# PARTICLE PHYSICS

## COLUMBIA SCIENCE HONORS PROGRAM

WEEK 5

EXPERIMENTAL METHODS

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# COURSE POLICIES

- Attendance
  - Up to four excused absences
    - Two with notes from parent/guardian
    - shpattendance@columbia.edu
  - Valid excuses:
    - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
  - Invalid excuses:
    - Sleeping in, missing the train…
  - I will take attendance during class

- No cell phones

- Ask questions!

# LECTURE MATERIALS

- https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

- Questions: cristovao.vilela@stonybrook.edu

LAST WEEK…

# QUANTUM MECHANICS

PARTICLES AND WAVES

# WHAT IS QUANTUM MECHANICS?

- Quantum mechanics is the study of nature at very small scales – specifically when the energies and momenta of the system are of the order of Planck's constant:

$$\hbar = \frac{h}{2\pi} = 6.6 \times 10^{-16}\,\mathrm{eV\,s}$$

- On a quantum level, particles exhibit a number of non-classical behaviors:
  1. Quantization of energy, momentum, charge, spin, …
  2. Particles exhibit wave-like effects: interference, diffraction, …
  3. Systems can exist in a superposition of states

# THE DE BROGLIE HYPOTHESIS
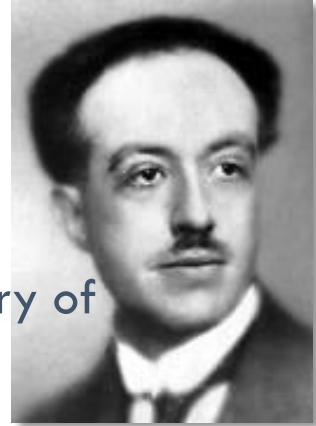
- de Broglie's suggestion was a bold statement about the symmetry of Nature.

- Proposal: the wave aspects of matter are related to its particle aspects in quantitatively *the same way* that the wave and particle aspects of light are related.

- Hypothesis: for matter and radiation, the total energy (E) of a particle is related to the frequency (f) of the wave associated with its motion by:

$$E = hf$$

- If E=pc (recall SR), then the momentum p of the particle is related to the wavelength λ of the associated wave by the equation:
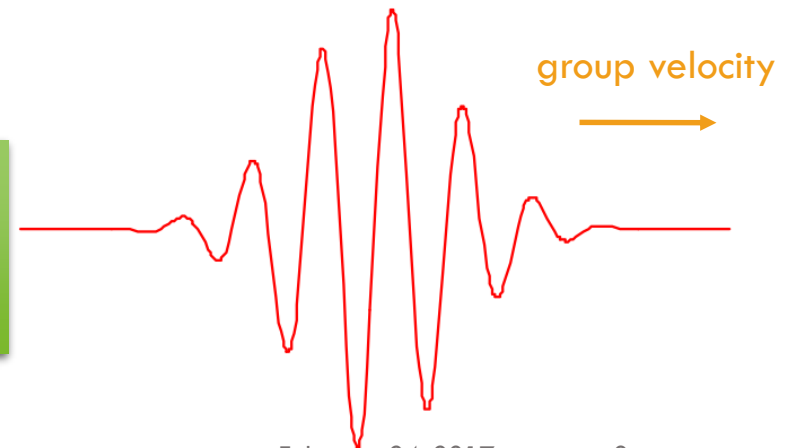
$$p = \frac{h}{\lambda}$$

# THE DE BROGLIE HYPOTHESIS

**de Broglie relation**

$$\lambda = \frac{h}{p} \qquad p = \frac{h}{\lambda}$$

- *It holds even for **massive particles.***

- It predicts the de Broglie wavelength of a matter wave associated with a particle of momentum p.

de Broglie hypothesis: particles are also associated with waves, which are extended disturbances in space and *time.*

group velocity

# ELECTRON DIFFRACTION

- Scattering electrons off crystals also creates a diffraction pattern!

- Electron diffraction is only possible if electrons are waves.

- Hence, electrons (matter particles) can also behave as waves.
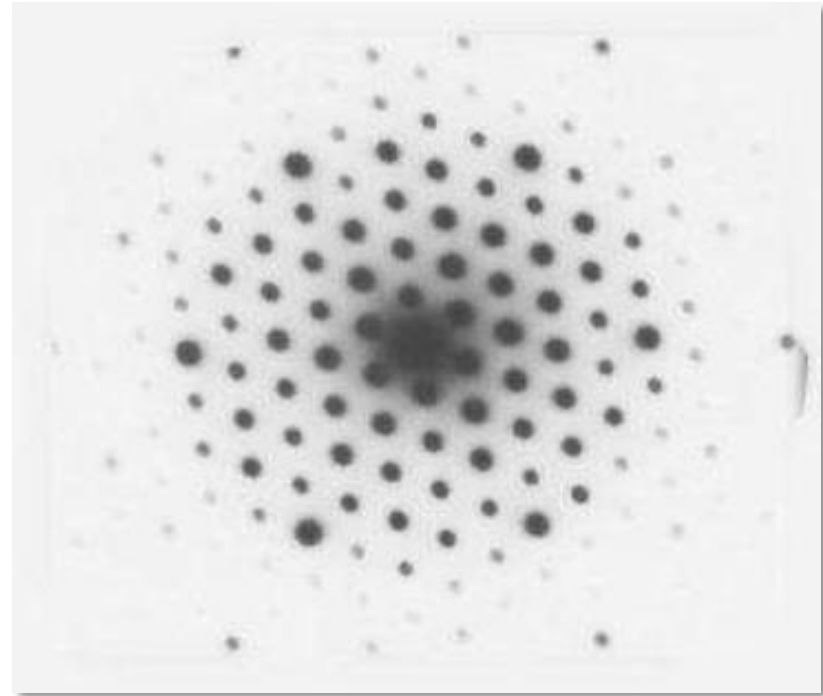


Diffraction pattern created by scattering electrons off a crystal. (This is a negative image, so the dark spots are actually regions of constructive interference.) Electron diffraction is only possible if electrons are waves.

# OBSERVATION OF ELECTRON DIFFRACTION

- Electron diffraction was first observed in a famous 1927 experiment by Davisson and Germer.

- They fired 54 eV electrons at a nickel target and observed diffraction peaks consistent with de Broglie's hypothesis.
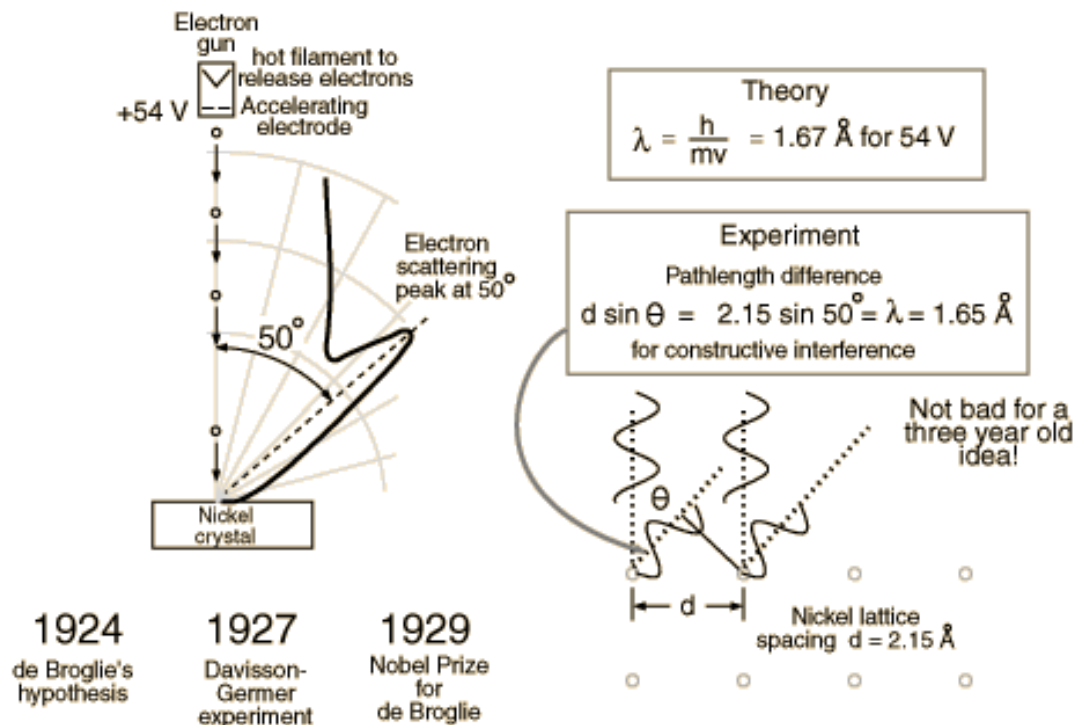
# UNDERSTANDING MATTER WAVES

- Let's think a little more about de Broglie waves.

- In classical physics, energy is transported either by waves or by particles.

  - Particle: a definite, localized bundle of energy and momentum, like a bullet that transfers energy from gun to target.

  - Wave: a periodic disturbance spread over space and time, like water waves carrying energy on the surface of the ocean.

- In quantum mechanics, the same entity can be described by both a wave and a particle model:

  - Electrons scatter like localized particles, but they can also diffract like extended waves.

# QUANTUM WAVES SUMMARIZED

- An elementary particle like a photon can act like a particle (Compton scattering) or a wave (diffraction), depending on the type of experiment / observation.

- If it's acting like a particle, the photon can be described by its position and momentum x and p. If it's acting like a wave, we must describe the photon with a wave function $\psi(x,t)$.

- Two waves can always be superimposed to form a third:
  - $\psi = \psi_1 + \psi_2$.
  - This is what gives rise to interference effects like diffraction.

- The wave function for a moving particle (a traveling wave) has a simple sinusoidal form.
  - But how do we interpret $\psi(x,t)$ physically?

# INTERPRETATION OF THE WAVE FUNCTION

- We have seen that a particle can be described by a wave function ψ(x,t).

- For any wave, we define the wave's intensity I to be:

$$I = |\psi(x,t)|^2 = \int \psi(x,t)\,\psi(x,t)^* \, dx$$

   where the asterisk signifies complex conjugation. Note that for a plane wave this is a constant:

$$I = |\psi(x,t)|^2 = |A|^2$$

- Let's use the concept of intensity and a simple thought experiment to get some intuition about the physical meaning of the de Broglie wave function.

# THE DOUBLE SLIT EXPERIMENT

- Experiment: a device sprays an electron beam at a wall with two small holes in it. The size of the holes is close to the electrons' wavelength $\lambda_{dB}$.

- Behind the wall is a screen with an electron detector.

- As electrons reach the screen, the detector counts up how many electrons strike each point on the wall.

- Using the data, we plot the intensity I(x): the number of electrons arriving per second at position x.
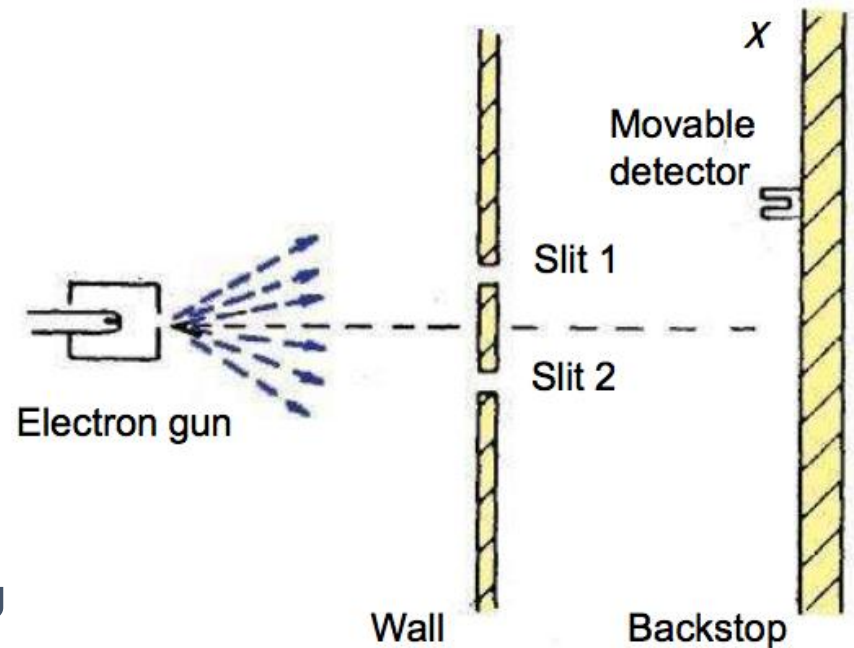
# THE DOUBLE SLIT EXPERIMENT

- The classical result:
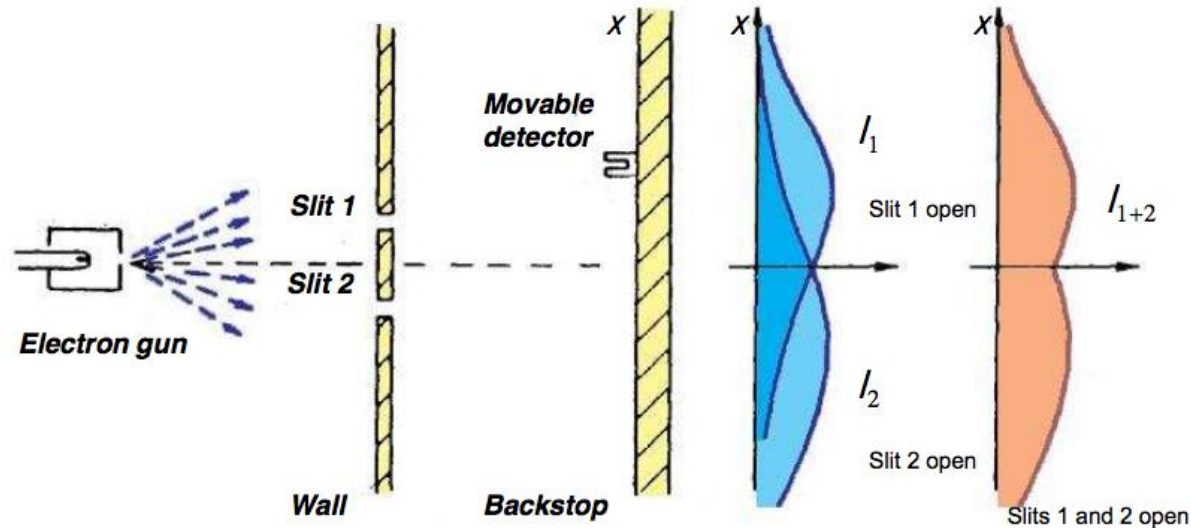


- If electrons were classical particles, we would expect the intensity in front of each slit to look like a bell curve, peaked directly in front of each slit opening.

- When both slits are open, the total intensity $I_{1+2}$ on the screen should just be the sum of the intensities $I_1$ and $I_2$ when only one or the other slit is open.
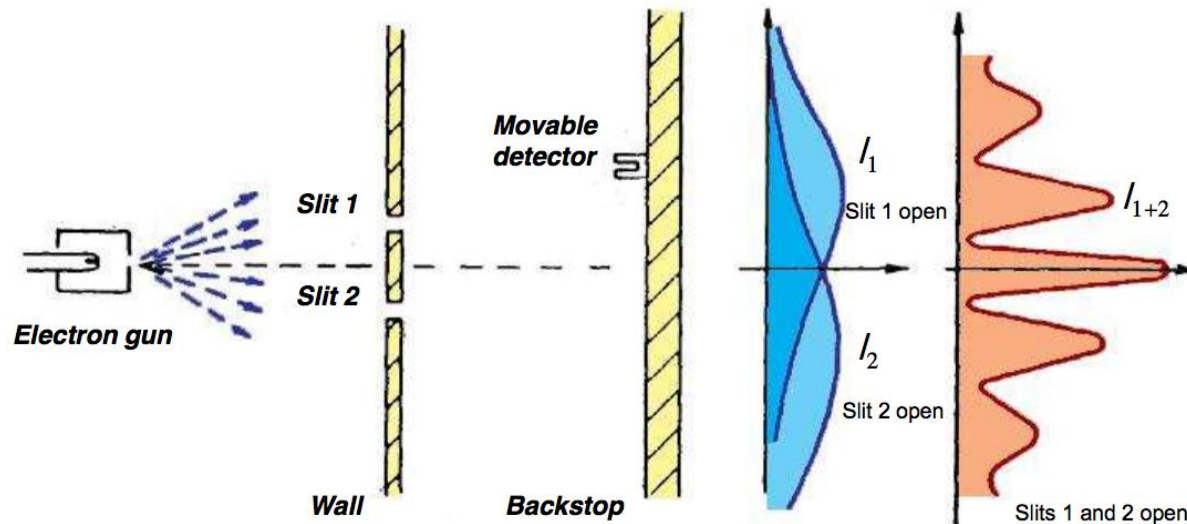
# THE DOUBLE SLIT EXPERIMENT

- In reality:
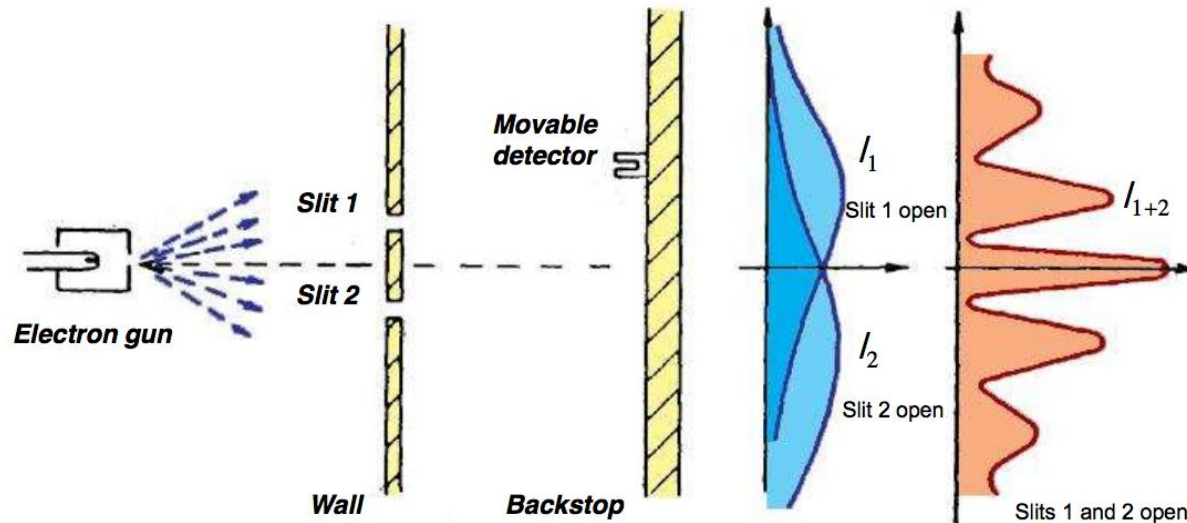


- When we perform the real experiment, a strange thing happens.

- When only one slit is open, we get the expected intensity distributions.

- But when both slits are open, a wave-like diffraction pattern appears.

- Electrons act* like waves!

  *When fired through two slits placed a de Broglie wavelength apart.
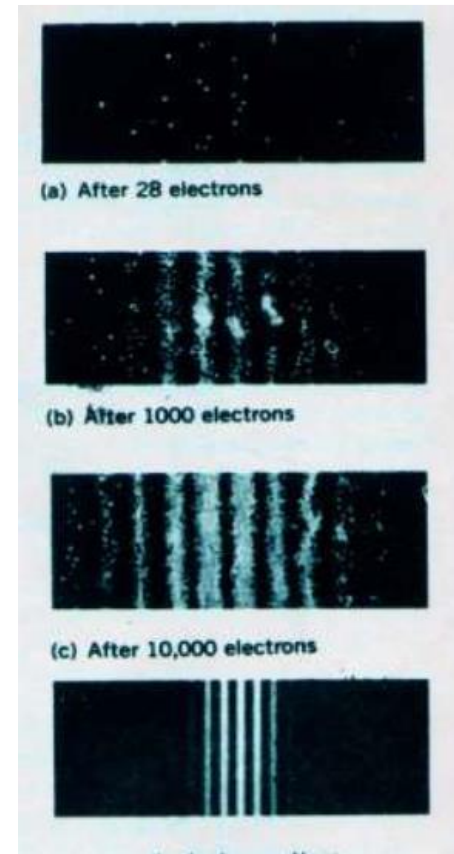
# WAVE FUNCTION INTERPRETATION



- In terms of waves, the wave function of an electron at the screen when only slit 1 is open is $\psi_1$, and when only slit 2 is open it's $\psi_2$.

  - Hence, the intensity when only one slit is open is either $I_1 = |\psi_1|^2$ or $I_2 = |\psi_2|^2$.

- With both slits open, the intensity at the screen is $I_{1+2} = |\psi_1 + \psi_2|^2$, not just $I_1 + I_2$!

- When we add the wave functions, we get constructive and destructive interference; this is what creates the diffraction pattern.

# WAVE FUNCTION AND PROBABILITY

- If electrons create a diffraction pattern, they must be waves. But when they hit the screen, they are detected as particles.

  - How do we interpret this?

- Max Born: Intensity $I(x)=|\psi(x,t)|^2$ actually refers to **probability** a given electron hits the screen at position x.

- In quantum mechanics, we don't specify the exact location of an electron at a given time, but instead state by $I(x)=|\psi(x,t)|^2$ the probability of finding a particle at a certain location at a given time.

*The probabilistic interpretation gives physical meaning to ψ(x,t): it is the "probability amplitude" of finding a particle at x at time t.*



(a) After 28 electrons

(b) After 1000 electrons

(c) After 10,000 electrons

Diffraction pattern from an actual electron double slit experiment. Notice how the interference pattern builds particle by particle.

# IS THERE A CONTRADICTION?

- We now understand the wave function in terms of the probability of a particle being some place at some time.

  - However, there is another problem to think about.

- Since the electrons diffract, they are waves; but when they hit the screen, they interact like particles. And if they are particles, then shouldn't they only go through one slit at a time?

- If this is the case, how can an electron's wave undergo double slit interference when the electron only goes through one slit?

  - Seems impossible…

- To test what's going on, suppose we slow down the electron gun so that only one electron at a time hits the wall.

- We then insert a device over each slit that tells us if the electron definitely went through one slit or the other.

# DESTROYING THE INTERFERENCE PATTERN
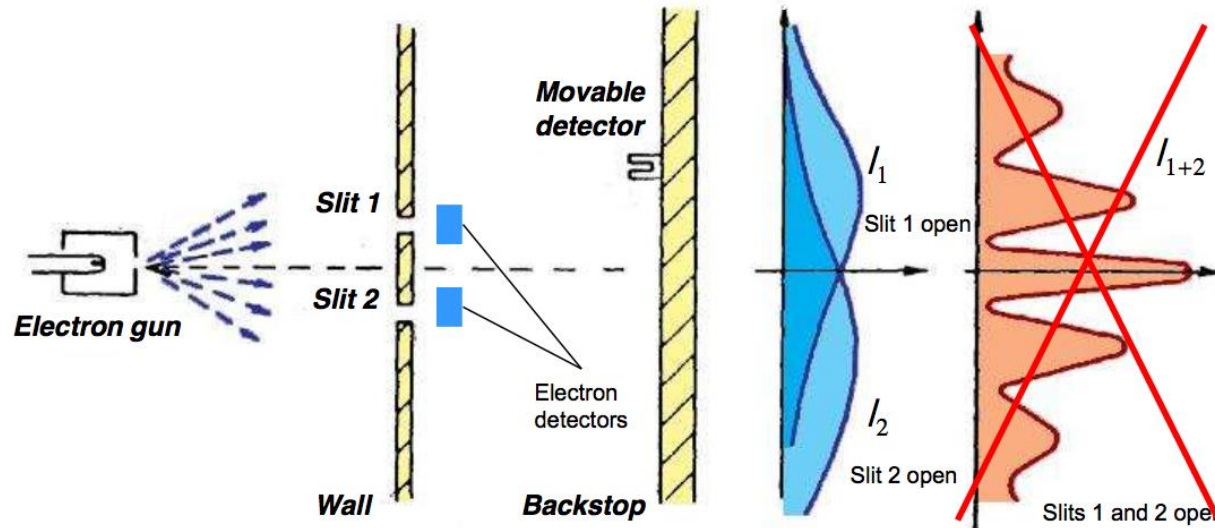


- We add electron detectors that shine light across each slit.

- When an electron passes through one of the slits, it breaks the beam, allowing us to see whether it traveled through slit 1 or slit 2 on its way to the detector.

- Result: if we try to detect the electrons at one of the two slits in this way, the interference pattern is destroyed! In fact, the pattern now looks like the one expected for classical particles

# COMPLEMENTARITY

- Why did the interference pattern disappear?

- Apparently, when we used the light beam to localize the electron at one slit, we destroyed something in the wave function $\psi(x,t)$, that contributes to interference.

- Principle of Complementarity (N. Bohr): if a measurement proves the wave character of radiation or matter, it is impossible to prove the particle character in the same measurement, and vice-versa.

- The link between the wave and particle models is provided by the probability interpretation of $\psi(x,t)$: the wave function gives the probability of finding the particle at some position.

# THE UNCERTAINTY PRINCIPLE

- There seems to be some fundamental constraint on quantum mechanics that prevents matter from acting wave-like and particle-like simultaneously.

- Moreover, it appears that our measurements can directly affect whether we observe particle or wave-like behavior.

- These effects are encapsulated in the Uncertainty Principle.

- Heisenberg: quantum observations are fundamentally limited in accuracy.

# THE UNCERTAINTY PRINCIPLE

- According to classical physics, we can (at the same instant) measure the position x and momentum $p_x$ of a particle to infinite accuracy if we like. We're only limited by our equipment.

- However, Heisenberg's uncertainty principle states that an experiment cannot simultaneously determine the exact values of x and $p_x$.

- Quantitatively, the principle states that if we a particle's momentum $p_x$ to an accuracy $\Delta p_x$, and its position x to within some $\Delta x$, the precision of our measurement is **inherently** limited such that:

$$\Delta p_x \Delta x \geq \frac{\hbar}{2}$$

# USING THE UNCERTAINTY PRINCIPLE

- Does the Uncertainty Principle mean that we can't measure position or momentum to arbitrary accuracy?

- No. The restriction is not on the accuracy to which x and $p_x$ can be measured, but rather on the product $\Delta p_x \Delta x$ in a *simultaneous* measurement of both.

- The Uncertainty Principle implies that the more accurately we know one variable, the less we know the other. If we could measure a particle's $p_x$ to infinite precision, so that $\Delta p_x = 0$, then the uncertainty principle states:

$$\Delta x \geq \frac{\hbar/2}{\Delta p_x}$$

$$\Delta p_x \to 0 \,, \ \Delta_x \to \infty$$

- In other words, after our measurement of the particle's momentum, we lose all information about its position!

# THE UNCERTAINTY PRINCIPLE

- The Uncertainty Principle also applies to measurements of energy E and the time t. It states that:

$$\Delta E \Delta t \geq \frac{\hbar}{2}$$

- Example: estimate the mass of virtual particles confined to the nucleus (see Lecture 2 on estimating Yukawa's meson mass).

- Example: Δt could be the time during which a photon of energy spread ΔE is emitted from an atom.

- This effect causes spectral lines in excited atoms to have a finite uncertainty Δλ ("natural width") in their wavelengths.



Breit-Wigner line shape

$E_0 = m_0 c^2$
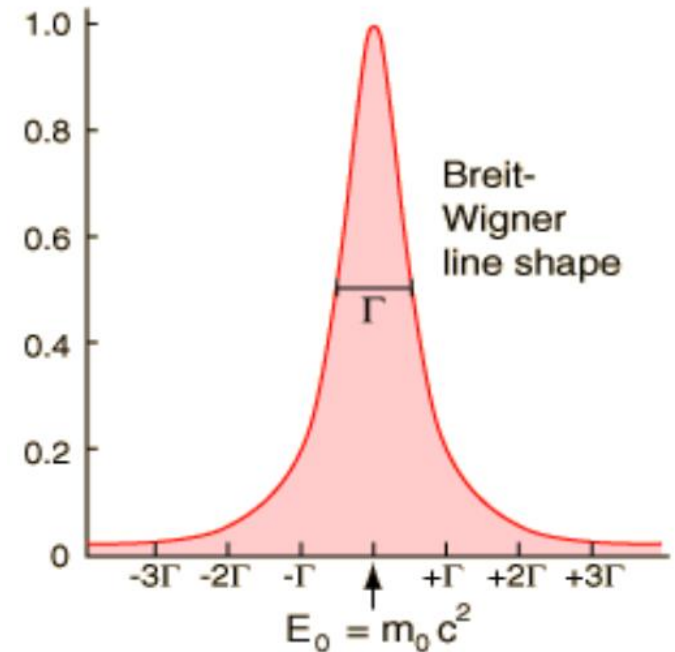
Atomic spectral lines, the result of transitions that take a finite time, are not thin "delta function" spikes, but actually have a natural width due to the Uncertainty Principle.

# UNCERTAINTY AND THE DOUBLE SLIT

- Now that we know the Uncertainty Principle, we can understand why we can't "beat" the double slit experiment and simultaneously observe wave and particle behavior.

- Our electron detector Compton scatters light off of incoming electrons.

- When an electron passes through one of the slits, we observe the scattered photon and know that an electron went through that slit.

- When this happens, the photon transfers some of its momentum to the electron, creating uncertainty in the electron's momentum.



Emitter

Slit 1

Photon beam used to detect electrons

Incoming electron

Observer sees the scattered photon.

Receiver

Wall
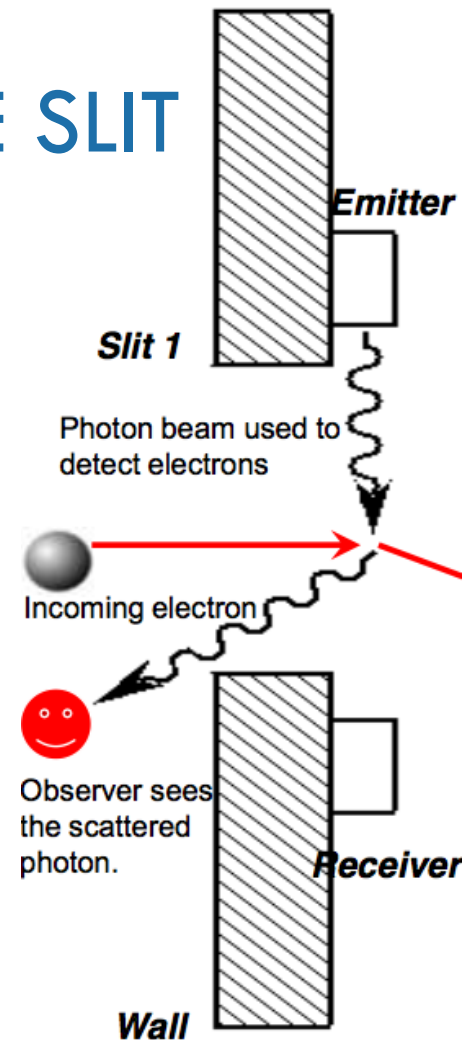
Detection photon Compton scatters off an incoming electron, transferring its momentum. But there is uncertainty in the momentum transfer.

# UNCERTAINTY AND THE DOUBLE SLIT

- If we want to know the slit used, the photon's wavelength must be smaller than the spacing between the two slits.

- Hence, the photon has to have a large momentum (remember, λ=h/p).

- As a result, a lot of momentum gets transferred to the electron - enough to effectively destroy the diffraction pattern.

Incident plane wave

Single slit envelope

$\Delta p_y$

electron detected here; an uncertainty Δpy is created.

If the wavelength of the scattering photon is small enough to pinpoint the electron at one of the slits, the resulting momentum transfer is large enough to "push" the electron out of the interference minima and maxima. The diffraction pattern is destroyed.
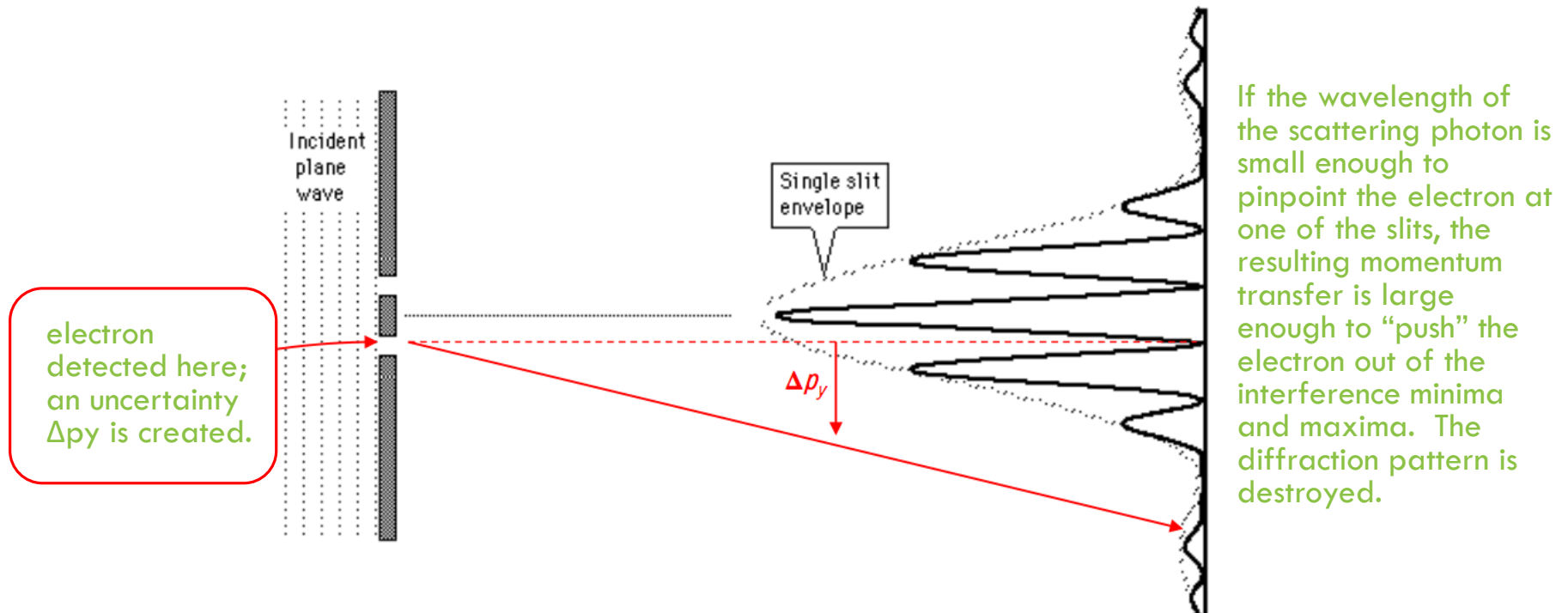
# UNCERTAINTY AND THE DOUBLE SLIT

- If we try to pinpoint the electron at one of the slits, its momentum uncertainty gets so big that the interference pattern vanishes.

- Can you think of a way to get around this problem?

- We could use lower energy photons; but that dropping of the photon momentum simultaneously increases the photon wavelength…

- It turns out, that just when the photon momentum gets low enough that electron diffraction reappears, the photon wavelength becomes larger than the separation between the two slits (see *Feynman Lectures on Physics*, Vol. 3).

- This means we can no longer tell which slit the electron went through!

# WHY THE UNCERTAINTY PRINCIPLE

- Let's review what we have said so far about matter waves and quantum mechanics.

- Elementary particles have associated wave functions $\psi(x,t)$. The intensity of the wave, $I(x)=|\psi(x,t)|^2$, gives the probability of finding the particle at position x at time t.

- Quantum mechanics places a firm constraint on the simultaneous measurements we can make of a particle's position and momentum: $\Delta p_x \Delta x \geq \hbar/2$.

- This last concept, the Uncertainty Principle, seems very mysterious. However, it turns out that it is just a natural consequence of the wave nature of matter: all waves obey an Uncertainty Principle!

# WAVE FUNCTIONS SHOULD BE FINITE

- If a wave function is infinite in extent, like $\psi = A\sin 2\pi(x/\lambda - \nu t)$, the probability interpretation suggests that the particle could be anywhere: $\Delta x = \infty$.

- If we want particles to be localized to some smaller $\Delta x$, we need one whose amplitude varies with x and t, so that it vanishes for most values of x. But how do we create a function like this?



Left: a wave function with constant amplitude means that its corresponding particle is equally likely to be at any value of *X*.
Right: a finite wave function, or "wave packet," corresponds to a localized particle with $\Delta X \neq \infty$.
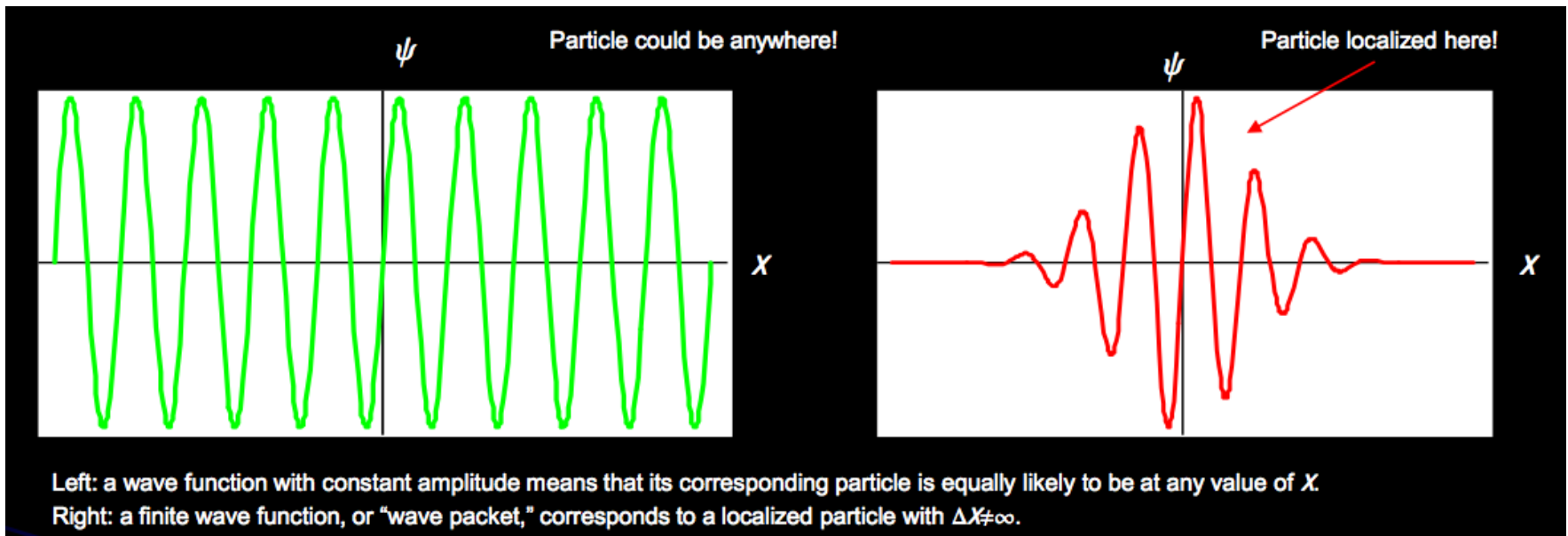
# BUILDING WAVE PACKETS

- In order to get <u>localized</u> particles, their corresponding wave functions need to go to zero as x→±∞.  Such a wave function is called a wave packet.

- It turns out to be rather easy to generate wave packets: all we have to do is <u>superimpose</u>, or add up, several sinusoids of different wavelengths or frequencies.

- Recall the Principle of Superposition: any wave $\psi$ can be built up by adding two or more other waves.

- If we pick the right combination of sinusoids, they will cancel at every x other than some finite interval (Fourier Theorem).

# SUPERPOSITION EXAMPLE: BEATS

- You may already know that adding two sine waves of slightly different wavelengths causes the phenomenon of beats (see below).

- A typical example: using a tuning fork to tune a piano string. If you hear beats when you strike the string and the tuning fork simultaneously, you know that the string is slightly out of tune.

The sum of two sine waves of slightly different wavelengths results in beats. The beat frequency is related to the difference between the wavelengths. This is a demonstration of how adding two sinusoids creates a wave of varying amplitude.
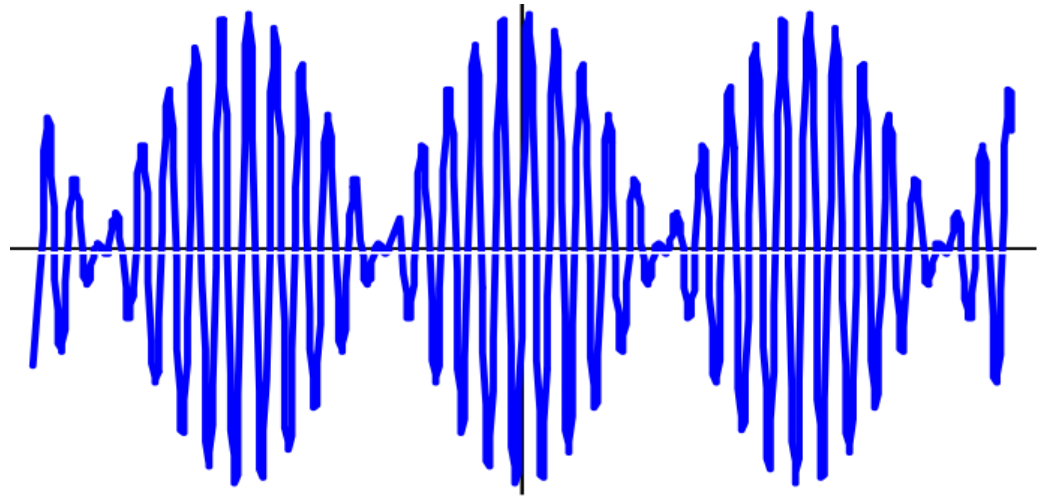
# THE CONTINUUM LIMIT

- So, evaluating a sum of sinusoids like:

$$\psi = \sum_k A_k cos\left(kx\right)$$

where k is an integer that runs between $k_1$ and $k_2$, we can reproduce any periodic function.

- If we let k run over all values between $k_1$ and $k_2$ — that is, we make it a continuous variable —then we can finally reproduce a finite wave packet.

By summing over all values of k in an interval $\triangle k = k1-k2$, we are essentially evaluating the integral

$$\psi = \int_{k_1}^{k_2} dk A\left(k\right) cos\left(kx\right)$$

In such a "continuous sum", the component sinusoids are all in phase near x=0. Away from this point, in either direction, the components begin to get out of phase with each other. If we go far enough out, the phases of the infinite number of components become totally random, and cancel out phases of component sinusoids completely.

Phases of component sinusoids completely cancel out here.
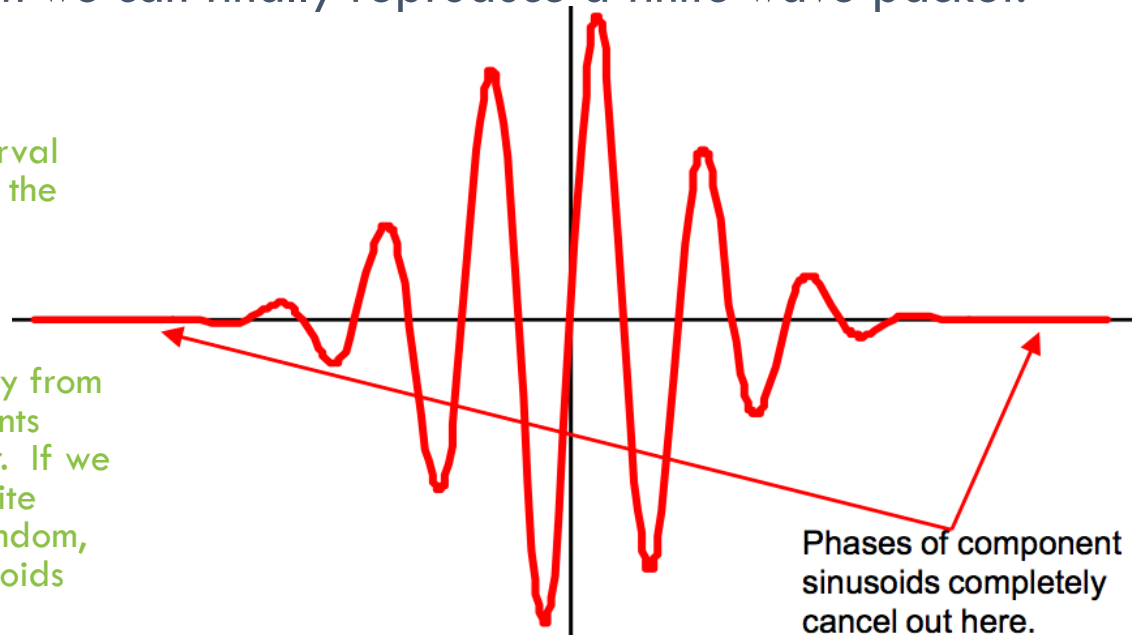
# CONNECTION TO UNCERTAINTY

- So, we can sum up sinusoids to get wave packets.

    - What does this actually mean?

- Intuition: we want a wave function that is non-zero only over some <u>finite interval $\Delta x$</u>.

- To build such a function, we start adding sinusoids whose inverse wavelengths, $k=2\pi/\lambda$, take on values in some finite interval $\Delta k$.

- Here's the point: as we make the interval $\Delta k$ bigger, the width of the wave packet $\Delta x$ gets smaller. This sounds like the Uncertainty Principle!

# CONNECTION TO UNCERTAINTY



Precisely determined momentum

A sine wave of wavelength λ implies that the momentum is precisely known. But the wavefunction and the probability of finding the particle $\Psi^*\Psi$ is spread over all of space!

$$p = \frac{h}{\lambda}$$

p precise
x unknown
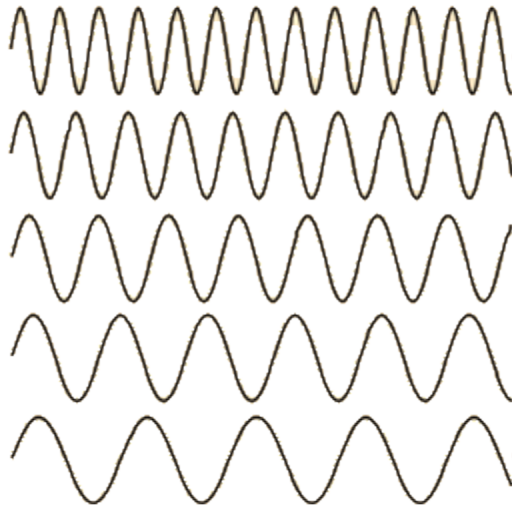
Adding several waves of different wavelength together will produce an interference pattern which begins to localize the wave.

$\lambda_{avg}$

$\Delta x$
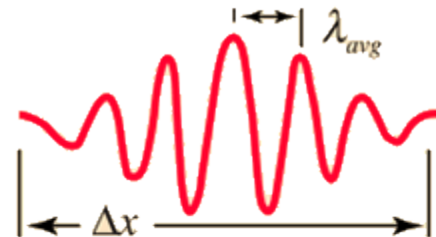
But that process spreads the momentum values and makes it more uncertain. This is an inherent and inescapable increase in the uncertainty $\Delta p$ when $\Delta x$ is decreased.

$$\Delta x \Delta p > \frac{\hbar}{2}$$

http://hyperphysics.phy-astr.gsu.edu

# WAVE-RELATED UNCERTAINTIES

- As we sum over sinusoids, making the range of k values Δk larger, we decrease the width of the resulting function.

- In fact, there is a fundamental limit here that looks just like the position-momentum uncertainty relation.

- For any wave, the minimum width Δx of a wave packet composed from sinusoids with range Δk is Δx=1/(2Δk), or:

$$\Delta x \Delta k \geq \tfrac{1}{2}$$

- There is a similar relation between time and frequency:

$$\Delta t \Delta \omega \geq \tfrac{1}{2}$$

# CONNECTION TO QUANTUM MECHANICS

- If k=2π/λ, and λ=h/p, then the uncertainty relation for waves in general tells us:

$$\Delta x \Delta k \geq \tfrac{1}{2} \implies \Delta x \tfrac{2\pi}{\Delta\lambda} \geq \tfrac{1}{2} \implies \Delta x \tfrac{2\pi\Delta p}{h} \geq \tfrac{1}{2}$$
$$\Delta x \Delta p \geq \tfrac{\hbar}{2}$$

- We recover the Heisenberg uncertainty relation!

- By a similar argument, we can show that the frequency-time uncertainty relation for waves implies the energy-time uncertainty of quantum mechanics.

- Hence, there is nothing really mysterious about the Uncertainty Principle; it arises rather naturally from properties of (localized) waves.

# SUMMARY

- Quantum mechanics is the physics of small objects.

    - Its typical energy scale is given by Planck's constant.

- In quantum mechanics, variables like position, momentum, energy, etc. tend to take on discrete values (often proportional to h).

- Matter and radiation can have both particle and wave-like properties, depending on the type of observation.

- The Uncertainty Principle tells us that there is a fundamental limit to the precision with which we can measure certain pairs of observables.

- Objects can never be wavelike or particle-like simultaneously.

# SCHEDULE

1. ~~Introduction~~

2. ~~History of Particle Physics~~

3. ~~Special Relativity~~

4. ~~Quantum Mechanics~~

5. **Experimental Methods**

6. The Standard Model - Overview

7. The Standard Model - Limitations

8. Neutrino Theory

9. Neutrino Experiment

10. LHC and Experiments

11. The Higgs Boson and Beyond

12. Particle Cosmology

# EXPERIMENTAL METHODS IN PARTICLE PHYSICS

## HOW WE STUDY PARTICLES IN THE LAB

# TODAY'S AGENDA

- What do we want to **know** and what do we **measure**?

- Passage of particles through **matter**

  - Ionization

  - Scintillation

  - Cherenkov radiation

- Particle detectors

- Modern experiments

# STANDARD MODEL PARTICLE PROPERTIES

# WHAT WE WANT TO KNOW

- Particle **properties**:

  - **Mass**

  - **Spin**

  - **Charge**

- Particle **interactions**:

  - What happens when particles **collide** with each other?

    - What are the interaction **products**?

    - With what **probability** do different types of interactions occur?

      - How long does it take for an **unstable** particle to **decay**?

        - … and what particles does it decay to?

      - Are there extremely **rare interactions** that we haven't measured yet?

- Do **new** particles exist that we don't know about yet?

  - Can we **produce** them in high energy collisions?

# WHAT WE MEASURE

- Particle **trajectories**

  - … and how they **bend** in **magnetic** fields

- Particle **energies**

- **Events**:

  - **Collection** of particle tracks and energy deposits resulting from an interaction.

  - **Topology**: what particles are produced in the event

  - **Angles** between particles, imbalances in **momentum**, etc…

WHEN TWO APPLES COLLIDE, THEY CAN BRIEFLY FORM EXOTIC NEW FRUIT. PINEAPPLES WITH APPLE SKIN. POMEGRANATES FULL OF GRAPES. WATERMELON-SIZED PEACHES.

THESE NORMALLY DECAY INTO A SHOWER OF FRUIT SALAD, BUT BY STUDYING THE DEBRIS, WE CAN LEARN WHAT WAS PRODUCED.

THEN, THE HUNT IS ON FOR A STABLE FORM.

xkcd.com
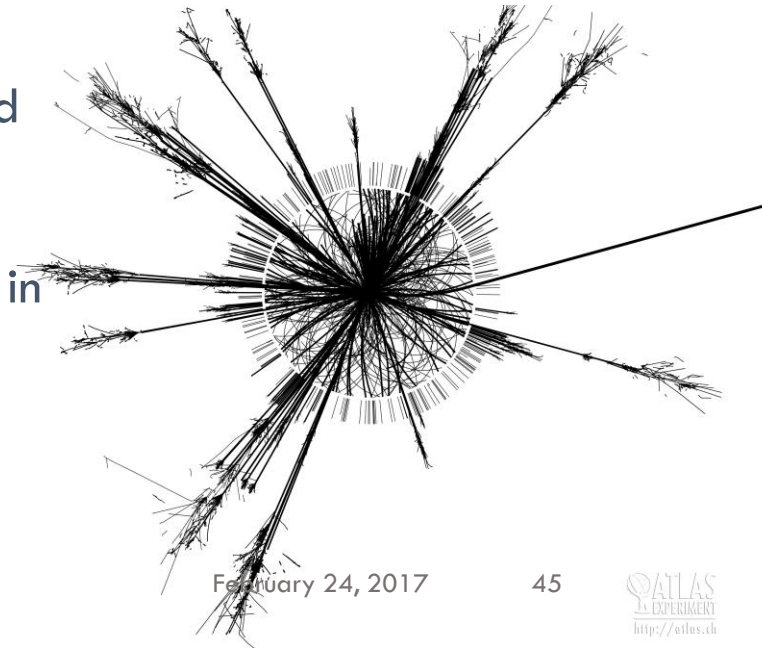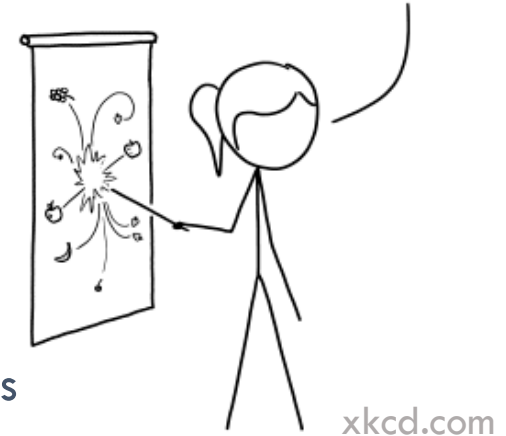
# WHAT WE **ACTUALLY** MEASURE

- Particles interact with **detector materials** and either:

  - **Change** the material's properties in an observable way, or

  - Produce some kind of **disturbance** in the medium.

    - Such as emission of **light** or inducing an **electrical signal** on an electrode.

- "Vintage" techniques:

  - Chemical imprints left on **photographic** plates.

  - "**Clouds**" in supersaturated vapours.

  - Traces of "**bubbles**" in superheated liquids.

  - **Sparks** in a gas with a very high electric field applied to it.

antiproton

proton

pion

pion

100 μm
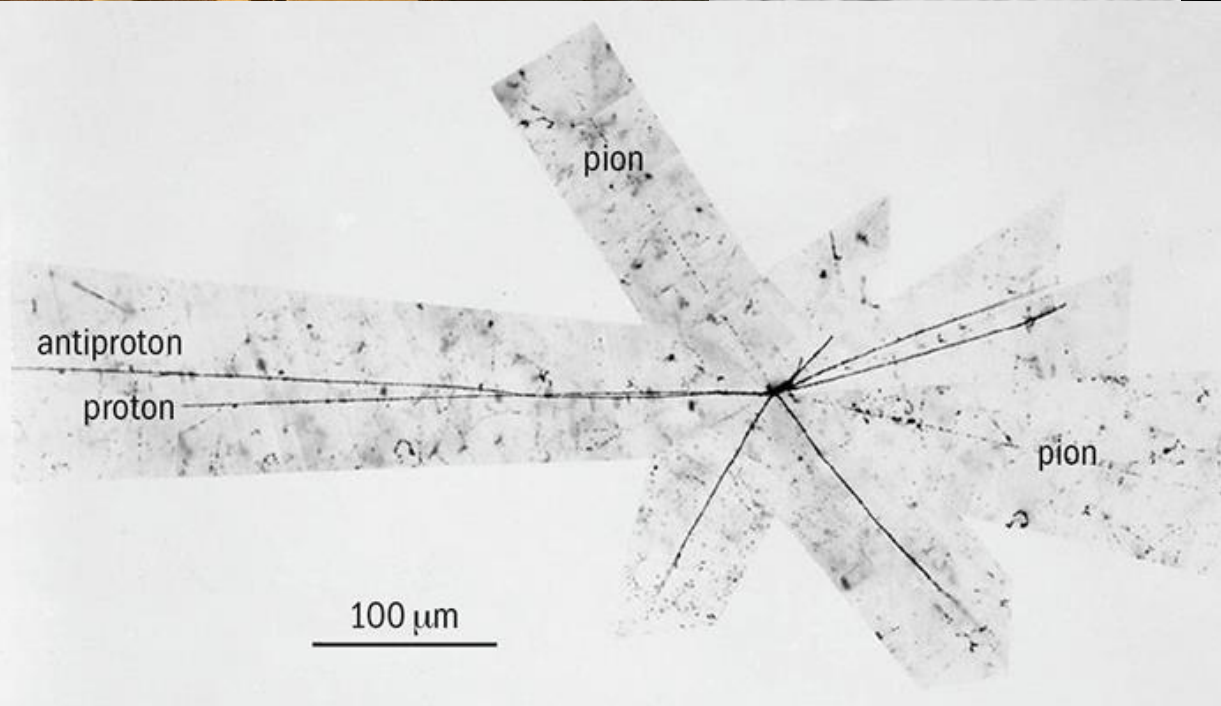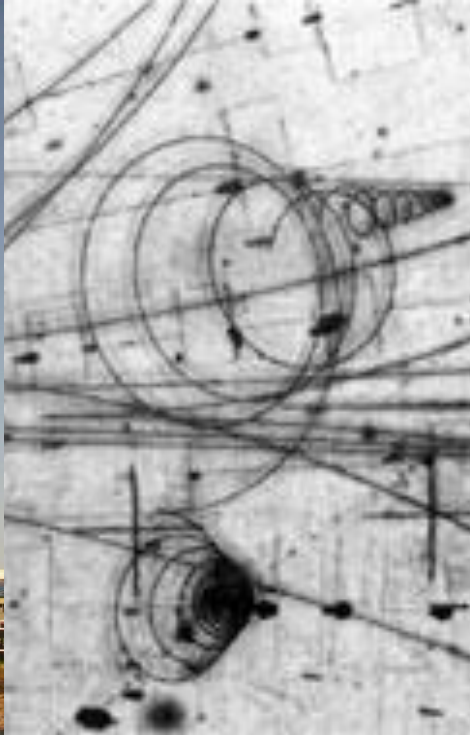
# WHAT WE **ACTUALLY** MEASURE

- **Modern** techniques:

    - Electrical signals induced by **moving charges** close to electrodes.

    - **Light** that is converted into electrical signals.

    - Very small **vibrations** in crystalline structures (heat), converted into electrical signals.

        - Mostly used for dark matter searches.

    - **Acoustic** signals picked up by very sensitive microphones and converted into electrical signals. (Very rare!)

- Electrical signals are "**digitized**":

    - Read in by a **computer** system and stored in **digital** format.

    - Some experiments generate very large amounts of **data**.

        - Significant storage and computing challenges!

# PARTICLE INTERACTIONS WITH MATTER

# FIRST EXPERIMENTS IN PARTICLE PHYSICS

- By the 1890's, new, unstable elements (radioactivity) were being investigated by M. Curie, P. Curie, H. Becquerel, E. Rutherford, et al.

- Radioactivity: describes the emission of particles from atomic nuclei as a result of nuclear instability.

- The fact that atoms seemed to spontaneously split apart also suggests they are not fundamental particles.

# FIRST EXPERIMENTS IN PARTICLE PHYSICS

- At the time, it was known that unstable elements tended to emit three types of particles, which were differentiated by their electric charge.
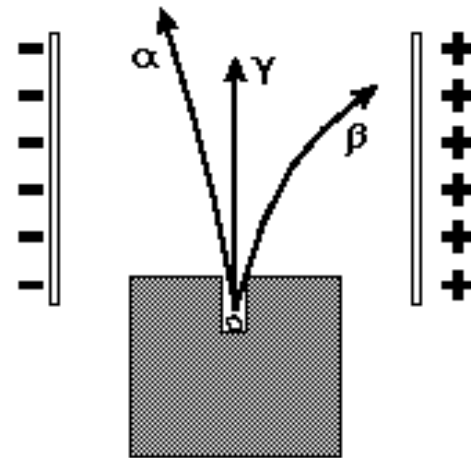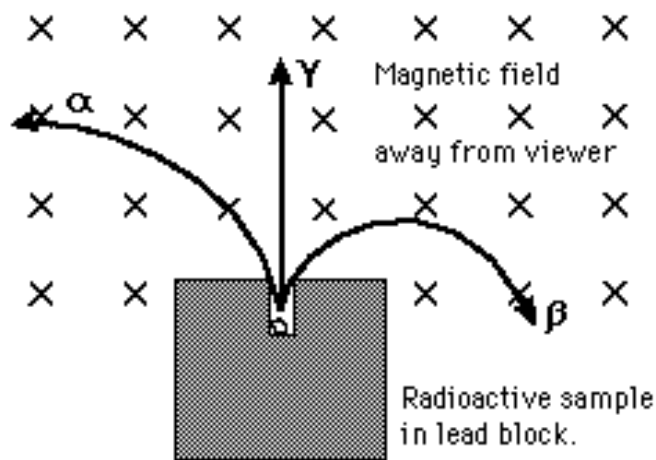


| | Electric charge | Mass |
|---|---|---|
| Alpha (α) | +2 | 4 x Mp |
| Beta (β) | -1 | 1/1800 x Mp |
| Gamma (γ) | Neutral | |

# PASSAGE OF PARTICLES THROUGH MATTER

- Alpha, beta, gamma radiation:
  - Classified according to how they bend in a magnetic field.
  - Also differentiated by how easily they can be stopped.



Paper  Aluminium  Lead
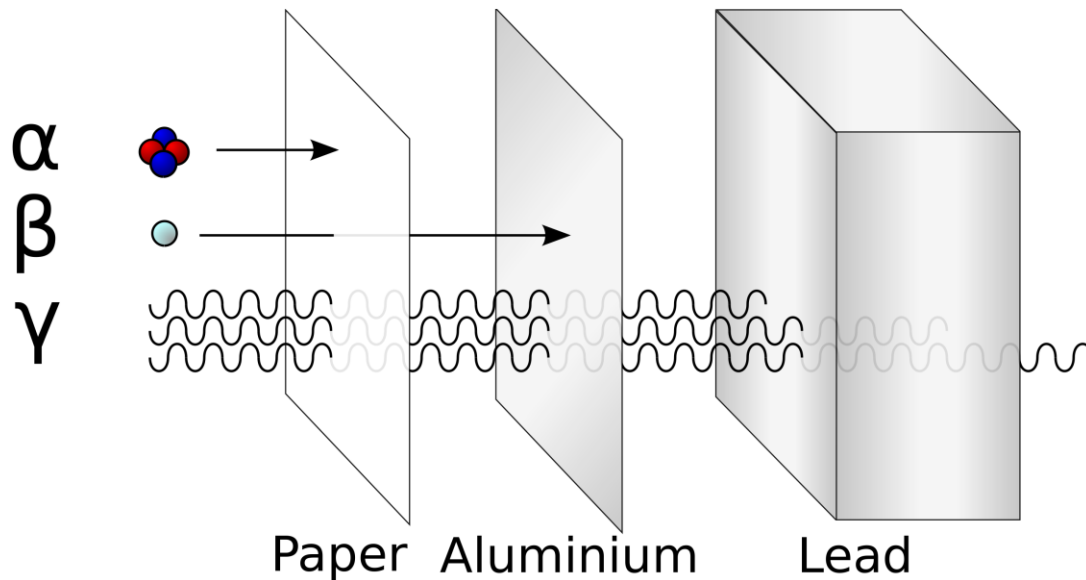
*Why do different particles have different penetrating power?*

# PASSAGE OF PARTICLES THROUGH MATTER

- Alpha, beta, gamma radiation:
  - Classified according to how they bend in a magnetic field.
  - Also differentiated by how easily they can be stopped.

α
β
γ

Paper   Aluminium   Lead
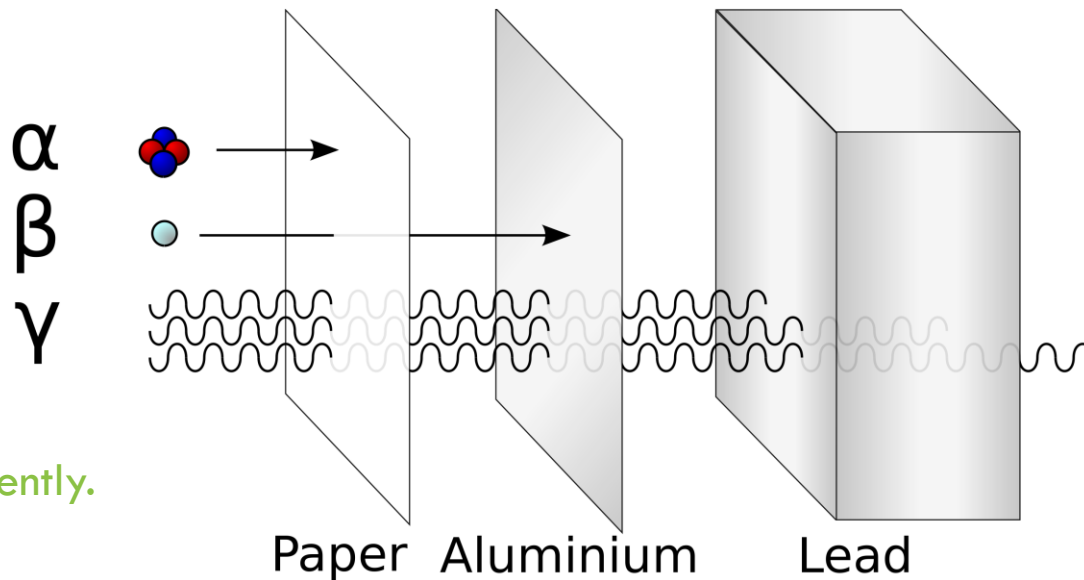
Charged particles interact more frequently. They ionize matter (directly) and lose energy in the process.

Neutral particles interact less often, losing less energy. They ionize matter indirectly.

# STOPPING POWER
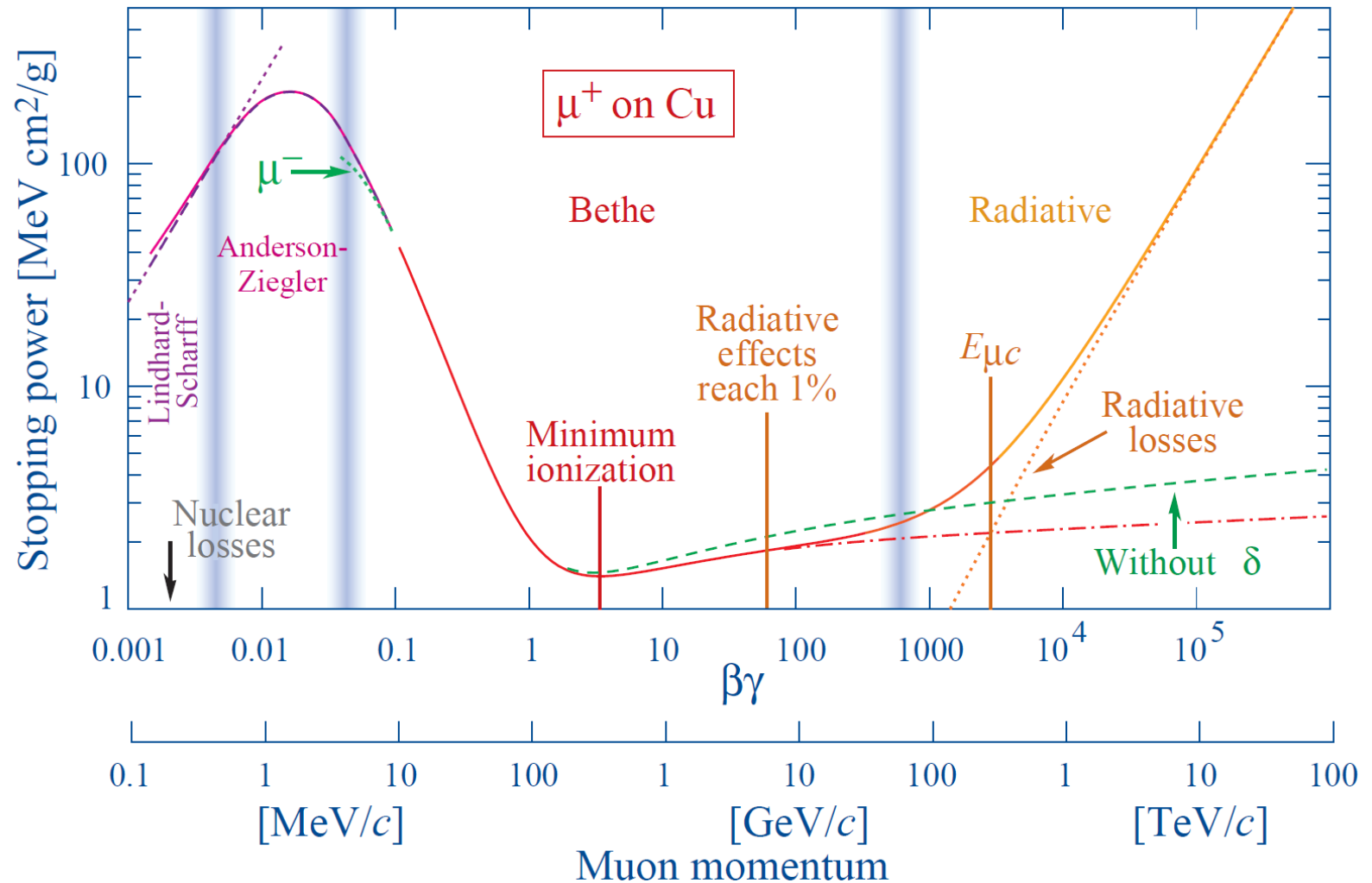
# STOPPING POWER
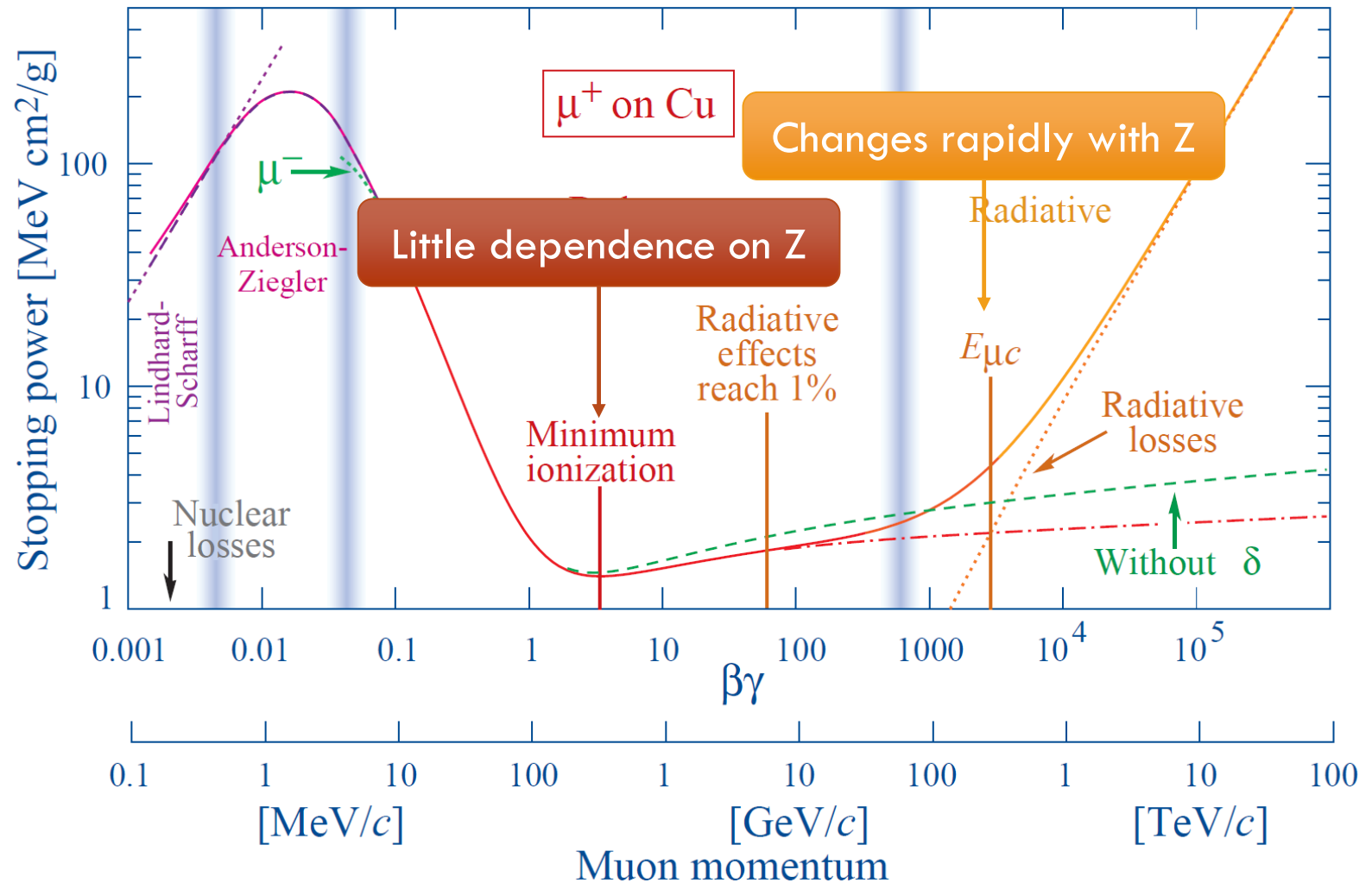
# PARTICLE DETECTION

- Different particles undergo different interactions, leading to different detector signatures.

- Exploit this to identify particle types.

| Particles | Type of interaction | Signature |
| --- | --- | --- |
| neutrinos | weak (very rarely) | missing energy, interaction products |
| electrons | electromagnetic | **track** and electromagnetic **shower** |
| muons | electromagnetic | penetrating **track** |
| p, K, π | electromagnetic, strong, weak | **track** and hadronic **shower** |
| photons | electromagnetic | electromagnetic **shower** |
| neutrons, $K^0$ | strong, weak | hadron **shower** |

# LAYERED DETECTORS

innermost layer ⟶ outermost layer

| tracking system | electromagnetic calorimeter | hadronic calorimeter | muon system |

**Photons**
No ionization in low density tracker

**Electrons**
Ionize tracker, radiative losses lead to shower

**Muons**
Minimum ionizing particles, little energy loss

**Charged hadrons**
Fully absorbed in dense hadronic calorimeter

**Neutral hadrons**
No direct ionization

C. Lippmann – 2003

**Non-destructive measurement**    **Destructive measurements**

# PARTICLE DETECTION
## 1. MEASUREMENT BY ELECTROMAGNETIC ENERGY LOSS

- Applies to all charged particles
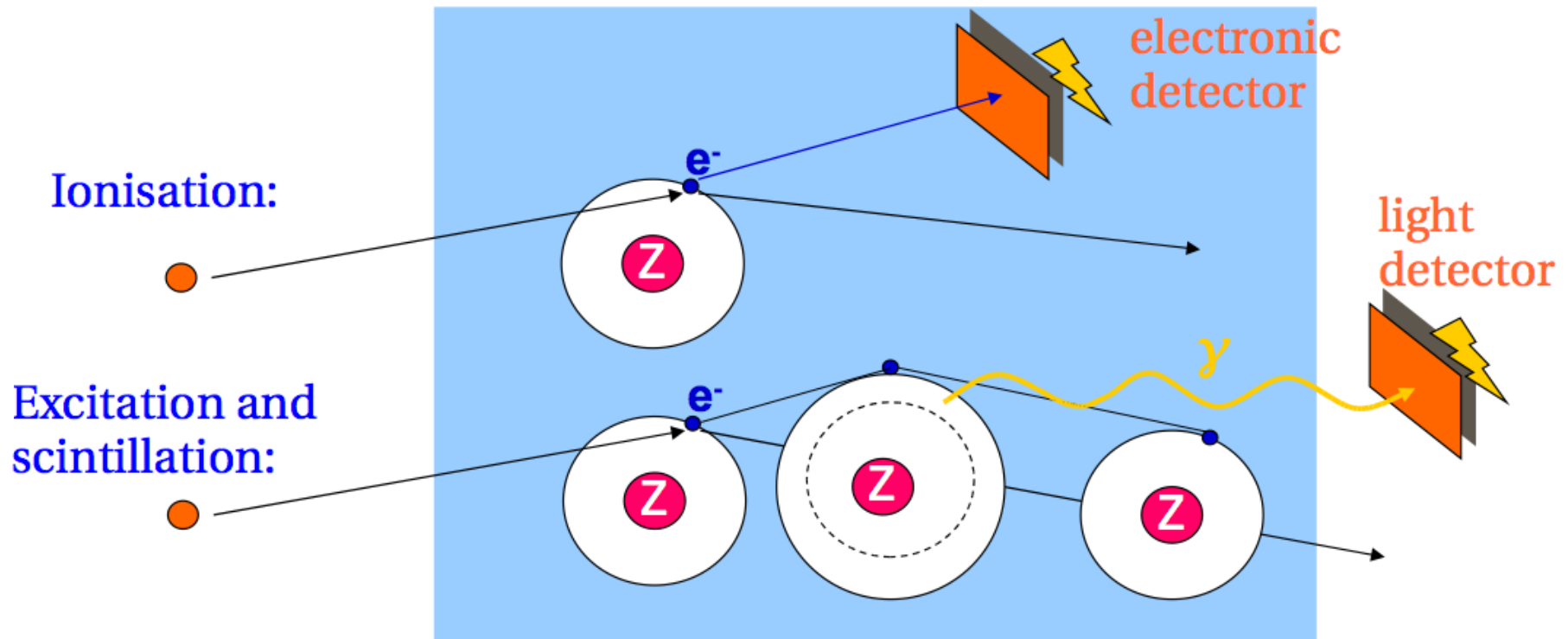
# IONIZATION

- **Ion:** positively or negatively charged particle (or part of atom)

- Ions can be produced when enough energy is given to remove one or more electrons from an atom:
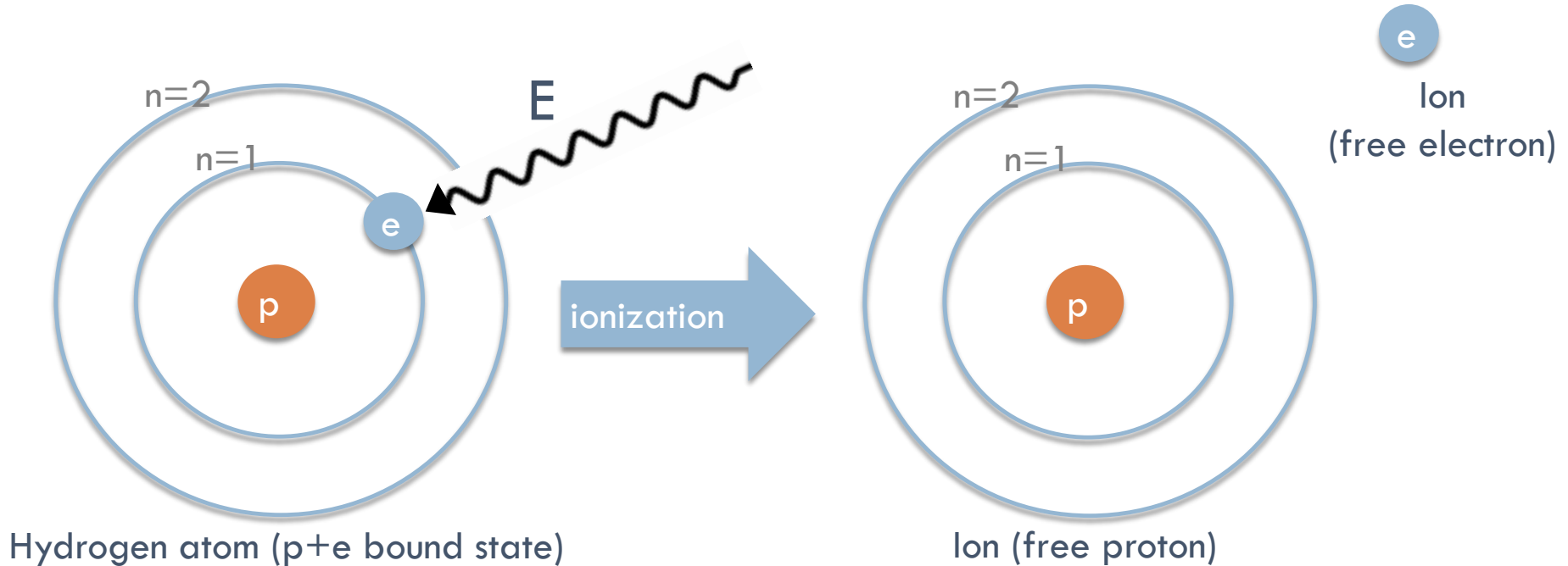
E

e

Ion
(free electron)

n=2

n=1

e

p

ionization

n=2

n=1

p

Hydrogen atom (p+e bound state)

Ion (free proton)

# IONIZATION

Bethe energy loss formula

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \left[ln\left(\frac{2m_e c^2 \beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

$-\dfrac{dE}{dx}$  Energy loss per distance traveled

$\beta = \dfrac{v}{c}$  Particle velocity

$z$  Particle charge (in units of electron charge)

$n$  Density of electrons in material

$I$  Mean excitation potential of material

$\varepsilon_0$  Vacuum permittivity

$e$  Electron charge

$m_e$  Electron mass

$c$  Speed of light in vacuum
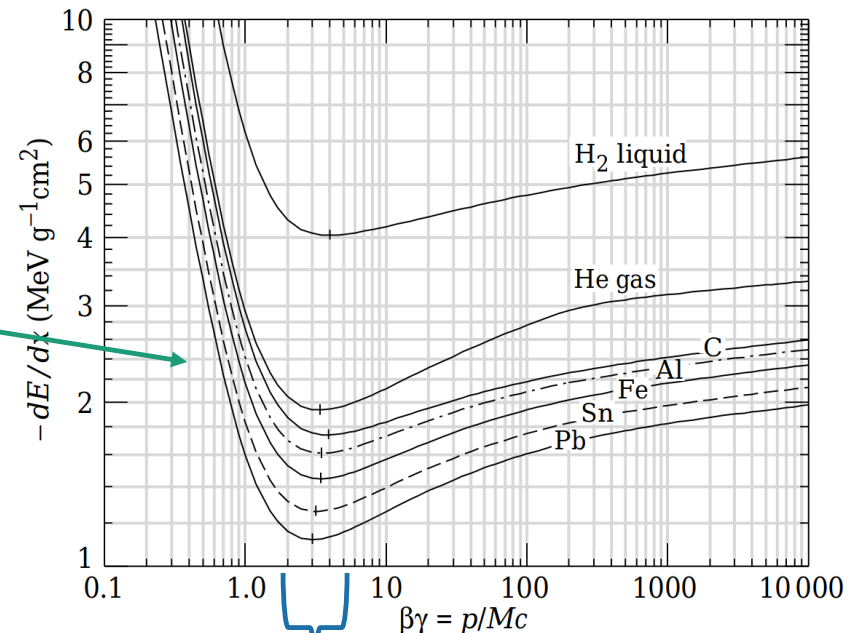
Minimum Ionizing Particles

# IONIZATION

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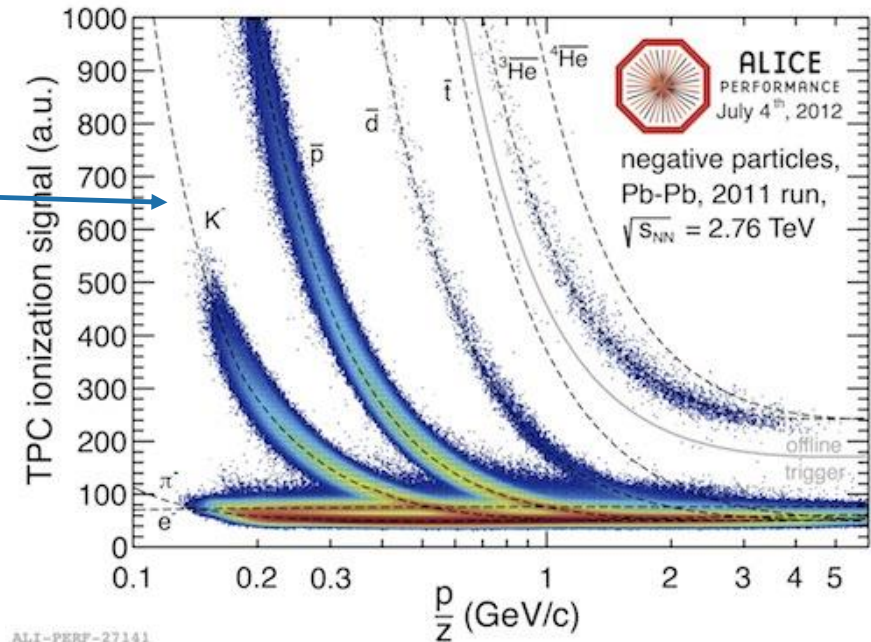


$$p = \frac{1}{\sqrt{1-\beta^2}}m$$

# SCINTILLATION

- Scintillation is the emission of light of a characteristic wavelength spectrum, following the absorption of radiation.

  - The emitted radiation is usually less energetic than that absorbed.

- Scintillation occurs in:

  - Some types of organic molecules with complicated electronic structures

    - p-Terphenyl: $C_{18}H_{14}$

    - "PPO": $C_{15}H_{11}NO$

  - Inorganic crystals and gases / liquids

    - NaI, $CaF_2$

    - He, Ar, Xe

# (SAME IDEA AS) ATOMIC EXCITATION

- An atom is excited when it has the potential to spontaneously produce energy.

  - This happens when one or more of the electrons occupy a higher-energy state.

  - When the electron returns to a lower energy state, the energy difference is given off in the form of radiation.

- The lowest energy state is the ground state.
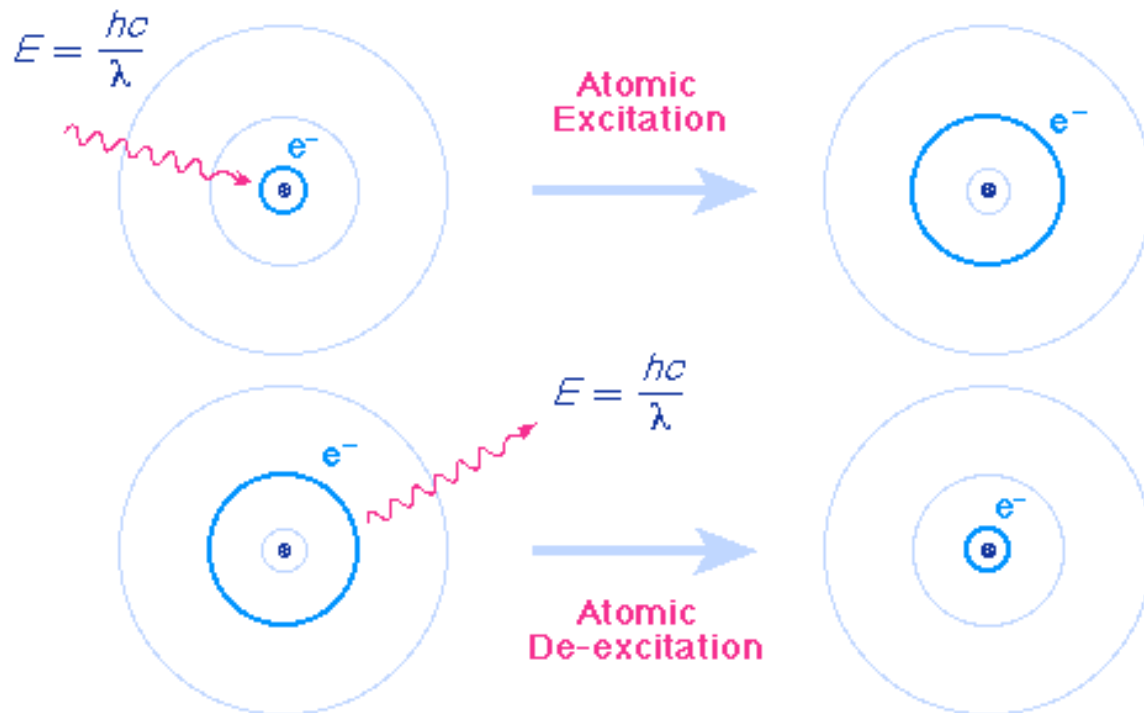


$$E = \frac{hc}{\lambda}$$

Atomic Excitation

$$E = \frac{hc}{\lambda}$$

Atomic De-excitation

# CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving faster than the speed of light in a medium (v>c/n) emits Cherenkov radiation.
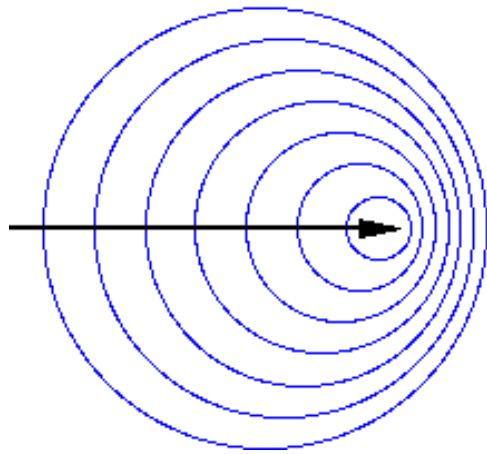


As a particle passes through matter, the surrounding atoms polarize and depolarize, and a weak electromagnetic wave spreads out from the position of the particle.
For a particle traveling more slowly than light, wave-fronts originating at different times can never meet, and no interference is possible.
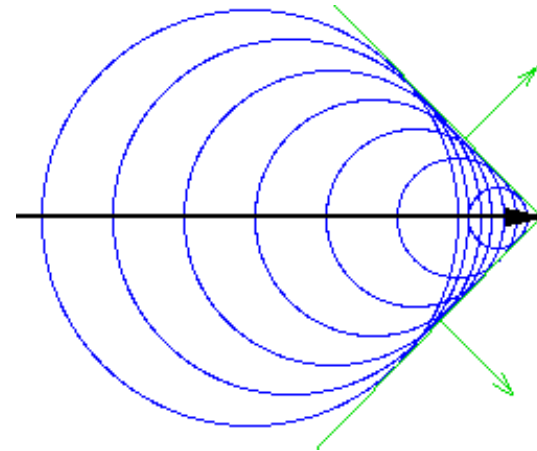
For a particle traveling faster than light, the wave-fronts do overlap, and constructive interference is possible, leading to a significant, observable signal.

# CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving faster than the speed of light in a medium (v>c/n) emits Cherenkov radiation.



Duck moving slower than the speed at which water waves travel.
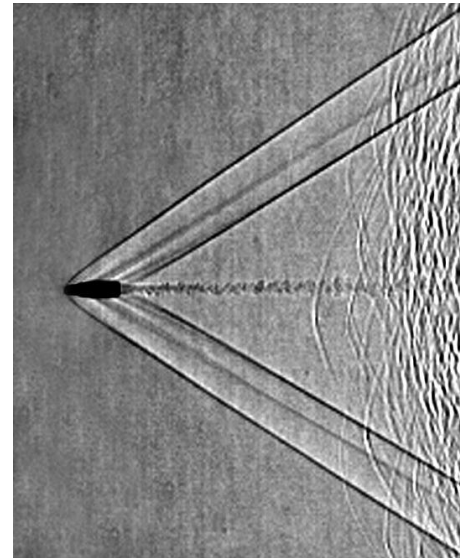


Bullet moving faster than the speed at which air waves travel – the speed of sound.

# CHERENKOV RADIATION

- Cherenkov effect: a charged particle moving faster than the speed of light in a medium (v>c/n) emits Cherenkov radiation.
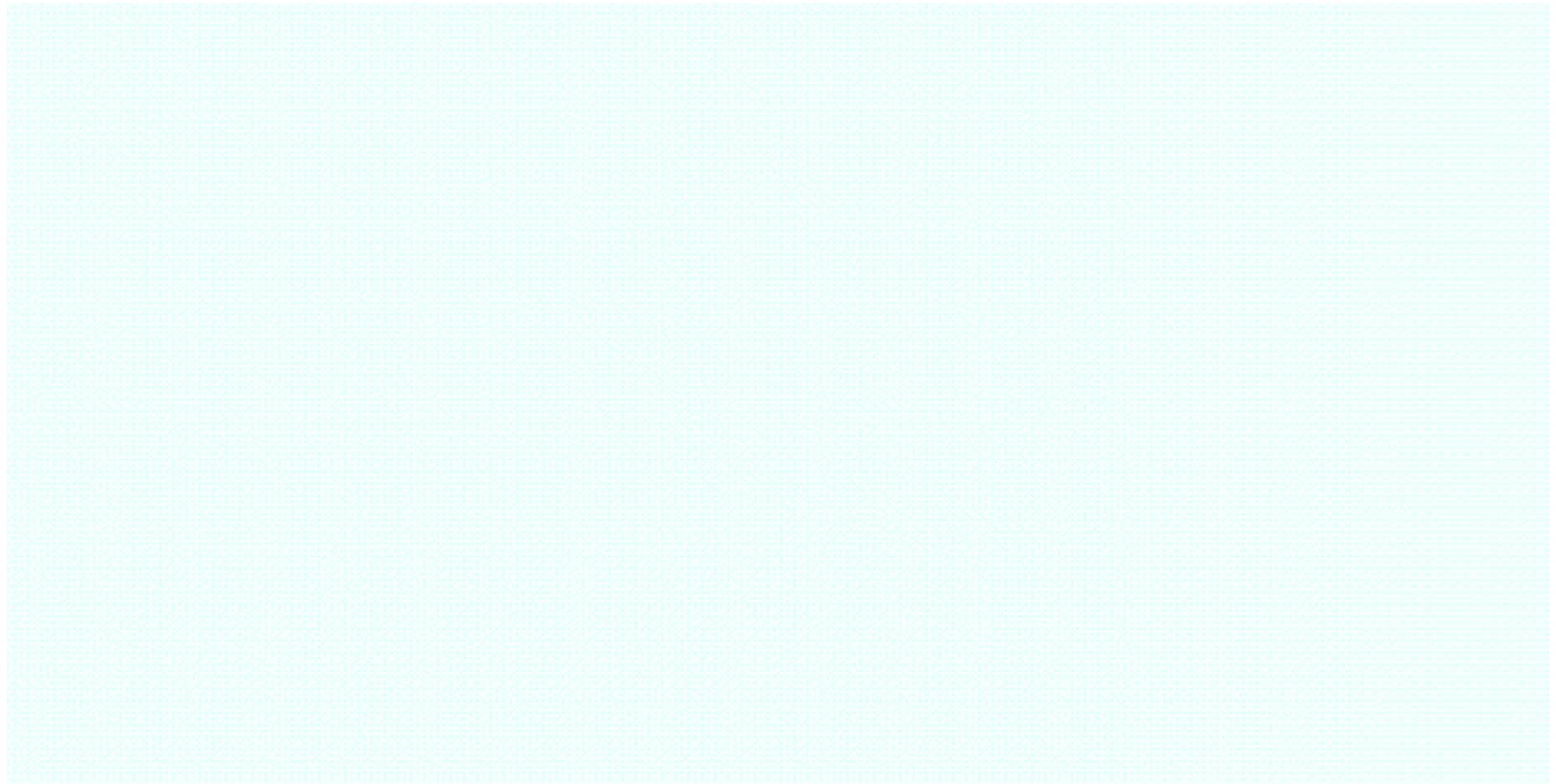
# CHERENKOV RADIATION

- In a medium of refractive index n, the speed of light is c/n, and there is no reason why the speed of the particle, βc, cannot be greater than c/n.
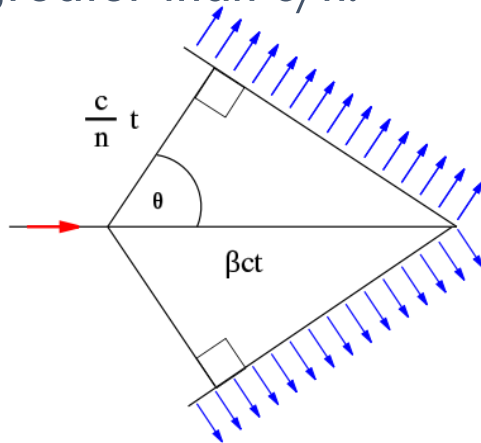
$$cos\theta_c = \frac{\frac{c}{n}t}{\beta c t} = \frac{1}{\beta n}$$

- A highly relativistic particle passing through a medium is observed to emit visible light known as Cherenkov radiation if β>1/n. As can be seen from the above diagram, a cone of light radiates out from each point on the particle's track.

- The Cherenkov cone angle is related to the particle's β.

# CHERENKOV RADIATION

- The characteristic blue glow of nuclear reactors is due to Cherenkov radiation.

# LIGHT DETECTION

- A photomultiplier tube (PMT) is a commonly used instrument for detecting visible photons.

- Basic of operation: photoelectric effect

  - Single photons converted to electrons and multiplied to a measurable electronic signal.

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# LIGHT DETECTION

- Light falls on a photocathode and a photoelectron is emitted (photoelectric effect).
  - Quantum Efficiency depends on cathode and wavelength (QE~25%).

- Photoelectron focused and accelerated towards the first dynode by electric field.

- Photoelectron strikes dynode and several electrons are emitted (on average n~5).

- Several dynodes (~10) give high gain ($10^7$).

- High speed: few nanoseconds transit time!

- Gain can be much lower in magnetic fields, depending on orientation.
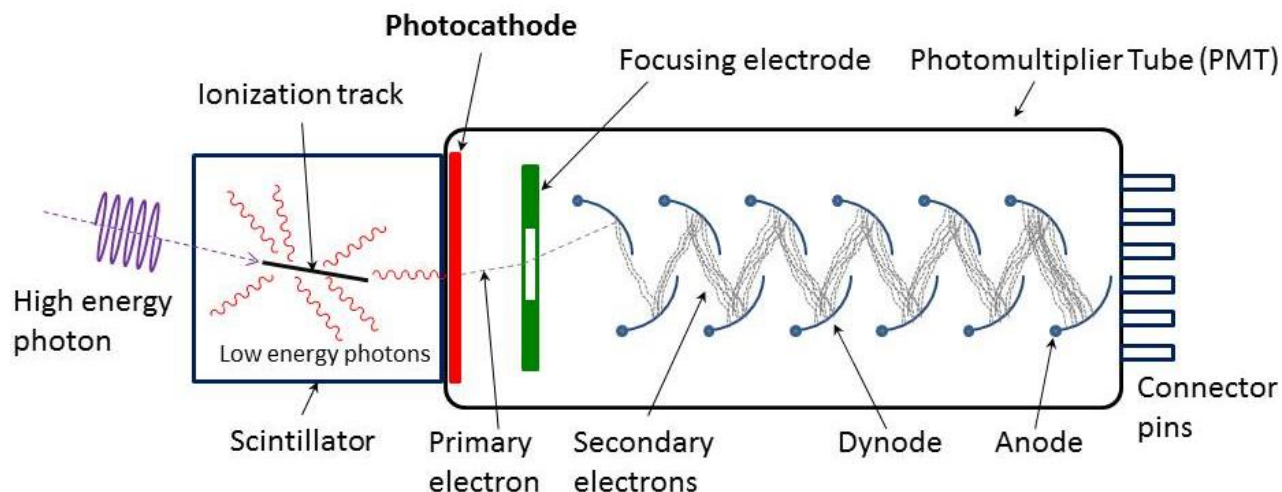
# PHOTON INTERACTIONS IN MATTER

- Photoelectric effect ✓

- Compton scattering ✓

- Pair production (today)


- How does each process contribute to the total energy loss?

# PHOTON INTERACTIONS IN MATTER

- Absorption coefficient of Al

  Z = 13
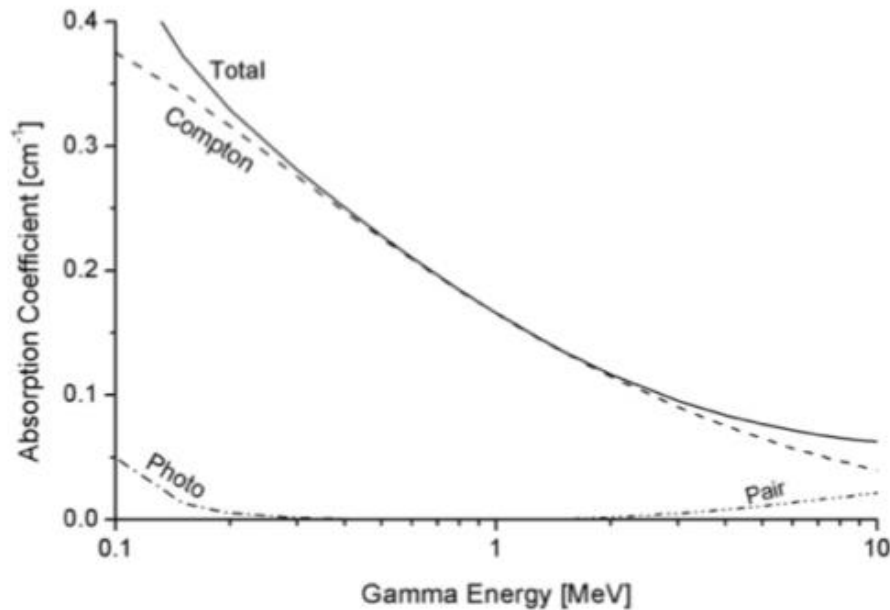
- Absorption coefficient of Pb

  Z = 82

  Higher Z materials favour photon absorption by photoelectric effect
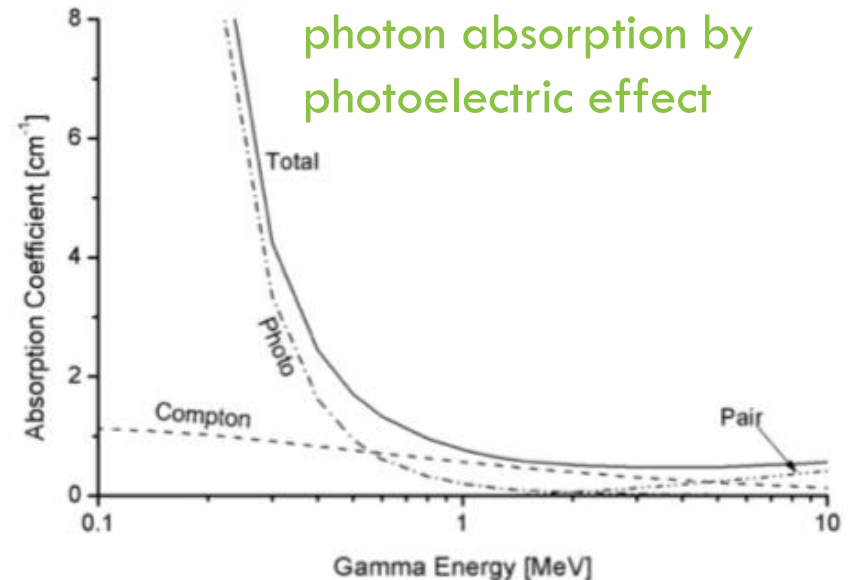


Probability of interaction depends on number of protons (Z)

# PHOTON INTERACTIONS IN MATTER
## PAIR PRODUCTION

- Dominant process at high energy – above 4 MeV for lead (material dependent).
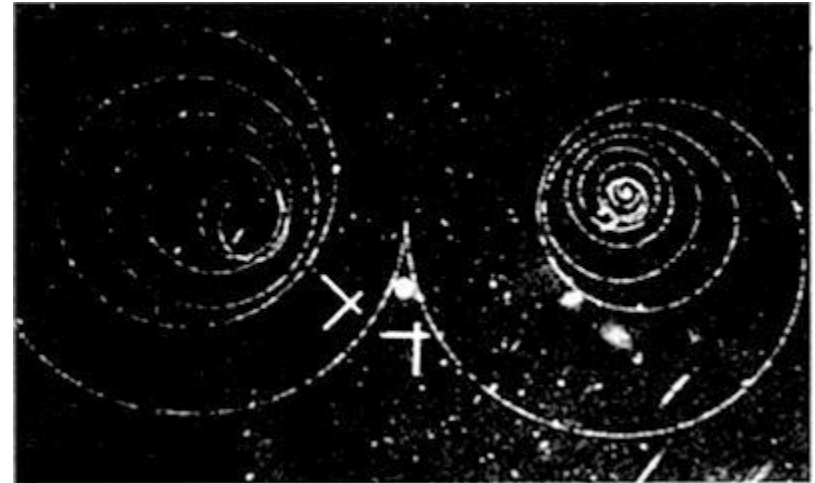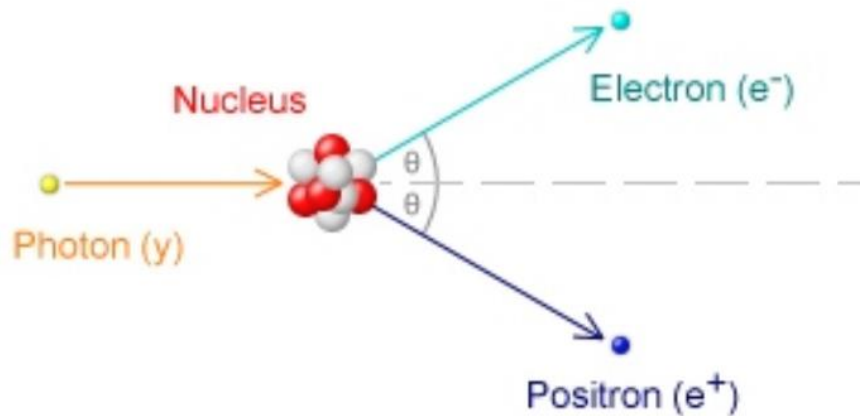




Pair production in a bubble chamber

# ELECTRON INTERACTIONS IN MATTER
## BREMMSTRAHLUNG
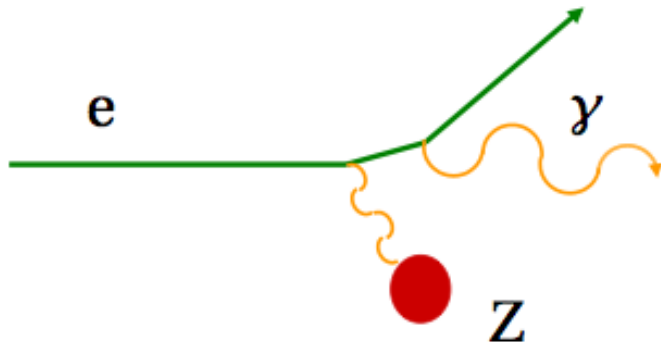


- Bremsstrahlung: $e\,Z \rightarrow Z\,e\,\gamma$ electromagnetic radiation produced by the deceleration of an electron, when deflected by an atomic nucleus.

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$X_0[cm] = \frac{716}{\rho[g/cm^3]} \frac{A}{Z} \frac{1}{(Z+1)\ln(287/\sqrt{Z})}$$

$X_0$ is the mean distance over which a high-energy electron loses all but $1/e$ of its energy.

Pb: $X_0 = 0.56$ cm

Si: $X_0 = 8.9$ cm

$$\Leftrightarrow E = E_0 e^{-x/X_0}$$

# PAIR PRODUCTION AND BREMMSTRAHLUNG

- Pair production and Bremsstrahlung radiation are complementary processes: both lead to electromagnetic showers.
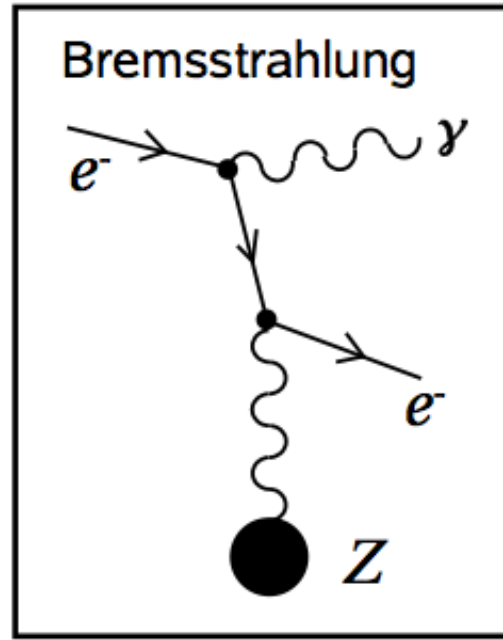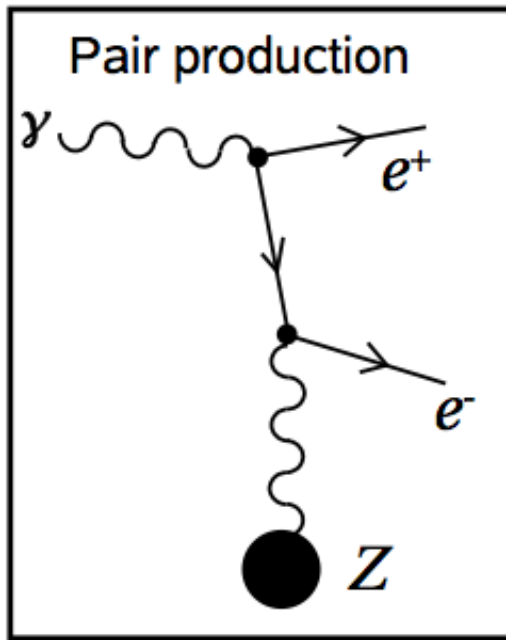


- Very similar Feynman diagrams

- Just two arms swapped

- At high energy: $\sigma_\gamma = \frac{7}{9}\sigma_e$

# ELECTROMAGNETIC SHOWERS

- The number of particles increases as a $2^N$, where N is the number of $X_0$ over which the shower has developed.

- $X_0$ is the "radiation length".

- The length of the shower depends on the primary electron energy.



| $x$ | 0 | $X_0$ | $2X_0$ | $3X_0$ | $4X_0$ | |
|------|------|---------|---------|---------|----------|---------|
| $N$ | 1 | 2 | 4 | 8 | 16 | 0 |
| $<E>$ | $E_0$ | $E_0/2$ | $E_0/4$ | $E_0/8$ | $E_0/16$ | $<E_c$ |
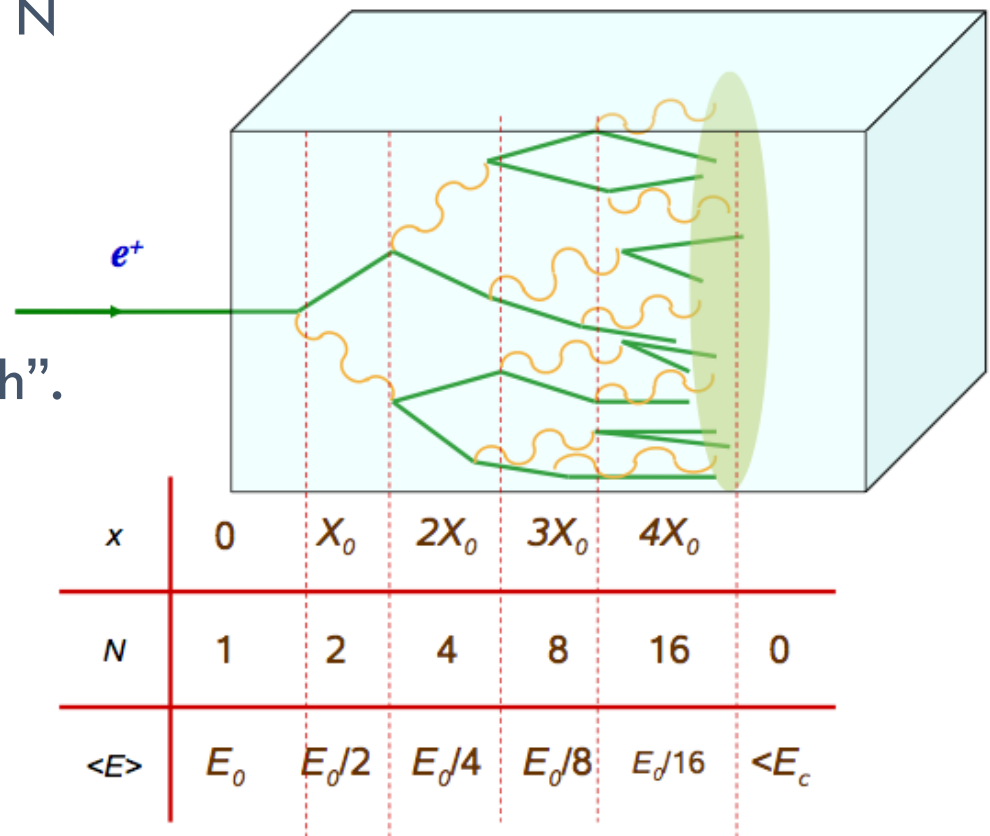
# ELECTROMAGNETIC SHOWERS

- Cloud chamber image of a shower between lead plates.
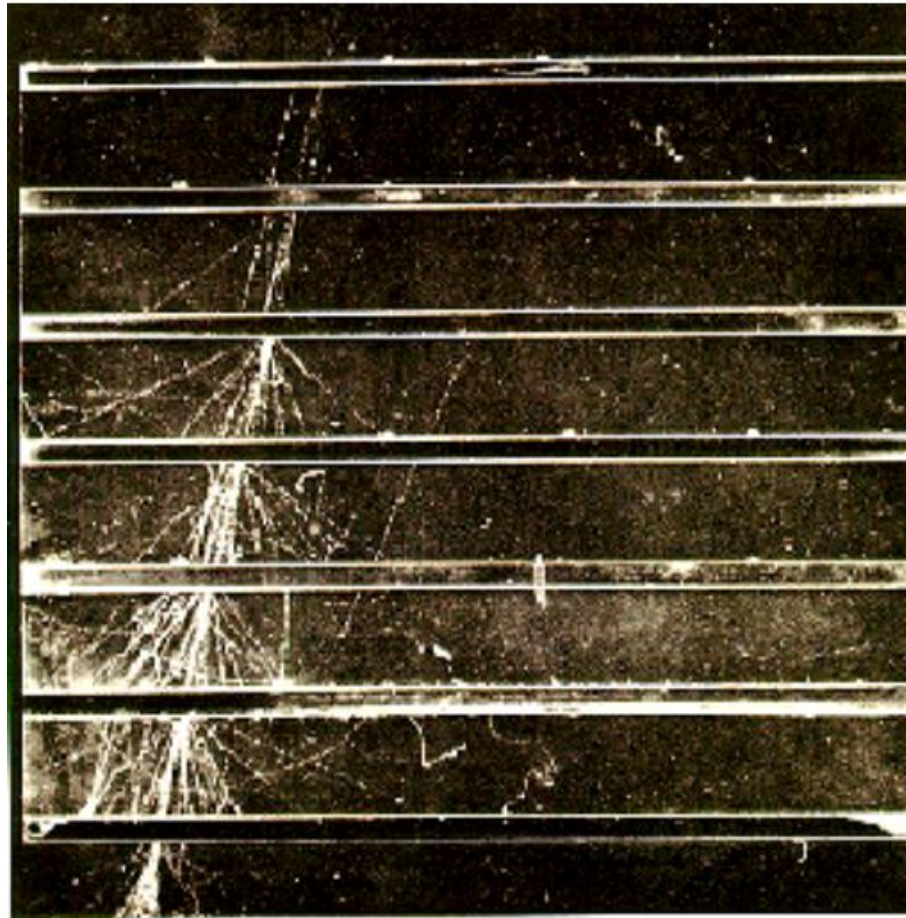
# PARTICLE DETECTION
## MEASUREMENT BY HADRONIC ENERGY LOSS
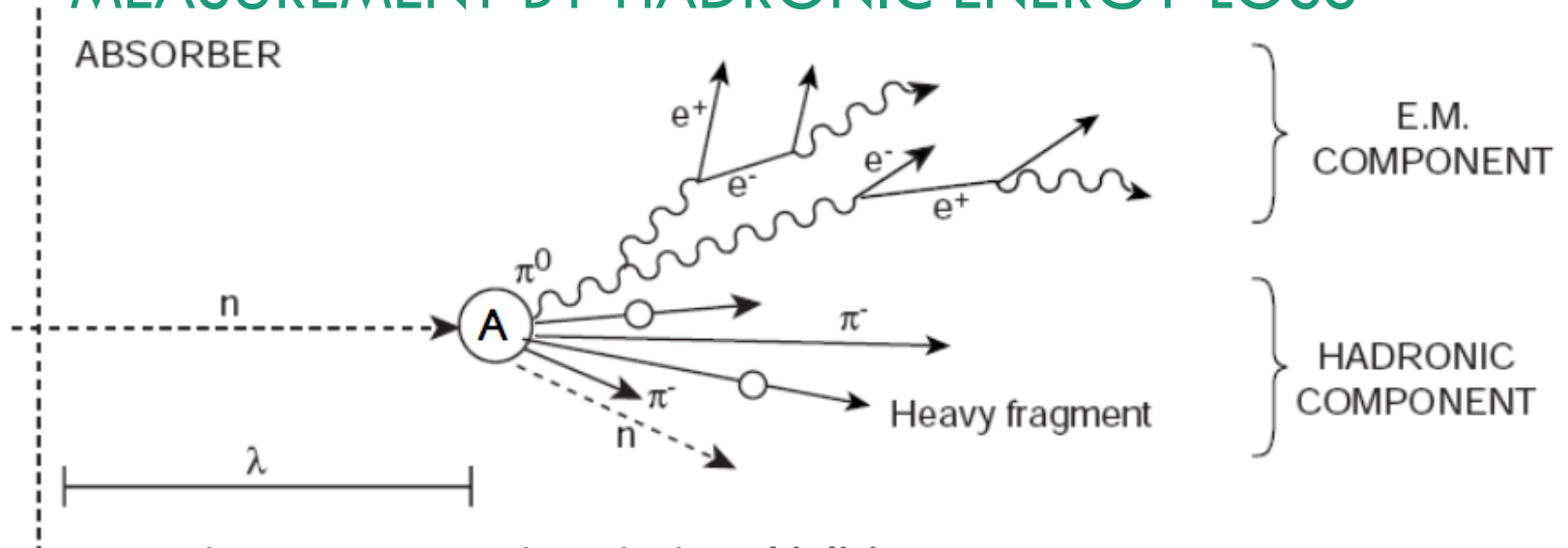


- Hadronic interactions have high **multiplicity**:
  - Shower is to 95% contained in ~7λ at 50 GeV (1.2 m of iron).

- Hadronic interactions produce $\pi^0$:
  - $\pi^0 \to \gamma\gamma$, leading to **local EM showers**.

- Some energy loss in nuclear breakup and neutrons ("**invisible** energy")

- Stronger **fluctuations** in a hadronic shower:
  - **Worse** energy resolution.

# HADRONIC VS EM SHOWERS
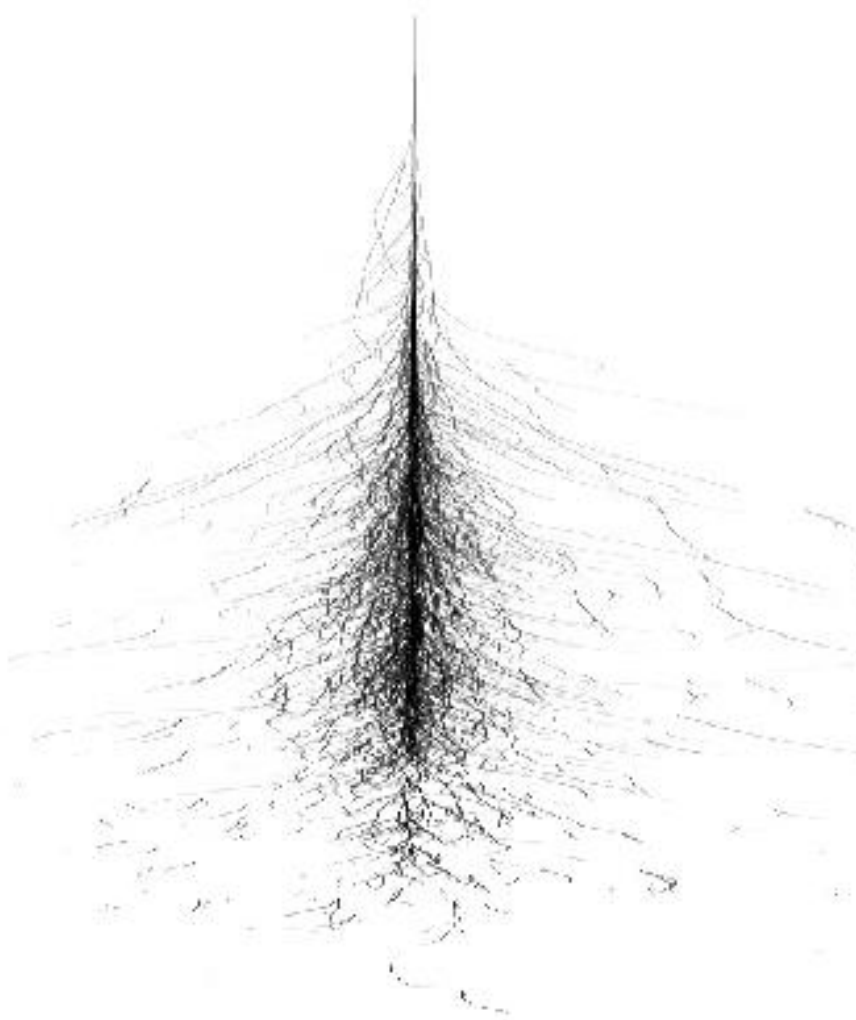


Gamma shower
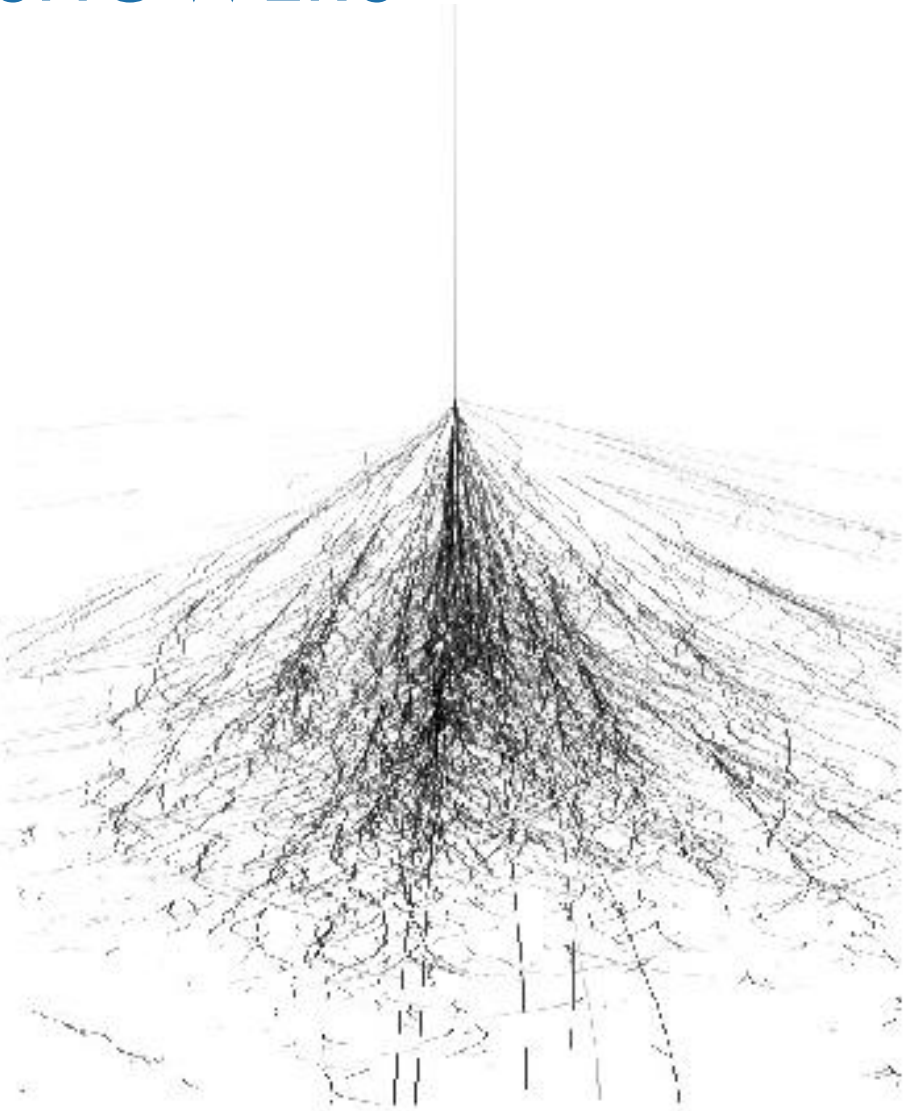
Hadronic shower

# HADRONIC VS EM SHOWERS
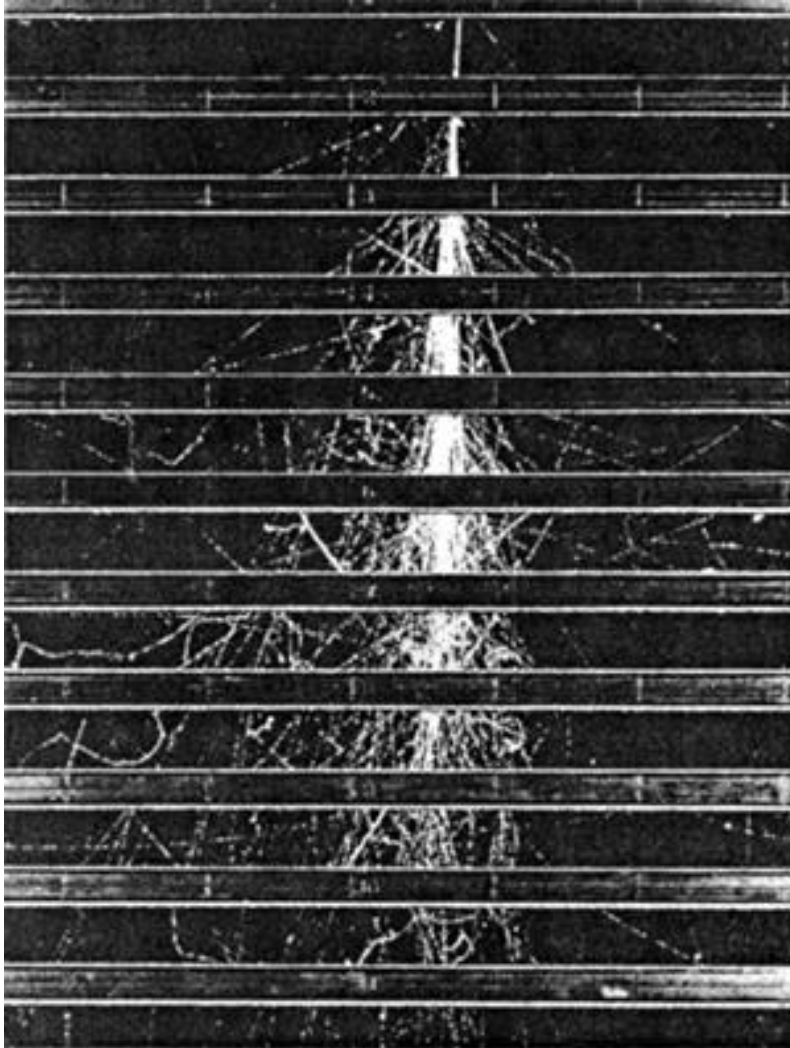
# DETECTING PARTICLES

# PARTICLE DETECTORS

- Detectors usually specialize in:

    - Tracking: measuring positions / trajectories / momenta of charged particles, e.g.:

        - Silicon detectors

        - Drift chambers

    - Calorimetry: measuring energies of particles:

        - Electromagnetic calorimeters

        - Hadronic calorimeters

- But they can also be a combination.

# PARTICLE DETECTORS

- Design Criteria:

    - Coverage and hermeticity:

        - Captures all particles produced in an interaction.

        - No holes, no cracks, no dead regions.

    - Resolution:

        - Resolve all particles (high granularity, each "granule"/channel read out individually).

        - Measure energies and directions with high precision.

    - Constraints:

        - Cost and available technology.

# ENERGY RESOLUTION

- The ability to differentiate amounts of energy deposition.
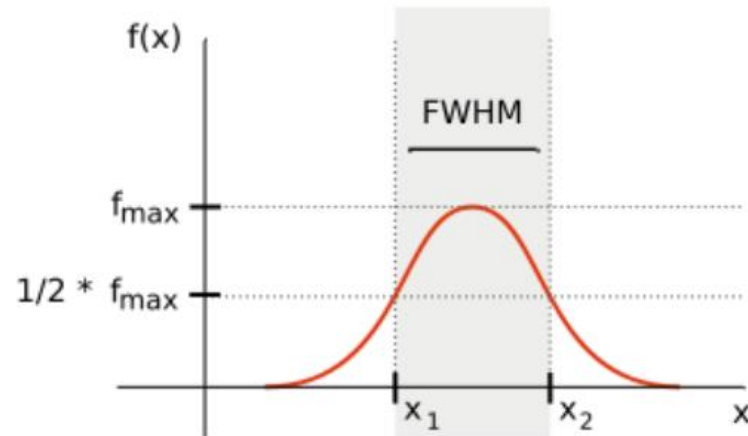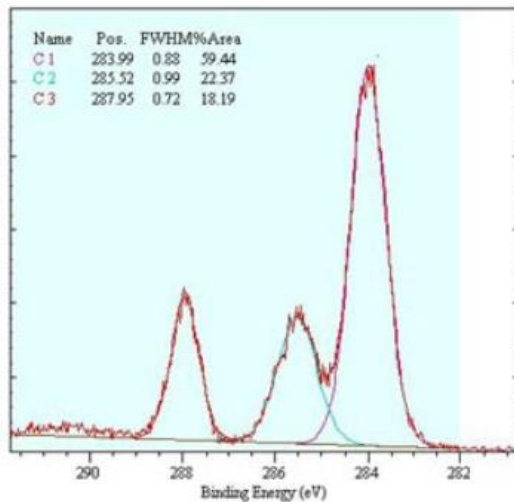


- Quantitatively described by the **full width at half maximum:**

$$\text{FWHM} = 2\sqrt{2ln2}\sigma \approx 2.35\sigma$$

- It determines when two peaks can be separated.

# ENERGY RESOLUTION

# CHERENKOV DETECTORS



Cerenkov radiation cone

$\nu_\mu$     $\mu$
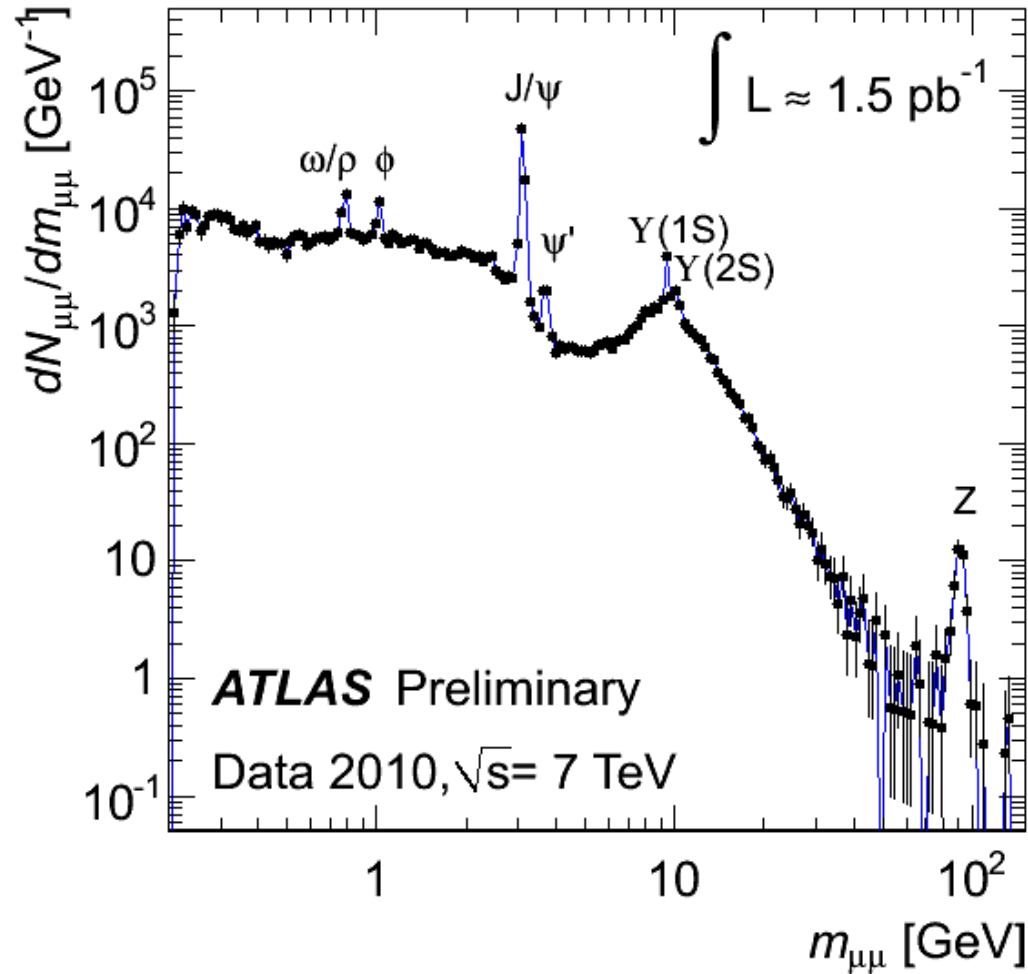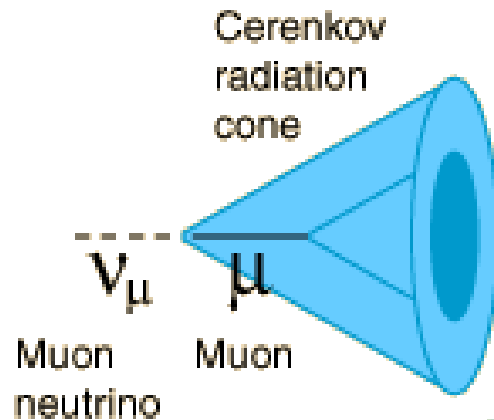
Muon neutrino     Muon

The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

$\nu_e$

Electron neutrino     Electron shower
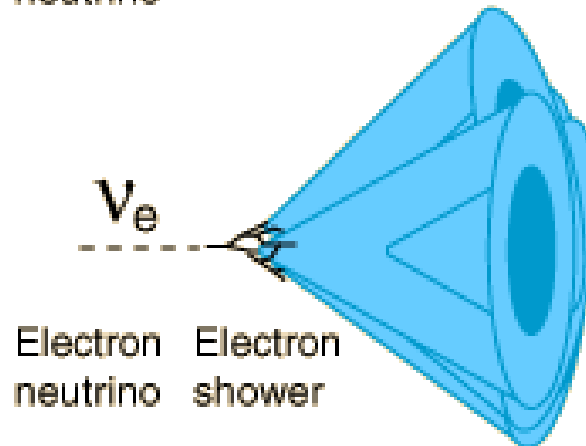
The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

# CHERENKOV DETECTORS

- Super-Kamiokande in Japan.

  - The world's largest neutrino detector!

# NEUTRINO DETECTION AT SUPER-K

- Electrons and muons resulting from neutrino interactions in the water

# NEUTRINO DETECTION AT SUPER-K

# IONIZATION DETECTOR

**Charged particle**

**primary ionization**

**cathode**

**gas**

**anode**

**Drifting electrons**
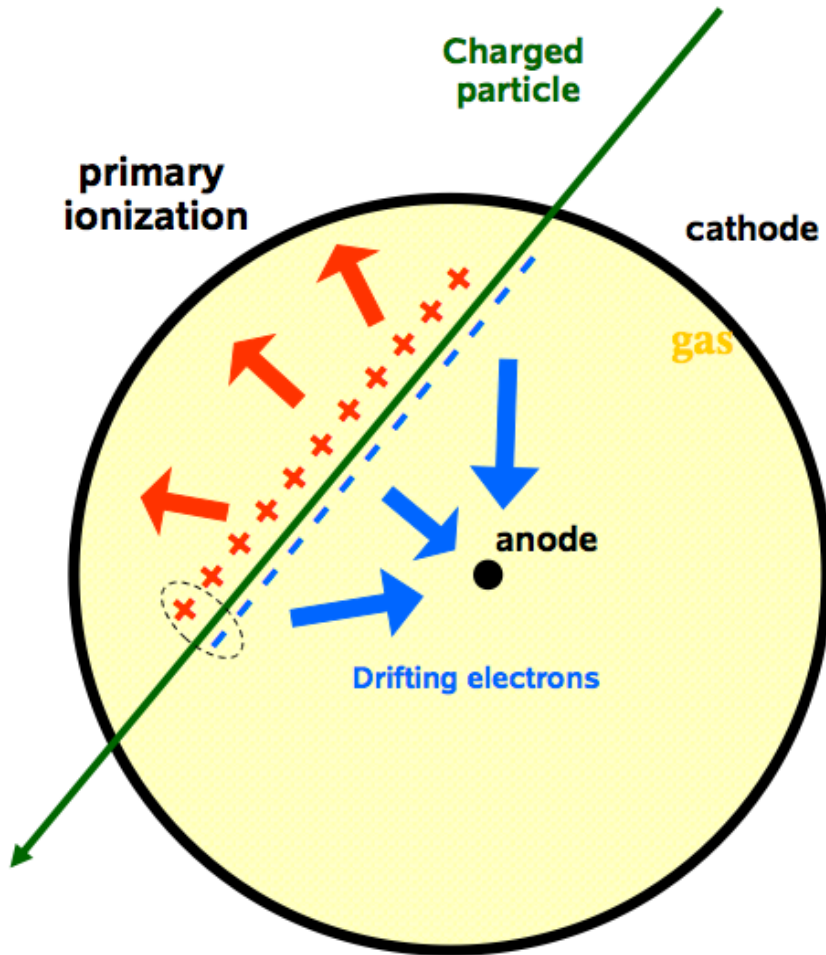
- Drifting electrons should not be trapped:
  - ▶ Use noble gas, e.g. Ar.
- Want large primary ionzation yield:
  - ▶ Ar gives 25 ions/cm at normal T, p for a minimm ionizing particle.
- The primary electrons may ionize further atoms:
  - ▶ ×3 or ×4 increase.
- Xe and/or higher pressure are even better (and more expensive).

Induced electrical signal on anode can be measured to estimate number of drift electrons: E lost to ionization.

# IONIZATION DETECTOR

- Geiger counter
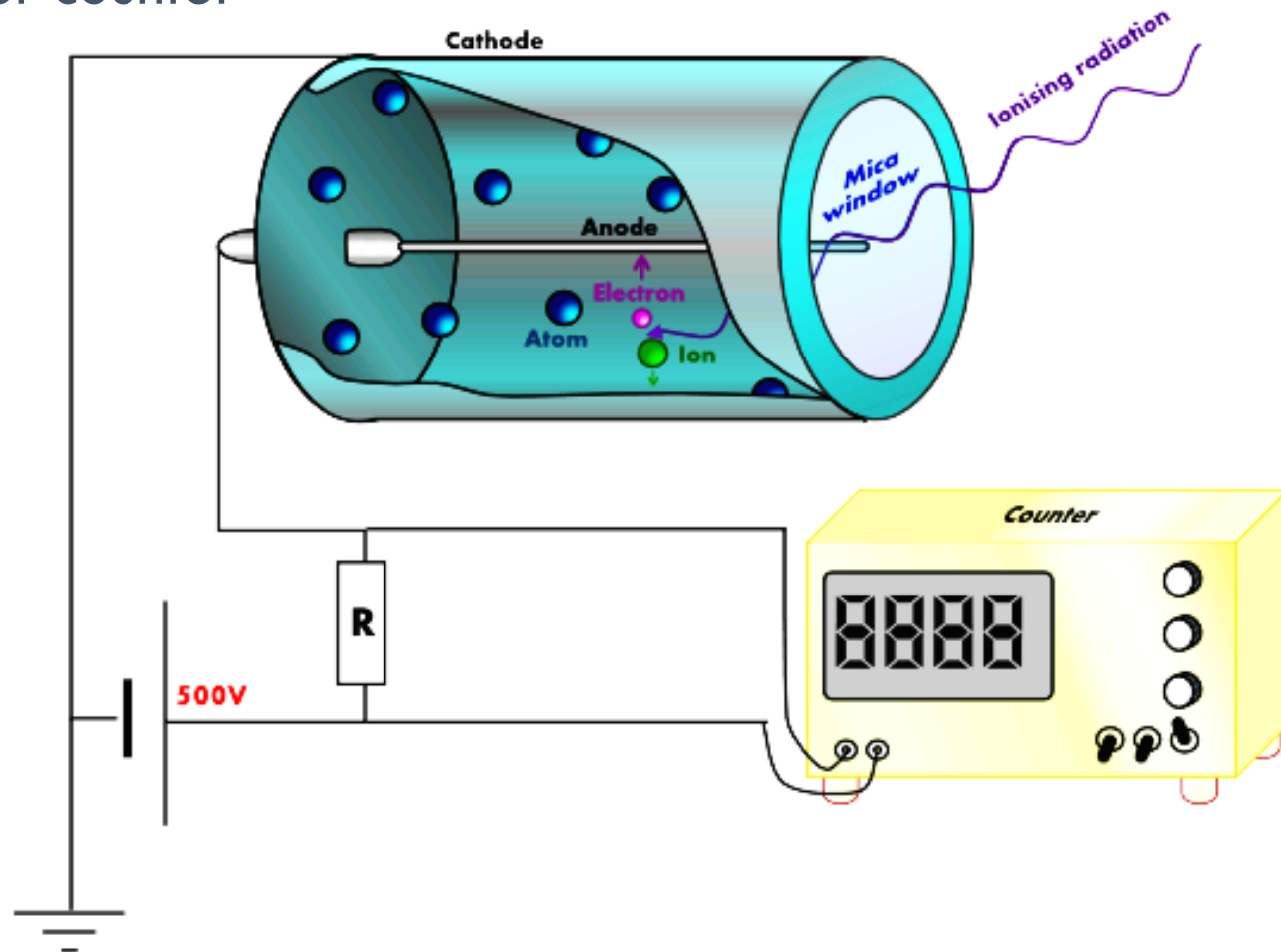
# TIME PROJECTION CHAMBER

- Exploits ionization energy losses of charged particles.

- Electrons are drifted onto a fine grained plane of wires, and the particle trajectories can be mapped out, along with their ionization energy loss, dE/dx
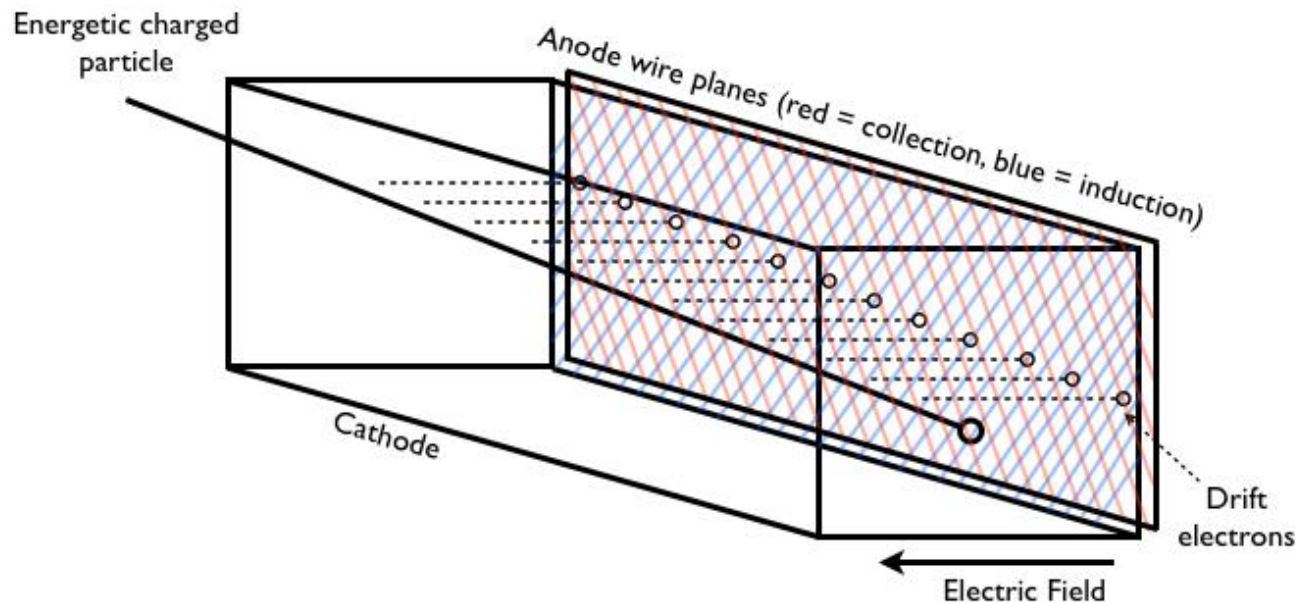
# TIME PROJECTION CHAMBER

- MicroBooNE liquid argon TPC at Fermilab
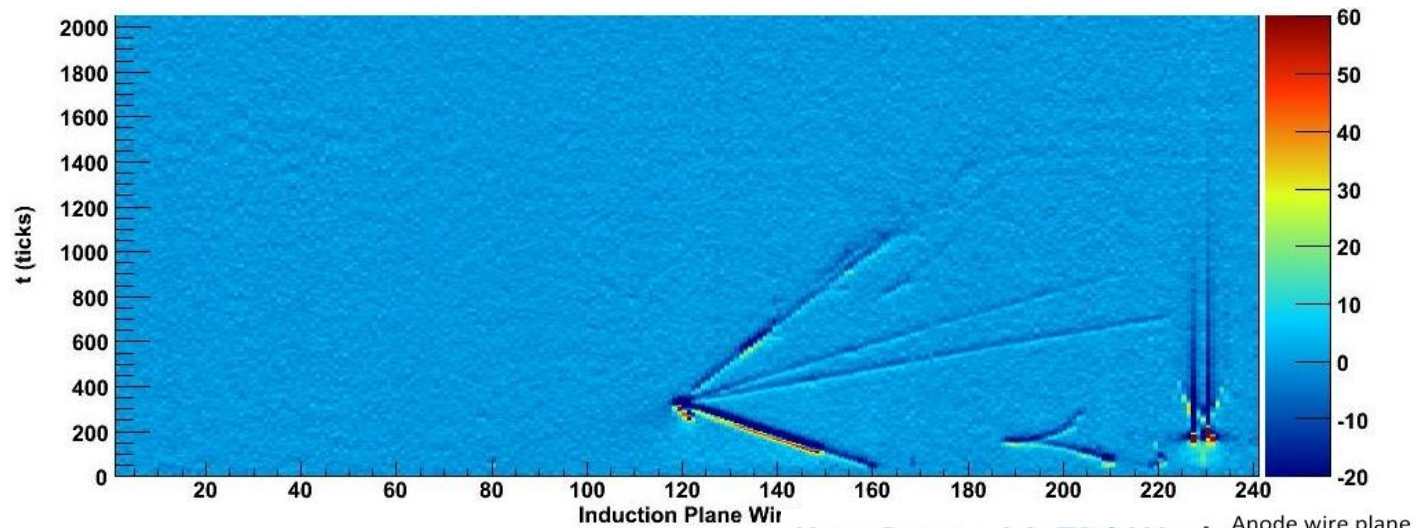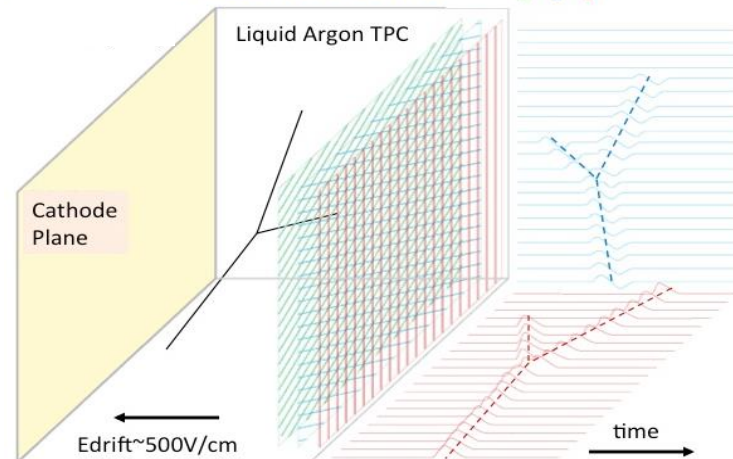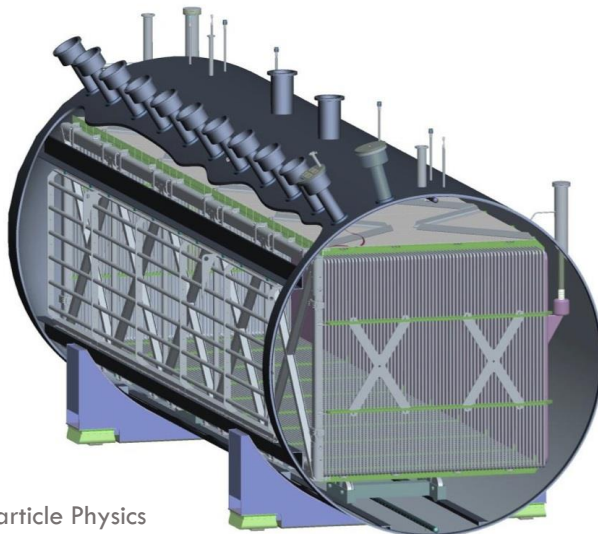
# SCINTILLATION DETECTORS

- Emitted light depends on detector material.

  - Usually in the visible to UV range.

- Sometimes requires the use of wavelength-shifting materials to shift UV light to visible, so it can be efficiently measured by commonly used photomultiplier tubes.
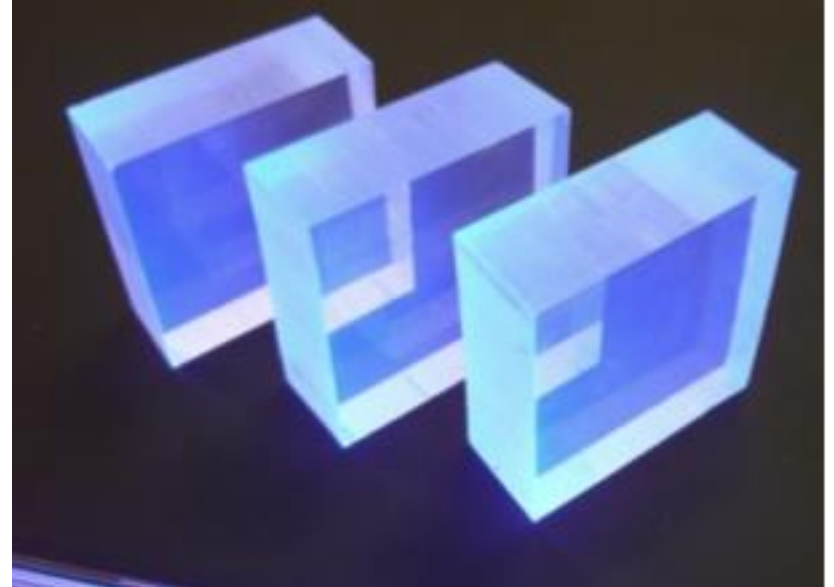
# MODERN EXPERIMENTS

# PARTICLE SOURCES

- Particle physics experiments use different sources of particles

- Artificial beams produced in accelerators
    - Colliders – beams are made to collide against each other.
        - Highest energy interactions from artificial sources
    - Beams are aimed at fixed targets / detectors
        - Lower energy, but typically more intense

- Natural sources
    - Particles resulting from cosmic ray interaction in the atmosphere
    - Radioactive sources
    - Astrophysical sources
    - Dark matter ?

# PARTICLE COLLIDERS AROUND THE WORLD

| | | | | |
|---|---|---|---|---|
| SLAC, California | SLC | 1989-1998 | $e^- e^+$ | 50 GeV $e^-$ and 50 GeV $e^+$ |
| | PEP II | 1997-2008 | $e^- e^+$ | 9.0 GeV $e^-$ and 3.1 GeV $e^+$ |
| Fermilab, nr Chicago | Tevatron | 1987-2009 | $p \bar{p}$ | 980 GeV $p$ and 980 GeV $\bar{p}$ |
| CERN, Geneva | LEP | 1989-2000 | $e^- e^+$ | $E_{CM}$: 89 to 206 GeV |
| | LHC | 2008-… | $p\,p$ | $E_{CM}$: 14 TeV |
| DESY, Hamburg | HERA | 1990-2007 | $e^- p$ | 920 GeV $p$ and 30 GeV $e^-$ |
| KEK, near Toyko | KEKB | 1999-… | $e^- e^+$ | 8.0 GeV $e^-$ and 3.5 GeV $e^+$ |
| Brookhaven National Lab, Long Island | RHIC | 2000-… | AuAu, CuCu | 200 GeV/nucleon |

# CERN'S ACCELERATOR COMPLEX



CMS
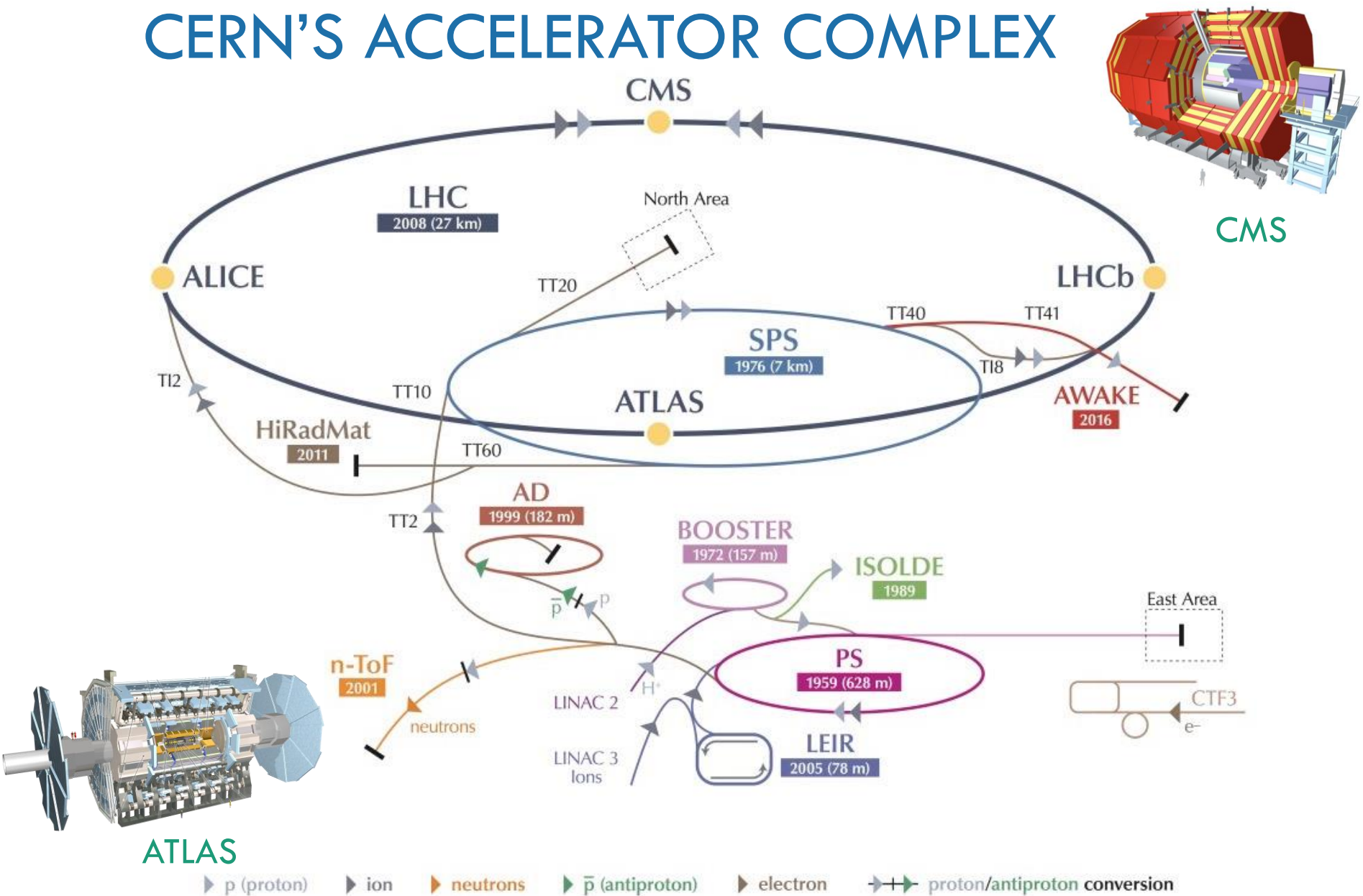
ATLAS

# A GENERAL PURPOSE DETECTOR



p →

p ←

beam pipe

tracking and vertexing

EM calorimeter

hadronic calorimeter

muon chambers

# THE CMS DETECTOR



22 m

15 m

# A SLICE OF CMS



Key:
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon

Transverse slice through CMS

4T

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

2T

Iron return yoke interspersed with Muon chambers

0m    1m    2m    3m    4m    5m    6m    7m
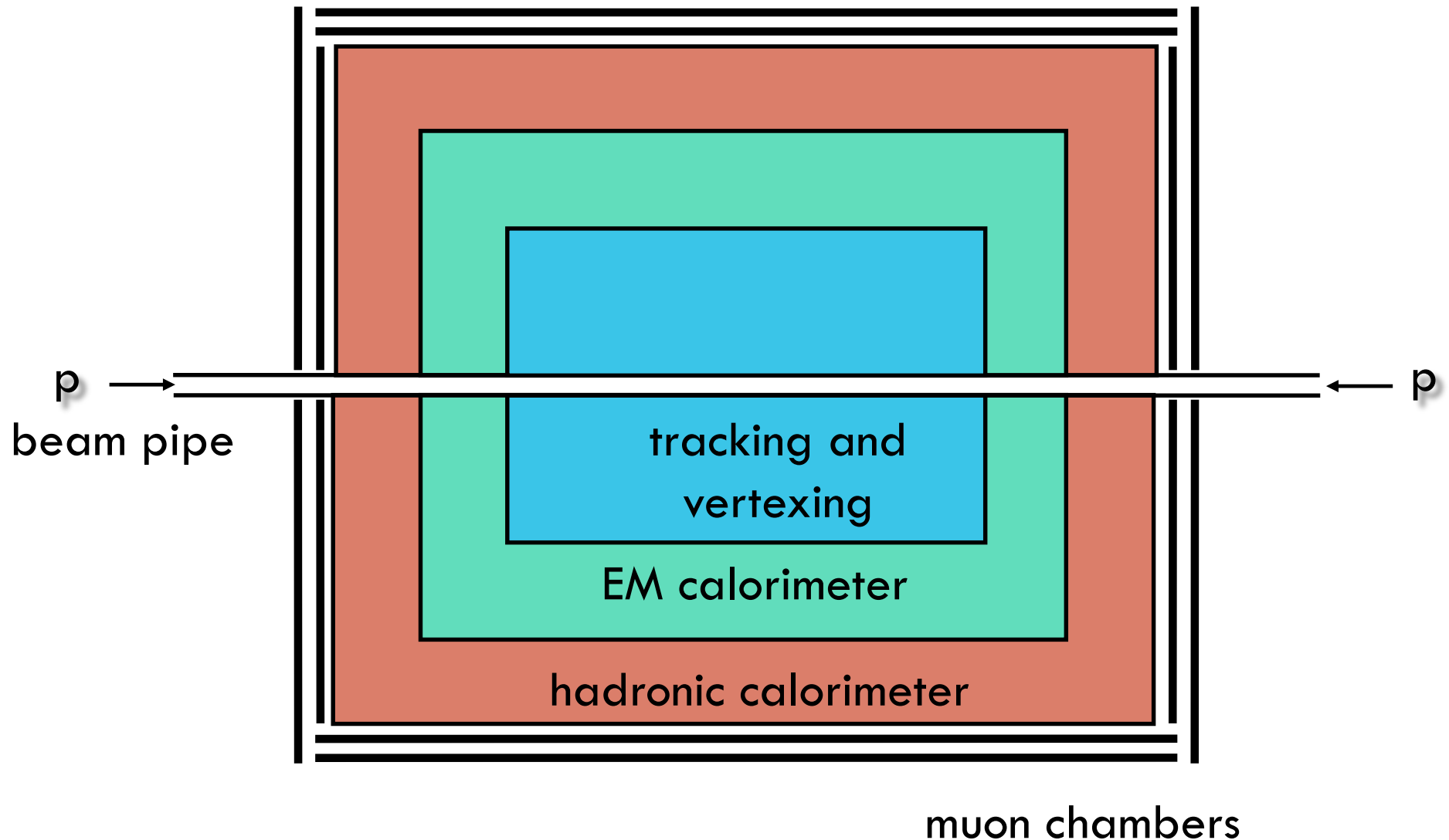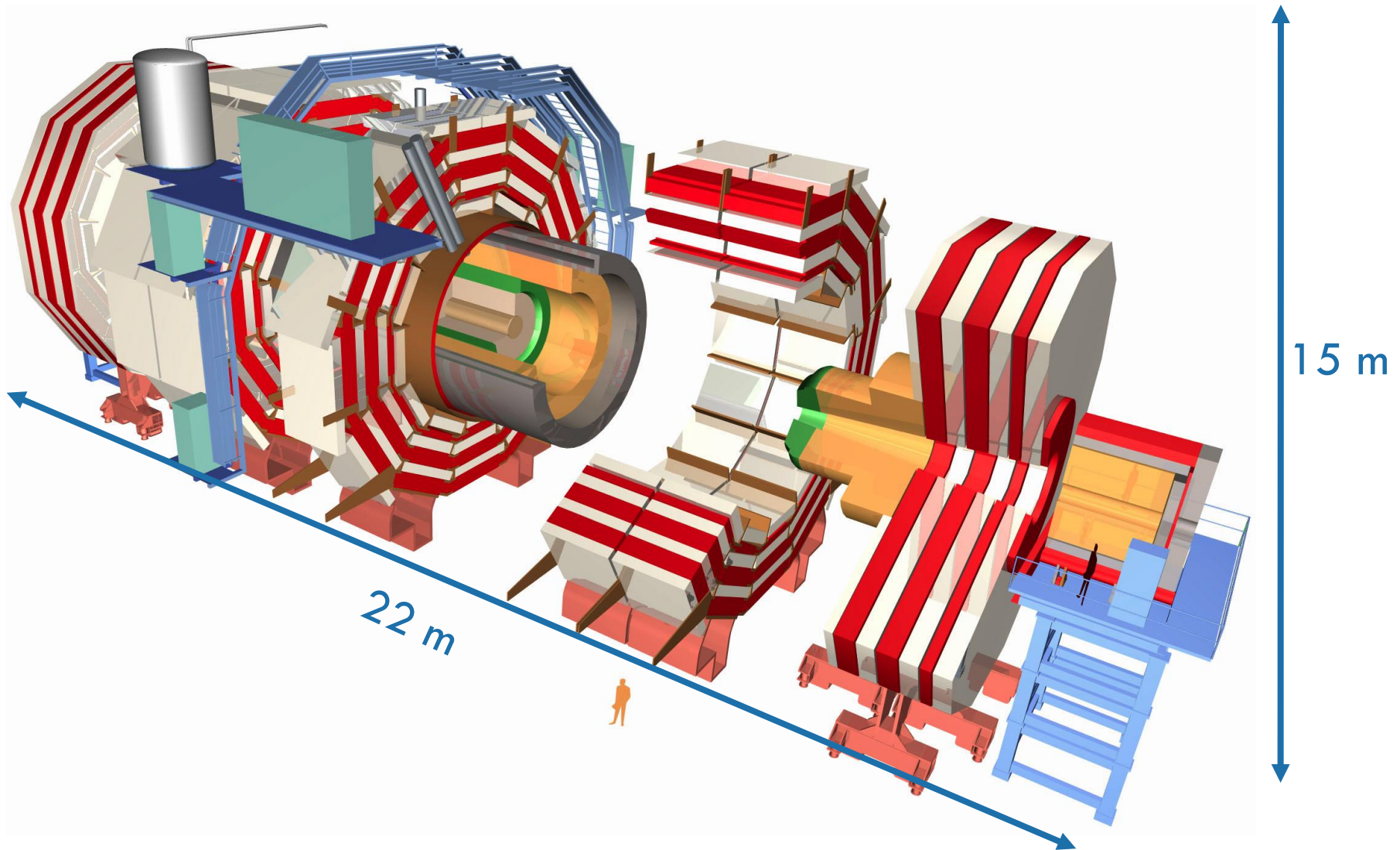
t = s/c    3 ns         10 ns              20 ns
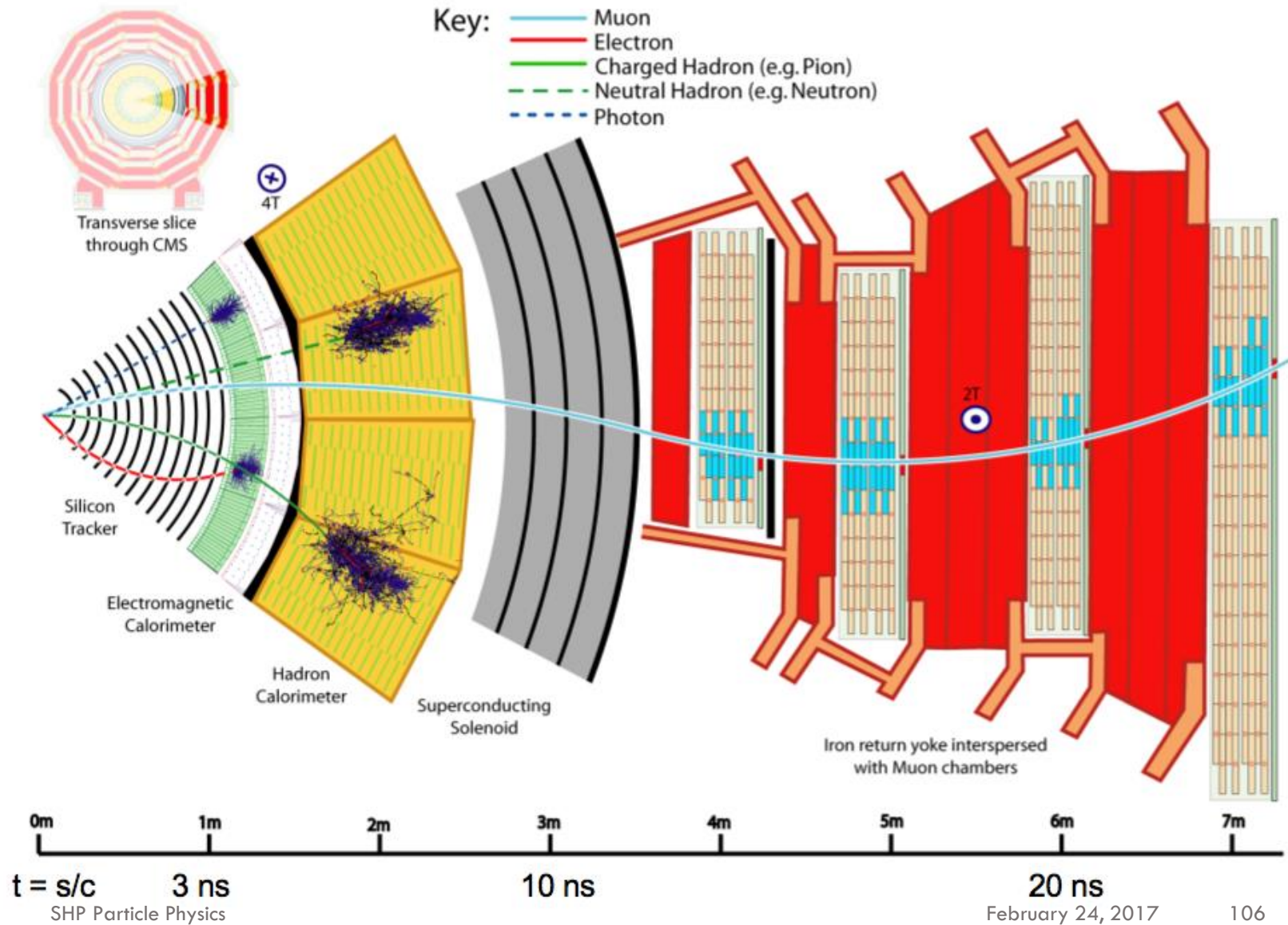
# MAGNET SYSTEMS



- Solenoid and toroidal magnets.

- Solenoid coils in CMS and ATLAS:

  - Field direction along beam axis.

  - Homogenous field inside the coil.

  - e.g. CMS superconducting magnet

    - I = 20 kA, B = **4 T**

    - Temperature 4K.

- For comparison, Earth's magnetic field at surface is ~50 µT.
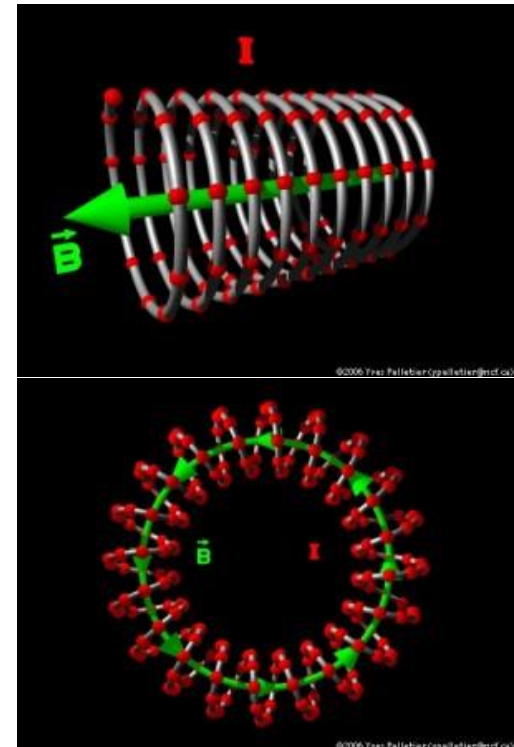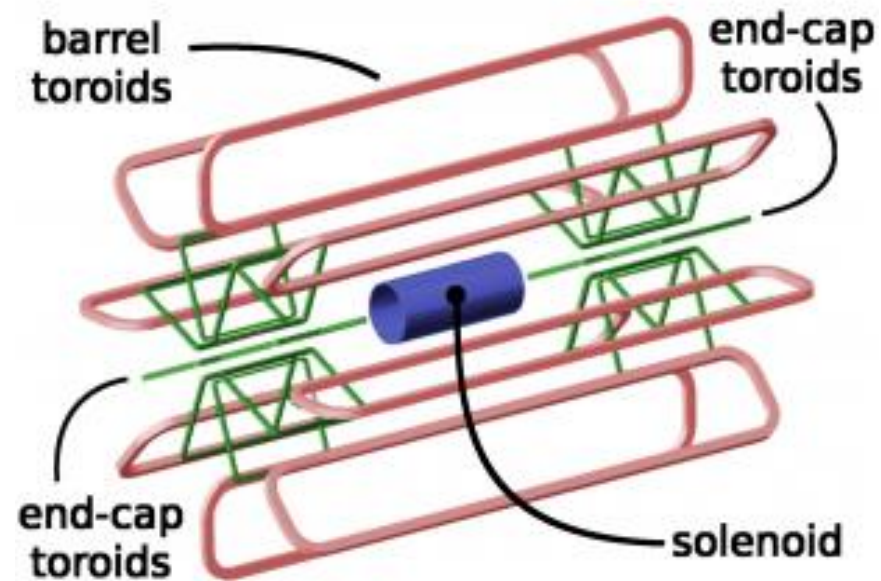
# EVENT SIGNATURES

Higgs → 4 muons
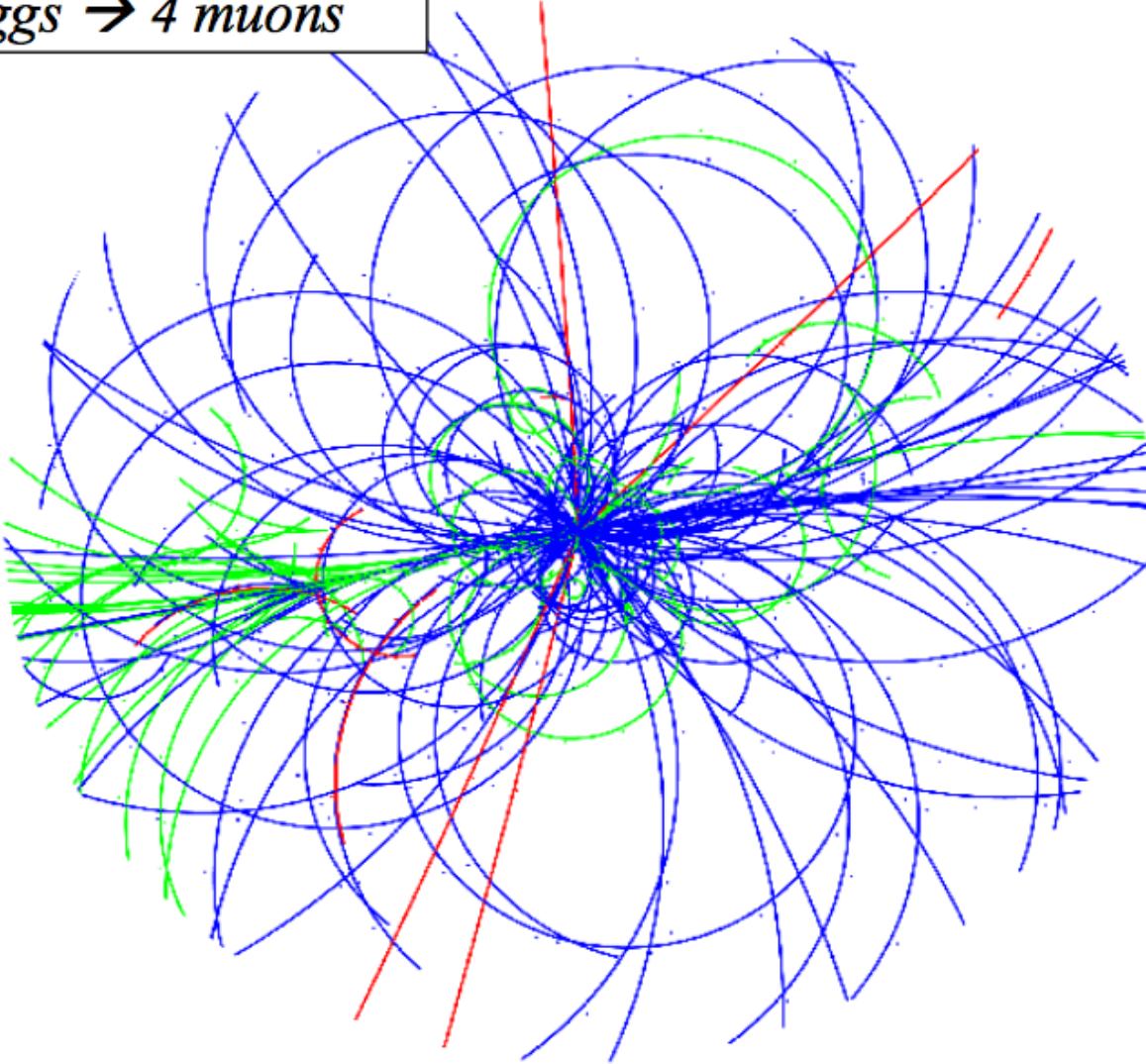
Charged particles bend in the magnetic field

The lower the particle momentum the more they bend.

Straight tracks from high momentum particles are the most interesting!

# A REAL EVENT
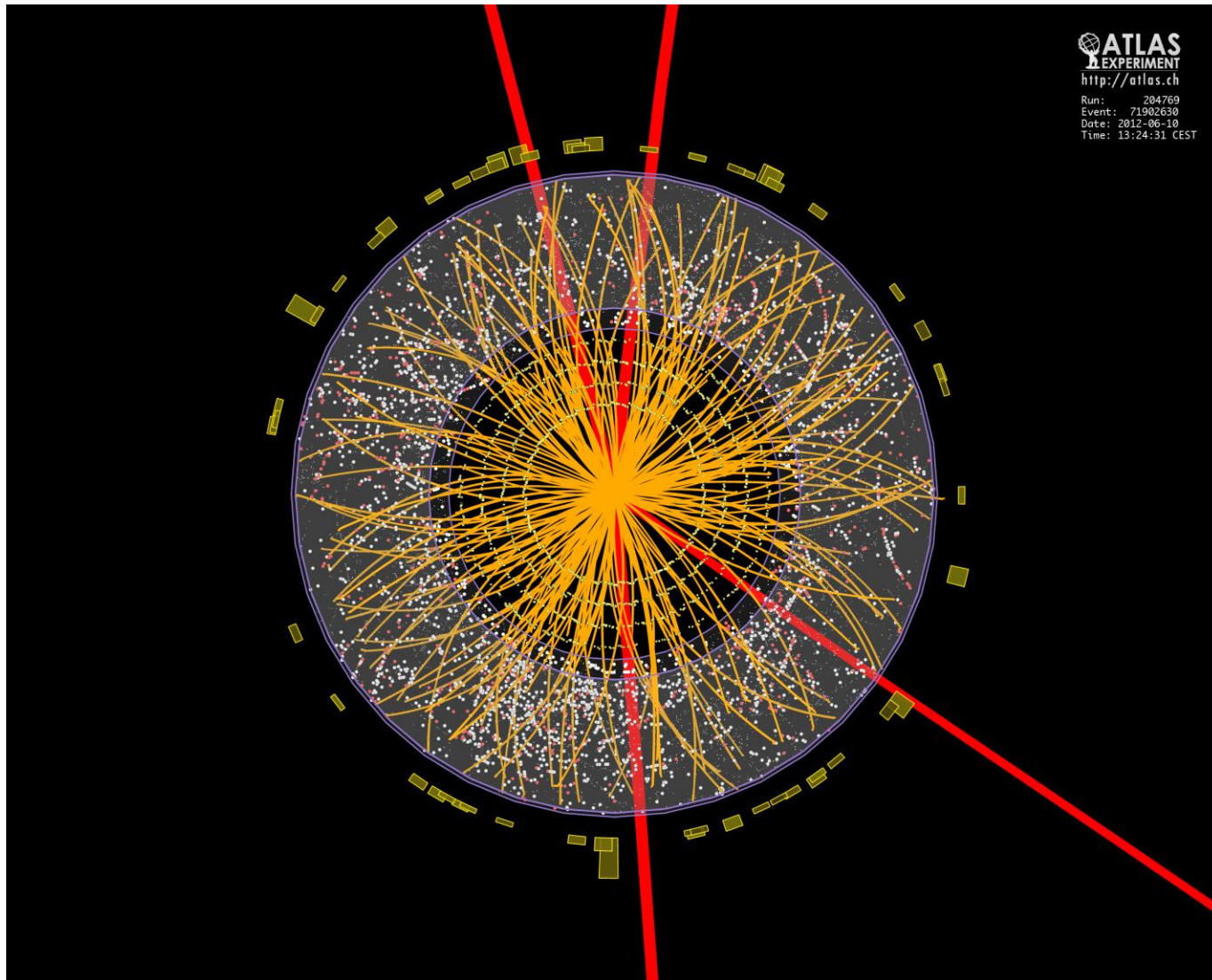
# T2K: ND280
## A GENERAL PURPOSE NEUTRINO DETECTOR

- Beam of neutrinos produced at the J-PARC proton accelerator in Japan



B = 0.2T

UAI Magnet

P0DECal

Barrel ECal

Downstream ECal

To Super-K

Neutrinos

P0D    TPC    TPC    TPC

Plastic scintillator and Pb

FGDs

Argon gas

Segmented plastic scintillator
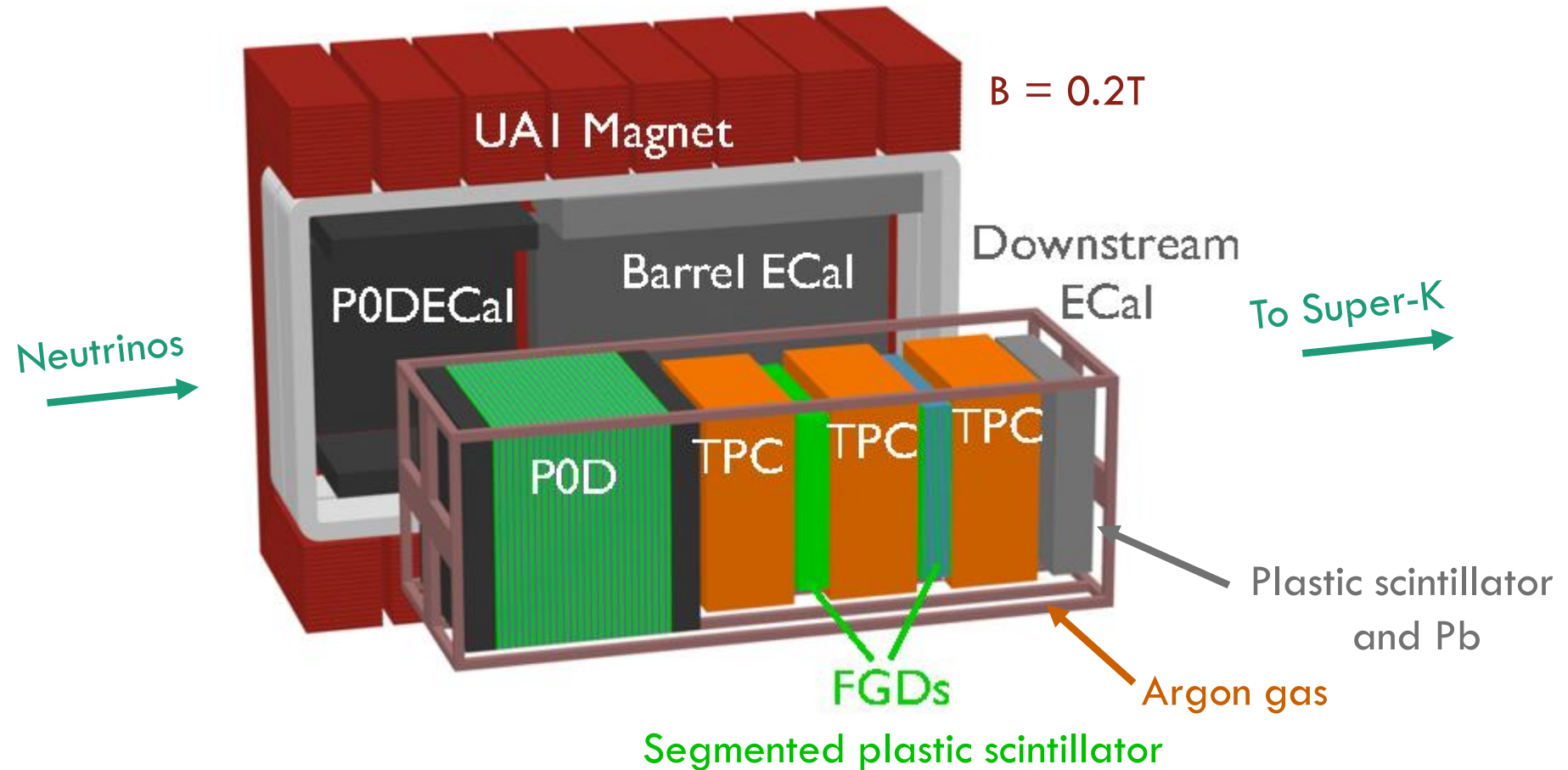
# THE ND280 DETECTOR
## WITH MAGNET OPEN FOR MAINTENANCE
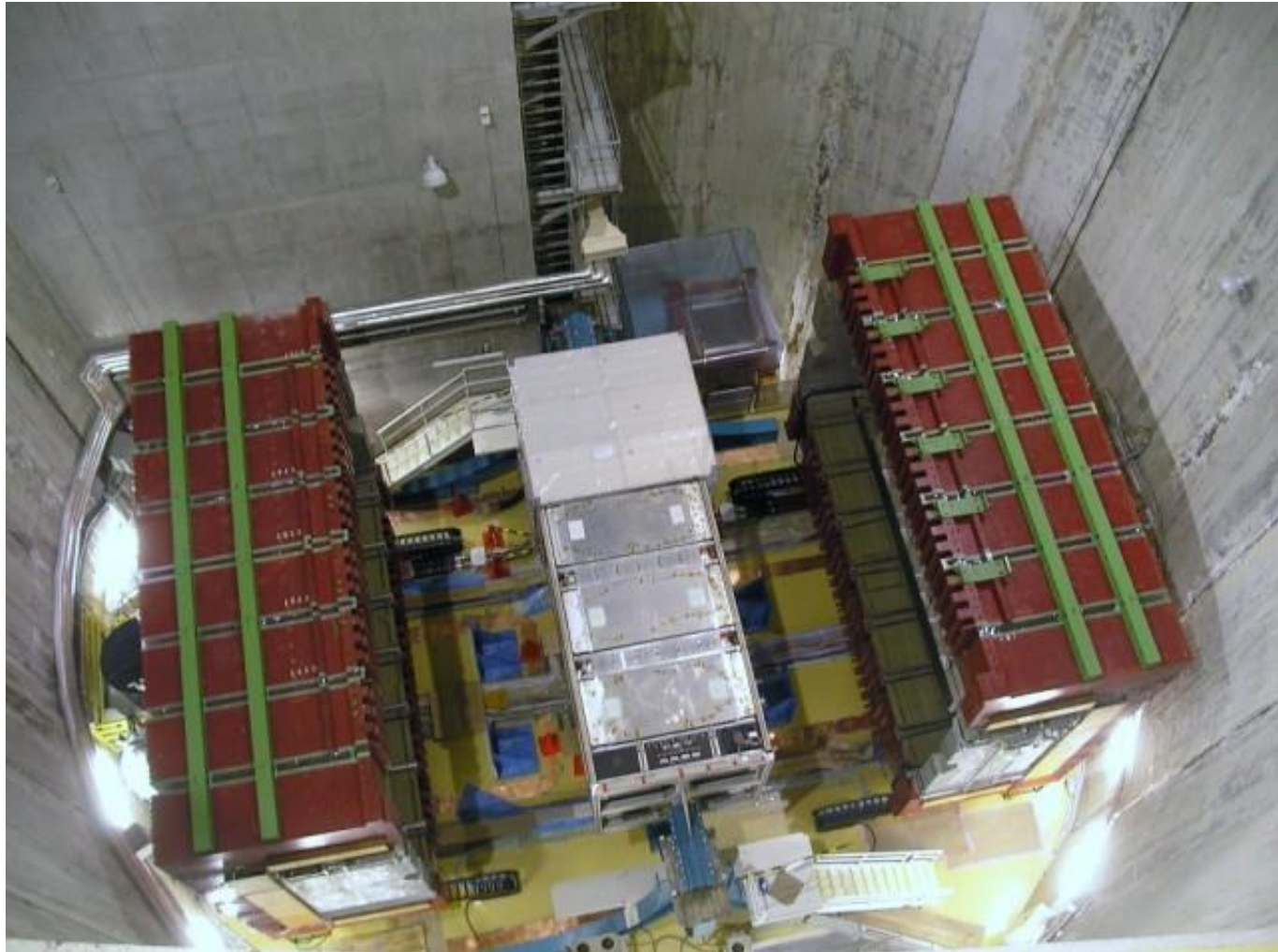
# A NEUTRINO INTERACTION IN ND280
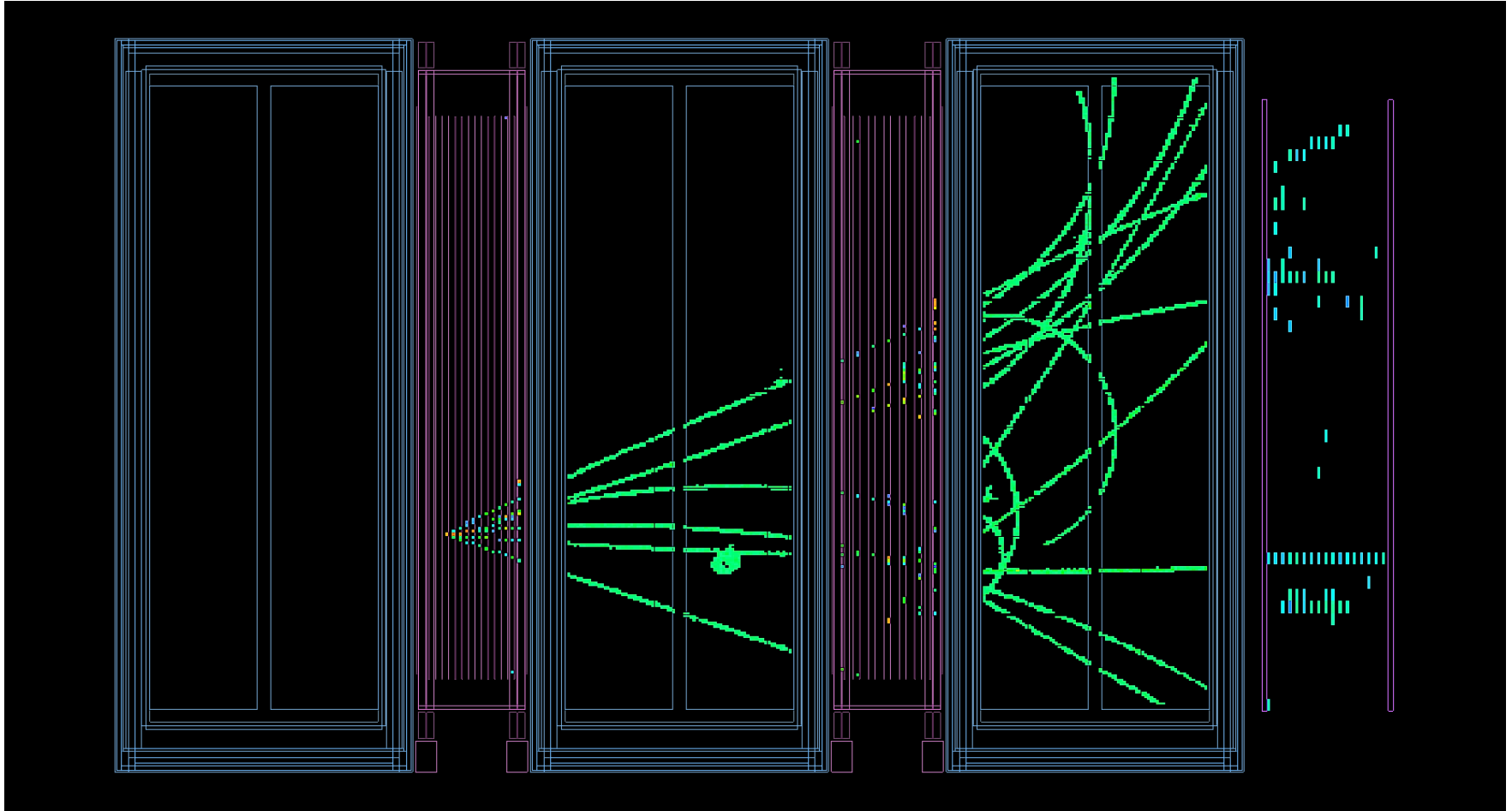
# WHAT ABOUT DARK MATTER?

- Does not interact through weak, electromagnetic, or strong force.

- But it **might interact**, very very weakly.

- We need very "quiet" (cryogenic, deep underground) detectors to see dark matter interactions.

  - Scattering off of nuclei ➞ transfer of kinetic energy.

# THE LUX DARK MATTER EXPERIMENT

- The Large Underground Xenon (LUX) and XENON-1t experiments look for evidence of weakly interacting massive particle (WIMP) dark matter interactions.

- A few hundred to a ton of liquid xenon as the TPC medium.

- Aim to directly detect galactic dark matter in underground laboratories about 1 mile deep

- The detectors are shielded from background particles by a surrounding water tank and the earth above.

- This shielding reduces cosmic rays and radiation interacting with the xenon.



S1

$\gamma$

Particle

52 phe

S2

E field

$\Delta t$

$e^-$

4540 phe



S1
52 phe

S2
4540 phe

$\Delta t$

phe/10 ns

Time [$\mu s$]
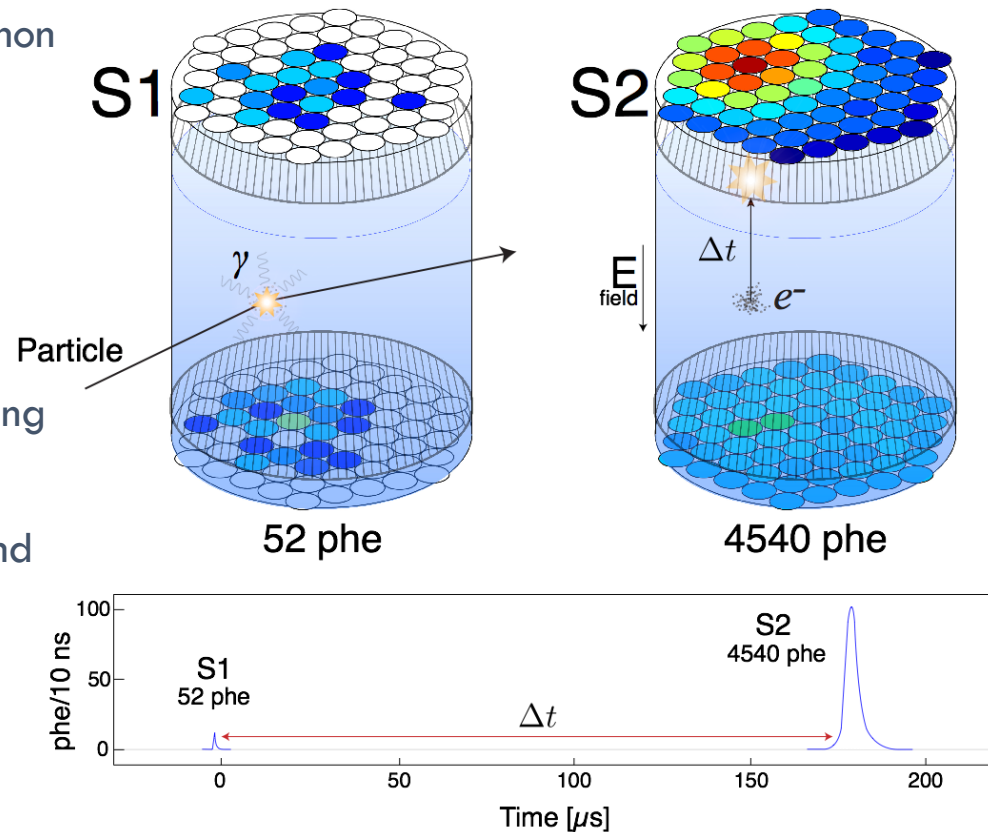
# PARTICLE DETECTORS AT THE SOUTH POLE

# PARTICLE DETECTORS AT THE SOUTH POLE

Why do we go to such remote places for science?

# ICE FISHING FOR SPACE NEUTRINOS!

- IceCube detector at the South Pole
  - A neutrino detector: a neutrino telescope.
- Looks for extra-terrestrial sources of neutrinos.
  - Like taking an "X-ray" picture of the Universe.
- Use the Antarctic ice as a Cherenkov detector!
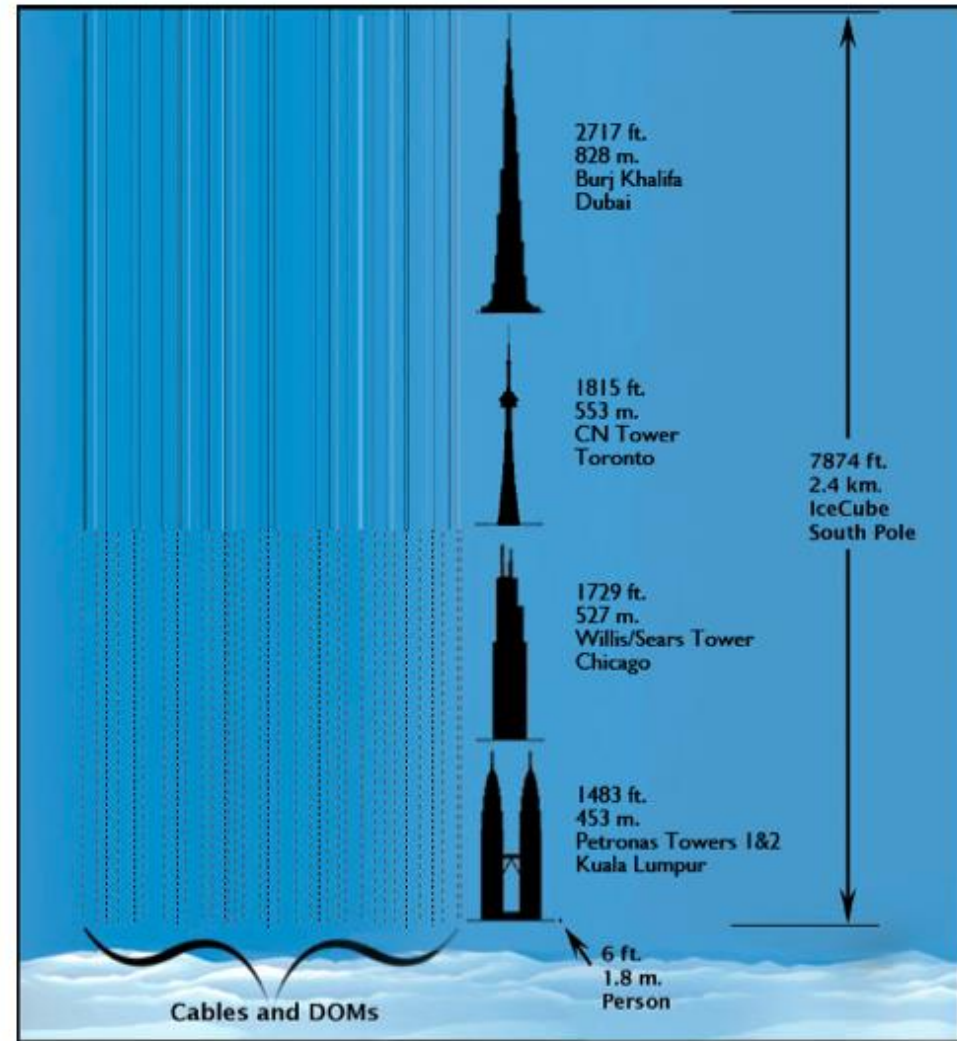


2717 ft.
828 m.
Burj Khalifa
Dubai

1815 ft.
553 m.
CN Tower
Toronto

7874 ft.
2.4 km.
IceCube
South Pole

1729 ft.
527 m.
Willis/Sears Tower
Chicago

1483 ft.
453 m.
Petronas Towers 1&2
Kuala Lumpur

6 ft.
1.8 m.
Person

Cables and DOMs

IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached

# ICE FISHING FOR SPACE NEUTRINOS!

- Made up of strings of thousands of basketball-sized photon detectors
  - Digital Optical Modules
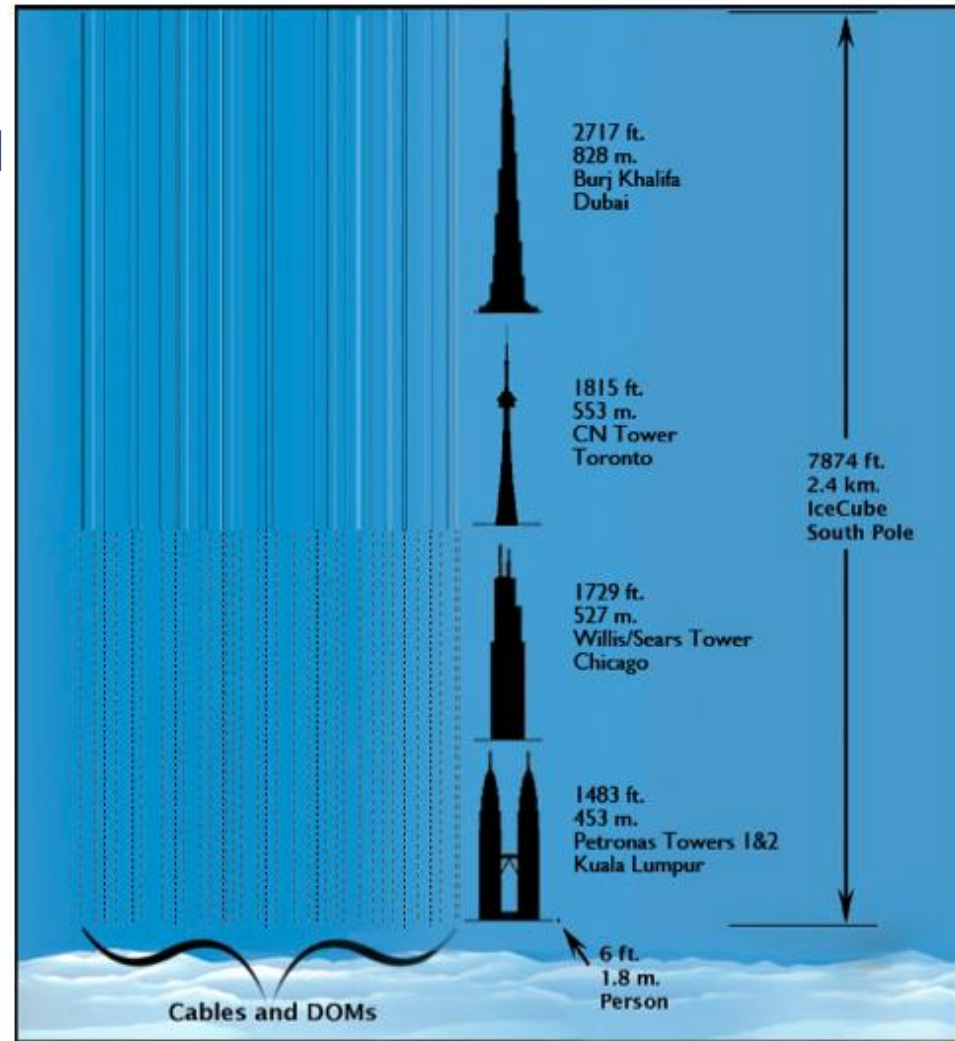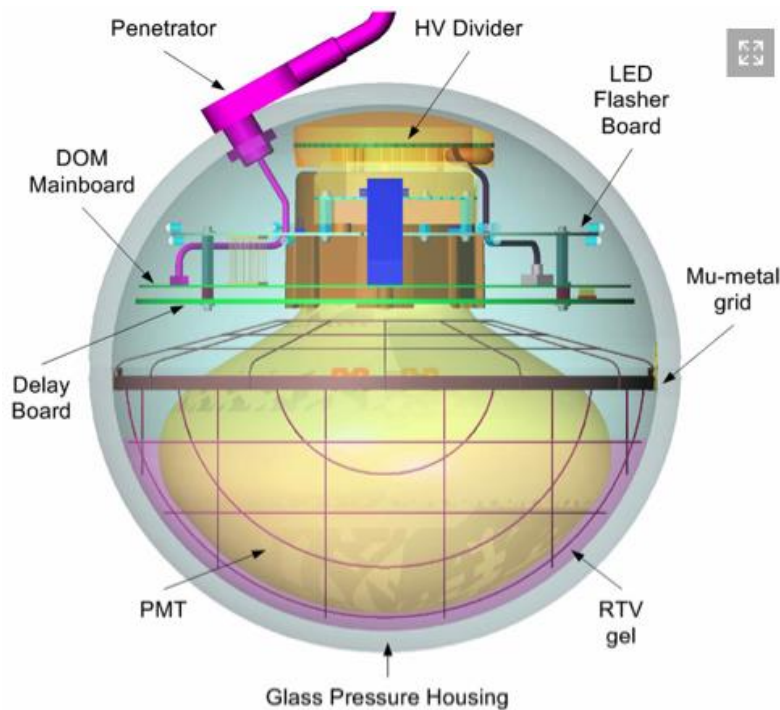


Labels: Penetrator, HV Divider, LED Flasher Board, DOM Mainboard, Mu-metal grid, Delay Board, PMT, RTV gel, Glass Pressure Housing



2717 ft.
828 m.
Burj Khalifa
Dubai

1815 ft.
553 m.
CN Tower
Toronto

7874 ft.
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*IceCube in Scale: The dashed lines above represent the portion of the cables that have DOMs attached*

# THE ICECUBE DETECTOR
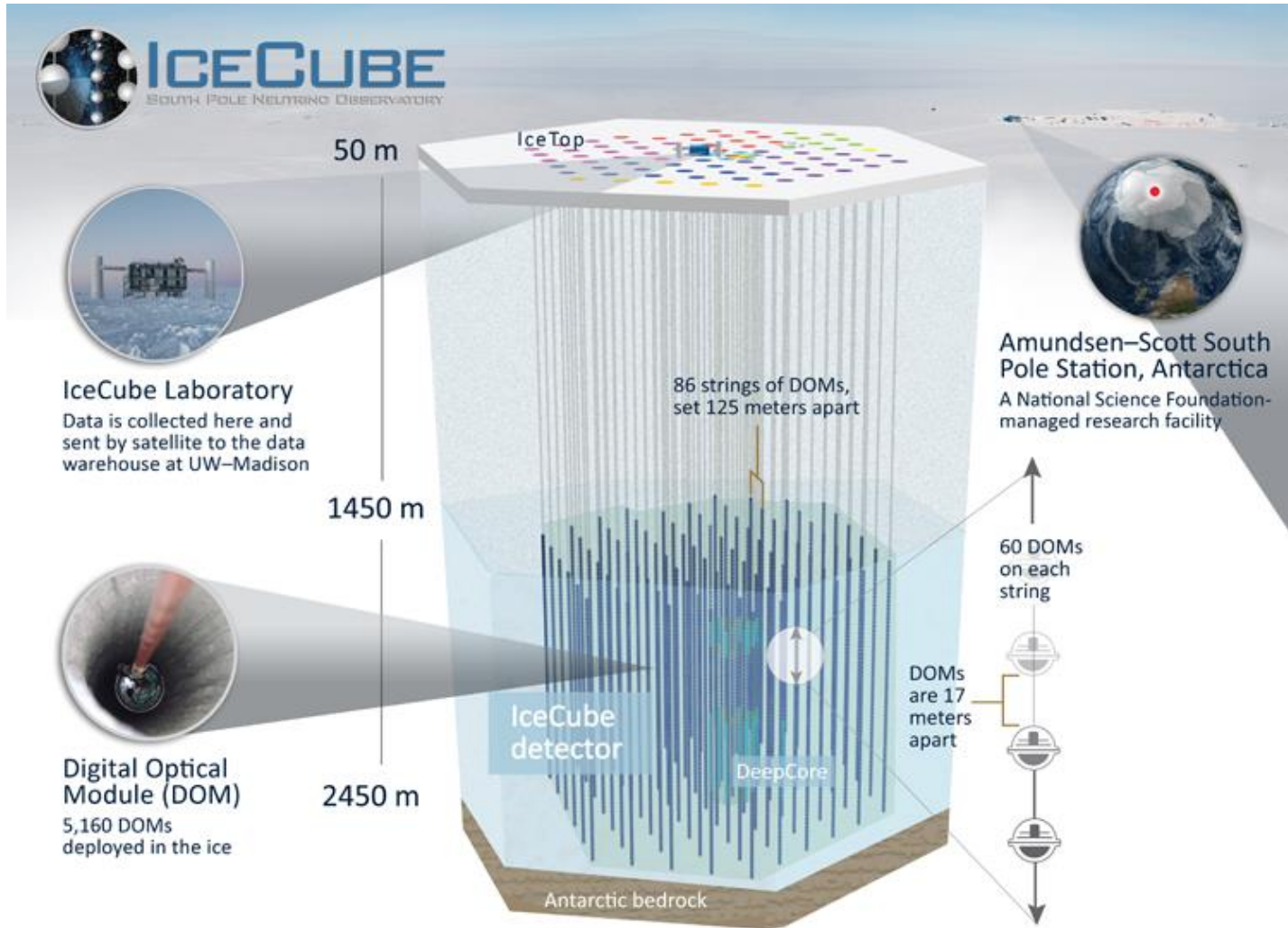
# ICECUBE PHYSICS

- Used to study extra-galactic, extremely high-energy sources.

    - Neutrinos, being nearly massless and without charge, are ideal messengers. They carry directional information.

    - Charged particles are bent by magnetic fields, neutrons decay before reaching the earth and high-energy photons are absorbed.

- E.g. gamma ray bursts: hadronic or electromagnetic origin?

- Can only be done in the South Pole!

- Vast, extremely clean ice; it's there for free!

    - Recall, detector constraints: cost and detector technology

# BERT, ERNIE AND MANY OTHERS

- In 2013, IceCube announced that it had detected 28 neutrinos likely originating from outside the Solar System.
  - These are ultra-high energy (**P**eV) neutrino events.
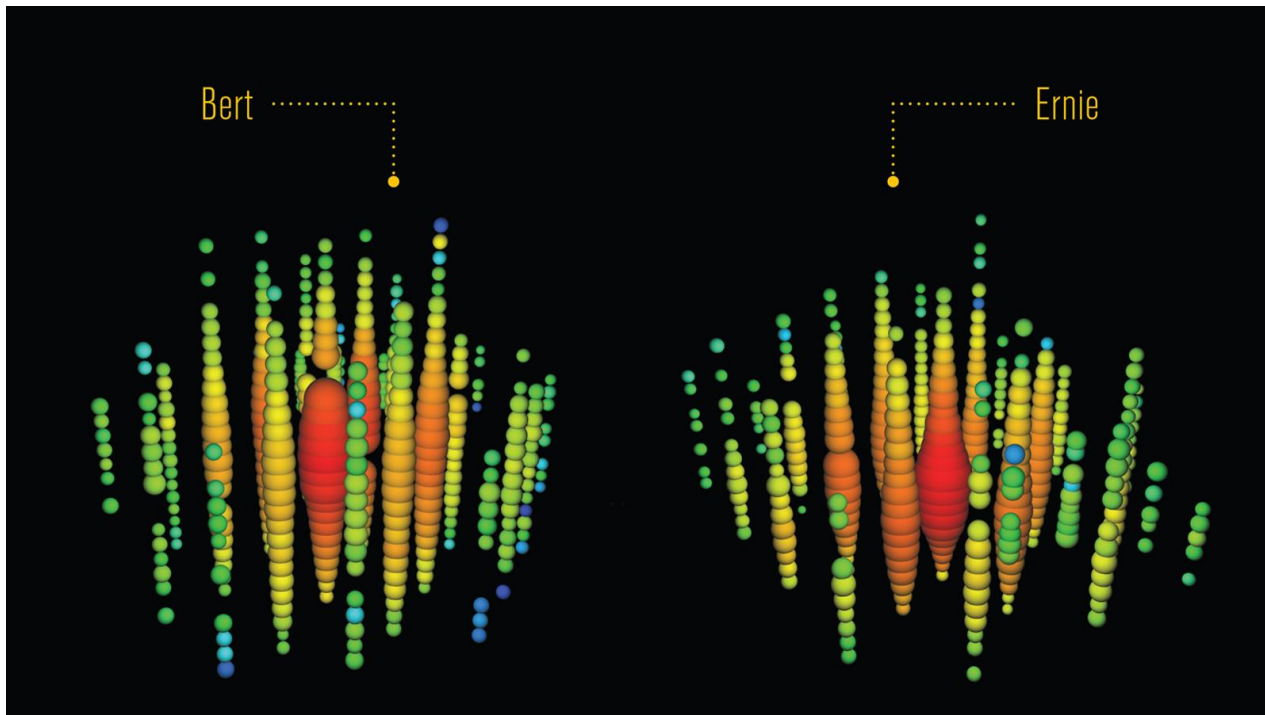
# THAT'S ALL FOR THIS WEEK

- Next week:

  - An overview of the Standard Model

BONUS

# THE ATLAS DETECTOR
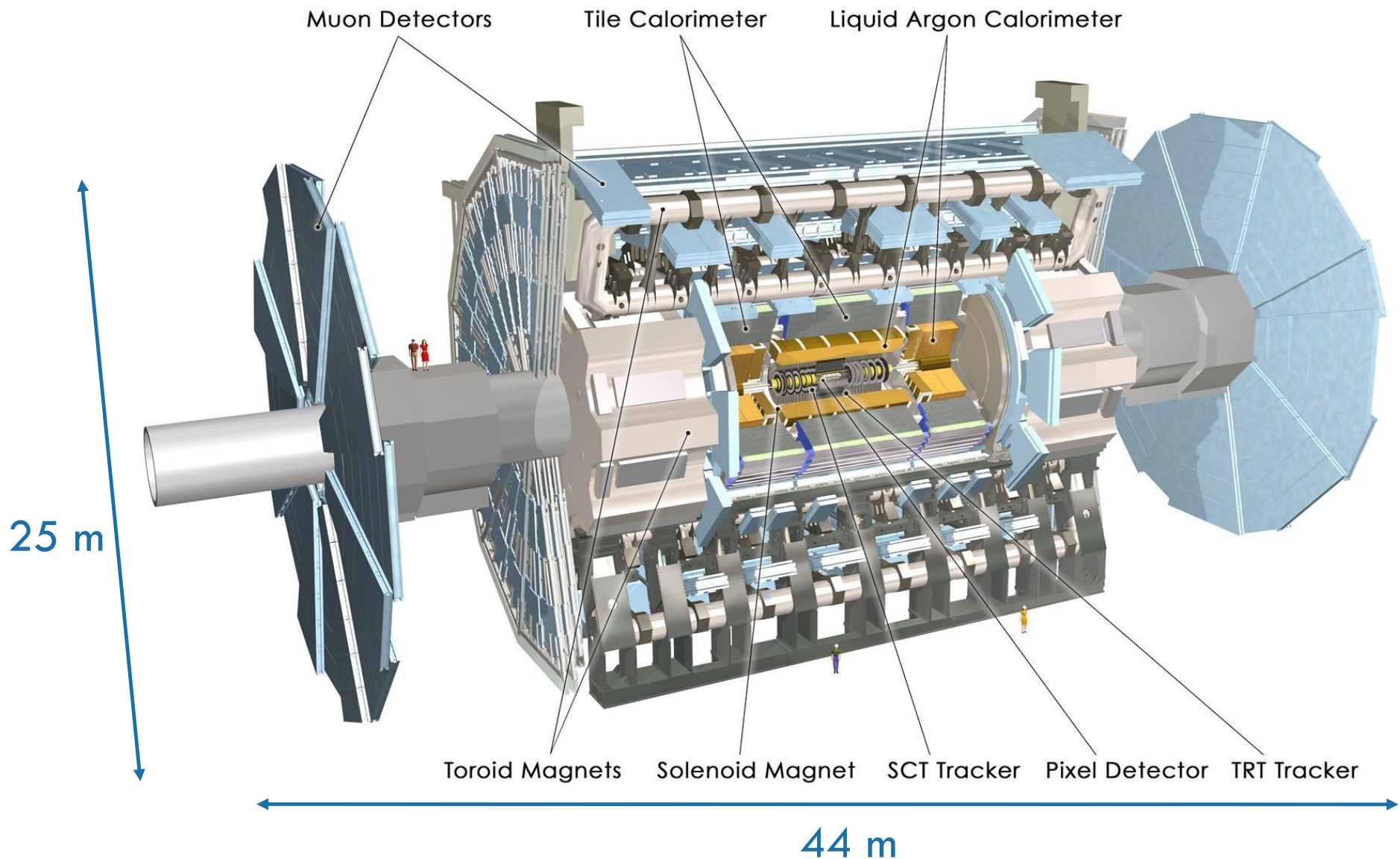


Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter

25 m

44 m

Toroid Magnets   Solenoid Magnet   SCT Tracker   Pixel Detector   TRT Tracker

# THE ATLAS DETECTOR

# THE ATLAS DETECTOR
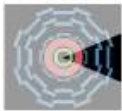
# SOLID-STATE DETECTORS

incident electrons

electron-holes pairs

Thin Au layer

Schottky junction

Depleted layer

E

N doped Silicon

N Substrate

detector current
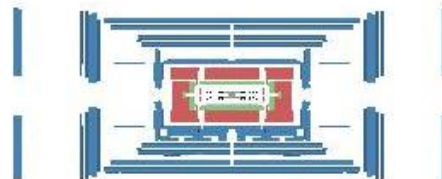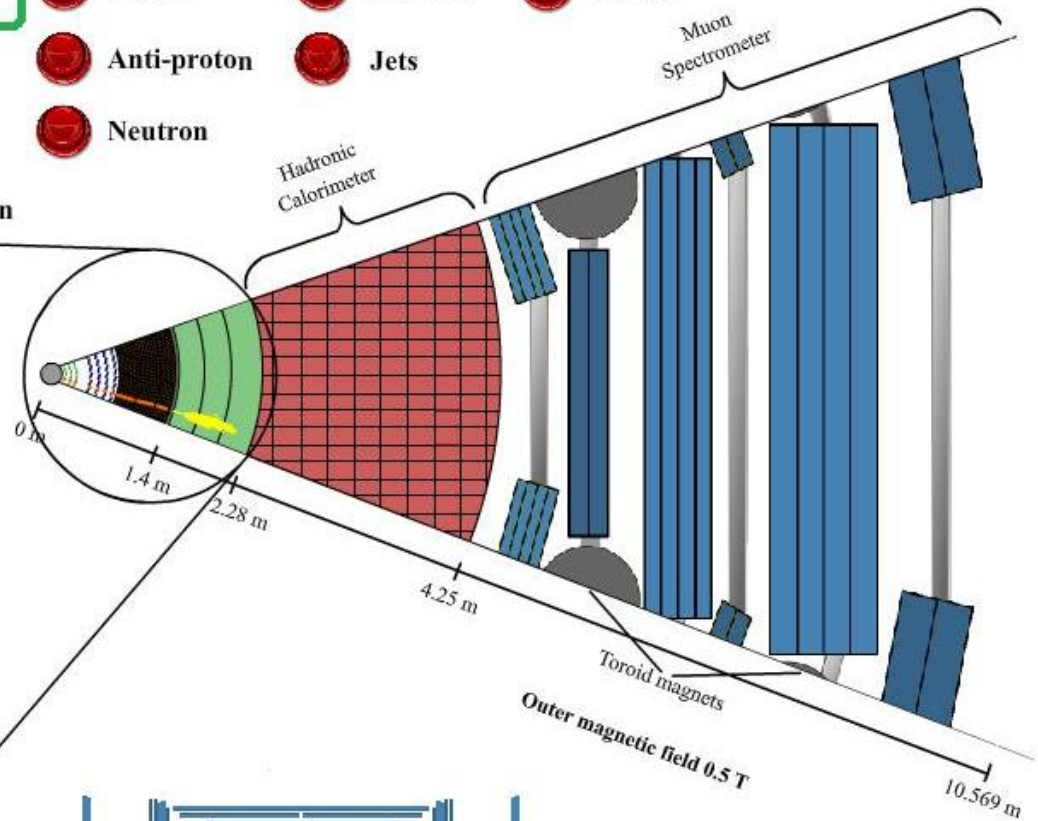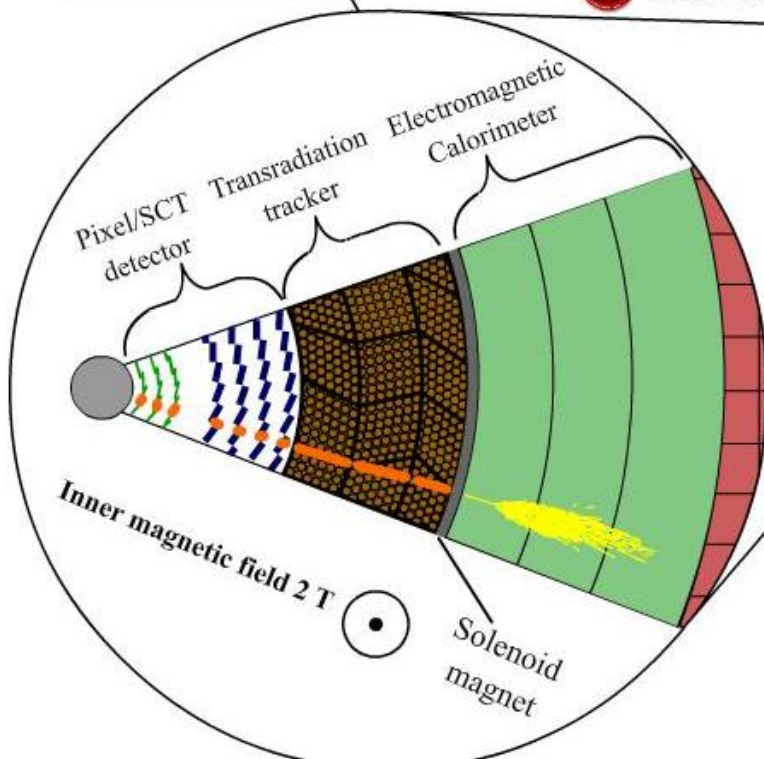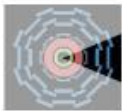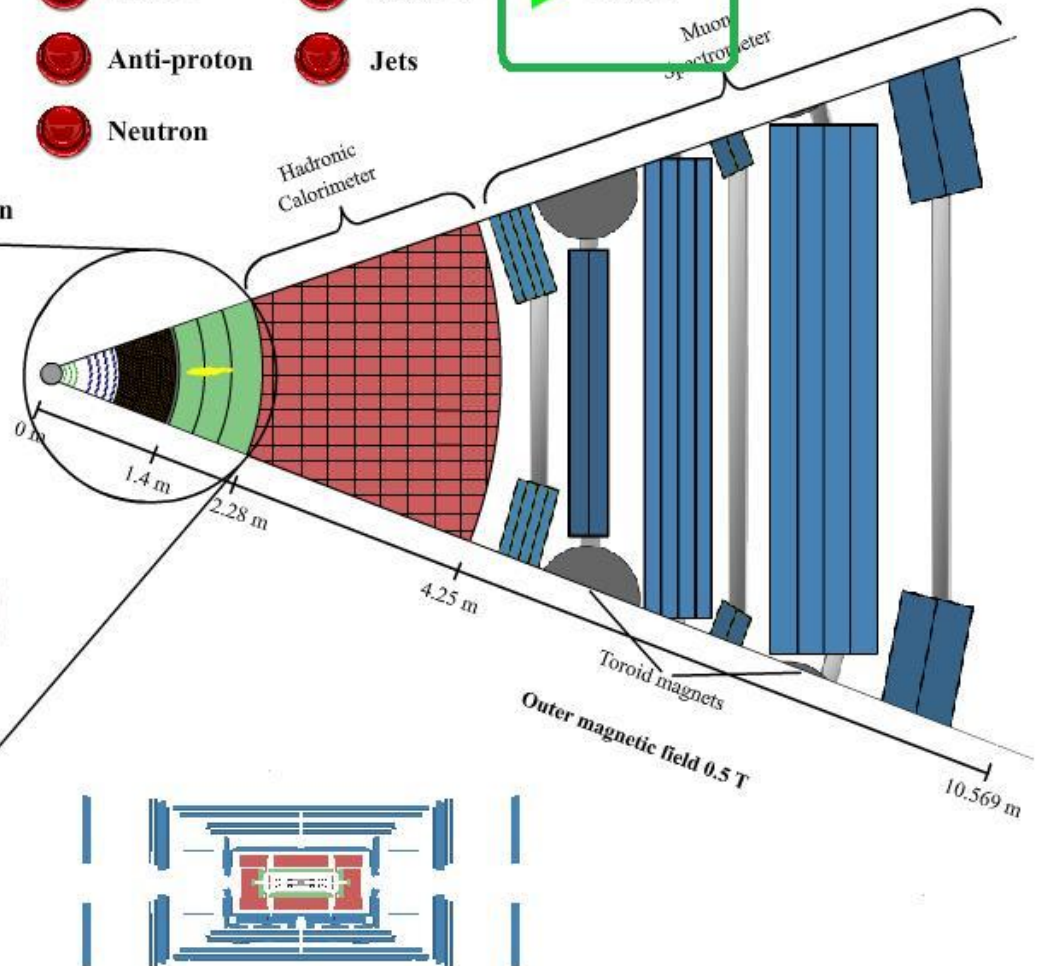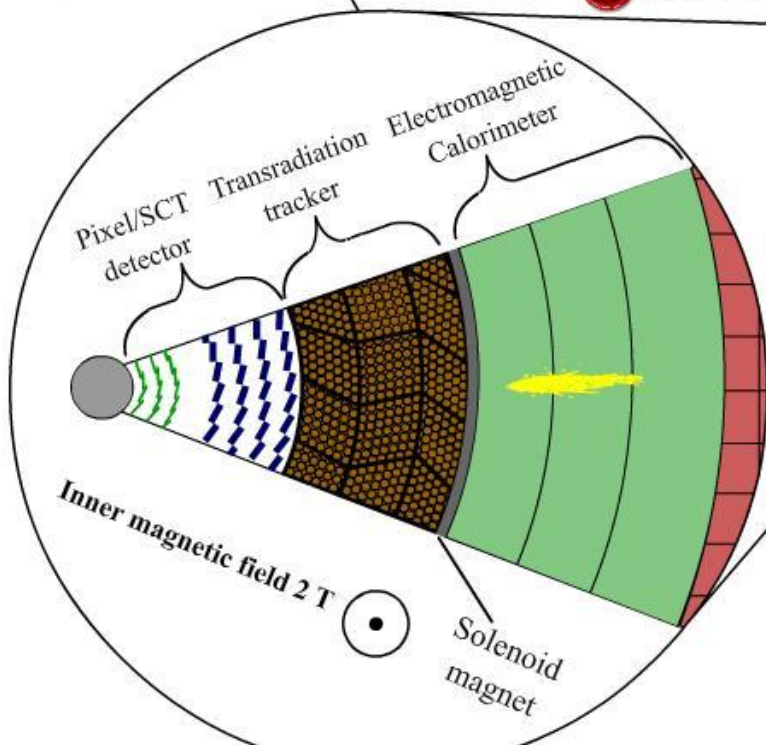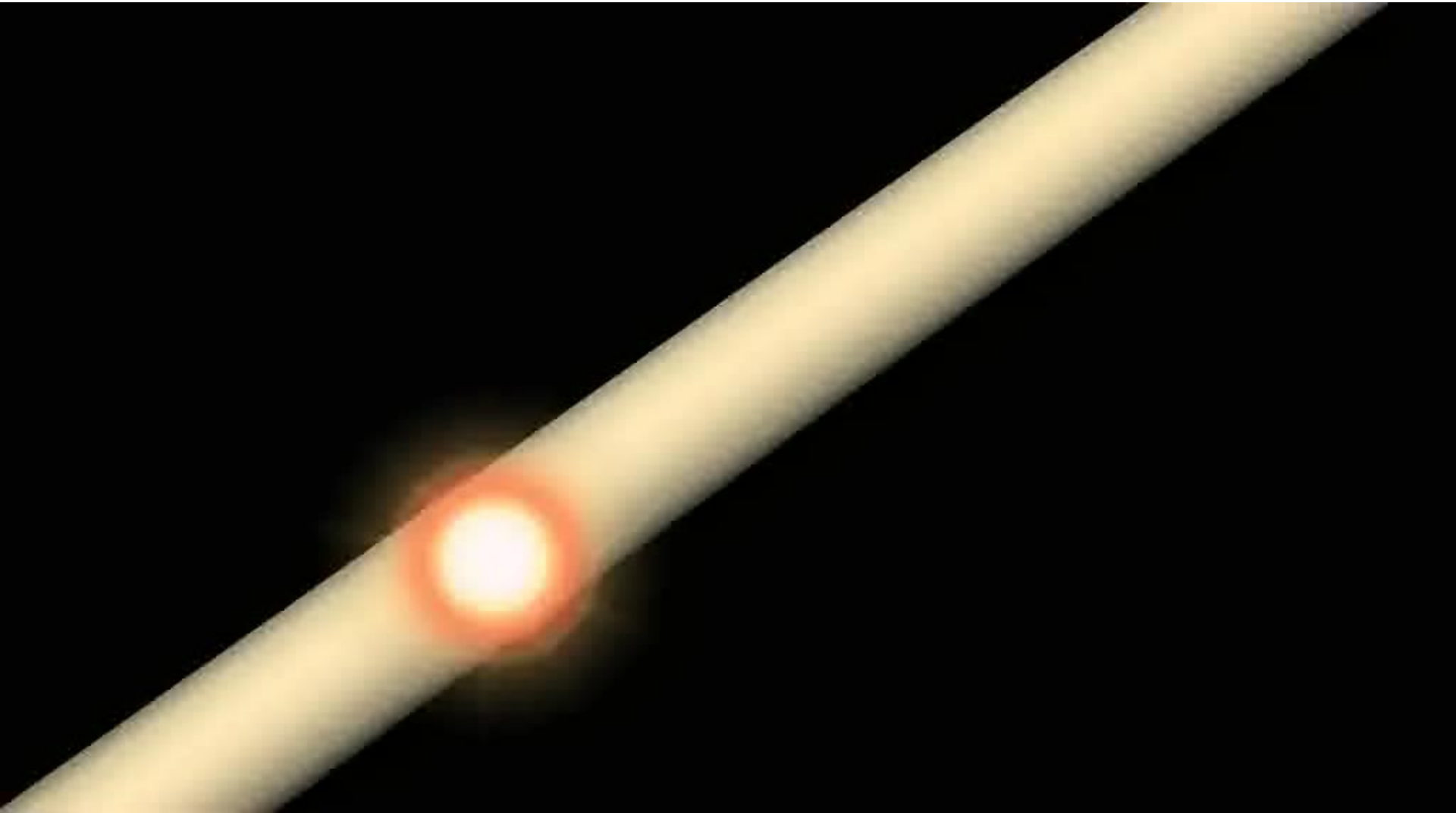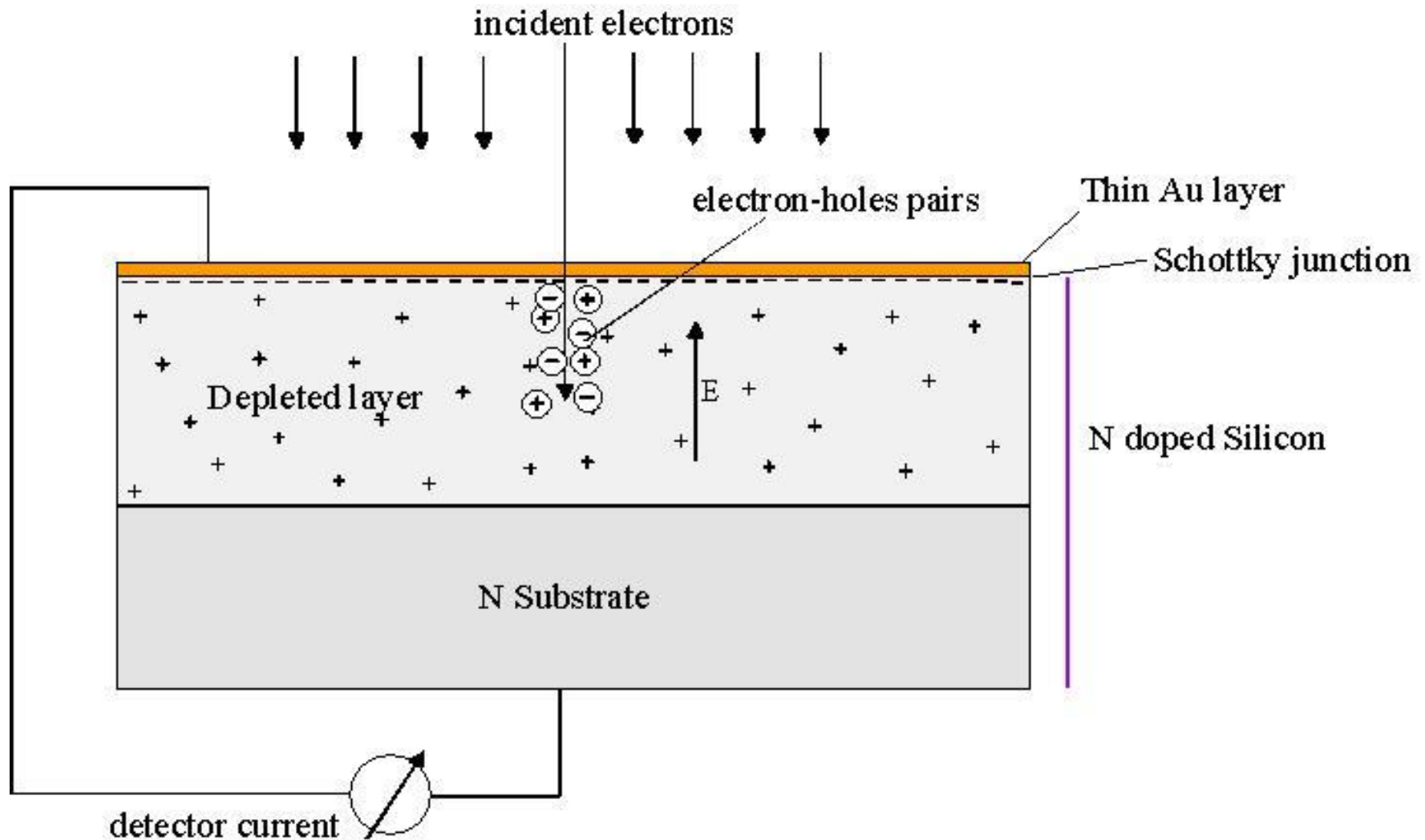
# SOLID-STATE DETECTORS
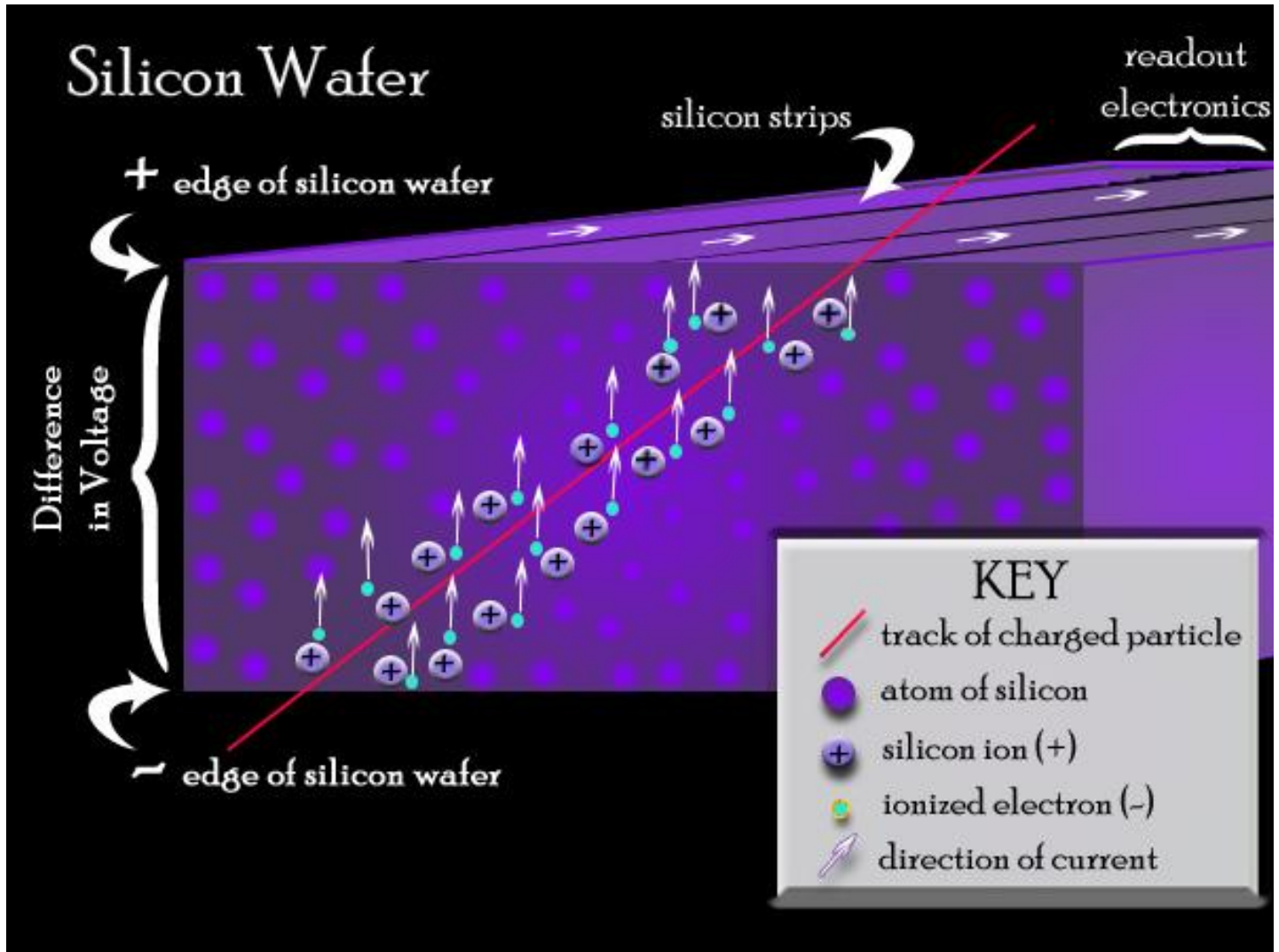
# PERTURBATION THEORY

- Use a power series in a parameter $\varepsilon$ (such that $\varepsilon << 1$) - known as perturbation series - as an approximation to the full solution.

- For example:

$$A = A_0 + \epsilon A_1 + \epsilon^2 A_2 + ...$$

- In this example, $A_0$ is the "leading order" solution, while $A_1$, $A_2$, … represent higher order terms.

- **Note:** if $\varepsilon$ is small, the higher-order terms in the series become successively smaller.

- Approximation:

$$A \approx A_0 + \epsilon A_1$$

# PERTURBATION THEORY IN QFT

- Perturbation theory allows for well-defined predictions in quantum field theories (as long as they obey certain requirements).

- Quantum Electrodynamics (QED) is one of those theories.

- Feynman diagrams correspond to the terms in the perturbation series!
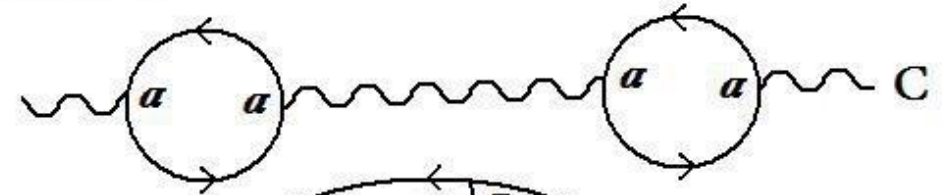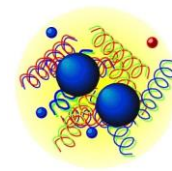
order 0:
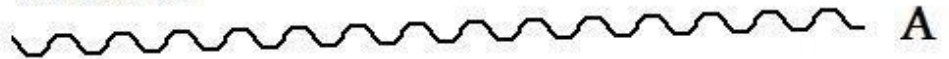
order 2:

order 4:
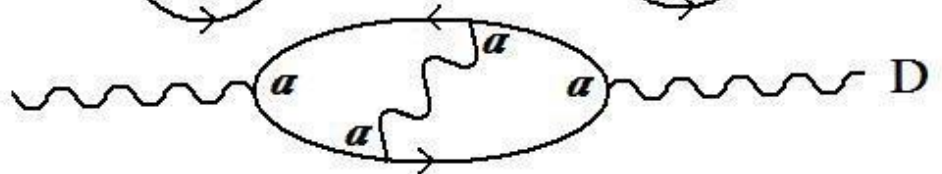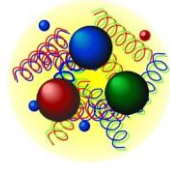
$$P = \quad A + B\,a^2 + (C + D)\,a^4 + \ldots$$

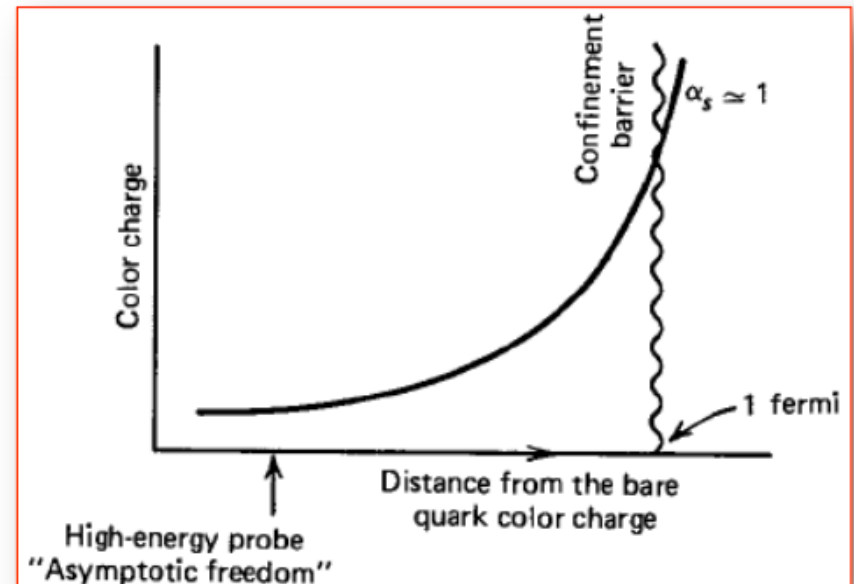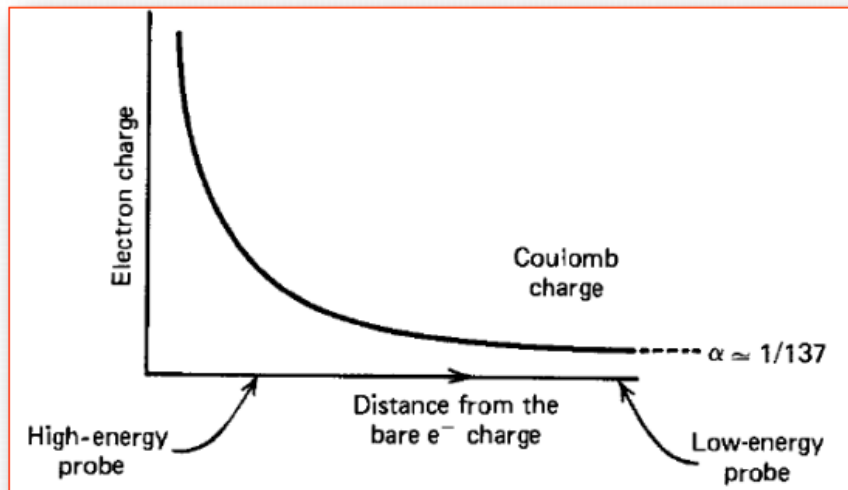Diagrams define a series in $a$

# QUANTUM CHROMODYNAMICS (QCD)

- Theory of strong interactions. Recall: gluons are the force carriers.

- Confinement: why we don't see free quarks.

- Asymptotic freedom: at very high energies, the interaction scale is smaller than at low energies, and we're in the perturbative regime.
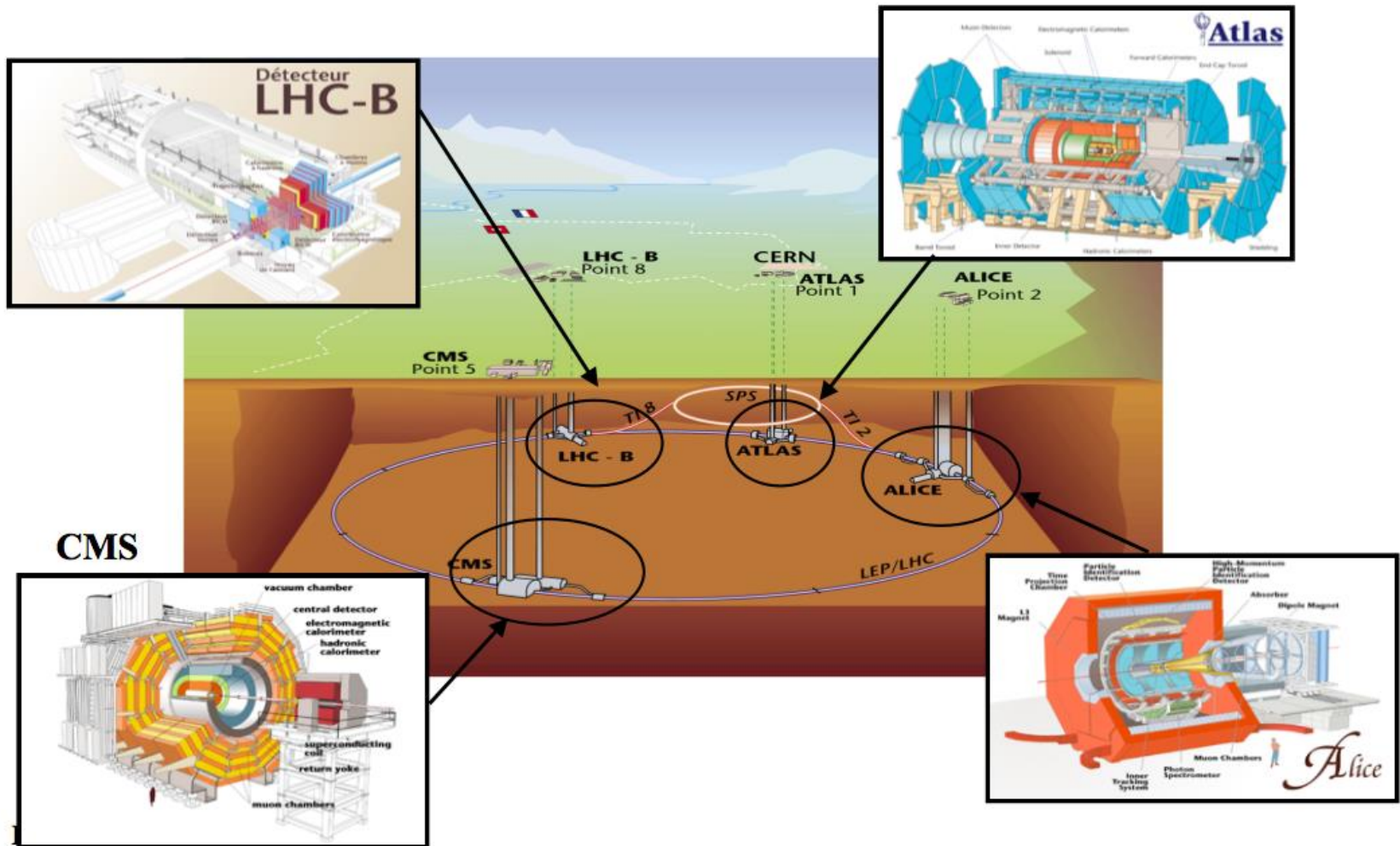


meson

baryon



Electron charge

Coulomb charge

$\alpha \simeq 1/137$

High-energy probe

Distance from the bare $e^-$ charge

Low-energy probe



Color charge

Confinement barrier

$\alpha_s \simeq 1$

1 fermi

High-energy probe "Asymptotic freedom"

Distance from the bare quark color charge

# COLLIDER EXPERIMENTS



LHC Experiments underground

# WHY BUILD THE LARGE HADRON COLLIDER?

- Large accelerator complex:

    - Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.

    - The LHC accelerates protons and heavy ions; older generation accelerators collided e.g protons - anti-protons, and electrons - positrons, …

- Why accelerate particles?

    - High beam energies ➡ high $E_{CM}$ ➡ more energy to create new particles!

    - Higher energies probe physics at shorter distances. De Broglie wavelength:

$$\frac{\lambda}{2\pi} = \frac{\hbar c}{pc} \approx \frac{197\,\mathrm{MeV\,fm}}{p\,[\mathrm{MeV/c}]}$$

        - e.g. 20 GeV/c probes a distance of 0.01 fm.

- An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.

# PROTON-PROTON COLLISIONS

- Quantum Chromodynamics theory is expressed in terms of quarks and gluons (partons)

    - We are colliding composite objects.

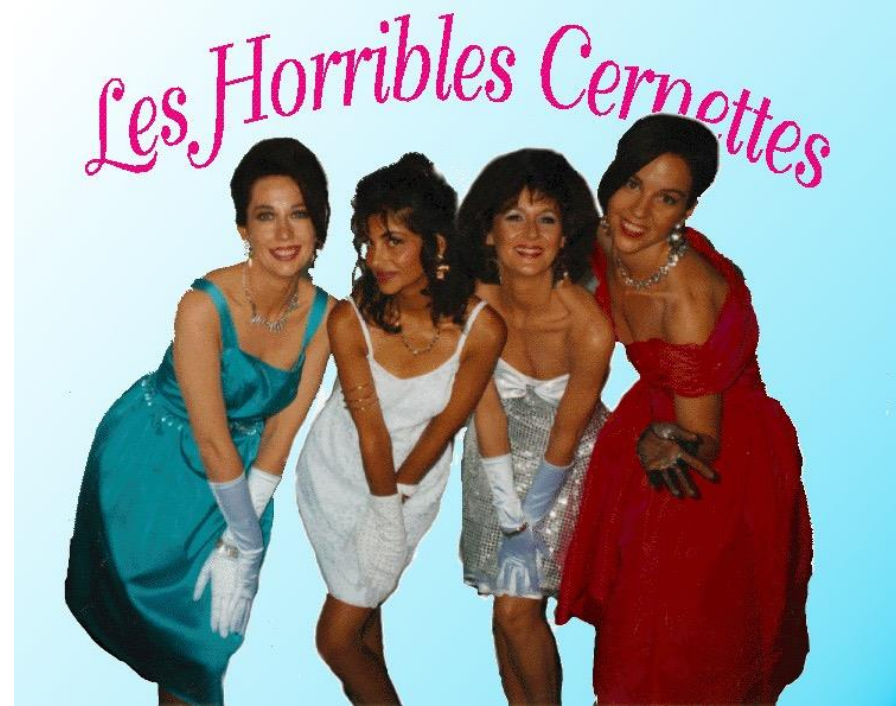- At the LHC energies, quarks and gluons collide and the actual collision energy is a fraction of the total:

$$\sqrt{\hat{s}} << \sqrt{s} = E_{\mathrm{cm}} = 2E_p$$
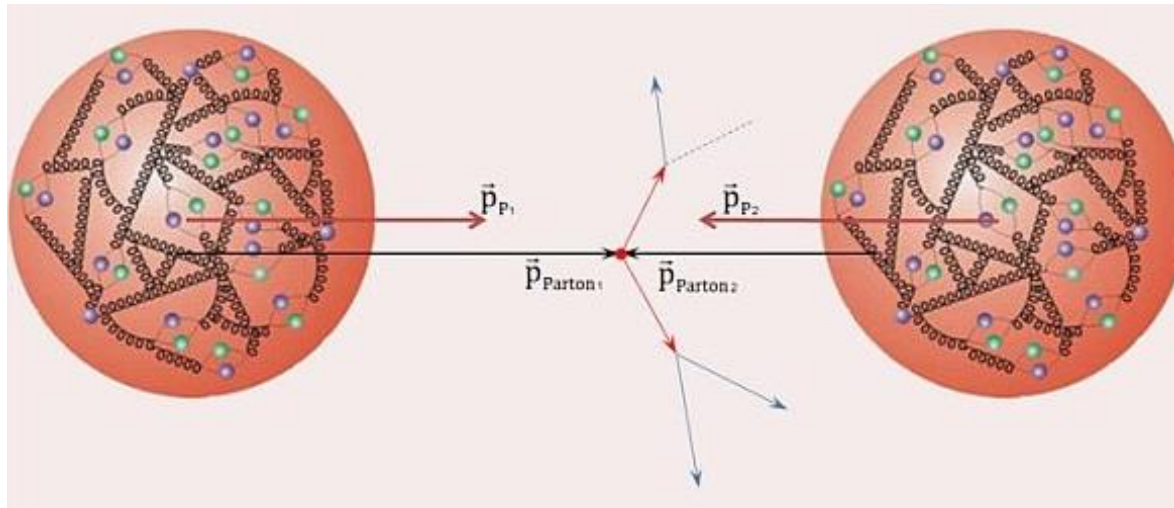
# CERN
## EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH





- Founded in 1954. Currently operates a network of six accelerators.

- A few of the scientific and computing achievements:

    - Neutral currents in Gargamelle bubble chamber

    - W/Z bosons in UA1 and UA2 experiments
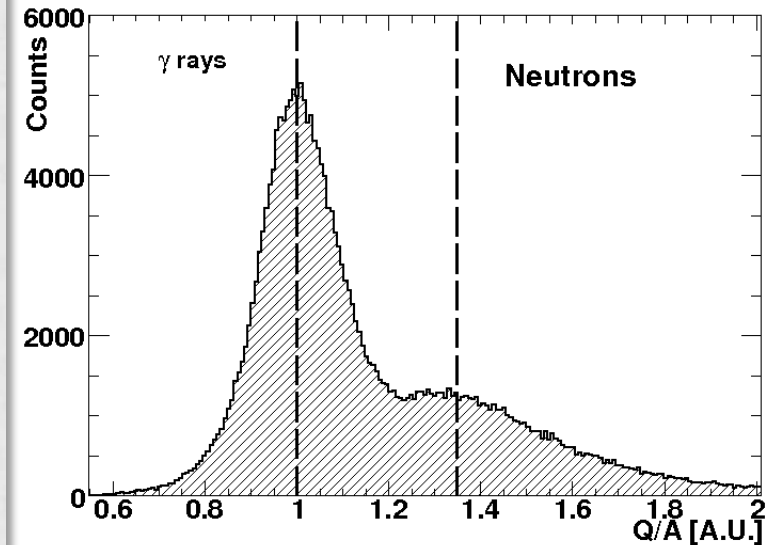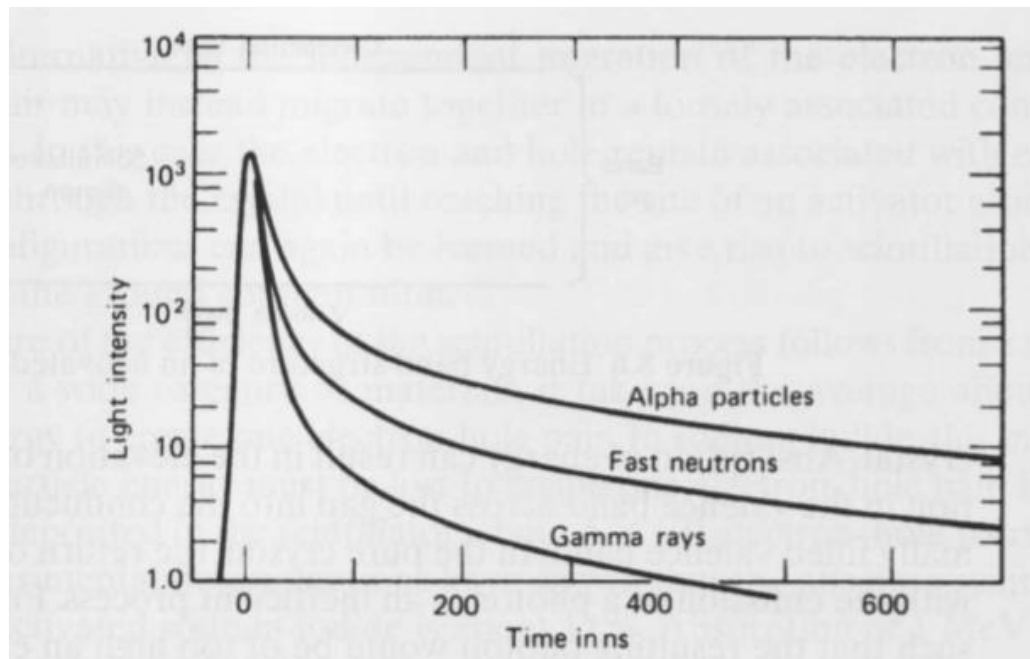
    - The World Wide Web!

# SCINTILLATION

- Depending on the particle dE/dx, the fast and slow states are occupied differently

- The relative intensities in the light output of these states depend on the ionizing particle type

- This property of scintillators allows for pulse shape discrimination: it is possible to identify which particle was detected by looking at the scintillation light times
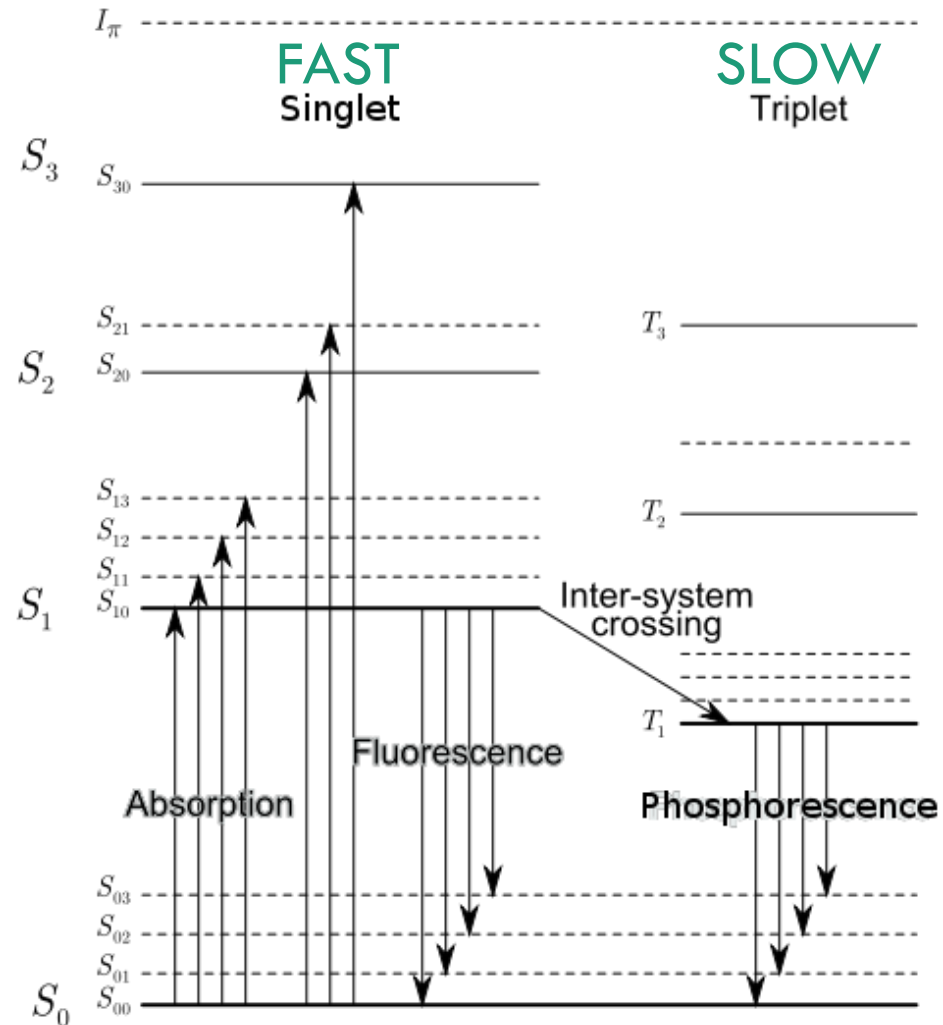
# SCINTILLATION

- Pulse shapes can be used to discriminate among different particle types:

# ASIDE
## A NOTE ABOUT CROSS-SECTIONS

- A measure of interaction probability in particle physics.

- "Effective area of collision"

- Used to calculate predicted interaction rates:

$$N = \Phi \times \sigma$$

**Interaction rate**
events/second

**Flux of incoming particles**
particles/cm$^2$/second

**Cross-section**
cm$^2$

# ASIDE
## A NOTE ABOUT CROSS-SECTIONS

- A measure of interaction probability in particle physics.

- "Effective area of collision"

- Used to calculate predicted interaction rates:

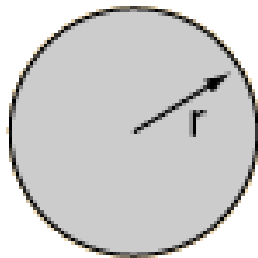$$N(E) = \Phi(E) \times \sigma(E)$$

**Interaction rate**
events/second

**Flux of incoming particles**
particles/cm$^2$/second

**Cross-section**
cm$^2$

# ASIDE
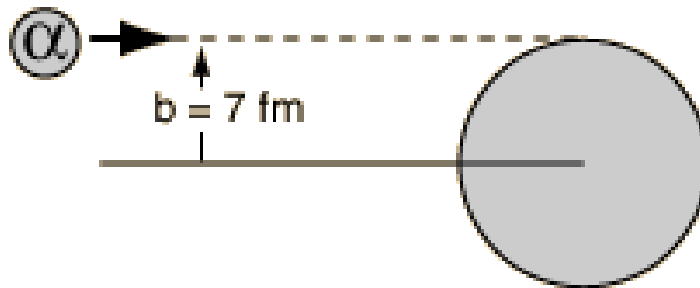## A NOTE ABOUT CROSS-SECTIONS

- Example:

$r = 7 \text{ fermi} = 7 \times 10^{-15} \text{ m}$

$A = \pi r^2 = 154 \text{ fermi}^2 = 1.54 \times 10^{-28} \text{ m}^2$

$A = 1.54 \text{ barns}$

$1 \text{ barn} = 10^{-28} \text{ m}^2 = 100 \text{ fm}^2$

Gold nucleus
Z=79, A=197

$b = 7 \text{ fm}$

A 6 MeV alpha particle approaching a gold nucleus with an impact parameter equal to the gold nuclear radius of 7 fm would be scattered through an angle of almost 140°. We would say that the cross section for scattering at or greater than 140° is 1.54 barns.

# ASIDE
## A NOTE ABOUT CROSS-SECTIONS

- Example:

- Rutherford worked out the scattering cross-section for alpha particles of kinetic energy KE scattering off a single nucleus with atomic number Z. The cross-section for scattering at a greater angle than some chosen angle is:

$$\sigma = \pi Z^2 \left( \frac{ke^2}{KE} \right)^2 \left( \frac{1 + \cos\theta}{1 - \cos\theta} \right)$$

Depends on chosen angle (geometric nature of cross-section).
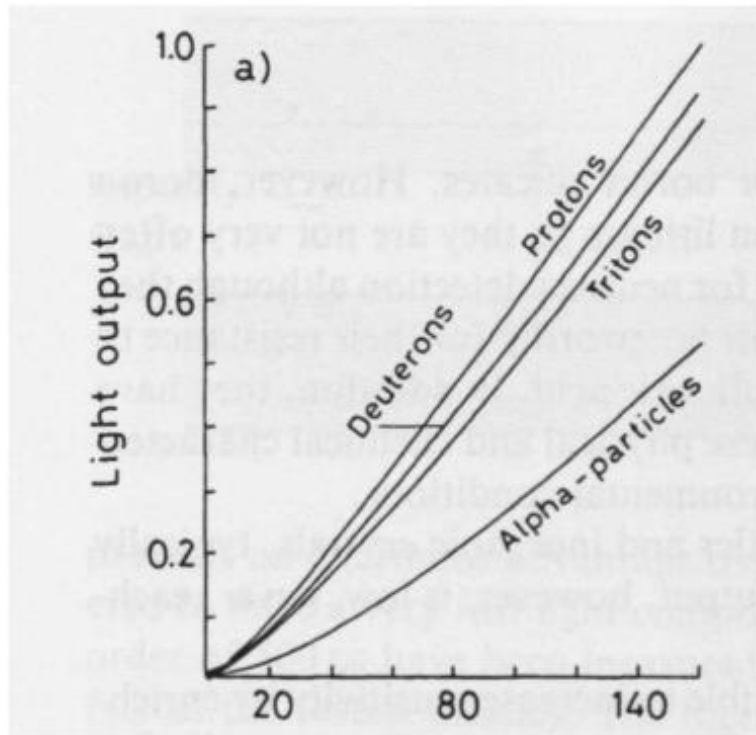Increases with $Z^2$, the number of protons in a nucleus.
Depends on k, the Coulomb force constant (strength of electromagnetic interaction).
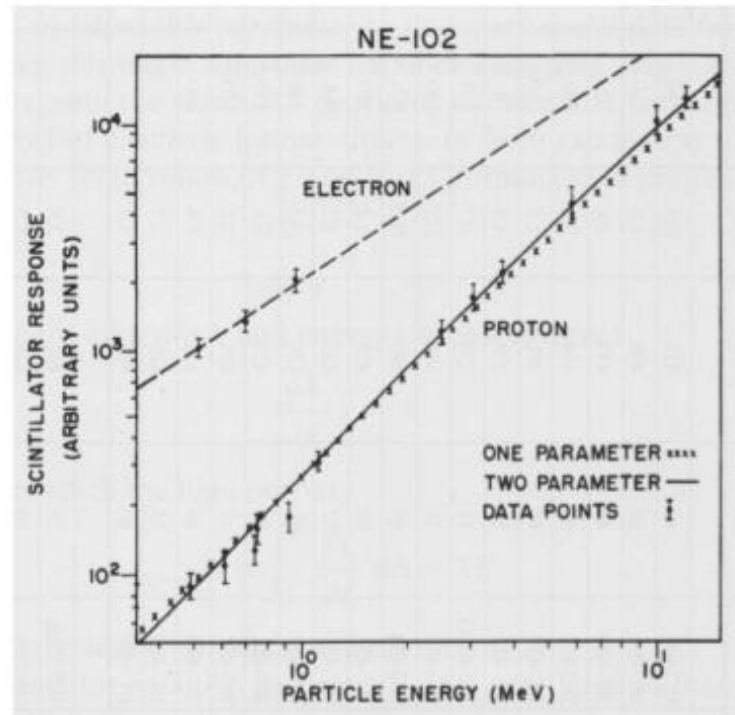Decreases with the kinetic energy squared ($KE^2$) of the incoming particle.

# SCINTILLATION DETECTORS
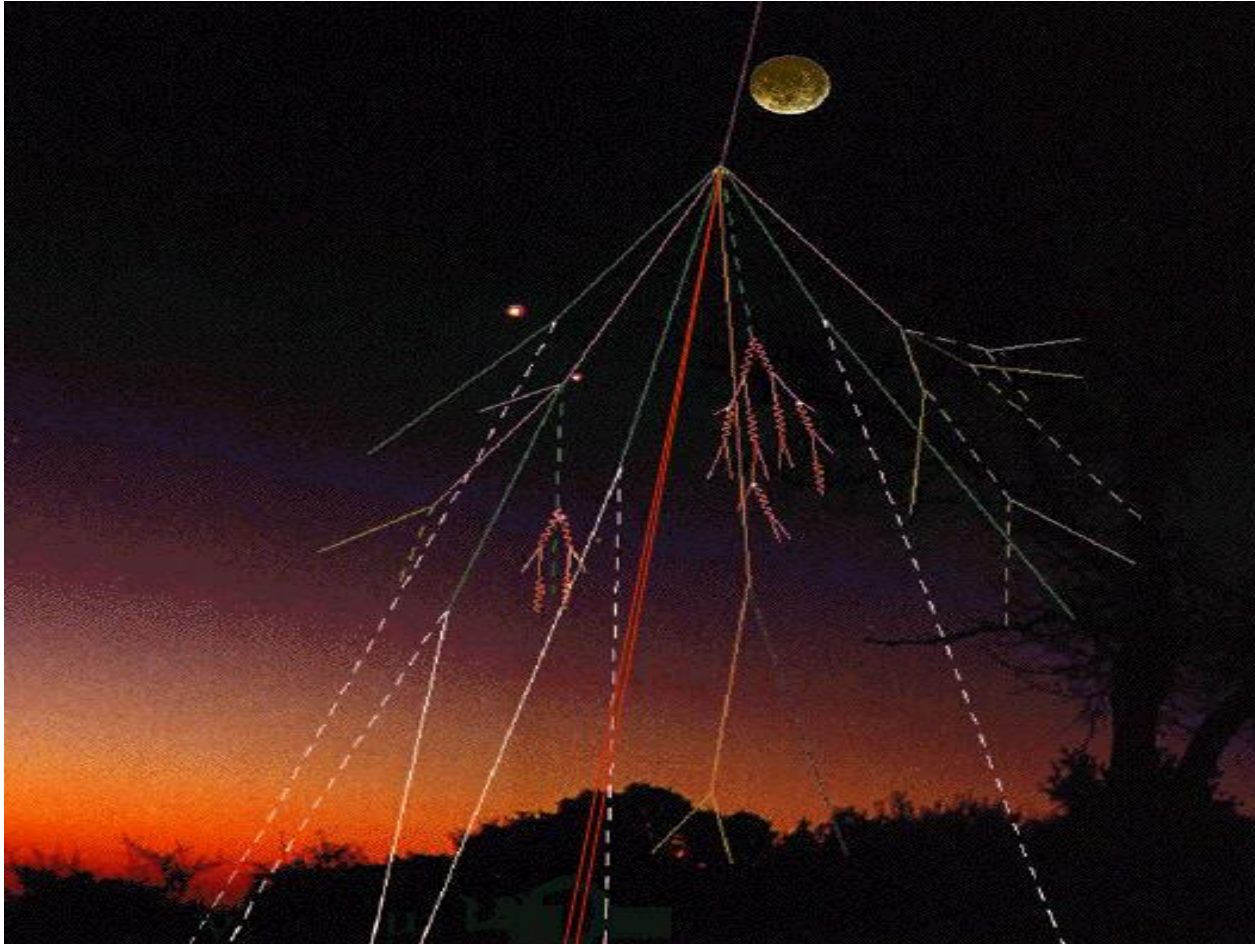
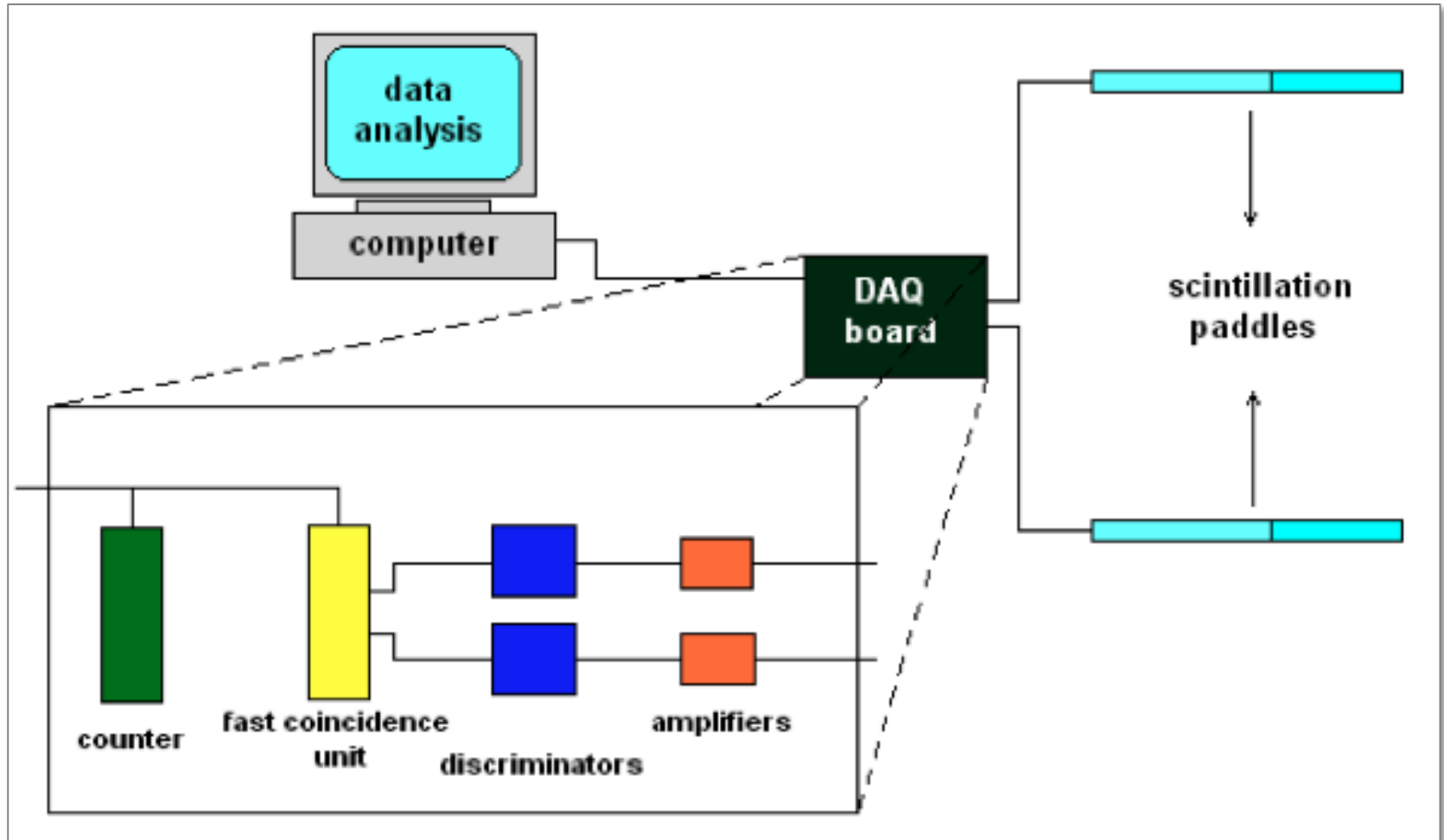- Light output and type of particles / radiation.



NE-102 = common plastic scintillator

# APPLICATION OF SCINTILLATION DETECTORS

- Cosmic ray muon detection

# COSMIC RAY MUON DETECTION
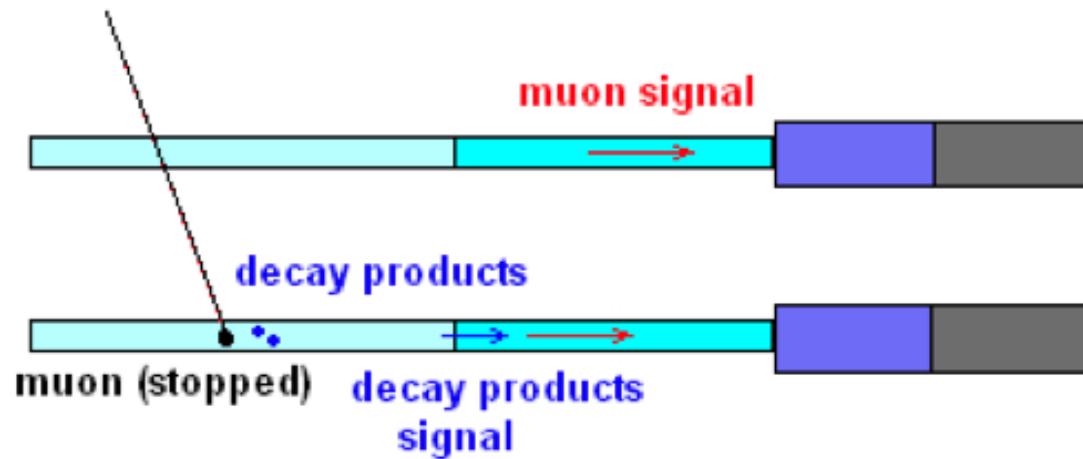
# COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime



muon signal

decay products

muon (stopped)    decay products signal

1. Measure $t_{decay}$ (difference between muon signal and decay signal in the second scintillator paddle) of a sample $N_0$ of low energy muons.

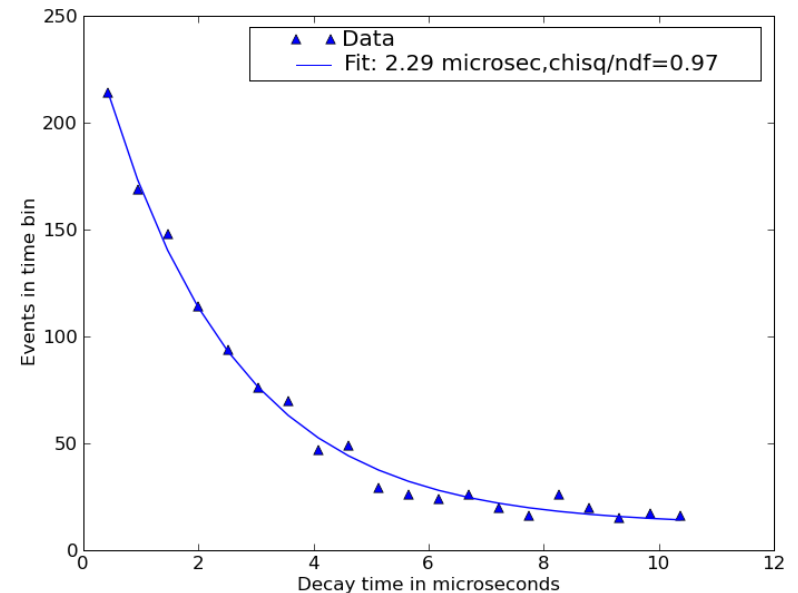2. Fit the data to an exponential curve of the form:

$$N(t) = N_0 e^{-t/T}$$

where $T$ = muon lifetime

# COSMIC RAY MUON DETECTION

- Measurement of the muon lifetime

Lifetime T:
T = 2.29μs
$T_{th}$ = 2.1970μs



1. Measure $t_{decay}$ (difference between muon signal and decay signal in the second scintillator paddle) of a sample $N_0$ of low energy muons.

2. Fit the data to an exponential curve of the form:

$$N(t) = N_0 e^{-t/T}$$

where T = muon lifetime