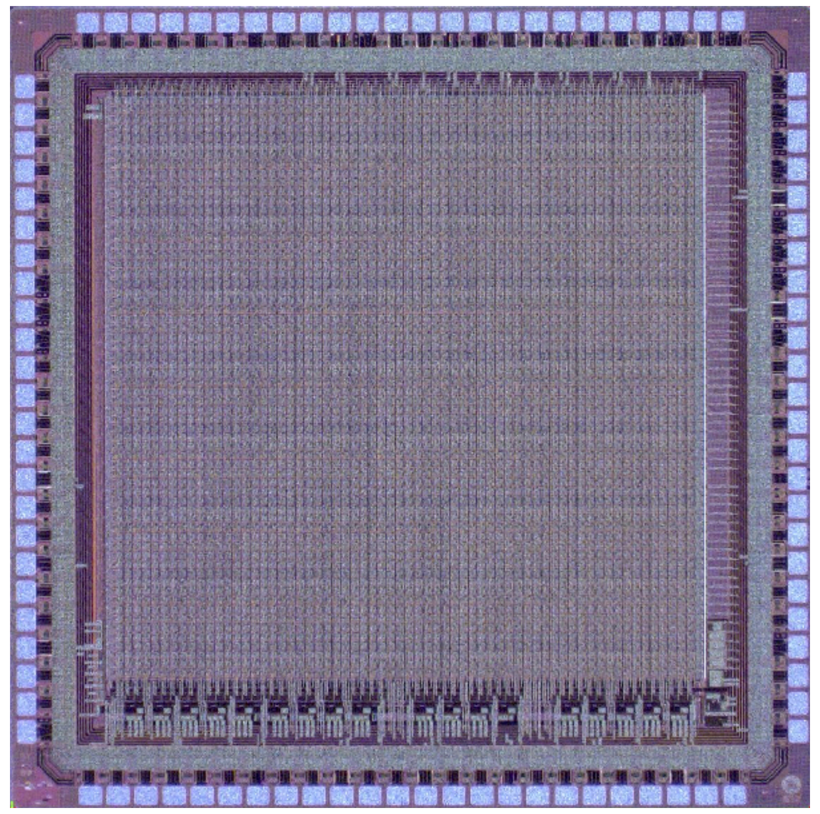
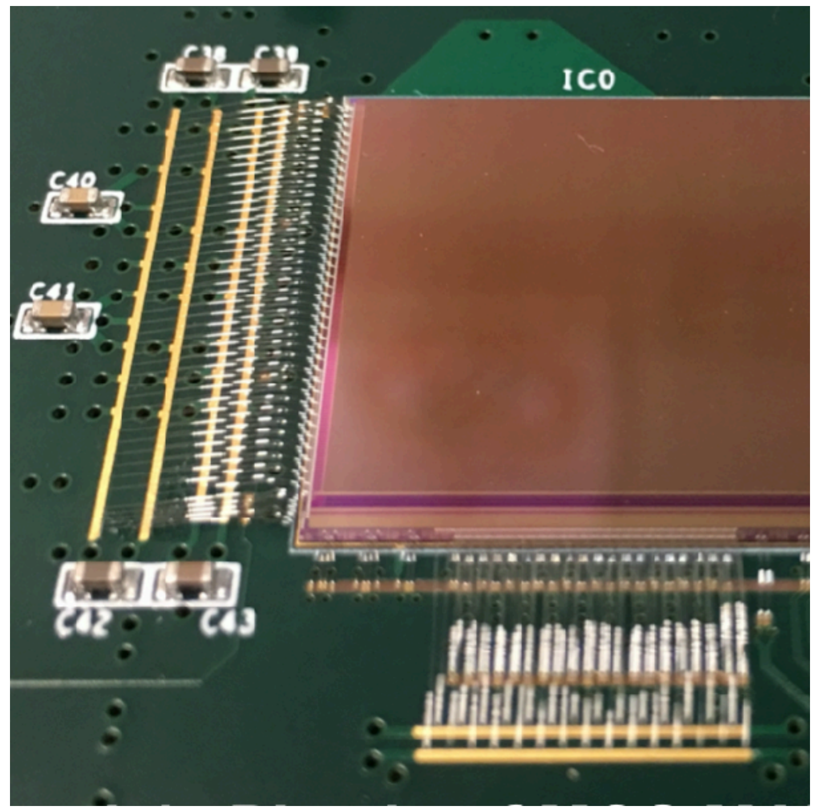
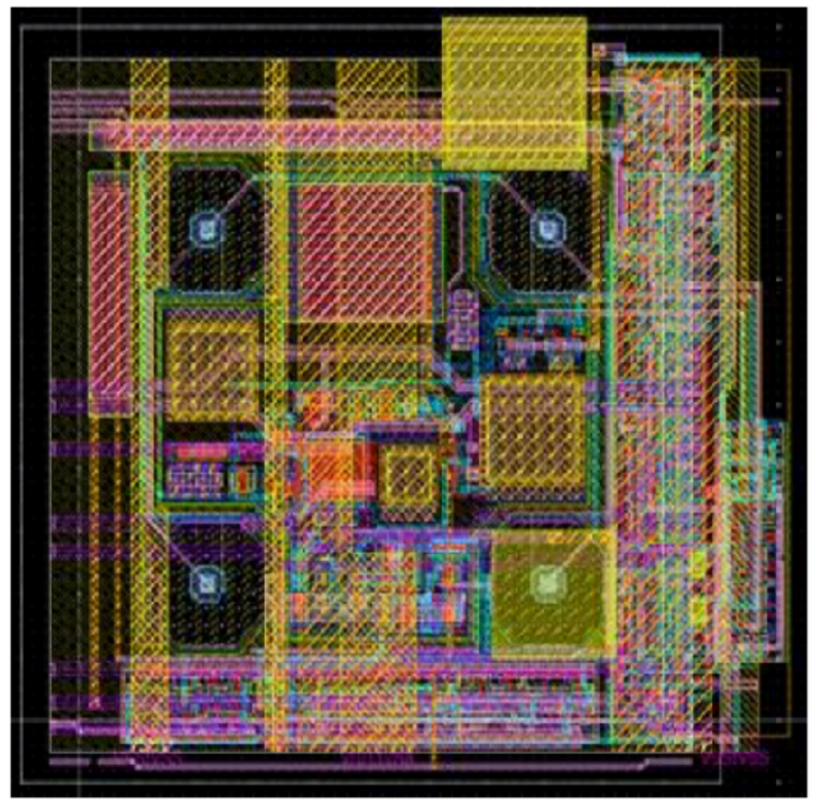
Detectors

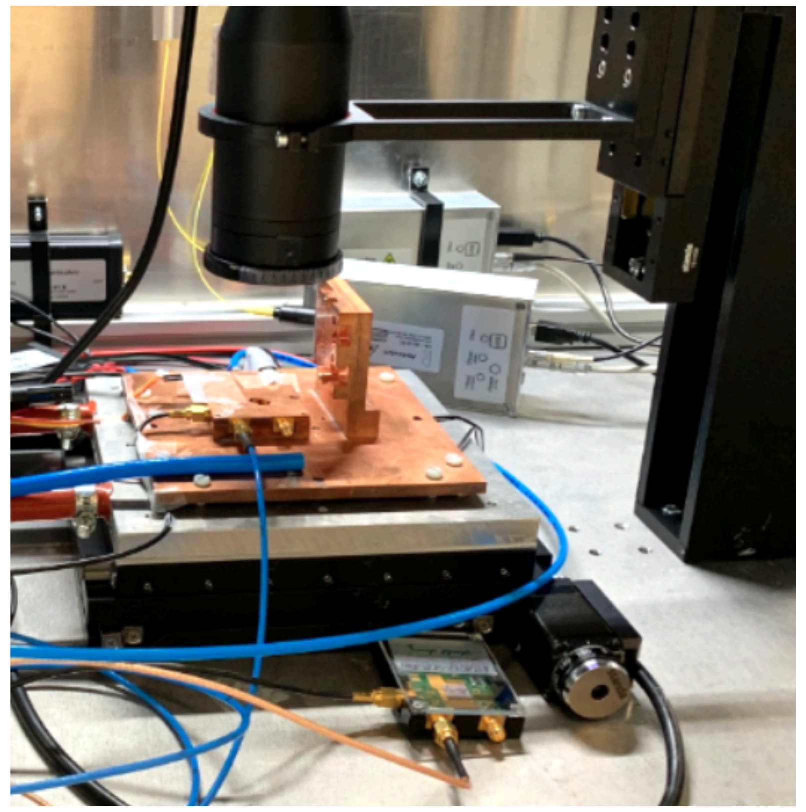
Particle Detectors for Particle and Astroparticle Experiments

Prof. Dr. Steven Worm

July 28-29, 2025

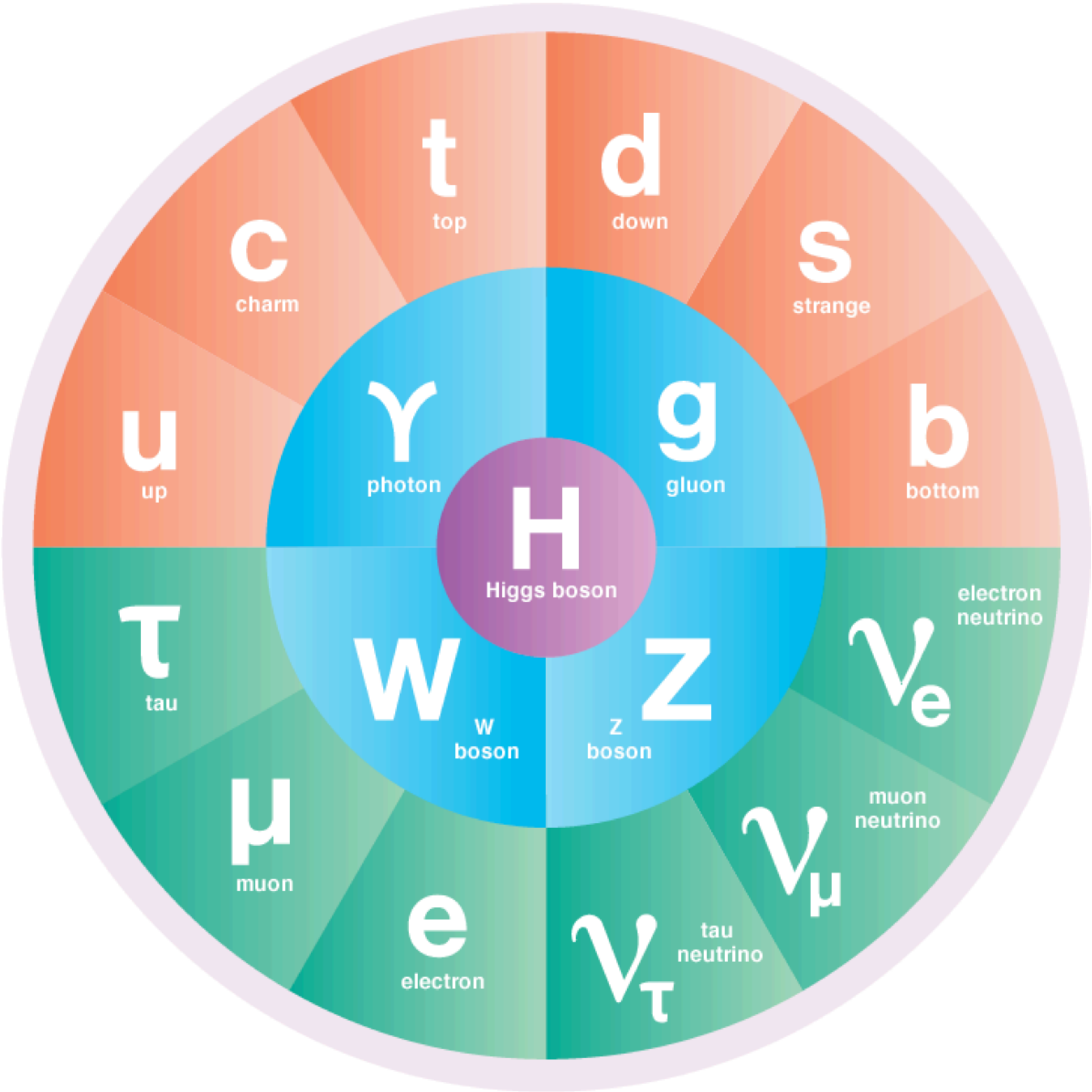


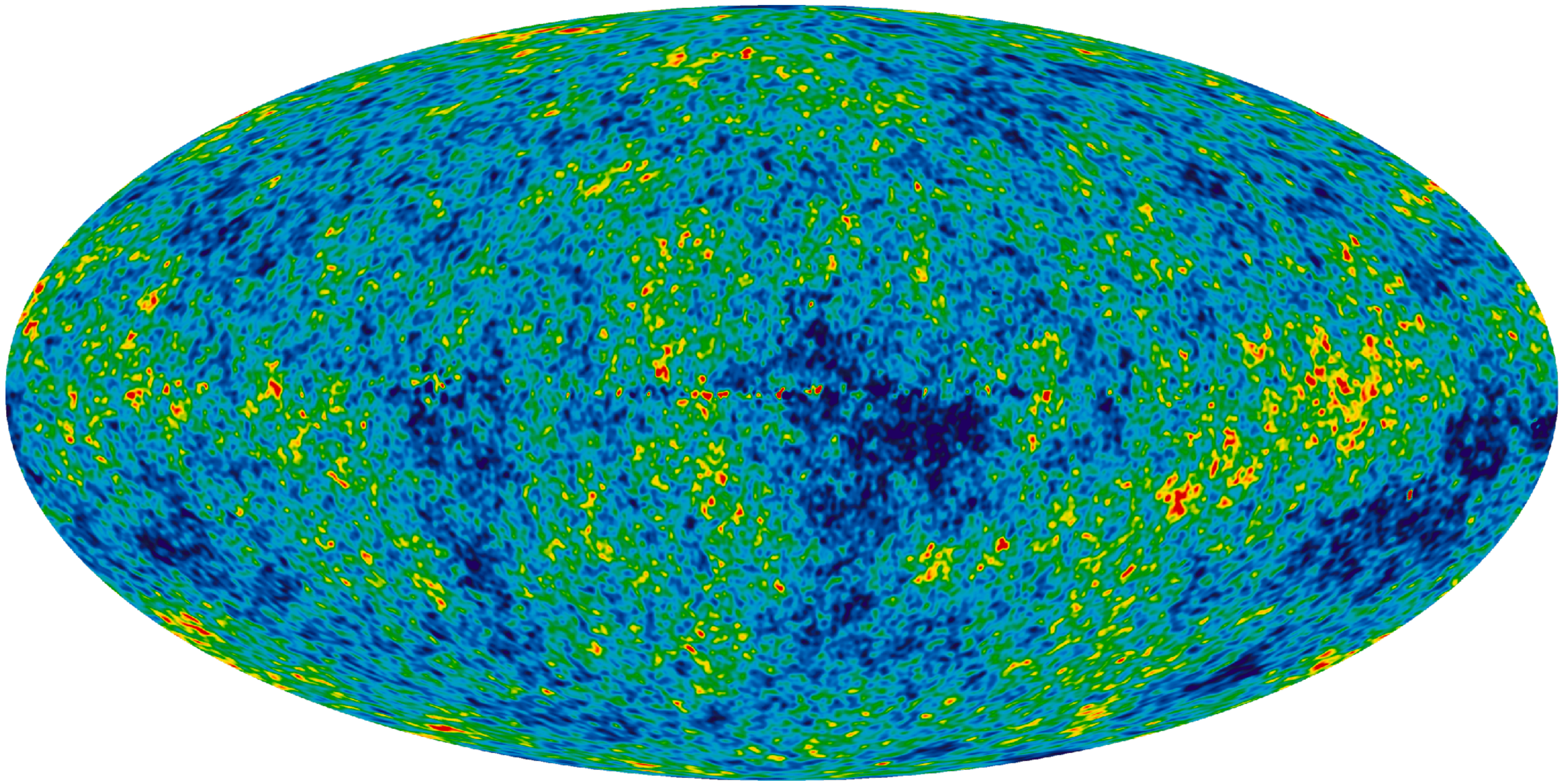



Detector Lecture Overview

- Detectors and their place in science
- Particle Interactions With Matter
- Particle Detector Examples
  - Gas Detectors / Wire Chambers
  - Semiconductor Detectors
  - Scintillators / Photodetectors
  - Calorimeter
  - Cherenkov / Transition Radiation
- Signal Processing / Systems / Triggering
- Quantum Sensing
- Modern Detector Examples (and Problems)

Standard Models of Particles and Cosmology





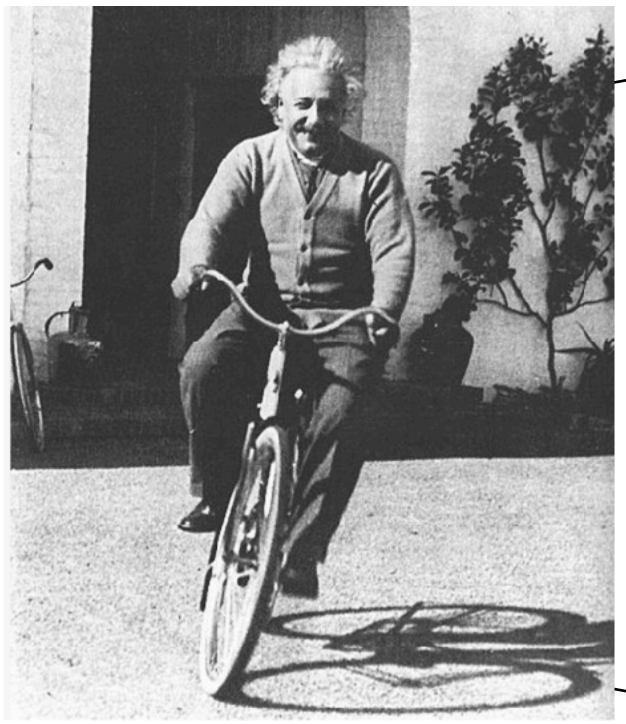
Particle Standard Model

- Fundamental particles
- Forces, interactions

Cosmological Standard Model (ΛCDM)

- Cosmic microwave background
- Structure of galaxies, amount of H, He, Li
- Accelerating expansion of the universe

Advancements in Particle & Astroparticle Physics

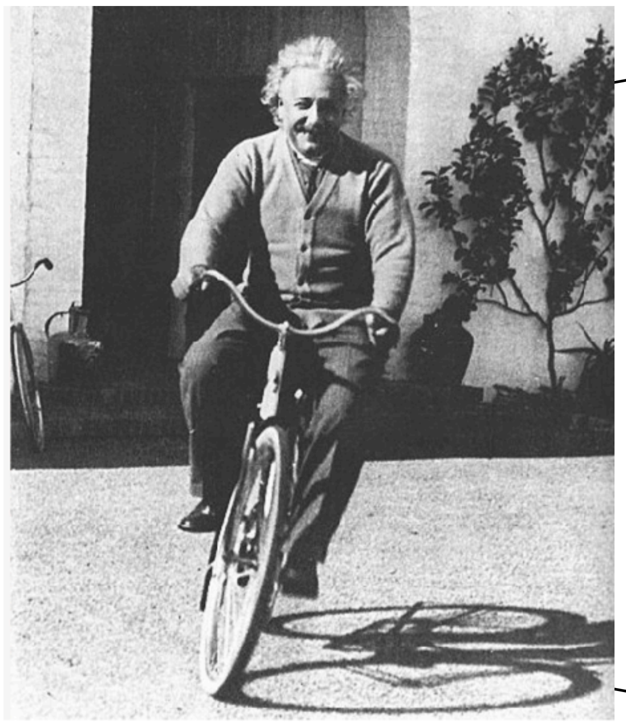


Theoretical Insight

Interplay of theory and experiment is essential

Better Understanding of the World

Advancements in Particle & Astroparticle Physics



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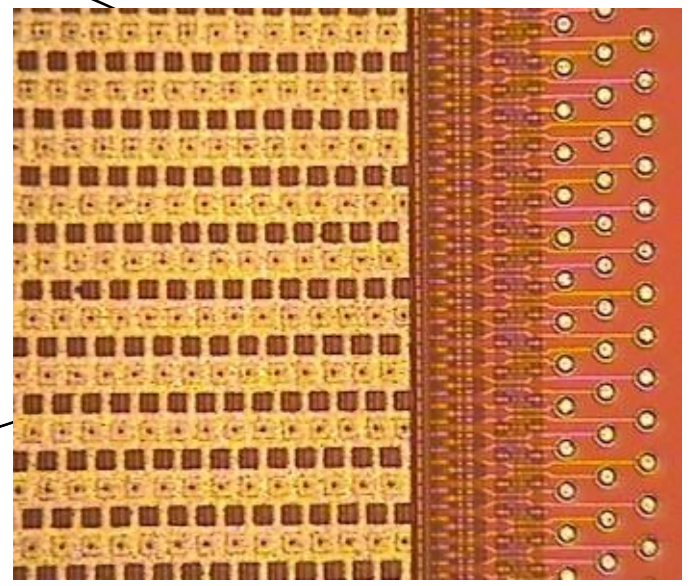
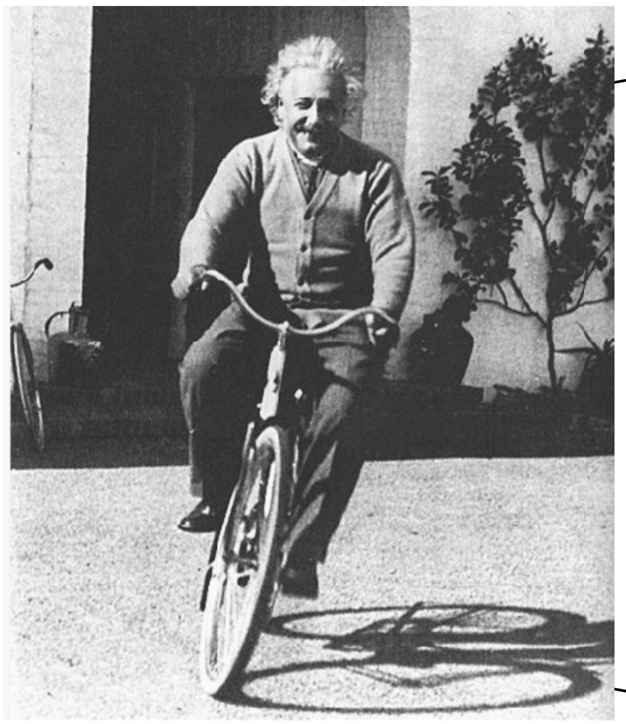
Better Understanding of the World

New Detector Technology
With new developments come new capabilities



Advancements in Particle & Astroparticle Physics



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Accelerator Advances
With accelerators we can create and study new interactions

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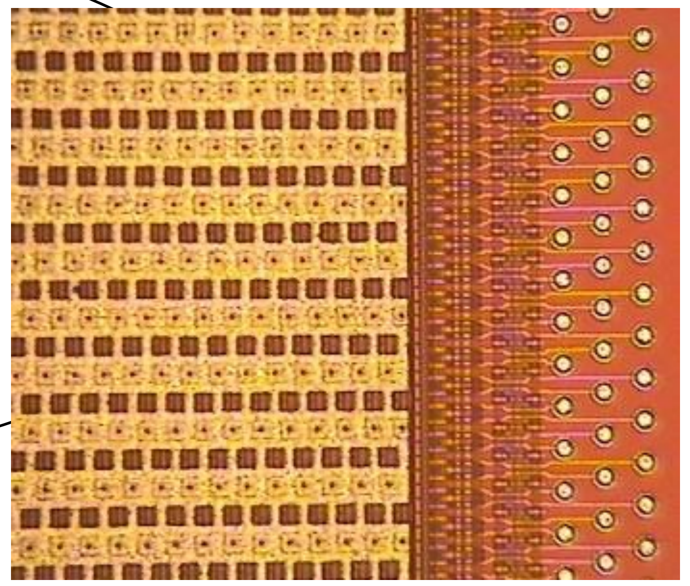
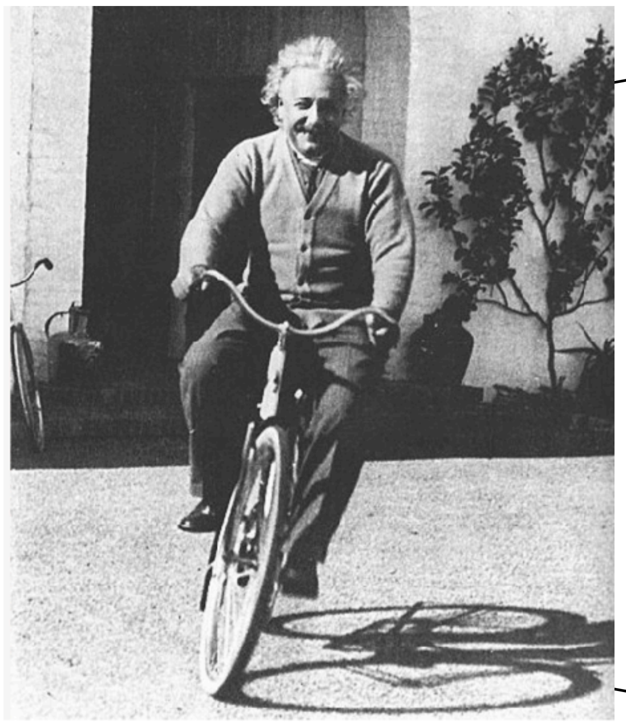


Advancements in Particle & Astroparticle Physics



Theoretical Insight
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Accelerator Advances
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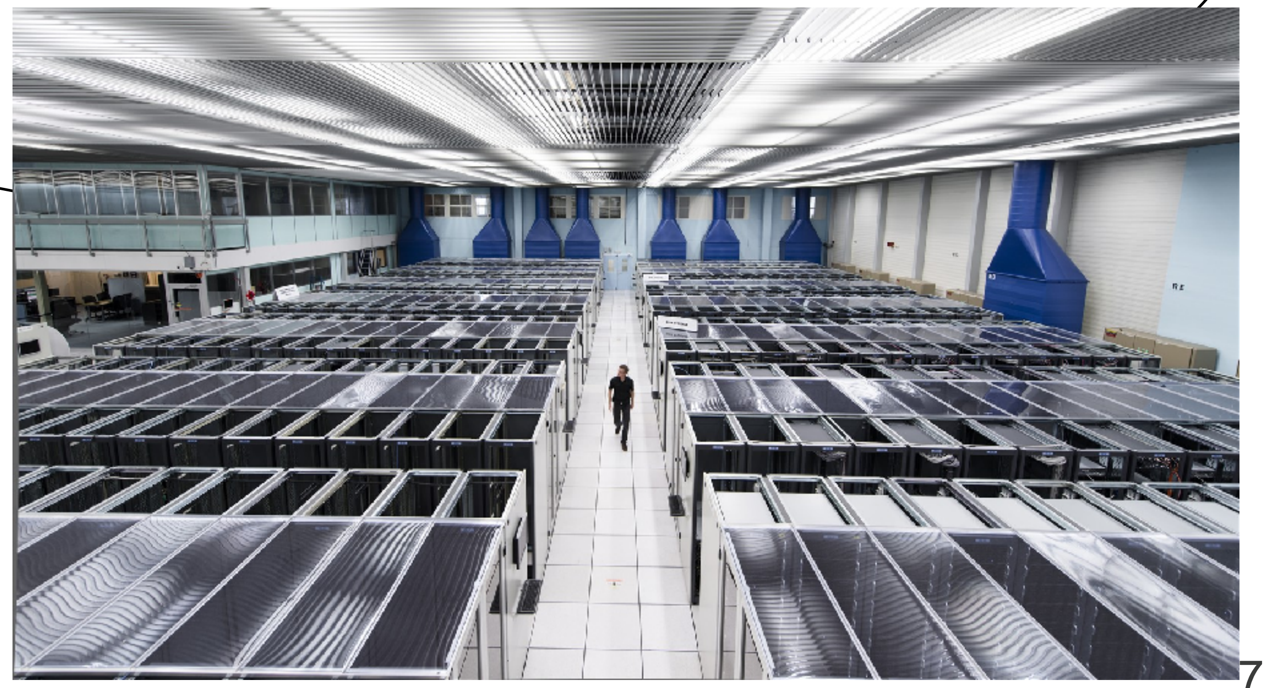
Better Understanding of the World

Computing Advances
Big Data, Machine Learning, Artificial Intelligence…



New Detector Technology
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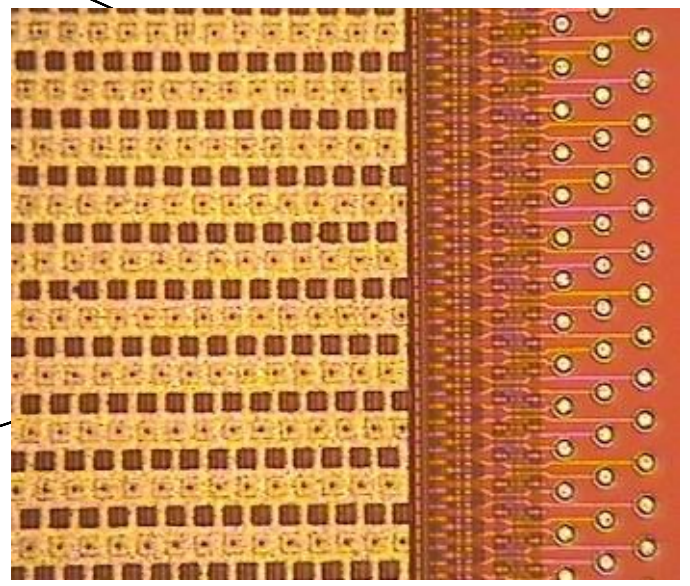
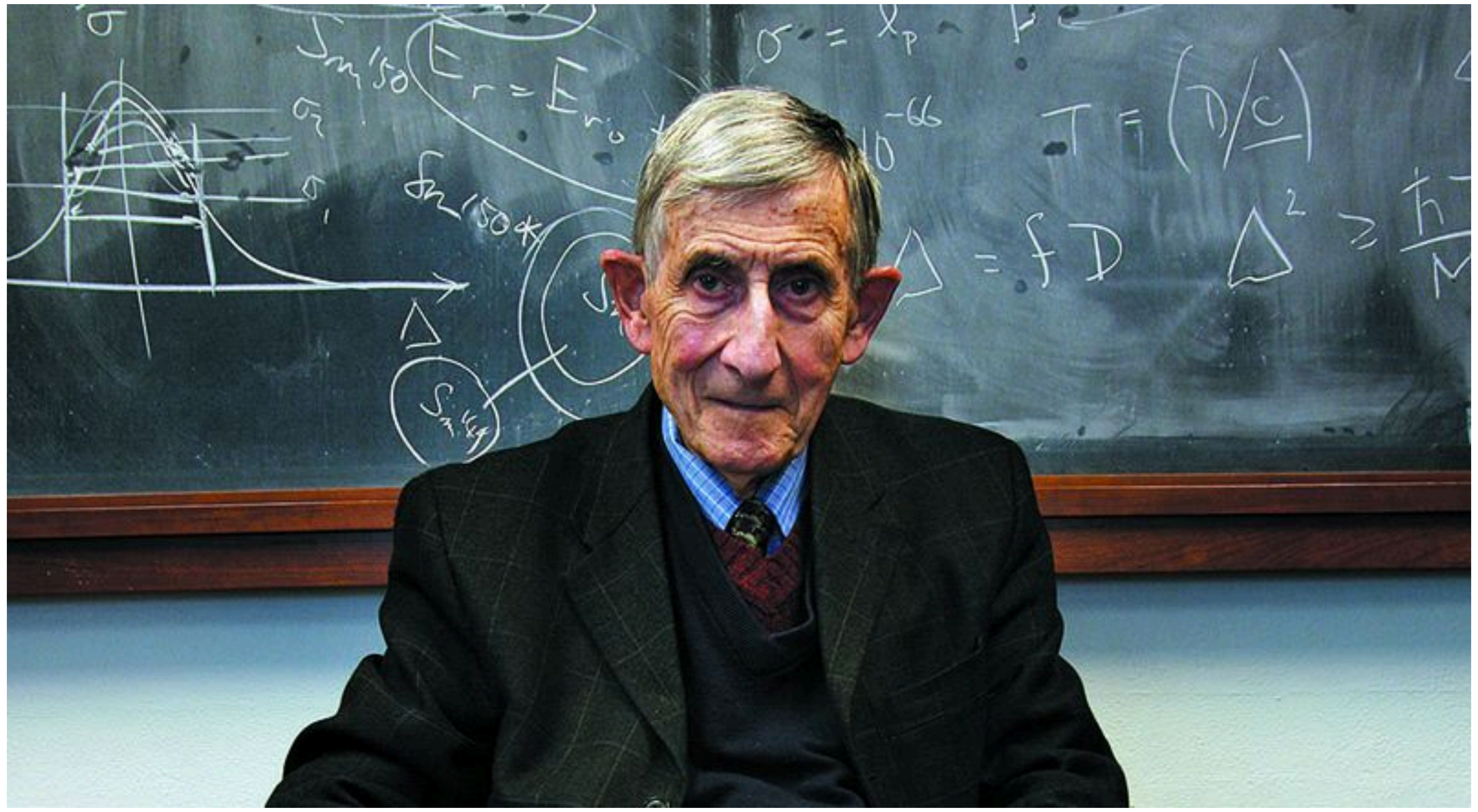




“New directions in science are launched by new tools much more often than by new concepts.

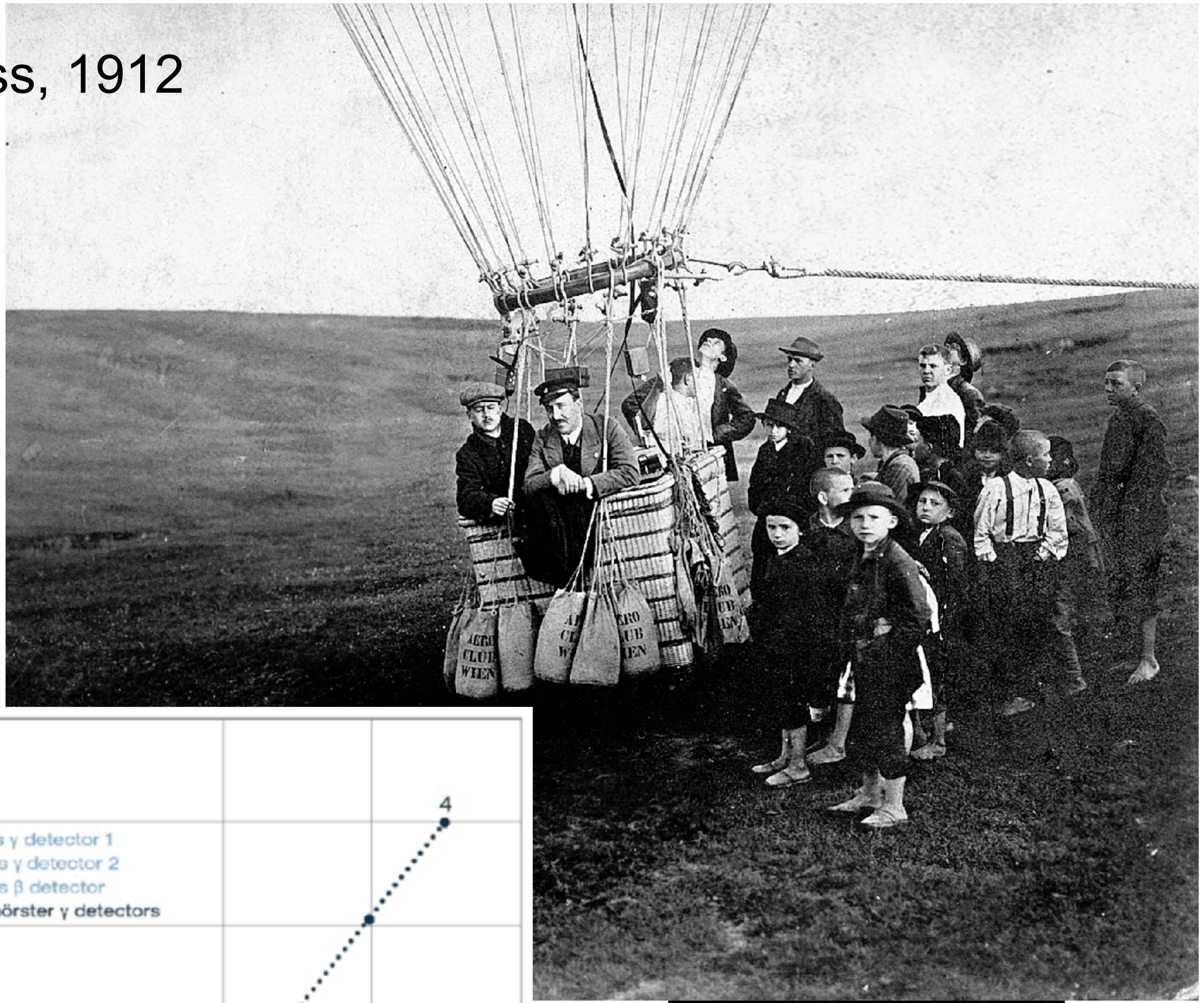
The effect of a concept-driven revolution is to explain old things in new ways.

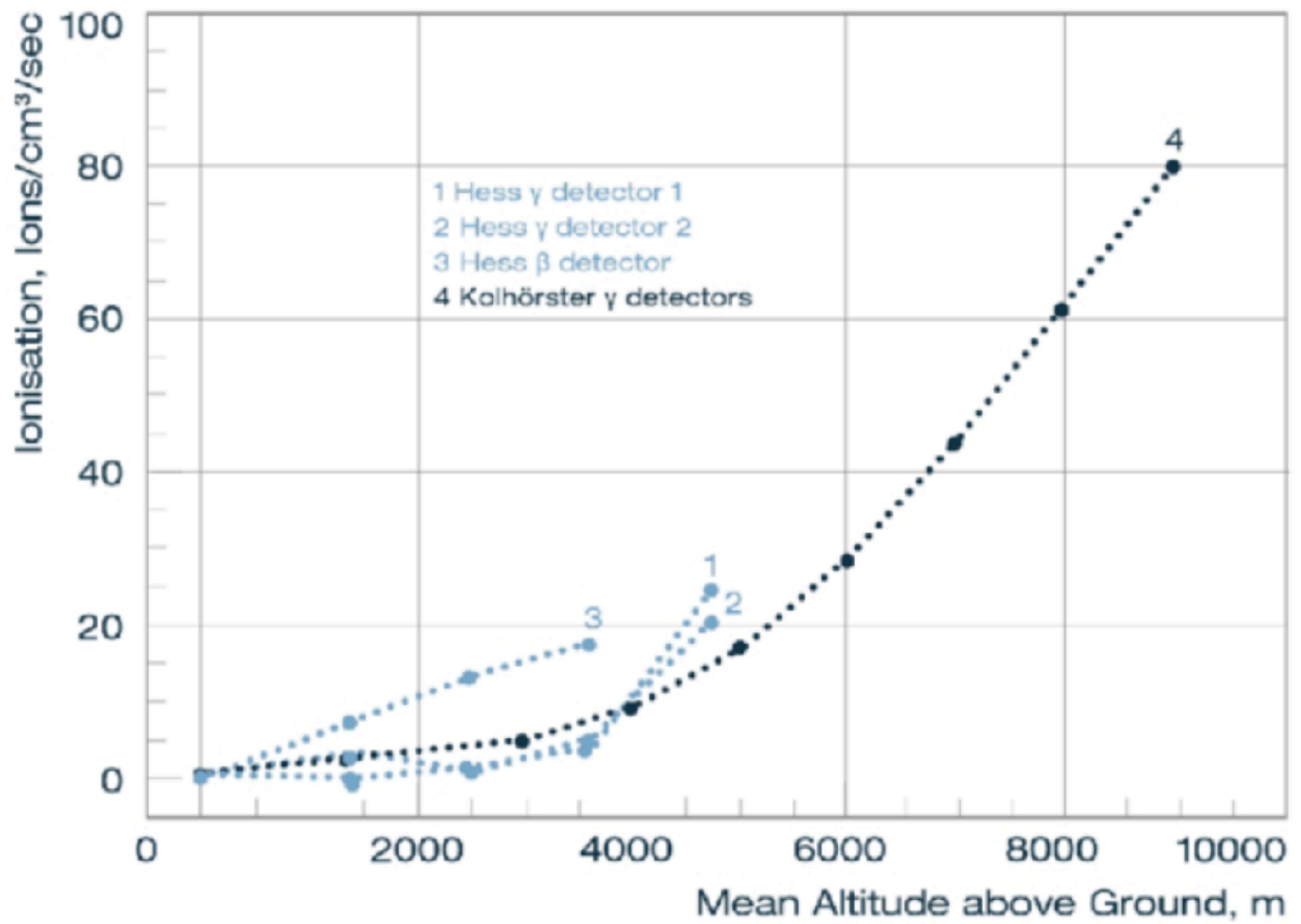
The effect of a tool-driven revolution is to discover new things that have to be explained”

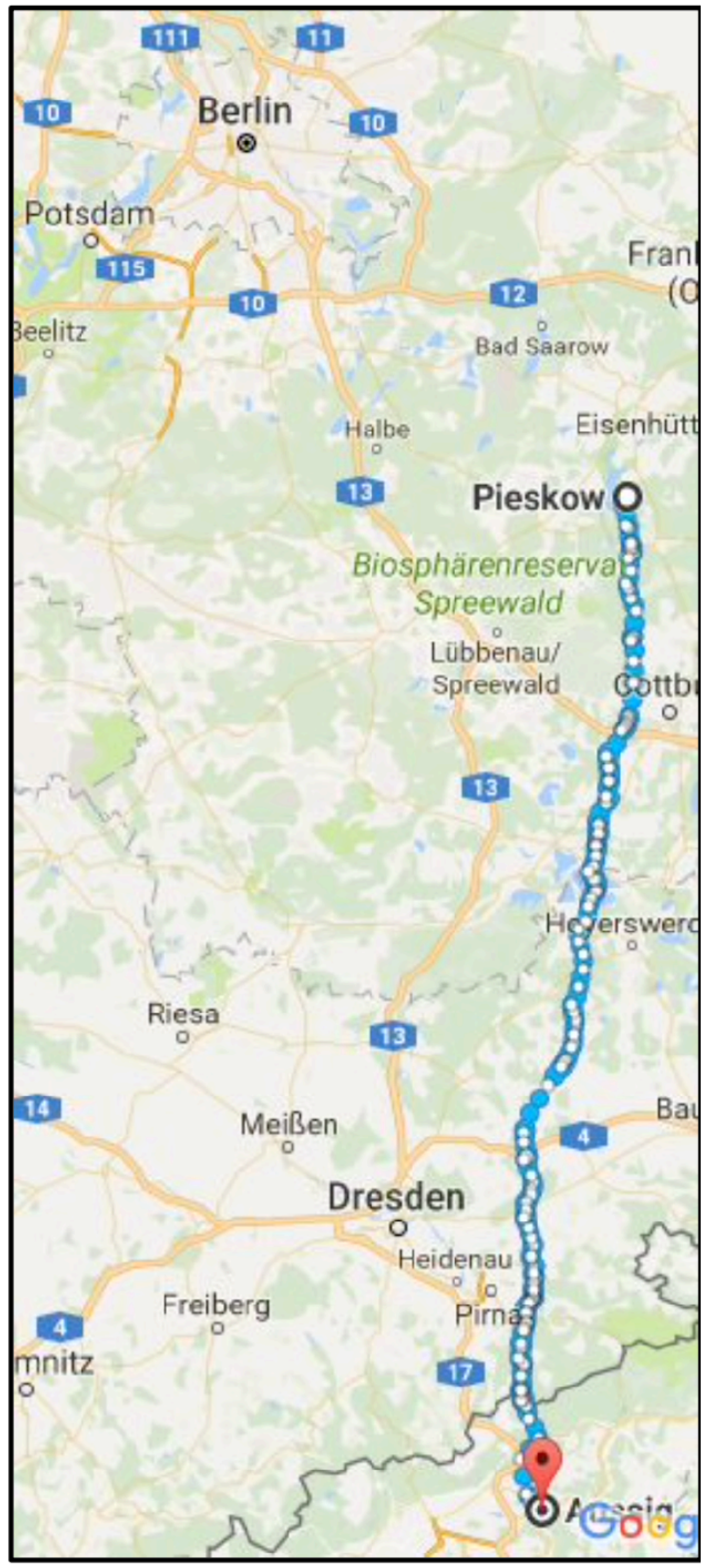
—*Freeman Dyson ‘Imagined Worlds’*

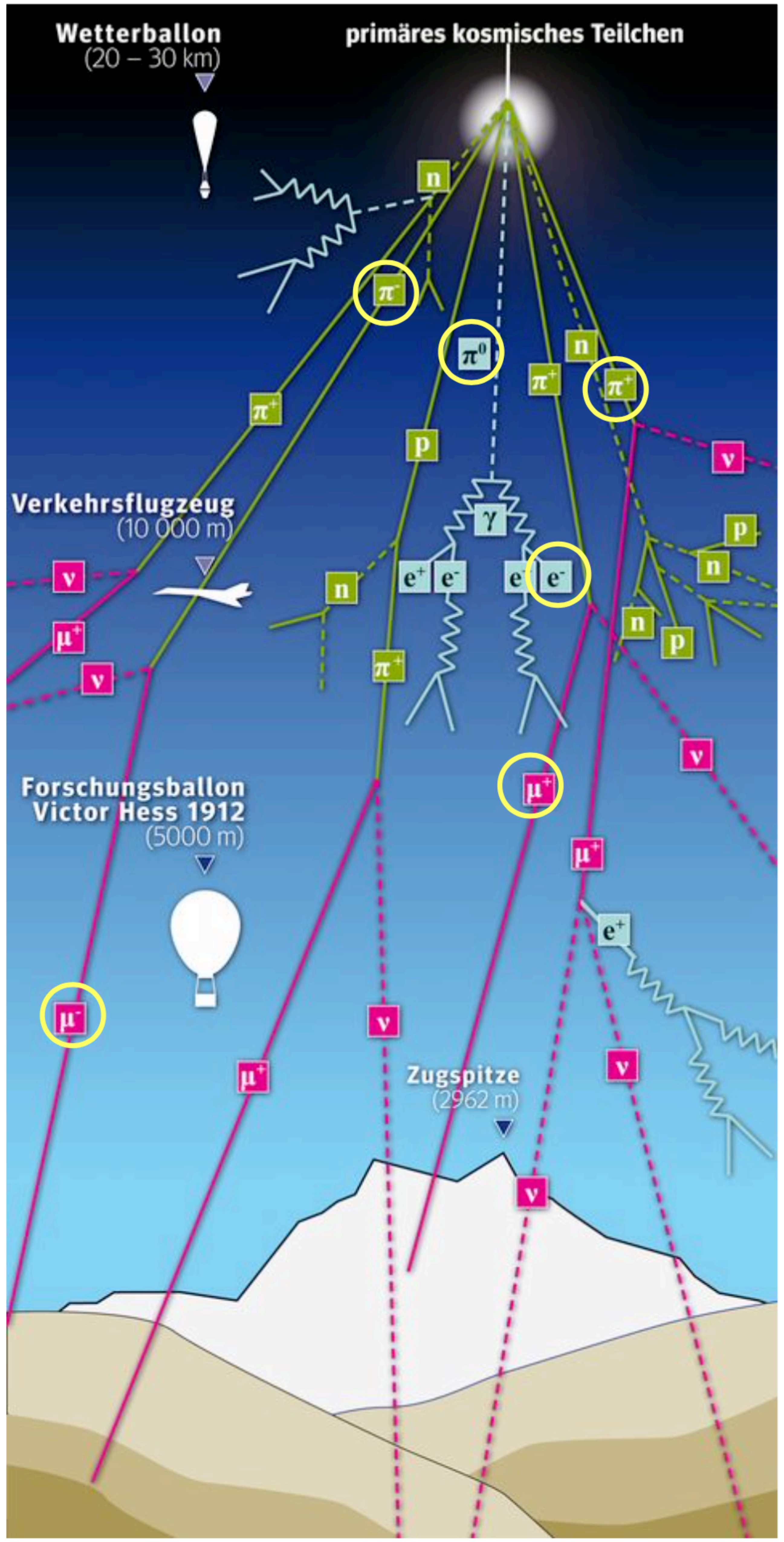
Discovery of Cosmic Rays

- Victor Hess, 1912









The “Particle Zoo”

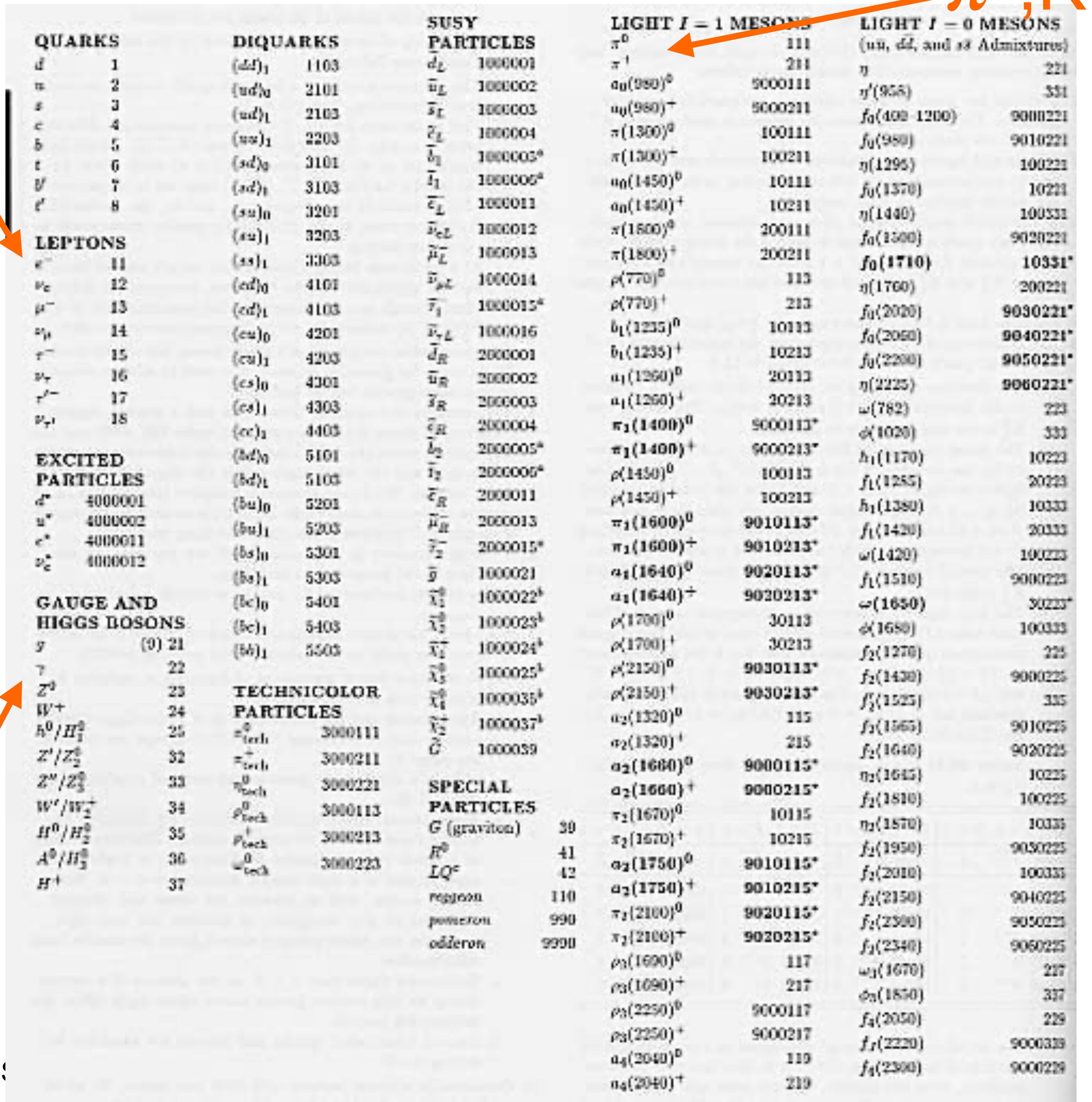
- Between 1930 ~ 1980, lots of ‘elementary’ particles discovered
  - Many from two and three quark structures, different spin states…
  - For particle detection, we mainly worry about the particles that stick around for a (relatively) long time

$\pi^{\pm}$,K

p,n

e,μ

γ



QUARKS

d	1
u	2
s	3
c	4
b	5
t	6
b′	7
t′	8

LEPTONS

e⁻	11
νe	12
μ⁻	13
νμ	14
τ⁻	15
ντ	16
τ′⁻	17
ντ′	18

EXCITED PARTICLES

d*	4000001
u*	4000002
e*	4000011
νe*	4000012

GAUGE AND HIGGS BOSONS

g	(9) 21
γ	22
Z0	23
W+	24
h0/H1 0	25
Z′/Z2 0	32
Z″/Z3 0	33
W′/W2 +	34
H0/H2 0	35
A0/H3 0	36
H+	37

DIQUARKS

(dd)1	1103
(ud)0	2101
(ud)1	2103
(uu)1	2203
(sd)0	3101
(sd)1	3103
(su)0	3201
(su)1	3203
(ss)1	3303
(cd)0	4101
(cd)1	4103
(cu)0	4201
(cu)1	4203
(cs)0	4301
(cs)1	4303
(cc)1	4403
(bd)0	5101
(bd)1	5103
(bu)0	5201
(bu)1	5203
(bs)0	5301
(bs)1	5303
(bc)0	5401
(bc)1	5403
(bb)1	5503

TECHNICOLOR PARTICLES

π0tech	3000111
π+tech	3000211
η0tech	3000221
ρ0tech	3000113
ρ+tech	3000213
ω0tech	3000223

SUSY PARTICLES

d̃L	1000001
ũL	1000002
s̃L	1000003
c̃L	1000004
b̃1	1000005a
t̃1	1000006a
ẽL	1000011
ν̃eL	1000012
μ̃L	1000013
ν̃μL	1000014
τ̃1	1000015a
ν̃τL	1000016
d̃R	2000001
ũR	2000002
s̃R	2000003
c̃R	2000004
b̃2	2000005a
t̃2	2000006a
ẽR	2000011
μ̃R	2000013
τ̃2	2000015a
g̃	1000021
χ̃1 0	1000022b
χ̃2 0	1000023b
χ̃1 +	1000024b
χ̃3 0	1000025b
χ̃4 0	1000035b
χ̃2 +	1000037b
G̃	1000039

SPECIAL PARTICLES

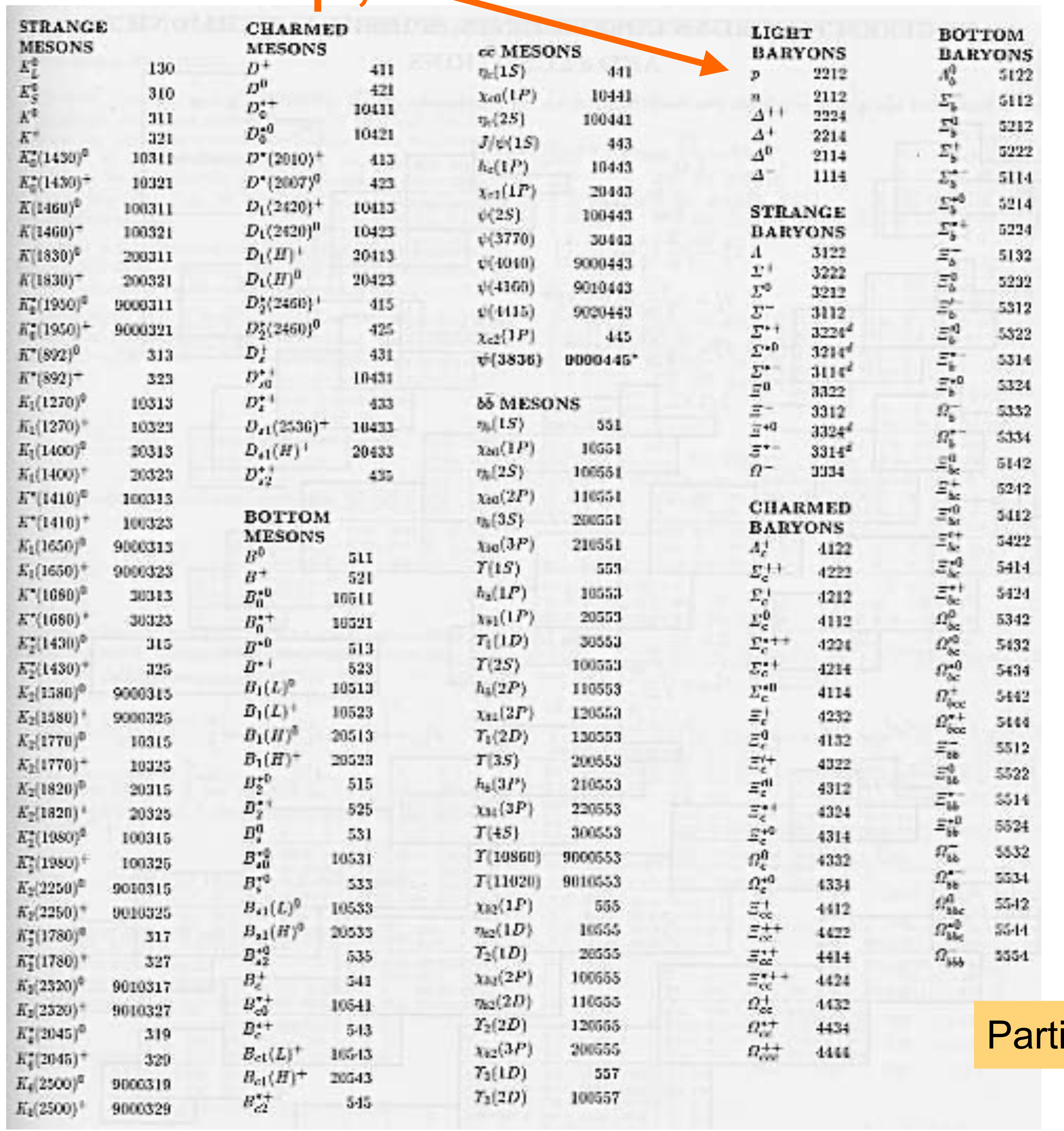
G (graviton)	39
R0	41
LQc	42
reggeon	110
pomeron	990
odderon	9990

LIGHT I = 1 MESONS

π0	111
π+	211
a0(980)0	9000111
a0(980)+	9000211
π(1300)0	100111
π(1300)+	100211
a0(1450)0	10111
a0(1450)+	10211
π(1800)0	200111
π(1800)+	200211
ρ(770)0	113
ρ(770)+	213
b1(1235)0	10113
b1(1235)+	10213
a1(1260)0	20113
a1(1260)+	20213
π1(1400)0	9000113*
π1(1400)+	9000213*
ρ(1450)0	100113
ρ(1450)+	100213
π1(1600)0	9010113*
π1(1600)+	9010213*
a1(1640)0	9020113*
a1(1640)+	9020213*
ρ(1700)0	30113
ρ(1700)+	30213
ρ(2150)0	9030113*
ρ(2150)+	9030213*
a2(1320)0	115
a2(1320)+	215
a2(1660)0	9000115*
a2(1660)+	9000215*
π2(1670)0	10115
π2(1670)+	10215
a2(1750)0	9010115*
a2(1750)+	9010215*
π2(2100)0	9020115*
π2(2100)+	9020215*
ρ3(1690)0	117
ρ3(1690)+	217
ρ3(2250)0	9000117
ρ3(2250)+	9000217
a4(2040)0	119
a4(2040)+	219

LIGHT I = 0 MESONS (uū, dd̄, and ss̄ Admixtures)

η	221
η′(958)	331
f0(400–1200)	9000221
f0(980)	9010221
η(1295)	100221
f0(1370)	10221
η(1440)	100331
f0(1500)	9020221
f0(1710)	10331*
η(1760)	200221
f0(2020)	9030221*
f0(2060)	9040221*
f0(2200)	9050221*
η(2225)	9060221*
ω(782)	223
φ(1020)	333
h1(1170)	10223
f1(1285)	20223
h1(1380)	10333
f1(1420)	20333
ω(1420)	100223
f1(1510)	9000223
ω(1650)	30223*
φ(1680)	100333
f2(1270)	225
f2(1430)	9000225
f2′(1525)	335
f2(1565)	9010225
f2(1640)	9020225
η2(1645)	10225
f2(1810)	100225
η2(1870)	10335
f2(1950)	9030225
f2(2010)	100335
f2(2150)	9040225
f2(2300)	9050225
f2(2340)	9060225
ω3(1670)	227
φ3(1850)	337
f4(2050)	229
fJ(2220)	9000339
f4(2300)	9000229



STRANGE MESONS

K0L	130
K0S	310
K0	311
K+	321
K0*(1430)0	10311
K0*(1430)+	10321
K(1460)0	100311
K(1460)+	100321
K(1830)0	200311
K(1830)+	200321
K0*(1950)0	9000311
K0*(1950)+	9000321
K*(892)0	313
K*(892)+	323
K1(1270)0	10313
K1(1270)+	10323
K1(1400)0	20313
K1(1400)+	20323
K*(1410)0	100313
K*(1410)+	100323
K1(1650)0	9000313
K1(1650)+	9000323
K*(1680)0	30313
K*(1680)+	30323
K2*(1430)0	315
K2*(1430)+	325
K2(1580)0	9000315
K2(1580)+	9000325
K2(1770)0	10315
K2(1770)+	10325
K2(1820)0	20315
K2(1820)+	20325
K2*(1980)0	100315
K2*(1980)+	100325
K2(2250)0	9010315
K2(2250)+	9010325
K3*(1780)0	317
K3*(1780)+	327
K3(2320)0	9010317
K3(2320)+	9010327
K4*(2045)0	319
K4*(2045)+	329
K4(2500)0	9000319
K4(2500)+	9000329

CHARMED MESONS

D+	411
D0	421
D0*+	10411
D0*0	10421
D*(2010)+	413
D*(2007)0	423
D1(2420)+	10413
D1(2420)0	10423
D1(H)+	20413
D1(H)0	20423
D2*(2460)+	415
D2*(2460)0	425
Ds+	431
Ds0*+	10431
Ds*+	433
Ds1(2536)+	10433
Ds1(H)+	20433
Ds2*+	435

BOTTOM MESONS

B0	511
B+	521
B0*0	10511
B0*+	10521
B*0	513
B*+	523
B1(L)0	10513
B1(L)+	10523
B1(H)0	20513
B1(H)+	20523
B2*0	515
B2*+	525
Bs0	531
Bs0*0	10531
Bs*0	533
Bs1(L)0	10533
Bs1(H)0	20533
Bs2*0	535
Bc+	541
Bc0*+	10541
Bc*+	543
Bc1(L)+	10543
Bc1(H)+	20543
Bc2*+	545

cc̄ MESONS

ηc(1S)	441
χc0(1P)	10441
ηc(2S)	100441
J/ψ(1S)	443
hc(1P)	10443
χc1(1P)	20443
ψ(2S)	100443
ψ(3770)	30443
ψ(4040)	9000443
ψ(4160)	9010443
ψ(4415)	9020443
χc2(1P)	445
ψ(3836)	9000445*

bb̄ MESONS

ηb(1S)	551
χb0(1P)	10551
ηb(2S)	100551
χb0(2P)	110551
ηb(3S)	200551
χb0(3P)	210551
Υ(1S)	553
hb(1P)	10553
χb1(1P)	20553
Υ1(1D)	30553
Υ(2S)	100553
hb(2P)	110553
χb1(2P)	120553
Υ1(2D)	130553
Υ(3S)	200553
hb(3P)	210553
χb1(3P)	220553
Υ(4S)	300553
Υ(10860)	9000553
Υ(11020)	9010553
χb2(1P)	555
ηb2(1D)	10555
Υ2(1D)	20555
χb2(2P)	100555
ηb2(2D)	110555
Υ2(2D)	120555
χb2(3P)	200555
Υ3(1D)	557
Υ3(2D)	100557

LIGHT BARYONS

p	2212
n	2112
Δ++	2224
Δ+	2214
Δ0	2114
Δ−	1114

STRANGE BARYONS

Λ	3122
Σ+	3222
Σ0	3212
Σ−	3112
Σ*+	3224d
Σ*0	3214d
Σ*−	3114d
Ξ0	3322
Ξ−	3312
Ξ*0	3324d
Ξ*−	3314d
Ω−	3334

CHARMED BARYONS

Λc+	4122
Σc++	4222
Σc+	4212
Σc0	4112
Σc*++	4224
Σc*+	4214
Σc*0	4114
Ξc+	4232
Ξc0	4132
Ξ′c+	4322
Ξ′c0	4312
Ξc*+	4324
Ξc*0	4314
Ωc0	4332
Ωc*0	4334
Ξcc+	4412
Ξcc++	4422
Ξcc*+	4414
Ξcc*++	4424
Ωcc+	4432
Ωcc*+	4434
Ωccc++	4444

BOTTOM BARYONS

Λb0	5122
Σb−	5112
Σb0	5212
Σb+	5222
Σb*−	5114
Σb*0	5214
Σb*+	5224
Ξb−	5132
Ξb0	5232
Ξ′b−	5312
Ξ′b0	5322
Ξb*−	5314
Ξb*0	5324
Ωb−	5332
Ωb*−	5334
Ξbc0	5142
Ξbc+	5242
Ξ′bc0	5412
Ξ′bc+	5422
Ξbc*0	5414
Ξbc*+	5424
Ωbc0	5342
Ω′bc0	5432
Ωbc*0	5434
Ωbcc+	5442
Ωbcc*+	5444
Ξbb−	5512
Ξbb0	5522
Ξbb*−	5514
Ξbb*0	5524
Ωbb−	5532
Ωbb*−	5534
Ωbbc0	5542
Ωbbc*0	5544
Ωbbb−	5554

Particle Data Book

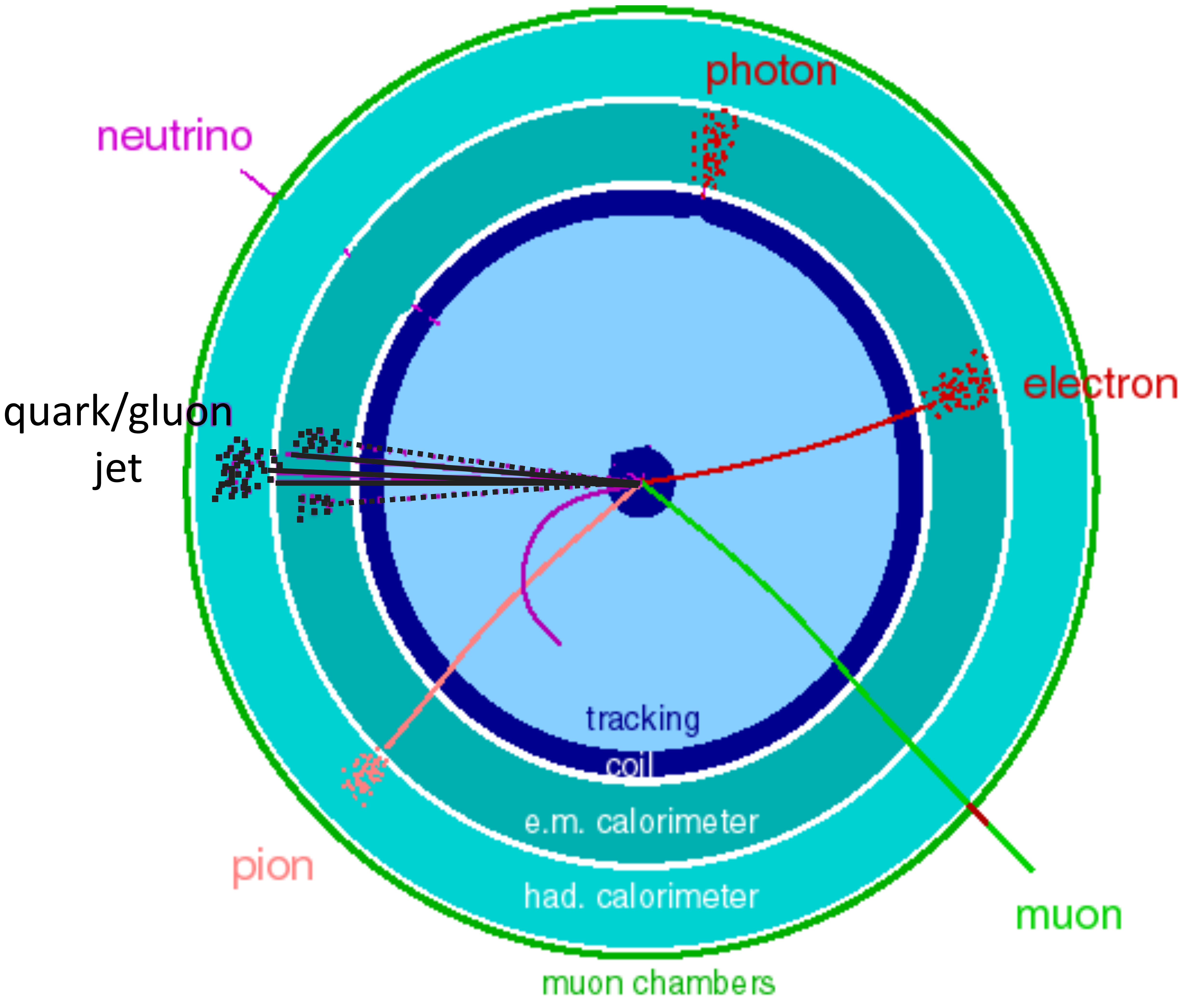
Particle or Astroparticle Experiments

- Typically separate out measurements by objective or particle type
  - Tracking of charged particles (where they went)
  - Momentum analysis (how the bend in a magnetic field)
  - Energy measurement (absorbed to find energy and location)
  - Particle identification (different particles, different methods)

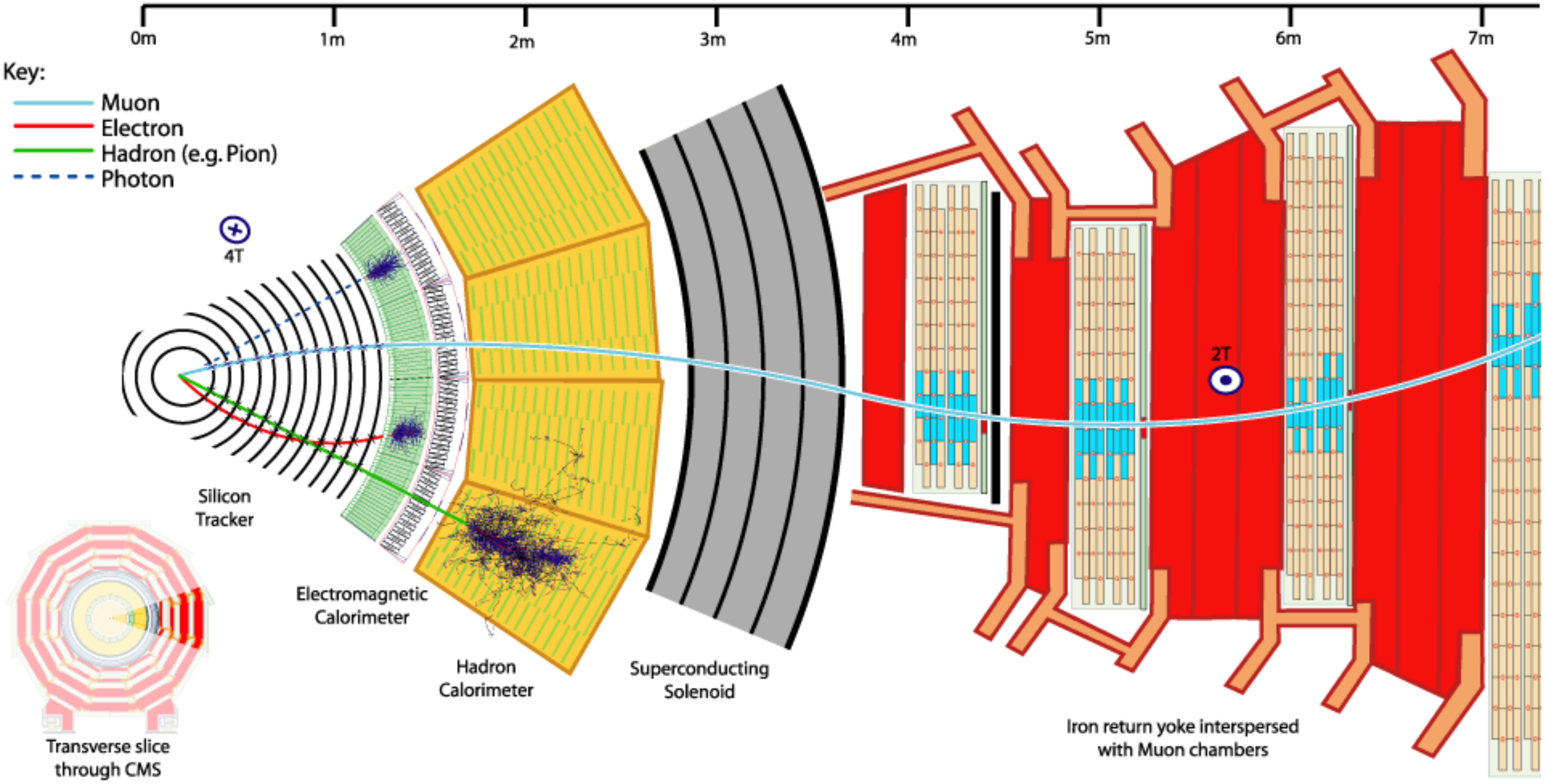
- There is a definite ordering to this, dictated by the particle properties
  - Non-destructive “tracking” is first: bend charged particles in a magnetic field, measure momentum and charge
  - Electromagnetic interactions: electrons and photons are absorbed, and energies measured in a calorimeter
  - Hadronic interactions: a massive detector helps to slow and absorb pions, measuring energy
  - Weak interactions: muons are highly penetrating (so they can wait until last)

Generic Particle Detector

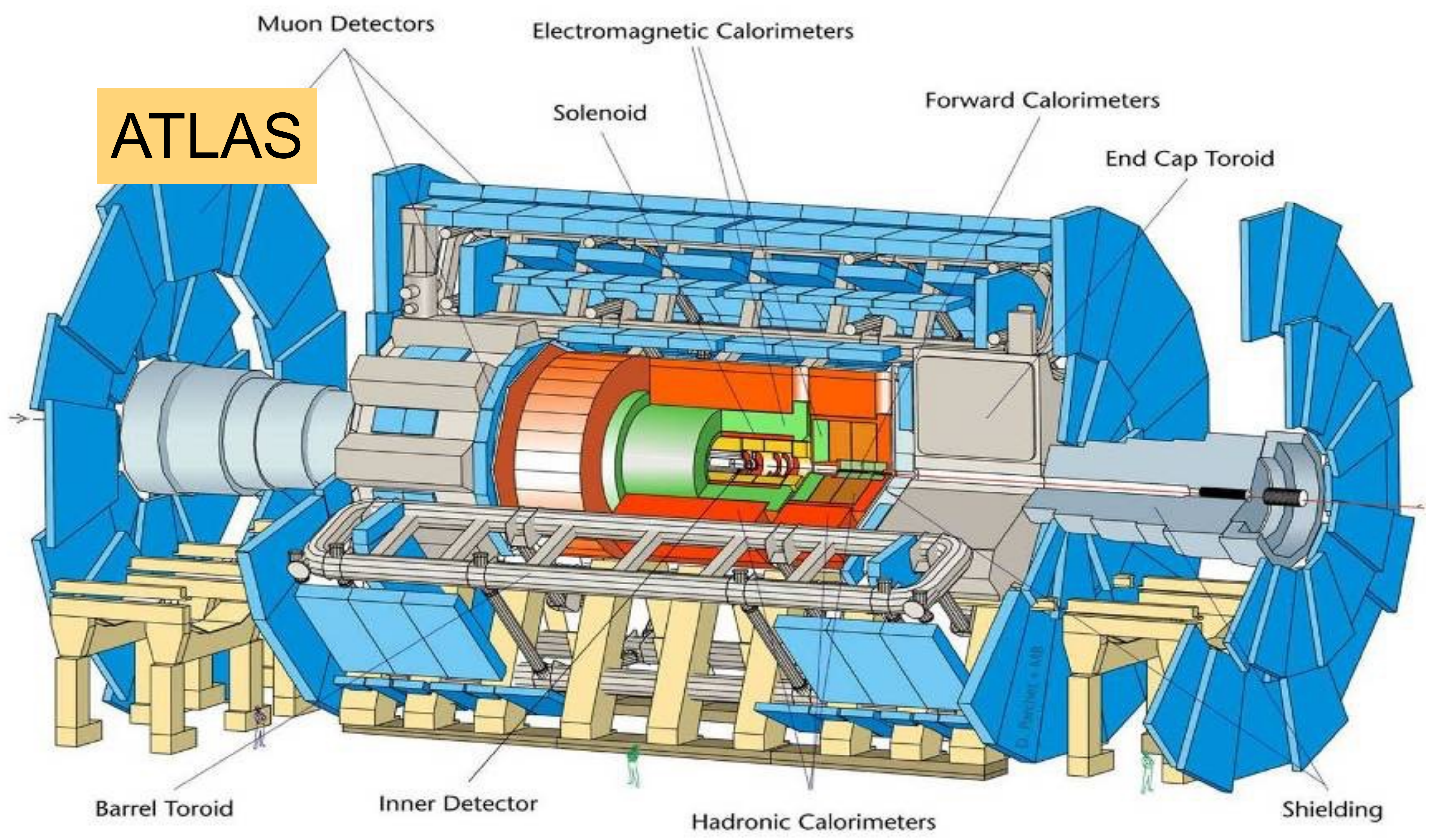
- Electron (e): track, contained cluster, E/P~1
- Photon (γ): EM cluster, no track
- Hadron jet (π,p,K): track, extended (had) cluster
- Neutron (n): hadronic cluster, no track
- Pion (π): track, extended (had) cluster
- Muon (μ): penetrating track
- Short lived (b): Displaced (mm) vertex
- Weak (ν …or dark matter!): Missing E_T

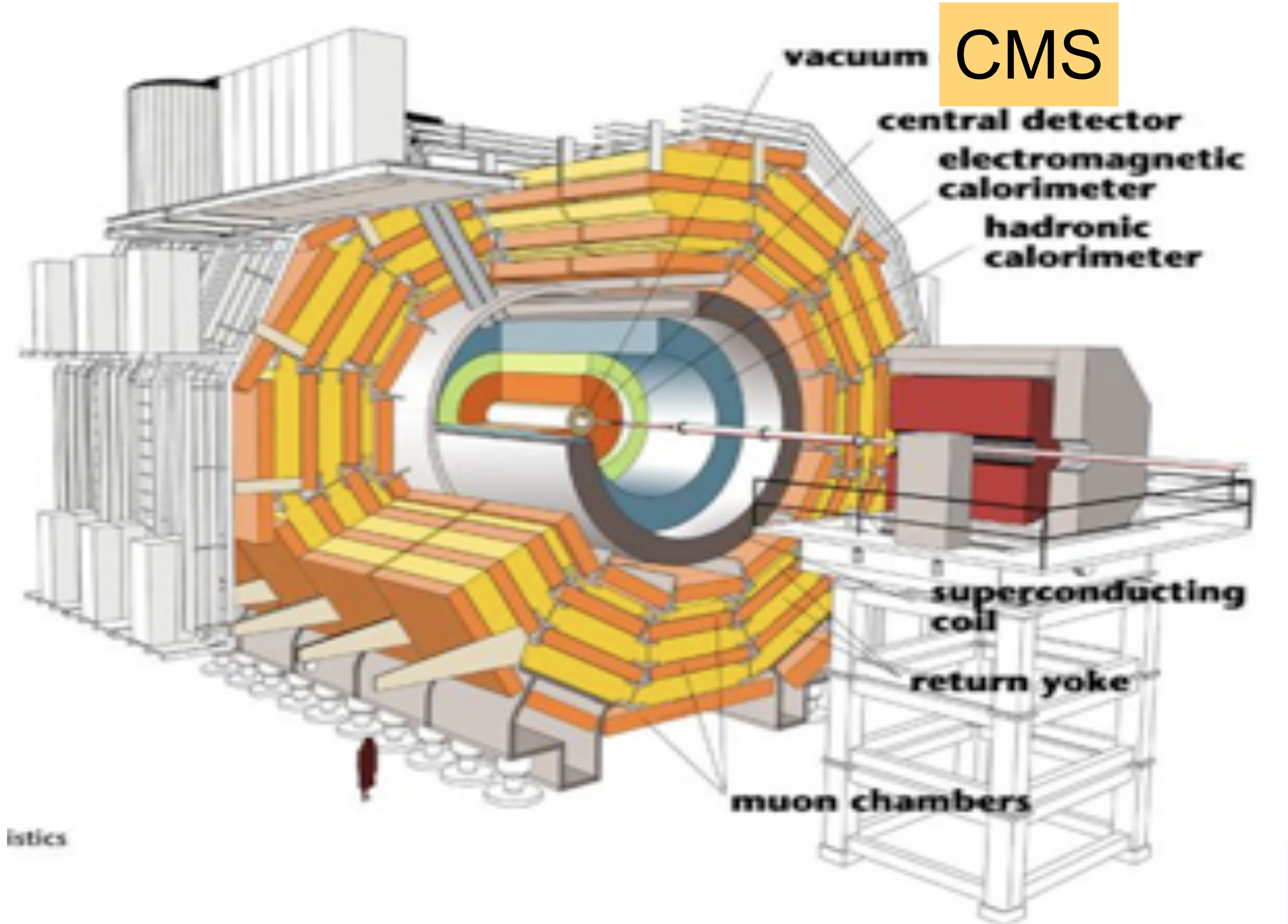


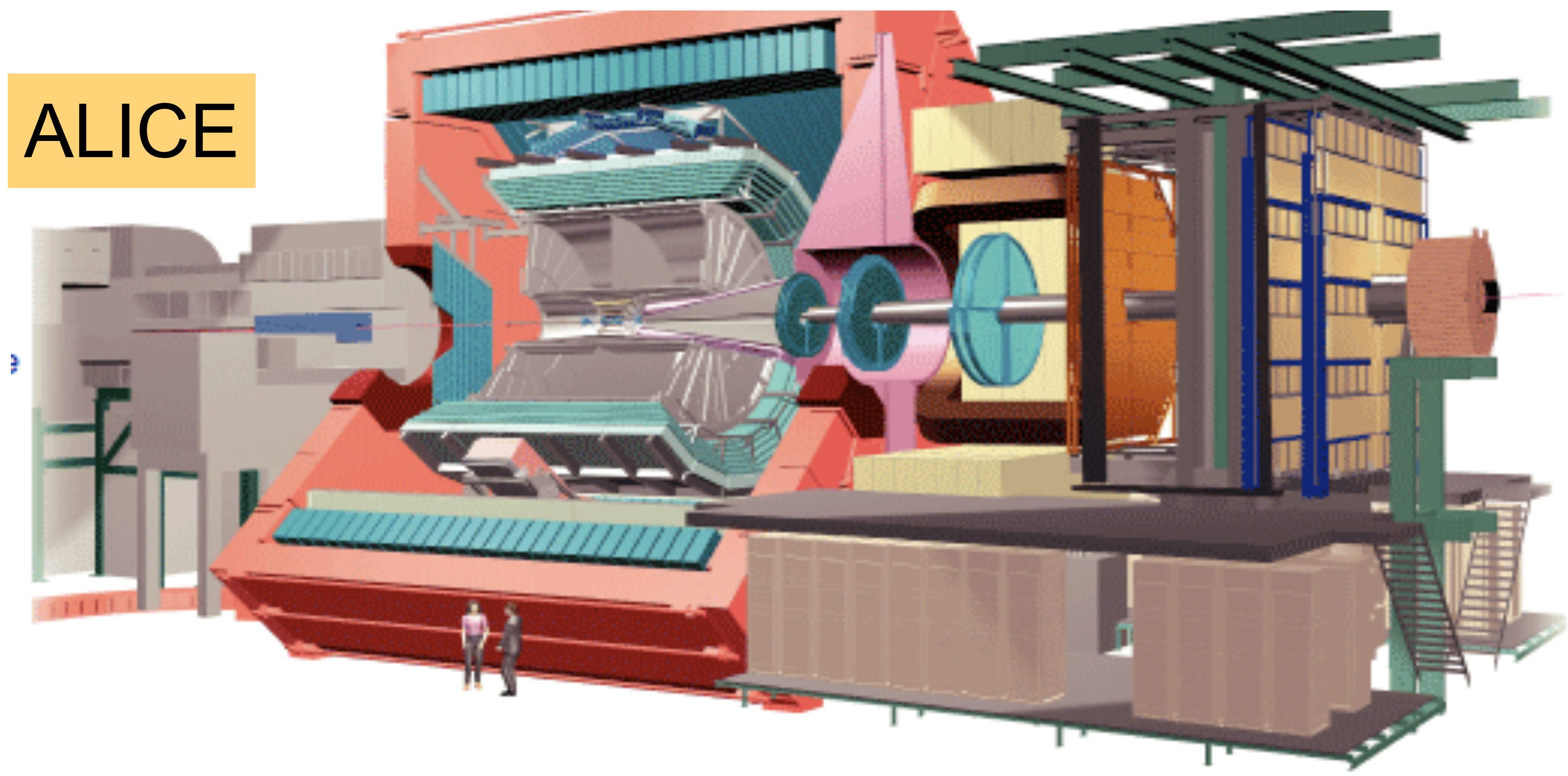
Typical Detector Layout (CMS)

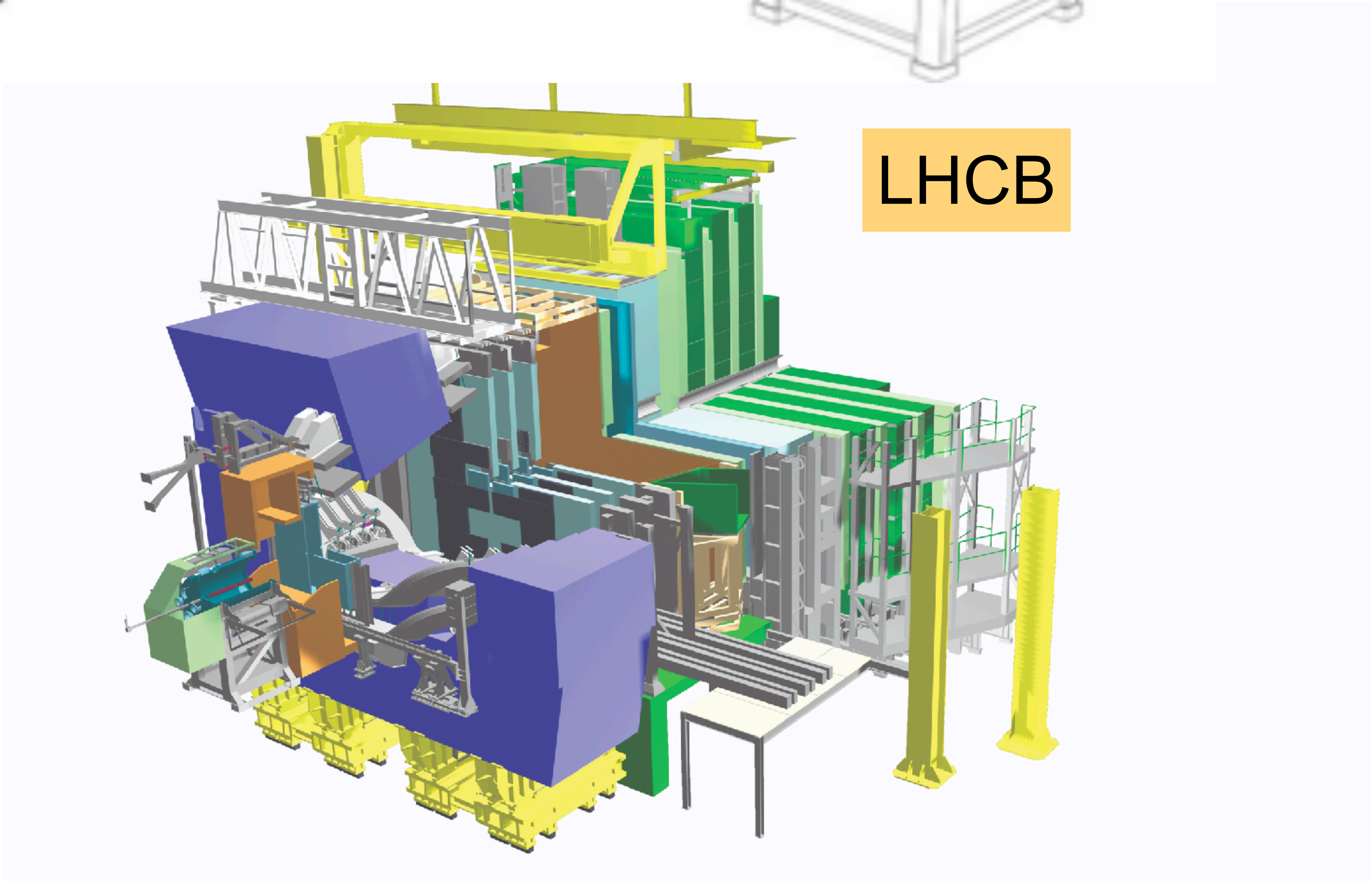


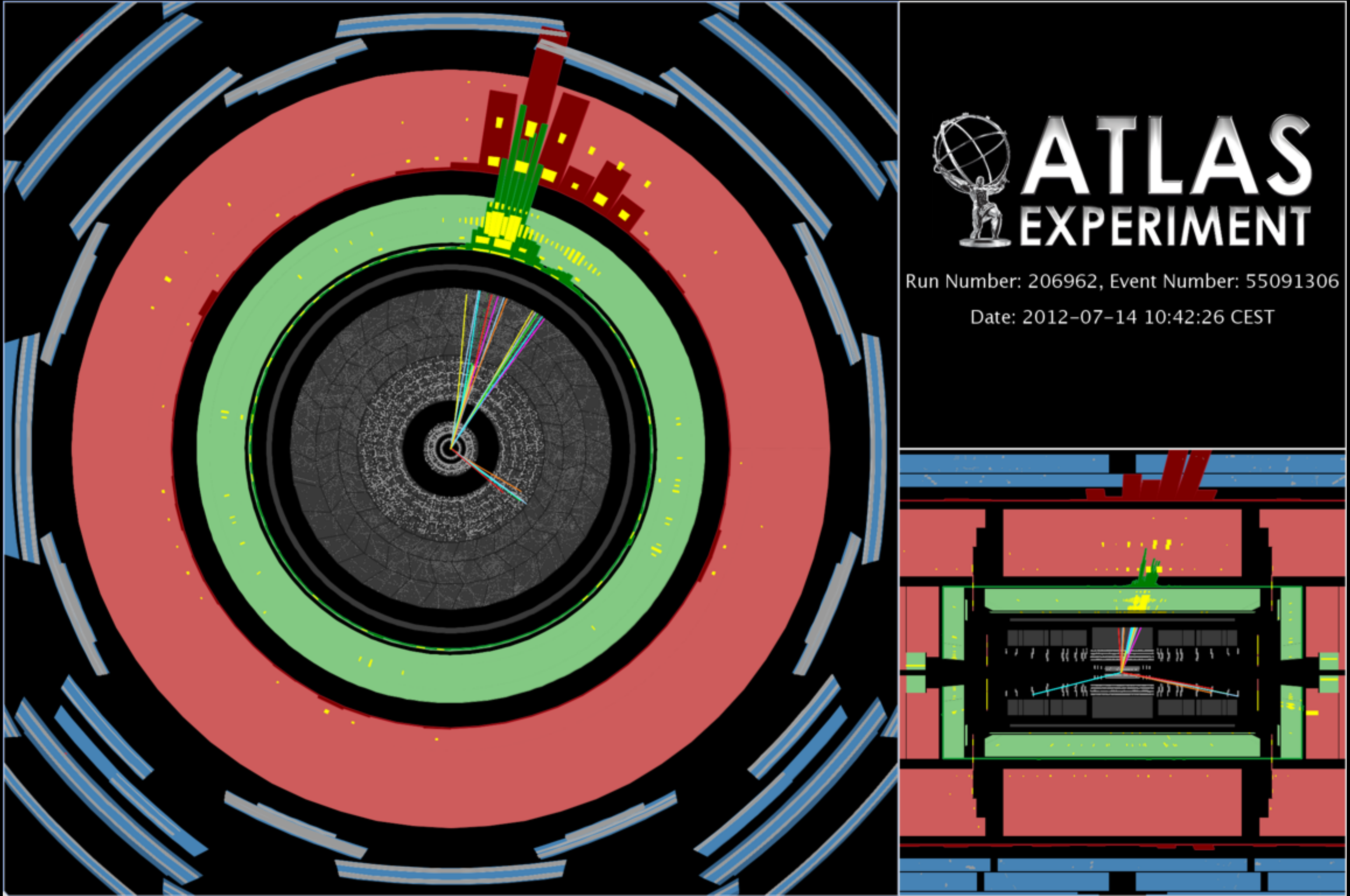
Collider Particle Detectors @ CERN










ATLAS EXPERIMENT
Run Number: 206962, Event Number: 55091306
Date: 2012-07-14 10:42:26 CEST


CMS

Particle Interactions

Only a few particles relevant or particle detection:

γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, n, ν_e, ν_μ…

- **Charged particle interaction**
  - Ionisation/Excitation
  - Bremsstrahlung
  - Multiple scattering
  - Cherenkov and transition radiation
- **Photon interactions**
  - Photoelectric effect
  - Compton scatter
  - Pair production
- **Hadronic interactions**
  - neutron capture
  - nuclear interactions
- **Neutrino interactions**

[https://pdg.lbl.gov/2025/reviews/contents_sports.html]
[https://pdg.lbl.gov/2025/reviews/rpp2024-rev-passage-particles-matter.pdf]

Particle Interactions

Electromagnetic →

- **Charged particle interaction**
  - Ionisation/Excitation - electron either excited to higher orbit or kicked out
  - Bremsstrahlung - electron slows and emits a photon
  - Multiple scattering - small-angle Coulomb scatter
  - Cherenkov and transition radiation - due to passage through dense media
- **Photon interactions**
  - Photoelectric effect - photon absorbed, electron emitted
  - Compton scatter - photon interaction emits an electron
  - Pair production - $\gamma \rightarrow e^{+} + e^{-}$

Strong Force →

- **Hadronic interactions**
  - neutron capture - neutron absorbed, γ emitted
  - nuclear interactions - interaction with nucleus

Weak Force →

- **Neutrino interactions**

Charged Particle Interactions: Bethe-Bloch

- Full treatment, with correction terms, is the Bethe-Bloch Equation:

$$-\frac{dE}{\rho dx} = K\frac{Z}{A}\frac{z^2}{\beta^2}\left(\frac{1}{2}\ln\frac{2m_0c^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} - \frac{C(\beta\gamma, I)}{Z}\right)$$

- where
  - I = mean excitation energy
  - K = $4\pi N_A r_e^2 m_e c^2$ = 0.307 MeV cm²/mol
  - T_{max}= max kinetic energy loss (per collision) = $2m_ec^2\beta^2\gamma^2$
  - delta and C/Z are corrections for high/low $\beta\gamma$
- Energy loss depends on particle velocity
  - For low momentum, follows $1/\beta^2$, C/Z correction important
  - For high momentum, Logarithmic rise from $-\frac{dE}{dx} \approx 2$ MeV cm²/g
  - Minimum Ionising Particle (MIP): energy loss has a minimum at $\beta\gamma \approx 3$

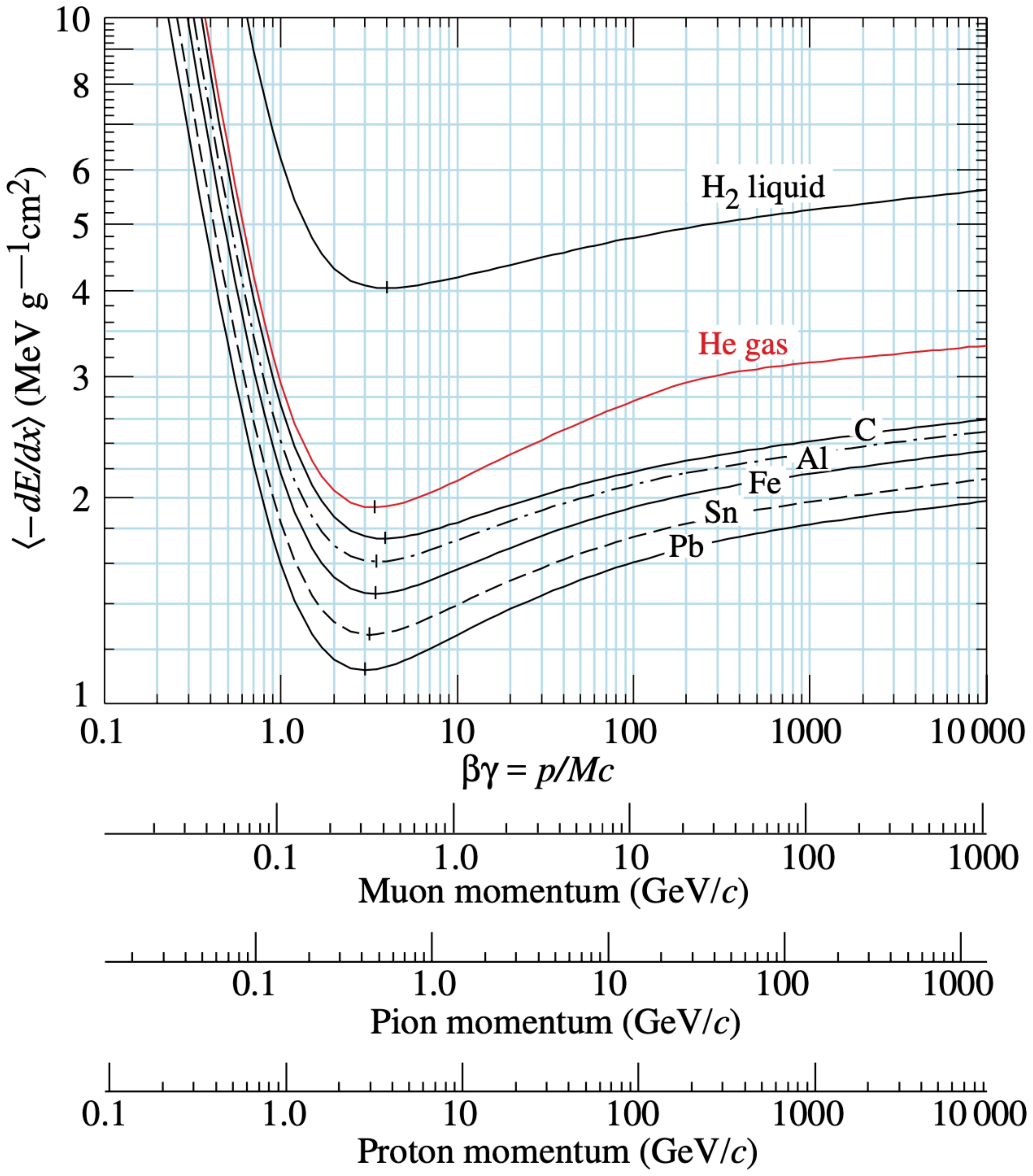
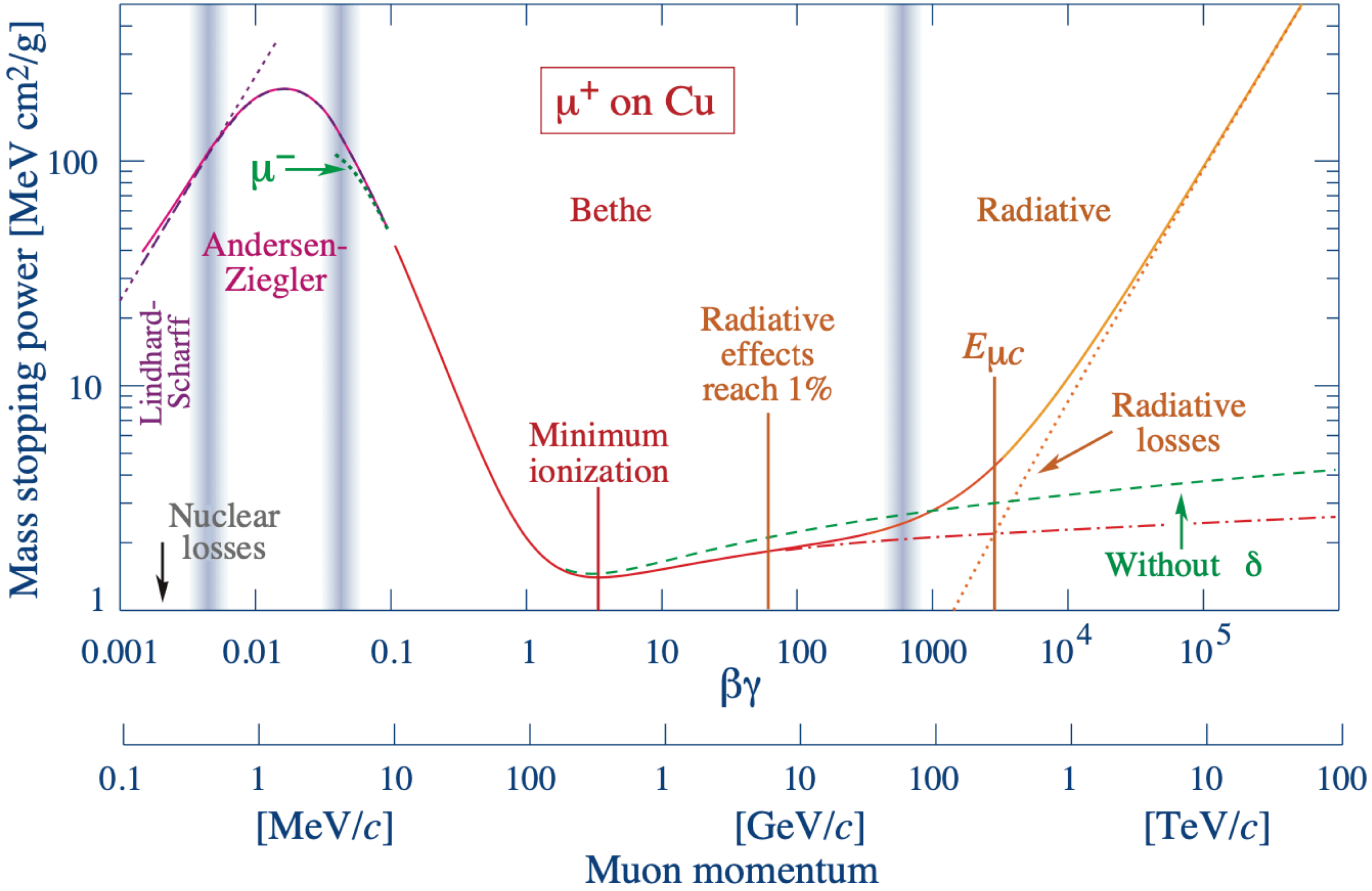


Figure 34.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 34.23.

[pdg.lbl.gov: S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)]

Charged Particle Interactions: Bethe-Bloch

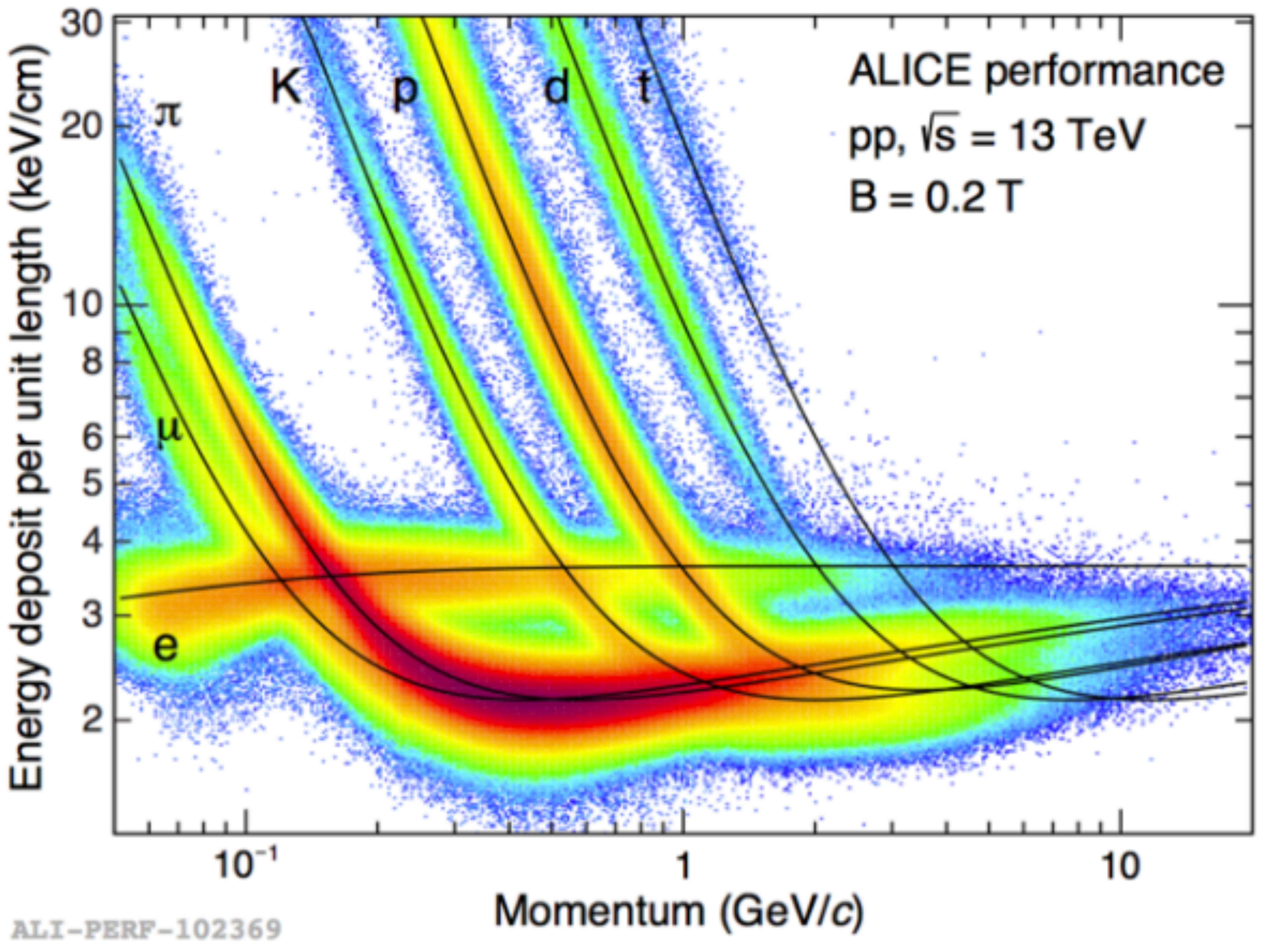
- What happens at low momentum? At high momentum?
  - Bethe-Bloch range in red, not for low $\beta\gamma$ (purple) or high $\beta\gamma$ (orange)
- Bethe-Bloch is an approximation, but good to a few %

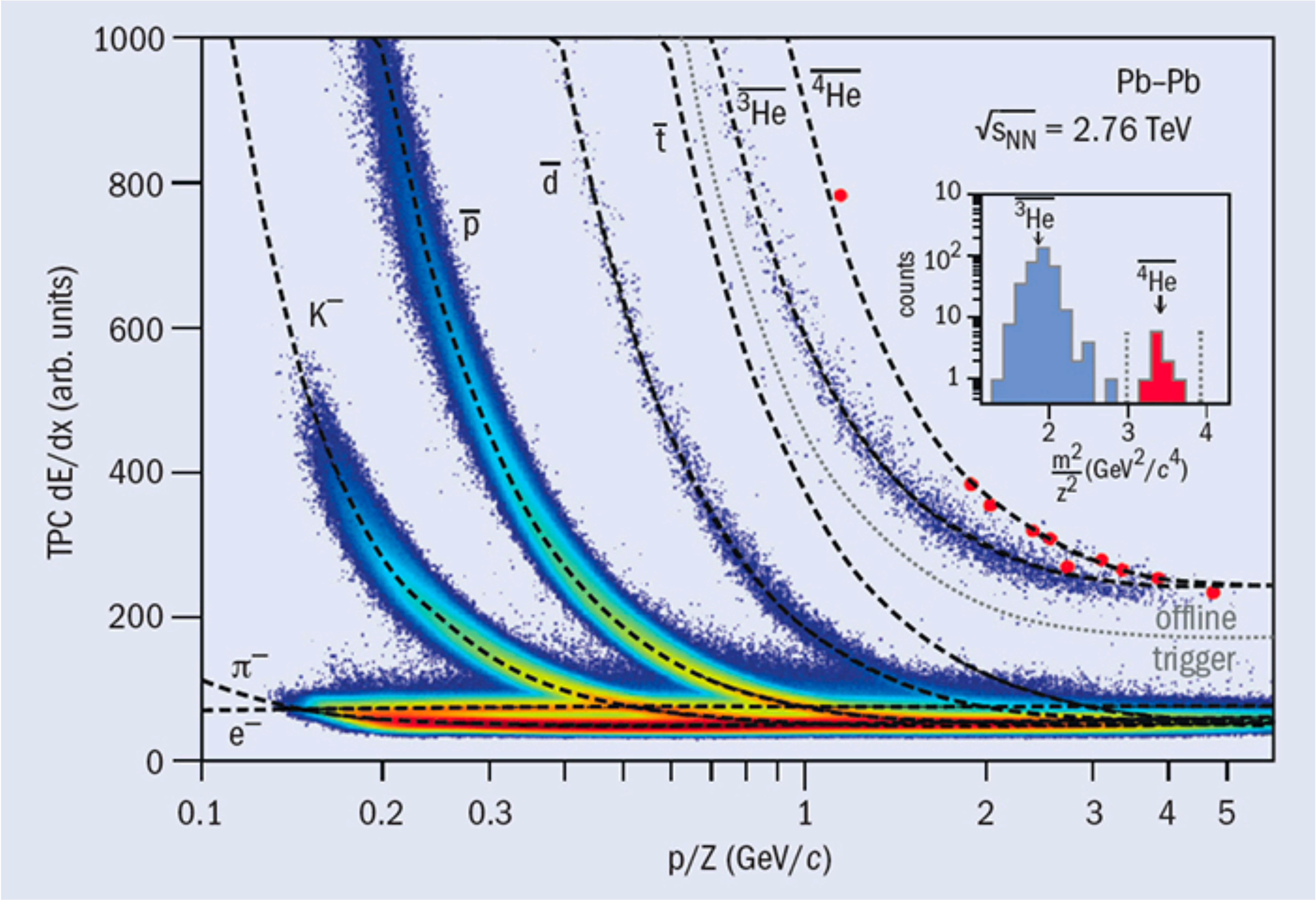


[PDG]

ALICE TPC

- Example of dE/dx used for particle identification in a Time Projection Chamber





[arXiv:1402.4476; Int.J.Mod.Phys.A 29 (2014), 1430044]

Charged Particles: Energy Loss, Fluctuations & Bragg Peak

- Statistical process, but energy lost in a path x (called the straggling function) deposited as a Landau
- Approximates a Gaussian only for very thick absorbers or large energy depositions

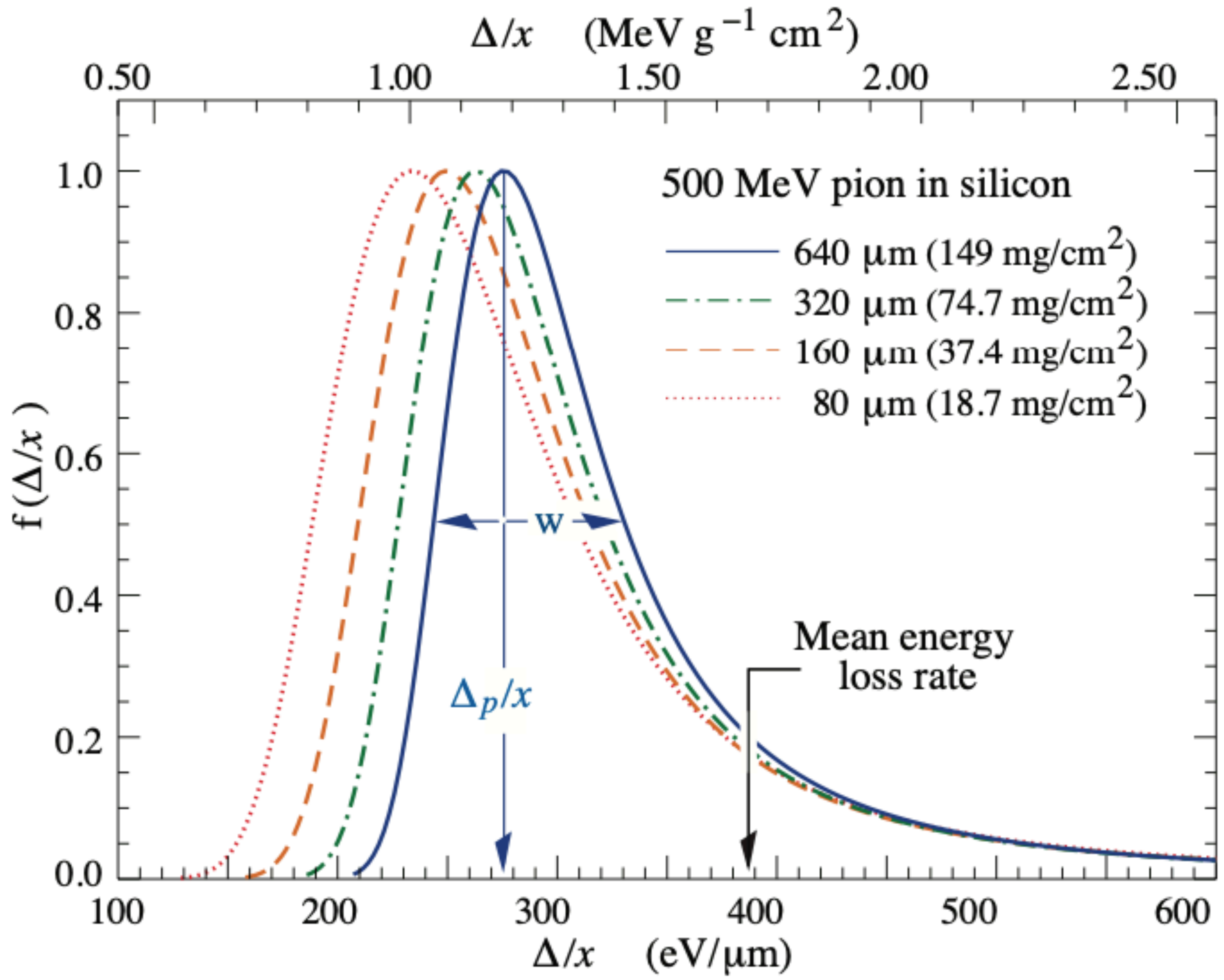
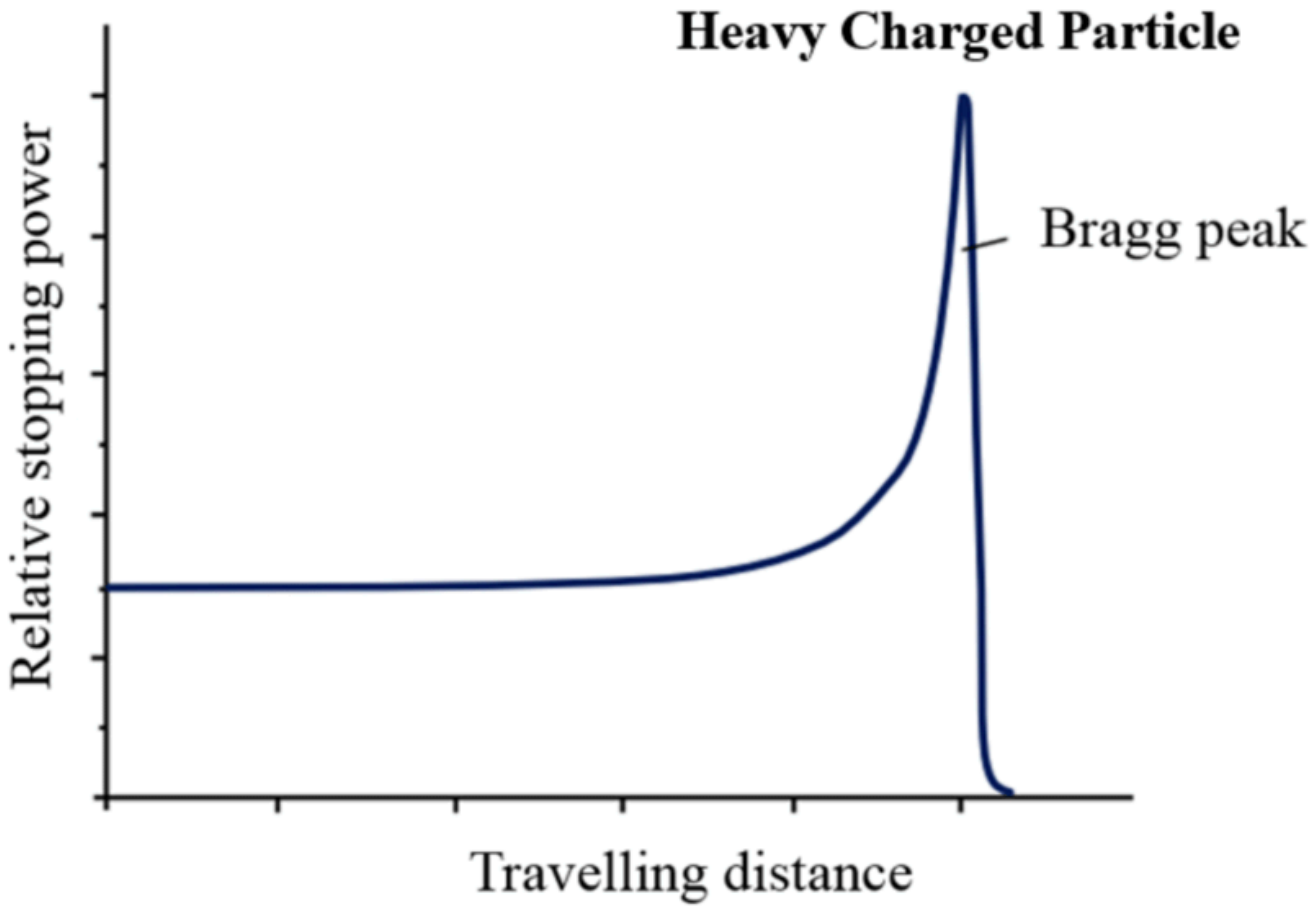


Figure 34.8: Straggling functions in silicon for 500 MeV pions, normalized to unity at the most probable value Δ_p/x. The width w is the full width at half maximum.



Charged Particles: Multiple Scattering

- For small (Coulomb) deflections, define angle:

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\theta_{\text{space}}^{\text{rms}}$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x}{X_0}\frac{z^2}{\beta^2}\right)\right]$$

$$= \frac{13.6\ \text{MeV}}{\beta c p}\sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

fast, single-charge

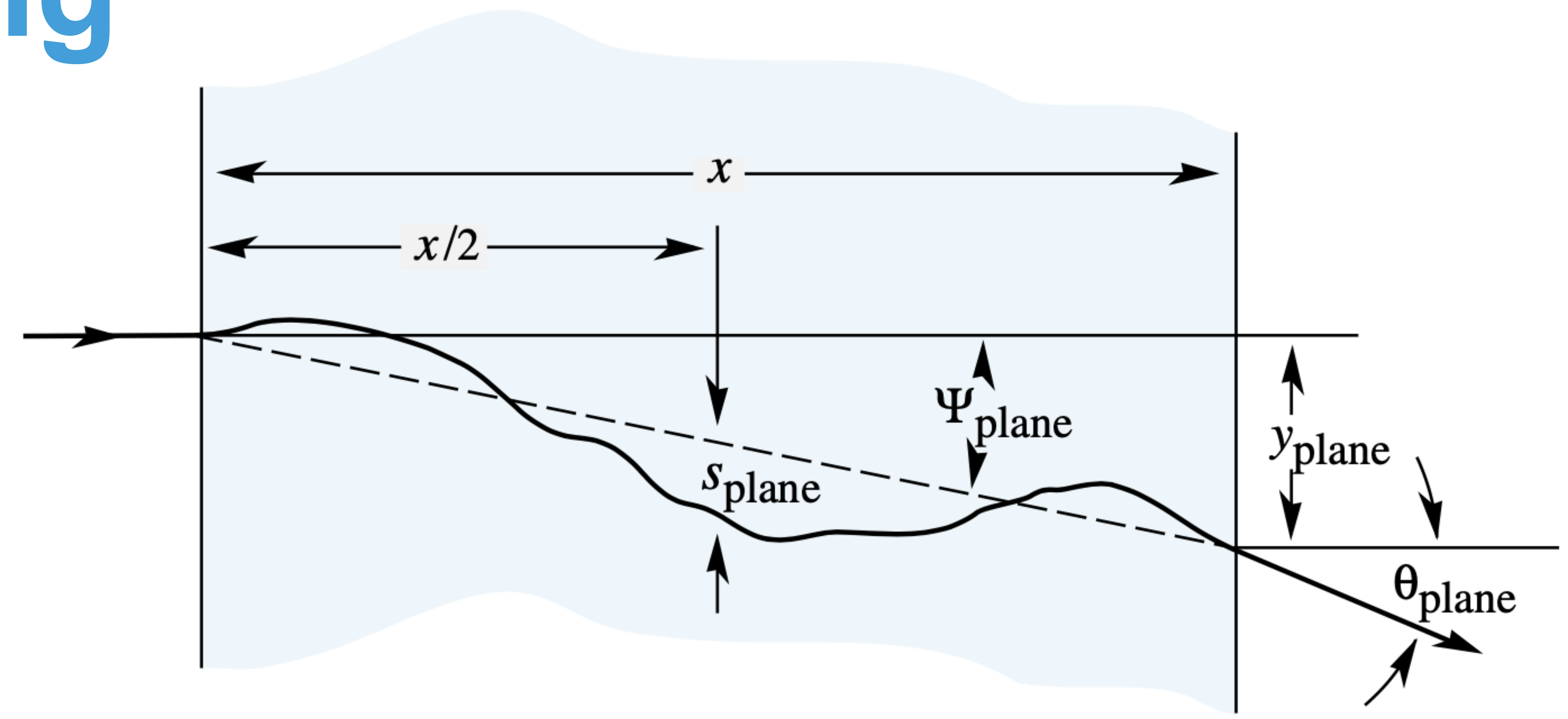
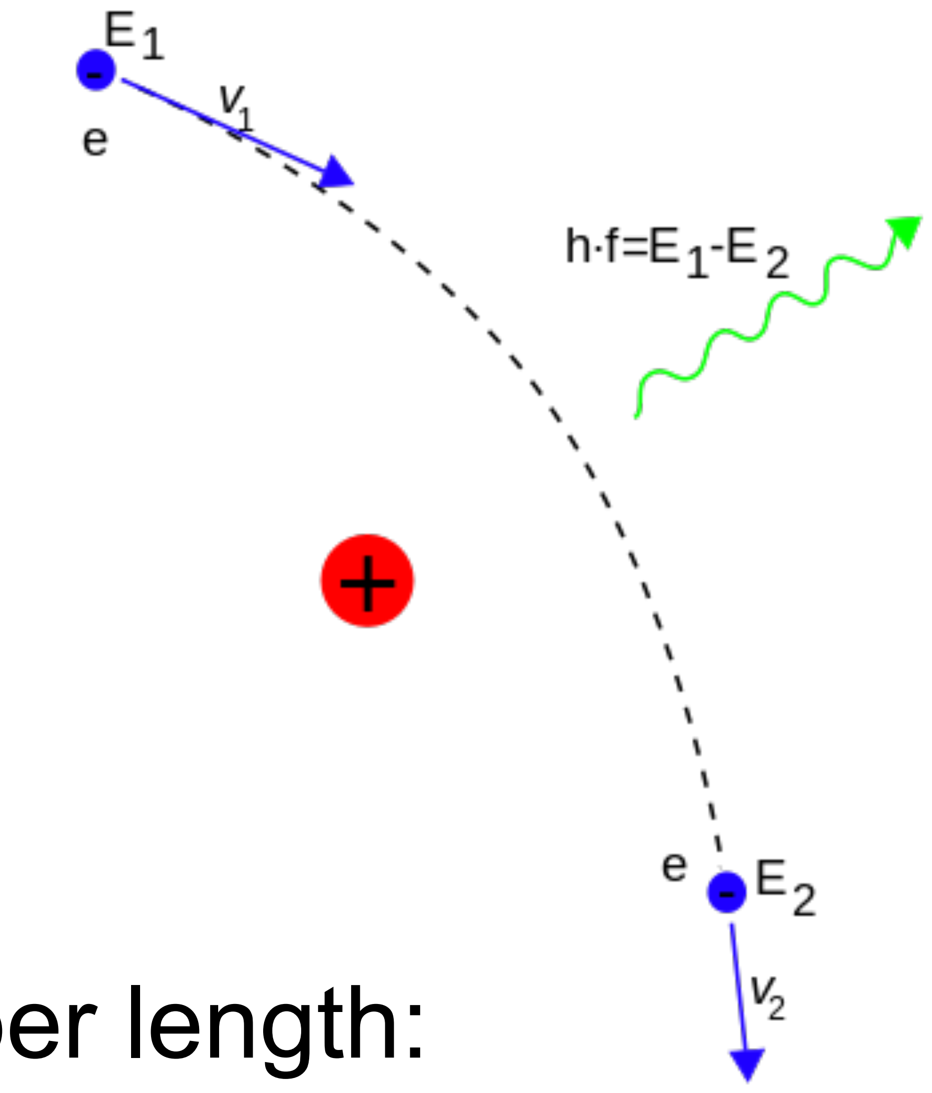


Figure 34.10: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

where $p, \beta c$, and z are the momentum, speed and charge, and x/X_0 is the thickness in radiation lengths

- Approximation (from Highland), but works well for ~98% of scatters and for small Z (and large x)
- For layers or inhomogeneities, can't simply add separate θ contributions
- Important for estimating positions and reconstructing tracks from measurement points

Charged Particles: Bremsstrahlung



- Important process for high β and low mass particles (e$^-$ and μ$^-$)
- Energy loss from Bremsstrahlung

$$-\frac{dE}{\rho dx} \propto \frac{E}{m}\frac{Z^2}{A}$$

- Averaging losses over the full Bremsstrahlung spectrum gives mean energy loss per length:

$$-\frac{dE}{dx} \approx 4\alpha N_A \rho \frac{Z^2}{A}\left(\frac{1}{4\pi\epsilon_0}\frac{e^2}{m_e c^2}\right) E \ln\frac{183}{Z^{1/3}}$$

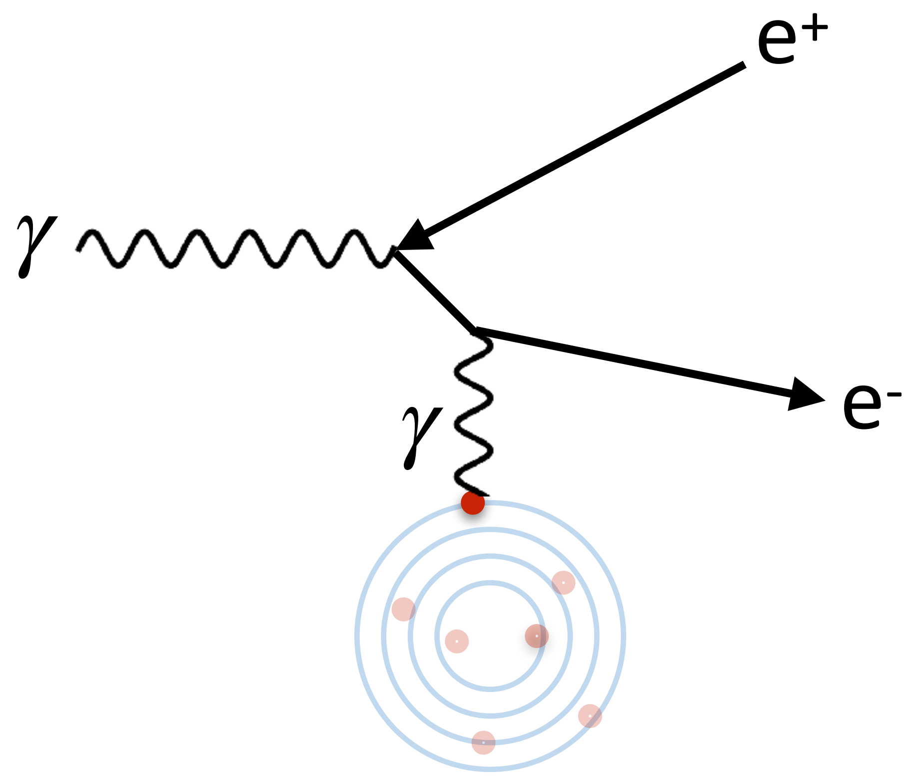
$$\left(\frac{dE}{dx}\right)_{\mathrm{rad}} = -\frac{E}{X_0} \qquad \Rightarrow \qquad E(x) = E_0 e^{-\frac{x}{X_0}}$$

- Where X_0 is the radiation length; after $x = X_0$, an electron has 1/e of its initial energy

Photons: Pair Production

- For $E_\gamma > 2m_e$ particle pair production is possible
- At high energies, pair production is dominant photon interaction (Bethe-Heitler)

$$\sigma_{\text{pair}}(E) \approx \alpha Z^2 r^2 \ln E_\gamma$$

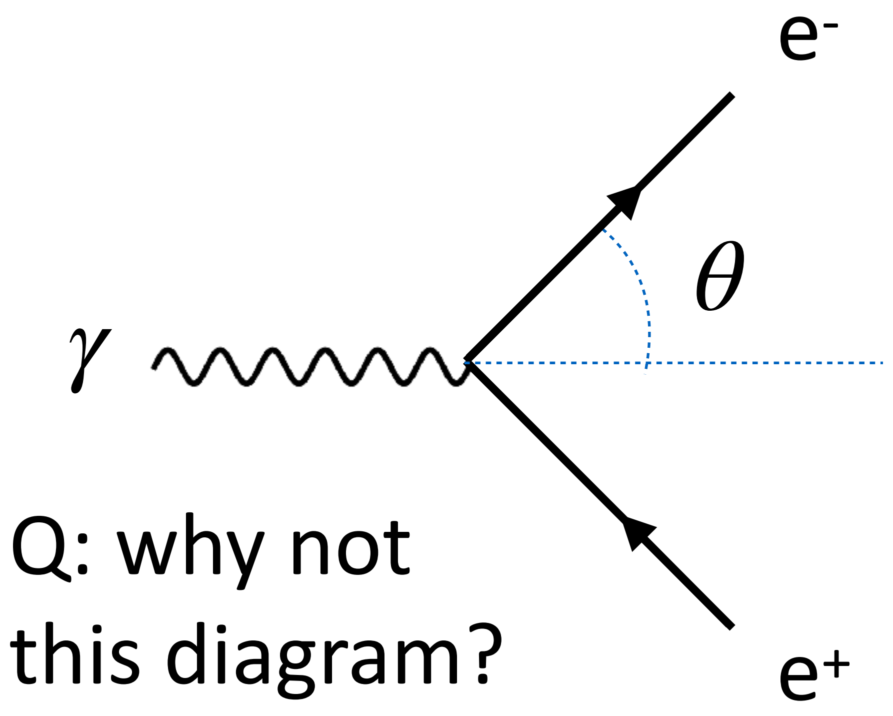


- Differential cross section is given by

$$\frac{d\sigma}{dx} = \frac{A}{X_0 N_A}\left(1 - \frac{4}{3}x(1-x)\right)$$

- where $x = E/k$ is the fractional energy transfer to the e^- (or e^+), and k is the incident photon energy
- Integrating, we get

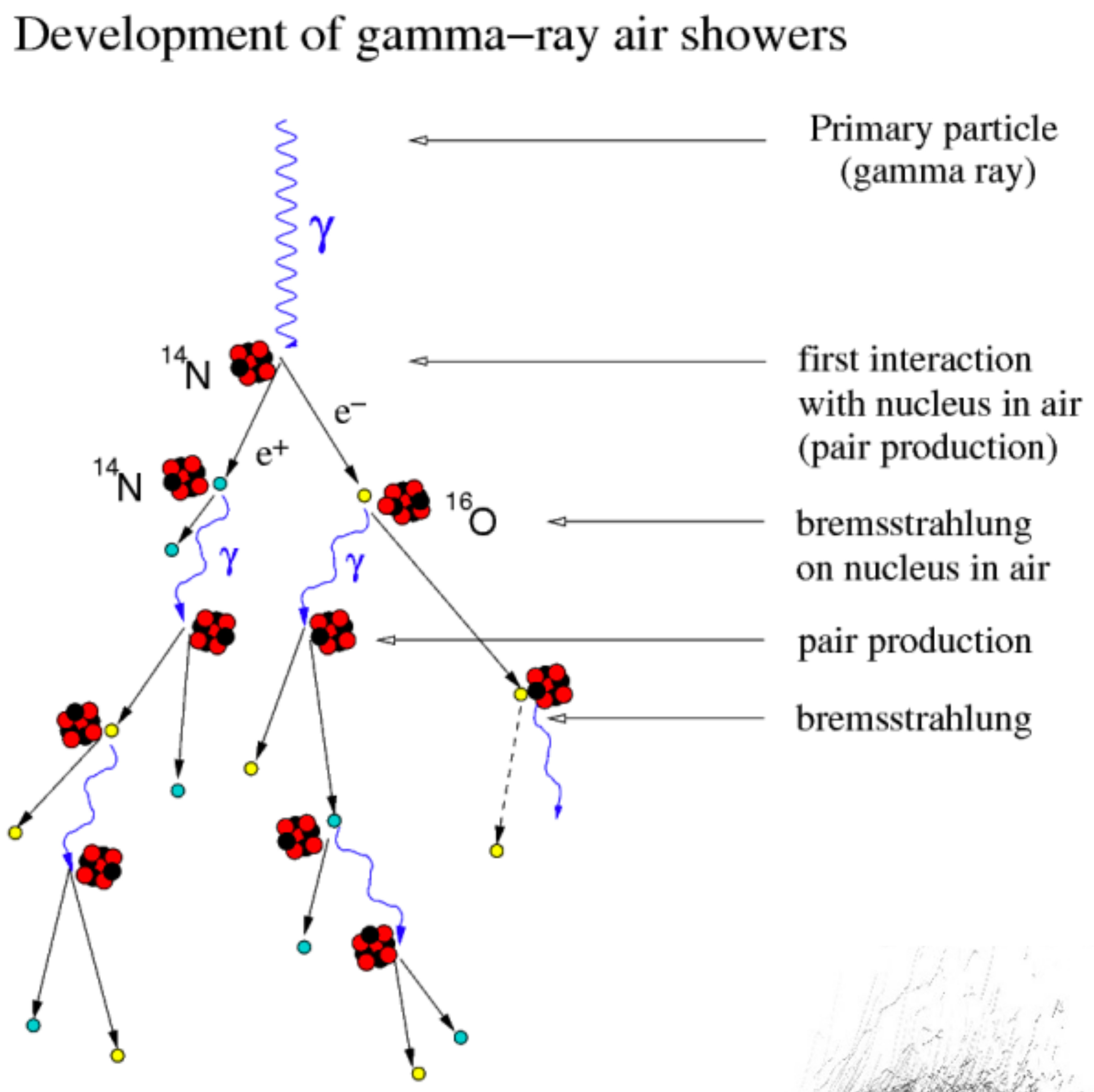
$$\Rightarrow \quad \sigma = \frac{7}{9}\frac{A}{X_0 N_A}$$



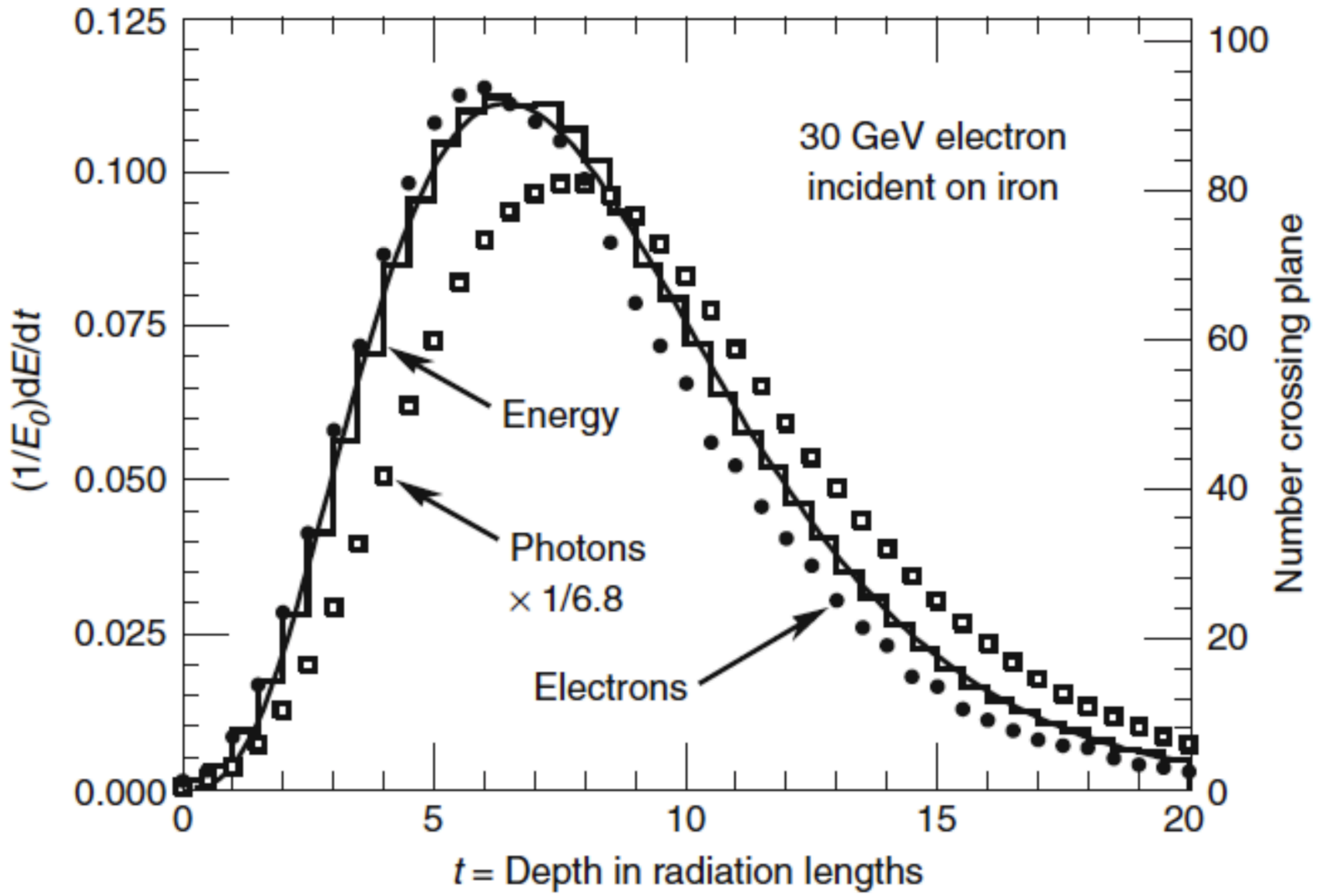
Q: why not this diagram?

Pair Production + Bremsstrahlung = EM Shower

- Essential for an EM Calorimeter (or Gamma-based astroparticle physics)



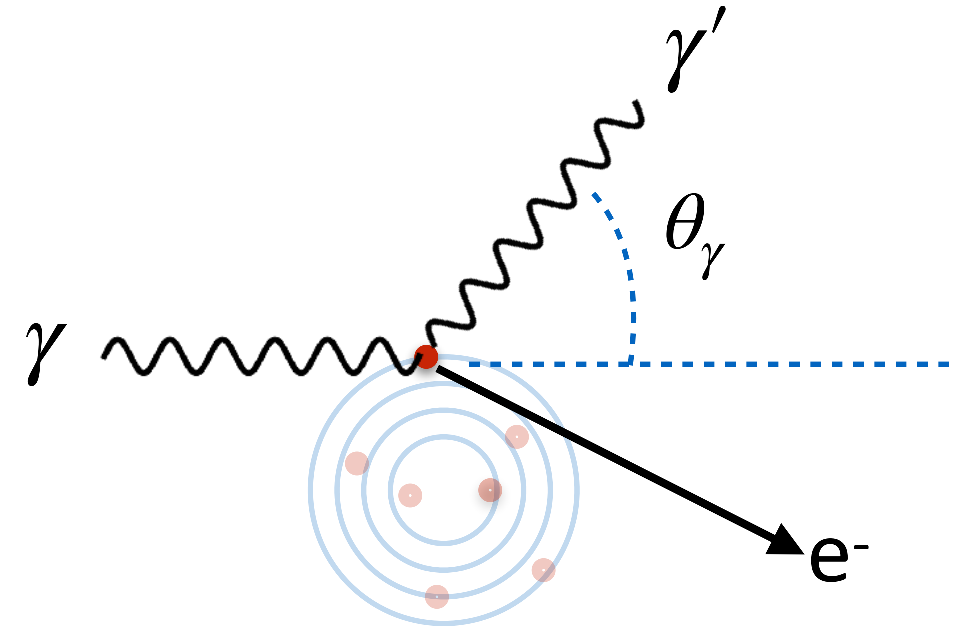
Electromagnetic shower



Photons: Compton Scattering

- Inelastic scattering of photons from quasi-free electrons (in the outer orbital shells)

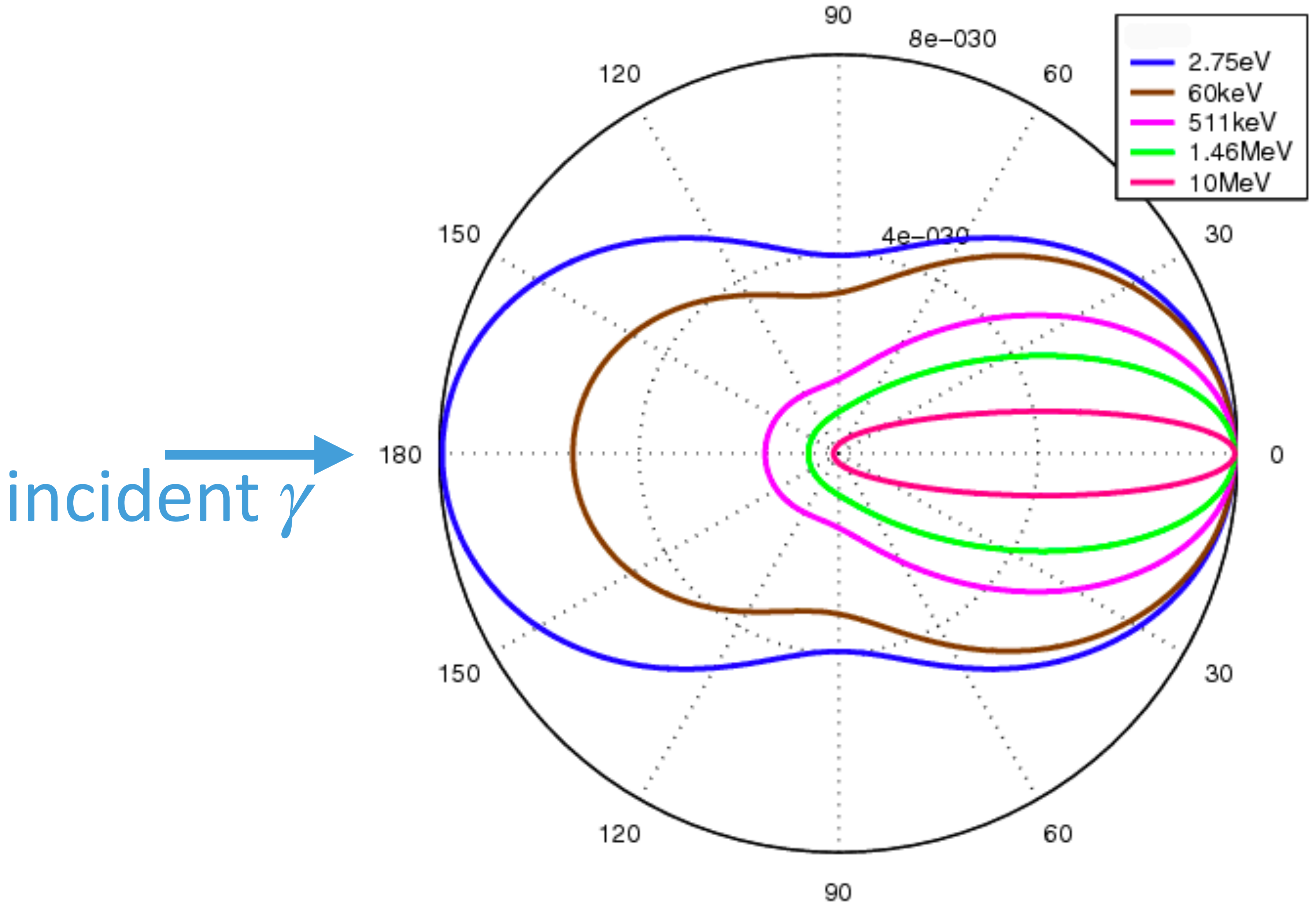
$$\frac{E_\gamma^f}{E_\gamma^i} = \frac{1}{1 + \frac{E_\gamma^i}{m_e c^2}(1 - \cos\theta_\gamma)}$$



- Discovered in 1922, full cross section from Klein and Nishina in 1929:

$$\sigma_C = \frac{\pi r_e^2}{E_\gamma / m_e c^2}\left(\ln\left(2\frac{E_\gamma}{m_e c^2}\right) + \frac{1}{2}\right)$$

- First real use of Dirac equation…

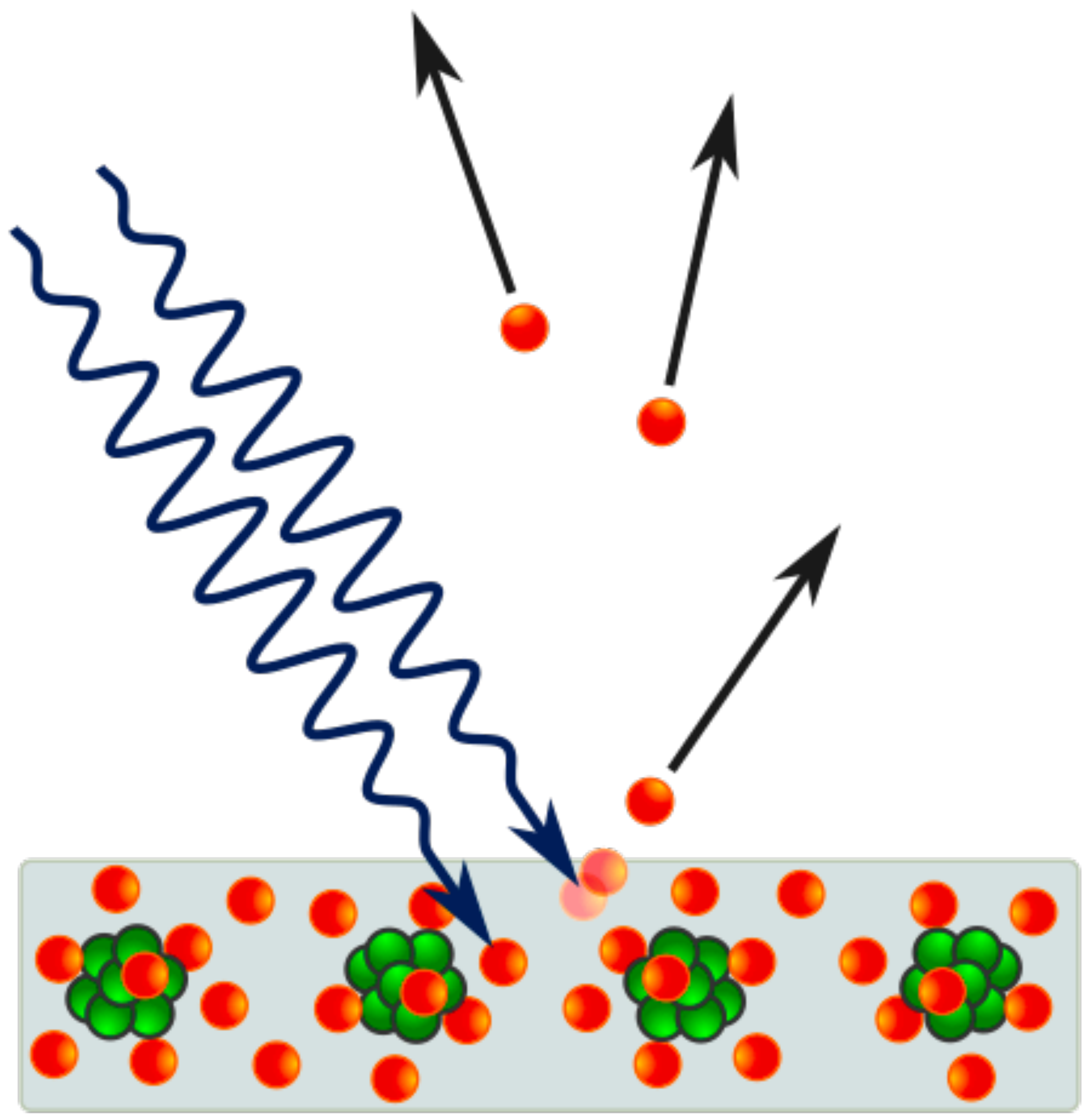


Photons: Photoelectric Effect

- Photon completely absorbed; energy transferred to electron
- For K-shell energies (internal orbit) with $E_\gamma > E_K$:

$$\sigma_\gamma^K = \sqrt{\frac{32(m_e c^2)^7}{E_\gamma}} \alpha^4 Z^5 (\frac{8}{3}\pi r_e^2)$$

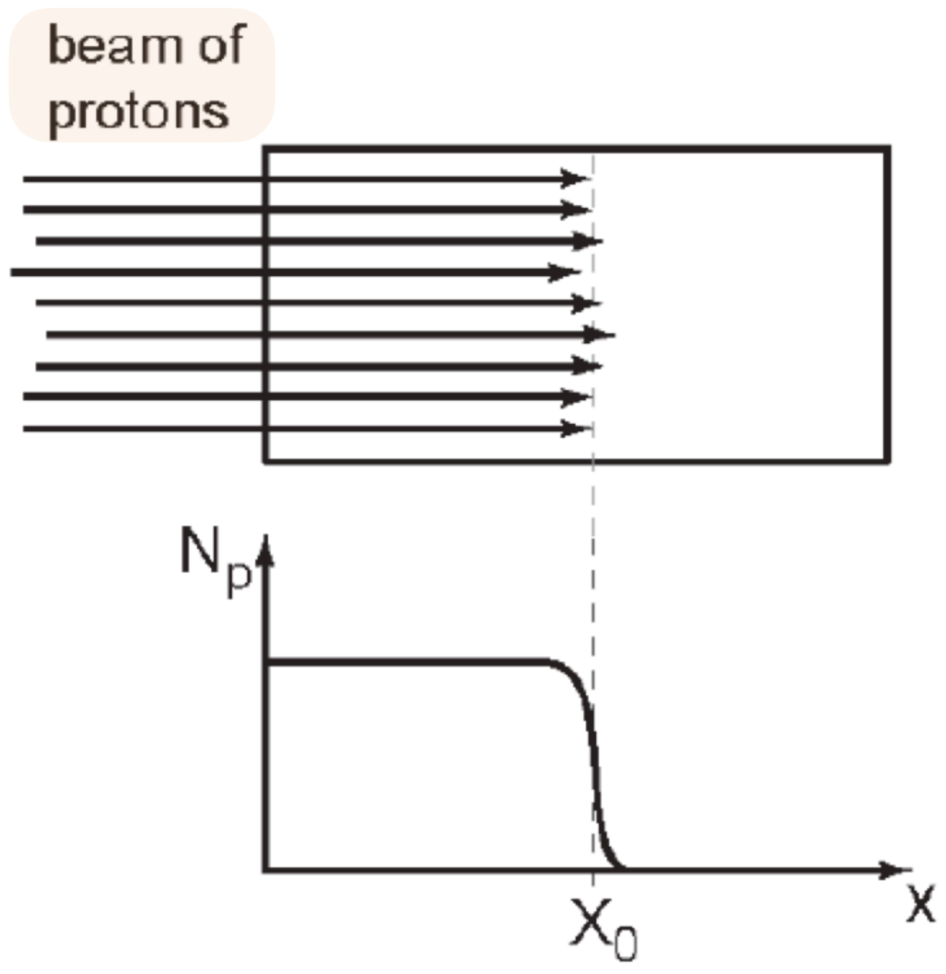
- Huge cross section at lower energies, as long as photon energy above threshold
- Not just K-shell, although absorption probability higher for tightly-bound K-shell e
- Several types of radiation possible (after excitation):
  - Photoelectron ejected directly
  - Characteristic X-rays emissions (from excited orbits)
  - Auger electrons (Meitner)
- Process very important for photomultipliers; it starts the cascade

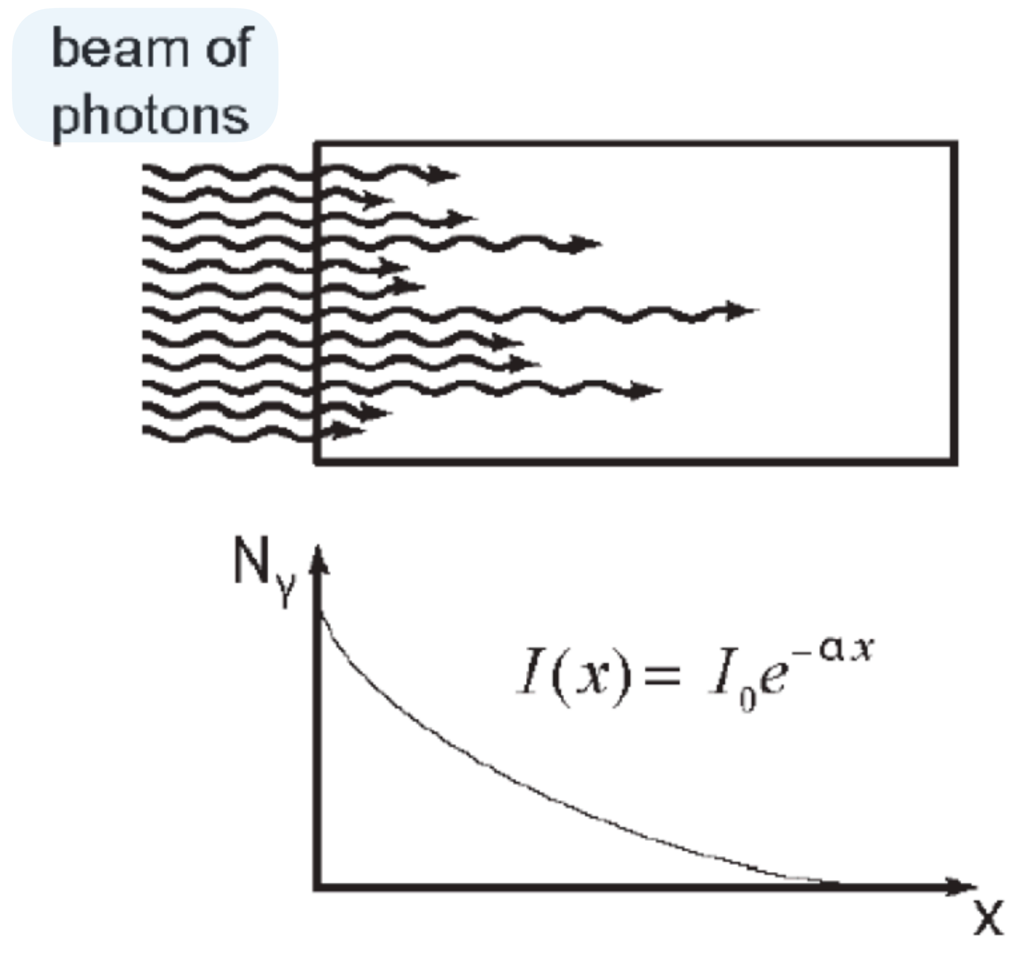


[PDG, Wikipedia (figure)]

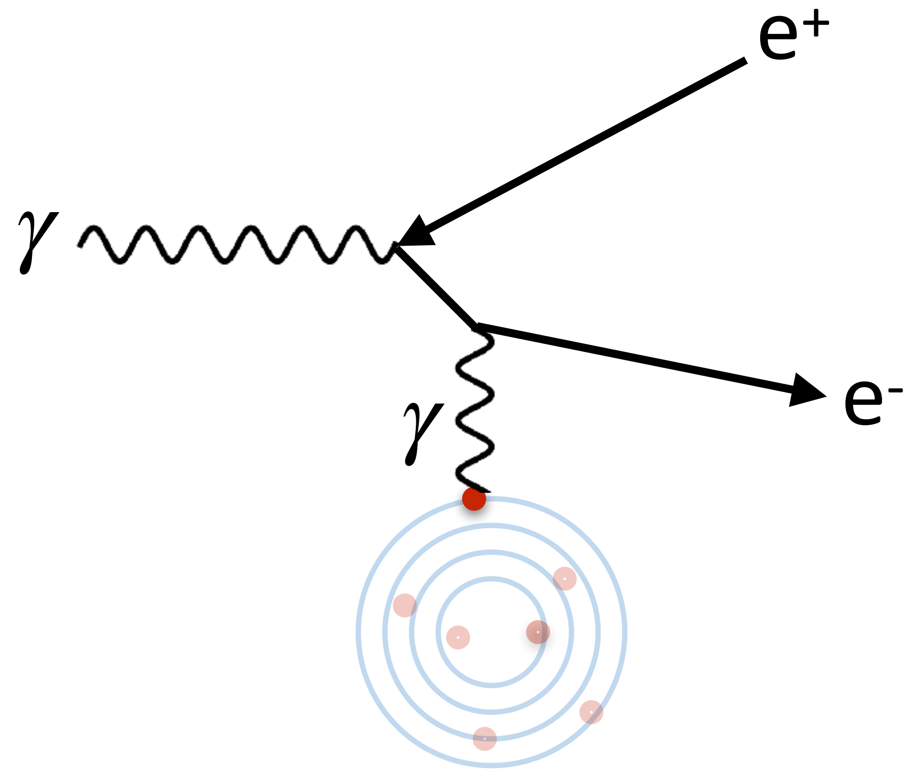
Photon Interactions

- Photon interactions often “catastrophic”
- Photon often absorbed, so treat as a flux
- Different effects at different energies
  - High E: pair production
  - Mid-E: Compton Scattering
  - Low-E: Photoelectric effect

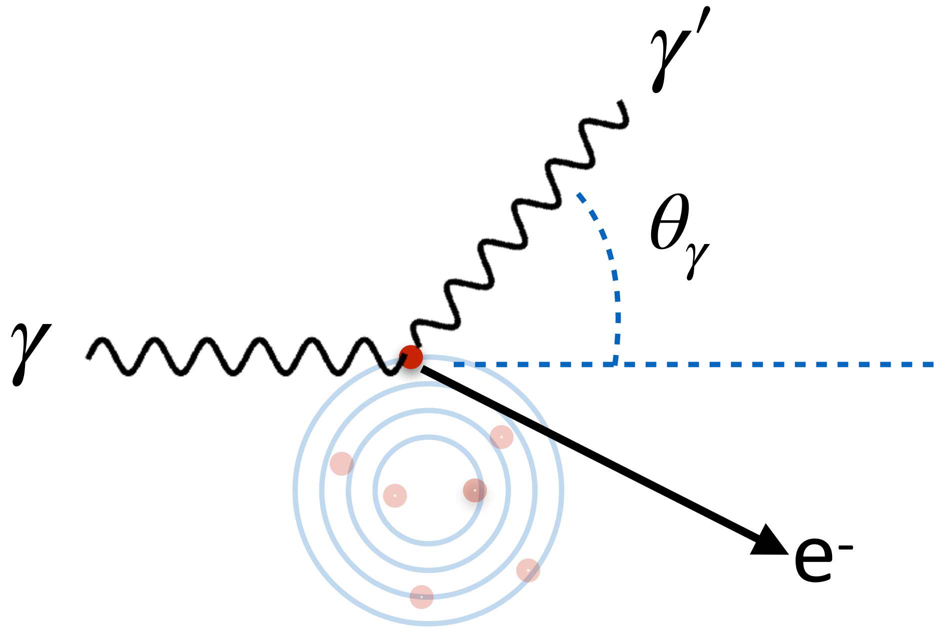




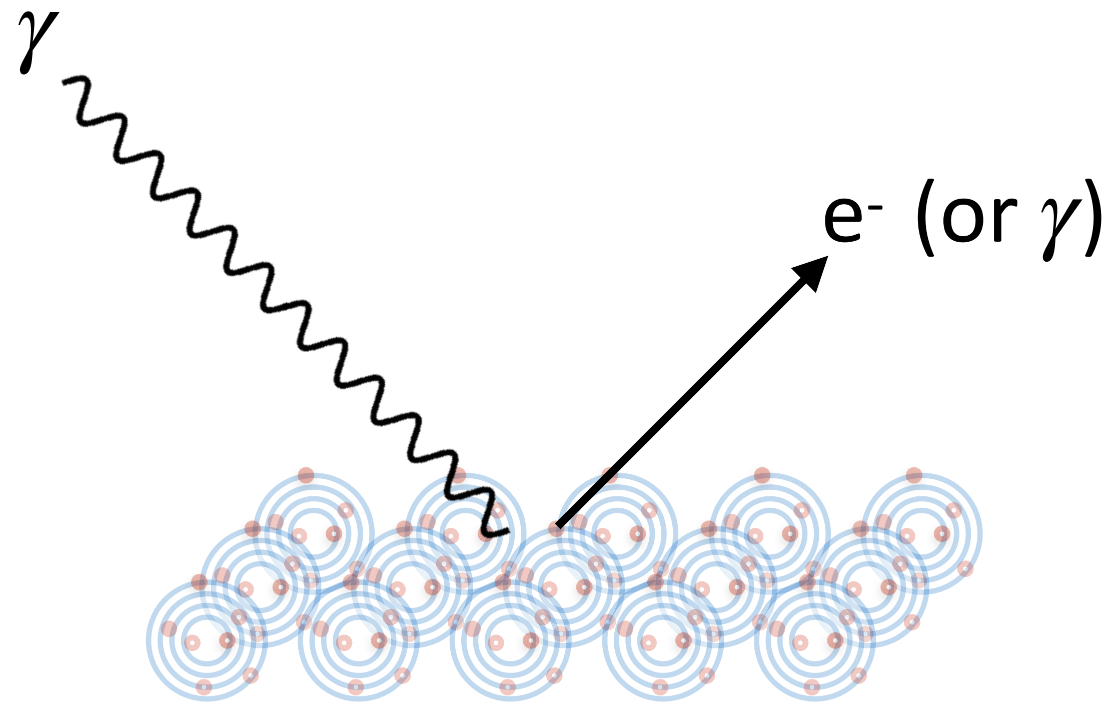
Pair Production



Compton Scatter



Photoelectric Effect



Photon Interactions - Summary

- Photoelectric processes dominate below a few 100 keV
- Narrow window of energies where Compton is dominant
- Pair production dominates above 1 MeV
- EM showers (Bremsstrahlung + Pair Production) dominant energy loss mechanism at high energies

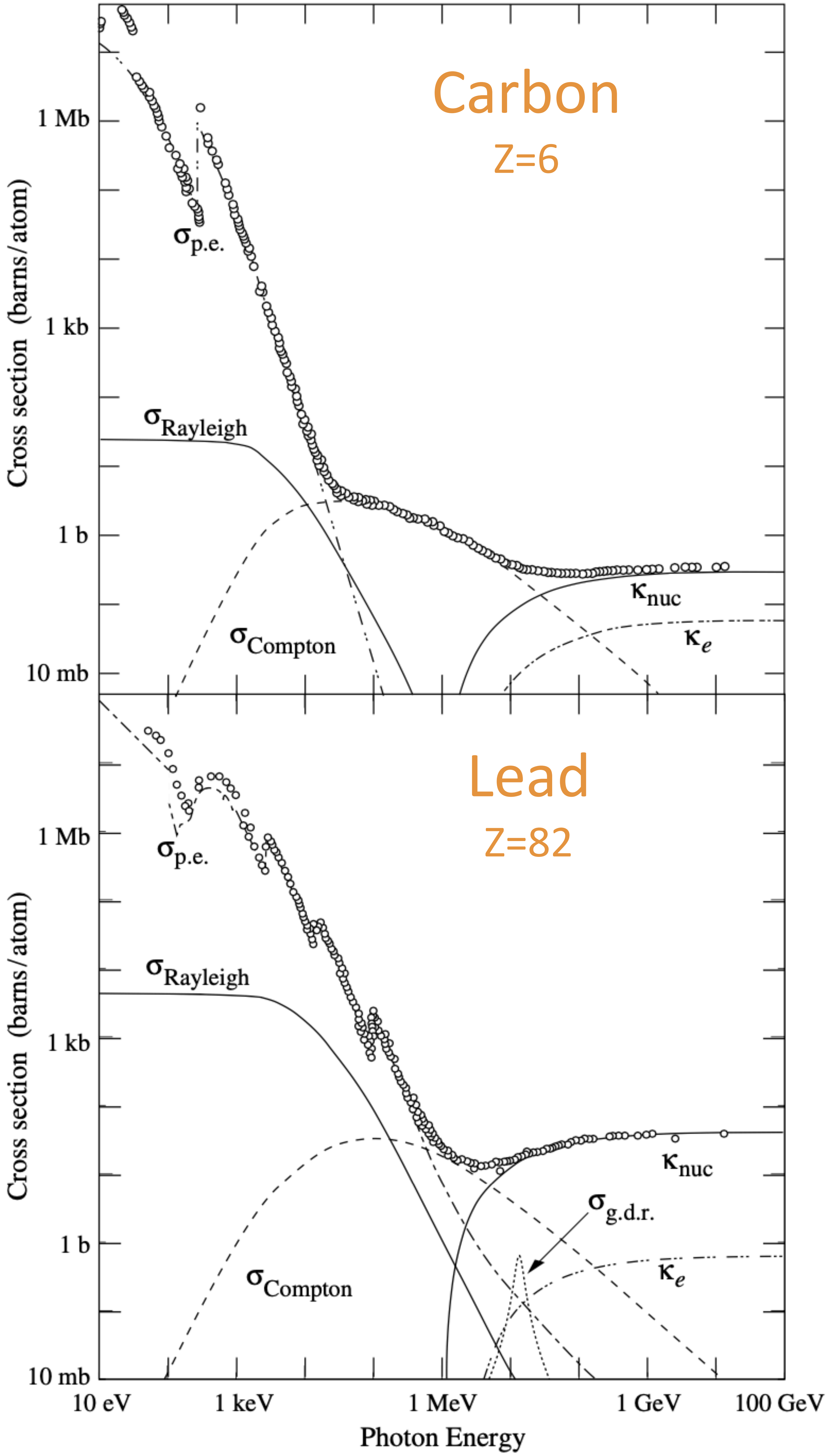


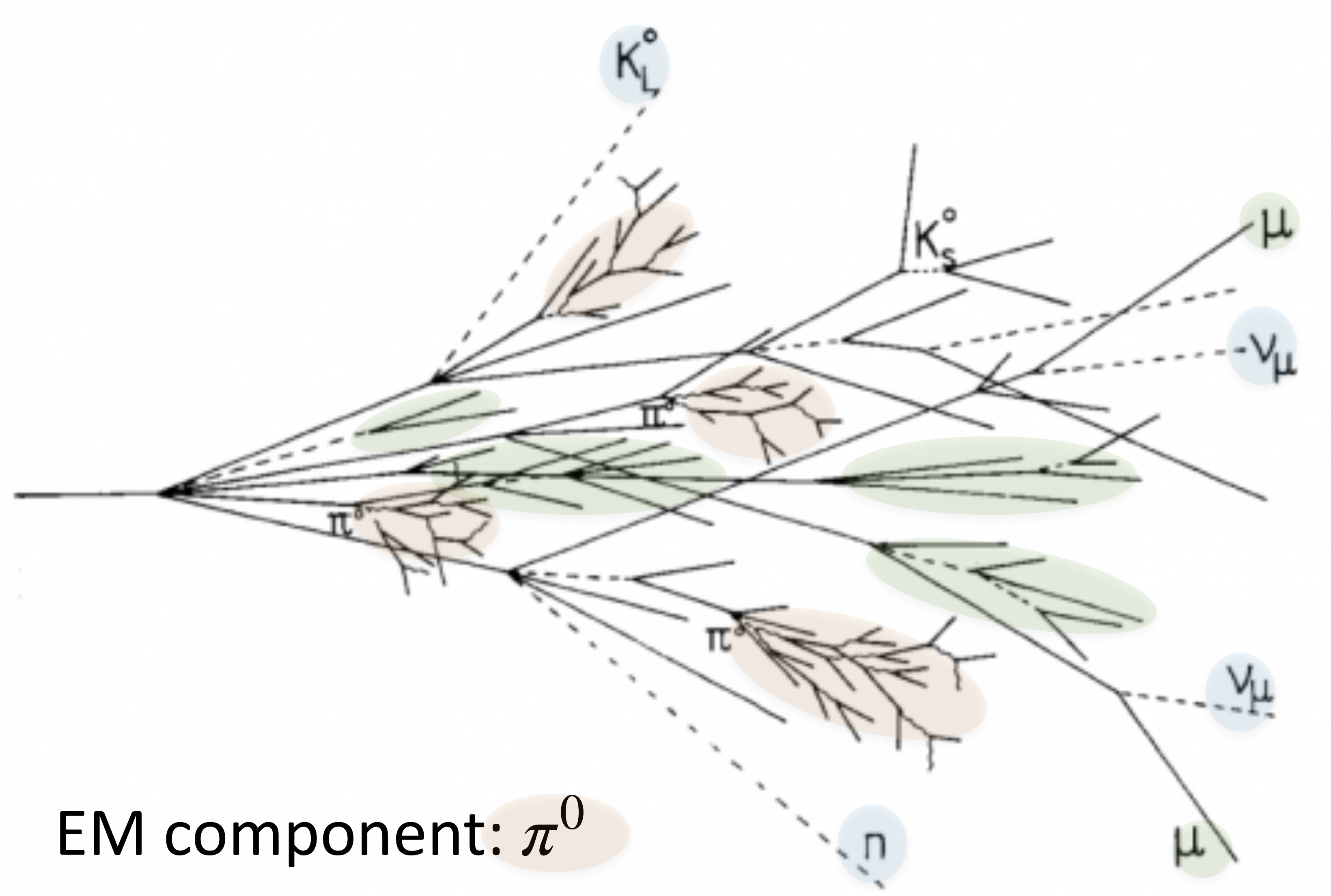
Figure 34.15: Photon total cross sections as a function of energy in carbon and lead, showing the contributions of different processes [50]:

$\sigma_{\text{p.e.}}$ = 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.

Symmetry Magazine

Strong Interactions and Hadronic Showers

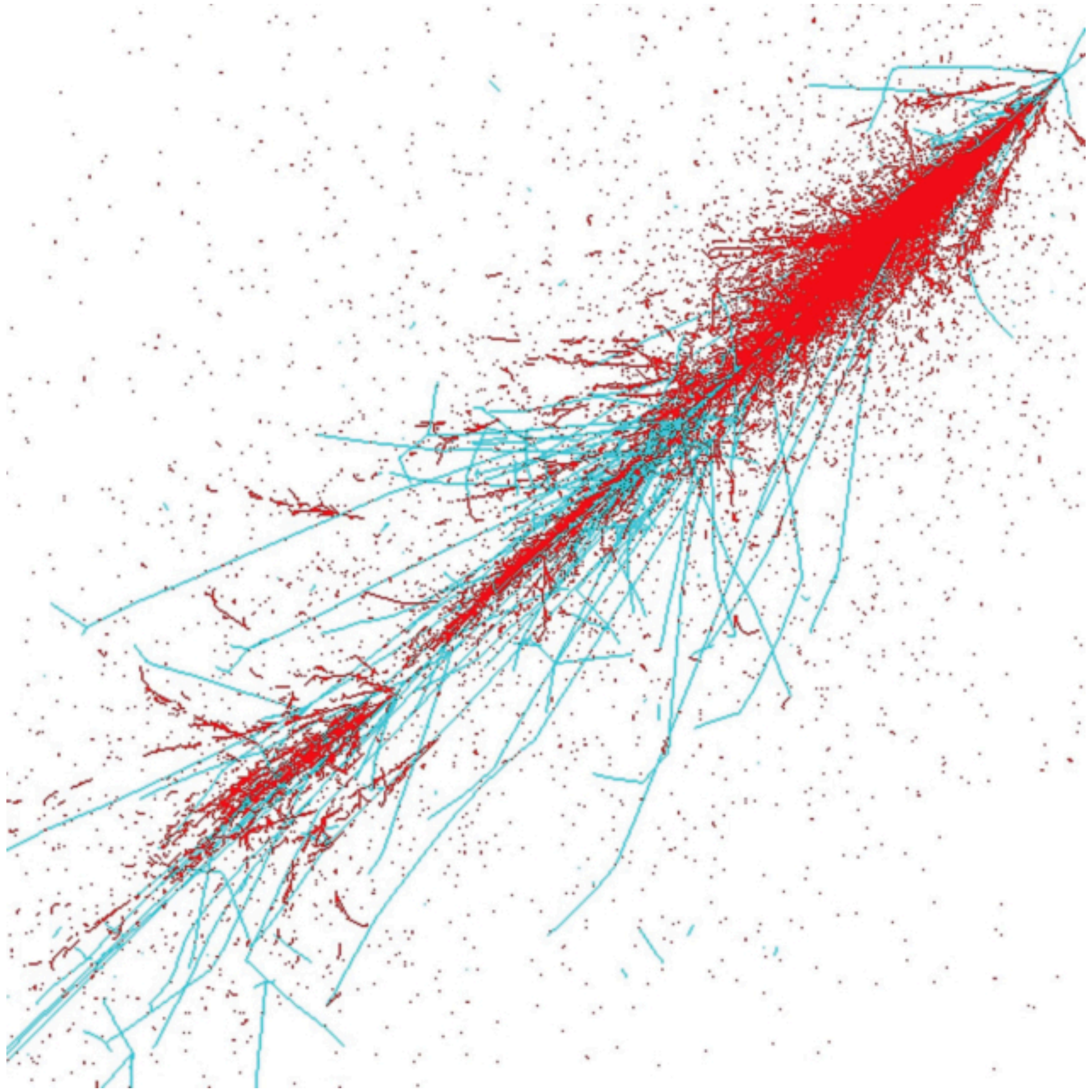
- In addition to ionisation, hadrons ($n, p, \pi^{\pm}, \pi^0, K\ldots$) can have strong interactions with matter
- Hadronic interactions (quarks, gluons) create showers of particles similar to EM cascades



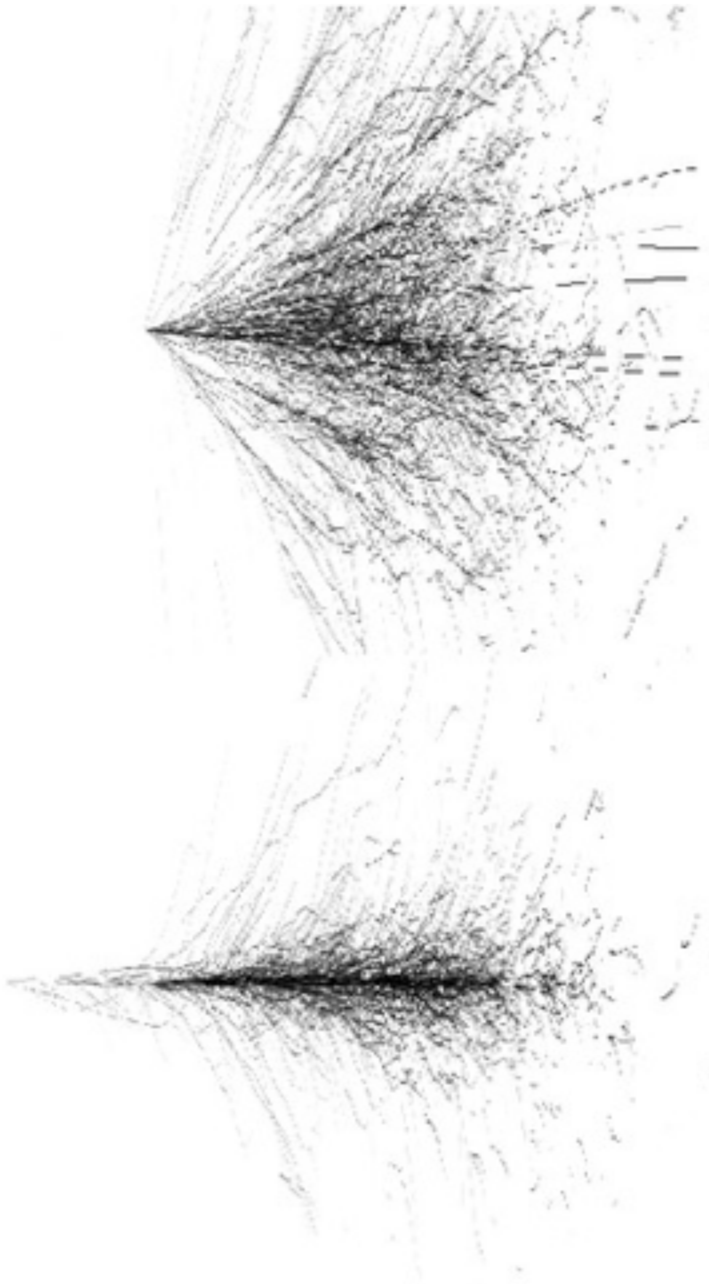
EM component: π^0

neutrals: n, ν, K_L^0

charged: $\pi^{\pm}, p, \mu, He$



https://physicsworld.com/a/where-the-energy-goes/
(simulation of 500 GeV proton on copper)



Hadronic Interactions - Properties

- High energy particle initiates a cascade (hadronic interaction)
  - create high energy charged particles ($\pi^{\pm}, p,$ etc) that make secondary cascades
  - π^0 (and η) decays to $\gamma\gamma$ and initiates an EM shower (Bremsstrahlung + pair production)
  - neutrinos escape, but some neutral particles (n) continue to interact

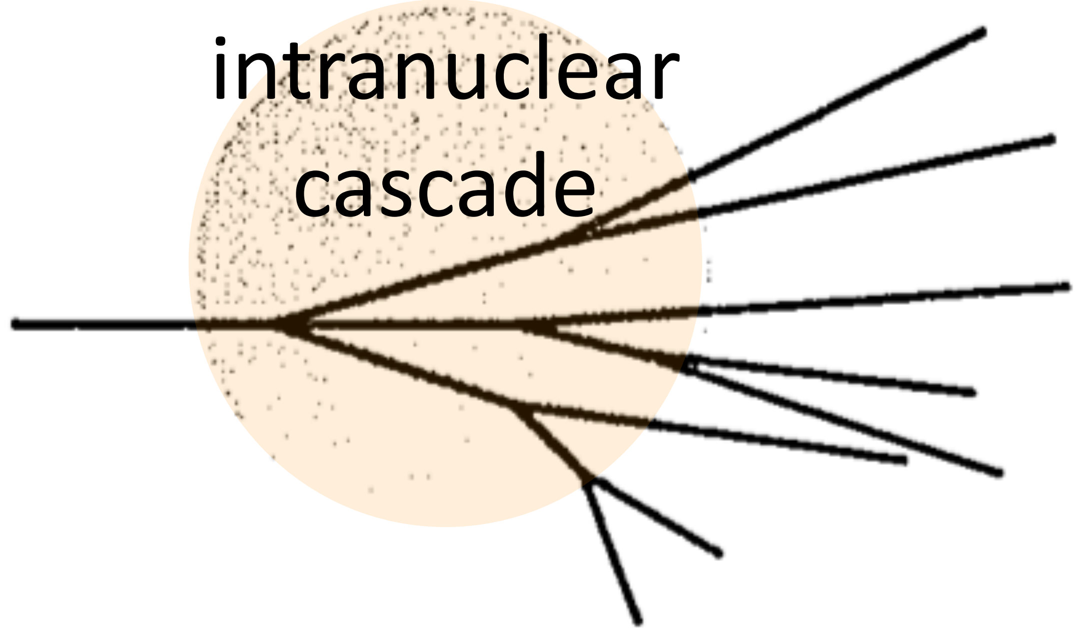
- Low energy particles decay or are absorbed
  - pions → muon + neutrino
  - muons → electron + neutrinos
  - neutrons → decays to proton+electron+antineutrino or is captured

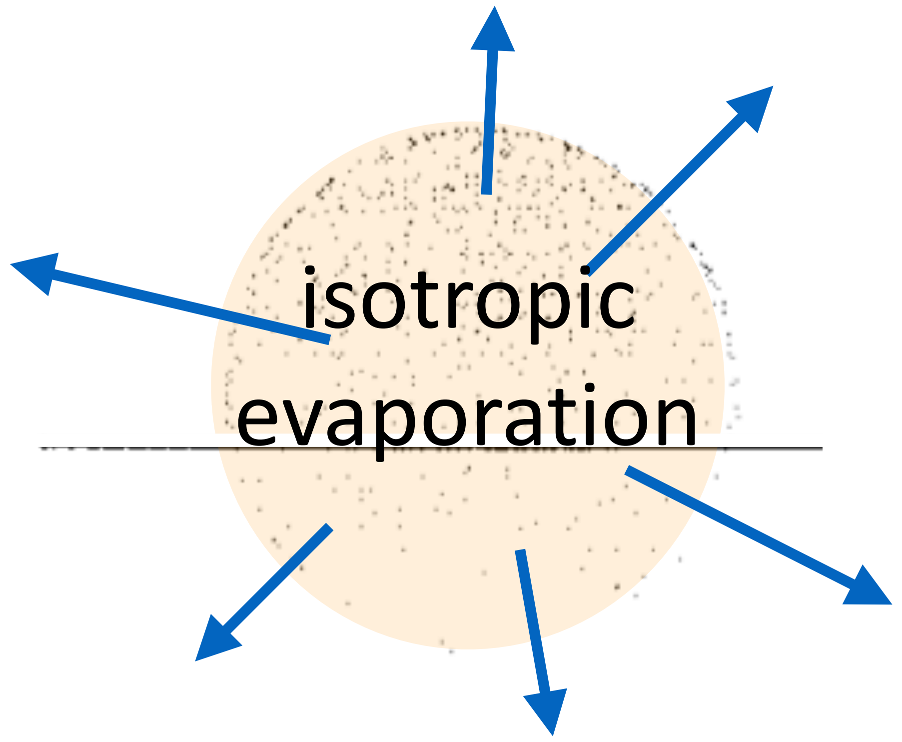
- Significant “invisible” energy
  - neutrinos escape undetected
  - binding energy of nucleons goes undetected

- Large statistical variations in energy deposition event-to-event (much more than for EM shower)

Spallation and Absorbers (Nuclear Energies)

- Two-stage process most likely for incoming $O(\mathrm{MeV})$ energy hadrons:
  1. Fast intranuclear cascade
     - collisions with nucleons, which initiate secondary collisions (cascade)
     - fast (>20 MeV) particles ejected, causing further interactions
     - spallation products mostly in the forward direction
  2. Slower evaporation stage
     - de-excitation of struck nucleus
     - isotropic "evaporation" of free nucleons, γ (few MeV), sometimes α, etc





- Huge diversity of interactions & response from absorber, eg Lead vs. Iron:
  - number of nucleons released is much bigger for lead; lower binding energy
  - many more neutrons vs protons in Pb; 4x more neutrons released
  - consequences: Pb gives more "invisible" energy, higher EM fraction
  - choice of absorber important for detector performance!

	Lead	*Iron*
Ionization by pions	19%	21%
Ionization by protons	37%	53%
Total ionization	56%	74%
Nuclear binding energy loss	32%	16%
Target recoil	2%	5%
Total invisible energy	34%	21%
Kinetic energy evaporation neutrons	10%	5%
Number of charged pions	0.77	1.4
Number of protons	3.5	8
Number of cascade neutrons	5.4	5
Number of evaporation neutrons	31.5	5
Total number of neutrons	36.9	10
Neutrons/protons	10.5/1	1.3/1

A.Kaplan, A.Tadday

Neutrons

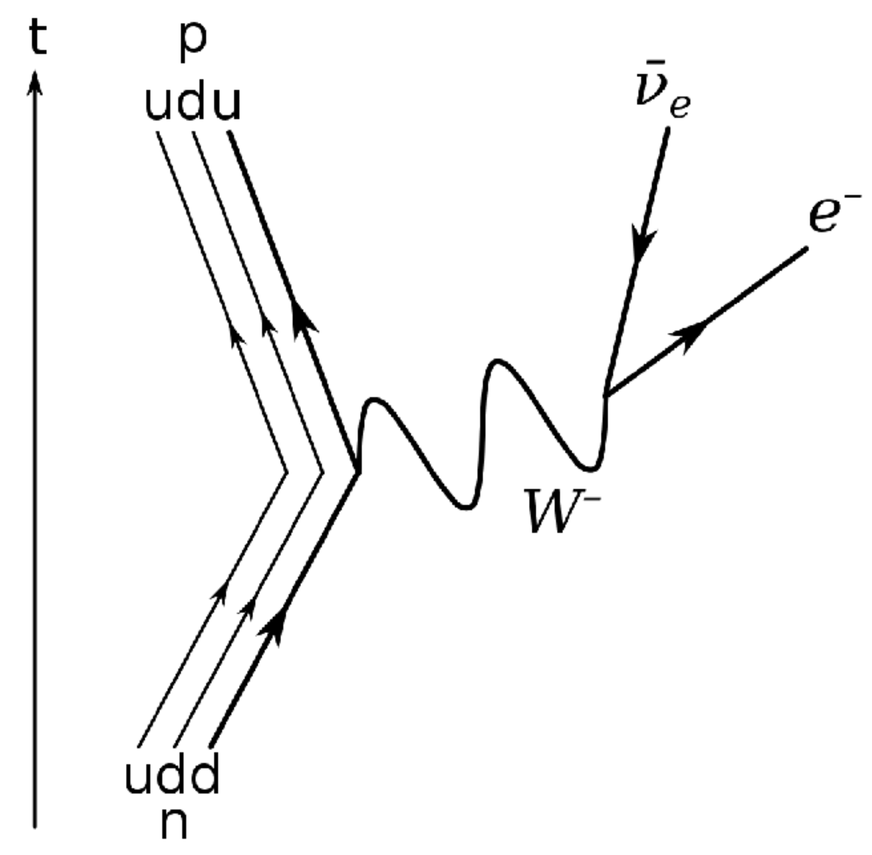
- Many neutrons result from spallation, evaporation
- Typical steps: neutrons lose energy via elastic/inelastic collisions, then react strongly (capture) or decay
  - Almost all neutrons in absorber (after a few ns) are from evaporation process
  - Energy spectrum follows Maxwellian distribution:

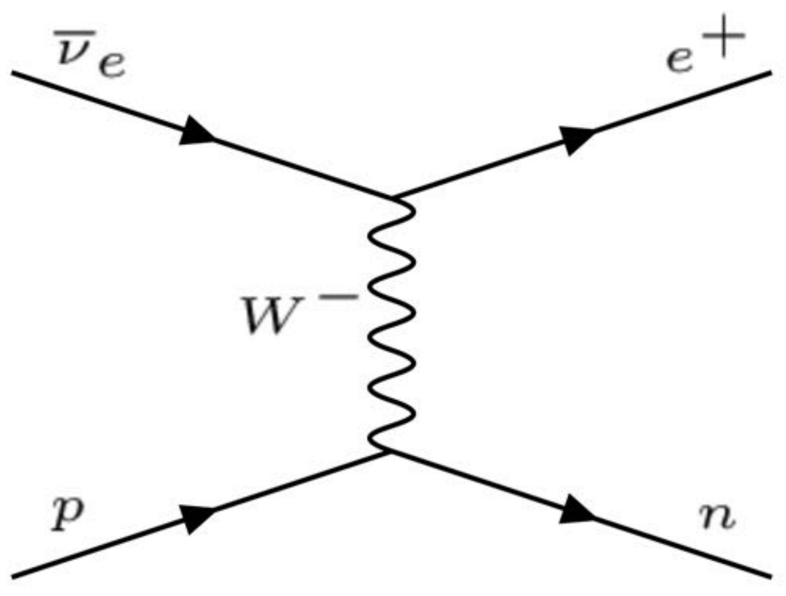
$$\frac{dN}{dE} = \sqrt{E}\,\exp(-E/T)$$

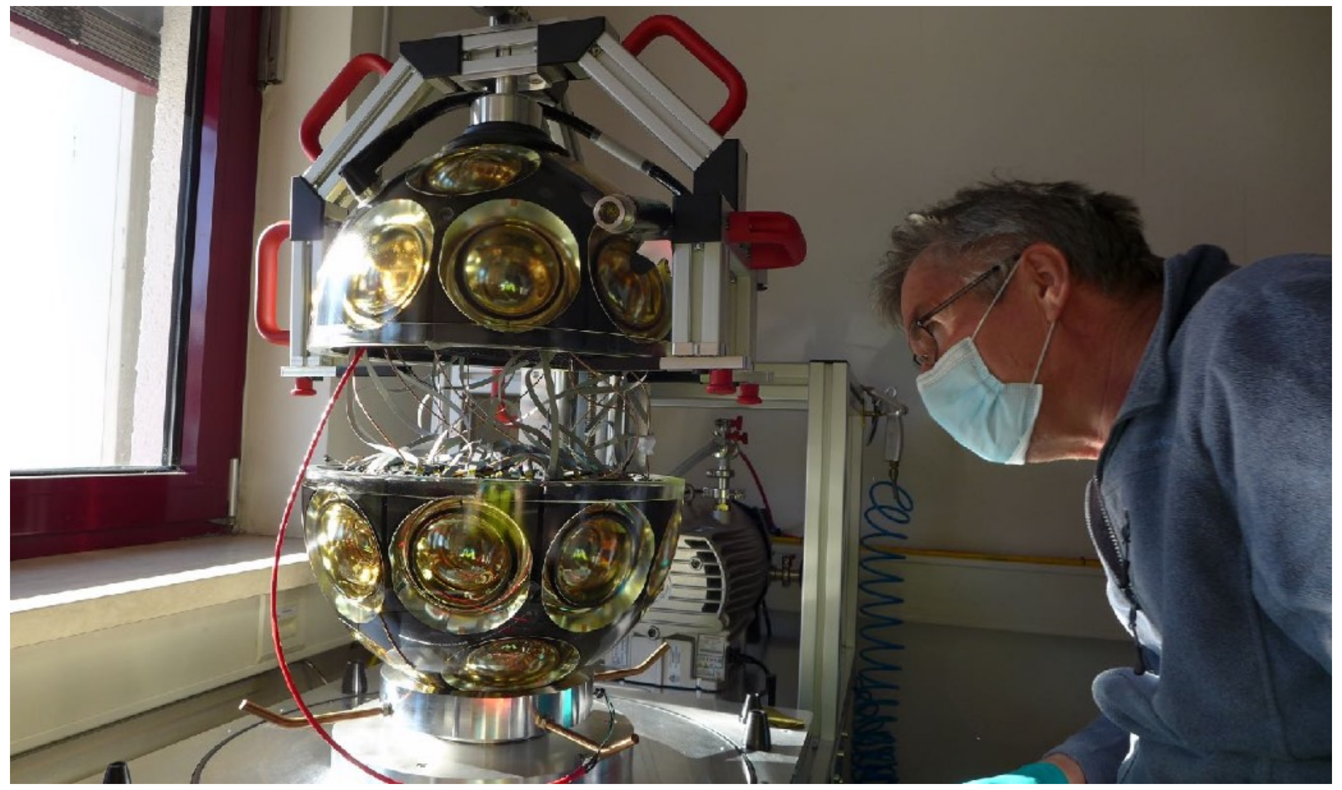
- Inelastic scatter ($n \rightarrow n' + \gamma$) at higher energies (MeV or greater)
- Elastic scatter at lower energies
  - quickly reduces the kinetic energy: 50% loss for collision with hydrogen (water, plastic), 3.4% Fe, 1% Pb
  - neutrons ‘thermalise’ after few μs ($E_{\mathrm{kin}} \sim 1/40\ eV$)
- Capture
  - neutrons ‘captured’ by a nucleus, emitting photon (binding energy): e.g. capture on hydrogen yields 2.22 MeV γ

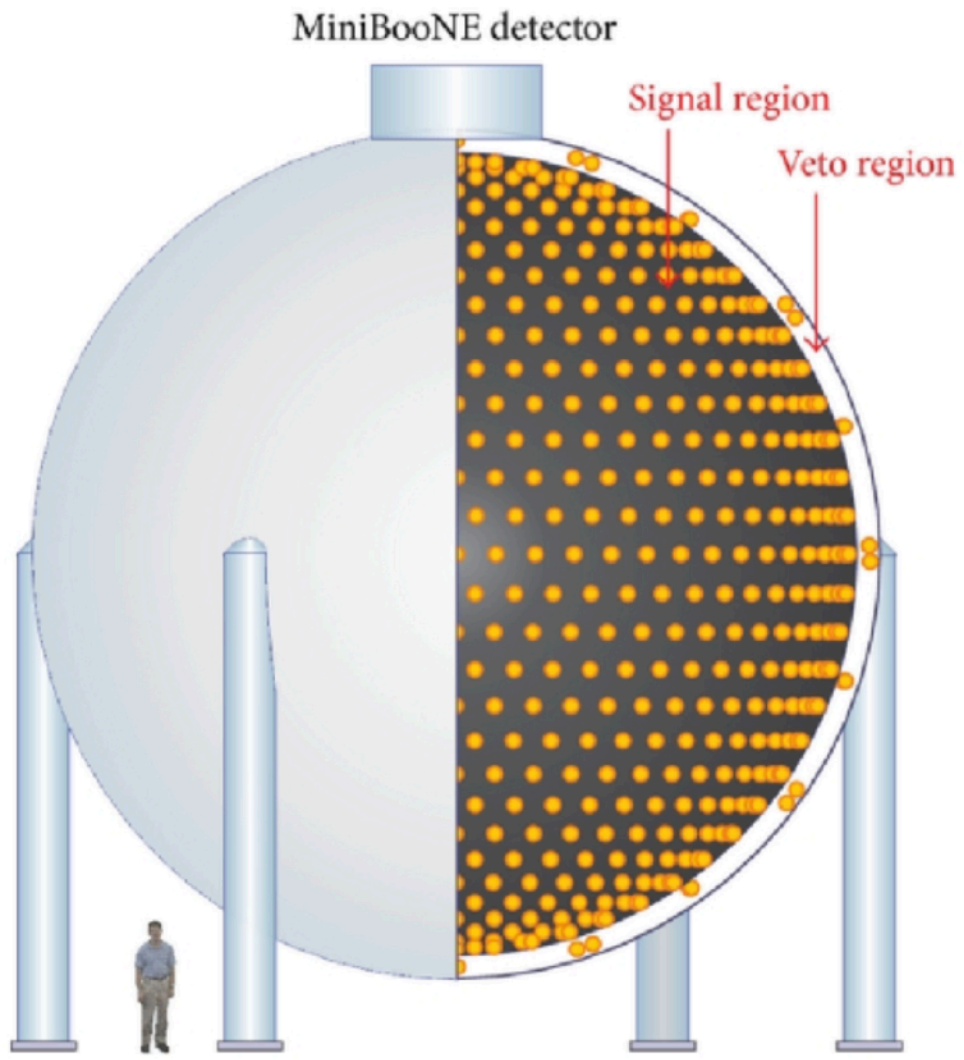
Neutrino Interactions (Weak Force)

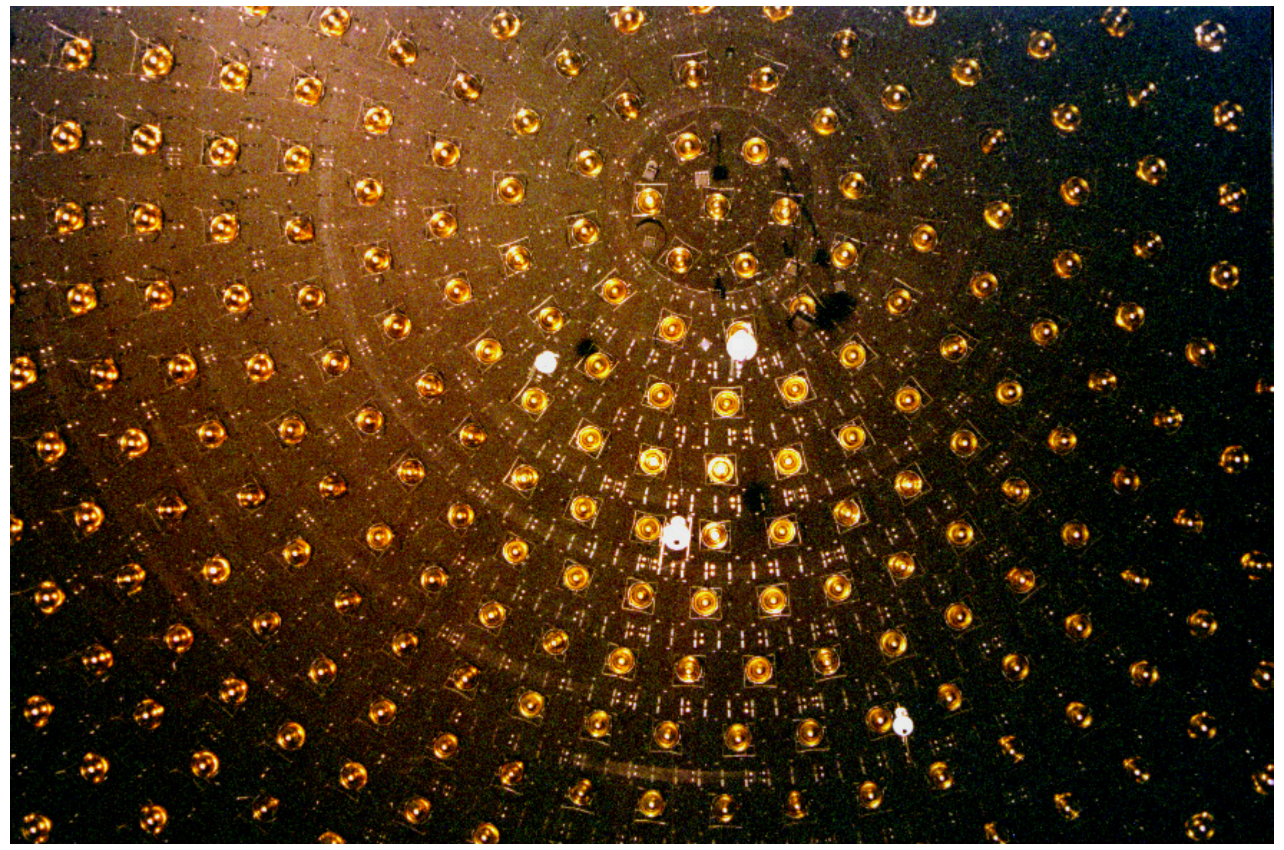
- Detected indirectly, from e or p
- Many detection techniques for neutrinos
  - Scintillators: Kamland, Borexino
  - Radiochemical methods: SAGE, GALLEX
  - Cherenkov detectors: SNO (photo), Kamiokande, MiniBooNE, KM3NeT, IceCube…
  - Radio detectors: ANITA
  - Tracking calorimeters: MINOS
- Many neutrino ‘telescopes’ now operating



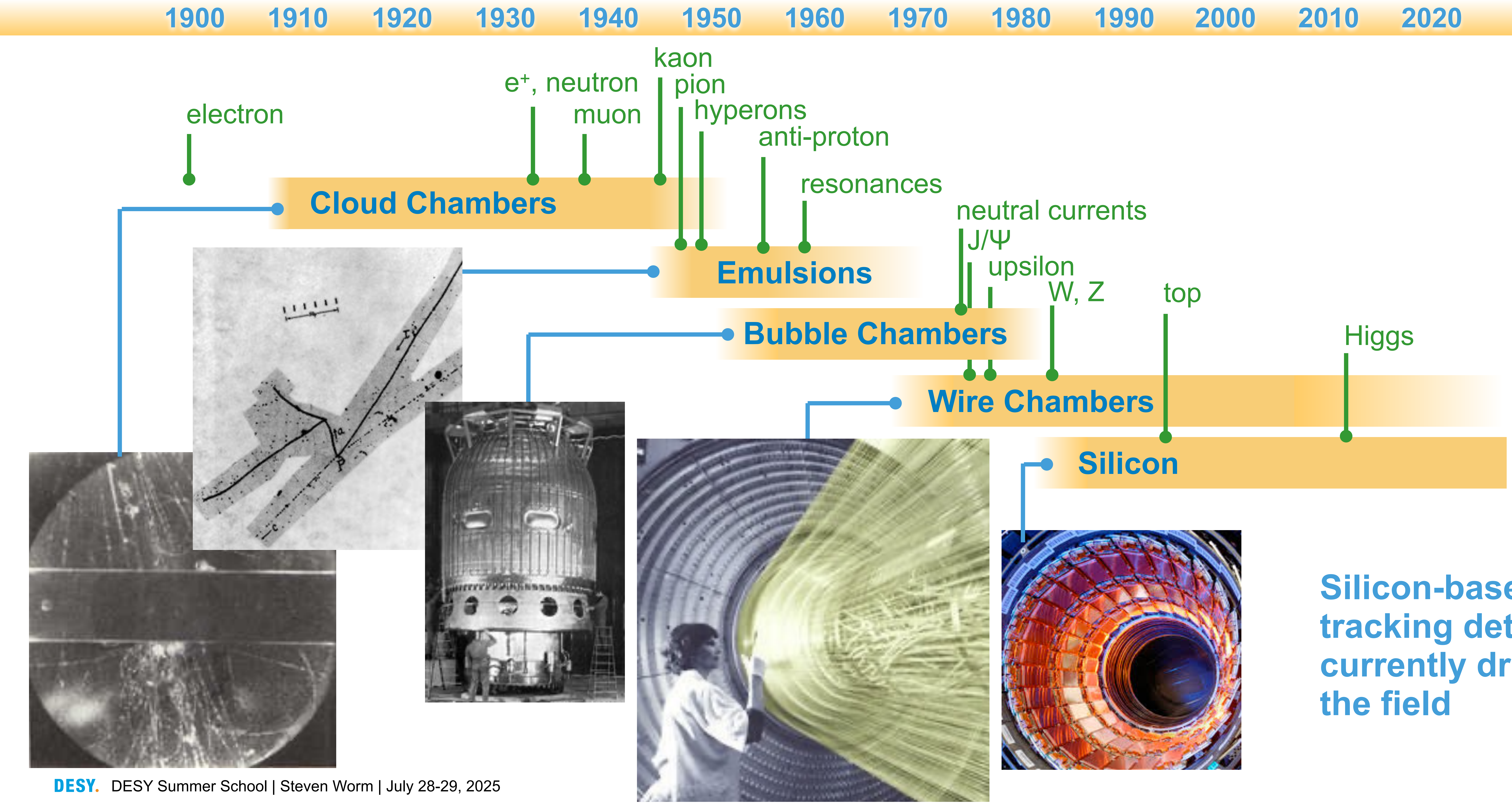








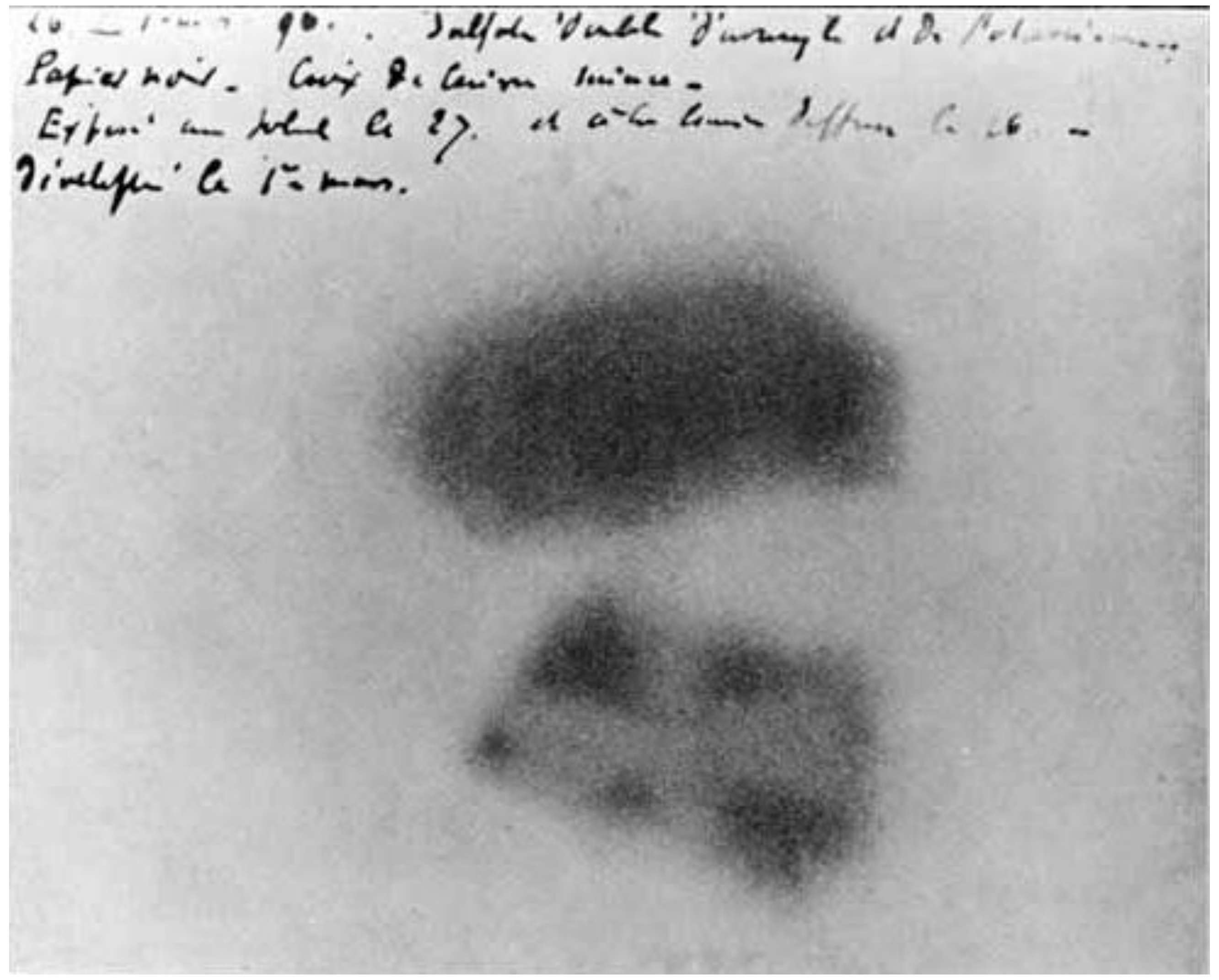
Particle Discoveries and Detector Technology

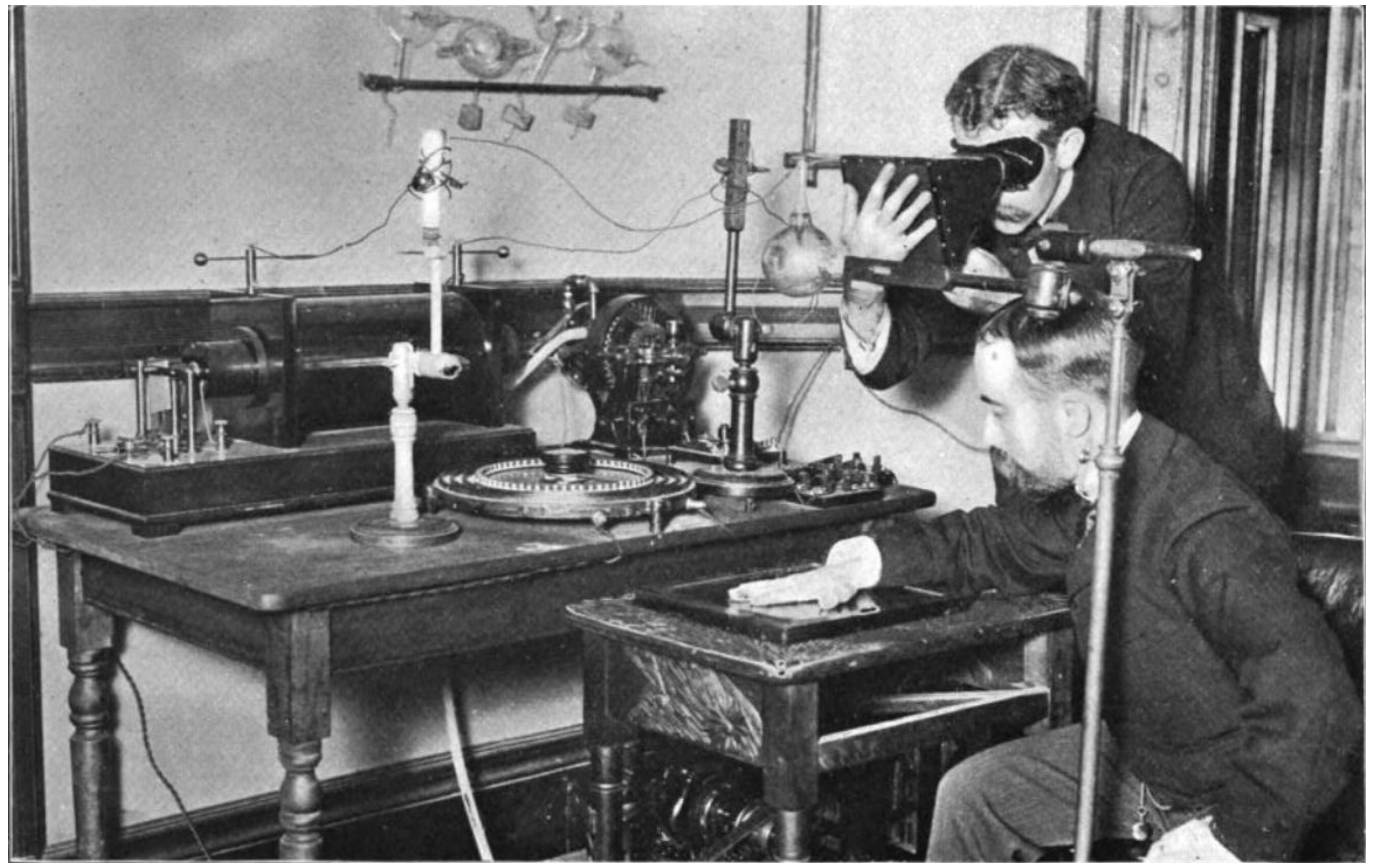


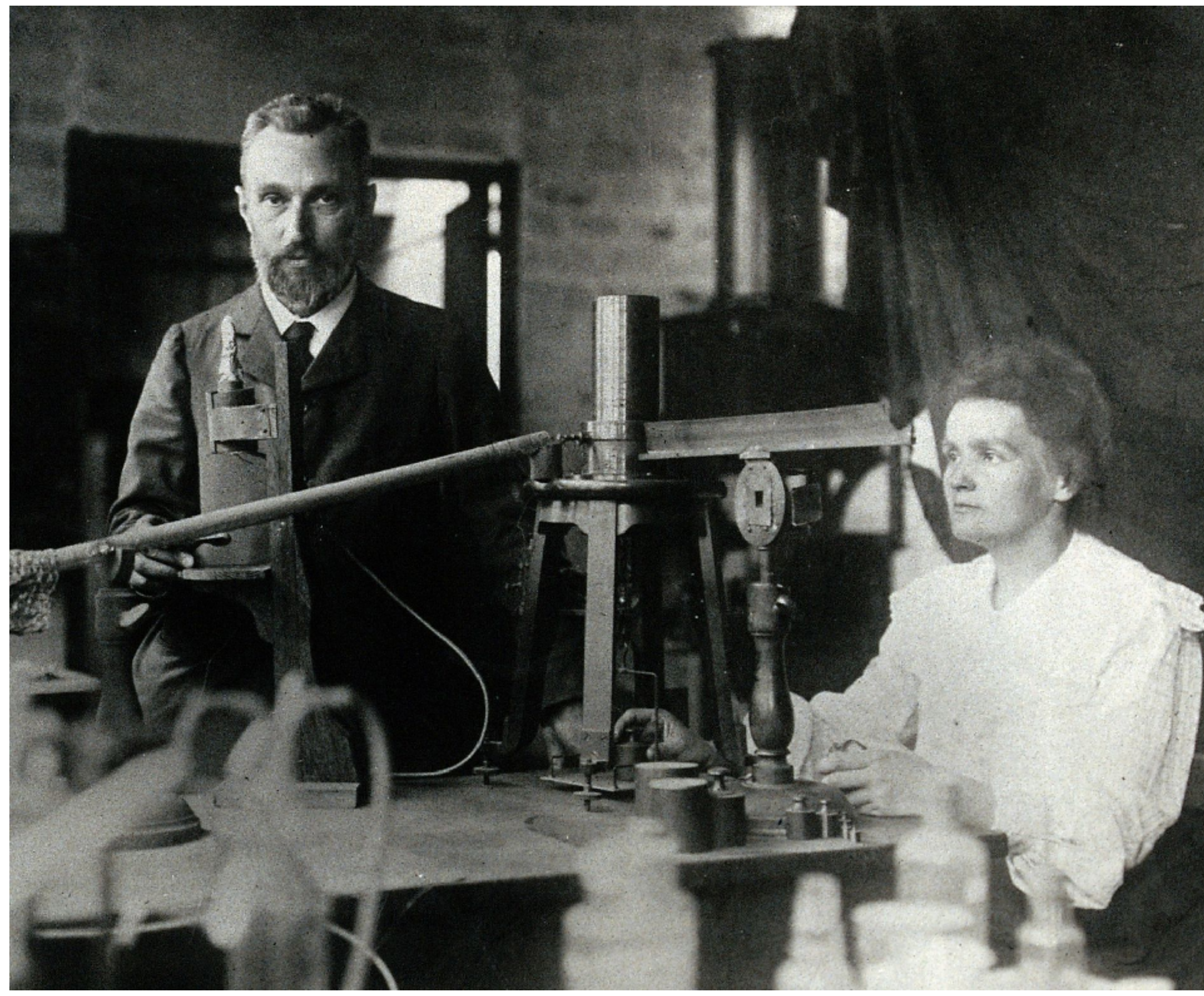
Silicon-based tracking detectors currently driving the field

Early History of Radiation

- From X-Rays to radioactivity, electrons, alpha particles
  - Röntgen discovers X-Rays in late 1895, send a mail (and photos) to Poincaré
  - Poincaré tries it out himself, gives lecture in Feb 1896 attended by Becquerel
  - Becquerel thinks it might be related to phosphorescence, and adds magnets to discover charged radiation
  - Curie gave the name "radioactivity", and as Becquerel's student, does a lot of the work (and later new elements, etc)
  - Rutherford figured out properties, names them alpha, beta, gamma (1899), conducts first particle experiments
- …all in just a few years!







[https://www.earthmagazine.org/article/benchmarks-henri-becquerel-discovers-radioactivity-february-26-1896, Wikipedia]

Emulsions

- Used in the early days (ie turn of century) by Röntgen, Bequerel → discovery of radiation
- Continued to be used (mid 1950's) because of the high resolution
  - Grain size of a developed silver halide cluster 10 nm - few μm (tiny!)
  - Picture is worth a thousand words…but you have to look!
- Ingredients:
  - A silver halide, gelatin-plasticiser, and water
  - Layer of emulsion ~600 μm thick on a plate
  - Often stack many plates together
  - Can 'load' plates w/ wires, foils, powders to better define a target
- How it works (basically just a photograph)
  - Charged particles ionize, deposit a lot of energy
  - Ionization (heat) causes silver halide grain to 'develop'
  - MIP makes ~270 developed grains per mm in standard emulsion
  - Slow/heavy particles make darker lines

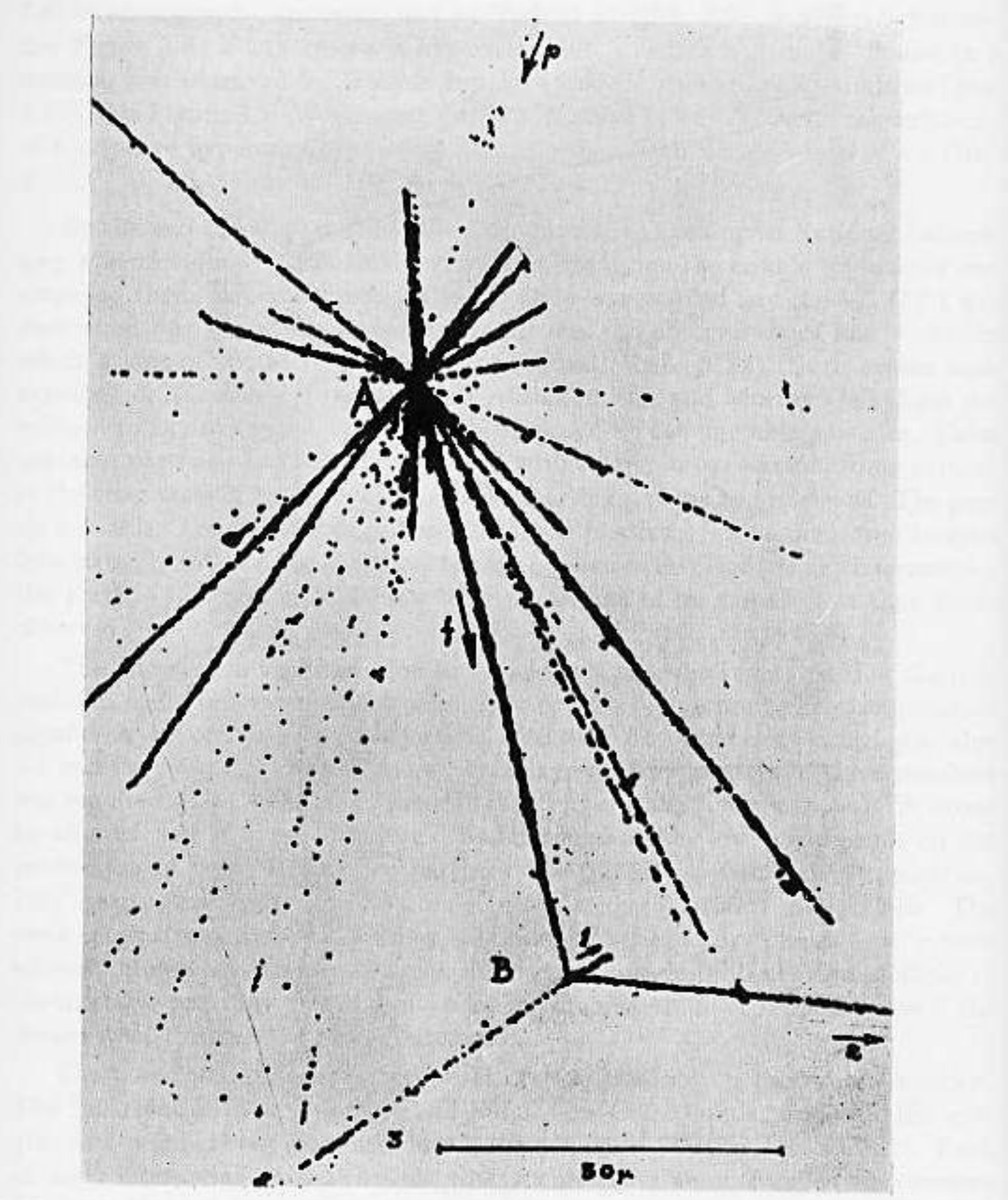
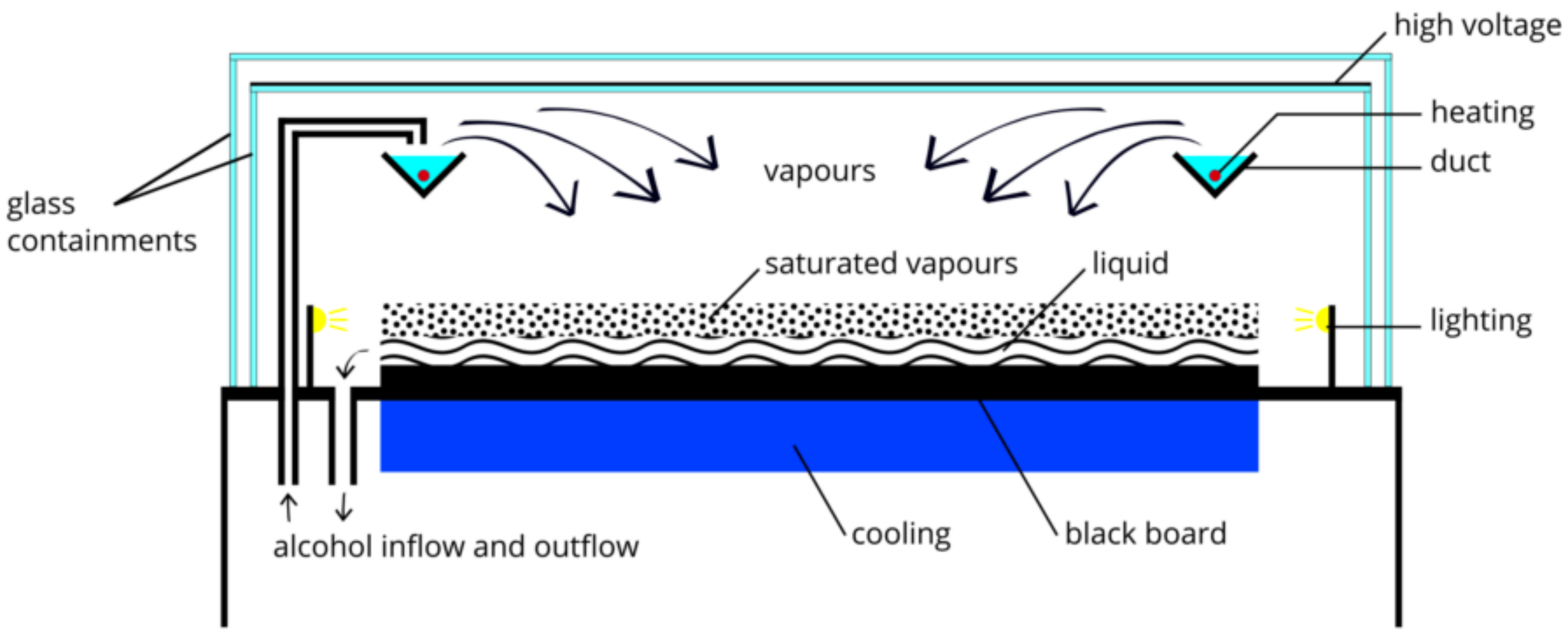


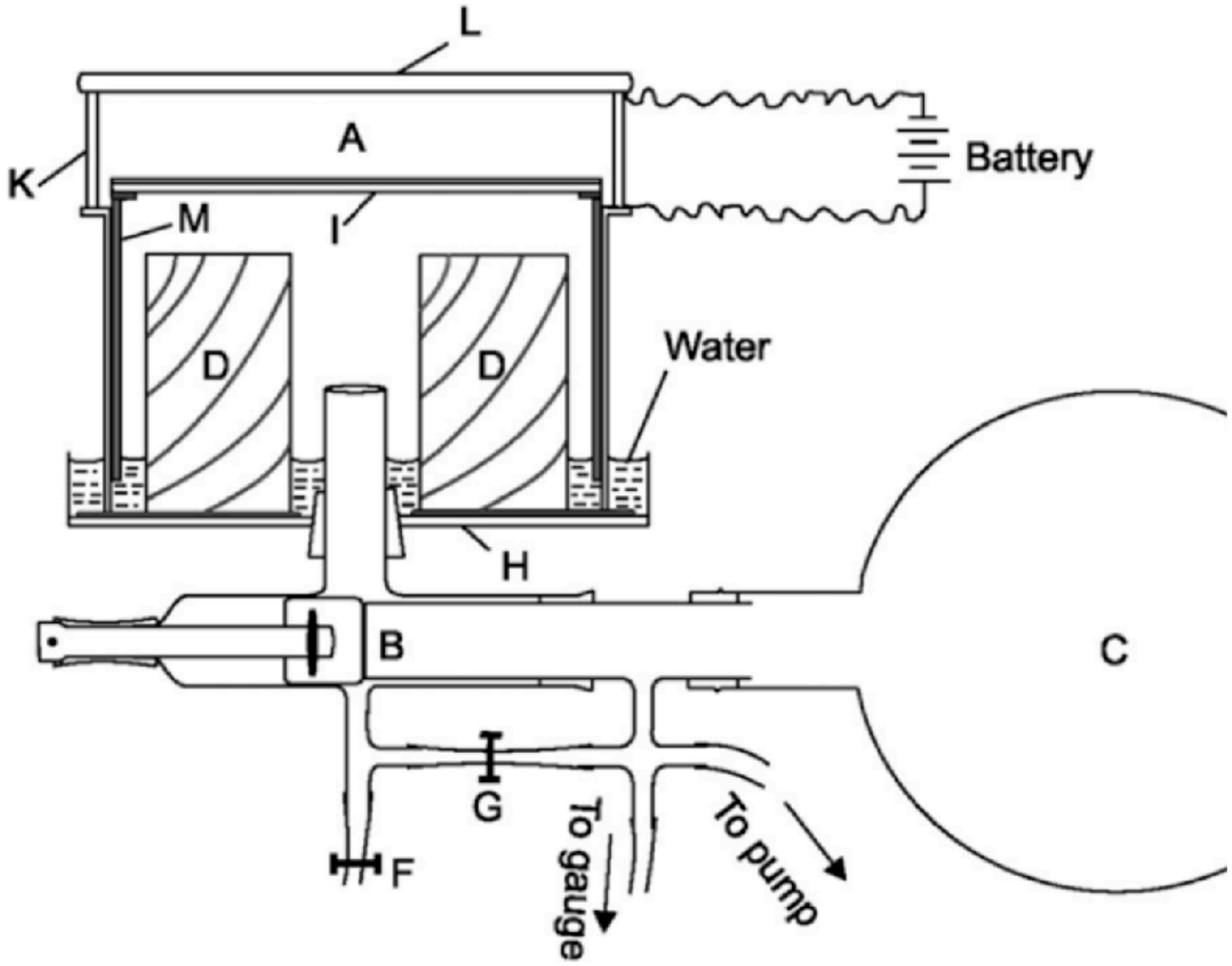
Figure 3.5: The star at A is caused by a cosmic ray (marked p) incident from above colliding with a silver or bromine atom in the emulsion. The track f is due to a nuclear fragment with charge about 5. Its decay at point B shows that it contained a hyperon. The scale at the bottom indicates 50 μm. (Ref. 3.10)

[see MoEDAL, SHiP]

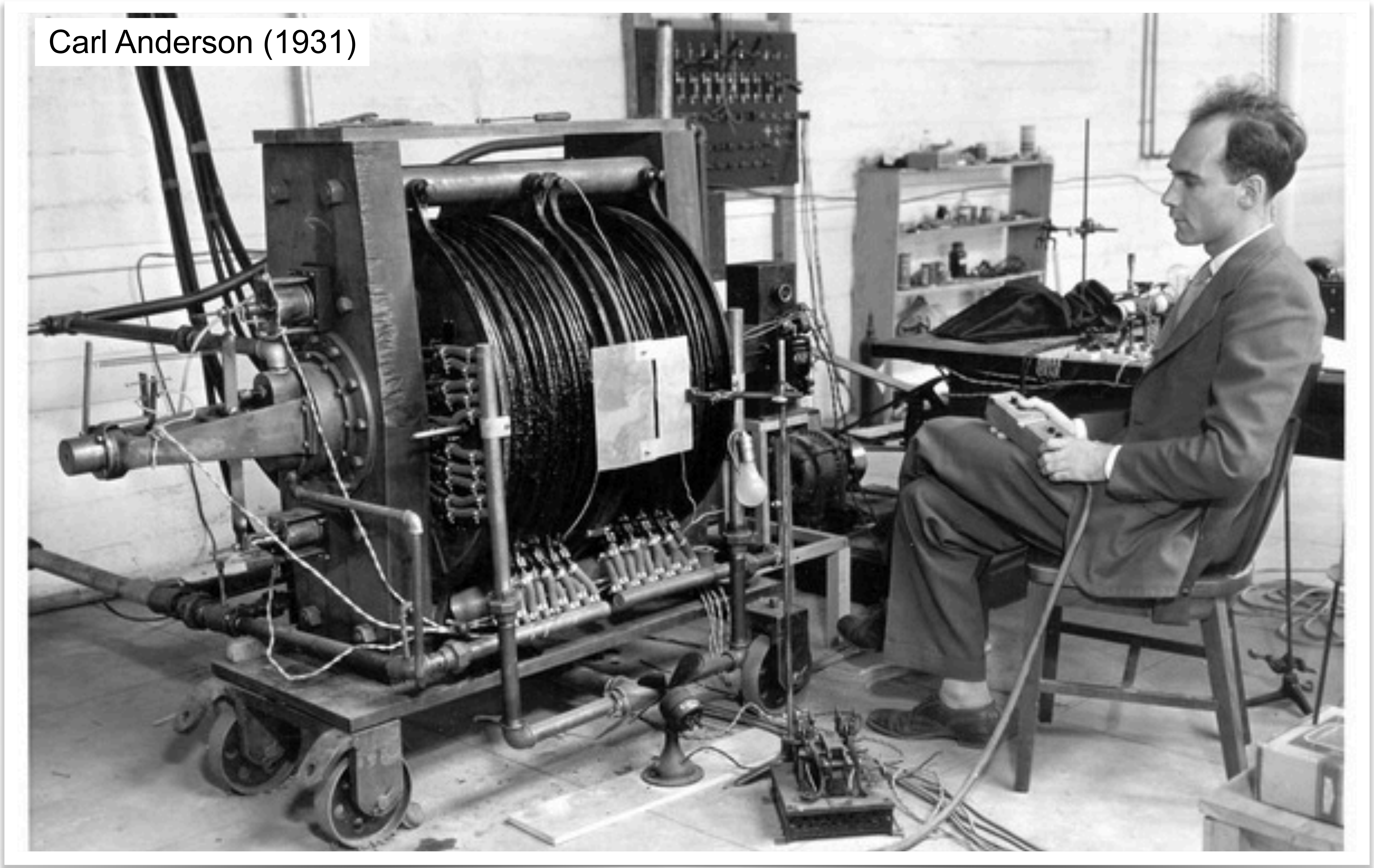
Cloud Chamber

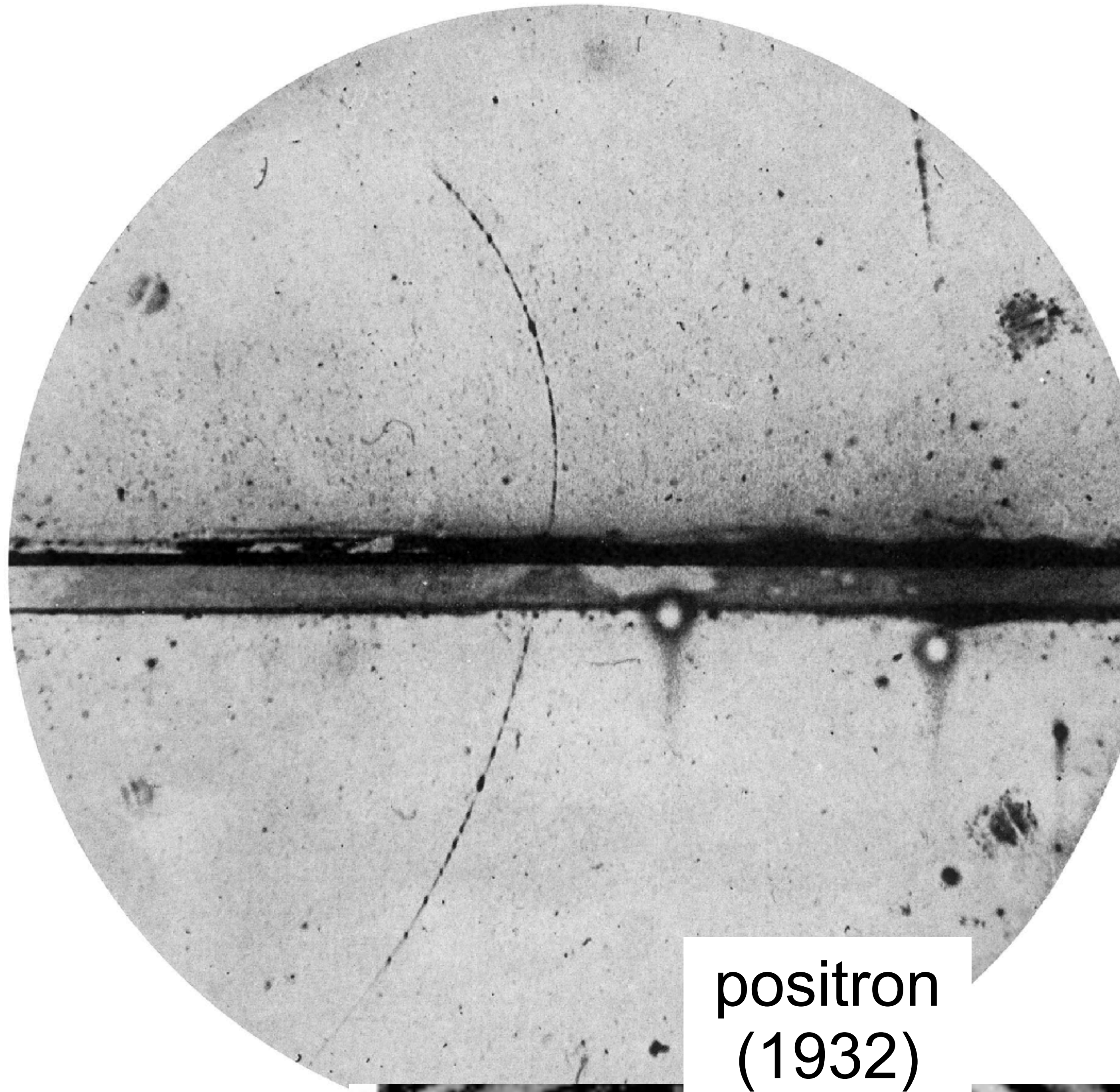
- Condensation is caused by ionizing particles passing through supersaturated air.
  - Invented in 1894, Wilson used it to see radiation (~1910, photo)
  - Used a piston to vary pressure and camera to record results
- Invention really took off when…
  - Magnets added to bend charged particles, and
  - Geiger counter hooked to cooling mechanism for trigger
- Workhorse for the field for many years, still great for outreach

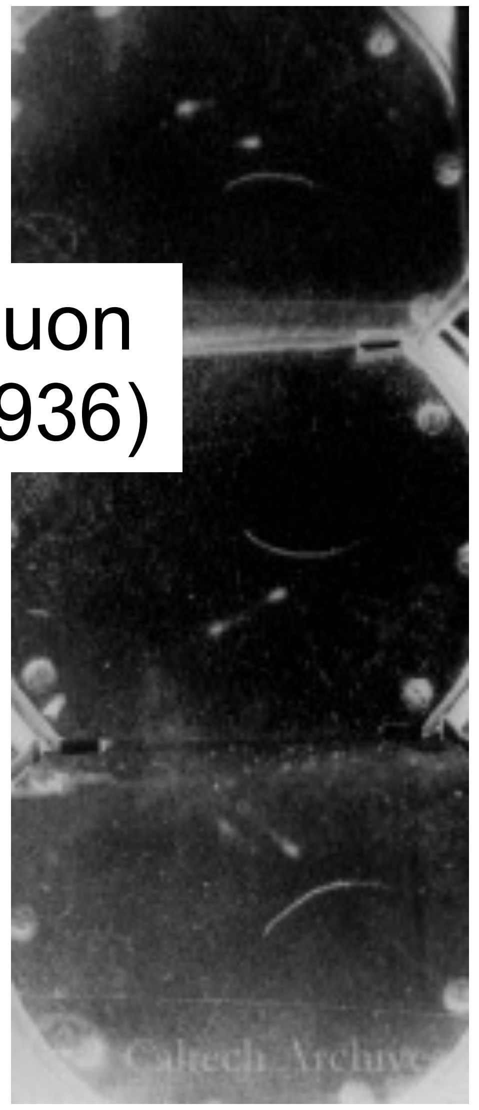


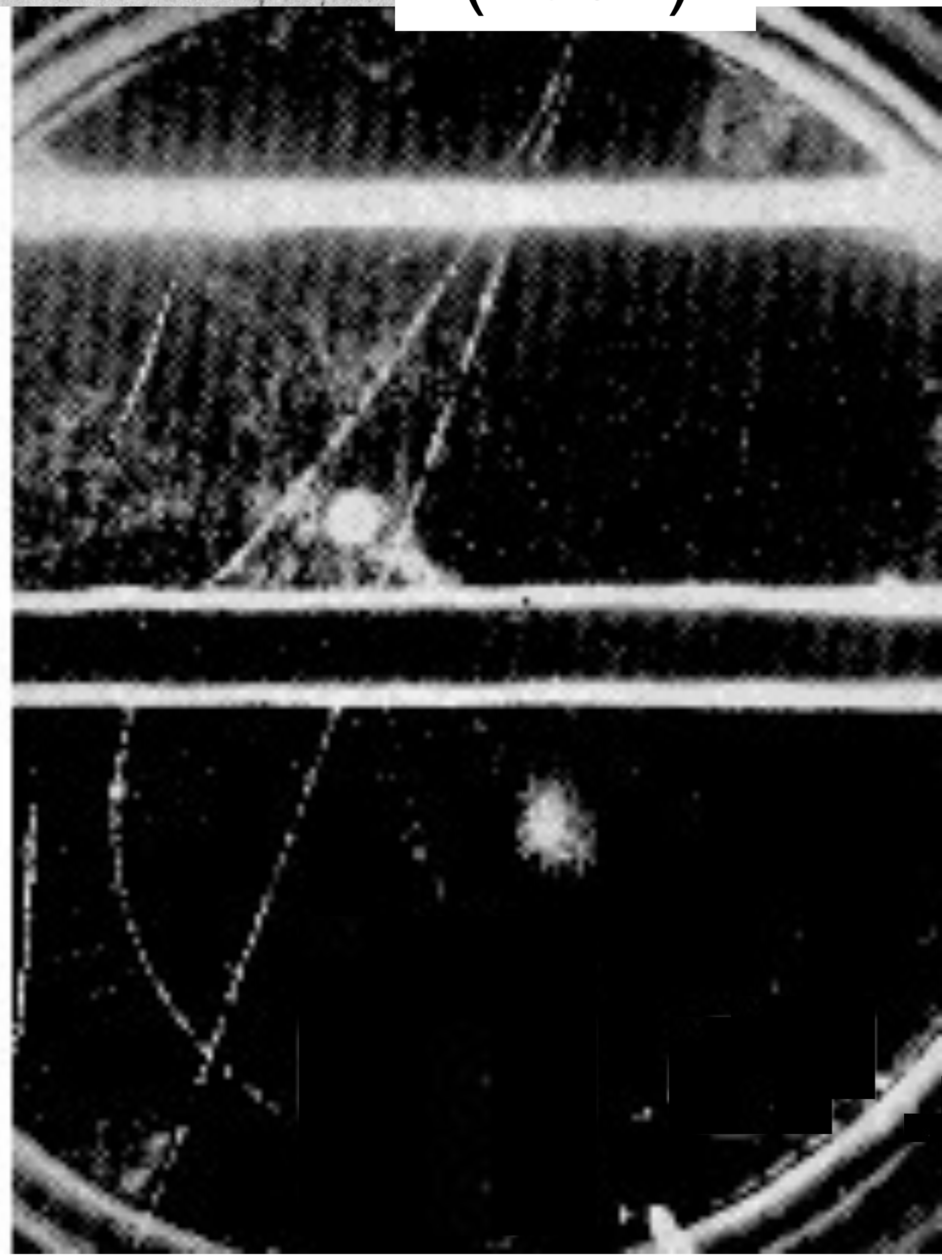


Early Cloud Chamber Experiments





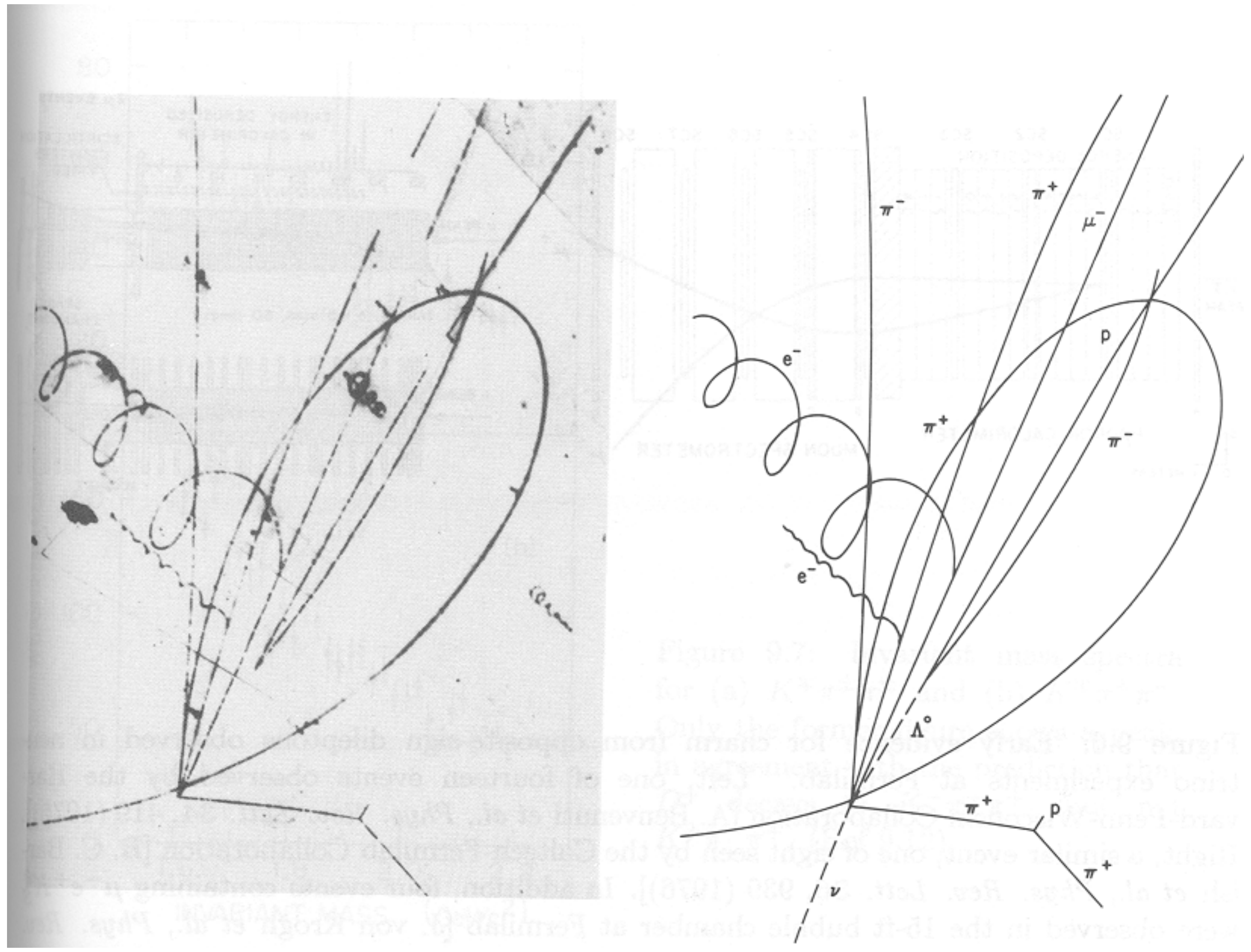




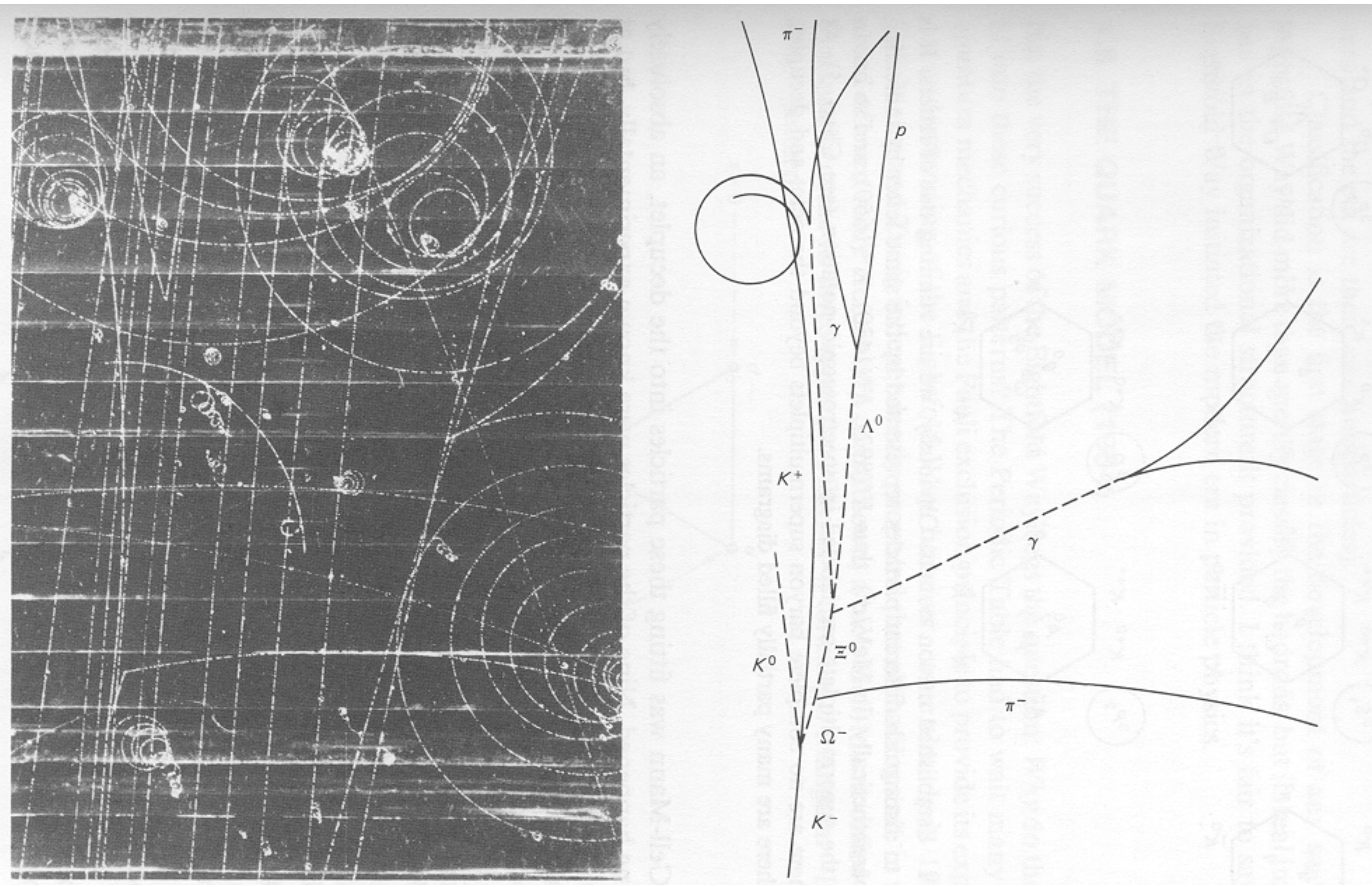
Detector Innovation → See New Things → *Nobel Prize*

Bubble Chamber

- Most important particle detector in the 60’s and 70’s: many particles identified with bubble chambers
  - Advantages: excellent resolution, large acceptance, mass measure for slow particles, can actually ‘see’ the particles
  - Disadvantages: have to look at all of the pictures one at a time (no ‘trigger’), poor momentum resolution for high $\vec{p}$

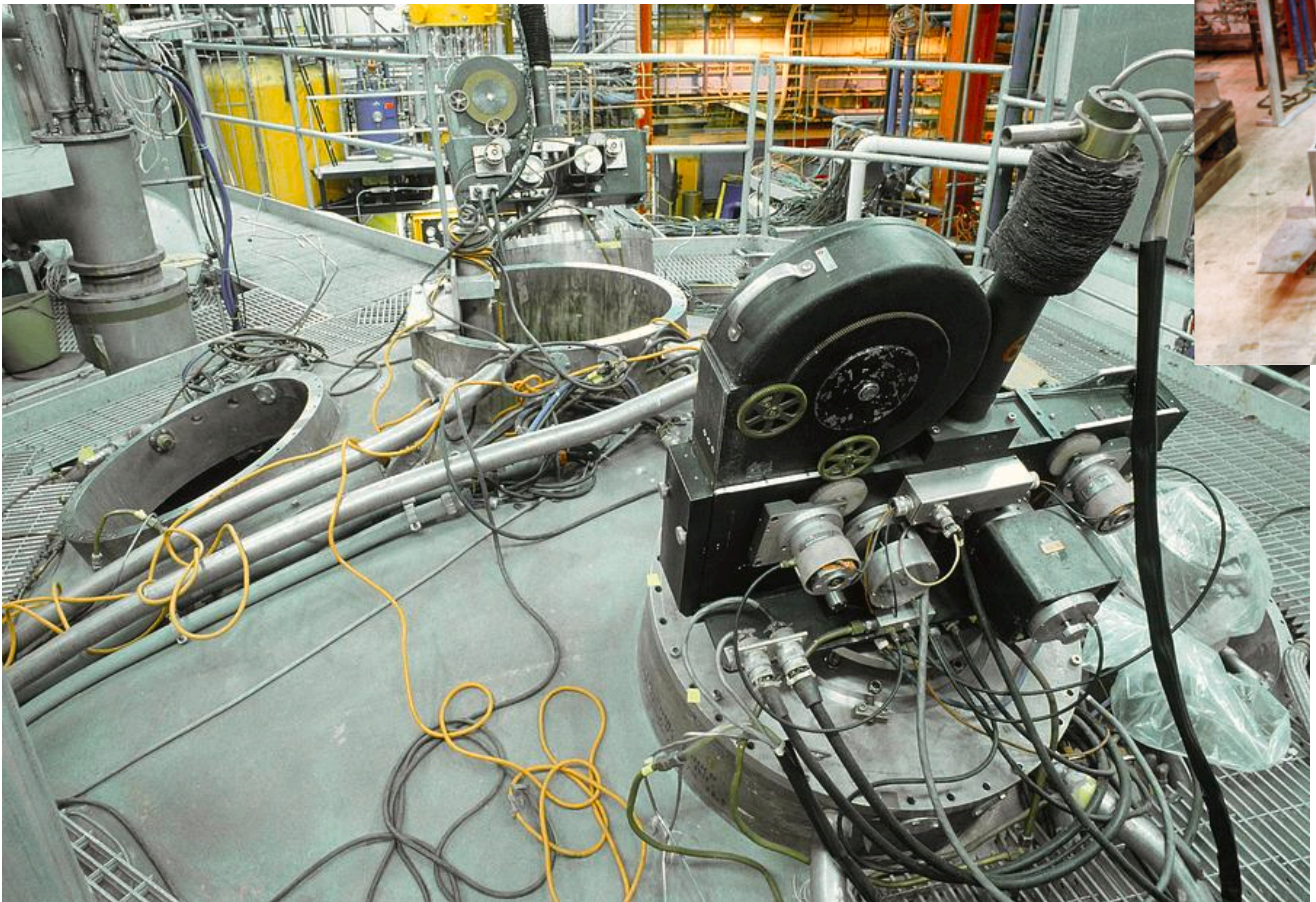


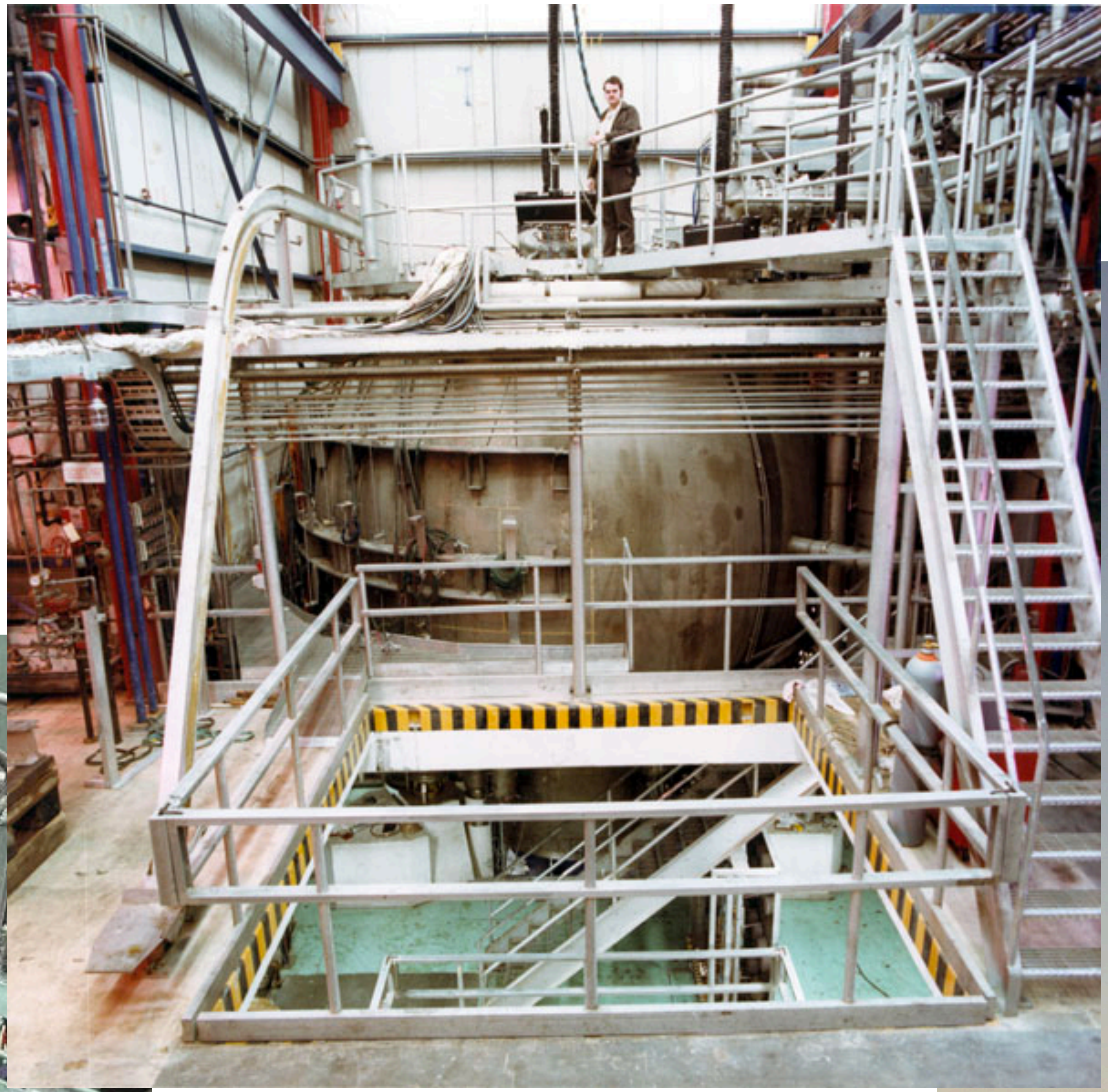
$\nu_\mu + p \rightarrow \Lambda_c^+ + \mu^- + \pi^- + \pi^+$



Discovery of the Ω^-

Fermilab 15-foot Bubble Chamber

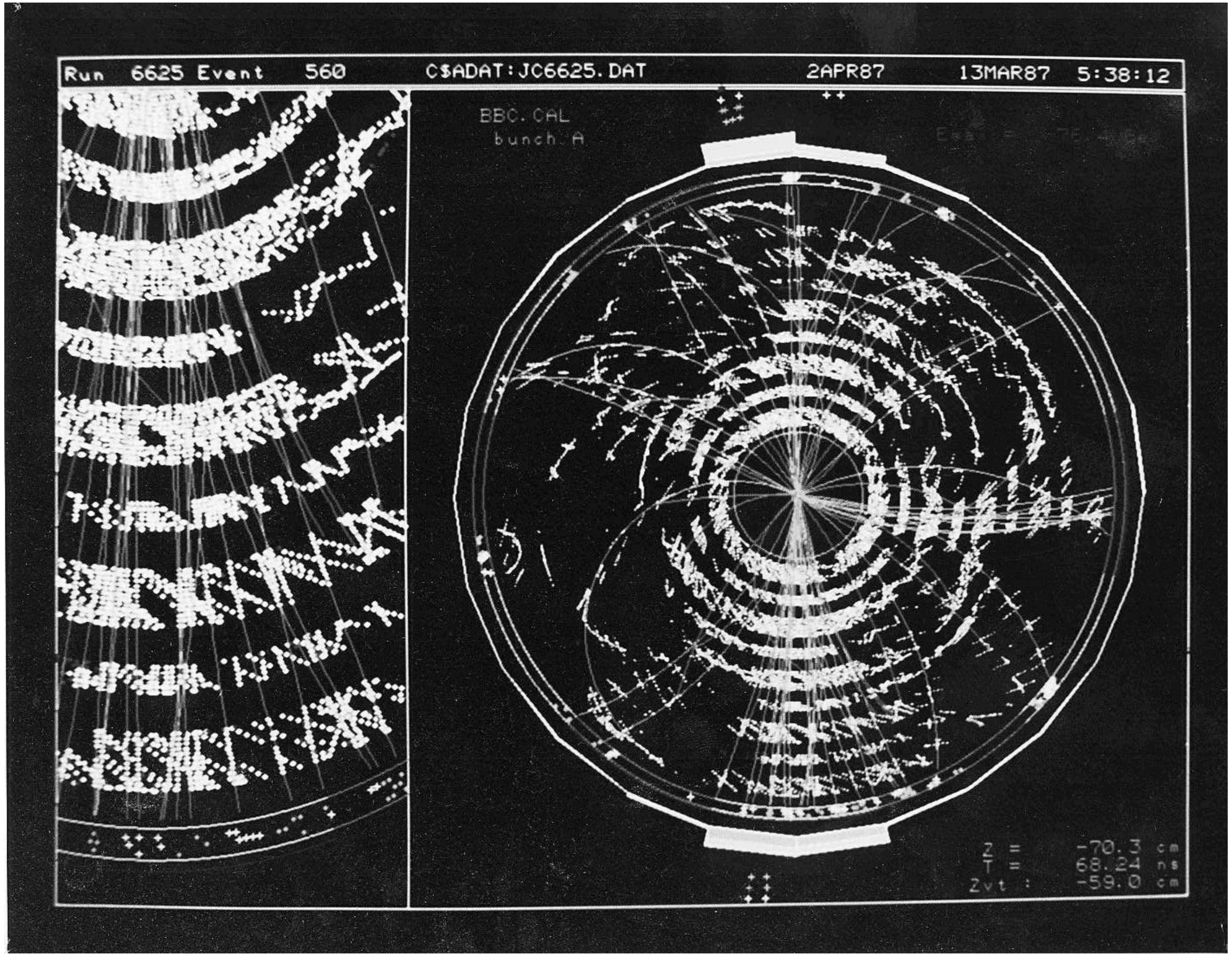




Big European Bubble Chamber (BEBC)

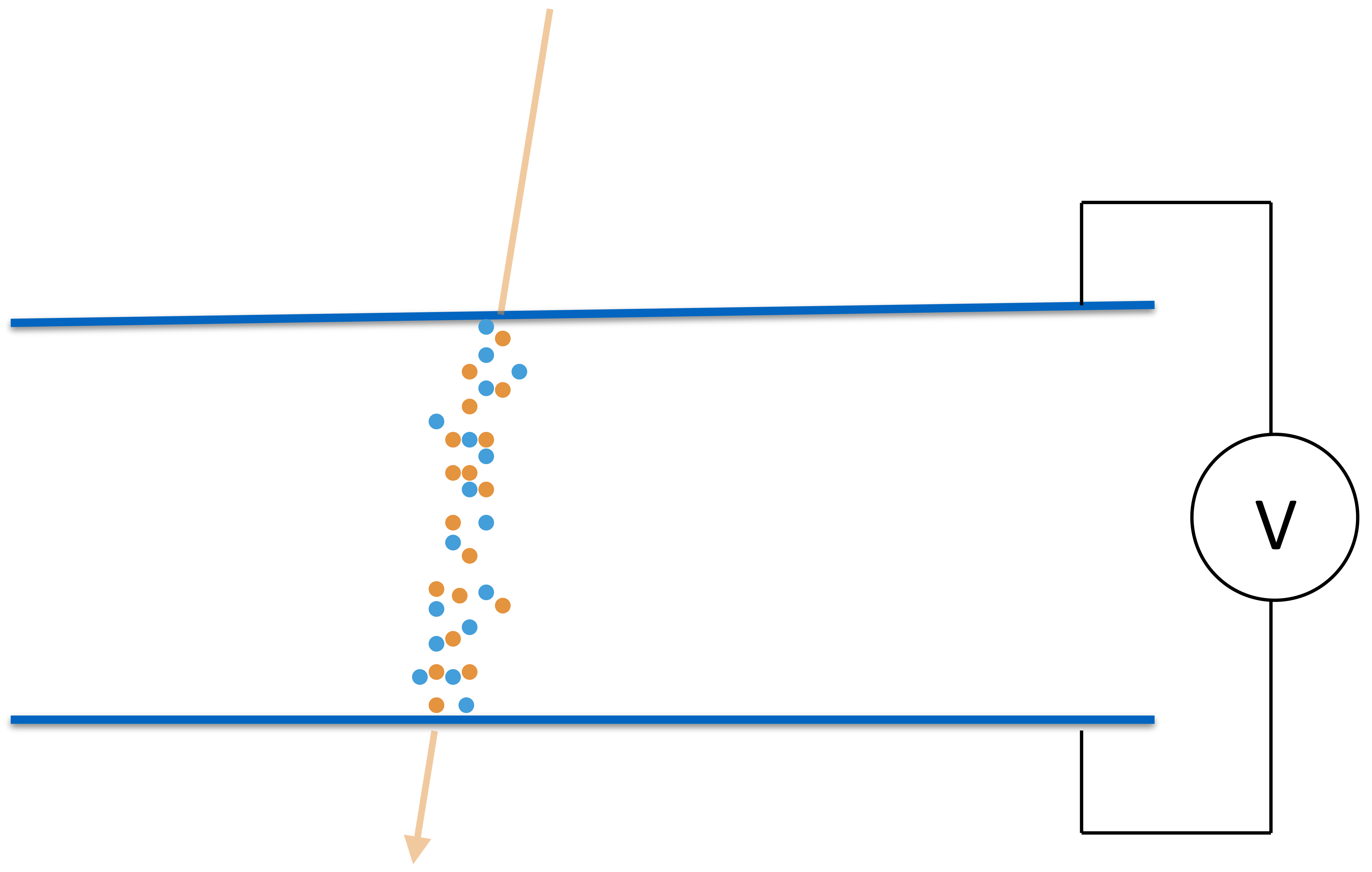
- circa 1977-1984
- 35 m^3 liquid hydrogen
- then world's largest superconducting magnet
- on SPS beamline (450 GeV)
- triggering, timing info
- 6 million photos

- Early tracking detectors used to “see” the particles
- To study them in detail, modern tracking detectors measure charged particle position…



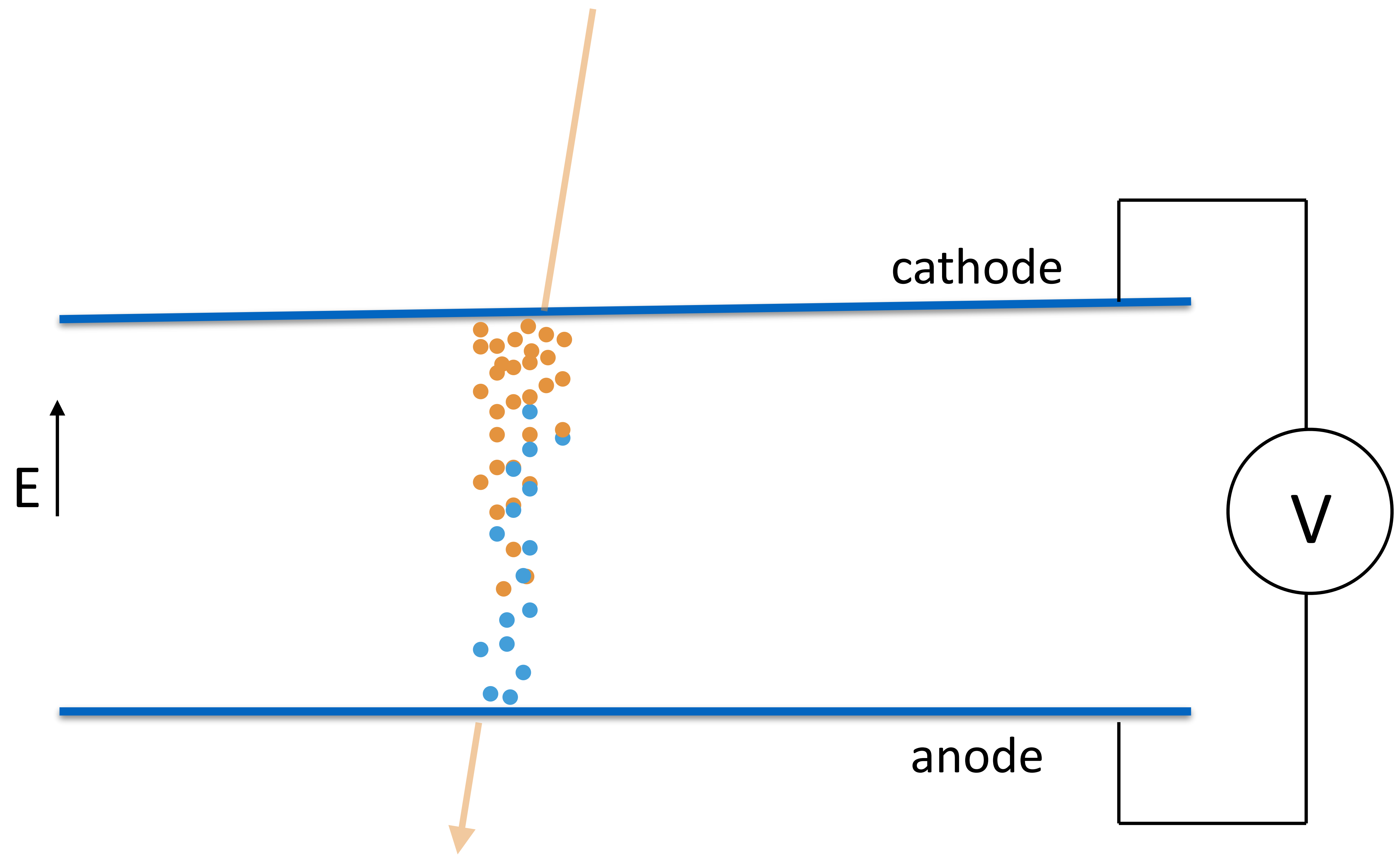
Ionisation Chambers

- Basic idea:
  - apply voltage (E field) across an ionization media (e.g. gas)
  - collect and amplify charge liberated during ionization
  - simple example: smoke detector



Ionisation Chambers

- Basic idea:
  - apply voltage (E field) across an ionization media (e.g. gas)
  - collect and amplify charge liberated during ionization
  - simple example: smoke detector
- Operational Details
  - secondary ionisation (delta electrons)
  - ionisation is Piossonian (+Fano factor)
  - too little Voltage: diffusion, recombination
  - too much Voltage: Geiger-Müller mode
  - just right: ionising or proportional signal
- Lacking external field, we see
  - Diffusion
  - Electron capture or recombination
  - Charge transfer
  - Ion pair recombination



Transport Properties of Electrons and Ions (with Field)

- Transport in gas with an E field and mobility μ (empirically determined): $v_D = \dfrac{\mu E}{P}$
- For a "cold" gas
  - E field determines the motion ($\vec{F} = m\vec{a} = e\vec{E}$)
  - $v_D \sim E$, $\mu \sim$ constant
- For a "hot" gas
  - acceleration from $\vec{E}$ is not a factor
  - $v_D \sim$ constant, $\mu \sim$ not constant
- For a large $\vec{E}$
  - high drift velocity, additional effects for ions and electrons
  - additional ionisations (amplification) → avalanche
  - gains up to 10^5: proportional
  - gains beyond 10^7—10^8: Geiger mode
  - very high voltages/gains: breakdown of gas (discharge)

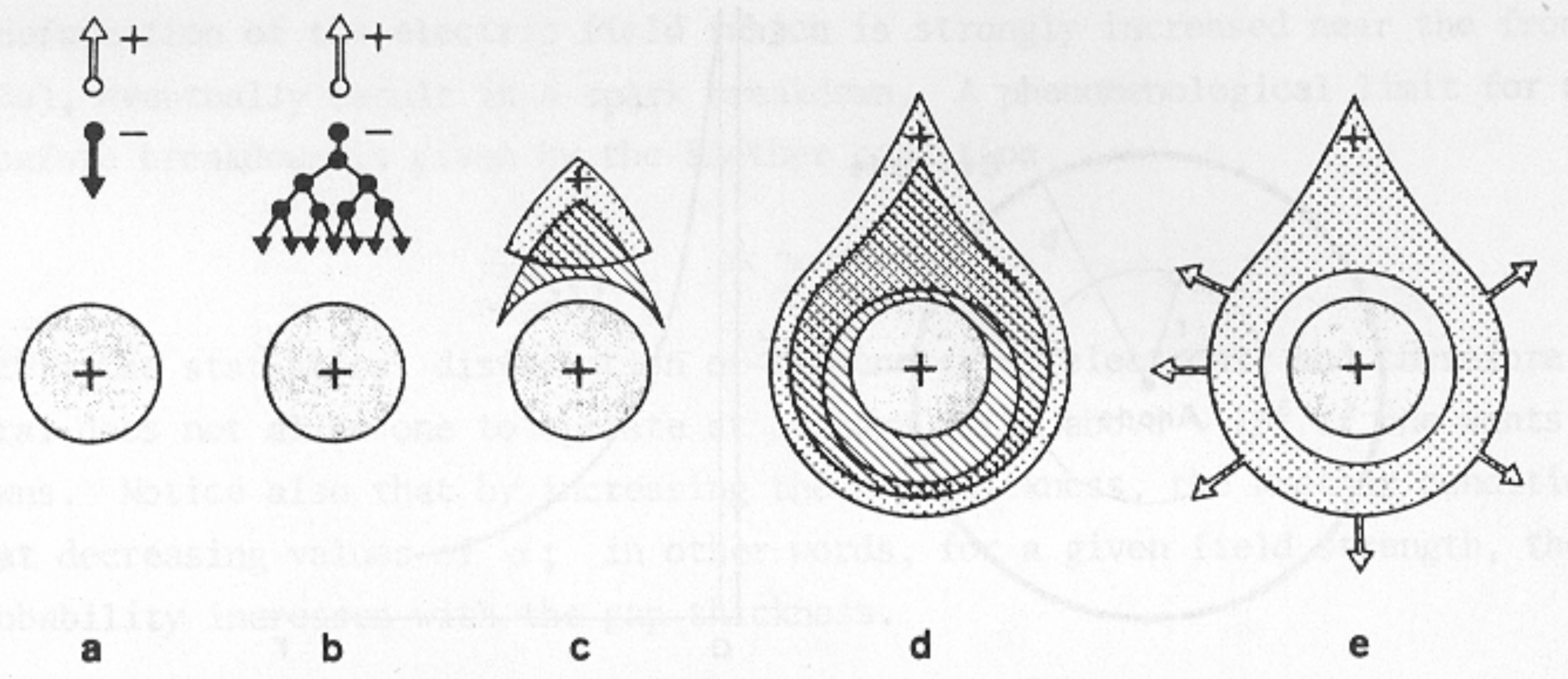
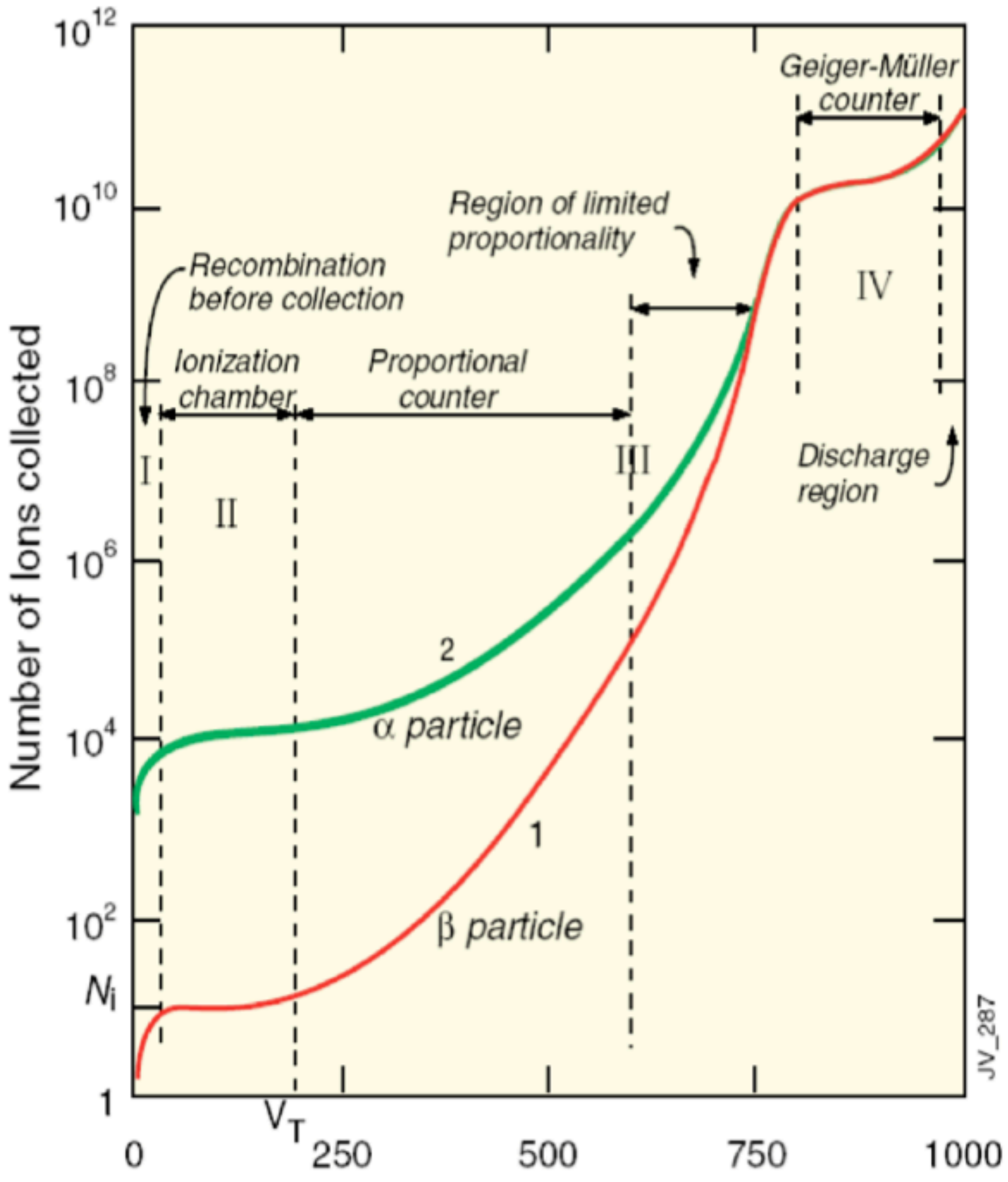


Fig. 49 Time development of an avalanche in a proportional counter[30]. A single primary electron proceeds towards the anode, in regions of increasingly high fields, experiencing ionizing collisions; due to the lateral diffusion, a drop-like avalanche, surrounding the wire, develops. Electrons are collected in a very short time (1 nsec or so) and a cloud of positive ions is left, slowly migrating towards the cathode.

Gas Amplification

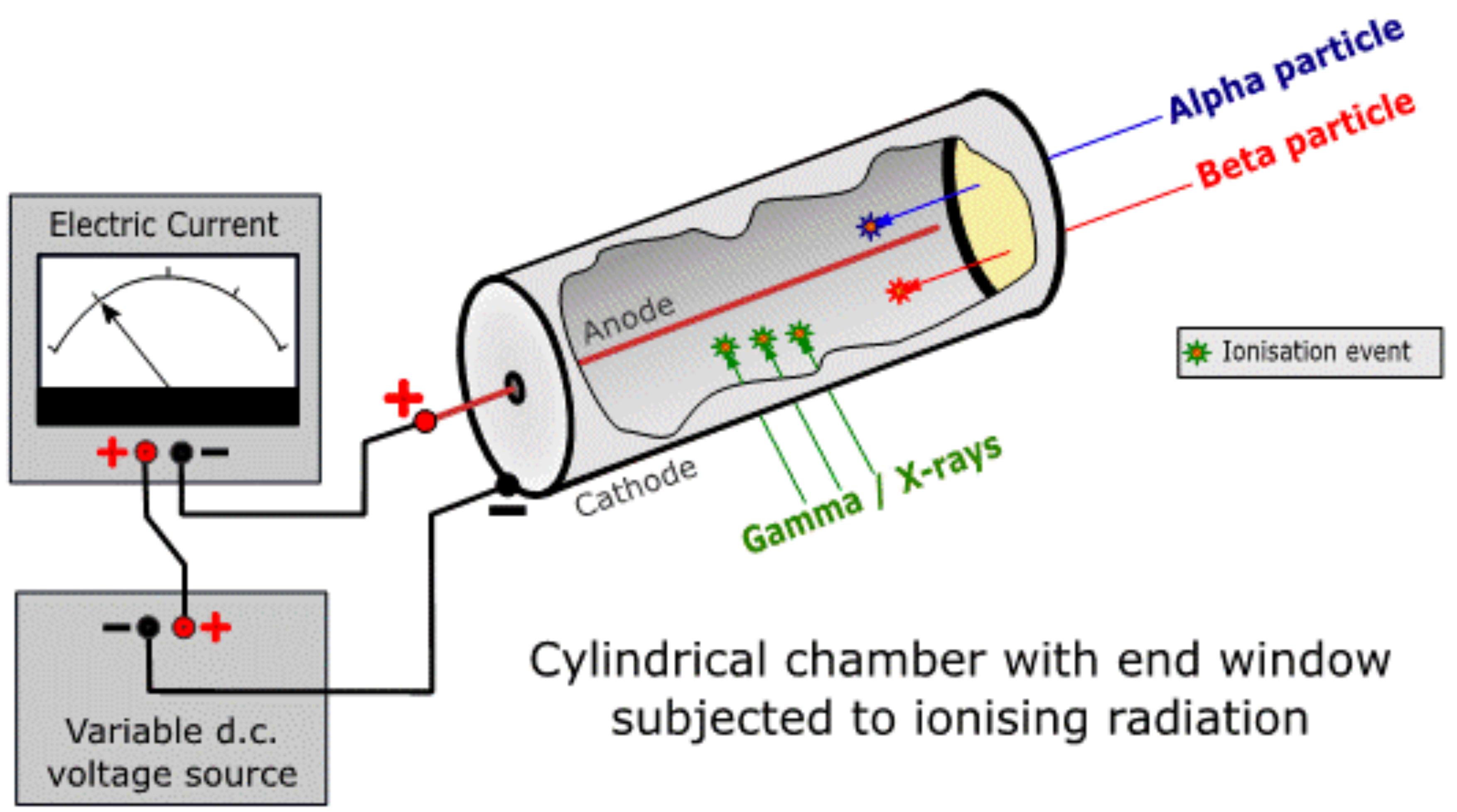
- Ionisation mode
  - no multiplication
  - full charge collected
- Proportional mode
  - modest gain 10^2—10^5
  - signal proportional to ionisation
  - useful for dE/dx identification
  - mix of gasses, quenching
- Limited Proportional mode
  - high/nonlinear gain
  - streamer chambers
  - strong quenching or shut off HV
- Geiger-Müller mode
  - not proportional (discharge)
  - HV interrupt operation

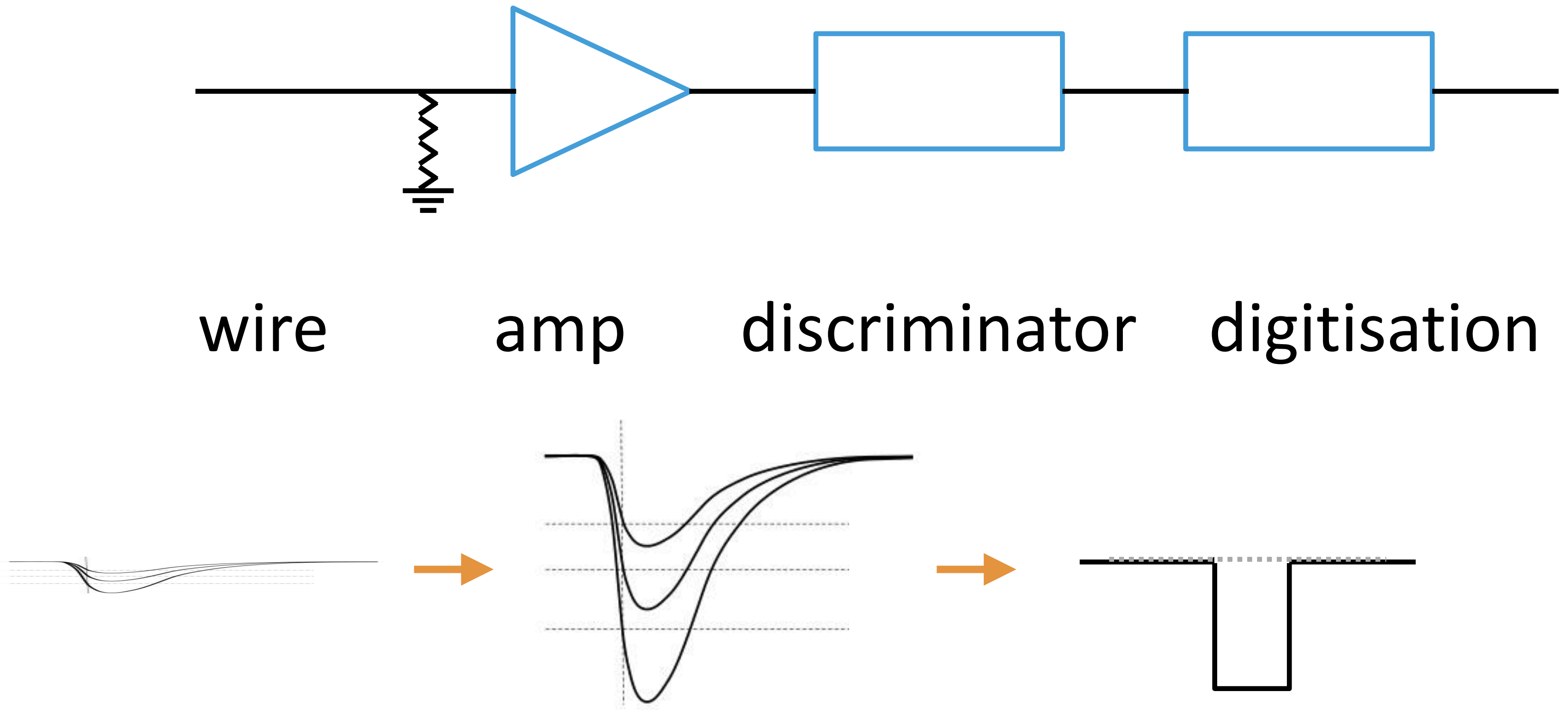


[W. Price]

Gas Ionisation Chamber Basics

- Wire chamber features
  - planar, cylindrical or rectangular gas volume ("chamber")
  - anode wire, e.g. Au plated W, dia. ~50 µm
  - cathodes at high voltage, ~1-2 kV
- Gas properties
  - typically noble gas (Ar) + UV quench gas (hydrocarbon)
  - polyatomic molecules
  - energy dissipation by vibration
  - ageing properties
  - cost: flow&exhaust vs. recirculate&clean
- Electronics
  - higher voltage: smaller transverse diffusion
  - readout: one circuit for each wire
  - fast, low noise amplification
  - modern solution: multi-channel ICs



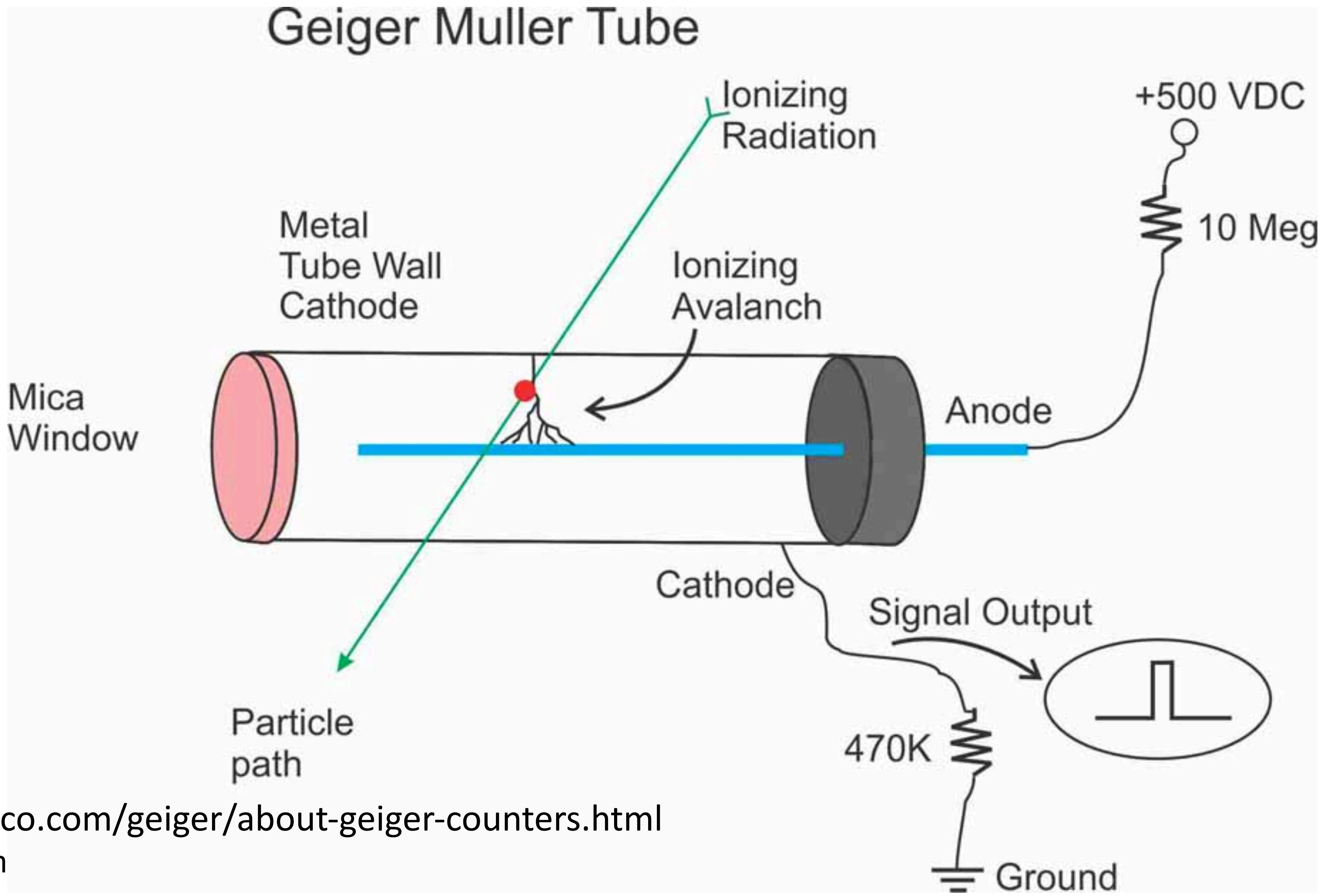


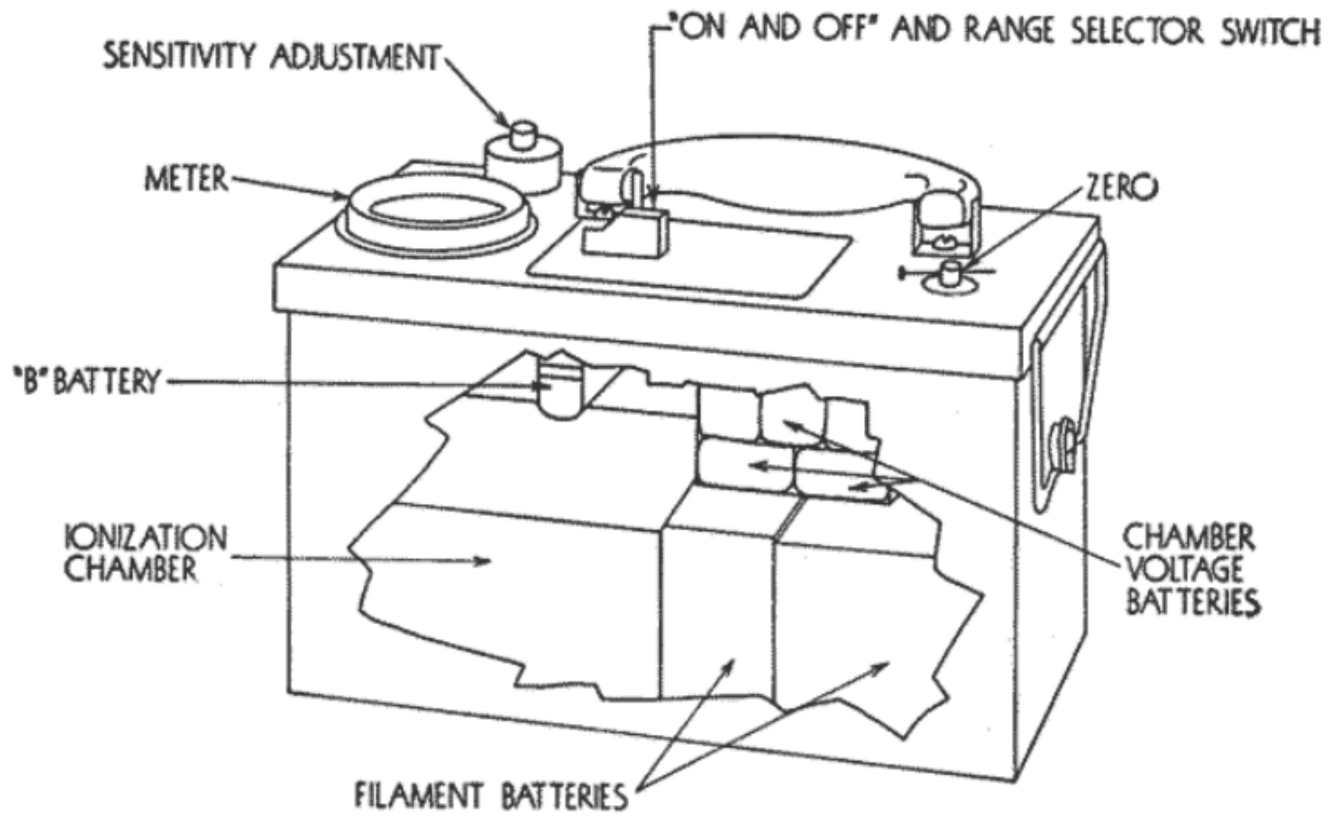
Geiger Counter

- Simple gas volume, high voltage
- Full discharge, so large signal
- Signal not proportional
- Often a long dead time (ms)
- See examples…

Original Geiger Counter

‘Modern’ examples



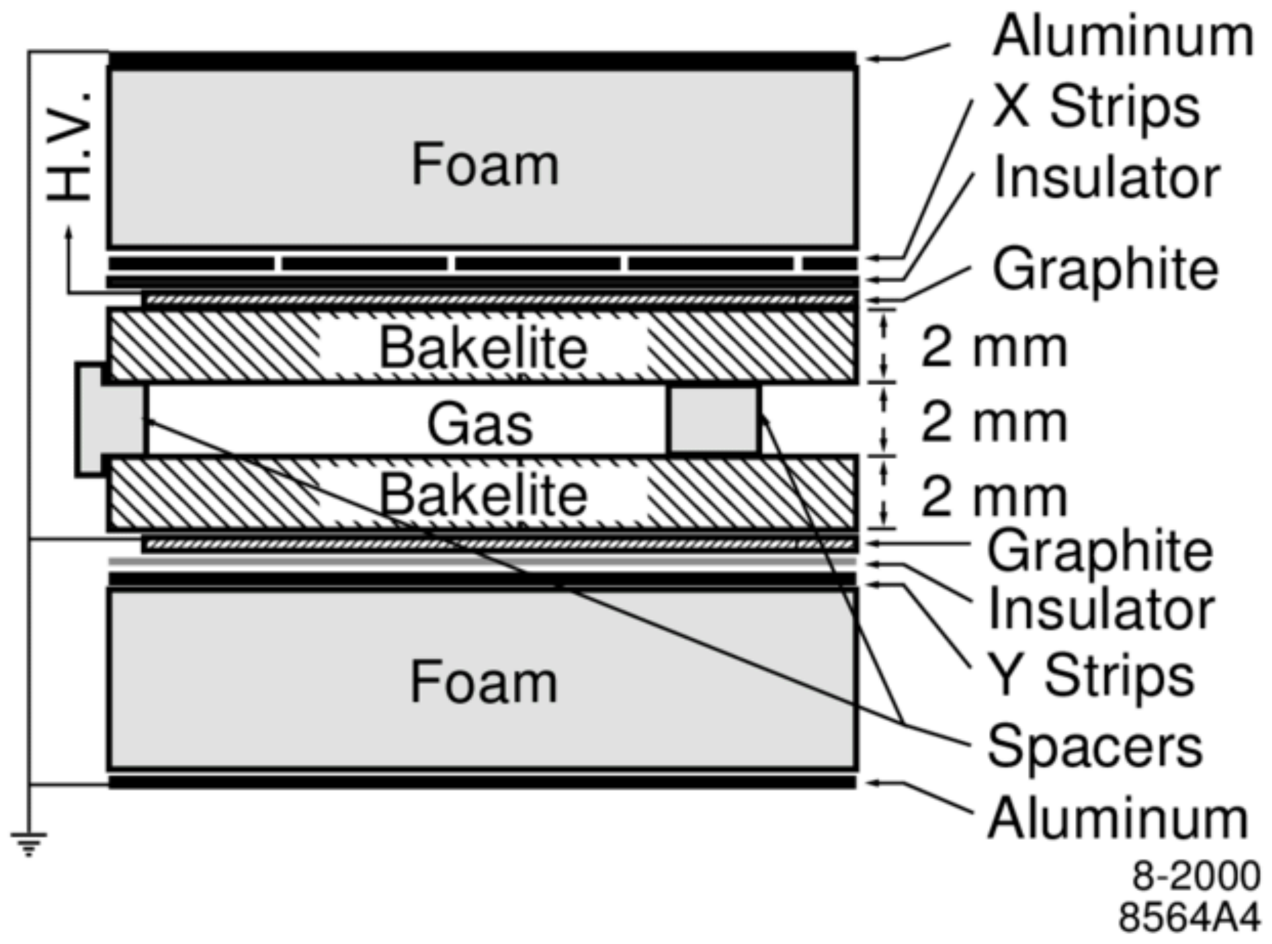


Ionization chamber for gamma (and beta) radiation.

https://www.imagesco.com/geiger/about-geiger-counters.html

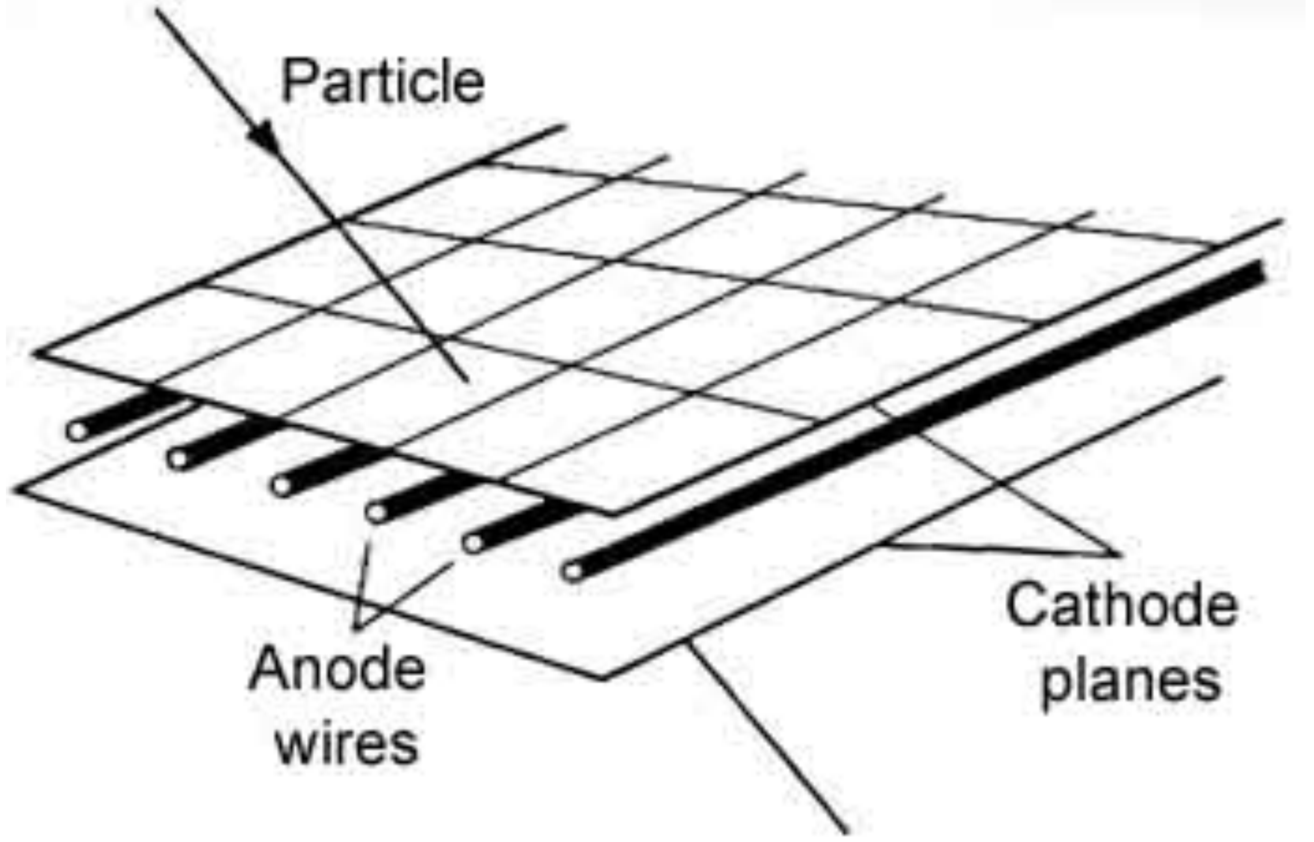
Resistive Plate Chamber (RPC)

- Typically large area planar structures
- High resistivity, so dead-time after discharge localised in a small region
- Used in many large experiments for muon detection (e.g. ATLAS)
  - 10000 m^2 coverage
  - 1 cm^2 spatial resolution
  - 10 ns time resolution
  - > 99% efficiency
- Operation
  - discharge region: 1-100 Hz/cm^2 — 100-1000 pC
  - avalanche region: 1 KHz/cm^2 — 10 pC



CMS Experiment and 10.1103/PhysRevD.74.032003

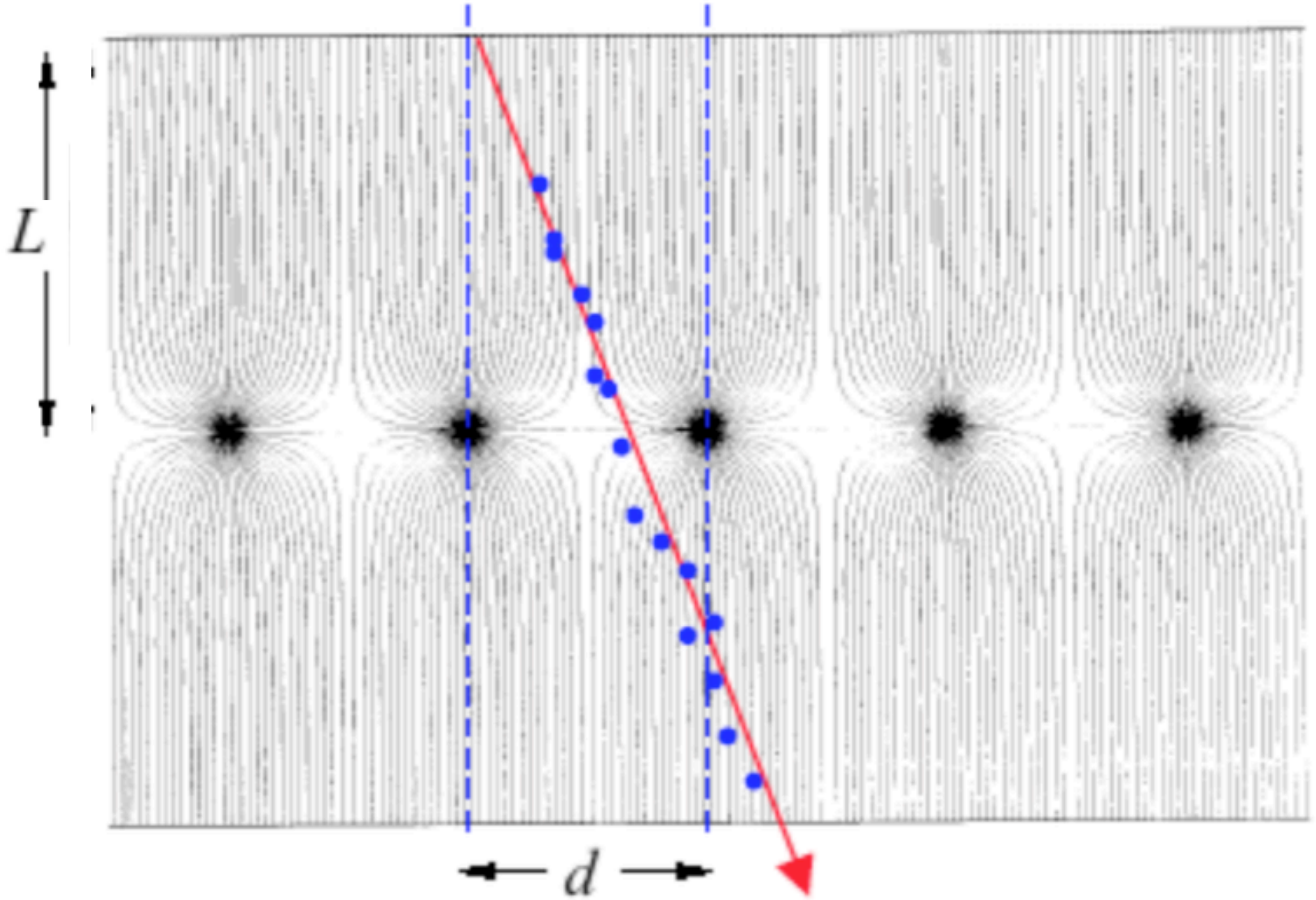
Multi-Wire Proportional Chamber (MWPC)



- Developed by Charpak in ~1970
- Field proportional, but high enough to generate secondary ionization
- Used for tracking and triggering—typically wires in a planar geometry
- Segmentation, with typically >1000 wires

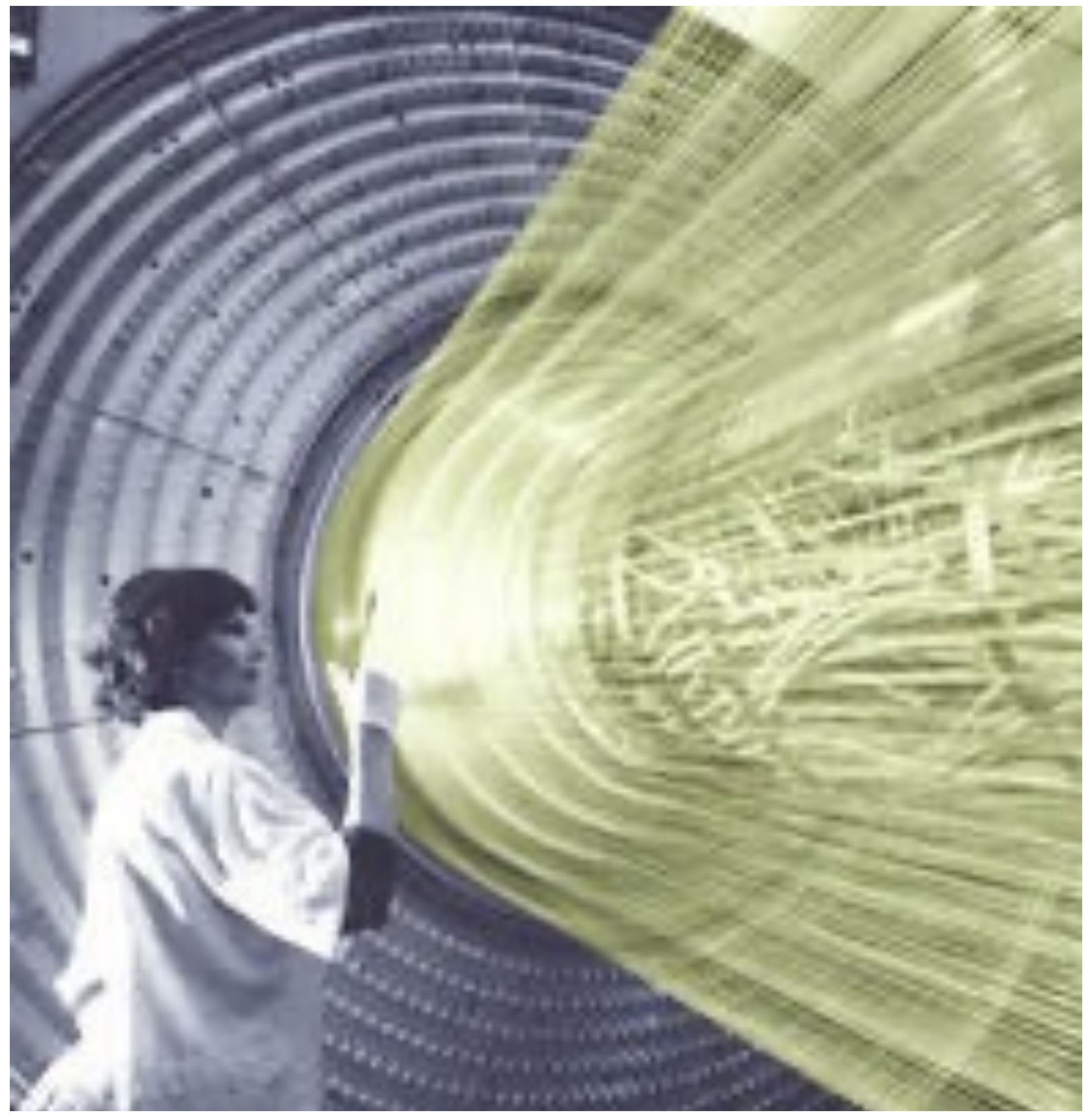
- Properties
  - Spatial resolution ~ $d/\sqrt{12}$
  - gas thickness (L) ~5-10 cm
  - wire spacing (d) ~1-5 mm

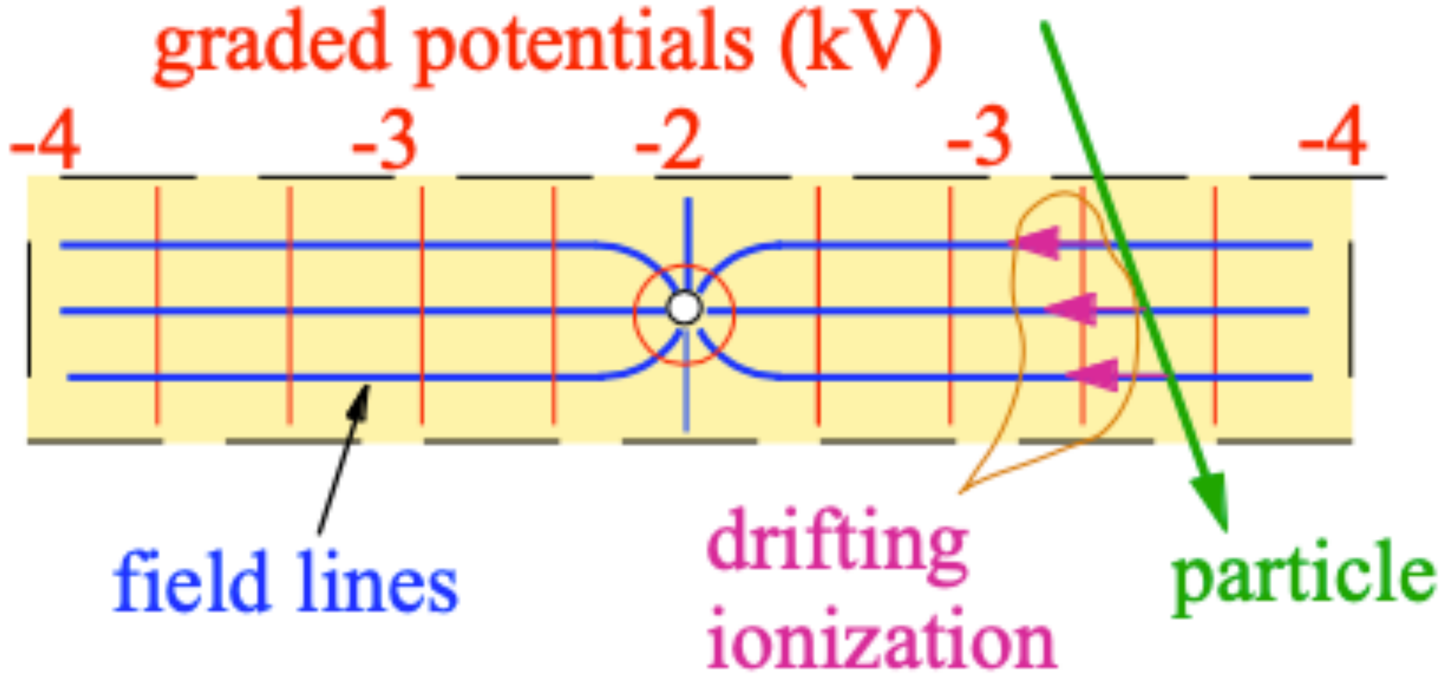
- Resolution
  - wire hit or no: 'binary'
  - flat probability distribution
  - resolution > 300 μm

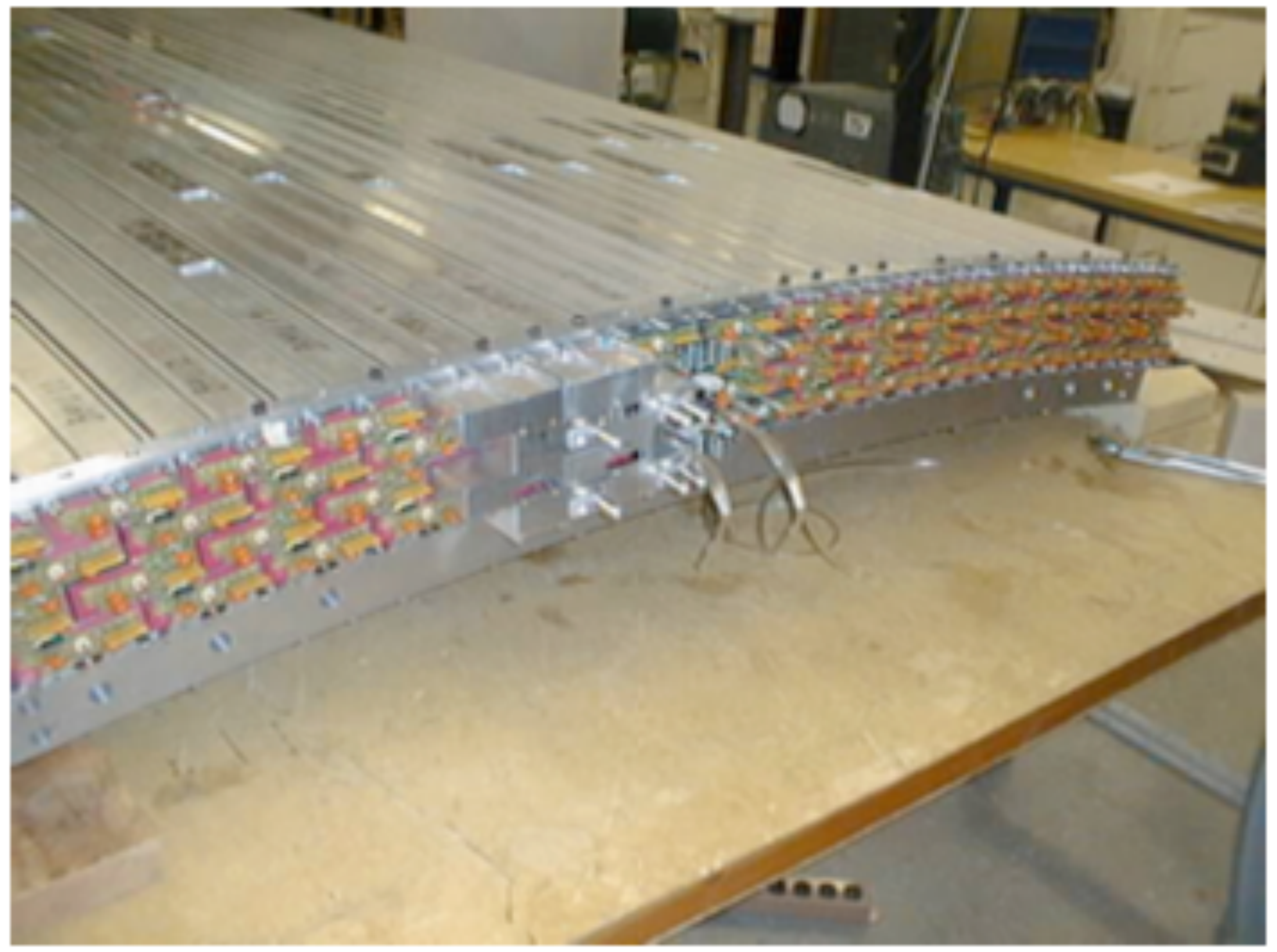


Drift Chamber

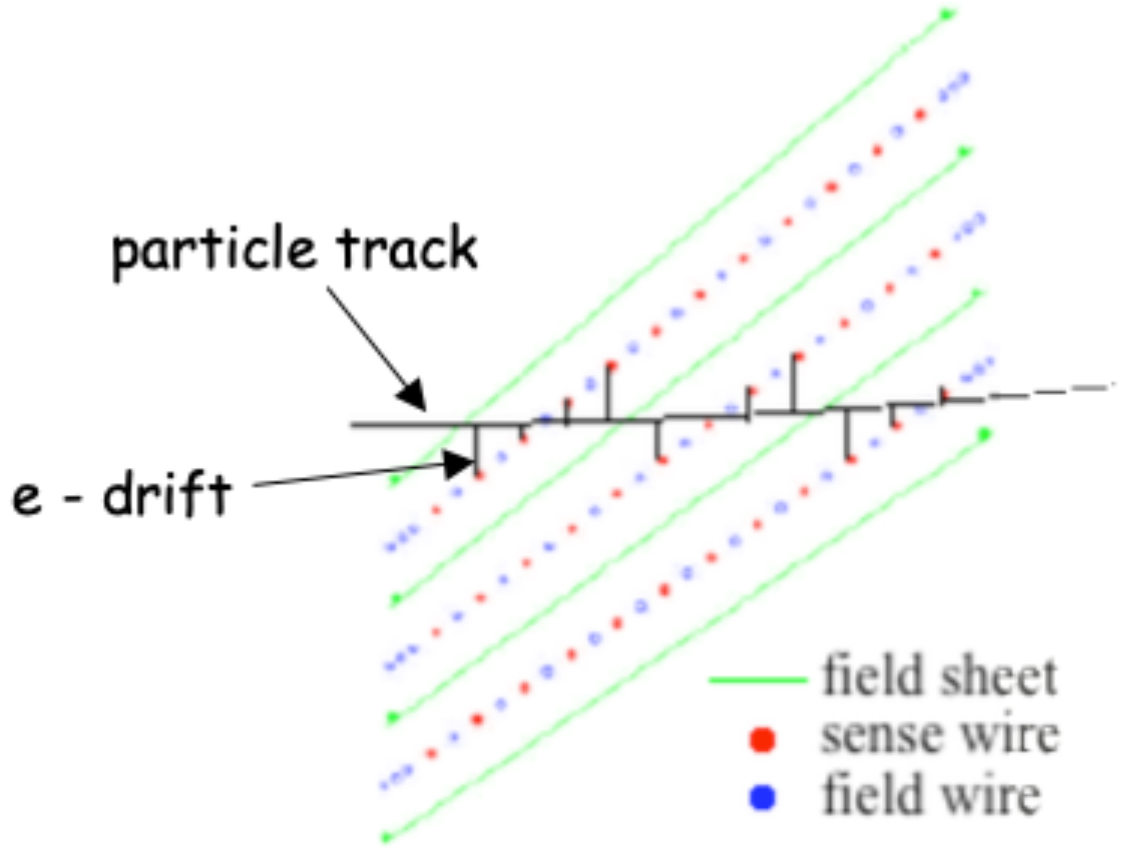
- Drift chamber detailed properties
  - similar to MWPCs, but lower voltage → no secondary ionization
  - only the primary ionization is drifted to collection points
  - can cover large areas; cylindrical and planar geometries the most common
- Using detailed timing of electron drift, reconstruct position
  - gas composition and characterisation is crucial
  - knowledge of the drift time in the gas → better (x10) position than with MWPCs
  - resolution of ~80μm attainable







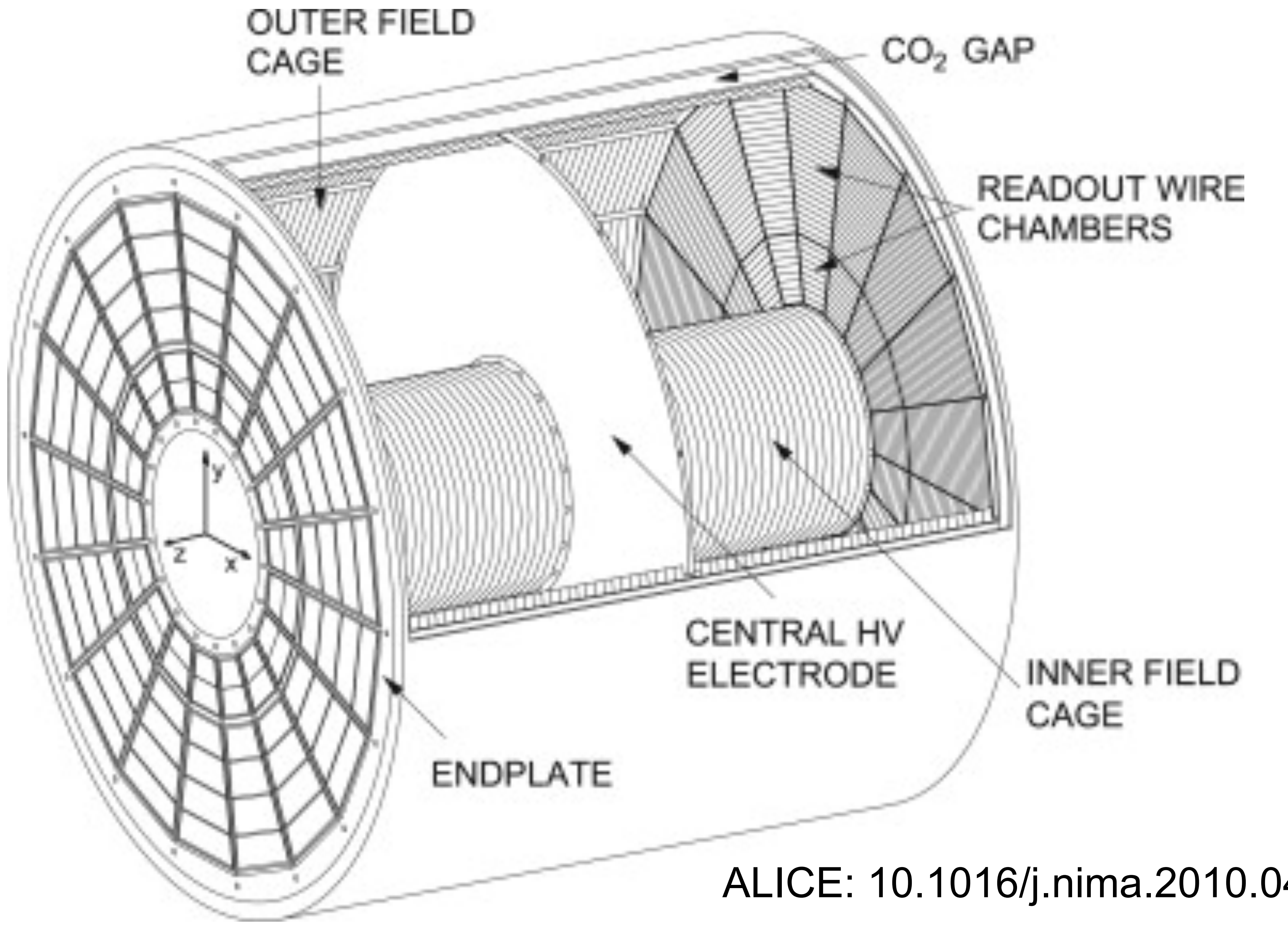
CDF Muon Detectors



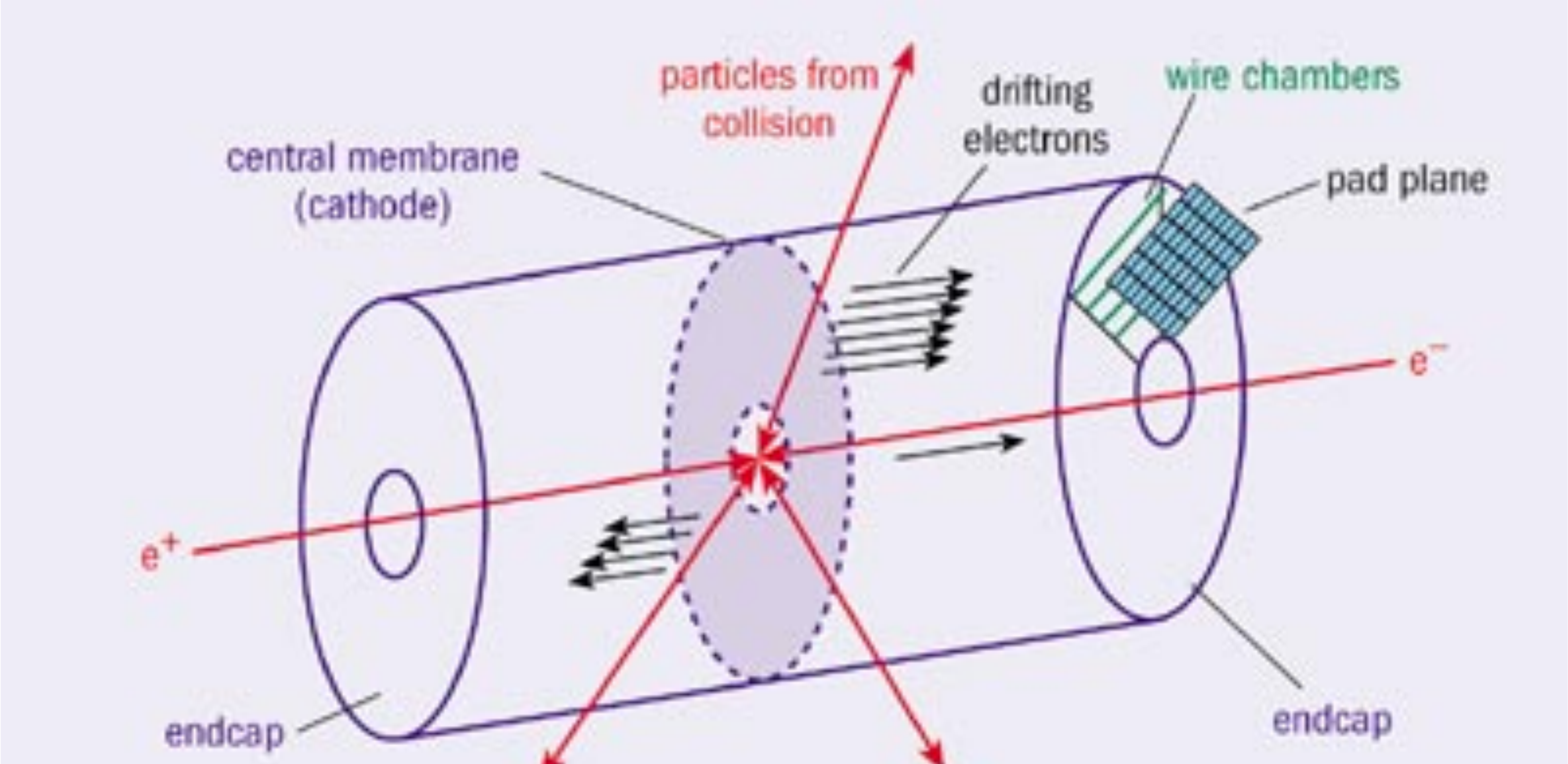
CDF Central Outer Tracker

Time Projection Chamber (TPC)

- Geometry
  - typically large cylinder with MWPC on two-side readout (x-y coordinates) and drift time for z
  - electrode gate in the middle (as a plane) for ions
  - electron drift to ends, pad or wire chamber readout
- Properties
  - gas admixture, e.g. Ar:Methan 90:10
  - wires signal: dE/dx and PID
  - resolution (z-axis 1mm, r,phi: 160 μm)
  - for a given E, diffusion < 1 μm
- ALICE TPC as an example
  - used for tracking + ID
  - low rates
  - large volume



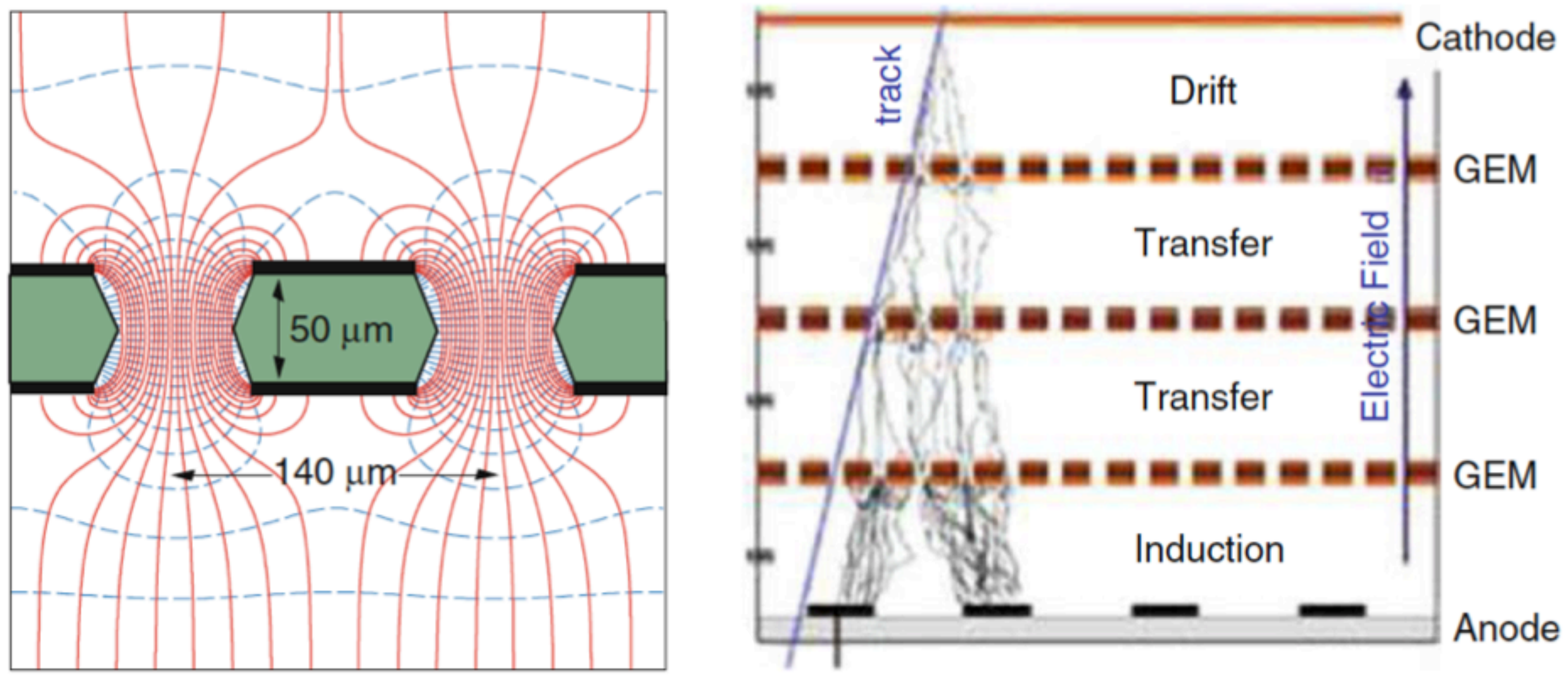
ALICE: 10.1016/j.nima.2010.04.042



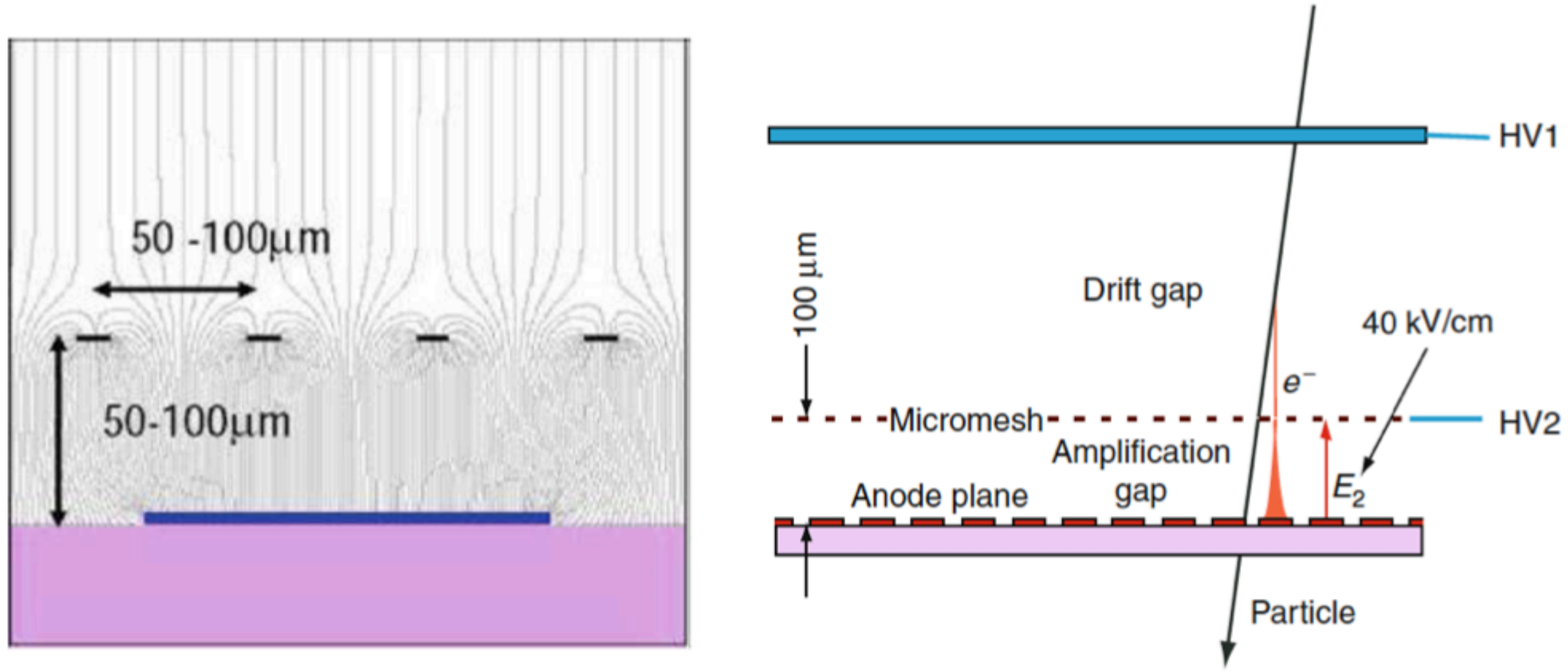
Cern Courier

Micro-Pattern Gas Detector

- GEMs
  - copper-insulator-copper layers + holes for avalanche
  - extremely small spacing possible (25-150 μm)
  - e.g. stacked design for gain (20x per layer, ~8k total)
  - 50 μm spatial resolution
- Micromegas
  - micromesh metal grid
  - drift + amplification areas (mm gap, 25-150 μm spacing)
  - charge collection on pads after amplification
- Properties
  - extremely fast (ns), high rates
  - reliable and simple operations
  - ~100% tracking efficiency



GEMs



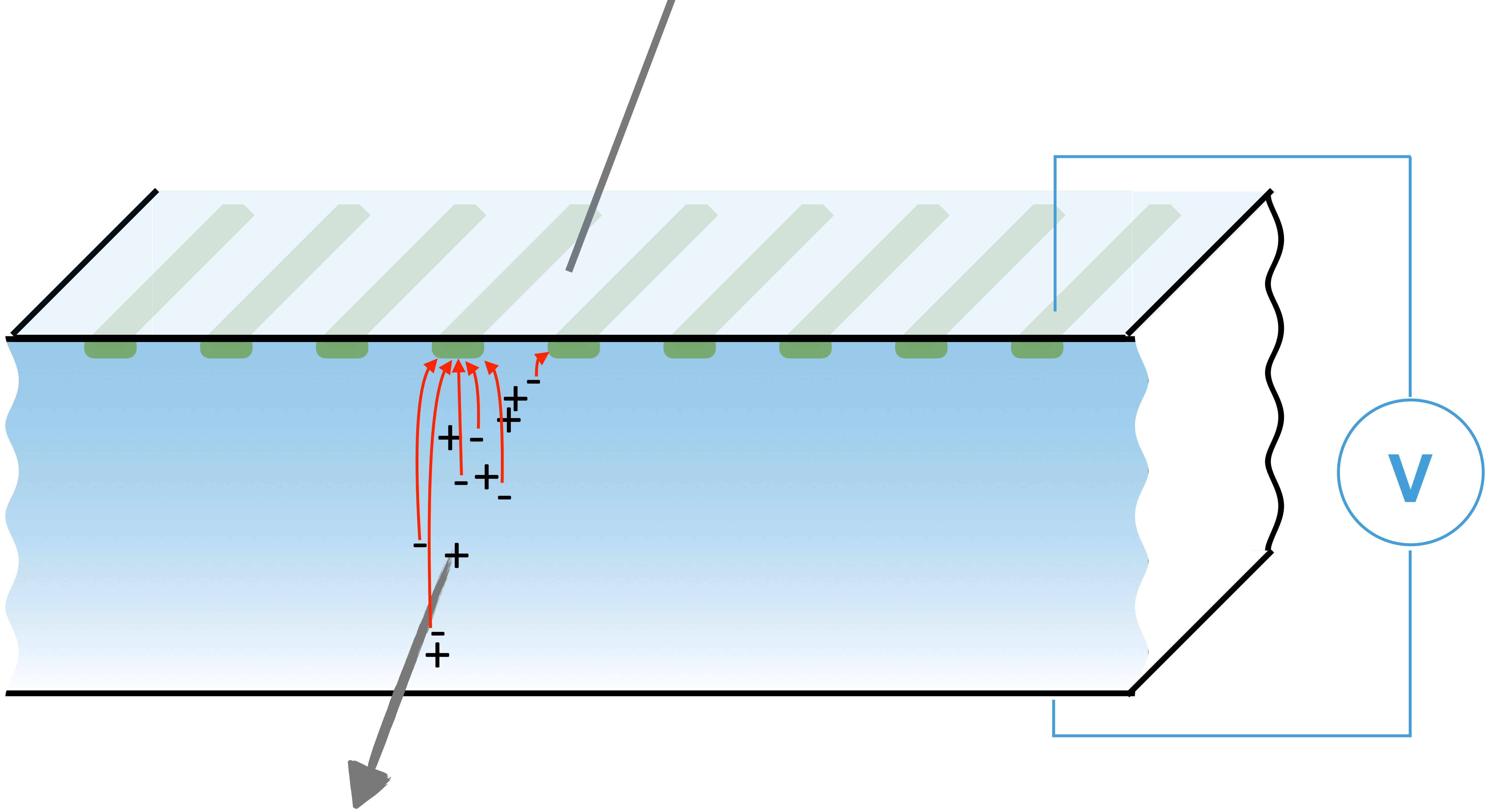
Micromegas

Silicon Particle Detectors

Silicon Particle Detector

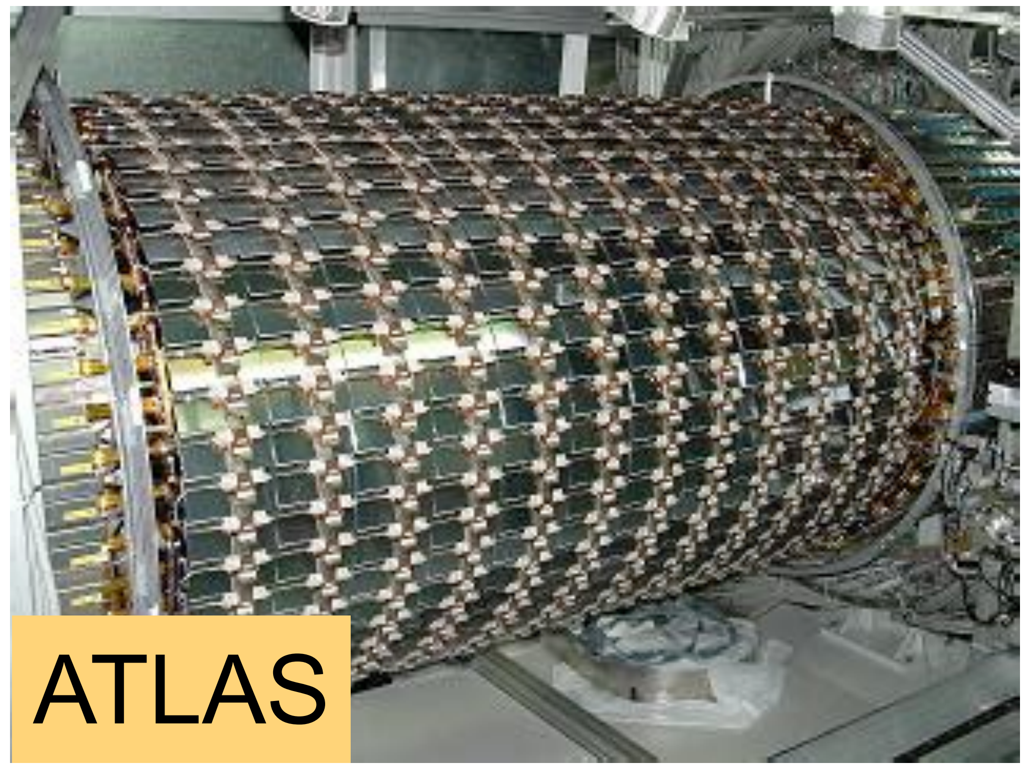
From p-n junction to simple detector

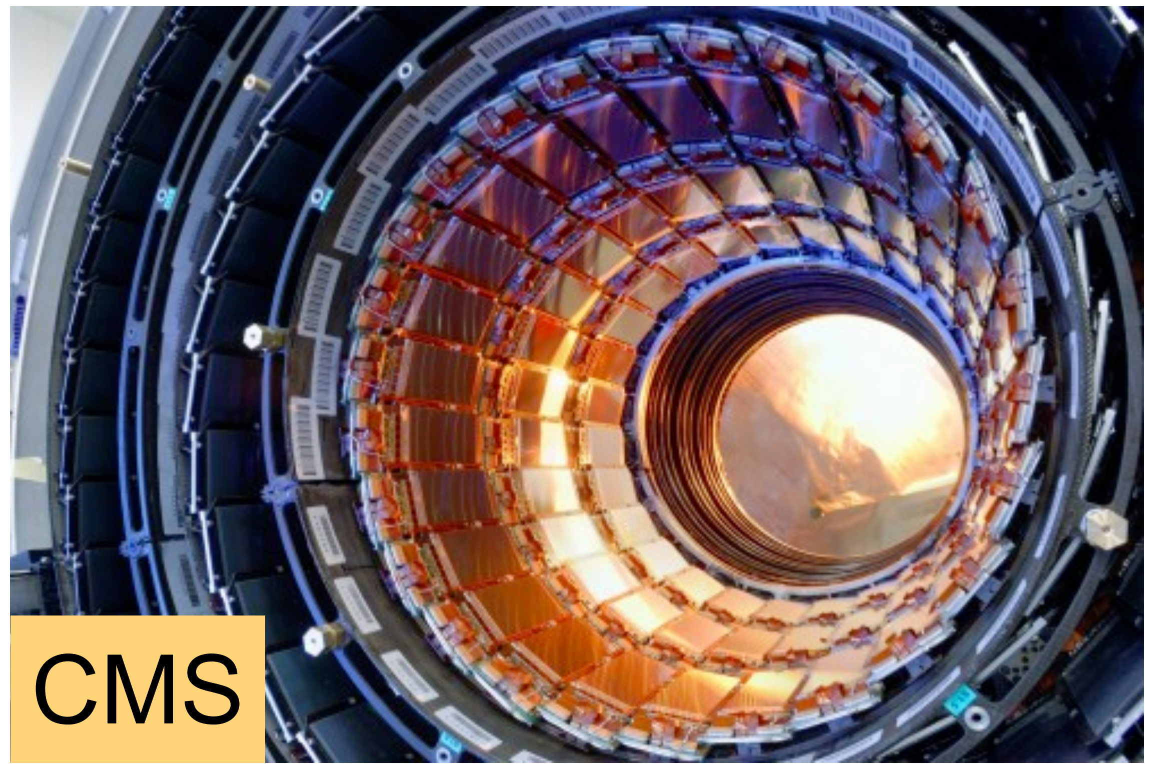
- Single-crystal Si, reverse-biased diode array
- Voltage gives E field (depletion)
- Complicated structures possible: strips, pixels

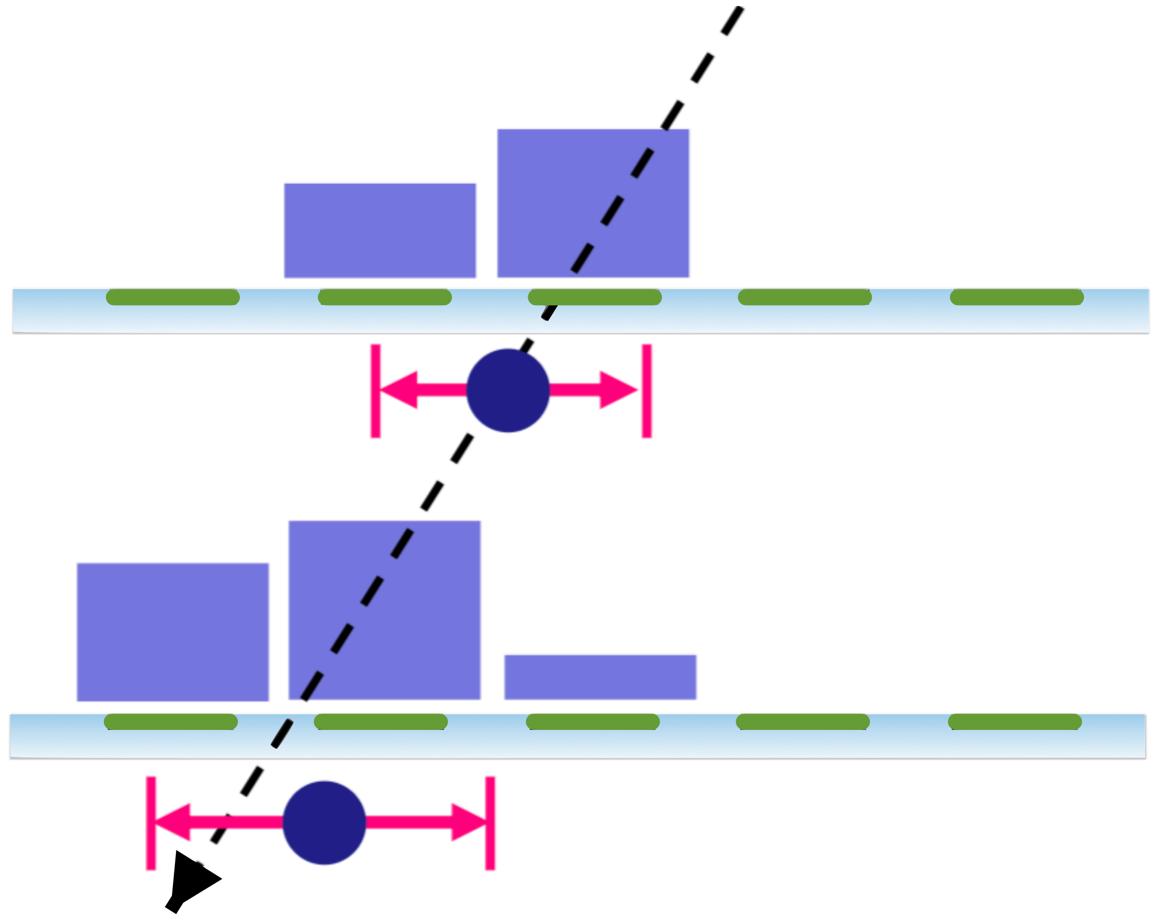


Electronics to read out signal, seed tracking

- On-detector amplification, threshold and/or pedestal subtraction, conversion to digital
- Adjacent pixels/strips combined into clusters
- Cluster position + resolution seed track finding







Tracking Chambers and Solid Media

- Ionization chamber medium could be gas, liquid, or solid
  - Push was towards higher precision tracking; the need for B vertex reconstruction provided a catalyst
  - Some technologies (ie bubble chambers) not applicable in collider environments

- High-precision tracking advantages with solid media
  - Easily ionized, relatively large amount of charge
  - Locally high density means less charge spreading
  - Fast readout possible

	Gas	Liquid	Solid
Density	Low	Moderate	High
Atomic number	Low	Moderate	Moderate
Ionization Energy	Moderate	Moderate	Low
Signal Speed	Moderate	Moderate	Fast

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Ionization Energy	Moderate	Moderate	Low
Signal Speed	Moderate	Moderate	Fast

- Advantages… but also challenges:

+ low multiple scattering overall ⟺ - high cost per surface (material, readout, cooling)
+ superb position resolution ⟺ - high number of channels
+ thin/close to interaction point ⟺ - low signals (with exceptions)
+ low ionisation energy ⟺ - solid: relatively high material budget

Semiconductor Basics – Band Gap

- As a gas, electron energy levels are discrete. In a solid, energy levels split and form a nearly-continuous band.
- If the gap is large, the solid is an insulator. If there is no gap, it is a conductor. A semiconductor results when the gap is small.
- Solid detector media with modest ionisation ⇒ semiconductor
- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionize an atom. The rest of the energy goes to phonon exitations (heat).

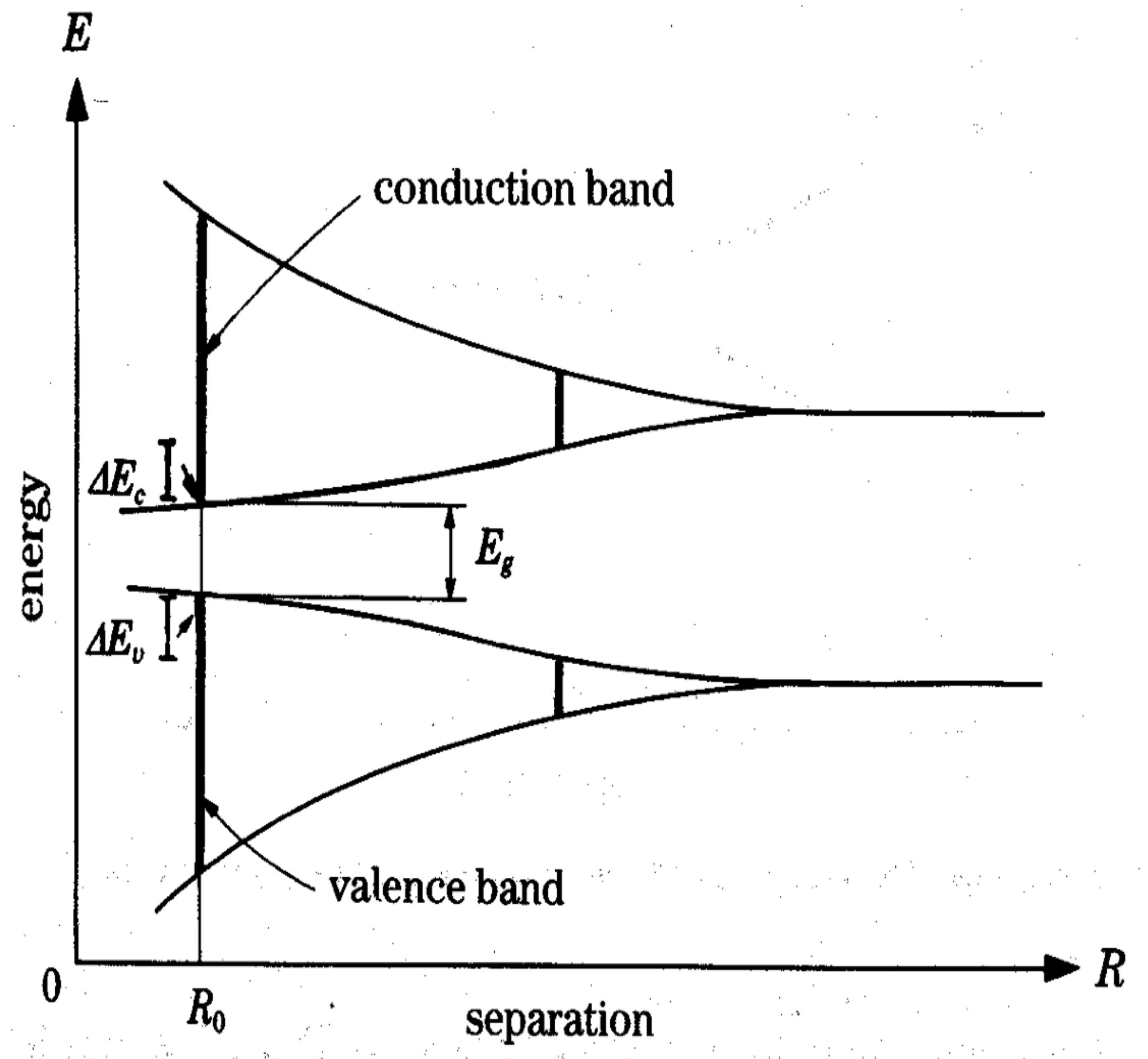
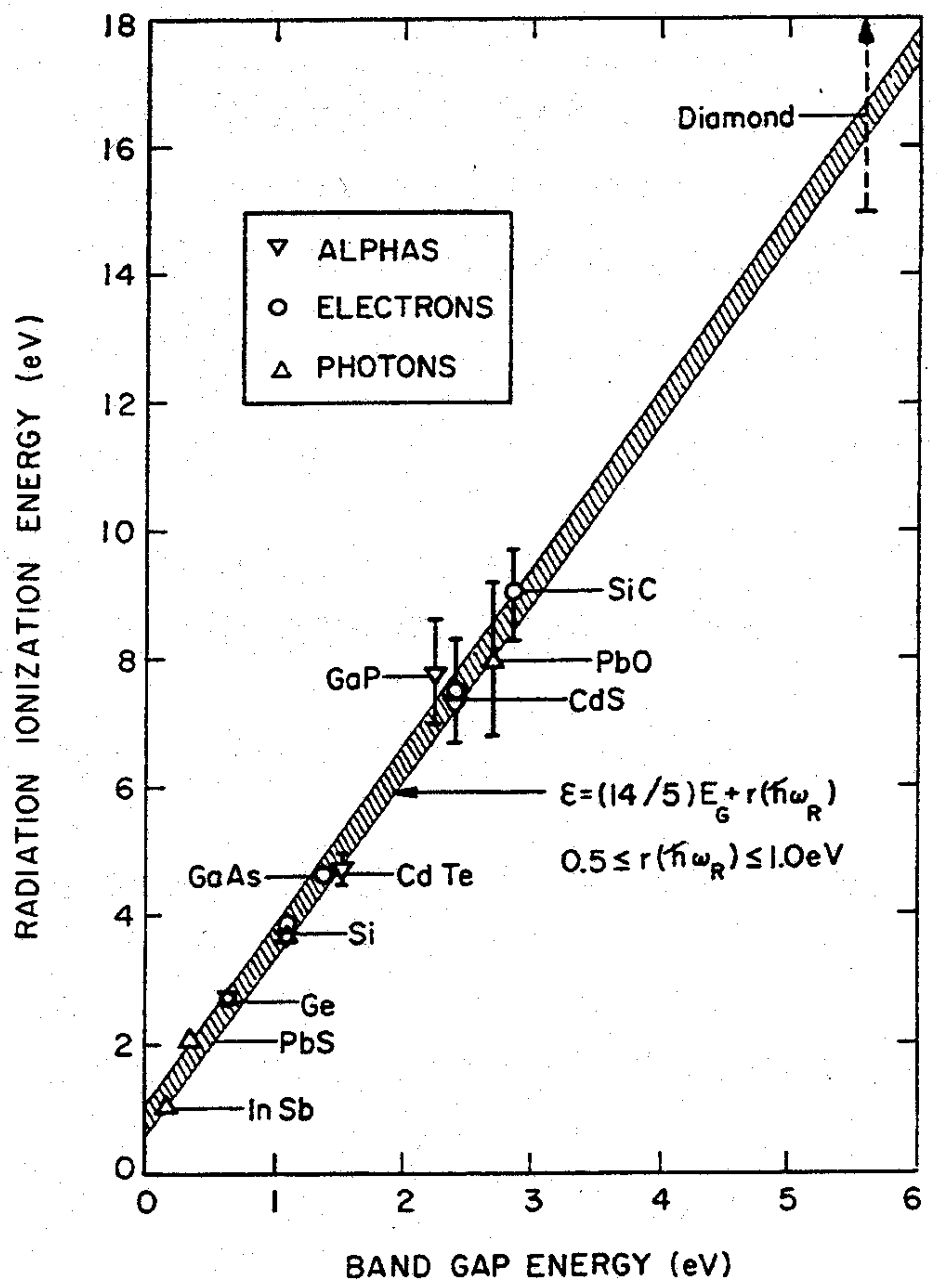


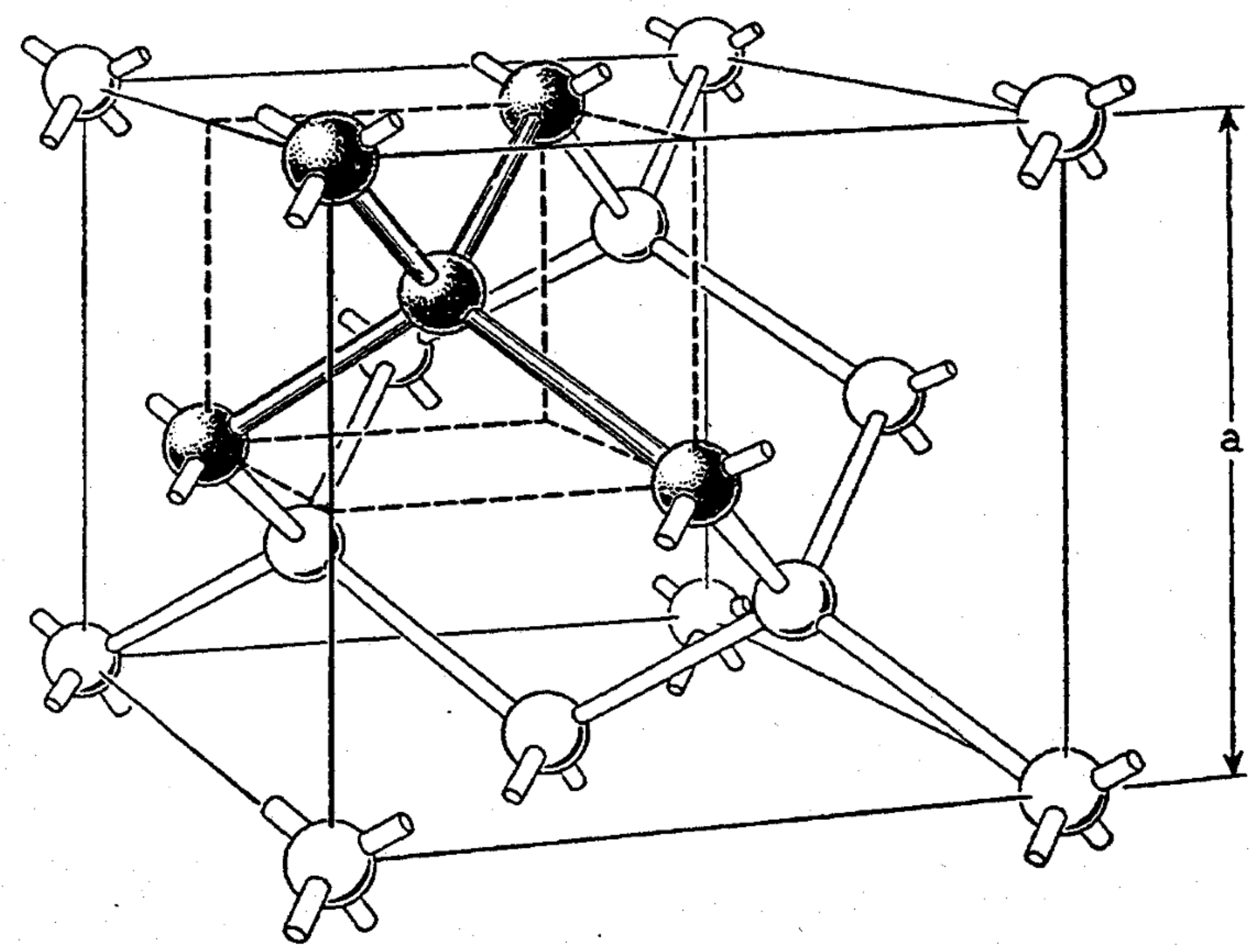
Fig. 1.2. Energy levels in a system of N atoms as a function of the separation R between the atoms. The equilibrium atomic separation is R_0.



[Leo: Techniques for Nuclear and Particle Physics Experiments]

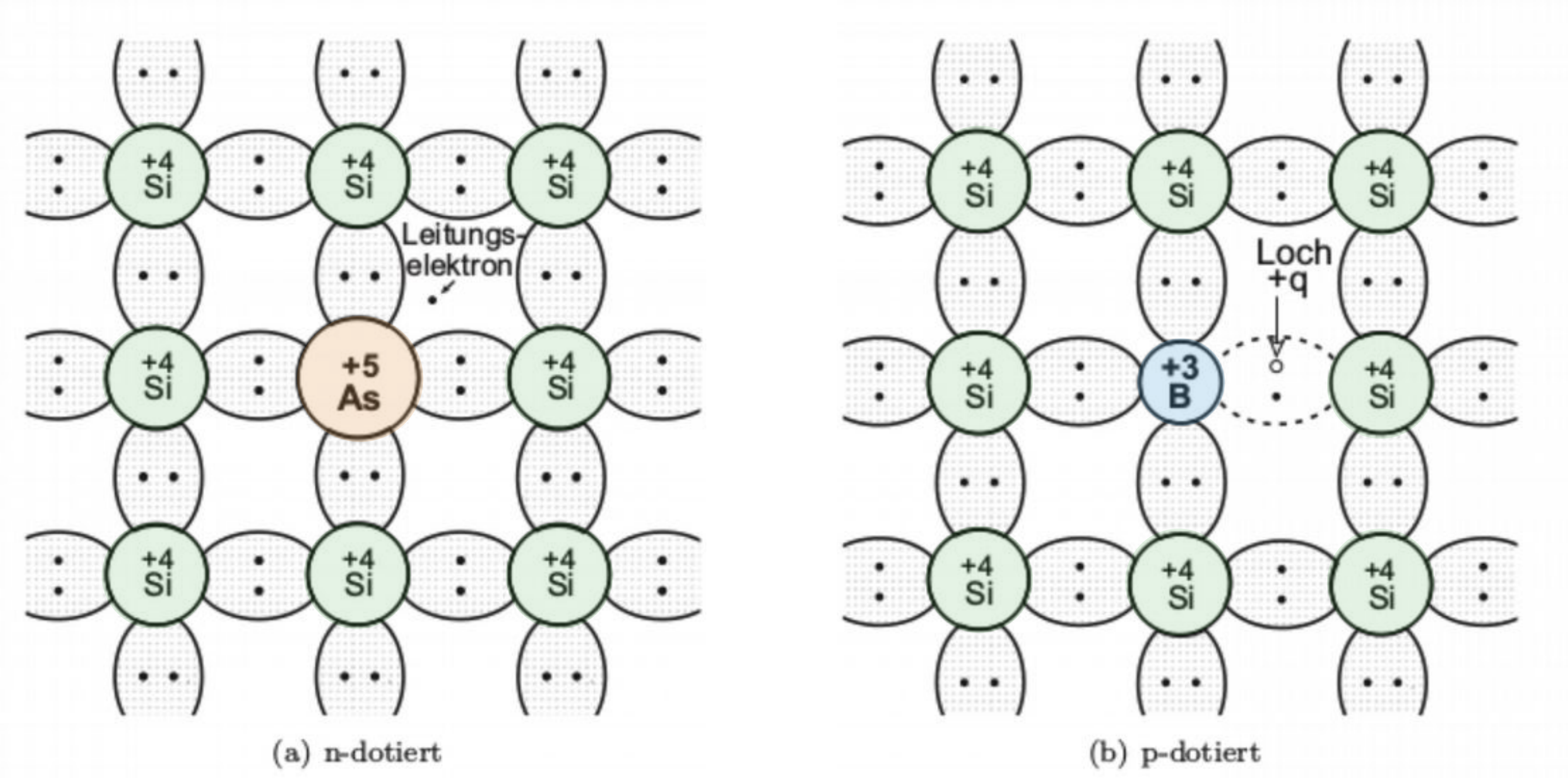
Advantages of Silicon

- Electrical properties are good
  - Forms a native oxide with excellent electrical properties
  - Ionization energy is small enough for easy ionization, yet large enough to maintain a low dark current
  - Can be cut into thin wafers, doped, etched, patterned with photolithography, combined with metals, etc
- Mechanical properties are good
  - Easily patterned to small dimensions, microstructured
  - Can be operated in air and at a wide range of temperatures
  - Crystal; can be re-oriented, assembled into complex geometries
- Availability and experience
  - Significant industrial experience and commercial applications
  - Readily available — one of the most abundant elements



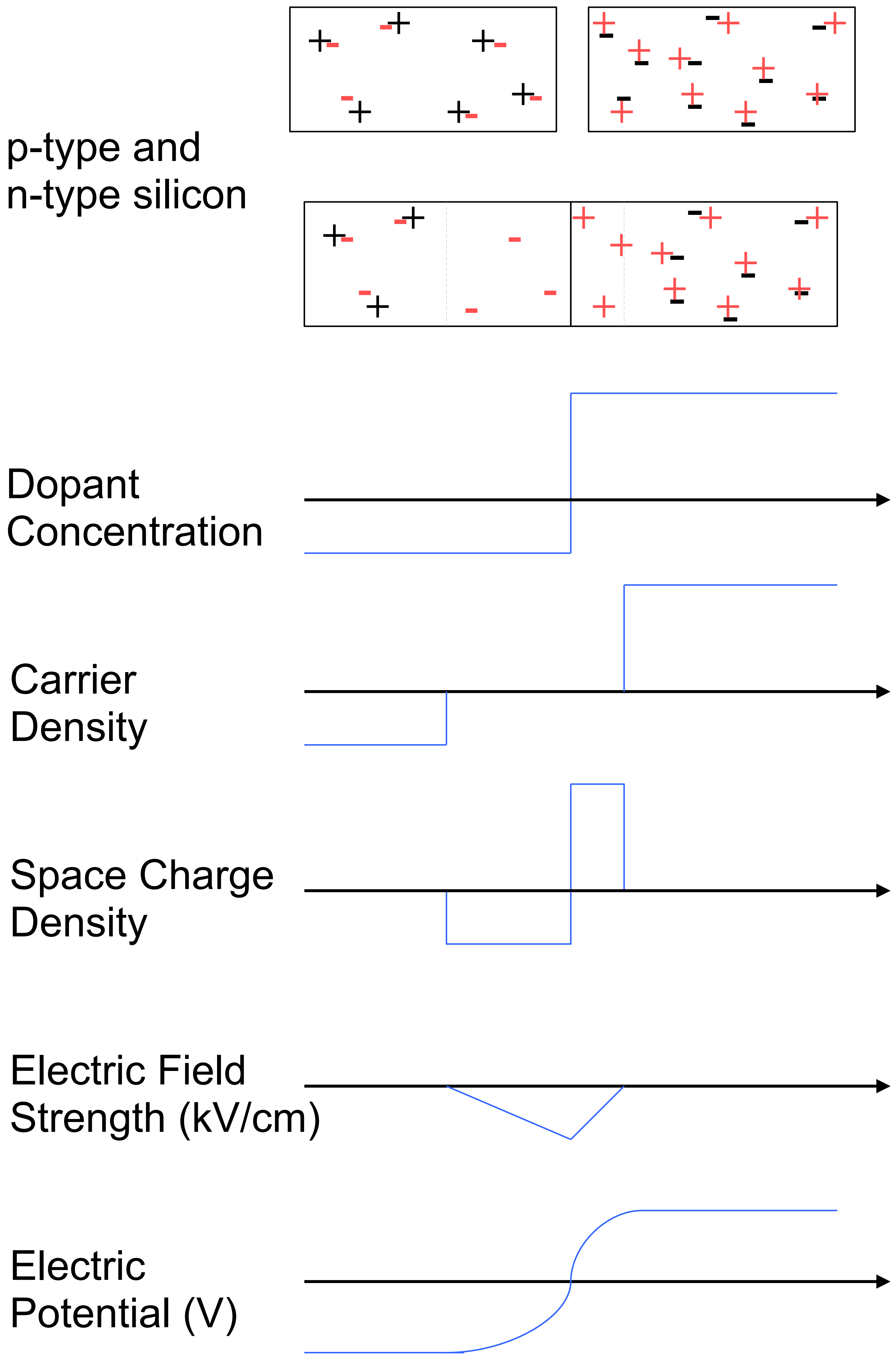
Silicon Impurities

- Impurities in the silicon crystal: from production or environment (C, O, N, also metals)
- Implanted impurities can give positive (p) or negative(n) electrical properties: doping (B, As, P…)
- Low-imputity silicon (float zone) used for detectors, as are standard (Czochralski) wafers



P-N Junction Basics

- p-type and n-type doped silicon — impurities with electrical properties, acting to create either a trapped negative or positive charge
- Together they form a region that is depleted of free charge carriers
- The depleted region contains a non-zero fixed charge and an electric field
- Ionization within this region drifts along field lines (rather than re-combining)
- The intrinsic potential in the junction can be artificially increased; this depleted region allows charge collection from a large volume with relatively little applied voltage



The p-n Junction as a Detector

- Space-charge region depends on the doping. Assuming it is uniform, the space-charge density (ρ) is:

$$\rho(x) = \begin{cases} -eN_A & \text{for } -x_p < x < 0, \\ +eN_D & \text{for } \quad 0 < x < x_n\,. \end{cases}$$

- For the Electric field E, the boundary conditions are that $E(-x_p) = E(+x_n) = 0$. Thus when the charges balance:

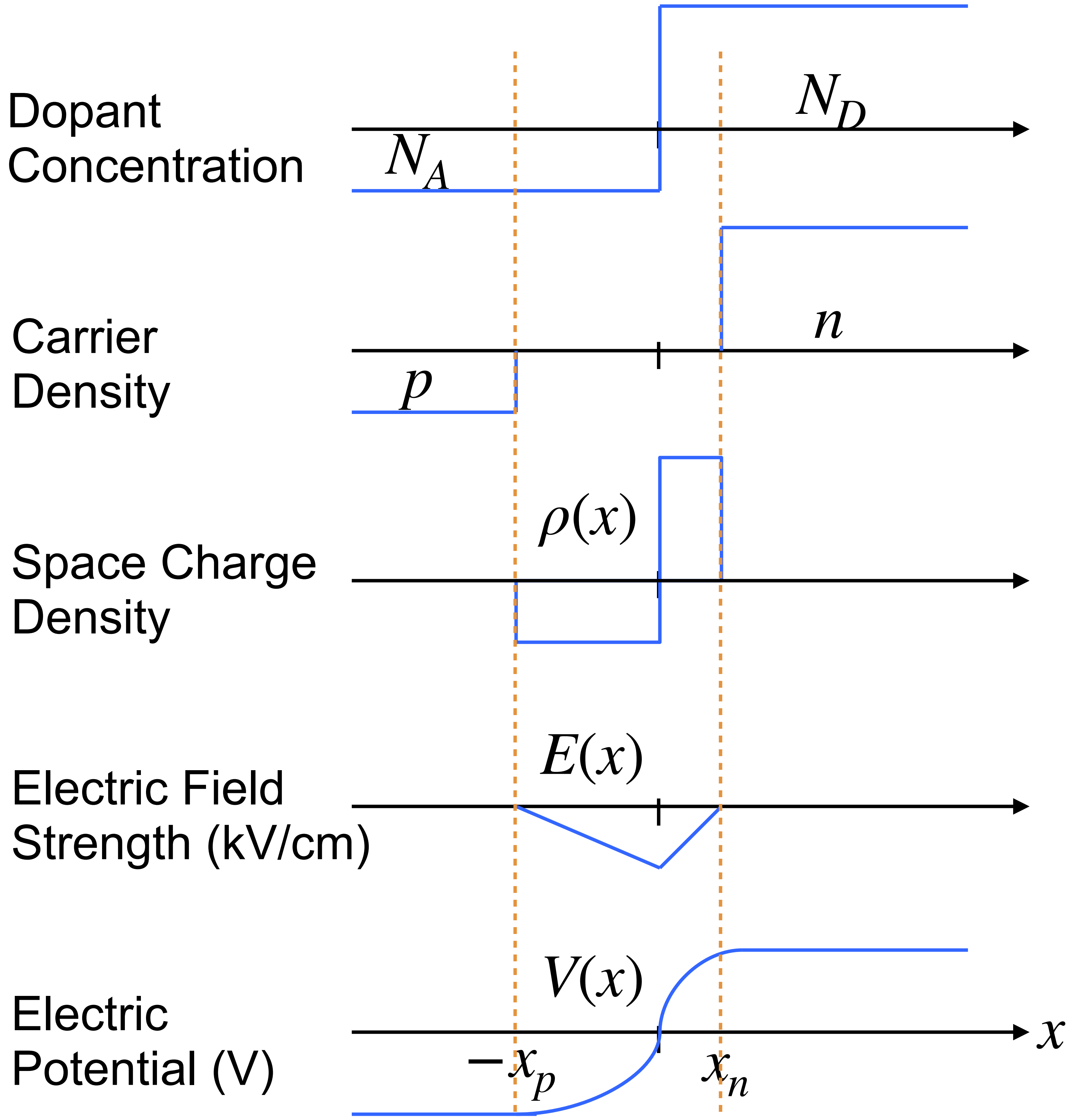
$$N_A x_p = N_D x_n$$

- From Poisson's equation with permittivity $\epsilon = \epsilon_r \epsilon_0$

$$\frac{d^2V}{dx^2} = -\frac{\rho(x)}{\epsilon}$$

- Integrating, and making use of $dV/dx = 0$ at $\mathrm{x} = -\mathrm{x_p}$ and $\mathrm{x_n}$

$$\frac{dV}{dx} = \begin{cases} \frac{eN_A}{\epsilon}(x + x_p) & \text{for } -x_p < x < 0, \\ -\frac{eN_D}{\epsilon}(x - x_n) & \text{for } \quad 0 < x < x_n\,. \end{cases}$$



The p-n Junction as a Detector

- Integrating again yields

$$V(x) = \begin{cases} \frac{eN_A}{\epsilon}(\frac{x^2}{2} + x_p x) + C & \text{for } -x_p < x < 0, \\ -\frac{eN_D}{\epsilon}(\frac{x^2}{2} - x_n x) + C & \text{for } \quad 0 < x < x_n \end{cases}$$

- where we can solve for C using $V(-x_p) = 0$ and $V(x_n) = V_0$, and obtain

$$V_0 = \frac{e}{2\epsilon}(N_D x_n^2 + N_A x_p^2)\,.$$

- Solving for x_n and x_p, we can then find the total depletion width of

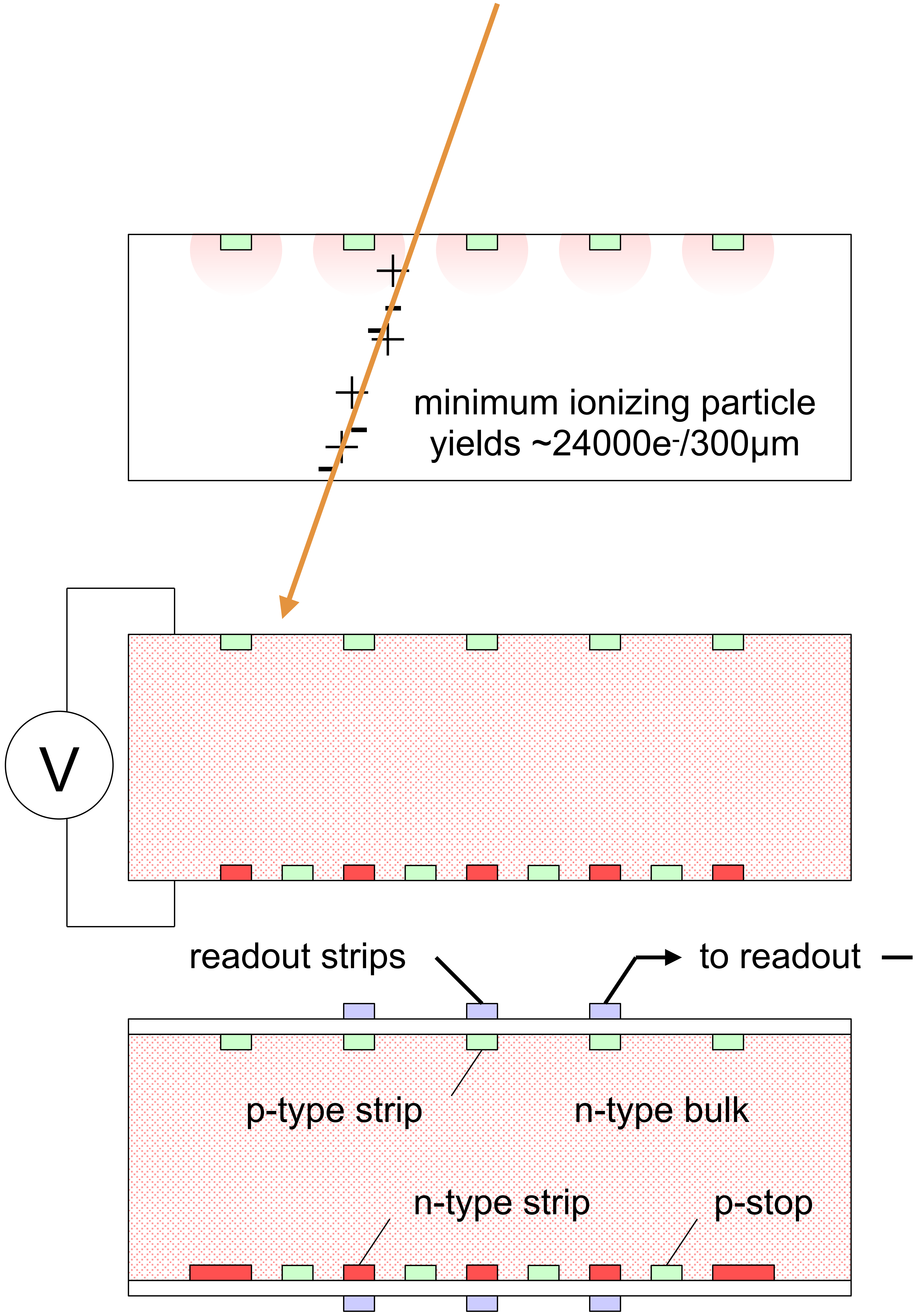
$$d = x_p + x_n = \sqrt{\frac{2\epsilon V_0}{e}\frac{(N_D + N_A)}{N_D N_A}}$$

- and when one concentration is much different than the other, for example $N_A \gg N_D$, then

$$d = x_n = \sqrt{\frac{2\epsilon V_0}{eN_D}}\,.$$

Silicon Strip Tracking Detectors

- Segmentation of the diode into strips allows localized readout
  - 60 µm average strip pitch
  - Can be segmented on both sides
- Reverse-biasing causes the entire region to deplete
  - p-n junction results in a relatively low operating voltage
  - Low dark current
- Typical strip sensors are n-type silicon bulk and p-type implanted strips
  - Integrated polysilicon bias resistors provide distribution of bias V
  - p-stops maintain strip isolation on the n side
  - AC-coupled readout helps protect readout circuitry; e.g. silicon held at depletion voltage, capacitively coupled readout at ground



Sensor/Diode Properties

- Diode leakage current is an important operational parameter

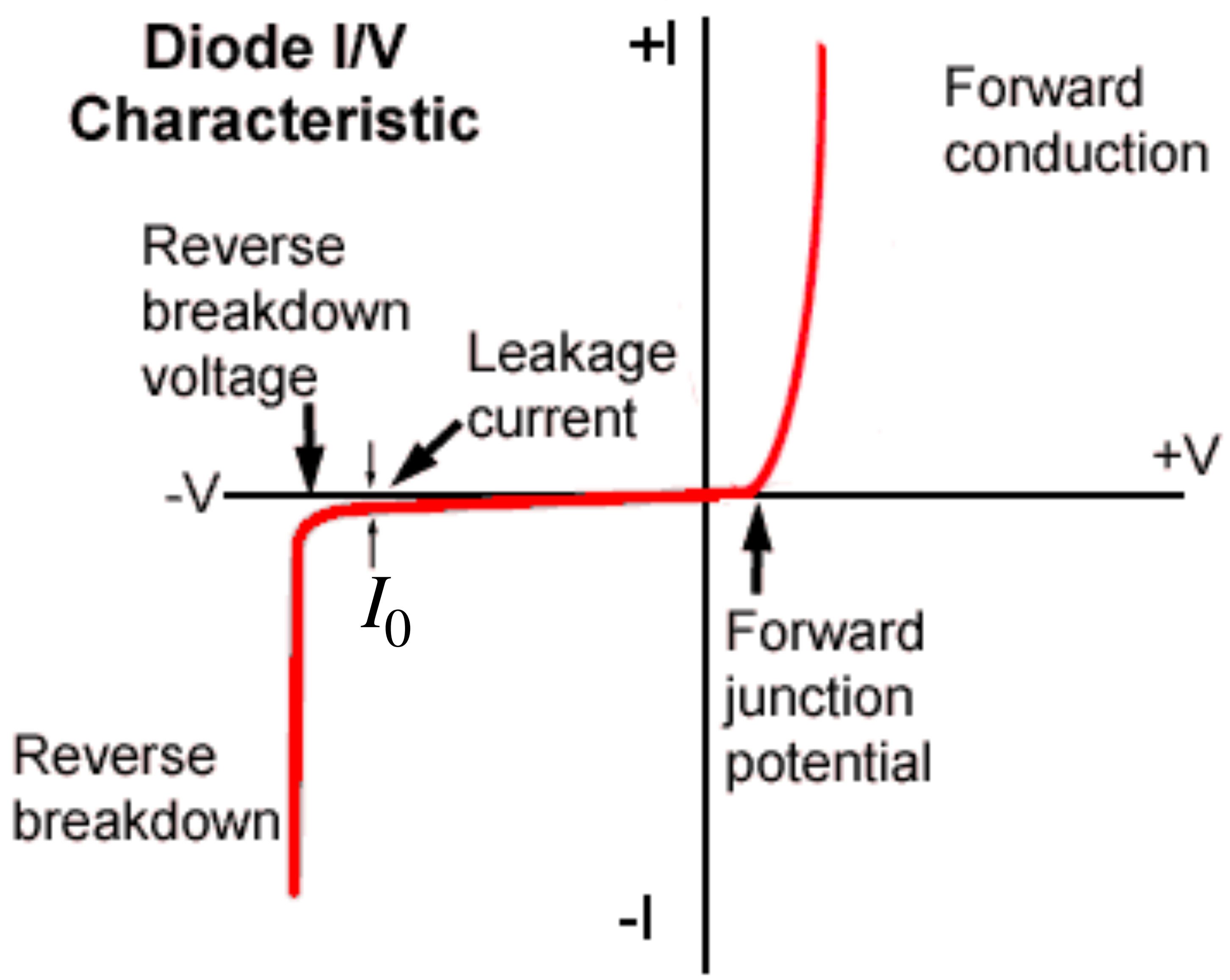
$$I = I_0\left(e^{\frac{eV}{KT}} - 1\right)$$

  - Sensor operated in "reverse bias" mode
  - Reverse voltage applied until "full depletion"

- Diode capacitance: large structures act as capacitors

$$\frac{C}{A} = \frac{\epsilon}{d}$$

  - where C is capacitance, A is area and d the thickness of the depletion region
  - for typical d of 0.3 mm, C/A is approximately 35 pF/cm^2



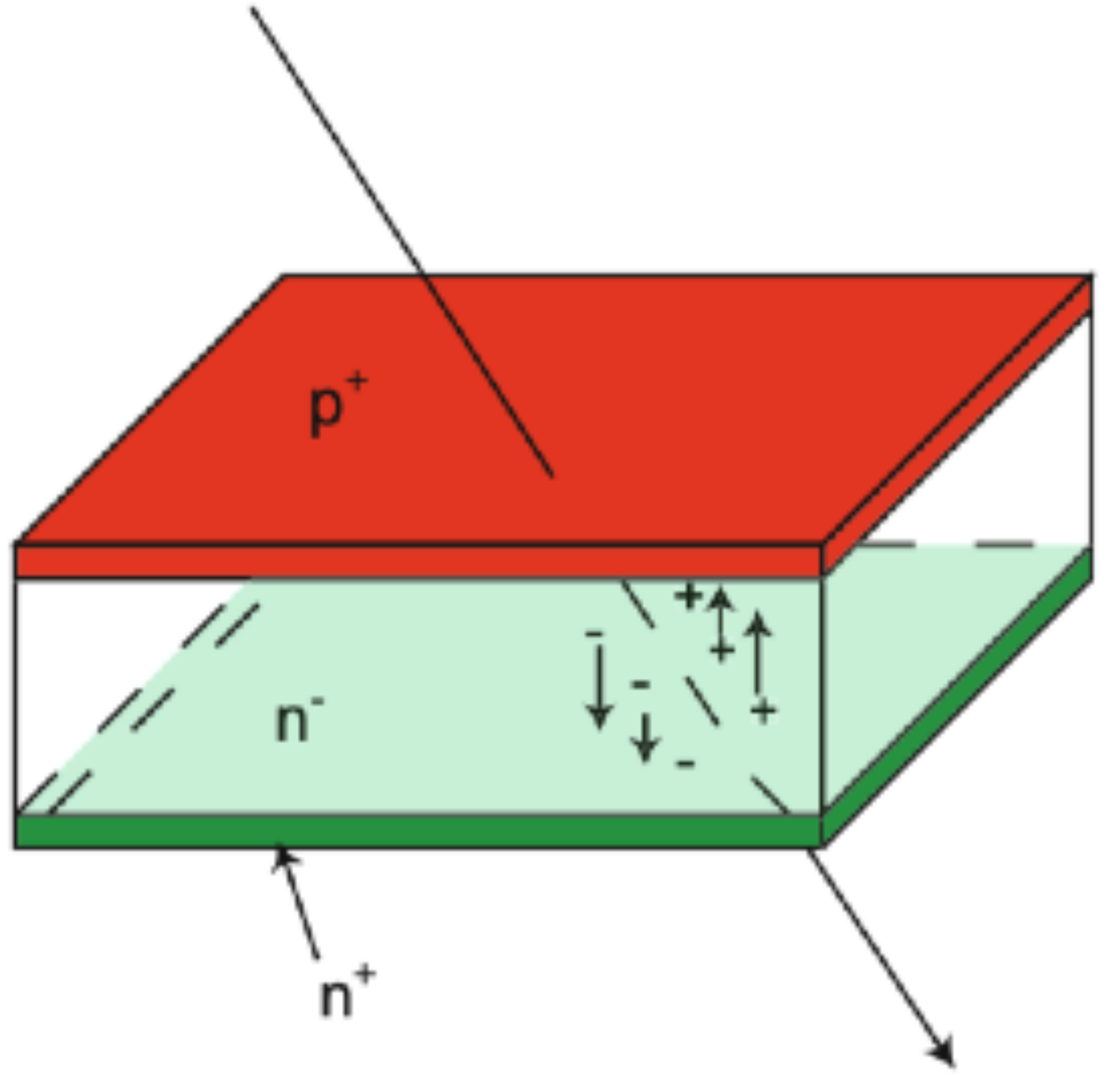
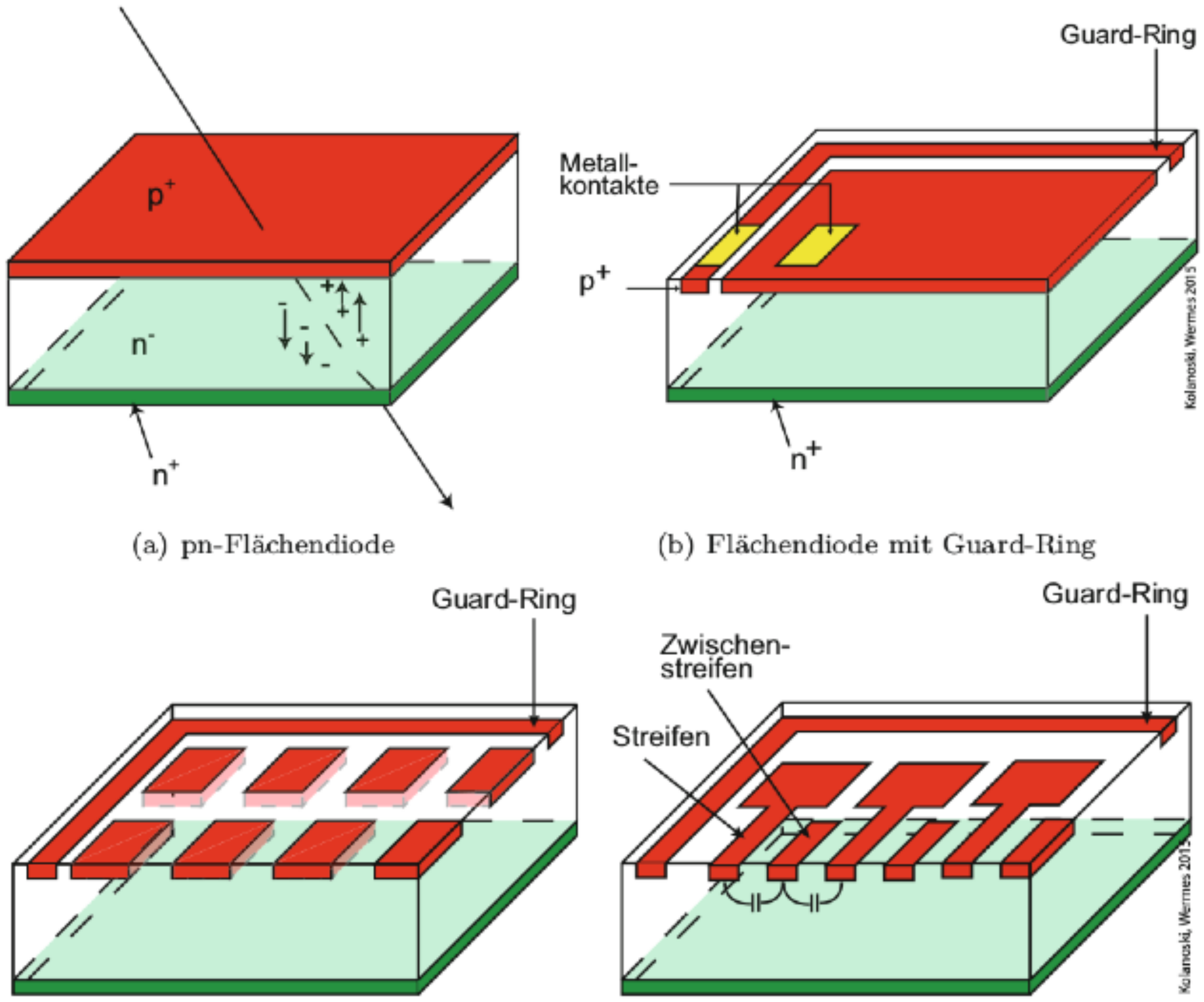


figure: https://www.learnabout-electronics.org/

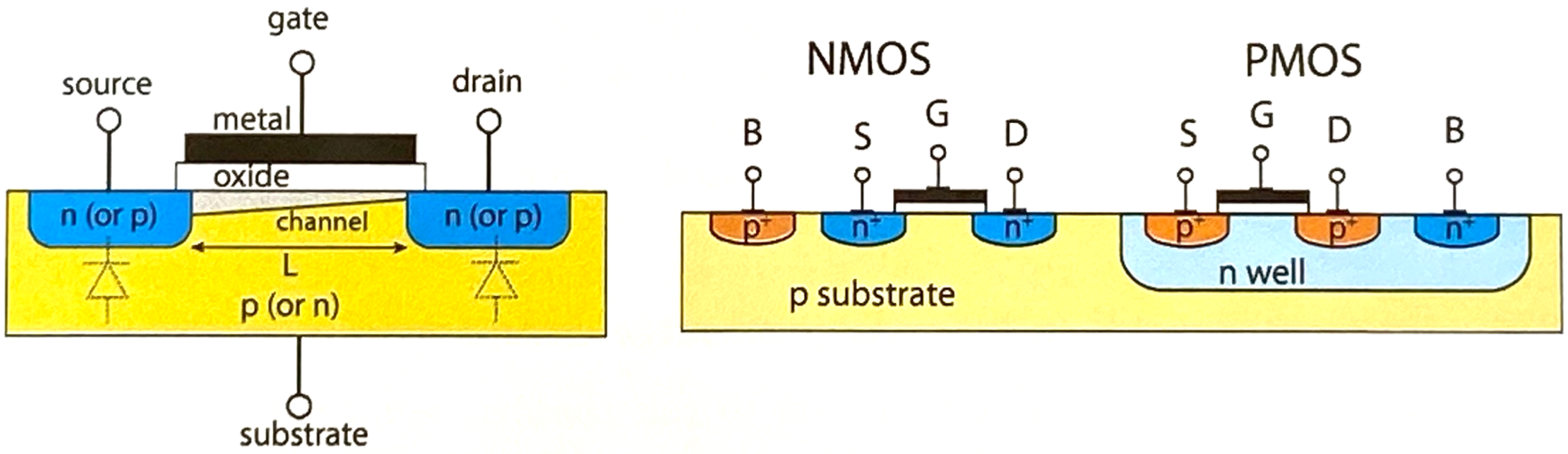
Standard Diode Sensor Geometries



[Kolanoski, Wermes]

CMOS Electronics

- Detectors now use modern electronics; transistors (1940's) and MOS electronics (1950-60's)
- Complimentary Metal-Oxide-Semiconductor (CMOS) used for readout electronics, pixel sensors, etc



(a) MOSFET. (b) CMOS.

- Next lecture… also radiation damage

stop here…?