History & Future of Radiation Detection

The Early Days

Imaging Detectors

Gas Detectors

Solid State Detectors

Scintillators

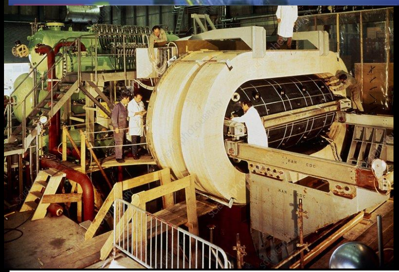
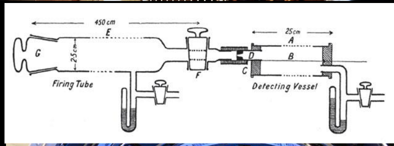
Photomultipliers

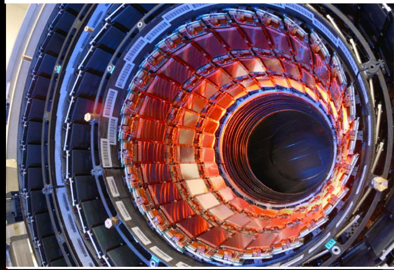
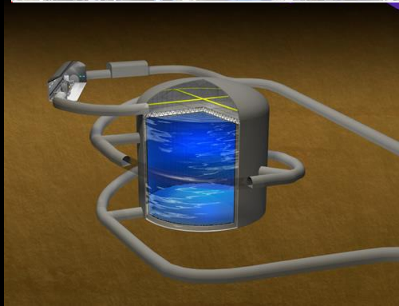
Outlook

Viktor Zacek, Université de Montréal

GRIDS TRIUMF & McDonald Institute, June 10, 2019



Setting the Stage

Freeman Dyson

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

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

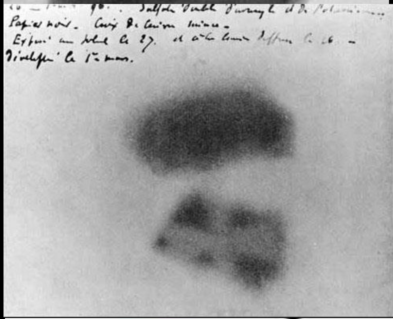
The effect of a tool-driven revolution is to discover new things that have to be explained"

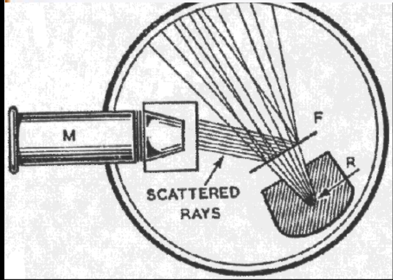
Freeman Dyson

New tools and technologies will be extremely important to go beyond LHC and the next generation of detectors in astroparticle physics

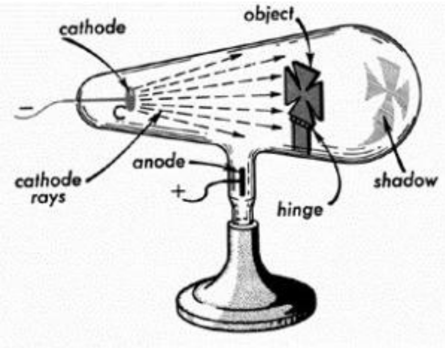
The Early Days

- **Photographic plates**
- **Electroscope**
- **Fluorescent screens**





The Early Days



W. Crook's cathode ray tube invented ~1870

Photographic plates

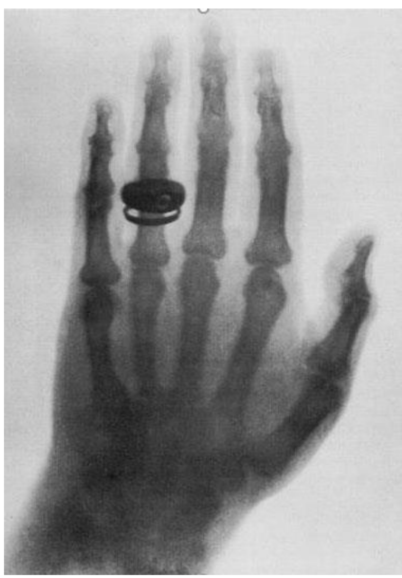
- On Nov. 8, 1895 W. Röntgen notices a faint glow on a cardboard coated with $Ba[Pt(CN)_4]$ when he turned on his Crooks - Cathode Ray tube, which was well shielded with a dark cover!!!

- Glow still present after traversing books on his desk!

- One month later he replaces the fluorescent by a photographic plate and takes 1st X-ray photograph …of his wife's hand!

Wilhelm C. Röntgen (1845 -1923)

Nobel Prize 1901



Frau Röntgen's Hand

…one year later over 1000 articles, > 50 books on X-rays!

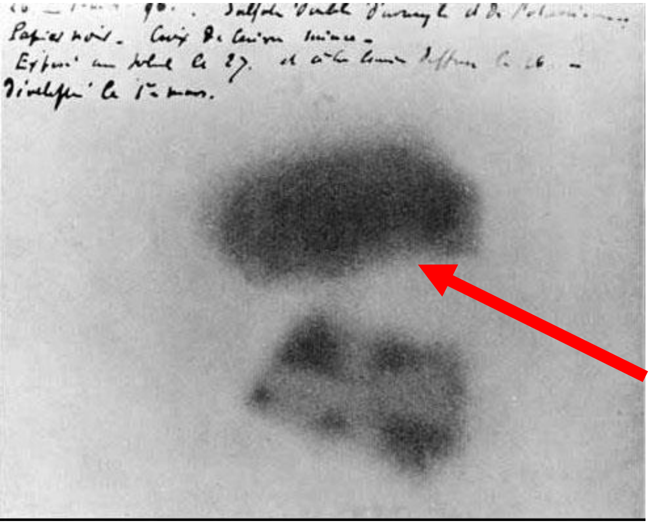
…some people want to burn all work on X-rays and execute its discoverer!

…one company advertises selling of X-ray proof underwear

…prohibition to use X-rays in opera glasses in theaters

$Ba[Pt(CN)_4]$ was at the time a known phosphorescent material

The Early Days



Position of U-salt on photographic plate

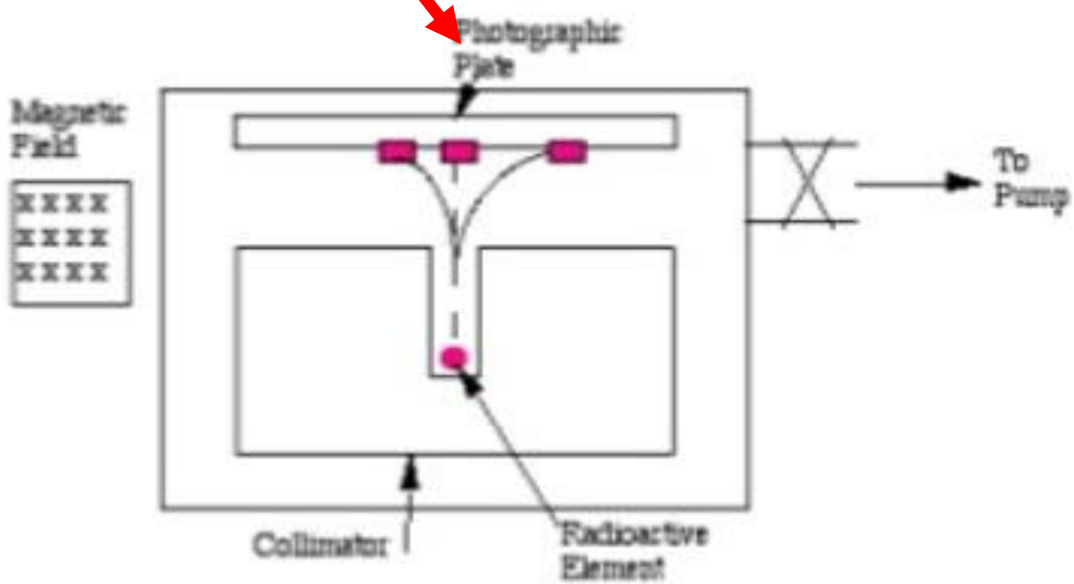
Photographic plates & Electroscope

- 1896 Henri Becquerel (mineralogist) discovers radioactivity: radiation emitted by Uranium salt shared certain characteristics with X-rays, but could be deflected by magnetic field !

Henri Becquerel (1852 -1908)

Nobel Prize 1903 (with M. & P. Curie)

- Becquerel notices also that the radiation discharges an electroscope



Charged particles emitted!

The Early Days

Viktor Hess
(1845 -1923)

Nobel Prize 1936

The Electroscope (1787 by A. Bennett) **:**

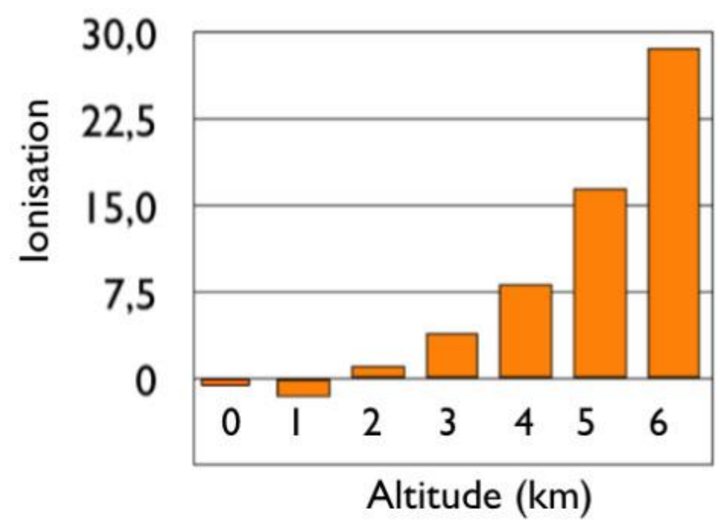
- When an electric charge is deposited, the 2 wings repel each other. If radiation ionizes air within the device, charge leaks away and wings come together…. used also by the Curies….

- 1899 J. Elstner, H. Geitel & C. Wilson find that electroscope loses charge w/o being exposed to radiation → is there radioactivity from the Earth?

(V. Hess)

- 1912 V. Hess carries an electroscope on a balloon up to 5300 m. One ascent during total solar eclipse! Increase of discharge with altitude!

Discovery of cosmic rays!



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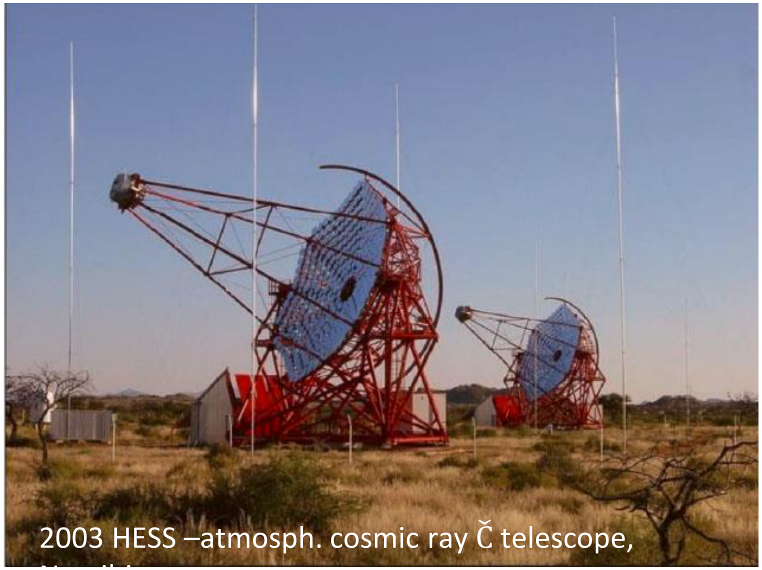
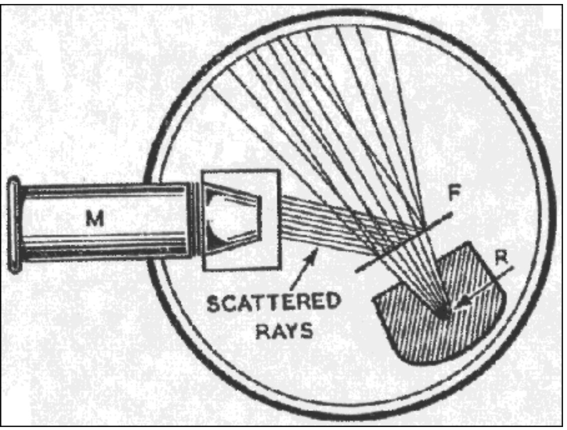


2003 HESS –atmosph. cosmic ray Č telescope,

The Early Days

Fluorescent Screens

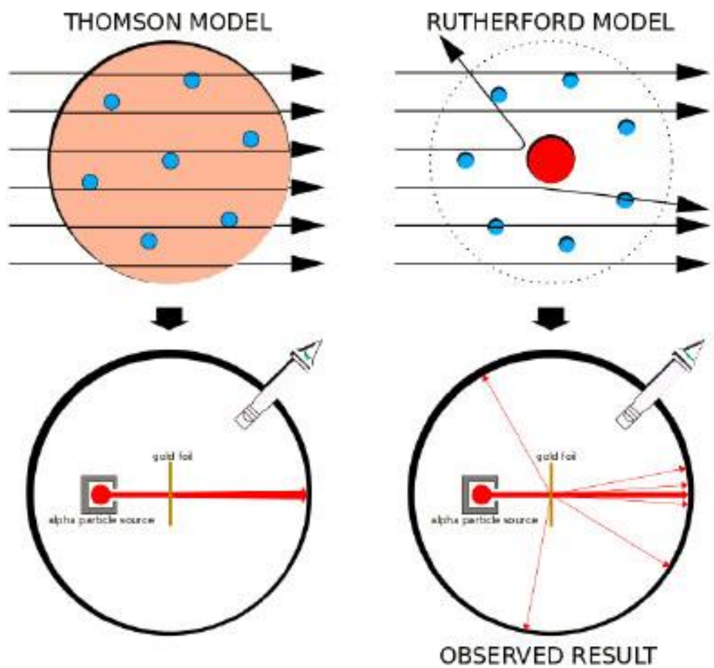


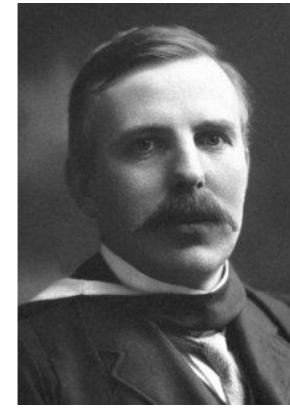
Sphintariscope (W. Crook 1903)
σπινθήρ = spark

Atropa belladonna or
Deadly night shade

- 1911 E. Rutherford at U. Manchester studies scattering of α – particles on a Gold foil and uses a Zinc Sulfate screen as detector (E. R. @ McGill from 1898 – 1907)

- As an α – particles hits the screen, a flash can be recorded by eye through the microscope





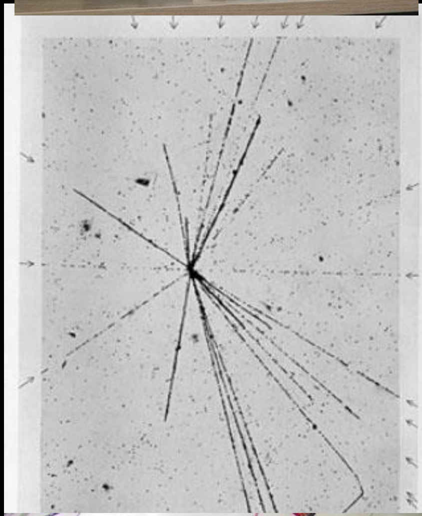
Ernest Rutherford
(1845 -1923)
Nobel Prize 1908

Discovery of the atomic nucleus!

The First Imaging Detectors

- Cloud Chambers
- Nuclear Emulsions
- Bubble Chambers

….details on Basic Detector Physics → Alison Lister's talk



The Cloud Chamber

- In 1895 Charles T. R. Wilson studies clouds as a meteorologist at the Cavendish labs (Cambridge)

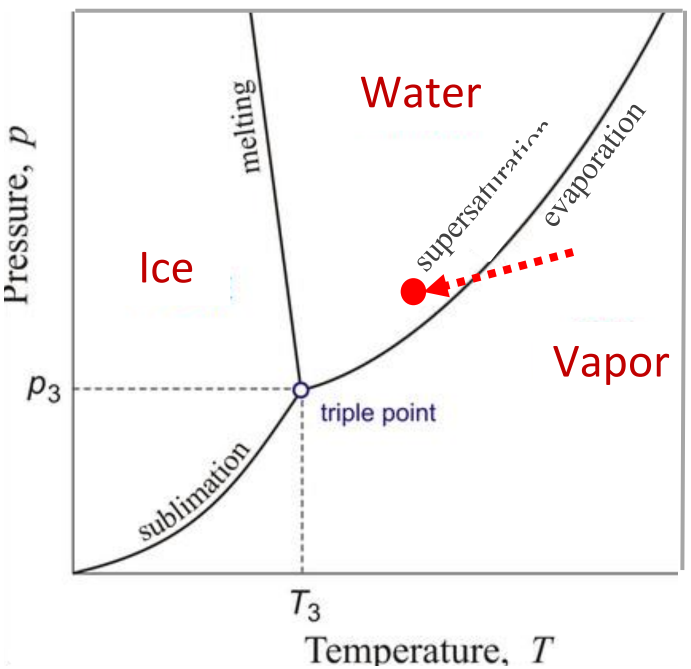
- Observation → less clouds in dust-free air !

- Carries container allowing expansion of humid air on mountain tops

- Thomson & Rutherford at Cavendish: X-rays cause ionization in gases

- 1906 W. exposes chamber to X-rays: sees dramatic increase in # of drops

C.T.R. Wilson (1869-1959)
Nobel Prize 1927
with A. Compton



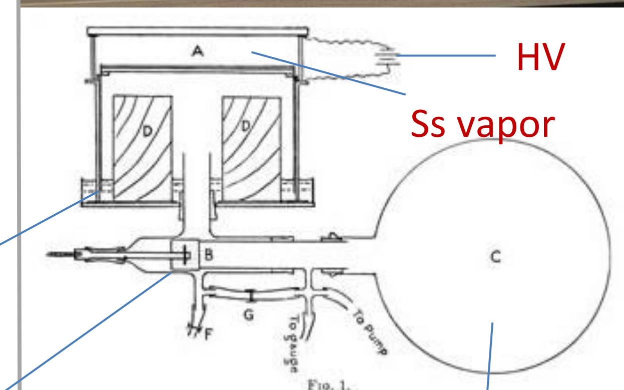
...a suspicion:

Water condenses around ionization when pressure is lowered and vapor becomes supersaturated

Particle track as mist - like trail of small water droplets

The Cloud Chamber

Perfected by Wilson in 1912 to detect radiation

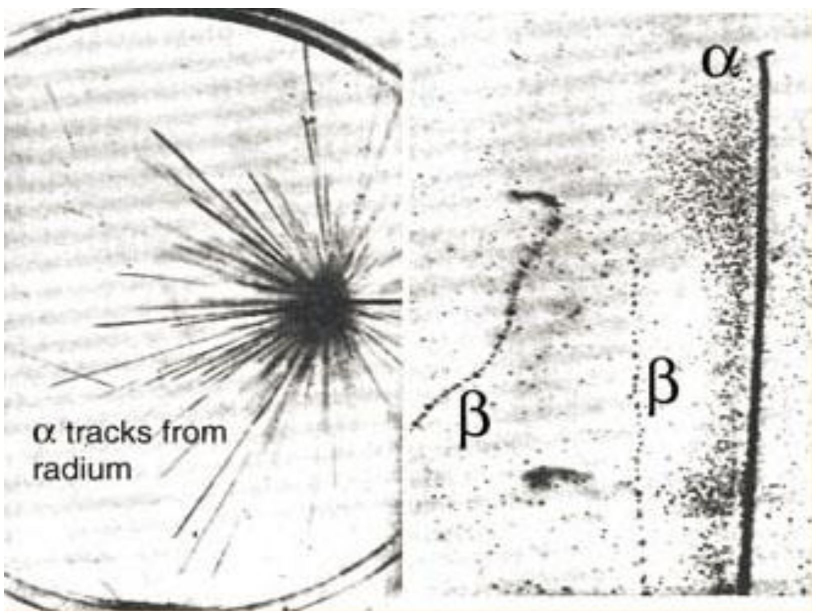


A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

A.M.W. : 'A study of flashes'

Another important ingredient:

- 1908 A.M. Worthington develops high speed photography using μs sparks
- CC becomes device to study different kinds of radiation



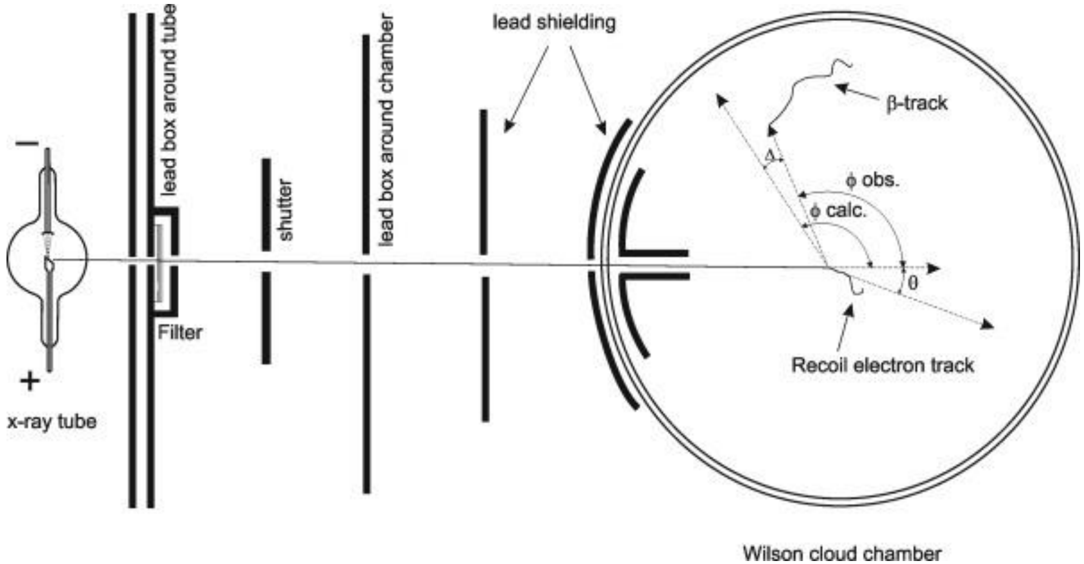
In Spring 1911 first images with α, β, x and γ-rays

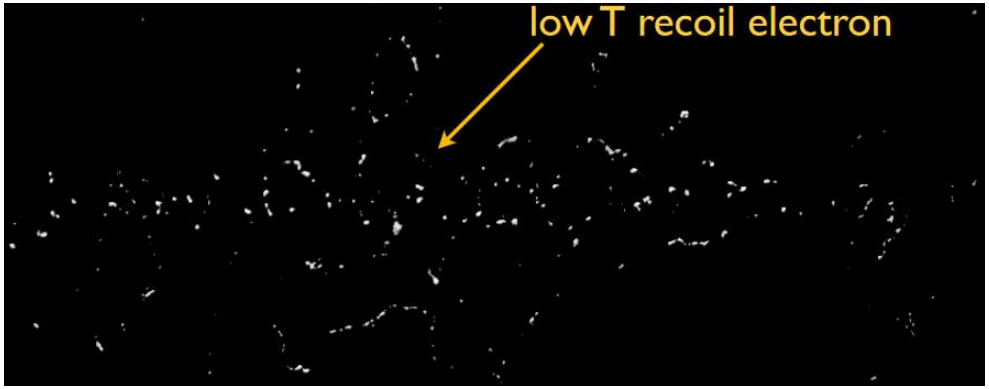
Prominent role in experimental particle physics from the 1920s to the 1950s

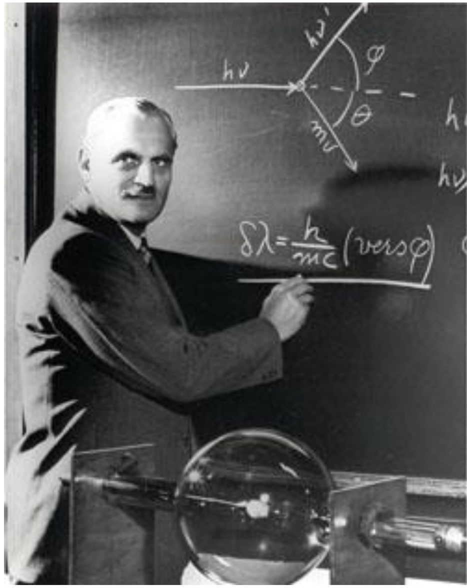
The Cloud Chamber - Discoveries

1923, A. Compton reports measurement of “shift” in frequency of x-rays scattered from electrons.

The “Compton recoil electron” is predicted. Should have low kinetic energy (T)







A. Compton (1982-1962)

Nobel prize 1927 with Wilson

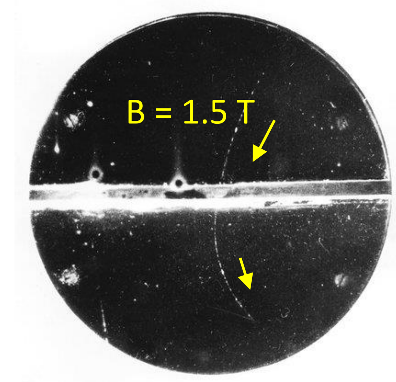
1923 Wilson uses X-ray tube & shows images of recoil electrons with low T supporting Compton’s claim for a quantum interaction between light & electrons

The Cloud Chamber – More Discoveries

CC was until the invention of the Bubble Chamber in 1950 the principal method for studying particle tracks (~ 40 y!)

- 1933 Discovery of positron by C.D. Anderson
  Nobel prize 1936 with V. Hess

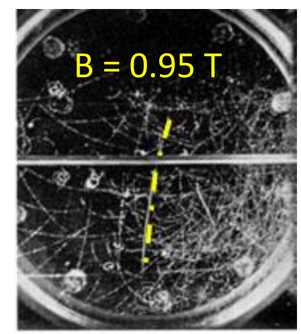
e^+



- 1933 Visualization of pair-production and e^+ annihilation
  by Blackett & Occhialini

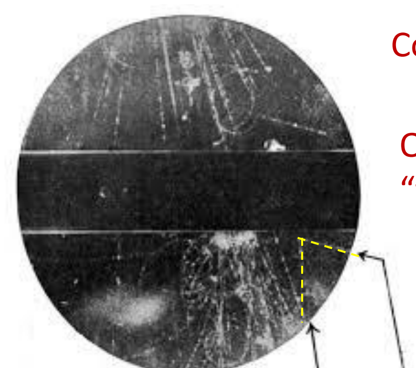
$\mu^\pm$

- 1937: Discovery of muon by C. D. Anderson and S. Neddermeyer   ”who ordered that?” (I. Rabin)



- 1947 Discovery of first strange particles (Kaons) by C. Butler & G. Rochester (V-particle)

K



$K^0 \rightarrow \pi^+\pi^-$

“The most original and wonderful instrument in scientific history” (E. Rutherford)

The CLOUD Project at CERN 2009 - 2019

Cosmics **L**eaving **Ou**tdoor **D**roplets

- Study microphysics betw. cosmic rays and aerosols under controlled conditions (solar variability?)
- 26 m^3 CC with N_2/O_2 + H_2O + other gases @ SPS beam
- UV – light for photolysis + E-field
- Humid air → adiab. expansion → beam interaction

Findings:

- Biogenic vapors emitted by trees have significant impact on cloud formation
- Correlation CR ↔ aerosol formation less important in presence of SO_2
- Pre-industrial climate conditions cloudier
- However "results seem not to support hypothesis that CR significantly affect climate"

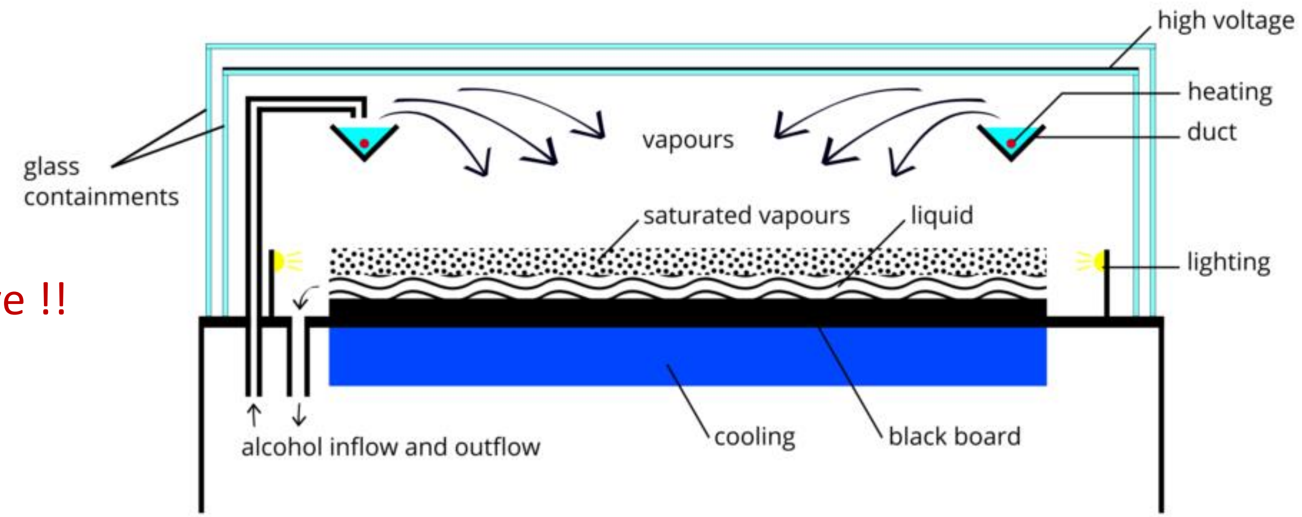
(Still somewhat controversial…)

17 Institutions / 9 Countries

The TRIUMF Diffusion Cloud Chamber

DCC invented in 1939
by A. Langsdorff

…continuously active !!



Today still CC's are an excellent instrument for educational purposes !

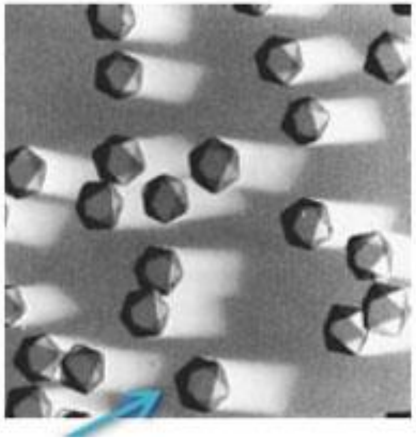
Nuclear Emulsions

Since early 20th century photography important for radiation studies, but no capability to see tracks

Marietta Blau (1894-1970)

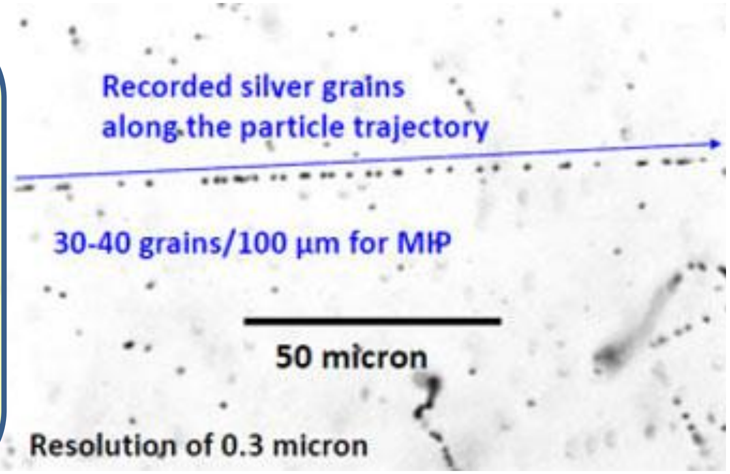
3 x nominated for the Nobel Prize!

- M. Blau was an Austrian physicist who pioneered the development of photographic methods for imaging nuclear processes in the 1920s and1930s.
- R&D on especially thick phot. emulsions 10 - 200 μm thick
- Analysis of emulsion with microscope
- Track density → info on dE/dx

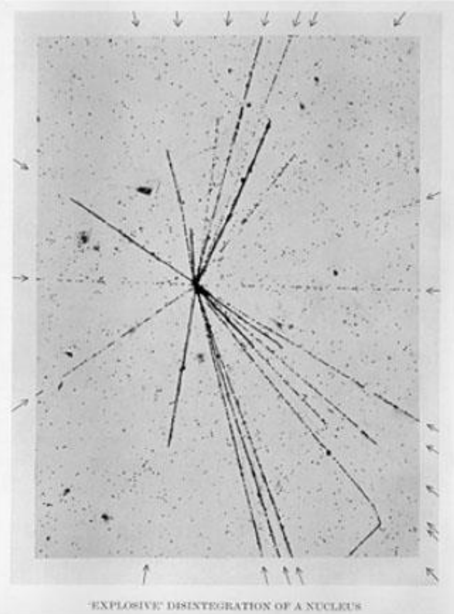


AgBr (~ 0.2 μm)

After the passage of charged particles through the emulsion, a latent image is produced.
The emulsion chemical development makes Ag grains visible with an optical microscope



Nuclear Emulsions - Discoveries



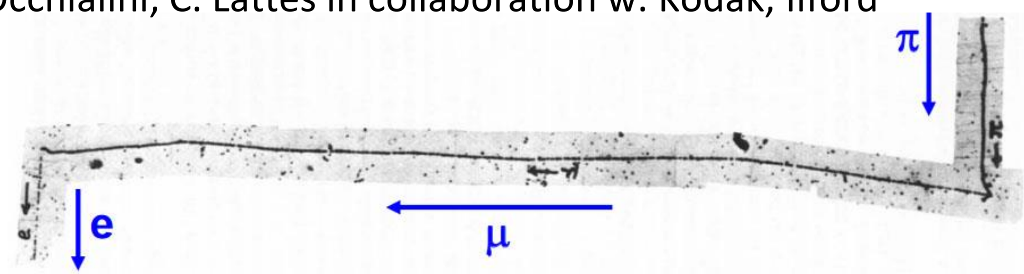
1937 M. Blau & H. Wambacher exposed NE over 5 months at 2300 m; they observe low-E protons and discover nuclear disintegration from cosmic ray interaction (spallation)

Cosmic ray station at Havelekar (2300m)

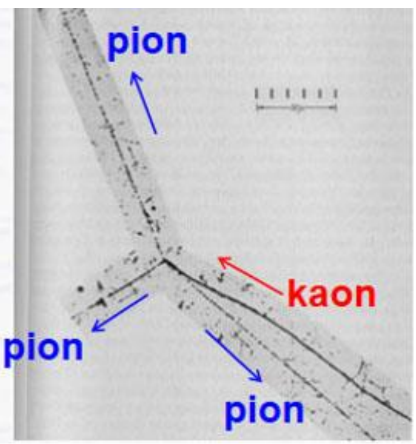
1946 G. "Beppo" Occhialini (@ U. Bristol) goes skiing in the Pyrenees, takes some NE plates with him on the Pic du Midi!

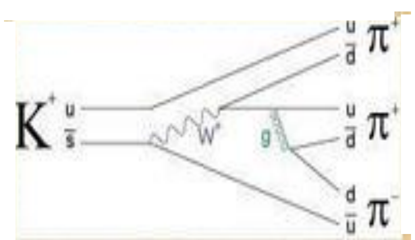
Pic du Midi (2900m)

1947 discovery of the pion in cosmic rays by C. Powell, G. Occhialini, C. Lattes in collaboration w. Kodak, Ilford



μ had on all plates the same length!!!
π and μ decay into unseen partners!





1949 discovery of the 3π decay of Kaons in cosmic rays by G. Rochester

C. Powell (1909 -1969)
Nobel Prize 1950

...today NE used in personal dosimeters

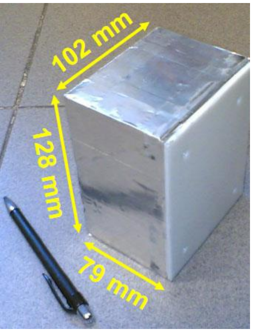
Oscillation Project with Emulsion-tRacking Apparatus (OPERA) (2003-2018)

Emulsions still attractive when large mass & high resolution required

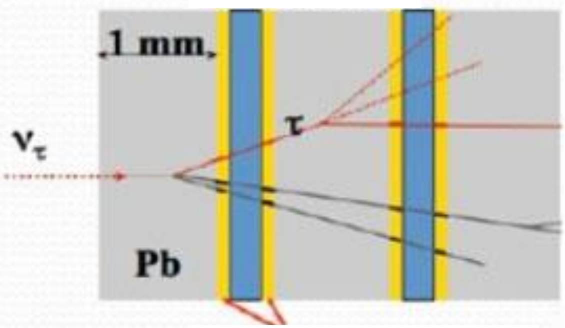
(…also CHORUS (CERN 1994) & DONUT (FNAL 1997) used NE for ν_τ detection)

OPERA at Gran Sasso Laboratory (LNGS)

- Search for $\nu_\mu \rightarrow \nu_\tau$ appearance oscillations in CERN ν_μ-beam
- Detection reaction: $\nu_\tau + N \rightarrow X + \tau^-$
- Need to reconstruct τ – decays of few 100 μm
- Resolution ~ 1 μm
- 1.7 ktons Pb + emulsion sheets → 1.5 x 10^5 bricks
- Electronic tracker for vertex finding
- 1.2 x 10^5 m^2 to be scanned @ ~ 70 cm^2/h/scanner

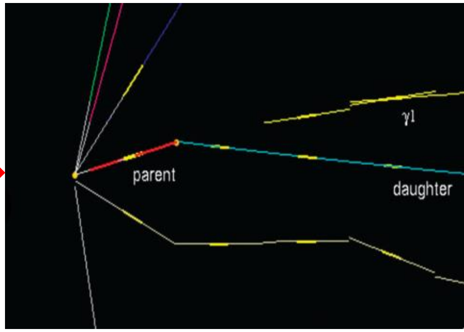


One Brick



Emulsion layers

Automatic microscopes (~ 34)



ν_τ - event

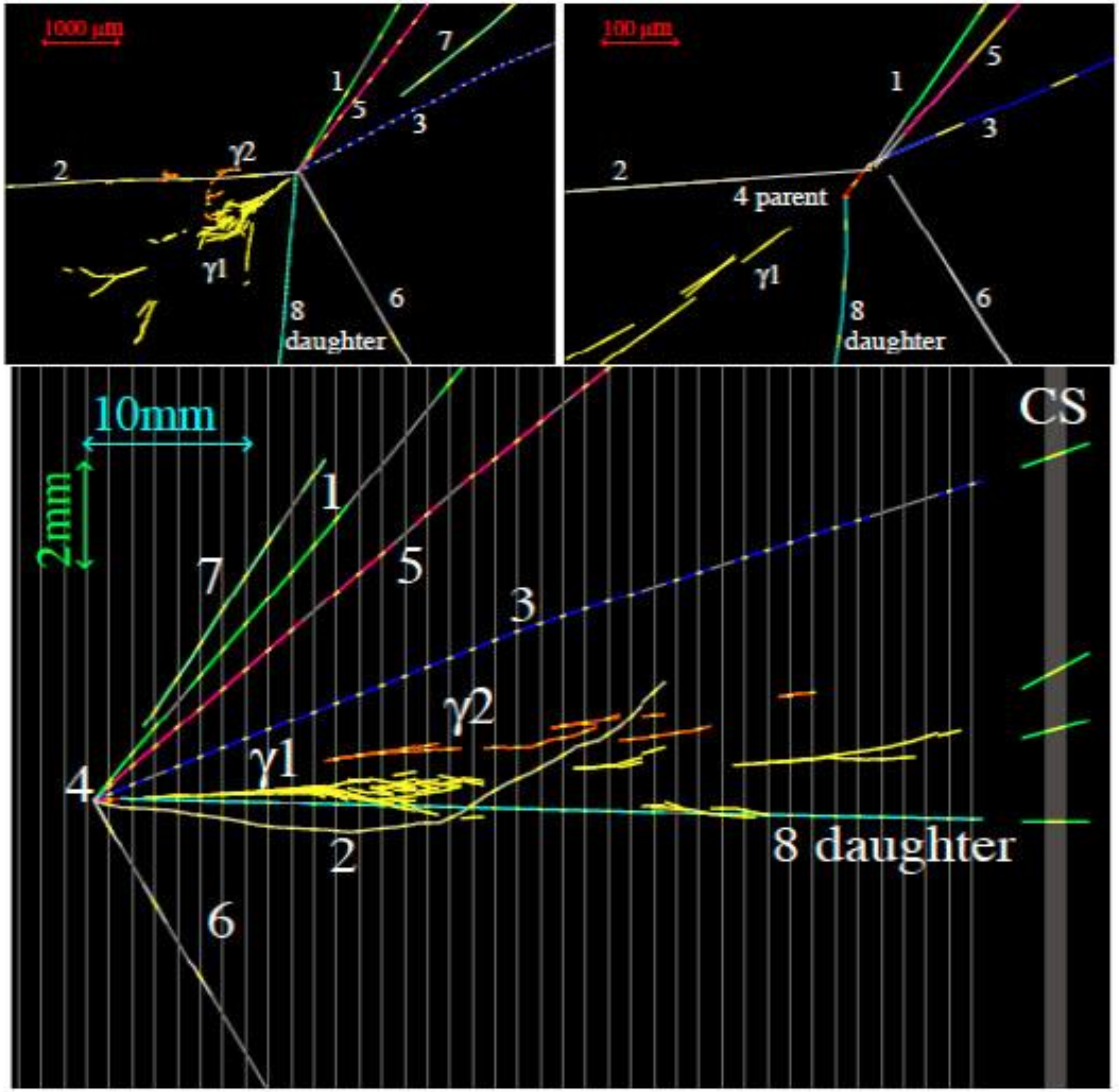


Figure 1: Display of the τ^- candidate event. Top left: view transverse to the neutrino direction. Top right: same view zoomed on the vertices. Bottom: longitudinal view.

Opera's First Tau Neutrino Event - July 2010

arXiv:1006.1623v1

- Beam stop: 2012
- Data analysis: → 2018

10 ν_τ - events!

arXiv: 1804.04912

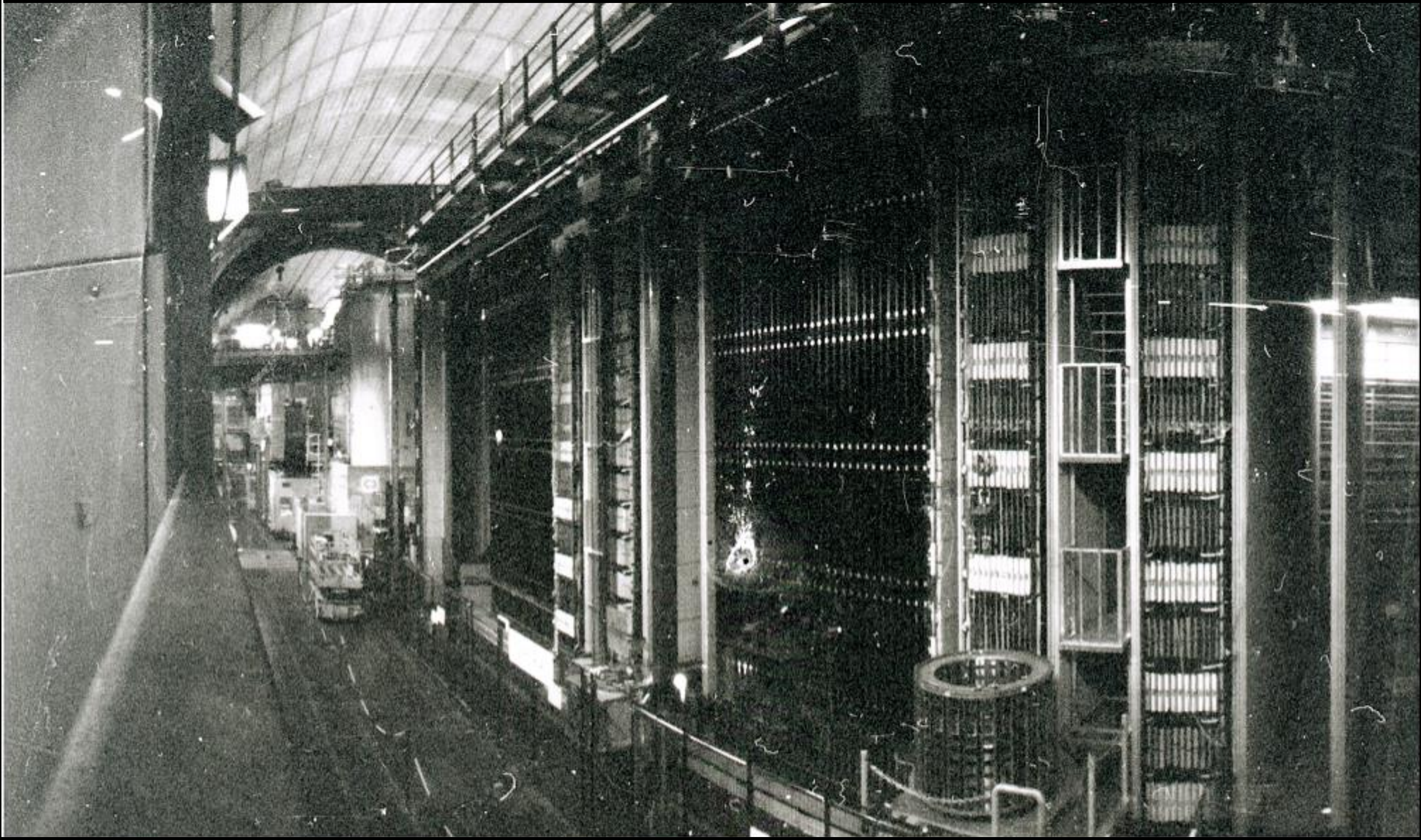
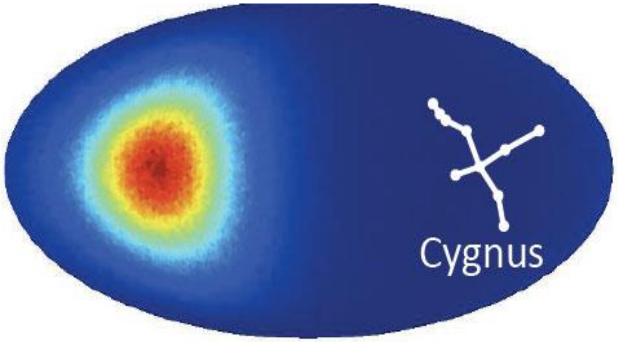


Image of the OPERA experiment located in the C hall of the Gran Sasso underground laboratories. The image was exposed on a nuclear emulsion slide inserted into a home-made photographic camera. Photo credits: D. Di Ferdinando (INFN – Bologna).

Nuclear Emulsion Wimp Search (NEWSdm)

Napoli, LNGS, INFN, Bari, Nagoya



Directional DM search beyond ν –wall!

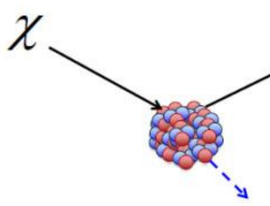
Dir. search on equatorial telescope $\rightarrow$ Cygnus

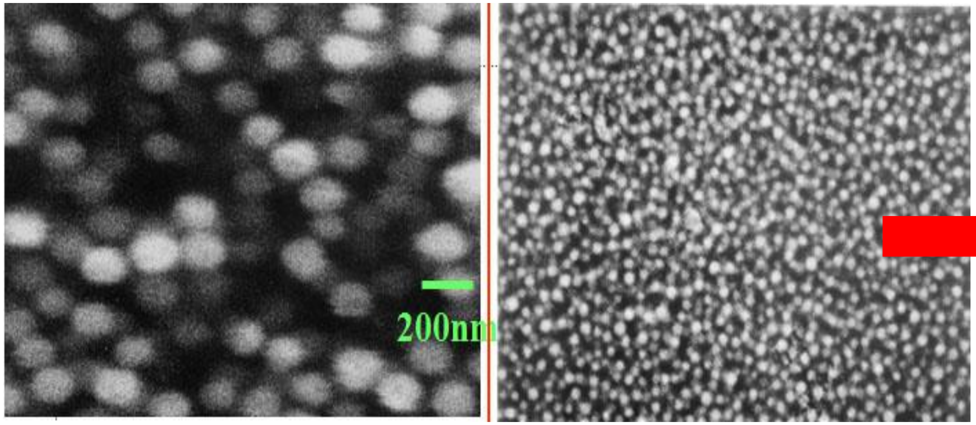
Solid target 3.2 g/cm^3 $\rightarrow$ 100 kg – 1ton

Emulsion grains: x 5 smaller

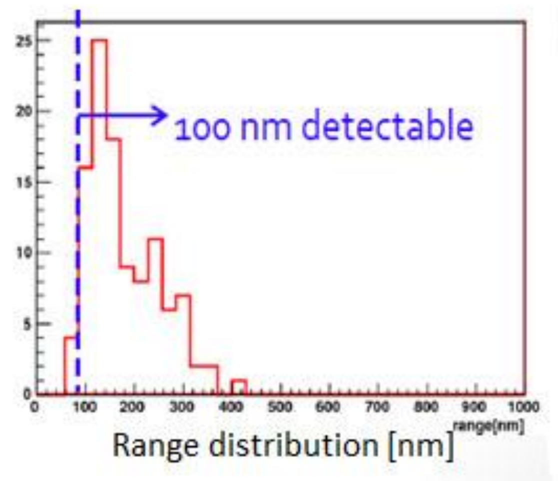
Autom. Scanning: x 10 faster

} than in Opera



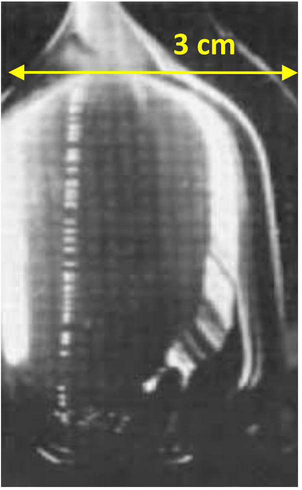


OPERA: AgBr crystal ~200nm NEWS: AgBr crystal ~ 40nm



Pilot run 2019 (LNGS)

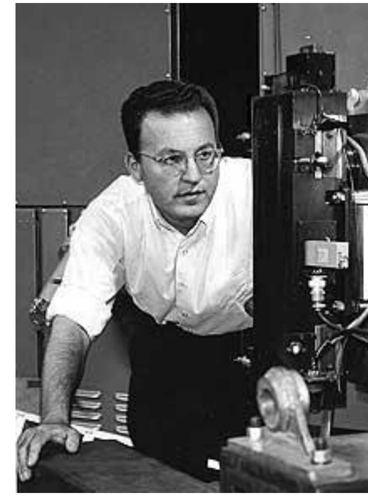
N. Tatsuhiro, Cosmic Frontier WS, SLAC March 2013



First track 1952!
Ether filling

The Bubble Chamber

- 1950's D. Glaser works at Caltech with Cloud Chambers
- finds their performance insufficient for accelerator applications
- ...and invents the Bubble Chamber in analogy with CC



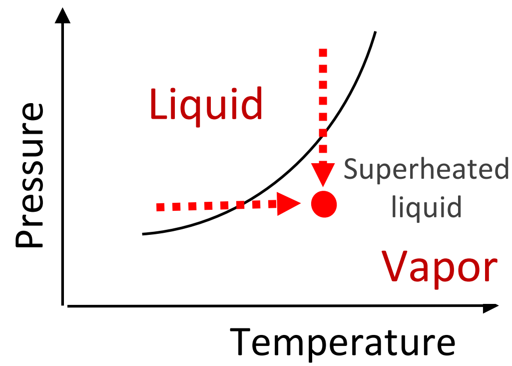
D. Glaser (1926 – 2013)
Nobel Prize 1960

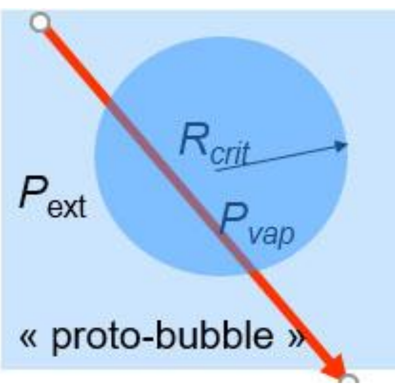
Supersaturated vapor

Superheated liquid

Bubbles forms if:

- particle creates heat spikes on its track
- with enough energy E_{min}
- deposited within R_{min}
- bubble growth: ~ 10 µm / msec





few nm

$$E_{dep} = \frac{dE}{dx} \cdot R_{min} \geq E_{min}$$

few eV

Urban myths:

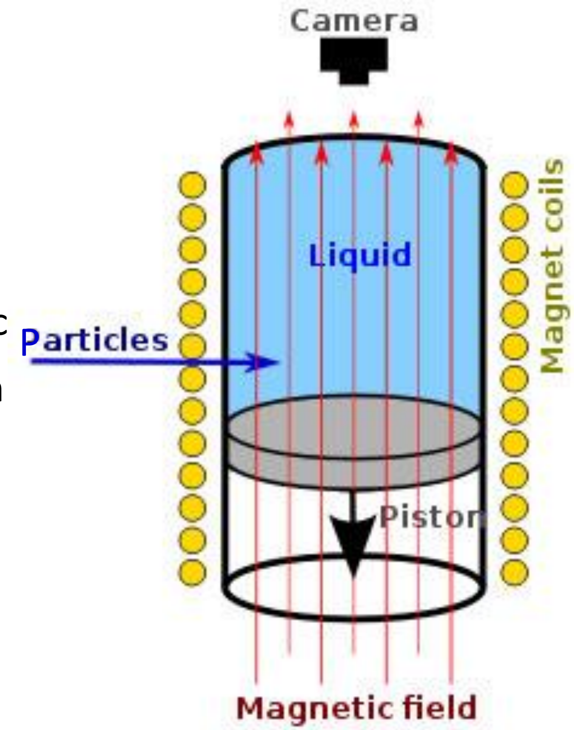
Glaser invented BC over a glass of beer ...wrong!

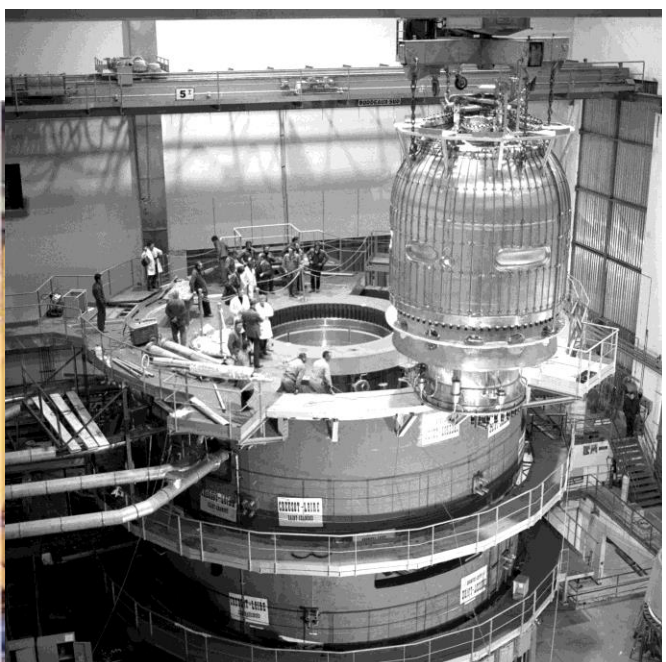
Glaser filled a prototype with beer......true!

Particle track: trail of small vapour bubbles

The Bubble Chamber

- Filled with a transparent liquid (H_2 @ 30K, Freon….)
- Rapid expansion synchronized with beam spills
- Bubble density x 10^3 of cloud chamber→ info on v/c
- Active target with 4π – acceptance & μm resolution
- B-field to measure momentum
- Event pictures taken with cameras on film

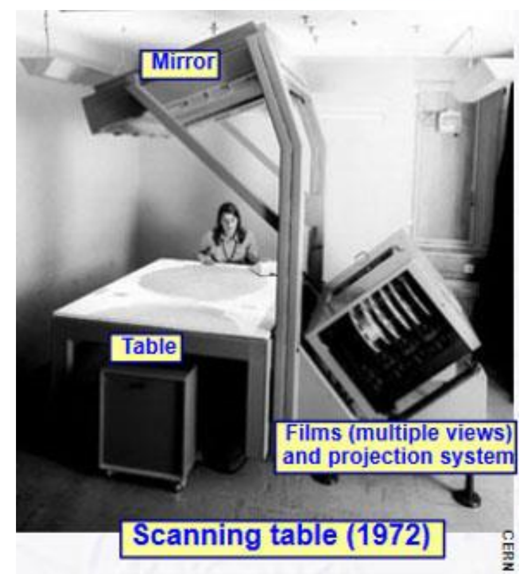




BEBC @CERN 3.7m LH_2 largest BC 1973 -1984

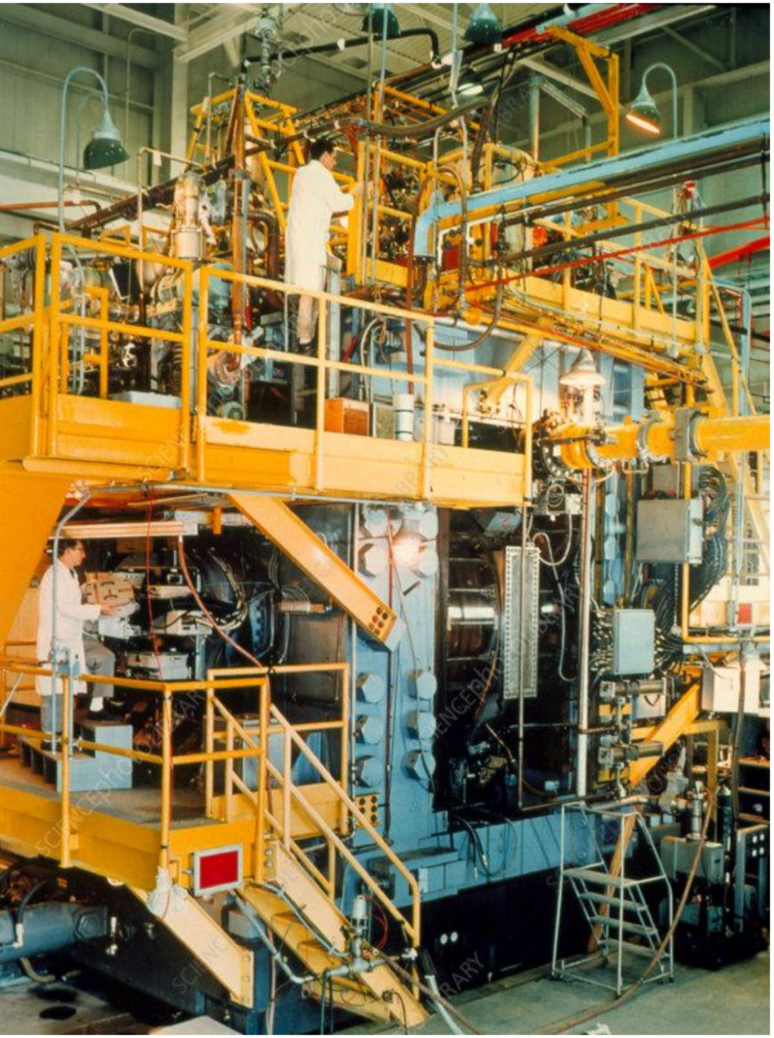
The size of the chambers grew quickly!

1954	6 cm
1955	10 cm
1956	25 cm
1957	180 cm
1963	203 cm
1973	370 cm



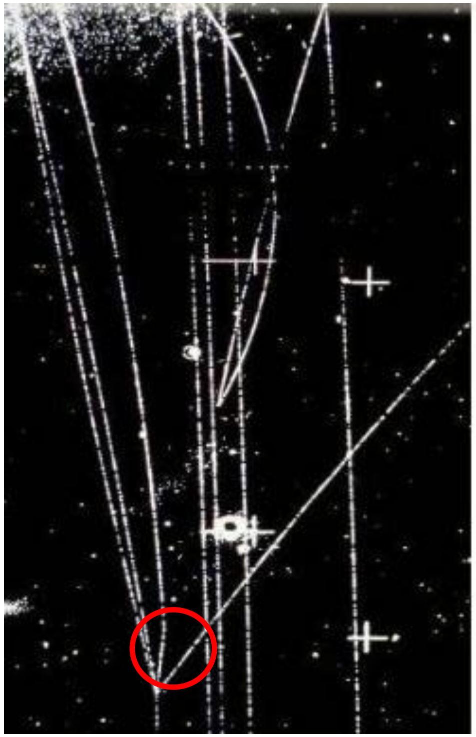
Millions of photographs to be scanned

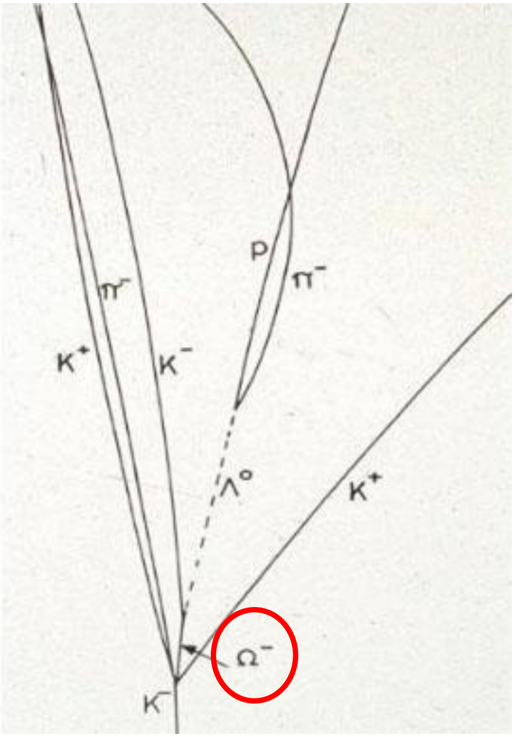
Bubble Chamber - Discoveries



80 ft LH_2 - BC at BNL (1963) 0.03 sec cycle

Discovery of the Ω (1963) predicted by Gell-Mann 1961
→ mass, charge, strangeness → quark model SU(3) confirmed





+ many other discoveries & observations

….Baryon resonances
….Charmed particles
….Multi- hadron production
….Deep inelastic neutrino scattering

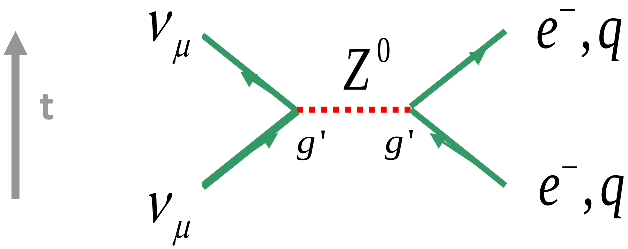
Bubble Chamber - Discoveries

- Gargamelle was a heavy liquid BC operated at the CERN PS/SPS neutrino beams from 1970 -1979

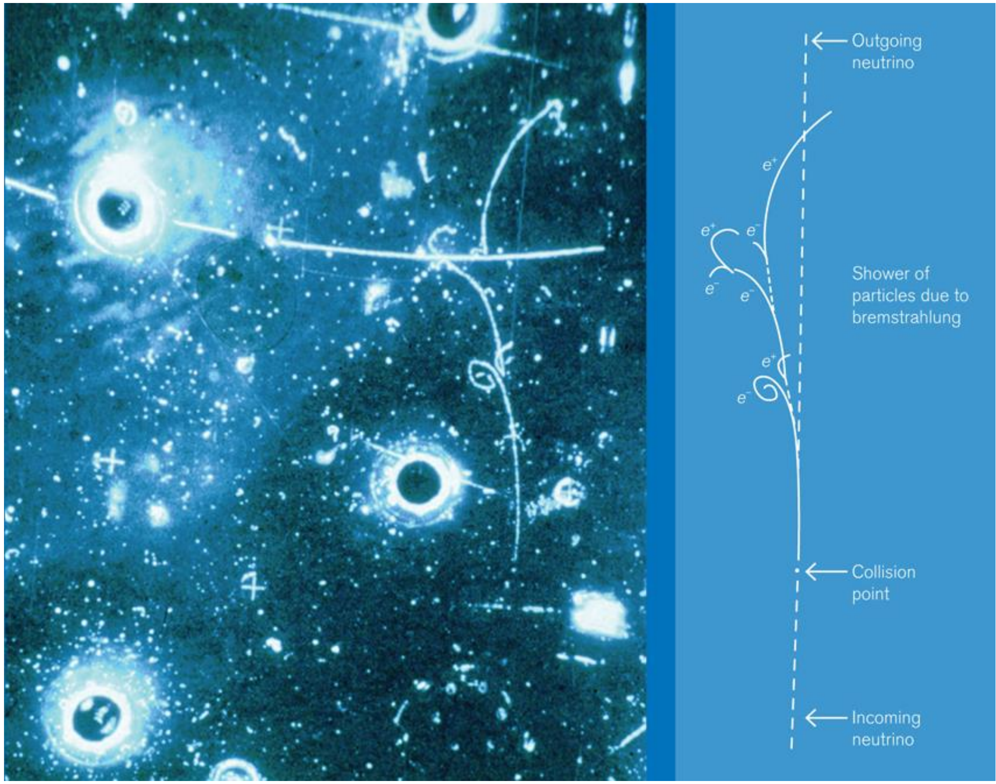
- The BC was 4.8 m long and 2m Ø. It was filled with 12 m^3 CBrF3 (freon) at 20 bar in a 2 T B- field

- In 1973 Gargamelle discovers leptonic and hadronic neutral current interactions as predicted by Glashow, Weinberg, Salam (1960, NP 1979)

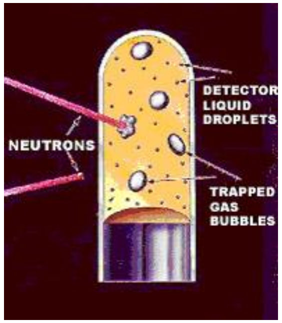
Giantess Gargamelle is the mother of Gargantua



Gargamelle at CERN today

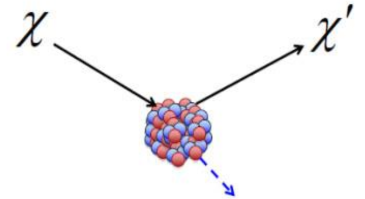


Bubble Chambers for Dark Matter Searches

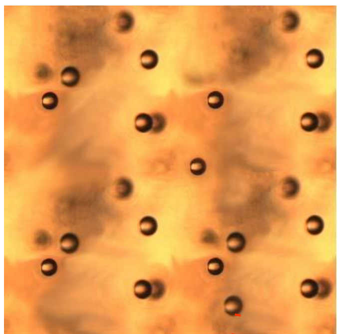


Personal n- dosimeter
BTI Chalk River (O)

- In 2004 pioneered for DM search by PICASSO at SNOLAB
- 150 µm droplets of C_4F_{10} dispersed in polymerized gel
- Each droplet is a bubble chamber! One bubble/WIMP!
- Bubbles recorded by piezo-electric transducers
- Operation at moderate superheat renders fluid sensitive to keV nuclear recoils only!

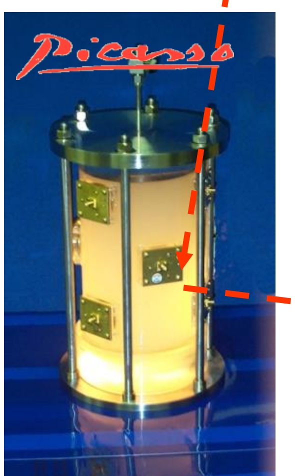


Recoil Energy ≈ 10 keV
Range ≈ 100nm

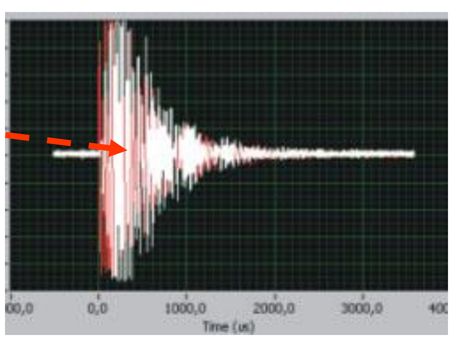


150 µm droplets (C_4F_{10})

- Insensitive to γ - background & Mips
- α - events are louder than nuclear recoils!
- Calibrated down to 1 keV!



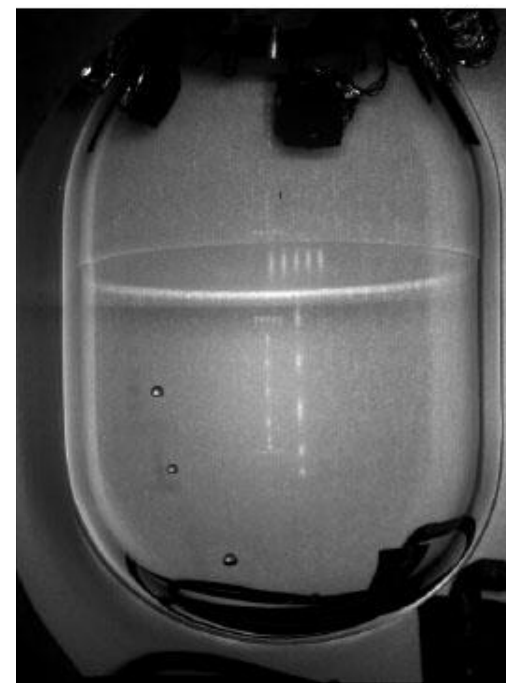
32 detectors (3.2 kg C_4F_{10} kg) @ SNOLAB



Acoustic piezo signal

More active mass in bulk BC!

Improved sensitivity!



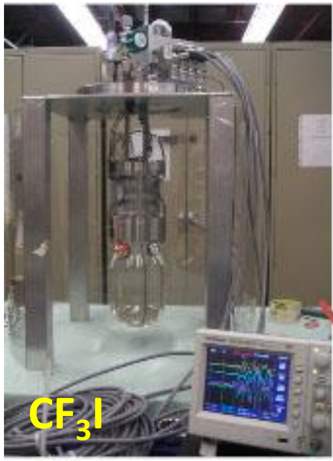
PICO 2.5 L C_3F_8

Bubble Chambers for Dark Matter Searches

....now PICO at SNOLAB

-2012

COUPP



2013-17

PICO-2L

PICO

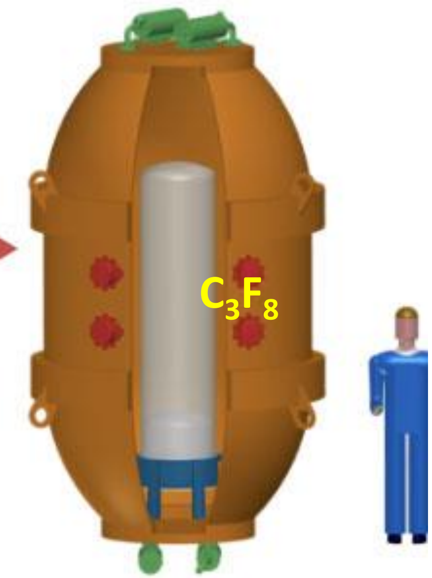
PICASSO

PICO-60

2019 -

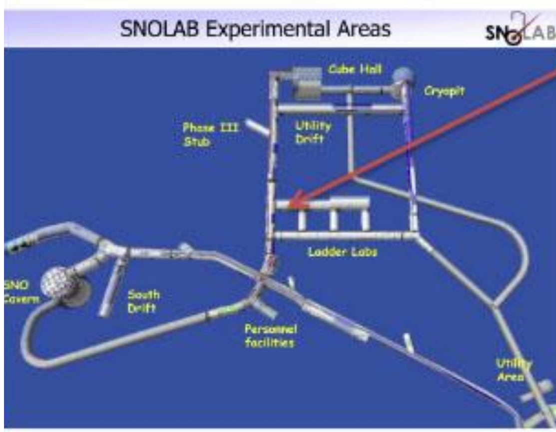
PICO-40L

PICO-500



PICO is world leader in the spin-dependent WIMP interaction sector

PICO 60

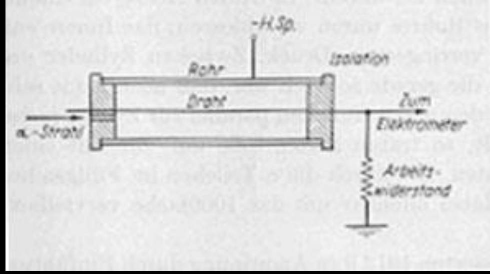


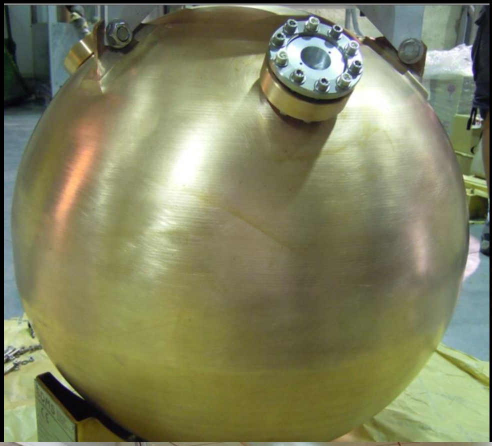
Filled with 40L C_3F_8 on June 30, 2016

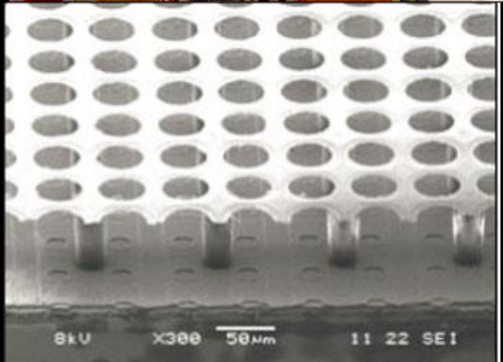
Gas Detectors

- Geiger Müller Counter
- Multiwire Proportional Counters (MWPC)
- Drift Chambers
- Micropattern Gaseous Detectors (MPGD)

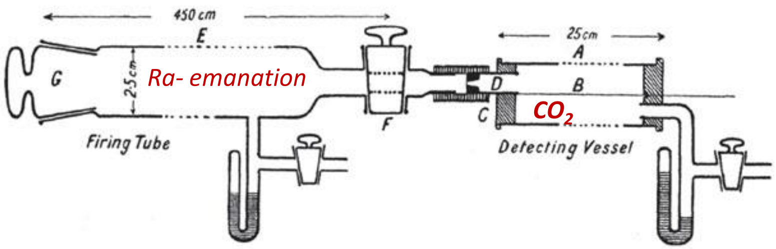
….details → talks by Daniel Santos, Pierre-André Amaudruz



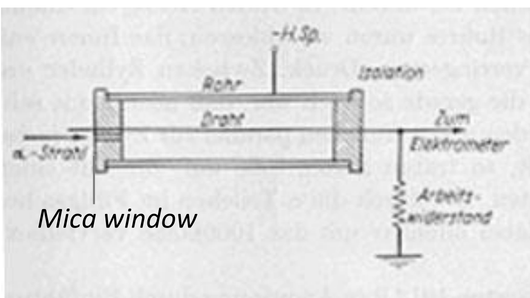




The Geiger - Müller Counter



Rutherford/Geiger 1908



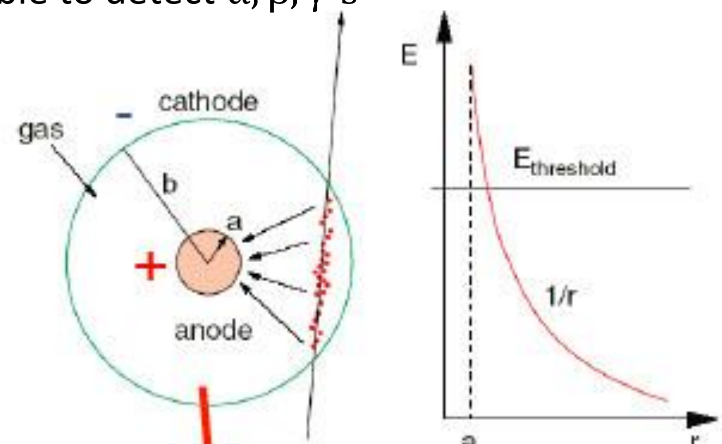
Geiger- Müller counter 1928

- 1906 H. Geiger PhD on "Electrical releases in gases"

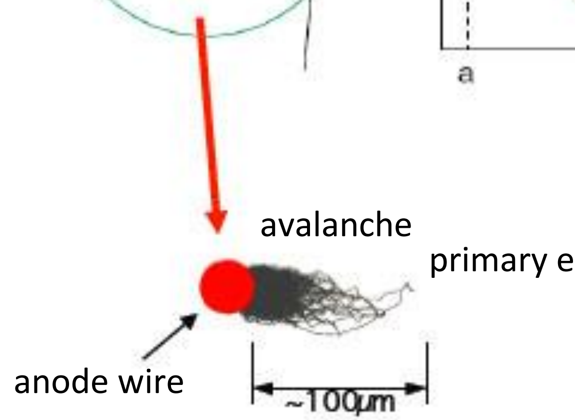
1882-1975 1905-1979

- 1908 Geiger (RA of Rutherford) develops a device to measure α- particles

- 1928 G. with PhD student W. Müller develops sealed tubes able to detect $\alpha, \beta, \gamma' s$

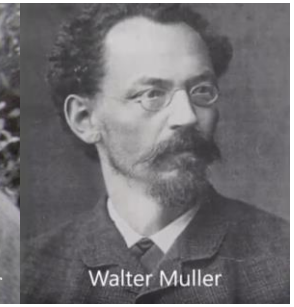


- Sealed tube filled with He, Ne, Ar (0.1b)
- Particles ionize gas, electrons drift to wire in increasing E- field
- Anode central wire 20 – 50 µm Ø at several 100 V
- Above 10 kV/cm → avalanche ionization
- Charge measured by electroscope

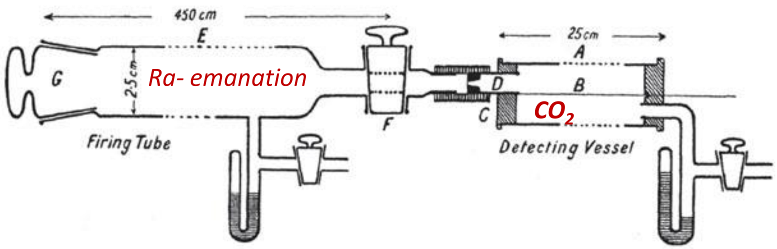


The Geiger - Müller Counter

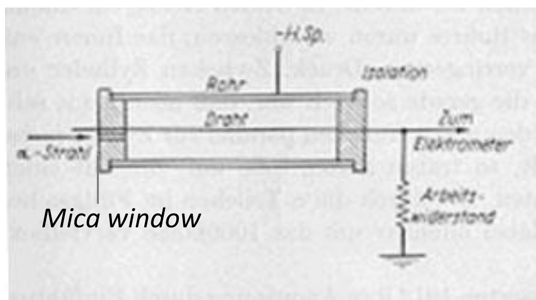
1882-1975



1905-1979



Rutherford/Geiger 1908



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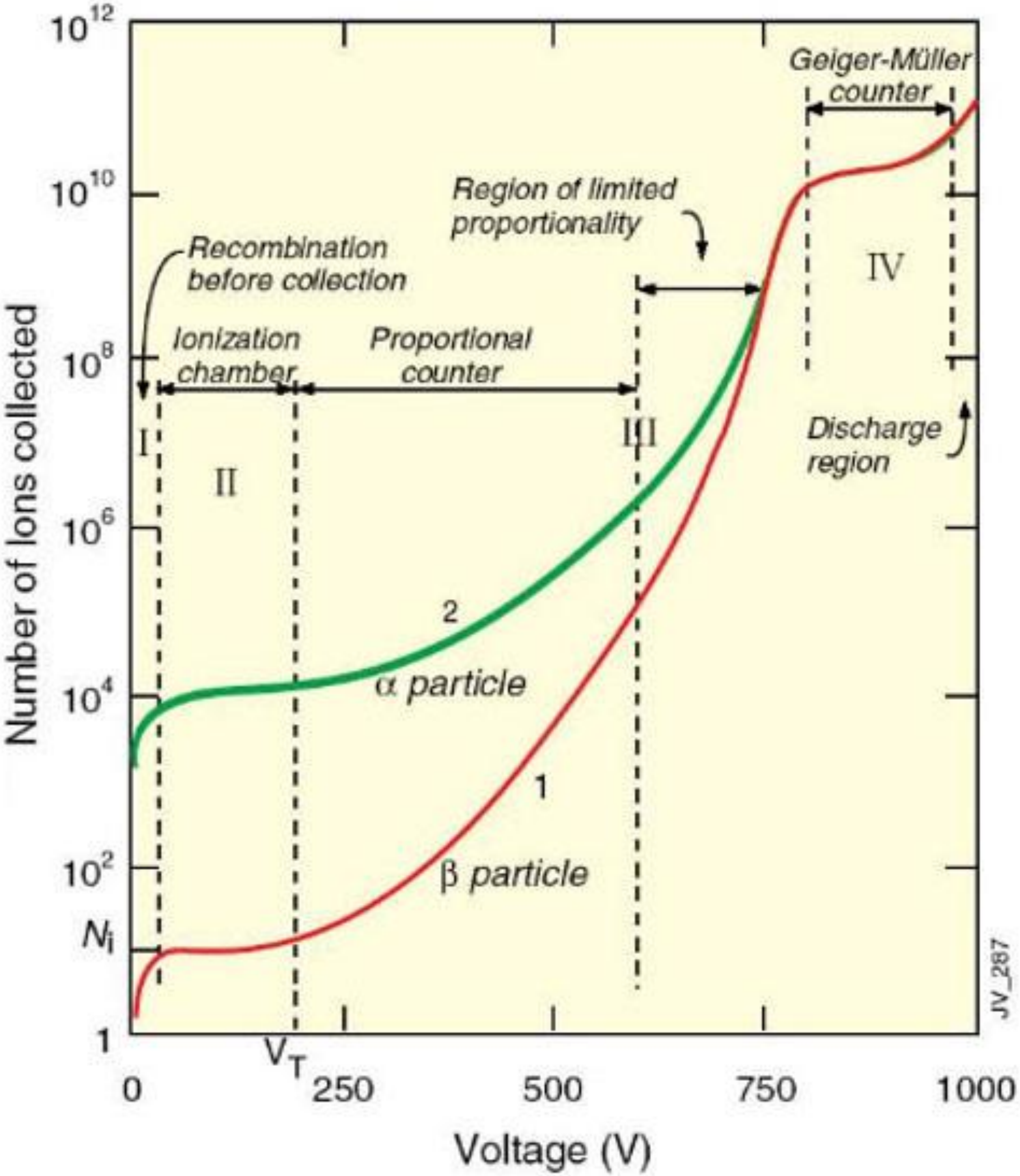
Wire Chambers – Regimes of Operation



(I) No charge collection

Ion recombination occurs before collection

(II) Ionization Mode

Ionization charge collected
no multiplication, gain =1

(III) Proportional Mode

Gas multiplication, charge on wire $\propto$ original ionization, gain $\sim 10^4$

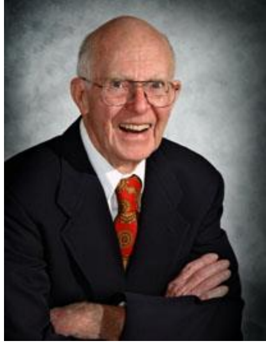
(III) Limited Proportional Mode

Also called "streamer mode", strong photoemission; secondary avalanches, gain $\sim 10^{10}$

(IV) Geiger Mode

Photoemission & discharge
Stopped by HV breakdown

Proportional Counters - Discoveries



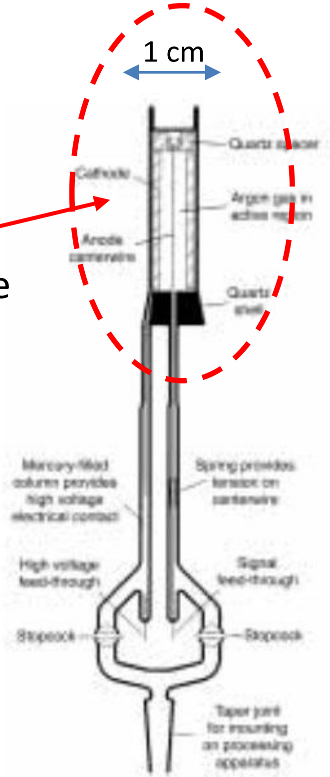
R. Davis (1914-2006)
Nobel Prize 2002

- 1965 R. Davis installs a tank filled with 615 tons of C_2Cl_4 in the Homestake Gold Mine at a depth of 1487 m to detect solar neutrinos

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^- \quad E_{th} = 0.8\, MeV$$

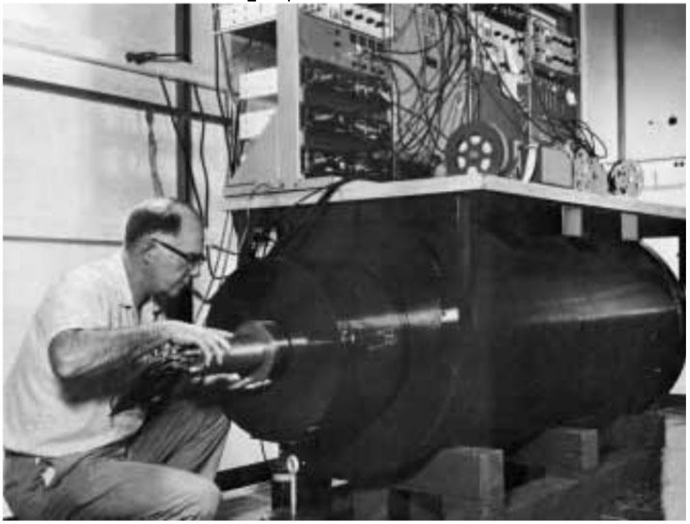
- Tank is bubbled with He-gas after few weeks to extract tens of ^{37}Ar atoms within several cm^3 of He

- Gas is filled into a tiny 0.3 cm^3 **proportional** chamber to count 2.8 keV Auger electrons from Electron Capture



$$^{37}Ar + e^- \rightarrow {}^{37}Cl + \nu_e \qquad T_{1/2} = 35\, d$$

615 tons of C_2Cl_4



Pre-bomb battleship gun barrels for counter shielding

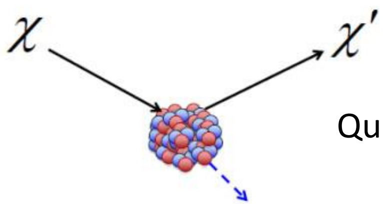
^{37}Ar Production rate by solar ν's :

Predicted:	1.48 ± 0.06	^{37}A atoms/day
Observed:	0.46 ± 0.04	^{37}A atoms/day

Solar Neutrino Problem!

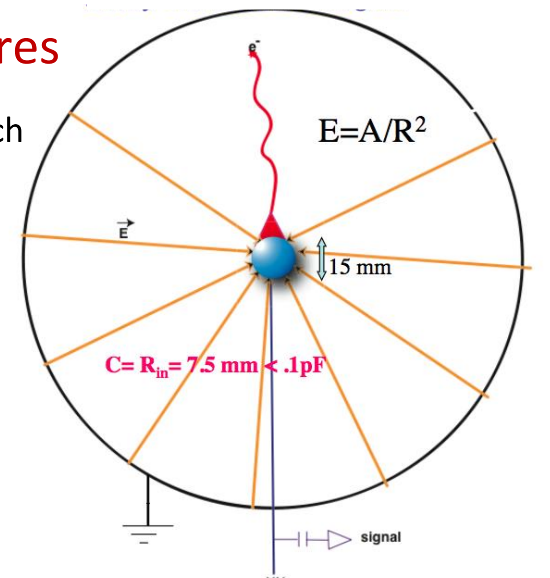
Similar technique used in 90's by GALLEX, SAGE (Ga ↔ Cl)

Proportional Counters – Recent Developments



New **E**xperiments **W**ith **S**pheres

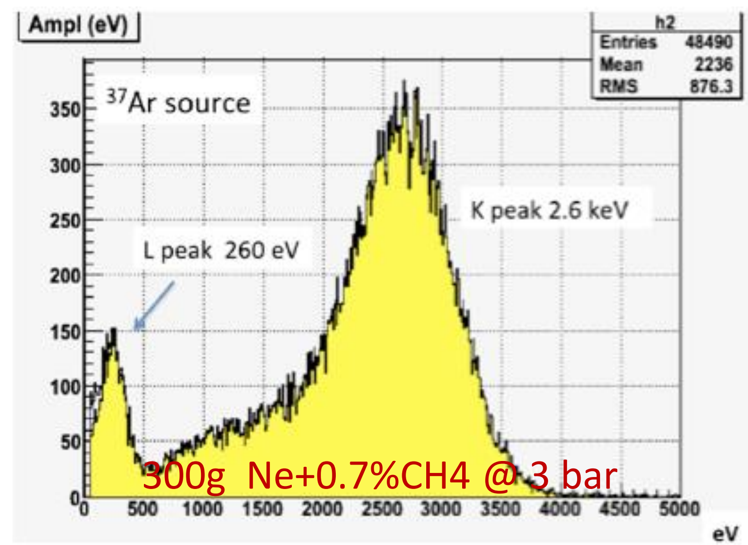
Queen's, SNOLAB, Saclay, LSM, Tessaloniki, Grenoble, Munich



I. Giomataris

Recoil Energy ≈ 10 keV
Range ≈ 100nm

- Spherical cavity + sensor
- Target: Ar, Ne, He, H (CH4)
- Large volume/mass (30g)
- Low threshold – low cap. < 1pF



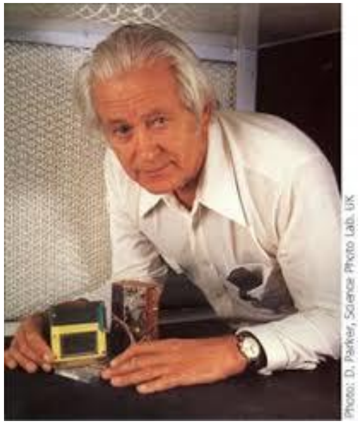
- E_{thr} = 120 eV demonstrated in Ne @3b
- Localisation by rise time
- 2 LEP cavities with 130 cm ∅ tested

NEWS-G : 1.4 m ∅ sphere to be installed at SNOLAB

Multiwire Proportional Chambers (MWPC)

G. Charpak, F. Sauli, J.C. Santiard

- GM tube ok for single tracks w. limited precision
- MWPC was invented at CERN 1968 by G. Charpak
- In a MWPC an array of many closely spaced anode wires in the same chamber act as independent **proportional** counters



G. Charpak (1924-2010)
Nobel prize 1992

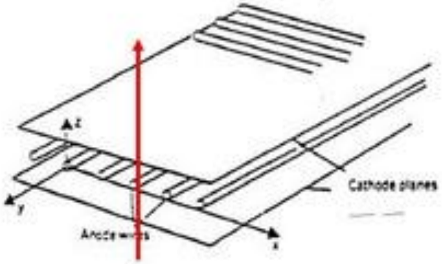
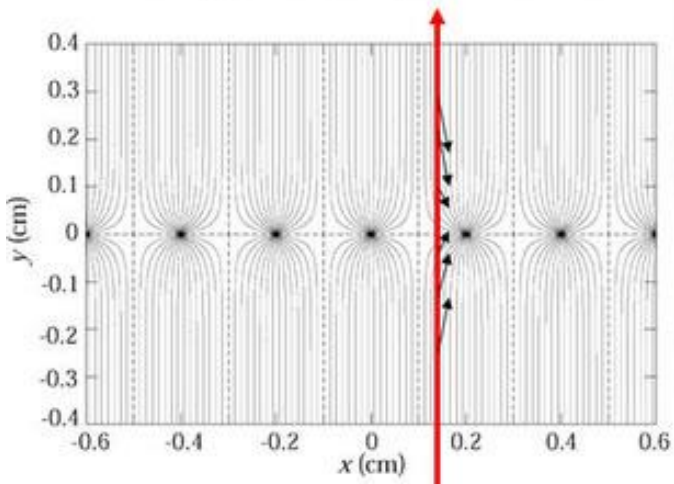


Abbildung 2.27: *Vieldrahtproportionalkammer.*

- Wire distance typically ~ 2 - 5 mm
  distance between cathode planes ~ 10 mm
- Accuracy is a fct of wire distance *d*
  $\sigma_x = d/\sqrt{12} \sim 300\mu m$ for d = 1mm
- 1 MHz/wire rate capability (BC 10Hz!)

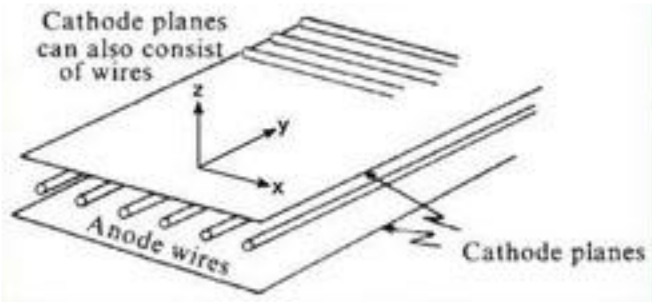


A revolution! From now on large area/volume tracking & imaging possible!

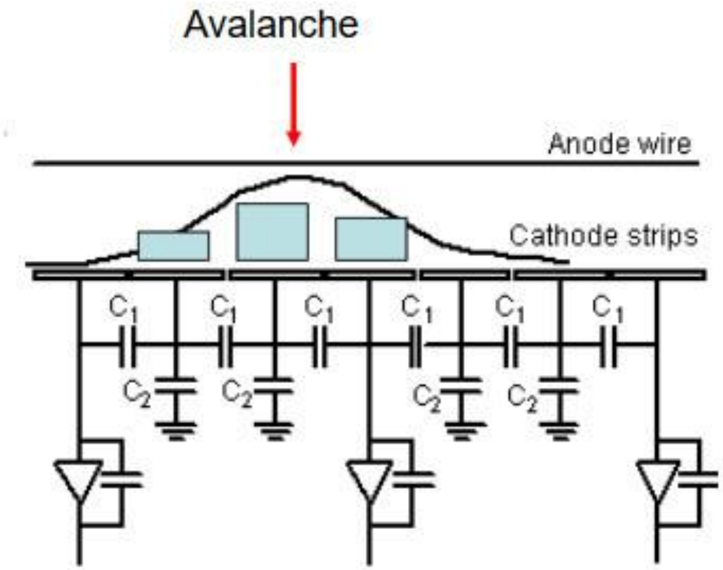
Multiwire Proportional Chambers (MWPC)

How to read the second coordinate?

- Charge division on resistive wire read out on both ends
- Comparison of arrival times at both ends
- Cathode plane segmented into strips



2D position sensing MWPC



- Movement of charges induces signals on wire and cathode
- Width (1σ) of charge distribution ≈ distance between wire and cathode
- Center of gravity defines particle trajectory
- 50 μm resolution possible

Now digital radiography possible with 10 times less dose!

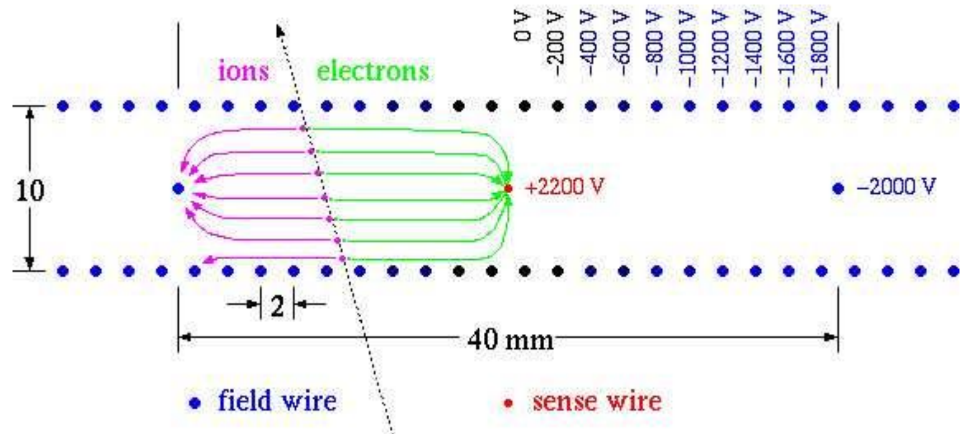
Drift Chambers

One problem with MWPC:
Spatial resolution is limited by wire spacing

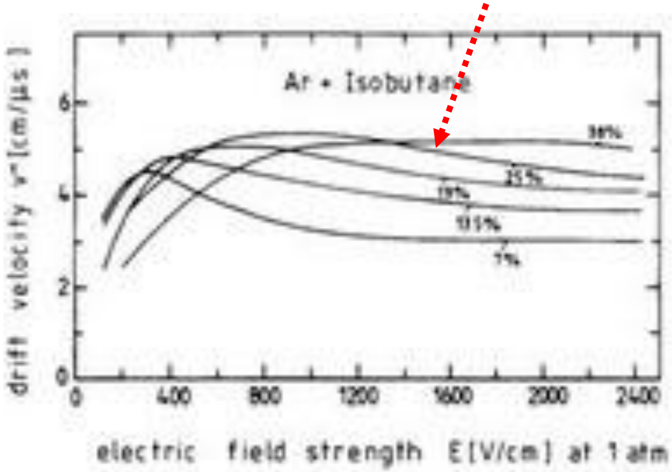
Solution :
Obtain position from drift time of primary ionization to anode wire

1971 Drift Chamber invented by A. Walenta, J. Heintze, D. Schürlein (Heidelberg)

Introduce alternating sequence of **"sense wires (+)"** & **"field wires (-)"**



$V_D \approx 5$ cm/μs



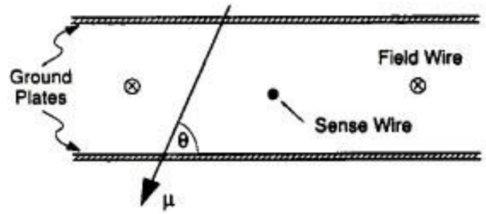
Need to know:

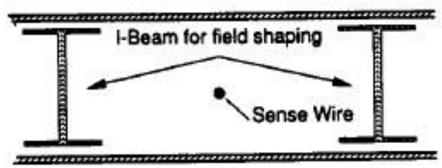
- Start signal (scintillator/beam X-ing)
- Drift velocity v_D

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

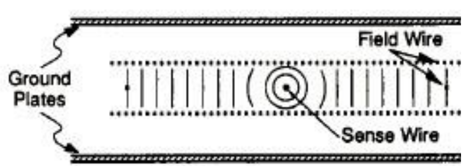
Drift Chambers - Geometries

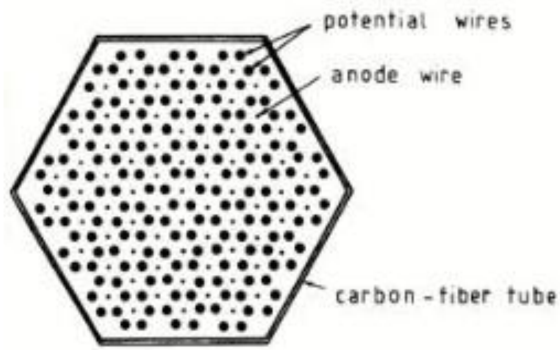
Electric Field ~1kV/cm



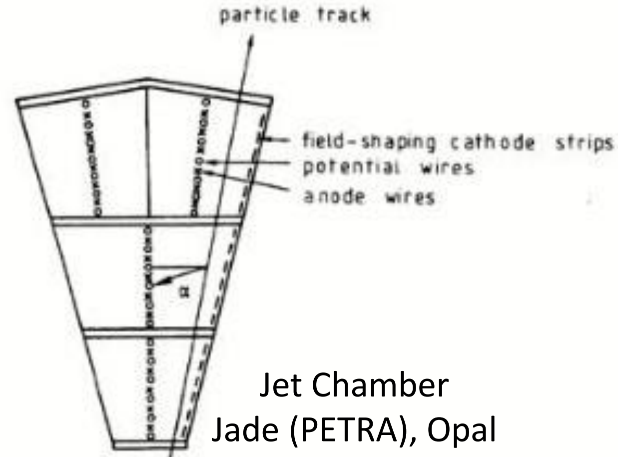


Drift cell
Muon tracker
(CMS, Collider)

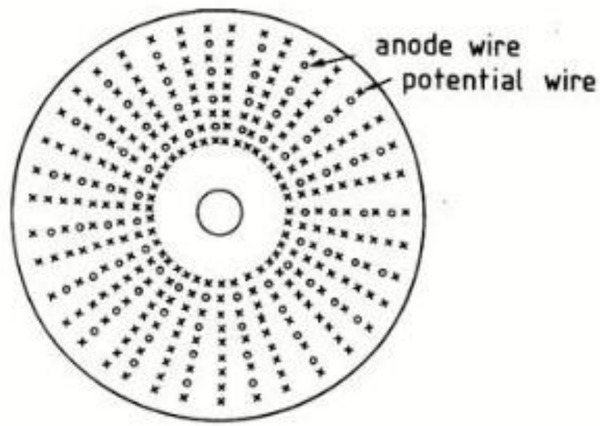




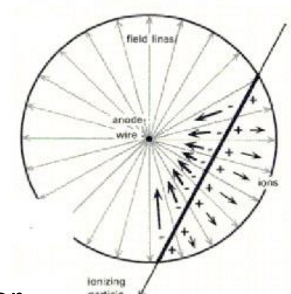
Hexcell DC
BaBar



Jet Chamber
Jade (PETRA), Opal (LEP) (Collider)

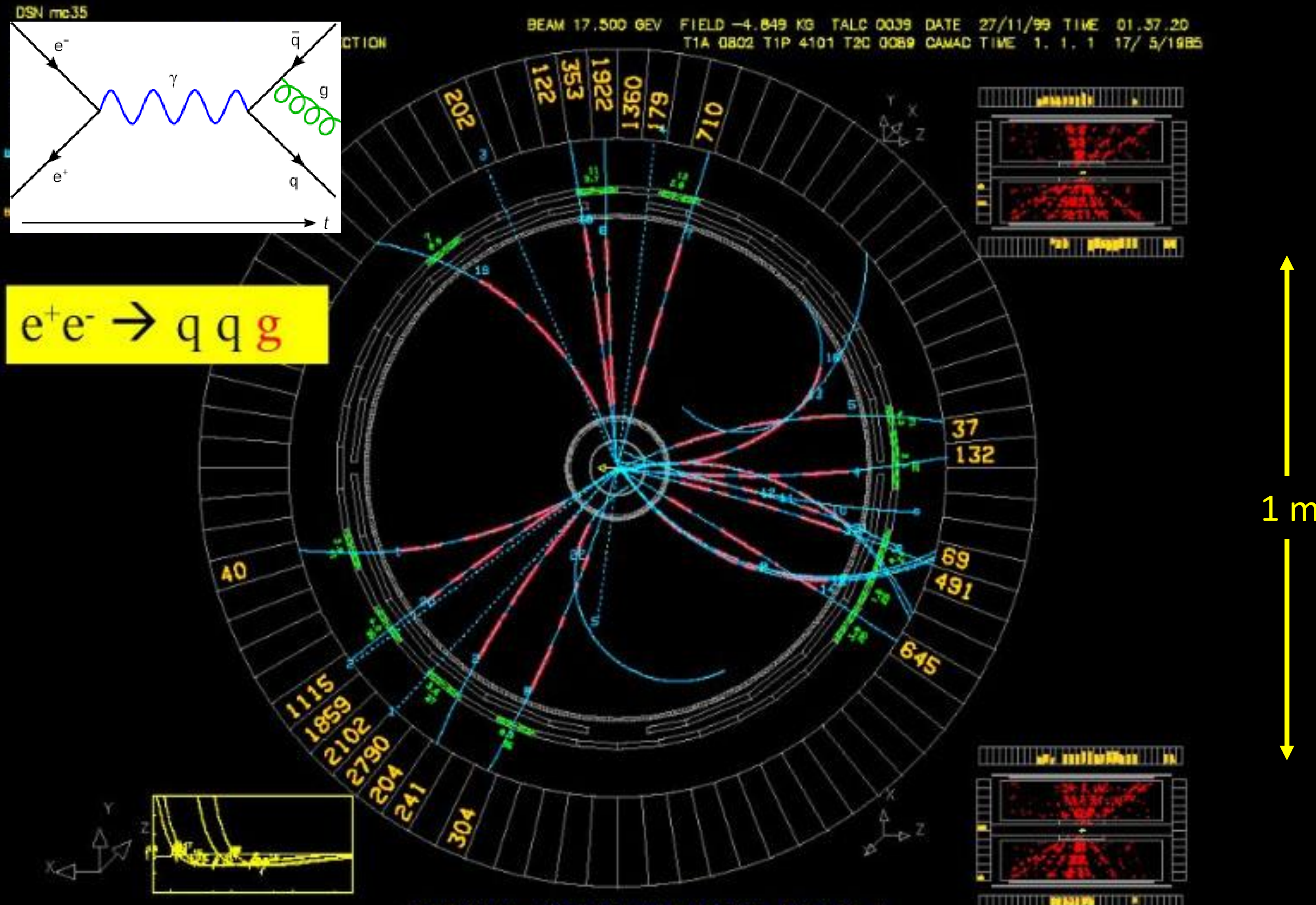


Cylindrical DC
(Collider)



Drift Tube
Muon tracker
(ATLAS, Collider)

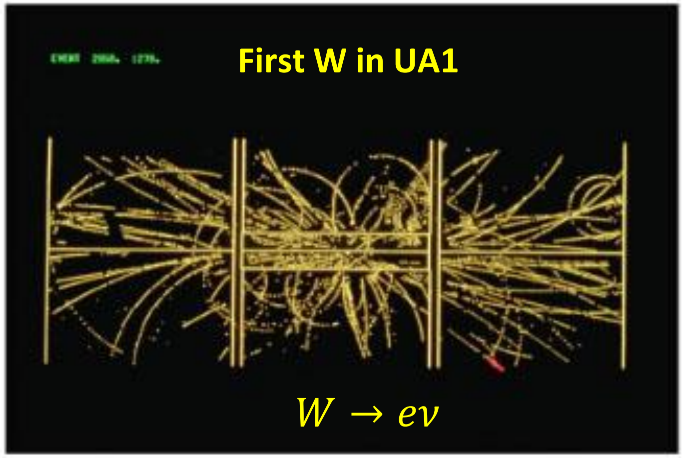
Drift Chambers – Discoveries (1979)



JADE @PETRA (Jet chamber)

3 –Jet event → Discovery of gluon

Drift Chambers – Discoveries



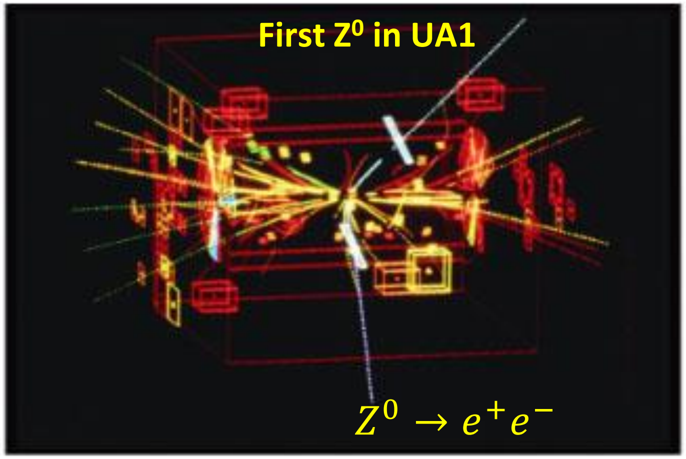
1983: discovery of the W and Z bosons by the UA1 and UA2 detectors at CERN -$Sp\bar{p}S$

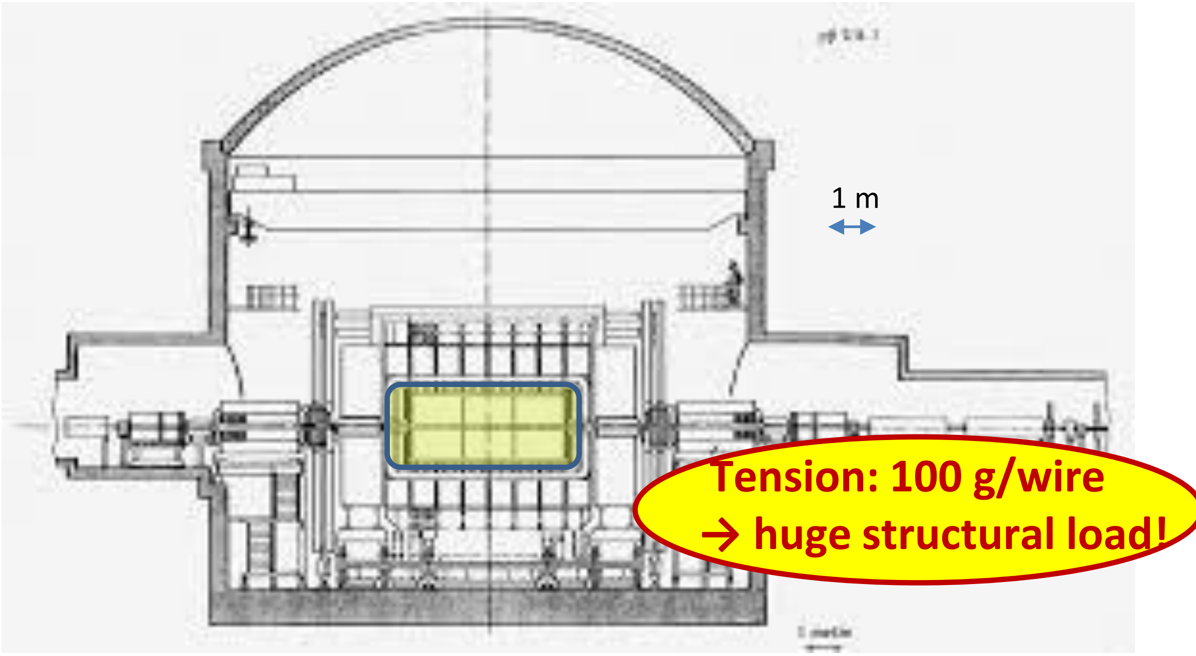
UA1 DC - 5.8 m long & 2.3 m Ø (Ar/C_2H_6)

170,00 field wires - 6125 sense wires!

B- field 0.7 Tesla

S. Van der Meer, C. Rubbia
Nobel Prize 1984





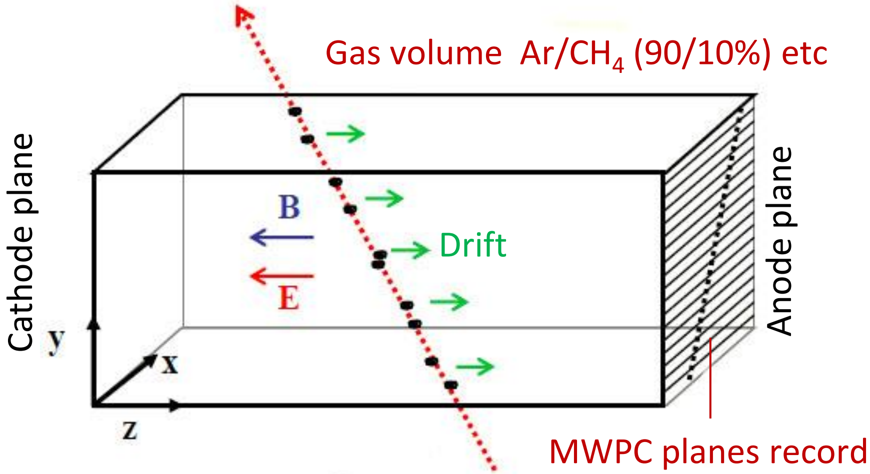
UA1 was the largest imaging drift chamber of its day!

Time Projection Chambers (TPC)

- 1974 invented by D. Nygren (Berkeley) for large volume 3D - imaging in the of PEP-4 detector at the e^+e^- collider PEP (SLAC)

David Nygren

"….one of those marvelous stories of frustration turned into opportunity" (D.N.)



- Gas volume with parallel E and B Field. B for momentum measurement, E for drift
- Drift ‖ to E ‖ to B reduces Lorentz force
- Diffusion is reduced by E ‖ B and by Ramsauer effect (up to a factor 100)
- Drift Fields 100-400V/cm. Drift times 10-100µs. Distance up to > 2.5m !

Some past & future gas TPC's:

- ALEPH, DELPHI – LEP/CERN
- STAR –RHICH/BNL
- ALICE – LHC pp, Pb-Pb collider
- ILD – ILC future pp collider

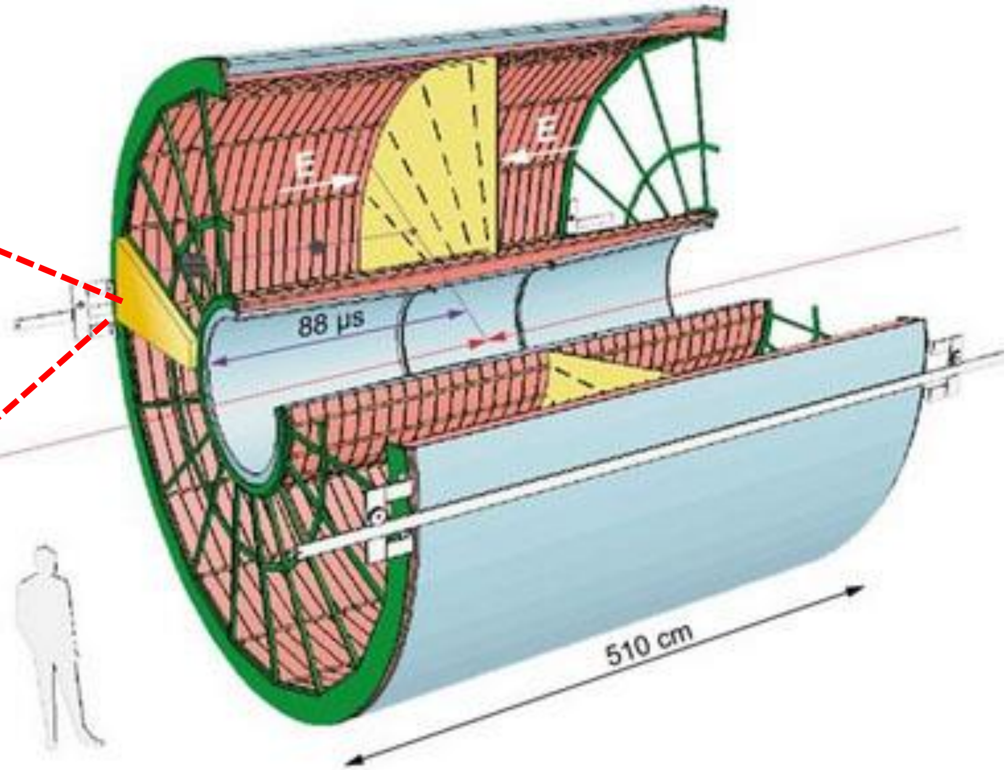
From now on VERY LARGE tracking and 3-d imaging devices possible!

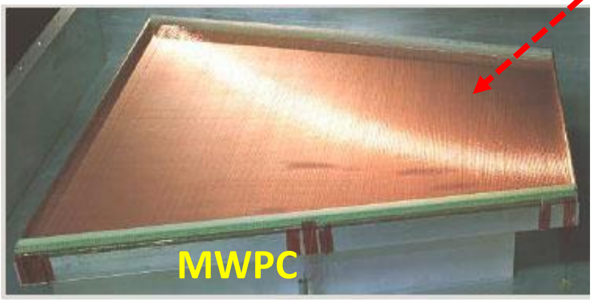
ALICE – **A** **L**arge **I**on **C**ollider **E**xperiment (LHC)

Study of quark – gluon plasma (2010 -)

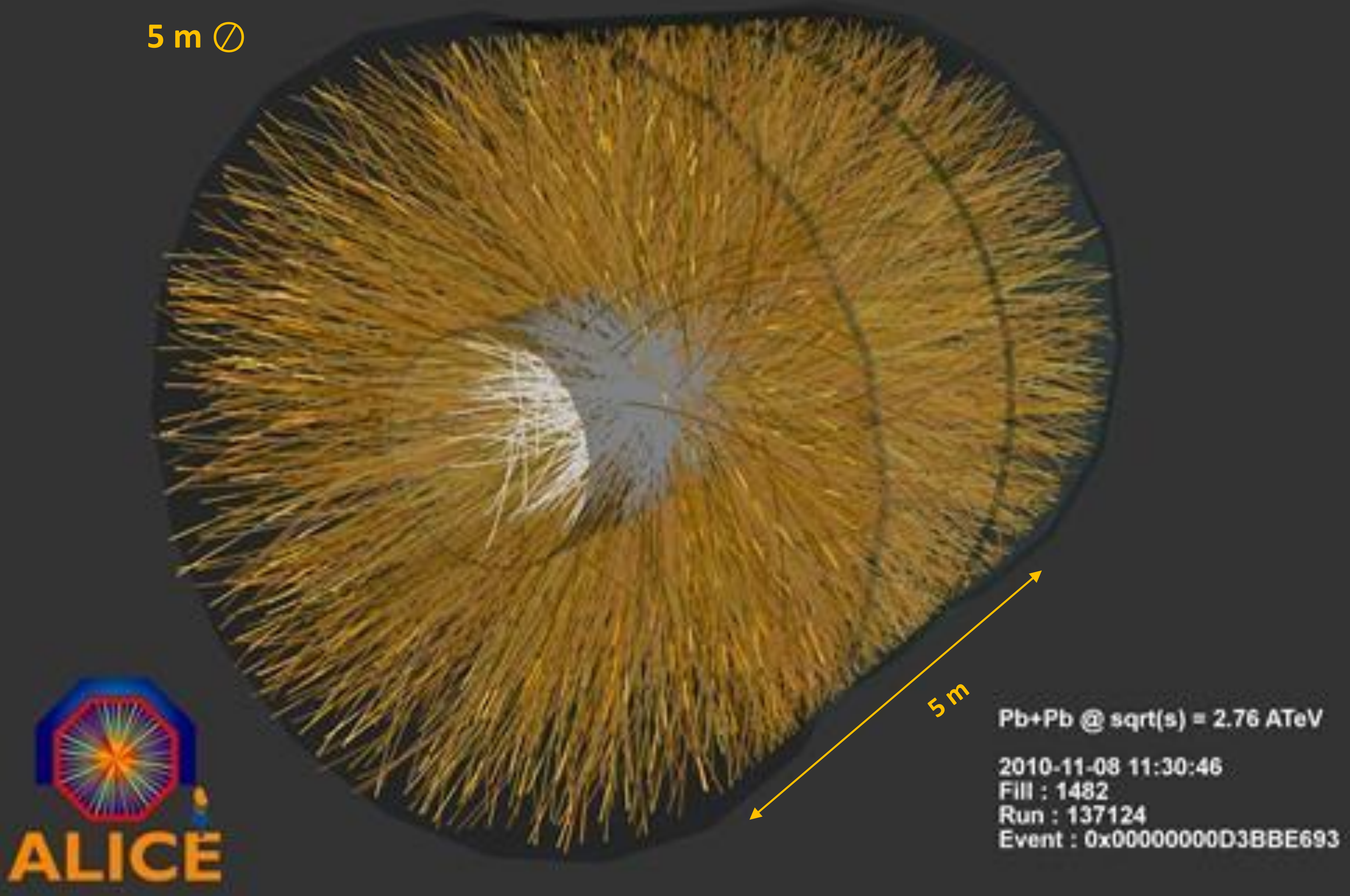
- Ne/CO_2 - 90/10 %
- HV-central plane - 100 kV
- B-field 0.5T
- 72 MWPC's
- 500 k read out channels
- Resolution 500 µm
- 50 kHz Pb –Pb collisions

Largest TPC ever built!





An event at ALICE (LHC)….largest TPC ever built



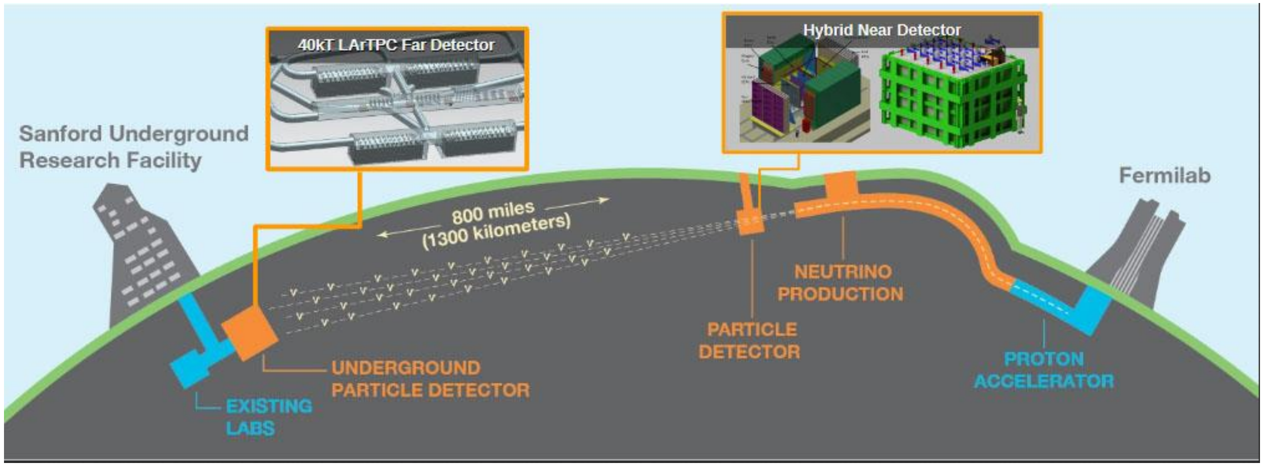
DUNE – A Giant Liquid Argon TPC

Noble Liquids→ Axel Halin's talk

1968 L. Alvarez suggests liquid noble gas detectors

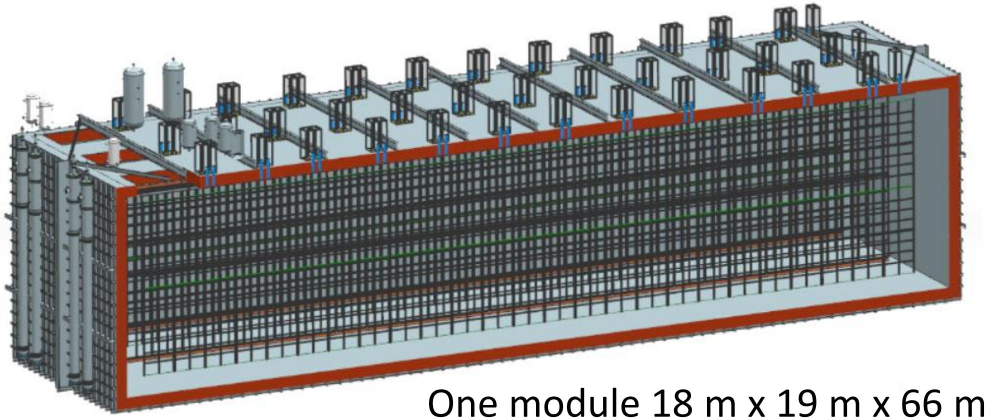
1977 idea pursued by C. Rubbia → **LAr TPC for ν – detection !** → ICARUS 760 t @ Gran Sasso

2026: DUNE - a 4 x 10 kton Liquid Argon TPC and ramping up now



Physics:
- ν-oscillations
- CP-violation
- SN – ν's
- p - decay

Specs:
- T_{op}= 87 K
- 153 wire anode planes
- Max. drift length 3.53 m
- Cathode 180 KV, 500V/cm
- 384 K channels



One module 18 m x 19 m x 66 m

Other LAr/LXe TPC's:
- EXO: LXe ββ – decay
- XENON, LUX, LV, DARWIN: LXe -DM search
- DARKSIDE, ARDM: LAr - DM search
- MicroBoone: 170 t LAr ν - oscill.

DUNE: Deep **U**nderground **N**eutrino **E**xperiment

I. Giomataris

MicroPatternGas Detectors (MPGD)

90's: replace wires in TPC's and MWPC's with 2-d structures with holes

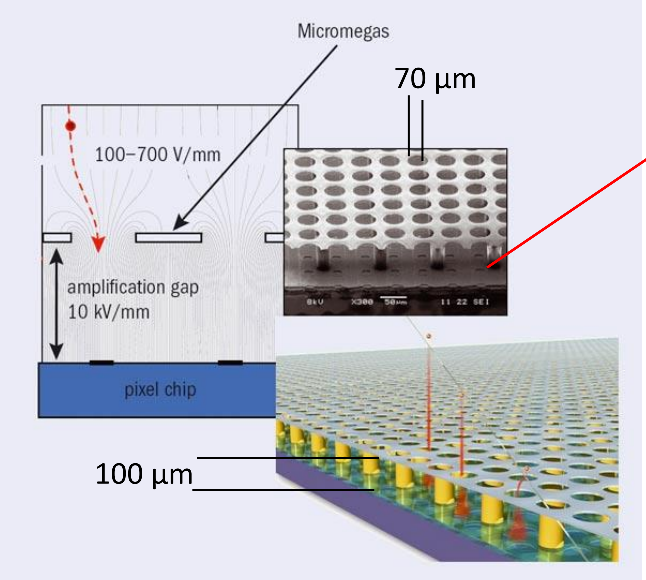
F. Sauli

MICROMEGAS (micromesh gas counter)

G. Charpak & I. Giomataris 1992

GEM (Gas Electron Multiplier)

F. Sauli 1997

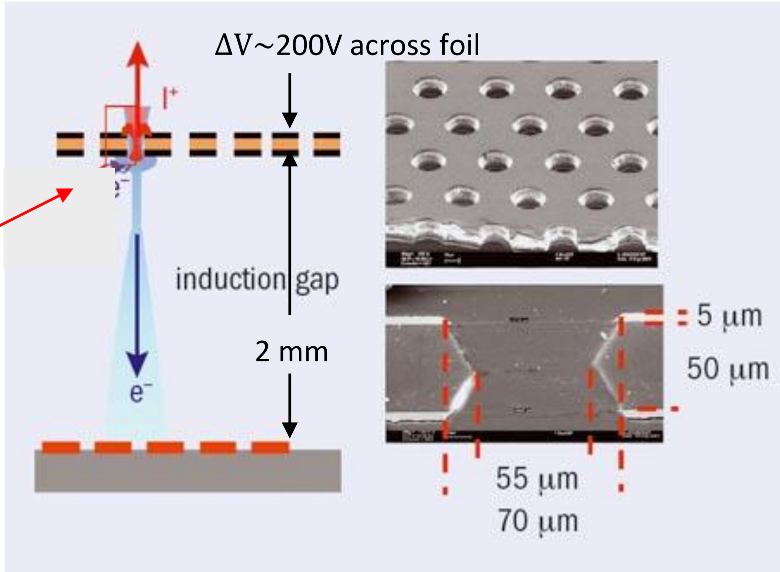


Small amplification gap → fast signals 100 ns

Strong field in small holes in polymer strip

Collect e^- on small pads, few mm^2

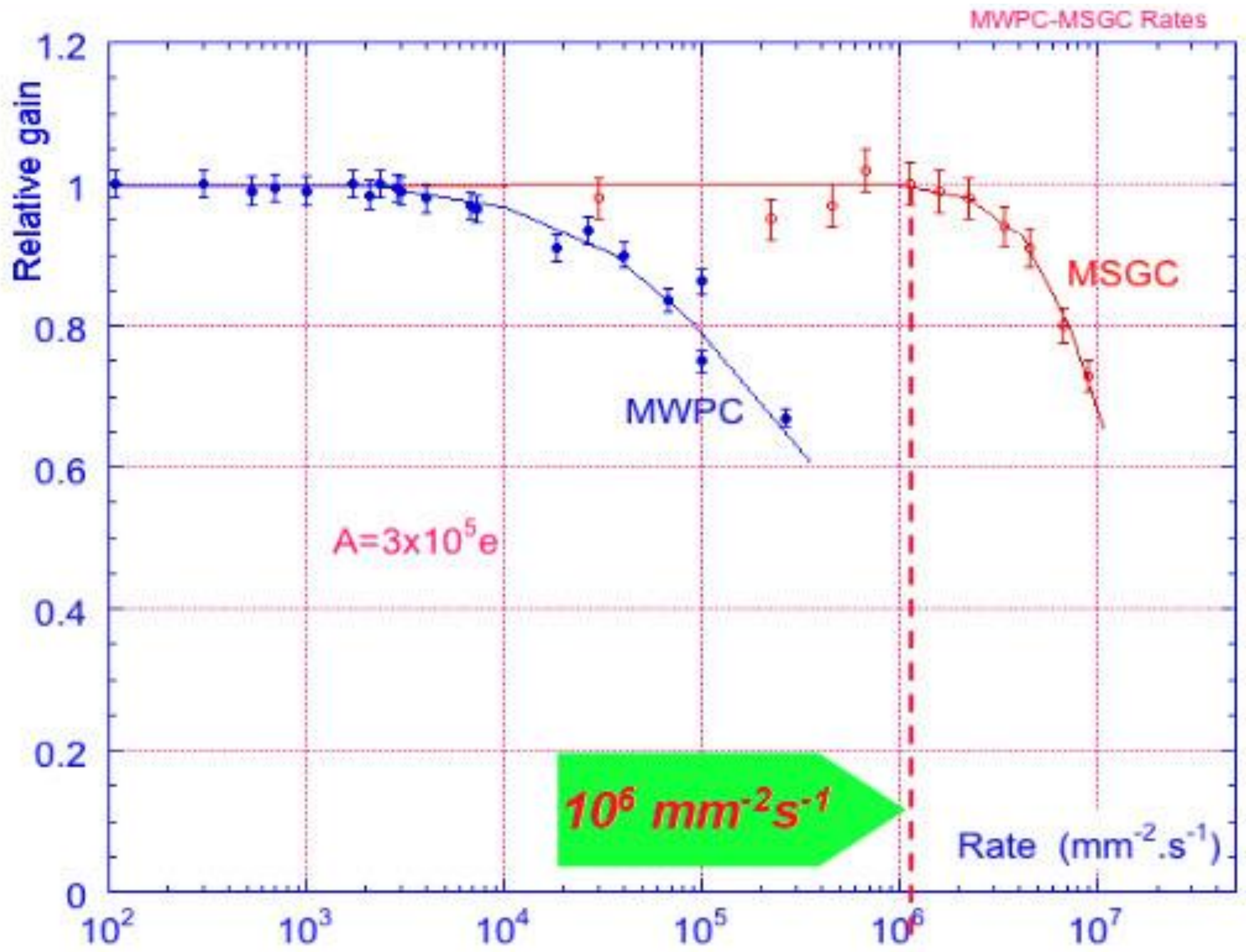
High gains > 10^3



Using large Area Lithography Techniques like for PCBs feature sizes of ~ 10 µm possible with high precision!

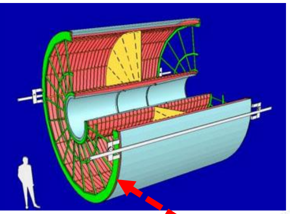
"MPGD's will revolutionize nuclear and particle physics like the MWPC" (G. Charpak in 1992)

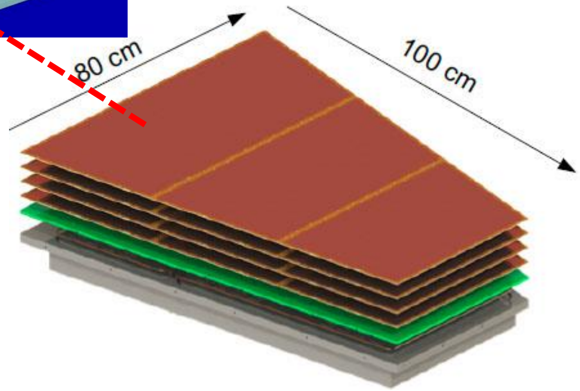
MicroPatternGas Detectors (MPGD)

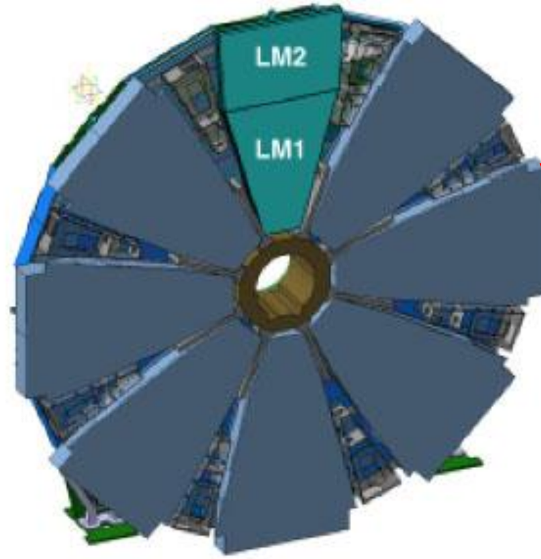


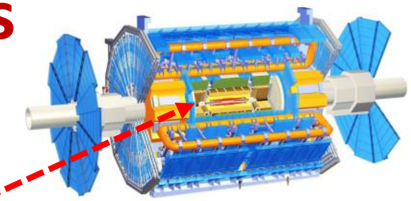
…high rate compatibility…not sensitive to B-field…slow ageing…industial production….

MPGD’s Recent Developments



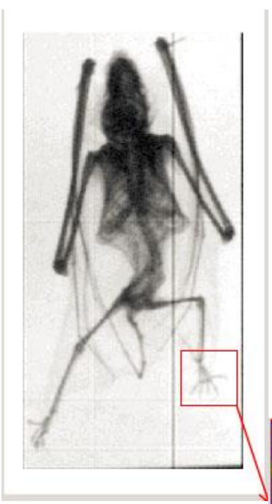


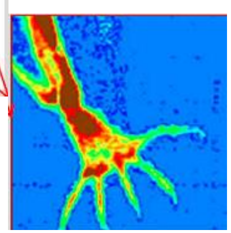




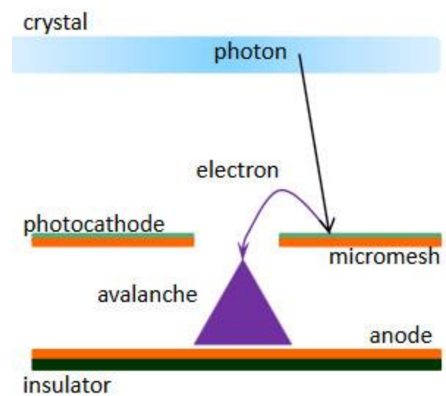
μΩ:
- ATLAS Upgrade for 2021
- End Cap μ- spectrometer
- 2 New Small Wheels (NSW)
- Large area μΩ (2 x 1200 m^2)
- 2.4 M channels

GEM:
- ALICE TPC upgrade for 2021
- Replace MWPC with 4-layer GEM
- X 100 gain in read-out rate (50kHz)





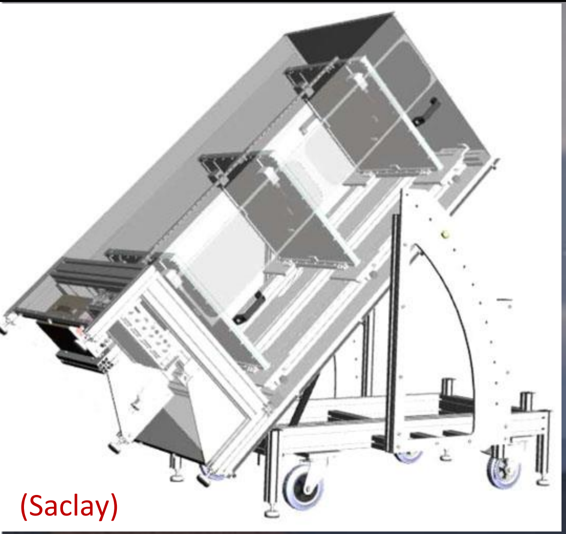
GEM:
- Radiography of a bat
- ^{55}Fe source 5.9 keV
- Using double GEM

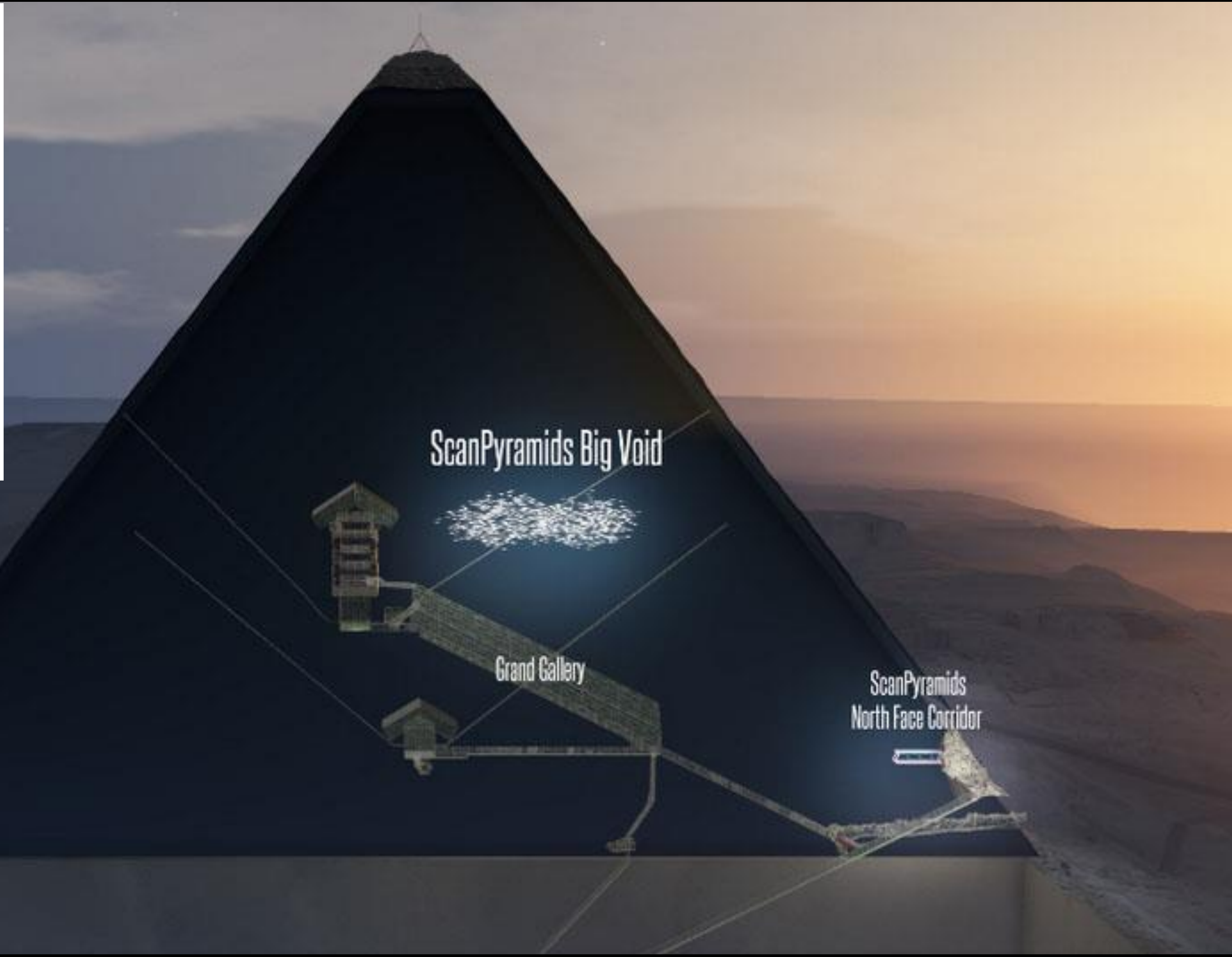


μΩ:
- Large area UV photon detector
- Photoconverter on μ - mesh
- High gain ~ 10^5
- Forest fire spark detection (FOREFIRE)

Also: COMPASS, CAST, T2K, ILC -TPC, ...

MPGD's in Archeology



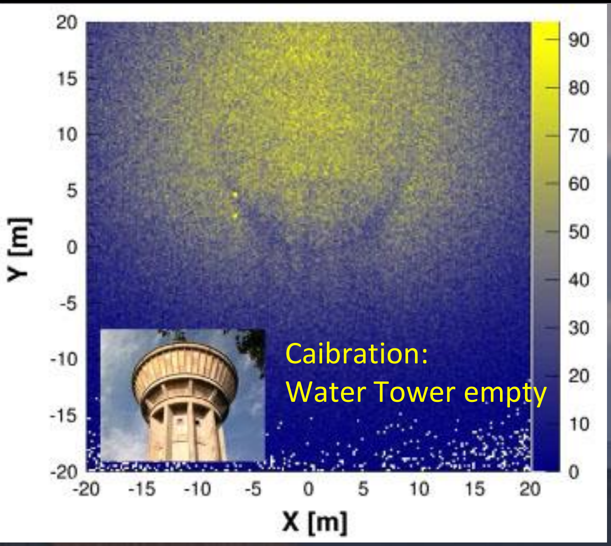


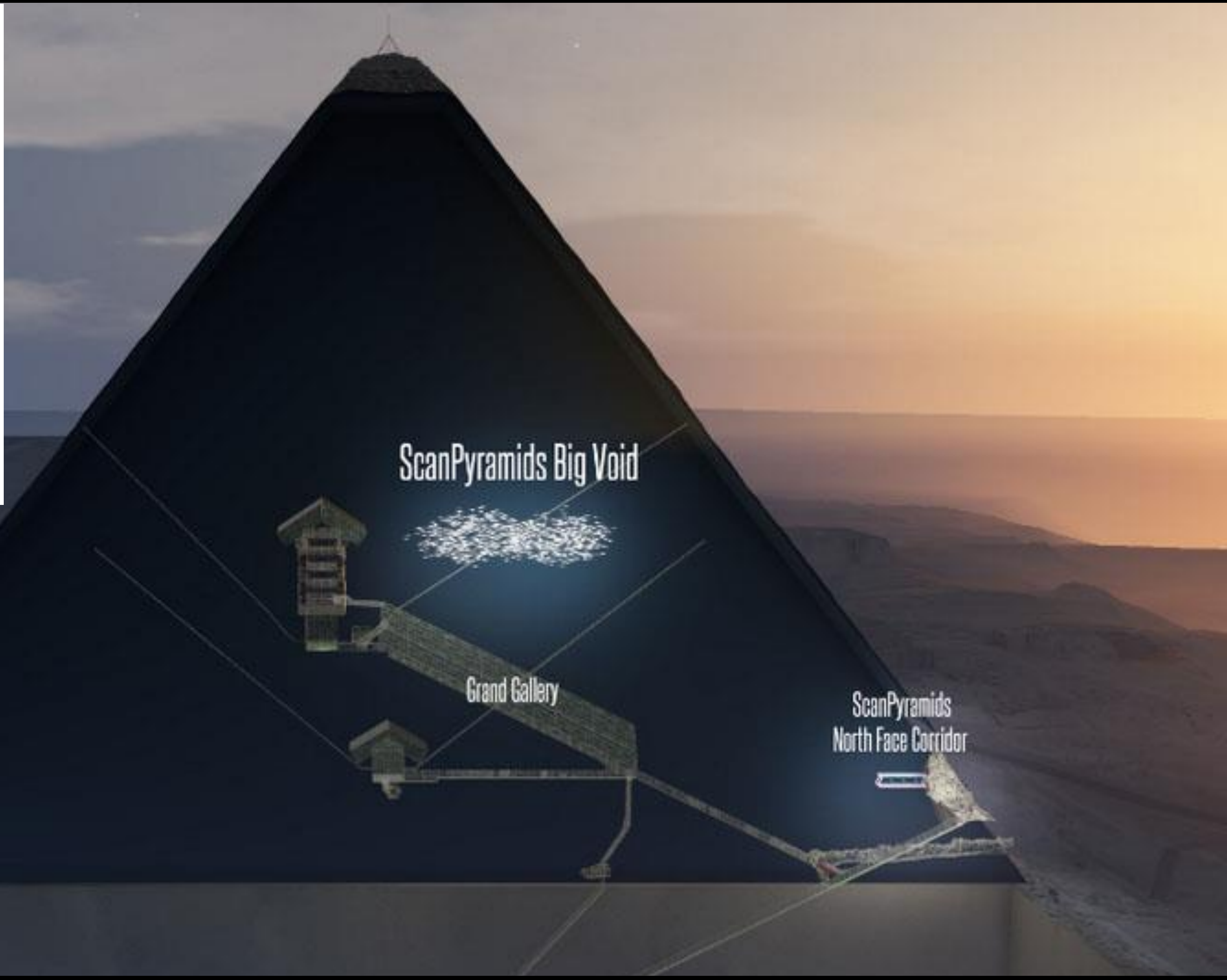
3 µΩ – planes 50 x 50 cm^2
300 µm resolution

2017: discovery of 30 m large void in Cheop's pyramid by muon tomography ...first observed with nucl. emulsion, then confirmed with micromegas based telescope

Nature volume 552, pages 386–390 (21 December 2017)

MPGD's in Archeology





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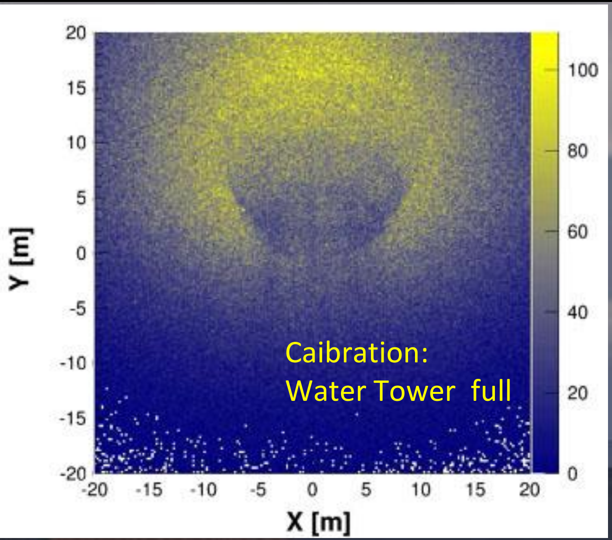
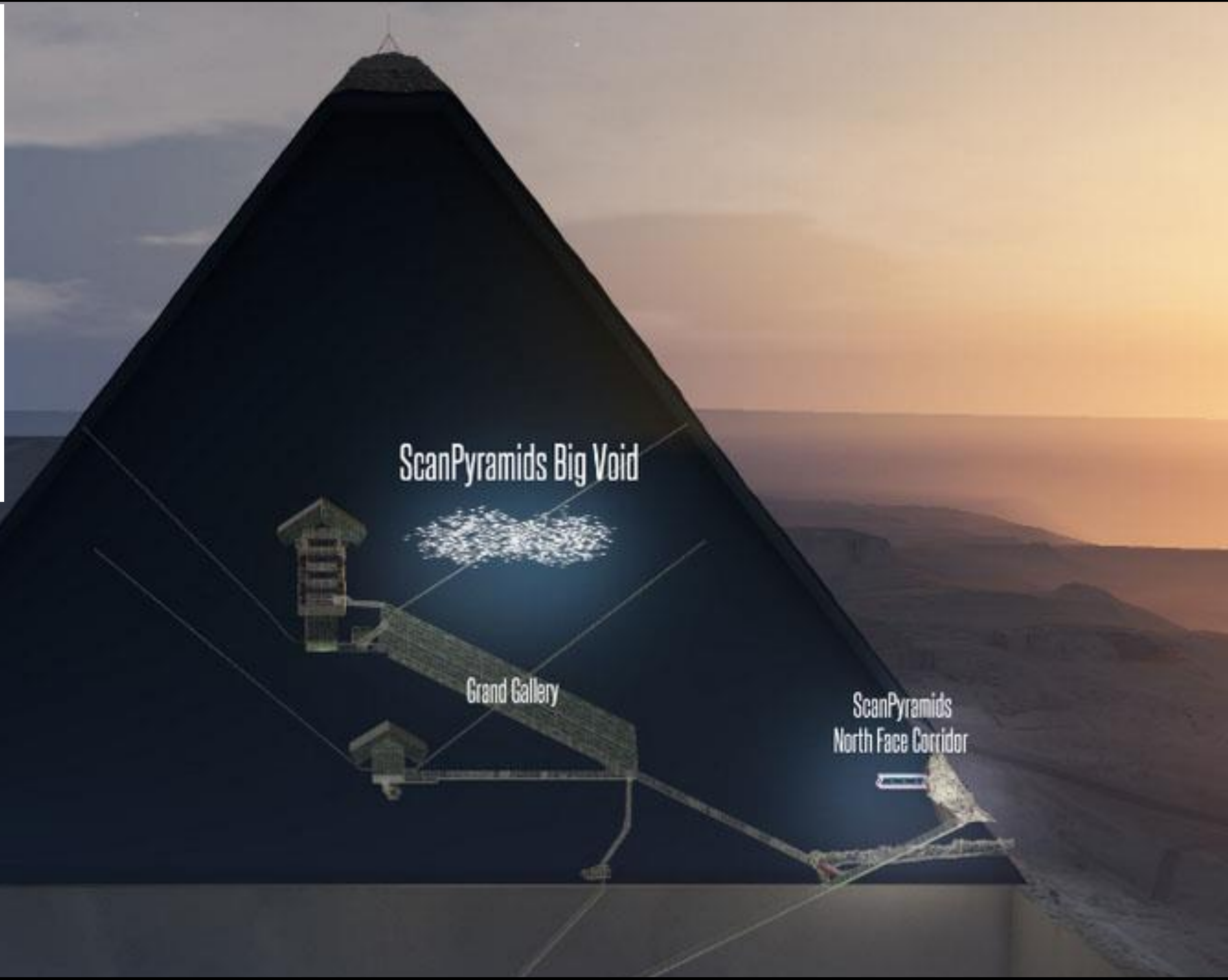
MPGD’s in Archeology





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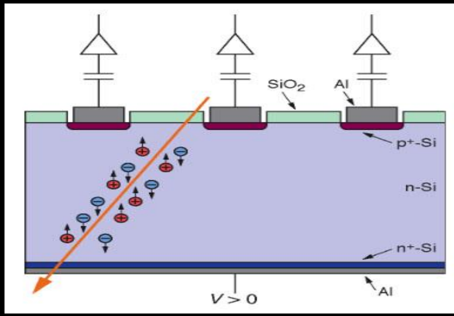
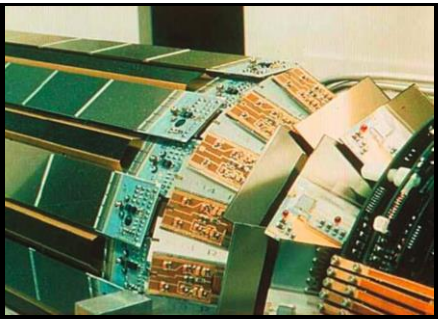
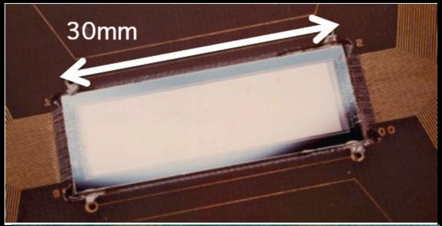
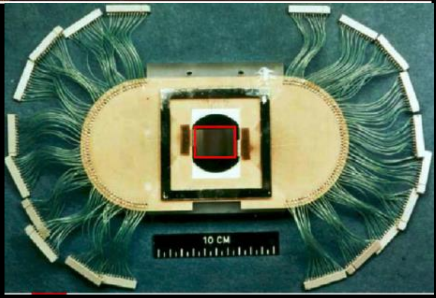
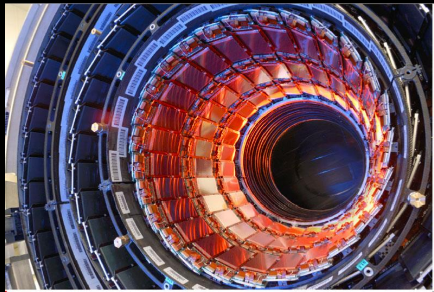
Solid State Detectors

- Silicon detectors
- Si-strip and pixel detectors
- Hybrid detecors
- Large scale applications

...details → talks by Nigel Hessey, Kate Paskal and Silvia Scorza

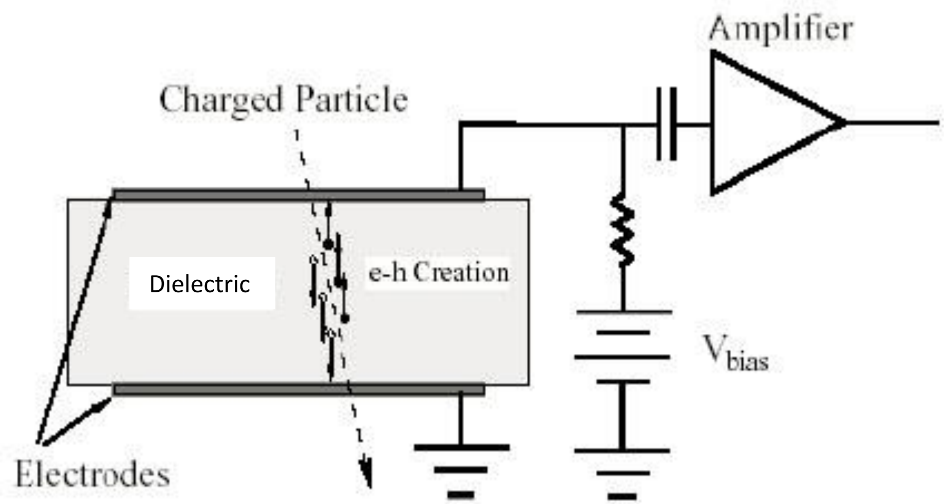


Solid State Detectors

1945 van Heerden operates the first crystal counter (AgBr)



- Sensitive dielectric between metallic electrodes
- Charged particles create e/hole pairs → a solid state ionization chamber! (Diamond, AgCl, TlBr…)

Advantages

- ρ_{solid} = 1000 x ρ_{gas}
- Fast charge collection v = 180 µm/µs
- Good energy resolution
- 13.3 eV per e-h (Diamond) (35 eV/ion-e in gas)

Drawbacks

- Large scale, high purity crystal growth challenging
- Electrical properties dominated by impurities

Today diamond counters considered for ILC/FCC → radiation hard !

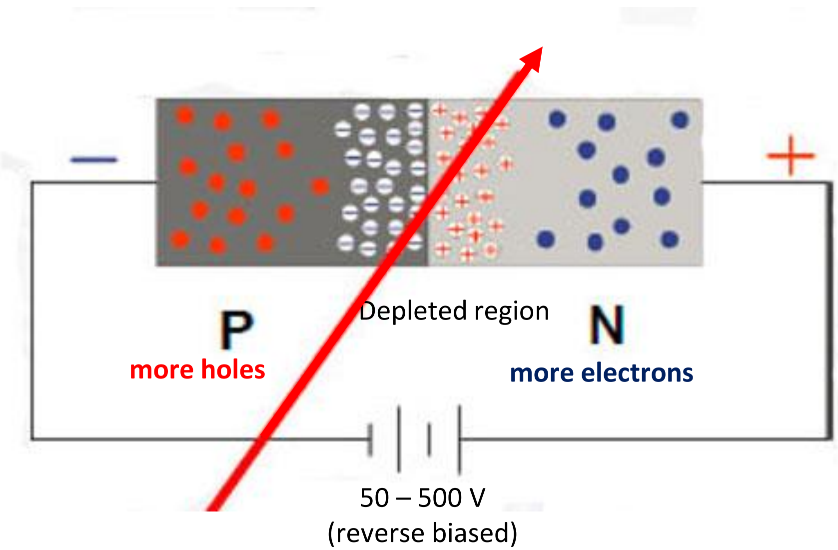
Solid State (Si) Detectors

1947 the Silicon revolution started with the invention of the transistor by J. Bardeen, W. Brittain and W. Stockley

- …but Silicon is a semiconductor (3.6 eV/e-h) → high leakage current @ 300K

- 1947 McKay and McAfee: operate Si-detector as a diode, where p-type and n-type doped Si are put in contact

J. Bardeen, W. Stockley, W. Brittain
Nobel Prize 1956



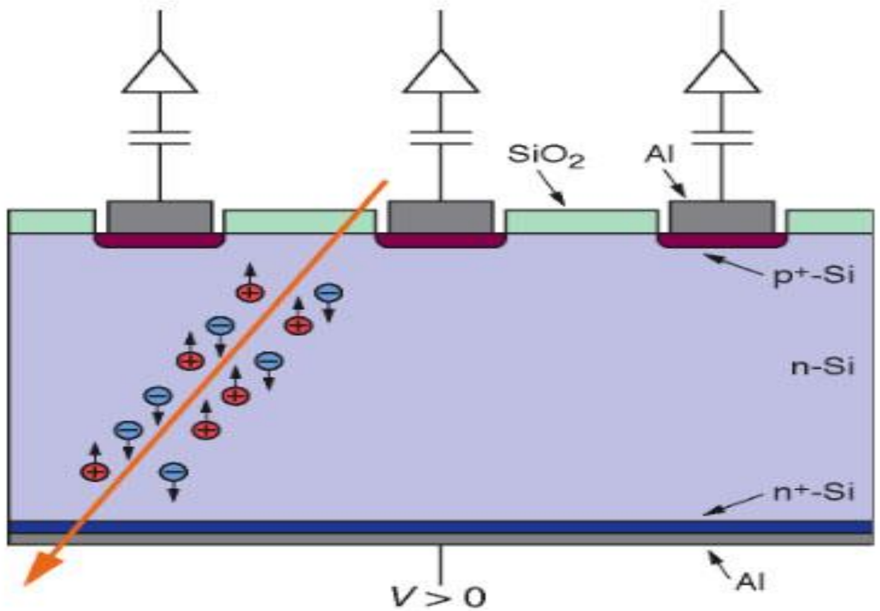
- Around p-n junction a depletion zone forms
- Zone free of charge carriers
- Thickness depends on voltage and doping
- Particle creates new e/h pairs sufficient to create signal

~ 25 k e/h pairs collected in 50 ns in 300 µm of Si

(1 cm Ar-gas: 100 e/ion pairs)

Silicon – Strip Detectors

Late 70's R&D driven by physics needs: search for new short- lived particles with $c\tau \approx 100$ μm & tracking near interaction region at accelerators



(n⁺, p⁺ → heavily doped)

- Si - crystal 3 x 3 cm^2 300 μm thick
- Subdivide top p-type layer into many strips
- Many diodes next to each other
- Position info like in MWPC
- Pitch ≈ 20 μm possible

1979 J. Kemmer (TU- Munich) transfers the highly developed planar process Si-technology for electronics to HEP detector fabrication

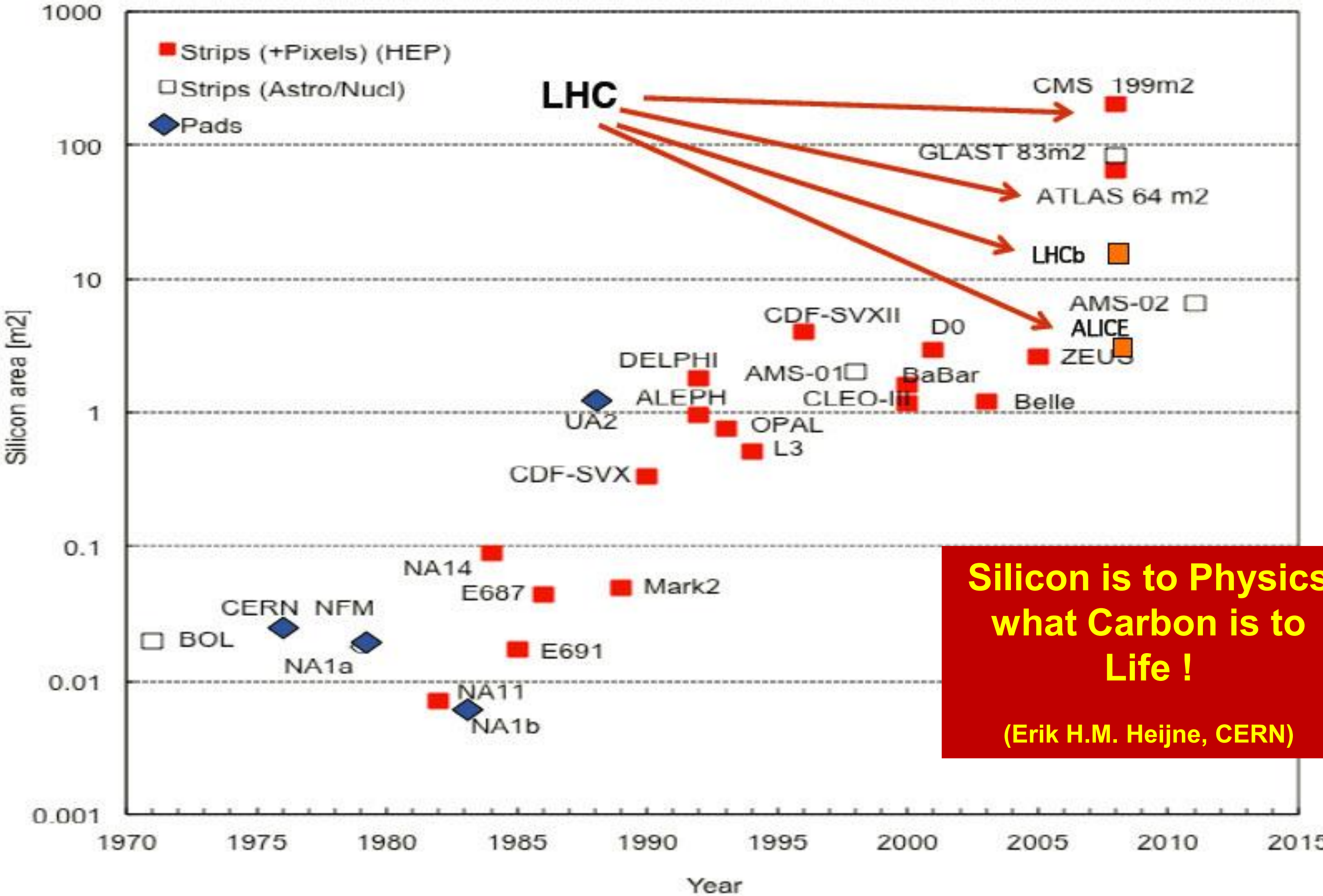
From now on large scale application of high resolution Si-detectors in practical every HEP experiment and also in X-ray astronomy and medical applications

Josef Kemmer
1938-2007
Founder of KETEC
(TU Munich)

J. Kemmer, NIM 169 (1980)499 (seminal single author paper!)

Si – Detectors: Increase of Si Area in HEP

ILD @ ILC
1800 m²



Silicon is to Physics what Carbon is to Life !

(Erik H.M. Heijne, CERN)

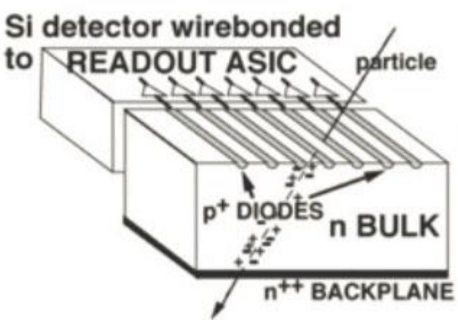
Main Types of Si - Sensors Today

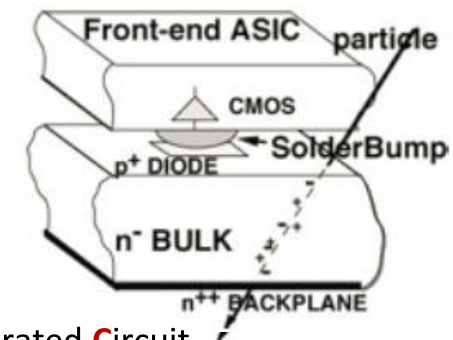
Si - Microstrip Detectors!
…to cover large areas!

Linear diode arrays 2-15 cm^2
depleted bulk ~ 300µm

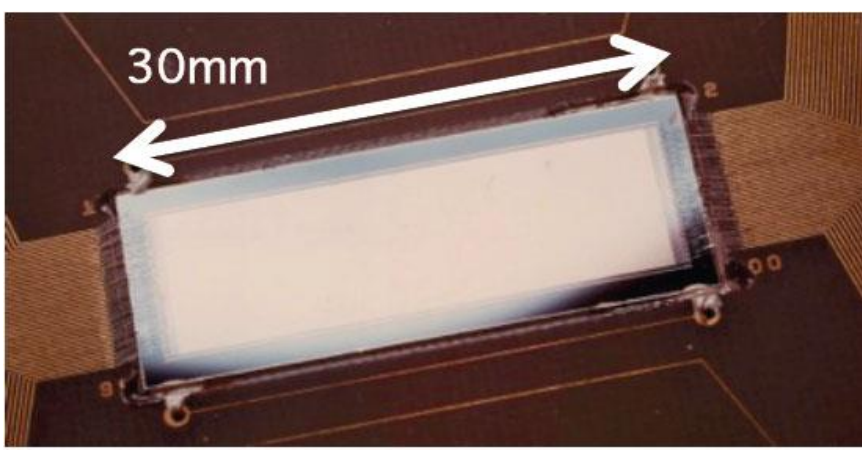
Si - Pixel Detectors!
…for highest densities!

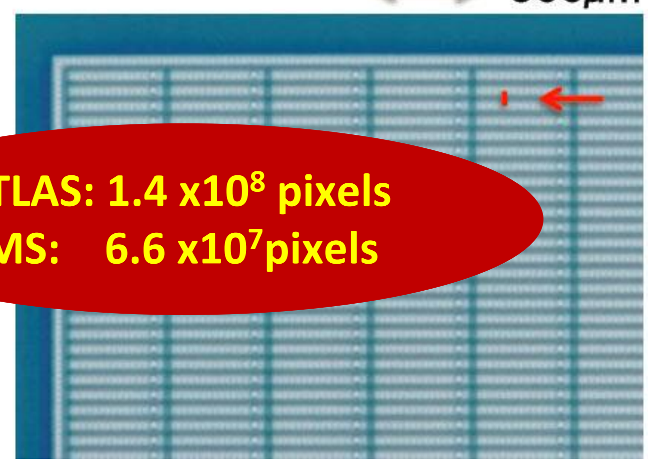
2D pixel matrix with bumps
diodes 30 µm – 500 µm
depleted bulk ~ 150µm





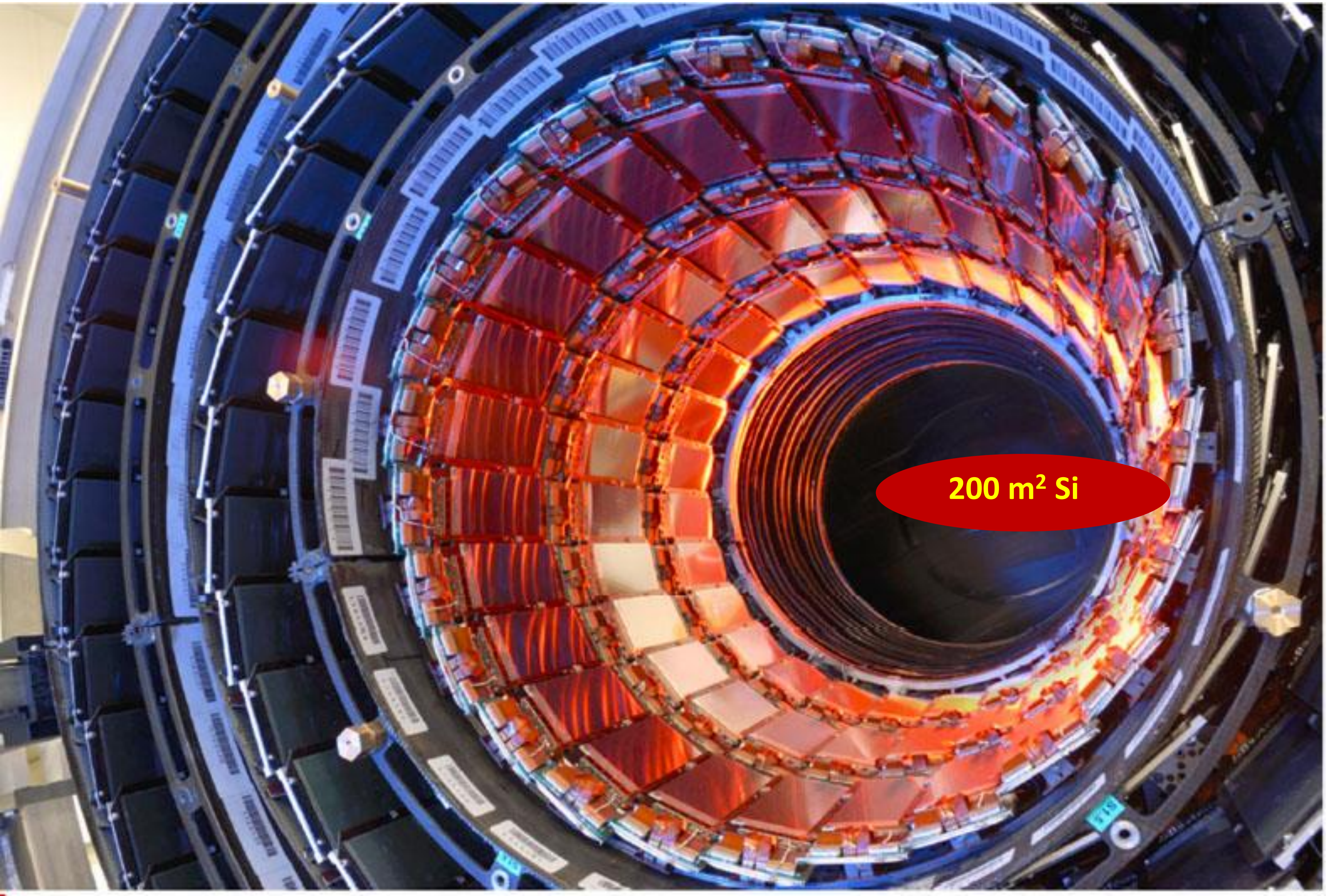
ASIC: **A**pplication **S**pecific **I**ntegrated **C**ircuit





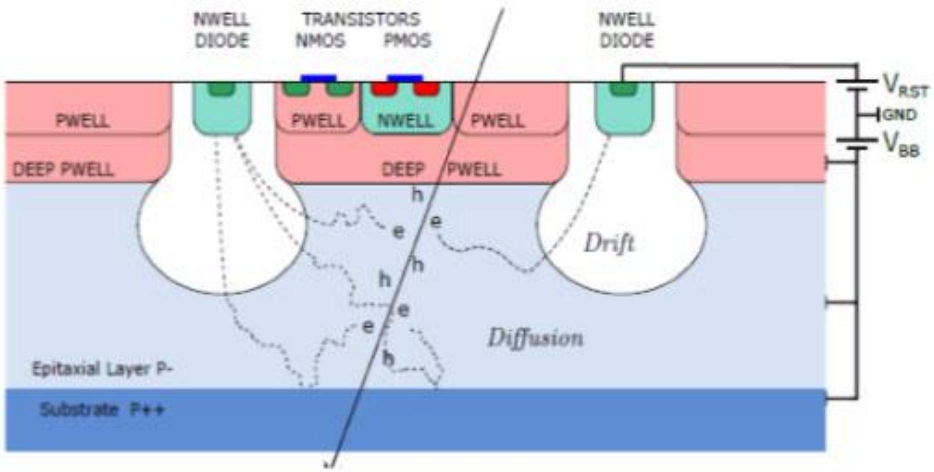
ATLAS: 1.4 x10^8 pixels
CMS: 6.6 x10^7pixels

CMS-Tracker - during installation 2007



Recent Developments – MAPS & 3D Devices

- **M**onolithic **A**ctive **P**ixel **S**ensor **MAPS –** ALICE Inner Tracker (2020)

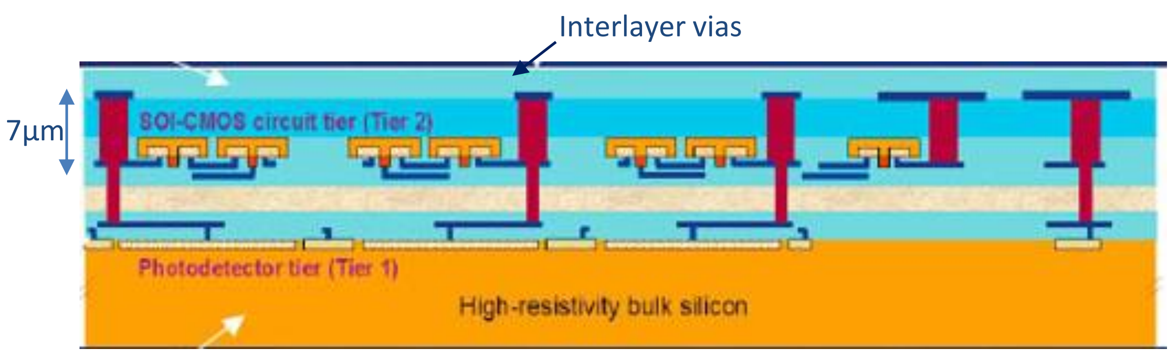


- 180 nm CMOS imaging process
- 512 x 1024 pixels on 15 mm x 30mm chip
- Electronics associated to one pixel
- Amplif., shaping, discrim., multi - event buffering
- low cost!

Continuous miniaturisation driven by industry!

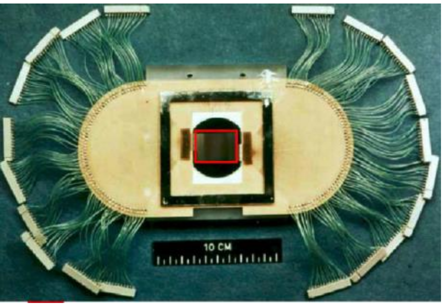
Transistor gate lengths:
1985: 2 μm / 2017: 5nm

- **3-D Circuit Integration - ILC – SID Vertex detector** (MIT/ FNAL)



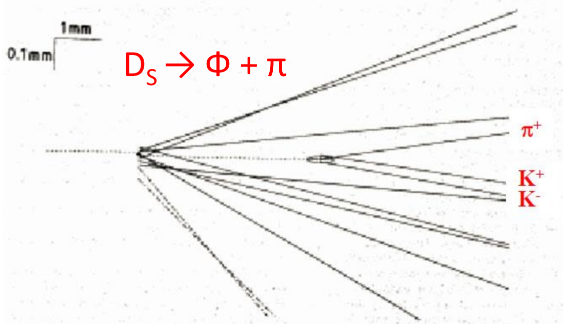
- 2+ layers of semiconductor devices
- Interconnected in monolithic circuit
- 10x10 μm chrono-pixels (w. time stamp)
- Resolution < 5μm in x, y
- Timing < 50 μs

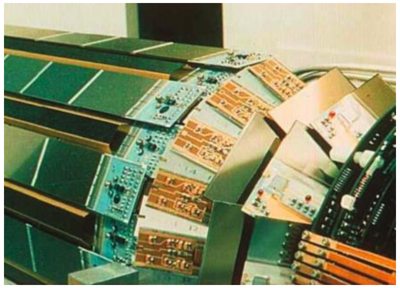
Si - Detectors – Some Discoveries



Ratio detector surface to nearby electronics surface 1:300 !

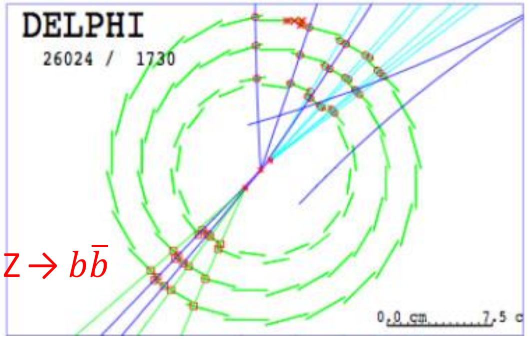
- 1983 first operational Si-strip telescope NA11 at CERN
  8 planes, 24 cm^2, 20 µm pitch, 4.5 µm res.
  $\pi \to$ Be $\to$ X + Charm (D^+, D^0, D_S…)

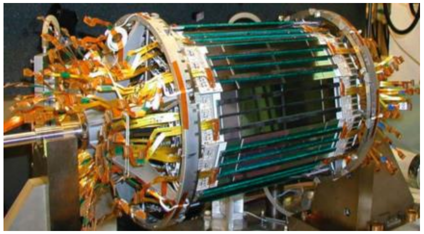




DELPHI: 1.5 m^2 Sensor surface
l = 1m, ∅= 20 cm; 3 layers

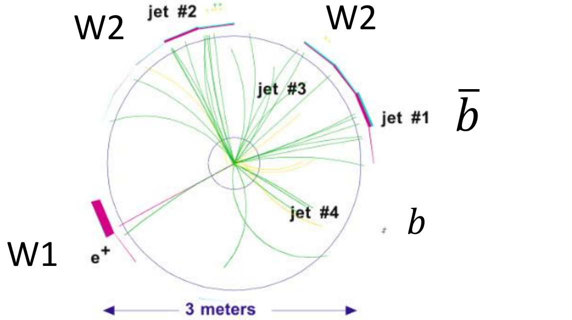
- In 90's all 4 LEP experiments installed Si-vertex detectors
  Goal: lifetime and ID of c-, b- quarks, τ
  Search for $H \to b\bar{b}$ ….but not found!

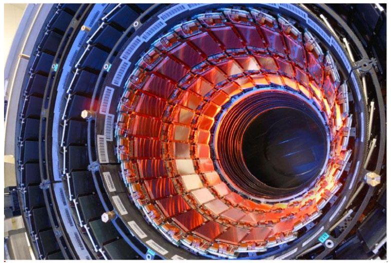




CDF vertex detector SVX II
3 layers, 720 detectors

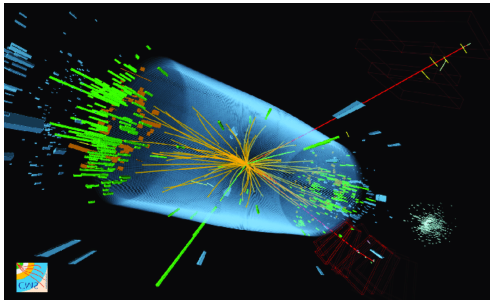
- '92 CDF 1st Si detector at had. collider
  Tevatron $p\bar{p}$ collision every 3.5 µs
  Discovery of t - quark
  $p\bar{p} \to t\bar{t} \ \to W^+b, W^-\bar{b}$
  1 lepton, 4 jets, 2 tagged b +ME





CMS Si- tracker

- 2012 CMS/ATLAS report discovery of Higgs (M = 125 GeV), results driven by
  $H \to \gamma\gamma, ZZ, W^+, \tau\bar{\tau}, \ \ b\bar{b}$ (2018)
  All 4 LHC detectors operate Si-trackers



Scintillators

- Inorganic crystals
- Liquid & plastic scintillators
- Search for the ideal scintillator

....details → talks by Graig Woodey, Kate Paskal and Aksel Halin

Scintillators

Use of scintillation to detect radiation is now more than a century old!

Early Phase (1903- 1944):

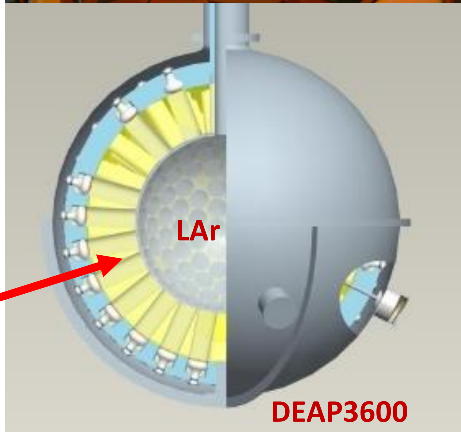
- $CaWO_4$ used by W. Roentgen
- 1903 J. Elstner, H. Geitel employ ZnS in sphintariscope → Crookes & Rutherford
- 1944 S. Curran & W. Baker coat ZnS on PMT photocathode

2nd Phase (1948 - 80's):

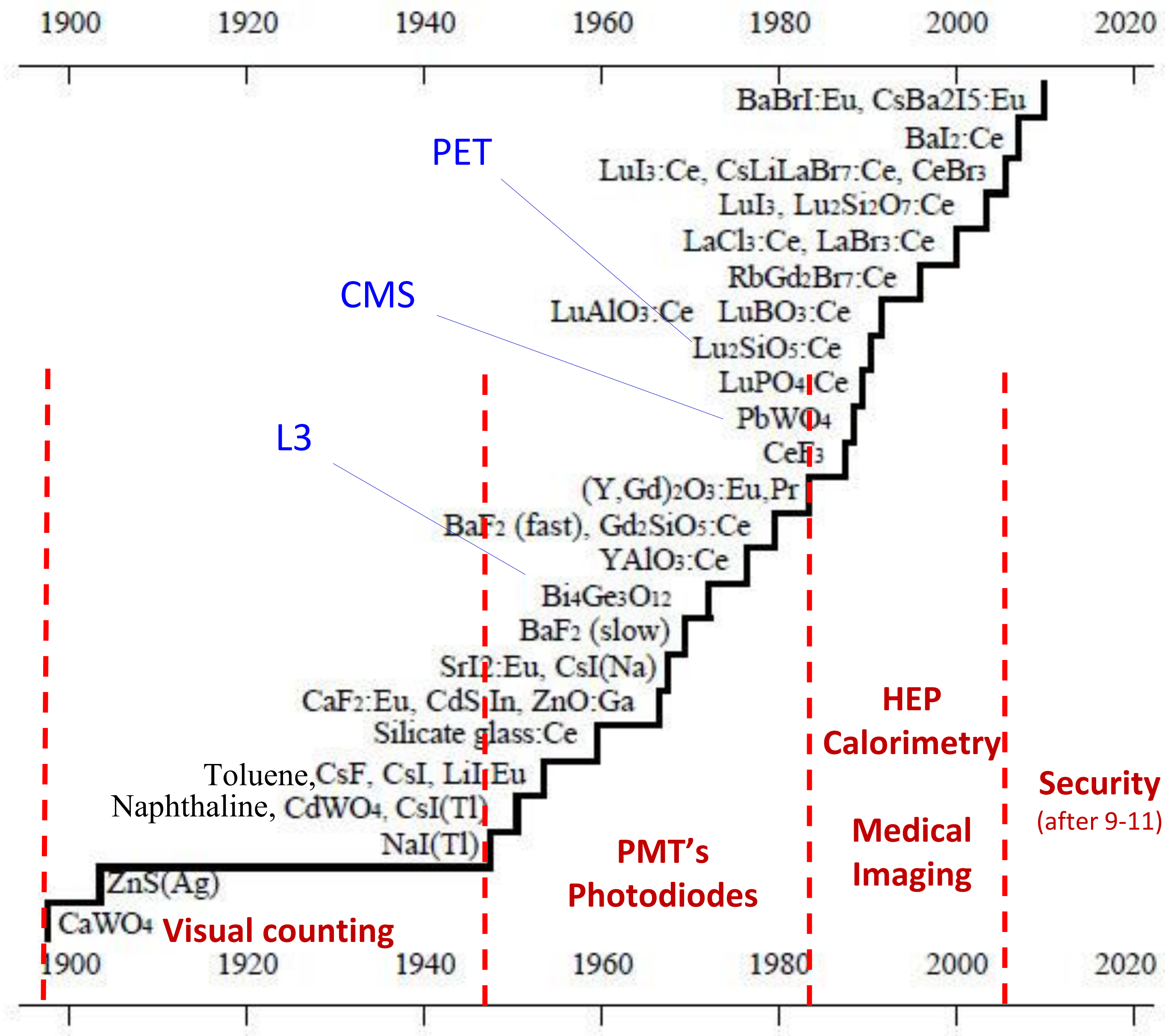
- 1948 H. Kallmann, L. Herford discover liquid scintillator (naphthaline)
- 1948 NaI(Tl) found by R. Hofstadter et al.
- Patented in 1950 by J. Harshaw (HCC)
- 1979 Crystal ball /SLAC 2m Ø NaI sphere
- CsI, BGO, rare earth doped scintill.

3rd Phase (80's- today):

- Renaissance driven by medical imaging (PET, SPECT), HEP-calor. BGO, PWO_4 etc.
- $LaBr_3$, $LaCl_3$ etc → light yields close to theoretical limit!
- Large scale applications of LAr/LXe

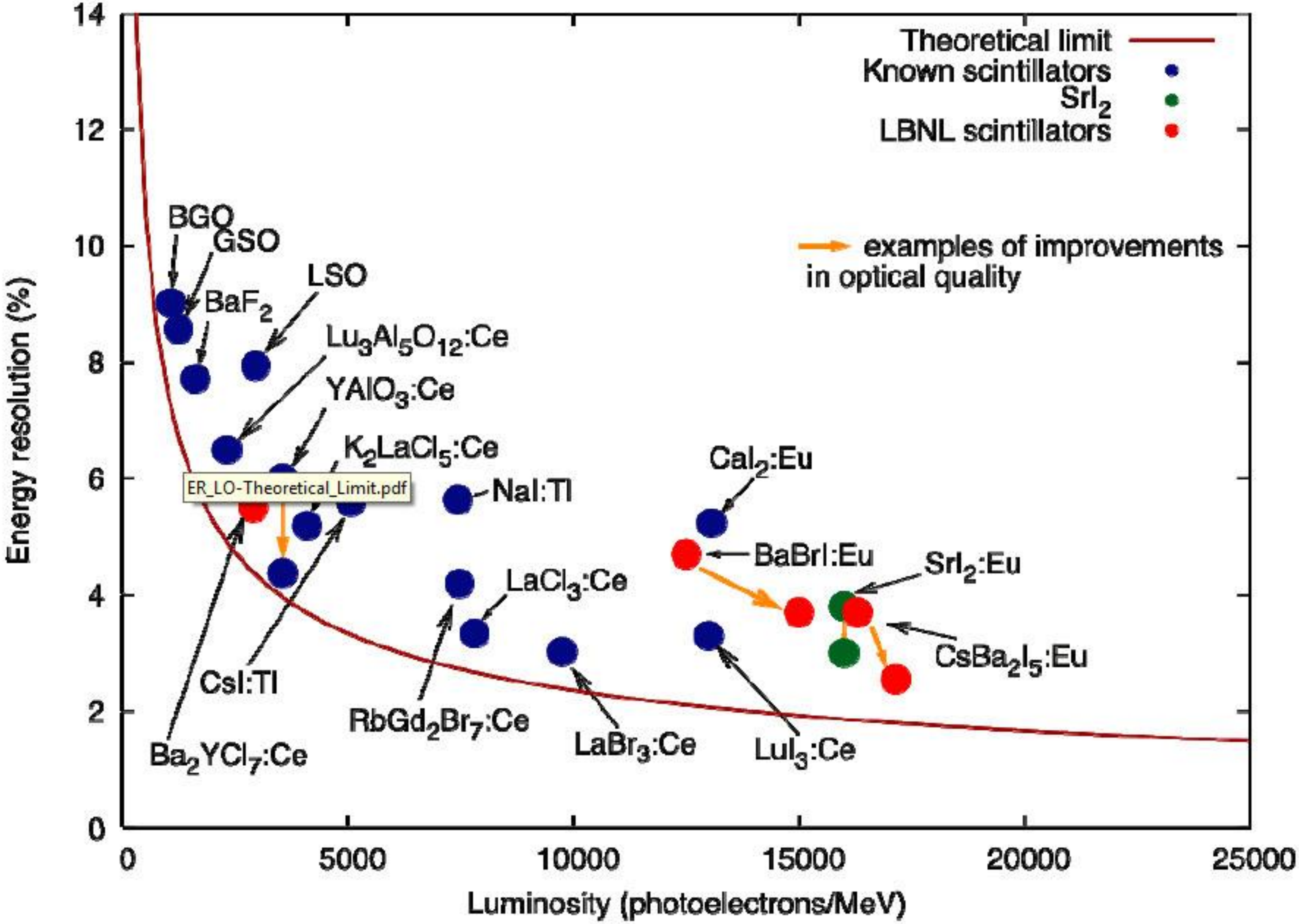


Scintillator History



From ISMA, SCINT 2009 conference (update of S.E Derenzo et al.; NIM A505(2003)111

Recent Scintillators – Energy resolution



From E. D. Bourret Workshop Nuclear Medicine, Physics, Engineering and Practice, 2011, Kharkov, Ukraine .

...mass production is the challenge for the future!

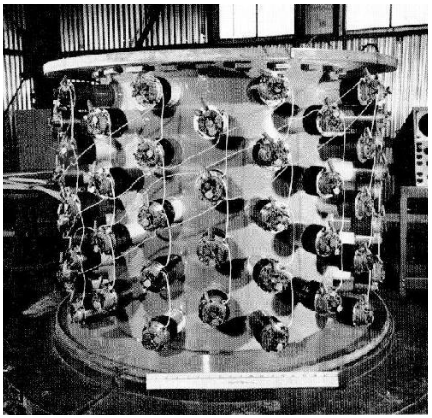
Discoveries with Scintillators

The 1st Big Science experiment after WWII

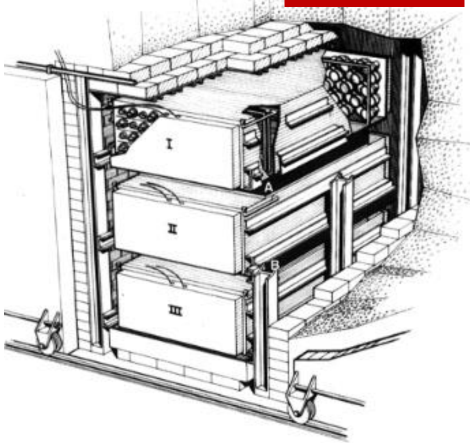
1956: first observation of neutrinos by Clyde Cowan & Fred Reines

Plan A: use an atomic bomb – project “Poltergeist”

Plan B: go to a nuclear reactor (Hanford then Savannah River)



The Hanford experiment called “Herr Auge” – **90 PMT’s**



The Savannah River experiment – **110 PMT’s**

- Inverse β- decay in $CdCl_3$ - water solution
- Liquid scintillator + PMT’s
- Underground 11 m @ 12 m from core (SR)
- 10^{13} ν/scm^2; 3 evts/h; 3 months exposure

prompt signal

$$e^+ + e^- \rightarrow 2\gamma$$

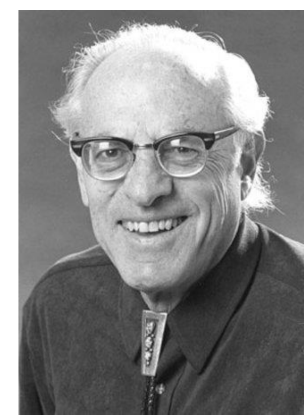
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Capture on Cd or H
delayed signal

Modern experiments are still quite similar:

- Gd loading of scintillator
- Larger detectors
- Deeper underground, better shielding

Clyde Cowan
1919-1974



Frederick Reines
1918-1998
Nobel Prize 1995

RADIO-SCHWEIZ AG. **RADIOGRAMM - RADIOGRAMME** RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK			Brieftelegramm		

74 15.VI. 56 —1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

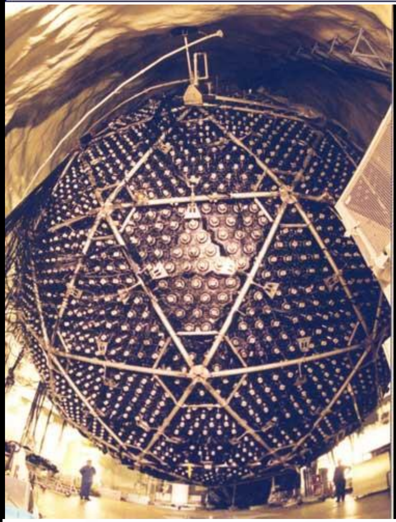
BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

Pauli's reply: "Thanks for message. Everything comes to him who knows how to wait"

Photomultipliers

- The Photomultiplier Tube
- Gas PMT's
- Silicon PMT's
- Hybrid detectors
- Future Large Scale Applications


The Photomultiplier Tube (PMT)

PMT's appeared around 1930 and are today ubiquitous in HEP, astroparticle, cosmic ray physics, medicine, archeology, art….

PMT's were predicated on:

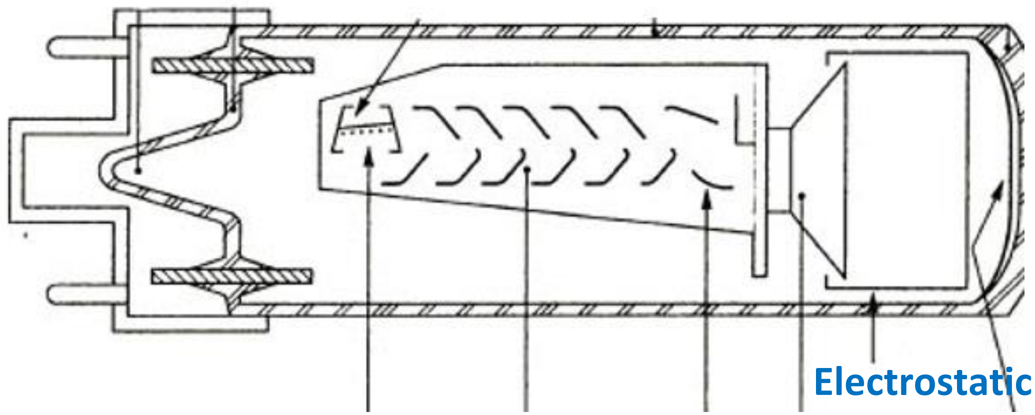
- discovery of photoelectric effect (H. Hertz, 1887)
- discovery of secondary e⁻ - emission (Villard, 1899)
- vacuum technology - photo electric tubes
  → beginnings of 'CRT television' (1925 T. Takayanagi)

…but who invented the PM?

*1905 A. Einstein "explained" the photo electric effect….

The Photomultiplier Tube (PMT)

PMT's appeared around 1930 and are today ubiquitous in HEP, astroparticle, cosmic ray physics, medicine, archeology, art….



PMT's were predicated on:

- Discovery* of photoelectric effect (H. Hertz, 1887)
- discovery of secondary e⁻ - emission (Villard, 1899)
- vacuum technology - photo electric tubes
  → beginnings of 'television' (1920 !)

…but who invented the PM?

*1905 A. Einstein "explained" the photo electric effect….

The Photomultiplier Tube (PMT)

…but who invented the PM?

….that's a controversial issue !!!

- 1930 L. A. Kubetsky (24 y old!) presents in Leningrad a device to amplify photoelectron currents

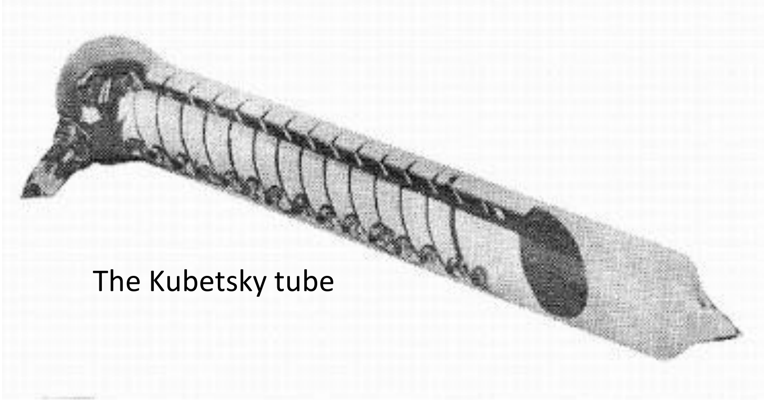
- Uses a AgOCs photocathode, a system of dynodes with gain ~ 10^4 and magnetic focusing

- 1934 V. Zworykin working at RCA/US visits Leningrad

- Kubetsky shows his tube and Zworykin is enthusiastic

- 1936 V. Zworykin. et al: (RCA) paper on PMT with multiple dynodes

Leonid A. Kubetsky
1906 - 1959

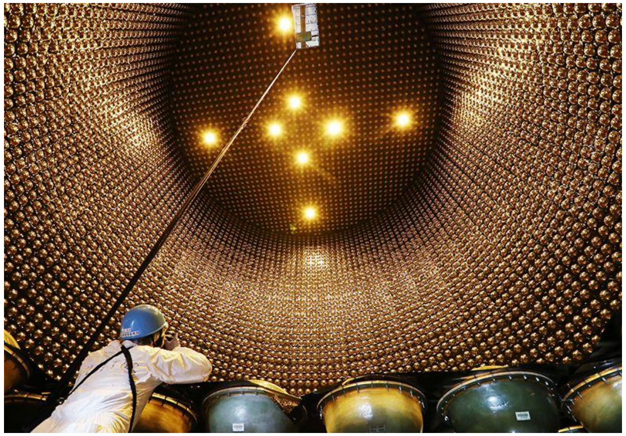


The Kubetsky tube

…today however: "The PMT was invented by RCA laboratories"!

B. K. Lubsandorzkiev, cern.ch/record/923550/files/0601159.pdf

Discovery of Solar ν - oscillations



SuperKamiokande – **13 000 PMT's** 50 cm ∅

(1956 Cowan & Reines 110 PMT's !)

1996 - 2008: SuperKamiokande

- 1000 m deep; 40 m high - 20 m ∅
- Č - detector: 50 kt H_2O
- Compare ν - e^- rate to Standard Solar Model (SSM) prediction

$$NC + CC: \quad \nu_e + e^- \rightarrow \nu_e + e^-$$

$$\frac{Data}{SSM} = 0.47 \pm 0.015$$

(+1998 oscill. of atmospheric ν_μ's)

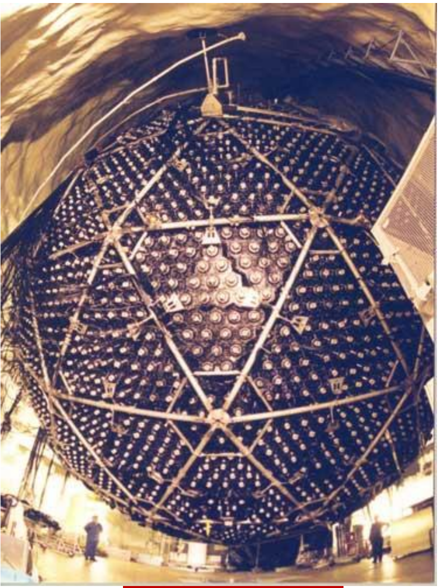
T. Kajita & A. B. McDonald
Nobel Prize 2015

1999 – 2006: **S**udbury **N**eutrino **O**bservatory (**SNO**)

- 2100 m deep in Creighton mine, Sudbury (ON)
- Č - detector: 1.0 kt of D_2O in 12m ∅ acrylic vessel
- Compare neutral and charged current solar ν - reactions

CC: $\nu_e + d \rightarrow p + p + e^-$ $\quad 5 < E_\nu < 15\ MeV$

NC: $\nu_x + d \rightarrow n + p + \nu_x$ $\quad \nu_x = \nu_e, \nu_\mu, \nu_\tau$



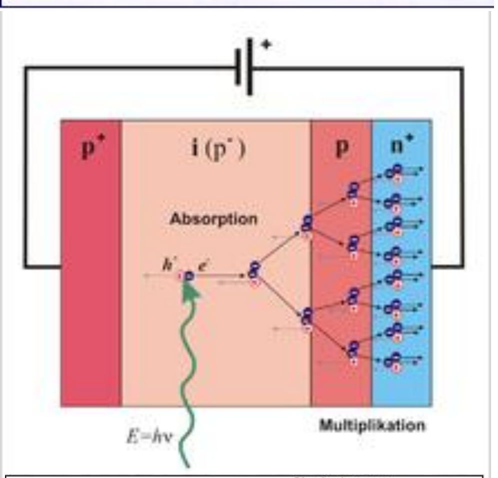
SNO **10 000 PMT's** 20.4 cm ∅

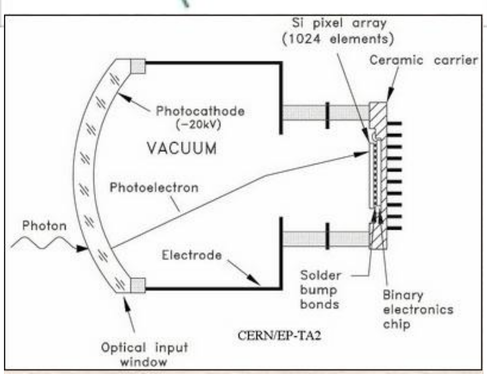
$$\frac{\Phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033$$

→ Physics BSM !

Photomultipliers – Recent Developments

Since almost 90 years R&D is ongoing and driven by physics and applications



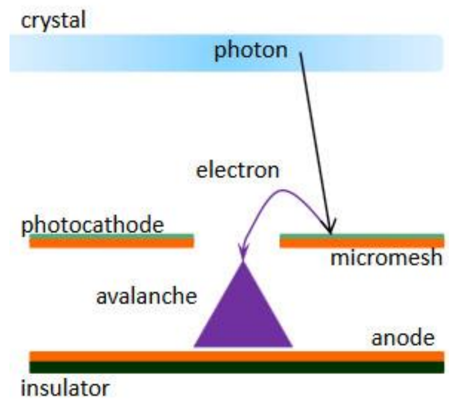


Vacuum based (classic PMT)

- QE ~ 25%; Gain ~ 10^6
- No spatial resolution
- Photocathodes up to 8000 cm^2

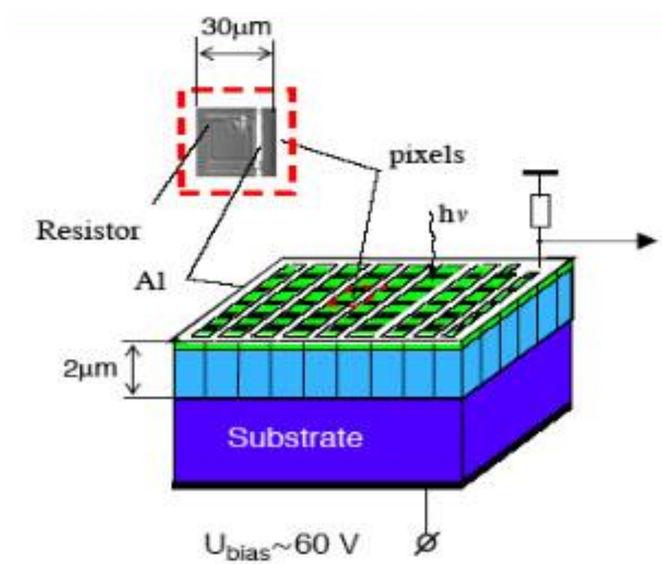
Gas based (MPGD)

- Photocathodes or - sensitive vapor
- E.g. Triethylamine (TEA) 7.5 eV
- Large area w. position resolution



Silicon based (SiPM)

- Are arrays of avalanche photo diodes
- Single photon sensitivity (SPAD)
- gain 10^6 in Geiger mode
- QE 40-60% & fast (sub-ns)
- Pixel 10 – 100 µm; 4 x 4 mm^2



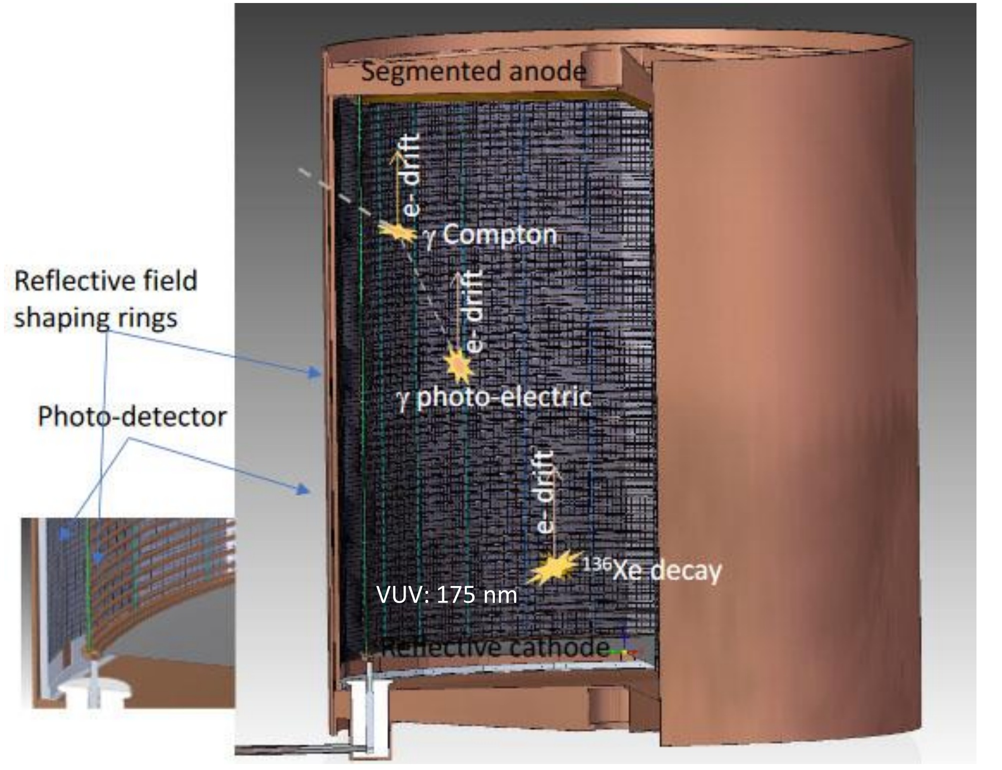
Hybrids - mixture of above (HPD)

- Large area single photon detection
- QE~ 25%; photocath. up to 1000 cm^2
- APD array in Geiger mode 0.1 – 1 cm^2
- Gain ~ 10^3 ; spat. resol. ~ 50 µm

SiPM's – R&D for Future Applications

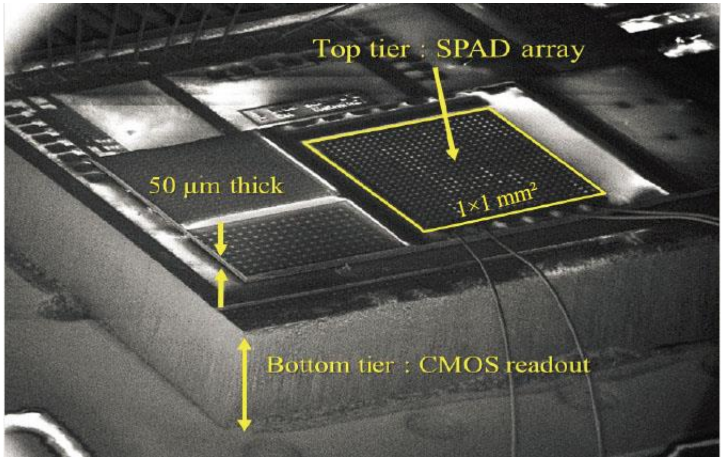
- 2006: First large scale applications: CALICE H-CAL & T2K near (56K channels)
- nEXO Search for $0\nu - \beta\beta$ Decay

- 5 ton LXe -TPC operated at -120^0 C
- 4 - 5 m^2 covered by SiPM's
- Single VUV photon sensitive
- QE > 15% & low noise < 0.1 ph.e.
- Very low radioactivity



- New concept: 3Ddigital SiPM

- Photon to bit conversion with time tag
- Connect each diode on photo det. chip to quenching electronics chip



3DdSiPm prototype from U. Sherbrook
22 x 22 SPAD array in CMOS process

- Intense R&D in Canada

- U. Sherbrooke; electronics, assembly
- DALSA Bromont; photo detector
- TRIUMF, McGill, Carleton → 1.5M$ CFI
- Aim 3DdSiPM 1x1 cm^2
- Cost < 2M$/m^2
- 2020 large scale production

Also:
NEXT -100 (7k SiPM)
Dark side 15 m^2 ?
SNO+ (LAB scint.) ?

Conclusions

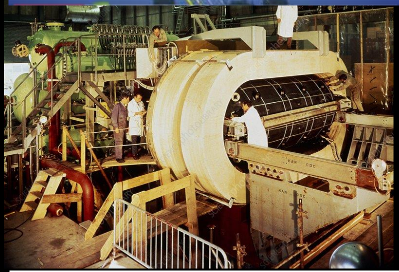
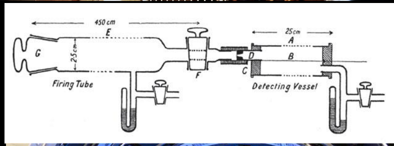
Looking back:

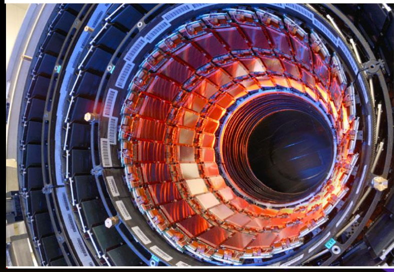
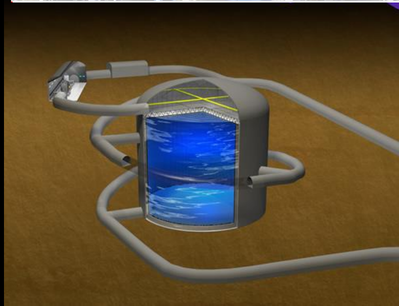
- for **> ½ a** century an exciting story of fascinating developments
- detectors enabled important discoveries + precision measurements
- developments had major impact on industry, medical and science applications outside of physics

Looking forward:

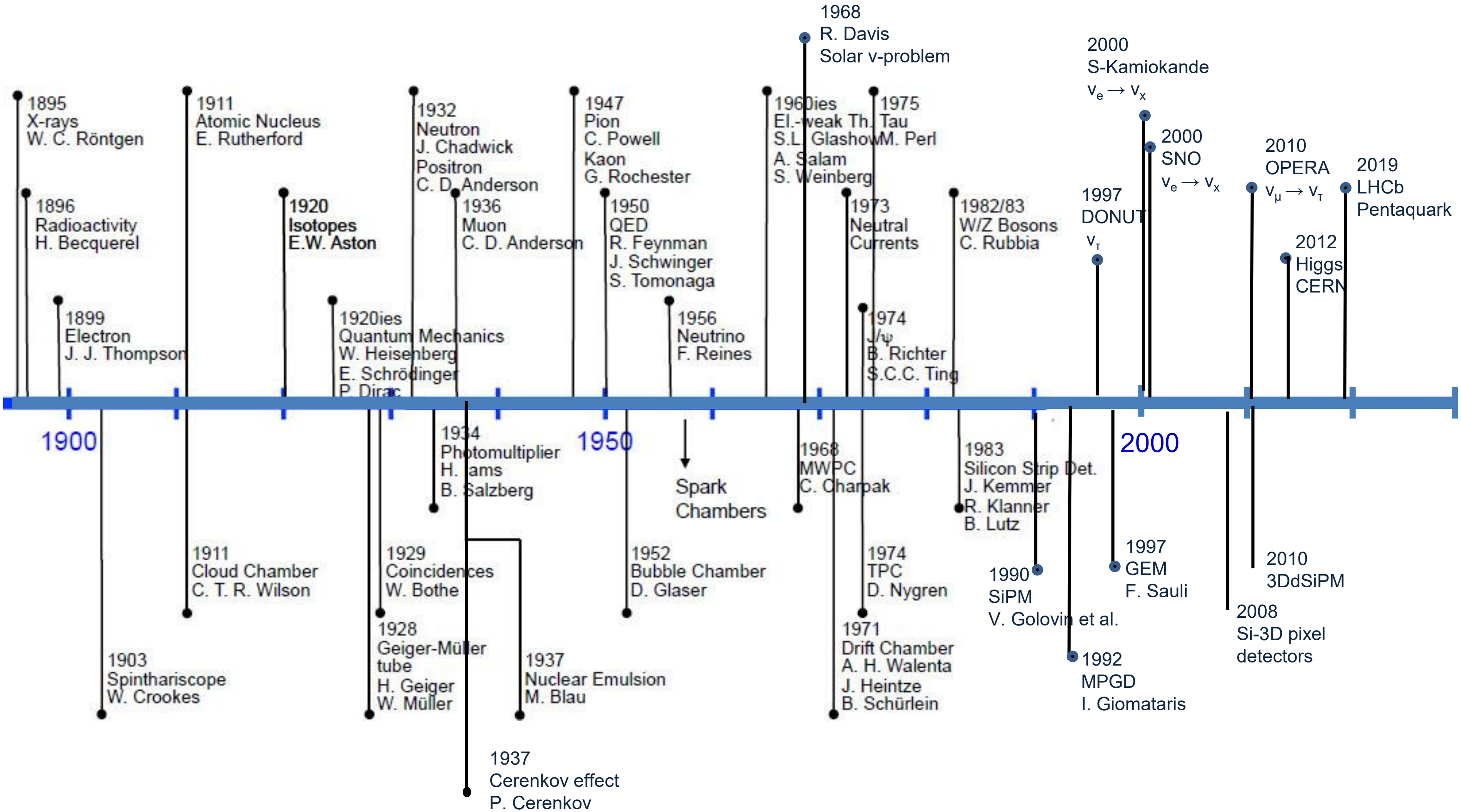
- rapidly developing technologies bring new opportunities
- Increasing segmentation and pixelization reduce noise, increase radiation hardness and reduce cost
- Future experiments will rely on newest electronics and need timely R&D efforts, expertise and resources worldwide
- New science ideas, new experimental facilities, like LHC, ILC, and next generation ν- and astro-particle physics projects leave room for new ideas and serendipity



Detection Techniques & Discoveries



from M. Hauschild, 1st EIROForum School on Instrumentation, 2009

Interesting Books and Links

also called the … BIBLE

G. F. Knoll, *Radiation Detection and Measurements*, Wiley

K. Kleinknecht, *Detectors for particle Detection*, Cambridge University Press

F.N. Flakus, *Detecting and measuring ionizing radiation* – a short history
https://www.iaea.org

M. Hauschild, *History of Instrumentation*, EIROforum School on Instrumentation, 2009
https://slideplayer.com/slide/11352823/

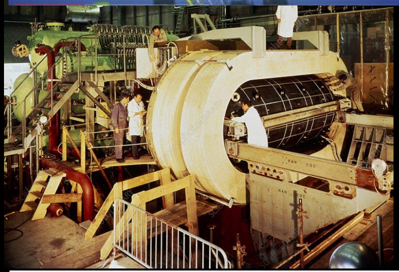
W. Riegler, *Particle Detectors*, CERN Summer School Lecture 2008,
https://slideplayer.com/slide/6855375/

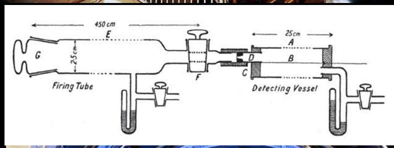
D. Nygren, *A Particular History of Particle Detection* GRIDS , TRIUMF 2018
https://meetings.triumf.ca/indico/event/34/

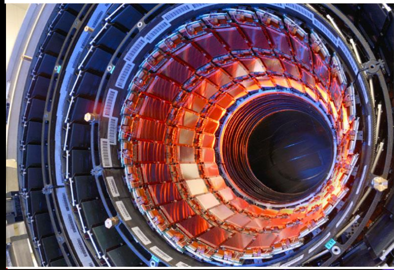
M. Krammer, *Silicon Detectors – Tools for Discovery in Particle Physics*
http://www.hephy.at/fileadmin/user_upload/Vortraege/KL-Talk.pdf

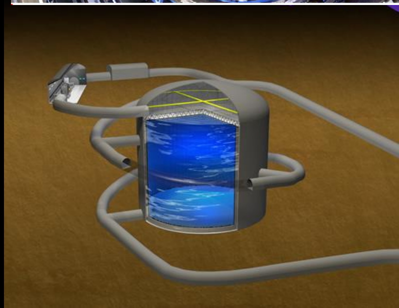
E. Hejine, *Silicon is to physics what carbon is to life*, Erice School 15 June 2018
http://www.ccsem.infn.it/issp2018/docs/talkHeijne.pdf

P. Le Du, *Radiation detection from past to future*, 2018
https://www.wesrch.com/medical/paper-details/pdf-ME14GW000TDUI-history-and- evolution-future-of-radiation-detector#page1



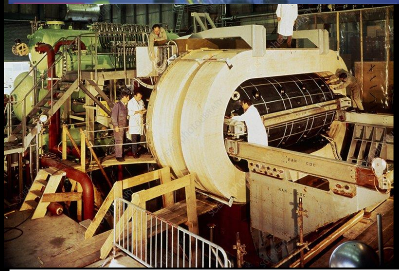


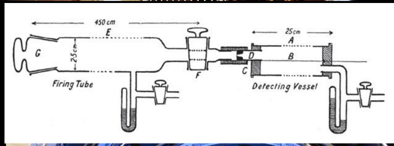


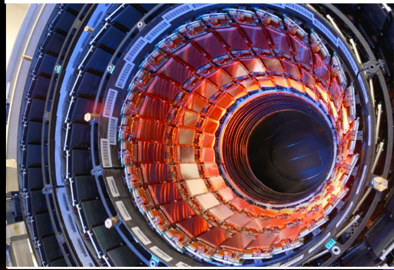


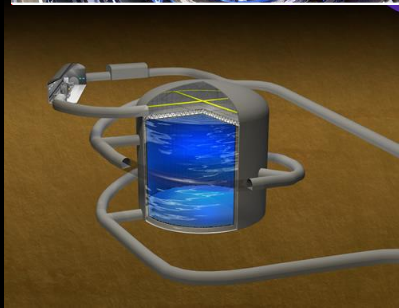
Addendum:

Cloud Chambers



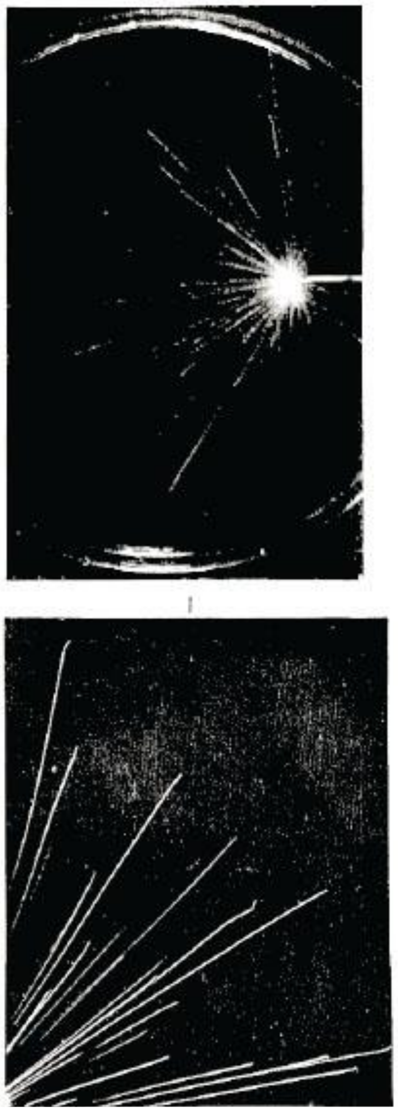






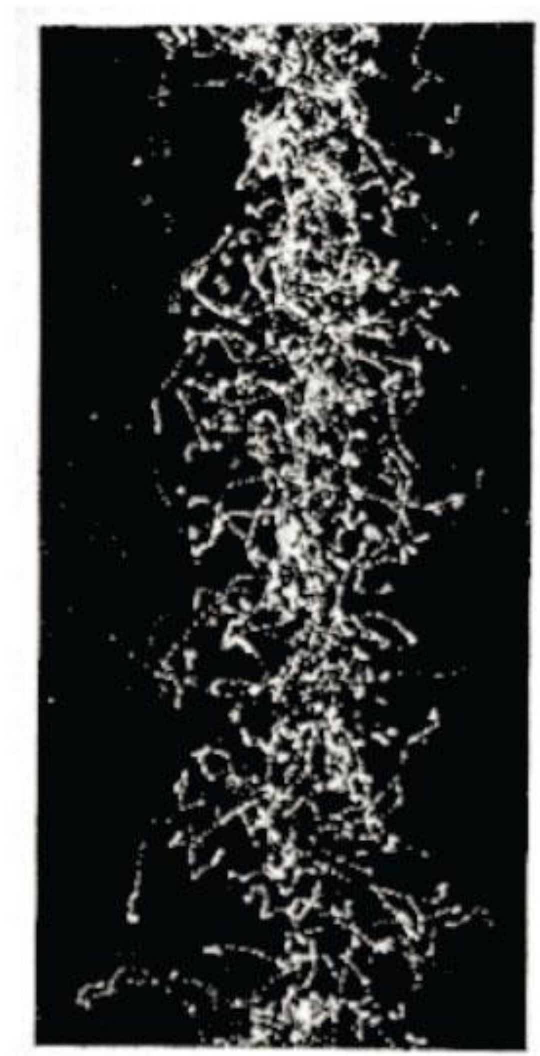
Cloud Chamber: seeing with (dE/dx)

Alphas

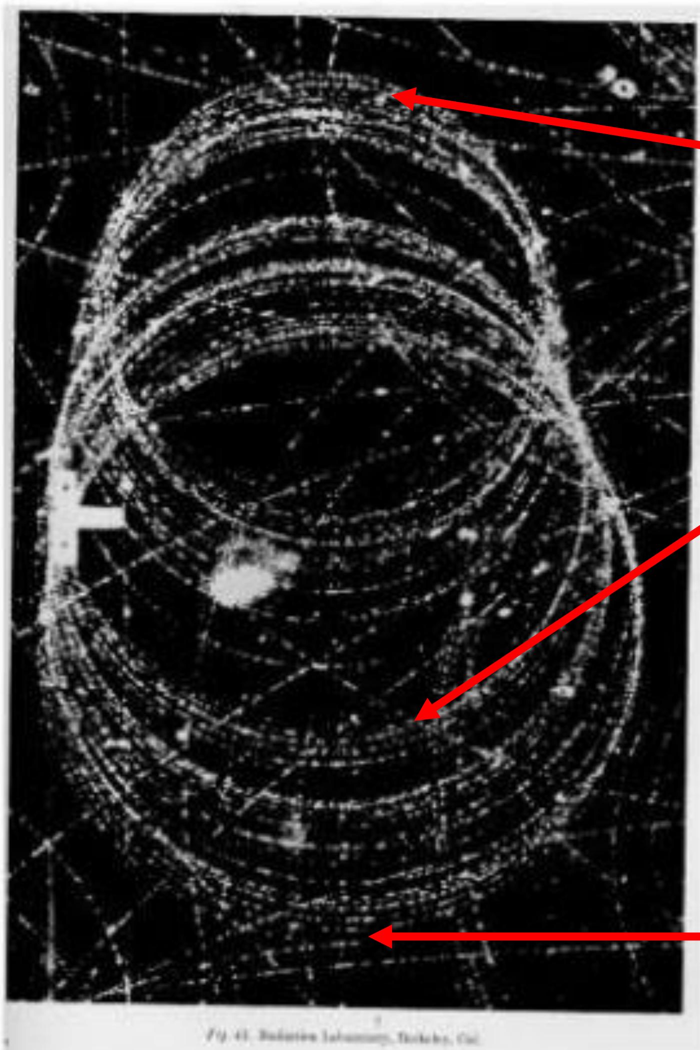


Betas

Gammas



The Cloud Chamber



12.4 MeV final energy

Sudden energy loss by bremsstrahlung here

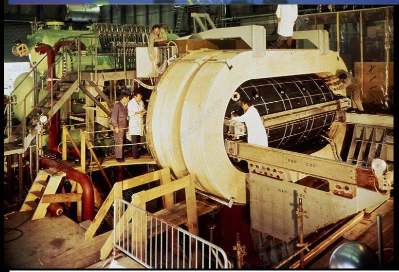
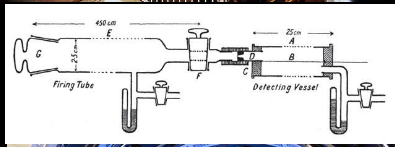
16 MeV initial energy

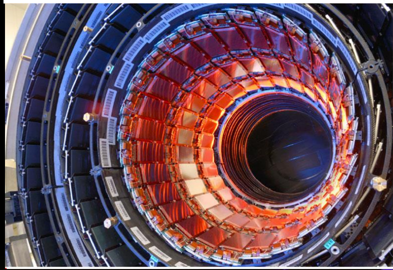
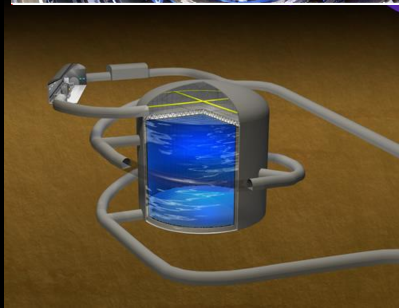
Fast electron in a magnetic field at the Bevatron, 1940

Addendum:

Gas Detectors



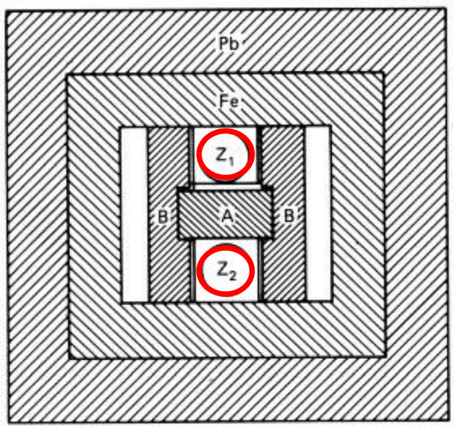



Counting in Coincidence

W. Bothe 1891-1957
Nobel Prize 1954

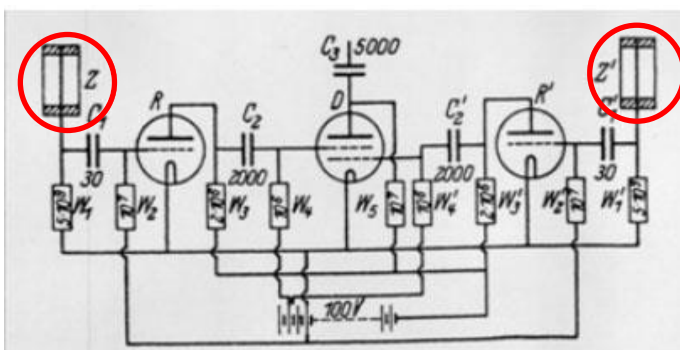
1928 W. Müller investigates sporadic discharges of Geiger - Müller counters and realizes that these are due to cosmic rays (V. Hess, 1911)

1929 Walther Bothe: "Zur Vereinfachung von Koinzidenzählungen" Z. Phys. 59 (1930)



- Two or more tubes in coincidence give information on direction of cosmic rays
- Uses two electrometers projected on a moving film role

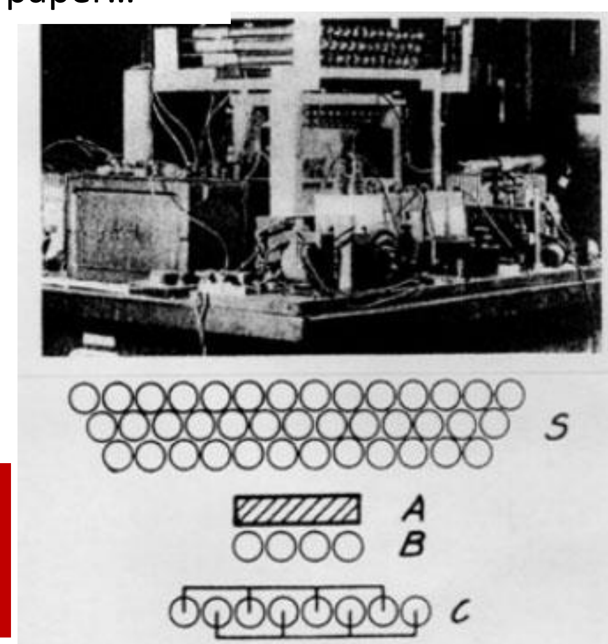
1929 Bruno Rossi reads Bothe's paper…



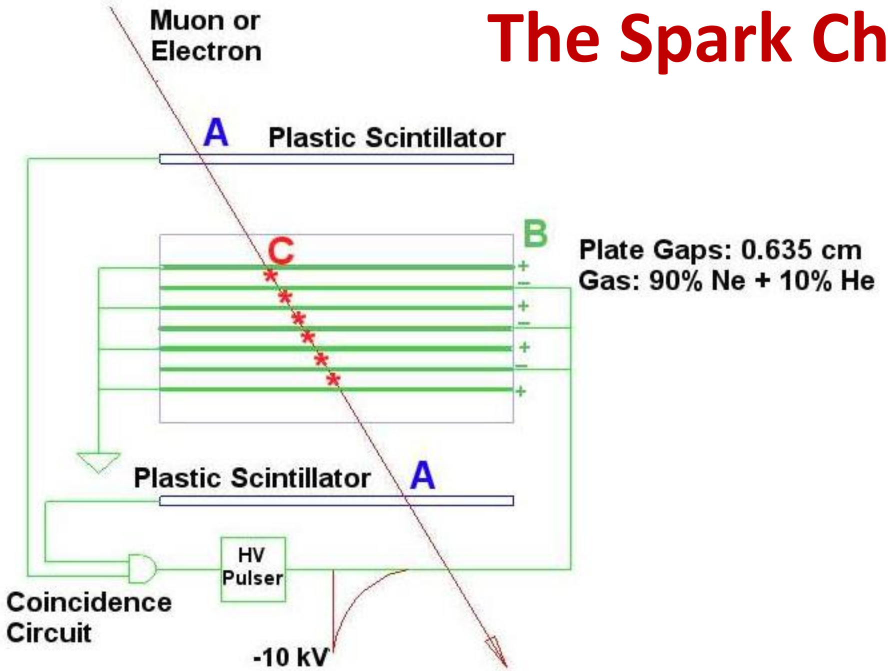
B.Rossi, Nature, 125(1930)2156

- Immediately invents an improved version
- Uses triode vacuum tubes
- Builds the first cosmic ray telescope 1934

Coinc. circuits become the basis for electronic instrumentation in nuclear and particle physics



The Spark Chamber



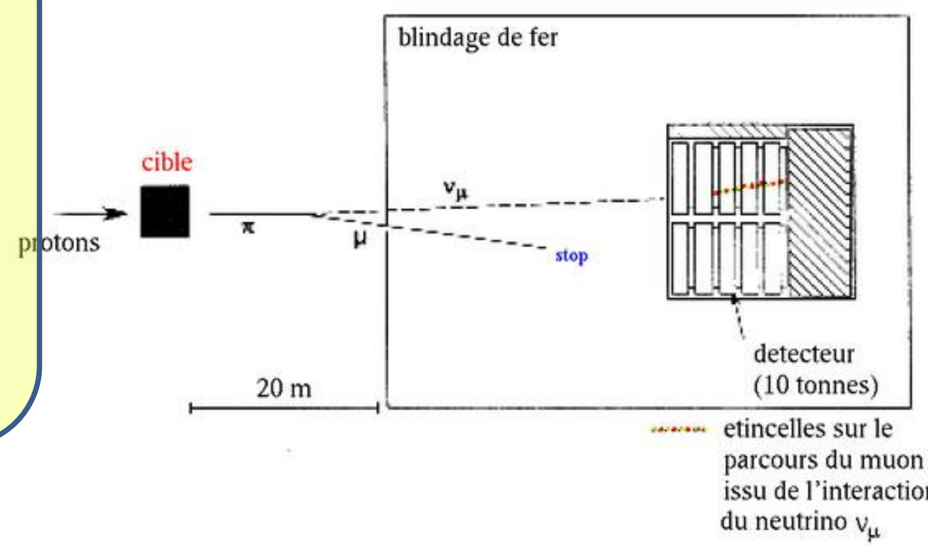
- Developed in early 60's
- Operated in **discharge mode**
- A charged particle traverses the detector and leaves ionization trail
- A short (~ ms) HV pulse triggered by scintillators is applied between the metal plates
- Sparks form in the place where ionization took place
- Resolution less than in BC, but can be synchronized with accelerator beam pulse

L. Ledermann, M. Schwartz, J. Steinberger
Nobel prize 1988

1962 discovery of ν_μ at Brookhaven AGS

ν-energy spectrum known from $\pi \to \mu$ and $K \to \mu$ decays

$\mu - e$ separation!
electrons: showers
muons: long tracks



The Spark Chamber

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

Fig. 2 (bottom right). Cross sections of (a) the Great Pyramid of Cheops and (b) the Pyramid of Chephren, showing the known chambers: (A) Smooth limestone cap, (B) the Belzoni Chamber, (C) Belzoni's entrance, (D) Howard-Vyse's entrance, (E) descending passageway, (F) ascending passageway, (G) underground chamber, (H) Grand Gallery, (I) King's Chamber, (J) Queen's Chamber, (K) center line of the pyramid.

6 FEBRUARY 1970

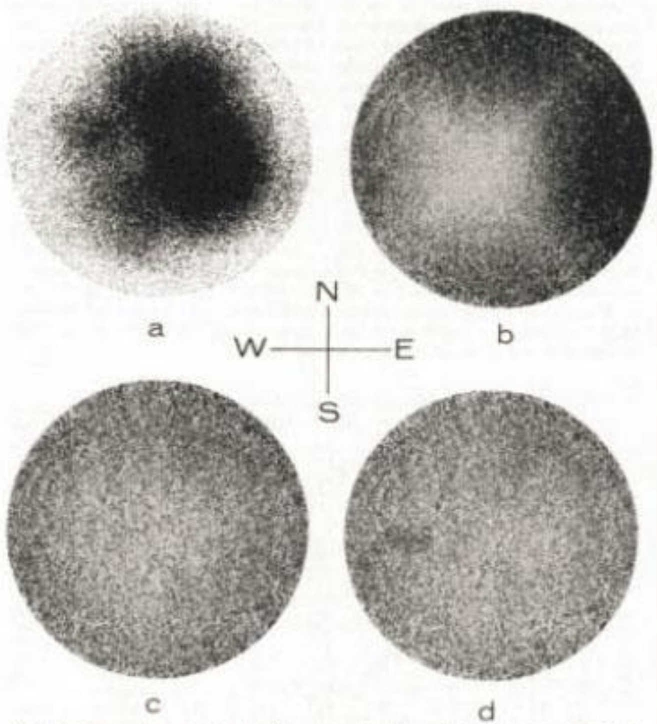
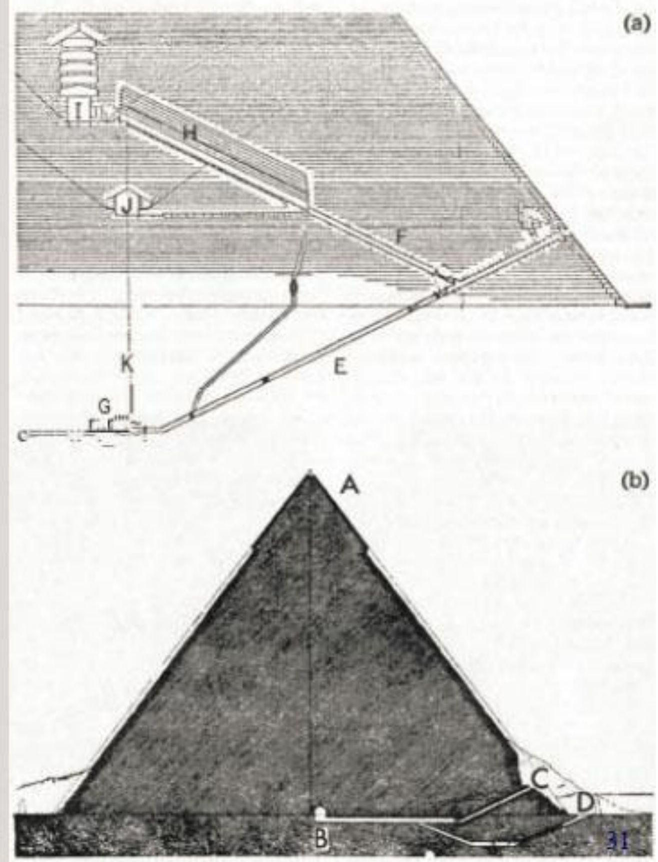


Fig. 13. Scatter plots showing the three stages in the combined analytic and visual analysis of the data and a plot with a simulated chamber. (a) Simulated "x-ray photograph" of uncorrected data. (b) Data corrected for the geometrical acceptance of the apparatus. (c) Data corrected for pyramid structure as well as geometrical acceptance. (d) Same as (c) but with simulated chamber, as in Fig. 12.

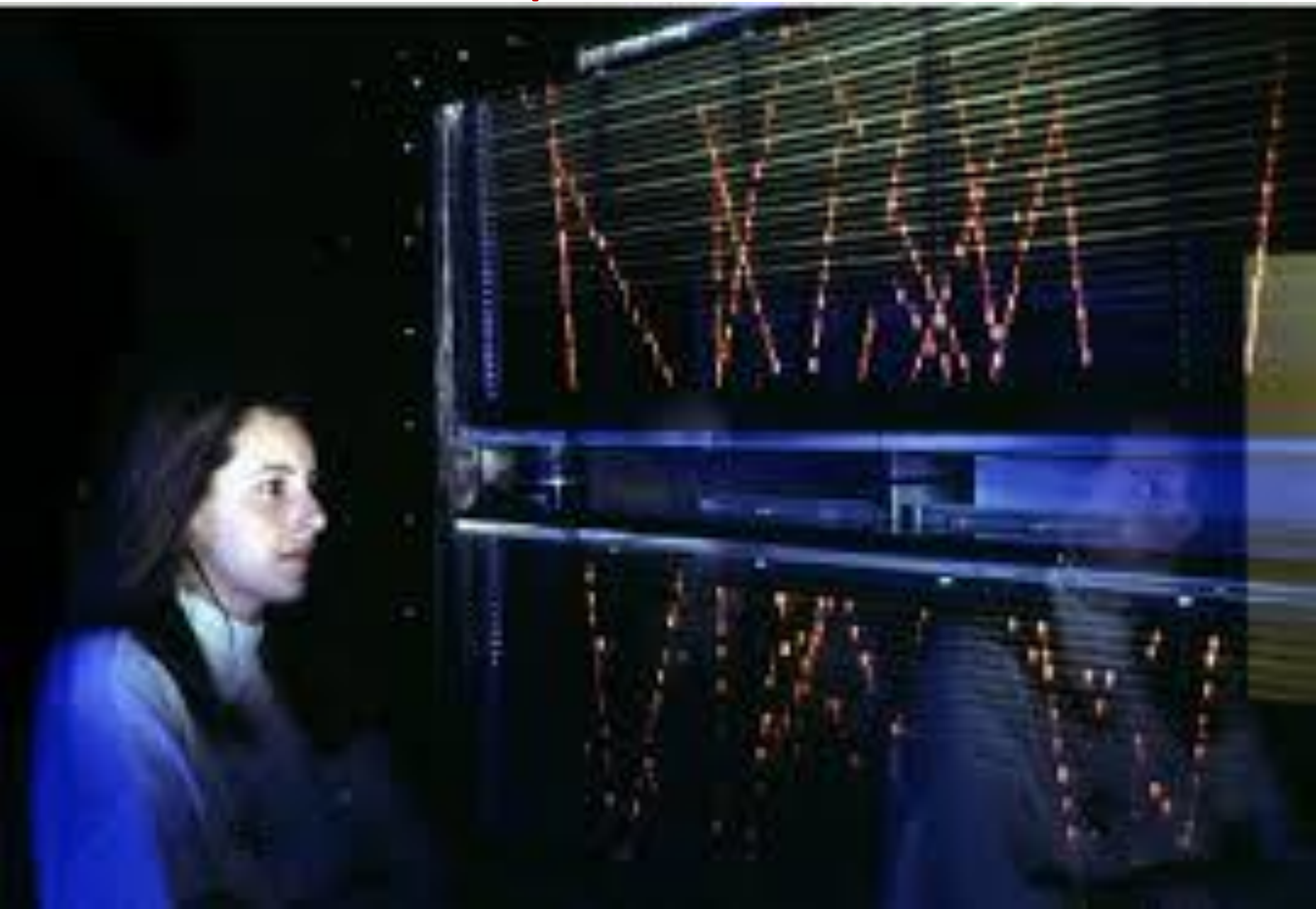
1960's…
Luis Alvarez used the attenuation of muons to look for chambers in the Second Giza Pyramid → Muon Tomography

He proved that there are no chambers present.



W. Riegler, Summerstudent Lectures 2008, CERN

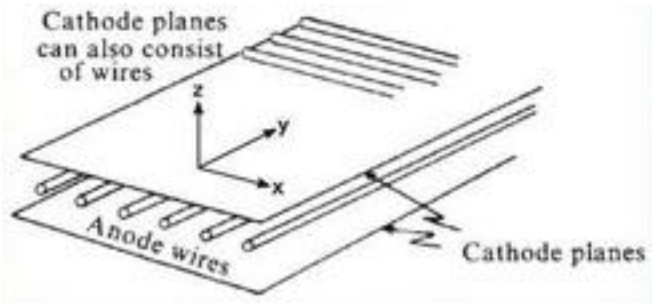
The Spark Chamber (CERN Microcosm Museum)



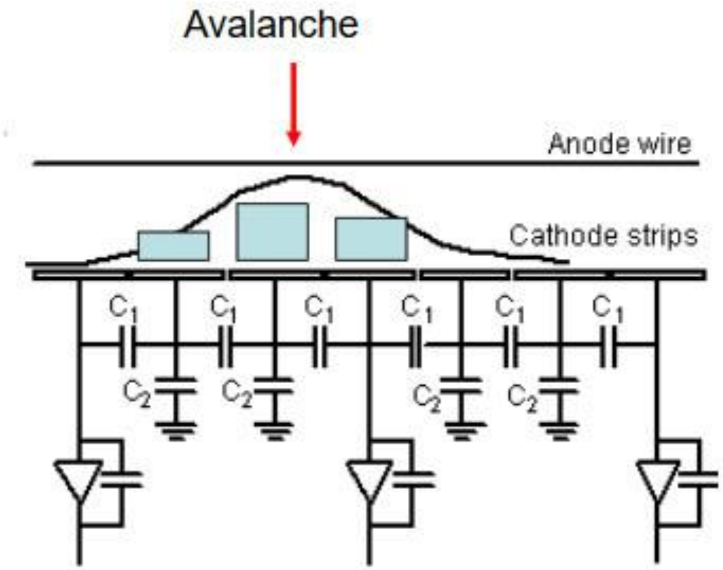
Multiwire Proportional Chambers (MWPC)

How to read the second coordinate?

- Charge division on resistive wire read out on both ends
- Comparison of arrival times at both ends
- Cathode plane segmented into strips



2D position sensing MWPC



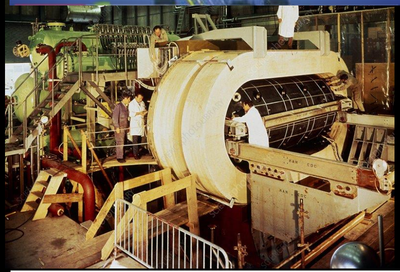
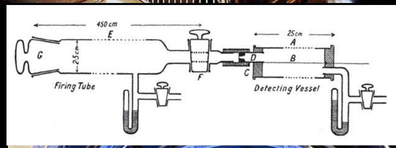
- Movement of charges induces signals on wire and cathode
- Width (1σ) of charge distribution ≈ distance between wire and cathode
- Center of gravity defines particle trajectory
- 50 µm resolution possible

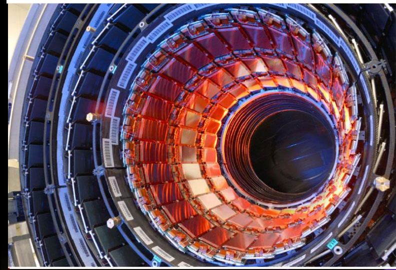
Now digital radiography possible with 10 times less dose!

Addendum:

Bubble Chambers



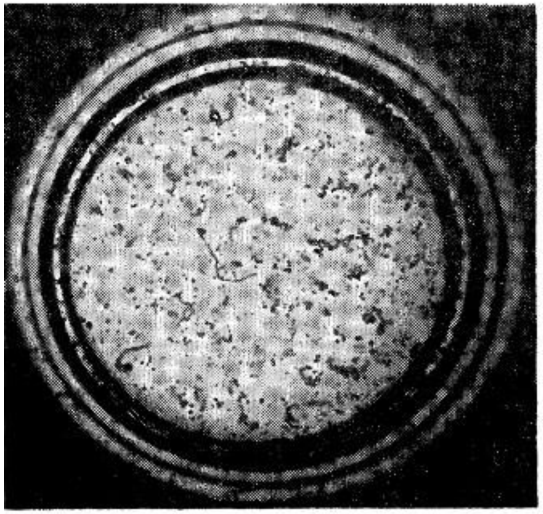



Bubble Chambers – Latest Developments

A quick step back in history!

Glaser (1956):

- No γ - induced bubbles in pure Xe at E_{th} = 1 keV !
- Bubble formation reappeared by quenching scintillation with 2% ethylene



Phys.Rev. **102**, 586 (1956)

A suspicion:

- In mono-atomic liquids e^--recoils do not contribute much to heat spike (CM –movement)
- Nuclear recoils however should remain unaffected!

In LAr & LXe sub-kev NR detection possible w/o sensitivity to gammas ??!!

Confirmed by recent tests at North-Western U.
arXiv: 1702.08861

Bubble Chambers – Latest Developments

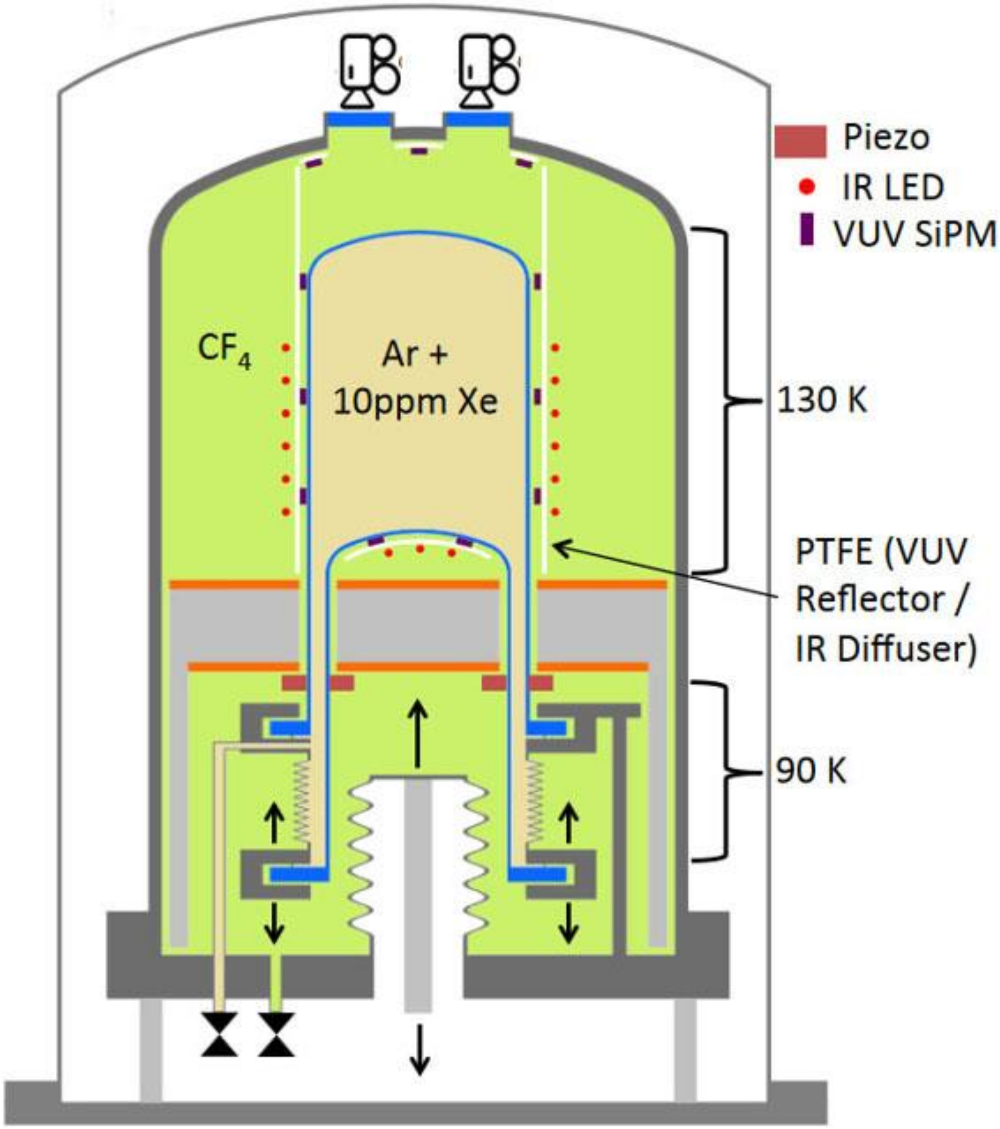
Next: a 10 Kg LAr - SBC

SBC Collaboration:
US, Canada, Mexico

Performance:
100 eV nuclear recoil detection
Background free ton year exposure

Physics:
1 -7 GeV WIMPs → ν - floor
Reactor CEvNS

Schedule:
FY18 Technical design
FY19/20 Assembly & commissioning

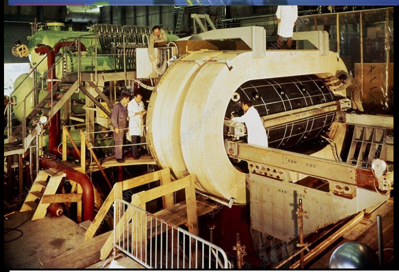
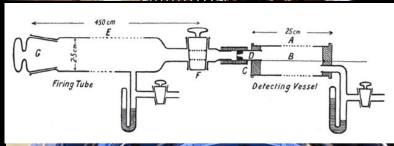


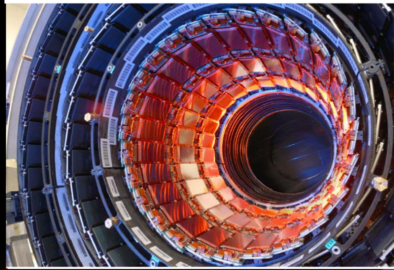
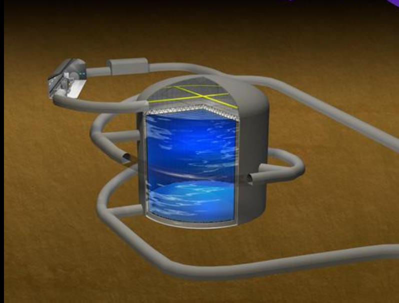
R. Neilson, Drexel U.
8/23/2018, DOE-HEP PI

Addendum:

Si-Detecors

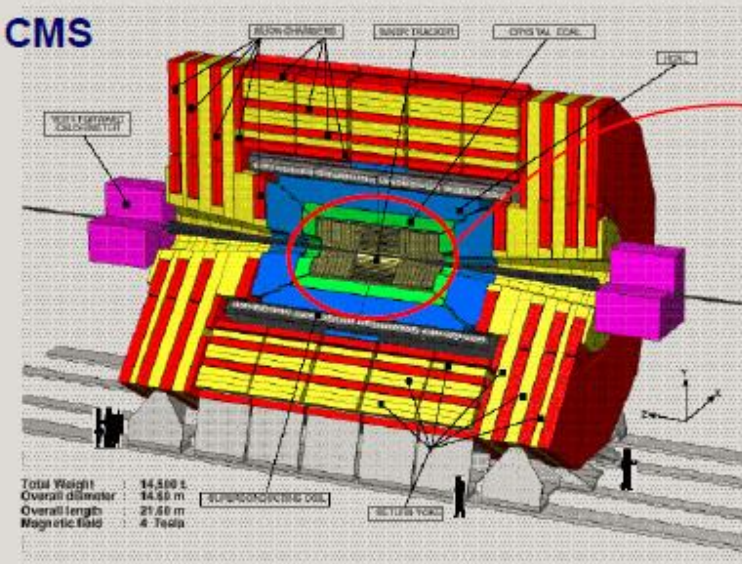


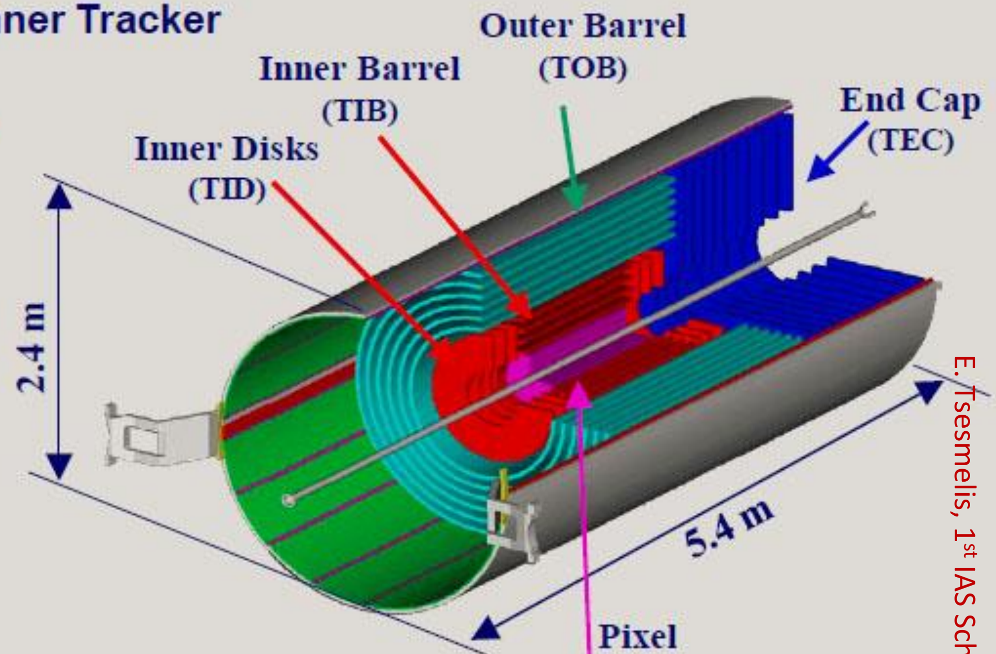



Example from LHC: The CMS Tracker

- CMS



- Inner Tracker



- CMS - Currently the Most Silicon

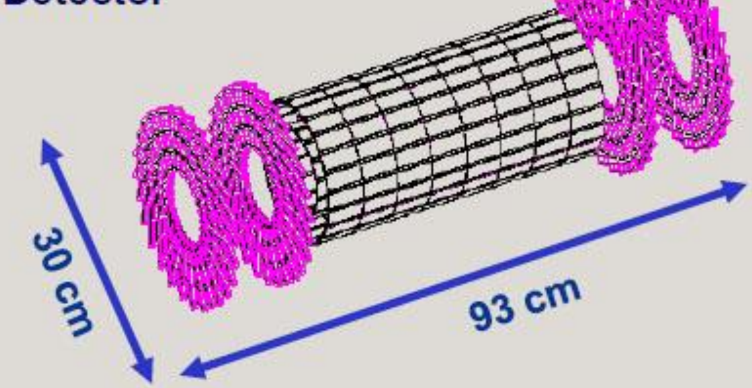
Micro Strip:

- ~ 214 m² of silicon strip sensors
- 11.4 million strips

Pixel:

- Inner 3 layers: silicon pixels (~ 1m²)
- 66 million pixels (100x150μm)
- Precision: σ(rφ) ~ σ(z) ~ 15μm
- Most challenging operating environments (LHC)

- Pixel Detector

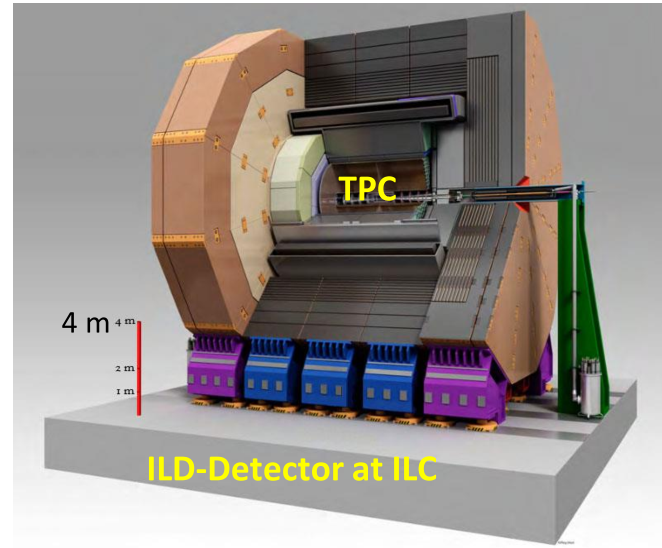


E. Tsesmelis, 1st IAS School, Singapore 2012

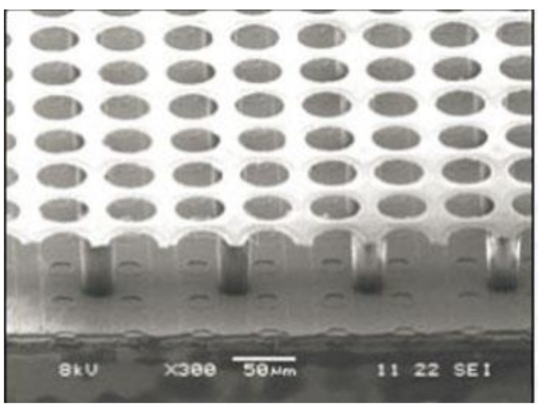
Recent Developments - Hybrid Technologies

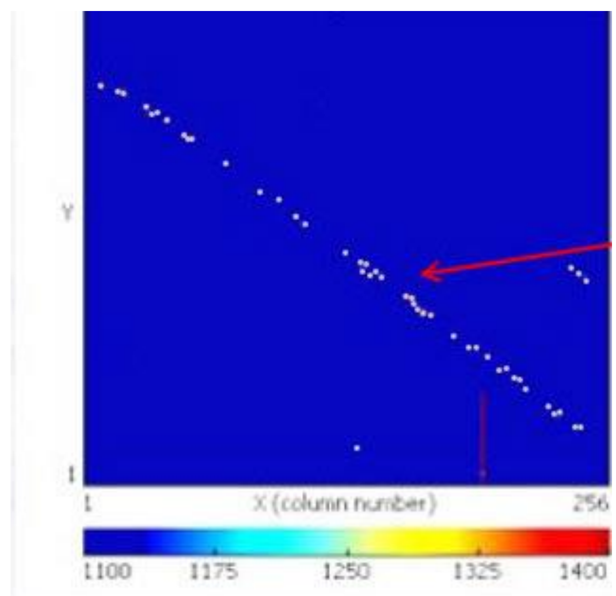
Combine MPGD with Si pixel detector

- Use Si- pixel arrays as active TPC pad-plane for ILD detector @ ILC
- TimePix: 256 x 256 pixels w. 55x55 μm^2 developed for medical applications (X-ray film replacement)
- Micromegas mesh provides gas amplification integrated on top of pixel chip



Planned Silicon surface: ~1800 m^2
(Tracker ~135 m^2, EMCal ~1650 m^2





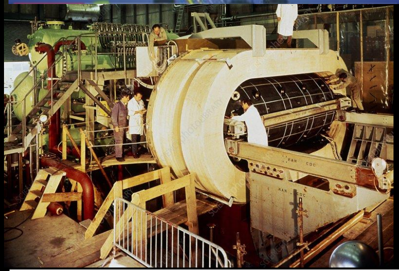
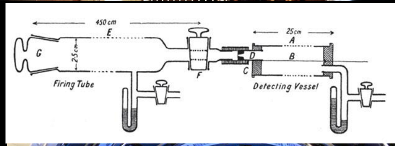
Ionization clusters

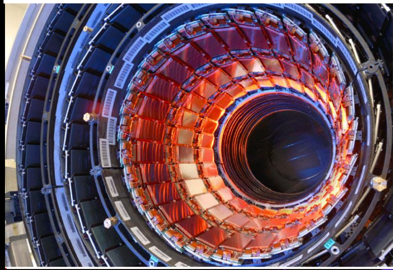
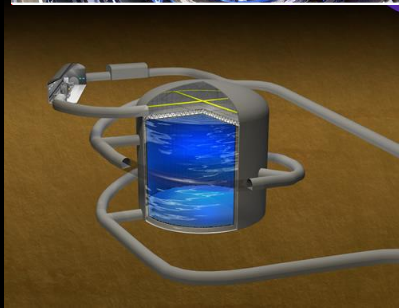
Individual ionization clusters visible
→ like in an electronic bubble chamber!

Addendum:

Photomultipliers



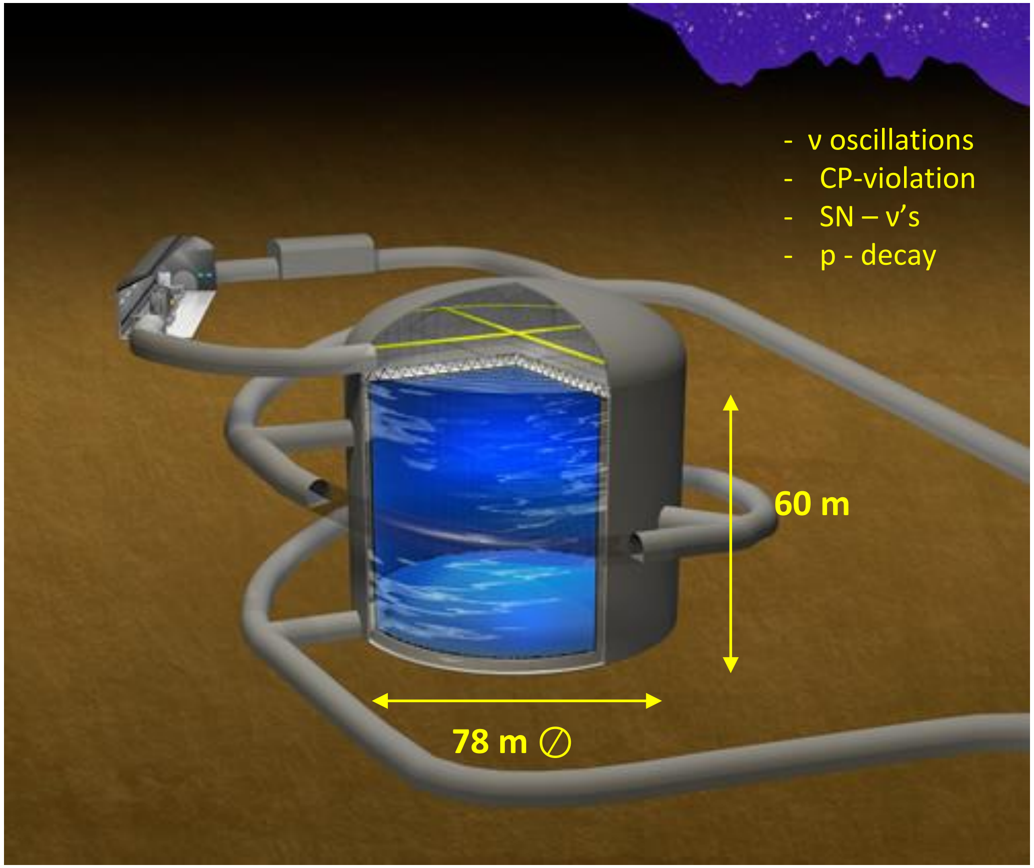



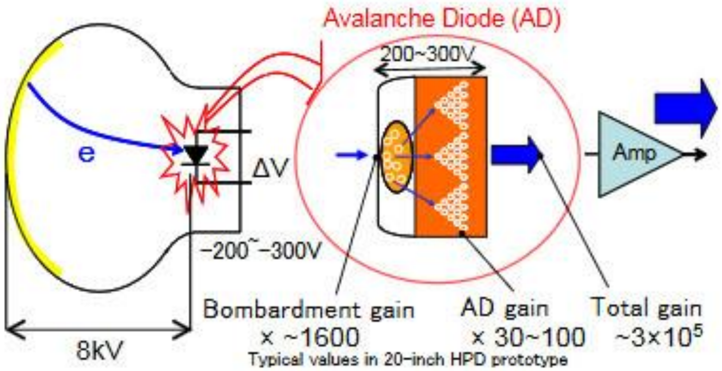



Hybrid PMT's (HPD) – Future Applications

Hyper - Kamiokande (Start 2020)

- 0.56 Mton water Č - detector
- In ν – beam 295 km from J-PARC
- HPD's considered for better timing
- 40 000 Large Aperture High Sensitive Hybrid PM's (LAHSHP – PM) 50 cm ∅
- QE 30% Hamamatsu (x2 Super K)



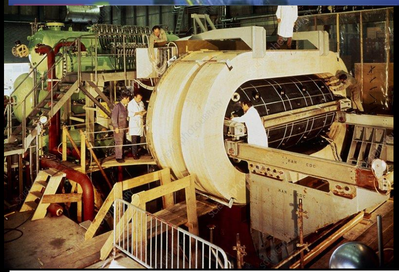


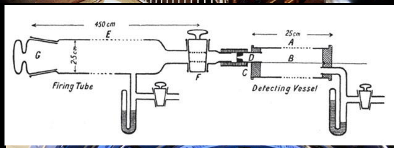
Other applications:
- LHCb -Rich

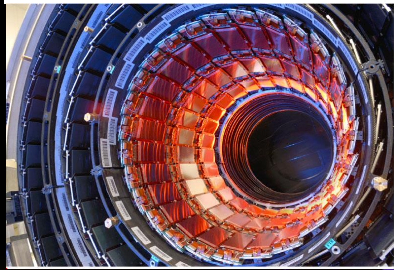
Advantage: maybe cheaper than SiPM (1/1000 Si-area)

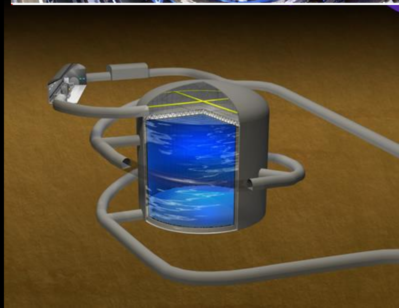
Addendum:

Scintillators

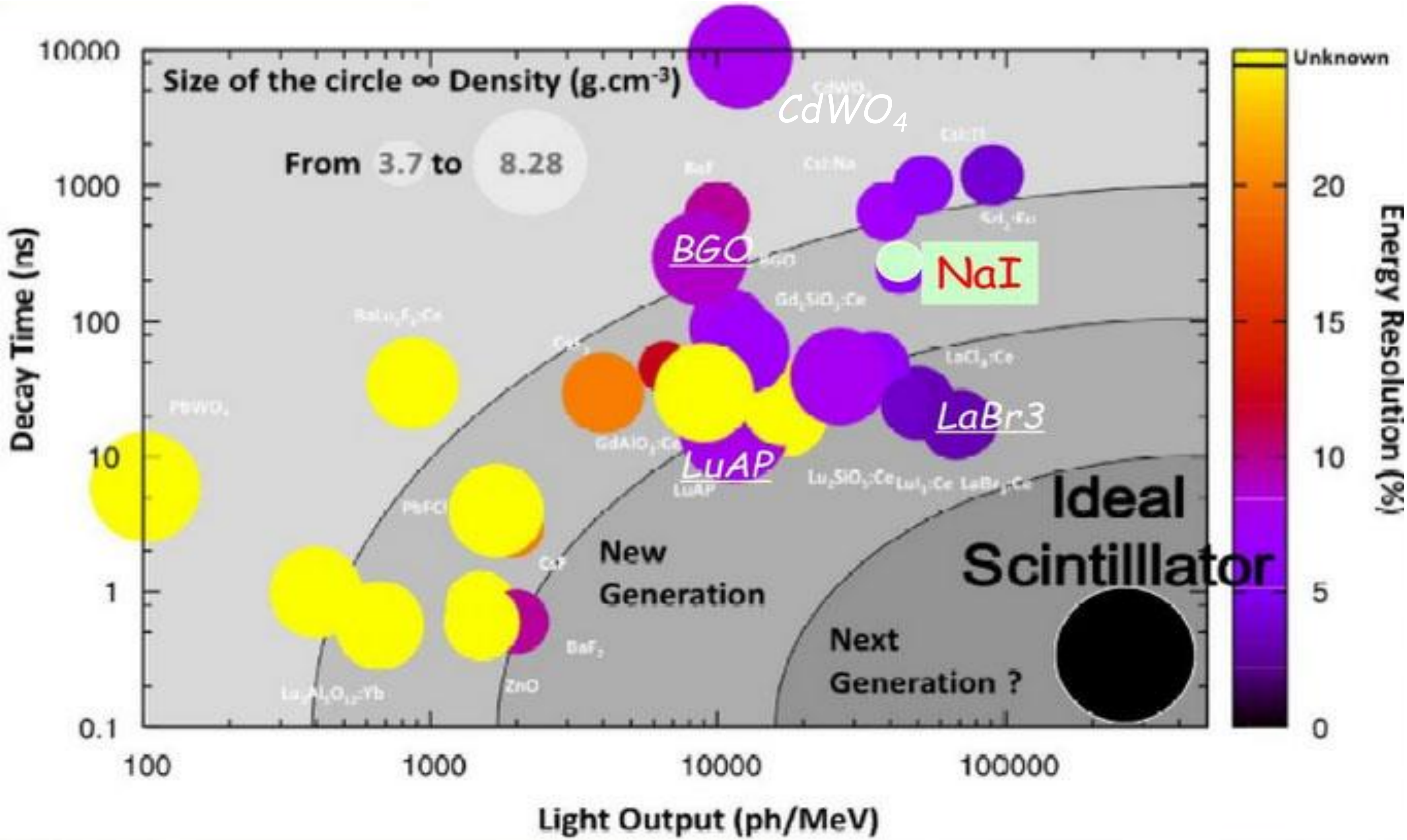








The Ongoing Search for the Ideal Scintillator....



...mass production is the challenge for the future!