Roger Rusack The University of Minnesota

SEEING THE LIGHT

Outline

In today's lecture I want to discuss why some materials scintillate and when they do how you detect that light.

Again I emphasize this is not an exhaustive discussion – more of an introduction to the main components we use in our detectors.

Sources

- Books:
  - "Techniques for Nuclear and Particle Physics Experiments" W. R. Leo.
  - "The Physics of Particle Detectors" D. Green
  - "Particle Detectors" C. Grupen and B. Schwartz.
  - "Inorganic Scintillators for Detector Systems" P. LeCoq et al.
- Publications:
  - Particle Date Book.
  - Various NIM articles.
- Talks
  - 'Detectors for Particle Physics' D. Bortoletto's CERN summer school 2015.
  - 'Experimental Techniques' T. S. Virdee, European School of HEP 1998.
  - "Introduction to Radiation Detectors and Electronics" Helmuth Spieler Lecture III. Scintillation Detectors

Many notes and comments and slides from friends and colleagues.

Some Definitions

Luminescence is light emitted by the excitation of the luminescent centers into response light source or due to electronic stimulation.

Scintillation light is the light that is emitted when ionizing radiation is the source of the energy. Scintillation is luminescence stimulated by ionizing radiation.

Phosphorescence is light emitted from long-lived luminescent sites after several time-constants of the primary emission. *Afterglow* is the amplitude of the signal.

Inorganic Scintillators

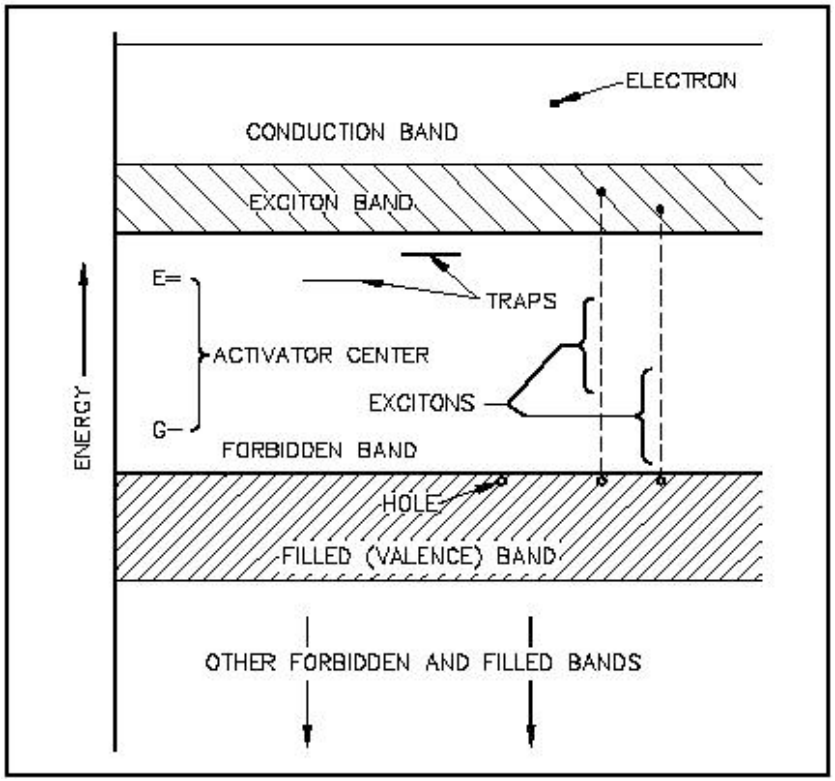
- Inorganic scintillators are generally used where high precision is required. Typical application are:
  - Medical imaging
  - Security – gamma detection.
  - Gamma Astrophysics.
  - HEP – Crystal Ball, L3,
- These are crystalline and fall generally into two categories: the oxides and the halides.
    - Sodium Iodide - NaI(Tl)
    - Cesium Iodide – CsI (Tl)
    - Barium Fluoride - BaF_2
    - LYSO ($Lu_{1.8}Y_{0.2}SiO_5(Ce)$)
    - $PbWO_4$
    - Bismuth Germinate – BGO - ($Bi_4Ge_3O_{12}$).
- Impurities like Thallium and Cerium are added intentionally to create activator sites with energy levels in the forbidden zone.

Luminescence

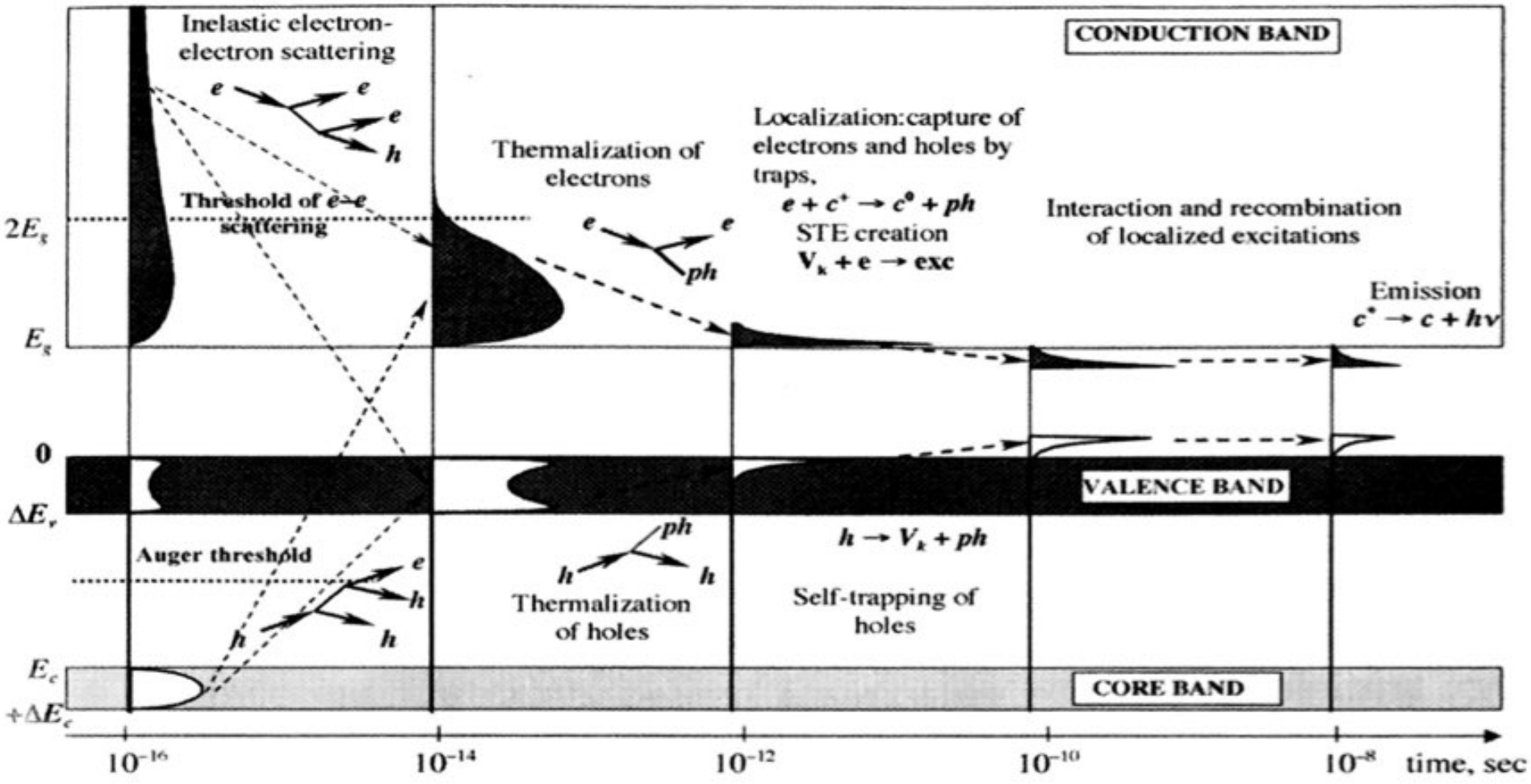
- Luminescence sources.
  - Impurities intentionally added during crystal growth to activate the scintillator.
    - Common activators are Thallium, Cerium and Presidium, introduce energy levels in the bandgap.
  - Defects
    - Vacancies in the lattice, interstitial and Frankel defects all have traps.
- Luminescent source activation:
  - e – h recombination,
    - Normally through a process of Auger converisons.
    - Sometimes Auger conversion is suppressed leading to electrn + deep hole recombination - BaF_2 fast UV signal.
  - Excitons migrating in the lattice transfer energy to an activation site.
  - Direct activation from ionization.

Scintillation Mechanisms

- Bandgap is usually in excess of 3 eV.
  - Conduction band is empty.
- When an ionizing particle promotes an electron from the valence to the conduction band, the electron is free to move within the crystal.
- The electron can form an exciton with the hole, which is also mobile.
- The electron can form an exciton with the hole, which is also mobile.
- It can transfer energy to an impurity site with an energy level in the forbidden zone.
- Light is emitted on de-xictaion to the ground state,



Simplified Model of Emission



From LeCoq et al.

Which Crystal?

- **Cost.**
- Density
  - Crystals are used for total absorption calorimetry ⇒ high density. X_o and the shower (Molière) radius should be short be small.
- Light yield
  - Want good conversion efficiency of the ionization energy to photons.
- Pulse duration:
  - Preferably short < 40 ns.
- Radiation hard:
  - Normally not an issue in e^+e^- machines, where the radiation levels are low.
  - Significant concern in hadron colliders.
- Wavelength of the emitted light.
  - PMTs are sensitive between 350 nm and 500 nm.
  - Silicon diodes, APDs and SiPMs can have a sensitivity in the red.
  - UV is difficult.
- Level of industrialization.

Some crystal types:

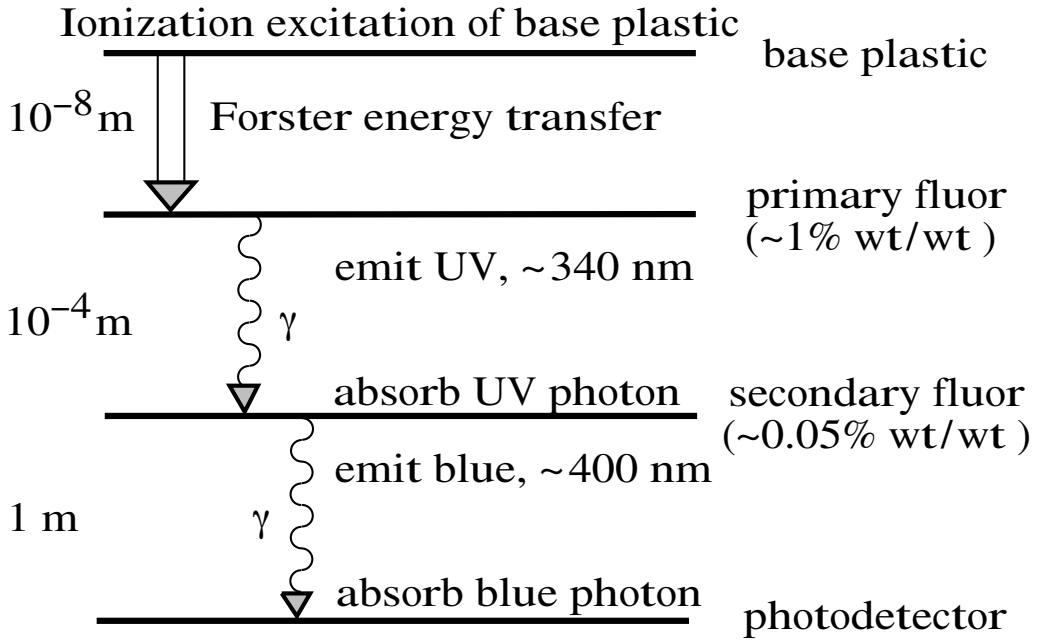
Scintillator Material	Density (gm/cm^3)	Radiation length (cm)	Wavelength Max emissions (nm)	Decay Time (ns)	Photons/MeV
NaI (Tl)	3.67	2.56	415	230	43,000
CsI(Tl)	4.51	2.43	560	630	38,500
BGO	7.13	1.12	505	300	8,200
$PbWO_4$	8.3	0.89	420	6	100
LYSO(Ce)	7.3	1.16	428	50	33,000
CsF	4.64	2.69	390	2-4	1,900
BaF_2	4.88	1.25	220/310	0.6/620	1,430/9,950

Organic Scintillators

While inorganic scintillators scintillate due to the band structure of the material, inorganic scintillators emit light due to luminescence at the molecular level.

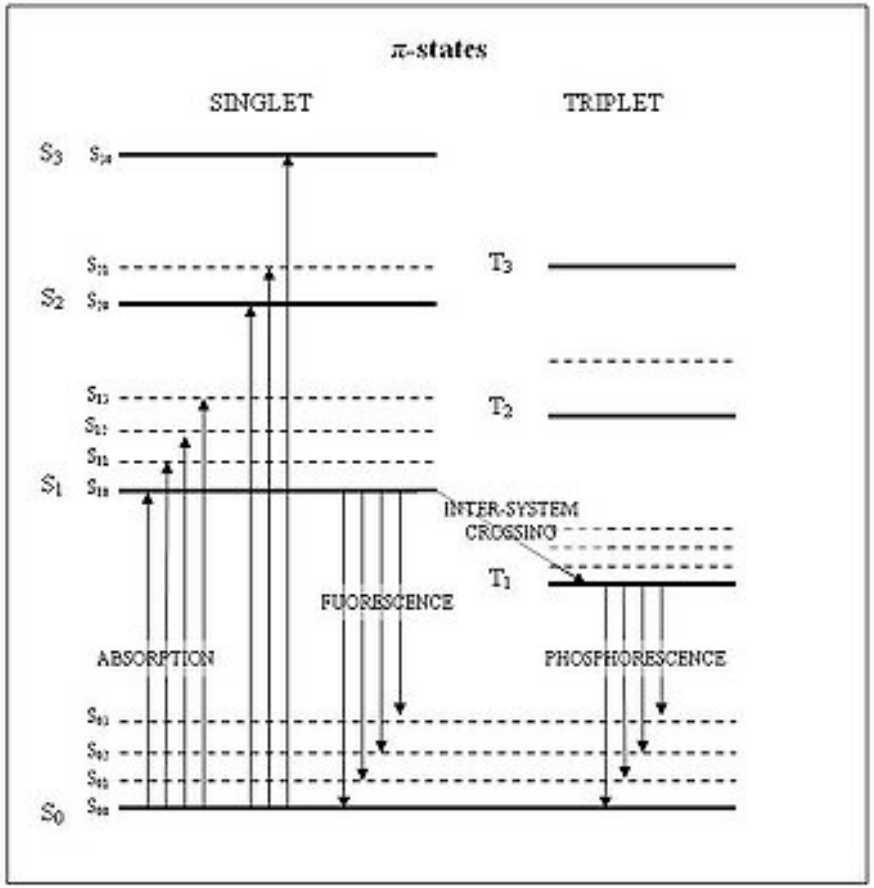
Organic scintillators have a base material – plastic for solids, mineral oil, toluene or PAB for liquids.

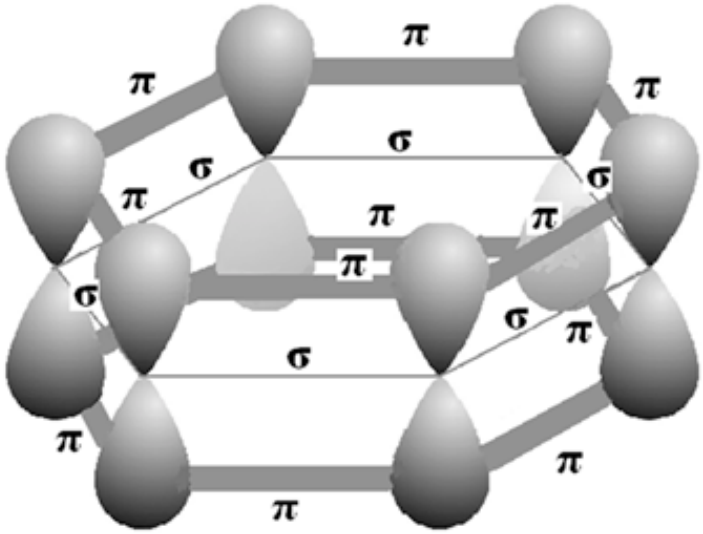
In a plastic scintillator, the plastic is energized by the ionizing radiation and the energy is transferred to fluors in a one or two step process convert the energy to optical wavelengths.



Plastic Scintillators

The source of light in organic scintillators is benzene molecules in toluene of styrene – Poly-vinyl-toluene PVT or polystyrene being the predominant options.





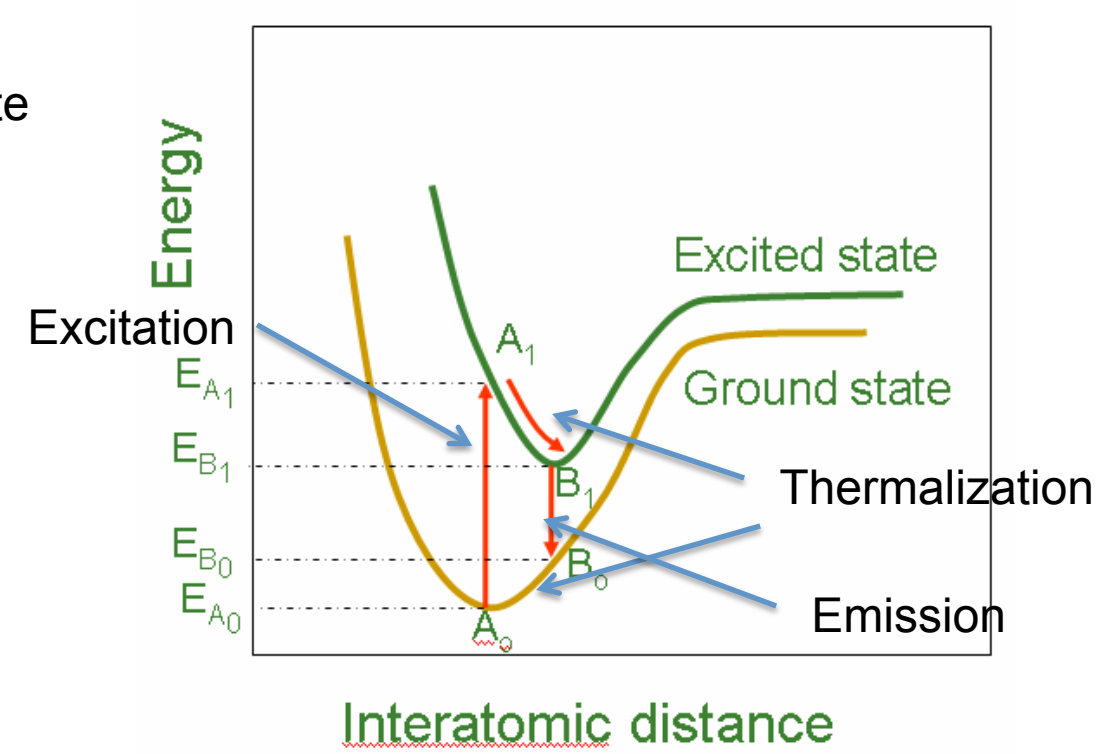
The π-electrons have singlet and triplet states. The decay of the S1 to S0 states are the primary source of scintillation in plastic scintillators. τ ~nsec.

Transfer from S1 to T1 states leads to phosphoresce τ ~msec

Plastic Scintillators

The energy absorbed to promote the molecule from the ground state is generally more than the photon's energy.

Stoke's Shift- The scintillation light is shifted from the absorption energy.



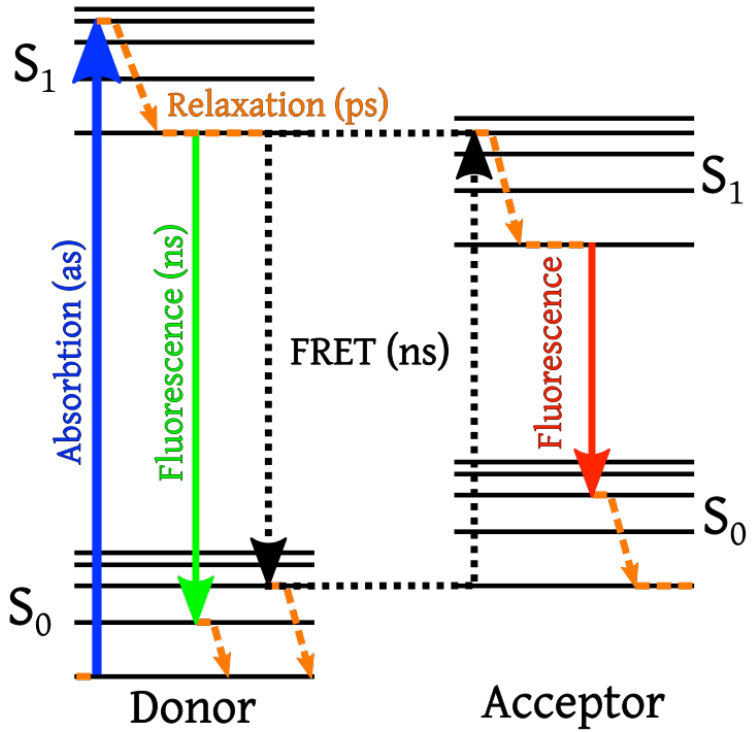
Plastic Scintillators

Practical scintillators generally have a matrix (solvent) that contains a benzene ring – styrene or toluene in PS or PVT plastic.

As the peak wavelength of emission of toluene and styrene is in the UV, secondary fluors are added with high concentration to the mix.

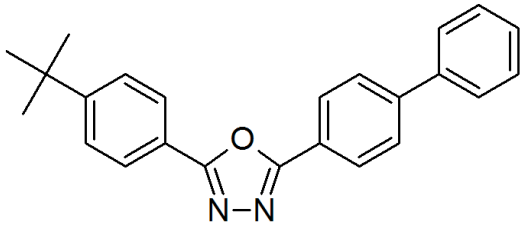
At high concentration the excitation energy is transferred to the fluor by a dipole-dipole interactions, known as a Förster Resonance Energy Transfer.

The optical efficiency is typically about 3% in a good scintillator, giving about 10,000 photons per MeV.



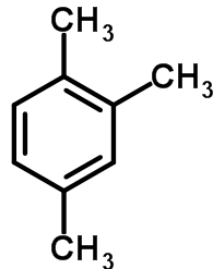
Liquid Scintillators

Liquid scintillators where toluene has been the solvent have been used in the past. In several large experiments mineral oil was used with the scintillator dissolved in it.



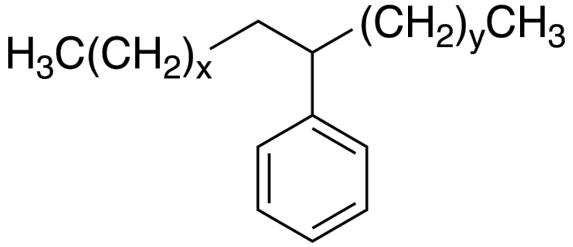
Butyl-PBD

In the 14 kton NOvA detector pseudocumene (trimethyl-benzene) is dissolved in mineral oil.



Trimethyl-benzene

More recently linear alkylbenzene (LAB) is used as a solvent this has the nice properies of being a bright scintillator and not attacking acrylic plastics.



Linear alphabenzene

Noble Gas/Liquid Scintillators

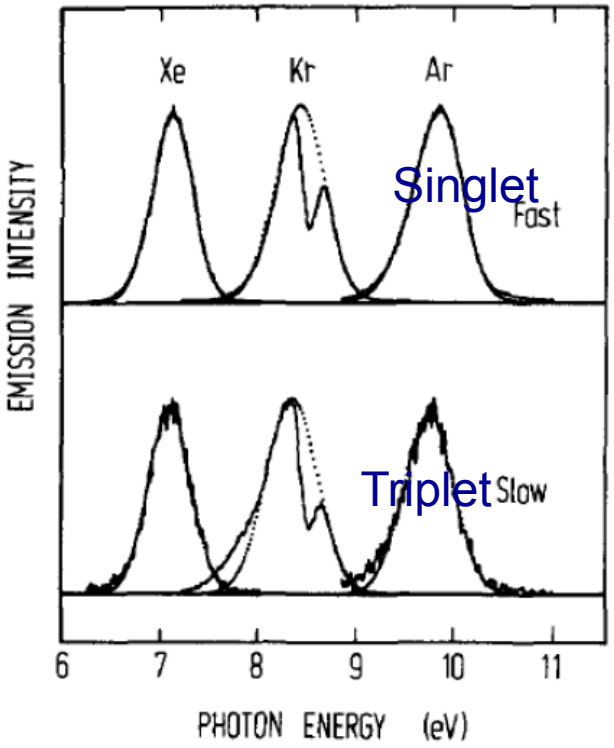
J Chem Phys vol 91 (1989)
1469 E Morikawa et al

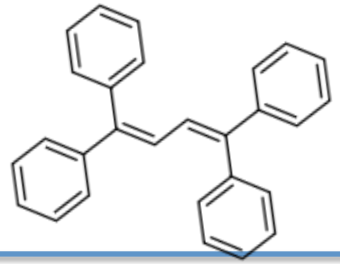
Argon Xenon and Krypton emit scintillation light in the far UV.

The physical process is the formation of excimers ($Ar^{+}Ar$) that de-exicite emitting a photon with a time constant of ~ 6 ns.

For liquid argon the peak wavelength is 128 nm. A wavelength shifter is required to shift to the optical region.

The fluorescent chemical Tetraphenyl Butadiene (TPB) is used in MicroBooNE and under discussion for DUNE





Radiation Damage

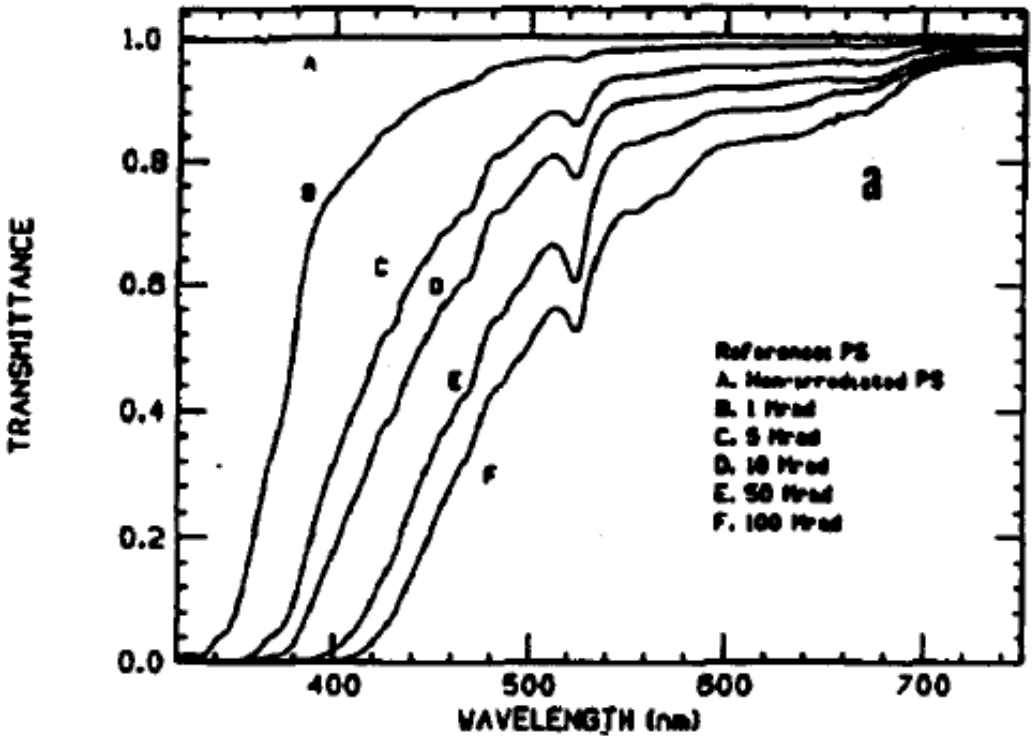
- Sources:
  - Color center creation – Scattering or absorption in light's pathway.
  - Intrinsic Damage.
- Inorganic Scintillators,
  - In crystals the main source of damage is the creation of color centers that absorb the scintillation light and lead to a reduction in light received.
  - NaI and CsI crystals are damaged after ~10 Gy.
  - BGO and $PbWO_4$ are intrinsic scintillators more radiation tolerant ~ 1 MGy of gamma and 10 kGy.
  - In $PbWO_4$ there are two effects:
    - Metastable states created by photons, with a lifetime of hours to weeks.
    - Long-lived states created by hadron interactions.

Radiation Damage in Plastics

Radiation damage in plastics is mostly the creation of color centers that absorb light at short wavelength.

Typically effects can be seen after total integrated doses of 2 -3 kGy in PS scintillators.

The damage depends on the atmosphere, with oxygen being bad for damage, but good for recovery,



C. Zorn *Rad Phys. Chem* 1993. 37.

Radiation Damage in Plastics

The degree of damage in scintillators depends also on the of the radiation dose. This ‘well-known’ effects was first reported by Wigmans and Sirois in 1988 and continues to be rediscovered about once very ten years.

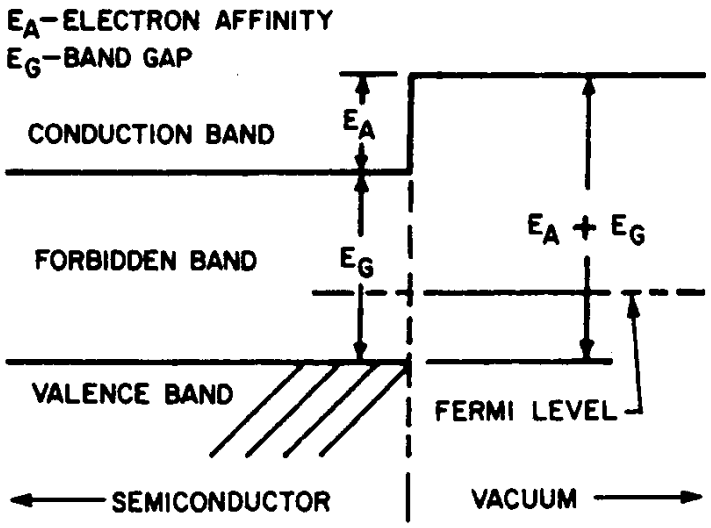
The explanation for this is generally assumed to be oxygen migration into the scintillator adding to the effect. The chemistry of this is not clear.

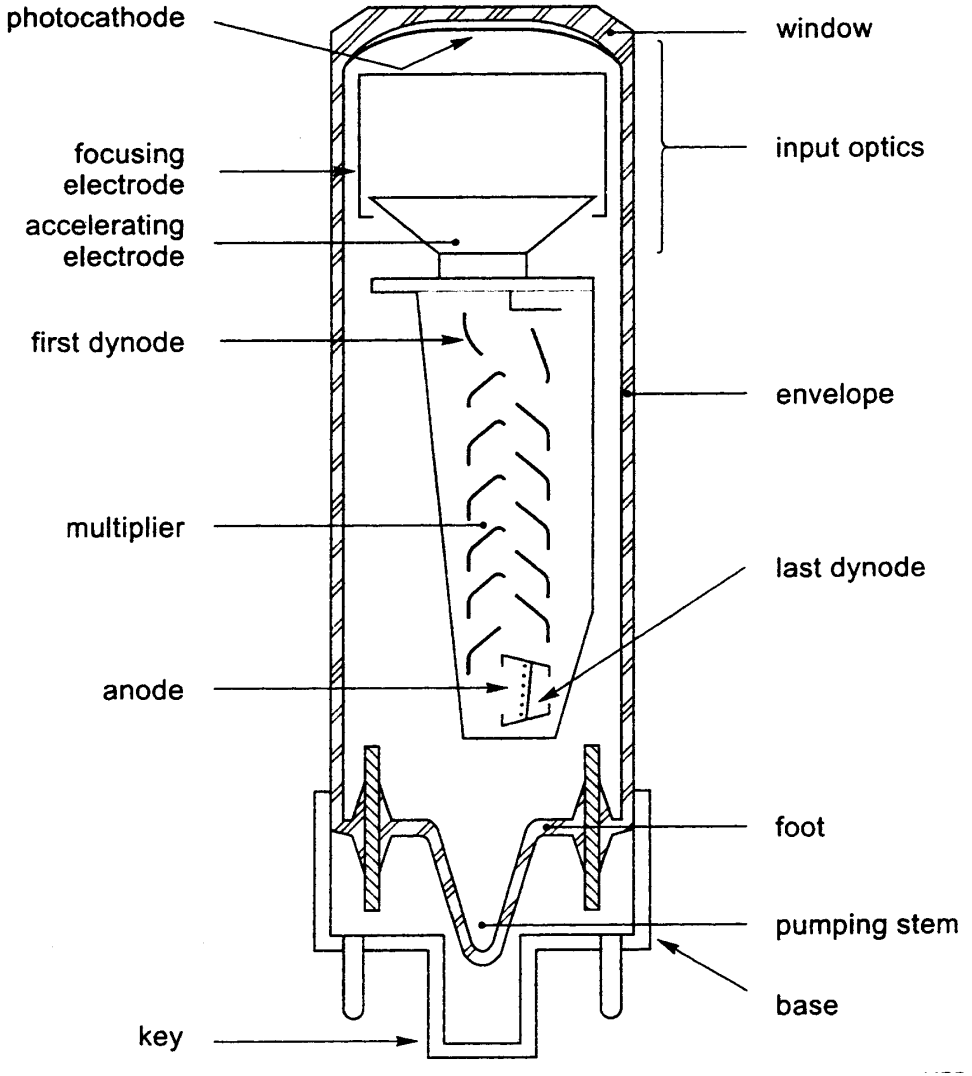
Organic or Inorganic?

- Inorganic Scintillators
  - Advantages
    - High light yield – 40,000 photons/MeV
    - High Density and short X_O – LYSO (1.1 cm) $PBWO_4$ (.89 cm)
    - Linearity of response.
  - Distadvantages:
    - Costs – expensive raw materials, growth in high temperature furnaces ⇒ complex and expensive manufacturing.
    - Temperature dependence.
    - Relatively slow light output – 40 – 50 nsec.
- Organics
  - Advantages:
    - Low Cost - Relatively easy to manufacture and shape.
    - Fast signals - ~3 – 5 nsec.
  - Disadvantage:
    - Low light yield.
    - Low density.

Detection of Light

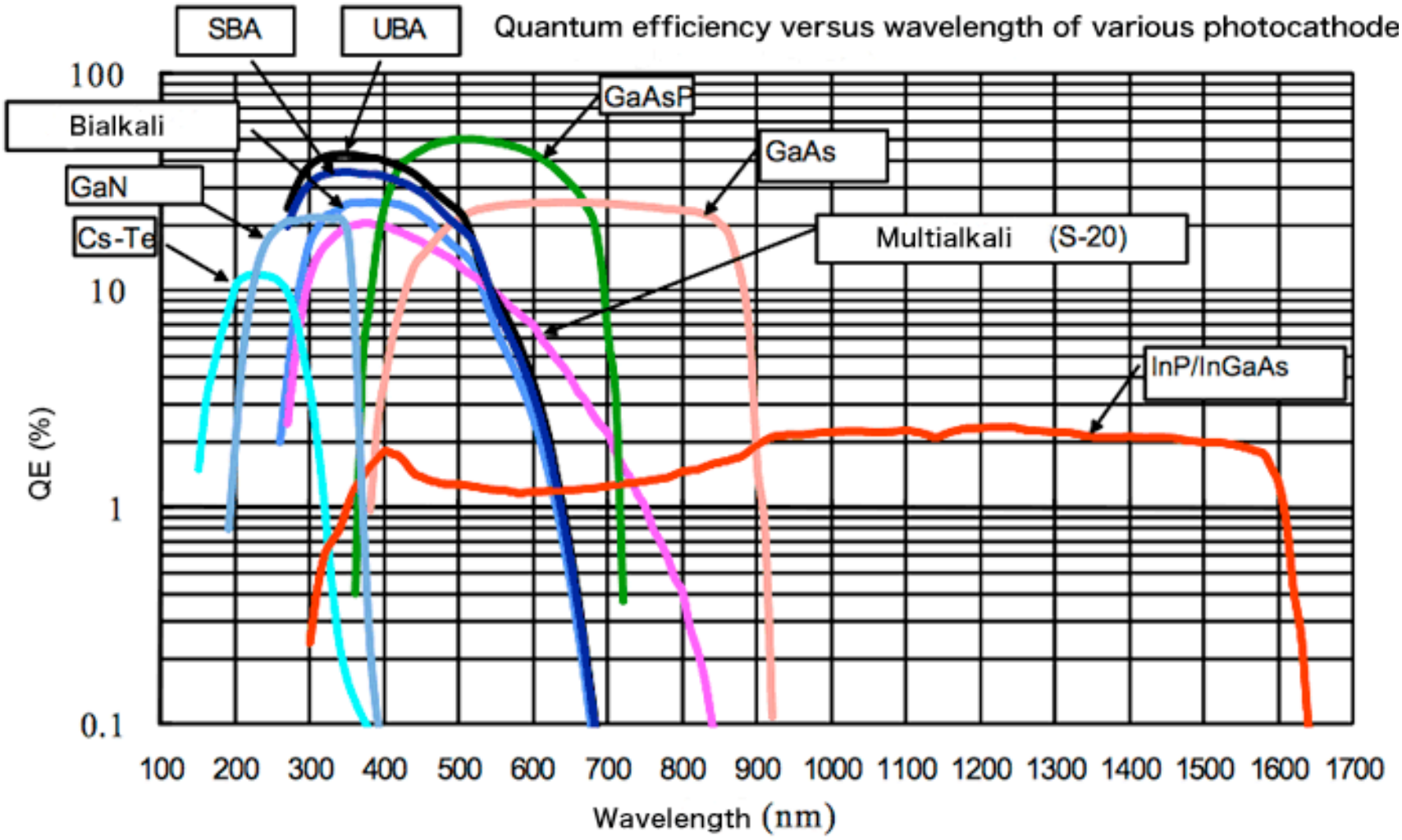
Photomultipliers have been the main choice for many applications.





Burle Handbook

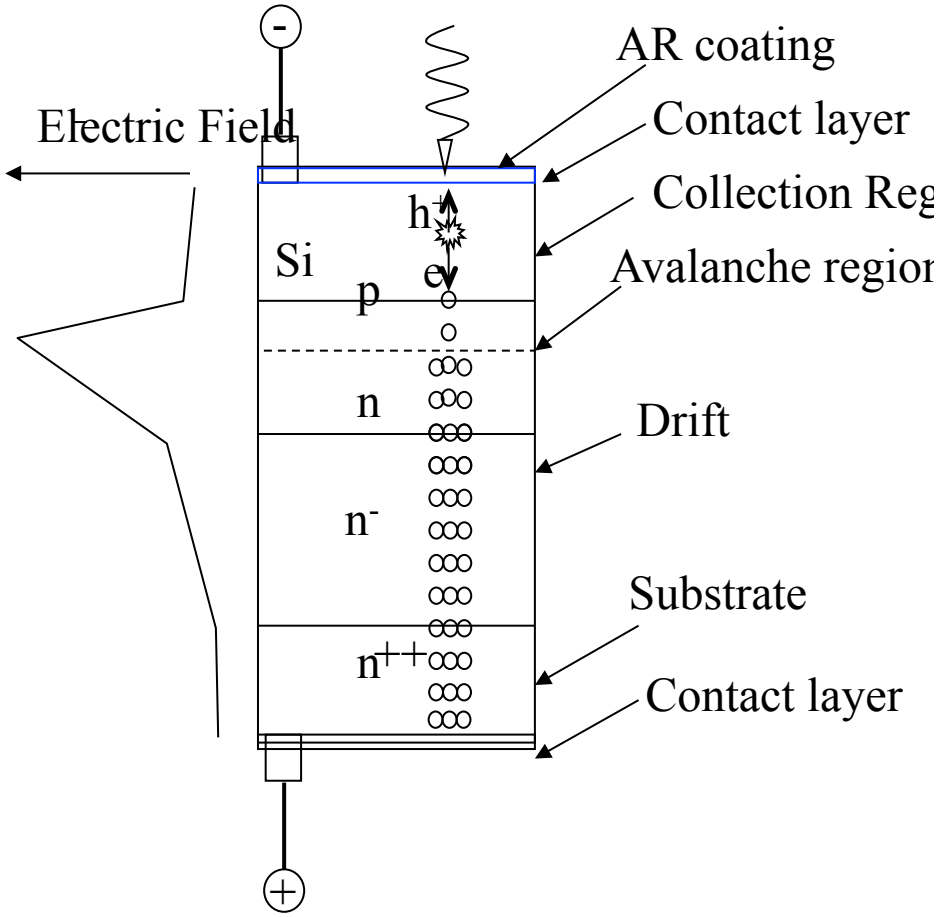
Quantum efficiency



Hamamatsu catalog

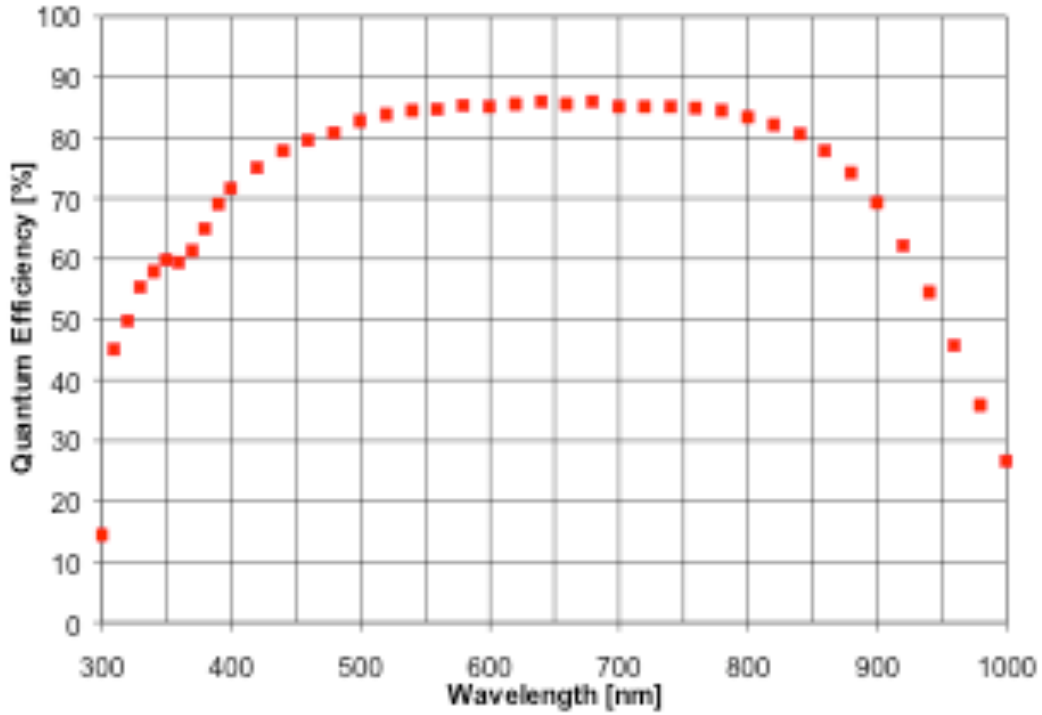
Semiconductors

- Silicon Diodes:
  - Unit gain, large area and low-cost.
  - Used in L3 and CLEO to readout BGO and CsI crystals.
- Avalanche photodiodes:
  - Silicon diodes with internal gain.
  - Internal gain is due to high E-field at the p-n junction that causes impact ionization.
- SiPMs (MPPC)
  - Array of APD pixels operated in Geiger mode.



Quantum Efficiency

QE of silicon diodes extends out to 1 μm and can be ~ 80%

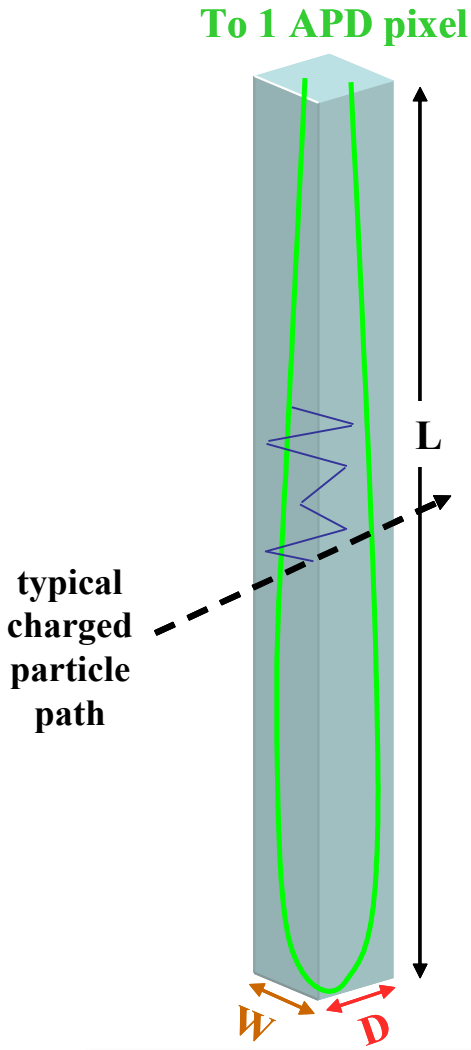


The range of the detection efficiency is limited by the the surface treatment (blue light) and the junction depth (red light).

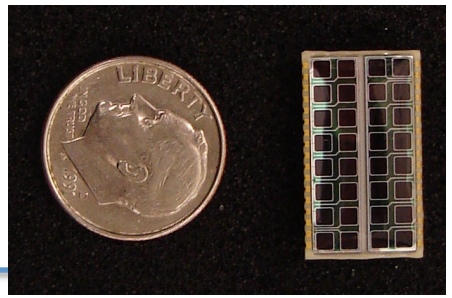
In SiPMs there is an additional geometrical effect that limits the detection efficiency.

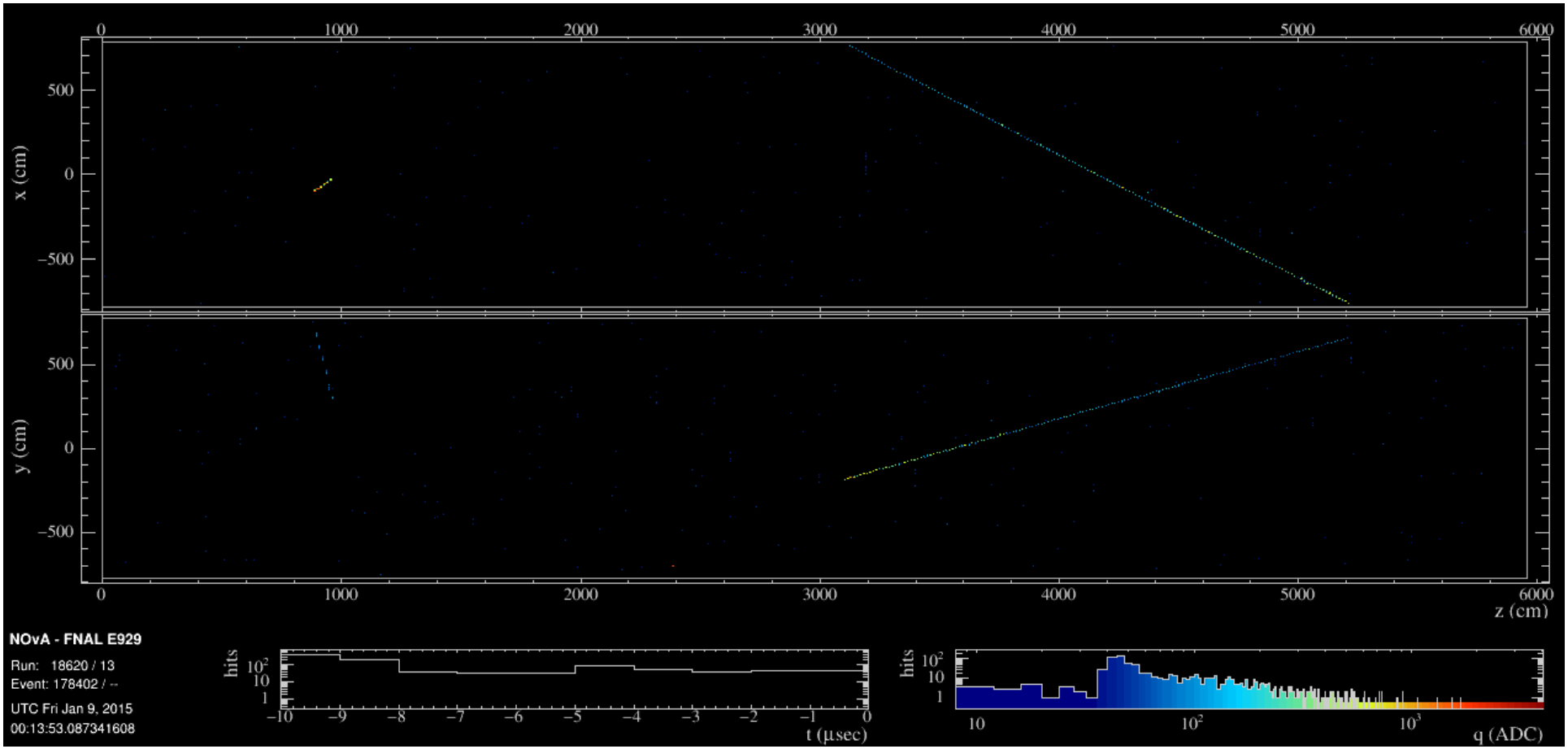
NOvA Design Choices:

- Needed a large mass –
  - Lowest cost medium ⇒ liqud scintillator.
- Simple containment system.
  - Start with material to make docks from Home Depot.
  - Add TiO_2 to improve light collection.
- Light collection in large detector:
  - Looped fiber inside PVC tube.
- Light detection:
  - Use APD structure from CMS adapted for fiber readout with gain 100.
  - 5 photons minimum signal.
- Readout:
  - Very low-noise amplifier designed specifically for low-rate event detection.



- Liquid Scintillator
  - 5.5% pseudocumene as scintillant
  - Mineral oil and waveshifters (PPO, bis-MSB)
- PVC cell for primary containment
  - Horizontals:3.87 cm x 6.0 cm x 15.7 m long
  - Verticals: 3.76 cm x 5.7 cm x 15.7 m long
  - Highly reflective, 15% titanium dioxide
  - Diffuse reflection keeps light local to track along the cell length to ± 25 cm
    - ~ cosine (angle to normal to wall)
- Looped wavelength shifting fiber to collect light
  - 0.8 mm diameter, double clad, K27 waveshifter
  - Almost perfect mirror, 3.6*light in 1 fiber
- Avalanche Photodiode
  - 85% quantum efficiency
  - Gain of 100, operate at -15°C
- Low noise amplifier

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