How can physicists explore the particle world?(I)

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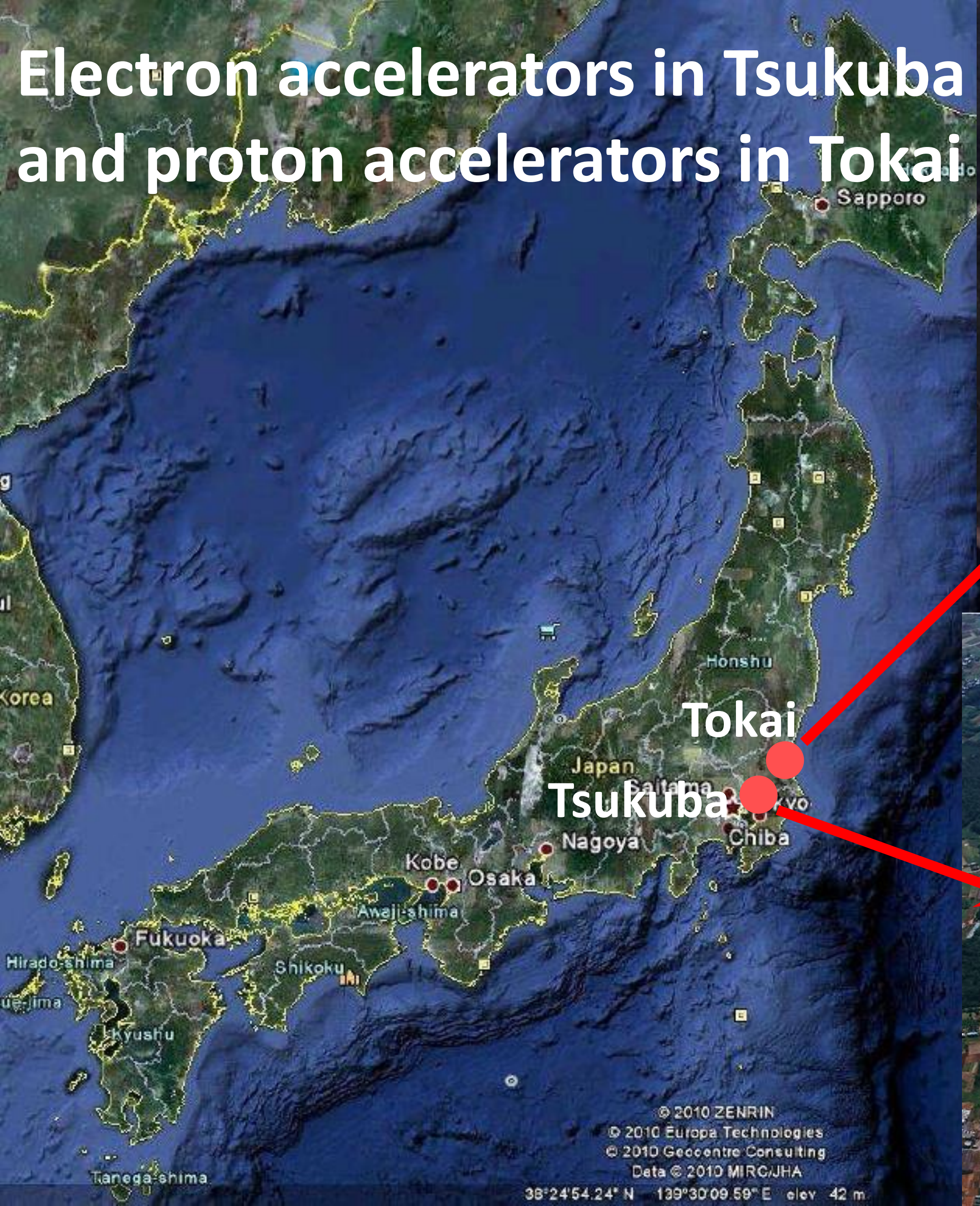
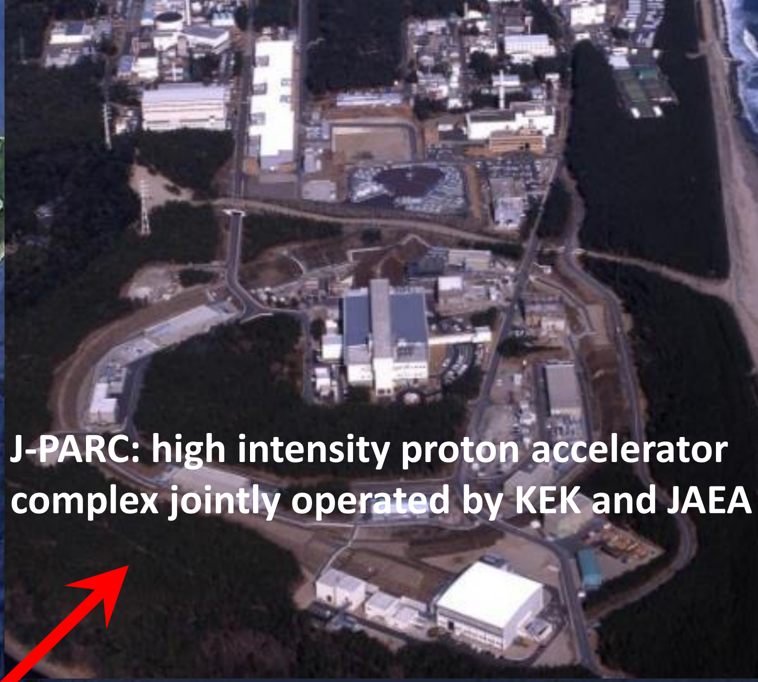
The 4th Asia Europe Pacific School of HEP

At Quy Nhon, Vietnam

Electron accelerators in Tsukuba and proton accelerators in Tokai





J-PARC: high intensity proton accelerator complex jointly operated by KEK and JAEA

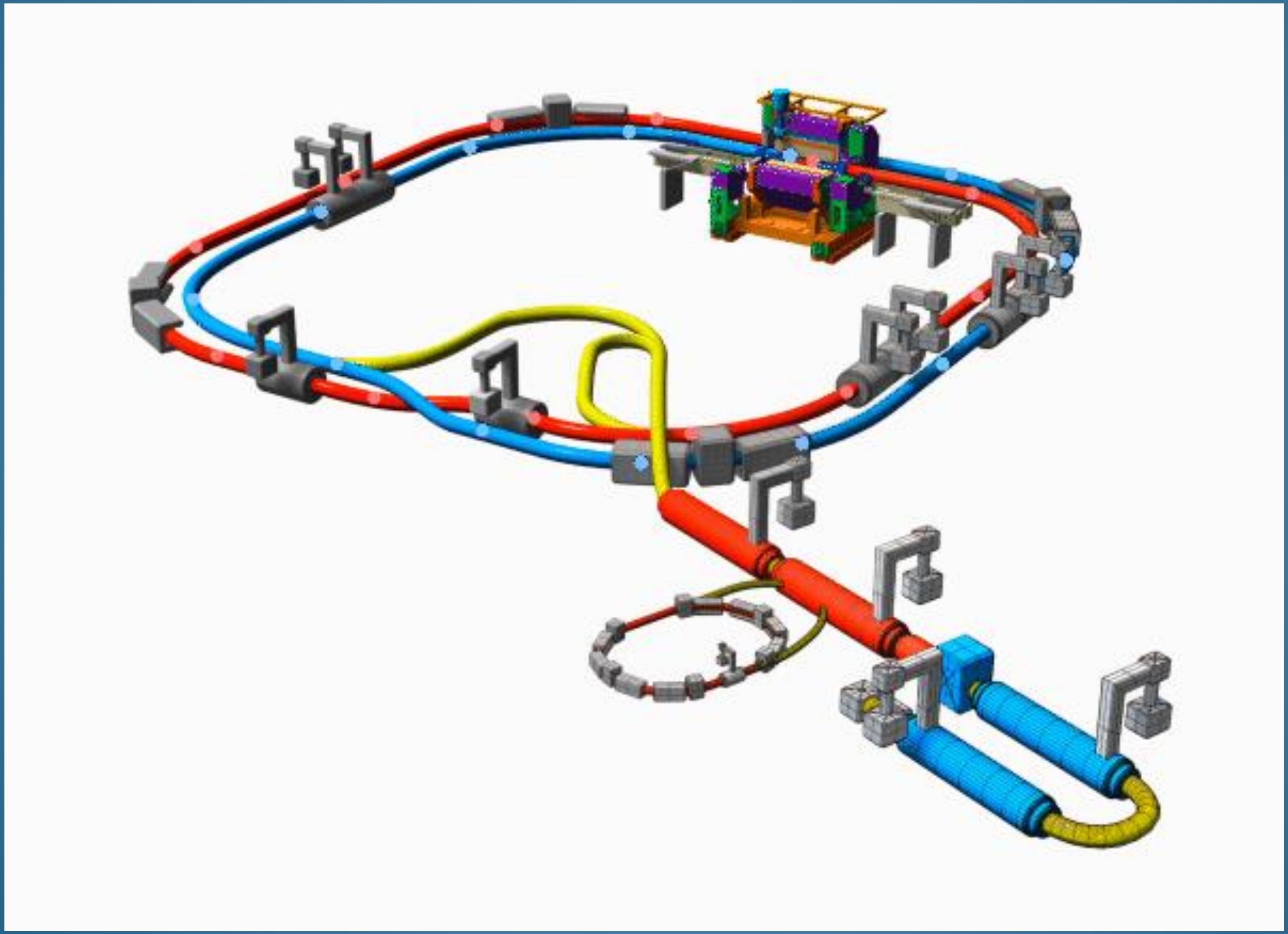
KEK Tsukuba: SuperKEKB, PF, ATF

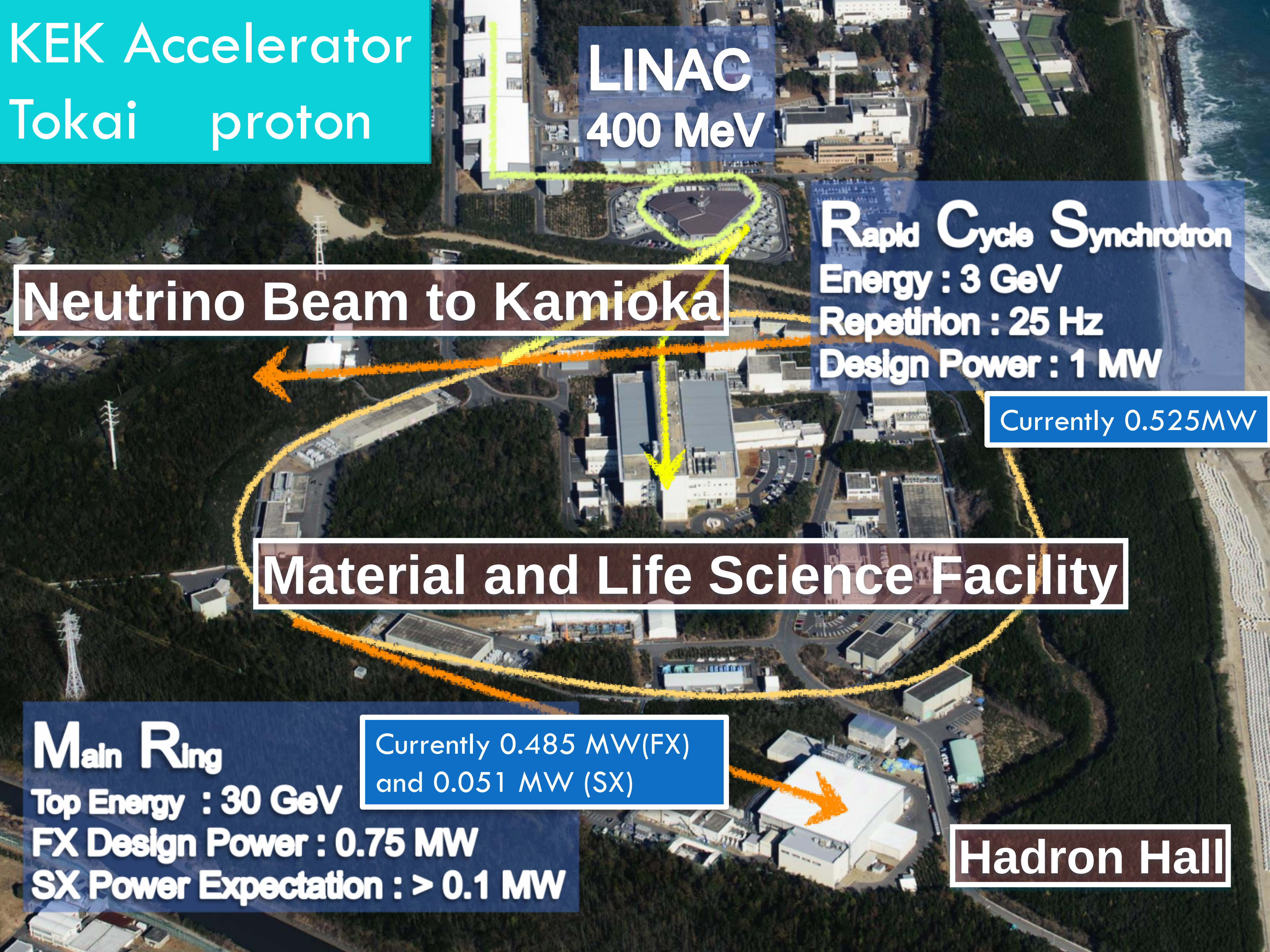
KEK Accelerators
Tsukuaba Electron/Positron

1km diameter
large accelerator ring
10m underground

SuperKEKB/
Belle II

PF PF-AR
(SRF)

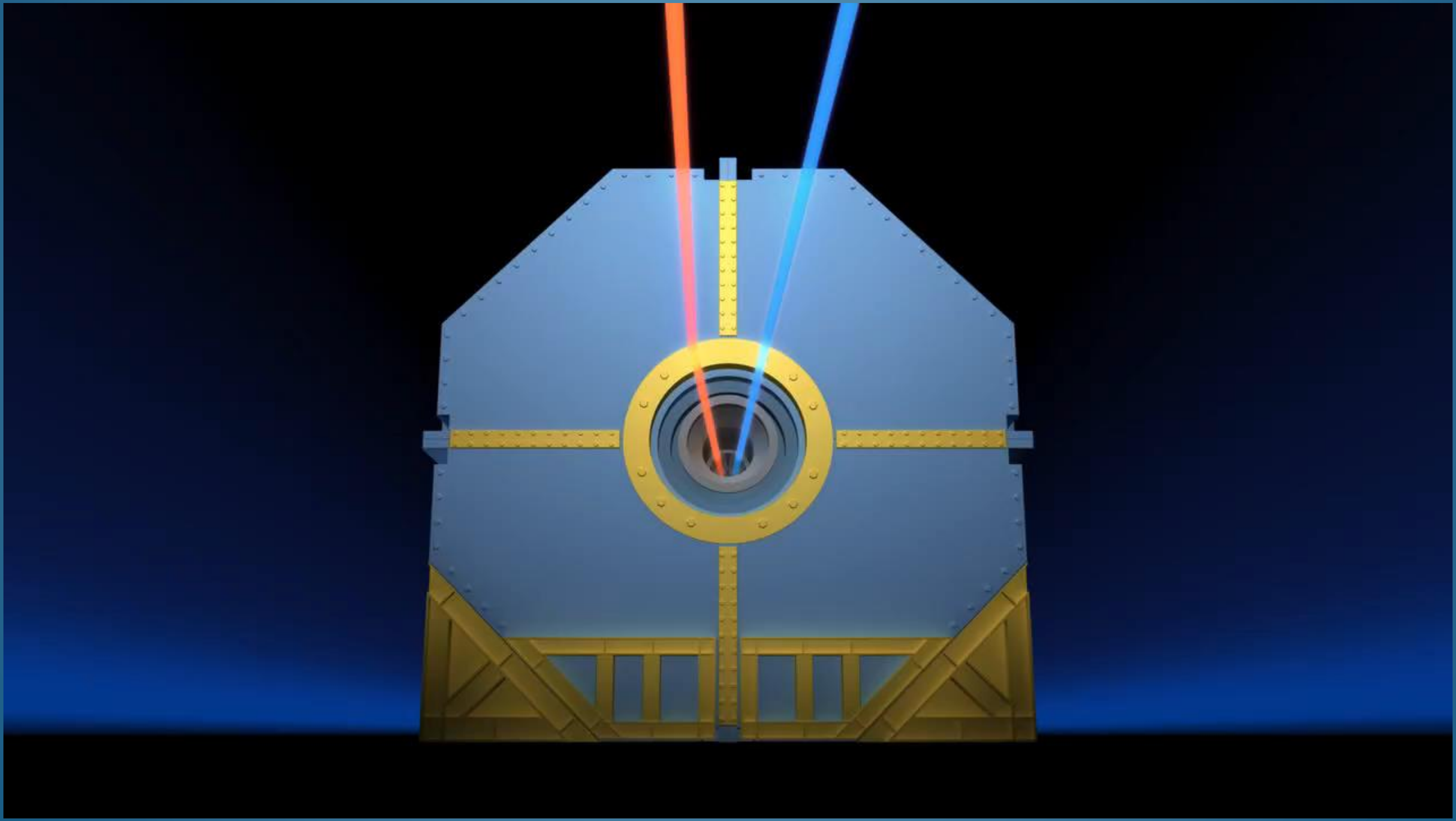



KEK Accelerator
Tokai proton
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetirion : 25 Hz
Design Power : 1 MW
Currently 0.525MW
Neutrino Beam to Kamioka
Material and Life Science Facility
Main Ring
Top Energy : 30 GeV
FX Design Power : 0.75 MW
SX Power Expectation : > 0.1 MW
Currently 0.485 MW(FX)
and 0.051 MW (SX)
Hadron Hall

Disclaimer

- This lecture was originally prepared for the students of PPSEA school (Partilce Physics School in South East Asea)
- The lecture is intended to give the most fundamental idea about the particle detector to students in early year master course students (and also theorists who have some interests on the topics).
- Elder sutudents may enjoy good break for their brain among high level lectures in this high-quality School.

Colliding beams



Why do we need this huge equipment?

To study the particles and their interactions…

1. Detect the emerging particles
2. Measure their kinematical quantities
   - Momentum, velocity, energy or mass….

   → Four momentum (E, p_x, p_y, p_z) using Lorentz relations
   - Charge
3. Determine mass/Identify particle species
4. Reconstruct the particle interactions/decays

Key concept

- Four vectors can be determined for final particles
- Four vector is conseverd through any interaction/decay

$$p_\mu^1$$

$$p_\mu^0$$

- You can reconstruct

  the initial (original interesting)

  Particle such as Higgs as

$$p_\mu^2$$

$$p_\mu^0 = p_\mu^1 + p_\mu^2$$

Review of Relativistic kinematics

- Formula from Einstein's Relativity

Equivalence among energy and mass

$$E = mc^2$$

Mass would increase according to its velocity

$$m = \gamma m_0$$

$$\gamma \equiv 1 \Big/ \sqrt{1 - \frac{v^2}{c^2}}$$

Important relations

$$\beta \equiv \frac{v}{c} \qquad \gamma \equiv 1 \Big/ \sqrt{1-\beta^2}$$

- momentum

$$p = mv = E/c^2 \cdot v = E/c \cdot v/c = E/c \cdot \beta$$

$$E = pc\beta$$

- Four vector and Lorentz invariance

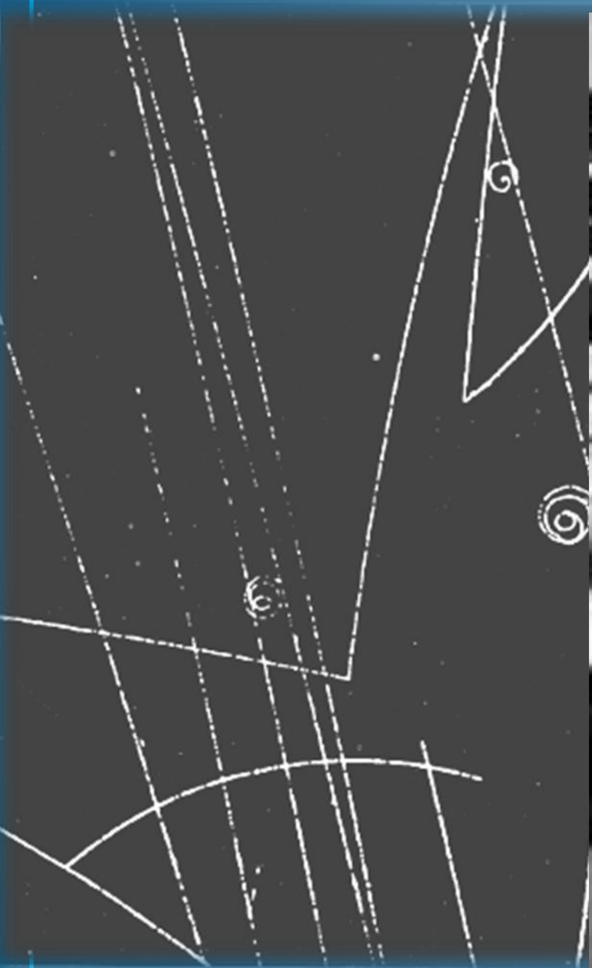
$$\vec{p} = (E, \mathbf{p}c) = (E, p_x c, p_y c, p_z c)$$

$$\left|\vec{p}\right|^2 = E^2 - \mathbf{p}^2 c^2 = E^2 - (p_x^2 + p_y^2 + p_z^2)c^2$$

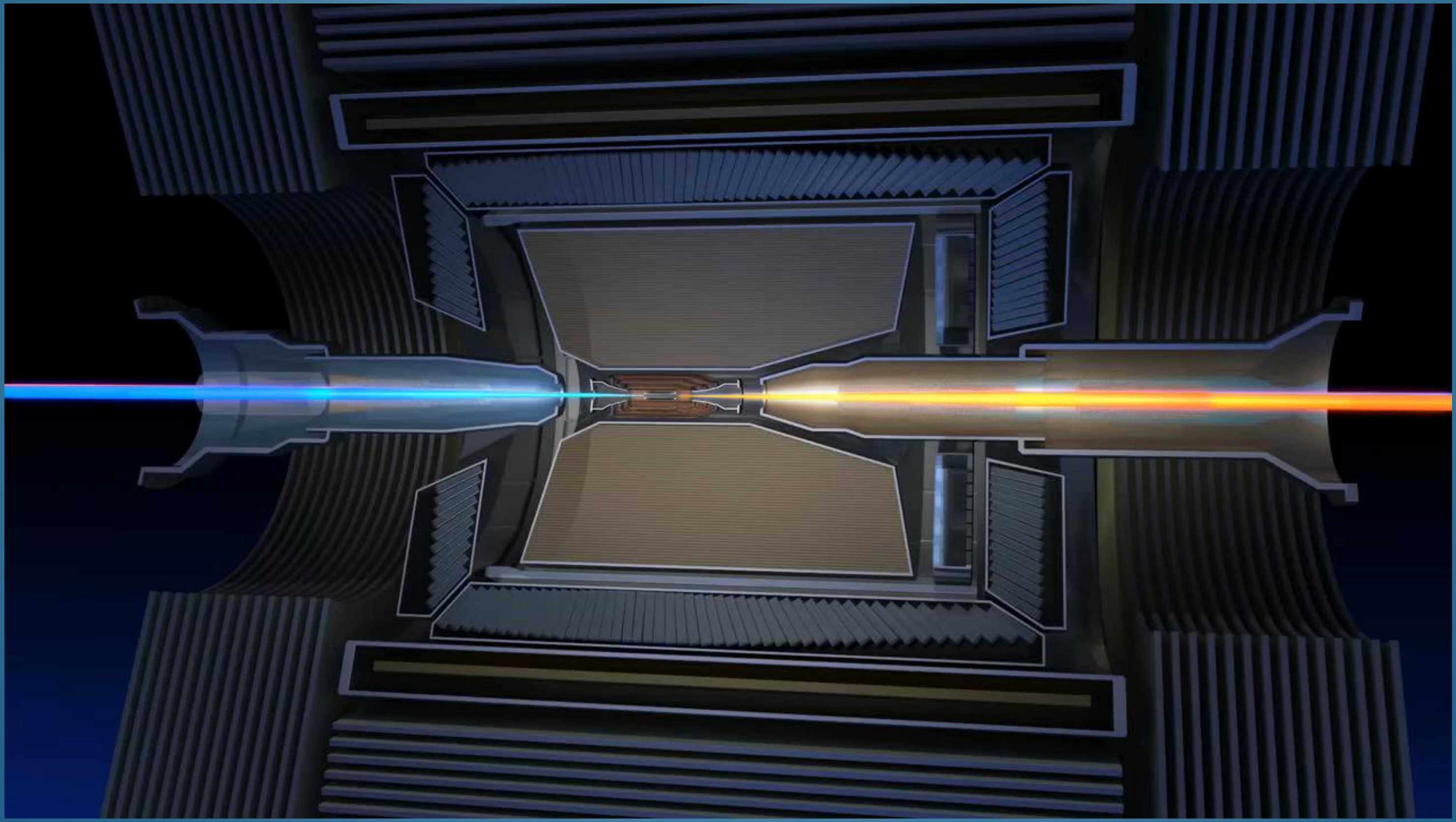
$$E^2 - p^2c^2 = E^2 - (E\beta)^2 = E^2(1-\beta^2) = \left(E/\gamma\right)^2$$

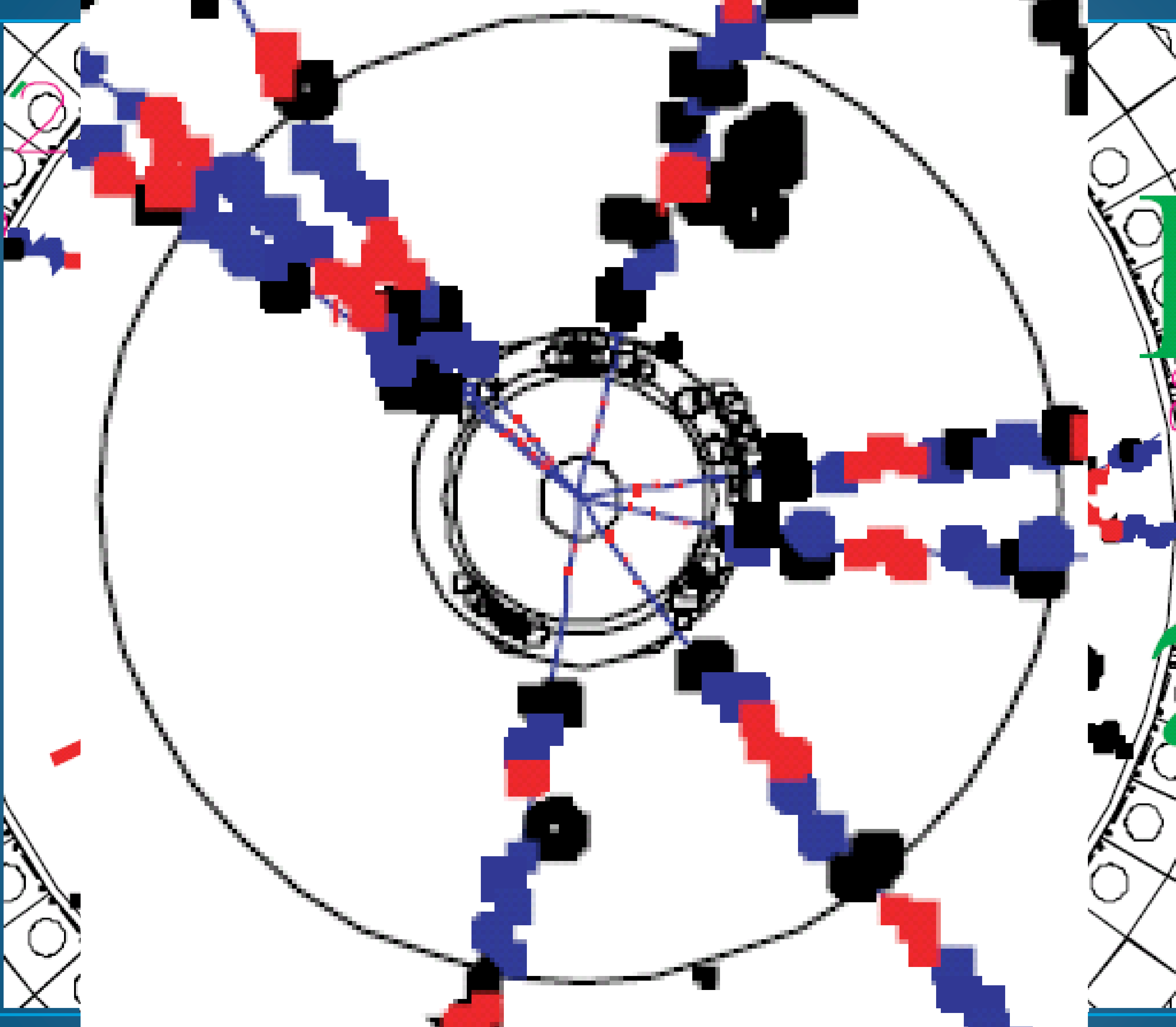
$$= \left(mc^2/\gamma\right)^2 = m_0^2 c^4$$

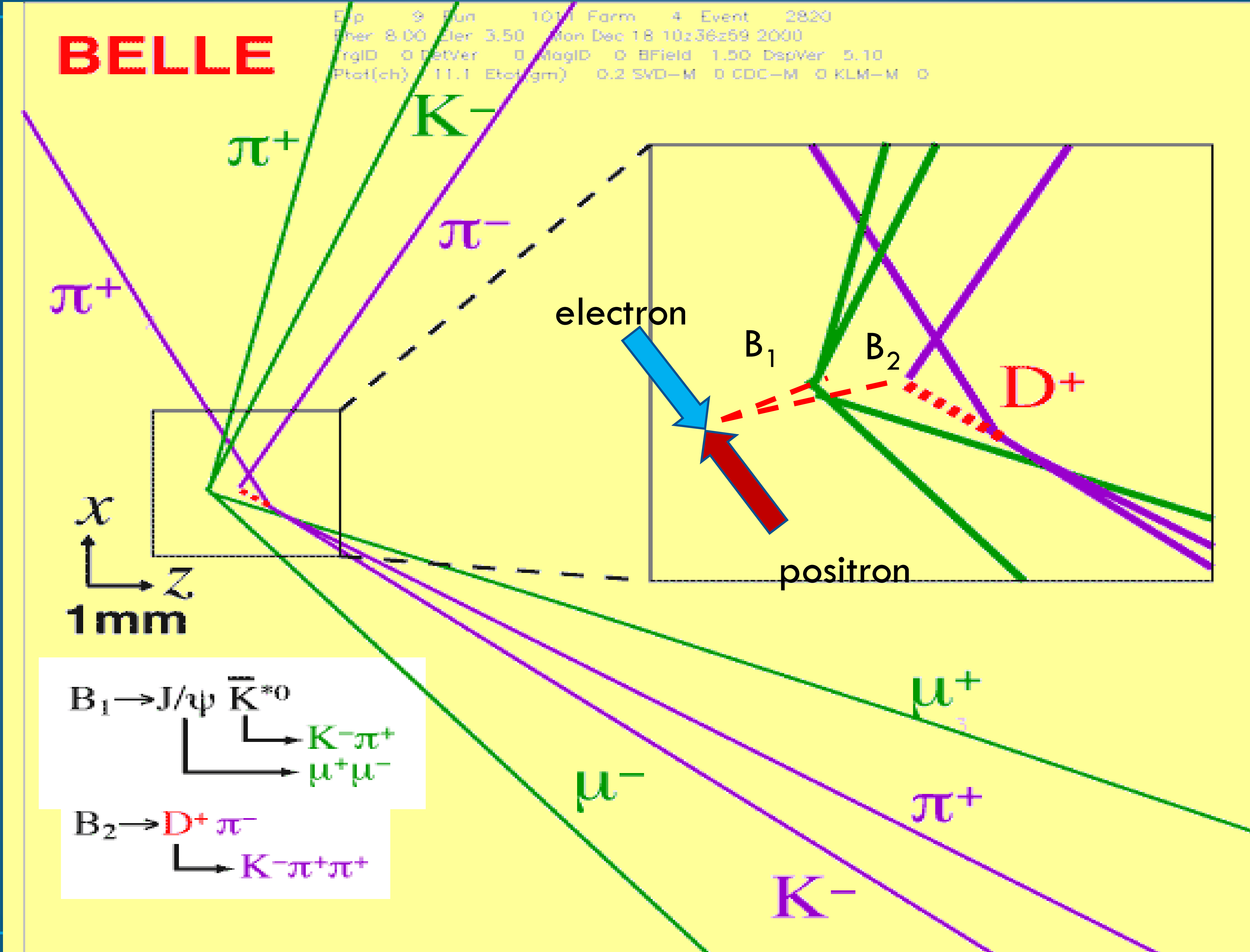
What can we actually do with the detector? Legacy experiments with Bubble Chamber



Collider experiment and detector






BELLE
Exp 9 Run 1011 Farm 4 Event 2820
Eher 8.00 Eler 3.50 Mon Dec 18 10:36:59 2000
TrgID 0 DetVer 0 MagID 0 BField 1.50 DspVer 5.10
Ptot(ch) 11.1 Etot(gm) 0.2 SVD-M 0 CDC-M 0 KLM-M 0
π^+
K^-
π^-
π^+
electron
positron
B_1
B_2
D^+
x
z
1mm
μ^+
μ^-
π^+
K^-
$B_1 \rightarrow J/\psi\ \bar{K}^{*0}$
$\rightarrow K^-\pi^+$
$\rightarrow \mu^+\mu^-$
$B_2 \rightarrow D^+\ \pi^-$
$\rightarrow K^-\pi^+\pi^+$

How to detect the particles ?

- Unable to see
- Unable to touch

→Try to find the faint trace of the particles

(Ionization, excitation of molecule)

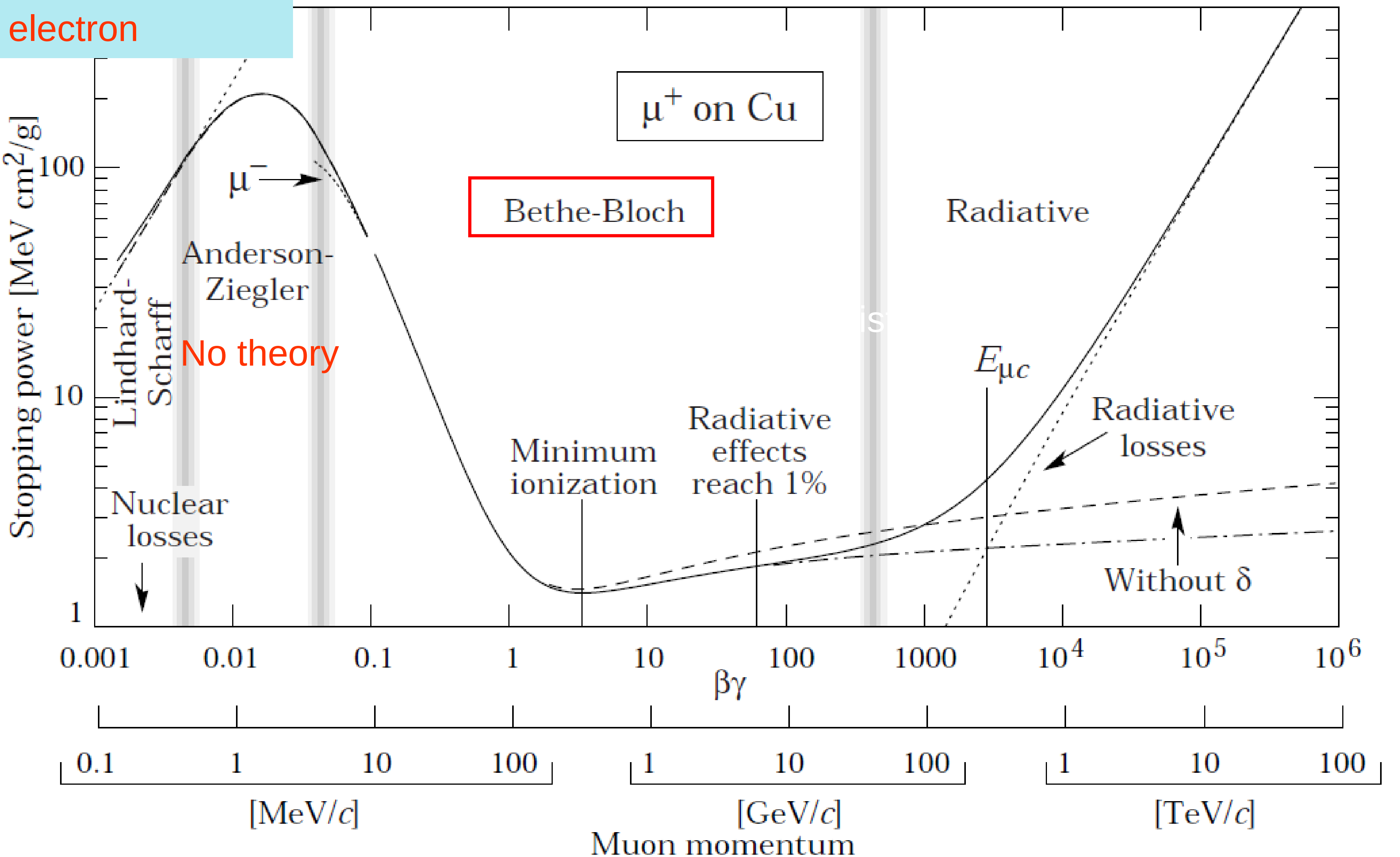
- Classical: Cloud chamber, bubble chamber, spark chamber, scintillator …..
- Modern：Drift chamber, TPC, silicon detector, scintillator….

→Try to catch the faint light emitted from the particles

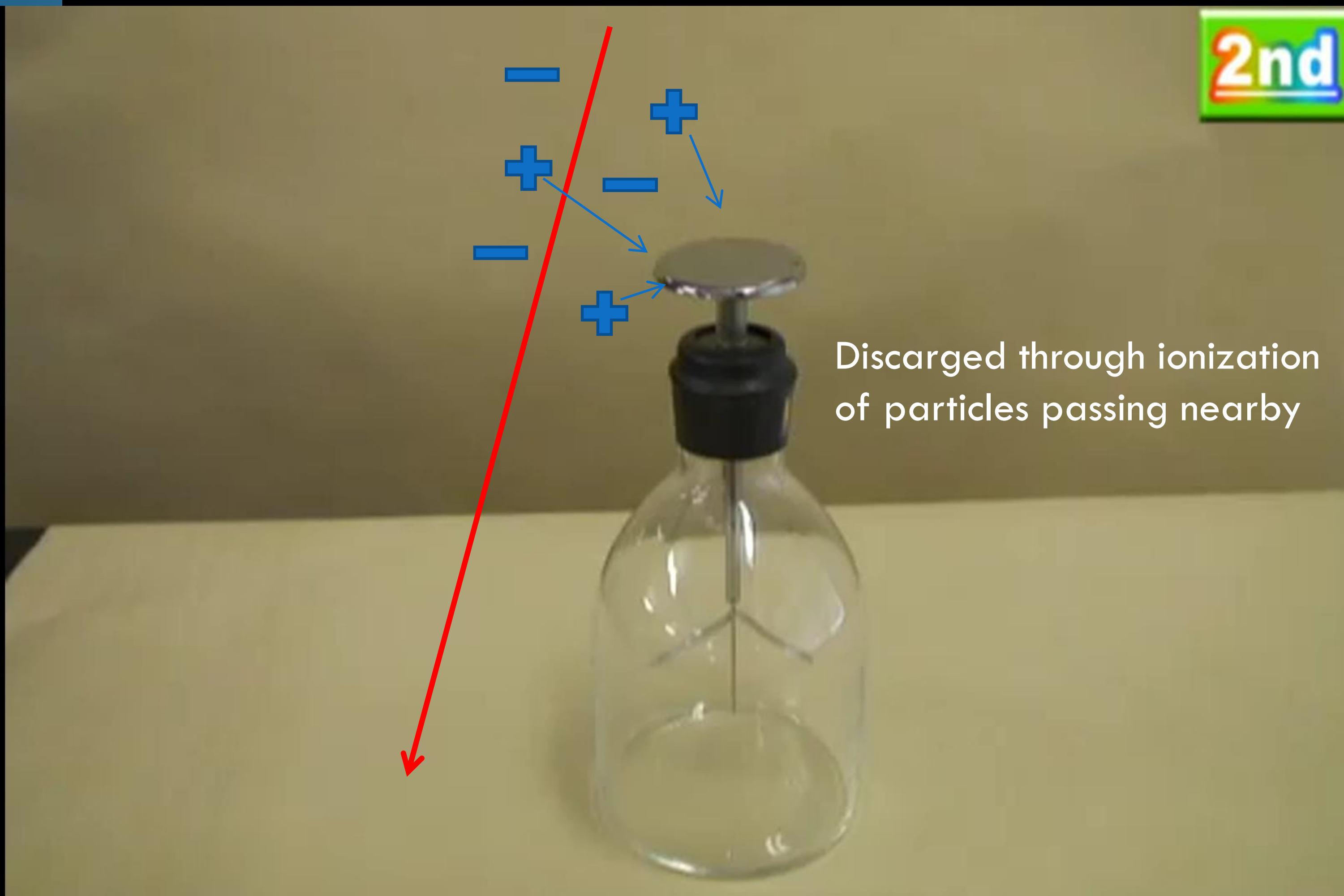
- Cherenkov radiation detector, transition radiation detector

Energy loss due to ionization

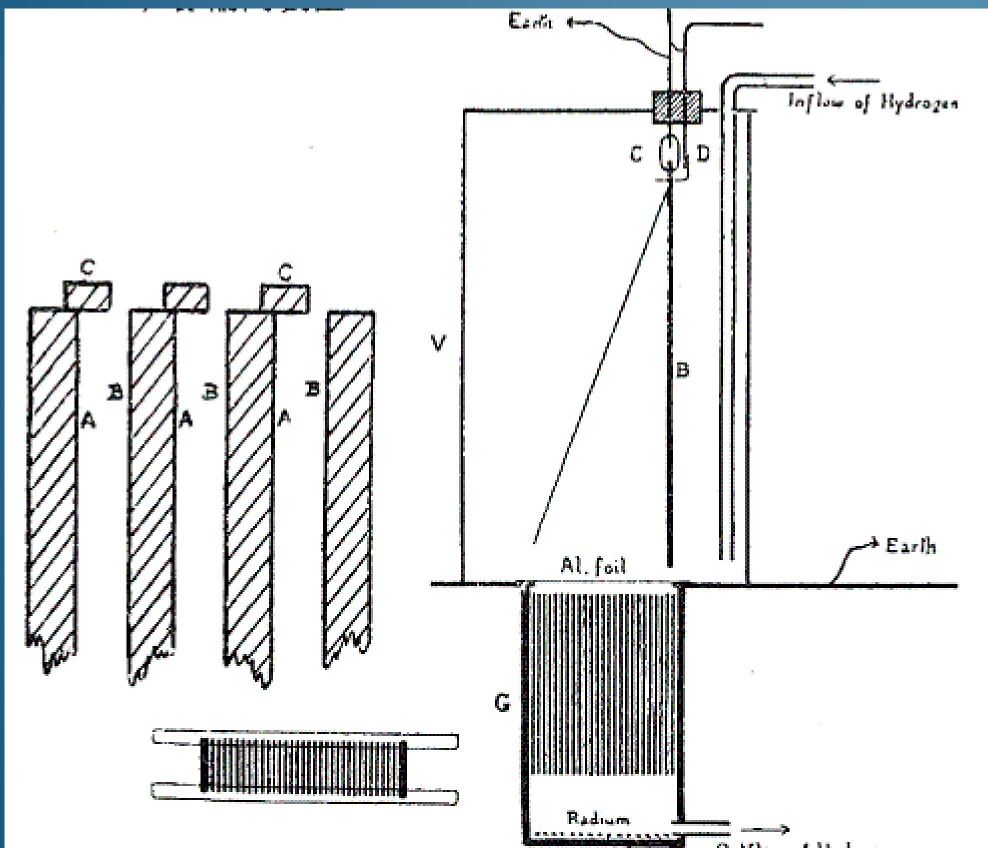
Similar velocity as atomic orbital electron



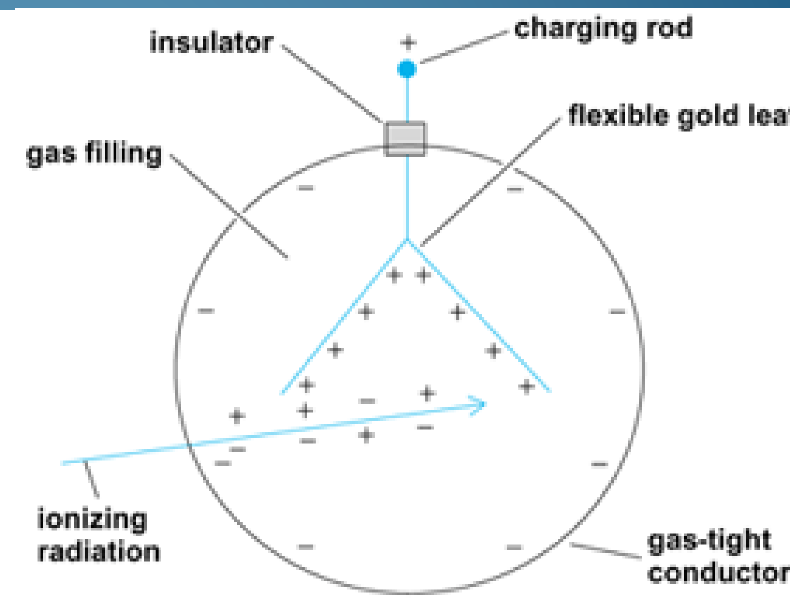
First particle detector using ionization: Leaf electroscope



How can we see ionization?
Very early attempt

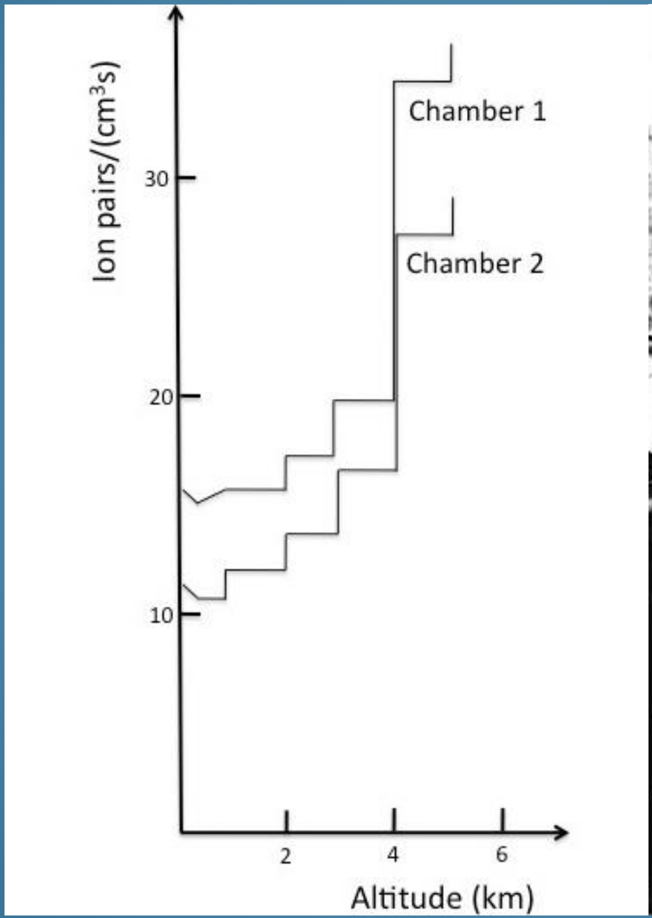


E. Rutherford, The Magnetic and Electric Deviation of the Easily Absorbed Rays from Radium, *Phil. Mag.*, **5** (1903), 177–187 より



Leaf electroscope carried by balloon to confirm the existence of Cosmic Ray for the first time.

Discharge seems quicker in higher altitude.



Dr. Hess was coming back from the ballon fight in 1912 August in which he discovered Cosmic ray for the ftirst ime
Source: American Physical Society.

To discover new elementary particle, radiation flux measurement is not sufficient.

- Need to observe radiation particle by particle, photon by photon , quanta by quanta ,

$$\text{Unit charge } Q \approx 10^{-19} Coulomb$$

$$V = Q/C \approx 10^{-19}/100\,pF \approx 10^{-19}/10^{-10} = 10^{-9} Volt = 1nV$$

It is impossible to see this tiny signal
→Small stimulation (Ionization, emission) may trigger visible large enough effect which make an observation possible.

We want to observe any direct sign of particle passing by Eyes. Tiny effect stimulated by particle (Ionization) may sometime trigger a visible signature in matter

Supersaturated Water solution of sodium acetate

http://www.youtube.com/user/ikemonmon

Supercooled solution and sudden crystallization caused by a tiny stimulation

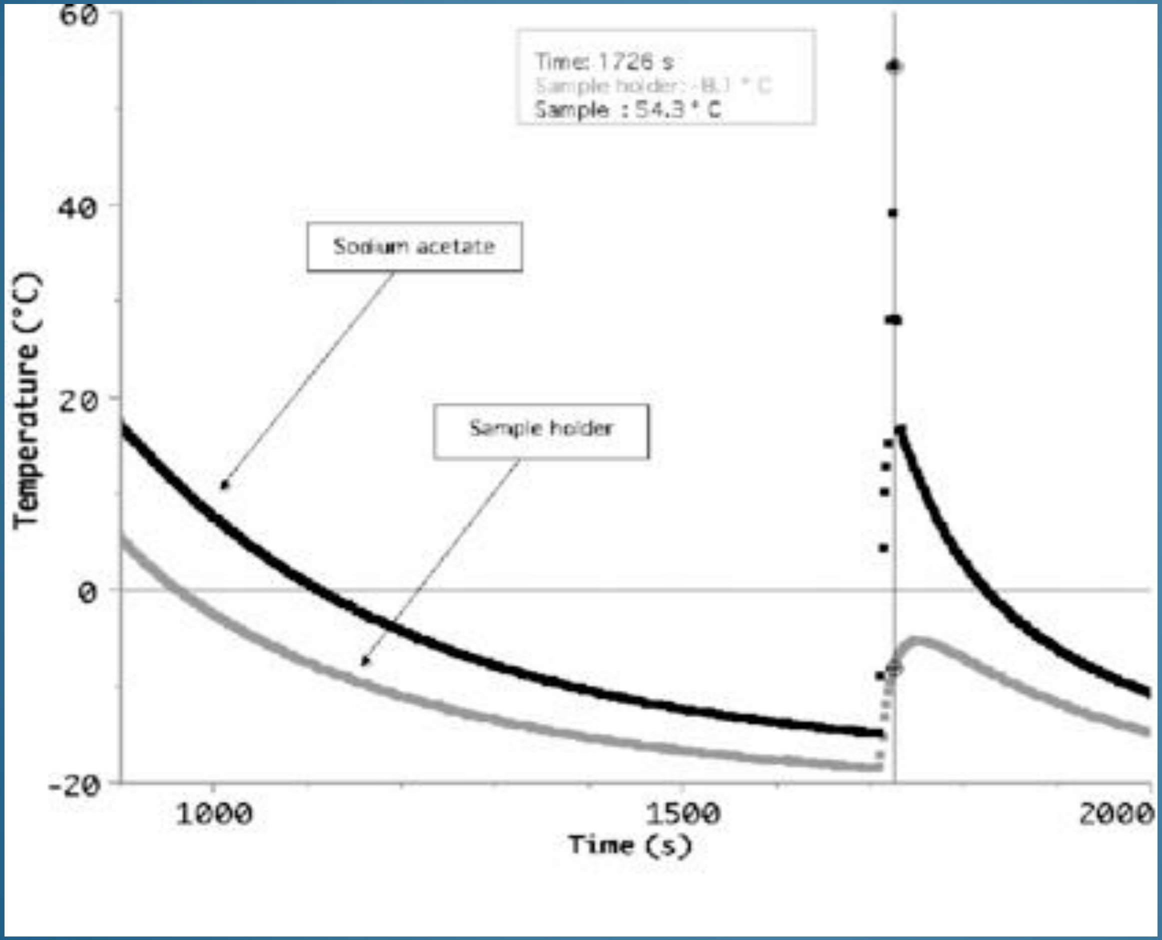
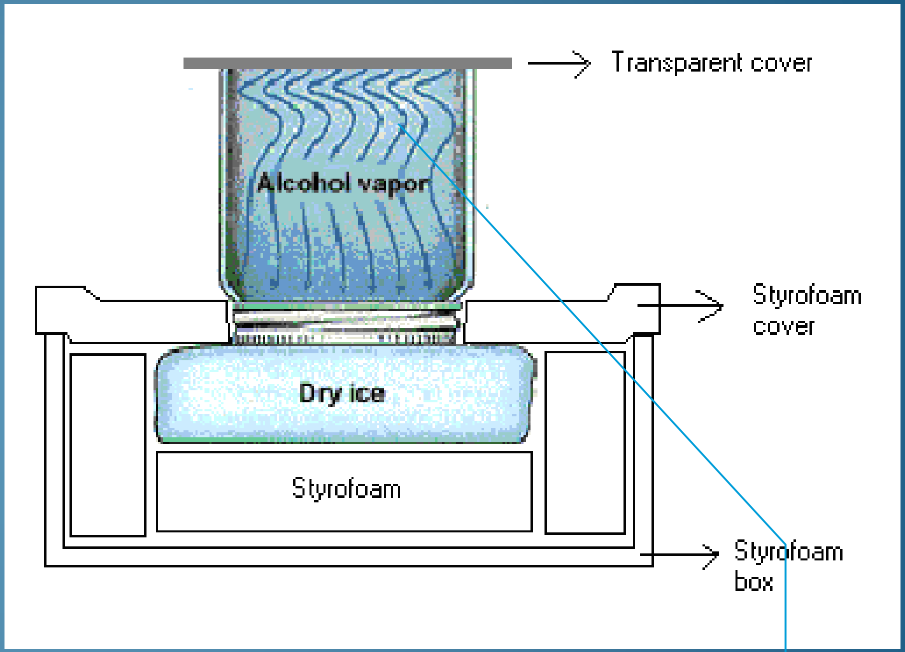


Figure 7 from Using Peltier cells to study solid–liquid–vapour transitions and supercooling Giacomo Torzo et al 2007 Eur. J. Phys. 28 S13 doi:10.1088/0143-0807/28/3/S02

Cloud chamber



Contrail

Generated in super saturated vapor

Particle detector you can build at home

Cloud chamber animation

Cloud chamber, energy loss and discovery of positron(1932)

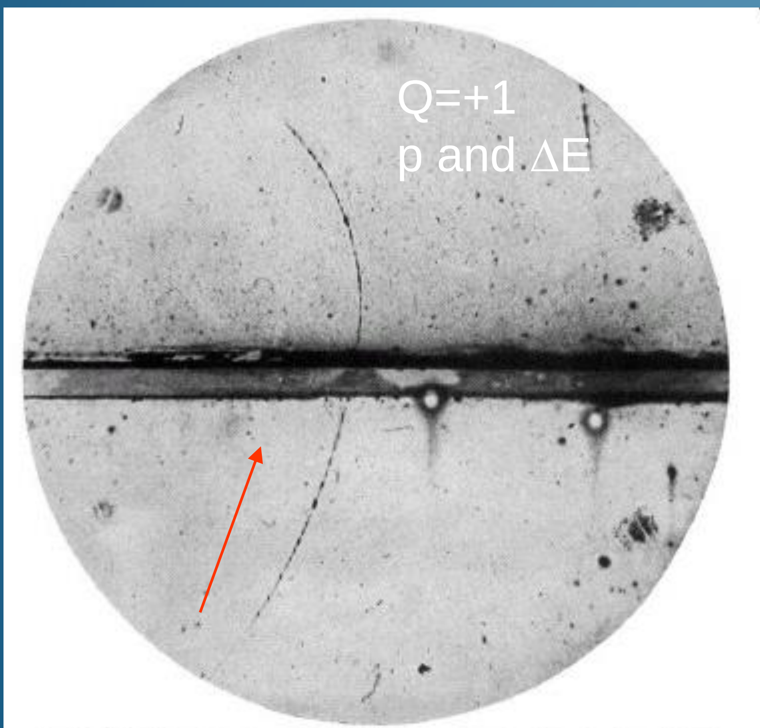


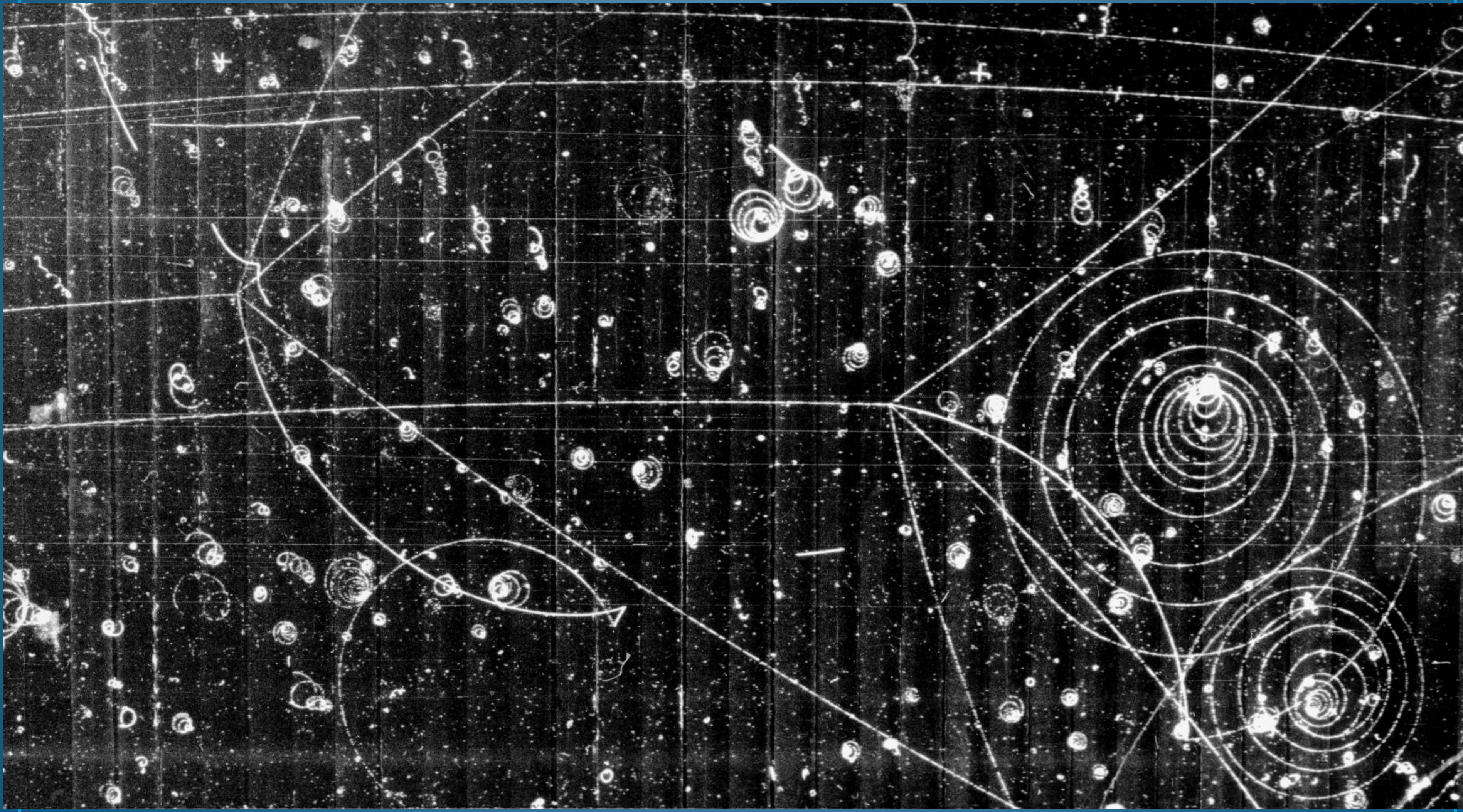
FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Anderson's cloud chamber picture of cosmic radiation from 1932 showing for the first time the existence of the anti-electron that we now call the positron. In the picture a charged particle is seen entering from the bottom at high energy. It then looses some of the energy in passing through the 6 mm thick lead plate in the middle. The cloud chamber is placed in a magnetic field and from the curvature of the track one can deduce that it is a positively charged particle. From the energy loss in the lead and the length of the tracks after passing though the lead, an upper limit of the mass of the particle can be made. In this case Anderson deduces that the mass is less than two times the mass of the electron. Caption credit: CERN

What can you tell from the Anderson's picture?

- Momentum of particle?
- Mass of particle?
- Charge of particle?
- Discovery or routine observation?

“Cloud” was replaced with “Bubble” shortly



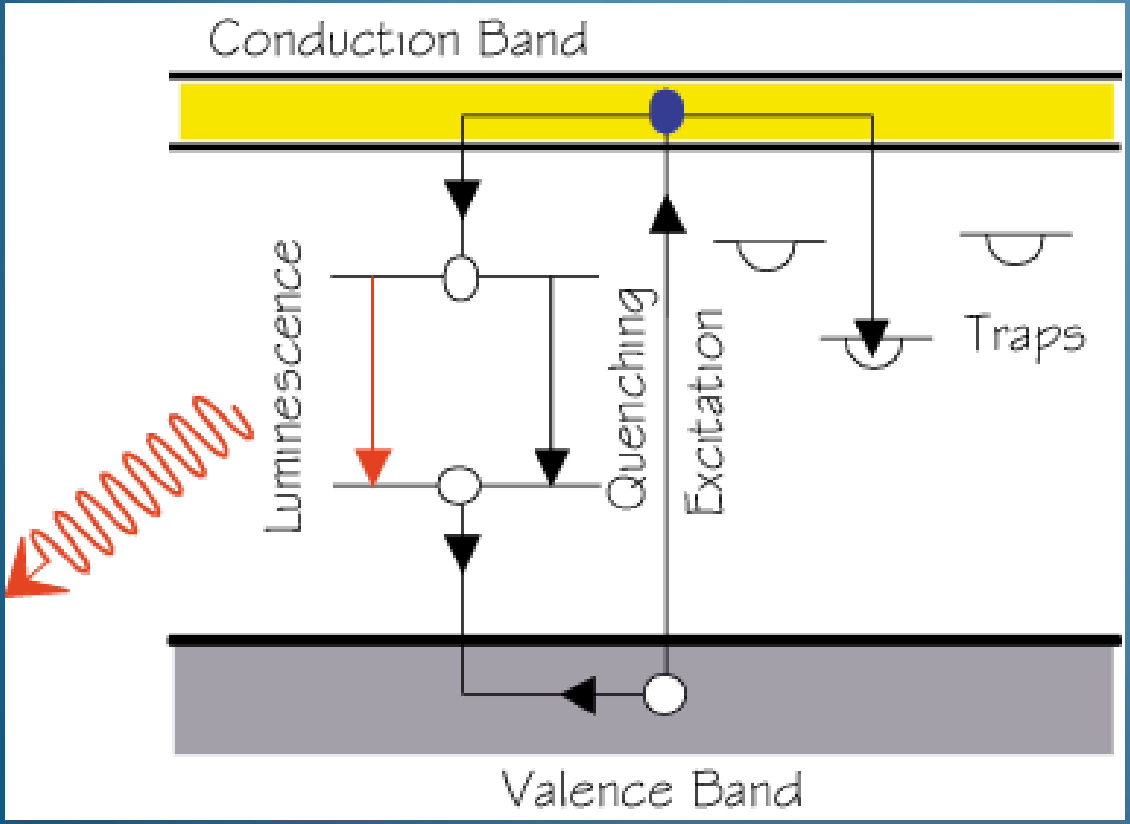
Excitation and scintillation

Aurora is a cosmic ray detector in the skay

Scitillation

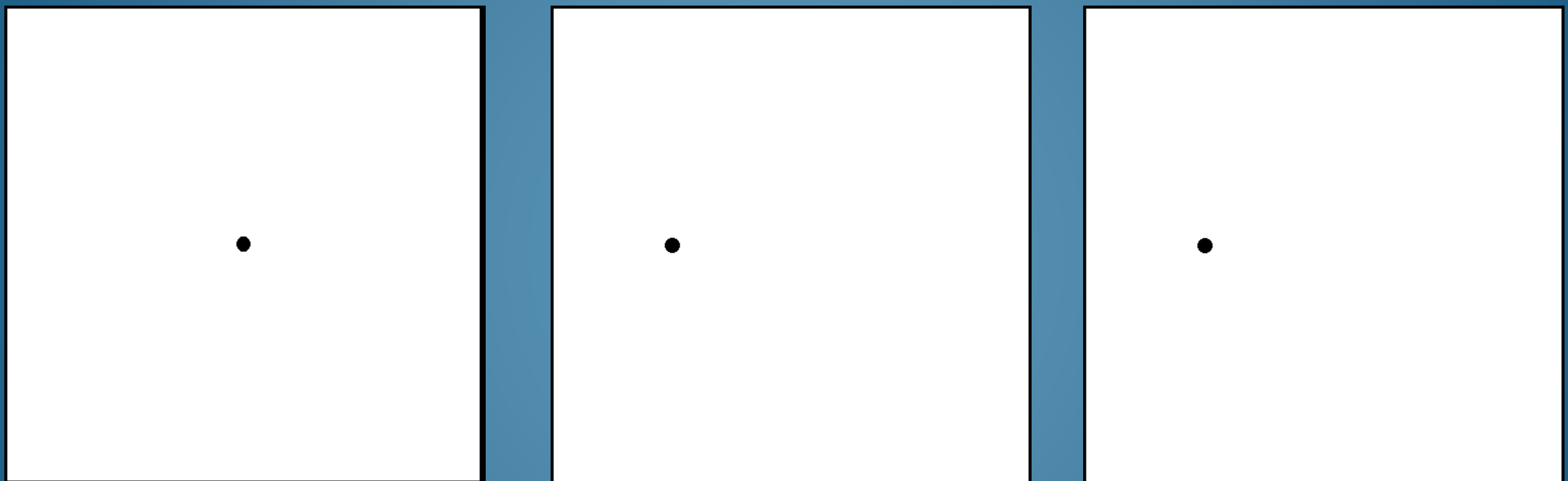
Demonstration

- UV LED light and scintillators



Cherenkov Radiation (1)

- Moving charge in matter



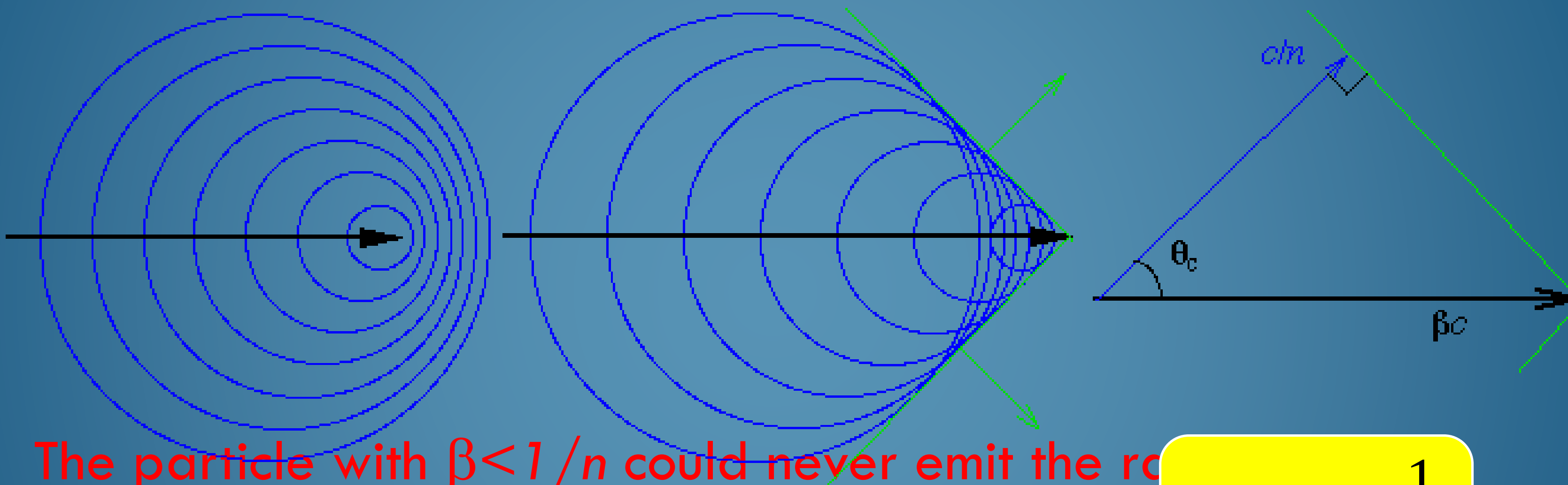
at rest

slow

fast

Cherenkov Radiation (2)

- Wave front comes out at certain angle

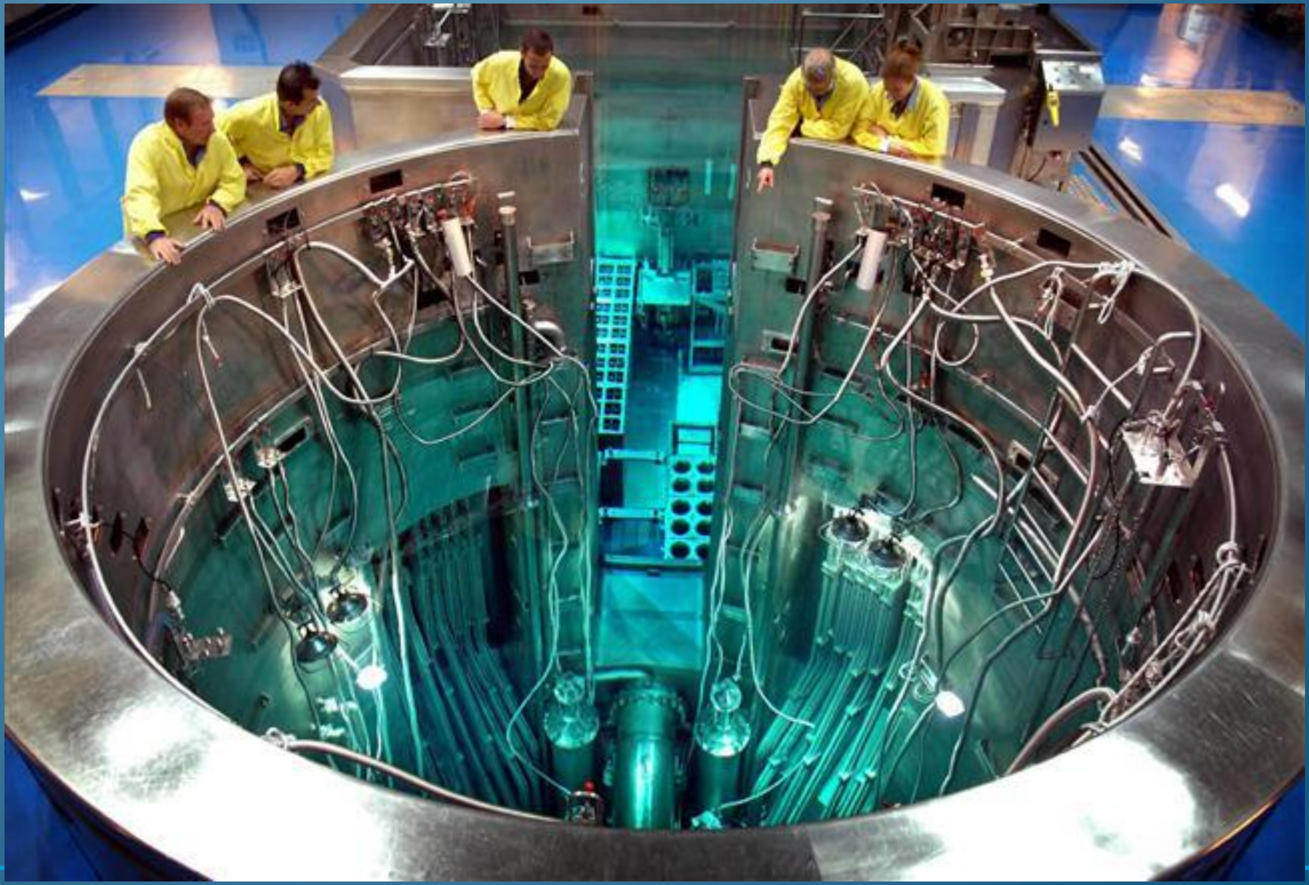


The particle with $\beta<1/n$ could never emit the ra

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

Cherenkov light in reactors

- OPAL –
- the Open Pool Australian Lightwater reactor

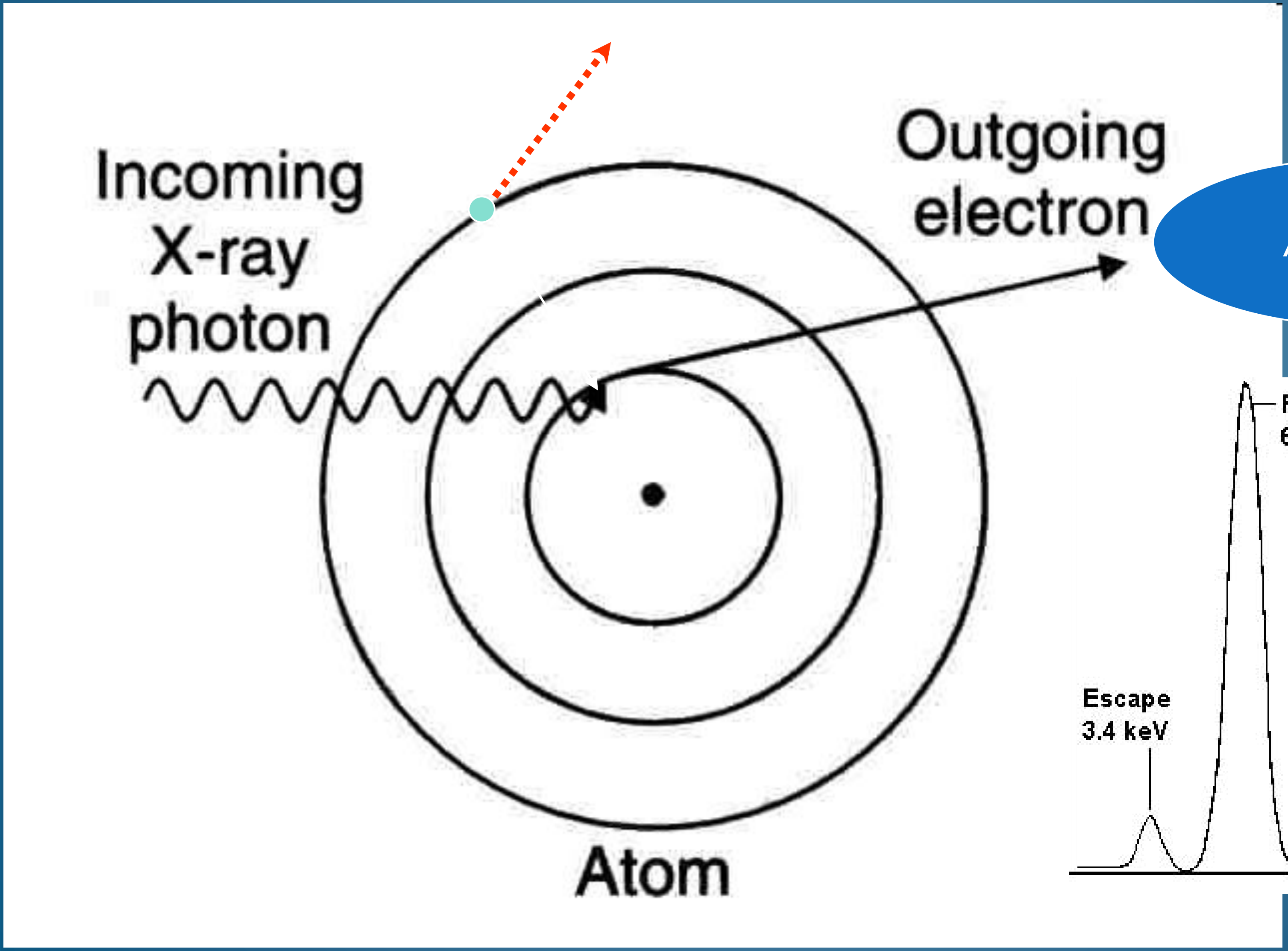


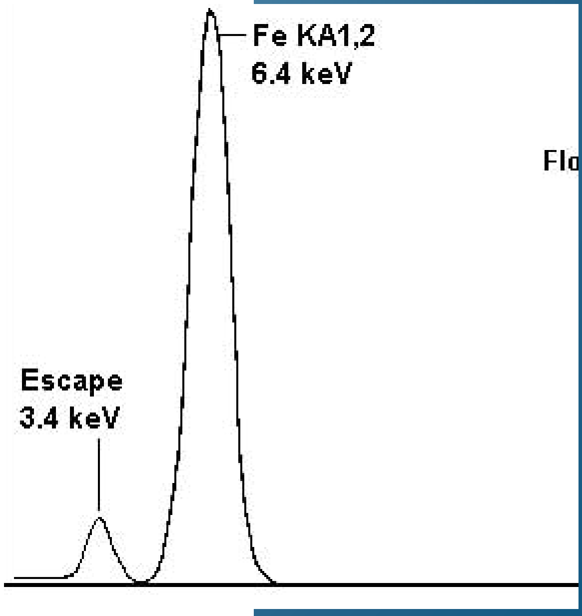
Intreraction of neutral particles

- Unable to see their ionizations
- Unable to detect their radiation

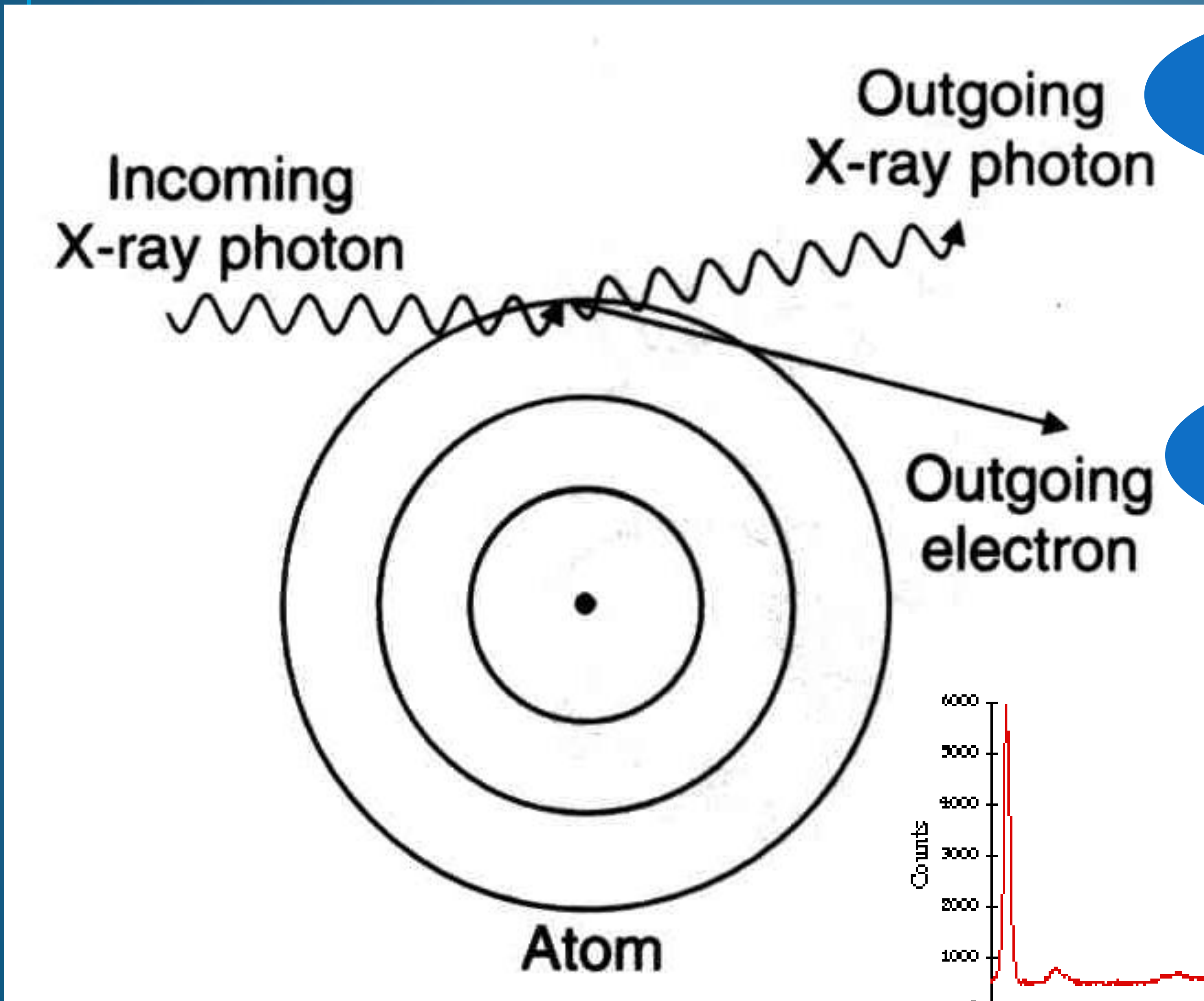
  - Photon, γ, X   Electromagnetic interaction
  - Neutron   strong   interaction with nucleus or nucleon
  - Neutrino   weak interaction with nucleon

Photoelectric effect



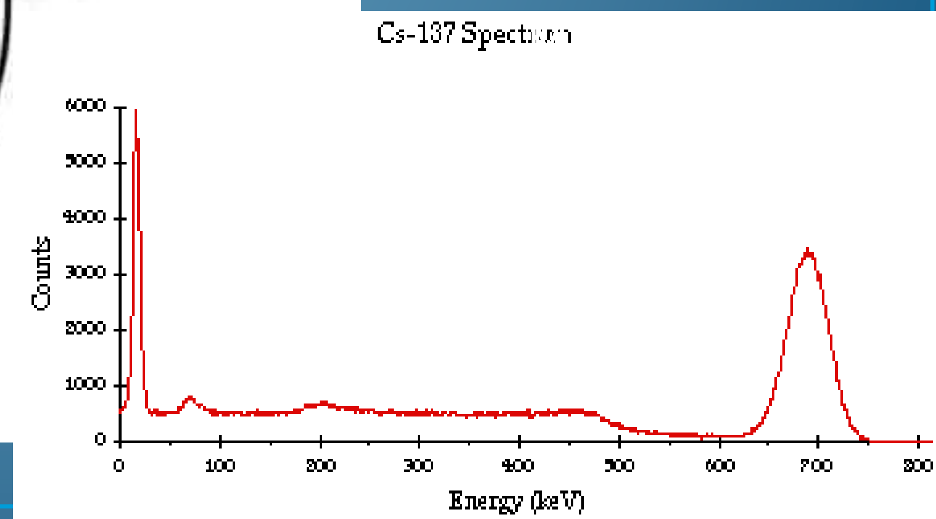


Compton scattering

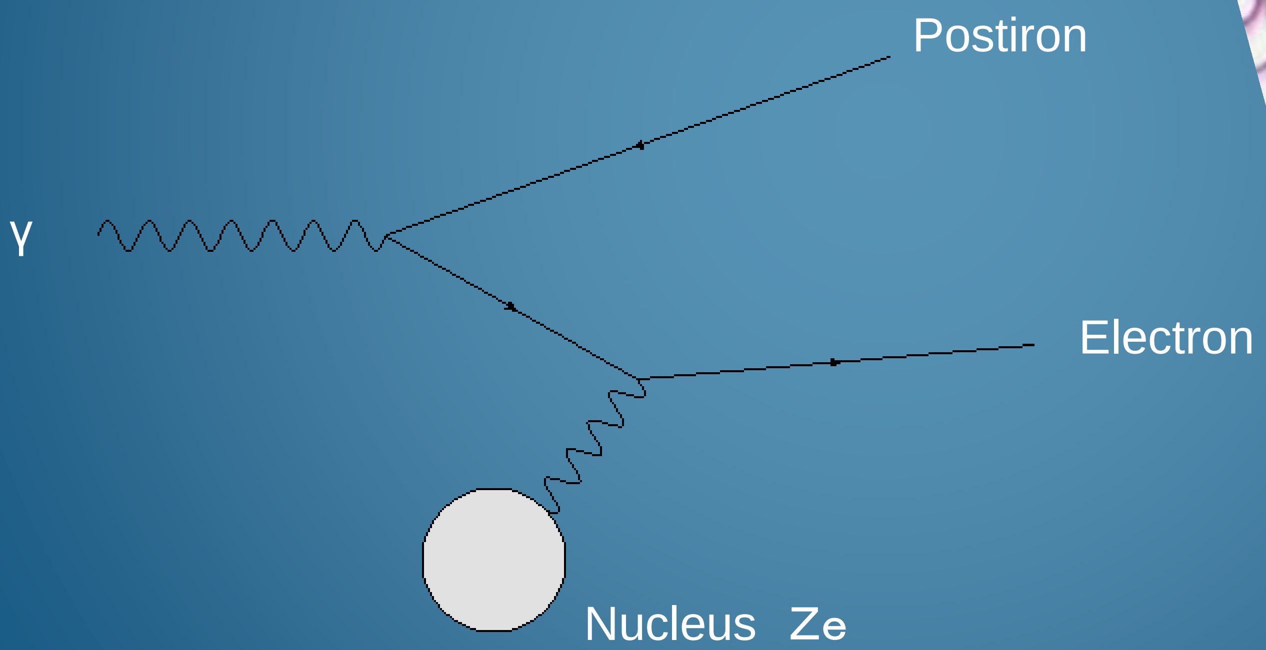


escaping

absorbed



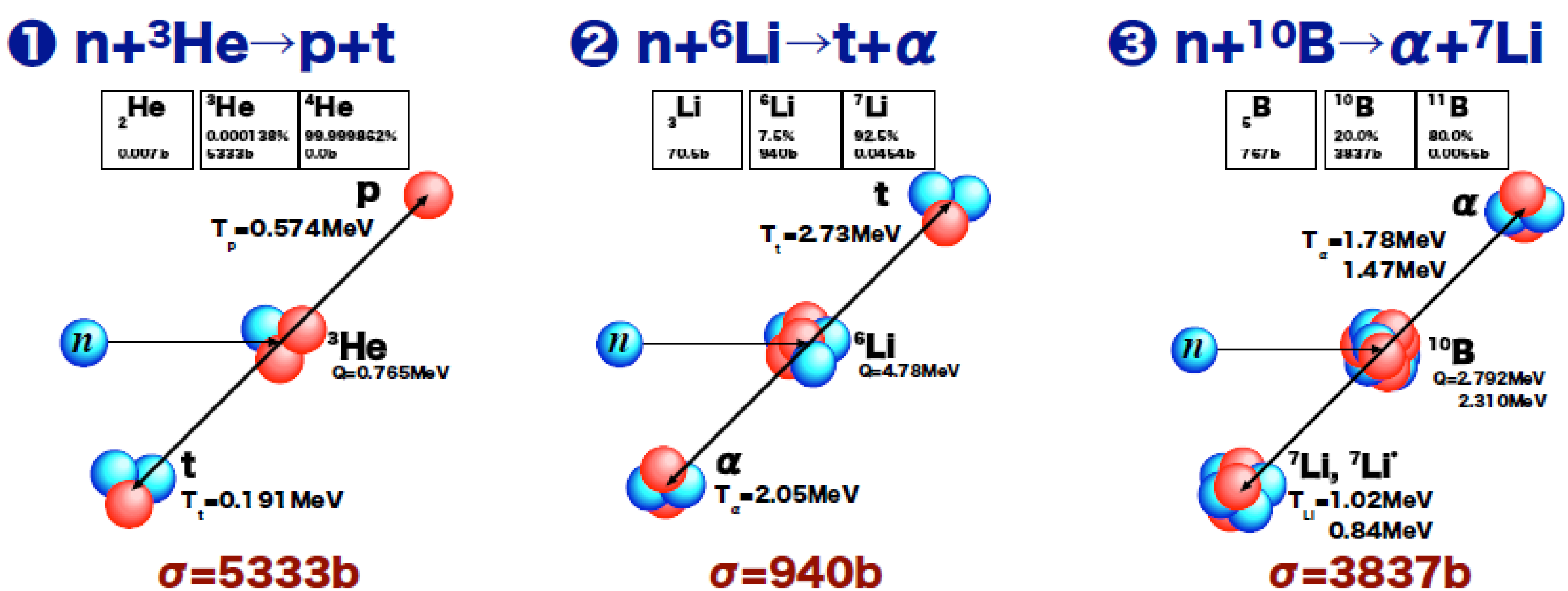
Pair Creation



Detection of Neutron

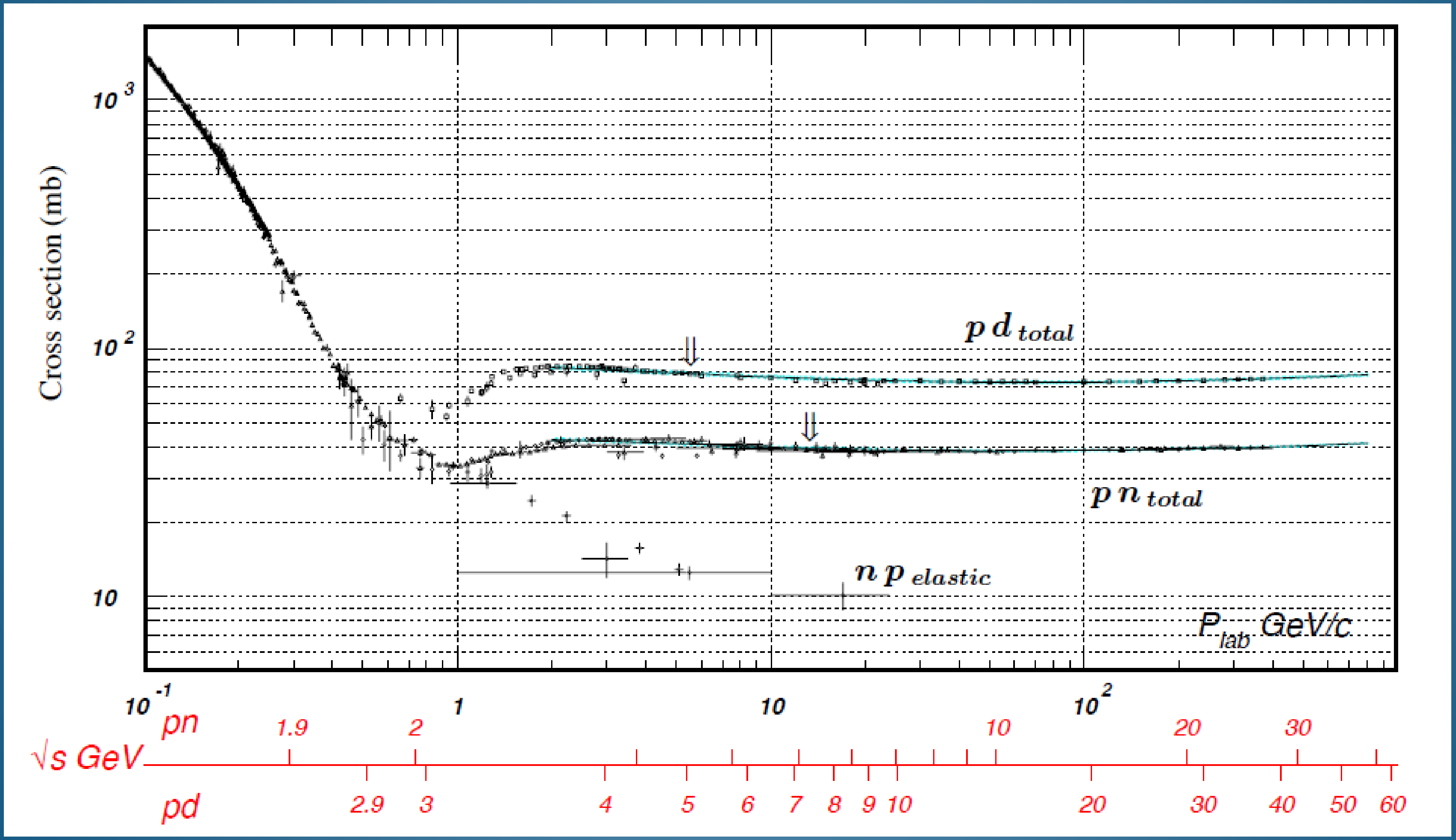
Low energy

Nuclear reaction useful to detect neutrons



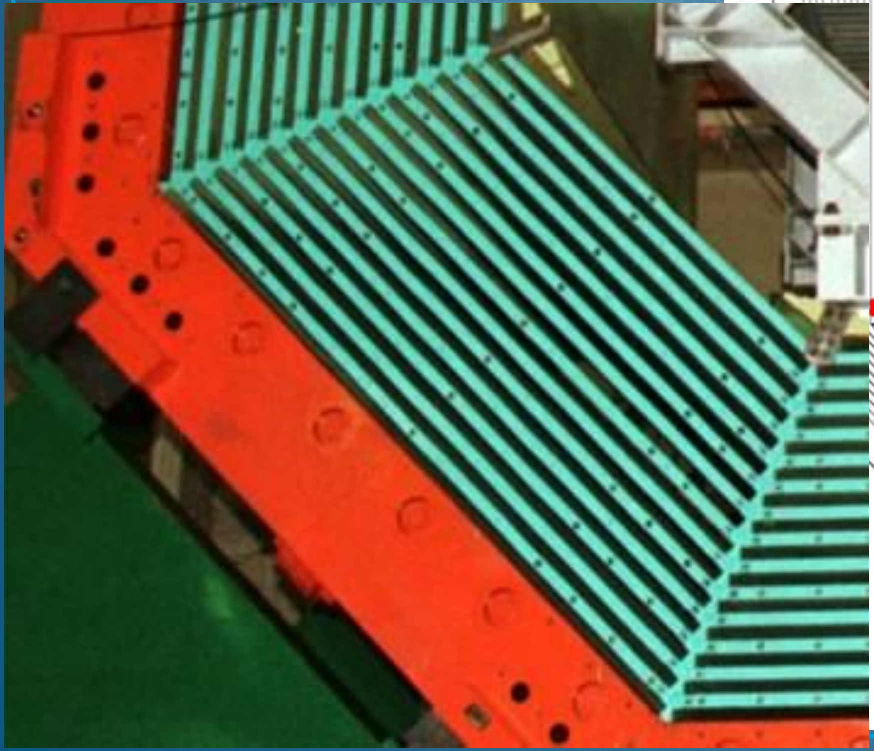
Shimizu

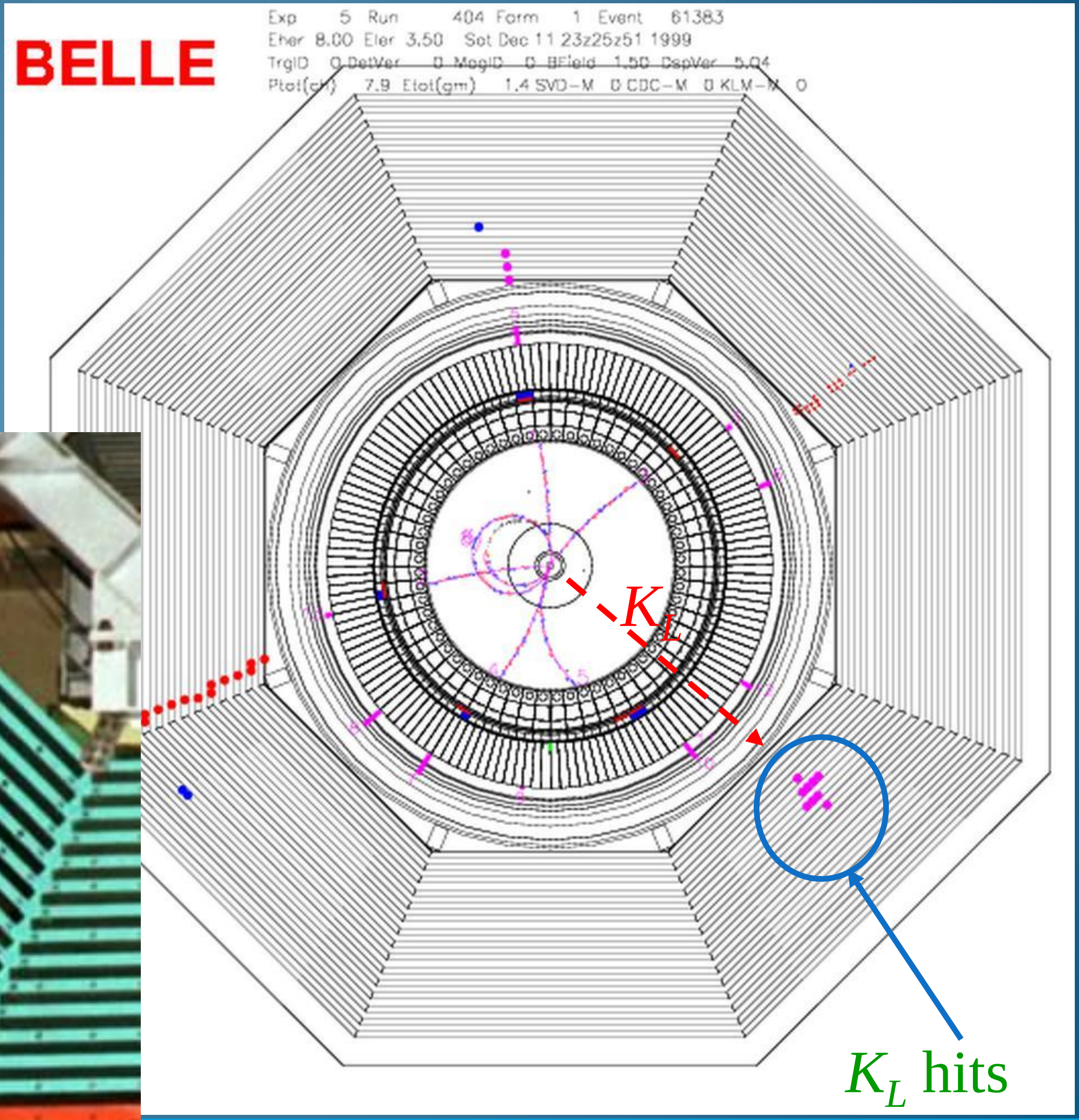
Neutron interaction at higher energy



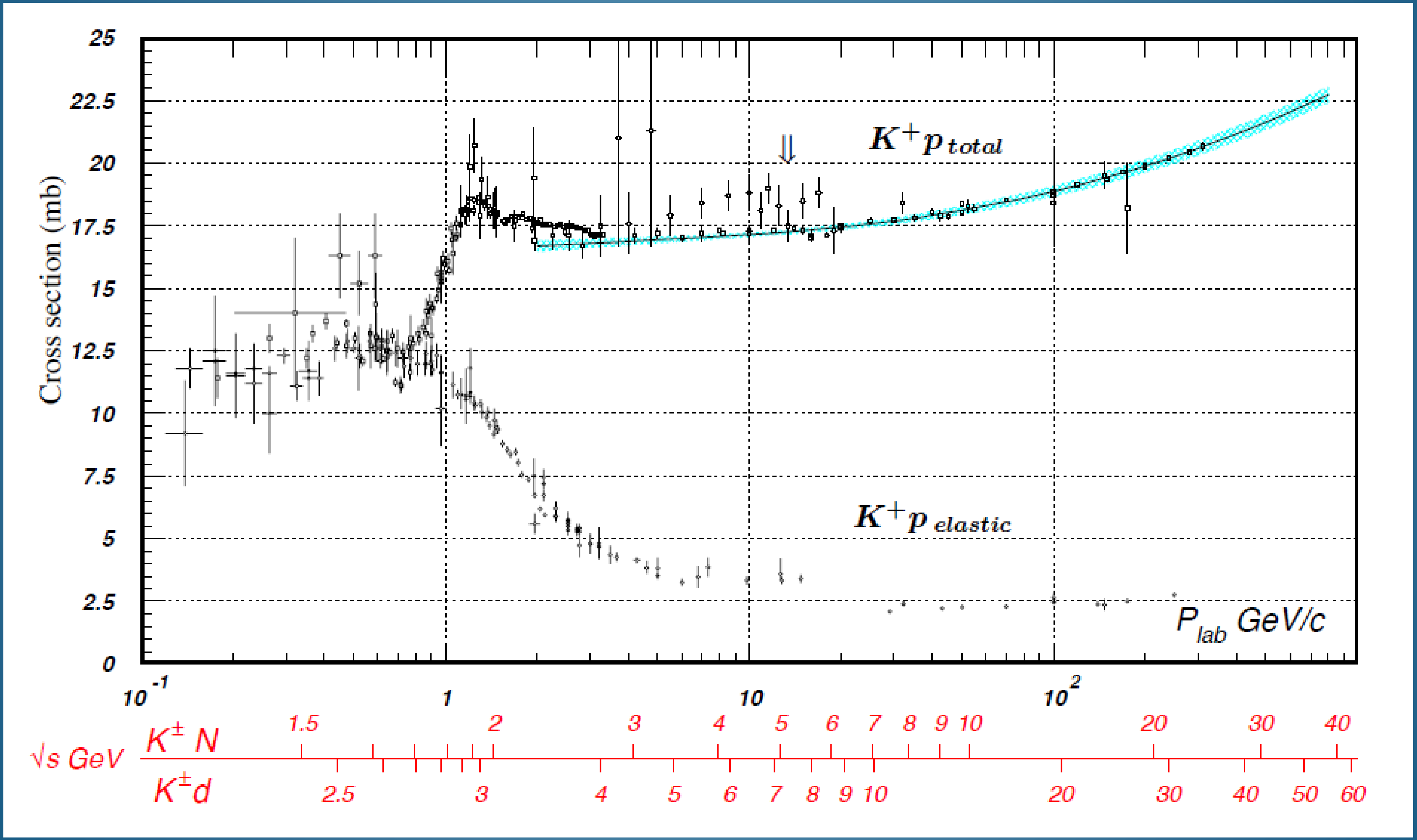
Neutral hadron/K_L detection

$$B^0 \to J/\Psi K_L$$

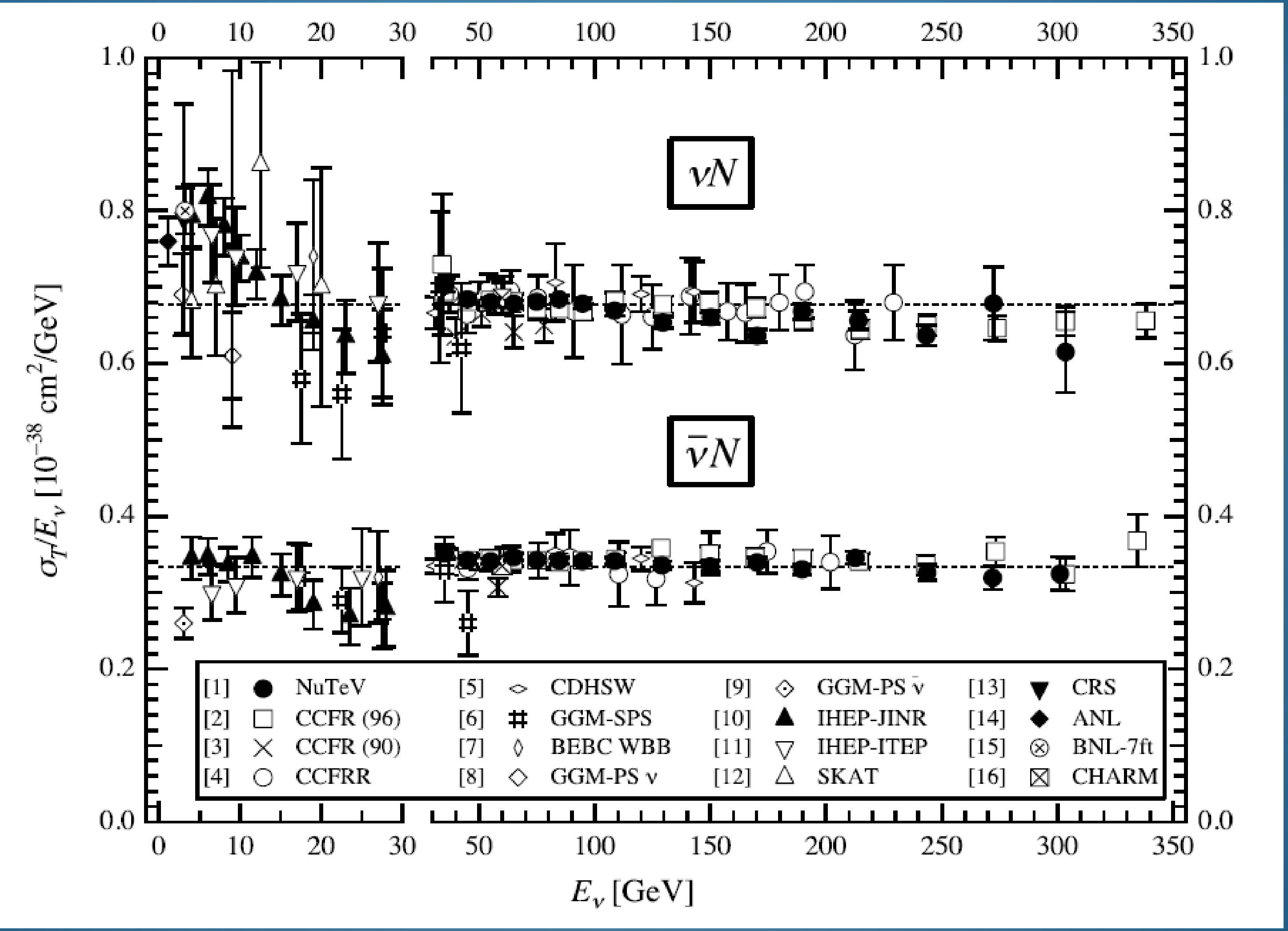




Hadron reaction cross section

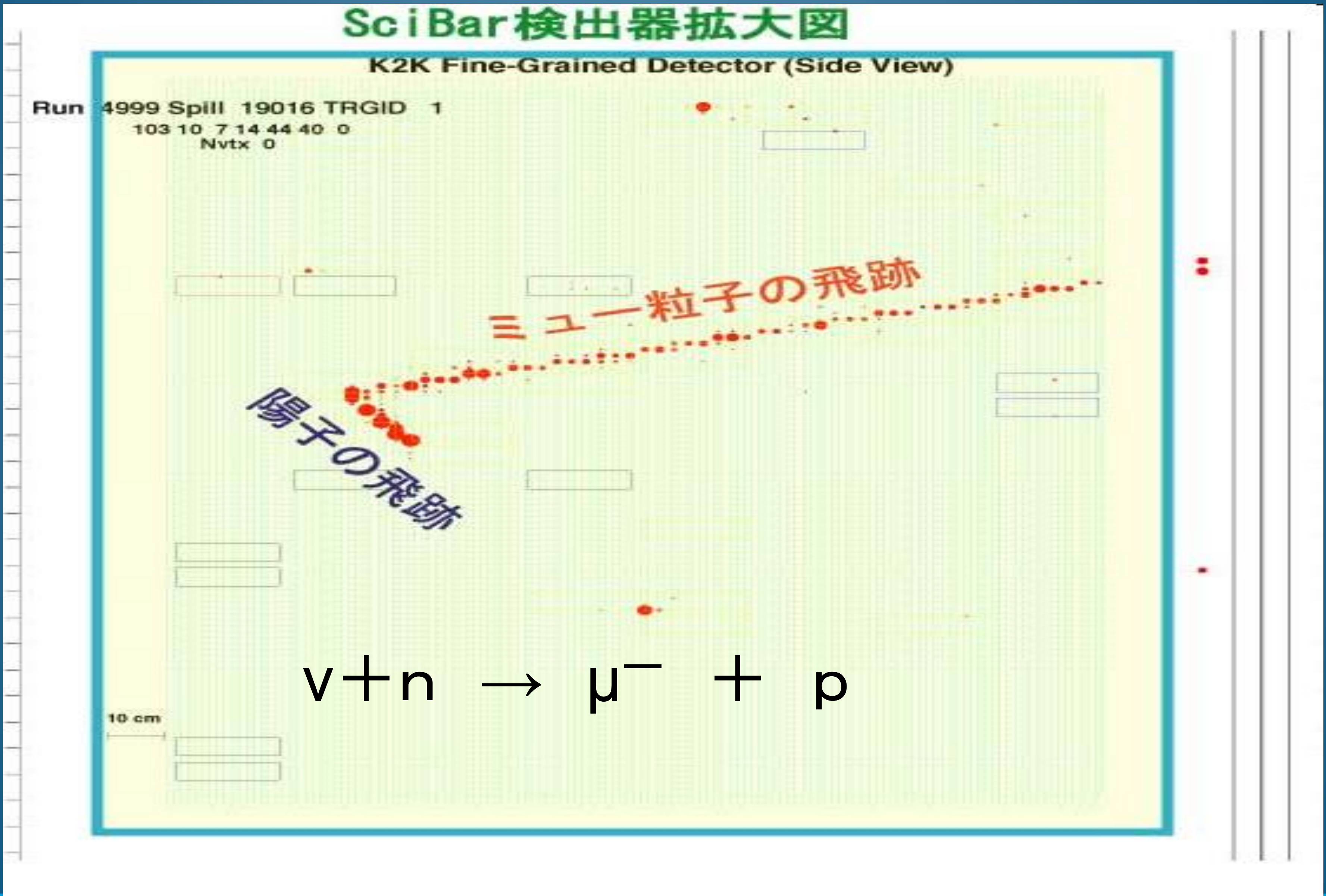


Finally neutrino detection..



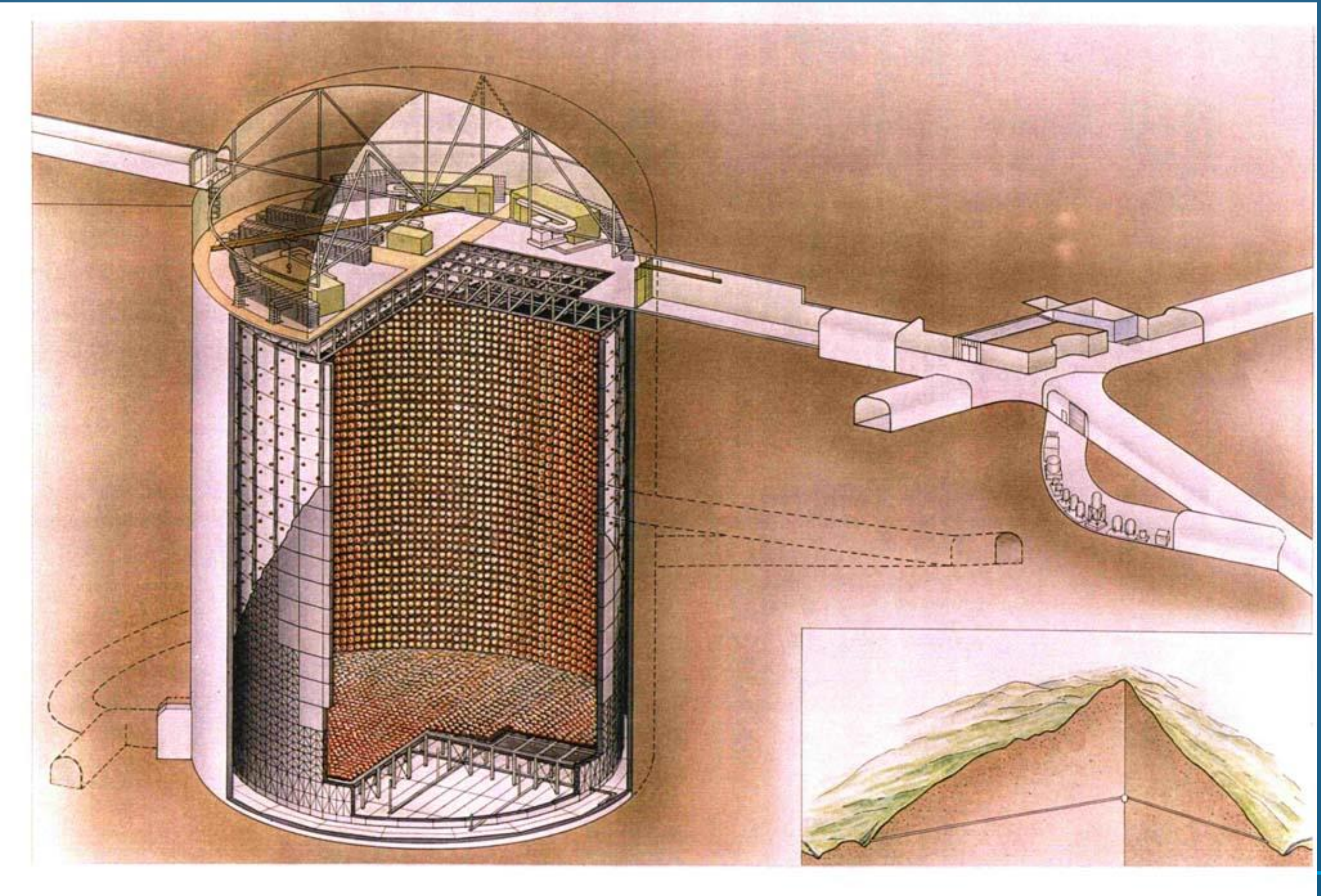
Exercise What is the detection efficiency of 1m thick iron

SciBar detector (K2K)

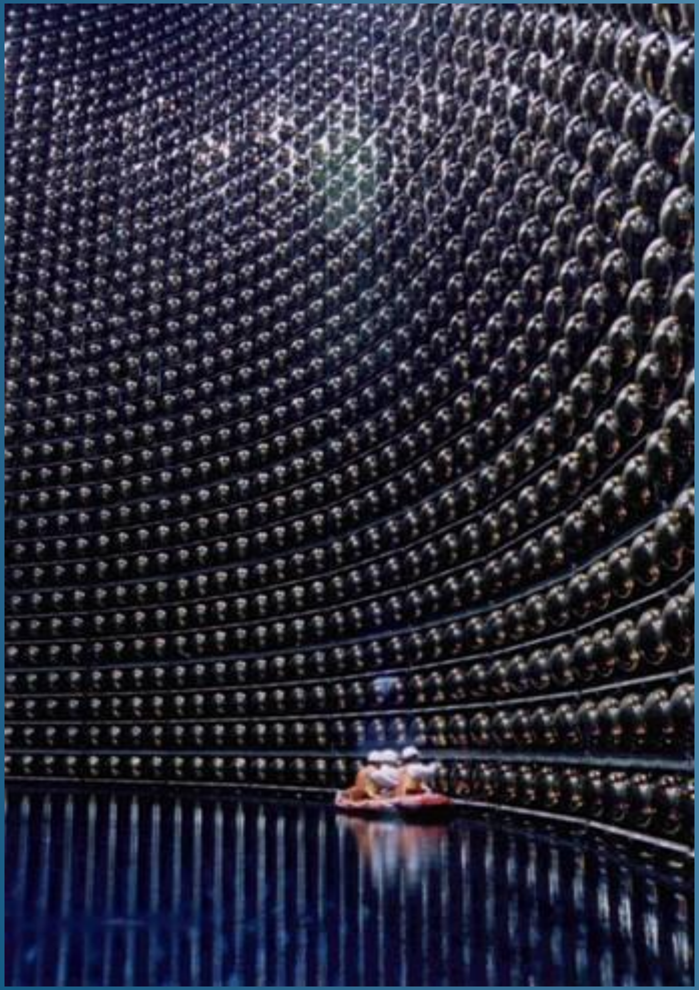


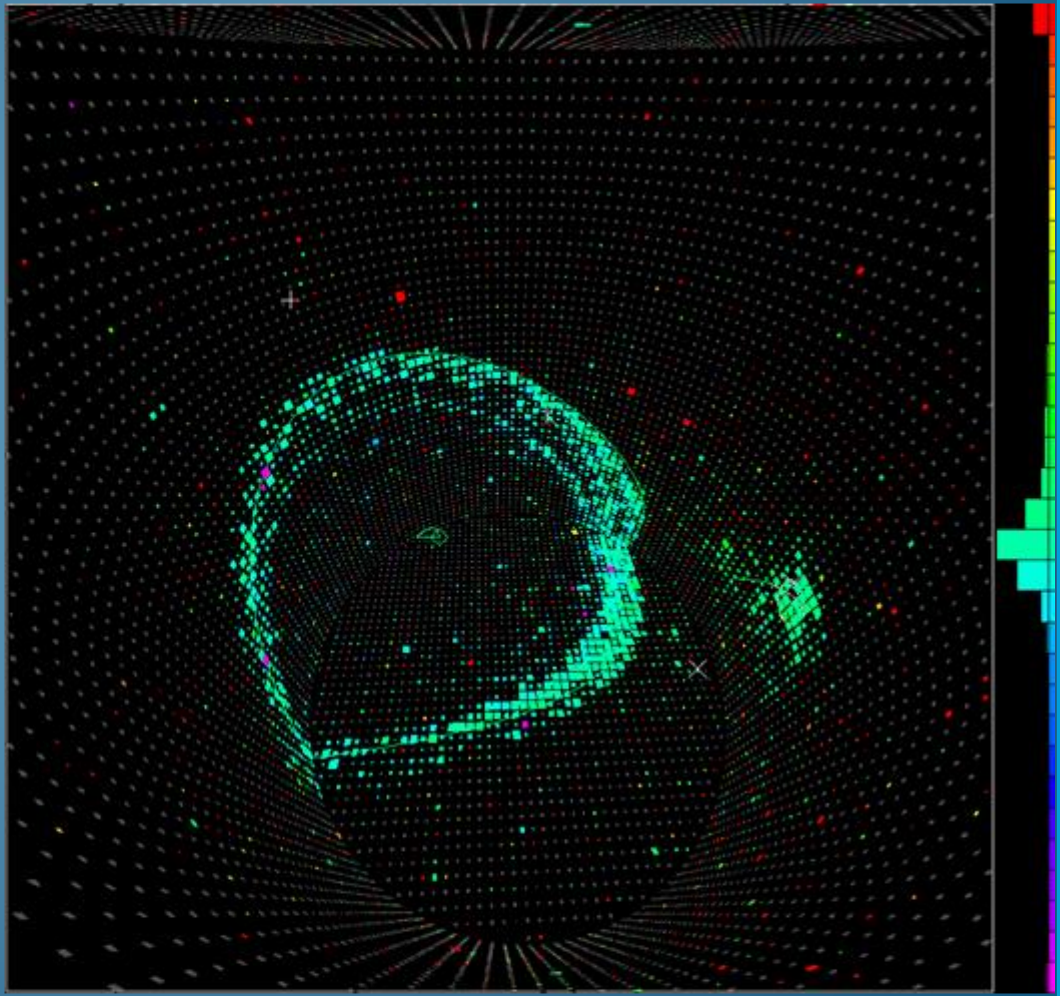
$$\nu + n \rightarrow \mu^- + p$$

Neutrino detection in Kamiokande

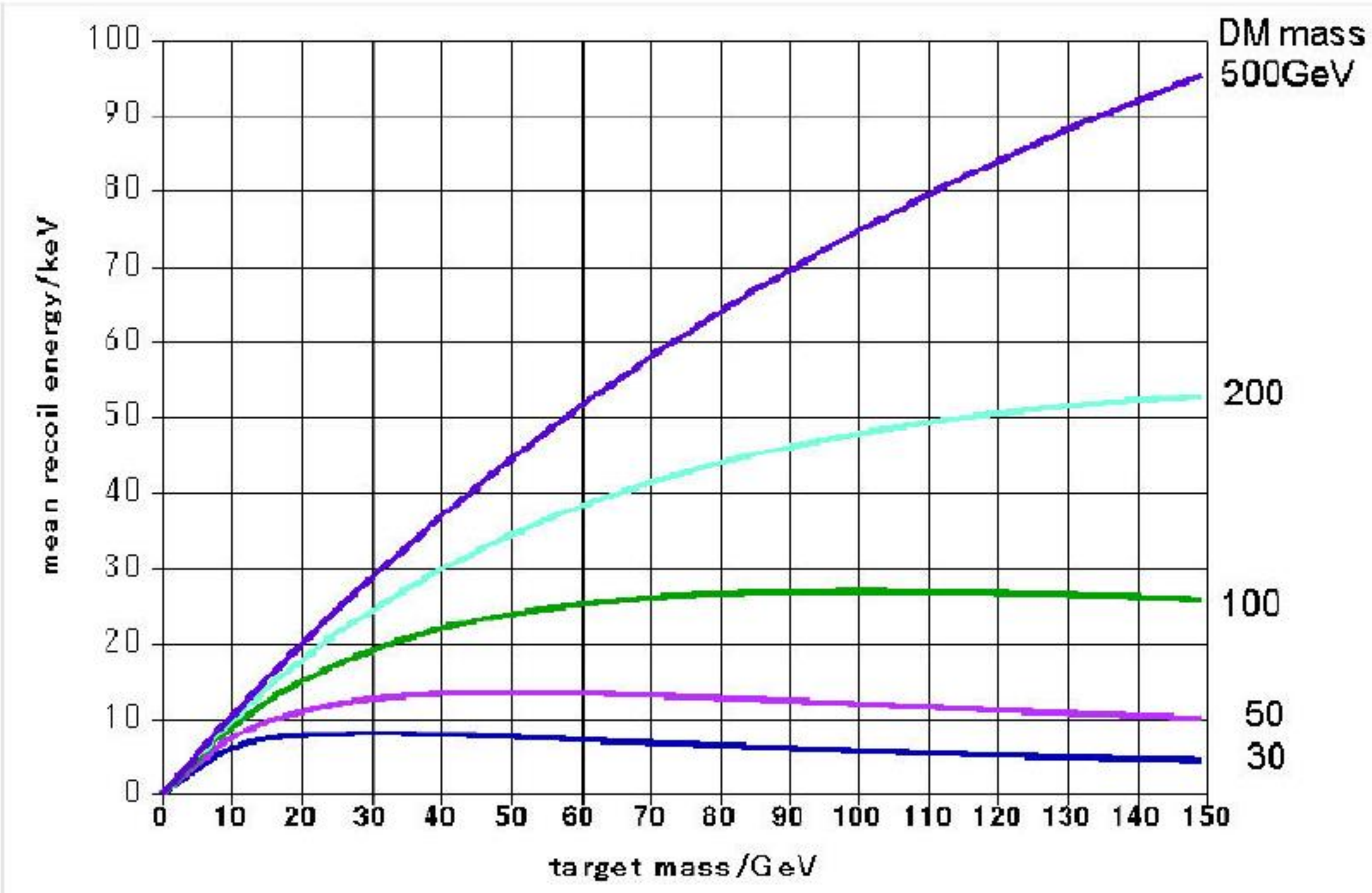


Water Cherenkov Detector





Dark Matter?

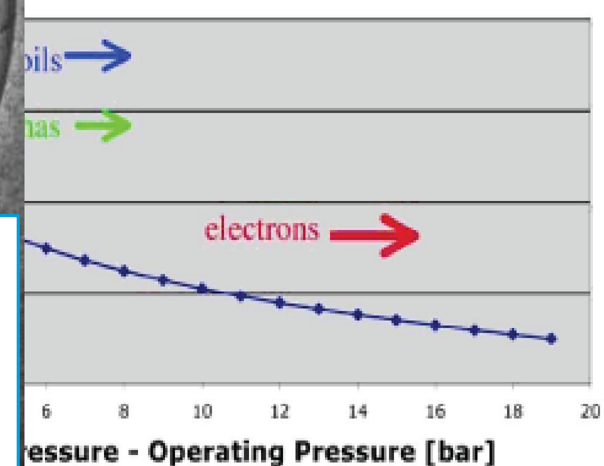

DM mass
500GeV
200
100
50
30
mean recoil energy/keV
target mass/GeV
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150

J. I. Collar/U. Chicago

rticles, yet sensitive to low-
l E-threshold)

A calibration event from PICO-2L shows boiling from multiple recoiling atomic nuclei. PICO-2L is designed to see a recoiling nucleus a from dark matter interaction

dX Nucleation Threshold



Summary at this point

- Detection of charged particles
  - Ionization
  - Excitation
  - Cherenkov radiation
  - Bremsstrahlung (Electron)
- Detection of Neutral particles
  - Nuclear reaction (Neutron, hadron)
  - Weak interaction (Neutrino)
  - Photoelectric/Compton scattering (Photon)
  - What about dark matter (??) We have to try any type of detection shceme. We don't know what it is.