

# Fast Timing and TOF in PET Medical Imaging

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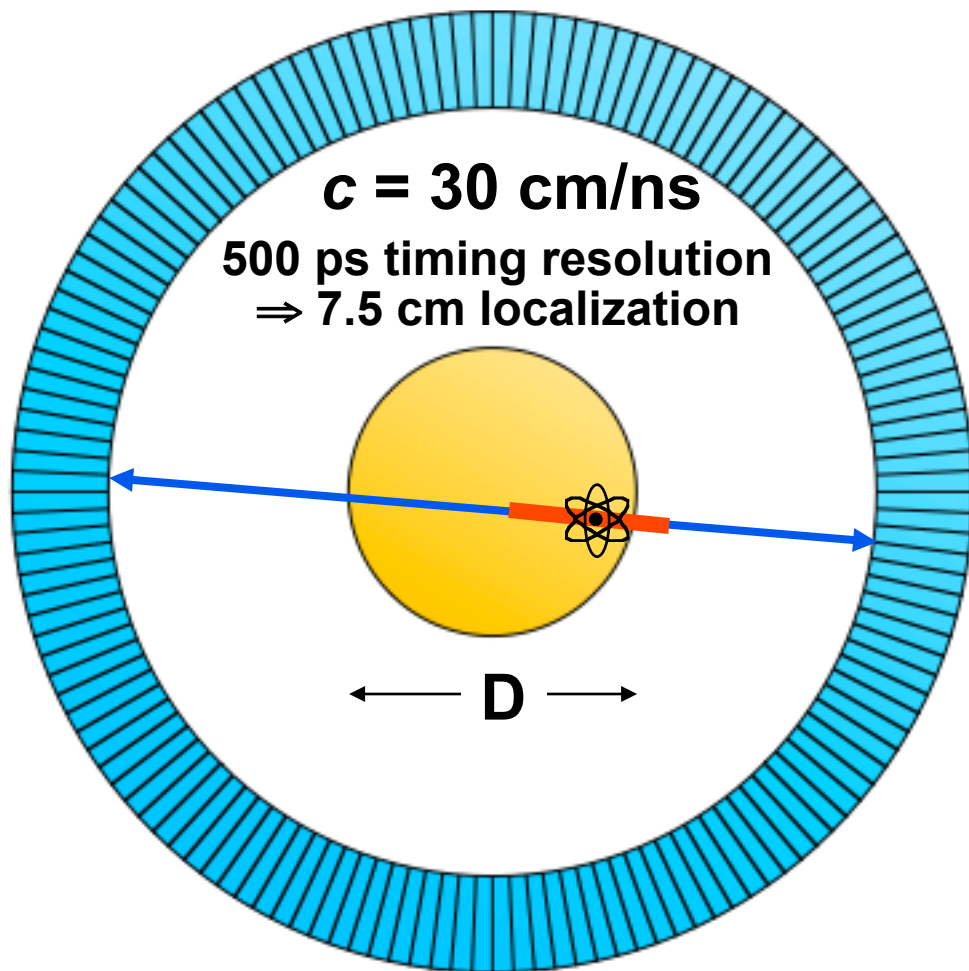
## **Outline:**

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- **Time-of-Flight PET**
- **History**
- **Present Status**
- **Future**

- This work was supported in part by the U.S. DOE (contract No. DE-AC02-05CH11231) and in part by the NIH (NIBIB grant No. R01-EB006085).
- Thanks to M. Ullisch and W.-S. Choong of LBNL, M. Casey, J. Young, and B. Bendriem of Siemens Medical Solutions, and Y. Hämisch of Philips.

# Time-of-Flight in PET



- Can localize source along line of flight.
- Time of flight information reduces **noise** in images.
- Variance reduction given by  $2D/c\Delta t$ .
- 500 ps timing resolution  
 $\Rightarrow 5x$  reduction in variance!

- Time of Flight Provides a *Huge* Performance Increase!
  - Largest Improvement in Large Patients

# PET: Impaired Image Quality in Larger Patients

**Slim Patient**



**Large Patient**

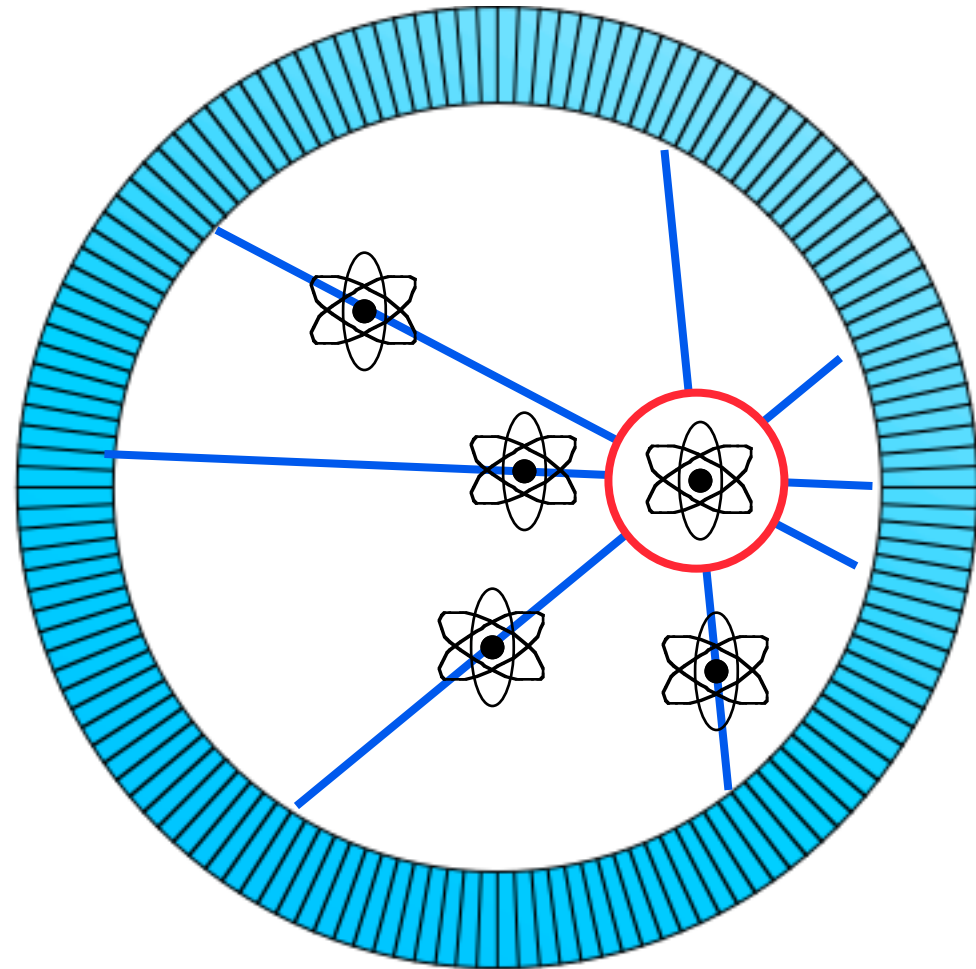


- For an equivalent data signal to noise ratio, a 120 kg person would have to be scanned 2.3 times longer than a 60 kg person <sup>1)</sup>

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1) **Optimizing Injected Dose in Clinical PET by Accurately Modeling the Counting-Rate Response Functions Specific to Individual Patient Scans.** Charles C. Watson, PhD et al Siemens Medical Solutions Molecular Imaging, Knoxville, Tennessee, JNM Vol. 46 No. 11, 1825-1834, 2005

# Statistical Noise in PET



~~If there are  $N$  counts in  
the image,~~

$$\text{SNR} = \frac{N}{\sqrt{N}}$$

**Signals from Different Voxels are Coupled  
⇒ Statistical Noise Does Not Obey Counting Statistics**

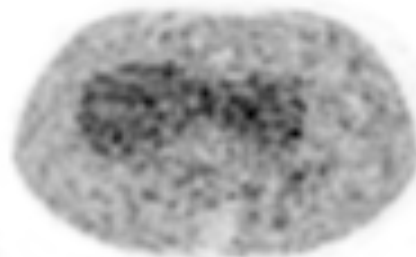
# Whole-Body TOF Simulations

2x10<sup>6</sup> Trues, 1x10<sup>6</sup> Randoms, Attenuation Included  
OP-OSEM w/ TOF Extensions, 2 Iterations, 14 Subsets

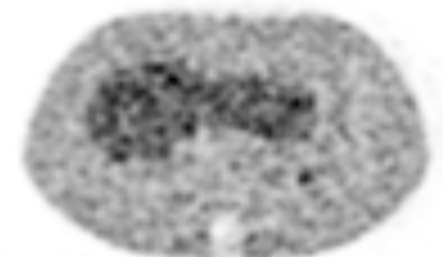


**Phantom**

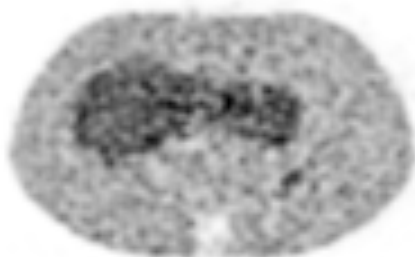
**(1:2:3 body:liver:tumor)**



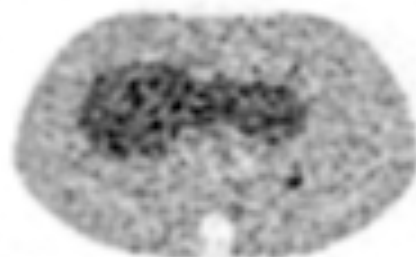
**Conventional**



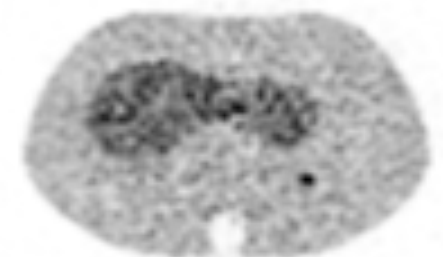
**1.2 ns**



**700 ps**



**500 ps**

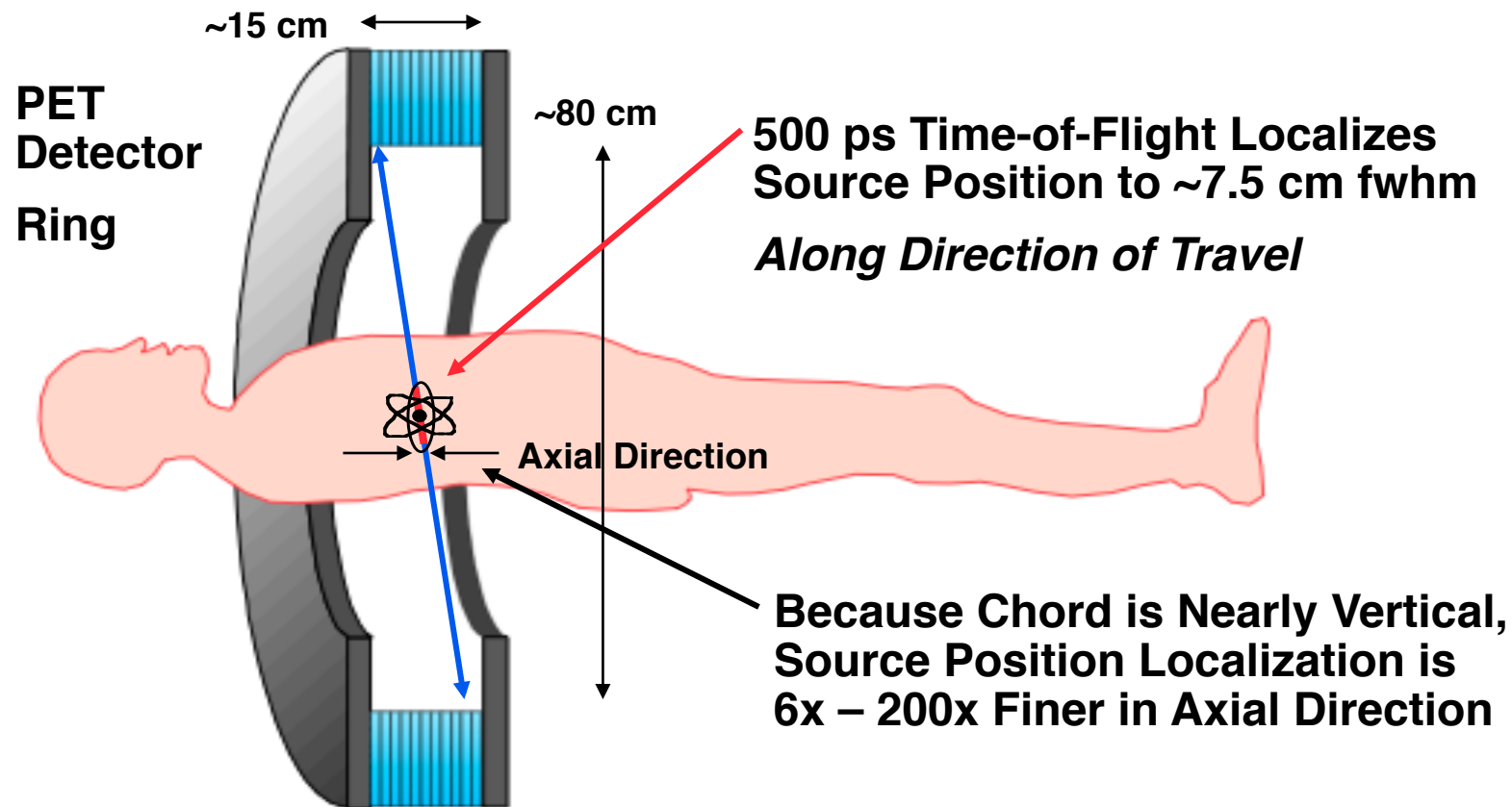


**300 ps**

**Clear Improvement Visually**

\*Data courtesy of Mike Casey, CPS Innovations

# Axial Position Determined Accurately w/ TOF



- Can Assign Chord to Correct Axial Plane
- Reduces Axial Blur in Reconstructed Image
- Turns 3-D Reconstruction into 2-D — *Much Faster!*



# **TOF PET Cameras Built in the 1980' s**

- **~One dozen TOF cameras constructed**
- **Some were commercial cameras**
- **500 ps timing resolution**
- **CsF and/or BaF<sub>2</sub> scintillator**
- **~1 cm spatial resolution**
- **1–4 layers**
- **Advantages of TOF were experimentally verified**

**TOF PET Demonstrated**

## **Problems With TOF in the 1980' s**

- **CsF & BaF<sub>2</sub> have drawbacks (compared to BGO)**
  - **Lower density & atomic number (worse spatial resolution & efficiency)**
  - **“Fast” emission of BaF<sub>2</sub> is in UV (quartz PMTs, no transparent glues)**
- **Few “fast” PMTs (most 2” diameter, all expensive)**
- **GHz electronics was “beyond state-of-the-art”**
  - **Time alignment and stability problems**

**Non-TOF PET with BGO Dominates**

# Technology Changes in the 1990's

- GHz electronics becomes routine
- Fast, inexpensive, 1" diameter PMTs developed
- LSO scintillator developed.  
Compared to BGO, LSO has:
  - Similar density & atomic number (good spatial resolution & efficiency)
  - Similar energy resolution
  - Better timing resolution & dead time

**•TOF Bottlenecks Removed**  
**•People *Realize* that TOF is Possible Again**

# The 2000's — The LSO Explosion in PET

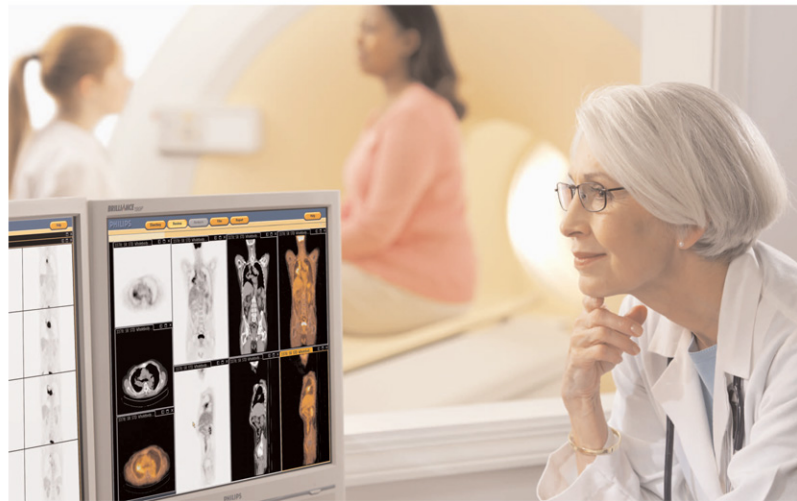
- 220 ps coincidence timing resolution demonstrated with small crystals
- 350 ps coincidence timing resolution demonstrated with PET-shaped crystal
- 550 ps coincidence timing resolution demonstrated for PET detector module
- First Commercial LSO PET camera in 2001

- Camera **not designed for TOF** run in TOF mode
  - 1.2 ns timing resolution (electronics limited)

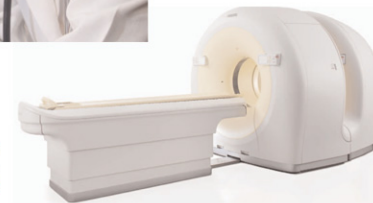
# Commercial TOF PET Available in 2006

Can time of flight change PET/CT imaging?

PET/CT Satellite Lunch Symposium  
Saturday, March 4<sup>th</sup>, Vienna, Austria

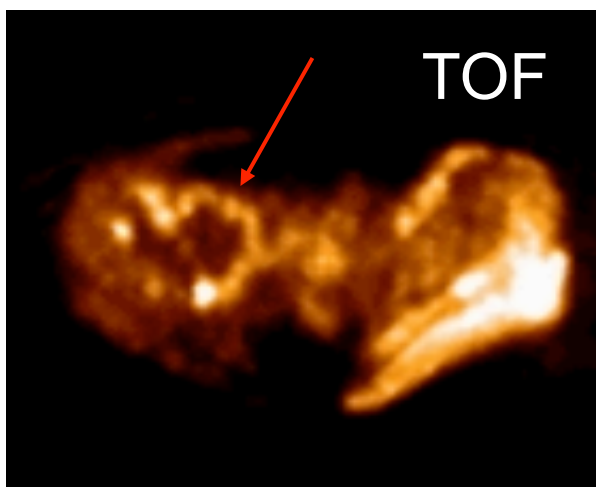
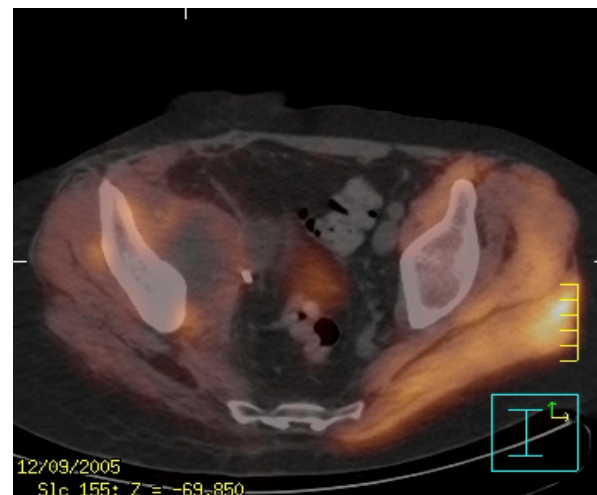
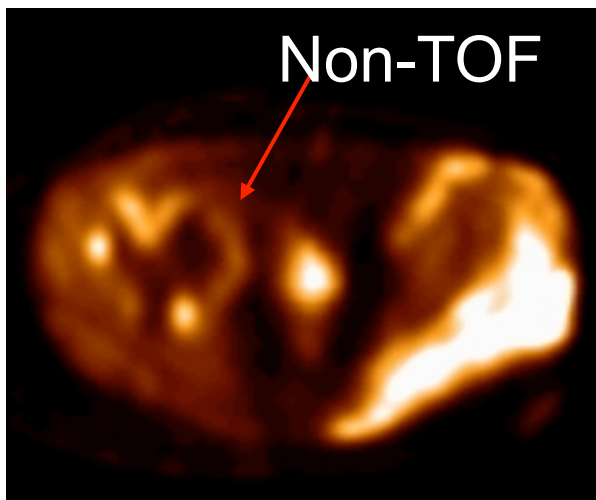


**PHILIPS**



- **Uses LYSO: ~550 ps Timing Resolution**
- **Similar Prototype Camera Developed by Siemens**

# TruFlight™: Enhanced Diagnostic Confidence



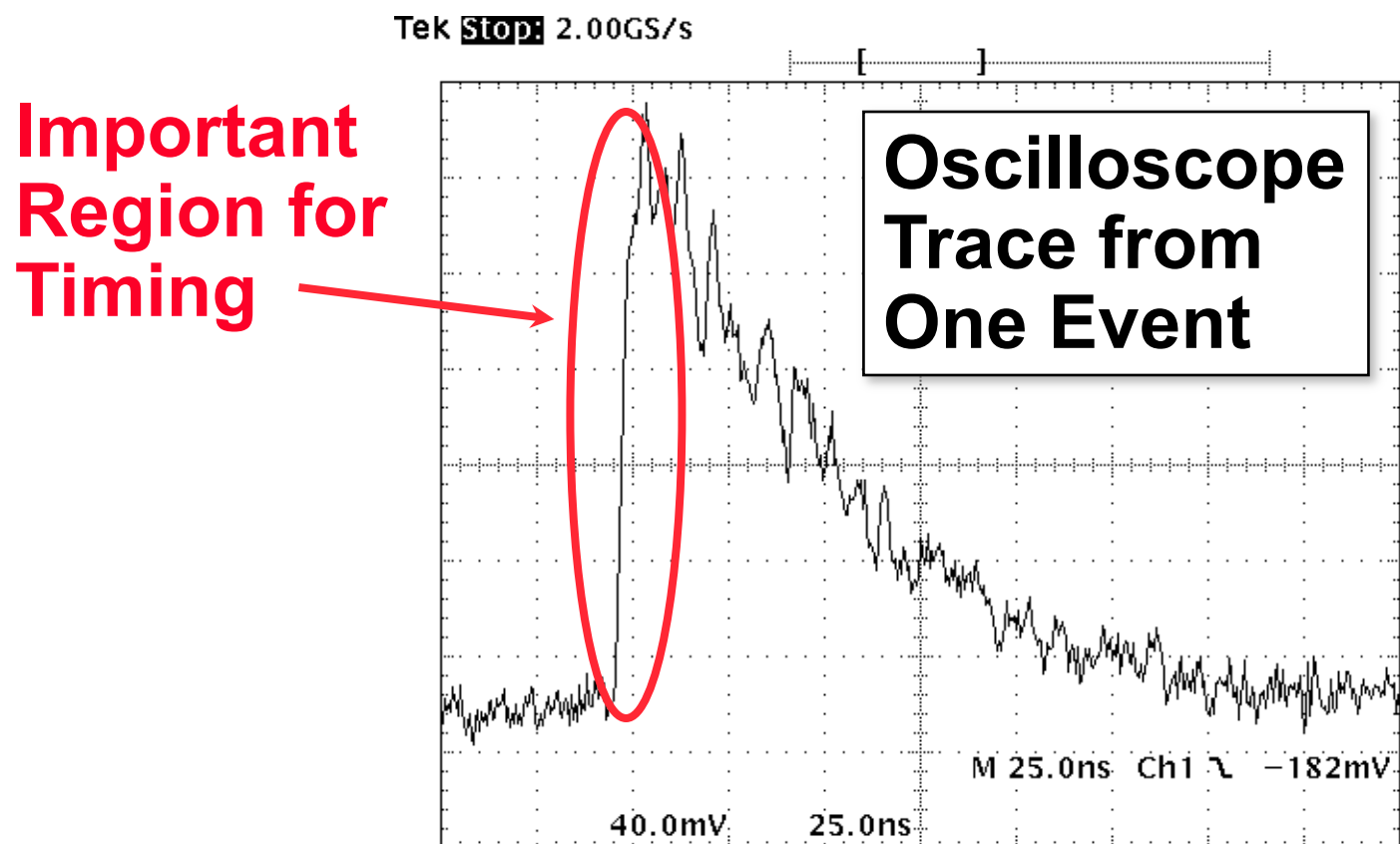
Lymphoma within right iliopsoas muscle with central area of necrosis

*improved delineation of lymphoma activity*

116 kg; BMI = 31.2  
14 mCi; 2 hr post-inj

**Why is PET Timing Resolution  
Only ~550 ps?**

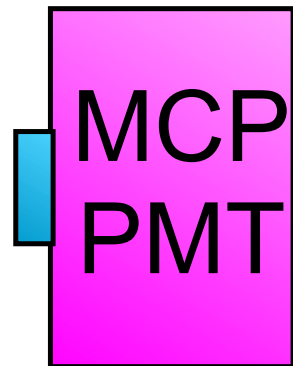
# Raw Signal From Photomultiplier Tube



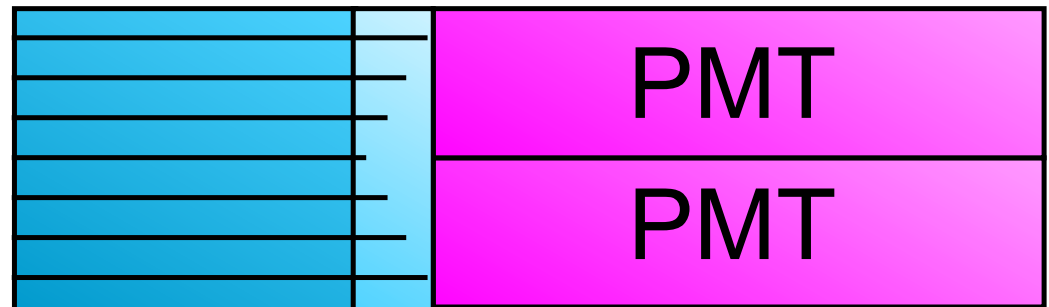
- **Small Signal Level — 0.000000511 TeV**
- **Small Fraction of Scintillation Light in Leading Edge**
- **Fundamental Limit Due to Statistical Fluctuations**

# Module Design Limits PET Timing Resolution

## Ideal for Timing



## Standard PET Module

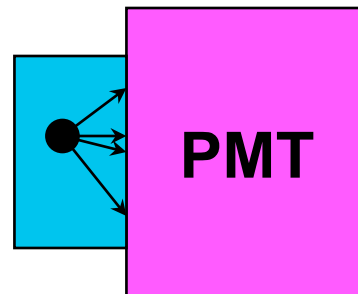


- Interaction Time

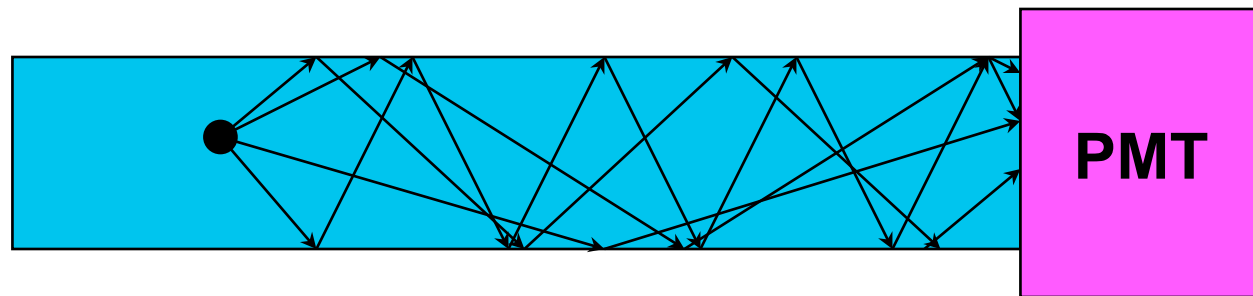
- Measure Interaction Time
- Measure Interaction Position
- Measure Deposited Energy
- Have High Detection Efficiency
- Fit in Close Packed Array
- Be Economical

**PET Detectors Must Do More Than Just Timing!**  
**⇒ Currently Far From Fundamental Limit**

# Crystal Geometry Affects Light Transport

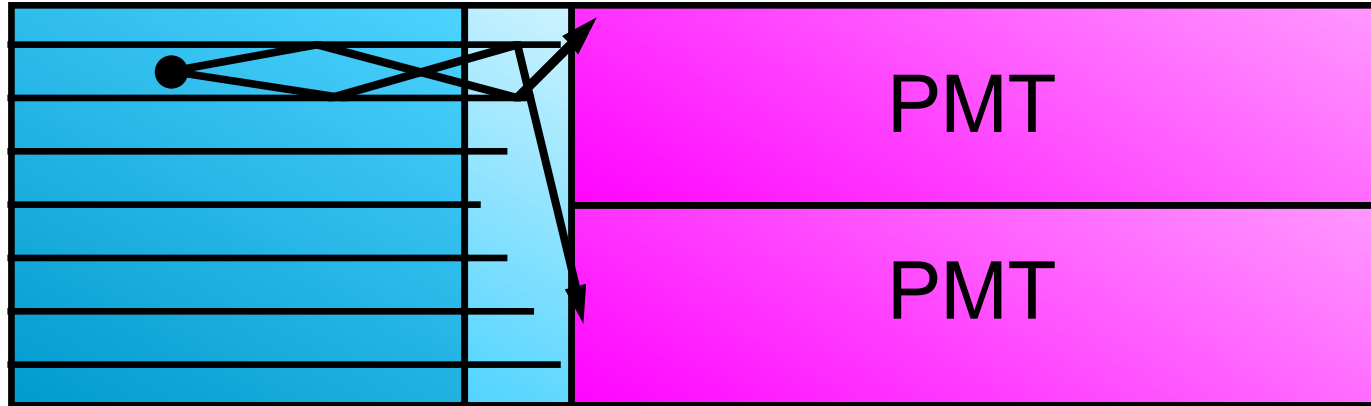


**Scintillator Crystals**



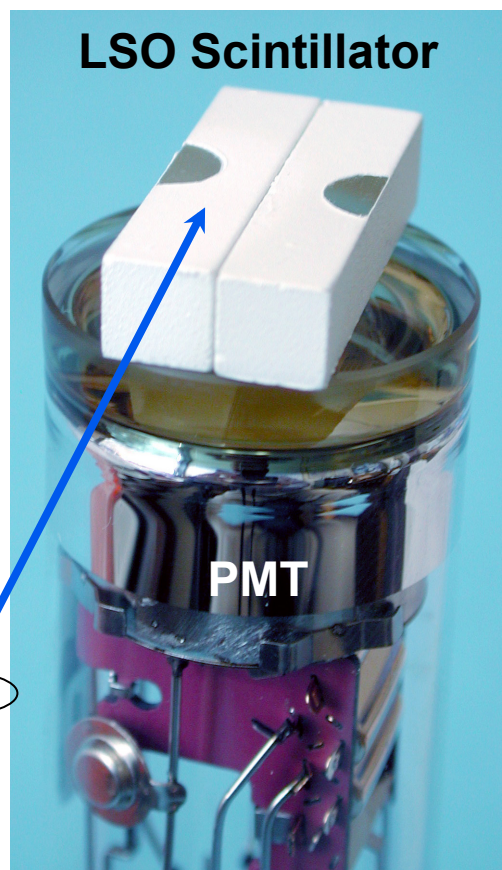
- **More Reflections in Long, Thin Crystals**
- **Adds ~300 ps to Timing Resolution**

# Block Detectors Use “Light Sharing” To Identify Crystal of Interaction



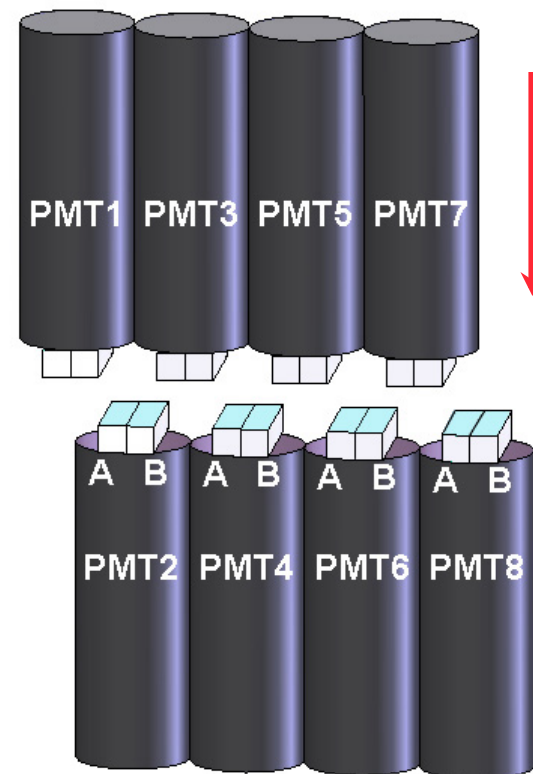
- Light Sharing Degrades Timing Resolution
  - Adds ~400 ps to Timing Resolution

# Alternative Geometries Provide Better Timing



- **Side-Coupled Crystal Geometry has shorter optical path length and fewer reflections.**
  - ⇒ **Less Time Dispersion**
  - ⇒ **Better Time Resolution**
- **Small hole in “top” of reflector allows light to be detected by opposing PMT and so decode crystal of interaction.**

Exploded View of Ring



- **Module Achieves 155 ps Timing Resolution**
- **Limited to Single Ring**

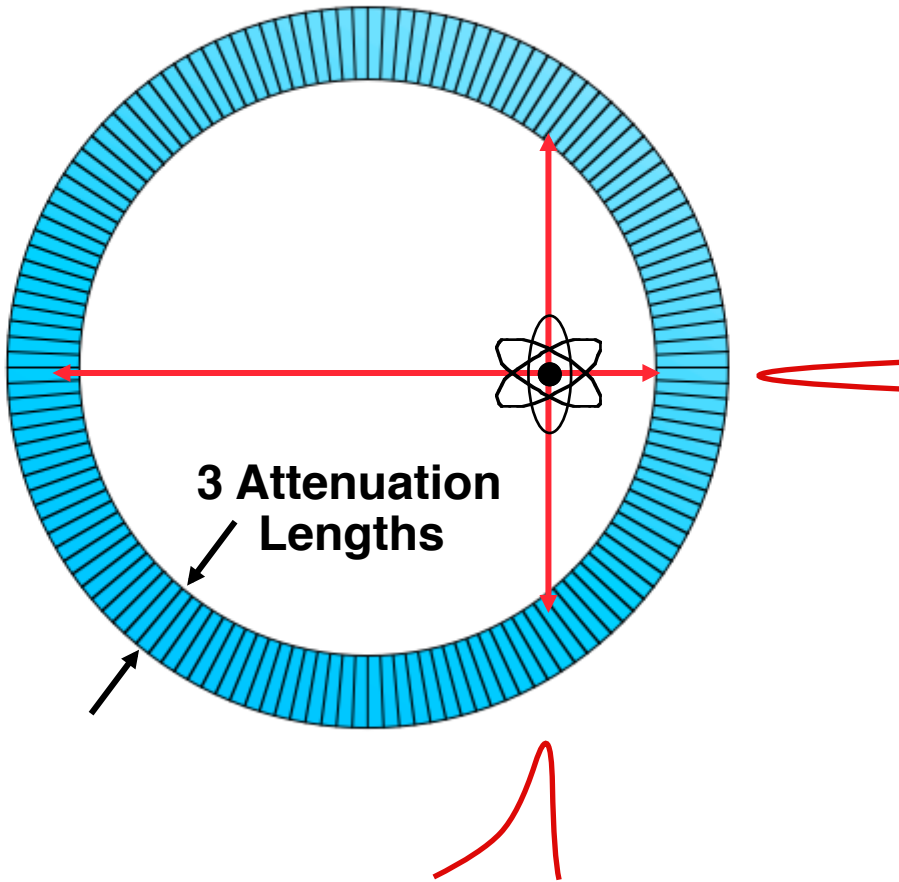
# Improve Limits with New Scintillators?

<b>Hardware</b>	<b><math>\Delta t</math> (ps)</b>	<b>TOF Gain</b>
BGO Block Detector	3000	0.8
LSO Block (non-TOF)	1400	1.7
LSO Block (TOF)	550	4.2
LaBr <sub>3</sub> Block	350	6.7
LSO Single Crystal	210	11.1
LuI <sub>3</sub> Single Crystal	125	18.7
LaBr <sub>3</sub> Single Crystal	70	33.3

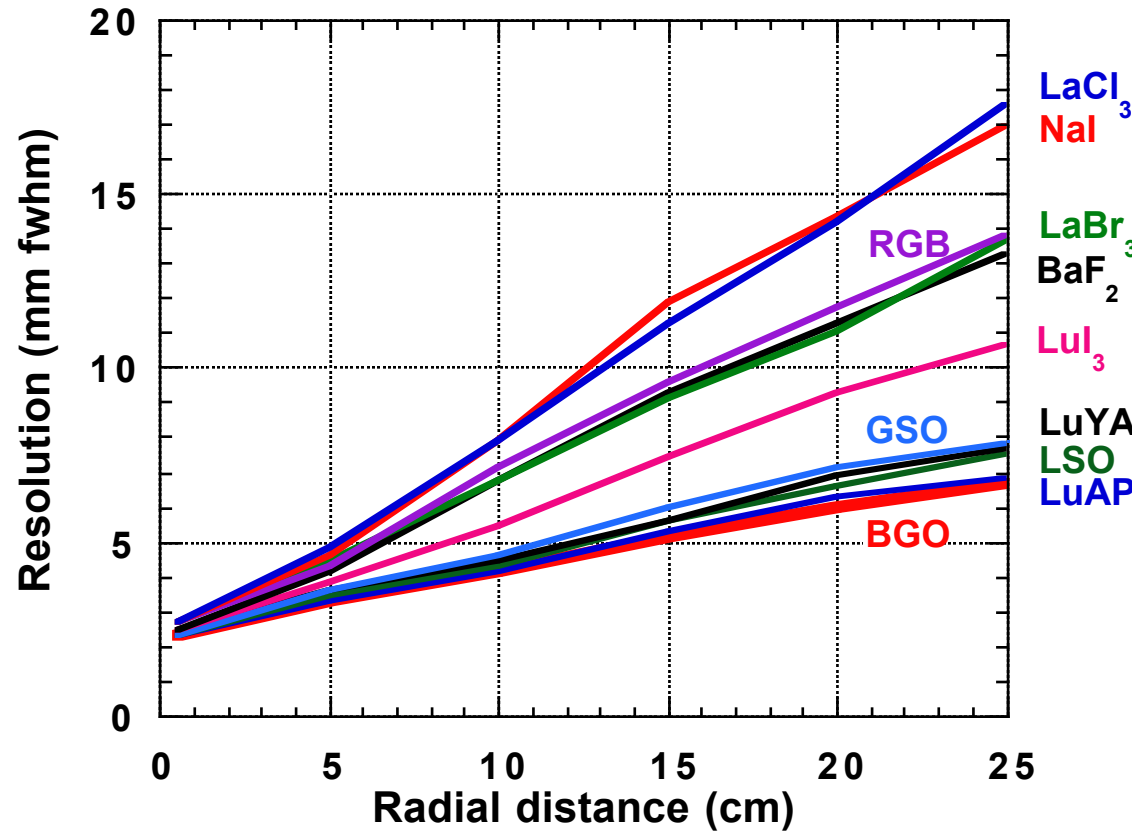
**Research LaBr<sub>3</sub> Camera Built by U. Penn**  
**~350 ps Intrinsic Detector Resolution**  
**420–500 ps Camera Resolution (Electronics Limited)**

# Low Density $\Rightarrow$ Radial Elongation

## Penetration Blurs Image

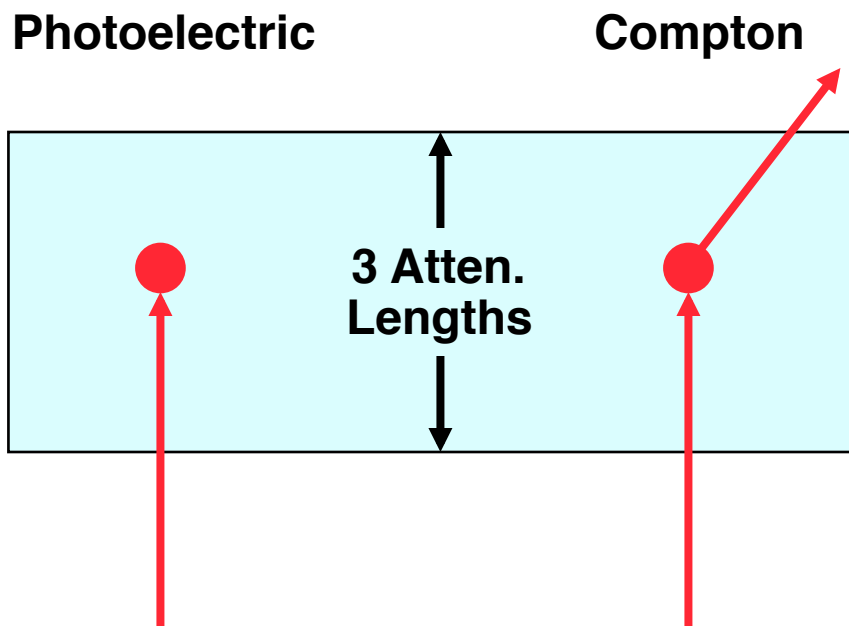


## Resolution vs. Position

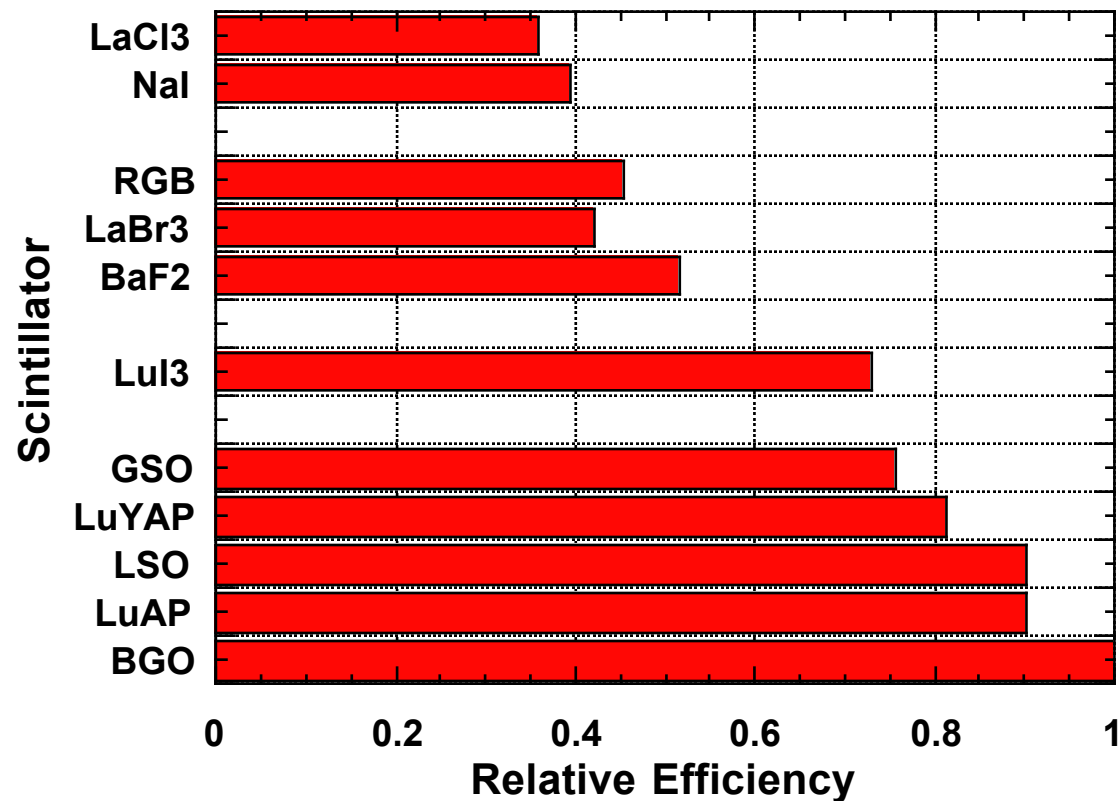


**LaBr<sub>3</sub> (& BaF<sub>2</sub>) Have More Degradation Than LSO**

# Low Photoelectric Fraction ⇒ Low Coincidence Efficiency



Both Photons Deposit  $>350$  keV



**LSO Has 2x the Coincidence Efficiency of LaBr<sub>3</sub>**

# Improvements In Scintillators Needed

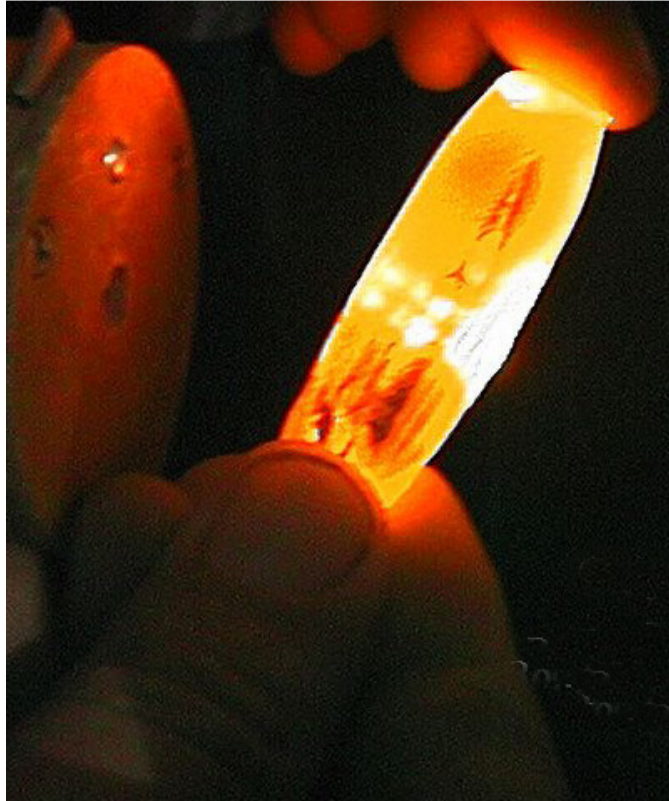


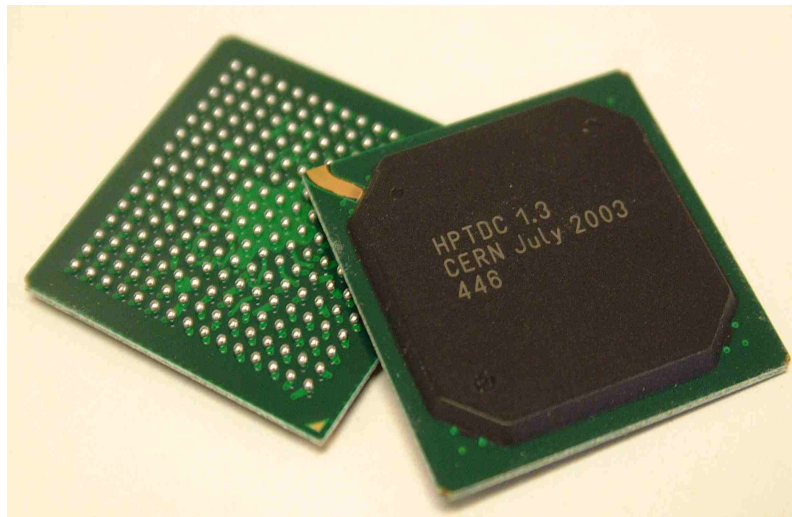
Image courtesy of Paul Lecoq, CERN

## Combine Best Properties of:

- $\text{LaBr}_3:30\% \text{ Ce}$ 
  - Timing resolution  $<100 \text{ ps}$
  - Energy resolution  $<4\%$
- $\text{LuI}_3:\text{Ce}$ 
  - Light output  $>100,000 \text{ ph/MeV}$
- $\text{PbWO}_4$ 
  - Density  $>8 \text{ g/cc}$
  - High atomic number
  - Inexpensive

**PET Performance Determined by Scintillator**

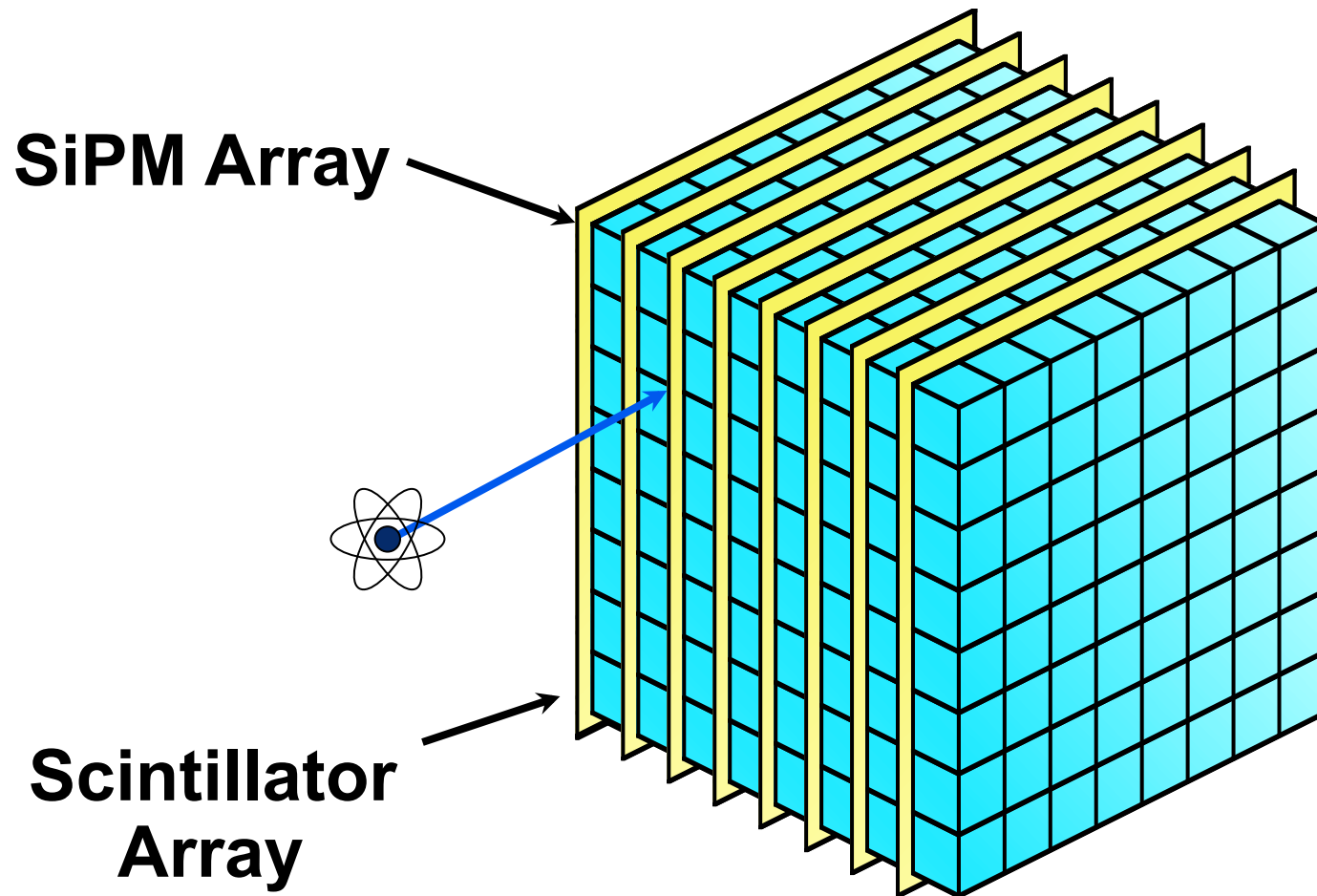
# Improvements In Electronics Needed



- Excellent TDC ASICs available
- Need High Performance Discriminator
  - CFD delay line difficult in ASICs
- Need integrated **PET-specific** ASICs
  - High-precision timing (CFD / Discriminator & TDC)
  - Energy measurement
  - Crystal identification
  - Calibration & testing

**ASIC & Non-ASIC Solutions Underway Today**

# Future TOF PET Design?



- 155 ps Timing Resolution & Depth of Interaction
- 11x Reduction in Variance in Practical Geometry

# Conclusions

## **Benefits of TOF are *HUGE*:**

- 5x effective efficiency gain w/ 500 ps timing
- Greatest improvement in large patients
- Faster reconstruction algorithm convergence

## **Rebirth of TOF PET Due To New Scintillators:**

- 550 ps for LSO, 420 ps for LaBr<sub>3</sub>

## **Still *LOTS* To Do:**

- Electronics
- Module Design
- Reconstruction
- Photodetectors
- Scintillators
- Evaluation

**Much More Improvement To Come!**