Review on Scintillators

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Outline:

– Current Trends
– Benefits for SPECT
– Benefits for PET

Many New Ce^{3+} Scintillators. Why Ce^{3+}?

Activator Requirements:

- **One optically-active electron** when in preferred valence state (no electron-electron interactions).
- Transition is **spin-parity allowed** (decay lifetime is short, quenching reduced).
- **Atomic diameter** similar to heavy metal ions ("fits" into lattices of dense host compounds).
- **Not radioactive** (no background signal).

Lack of Cooperation from Chemists!

⇒ Only Ce^{3+} Meets These Requirements

- *A. J. Wojtowicz, E. Berman, and A. Lempicki, IEEE Trans. Nucl. Sci. NS-39, pp. 1542–1548 (1989).*

In the Beginning (1989)…

CeF_3:

- Halide
- Cerium is a main constituent (not a dopant)
- Scintillation Properties:
  30 ns primary decay lifetime
  4,000 photons / MeV

Cerium "Noticed" in Scintillation

- *D. F. Anderson, IEEE Trans. Nucl. Sci. NS-36, pp. 137–140 (1989).*
- *W. W. Moses and S. E. Derenzo, IEEE Trans. Nucl. Sci. NS-36, pp. 173–176 (1989).*

In the 1990's…

Lu_2SiO_5:Ce

- Oxide
- Cerium is a dopant
- Scintillation Properties:
  40 ns primary decay lifetime
  25,000 photons / MeV
- *Dramatic* (6x) increase in luminosity

Oxides Dominate

- *C. L. Melcher and J. S. Schweitzer, IEEE Trans. Nucl. Sci. NS-39, pp. 502–504 (1992).*

Many Oxide Hosts Doped with Cerium

Some Ce doped scintillators studied since SCINT95

HOST	DOPANT Conc-mol%	λ nm	LIGHT YIELD photons/MeV	τ ns/μs	DENSITY ρ g/cm³	ρZ_{eff}^4 ($\times 10^{-6}$)	REFERENCE
$LuAlO_3$	0.1-1	360	11,000/11,000	18/~10^4	8.3	148	2, 3, 4, 5*
$Lu_xR_{1-x}AlO_3$ (R=Gd,Y)							6, 7*
LuF_3	0.04	310	8,000	23/~μs	8.3	159	8
BaY_2F_8	0.7-10	330	100/1,000	40/~μs	5.0		9
$BaLu_2F_8$	1	320	100/1,000	40/~μs	7.1	112	9
Hf_2CeF_{11}		~310	~10,000				10*
$LiYSiO_4$	5	410	10,000	38	3.8	4	11
$LiLuSiO_4$	~1	420	30,000	42/	5.5	89	12*
$Rb_3Lu(PO_4)_2$	1	410	~30,000	34/~μs	~4.7		13*
$K_3Lu(PO_4)_2$	0.5	410	~50,000	37/~μs	~4.0		13*
Lu_2S_3	1	590	28,000/ >5,000	32/>μs	6.2	123	14*
$LuBO_3$(calc)	1	380	~27,000	~23/	6.9	131	13*, 15*
$LuBO_3$(vate)	0.1	410	~26,000	39/	7.4	140	13*, 15*
$LaLuO_3$		450			8.4	138	16*
CsI					4.5	38	
Gd_2O_2S					7.3	101	
Lu_2SiO_5					7.4	140	
$Bi_4Ge_3O_{12}$ (BGO)					7.1	227	

There's Something About Lutetium…

- *C. W. E. van Eijk, Proceedings of SCINT 97, the International Conference on Inorganic Scintillators and Their Applications, pp. 3–12 (1997).*

In the Early 2000's…

$RbGd_2Br_7$:Ce, $LaCl_3$:Ce, $LaBr_3$:Ce, $CeBr_3$

- **Halides**
- **Cerium is a dopant *or* a constituent component**
- **Scintillation Properties:**
  20 – 30 ns primary decay lifetime
  50,000 – 70,000 photons / MeV
- ***Further* (2x – 3x) increase in luminosity**

There's Something About Halides…

- ***Summarized in W. W. Moses, Nucl. Instr. Meth. A-537, pp. 317–320 (2005).***

Today…

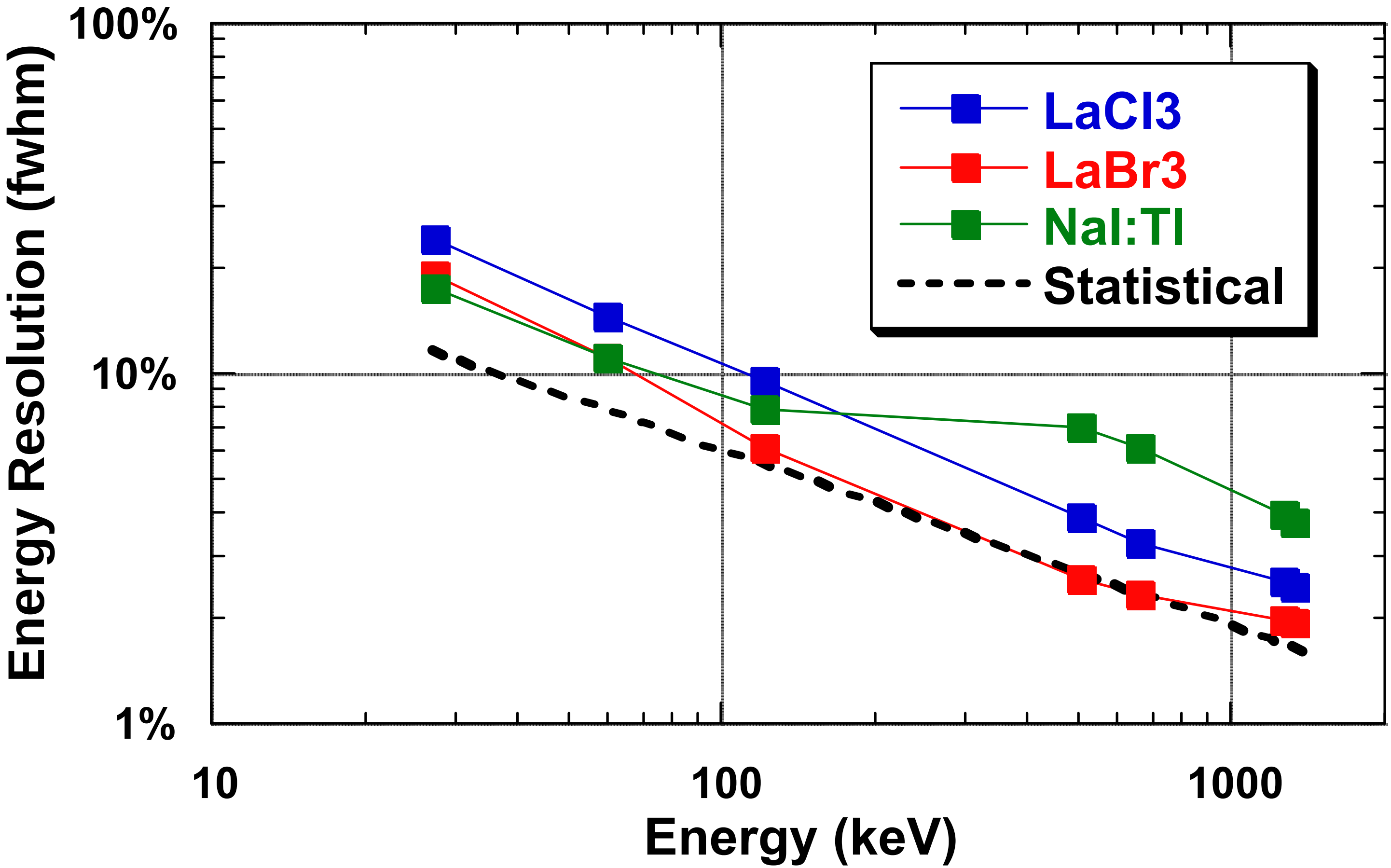
LuI_3:Ce

- Lutetium *and* Halide
- Cerium is a dopant
- Scintillation Properties:
  25 ns primary decay lifetime
  100,000 photons / MeV
- *Another* (1.5x – 2x) increase in luminosity (now ~at fundamental limit)

here's Something About Lutetium Halide

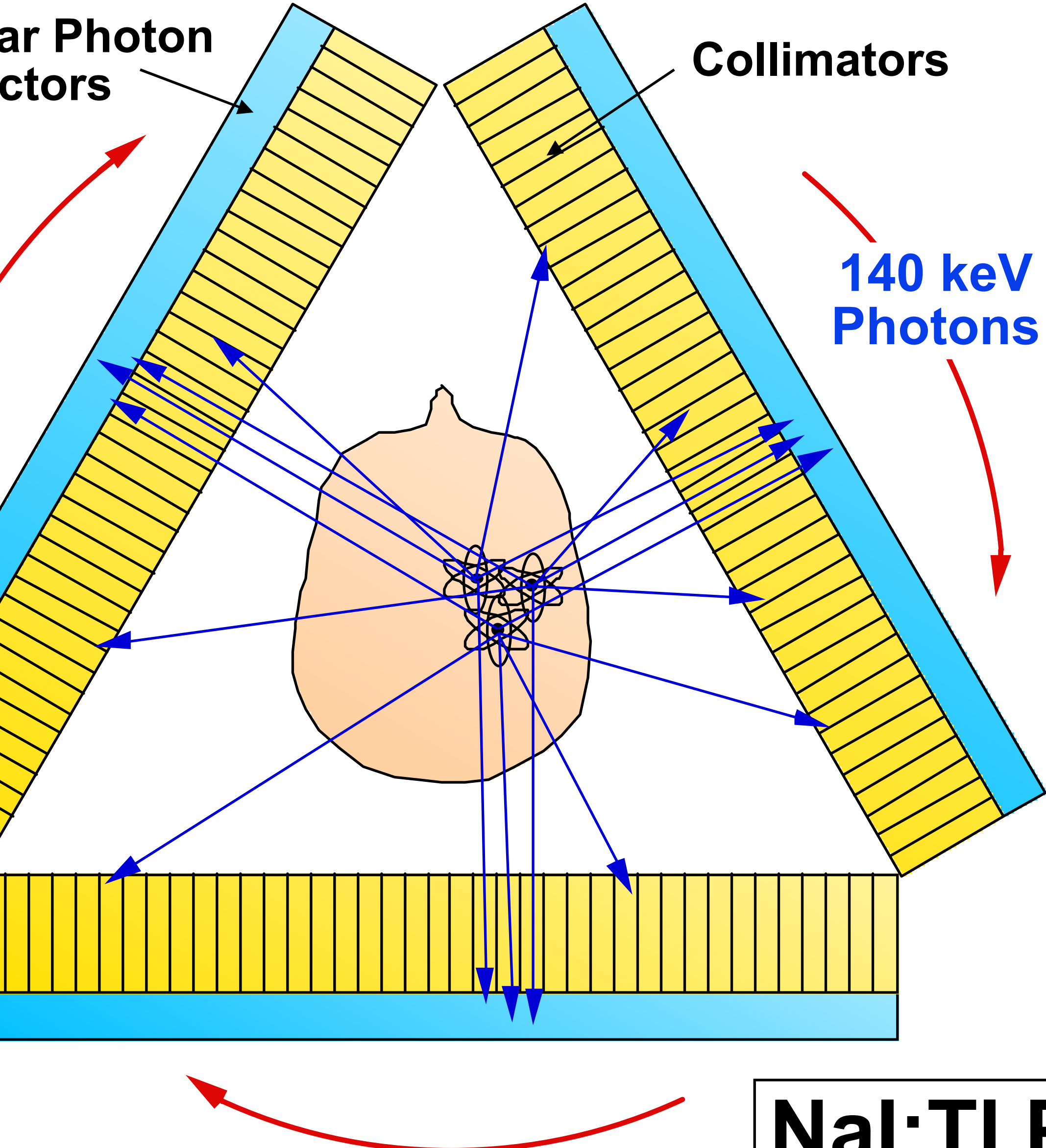
- *K. S. Shah, J. Glodo, M. Klugerman, W. Higgins, et al., IEEE Trans. Nucl. Sci. NS-51, pp. 2302–2305 (2004).*

Tomorrow???



Improved Energy Resolution?

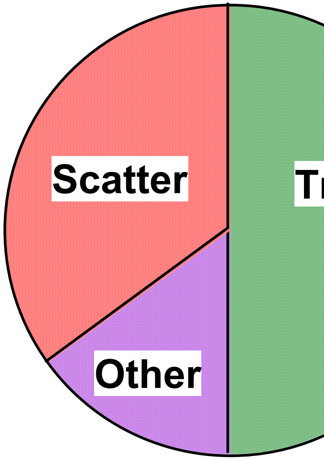
SPECT Scintillator Requirements



- **High Light Output** (>35,000 photons / Me
- **High Photofraction** (>80% at 140 keV)
- **High Density** (>3.5 g/cc)
- **Low Cost** (<$15/cc)
- **Wavelength Match to P** (300–500 nm)
- **Short Decay Time** (<1 µs)

NaI:Tl Predominately Use

Opportunities for SPECT Scintillators



- **Better Energy Resolution**
  - Presently 9% fwhm for 140 keV
  - Over 35% of SPECT events are scatter
  - Scatter fraction linearly proportional to resolution
  - Other effects dominate if resolution <4% fwhm
- **Higher Luminous Efficiency**
  - Fewer PMTs for same intrinsic resolution

NaI:Tl Used for >40 Years...

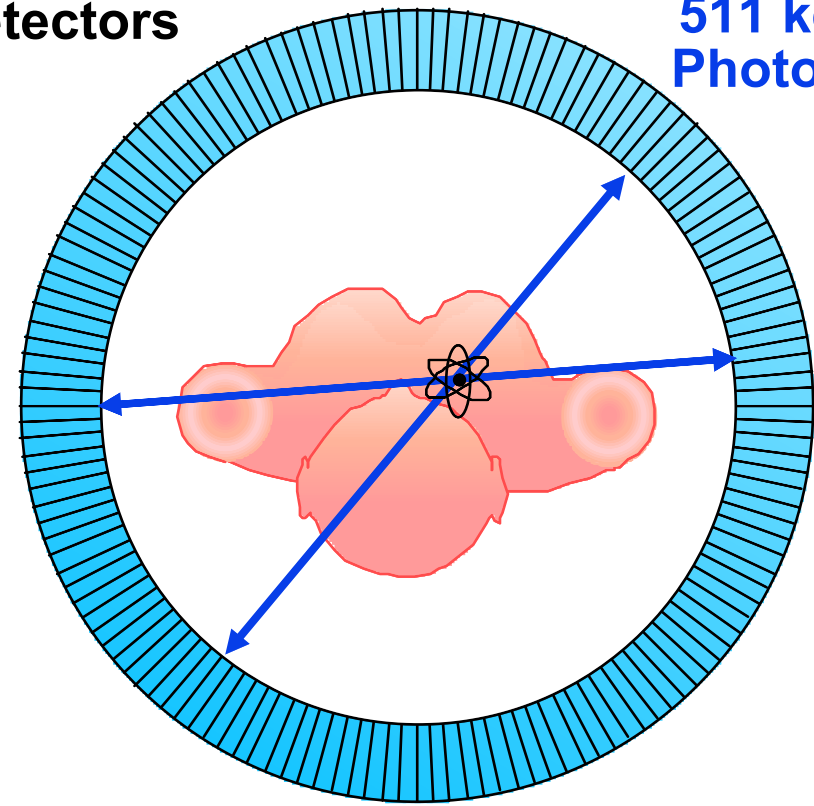
Promising SPECT Scintillators

	NaI	$RbGd_2Br_7$	$LaCl_3$	Ce/LaB
tural Radioactivity?	No	Yes	No	No
minosity (ph/MeV)	38,000	56,000	50,000	60,000
ergy Resol. (@ 140 keV)	8%	10%	10%	6%
nsity (g/cc)	3.7	4.7	3.9	~~5.3~~
ten. Length (mm, 140 keV)	4.9	3.5	4.5	3.8
otofraction (@ 140 keV)	84%	82%	80%	79%
avelength (nm)	415	430	350	370
cay Time (ns)	230	45	20	25
groscopic?	Yes	Yes	Yes	Yes

eBr_3 & $LaBr_3$ have Better Lums & Energy Res

- **No Other Performance Drawbacks!**

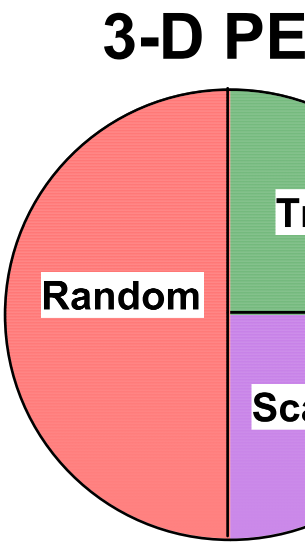
PET Scintillator Requirements



- **Short Attenuation Length**
  (<1.2 cm at 511 keV)
- **High Photofraction**
  (>30% at 511 keV)
- **Short Decay Time**
  (<300 ns)
- **Low Cost**
  (<$30/cc)
- **High Light Output**
  (>8,000 photons / MeV)
- **Wavelength Match to PM**
  (300–500 nm)

BGO & LSO Predominately Used

Opportunities for PET Scintillators



Better Energy Resolution

– Scattered events often outnumber true events

Higher Luminous Efficiency

– Fewer PMTs for same spatial resolution

Better Timing Resolution

– Reduce random events (up to 50% of total events)

– Time-of-flight PET to reduce noise variance (by ~5x)

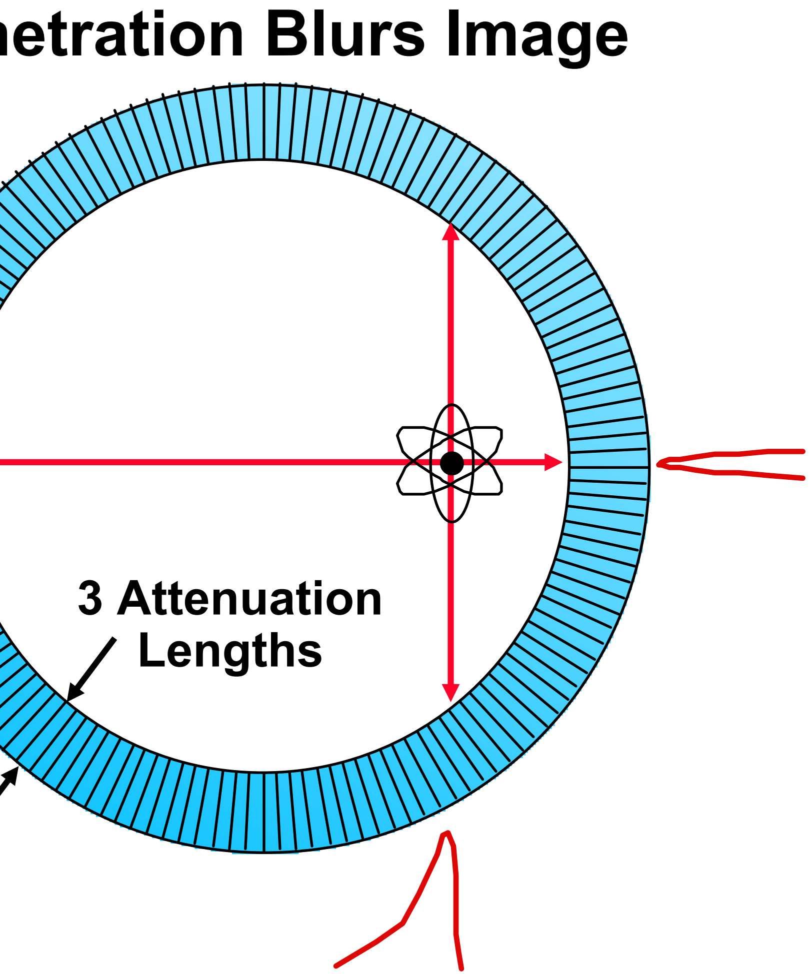
• **There is Significant Room for Improvement (Even Over LSO)**

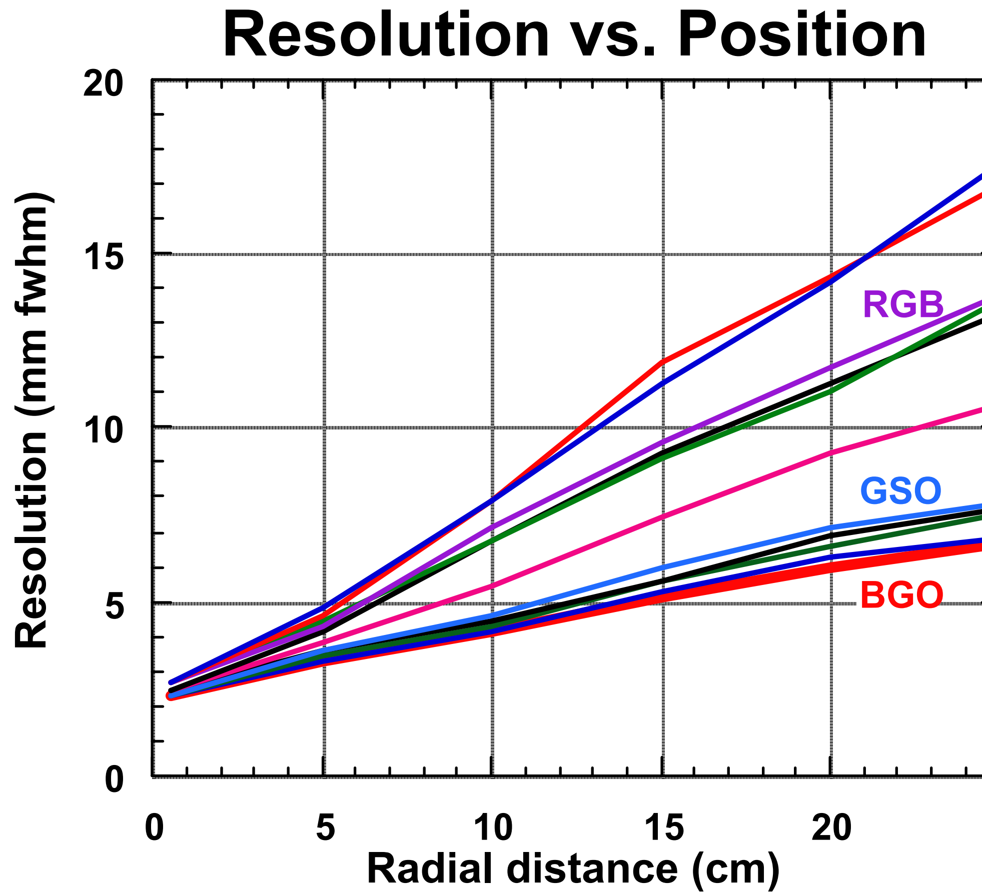
Promising PET Scintillators

	BGO	LSO	Ce/$LaBr_3$	LuI
uminosity (ph/MeV)	8,200	25,000	60,000	100,0
nergy Resol. (@ 511 keV)	12%	10%	3%	4%
ecay Time (ns)	300	40	25	30
ensity (g/cc)	7.1	7.4	~~5.3~~ 5.0	5.6
tten. Length (mm, 511 keV)	11	12	24	18
hotofraction (@ 511 keV)	43%	34%	14%	29%
/avelength (nm)	480	420	370	470
atural Radioactivity?	No	Yes	No	Yes
ygroscopic?	No	No	Yes	Yes

eBr_3, $LaBr_3$ & LuI_3 have Better Energy Resolution, bu
Worse Attenuation Length & Photoelectric Fraction

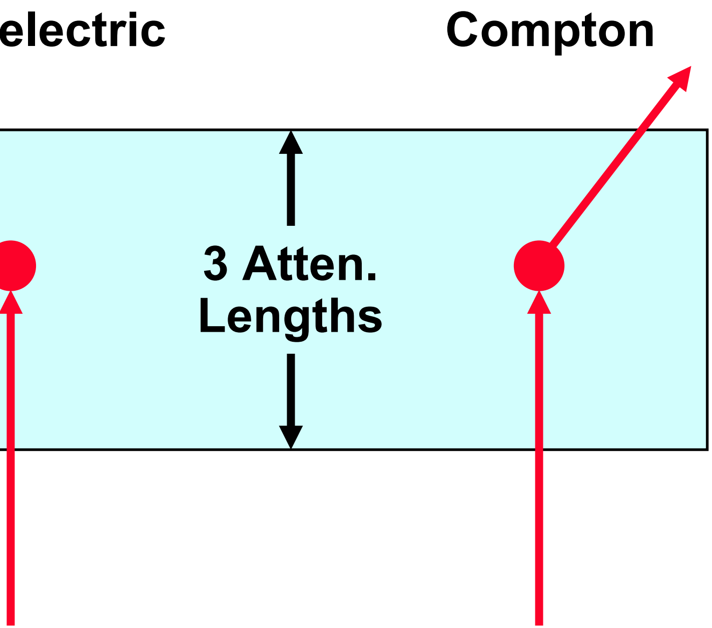
Low Density ⇒ Radial Elongation

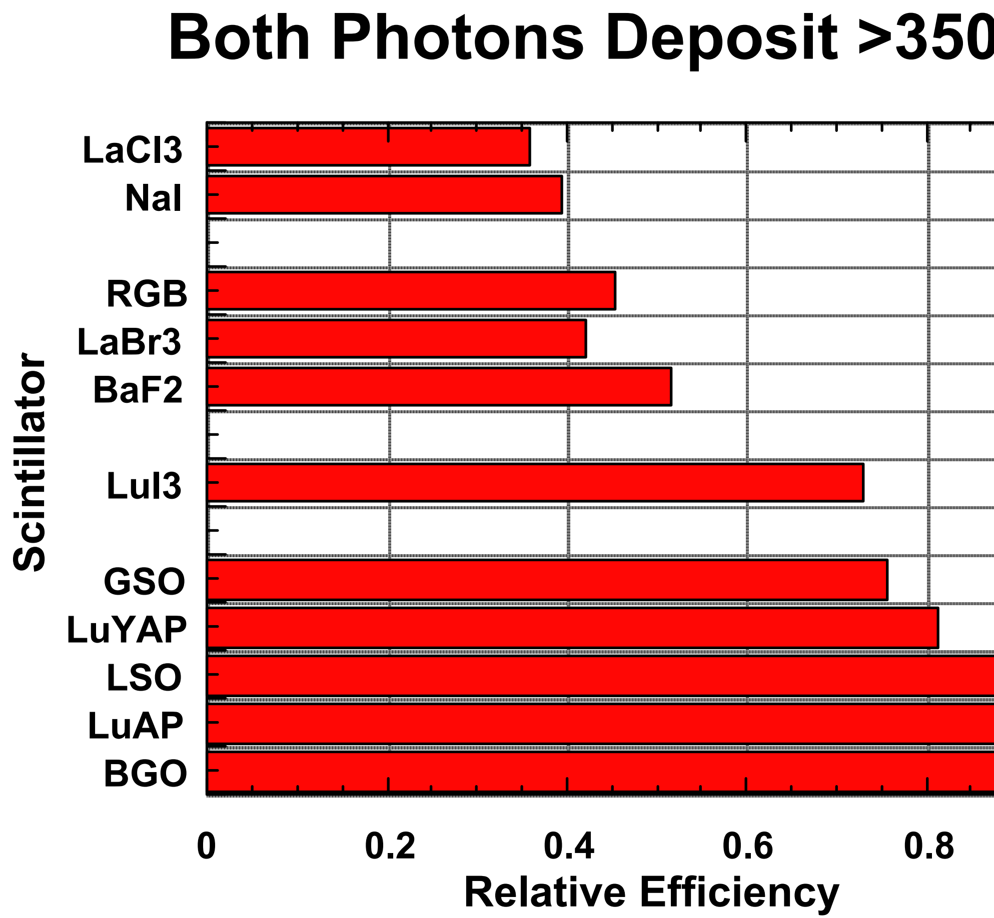




ome Degradation with LuI_3, More with Ce/LaB

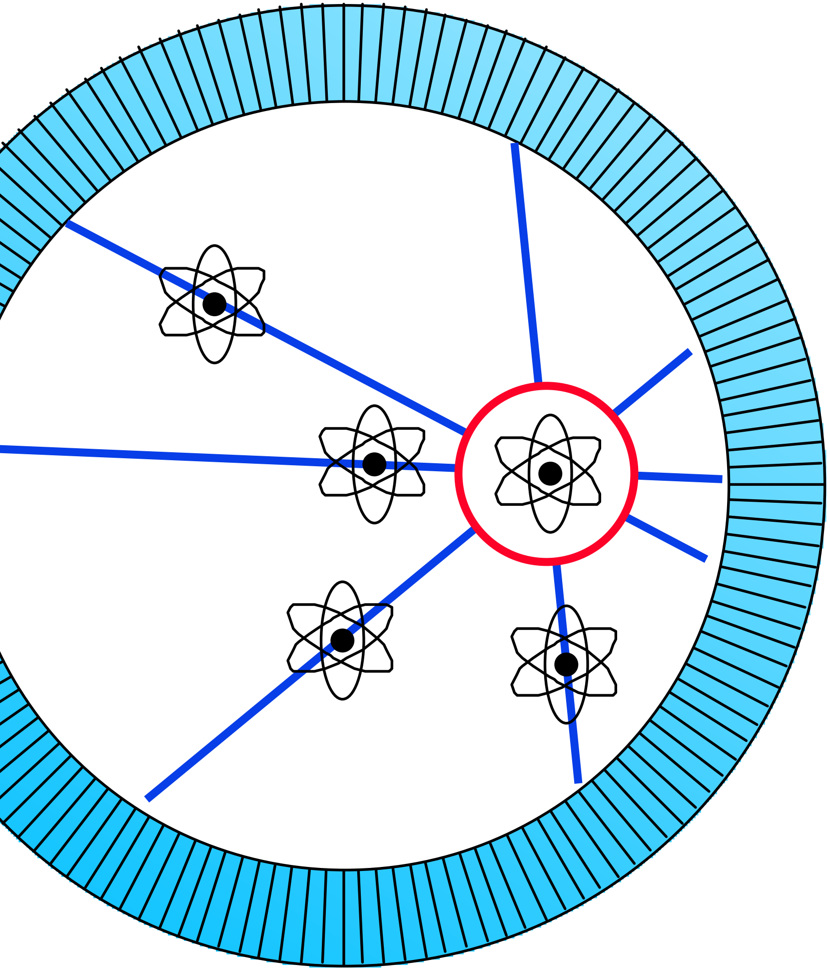
Low Photoelectric Fraction
⇒ Low Coincidence Efficiency





ome Degradation with LuI_3, More with Ce/LaB

Statistical Noise in PET



If there are 10^6 counts in the image,

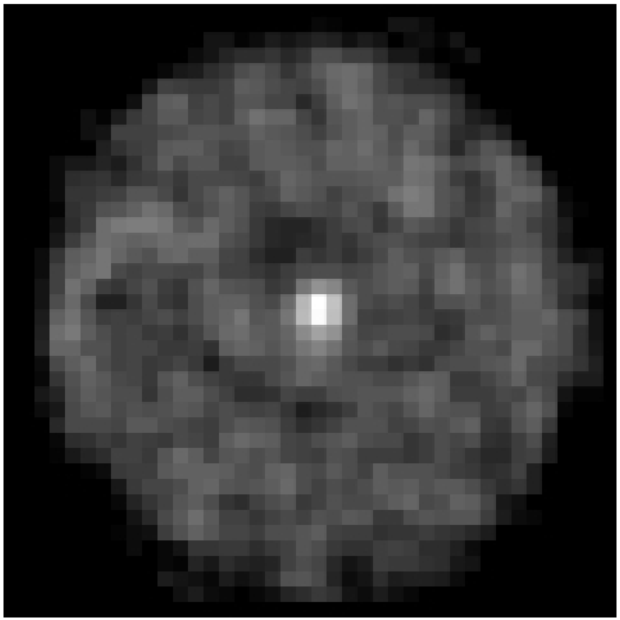
$$\text{SNR} = \frac{10^6}{\sqrt{10^6}} = 10^3$$

Signals from Different Voxels are Coupled

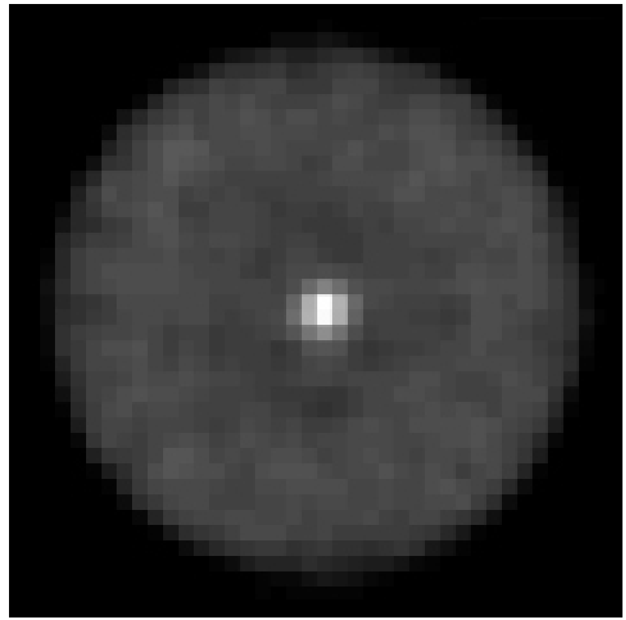
⇒ Statistical Noise Does Not Obey Counting Statisti

Very Visible Reduction in Noise

Non-TOF



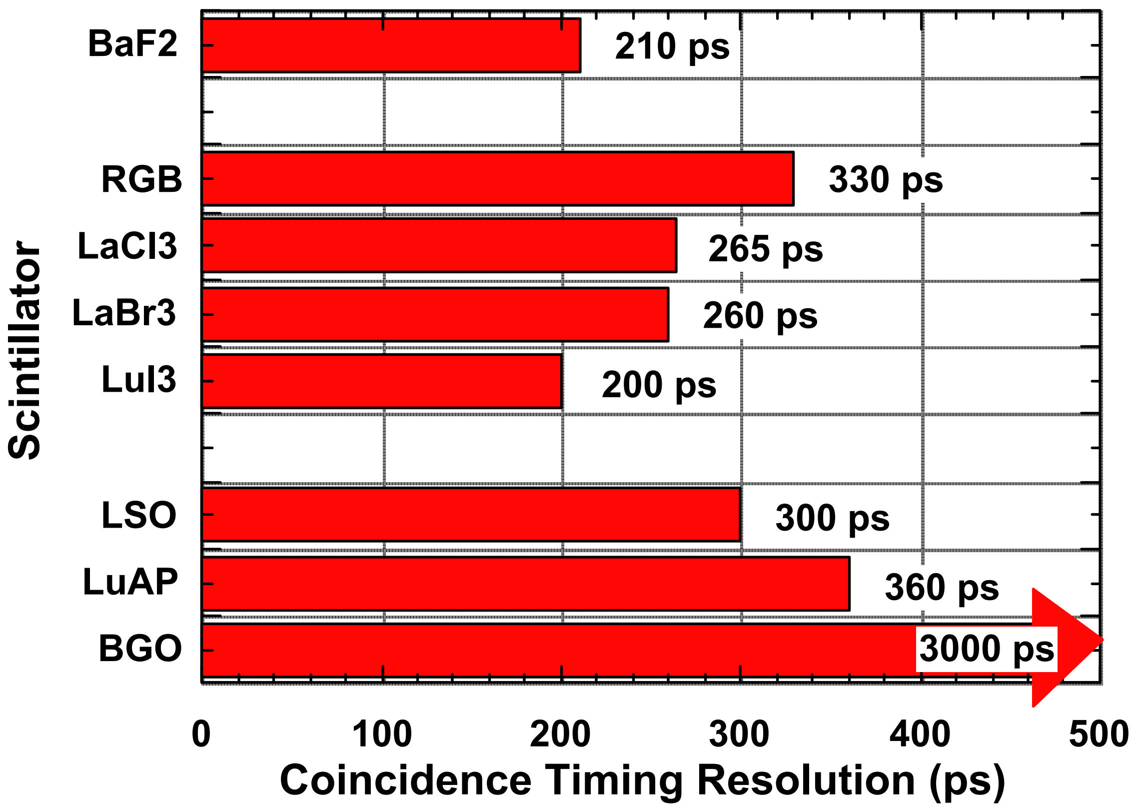
TOF



35 cm dia. w/ 1 cm dia. 6:1 hot spot
300k events, T:S:R = 1:1:1, 500 ps fwhm

Improvement Largest for Large Patients!

Coincidence Timing Resolution



- **New Scintillators Capable of Time-of-Flight**

500 ps Resolution ⇒ 5x Reduction in Noise Varianc

Conclusions

For SPECT:

- $CeBr_3$ and $LaBr_3$ are compelling
  - Better light output & energy resolution than NaI:Tl
  - Shorter attenuation length than NaI:Tl
  - No other performance drawbacks!

For PET:

- LuI_3 is *very* interesting, but has some tradeoffs
  - Energy resolution, light output, & timing excellent
  - Worse attenuation length & photoelectric fraction
- $LaBr_3$ and $CeBr_3$ have more severe tradeoffs
  - Atten. length & photoelectric fraction much worse

Economic Growth is *Absolutely* Necessary

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