AN OVERVIEW OF SCINTILLATORS AND THEIR APPLICATIONS IN HIGH ENERGY PHYSICS

By Blake D. Leverington

OUTLINE

- Introduction

- Inorganic Scintillators
  - Excitons and Activators
  - Stokes Shift and the Franck-Condon Principle
- Organic Scintillators
  - The Foerster Resonant Energy Transfer (FRET) Mechanism

- The LHCb Scintillating Fibre Tracker

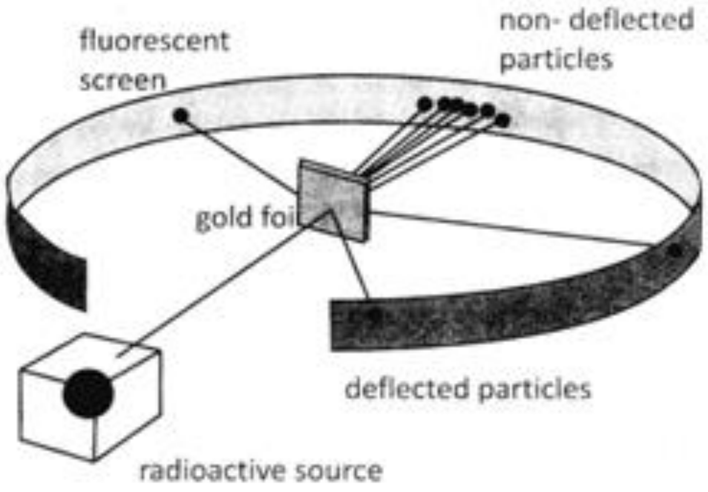
“Scintillation is a luminescence induced by ionizing radiation in transparent dielectric media.”

Taken from:

Inorganic Scintillators for Detector Systems
Physical Principles and Crystal Engineering
Second Edition
Paul Lecoq • Alexander Gektin • Mikhail Korzhik

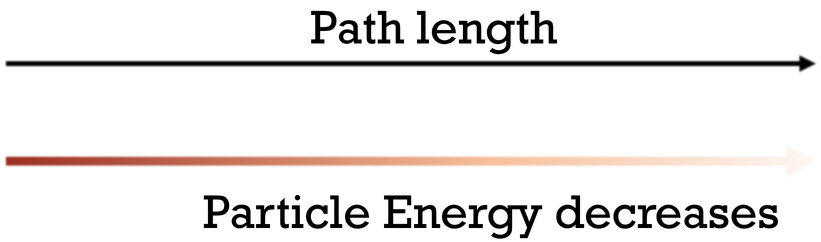
- Detectors for radioactive particles
  - *The modern era of particle physics began with Rutherford using Zinc Sulfide to observe alpha particles in 1899.*

Ernest Rutherford
(1871-1937)



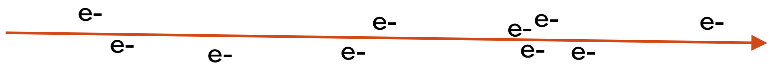
IONIZATION PROCESS IN MATERIALS

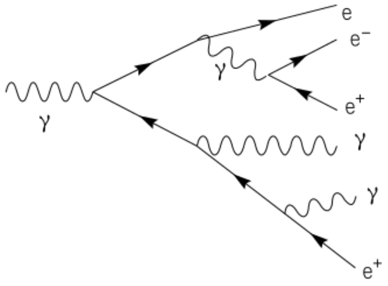
- Neutrons and hadrons
  - Nuclear interactions (pi0 showers, beta or gammas, knock-on electrons)
  - Ionization of atoms (stripped electrons)
- Electrons and photons
  - Bremsstrahlung, pair production (high E) → electromagnetic shower
  - photo-absorption (low to med E)
  - Compton scattering dominates below 1 MeV
- Lots of "hot" electrons produced
  - Convert this to a signal!



Path length

Particle Energy decreases





TYPES OF SCINTILLATOR

- **Inorganic Scintillators**

  - Crystals (hundreds, such as $PbW0_4$)

  - High Z atoms
  - High density (3-8 g/cm^3)
    - Good for compact calorimeters
  - High light yield (10-100 kph/MeV)
    - Good resolution for calorimetry
  - Slower ns – us decay times
    - Can be bad for timing resolution
    - afterglow
  - Expensive (production)
  - Hygroscopic (will reduce light yield)
  - Temp dependent Light yield (%/degree)

- **Organic Scintillators**

  - Crystals (anthracen, naphthalene, stilbene, etc)
  - Liquids (in organic solvents, benzene ring needed)
  - Plastic (organic fluors in a base polymer)

  - Lower Z / density (1-2 g/cm^3)
  - Lower light yield (1-10 kph/MeV)
  - Fast ns decay times
    - Good timing resolution

  - Cheaper
  - Shapeable/machinable
  - Independent of temperature (-60 -- +20)

- Gases (nitrogen + noble gases)
- Glasses (boron silicates)

INORGANIC CRYSTALS

- In the case of ordered materials like crystals, <keV electrons begin to couple with the lattice

Mobility of electrons

- Some electrons are ionized and free(E>Eion)
- Some electrons are excited from the valence band to the **conductance band** (or just above and relax) (E>~Eg)
- Some loosely bind with a hole and **form an exciton** (E<~Eg)

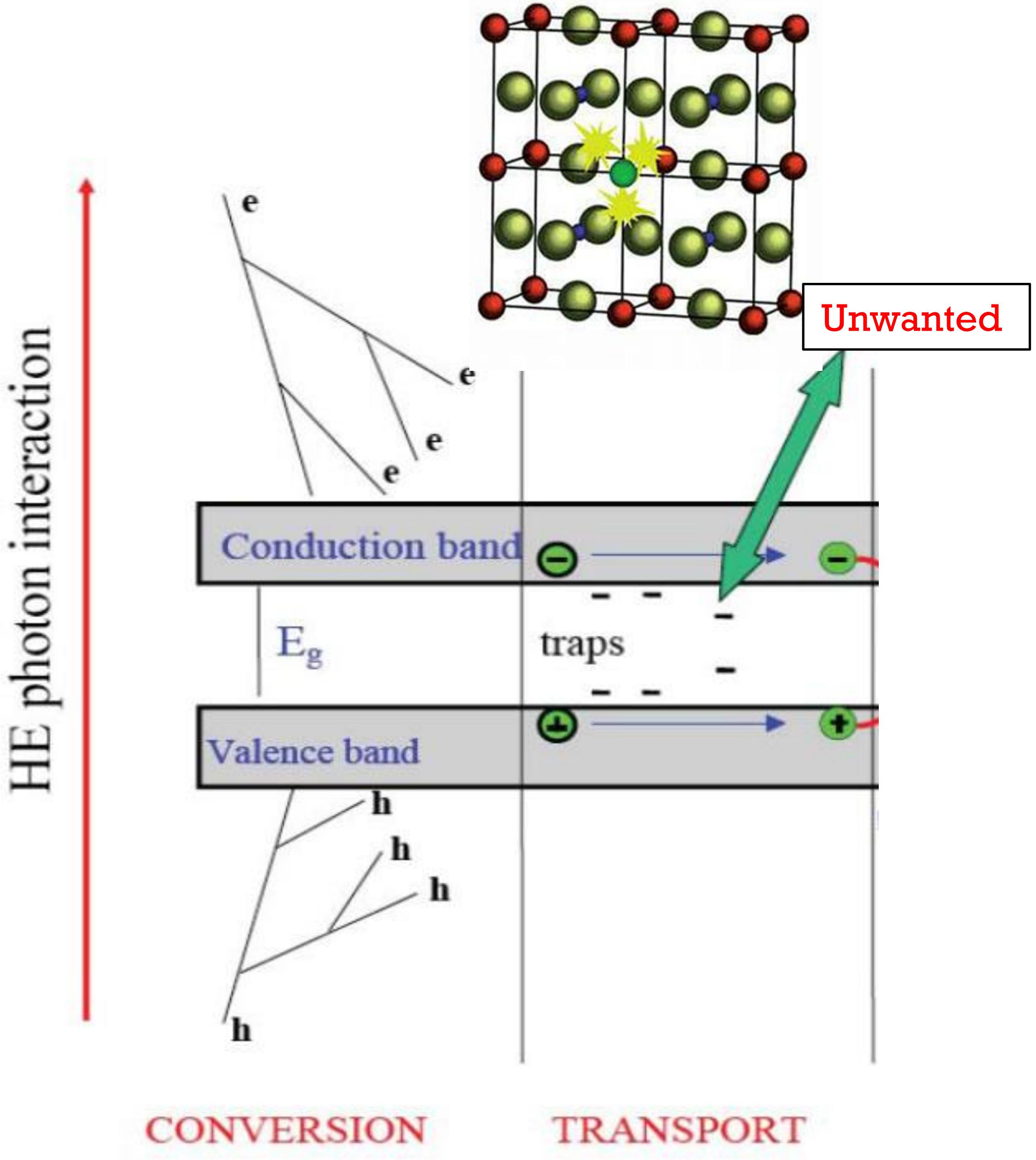
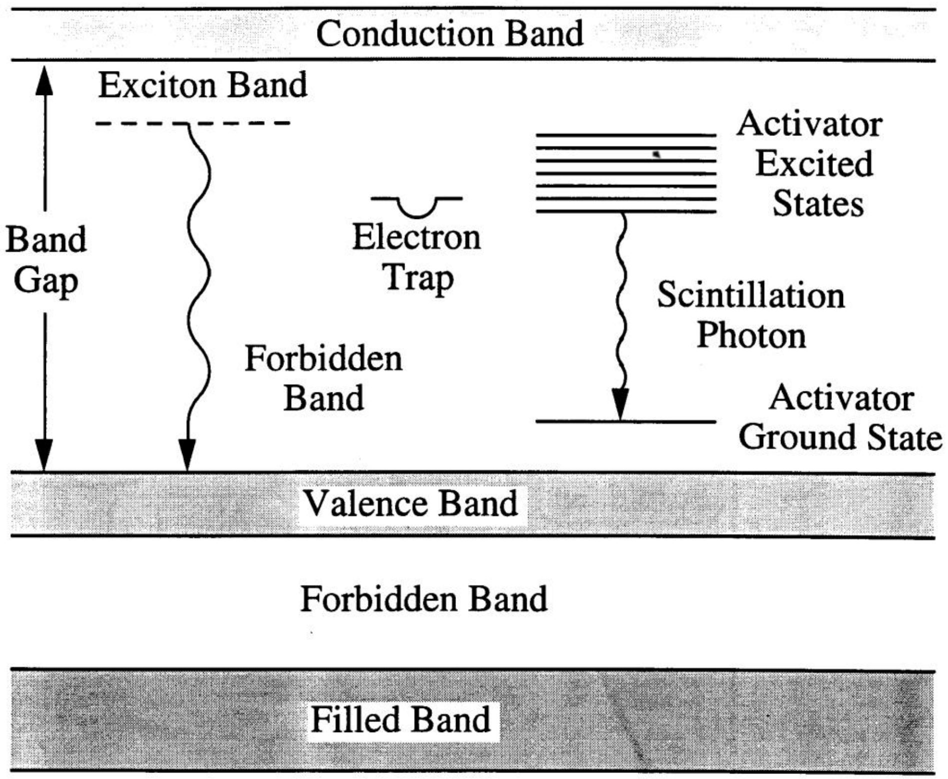


Image from https://crystalclear.web.cern.ch/crystalclear/scintmechanisms.html

INORGANIC SCINTILLATOR

- The crystal must contain luminescent centers to be a scintillator
  - Intrinsic
  - Extrinsic
- Beware of traps (defects) – reduces conversion efficiency, delays emission
- Once the electrons or energy can travel, high probability of absorption by a luminescent center
  - **Relaxes to its ground state -> photon emission**



S.E. Derenzo, *Scintillation Counters, Photodetectors and Radiation Spectroscopy*, IEEE Short Course *Radiation Detection and Measurement*, 1997 Nuclear Science Symp.

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    - Internal defects allow for exciton recombination (eg. BGO)
  - Extrinsic
    - Defects and Impurities
    - **Doped with ions (activator)**
    - Combination of activator ions and with impurities

Many paths to luminescence

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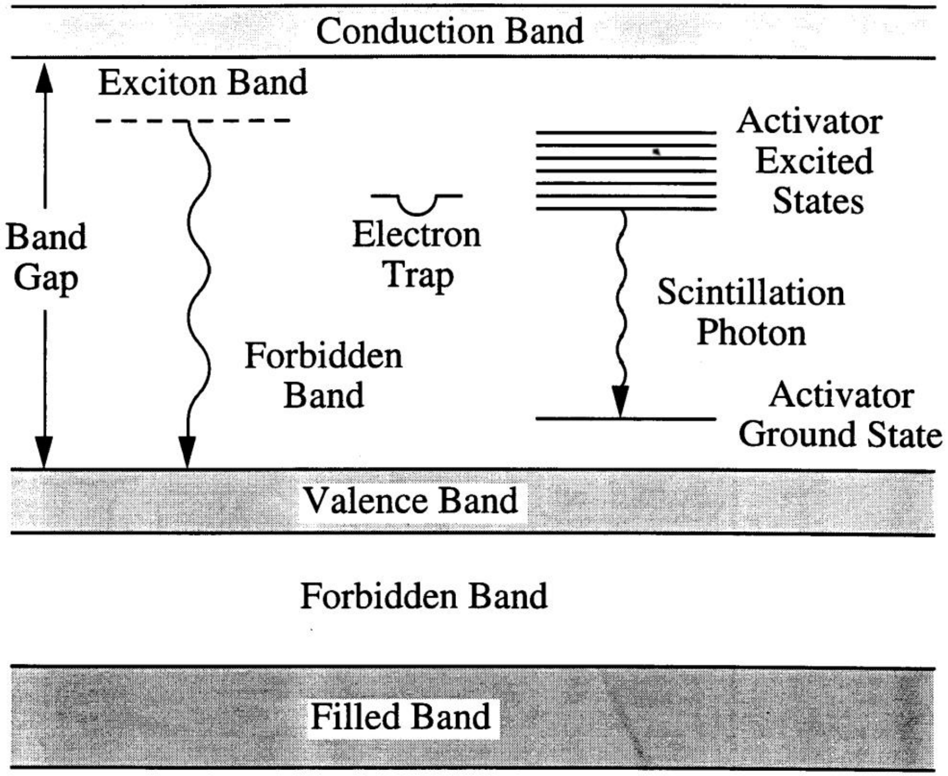

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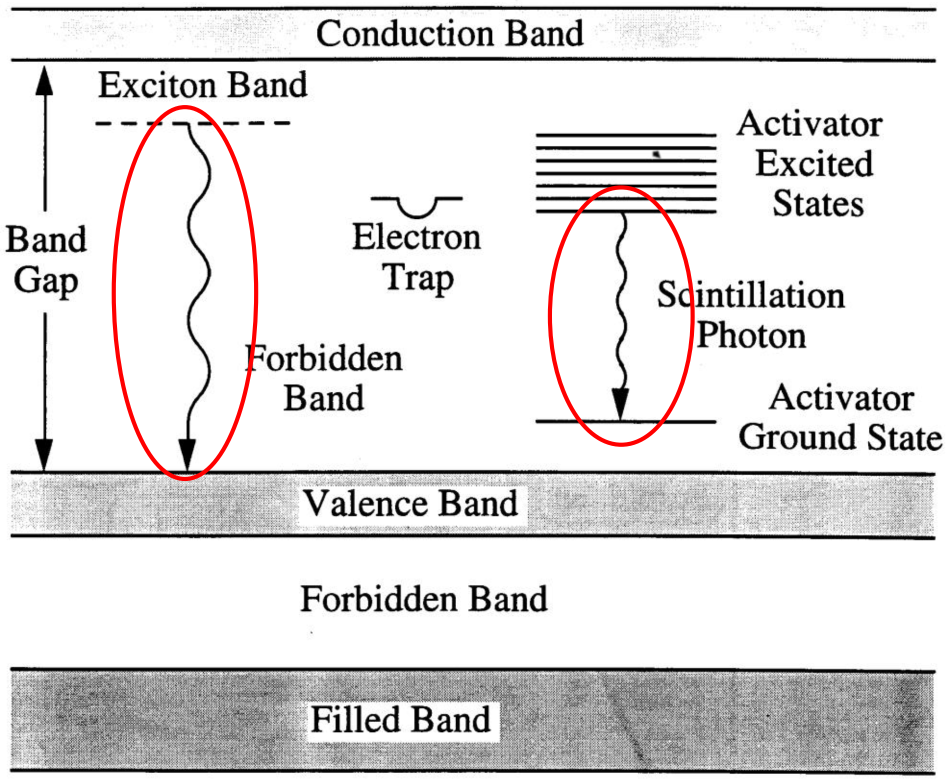
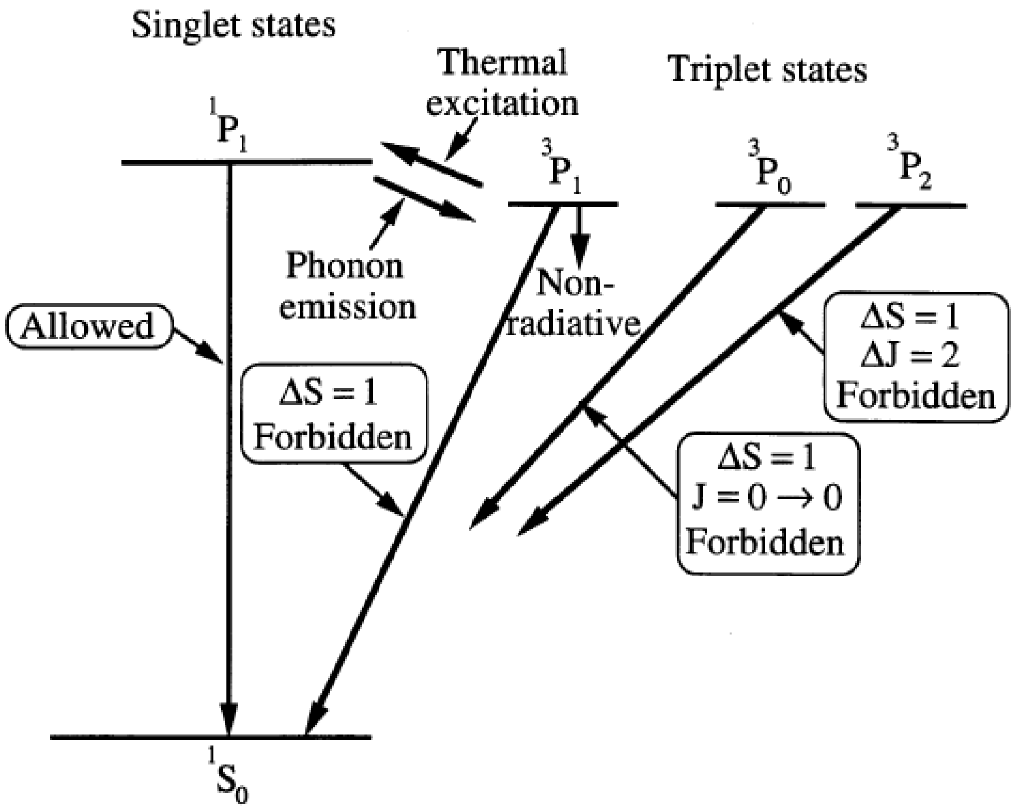
An **exciton** is a loosely bound (0.01 eV) e-h pair that can move within the crystal; integer spin



S.E. Derenzo, *Scintillation Counters, Photodetectors and Radiation Spectroscopy*, IEEE Short Course *Radiation Detection and Measurement*, 1997 Nuclear Science Symp.

LUMINESCENCE

- Time to excited state is very fast
  - (femtoseconds)
- Radiative emission from Singlet states
  - Fluorescence
  - Fast (nanoseconds)
- Radiative emission from Triplet states
  - Phosphorescence
  - Slow (microseconds)
- Quenching will compete with these processes
  - Relaxation to ground state through vibrational modes



EXAMPLE SCINTILLATOR

$$\boxed{LY\left(\frac{ph}{MeV}\right) = N_{e-h}SQ = \left(\frac{10^6}{\beta E_g}\right)SQ}$$

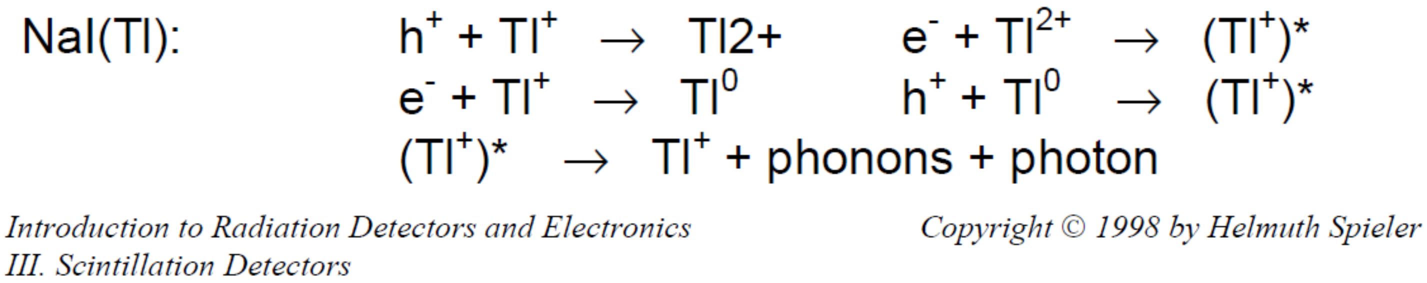
$N_{e-h} = number\ of\ e-h\ pairs$

$E_g = band\ gap\ energy$

$\beta = ionisation\ energy\ conversion\ eff.$
(typically ~ 2-7)

$S = carrier\ transfer\ efficiency$
(least well known: material, temperature, impurity dependent)

$Q = q.e.of\ luminescent\ center$



NaI(Tl): $h^+ + Tl^+ \rightarrow$ Tl2+ $\qquad e^- + Tl^{2+} \rightarrow (Tl^+)^*$

$e^- + Tl^+ \rightarrow Tl^0 \qquad h^+ + Tl^0 \rightarrow (Tl^+)^*$

$(Tl^+)^* \rightarrow Tl^+$ + phonons + photon

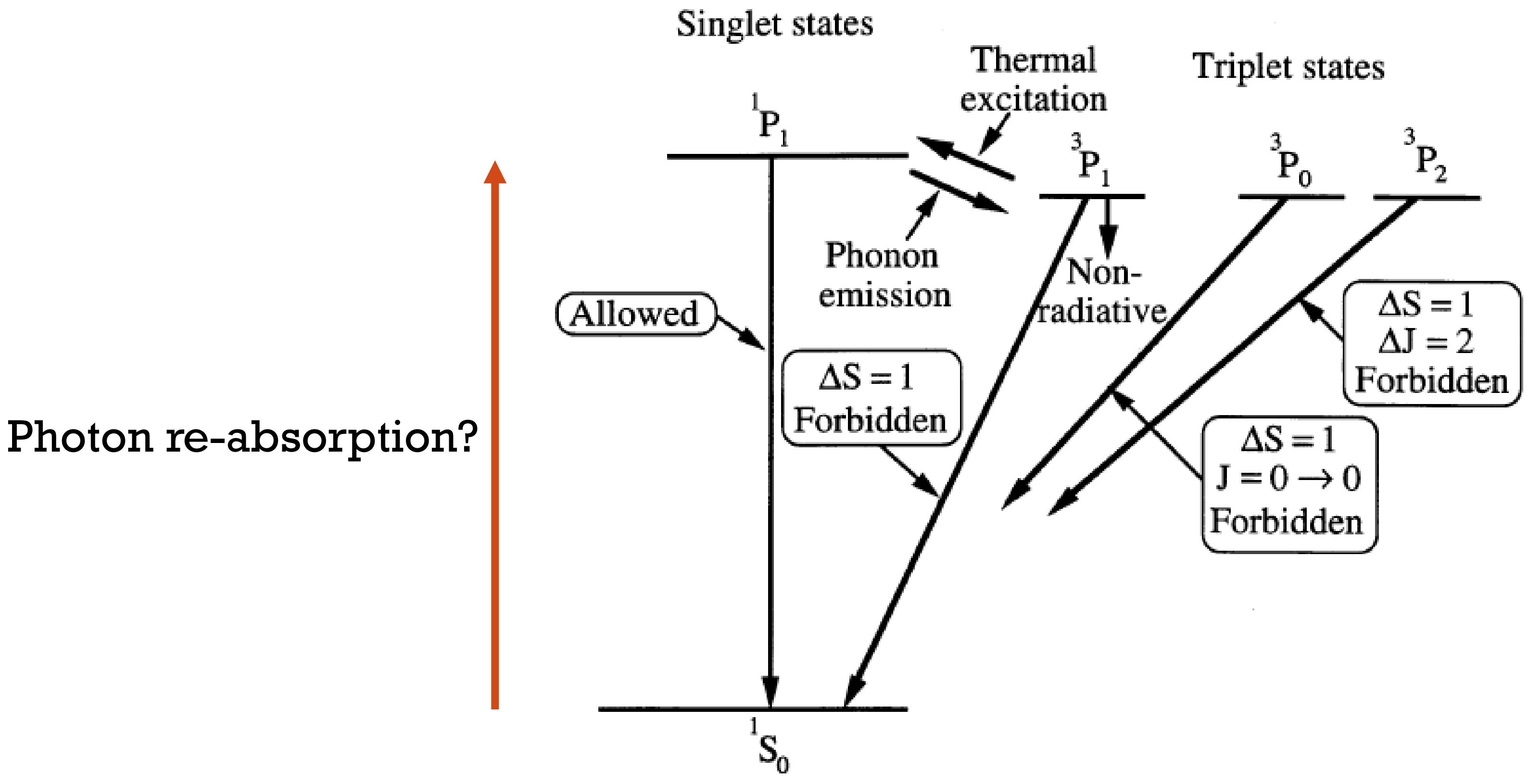
Introduction to Radiation Detectors and Electronics *Copyright © 1998 by Helmuth Spieler*
III. Scintillation Detectors

(NaI(Tl)) has a light output ~ 40,000 photons per MeV of energy deposit.

- Q (Tl$^+$) ~ 1
- Rise time is fairly fast (τ_R ~ 10 ns).
  - Slow rise times are from slow carriers
- the decay time is rather slow (τ_D ~ 250 ns).
  - some transitions are forbidden (phosphorescence)

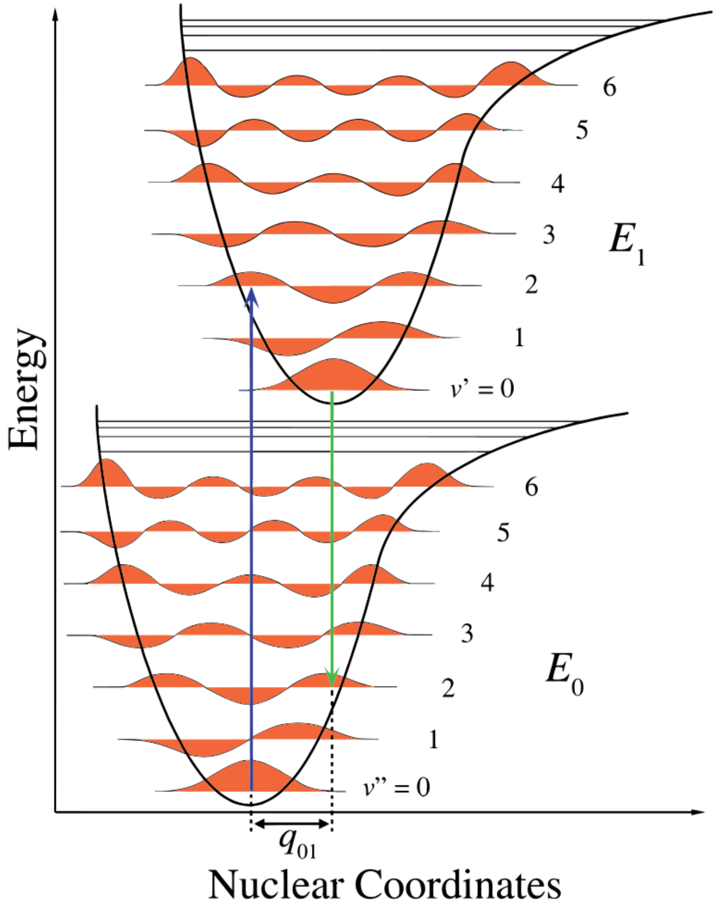
M.J. Weber / Nuclear Instruments and Methods in Physics Research A 527 (2004) 9–14

WHY ARE THE PHOTONS NOT REABSORBED INSTANTLY?



STOKES SHIFT AND THE FRANCK-CONDON PRINCIPLE

- Franck-Condon principle (semi-classical)
  - The electronic transitions are much faster than the nuclear motions
  - new vibrational level must be instantaneously compatible with the nuclear positions and momenta of the vibrational level of the molecule
  - transitions between vibrational sublevels ν=0 and ν=2 and ν=1→ν=0 are favoured over ν=0→ν=0
  - $h\upsilon < E_{abs}$ (Stokes Shift) = longer wavelength



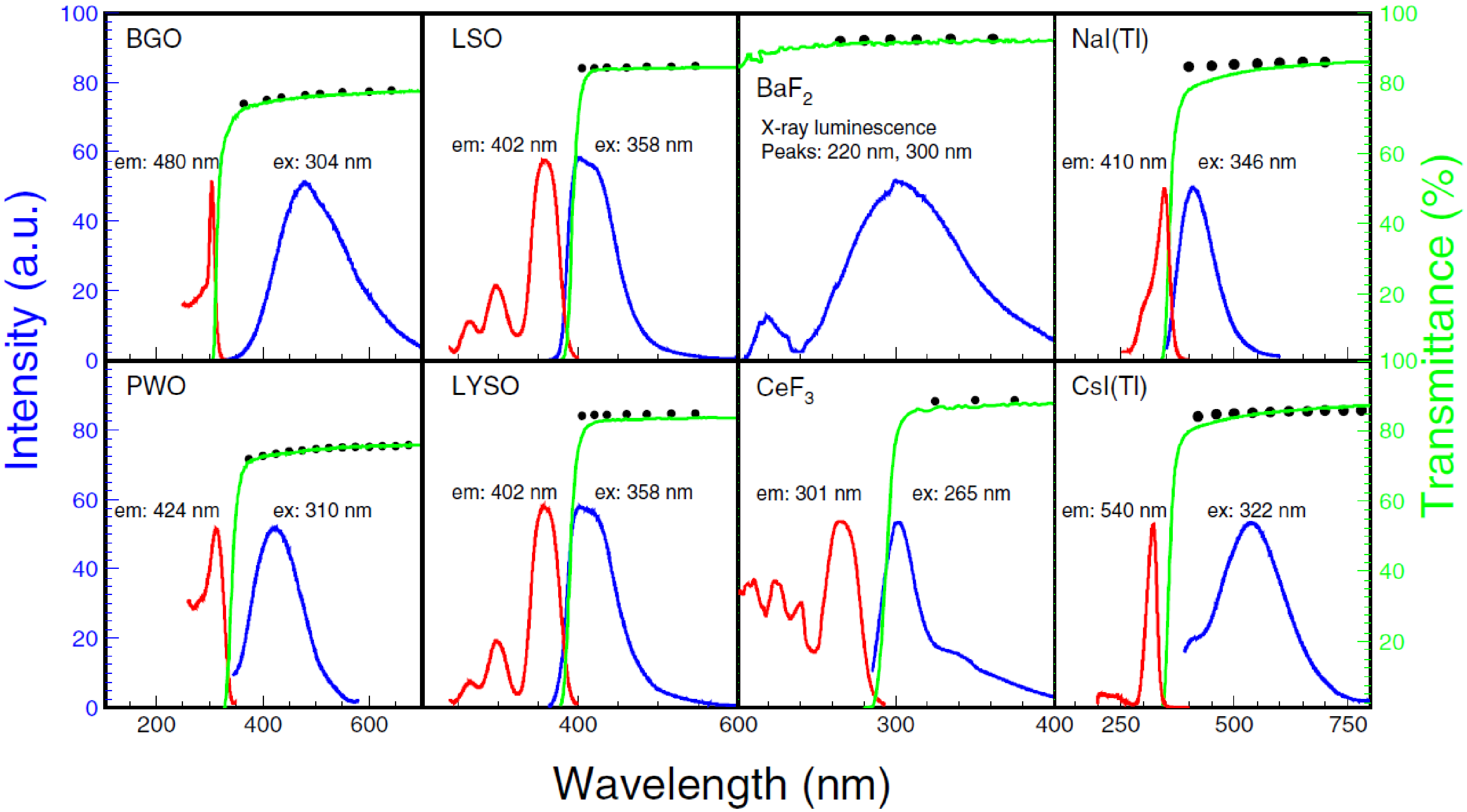
Excitation $E_{0,0} \overset{fs}{\Rightarrow} E_{1,2}$

Relaxation $E_{1,2} \overset{ps}{\Rightarrow} E_{1,0}$

Radiative $E_{1,0} \overset{ns}{\Rightarrow} E_{0,2}$

By Samoza, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=33461268

Inorganic Scintillator Absorption and Emission spectra & Transmission

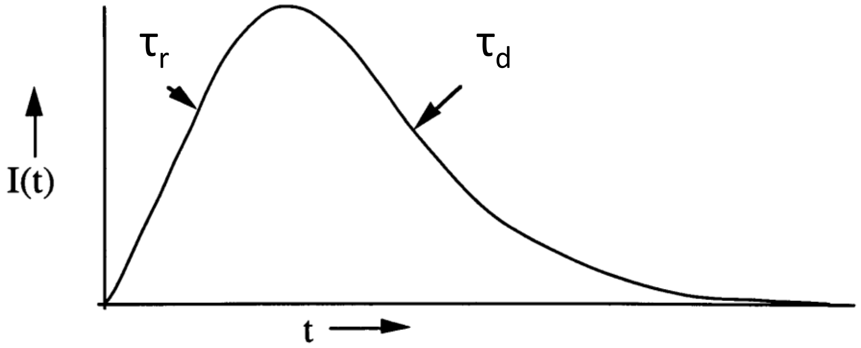


2007 IEEE Nuclear Science Symposium Conference Record N49-1, Rihua Mao et al.

TIMING (SIMPLE APPROXIMATION)

- Rise time, τ_r , due to transfer time from vibration modes to luminescent centres
- Decay time, τ_d , due to emission and quenching of luminescent centres

$$I(t) = I_0(e^{-t/\tau_d} - e^{-t/\tau_r})$$



- Timing resolution dependent on the arrival time, t_{1st} ,of the first photon

$$t_{1^{st}} = {}^{\tau_d}/_{N_{ph}} \text{ for } \tau_r < {}^{\tau_d}/_{N_{ph}}$$

$$t_{1^{st}} = \sqrt{{}^{2\tau_r\tau_d}/_{N_{ph}}} \text{ for } \tau_r > {}^{\tau_d}/_{N_{ph}}$$

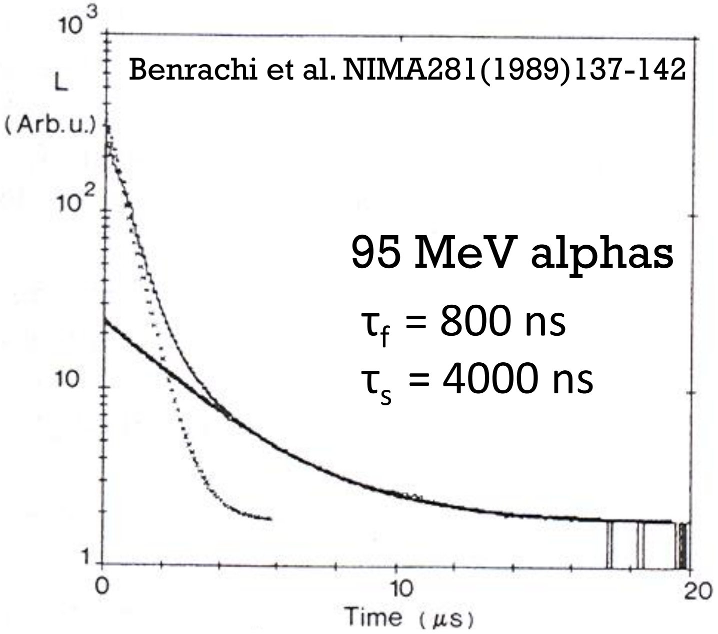
From "Inorganic Scintillators for Detector Systems," Paul Lecoq

PARTICLE ID

- For CsI(Tl), the pulse shape has two distinct components, fast and slow

$$I(t) = \frac{h_f}{\tau_f} e^{\frac{-t}{\tau_f}} + \frac{h_s}{\tau_s} e^{\frac{-t}{\tau_s}}$$

- τ_f is dependent on ionization density
  - Excitation to states with forbidden decays more likely
- τ_s is independent
- $R = {}^{h_s}/_{(h_s+h_f)}$ increases with ionization density

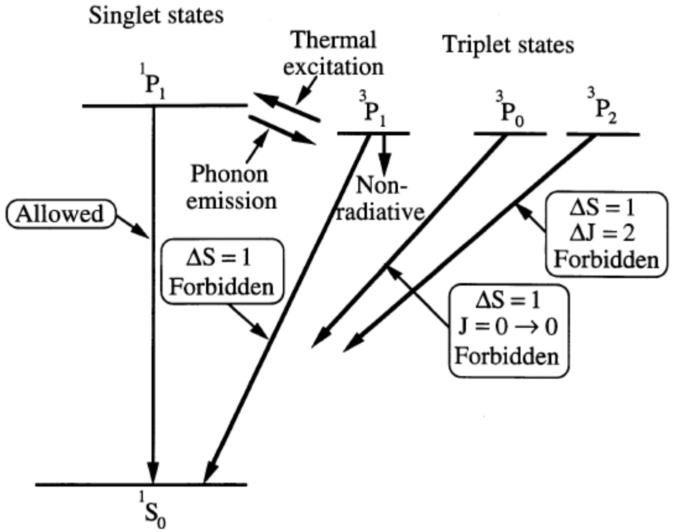


Benrachi et al. NIMA281(1989)137-142

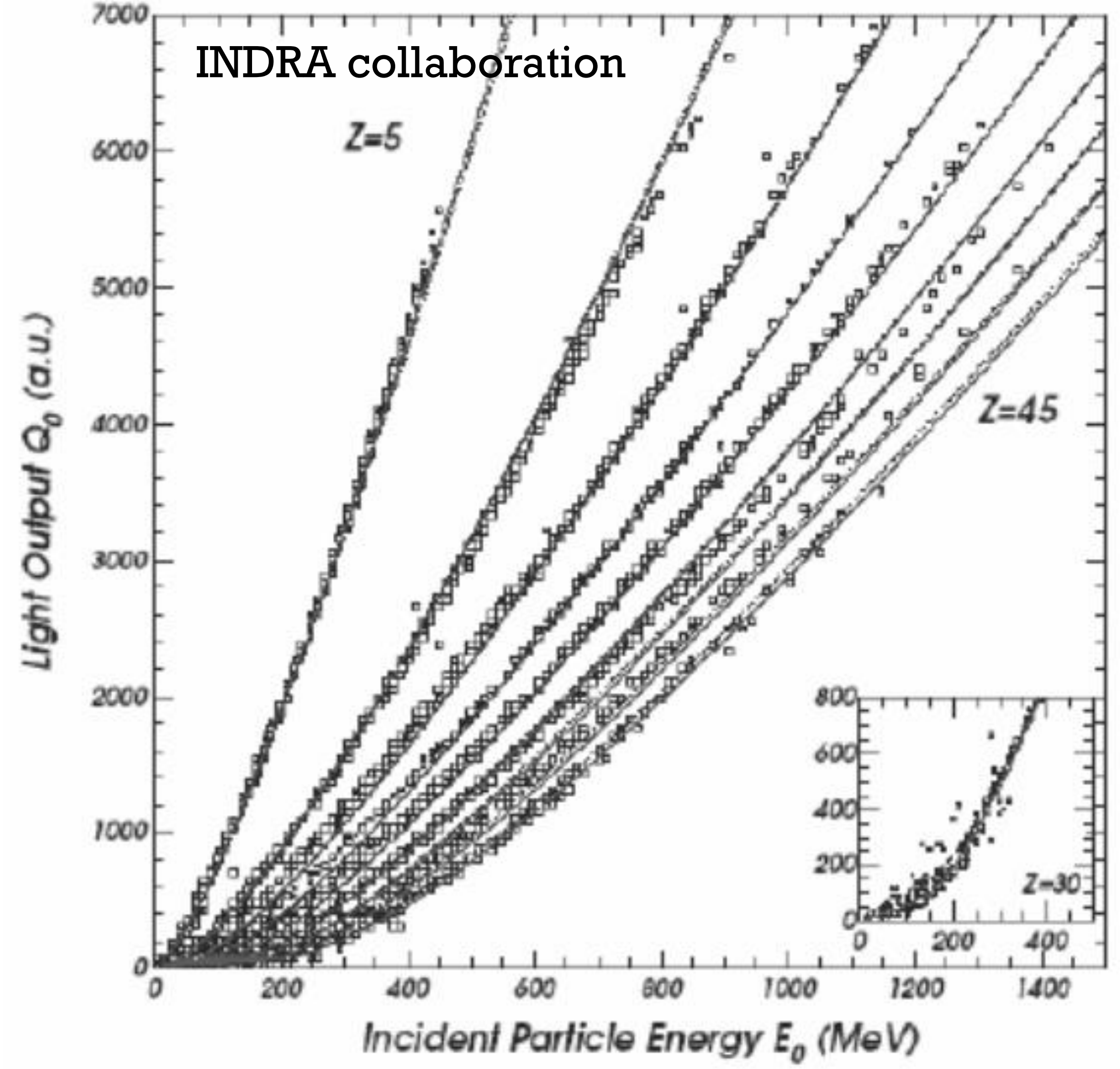
95 MeV alphas

τ_f = 800 ns

τ_s = 4000 ns



Inorganic Scintillator CsI(Tl)


INDRA collaboration

Example: n-γ discrimination

P. Sperr, H. Spieler, M.R. Maier, NIM **116**(1974)55

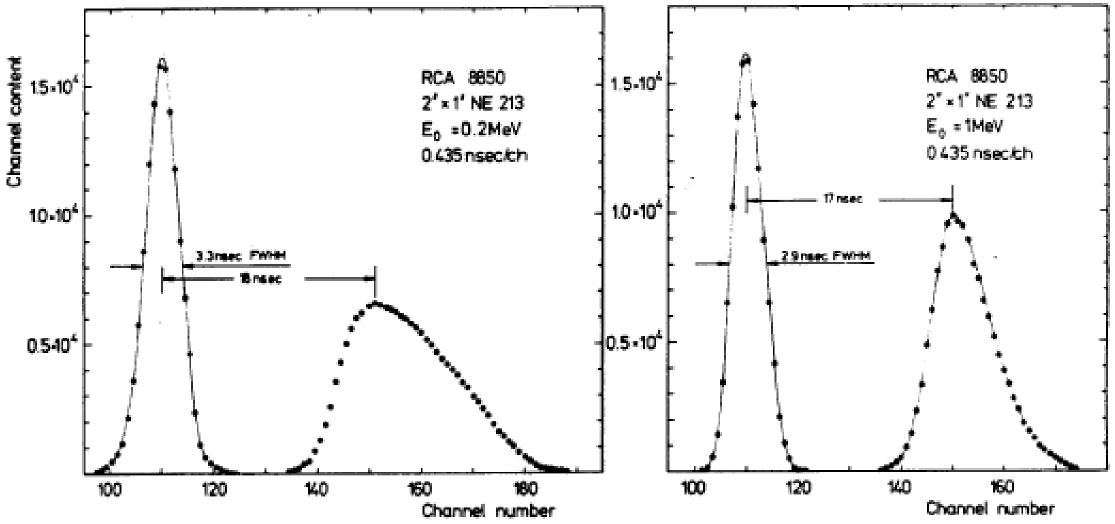


Fig. 5. Neutron–gamma timing distributions with a small scintillator (2″ diam. × 1″) for two threshold energies.

OTHER RELEVANT PROPERTIES

- Refractive index:
  - Coupling efficiency to photodetectors
  - High (1.5-2)
- Transmission of emitted photons
    - Optical transparency of the crystal
- Density:
  - Compactness = cost * volume
- Small Moliere radius (high density, lower Z)
  - RM~X0 (Z + 1.2)/37.74).
  - Smaller EM shower radius = better separation
- Radiation and Interaction length
  - Shower containment improves energy resolution
- Temperature dependence
- Wavelength matching to photodetector quantum efficiency

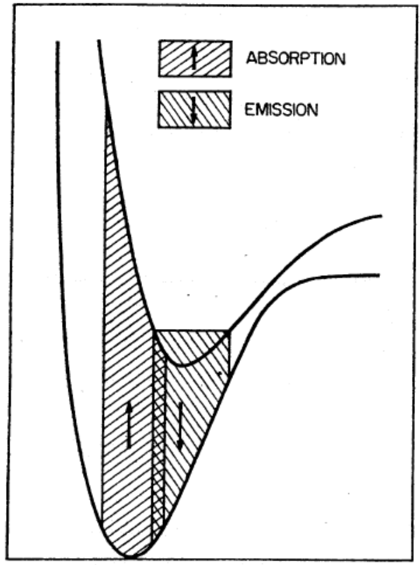
Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3
Melting Point (ºC)	651	621	621	1280	1050	2050	1123
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20
Hygroscopicity	Yes	Slight	Slight	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	310	300 220	480	402	425 420
Decay Time [b] (ns)	245	1220	26	650 0.9	300	40	30 10
Light Yield [b,c] (%)	100	165	3.7	36 4.1	21	85	0.3 0.1
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5

Complex interaction of luminescent centres results in multiple decay time components

A more extensive HTML table is available at: http://scintillator.lbl.gov

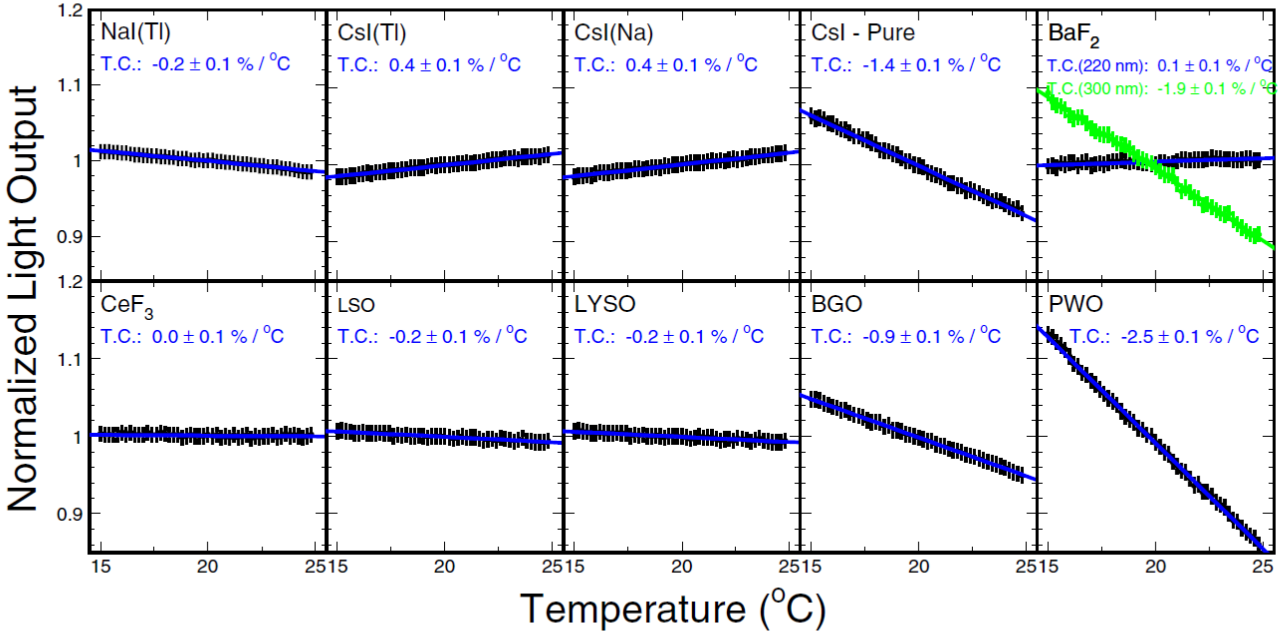
TEMPERATURE DEPENDENCE

- At higher temperatures, the vibrational states widen
- Simple case: Overlapping ground states result in reabsorption (quenching) and loss of light yield



J.B. Birks, The Theory and Practice of Scintillation Counting, New York, 1964

- Improves the timing, however



2007 IEEE Nuclear Science Symposium Conference Record N49-1, Rihua Mao et al.

ENERGY RESOLUTION

$$\frac{\delta_M}{M} = \frac{1}{2}\left[\frac{\delta E_{\gamma_1}}{E_{\gamma_1}} \oplus \frac{\delta_{E_{\gamma_2}}}{E_{\gamma_2}} \oplus \frac{\overset{\substack{\text{granularity}\\ \downarrow}}{\delta_\theta}}{\tan\left(\theta/2\right)}\right]$$

- Mass resolution through 2 photon decay channel (i.e. H->gamma gamma)
- Want **∂E/E = 0.5%** for 100 GeV photons
- a=2% is achievable for modern <u>homogenous</u> EM calorimeters

$$\frac{\delta E}{E} \sim \frac{1}{\sqrt{N}}$$

- B<0.5% is hard
  - Need X0~25 for 100GeV photons
  - The shower is contained in the readout cluster
  - Temperature dependence can increase b_F; also production variation

$$\delta E\gamma/E\gamma = \overset{\substack{\text{statistical}\\ \downarrow}}{a}/\sqrt{E} \oplus \underset{\substack{\uparrow\\ \text{constant}}}{b} \oplus \overset{\substack{\text{noise}\\ \downarrow}}{c}/E$$

$$b^2 = \underset{\substack{\nwarrow\\ \text{Shower leakage}}}{b_{\mathrm{L}}^2} \oplus \underset{\substack{\uparrow\\ \text{Non-uniformity}}}{b_{\mathrm{F}}^2} \oplus \underset{\substack{\nwarrow\\ \text{Inter-calibration}}}{b_{\mathrm{c}}^2}$$

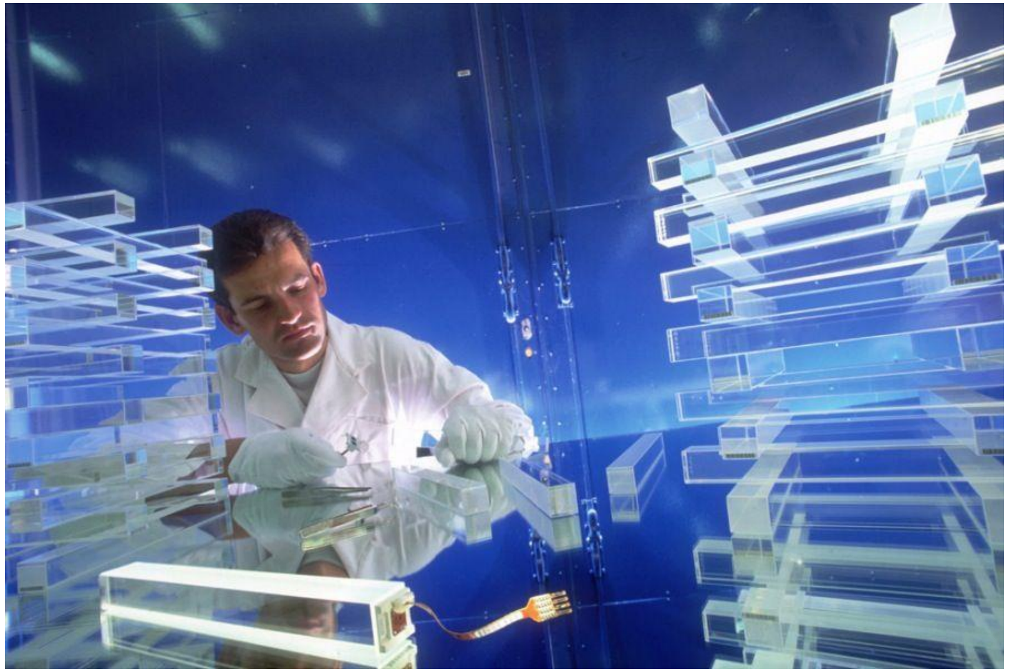
From "Inorganic Scintillators for Detector Systems," Paul Lecoq

DETECTORS WITH INORGANIC SCINTILLATOR

High Energy Physics

- CMS (LHC):
  - 76150 PbWO4 crystals (80 tons, 11m^3)
  - Depth of 25 X0
  - 40ns shaping (CMS TDR)
  - 45 mrad/√E angular precision
  - Resolution of 1-2%

- Babar (SLAC)
  - 6580 CsI(Tl) crystals(6m^3)
  - Depth of 17 X0
  - 270ns integration
- Many other calorimeters…



Lead tungstate crystals used in the CMS ECAL.

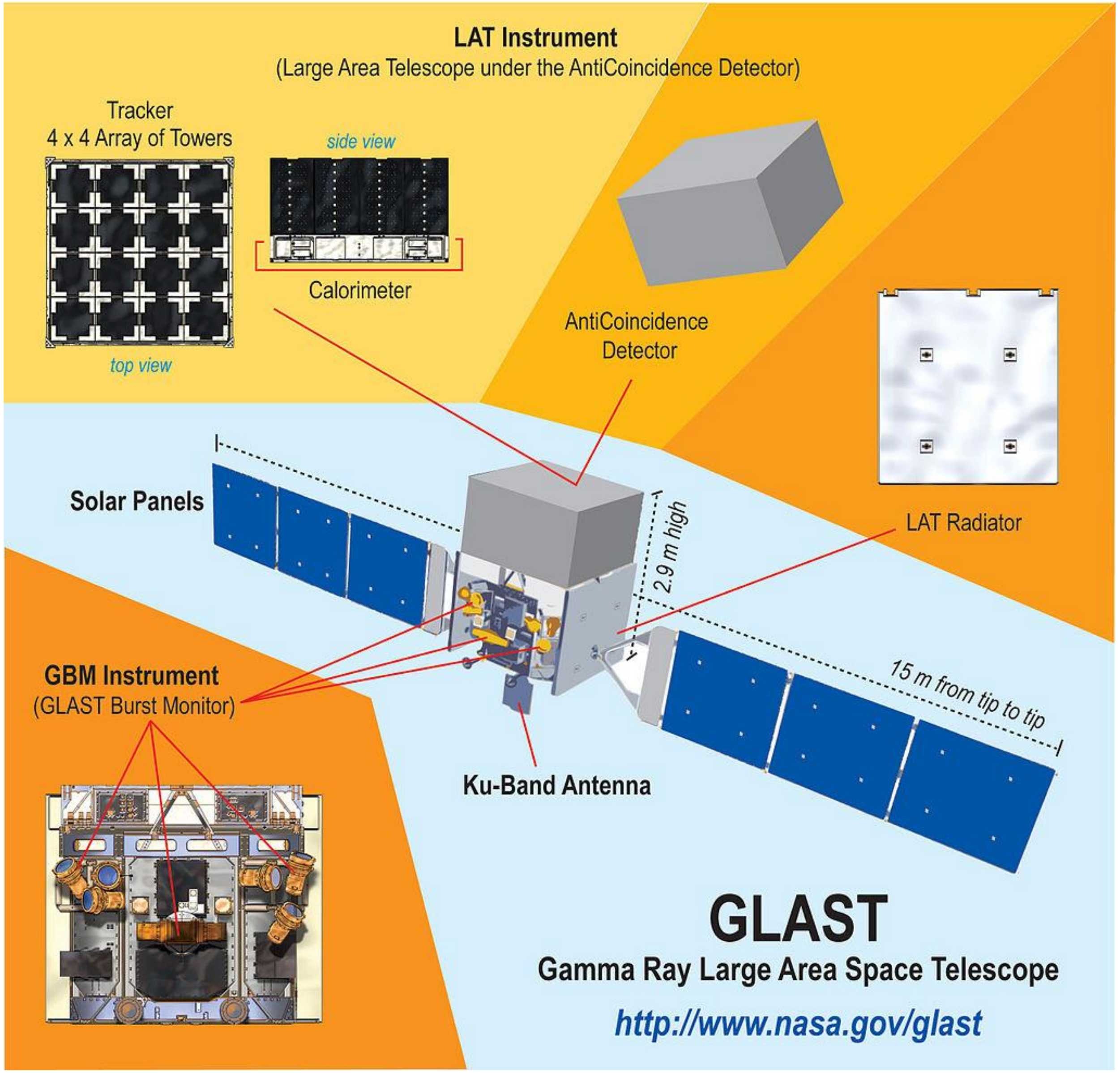
http://cms.web.cern.ch/news/crystal-calorimeter

ATROPHYSICS

Fermi Gamma-ray Space Telescope (FGST) -- formerly GLAST

- silicon microstrip detector + calorimeter

- 1536 CsI(Tl) crystals (0.3m^3)
- 20 MeV – 300 GeV dynamic range
- 20% energy resolution

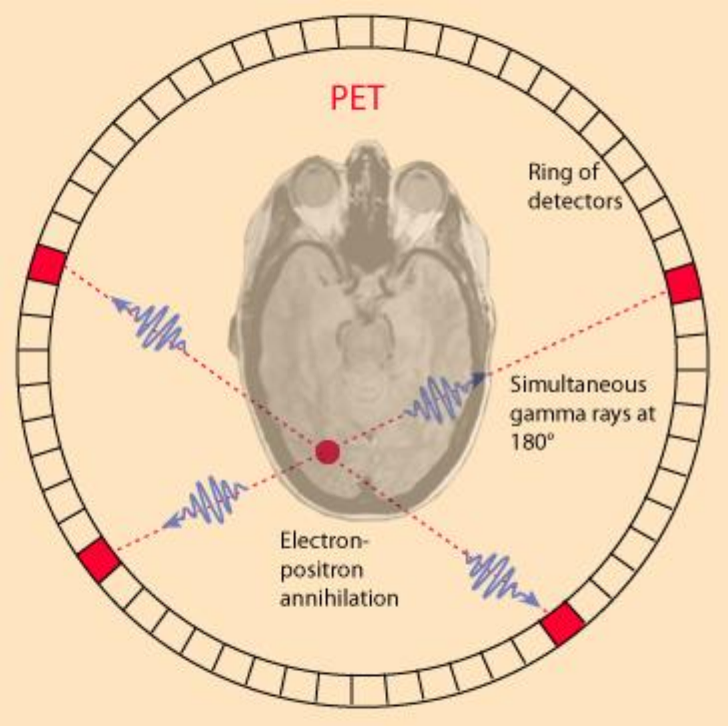


- By NASA - http://www.nasa.gov/mission_pages/GLAST/multimedia/glast_vector.html

MEDICAL APPLICATIONS

- **PET detectors**
  - BGO, LSO, LYSO crystals
  - Requires <ns timing resolution
    - Reduces signal to noise ratio
  - Also good E resolution → $M(e^+ + e^-)$

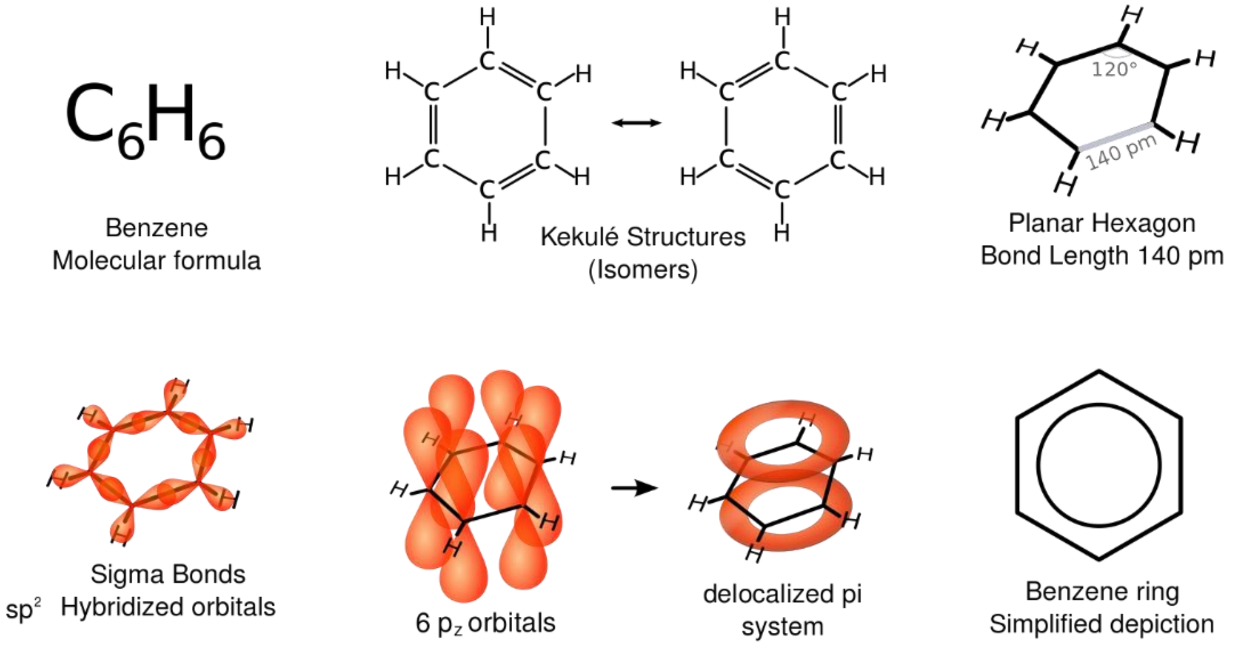
- X-ray, CT, etc.



From http://hyperphysics.phy-astr.gsu.edu/hbase/NucEne/nucmed.html

ORGANIC SCINTILLATORS

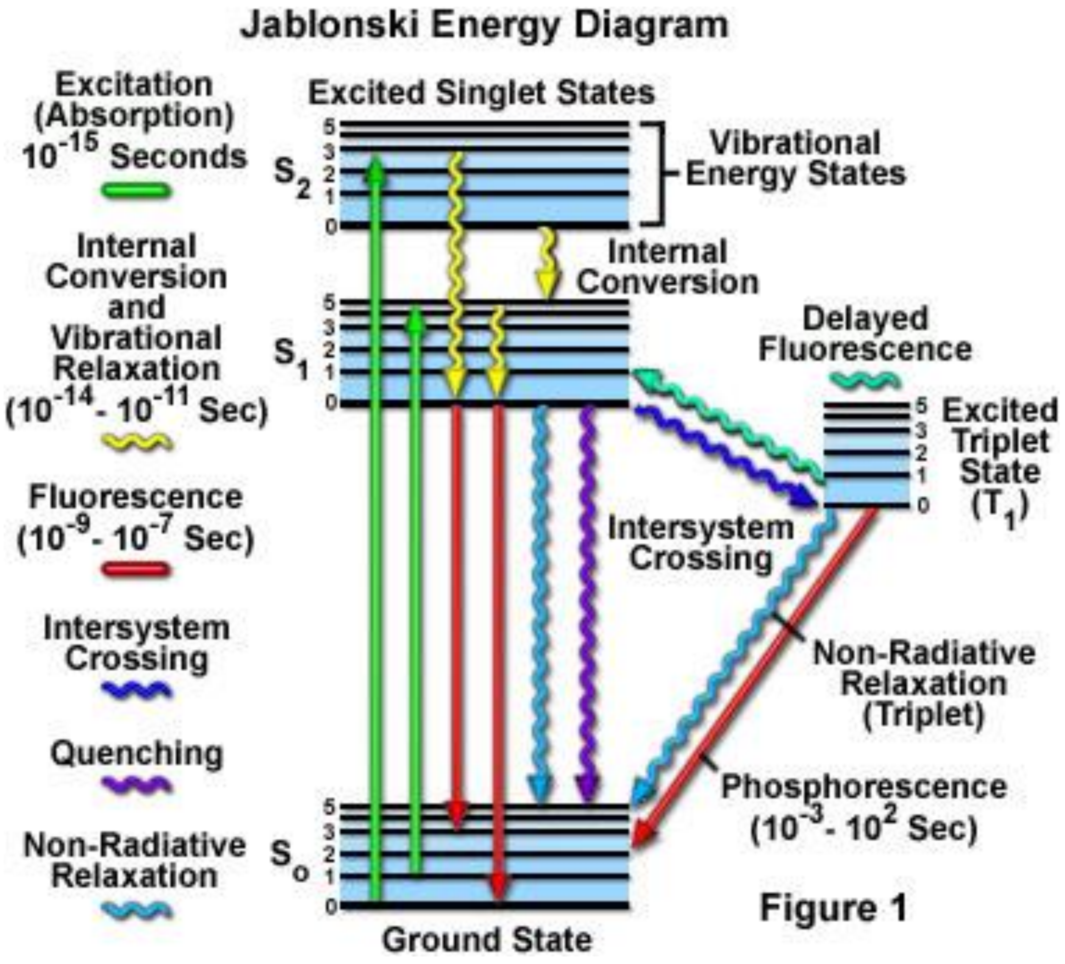
- contain aromatic molecules
  - i.e. they have a **benzene ring**
  - scintillation results from the physics of the benzene ring coupled to the molecule
- σ-bonds are in-plane with a bond angle of 120°, from sp2 hybridization
- π-orbitals are out-of-plane; the π-electrons overlap and are completely delocalized
- Scintillation light is produced from the de-excitation of the molecule



By Vladsinger - Own vector drawing based on layout of en:File:Benzol trans.png., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=7536474

FLUORESCENCE

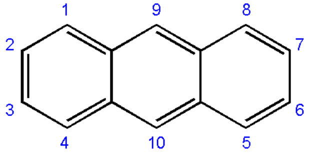
- Ionisation energy excites molecule to S_{1N} or higher (τ = fs)
  - Relaxes to S_{10} (τ = ps)
- Can decay radiatively to S_{0N} state (τ=ns)
  - Stokes shift as a result of Franck-Condon principle
  - Relaxes to S_{00} state
- Overlap with the ground state results in non-radiative decays (quenching)
- T1 ←→S0 forbidden by spin/parity (τ>ms)



http://micro.magnet.fsu.edu/primer/techniques/fluorescence/fluorescenceintro.html

TYPES OF SCINTILLATOR

- **Crystals:**
  - Anthracene : highest light output for organic scint.
    - 17,400 photons/MeV
  - Stilbene, TPB, etc.
  - good for n/gamma separation
  - Expensive!



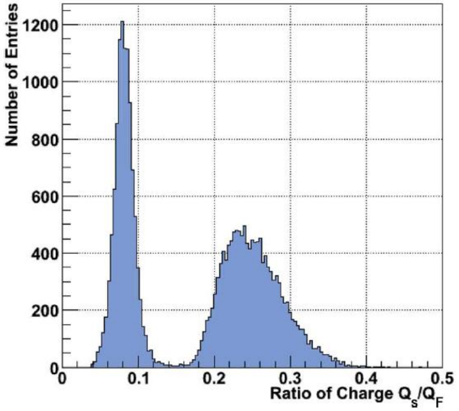
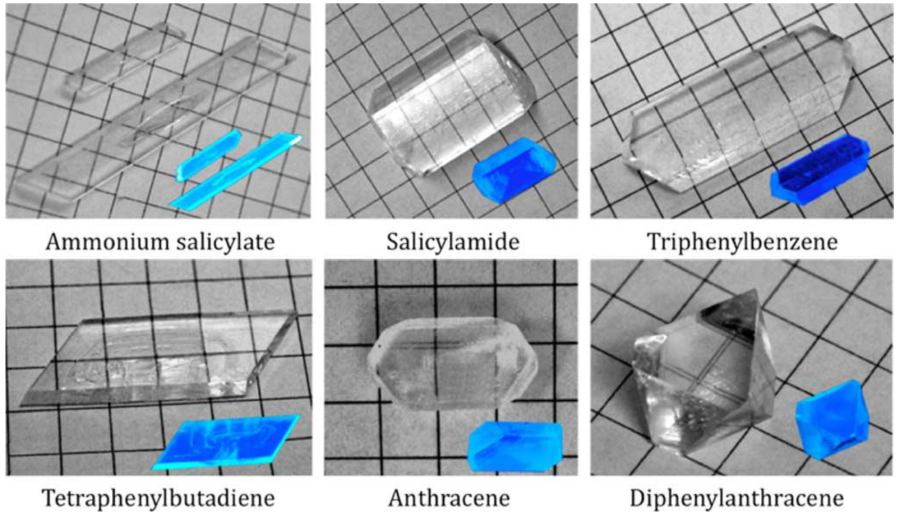
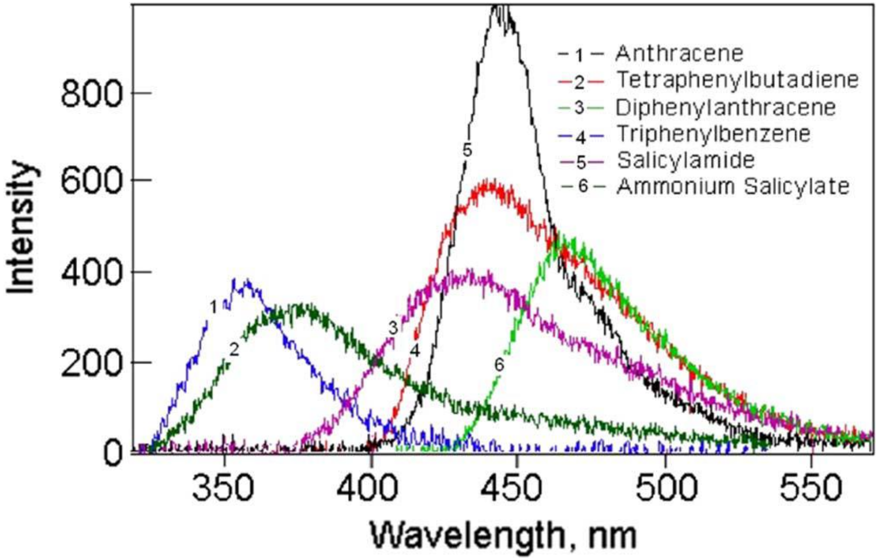


Fig. 4. Neutron/Gamma separation profile for triphenylbenzene (top) and tetraphenylbutadiene (bottom).

Hull et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 56, NO. 3, JUNE 2009 p.899-903

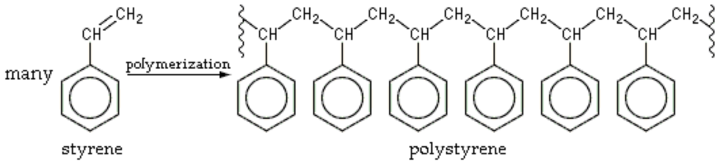




LIQUID AND PLASTIC SCINTILLATORS

- The bulk of the mass is a solvent which absorbs the ionization energy
    - Benzene (liquid), Linear alkylbenzene (liquid), polystyrene (plastic), PVT (plastic), etc.
- Non-radiative dipole-dipole transfer to primary fluor molecules
    - Another organic scintillator added (1%/Volume)
    - Foerster Resonant Energy Transfer (next slide)
- Emits a photon which is absorbed and re-emitted by the wavelength shifter
    - Yet another organic scintillator (0.1%)

- Example: polystyrene



- The radiative and non-radiative (quenching) transfer rates for polystyrene, k_R and k_{NR}:

$$k_R = 1.98 \times 10^6 s^{-1}$$
$$k_{NR} = 5.02 \times 10^7 s^{-1}$$

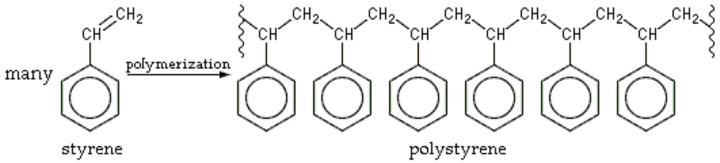
- The radiative yield quantum efficiency, q_R, and decay time, τ_R

$$\left.\begin{aligned} q_R &= \frac{k_R}{k_R + k_{NR}} = 0.038 \\ \tau_R &= \frac{1}{k_R} = 500ns \end{aligned}\right\} \text{Terrible!}$$

LIQUID AND PLASTIC SCINTILLATORS

- The bulk of the mass is a solvent which absorbs the ionization energy
  - Benzene (liquid), Linear alkylbenzene (liquid), polystyrene (plastic), PVT (plastic), etc.
- Non-radiative dipole-dipole transfer to primary fluor molecules
  - Another organic scintillator added (2%/Volume)
  - Foerster Resonant Energy Transfer (next slide)
- Emits a photon which is absorbed and re-emitted by the wavelength shifter
  - Yet another organic scintillator (0.1%)

- Example: polystyrene



- The radiative and non-radiative (quenching) transfer rates for polystyrene, k_R and k_{NR}:

$$k_R = 1.98 \times 10^6 s^{-1}$$
$$k_{NR} = 5.02 \times 10^7 s^{-1}$$

- The radiative yield quantum efficiency, q_R, and decay time, τ_R

$$\left.\begin{array}{l} q_R = \dfrac{k_R}{k_R + k_{NR}} = 0.038 \\ \\ \tau_R = \dfrac{1}{k_R} = 500ns \end{array}\right\} \text{Terrible!}$$

F.R.E.T

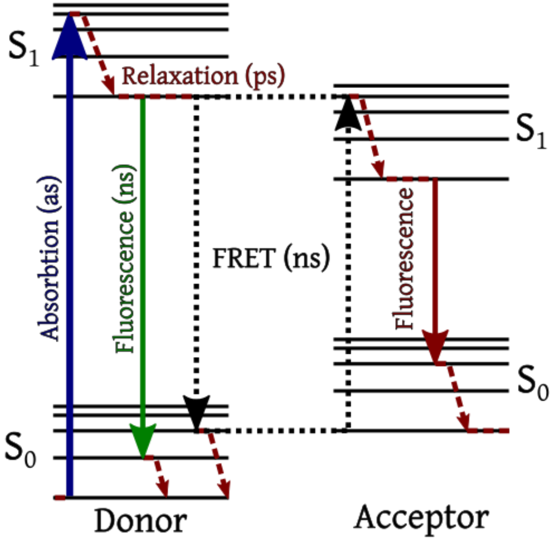
- can add a second organic scintillator to compete for the energy transfer via **Förster Resonance Energy Transfer** (FRET)
- Non-radiative dipole–dipole coupling between donor and acceptor molecule
  - Like near-field communication
  - Exchange of a virtual photon
- Transfer rate and efficiency is concentration dependent (maximize) $\leftarrow \frac{1}{R^6}$
  - Beware of self-absorption

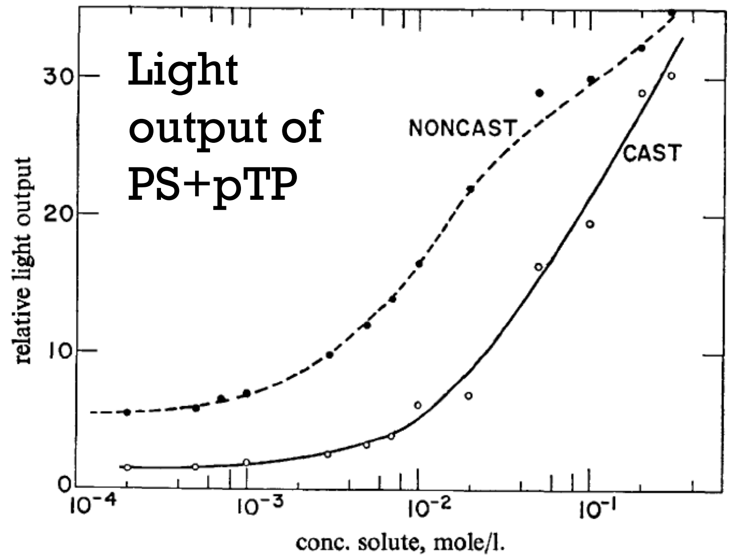
$$c \approx 10^{-3} \rightarrow 10^{-1}\, mol/l$$
$$k_T \approx 10^9 \rightarrow 10^{10} l mol^{-1} sec^{-1}$$

$$q_T = \frac{k_T c}{k_R + k_{NR} + k_T c} \approx 1$$

All the energy is transferred to the second fluor and very quickly (<ns)!

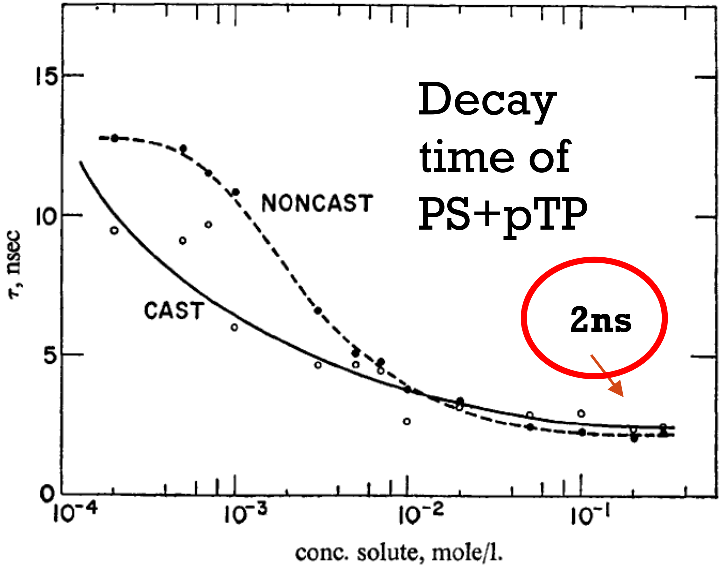
$$\tau_{PS} = \frac{1}{k_R + k_{NR} + k_T c}$$





Light output of PS+pTP

.—Light output against concentration of p-terphenyl in polystyrene.



Decay time of PS+pTP

2ns

Louis J. Basile
Trans. Faraday Soc., 1964,60, 1702-1714

DOI: 10.1039/TF9646001702

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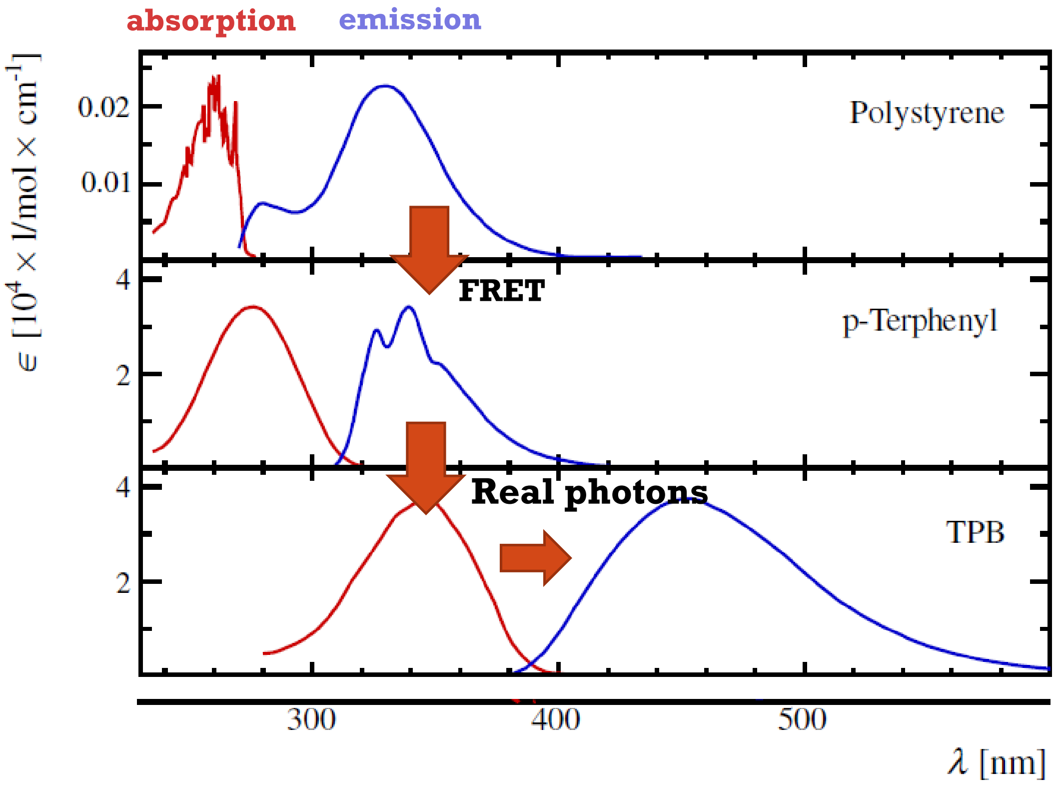
  - Benzene (liquid), Linear alkylbenzene (liquid), polystyrene (plastic), PVT (plastic), etc.
- Non-radiative dipole-dipole transfer to primary fluor molecules
  - Another organic scintillator added (2%/Volume)
  - Foerster Resonant Energy Transfer (next slide)
- Emits a real photon which is absorbed and re-emitted by the wavelength shifter
  - Yet another organic scintillator (0.1%)
  - Longer wavelength = better transmission



$\tau_R = 500ns$

$\tau_R = 2.0ns$

$\tau_R = 1.7ns$

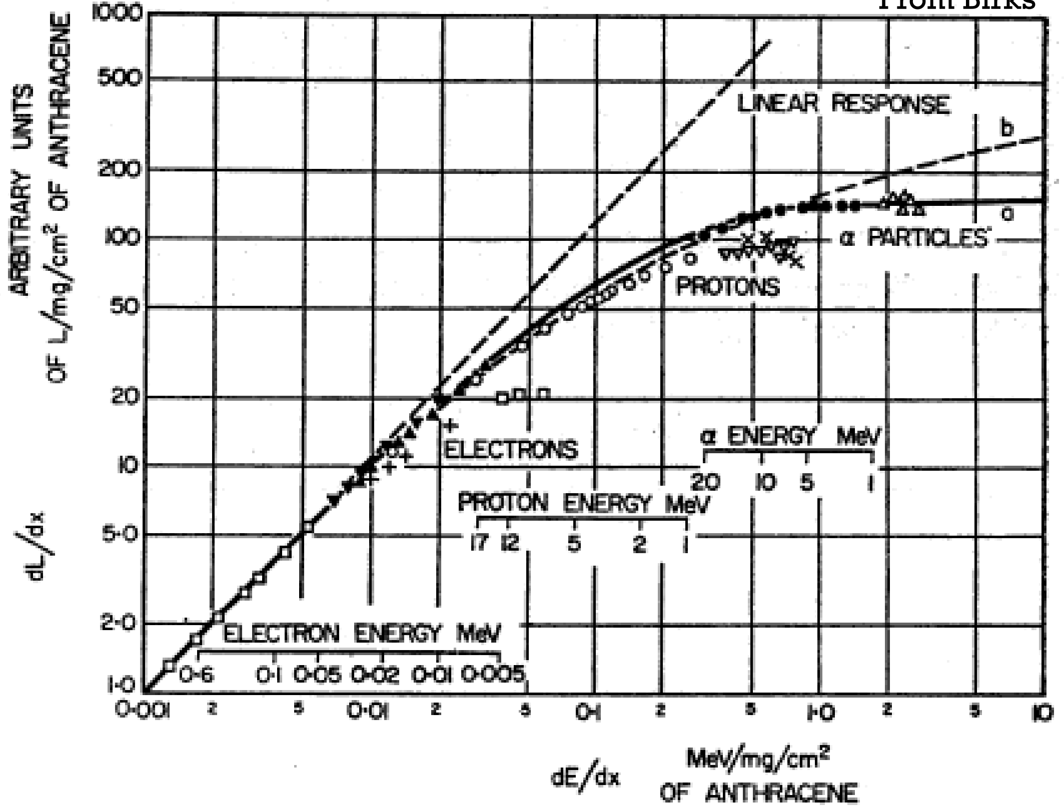
$$\tau_{total} = 2.0 \oplus 1.7\ ns = 2.8ns$$

SATURATION: BIRKS' LAW

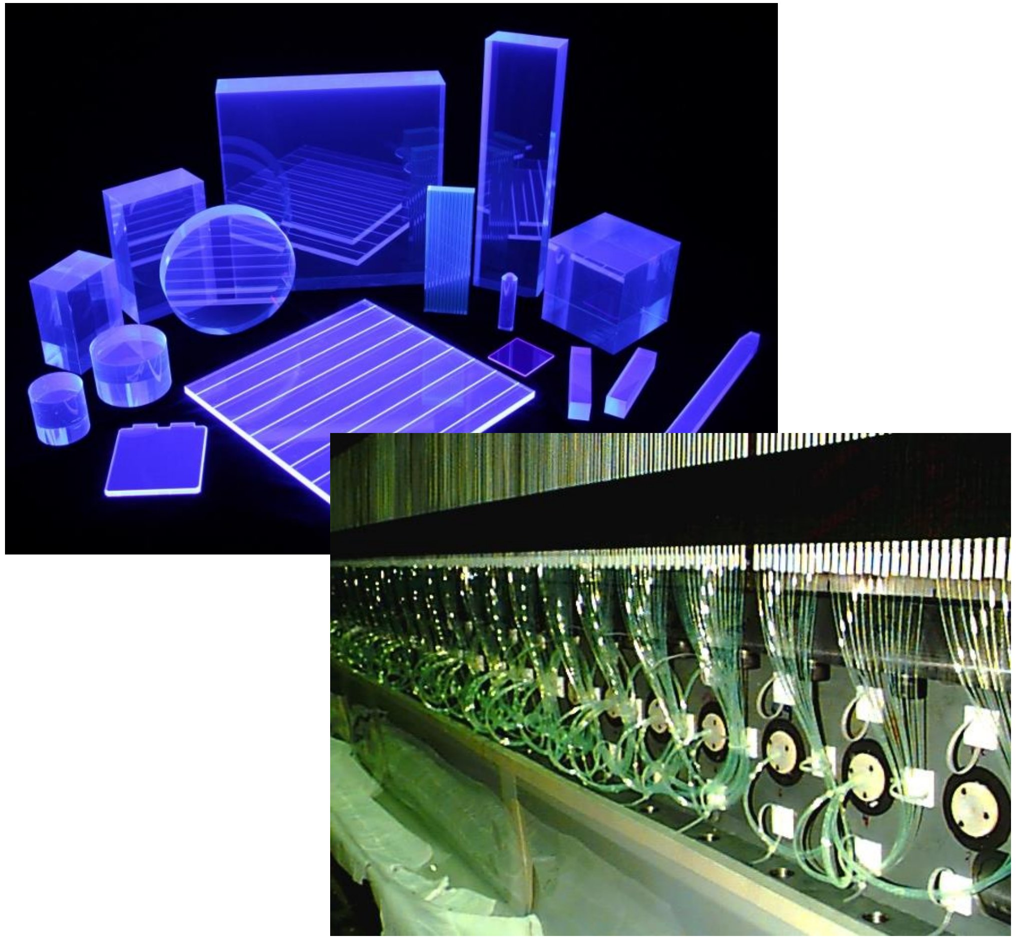
- Assume linear light output for small dE/dx
  - $dL/dx = A\, dE/dx$
- density of excitation is proportional to energy density
  - $B\, dE/dx$
- k is the fraction of excitation that is quenched
  - Interaction between nearby excitations results in non-radiative transfers

$$\frac{dL}{dx} = \frac{A\frac{dE}{dx}}{1 + kB\frac{dE}{dx}}$$

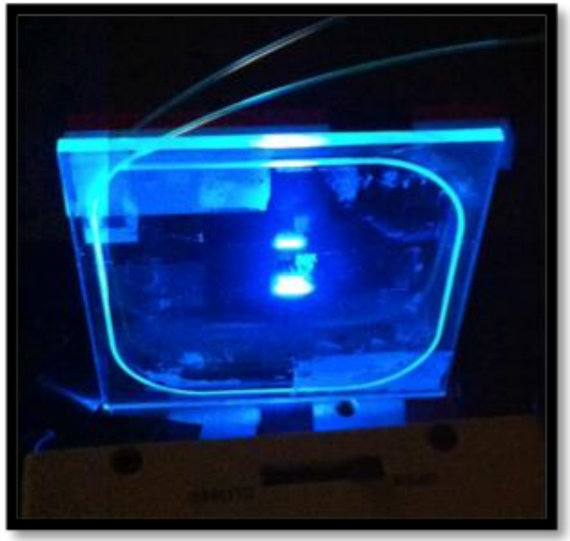
From Birks



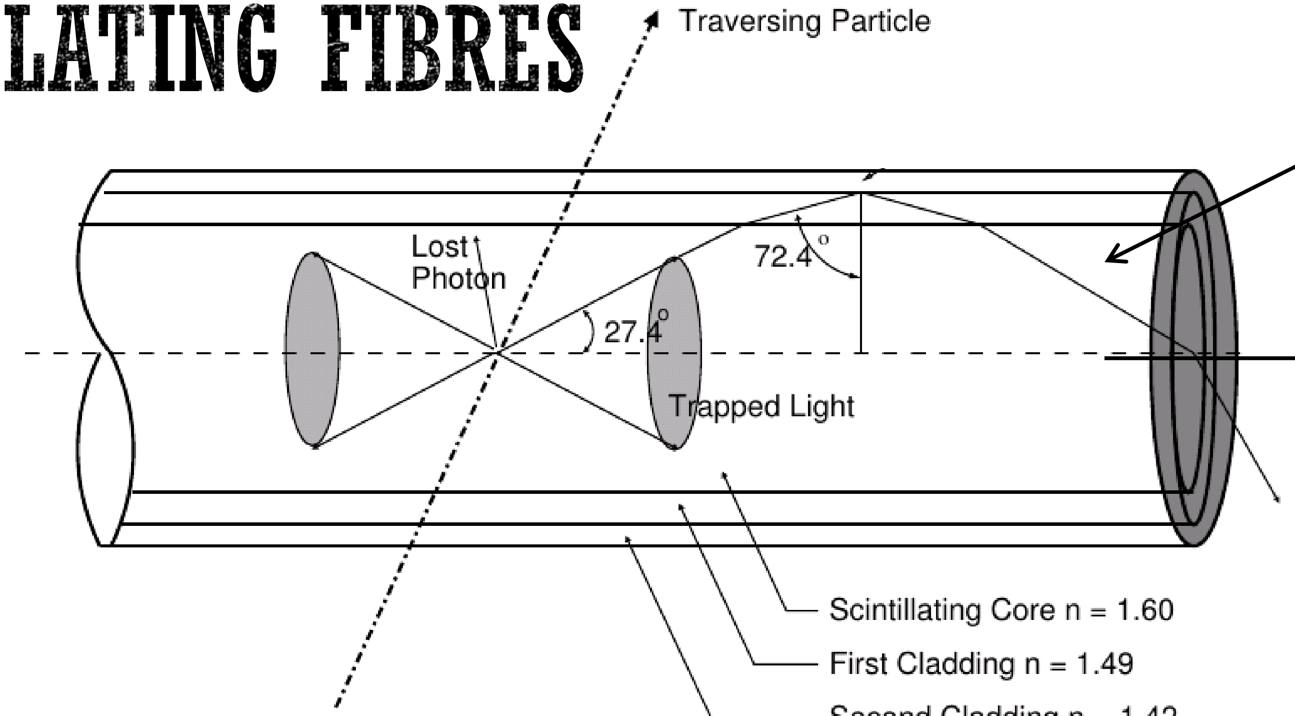
FORMS



- Fast and cheap (relatively)
- Simpler to produce compared to crystals
  - Cast, injection mold or extrusion is possible
  - Large sheets or volumes can be produced relatively quickly
- Standard operating practices:
  - couple a waveguide and a PMT
  - Embed wavelength shifting fibres and transport to smaller size photodetectors



SCINTILLATING FIBRES

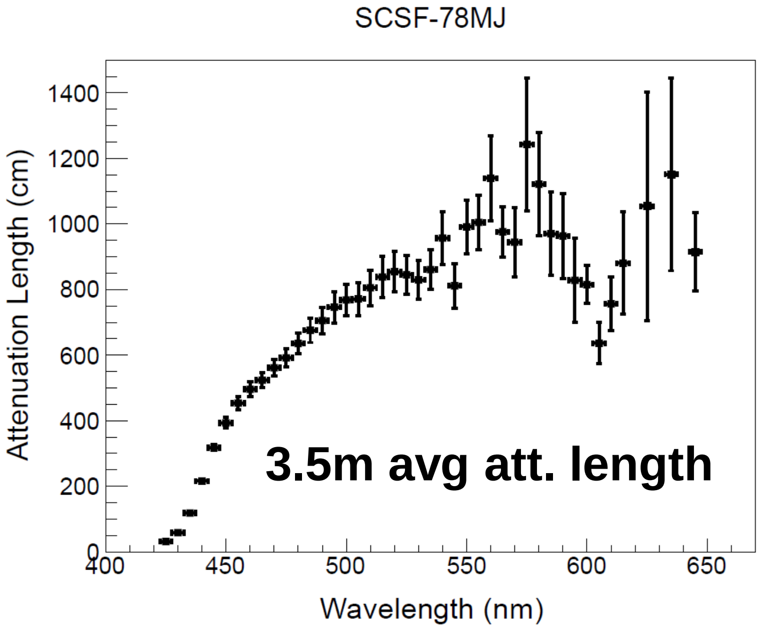


(scintillator)
Polystyrene core with 2 dyes

Only a few photons after 2.5m

300 photons per MIP produced
(only 5% captured)

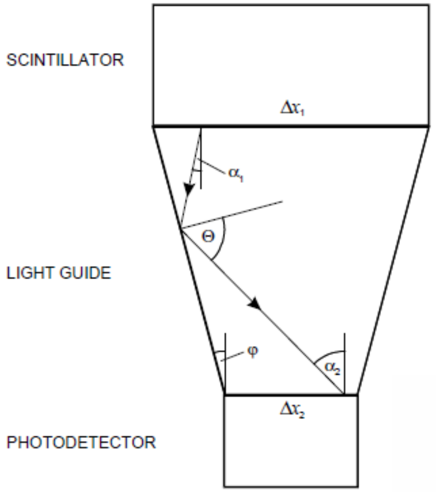
- Scintillator is melted and extruded with a small diameter (0.25 – 2mm)
  - Round or square profiles
- One or two lower refractive index plastics added to improve collection efficiency (3-5% eff.)

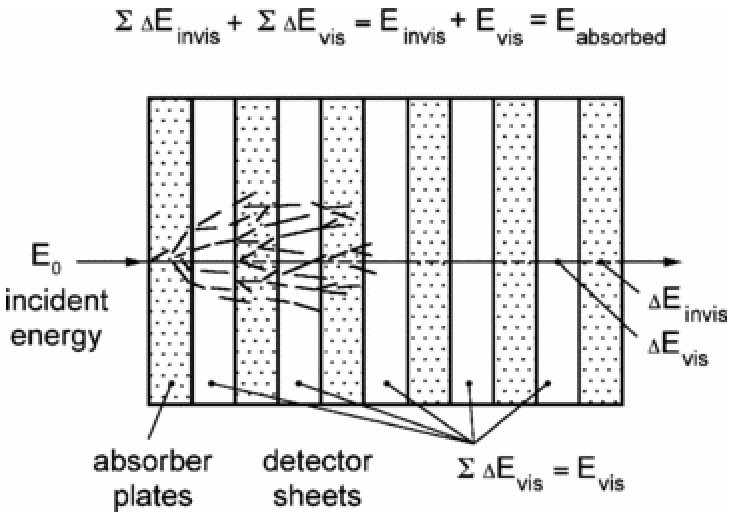


3.5m avg att. length

EXAMPLE DETECTORS

- Triggers for timing
  - Low Z, density, fast decay time
- Sampling Calorimeters
  - Layers of scintillator + high-Z passive material
    - Tile calorimeters
    - Spaghetti calorimeters (fibres)
- Neutron detectors (liquid, some new plastic)
  - Good hydrogen content
- Liquid Scintillator Baths
  - Easy to add additional materials
  - Neutrino detector (SNO+)





ATLAS TILE CALORIMETER

- Steel + scintillator + w.s. fibres
- Hadronic calorimeter

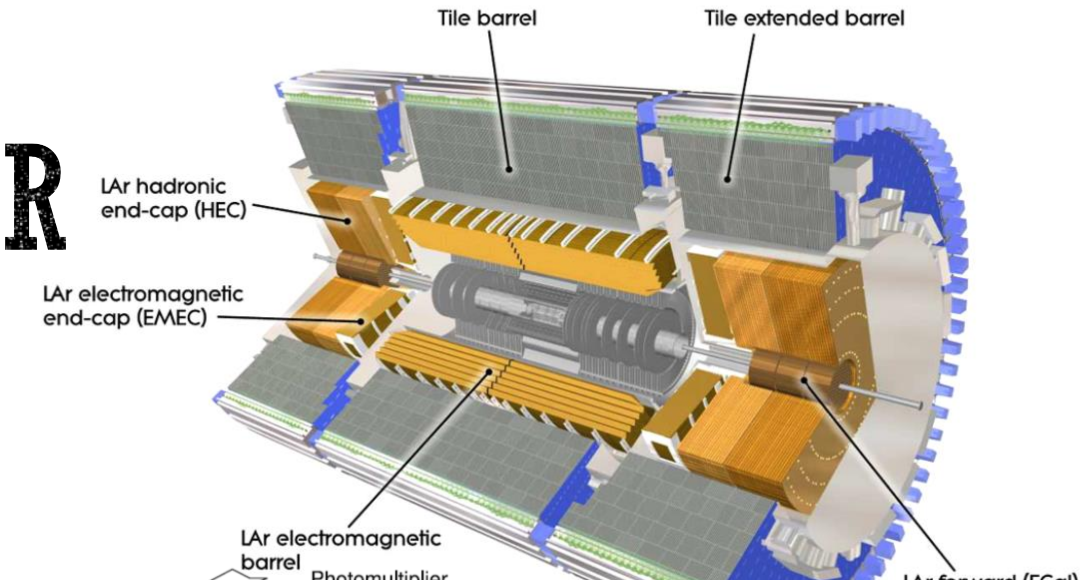
$$\frac{\delta E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$$

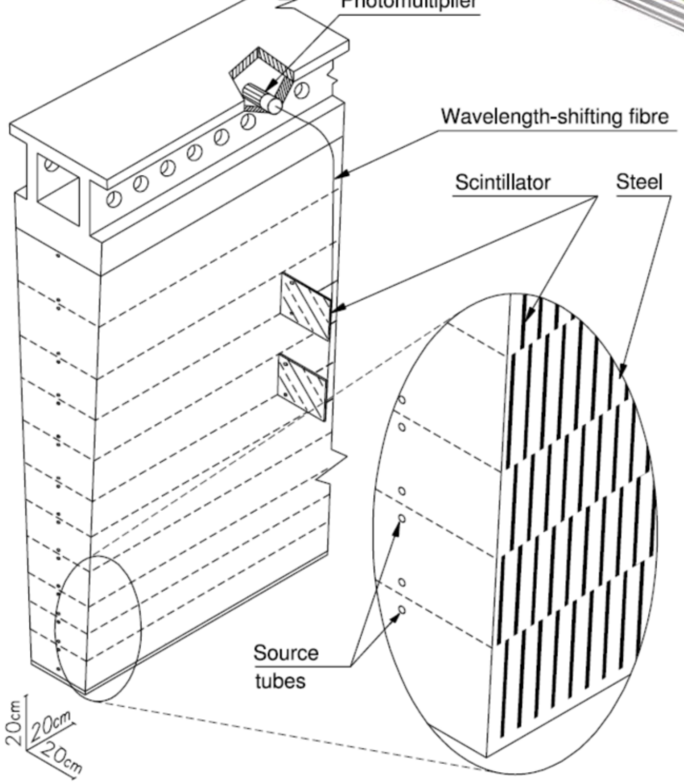
Testbeam, ATLAS NIMA 621, Sep 2010, 134-150

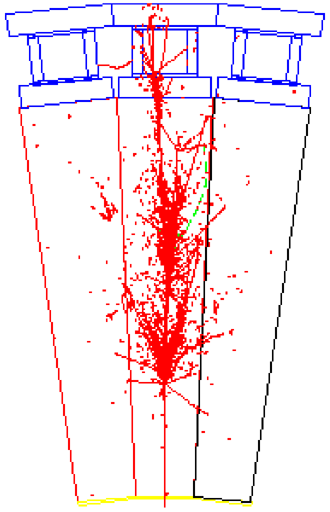
- 460,000 tiles in 5182 cells (60 tons)
- Polystyrene + 1.5% PTP and 0.04% POPOP
  - Injection molding

http://cds.cern.ch/record/1075711/files/cer-002731189.pdf

- PMT as photodetector

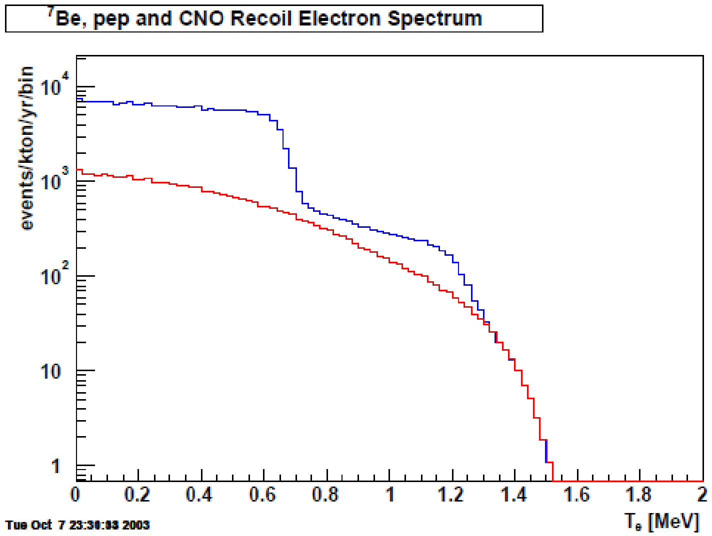




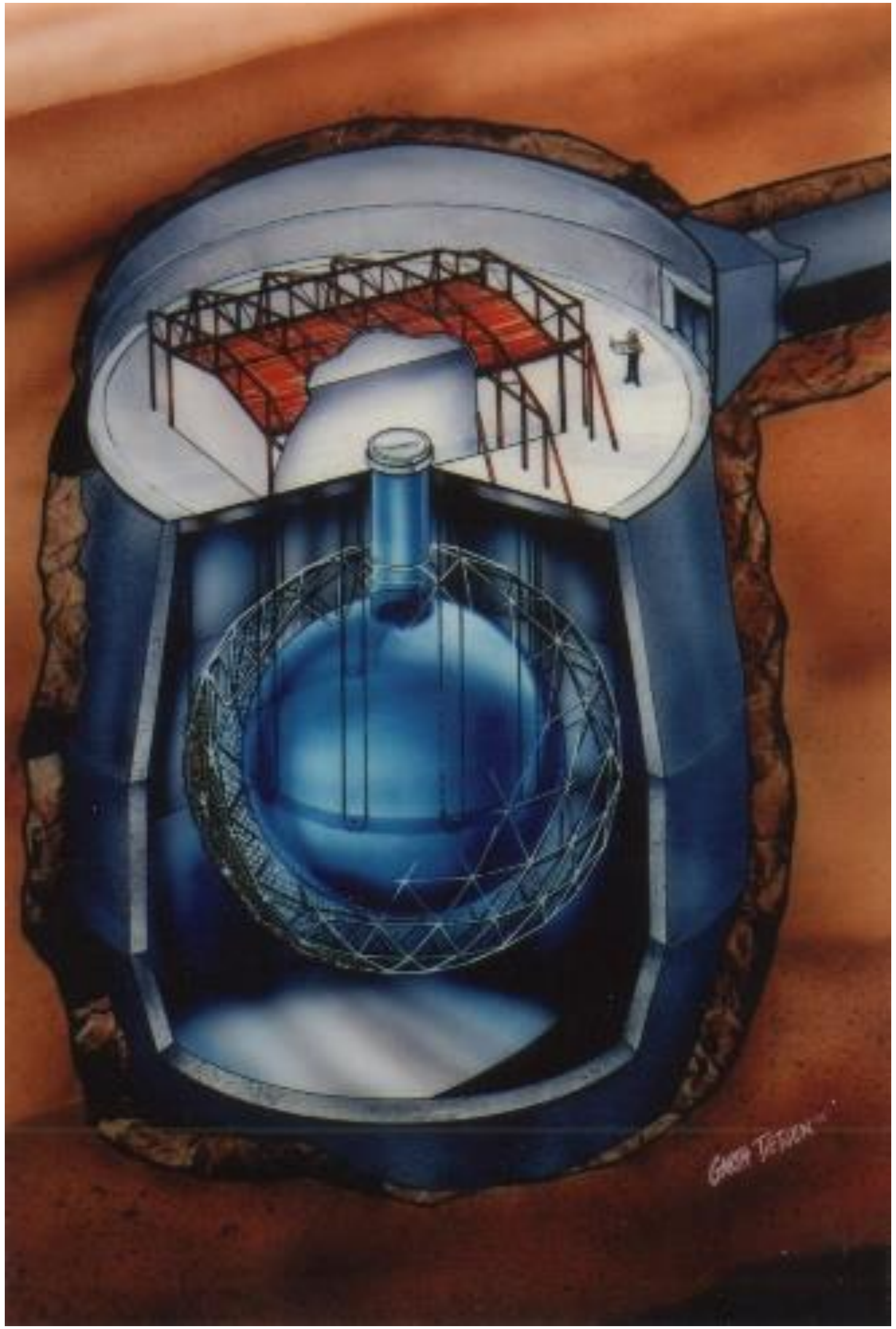


SNO+

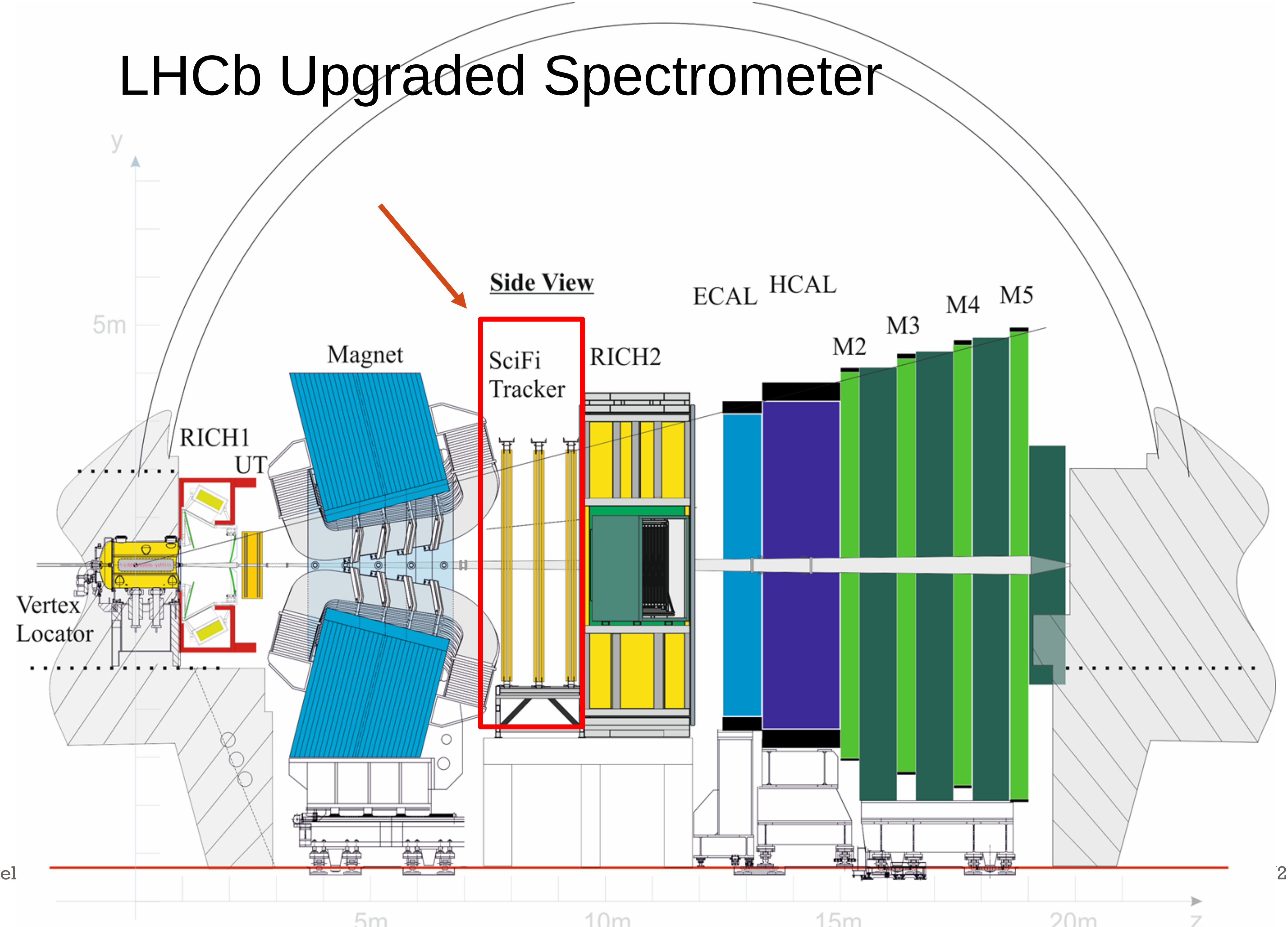
- 1 kiloton of liquid scintillator (linearalkylbenzene-LAB)
- 50x more light than Cherenkov
- Solar-, geo-neutrino study and neutrinoless double beta decay search (SNO++)



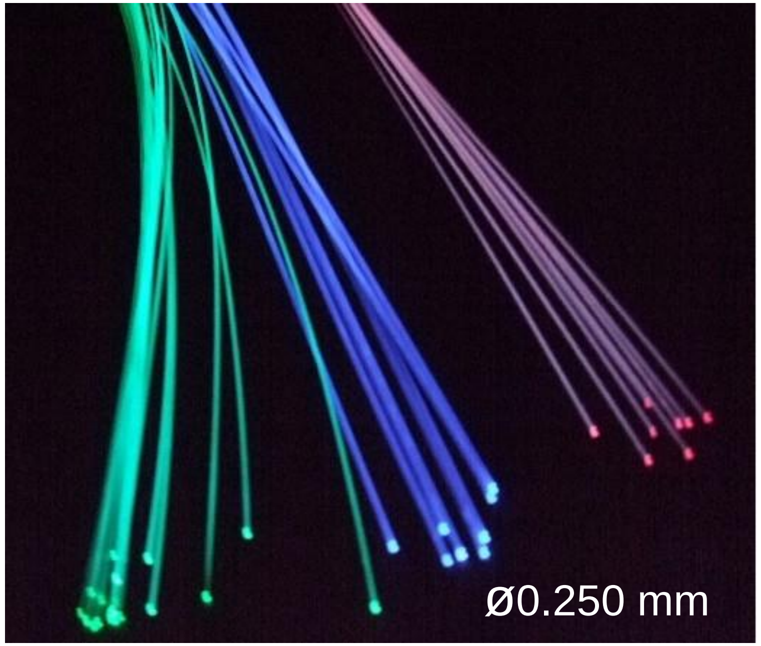
Chen, Nuclear Physics B (Proc. Suppl.) 145 (2005) 65–68



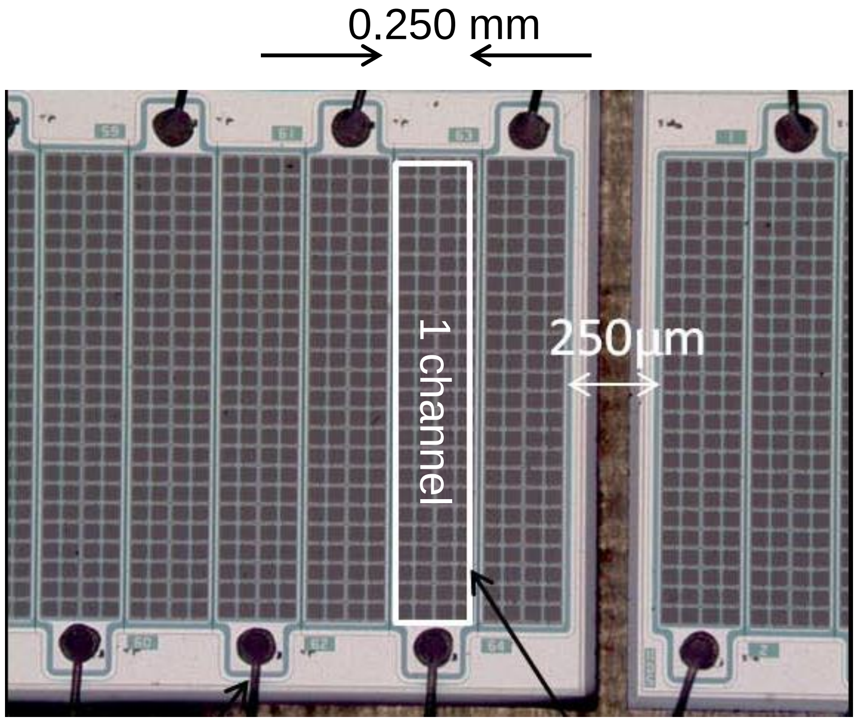
LHCb Upgraded Spectrometer



THE SCIFI TRACKER



Scintillating fibres



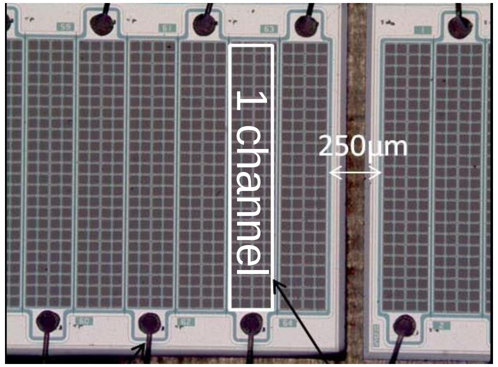
An array of pixelated silicon photomultipliers

TRACKER REQUIREMENTS

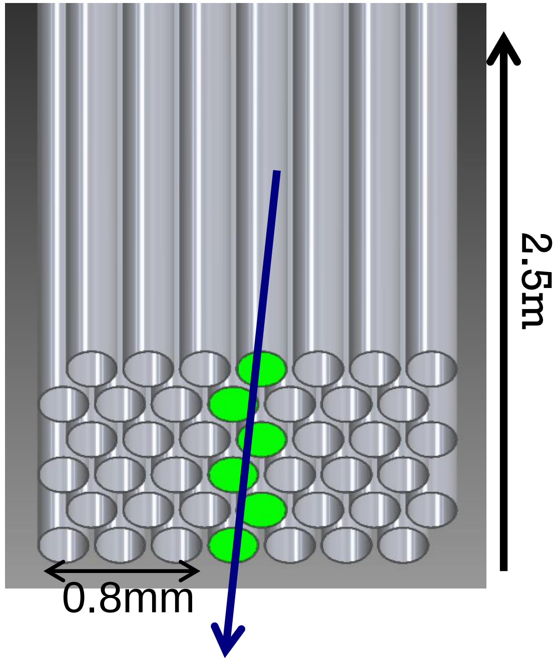
- Hit detection efficiency: single hits ~ 99% → Track reconstruction
- Low material budget for single detector layer ~1% X0 → Multiple scattering, Nuclear interactions
- Spatial resolution better: 100 μm in x-direction → Momentum resolution
- 40 MHz readout without dead time → Data rate / efficiency
- Radiation environment: Fibres: up to 35 kGy, → Signal/noise ratio
- SiPMs: approx. $1\cdot 10^{12}$n/cm^2 fluence + 100 Gy ionizing dose

BASIC PRINCIPLE

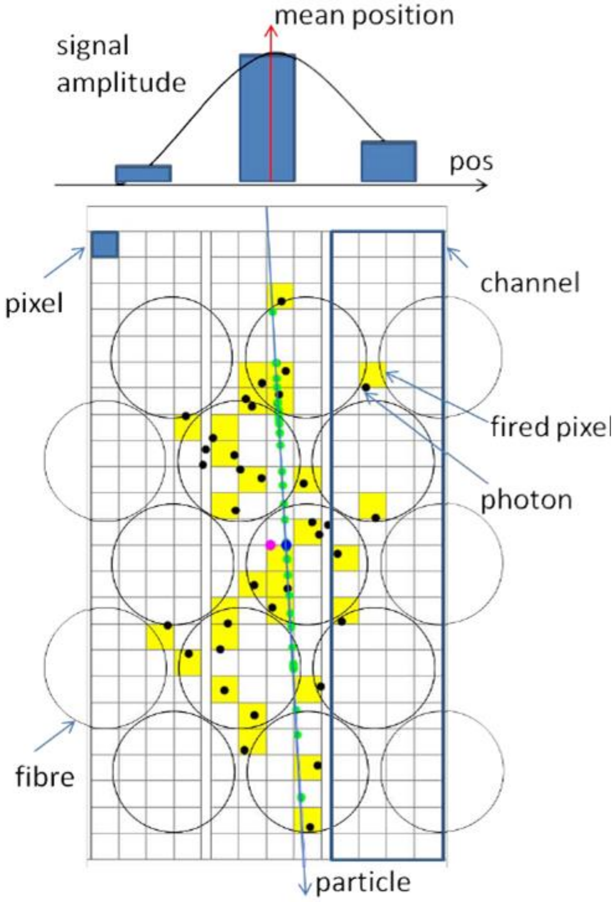
SiPM array



Scintillating Fibres (0.250mm diameter)

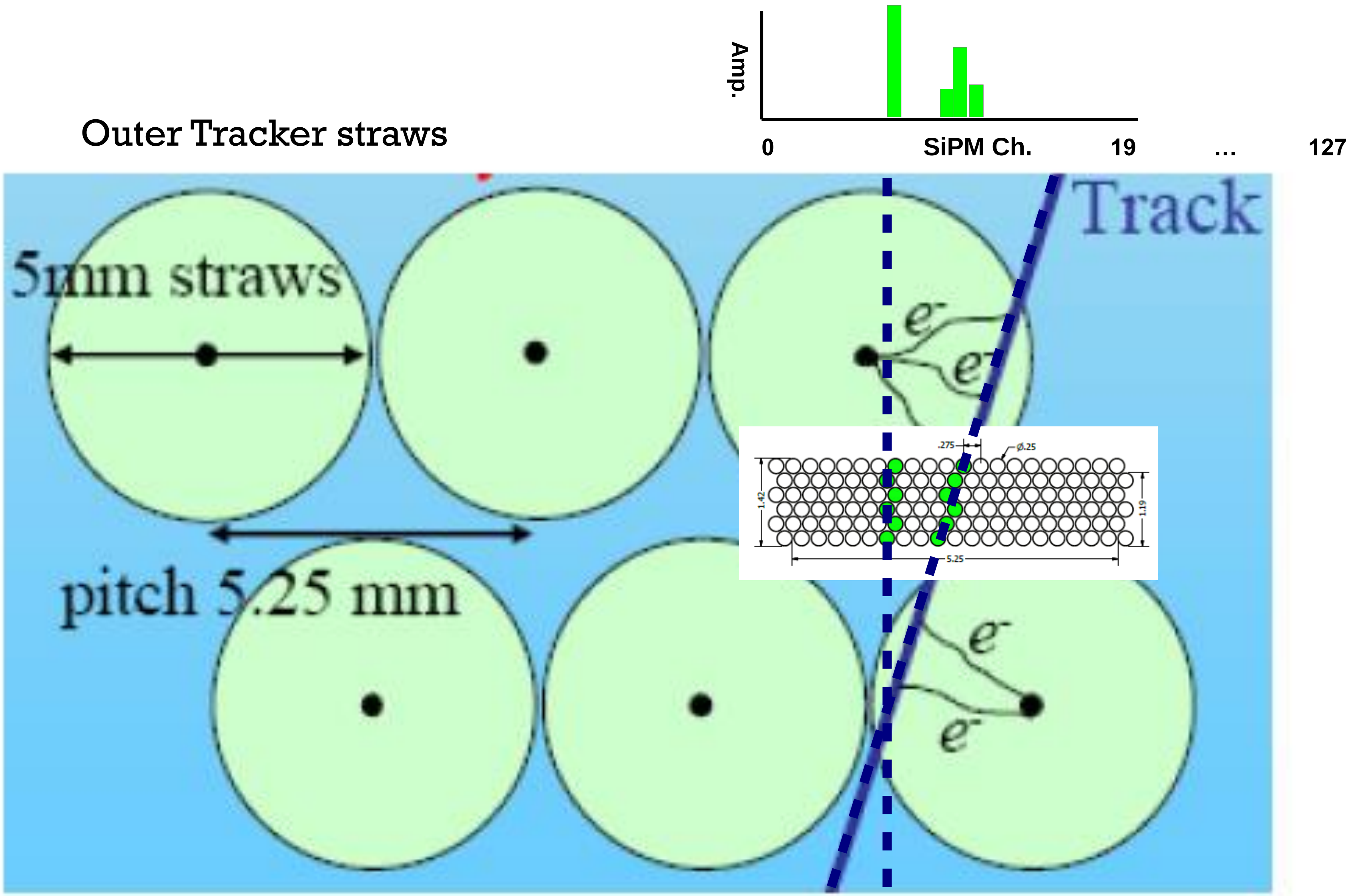


Signal cluster



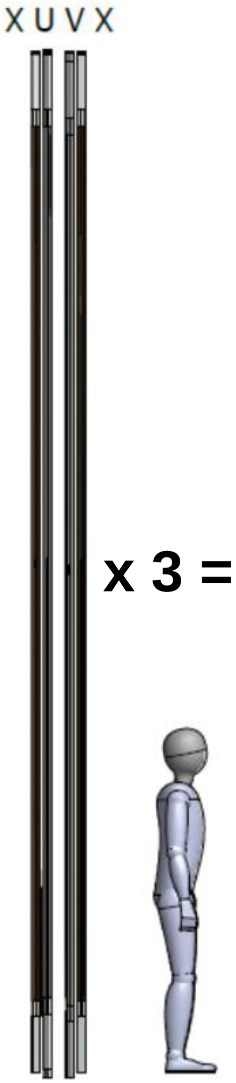
Typically one observe 15-20 photoelectrons for 5 layers of fibre

Outer Tracker straws

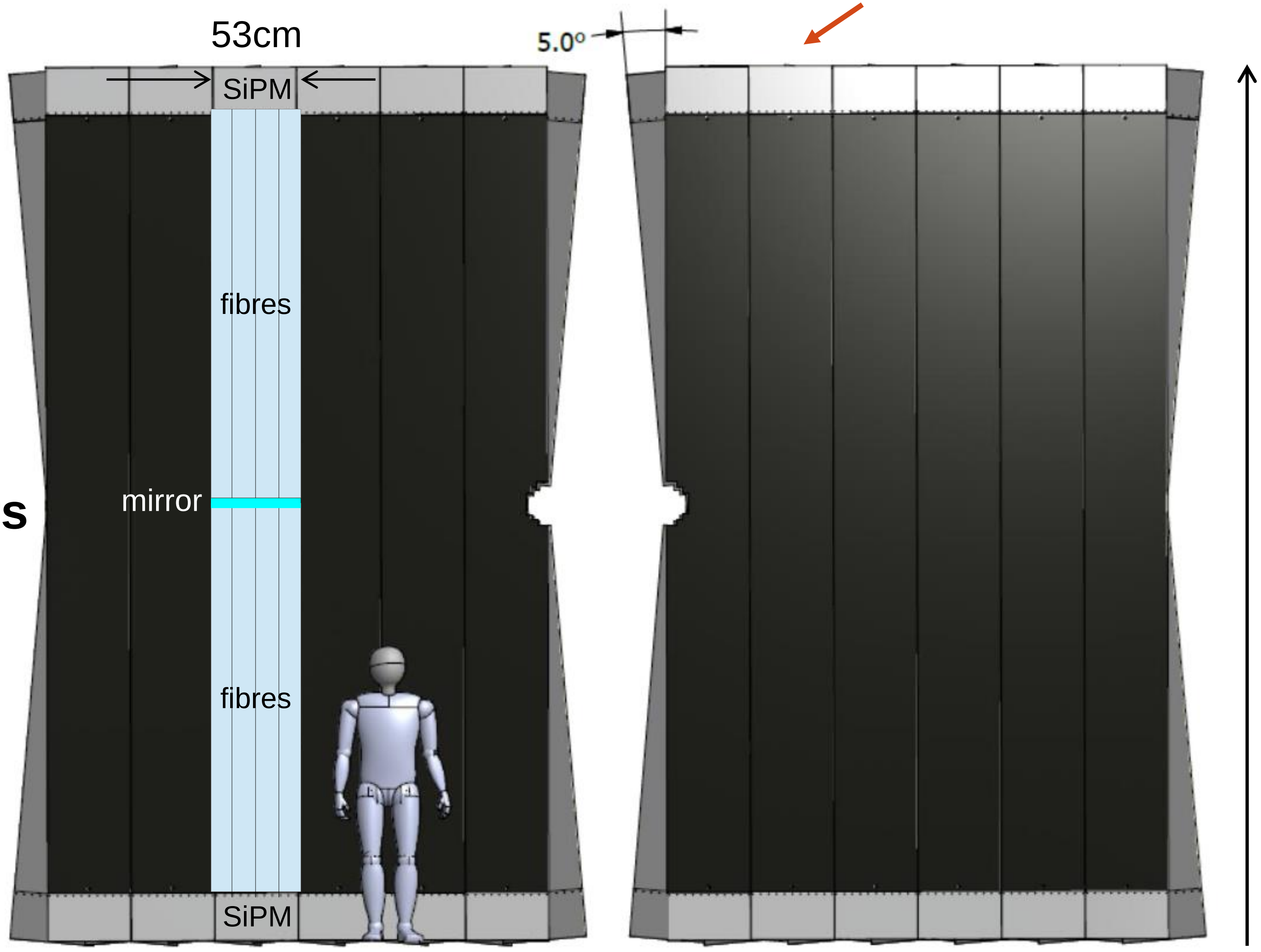


Approximately to relative scale

Modules are assembled in Heidelberg



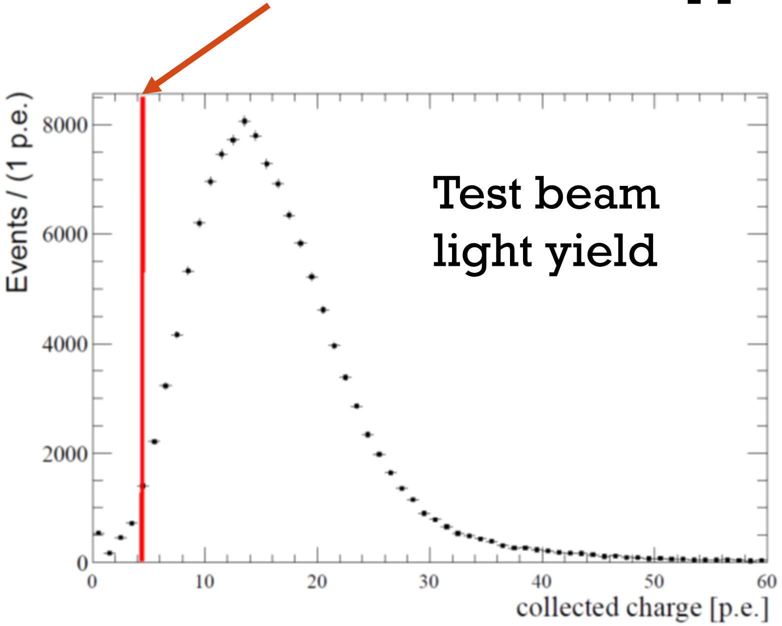
x 3 = 12 layers



CHALLENGES

- **Timing**
  - 2.8ns decay time of scintillator
  - 2.5m path length (15ns spread in arrival times)
  - 10ns pre-amp shaping time
    - Some charge is collected in the neighbouring bunch crossing
  - 25ns bunch crossing
  - PACIFIC asic being designed in Heidelberg

- **Light yield / hit efficiency**
  - 16-18 mean photoelectrons detected near the mirror
  - Sqrt(N) fluctuation in light yield
  - Threshold for dark noise suppression



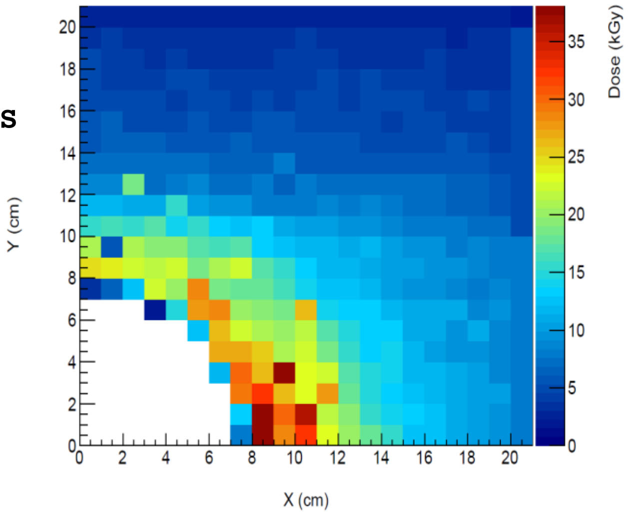
IONIZING RADIATION

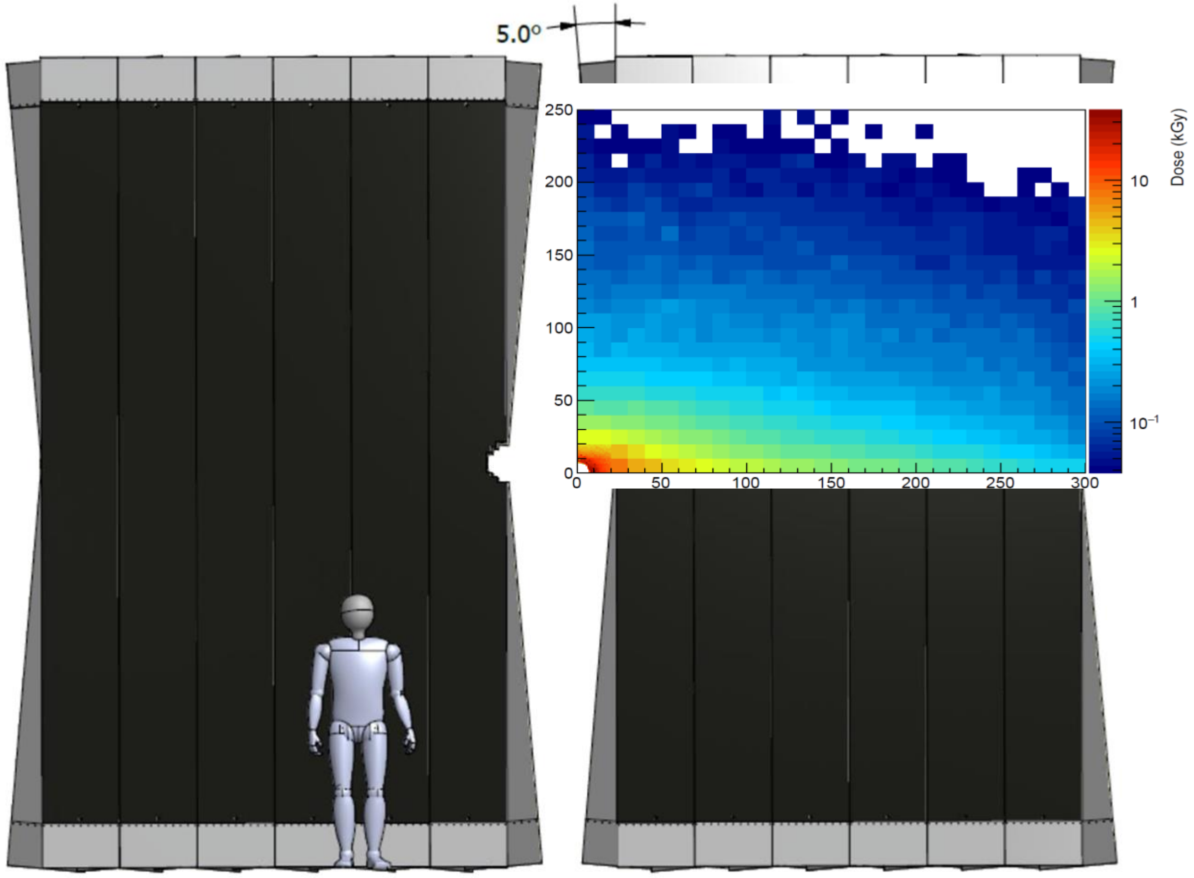
- Highest ionizing radiation damage is near the beam pipe

Max = 35 kGy @ 50fb^{-1}

- Reduces quickly away from the beampipe

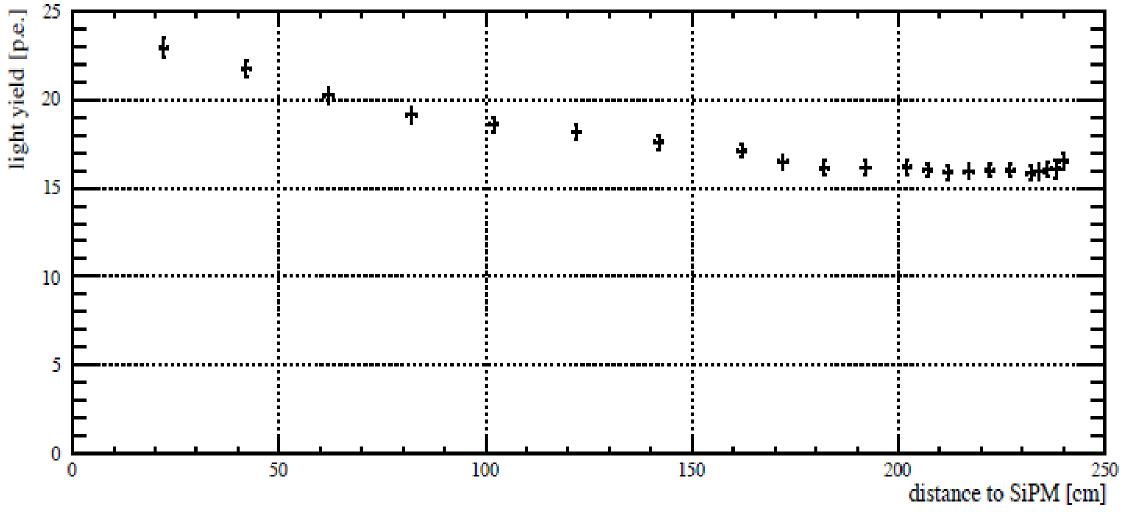
FLUKA simulations





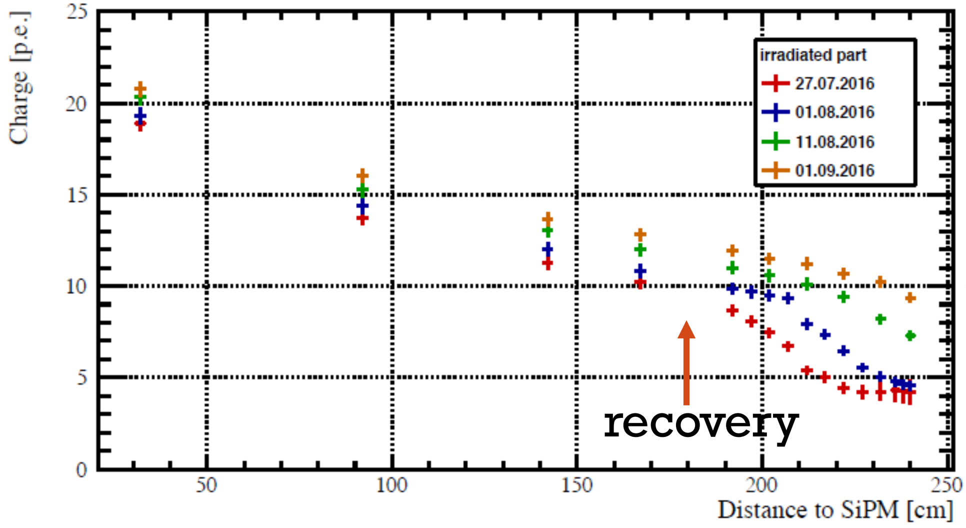
RADIATION DAMAGE

- Before irradiation



Distance in Y (cm)

- After 50 fb^{-1} irradiation (in worst region)
  - Transmission decreases from additional absorption centers



recovery

40% signal loss

Distance in Y (cm)

Improvements

- New SiPM with 50% PDE (vs 40%)
- Production fibre light yield has increased 10%

CONCLUSION

- Scintillators play a large roll in radiation detection and High Energy physics
- The physics is based on solid state crystals (inorganic) or organic molecules
- The scintillator is chosen based on the application
    - A wide range of properties
- The LHCb Scintillating Fibre tracker is the largest fibre tracker ever built
    - Must operate in a demanding environment = many challenges

GLOSSARY

- An **exciton** is a bound state of an electron and an electron hole which are attracted to each other by the electrostatic Coulomb force. It is an electrically neutral quasiparticle that exists in insulators, semiconductors and in some liquids. The exciton is regarded as an elementary excitation of condensed matter that can transport energy without transporting net electric charge. - Wikipedia
- a **phonon** is a collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, like solids and some liquids. Often designated a quasiparticle, it represents an excited state in the quantum mechanical quantization of the modes of vibrations of elastic structures of interacting particles. – Wikipedia
- **Hygroscopy** is the phenomenon of attracting and holding water molecules from the surrounding environment, which is usually at normal or room temperature. This is achieved through either absorption or adsorption with the absorbing or adsorbing substance becoming physically changed somewhat. This could be an increase in volume, boiling point, viscosity, or other physical characteristic or property of the substance, as water molecules can become suspended between the substance's molecules in the process. --Wikipedia