# The Art of Experiment and the Pace of Discovery in Particle Physics

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# A history... selective & biased

- A personal perspective on this fascinating story
  - *emphasis: opportunities, found and missed* –

- This limited review must leave out some good items
  - scintillators, silicon devices, photodetectors, ASICs, …

- Acknowledgment: slides borrowed from
  - **Michael Hauschild, 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, systems, networks, collaborations…

# "Image & Logic"

- At the beginning, ***imaging*** techniques dominated, persisting into the 2000's
  - we will look at those first

# "Image & Logic"

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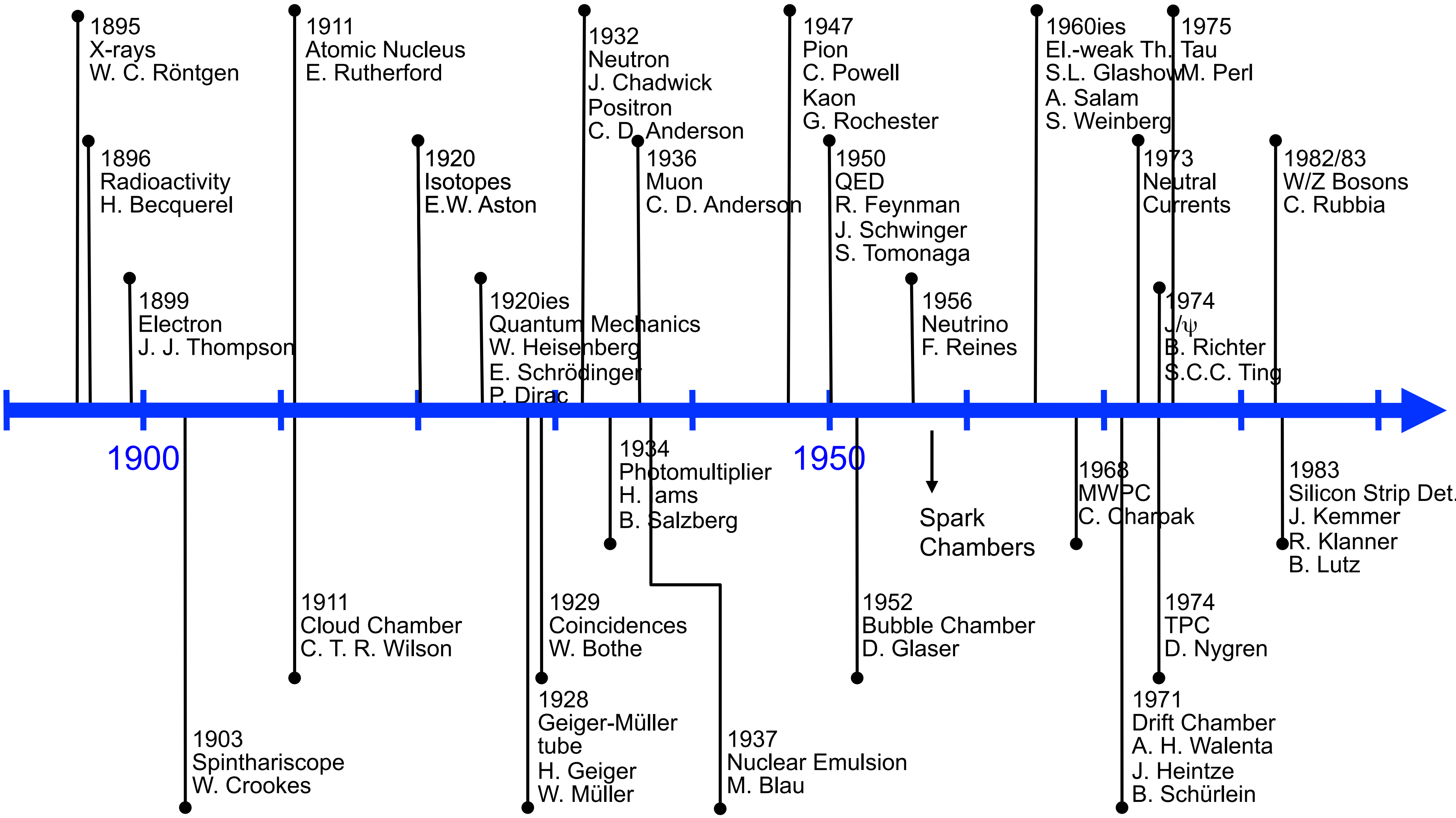
  - we will look at those first
- Even from an early time, ***electronic*** ideas emerged, kindling further progress
  - today, electronic techniques dominate

# Timeline of Particle Physics and Instrumentation



# Signals $\Rightarrow$ Physical information

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

- Energy
- Momentum
- Velocity
- Trajectory direction
- Particle type
- Charge
- Patterns
- Causality
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**Common principle: physical gain mechanism**

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**Common enemies: intrinsic noise or backgrounds**

# Spinthariscope -1903

## large energy deposit + sensitive eye = detection

- In 1903, William Crookes spills expensive radium salt accidentally on a Zinc Sulfide screen
- Eager to recover it, he looks at the screen under a microscope…
- Crookes notices flashes of light !
- Crookes invents ***Spinthariscope***, from the Greek word "spintharis", meaning "spark" ….

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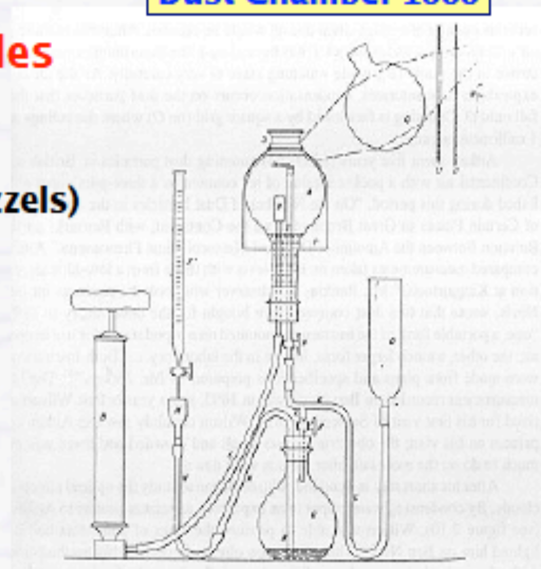
- Crookes invents ***Spinthariscope***, from the Greek word “spintharis”, meaning “spark” …
- **But my glow-in-the-dark wrist watch showed these flashes too !**

# Early Image Detectors

- Second half of 19$^{th}$ 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

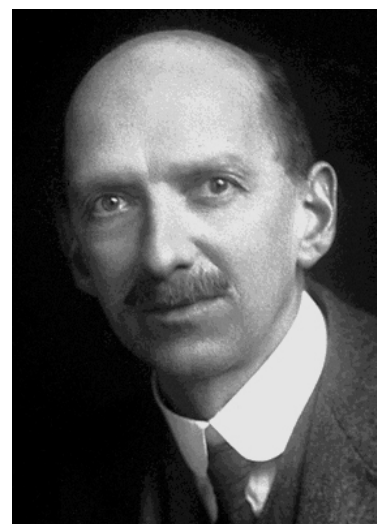
Dust Chamber 1888



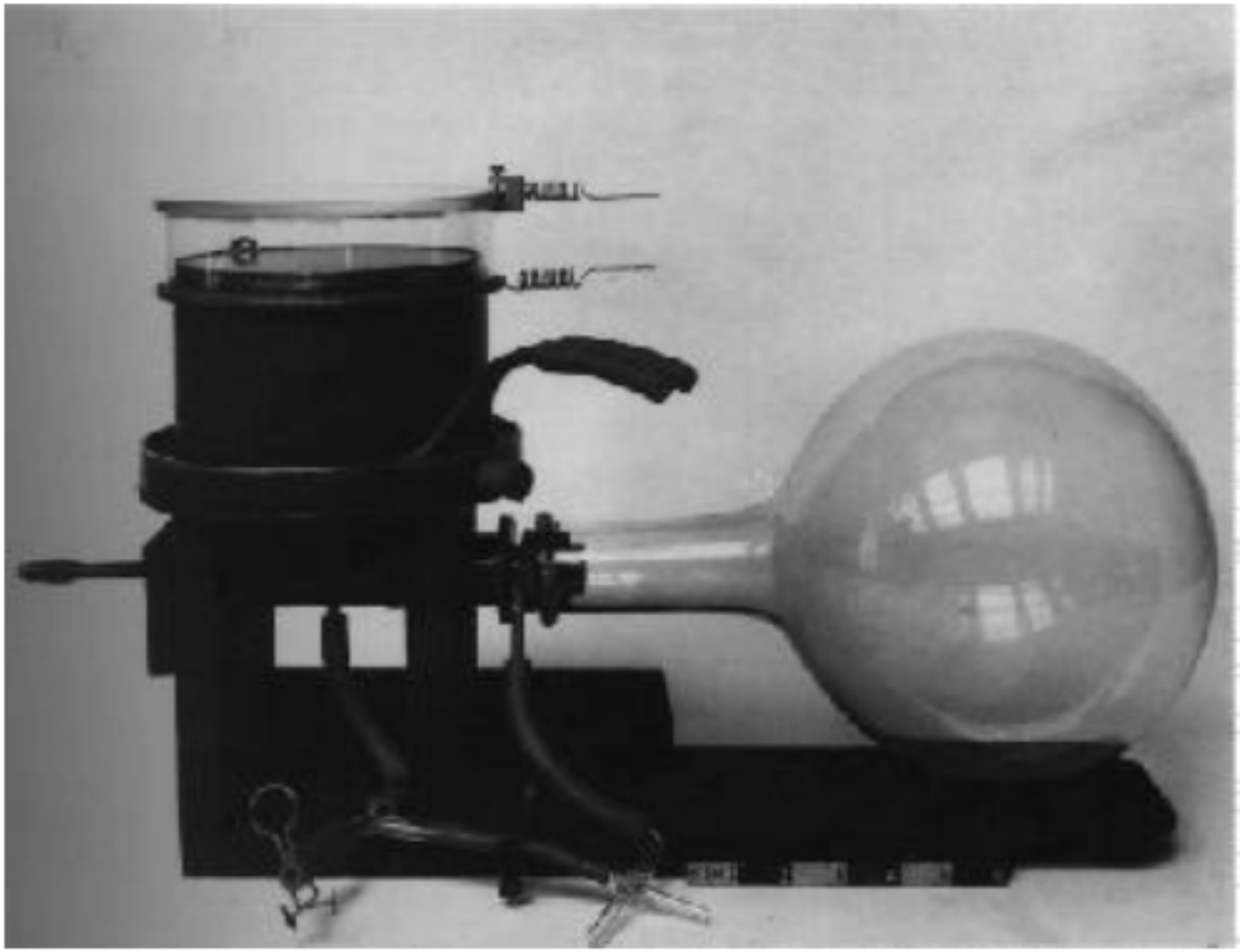
# C.T.R. Wilson and his Cloud Chamber

- Wilson was a Scottish meteorologist at the Cavendish Labs
- He was fascinated by clouds in the Highlands: the 'Brocken Spectre'

- Wilson builds a chamber to play with purified air, with changes in dust, pressure, temp, etc.
- He finds that vapors condense around ionization when pressure ↓ & volume becomes supersaturated
- **Cloud chambers were productive for a long time, even into the 60's**



# Cloud Chamber



Wilson Cloud Chamber 1911

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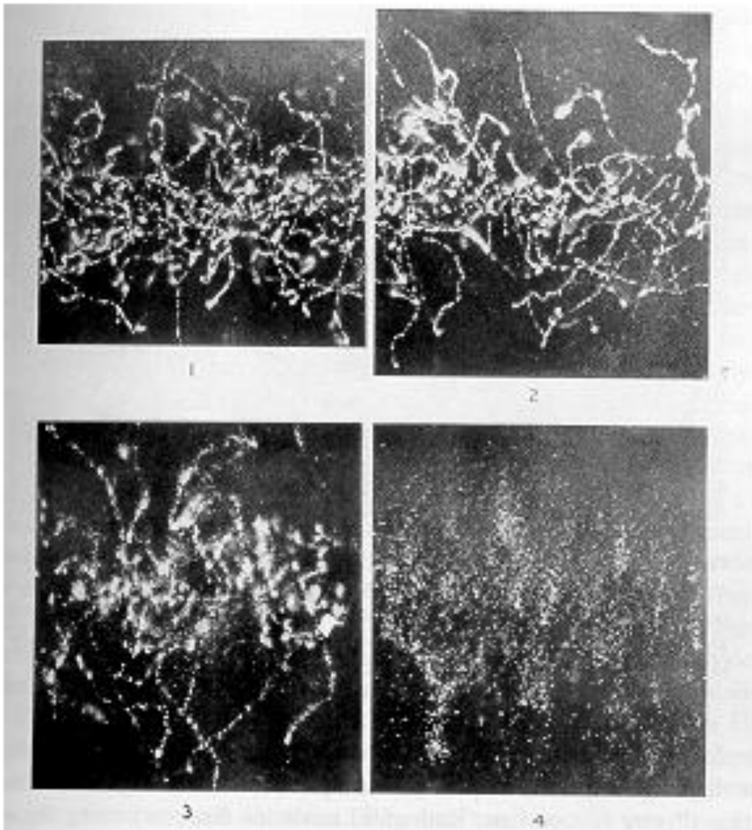
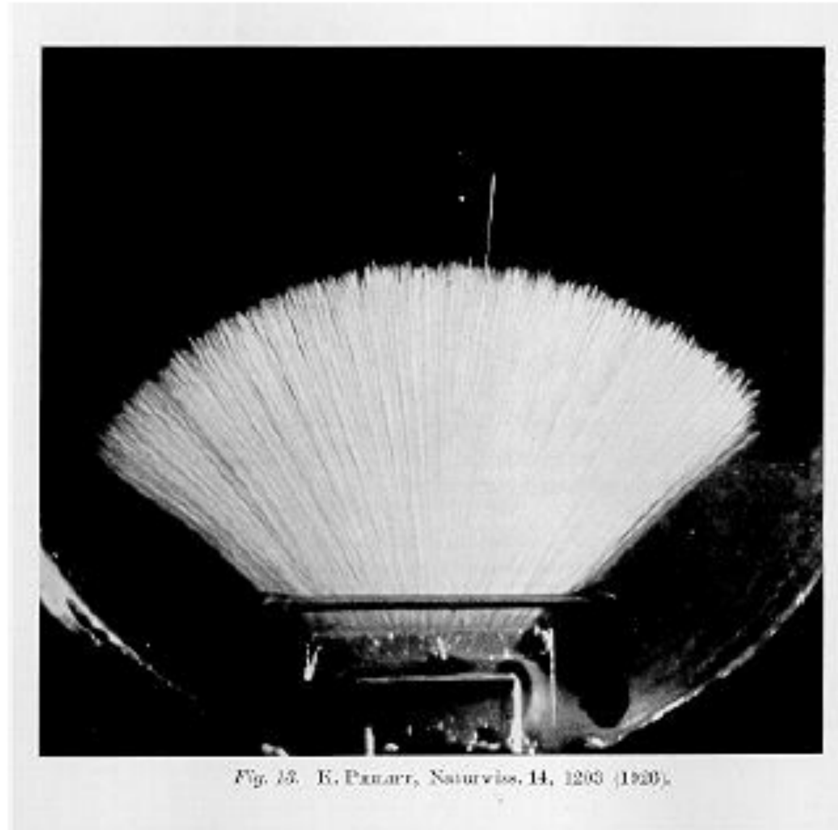
# Cloud Chamber



X-rays, Wilson 1912



Alphas, Philipp 1926

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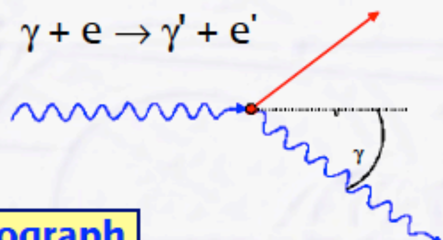
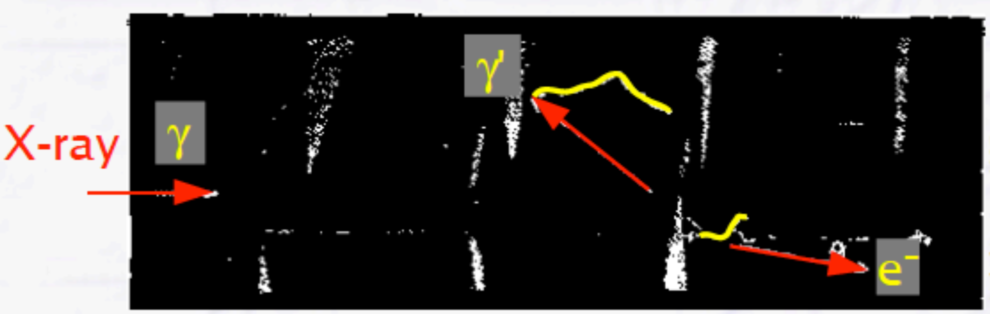
# Cloud Chamber II


- 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



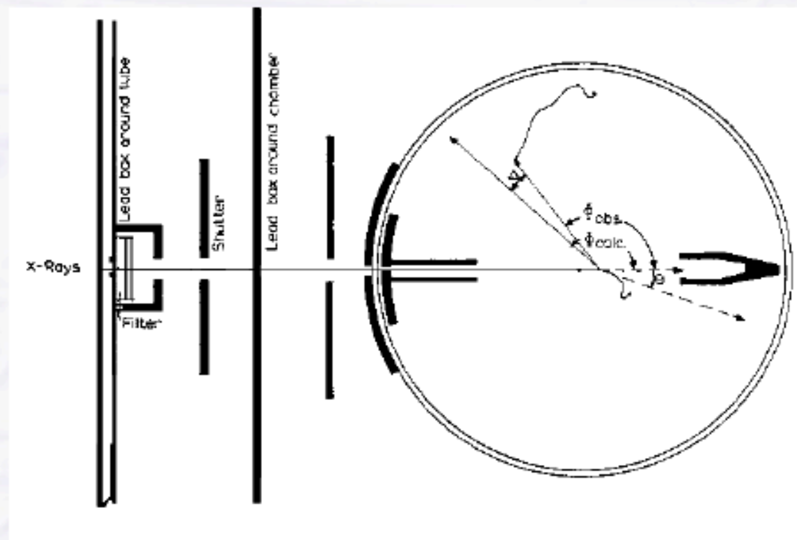
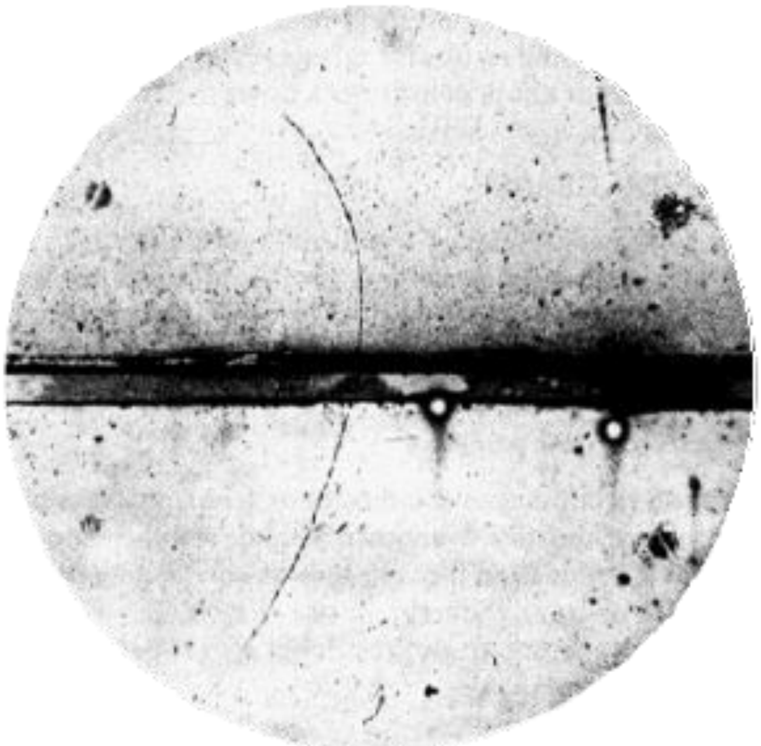




Fig. 10. An electron recoiling at an angle θ should be associated with a photon deflected through an angle φ.

Nobel Lecture 1927

# Cloud Chamber III



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.

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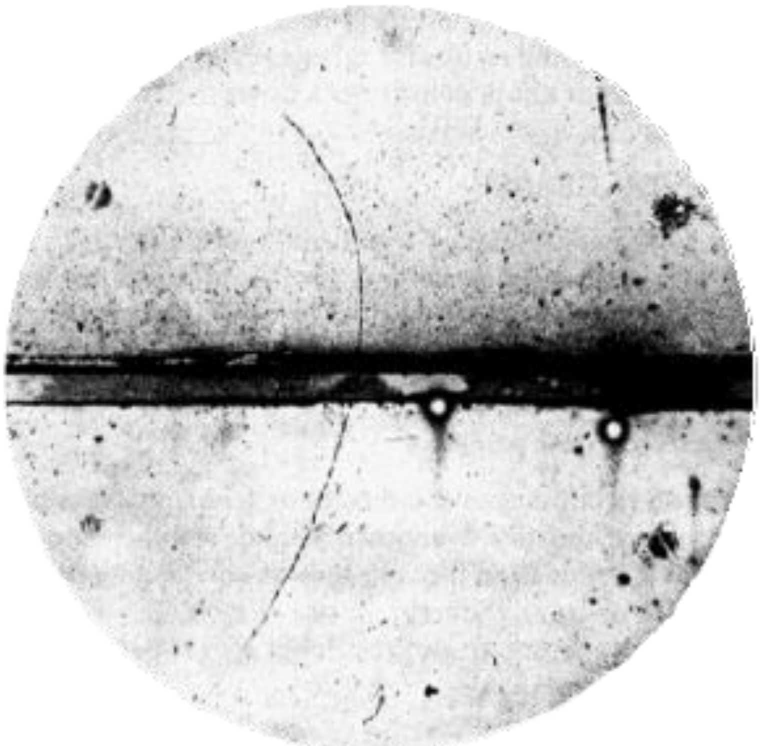

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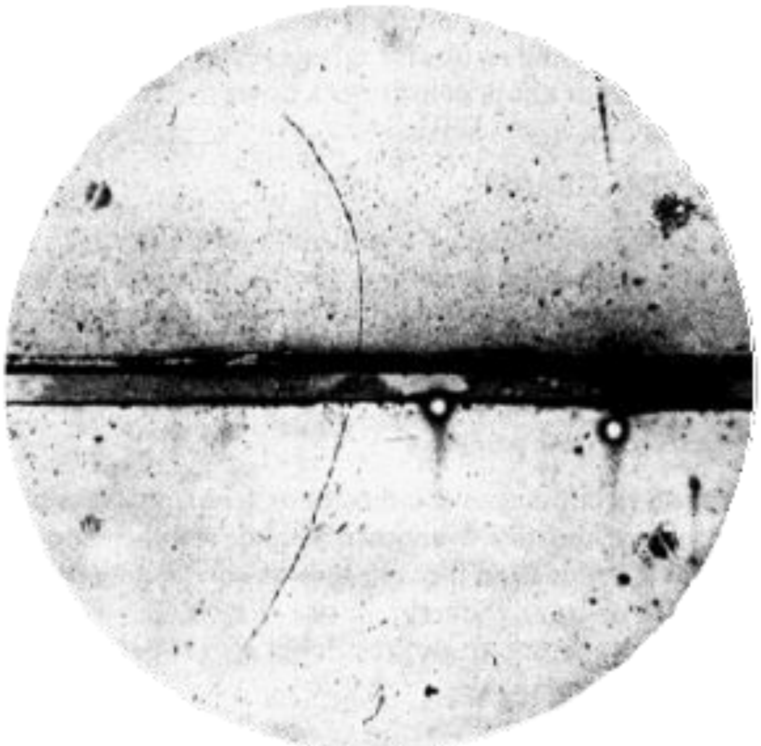

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Nobel Prize 1936

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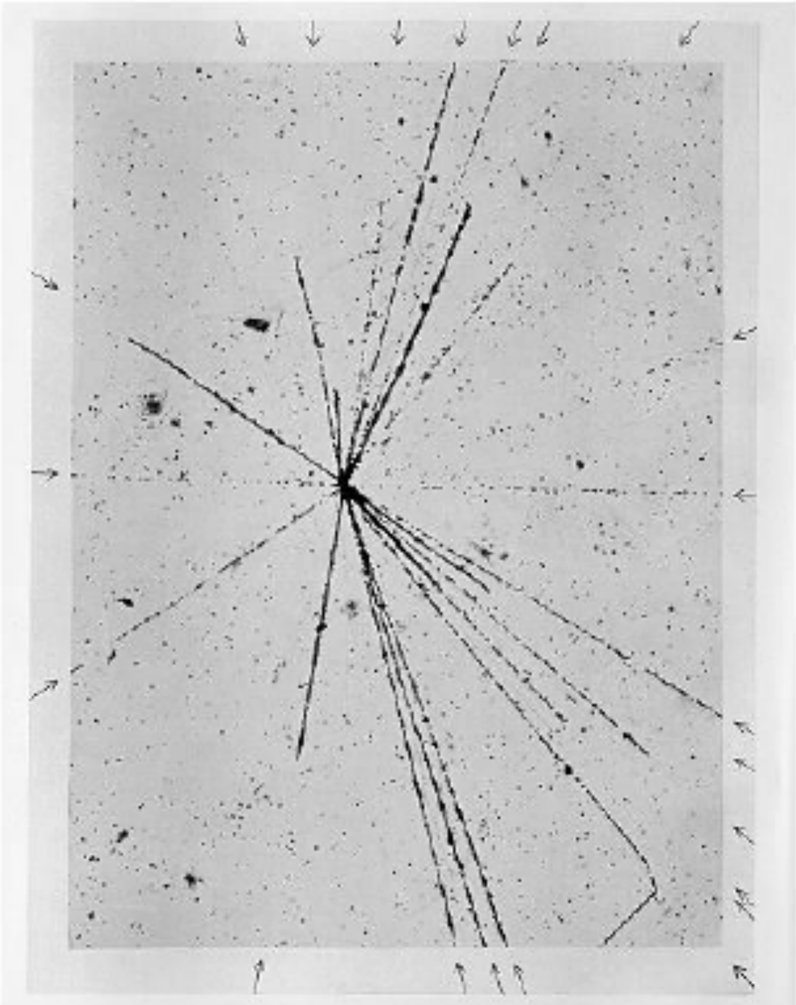
No Nobel prize for them!
Or for Dmitri Skobeltsyn (1929)…

# Nuclear Emulsion I



'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.

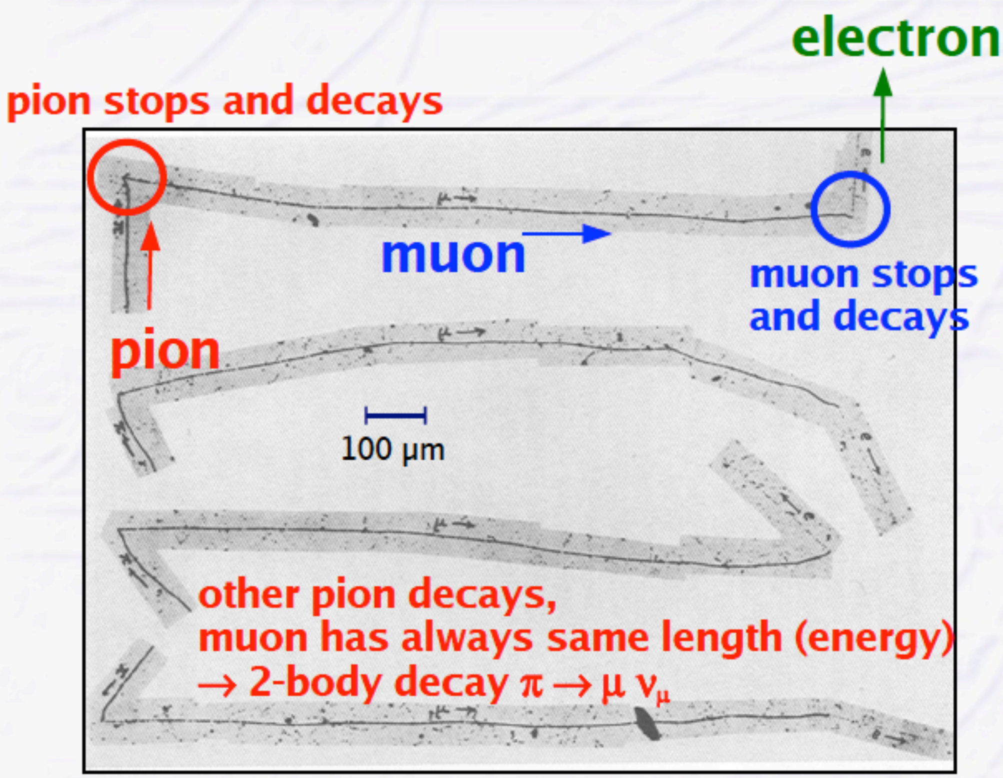
E.g.
Emulsions were exposed to cosmic rays at high altitude for a long time (months) and then analyzed under the microscope.
In 1937, nuclear disintegrations from cosmic rays were observed in emulsions.

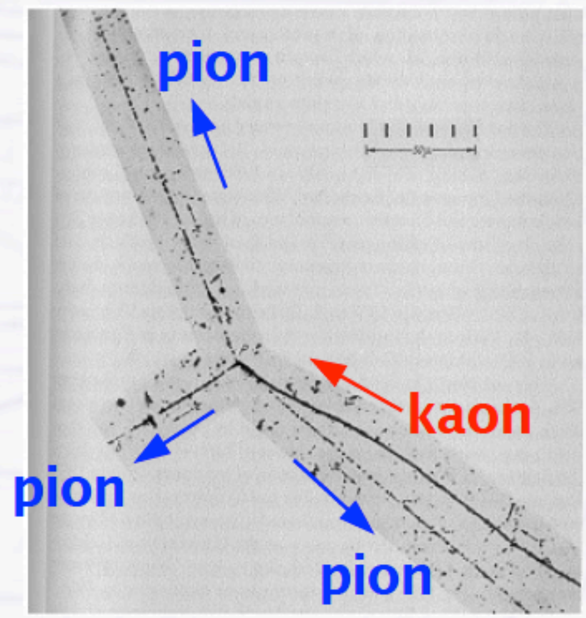
The high density of film compared to the cloud chamber 'gas' made it easier to see energy loss and disintegrations.

# Nuclear Emulsion II

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

Cecil Powell



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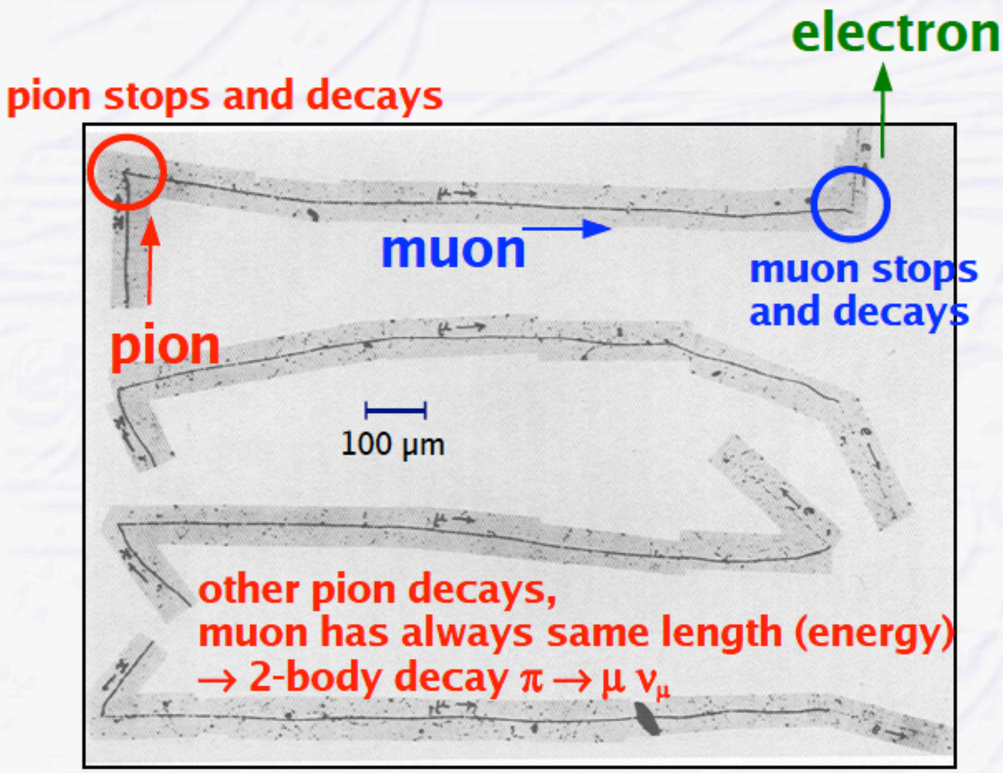
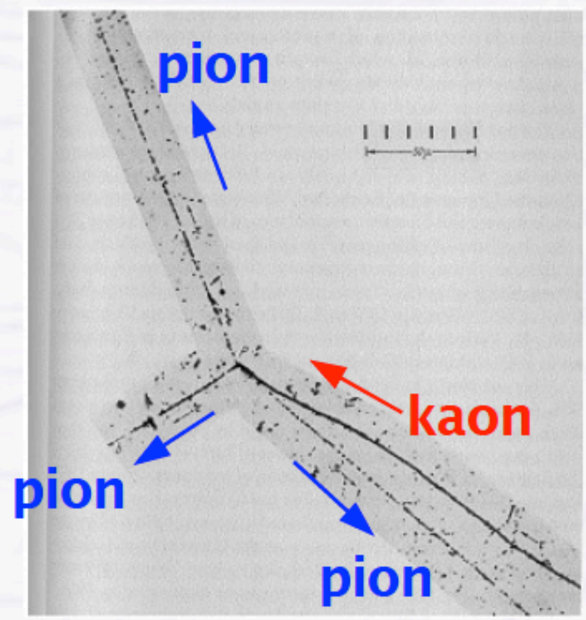
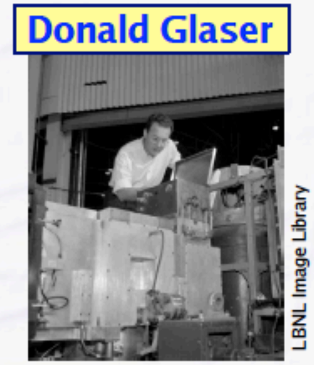
Marietta Blau was written out of the story!

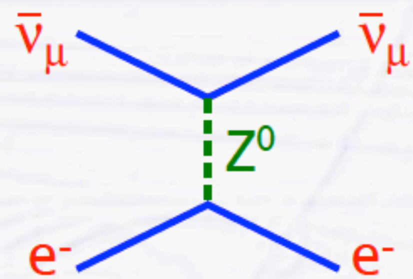



# Bubble Chamber I

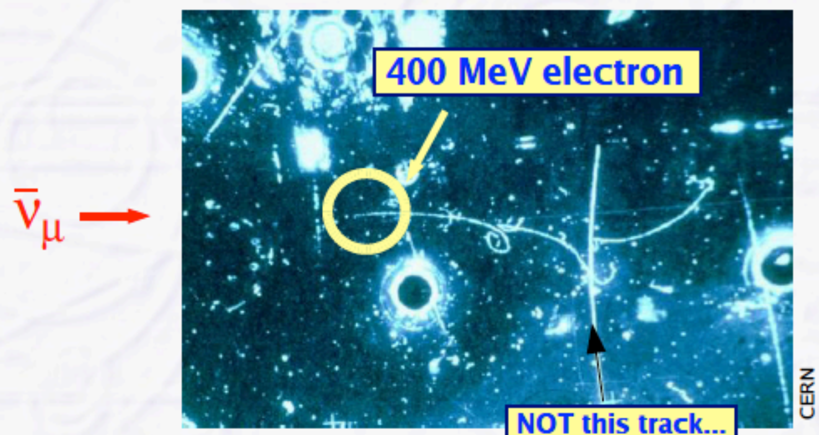
- Intented 1952 by Donald Glaser (Noble Prize 1960)
  - similar to could chamber
  - → chamber with liquid (e.g. $H_2$) at boiling point ("superheated")
  - → charged particles leave trails of ions
  - formation of small gas bubbles around ions




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

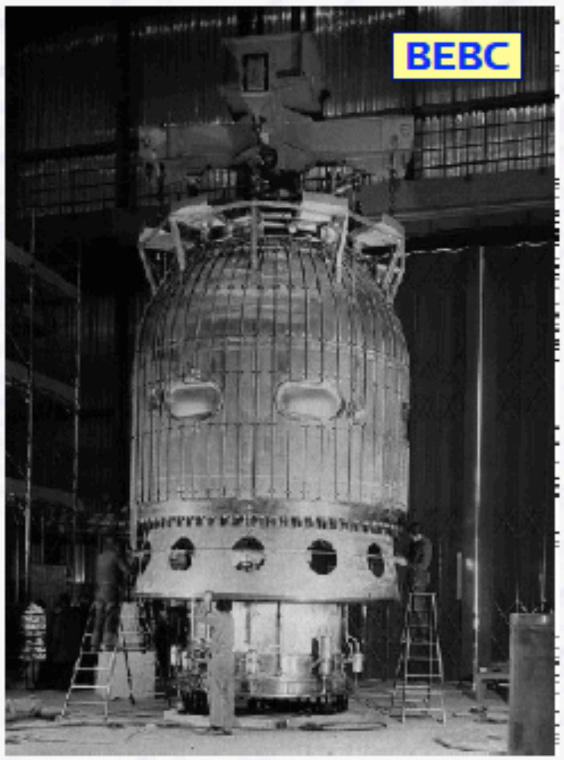




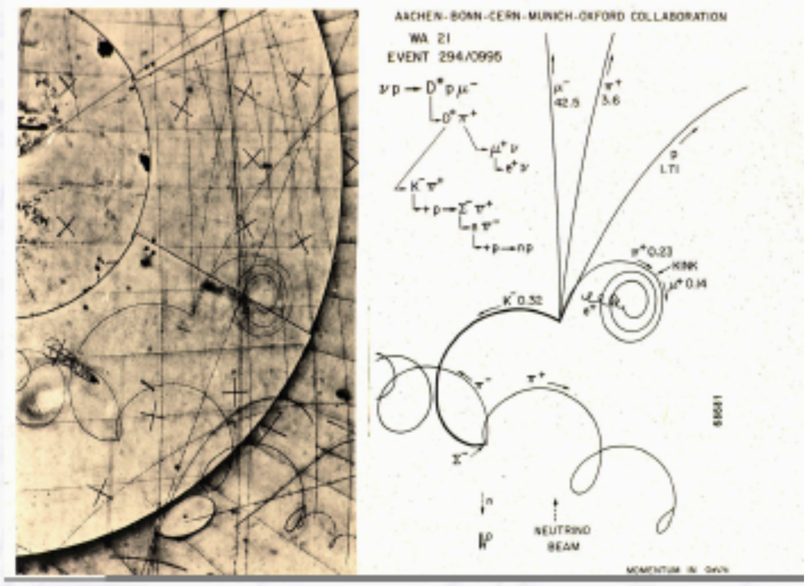


# Bubble Chamber II

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

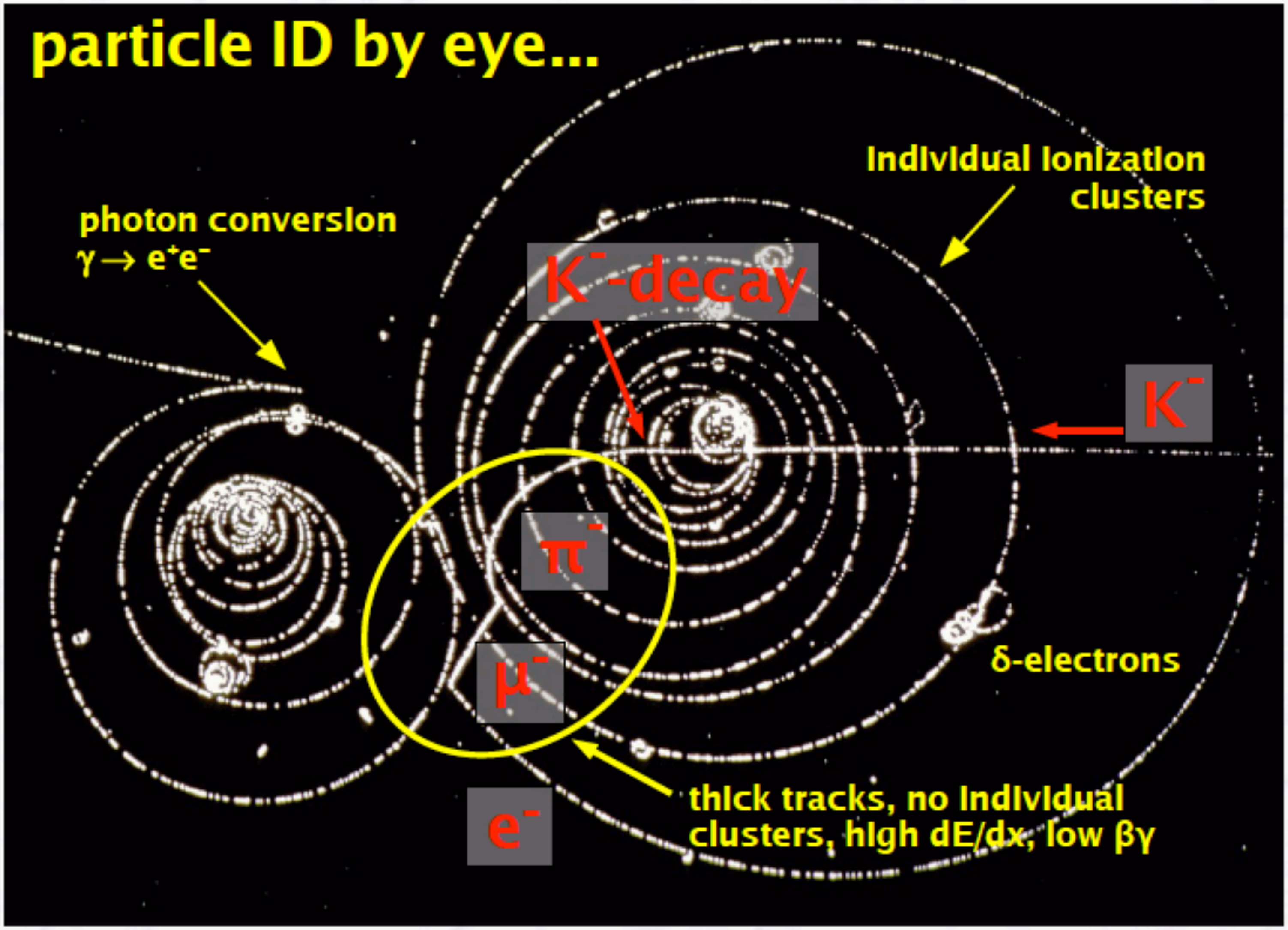






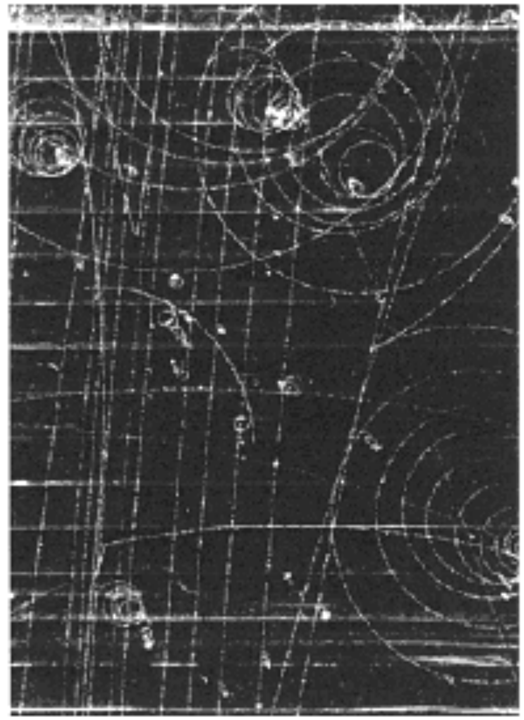

production of D* meson
with long decay chain

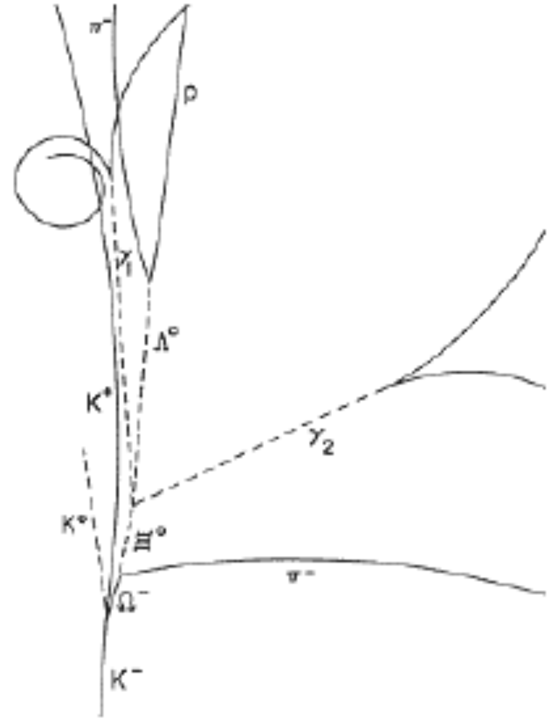
# Bubble Chamber III



# Bubble Chamber

The 80-inch Bubble Chamber






**BNL, First Pictures 1963, 0.03s cycle**

**Discovery of the $\Omega^-$ in 1964**

13 February 2019

# Bubble Chambers

- Beautiful images, but very tedious:
  - maximum rate of expansion, few/second
  - thousands of km of film to scan
- Bubble chambers died off quickly when electronic techniques matured.

# Bubble Chambers

- Beautiful images, but very tedious:
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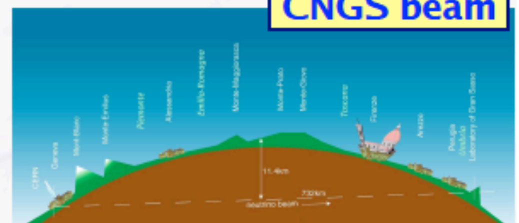
- Bubble chambers died off quickly when electronic techniques matured.
- Now: Bubble chambers are back!
  - Dark matter searches need rejection of gamma ray backgrounds: rejection factor: $<10^8$ or higher!

They’re back too!

# Nuclear Emulsion III

CNGS beam

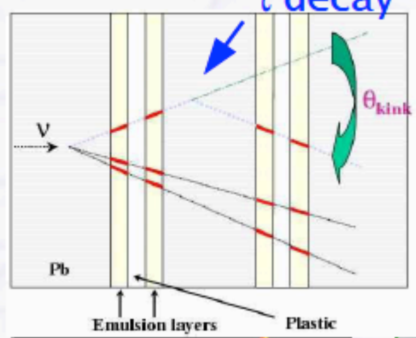


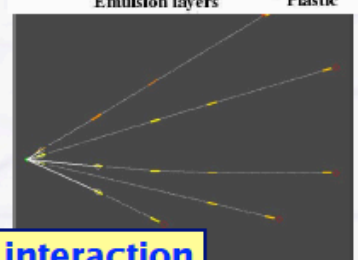
- **Still used in actual experiments with highest precision requirements over a large volume**
  - → $\nu_\mu$ beam sent from CERN to Gran Sasso Underground lab in Italy (732 km)
  - → OPERA experiment is searching for $\nu_\tau$ appearance after neutrino oscill. $\nu_\mu \rightarrow \nu_\tau$
    -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

single brick

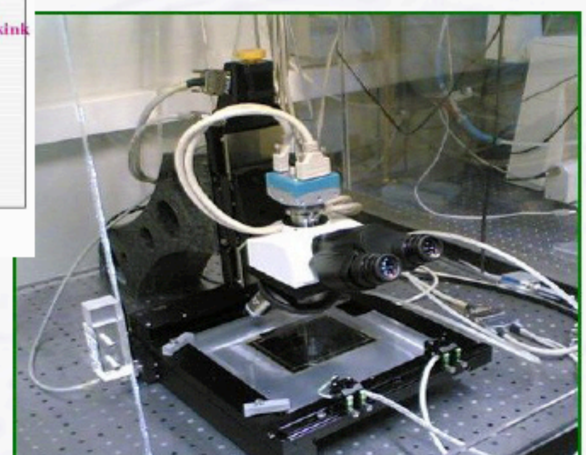

OPERA at Gran Sasso

$\tau$ decay



$\nu_\mu$ interaction



automatic emulsion scanning

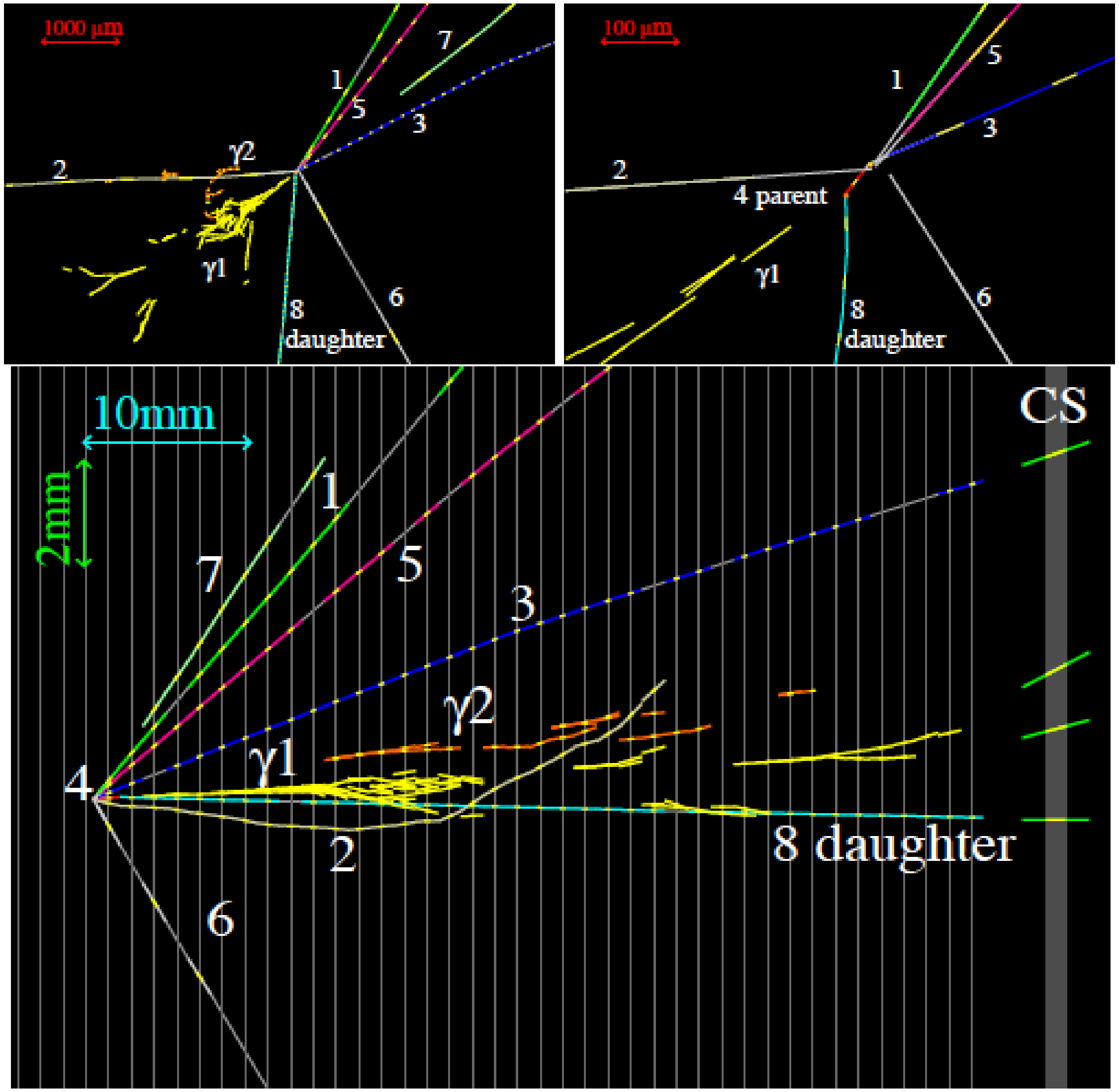



Figure 1: Display of the $\tau^-$ candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

# Nuclear Emulsion III

## Opera's First Tau Neutrino Event -

July 2010

arXiv:1006.1623v1

# Where does the story of "electronic" particle detection 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

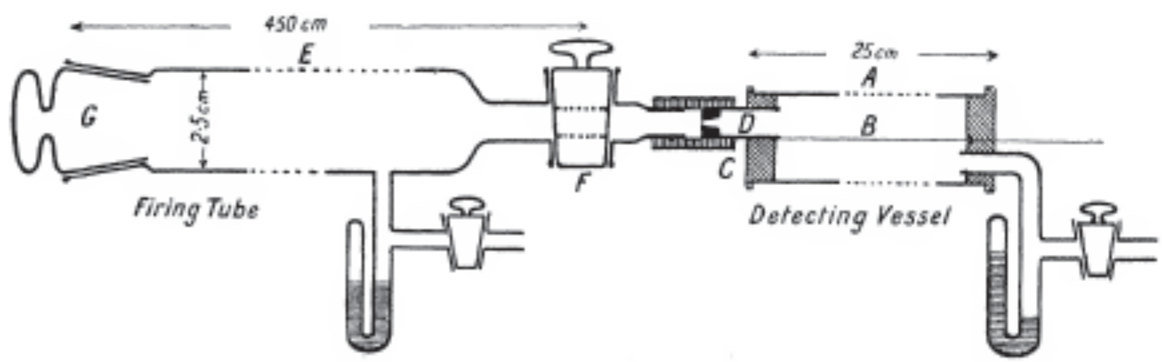



FIG. 1.

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…

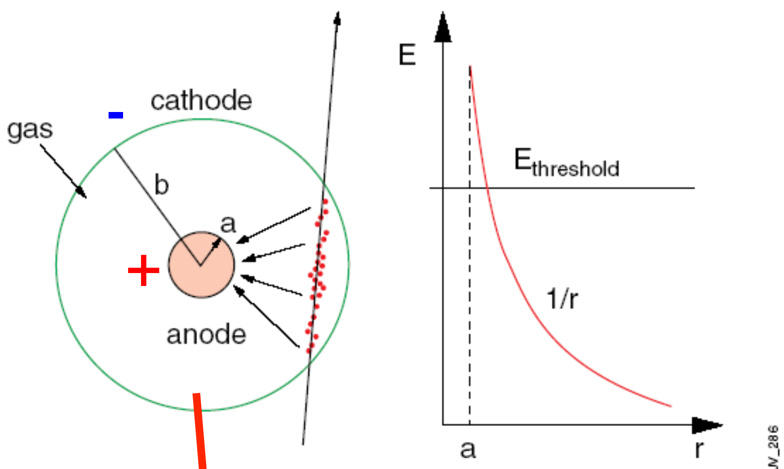
"We then had recourse to a method of automatically magnifying the electrical effect due to a single α-particle. For this purpose we employed the principle of production of fresh ions by collision. In a series of papers, Townsend [2] has worked out the conditions under which ions can be produced by collisions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

# Rutherford and Geiger…

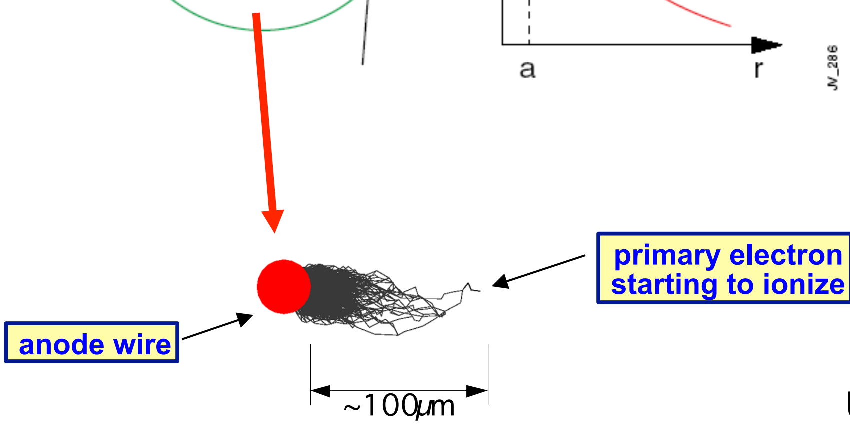
…"In this way, the small ionization produced by one α-particle in passing through the gas could be magnified several thousand times. The sudden current due to the entrance of an α-particle in the testing vessel was thus increased sufficiently to give an easily measurable movement of an ordinary electrometer."

# 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

*How was the Geiger-Muller counter really "invented"?*

- In 1926, Müller was given a old brass tube with a wire inside––Spitzenzahler ("spark counter")– 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.

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

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- Spitzenzahler is detecting radium γ-rays!

# The discovery is revealed

- Müller tests his new device for 5 days;
- Müller 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."

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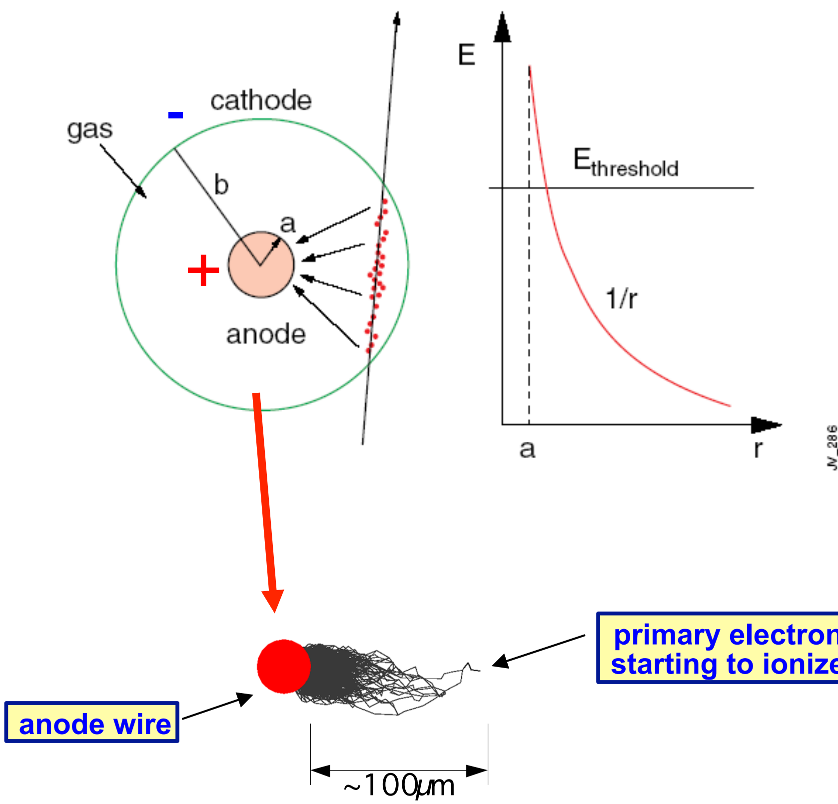
- No patent is sought, and the device is made freely available through publication.

# Geiger-Müller Tube

- Problem: Long recovery times for ions to clear ~100-1000 Hz maximum rate
  Tube filled with inert gas (He, Ne, Ar) + vapor (alcohol or halogen)




**Measurable signal on wire ?**

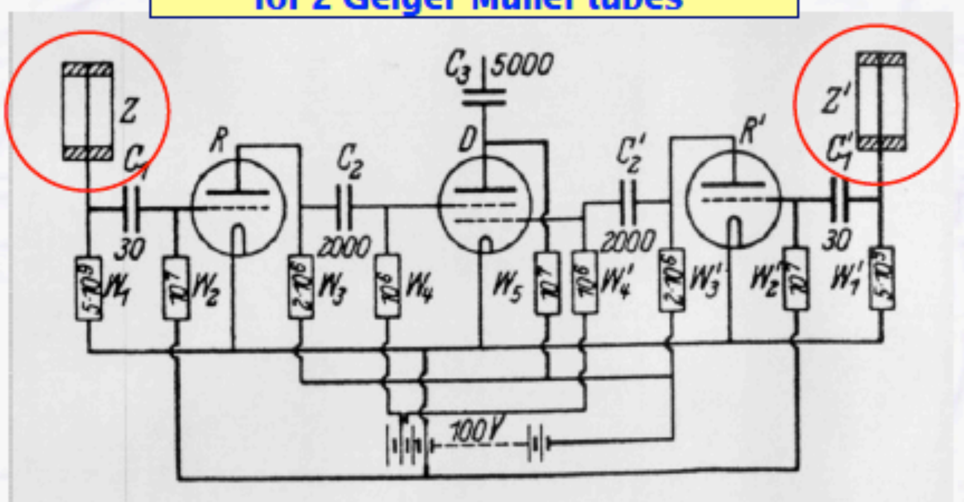
- Why / how does the avalanche spread along the whole length of the wire ?
- Answer: the avalanche is spread by UV photons emitted by argon: first excited state is 12.14 eV, above the ionization potential of molecular additive. Excited argon atoms live long enough to radiate UV photons; ionic charge exchange to molecules leads to non-radiative neutralization at cathode…
- ➔ Huge signals ! Were G-M lucky ?

# Coincidence Units

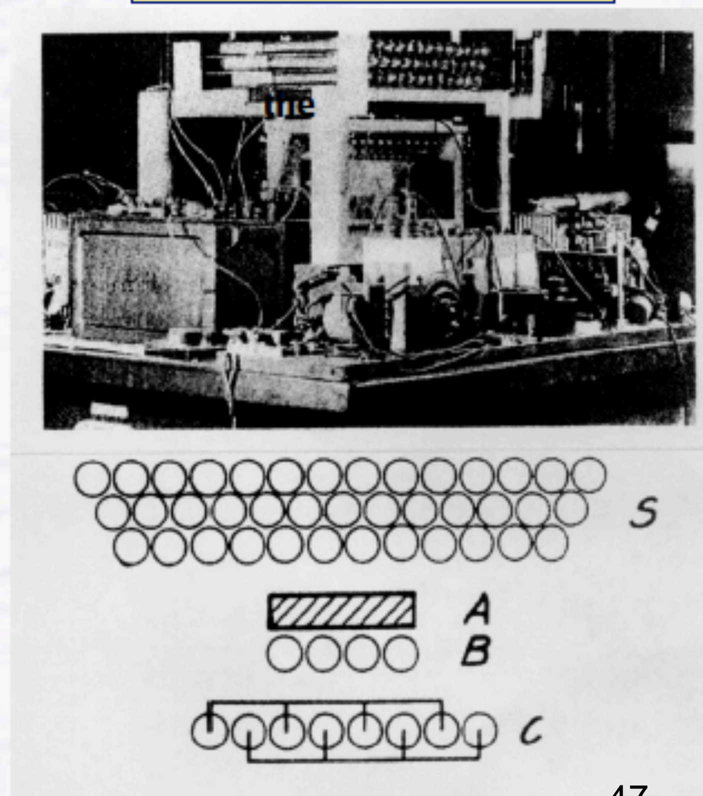
Walther Bothe

- **"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

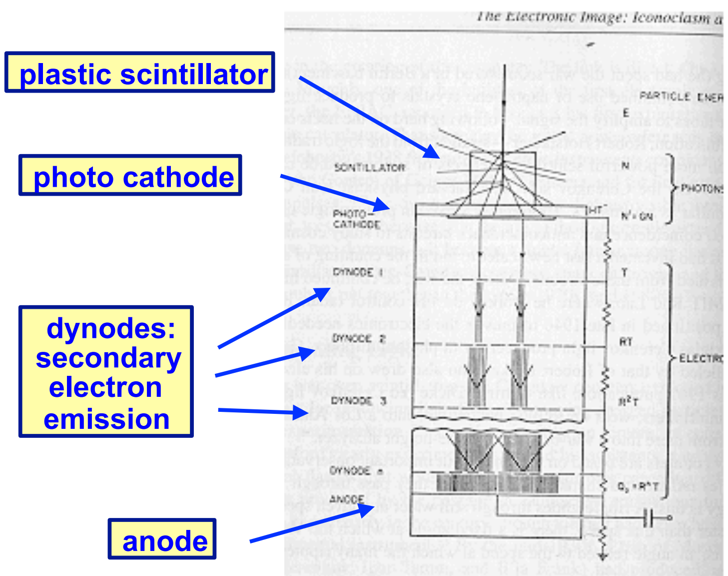



cosmic ray telescope 1934



# Photo Multiplier Tubes (PMT)

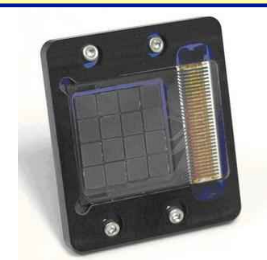
- Invented in 1934 by Harley Iams and Bernard Salzberg (RCA)
  - based on photo effect and secondary electron emission
  - sensitive to single photons, replaced human eye + belladonna at scintillator screen
  - → first device had gain ~8 only, but already operated at >10 kHz
  - → (human eye: up to 150 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

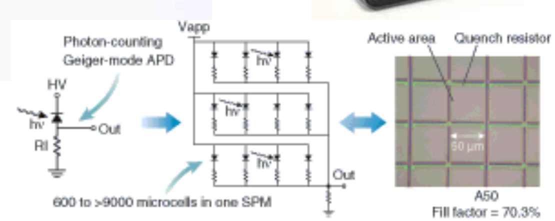



classic PMT

UAM

Silicon PM = array of avalanche photo diodes



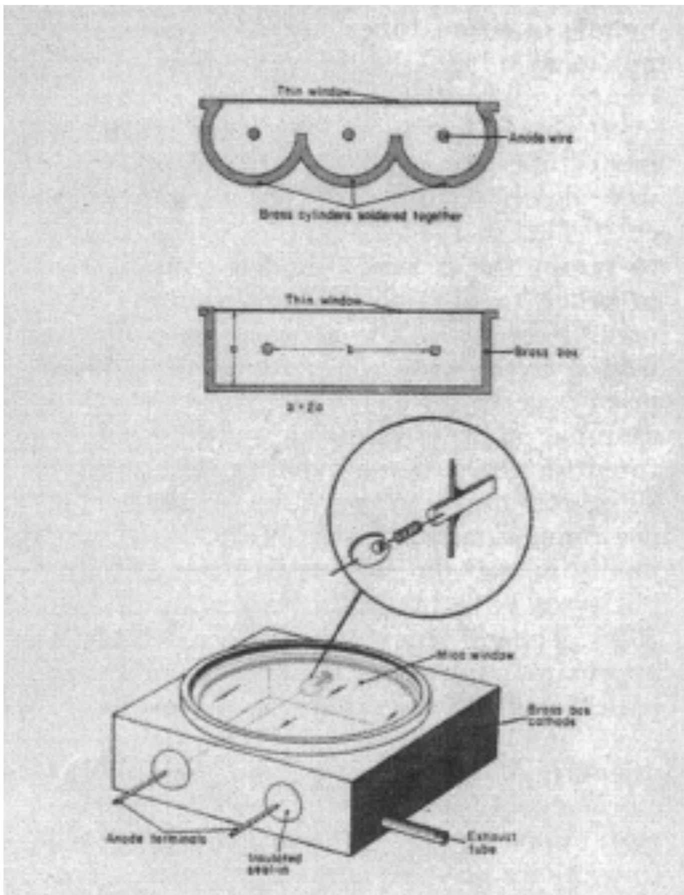


**Proportional Counters**

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

Several multi-wire common-enclosure geometries

Wires ganged together to produce a single signal



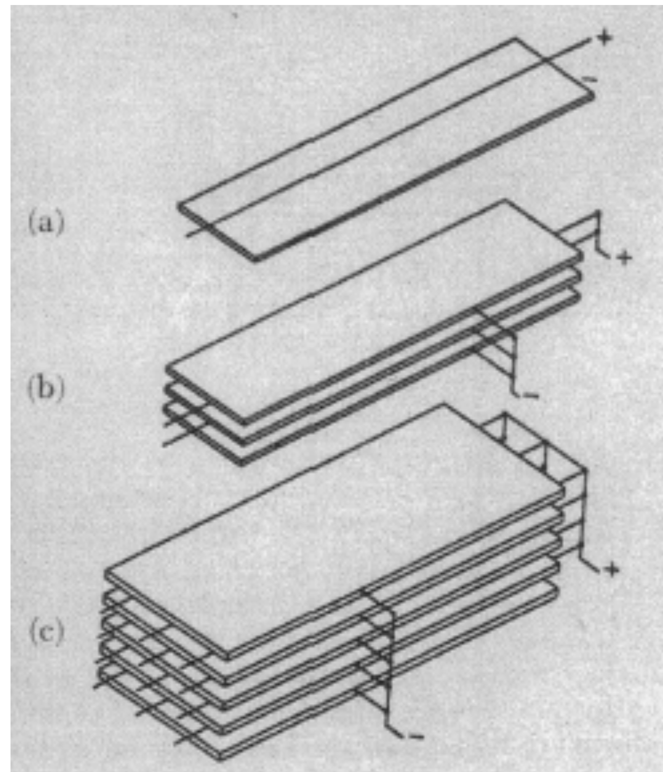
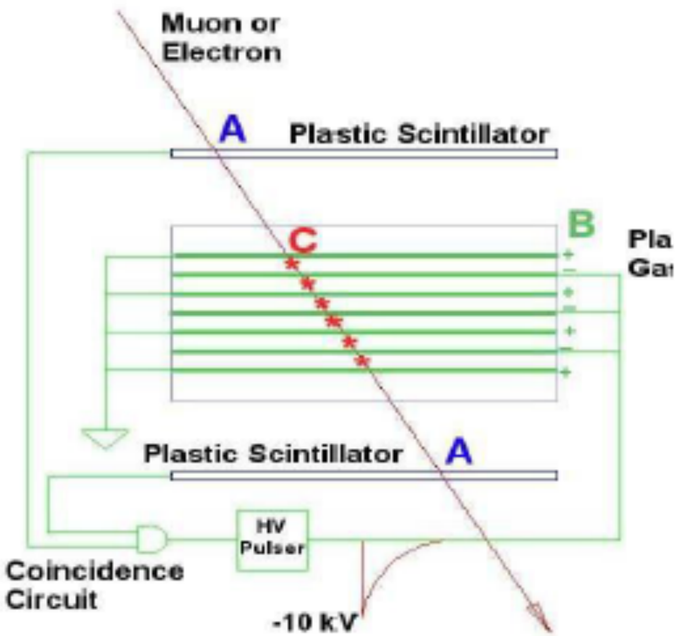




Fig. 20—Multiple plate and wire construction of a gamma-ray counter.

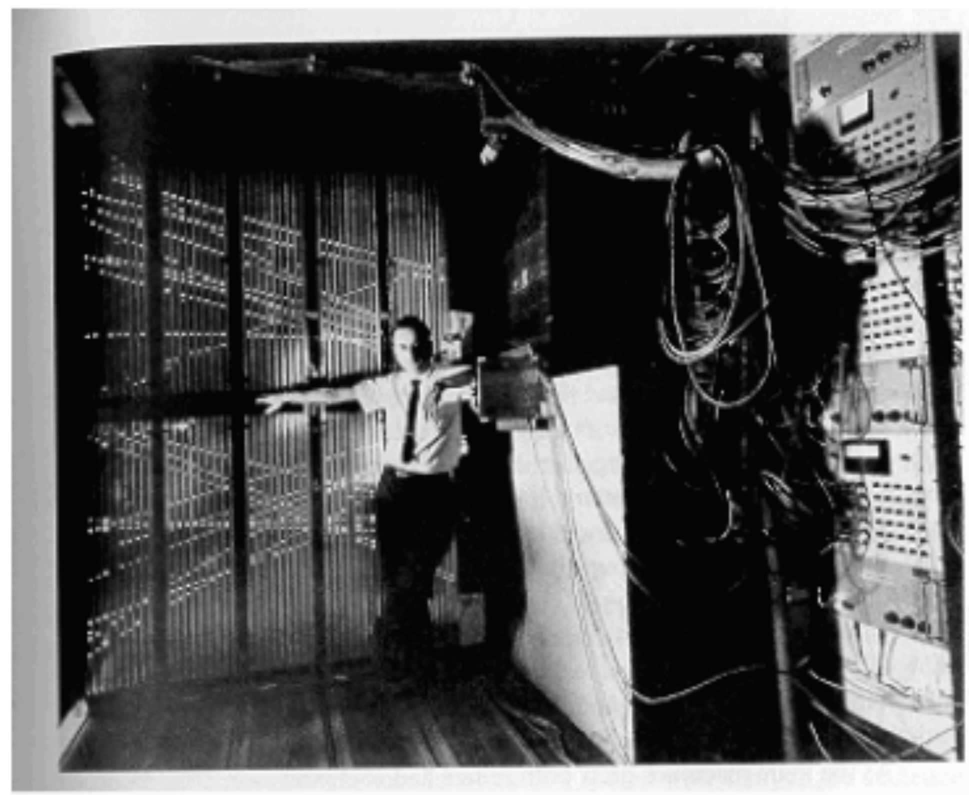
# Spark Counters




The Spark Chamber was developed in the early 60ies.

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

1988 Nobel Prize for $\nu_\mu$



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.

13 February 2019

# Spark Chambers…

- Initially, optical devices with film cameras
- Soon, magnetostricitive sensing of spark current was developed → 100 Hz?
- And then, suddenly, spark chambers were gone, except for display units at science fairs

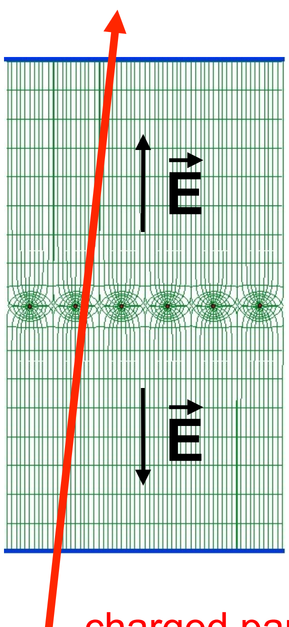
- What happened ?

# Multi-Wire Proportional Chambers

- Multi Wire Proportional Chamber (MWPC) 1968 by Georges Charpak,
  - put many wires close together with individual signal circuits
  - integrated electronics was key to success
  - short distance between two parallel plates → MHz rates!

**Georges Charpak**

Nobel Prize: 1992

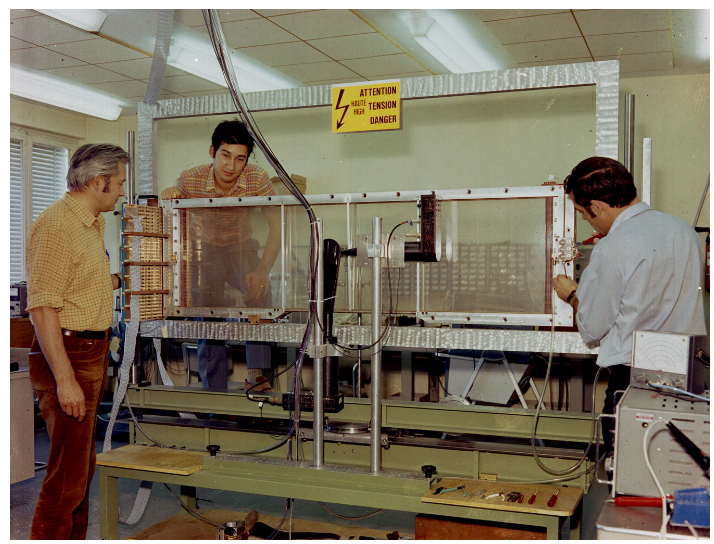



cathode plane (-)

anode plane (+),
many wires,
2 – 3 mm apart

cathode plane (-)

charged particle



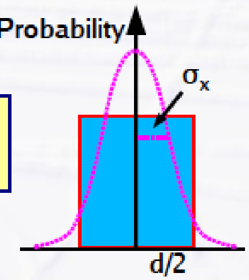
CERN

**Georges Charpak, Fabio Sauli and Jean-Claude Santiard**

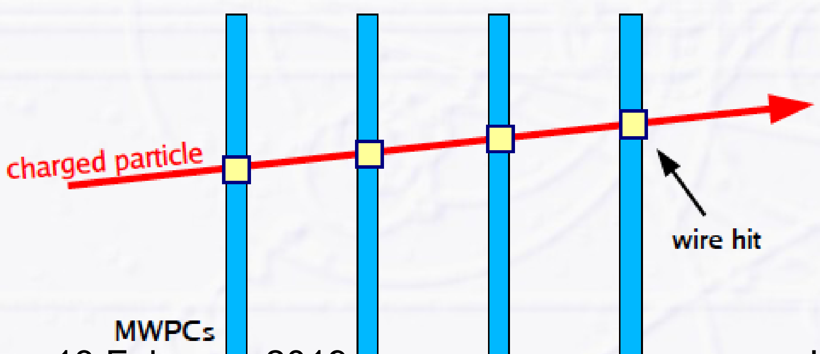
# Multi Wire Proportional Chambers II

- 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)

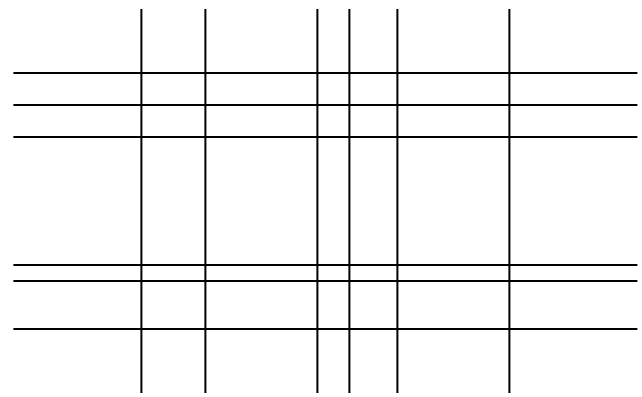



can reconstruct track with e.g. 4 points

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 <x,y>?*

# The dreaded $N^2$ ambiguity

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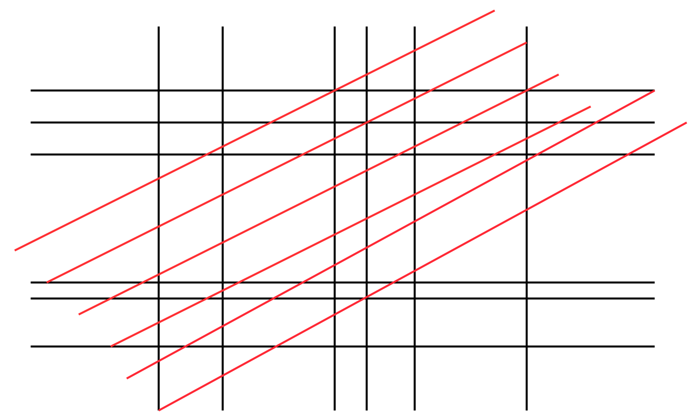
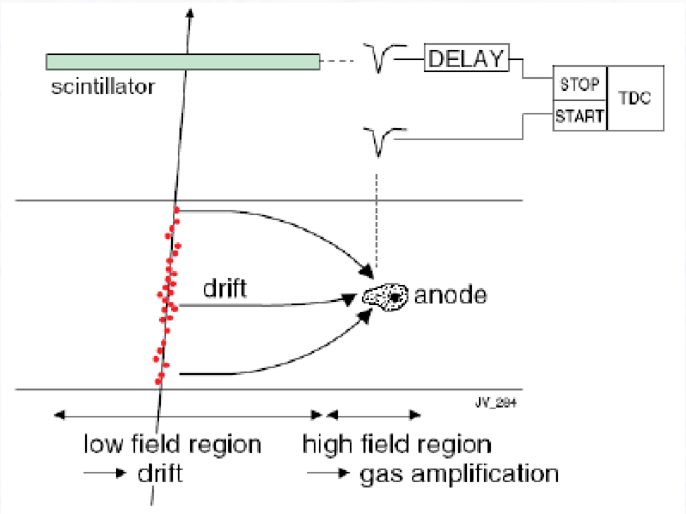
- You have $N^2$ possible combinations of <x,y>.
- More chambers at various angles…?
- *Which are the right <x,y>?*
- *Unpleasant for N > ~10*
- *Anguish rises ~ $N^3$ ?*



# 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)

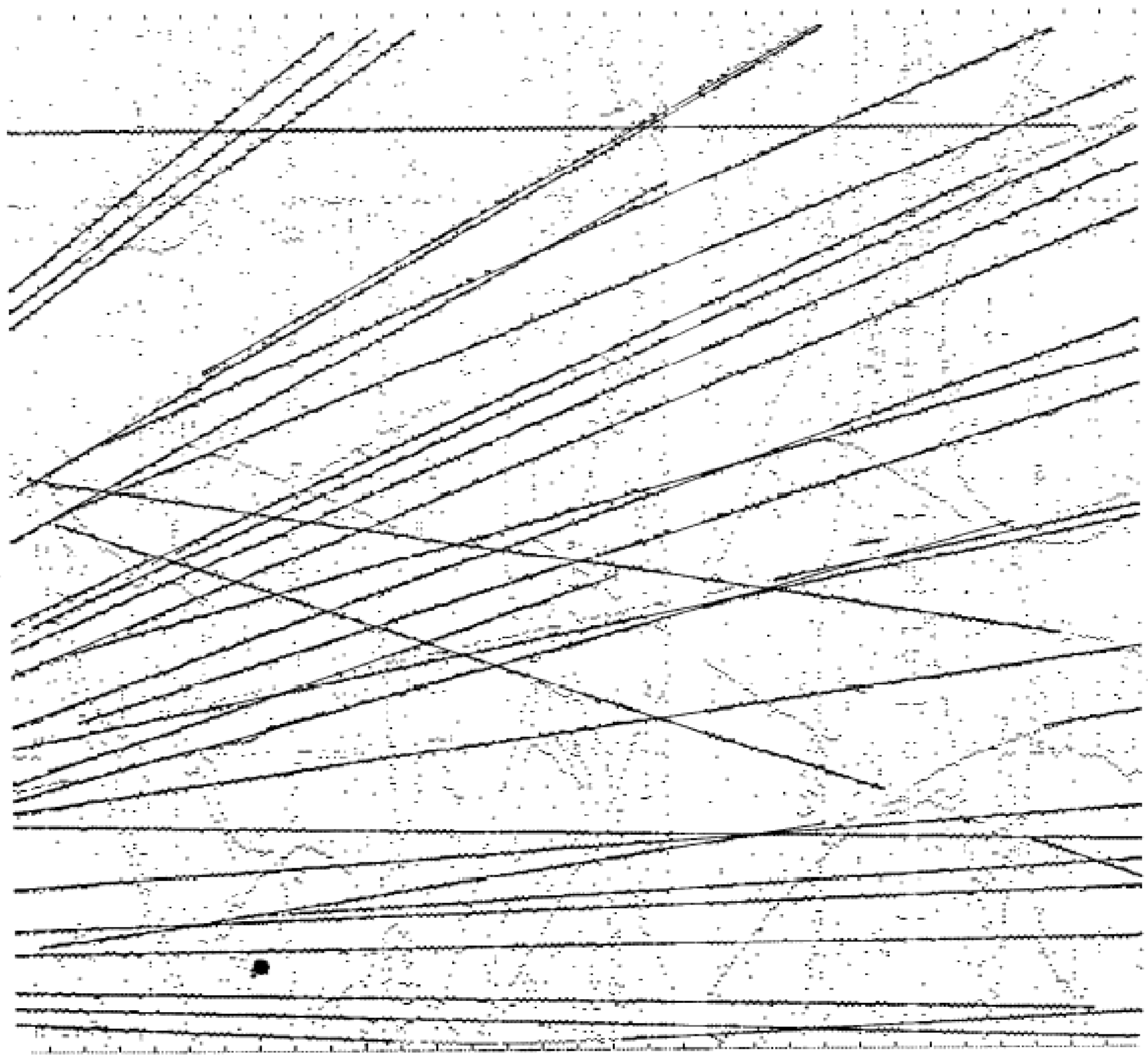
$$s = \int_{t_{start}}^{t_{stop}} v_D \, d t$$

E x B ≠ 0 ⇒ Track distortion!



"Particle Detection with Drift Chambers", Blum, Riegler, Rolandi

Wade Allison 1972 - Identification of Secondaries by Ionization Sampling -



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

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.

Wade Allison 1972 - Identification of Secondaries by Ionization Sampling -

# Starting to look like bubble chamber images!

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.

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- Epiphany: Diffusion transverse to fields can be suppressed !
- Quick visit to LBNL library: I find Townsend's book "Electrons in Gases"

## "Electrons in Gases", by Sir J. S. E. Townsend, Hutchinson Scientific,



$U$ is $2U^2/3$ and the rate of change $(d\overline{r^2}/dt)$ of the mean square of the distance from the axis of $y$ is $4U^2T/3(1+\omega^2T^2)$ or $4lU/3(1+\omega^2T^2)$.

The coefficient of diffusion $K_h$ (in the directions perpendicular to the direction of the magnetic force) of electrons moving with the velocity of agitation $U$ is therefore given by the equation

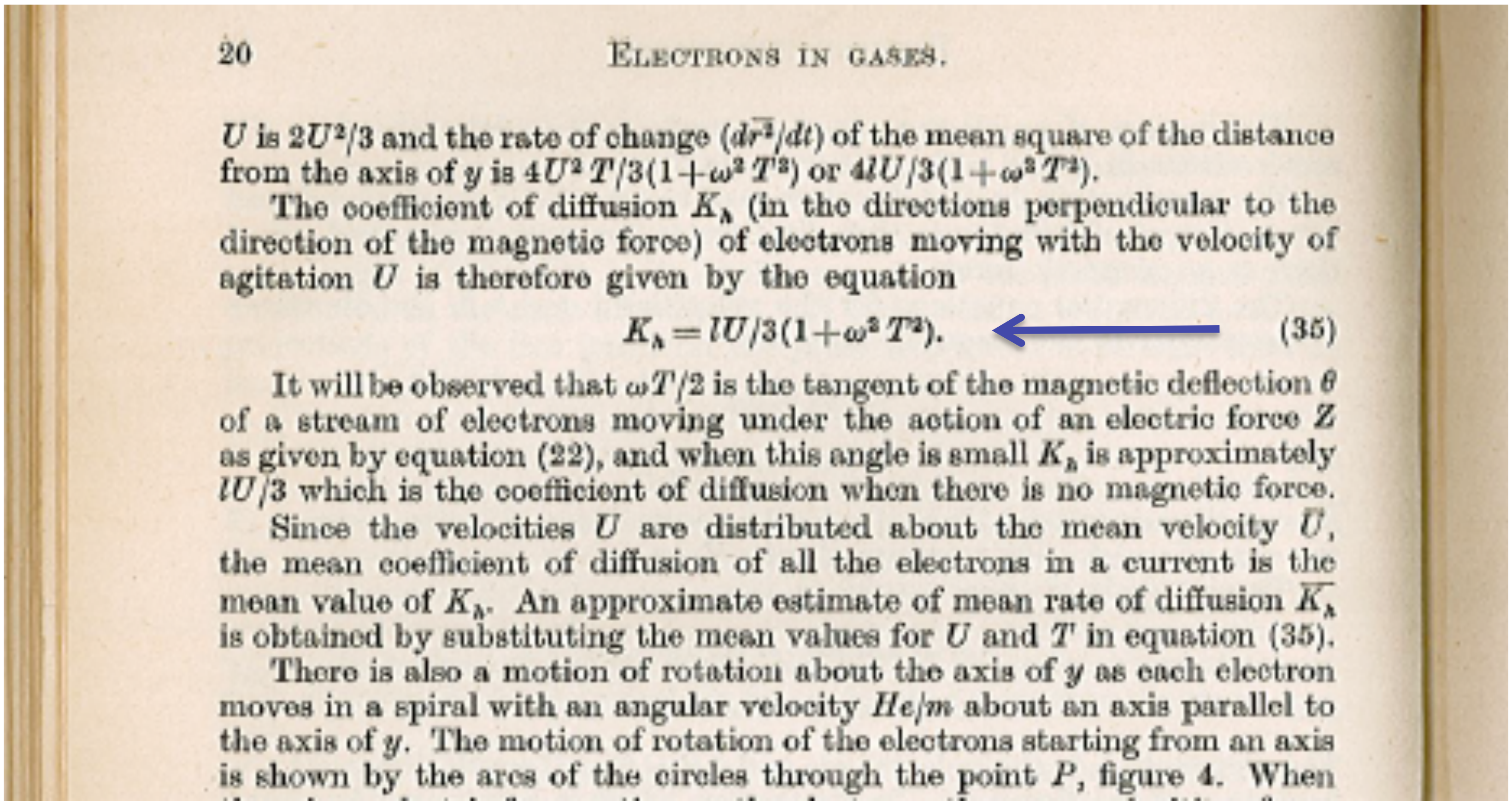
$$K_h = lU/3(1+\omega^2T^2). \qquad (35)$$

It will be observed that $\omega T/2$ is the tangent of the magnetic deflection $\theta$ of a stream of electrons moving under the action of an electric force $Z$ as given by equation (22), and when this angle is small $K_h$ is approximately $lU/3$ which is the coefficient of diffusion when there is no magnetic force.

Since the velocities $U$ are distributed about the mean velocity $\overline{U}$, the mean coefficient of diffusion of all the electrons in a current is the mean value of $K_h$. An approximate estimate of mean rate of diffusion $\overline{K_h}$ is obtained by substituting the mean values for $U$ and $T$ in equation (35).

There is also a motion of rotation about the axis of $y$ as each electron moves in a spiral with an angular velocity $He/m$ about an axis parallel to the axis of $y$. The motion of rotation of the electrons starting from an axis is shown by the arcs of the circles through the point $P$, figure 4. When

“Electrons in Gases”, by Sir J. S. E. Townsend, Hutchinson Scientific, **1948 !**





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# 1948 !

But - it is even worse than that!

Townsend refers to his paper in Proc. R. Soc. Lond. A **86,** p571-577 published in **1912!**

# 1912 !

The velocities $A_s$ are independent of the times $t_s$, so that the mean value of $A^2$ may be substituted for $A_s^2$ in this expression. Also, since $A_s$ is the velocity in the plane $xy$, the mean value of $A_s^2$ is $\frac{2}{3}V^2$, V being the mean velocity of agitation of the ions; and, since the series of cosines $\Sigma \cos \omega t_s$, is equal to $N/(1+\omega^2 T^2)$, the above expression reduces to

$$\frac{d\rho^2}{dt} = \frac{2N}{NT\omega^2} \times \frac{2V^2}{3} \times \frac{\omega^2 T^2}{1+\omega^2 T^2} = \frac{4V^2 T}{3(1+\omega^2 T^2)}.$$

The rate of diffusion K along the direction of the magnetic force is $\frac{1}{3}\lambda V$ or $\frac{1}{3}V^2 T$. Hence

$$\frac{d\rho^2}{dt} = \frac{4K}{1+\omega^2 T^2},$$

!

# 1912 !

Rarely has something
so simple
and so useful
been ignored by
so many people
for so long!

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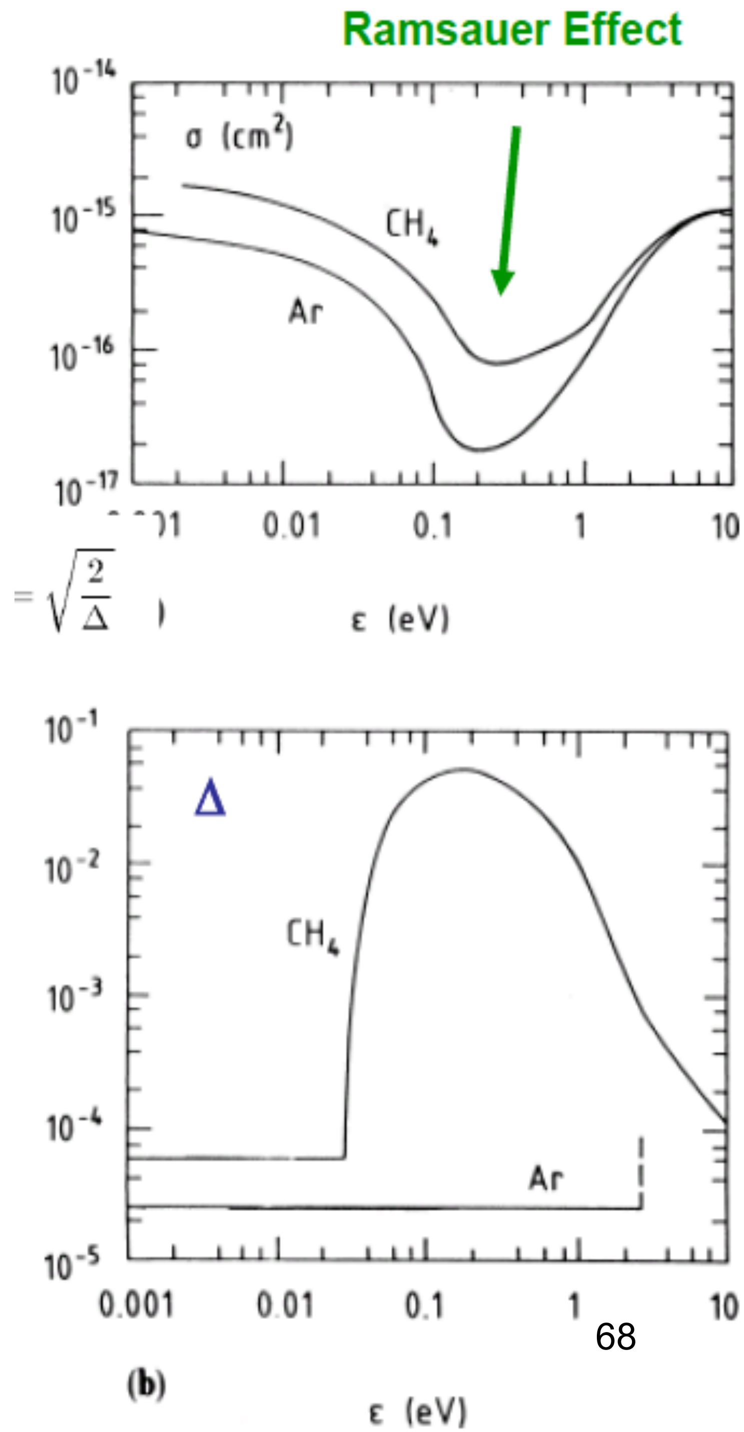
- Quick visit to LBNL library: I find Townsend's book "Electrons in Gases"
  - $\sigma = (2DT)^{1/2}$ D is diffusion constant, T is total elapsed time (drift time here)
  - $D_m = D/(1 + (\omega\tau)^2)$ $\omega$ is cyclotron frequency, $\tau$ is mean collision time
  - So Yes, $\omega\tau >>1$, in principle, but how?

# 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.
- 



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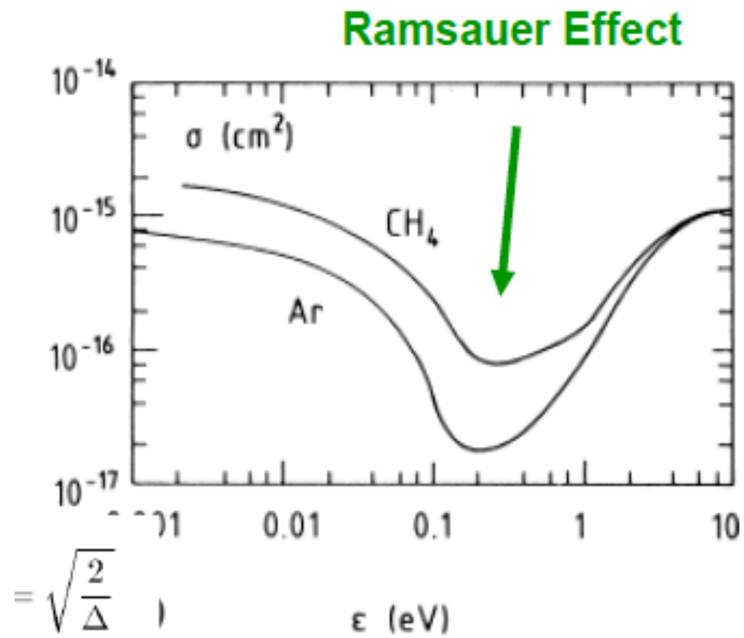
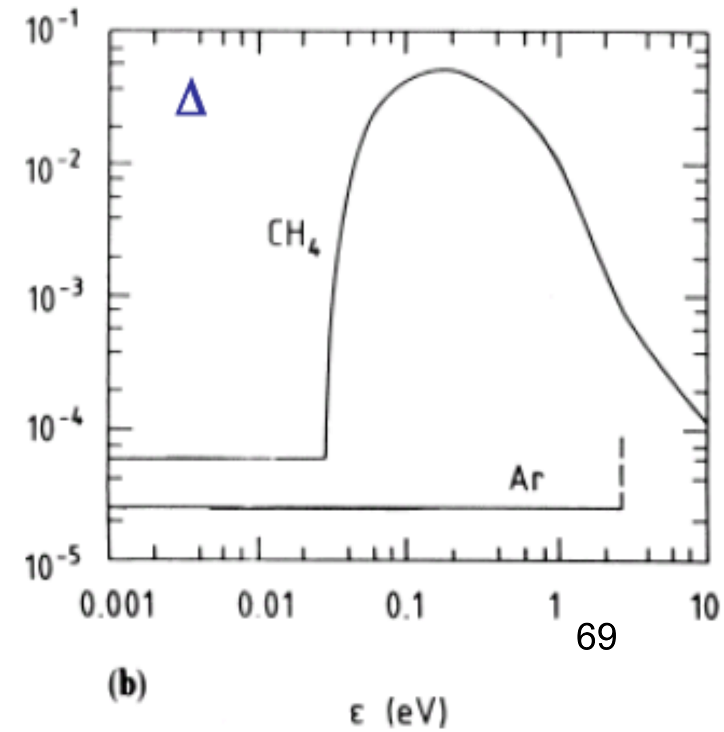



- $\tau$ is very large for $\varepsilon \sim 0.25$ eV
- $\omega\tau >>1$ Yes !!

  PEP-4 TPC B ~ 1 T

  8.5 bars Ar/$CH_4$ (90/10)

  $\omega\tau \geq 10$



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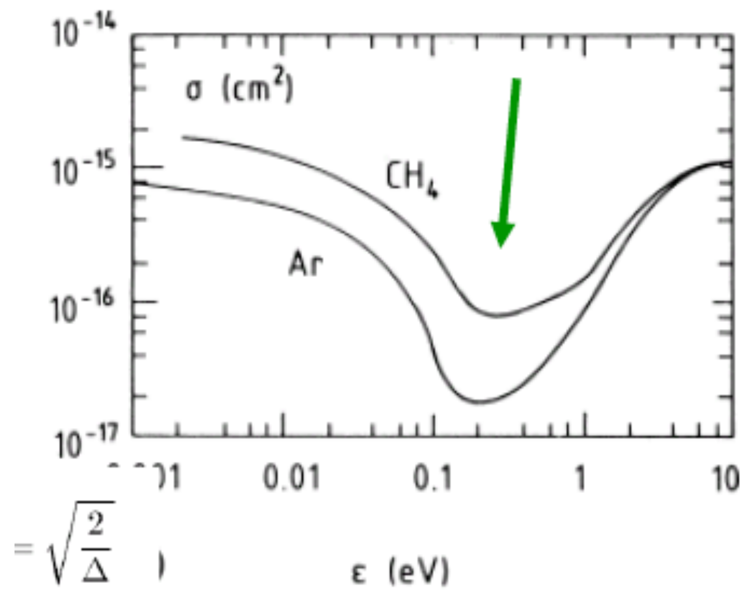


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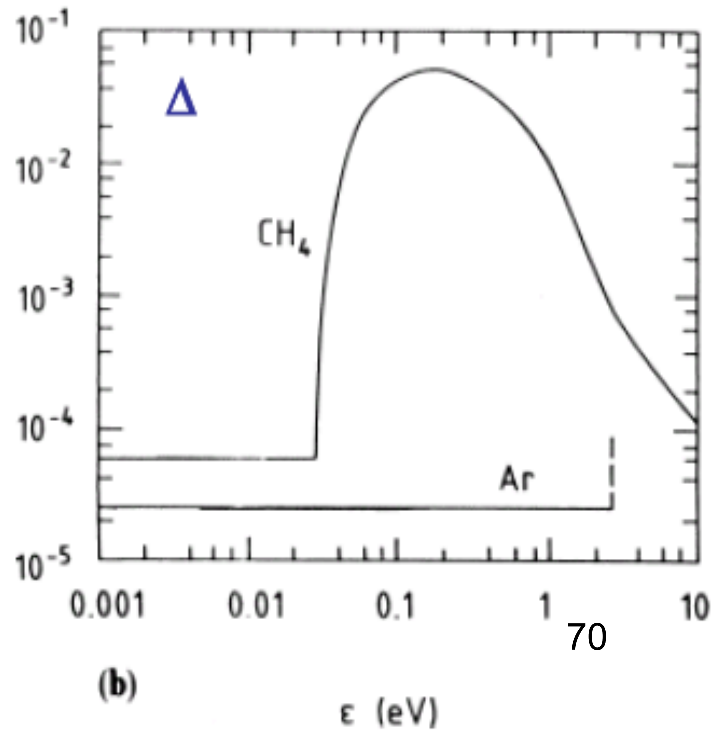
  8.5 bars Ar/$CH_4$ (90/10)

  $\omega\tau \geq 10$

  $D_m$ is reduced by ~two orders of magnitude with B field on!

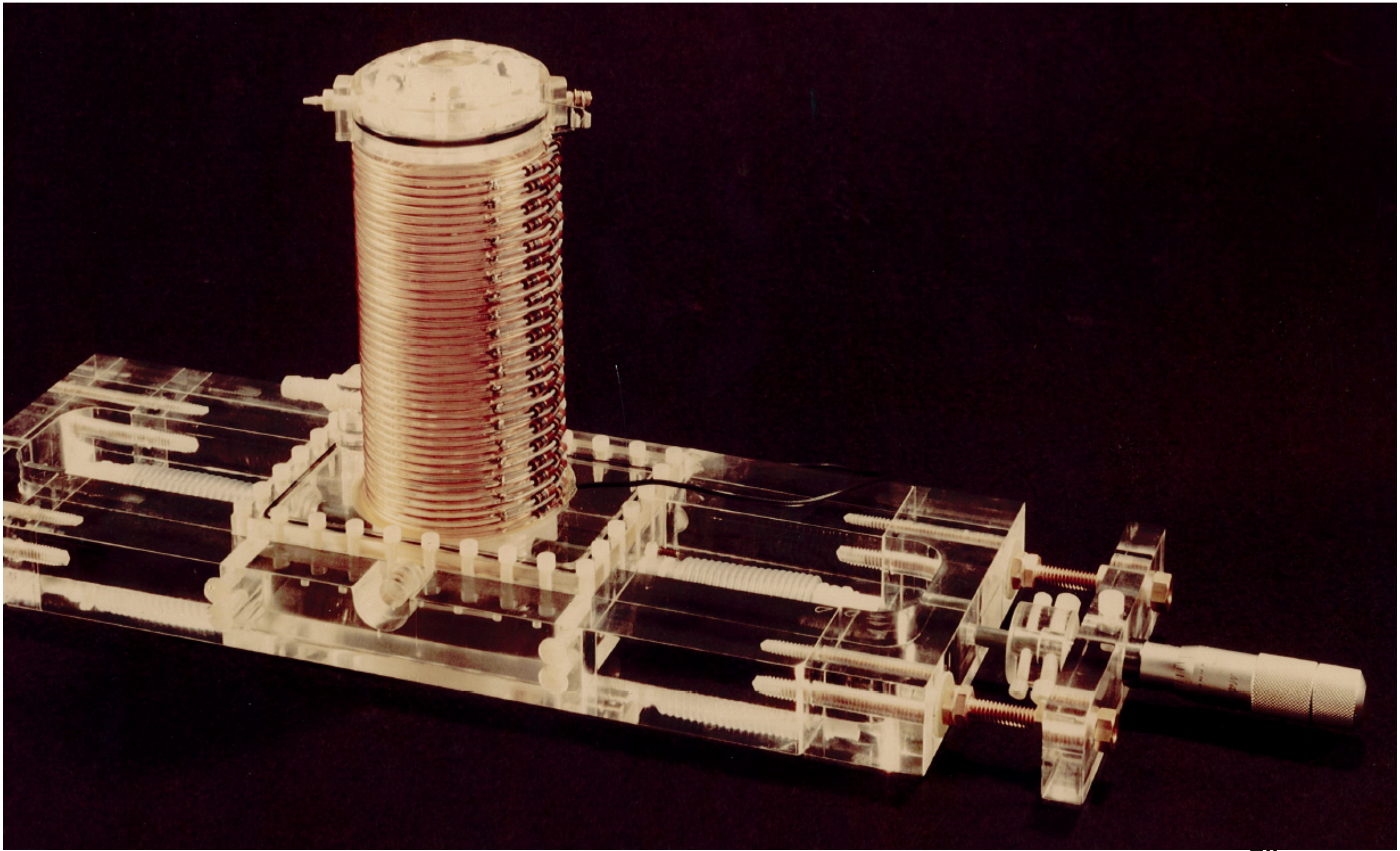
- Quantum mechanics in action!



# Time Projection Chamber…?

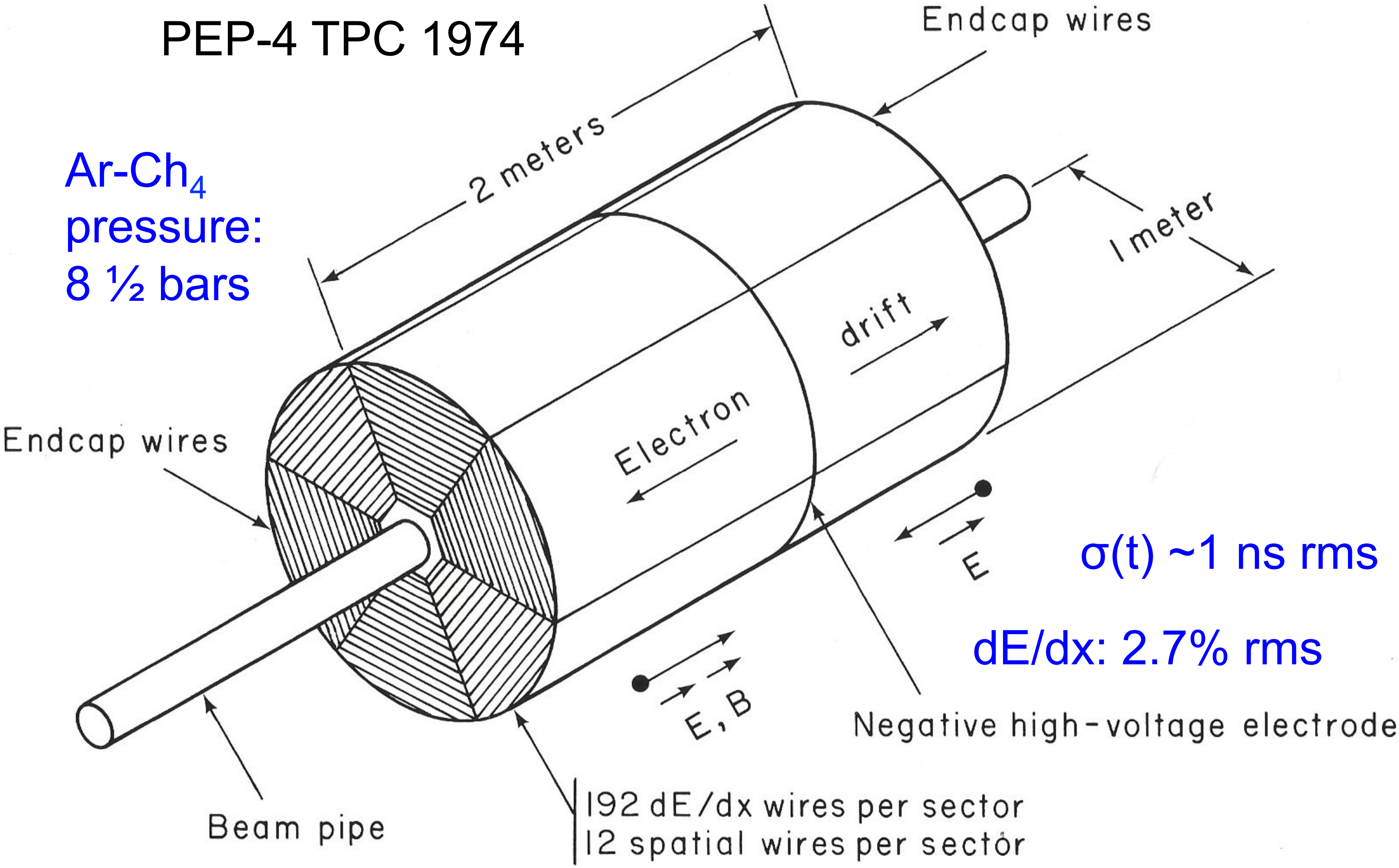
- If $\omega\tau >> 1$, then track images in gas can be transported by an E-field over large distances with little loss of information !
- If track images are drifted to a readout plane with 2D (**x-y**) +timing information, then the raw data is intrinsically 3-D !
- projection in time, knowing drift velocity, then gives third coordinate **z**. → "TPC"

## LBL - 1974: A device was built to understand diffusion in magnetic fields



# PEP-4 TPC 1974

Ar-$Ch_4$
pressure:
8 ½ bars




σ(t) ~1 ns rms

dE/dx: 2.7% rms

XBL 808-1709


PEP-4
TPC Sector

# Electronic Advances - 1970’s

- 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?

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  - Can we use this new-fangled charge-coupled device (CCD)?
  - Linear array for delay-line applications existed (**Fairchild**)
  - Capture information at **super-high**-rate: 10 MHz
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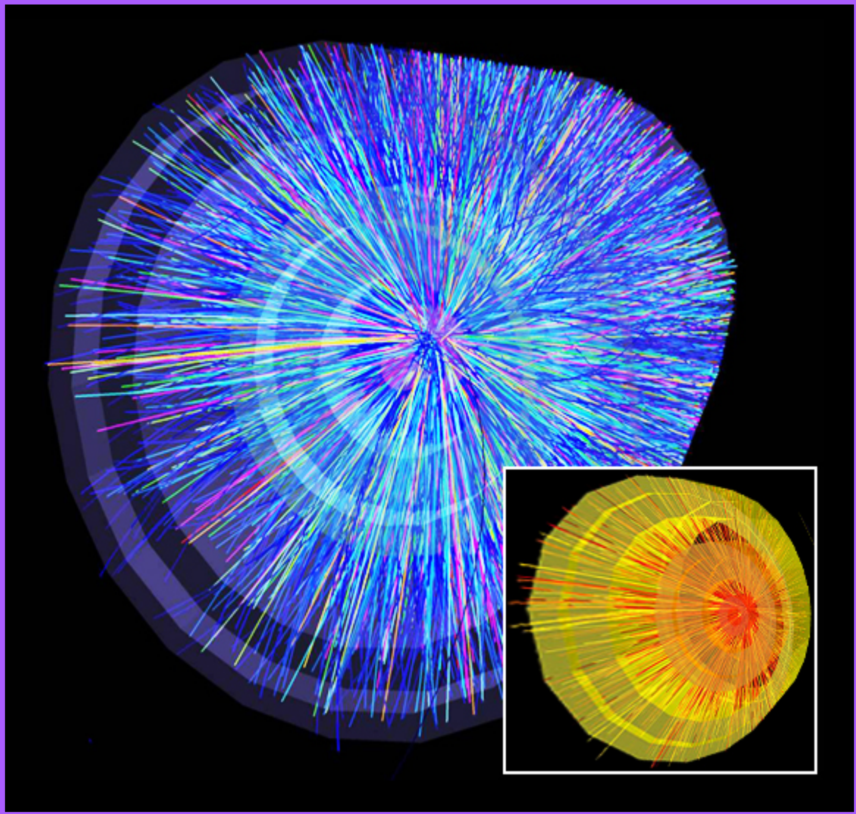
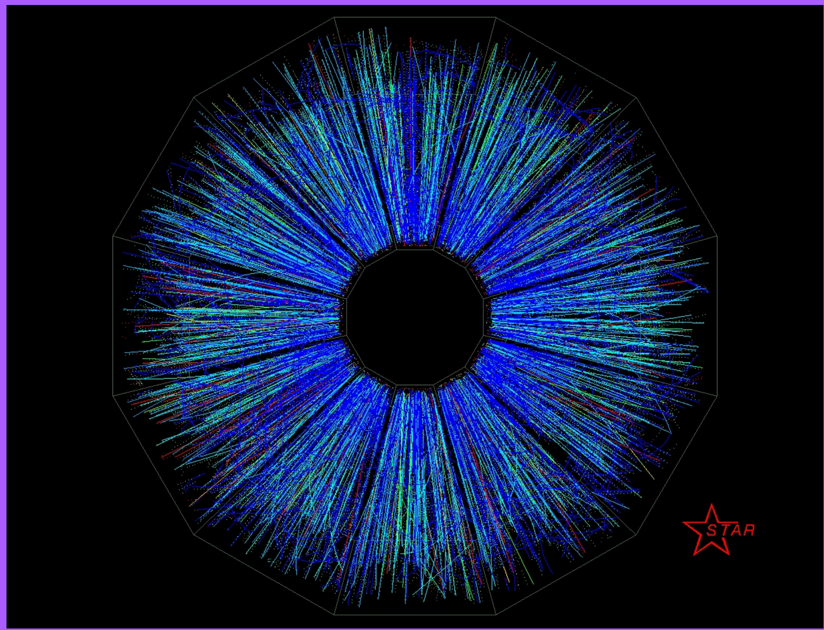
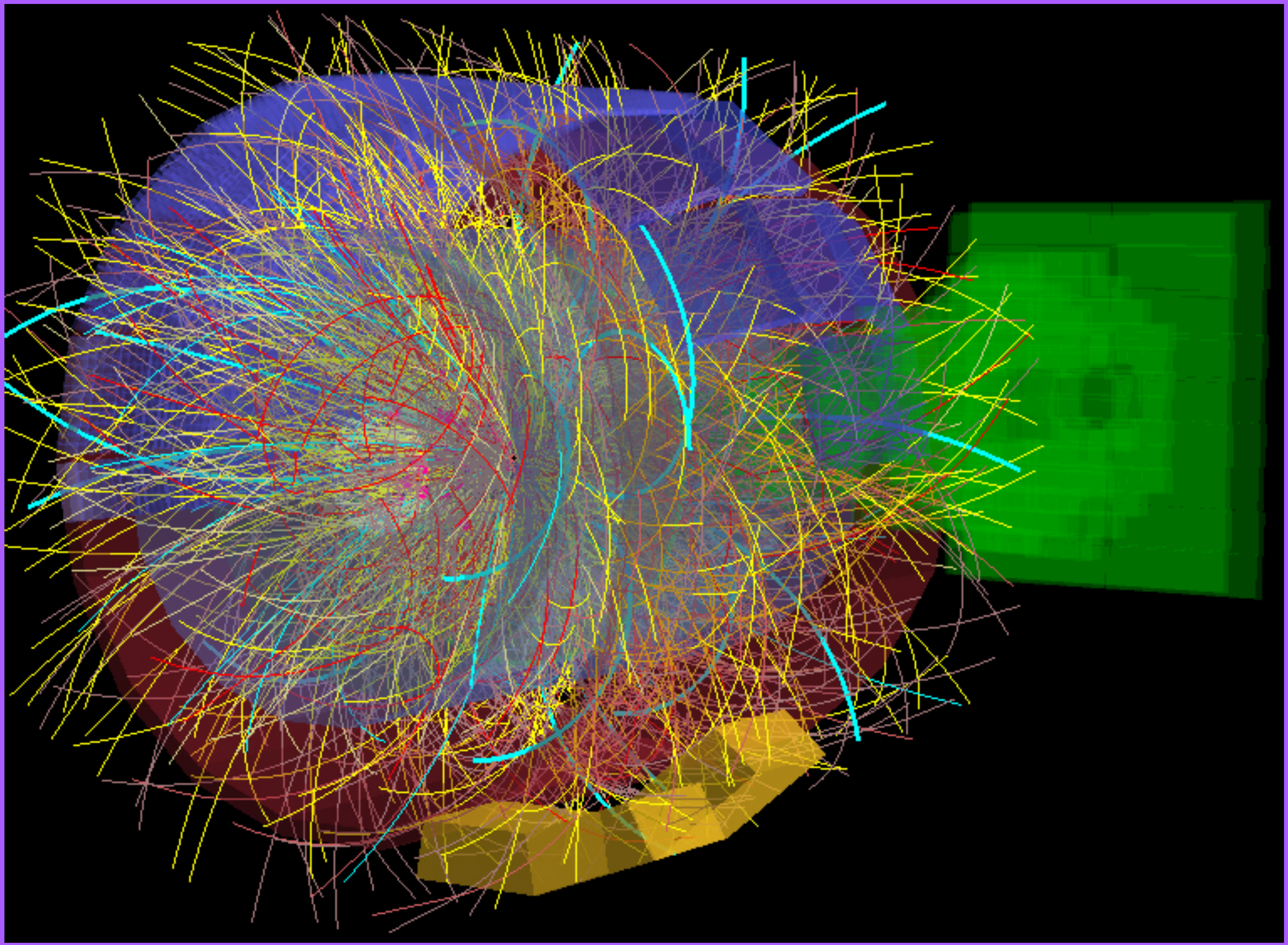
  - Capture information at **super-high**-rate: 10 MHz
  - Digitize captured analog information <1 MHz when trigger occurs
- When clock frequency switched, CCD device didn't work!
  - Fairchild graciously redesigned the internals to avoid "corners"
  - *An enabling technology* - essential to ultimate success of PEP-4.

# Large TPCs in action today

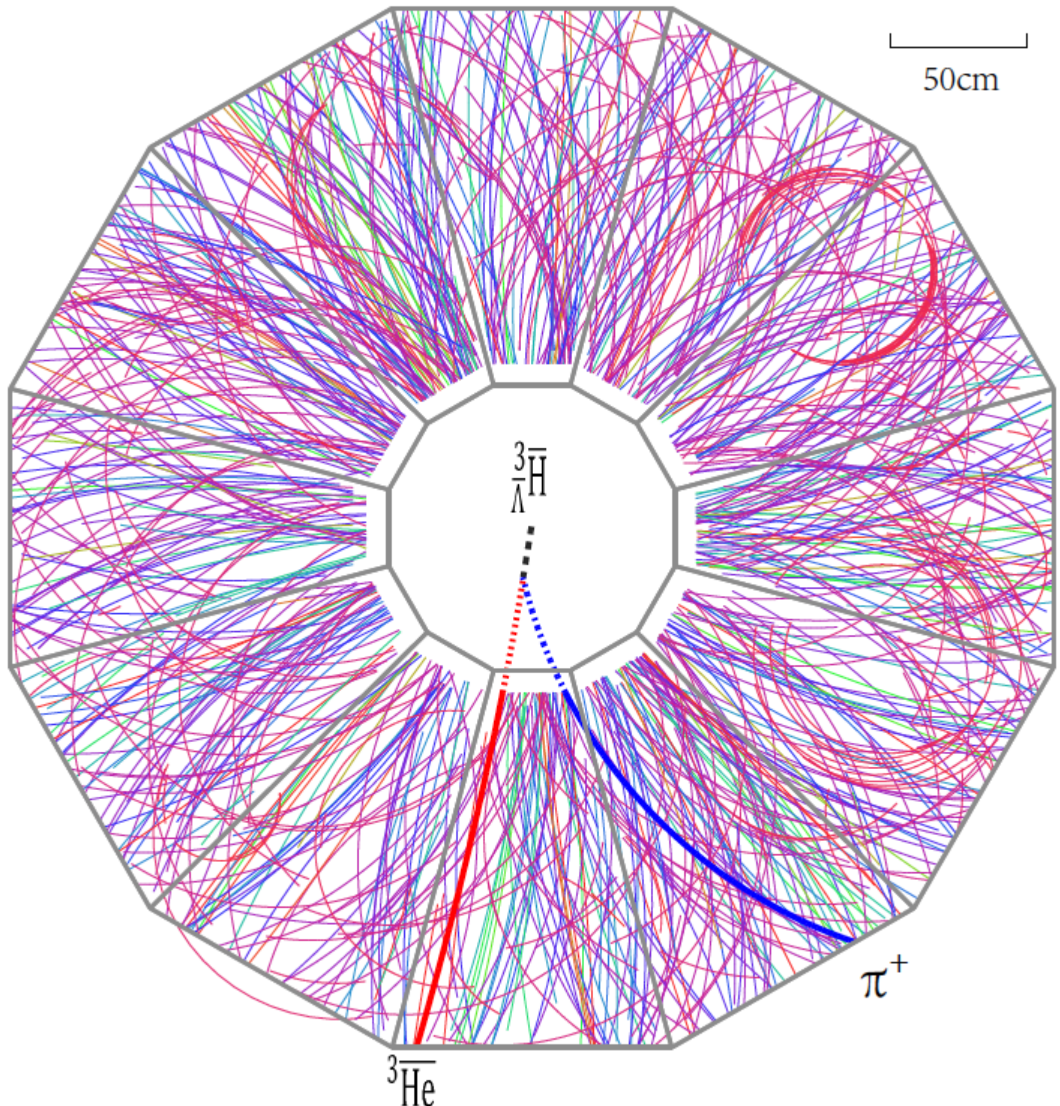




# ALICE event



# My favorite event…




Credit: STAR Collaboration

**STAR TPC:**

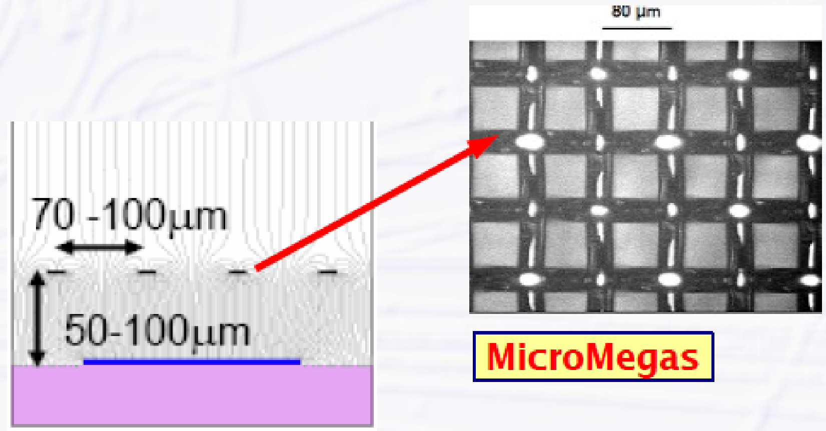
Production of anti-strange $^{3}H$ followed by decay to anti-$^{3}He$

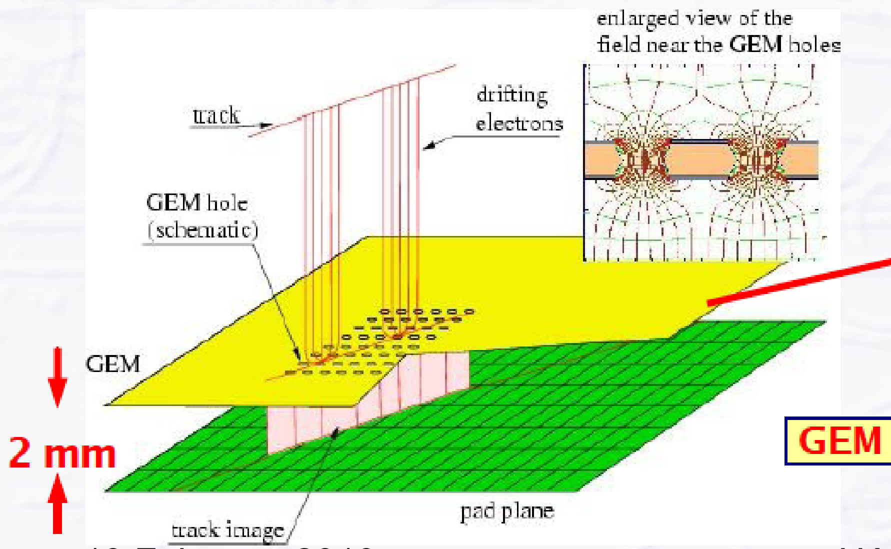
# Many Diverse TPC Applications

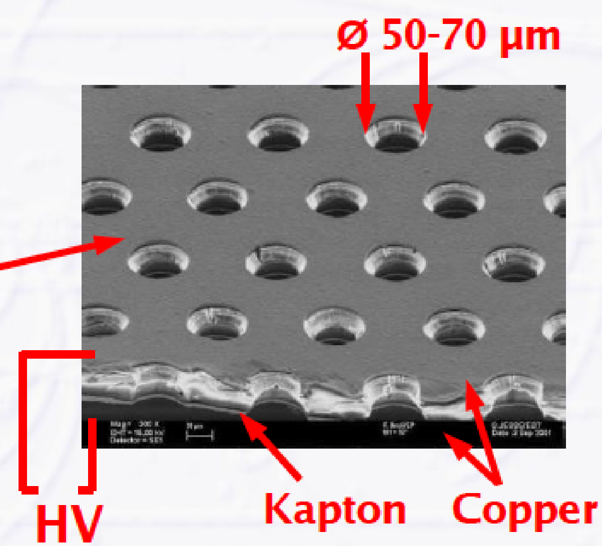
- $e^+ e^-$ collisions
  - PEP-4/9
  - TOPAZ
  - DELPHI
  - ALEPH
- P-bar-p collision (CDF, D0)
- pp collisions (FNAL)
- *v* - *N* collisions
  - T2K
  - ICARUS
  - Spherical TPC
  - DUNE
- n - (p or He) recoils
- accelerator commissioning
- Rare decays and events
  - $\mu \rightarrow e\,\gamma$ TRIUMF,…
  - $\beta\,\beta$ decay UCI, EXO, NEXT-XXX
  - WIMP - *N* collisions
  - axion searches (CAST)
- Space & Astronomy
  - x-ray polarimetry, imaging
- $\gamma$-p (LEGS - BNL)
- $\mu$-lifetime ($\mu$cap - PSI)
- *N* - *N* collisions
  - NA35, 36, 49
  - STAR
  - ALICE
  - SAMURAI
- ?

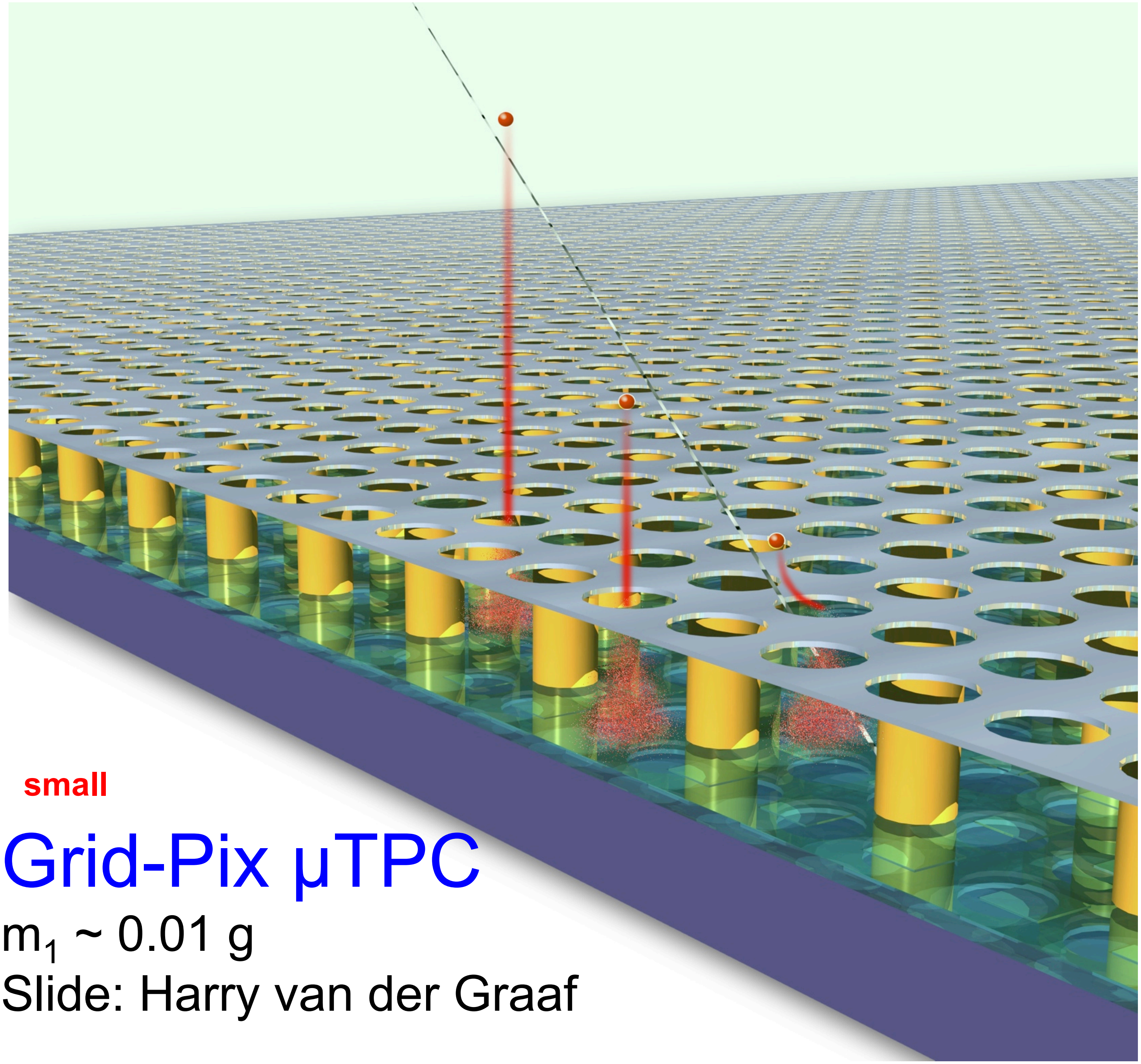
# Recent Developments: Micro Pattern Gas Detectors (MPGD)

- 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$^2$





small

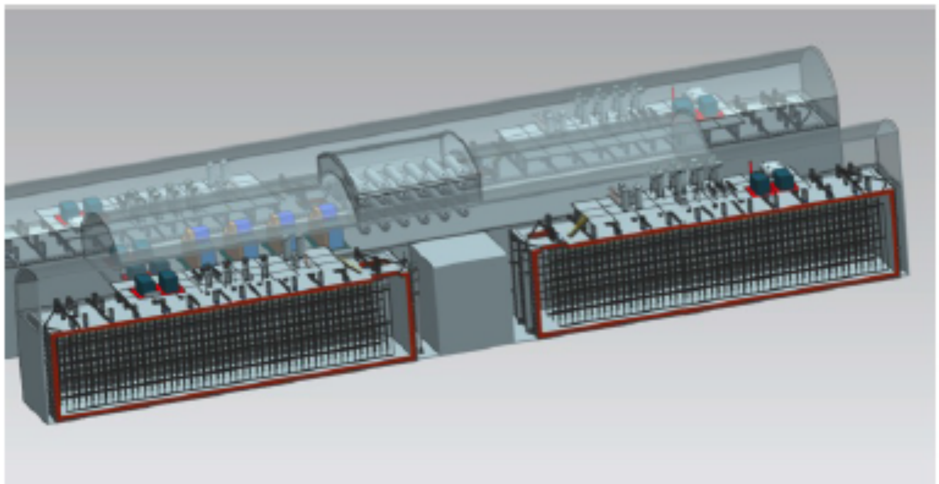
# Grid-Pix µTPC

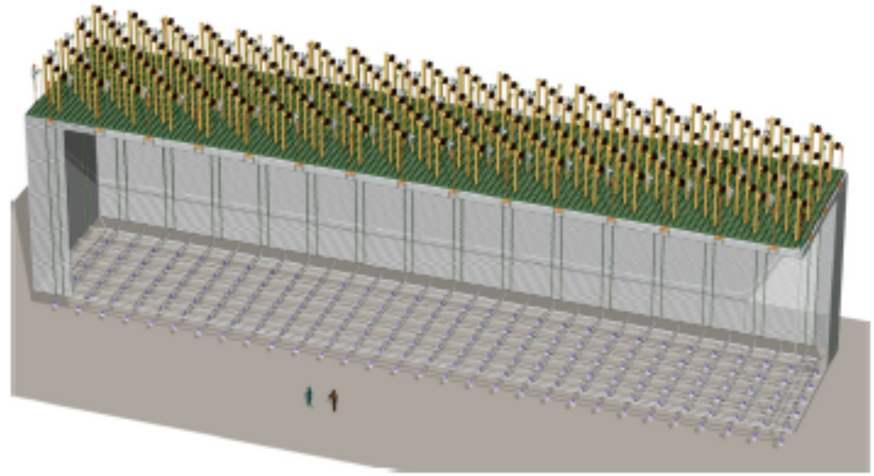
$m_1 \sim 0.01$ g

Slide: Harry van der Graaf

# DUNE

# LARGE



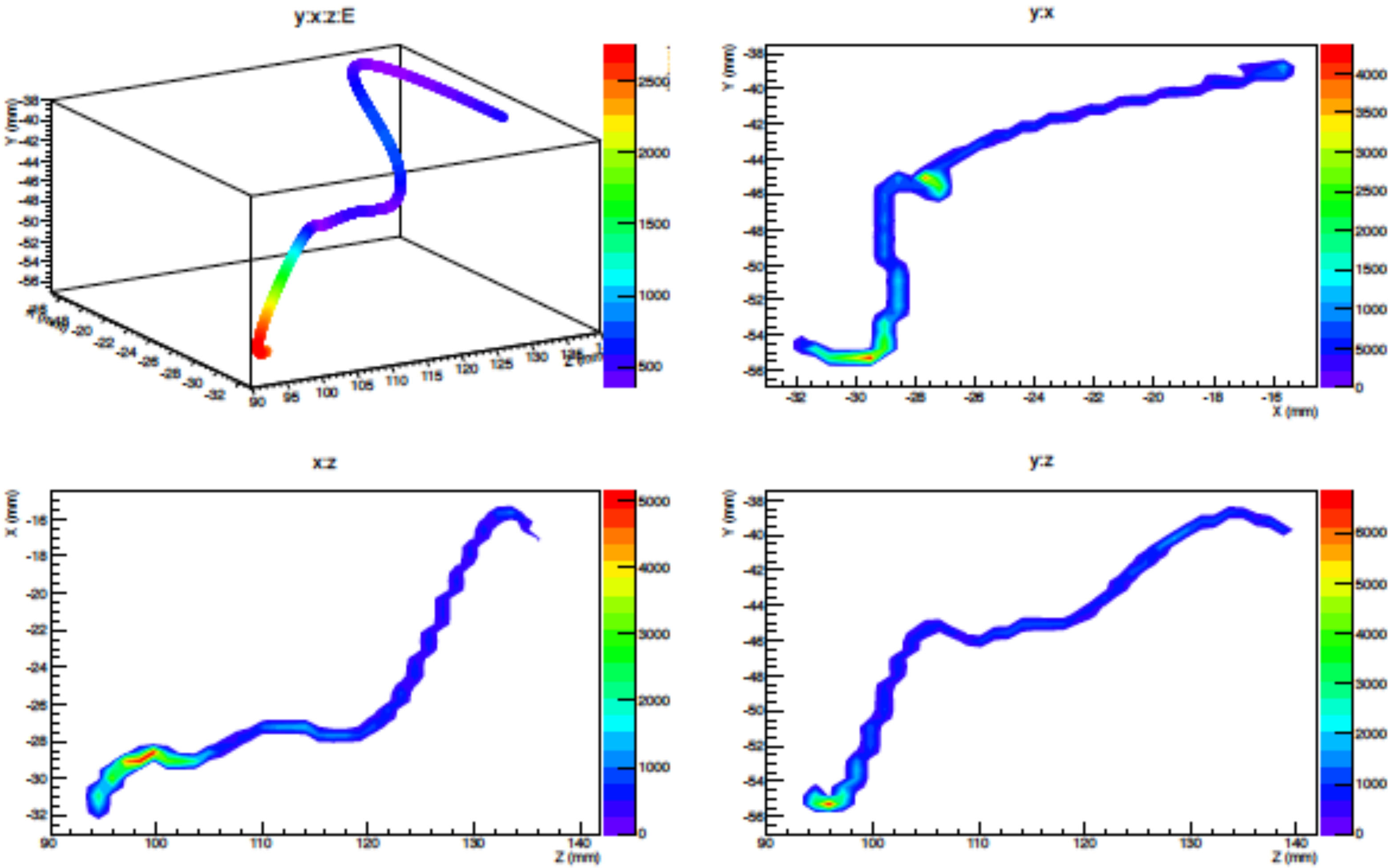


Liquid Argon TPC

$M_2$ = 10 kton

**$m_2/m_1$ ratio:** **~ $10^{12}$**

## **DATA:** Real track from $^{137}$Cs γ-ray – reconstructed with SiPMs

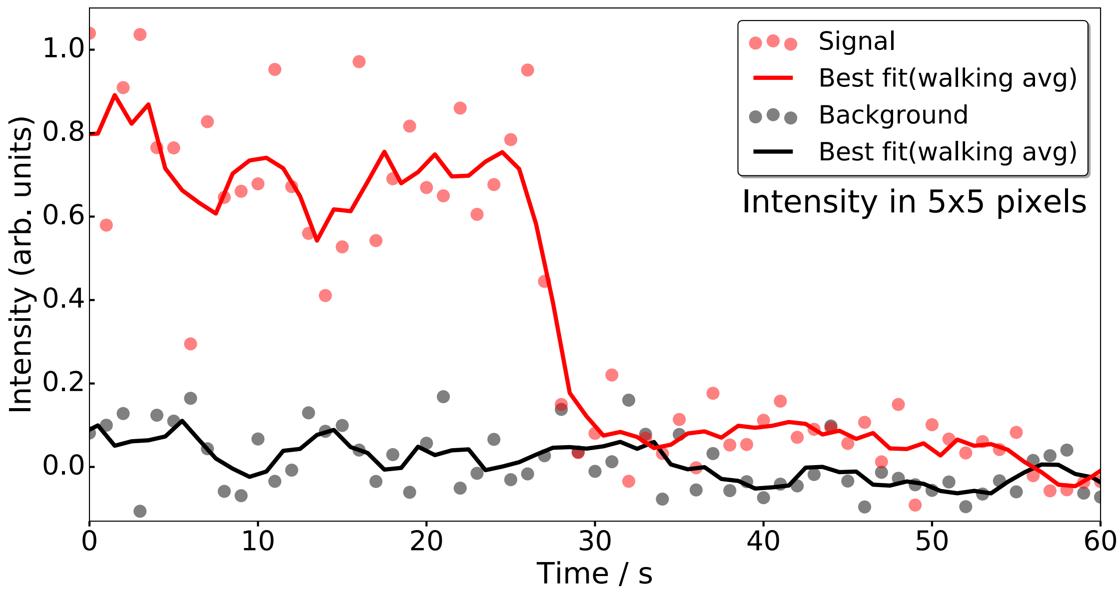


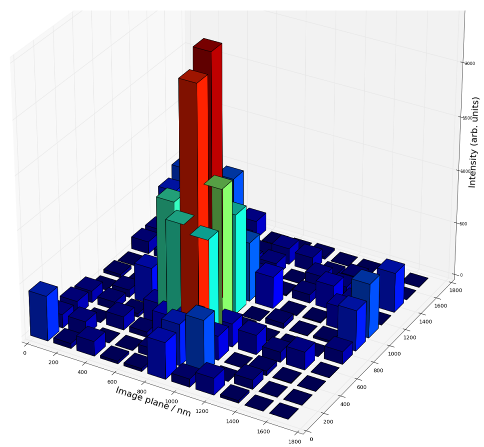

**DATA** from NEXT-DEMO IFIC, Valencia

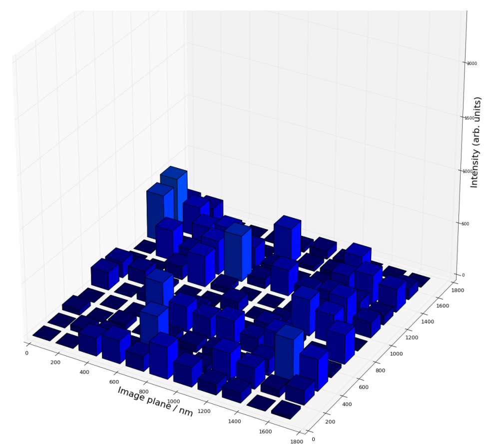
Search for 0*ν*-*ββ* decay in $^{136}$Xe → $^{136}$Ba

# Single Barium ion Detection!

## Single Molecule Fluorescence Imaging





**Single** step photo-bleaching confirms single-molecule interpretation

One second exposures before and after bleaching

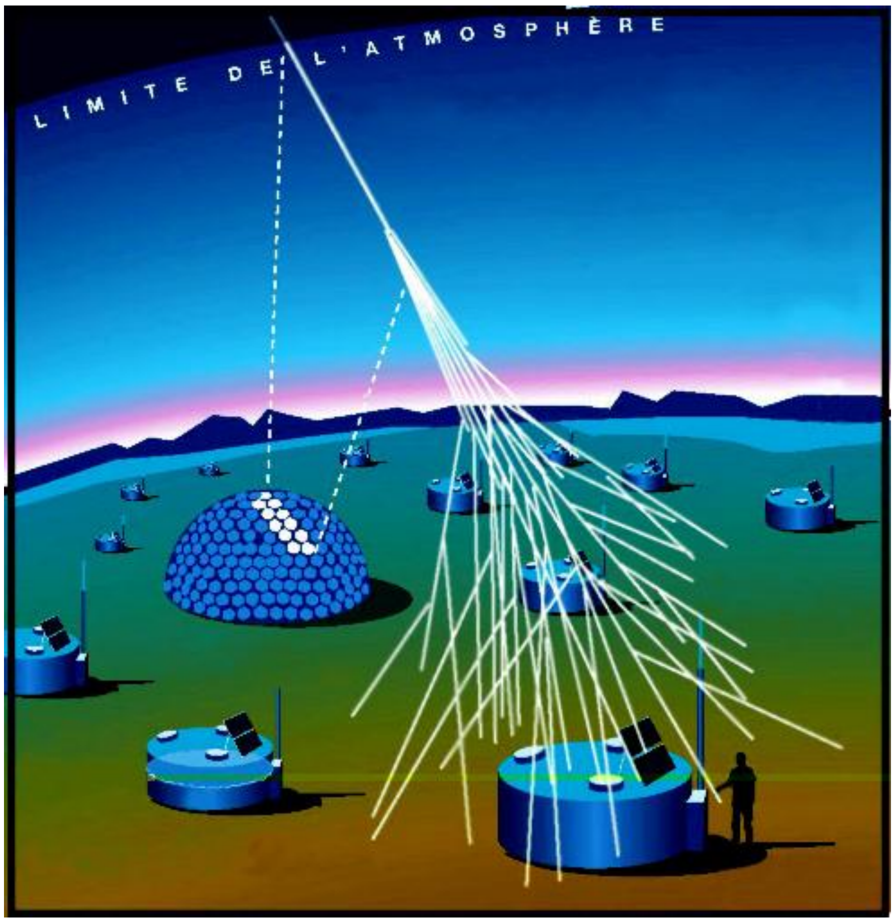
12.9 σ detection
2 nm rms localization

Detection of $Ba^{++}$ daughter eliminates all γ-ray events

# Epochs: A Century of Punctuated Equilibria

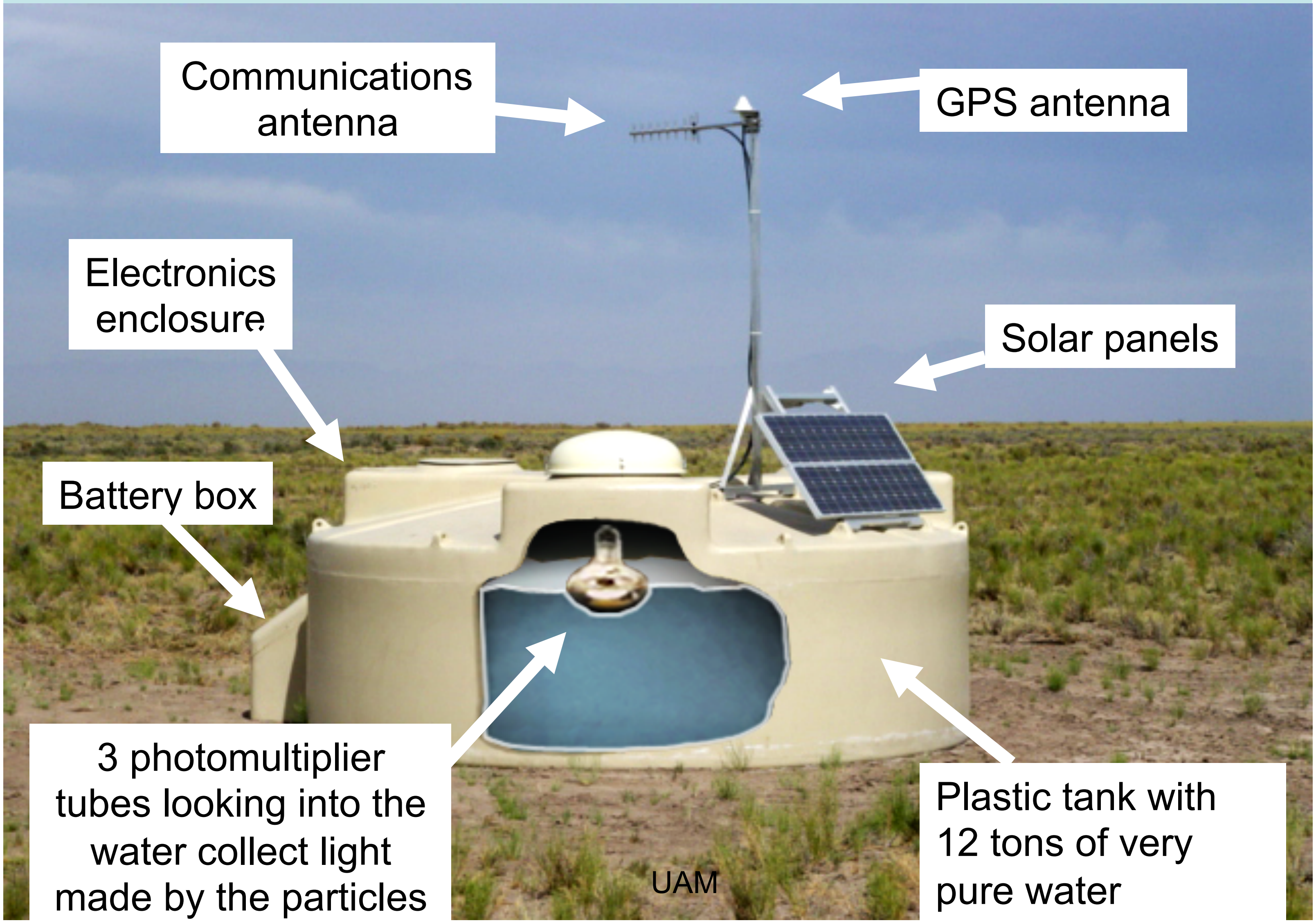
- First discoveries - "Bronze age"
  - many particles inducing visible images
- Single particle detection - "Age of discovery"
  - large amplification through avalanches
- Complex event reconstruction - "Golden age"
  - MWPC, MPGD, TPC, …
- Present era - "*megalithic age?*"
  - **huge**: data, systems, networks, collaborations…

# The Auger Observatory: megalith #1




- A large surface detector array (1600 water tanks for Cherenkov light) combined with fluorescence detectors results in a unique 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 calorimetric energy calibration from the fluorescence detector to the event gathering power of the surface array.

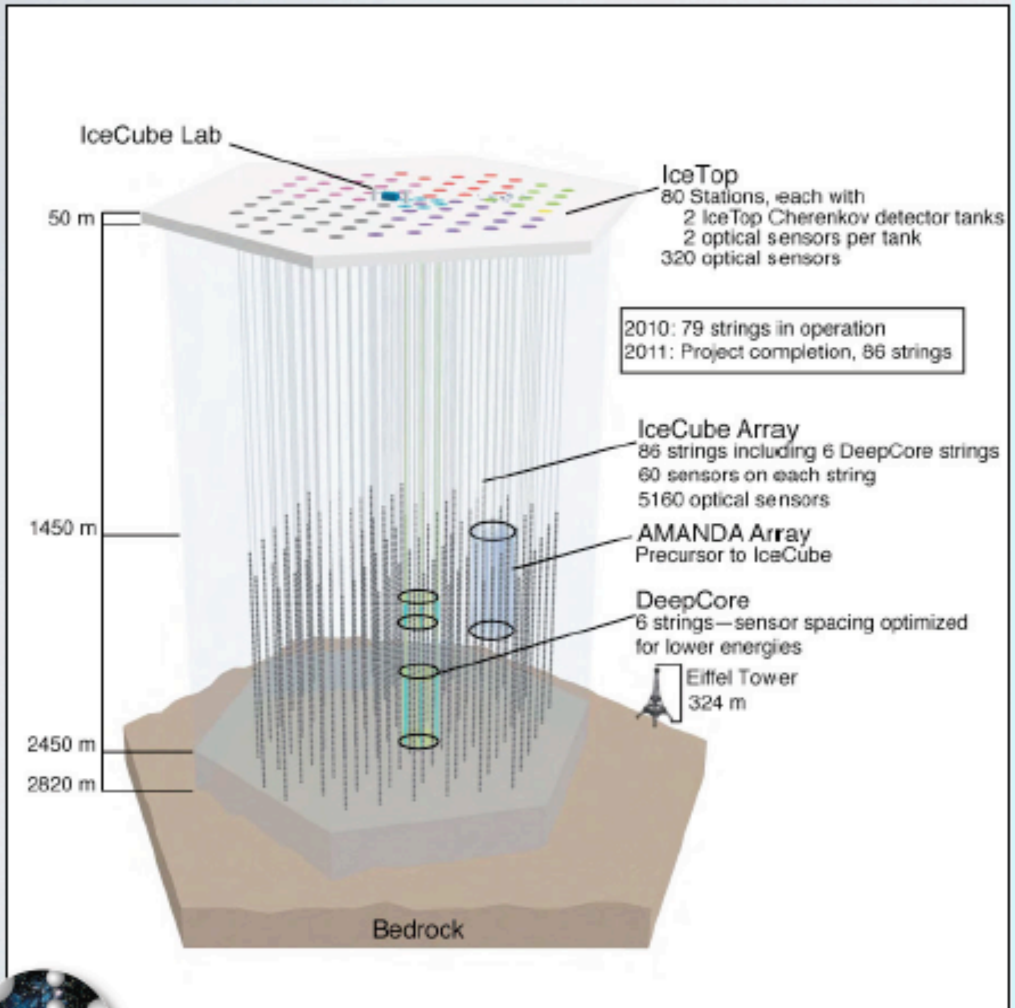
# **Auger** surface array station –
# –devolution of function to sensors



# THE ICECUBE OBSERVATORY


Lesson: how one thing may lead to another

# IceCube at the south pole – megalith #2



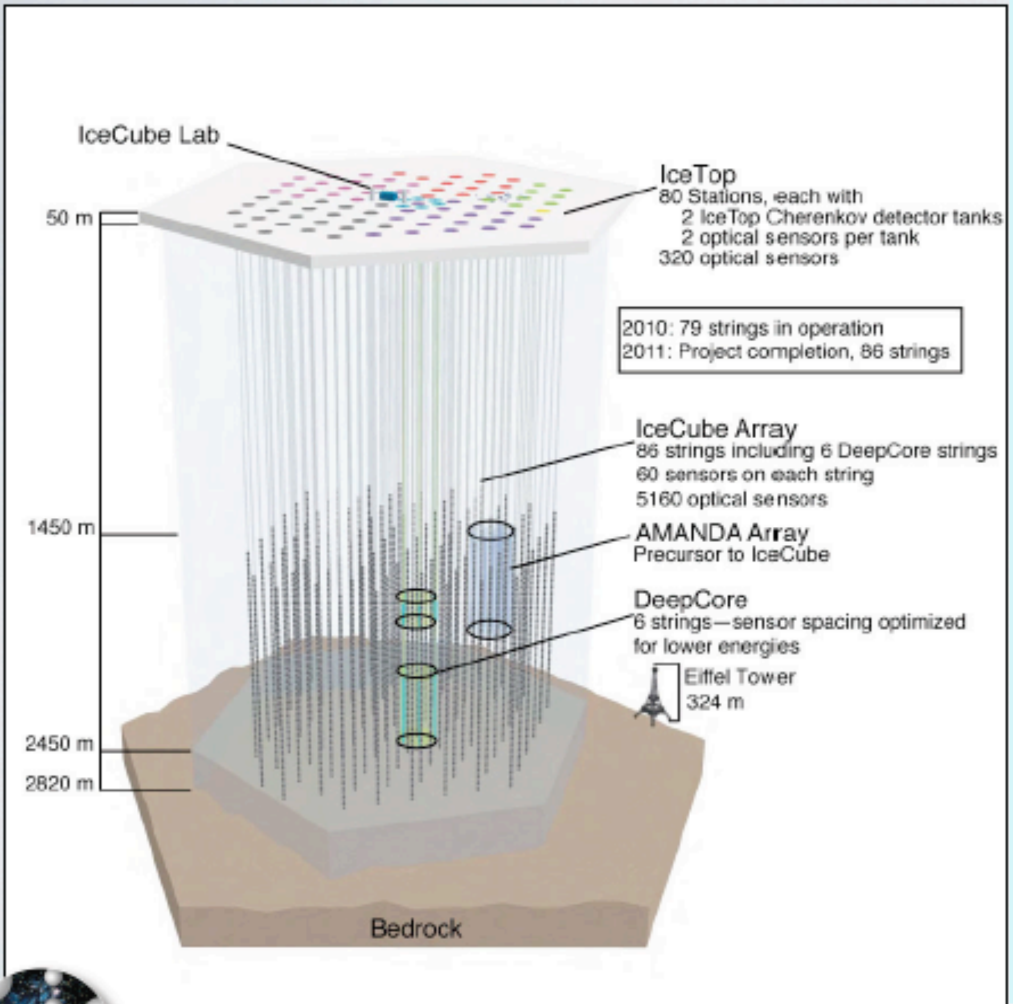

*AMANDA, the precursor to IceCube was based on a centralized analog DAQ.*

*PMT signals were degraded severely by transmission over 2-km long cables*

*Was it possible to switch to a DAQ based on a low-power decentralized digital network?*

*Wanted: low-power 14-bit 400MHz ADC; not available in the 90's ! What to do ?*

# IceCube at the south pole – a megalith




***Solution:***

*Digital Optical Module (DOM)*

86 strings completed >5000 DOMs in January 2011

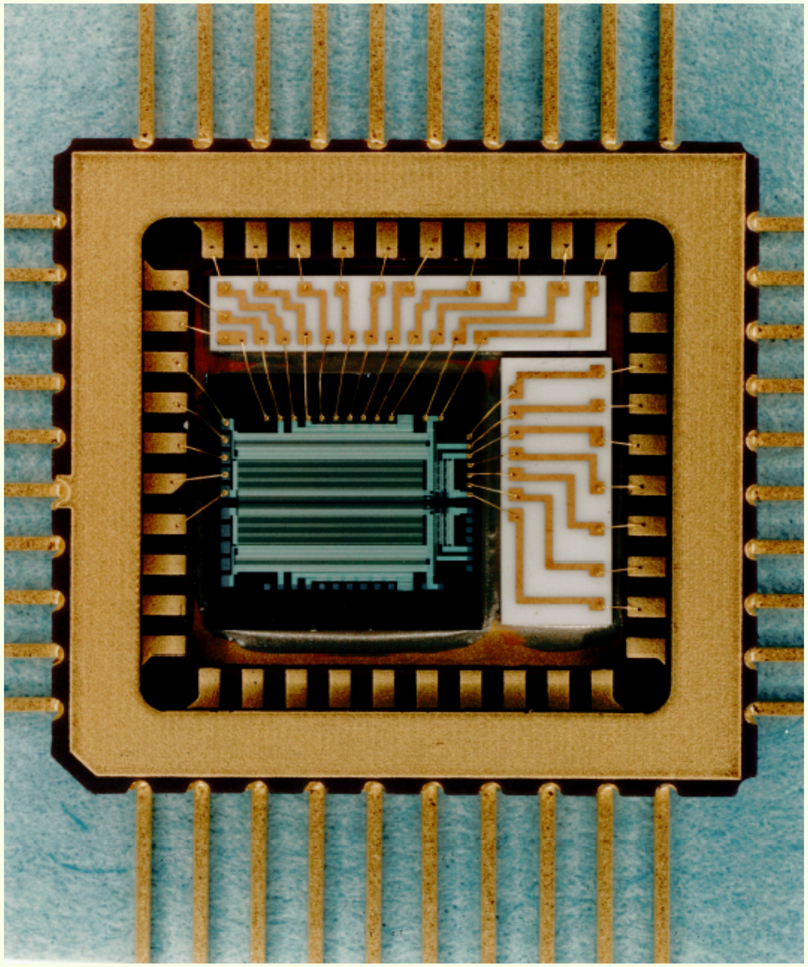
~2 ns rms resolution over 1km$^3$ volume, >98% alive

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

The DOM was made possible by a single device: *Analog Transient Waveform Digitizer*

## (1996): 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

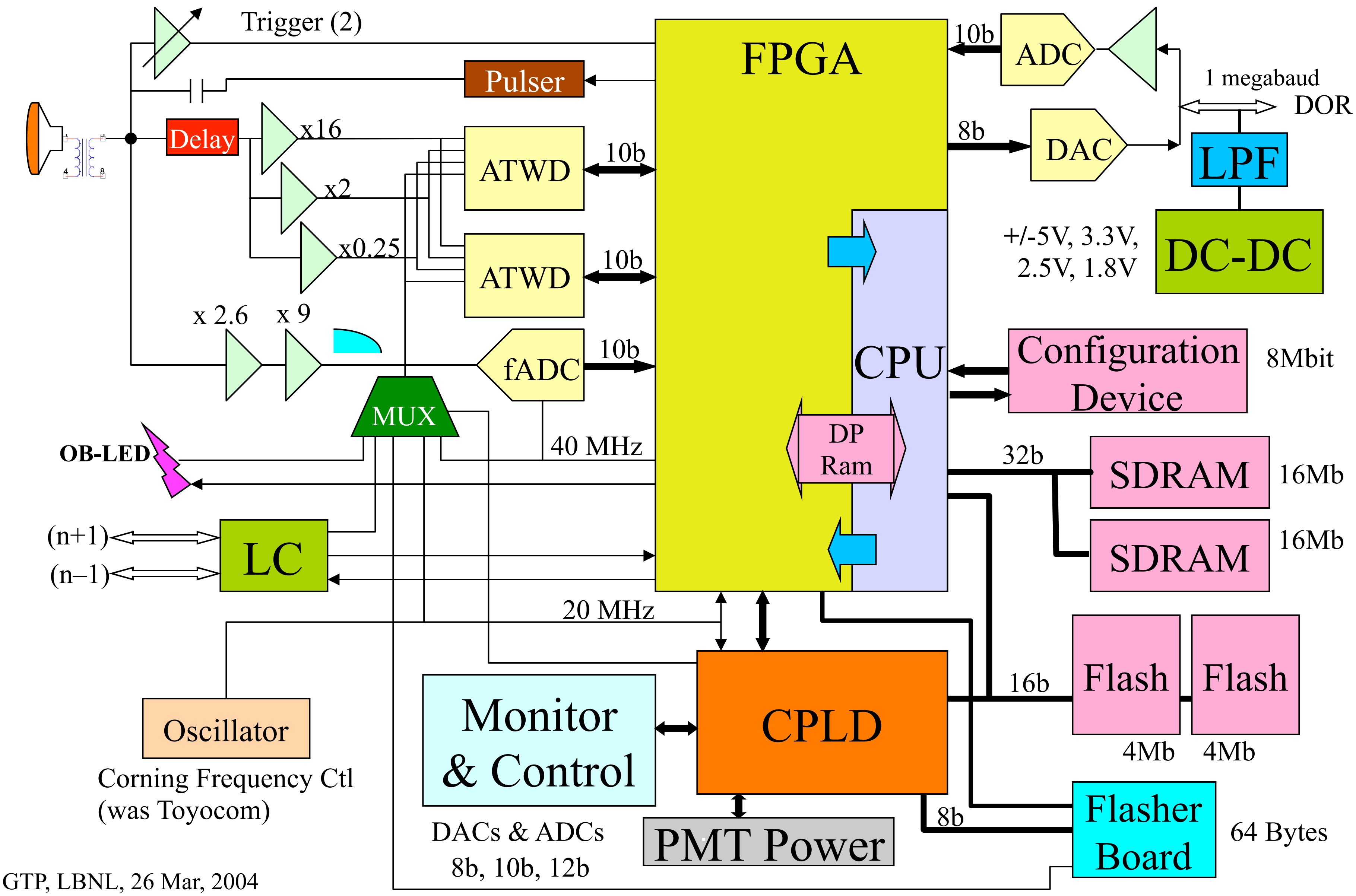
synchronous sampling: variable from 200 - 1000 MHz!

2.5 μm technology; so last century!

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

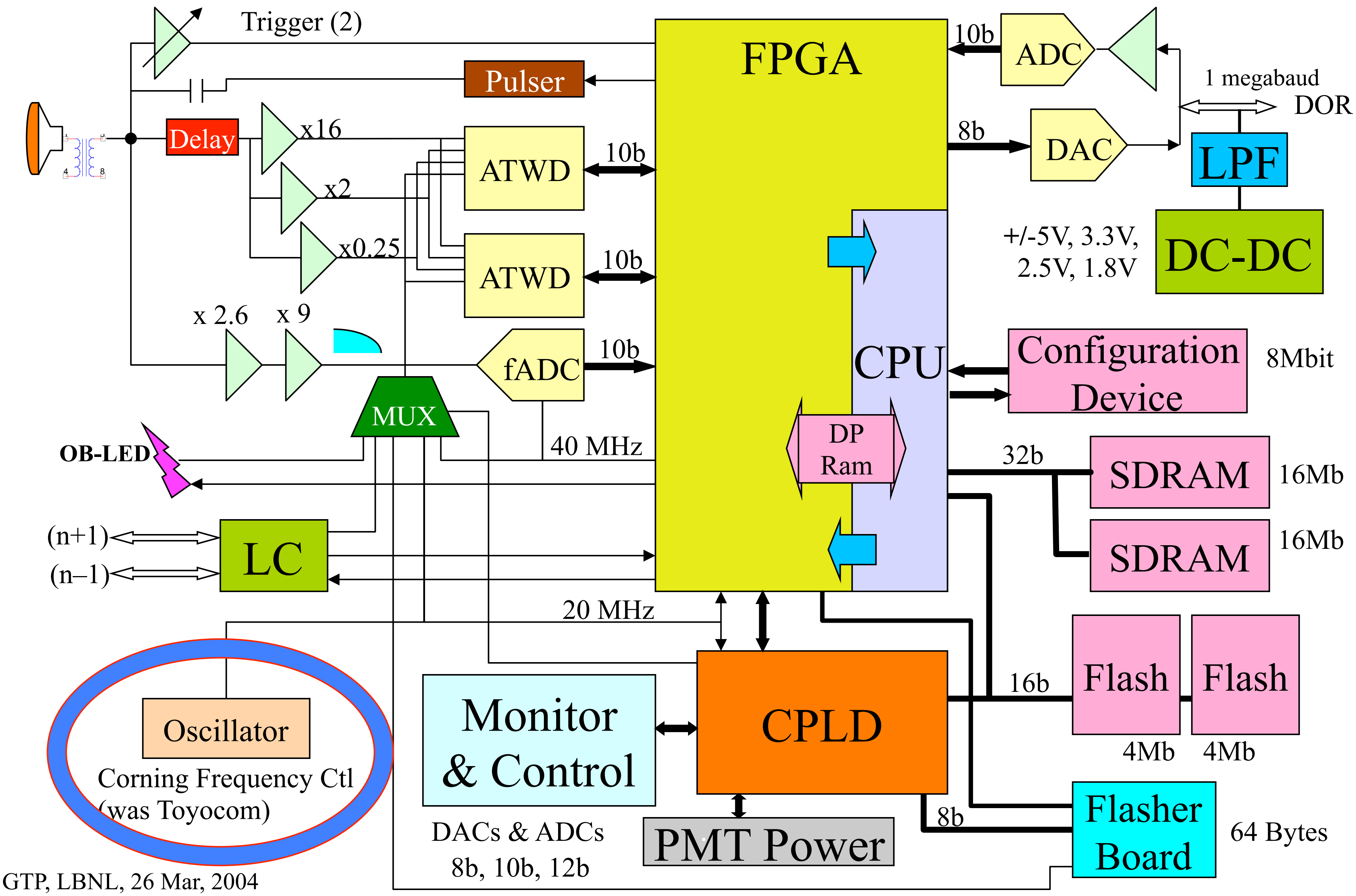
Stuart adds internal ADC - ready!

# Digital Optical Module Block Diagram




GTP, LBNL, 26 Mar, 2004

# Digital Optical Module Block Diagram



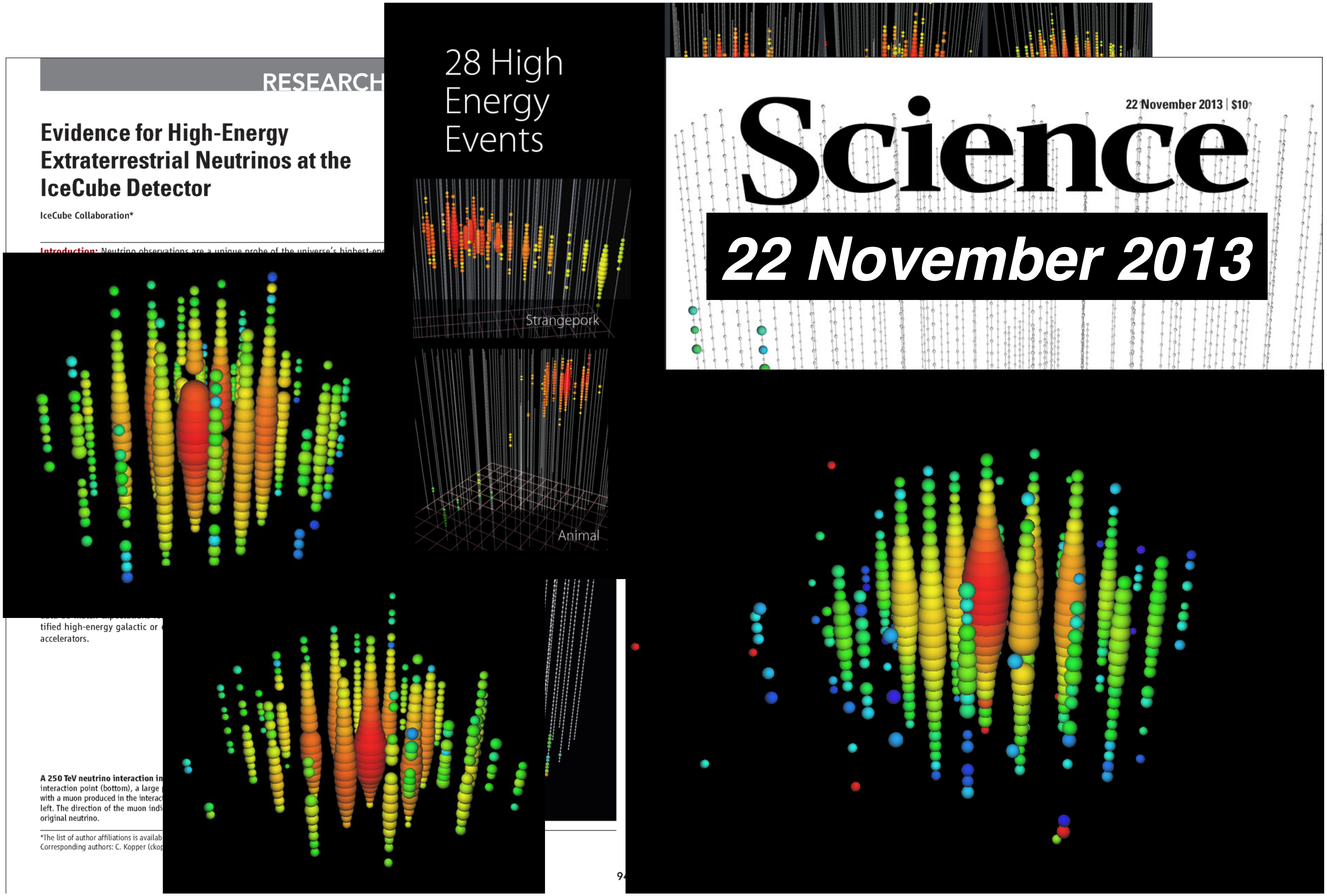

GTP, LBNL, 26 Mar, 2004

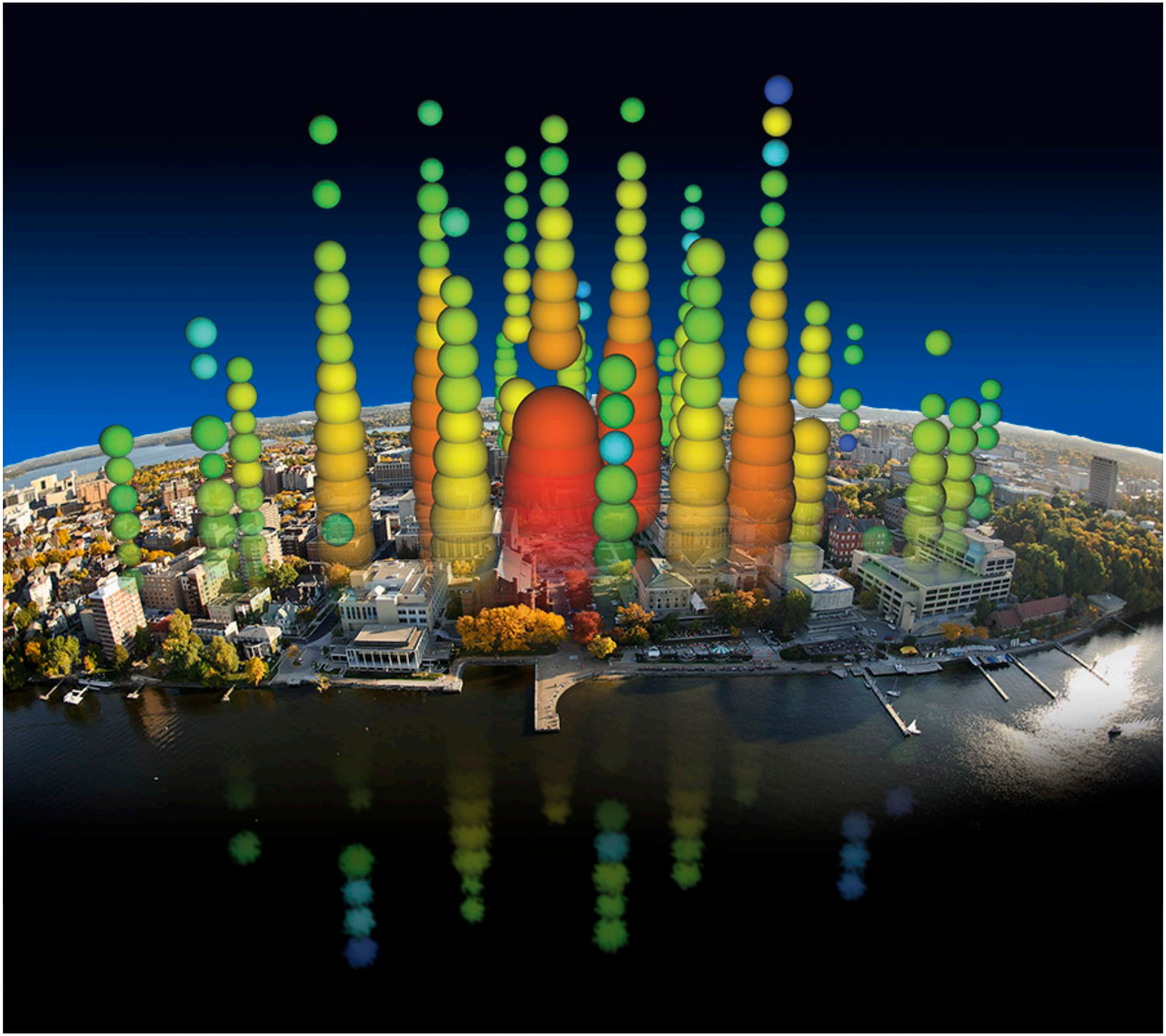
# Timing up IceCube

- Send a large bipolar pulse down to DOM: “what time do you have?”
- DOM captures waveform, local time, waits a bit
- DOM then sends identical bipolar pulse back up: “Here is my local time.”
- Surface DAQ captures return pulse timing + info.
- From these two pulses + messages, cable length and local time are found: ±2 ns rms
- Critical: oscillator stability: $\delta f/f < 1 \times 10^{-9}$ per second

# DOM: complete success!

- "Obvious" now, but not so in late 90's
- Perspective:
  - A single device, the ATWD, was the enabling element for a total reformation of information capture in IceCube.
    - Maximal devolution of function to periphery

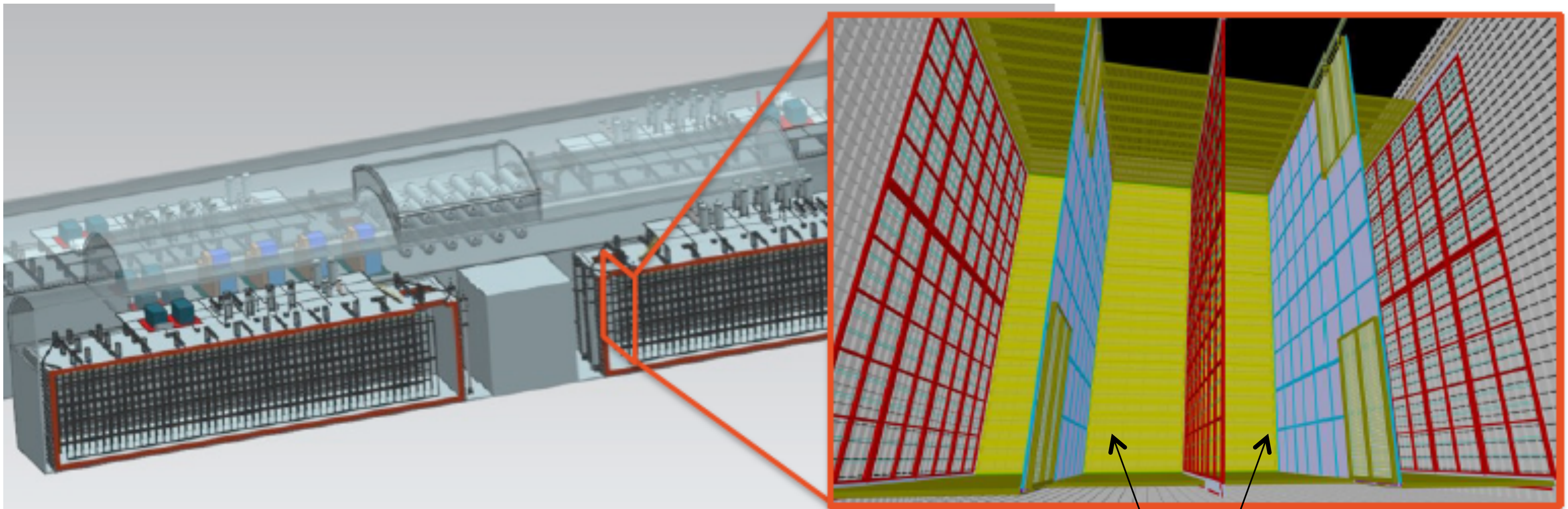

RESEARCH
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
IceCube Collaboration*
tified high-energy galactic or
accelerators.
A 250 TeV neutrino interaction in
interaction point (bottom), a large
with a muon produced in the interac
left. The direction of the muon indi
original neutrino.
28 High Energy Events
Strangepork
Animal
Science
22 November 2013 | $10
22 November 2013



# DOM: complete success!

- “Obvious” now, but not so in late 90’s
- Perspective:
  - A single device, the ATWD, was the enabling element for a total reformation of information capture in IceCube.
    - Maximal devolution of function to periphery
  - How might this idea be applied elsewhere?

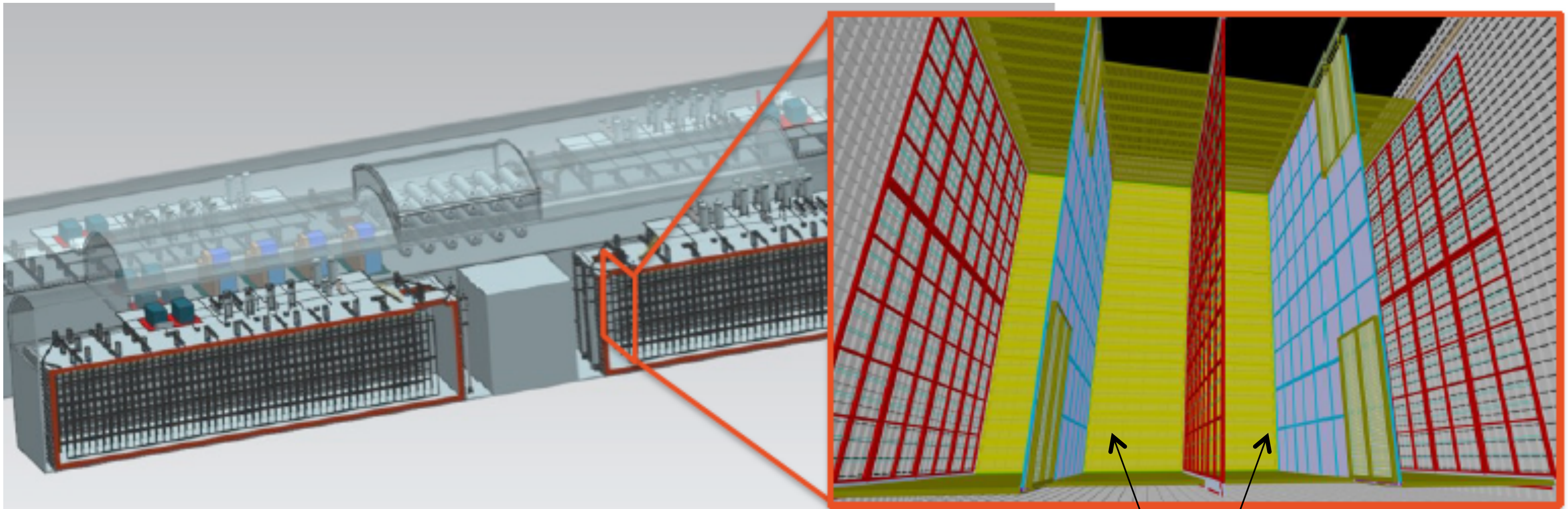
# Megalith #3
# Deep Underground Neutrino Experiment: DUNE



Flagship project of US HEP program
Goal: 40 kilotons of LAr TPCs !

3.6 m drift of electrons through LAr to planes of wrapped wires

# Megalith #3
# Deep Underground Neutrino Experiment: DUNE



Flagship project of US HEP program
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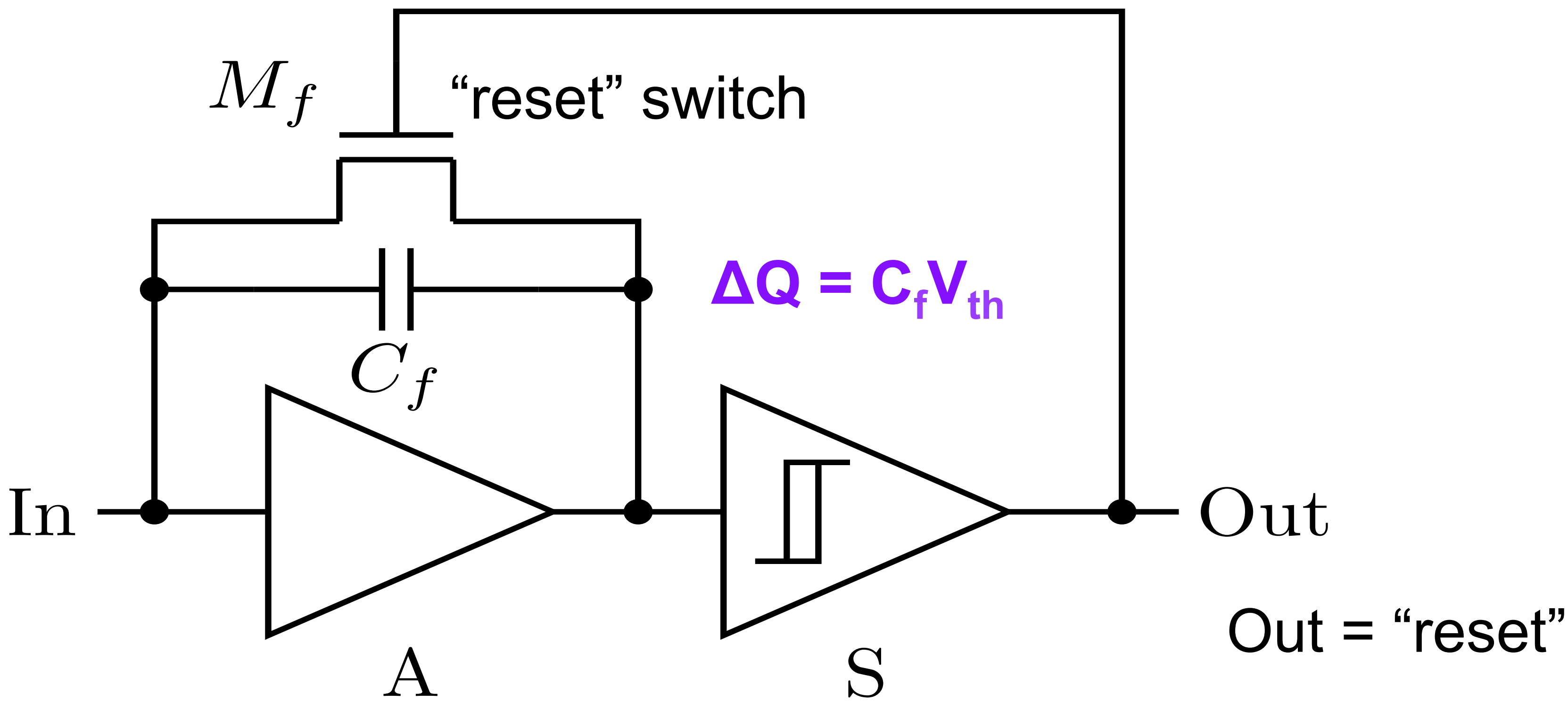
3.6 m drift to planes of wrapped wires

Issue: spatial projections → ambiguities in event reconstruction

# Why not "pixelate" DUNE?

- 3-D raw data → robust reconstruction
- New ideas may make this attractive
- Challenges:
  - Can the detector be mainly off, then instantly "on"?
  - Can the detector be made sufficiently robust?
- Q-Pix concept: novel waveform capture
- Maximum devolution, just like IceCube

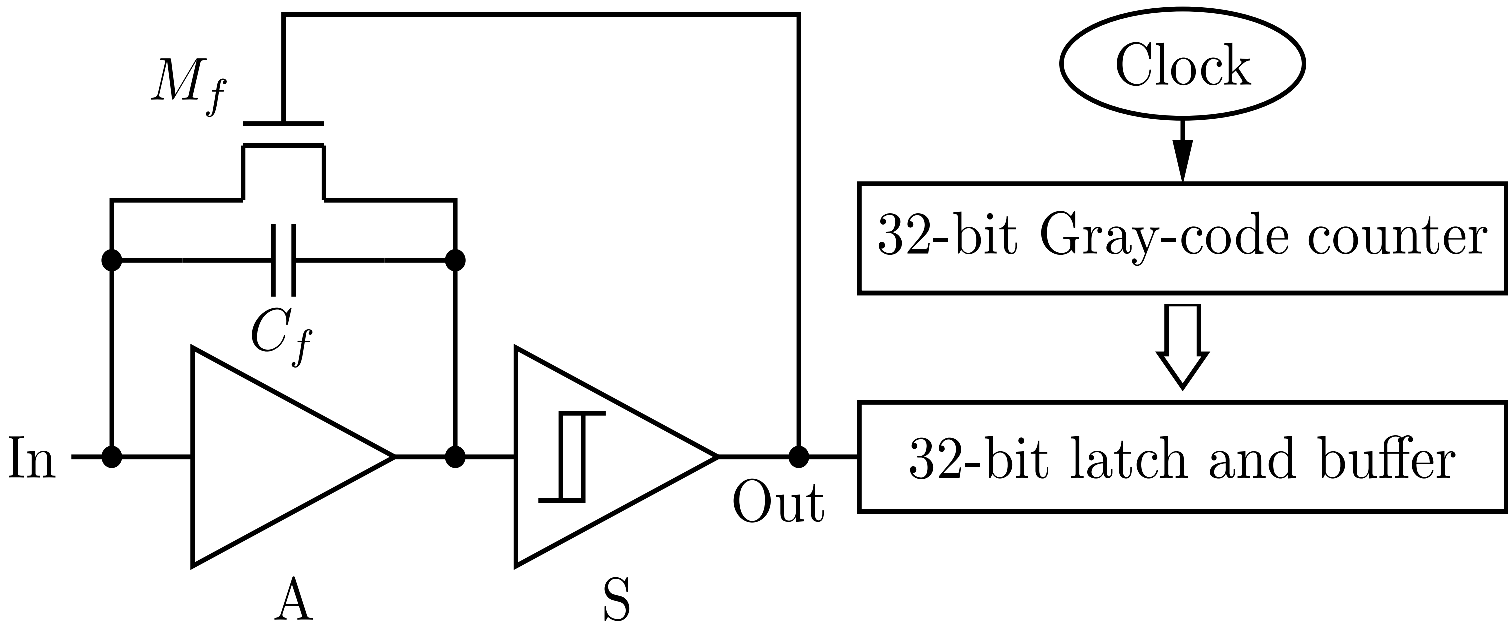
# “Charge-Integrate-Reset” (CIR)



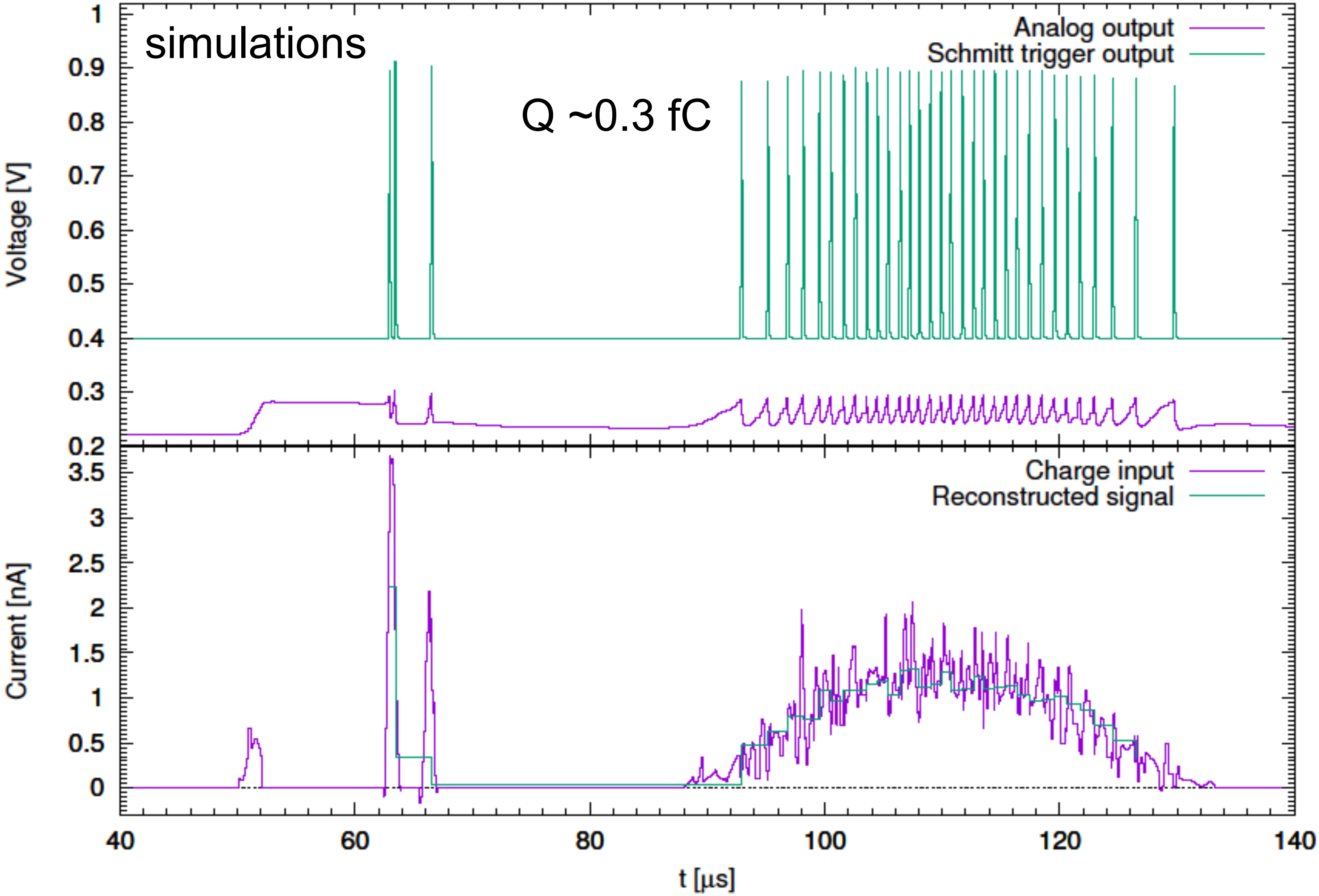

A = Charge sensitive amplifier  S = Schmitt trigger

$V_{th}$ = threshold

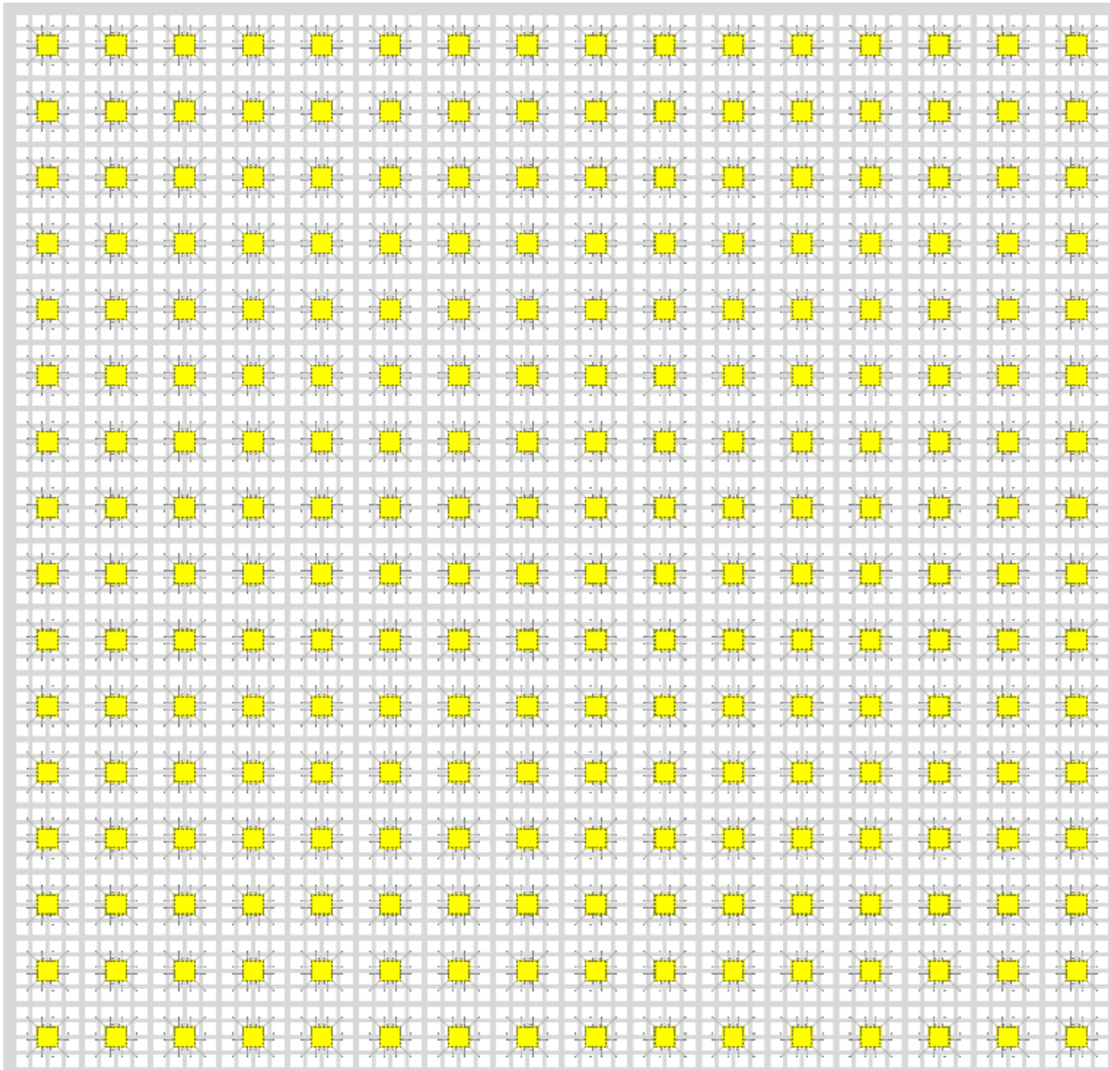
# Measure time of “reset”




Clock: local (within ASIC) oscillator free-running at 50 MHz
Reset time differences measure “time-to-charge”; ΔQ is fixed
Waveforms of arbitrary complexity are captured.


simulations
Q ~0.3 fC
Analog output
Schmitt trigger output
Voltage [V]
Charge input
Reconstructed signal
Current [nA]
t [µs]

# Q-Pix for DUNE ?



Q-Pix: silicon is inexpensive now

16 x 16 **Tile** of 256 ASICs, = 4092 pixels
**Tile** size:
256 x 256 $mm^2$

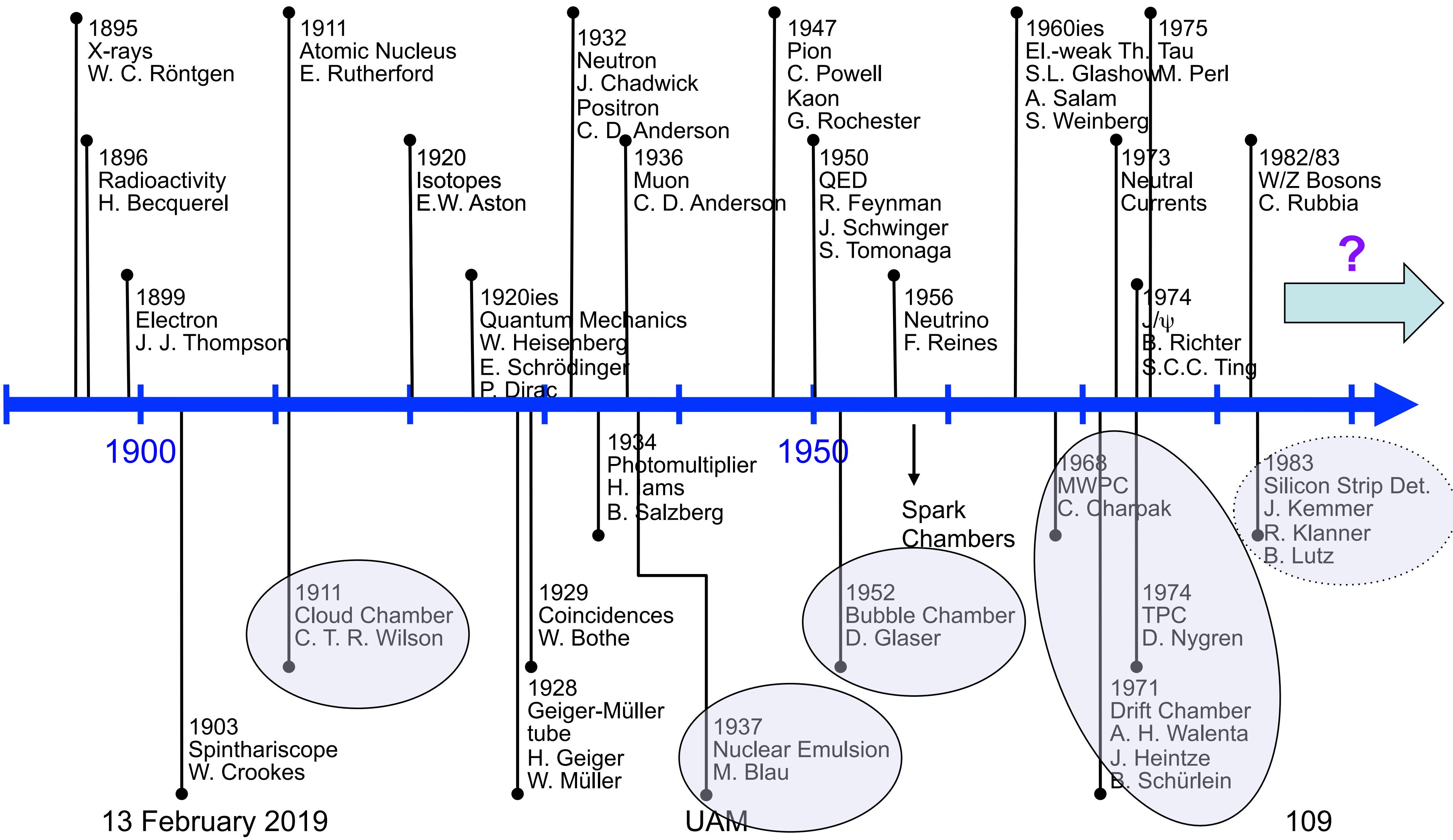
DAQ network is dynamically established!

Each ASIC has its own clock !

# Q-Pix remains to be demonstrated…

- Q-pix concept derives from IceCube
  - maximum devolution of functionality
  - Here $\delta f/f \sim 1 \times 10^{-6}\ s^{-1}$, much easier.
- Time-to-charge concept seems new!
- Q-Pix may turn out to provide optimum discovery capability for DUNE FD…
  - Exciting times lie ahead!

# Timeline of Particle Physics and Instrumentation



# Perspective

- More fascinating history exists than can be told today
- Some good ideas were grasped rather late…
- Know something beyond your computer screen…
- History shows the importance of paying attention!
- Find and befriend that rare exceptional engineer!
- History shows that really new ideas are still possible

# Thank you