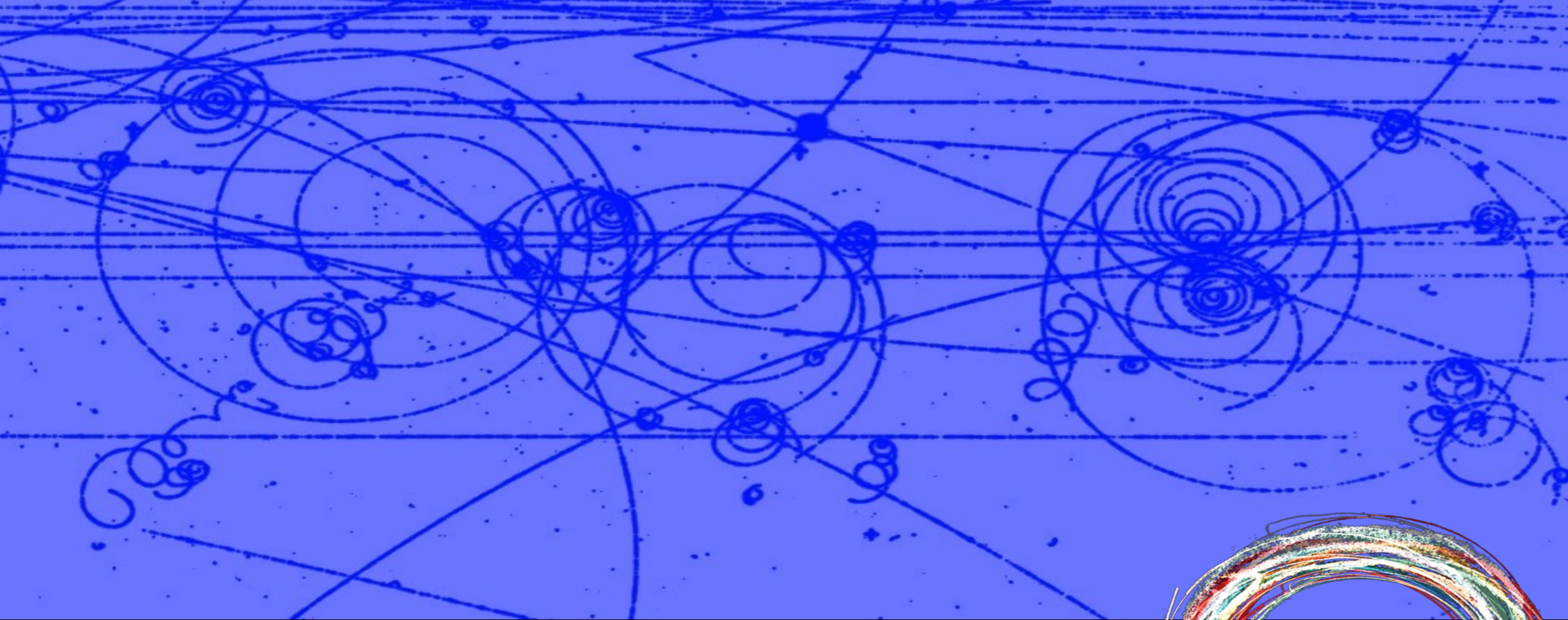
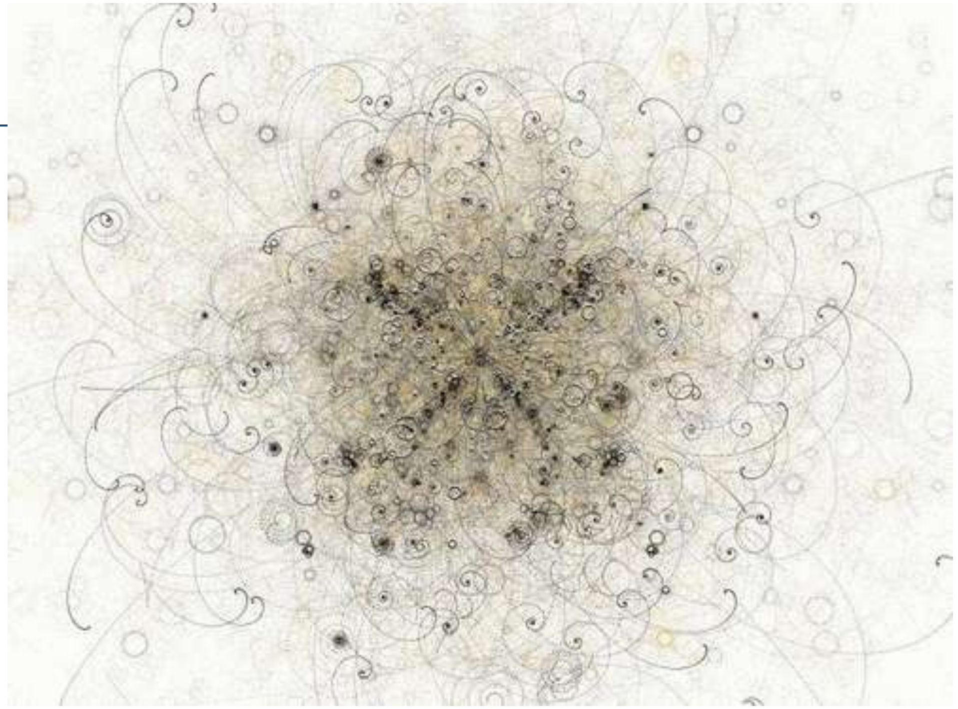


LECTURE 10
PARTICLE DETECTORS

PHY 493/803

Announcements



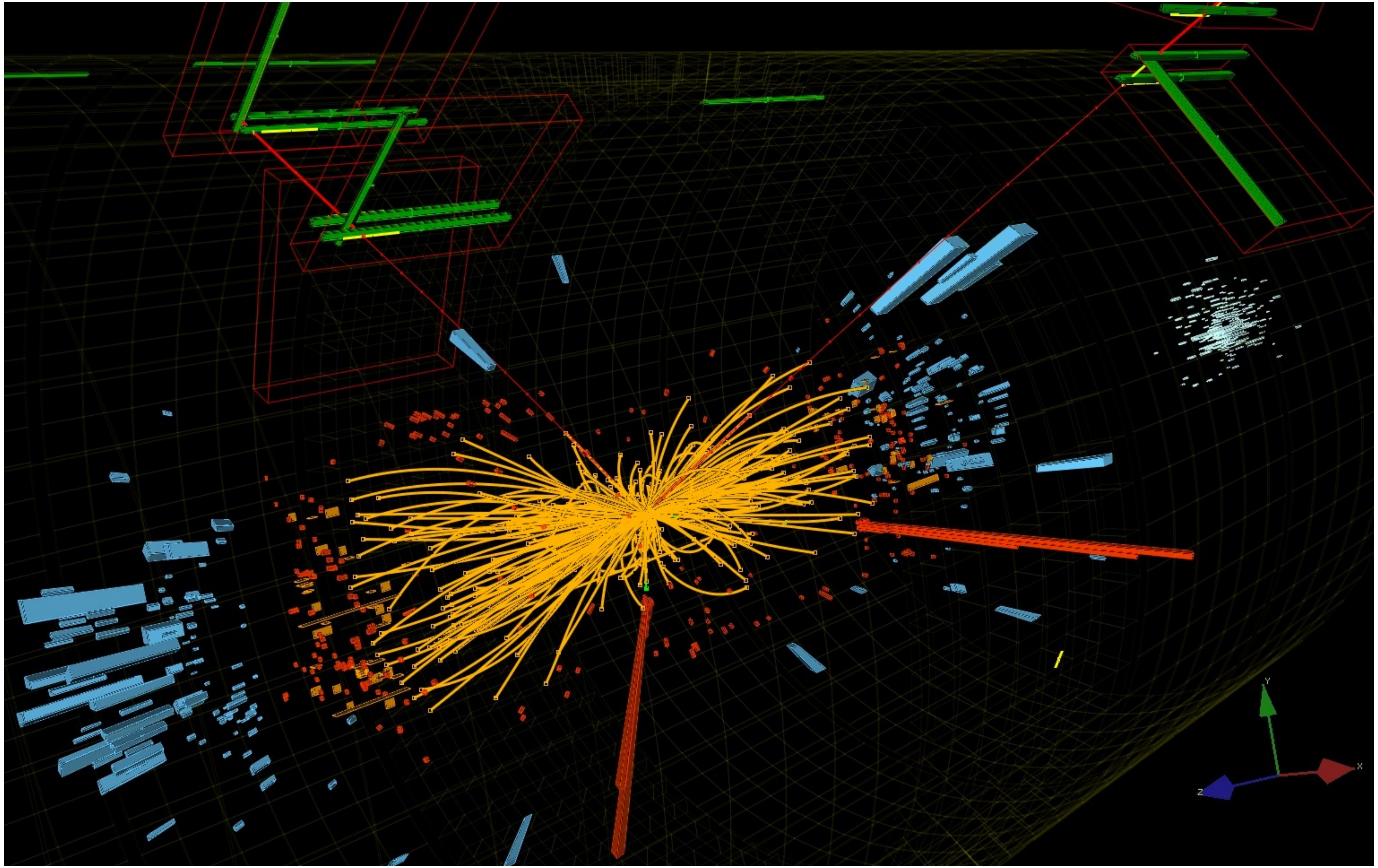
Quiz:
- Assorted quizzes from earlier weeks. Pick up after class.
- Next quiz today

Homework:
Fourth HW posted. Due date **March 24 at 3pm** on gradescope

Paper:
-Outlines returned on gradescope – please take a look; reach out if you have questions
-Draft deadlines:
- **<u>Optional</u>**, 3/28 in class: bring a paper copy to me by this date if you want feedback
- For credit, 4/11 at 3pm, on gradescope

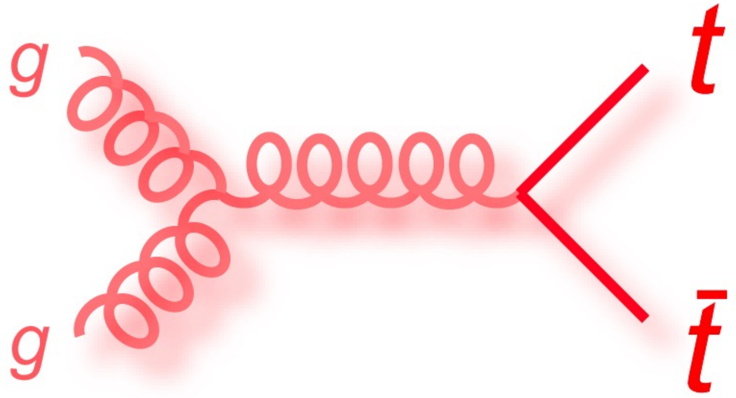
Midterm:
-Pick up graded midterms after class
-Will be curved to add 10 points to the score at the top of the page
- Note: your grade is the sum of your best four questions on the exam, the fifth question is not extra credit. in P803 it is the sum of question 5 and your best other three questions

Measuring Particles



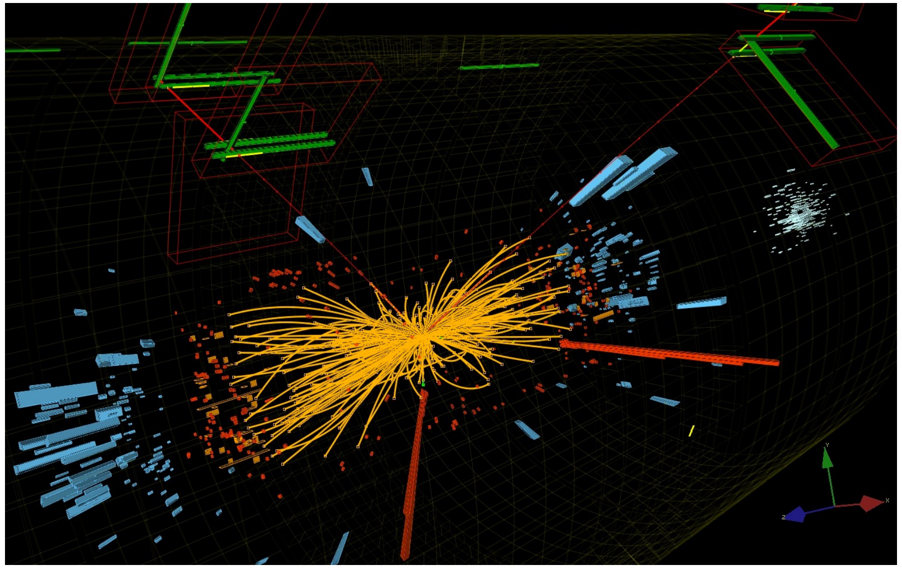
Particle detection

“Reconstruction” is the process of going from a signal in a detector to the particle properties

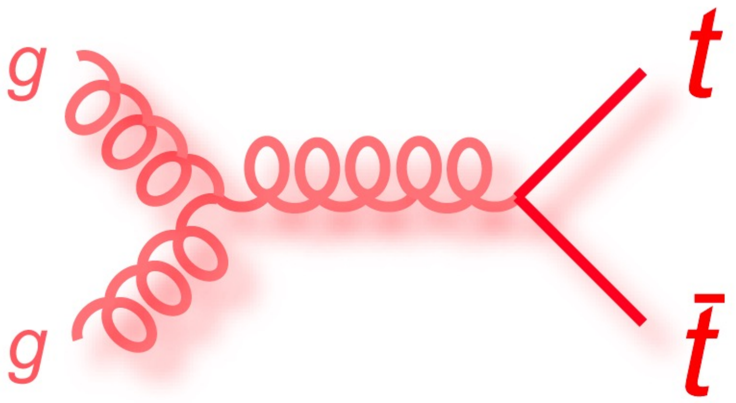


Would like to know:

1) How many particles were produced
2) The momentum of each particle
3) The energy of each particle
4) The charge of each particle
5) The mass of each particle
6) Spin & lifetime info also helpful

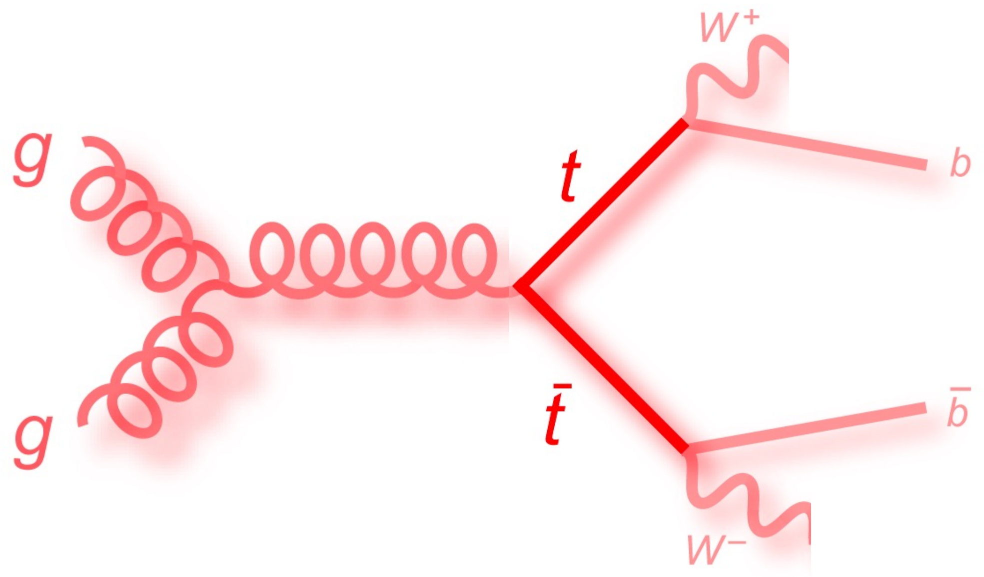


Typical interaction at the LHC



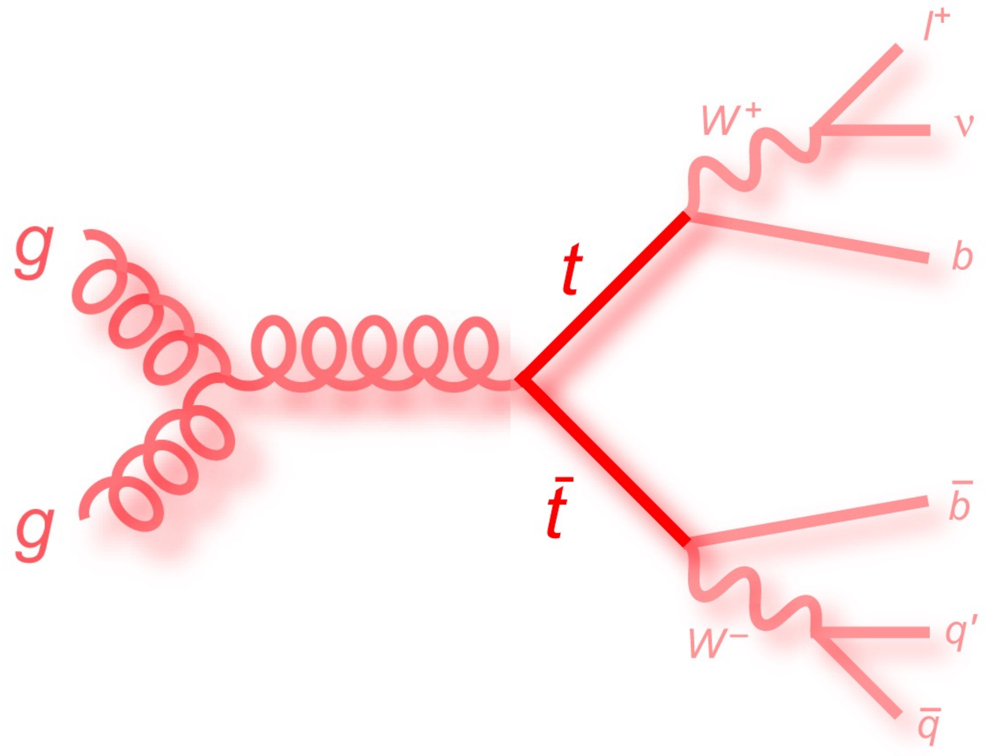
But:
- Top quarks decay
- Lifetime is too short for top quark to reach detector

Typical interaction at the LHC



But:
- W bosons decay
  - Lifetime is too short for W bosons to reach detector
- B-quarks hadronize into B mesons and baryons
  - Their lifetime is often too short to reach detector, further decays
- Tau lepton decays, lifetime is too short to reach detector
- Neutrinos escape detection

Typical interaction at the LHC



What's left for the detectors to detect?

- Electrons (and photons)
- Muons
- Quark jets
  - Mesons and baryons
  - Identify b-quark jets indirectly through their secondary vertices
- Infer present of neutrinos indirectly through momentum balance

Particle Detection & Identification

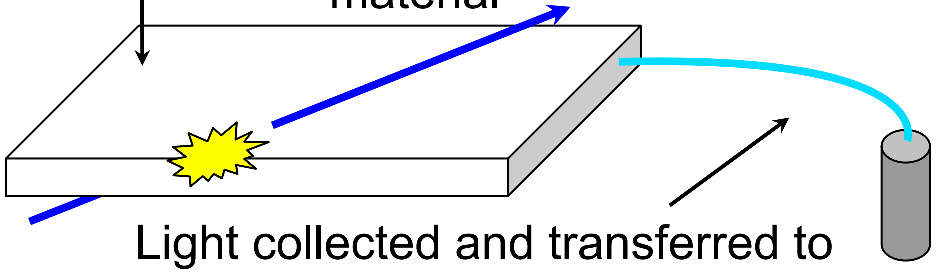
- There is no single detector that is best for every application.
- In practice, experimentalists use a number of different detectors

Gas	– gas ionization used to estimate position & energy → **tracking detectors**
Calorimeters	– intended to stop a particle & measure energy in the process → **energy & position measurement**
Spectrometers	– tracking detector in a magnetic field → **momentum & position measurement**
Scintillators	– excellent time resolution → **trigger of the system – timing information**
Solid-state	– employs the properties of semi-conductors → **excellent position & energy resolutions**
Cherenkov	– measure the velocity of a charged particle → **particle identification and timing information**

Particle Detection Basics

Scintillation light generated by excitation from particle charge

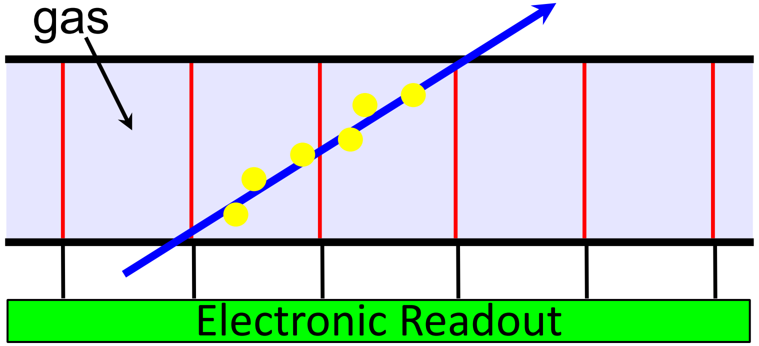
Plastic doped with scintillating molecules or crystal scintillating material



Light collected and transferred to photo-detector via fiber optics.

Gas ionization created by passing particle charge

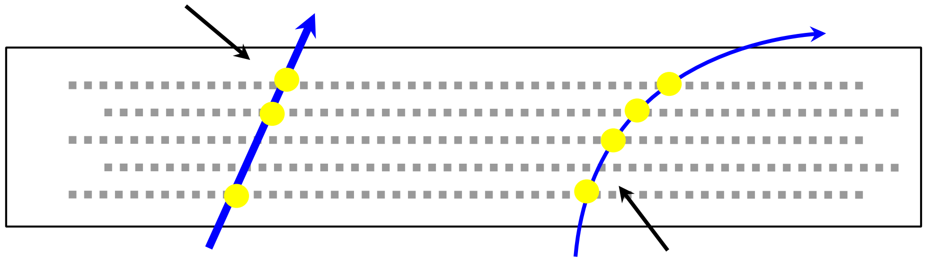
Pressurized gas



Ions are collected on anode wires **(red)** and signal recorded via electronic readout

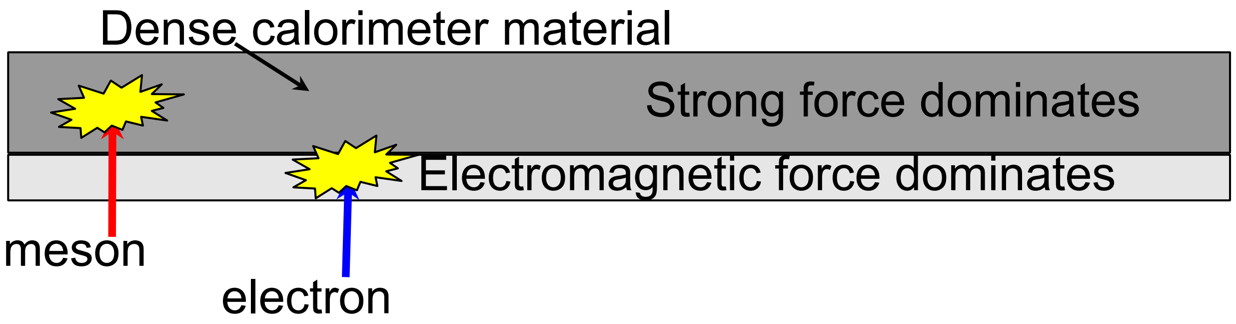
Semiconductor ionization created by passing particle charge

Particles ionize thin silicon layers and this charge can be collected to identify a "track"



By placing in a solenoidal magnetic field, Lorentz force on particle measures momentum

Energy measurement via calorimetry



Using dense materials sensitive to different interactions, stop particles and measure energy.

Particle Detection & Identification

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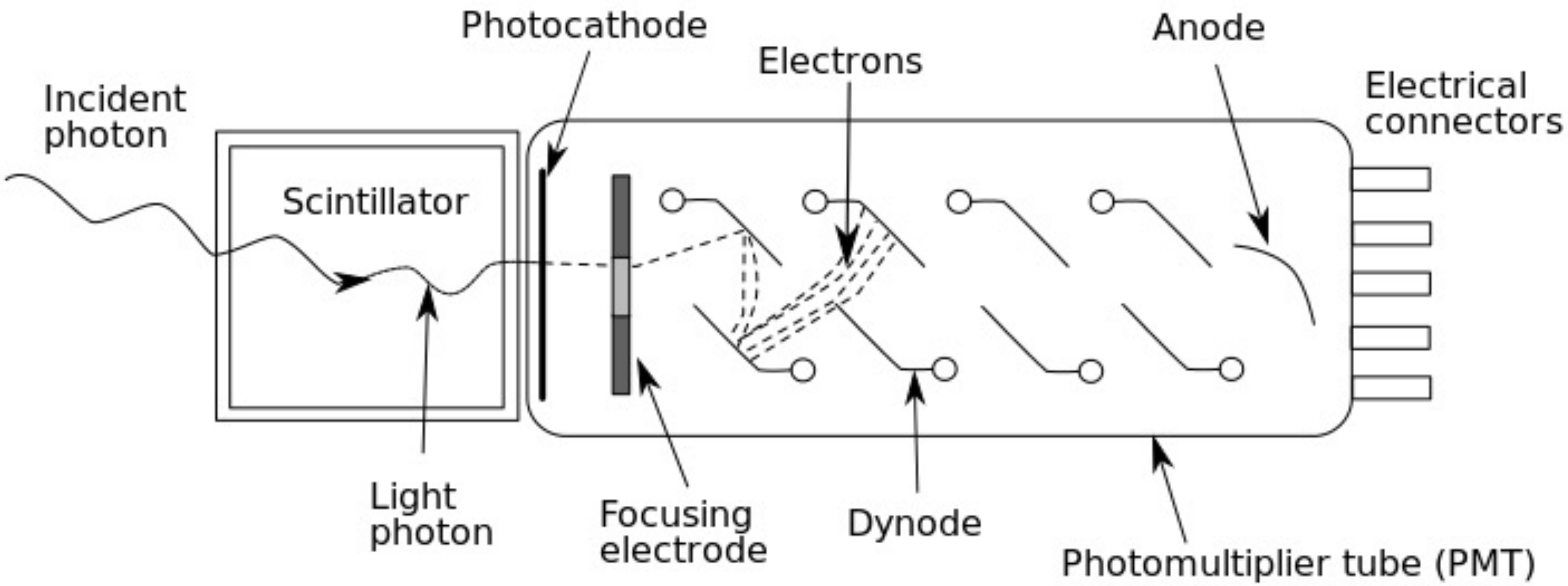
Light Detectors

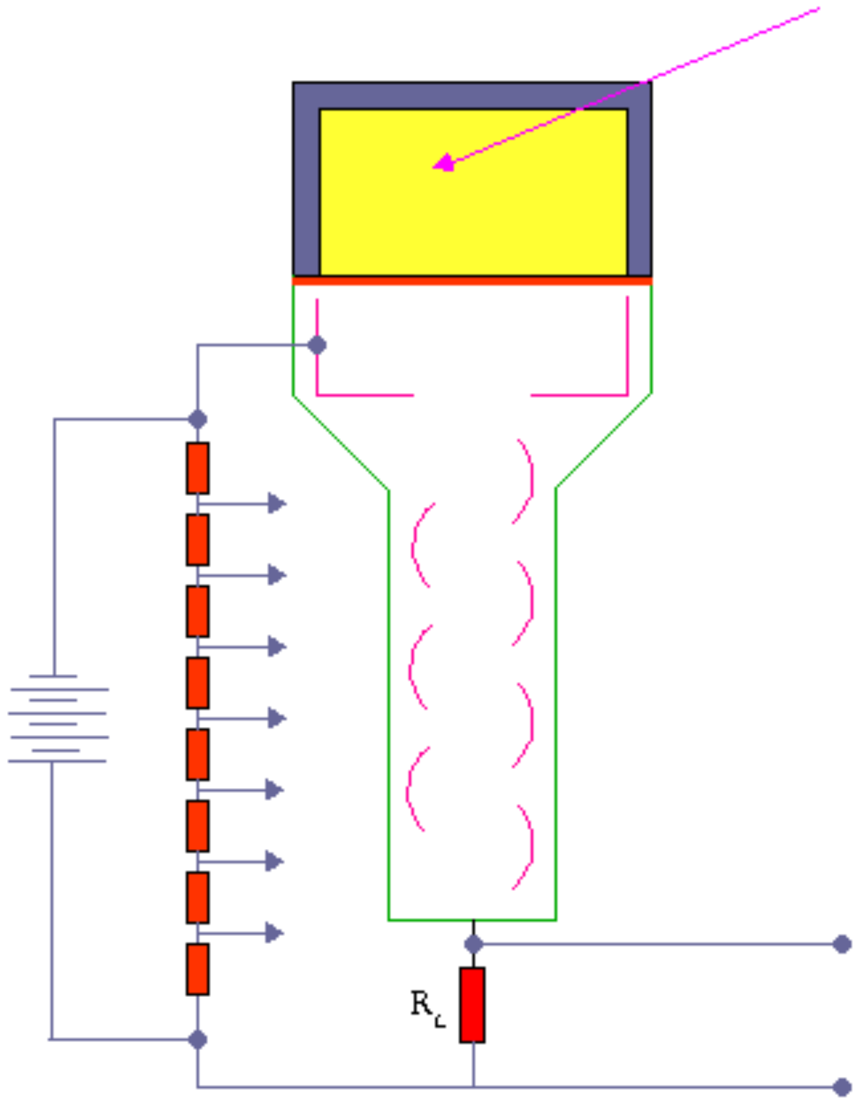
The Photomultiplier Tube

It's all in the name!

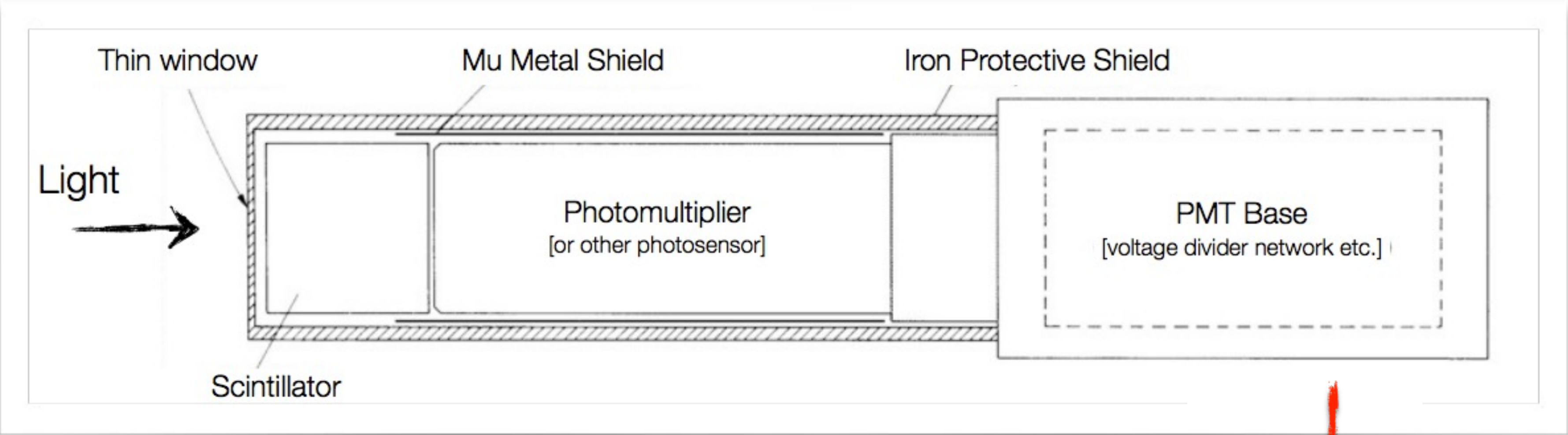
- The Photomultiplier Tube (PMT or Phototube) is designed to amplify the signal of a single photon
- Primary photon signal generated by the photo-electric effect
- ”Gain” in signal is achieved by collecting electrons through a series of voltage drops between ”Dynodes”.

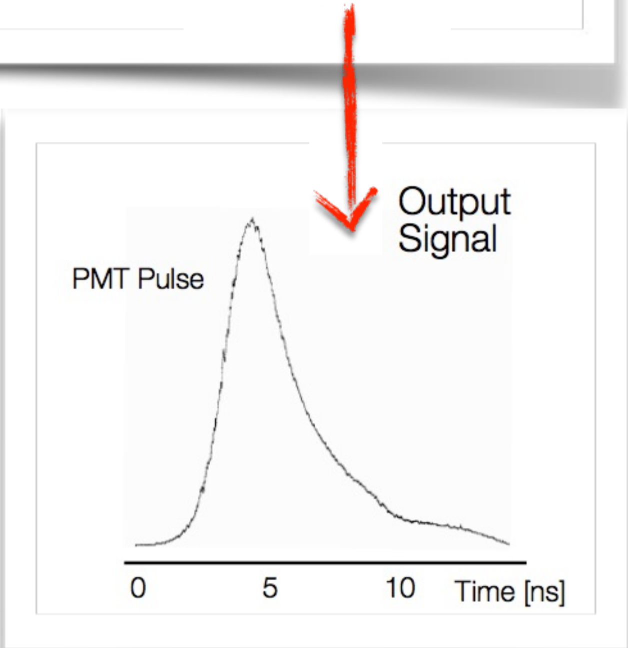


The Photomultiplier Tube



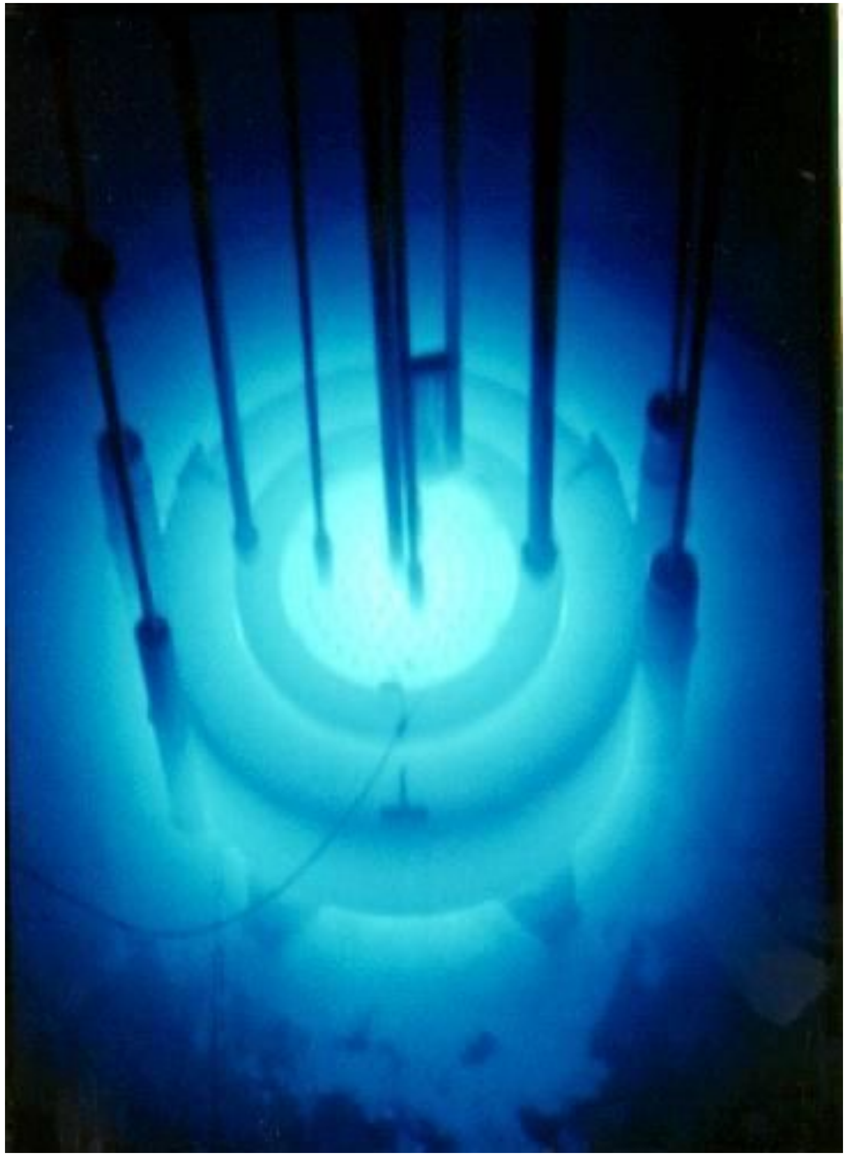
Basic Light Counter Setup





Photosensors:
- Photomultipliers
- Micro-Channel Plates
- Hybrid Photo Diodes
- Visible Light Photon Counter
- Silicon Photomultipliers

Cherenkov radiation

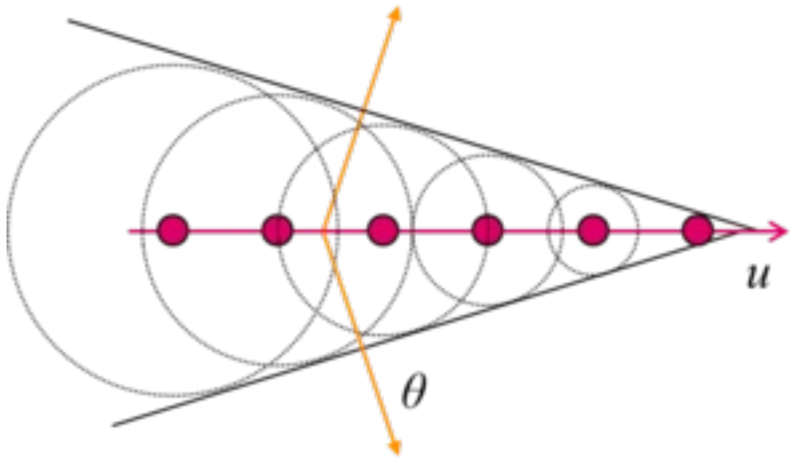


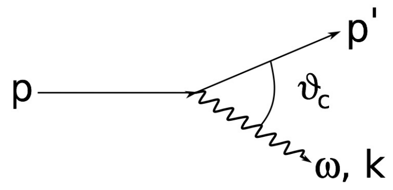
Cherenkov Radiation

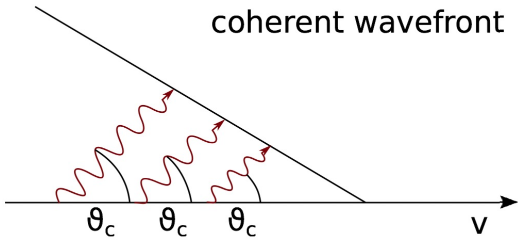
- Cherenkov light is produced when charged particles have speed of: $$v > \frac{c}{n}$$
- Minimum momentum to produce Cherenkov light: $$p_{min} = \frac{mc}{\sqrt{n^2 - 1}}$$
  - Called "Cherenkov threshold"
- Light is produced in a cone around trajectory of particle

- The medium is a dielectric
- Index of refraction of the medium $n = \frac{c}{c_m}$, where c_m is the speed of light in the medium
  - Water: n=1.3

Cherenkov radiation







- Photons are emitted at characteristic angle θ_c

$$\cos\theta_c = \frac{\omega}{kv} = \frac{1}{n\beta}$$

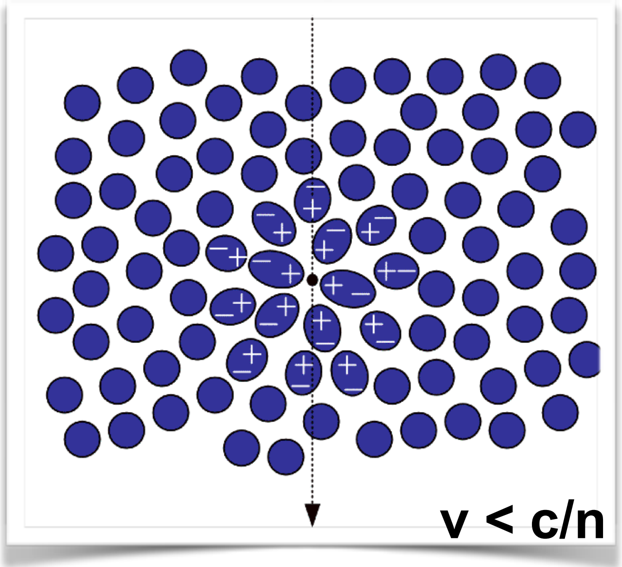
- Coherent wavefront of Cherenkov light
- Photons are soft, short wavelength $\omega \ll \gamma M c^2$
- Energy loss is negligible compared to ionization

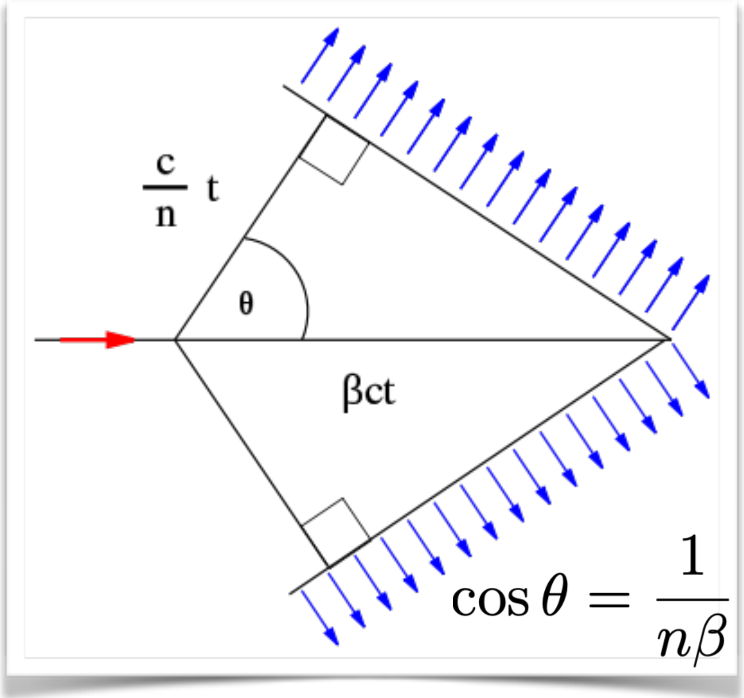
Cherenkov Radiation

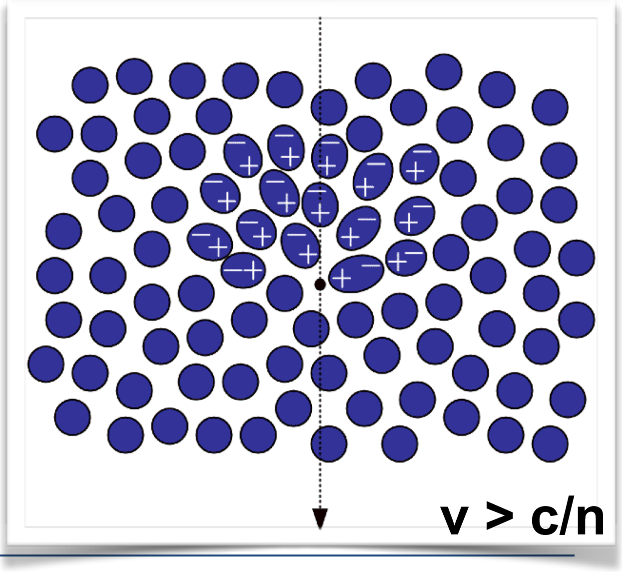
Cherenkov Radiation

<u>A polarization effect:</u>

- Charged particles polarize the dielectric medium as they pass through
- For v<c/n, the polarization is symmetric and there is no coherent electric field induced at long distances.
- For v>c/n, the polarization is asymmetric and the collapse of the polarization state causes the atoms to emit Cherenkov radiation.

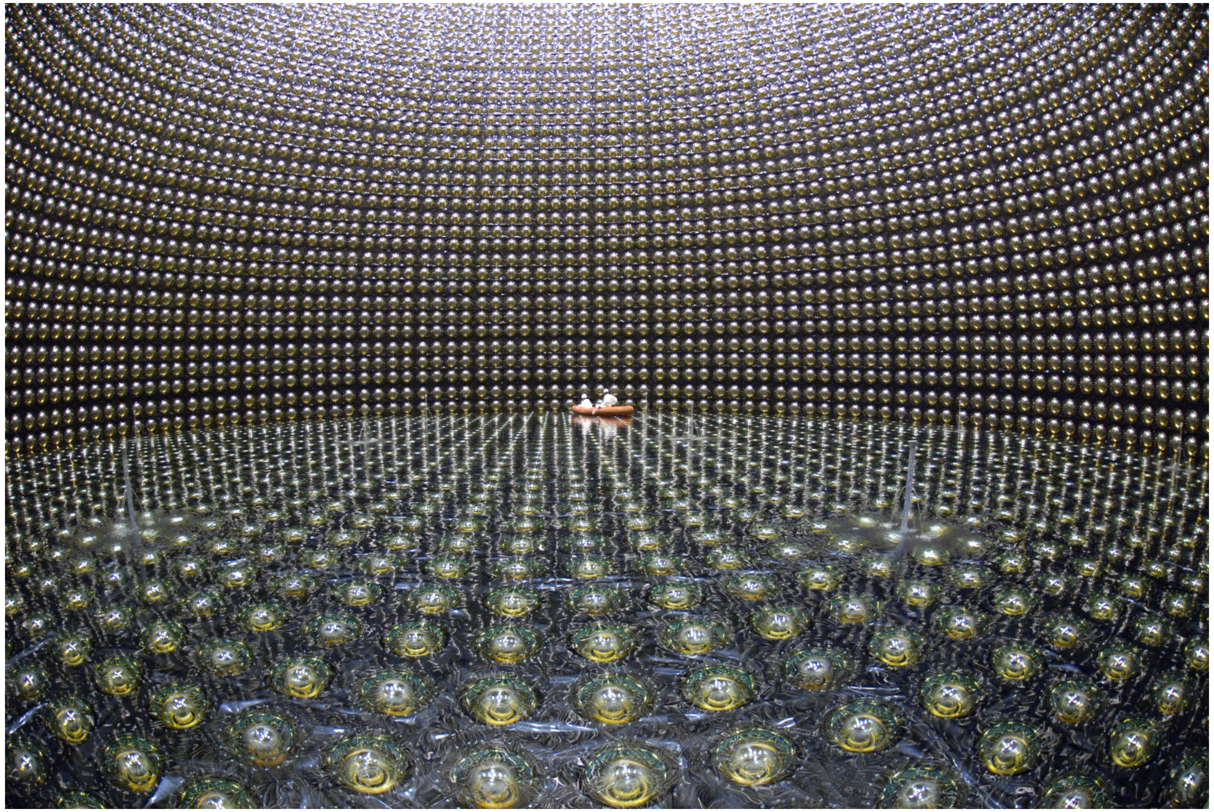




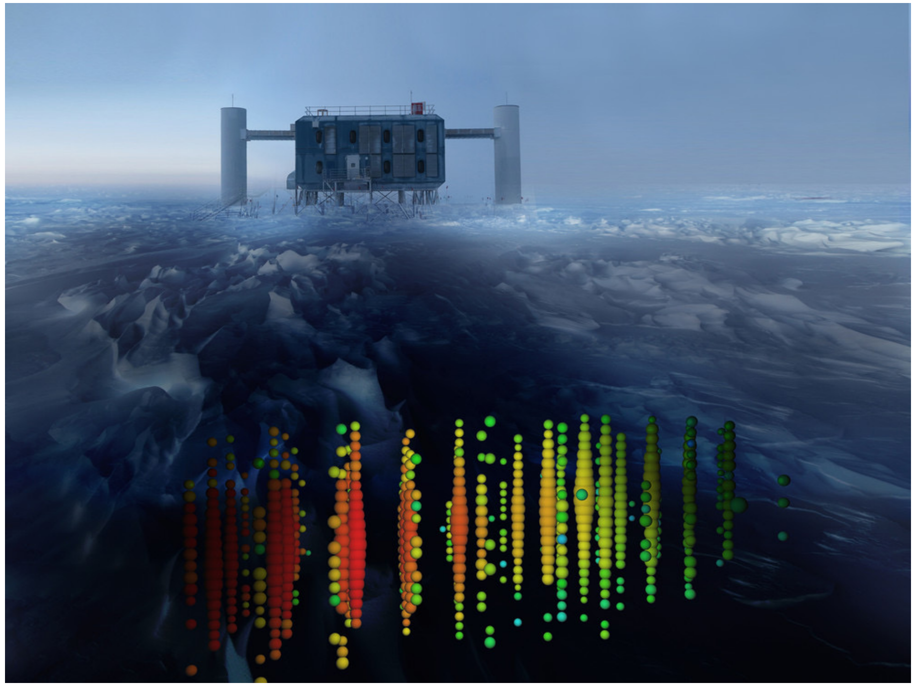


Cherenkov Detectors

Super Kamiokande

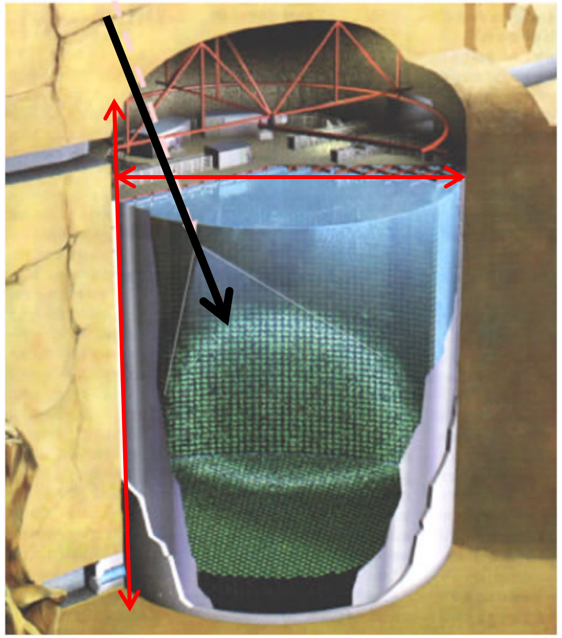


IceCube

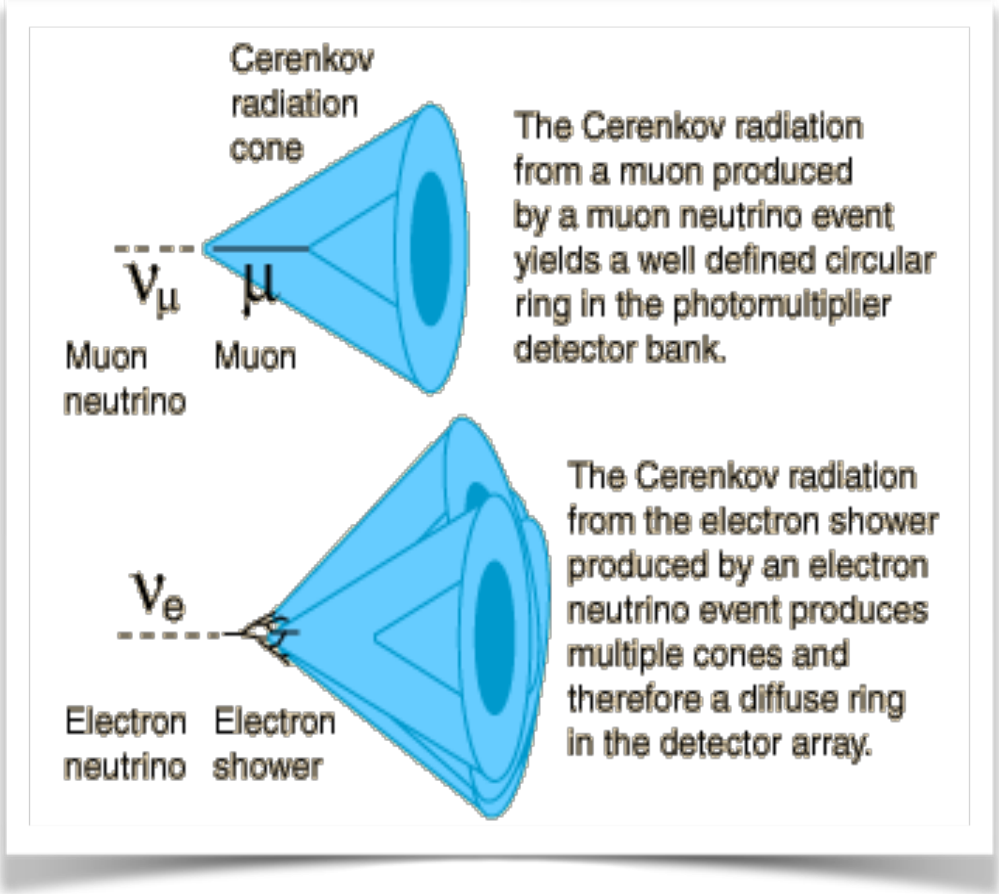


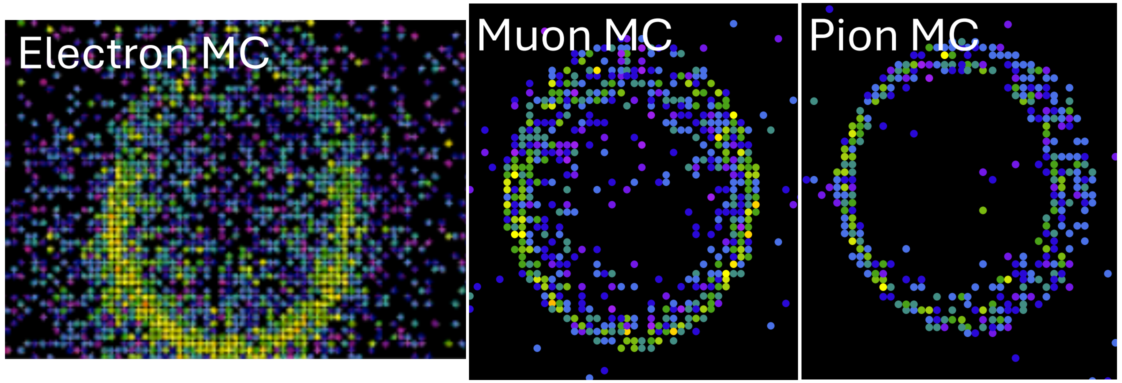
Example: Super-Kamiokande detector

- Neutrino oscillation measurements and proton decay searches
- Super-K: 50,000 tons of water
- 13,000 photodetectors
- Recording Cherenkov radiation of charged particles produced in neutrino interactions in the detector

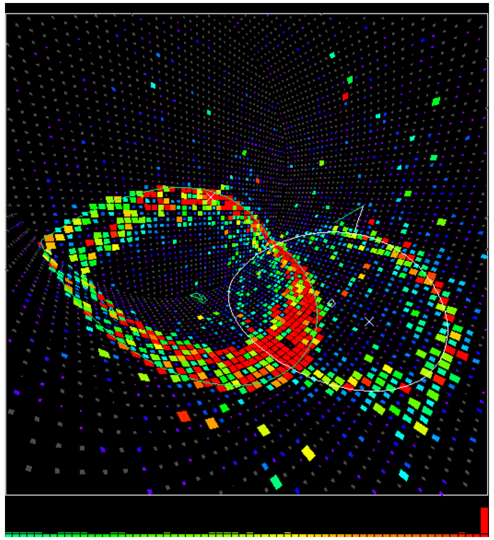


Cherenkov Detectors

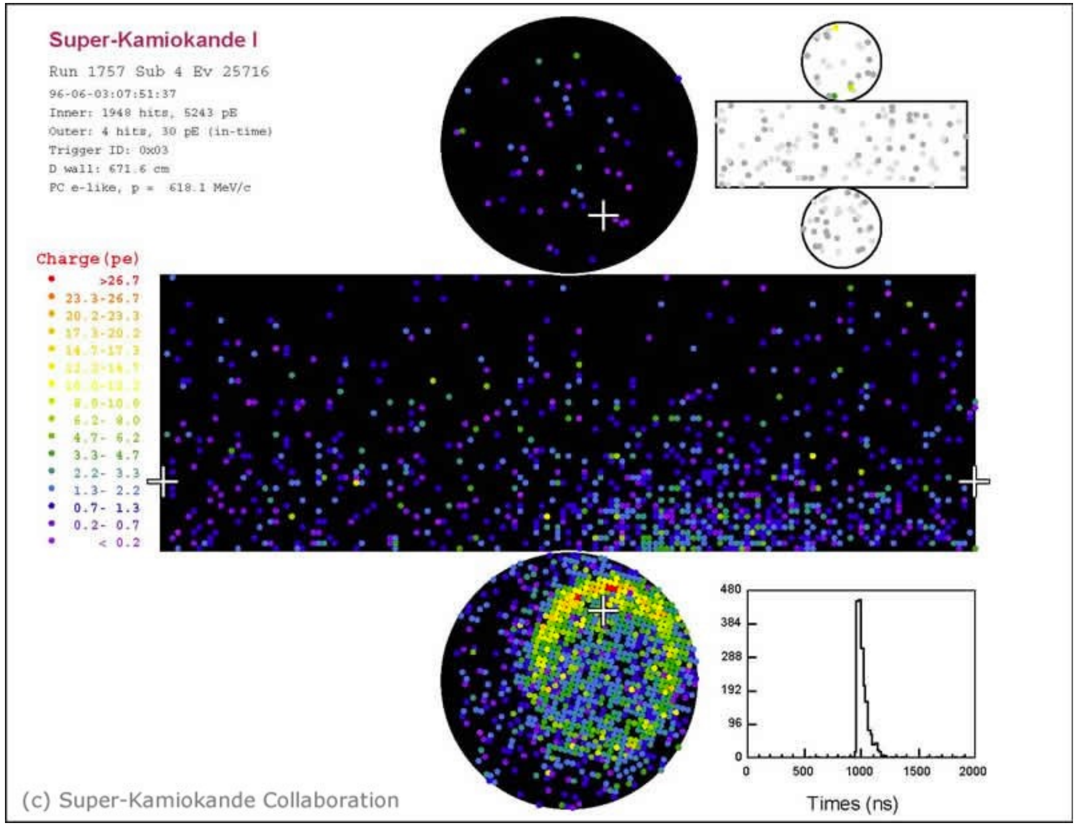




Multi-Ring Events

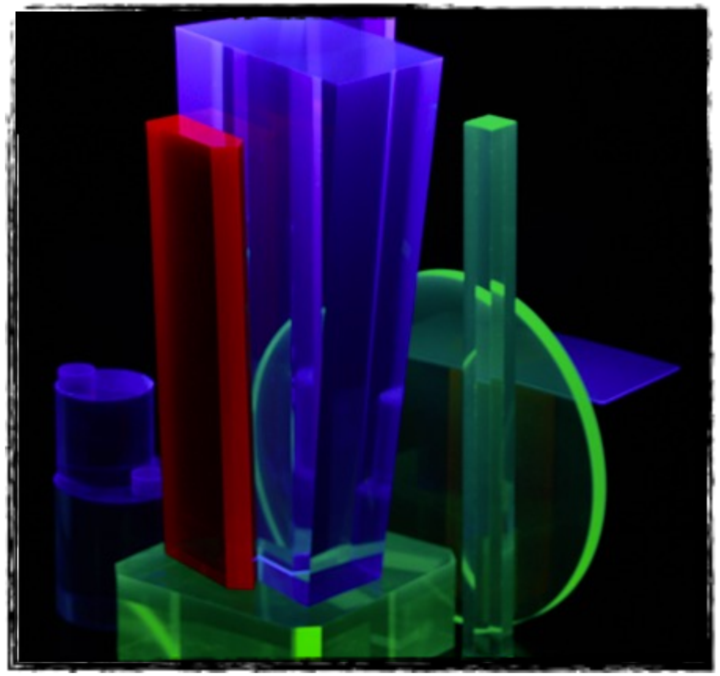


Super-K event Example



Live Event Display: https://www-sk.icrr.u-tokyo.ac.jp/realtimemonitor/

Scintillators



Principle:

- Charged particles lose energy in material
- Atomic excitation
- dE/dx converted into visible light via luminescence
- Detection via photosensor, [e.g. photomultiplier, human eye …]

Main Features:

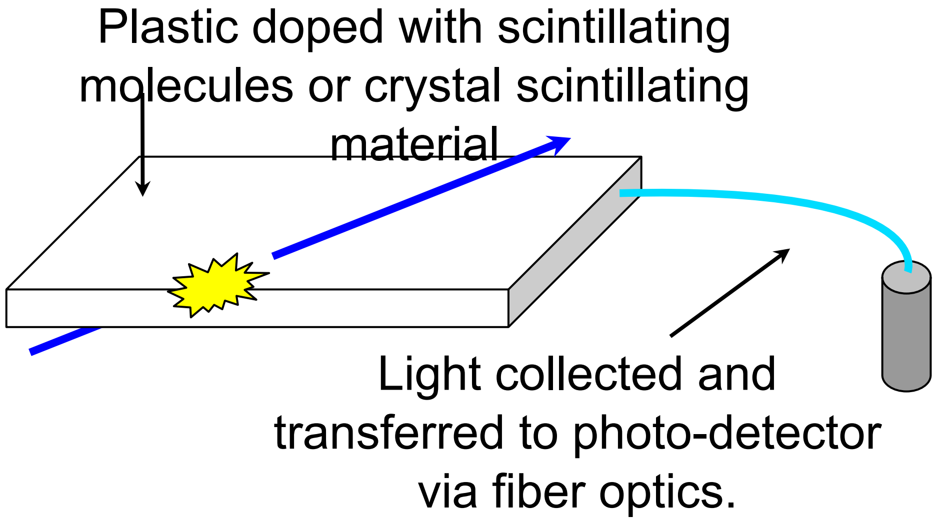
- Sensitivity to energy
- Fast time response
- Pulse shape discrimination

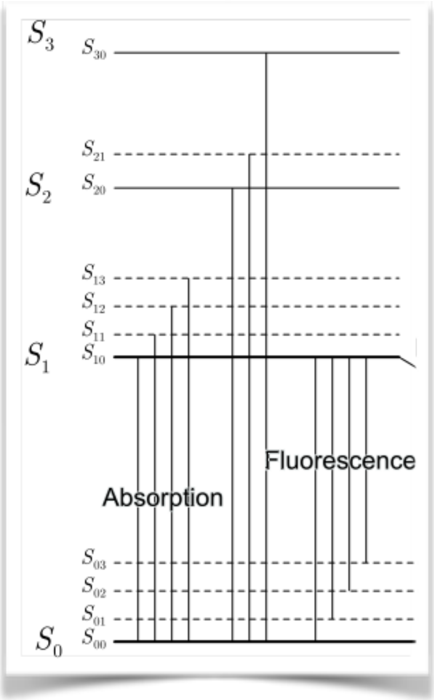
Requirements:

- High efficiency for conversion of excitation energy to fluorescent radiation
- Transparency to its fluorescent radiation to allow transmission of light
- Emission of light in a spectral range detectable for photosensors
- Short decay time to allow fast response

Scintillation Detectors

Scintillation light generated by excitation from particle charge

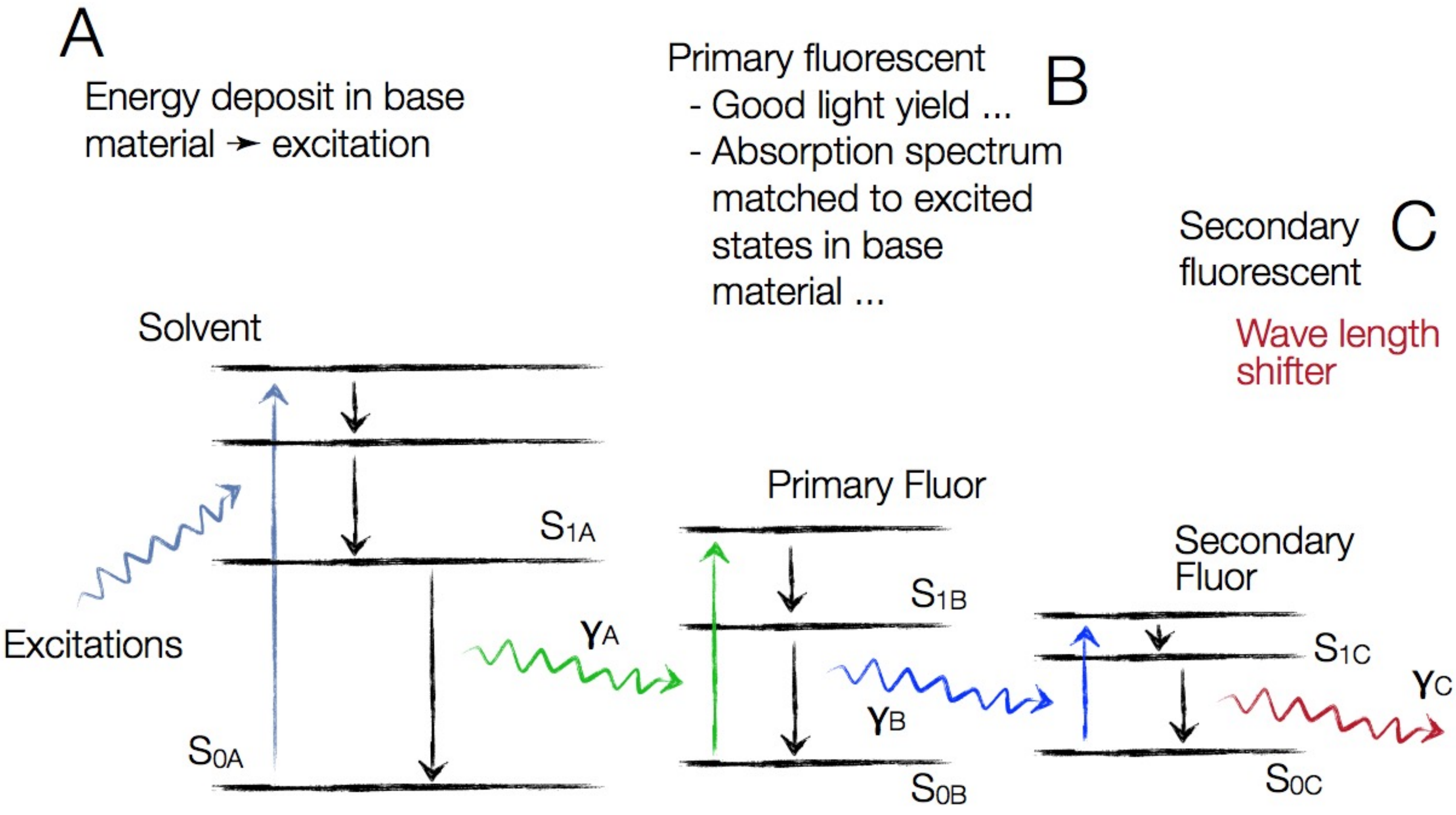




Scintillation detectors:

- The charged particles lose their energy due to excitation and ionization in the medium of the detector.
- In *scintillators* one can expect to obtain a small fraction of the excitation energy as visible (or UV region) light. Typically 50-300 eV per excitation.

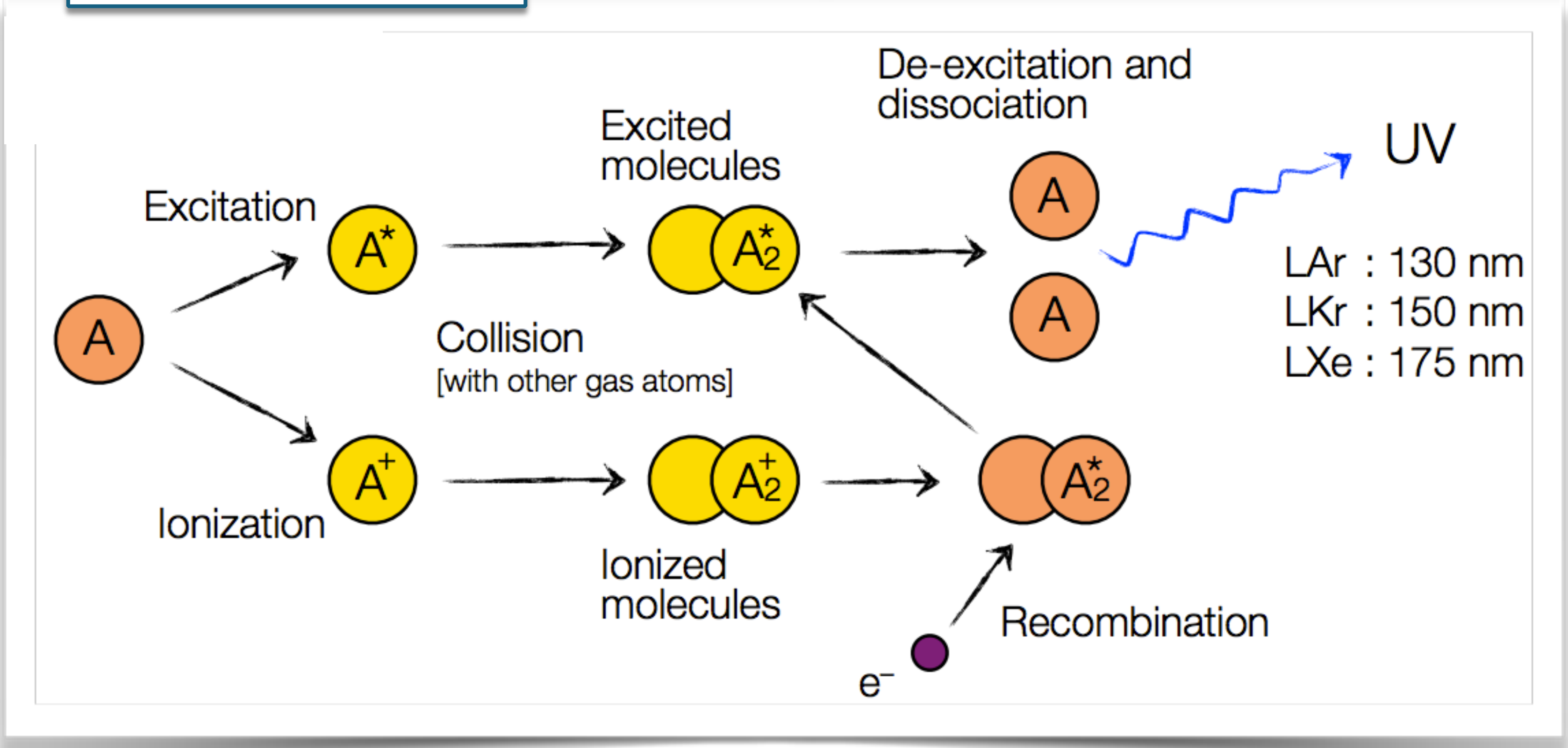
Scintillator Example



Scintillation in Nobel Gases

Materials:
- Helium (He)
- Liquid Argon (LAr)
- Liquid Xenon (LXe)
- …

Decay time constants:
- Helium : τ1 = .02 μs, τ2 = 3 μs
- Argon : τ1 ≤ .02 μs



Scintillator Examples

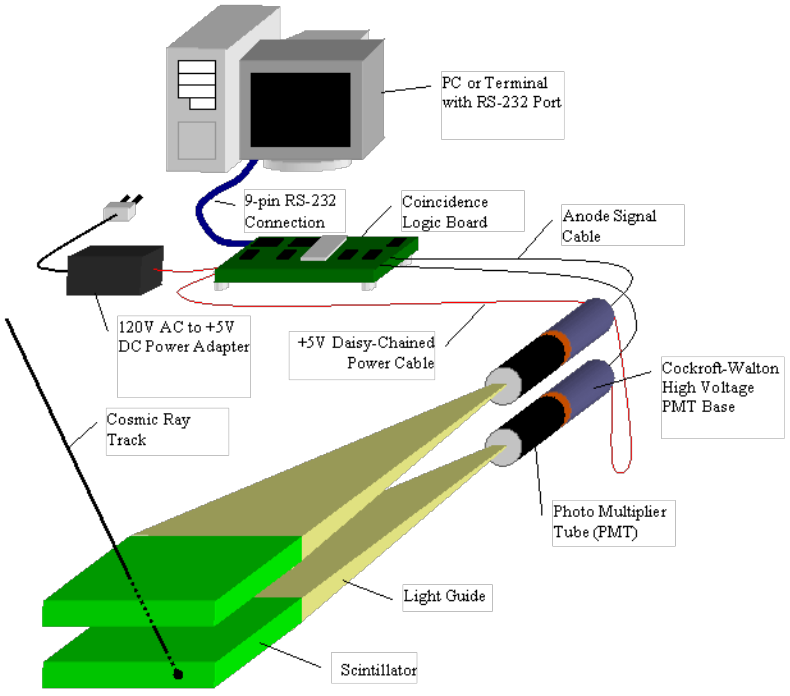
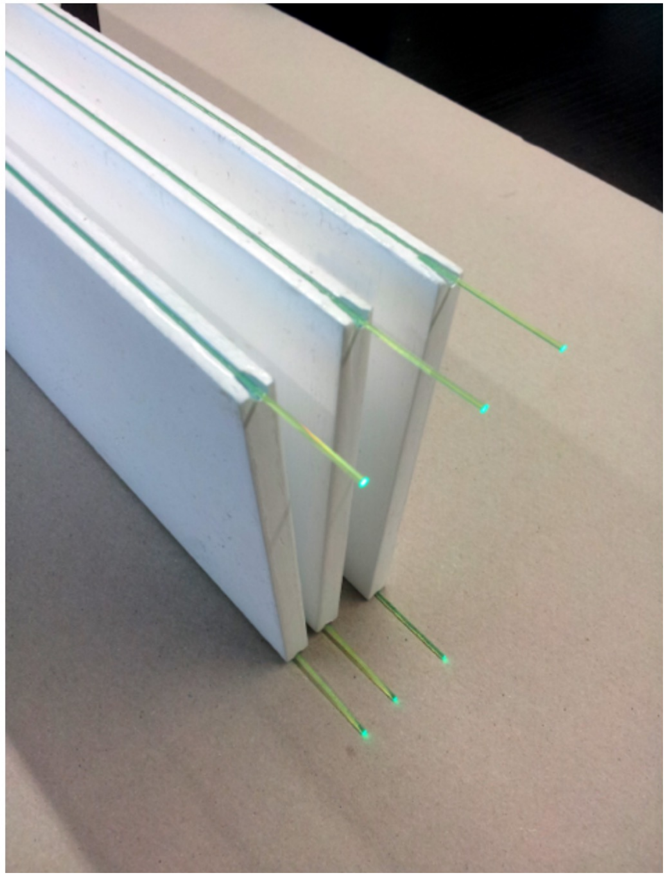
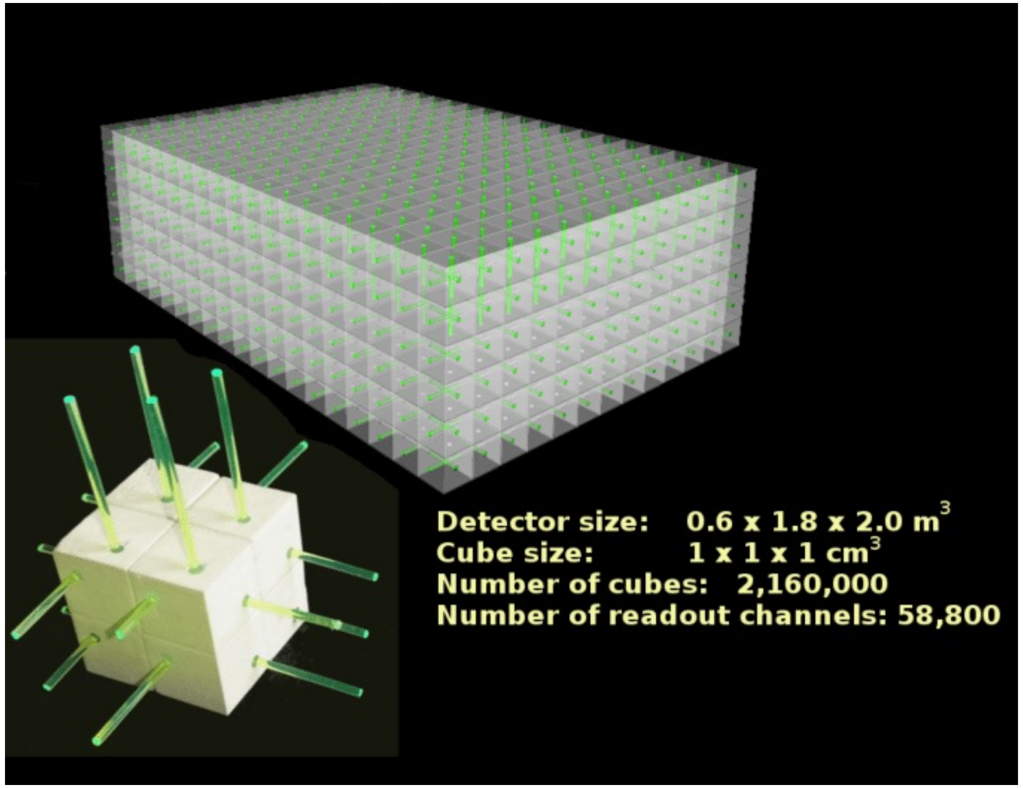


Figure 1. QuarkNet Cosmic Ray Detector System

MicroBooNE Cosmic Ray Tagger



T2K Super FGD



Inorganic Crystals

Materials:

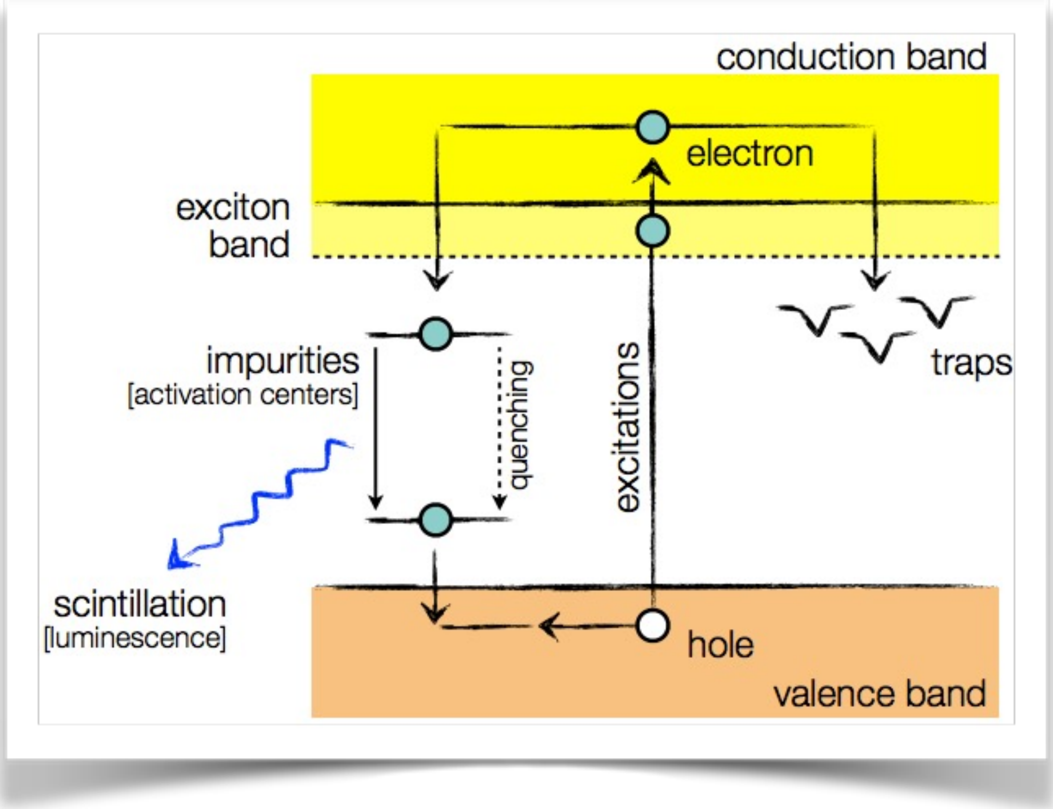
- Sodium iodide (NaI)
- Cesium iodide (CsI)
- Barium fluoride (BaF2)
- ...

Mechanism:

- Energy deposition by ionization
- Energy transfer to impurities
- Radiation of scintillation photons

Time constants:

- Fast: recombination from activation centers [ns ... μs]
- Slow: recombination due to trapping [ms ... s]



Energy bands in impurity activated crystal showing excitation, luminescence, quenching and trapping.

~200-300 eV per electron-hole pair