Basics of Particle Detection

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Some textbooks and references

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

Outlines

- General concept of particle detection
- Passage of particles through matter
- Detector functionalities
  - Particle identification
  - Tracking
  - Calorimeter
- Application of particle detection

Aim of this short course is to provide foundations/background for other relatively advanced lectures in particle detectors and for hardware training.

Forewords

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

One of the school's key goals is to provide a foundational basis that will not only help you answer certain questions, but will also prompt you to ask more from both theoretical and experiential perspectives.

Astonishing thing: **human, a tiny creature, think seriously about the vast Universe**

Our Vietnam on the Earth

One should find myself privileged to be scientist!

Our Solar System in the Milky Way

Our Milky Way in the "observable" Universe

https://apod.nasa.gov/debate/2020/Tarter100th.html

Try to ask AI

- **Can AI suggest neutrino-related questions that have never been asked by human?**
- **Can AI suggest experiments to address the above-posed questions?**

(By the way, AI 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.)

Useful relativistic relationships

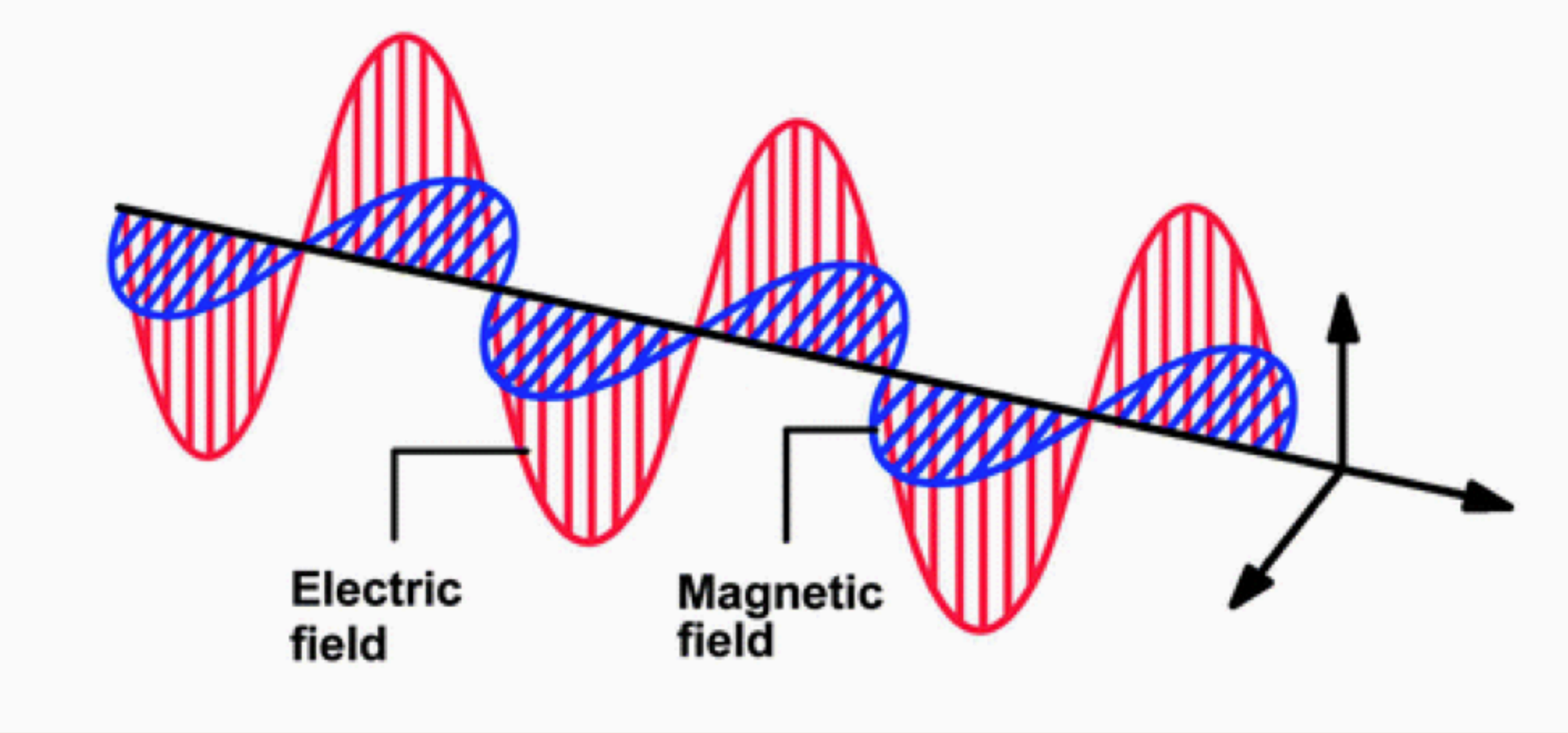
- $\beta = \dfrac{v}{c}$ $(0 \le \beta < 1)$; $\gamma = \dfrac{1}{\sqrt{1 - v^2/c^2}} = \dfrac{1}{\sqrt{1 - \beta^2}}$ $(1 \le \gamma < \infty)$
- Relativistic **mass** $m_r = \gamma m_0$
- Relativistic **momentum** $p_x = m_r v_x = \gamma m_0 v_x = \gamma m_0 \beta_x c$
- Relativistic **energy** $E = m_r c^2 = \gamma m_0 c^2$
- 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 QM, it is allowed with the relation $E = pc$ for the free particle
  - However, *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	$(\text{GeV}/\hbar)^{-1}$	GeV^{-1}
Length	m	$(\text{GeV}/\hbar c)^{-1}$	GeV^{-1}
Area	m^2	$(\text{GeV}/\hbar c)^{-2}$	GeV^{-2}

Energy of photon: useful conversion



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

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

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

Energy of relativistic particle is expressed in eV, keV…

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

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

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

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

Why we can’t simply observe the light quanta?

A lot photons...

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

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

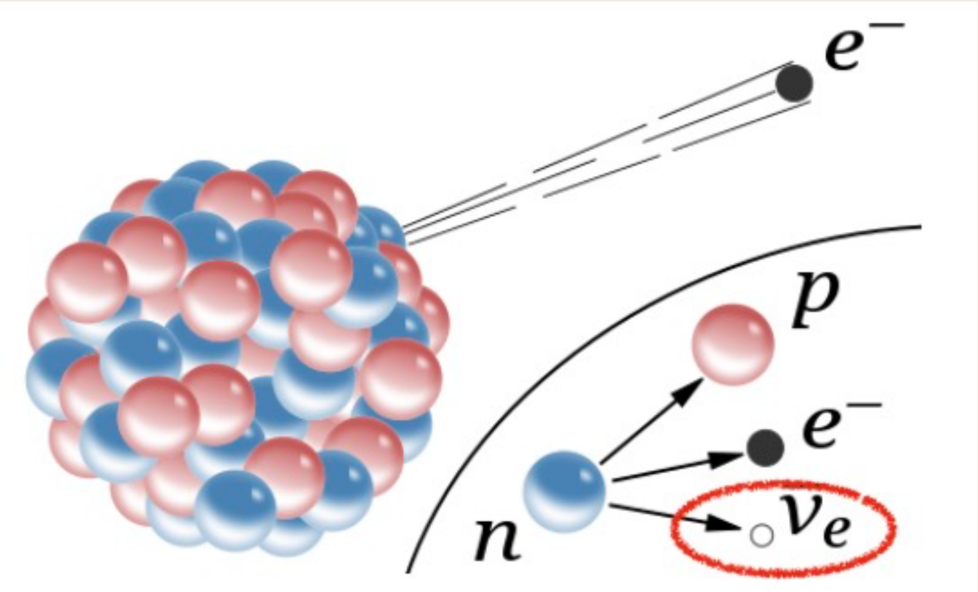
$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}[m/s]}{405 \times 10^{-9}[m]} = 7.4 \times 10^{14}[s^{-1}] = 7.4 \times 10^{14}[Hz]$$

Number of photons emitted per second

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

General concept of particle detectors

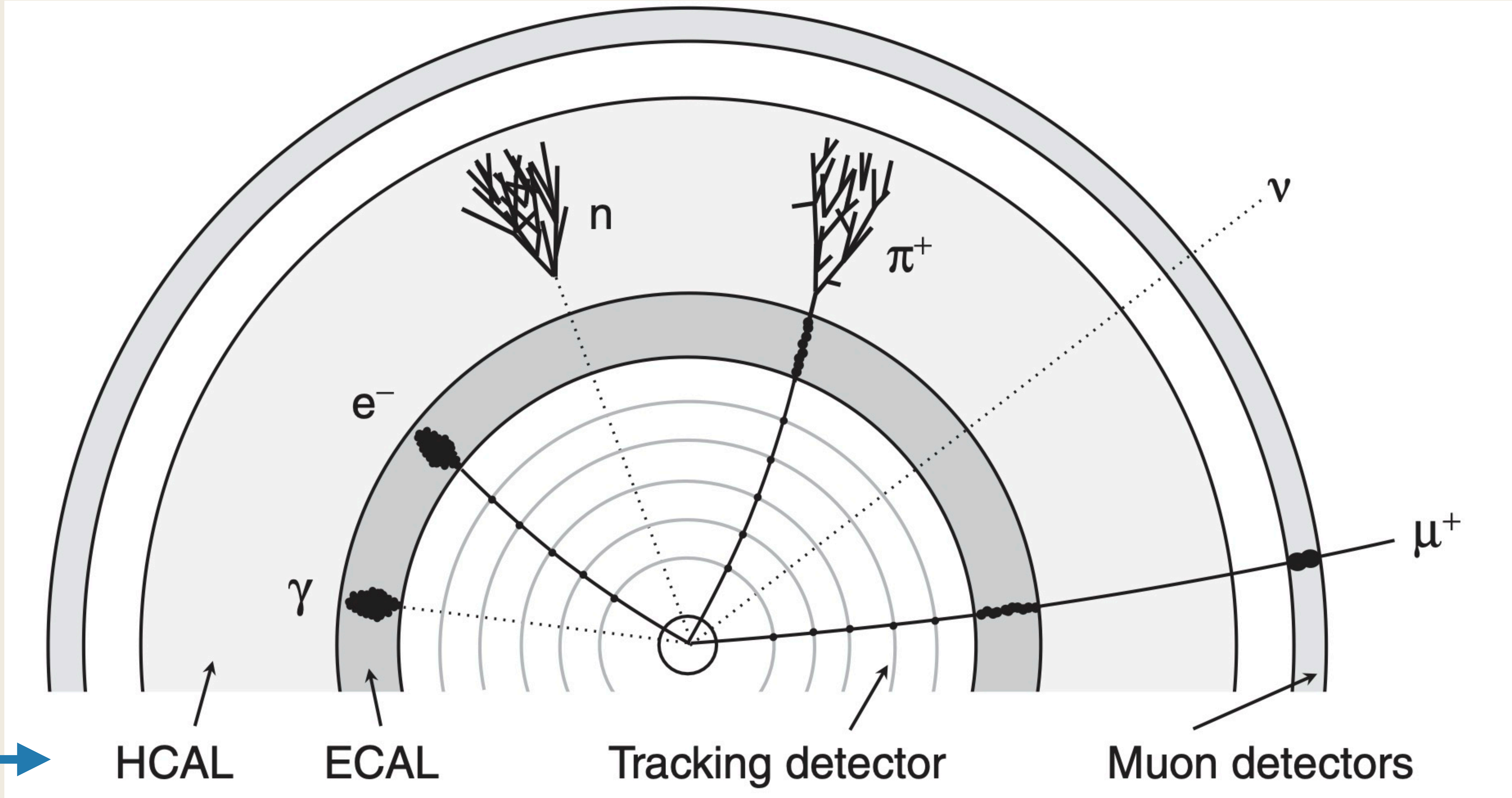
Particle interaction



- **We can't see the interaction itself but the <u>end products</u> of the interaction**
  - Eg. Story of Pauli's proposal 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



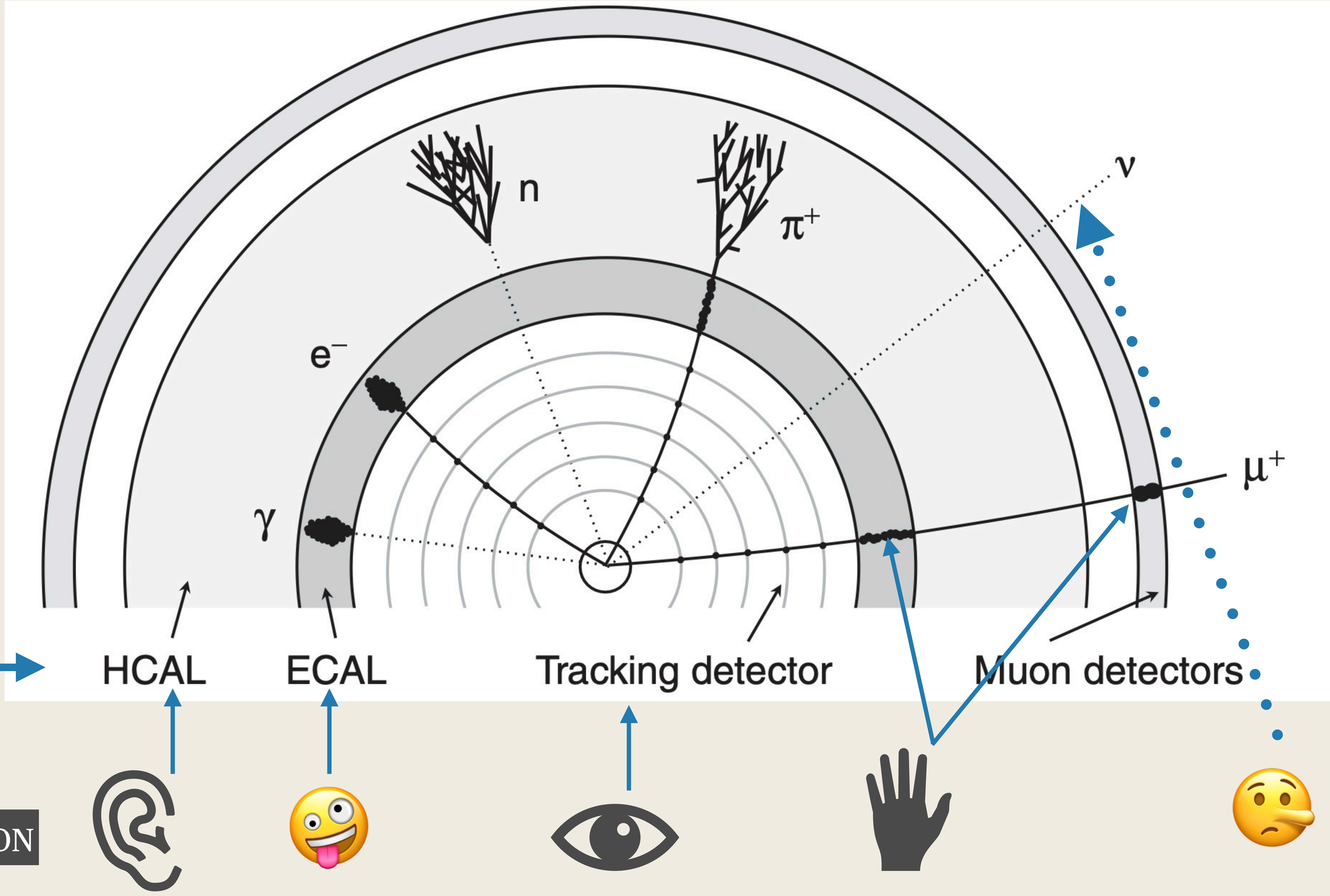
Ignore these technical terms

You can consider them as "sense organ" of the detector

Can you try to match: eyes, ear, nose, tongue, skin

Example of particle signatures in the detector

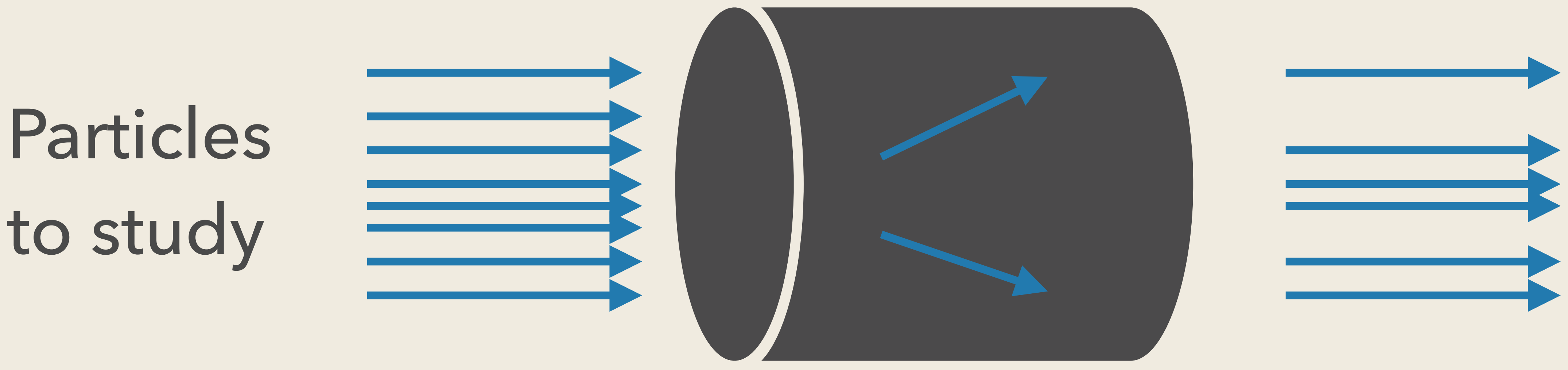
Ignore these technical terms



SOME SUGGESTION

Main body of particle detector

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



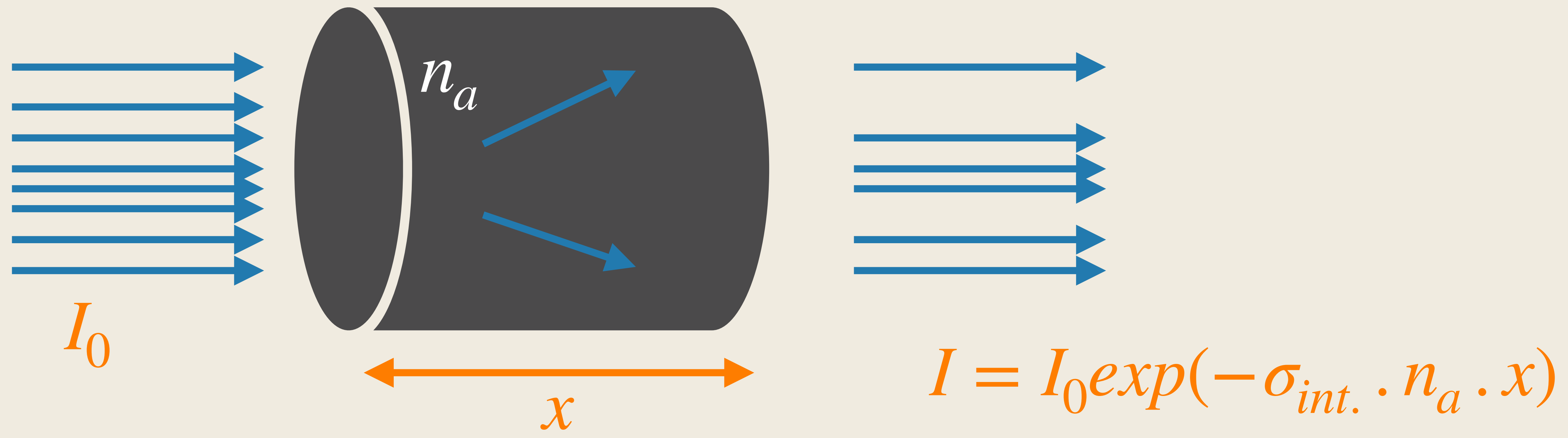
Detector = matter medium

“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 $n_a = \dfrac{N_A \times \rho}{A}$ 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, $\lambda_{int.} = \dfrac{1}{\sum_i n_i \sigma_i}$



Cross section and example

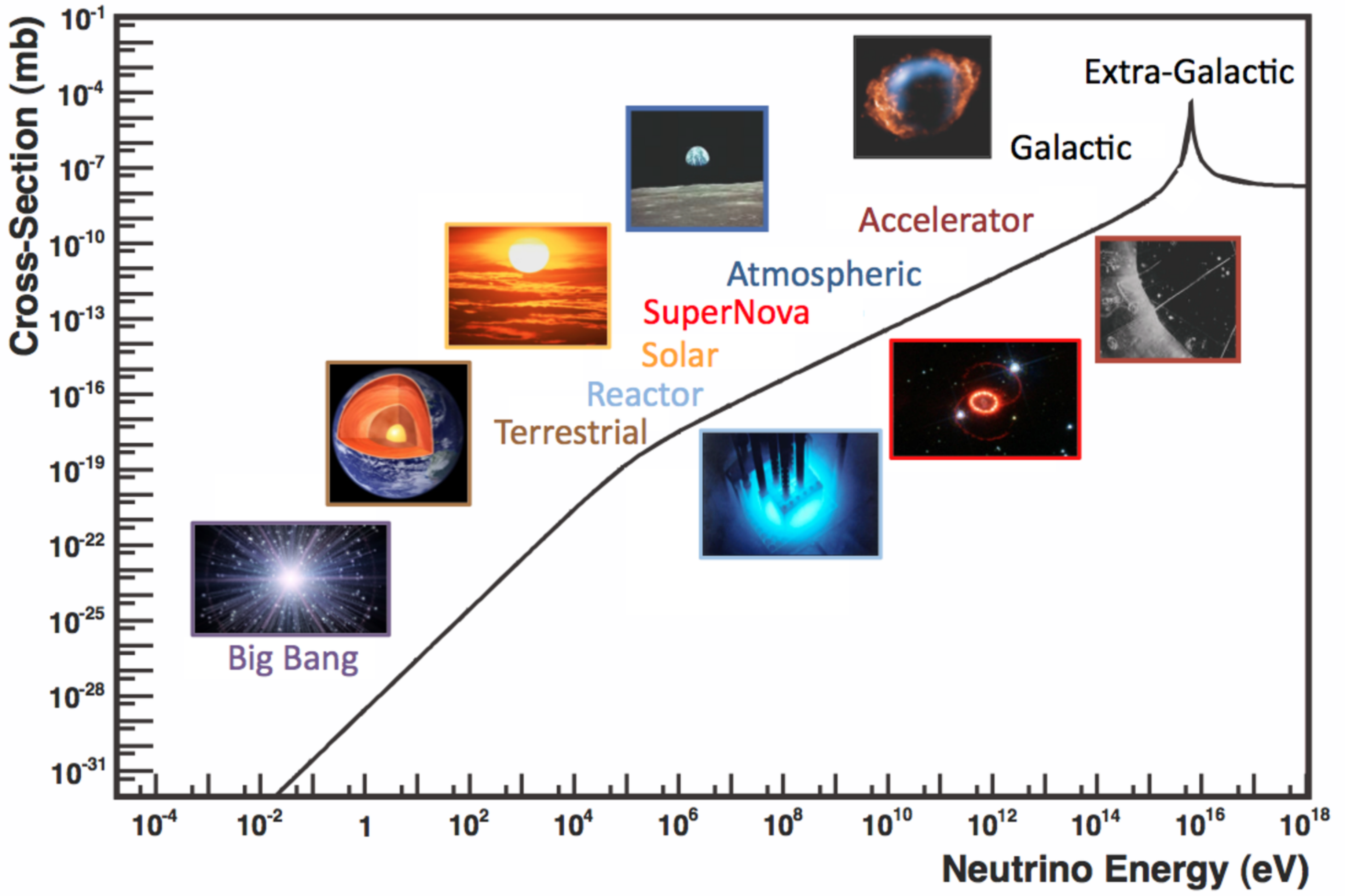
- $1\text{barn} = 10^{-24} cm^2$
- 1mb = 1 milibarn = $10^{-27} cm^2$
- 1pb = 1 picobarn = $10^{-36} cm^2$
- 1fb = 1 femtobarn = $10^{-39} cm^2$

- Strong force $p + p \rightarrow X, \sigma$ ~ 45mb (*scale = 1*)
- Electromagnetic force $\gamma + p \rightarrow X, \sigma$ ~ 0.15mb (~1/300)
- Weak force $\nu_\mu + N \rightarrow X, \sigma$ ~ 7fb (*~1/6400000000000*)

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.



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

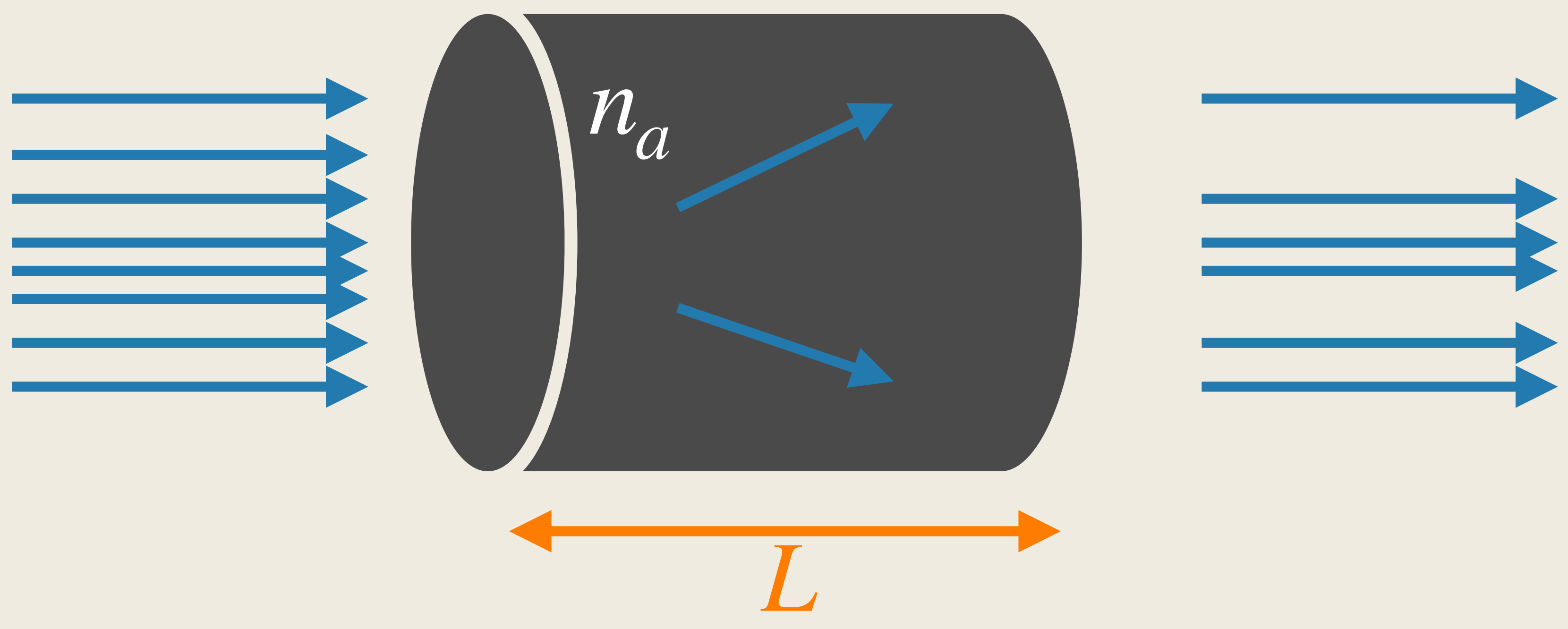
For reactor ν at few MeV, $\sigma \sim 10^{-43}\ cm^2$

For 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, $\sigma_A = \sigma_{pp} \, . A^{0.77}$
  - $$\lambda_p = \frac{A}{N_A \rho \sigma_{tot.}} = \frac{56[g/mol]}{6.02 \times 10^{23}[1/mol].7.87[g/cm^3].56^{0.77}.25 \times 10^{-27}[cm^2]} \approx 21\text{cm}$$

- **For 100GeV neutrino entering a iron slab**
  - $$\lambda_\nu = \frac{56}{6.02e23 \times 7.87 \times 0.7e^{-38} \times 1000} \approx 1.7e^{13}\text{cm}$$ > 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
  - Total sand grain on the Earth ~ 10^{18}
  - Solar neutrino flux at the Earth $\Phi = \frac{N}{4\pi R^2} \approx \frac{2 \times 10^{38}}{4\pi(1.5 \times 10^{13})^2} \approx 7 \times 10^{10} cm^{-2} s^{-1}$
  - 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 $\sigma = 10^{-43} cm^2$

$$N[s^{-1}] = \Phi \times \sigma \times N^e_{SK} = 7e10 \times 10^{-43} \times 1.67 \times 10^{34} \approx 117[s^{-1}]$$

  - 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

Conceptual particle detector

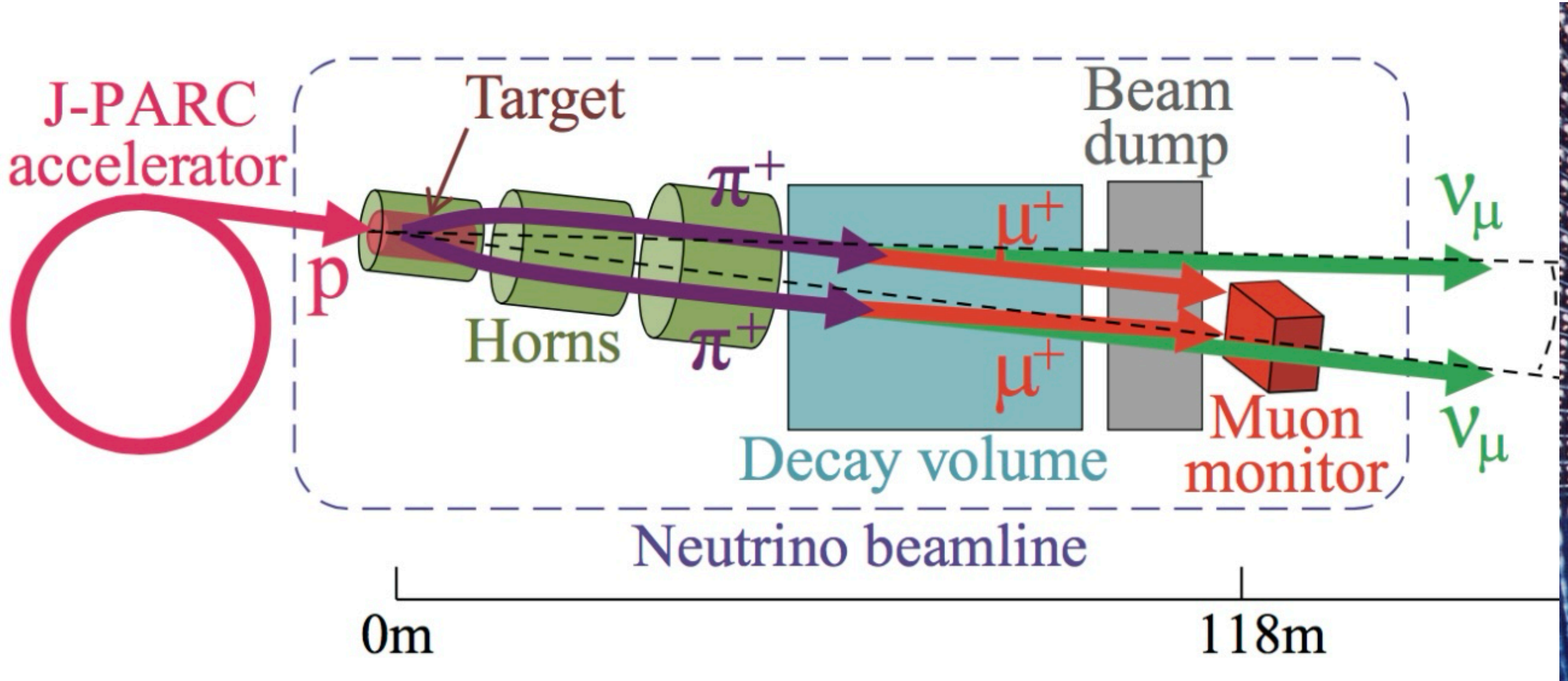
Ideally (*here particles = end products of the interaction*)

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

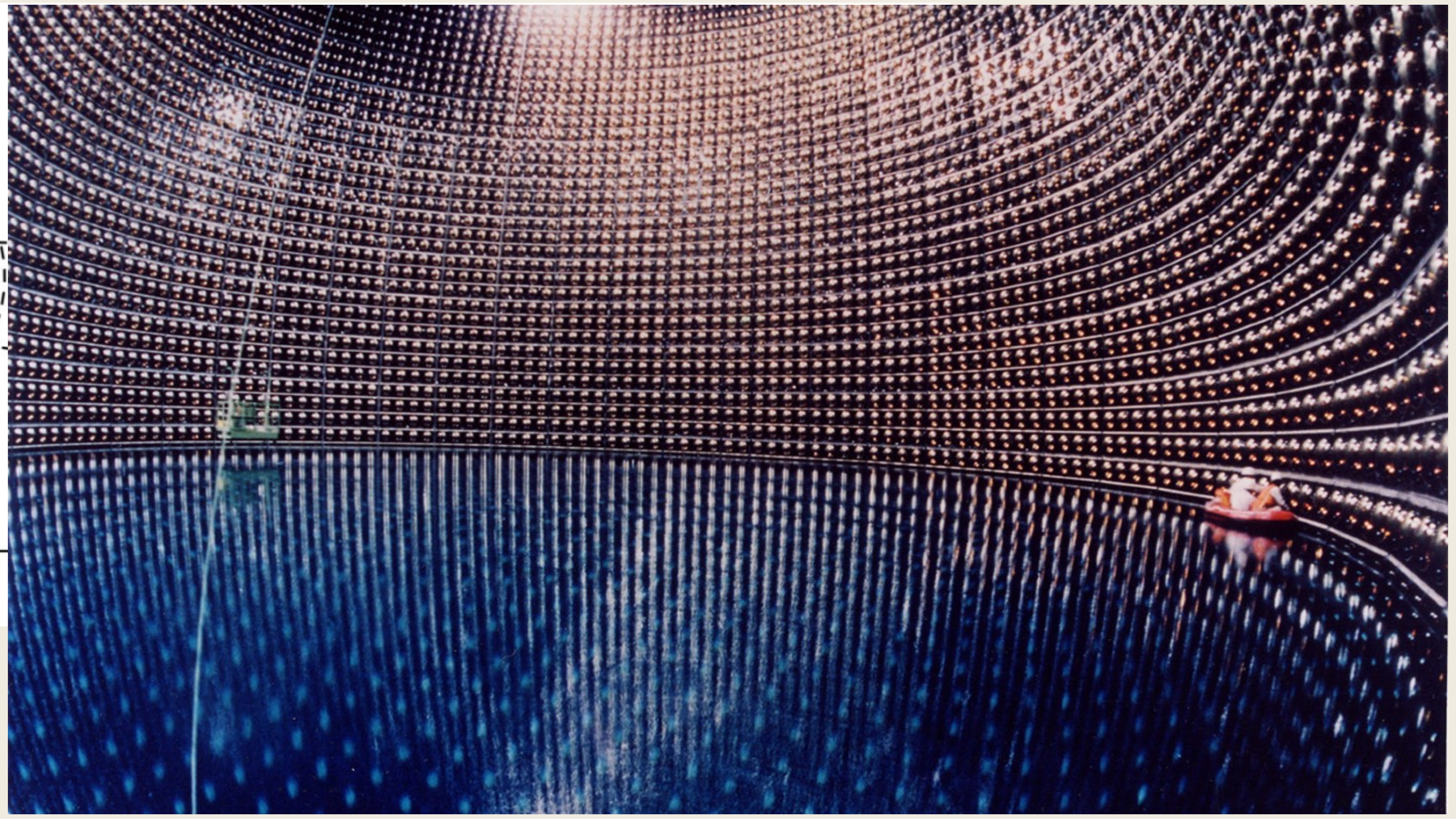
- Additional features
  - Record **High rate events**: collider, near detector of neutrino experiments
  - **Radiation tolerance**: eg collider; MUMON detector of T2K ; caused eg. displacement of the lattice atom/ defection
  - **Continuous operation** for ~ 10 years with little/no intervention
  - **Compromise**: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

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**



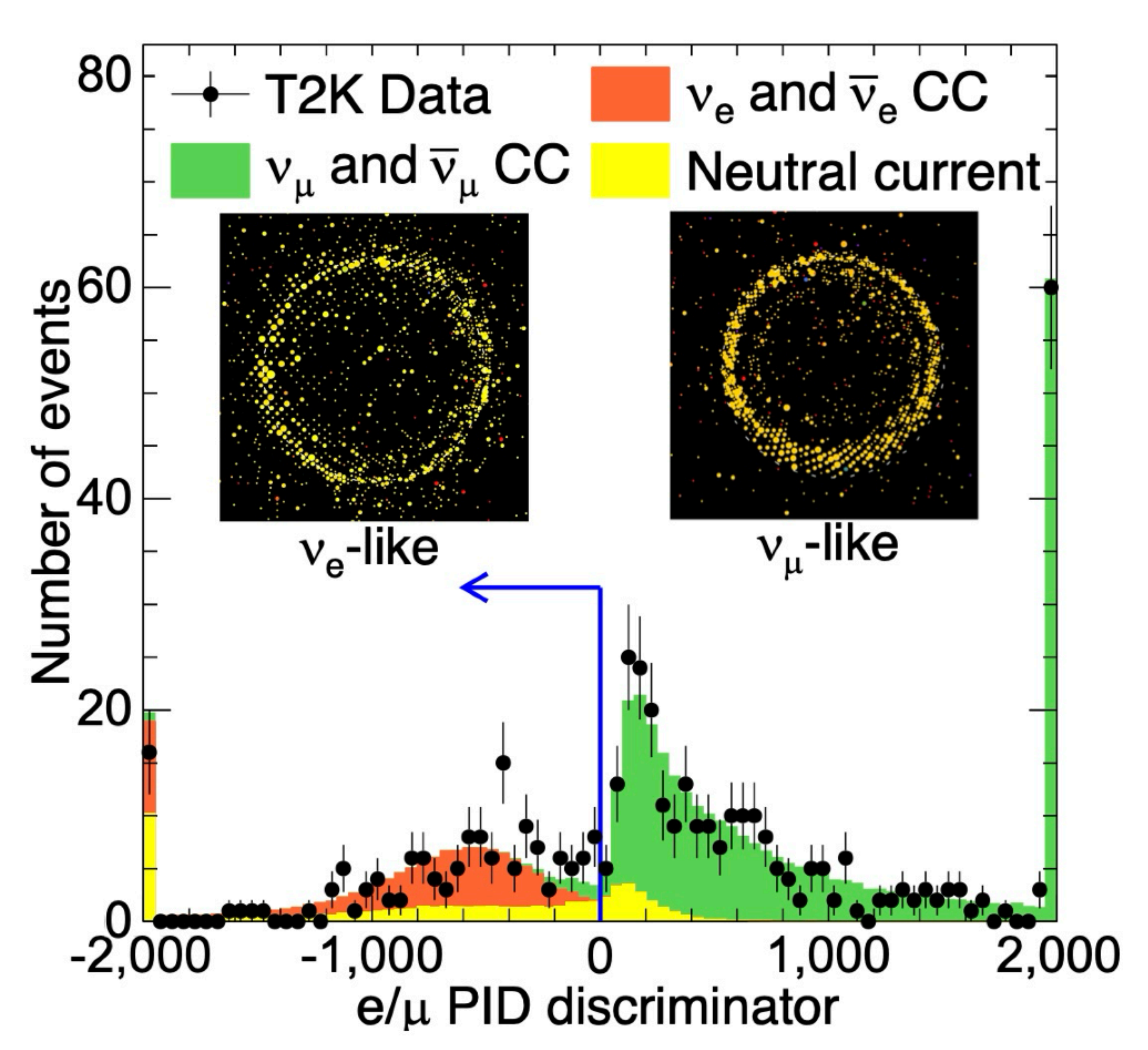
(1) J-PARC neutrino beam



(2) pure water/ Gd-loaded

(3) Photosensor

(4)

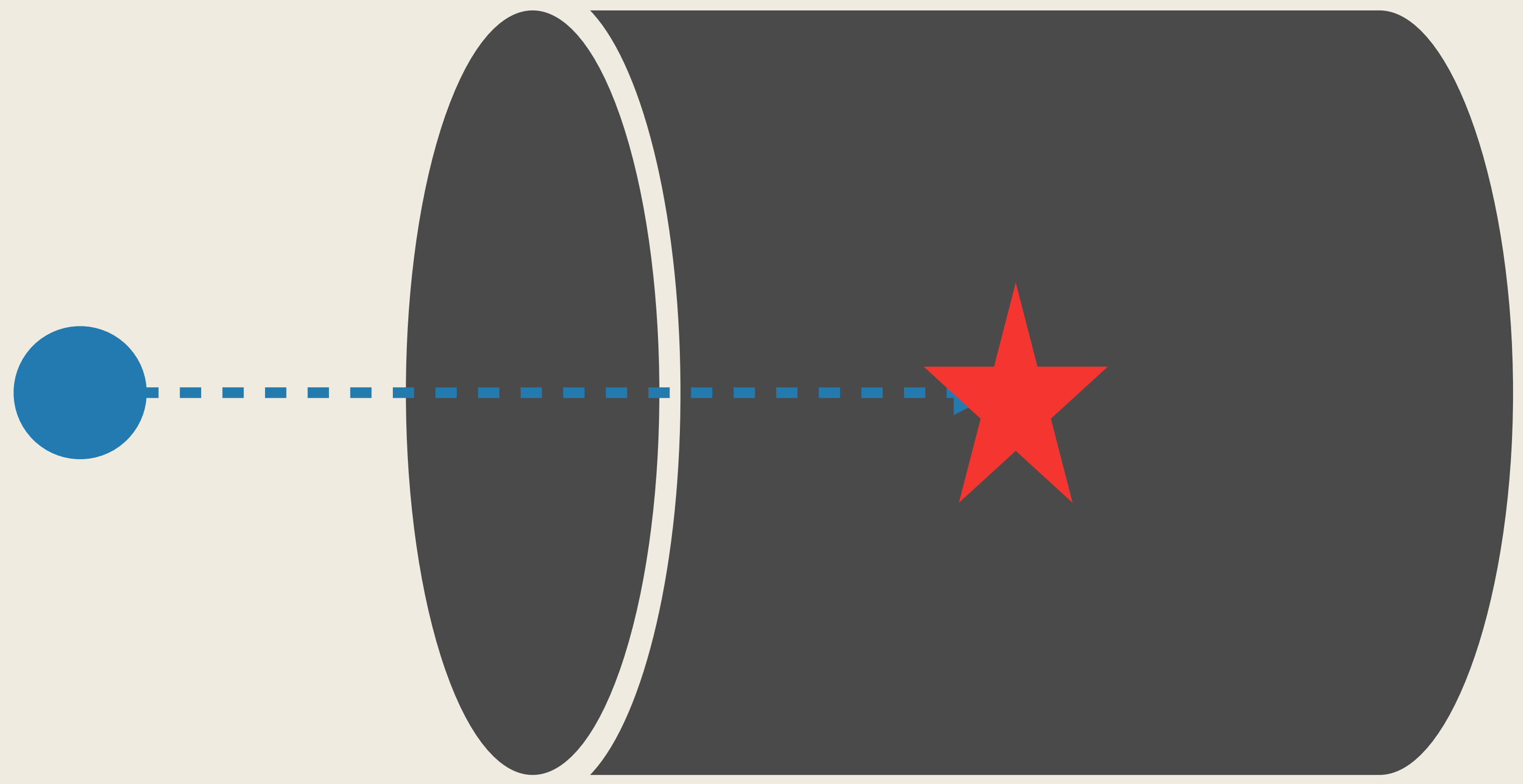


Bodies of particle experiment

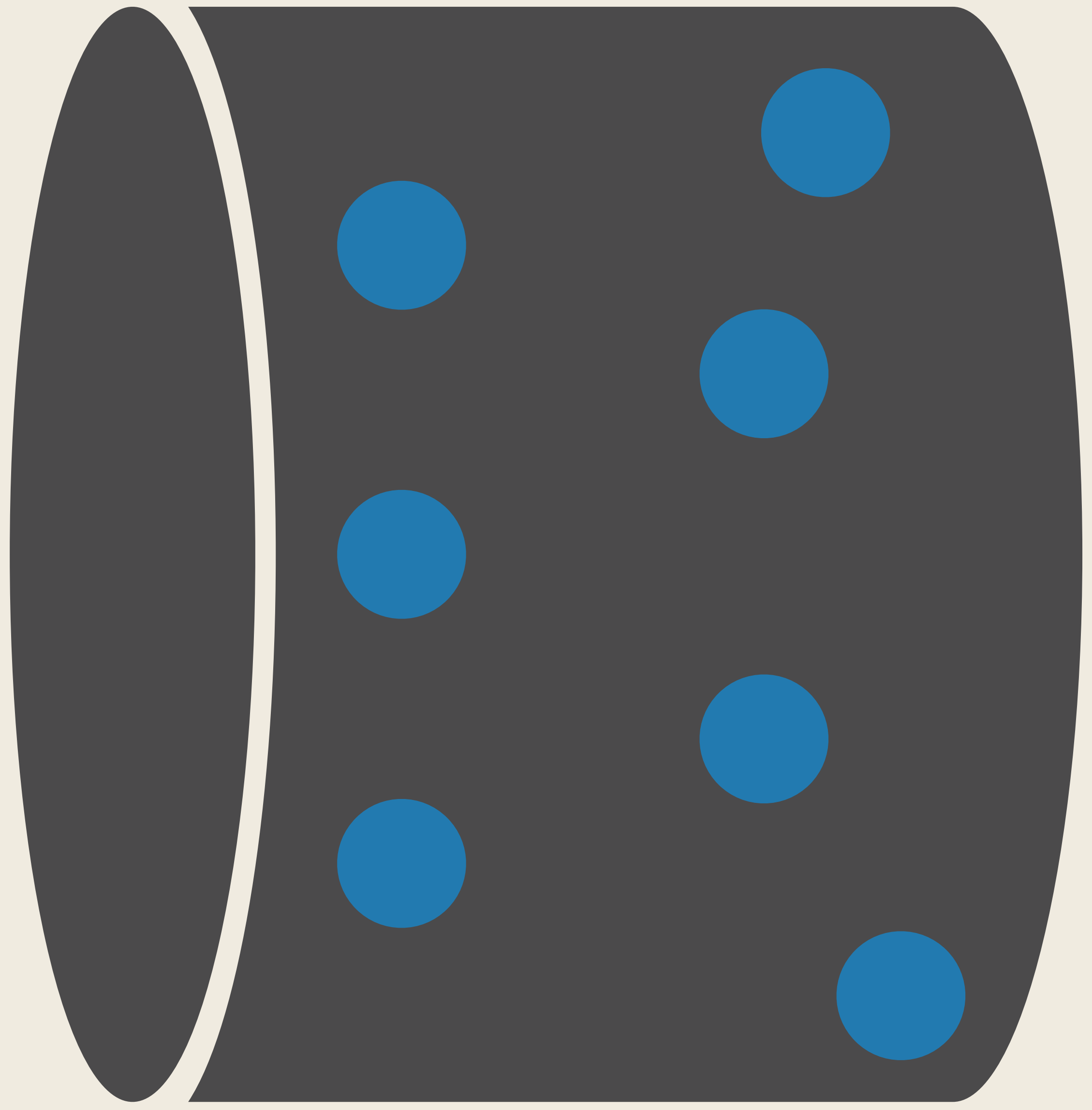
- The essential:
  - (1)**Particle sources**: can be man-made or natural source
    - (2)*Active* **volume for particle interactions**
      - (3)Apparatus to **“capture/visualize” the interaction process**
        - (4)System for **signal processing and analysis**
- **Supporting setup**
  - Passive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

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.



Working principle of particle detectors

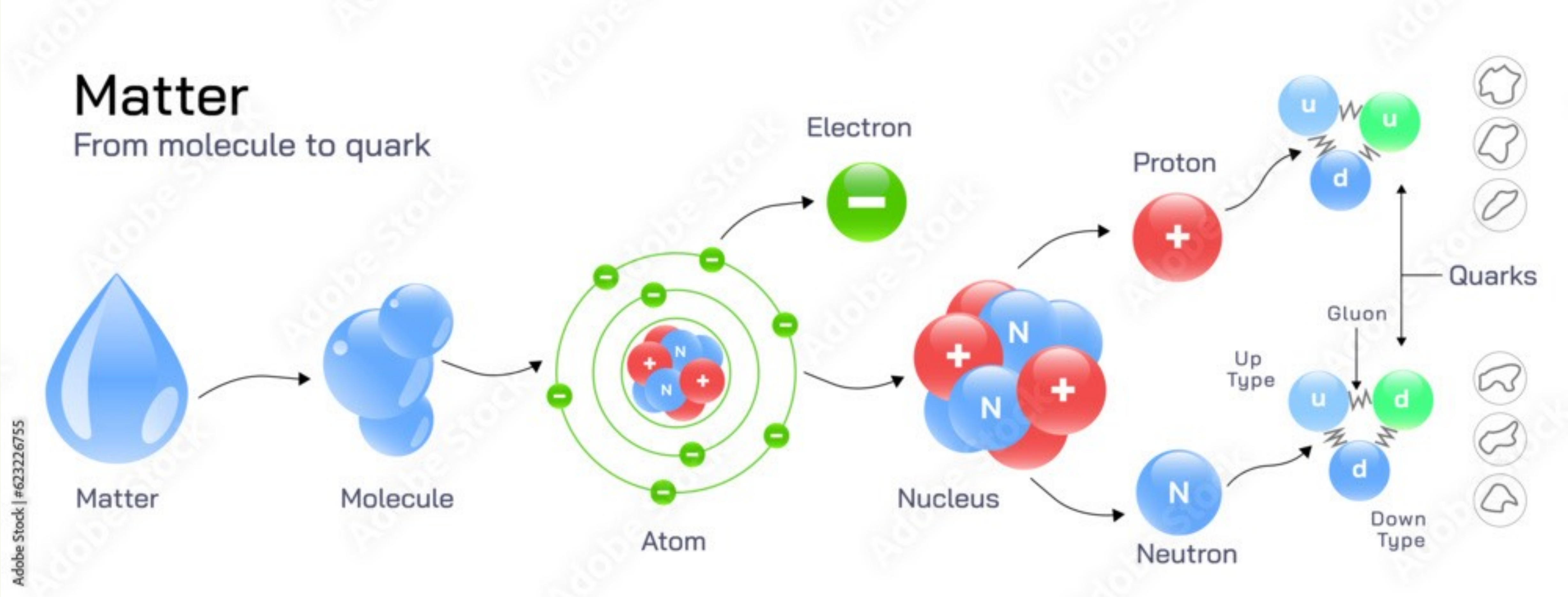
Any effect of particle inducing observable distinction when interacting with matter can be used as working principle of particle detector

					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

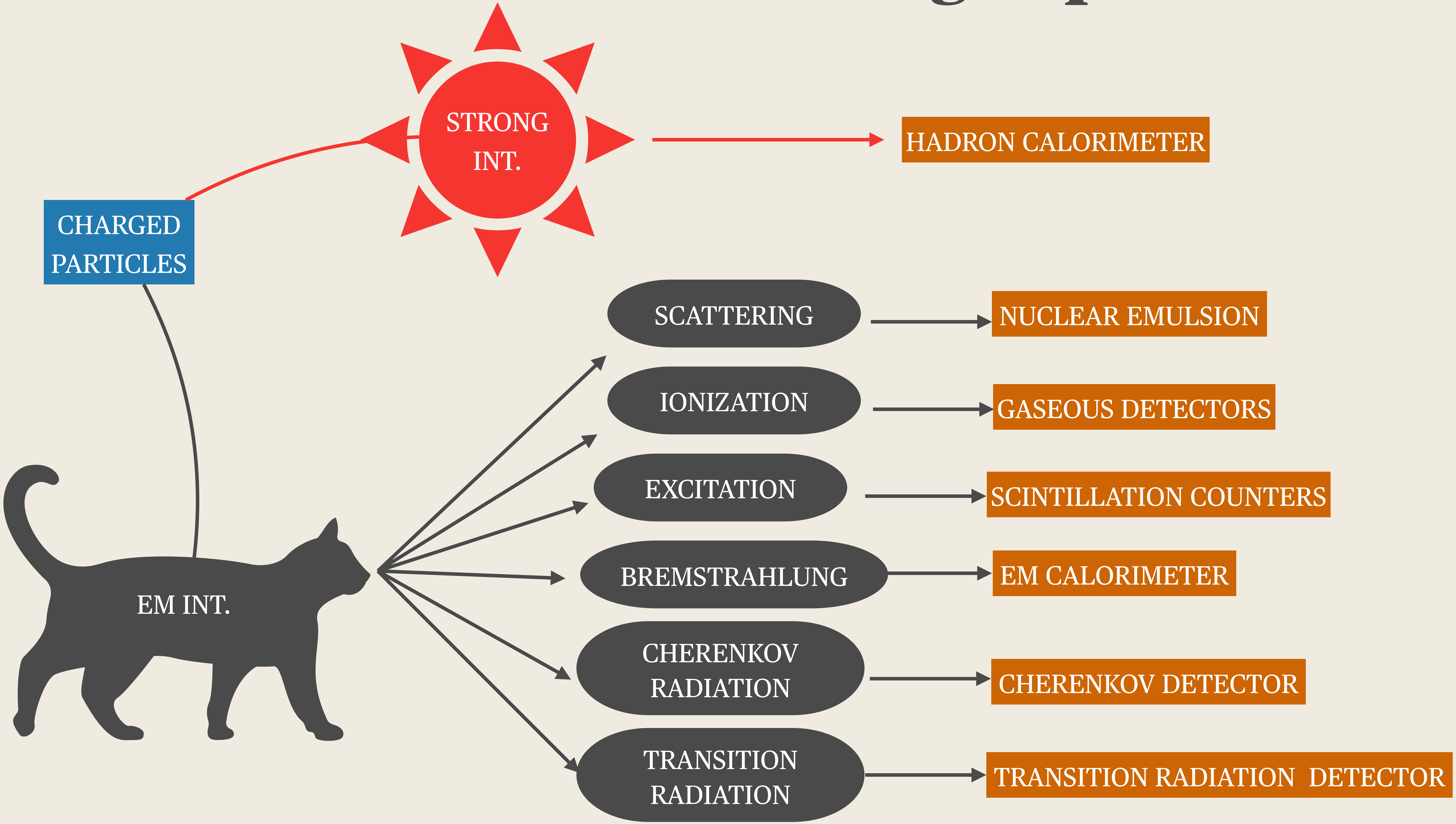
Any effect of particle inducing observable distinction when interacting with matter can be used as working principle of particle detector



Fundamental effects:

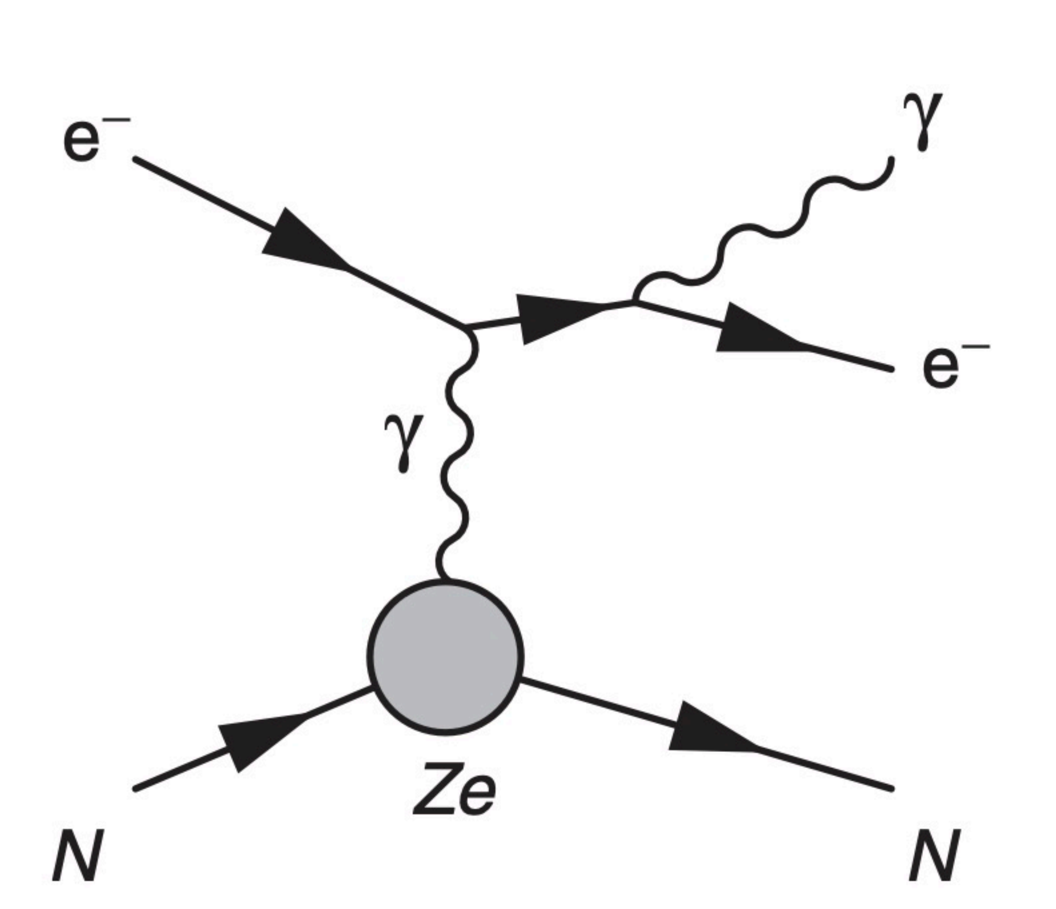
- **Coherent scattering** (*keep targeting atom intact*), release some recoiled energy
- **Ionize atom** by liberating electron
- **Excite the atom/molecule** and produce new particle(s)
- **Emit photon(s)**: Cherenkov radiation, transition radiation, scintillation, fluorescence
- **Break down nucleus**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

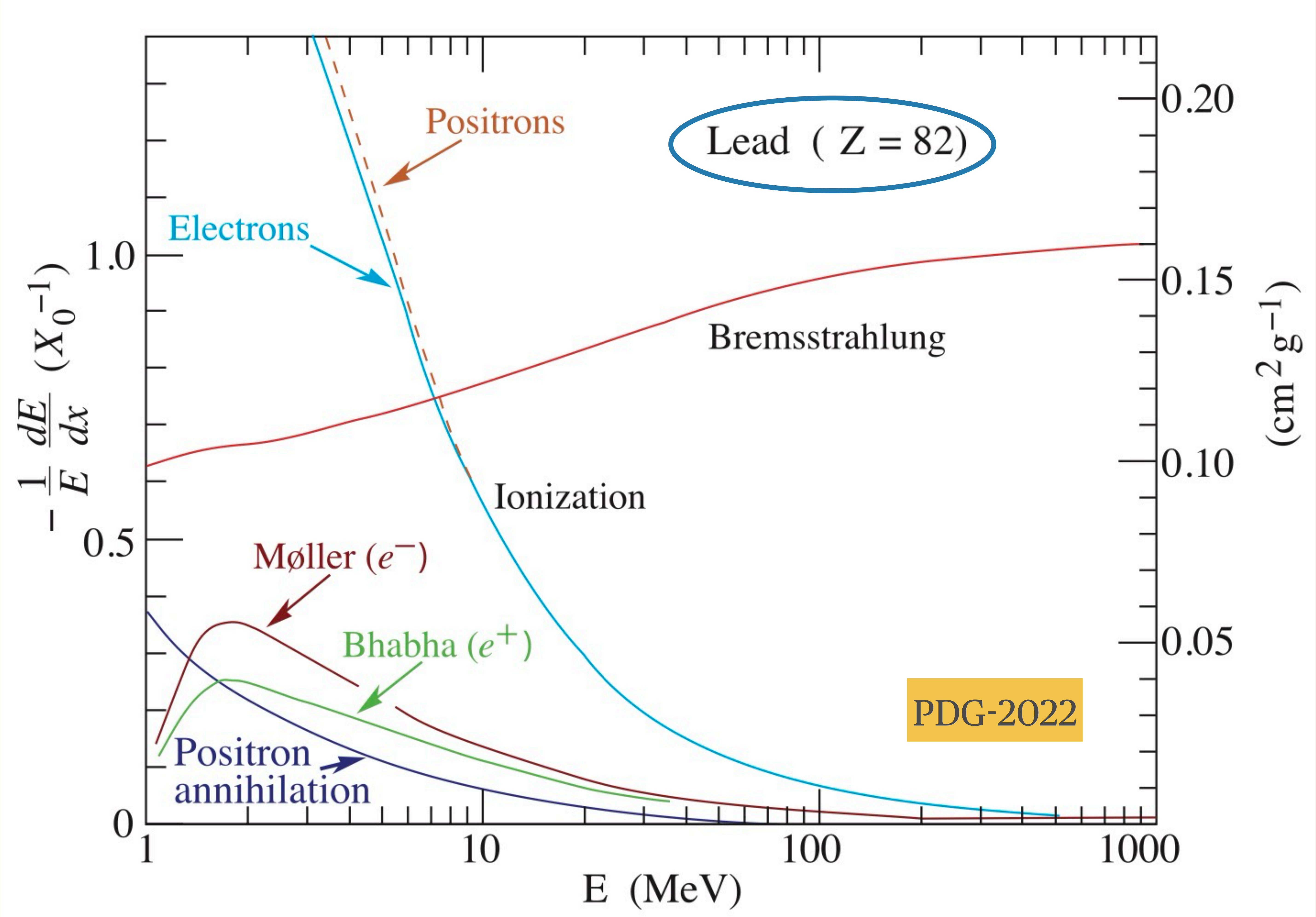
Detection of charged particles



Interaction of electron/positron

- At low-energy (less than $E_c = \dfrac{800\ [MeV]}{Z}$) energy loss, dominated by ionization
- What we are interested is 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

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

$$\beta = \frac{v}{c}$$

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

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

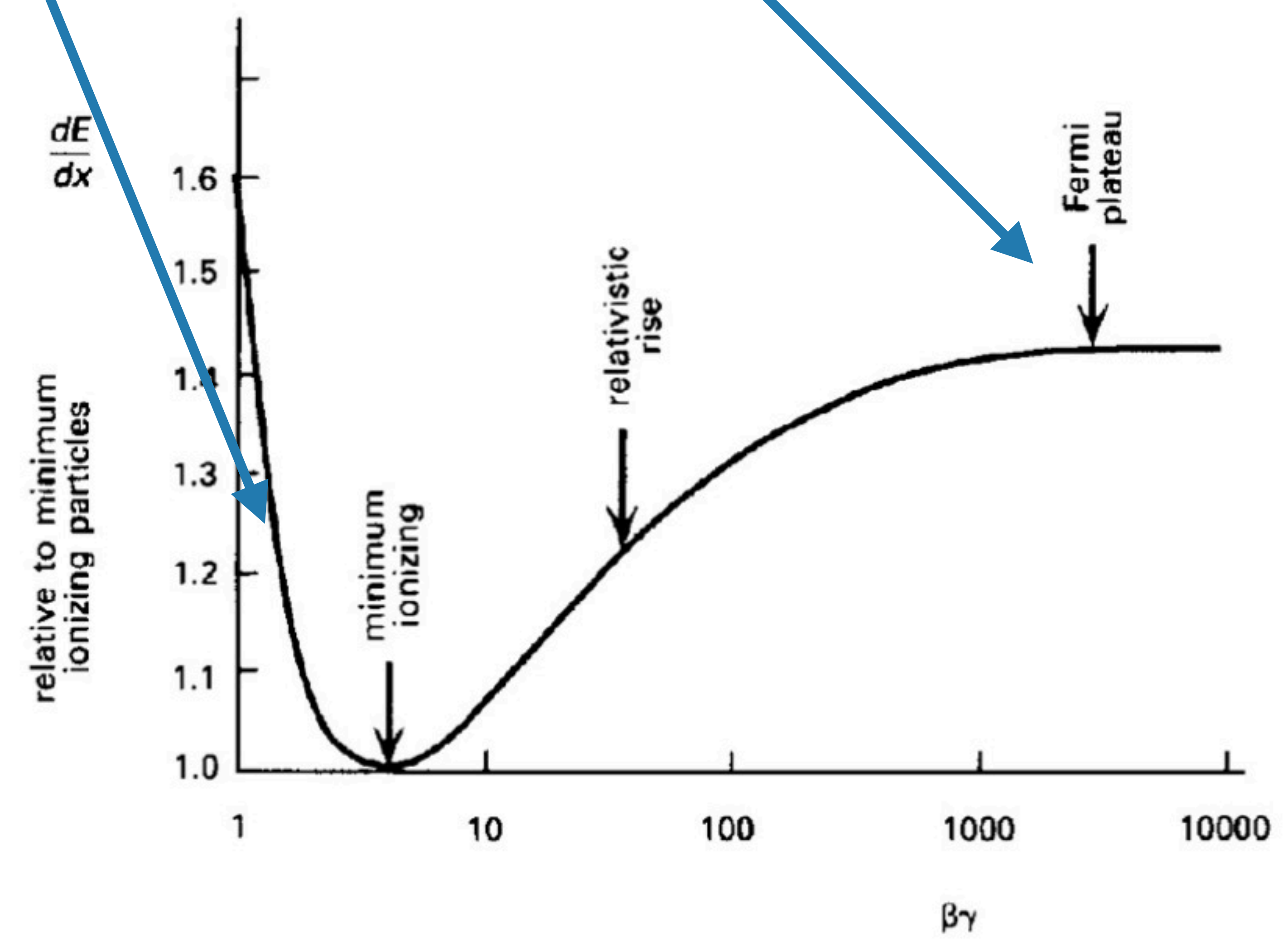
c = speed of light

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*)

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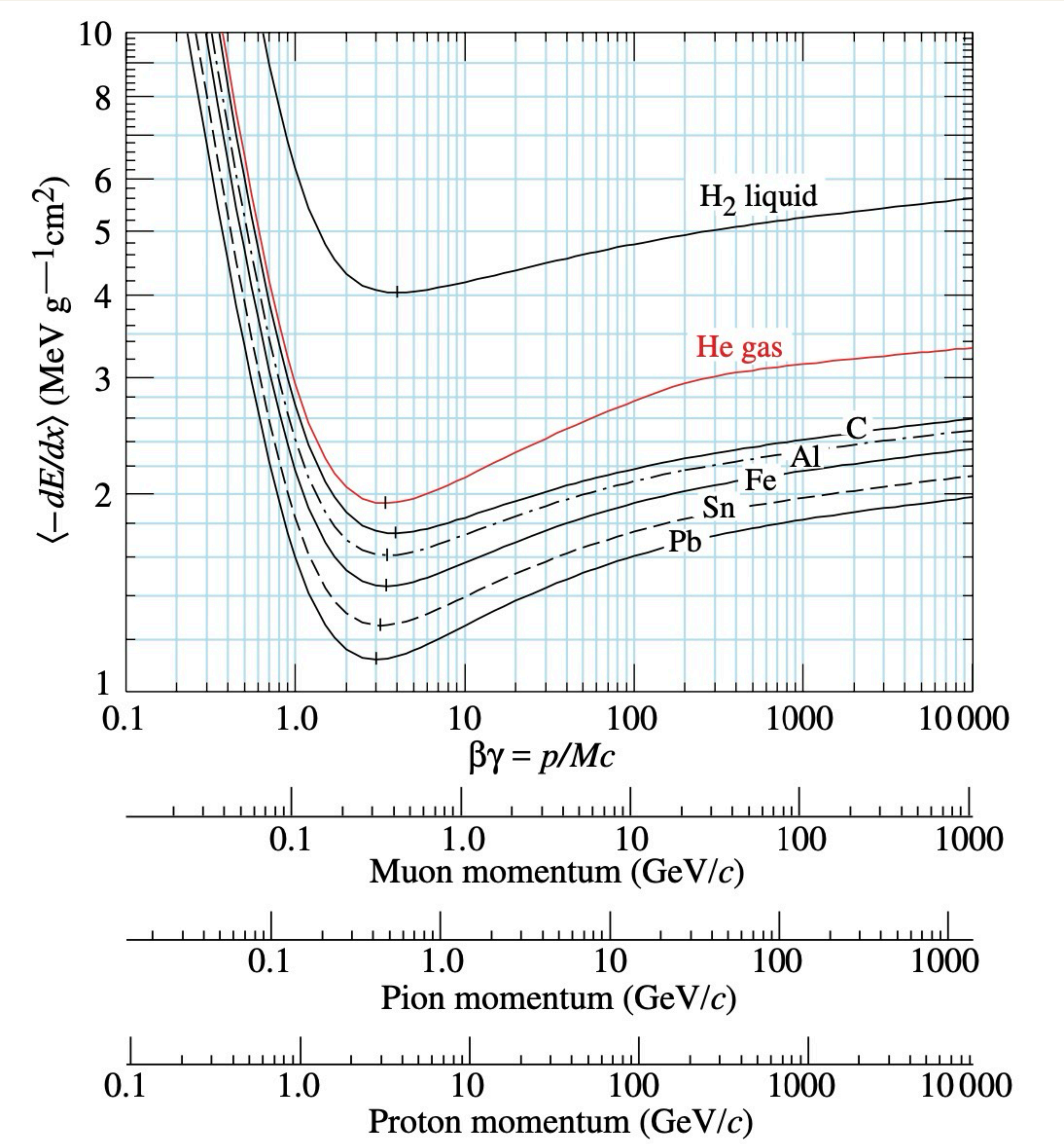
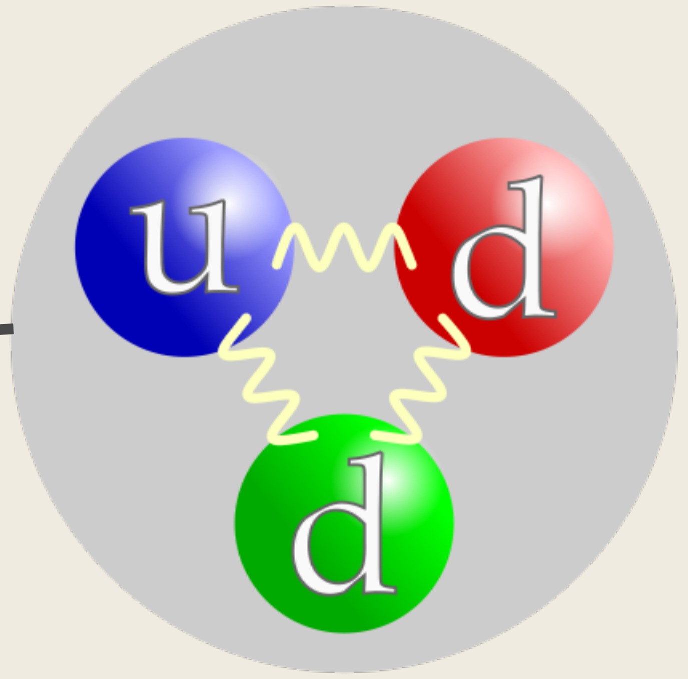


- dE/dx at MIP depend on material choice
- For muon loss on C (*like scintillator*), MIP is when muon momentum is about 3 GeV (eg. Cosmic-ray muons)
  - $< dE/dx > \approx 1.8 - 2.2\ MeVg^{-1}cm^2$ for few GeV muons
  - One can use this to compute the amount of scintillation light produced

Detection of neutral particles

NEUTRAL PARTICLES



EXCITATION / PHOTON EMISSION

NEUTRON COUNTER, EM CALORIMETER...

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

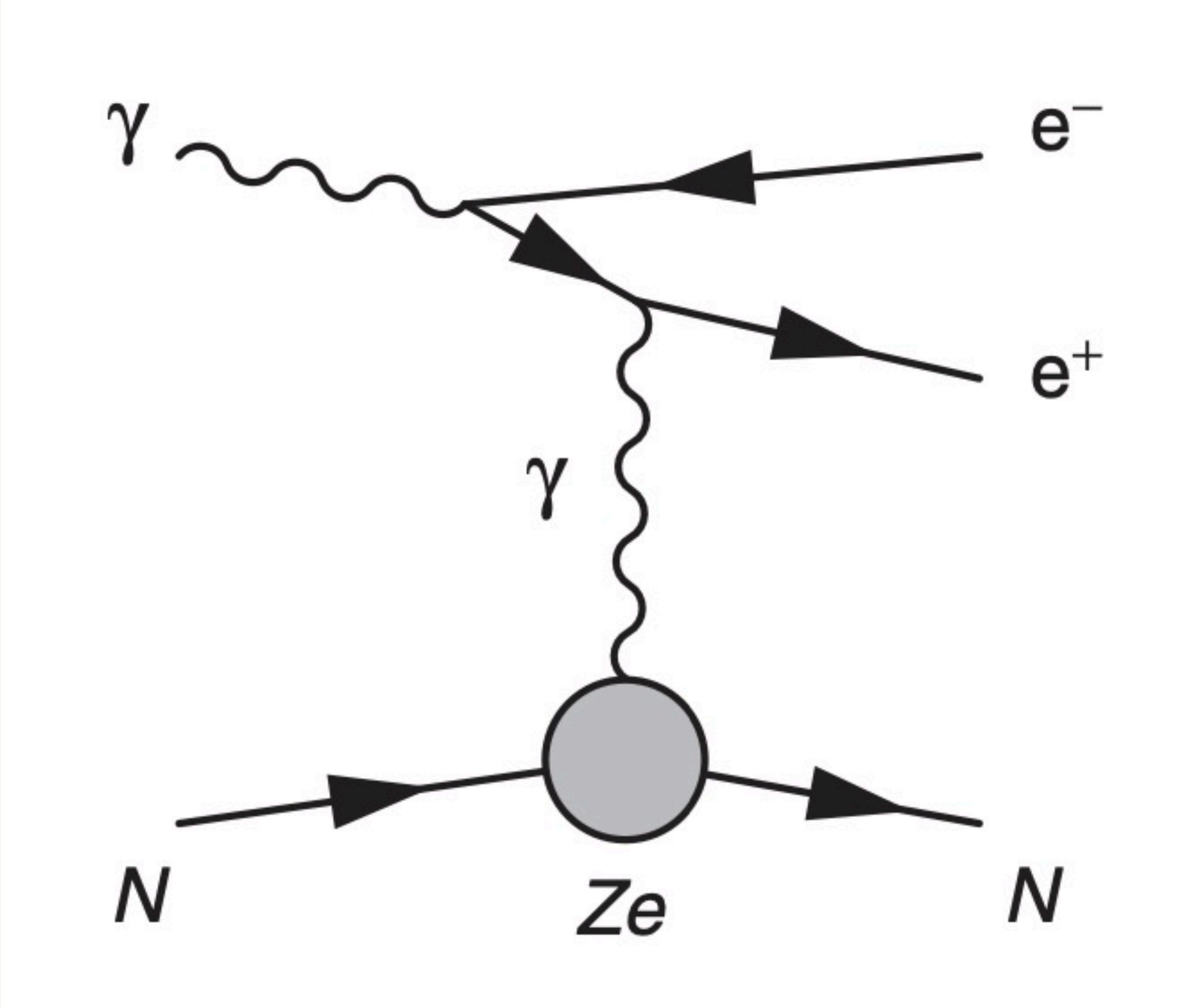
EM CALORIMETER...

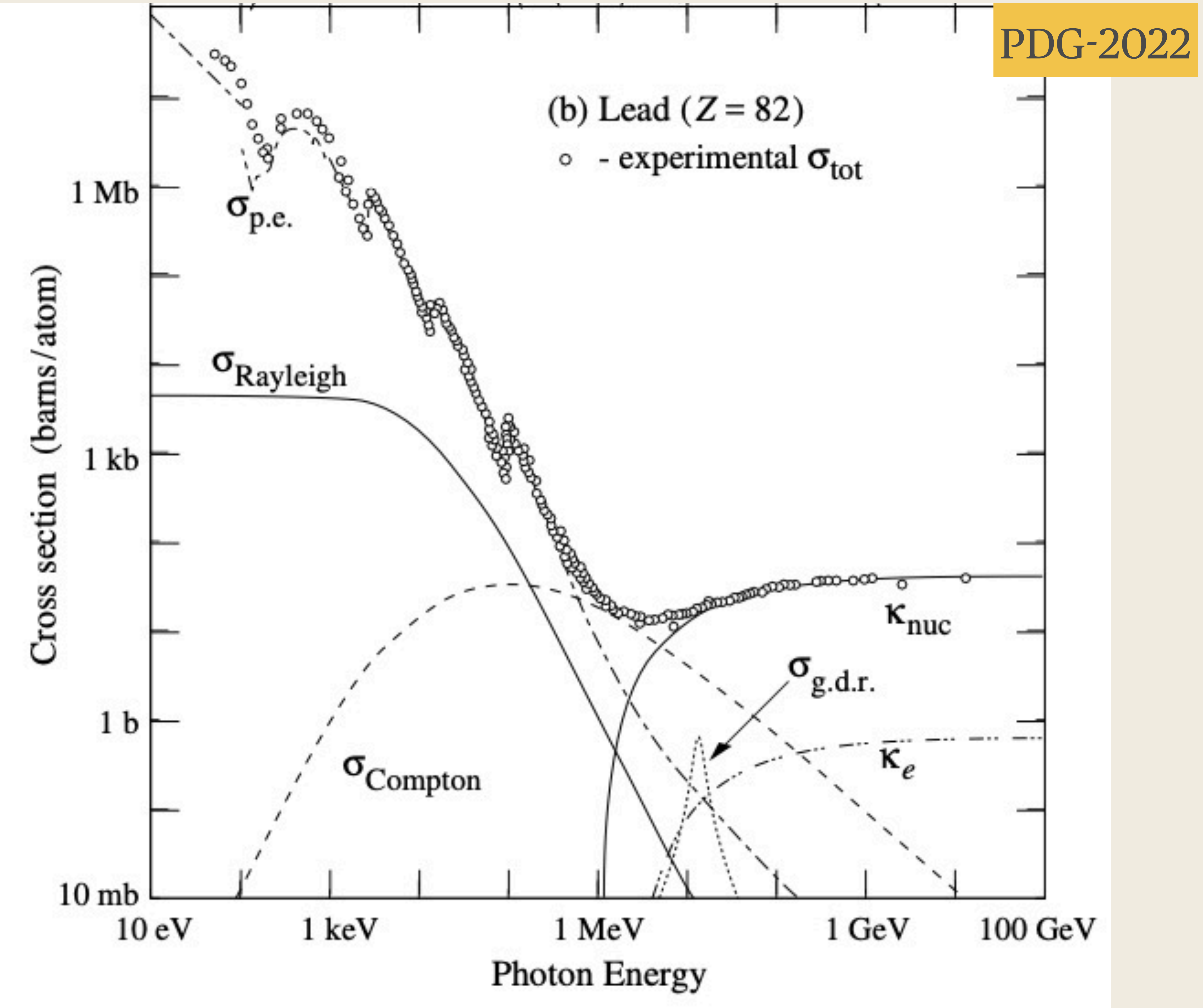
WEAK INT.

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

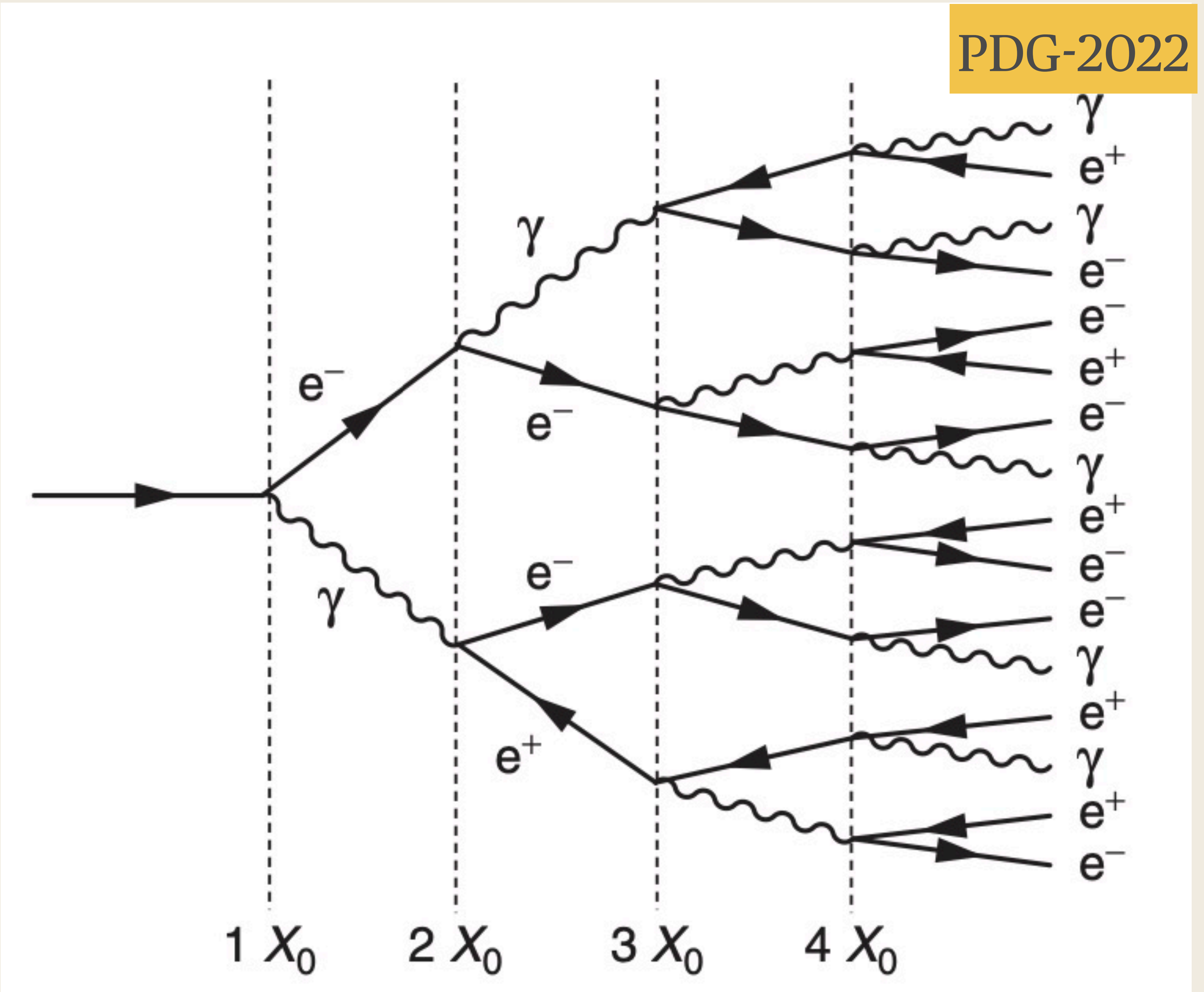




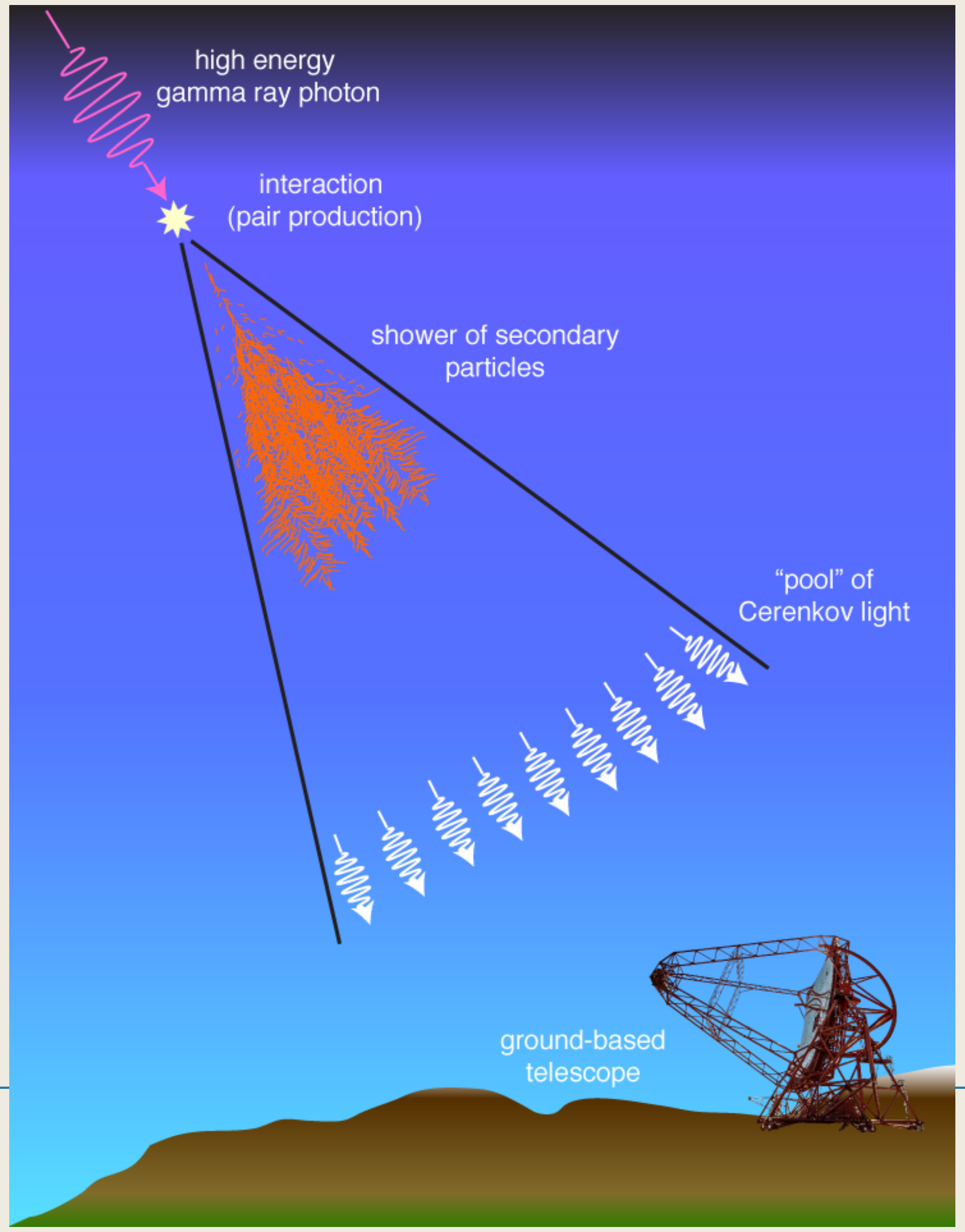
$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_{e} = Pair production, 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
  $E_c \approx 10\ MeV$

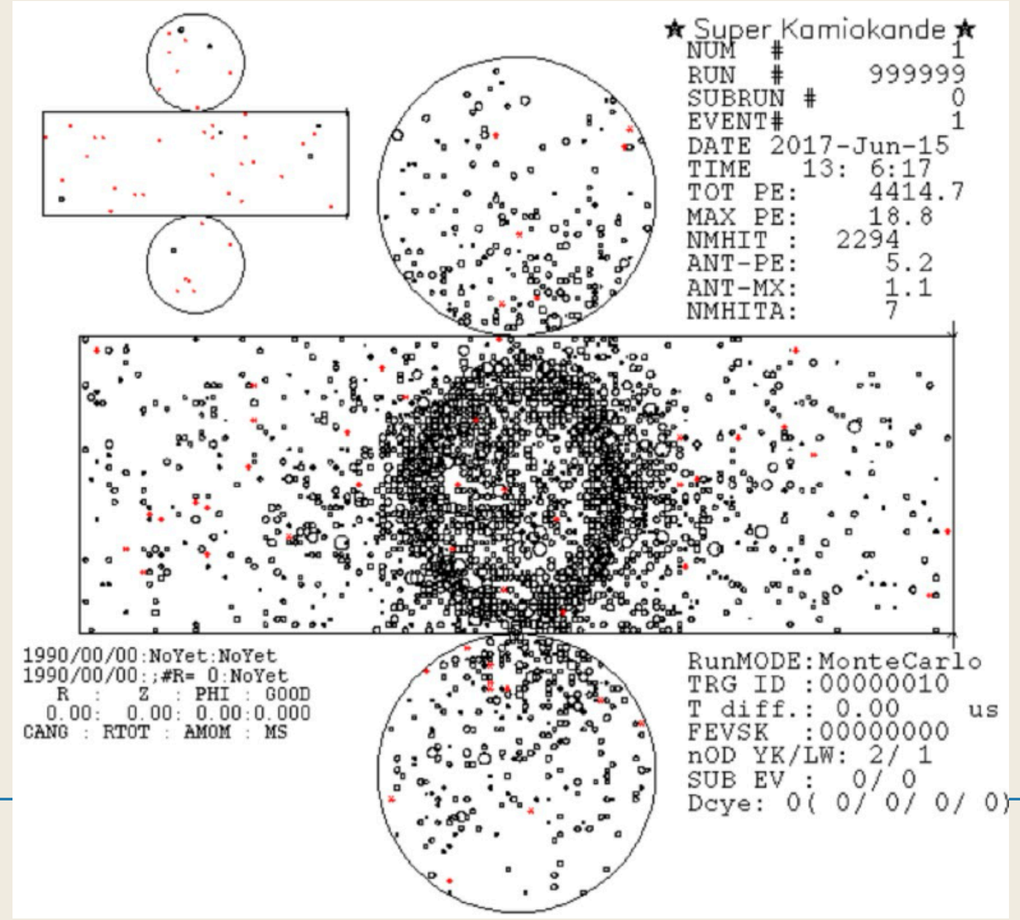


Eg. EM shower developed by gamma ray



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

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

~Marcel Proust~

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...**

End of lecture #1