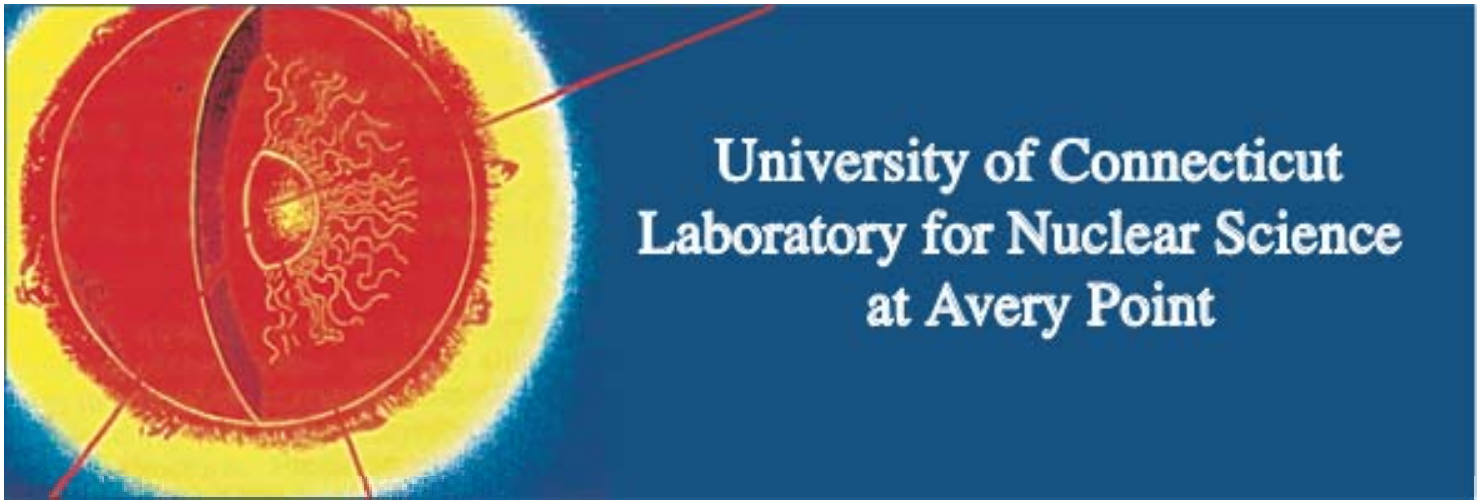

Applications of Two-Phase (Liquid/Gas) Xenon Gamma Cameras to the Detection of Special Nuclear Material and PET Medical Imaging

Nicholas E. Destefano
University of Connecticut
Yale University

- Noble Liquid Detector
- Applications of Xenon TPC Detectors
- The PIXeY Detector

DOE grant Number DE-SC0004599 ANS&T Washington, D.C. August 22, 2011

Applications of Two Phase (Liquid/Gas) Xenon Gamma Cameras to the Detection of Special Nuclear Material and PET Medical Imaging

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Detector Materials

	Energy resolution (σ @ 662 keV)	Position resolution (cm)	Density (g/cc)	Cost ($/kg)	Detector element thickness (cm)	n/gamma discrimination
Plastic scintillator	Poor	~10	1	~30	~20	No
Liquid scintillator	17%	~10	0.9	~30	~20	Yes
Sodium Iodide	5%	~ few cm	3.7	~800	~10	No
CZT	0.33%	~0.1	5.8	~50,000	~1	No
Germanium	0.17%	~0.3	5.3	~20,000	~5	No
Liquid xenon	2.5-5%	~0.1	3	~1,000	~20	Yes

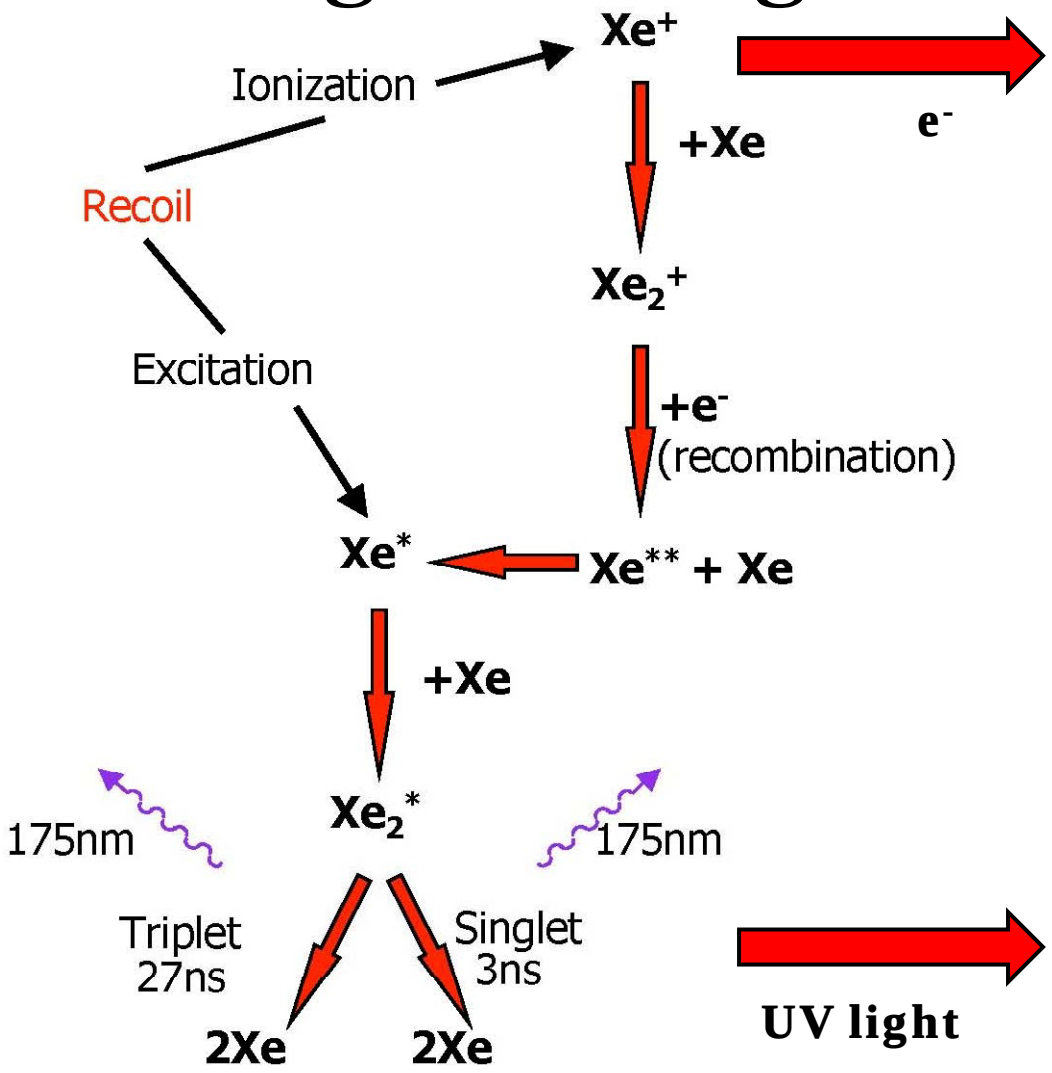
Liquid xenon combines:

- Energy resolution between CZT and sodium iodide
- Cost of sodium iodide
- Position resolution of CZT
- Scalability of organic scintillator

Additional Properties:

- 6-cm attenuation length at 1 MeV
- ~25 ns response
- 13.6 eV/e^-

Xe Charge and Light Production

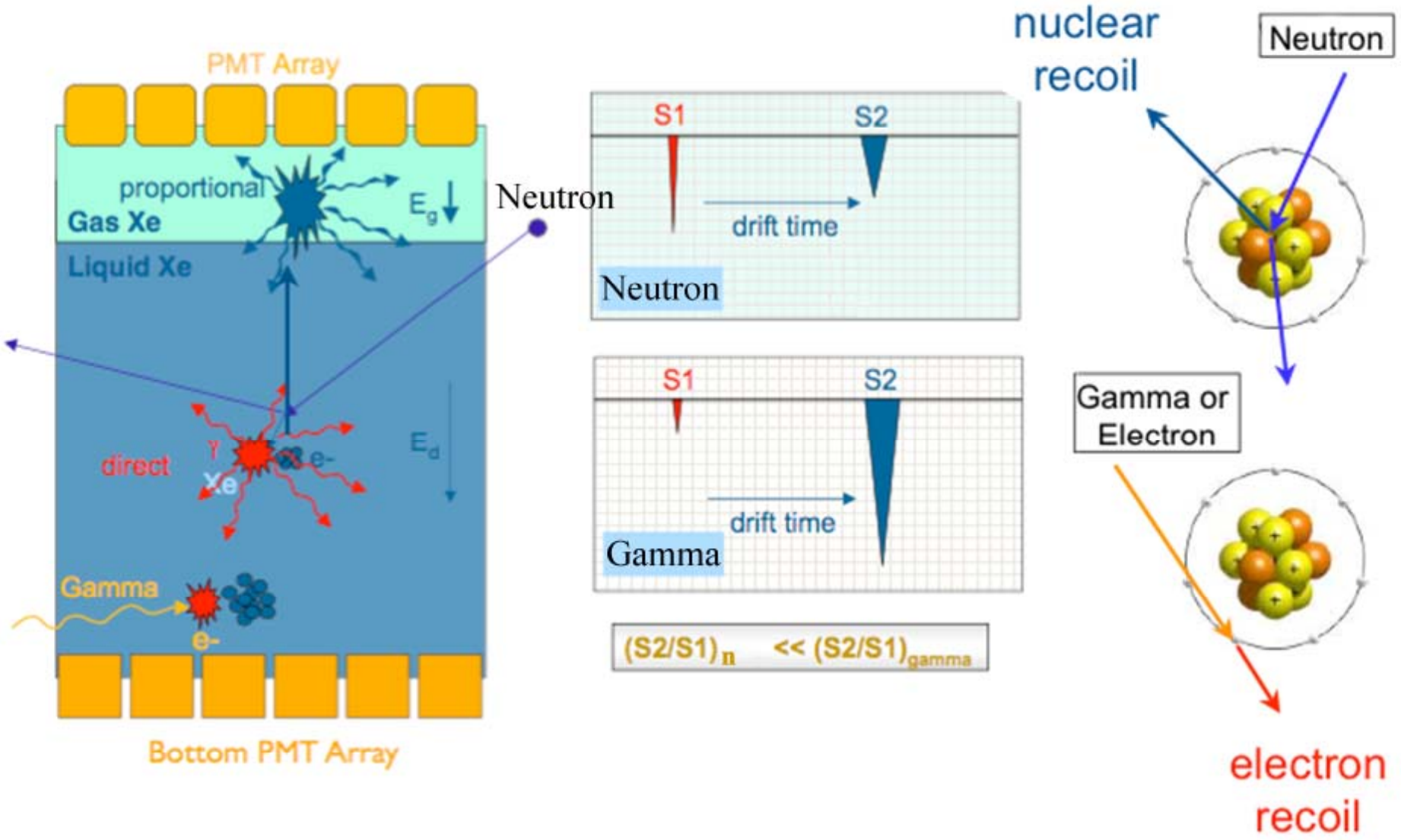


Secondary signal: ionization electrons.

Recaptured electrons.

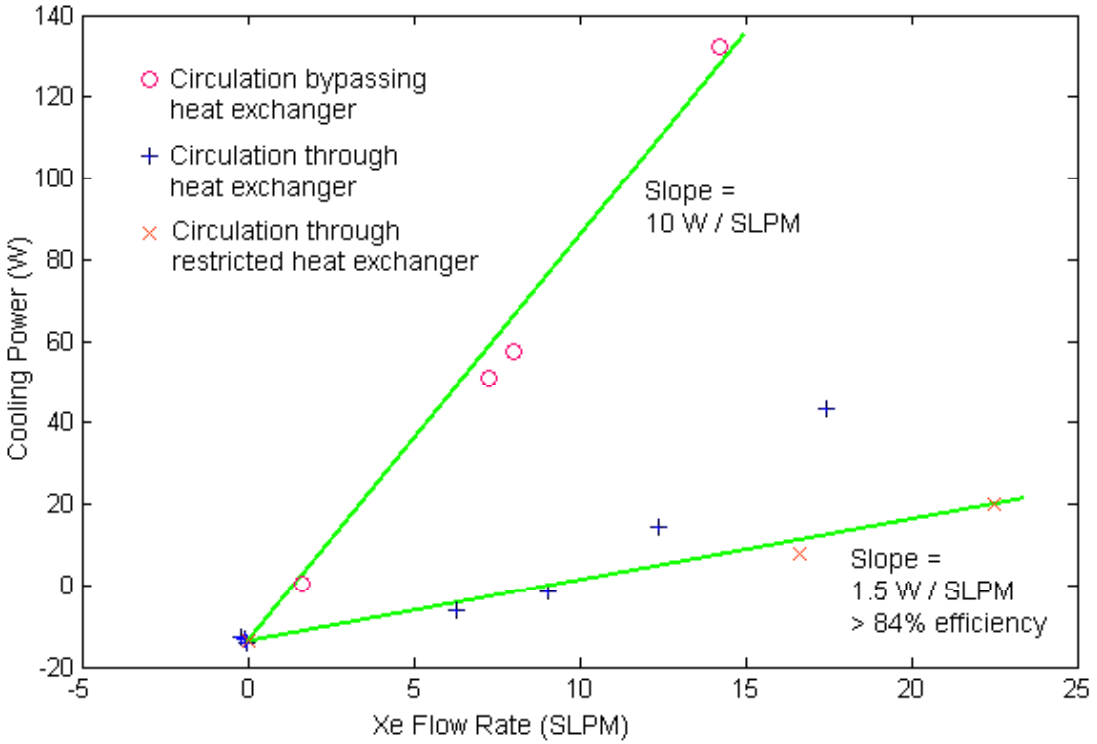
Primary light signal.

Two-phase Xe Detectors: How They Work



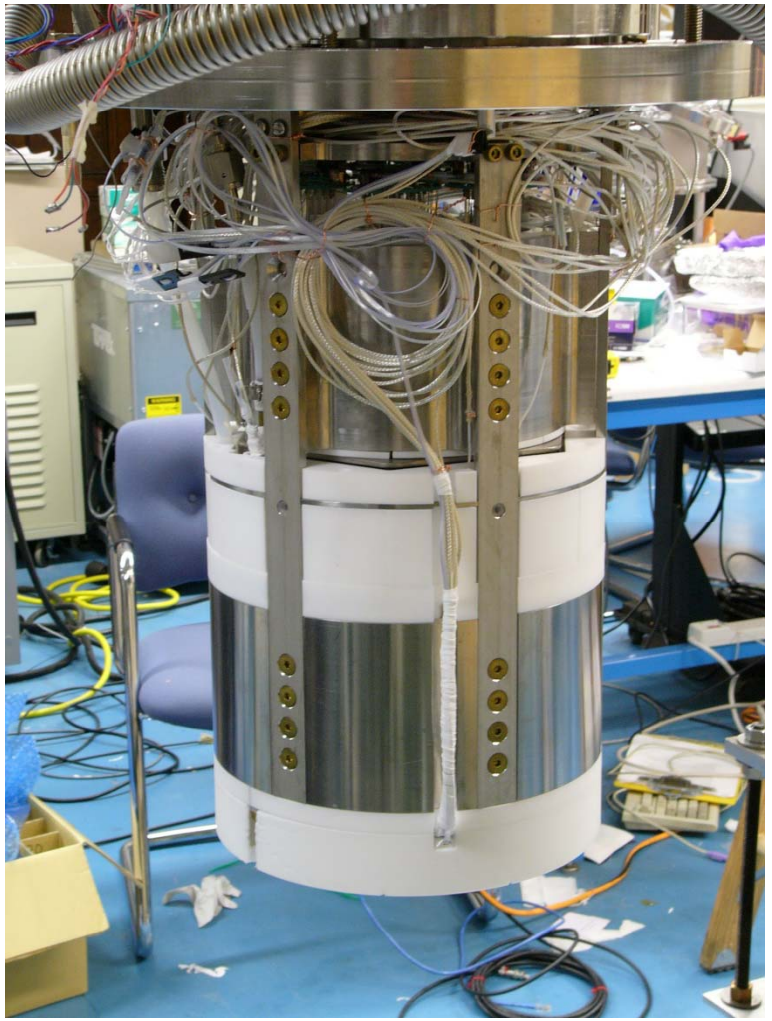
Project Goals

- Development and commissioning of cryogenics
- Monte Carlo simulations of Compton imaging
- Demonstration of superior energy resolution in dual phase operation

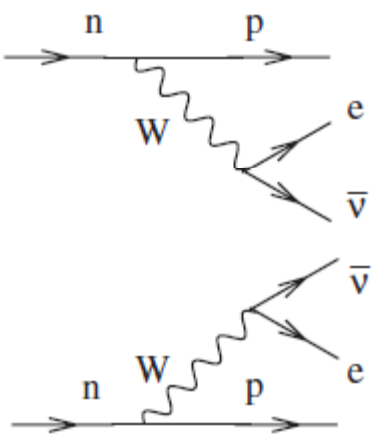


Noble Liquid Detector Applications

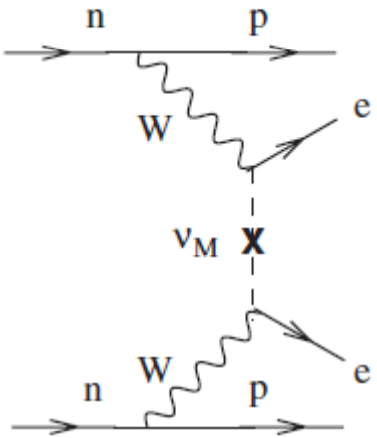
- Fundamental Physics
- Passive/Active Cargo Inspection of Special Nuclear Materials (SNM) With Compton Imaging
- Three Photon PET



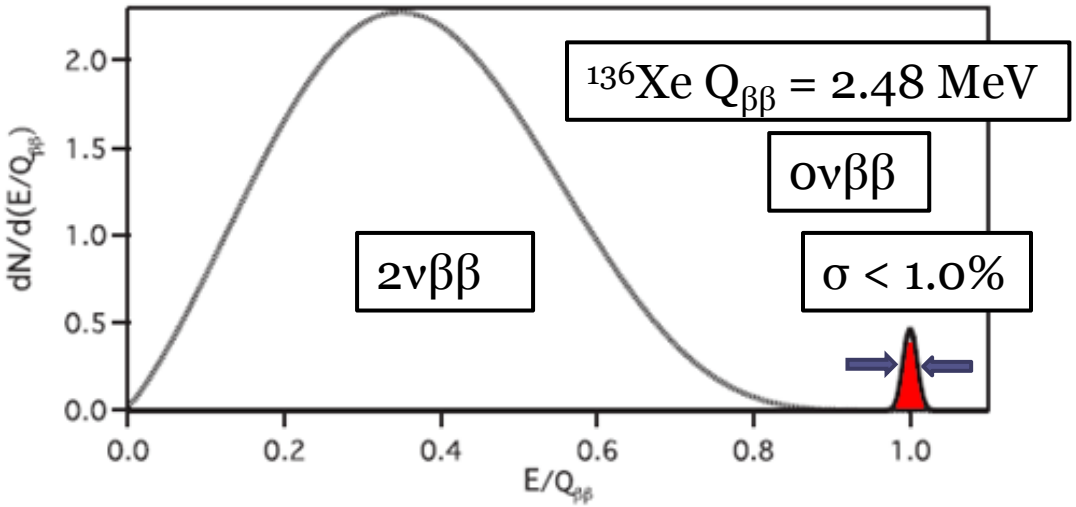
Double Beta Decay

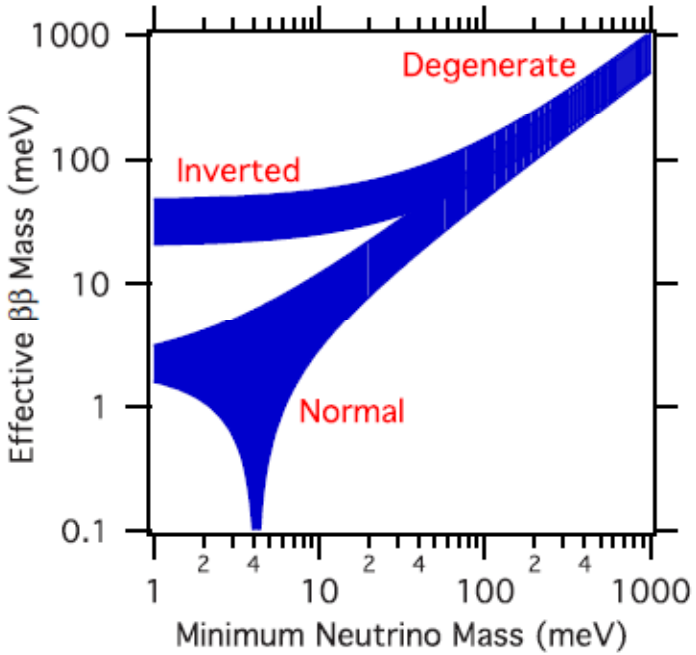


Two neutrino double beta decay (2νββ)



Neutrinoless double beta decay(0νββ)

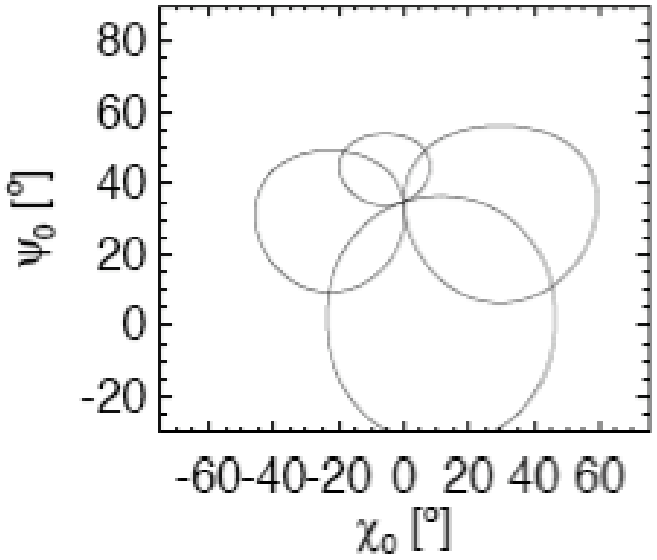


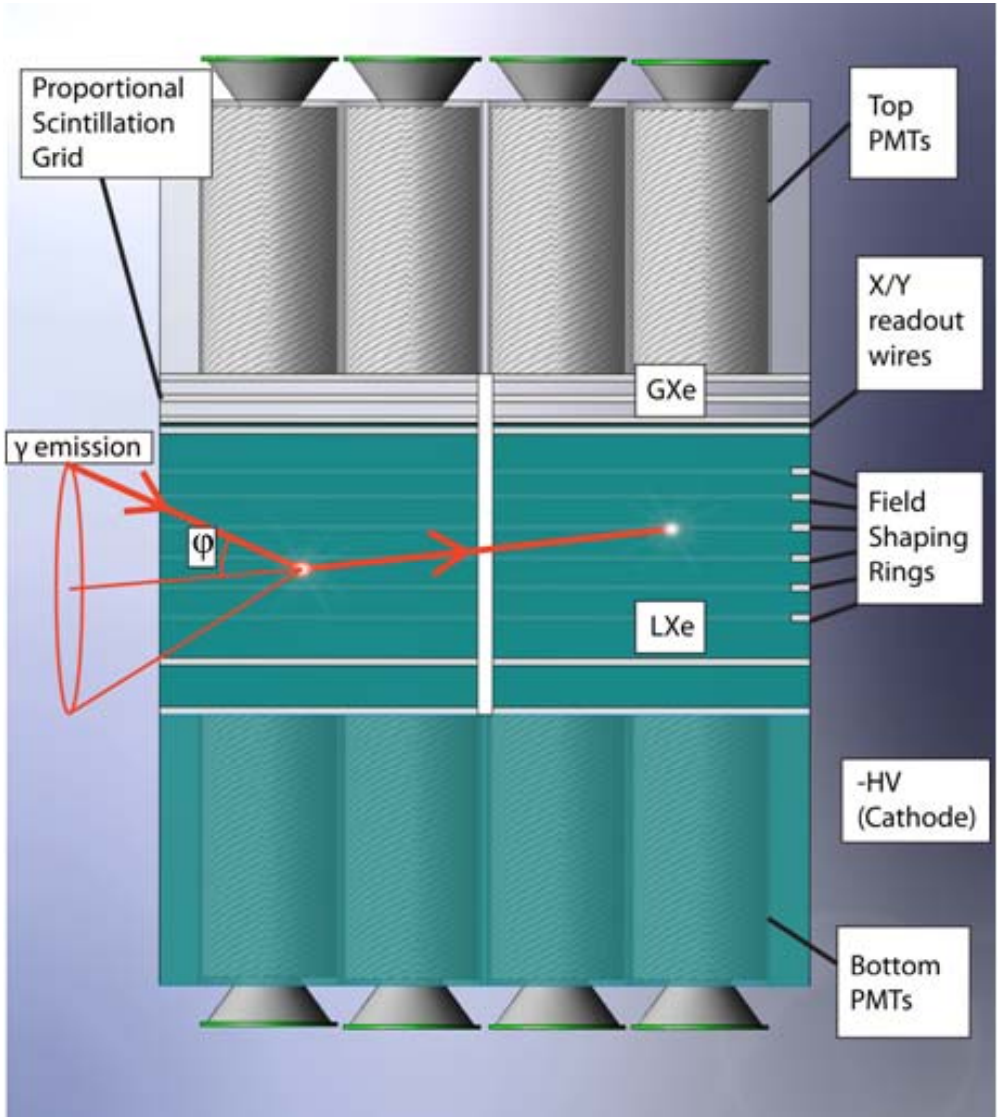


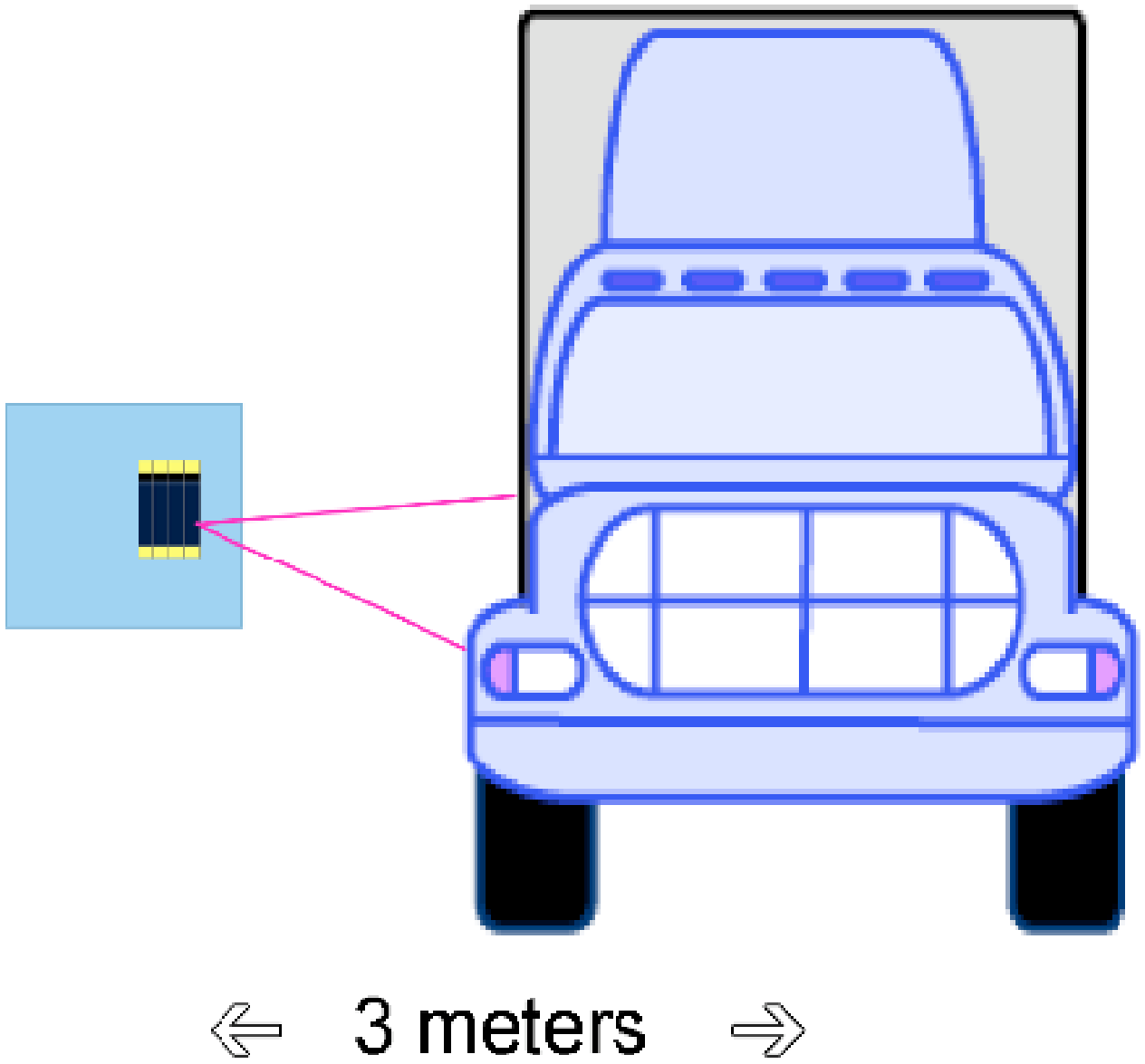
Compton Imaging

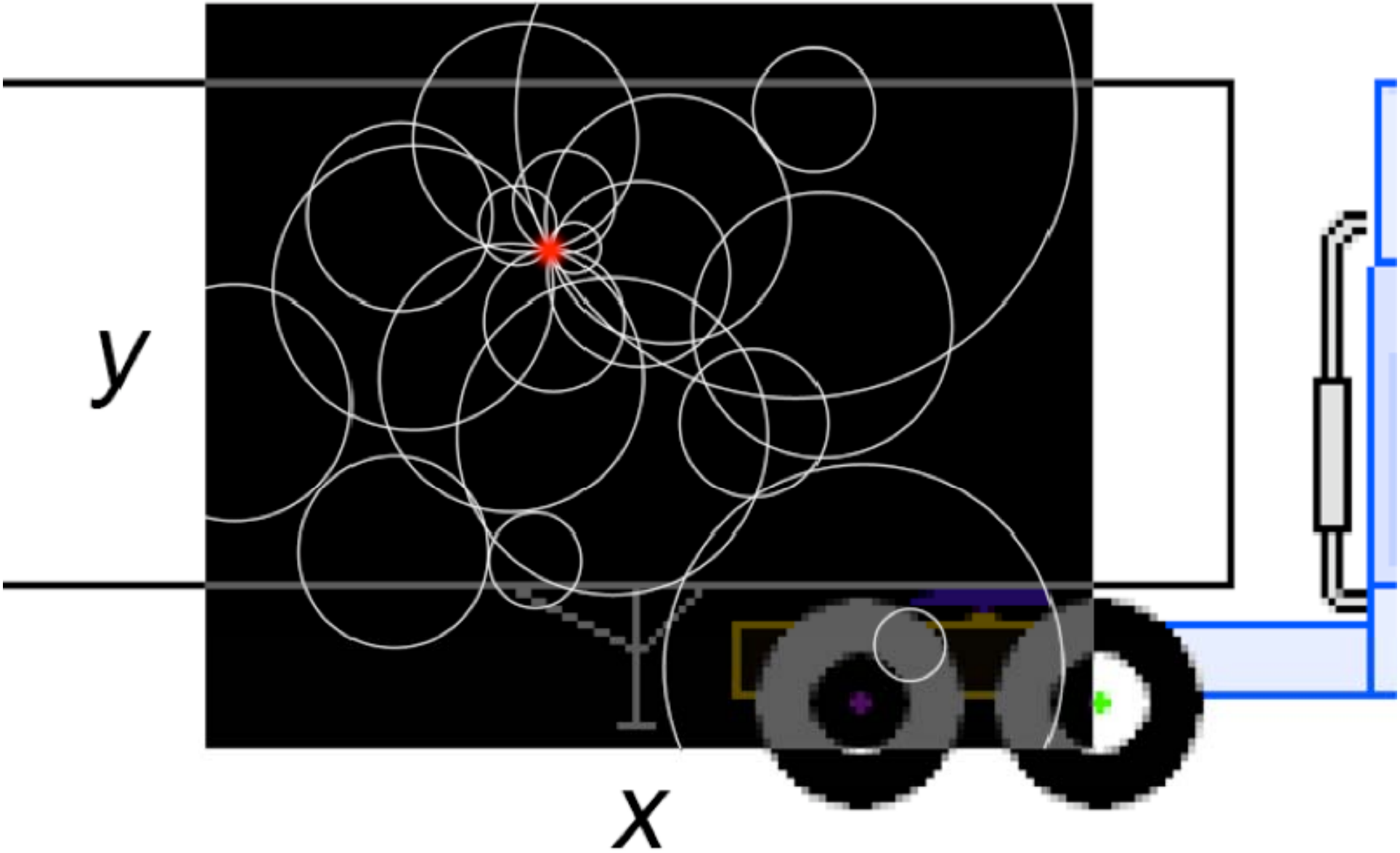
$$E'_\gamma = \frac{E_\gamma \cdot m_e c^2}{E_\gamma \cdot (1 - cos\varphi) + m_e c^2}$$

$$\varphi = arccos\left[1 - m_e c^2 \cdot \left(\frac{1}{E_\gamma - E_1} - \frac{1}{E_\gamma}\right)\right]$$



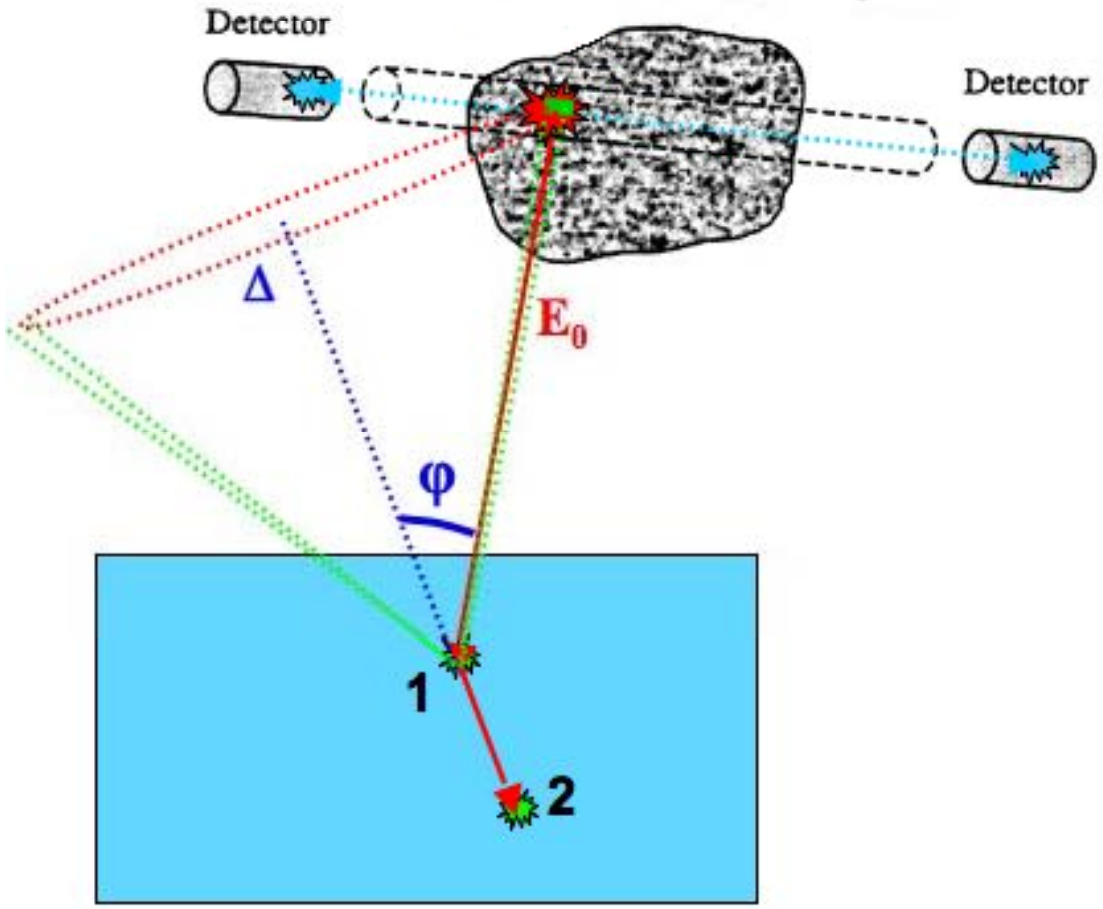



3 meters

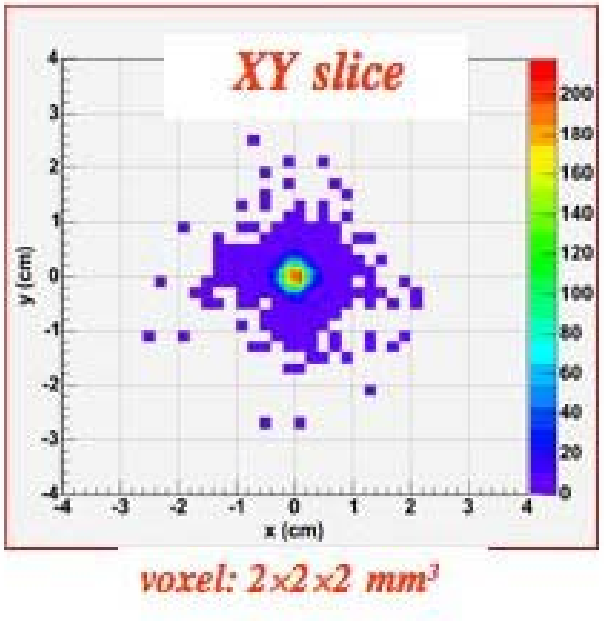

y
x

Simulation of Three Photon PET

(With a Compton Gamma-Camera and a 3γ emitter)



- 3 photon PET: ~2.2-mm spatial resolution
- Alternative to MicroPET with comparable resolution



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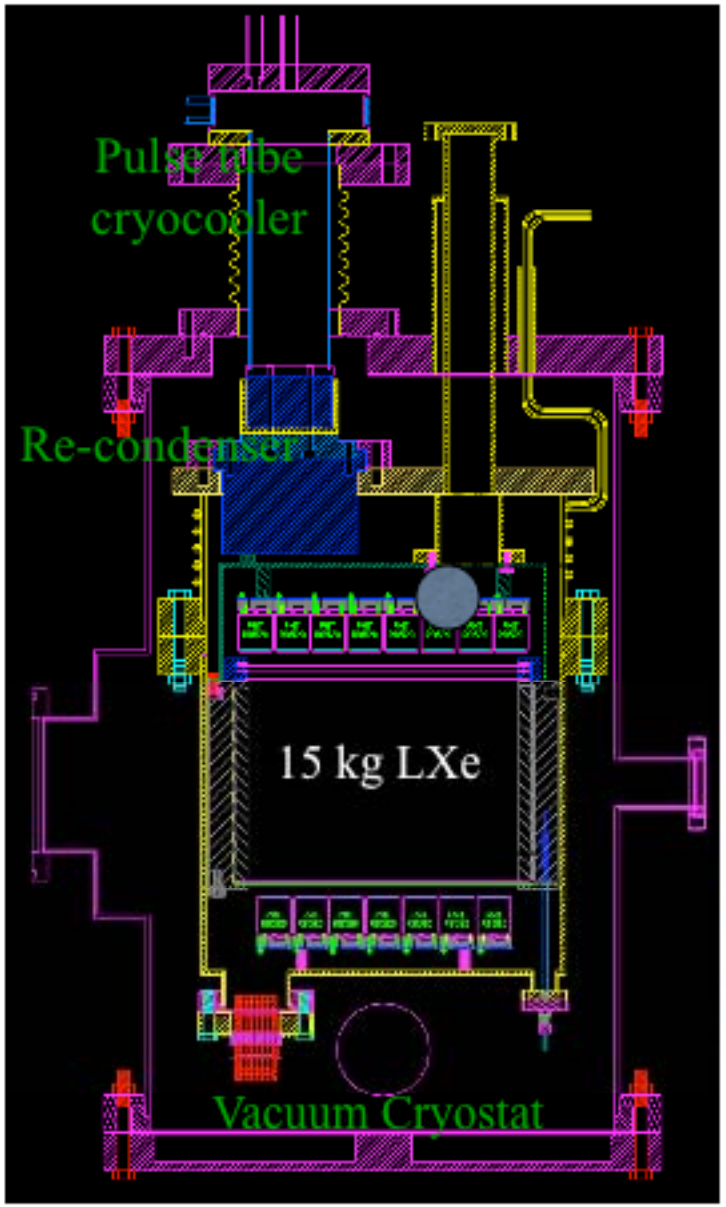
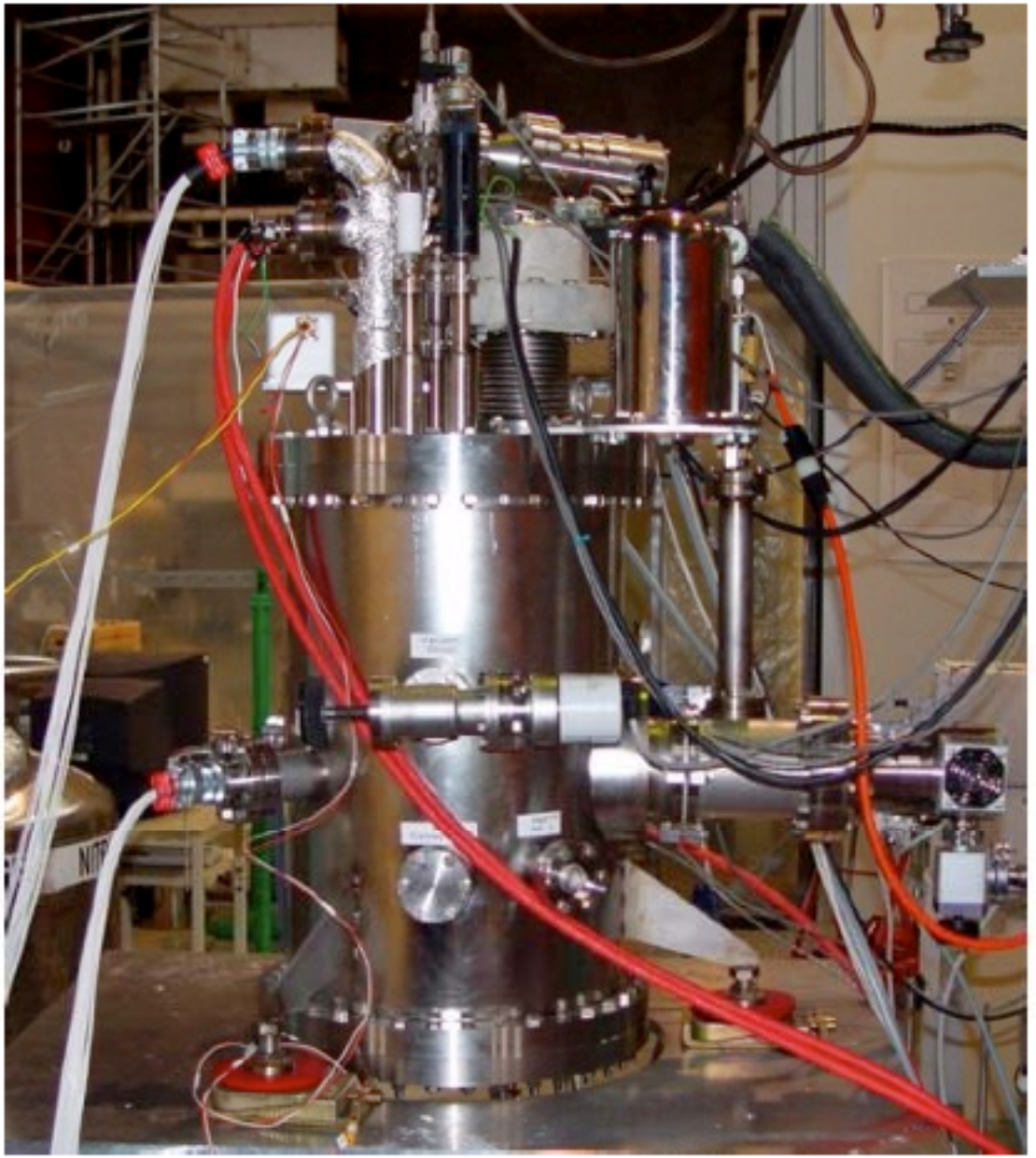
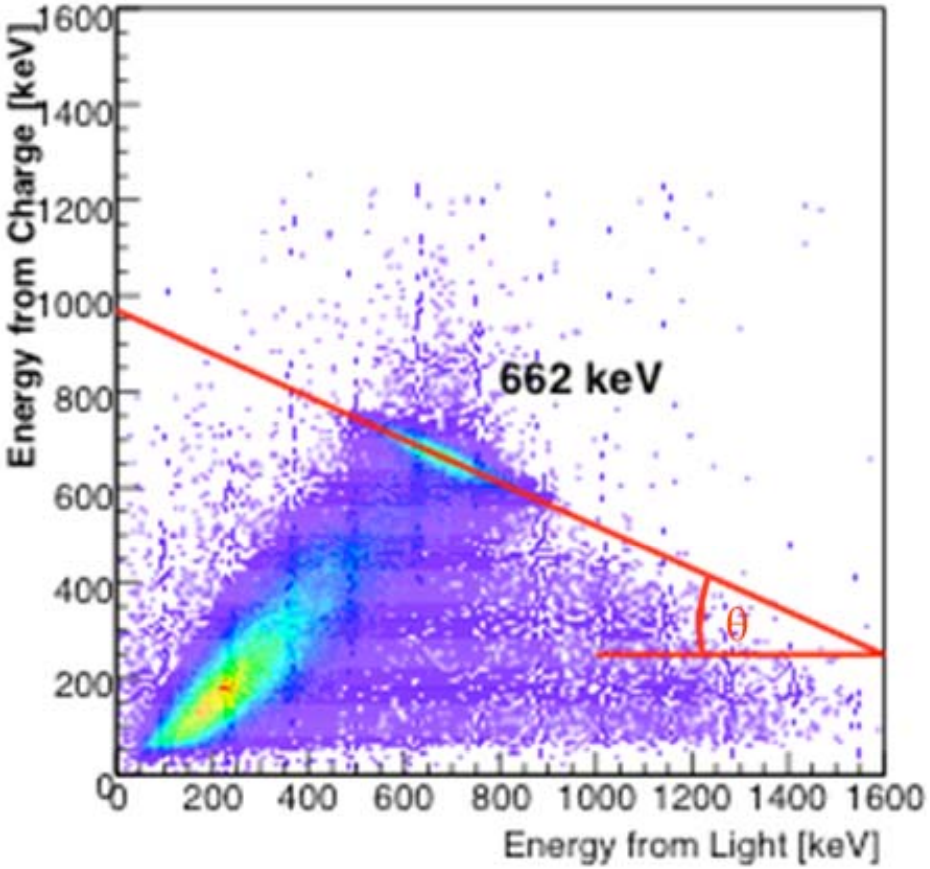
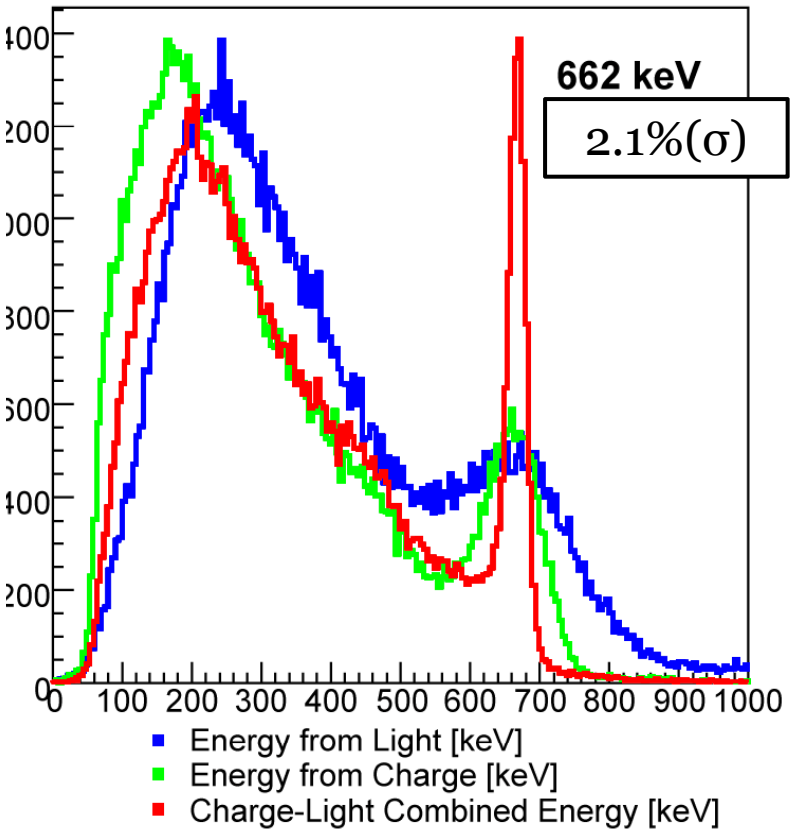
The XENON10 Detector





Xenon10





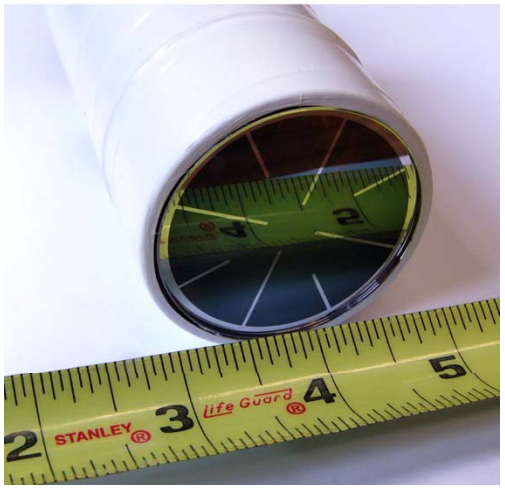
Anti-correlation considerably improves energy resolution.

arXiv: 1001.2834

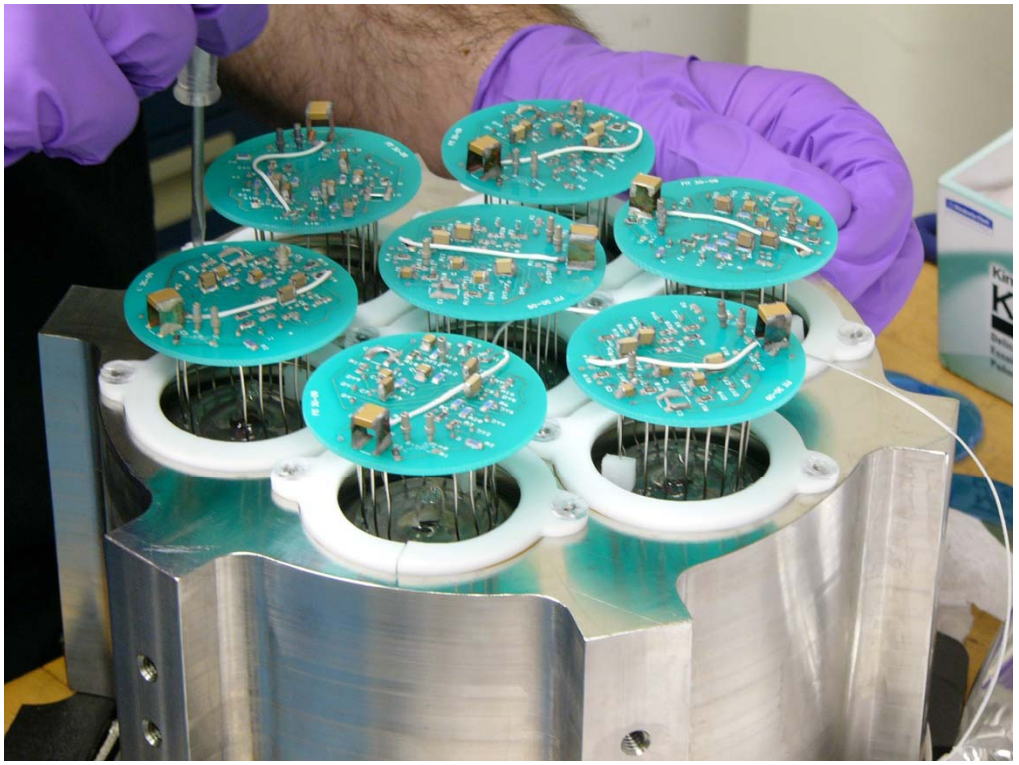
PIXeY – Particle Identification in Xenon at Yale

- Separate drift and proportional scintillation fields
- Optimize energy resolution

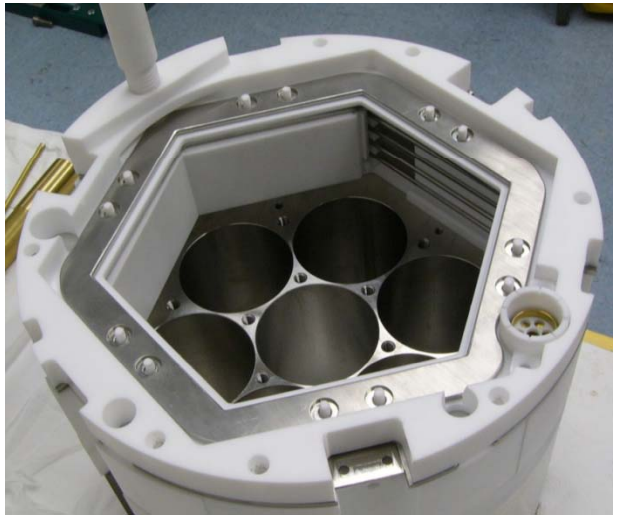
Photomultiplier Tubes

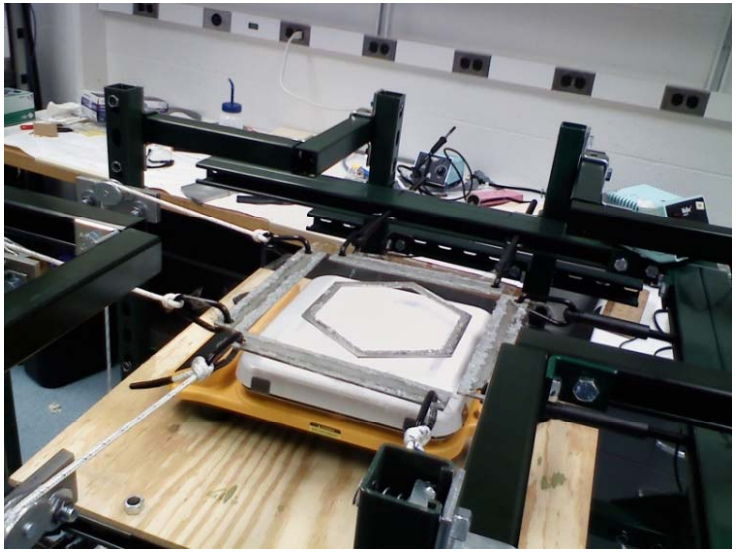


- 14 two-inch Hamamatsu R8778 PMTs
- Quantum efficiency ~35%

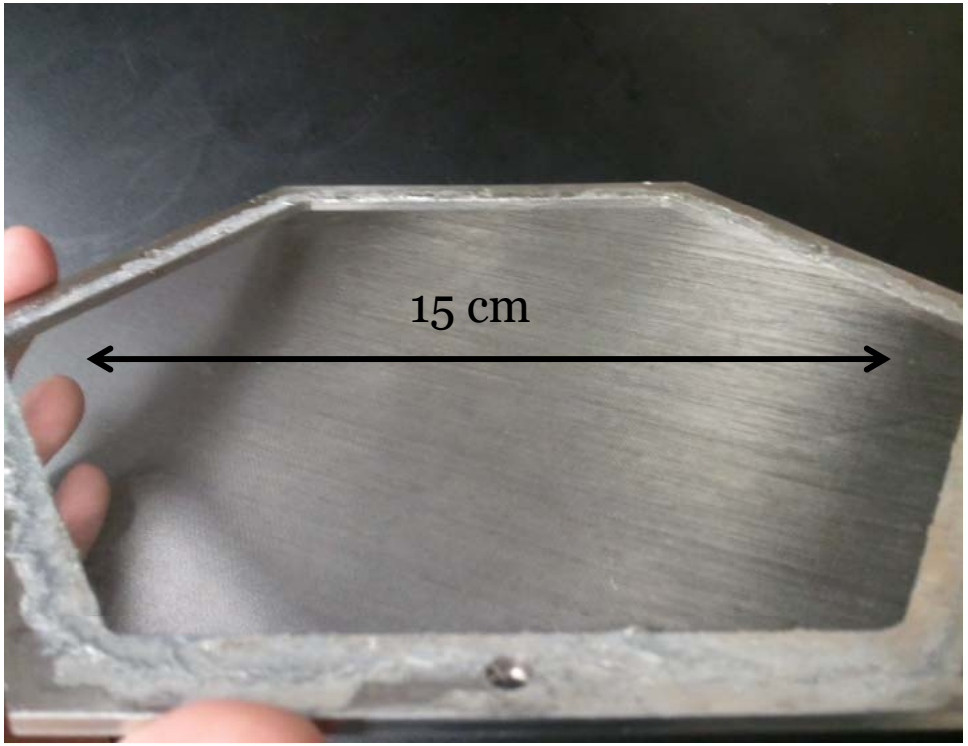


Mesh Grids

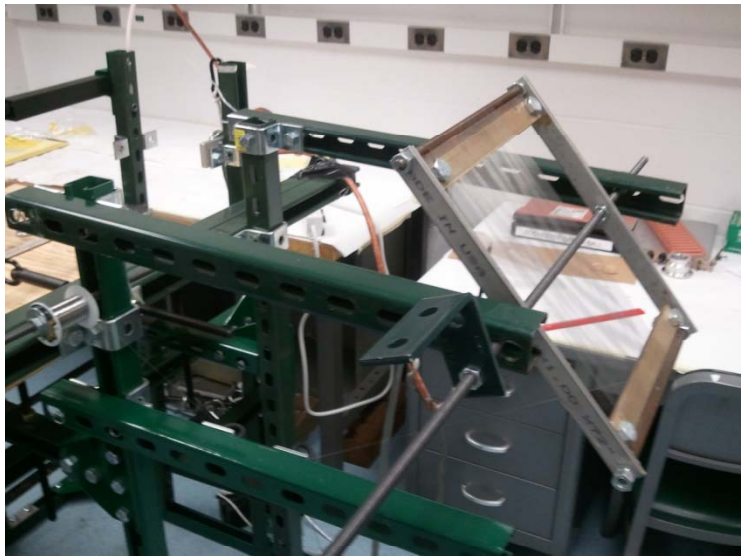


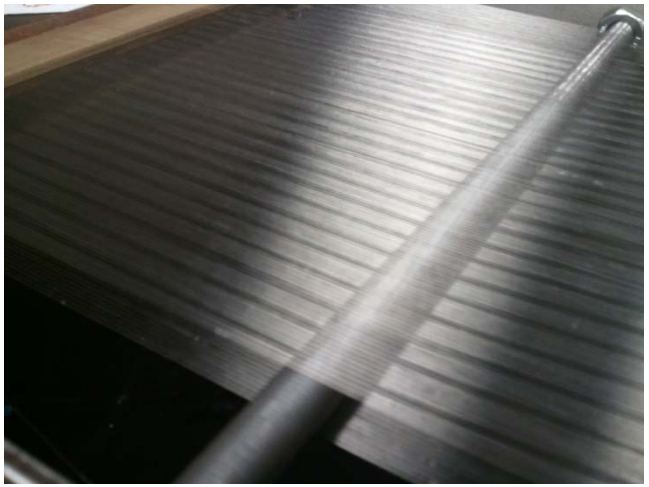


- Grids establish electric field, as well as protect PMTs
- Optical Transparency: 88%
- Completed construction, currently installed.

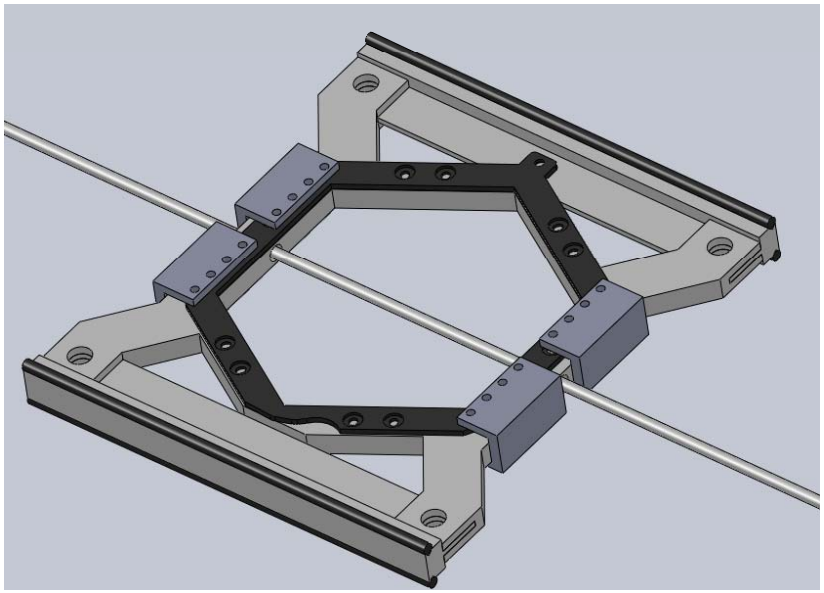


Parallel Single Wire Grids



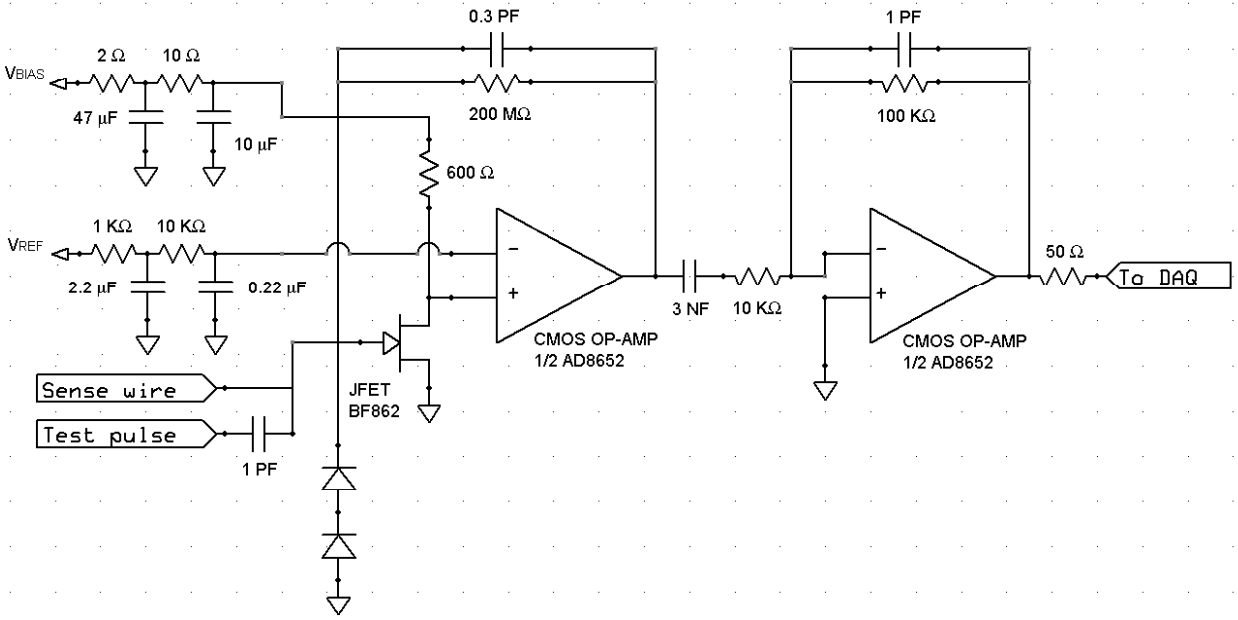


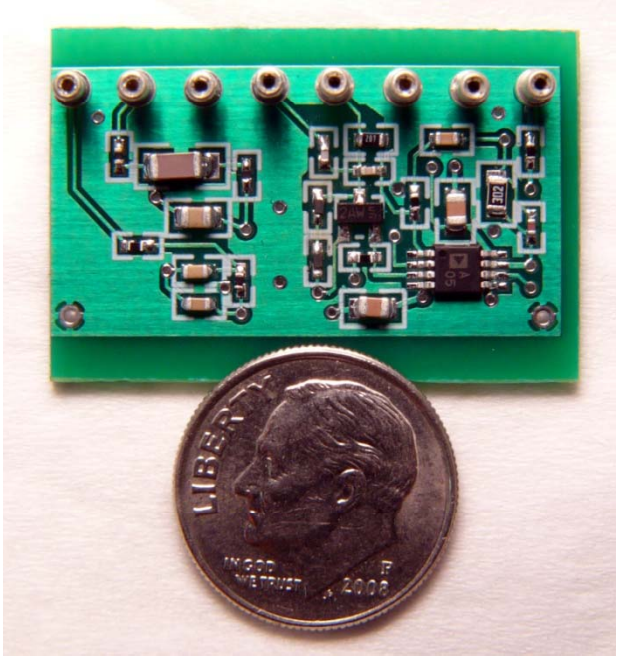
- Higher strength for given optical transparency
  - Less grid deflection
  - Greater field uniformity
  - Better energy resolution
- Can be custom made for each application



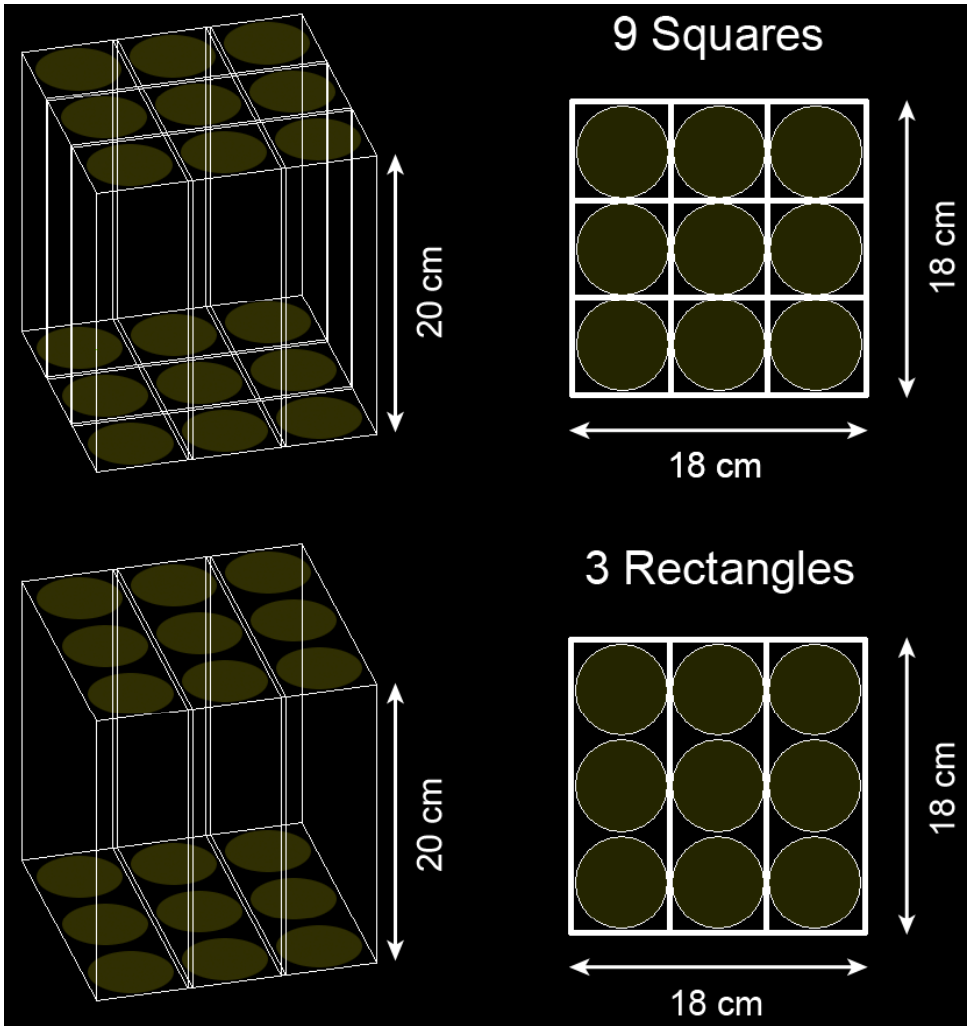
Low Noise Wire Readout Charge Preamplifiers

- Read individual wires in LXe
- With 3 mm wire pitch, expect < 1 mm position resolution
- Gain: 5.33 μV/e^-
- Noise: 120 e^-
- Preamplifiers planned to be mounted inside detector, at LXe temperature
- Design used for GERDA germanium double beta decay experiment
- Testing underway

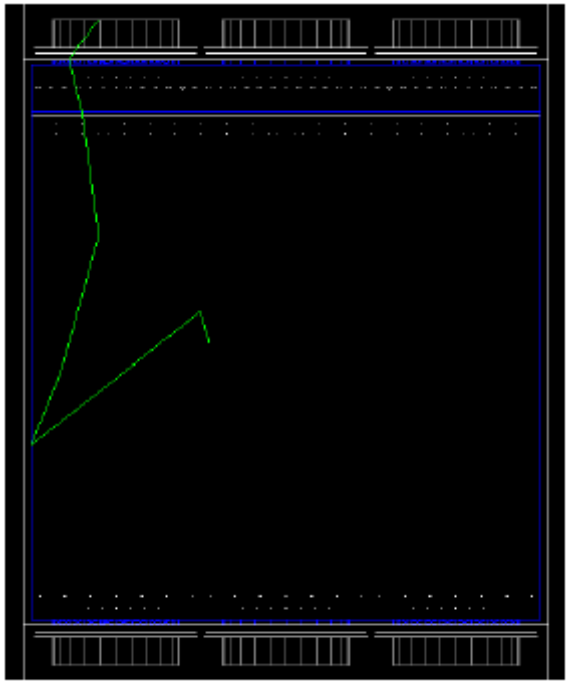




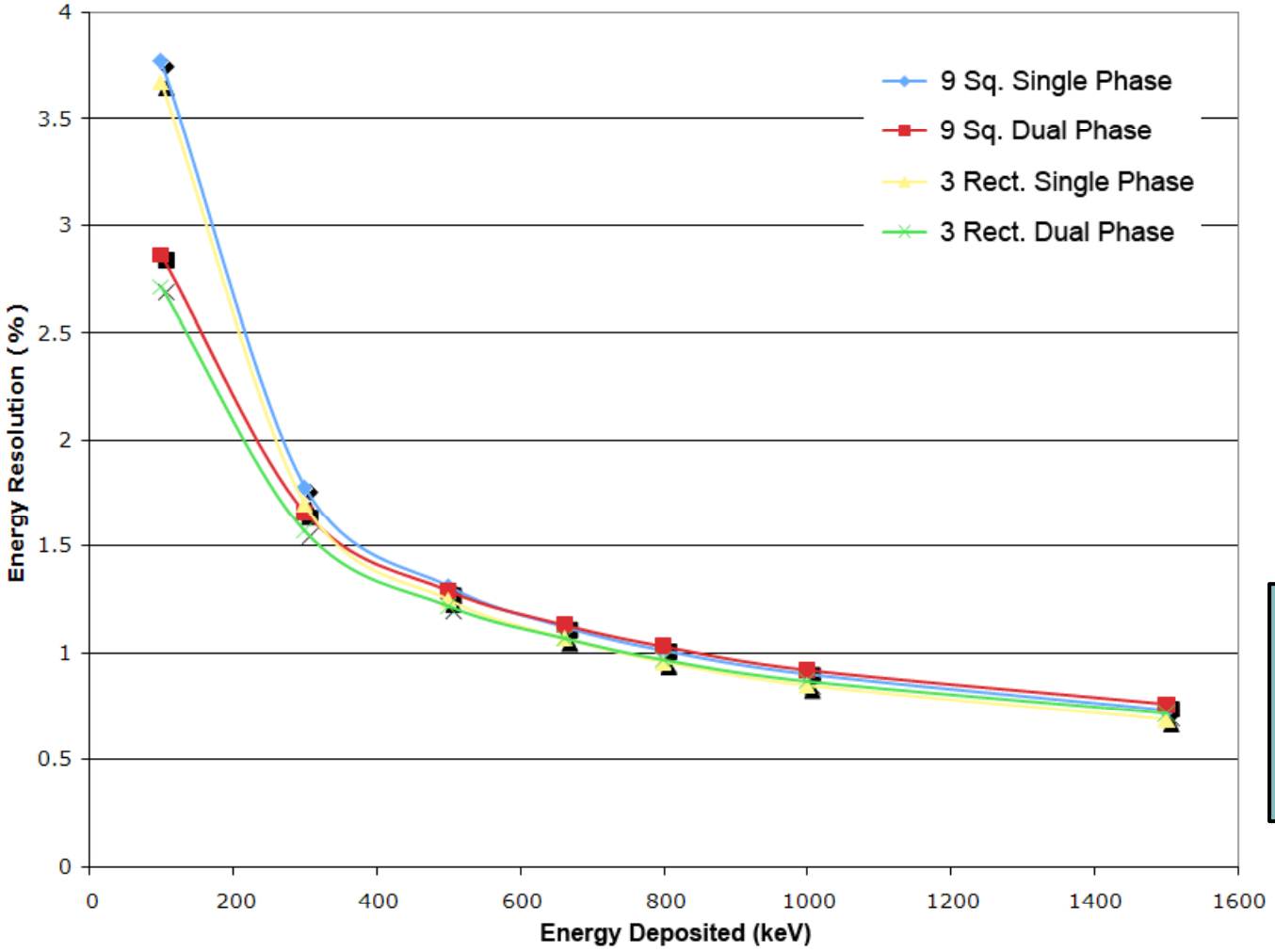
Monte Carlo Studies With GEANT4



- Ten detector geometries studied, to optimize efficiency and resolution
- Varied parameters: height, single/dual phase, partitioning

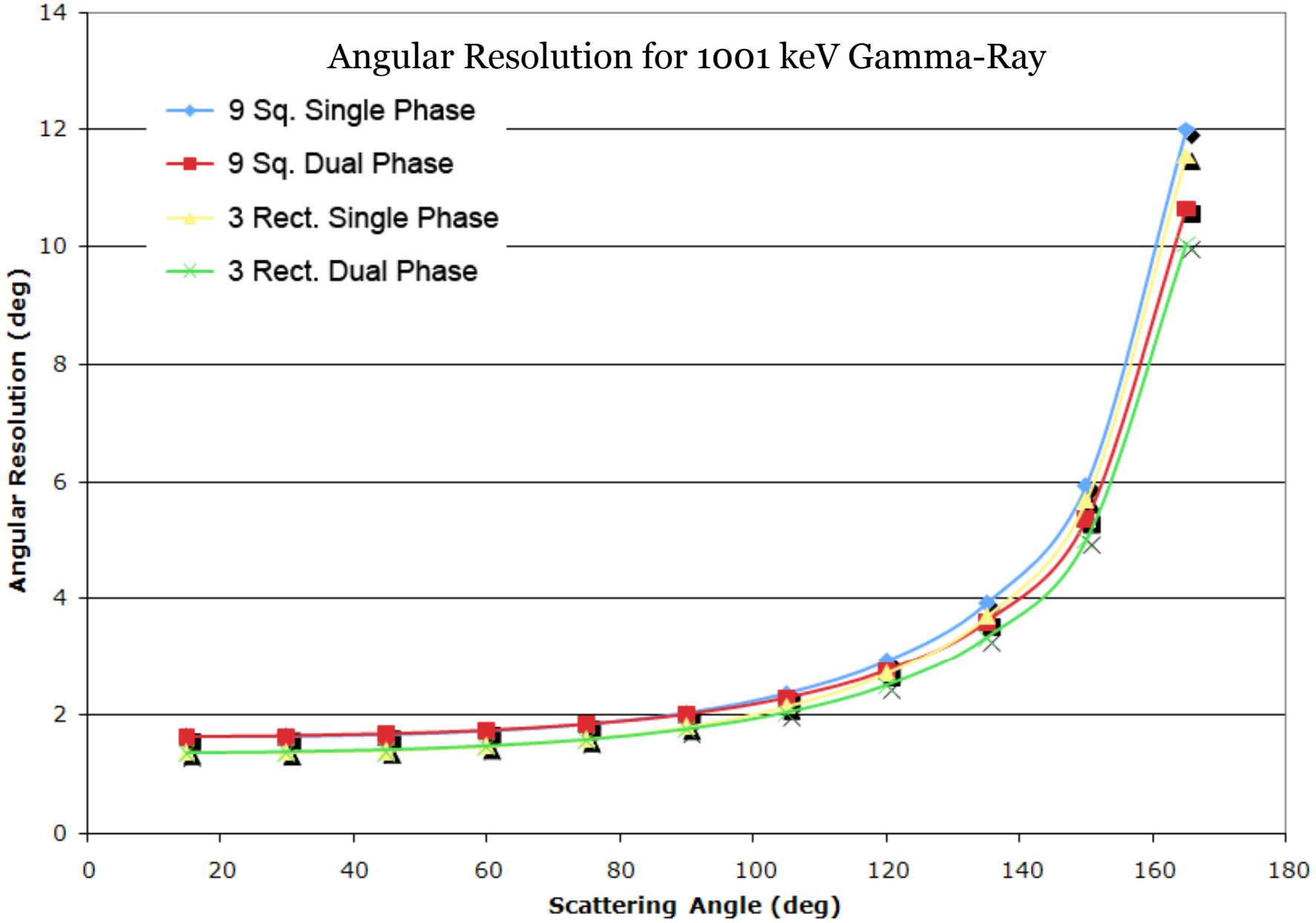


Energy Resolution



- Teflon reflectivity properties in GEANT4 class simulator
- PMTs with quantum efficiency of 35%
- 10% reflectivity grids
- 1-mm position resolution

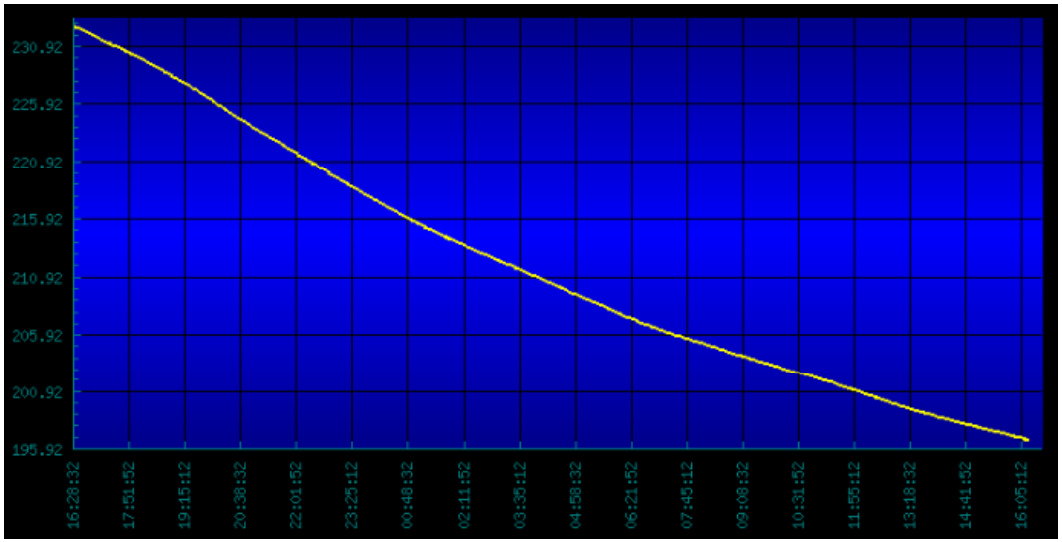
Three rectangle configuration optimal at low energies (<300 keV)

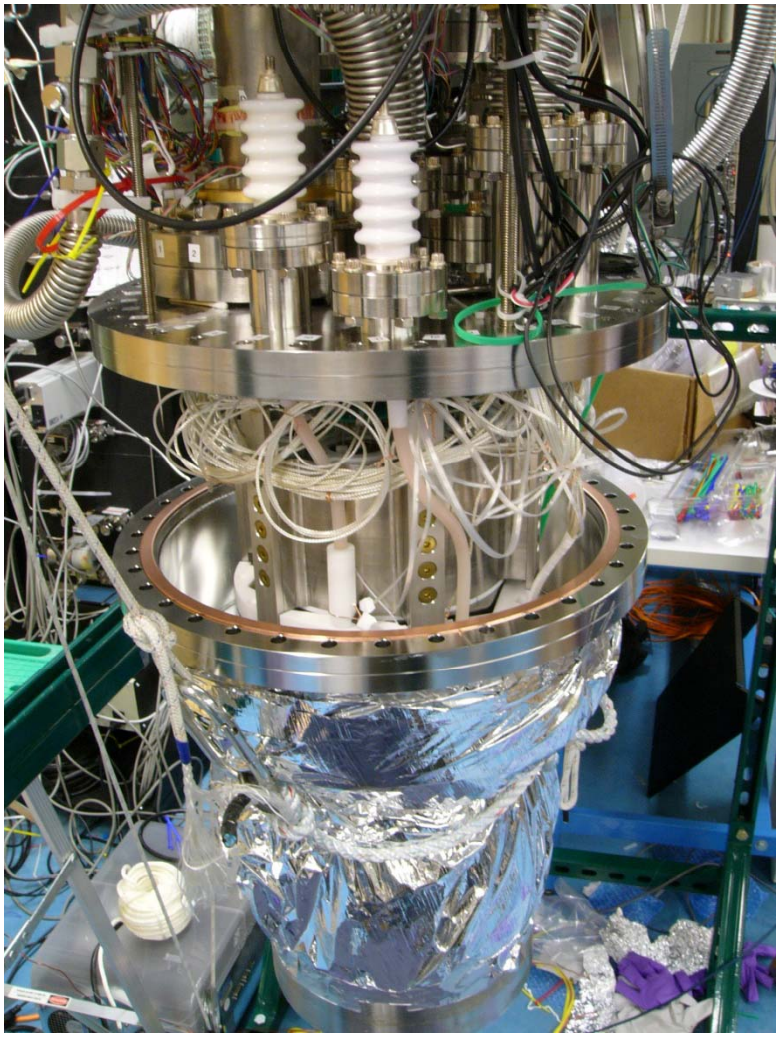

Angular Resolution for 1001 keV Gamma-Ray
9 Sq. Single Phase
9 Sq. Dual Phase
3 Rect. Single Phase
3 Rect. Dual Phase
Angular Resolution (deg)
Scattering Angle (deg)
0
2
4
6
8
10
12
14
0
20
40
60
80
100
120
140
160
180

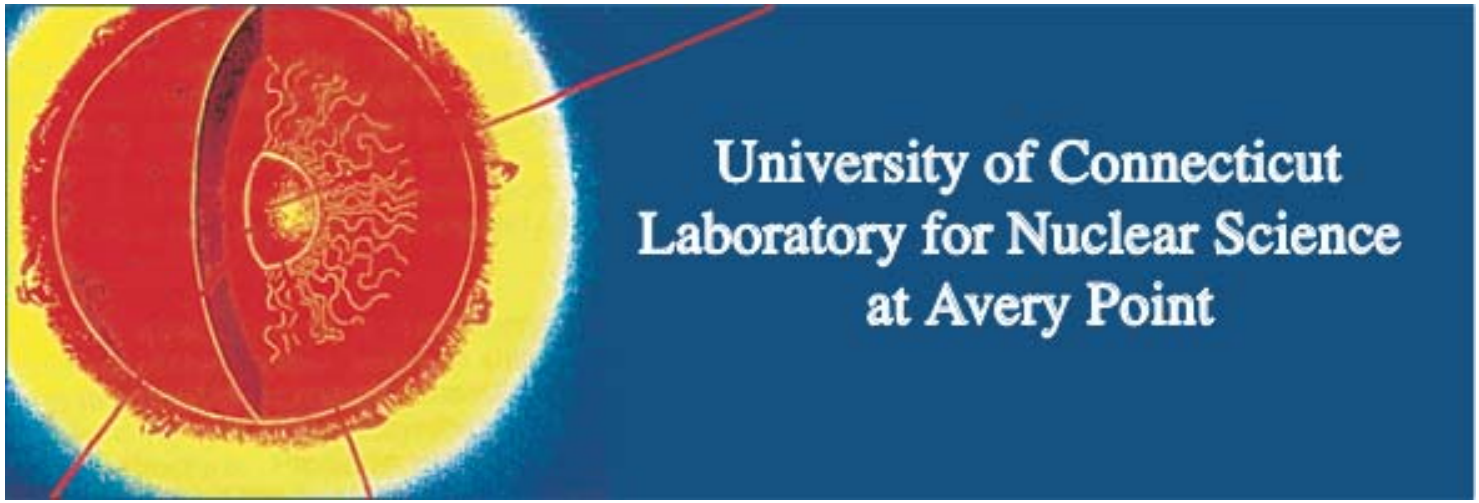
Current Status

- Internals installed
- Outer can installed
- Xenon purified
- Gas in inner volume
- Detector cooling

Temp(K) of internals







- ✓ Cryogenic system installation and implementation
- ✓ Monte Carlo simulations demonstrating the energy resolution of a liquid xenon Compton imager
- o Demonstration of energy resolution in PIXeY

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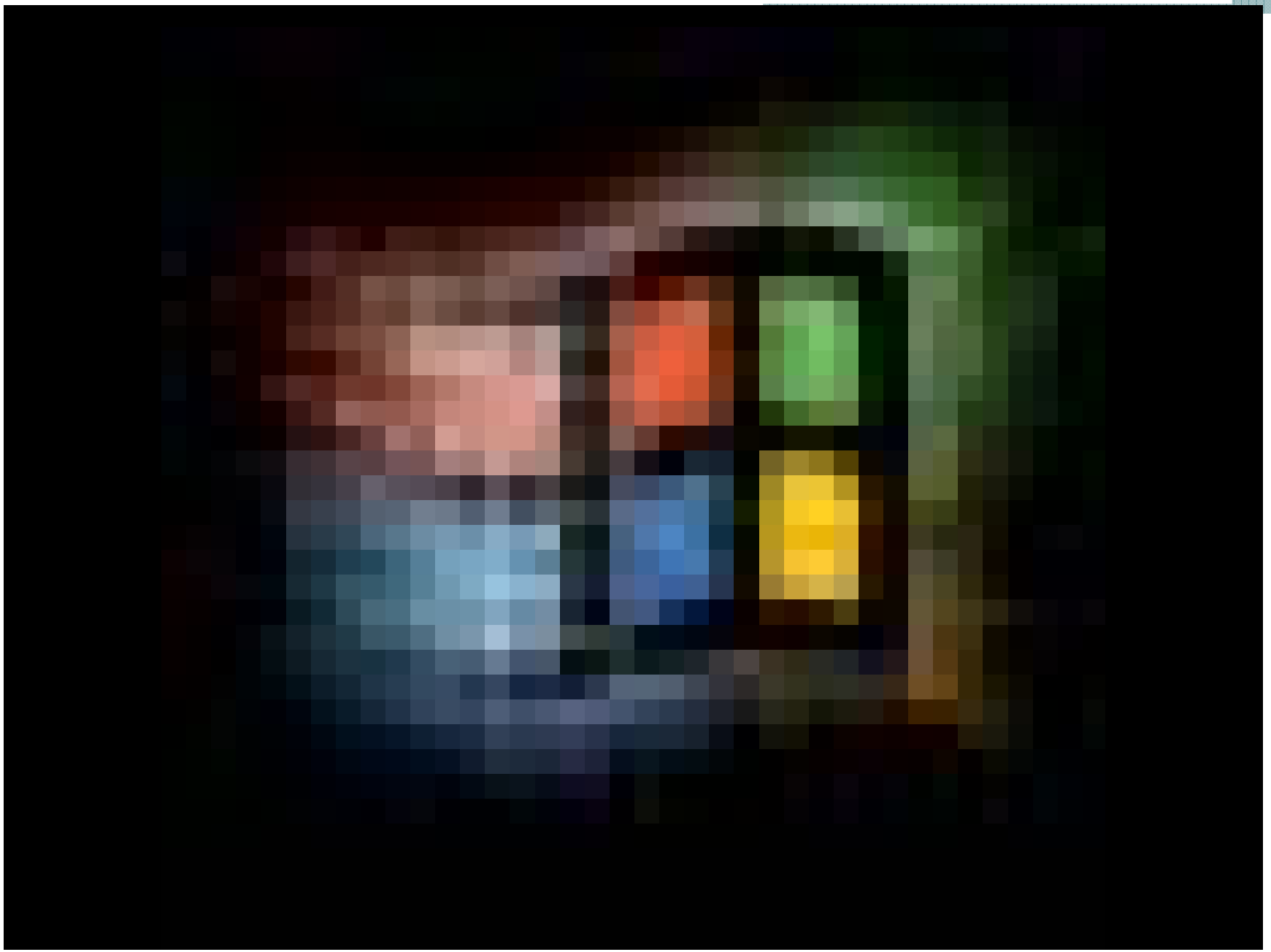
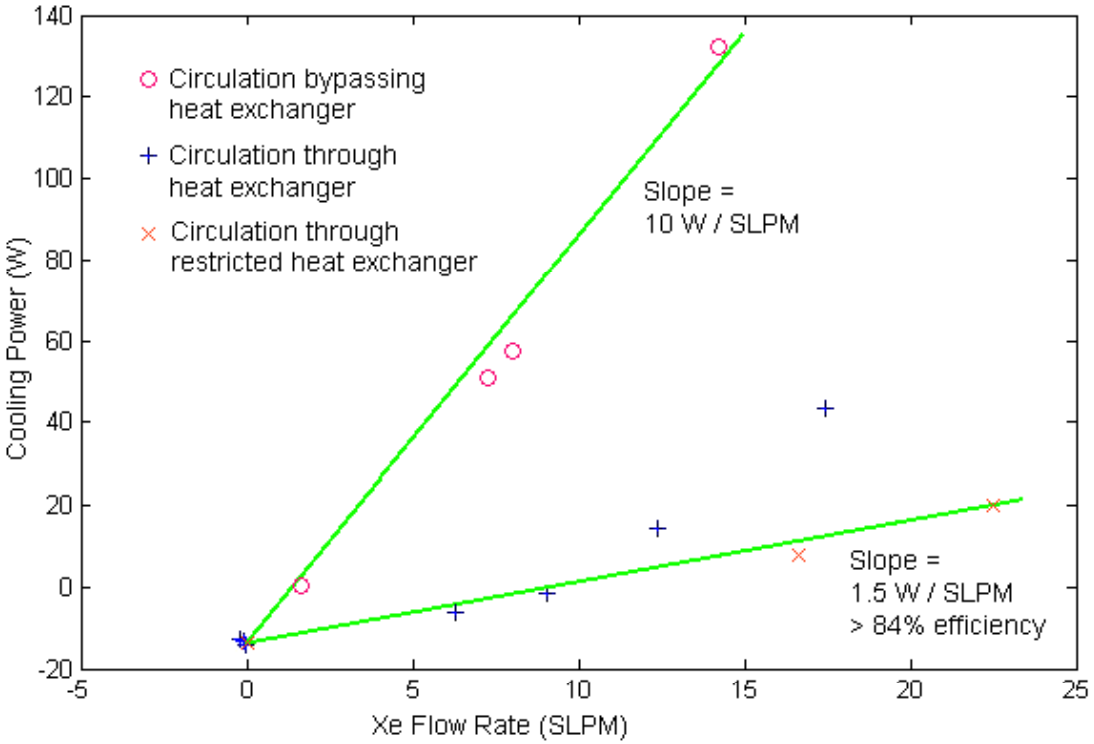
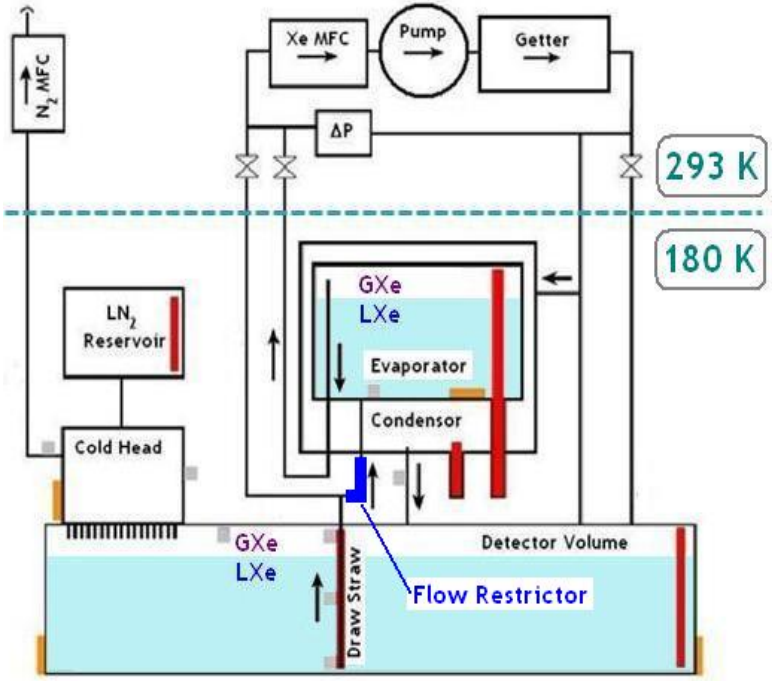


Cryogenics in PIXeY

- Impurities effect lifetime of drift electrons
- Decreases energy resolution
- < 1 ppb oxygen ideal

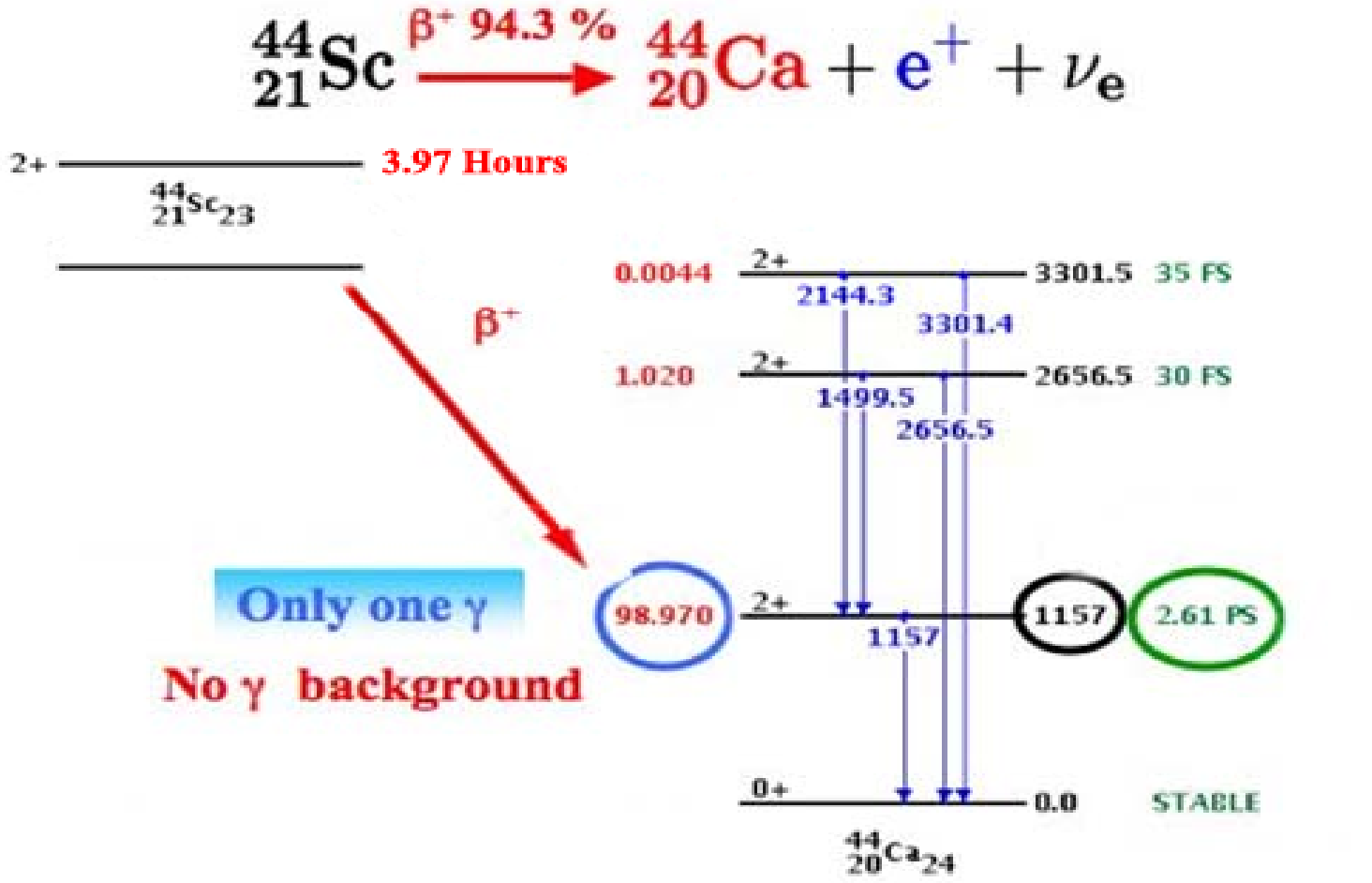
- Circulation system maintains Xenon purity
- LN_2 Cold Head provides cooling power
- Heat Exchanger reduces cooling power needed





✓ Has been installed, tested, and commissioned

Three Photon PET



Other 3 photon PET isotopes: ^{14}O, ^{14}C, ^{42m}Sc, ^{48}V, ^{50}Mn, ^{52m}Mn, ^{54}Co, ^{55}Co, ^{60}Cu, ^{66}Ga, ^{67}Ge, ^{70}As, and ^{73}Se.

J.D. Kurfess *et al.*, IEEE , **2** (2001)1166.