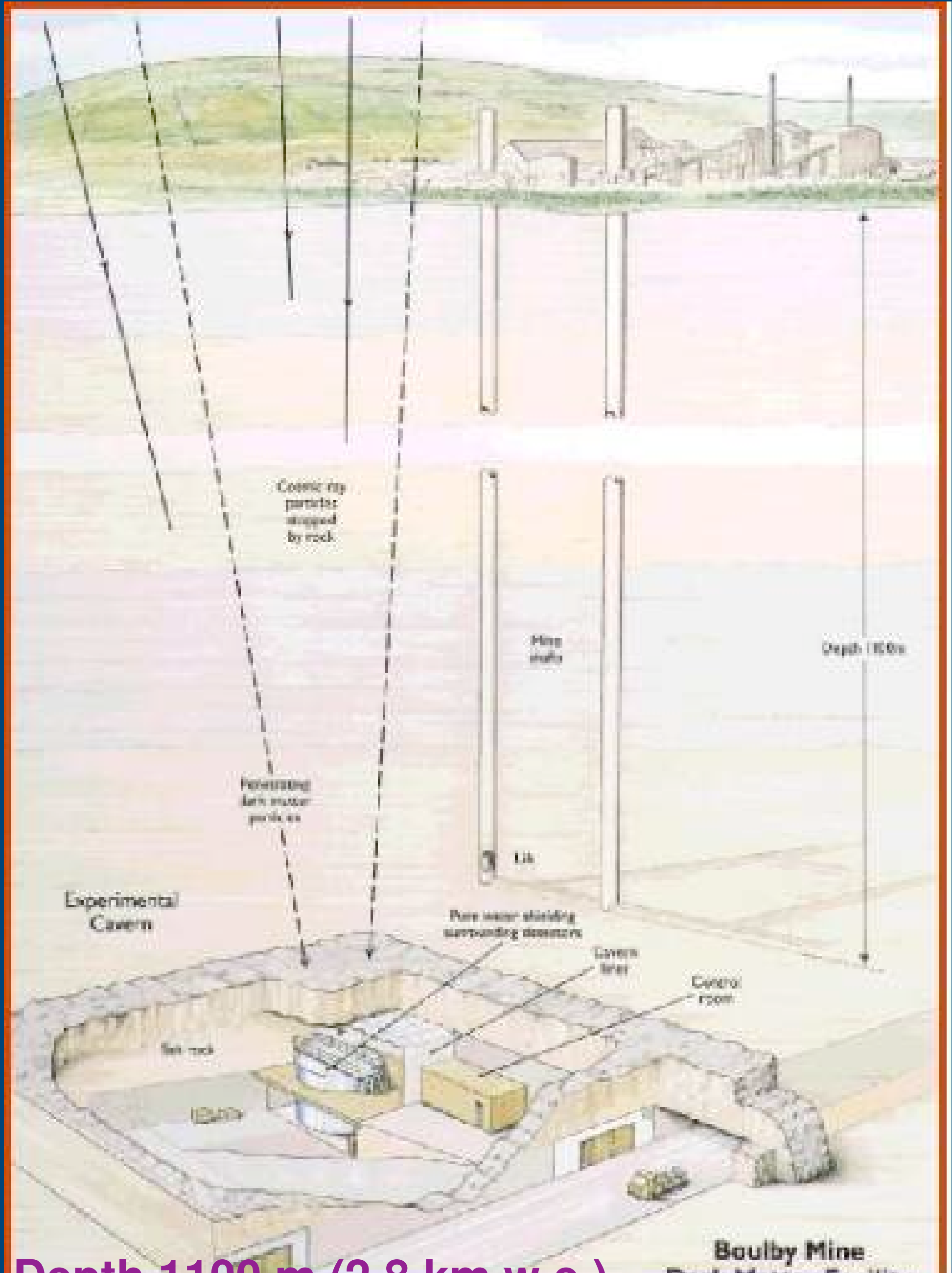




- Completion due end 2001

Zeplin III

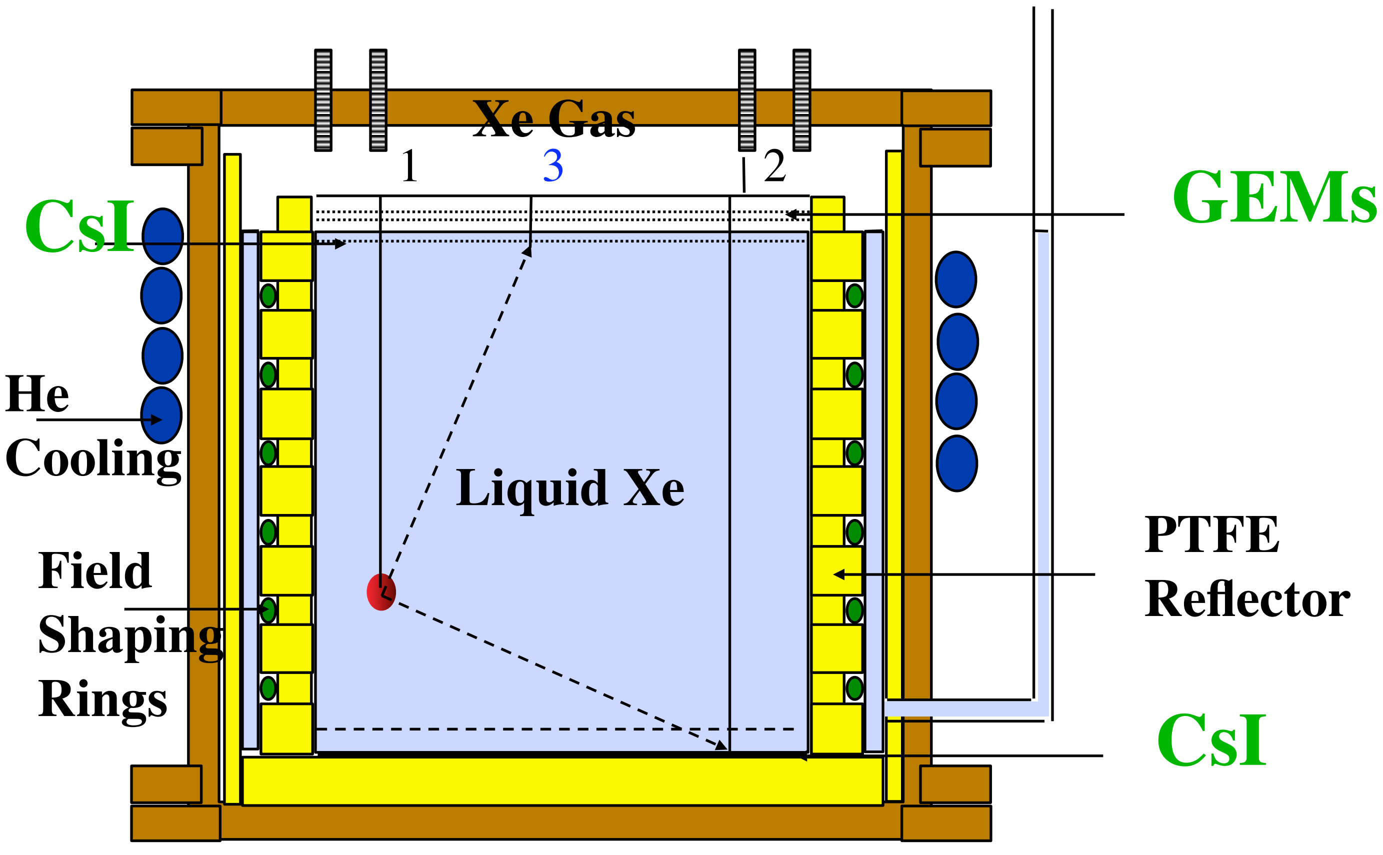
- Xenon detector for WIMP search
- Nuclear recoils from elastic scattering (WIMP – nucleus)
- Operate underground, at Boulby

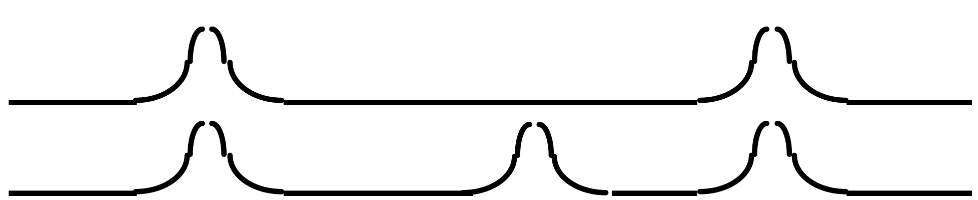


Depth 1100 m (2.8 km w.e.)

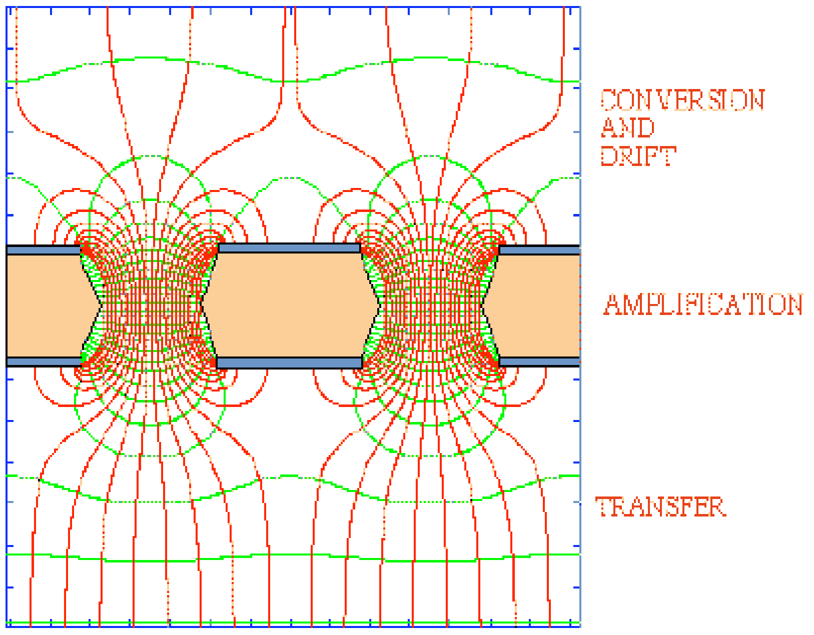
PMT Removal for Scale-Up?

- Sheffield test cell





Nuclear recoil signal events contain no (for low drift field) primary ionization between these two pulses.



CsI photocathodes in LXe: E.Aprile, NIMA 338 (1994), 328; NIMA 343 (1994), 121.

GEM phototubes in noble gases:http://gdd.web.cern.ch/GDD/A.Buzulutskov, NIMA, 443 (2000), 164.

Summary of 1 Phase LXe

Phase	Project	Physics	Xe weight	detector	readout	year	location	collaboration
1	EXO	double beta	10ton ($3m^3$) 1ton 200kg	TPC	x, y anode wires ; APD for lights , laser - ID	for 10 years for 5 years Nov., 2006	WIPP, NM, USA	Enriched Xenon Observator, US(SLAC), Canada, Swiss, Russia
1	XMASS	DM solar ν double beta	20ton 1ton (800kg) 100kg (30 ℓ)	lights	PMT	 2006	Kamioka	Japan, Korea, Russia
1	MEG	μ -> e γ	800 - 900 ℓ 70 ℓ	lights	PMT	Nov., 2006 2003	PSI	Japan, Italy, Switzerland, Russia, USA
1	LXe-GRIT	cosmic γ	2.4 ℓ	TPC	x, y anode wires ; PMT for lights	1997, 1999, 2000	NSBF (National Science Baloon Facility),NM, USA	Columbia university
1	LXe-PET	PET	64.8 ℓ	TPC	segmented pads	2007 (prototype)	Nantes Cyclotron	France, Japan
1	PETYA	PET		drift chamber	anode wires or mini-strip ; PMT, APD for lights	2002 (prototype)	Univ. of Coimbra	Portugal
1	TOF-PET	PET	77.8 ℓ 12 ℓ	lights	PMT	 2003	Waseda univ., NIRS	Japan
1	XEPET	PET	test w/ 8.5 ℓ in 2005	TPC	12 seg. 96wires & 96strips/seg.	2006-2008	TRIUMF	CANADA

Summary of 2 Phase LXe

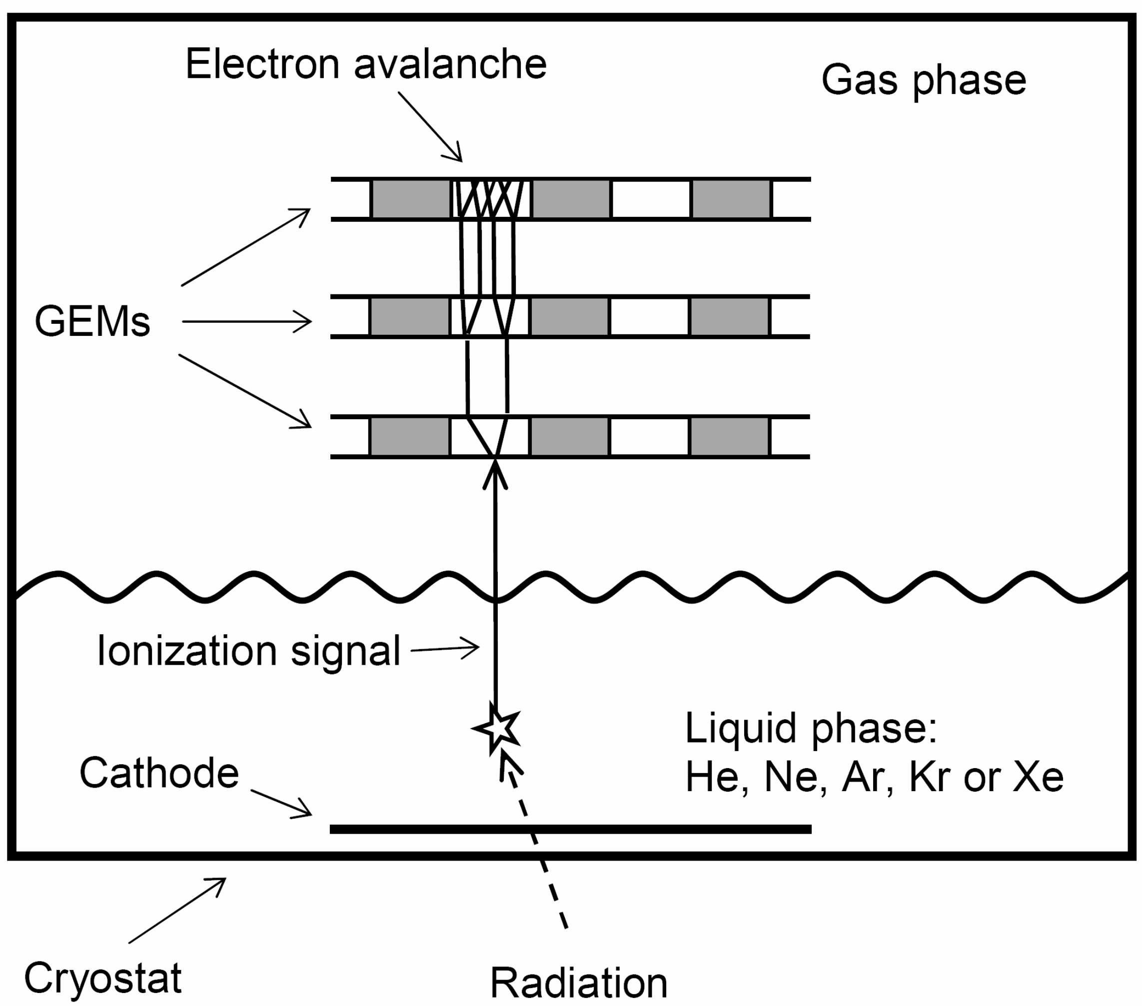
Phase	Project	Physics	Xe weight	detector	readout	year	location	collaboration
2	LXeComp/^{44}Sc	PET	100 ℓ	TPC	anode pads ; GPM for lights	simulation	Nantes Cyclotron	France, Israel, Japan
		micro-PET	13.8 ℓ , 6.9 ℓ			simulation		
			0.1 ℓ			2005		
2	GEM-based	PET		TPC	GEM	2003	Budker Institute	Russia
2	US patent 5665971	PET		TPC		1997	Columbia university	USA
2	XENON	DM (WINP)	1ton:100kgx10	TPC	PMT, GEM		Gran Sasso underground lab	US, Italy,Portugal
			100kg			design		
			10kg			2006		
			3kg			2005		
2	ZEPLIN	DM (WINP)	1ton (IV?)	TPC	PMT, GEM		Boulby, UK	UK, US, Italy, Russia, Portugal
			30kg (II)			2006		
			6kg (III)			2006		

Detector

2005

GEM: Gas Electron Multipliers

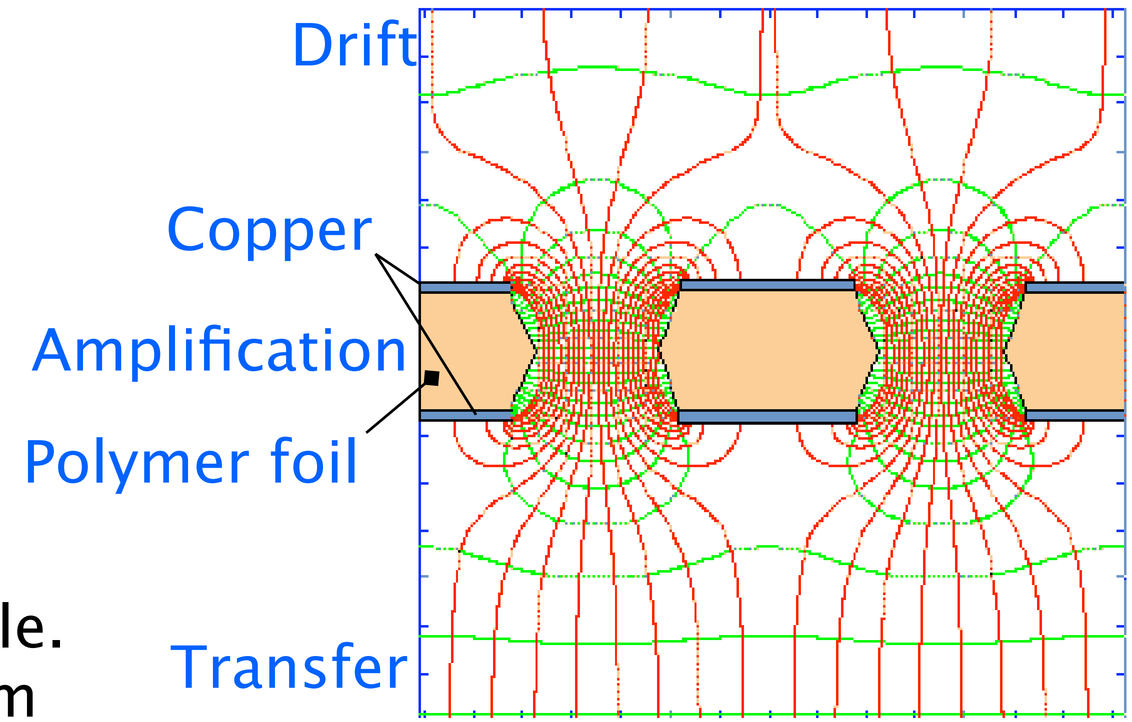
Two-phase argon and xenon avalanche detectors based on Gas Electron Multipliers
A. Bondar, A. Buzulutskov , A. Grebenuk,D. Pavlyuchenko, R. Snopkov, Y. Tikhonov
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia.
www.arxiv.org physics/0510266



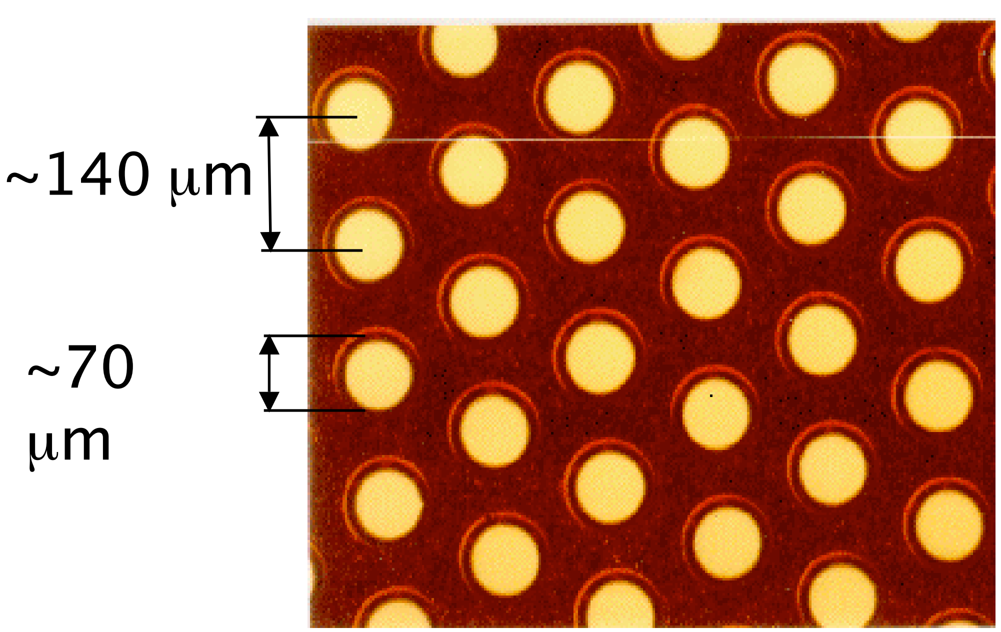
Foils : 28×28 mm^2 each, and a cathode mesh were mounted in a cryogenic vacuum-insulated chamber of a volume of 2.5 l. The distances between the first GEM and the cathode, and between the GEMs, were 6 and 2 mm, respectively.

The Gas Electron Multiplier GEM

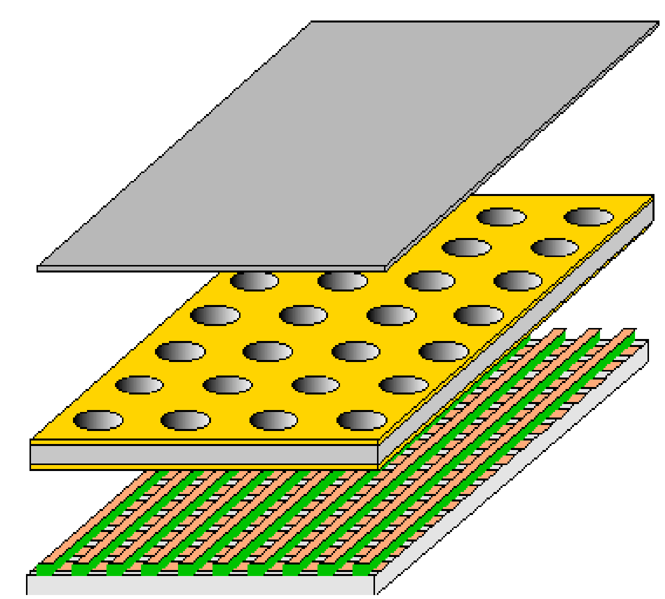
A GEM (F. Sauli, 1997) is a thin metal-insulator-metal structure, densely perforated with small holes. A voltage across the metal layers generates a sufficiently strong field within the holes to focus the electrons and multiply them.

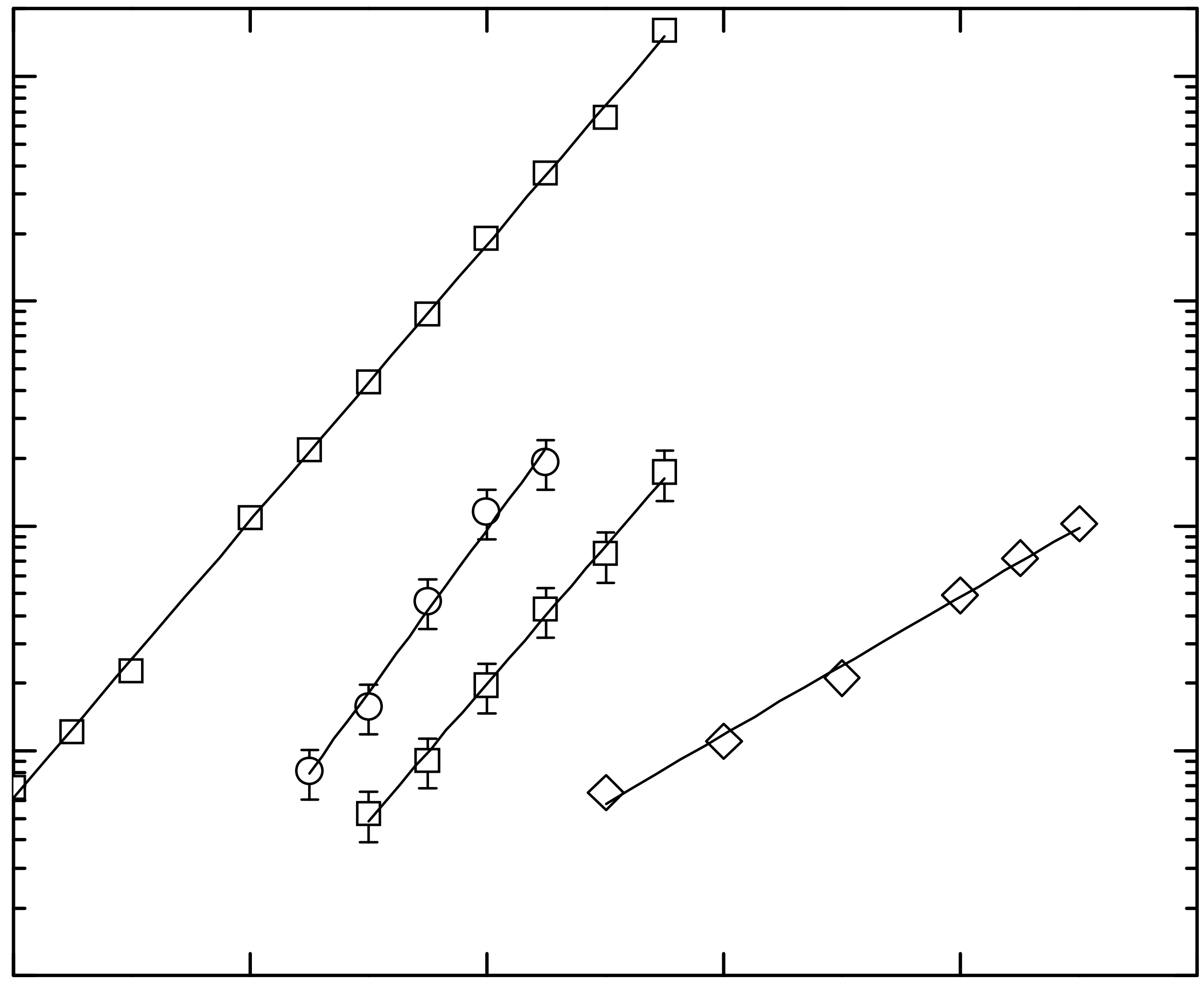


The GEM is technically realized at CERN through copper-coating on 50 μm thick kapton (polymer) foil, with chemically etched holes of conical profile. A standard GEM has a hexagonal pattern of 70 μm diameter holes in the metal, 55 μm in the foil, with a pitch of 140 μm.



A 2D readout of strip anodes on the transfer side of the GEM can provide ~ 1 mm spatial resolution.



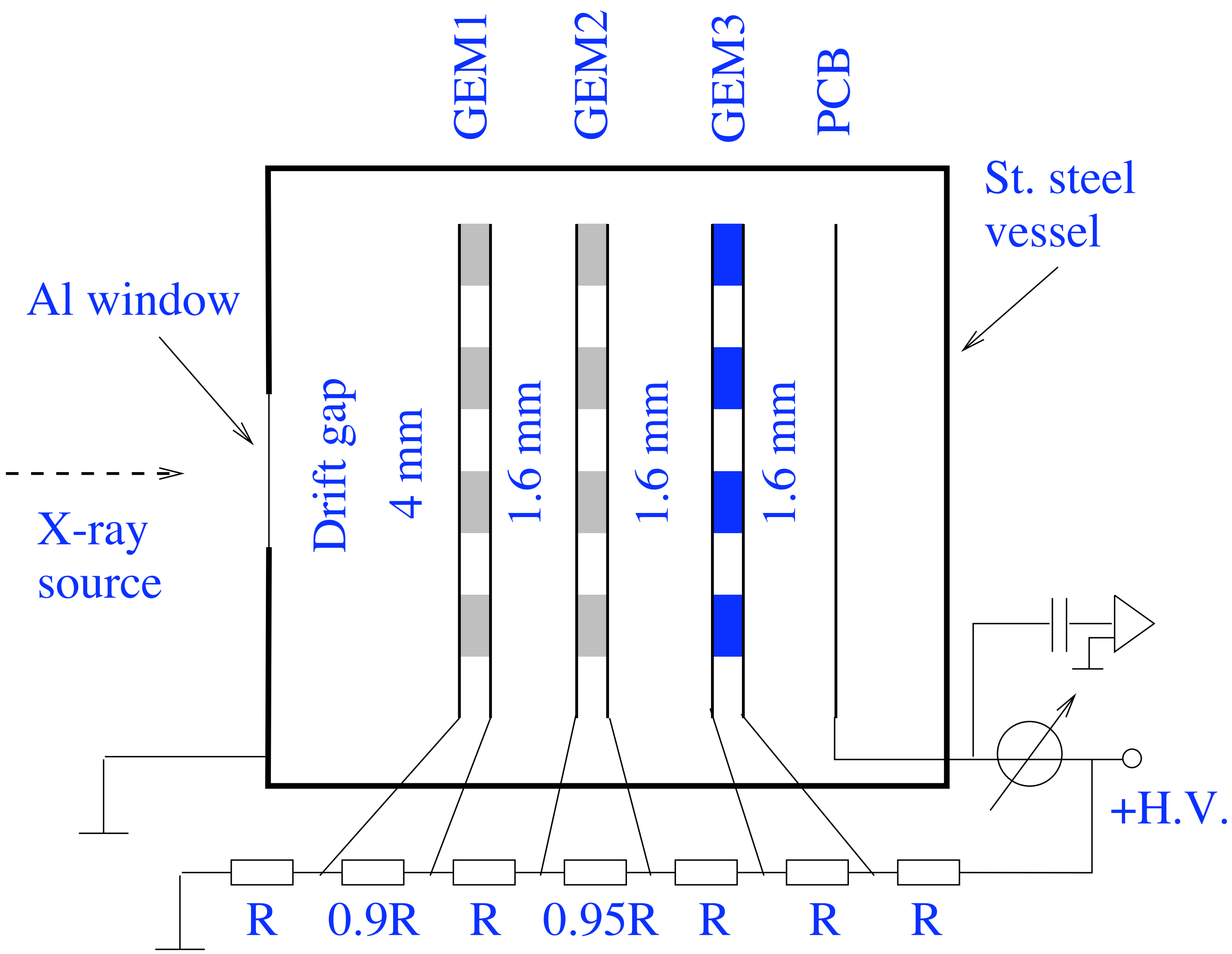


Preliminary results were obtained in the two-phase Xe avalanche detector: the maximum gain of the triple-GEM in two-phase Xe and Xe+2%CH4 was about 200.

High pressure operation of the triple-GEMdetector in pure Ne, Ar and Xe

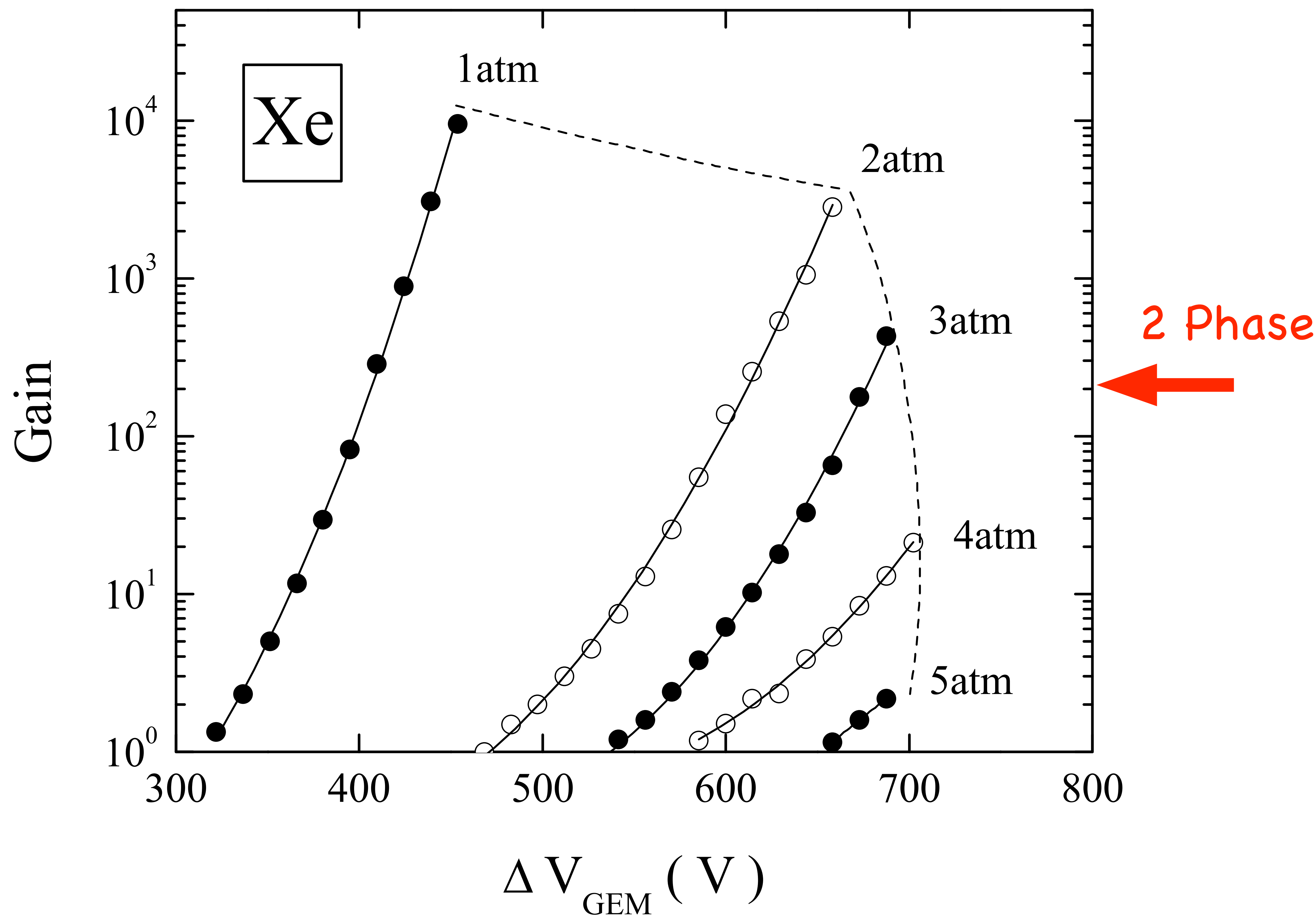
A. Bondar, A. Buzulutskov *, L. Shekhtman
Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

http://xxx.sf.nchc.gov.tw/abs/physics/0103082



GEM foils (50 μm thick kapton, 80 μm diameter and 140 μm pitch holes, 28×28 mm^2 active area) and a printed curcuit board (PCB), mounted in cascade with 1.6 mm gaps

the density of noble gases near the boiling point, at normal pressure, is higher compared to that at room temperature.
Xe : higher density by 1.6 times



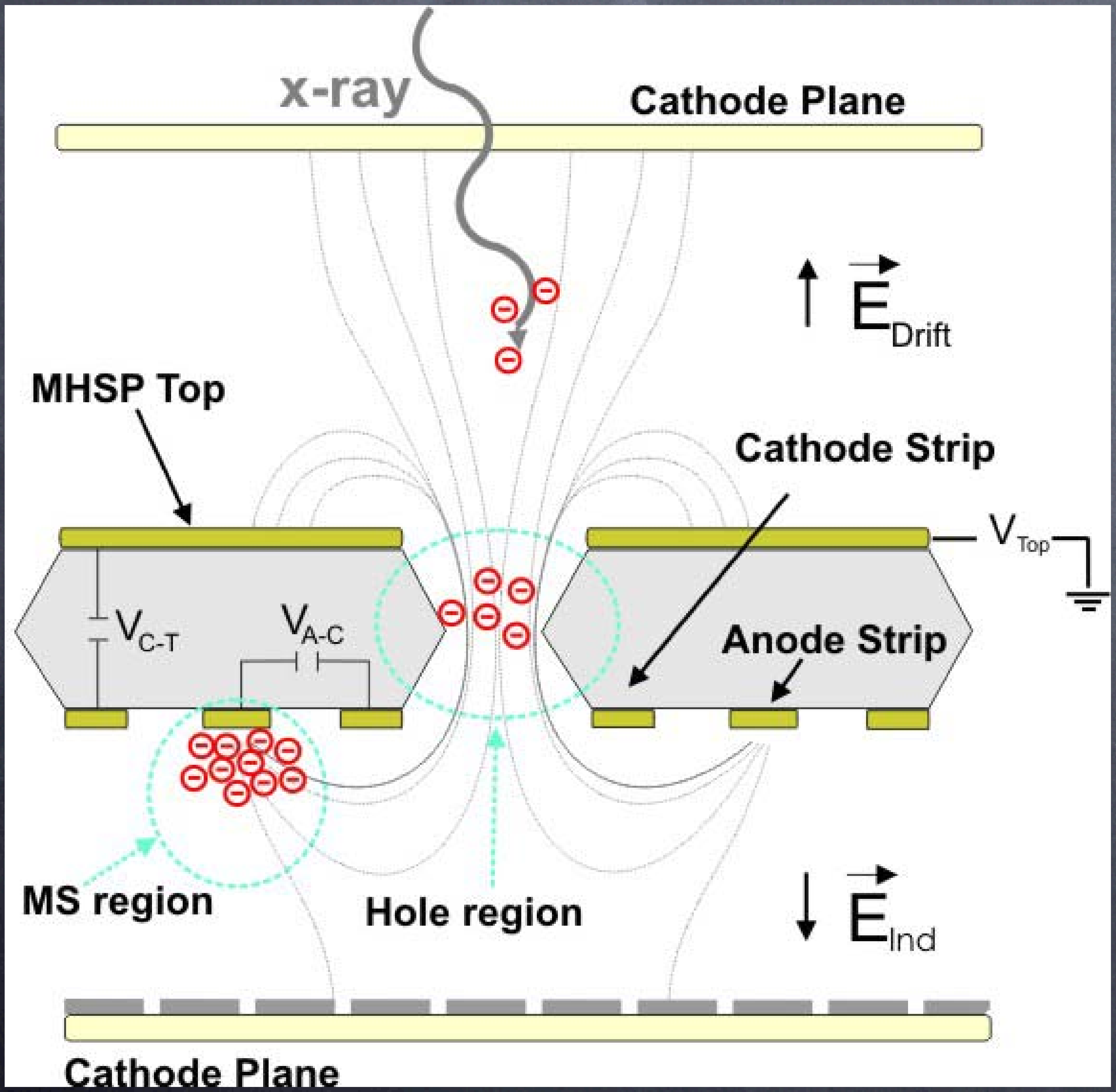
Xe
1atm
2atm
3atm
4atm
5atm
Gain
10^4
10^3
10^2
10^1
10^0
300
400
500
600
700
800
ΔV_{GEM} (V)
2 Phase

MHSP : Micro-Hole & Strip Plate electron multiplier

hole multiplication followed by anode-strip multiplication

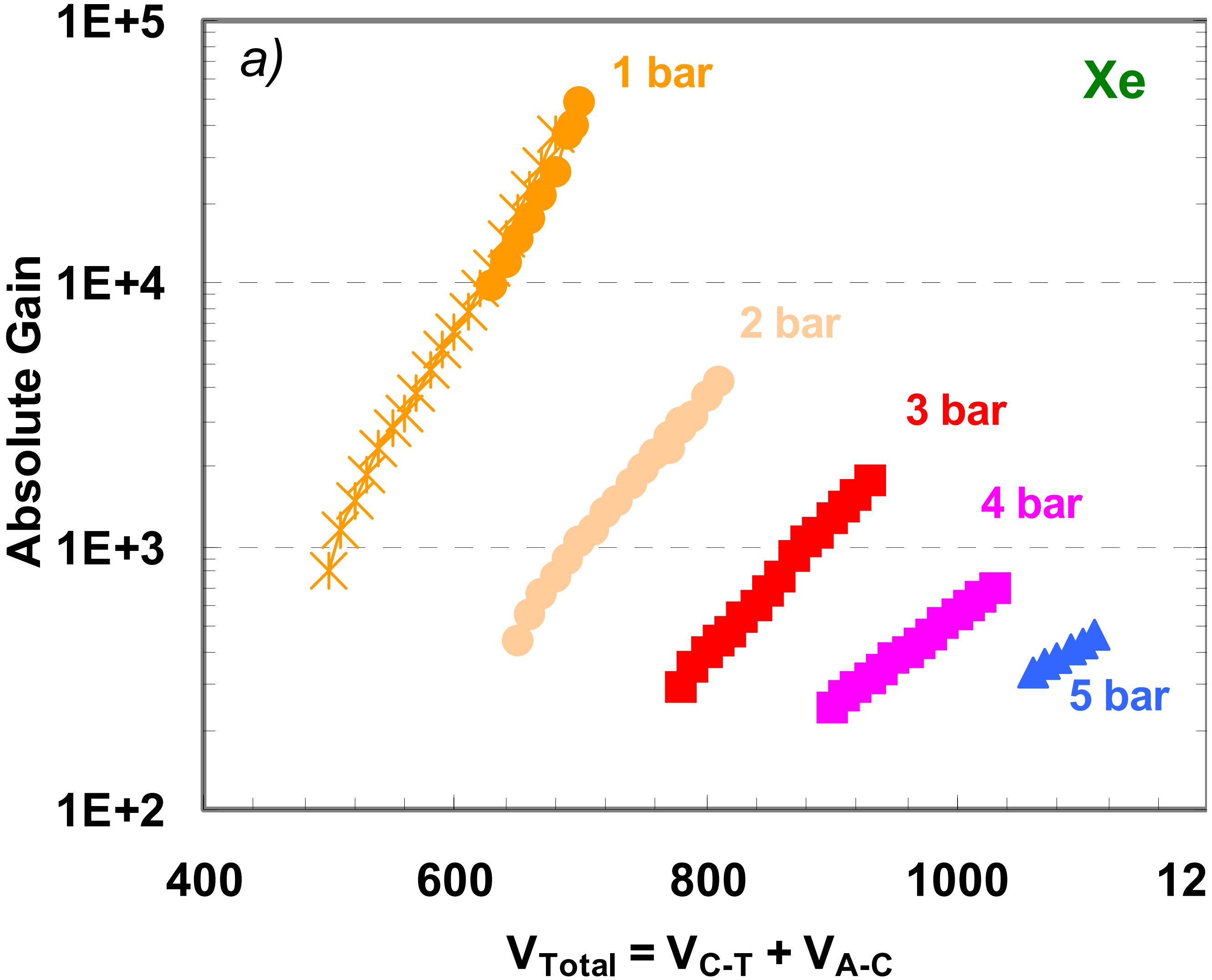
GEM-like MSGC-like

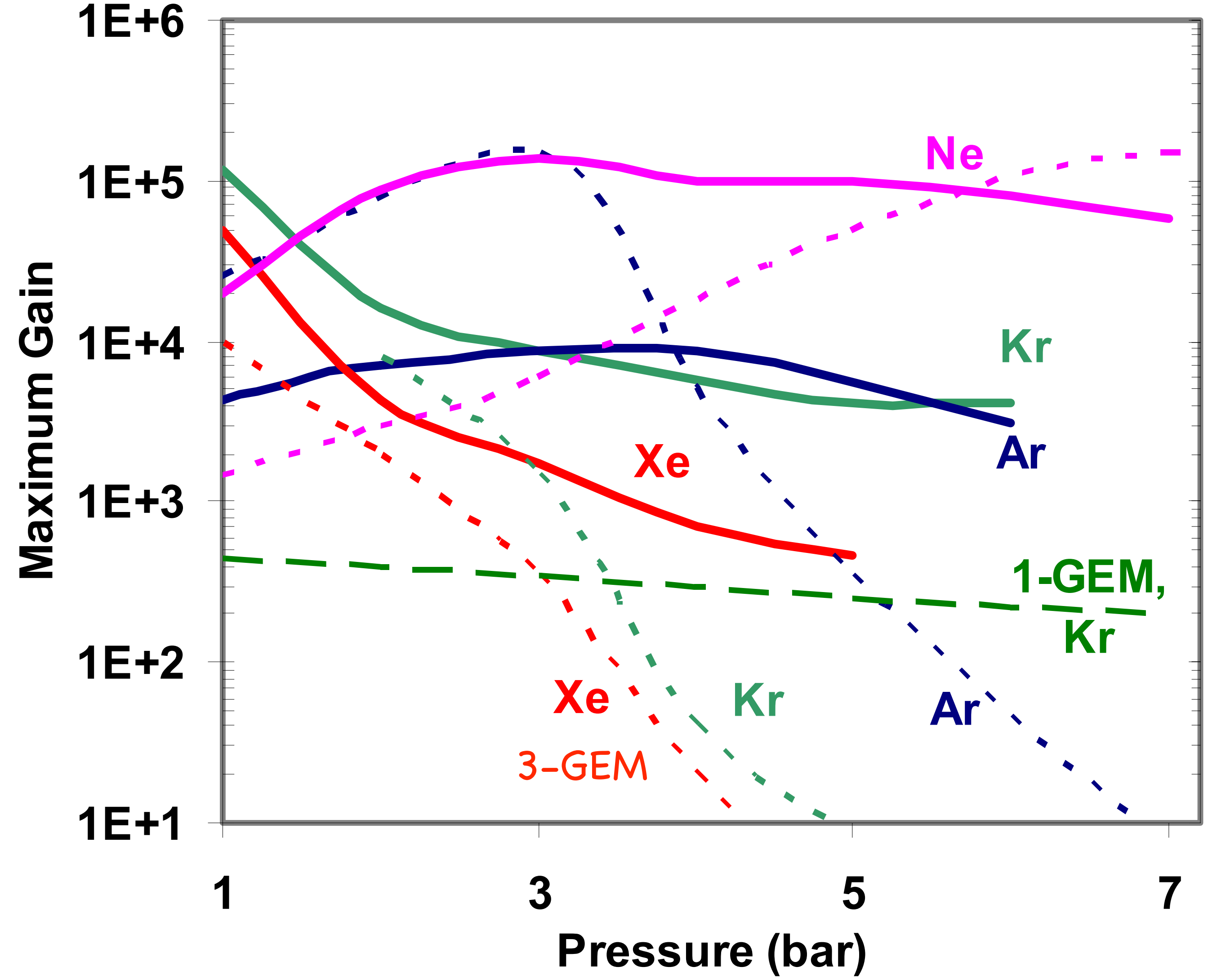
good optical screening of avalanche photons



28 x 28 mm^2, 50 μm thick Kapton with a 5 μm copper clad coating on both sides.

bi-conical holes of about 40/70 μm in diameter, arranged in an asymmetric hexagonal lattice of 140- and 200-μm pitch in the direction parallel and perpendicular to the strips pattern in the bottom side, with the holes centered within the cathode strips, ~100 μm wide, while the anodes, ~35 μm wide, run between them, in a 200 μm pitch





arxiv.org/pdf/physics/0601120

Operation of MHSP multipliers in high pressure pure noble-gas F. D. Amaroa, J. F. C. A. Velosoa,b, A. Breskinc, R. Chechikc, J. M. F. dos Santosa,*

aPhysics Dept., University of Coimbra, 3004-516 Coimbra, Portugal bPhysics Dept., University of Aveiro, 3810-193 Aveiro, Portugal cDept. of Particle Physics, The Weizmann Institute of Science, 76100 Rehovot, Israel

Small Animal PET

Small Animal PET

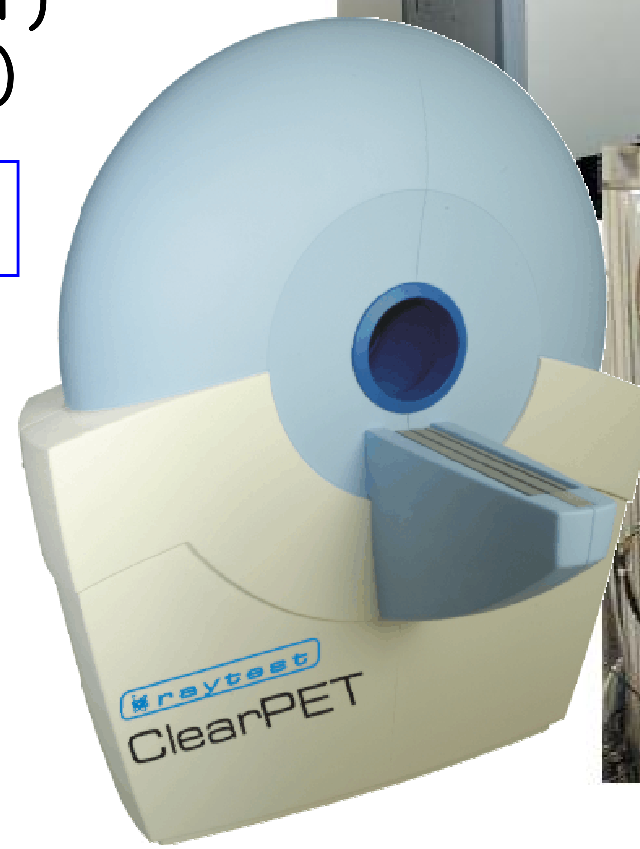
microPET, ClearPET

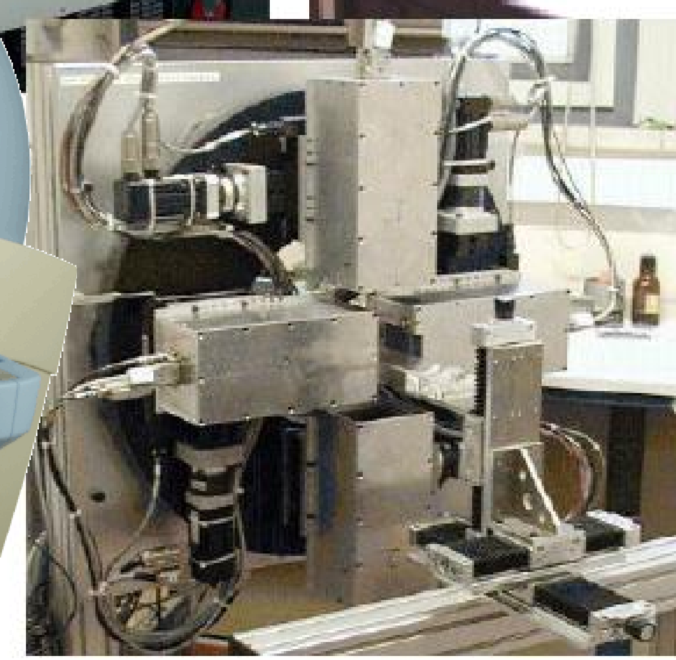
HIDAC (MWPC with Pb converter)
RPC-PET (RPC with Cu converter)

Spatial resolution: 2mm FWHM

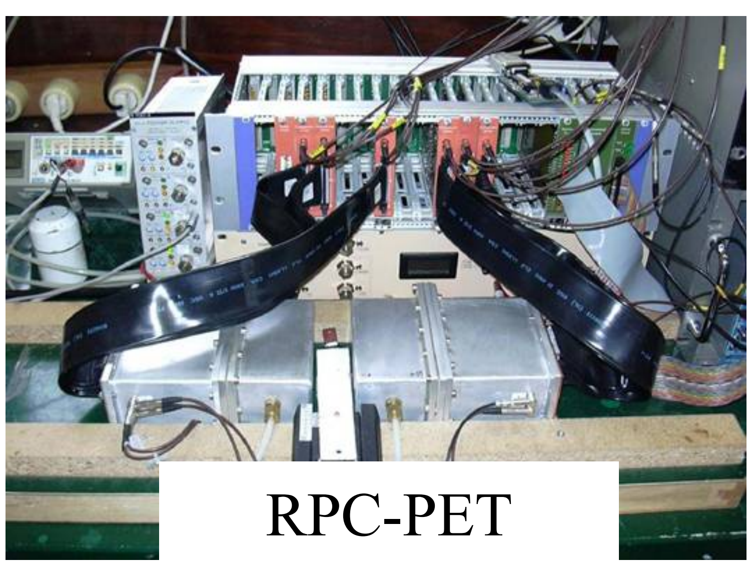
HIDAC

microPET ™





YAP-PET

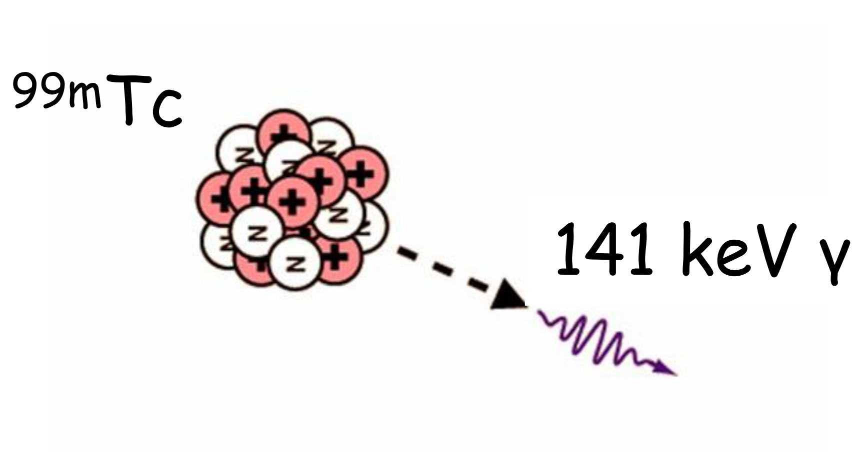


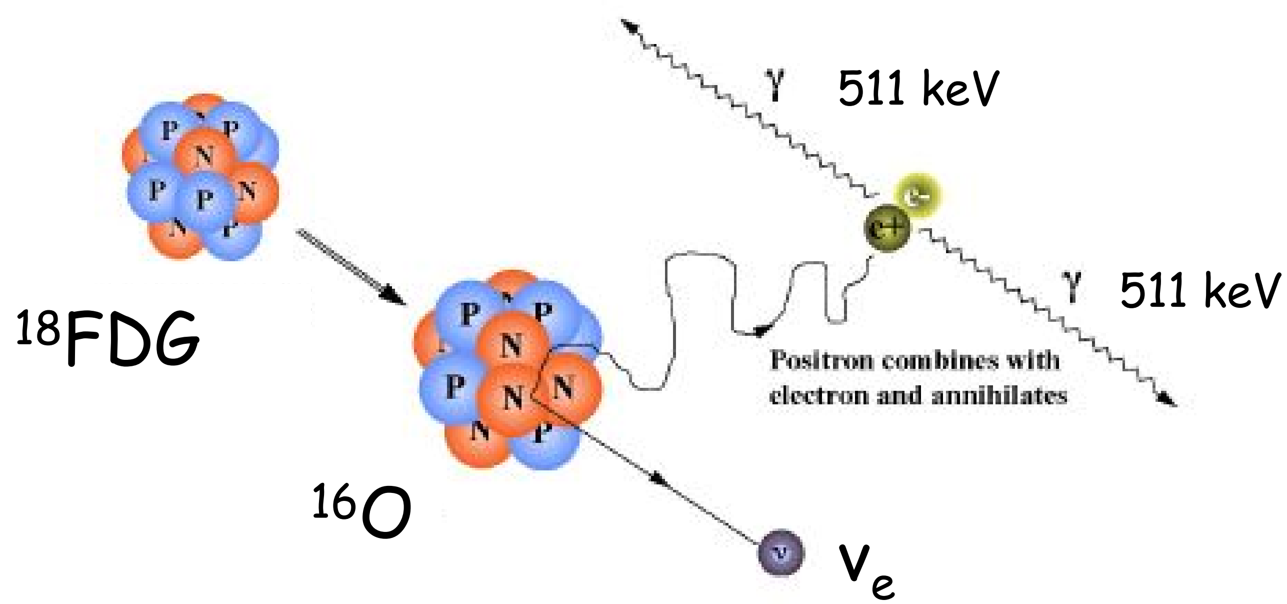
RPC-PET

SPECT and PET

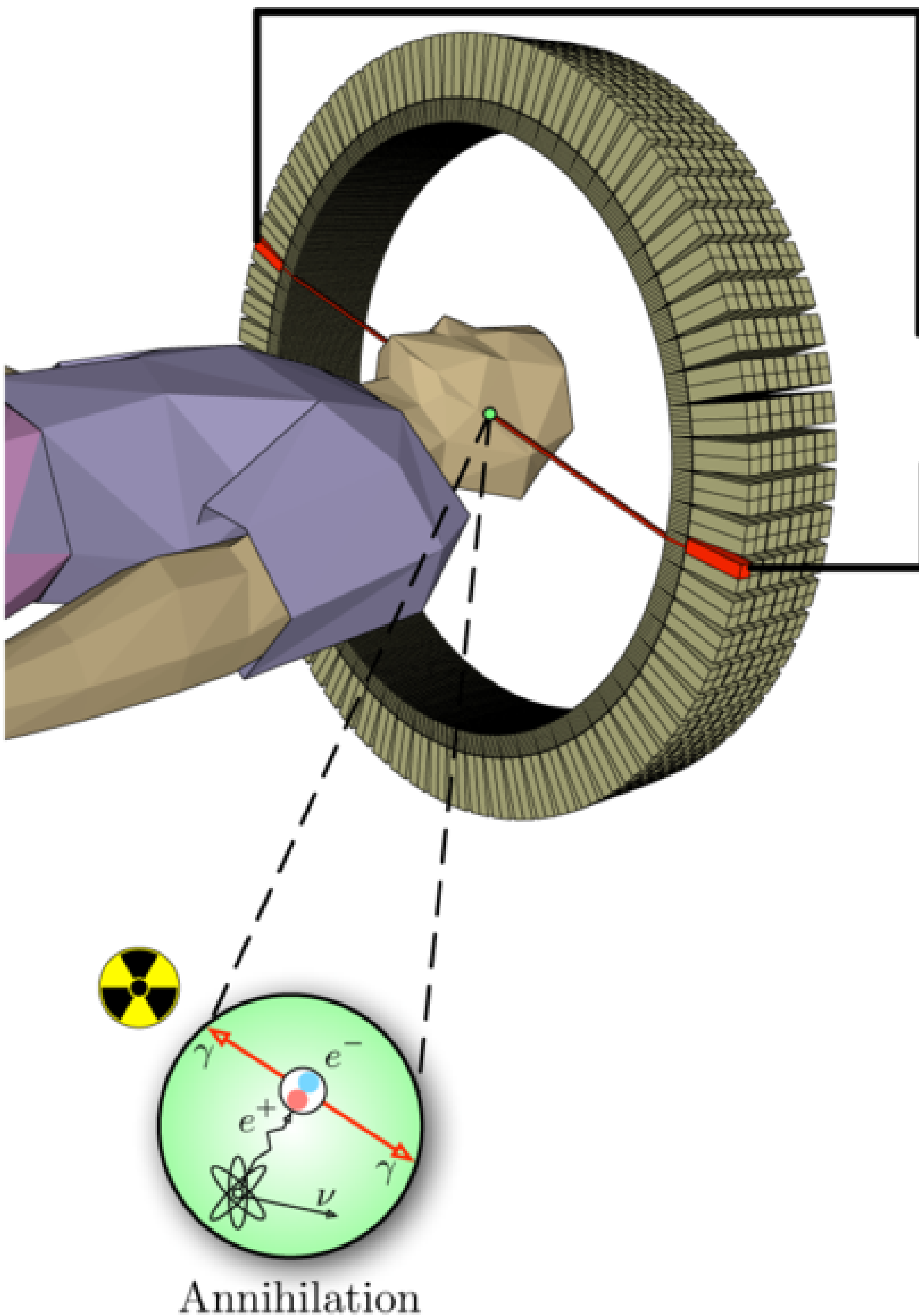
morphologic and physiologic

SPECT	PET



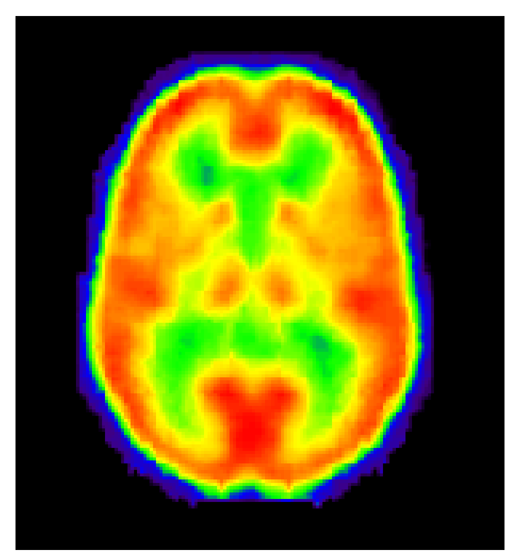


Positron Emission Tomography



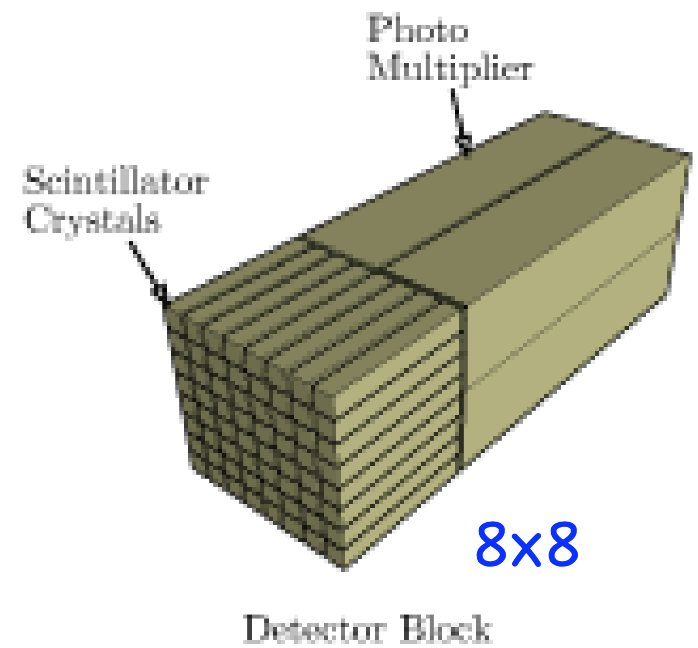
Coincidence unit of 2 anti-parallel photons

Tomographic reconstruction



Scintillator crystal
Multi-anode PMT

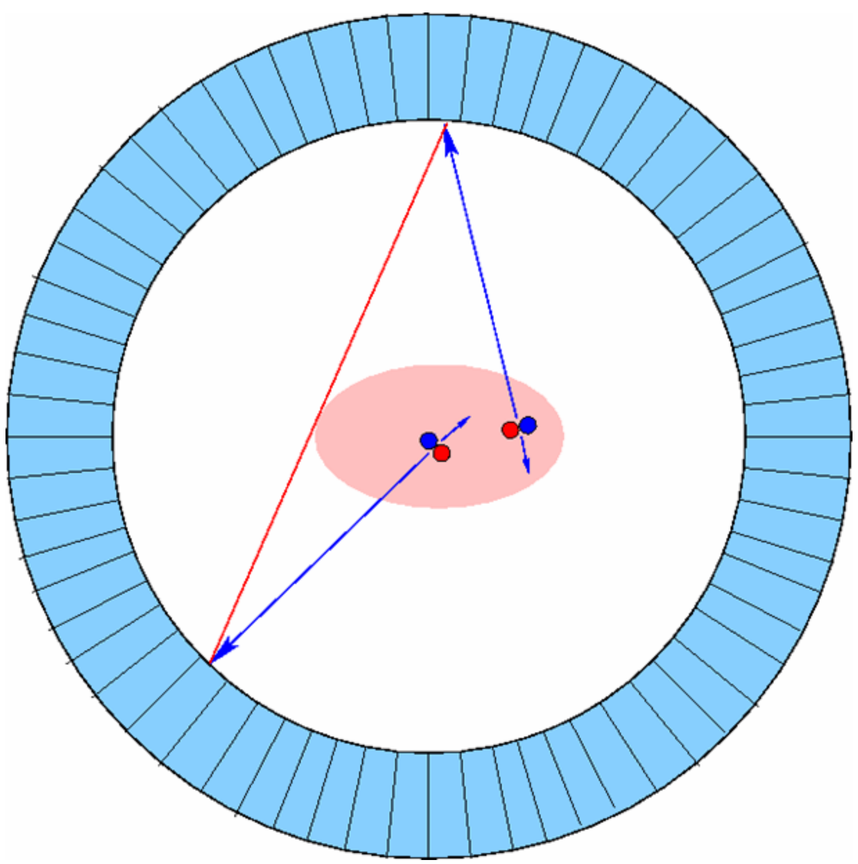
$2 \times 2 \times 10\,mm^3$
micro-, Clear-PET



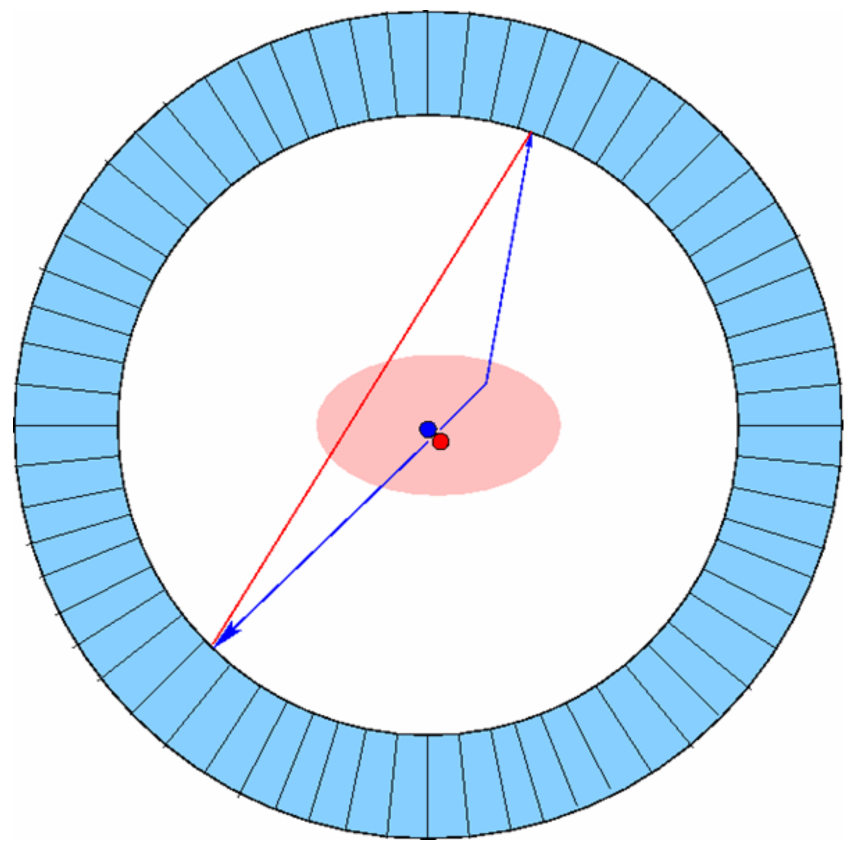
Typical image resolution
5 ÷ 10 mm

PET Image Degradation Sources

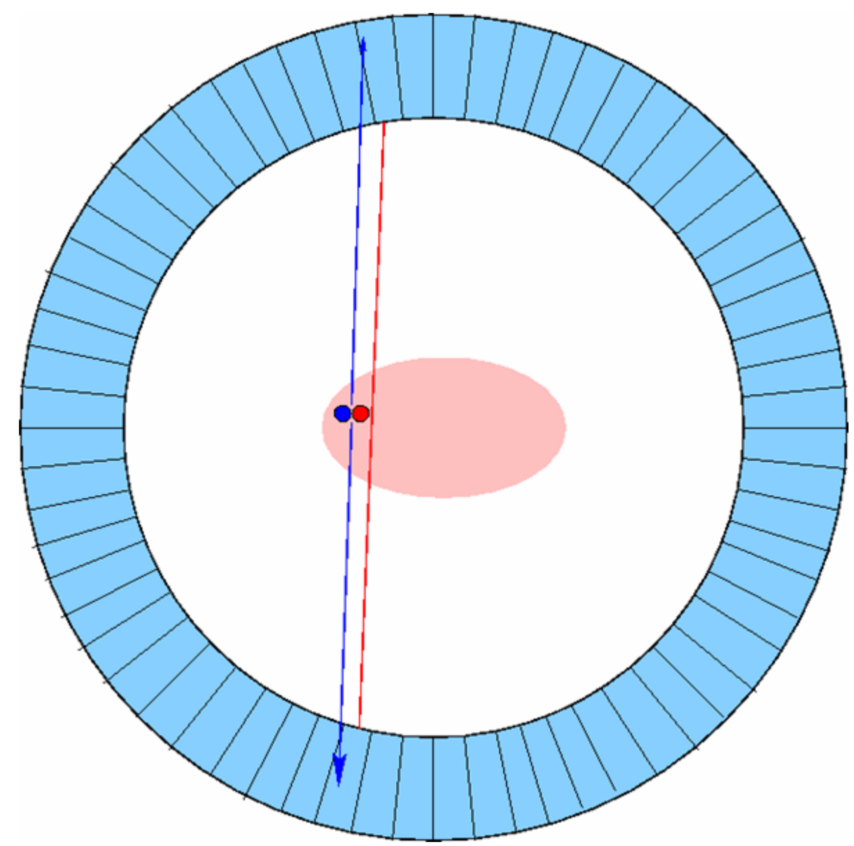
Random coincidences



Scattered events



Off-center emission Parallax error



HIDAC High Density Avalanche Chamber

QUAD-HIDAC-16

Oxford Positron System, UK

16-Module : 4 layers/QUAD

32-Module : 8 layers/QUAD

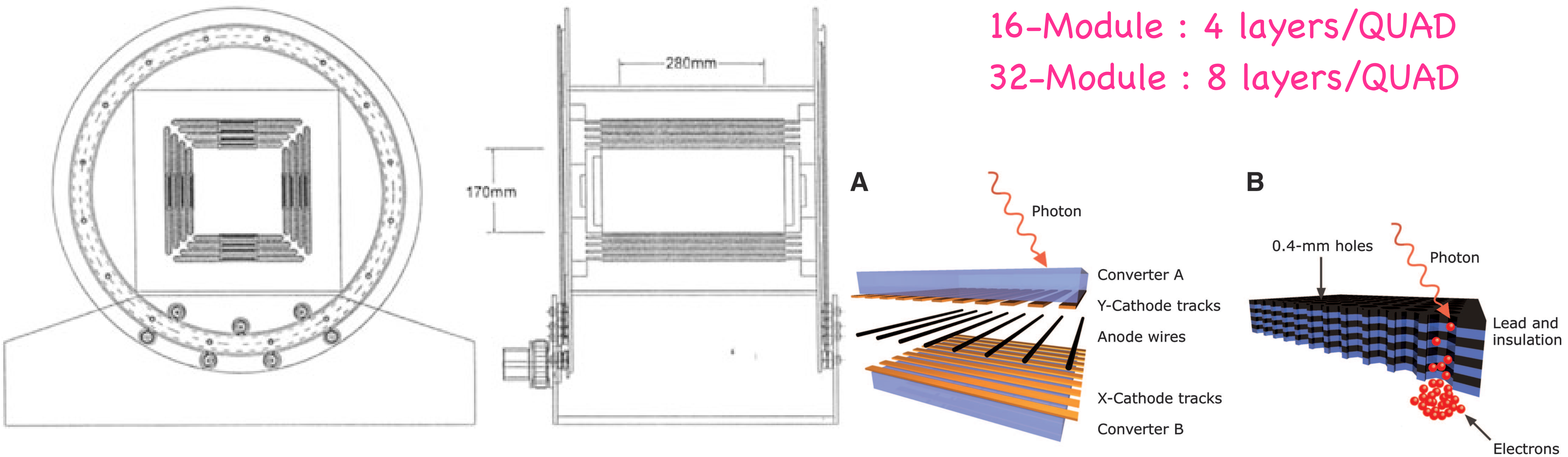


Figure 1. Schematic design of quad-HIDAC tomograph detector configuration. The 16 modules are clearly visible.

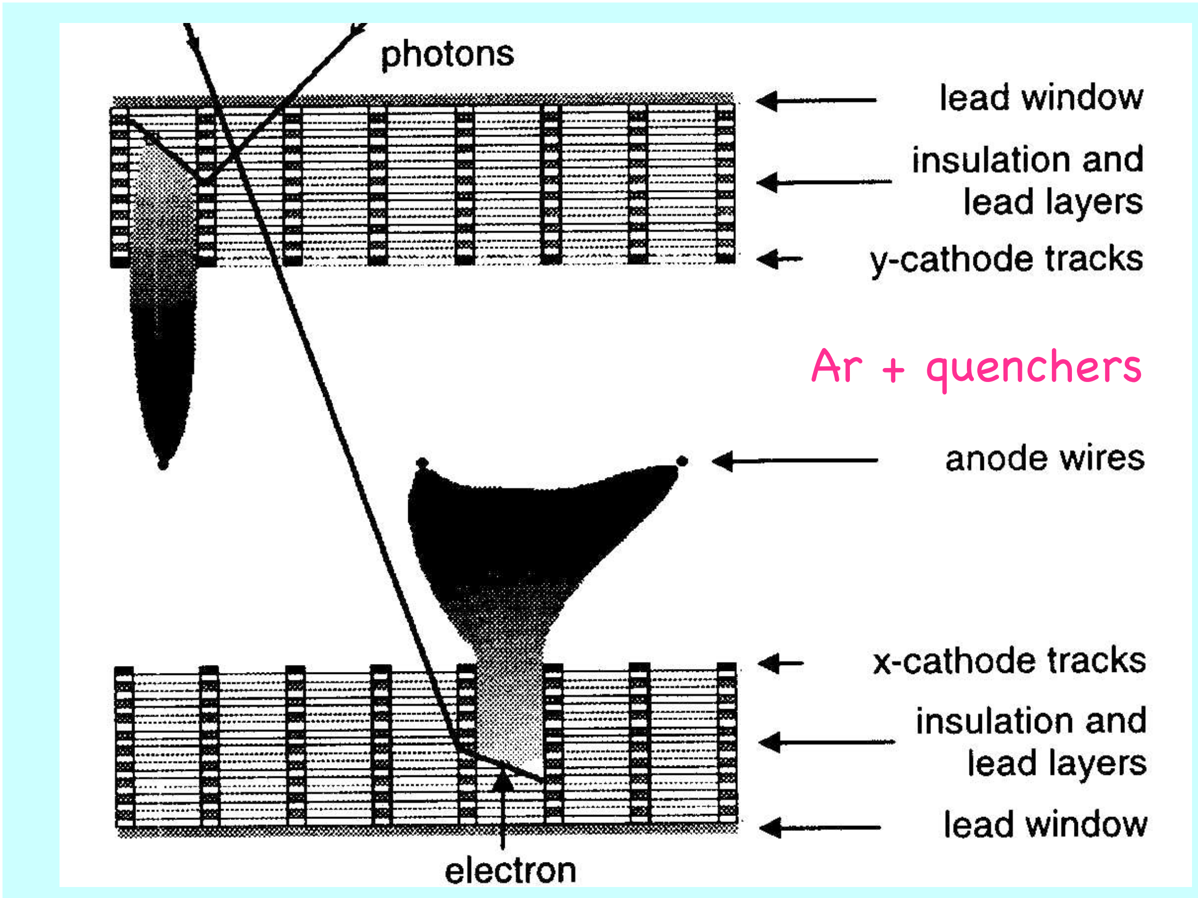


Table 1. Selected system parameters of 16-module quad-HIDAC small animal PET tomograph. The reconstructed image size is specified in terms of diameter and length of the field-of-view.

Detector	
Hole diameter	0.4 mm
Separation between hole centres	0.5 mm
Cathode track separation	1 mm
Anode wire separation	1.5 mm
Lead thickness/module	$12 \times 50\ \mu m$
Coincidence window	40 ns
Dimensions	
Detector length	280 mm
Inner detector separation	170 mm
Data sets	
List mode file size	$\sim$100 MB/10^7 counts
Typical binning percentage	90%
Reconstructed image size: 60 mm × 100 mm at 0.3 mm	52 MB
Sampling distance	0.1 mm–1 mm variable

RPC-PET

Portugal, Spain

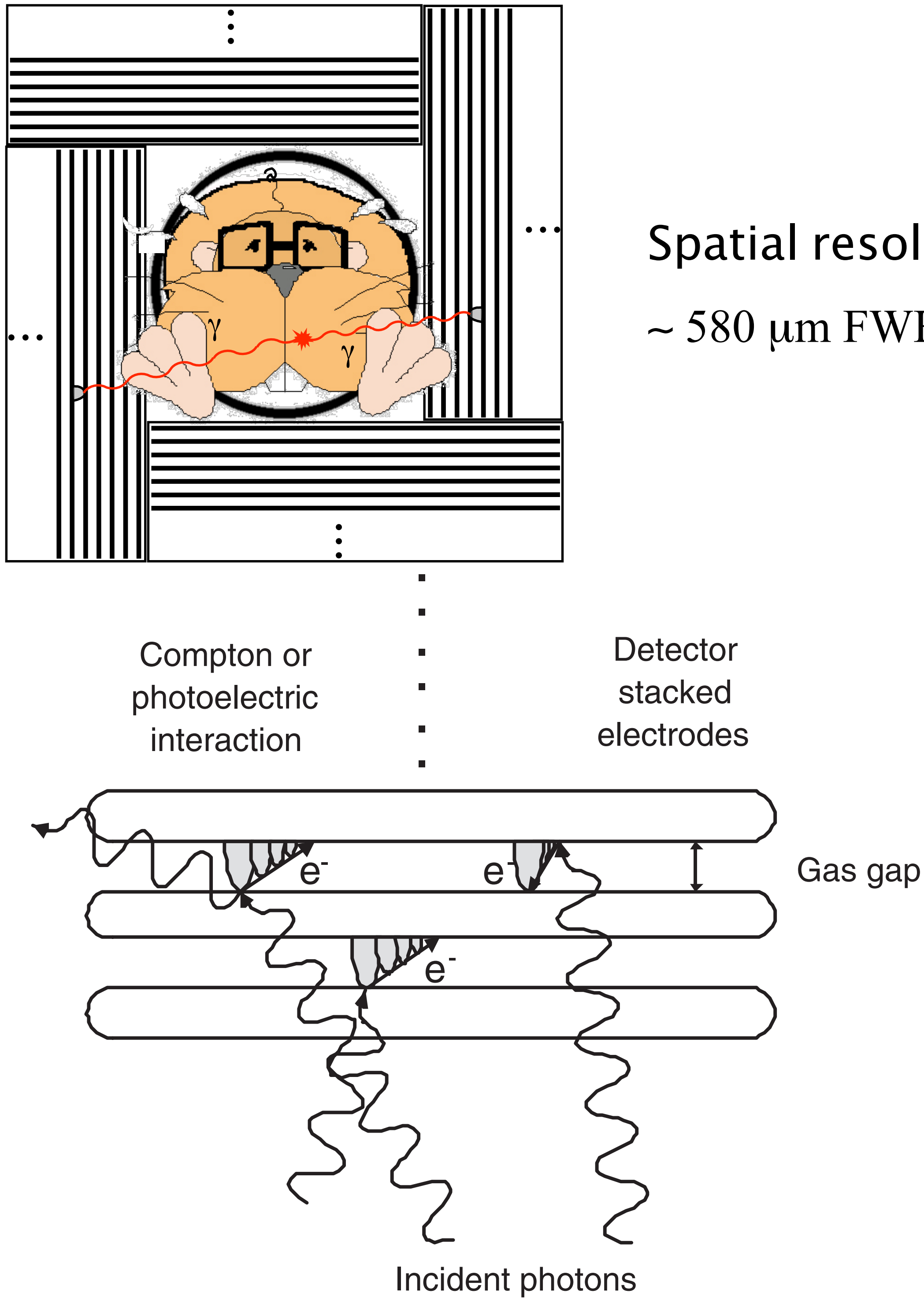


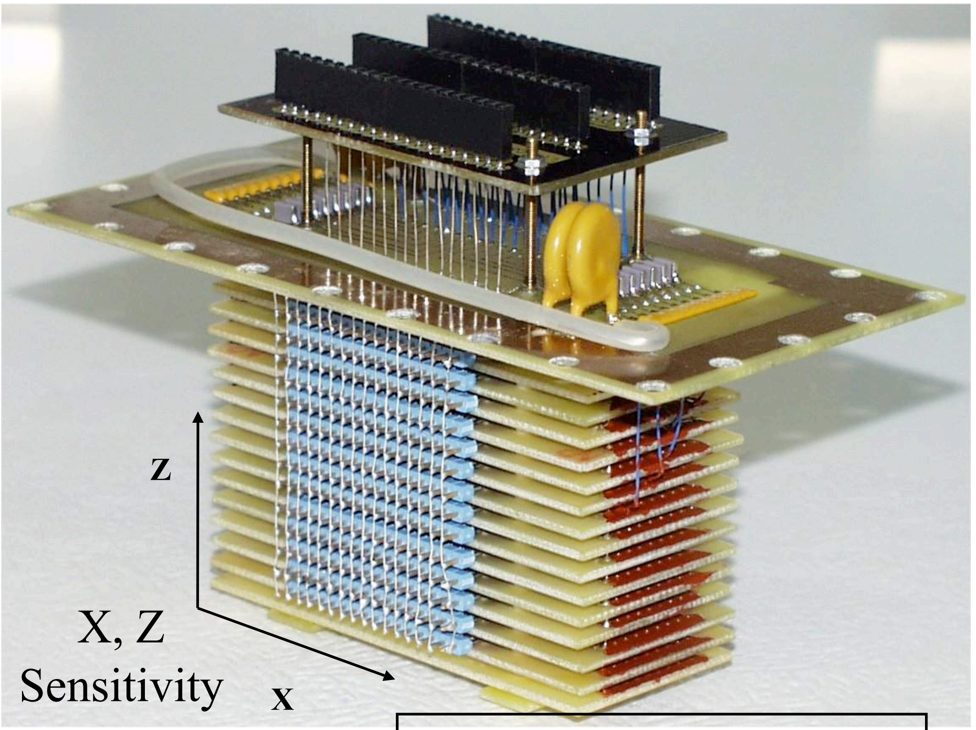
Fig. 1. Schematic view of the detecting element, showing the detection process of the incident gamma photons, which take profit of the stacked construction of the RPCs.

Spatial resolution

~ 580 µm FWHM

the metallic cathode of one RPC on one side and on the opposite side the resistive anode of the next RPC

in $C_2H_2F_4$ 85 %, SF_6 10%, C_4H_{10} 5%

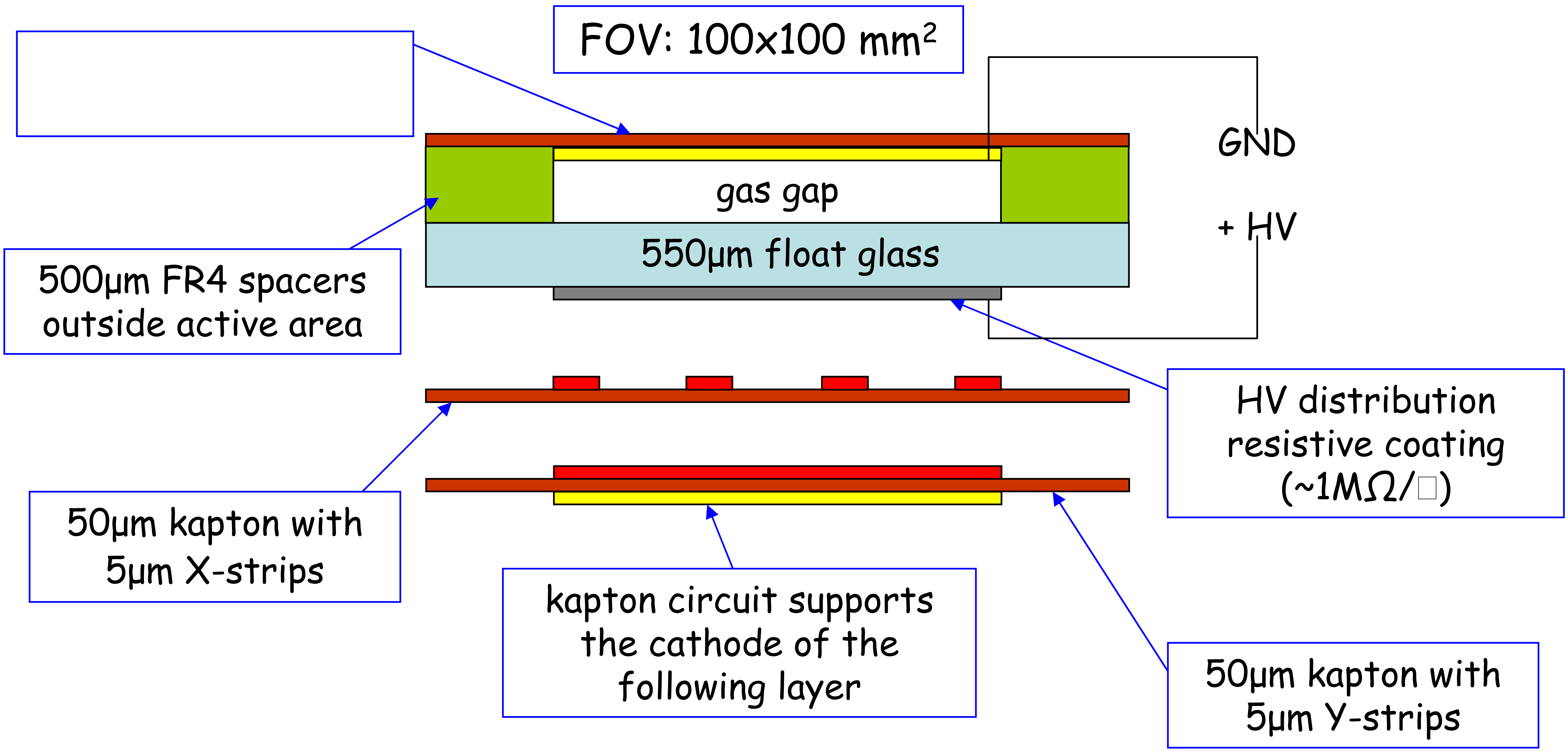


Active area 32 x 10 mm^2

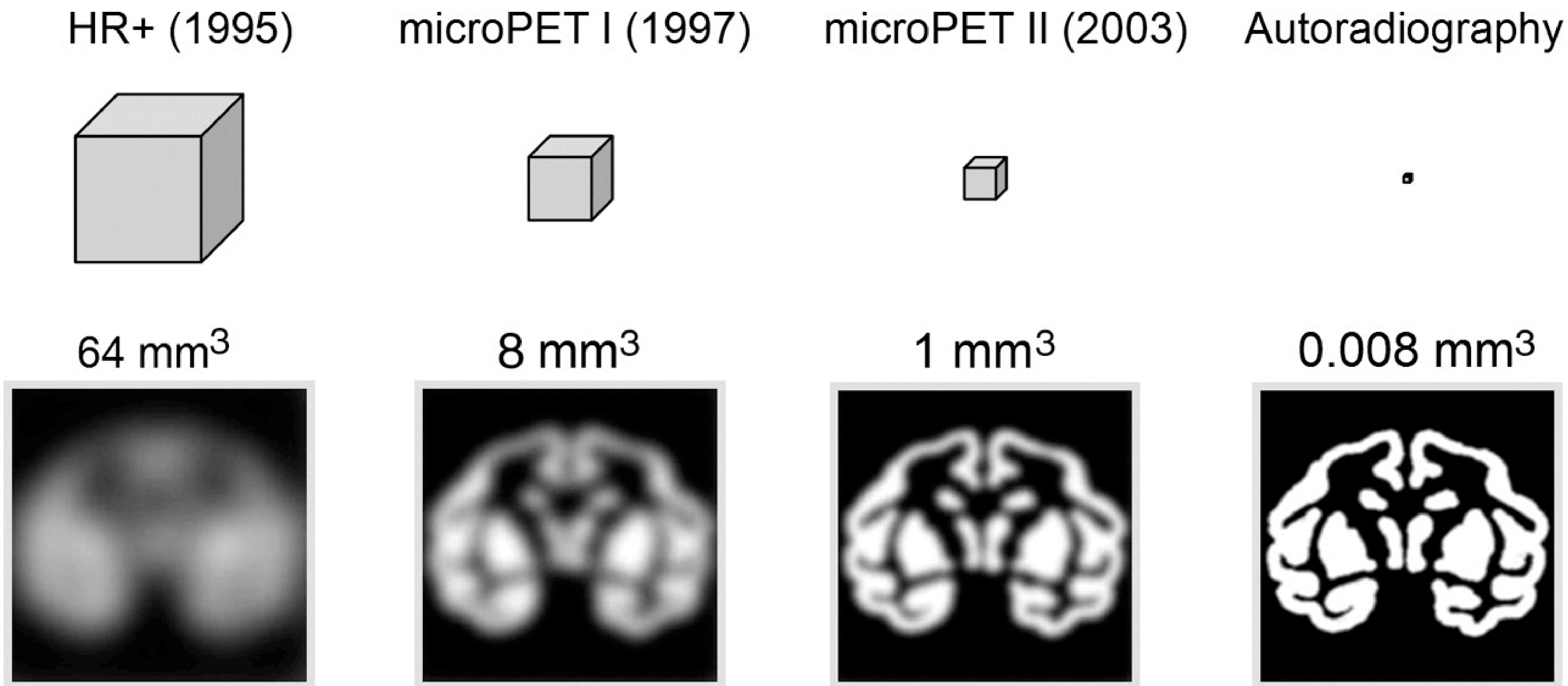
- **Copper** (on a PCB) and **glass electrodes**.
- 0.3 mm Gap.
- 32 1-mm wide X pickup strips.
- Not optimized for high efficiency.

Hybrid Parallel Plate Counter

Hybrid: the anode is resistive (glass), the cathode is conductive (gold)



Many single layers are stacked to realize one detector



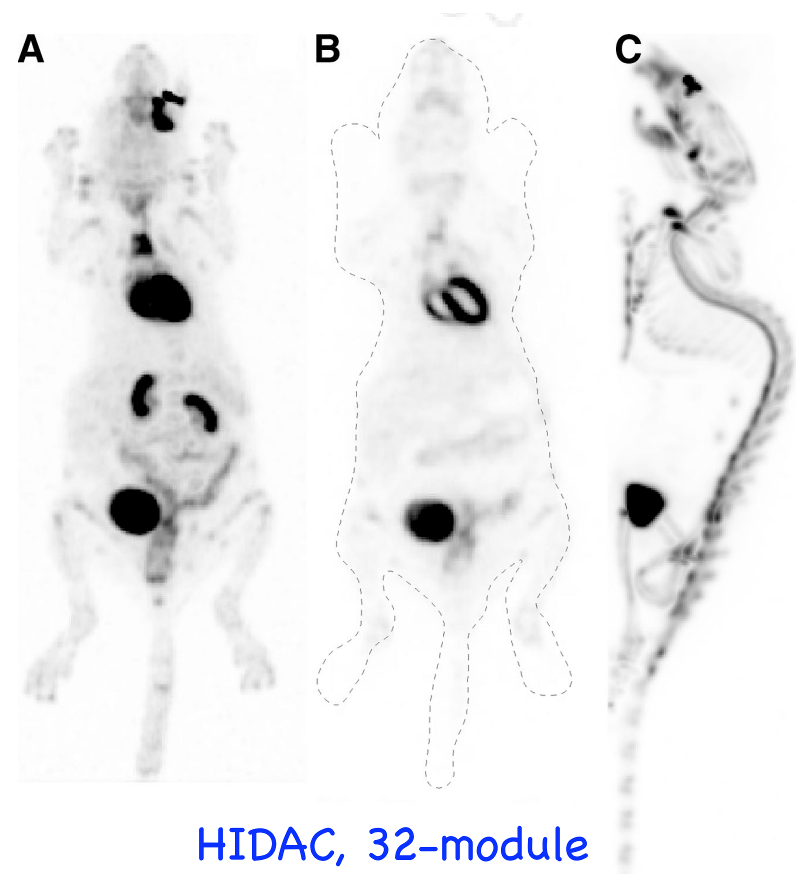


FIGURE 6. (A and B) Images (OPL-EM) of 22-g mouse, acquired in 15 min, 1 h after injection of ^{18}F-FDG show maximum intensity projection (A) and a single central slice (B). (C) Maximum intensity projection of 27-g mouse, 1 h after injection of ^{18}F fluoride.

Summary of small animal PETs

TABLE II. COMPARISON BETWEEN DIFFERENT SMALL ANIMAL PET PARAMETERS AND THE EXPECTED PARAMETERS OF THE RPC-PET.

Scanner	Image Spatial resolution, FBP (mm)	Time resolution (ns FWHM)	FOV (mm Ø x mm)	Central point absolute sensitivity (cps/kBq)	Source (mm Ø x mm)	Peak NEC (kcps)
microPET II® [1],[15]	1.1	3	160 x 49	23 - 33	25 x 70 mouse size 60 x 150 rat size	235 at ~2.35 MBq/cm^3 24.6 at ~0.19 MBq/cm^3
YAP-PET [2],[16]	1.6	2	40 x 40	18 at (Ø = 150 mm)	-	90 (not peak) at ~16.6 MBq
Quad HIDAC (32 modules) [7],[17]	0.95	-	170 x 280	18	-	100 at ~0.2MBq/cm^3
RPC-PET	0.5*	0.3	60 x 100	21**	25 x 70 mouse size	318** at ~ 2.63 MBq/cm^3

* Measured, ** Simulated

ClearPET	1.25-2	5.7	(135-225)x110		(125-200)x110	

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MEG-TPC

LXe-PET : no segmentation with PMT, TPC

83.2 l, 80cmΦ , 12cm depth, 24cm axial length

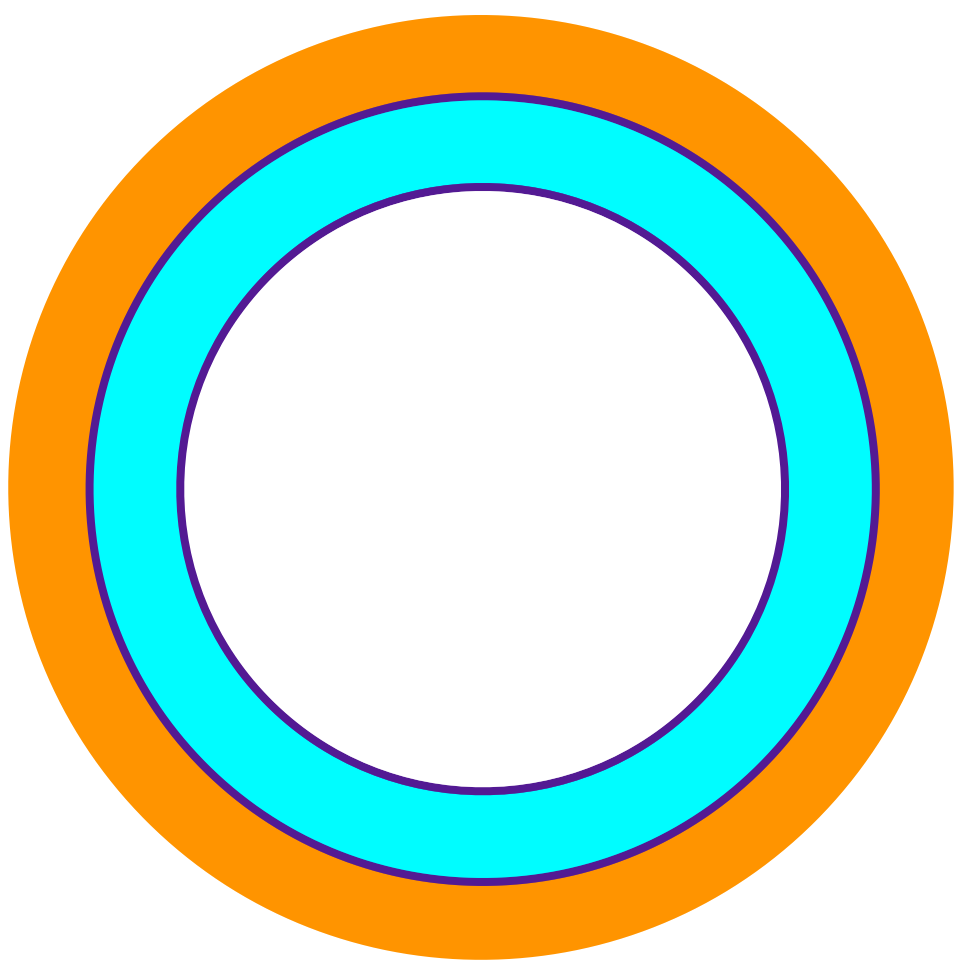
(1)

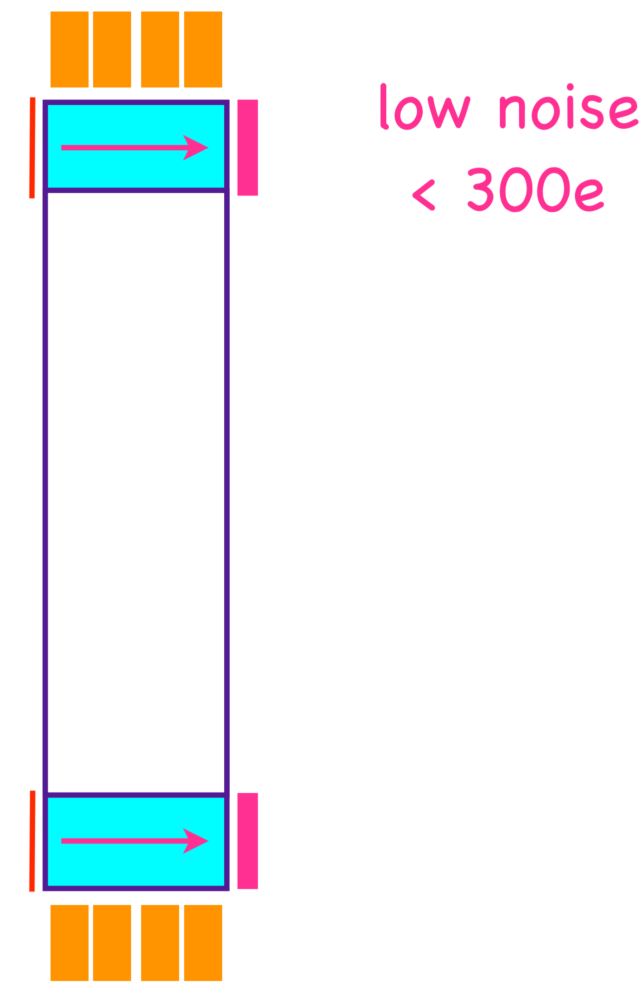
2"PMT : 4x54=216

Spatial resolution = 2 mm
Time resolution = 1 nsec
timing for the TPC

TPC : 48kV

52.2μsec/24cm
(2.3mm/μsec)
continuous readout
with time stamp by PMT





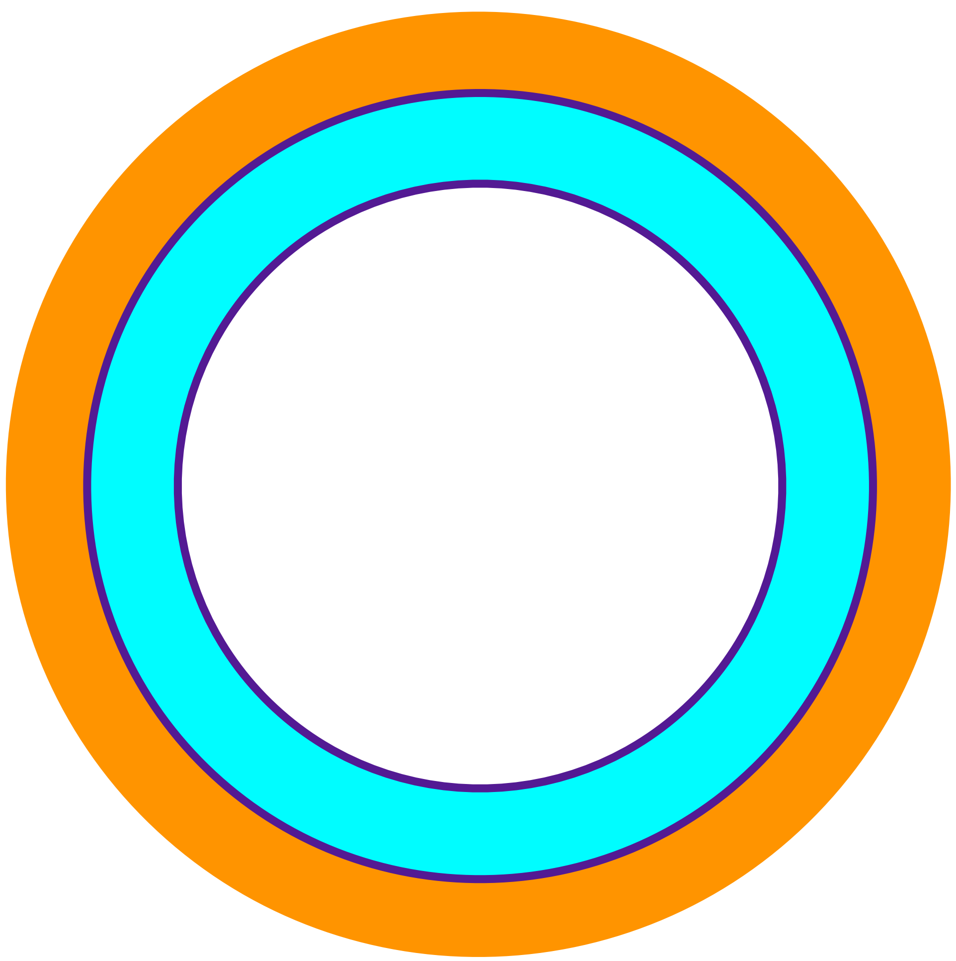
LXe-PET : no segmentation with PMT, TPC

83.2 l, 80cmΦ , 12cm depth, 24cm axial length

(2) 2"PMT : 4x54=216

Spatial resolution = 2 mm
Time resolution = 1 nsec
timing for the TPC

TPC : 48kV
52.2μsec/24cm
(2.3mm/μsec)
continuous readout
with time stamp by PMT



detection in 2 phase
GEM, MHSP