Physics of Particle Detectors

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Summer Lecture Series
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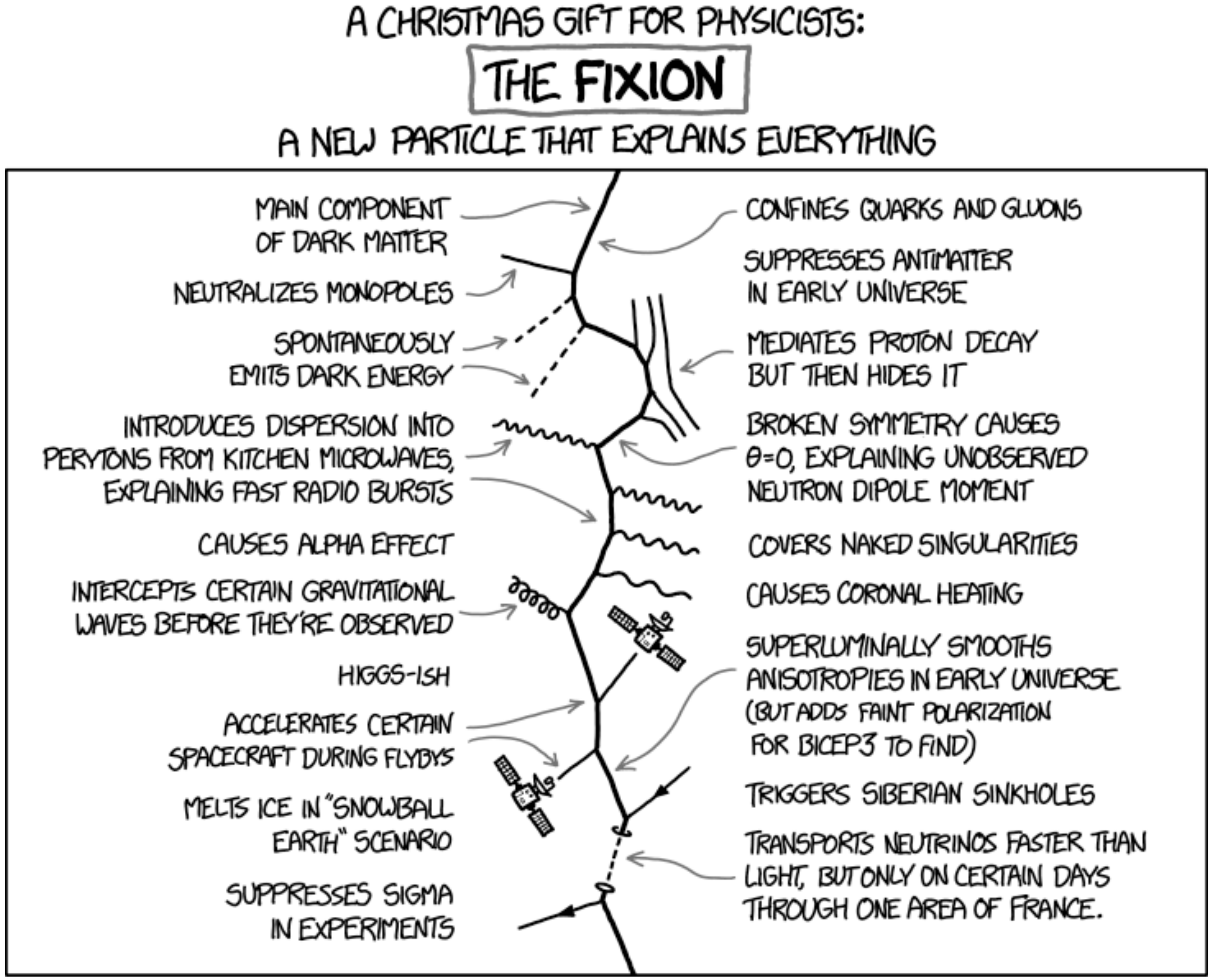
What are we trying to do in particle physics?

- Discover new particles
  - Known unknowns (dark matter, dark energy, etc)
  - Unknown unknowns

- Make precision measurements of particles and properties, probing the framework of the standard model, searches for symmetry violations.

- Probe the origin and early state of the universe (i.e. why more matter than anti-matter).

- And more!

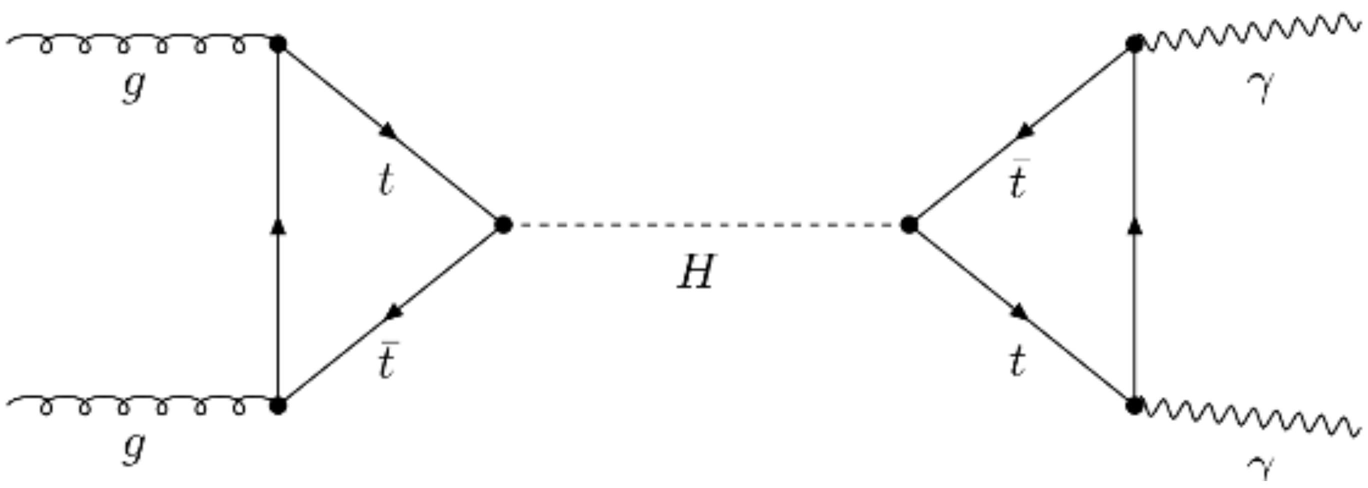


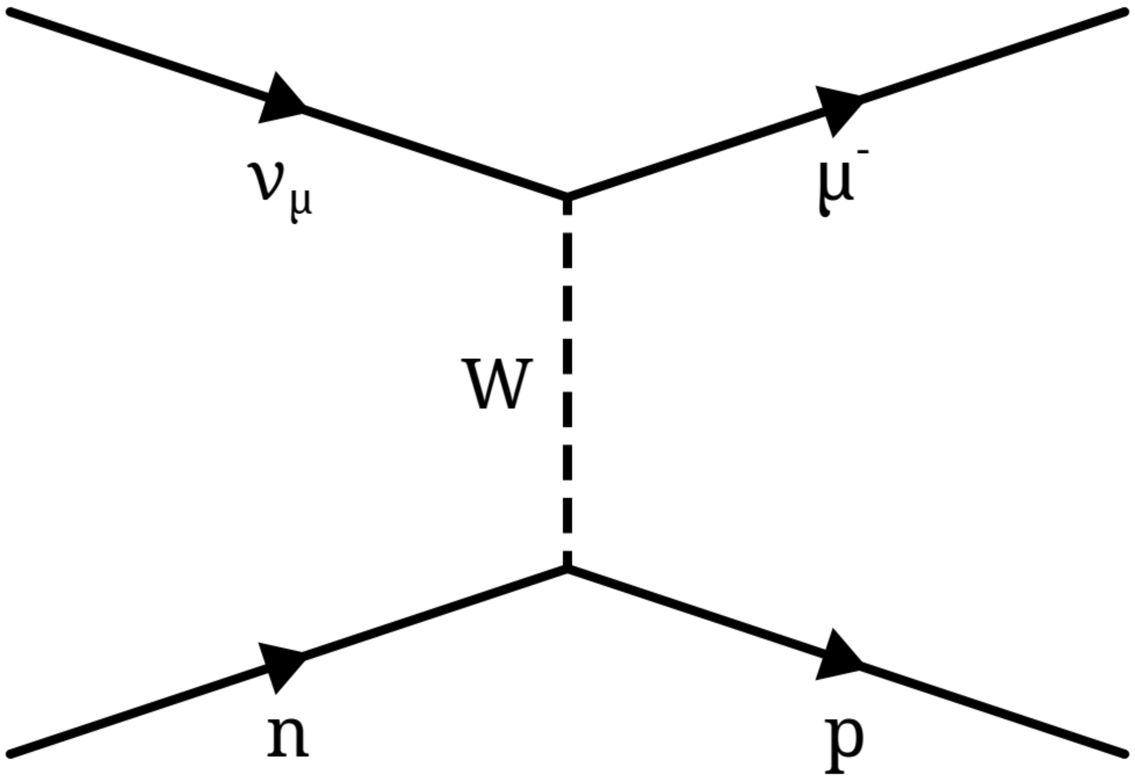
Asking the question

- What is the mass of the Higgs boson?

- What is the rate of electron and muon neutrinos observed from the atmosphere?

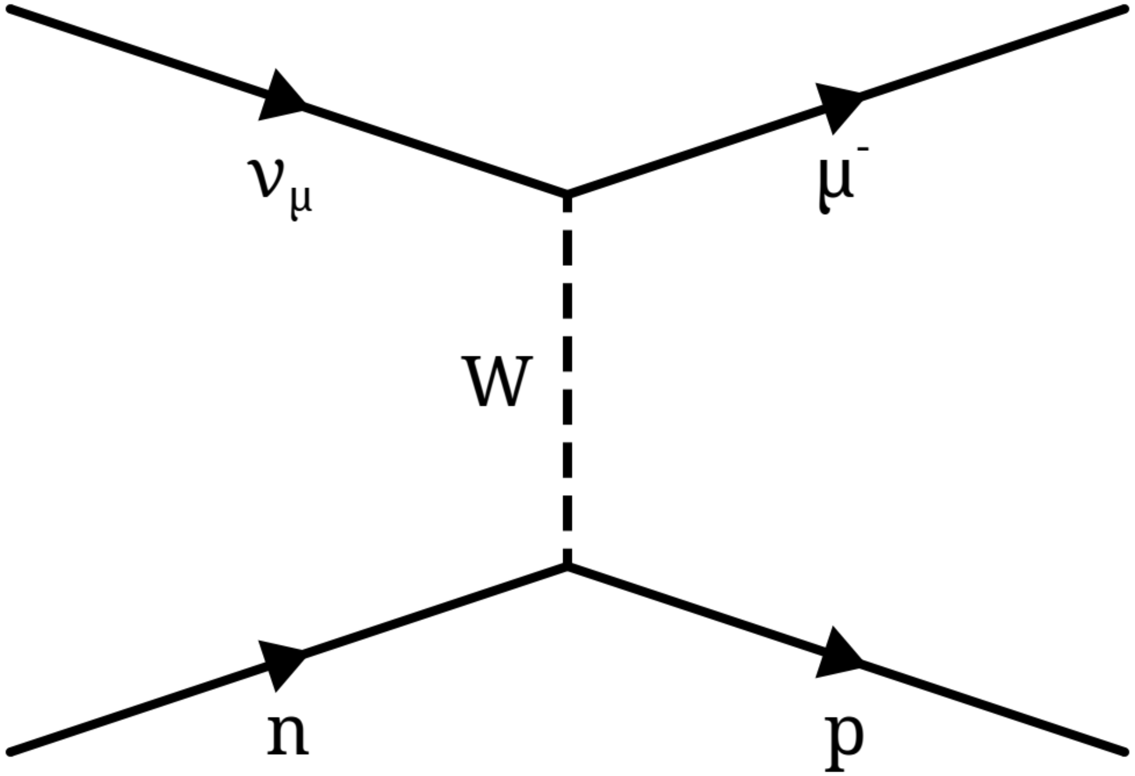
What do we look for: Theory





How do we do that: Detection Methods

Indirect Observation



Direct Observation

We infer that a neutrino was present in the interaction based on reconstructing the momentum and energy of the outgoing particles and conservation principles.

We observe the muon and proton producing tracks in our detector.

How do we do that: Designing a detector

- What is the primary physics goal of my experiment?
  - Are there other measurements I can make with the same detector, or could make if I modified the design?

- How do I identify a signal event and conclusively separate it from background?
  - How energetic is the event?
  - How frequent is the event, how frequent is the background?
  - How hard is it to separate the two?

- What are the constraints on my detector design?
  - How big does the detector need to be?
  - How long does it have to run?
  - Does the detector have to be underground, in an accelerator, in space, in the ocean, etc?
  - What are the data rates of the experiment? Do events pile up on top of each other?
  - Does my detector have special requirements, ex: radiation hard materials, cryogenics, fast timing, low radioactivity materials, etc

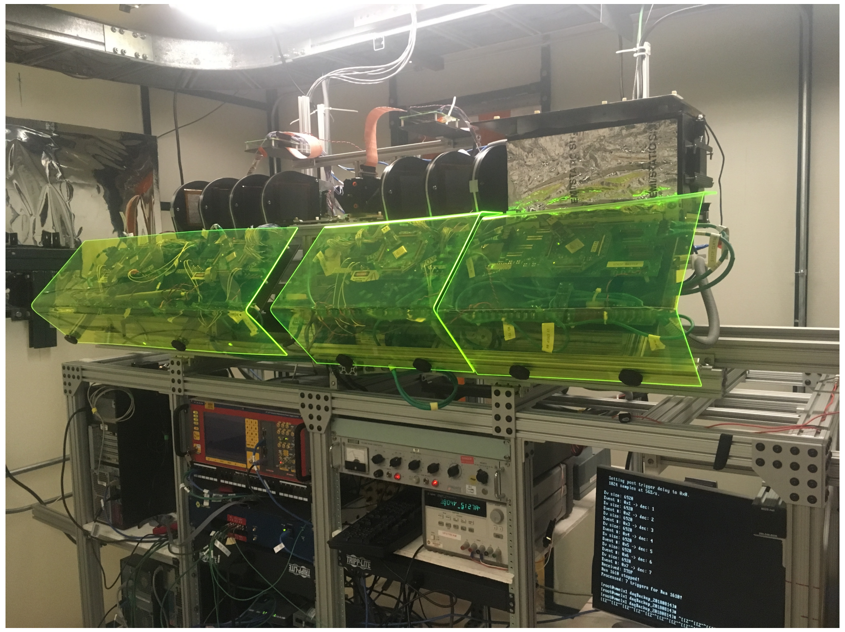
- How do I maximize the physics potential of the experiment at manageable cost?

How do we do that: Designing a detector

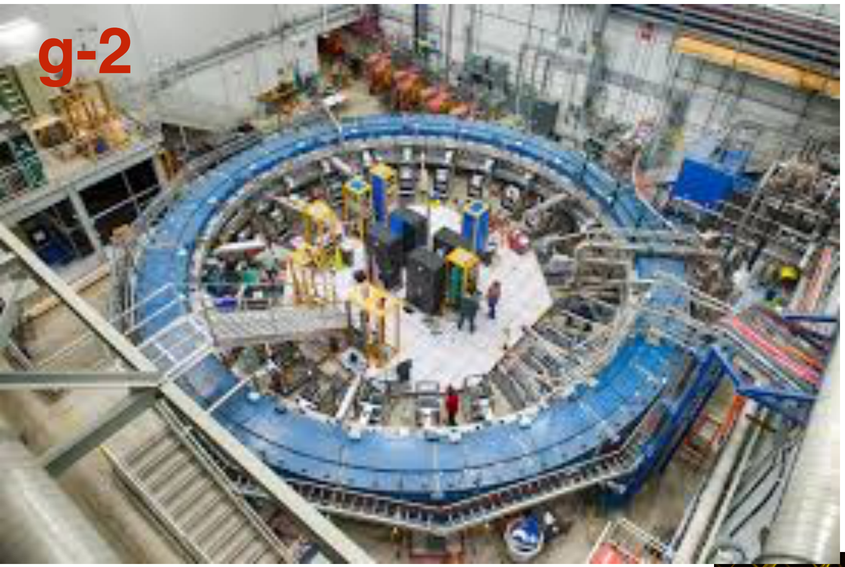
- It is possible our experiment requires a detector technology that has never been used before.

- Before spending millions of dollars to build a large detector, we develop prototypes and small tests to ensure that the larger experiment will work when we get there.

- At Fermilab we have a Test Beam Facility (ftbf.fnal.gov) and an Irradiation Test Area to test detectors and components in beams and subject them to radiation before building the full experiment.



The end result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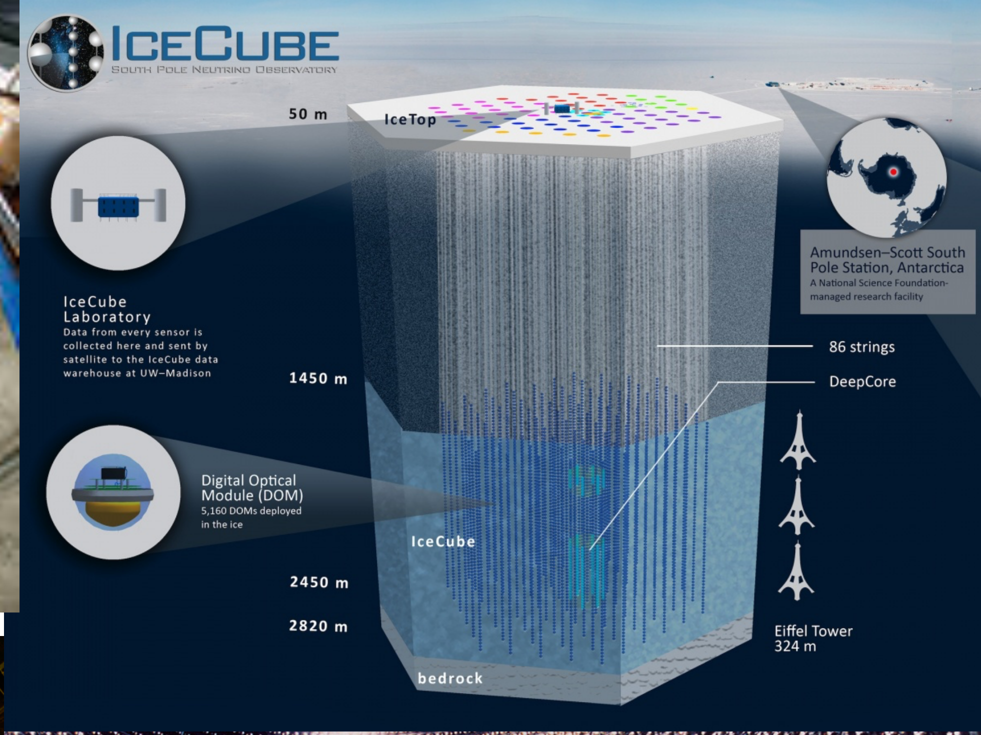
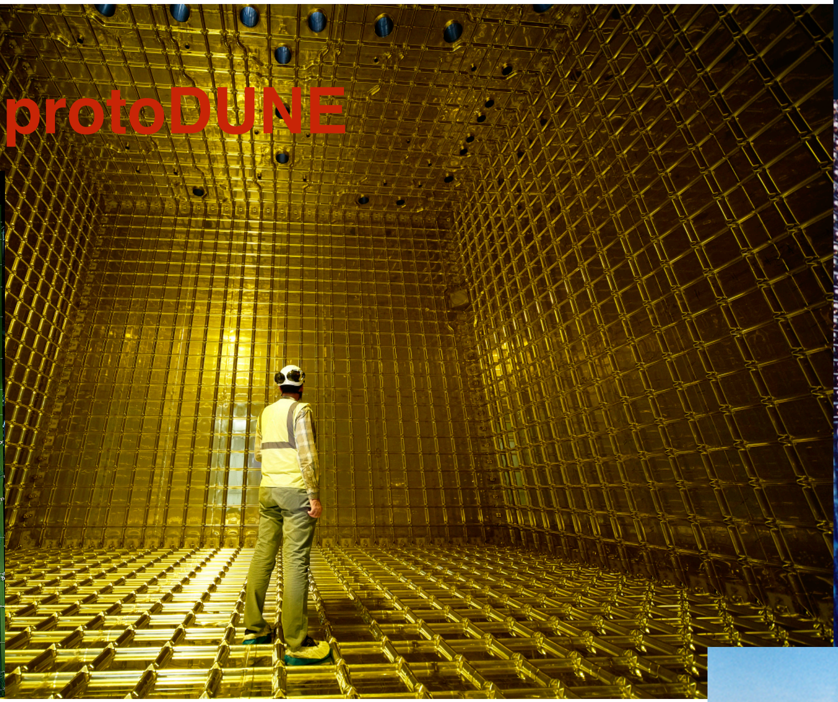
NOvA




CMS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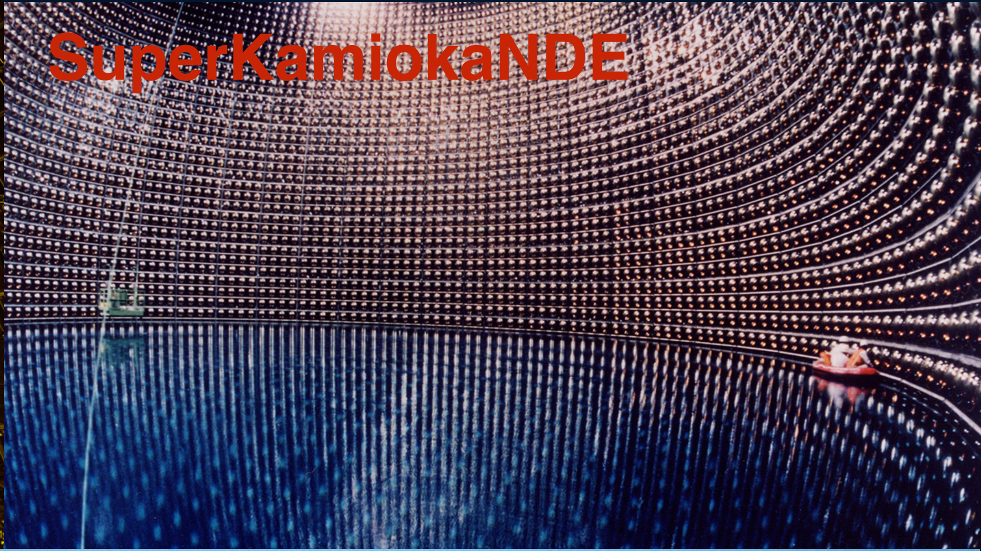
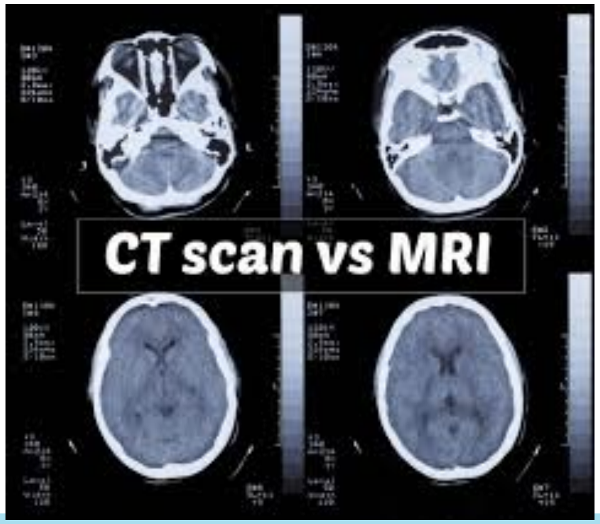

SuperKamiokaNDE


Crayfis




Ligo

What do we look for: Experiment

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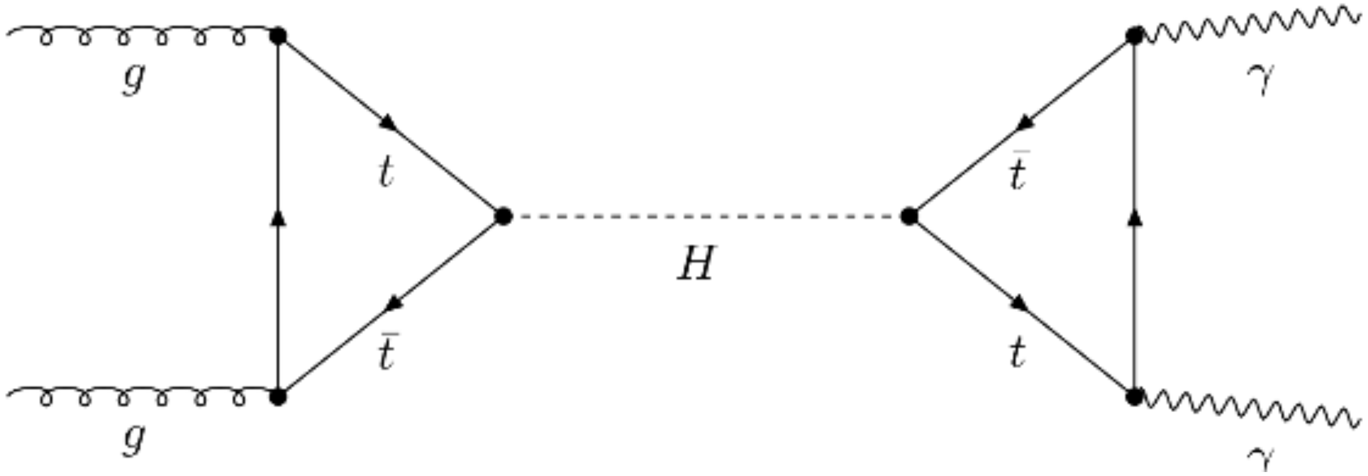
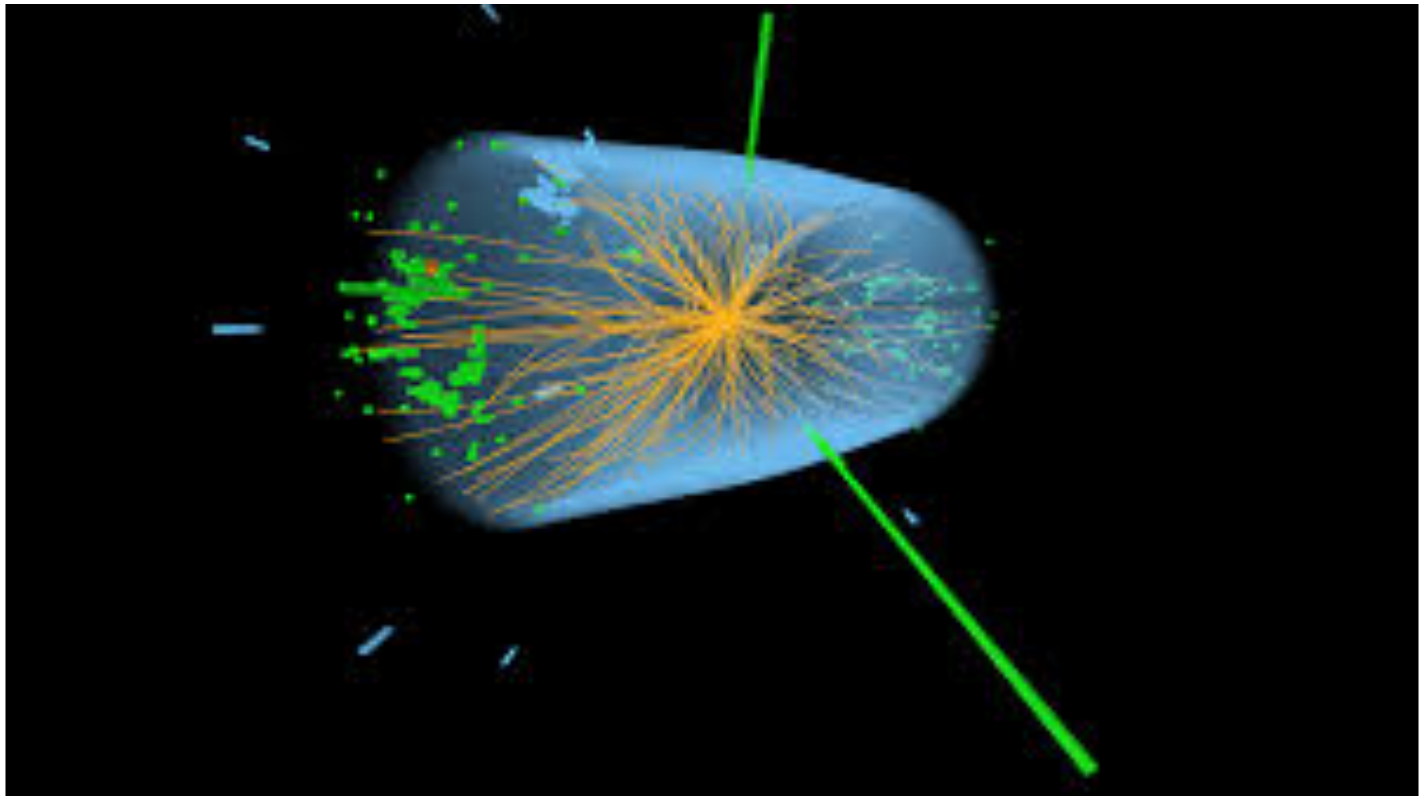
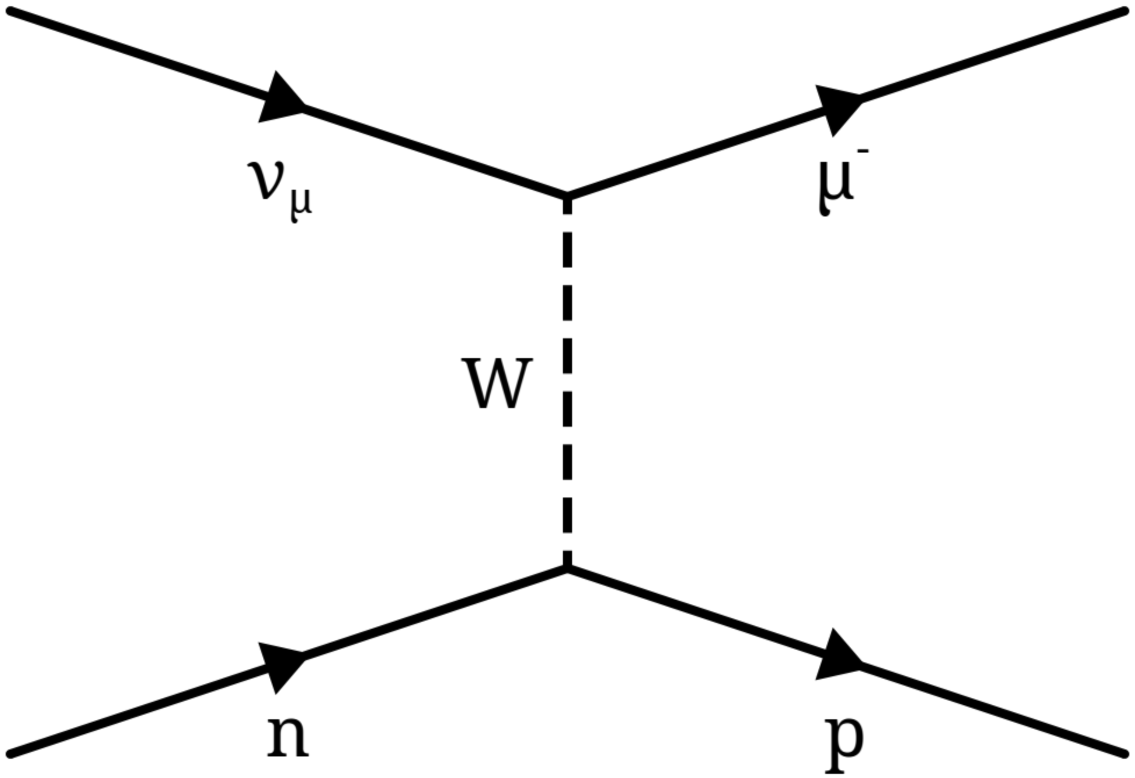
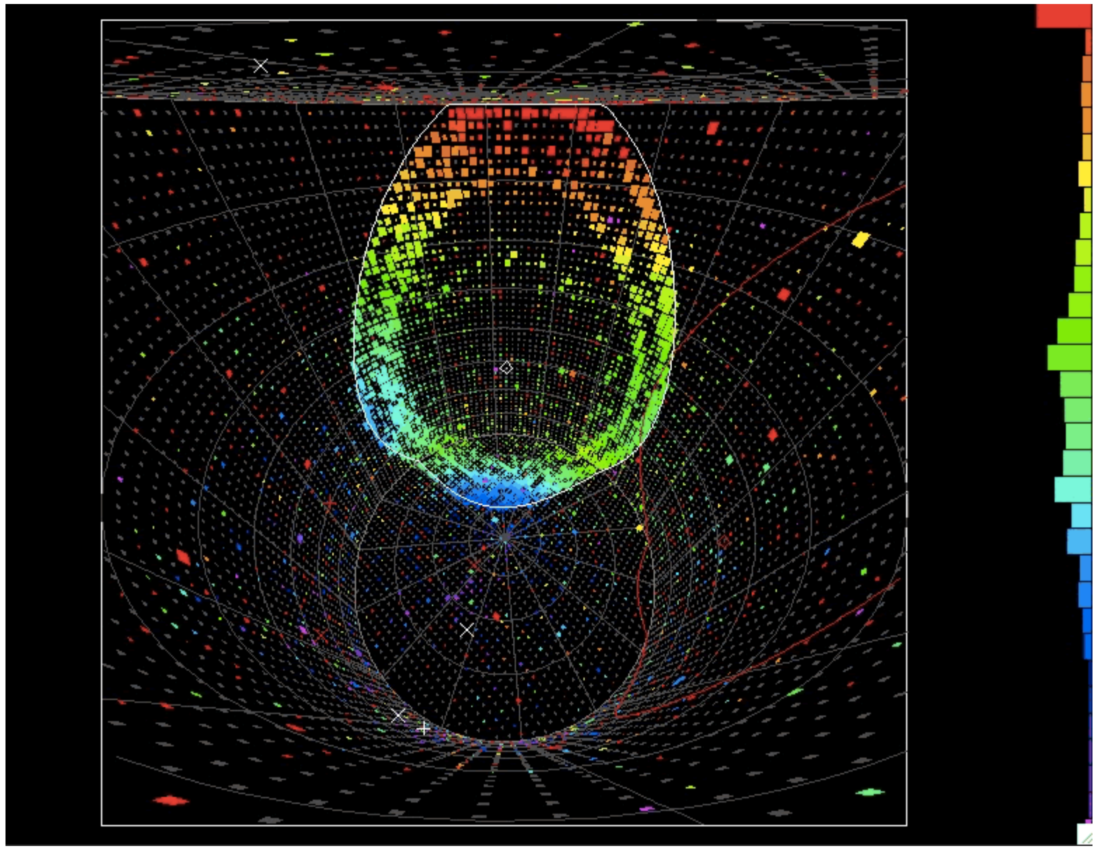




SuperKamiokaNDE



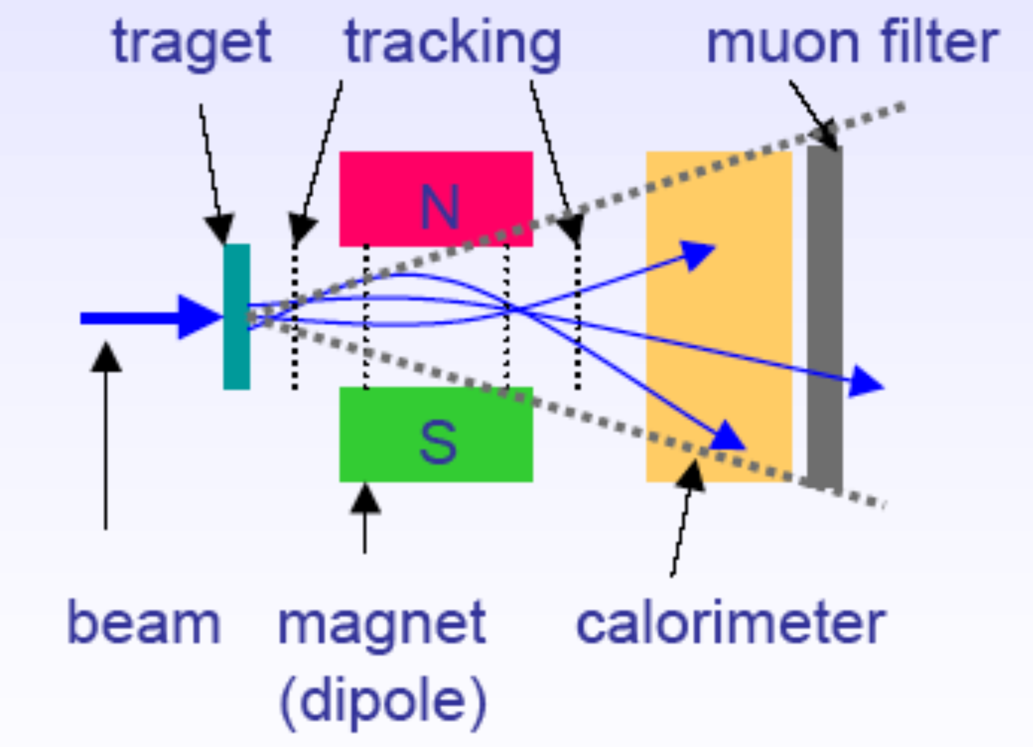


Narrowing focus

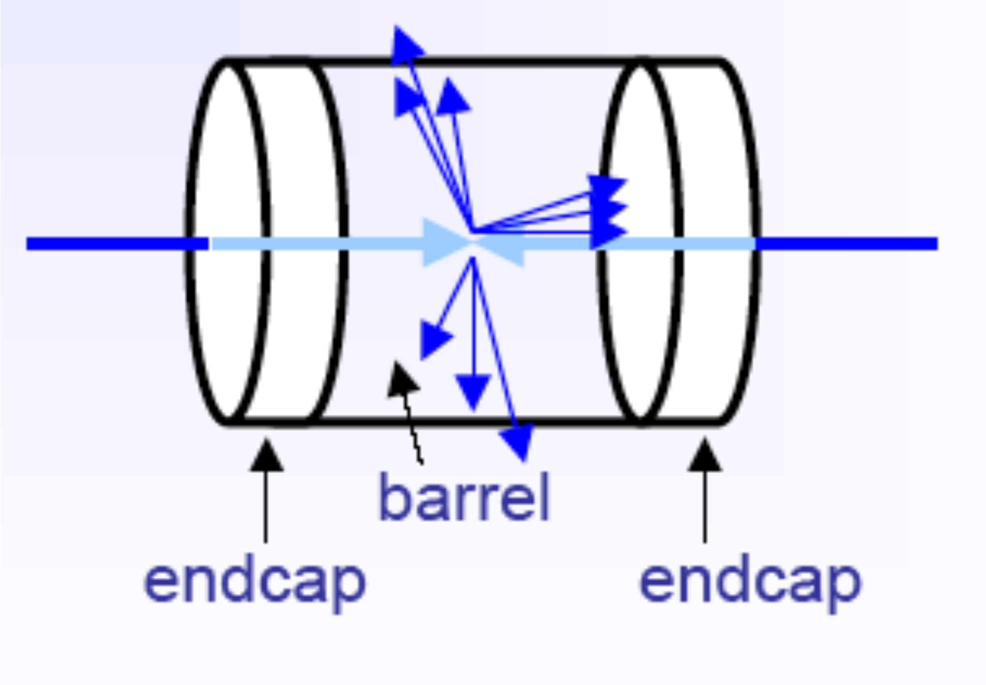
We can detect particles from all different sources with a wide variety of detectors. I'm going to focus now on beams of particles we produce artificially in accelerators.

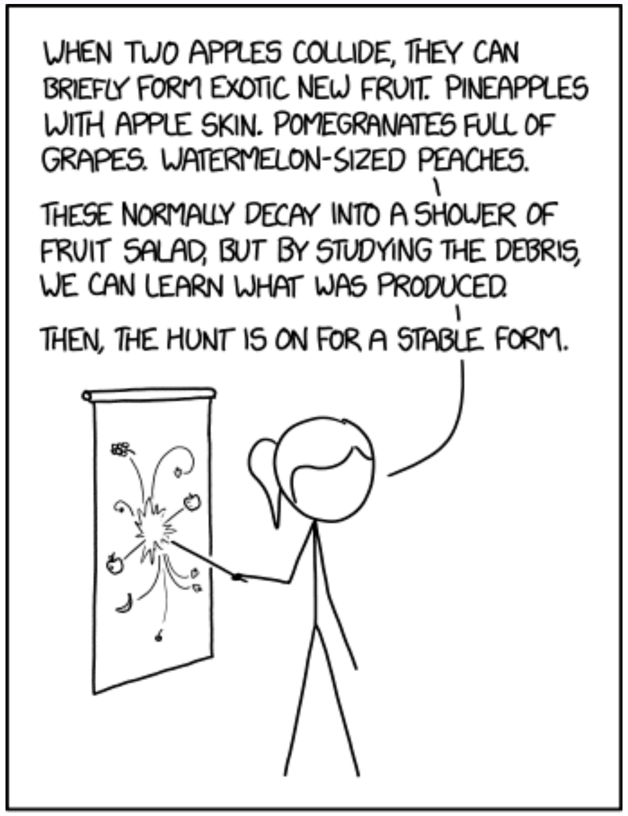
Detector Geometries

Fixed Target

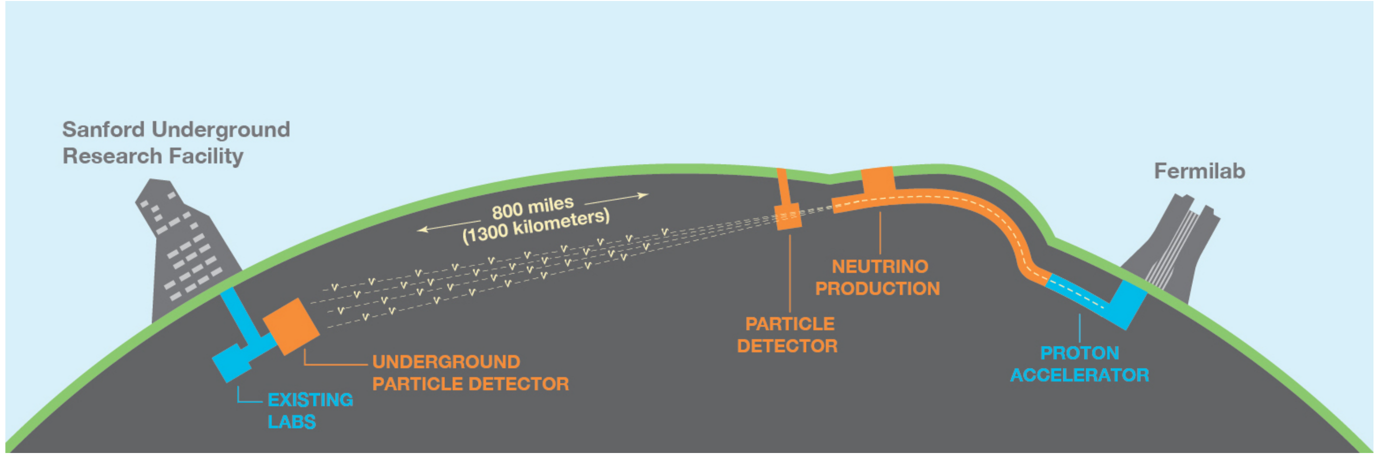


Collider



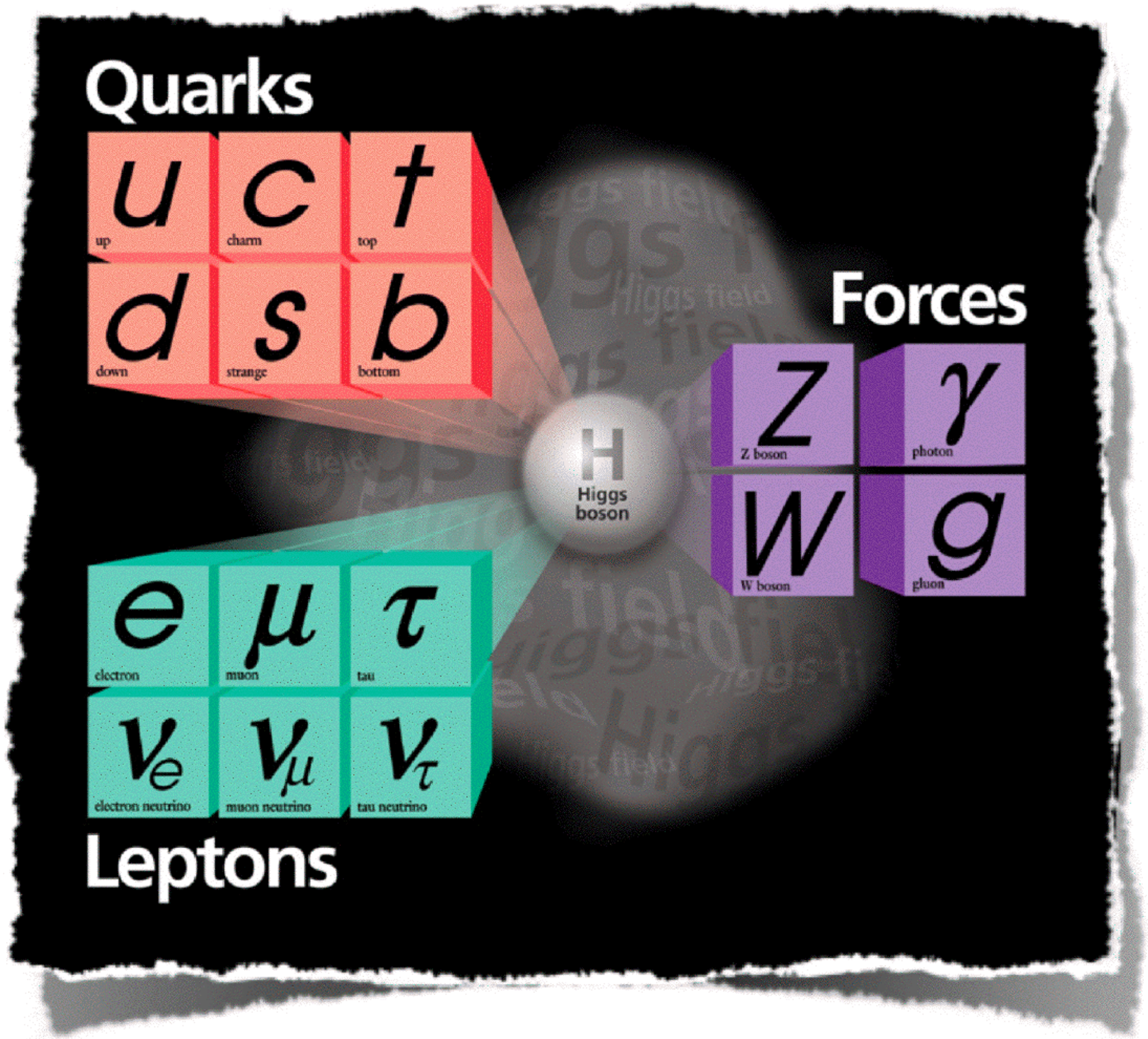


HOW NEW TYPES OF FRUIT ARE DEVELOPED



What are we seeing in our detectors

The Usual Suspects



The Unusual Suspects

- Dark Matter
- SUSY particles
- Sterile Neutrinos
- Magnetic Monopoles
- Etc

Distinguishing a Particle

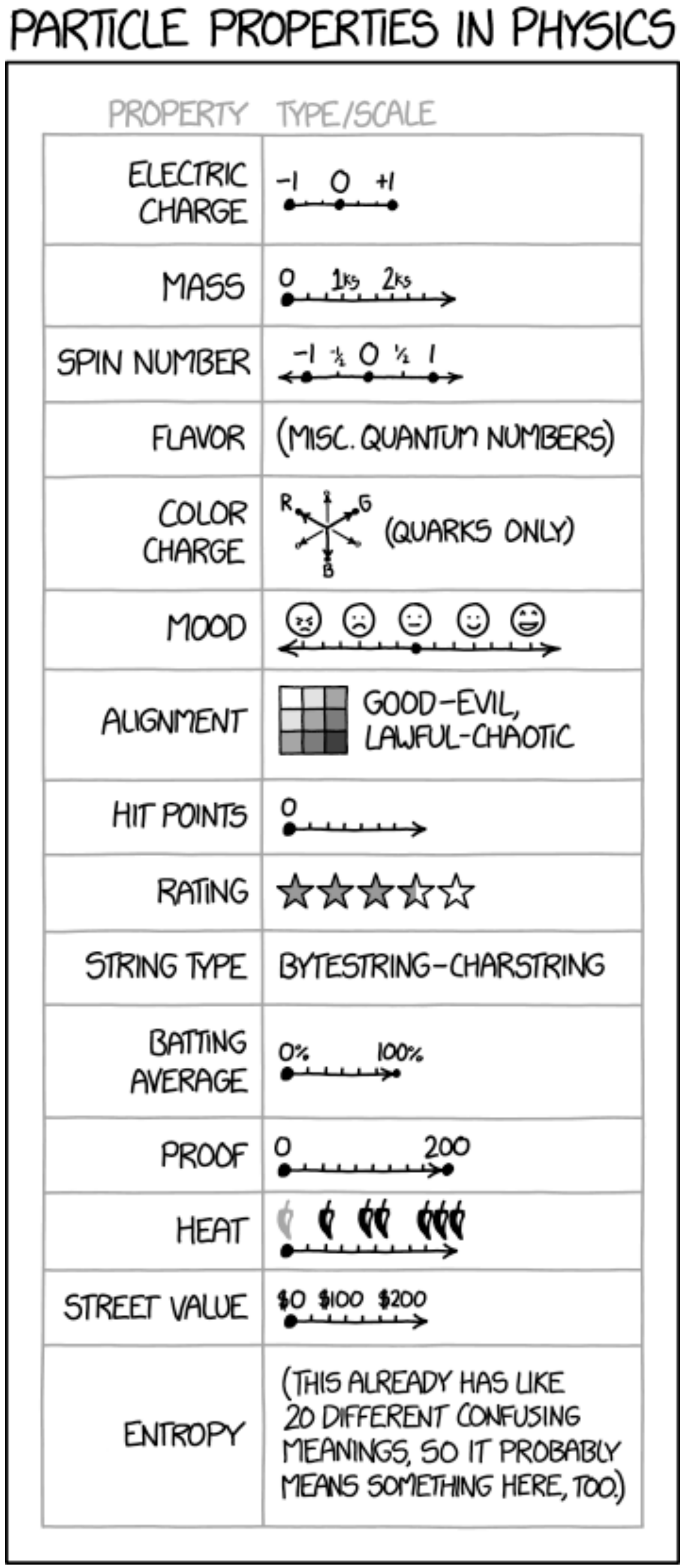
- Particles have a unique set of numbers that define them
    - mass, charge, spin, etc

- Conservation of energy

- Conservation of momentum

- Charge/Parity/Time (CPT) conservation or violation

- Particle lifetime



PARTICLE PROPERTIES IN PHYSICS

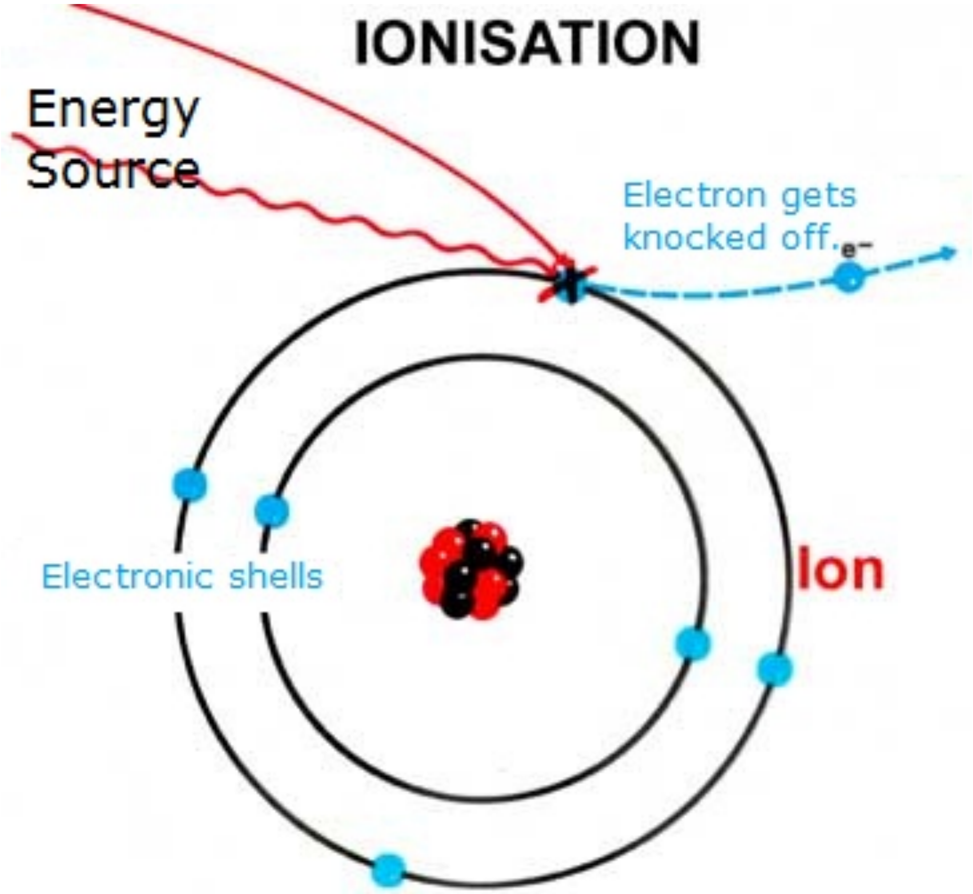
PROPERTY	TYPE/SCALE
ELECTRIC CHARGE	-1 0 +1
MASS	0 1KS 2KS
SPIN NUMBER	-1 -½ 0 ½ 1
FLAVOR	(MISC. QUANTUM NUMBERS)
COLOR CHARGE	R G B (QUARKS ONLY)
MOOD	😠 ☹ 😐 ☺ 😃
ALIGNMENT	GOOD–EVIL, LAWFUL–CHAOTIC
HIT POINTS	0
RATING	★★★⯪☆
STRING TYPE	BYTESTRING–CHARSTRING
BATTING AVERAGE	0% 100%
PROOF	0 200
HEAT	🌶 🌶 🌶🌶 🌶🌶🌶
STREET VALUE	$0 $100 $200
ENTROPY	(THIS ALREADY HAS LIKE 20 DIFFERENT CONFUSING MEANINGS, SO IT PROBABLY MEANS SOMETHING HERE, TOO.)

Let’s look at some tools for particle detection

- Ionization
- Scintillation
- Particles in magnetic fields
- Cherenkov radiation
- Calorimetry
- Time projection chambers

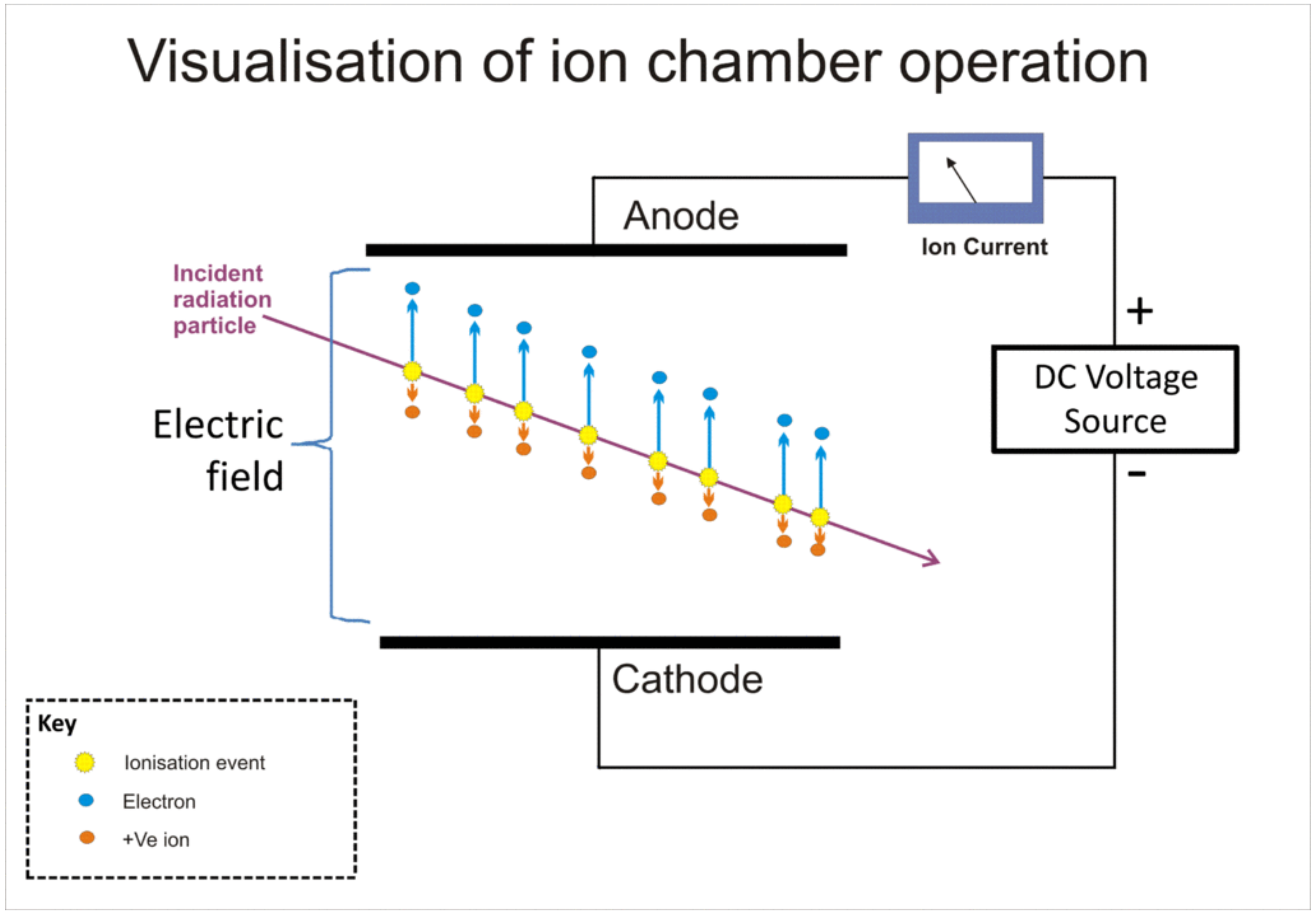
Ionization

- Ionization is the removal or addition of an electron to an atom to make it positive or negative.



Ionization

- Charged particles traveling through a medium (gases, liquids, plastics, crystals, silicon sensors, etc) can produce ionization
- Add an electric field to separate free electrons and positive charged atoms
- Collect charge on sensors for energy reconstruction, tracking, timing

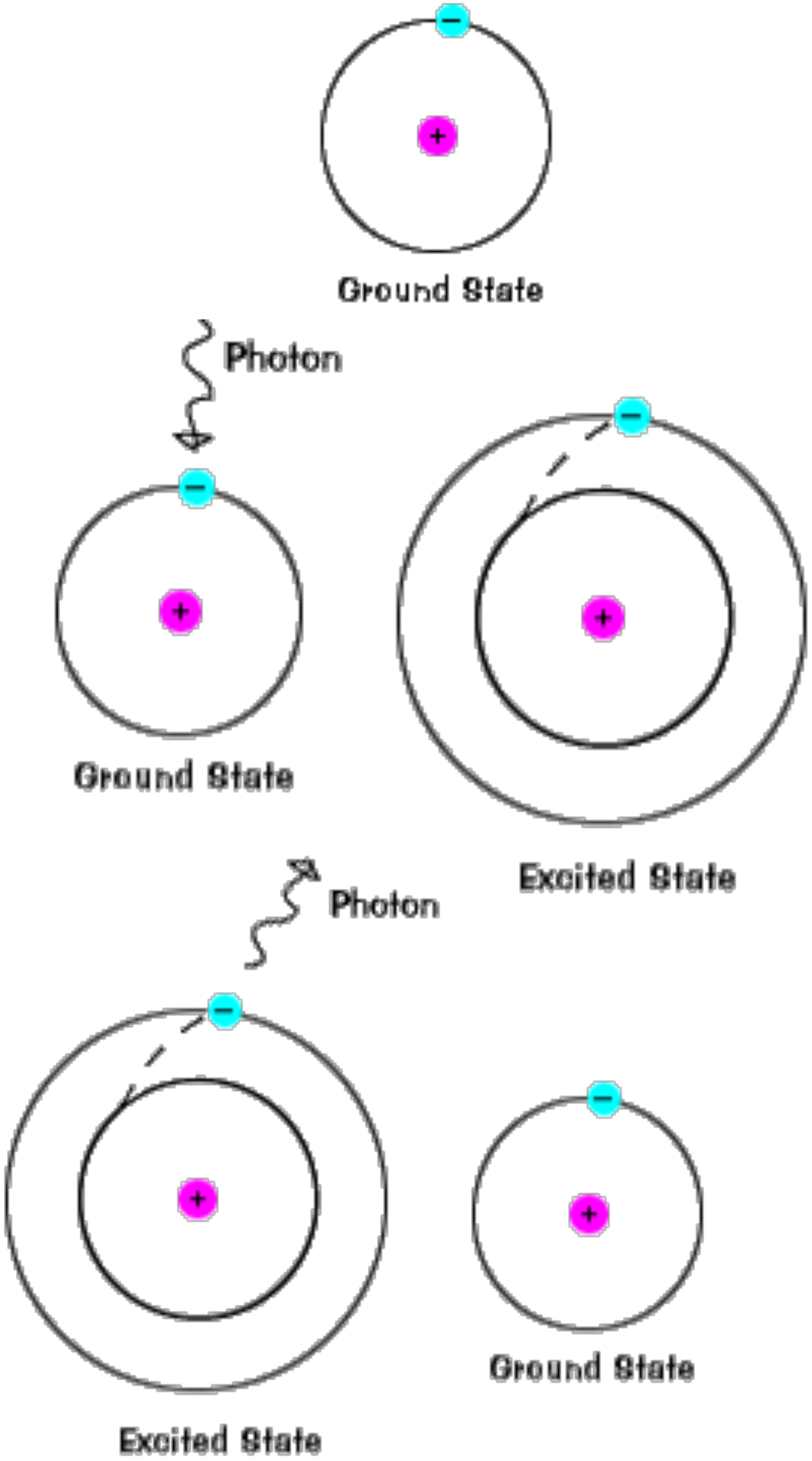


Scintillation Light

- Liquid, solid, or gaseous materials that produce light via de-excitation after absorbing energy from a passing particle

$$n = n_0 \frac{dE/dx}{1+BdE/dx}$$

- Number of photons produced. B is Birk's constant, accounting for scintillator saturation
-



Scintillation Light

- Materials can be organic or inorganic. Delay time for emitting light depends on material.

- Commonly wave shifters are incorporated so emitted light is not reabsorbed.

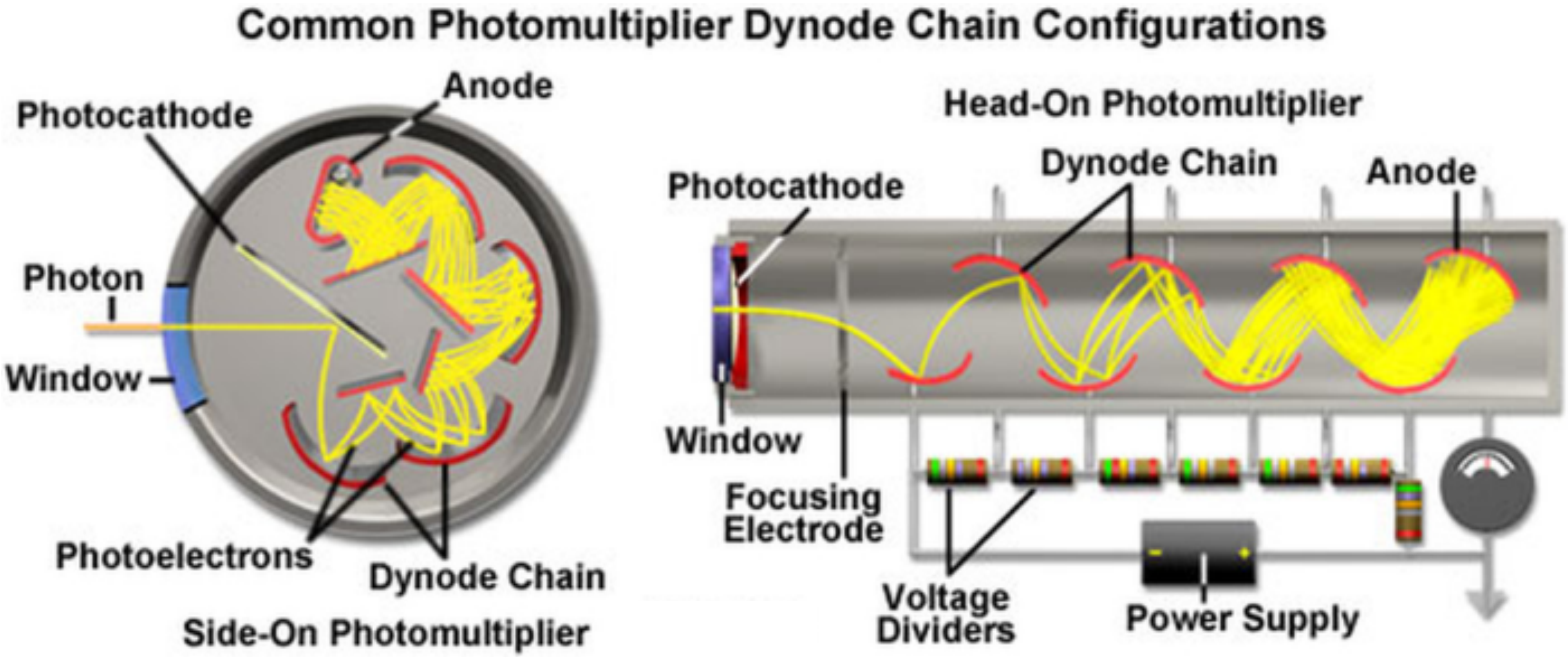
- Provides information on particle energy, tracking, timing.

Photomultiplier Tubes

- Photons incident on photocathode produce photoelectrons via photoelectric effect

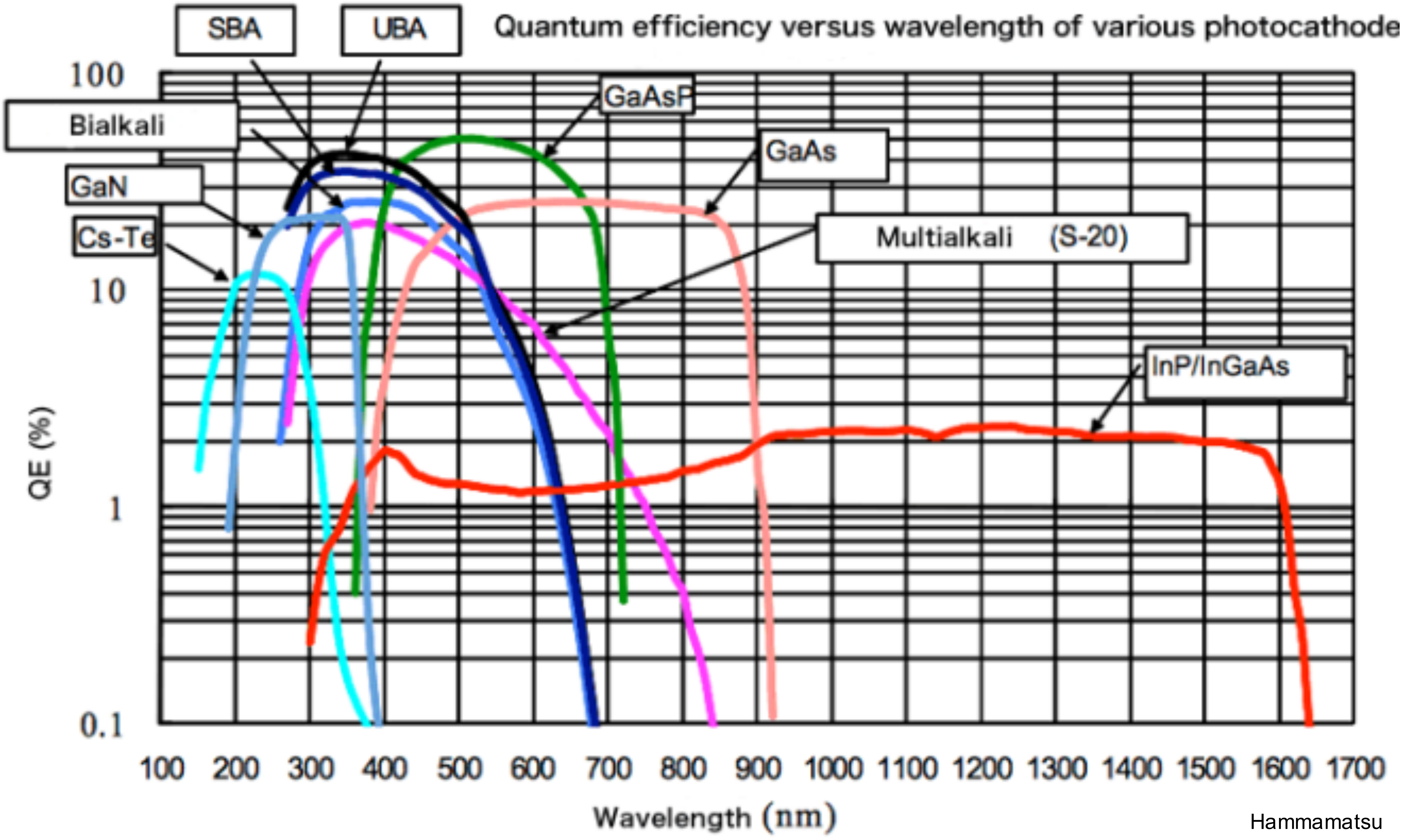
- Gains around 10^6 are typical

- Tubes come in variety of temperatures, operating characteristics




Hammamatsu

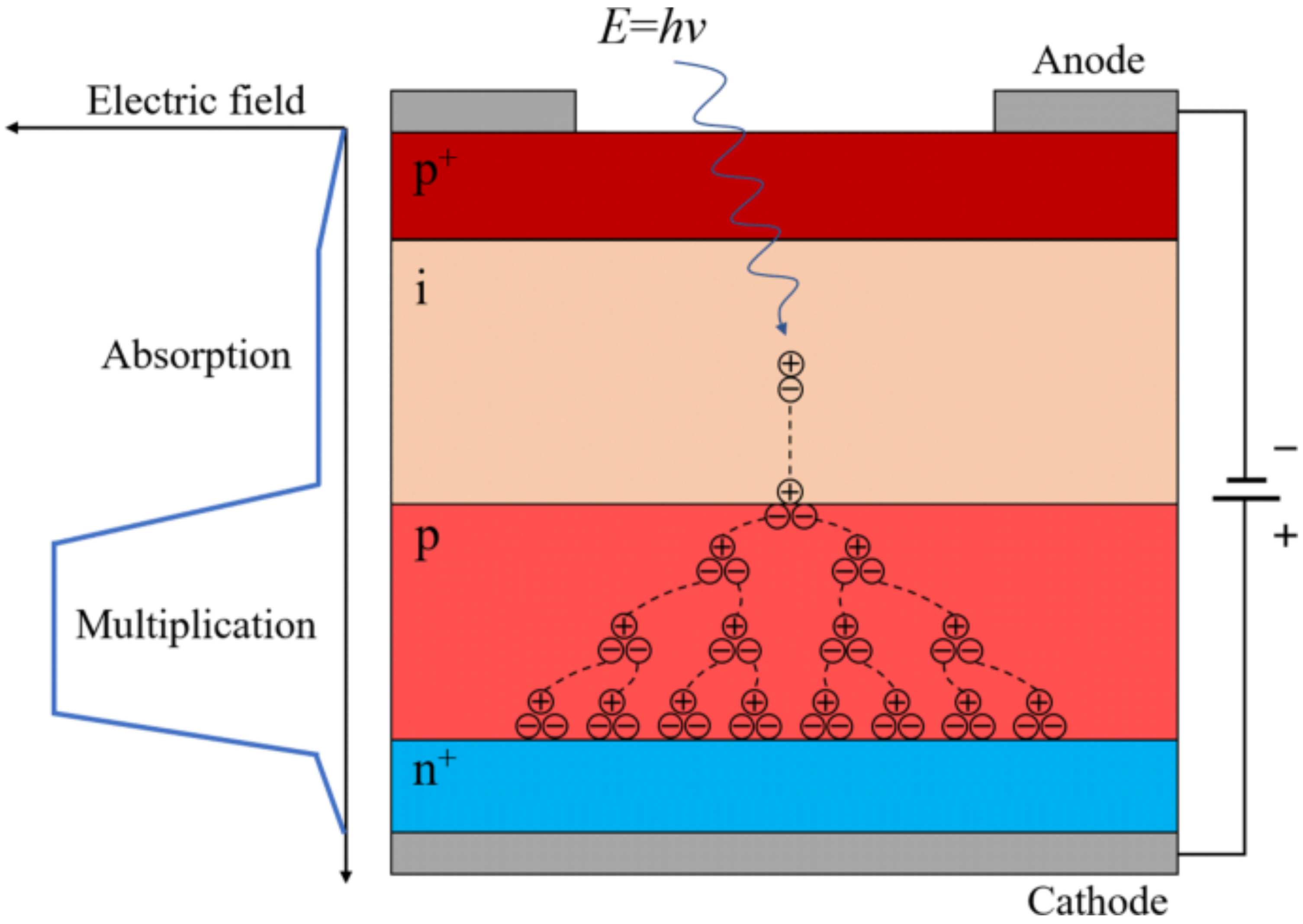
Photomultiplier Tubes



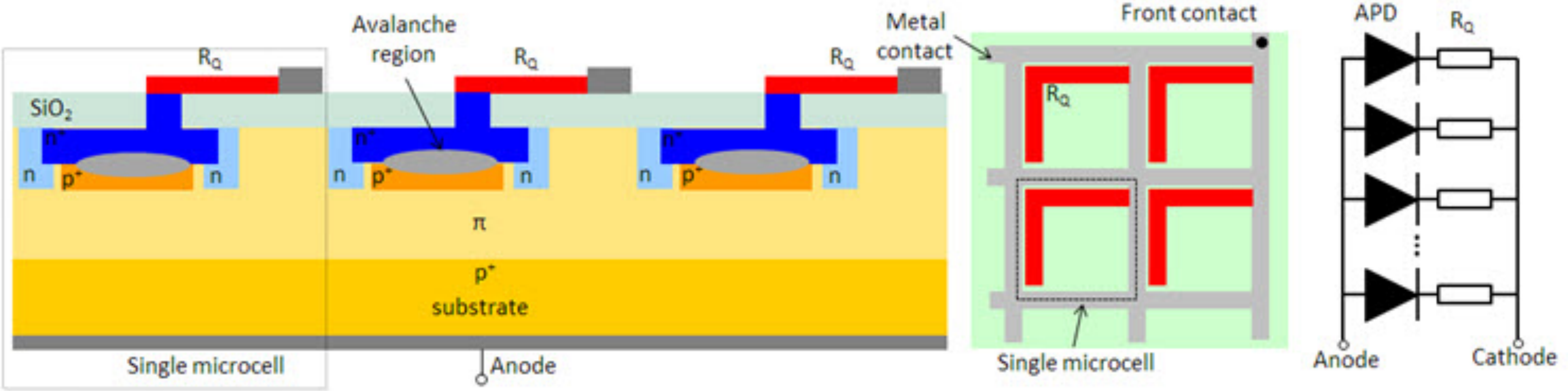
Hammamatsu

Avalanche Photodiodes

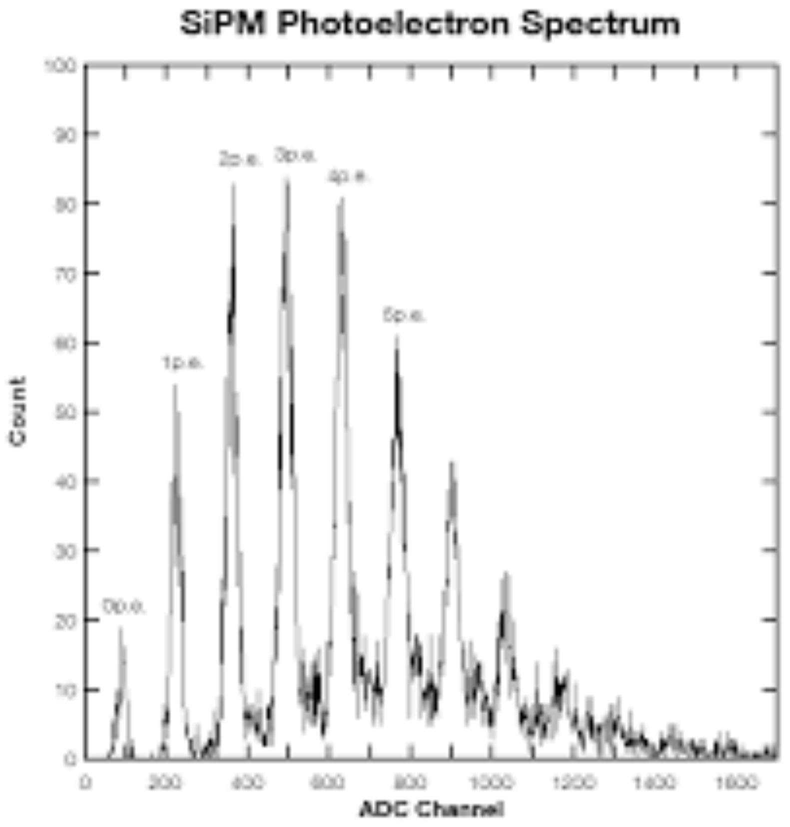
- High quantum efficiencies, lower operating voltages
- Sensitive to operating voltages
- Lower temperatures to reduce dark currents
- Typically much smaller coverage areas



Silicon Photomultipliers



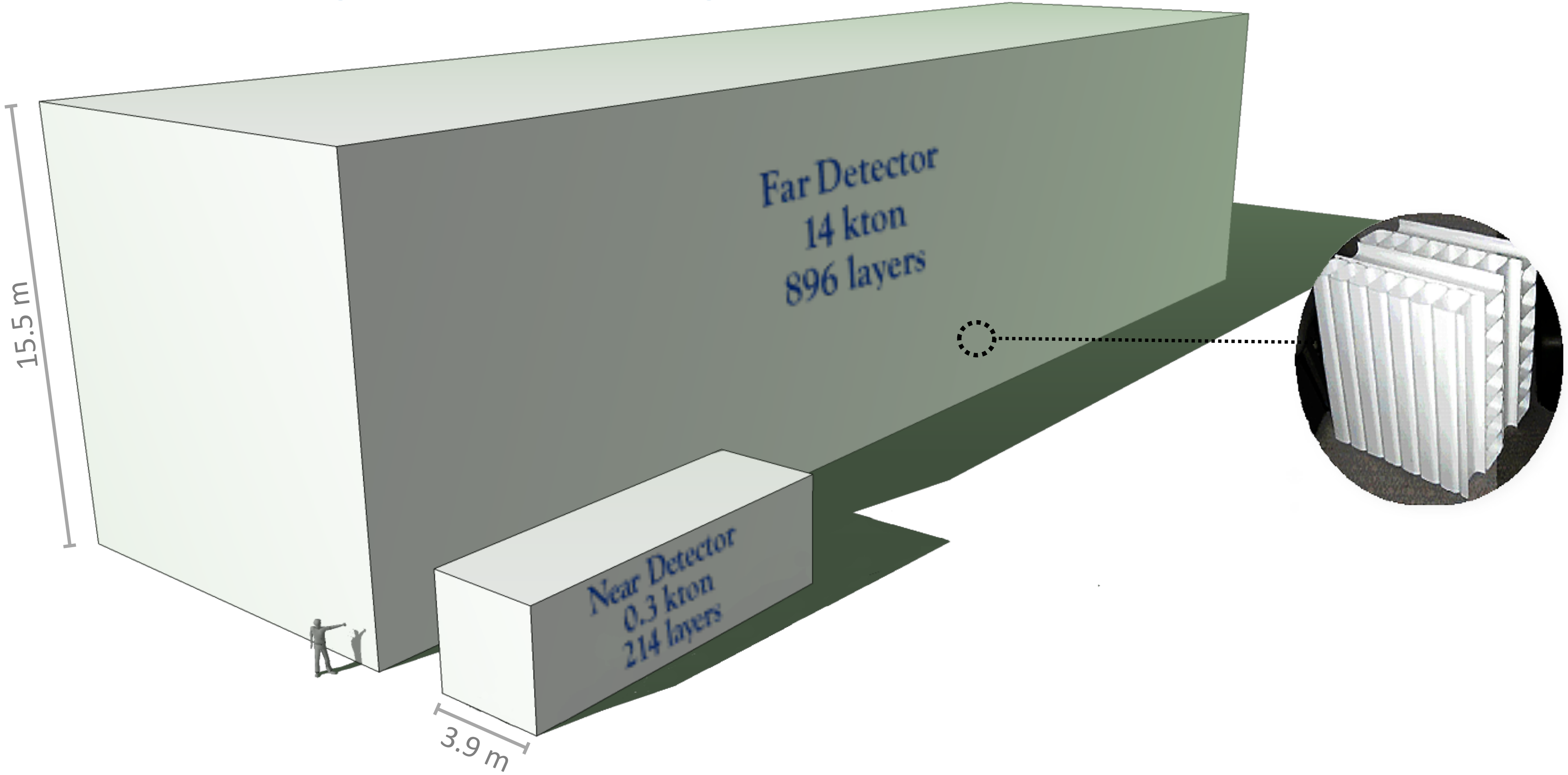
https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html

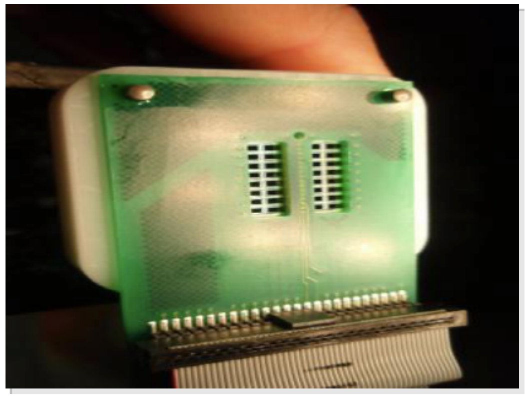


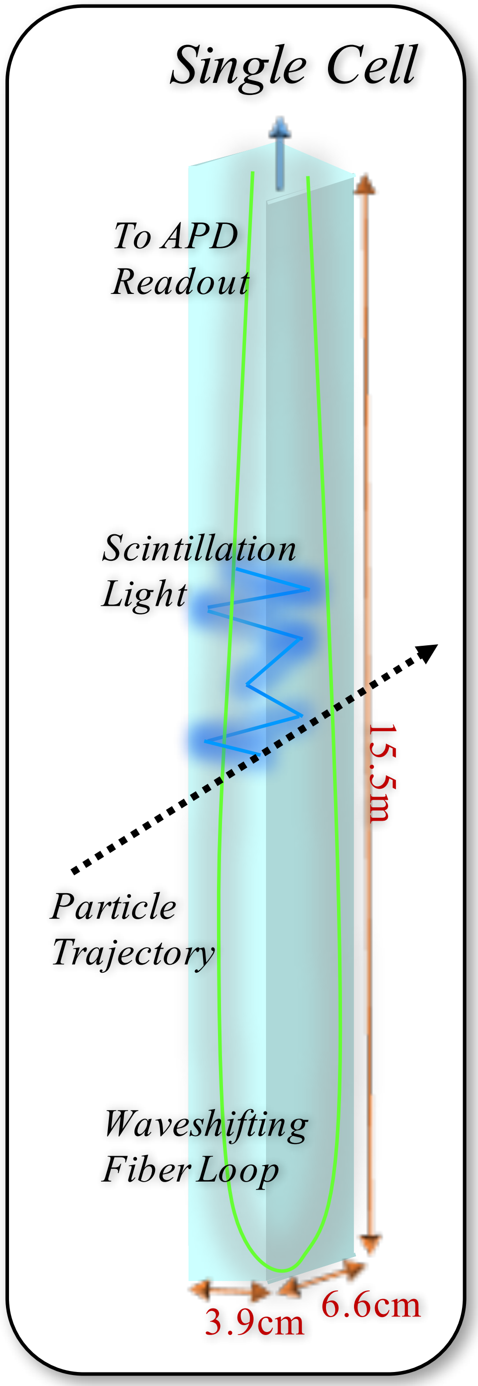
https://www.sensl.com/downloads/ds/TN%20-%20Intro%20to%20SPM%20Tech.pdf

- Series of micro-cells operating at over-voltage in geiger mode
- gains of ~10^6
- count individual photons

Choosing Technology: NOvA

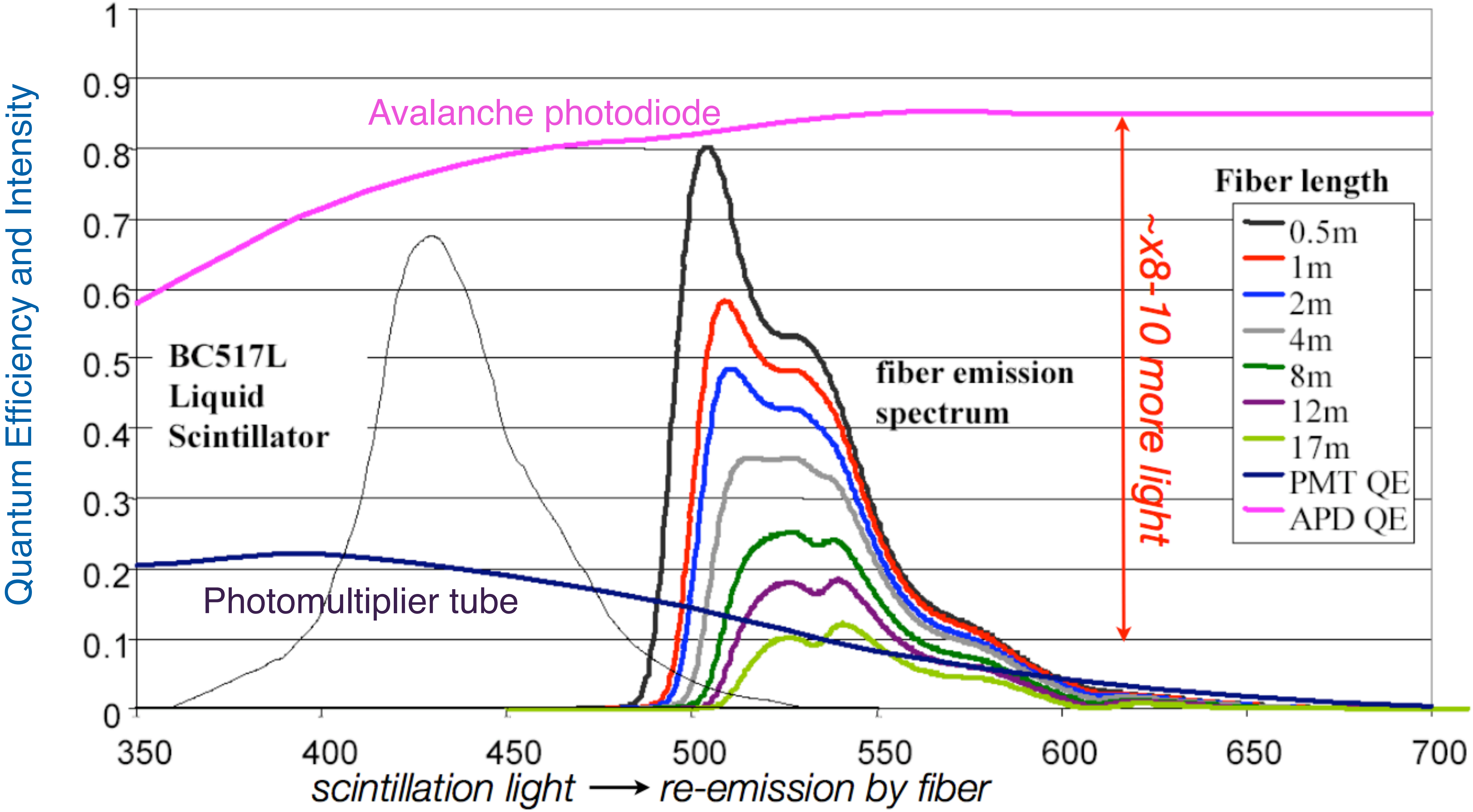






- Grid of long cells filled with a scintillating material
- Optical fiber to collect light coupled to a readout device
- How do we optimize design to maximize number of observed photons?

Choosing Technology: NOvA

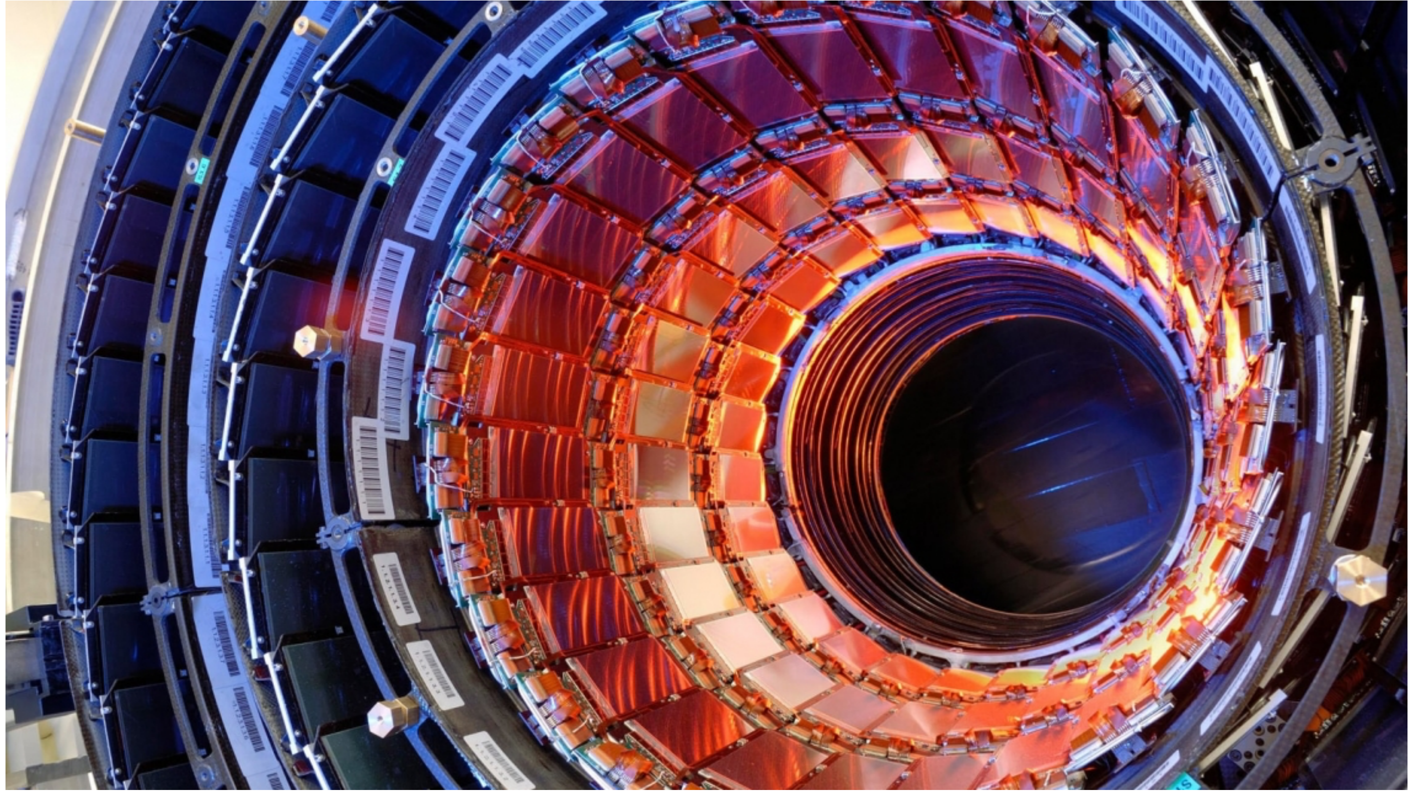


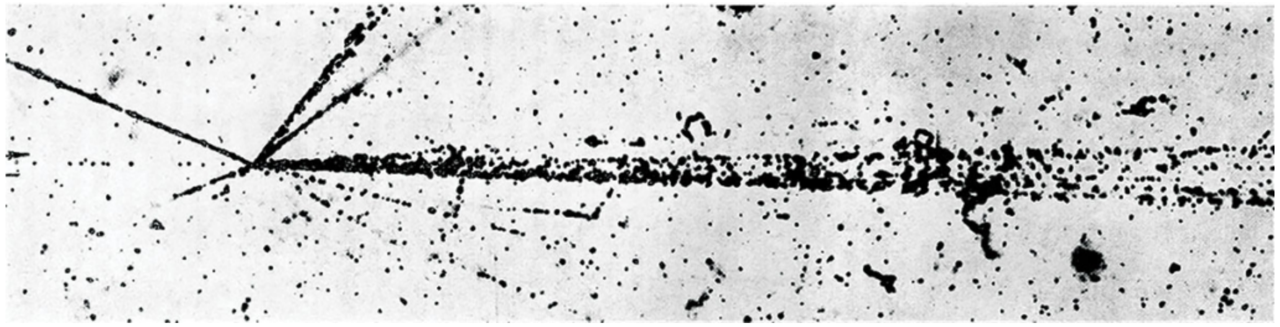
Match efficiency of detector components to work together and increase observed light.

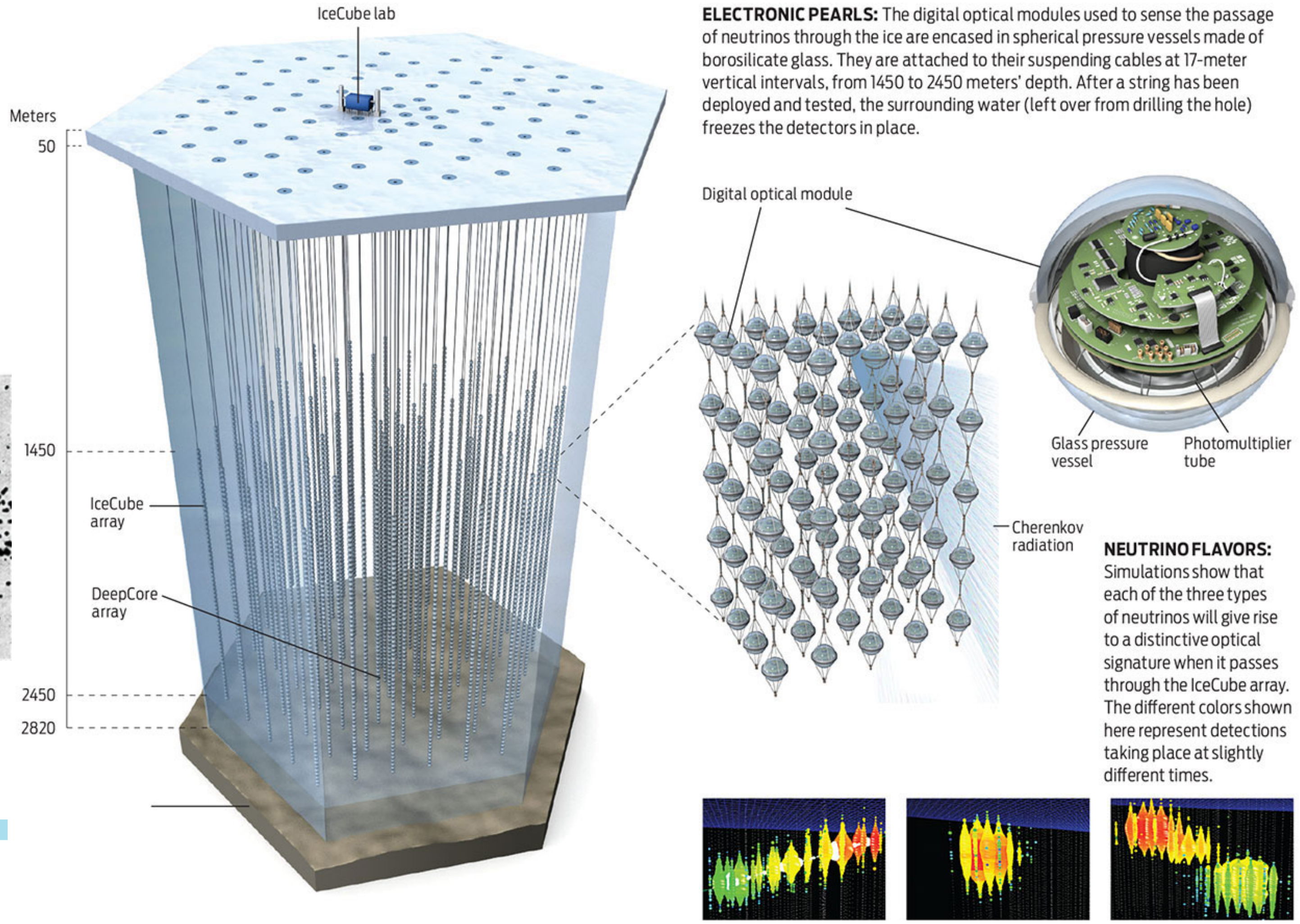
Tracking (charged) particles

- We can use ionization and scintillation to track particles in discrete steps

- We want the best tracking resolution required to make the physics measurement
  - Minimize dead material which degrades energy resolution
  - More channels -> higher cost
  - More channels -> larger data rates, processing times







ELECTRONIC PEARLS: The digital optical modules used to sense the passage of neutrinos through the ice are encased in spherical pressure vessels made of borosilicate glass. They are attached to their suspending cables at 17-meter vertical intervals, from 1450 to 2450 meters' depth. After a string has been deployed and tested, the surrounding water (left over from drilling the hole) freezes the detectors in place.

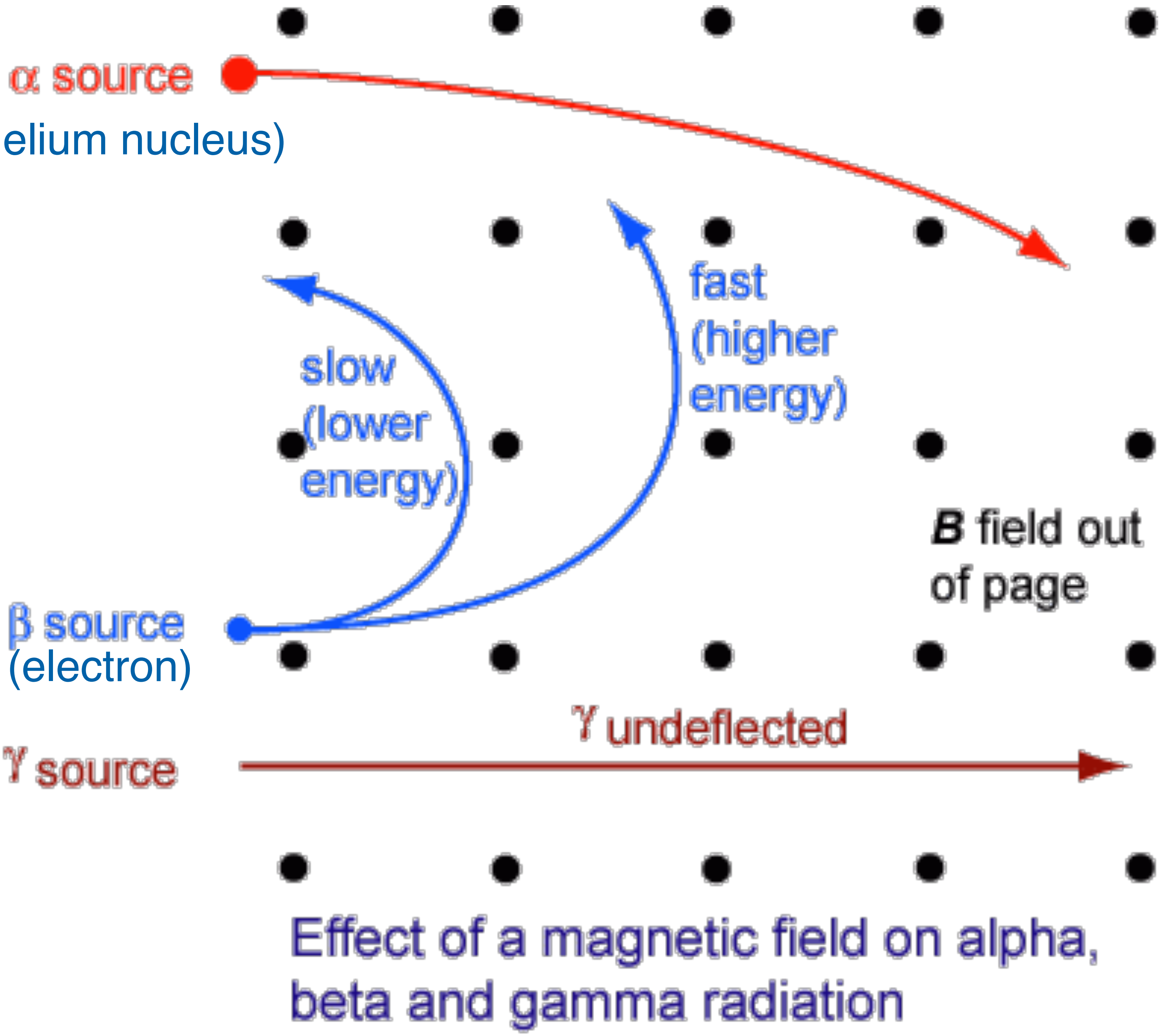
NEUTRINO FLAVORS: Simulations show that each of the three types of neutrinos will give rise to a distinctive optical signature when it passes through the IceCube array. The different colors shown here represent detections taking place at slightly different times.

Tracking in a Magnetic Field

- Momentum reconstruction via curvature
- Charge separation, can distinguish particles and anti-particles
- Only applicable to charged particles

$$F = \frac{mv^2}{r} = qvB$$

$$r = \frac{mv}{qB}$$

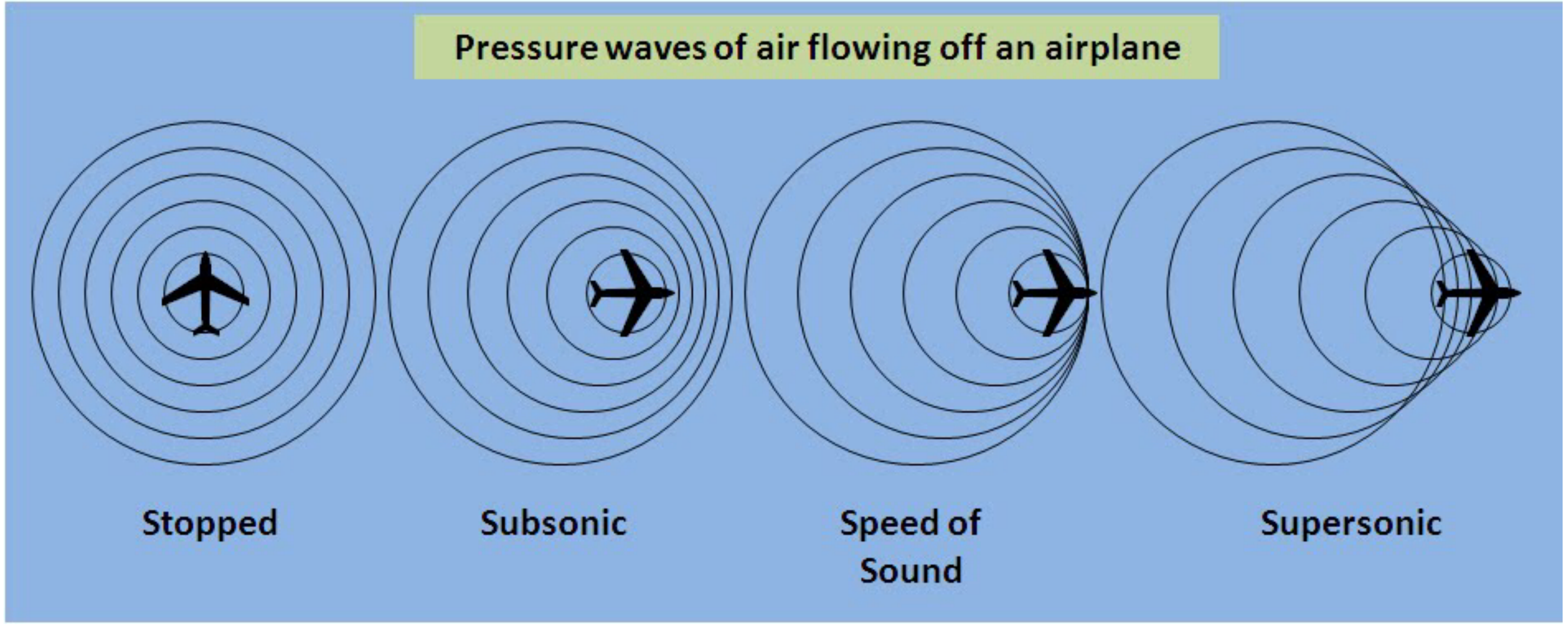


Effect of a magnetic field on alpha, beta and gamma radiation

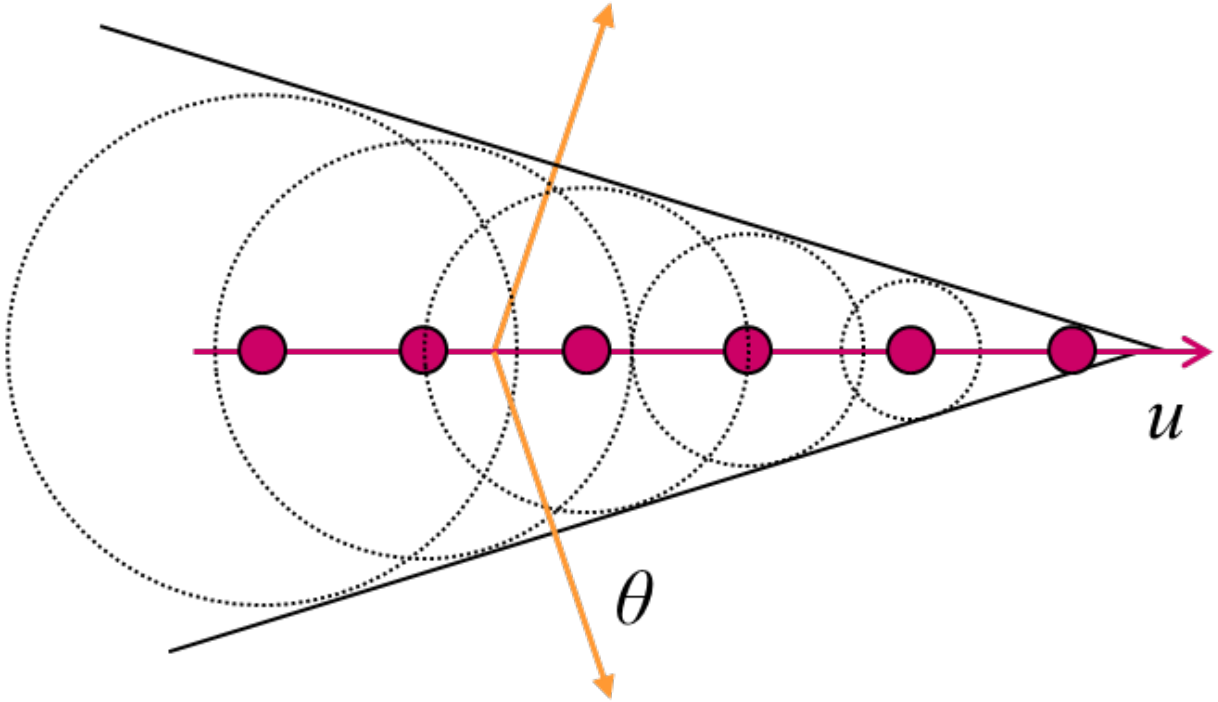
https://www.miniphysics.com/ss-deflection-of-radioactive-particles.html

Cherenkov Radiation

- Traveling faster then the speed of sound produces a shock wave:

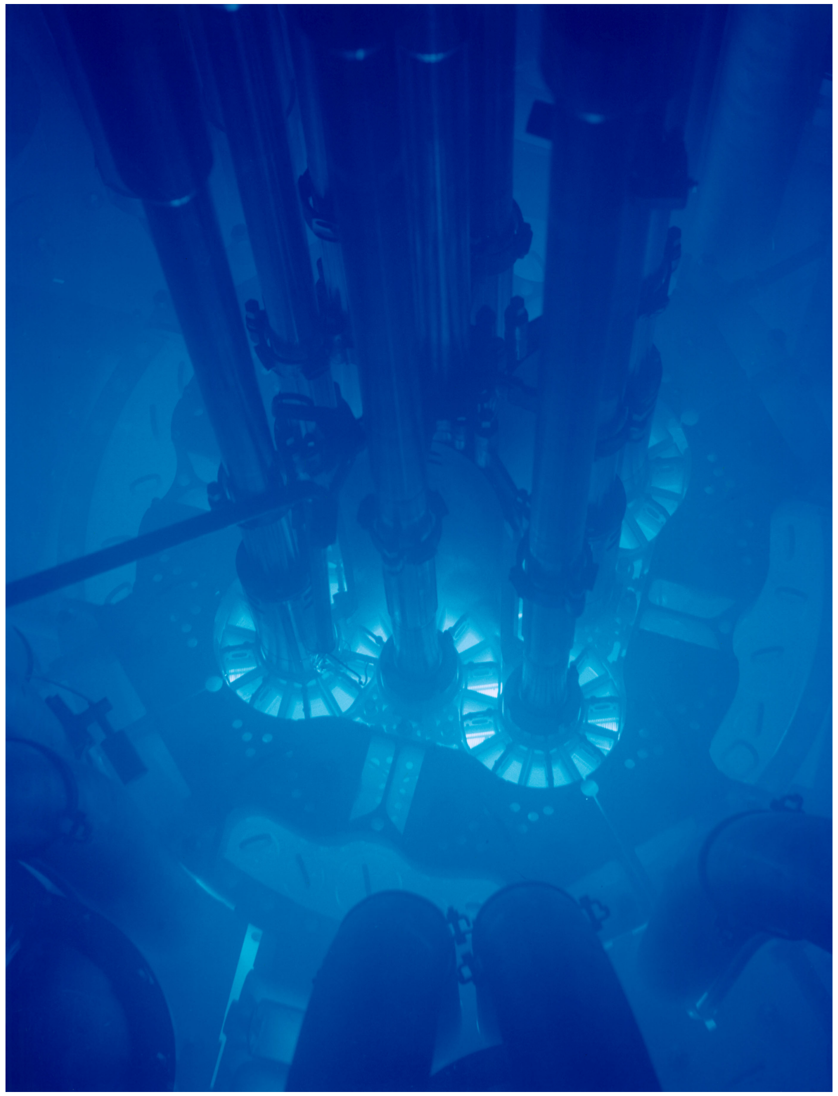


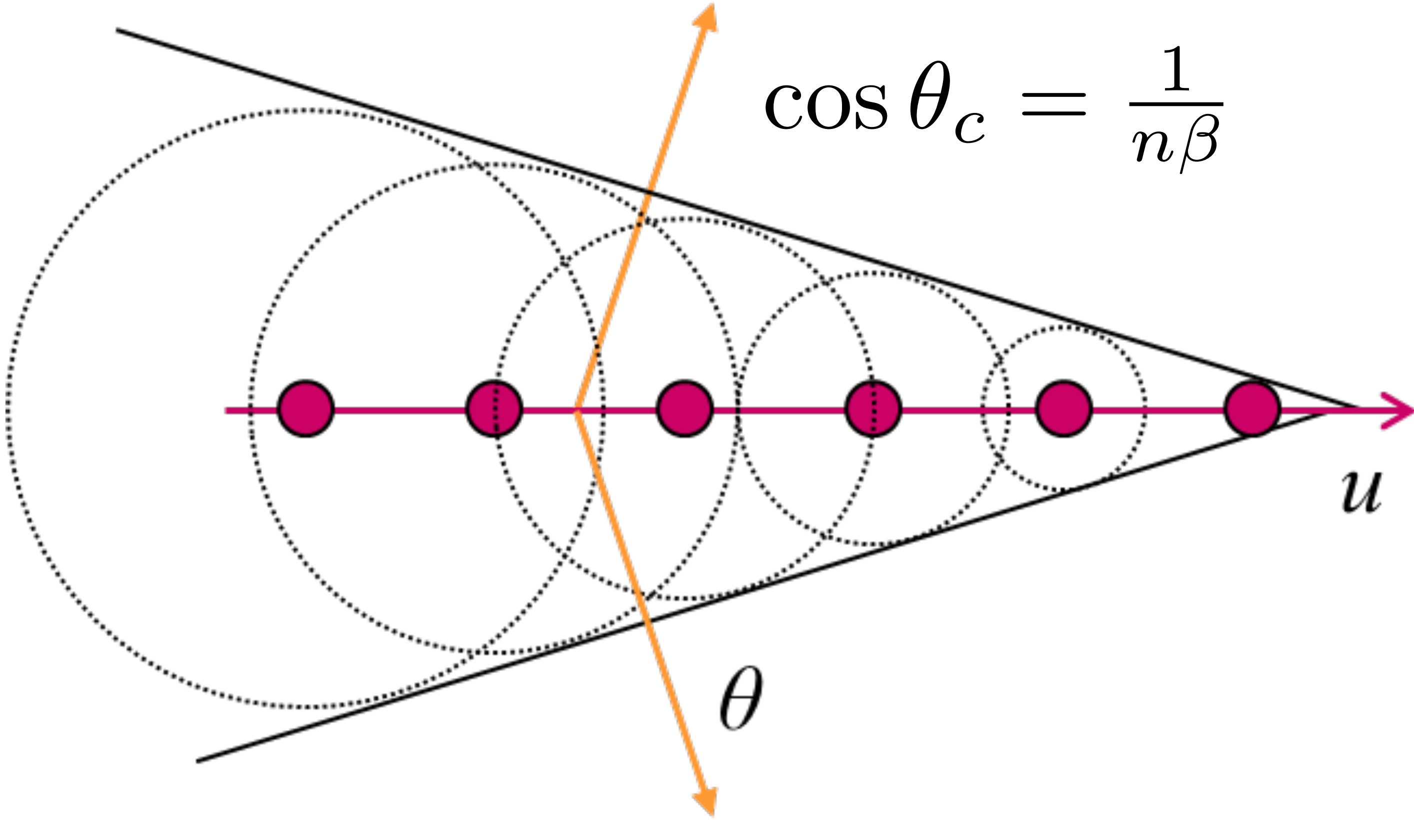
- The same is true for particles traveling faster than the speed of light in a particular medium.



Cherenkov Radiation

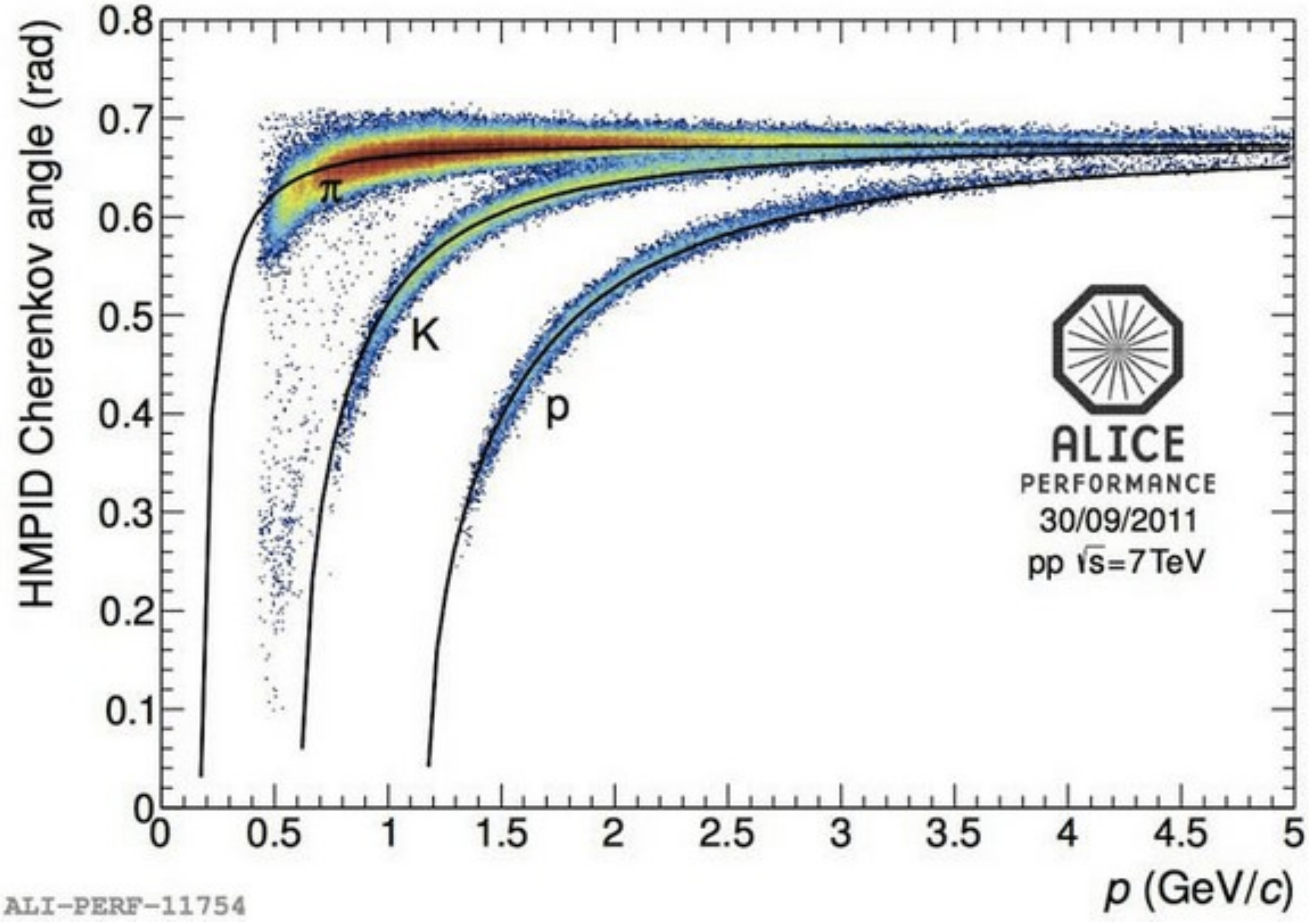
- c: speed of light in a vacuum
- n: index of refraction for a medium
- β: velocity of particle (v/c)
- Cherenkov radiation requires c/n < β < c





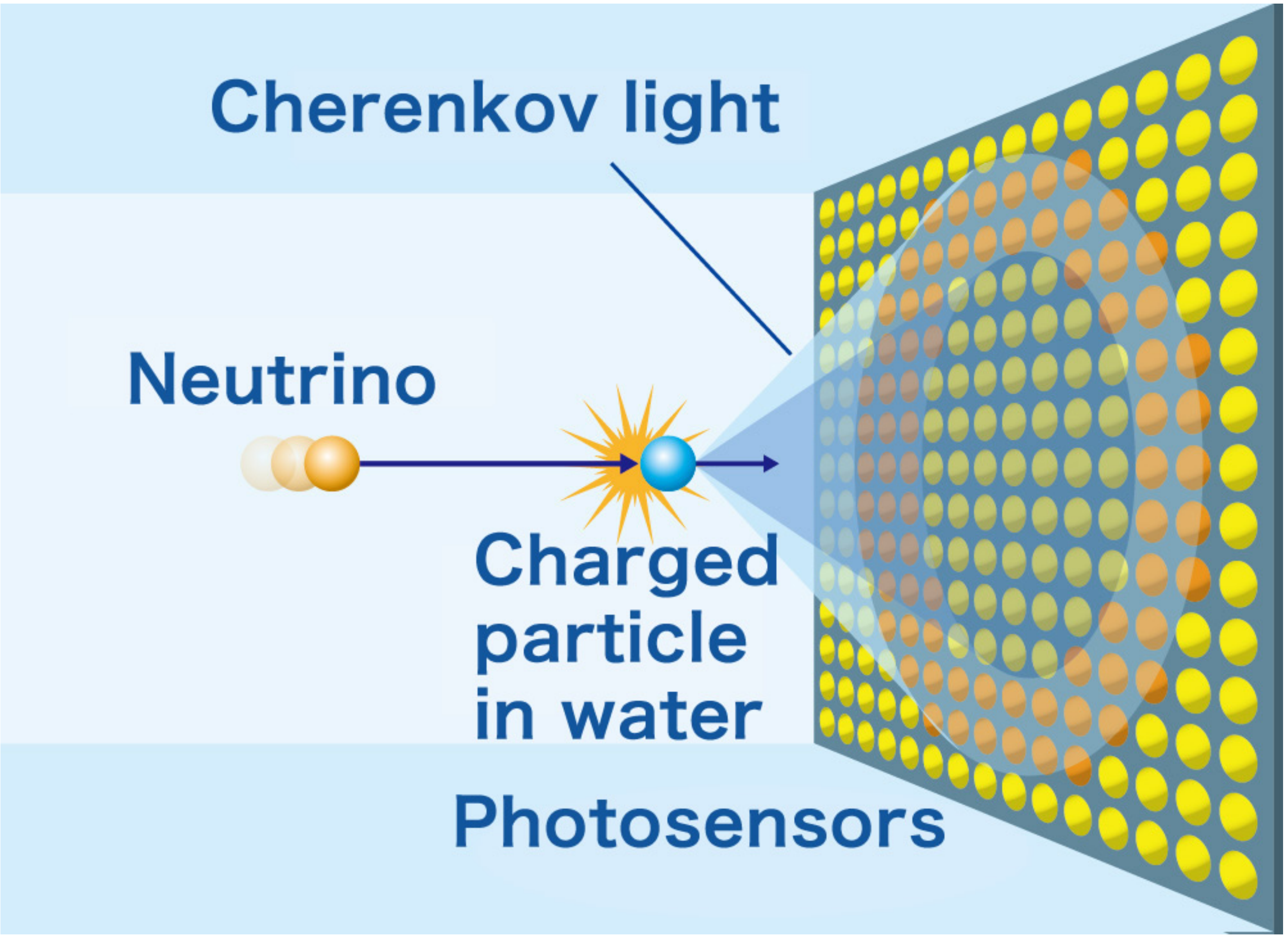
Cherenkov Radiation

- angle depends on velocity, mass, and material
- can provide directionality, timing, particle identification, energy
- combination of particle mass and detector medium produce thresholds

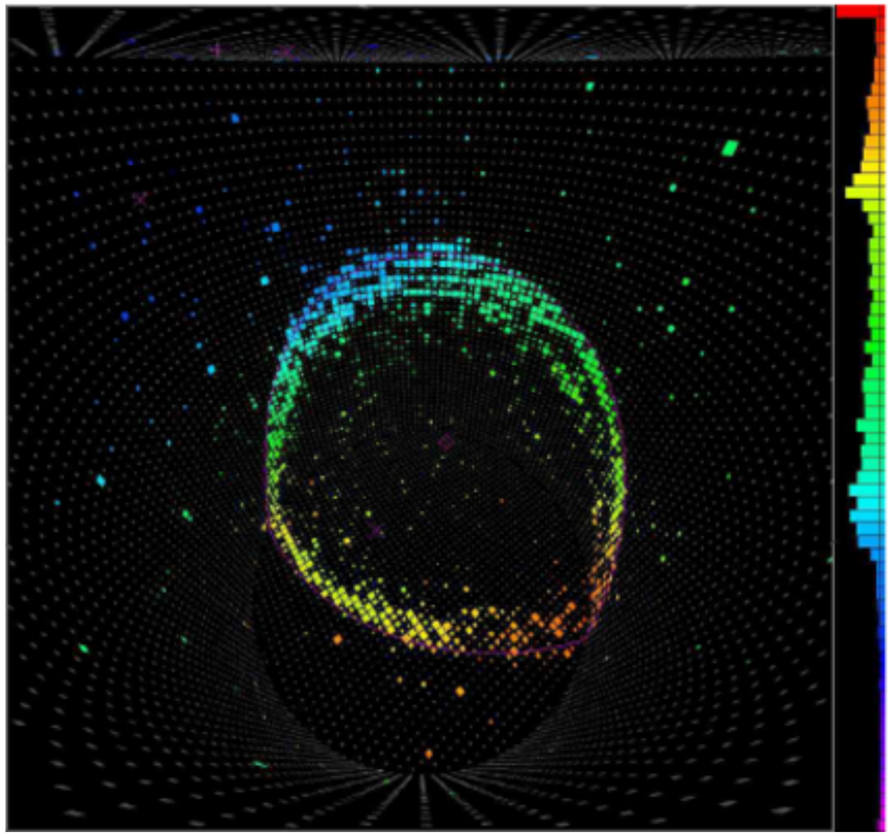


Cherenkov Radiation

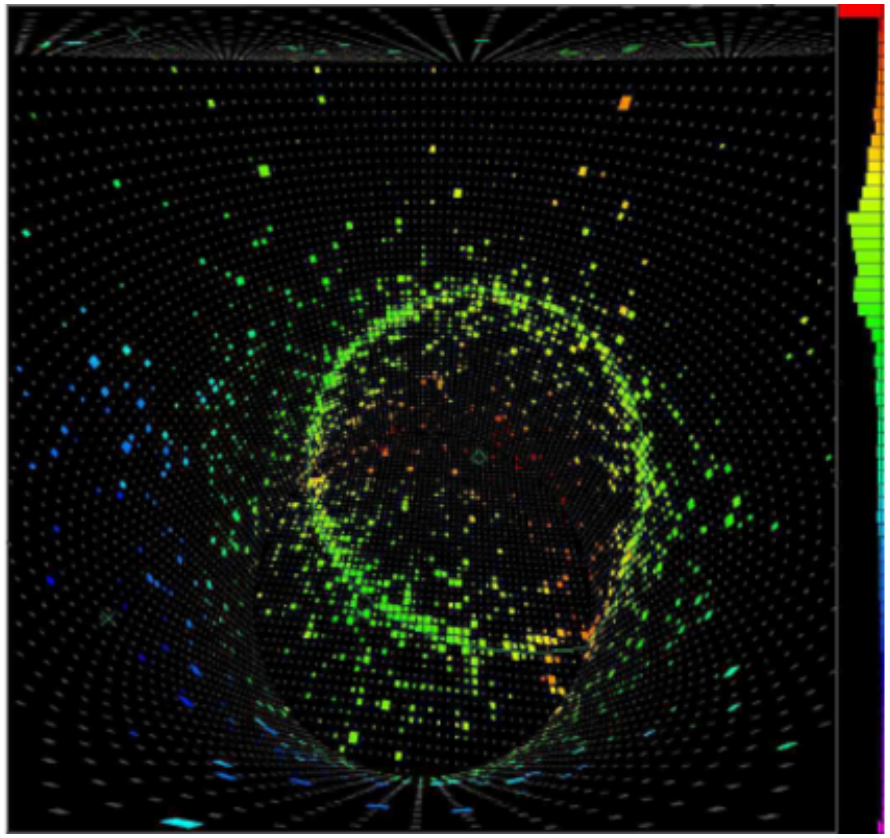
- Water cherenkov detectors: identify particles by ring topology
- Particle identification from ring topology



Simulated Muon Neutrino Interaction



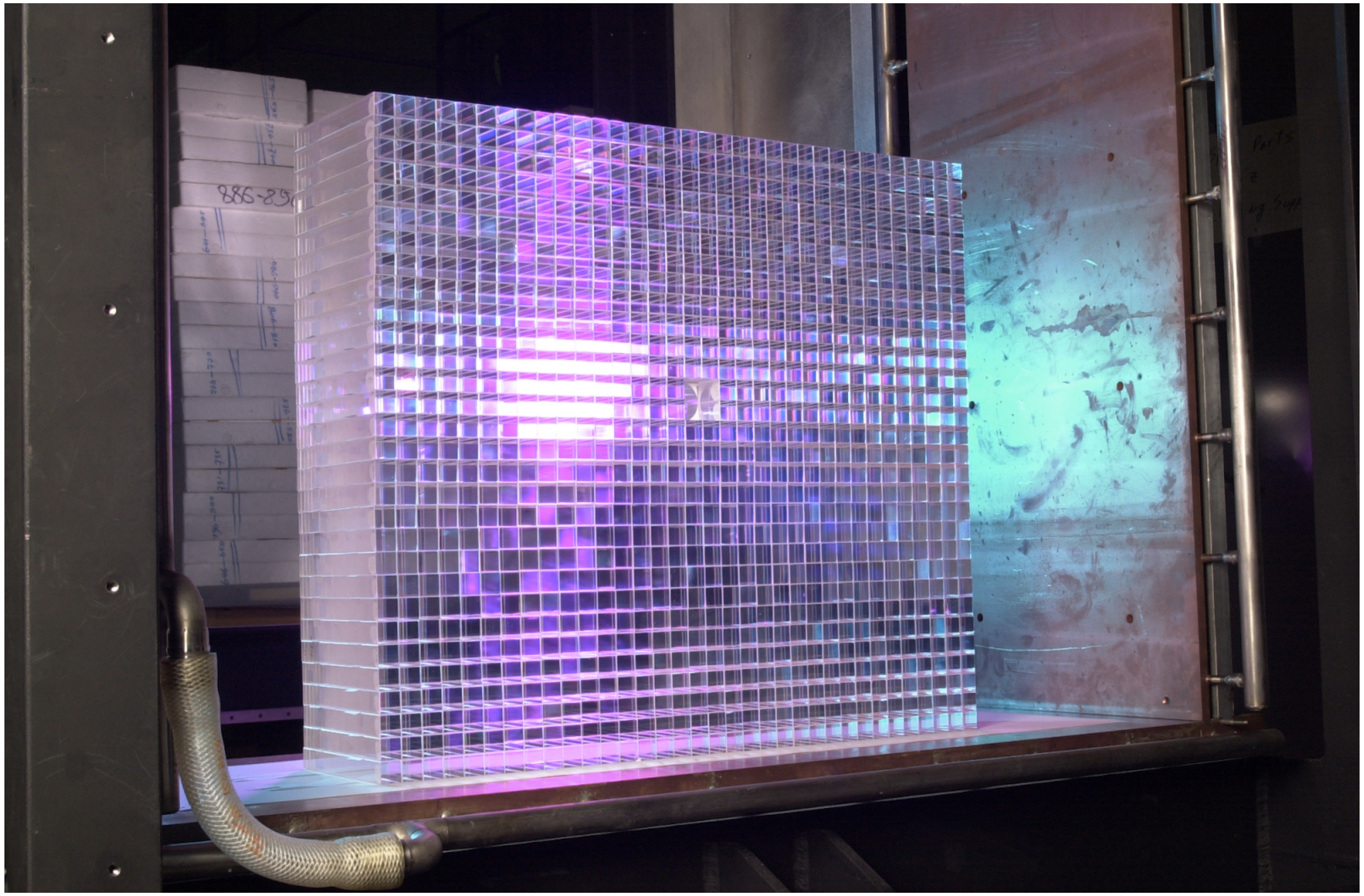
Simulated Electron Neutrino Interaction



Calorimetry

- Measuring the energy a particle loses passing through a detector.

- To fully characterize the energy of a particle you need to stop it.



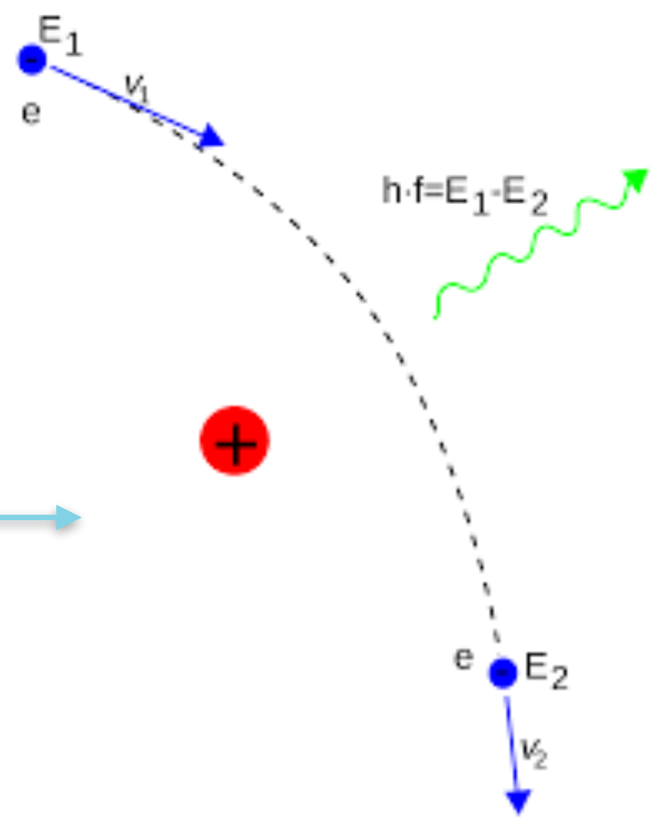
Energy Loss

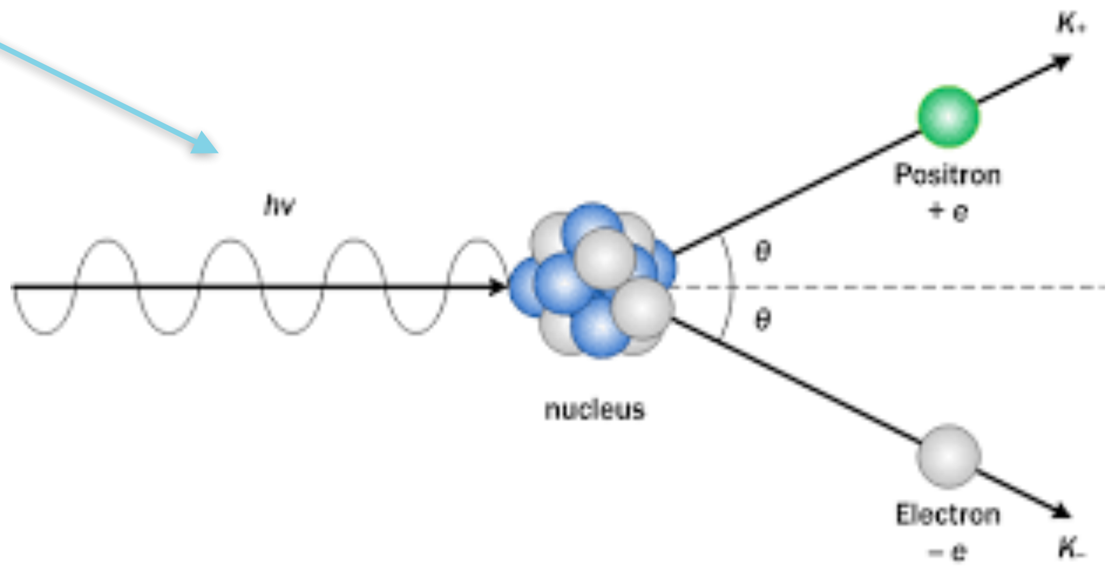
- Many ways for particles to lose energy

- Electromagnetic interactions
  - Bremsstrahlung
  - Pair production
  - Photoelectric effect
  - Cherenkov radiation
  - Scattering
  - Ionization
  - Scintillation

- Strong interactions
  - Hadronic showers

- Weak interactions
  - Neutrinos





Bethe-Bloch Equation

- 1932, relativistic energy loss of charged “massive” particles

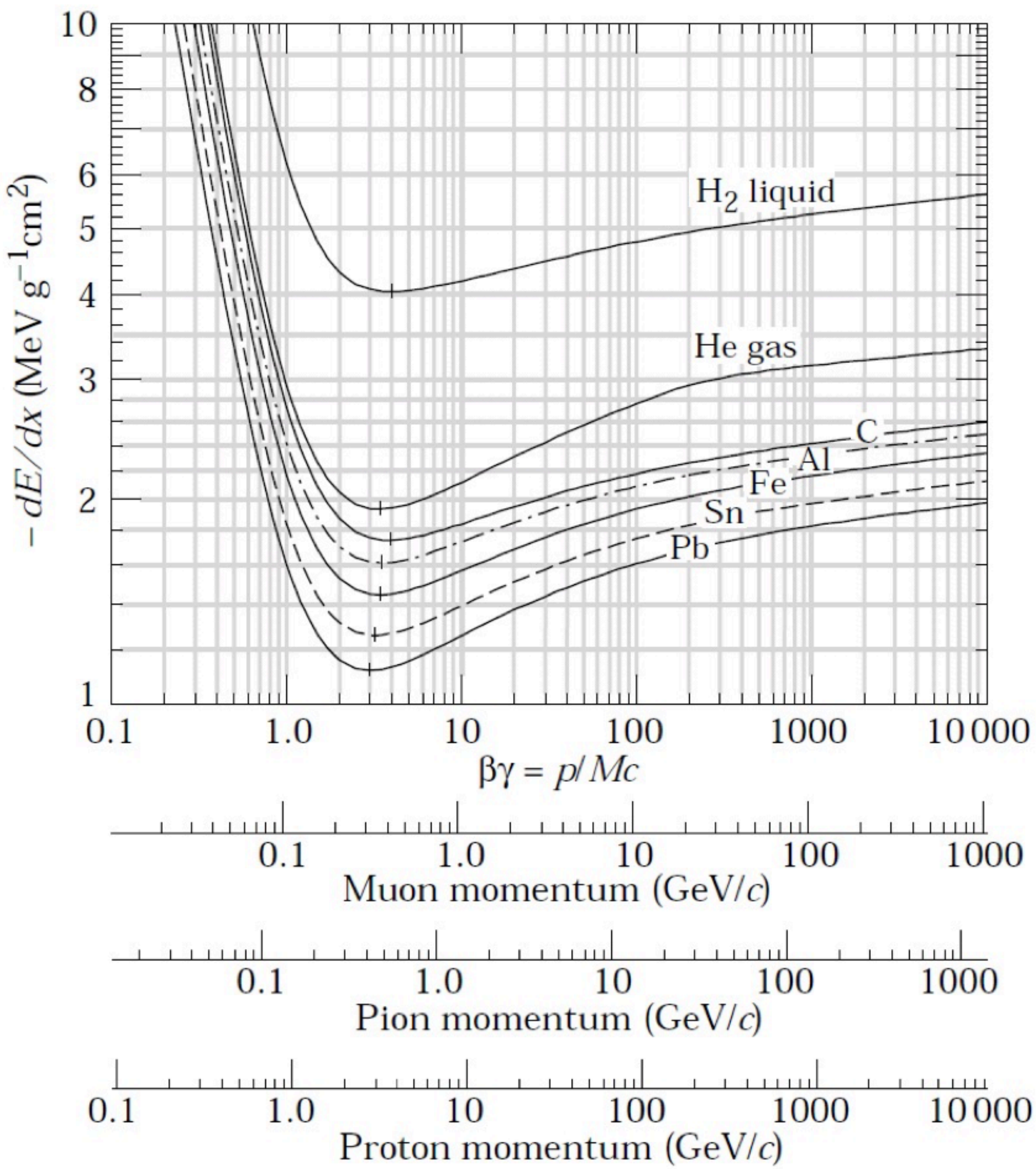
$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

- A, Z: atomic mass and atomic number of absorber
- z: charge of incident particle
- β,γ : relativistic velocity, relativistic factor of incident particle
- δ(βγ): density correction due to relativistic compression of absorber
- I: ionization potential
- T_{max}: maximum energy loss in a single collision
- dE/dx has units of MeV cm^2/g

- Formula does not cover electrons which requires more corrections

Minimum ionizing particles

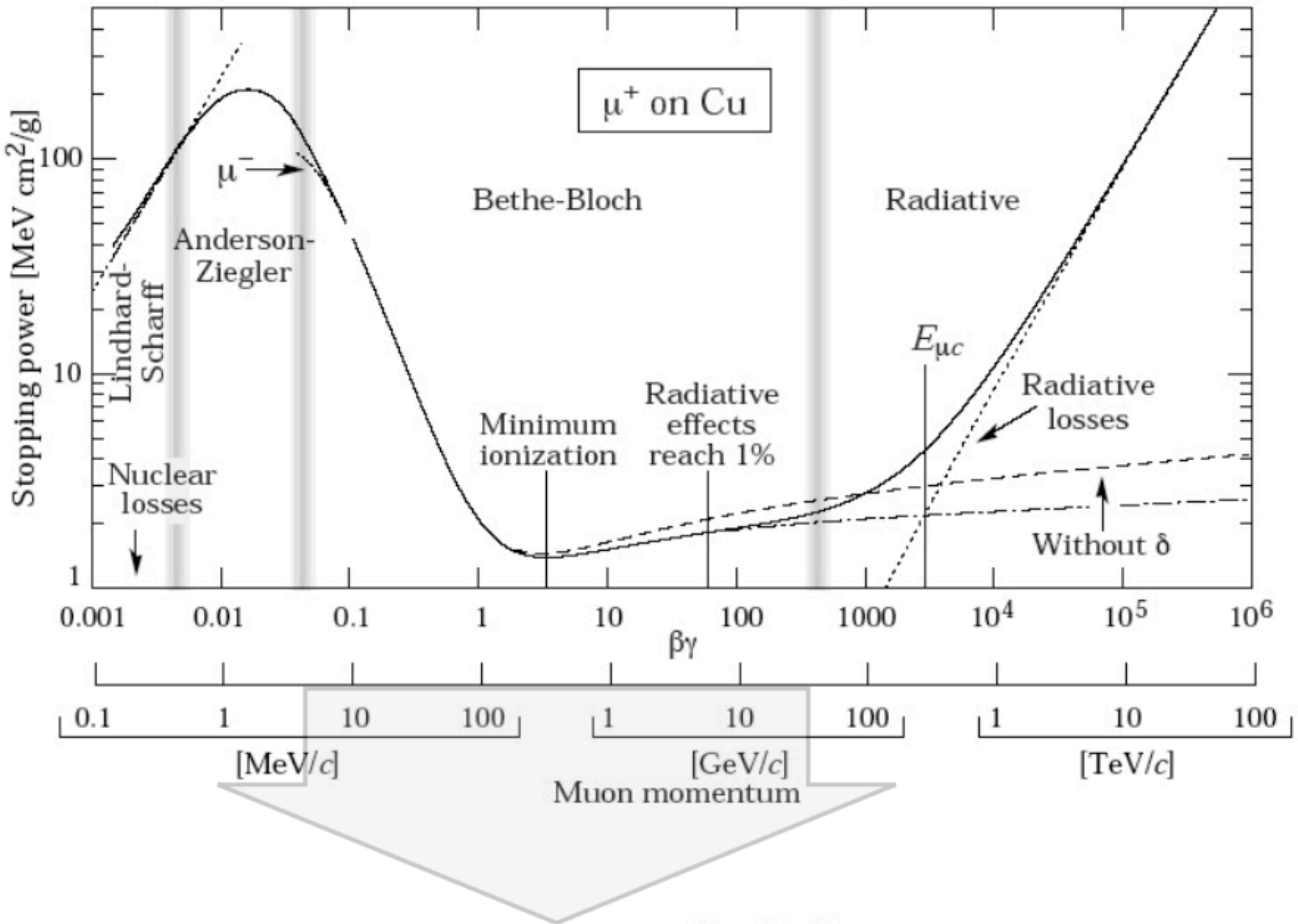
- Bethe-Bloch has same shape independent of material.
- Minimum position in about the same spot where energy loss comes from ionization.
- dE/dx combined with energy or momentum measurements for particle identification.



Energy loss: Muons

- Muons with momentum between 0.1 and 100 GeV lose energy almost entirely through ionization

- For a given medium can determine muon energy to about 3% by range



W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Energy Loss: Electromagnetic Showers

Due to small mass, energy loss due to brems more important

W.-M. Yao et al., Journal of Physics G 33, 1 (2006)
available on the PDG WWW pages (URL: http://pdg.lbl.gov/)

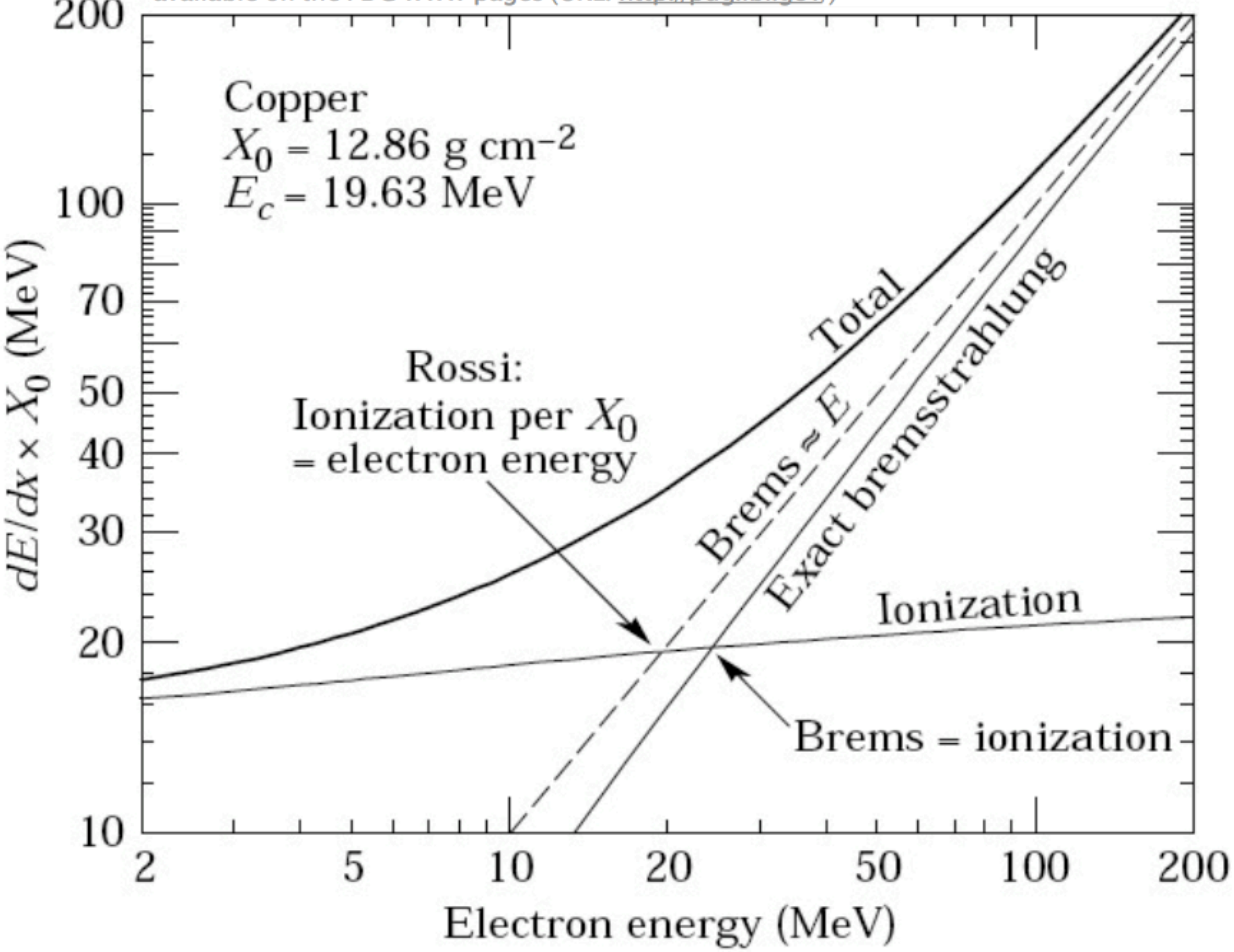
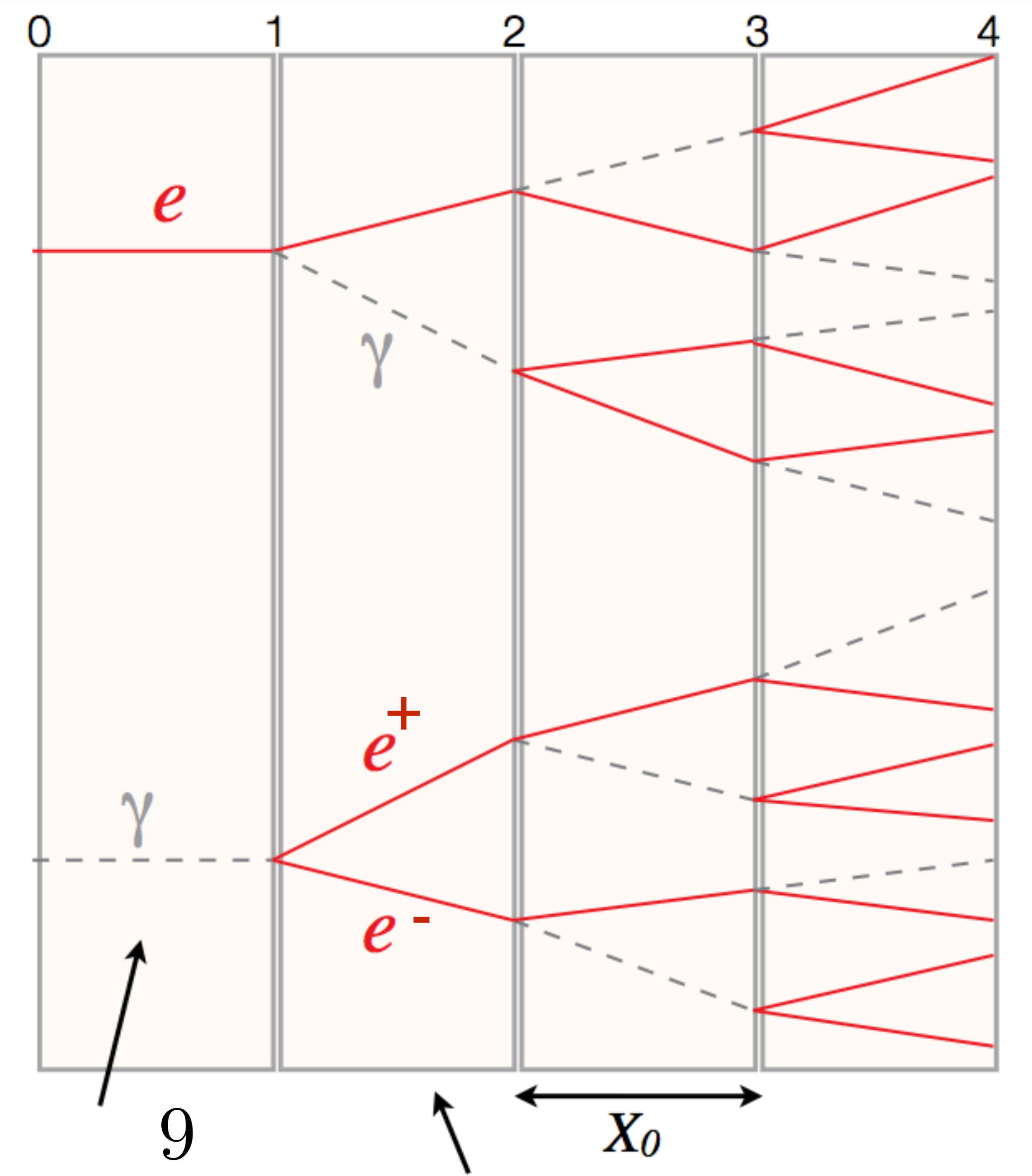


Figure 27.12: Two definitions of the critical energy E_c.



$$\lambda_p = \frac{9}{7}\chi_0$$

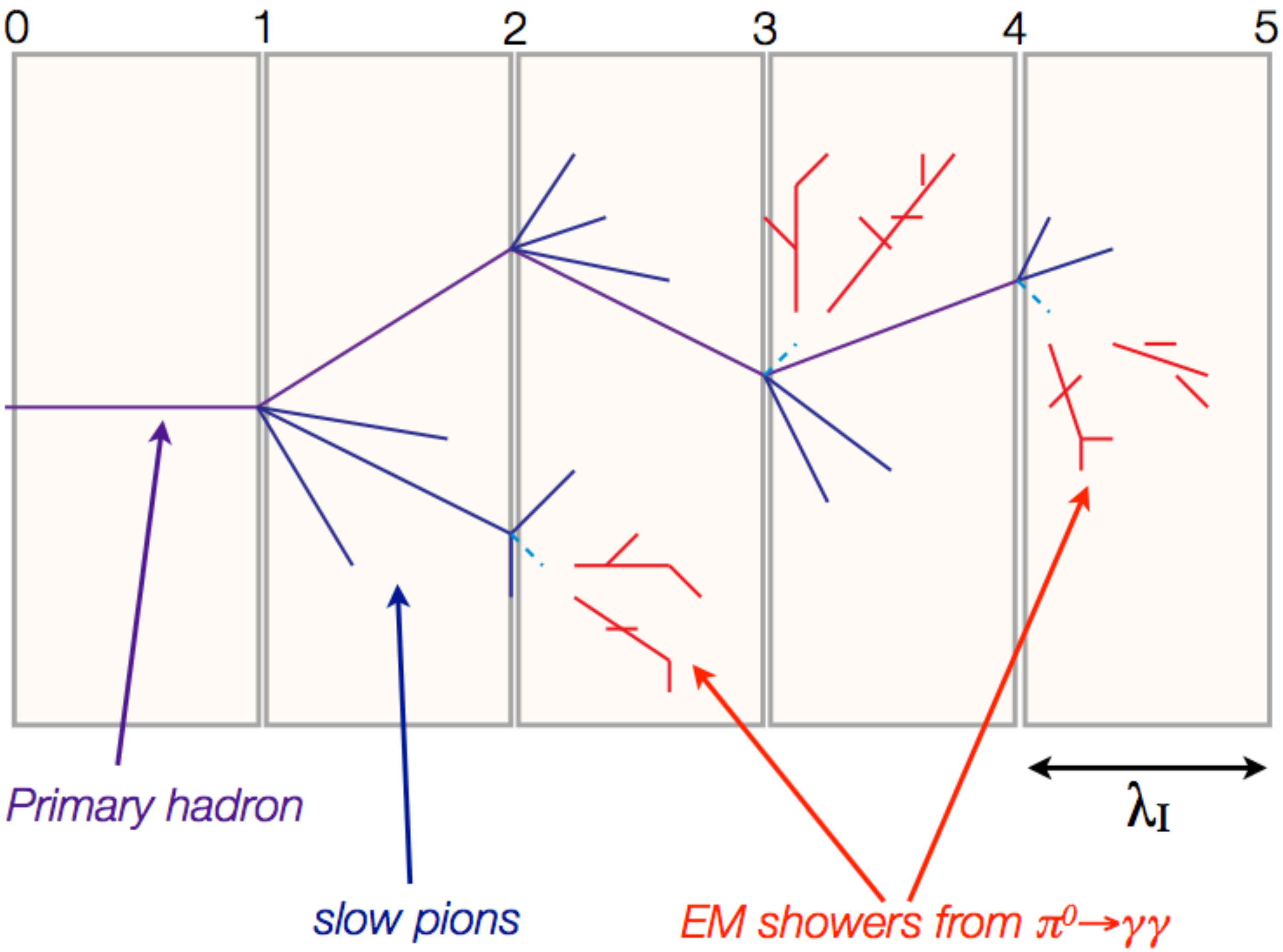
Twice as much energy at start of shower

$$E_c \approx \frac{800\text{ MeV}}{Z+1.2}$$

Radiation length is distance electron loses 1/e energy via radiation

$$R_M = \frac{21.2\text{ MeV}}{E_C}\chi_0$$

Energy Loss: Hadronic Showers



CHARM-II collaboration, NIM A277 (1989) 83-91.

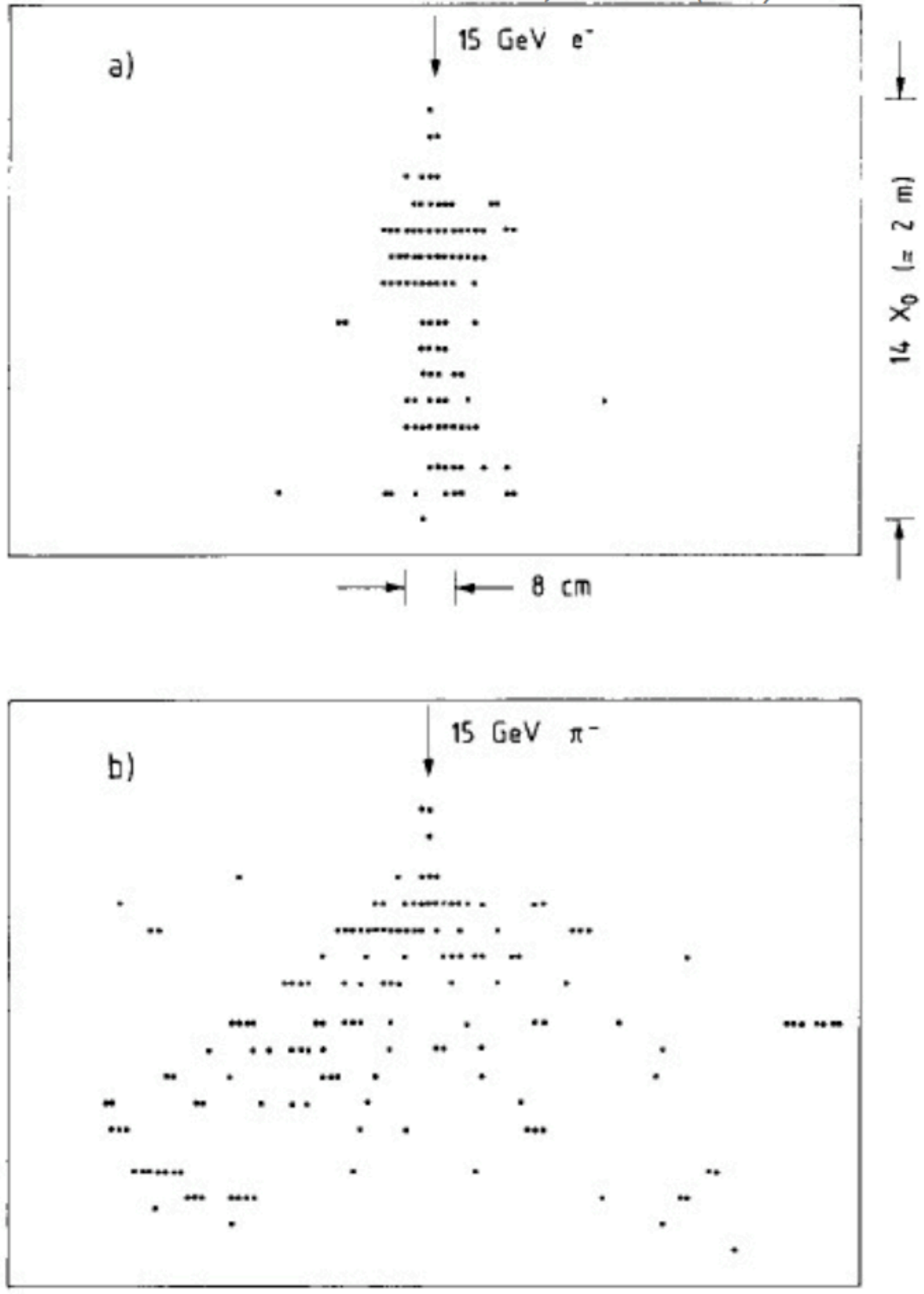
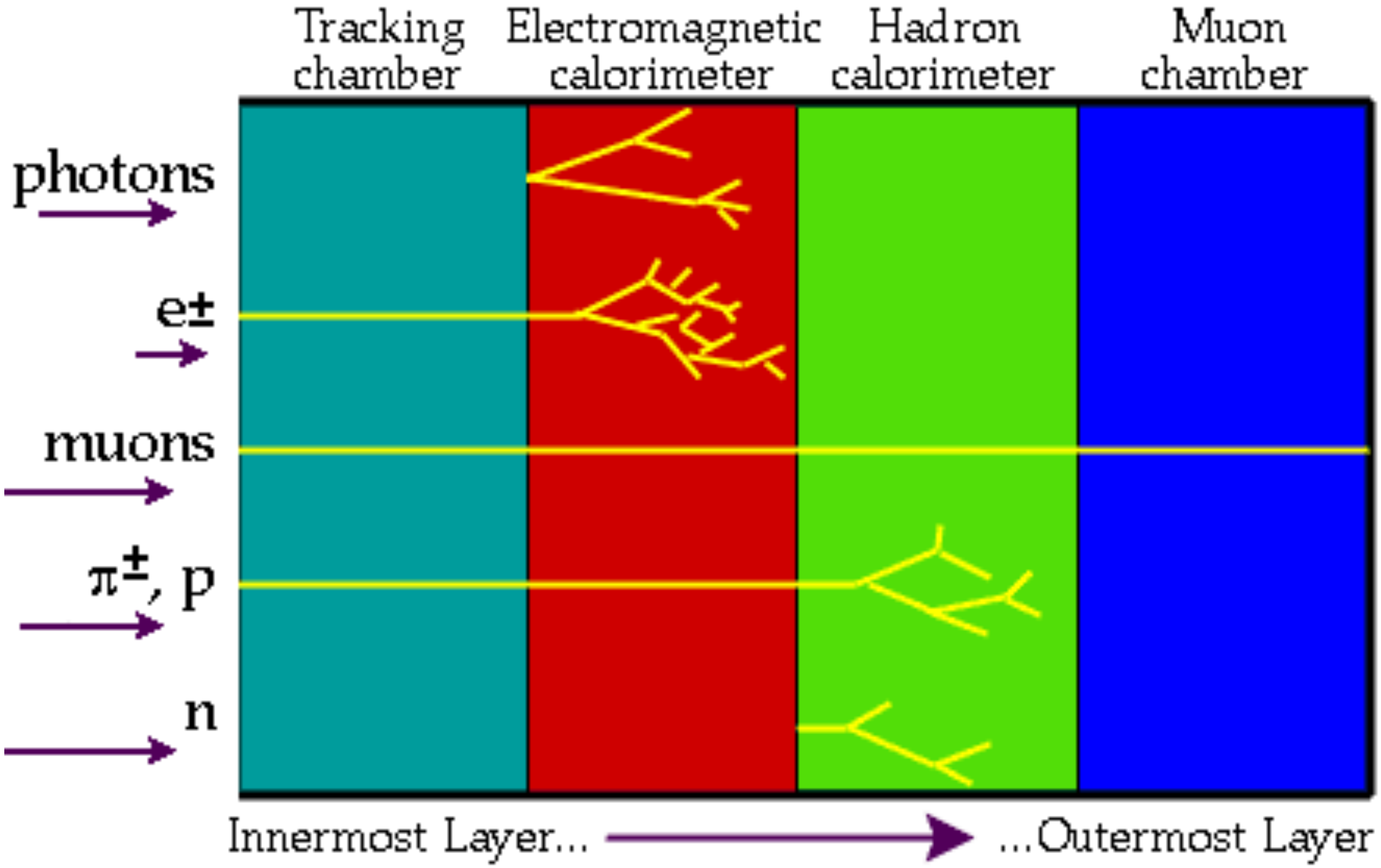


Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.

Calorimetry

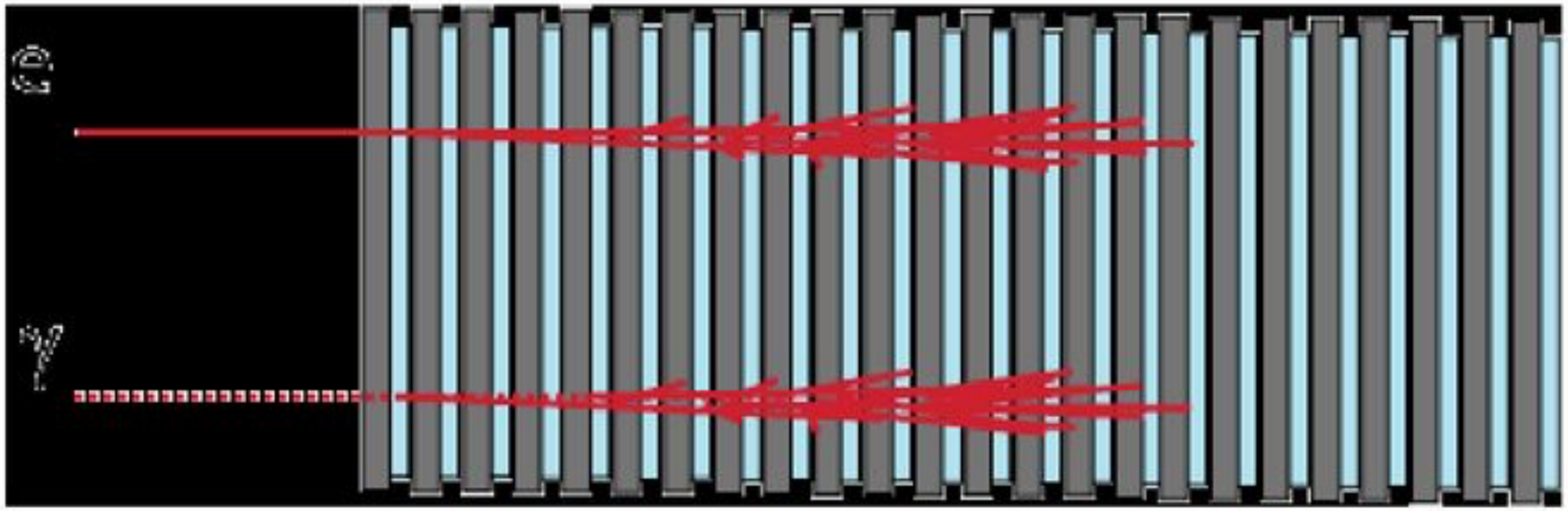
- Calorimeters come in different types
  - Electromagnetic vs hadronic

- Detector materials and particles/energies of interest effect design and placement of calorimeter



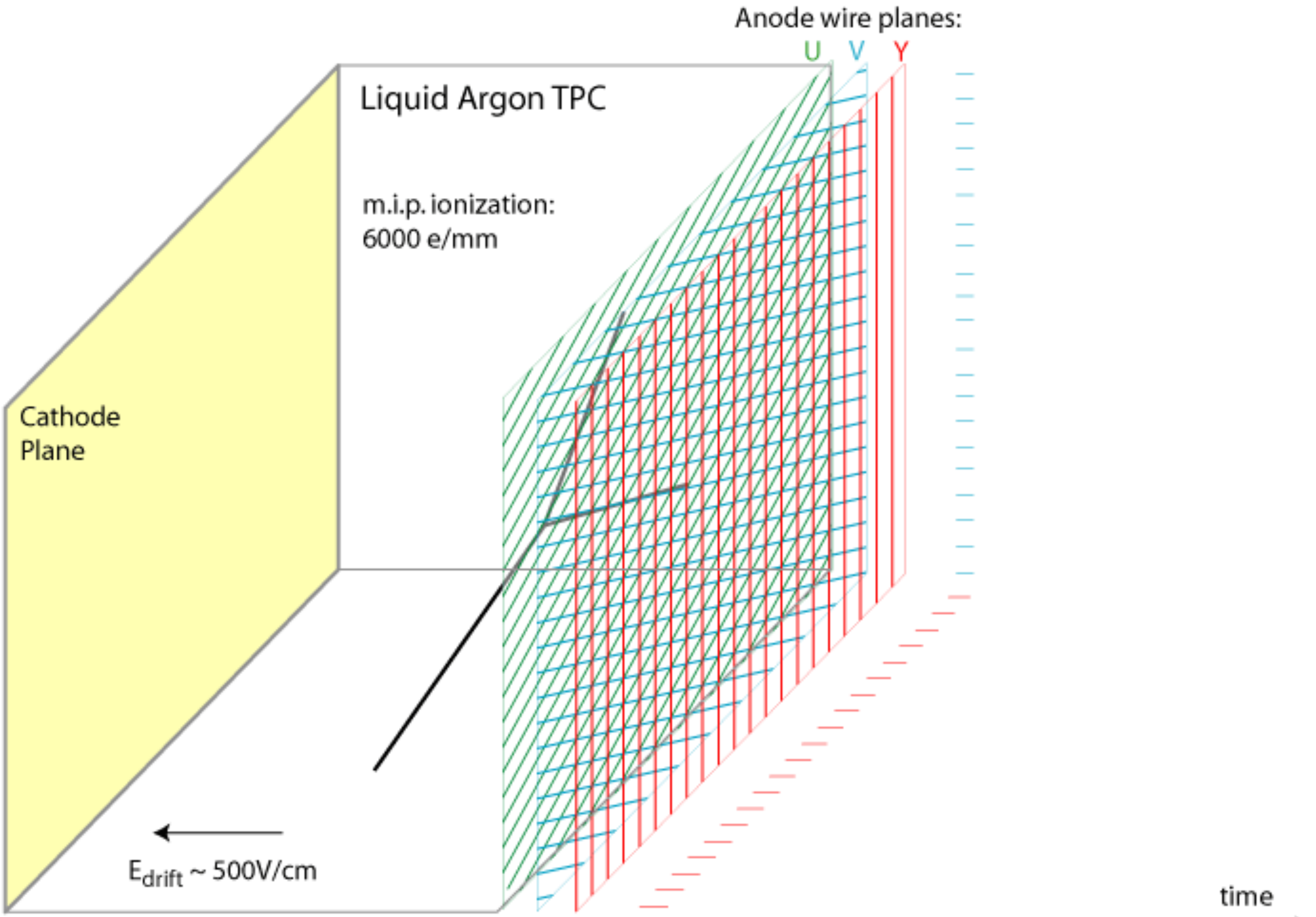
Types of calorimeters

Sampling Calorimeter



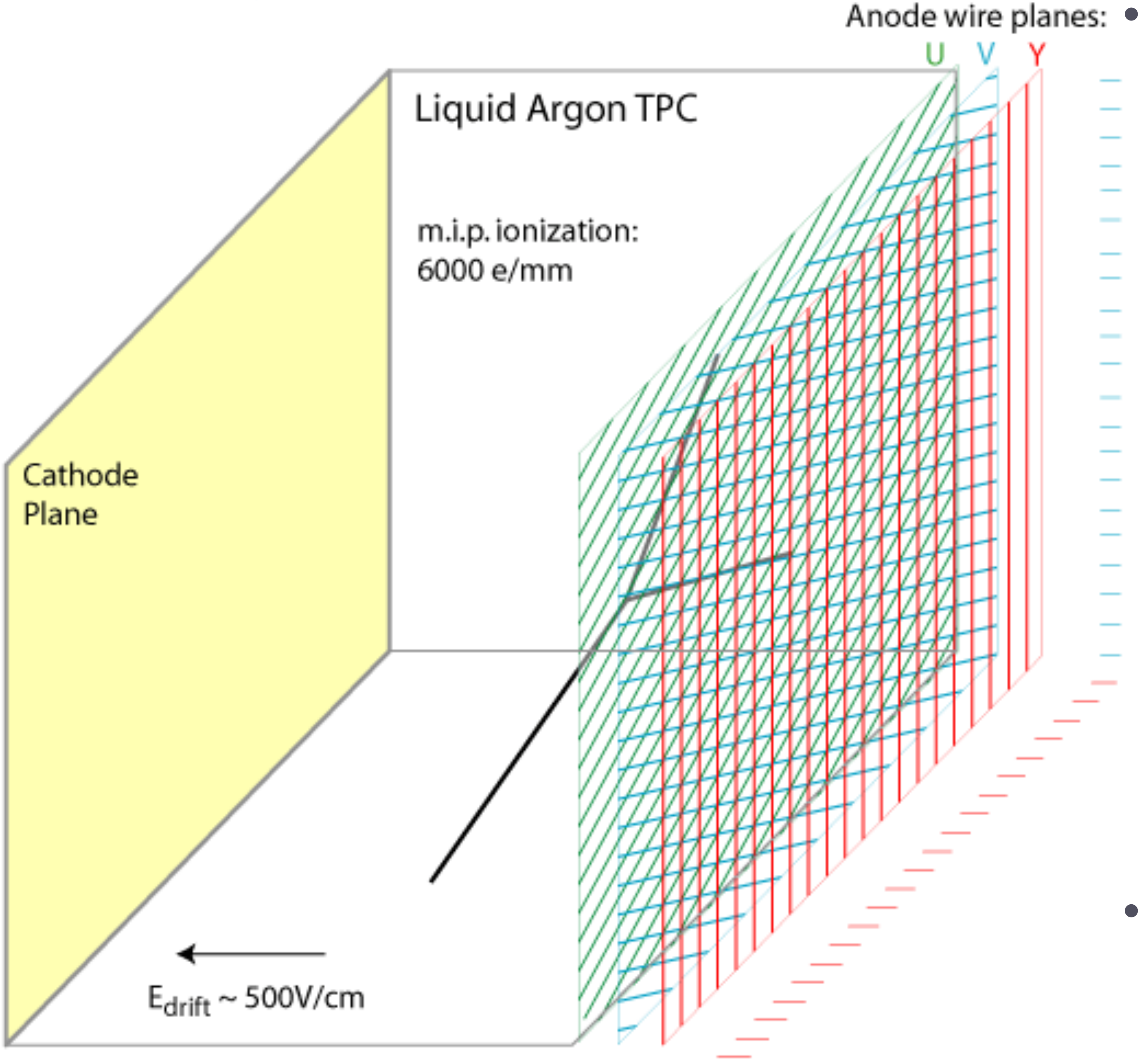
Homogeneus Calorimeter

Liquid Argon Time Projection Chambers



Interacting particles produce scintillation light (time) and ionize medium. Applying an electric field and collection plane provides precision tracking.

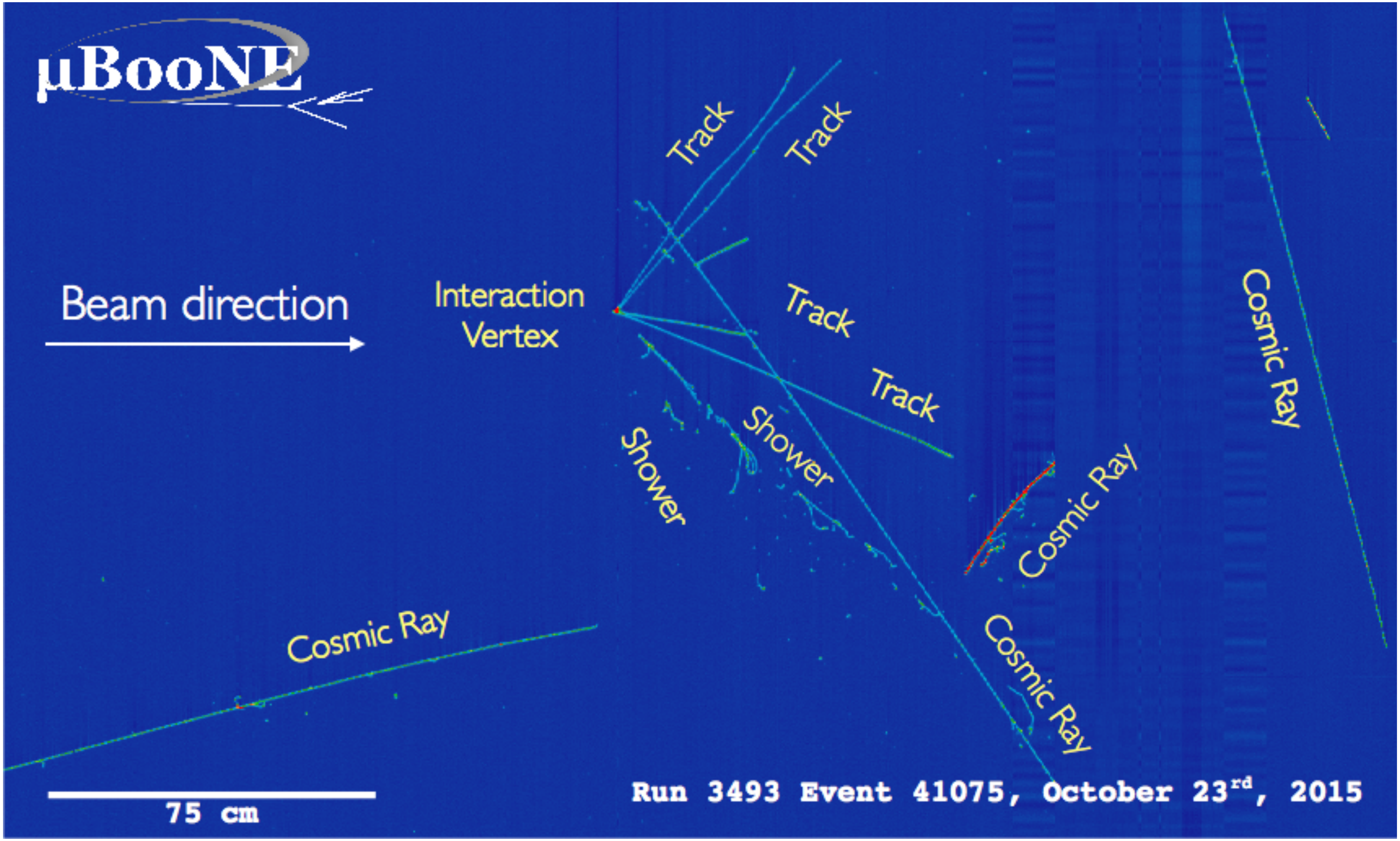
Liquid Argon Time Projection Chambers



- What advantages would liquid argon have as a detector medium?
  - Nobel element so little interaction with electrons resulting from ionization as they drift.
  - Produce scintillation light in addition to ionization, gives you event time.
  - Relatively inexpensive -> large volume
  - High density -> more interactions

- Provide tracking, calorimetry, particle ID all in one.

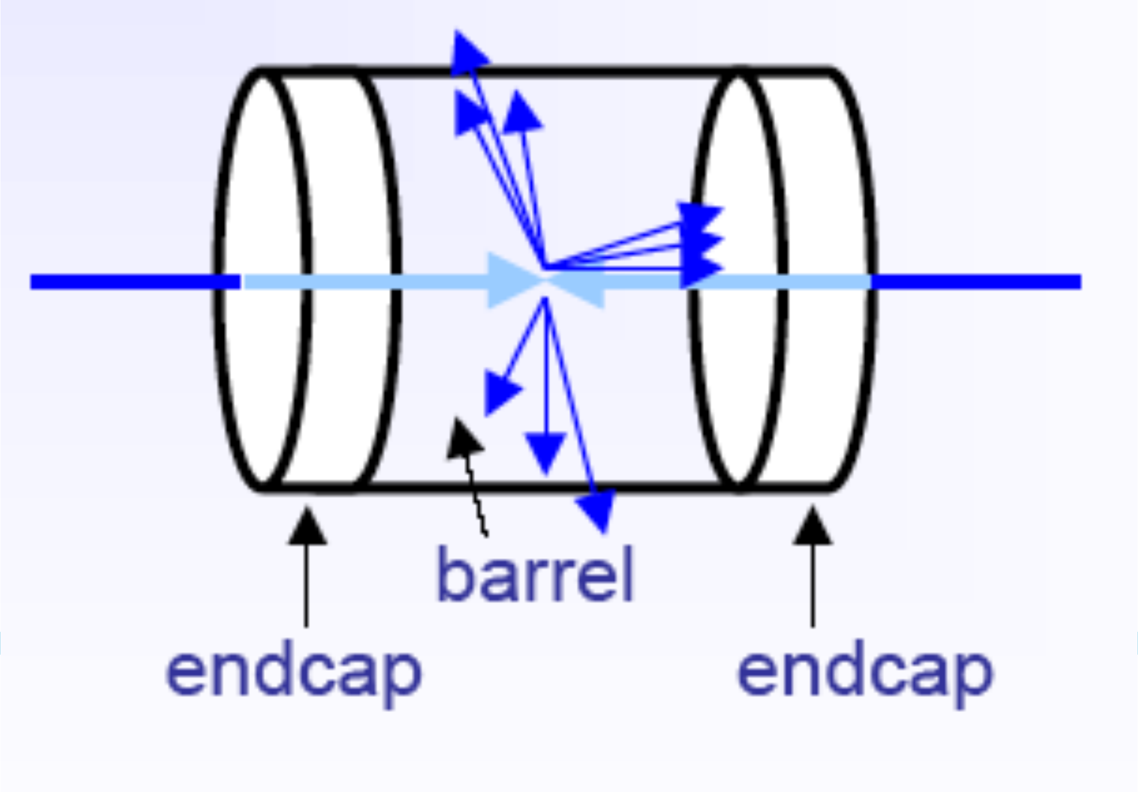
Liquid Argon Time Projection Chambers



http://inspirehep.net/record/1600791/plots#2

Putting is all together: Collider Experiment

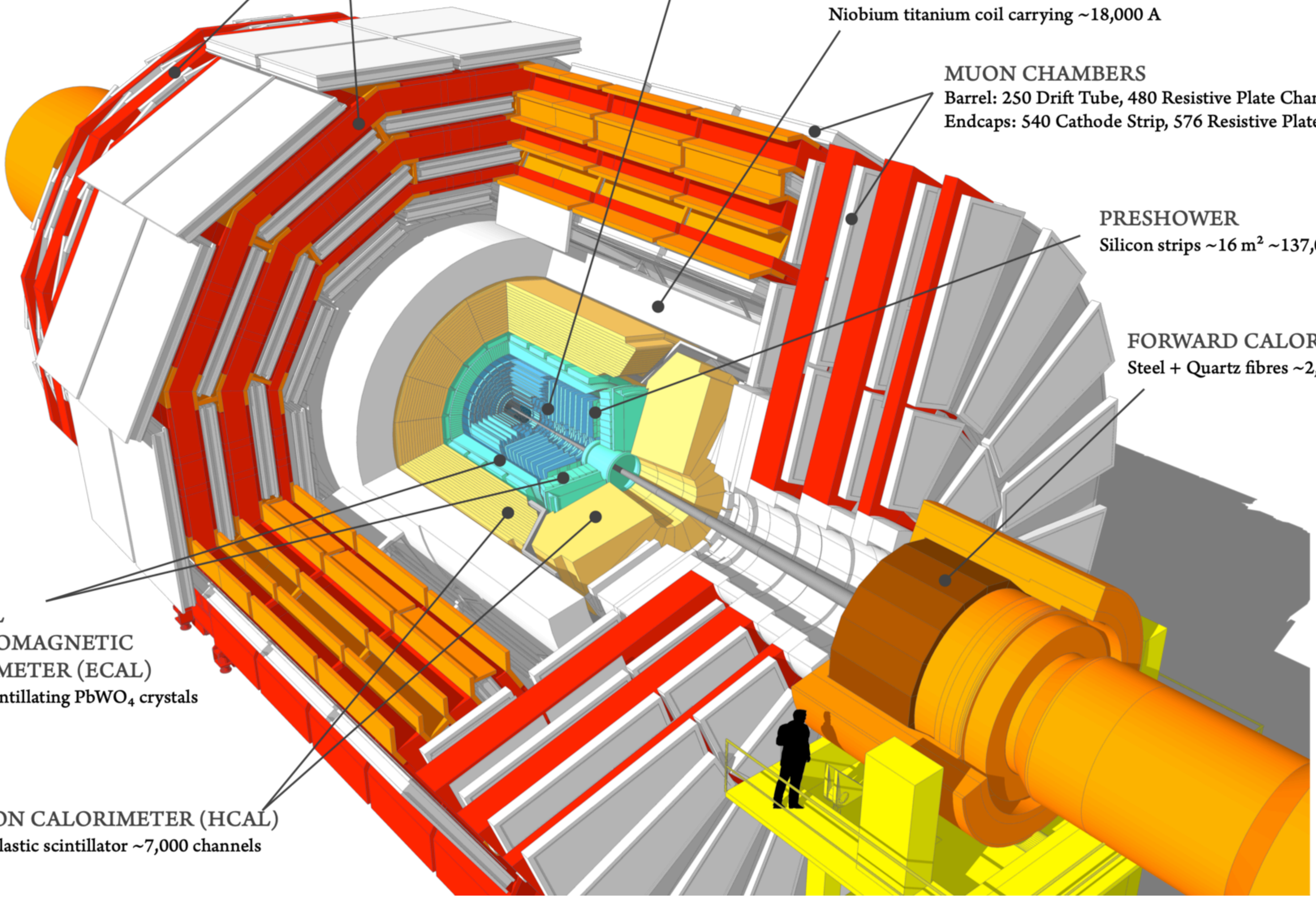
- Accelerator steers particles to collide in center of detectors —> Particles radiate outward, build detector in rings
- High multiplicity of interactions —> granular detector, fast technologies, radiation hard components
  - High Luminosity LHC era looking at 140-200 interactions in a 5 cm area, in ~200 picoseconds
- High energy interactions —> Large and massive detector to fully contain interactions
- Multiple detector technologies employed to efficiently collect and ID different particles



https://cds.cern.ch/record/2665537/

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm²) ~1.9 m² ~124M channels
Microstrips (80–180 μm) ~200 m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000 A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16 m² ~137,000 channels

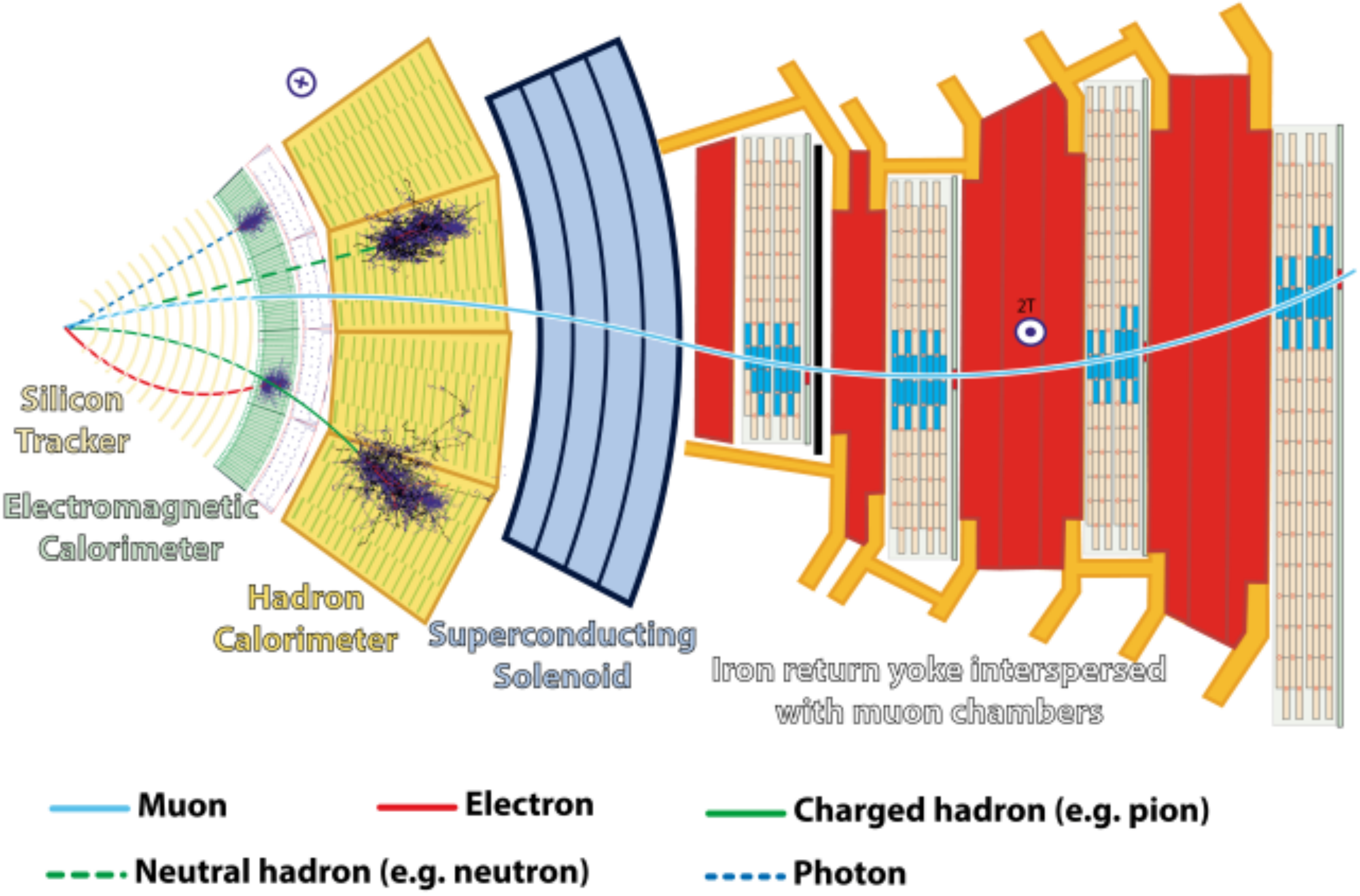
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

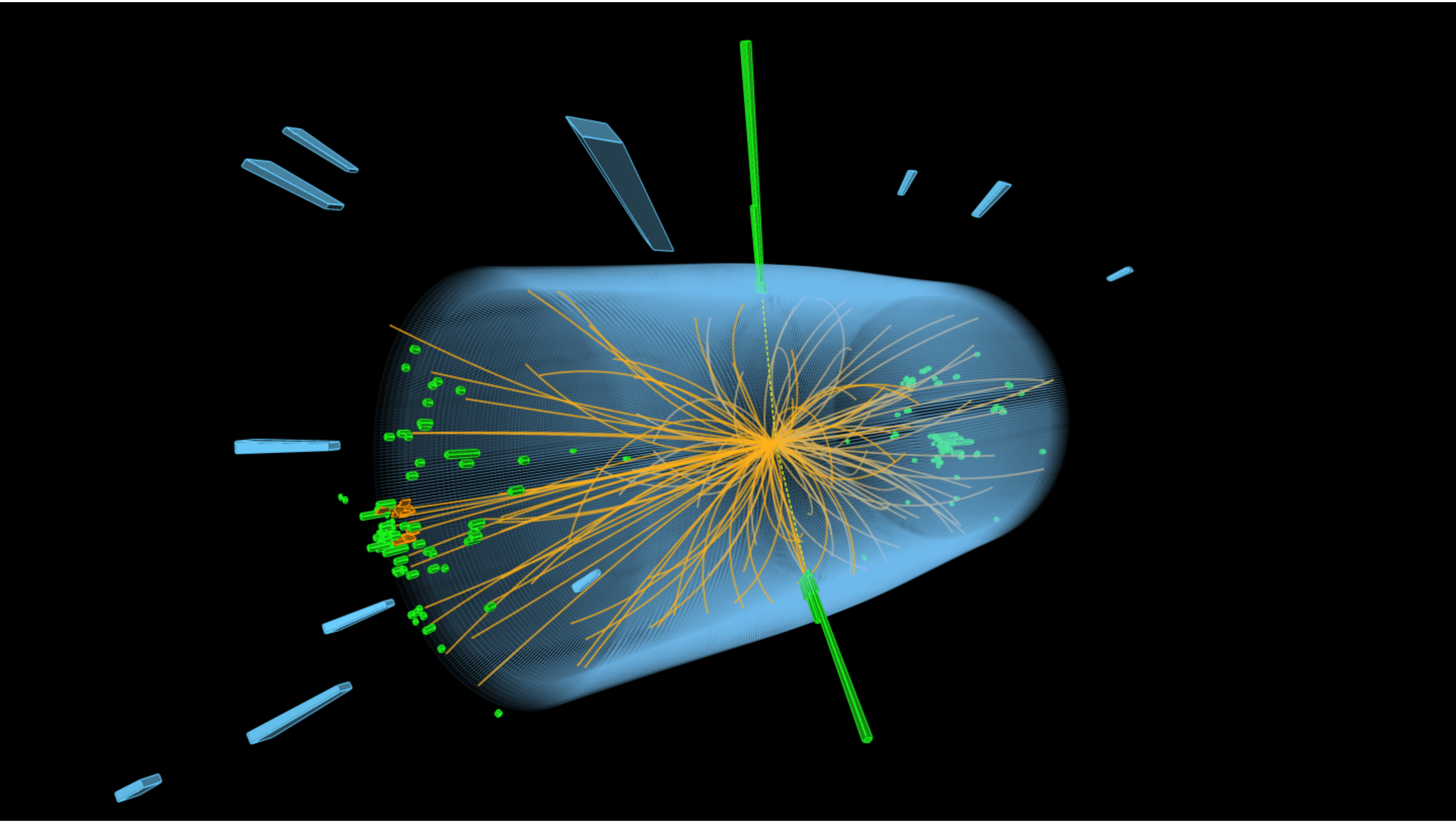
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

https://cds.cern.ch/record/2120661

CMS

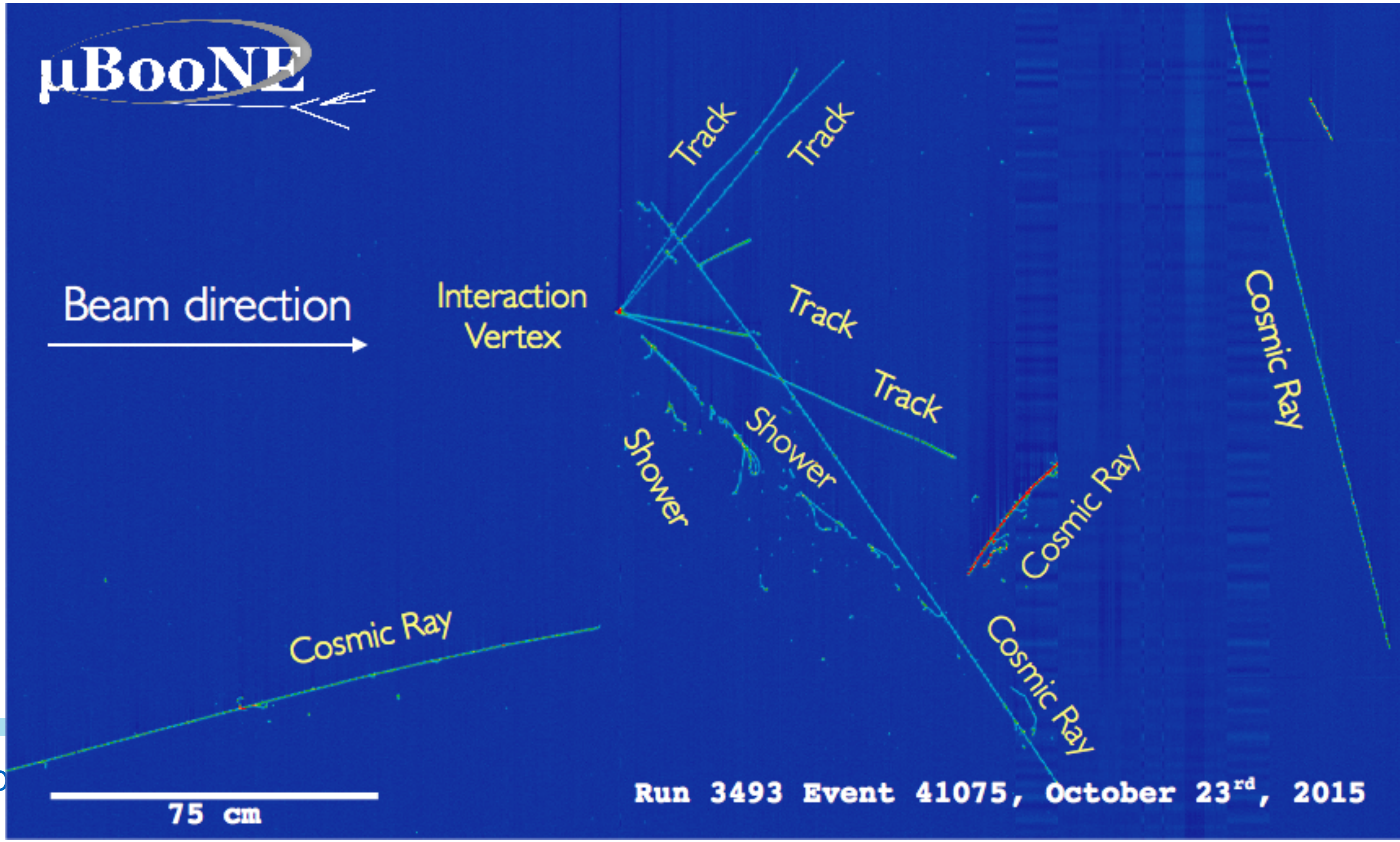


CMS

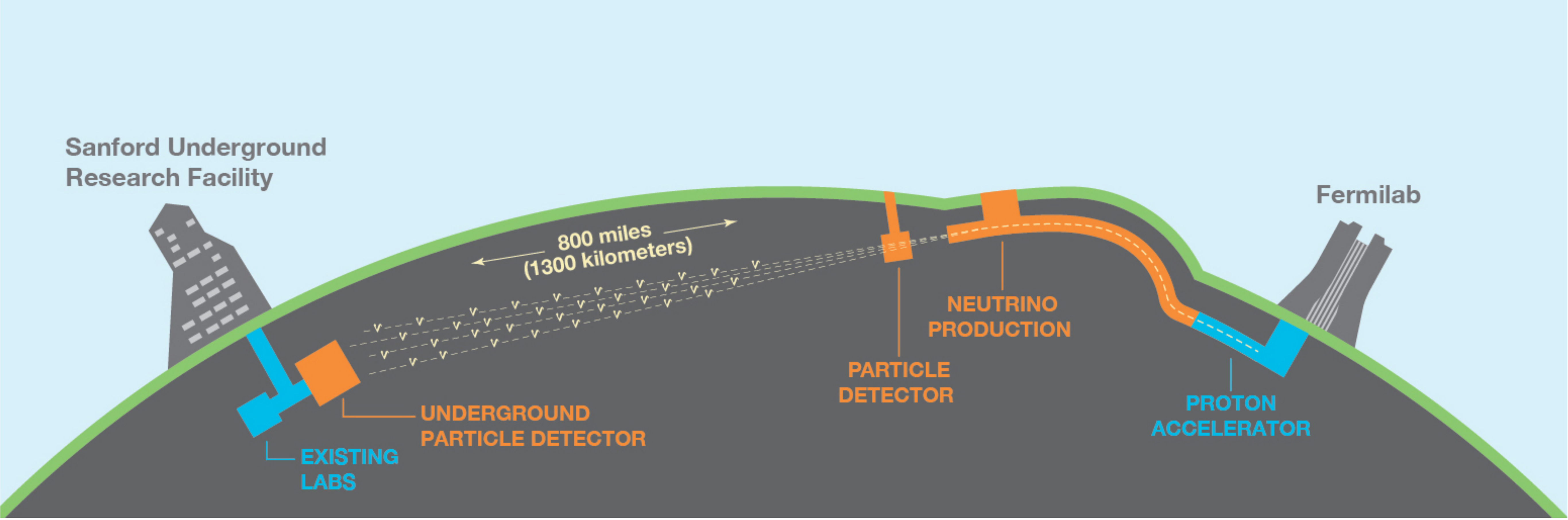


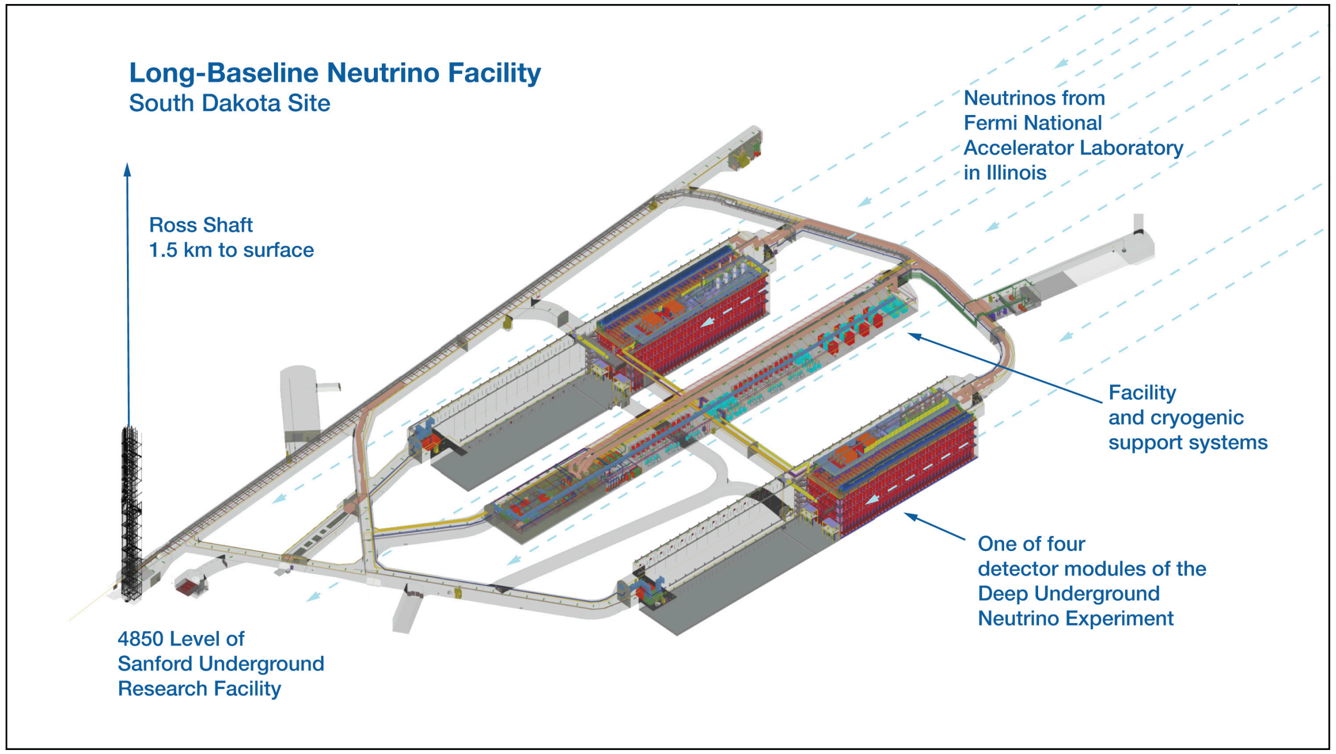
Putting is all together: Neutrino Experiment

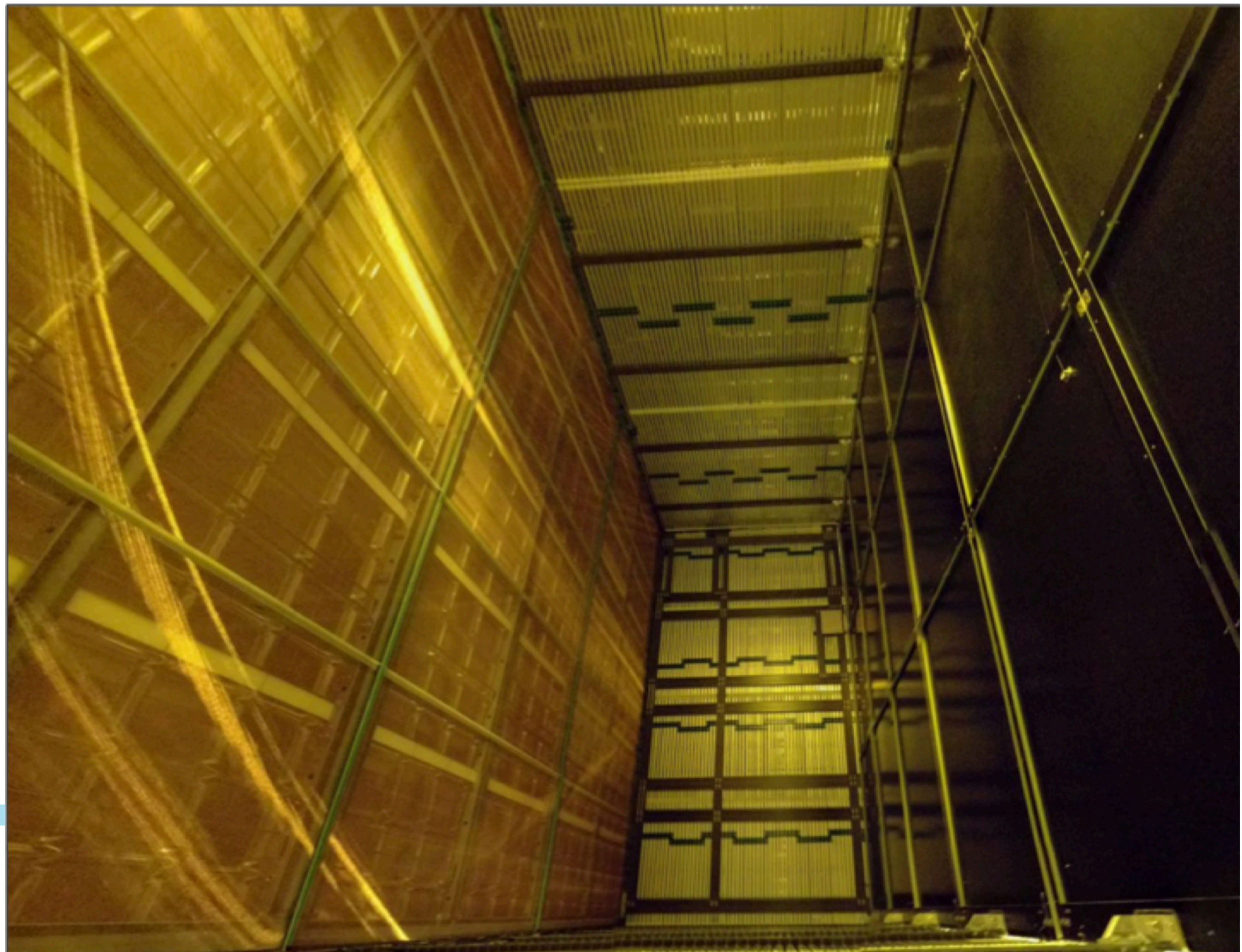
- Interactions are rare due to low mass and only interacting through weak nuclear force.
  - Build a detector as large as possible in target mass
  - Use an intense source of neutrinos
  - Run the experiment as long as possible
  - Minimize background sources
  - Good energy resolution, fully contain the event
  - Good particle identification



Putting it all together: DUNE







Summary

- Many technologies for identifying particles (far more than covered today!).
- Optimize detector design to satisfy a set of physics goals, there is no one way to build an experiment.
- We have a lot of tools we can use to detect particles: ionization, scintillation, magnetic fields, calorimetry
- As much effort or more can go into designing and building a detector as collecting and analyzing the data. Many detector concepts require technological innovations to become reality.