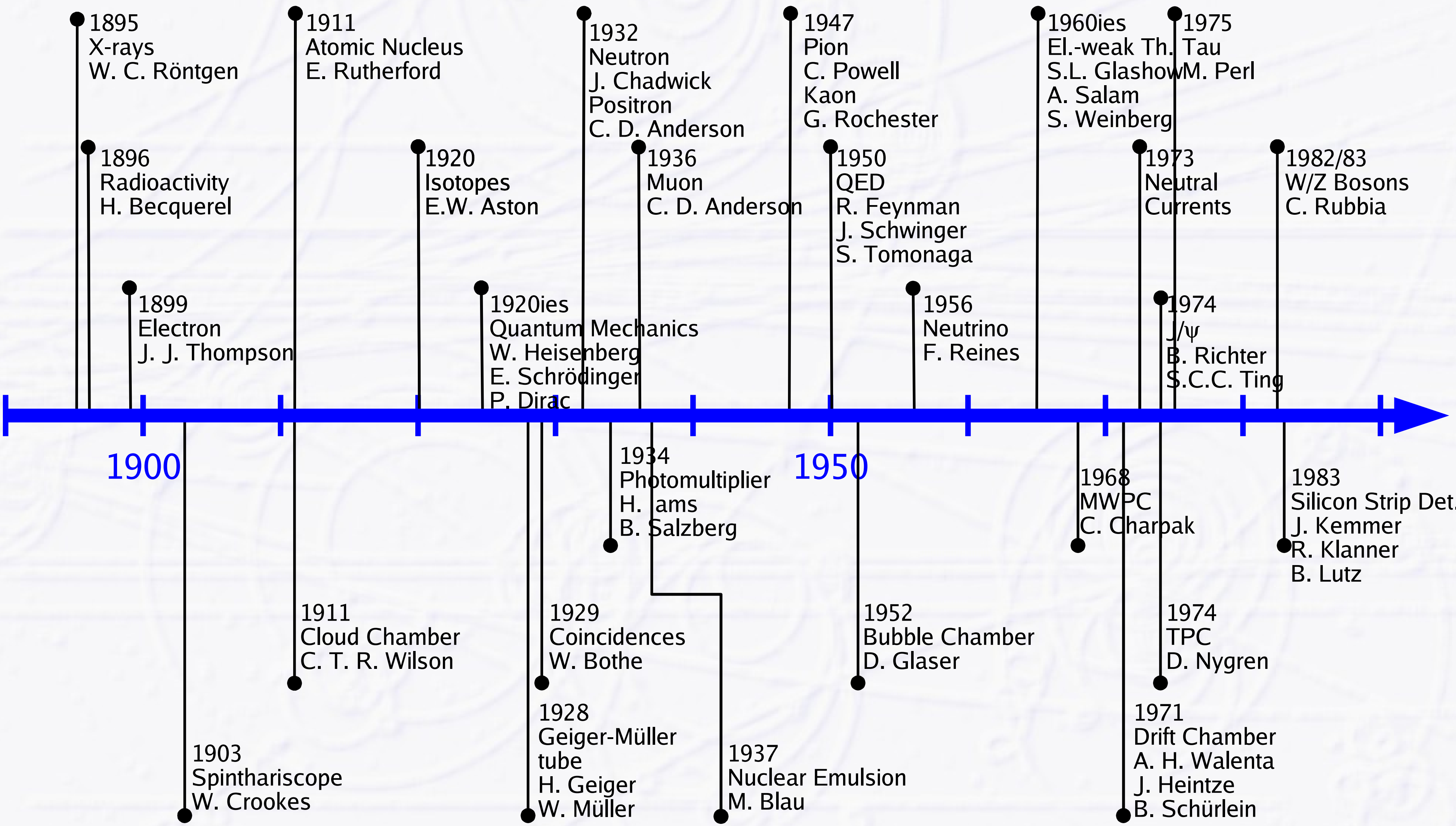
History of Instrumentation

Artist's View of a Bubble Chamber by a CERN physicist

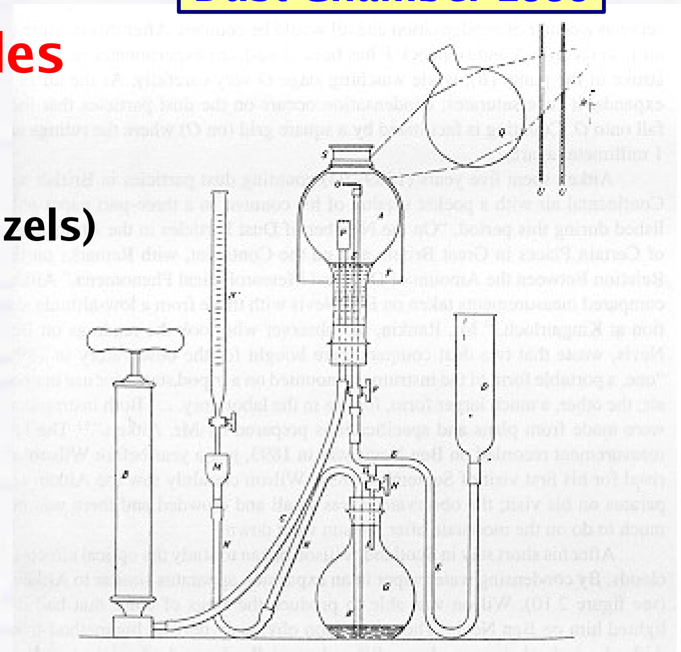
Timeline of Particle Physics and Instrumentation



Early Image Detectors

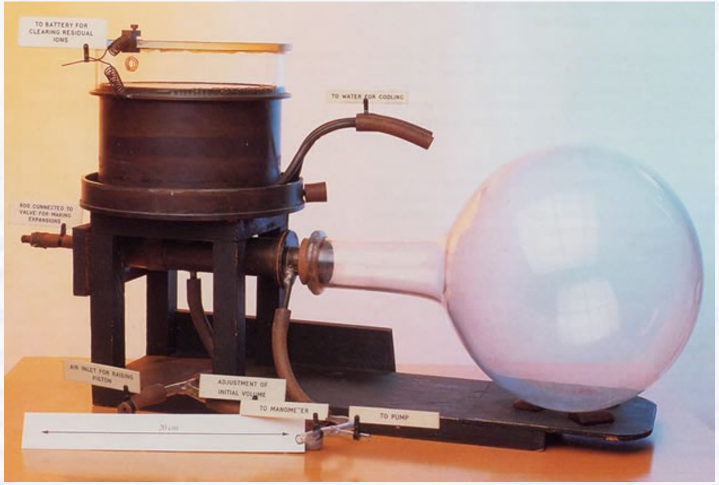
- Second half of 19th century
  - growing interest in meteorological questions
    - climate, weather phenomenon, cloud formation
  - people started to study condensation of water vapour in the lab
    - also motived by raising use of steam engines
- John Aitken built a "Dust Chamber" 1888
    - water vapour mixed with dust in a controlled way
  - result: droplets are formed around dust particles
  - further speculations
    - electricity plays a role (from observations of steam nozzels)
- Charles T. R. Wilson became interested
  - first ideas to build a cloud chamber 1895
    to study influence of electricity/ions
    - also to solve question why air shows
      natural slight conductivity

Dust Chamber 1888



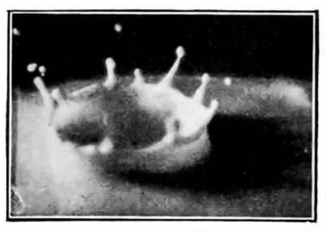
Cloud Chamber I

- **Cloud chamber (1911 by Charles T. R. Wilson, Noble Prize 1927)**
  - chamber with saturated water vapour
  - charged particles leave trails of ions
    - water is condensing aound ions
  - visible track as line of small water droplets

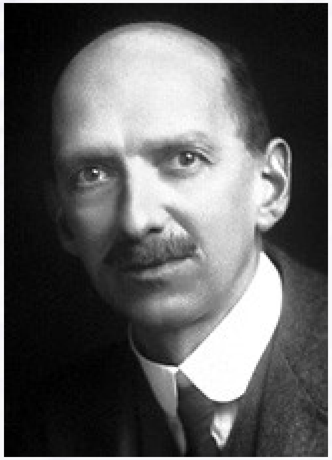


UK Science Museum

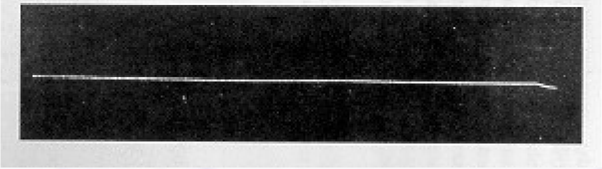
- **Also required**
  - high speed photographic methods
    - invented by Arthur M. Worthington 1908 to investigate the splash of a drop
    - ultra short flash light produced by sparks

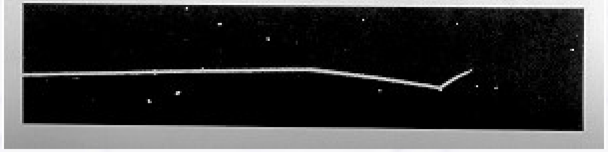


Charles T. R. Wilson



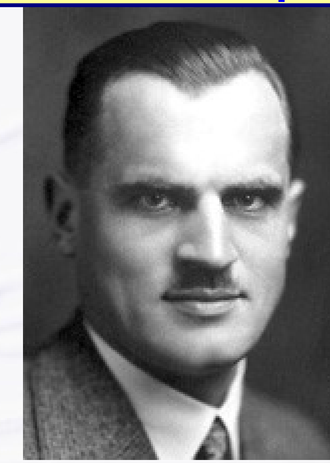
- **First photographs of α–ray particles 1912**





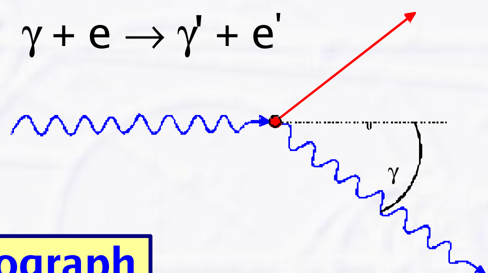
Cloud Chamber II

Arthur H. Compton

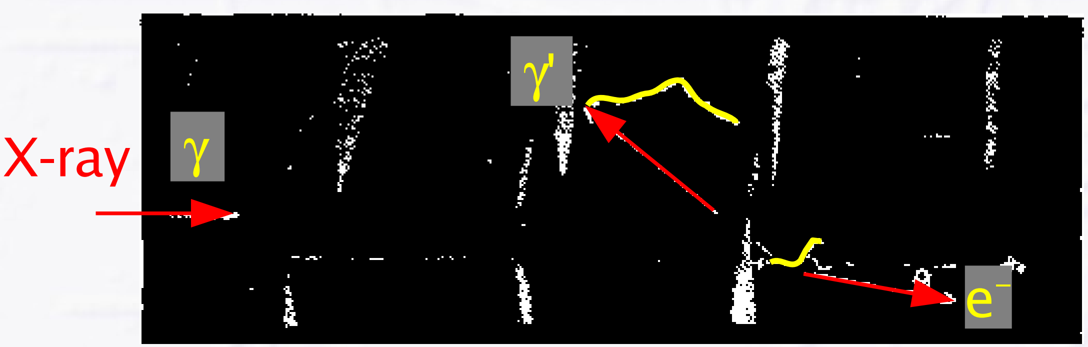


- **Arthur H. Compton used the cloud chamber in 1922 to discover scattering of photons on electrons (Compton effect)**
  (Nobel Prize 1927 together with Charles T. R. Wilson)
  - **X-rays emitted into cloud chamber**
    - **photon scattered on electrons (recoiling electron seen in cloud chamber)**
    - **photon with reduced energy under certain angle visible by photo effect or Compton effect again**

$$\gamma + e \rightarrow \gamma' + e'$$



original photograph



Nobel Lecture 1927

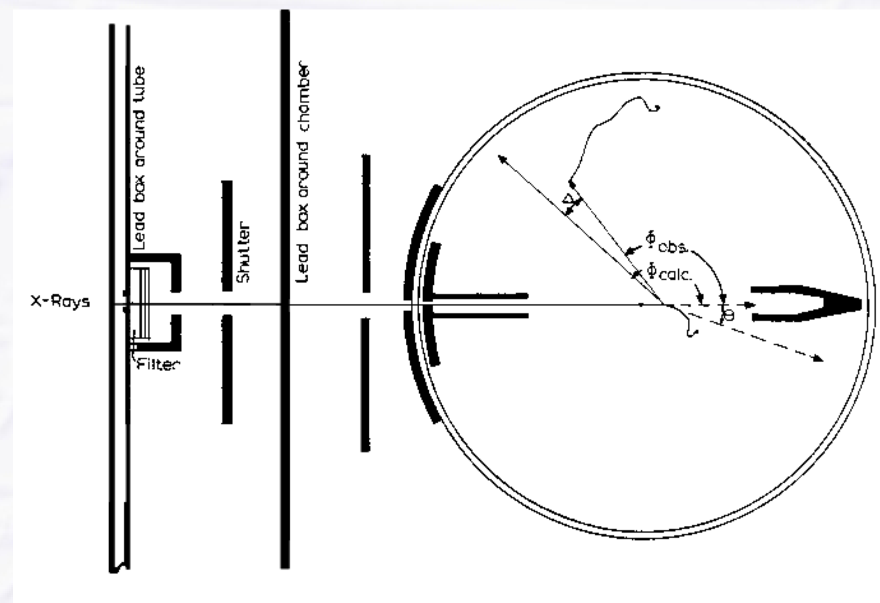


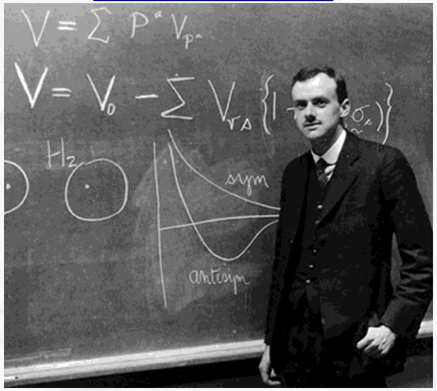
Fig. 10. An electron recoiling at an angle θ should be associated with a photon deflected through an angle φ.

Nobel Lecture 1927

Cloud Chamber III

- Was also used for the discovery of the positron
  - predicted by Paul Dirac 1928 (Nobel Prize 1933)
  - found in cosmic rays by Carl D. Anderson 1932 (Nobel Prize 1936)

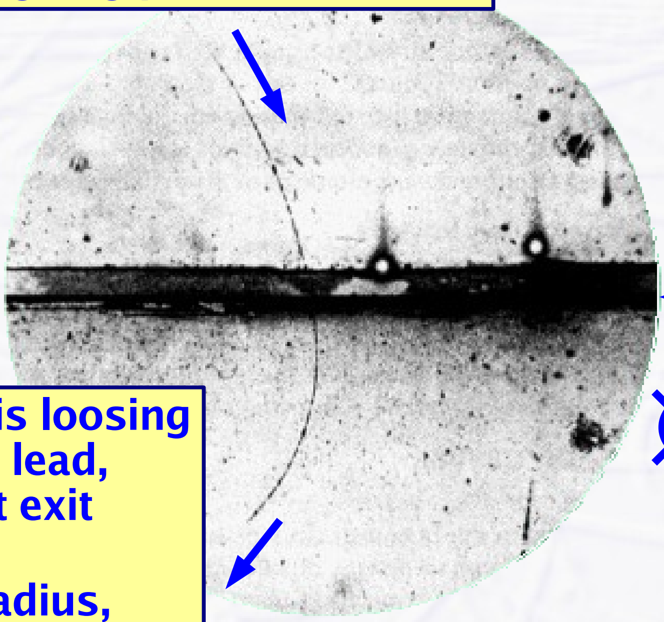
Paul Dirac



Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Isidor Isaac Rabi said: "Who ordered that?"

downward going positron, 63 MeV

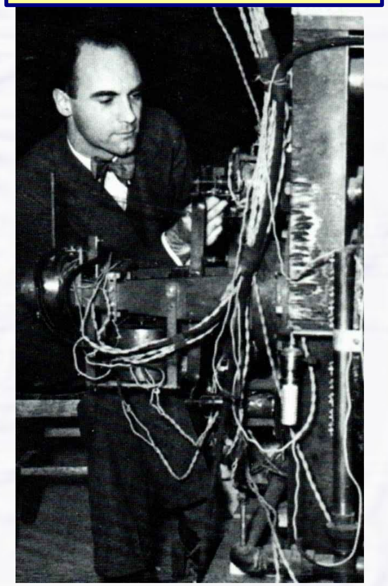


6 mm lead plate

⊗ 1.5 T magnetic field

positron is loosing energy in lead, 23 MeV at exit → smaller radius, this defines the track direction!

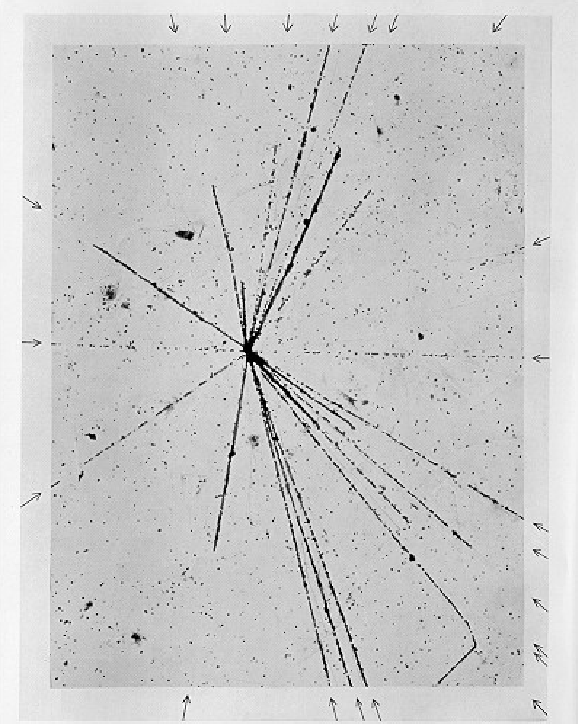
Carl D. Anderson



Nuclear Emulsion I

- **Pioneered by Marietta Blau between 1923 – 1938 (no Nobel Prize)**
  - photographic emulsion layer, 10 – 200 μm thick, uniform grains of 0.1 – 0.3 μm size
  - very high resolution for particle tracks
    - analysis of developed emulsion by microscope

Marietta Blau



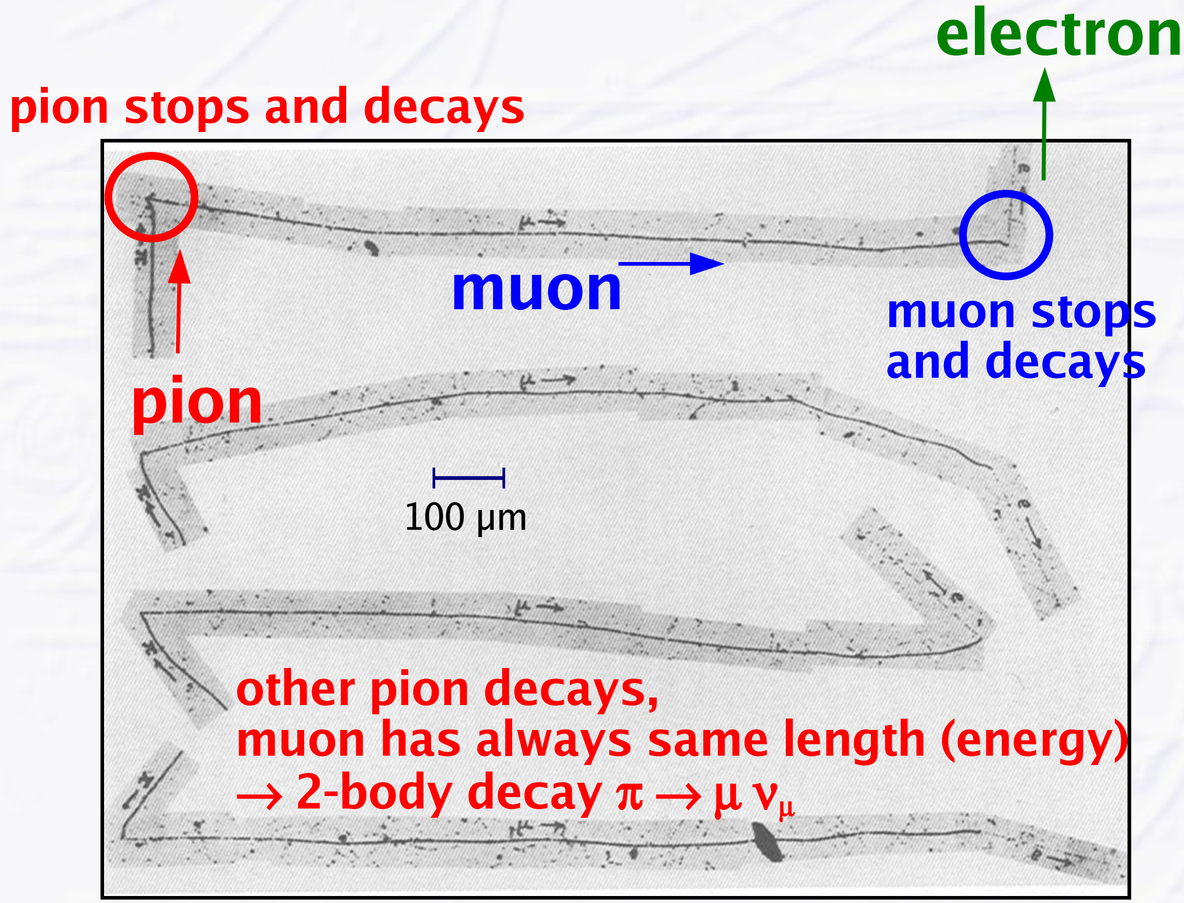
'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

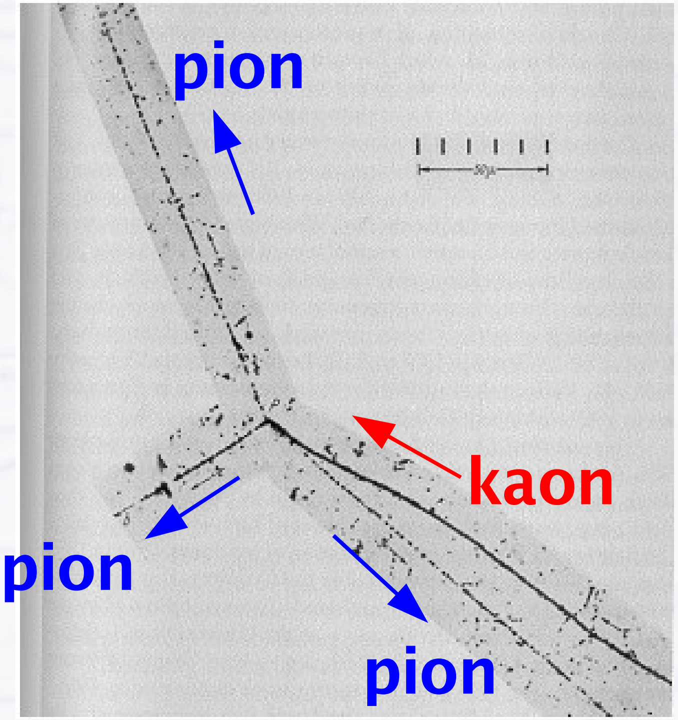
nuclear disintegration from cosmic rays, observed1937 for the first time

- **Since early 20^{th} century**
  - important role of photography to study radioactivity
  - but capability to make individual tracks visible not seen until nuclear emulsion technique was developed

Nuclear Emulsion II

- Discovery of the pion in cosmic rays by Cecil Powell 1947 (Nobel Prize 1950)
- Discovery of the kaon 1949 (G. Rochester)

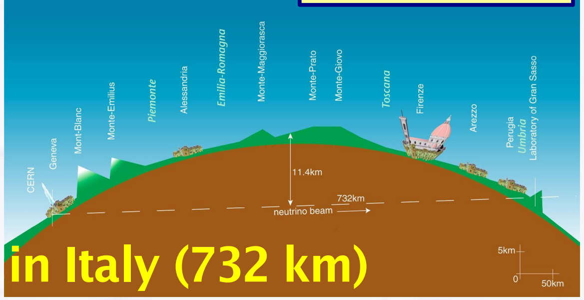


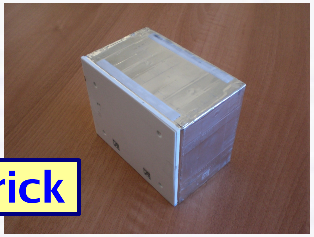


Nuclear Emulsion III

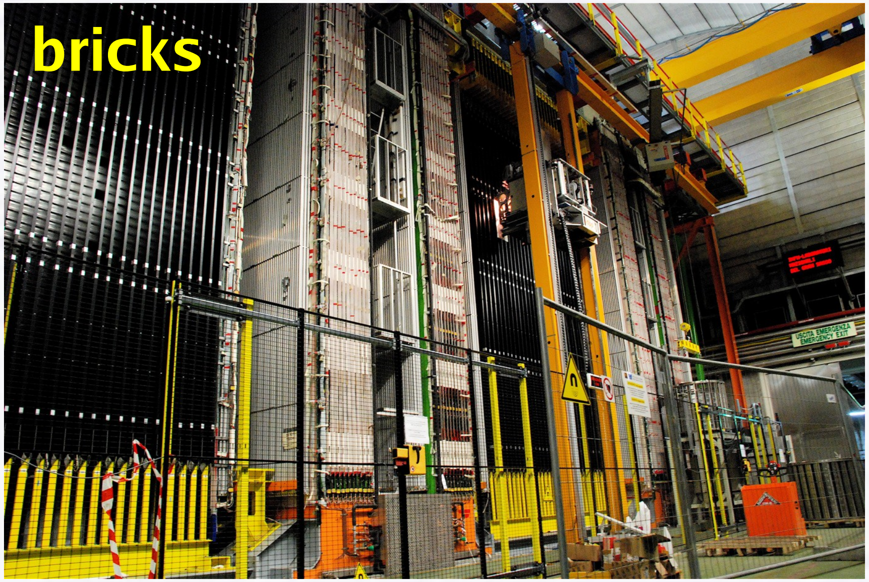
- **Still used in actual experiments with highest precision requirements over a large volume**
  - ν_μ beam sent from CERN to Gran Sasso Underground lab in Italy (732 km)
  - OPERA experiment is searching for ν_τ appearance after neutrino oscill. $\nu_\mu \to \nu_\tau$
    - need to reconstruct τ decays (ν_τ + N $\to \tau^-$ + X) (few ~100 µm track length)
    - 235'000 “bricks” (1.7 ktons) of lead + emulsion sheets

CNGS beam



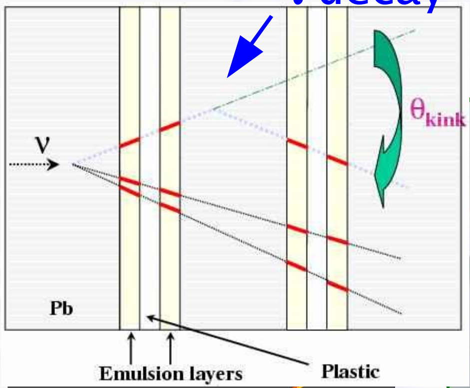


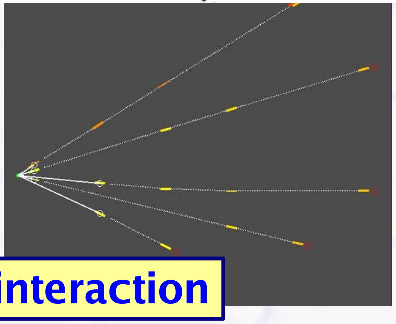
single brick



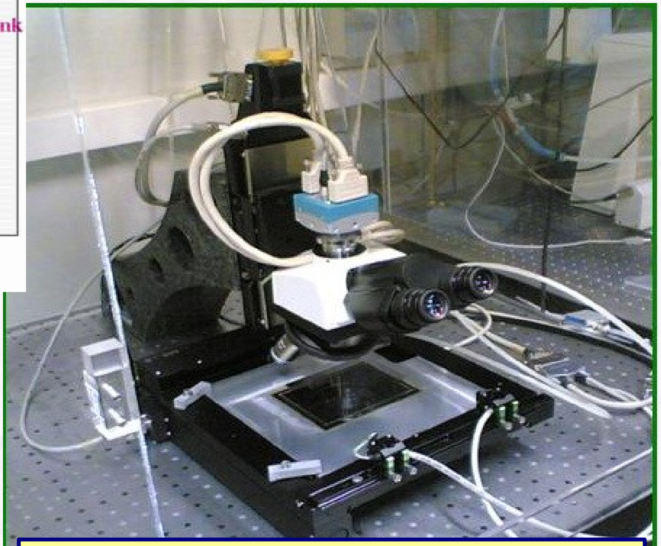
OPERA at Gran Sasso

τ decay





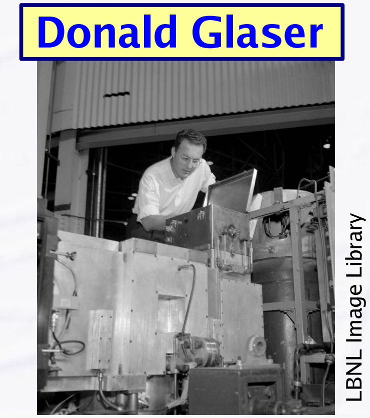
ν_μ interaction



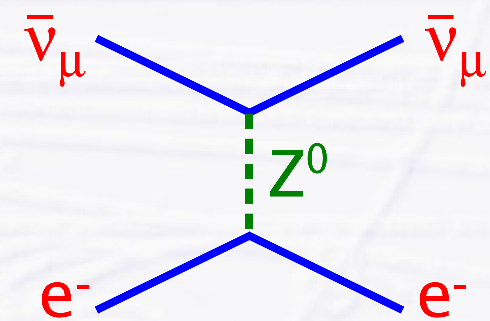
automatic emulsion scanning

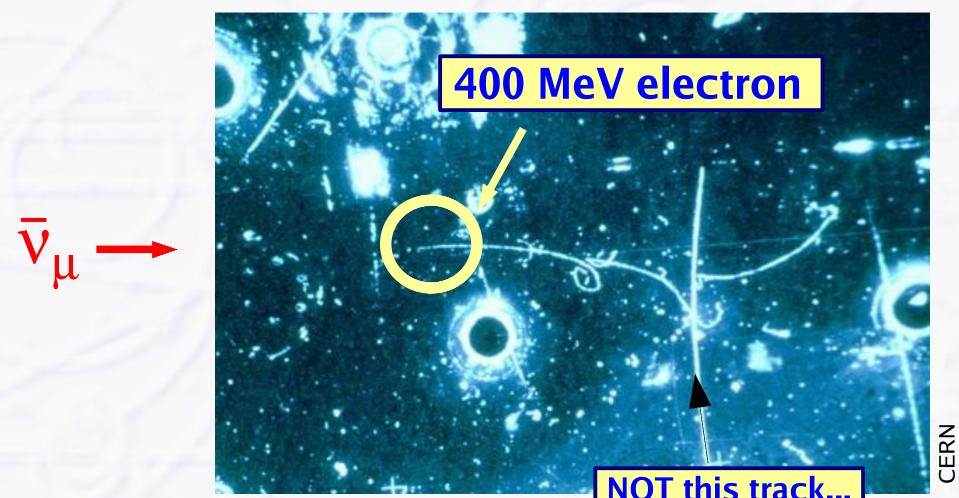
Bubble Chamber I

- **Intented 1952 by Donald Glaser (Noble Prize 1960)**
  - similar to could chamber
  - → chamber with liquid (e.g. H_2) at boiling point ("superheated")
  - → charged particles leave trails of ions
  - formation of small gas bubbles around ions



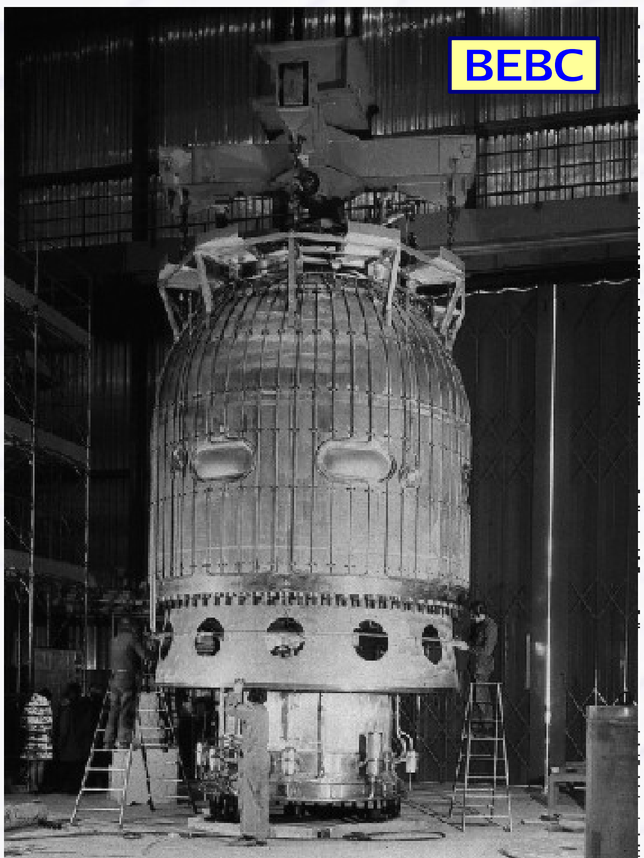
was used at discovery of the "neutral current"
(1973 by Gargamelle Collaboration, no Noble Prize yet)

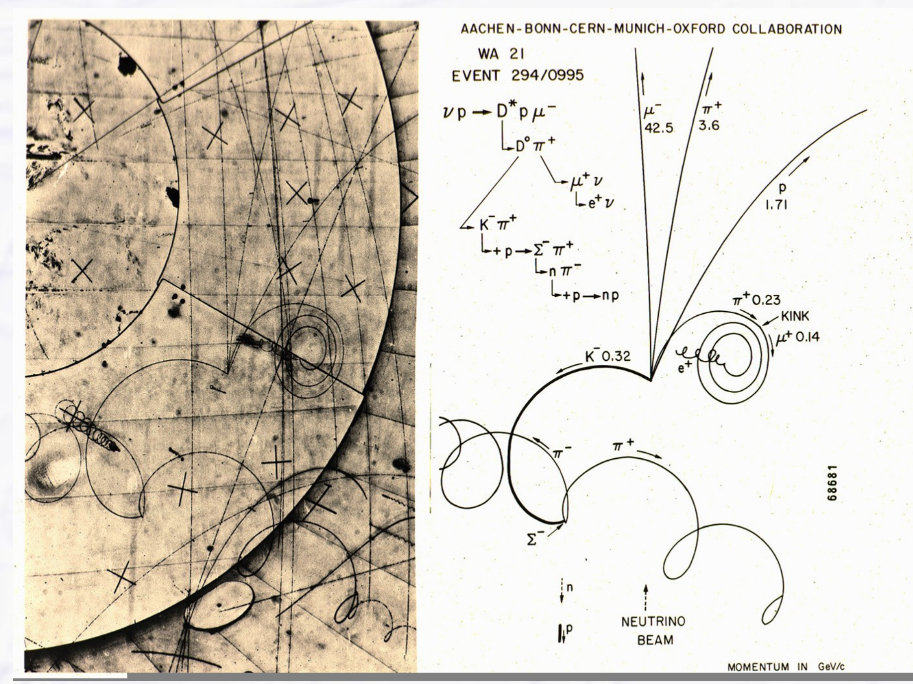




Bubble Chamber II

- **BEBC (Big European Bubble Chamber) at CERN, 1973 – 1984**
  - **largest bubble chamber ever built (and the last big one...), ∅ 3.7 m**
  - **6.3 million photographs taken, 3000 km of developed film**
  - **now displayed in permanent exhibition at CERN**

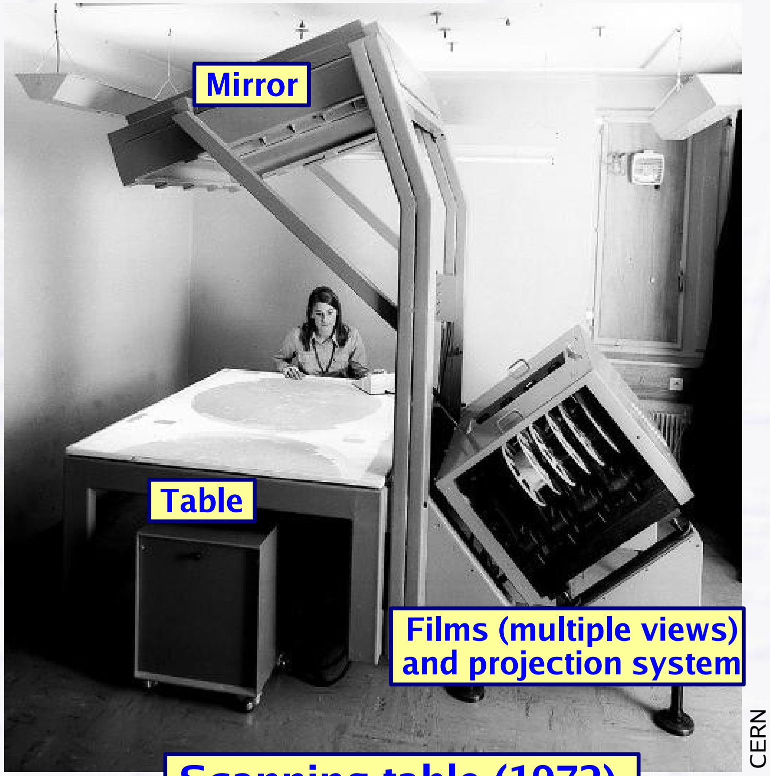




production of D* meson
with long decay chain

Bubble Chamber III

- **Advantages of bubble chambers**
  - liquid is
    BOTH detector medium AND target
  - high precision
- **Disadvantages**
  - SLOW!!!
    - event pictures taken with cameras on film
    - film needs to be developed, shipped to institutes
    - and optically scanned for interesting events
  - Need FASTER detectors (electronic!)



Scanning table (1972)

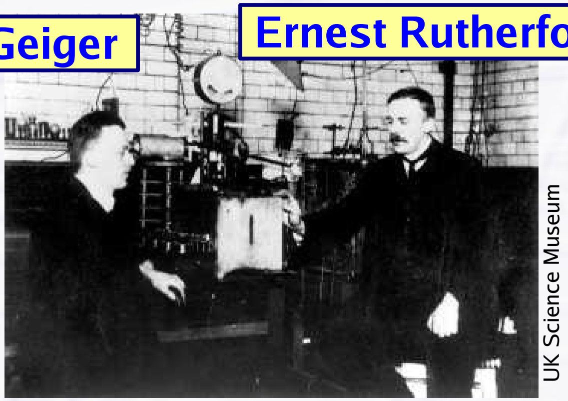
- **However:**
  Some important social side effects of bubble chamber era...
  - scanning was often done by young “scanning girls” (students)...
  - ...who later got married with the physicists...

Early "Electronic" Detectors - Spinthariscope

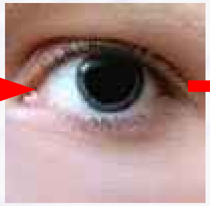
- **1911: Ernest Rutherford + studied (elastic) scattering of α particles on gold atoms** (famous Rutherford experiment)
  - ➛ discovery of atomic nucleus:
    small (heavy) positively charged nucleus orbited by electrons
- **Zinc sulfide screen with microscope (spinthariscope by William Crookes 1903) was used to detect scattered α particles**
  - ➛ light flash was observed by eye
    - to increase light sensitivity, "bella donna" (from the deadly night shade plant = Tollkirsche) was often used to open eye's pupil

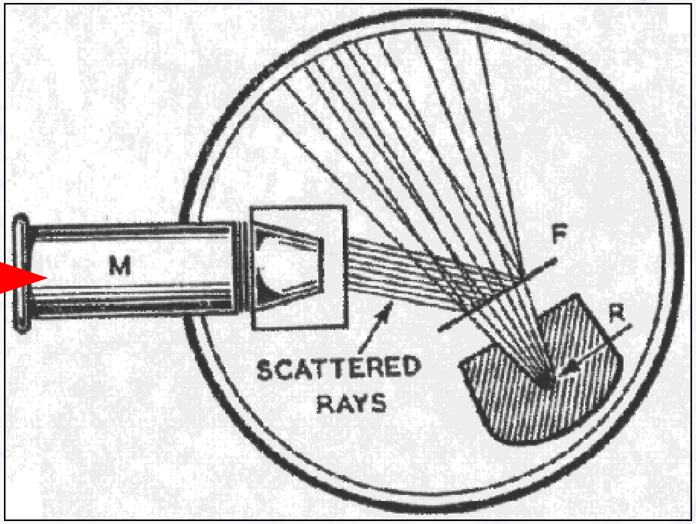
Hans Geiger

Ernest Rutherford

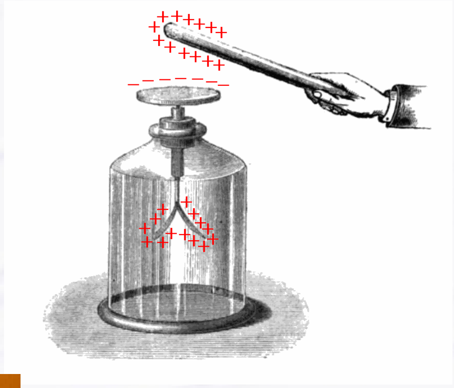


deadly night shade

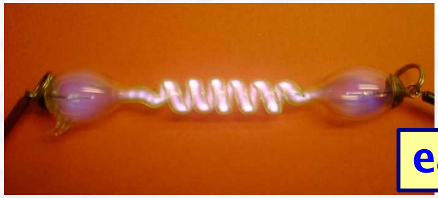




Early Electronic Detectors - Electroscope

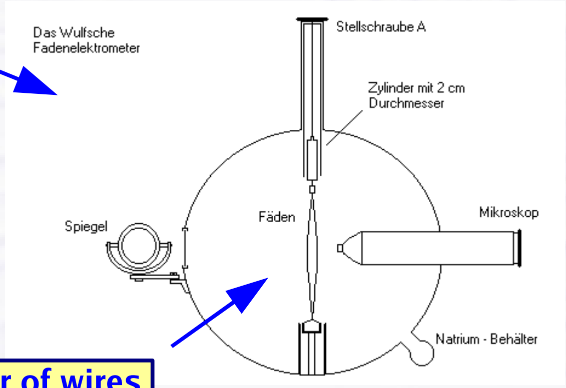


- Gold-leaf electroscope already invented 1787 by Abraham Bennet
- End of 19th century raising interest on electricity in gases
  - cathode ray tubes, glow discharges
  - observation:
    charged electroscope is loosing its charge in dry air after some time
    - source of conductivity? ionisation by recently discovered radioactivity?



early cathode ray tube

- Victor Hess discovered cosmic rays 1912 (Nobel Prize 1936)
  - used calibrated string electrometer by Theodor Wulf
  - found increasing ionisation at higher altitudes at a series of balloon ascents
    - not related to sun radiation!

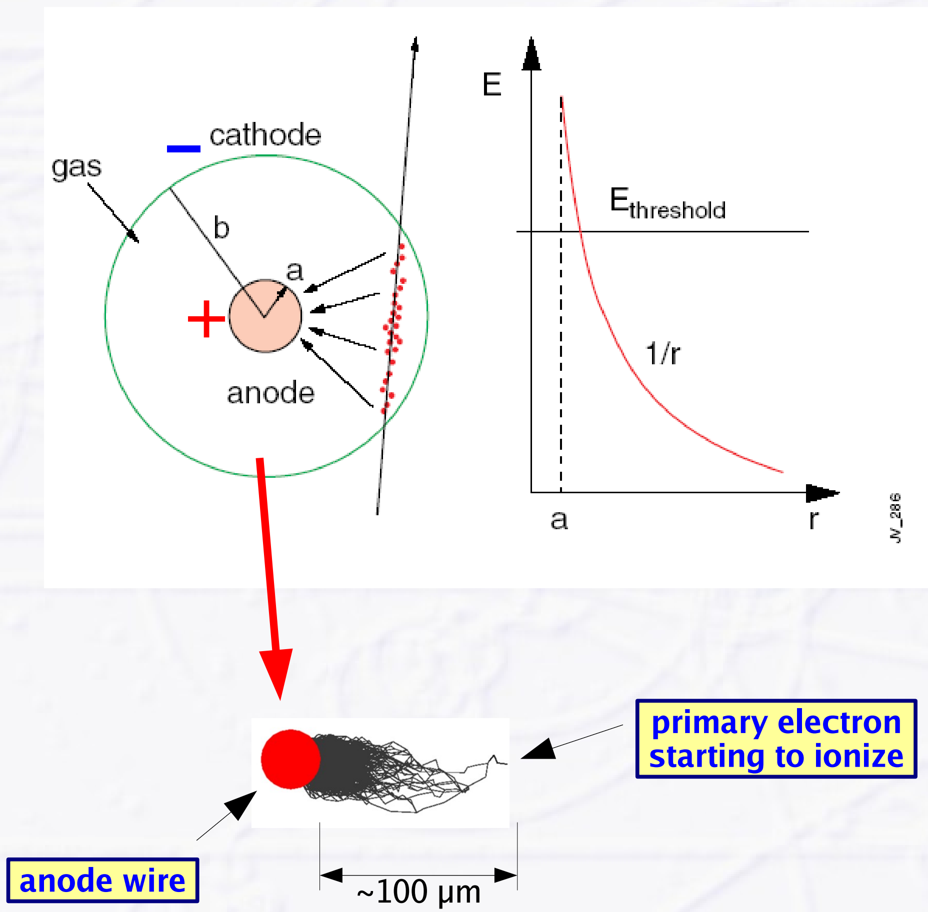


pair of wires

Victor Hess in balloon

Geiger-Müller Tube

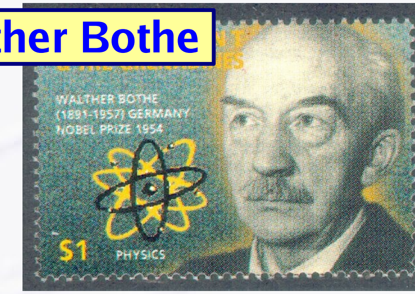
- **The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)**
  - Tube filled with inert gas (He, Ne, Ar) + organic vapour
  - Central thin wire (20 – 50 µm ∅) , high voltage (several 100 Volts) between wire and tube



- Strong increase of E-field close to the wire
  - electron gains more and more energy
- above some threshold (>10 kV/cm)
  - electron energy high enough to ionize other gas molecules
  - newly created electrons also start ionizing
- avalance effect: exponential increase of electrons (and ions)
- measurable signal on wire
  - organic substances responsible for “quenching” (stopping) the discharge

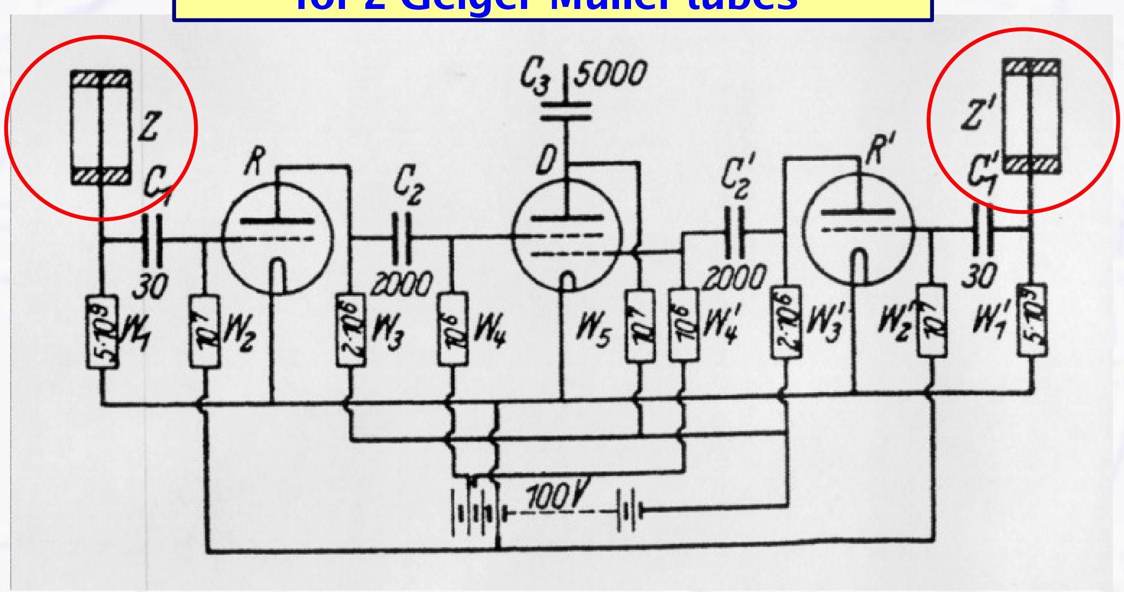
Coincidence Units

Walther Bothe



- “Zur Vereinfachung von Koinzidenzzählungen”, Walther Bothe 1929 (Nobel Prize 1954)
  - single tube has no information on direction of incoming particle
    - two or more tubes giving signals within the same time window give direction
    - also information if two particles come from the same decay

coincidence unit with vacuum tubes for 2 Geiger-Müller tubes



cosmic ray telescope 1934

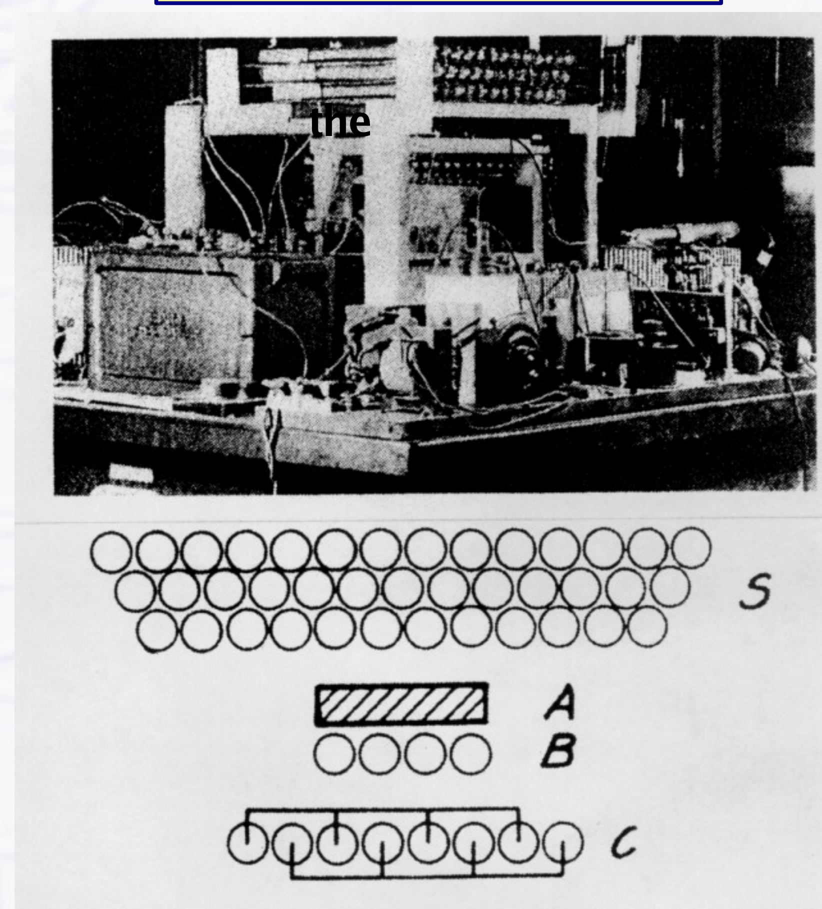
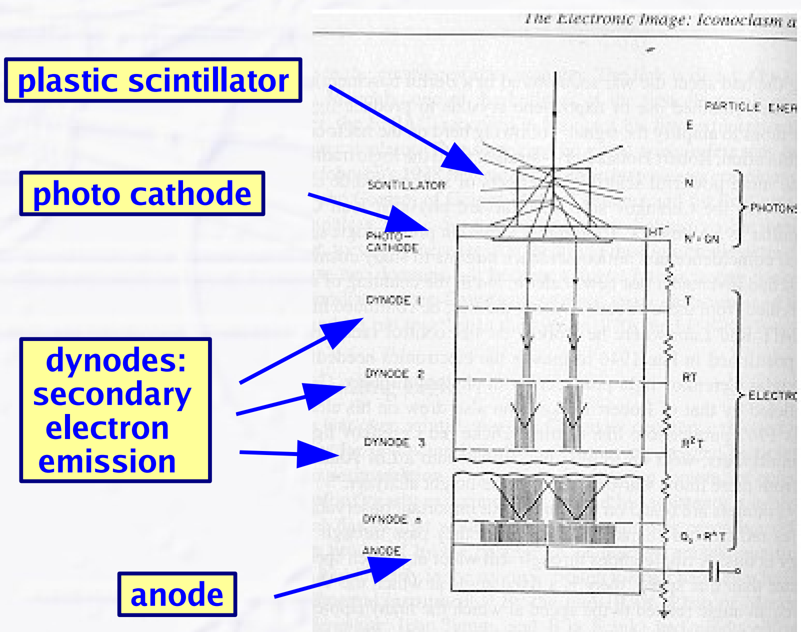


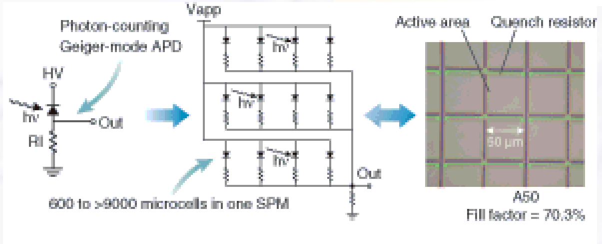
Photo Multiplier Tubes (PMT)

- **Invented 1934 by Harley Iams and Bernard Salzberg (RCA Coorperation)**
  - based on photo effect and secondary electron emission
  - sensitive to single photons, replaced human eye + belladonna at scintillator screen
- **first device had gain ~8 only but already operated at >10 kHz (human eye: up to 150 counts/minute for a limited time)**
  - nowadays still in use everywhere, gain up to 10^8
  - recent developments: multi-anode (segmented) PMTs, hybrid and pure silicon PMs



classic PMT

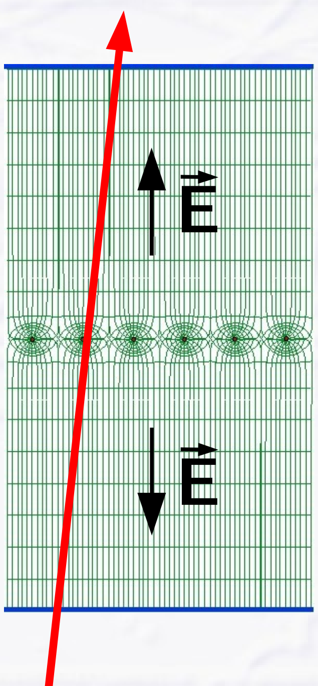
Silicon PM = array of avalance photo diodes



Multi Wire Proportional Chambers I

- **Geiger-Müller tube just good for single tracks with limited precision** (no position information inside tube)
  - ➨ **in case of more tracks more tubes are needed or...**
- **Multi Wire Proportional Chamber (MWPC)** (1968 by Georges Charpak, Nobel Prize 1992)
  - ➨ **put many wires with short distance between two parallel plates**

Georges Charpak

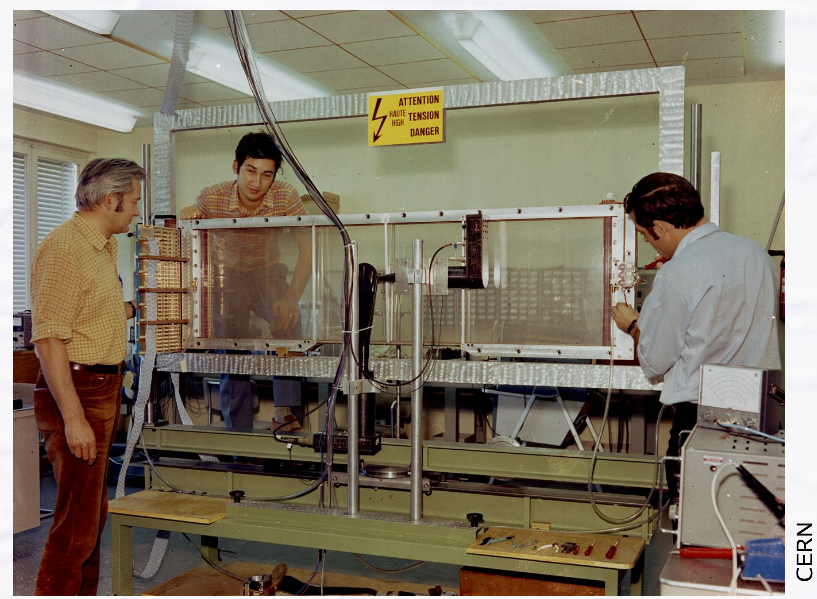


cathode plane (-)

anode plane (+), many wires, a few mm apart

cathode plane (-)

charged particle

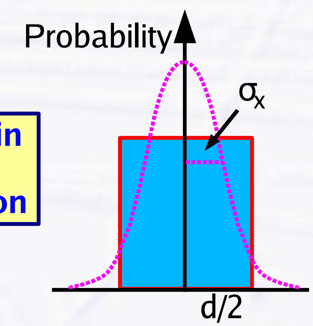


Georges Charpak, Fabio Sauli and Jean-Claude Santiard

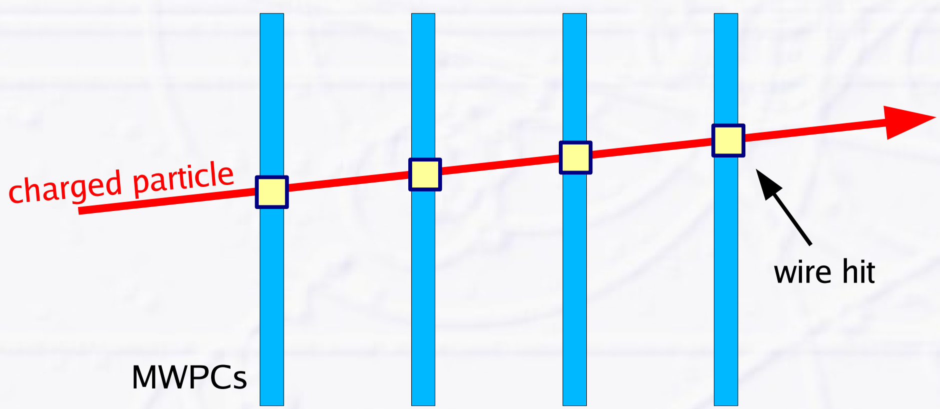
Multi Wire Proportional Chambers II

- **Multi Wire Proportional Chamber (MWPC)**
  - was first electronic device allowing high statistics experiments
  - with multiple channels and reasonable resolution
- **Typically several 100 – 1000 wires, ~ 1 mm spacing**
  - if charged particle is passing the MWPC → one wire gives signal
  - resolution: $\sigma_x \approx \frac{d}{\sqrt{12}}$ e.g. for d = 1 mm → ~300 µm

we don't know where the particle went through within the 1 mm spacing = "flat" probability distribution, this is the width of an equivalent Gaussian distribution



- **If many MPWCs are put one after each other**
  - each particle creates one point per MWPC (~300 µm resolution per point)

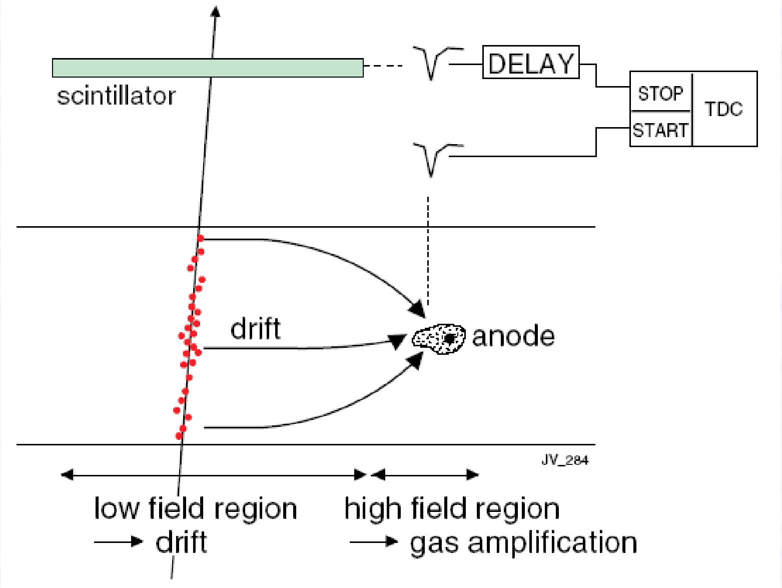


can reconstruct track with e.g. 4 points

one coordinate only, use additional MWPCs tilted by 90° to get other coordinate

Drift Chamber

- **Resolution of MWPCs limited by wire spacing**
  - ➔ **better resolution → shorter wire spacing → more (and more) wires...**
    - larger wire forces (heavy mechanical structures needed)
    - (too) strong electrostatic forces when wires too close to each other
- **Solution by A. H. Walenta, J. Heintze, B. Schürlein 1971**
  - ➔ **obtain position information from drift time of electrons** (fewer wires needed)
    - drift time = time between primary ionization and arrival on wire (signal formation)



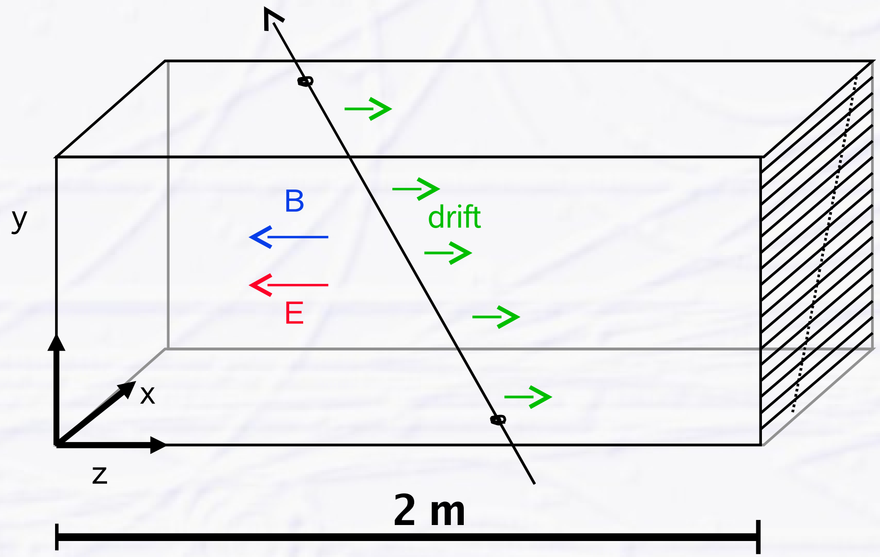
start signal (track is passing drift volume) has to come from external source: scintillator or beam crossing signal

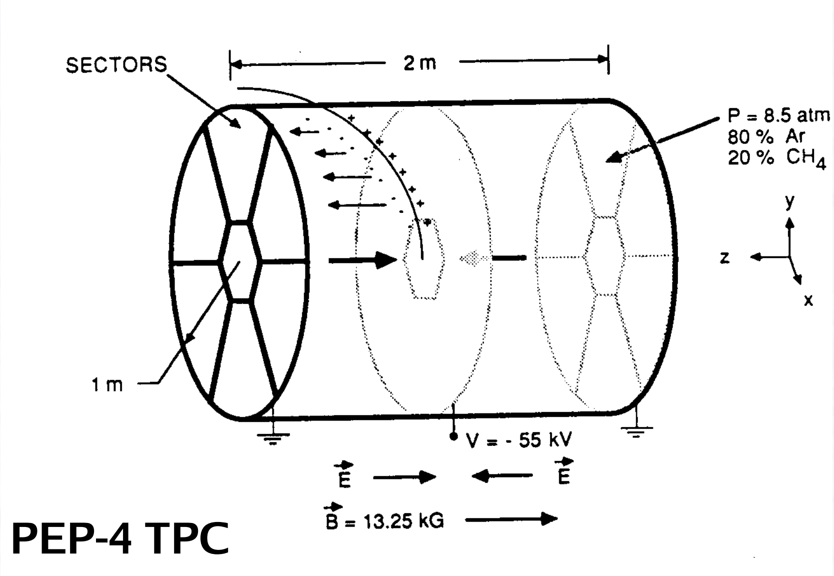
- **Need to know drift velocity v_D to calculate distance s to wire (= track position within the detector)**

$$s = \int_{t_{start}}^{t_{stop}} v_D \, dt$$

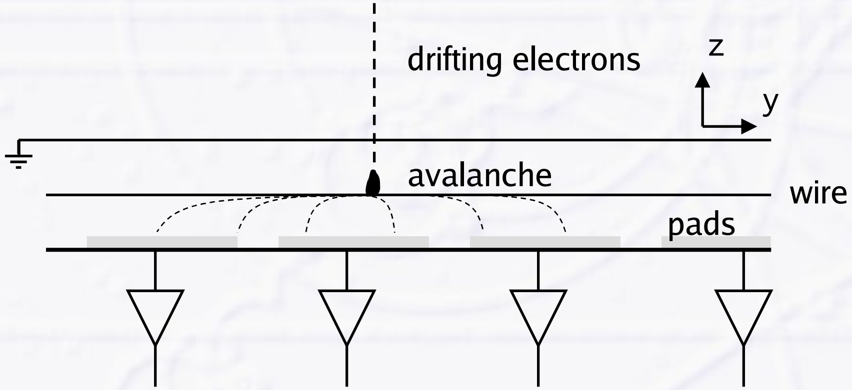
Time Projection Chamber (TPC)

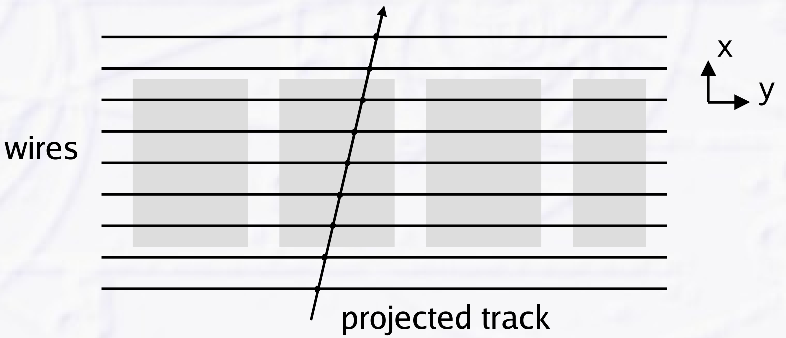
- A 3D-imaging chamber with rather long drift length





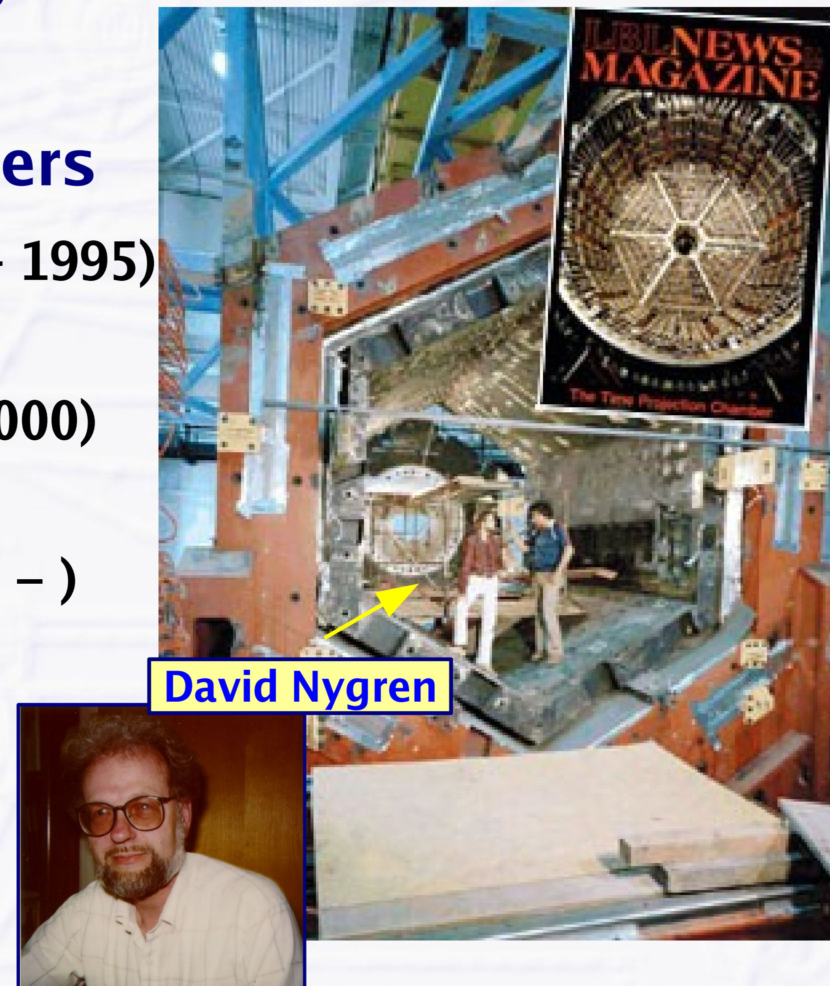
- homogeneous B- and E-fields
- anode plane equipped with MWPC wire chambers





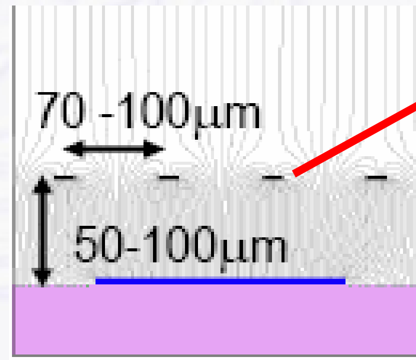
Time Projection Chamber (TPC)

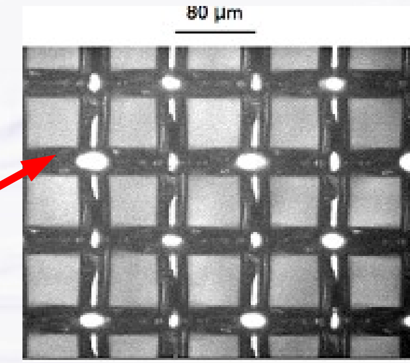
- **Invented by David Nygren (Berkeley) in 1974**
- **Proposed as central tracking device for the PEP-4 detector at the PEP e^+e^- collider at SLAC 1976**
- **More (and even larger) TPCs were built or are planned at other colliders**
  - TRISTAN (KEK, 2 x 32 GeV e^+e^-, 1986 – 1995)
    - TOPAZ
  - LEP (CERN, 2 x 104 GeV e^+e^-, 1989 – 2000)
    - ALEPH, DELPHI
  - RHIC (BNL, 2 x 100 GeV/nucleus, 2001 –)
    - STAR
  - LHC pp and Pb-Pb collider (CERN)
    - ALICE
  - ILC e^+e^- collider
    - ILD



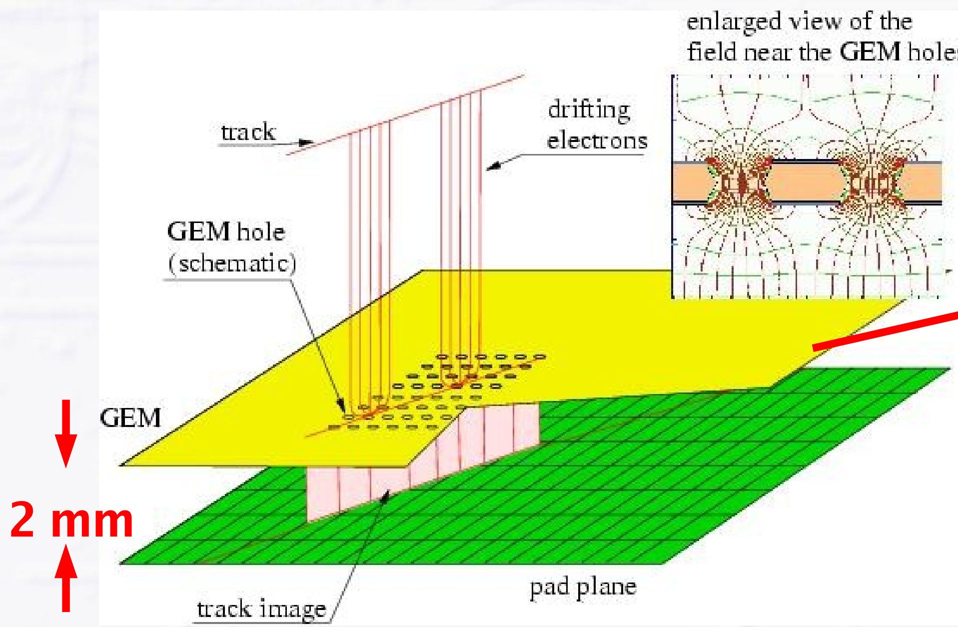
Recent Developments: Micro Pattern Gas Detectors (MPGD)

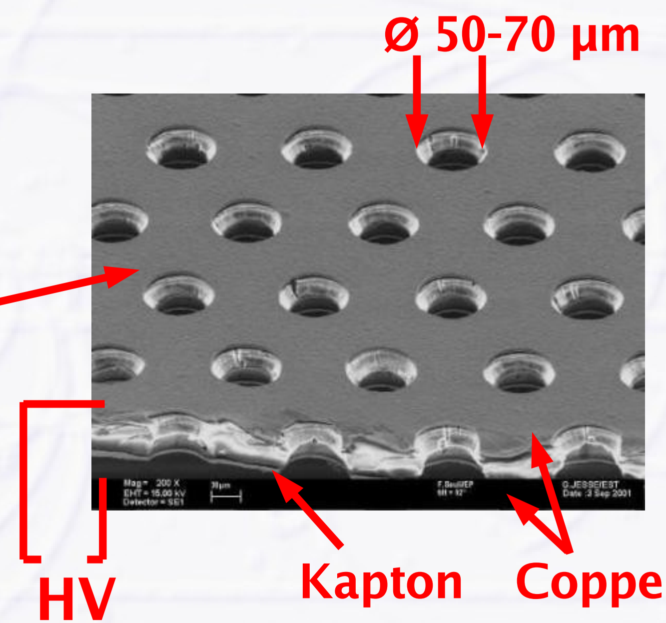
- **Replace wires at TPC with Micro Pattern Gas Detectors**
  - MicroMegas (metallic micromesh)
  - GEM (Gas Electron Multiplier)





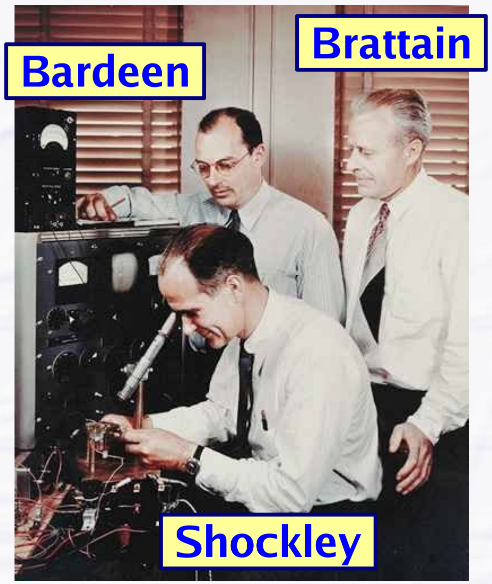
- **Concept**
  - 2D structures
    with holes + underlying pads
  - Gas amplification inside holes,
    collect electrons on small pads,
    few mm^2



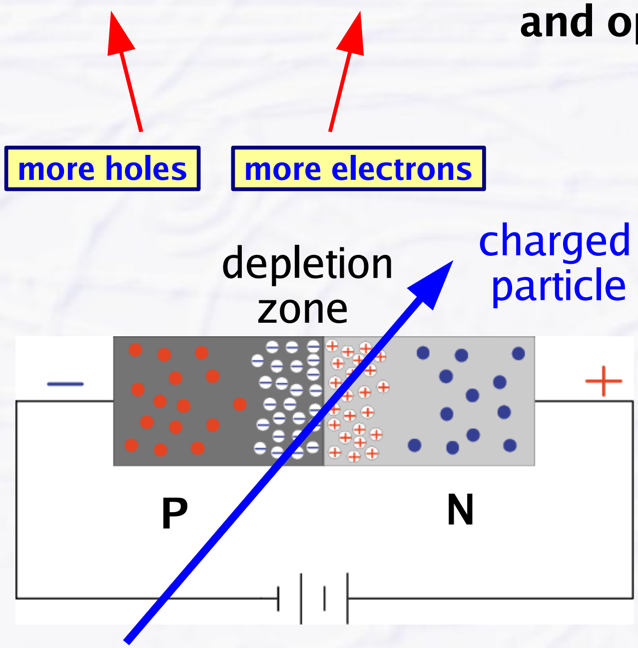


Solid State Detectors

- **First transistor was invented 1947 by William B. Shockley, John Bardeen and Walter Brattain (Nobel Prize 1956)**
  - transistors and diodes became common soon after



- → **Germanium diodes were used for particle detection**
  - p-type and n-type doped silicon material is put together and operated with reversed voltage



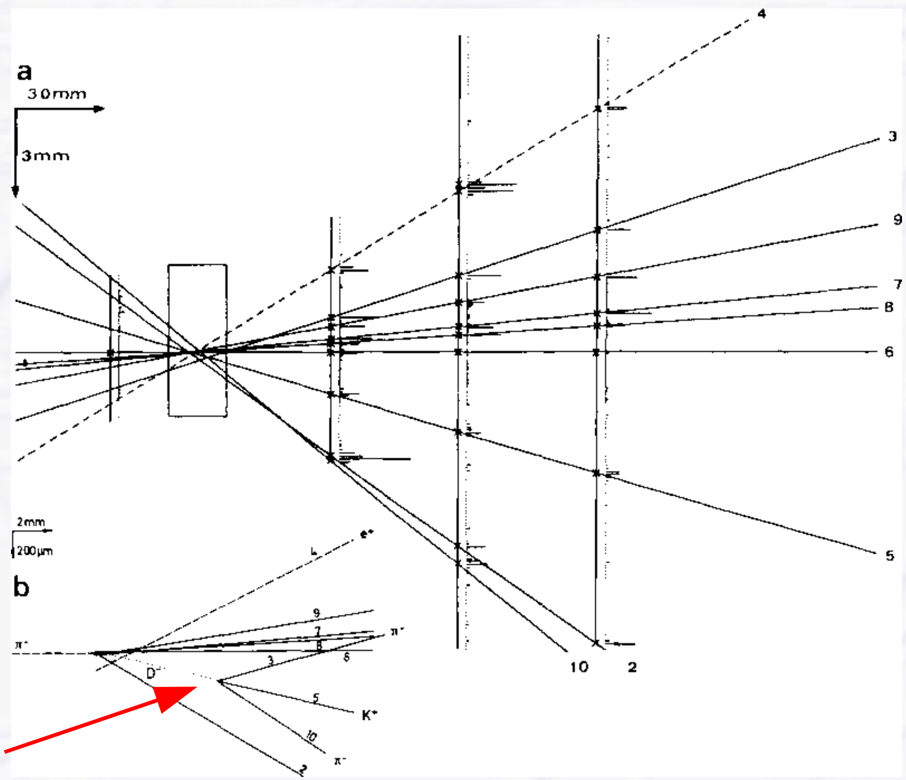
- → **around junction of p- and n-type material depletion zone is created**
- → **zone free of charge carriers**
  - no holes, no electrons
  - thickness of depletion zone depends on voltage, doping concentration

charged particle typically creates 20'000 – 30'000 electron/hole pairs in 300 μm thick material -> sufficient signal size

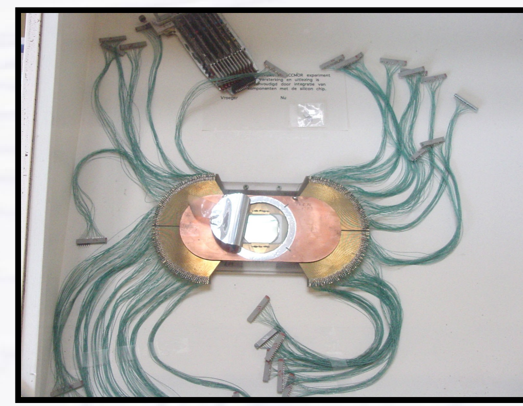
The first Silicon Strip Detector

- **First operational silicon strip detector used in an experiment (NA11 at CERN) by J. Kemmer, R. Klanner, G. Lutz et al. 1983**
  - **G. Lutz was founder of MPI Halbleiterlabor in Munich**
  - **NA11 aimed to search for new short lived particles**
    - **first observation of D_s**
      many branching ratio and lifetime measurements

Max-Planck-Institut
Halbleiterlabor



D⁻ decay

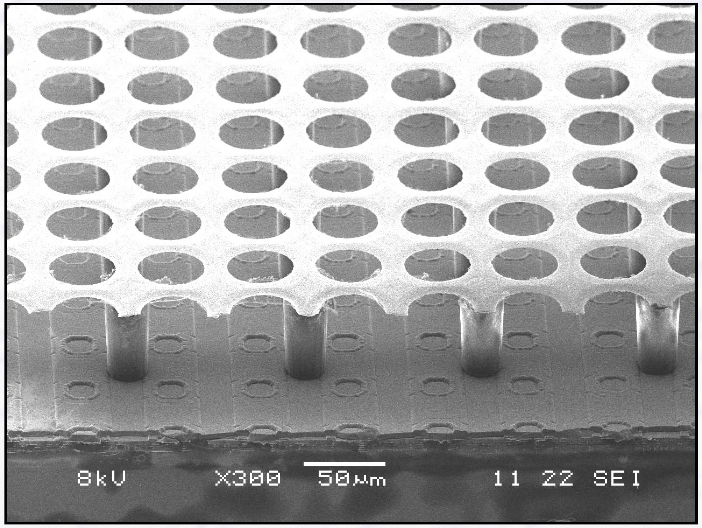


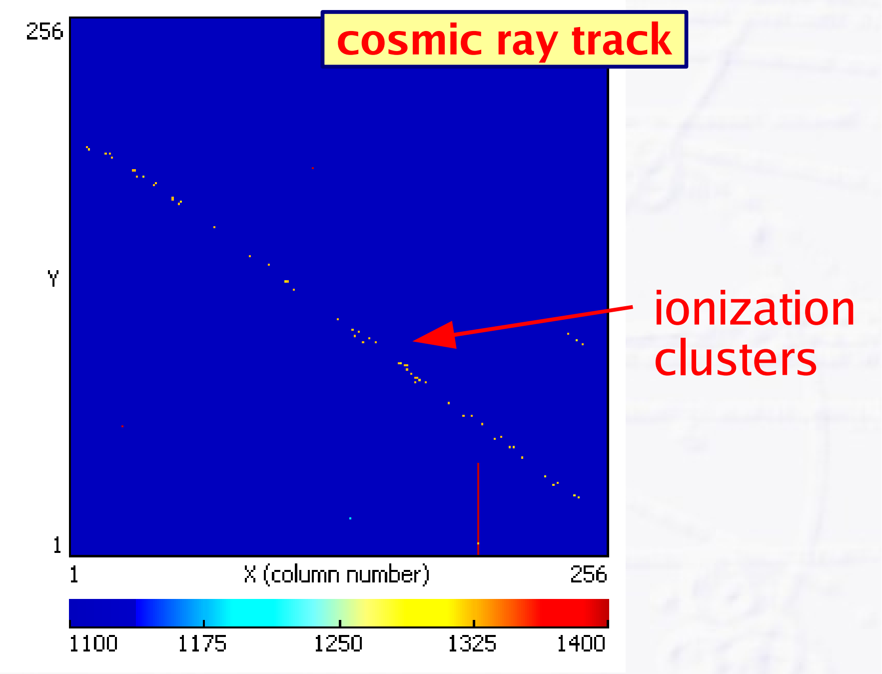
8 silicon strip planes
(4 groups of 2 planes each with tilted strips to measure xy coordinate)

24 x 36 mm^2 size per chip
1200 strips, 20 μm pitch
240 read-out strips
4.5 μm single hit resolution

Recent Developments: Hybrid Technologies

- **Combine MPGD gaseous detector with silicon pixel detector**
- **Use MediPix2/TimePix chip as active TPC "padplane" for ILC detector**
  - **MediPix2 = 256x256 pixels with 55x55 μm2 size for medical applications (X-ray film replacement)**
  - **MicroMegas mesh (provides gas amplification) integrated on top of pixel chip**

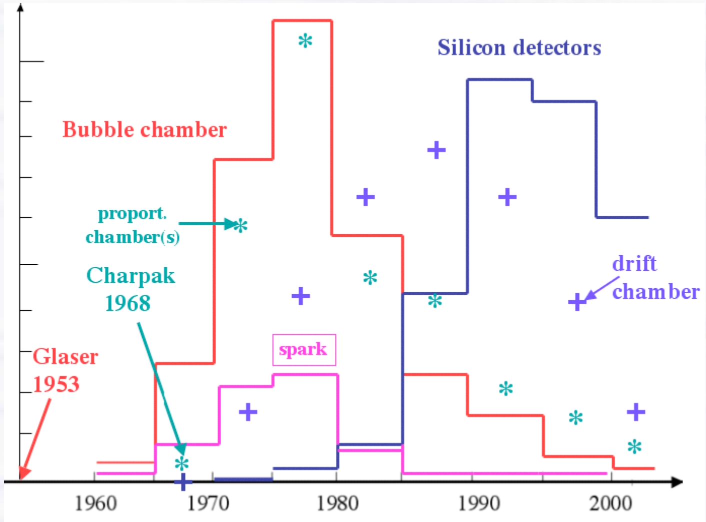




- **Individual ionization visible: the digital Bubble Chamber is in reach**

Detector History

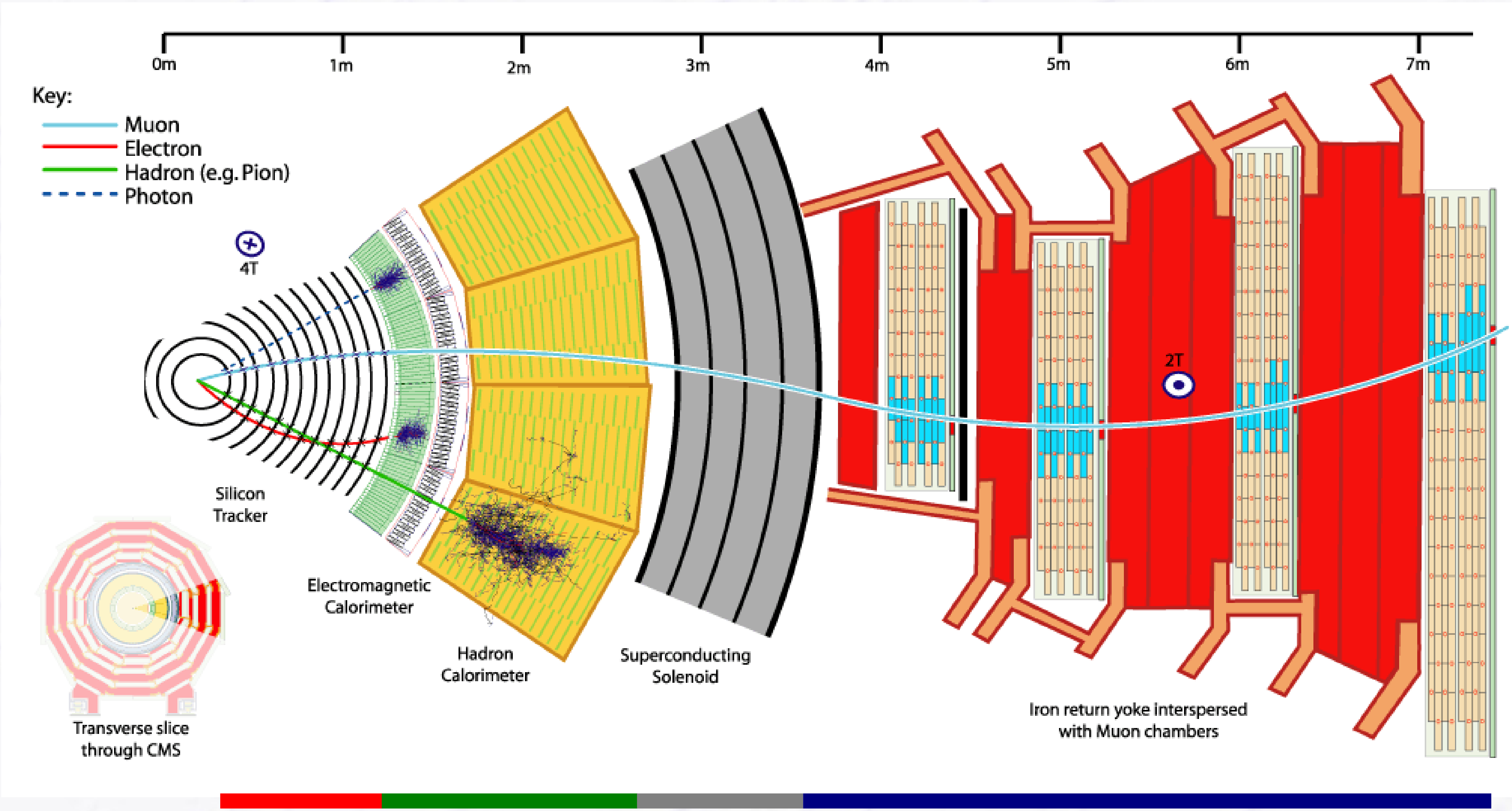
- Cloud Chambers, Nuclear Emulsions + Geiger-Müller tubes dominated until the early 1950s
  - Cloud Chambers now very popular in public exhibitions related to particle physics
- Bubble Chambers had their peak time between 1960 and 1985
  - ➔ last big bubble chamber was BEBC at CERN
- Wire Chambers (MWPCs and drift chambers) started to dominate since 1970s
- Since late 1980s solid state detectors are in common use
  - started as small sized vertex detectors (at LEP and SLC)
  - ➔ now ~200 m^2 silicon surface in CMS tracker



- Most recent trend: hybrid detectors
  - ➔ combining both gaseous and solid state technologies

A typical Today's Particle Detector

- **Cut-away view of CMS**



Tracker **Calorimeter** **Coil** **Muon Detector and iron return yoke**