Nuclear Emulsions

Video of the lecturer

The oldest particle detector with unsurpassed accuracy
and very innovative readout technologies

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Emulsion chemical composition an example of modern emulsions

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OPERA films

Element	Mass fraction
Ag	38.34
Br	27.86
I	0.81
C	13.0
N	4.81
O	12.43
H	2.4
S	0.1
Si	0.1
Na	0.1
K	0.05

	Fuji ET7B	Tested gel	OPERA film
Average diameter of the crystal	0.240 µm	0.236 µm	0.200 µm
Divergence of the diameter	0.078 µm	0.021 µm	0.016 µm
Volume occupancy of AgBr	0.50	0.50	0.31
Number of crystals per 100 µm	262	313	230
Grain density for MIP (/100 µm)	38	45	36
Detection efficiency per crystal	0.14	0.14	0.17
Machine-coating possibility	×	×	◯

Nano Imaging Tracker films

11 (NIT) to 29 (U-NIT) crystals/µm

$$\frac{dn}{dx} = \text{Crystal linear density}$$

$$\frac{dn}{dx} = \frac{3}{4}\frac{\alpha}{R}$$

R = crystal radius

α = volume occupancy

Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition

Main difference w.r.t. photographic films

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- The ratio of silver halide to gelatine is up to ten times larger in nuclear emulsions (higher sensitivity)
- Nuclear emulsion is typically from 10 to 100 times thicker (3D reconstruction)
- Developed silver grains are smaller and more uniform

Detection principle

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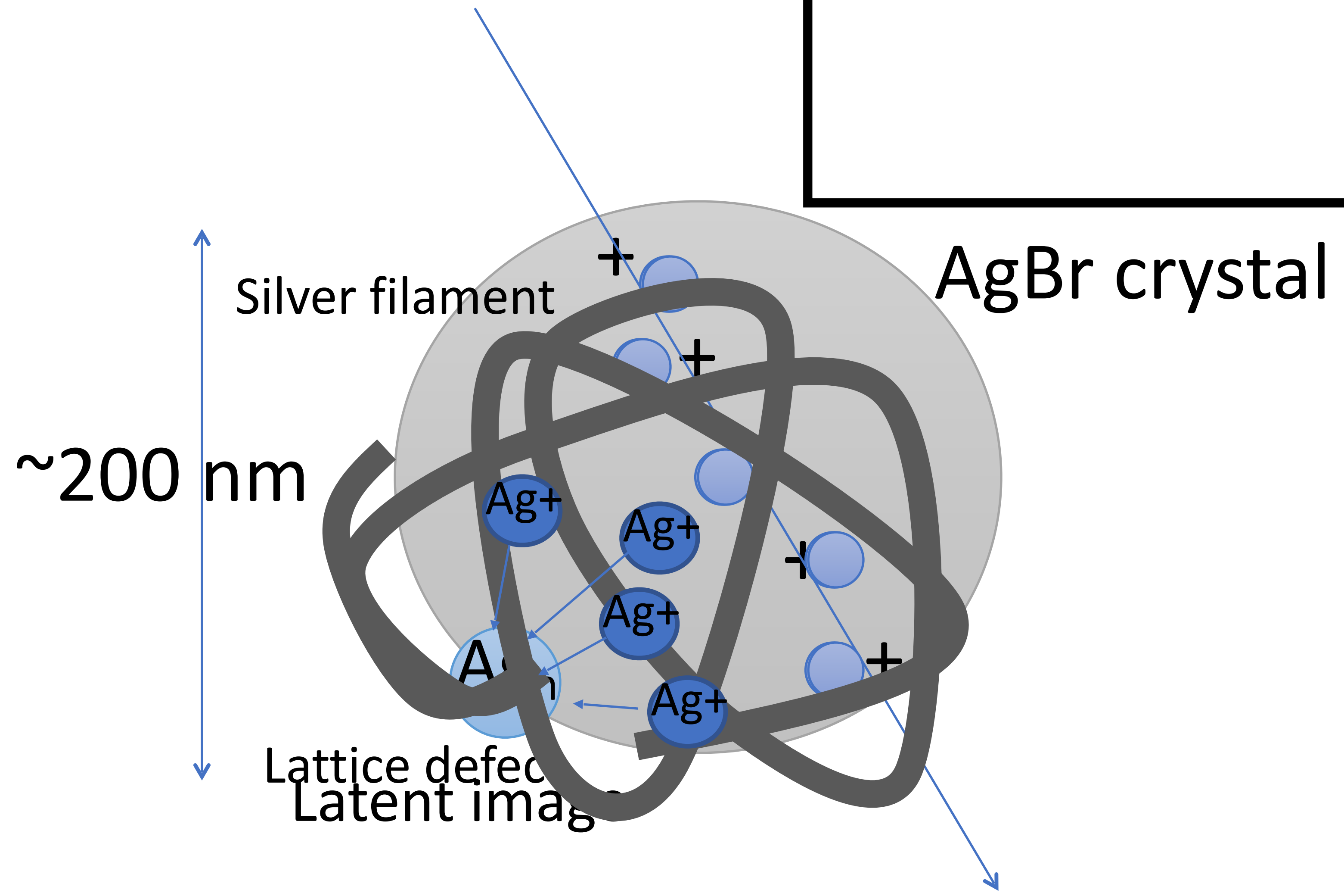
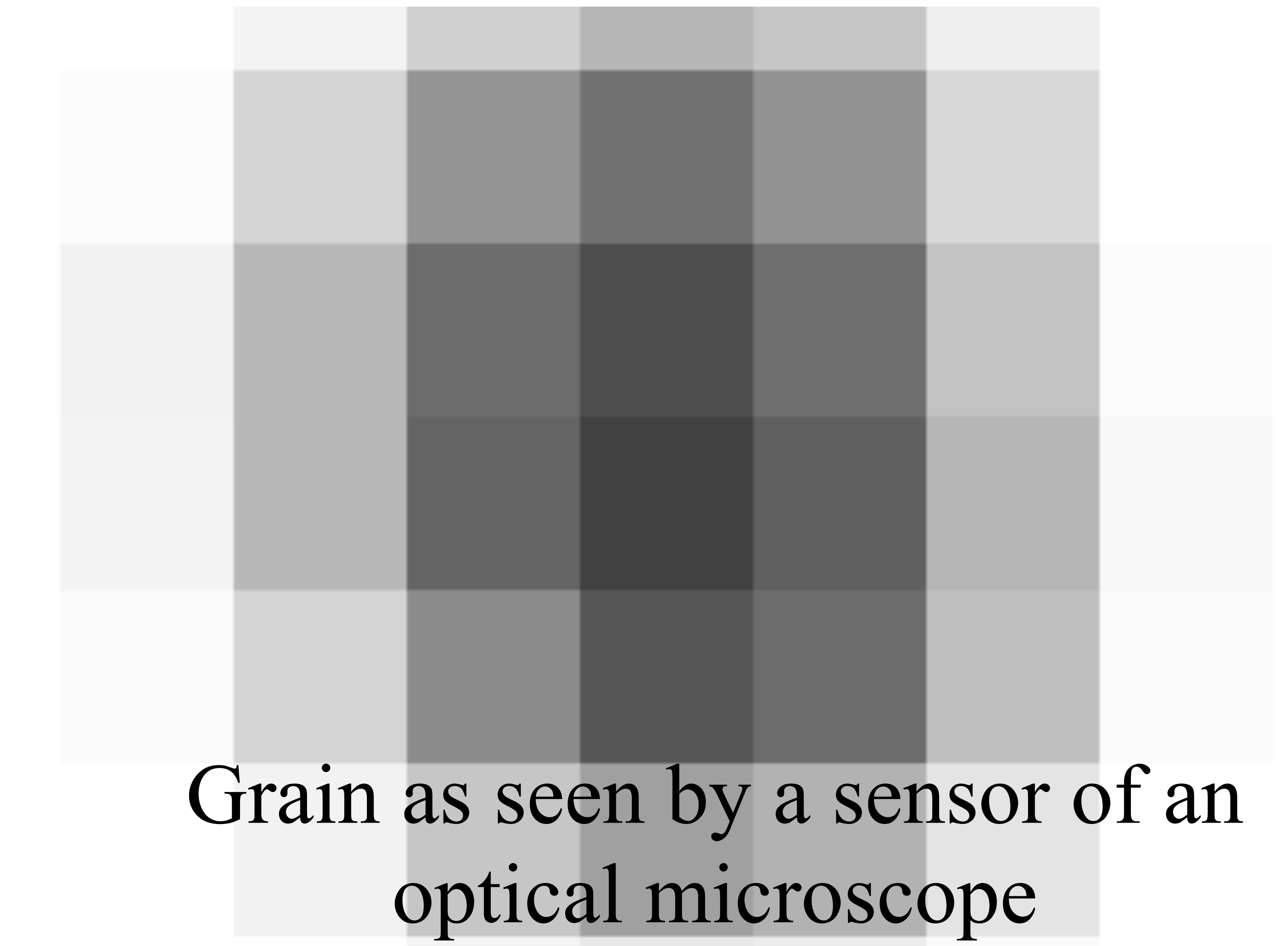
1. Ionization induced by a particle
   - 2.6 eV band gap
2. Electrons trapped at a lattice defect on the crystal surface
   - Attract interstitial silver ions
   - Produce a "latent image" = Ag_n
3. Chemical amplification of signal
   - Development → silver filaments
   - 10^7 - 10^8 amplification
4. Dissolve crystals
5. Observe it at optical microscopes





Grain as seen by a sensor of an optical microscope

Detection principle

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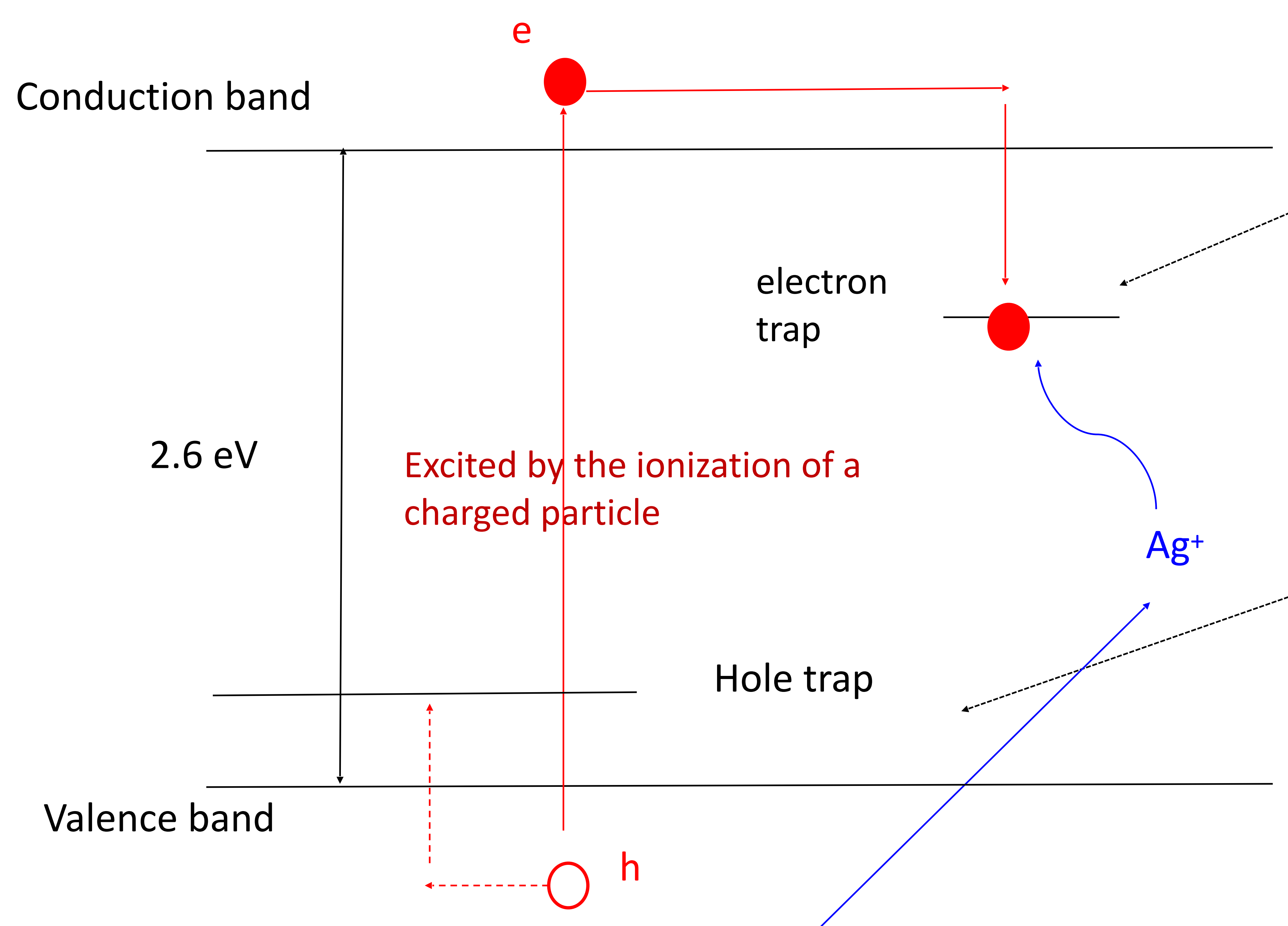


Electron trap

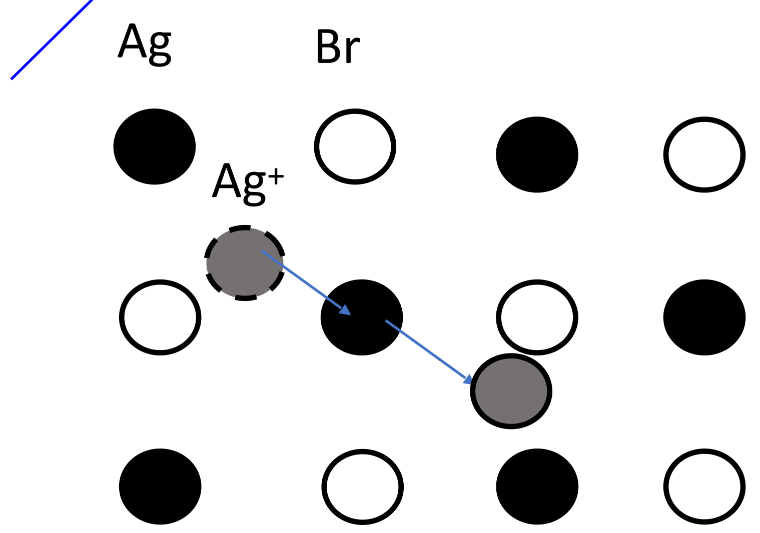
- ☑ surface kink site
- ☑ artificially doped (e.g., AuS, S_2, Fe, ・・)
- ☑ crystal defect
- ☑ Ag_2 on P-center (positive kink site)

Hole trap

- ☑ Iodide doped
- ☑ Ag_2 on R-center (neutral kink site)

Interstitial Silver Ions

AgBr is an ionic crystal. Crystal defects generate interstitial silver ions due to ionic conductivity



$$e^- + Ag^+ \rightarrow Ag$$

$$Ag + e^- + Ag^+ \rightarrow Ag_2$$

$$Ag_{n-1} + e^- + Ag^+ \rightarrow Ag_n$$

Latent image specks

n >4 In standard photographic theory

Detection principle

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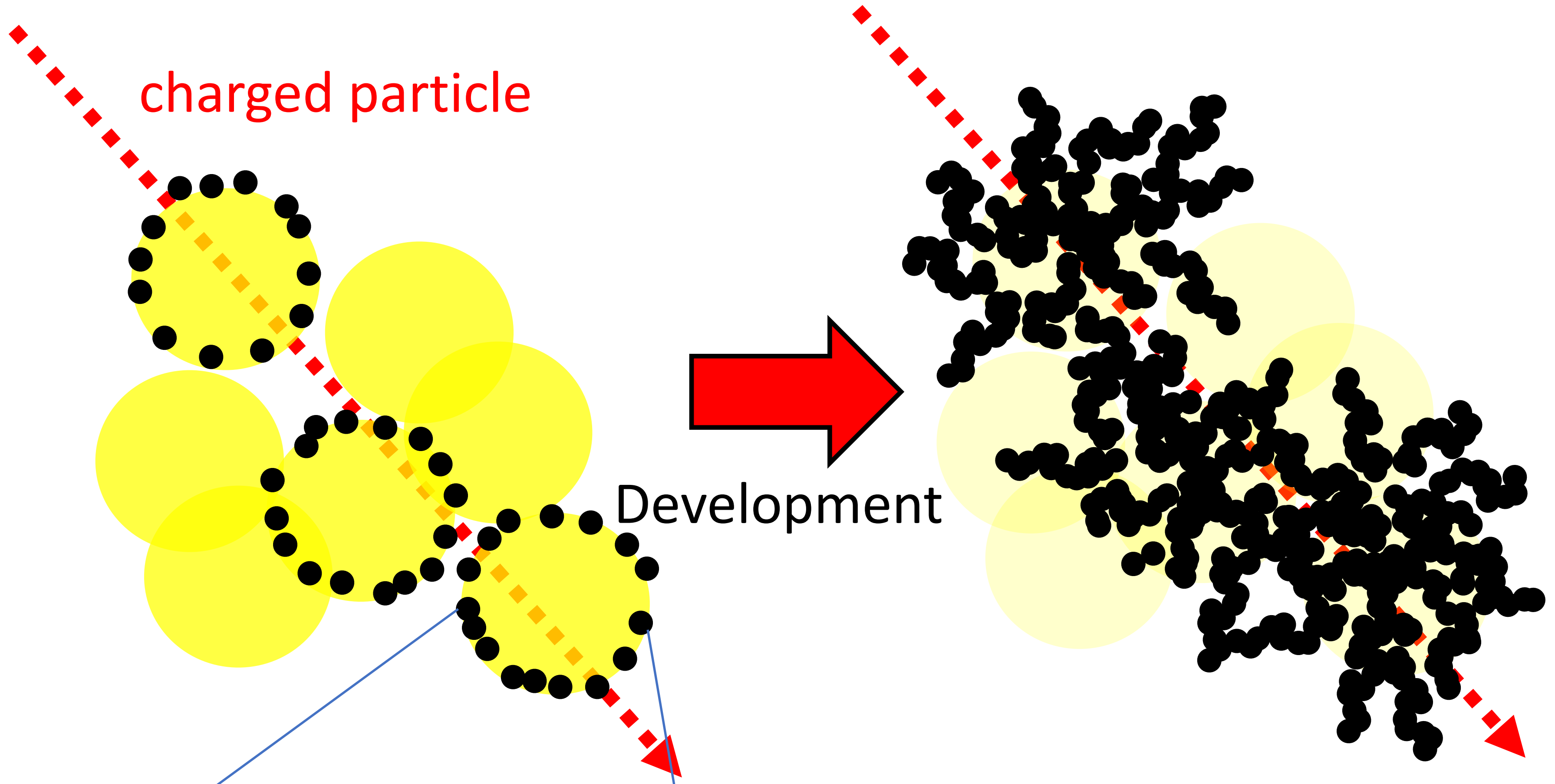
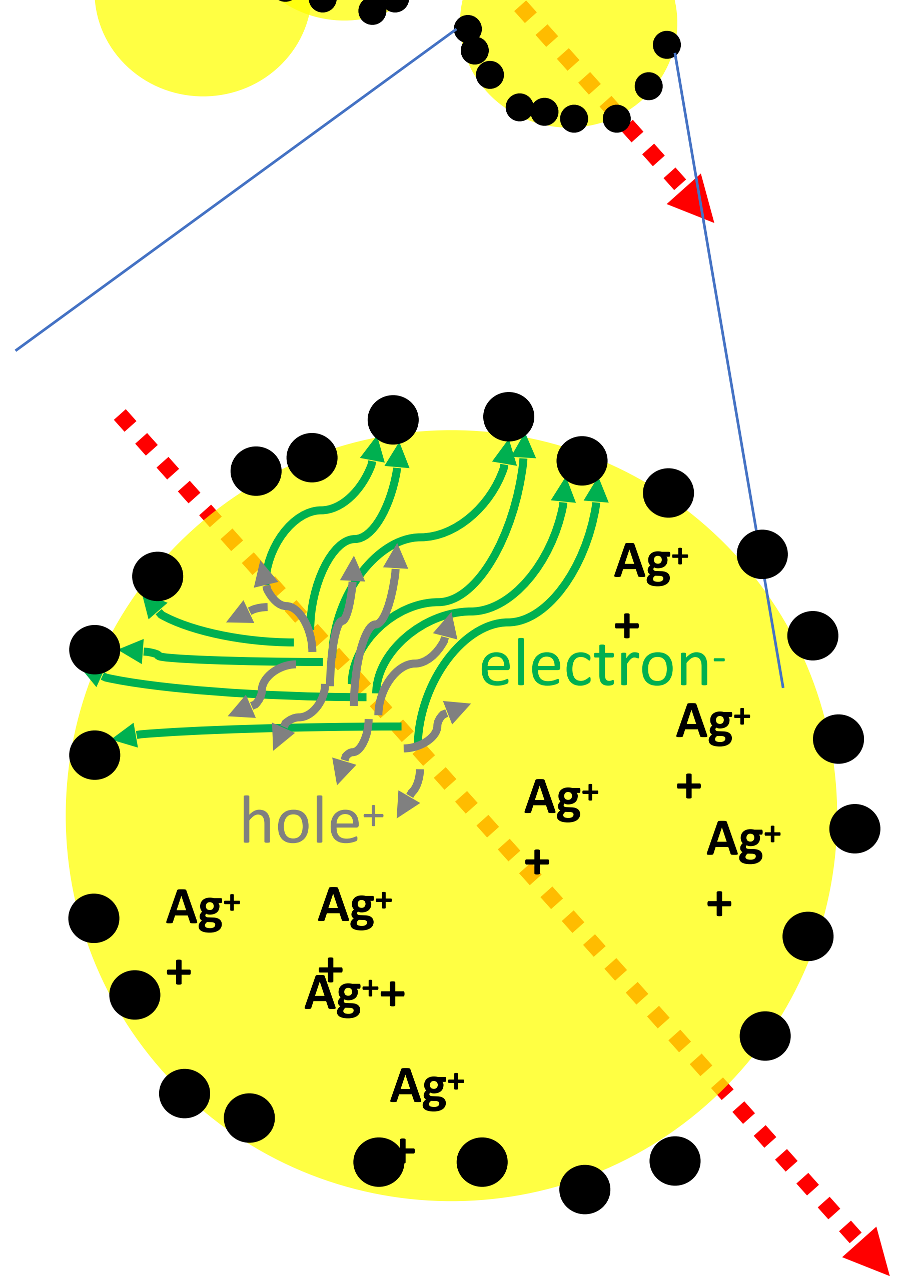




$e^- + Ag^+ \rightarrow Ag$

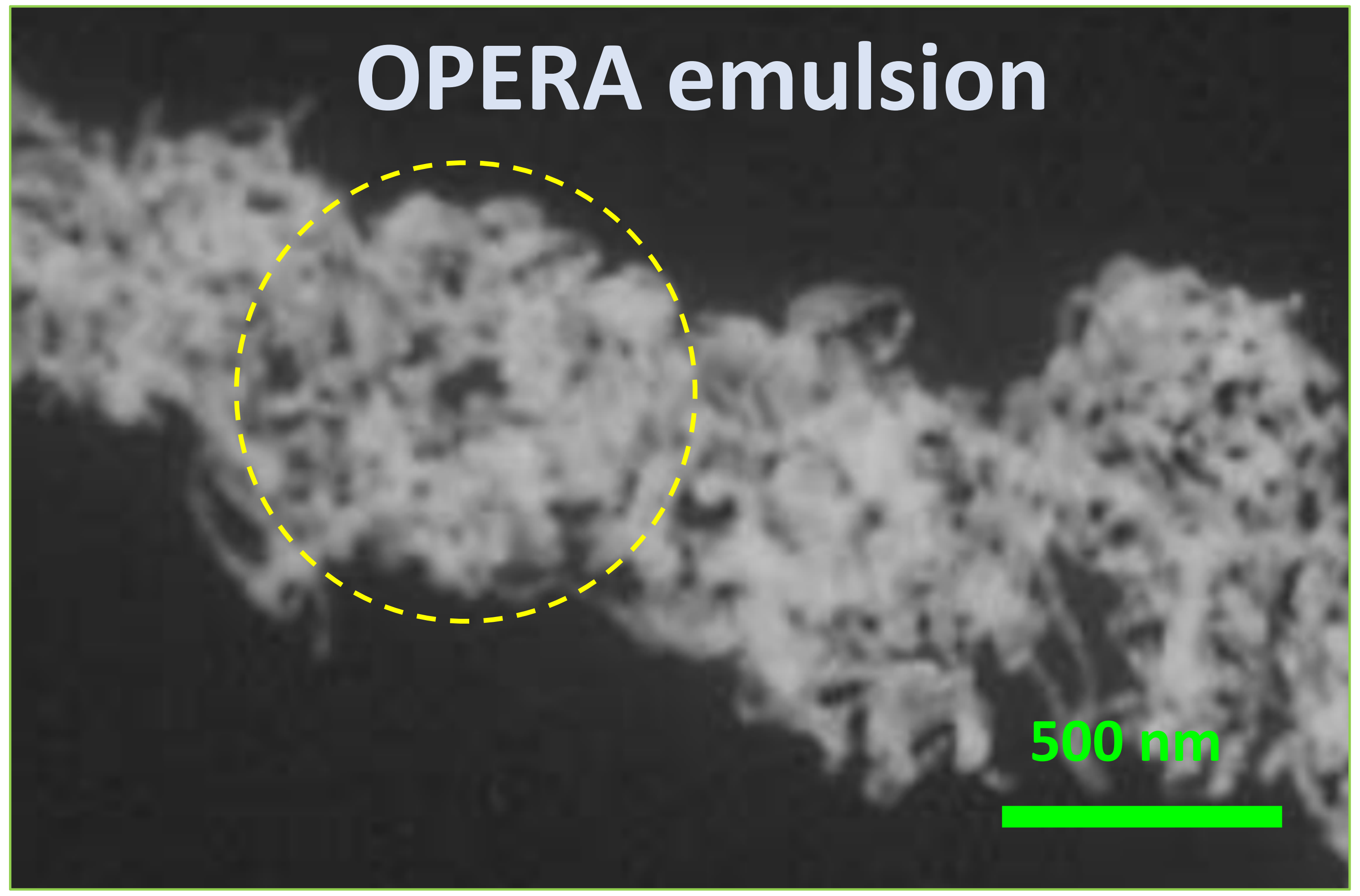
$Ag + e^- + Ag^+ \rightarrow Ag_2$

$Ag_{n-1} + e^- + Ag^+ \rightarrow Ag_n$

Number and size depend on the type of charged particles (dE/dx)

Crystal size : ~ 200 nm

Electron microscope image of α-ray



hundreds of Ag_n per crystal

Development process

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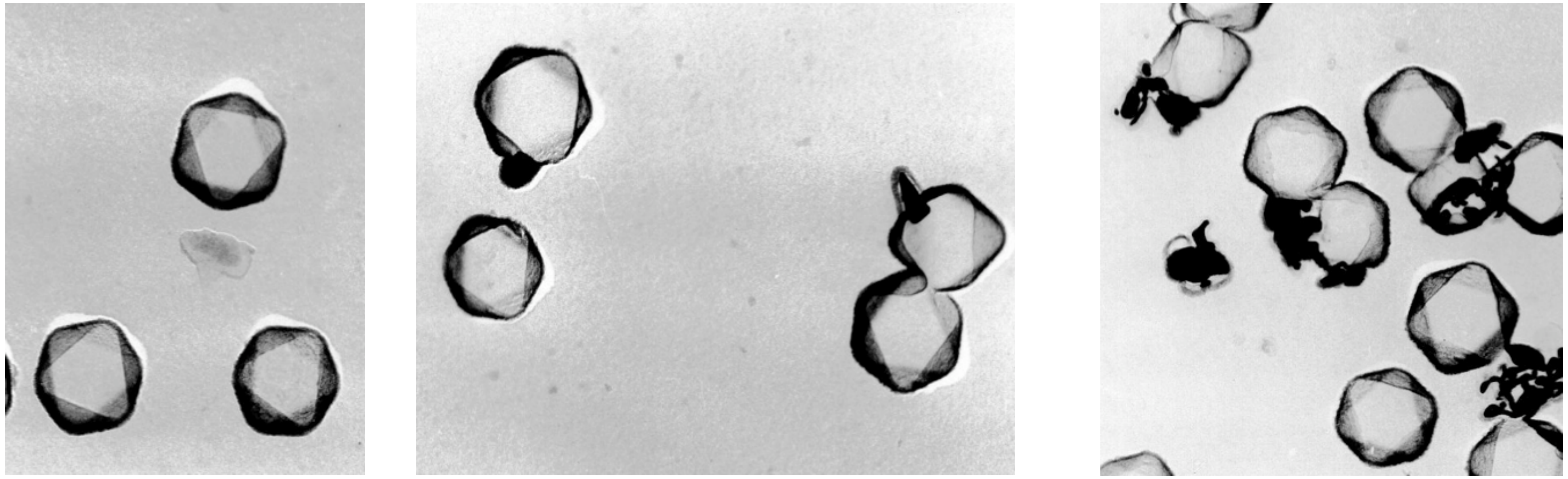
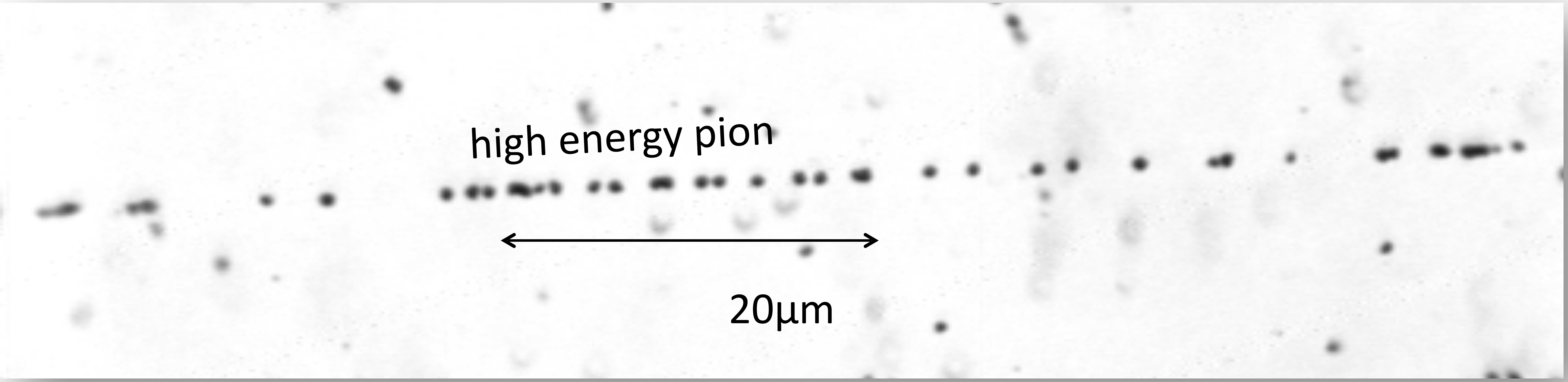


The Silver Halide Grains (diameter of 0.2 micron)



The role of gelatine

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- The gelatine provides a 3D substrate to locate the crystals of silver halide and prevent them to migrate during the chemical development: keep the original position
- It can absorb large quantities of water
- The gelatine molecules are adsorbed to the ions on the surface of the halide, so that the grains are held fixed, like flies on a spider web

Production process

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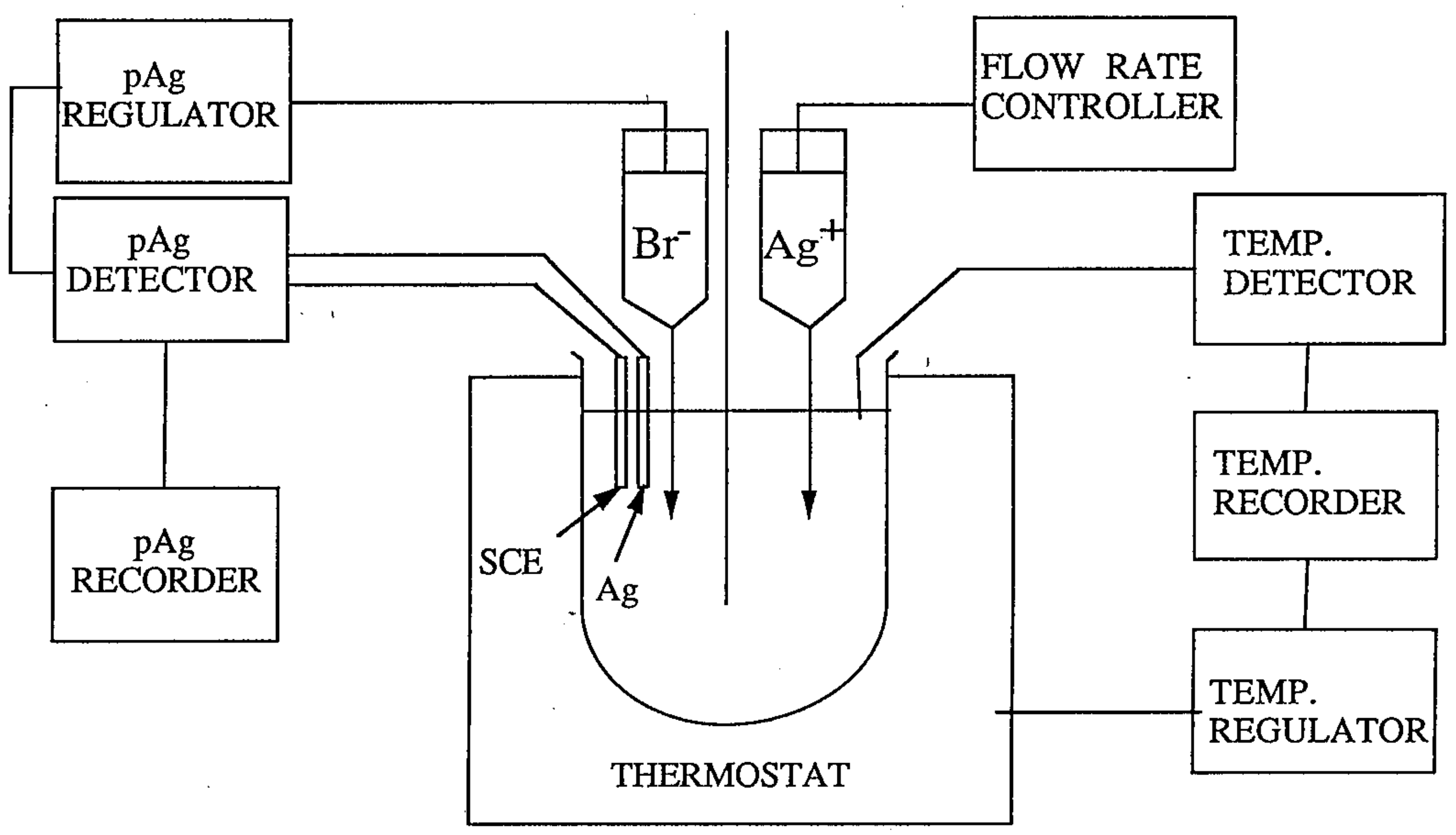
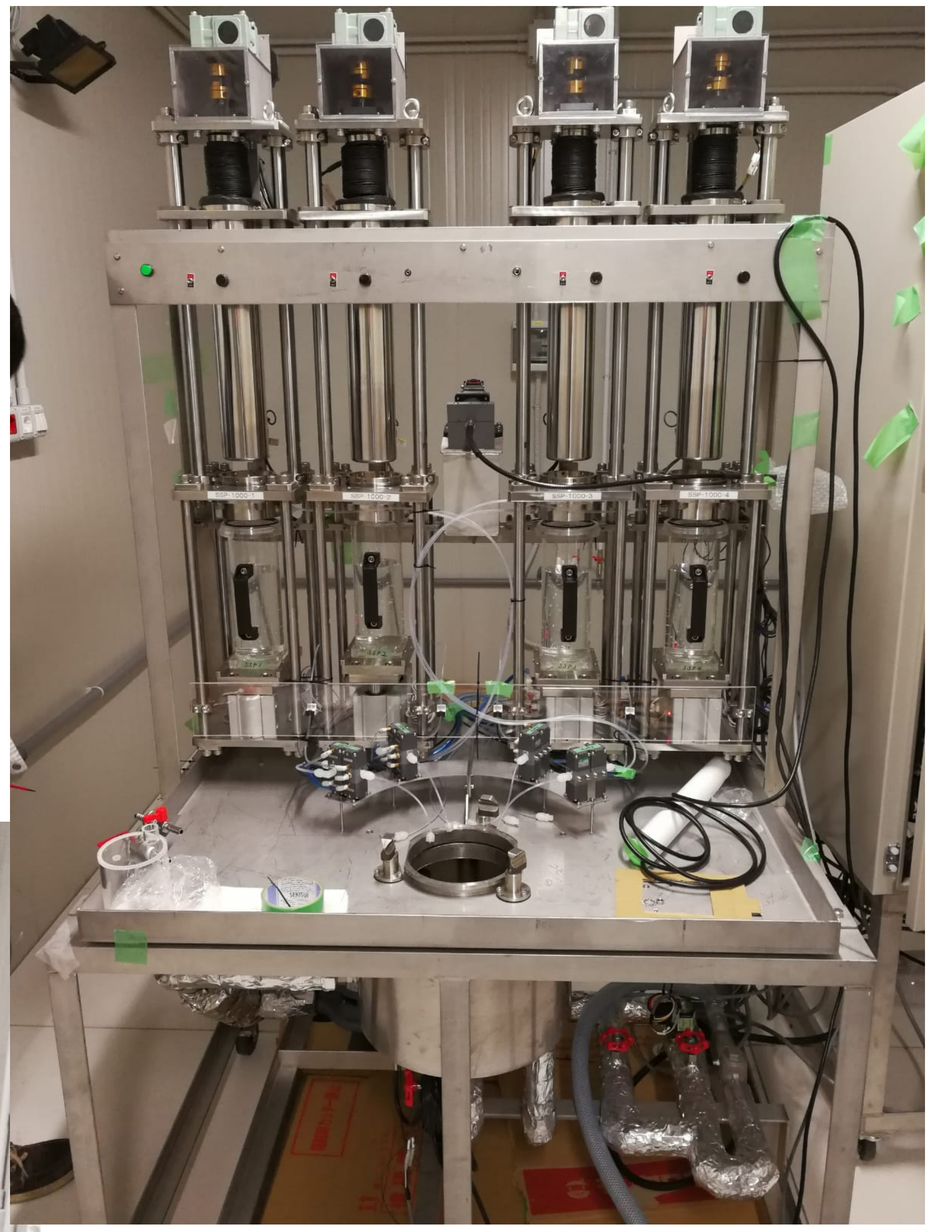


Gelatin aqueous solution

$AgNO_3$ + KX → AgX + KNO_3 in an aqueous gelatin solution

K can be replaced by Na

Production machine installed underground at Gran Sasso (Italy)



Production process

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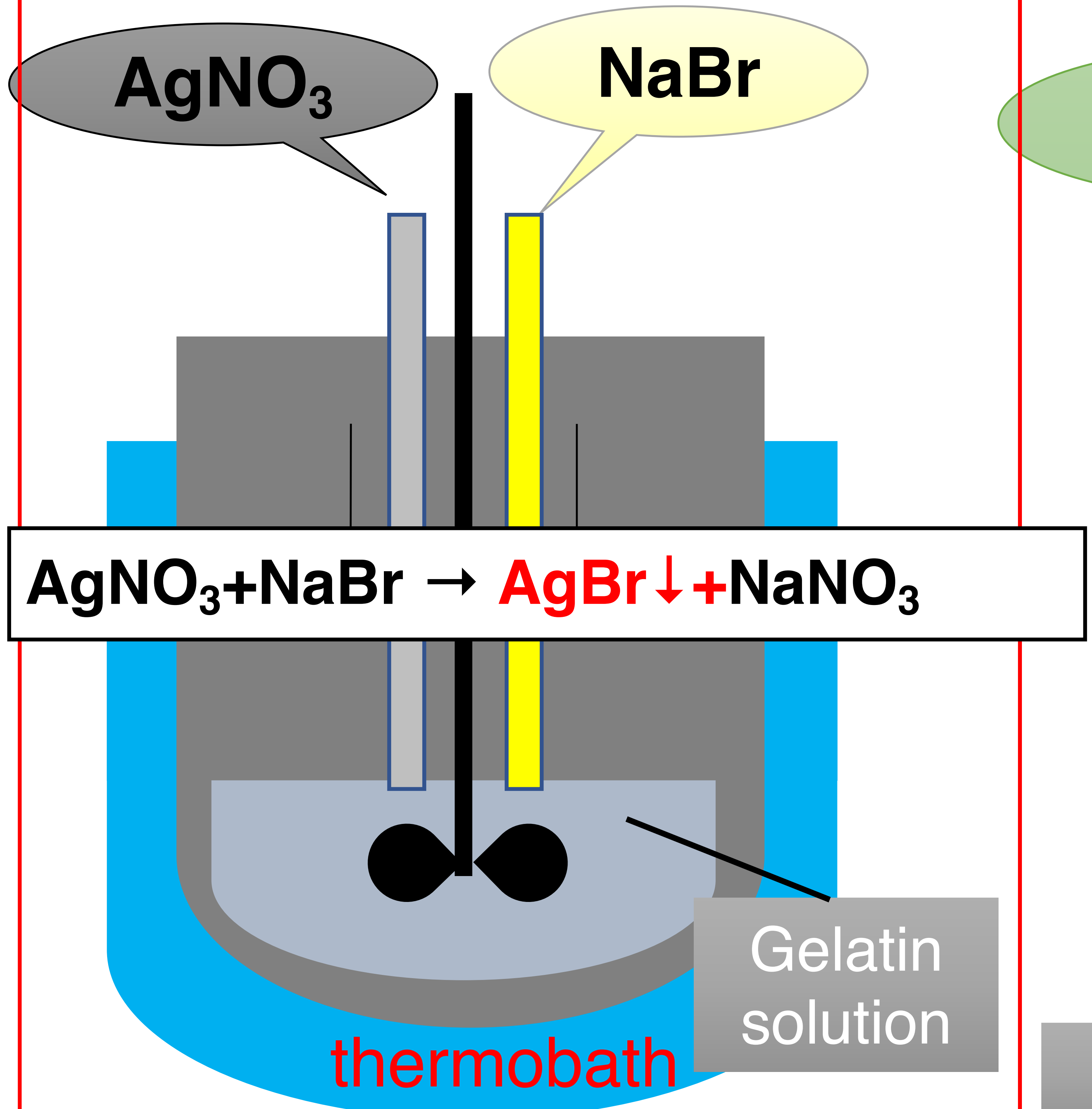
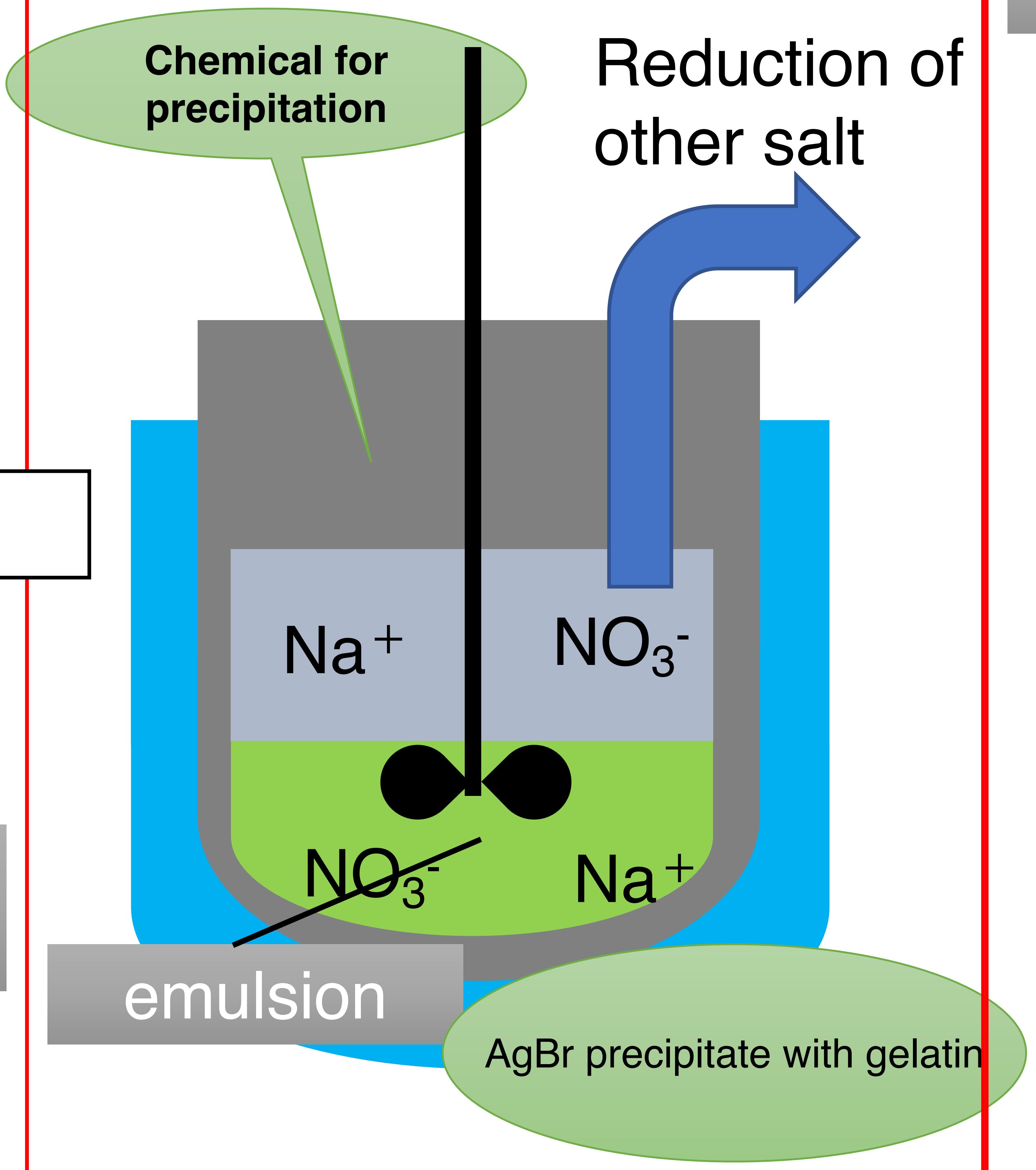
Crystal formation

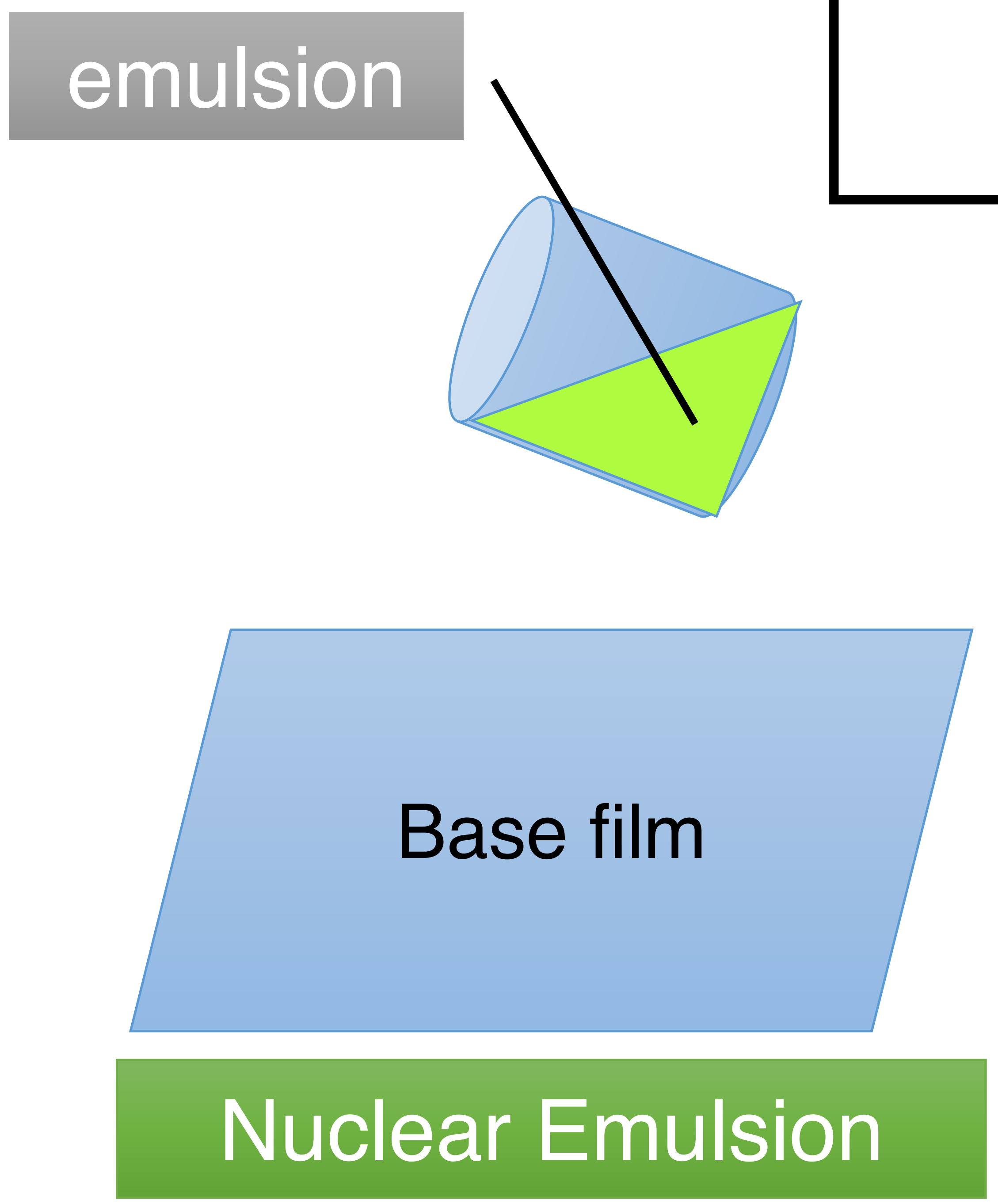


Control the AgBr crystal size
Temperature, insertion speed
Concentration of chemical, pAg control, rotation speed

wash/salt reduction



Apply



Control of dry condition

Temperature, humidity,
Thickness etc.

Film production

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Control of AgBr crystal size, density

Desalination

Reduction of Na, NO_3

Sensitization

Au+S sensitization
→ tuning of the
sensitivity (grains/µm
at a given dE/dx)

Nuclear emulsion technology: the birth

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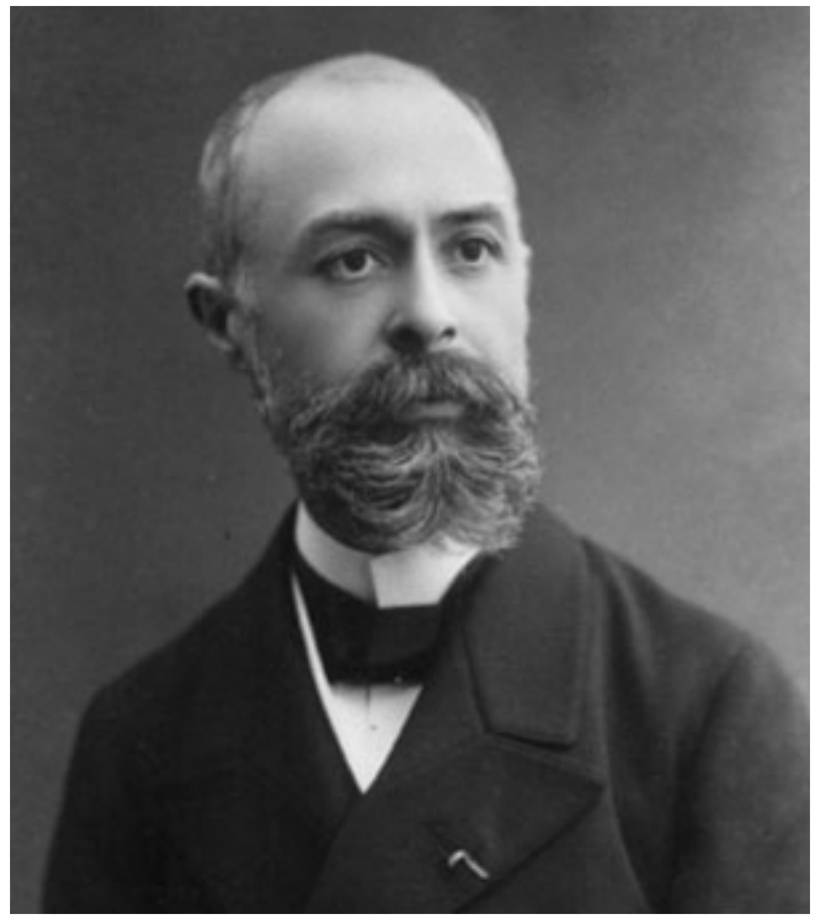
1896 Bequerel (Nobel Prize in 1903) discovers the radioactivity by observing the blackening of photographic films due to uranium salts

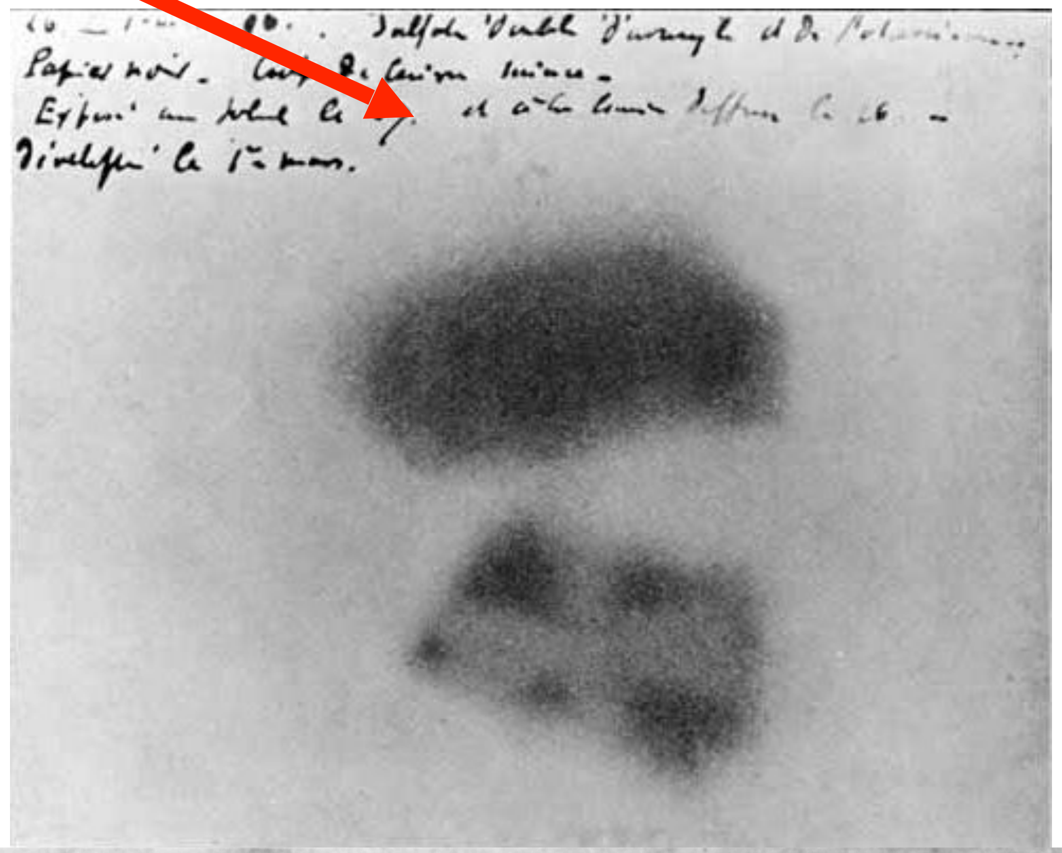
He had accidentally placed an uranium ore on top of a photographic plate. After several experiments, he concluded that this was due to uranium emission different from X-rays

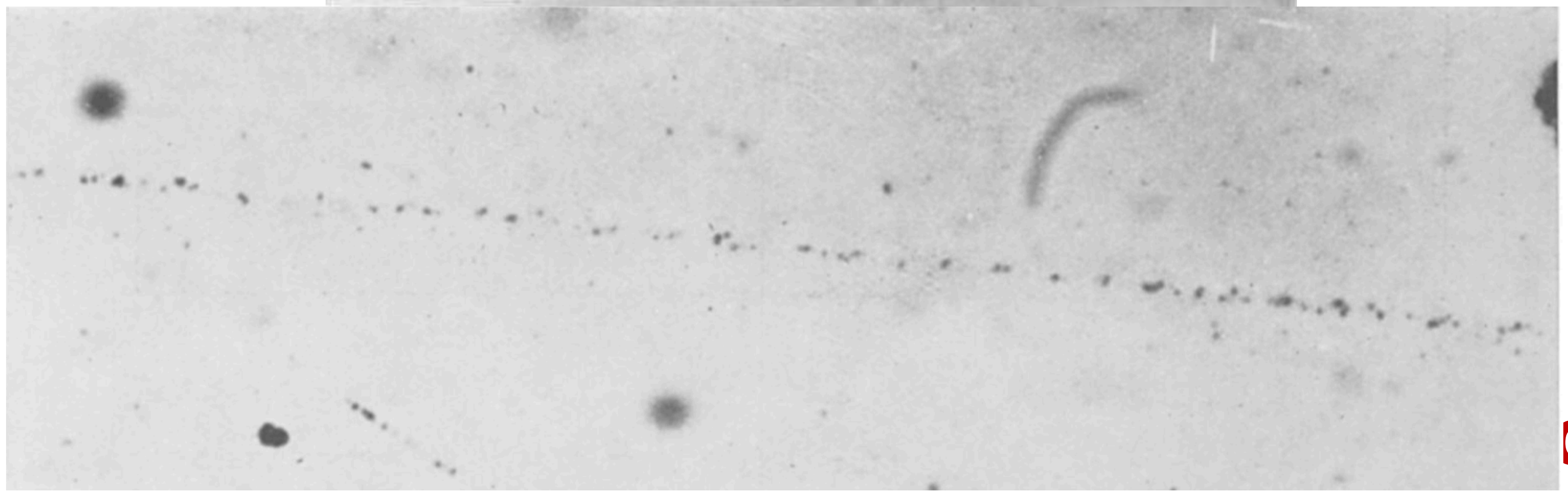
1910 Kinoshita observes tracks of α particles

- Important developments of the emulsion sensitivity in 1930s and 1940s thanks to the Bristol group led by Powell who developed films sensitive to electrons
- Emulsions originally 50 μm thick (surface placed parallel to the direction of the particles)



Metal cross





Nuclear emulsion technology: developments

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- R&D to develop thicker films (up to 1 mm) to contain all the charged particles produced therein
- After the Second World War, very active collaboration between academic groups and photographic industries (Kodak, Ilford)
- 1970s and 1980s: With the development of electronic detectors, emulsions are less used
- Revolution in the readout technique in the late 1980s. In the 1990s fully automated optical microscopes for the readout provide a revival of the technology

Nuclear emulsion technology: current era

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2000s: the era of the OPERA experiment, the largest ever emulsion experiment with an industrial production of films by the Fuji Film Company (110000 m^2)

2010-: technology established and OPERA provides its unique results. Faster scanning system are developed

New era with nanometric films for nanometric accuracy: breakthrough in the readout technologies

Thanks to ultra-fast scanning systems and nanometric accuracy new enterprises are possible: NEWSdm, SHiP and SND experiments

The Discovery of the Pion

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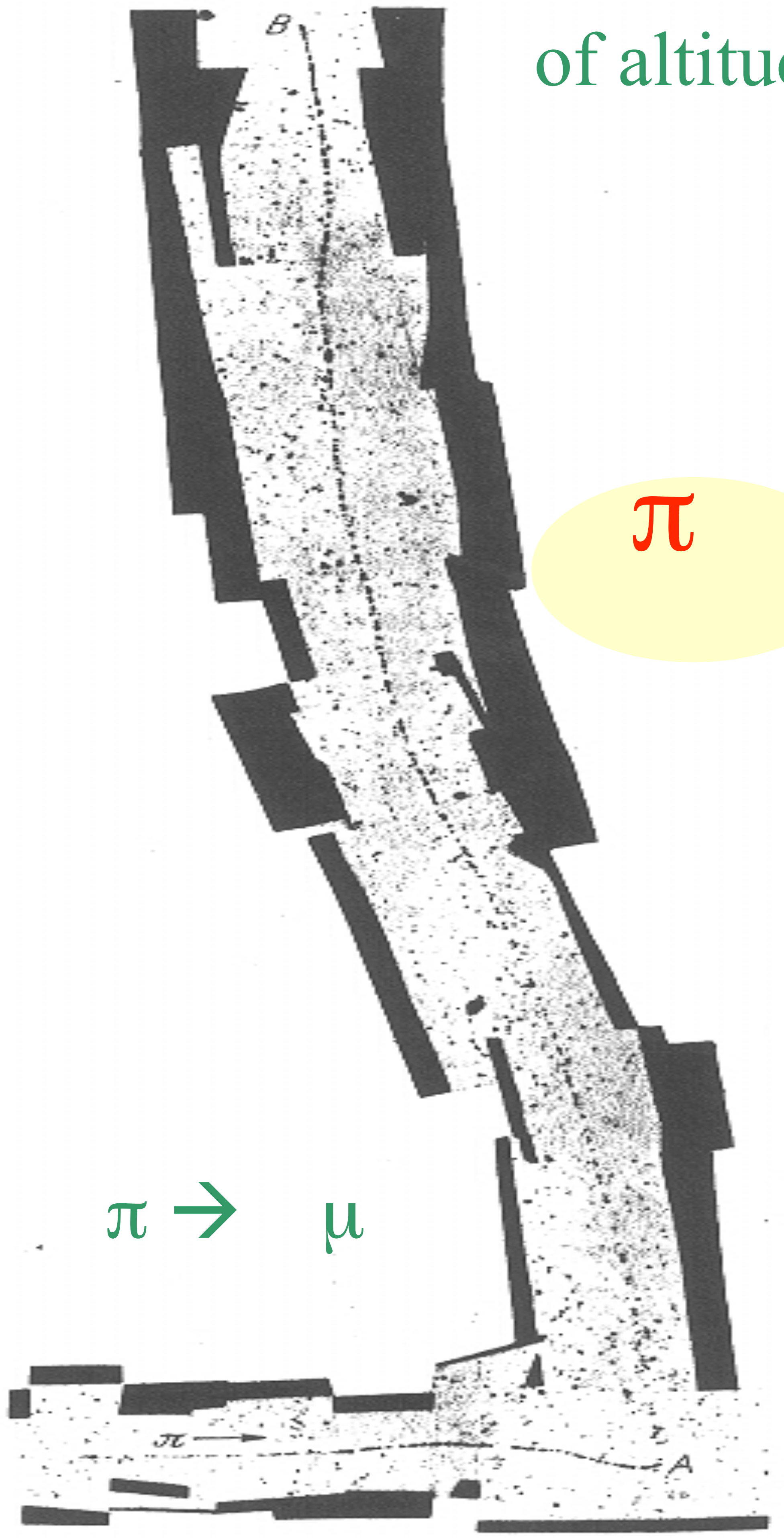

Cosmic ray study on an airplane at about 9km of altitude and at Pic du Midi

600 μm thick emulsion with a new kind of gelatine to register the passage of ionizing particles

Powell used these emulsions to solve the mystery of the Yukawa meson in 1947

Lattes, Muirhead, Occhialini and Powell,
OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS, Nature 159 (1947) 694.

Powell got the Nobel Prize in 1950. The Committee underlined the simplicity of the detector used.

Emulsions in a particle physics experiment

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Used to instrument the target region of experimental apparatus in order to study the properties of the incoming particles and/or the interaction products

Two techniques:

- "Bulk": target fully made of emulsion films (visualizer detector), old fashion
- Emulsion Cloud Chamber (ECC): target made of passive material interleaved with nuclear emulsions acting as trackers with micrometric resolution (vertex detector with additional performance depending on the structure), modern way

Bulk emulsions

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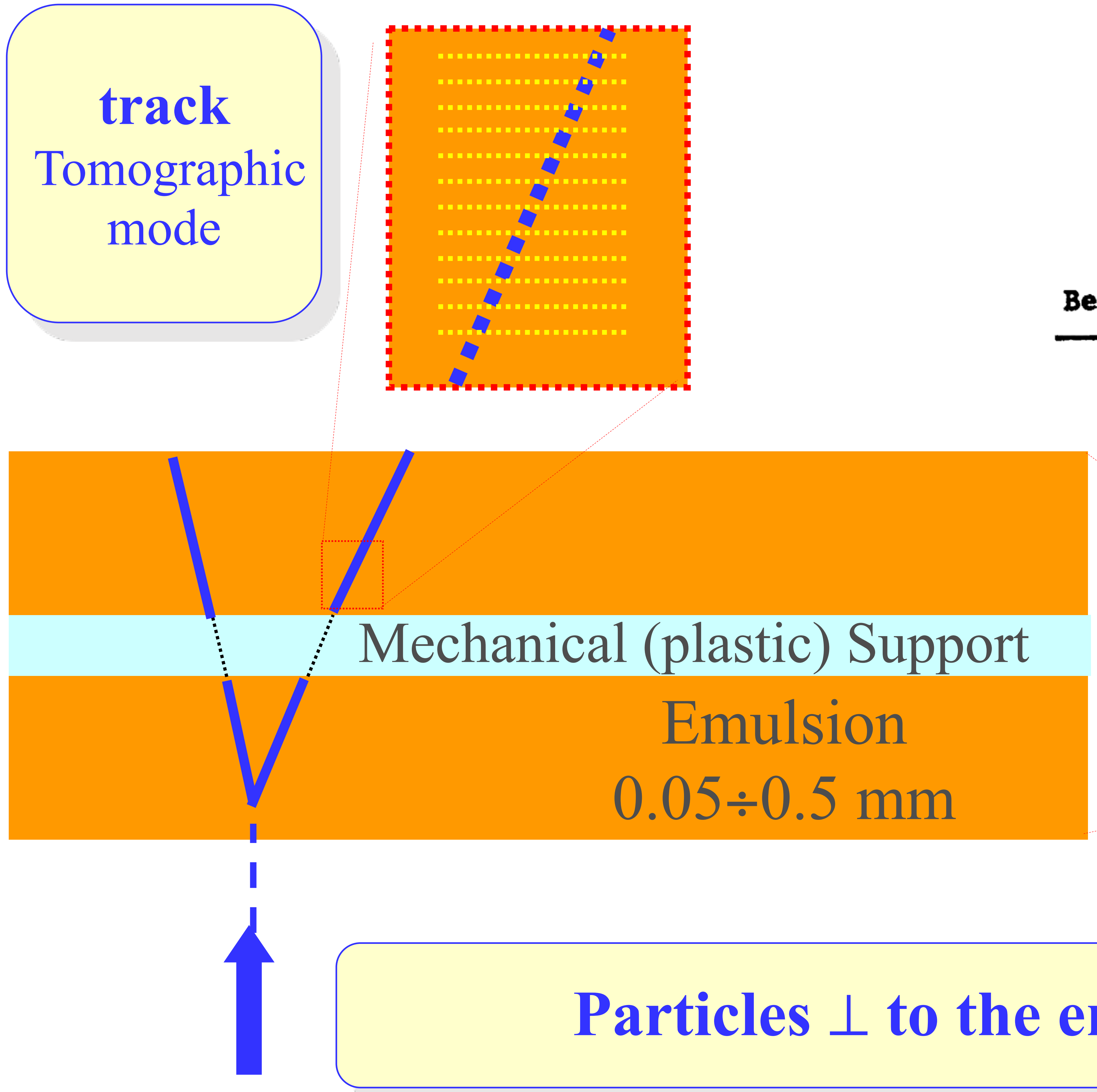
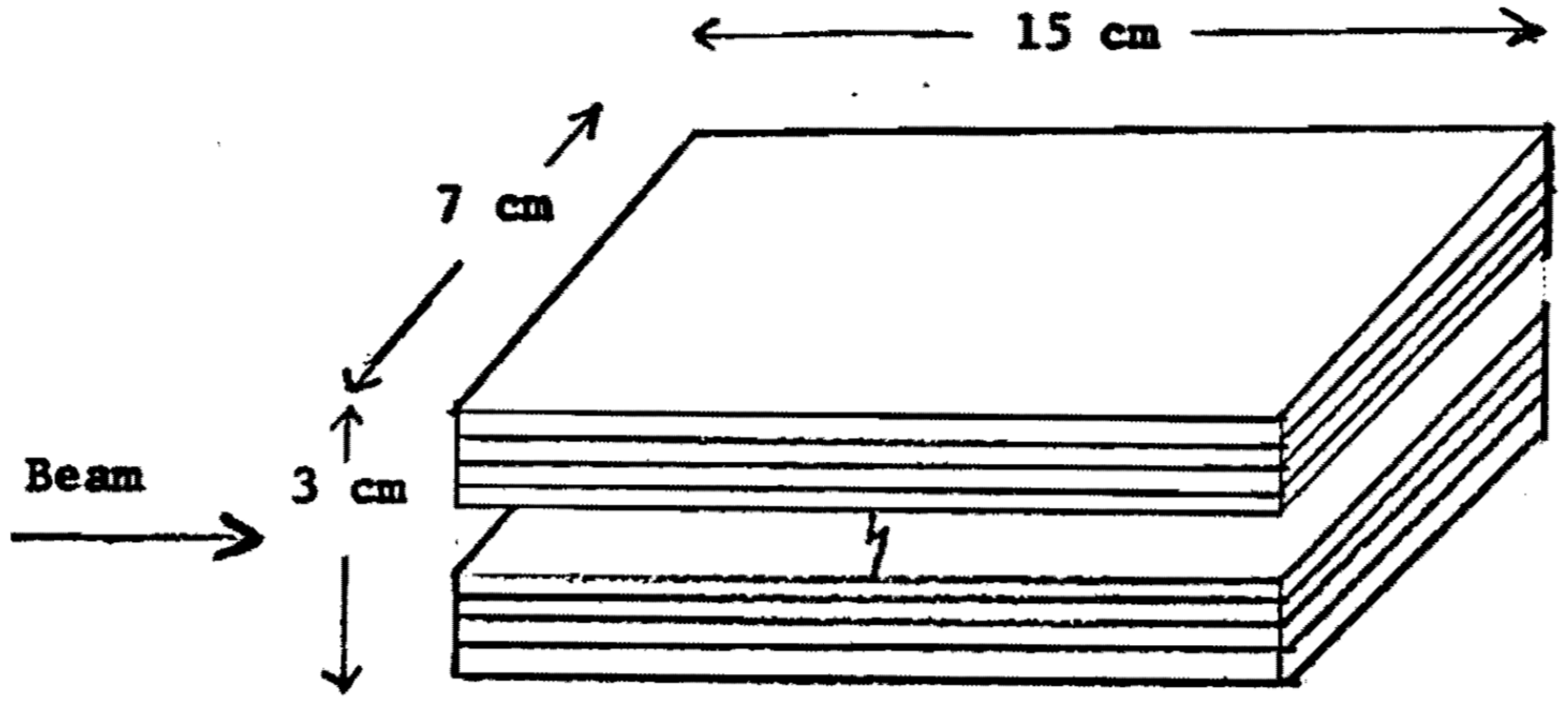
Emulsion films

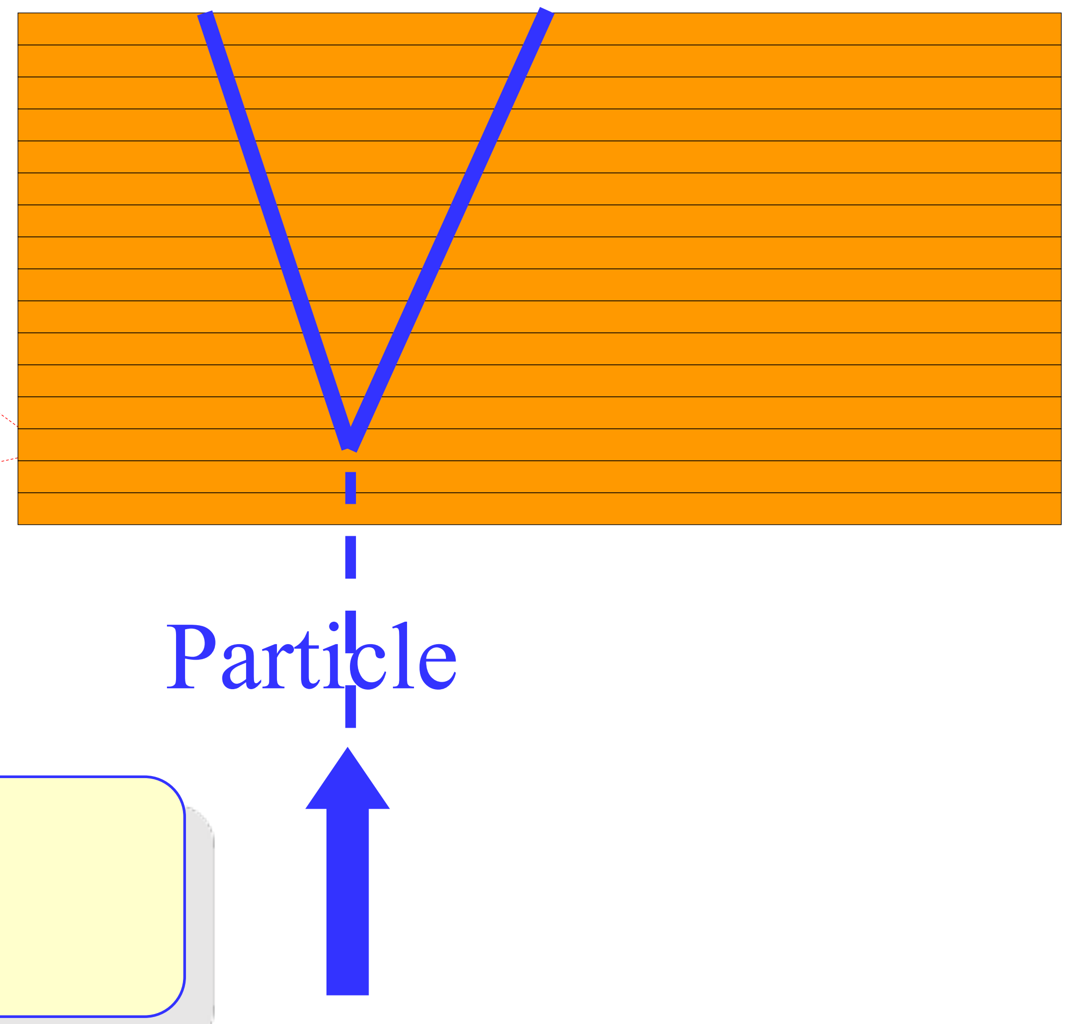


Particles || to the emulsions



FIG? 1

50 Ilford G-5 pellicles, 600 microns thick



Particles ⊥ to the emulsions

Emulsion Cloud Chamber

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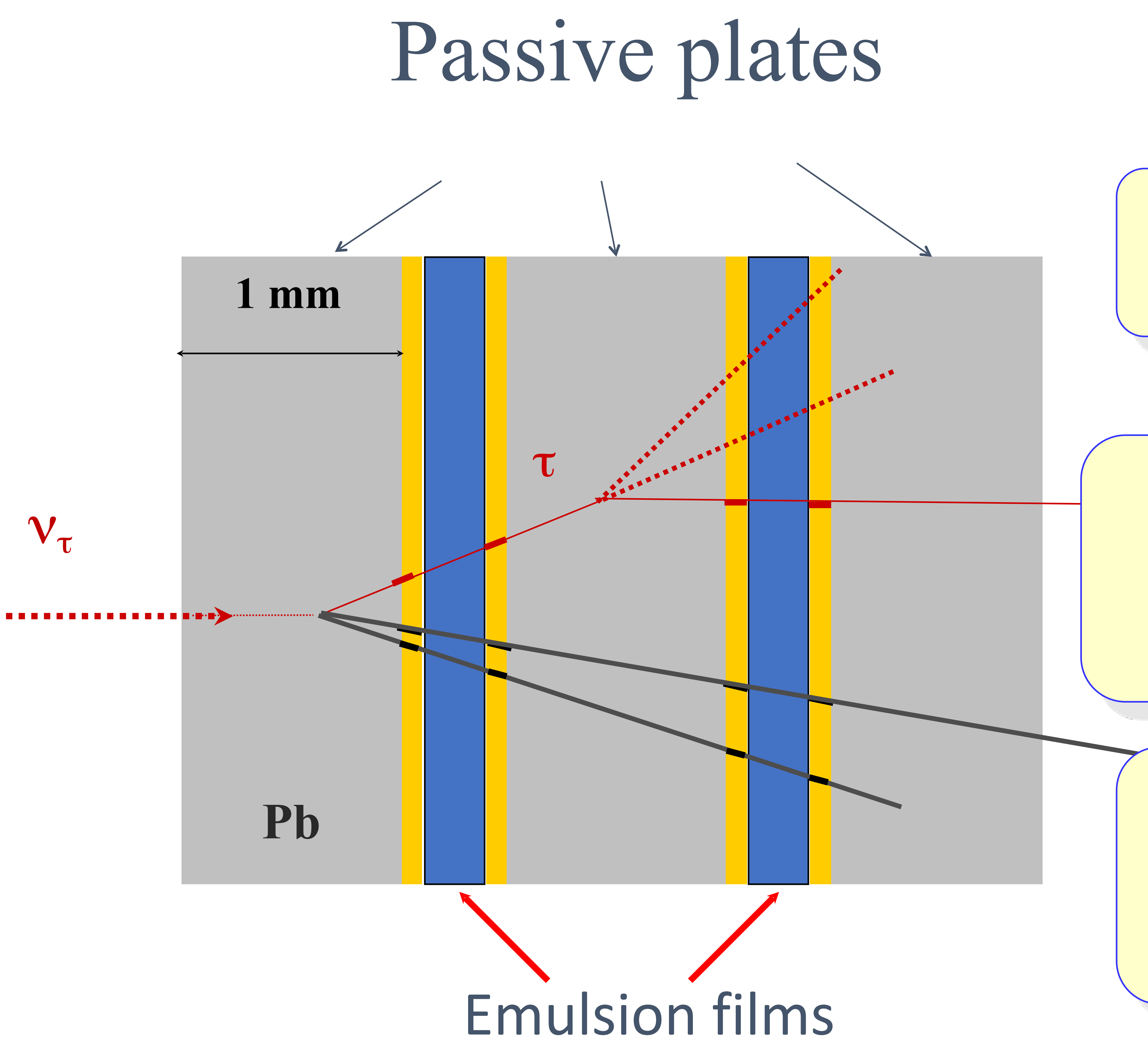

Particles ⊥ to emulsions

Track segments in each film, connected to form long tracks

No visual inspection of the vertex

Comparison of the two approaches

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- “Bulk”: visual inspection at the microscope to distinguish between decays from hadronic interactions (nuclear recoil and/or nuclear evaporation), combined with electronic detectors for time stamp, kinematical measurements and muon identification
- ECC: compact and relatively cheap target with large masses (low fluxes and/or cross-sections), momentum measurement through the detection of the multiple Coulomb scattering in passive materials, e.m. shower identification. Hybrid setup is used to provide the time stamp and to restrict the analysis region, when needed

First observation of "charmed" hadrons

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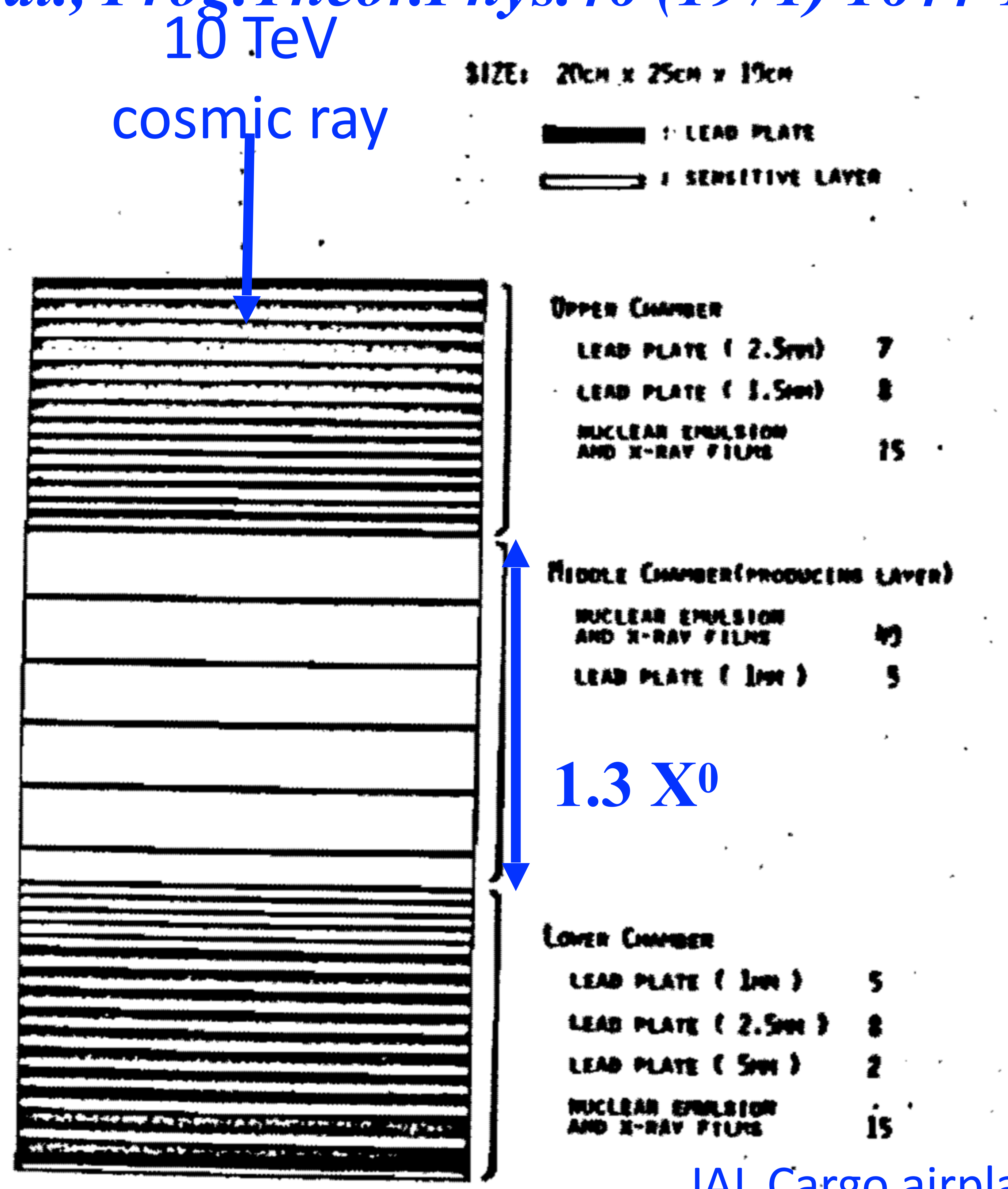
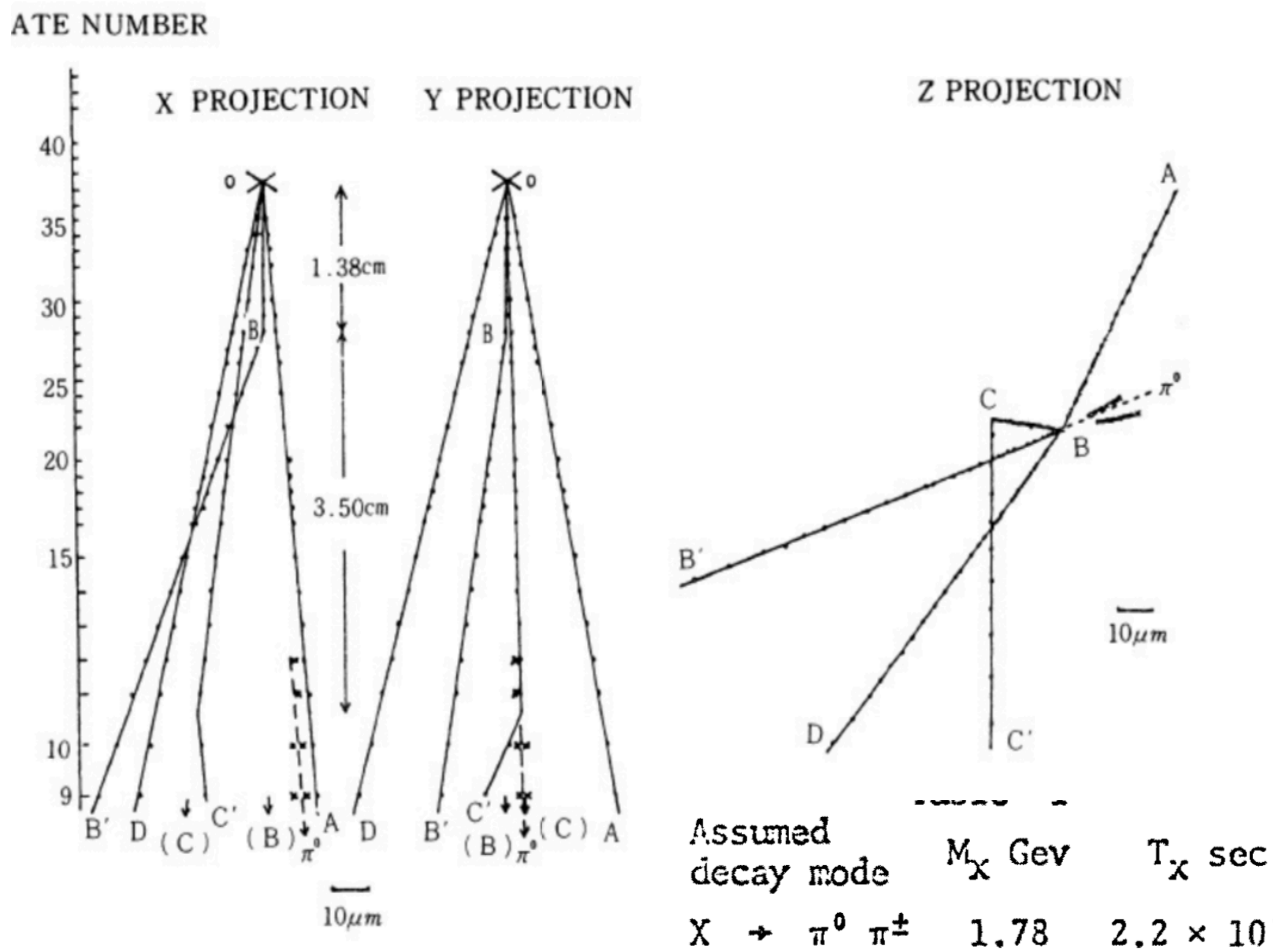
A possible decay in flight of a new type particle
Niu et al., Prog.Theor.Phys.46 (1971) 1644-1646.



3 years earlier!

JAL Cargo airplane
from Aug to Dec 1969
~500 hours



Assumed decay mode	M_X Gev	T_X sec.
$X \to \pi^0 \pi^\pm$	1.78	2.2×10^{-14}
$X \to \pi^0$ p	2.95	3.6×10^{-14}

Discovery of a narrow resonance in e^+e^- annihilation, PRL 33 (1974) 1406-1408

First observation of “beauty” hadron decay

Direct Observation of the decay of Beauty particles into charm particles, PLB 158 (1985) 186, WA75 experiment at CERN

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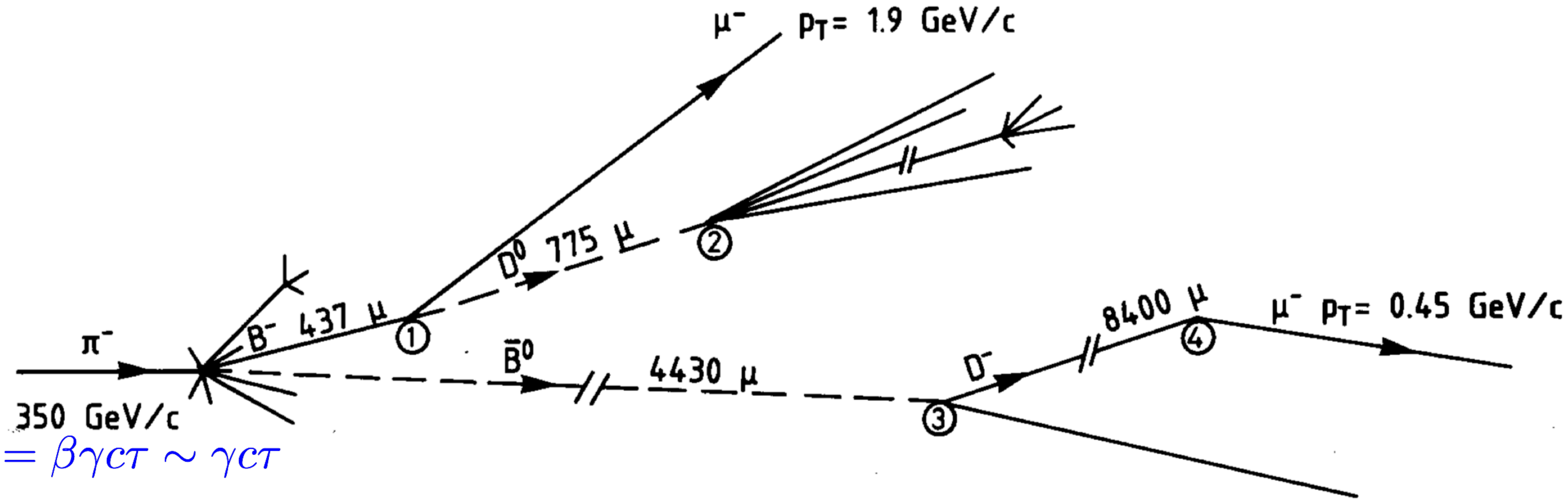
Volume 158B, number 2 PHYSICS LETTERS 8 August 1985



$$L = \beta\gamma c\tau \sim \gamma c\tau$$

$$\gamma \sim \frac{1}{<\vartheta>}$$

Petrera, Romano, NIM 174 (1980) 61

$$c\tau \sim L <\vartheta>$$

Two particles with “beauty” quark content are produced and decay (10^{-12} s) producing “charmed” particles that in turn decay

Diffractive Ds production in CHORUS

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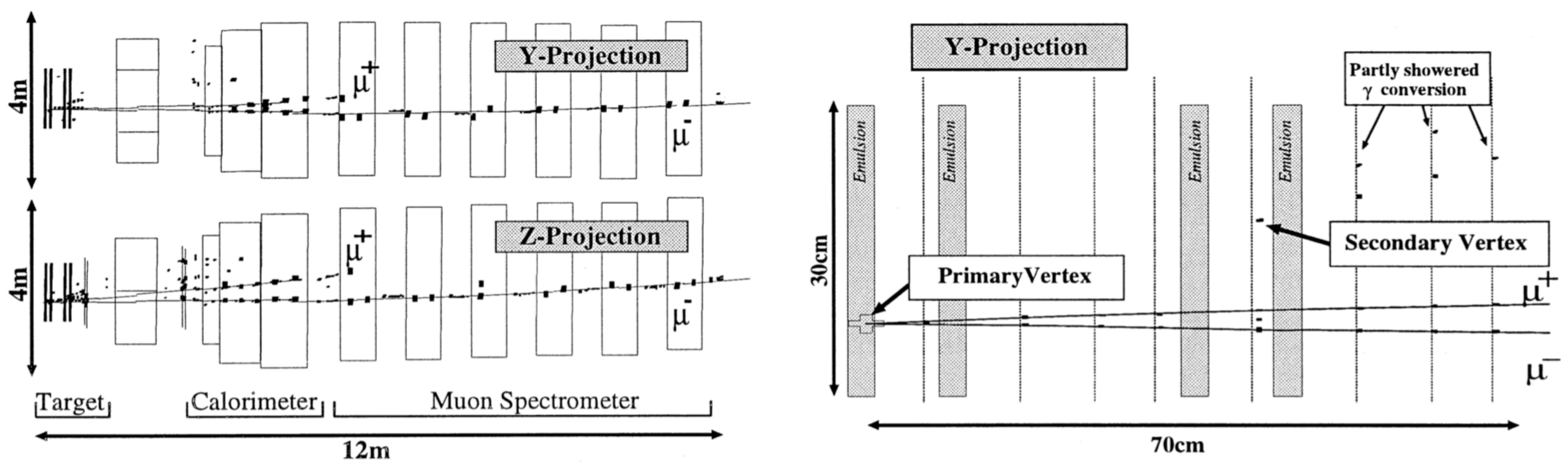
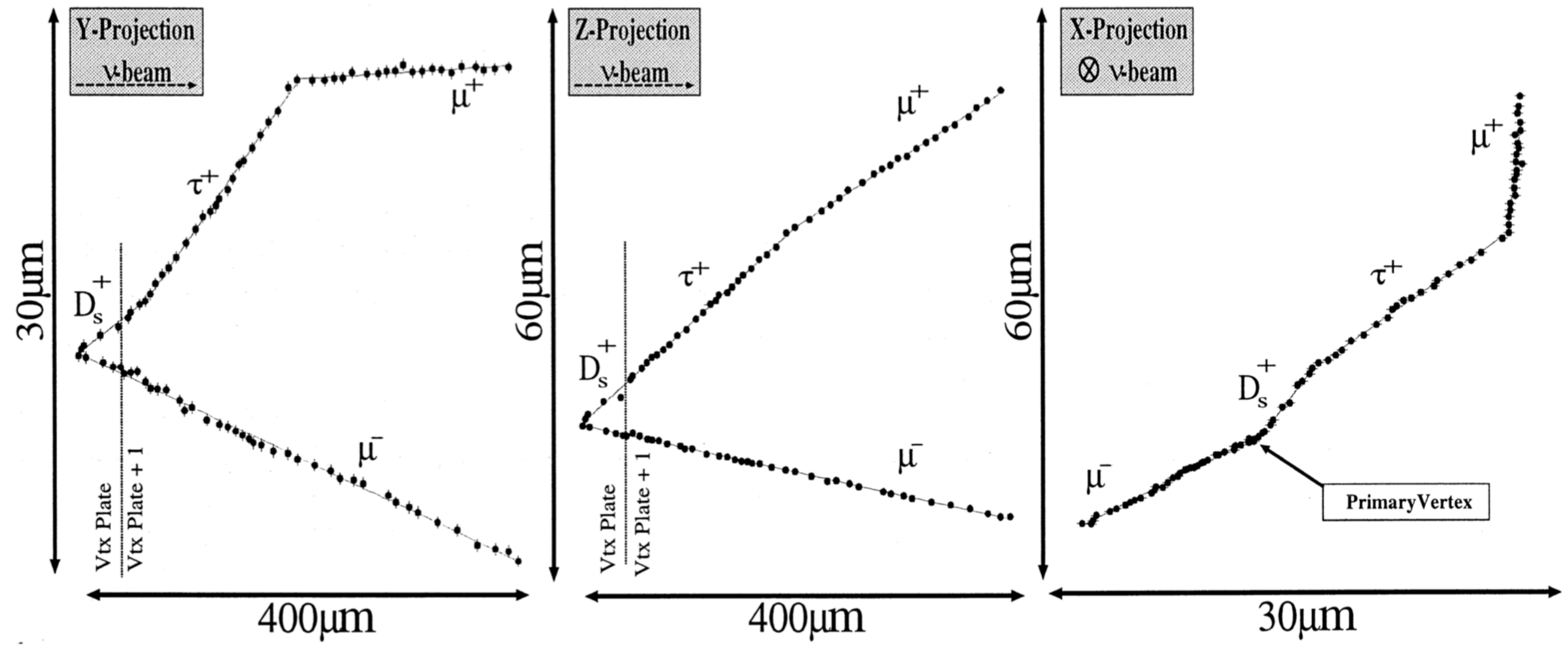
Phys. Lett. B435 (1998) 458, CHORUS experiment at CERN



800 kg emulsion target



$$\nu_\mu\, n \longrightarrow \mu^- D_s^{+*} n$$
$$\quad \hookrightarrow D_s^+ \gamma$$
$$\quad\quad \hookrightarrow \tau^+ \nu_\tau$$
$$\quad\quad\quad \hookrightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$

First observation of the associated charm production in neutrino CC interactions

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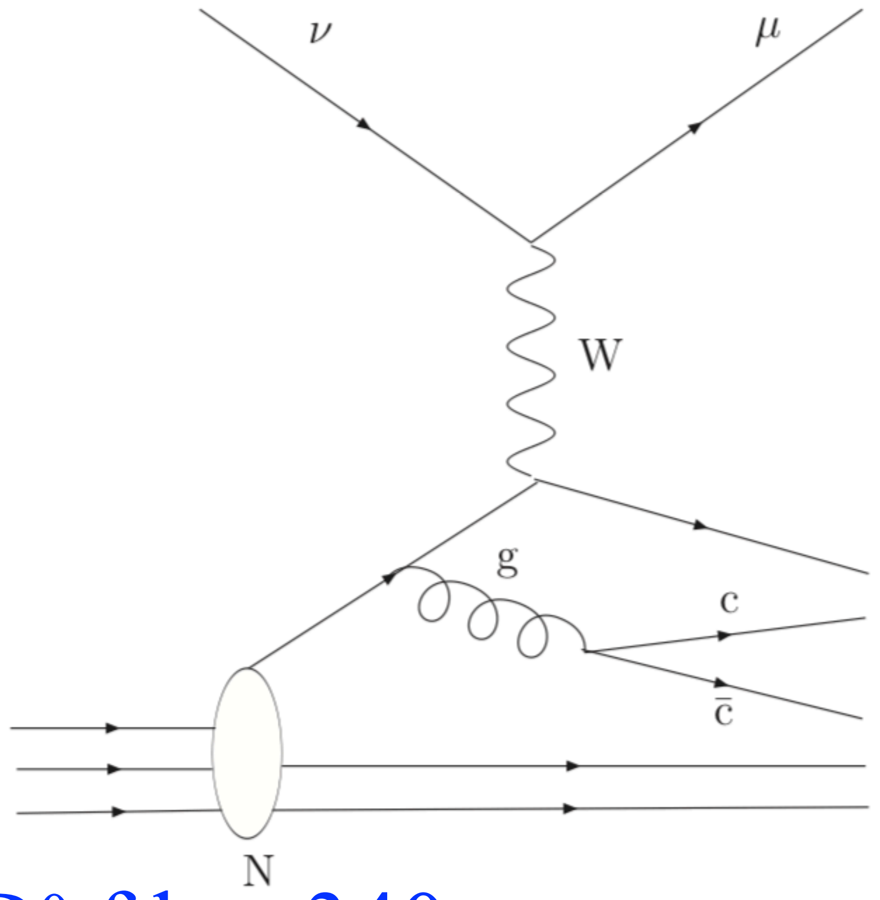
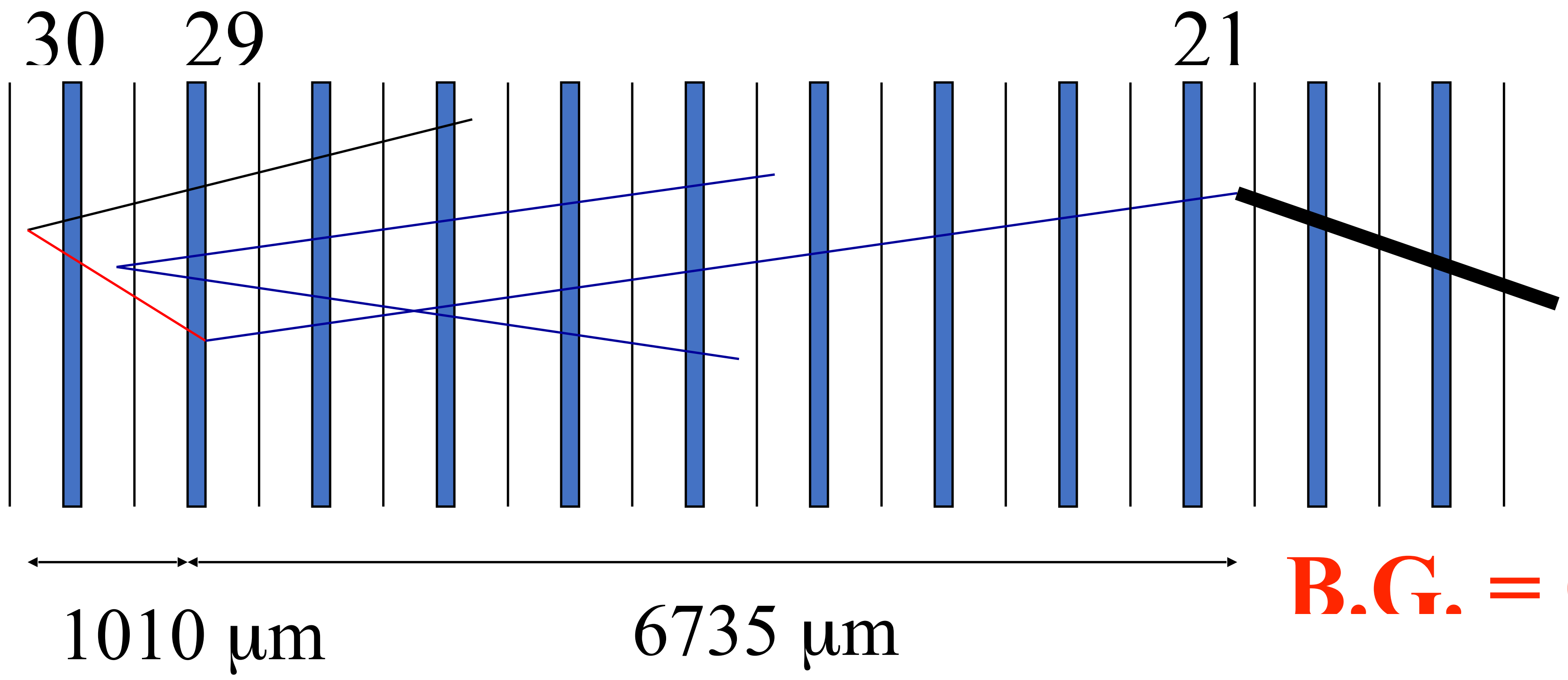
Phys. Lett B 539 (2002) 188, CHORUS Experiment at CERN





$N_s = 2$

$N_h = 6$

B.G. = 0.04±0.01

D^0 f.l. = 340 μm

1st vertex

ϑ_{kink} = 420 mrad

f.l. = 1010 μm

2ry vertex

ϑ_2 = 310 mrad

f.l. = 7560 μm

$p\beta = 500^{+180}_{-110}$ MeV/c

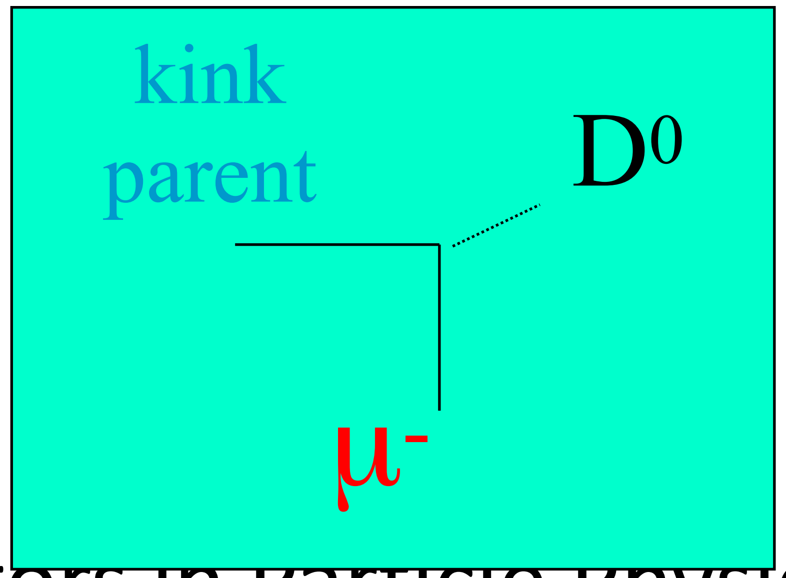
dE/dx → proton

P = 0.78 GeV/c

$P_\perp >$ **330 MeV/c**

List of particles measured at primary and secondary vertices

Particle ID	θ_Y (rad)	θ_Z (rad)	$\tau = L\langle\theta\rangle/c$
μ^-	0.009	0.104	
C^0	−0.047	−0.055	2.8×10^{-13} s
Particle 1	−0.102	0.020	1.4×10^{-12} s
C^0 daughter	0.267	0.188	
C^0 daughter	−0.139	−0.054	
Particle 2	−0.495	−0.120	



transverse plane

QUIZ - 1

- Electronic detectors and their readout electronics have a typical time window where they record an event. What is the typical time window for an emulsion detector?

- List differences between “bulk” and ECC approaches in the emulsion technology

- List main advantages and drawbacks of the emulsion technology compared to other detectors and in particular to other tracking devices