Liquid Xenon for medical imaging and physics applications

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TRIUMF

Outline

- Property of liquid Xenon
  - Key feature: Light-charge sharing
- Liquid Xenon for physics
- Liquid Xenon for Positron Emission Tomography
  - Concept
  - Prototype
  - Expected performances
- Summary

Key properties of noble liquids

	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e-/MeV]	scintillation [photon/MeV]
He	2 (4)	4.2	0.13	39,000	22,000
Ne	10 (20)	27.1	1.21	46,000	30,000
Ar	18 (40)	87.3	1.40	42,000	40,000
Kr	36 (84)	119.8	2.41	49,000	25,000
Xe	54 (131)	165.0	3.06	64,000	68000*

Zero electric field
Some uncertainties

Infinite electric field

LXe: high density, lots of charge and light

Gaitskell 2005

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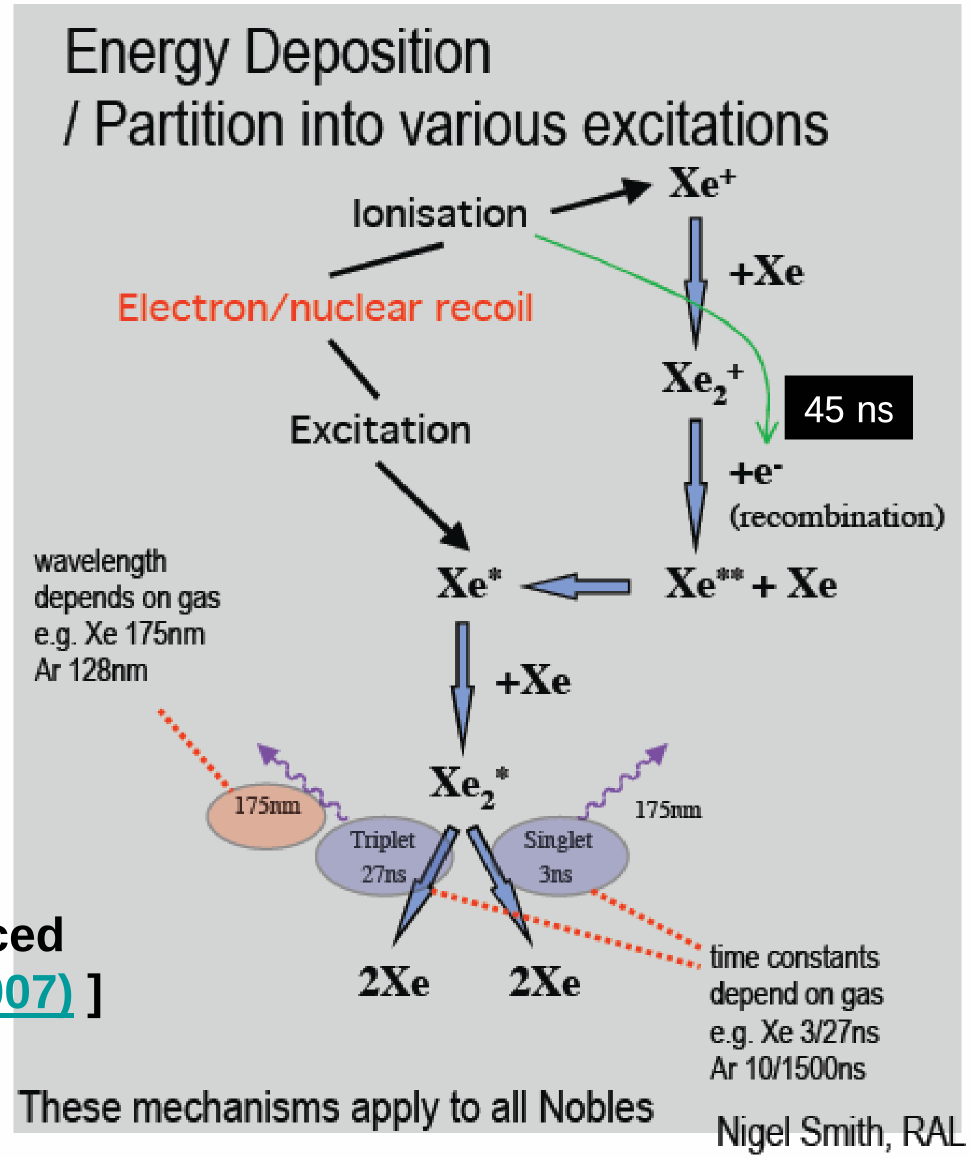
Energy loss in noble liquid Scintillation, ionization and heat

$$R^* + R \rightarrow R_2^* \rightarrow 2R + h\nu$$

or

$$R^+ + R \rightarrow R_2^+,$$
$$R_2^+ + e^- \rightarrow R^{**} + R,$$
$$R^{**} \rightarrow R^* + \text{heat}$$
$$R^* + R \rightarrow R_2^* \rightarrow 2R + h\nu$$

Deep UV light
Ionization
Heat (IR, phonon)



Electron-ion recombinations enhance scintillation light

Light and charge are anti-correlated

1 electron-ion lost ⇒1 UV photon produced
[Aprile et al., Phys. Rev. B 76, 014115 (2007)]

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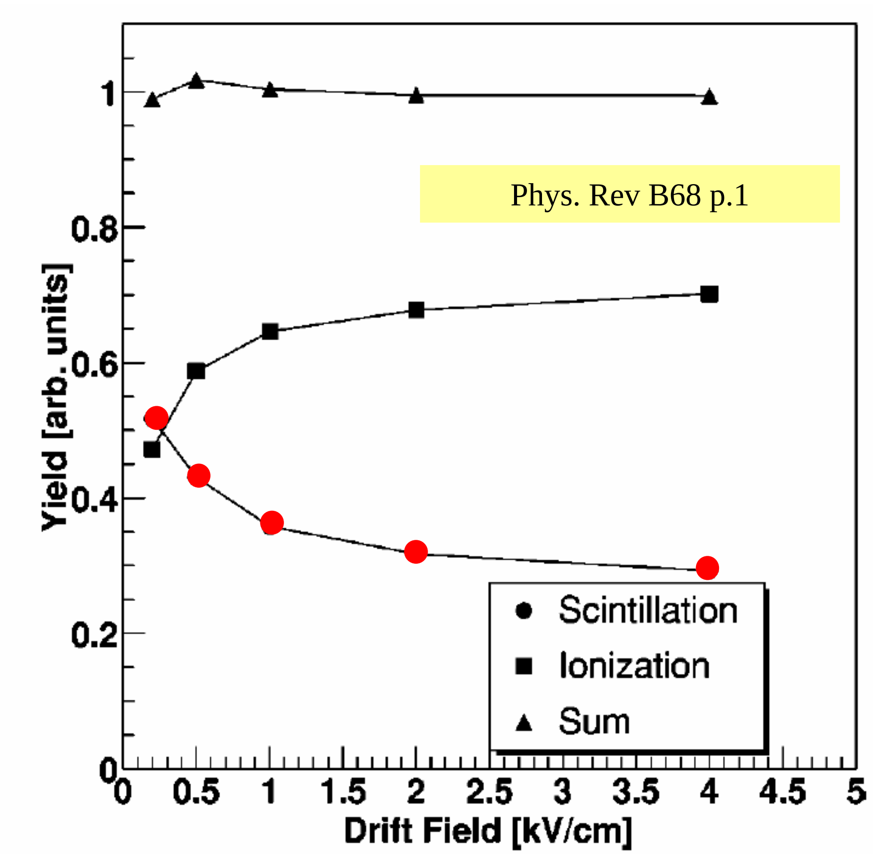
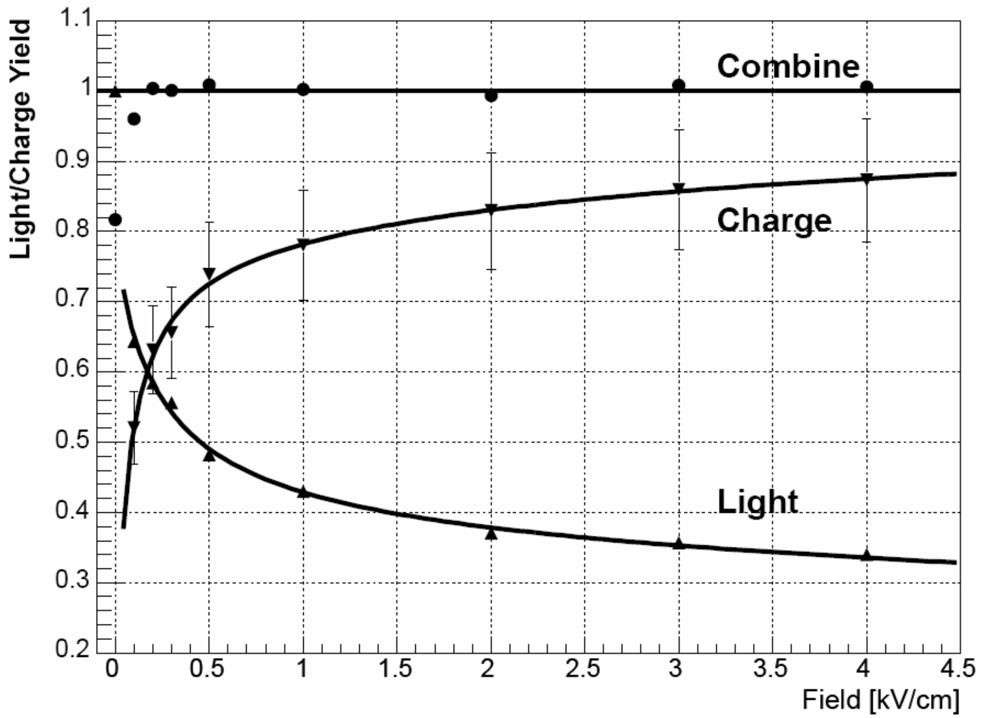
Effect of electric field



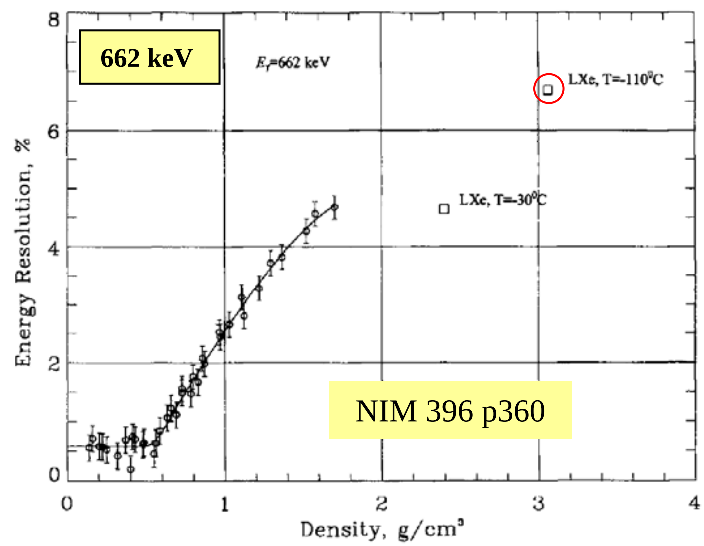


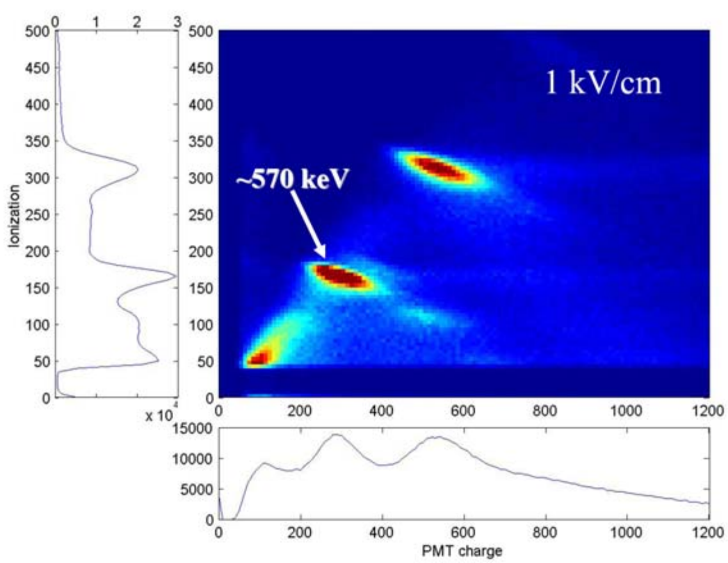
Aprile et al., Phys. Rev. B 76, 014115 (2007)

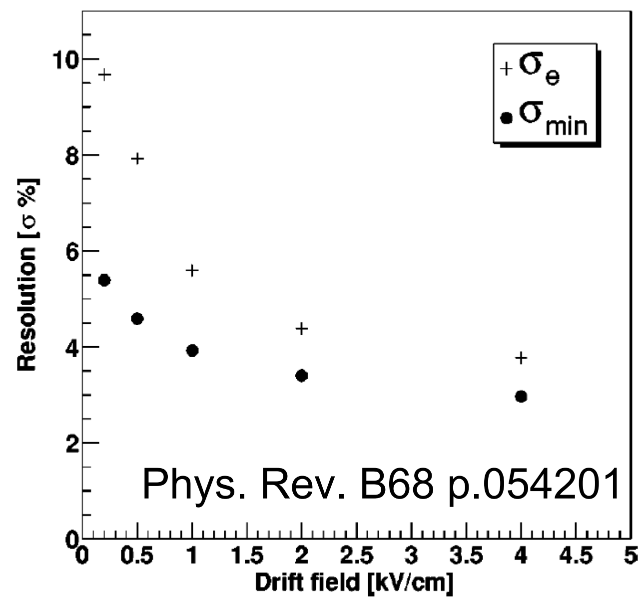
Note the discrepancy in charge fraction between papers
Scintillation light is normalized differently.

Event by event variation

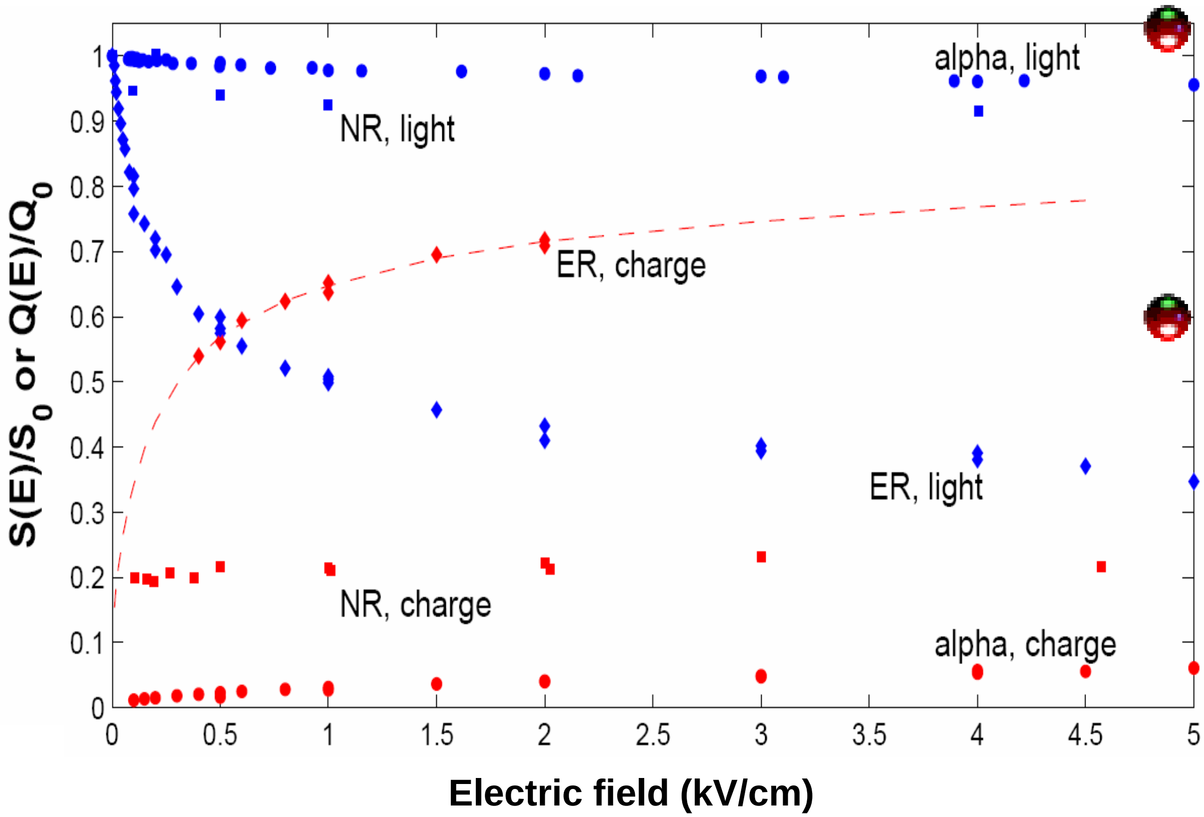
- Energy resolution from ionization much worse than Fano limit
  - Density fluctuations
    - Variation of recombination
  - Correlation with scintillation improves resolution







Difference between electron recoil and nuclear recoil



- Electron recoil induced by γ and charged particles
- Nuclear recoil induced by neutrons or wimp

Aprile et al., Phys.Rev.Lett.97:081302(2006).

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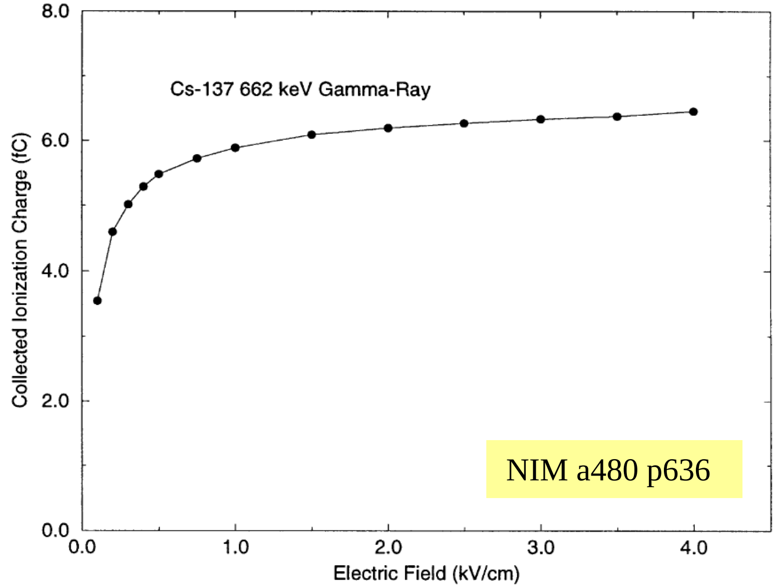
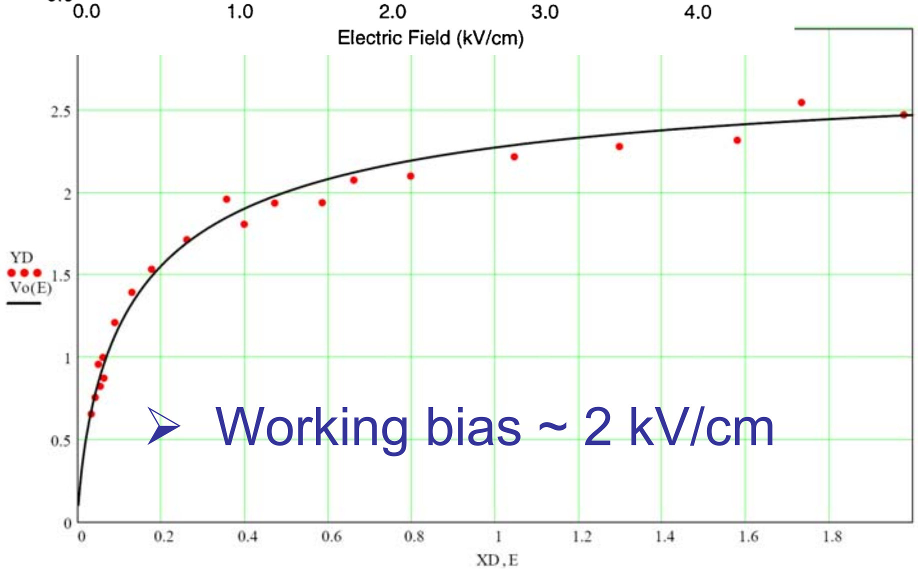
Measuring ionization

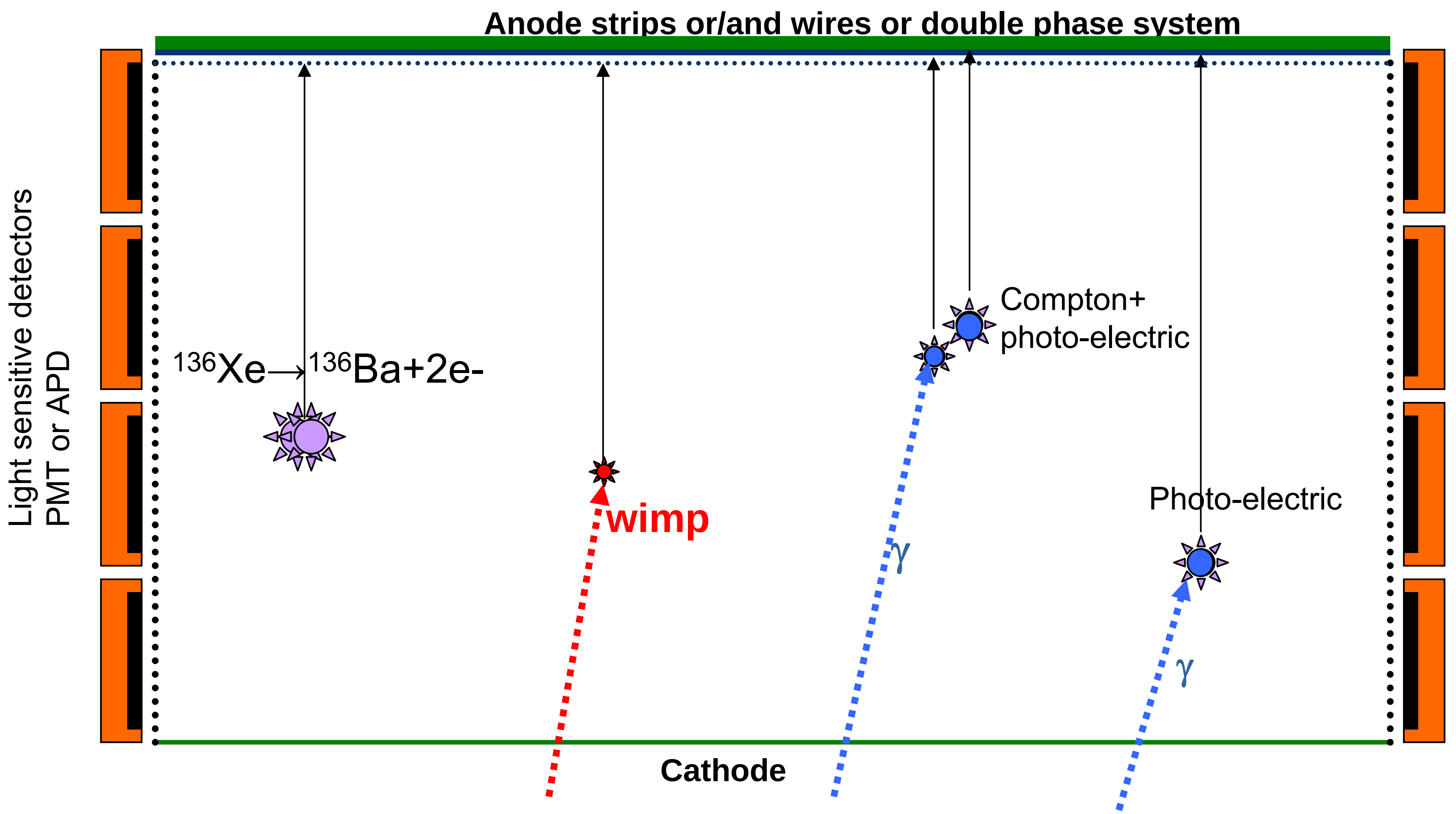




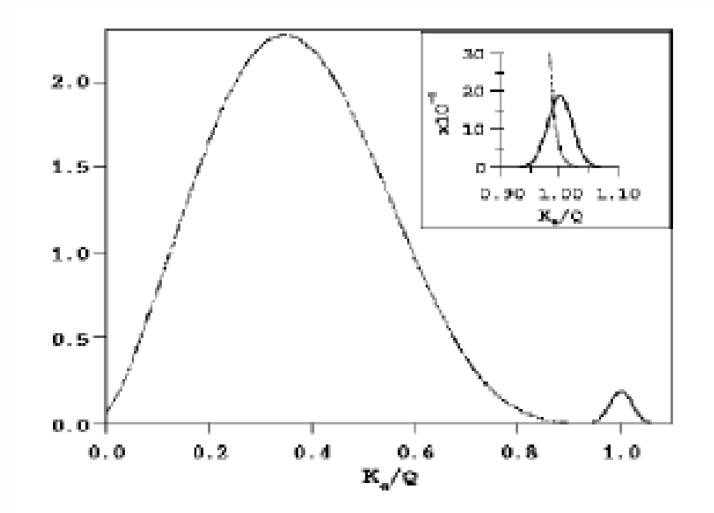
- ➢ Working bias ~ 2 kV/cm

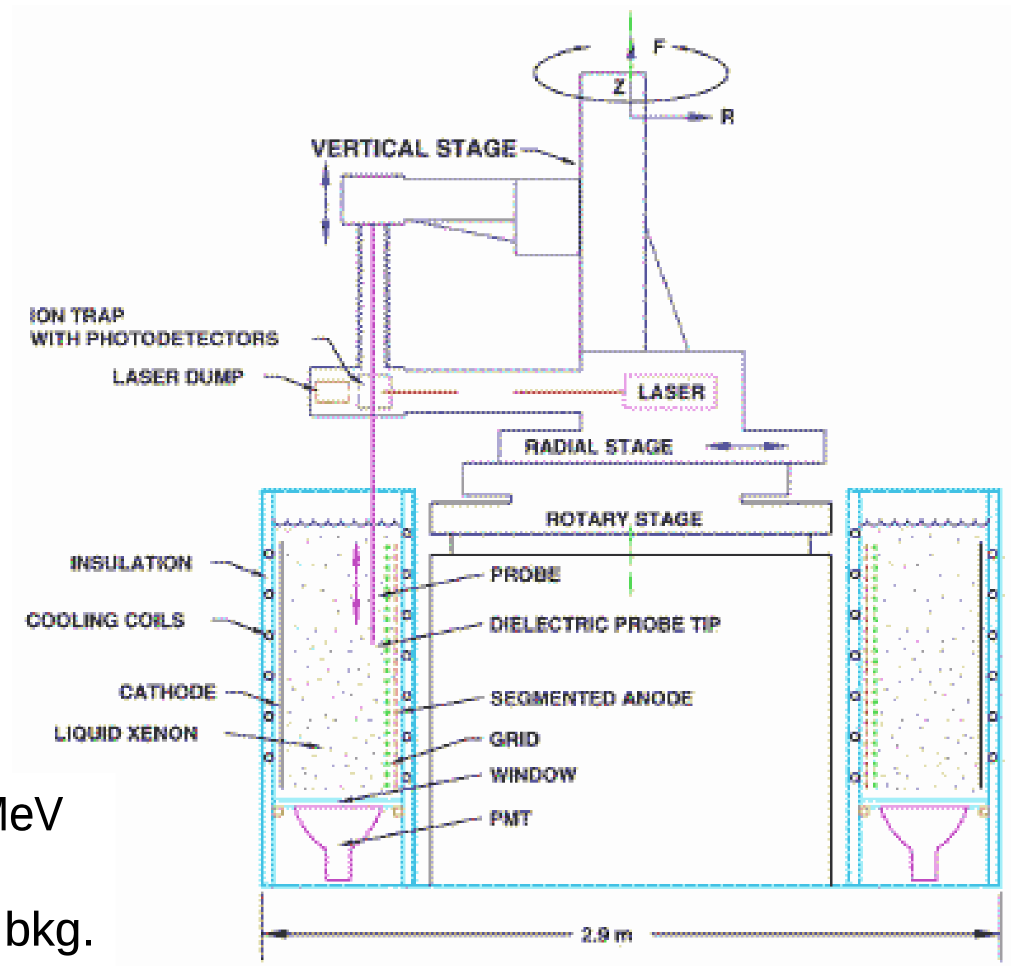
- Ionization saturates to 15.6 eV/pair
  - Recombination ~ 5% at 2kV/cm
- Electron lifetime
  - With 1 ppb impurity = 1 ms
- Drift velocity
  - 2.5mm/μs at 2kV/cm
    - 100 μs for 25 cm drift
- Very small diffusion
  - Primary electron range dominates
    - About 1 mm at 511 keV

3D imaging in liquid Xenon



EXO: Search for Neutrinoless Double Beta Decay in ^{136}Xe





- LXe TPC for Energy Peak (2e) at 2.5 MeV
- Light and charge for energy resolution
- Ba^+ ion daughter extraction to reduce bkg.
- Aim for $>10^{28}$ years; 10 meV sensitivity

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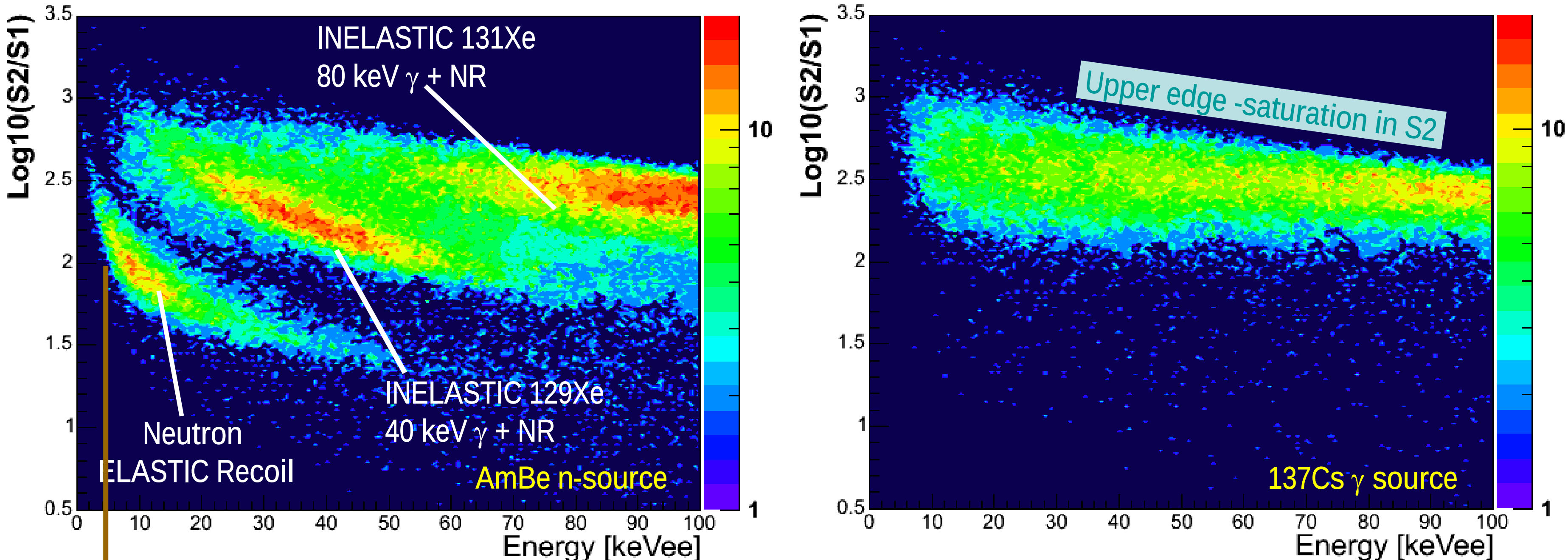
Key to dark matter searches

Log10(S2/S1) ~ Charge/light



A. Aprile et al. Phys.Rev.Lett. 97 (2006) 081302

5 keVee energy threshold = 10 keV nuclear recoil

Key: fraction of light and charge depends on density of ionization
Lower charge/light ratio for nuclear recoil (WIMP)
Issue: small signal Q~500 e- (need very low noise or amplification)

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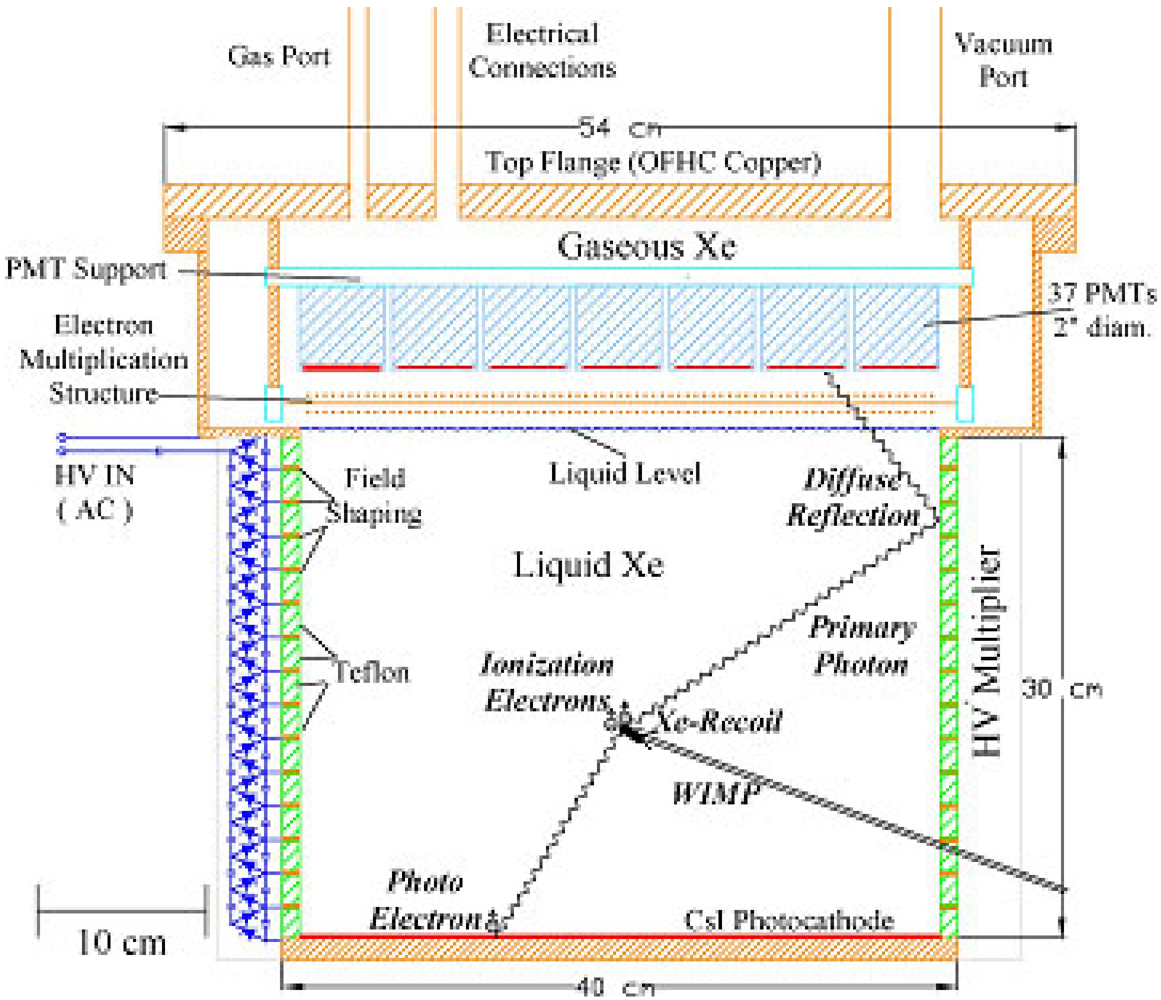
XENON 10 principle



2 phases: gas and light

- Scintillation detected directly
- Charge detected after drift
  - Amplified in gas
  - Measure scintillation light during amplification

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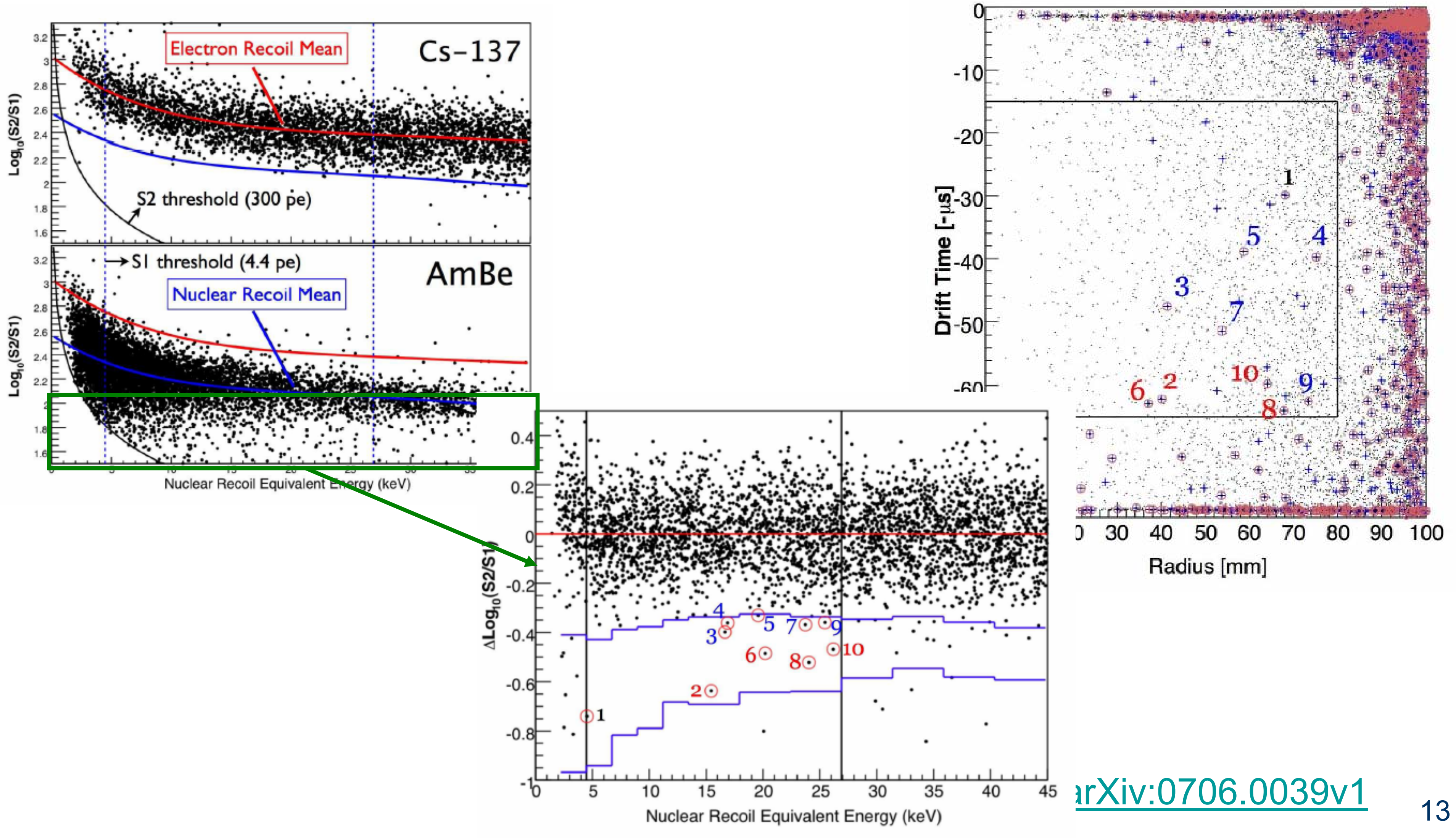
Searching nuclear recoil candidates



arXiv:0706.0039v1

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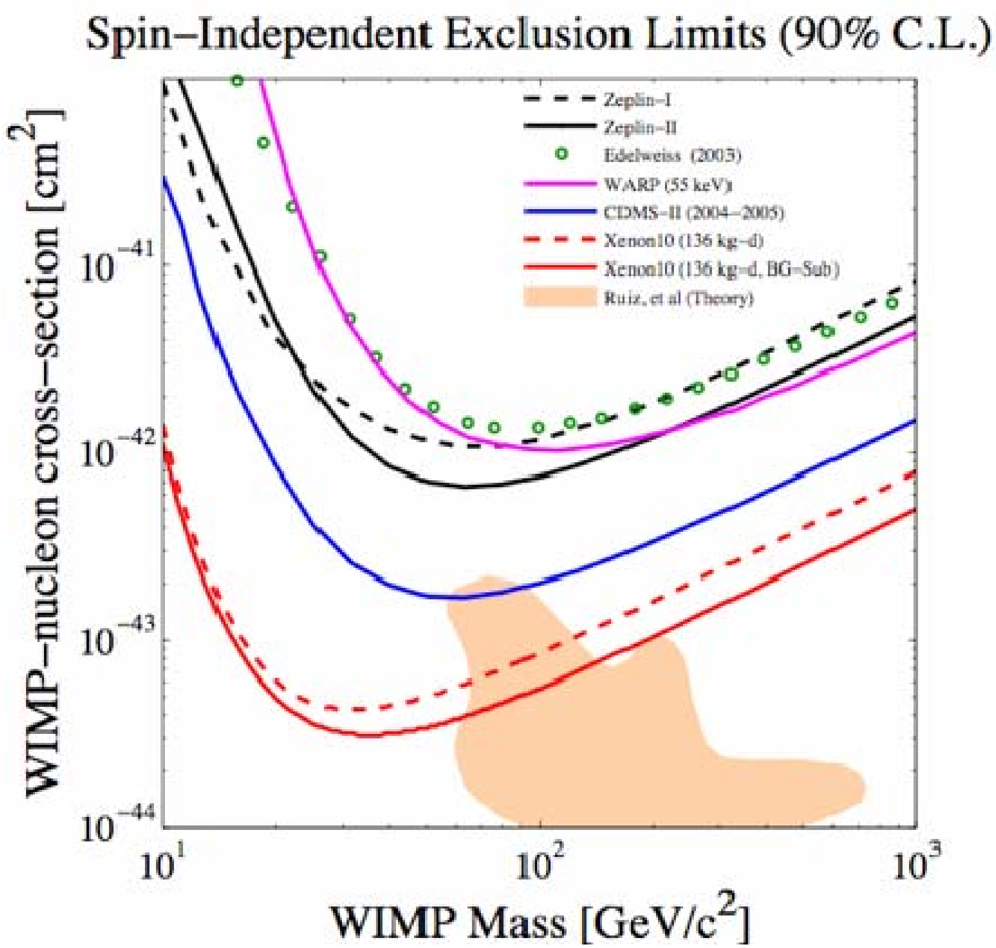
All events consistent with background



Very significant improvement over Germanium based detector
Next step: bigger detector

Liquid Xenon for Positron Emission Tomography

- Efficiency: 70-95%
- Position resolution < 1 mm
  - Depth of interaction resolution ~1-5mm
- Two hit separation < 10 mm
  - Allow reconstructing consecutive Compton interactions
- Timing resolution 1ns or better
- Energy resolution 5% (FWHM) or better @ 511 keV
- High counting rate
- Low cost (no patent)

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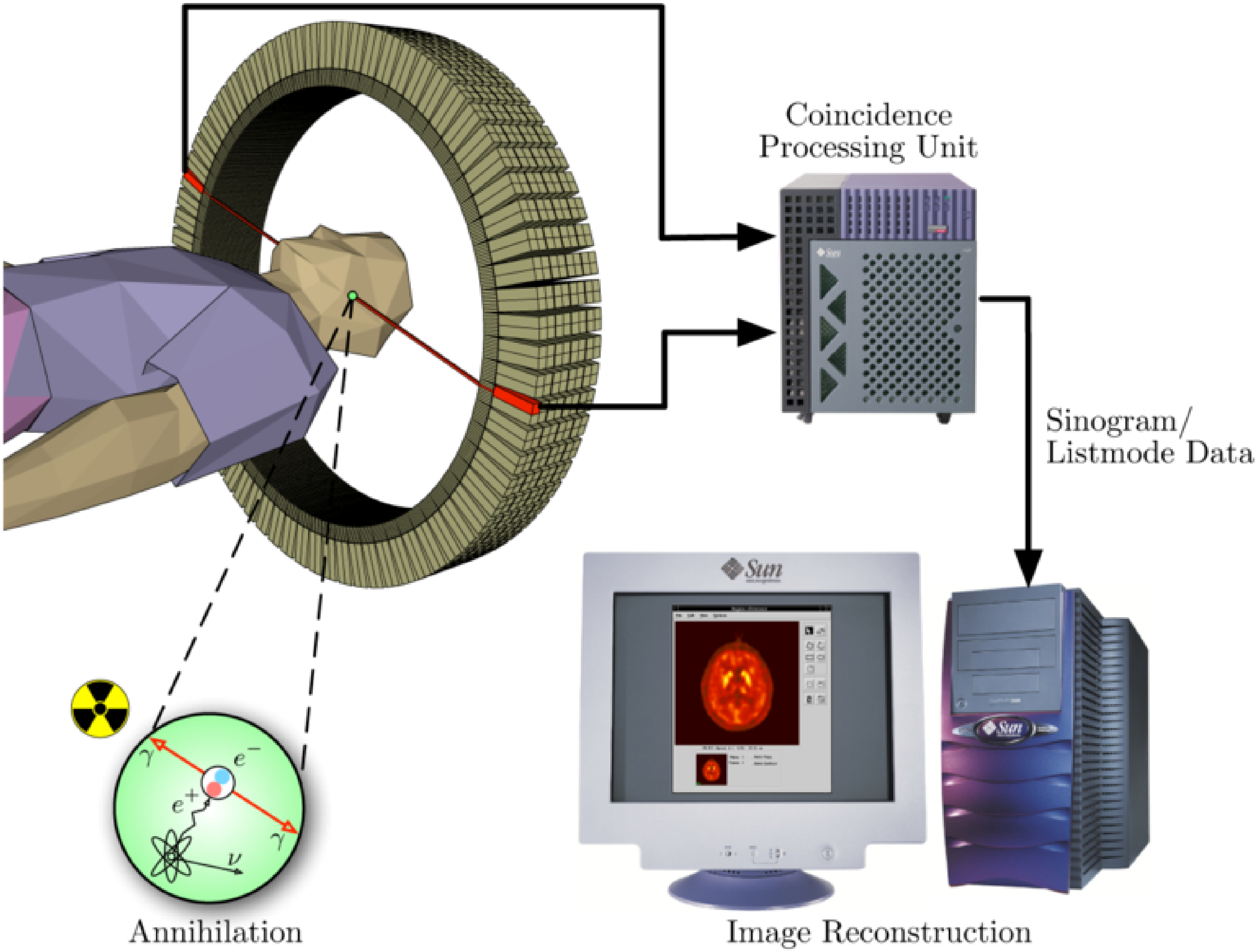
Positron Emission Tomography



Micro-PET

- Research scanner
  - For small animal
  - Small diameter
  - High resolution

- Typical performance (LSO)
  - Efficiency: 85%
  - Position resolution: 6 mm
    - Depth of interaction issue
    - Resolution at center of field of view < 1.3 mm
  - Timing resolution: 3 ns (FWHM)
  - Energy resolution: <18% (FWHM) @ 511 keV

Comparing liquid Xenon to solid scintillators

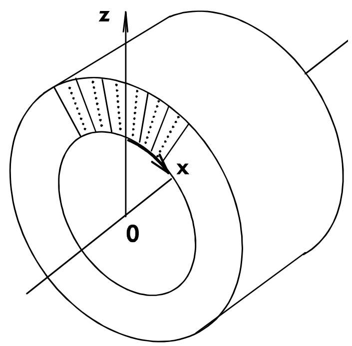
- Scintillation

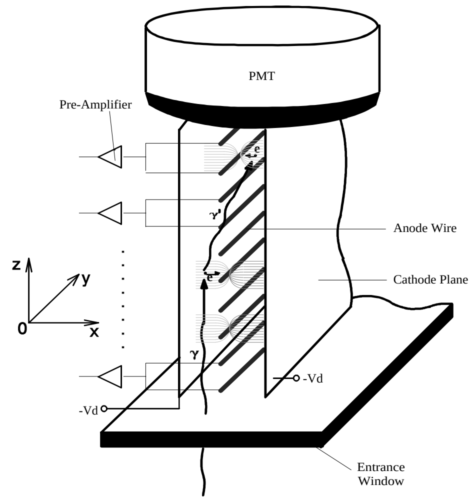
Scintillator	BGO	LSO	LXe	Pros/cons
Density, g/cc	7.1	7.4	3.1	-
Yield, photons/keV	6.4	32	68 (EField=0)	+
Decay time, ns	300	40	2.2 (27, 45)	+
Wavelength, nm	480	420	178	-
Photo-fraction	42%	33%	22%	-

- Measure ionization as well: more quanta
  - Full collection of electron with electric field
    - Slow drift, no improvement in timing
  - Greatly Improve position and energy resolution

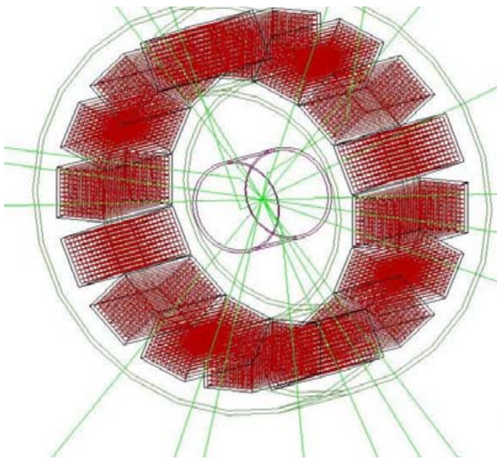
Sample of LXe PET being developed

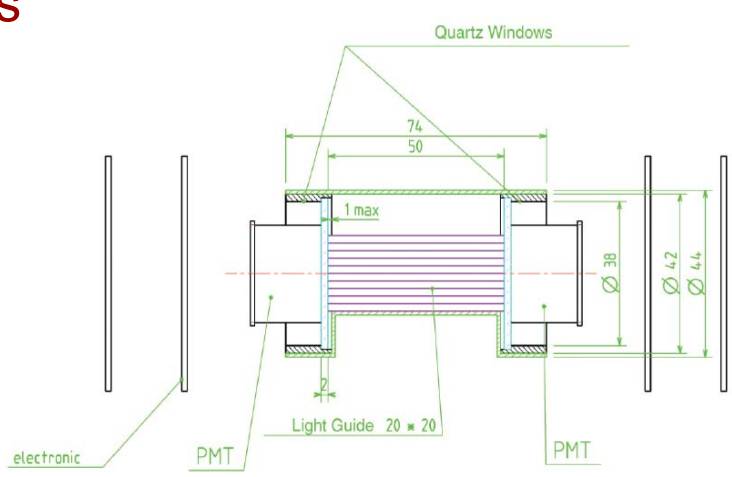
- LIP: scintillations and ionizations





- Grenoble: only scintillations





Our solution

- Measure both scintillation and ionization
  - Optimum energy and position resolution
- Ionization (Time Projection Chamber)
  - Electron drift time provides one coordinate
  - Wires and anode strips for other 2 coordinates
  - Good position resolution
  - Good two-hit separation
    - Crucial for Compton reconstruction
- Scintillation light
  - Trigger
    - Define a region of interest in the drift volume
    - Reduce pile-up by matching with ionization cluster position
  - Provide timing resolution

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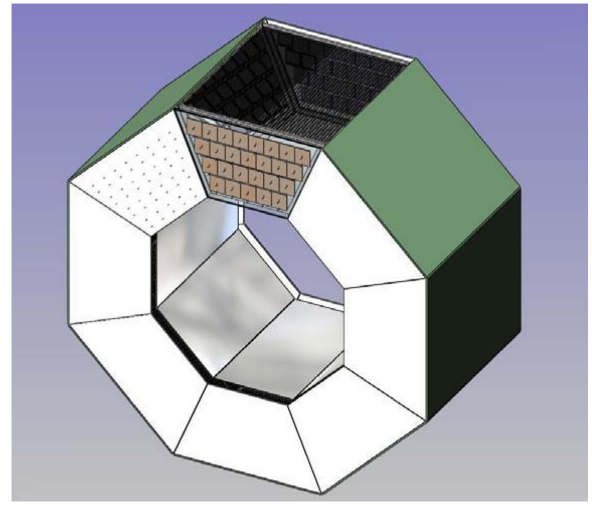
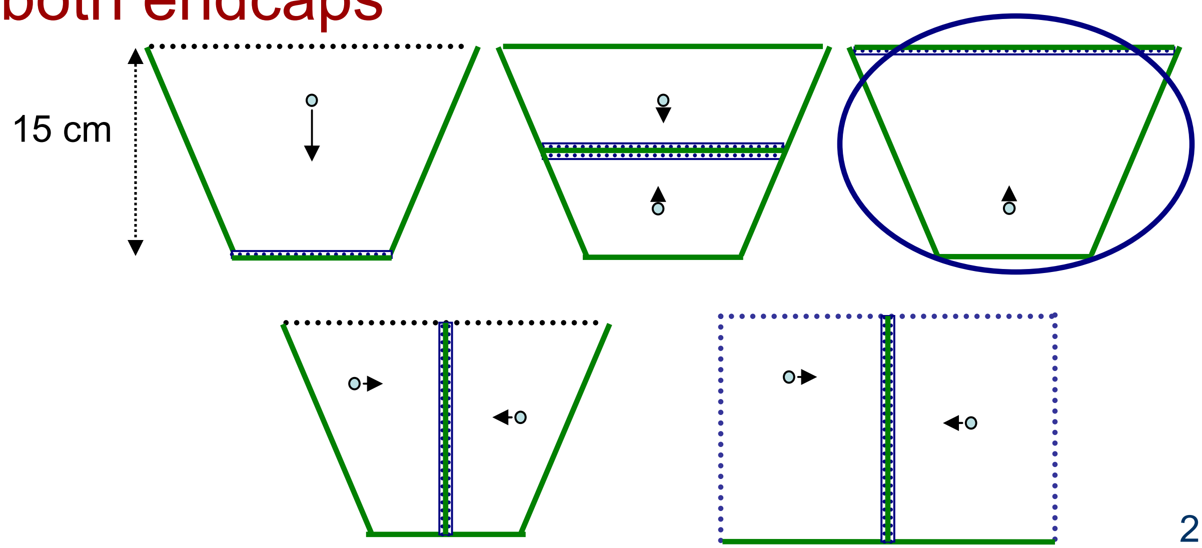
Detector geometry



- Number of sectors
  - 8,10, 12
    - 12 optimum for pile-up rejection
- Electron drift
  - Radial, axial, azimuthal
    - Radial towards outer radius
- Light sensors cover both endcaps



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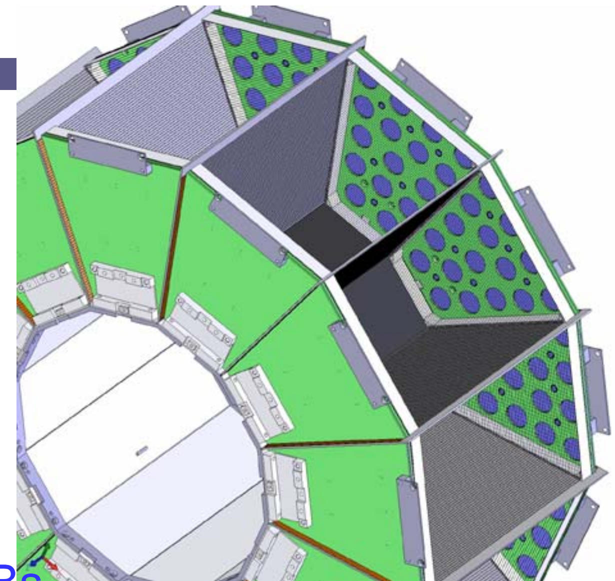
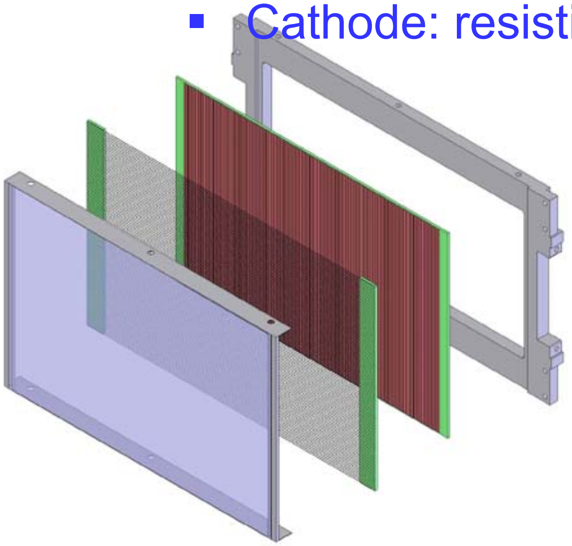
Full scale prototype

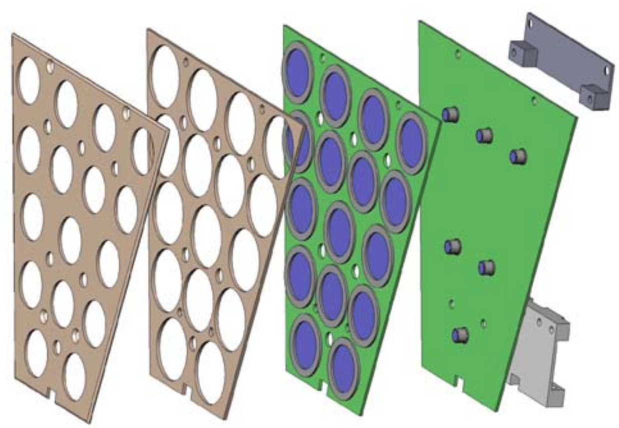


- 12 sectors.
  - Field cage formed with strips (between sectors) and wires (ends)
  - Cathode: resistive kapton on ceramic plates



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

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



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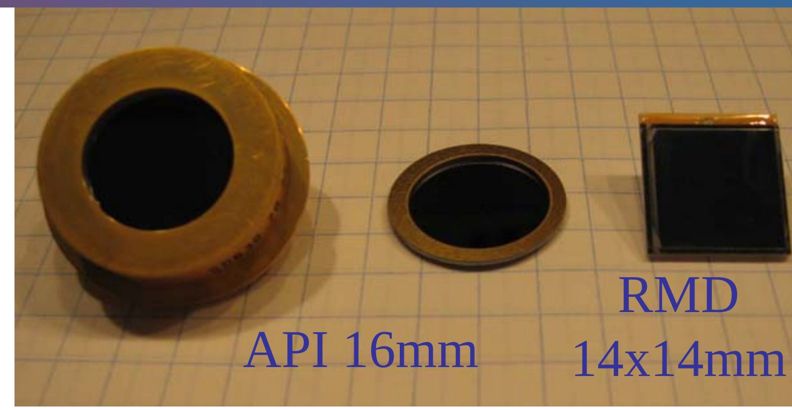
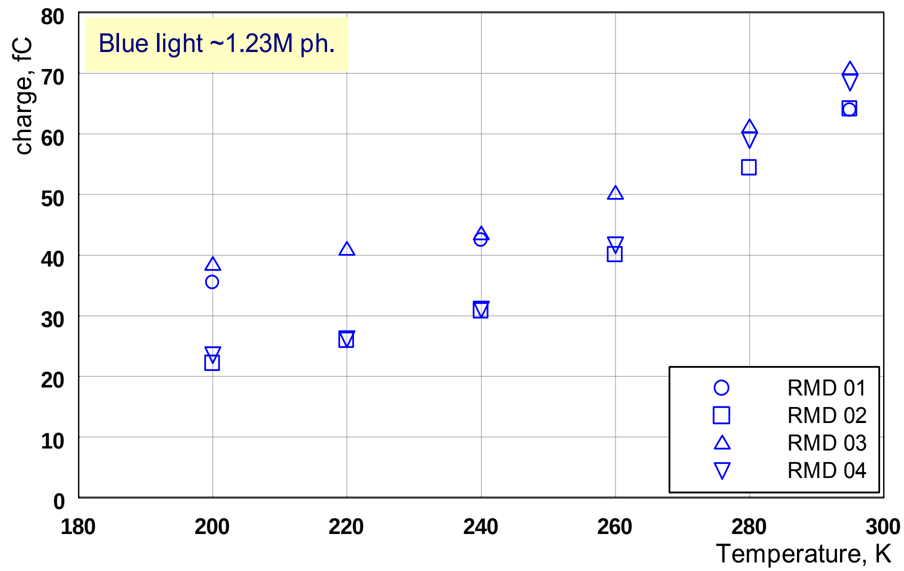
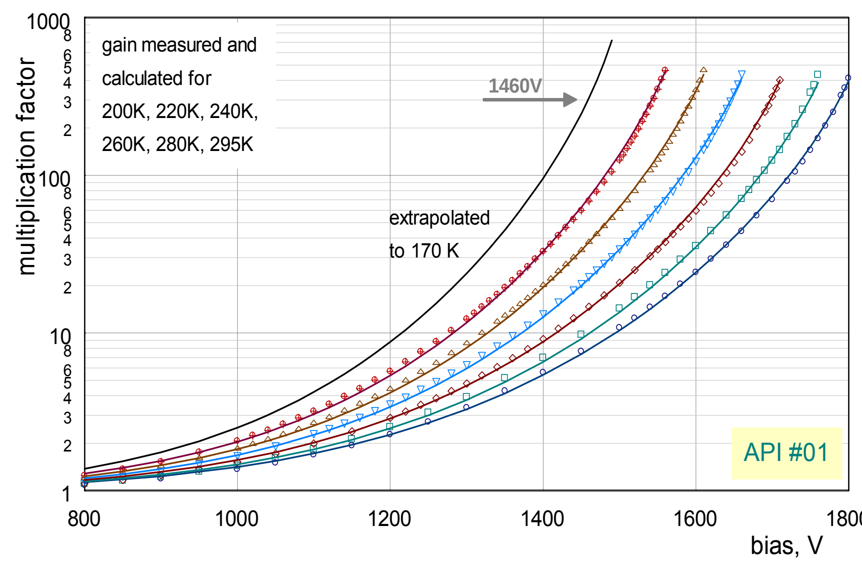
Light detection with APD

- PMT
  - Low QE not compact
- APD
  - Work at low T
  - QE~0.5-100% for UV light
  - Fast
  - Large area from API and RMD
    - But RMD QE drops with T

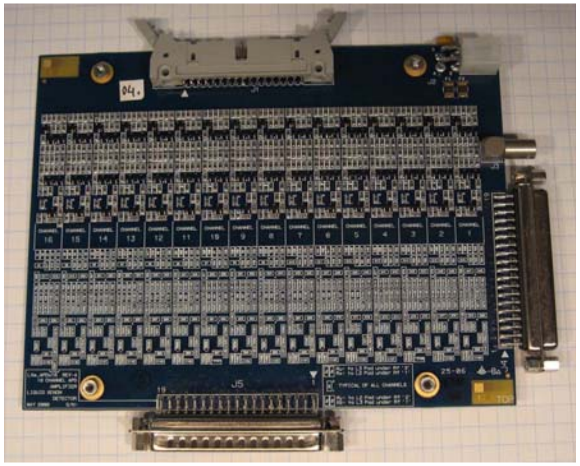




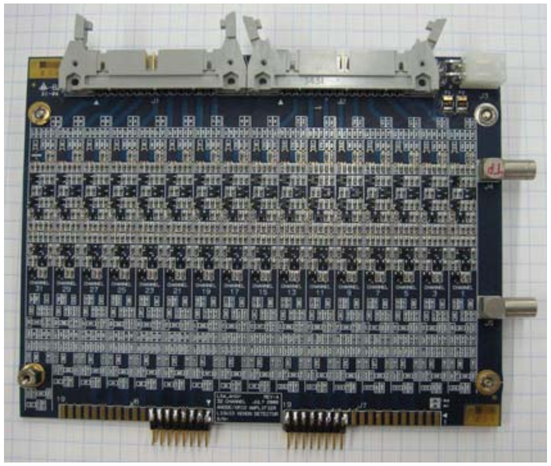


Custom electronics

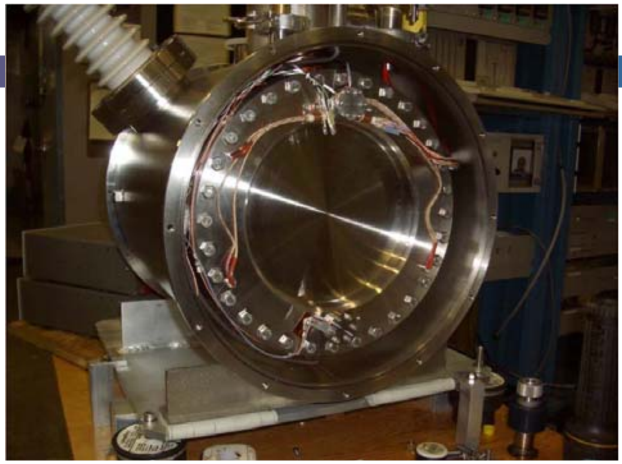
- Light detection
  - Fast and low noise for Cd = 200 pF
    - Signal ~ 20,000 electrons
  - BJT gives 4000 e- ENC for 20 ns peaking time
  - 16 channels



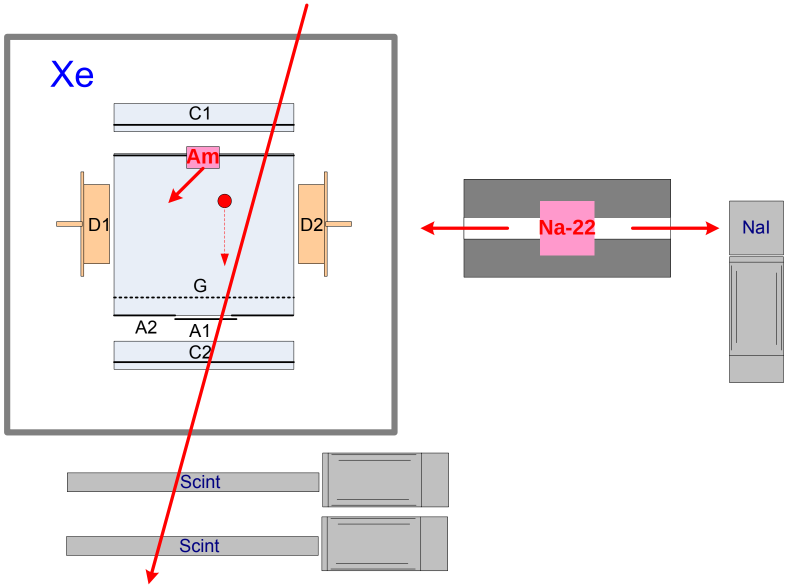
- Ionization signal
  - Low noise, rather slow for Cd = 30 pF
  - JFET gives 600 e- ENC for 270 ns shaping time
  - 32 channels



Small scale prototype



- Run May-August 2006
  - 8.5 l cryostat
  - 3x3x3 cm^3 TPC
    - 2 anodes
    - 1 grid (active)
    - Readout with 20 MHz digitizer
  - 2 16 mm APD
    - Readout with 1 GHz digitizer
- Main measurements
  - Cosmics
  - Na22 source of 511 keV
- Good electron lifetime achieved



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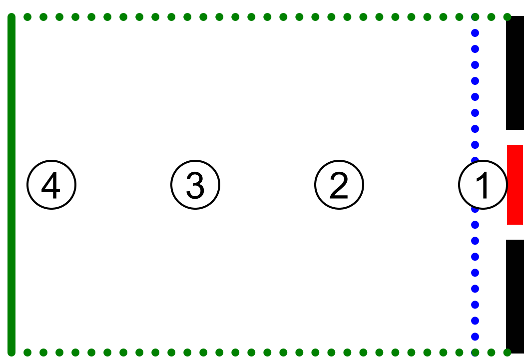
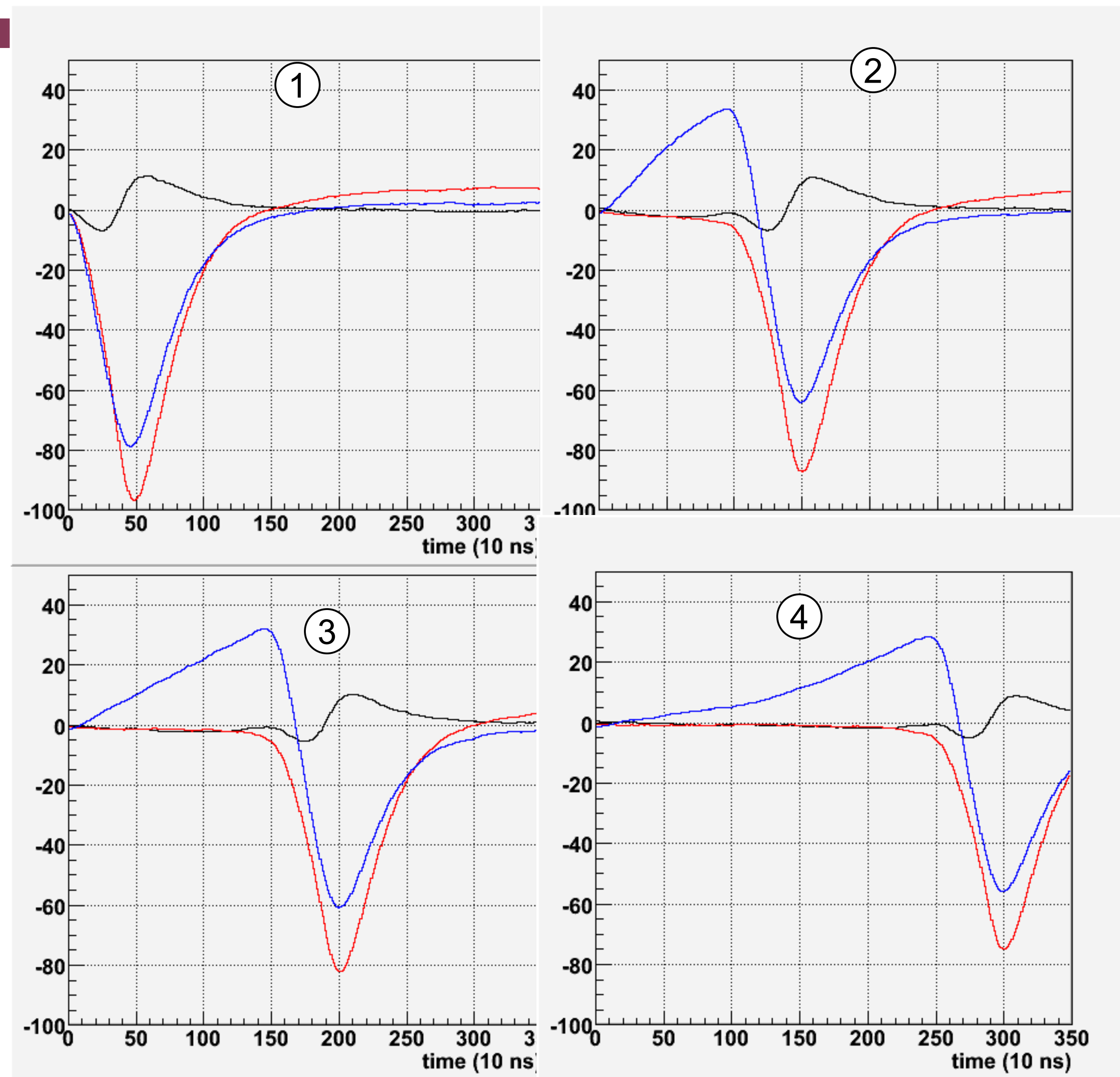
Understanding current
Work like an ionization chamber

Grid, **anode 1**, **anode 2**





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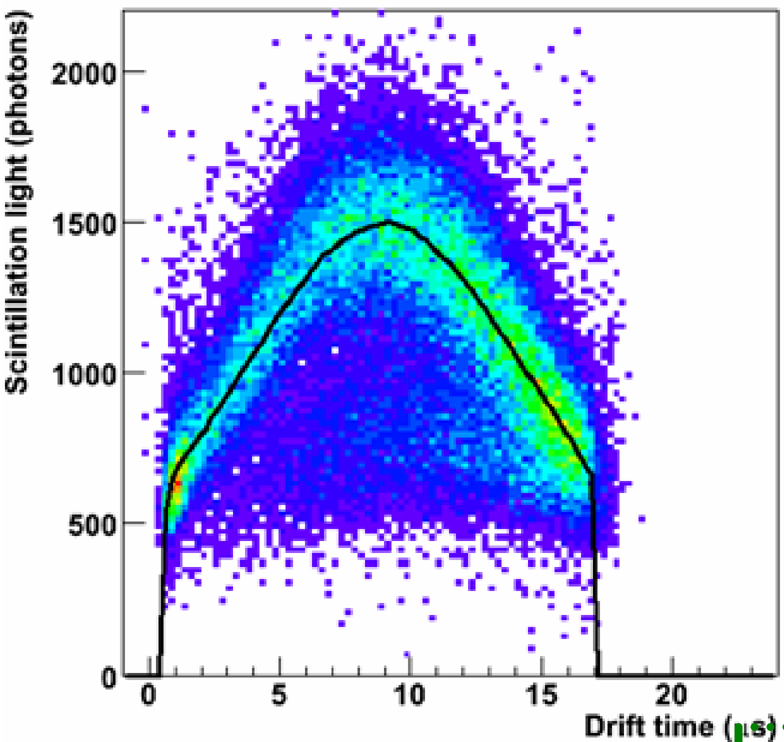
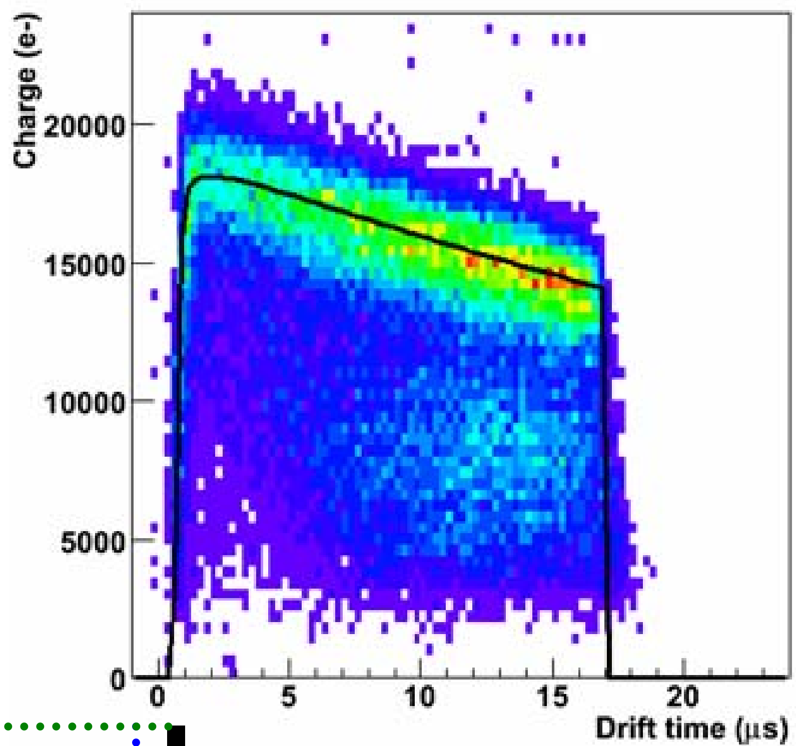
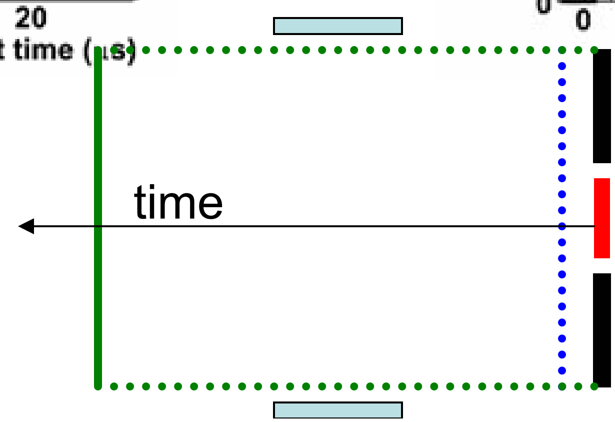
Light and charge collection in small chamber prototype







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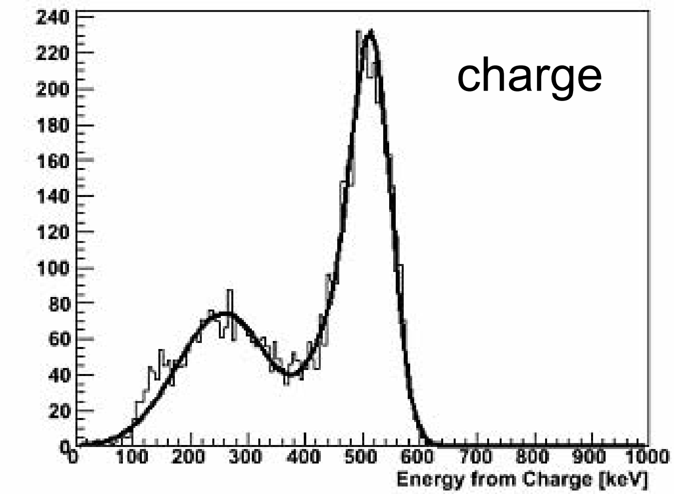
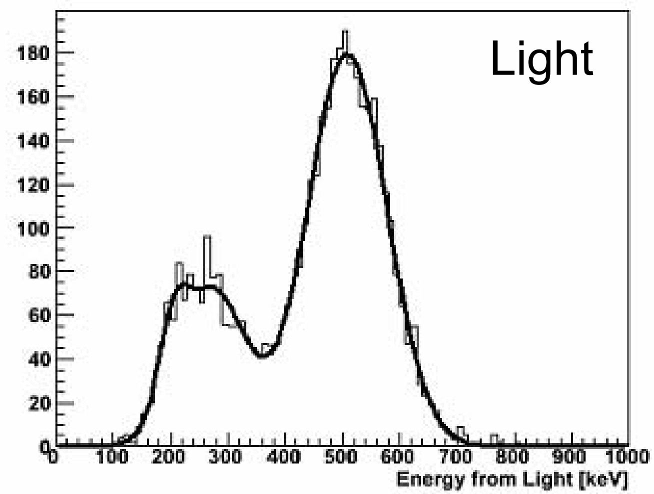
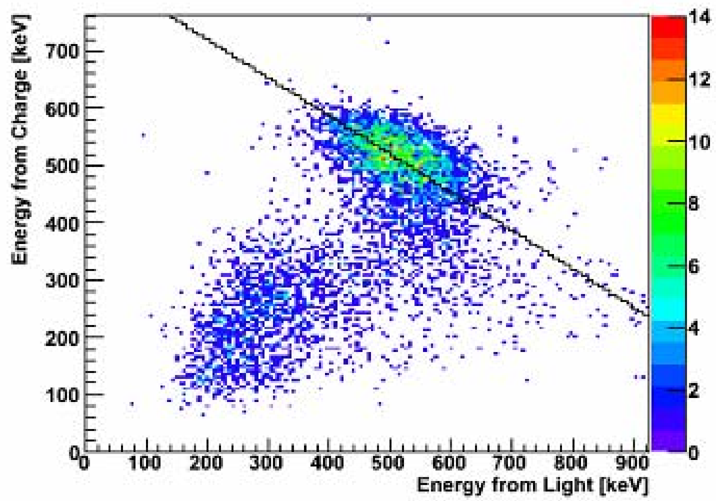
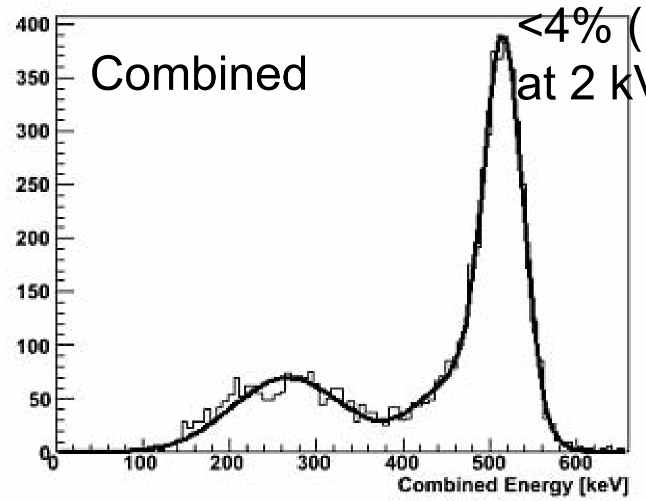
Combining light and charge for optimum resolution









<4% (FWHM) resolution
at 2 kV/cm

Astrid Muenich

Lessons learn from small chamber prototype

- Achievements:
  - 200 μs electron lifetime
    - Need to demonstrate scalability to next prototype
  - 1 ns timing resolution
  - 4% (FWHM) energy resolution
- Issues
  - No absolute light calibration
  - After canceling light/charge fluctuations, resolution dominated by APD noise and solid angle fluctuations (light-position correlation)

Estimating the micro-PET performance by simulations

- Geant 4 for photon interactions
- Parameterize detector response
  - Energy, timing and position resolution
  - Hit merging
  - Efficiency (effective)
- Calculate count rates from the probabilities of detecting 0, 1 and 2 photons per annihilations
- Develop an algorithm for reconstructing Compton interaction sequence
  - Crucial to find the first interaction point
    - Choosing the wrong point worsen resolution
  - Useful to reject background

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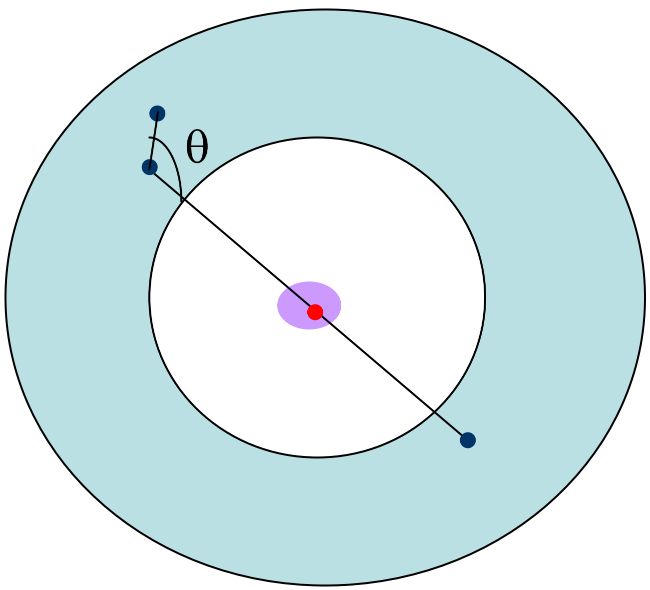
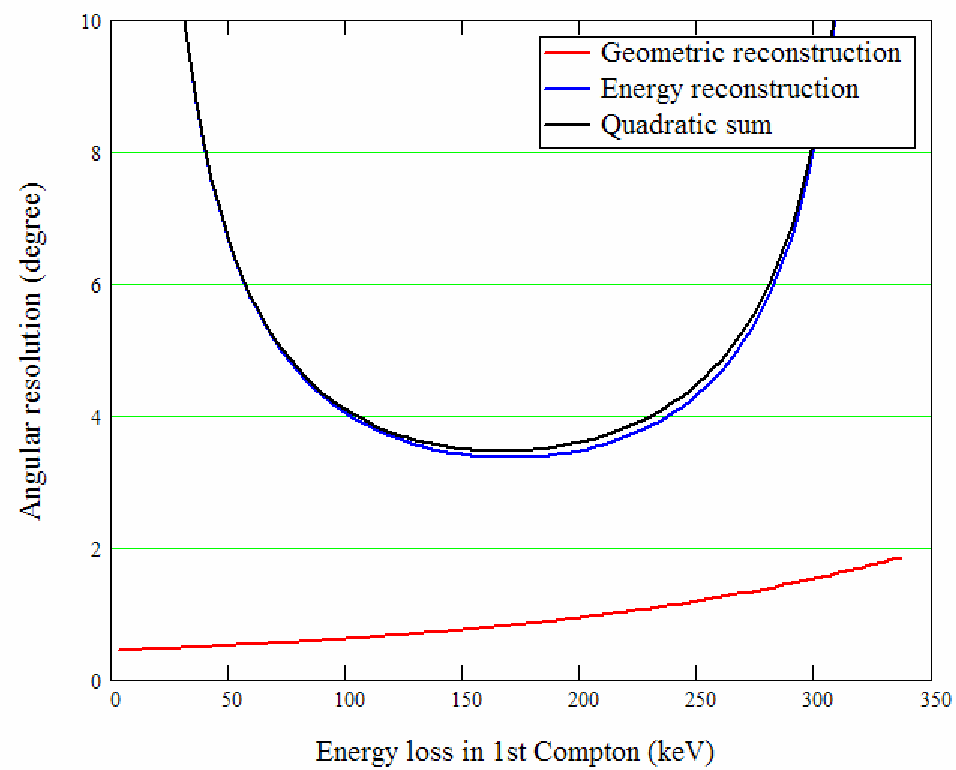
511 keV photon interaction Using Compton information

- Probability of interaction fo 511 keV
  - 3.6 cm attenuation length
  - 30% photo-electric
  - 70% Compton





$$\theta = \cos^{-1}(1 - me \cdot \frac{Eloss - Ei}{Eloss \cdot Ei})$$

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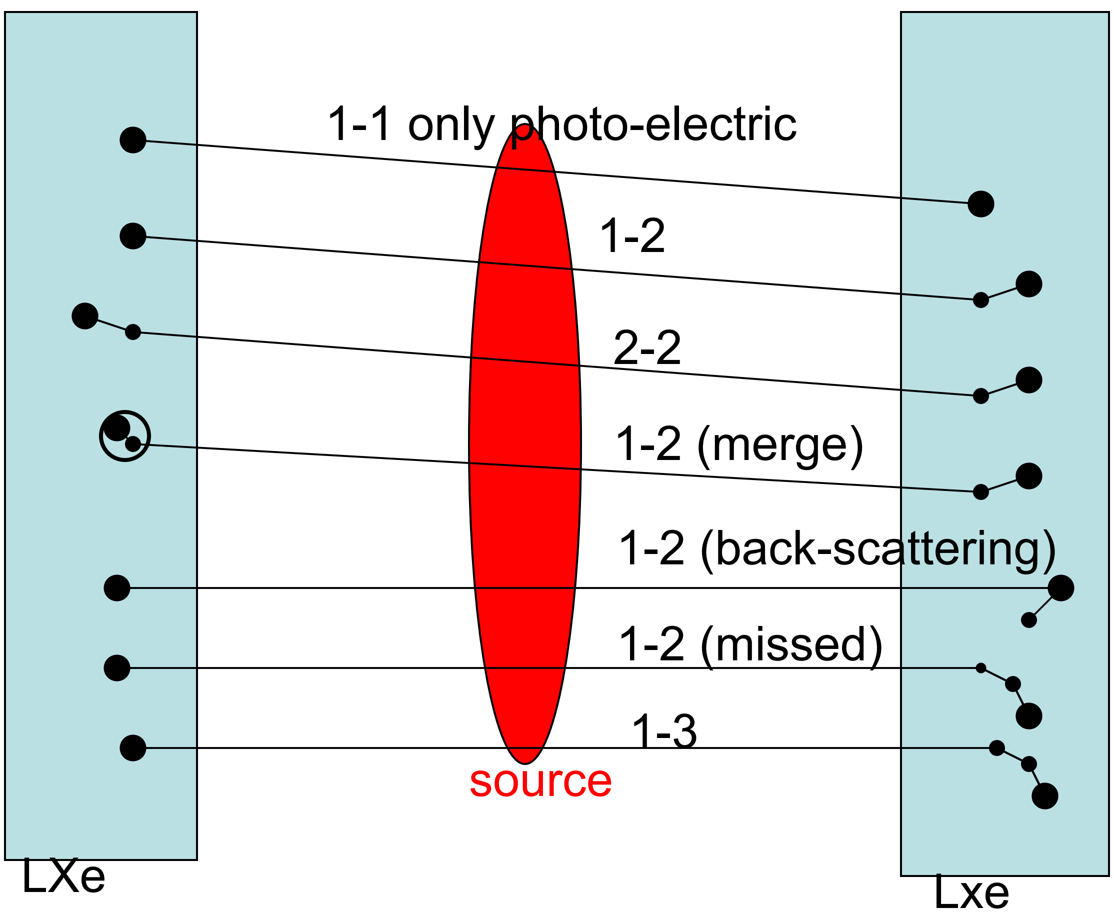
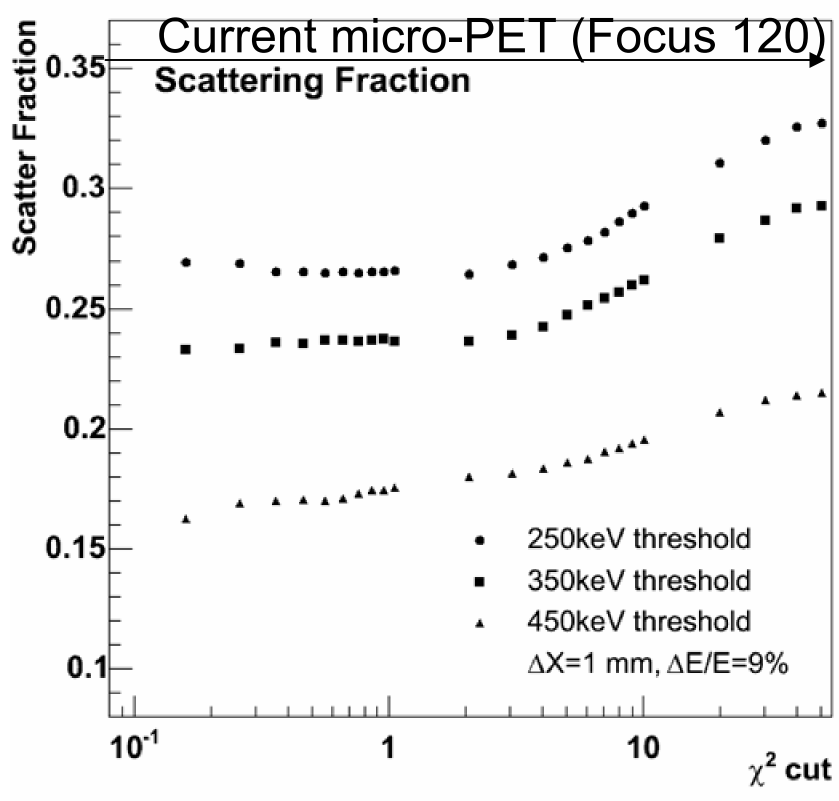
Many different Compton configurations



- Crucial to select right first point
- Minimum energy threshold per point is 50 keV
- Some points merge
  - Merging recover some low energy points
- Backscattering significant

Reducing the background

- Background sources
  - Scatter in patient
    - Lower energy photon
    - Wrong geometrical Compton angle
  - Random: 2 photons from 2 different annihilations
    - Uncorrelated line of response
    - Often, one of the photons undergoes a scatter before reaching the detector



Compton criteria

UBC student Philip Lu

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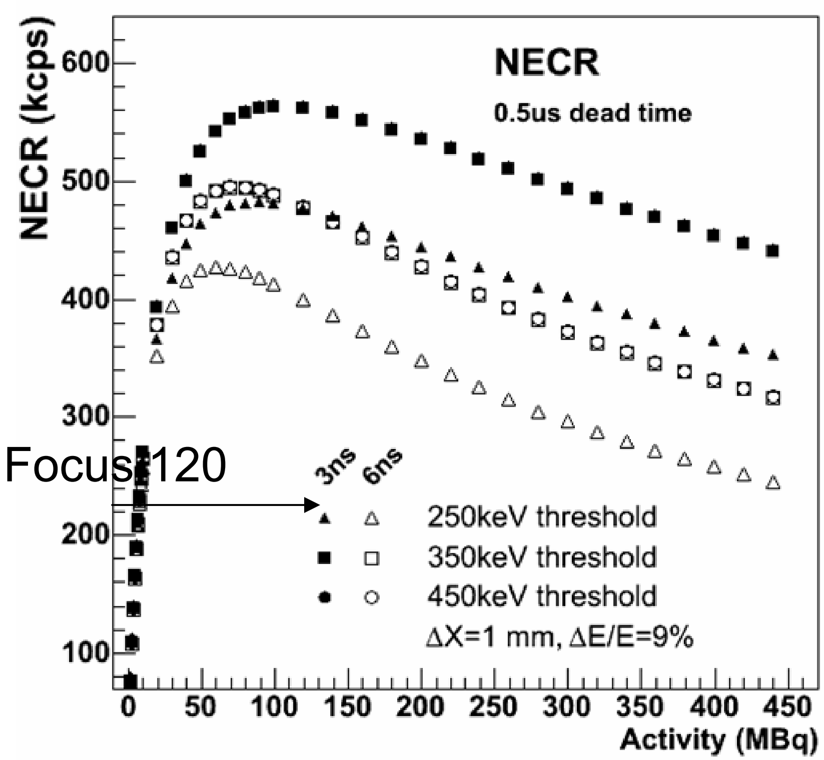
Optimizing the count rate

- No Compton χ^2 cut is best for maximizing counting rate
  - ❑ Reduce true much compare to background rejection
- Dead time in this calculation = 500 ns
  - ❑ Very tough to achieve

$$NECR = \frac{True^2}{True + Scatter + Random}$$



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Rat size phantom

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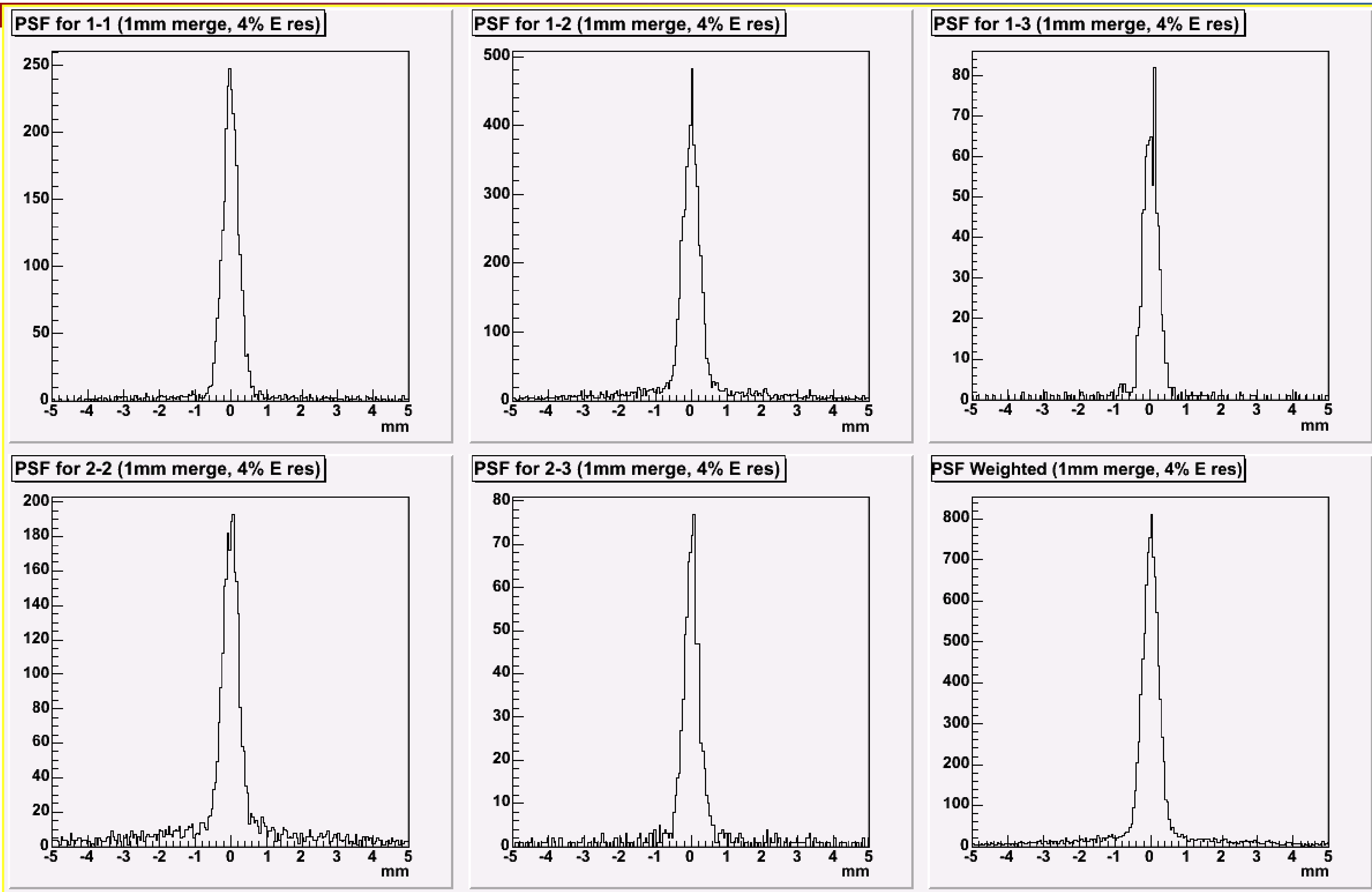
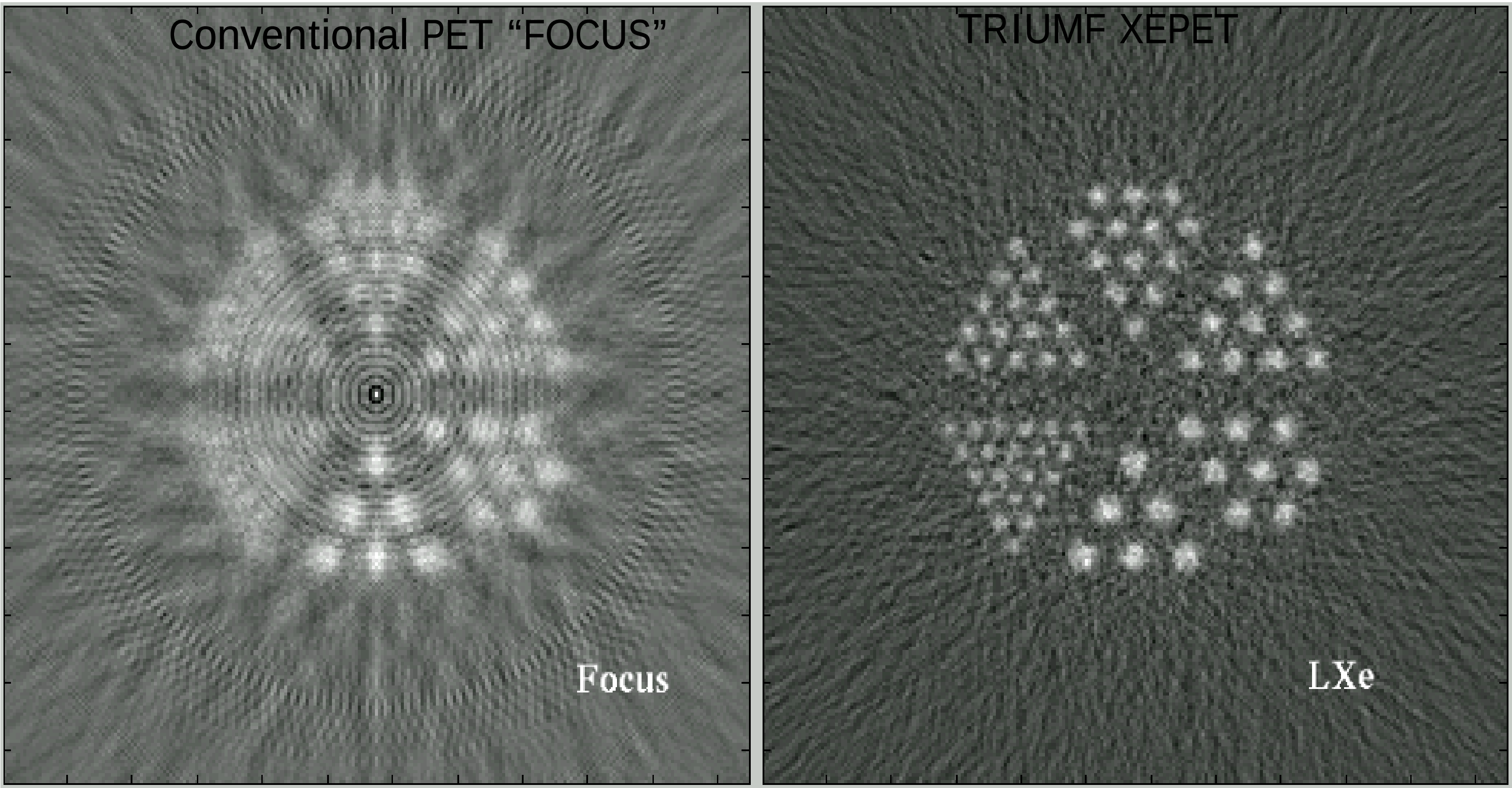
Image quality for different Compton configuration



Comparison of PET Image Simulations



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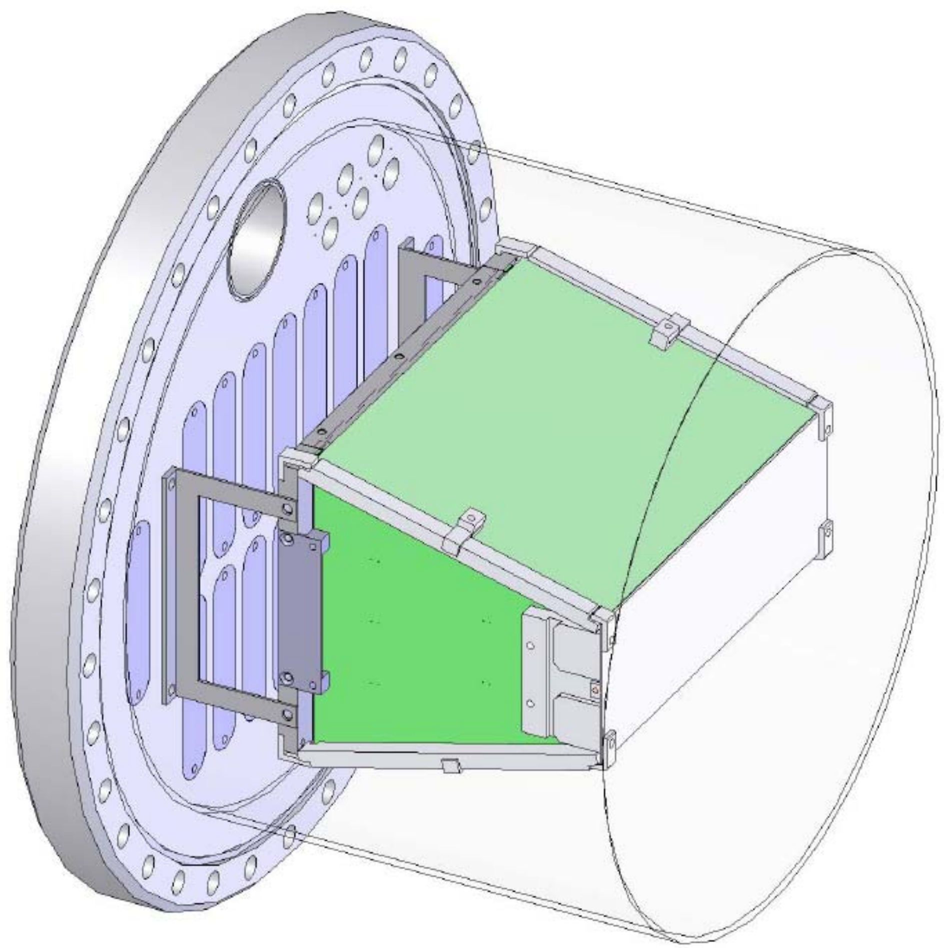
Derenzo Phantom in water:
1mm dia. Minimum feature size.

Continuing R&D program for PET

- End of 2007-2008 sector prototypes
  - Fits in existing cryostat
  - 96 anode strips, 96 grid wires
  - 32 APDs in ends
- Applied to CHRP for 2 sector prototype in 2008-2009
  - μPET cryostat
  - Final sector design
  - Final electronics and readout
  - Develop trigger
- 2010(?) μPET prototype
  - Fully (half) populated
  - Computing
    - data farm
    - Develop onlin reconstruction
    - Image reconstruction



Summary

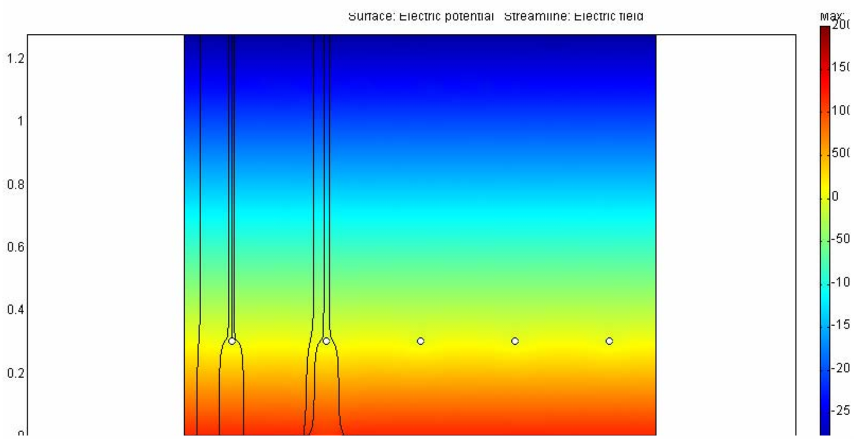
- Liquid Xenon is very promising for PET
  - Short attenuation length
  - Superior energy and position resolution
  - Compton reconstruction
- And for physics
  - Double beta decay
  - Dark matter search
    - XENON10 leading the pack
- Challenges ahead for TRIUMF LXe PET
  - Achieving ppb purity with lots of material
  - Designing custom electronics is necessary
    - Low noise, especially for APD
    - Triggering electronics
    - Minimize dead time
  - Data analysis must allow rapid diagnostic
    - Online processing
    - Rather complicated analysis

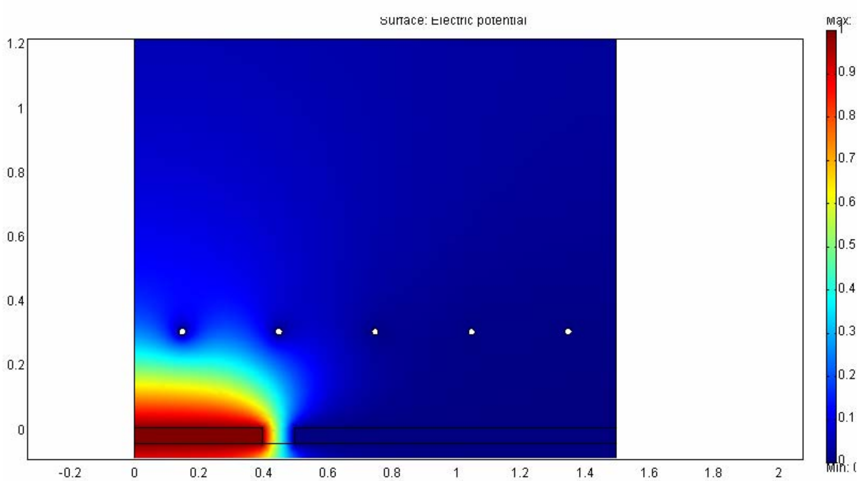
This work is supported by CFI-UBC-BCKDF and TRIUMF Tech Transfer Division and Science Division

Back-up

Fabrice Retière

Calculating current





- Drift field
  - Electron trajectory
- Weighting field
  - Induced current
    - Ramo theoem
- Preamp-shaper response function