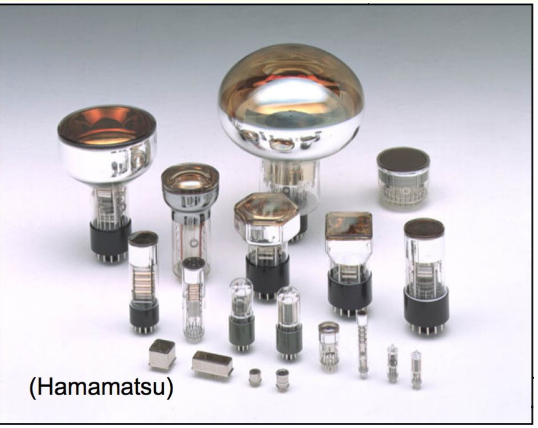
Topics, Attribution, & Literature

- Today we'll talk about…
  - Photodetectors
    - Intrumentation for converting scintillation photons into electronic signal
  - Non-proportionality in scintillators
    - Causes and consequences for energy resolution
- Attribution
  - The majority of the material for these lectures is derived from the 2015 IEEE short course on scintillation detectors by Dr. Stephen Derenzo
- Literature
  - W. Moses et al: The Origins of Scintillator Non-Proportionality
  - S. Payne et al: Nonproportionality of Scintillators: Theory and Experiment
  - Bora: Photon Statistics in Scintillation Crystals

Overview: Photodetectors

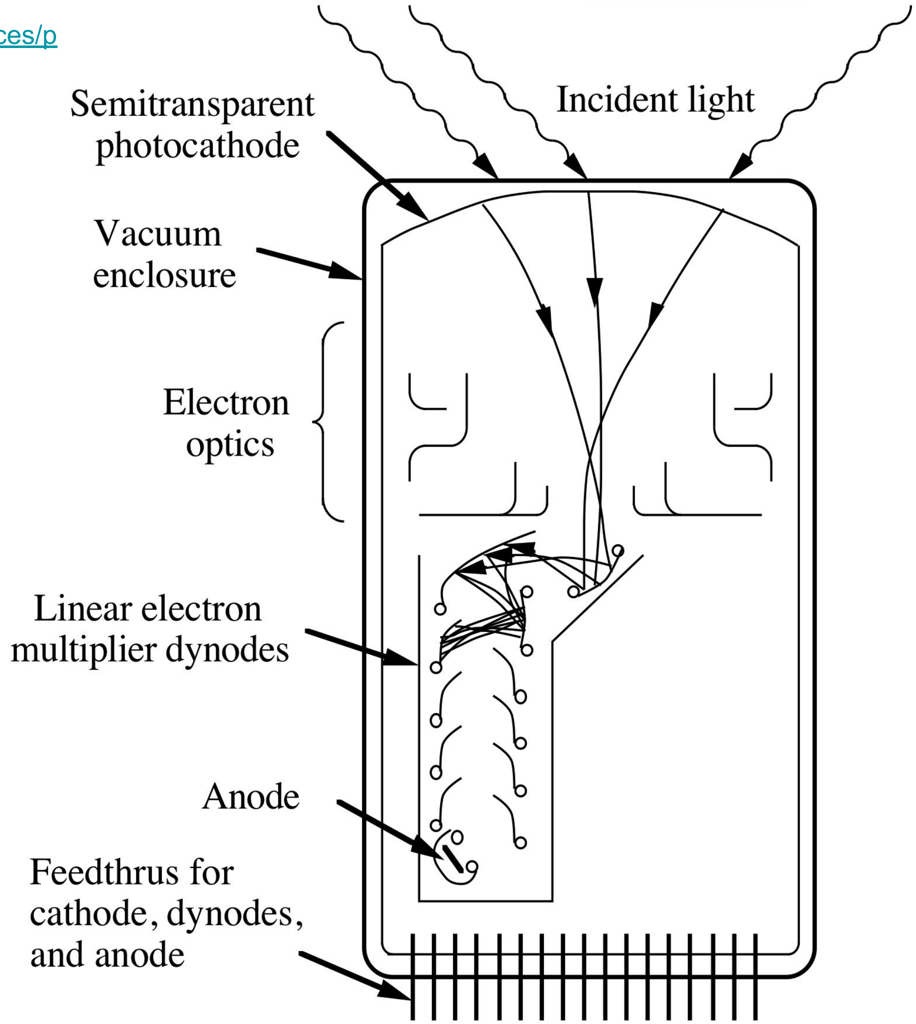
- Convert scintillation photons into electric signal for subsequent measurement
- Desirable properties of a photodetector include:
  - High photodetection efficiency
    - Often expressed as *Quantum Efficiency*, $Q.E. = N_{photoelectrons}/N_{incident\ photons}$
  - Low electronic noise contributions
  - Large active area
  - Stability over time, temperature, etc.
- Main classes of photodetector:
  - Vacuum-based: e.g. Photomultiplier tube (PMT) Microchannel plate
  - Solid state: Photodiode (PD), Avalanche photodiode (APD), Silicon photomultiplier (SiPM)
  - Vacuum/SS Hybrids

Photomultiplier Tube (PMT)



https://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE.pdf

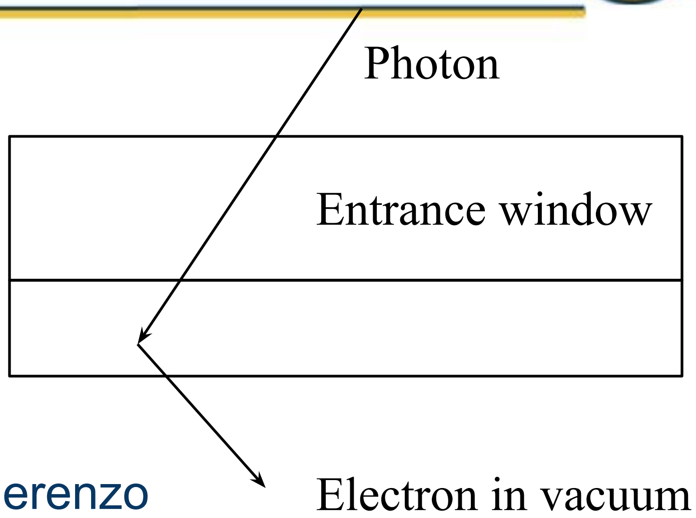
- Very high gain O(10^6 - 10^7)
- Peak Q.E.
  - ~25% for Bialkali (BA) photocathode
  - Up to ~40% for UBA
- Low noise (single-electron sensitivity)
- Fast time response
  - RT ~1ns
- Many sizes/shapes, including large area
- Sensitive to B-field
- Require large biases



Knoll Fig. 9.1

Photocathode

- Q.E. depends on incident photon energy
  a. Create e^-/h pair
  b. E^- transport to surface
  c. Overcome potential barrier (work function)
- Trade-off between photon abs. / e^- emission with thickness
  - Choose PC that matches scintillator emission
  - Consider window material
    - E.g. quartz for UV sensitivity
- E.g. Bialkali (K_2CsSb)
  - Peak QE @ ~400nm (blue)



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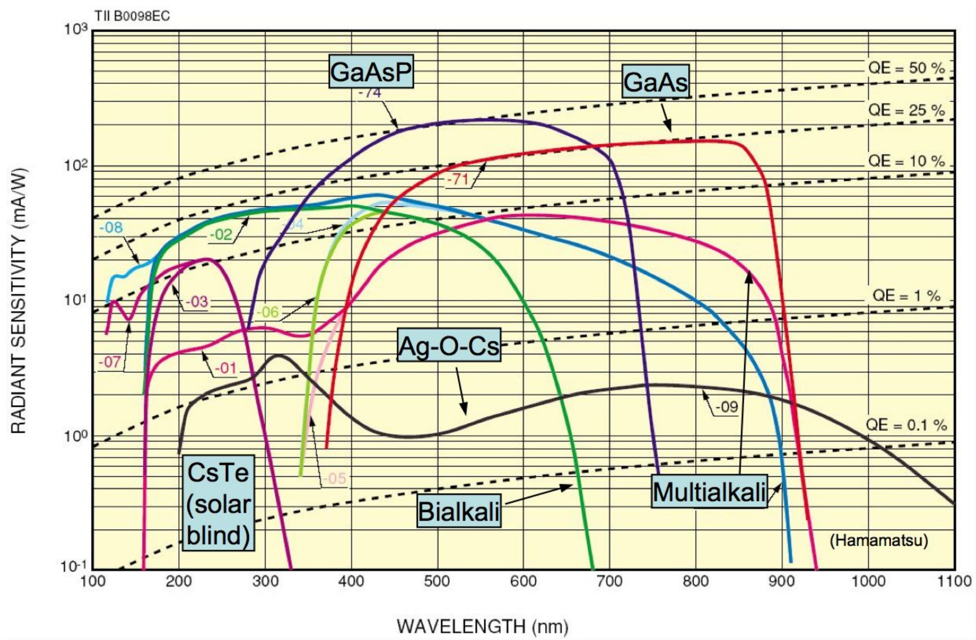
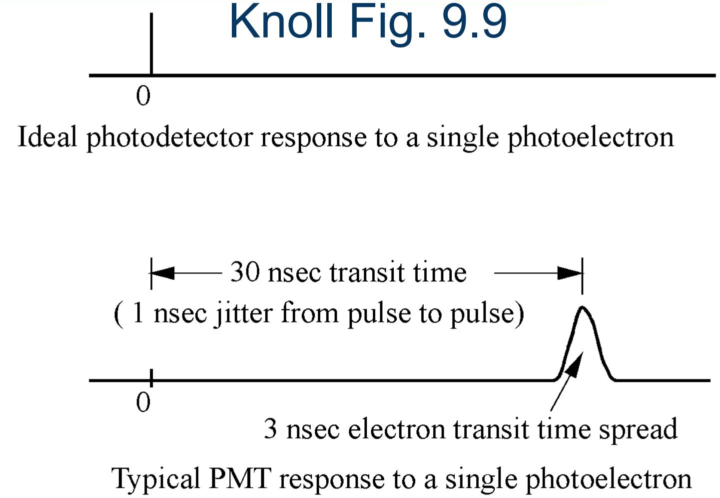


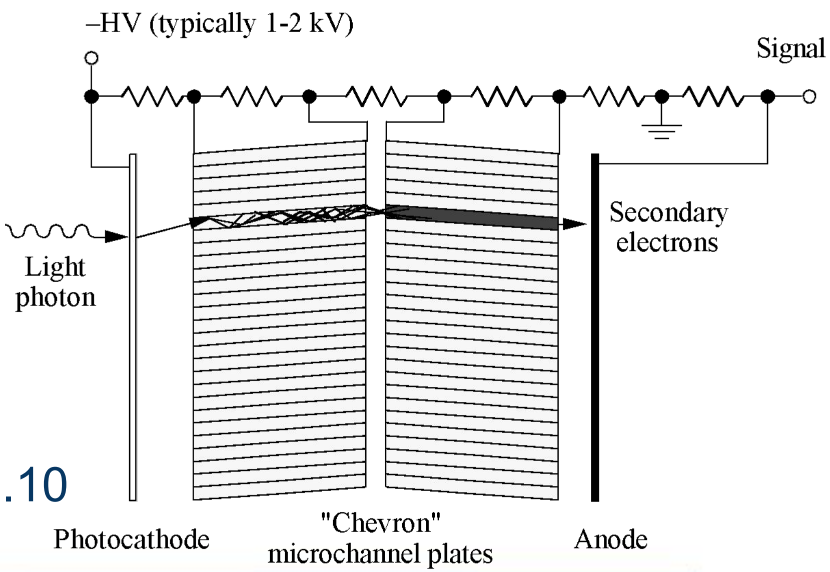
Electron Multiplication

- Multi-stage dynode structure
  - Multiplication via 2^{nd}ary e^- emission
  - Very high gain: $\alpha\delta^N$
  - G very sensitive to HV
  - Finite transit time (delay)
    - Jitter →PC e^- @ 1st stage

Knoll Fig. 9.9



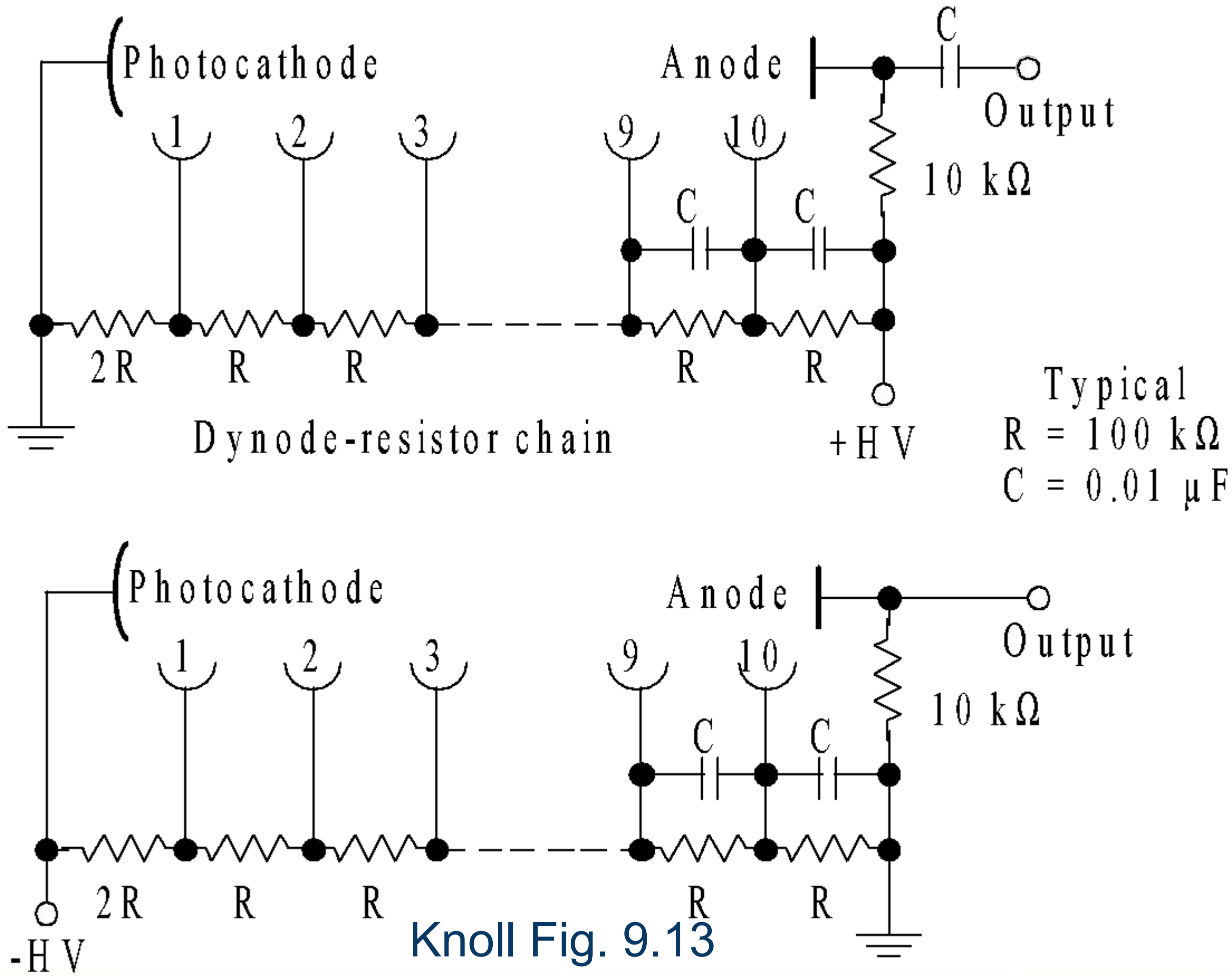
- Other multiplication structures
  - E.g. microchannel plate



Knoll Fig. 9.10

PMT Bases

- Resistive-divider network to apply dynode voltages



Knoll Fig. 9.13

PMT Bases

- Resistive-divider network to apply dynode voltages

	Advantages	Disadvantages
Positive HV	1) Photocathode at ground potential	1) Anode at HV – coupling capacitor required- failure can damage electronics 2) d.c. signals blocked; bipolar pulses with zero area 3) Negative pulse component makes baseline unstable
Negative HV	1) Anode at ground potential 2) Can measure total signal by simple integration	1) To prevent ion migration in glass a photocathode shield at HV is required => electrical shock hazard

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Solid State Photodetectors: Photodiodes

- Advantages
  - Can have very high Q.E.
    - 70-90%
  - Insensitive to B-field
- Disadvantages
  - Gain = 1
  - Leakage current →Noise
    - No single e$^-$ sensitivity
    - Can be cooled to improve SNR
- Small size diodes

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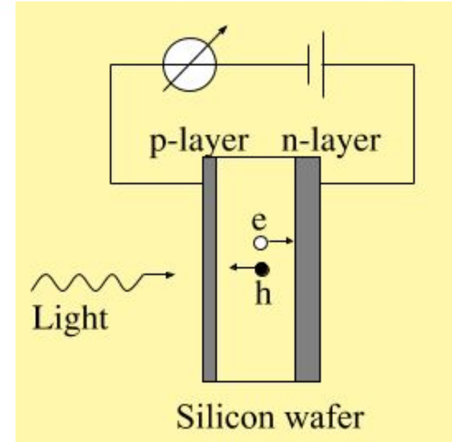
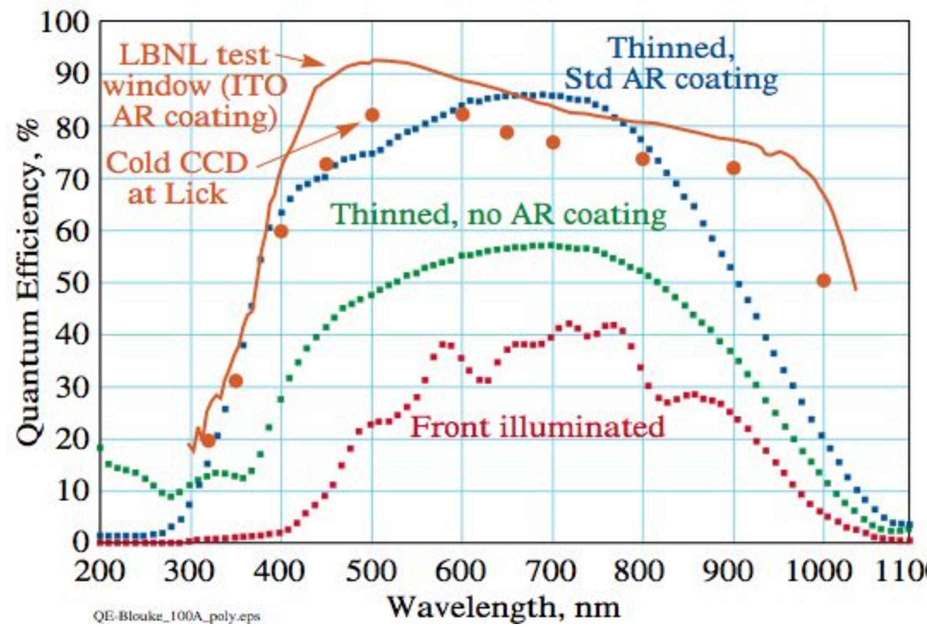
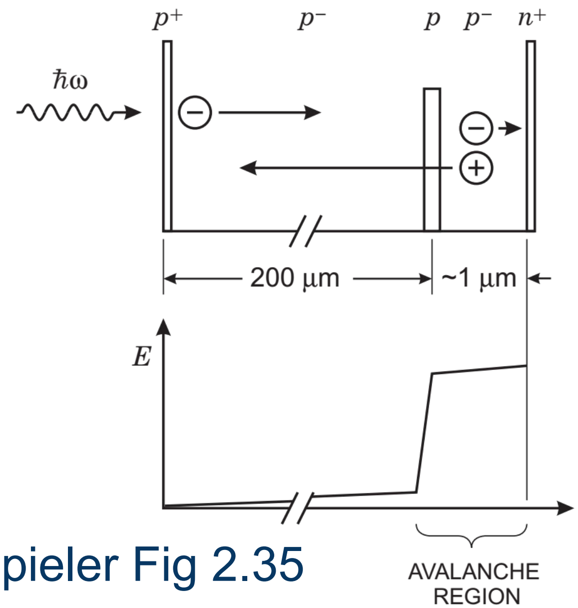




Reference: Blouke and Nelson, SPIE 1900 (1993), 228-240

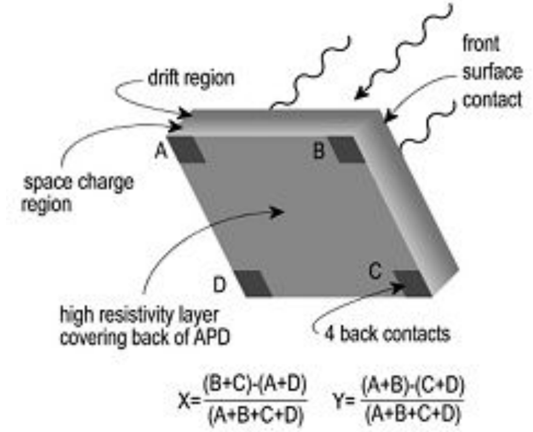
Solid State Photodetectors: APD

- Avalanche Photodiode (APD)
  - PD advantages with gain
    - Q.E. ~70%
    - Wide spectral response
    - Insensitive to B-field
- Controlled avalanche mechanism
  - E.g. reach-through architecture
- Gain ~100 - 1000



Spieler Fig 2.35

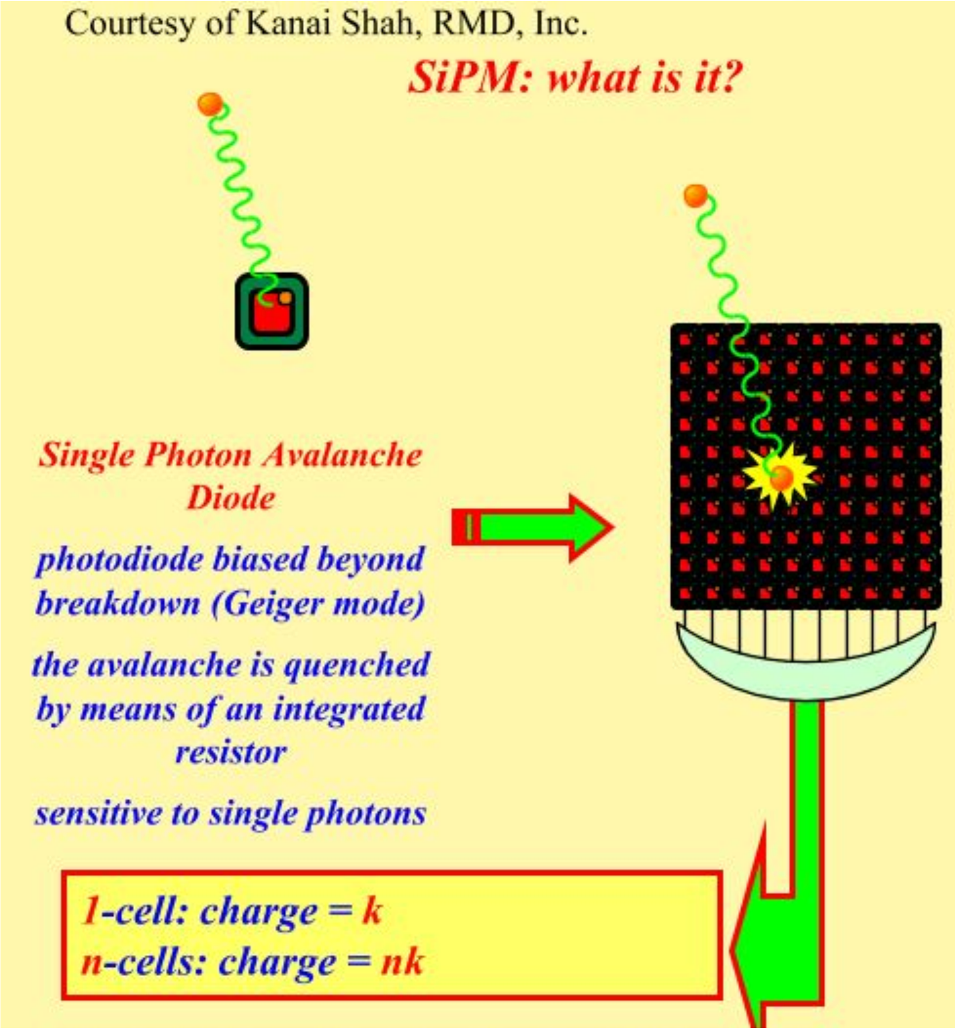
- Position-sensitive APD (PSAPDs)
  - Monolithic APD with segmented readout
  - Imaging applications



http://rmdinc.com/avalanche-photo-diodes/

Solid State Photodetectors: Silicon Photomultiplier (SiPM), Geiger-mode APD, Multipixel Photon Counter (MPPC)

- Basic principle: single photon counting with large gain
  - SiPM/MPPC = array of single-photon avalanche diodes (SPADs)
- Full Geiger-mode operation
- Properties
  - Advantages of solid state
  - Very high gain (~10^6)
  - Fast response (~100 ps RT)
  - ~100V applied bias
- Issues
  - HV/Temp sensitivity (avalanche)
  - High dark pulse rate
  - Cross-talk & after pulsing



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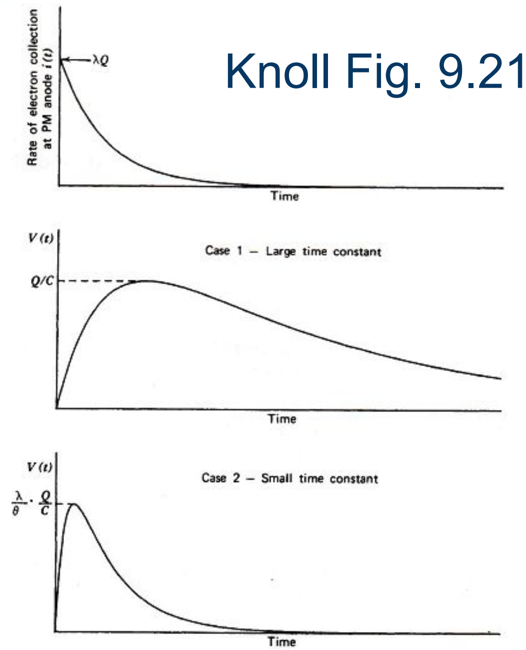
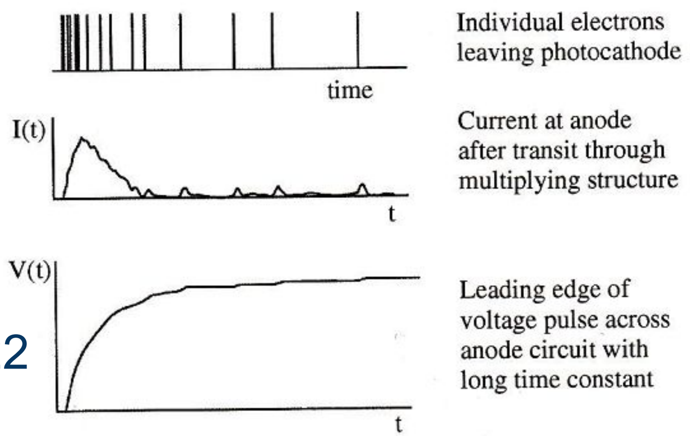
Scintillator Pulse Shape Analysis

- Pulse mode operation
  - Output voltage signal on per-event basis
- Signal depends on time constant
  - τ << scint. decay time
    - Full charge not integrated
    - Preserve shape of current pulse
  - τ >> scint. decay time
    - Signal amplitude proportional to total charge (spectroscopy)
- Dependence of time const. scint. decay time



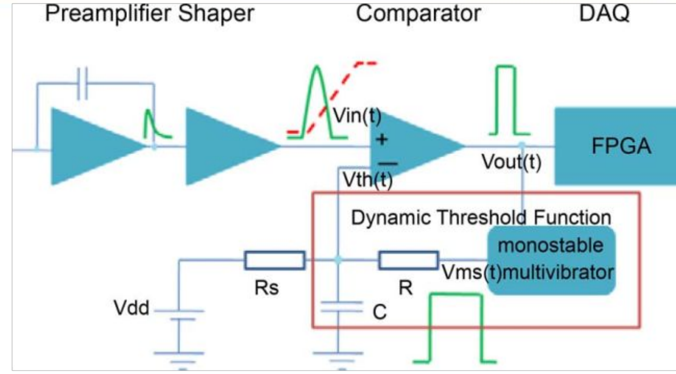
Knoll Fig. 9.21

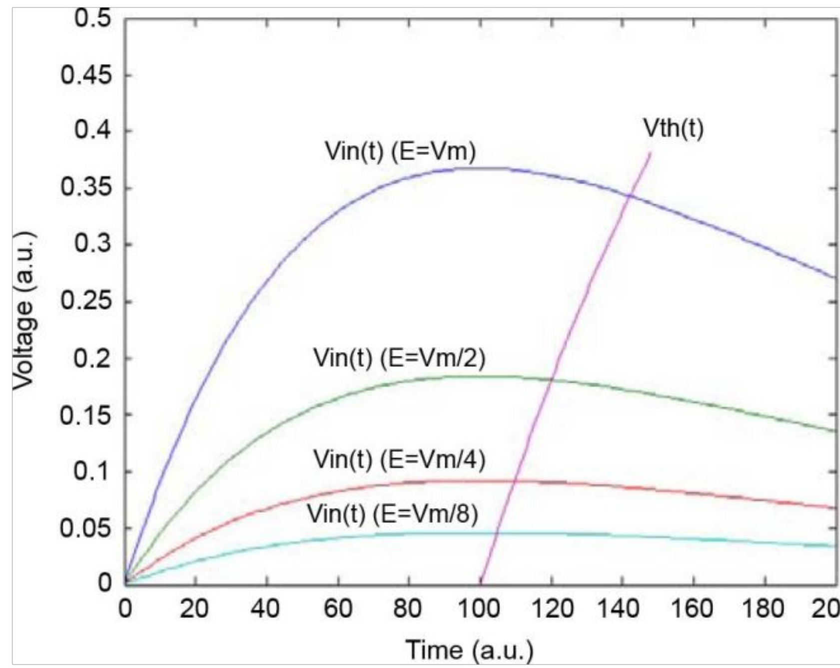


Knoll Fig. 9.22

Scintillator Pulse Shape Analysis

- Alternatives to conventional pulse height analysis for scintillator spectroscopy
  - Time-over-threshold (ToT)
- ToT Benefits
  - Simplicity
    - Low-power
    - High channel density
- Applications for multipixel systems with moderate energy resolution requirements





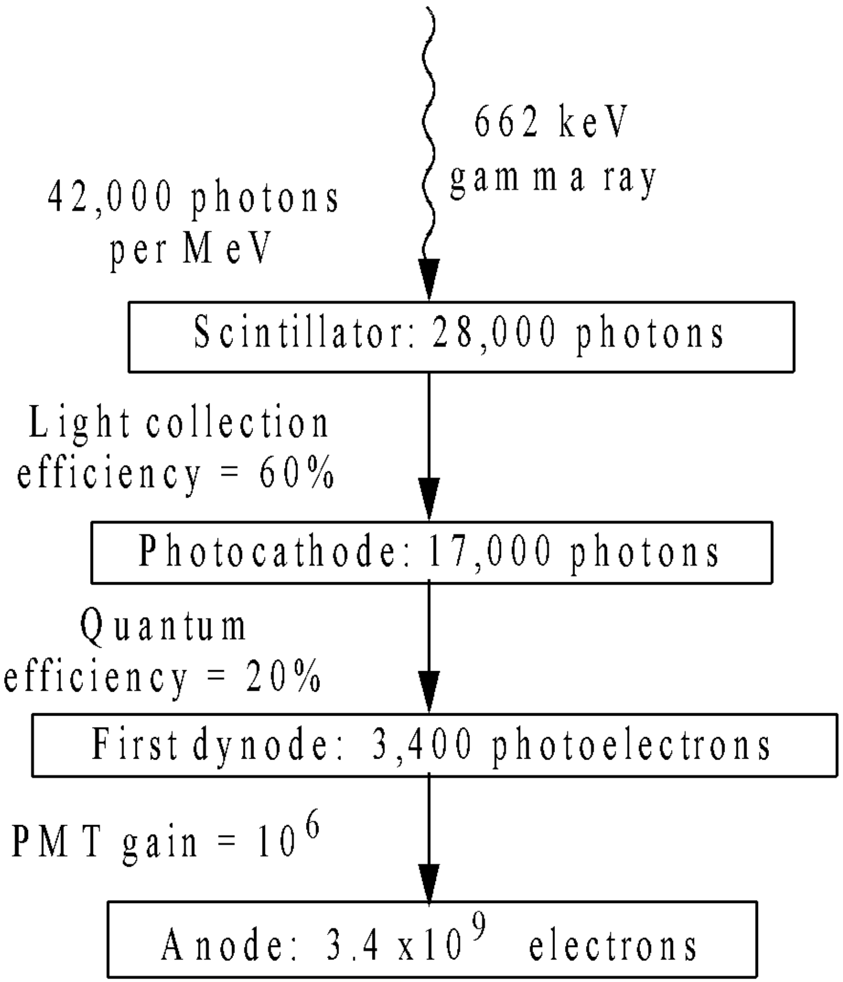
https://ieeexplore.ieee.org/document/6308744

Energy Resolution in Gamma-Ray Spectroscopy with Inorganic Scintillators

- Factors that affect energy resolution of scintillators
  - Scintillation efficiency (scint. photons / deposited keV)
    - Uniformity of scintillation efficiency in the detector
  - Non-proportionality of light output w/ electron energy
  - Self-absorption / re-emission process
  - Light collection efficiency & uniformity
  - Photodetector Q.E. @ scint. Photon wavelength
  - Photodetector Q.E. & gain uniformity across input
  - Photodetector gain drift during acquisition
    - Gain-stabilization may be required

Example: 662 keV in NaI(Tl)

- Assume Poisson
- Gain **does not affect** resolution!



$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{3,400}} = 1.7\% \quad \text{rms}$$

$$2.35 \times \frac{\Delta E}{E} = 4.0\% \quad \text{fwhm}$$

Best measured value for NaI(Tl) 5.6% fwhm
Typical value for NaI(Tl) 7%
Best measured value for pure NaI 3.8%
see http://scintillator.lbl.gov
New codoping => 4.9% fwhm

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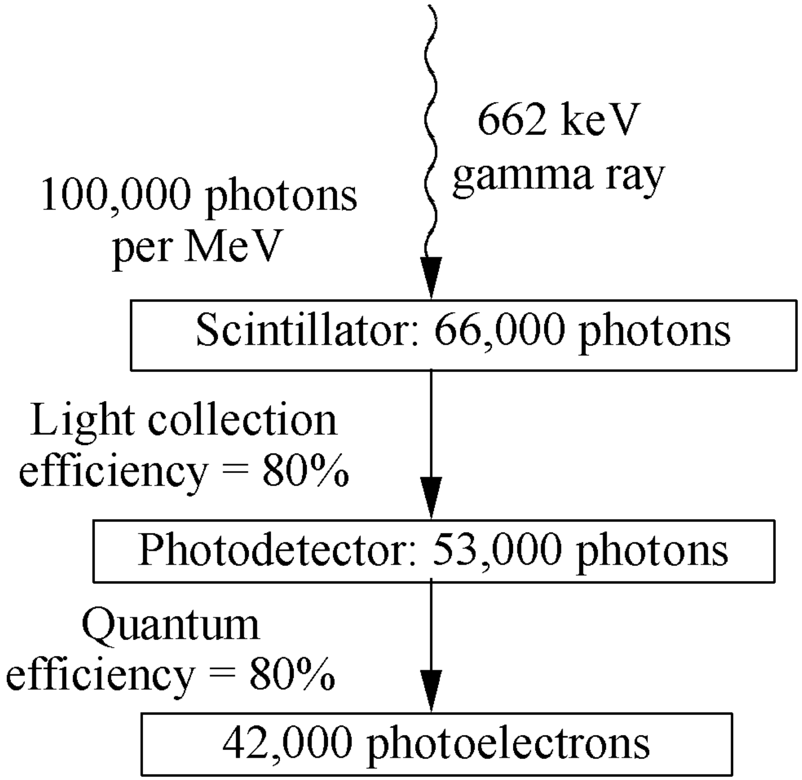
Thought Experiment: Ultimate Scintillator Energy Resolution

- Assume Poisson process (stay tuned)



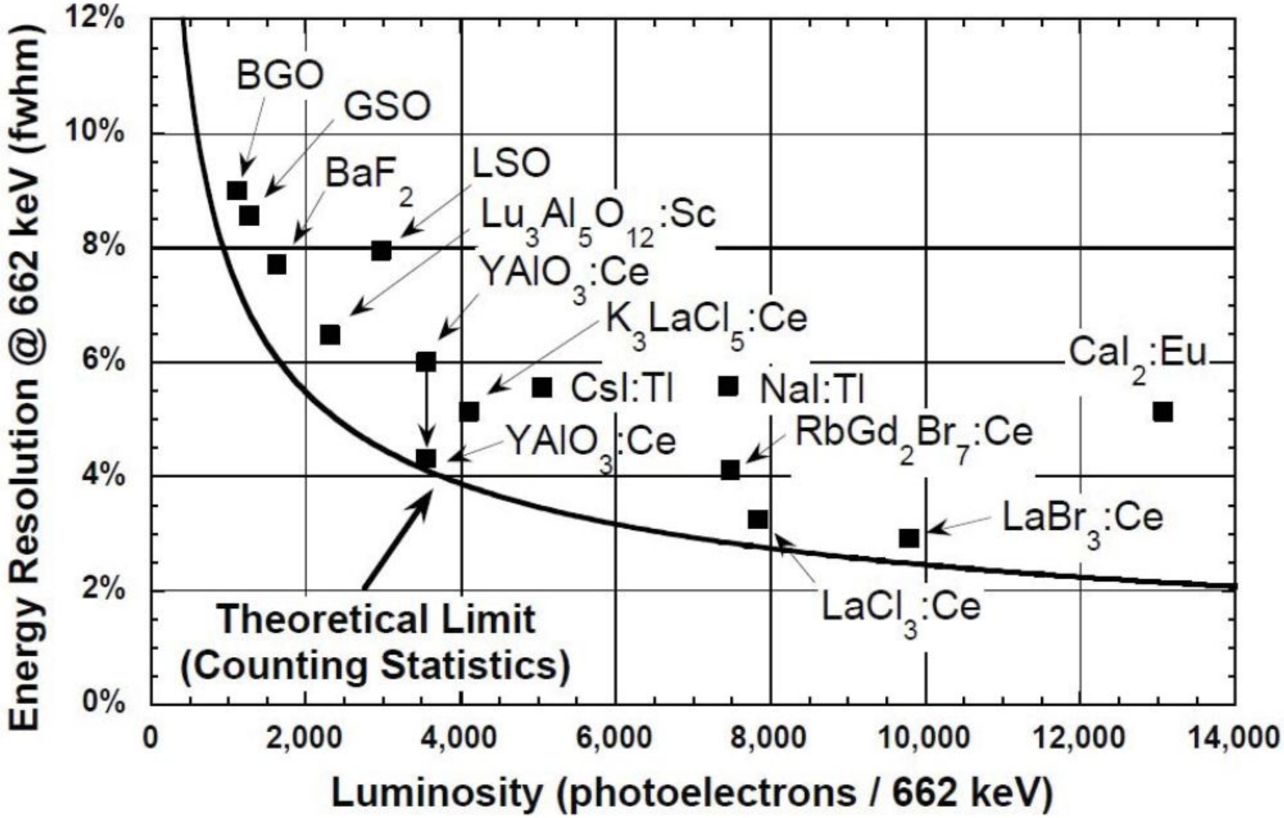
$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$$

$$\frac{\Delta E}{E} = \frac{1}{\sqrt{42{,}000}} = 0.49\% \ \ \text{rms}$$

$$2.35 \times \frac{\Delta E}{E} = 1.2\% \text{ fwhm}$$

Best measured value 2.0% fwhm (several examples are in http://scintillator.lbl.gov)

Observed Energy Resolution in Inorganic Scintillators

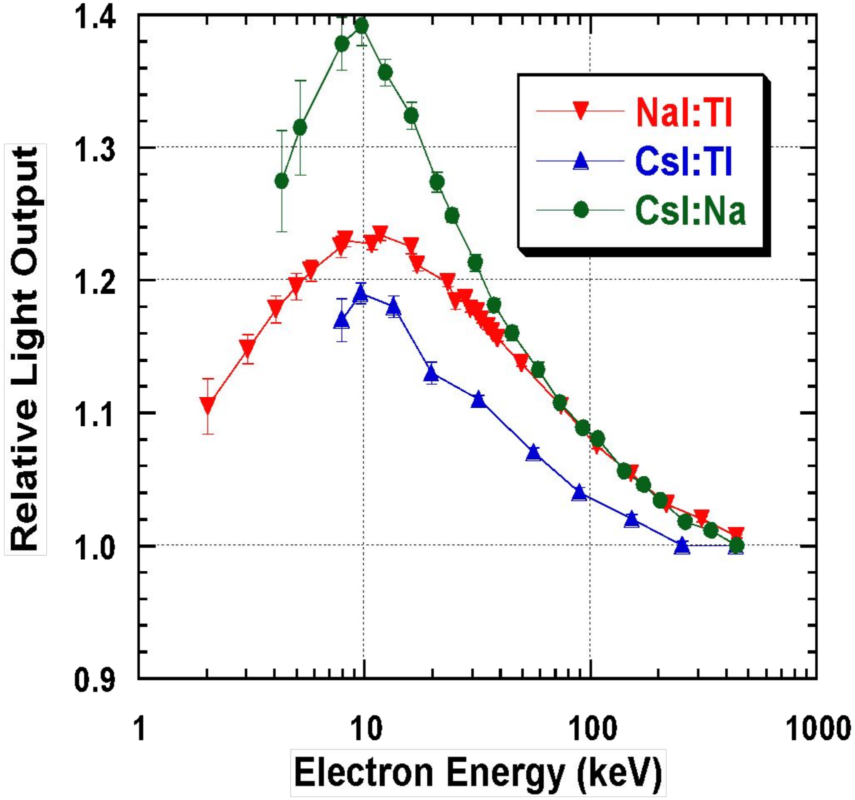


https://pubarchive.lbl.gov/islandora/object/ir%3A119312

- Solid line = **Poisson** limit
- **Why do nearly all scintillators has poorer energy resolution than predicted by Poisson counting statistics?**

Scintillator Non-proportionality

- Light output per keV depends on energy



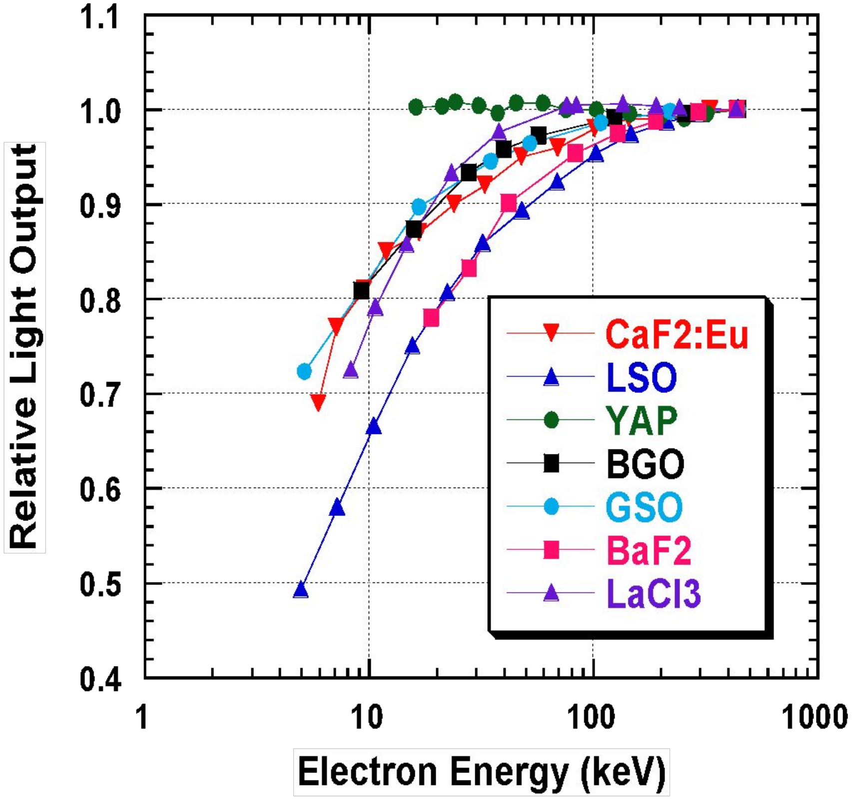
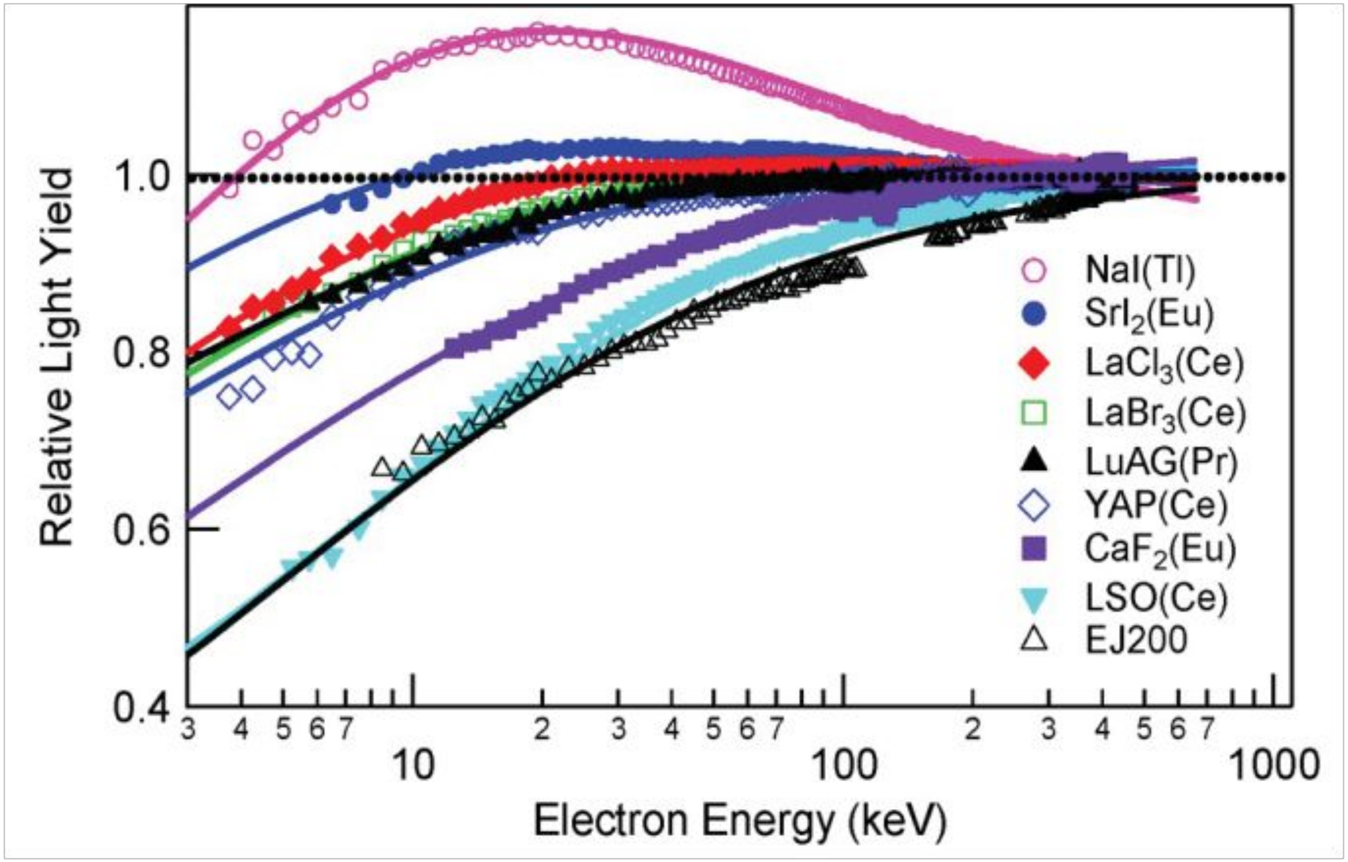


Figure 8.8 From W. Mengesha, T. Taulbee, B. Rooney and J. Valentine, "Light yield nonproportionality of CsI(Tl), CsI(Na), and YAP," *IEEE Trans Nucl Sci* 45, pp. 456-461, 1998.

Ideal (proportional) response →Horizontal line at 1.0

Scintillator Non-proportionality

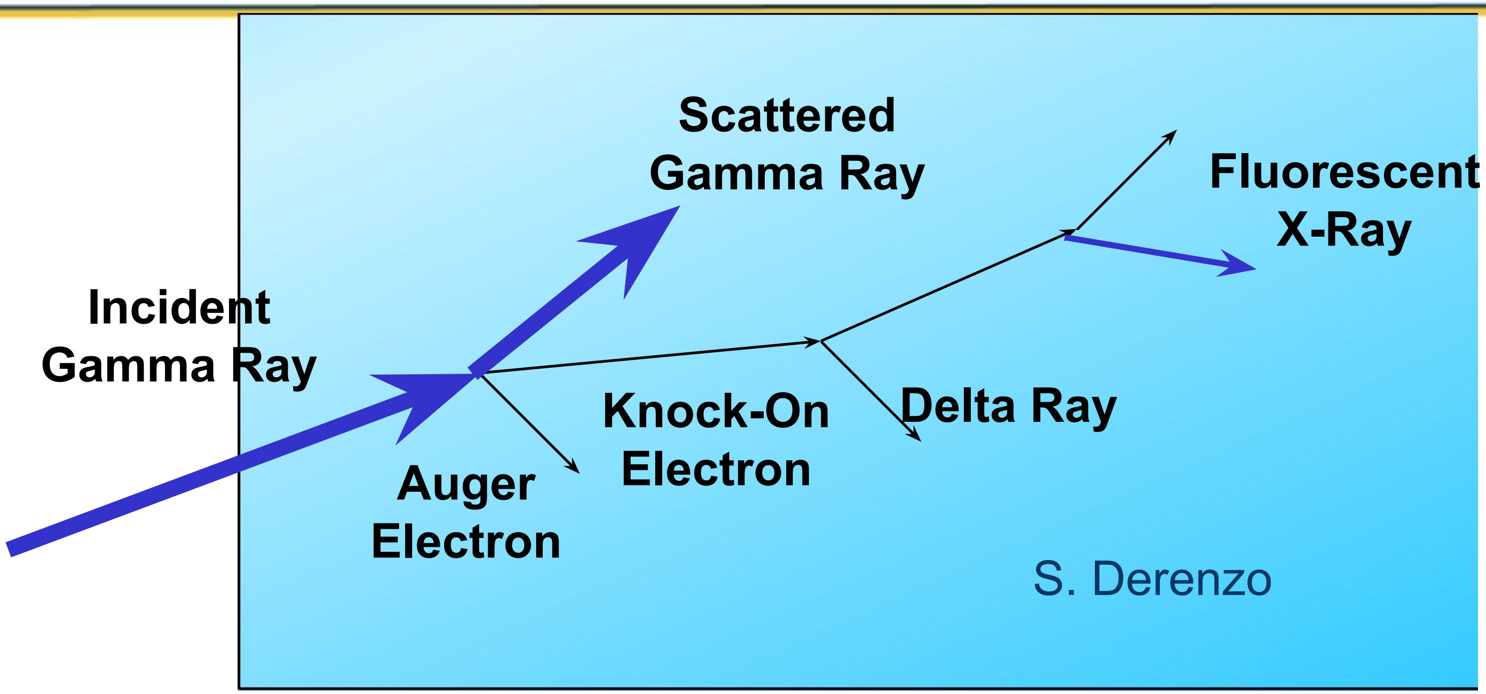
- Light output per keV depends on energy



Payne et. al. Nonproportionality of Scintillators: Theory and Experiment, IEEE 2011

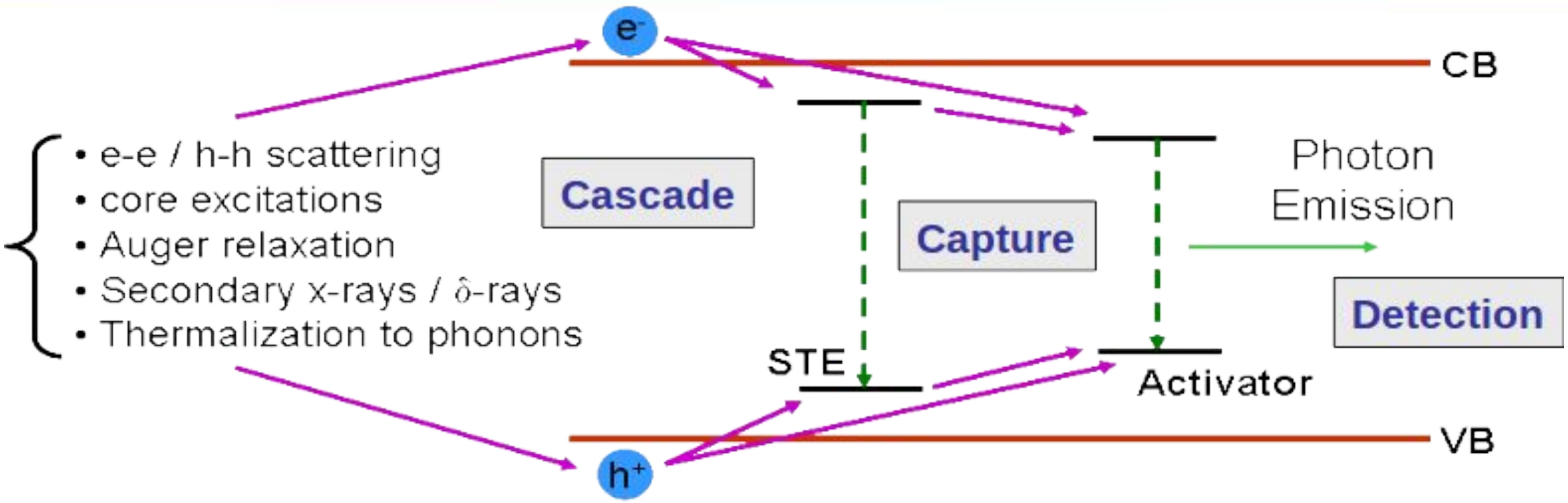
Ideal (proportional) response →Horizontal line at 1.0

Origin of Nonproportionality



- Scintillation efficiency depends on dE/dx
  - Competition between scintillation (radiative) & quenching (non-radiative) processes depends on ionization density
  - For a given amount of energy, variation in number and type of carriers →variation in dE/dx
- It is this *additional variance* that degrades energy resolution

Origin of Nonproportionality



Payne et. al. Nonproportionality of Scintillators: Theory and Experiment, IEEE 2011

Photoelectron efficiency η_{scint} product of cascade-capture-detection efficiencies:

$$\eta_{scint} = \eta_{CAS}\, \eta_{CAP}\, \eta_{C\text{-}DET}$$

Since uncorrelated, can add variances in quadrature:

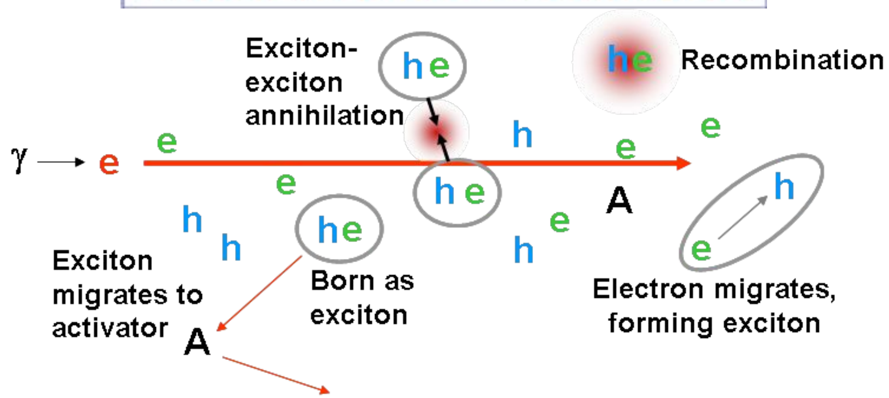
$$(d\eta_{scint}/\eta_{scint})^2 = (d\eta_{CAS}/\eta_{CAS})^2 + (d\eta_{CAP}/\eta_{CAP})^2 + (d\eta_{C\text{-}DET}/\eta_{C\text{-}DET})^2$$

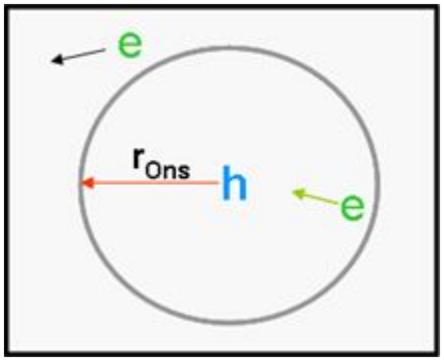
Carrier capture term, $(d\eta_{CAP}/\eta_{CAP})^2$, mainly responsible for nonproportionality

Nonproportionality Models

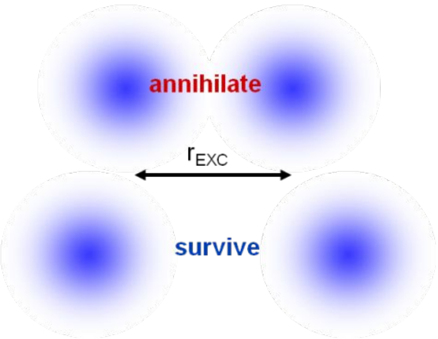
- **"Minimalist" model**
  - Only consider exciton transfer to lumin. Centers
  - Results in 2-param model
  - Ignores time dependence, radiative e/h recombination

Cascade and carrier transport





Onsager mechanism



Birks mechanism

$$L = \{ 1 - \eta_{e/h} \exp[- (dE/dx) / (dE/dx)_{ONS}]\} / \{ 1 + kB\ (dE/dx) \}$$

$\eta_{e/h}$ fraction of initial e and holes that do not form excitons	RISE Exciton formation Onsager Theory	FALL Exciton annihilation Birks Equation

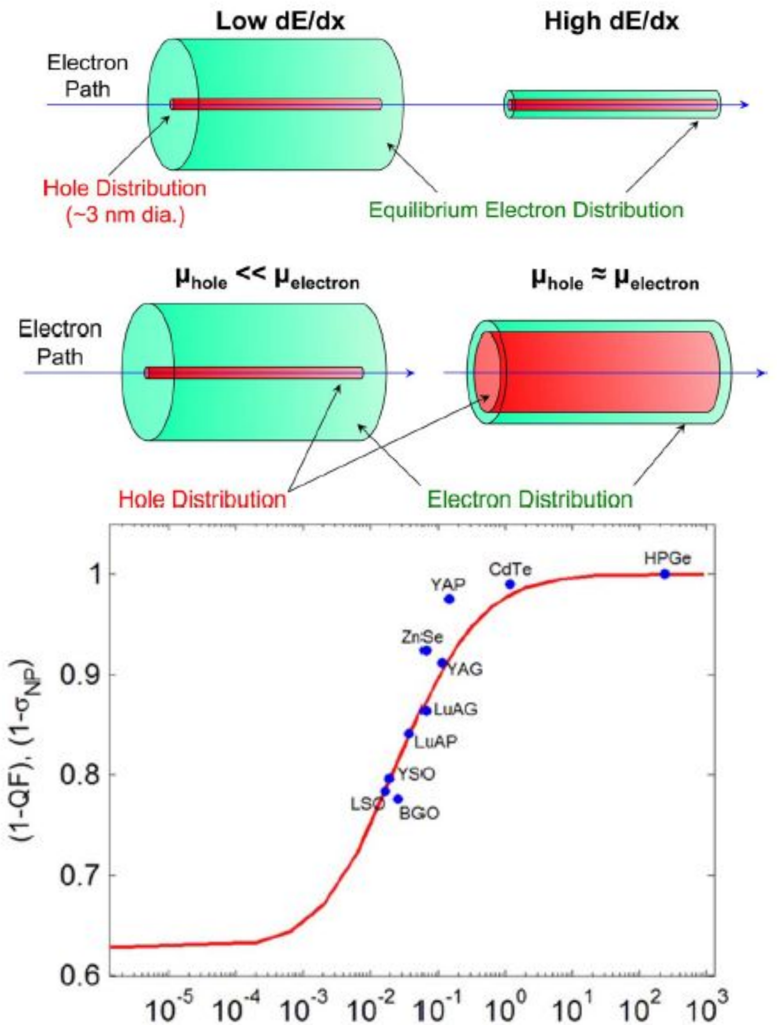
Two fit parameter: $\eta_{e/h}$ and kB

Nonproportionality Models

- **Kinetic model** $-d\rho/dt = (R_1 + K_1)\rho + (R_2 + K_2)\rho^2 + K_3\rho^3$
  - Model ionization density ρ as f(time) with multi-order terms
    - E.g. trapping →1st order process, 2-body Auger quenching →2nd order
  - At high ρ, highest order terms (i.e. quenching terms) dominate over radiative terms →**scintillation eff. Drops with higher ρ**
  - At low ρ, lowest-order terms dominate
    - Results in different behaviors depending on material
      - E.g. Exciton-mediated luminescense (LSO:Ce, LuAG) vs. e/h-mediated luminescense (NaI(Tl))
- Practical limitations of Kinetic model
  - High-parameter model
  - Difficult to extract general insight given dependence on specific luminescense mechanism

Nonproportionality Models

- **Diffusion Model**
  - Consider carrier motion from electrostatic forces/diffusion
    - O(ps) vs. O(ns) for quenching / scintillation
- Dependence on μ_e, μ_h
  - $\mu_h << \mu_e$
    - Recomb. & luminosity depend strongly on dE/dx
  - $\mu_h \sim \mu_e$
    - High recomb. & luminos.
      - High μ→less quenching→more proportional behav.



(1-QF): Calculated fraction of carriers that survive 10 ps in high-density ionization track

(1-σ_{NP}): Scint. Eff. (or collection efficiency for semicond.) at low e$^-$ energy

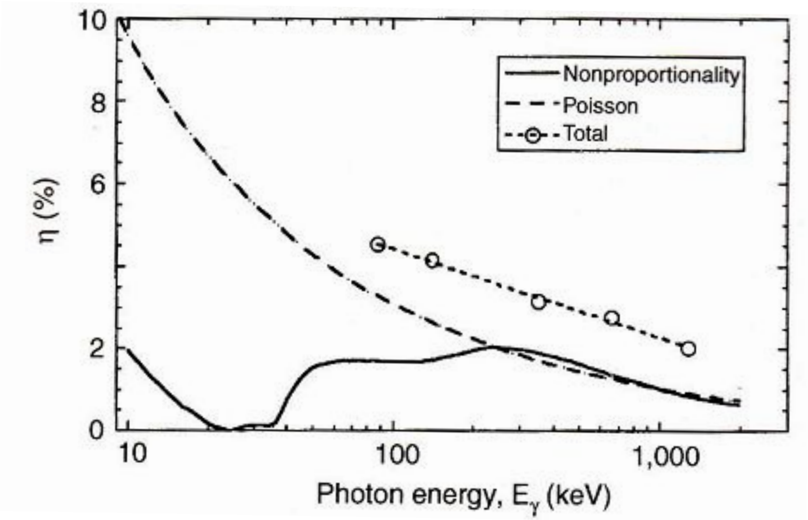
Diffusion coefficient → D_{eff} (cm^2/s)

The Origins of Scintillator Non-Proportionality

Effect of Nonproportionality on Resolution

- Magnitude of fluctuation (i.e. variance) due to nonproportionality effects on same order as counting statistics
- Deviation can be captured in Fano factor
  - High-energy electron cascade
    - Similar to semicond. Mechanism
    - Sub-Poisson ($F_{cascade}$ < 1)
  - Conversion to optical photons
    - Independent, “rare” event
    - Poisson process ($F_{opt.\ phot.}$ = 1)
  - Nonproportionality
    - Increased variance in # of scintil. Photons
    - Super-Poisson ($F_{nonprop.}$ > 1)
- From: [Photon Statistics in Scintillation Crystals]

Knoll Fig. 10.23



Measuring Scintillator Nonproportionality

Scintillation Light Yield Nonproportionality Characterization Instrument (SLYNCI)