Photodetectors for Nuclear Medical Imaging

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Outline:

- Overview of Nuclear Medicine
- Current SPECT & PET Instrumentation
- Potential for New Photodetectors

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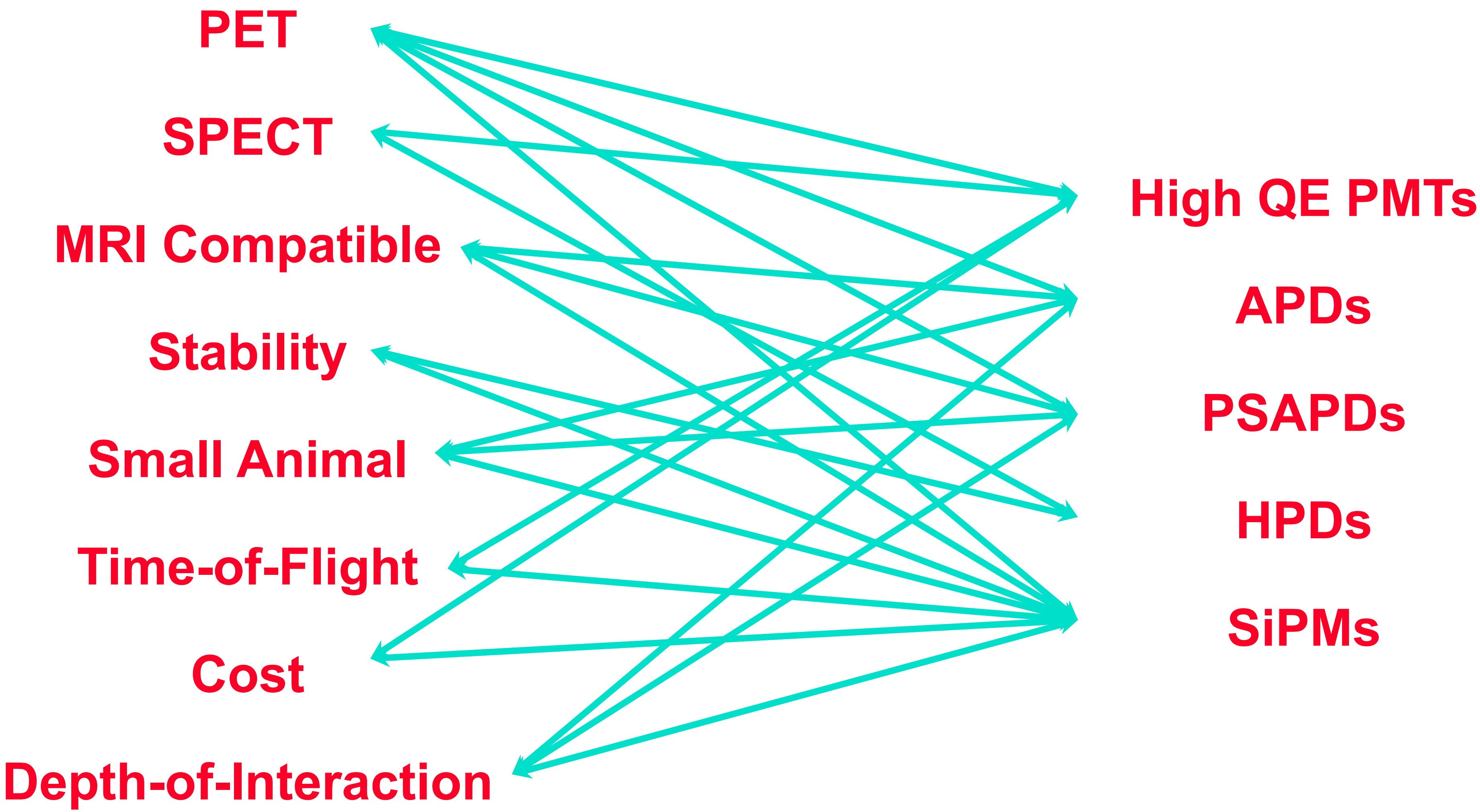
Needs & Technologies



Linkage is Complex…

Photodetector Technologies

High Quantum Efficiency PMTs

Gain ~10^6, 35%–50% QE (instead of 25%).

APDs

Si device, gain ~10^2, small pixels, QE > 90%.

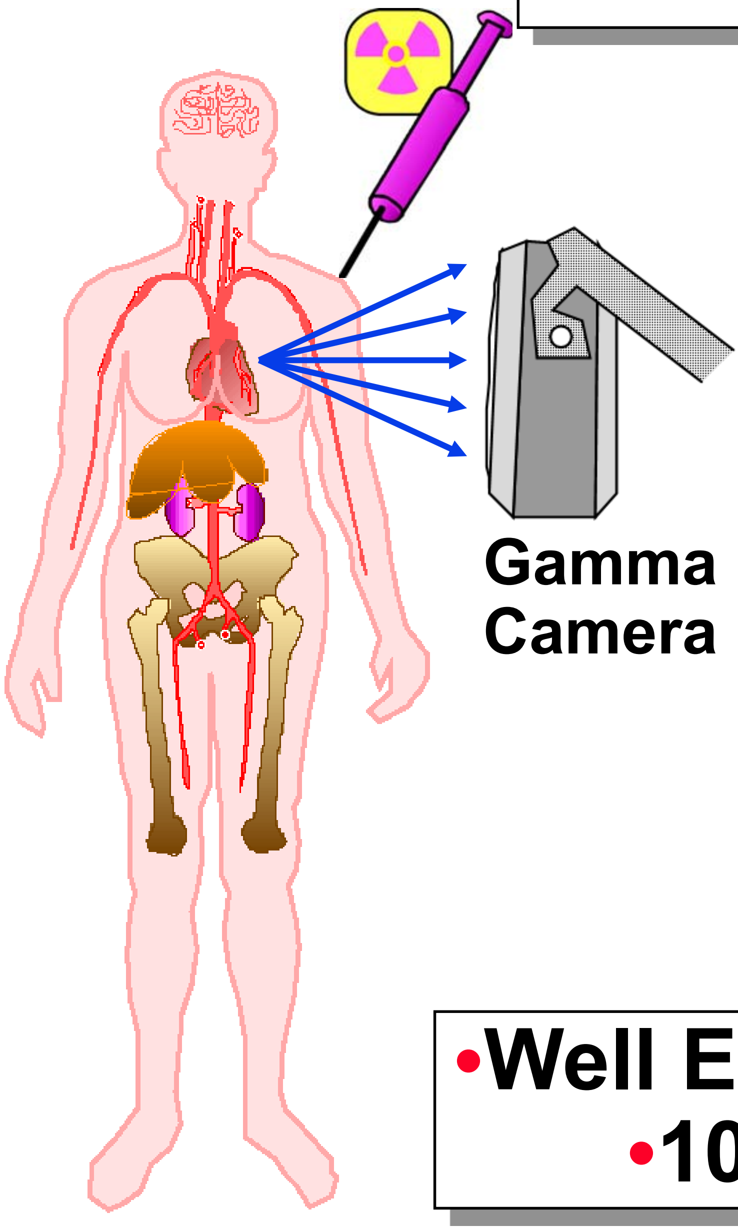
Hybrid Photodiodes (HPDs)

Gain 10^4–10^6, 25% QE, *very* uniform gain, good single p.e. resolution, can be pixellated.

Silicon Photomultipliers (SiPMs)

Si devices, gain ~10^6, small pixels, good single p.e. resolution, QE up to ~40%.

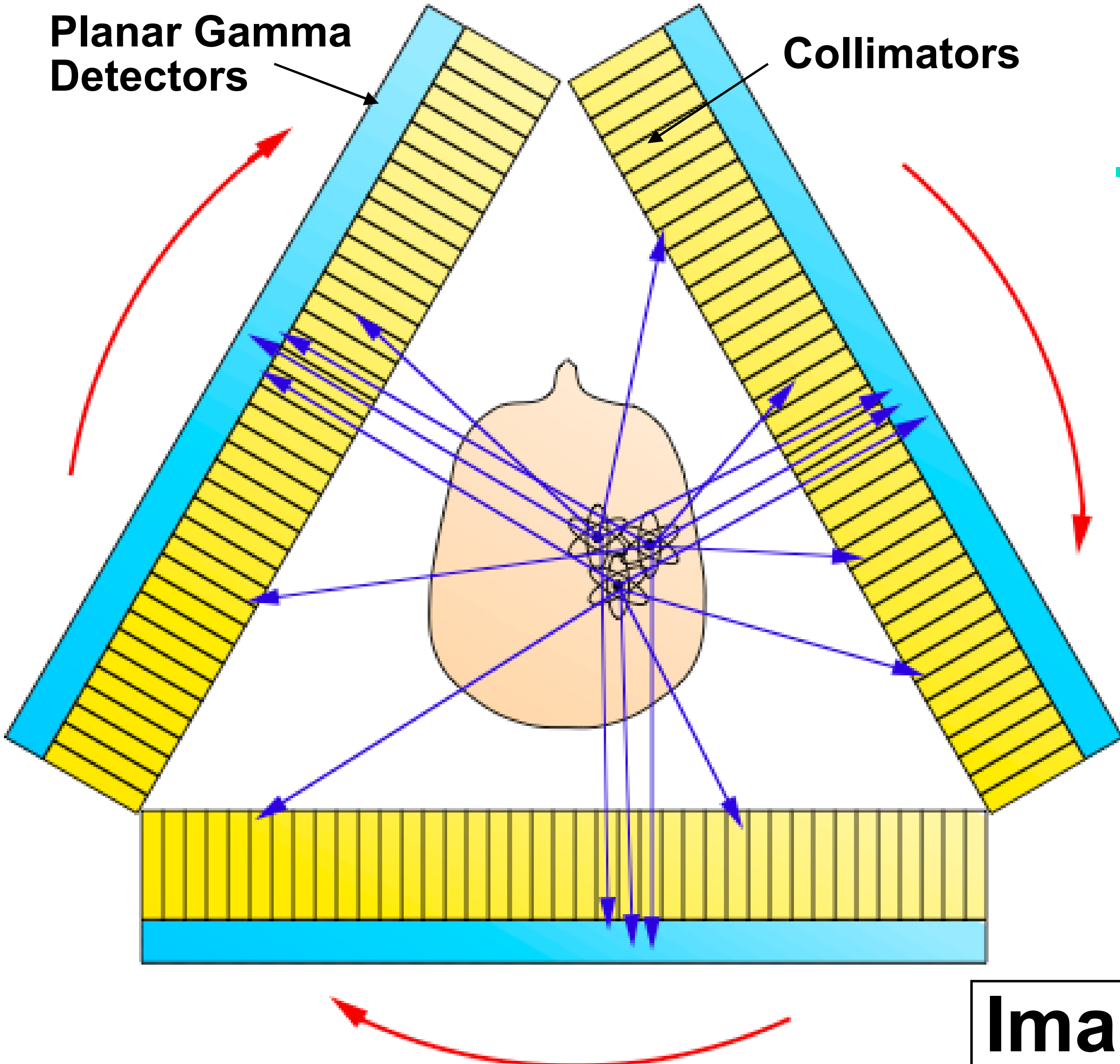
Nuclear Medicine



- Patient injected with *small* amount of radioactive drug.
- Drug localizes in patient according to metabolic properties of that drug.
- Radioactivity decays, emitting gamma rays.
- Gamma rays that exit the patient are imaged.

•Well Established Clinical Technique
•10 Million Studies Annually

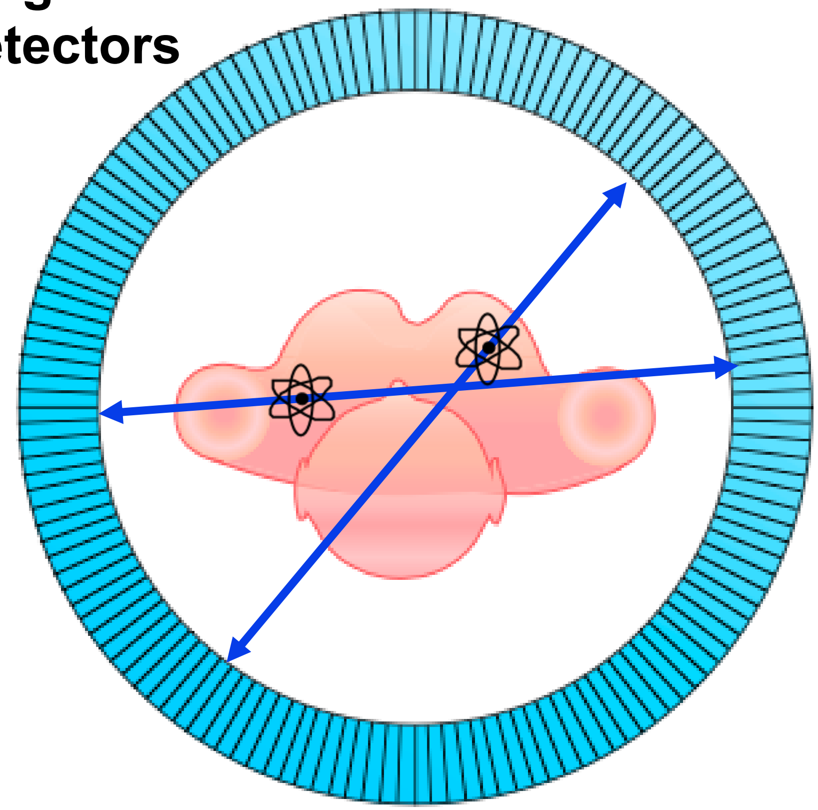
Single Photon Emission Computed Tomography (SPECT)



- One, two, or three imaging heads (cost / performance tradeoff)
- Direction of gamma defined by mechanical (parallel hole) collimators.
- Multiple views obtained by rotating the imaging heads around the patient.

Images 140 keV Photons

Positron Emission Tomography (PET)



- Radionuclide decays by emitting a positron (β^+).
- β^+ annihilates with e^- from tissue, forming back-to-back 511 keV photon pair.
- 511 keV photon pairs detected via time coincidence.
- Positron lies on line defined by detector pair.

- **Detects Pairs of Back-to-Back 511 keV Photons**
- **No Collimator Needed $\Rightarrow$ Much Higher Efficiency**

Desires

Research

- High Spatial Resolution (small animal)
- MRI Compatible
- Depth-of-Interaction
- Time-of-Flight (PET only)

Commercial

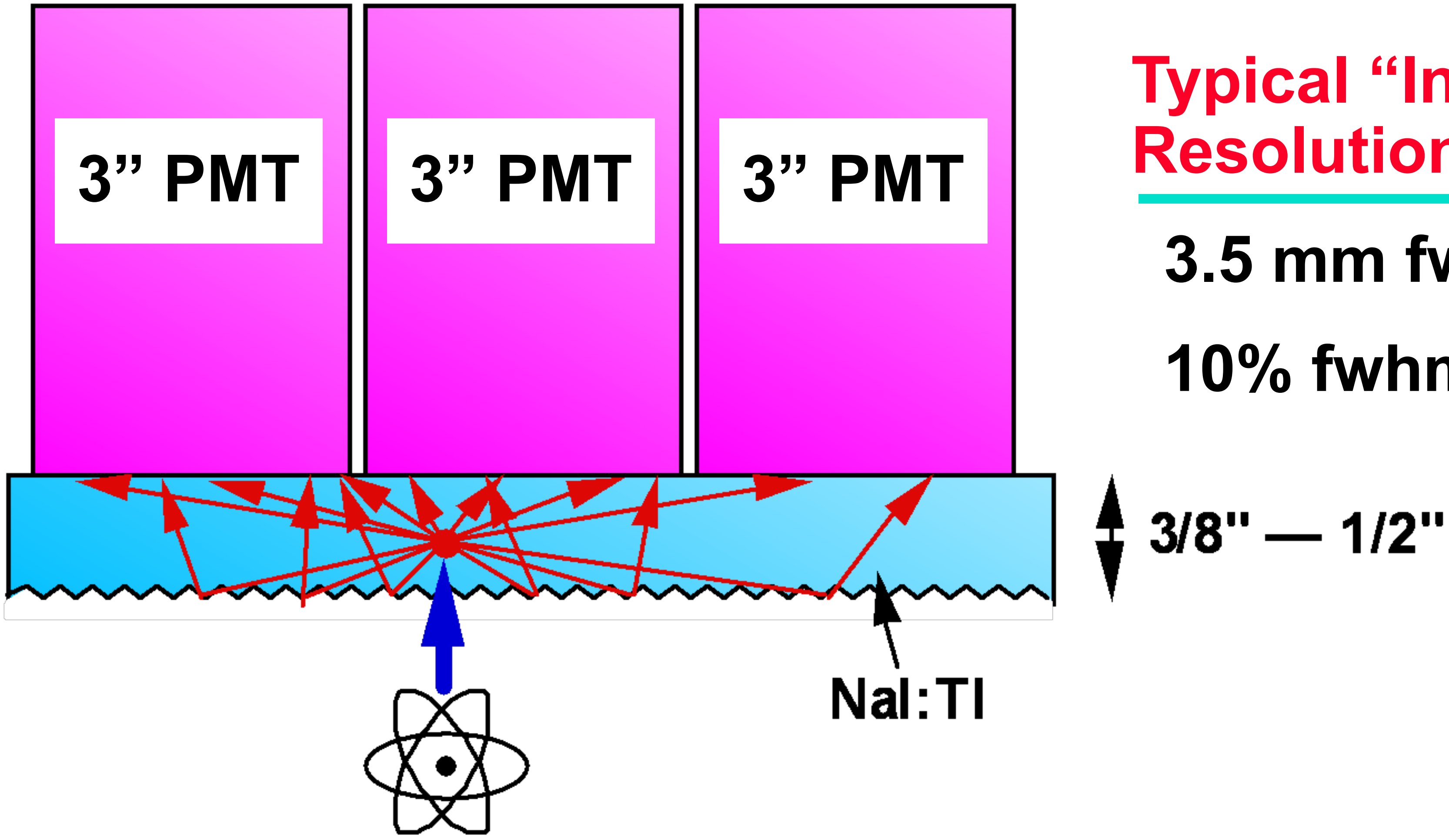
- Stability
- Cost / Unit Area

  ⇒ Cover ~0.5 m^2 @ \$2 / cm^2 (SPECT)

  \$16 / cm^2 (PET)

How Can New Phototdetectors Satisfy These Desires?

Starting Point for SPECT Detector: "Anger Camera"



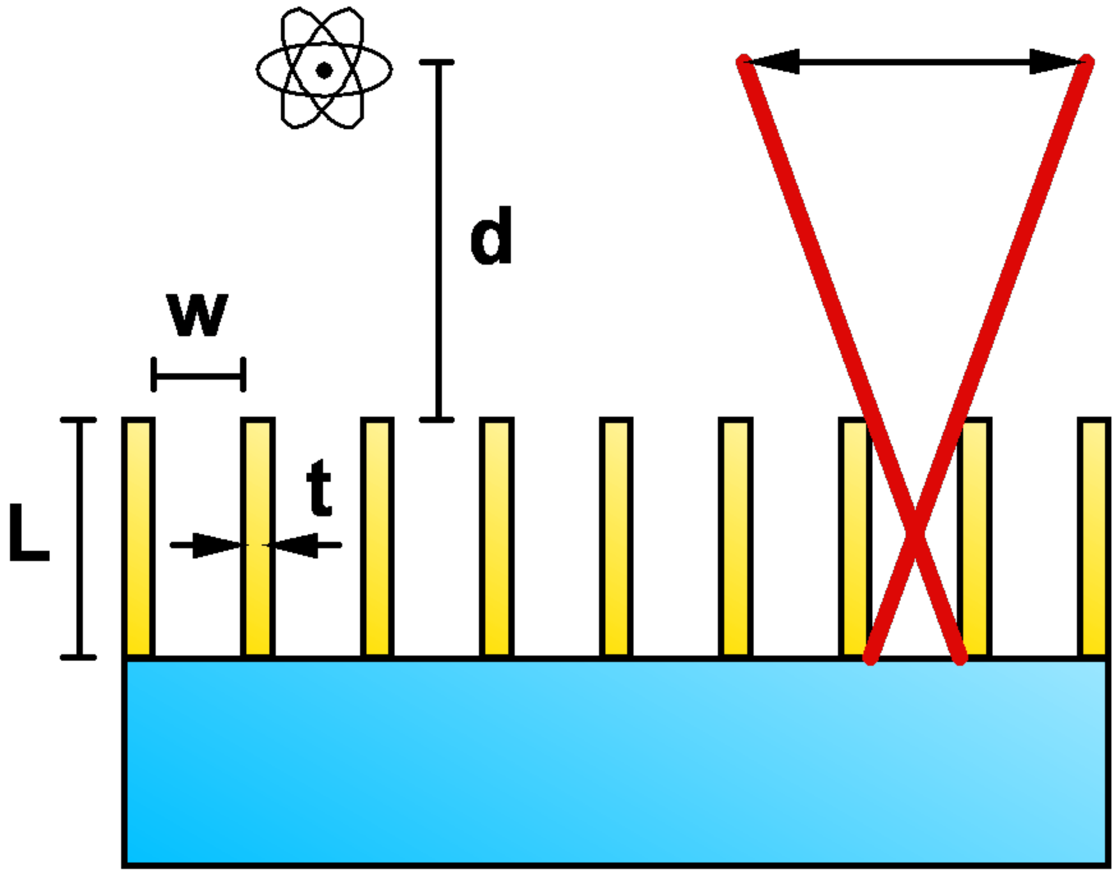
Typical "Intrinsic" Resolution:

3.5 mm fwhm spatial

10% fwhm energy

Position Measured by PMT Analog Signal Ratio

SPECT Collimator Tradeoffs



$$\text{Resolution} = 2\frac{w}{L}\left(d + \frac{L}{2}\right)$$

$$\text{Efficiency} \propto \left(\frac{w}{L}\right)^2$$

Typical Values:

w= 2 mm
L= 30 mm
t= 0.25 mm

Resol. (@5 cm) = 6 mm
Efficiency = 0.02%

Collimator Dominates Spatial Resolution & Efficiency

SPECT Detector Requirements

Photomultiplier Tubes (~50 / head)

Scintillator Crystal (NaI:Tl, 50 cm square x 1 cm thick)

At 140 keV:

- **High Efficiency** (>85%)
- **Good Energy Resol.** (<15 keV fwhm)
- **High Spatial Resol.** (<4 mm)
- **Low Cost** (<$15/cm^2)
- **"Short" Dead Time** (<2000 μs cm^2)

Based on Existing "Anger Cameras"

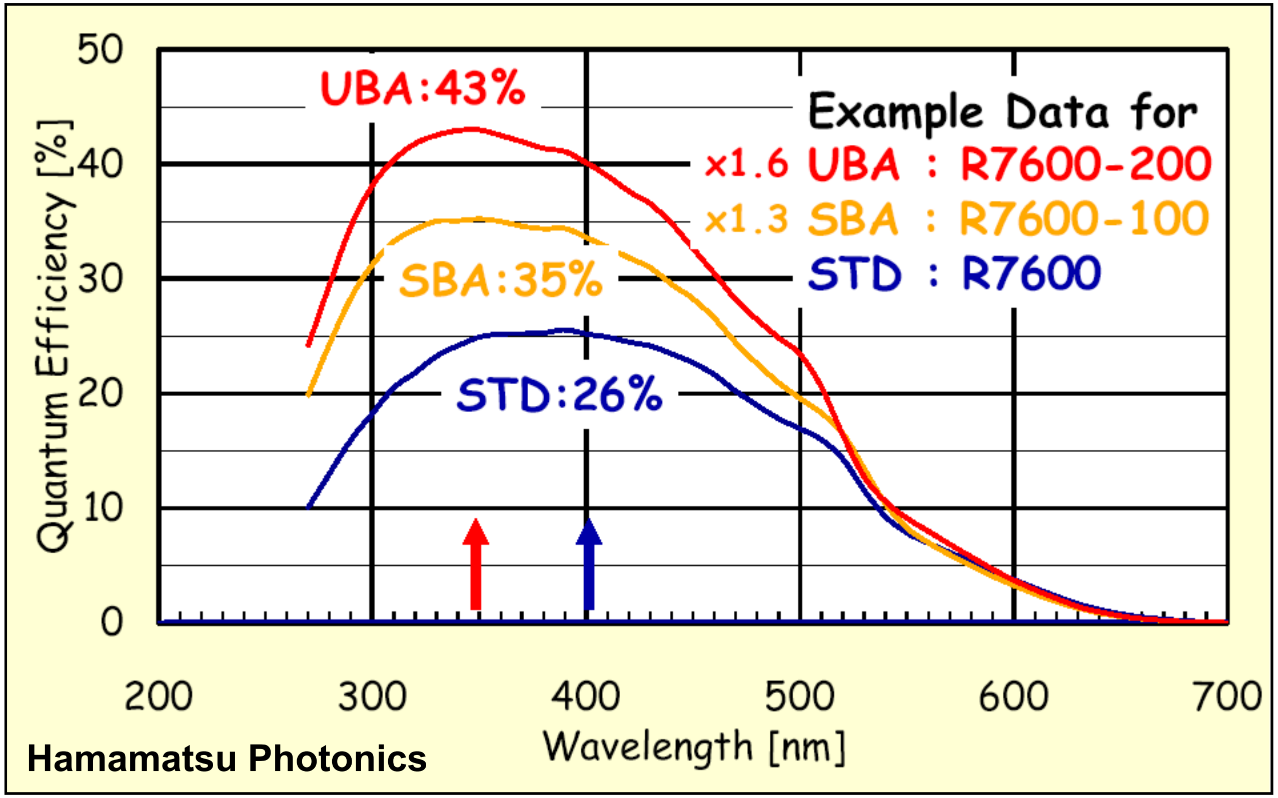
*Image courtesy of L. Shao, Philips Medical Systems

How Can Photodetectors Improve SPECT?

- **Spatial Resolution?**
  No — limited by collimator
- **Efficiency?**
  No — limited by collimator
- **Dead Time?**
  No — limited by collimator
- **Energy Resolution?**
  No — limited by scintillator
- **Cost?**
  Possibly — high QE PMTs
- **Stability?**
  Possibly — HPDs

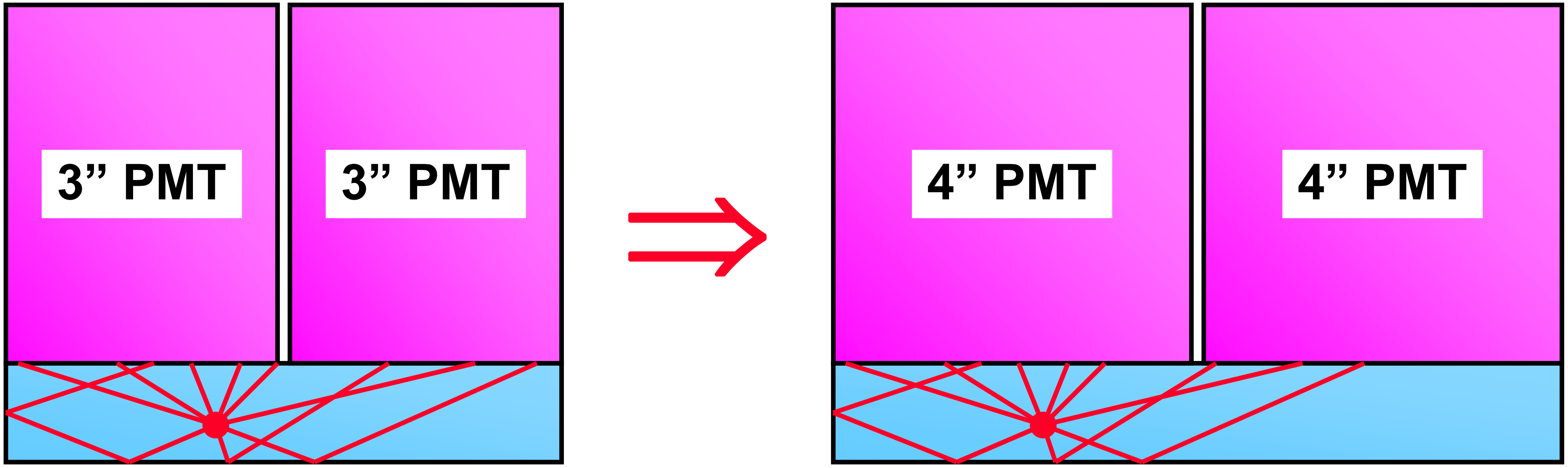
Not Many Possibilities…

High Quantum Efficiency PMTs



+ High Quantum Efficiency (>50% reported)
+ Just Like Conventional PMTs, but Higher QE
– Higher Dark Count Rate
– Cost

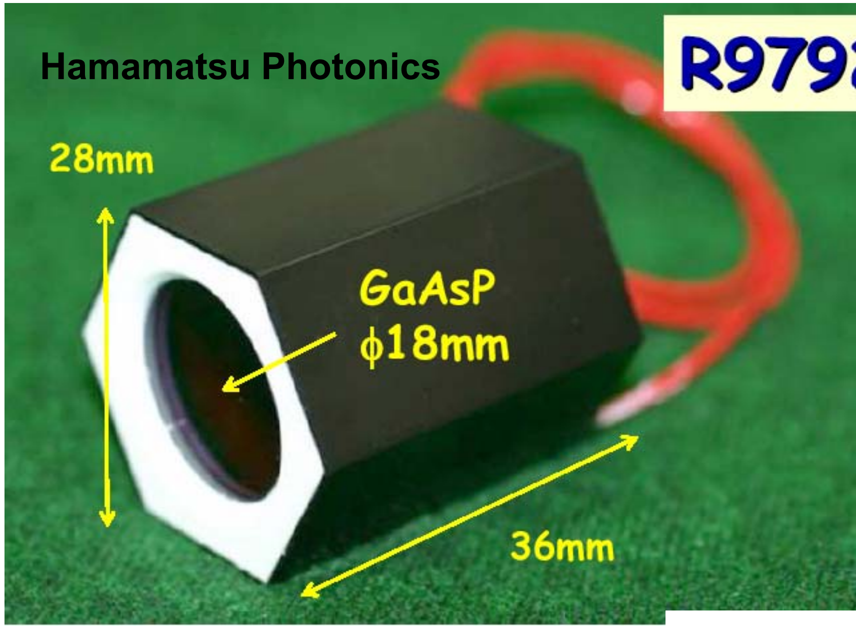
How Can SPECT Cost Be Reduced?

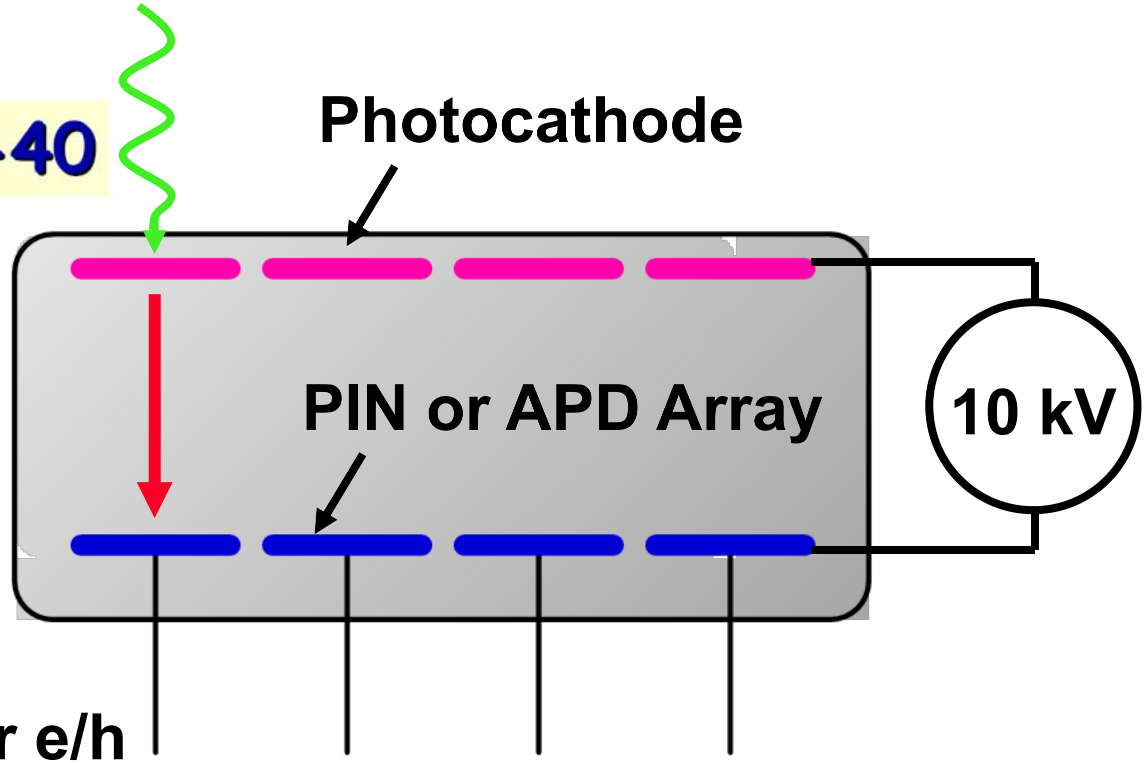


- Higher QE PMT ⇒ More Photons Detected
- Intrinsic Resolution ∝ Pixel Size / $\sqrt{\text{\# Photons}}$
- PMT Cost ~Independent of PMT Diameter

Get Same Spatial Resolution with Fewer High QE PMTs

Hybrid Photomultiplier Tubes (HPDs)

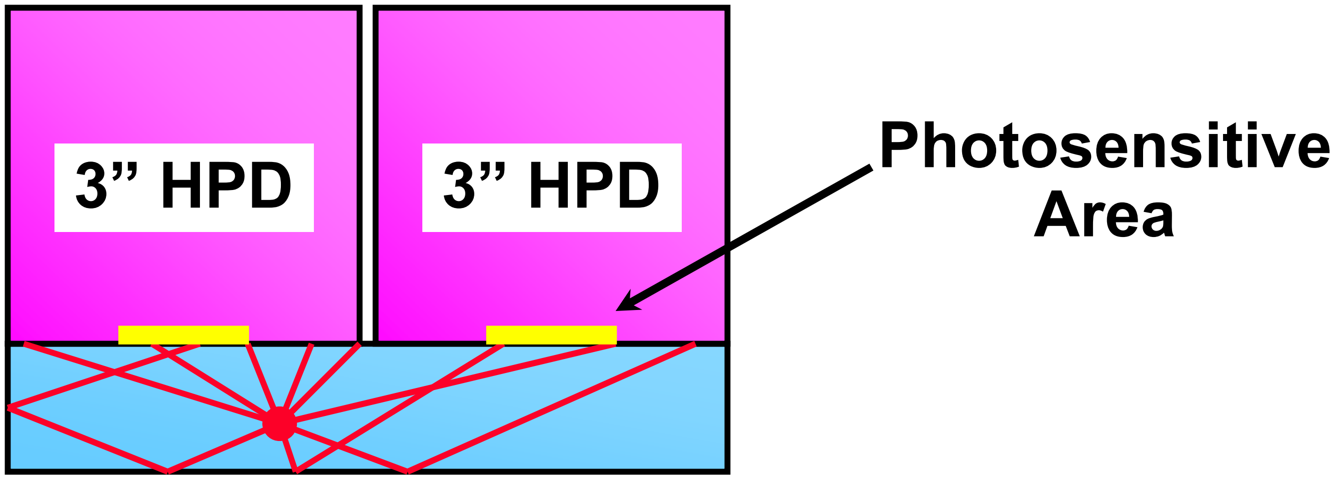




3.6 eV per e/h
⇒ Gain ≈ 3000 x PIN/APD Gain

+ Pixellated, Gain is *Very* Stable
+ Single Photon Counting, Very Narrow Single PE Peak
– Large Dead Area, Lower Gain than PMT

Can Stability Be Improved?



- Anger Decoding (Positioning) Depends Strongly on Photodetector Gain
- Conventional PMTs are Notorious for Gain Drift
- Frequent Calibrations Required (~Weekly)

• HPD Stability VERY Attractive
• HPD Cost & Dead Area Are Potential Problems

Hybrid Photodetectors

Potential Applications

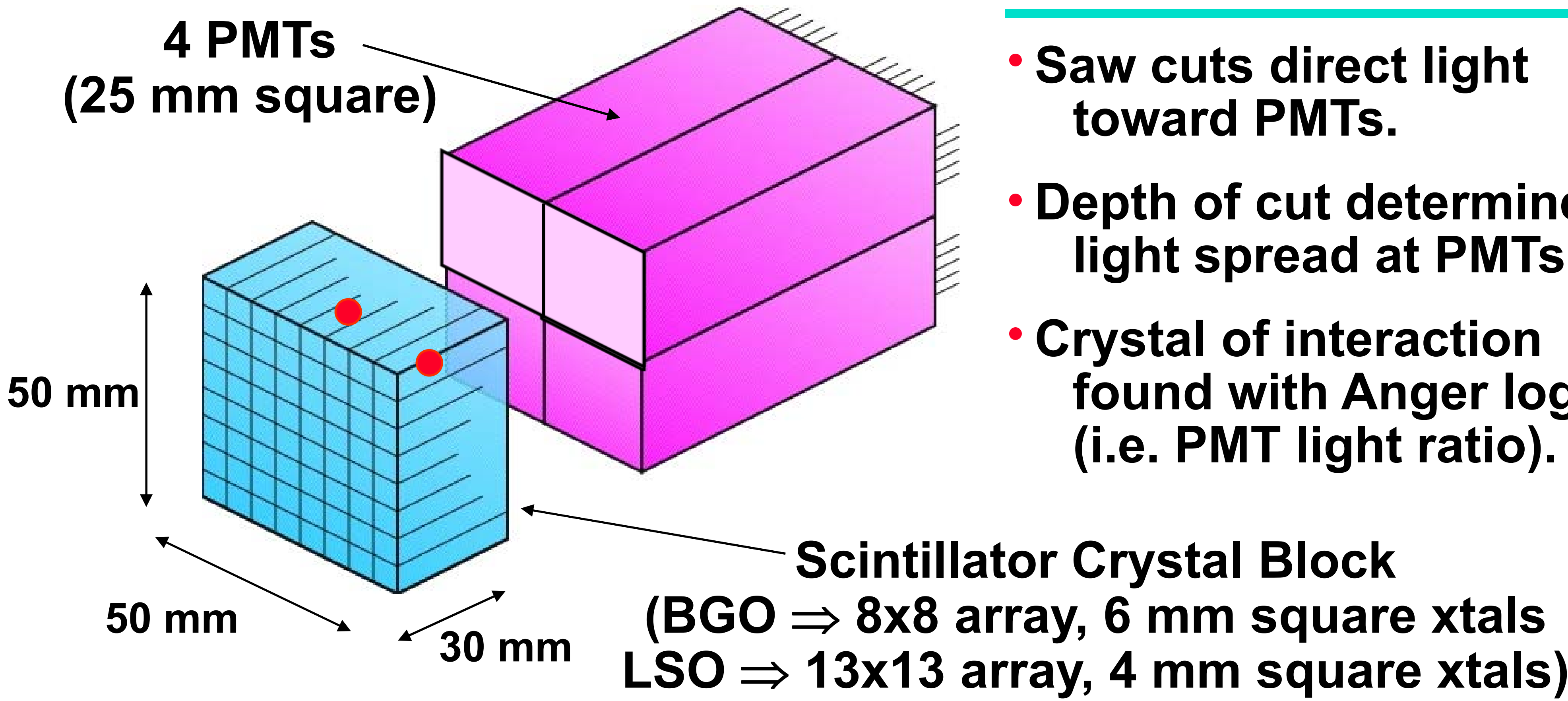
- Improve Stability for Clinical SPECT
  (calibrate once at the factory)
- Improve Stability for Clinical PET
  (calibrate once at the factory)

Possible Drawbacks

- Cost per Unit Area Unlikely To Be Competitive
- Large Dead Area

Drawbacks Will Be Difficult to Overcome…

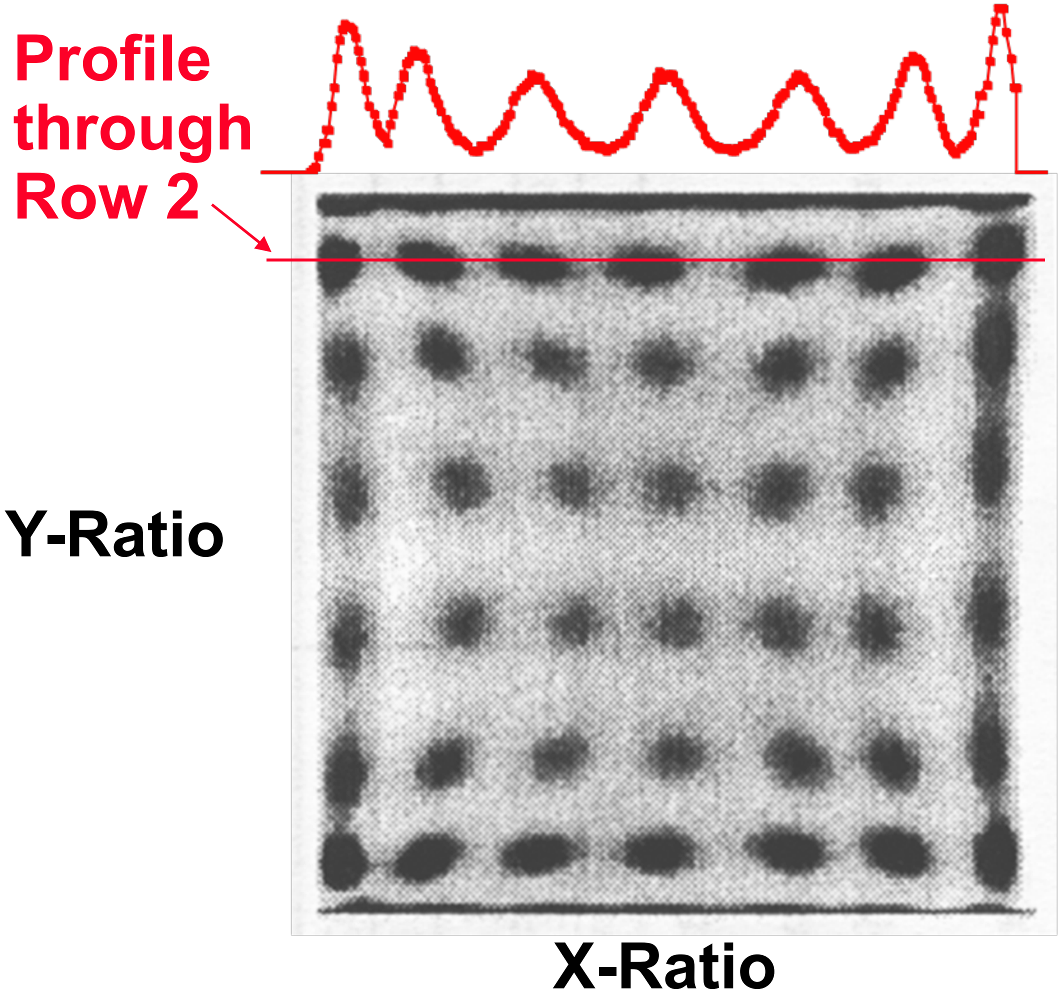
Starting Point for PET Detector: "Block Detector Module"



- Saw cuts direct light toward PMTs.
- Depth of cut determines light spread at PMTs.
- Crystal of interaction found with Anger logic (i.e. PMT light ratio).

Good Performance, Inexpensive, Easy to Pack

Crystal Identification with Anger Logic



- Uniformly illuminate block.
- For each event, compute X-Ratio and Y-Ratio, then plot 2-D position.
- Individual crystals show up as dark regions.
- Profile shows overlap (i.e. identification not perfect).

Can Decode 64 Crystals with BGO, 169 with LSO

Conventional PET Detector Requirements

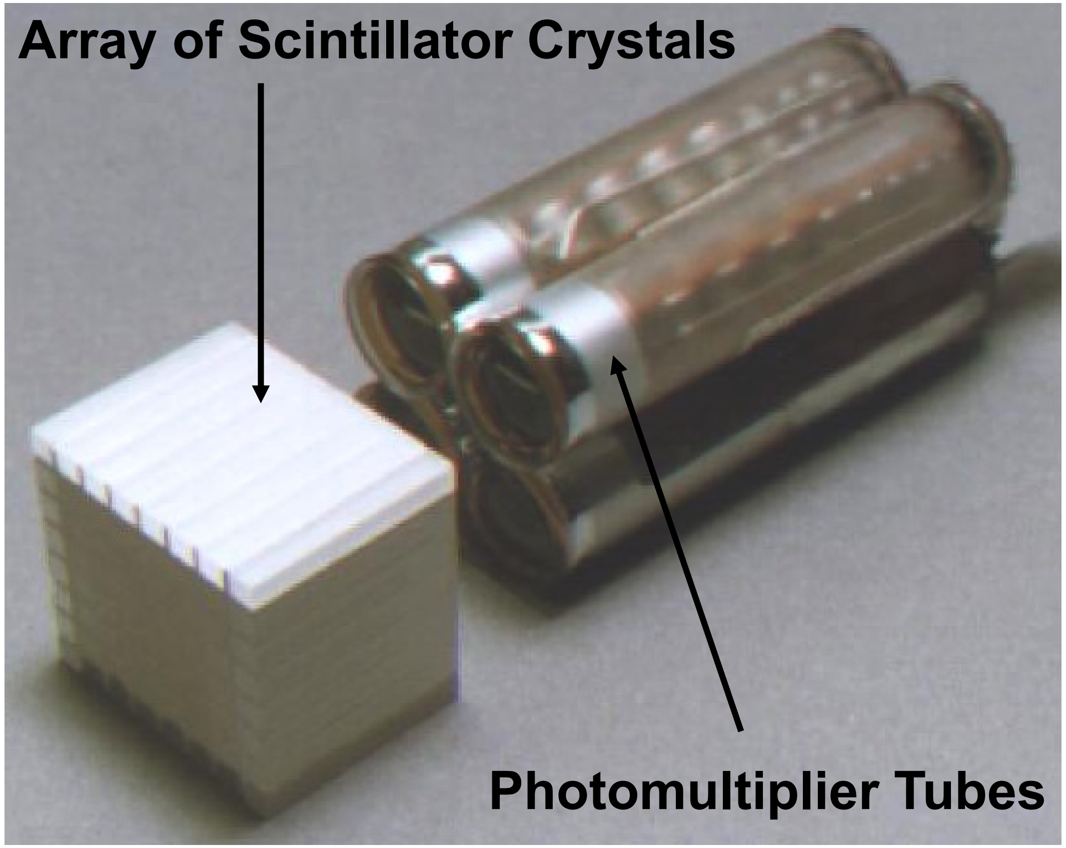


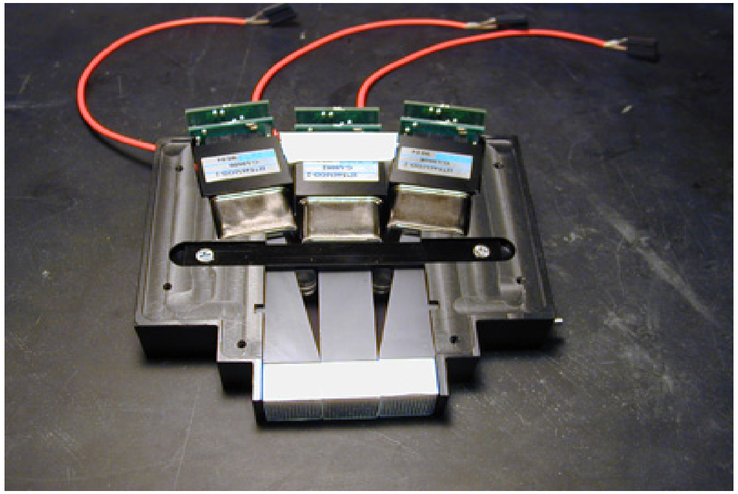
*Image courtesy of M. Casey, CPS Innovations

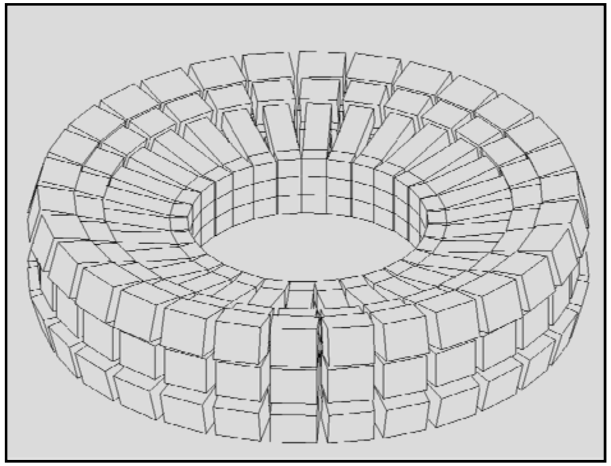
At 511 keV:

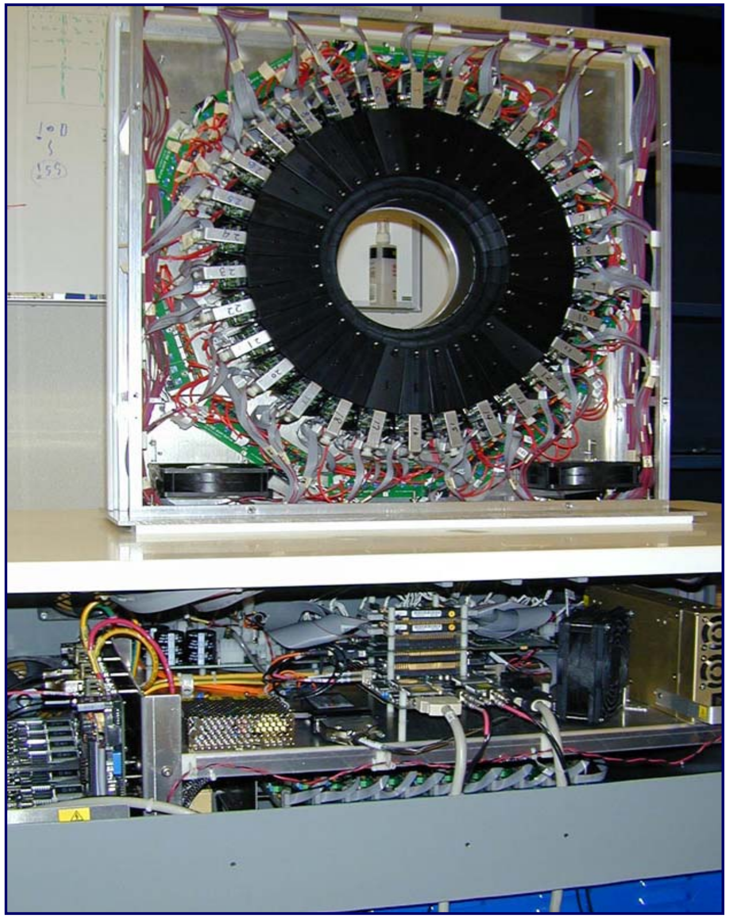
- **High Efficiency** (>85%)
- **High Spatial Resolution** (<5 mm)
- **Low Cost** (<$100/cm^2)
- **Short Dead Time** (<1 μs cm^2)
- **Good Timing Resolution** (<5 ns fwhm)
- **Good Energy Resolution** (<100 keV fwhm)

Based on BGO or LSO "Block Detector"

Small Animal PET







microPET II

17,640 LSO crystals
(0.95x0.95x12.5 mm)

15 cm ring diameter

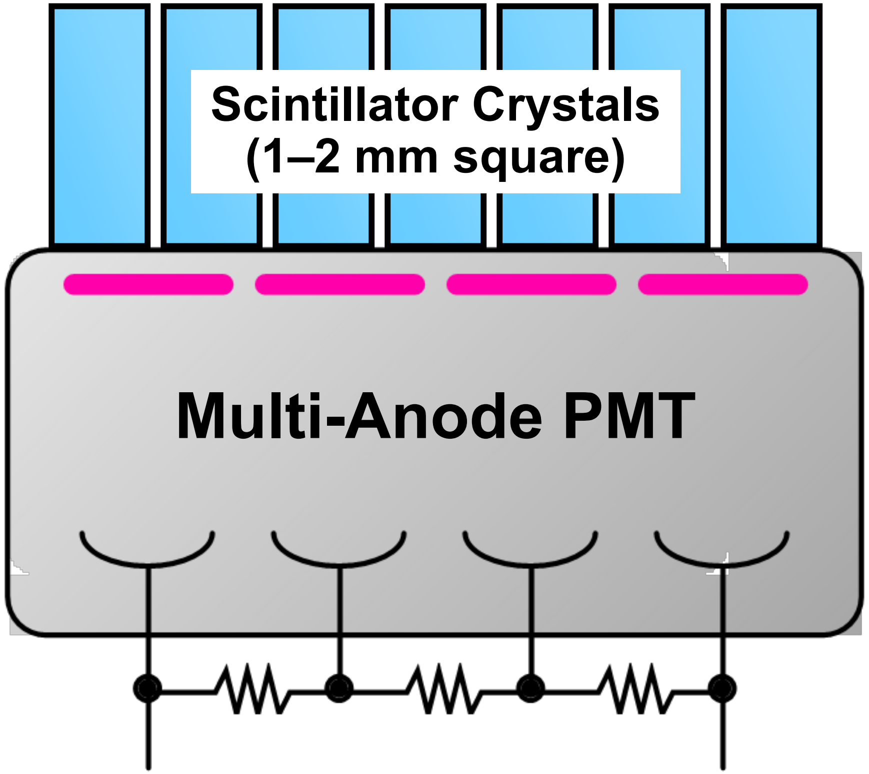
8 cm transverse FOV

4.9 cm axial FOV

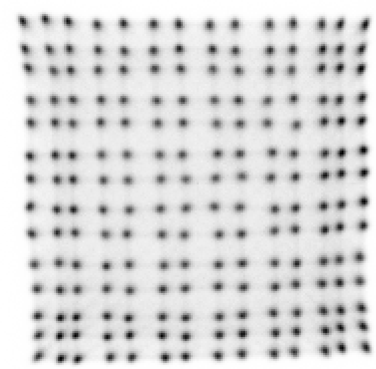
~1.2 mm resolution

~2.5% sensitivity

Detector Module for Small Animal Camera



Flood Map



14x14 Crystals
1 mm square x 12.5 mm

- 4 PMTs ⇒ Multi-Anode PMT
- Current Division Mimics Anger Logic
- Dead Area ⇒ Light Guides Couple PMT to Crystals

How Can Photodetectors Improve PET?

- **Spatial Resolution?**

  Yes — high QE PMTs, APDs, SiPMs
- **Efficiency?**

  Possibly — APDs, SiPMs
- **Timing Resolution?**

  Yes — high QE PMTs, SiPMs
- **Energy Resolution?**

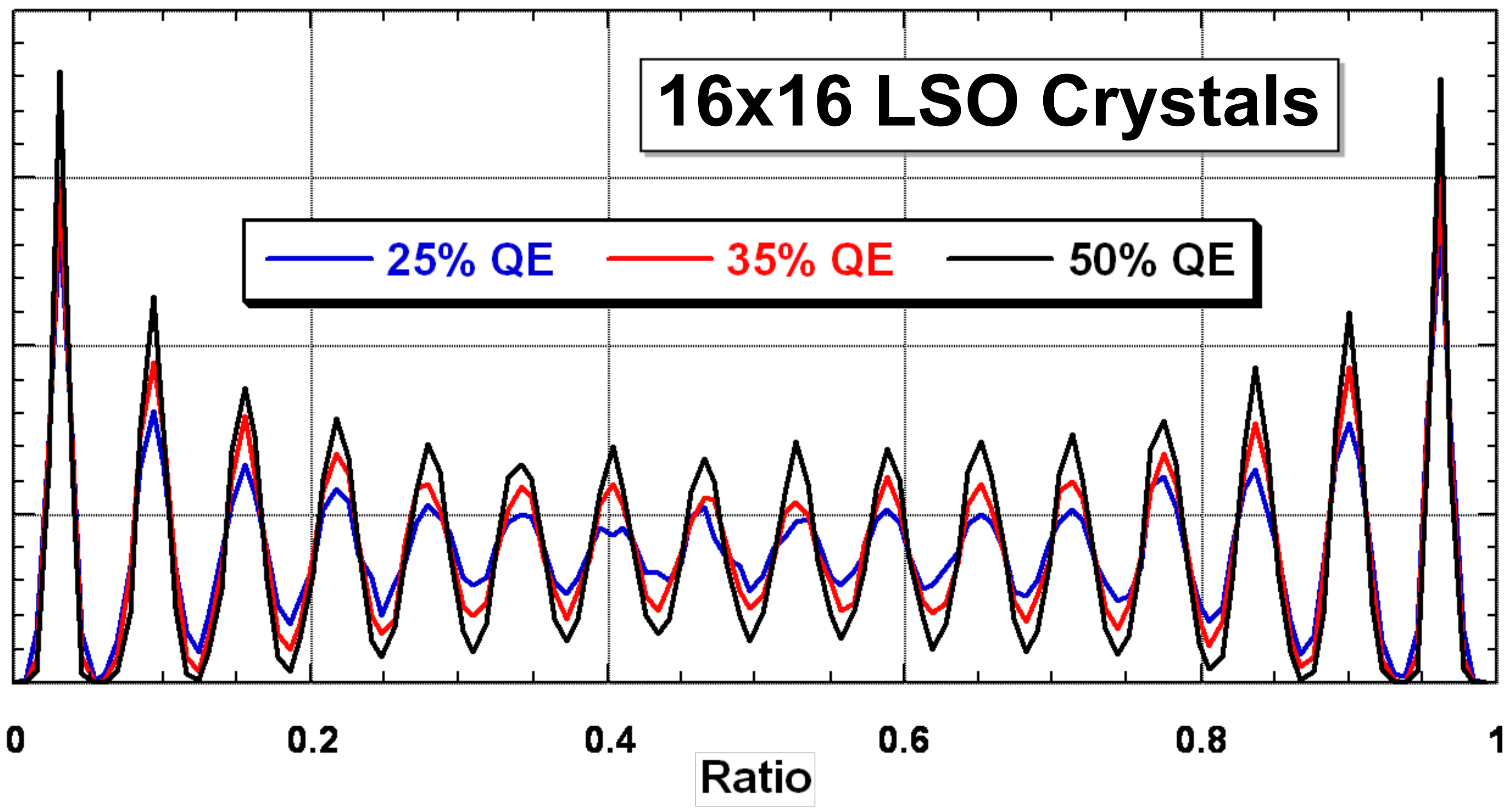
  No — limited by scintillator
- **Cost?**

  Possibly — high QE PMTs
- **Stability?**

  Possibly — HPDs

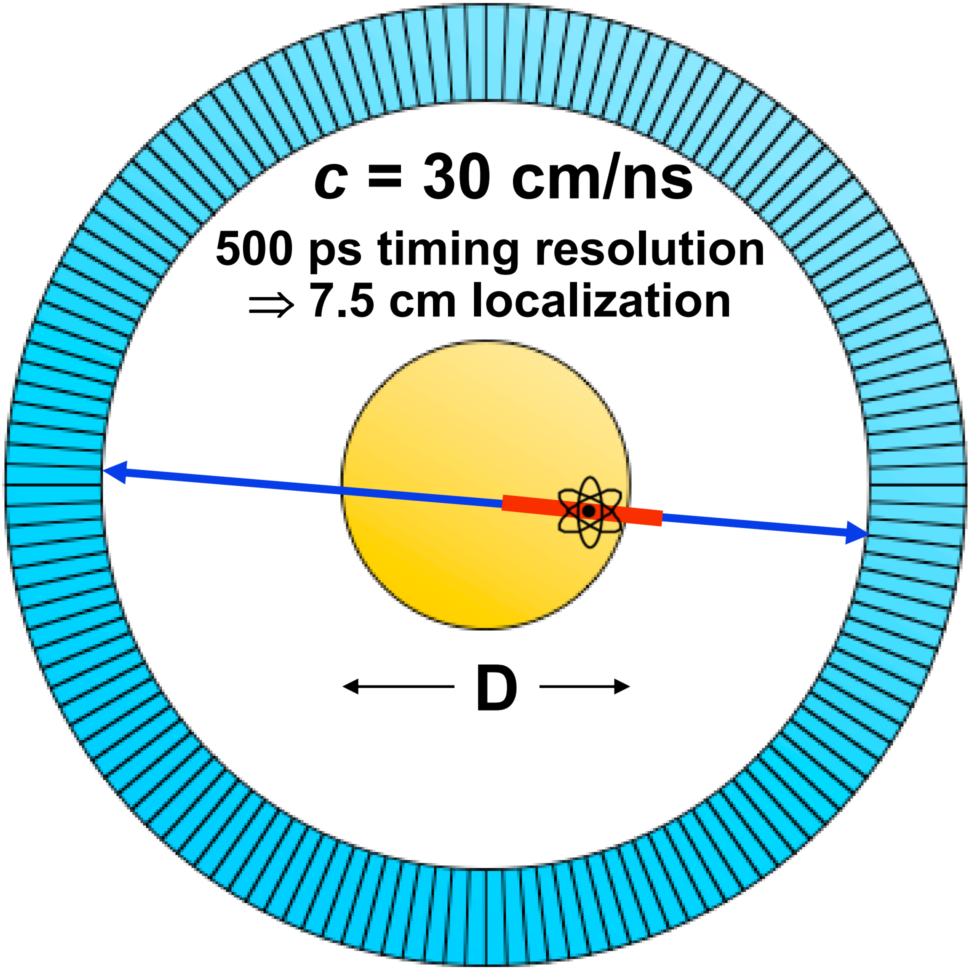
Many Possibilities…

High Quantum Efficiency PMTs



- Decode More Crystals ⇒ Improve Spatial Resolution
- Larger PMT ⇒ Reduce Cost?

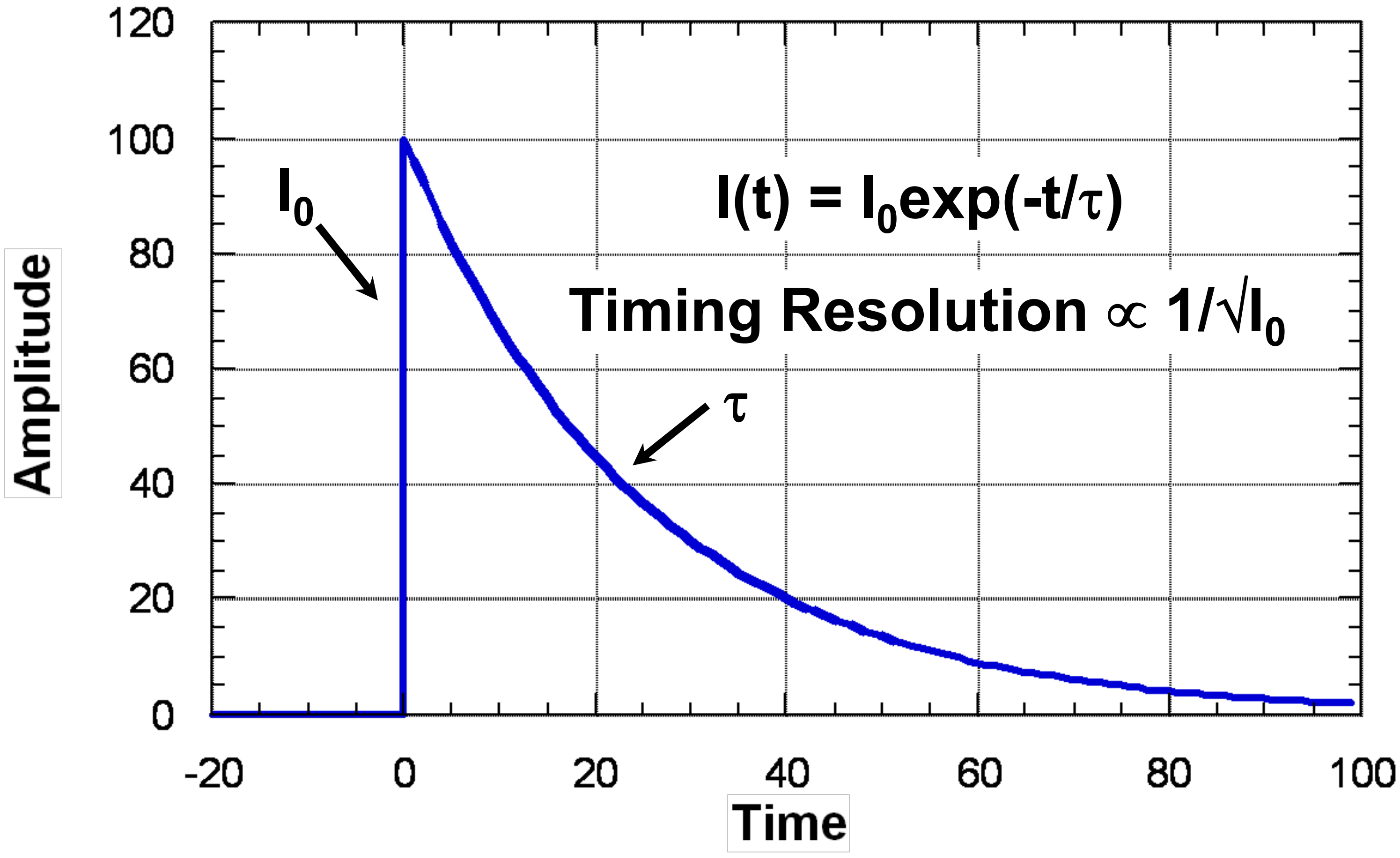
Time-of-Flight in PET



- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Time of flight cameras built in the 80's with BaF_2 and CsF.
- These scintillators forced compromises that prevented TOF from flourishing.
- New scintillators (LSO & $LaBr_3$) have resurrected TOF PET.

- Variance Reduction Given by $2D/c\Delta t$
- 600 ps Timing Resolution ⇒ 4x Reduction in Variance!

High Quantum Efficiency PMTs



- Increased QE ⇒ Better Timing Resolution
- Valuable for Time-of-Flight PET

High Quantum Efficiency PMTs

Potential Applications

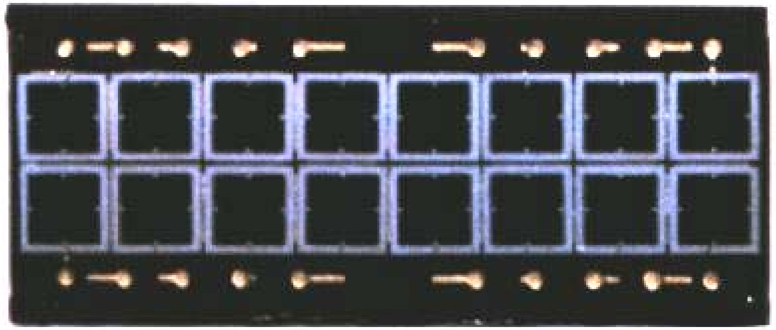
- Reduce Cost in Clinical SPECT & PET
  (get same spatial resolution w/ fewer PMTs)
- Improve Timing Resolution for TOF PET
  (higher initial photoelectron rate)

Possible Drawbacks

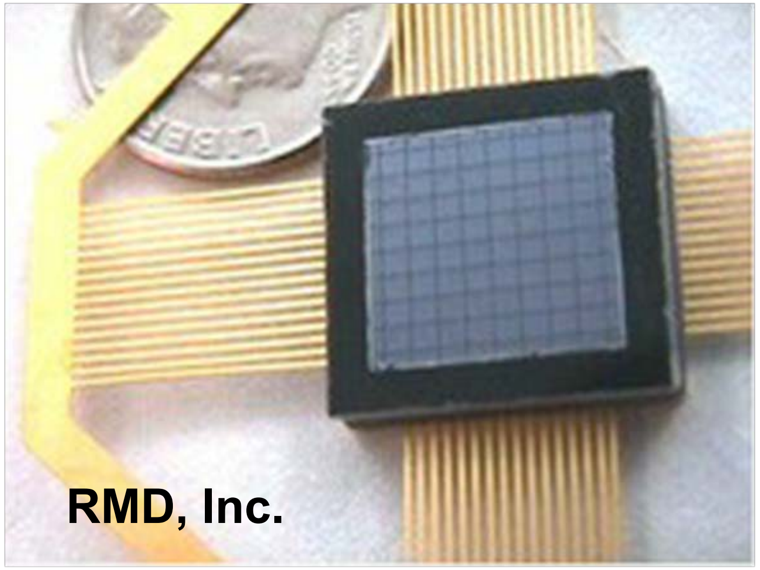
- Cost per Unit Area May Not Be Competitive

It All Depends on the Cost / Area…

Avalanche Photodiode Arrays

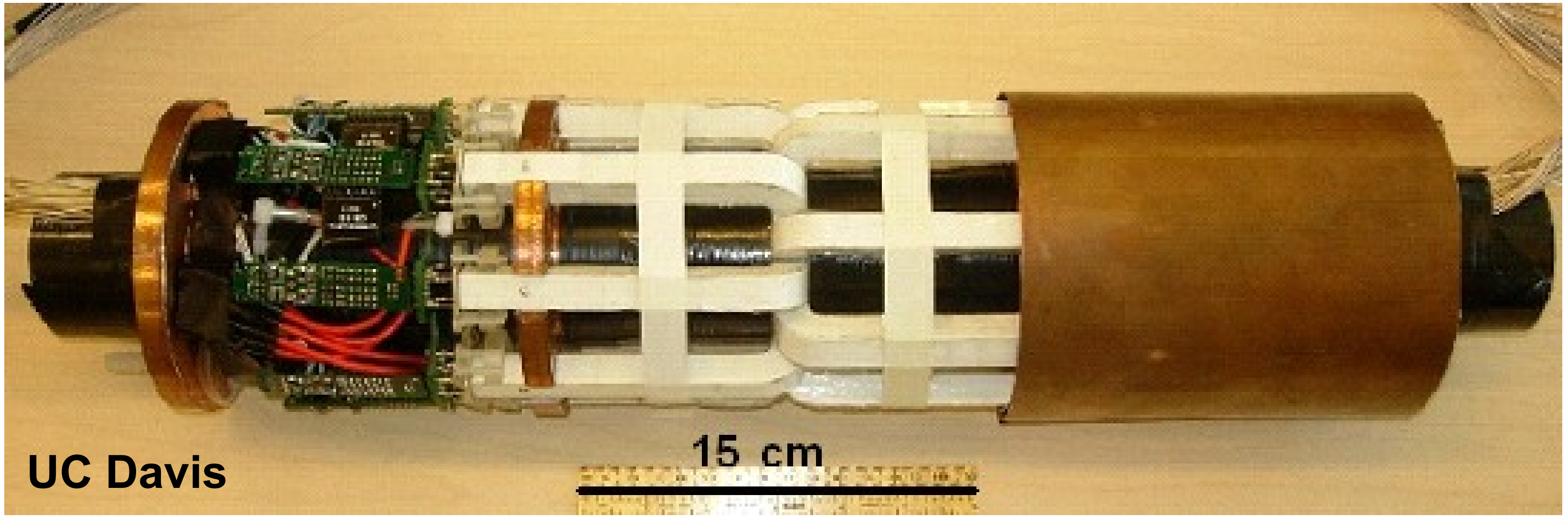


Hamamatsu Photonics



+ High Quantum Efficiency (90% Possible)
+ Small Pixels (Individually Couple to Crystals)
+ Compact, Insensitive to Magnetic Fields
– Large Dead Area
– Lower Gain than PMT
– Poor Signal to Noise Ratio, Noise Scales w/ Area
– Reliability & Cost, # of Electronics Channels

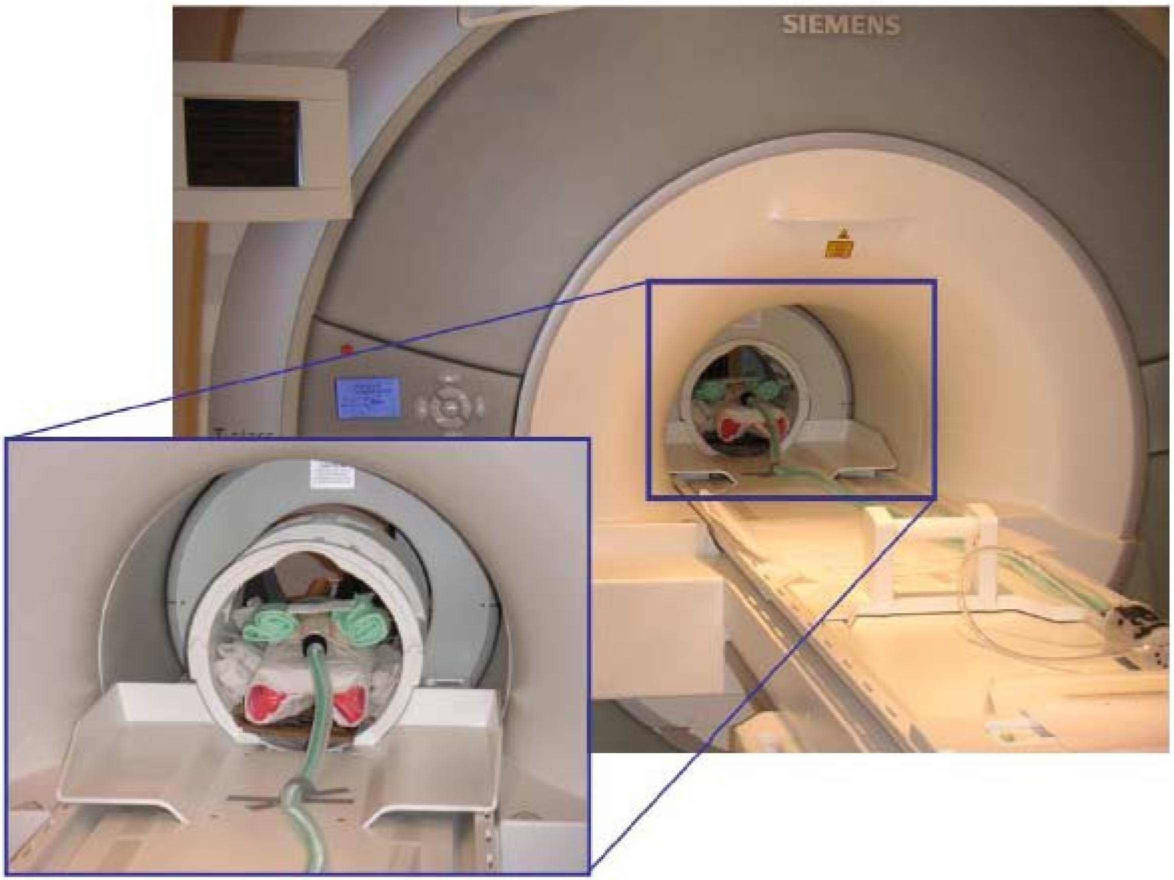
Simultaneous PET/MRI



- Combine Anatomic Information from MRI w/ Functional Information from PET
- Need Phototdetectors that are Insensitive to B Fields
- Desired for Both Human and Small Animal

Several Prototype PET/MRI Cameras Built Using APDs

Simultaneous PET/MRI

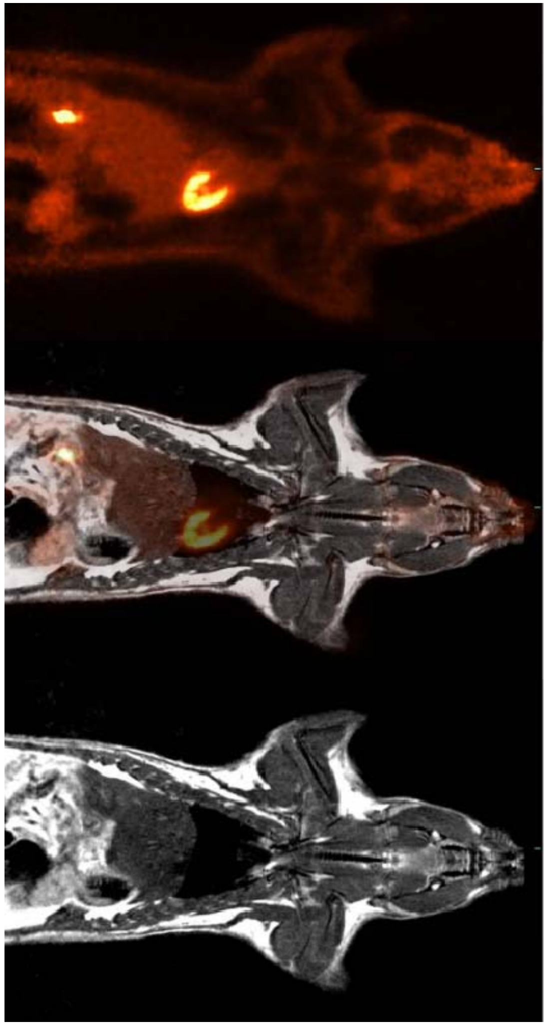


Rat

PET

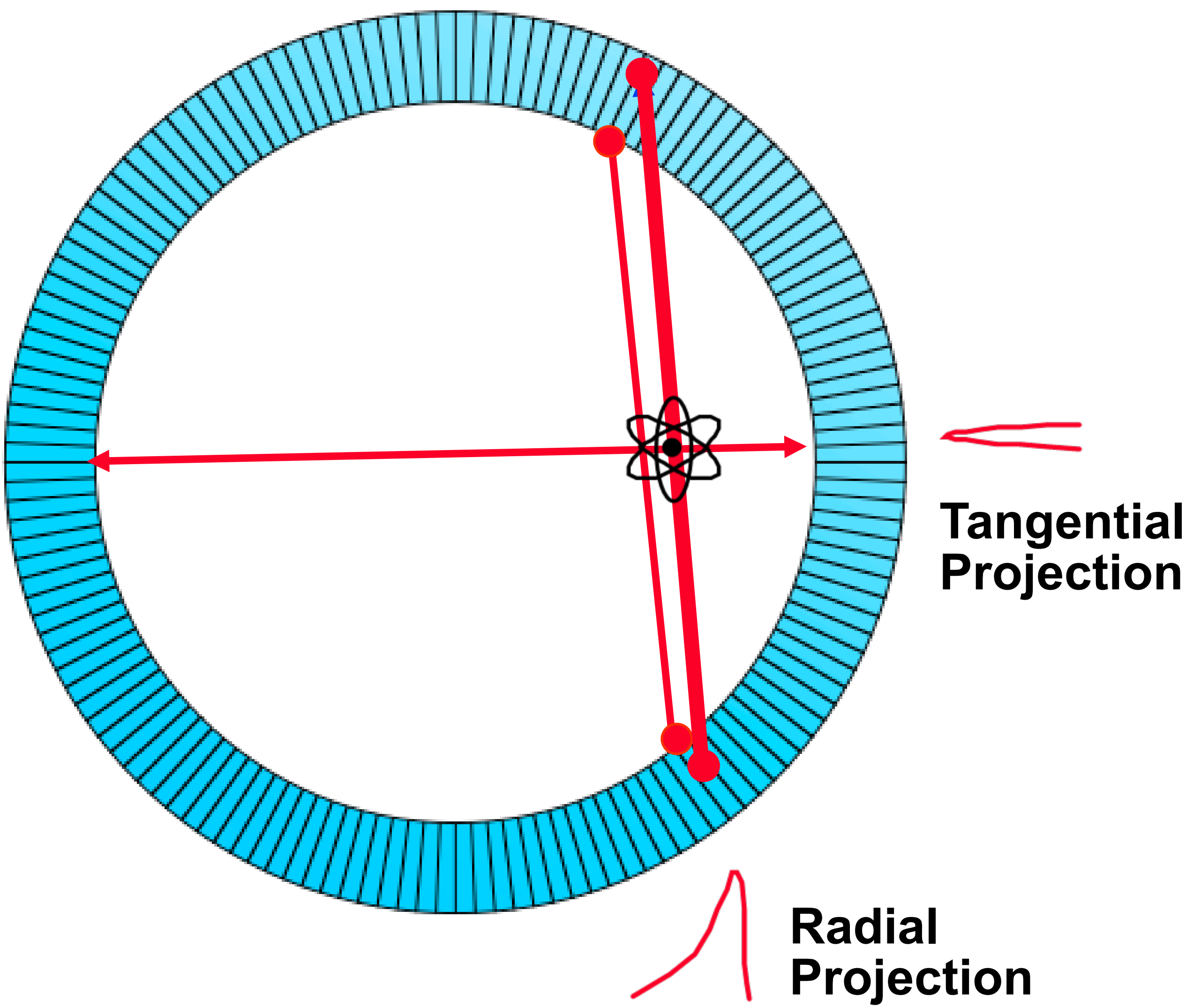
Merged

MRI



Human Brain / Animal PET/MRI Camera Using APDs

Radial Elongation



- Penetration of 511 keV photons into crystal ring blurs measured position.
- Blurring worsens as detector's attenuation length increases.
- Also known as *Parallax Error* or *Radial Astigmatism*.
- Can be removed (in theory) by measuring depth of interaction.

Depth-Encoding PET Detector Module

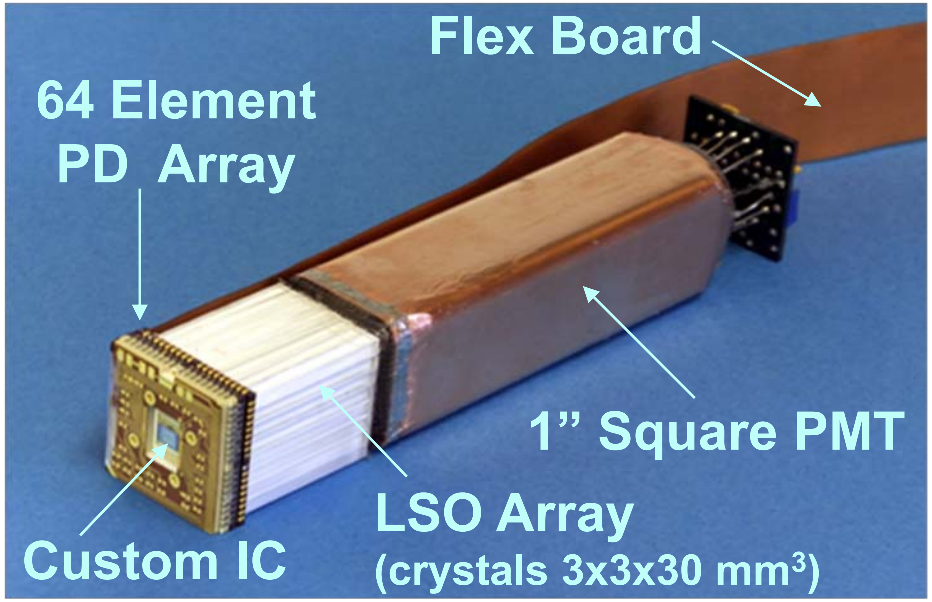
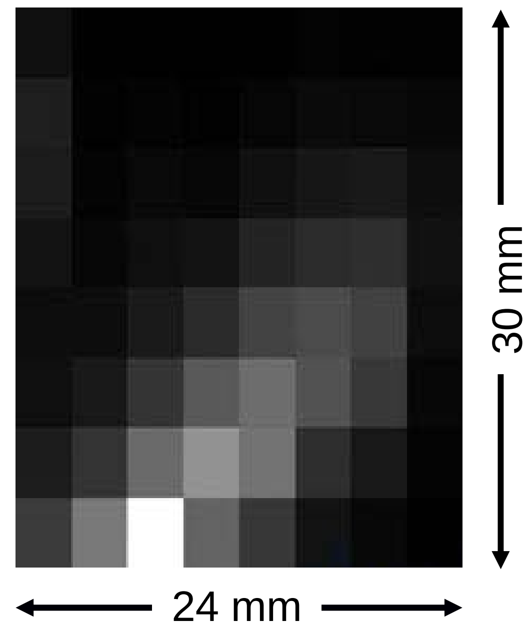


Image of Collimated Gamma Rays



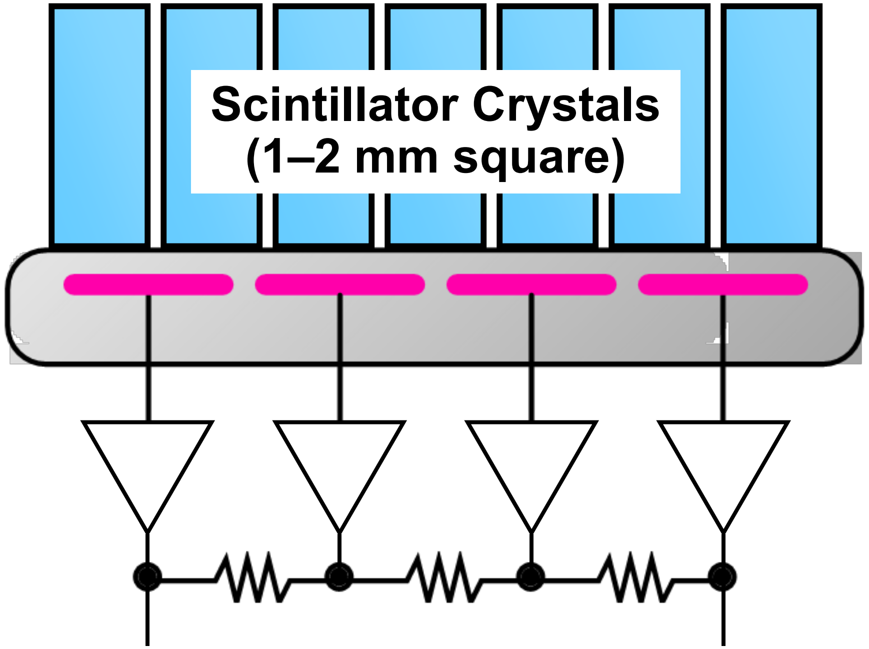
- PMT Provides Timing Pulse
- PD Array Identifies Crystal of Interaction
- PD+PMT Provides Energy Discrimination
- PD / (PD+PMT) Measures Depth of Interaction

Key Photodetector Feature is Compactness

Typical APD Module Readout

Advantages:

- Channels Are Independent
- High Rate
- Minimum Noise (Low C, Low I)
- Complex Readout (thresholding, nearest neighbors, multi-hit rejection, etc.)

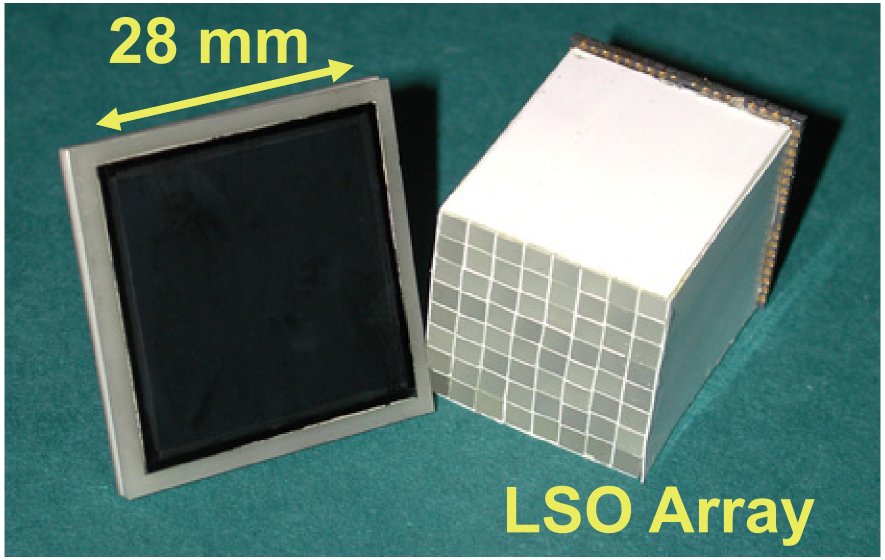


Disadvantages:

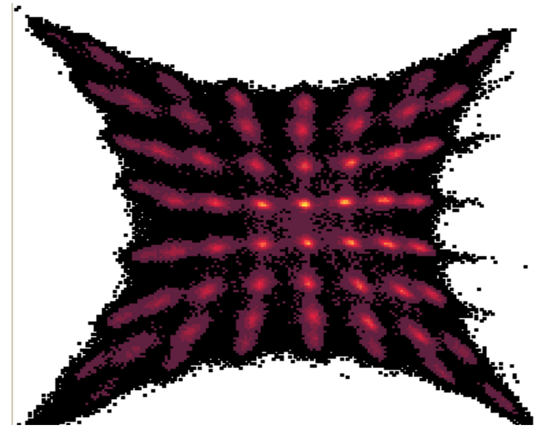
- High # Channels ($\propto$ linear_dim^2)
- High Connection Density
- High Power Consumption
- Complex Readout

- Individual Amplifiers for Each Pixel
- Necessary to Minimize Noise
- Can Do Current Division After Amplifiers

Position-Sensitive APD (PSAPD)



Flood Map,
–20° C



- 15% fwhm Energy Resolution
- 3 ns fwhm Timing Resolution

- Similar to APD Array Read Out with Current Division
- Cooling Often Needed to Reduce Noise

*Data and image courtesy of K. Shah, RMD, Inc.

APDs & PSAPDs

Potential Applications

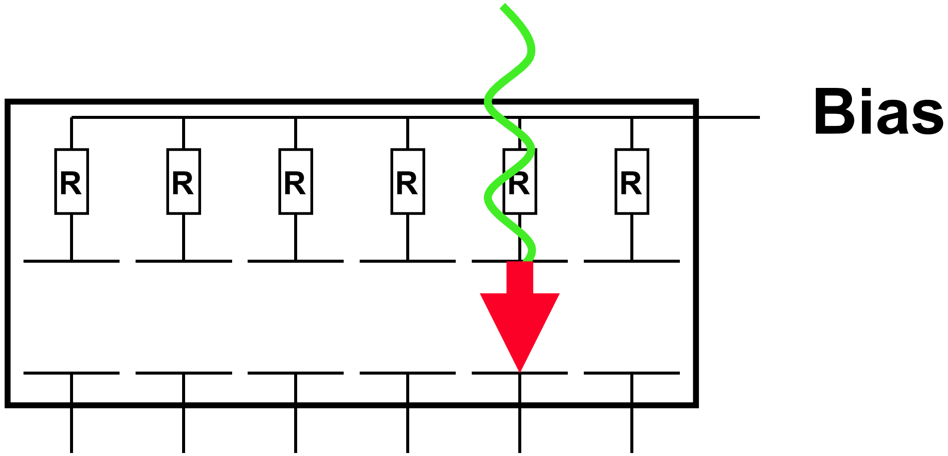
- Simultaneous PET/MRI
  (insensitive to magnetic fields)
- Depth of Interaction for Clinical PET
  (measure light ratio on both ends of crystal)
- Depth of Interaction for Animal or Breast PET
  (measure light ratio on both ends of crystal)

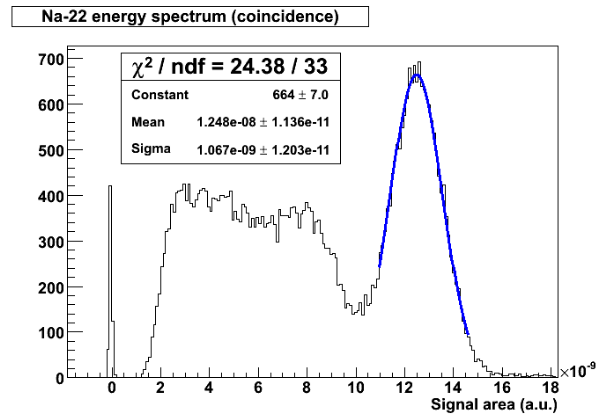
• Possible Drawbacks

- Cost per Unit Area May Not Be Competitive
- Tradeoff Between Number of Electronics
  Channels and Signal-to-Noise Ratio
- Worse Timing Resolution than PMT

• Already Incorporated in Some Cameras
• May Be Replaced By Other Technologies?

Silicon Photomultipliers (SiPMs)

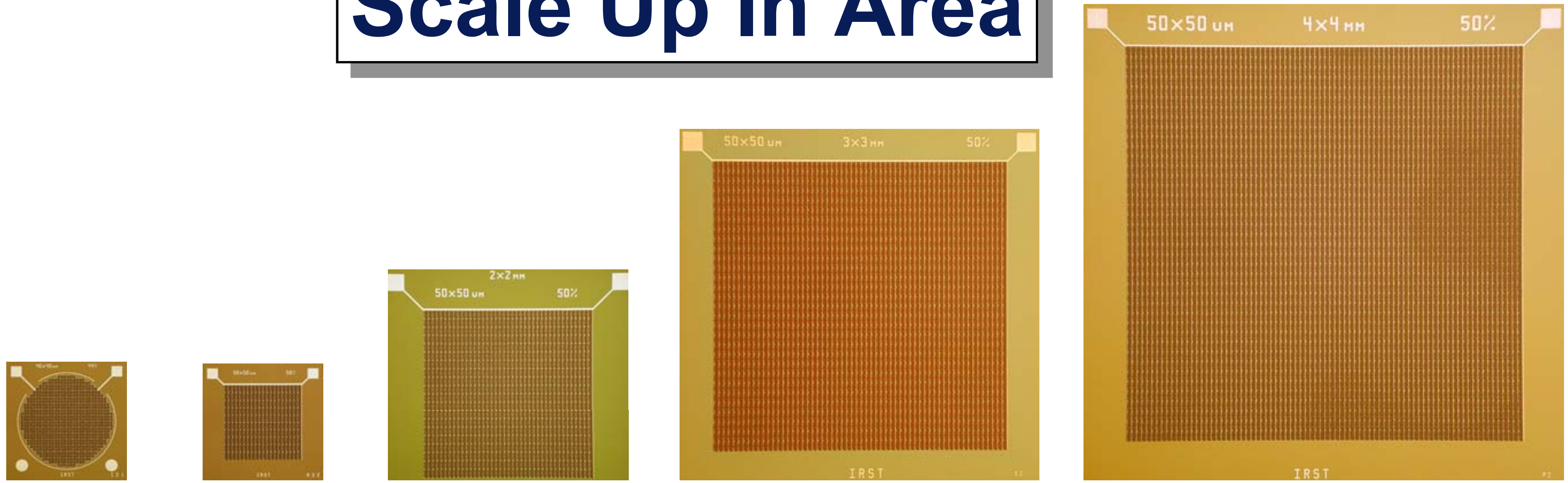




20% fwhm Energy Resolution

+ High Quantum Efficiency (~40% Possible)
+ Small Pixels (Individually Couple to Crystals)
+ Insensitive to Magnetic Fields
+ Good Stability?
– Large Dead Area
– Reliability & Cost, # of Electronics Channels
– **Scale-Up to Large Areas Difficult**

Scale Up In Area



circular (1mm diam)   1x1mm   2x2 mm   3x3 mm (3600 cells)   4x4 mm (6400 cells)

PBK-irst, Trento

Issues:

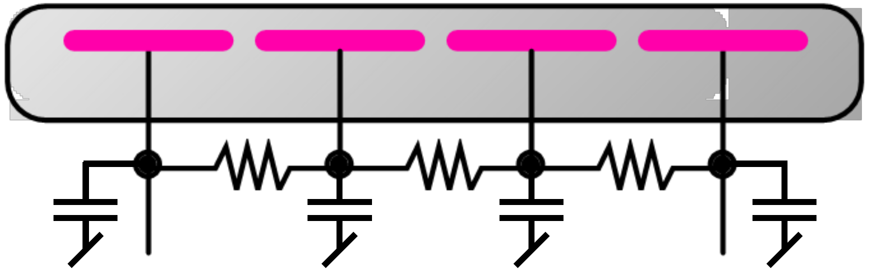
- **Dark Count Rate High, Proportional to Area**
- **Capacitance High, Proportional to Area**

⇒ 1x1 mm Common, 3x3 mm Rare, None >4x4 mm

- **Very Few Monolithic Arrays**

If PET Only Required a Single Pixel, SiPMs Would Be Commonly Used Today…

Readout Electronics For SiPMs



Individual Pixel Readout?

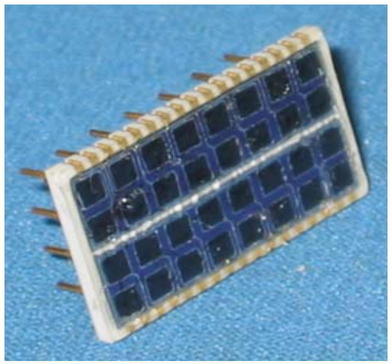
- ~50k Scintillator Pixels / Camera
- 100 mW / ADC $\Rightarrow$ 5 kW / Camera
- Lots of Connections / Packaging Issues

Current Division Readout?

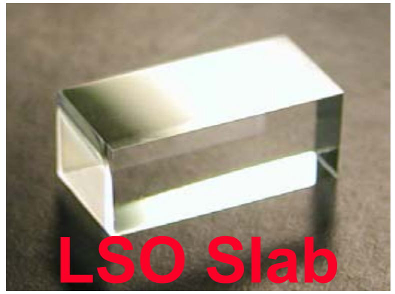
- Large C & Division Resistors Degrades Timing
- Use On-Device Electronics to Buffer?

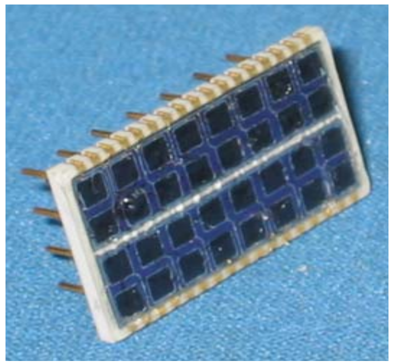
Not Impossible, But Needs Serious Thought!

Improve PET Efficiency

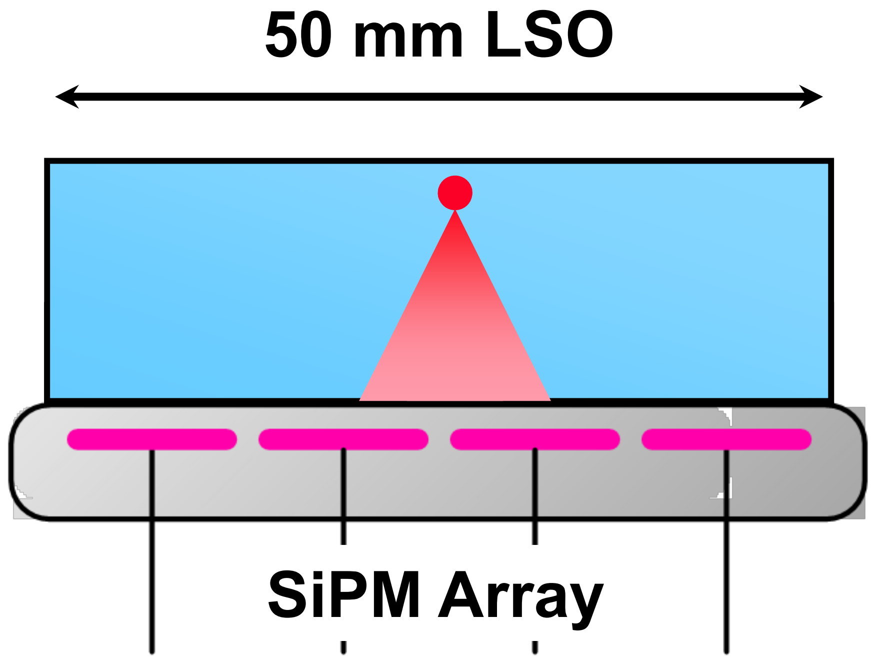


APD Array





APD Array



+ Continuous Xtal Reduces Dead Volume & Handling
+ 1–2 mm Resolution w/ 5–10 mm Thick Slab
+ With High QE Photodetector, Increase to 25 mm thick?
+ Width of Light Distribution Measures DOI

*Images courtesy of S. Tavernier, Vrije Univ.

What SiPM Advances Are Necessary Before They Are Used for PET?
(In Order of Decreasing Importance)

Scale Up Area

- Whole-Body PET Camera has 50k crystals, each 4x4 mm
  $\Rightarrow$ 800k 1 mm^2 pixels
- Minimum Package Size 2.5 cm x 2.5 cm (monolithic or hybrid)
- Minimum Pixel Size 3 mm x 3 mm (4 mm x 4 mm preferable)

Practical Readout Electronics

- "Anger Logic" without severe performance drawbacks
- Low power individual channel (implies ASIC + packaging)
- On-sensor CMOS

What SiPM Advances Are Necessary Before They Are Used for PET II?
(In Order of Decreasing Importance)

Stabilize Output

- Cannot have photopeak drift with time
  $\Rightarrow$ Product of PDE and Gain is constant
- Inherent Stability
- Calibration (temperature sensor w/ data correction)
- Active Feedback (temperature sensor w/ bias V adjust)

Reduce Cost

- $??? / cm^2 APD Array
- $150 / cm^2 Multi-Anode PMT
- $15 / cm^2 Conventional PMT

What SiPM Advances Are Necessary Before They Are Used for PET III?
(In Order of Decreasing Importance)

Increase Photon Detection Efficiency

- SNR meets present specifications w/ ~10% PDE
- Imagine what you can do with 90% QE!!!

Dark Count Rate (Not Really Important)

- Adequate SNR at 1 MHz / cm^2 — little gain from reduction

Saturation

- “True” 511 keV photopeak position & width unimportant
- Scatter rejected with window placed on either side of photopeak

Conclusion

High QE PMTs

- Several Potential Benefits
- Limiting Factor Will Be Cost

SiPMs

- MANY Potential Uses
- Significant Technical Challenges Must Be Overcome First
- Challenges Are Not Fundamental — CAN Be Solved