A Particular History of Particle Detection

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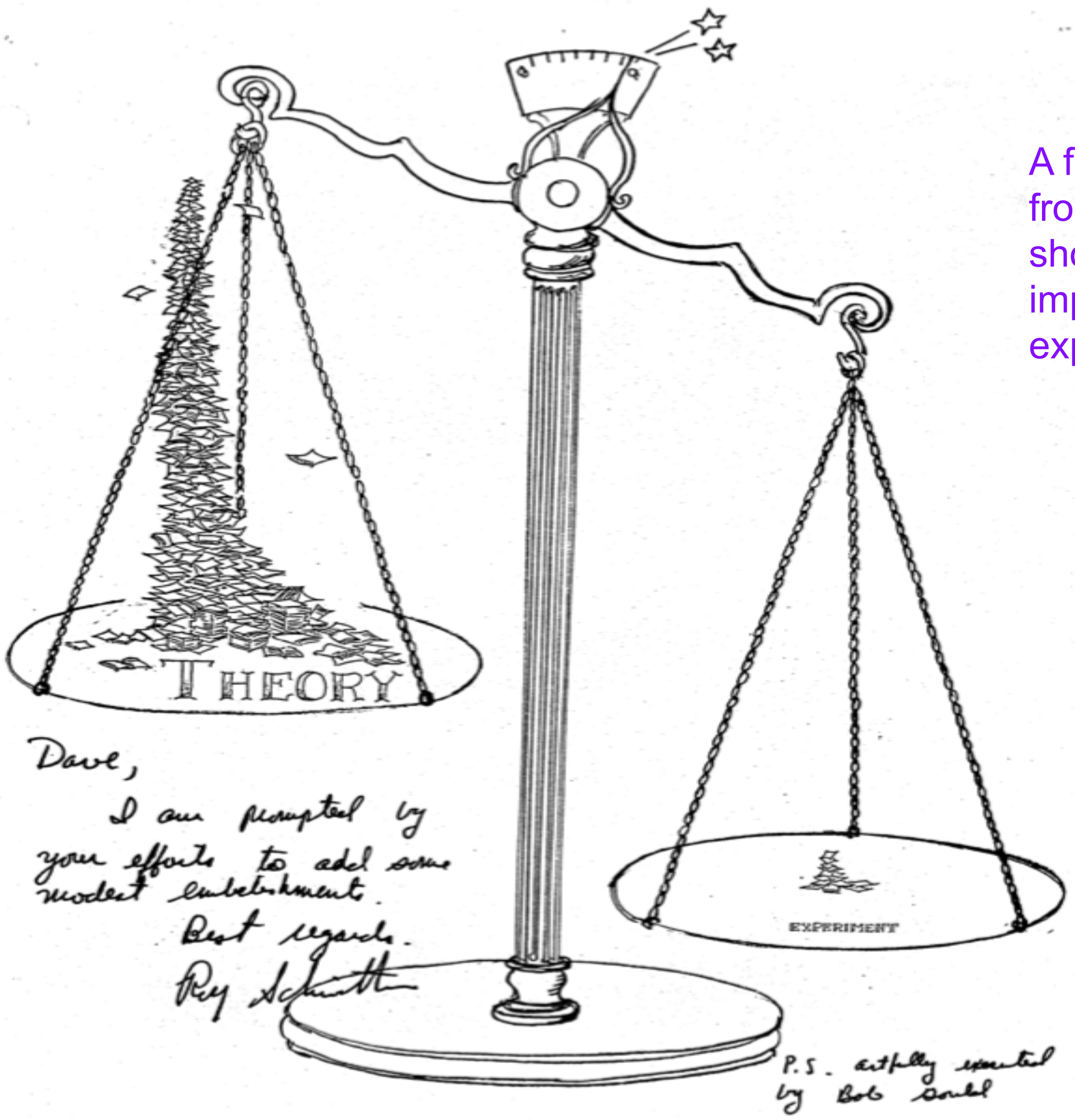
EDIT School – FNAL
5 March 2018



Dave,

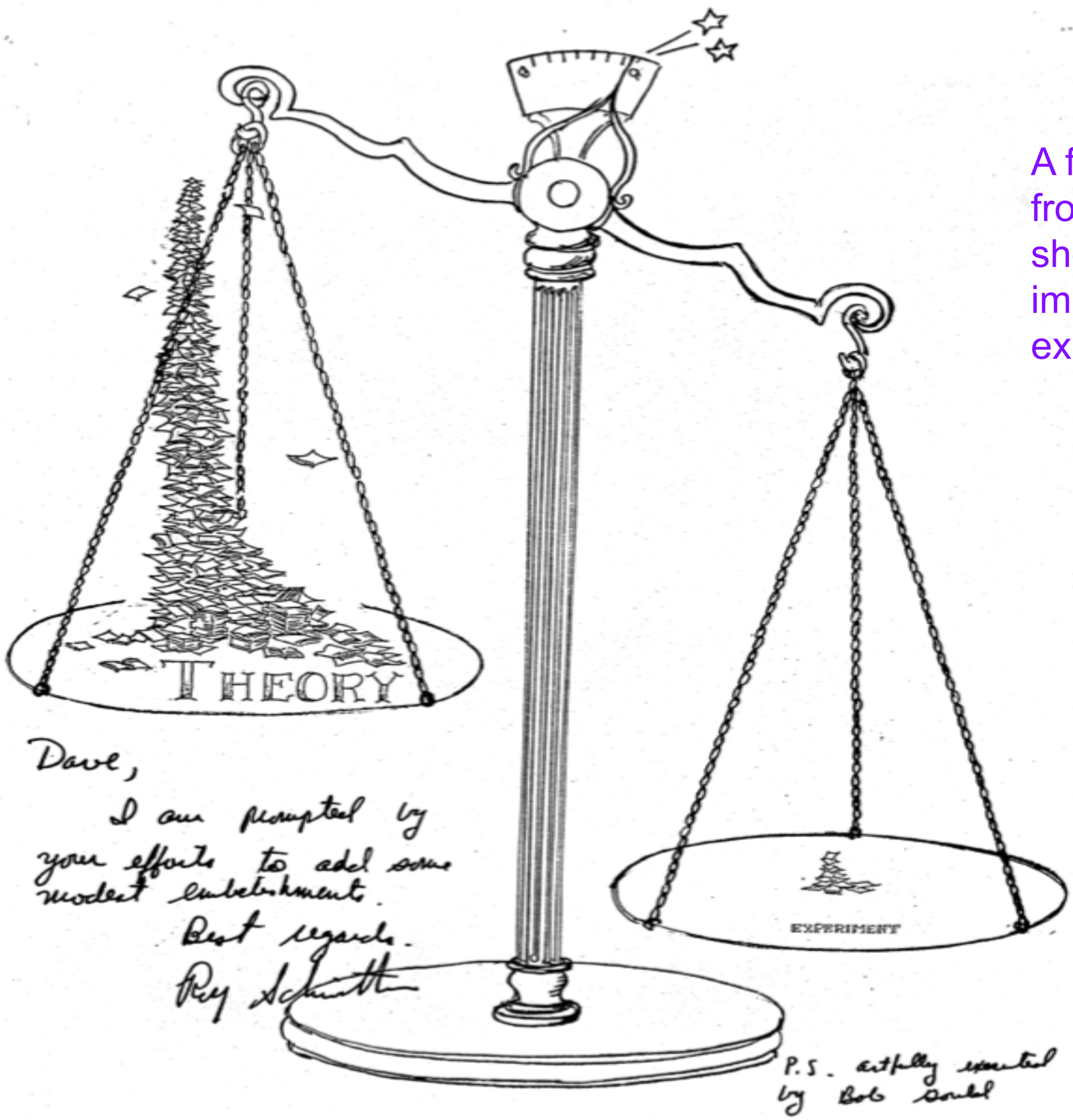
I am prompted by your efforts to add some modest embellishment.

Best regards.

Roy Schwitters

P.S. artfully executed by Bob Gould

A famous drawing from the 1970’s showing the relative importance of experiment vs theory



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Best regards.
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A famous drawing from the 1970’s showing the relative importance of experiment vs theory

But something else is present here...

an instrument!

History of Particle Detectors -

- This history is interesting …
  - *Vigorous evolution, with creativity and serendipity*
- This history is useful …
  - *Pay attention !*
- Where are the future avenues for progress ?

History of Particle Detectors -

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- This history is useful …
  - *Pay attention !*
- Where are the future avenues for progress ?
  - *Beyond my pay grade…*

A biased history...

- A fairly personal perspective on this fascinating story - *to indicate opportunities both found and missed* - and to look for lessons toward future advances.

- A comprehensive - and necessarily superficial - review of all developments would miss this.

- Acknowledgments:
  - **Michael Hauschild, Bill Moses, Werner Riegler,…**

Epochs: A Century of Punctuated Equilibria

- First discoveries - "Bronze age"
  - many particles inducing visible signals
- Single particle detection - "Age of discovery"
  - large amplification achieved
- Complex event reconstruction - "Golden age"
  - tracking, energy measurements, particle ID
- Present era - *megalithic age?*
  - **huge**: data bases, systems, sophistication

“Image & Logic”

- At the beginning, visual techniques dominated, persisting into the 2000’s
  - we will look at those first

“Image & Logic”

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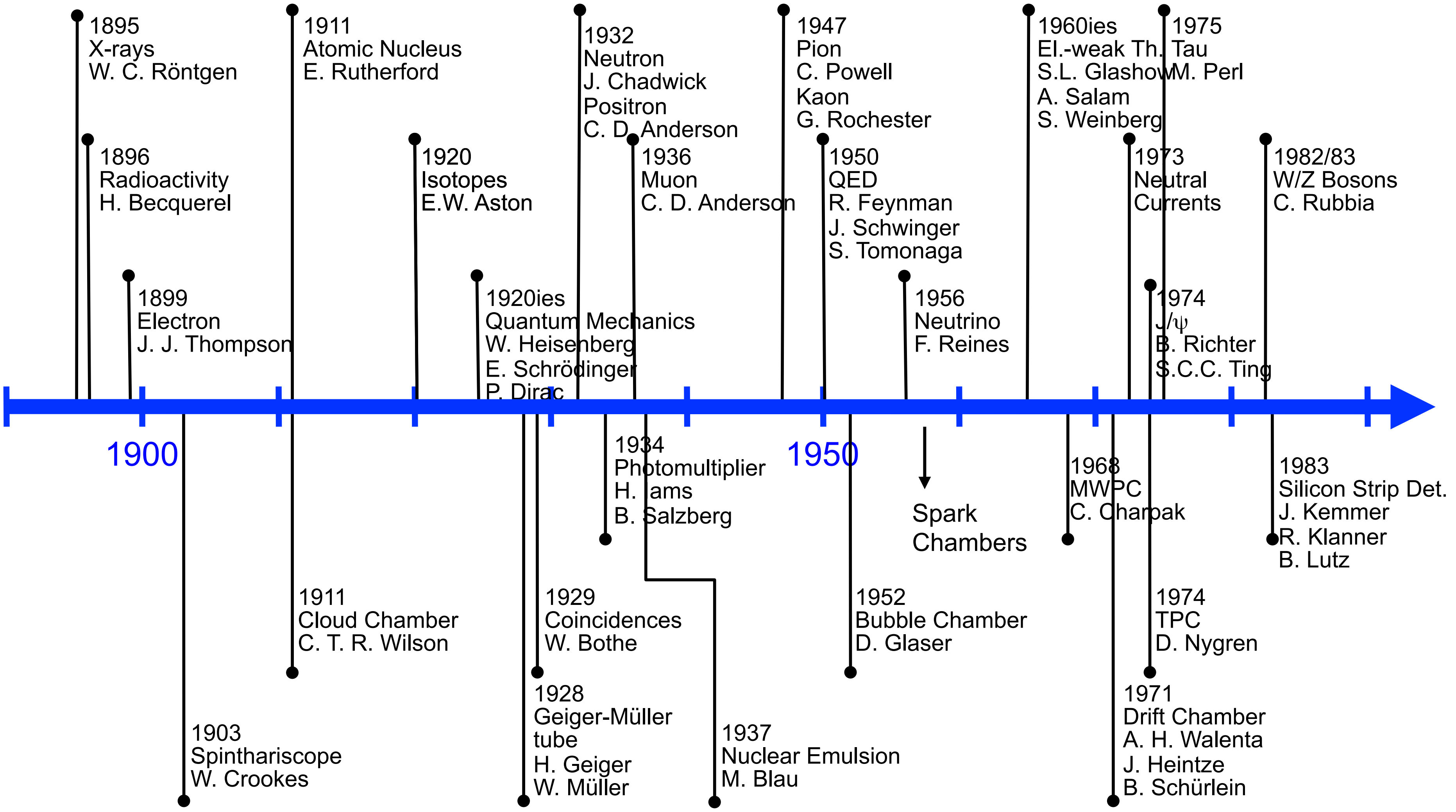
  - we will look at those first
- Even from an early time, electronic ideas emerged, kindling further progress
  - today, electronic techniques dominate

Timeline of Particle Physics and Instrumentation



1895
X-rays
W. C. Röntgen

1896
Radioactivity
H. Becquerel

1899
Electron
J. J. Thompson

1911
Atomic Nucleus
E. Rutherford

1920
Isotopes
E.W. Aston

1920ies
Quantum Mechanics
W. Heisenberg
E. Schrödinger
P. Dirac

1932
Neutron
J. Chadwick
Positron
C. D. Anderson

1936
Muon
C. D. Anderson

1947
Pion
C. Powell
Kaon
G. Rochester

1950
QED
R. Feynman
J. Schwinger
S. Tomonaga

1956
Neutrino
F. Reines

1960ies
El.-weak Th.
S.L. Glashow
A. Salam
S. Weinberg

1973
Neutral
Currents

1974
J/ψ
B. Richter
S.C.C. Ting

1975
Tau
M. Perl

1982/83
W/Z Bosons
C. Rubbia

1903
Spinthariscope
W. Crookes

1911
Cloud Chamber
C. T. R. Wilson

1928
Geiger-Müller
tube
H. Geiger
W. Müller

1929
Coincidences
W. Bothe

1934
Photomultiplier
H. Iams
B. Salzberg

1937
Nuclear Emulsion
M. Blau

1952
Bubble Chamber
D. Glaser

Spark
Chambers

1968
MWPC
C. Charpak

1971
Drift Chamber
A. H. Walenta
J. Heintze
B. Schürlein

1974
TPC
D. Nygren

1983
Silicon Strip Det.
J. Kemmer
R. Klanner
B. Lutz

Signals ⇒ Physical information

- Ionization - “free” charge
- Scintillation - “free” light
- Cherenkov radiation
- Transition radiation
- Magnetic induction
- Phonons, acoustic, heat
- ....?

- Energy
- Momentum
- Velocity
- Trajectory direction
- Particle identification
- Charge
- Patterns
- Causality
- Time

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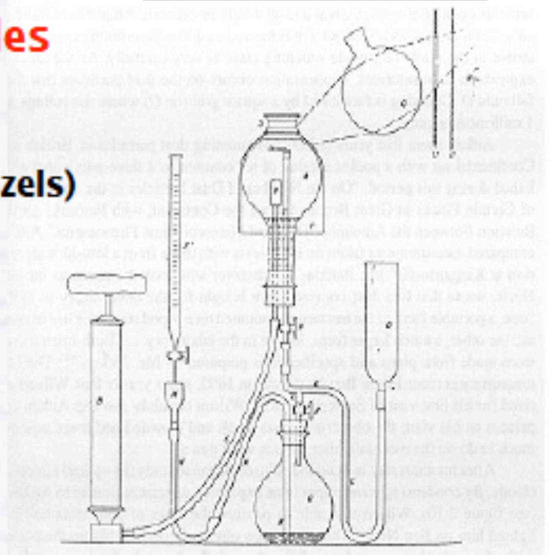
Common principle: physical gain mechanism

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

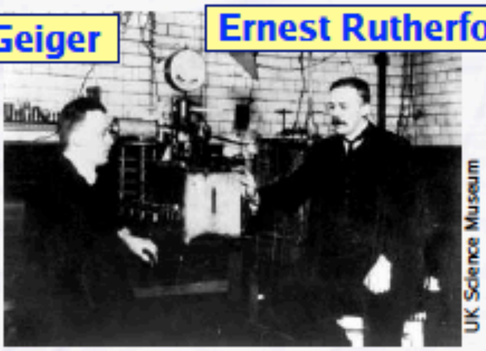


Dust Chamber 1888

Early “Electronic” Detectors - Spinthariscope

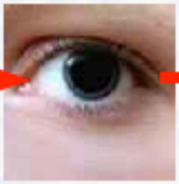
- **1911: Ernest Rutherford + studied (elastic) scattering of α particles on gold atoms (famous Rutherford experiment)**
  - **discovery of atomic nucleus:**
    small (heavy) positively charged nucleus orbited by electrons
- **Zinc sulfide screen with microscope (spinthariscope by William Crookes 1903) 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

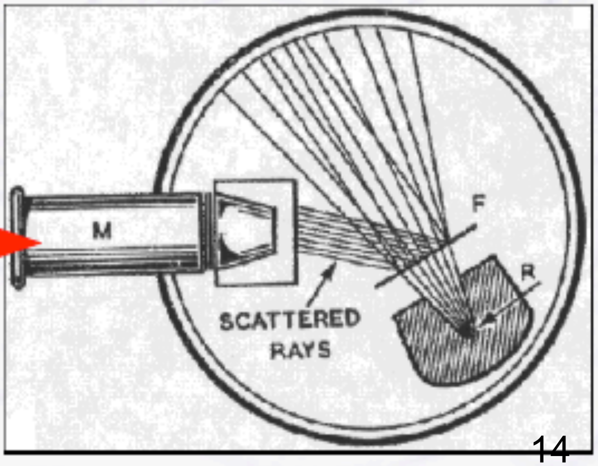
Hans Geiger **Ernest Rutherford**



UK Science Museum

deadly night shade





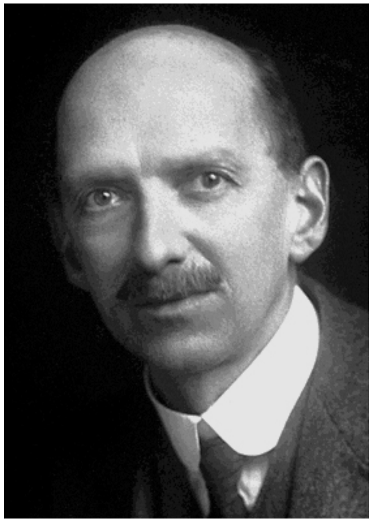
Spinthariscope -1903

large energy deposit + sensitive eye = detection

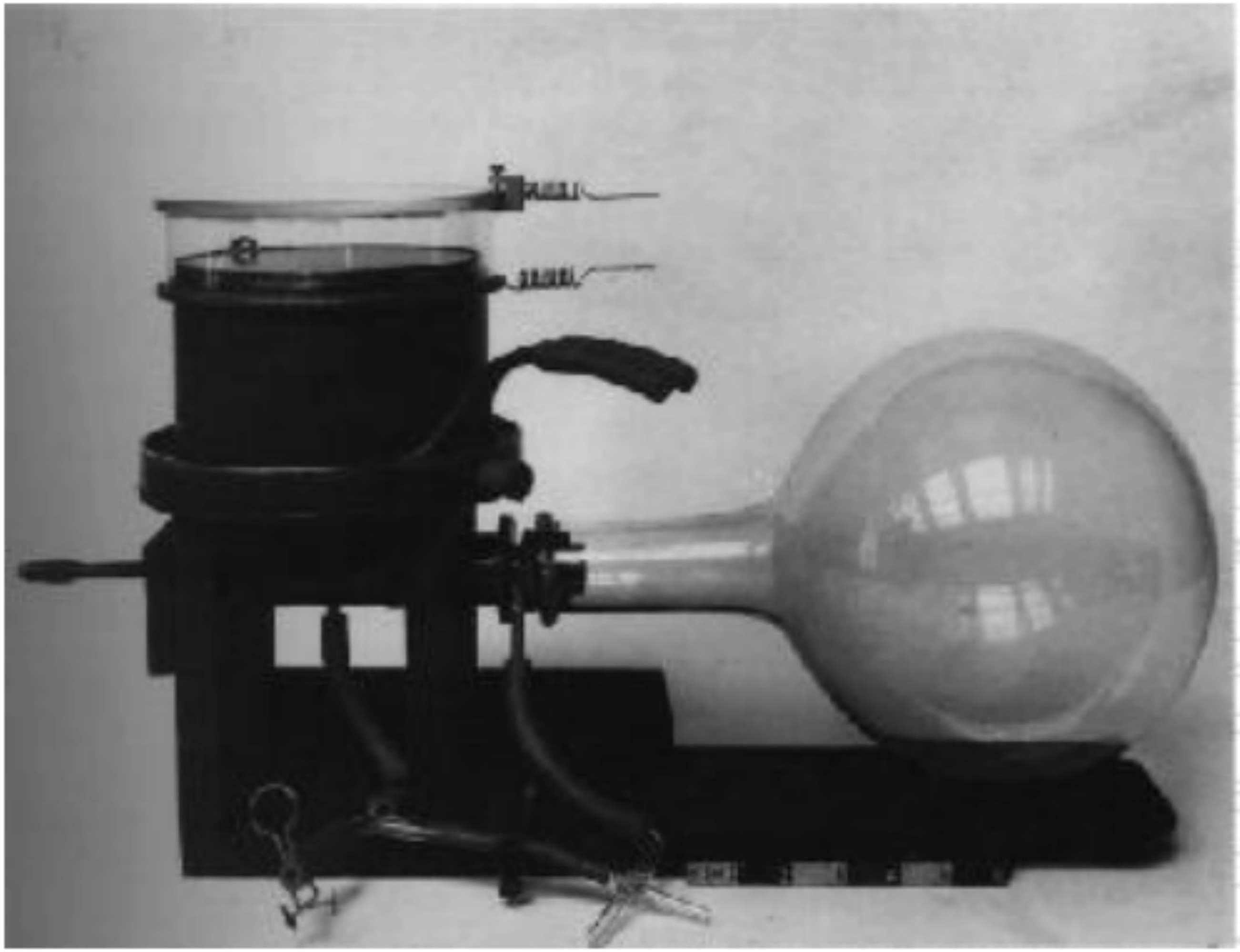
- “In 1903, while observing the apparently uniform fluorescence on a zinc sulfide screen created by the radioactive emissions (mostly alpha radiation) of a sample of radium, William Crookes spilled some of the radium sample, and, owing to its extreme rarity and cost, he was eager to find and recover it. Upon inspecting the zinc sulfide screen under a microscope, he noticed separate flashes of light created by individual alpha particle collisions with the screen. Crookes took his discovery a step further and invented a device specifically intended to view these scintillations. It consisted of a small screen coated with zinc sulfide affixed to the end of a tube, with a tiny amount of radium salt suspended a short distance from the screen and a lens on the other end of the tube for viewing the screen. Crookes named his device after the Greek word 'spintharis', meaning "a spark".”
- - from Wikipedia

C.T.R. Wilson and his Cloud Chamber

- Wilson was a Scottish meteorologist at the Cavendish Labs
- Fascinated by clouds in the Highlands, especially the 'Brocken Spectre'
- Built a chamber to play with purified air, with changes in dust, pressure, temp, etc.
- Found that vapors condense around ionization when pressure is lowered and volume becomes supersaturated

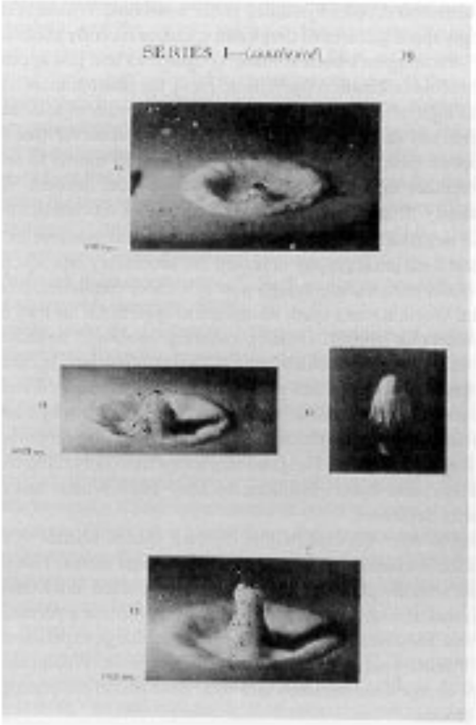


Cloud Chamber

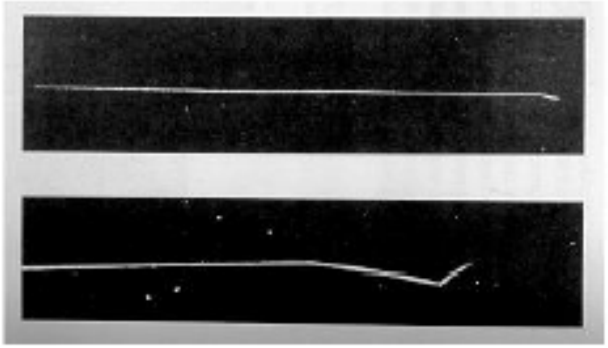


Wilson Cloud Chamber 1911

Cloud Chamber



Worthington 1908



Early Alpha-Ray picture, Wilson 1912

Using the cloud chamber Wilson also did rain experiments i.e. he studied the question on how the small droplets forming around the condensation nuclei are coalescing into rain drops.

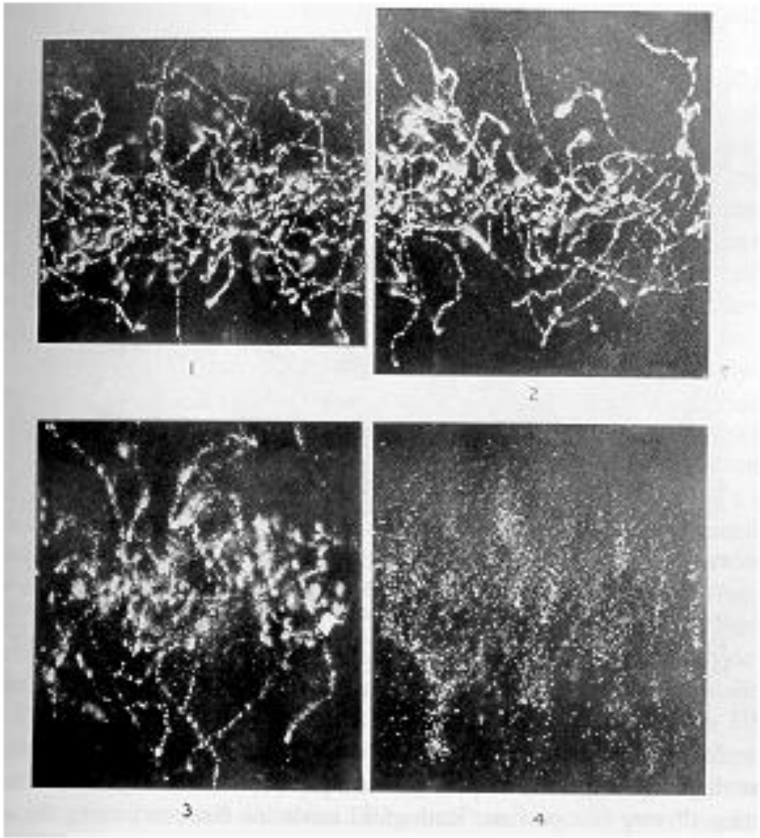
In 1908 Worthington published a book on 'A Study of Splashes' where he shows high speed photographs that exploited the light of sparks enduring only a few microseconds.

This high-speed method offered Wilson the technical means to reveal the elementary processes of condensation and coalescence.

With a bright lamp he started to see tracks even by eye !

By Spring 1911 Wilson had track photographs from from alpha rays, X-Rays and gamma rays.

Cloud Chamber



X-rays, Wilson 1912

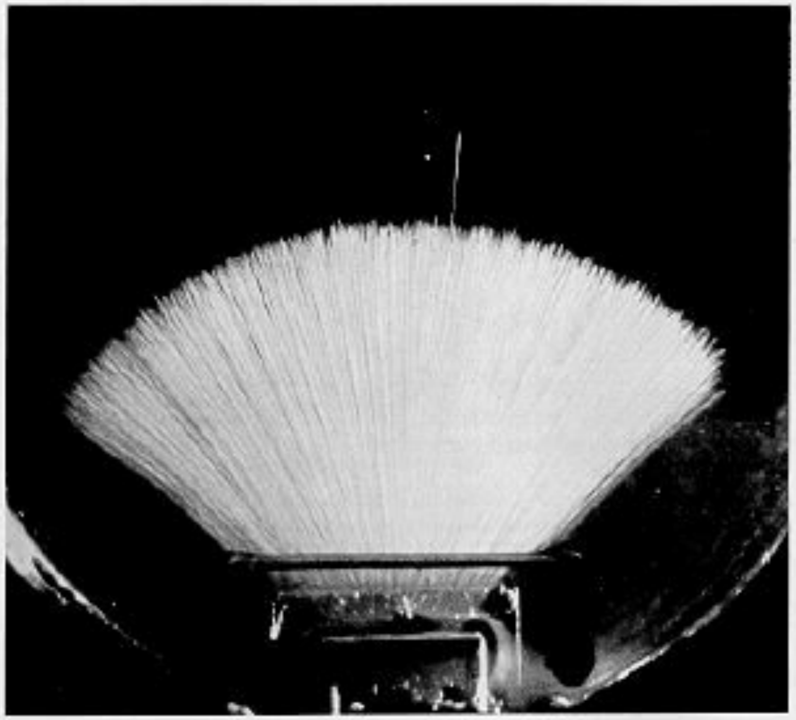


Fig. 13. K. Philipp, Naturwiss. 14, 1203 (1926).

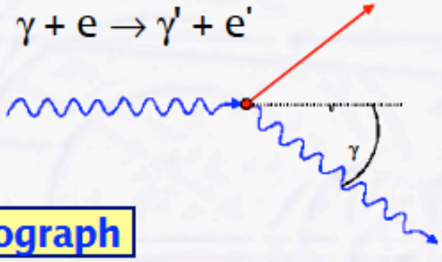
Alphas, Philipp 1926

Cloud Chamber II

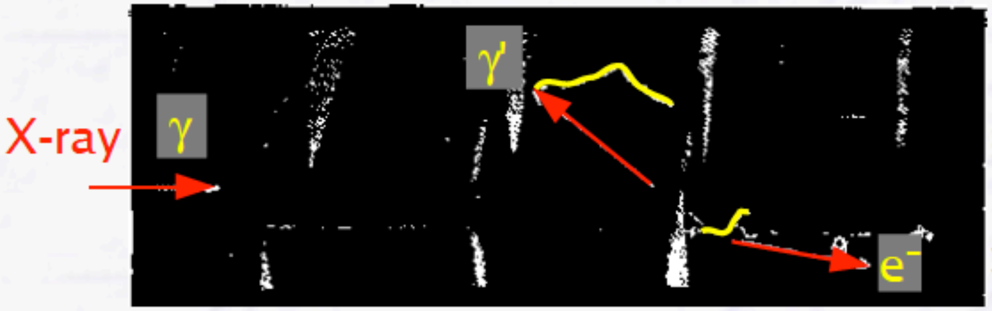
Arthur H. Compton

- 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

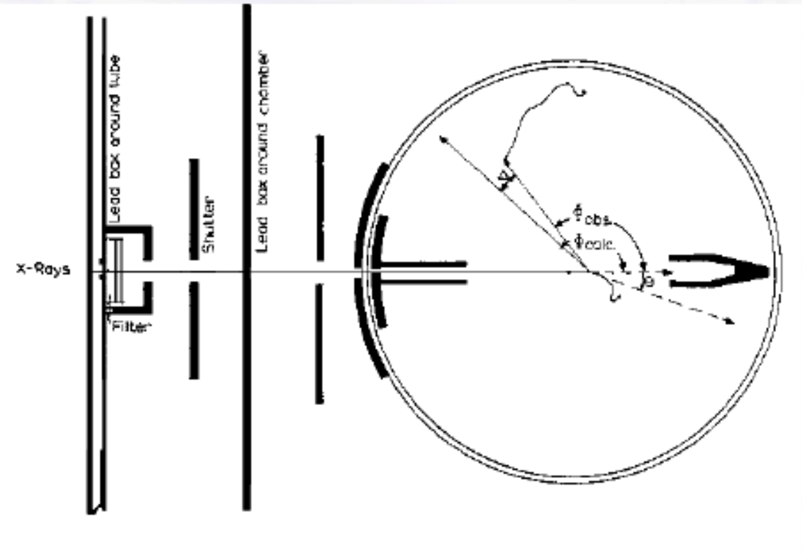
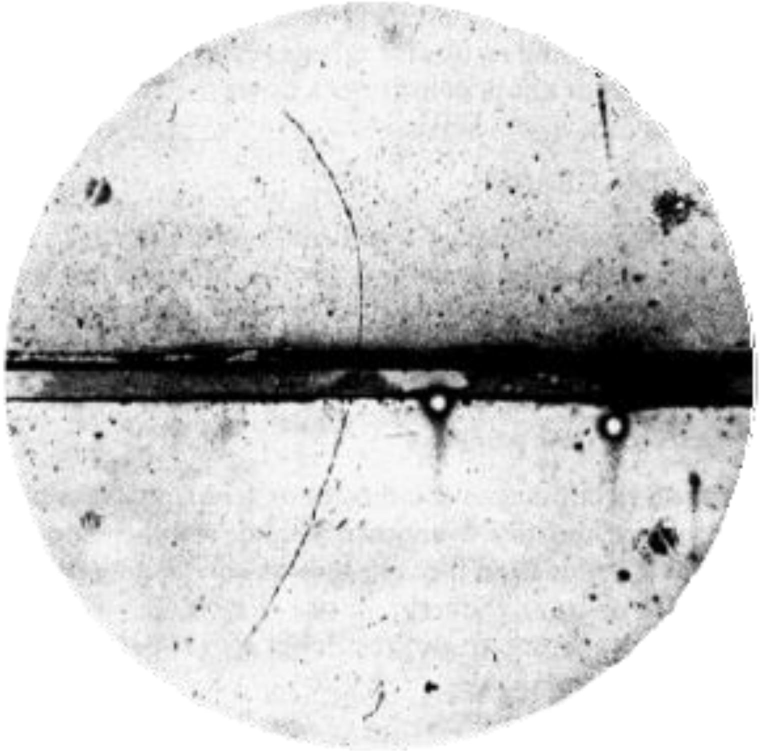


Fig. 10. An electron recoiling at an angle θ should be associated with a photon deflected through an angle φ.

Nobel Lecture 1927

Cloud Chamber



Positron discovery,
Carl Andersen 1933

Magnetic field 15000 Gauss, chamber diameter 15cm. A 63 MeV positron passes through a 6mm lead plate, leaving the plate with energy 23MeV.

The ionization of the particle, and its behaviour in passing through the foil are the same as those of an electron.

Cloud Chamber

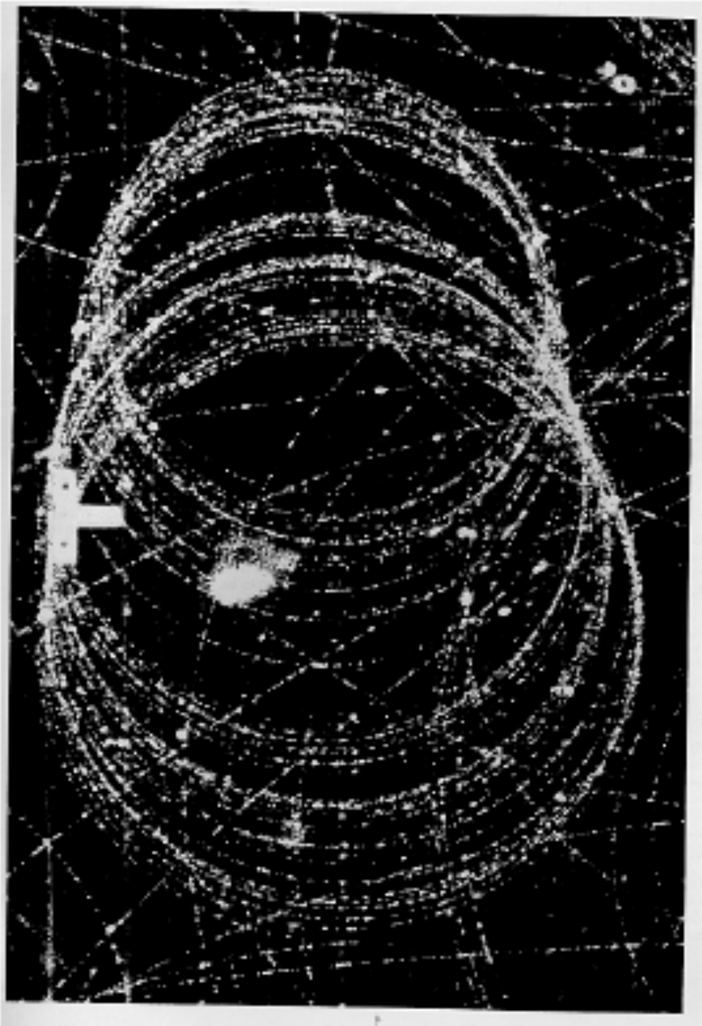


Fig. 43. Radiation Laboratory, Berkeley, Cal.

The picture shows and electron with 16.9 MeV initial energy. It spirals about 36 times in the magnetic field.

At the end of the visible track the energy has decreased to 12.4 MeV. from the visible path length (1030cm) the energy loss by ionization is calculated to be 2.8MeV.

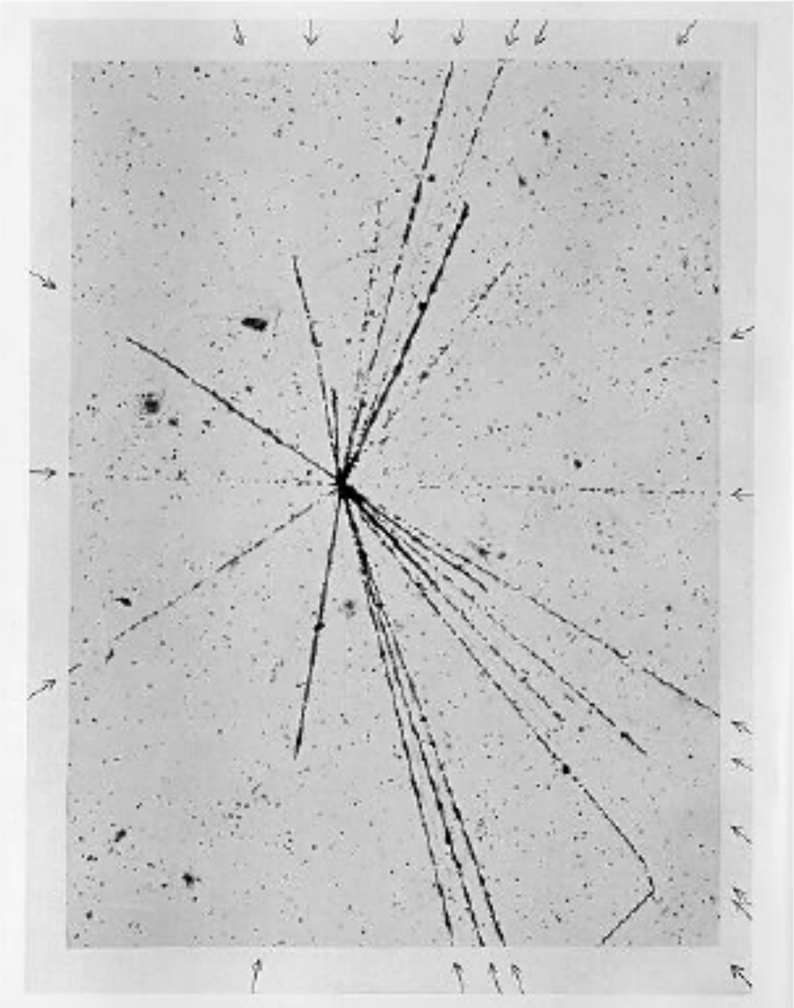
The observed energy loss (4.5MeV) must therefore be cause in part by

Bremsstrahlung. The curvature indeed shows sudden changes as can

Most clearly be seen at about the seventeenth circle.

Fast electron in a magnetic field at the Bevatron, 1940

Nuclear Emulsion


'EXPLOSIVE' DISINTEGRATION OF A NUCLEUS

Film played an important role in the discovery of radioactivity but was first seen as a means of studying radioactivity rather than photographing individual particles.

Between 1923 and 1938 Marietta Blau pioneered the nuclear emulsion technique.

E.g.

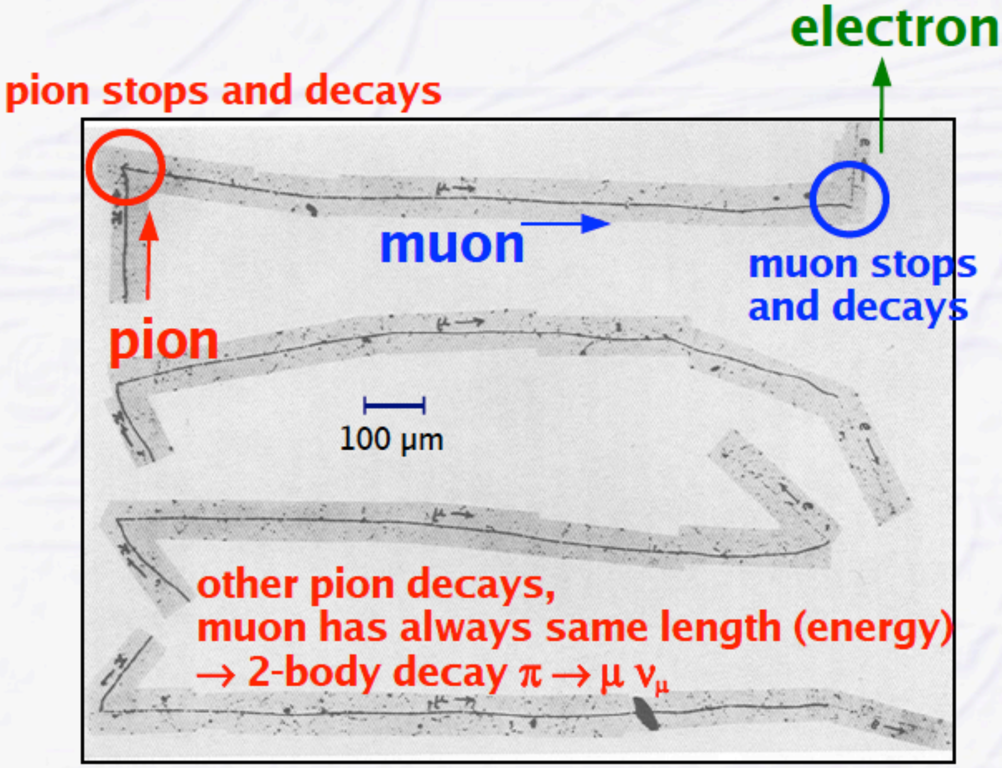
Emulsions were exposed to cosmic rays at high altitude for a long time (months) and then analyzed under the microscope.

In 1937, nuclear disintegrations from cosmic rays were observed in emulsions.

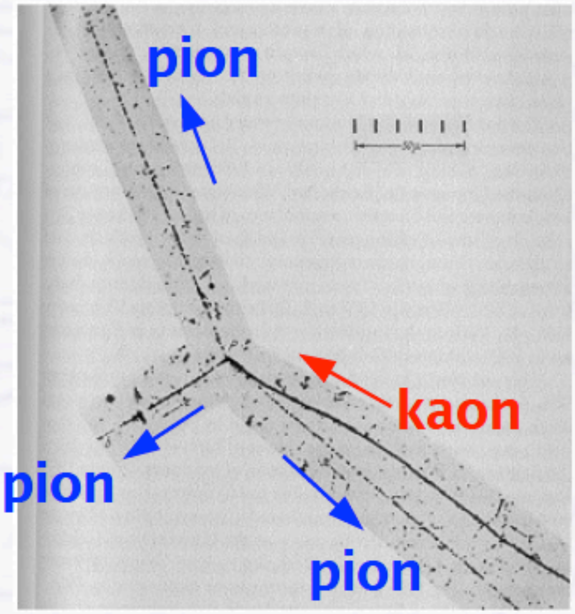
The high density of film compared to the cloud chamber 'gas' made it easier to see energy loss and disintegrations.

Nuclear Emulsion II

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



other pion decays, muon has always same length (energy) → 2-body decay $\pi \rightarrow \mu\, \nu_\mu$



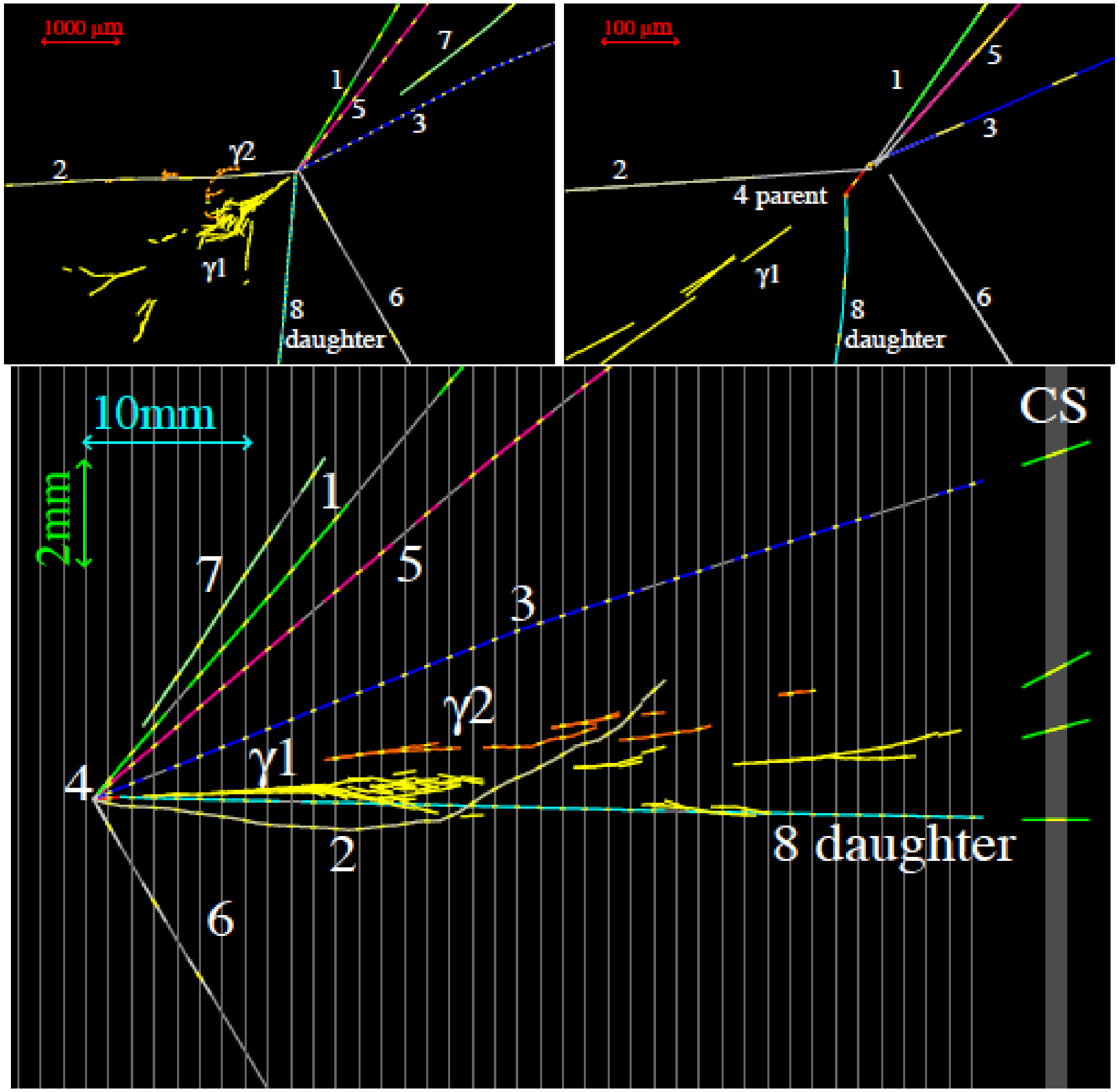


Figure 1: Display of the τ^- candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

Opera's First Tau Neutrino Event -

July 2010

arXiv:1006.1623v1

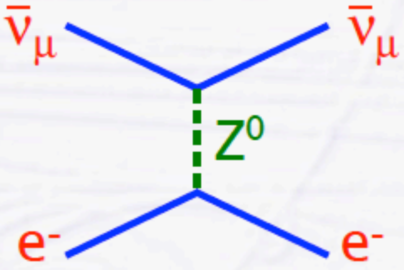
Bubble Chamber I

- 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

Donald Glaser

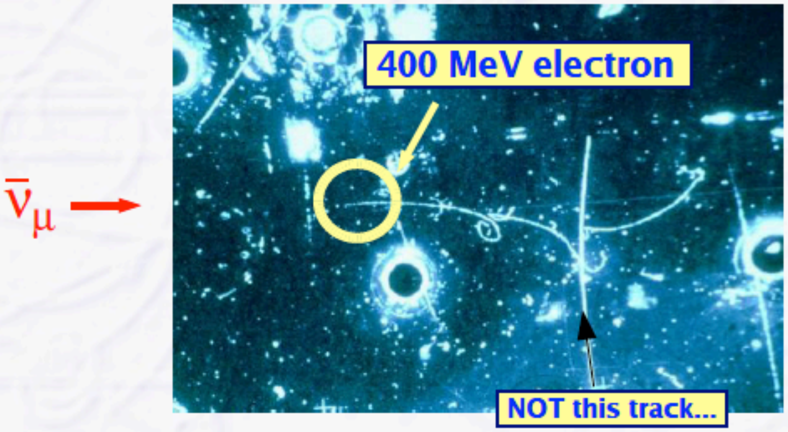
LBNL Image Library

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



Gargamelle bubble chamber

CERN



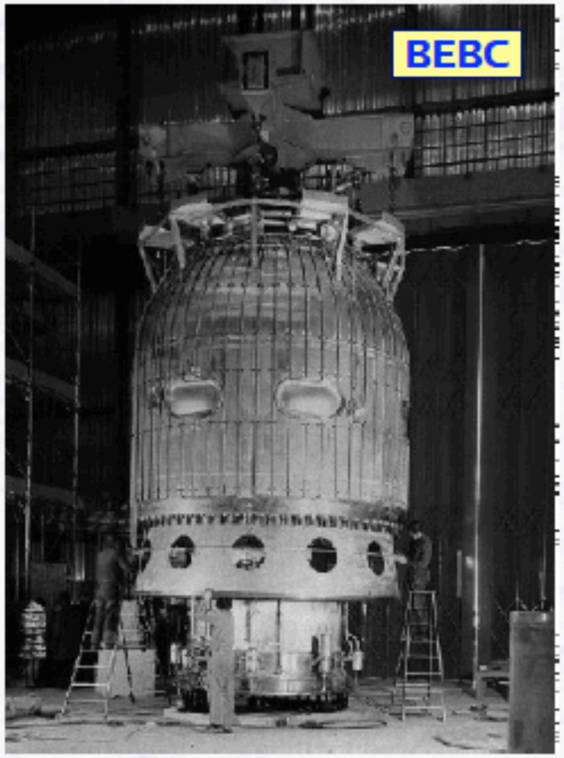
400 MeV electron

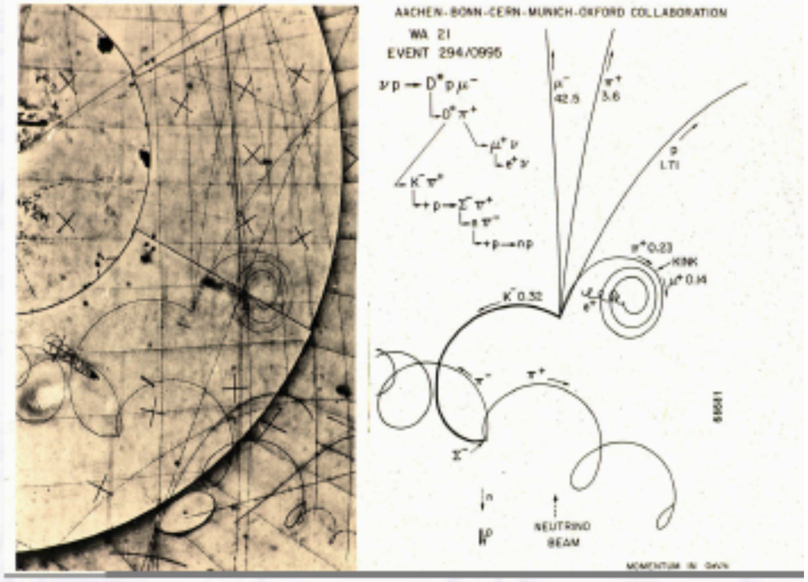
NOT this track...

CERN

Bubble Chamber II

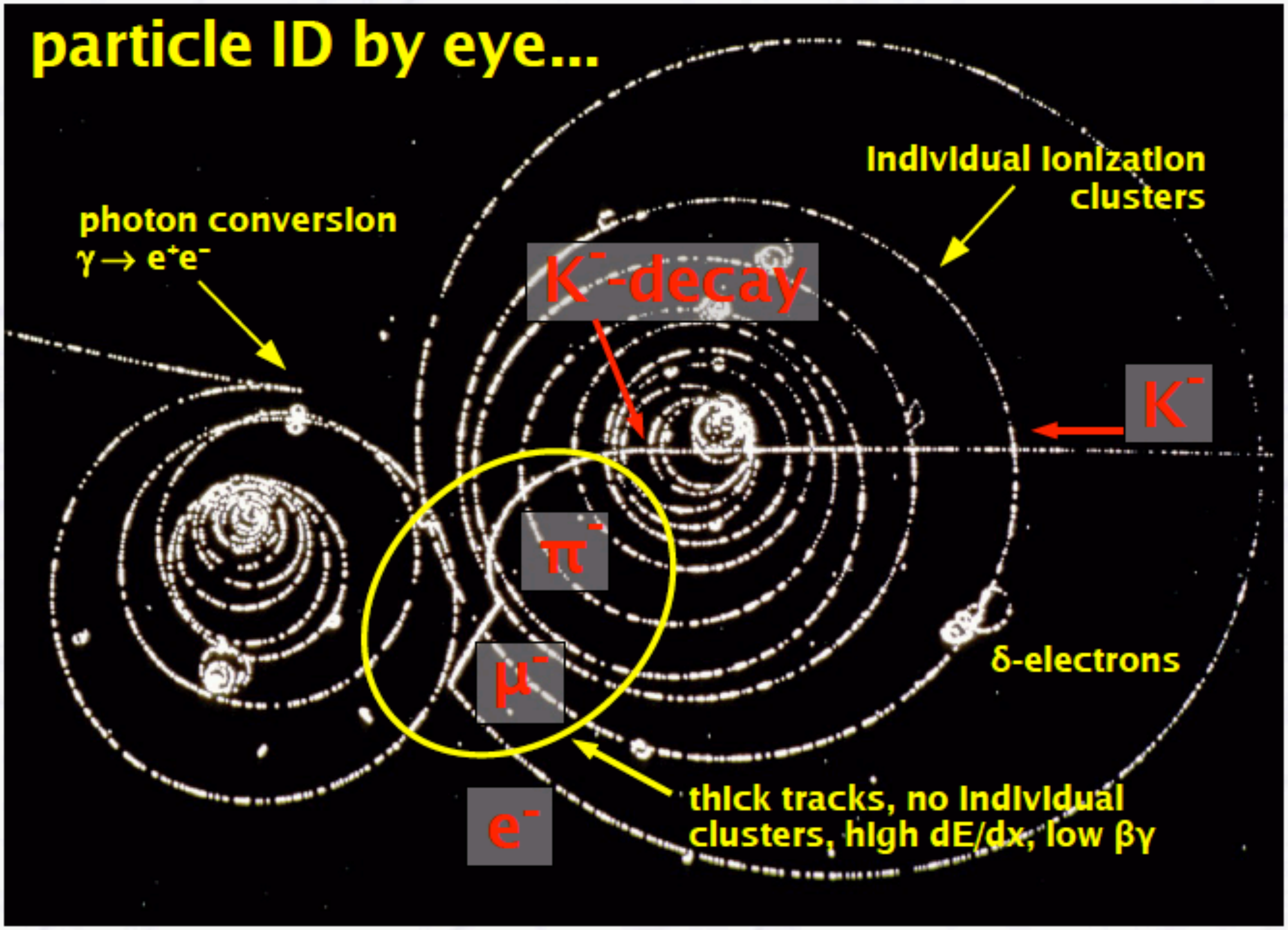
- BEBC (Big European Bubble Chamber) at CERN, 1973 – 1984
  - largest bubble chamber ever built (and the last big one...), Ø 3.7 m
  - 6.3 million photographs taken, 3000 km of developed film
  - now displayed in permanent exhibition at CERN





production of D* meson
with long decay chain

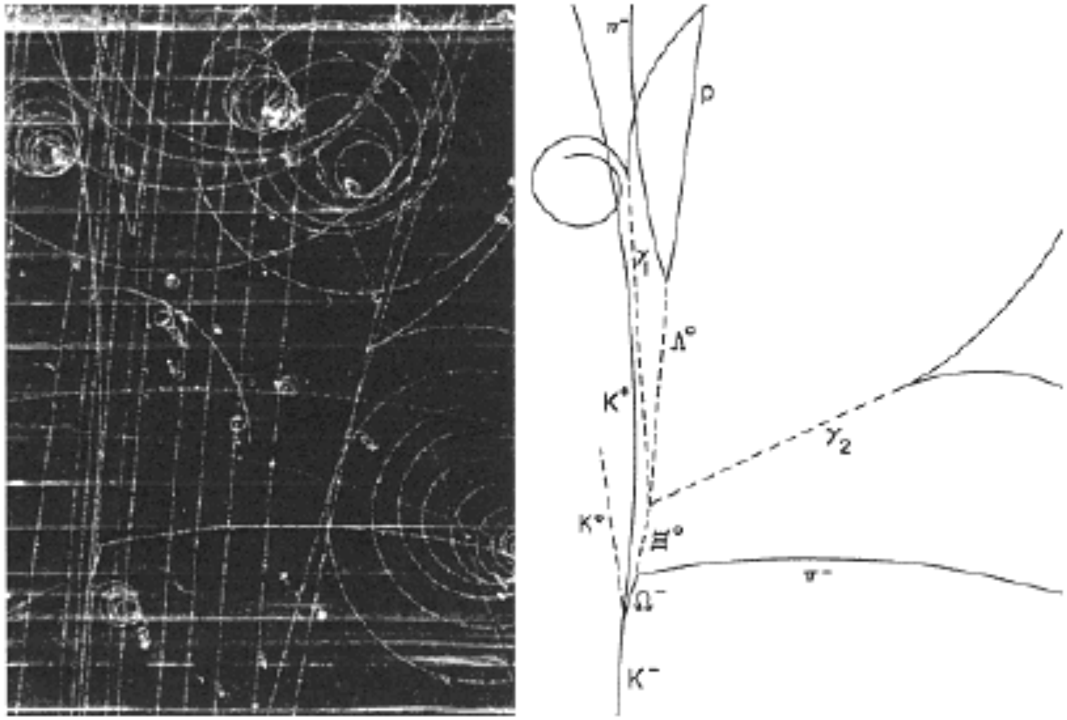
Bubble Chamber III



Bubble Chamber

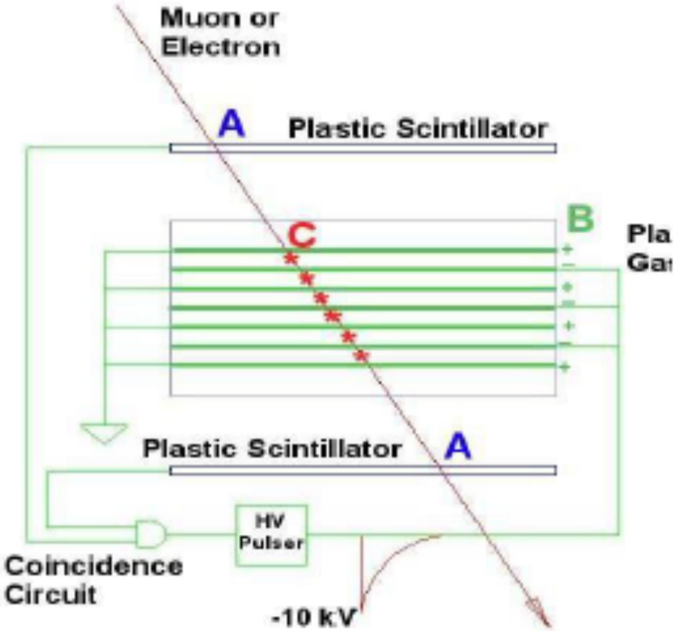
The 80-inch Bubble Chamber

BNL, First Pictures 1963, 0.03s cycle



Discovery of the Ω^- in 1964

Spark Counters

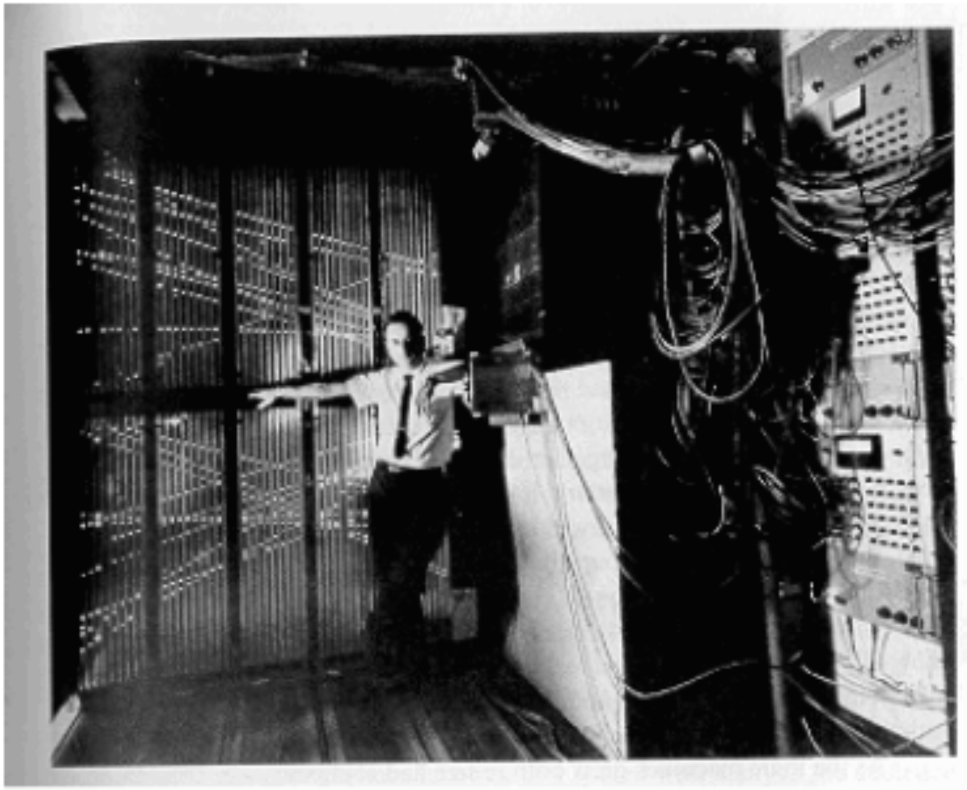


A charged particle traverses the detector and leaves an ionization trail.

The scintillators trigger an HV pulse between the metal plates and sparks form in the place where the ionization took place.

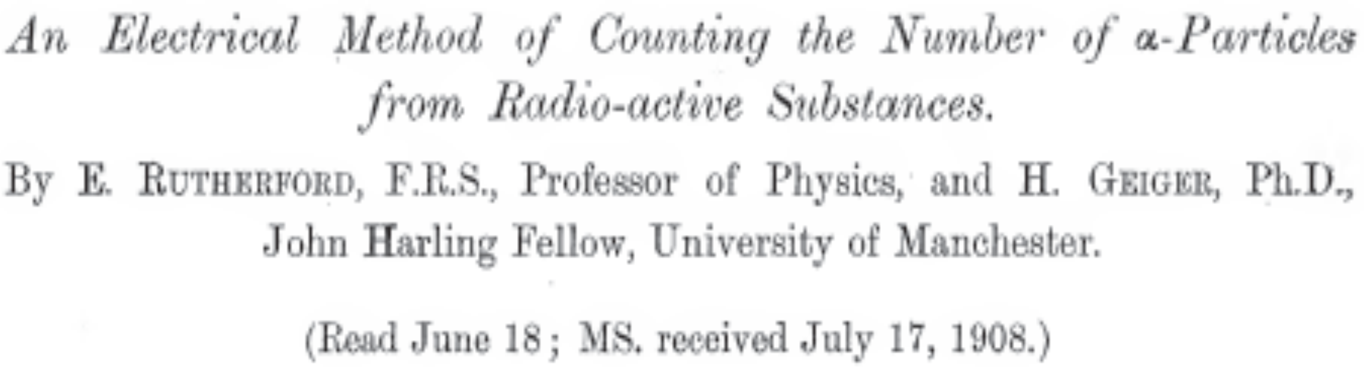
The Spark Chamber was developed in the early 60ies.

Schwartz, Steinberger and Lederman used it in discovery of the muon neutrino



Where does the story of "electronic" particle detection really begin? ~1908

- Ernest Rutherford and Hans Geiger publish the first electrical detection of single ionizing events, in the Philosophical Magazine of the Royal Society:



An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. RUTHERFORD, F.R.S., Professor of Physics, and H. GEIGER, Ph.D., John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)

“It has been recognized for several years that it should be possible by refined methods to detect a single α-particle by measuring the ionization it produces in its path. ”

Experimental Arrangement.—Before considering the various difficulties that arose in the course of the investigations, a brief description will be given of the method finally adopted. The experimental arrangement is shown in fig. 1. The detecting vessel consisted of a brass cylinder A, from 15 to

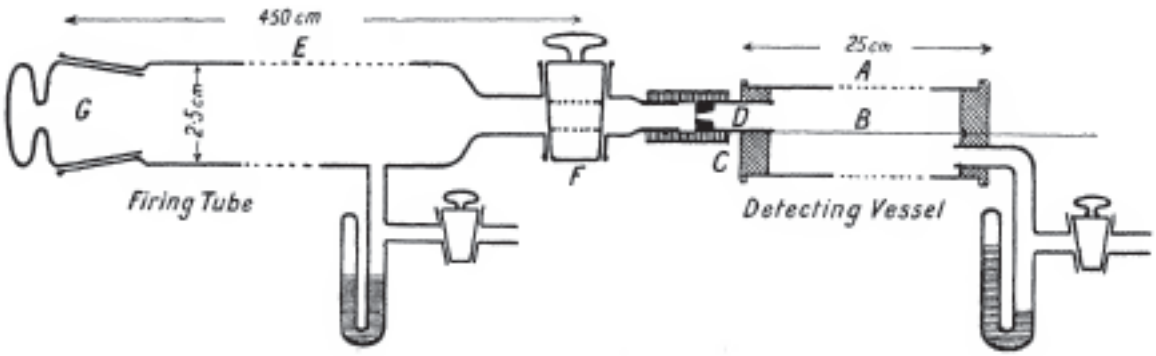


Fig. 1.

25 cm. in length, 1·7 cm. internal diameter, with a central insulated wire B passing through ebonite corks at the ends. The wire B was in most experiments of diameter 0·45 mm. The cylinder, with a pressure gauge attached,

Rutherford and Geiger…

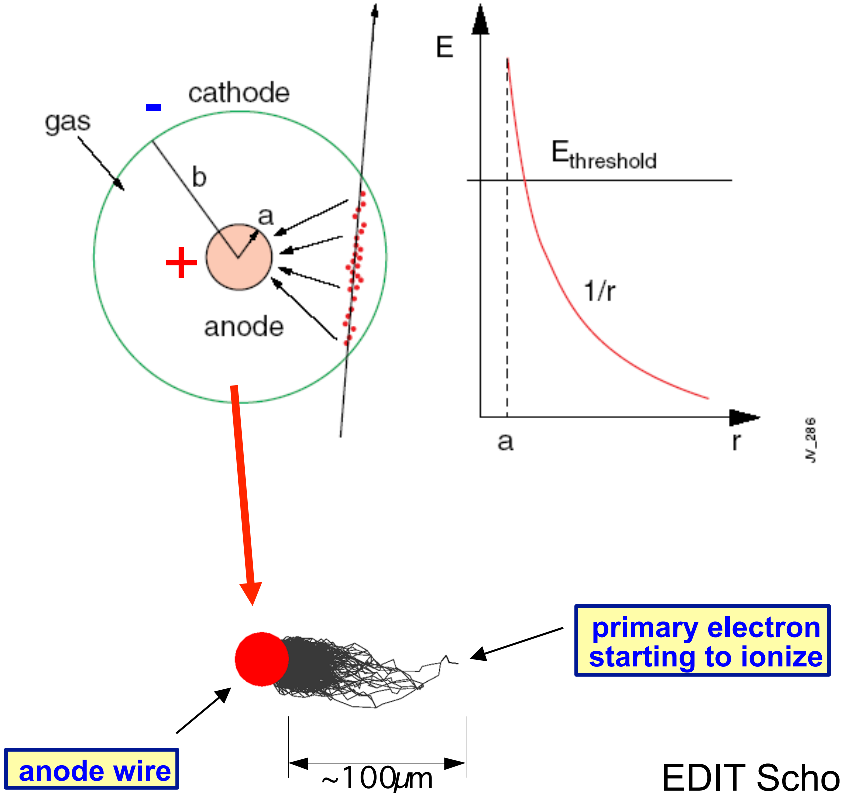
"We then had recourse to a method of automatically magnifying the electrical effect due to a single α-particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend [2] has worked out the conditions under which ions can be produced by collisions with the neutral gas molecules in a strong electric field."…

Rutherford and Geiger…

…"In this way, the small ionization produced by one α-particle in passing through the gas could be magnified several thousand times. The sudden current due to the entrance of an α-particle in the testing vessel was thus increased sufficiently to give an easily measurable movement of an ordinary electrometer."

Geiger-Müller Tube

- The Geiger-Müller tube (1928 by Hans Geiger and Walther Müller)
  - Tube filled with inert gas (He, Ne, Ar) + organic vapour (alcohol)
  - Central thin wire (20 – 50 µm ∅) , 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**
- **avalanche process: exponential increase of electrons (and ions)**
- **measurable signal on wire**
  - **G-M discharge spreads along wire**
  - **proportional mode: no spreading**

THE JAPAN TIMES, TUESDAY, OCTOBER 7, 1958

Science Report

Co-Inventor of Geiger Counter Is Still Alive

self was standing at a certain place before the tube, they ceased; when he walked to other places in the room, they started again in the same way as before.

The mystery was solved and a great day in atomic history dawned when Dr. Muller open-

ing like gold
burst out: "We
people who
wonderful inst
make it know
physicists wil

Many physic
themselves to
and the nex

Scoop: *How was the Geiger-Muller counter really invented?*

Lesson: pay attention !

- In 1926, Muller was given a old brass tube with a wire inside –"Spitzenzahler"–made by Geiger in 1913 under the guidance of Rutherford, to study spark discharges.
- Muller discovered the Spitzenzahler behaved strangely, and sometimes produced pulses on its own, with varying rate.

How was the Geiger-Muller counter really invented?

- Muller paced around the room, unable to understand the refractory behavior of the Spitzenzahler.

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- Muller paced around the room, unable to understand the refractory behavior of the Spitzenzahler.
- He eventually realized that when he was standing in a certain position, the rate was greatly reduced.

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- Muller opens the door to the room behind him…
- A colleague in the next room had some radium!
- Muller realizes his body is shielding the Spitzenzahler!

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- He eventually realized that when he was standing in a certain position, the rate was greatly reduced.
- The effect was reproducible!
- Muller opens the door to the room behind him…
- A colleague in the next room had some radium!
- Muller realizes his body is shielding the Spitzenzahler!
- Spitzenzahler is detecting radium γ-rays!

The truth revealed…

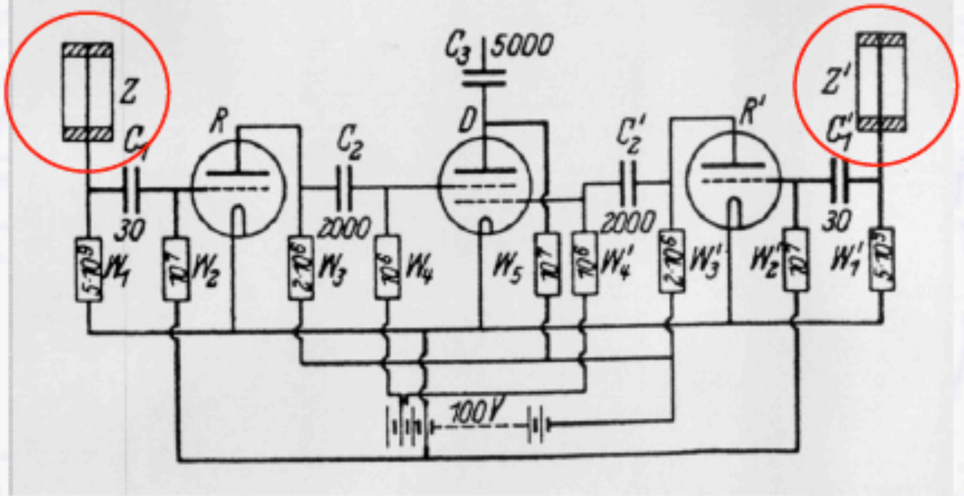
- Muller tests his new device for 5 days
- Muller shows it to Geiger on 9 May 1928
- Geiger exclaims:
  - "We are the only people who know of this wonderful instrument. We shall make it known, and a host of physicists shall use it."
- No patent is sought, and the device is made freely available through publication

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

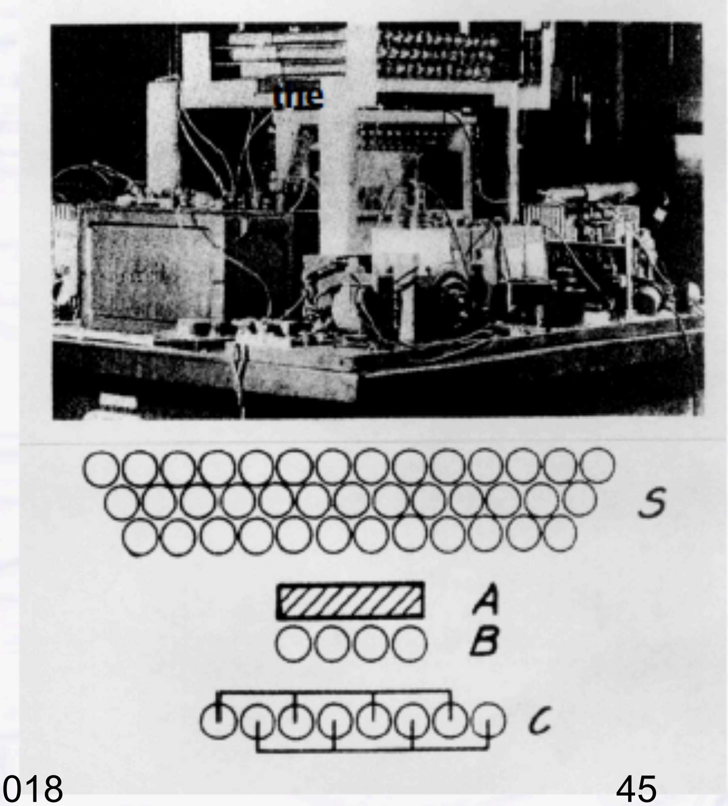
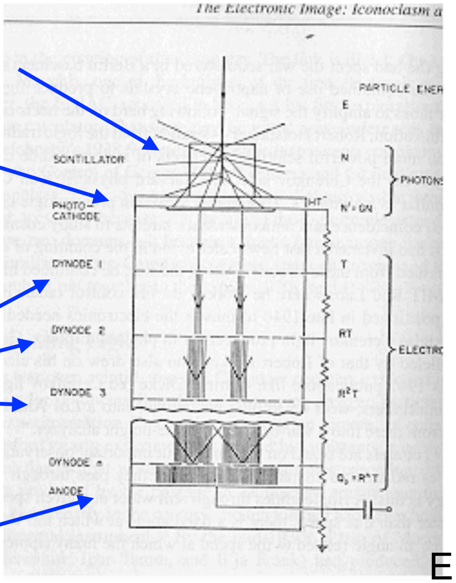


Photo Multiplier Tubes (PMT)

- Invented in 1934 by Harley Iams and Bernard Salzberg (RCA)
  - 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



plastic scintillator

photo cathode

dynodes: secondary electron emission

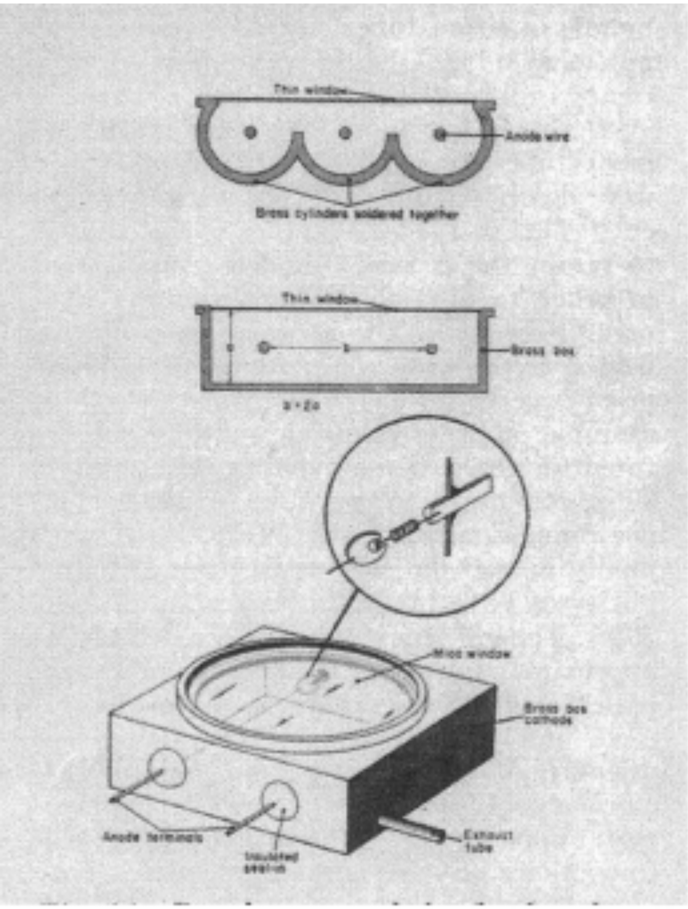
anode

classic PMT

Silicon PM = array of avalanche photo diodes

H. Friedman, *Proc. Institute of Radio Engineers* **37** (1949)

Multi-wire common-enclosure geometries!



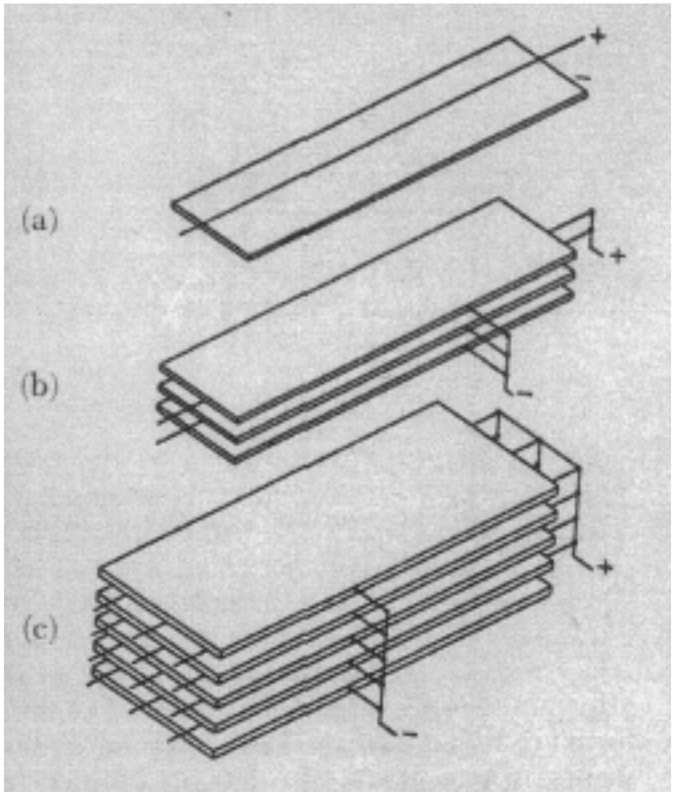
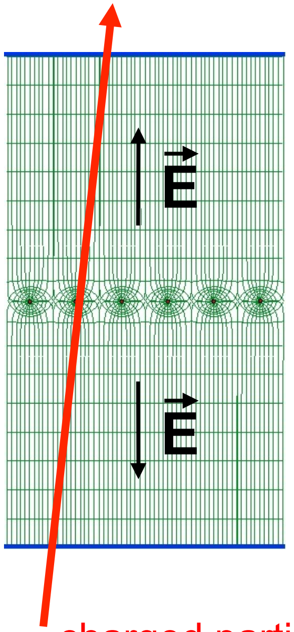


Fig. 20—Multiple plate and wire construction of a gamma-ray counter.

Multi Wire Proportional Chambers

Georges Charpak

- Geiger-Müller tube: Long recovery times for ions to clear
- Multi Wire Proportional Chamber (MWPC) 1968 by Georges Charpak,
- Nobel Prize 1992
  - put many wires close together with individual signal circuits
  - short distance between two parallel plates

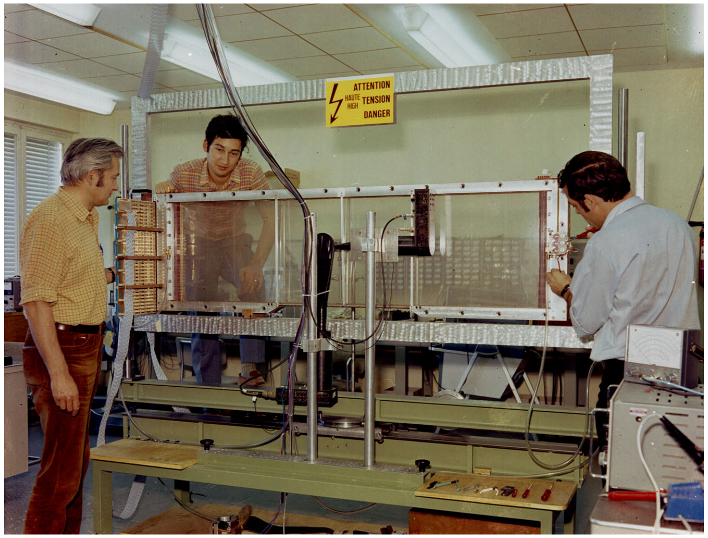


cathode plane (-)

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

cathode plane (-)

charged particle



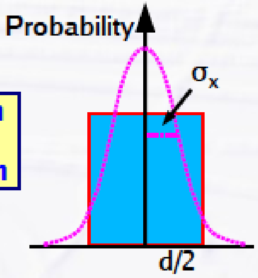
CERN

Georges Charpak, Fabio Sauli and Jean-Claude Santiard

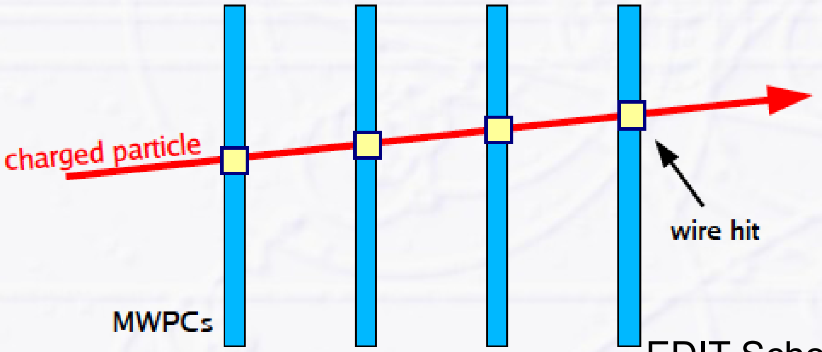
Multi Wire Proportional Chambers II

- **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)

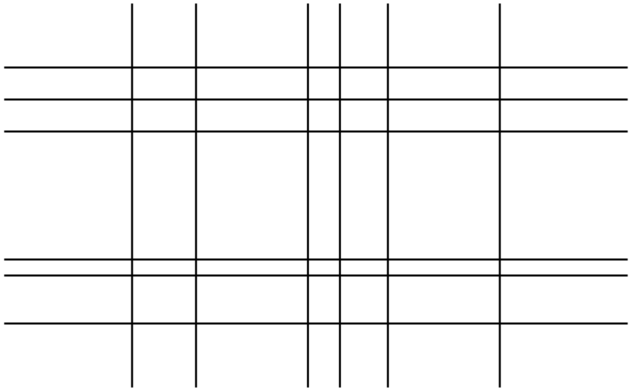


can reconstruct track with e.g. 4 points

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

The dreaded N^2 ambiguity

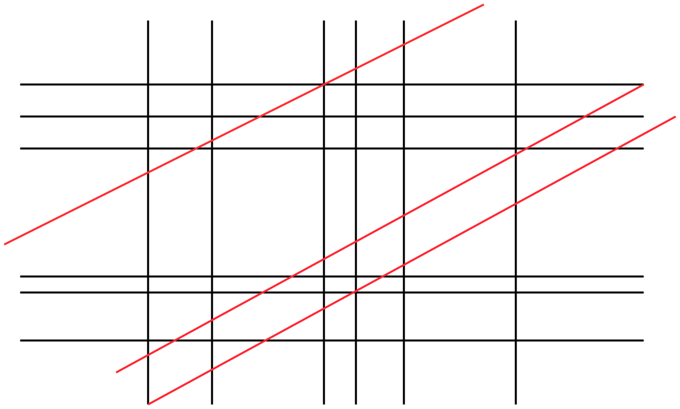
- Suppose you have a detector (MWPC,...) that measures separately the x and y coordinates of tracks.
- If N tracks appear simultaneously, then you have N x coordinates, and also N y coordinates. You have N^2 possible combinations of <x,y>.



- *Which are the right ones?*

The N^2 ambiguity resolved?

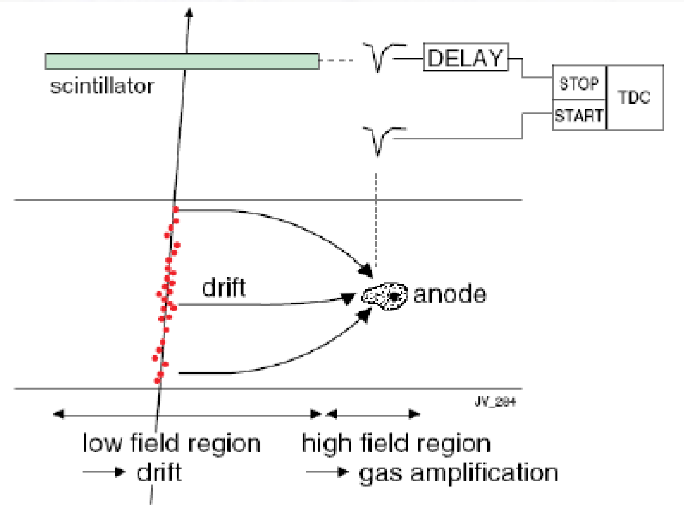
- Suppose you have a detector (MWPC,...) that measures separately the x and y coordinates of tracks.
- If N tracks appear simultaneously, then you have N x coordinates, and also N y coordinates. You have N^2 possible combinations of <x,y>.



- *Which are the right ones?*
- *Unpleasant for N > ~10*
- *Anguish rises ~ $N^{3\,?}$*

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)

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

E x B ≠ 0 ⇒

Track distortion!

“Particle Detection with Drift Chambers”, Blum, Riegler, Rolandi

Wade Allison 1972 - Identification of Secondaries by Ionization Sampling -

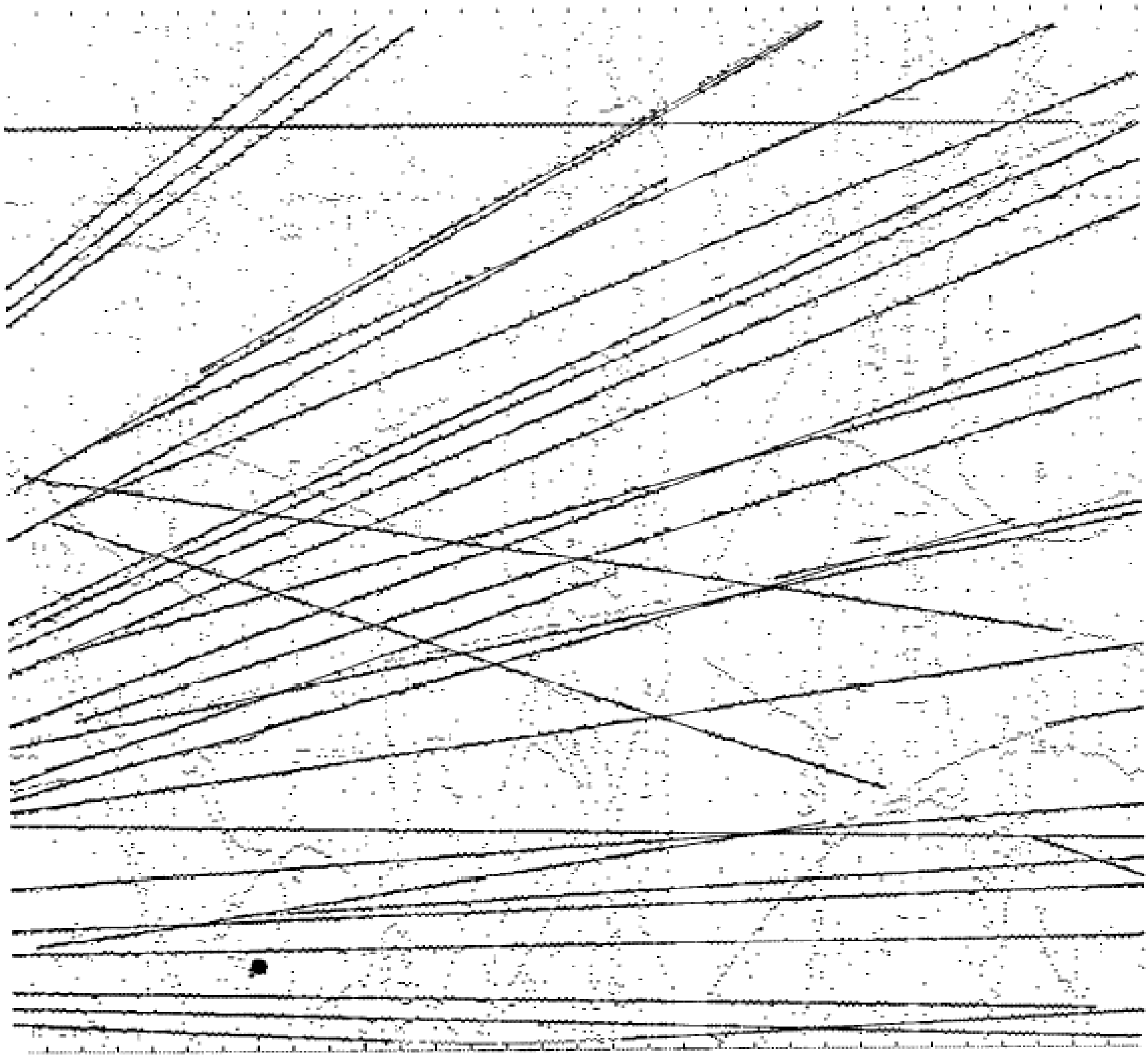


Fig. 17 Spatial data for a single event in ISIS2. Each point is a track hit and is associated with a measured pulse height (not shown). The horizontal axis (512cm) is the wire number. The vertical axis (2x200cm) is the drift direction. Tracks, low energy electrons and noise hits may be seen. Track vectors reconstructed in ISIS space are superposed on the raw data.

A rectangular box 5m long, 2m wide and 4m high, filled with argon-CO_2 at one bar pressure.

320 samples of ionization yielded 7.4% FWHM dE/dx resolution

DAQ:

Store pulse height and time whenever threshold is crossed

Origins of the TPC idea

- February 1974: COMPLETE FRUSTRATION, while trying to conceive a detector concept for SPEAR, an electron-positron collider at SLAC.
- Epiphany #1: if electric drift field is parallel to B,
  - then E x B distortion of tracks becomes negligible...!
- Epiphany # 2: Spark chamber tracks brighter, narrower when B-field on... !
  - Maybe diffusion transverse to fields is suppressed...?
  - $\sigma = (2DT)^{1/2}$
  - $D_m = D/(1 + (\omega\tau)^2)$ (Townsend 1912) ω is cyclotron frequency, τ is mean collision time
  - can $\omega\tau >> 1$?

Revelation

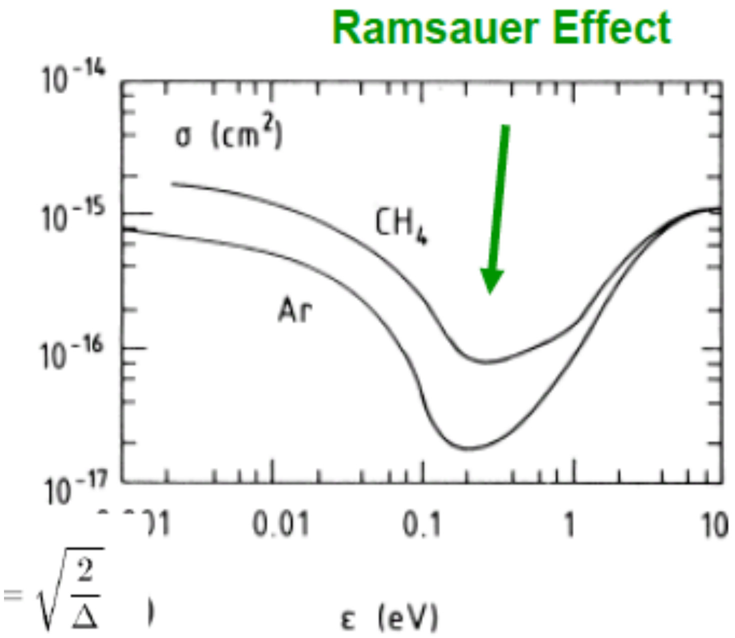
- In argon and methane, a sharp minimum exists in the electron-atom cross-section at ~0.25 eV; this is the Ramsauer-Townsend effect.

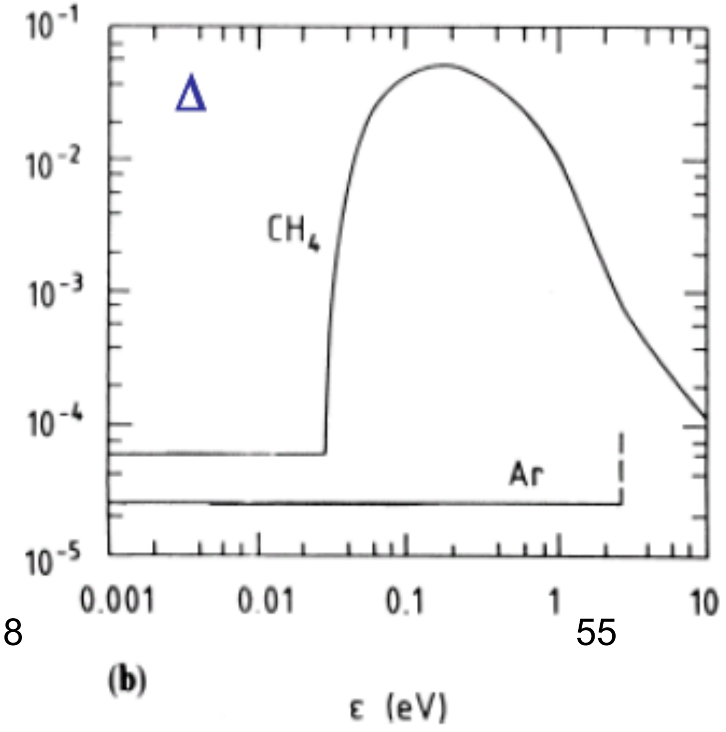
- This leads to a very large τ; hence $\omega\tau$ >>1

  Example: PEP-4 TPC B ~ 1 T
  8.5 bars Ar/CH_4 (90/10)

  D reduced by ~two orders of magnitude with B field on!

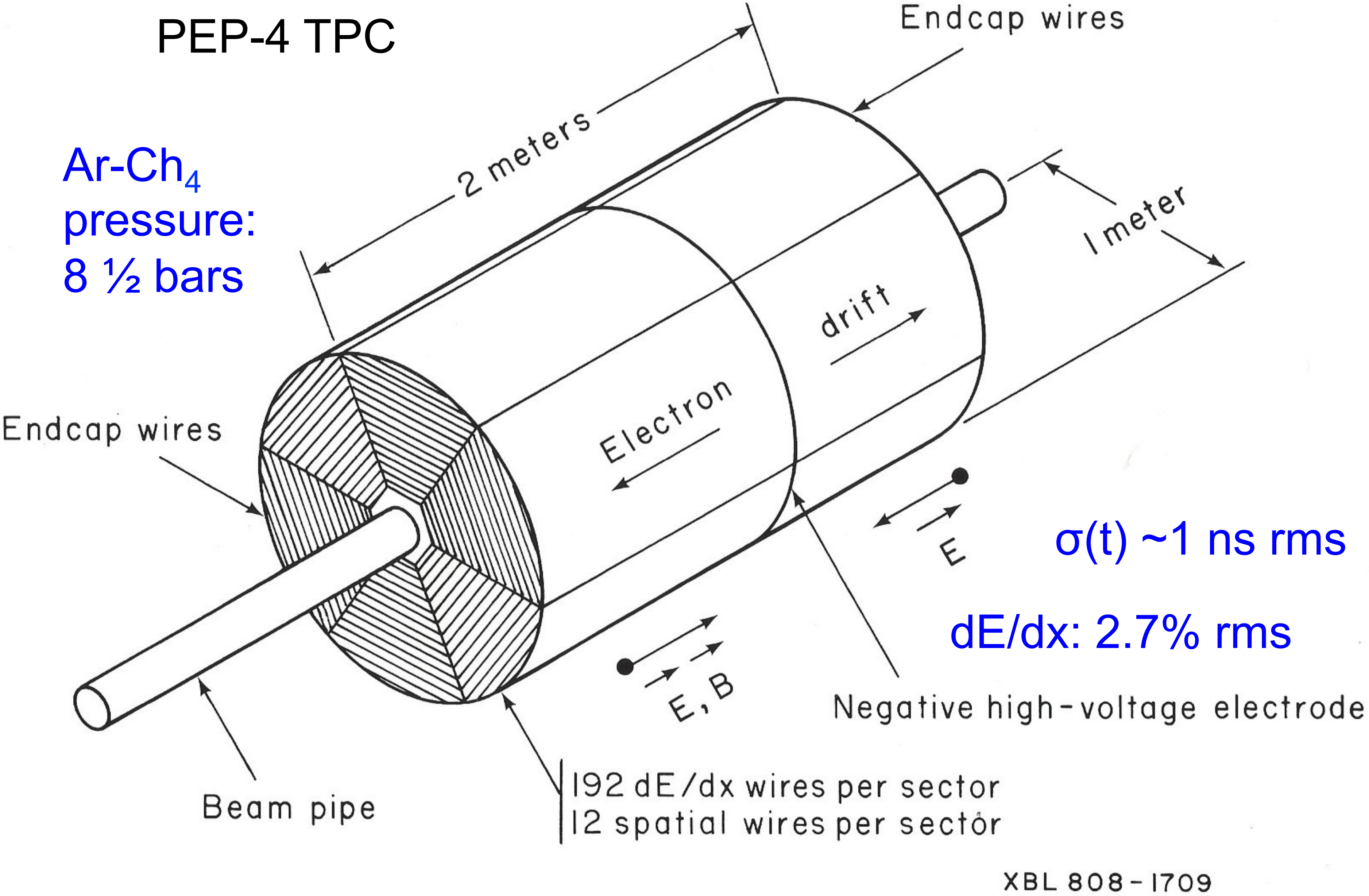
- Quantum mechanics in action!





PEP-4 TPC

Ar-CH_4 pressure: 8 ½ bars



σ(t) ~1 ns rms

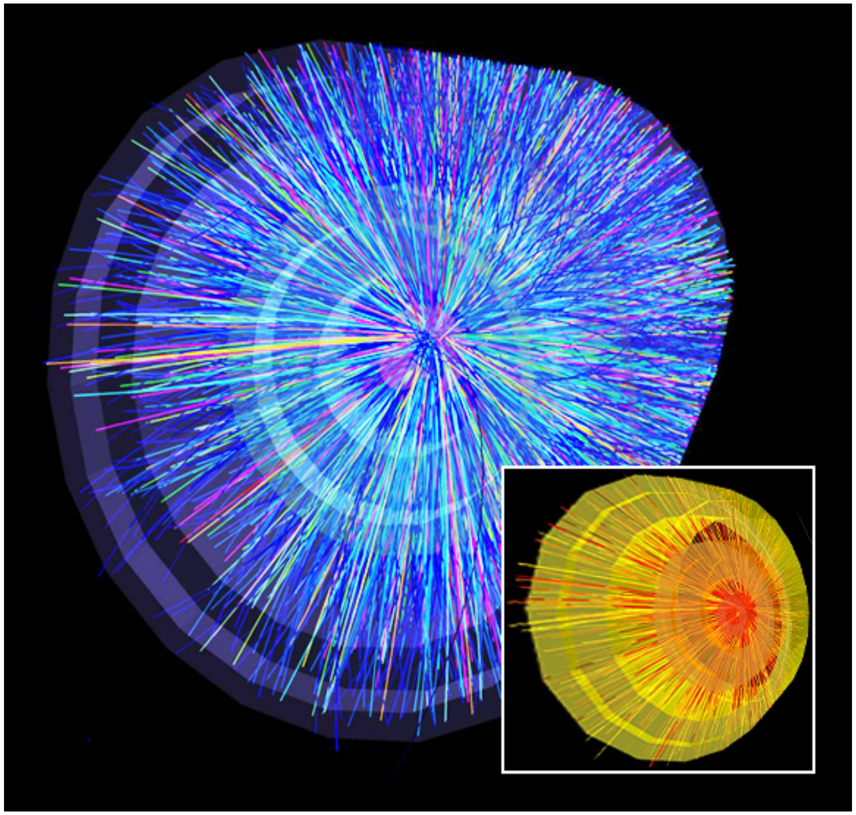
dE/dx: 2.7% rms

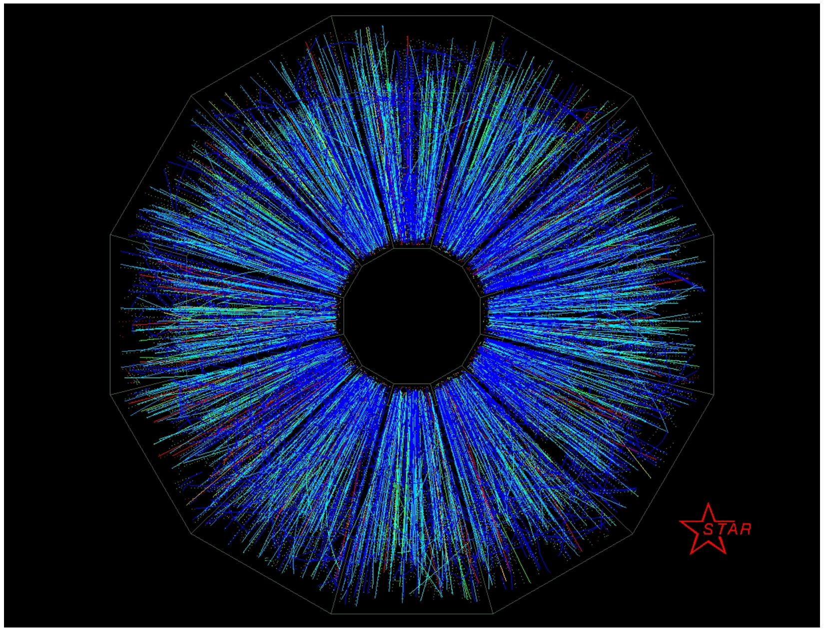
TPC Sector

Electronic Advances - 1970’s

- Scene: PEP-4 HQ (1975)
  - TPC provides superb information arriving at sectors...
  - Too many pad channels to use discrete S/H circuits!
  - How to read out the complex events foreseen at PEP?
- Idea: Let’s try continuous waveform sampling - !?
  - Can we use new-fangled charge-coupled device (CCD)?
  - Linear array for delay-line applications existed (**Fairchild**)
  - Capture information at **super-high**-rate: 10 MHz
  - Digitize captured analog information <1 MHz when trigger occurs
  - When clock frequency switched, CCD device didn’t work!
  - Fairchild graciously redesigned the internals to avoid “corners”
  - *An enabling technology* - essential to ultimate success of PEP-4.

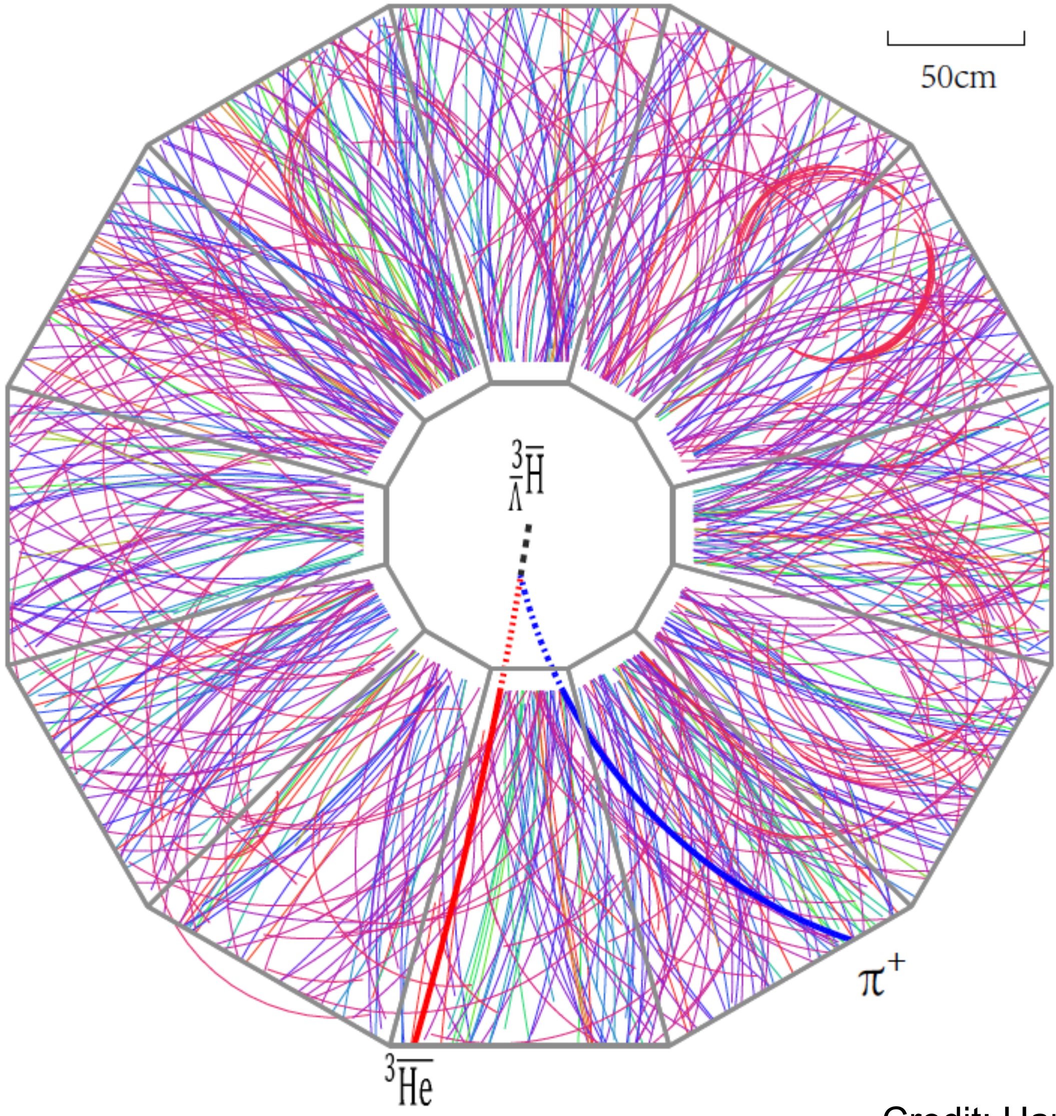
Large TPCs in action today





STAR TPC:

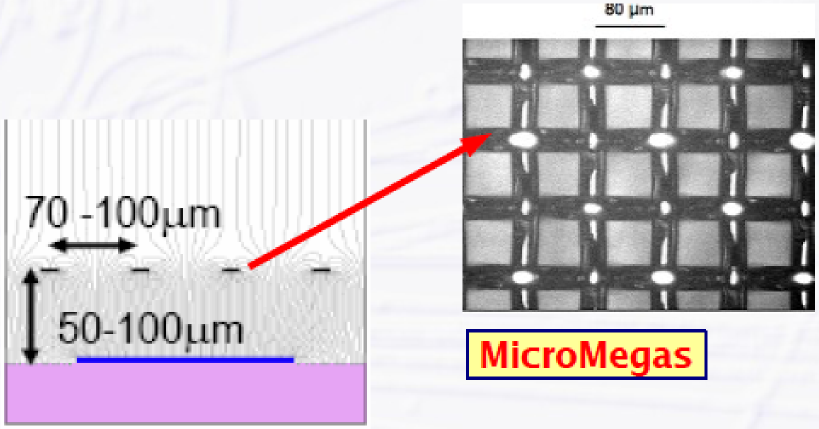
Production of anti-strange ^{3}H followed by decay to anti-^{3}He

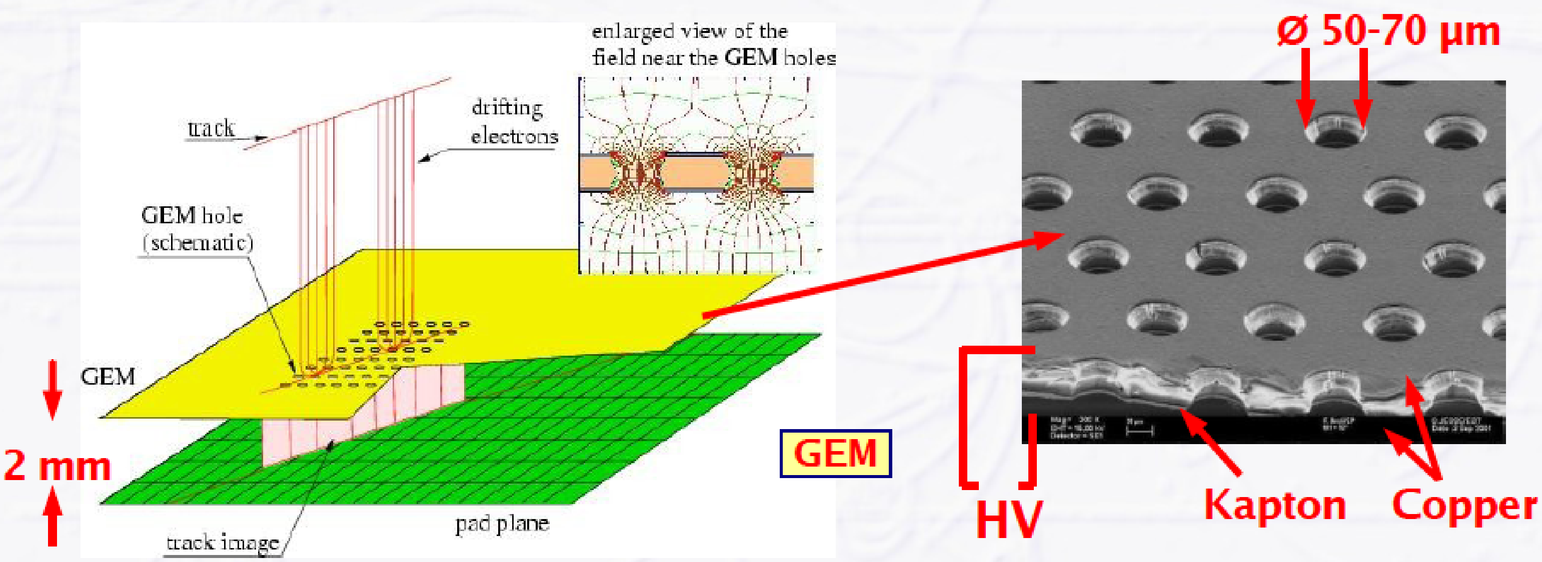


Credit: Hank Crawford

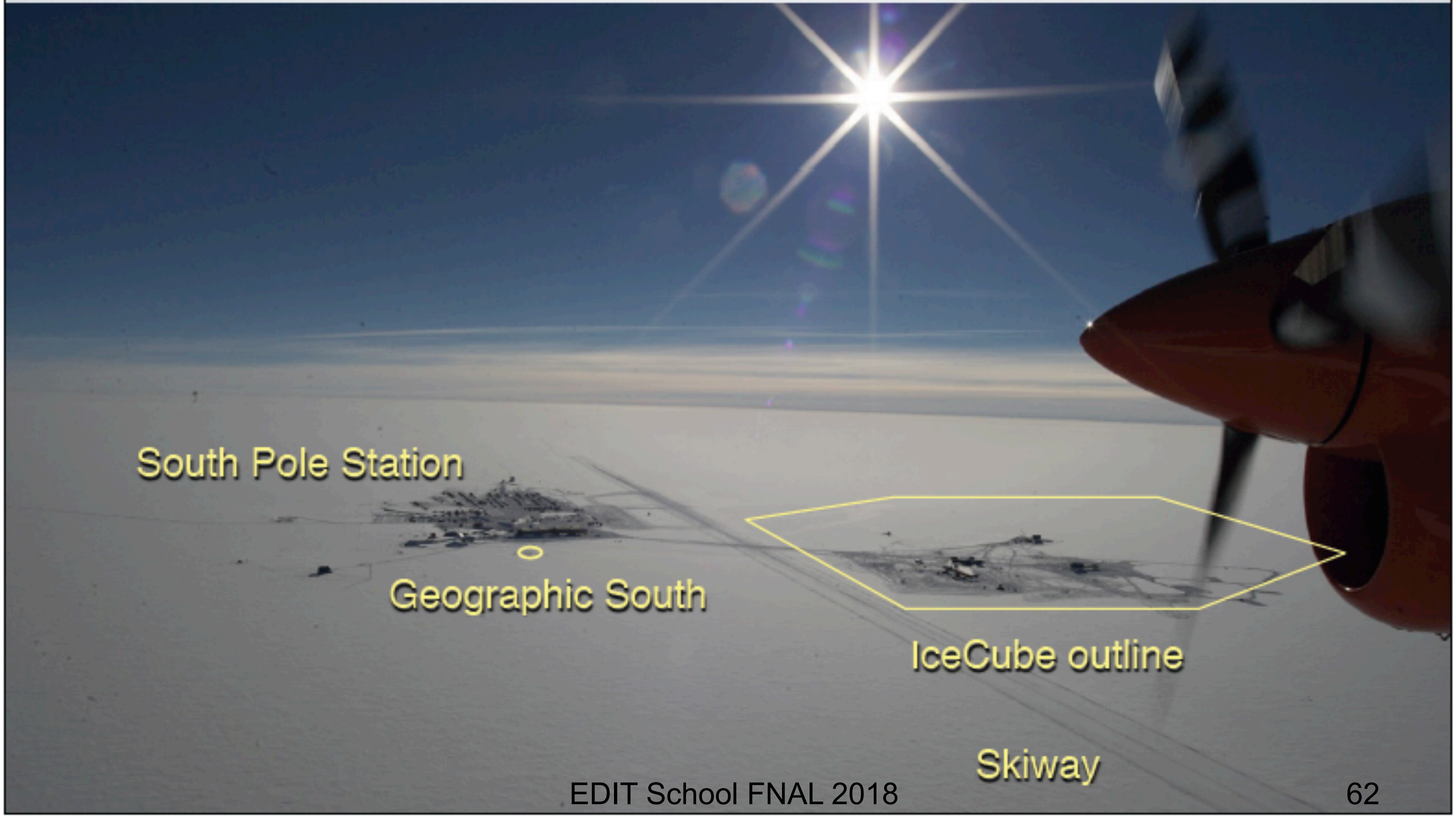
Recent Developments: Micro Pattern Gas Detectors (MPGD)

- 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 mm2

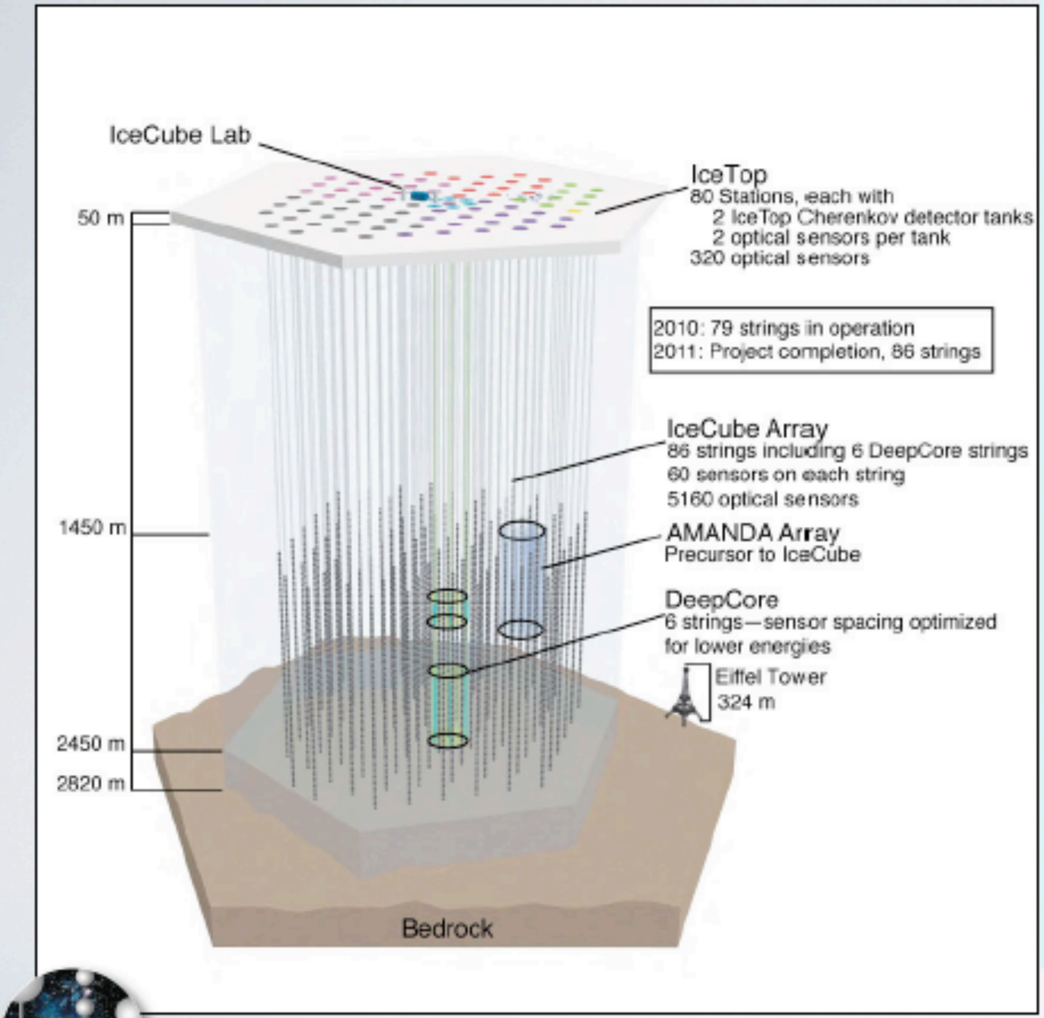




THE ICECUBE OBSERVATORY



IceCube at the south pole - megalith #1



How to go from AMANDA - a centralized analog DAQ - to a DAQ based on a low-power decentralized digital network?

Wanted: 14-bit 400MHz ADC

<u>Digital Optical Module (DOM)</u>

86 strings completed 5000 DOMs in January 2011

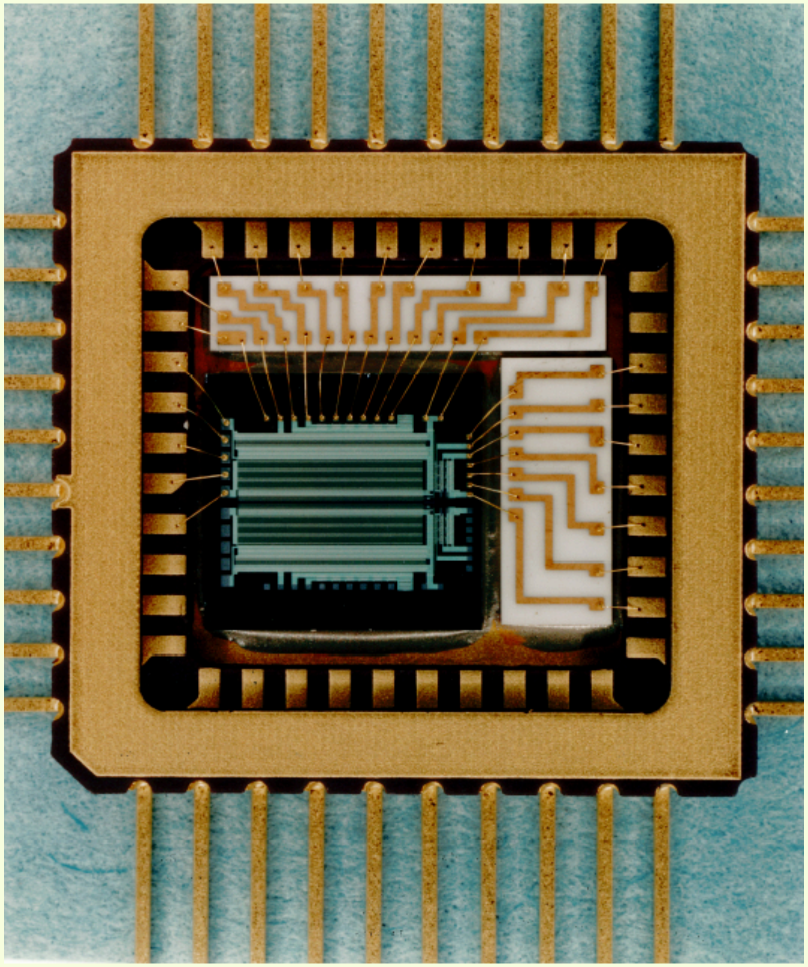
~2 ns rms resolution over 1km^3 volume, 98% alive

A prime example of functional devolution (decentralization) made possible by electronic advances.

Juan Antonio Aguilar - Lake Louise 2011

(1996): Why not use Stuart Kleinfelder's new ASIC?

Analog Transient Wave Recorder (ATWR)



Stuart's Master's thesis, UCB

***

Switched-capacitors: **low power**

Three input channels

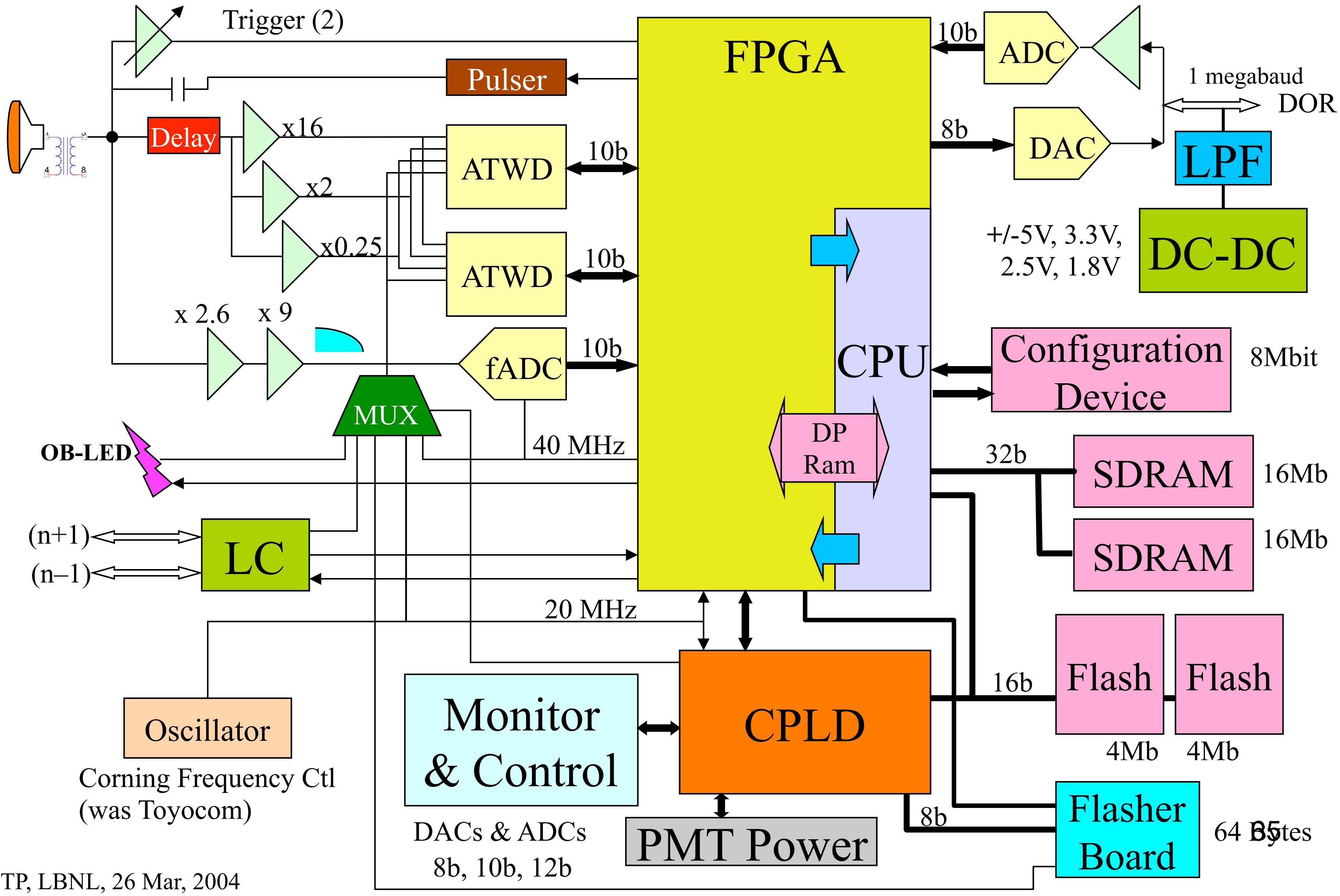
256 samples per channel

synchronous sampling: variable from 200 - 1000 MHz!

10 bit S/N, *but:* No internal ADC!

Stuart adds internal ADC - ready!

Digital Optical Module Block Diagram



GTP, LBNL, 26 Mar, 2004

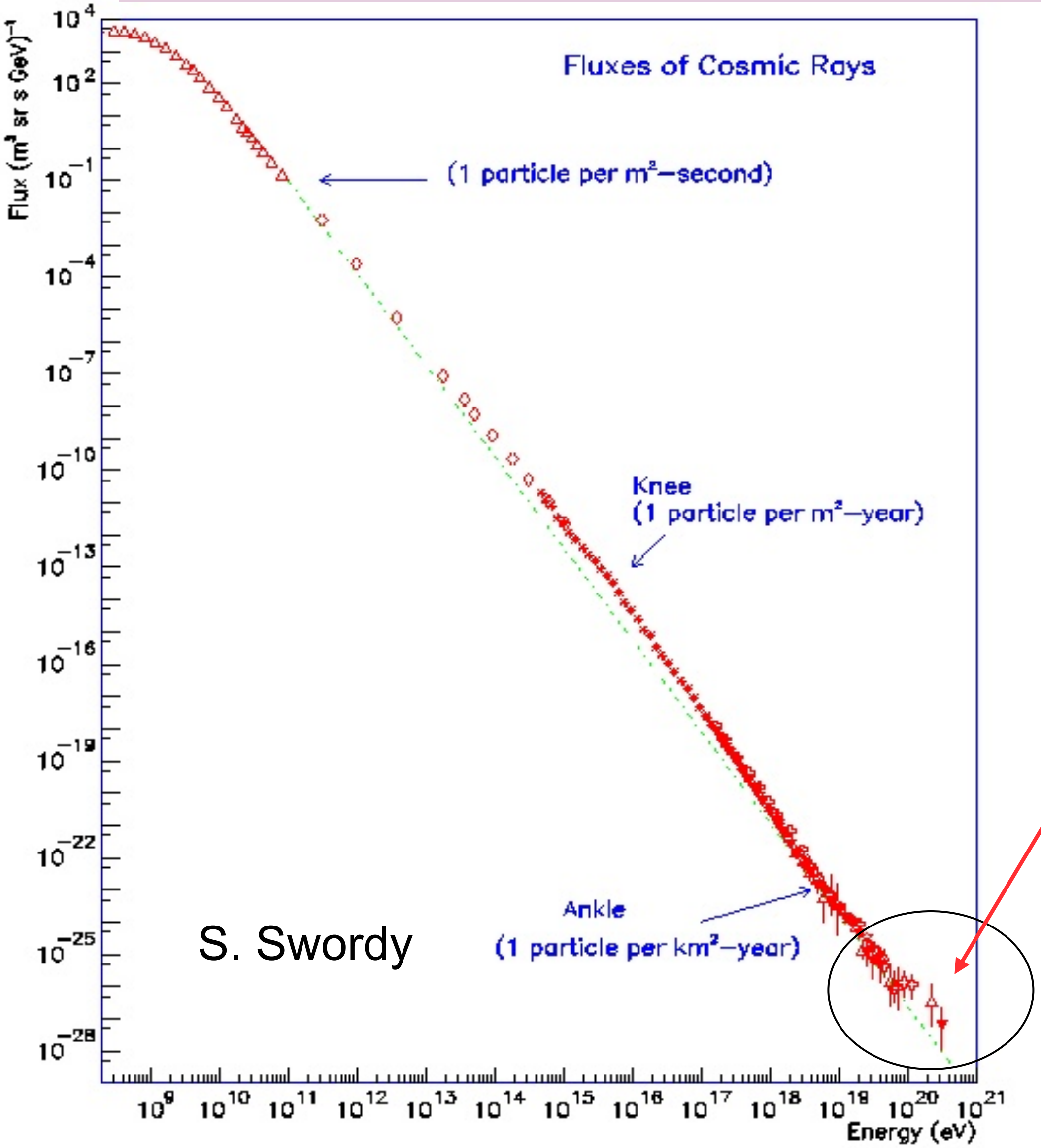
Timing up IceCube

- Send a bipolar down to DOM: “what time do you have?”
- DOM captures local time, waits a bit
- DOM then sends identical bipolar pulse back up: “Here is my local time.”
- From these two pulses + messages, cable length and local time are found: ±2 ns rms

Timing up IceCube

- Send a bipolar down to DOM: “what time do you have?”
- DOM captures local time, waits a bit
- DOM then sends identical bipolar pulse back up: “Here is my local time.”
- From these two pulses + messages, cable length and local time are found: ±2 ns rms
- “Obvious” now, but not so in late 90’s

Cosmic ray flux vs. Energy - megalith #2



S. Swordy

- (nearly) uniform power-law spectrum spanning 10 orders of magnitude in E and 32 in flux!

- structures :

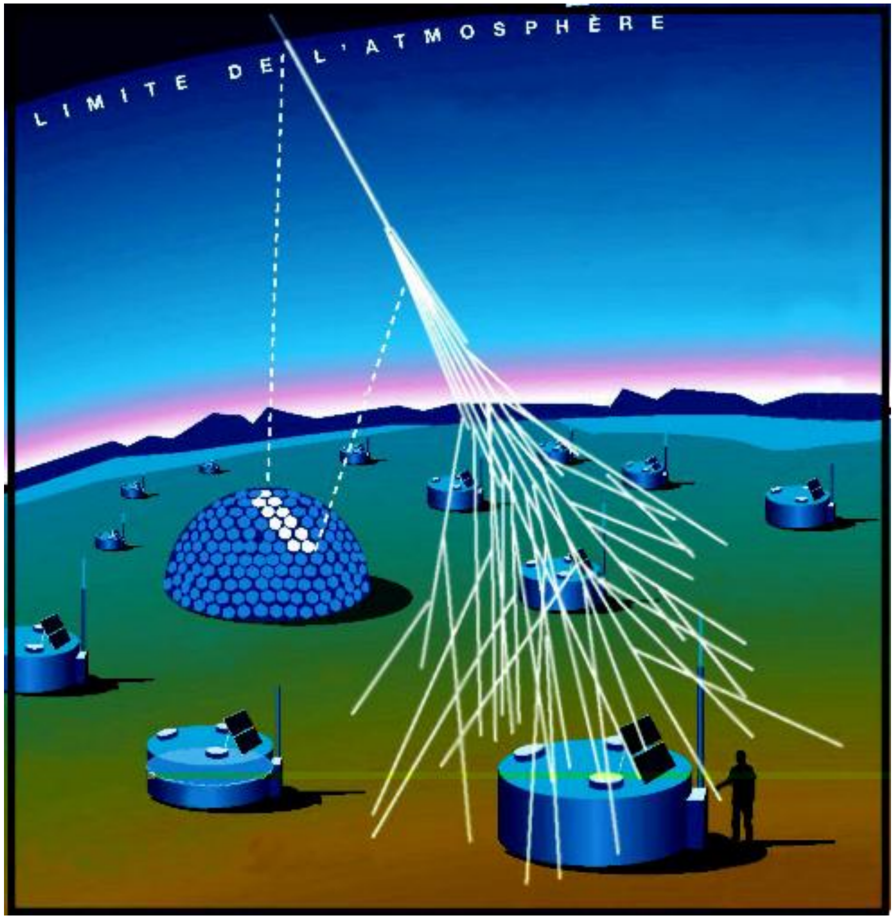
~ 3 – 5 10^{15} eV: knee
change of source? new physics?
~ 3 10^{18} eV: ankle
transition galactic – extragalatic?
change in composition?

UHECR!

- **One particle per century per km^2!**
- Many interesting questions!

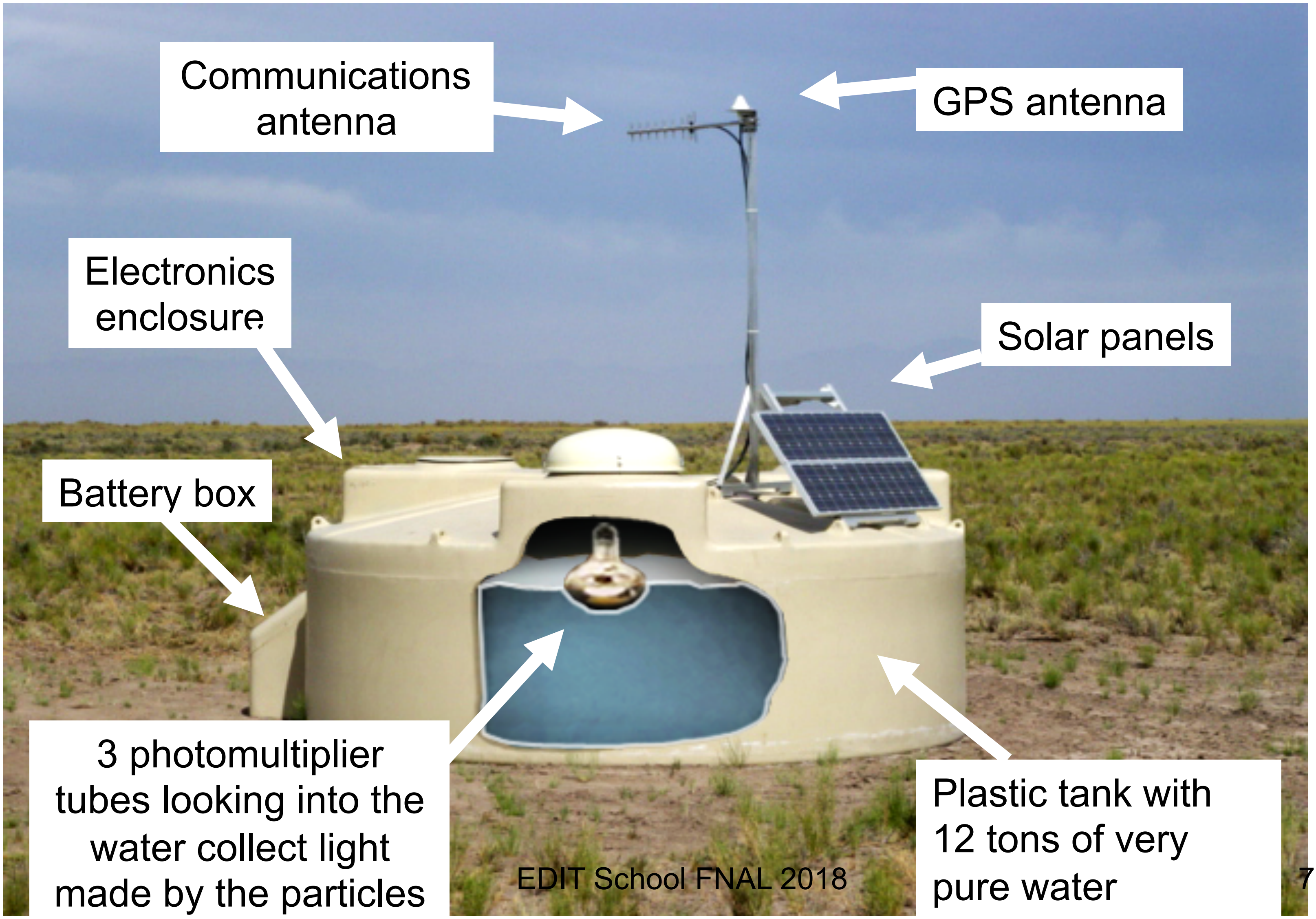
- Pierre Auger Observatory shows how **functional devolution** makes it possible to study rare processes

The Auger Observatory: Hybrid design



- A large surface detector array (1600 water tanks for Cherenkov light) combined with fluorescence detectors results in a unique and powerful design;
- Each tank operates as a stand-alone system for power, timing, and amplitude measurements, relayed by radio to central DAQ
- Simultaneous shower measurement allows for transfer of the nearly calorimetric energy calibration from the fluorescence detector to the event gathering power of the surface array.

Auger surface array station - devolution



Communications antenna

GPS antenna

Electronics enclosure

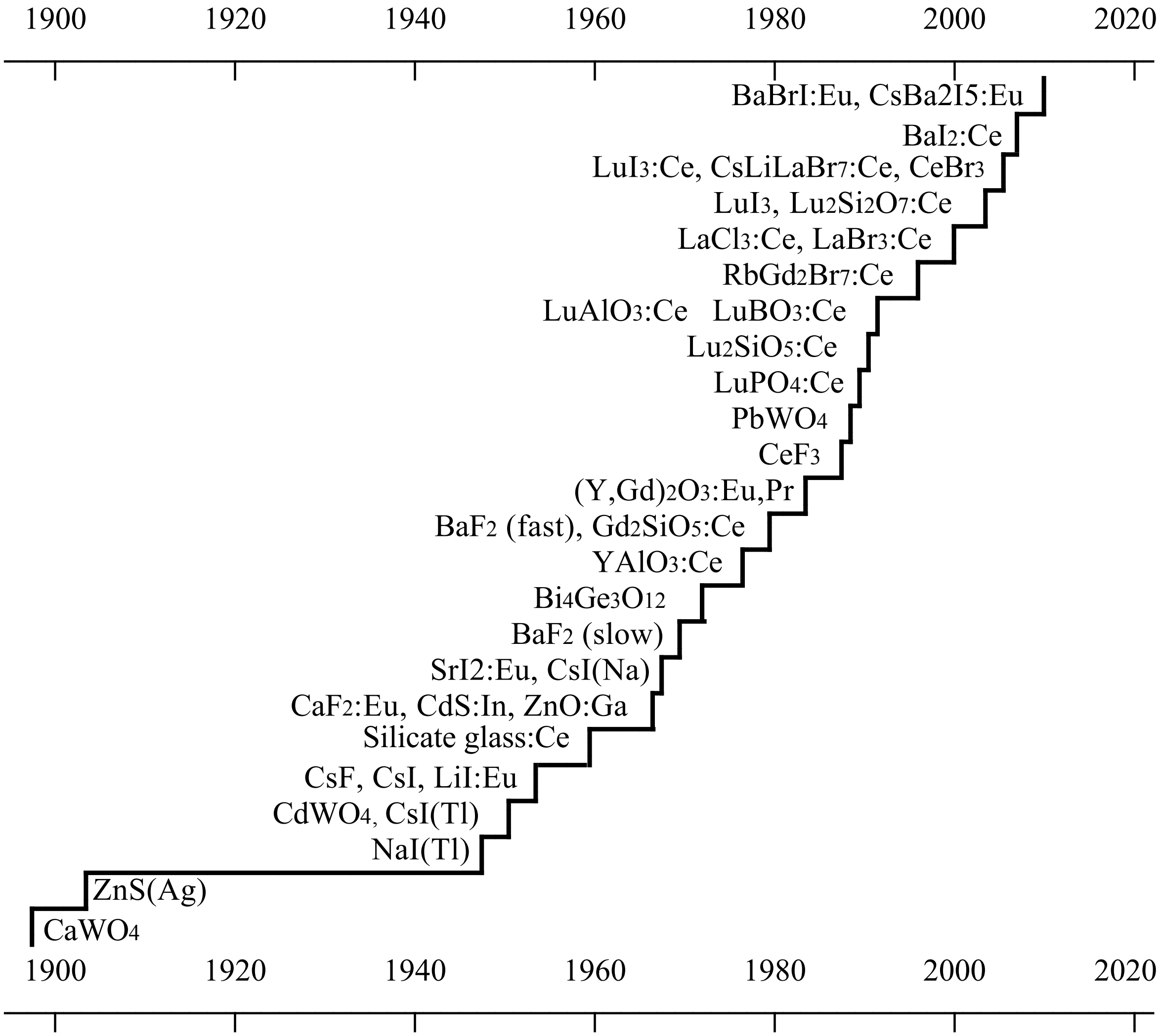
Solar panels

Battery box

3 photomultiplier tubes looking into the water collect light made by the particles

Plastic tank with 12 tons of very pure water

Some History of Scintillation Materials



Hofstadter 1975 “25 Years of Scintillation Counting”

IEEE Trans Nucl Sci NS-22, 13-25, 1975

“For comparative studies of luminescence I prepared several samples of crystalline anthracene, naphthalene, a glaze of NaI(Tl), crystalline KI(Tl), NaCl(Tl), KBr(Tl), CaWO4, etc., and in the dark laid them all on a simple spectroscopic photographic plate nearby each other. Then I put the loaded plate in a thin card- board box after covering the assembly in black paper. I placed a radium source above the samples about one half a meter away and exposed the crystals for about a half hour. I then removed the source, shook off the powders or crystals and then developed and fixed the photographic plate in the usual way. To my great surprise and pleasure, the area under the former position of the NaI(Tl) powder was intensely black while that under the other samples, even under the KI(Tl), was hardly affected. At this point I suspected that I had produced something spectacularly good, but I did not yet know that the NaI (Tl) would scintillate, or produce flashes or pulses with a short decay time. Shortly afterwards I prepared a polycrystalline sample of NaI(Tl) in a 1/2" quartz test tube which was sealed off and protected the NaI(Tl) sample from air so that no deterioration could occur during experimentation or use of the crystal sample.”

BGO: pay attention!

- **Marv Weber working at Raytheon on BGO:Nd laser material.**
- **At that time, Raytheon also interested in x-ray CT.**
- **Marv's best friend worked in the adjacent lab on CT.**
- **BGO placed in x-ray machine, luminescence observed.**
- **Publish paper on "Spectral and Luminescence Properties" in J. Appl. Phys. Only the final paragraph is on x-ray properties.**
- **Marv leaves Raytheon, does nothing more about BGO.**
- **Nestor & Huang at Harshaw read paper, grow BGO, measure scintillation properties, publish in IEEE TNS, …**
- **BGO dominates PET for >25 years.**

Serendipity and LSO

- **Chuck Melcher working at Schlumberger on new scintillators for well logging (fast, high-density, bright).**
- **Notices that P-47 phosphor (Y_2SiO_5:Ce) and GSO scintillator (Gd_2SiO_5:Ce) are fast and bright.**
- **Makes powders substituting Y/Gd with other trivalent atoms, as well as other metals (W, V, Ta,…) for Si.**
- **Bright signal observed in several samples.**
- **Crystals grown of brightest samples.**
- **Very good scintillation properties seen in crystalline LSO.**
- **Light output of first LSO crystals in top 10% of all LSO grown!**
- **All Siemens PET cameras sold since 2003 use LSO.**

Got Lucky on the First Sample!

Serendipity and $LaBr_3$:Ce

- **Derenzo & Moses working at LBNL on scintillator search.**
- **Purchase powder of $LaBr_3$ for testing.**
- **Powder is 99.9% pure.**
- **Remaining 0.1% very likely to have been Cerium.**
- **Material is hygroscopic, but Moses doesn't realize this and doesn't store sample properly.**
- **Sample absorbs water from atmosphere and "melts."**
- **$LaBr_3$ sample discarded, but scintillation properties of 412 other samples are measured.**
- **$LaBr_3$:Ce discovered >10 years later by Delft group.**

Got Unlucky on the First Sample!

Energy resolution ?

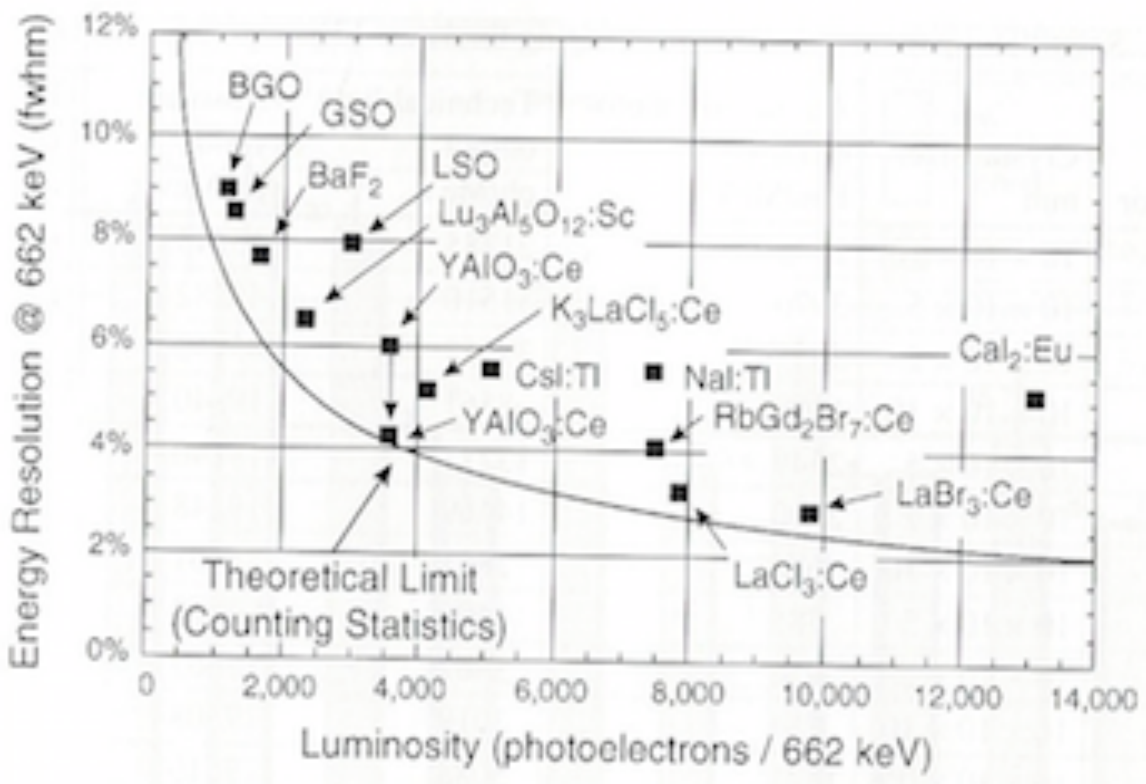


Fig. 5.2 Energy resolution measured for 662 keV γ-quanta vs luminosity of different scintillators for 662 keV excitation. Theoretical estimation – solid curve according to [7]

Energy resolution ?

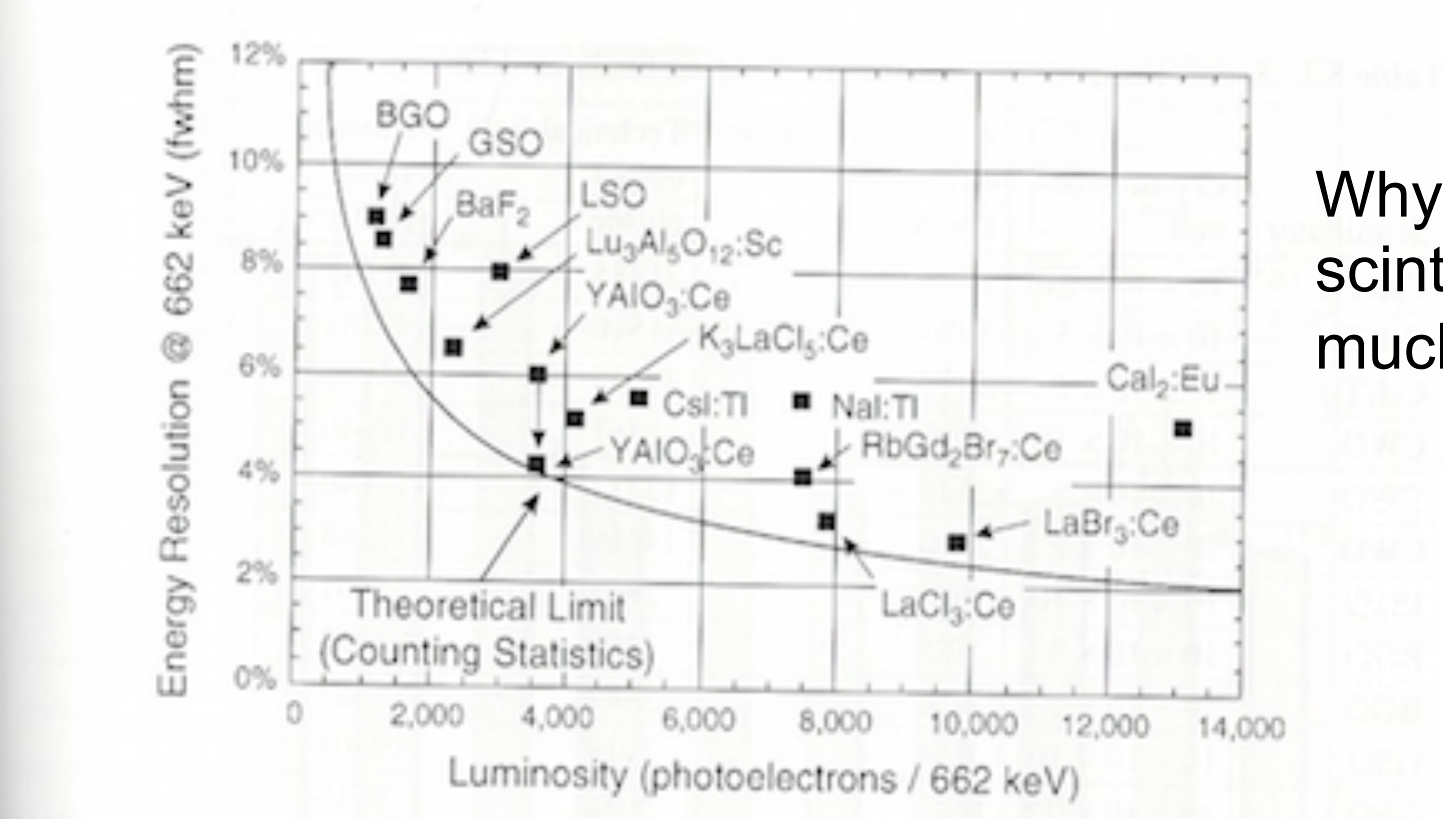


Fig. 5.2 Energy resolution measured for 662 keV γ-quanta vs luminosity of different scintillators for 662 keV excitation. Theoretical estimation – solid curve according to [7]

Why are some scintillators so much worse?

Energy resolution ?

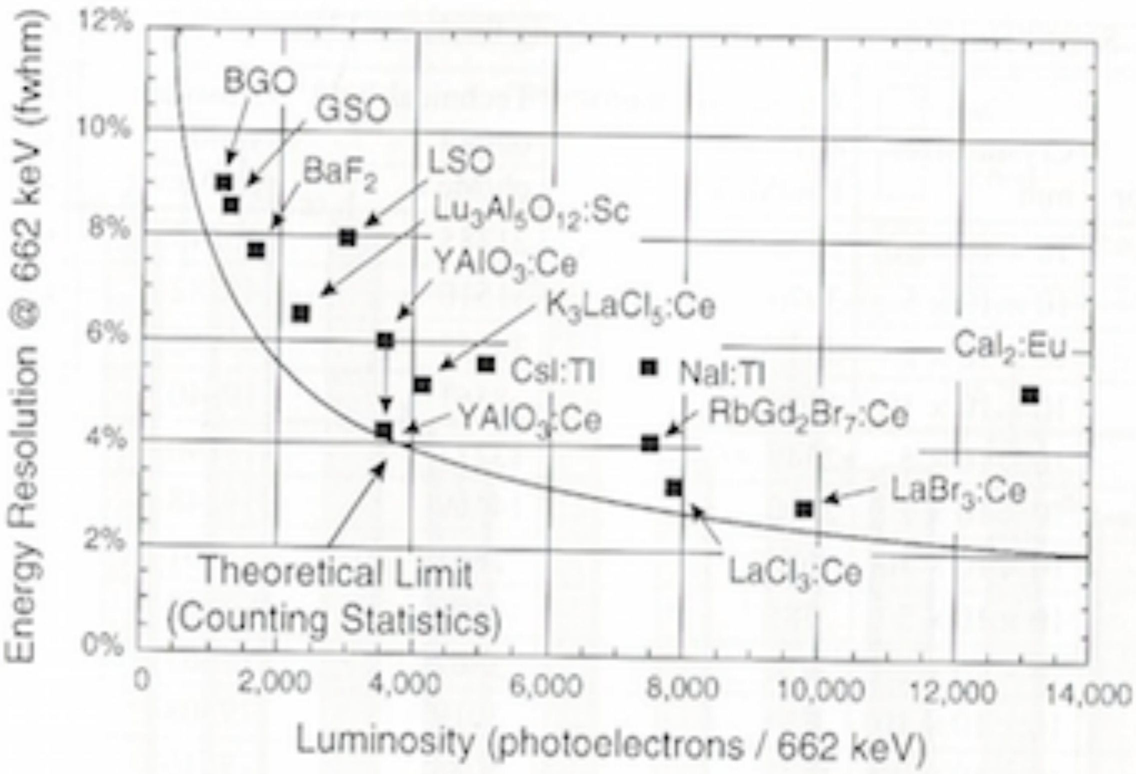
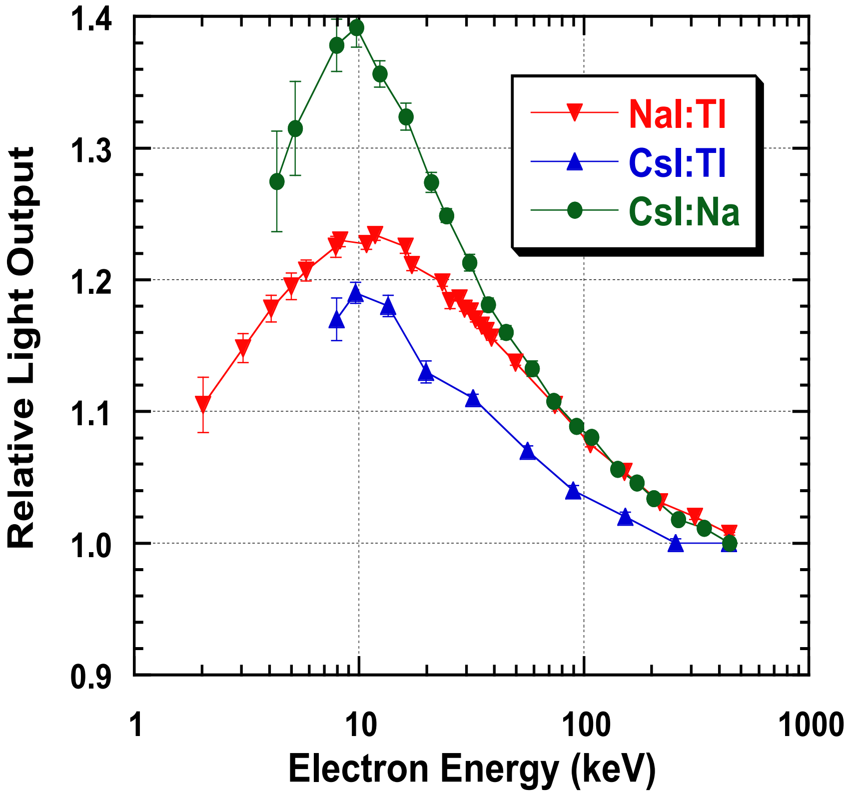


Fig. 5.2 Energy resolution measured for 662 keV γ-quanta vs luminosity of different scintillators for 662 keV excitation. Theoretical estimation – solid curve according to [7]

Why are some scintillators so much worse?

Is there an opportunity here?

Non-Proportionality— Light Output per keV Depends on Energy

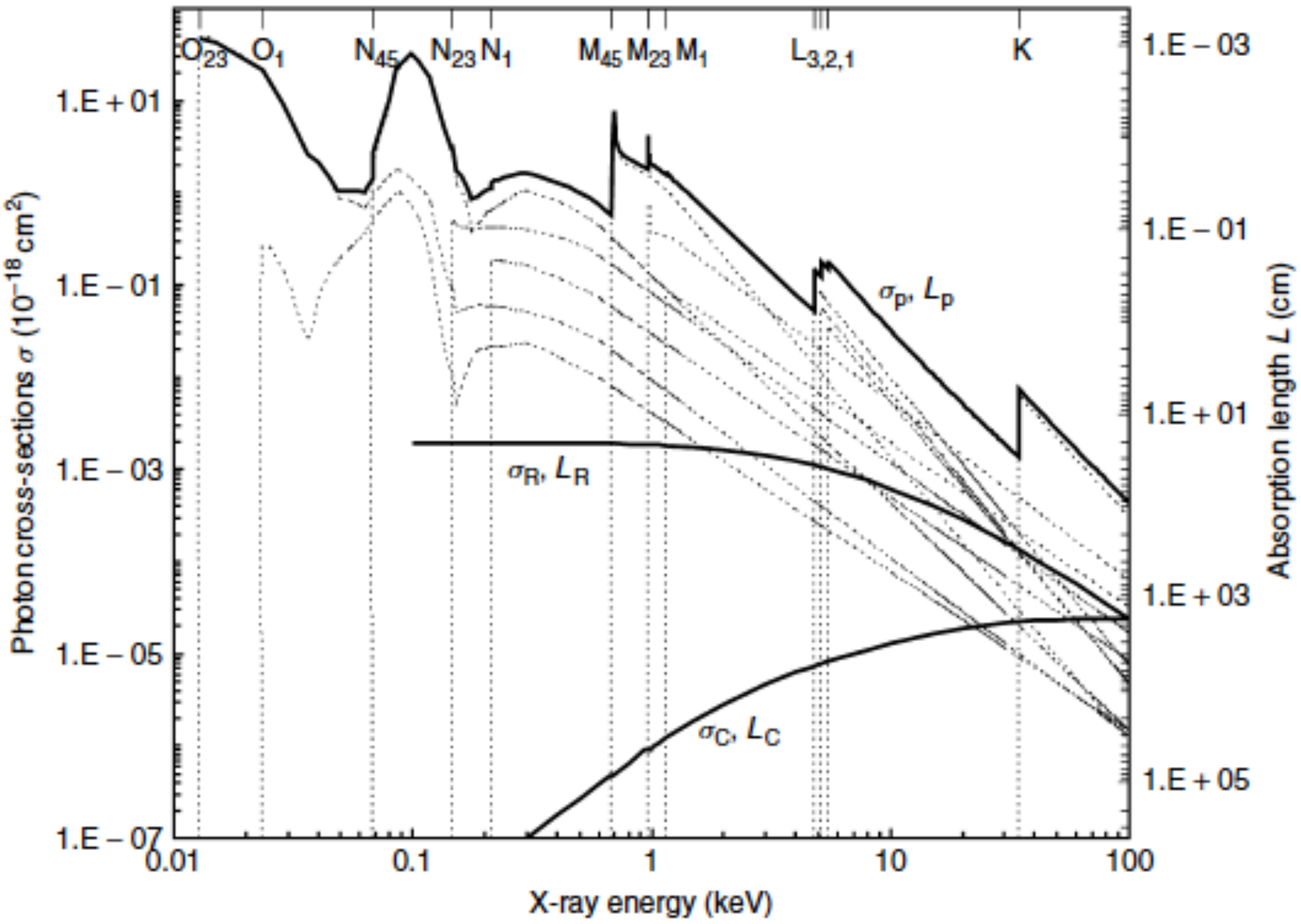


Ideal Scintillator Would Be a Horizontal Line

What's going on here?

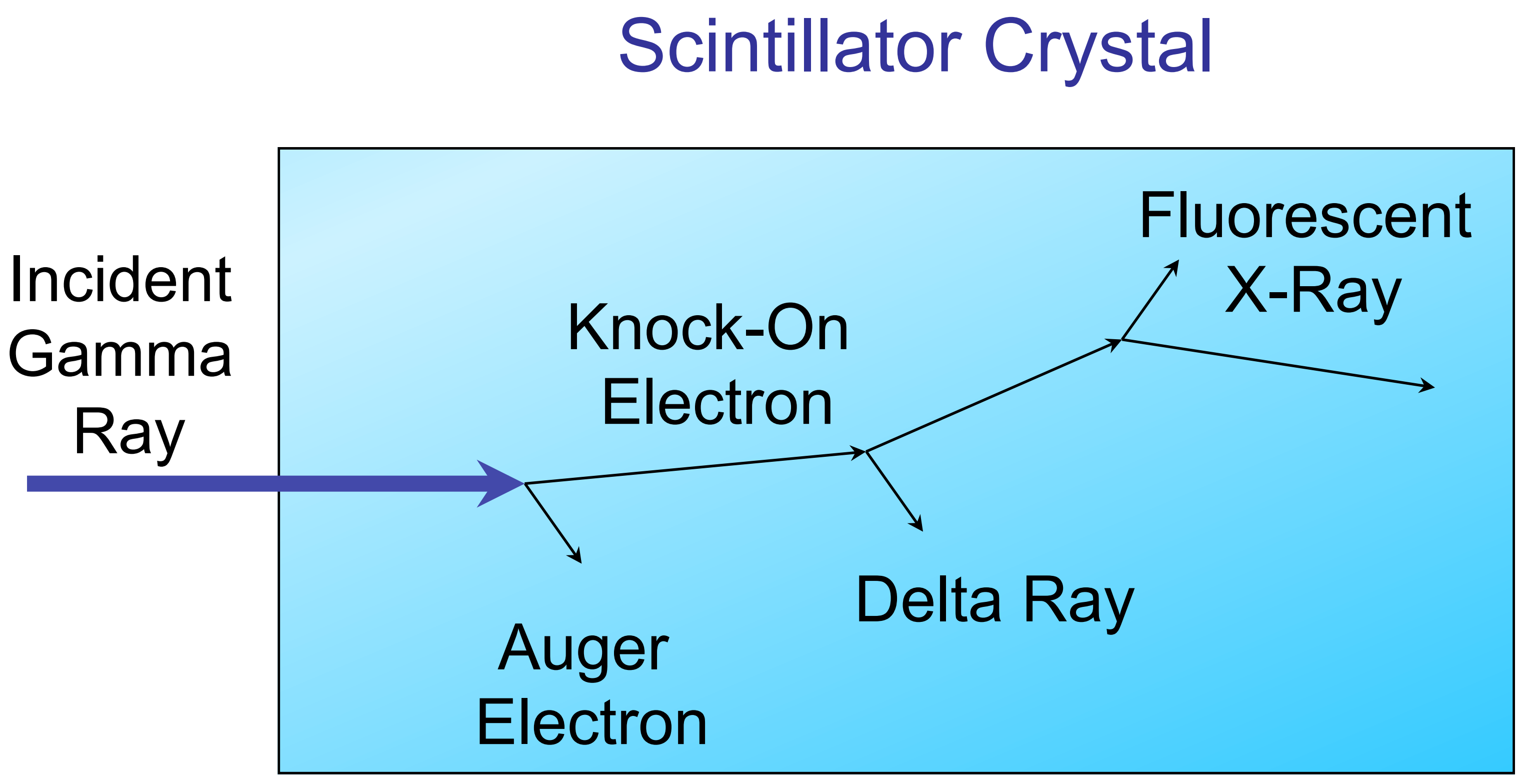
- *W. Mengesha, T. Taulbee, B. Rooney and J. Valentine, IEEE Trans. Nucl. Sci. NS-45, pp. 456-461, 1998.*

GAS PROPORTIONAL SCINTILLATION COUNTERS FOR X-RAY SPECTROMETRY



Credit: C. A. N. Conde

Non-Proportionality Degrades Energy Resolution



Several Energetic Electrons Are Produced
(different photons/MeV ⇒ different total # photons)

Atomic processes in xenon

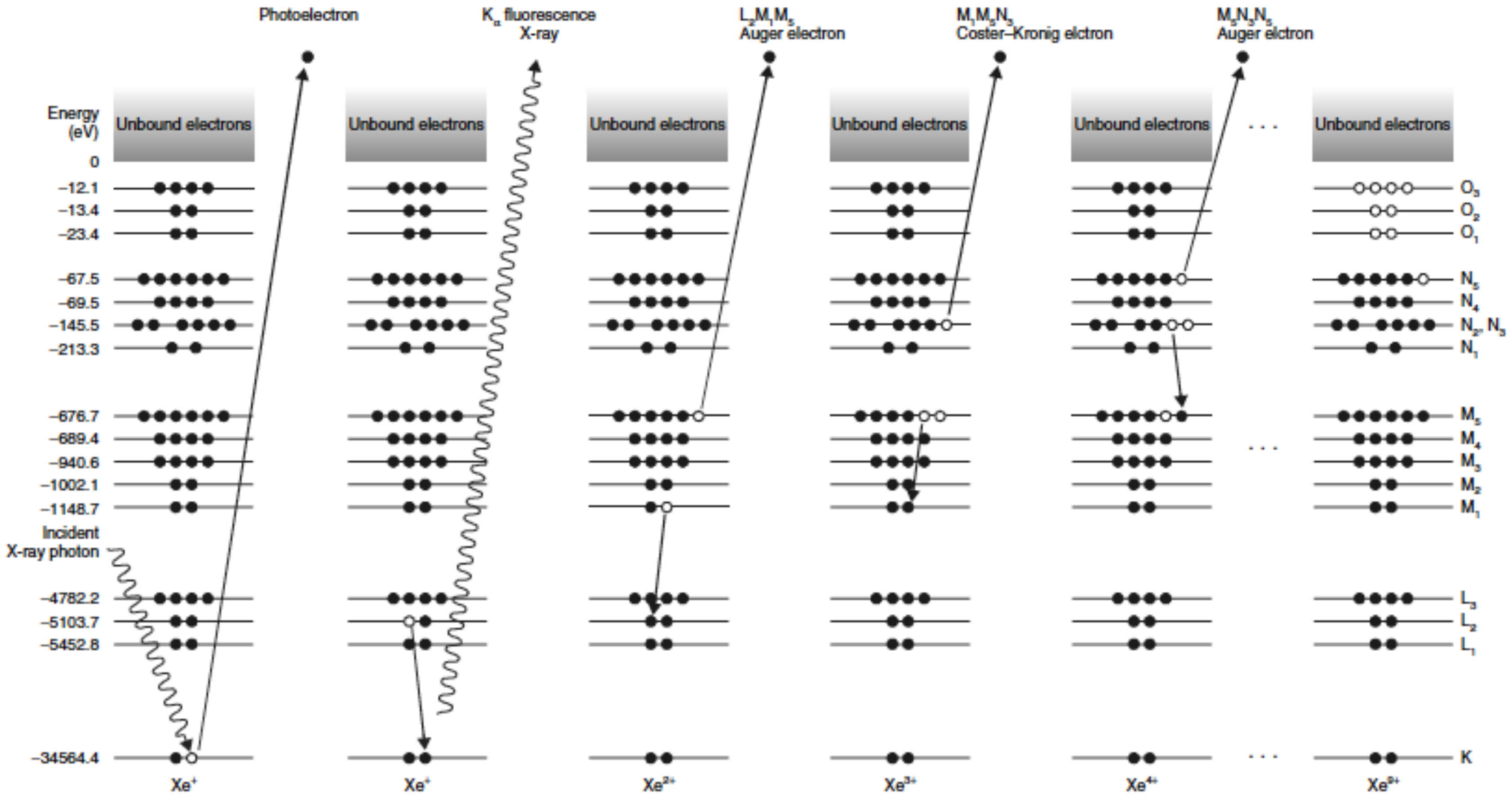


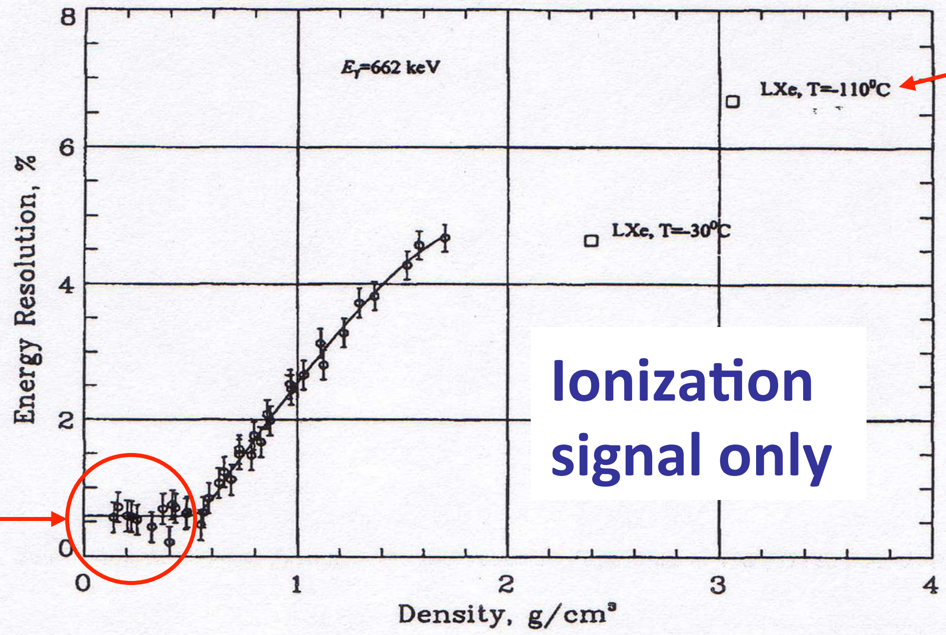
Figure 4.2.4 Typical decay cascade of a Xe^+ ion following the photoionization of a K shell in Xe. (Binding energies taken from http://ie.lbl.gov/atom.htm)

THE PHYSICS OF THE ABSORPTION OF X-RAYS IN GASES

Credit: C. A. N. Conde

Xenon: Strong dependence of energy partition fluctuations on density!

A. Bolotnikov, B. Ramsey / Nucl. Instr. and Meth. in Phys. Res. A 396 (1997) 360–370



Ionization signal only

Here, the fluctuations are <u>normal</u>

Large fluctuations between light/charge at LXe density

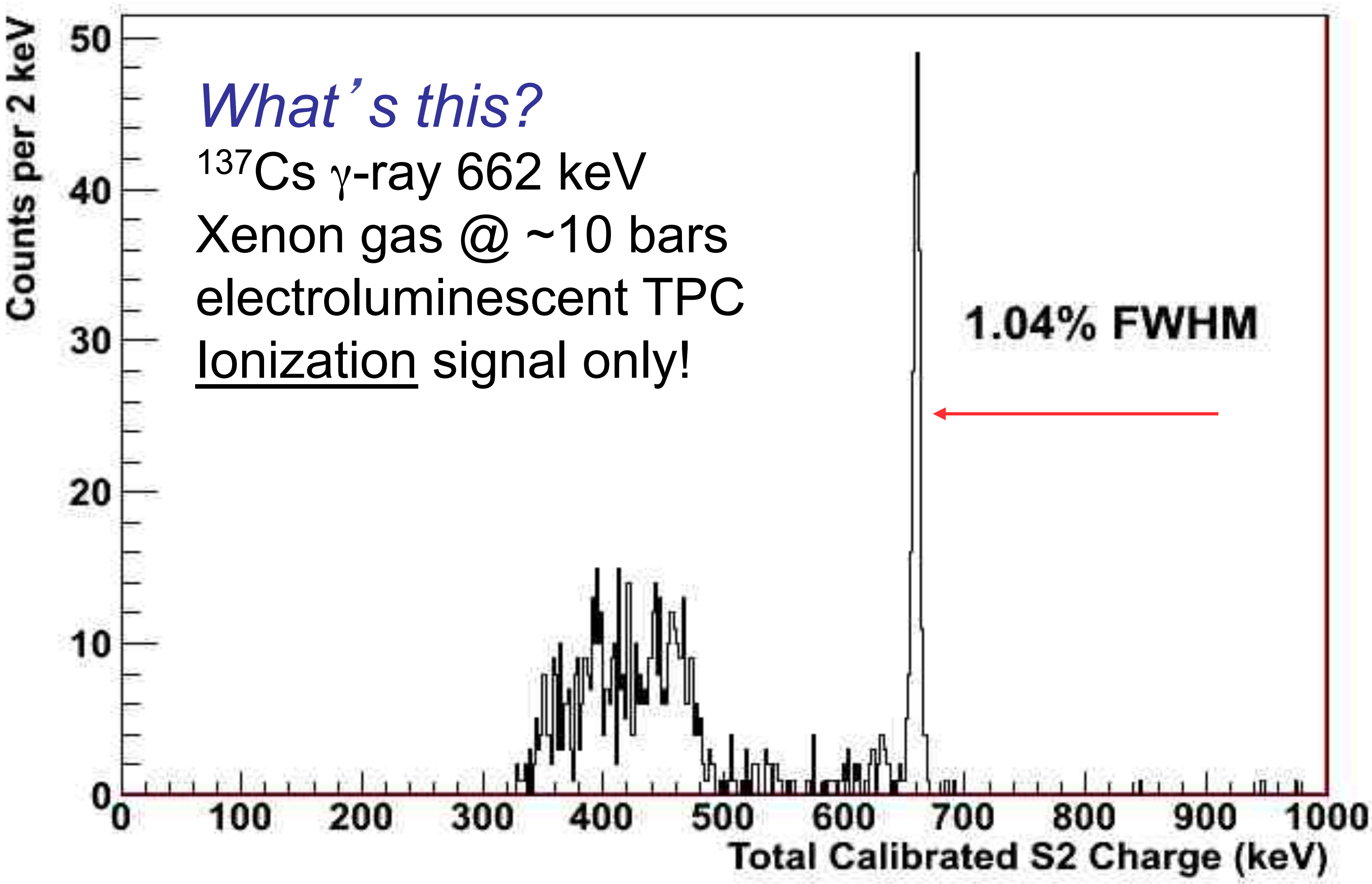
⇒

DM: S2/S1 suffers!

Fig. 5. Density dependencies of the intrinsic energy resolution (%FWHM) measured for 662 keV gamma-rays.

For ρ <0.55 g/cm^3, ionization energy resolution is "intrinsic"

Energy resolution in xenon - rather nice!



What's this?

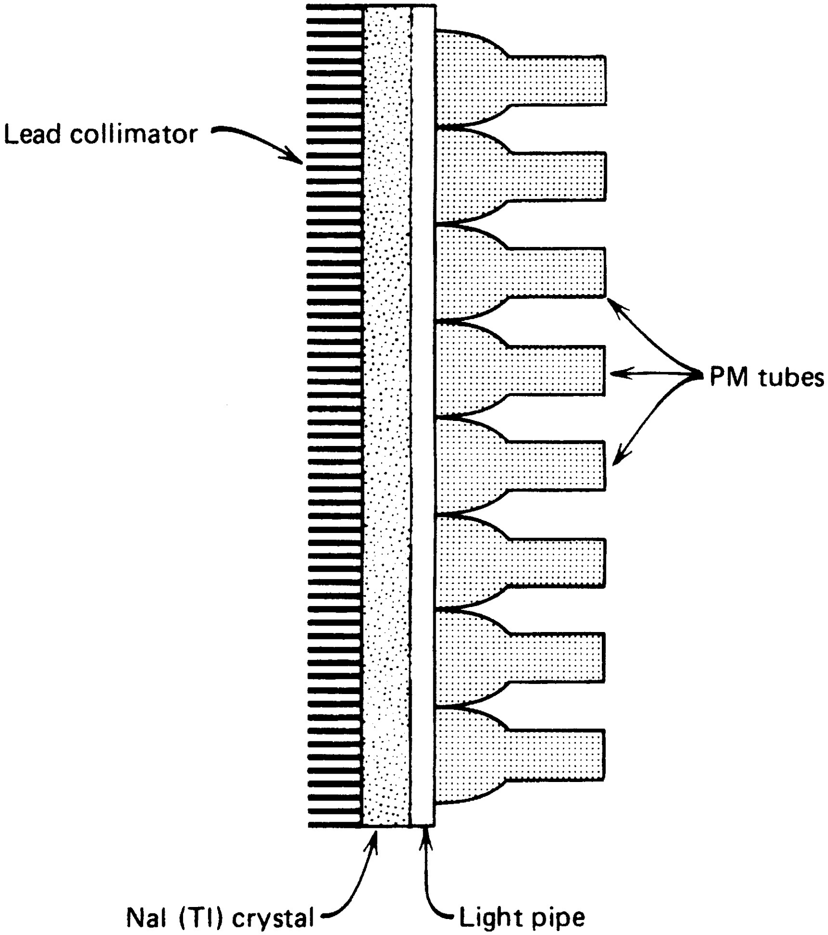
^{137}Cs γ-ray 662 keV

Xenon gas @ ~10 bars

electroluminescent TPC

Ionization signal only!

Scintillation: Gamma Camera

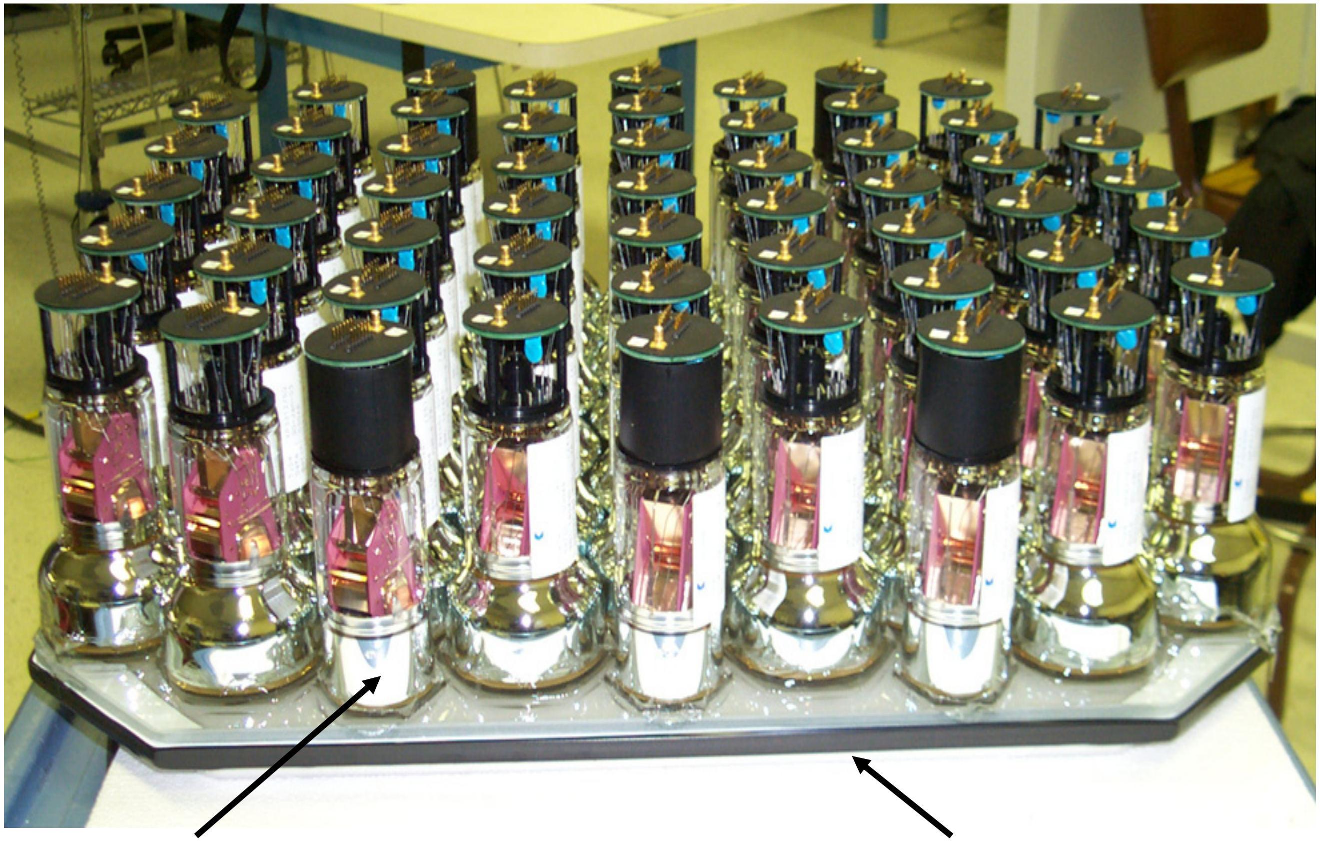


Elements of a two-dimensional position-sensitive scintillation detector, commonly called a gamma camera.

Developed by Hal Anger during the 1950's at the E.O. Lawrence "Rad Lab" (now called LBNL)

This "Anger Scintillation Camera" can be found in almost every hospital in the world. Used with ^{99m}Tc for brain imaging and ^{201}Tl for heart imaging.

Anger Camera



Photomultiplier
Tubes

Scintillator
Crystals
(NaI:Tl)

Image: L. Shao, Philips Medical Systems

PET Detector with PMTs

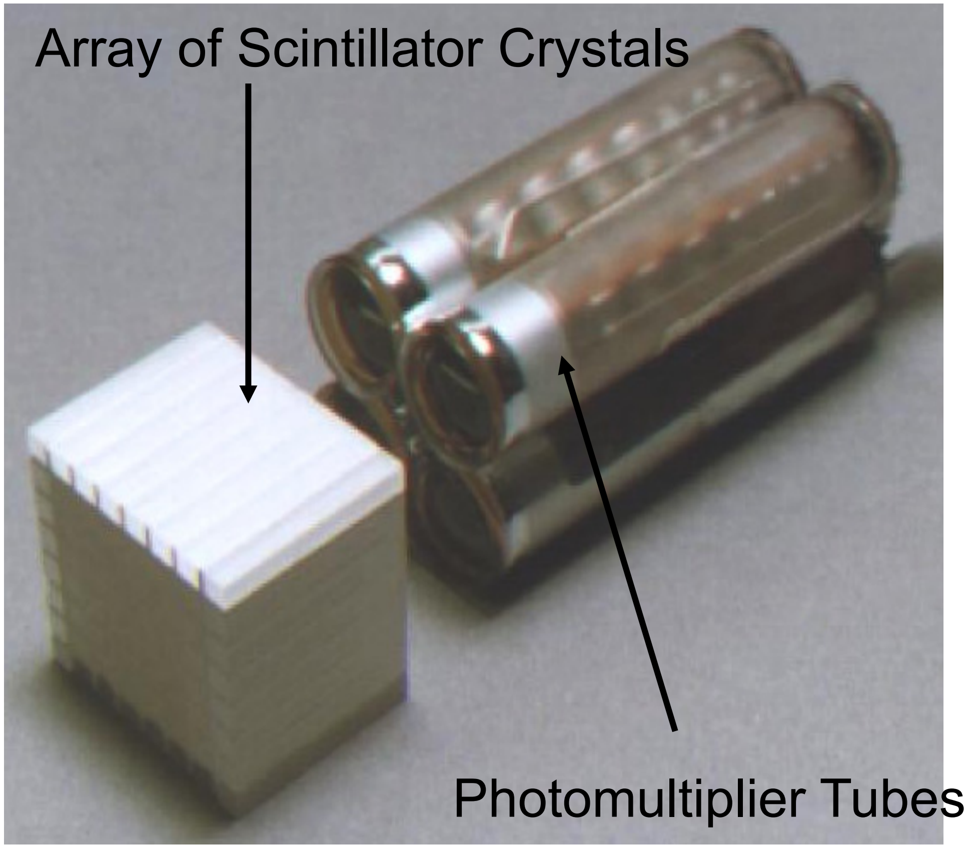


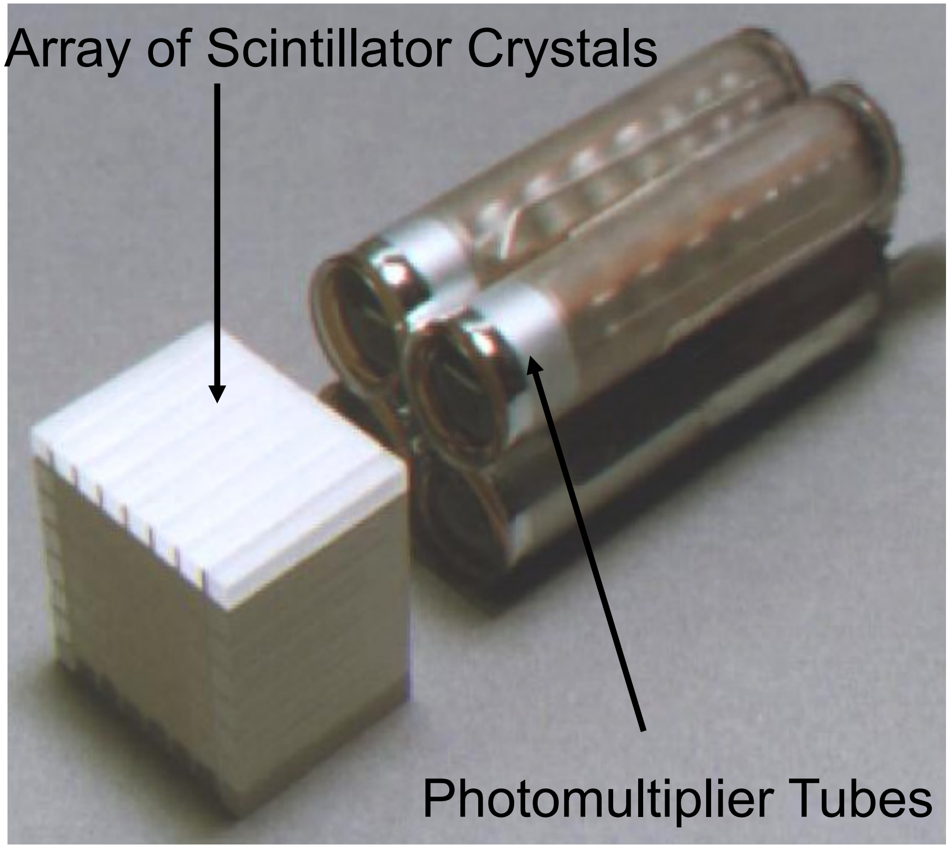
*Image courtesy of M. Casey, CPS Innovations

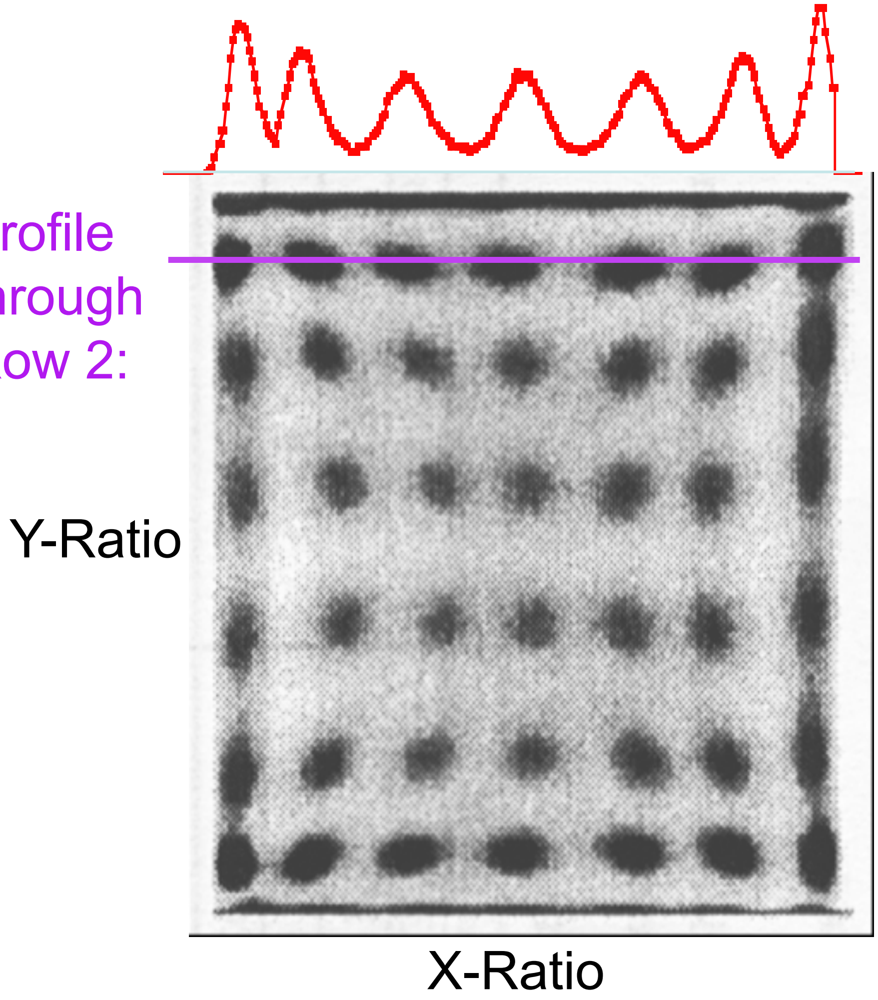
At 511 keV:

- High Efficiency (>85%)
- High Spatial Resolution (<5 mm)
- Low Cost (<\$100/cm^2)
- Short Dead Time (<1 μs cm^2)
- Good Timing Resolution (<5 ns fwhm)
- Good Energy Resolution (<100 keV fwhm)

Based on BGO or LSO “Block Detector”

Crystals Identified with Anger Logic




Profile through Row 2:

Can Decode Up To 64 Crystals with BGO

Another medical application!

Philips Micro-Dose System

First true photon-counting mammography system in every-day clinical use.

Based on **slot-scan** geometry with **edge-on silicon-strips** for high x-ray detection efficiency.

Factor of >3 less dose !

Developed at LBNL, then commercialized by Sectra, Sweden, (system now owned by Phillips). In use all over world; FDA approval in USA delayed until recently…

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I didn’t get the patent! **RATS**!

Bottom line - history...

- Why were some good ideas grasped so slowly?
- Easy pickings gone? - *Maybe*...
- Serendipity gone? - I don't think so!
- Where's the next great opportunity? ... your task!
- Know something beyond your computer screen…
- Find and befriend your exceptional rare engineer
- Pay attention to the weird stuff you encounter !

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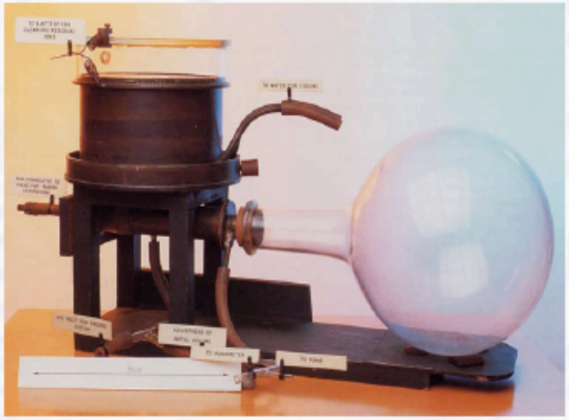
Over to you !

Thank you

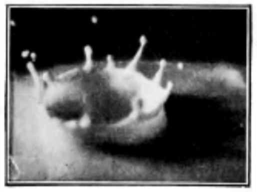
Cloud Chamber I

- **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

Charles T. R. Wilson

- **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

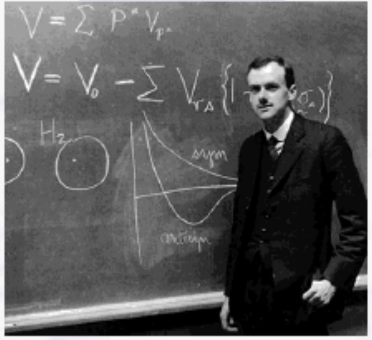


- **First photographs of α–ray particles 1912**

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)

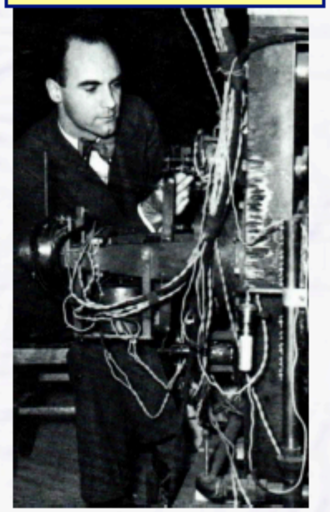
Paul Dirac



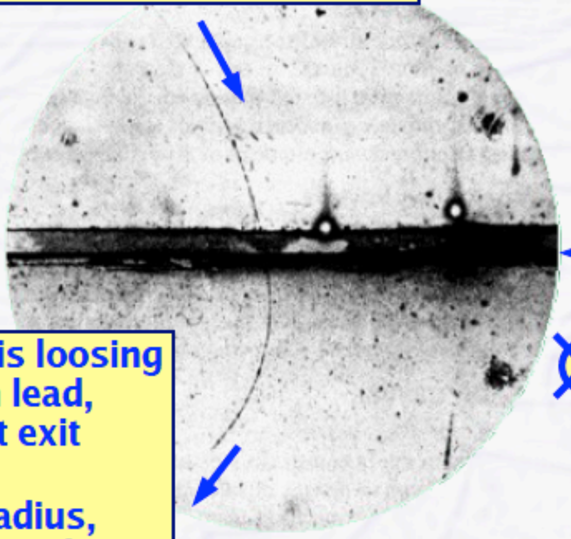
Anderson also found the muon in 1936, the first 2nd generation particle in the Standard Model

Isidor Isaac Rabi said:
“Who ordered that?”

Carl D. Anderson



downward going positron, 63 MeV



6 mm lead plate

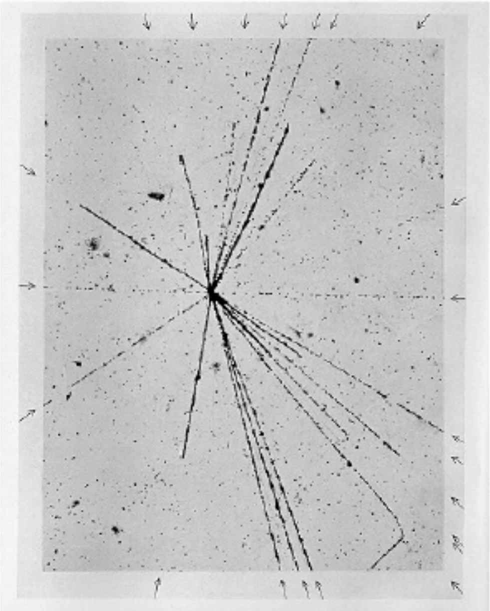
⊗ **1.5 T magnetic field**

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

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

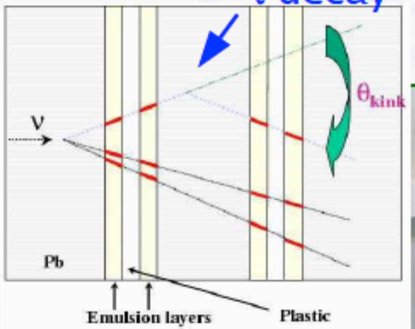
- Since early 20th century
  - important role of photography to study radioactivity
  - but capability to make individual tracks visible not seen until nuclear emulsion technique was developed

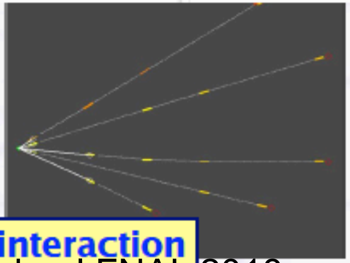
Nuclear Emulsion III

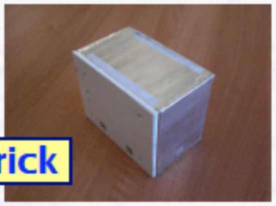

CNGS beam

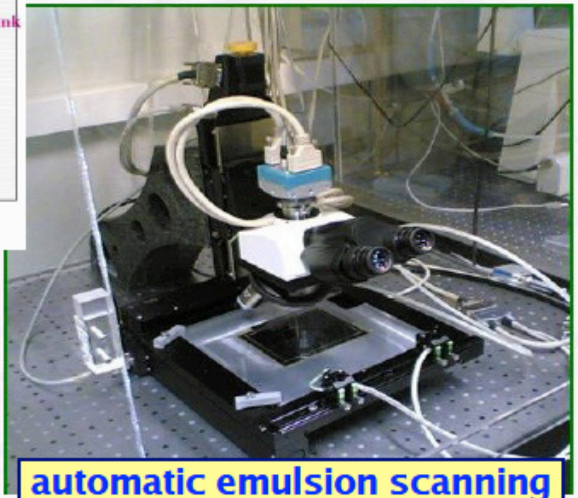
- Still used in actual experiments with highest precision requirements over a large volume
  - ν_μ beam sent from CERN to Gran Sasso Underground lab in Italy (732 km)
  - OPERA experiment is searching for ν_τ appearance after neutrino oscill. $\nu_\mu \rightarrow \nu_\tau$
    - need to reconstruct τ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

OPERA at Gran Sasso



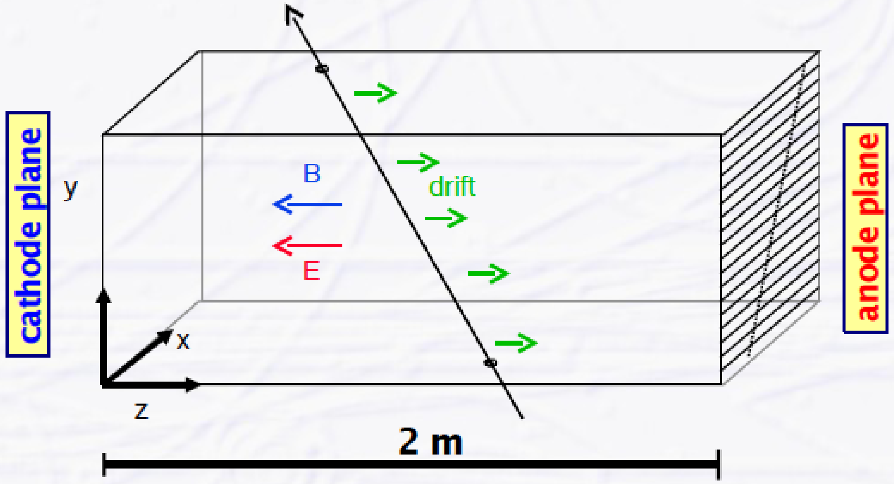

ν_μ interaction

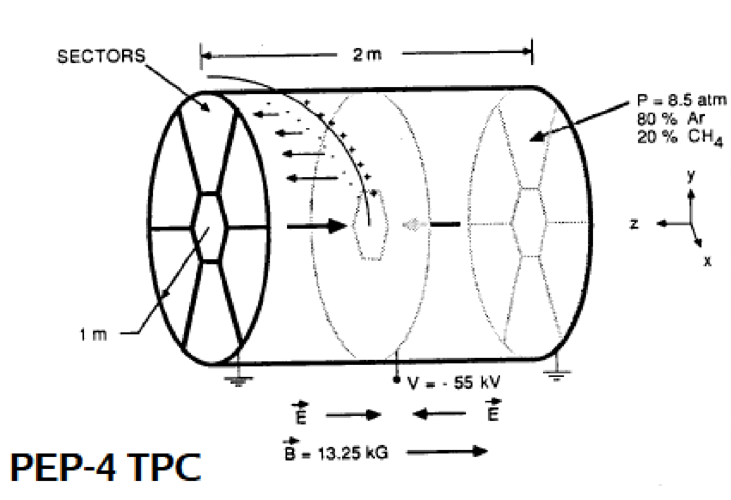

single brick


automatic emulsion scanning

Time Projection Chamber (TPC)

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



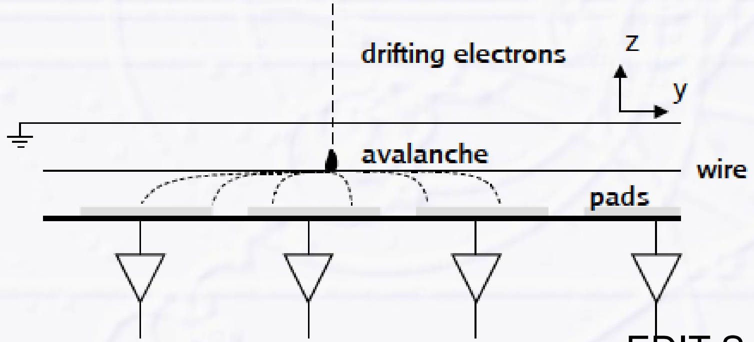


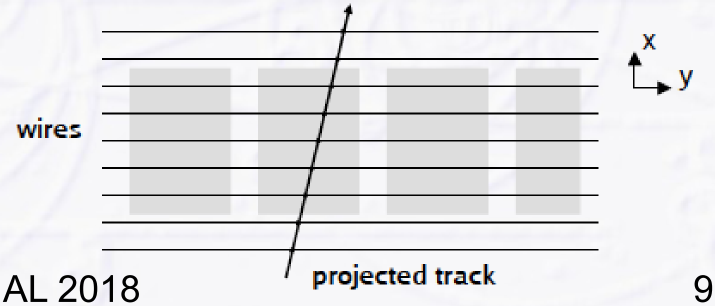
PEP-4 TPC

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

Problem: pads have to be large (otherwise not enough induced charge)

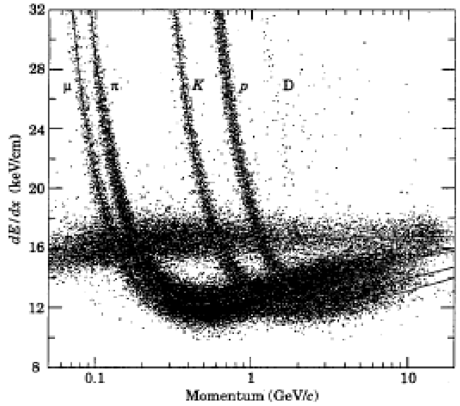
Limits number of points and double track resolution



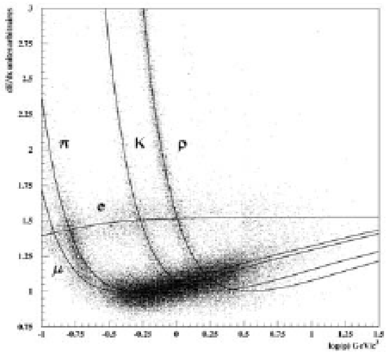


dE/dx performance

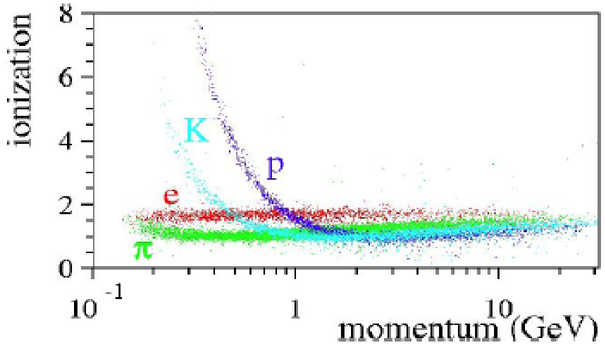
LBL TPC:



DELPHI TPC:

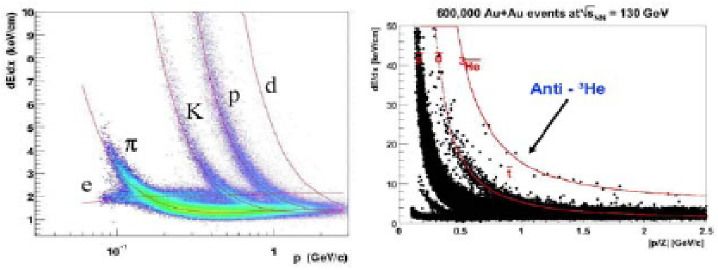


ALEPH TPC:

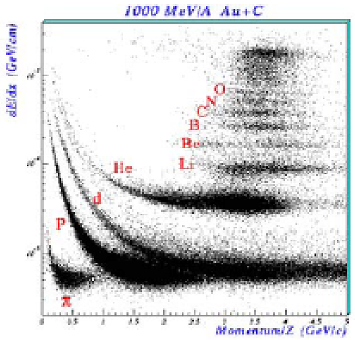


STAR TPC

Clean events: Au-Au:



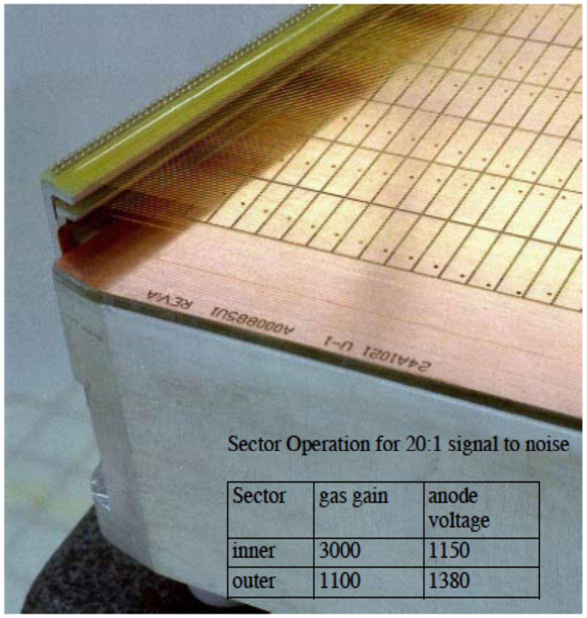
EOS TPC:



- **The LBL TPC performance at 8.5 bars is still the best in the non-relativistic region.**
- However, high pressure does not help at higher momenta, as the density effect reduces the height of the relativistic plateau.

Detecting plane in STAR TPC

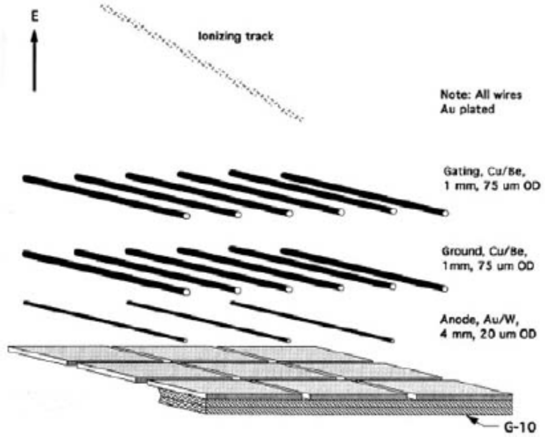
J.Thomas, 2003



Sector Operation for 20:1 signal to noise

Sector	gas gain	anode voltage
inner	3000	1150
outer	1100	1380

- **Gating Grid**
- **Ground Plane of Wires**
- **Anodes**



- **Advantage of wires: reliability and a good dE/dx**
- **Disadvantage: a large ExB contribution to resolution due to wires & pads (new micro-pattern detectors will not have the 2-nd term):**

$$\sigma^2_{\mathrm{resol}} \approx \frac{1}{N(h, w, b, \sigma_{\mathrm{single}})}\,\frac{\sigma^2_{\mathrm{single}}}{\cos^2\alpha} + \boxed{\frac{b^2(\tan\theta - \tan\psi)^2\cos^2(\theta-\alpha)}{12\,N_{\mathrm{eff}}(h, w, b, \sigma_{\mathrm{single}})}}$$

dE/dx

Parameter	LBL	ALEPH	DELPHI	STAR	ALICE	Na-49
Gas	80/20 Ar/CH_4	91/9 Ar/CH_4	80/20 Ar/CH_4	90/10 Ar/CH_4	85/10/5 Ne/CO_2/N_2	90/5/5 Ar/CO_2/CH_4
Gas pressure [bars]	8.5	1	1	1	1	1
Number of samples	185	330	192	210	~430	<185
Sample length [mm]	4	4	4	4	4-6	38
σ(dE/dx) [%]	2.7	4.5	6	7.5	5-7	~4.7

Top 5 Candidates vs. NaI(Tl)

Crystal	**$LaBr_3$:Ce**	**$Cs_2LiLaBr_6$:Ce**	**SrI_2:Eu**	**Ba_2CsI_5:Eu**	**BaBrI:Eu**		**NaI(Tl)**
Structure	Hexagonal	Cubic	Orthorhombic	Monoclinic	Orthorhombic		Cubic
Band Gap	6.2 eV	5.8 eV	5.4 eV	5.1 eV	5.3 eV		5.9 eV
Density	5.1	4.2	4.5	5.0	5.0		3.67
Decay time	17 ns	55 ns	1,200 ns	1,400 ns	500 ns		230 ns
Luminosity (ph/MeV)	60,000	60,000	100,000	97,000	87,000		42,000
Energy resolution @ 662KeV	2.8% (Delft)	3.0% (RMD)	3.0% (LLNL)	3.8% (LBNL)	4.3% (LBNL)		6-7%
Detection efficiency*	30%	26%	31%	36%	35%		23%