Basics of Particle Radiation Detectors

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Outlines

- Concept of particle radiation detection
- Passage of particles through matter
- Detector functionalities
  - Particle identification
  - Calorimeter
  - Tracking
- *Application of particle detection (if have time)*

Aim of this short lecture is to provide foundations/background for other relatively advanced lectures in particle detectors

Some textbooks and references

- References
  - Mark Thomson, "Modern Particle Physics"
  - Konrad Kleinknecht, "Detectors for particle radiation"
  - PDG https://pdg.lbl.gov/
    - "Passage of Particles Through Matter"
  - ...

Radiation: is the emission or transmission of energy in the form of waves or particles through space or a material medium

Includes:
Electromagnetic radiation
Particle* radiation
Acoustic radiation
Gravitational radiation

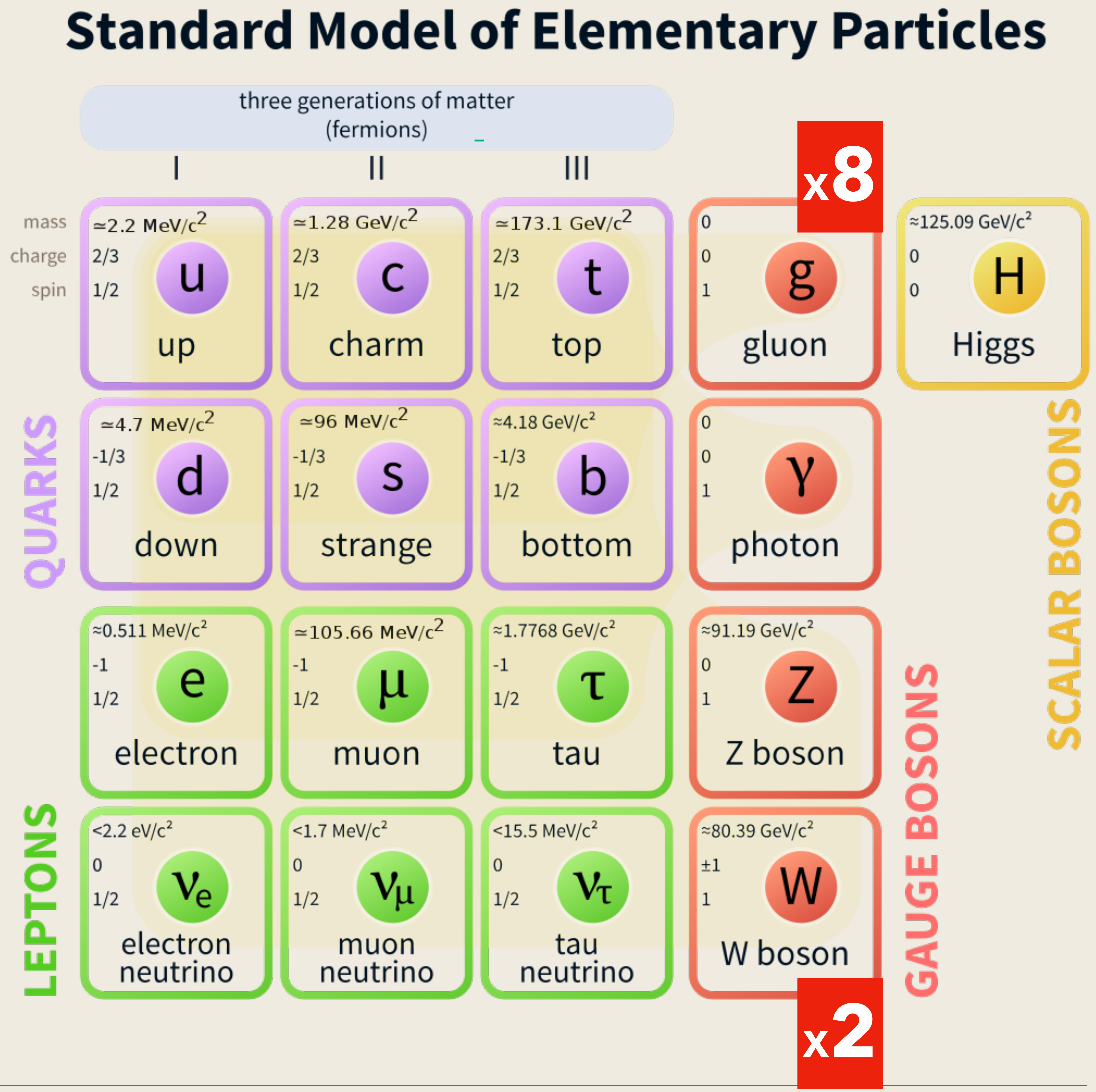
Particle* here is defined as non-zero rest energy/mass

Shortly use: Particle detector

"Periodic table" of elementary particle

Three central tasks of particle physics, so far:

- Identify all <u>elementary</u> particles → 25 particles (*and their anti-particle partners*)
- Understand how they interact with each other → **strong, weak, EM** force by exchanging corresponding *mediators*
- Theoretical model why Nature arrange in such way → follow gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$

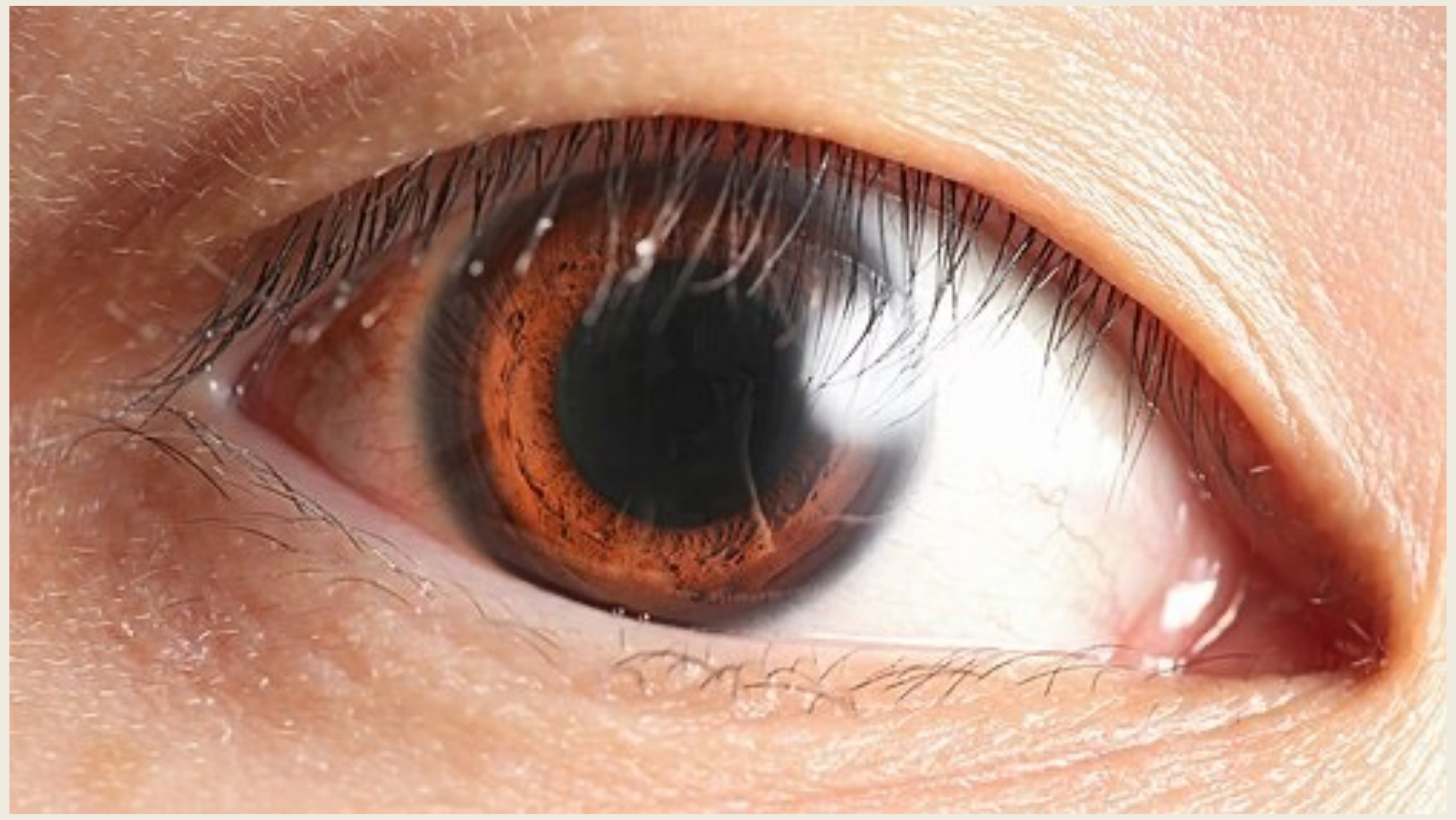


Particle detector is a *instrument (kind of classical device)* to detect, to track, and to identify the *particles (superposition of quantum states)*

- (Normally) Particle must reach detector to be observed
  - Produce some measurable signal via some *known* interaction with active detector materials
  - These signals are converted, processed, stored and analyzed

Essentially, need to know:

- Properties of particles and their interactions with matter
- Capability and functional limits of detectors



BIOLOGICAL PHOTODETECTOR

- Detect light in visible spectrum (*380-700nm*), peak around 555nm (*yellowish green*) in daylight
- Large dynamic range (~*1e6 time btw. the highest and lowest intensity can be seen*)
- Relatively slow response time (~ few tens of ms)
- Brains acts as an advanced image processor

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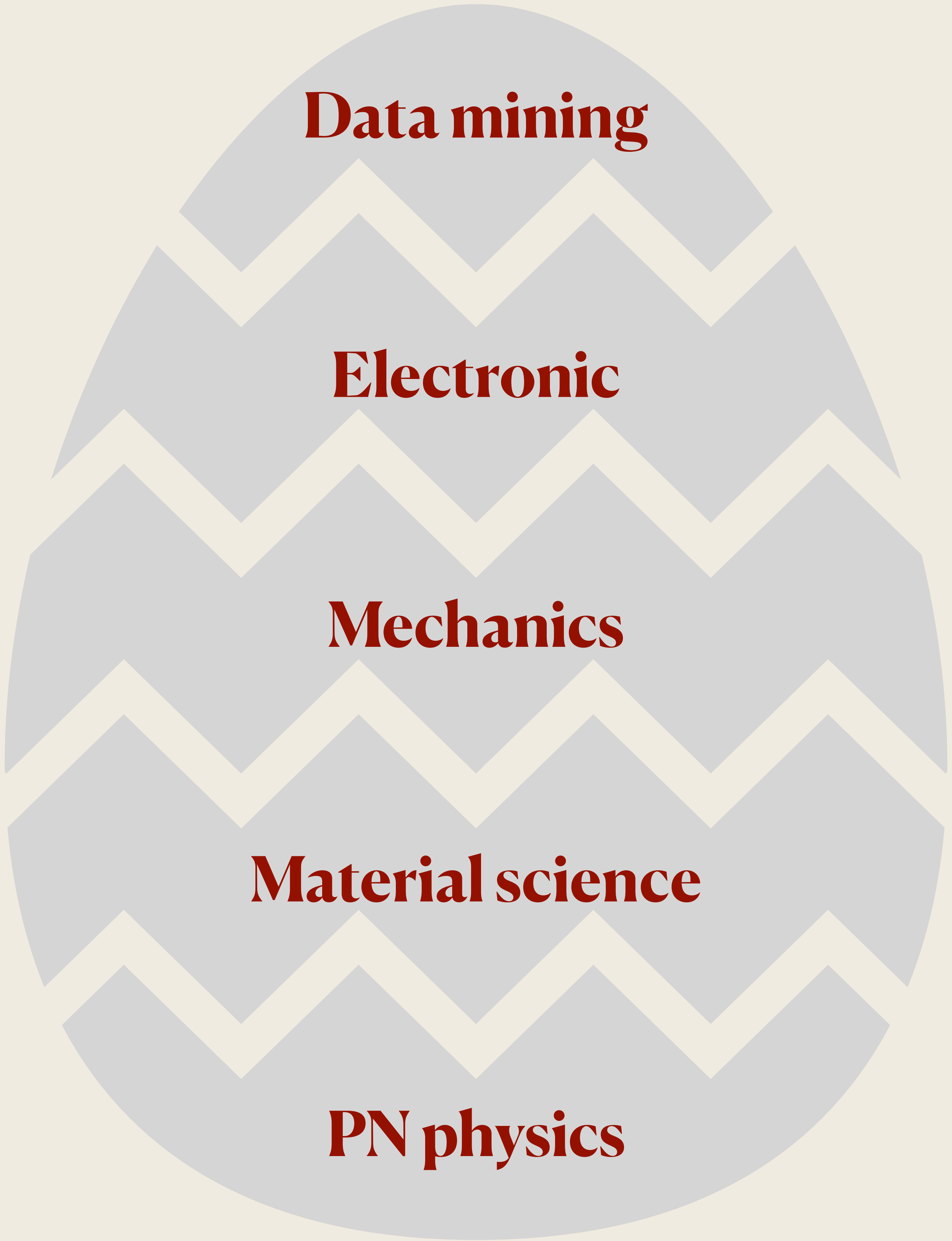
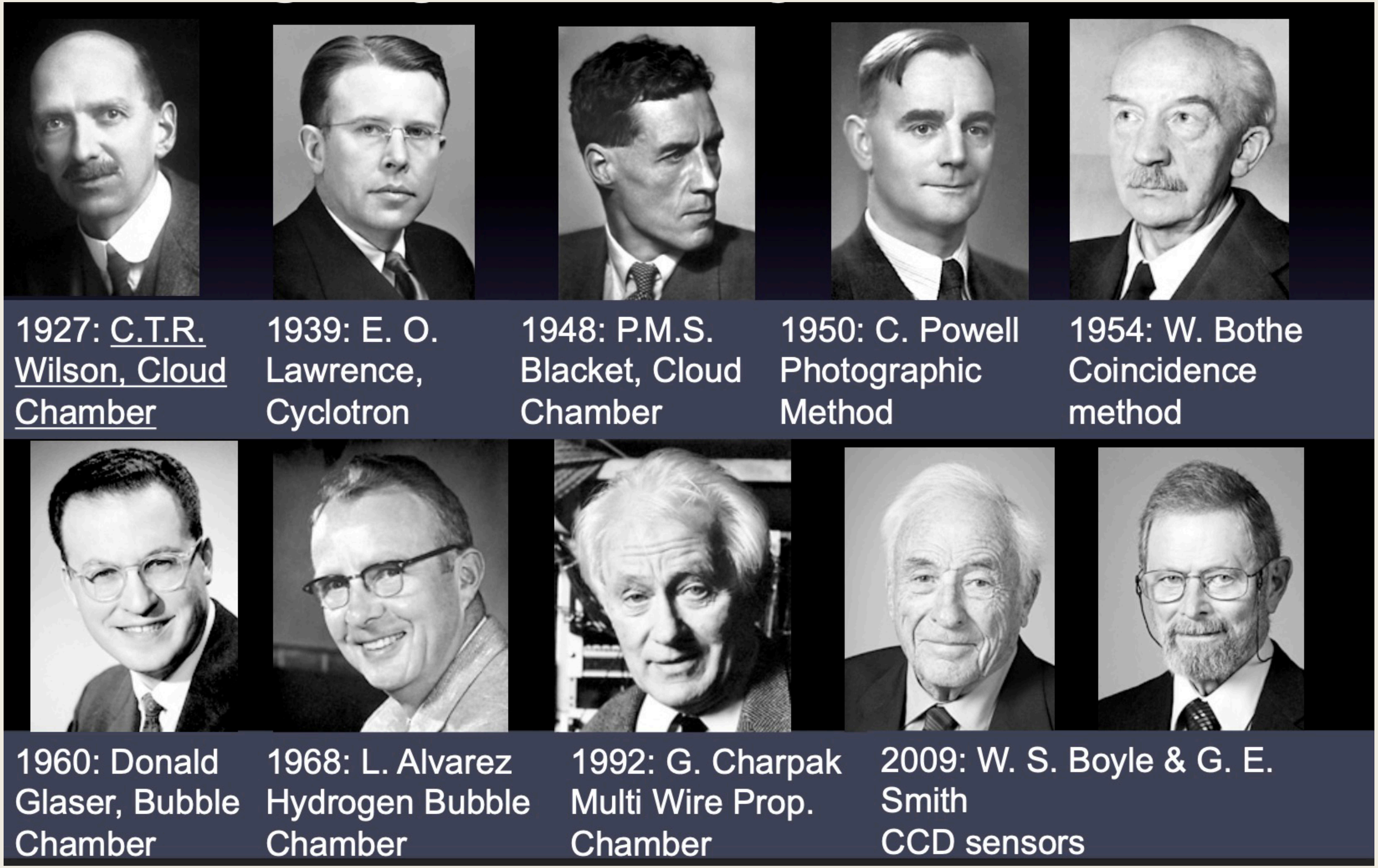


A complicate, interdisciplinary field

Nobel prize for instrumentation



“The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes”

~Marcel Proust~

“New directions in science are launched by new tools much more often than by new concepts”

~Freeman Dyson~

Useful relativistic relationships

MOST OF PARTICLES ARE RELATIVISTIC, DESCRIBED BY RELATIVISTIC QUANTUM MECHANICS & QUANTUM FIELD THEORY

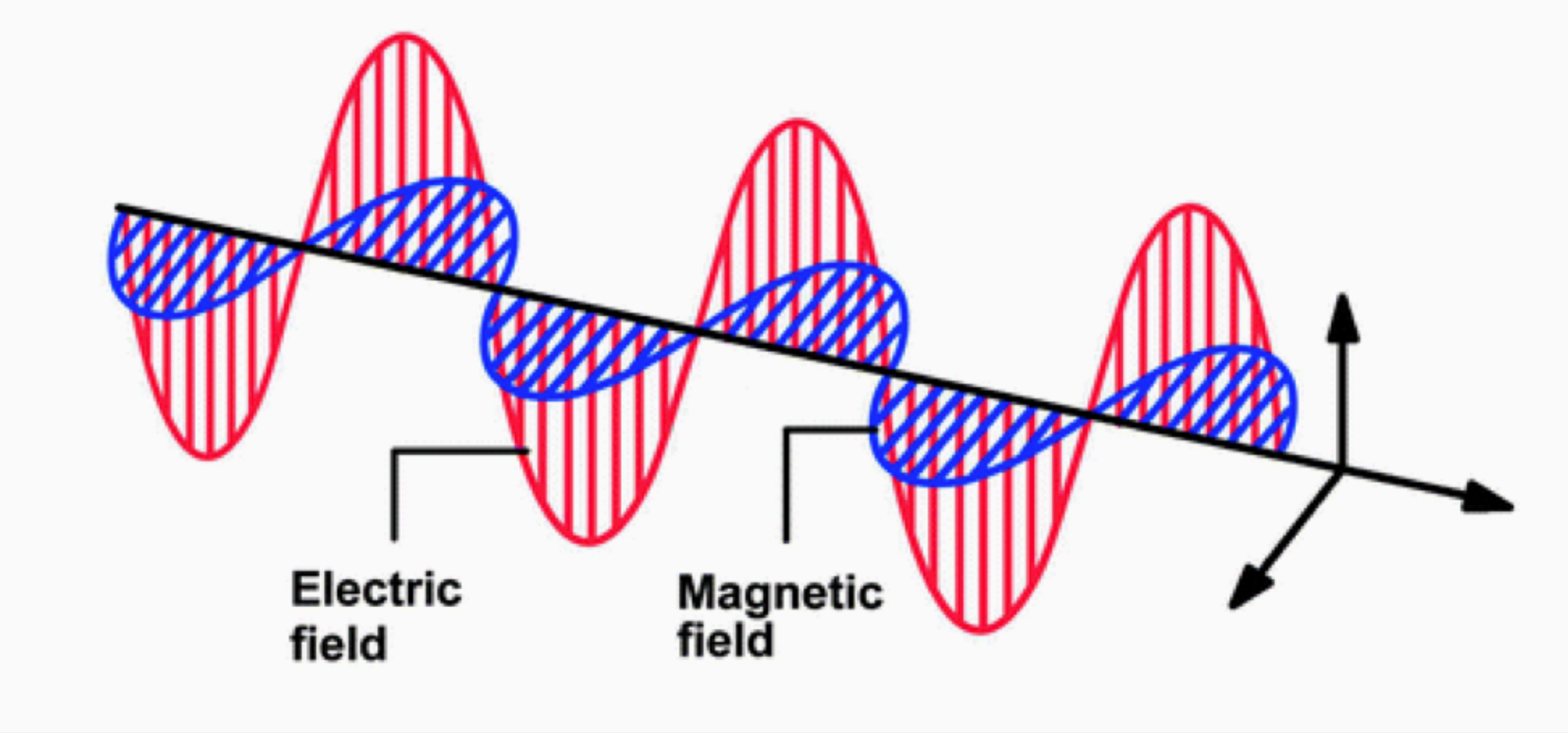
- $\beta = \dfrac{v}{c}\ (0 \leq \beta < 1);\ \gamma = \dfrac{1}{\sqrt{1 - v^2/c^2}} = \dfrac{1}{\sqrt{1-\beta^2}}\ (1 \leq \gamma < \infty)$
- Relativistic **mass** $m_r = \gamma m_0$
- Relativistic **momentum** $p_x = m_r v_x = \gamma m_0 v_x = \gamma m_0 \beta_x c$
- Relativistic **energy** $E = m_r c^2 = \gamma m_0 c^2$
- Relativistic momentum-energy relationship $E^2 = (pc)^2 + m_0^2 c^4$
- **Massless particle:** In the _classical mechanics_, *it is **nonsense** for the existence of massless particle*, however in _quantum mechanics (QM)_, it is allowed with the relation $E = pc$ for the free particle
  - *Special Relativity does not answer the question about **more or less energetic massless particle** but QM do* (related to wavelength/frequency $E = hf = \dfrac{hc}{\lambda}$)

Useful units

- **Energy** measured in eV: $1\ eV = 1.6 \times 10^{-19}\ J$
- **Momentum** measured in eV/c; **Mass** measured in eV/c^2
- Energy of LHC protons $E_{LHC} = 14 \times 10^{12}\ eV \approx 10^{-6}\ J$
- Energy of a **800kW-power proton beam**:
  - Computed from *2.26e14 of 30GeV protons per 1.36s*
  - **Total energy** $E_{tot.} = 2.3 \times 10^{14} \times 30 \times 10^9 = 6.9 \times 10^{24}\ eV \approx 1.1 \times 10^6\ J$
    - **Power**: $P = E_{tot.}/T = 1.1 \times 10^6\ J/1.36\ s \approx 800kW$
  - **Car** mass is $\approx 2 \times 10^3\ kg$; speed at 120 $km/h \approx 33\ m/s\ \rightarrow E_{kin.} \approx 1 \times 10^6\ J$

Quantity	[kg, m, s]	[$\hbar$, c, GeV]	$\hbar = c = 1$
Energy	kg m^2 s^{-2}	GeV	GeV
Momentum	kg m s^{-1}	GeV/c	GeV
Mass	kg	GeV/c^2	GeV
Time	s	$(\mathrm{GeV}/\hbar)^{-1}$	GeV^{-1}
Length	m	$(\mathrm{GeV}/\hbar c)^{-1}$	GeV^{-1}
Area	m^2	$(\mathrm{GeV}/\hbar c)^{-2}$	GeV^{-2}

Energy of photon: useful conversion



$$\nabla^2 E - \mu_0\epsilon_0 \frac{\partial^2 E}{\partial t^2} = 0$$

$$\nabla^2 B - \mu_0\epsilon_0 \frac{\partial^2 B}{\partial t^2} = 0$$

$E_{photon} = hf$ where $h = 6.626 \times 10^{-34} Js$

Energy of relativistic particle is expressed in eV, keV…

$$E_{photon} = hf = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34}[Js] \times 2.998 \times 10^{8}[m/s]}{10^{6}\lambda[\mu m]} = \frac{19.865 \times 10^{-20}[J]}{\lambda[\mu m]}$$

$\lambda_{\text{blue}} = [0.45 - 0.50][\mu m]$

$$E_{photon} = \frac{19.865 \times 10^{-20}[eV]}{1.602 \times 10^{-19}\lambda[\mu m]} \approx \frac{1.24[eV]}{\lambda[\mu m]}$$

$E_{\text{blue}} = [2.48 - 2.76][eV]$

Difficulty to observe a single photon?

$$E_{photon} = hf \text{ where } h = 6.626 \times 10^{-34} Js$$

A 405nm LED has optical power of 6mW, how many photons emitted in a second ?

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}[m/s]}{405 \times 10^{-9}[m]} = 7.4 \times 10^{14}[s^{-1}] = 7.4 \times 10^{14}[Hz]$$

Number of photons emitted per second

$$n_{photon} = \frac{6 \times 10^{-3}[W] \times 1[s]}{6.626 \times 10^{-34}[Js] \times 7.4 \times 10^{14}[s^{-1}]} = 1.2 \times 10^{15}$$

Wanna see single photon level ➜ must suppress ambient light

Build a particle detector?

- For what?
- Involved particles? and their signature ?

Questions to ask before building a detector

- What's the **motivation**?
- What's the **signal/messenger** ?
  - *Potential background and estimated signal-to-background ratio*
- What's **kind of information** you need
  - *It directly relates to the detection technique*
- What's the **appropriate technique the detect**
  - *Different techniques may have different background*
- What's the possibly observed **signal frequency** (*maximum and minimum*)
  - *Related to the signal rate itself, cross-section, detection efficiency, detector size…*
- What's requirement for **temporal and spacial (*directional*) resolution of the signal**?
  - Known or unknown signal sources? Know or unknown arrival time?
- Where's the **best place to put detector**?
  - One detector is sufficient? On the earth or orbit?
- Of course considering the **cost, maintenance, long-term operation**…
- ….

Driven mainly by curiosity

NEUTRINO PHYSICS

1. Where and what is dark matter?
2. How massive are neutrinos?
3. What are the implications of neutrino mass?
4. What are the origins of mass?
5. Why is there a spectrum of fermion masses?
6. Why is gravity so weak?
7. Is Nature supersymmetric?
8. Why is the Universe made of matter and not antimatter?
9. Where do ultrahigh-energy cosmic rays come from?
10. Did the Universe inflate at birth?

TEN NATURE'S GREATEST PUZZLES

Posed by Chris Quigg, 20 years ago, still waiting for the answers!!!

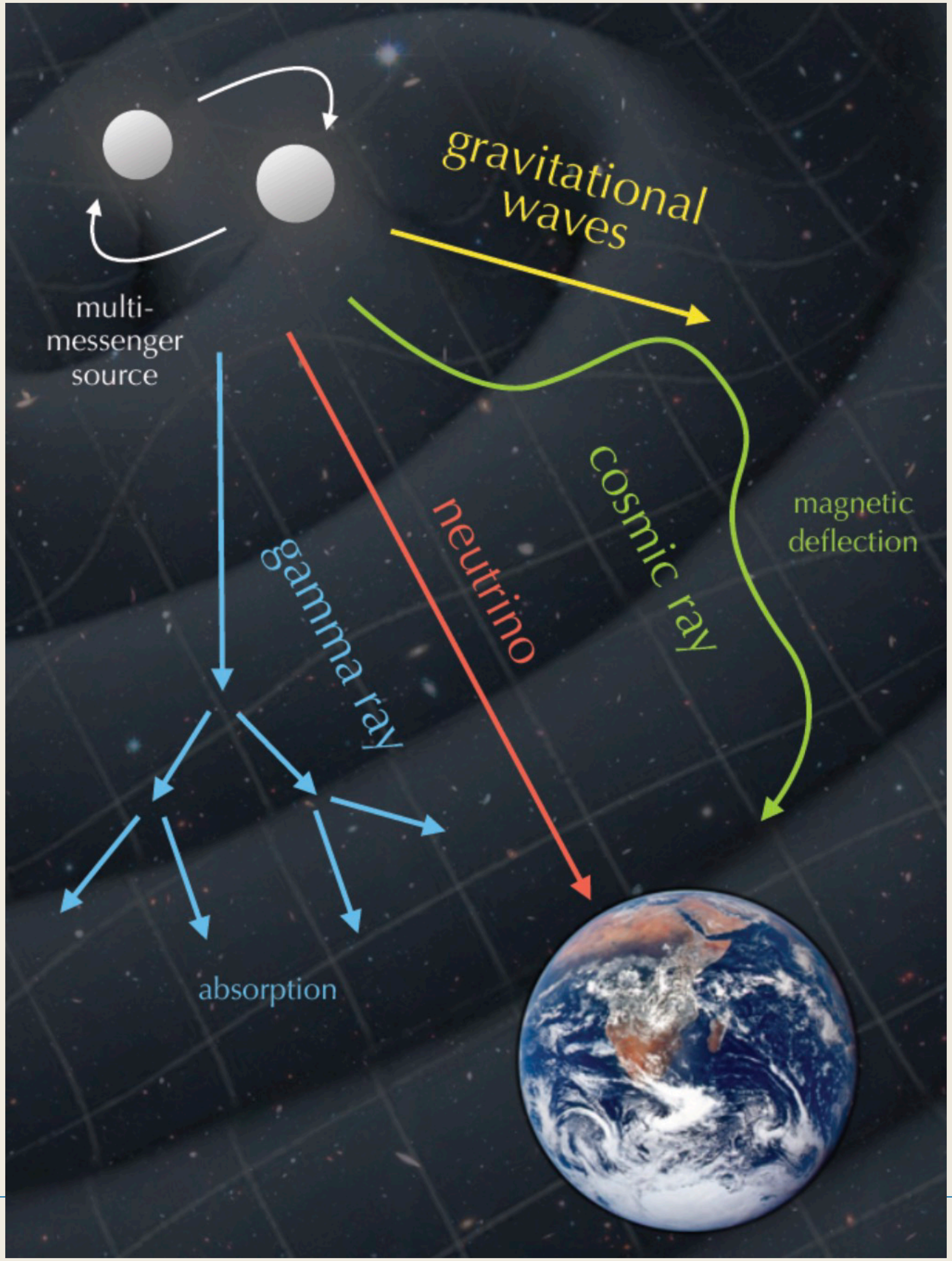
https://arxiv.org/abs/hep-ph/0502070

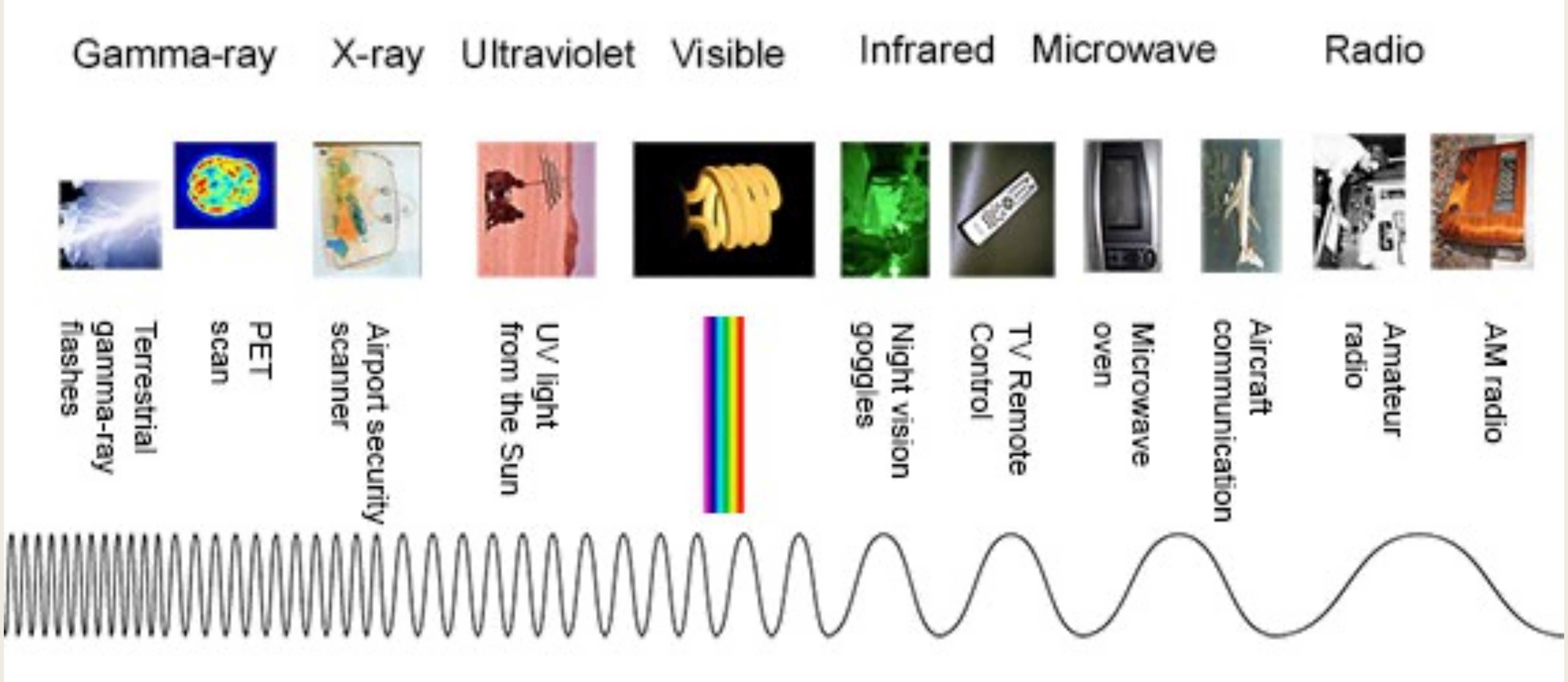
Four messengers to sense the distant world

1. **Light in all form (wavelength):** ***from beginning of astrophysics***
2. **Cosmic ray: 1909~**
3. **Neutrino: 1987~**
4. **Gravitational waves: 2021~**

Note: These become useful tools but still very interesting physics subjects!!!

Challenge: Human eyes can't see these. We need detector to observe and record.



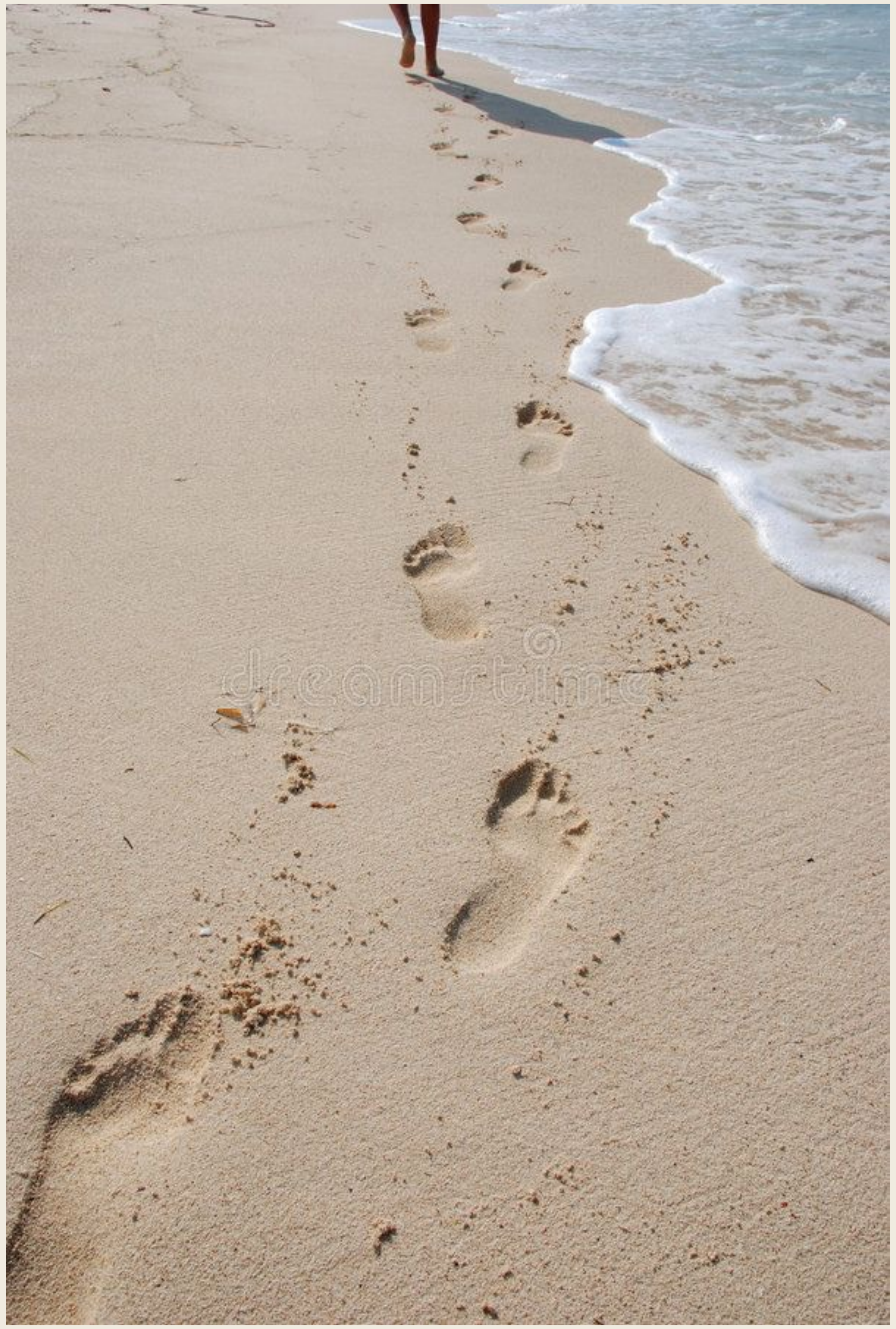


Only small portion of the EM radiation can be perceived by human eyes

https://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html

General principle of particle detection:
All *known* particles lose a fraction of their energy with some probability by some physical process when crossing matter (in detector)

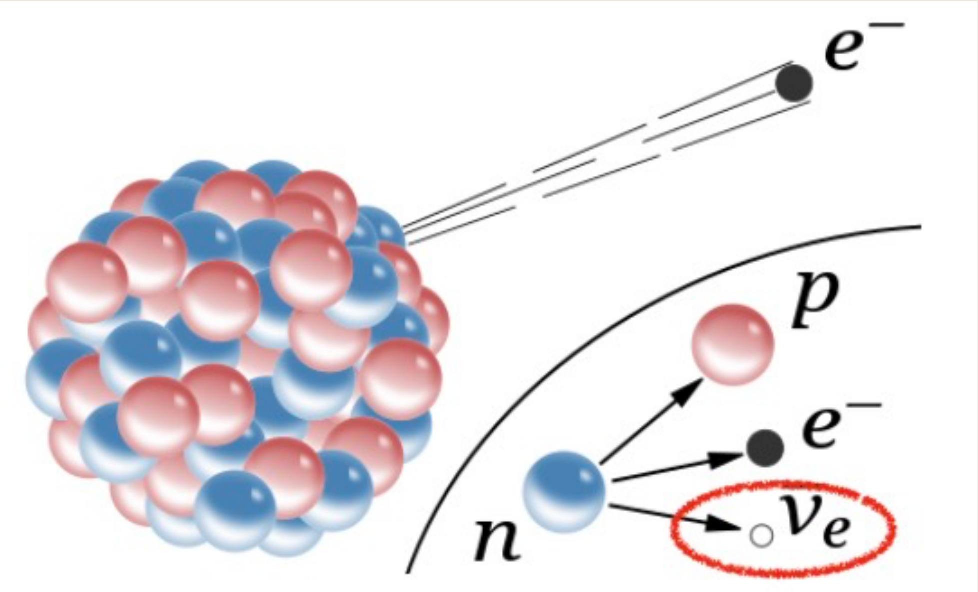
➜ leave some traces* to be detected and revealed their properties



* Some traces are easy to identify, some are not

Particle signature

- **We can't see the interaction itself but the <u>end products</u> of the interaction**
  - Eg. Story of Pauli's proposal (1930) of "invisible" end product in beta decay
  - *<u>End products</u>* are used to make sense of the underlying interaction
  - *<u>End products</u>* are detected via their interaction with matter
  - Only relatively "stable" end-products $\gamma, e^{\pm}, \mu^{\pm}, p, n, \pi^{\pm}, \alpha$ (or He^{2+}) can leave **visible track** in the detector.
    - Produced ν is stable but interact weakly, so mostly passing detector without any interaction → referred with so-called missing energy
    - Produced π_0 decay quickly into 2 photon (γ), which provides a quite distinct feature in detector

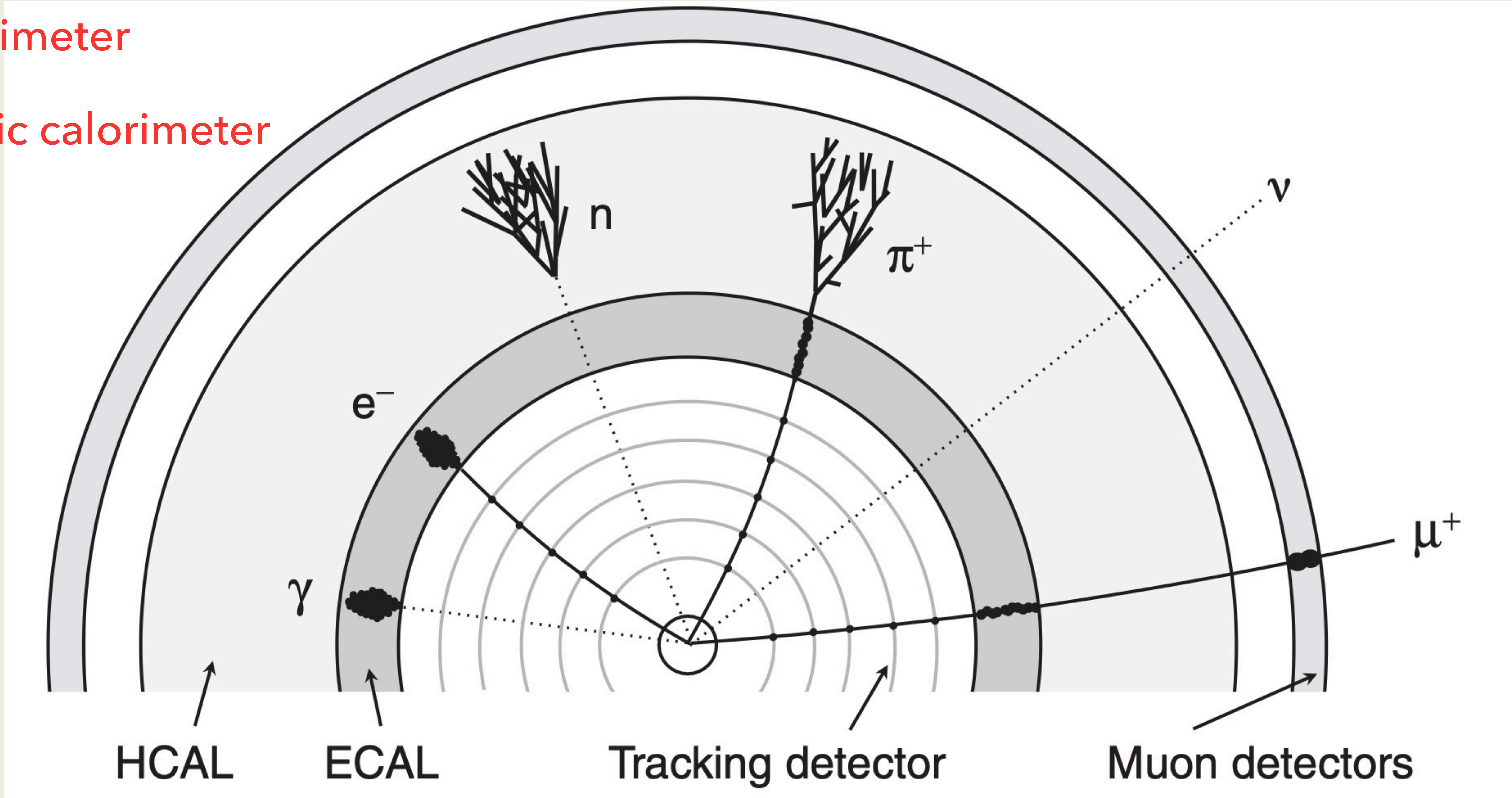


	Particle type	Rest mass [MeV/c]	Mean life τ [s]	Main decay mode
Photons	(γ)	0	Stable	–
Leptons	Electron (e^-), positron (e^+)	0.511	Stable	–
	Muon (μ^+, μ^-)	105.66	2.2×10^{-6}	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$ $\mu^+ \to e^+\nu_e\overline{\nu}_\mu$
Hadrons	Proton (p)	938.27	Stable	–
	Neutron (n)	939.57	880	$n \to pe^-\overline{\nu}_e$
	Charged pion (π^+, π^-)	139.57	2.6×10^{-8}	$\pi^- \to \mu^-\overline{\nu}_\mu$ $\pi^+ \to \mu^+\nu_\mu$
	Neutral pion (π^0)	134.98	8.5×10^{-17}	$\pi^0 \to \gamma\gamma$

EXAMPLE OF PARTICLE SIGNATURES IN THE DETECTOR

HCAL: Hadronic calorimeter

ECAL: Electromagnetic calorimeter



SEE THE DIFFERENCE IN THE SIGNATURE PATTERNS?

EXAMPLE OF PARTICLE SIGNATURES IN THE DETECTOR

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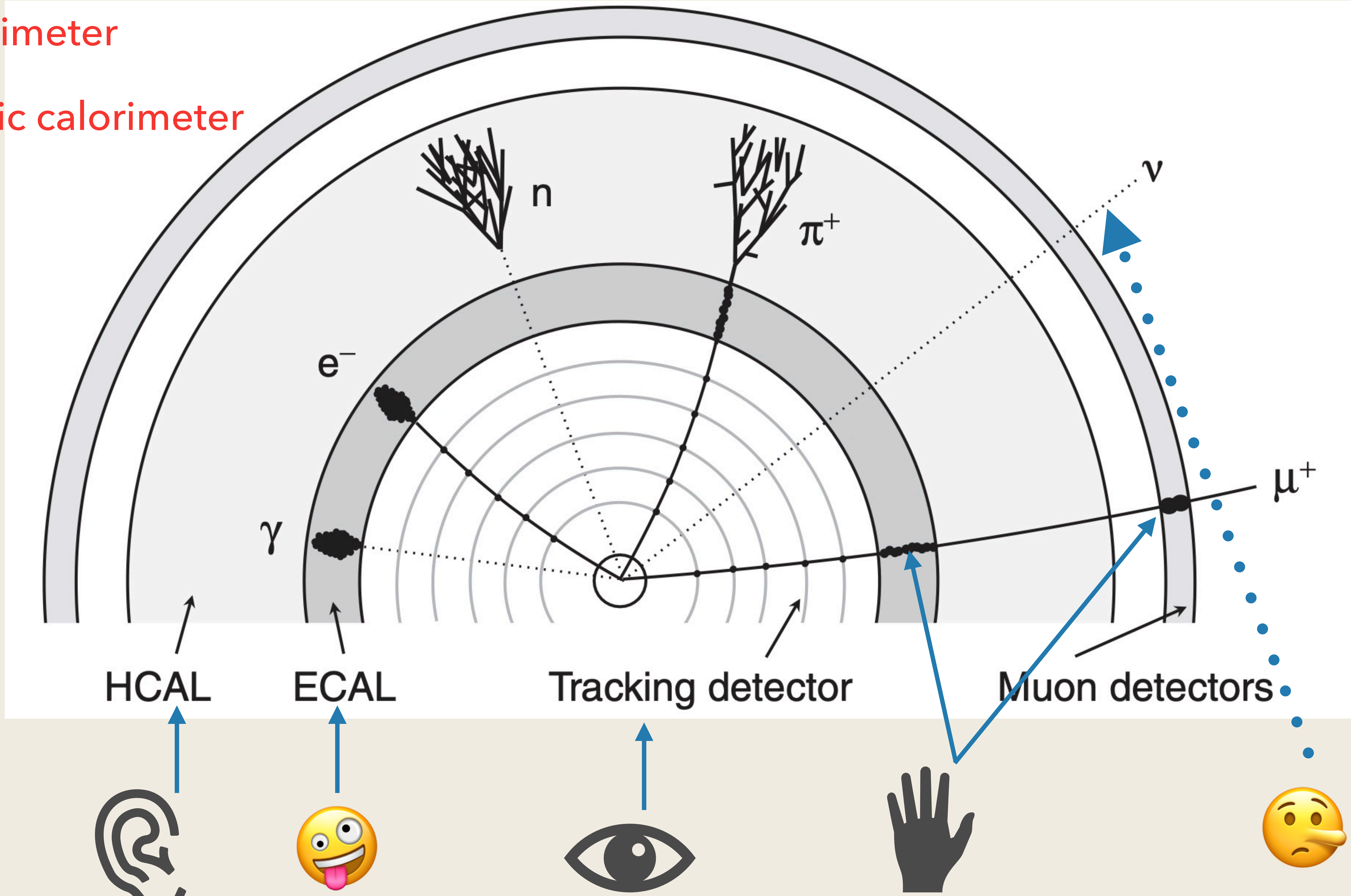
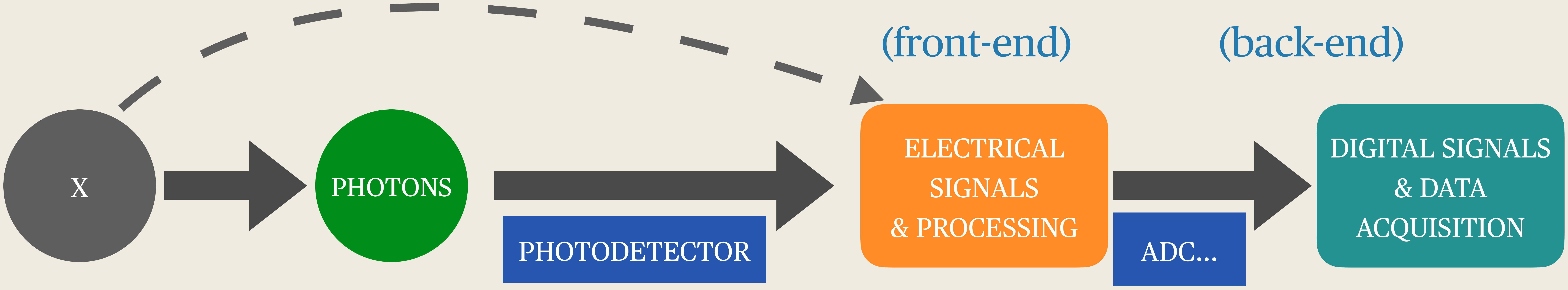


can consider them as "sense organ" of the detector

(eyes, ear, nose, tongue, skin)

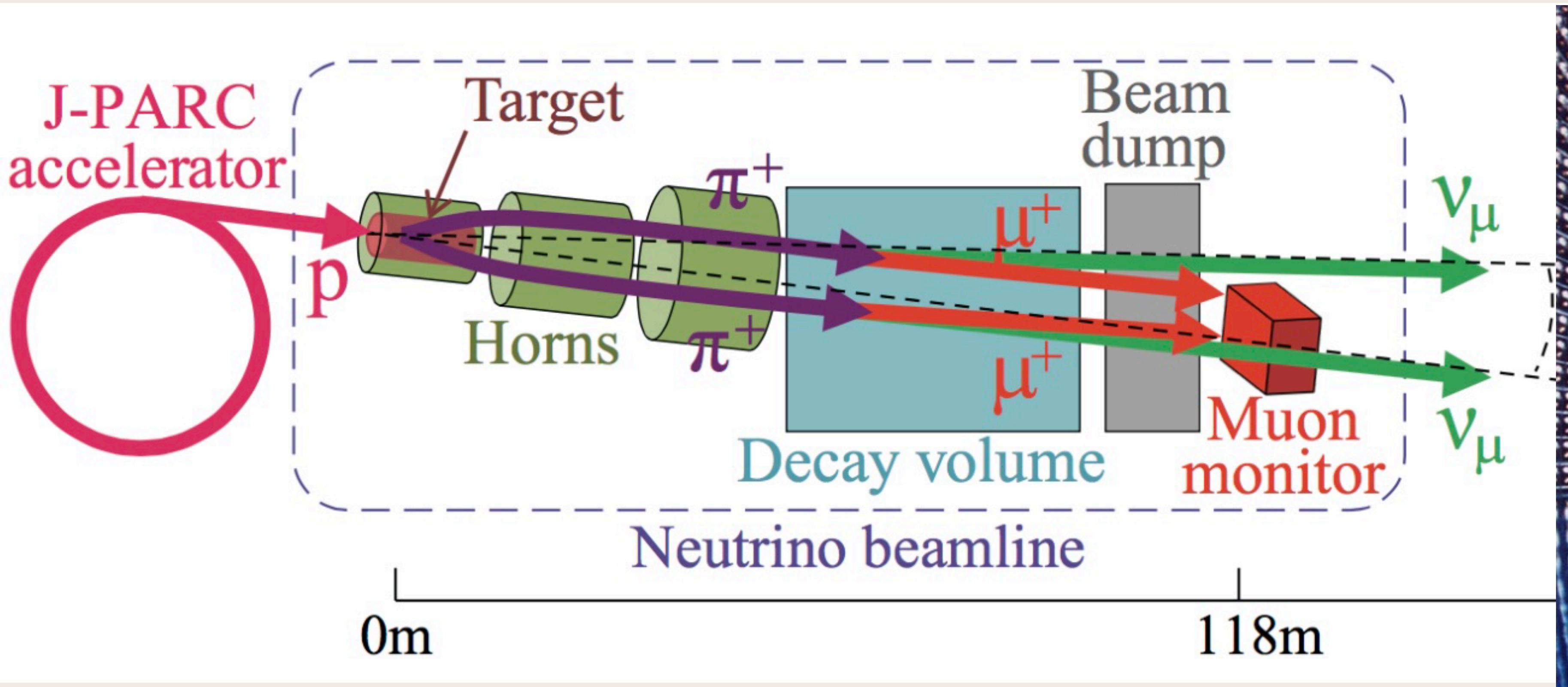
Bird view of particle radiation detection



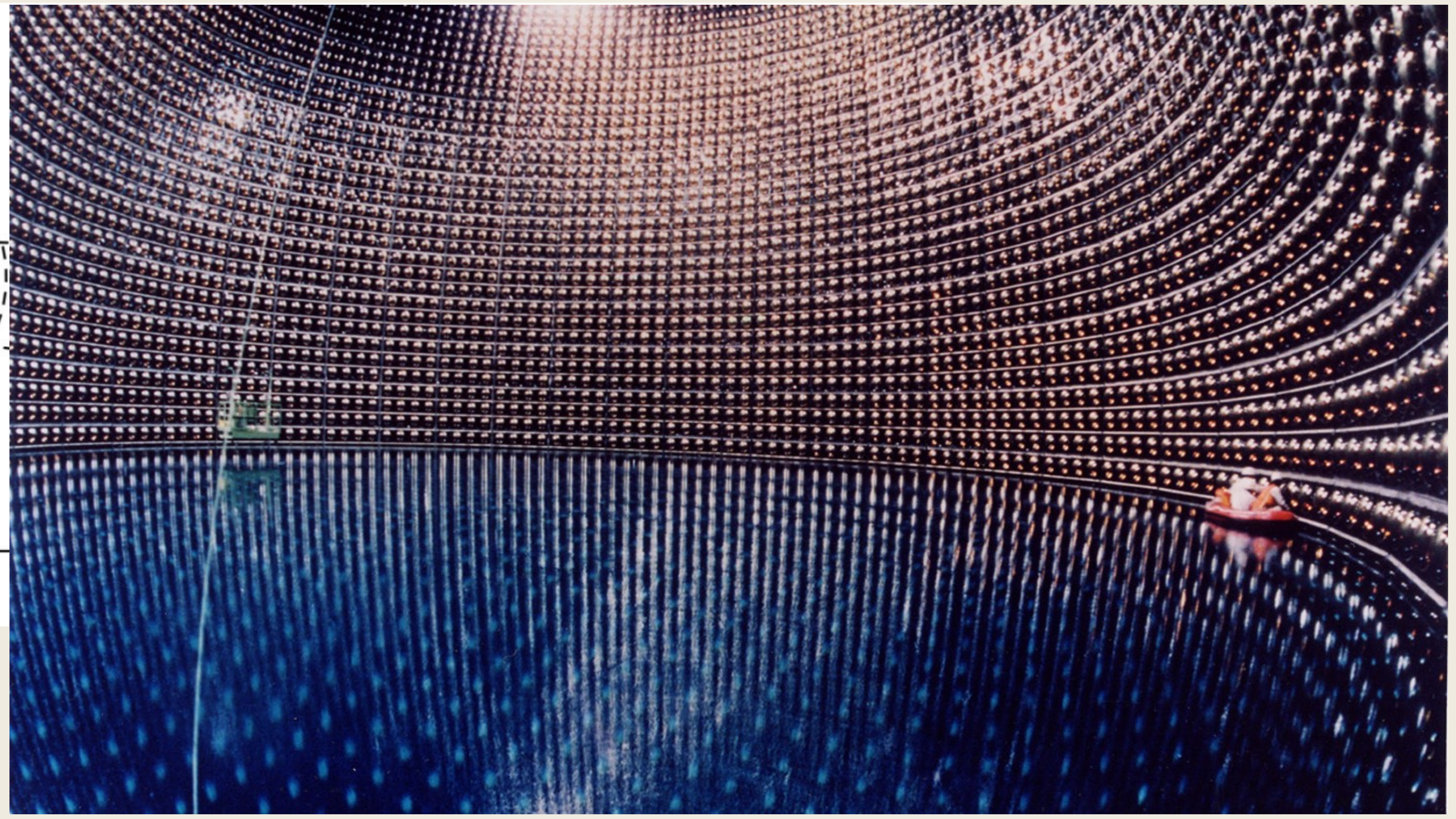
(*Modern detector*) be **electrical** in nature, i.e at *some points the information is converted into electrical impulses and proceeded with electronic devices. For storage and further analysis, converted to digital signals.*

Bodies of particle experiment

- The essential:
  - (1)**Particle sources**: can be man-made or natural source
    - (2)*Active* **volume for particle interactions**
      - (3)Apparatus to **"capture/visualize" the interaction process**
        - (4)System for **signal processing and analysis**



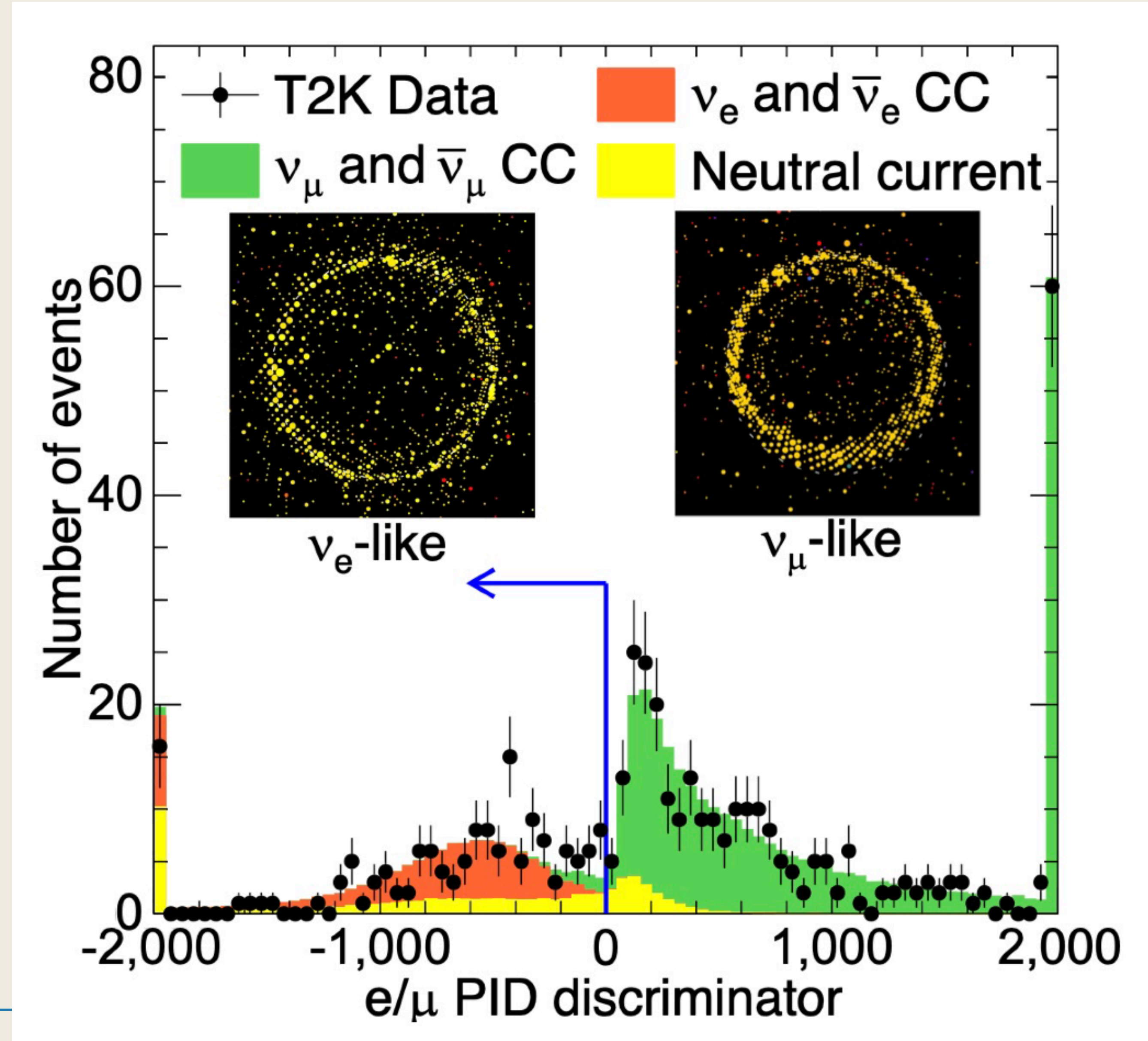
(1) J-PARC neutrino beam



(2) pure water/ Gd-loaded

(3) Photosensor

(4)

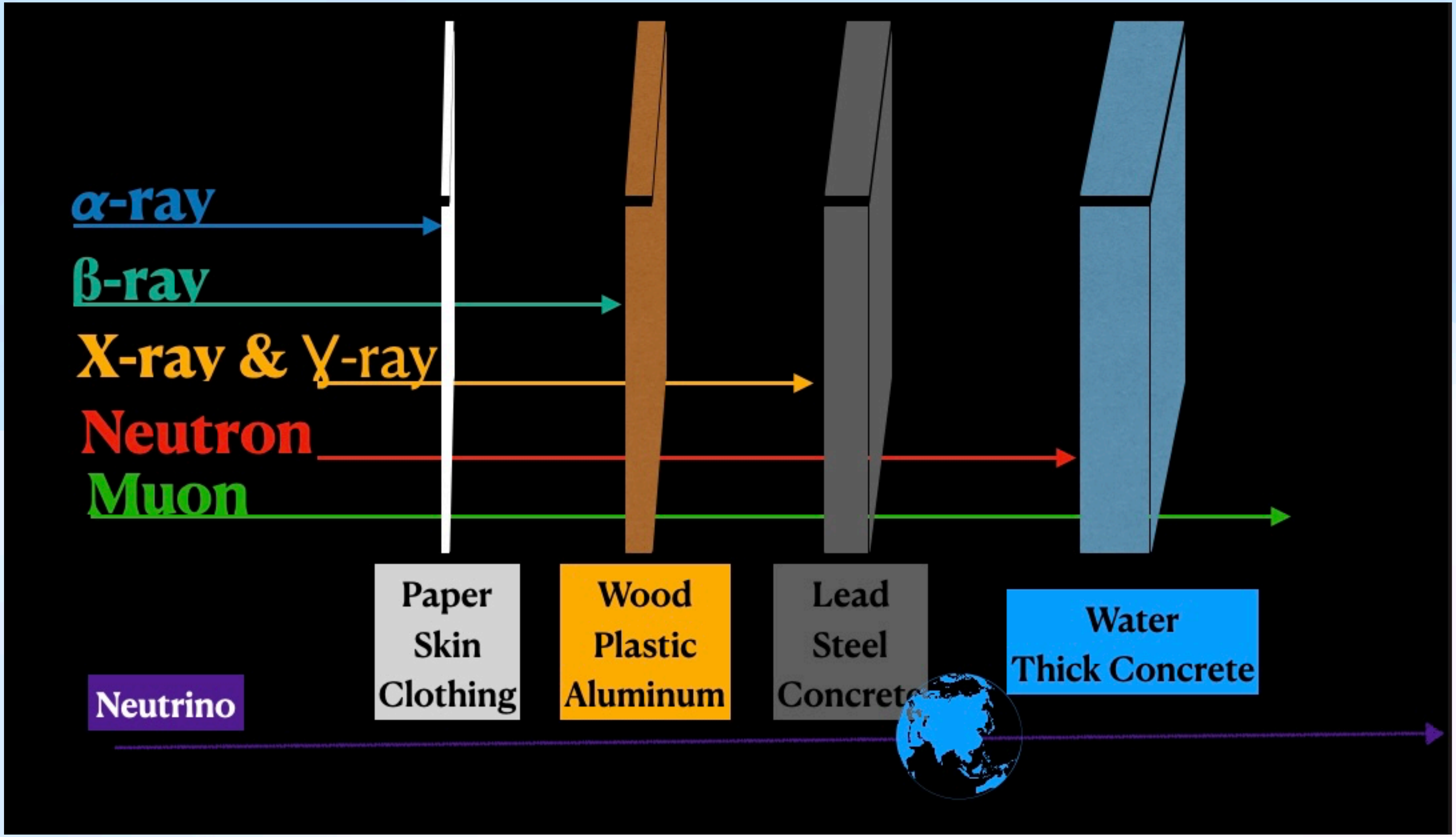


Bodies of particle experiment

- The essential:
  - (1)**Particle sources**: can be man-made or natural source
    - (2)*Active* **volume for particle interactions**
      - (3)Apparatus to **"capture/visualize" the interaction process**
        - (4)System for **signal processing and analysis**
- **Supporting setup**
  - Passive and active "Isolation"/shielding
    - Underground, high Z materials
    - Veto / outer detector
  - Additional detectors: to understand particle source, particle interaction, detector performance. Eg. Near detector complex in neutrino experiments
  - Additional facility to test/calibrate the detector's performance
  - …

Passage of particles through matter

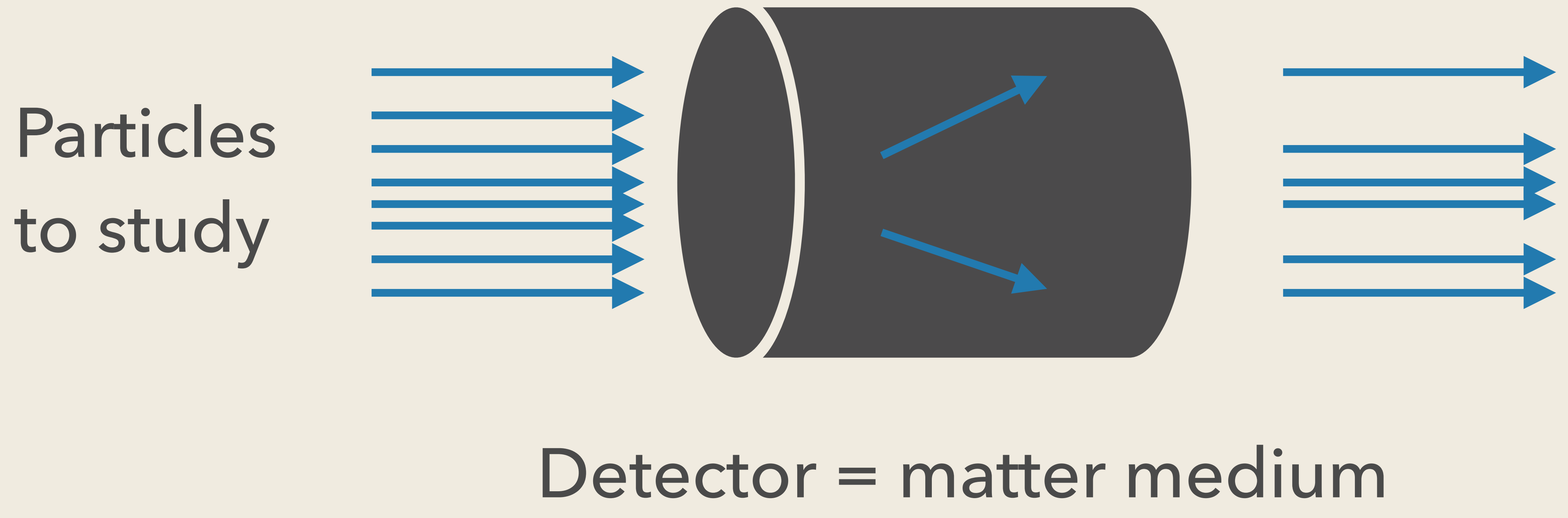
Trivial but important: particle/radiation must reach detector's active section to be detected



SO MATERIAL AMOUNT ALONG THE PARTICLE'S PATHWAY TO DETECTOR MUST BE TAKEN INTO ACCOUNT

Main body of particle detector

A matter medium to facilitate the particle-matter interaction and to make the end-products "visible"

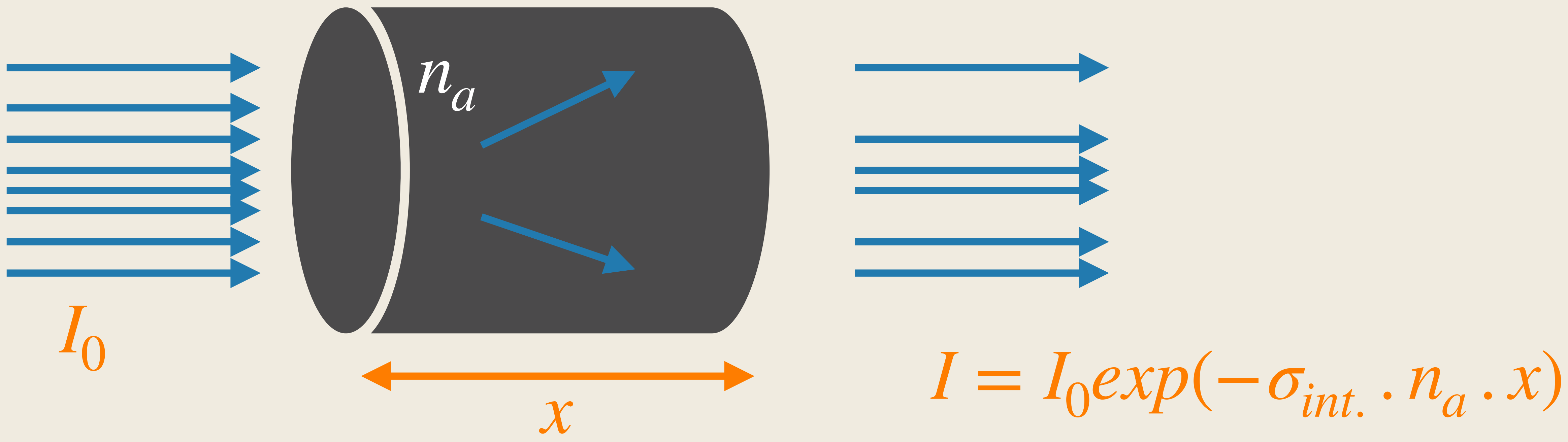


"Visible" here is not just for your eyes but any feasible techniques/ technology (photosensor, scintillator…)

Cross section and interaction length

- Consider flux of particle I_0 passing through a matter medium with atomic number A (*can be fixed target or active volume of a detector*) x
- Number of **scattering centers (s.c.)** per unit volume is $n_a = \frac{N_A \times \rho}{A}$ where N_A is Avogadro number and ρ is matter density
- The loss of incoming particle due to interaction is $dI = -I_0 \,.\, \sigma_{int.} \,.\, n_a \,.\, dx$
  - **Where $\sigma_{int.}$ is the interaction probability of an incident particle with scattering centers, interpreted as the effective area of the interaction**
- So remained flux $I = I_0 exp(-\sigma_{int.} \,.\, n_a \,.\, x) = I_0 exp(-x/\lambda_{int.})$
- $\lambda_{int.}$ called the **interaction length** (*or sometimes called mean free path*)

For mixed materials, $\lambda_{int.} = \frac{1}{\sum_i n_i \sigma_i}$



Cross section and example

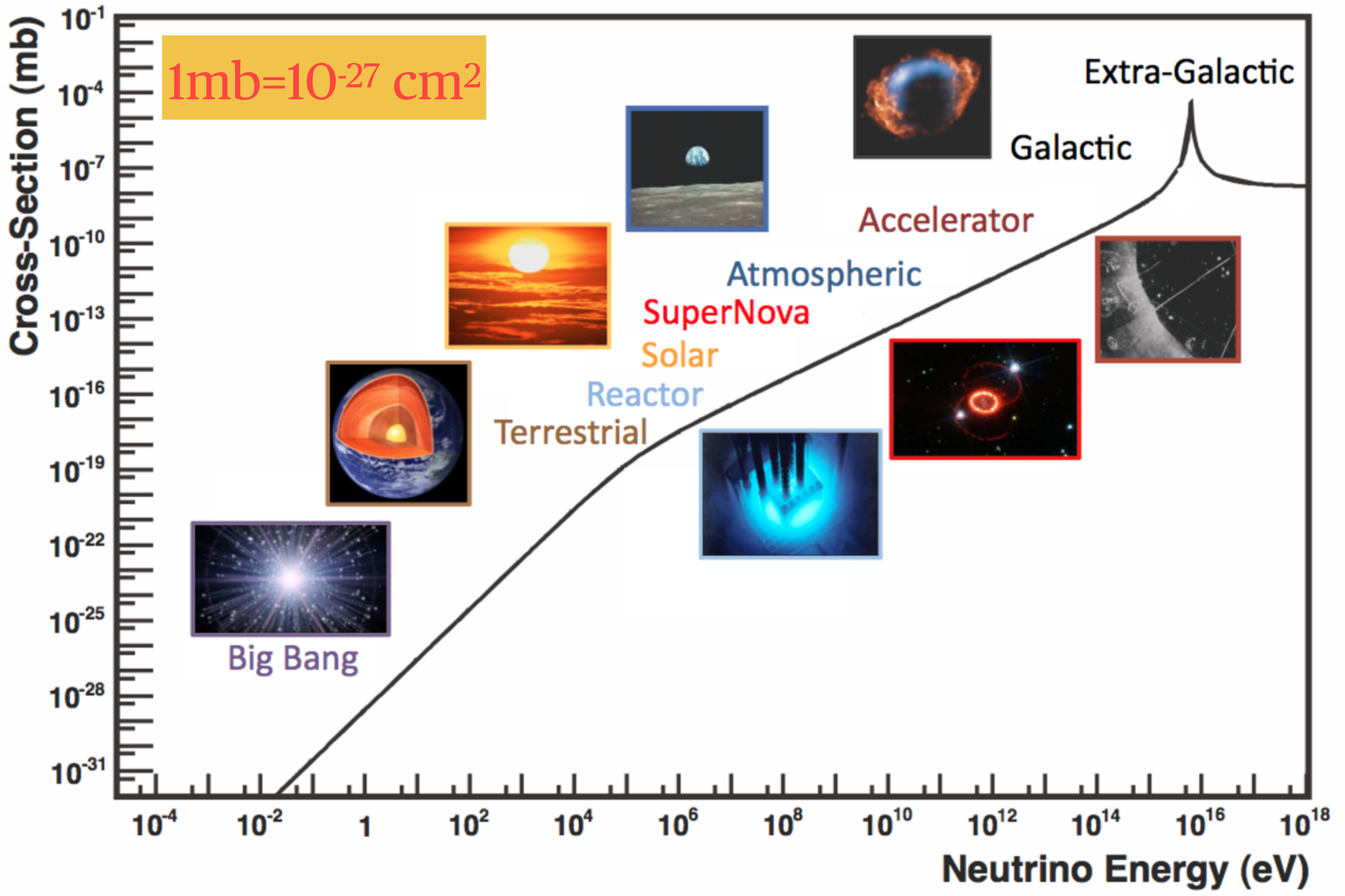
- $1\text{barn} = 10^{-24}cm^2$
- 1mb = 1 milibarn = $10^{-27}cm^2$
- 1pb = 1 picobarn = $10^{-36}cm^2$
- 1fb = 1 femtobarn = $10^{-39}cm^2$

- Strong force $p + p \to X$, σ ~ 45mb (*scale = 1*)
- Electromagnetic force $\gamma + p \to X$, σ ~ 0.15mb (~1/300)
- Weak force $\nu_\mu + N \to X$, σ ~ 7fb (*~1/6,400,000,000,000*)

(GIVE SOME SENSE OF INTERACTION STRENGTH)

Cross section depends on energy

Cross section of a specific interaction depends on **particle-involved energy** so interaction length as well as any measure (*eg. interaction rate*) related to cross section.



$$\sigma_{\overline{\nu_e}+e\rightarrow\overline{\nu_e}+e}(E) \sim 10^{-43}\frac{E_{\overline{\nu_e}}}{MeV}\ [cm^2]$$

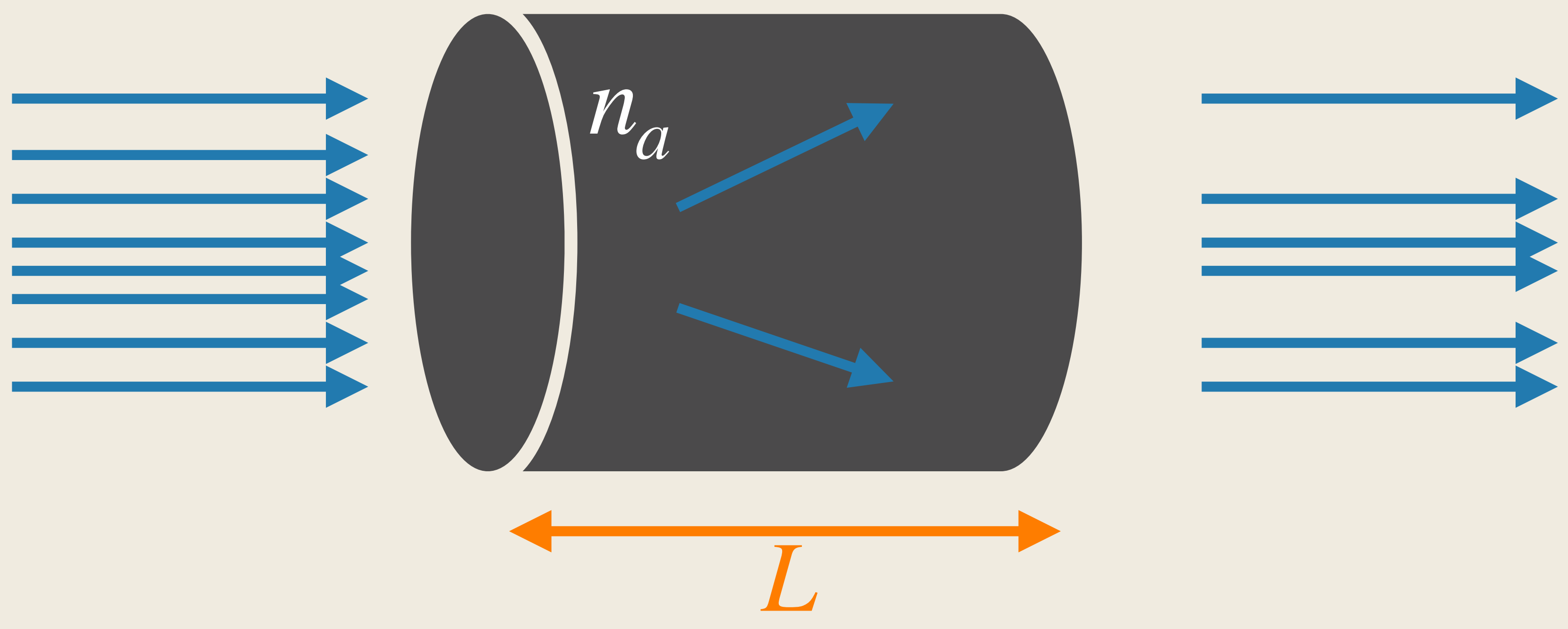
Reactor ν at few MeV,
$\sigma \sim 10^{-43}\ cm^2$

Atmospheric ν at few GeV
$\sigma \sim 10^{-40}\ cm^2$

Meaning of interaction length

Interaction probability $P_{(x=L)} = \int_0^L \frac{1}{\lambda_{int.}} \exp(-x/\lambda_{int.})dx = 1 - \exp(-L/\lambda_{int.})$

- Giving same number of incident particles, **longer L, i.e more scattering centers → more particle interactions**
- 63.2% (1-1/e) interaction happens when $L = \lambda_{int.}$
- 86.5% (1-1/e²) happen when $L = 2\lambda_{int.}$
- …



Interaction length : an example

- **10 GeV proton entering a iron slab, what is the interaction length?**
  - Given $\sigma_{tot.}(pp \to X) \approx 25$mb with p=10GeV , for materials with mass number A, $\sigma_A = \sigma_{pp}\,.\,A^{0.77}$
  - $\lambda_p = \dfrac{A}{N_A \rho \sigma_{tot.}} = \dfrac{56[g/mol]}{6.02 \times 10^{23}[1/mol].7.87[g/cm^3].56^{0.77}.25 \times 10^{-27}[cm^2]} \approx 21\text{cm}$
- **For 100GeV neutrino entering a iron slab**
  - $\lambda_\nu = \dfrac{56}{6.02e23 \times 7.87 \times 0.7e^{-38} \times 1000} \approx 1.7e^{13}$cm > 1 AU = earth-sun distance
- **So how can we stop neutrino?**
  - **Keep in mind that more scattering centers give more probability of interaction →make bigger detector with more intense source of particles**

Interaction rate

- One of the most useful detector technique is COUNTING of particle interaction
- No. of interactions in the detector for a given time t (second/day/ year) can be computed as

$$N_{int.}(t) = \Phi(t) \times \sigma \times N_{s.c.}$$

Flux of incident particles	Cross section	Scattering center

- In reality, energy-dependence of flux and cross section must be taken into account
- Other relevant is that imperfect detector can't detect all interactions, or detection efficiency is less than 1.

Eg. Neutrino interaction rate

- Sun produces 2×10^{38} electron neutrinos per second
  - *Ref: Total sand grain on the Earth ~* 10^{18}
  - Solar neutrino flux at the Earth $\Phi = \dfrac{N}{4\pi R^2} \approx \dfrac{2 \times 10^{38}}{4\pi(1.5 \times 10^{13})^2} \approx 7 \times 10^{10} cm^{-2} s^{-1}$
  - Due to limit in (energy) detection threshold, observed flux at Super-K detector is $\approx 2.3 \times 10^6 cm^{-2} s^{-1}$
- Super K detector: 50k tons of pure waters
  - Total electron (as No. of interaction centers) $N^e_{SK} = 10[e/atom] \times 5 \times 10^{10}[g] \times 6.02 \times 10^{23}[atom/mol]/18[g/mol] = 1.67 \times 10^{34}$
- No. Of interaction per second $N[s^{-1}] = \Phi \times \sigma \times N^e_{SK}$ where $\sigma = 10^{-43} cm^2$
  - Observed rate $N_{obs.}[s^{-1}] = \Phi \times \sigma \times N^e_{SK} = 2.3 \times 10^6 \times 10^{-43} \times 1.67 \times 10^{34} \approx 4 \times 10^{-3}[s^{-1}]$ or 350 events per day, still ~ one order larger than
    - In reality, suppressed by the fiducial mass, factor of 0.45
    - Detection efficiency
    - …

One of the first parameter to look at when building a detector is to estimate the total interaction rate (*consider ideal detector*) and observable rate (*after taking into account the detection limits*)

- Statistics (eg. *sensitivity to certain parameter*) is relevant

(YOU EXPERIENCE THIS WHEN SETTING THRESHOLD TO SEE COSMIC RAY IN THE LAB)

Conceptual particle detector

<u>Ideally</u> (*here particles = end products of the interaction*)

- Excellent **identification** of all particles
- Excellent **tracking** (*spatial and temporal*) of all particles
- Precise measurement of **energy/momentum** of all particles

- Additional features
  - Record **High rate events**: collider, near detector of neutrino experiments
  - **Radiation tolerance**: eg collider; MUMON detector of T2K ; caused eg. displacement of the lattice atom/ defection
  - **Continuous operation** for ~ 10 years with little/no intervention
  - **Compromise**: existing technology, money, space, time…

Working principle of particle detectors

Any effect of particle inducing observable distinction when interacting with matter can be used as working principle of particle detector

					strong	electromagnetic	weak
Quarks	down-type	d	s	b	✓	✓	✓
	up-type	u	c	t			
Leptons	charged	e^-	μ^-	τ^-		✓	✓
	neutrinos	ν_e	ν_μ	ν_τ			✓

These gives the overall framework to compute, but it likes “black-box”, not giving you features/observables to quantitatively measure.

Working principle of particle detectors

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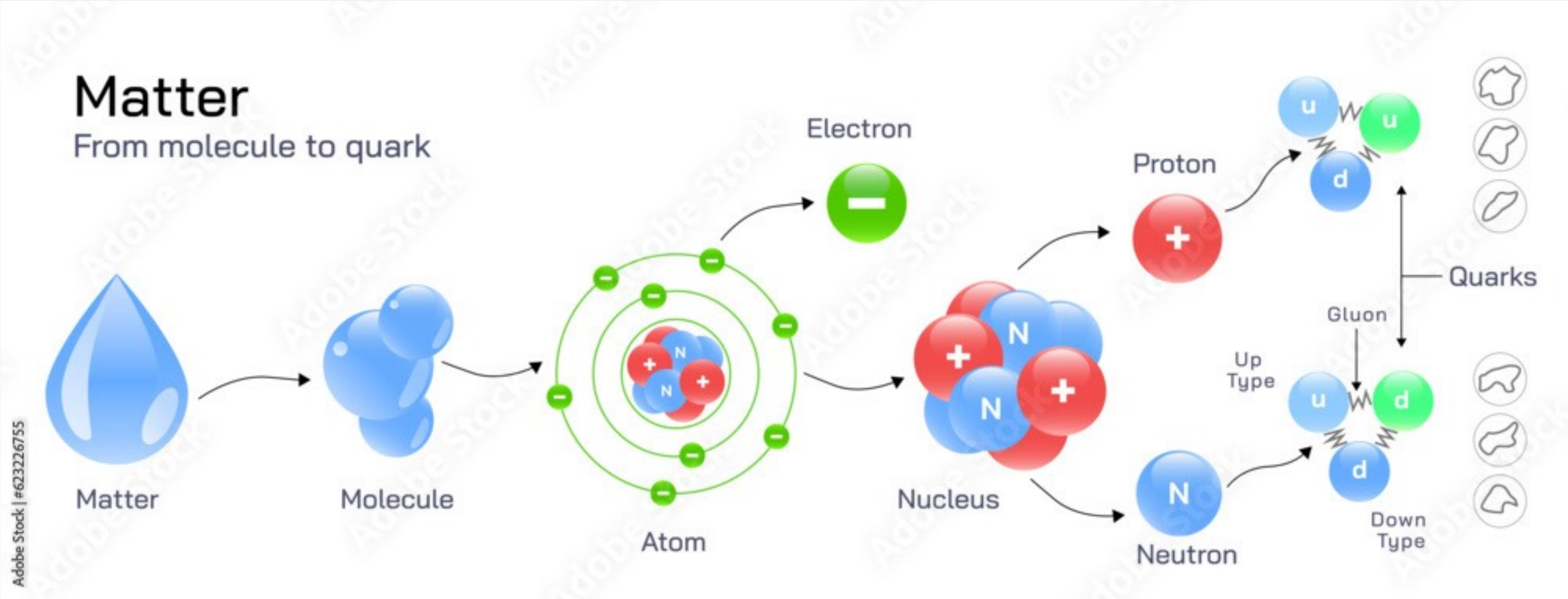
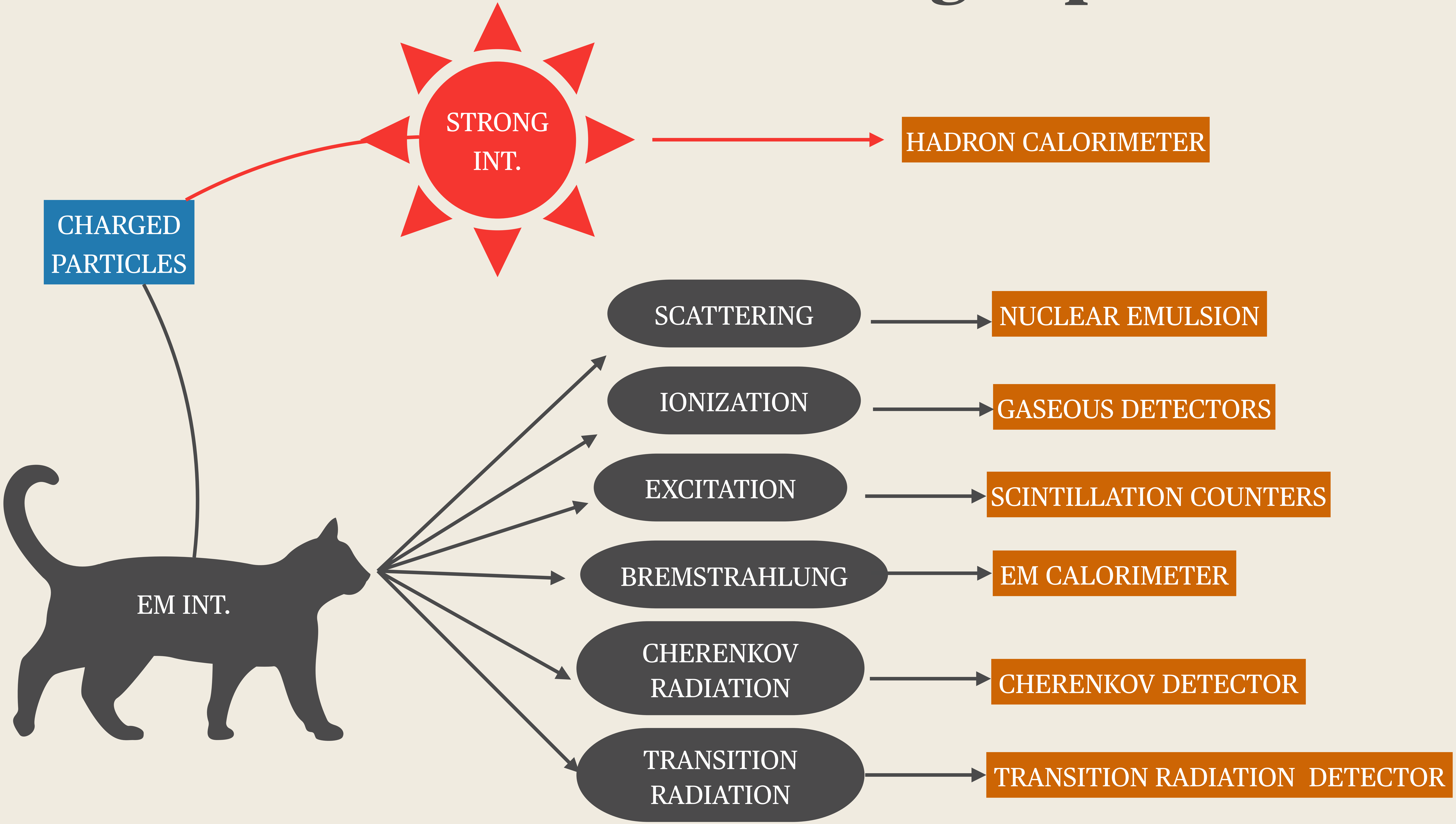


Fundamental effects:

- **Coherent scattering** (*keep targeting atom intact*), release some recoiled energy
- **Ionize atom** by liberating electron
- **Excite the atom/molecule** and produce new particle(s)
- **Emit photon(s)**: Cherenkov radiation, transition radiation, scintillation, fluorescence
- **Break down nucleus** via inelastic nuclear scattering results in number of particles

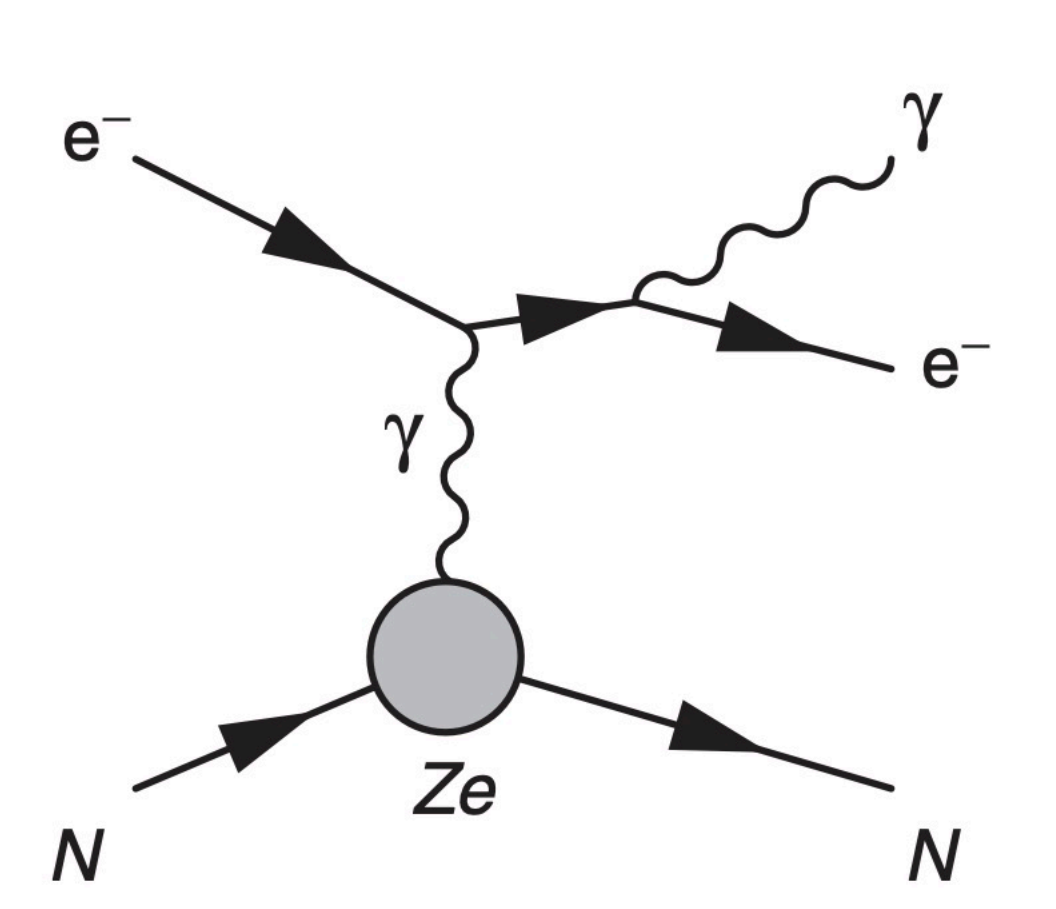
Detection of charged particles

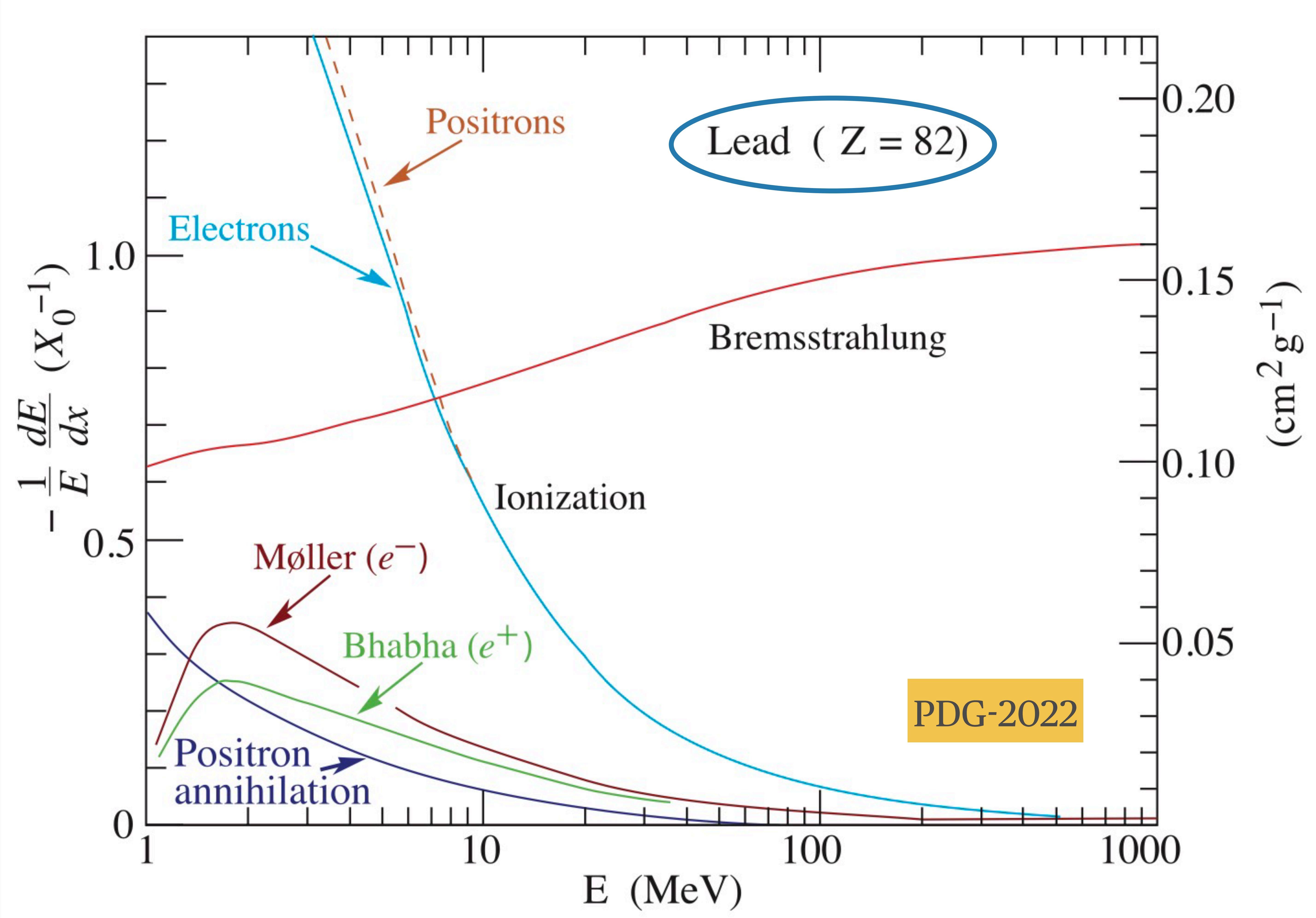


Interaction of light charged particles (electron/positron)

- At **low-energy** (less than $E_c = \frac{800\ [MeV]}{Z}$) energy loss, **dominated by ionization**

- At higher than E_c, dominated by **Bremsstrahlung**





“Heavy” charged particles

- Relativistic charged particles interact electromagnetically with atomic electron and lose energy through the ionization of the atoms
- **Bethe-block formula**, this applied for **higher mass** than m_μ, but **NOT applied for electron**

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e^2 c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left(\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right)$$

$$\beta = \frac{v}{c} \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$N_A = 6.022 \cdot 10^{23}\,\mathrm{mol}^{-1}$ = Avogadro number

$r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2}$ = classical electron radius

ε_0 – permittivity of free space

m_e^2 = electron mass

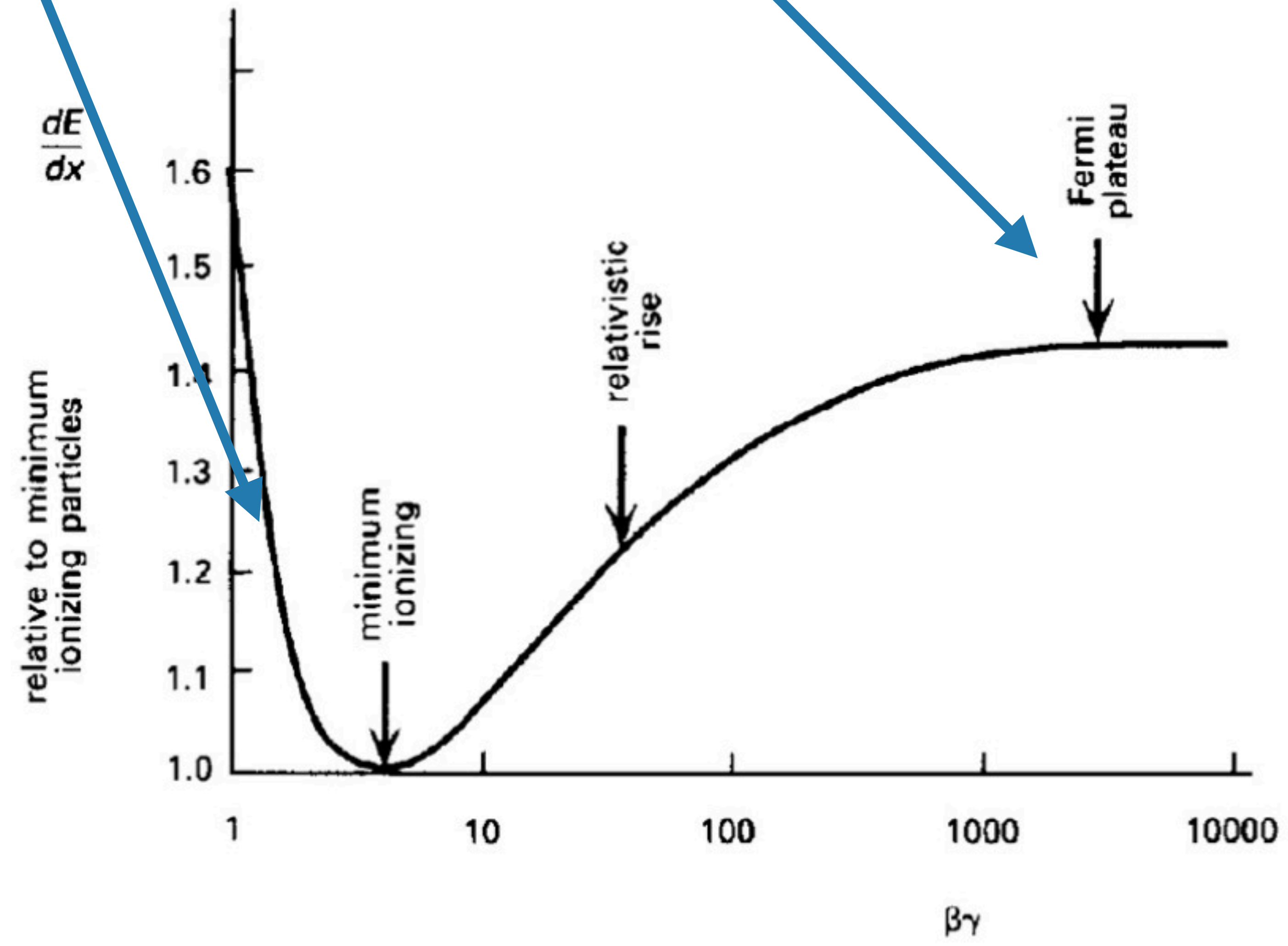
c = speed of light

z = charge of the incident particle

$\frac{Z}{A}$ = atomic number and weight of target

I = effective ionization potential

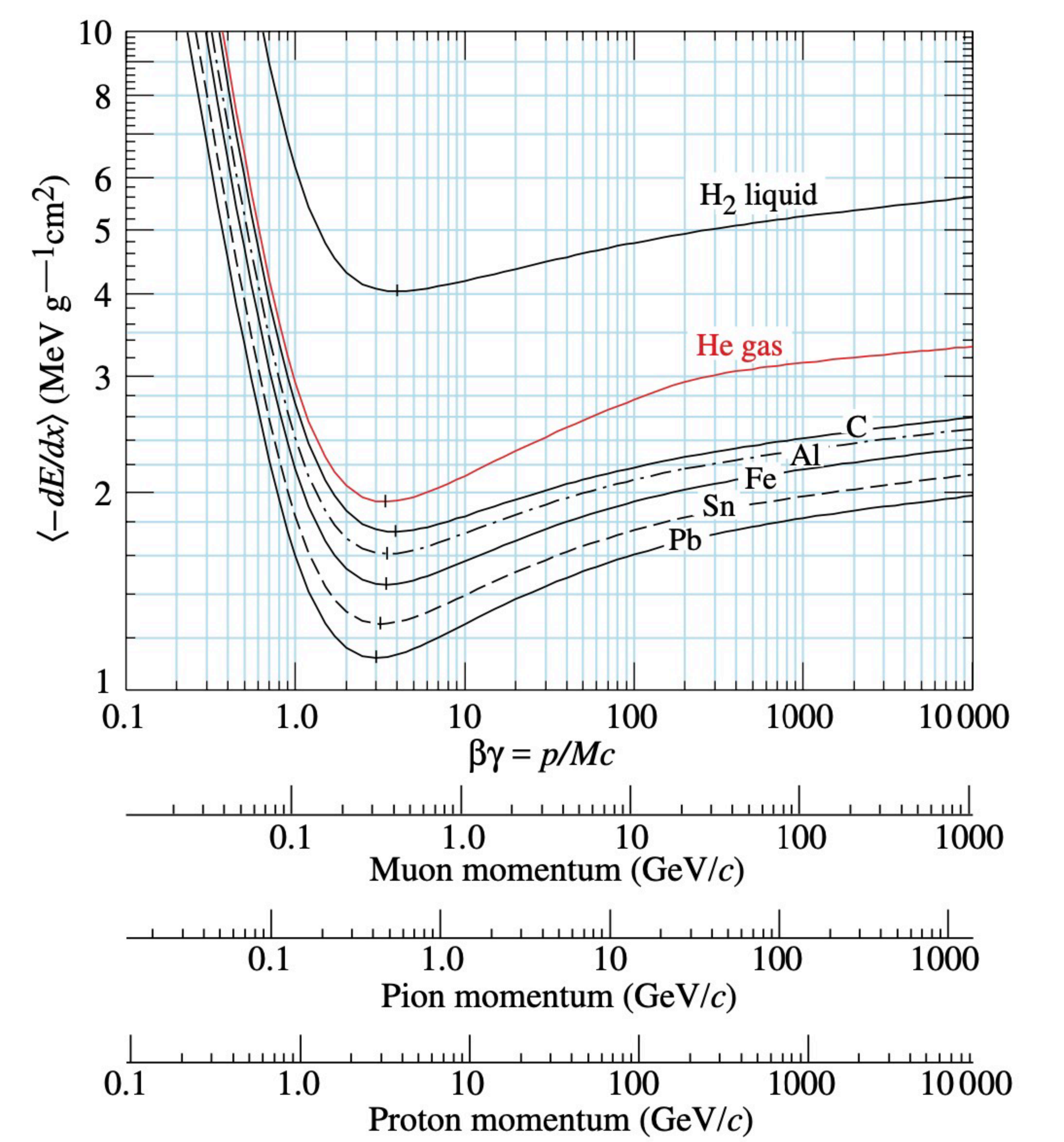
δ = density correction



- Low $\beta\gamma$, $< dE/dx > \propto 1/\beta^2$
  - Slower particle, more dE/dx since it feels stronger electric field
- **“Fermi plateau”** at high $\beta\gamma$
- Particles with $\beta\gamma \approx 3$ is called **minimum ionizing particle (MIP),** applied for most of relativistic particles (*eg. cosmic-ray muons*)

"Heavy" charged particles

- Relativistic charged particles interact electromagnetically with atomic electron and lose energy through the ionization of the atoms
- **Bethe-block formula**, this applied for **higher mass** than m_μ, but **NOT applied for electron**

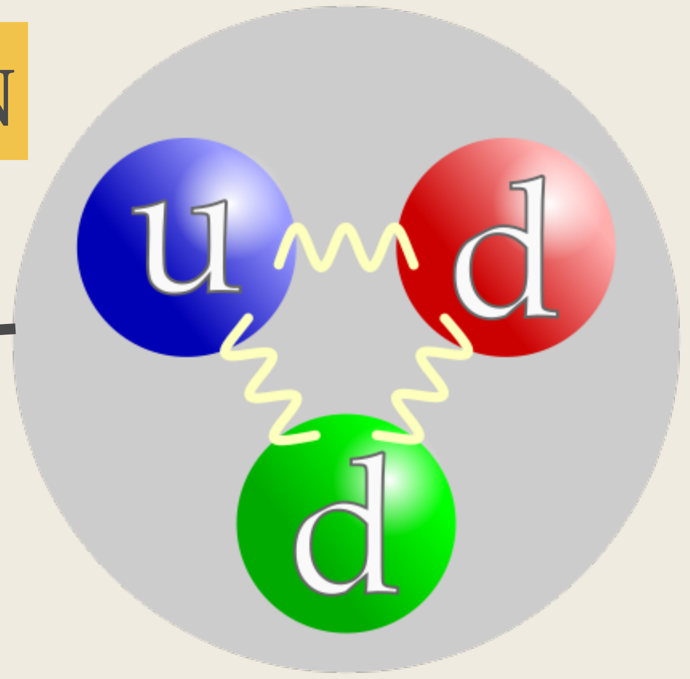


- dE/dx at MIP depend on material choice
- For muon loss on C (*like scintillator*), MIP is when muon momentum is about 3 GeV (eg. Cosmic-ray muons)
  - $< dE/dx > \approx 1.8 - 2.2\ MeVg^{-1}cm^2$ for few GeV muons
  - *One can use this to compute the amount of scintillation light produced*

Detection of neutral particles

NEUTRAL PARTICLES

NEUTRON



EXCITATION / PHOTON EMISSION

NEUTRON COUNTER, EM CALORIMETER…

PHOTON

RAYLEIGH, COMPTON SCATTERING, PHOTO-ELECTRIC EFFECT, PAIR-PRODUCTION

EM CALORIMETER…

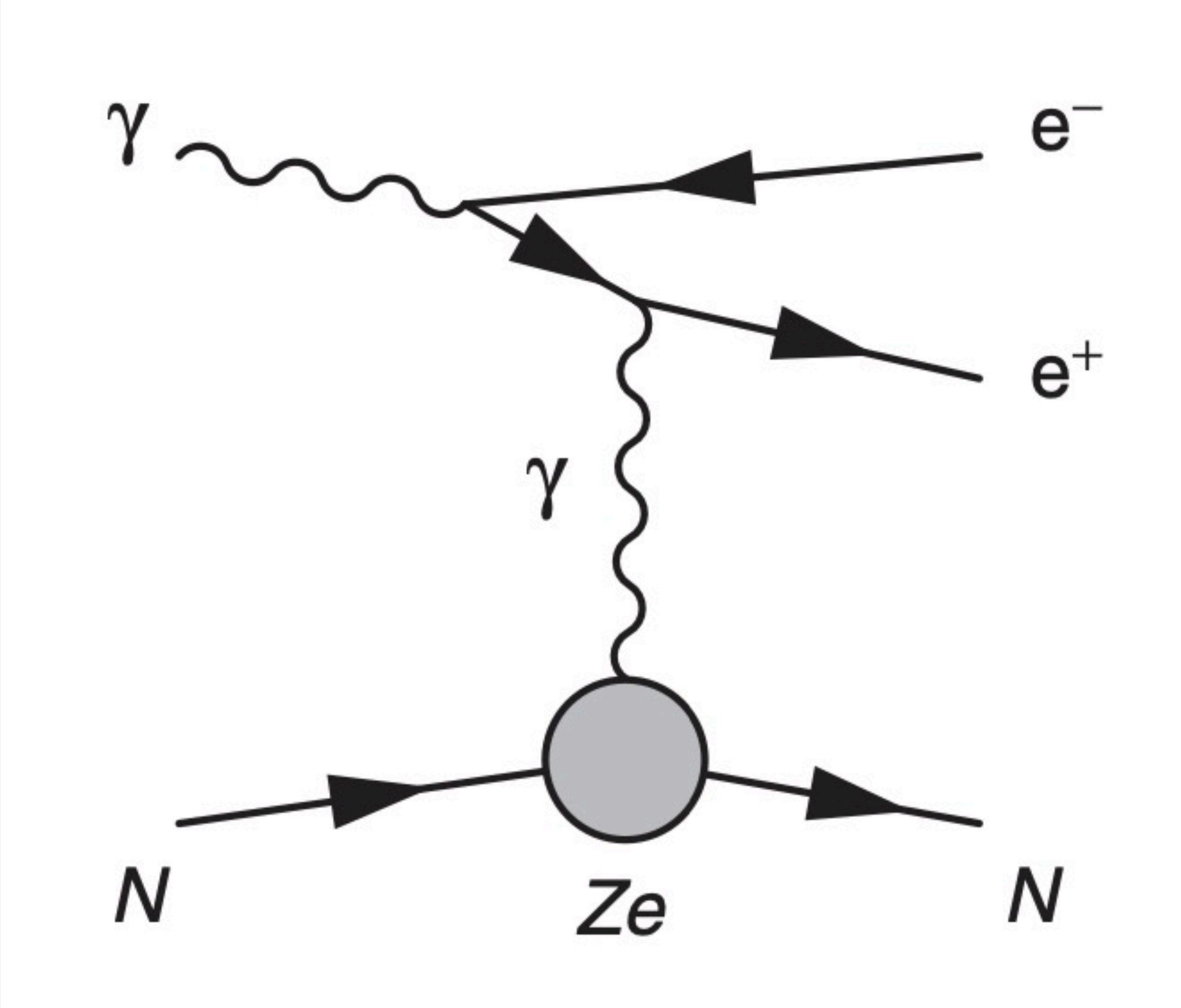
NEUTRINO

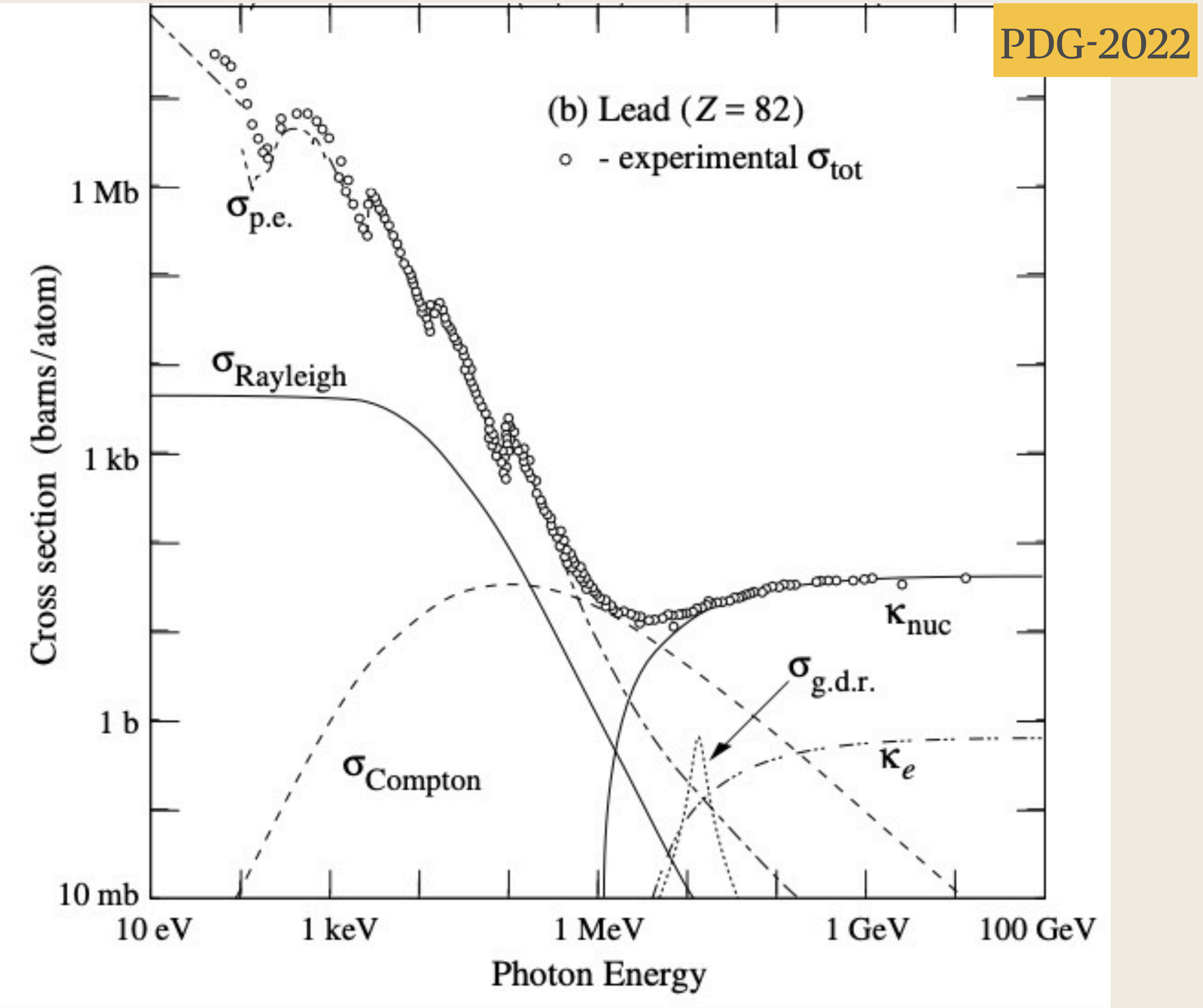
WEAK INT.

NEUTRINO DETECTOR

Interaction of Photon

- Dominated process depends on photon energy, also slightly on the interacting material
  - **Low energy** (eV-sub MeV): dominated by **photoelectric effect and Rayleigh scattering**
  - **Medium energy (**keV-sub GeV): dominated by **Compton scattering**
  - **High energy** (>MeV): e^+e^-−**pair production**

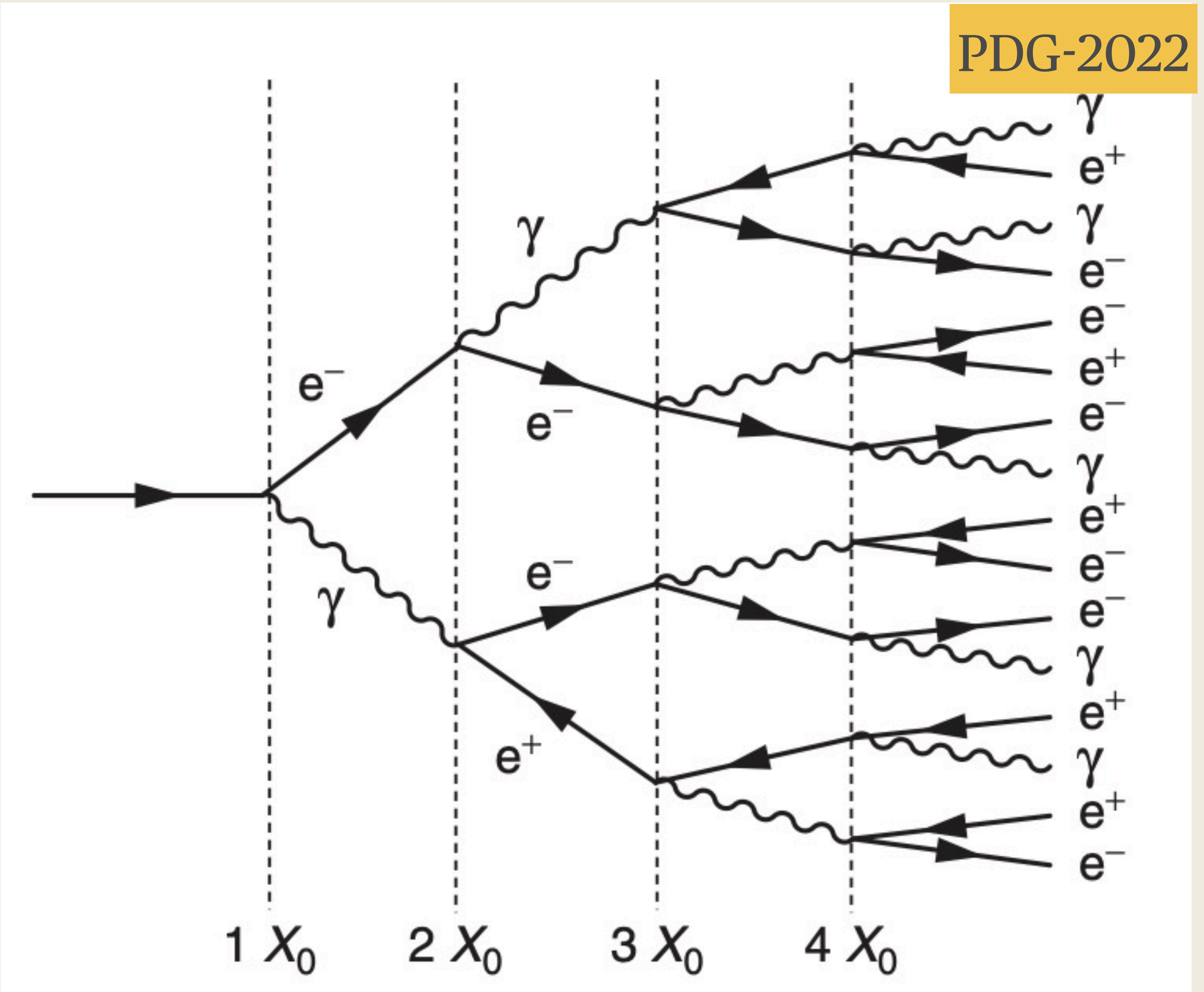




$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions, most notably the Giant Dipole Resonance [51]. In these interactions, the target nucleus is usually broken up.

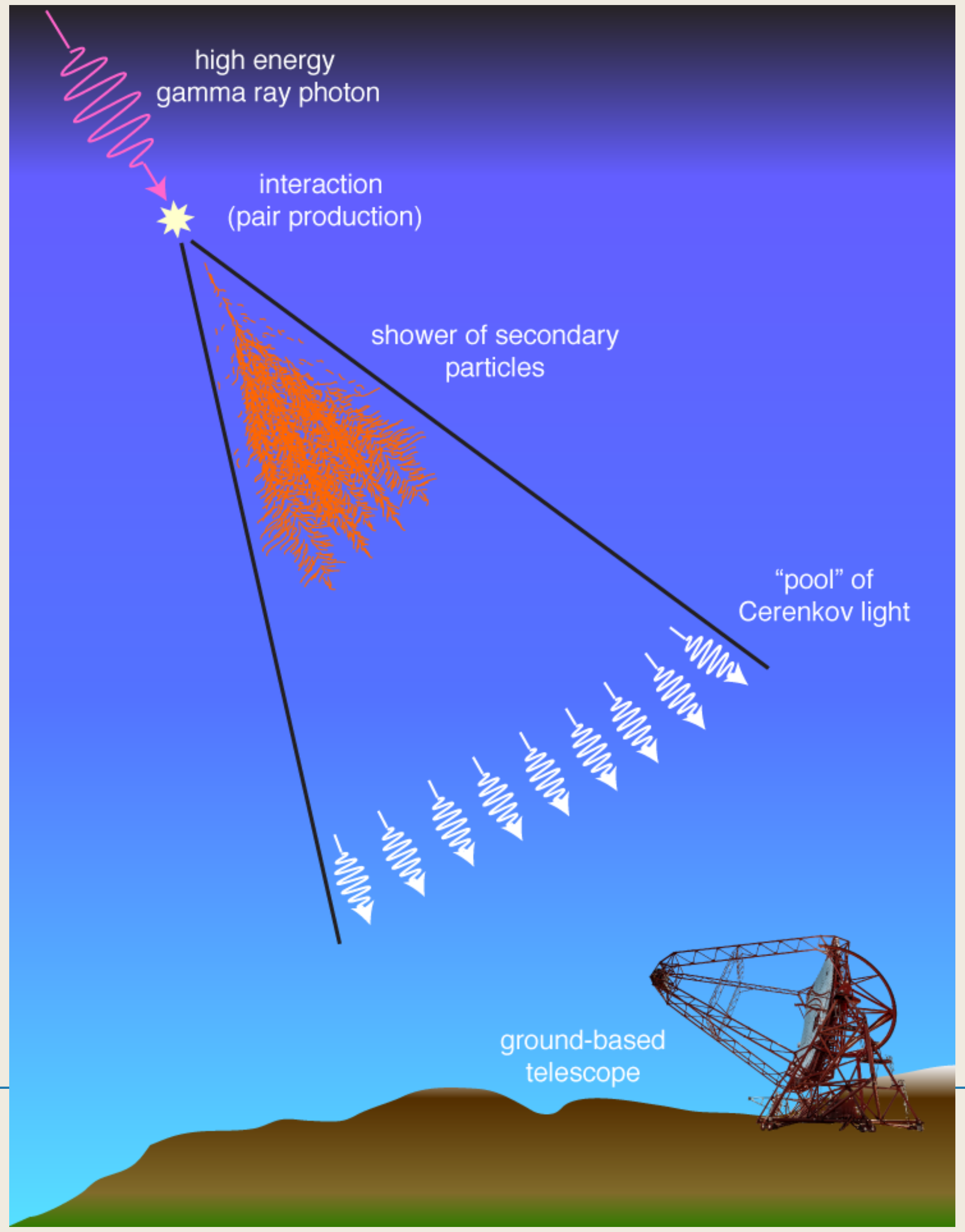
Electromagnetic shower

- At high energy, both Bremsstrahlung and pair production happen in a cascade manner →**Electromagnetic shower**
- Average energy of particle after X radiation length
  $$< E > = \frac{E}{2^x}$$
- Will the reach the maximum at $x_{max} = \frac{ln(E/E_c)}{ln2}$
- Eg. 100GeV developed ~ $13X_0$ or ~ 10cm in LEAD
  $E_c \approx 10\ MeV$



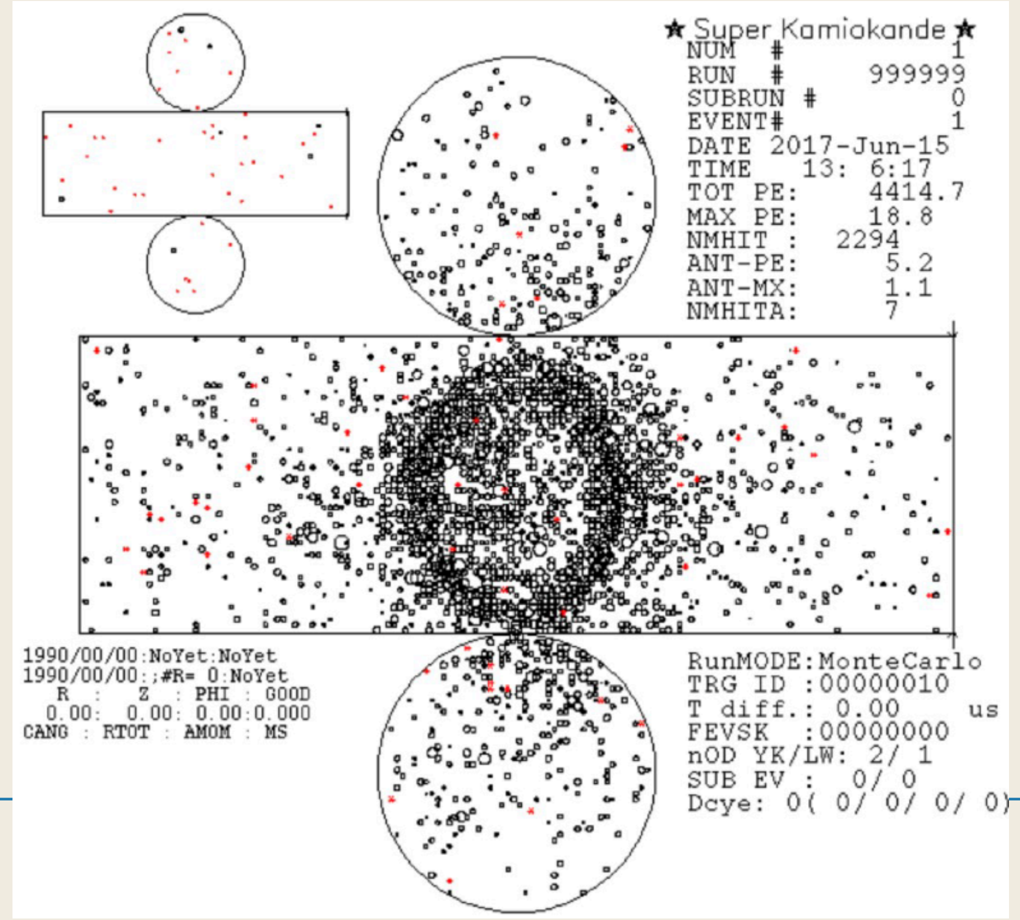
Eg. EM shower developed

by gamma ray



Eg. Fuzzy e-ring

In Cherenkov detector



Important point to keep in mind

- We don't see particle interaction directly, but its end products
- End products are detected via their interaction with active volume in the particle detector
- Any observable effect of particle when interacting with matter can be used as working principle of particle detector

↕

YOUR SUPPORTED EYES INTO THE PARTICLE WORLD

Categorize by detector functionality

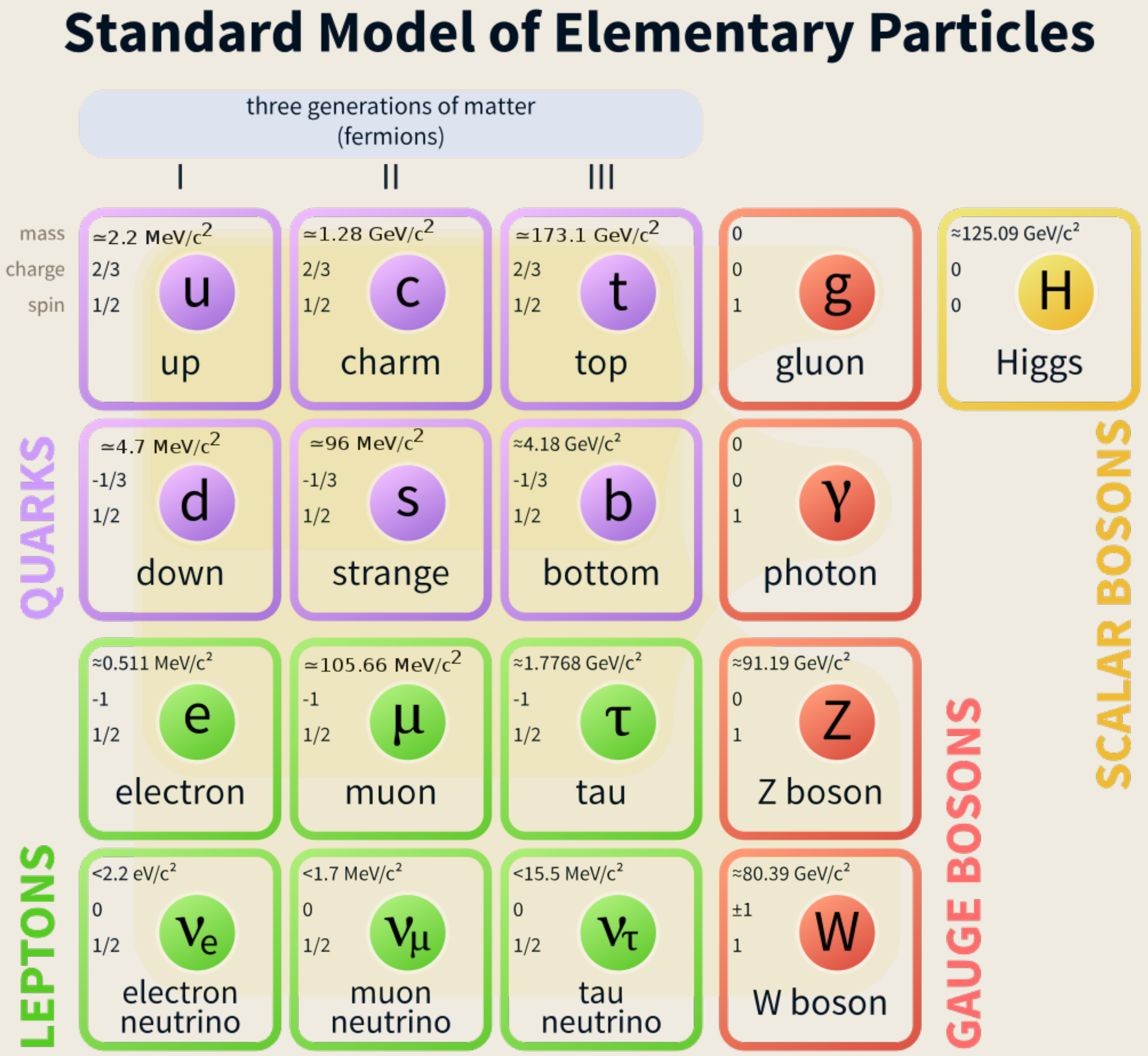
- **Particle identification**
  - Time-of-flight measurement
  - Ionization dE/dx
  - Cherenkov radiation
  - Transition radiation
  - …
- **Measurement of momentum**
  - Energy-loss range of particle
  - Curvature in magnetic field
  - Cherenkov radiation
  - …
- **Measurement of energy**
  - EM calorimeter
  - Hadron calorimeters
  - ….
- **Position or tracking particle trajectory**
  - Multiwire proportional chamber
  - Drift chamber
  - Time projection chamber..
  - Silicon detector
  - Scintillating fibers/cube/bar…
  - …
- **Timing**
  - Fast-response photosensor
  - Fast scintillator
  - …

Detector building d**epends on physical motivation, allowed technology, budge, space, time...**

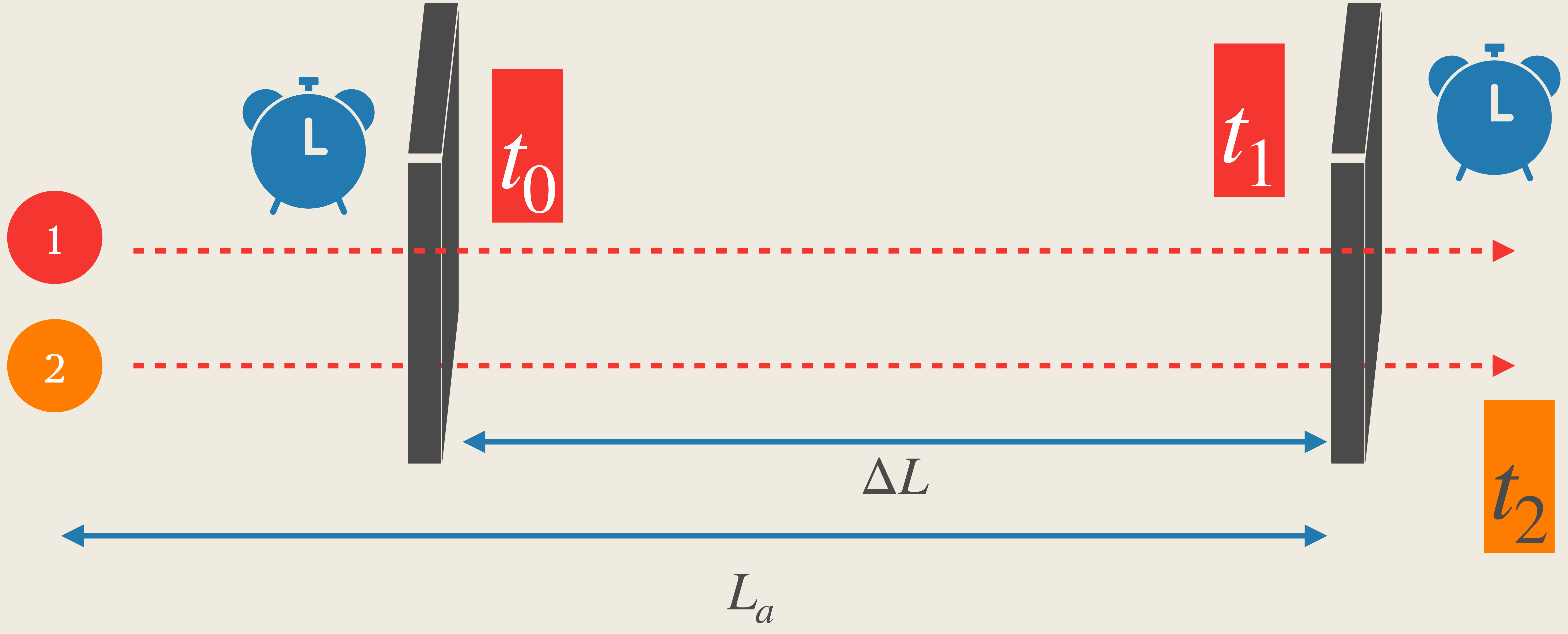
Particle identification (PID)

What kind of information used to identify particle?

- Mass
- Charge
- Spin
- "Flavor" (also "color")
    - Eg. *Electron neutrino and electron produced in pair*
- Allowed interaction processes and interaction strength
    - Eg. *Leptons (muon, electron, neutrino) do not have strong interaction*
- Prompt decay products (*eg. in case of W, Z, Higgs*)



PID w/ Time-of-flight (TOF)



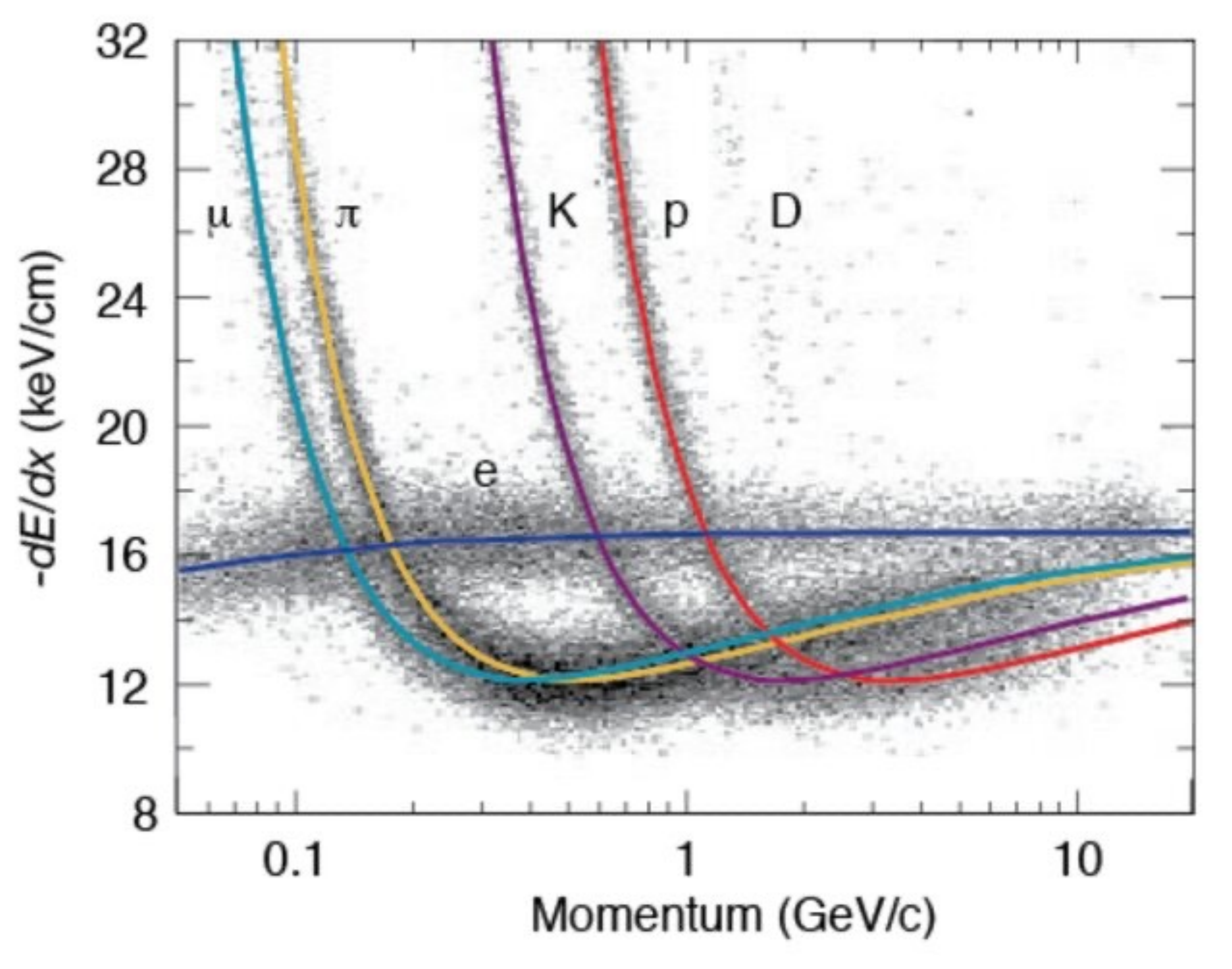
- Absolute TOF: $t_1 - t_0 = \dfrac{\Delta L}{\beta c} = \dfrac{\Delta L}{c}\sqrt{1 + \dfrac{m^2c^2}{p^2}}$

m CAN BE MEASURED IF ONE KNOWS $\Delta t_1, \Delta L, p$

- Relative TOF: $t_2 - t_1 = \dfrac{\Delta L}{\beta c} = \dfrac{L_a}{c}\left(\sqrt{1 + \dfrac{m^2c^2}{p^2}} - \sqrt{1 + \dfrac{m^2c^2}{p^2}}\right) \approx \dfrac{L_a c(m_1^2 - m_2^2)}{2p^2}$

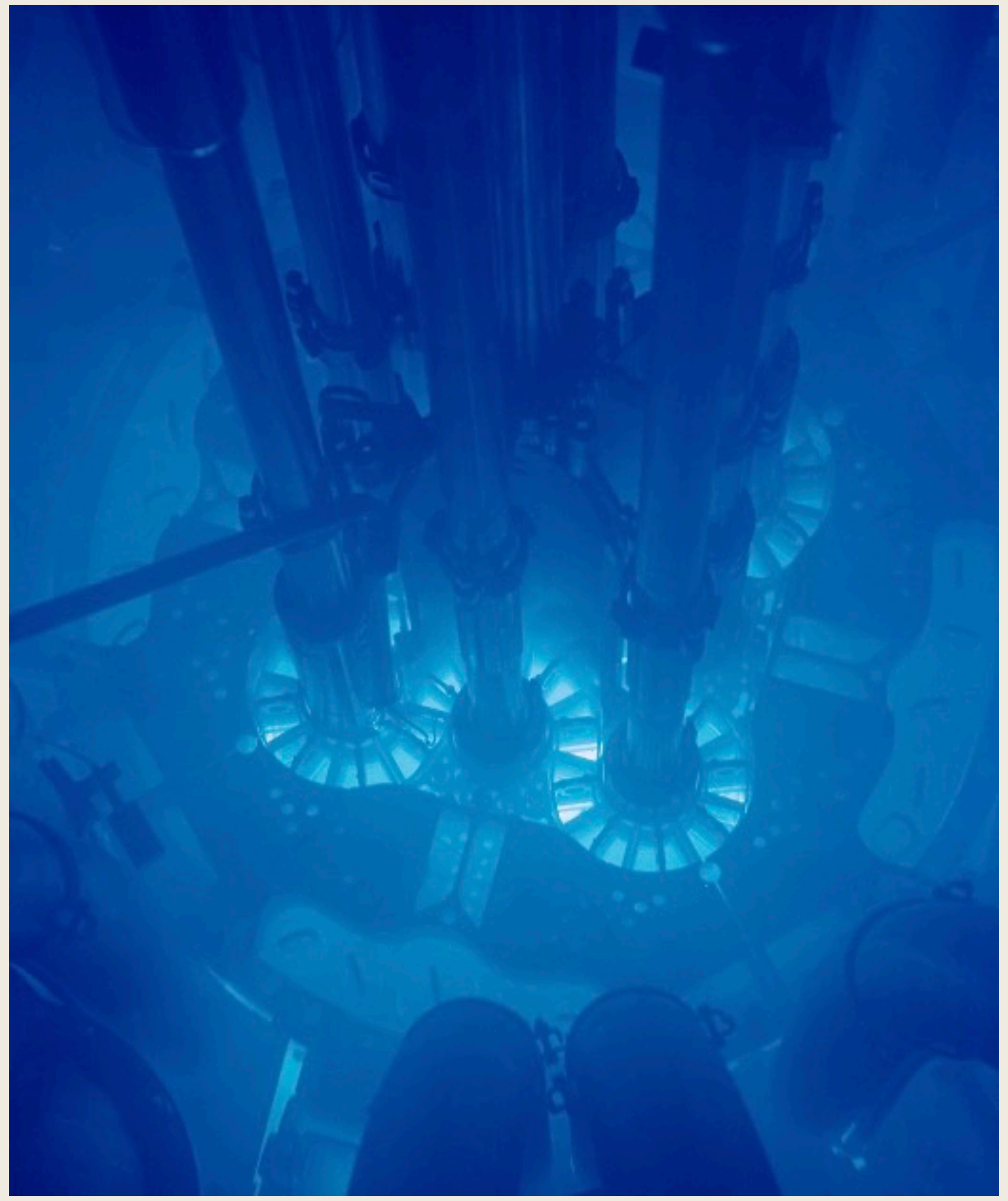
Particle identification using dE/dx

- If one can measure dE/dx simultaneously with momentum, particle can be classified
- Behavior of electron is different due to Bremsstrahlung process

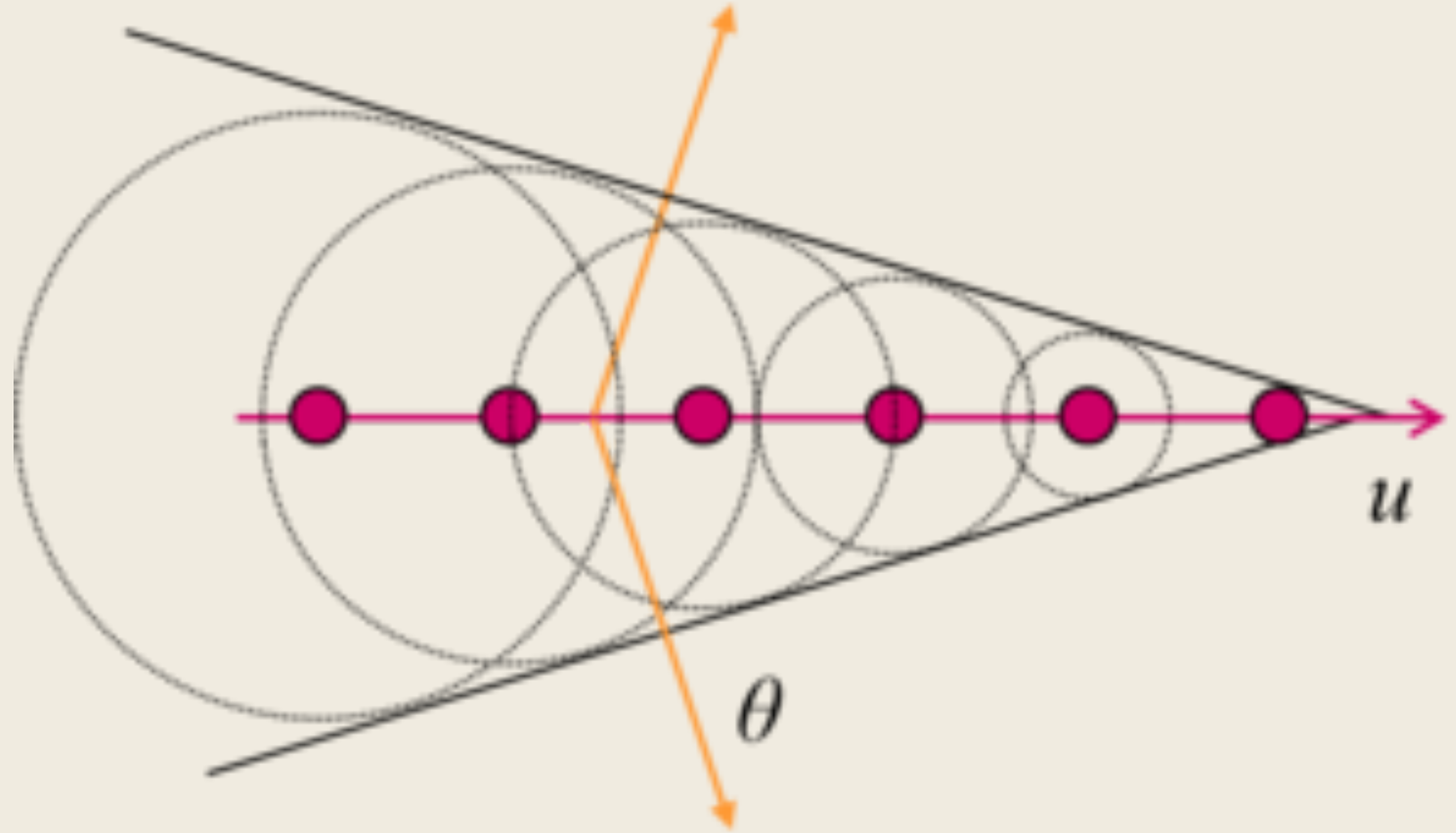


Cherenkov radiation for particle identification

- Discovered by Pavel A. Cherenkov in 1937
- It happens when a charged particle passing through a polarizable medium with speed higher than the speed of light in that medium.
  - $v = \beta c > c/n \rightarrow \beta n > 1$ where n is refractive index
- Mechanism: molecules are polarized in the direction of the charged particle moving
  - Excited molecules emit the light when back to the normal state
  - When particle moves faster than c/n, these emitted light added up constructively (interference) to emit the light at specific angle θ_C

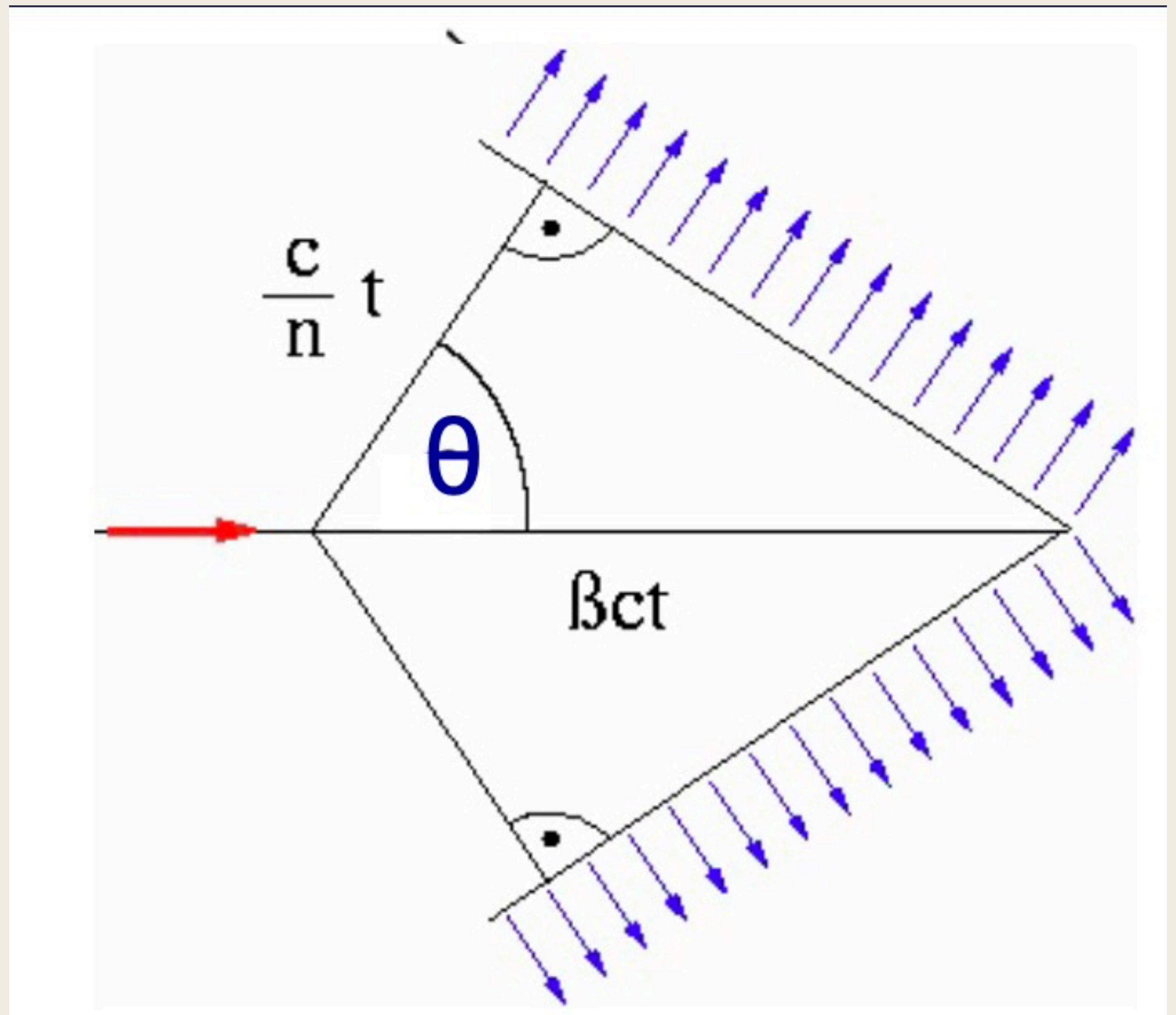


"Blue" water near reactor core



Cherenkov radiation for particle identification

- Threshold in Cherenkov radiation: $p_{th.} = \dfrac{mc/n}{\sqrt{1-n^{-2}}}$
  - In the air, threshold for pions is 5GeV/c but for Kaon is 20 GeV/c
  - In water, threshold for electron is 0.77 MeV, for muon is 160 MeV, for tau is 2.7 GeV

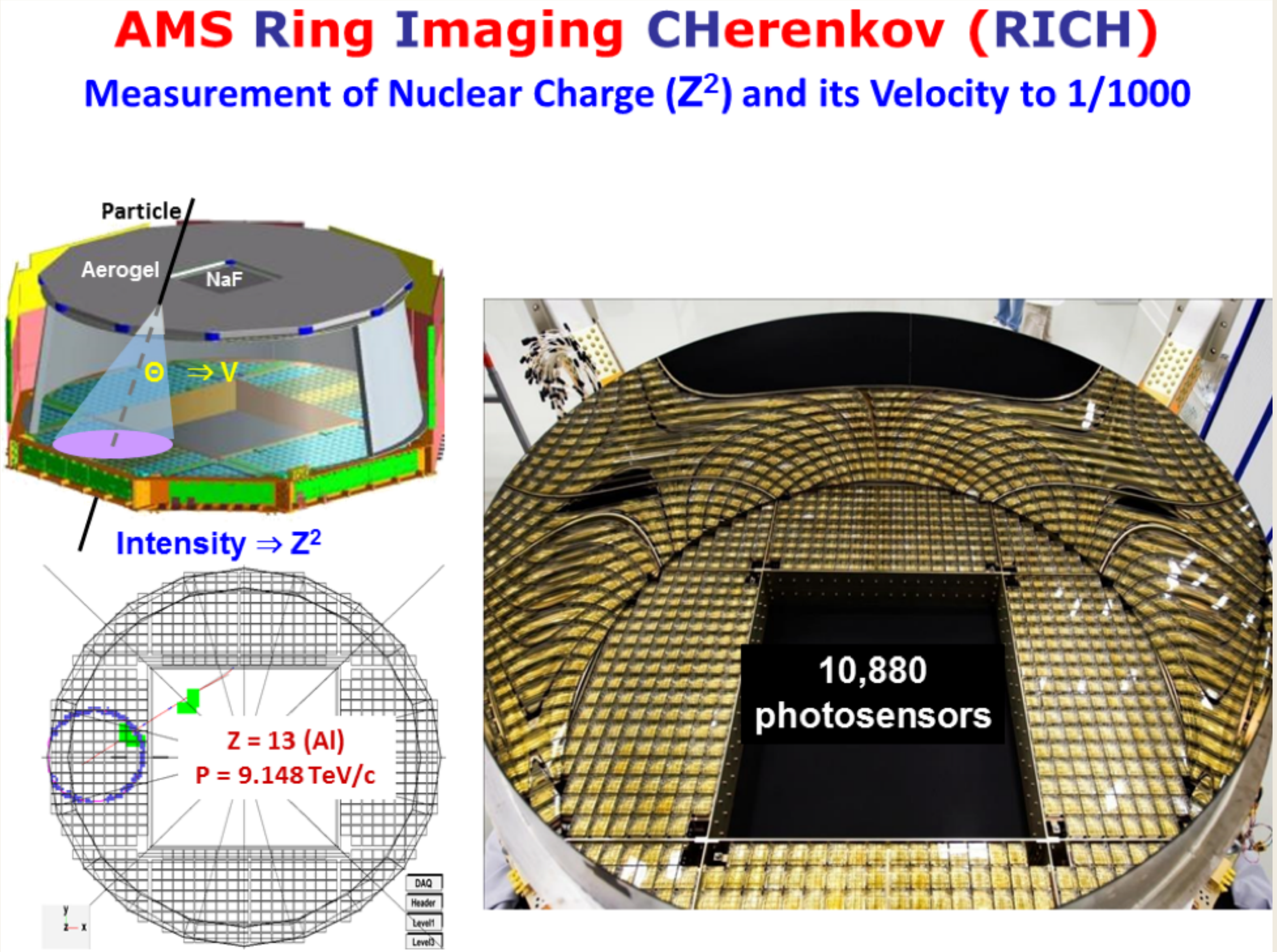


- Cherenkov angle $\cos\theta_C = \dfrac{1}{\beta n}$, **depend on** β
- Number of photons from Cherenkov radiation at a given wavelength $\dfrac{\partial^2 N}{\partial x \partial \lambda} = 2\pi\alpha(1 - 1/\beta^2 n^2)1/\lambda^2$
  - More photon at lower wavelength, so Cherenkov mostly at blue and UV range
  - **Also depend on** β

Cherenkov radiation for particle identification

Material	n-1	β_c	θ_c	photons/cm
solid natrium	3.22	0.24	76.3	462
Lead sulfite	2.91	0.26	75.2	457
Diamond	1.42	0.41	65.6	406
Zinc sulfite	1.37	0.42	65	402
silver chloride	1.07	0.48	61.1	376
Flint glass	0.92	0.52	58.6	357
Lead crystal	0.67	0.6	53.2	314
Plexiglass	0.48	0.66	47.5	261
Water	0.33	0.75	41.2	213
Aerogel	0.075	0.93	21.5	66
Pentan	1.70E-03	0.9983	6.7	7
Air	2.90E-03	0.9997	1.38	0.3
He	3.30E-05	0.999971	0.46	0.03

Cherenkov radiation for PID: RICH exp.

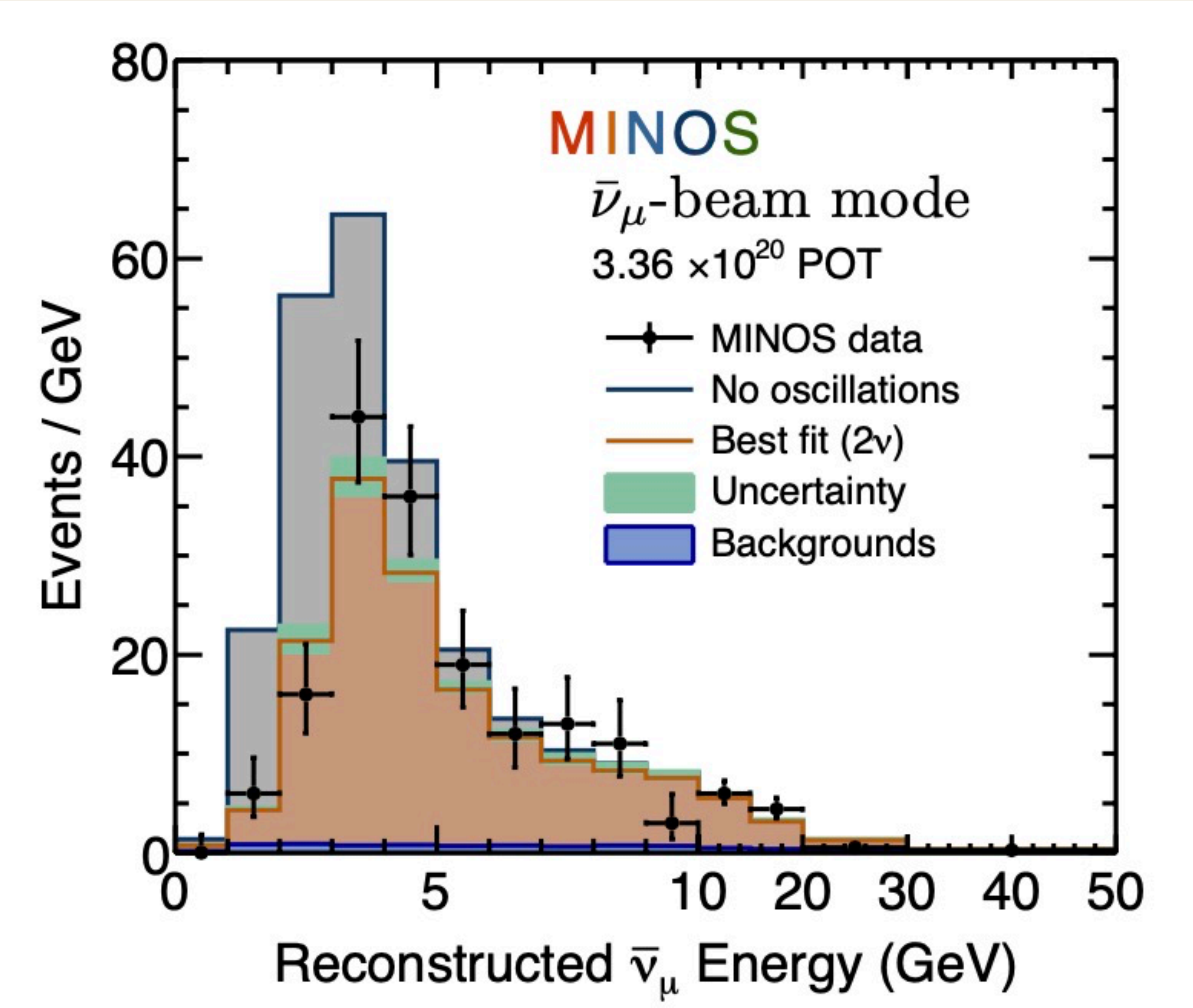


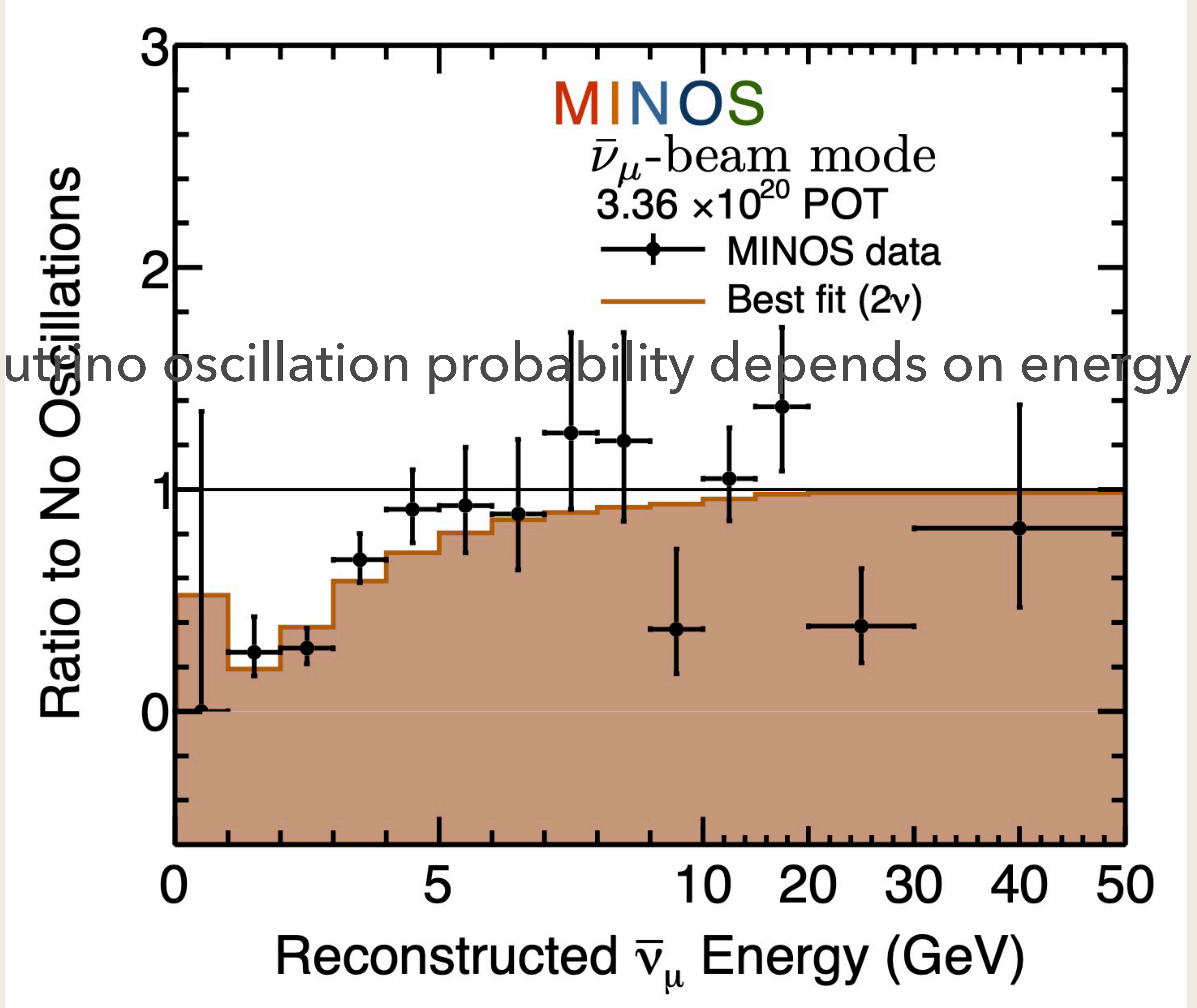
https://ams02.space/detector/ring-imaging-cherenkov-detector-rich

Measurement of energy: Calorimeter

Calorimeter for neutrino oscillation measurement

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu}$$



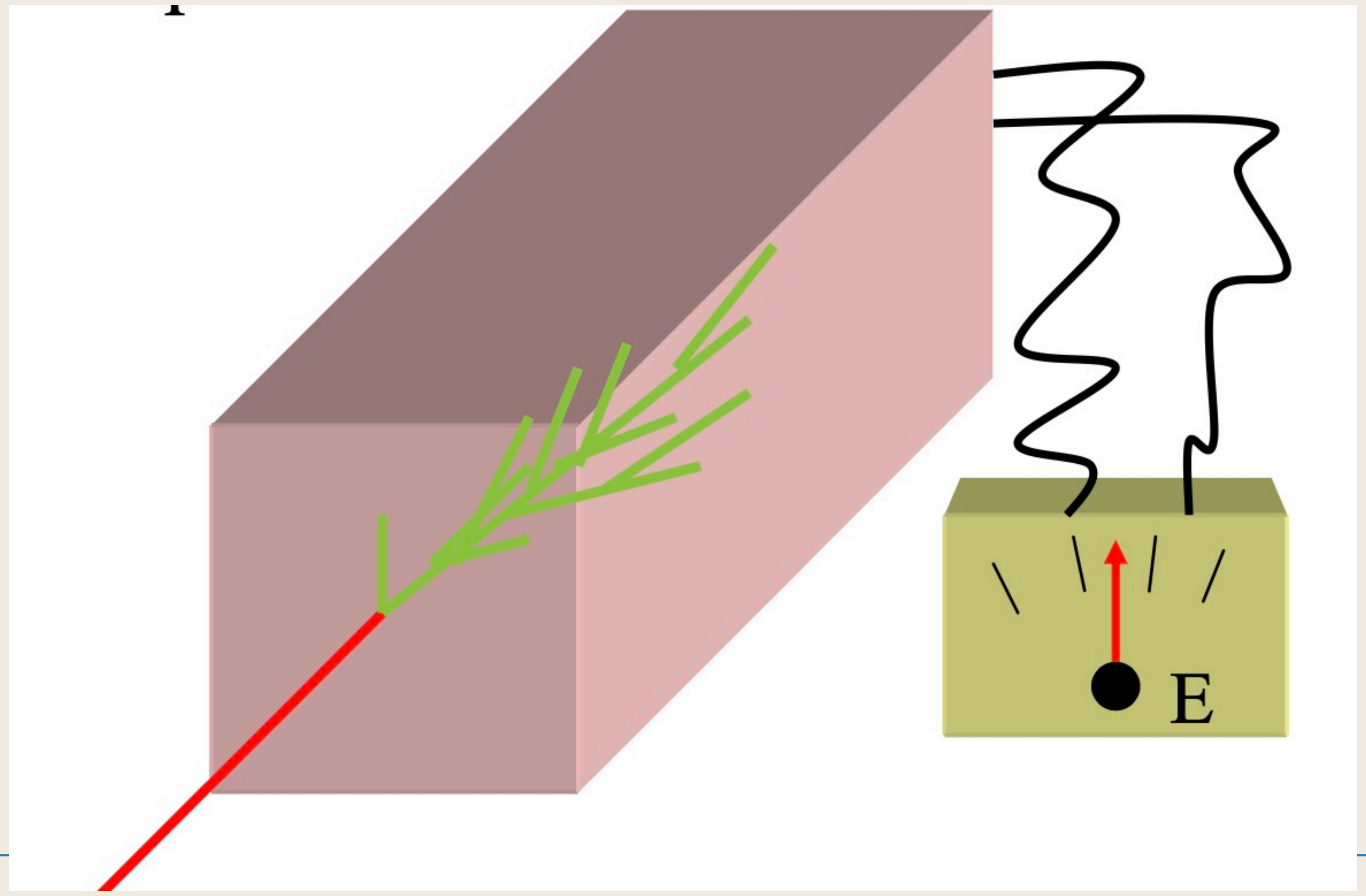


Neutrino oscillation probability depends on energy

Calorimeter: design consideration

Principle: detect particles through total absorption in matter volume of the detector

- **Large enough** and/or **high-density material** to **absorb all of the energy** of to-be-measured particles (*include both charged and neutral particle*)
- R**ecord signal (charge or light collection) to refer to the energy lost**
- Sufficiently **granular** to tell not just how much but where energy was deposited
- **Other practical consideration**: small enough to fit in detector, not too expensive, radiation hardness; fast read-out depending on event rate…



Energy resolution of calorimeter

- Spectrometer performance is characterized by "energy resolution" , typically as σ_E/E
  - Ideally $E \sim N;\ \ \sigma_E \sim \sqrt{N}$. So $\dfrac{\sigma_E}{E} \sim \dfrac{1}{\sqrt{E}}$
  - In reality $\dfrac{\sigma_E}{E} \sim \dfrac{a}{\sqrt{E}} \oplus b \oplus \dfrac{c}{E}$

STOCHASTIC TERM

CONSTANT TERM

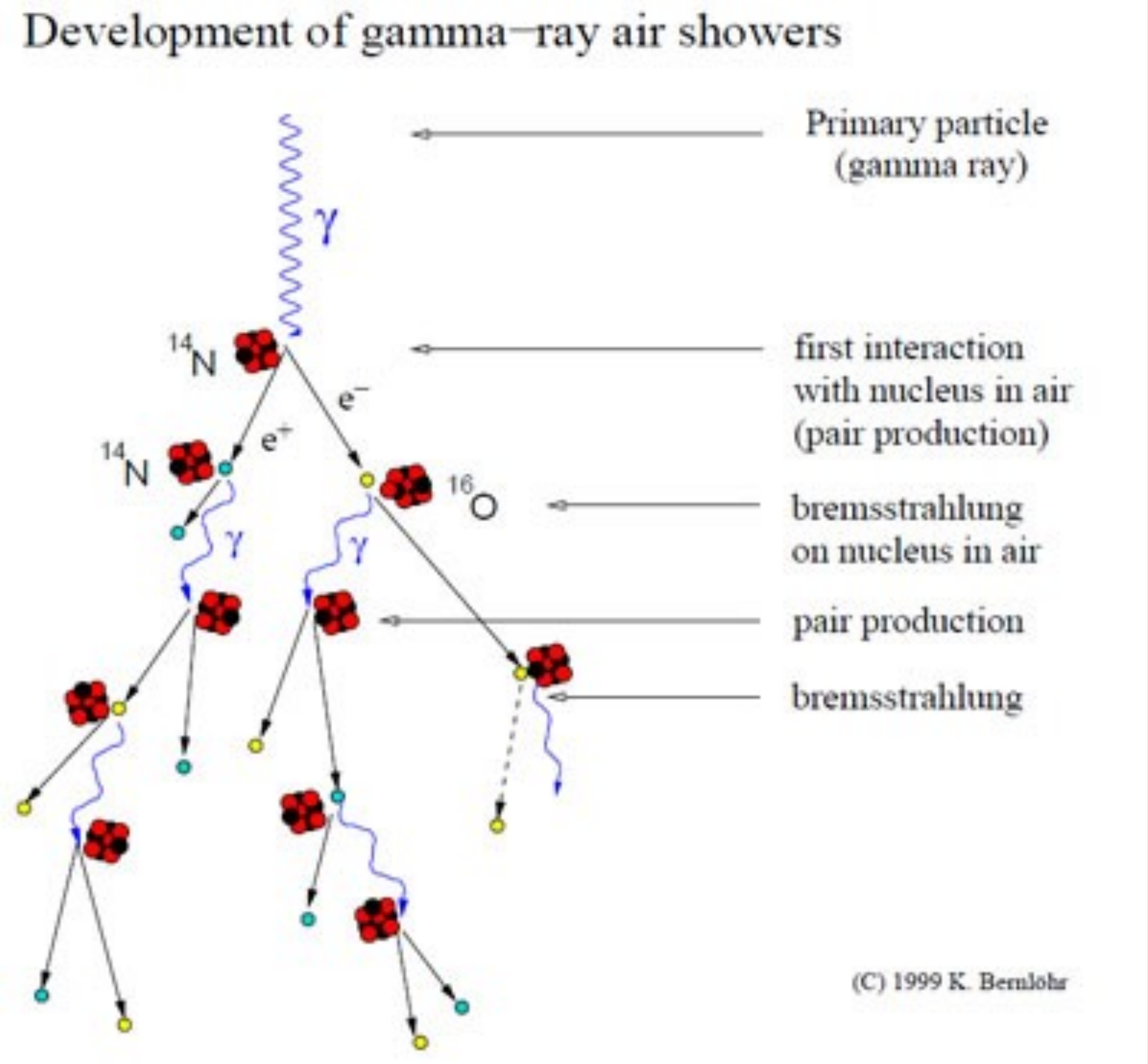
NOISE TERM

- Essential task: calibrate conversion btw. what observed (eg. scintillation light) to energy

Electromagnetic shower development

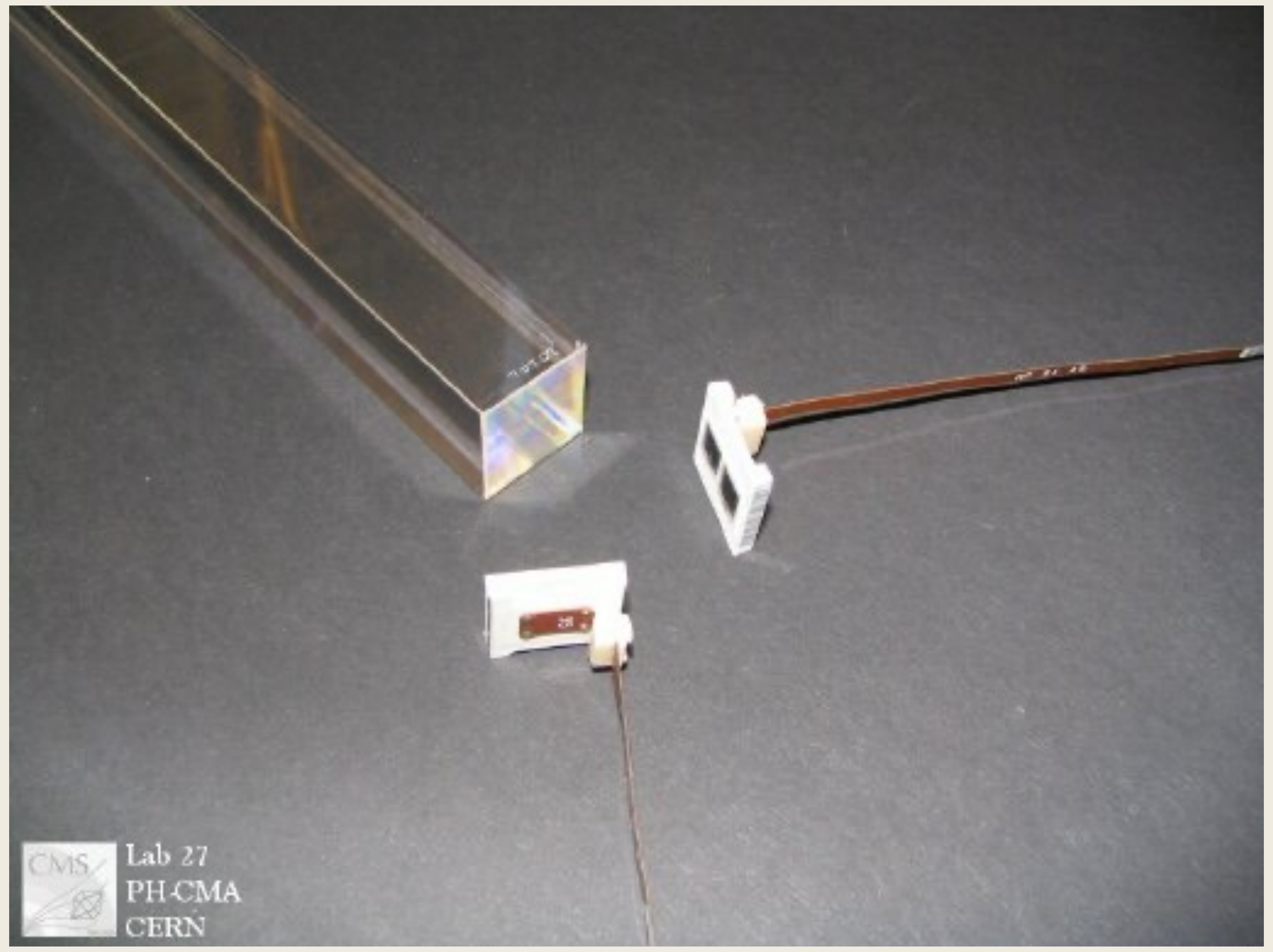
- Electromagnetic shower: High-energy photons produce pair of electrons and positrons
- Electrons and positrons radiate photons via Breamsstrahlung when travel through matter, interacting with fields of atoms
- One electron fall below critical energy, more energy loss via ionisation than bremsstrahlung and the shower stops growing

$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/\mathrm{GeV}}}.$$



Broadly two types: homogeneous and sampling

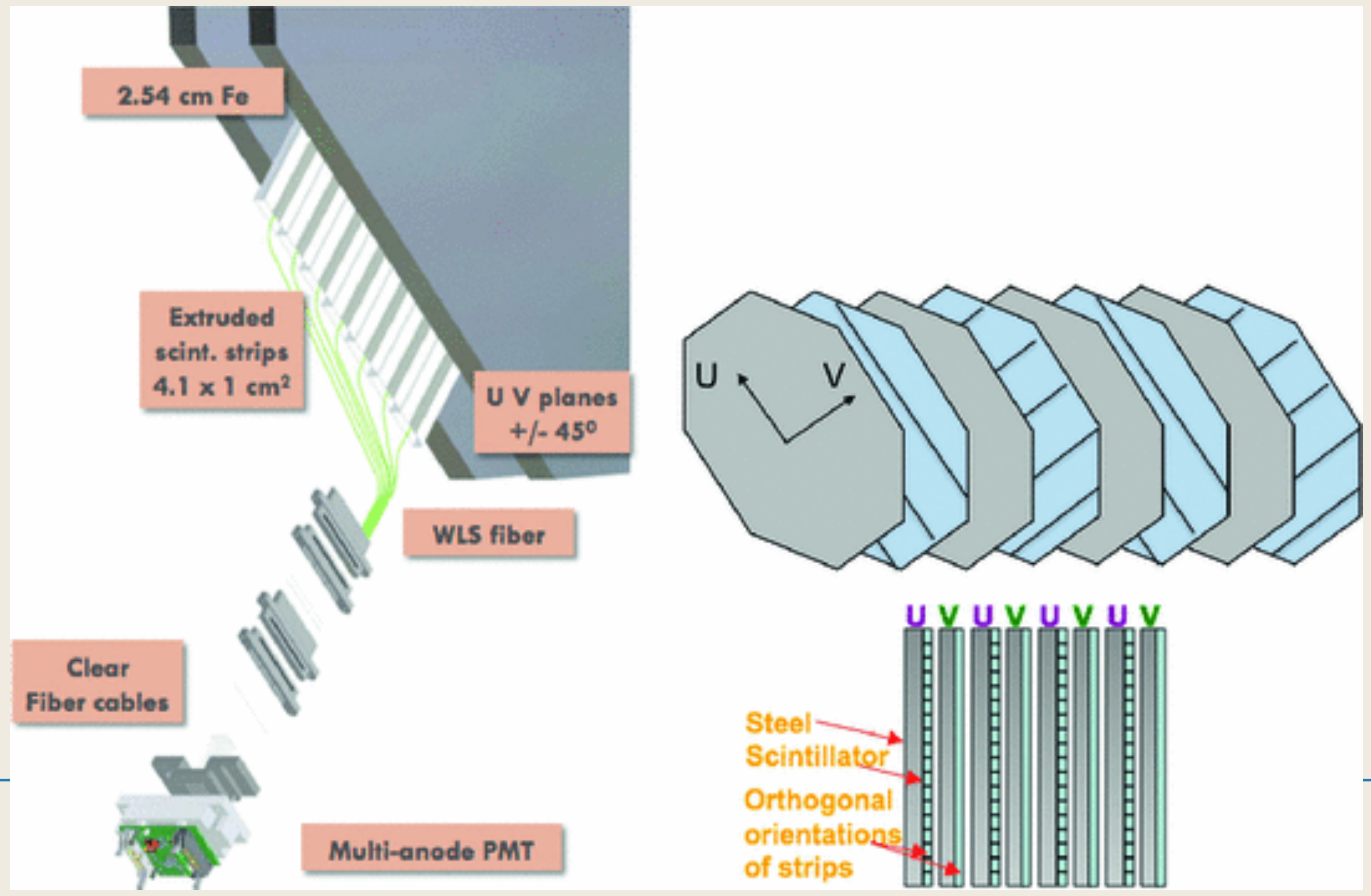
- Homogeneous type: all active volume, typically with high density transparent materials
  - Pros: excellent energy resolution
  - Cons: expensive; some limit in spatial resolution
- Sampling: consists of both passive (high Z materials like iron, tungsten) and active (scintillator) absorbers
  - Pros: cost-effective
  - Cons: not good energy resolution like the homogeneous type



CMS ECAL: USE 80,000 $PBWO_4$ CRYSTAL

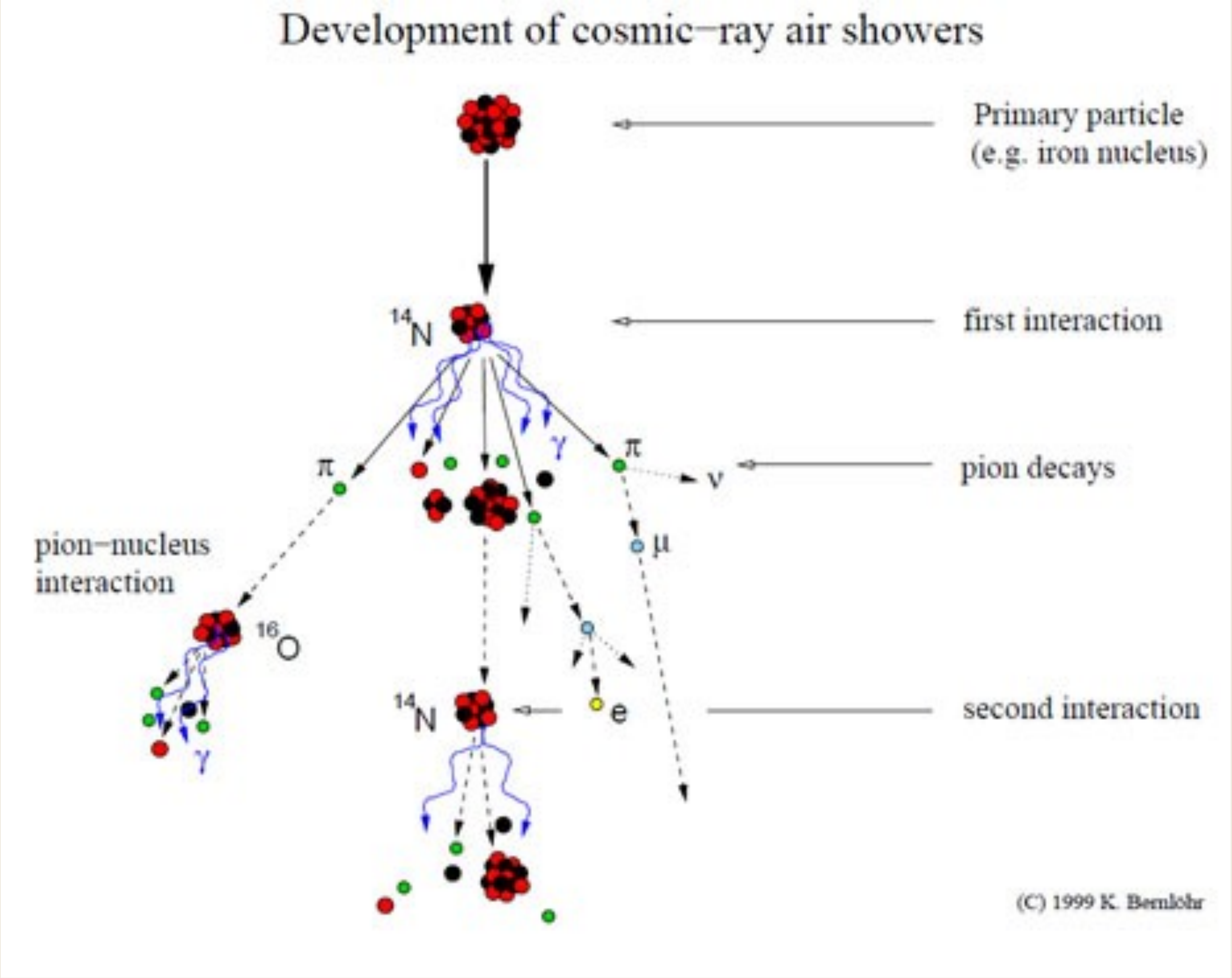
Can achieve $$\frac{\sigma_E}{E} \sim \frac{2.7\,\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.2}{E}$$

MINOS (+): STEEL-SCINTILLATOR SANDWICH



Hadronic shower development

- Driven by inelastic nuclear scattering
- Interaction length $\lambda_{int.} = 35\ [g/cm^2]\ A^{1/3}$, only depend on detector material
  - Eg. In iron, $\rho \approx 7.8\ g/cm^3$, A=28, interaction is about X_0= 13cm
  - Calorimeter thickness is about 9 X_0
- Complicated shower with pion, neutron, photon (from neutral pion), neutrino
- Some energy loss can't be observed, eg. Neutrino, nuclear binding energy …
- Typically, hadronic shower energy resolution is worse than EM shower



$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/\mathrm{GeV}}},$$

Hadron calorimeter thickness

Medium	Density ρ [g/cm^3]	Interaction length λ_{INT} [cm]
Copper (Cu)	9.0	15.1
Lead (Pb) (ATLAS)	11.4	17.1
Uranium (U) (ZEUS)	19.0	10.5
Iron (Fe)	7.9	16.8
Plastic scintillator	~1.0	~80
Concrete	~2.5	~40

For "full" containment calorimeter thickness needed is about 9 λ_{INT}:

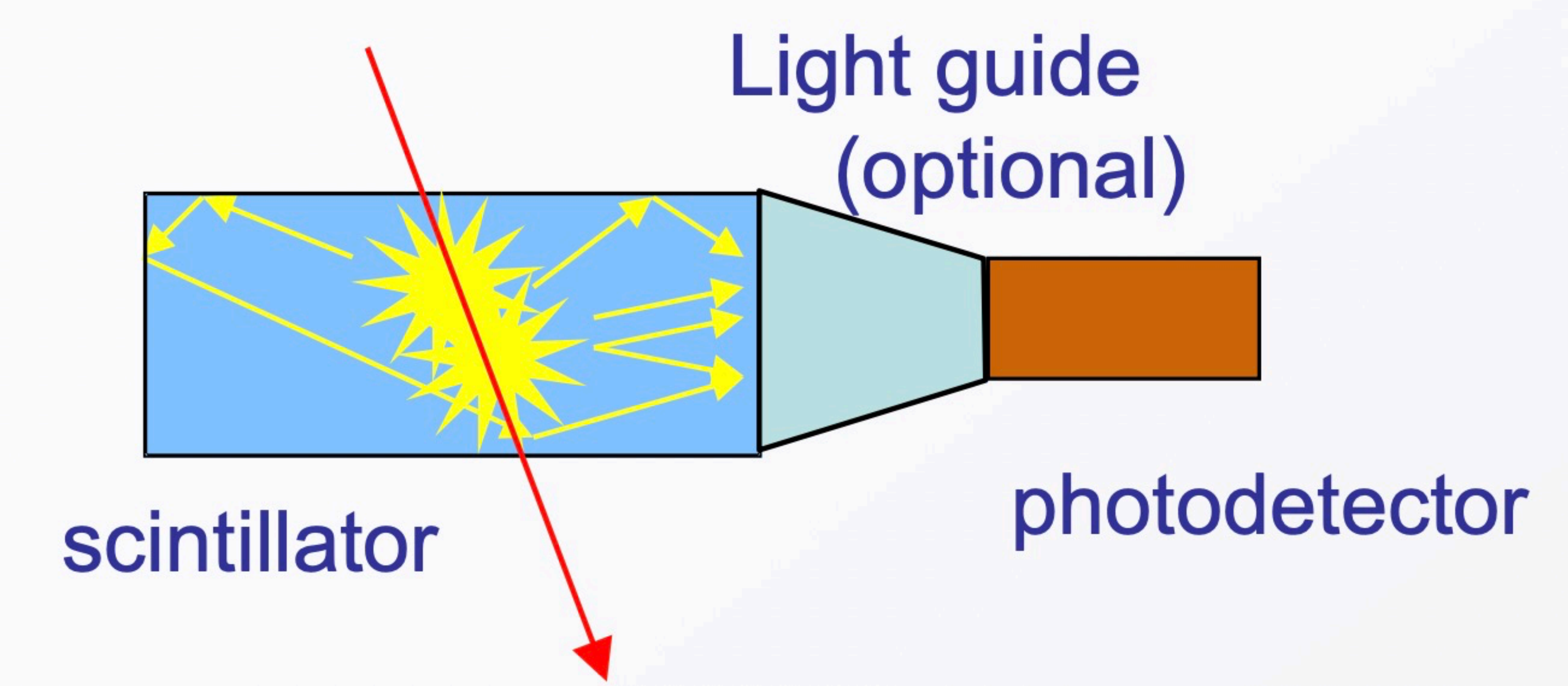
- **136 cm of copper**
- **154 cm of lead**
- **95 cm of uranium**
- **150 cm of iron**
- **~7 m of plastic-scintillator!!**
- **~3.6 cm of concrete**

Hadron calorimeters need to be deep!

Calorimeter techniques

- Common modern techniques used:
  - Gaseous/liquid Argon ionization
  - Scintillator detector
  - Cherenkov detector
  - …

Scintillation detector



- One of the most common techniques in PN physics
- To detect energy deposited by ionizing particles or photons
- Broadly categorized into: organic scintillator and inorganic scintillator
- Main detection characteristics: linearity to energy; fast response (fast rising time)

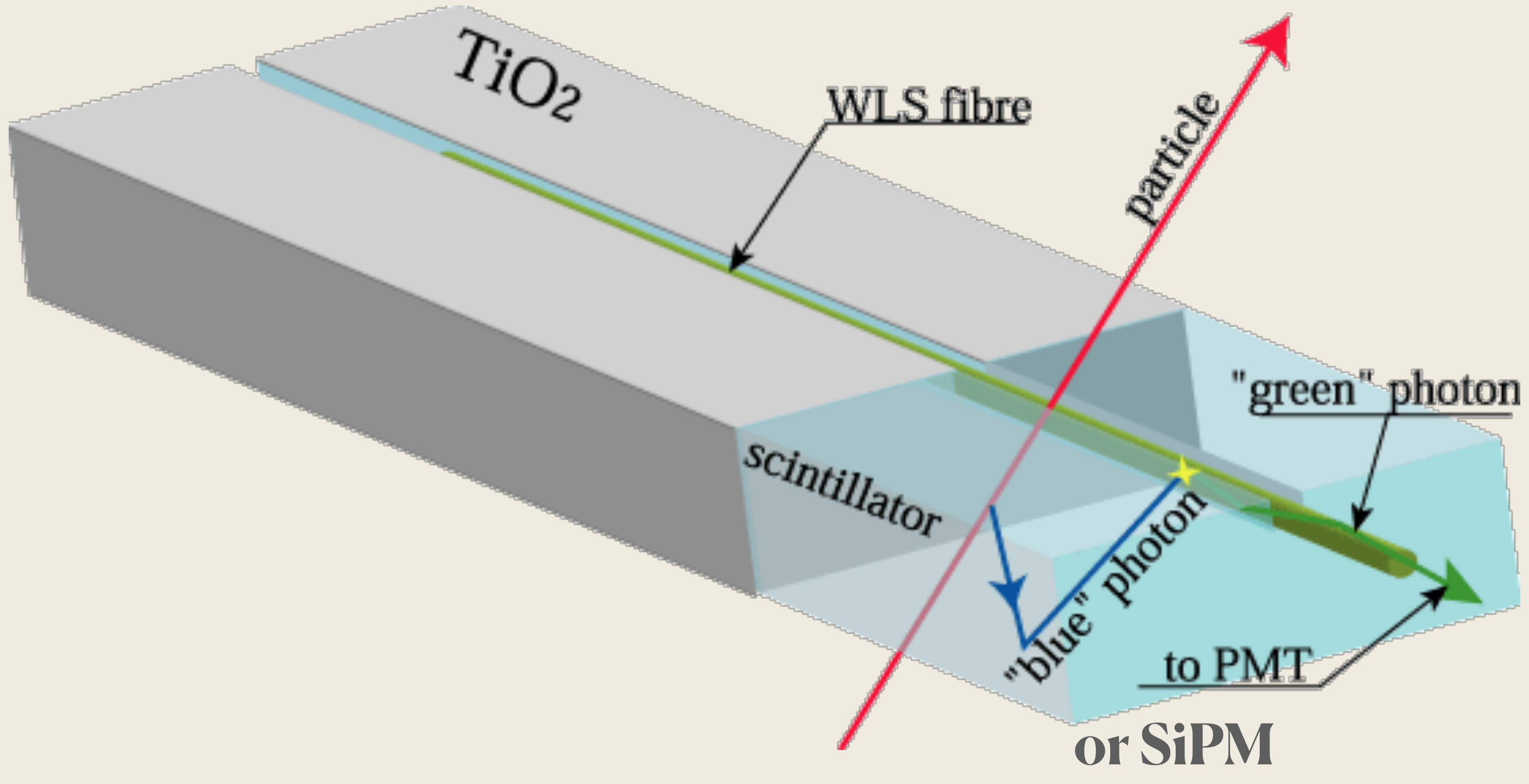
- Inorganic Scintillators
  - Advantages
    - high light yield [typical; $\varepsilon_{sc} \approx 0.13$]
    - high density [e.g. $PBWO_4$: 8.3 g/cm^3]
    - good energy resolution (→Calorimeters)
  - Disadvantages complicated crystal growth
  - large temperature dependence

Light yield $\varepsilon_{sc} \equiv$ fraction of energy loss going into photons

EXPENSIVE

- Organic Scintillators
  - Advantages
    - very fast ➔pulse shape discrimination possible
    - easily shaped
    - small temperature dependence
  - Disadvantages
    - lower light yield [typical; $\varepsilon_{sc} \approx 0.03$]
    - low density [e.g. 1 g/cm^3]
    - radiation damage

CHEAP



Sometimes need to use with WLS

And normally read out with fast photo-sensor

Tracking detector

Tracking detector

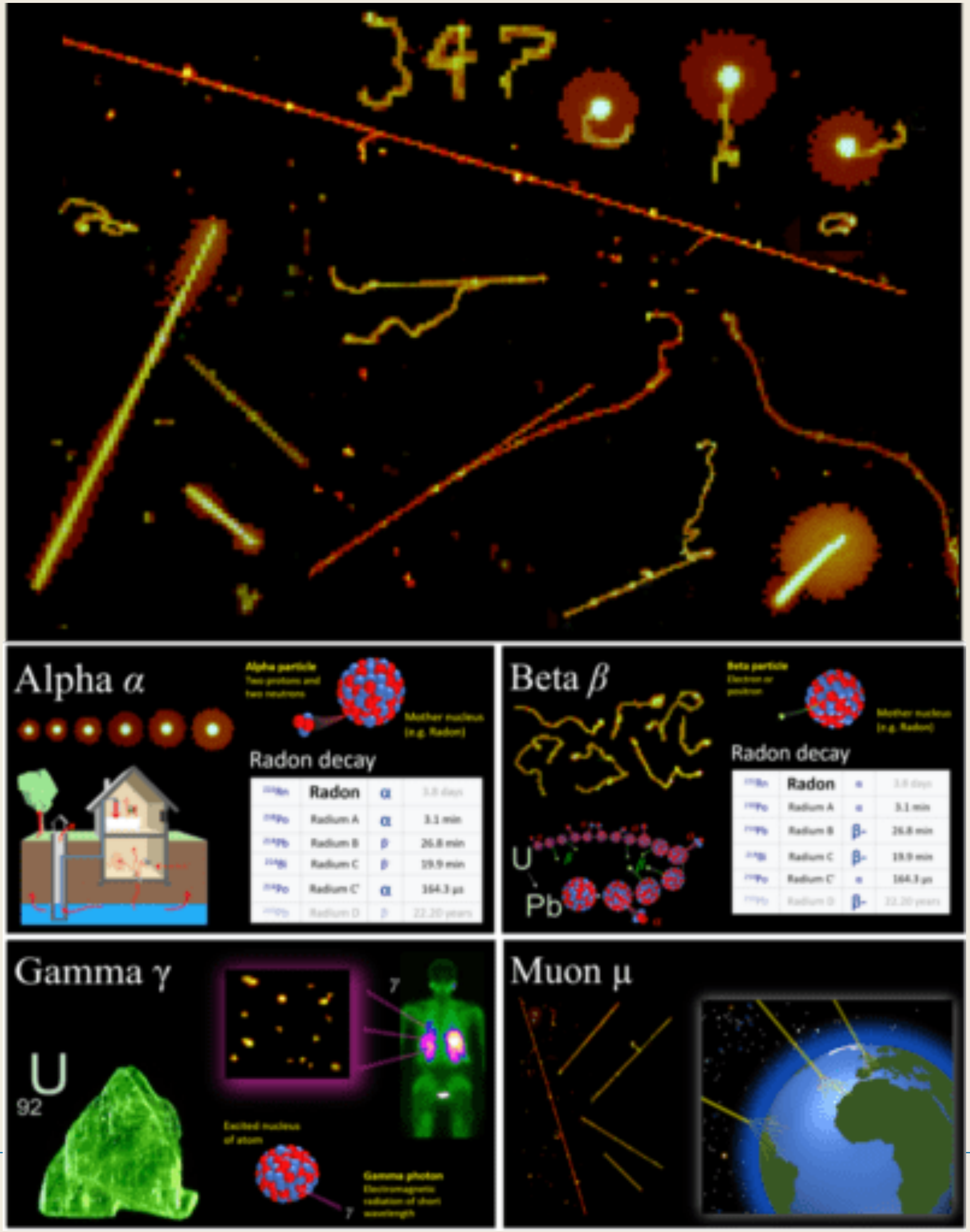
To reveals the path, or “track”, of a (charged) particle by providing

- Spatial information
- Temporal information
- *While tracking, the detector also provide (partly) information of particle energy via measuring of the energy loss*
- *Sometimes, tracking detector can be designed to measure some particle properties, eg. charge, and/or momentum.*

Eg. State-of-art of radiation tracking to the classroom

A transferred technology by CERN, being use by NASA

(Sometimes in the future, we hope to have this!)



https://advacam.com/application/education/

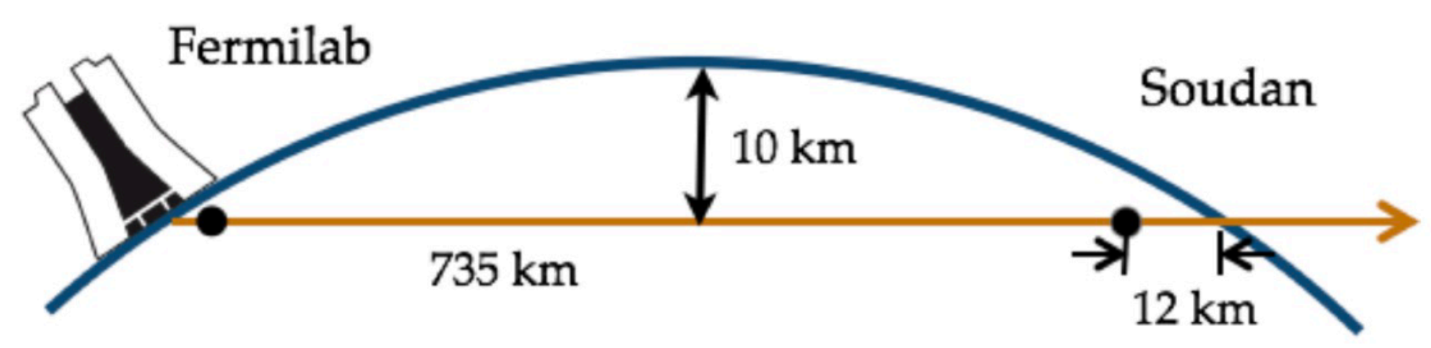
Principle for tracking

Charged particle passing through matter

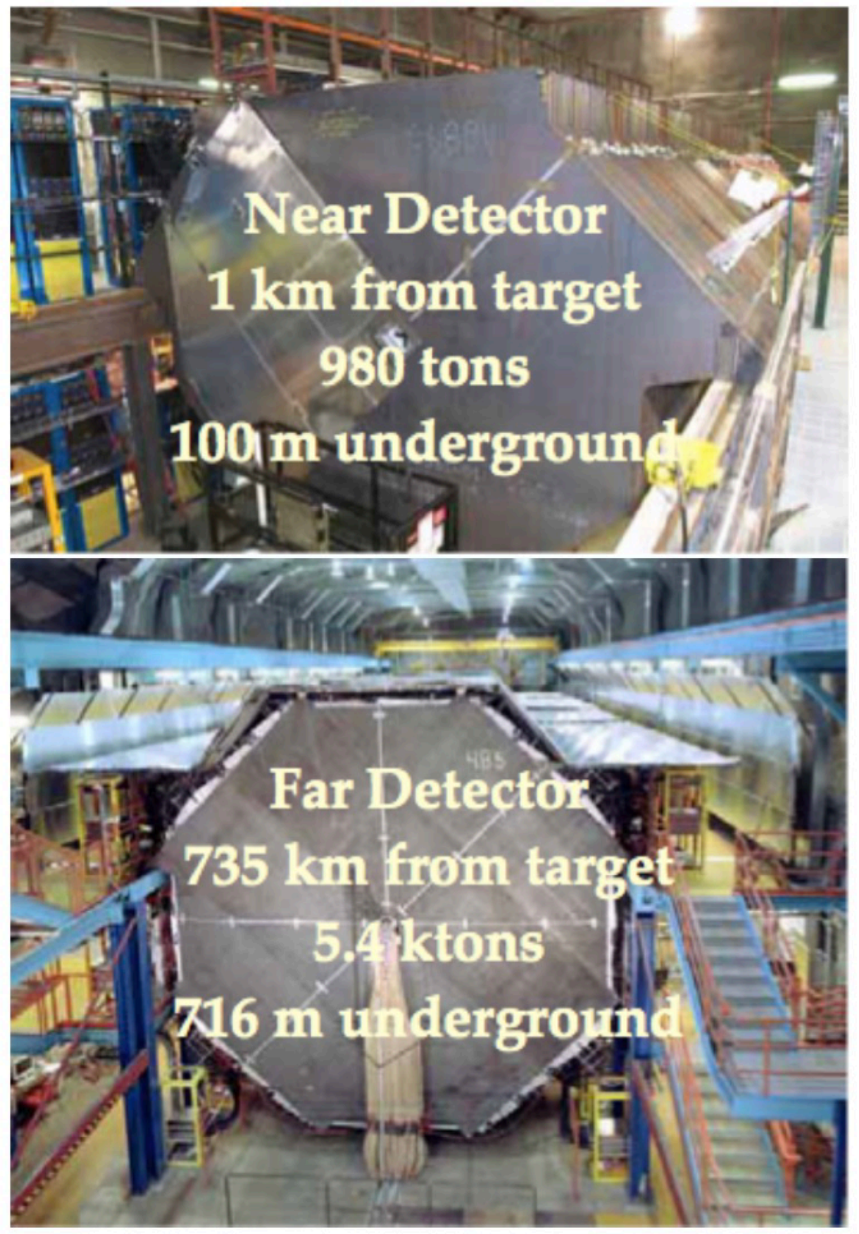
- Create **electron-ion pairs** in the gas
- **Electron-hole pairs** in semiconductor
- **Scintillation light** from excited molecules (liquid/plastic scintillators)
- **Cherenkov light** in the transparent materials
- …

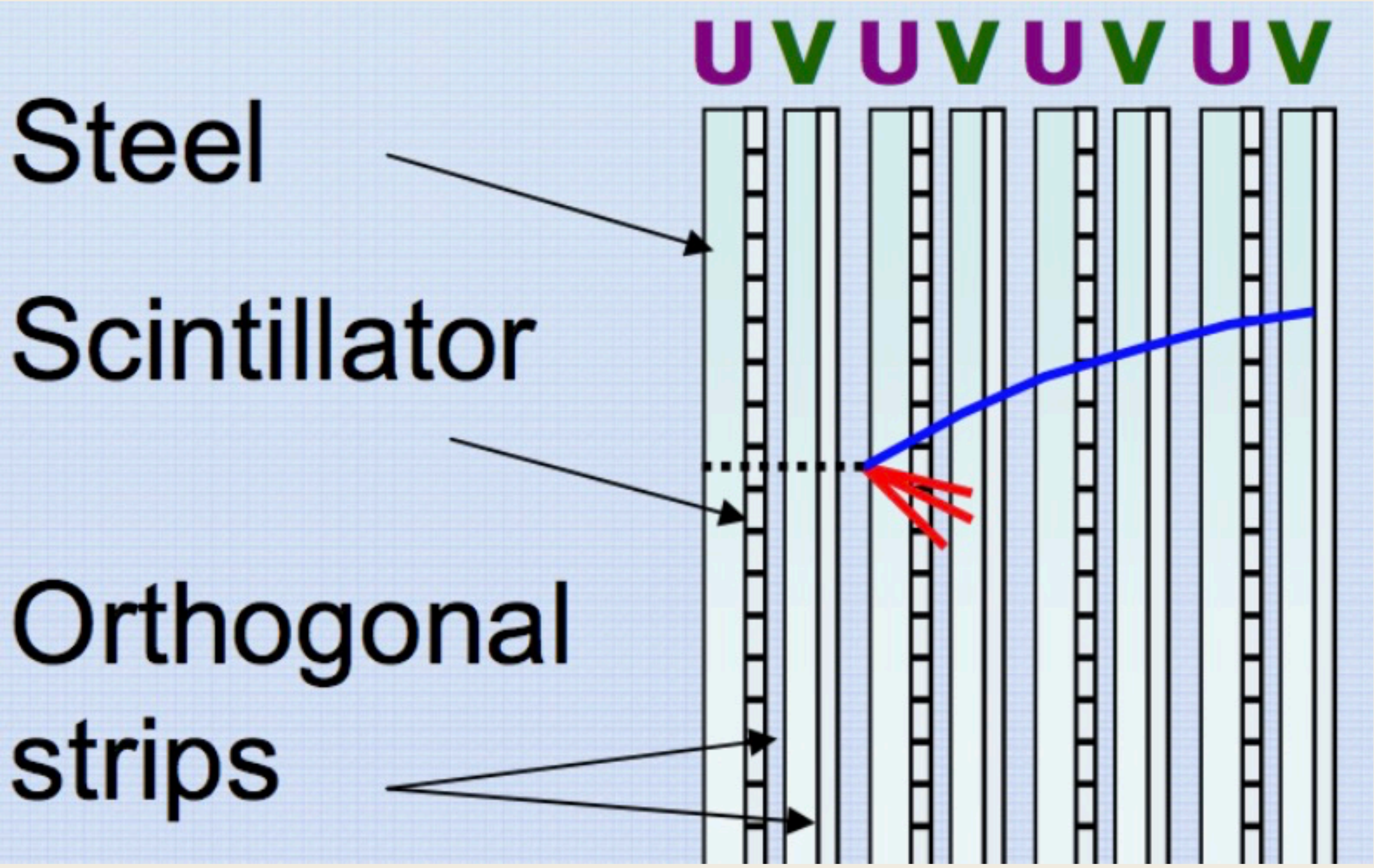
Understand these fundamental processes is critical for designing a tracking system.

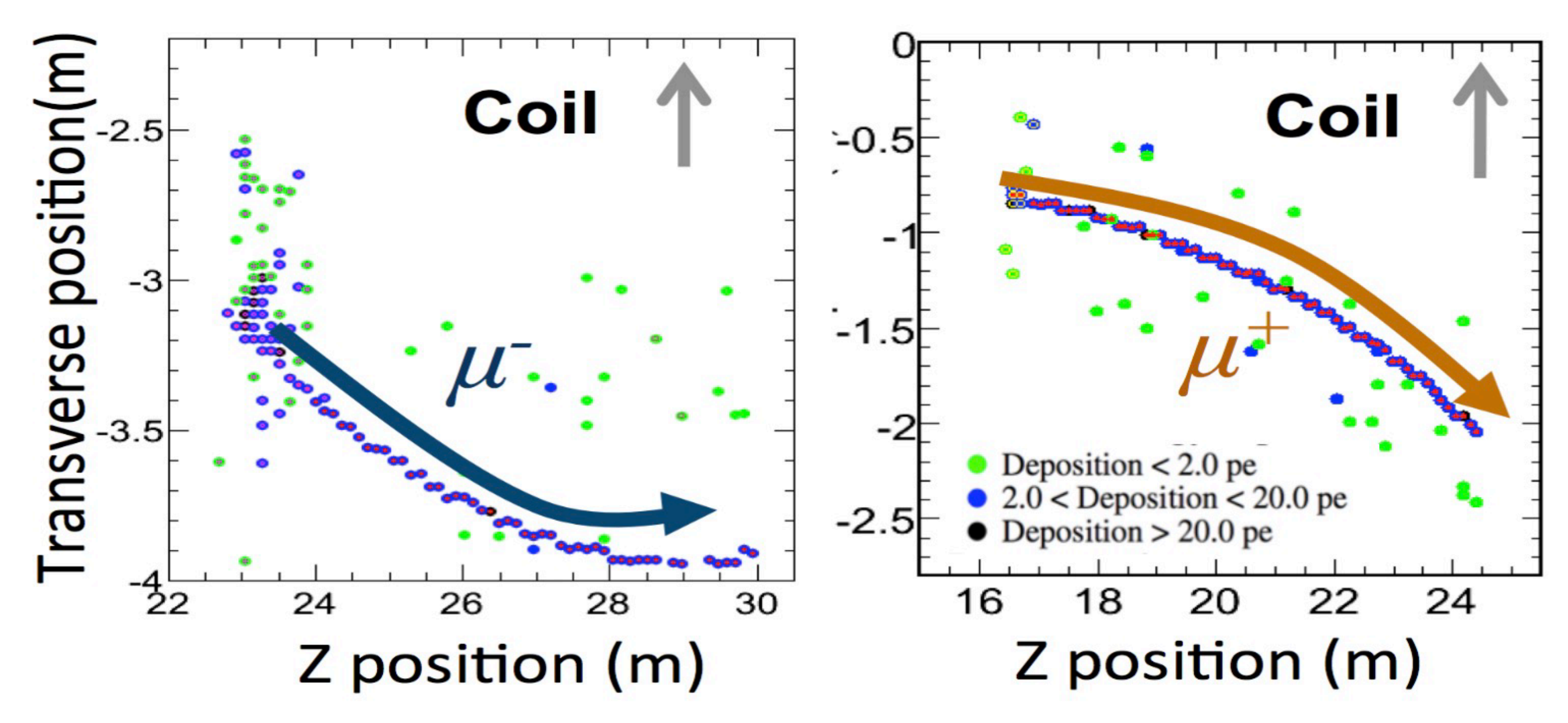
Eg: Tracking with MINOS experiment



- ✧ NuMI high intensity neutrino beam
- ✧ Near Detector at Fermilab, IL
- ✧ Far Detector at Soudan, MN
- ✧ Two-detector design to mitigate systematic uncertainties

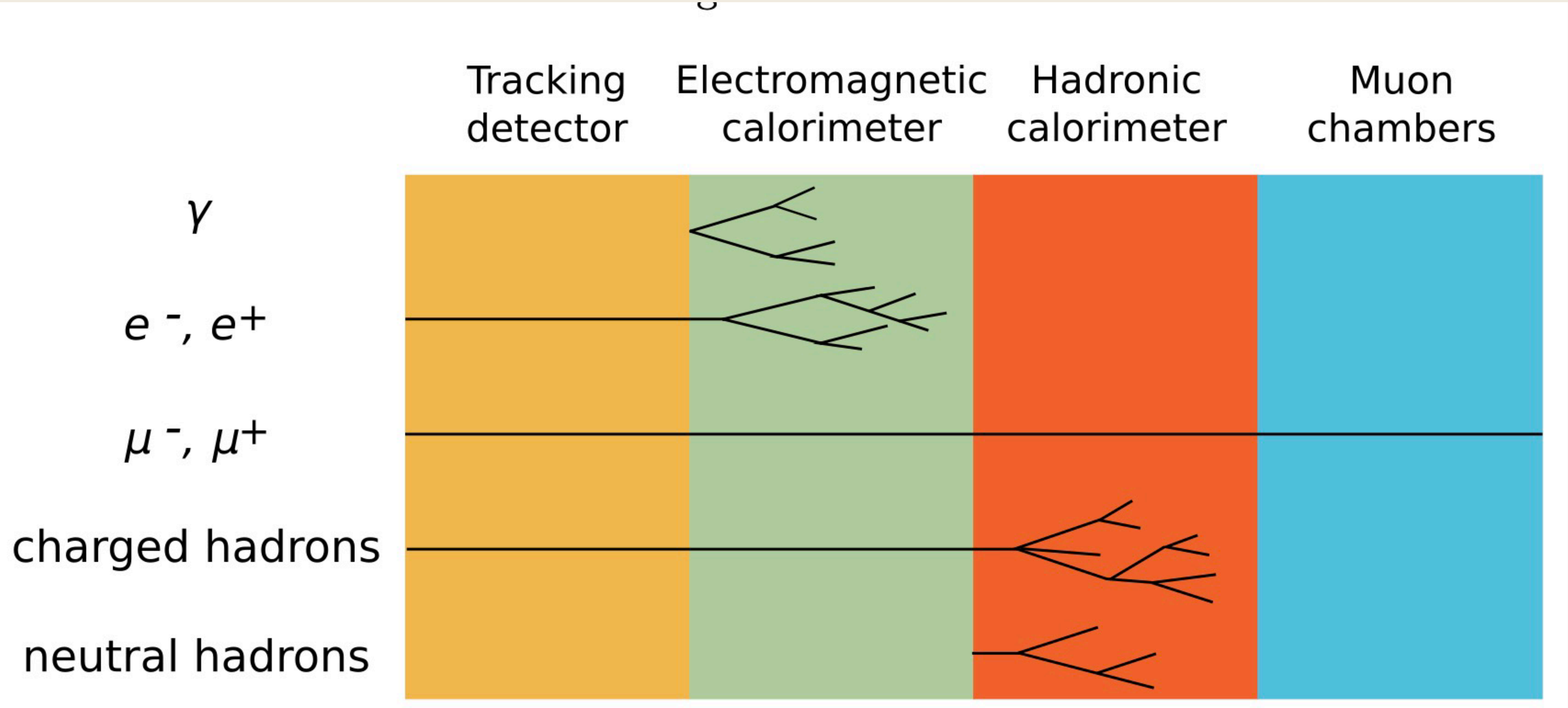






State-of-art of particle detector

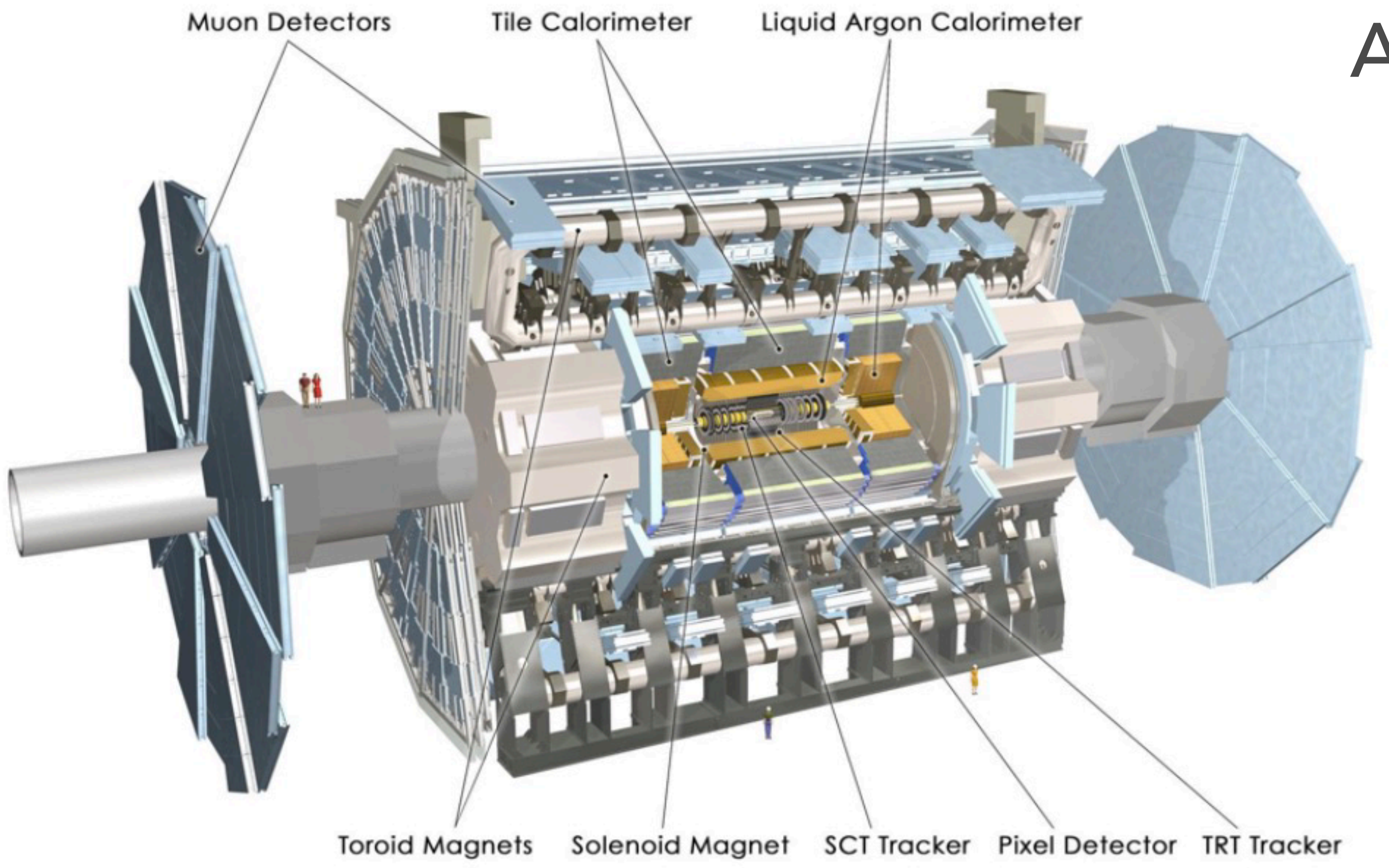
State-of-art of particle detection

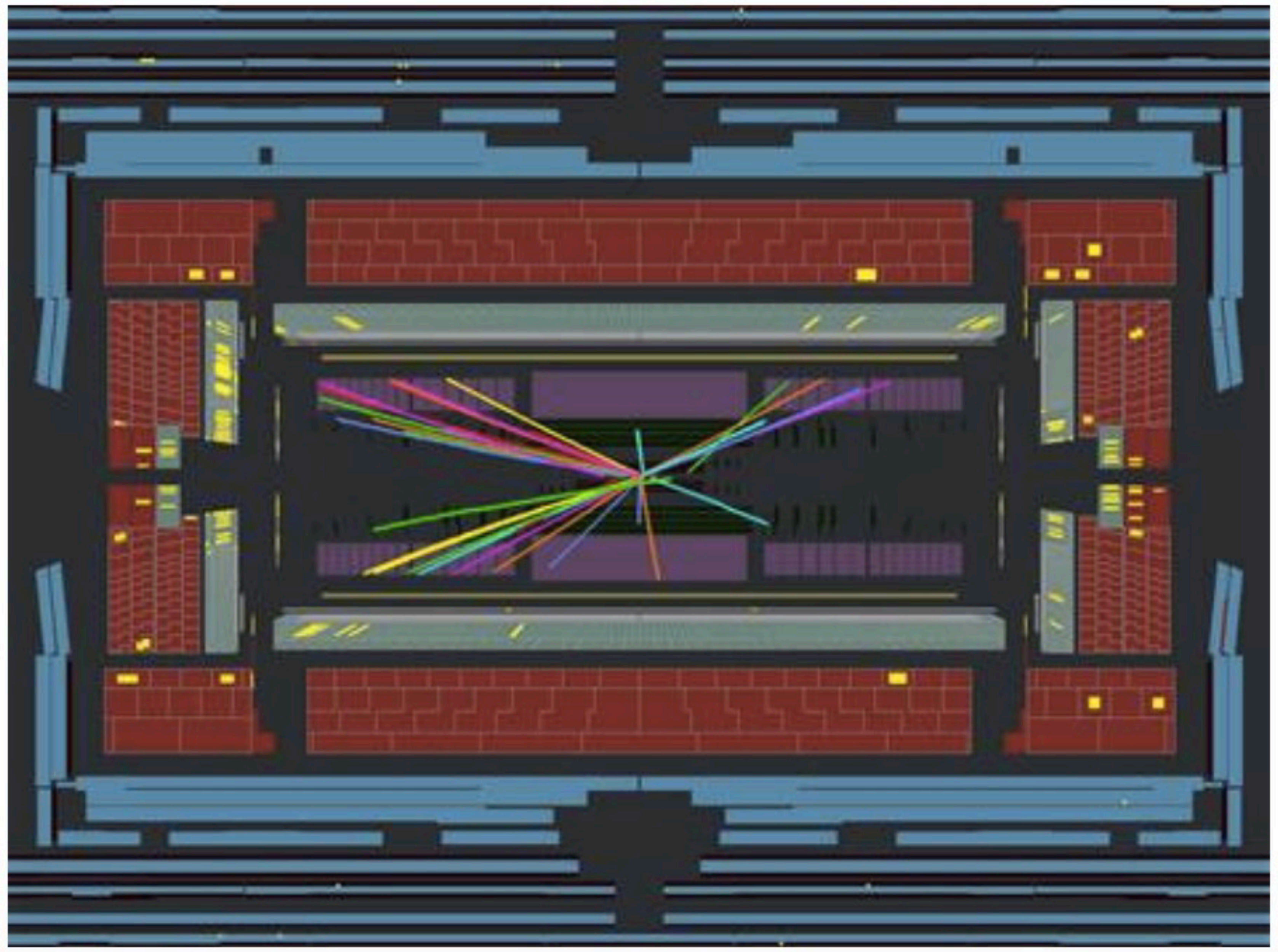


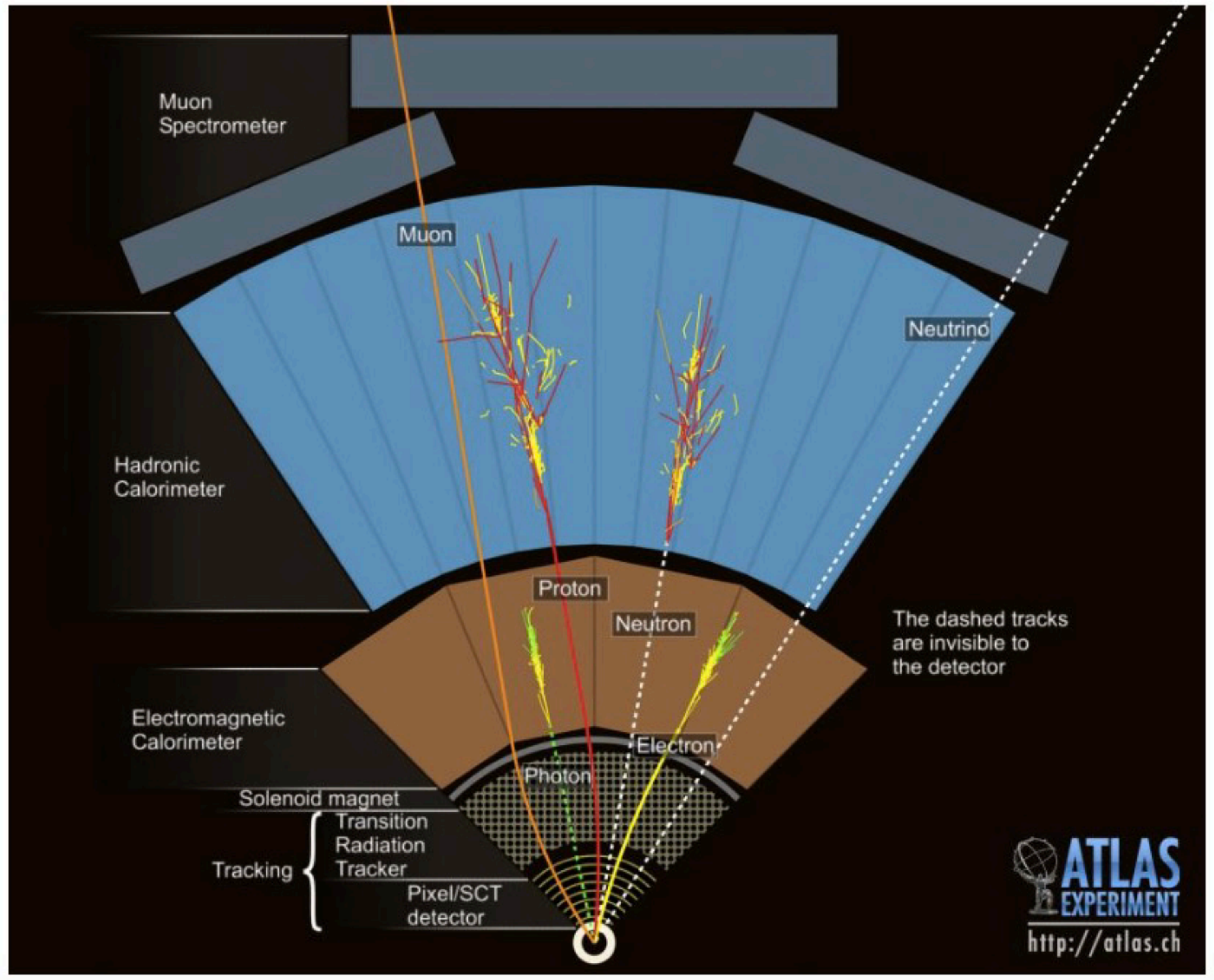
To put all sub-detector together for maximizing the physics potential output with other (*cost, space, radiation, power…*) consideration.

State-of-art of particle detection

ATLAST experiment







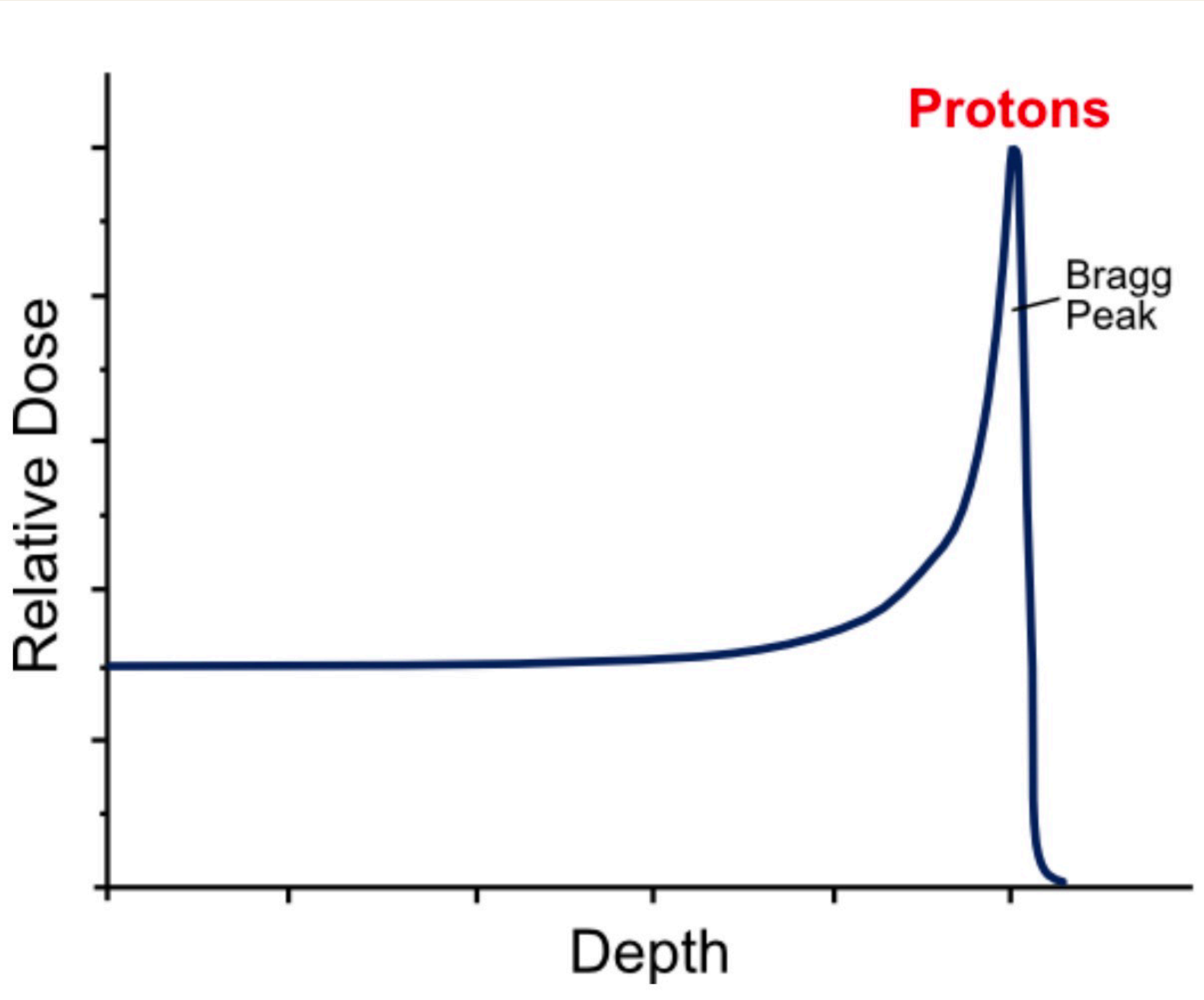
Application of particle detector

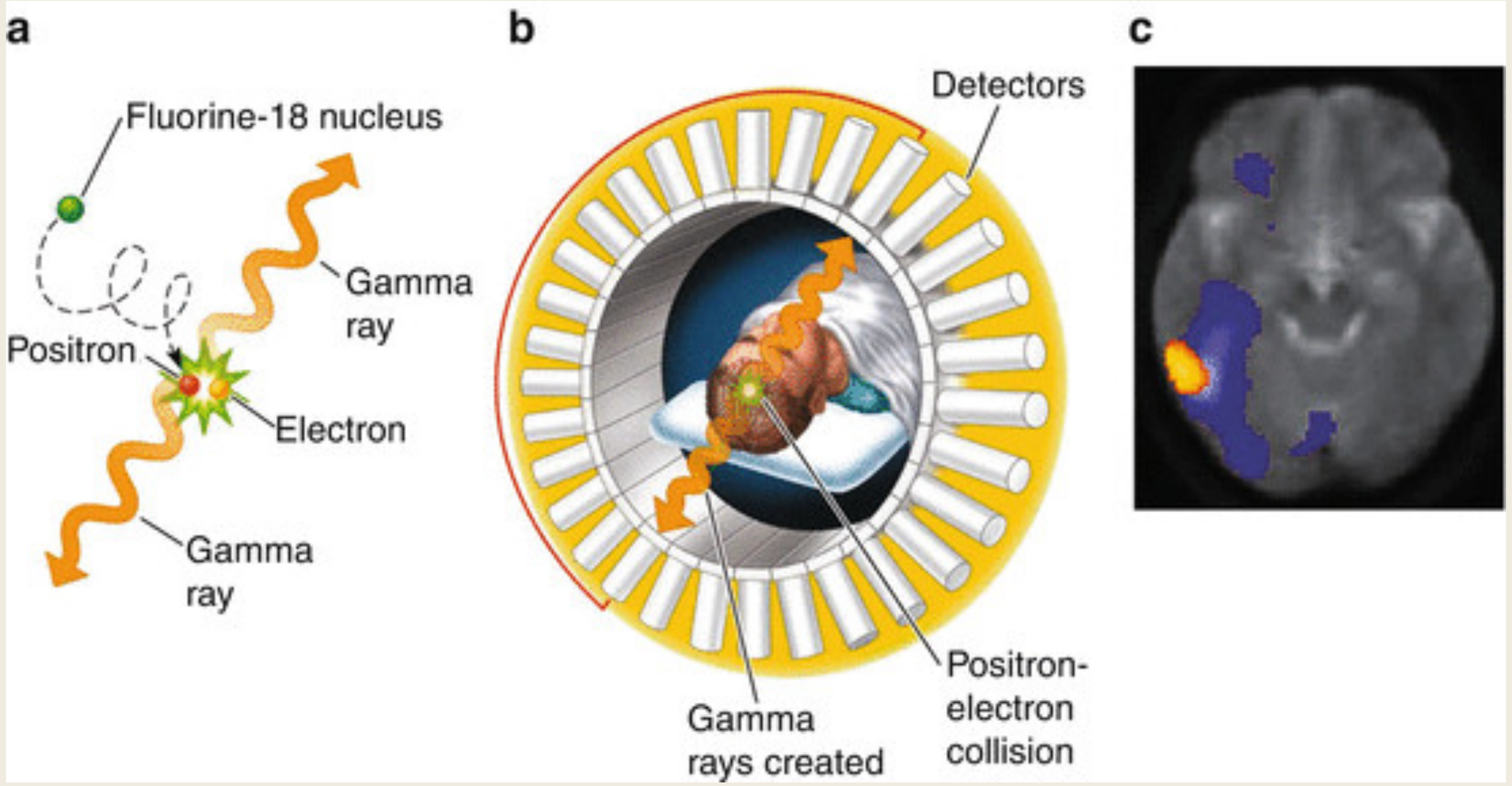
Interplay between science and technology

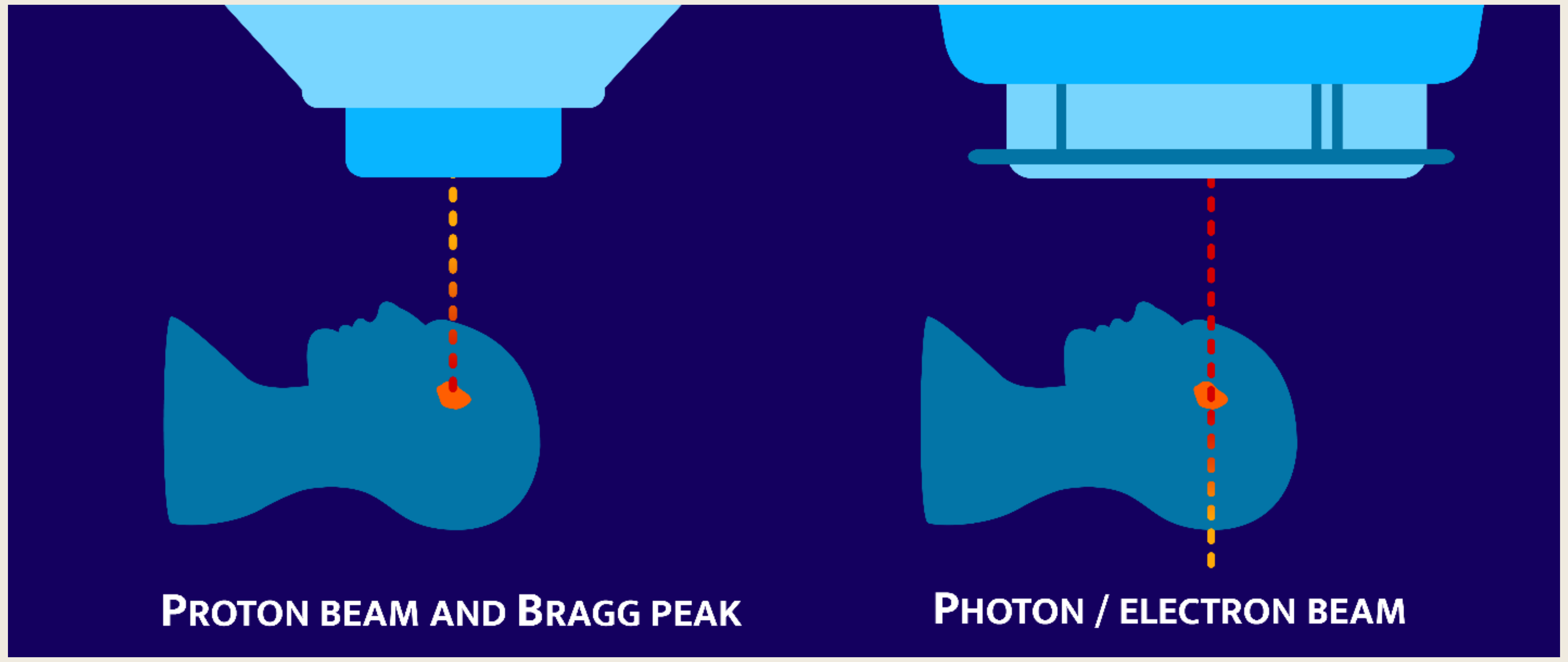
- **Transistor** *was not invented by people who wanted to build computers but by physicists who dealing with counting the nuclear particles*
- **Nuclear power** *was not developed by one who seek for new power but Curies, Rutherford, and Fermi*
- **Electron discovery** *(credited for by J.J. Thomson) was not for electronic industry but to understand the basics of atoms.*
- **Induction coils** *in motor cars and other vast application, not invented by who want to make motor transport but the principle of induction was discovered by M. Faraday*
- **Communication with electromagnetic waves,** *founded by H. Hertz who wanted to emphasized the beauty of physics*
- **Global positioning system (GPS**) *can't function well if not including the General Relativity*
- **Development of new materials and molecules** *benefits from precise mathematical techniques used in particle physics*
- **Word Wide Web** *was first invented by particle physicists to share information quickly and effectively around the world.*
- **Cancer therapy, drug development** thanks to the **particle accelerators**
- **Behind of almost all photodetectors is photoelectric effect, which is discovered by Hertz in 1887 and modeled by Einstein in 1905**
- **Photodetectors developed and improved for particle physics** *drive industrial application such as x-ray, medical scanning*
- **Help for national security**, *eg. cargo scanning, looking insides of the nuclear reactor*
- …

IN RESPONSE, ADVANCEMENTS IN TECHNOLOGY ARE CRITICAL FOR BASIC RESEARCH.

Some favorite applications: Proton therapy & PET



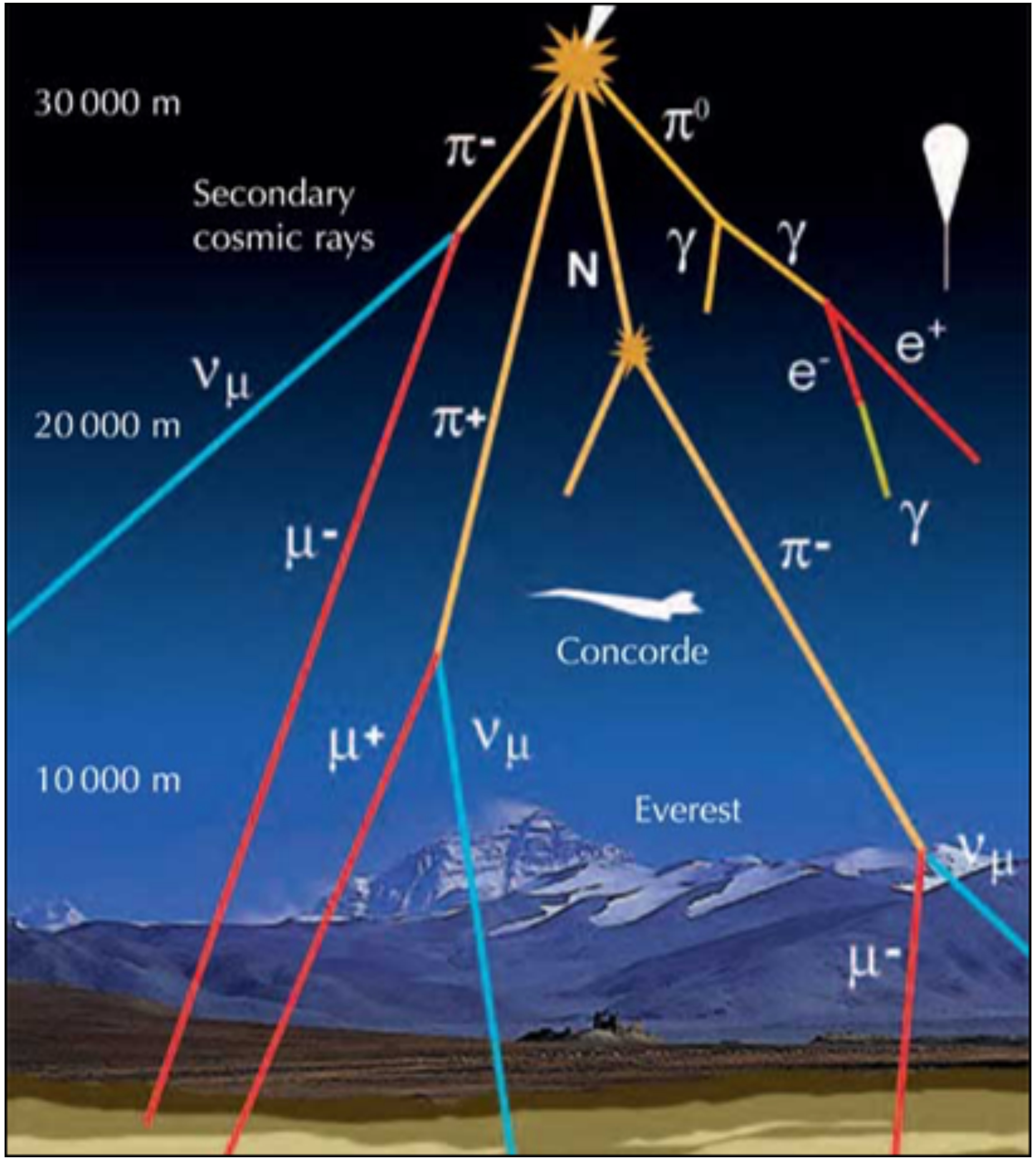




High energy astrophysical particles (eg. hydrogen & helium from the Sun) interact with the Earth's atmosphere ➔produce vast amount of muons, brother of electrons (almost identical except the mass)

~ 1 muon/cm²/min.

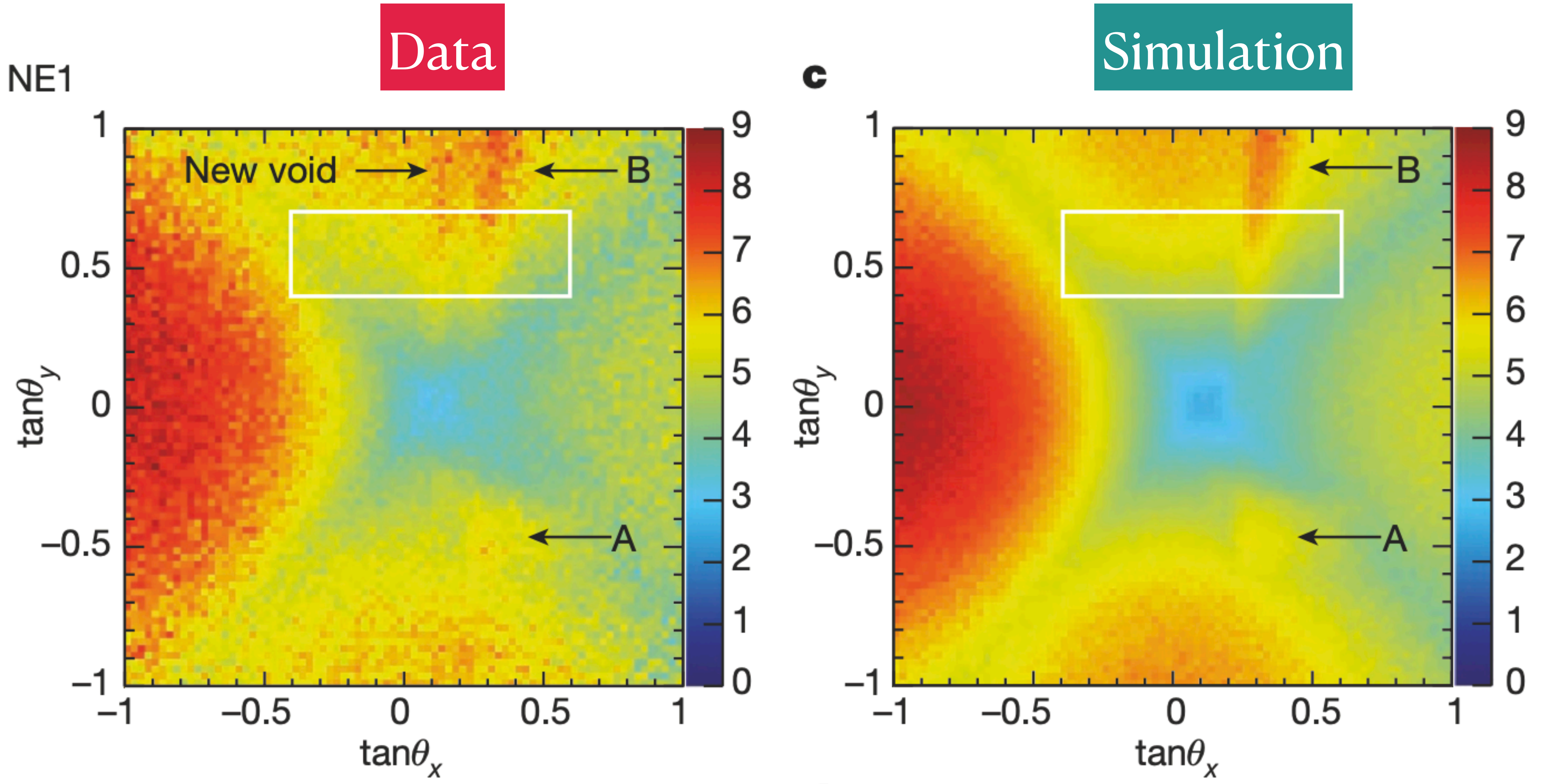
but you can't see them with your eyes



Muon can be used as light to see the hidden structure

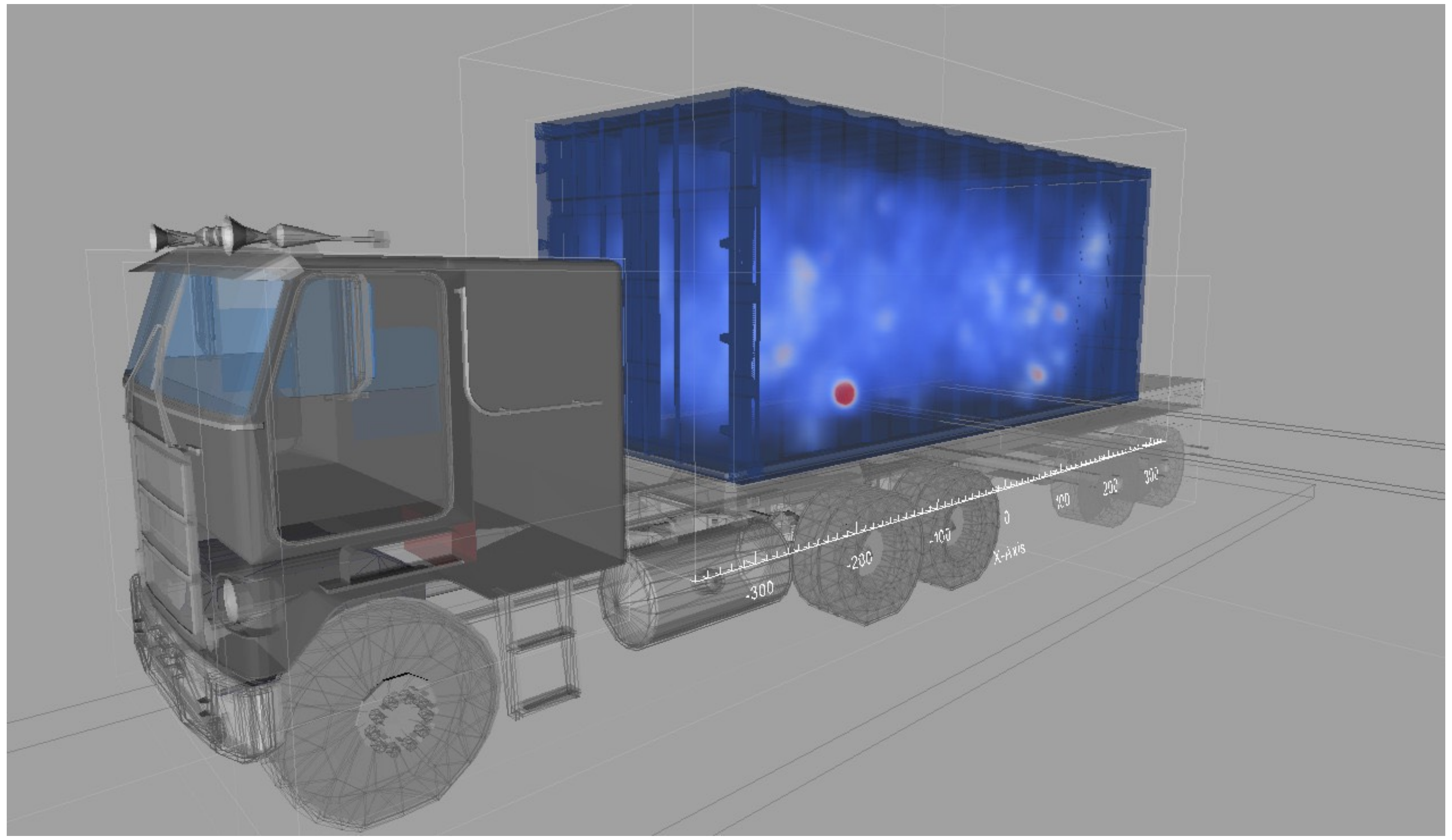
https://www.nature.com/articles/nature24647

What's inside of pyramid (where you can't reach)?



Color is corresponding to intensity of muons.
Red is with more muons detected

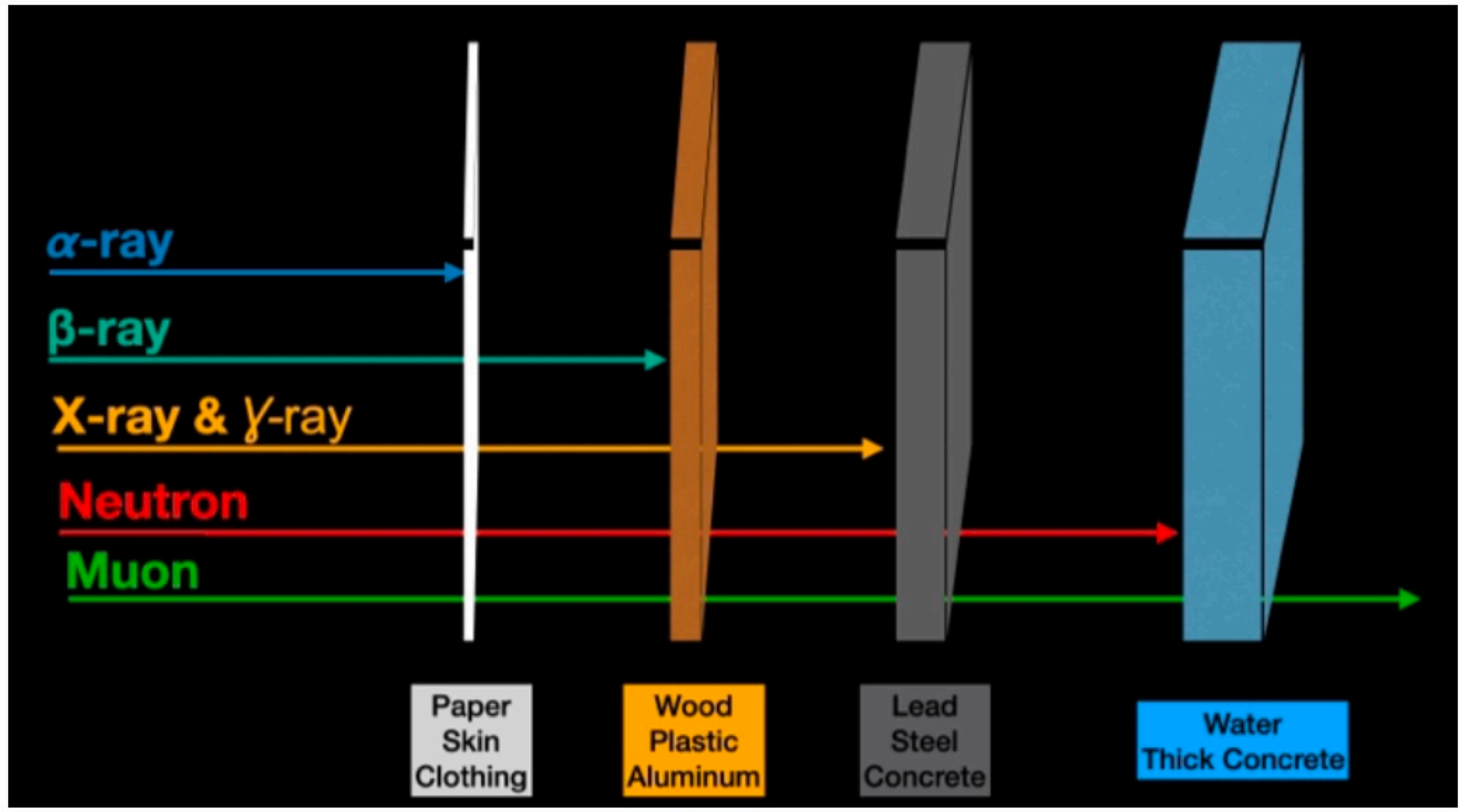
Some practical applications



http://mutomweb.pd.infn.it:5210

Decision Sciences' Discovery - A Multi-Mode Passive Detection System (MMPDS) enables the identification of security threats at both port and border/land port operations, while facilitating the legitimate flow of commerce. Discovery is the only existing technology capable of passively detecting shielded nuclear material, contraband or anomalies in commerce.

https://decisionsciences.com/our-product/#capabilities

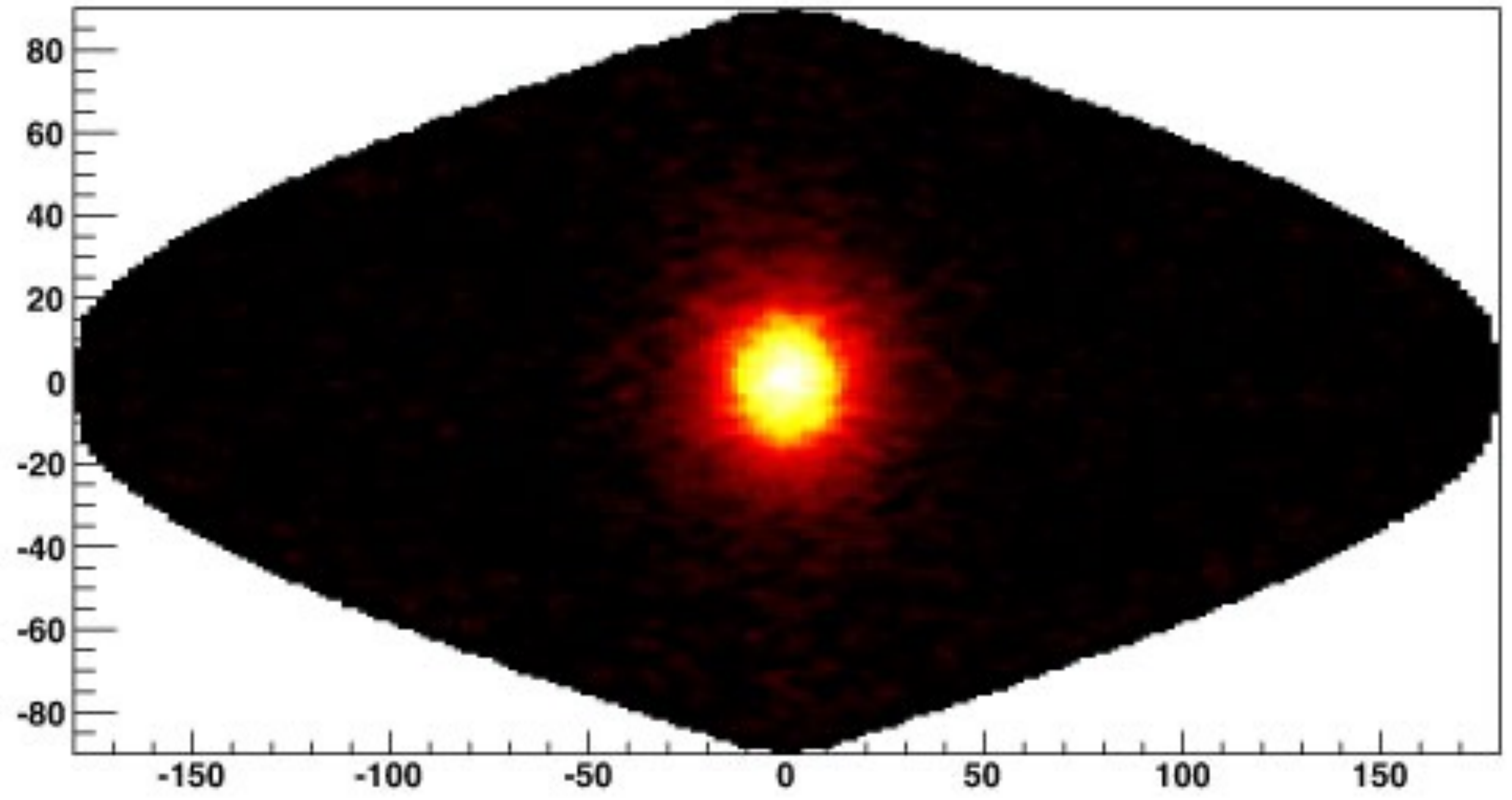


Can neutrino be a practical thing?

*"**I don't say that the neutrino is going to be a practical thing**, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, **these things make an enormous difference in how we live**"*
——**Fredrick Reines**, Nobel prize winner, co-discover of the neutrino, NYT 1997

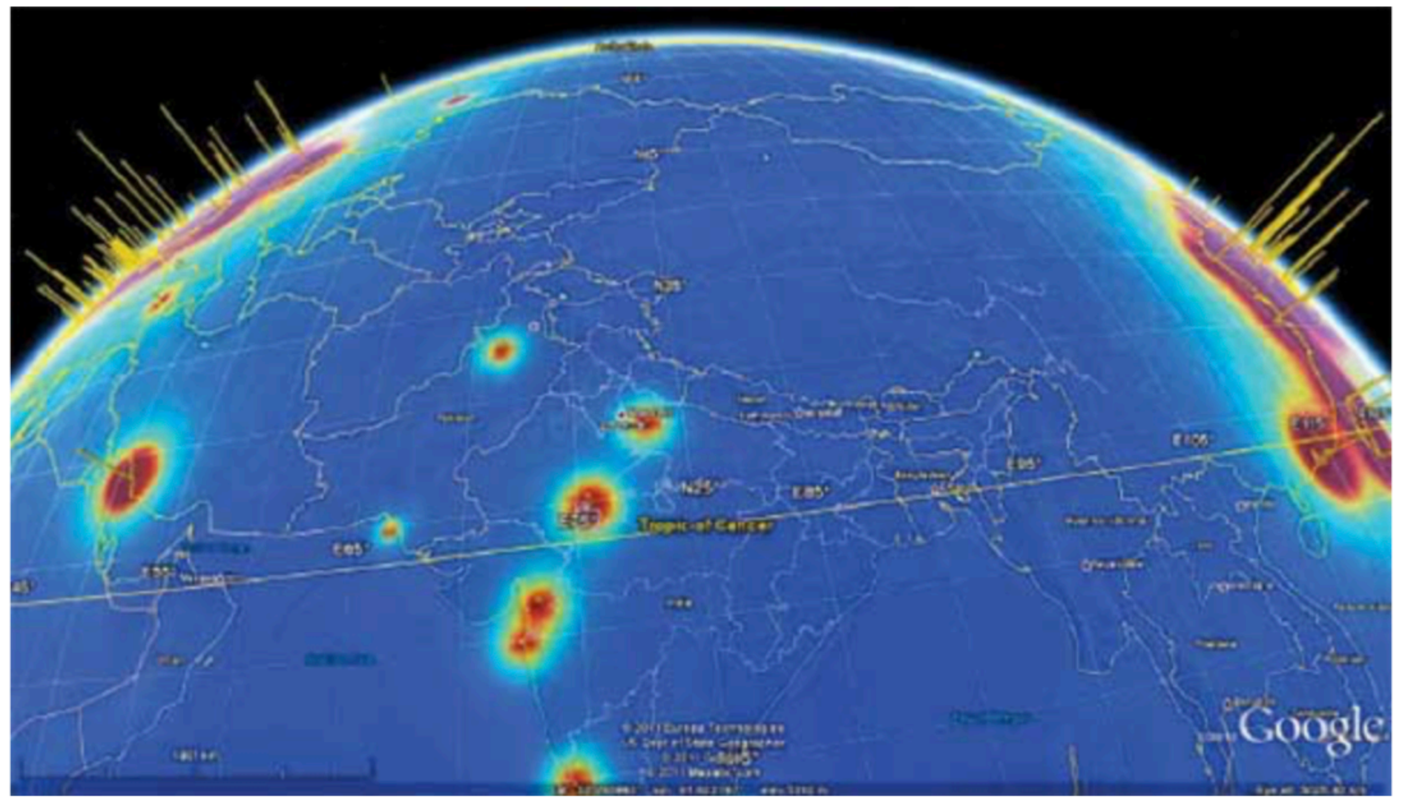
- Look inside of the Sun
- Tomography of the Earth
- Monitor the reactors
- Astrophysical messenger from the extragalactic
- (May less (?) practical at present) source, non-destructive light-speed communication, neutrino energy

Sun pictured with neutrino by Super-K



Neutrinos and National Security

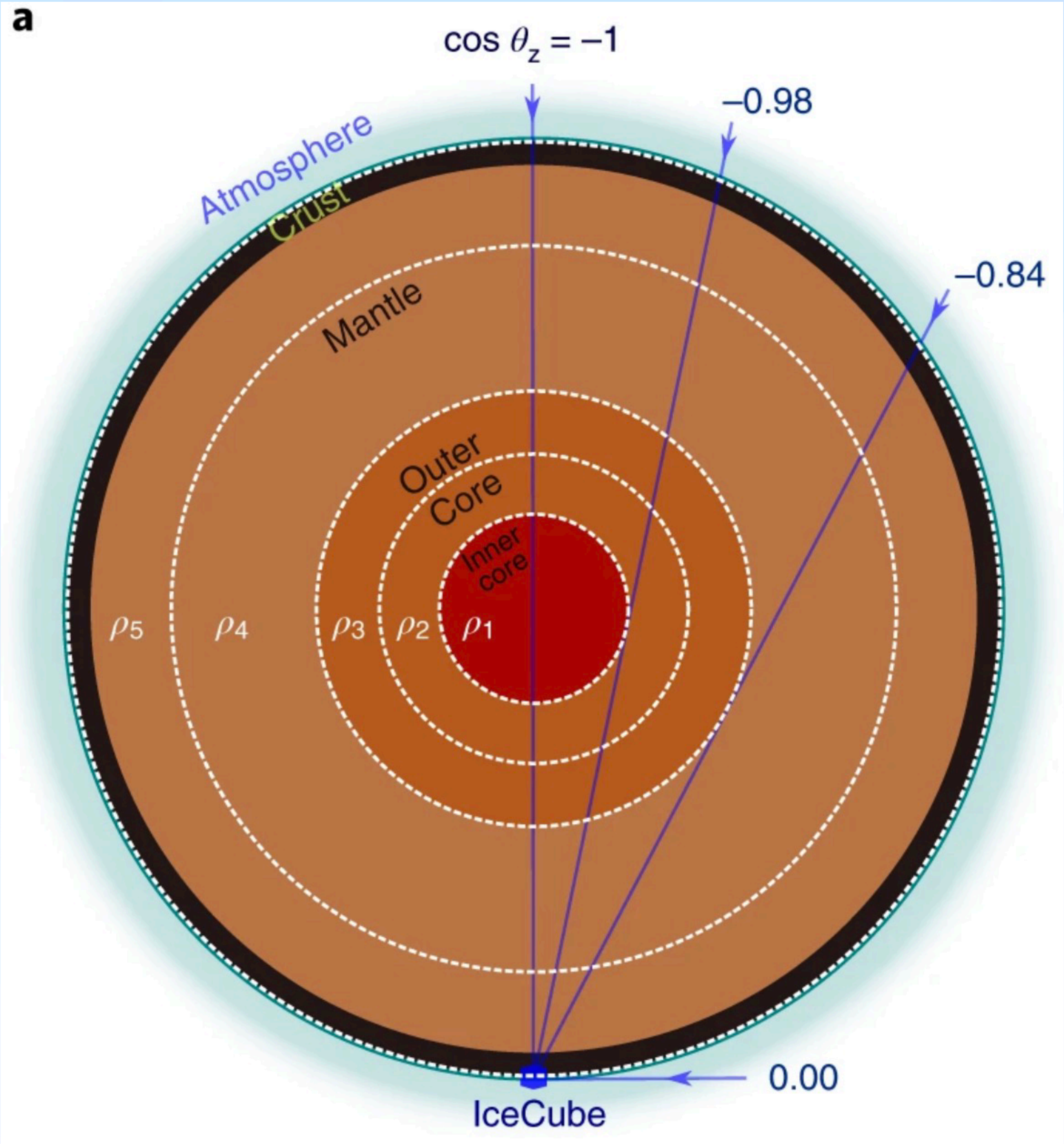
By Michael Lucibella



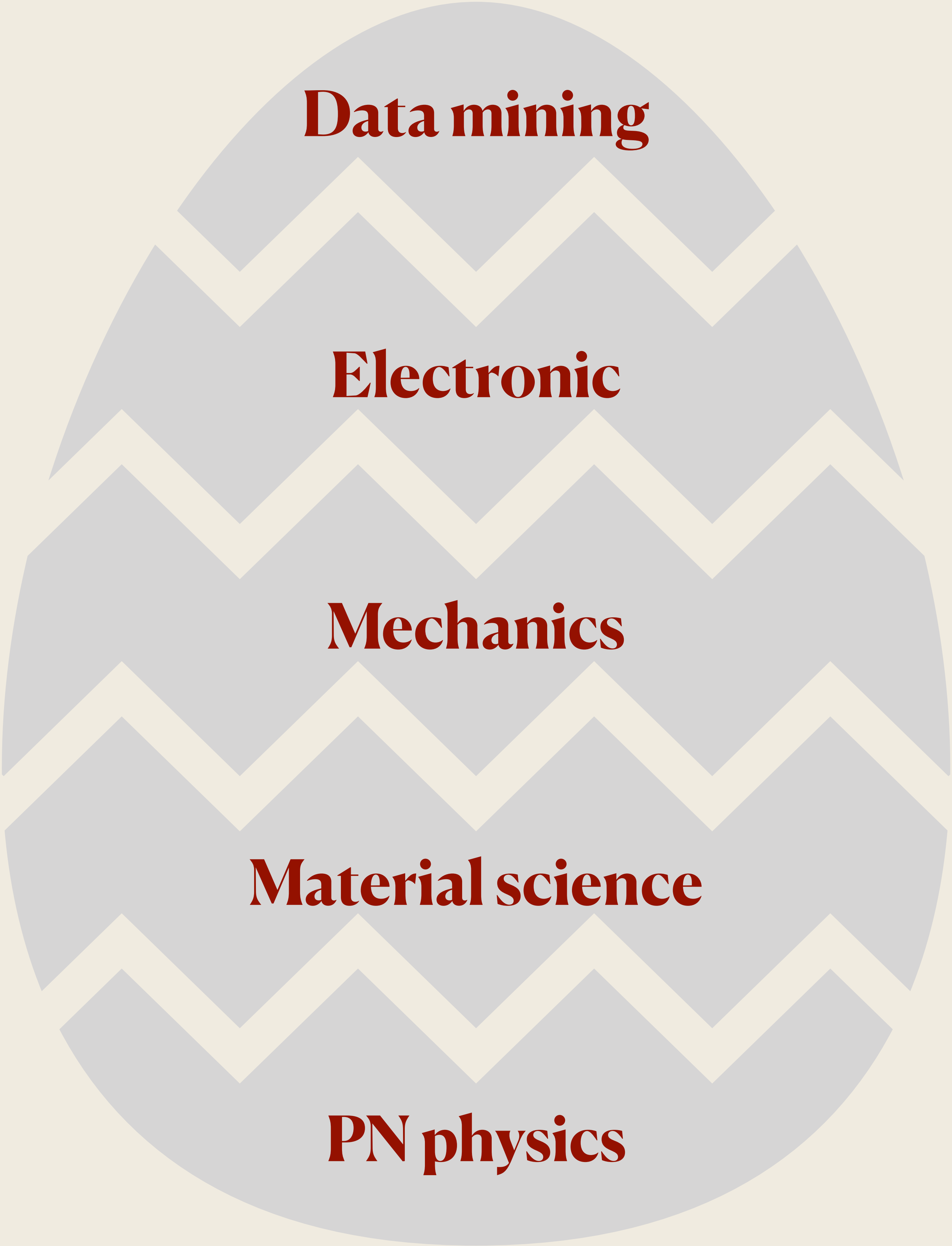
Global map of reactor neutrino emission.
Photo courtesy of Glenn Jocher and John Learned, University of Hawaii

Neutrino tomography of Earth

https://www.nature.com/articles/s41567-018-0319-1



Particle detector is a *instrument (kind of classical device)* to detect, to track, and to identify the *particles (superposition of quantum states)*



A complicate, interdisciplinary field

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes"

~Marcel Proust~

Good luck!

Backup

Forewords

In general, it is not difficult to find the solution to a certain question which is posed scientifically. The more difficult part is posing the right queries to steer your investigation.

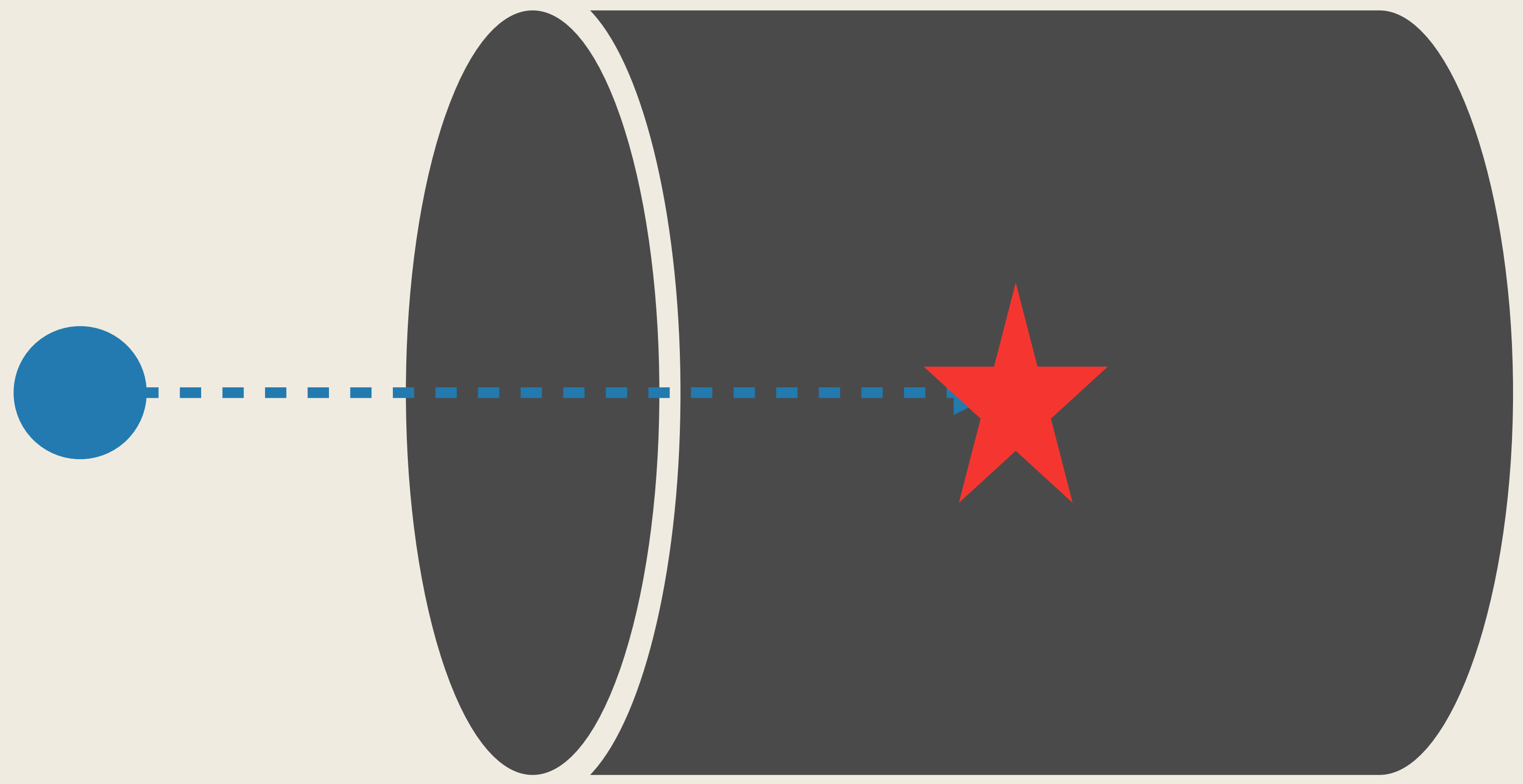
Try to ask AI

- **Can AI suggest elementary particle-related questions that have never been asked by human?**
- **Can AI suggest experimental setup to address the above-posed questions?**

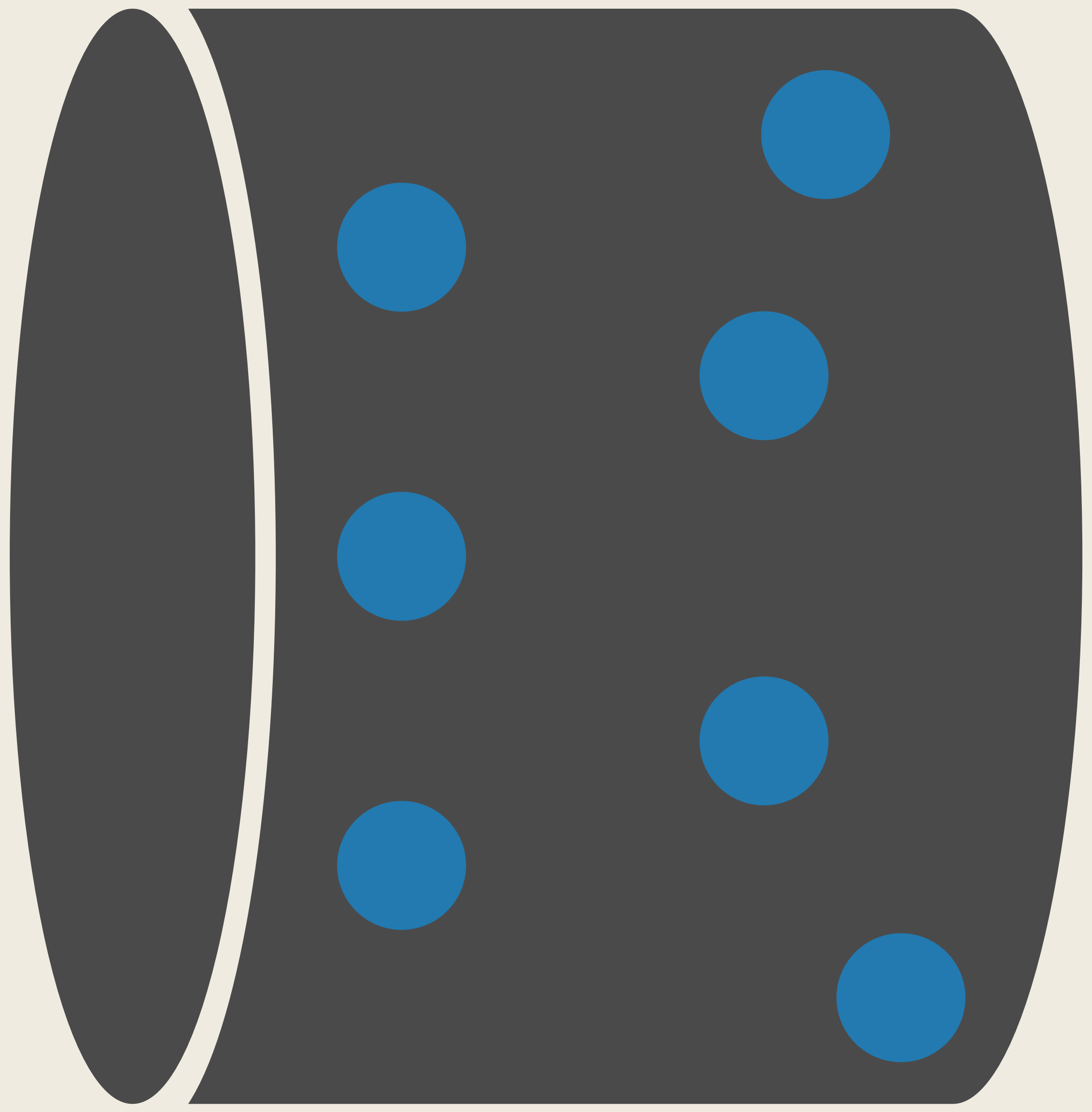
(By the way, AI for scientific research assistance will be more useful if you have extensive relevant expertise. Otherwise, it is difficult to figure out whether what AI says is good or bad from a scientific perspective.)

Main difference btw. Collider and Neutrino experiments

Collider experiments: We know where and when the interactions happen



Neutrino experiments: We don't know where the neutrino interaction happens. We may know when the neutrino interaction can happens, eg. neutrinos delivered from accelerator.



Why silicon?

Some characteristics of Silicon crystals

- Small band gap — E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV (≈ 30 eV for gas detectors)
- High specific density — 2.33 g/cm^3 ; dE/dx (M.I.P.) ≈ 3.8 MeV/cm ≈ 106 e-h/µm (average)
- High carrier mobility — μ_e =1450 cm^2/Vs, μ_h = 450 cm^2/Vs ⇒ fast charge collection (<10 ns)
- Very pure — < 1ppm impurities and < 0.1ppb electrical active impurities
- Rigidity of silicon allows thin self supporting structures
- Detector production by microelectronic techniques

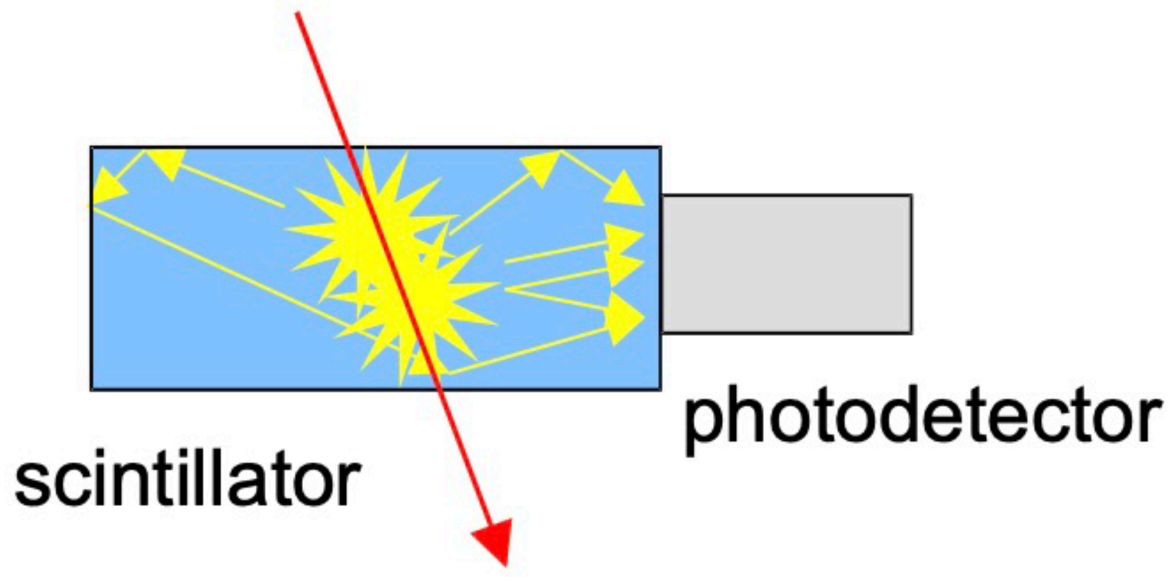
  ⇒ well known industrial technology, relatively low price, small structures easily possible

Alternative semiconductors

- Diamond
- GaAs
- Silicon Carbide
- Germanium

	Diamond	SiC (4H)	GaAs	Si	Ge
Atomic number Z	6	14/6	31/33	14	32
Bandgap E_g [eV]	5.5	3.3	1.42	1.12	0.66
E(e-h pair) [eV]	13	7.6-8.4	4.3	3.6	2.9
density [g/cm^3]	3.515	3.22	5.32	2.33	5.32
e-mobility μ_e [cm^2/Vs]	1800	800	8500	1450	3900
h-mobility μ_h [cm^2/Vs]	1200	115	400	450	1900

Scintillator



Energy deposition by a ionizing particle

→generation
→transmission
→detection
} of scintillation light

Two categories: Inorganic and organic scintillators

Inorganic
(crystalline structure)

Up to 40000 photons per MeV
High Z
Large variety of Z and ρ
Undoped and doped
ns to μs decay times
Expensive

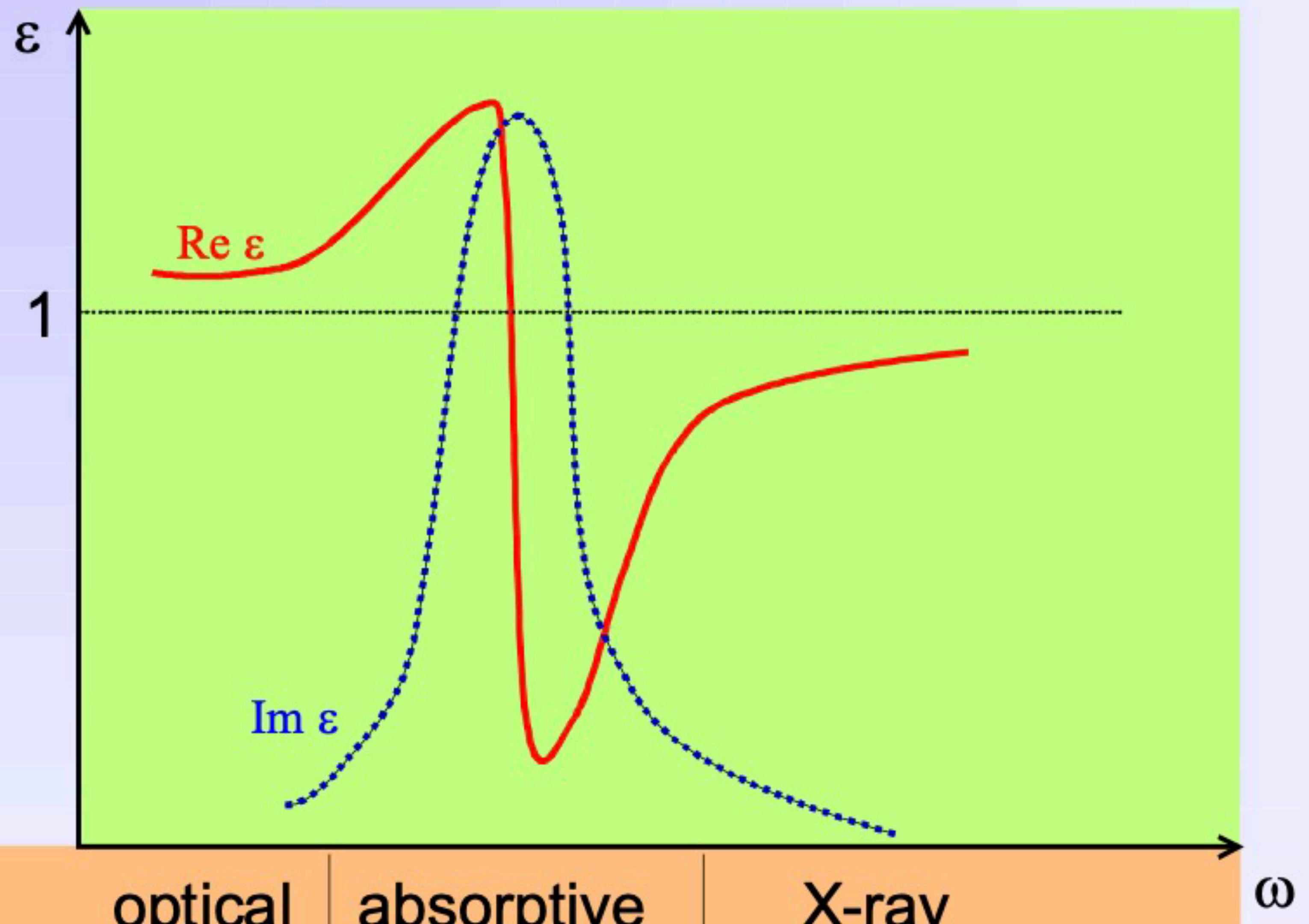
E.m. calorimetry (e, γ)
Medical imaging
Fairly Rad. Hard (100 kGy/year)

Organic
(plastics or liquid solutions)

Up to 10000 photons per MeV
Low Z
ρ~1gr/cm^3
Doped, large choice of emission wavelength
ns decay times
Relatively inexpensive

Tracking, TOF, trigger, veto counters,
sampling calorimeters.
Medium Rad. Hard (10 kGy/year)

Optical behavior of medium



regime:	optical	absorptive	X-ray
effect:	Cherenkov radiation	ionisation	transition radiation

Optical behaviour of medium is characterized by the complex dielectric constant ε

$\mathrm{Re}\sqrt{\varepsilon} = n$ Refractive index

$\mathrm{Im}\,\varepsilon = k$ Absorption parameter

Instead of ionizing an atom or exciting the matter, under certain conditions the photon can also escape from the medium.

⇨ Emission of **Cherenkov** and **Transition** radiation. (See later). This emission of real photons contributes also to the energy loss.

Cosmic-ray reaching Super-K

6. **Question 6** (10pts): Most of particle detectors are placed underground to reduce the bombard of cosmic ray muons. Super-Kamiokande detector, for example, is placed 1km underground. The high-energy muons, passing through the earth's rock characterized by equivalent atomic number $A = 22, Z = 11$ and density $\rho = 2.7g/cm^3$, loss their energy with function (units are placed inside of [...])

$$\frac{-1}{\rho[g/cm^3]}\frac{dE[MeV]}{dx[cm]} \approx 2.5[MeVg^{-1}cm^2] + 3.5 \times 10^{-6}[g^{-1}cm^2].E[MeV]$$

What is energy of comsic ray muons reaching to the Super-Kamiokande detector.

Answer:Using integration

$$\frac{dE}{a + bE} = -\rho dx$$

so

$$ln(a + bE_{obs}) - ln(a + bE_0) = -\rho bL$$

where E_0 is the initial energy of cosmic ray muon on the Earth surface. So to reach Super-Kamiokande detector $E_{obs} > 0$

$$ln(a) - ln(a + bE_0) < -\rho bL \rightarrow E_0 > \frac{a}{b}(e^{\rho bL} - 1) = 0.71e6 * 1.57 = 1.1e6[MeV]$$

Or to reach SK, cosmic ray muon must have energy larger than 1.1 [TeV].

Cherenkov threshold and No. Of photons

- The Cherenkov radiation emitted when $\beta > 1/n$ or $p_{th.} > \frac{mc}{n^2-1}$. So the energy threshold is $E_{th.} = \sqrt{p_{th.}^2 + m^2c^2} > \frac{mc}{\sqrt{1-n^{-2}}}$

So for electron, $> \frac{0.51\ MeV}{\sqrt{1-1.33^{-2}}} \equiv 0.77\ MeV$; for muon $> \frac{105.7\ MeV}{\sqrt{1-1.33^{-2}}} \equiv 160.3\ MeV$; for tau $> \frac{1.78\ GeV}{\sqrt{1-1.33^{-2}}} \equiv 2.70\ GeV$

- For second part, since $E = \frac{hc}{\lambda}$ so $\partial E/\partial\lambda = -\frac{hc}{\lambda^2}$, so

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{\partial^2 N}{\partial x \partial E}\frac{\partial E}{\partial \lambda} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n^2}\right)\frac{1}{\lambda^2} \qquad (1)$$

So $\frac{\partial^2 N}{\partial x \partial E}$ does not depend on the photon wavelength λ.

- using the integration

$$\frac{\partial N}{\partial x} = 2\pi\alpha(1 - 1/\beta^2 n^2)(1/\lambda_L - 1/\lambda_H)$$
$$\rightarrow N = 2\pi\alpha(1 - 1/\beta^2 n^2)(1/\lambda_L - 1/\lambda_H) \times L$$

Lorentz factor for the relativistic muon

$$\gamma = \frac{E_k}{m_0 c^2} + 1 = 4000/105.66 + 1 \approx 38.9$$
$$\rightarrow \beta = \sqrt{1 - 1/\beta^2} \approx 0.99967$$

Then

$$N = 2 \times 3.14 \times \frac{1}{137} \times (1 - 1/(1.33 * 0.99967)^2) \times \frac{e7}{6} = 3.3e4\ [photons]$$

Taken into account the geometrical coverage and detection efficiency, then the number of photons can be collected is

$$3.3e4 \times 0.4 \times 0.2 \approx 2640$$

Coincidence rate

Answer: - The coinncidence rate can be compute with the fomular $2 \times R_1 \times R_2 \times w$. The coincidence rate of two detectors with 10kHz noise is

$$f_{coin.} = 2 \times 10e3[s^{-1}] \times 10e3[s^{-1}] \times 1e - 6[s] = 200[Hz]$$

To achieve signal-to-background ratio of around 10, then the signal rate must be $200[Hz] * 10 = 2[kHz]$. With the rate of 1 muon per minute or 0.017 [Hz] per cm^2, so one need a detector size of $2000/0.017 = 117,647[cm^2]$ or $11.8[m^2]$

(There was a mistake in the released assignment, should mention the polarity $\geq$, not $\leq$)

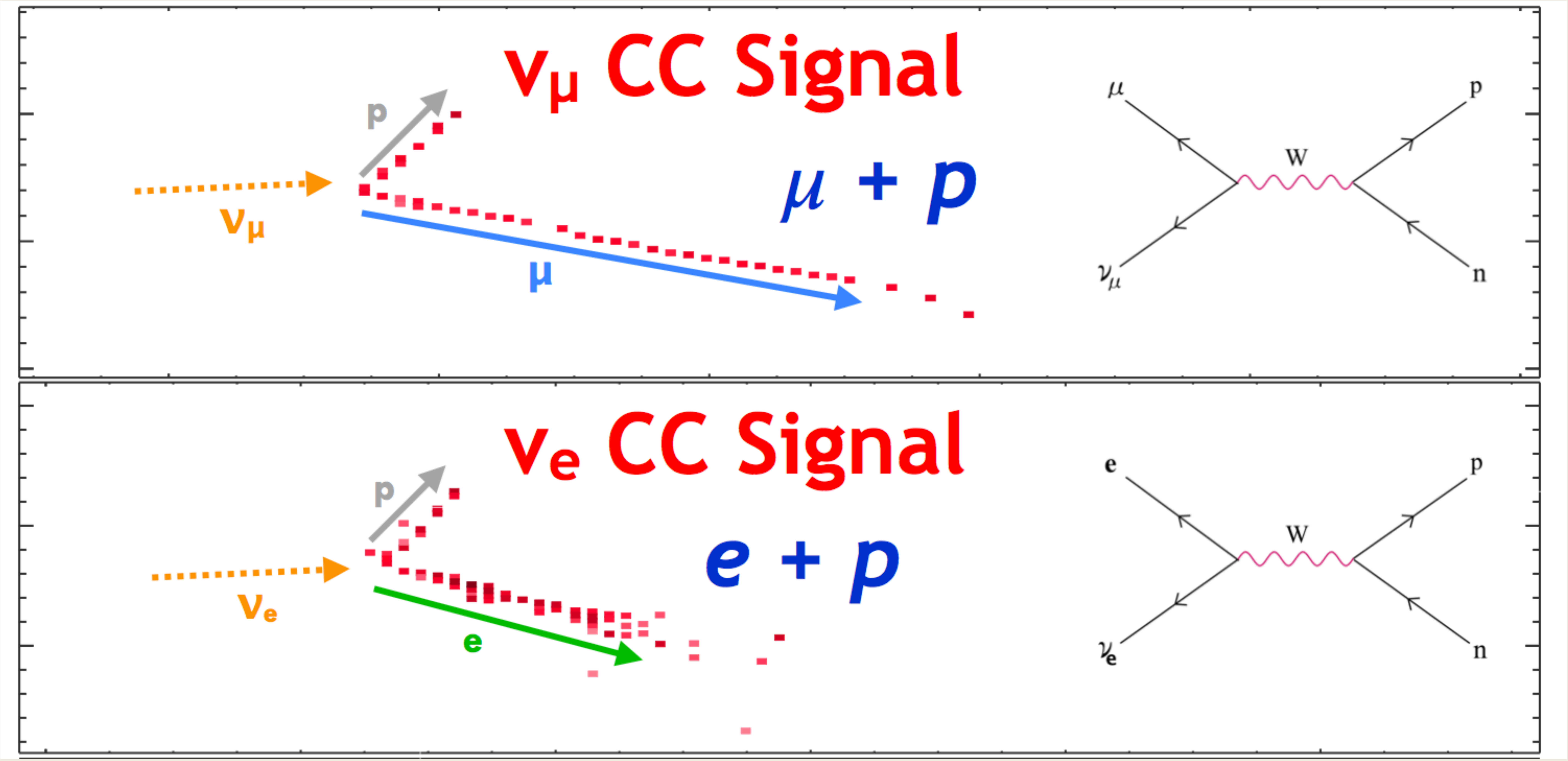
With 1% cross-talk, then noise when place at 2 p.e is $10kHz \times 1\% = 100$Hz, thus the coincidence rate is

$$f^{2p.e}_{coin.} = 2 \times 100[s^{-1}] \times 100[s^{-1}] \times 1e - 6[s] = 0.02[Hz]$$

To achieve signal-to-background ratio of around 10, then the signal rate must be 0.2[Hz]. Thus the detector error is $0.2/0.017 = 11.7[cm^2]$

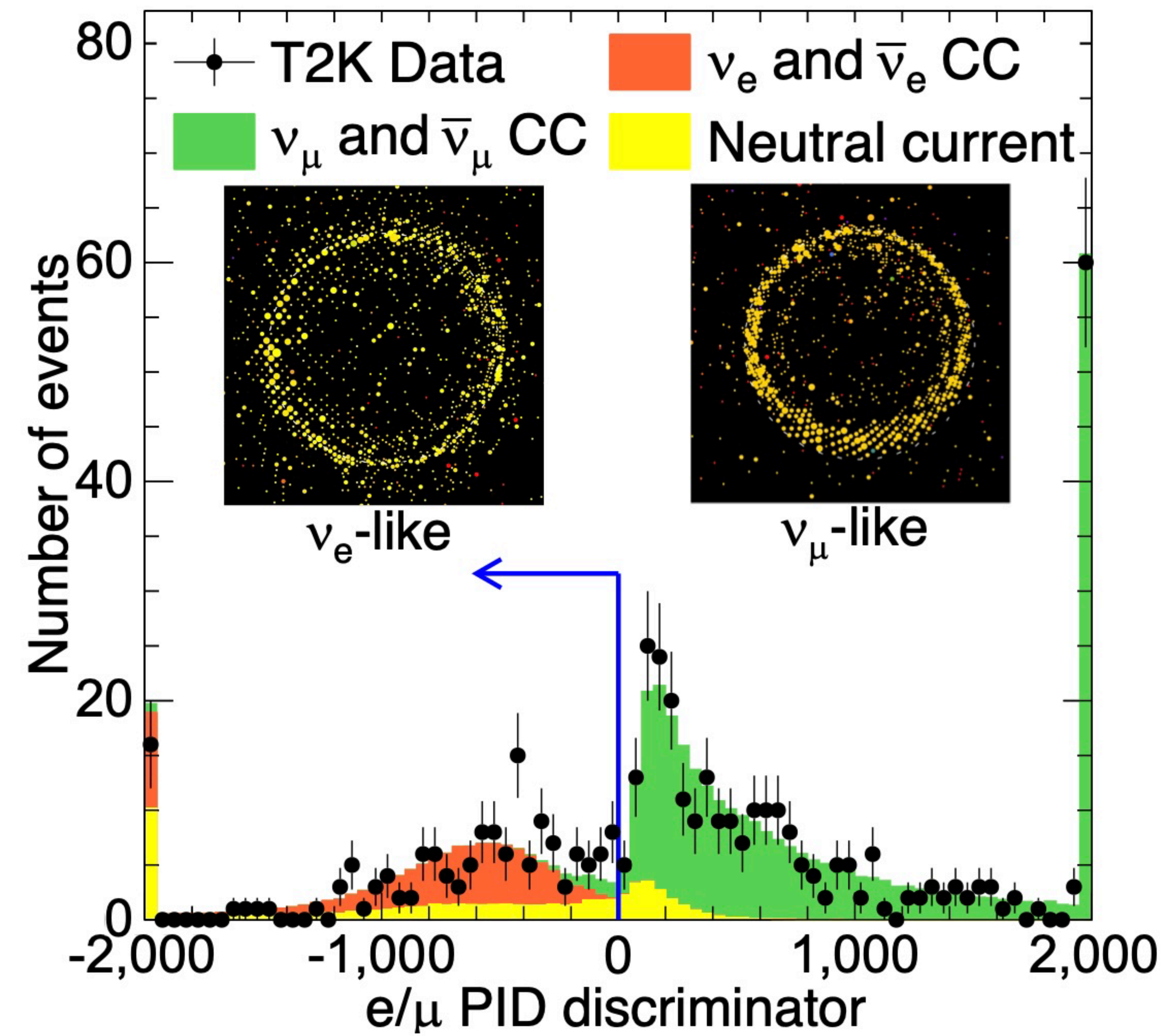
Ranging and Electromagnetic shower development

NOvA, scintillator technique

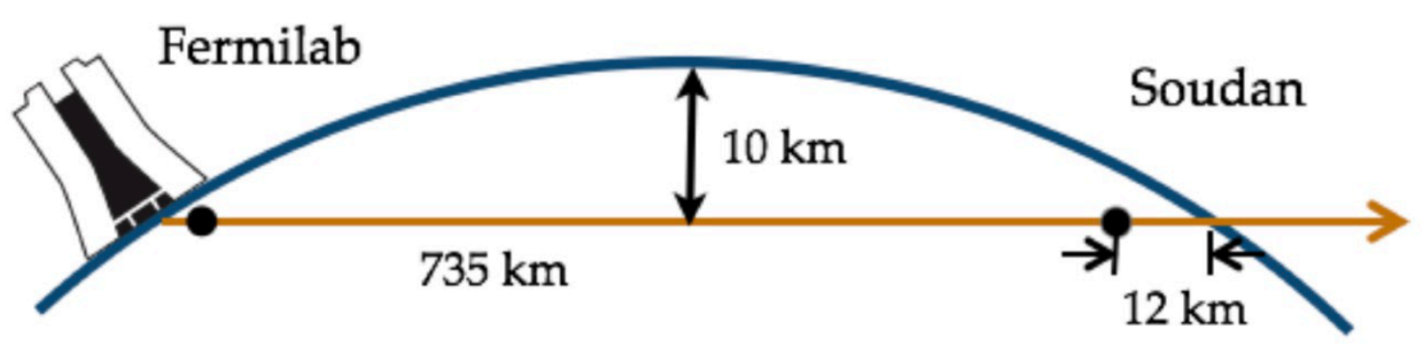


Electromagnetic shower development

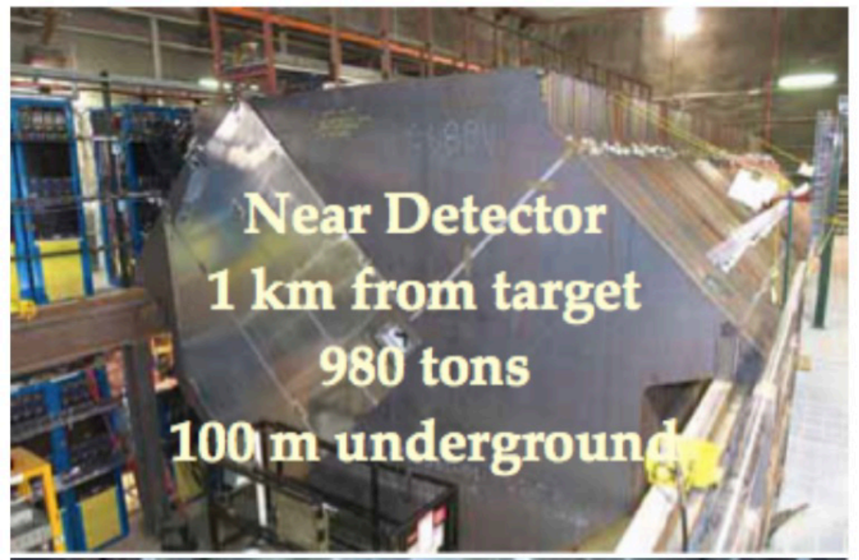
- Electron quickly develops electromagnetic shower and give a fuzzy ring pattern than muon
- **The *fuzziness* can be used as particle identity**
- *Also the Cherenkov threshold can be used for particle identity since it depends on particle*

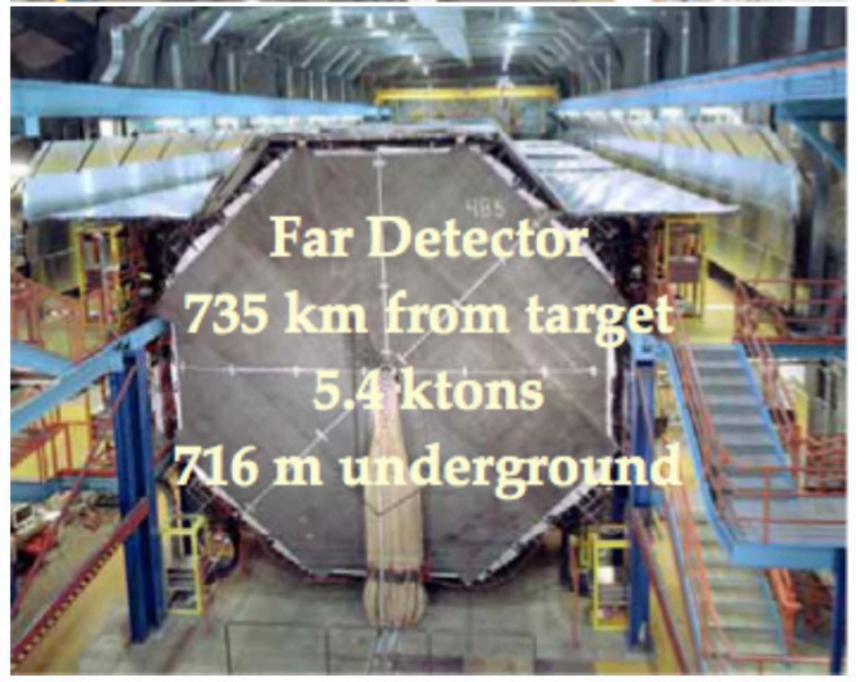


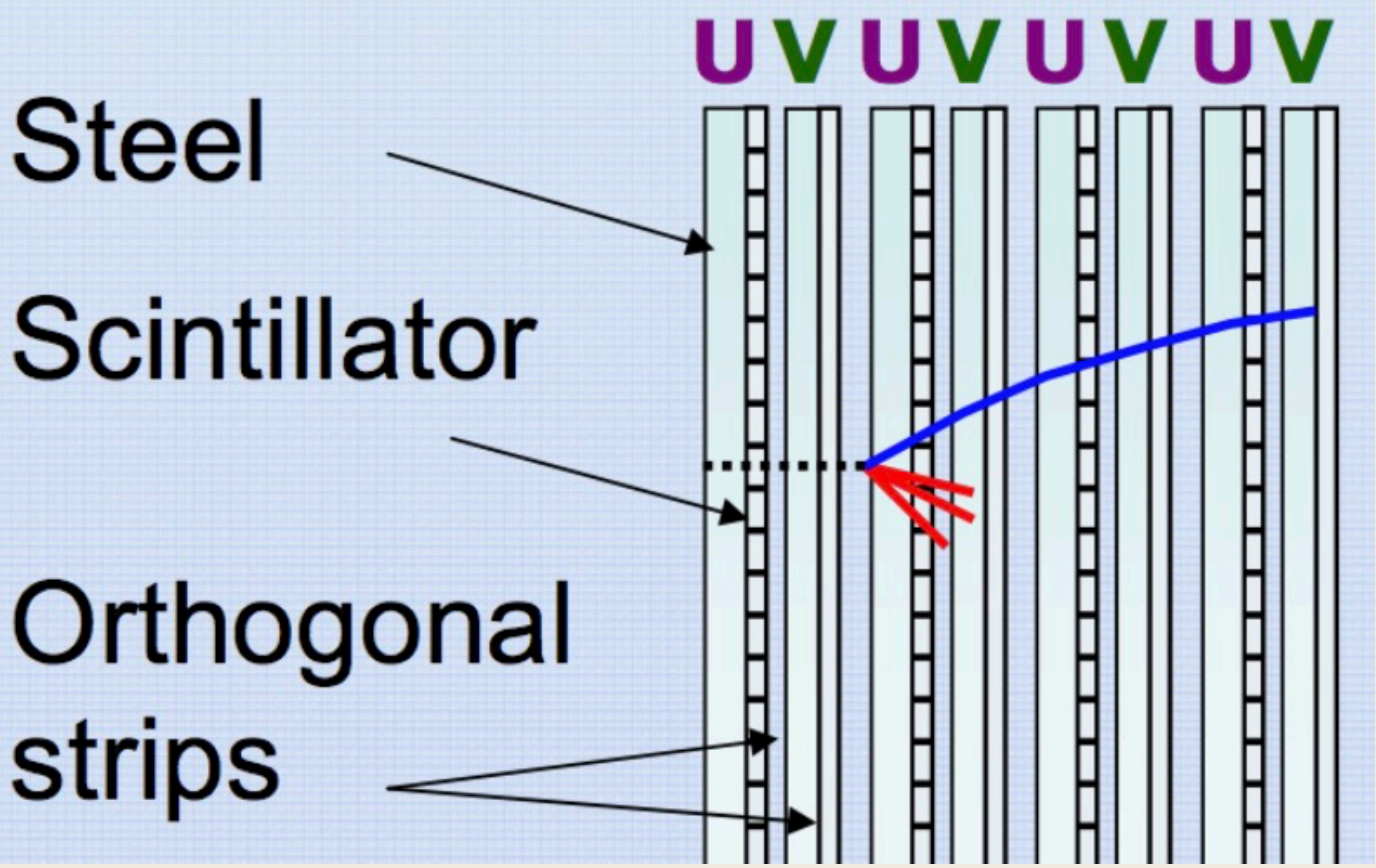
Eg: Tracking with MINOS experiment

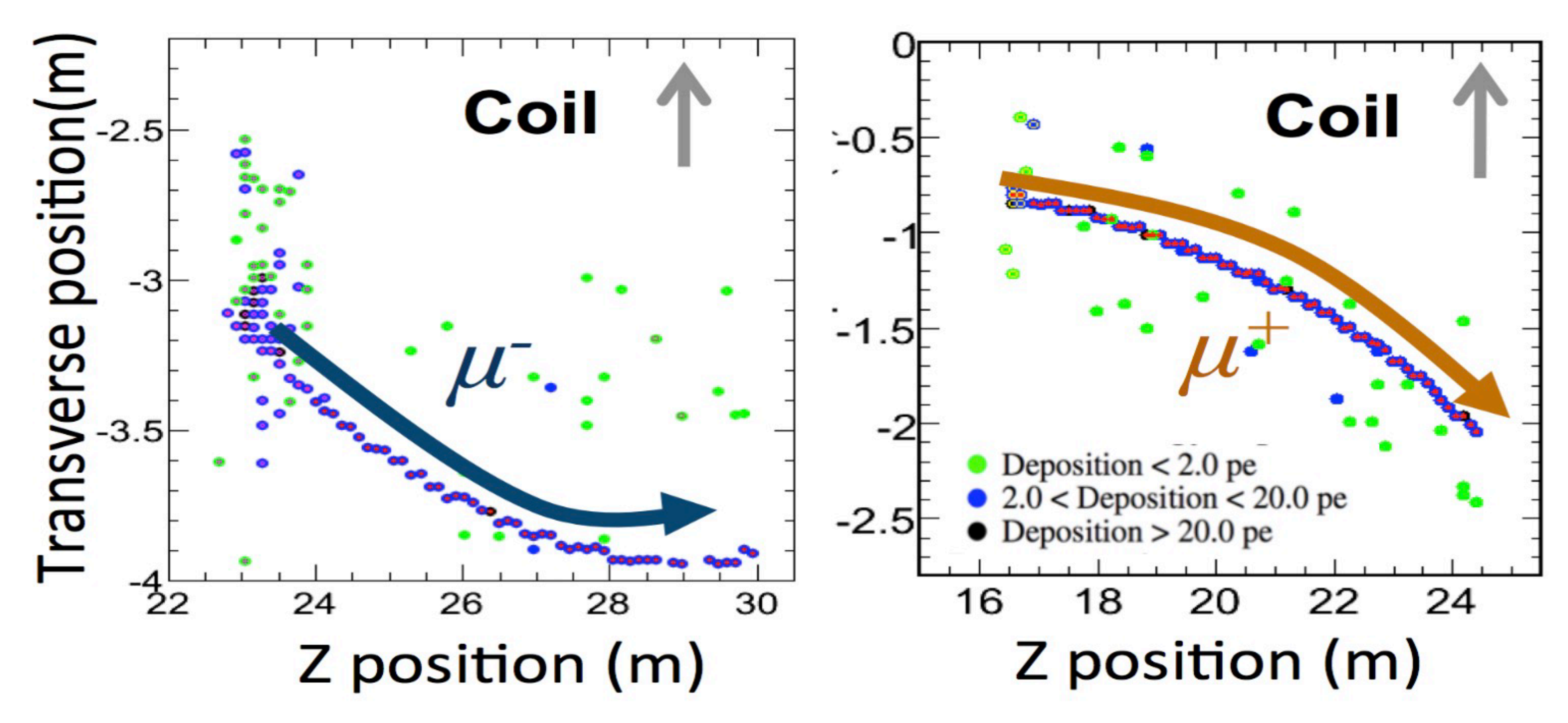


- NuMI high intensity neutrino beam
- Near Detector at Fermilab, IL
- Far Detector at Soudan, MN
- Two-detector design to mitigate systematic uncertainties



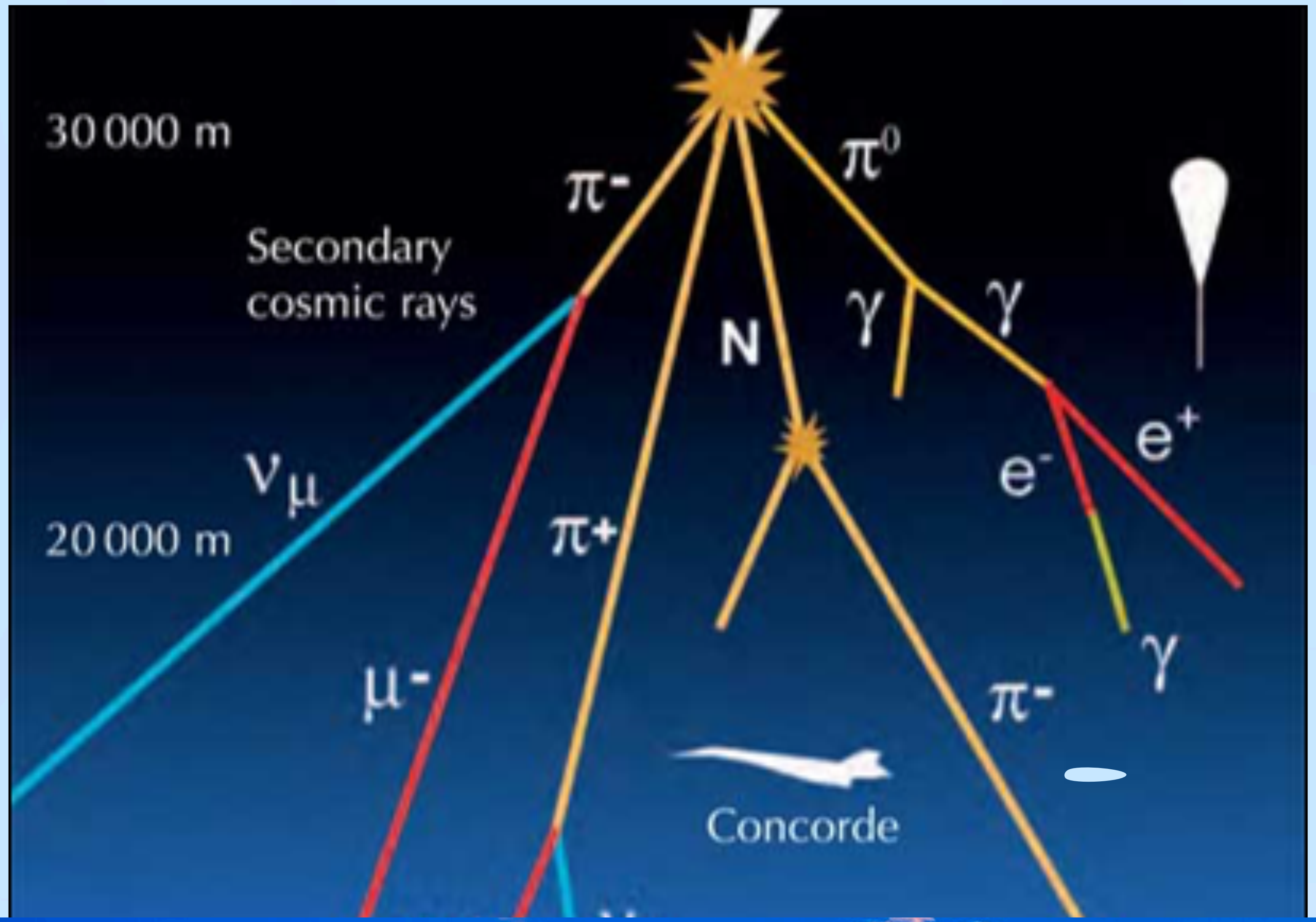




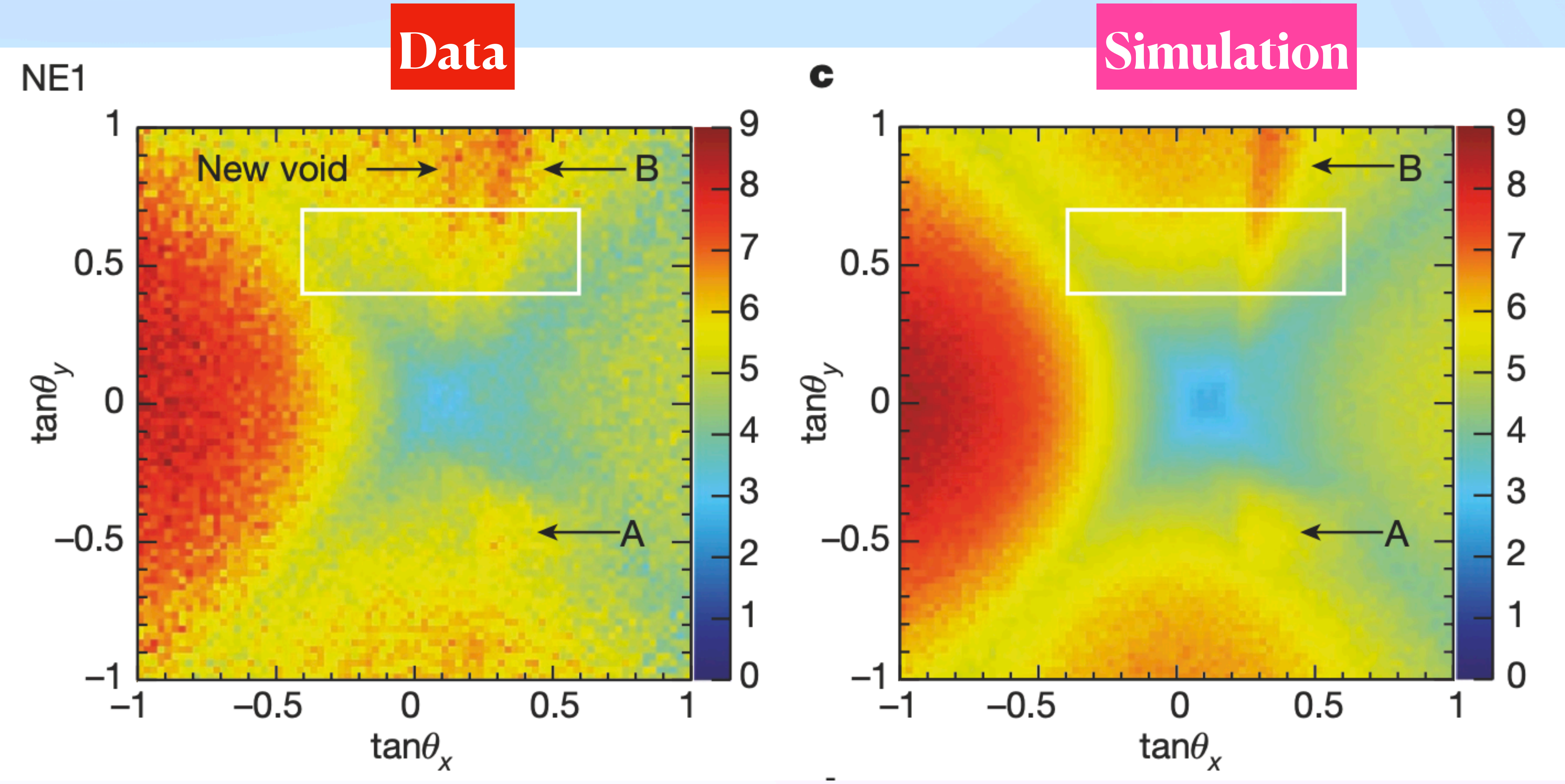


Muon can be used for a practical application

https://www.nature.com/articles/nature



called: muon radiography technique

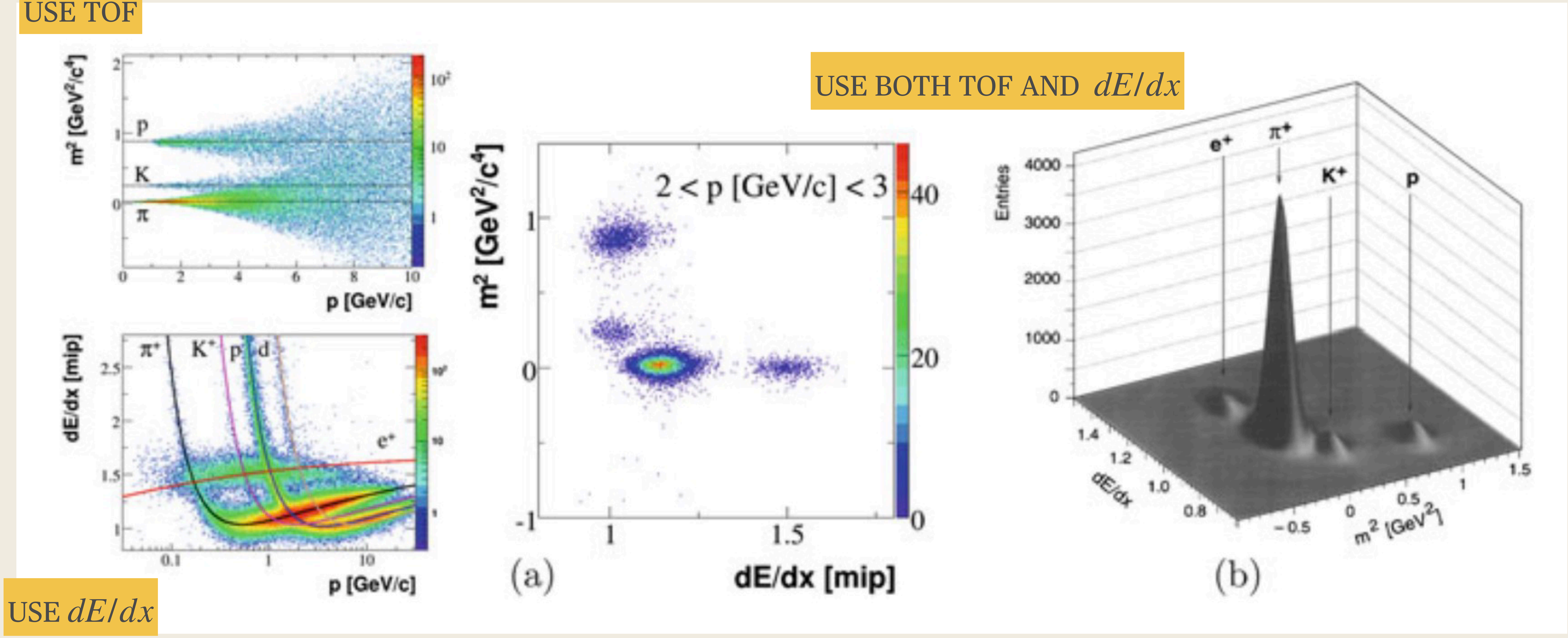


Color is corresponding to intensity of muons.
Red is with more muons detected

NA49 experiment

USE TOF

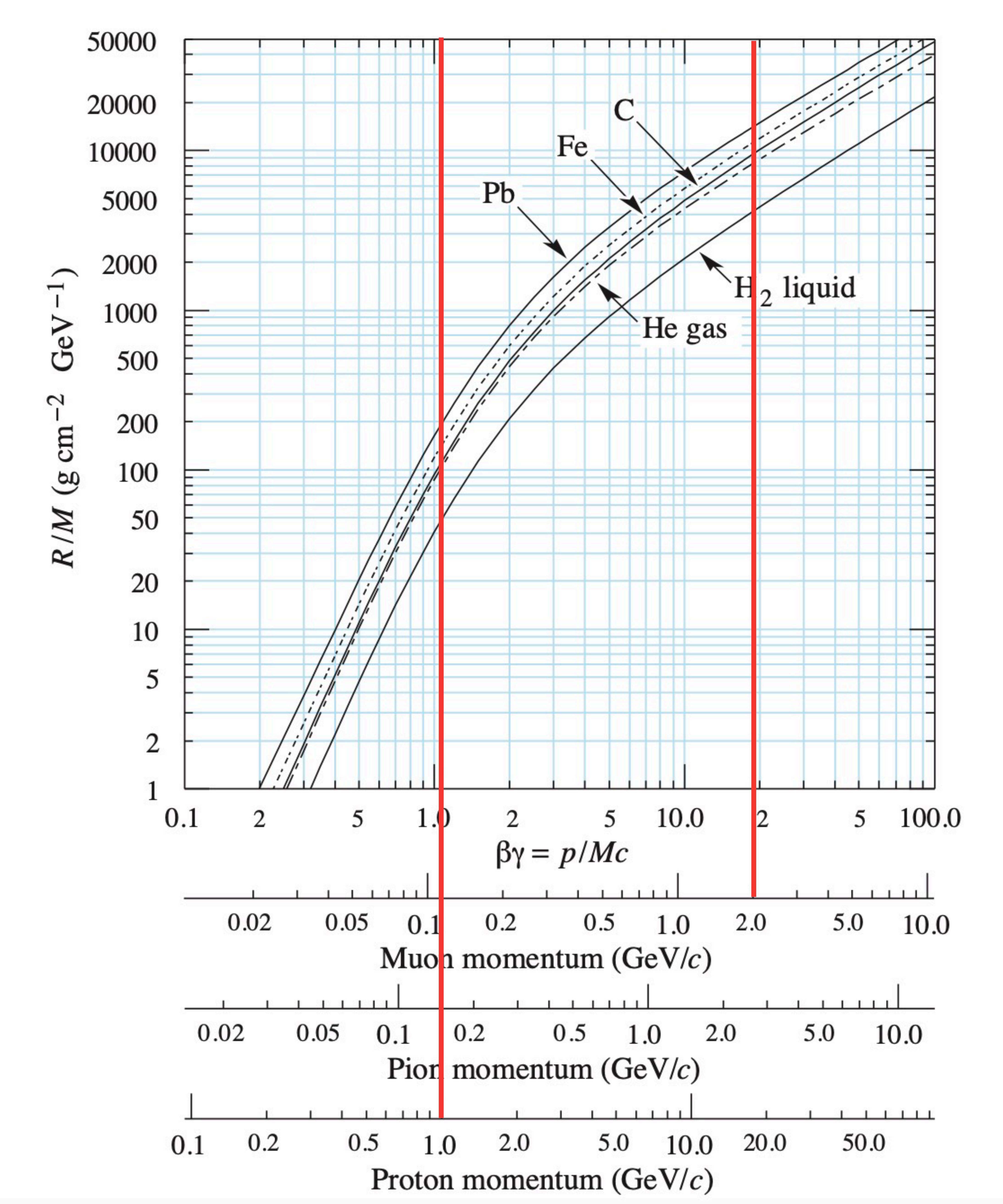
USE BOTH TOF AND dE/dx



USE dE/dx

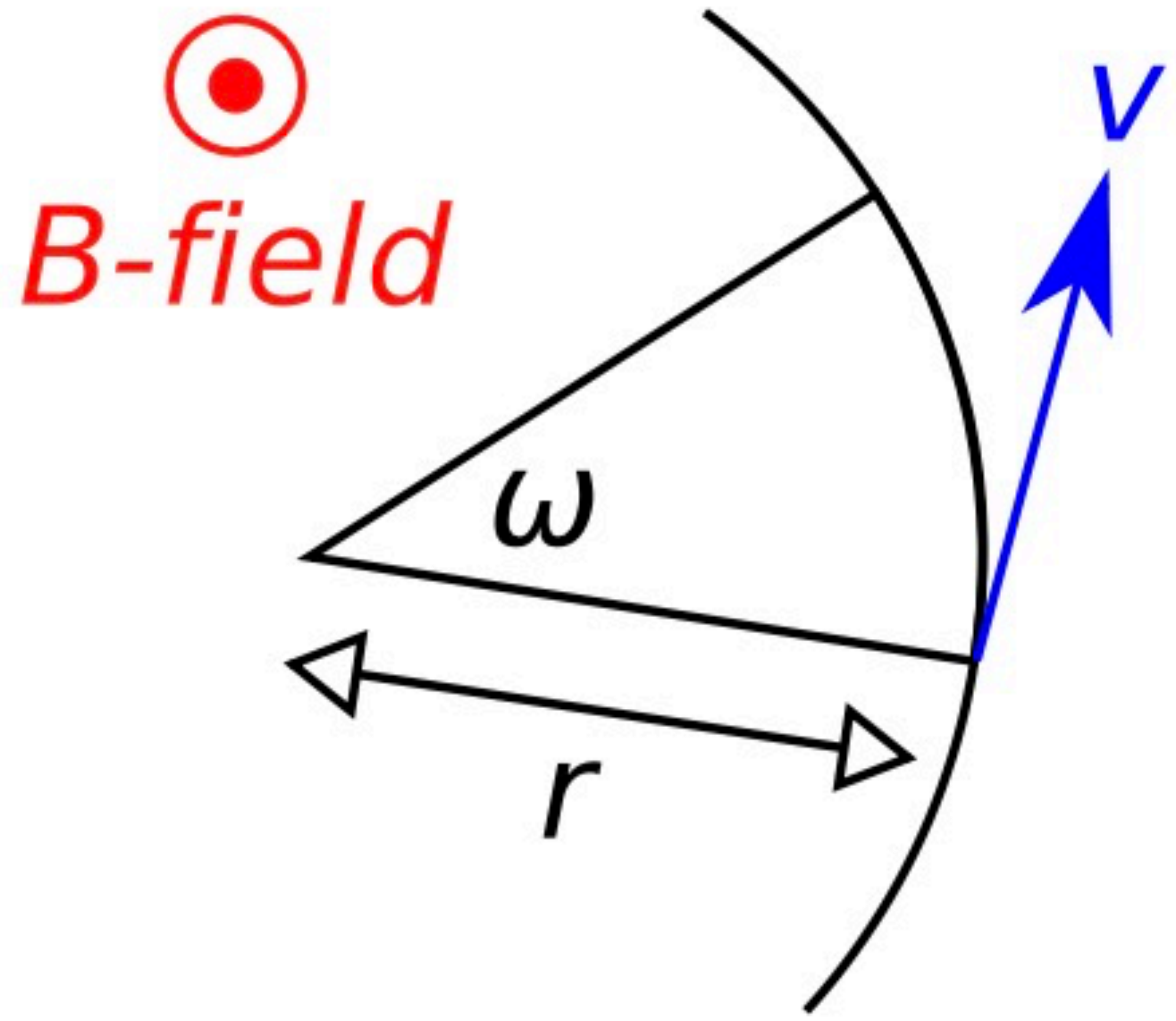
Momentum measurement

Range of particle slowing down to stop.



- For a particle of mass m and kinetic energy of E_0 entering matter, it loses energy via ionisation and excitation until stop $R(E_0) = \int_{E_0}^{0} \frac{1}{dE/dx} dE$
- Useful for muons below few 100 GeV
- Particle range is proportional to the particle momentum
- Eg:
  - 1GeV proton ($M_p = 0.938\ GeV$) on C (scintillator $\rho = 1.021\ g\,.\,cm^{-3}$), R/M =100$g\,.\,cm^{-2}GeV^{-1}$. So $R = 100 * 0.983/1.021 \approx 100\ cm \equiv 1\ m$
  - 2GeV muon ($M_\mu \approx 0.106\ GeV$) on C, $R/M = 10000\ g\,.\,cm^{-2}\,.\,GeV^{-1}$. So $R = 10000 * 0.106/1.021 \approx 1038\ cm \equiv 10.38\ m$

Momentum measurement w/ curvature in magnetic field



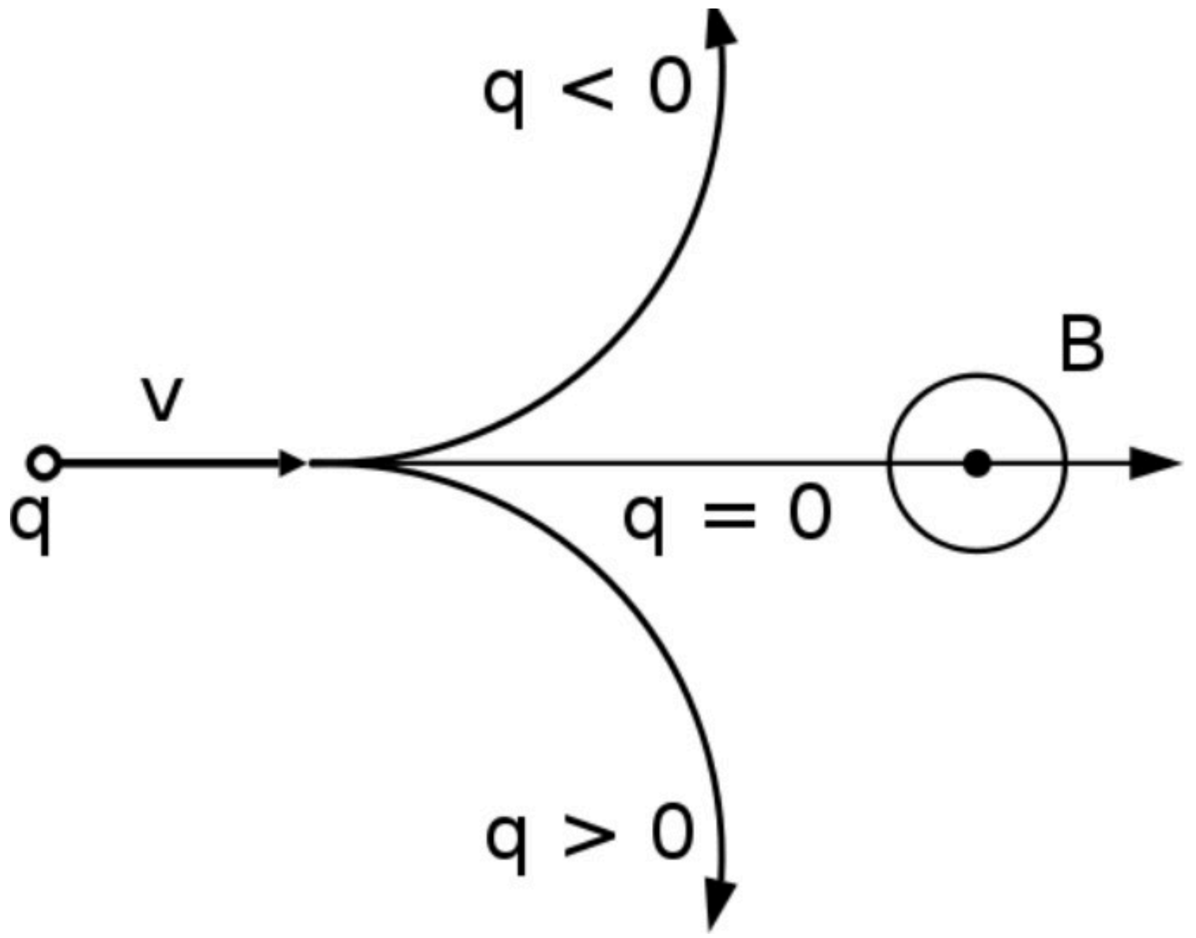


Figure 1: A particle with velocity v entering a magnetic field. In unit time the particle travels a distance v around the circle and turns through an angle ω.

$$F = qvB$$

$$ma = qvB$$

$$m\left(\frac{v^2}{r}\right) = qvB$$

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

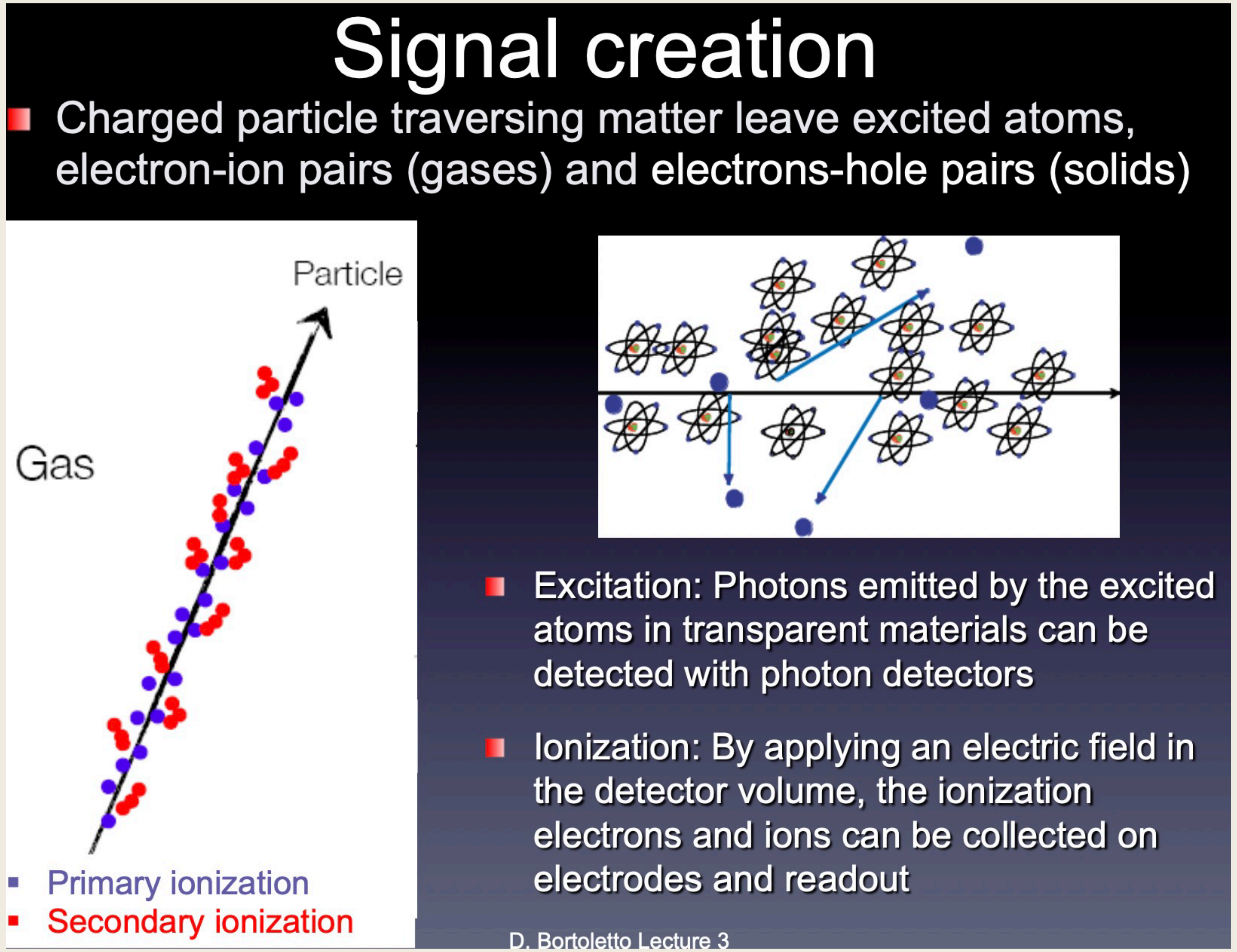
$$r = \frac{mv}{qB} = \frac{p}{qB}$$

$$r \propto p$$

- Radius of the curvature is proportional to the particle momentum
- If β can be measured independently, mass of particle can be inferred
- Direction curvature bend also can be used to distinguish positive and negative charge

Tracking detector

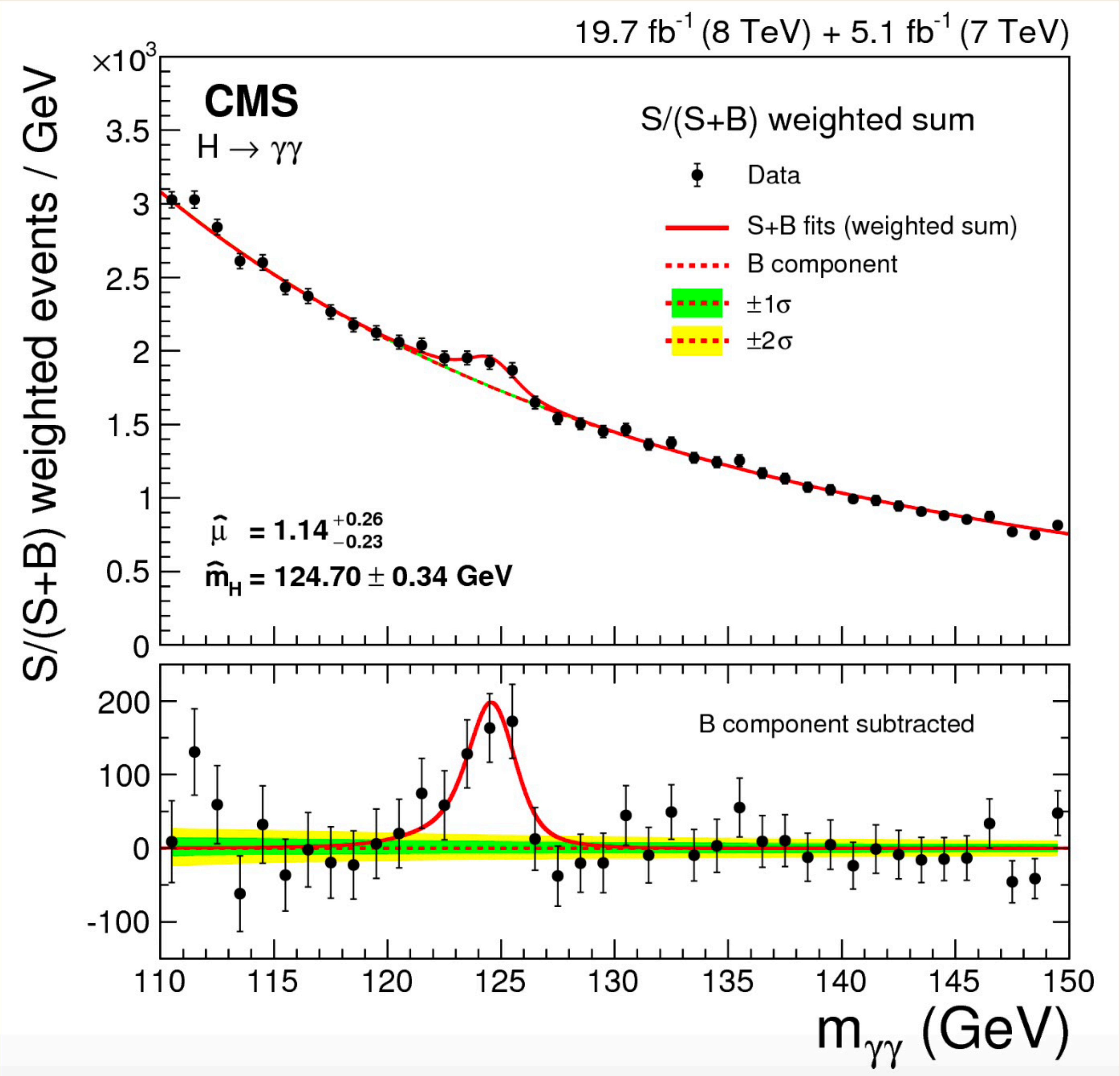
- Gas-based
- Semiconductor technology
- Scintillation (plastic or liquid or recent water-based liquid scintillator or liquid-O) detector
- Cherenkov detector



Importance of energy measurement

To determine the energy of particle with some level of precision using the "energy loss phenomena"

- You can't measure directly but reconstruct from the signal induced of energy loss of particle
- Energy loss is proportional to the particle energy
- For some physics (*eg. Higgs discovery, neutrino oscillation…*), measuring the energy precisely is vital



Higgs particle discovery thanks to the precise measurement of photon energy