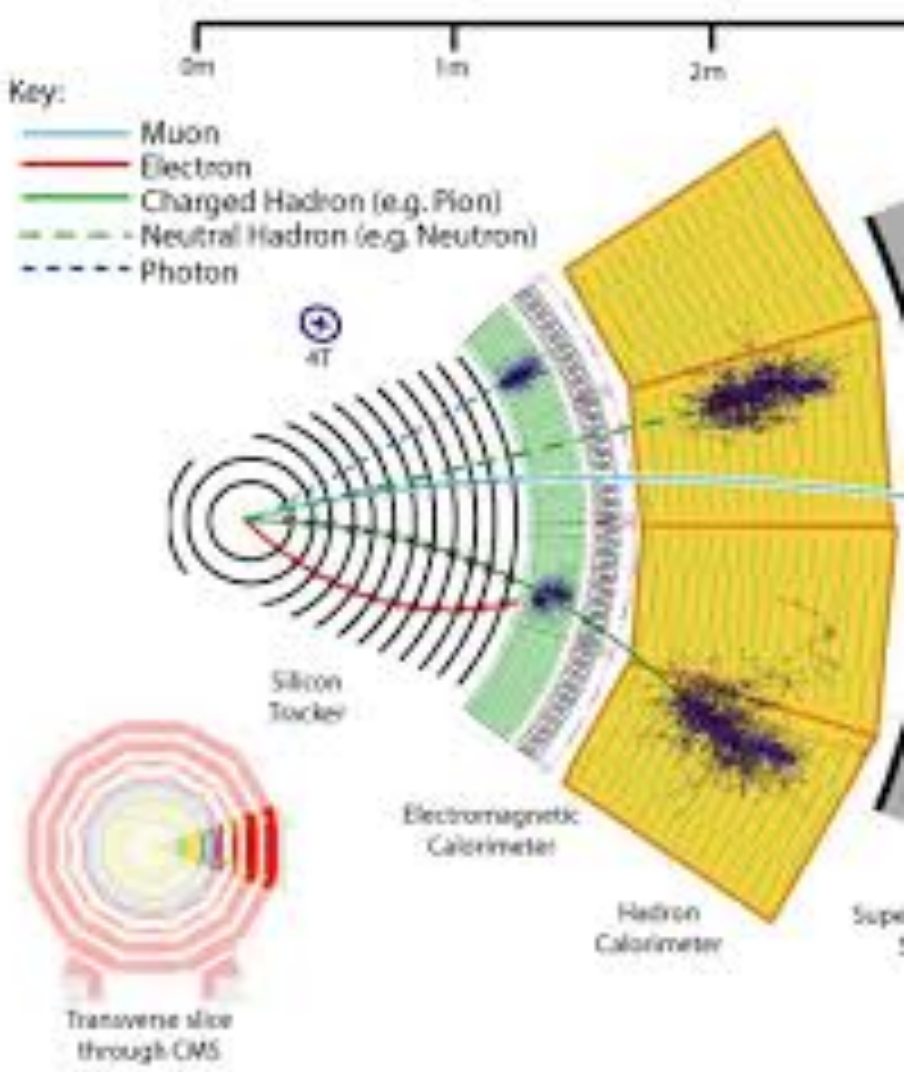

Instrumentation for Particle Physics – in four lectures

Lecture III: Tracking and Calorimetry

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University of New Mexico

African School of Physics 2021

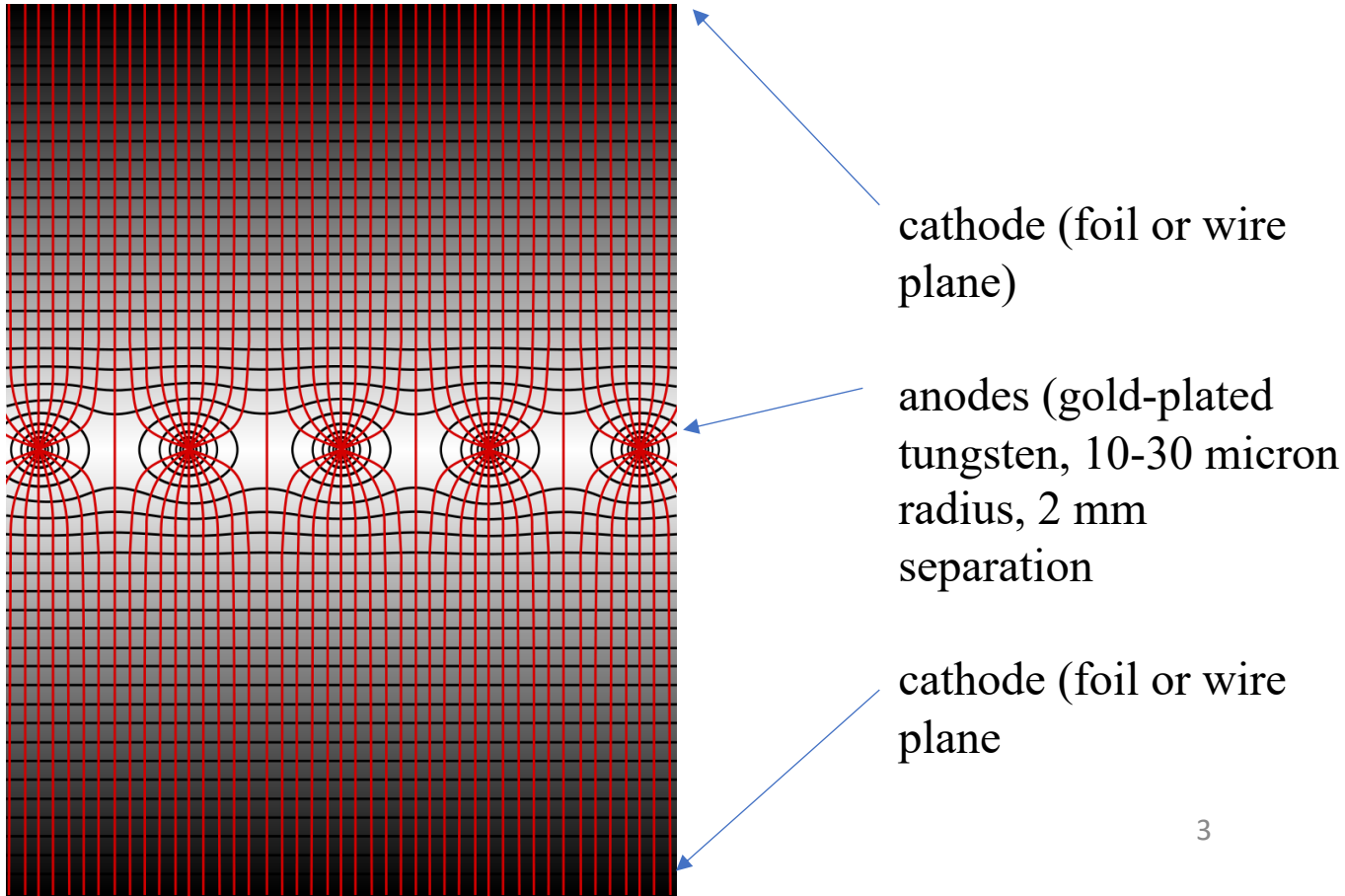
Tracking Detectors:
Measure particle trajectory (curvature, momentum) and point of origin (“vertex”)

Note: these lectures will not cover historical detector designs that are no longer in use.

The “ancestor” – and still in use: **Wire chambers**
The single wire proportional counter: invented* by Geiger and Rutherford in 1908.
Multiwire proportional chambers (MWPC) were invented** by Georges Charpak in 1968 (Nobel Prize 1992)

MWPC: A planar layer of proportional counters without separating walls
produces field lines (red) and equipotential lines (black) like this:

- A through-going charged particle ionizes gas, produces primary electrons and ions along the track
- Primary electron drifting toward anode is accelerated by the E field, starts avalanche (ions + more electrons)
- Avalanche multiplication ends when positive ion space charge reduces E field below critical value
- Electron cloud drifts toward anode, ion cloud drifts (more slowly) to cathode.



* H. Geiger and E. Rutherford, Proc. Royal Soc. A 81:141 (1908).
** G. Charpak et al., Nucl. Instr. Meth. A 62: 262 (1969).

MWPC design considerations:

Position resolution σ*, in the direction perpendicular to the wires,* for wire separation *d*:

$$\sigma = \frac{d}{\sqrt{12}} = 580 \text{ microns} \qquad (\text{for } d = 2 \text{ mm})$$

The wire separation is limited by ***electrostatic repulsion*** of the long anodes. Counterbalance this with ***wire tension.***

For anode voltage V, length ℓ, capacitance per length C, tension T, permittivity ε_0, ***the requirement for stability*** is:

$$T \geq \left(\frac{V \ell C}{d} \right)^2 \cdot \frac{1}{4\pi\varepsilon_0}$$

Capacitance depends on anode separation d, anode wire radius r, and perpendicular distance L from anode to cathode:

$$C = \frac{4\pi\varepsilon_0}{2\left(\frac{\pi L}{d} - \ln \frac{2\pi r}{d} \right)}$$

An anode wire of mass m ***sags under gravity*** (this reduces the homogeneity of the E field) by an amount:

$$f = \frac{m \ell g}{8T}$$

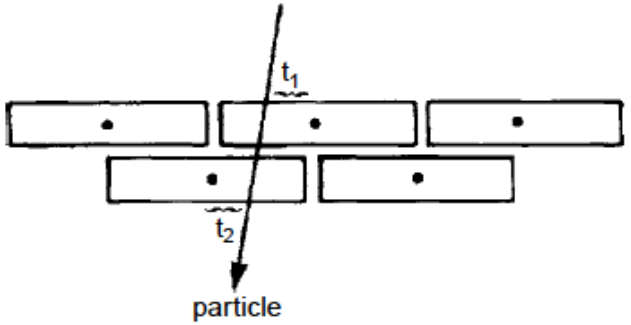
To improve spatial resolution in the direction along the wire:

-segment the cathode, then measure the charge induced on the cathode and calculate the center of gravity of the induced charge

- Resolution ~ 50 microns is typical for tracks perpendicular to the wire plane.

Using timing to improve the spatial resolution: **the drift chamber***

- Introduce potential wires between the anodes, to shape the drift field, ***seeking well-mapped drift velocity v⁻***.
- ***Measure the time t*** between particle traversal of chamber and electron cloud arrival at anode.



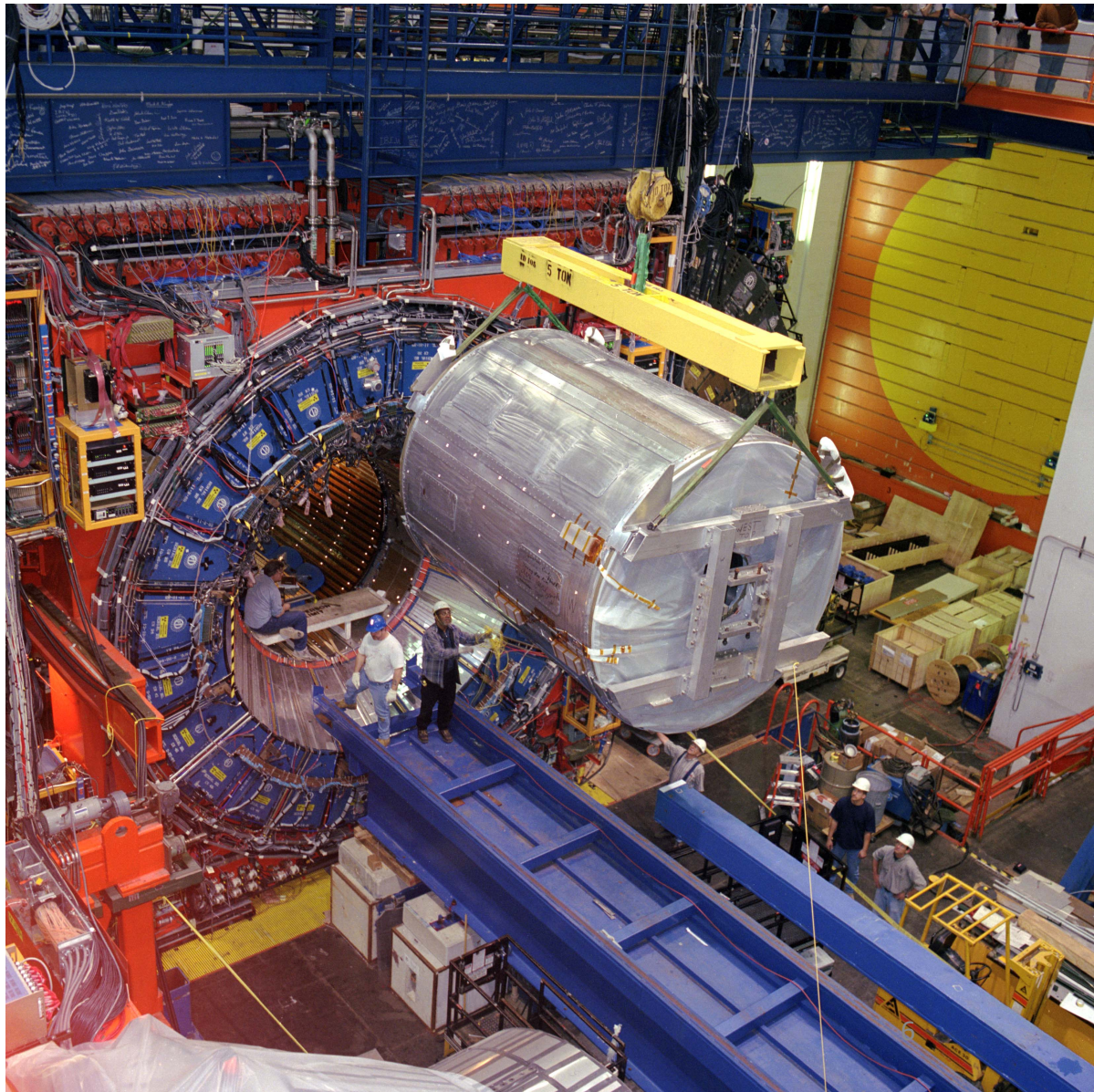
- ***Perpendicular distance x from track to anode*** is then

$$x = \int v^{-}(t)\,dt$$

- For electronic time resolution ~1ns, in smallish chambers not limited by mechanical tolerances, ***spatial resolution on σ_x~20μm*** (ignoring fluctuations in formation of the primary ionization, and diffusion of the cloud).

* A.H. Walenta et al., Nucl. Instr. Meth. A 92: 373 (1971).

Drift chambers can be big!
Installation of the the CDF Central Outer Tracker (drift chamber):



Varieties of modern wire chambers

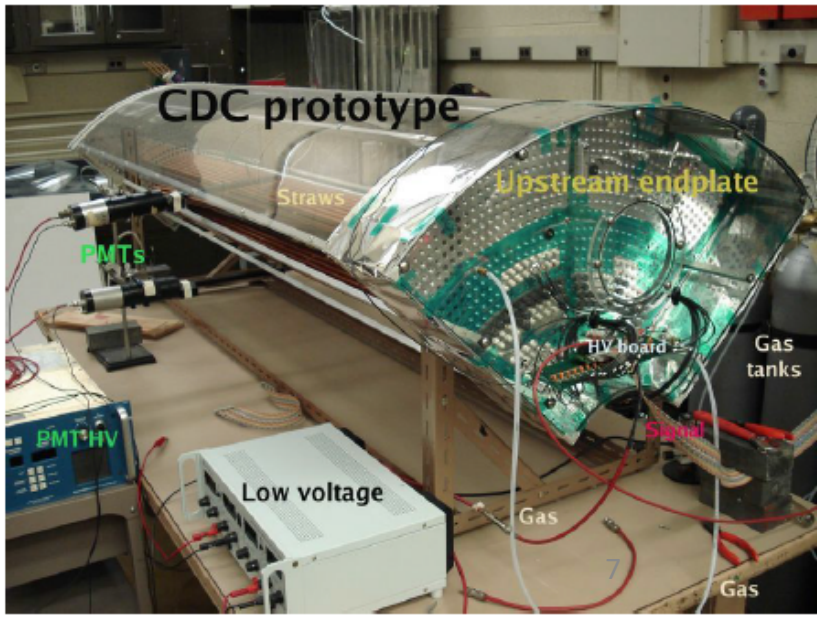
1) Cylindrical proportional and drift chambers

- Wires run axially, form cylindrical volumes
- Wires are stretched between 2 end plates, for total tension of tons
- Embed the chamber in an axial magnetic (B) field.
- Potential wire between each pair of anodes.
- Then these record track curvature to infer momentum p. For radius of curvature ρ,

$$p[\mathrm{GeV}/c] = 0.3B[\mathrm{T}]\cdot\rho[\mathrm{m}]$$

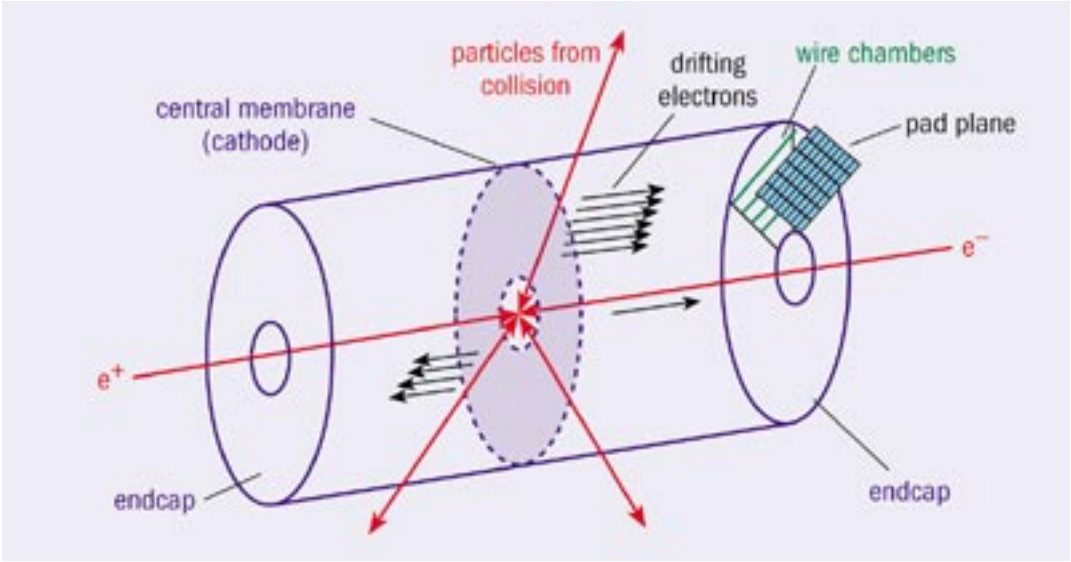
- To obtain axial position information: half of the anode wires are oriented at a small ***stereo angle*** (~2°) with respect to the z-axis.
- Drift cells can be ***"open" or "closed"*** depending on whether or not there is a field wire between every pair of anodes. Closed: shapes the field better, but costs more wires.
- *If a wire breaks* – a region of the chamber is disabled. To minimize this effect, ***surround each wire with a mylar foil (this is a "straw tube")*** and the full assembly is a "straw chamber"

¼ prototype of the GlueX straw chamber



2) Time projection chambers* (David Nygren, 1974) measure a 3-dimensional space point for every cluster of primary electrons, with *minimal multiple scattering*

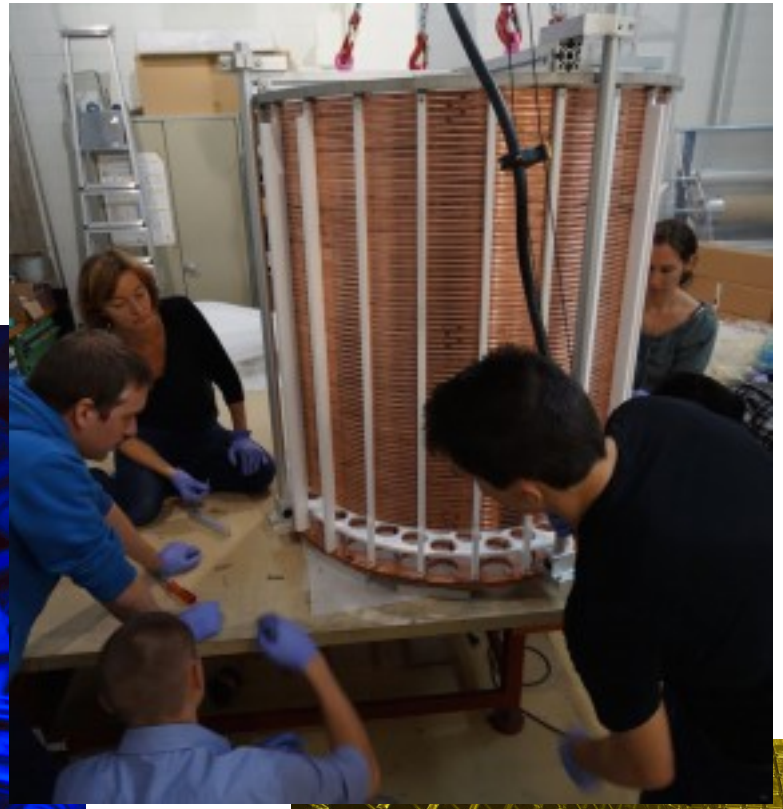
- one central electrode
- E and B fields both axial (no E✖B effect): charge drifts parallel to field lines.
- volume contains counting medium (gas or liquid) but no other components: minimal multiple scattering
- end plates are wire chambers



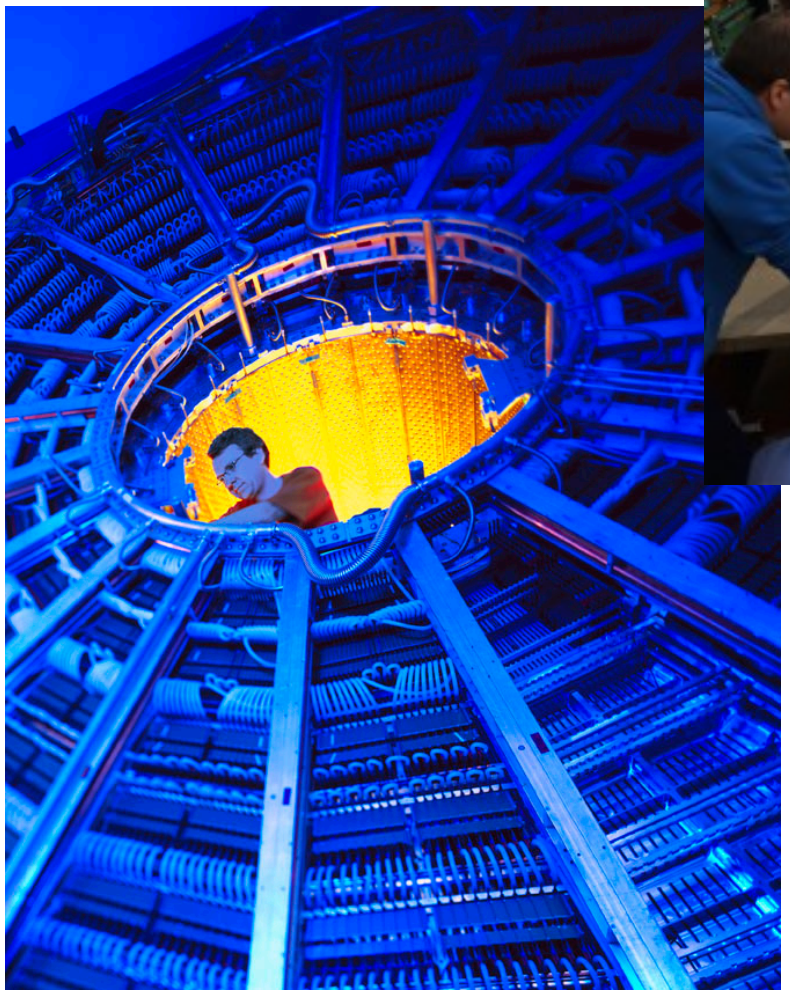
- Axial B field: suppresses perpendicular diffusion (charged particles spiral around the field lines)
- Arrival time of charge – determines the z coordinate of the event
- Anode wires in the endcaps – stretched in the azimuthal direction to measure radius r
- Cathode pads around the circumference of the end plates: to measure angle ϕ and radius r
- Analog signals on the anodes measure energy loss: particle ID

* D. Nygren et al., PEP-PROPOSAL-004, App. A6 (1976).

Modern TPC's: can achieve very large volume. Detection rate is limited by drift + analog readout times; no amplification in noble liquids.

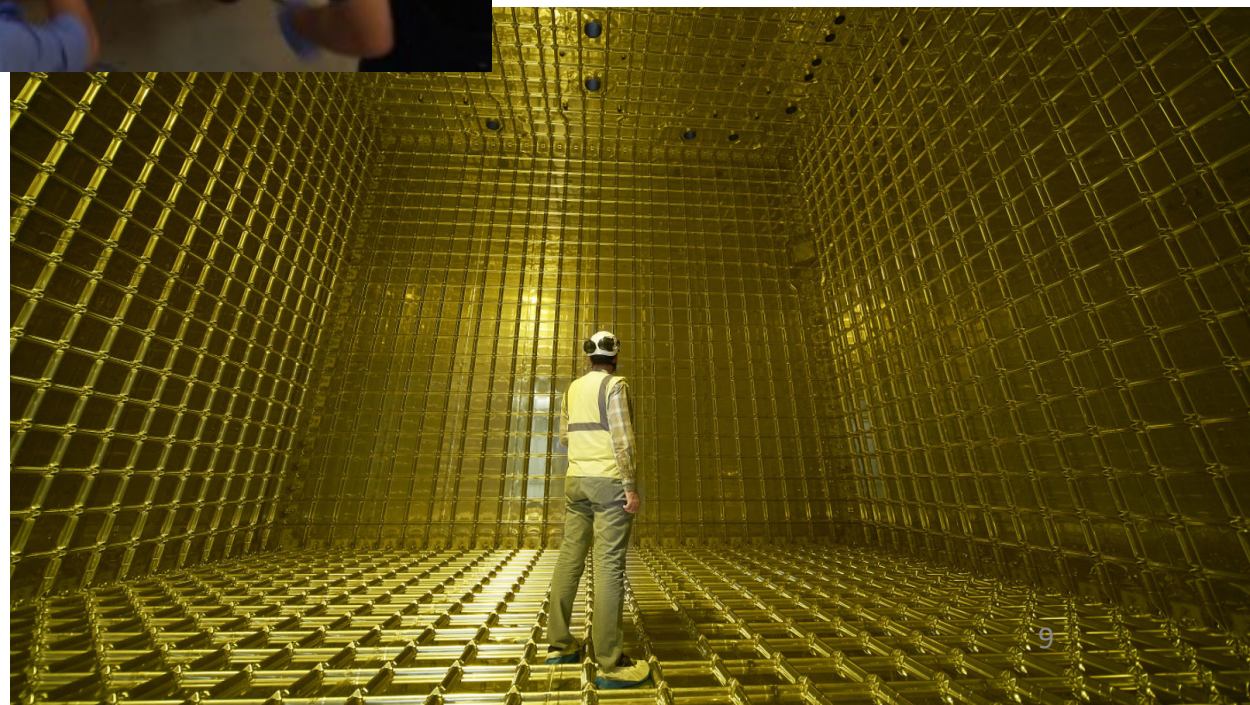


XENON dark matter experiment at Gran Sasso uses 62 kg dual phase (liquid/gas) Xe



ALICE at CERN uses Ne-CO_2 gas

Support structure for the liquid argon TPC (LArTPC) in DUNE



Improve resolution by *miniaturizing the ionization volume*: **Micro-pattern Gas Detectors**

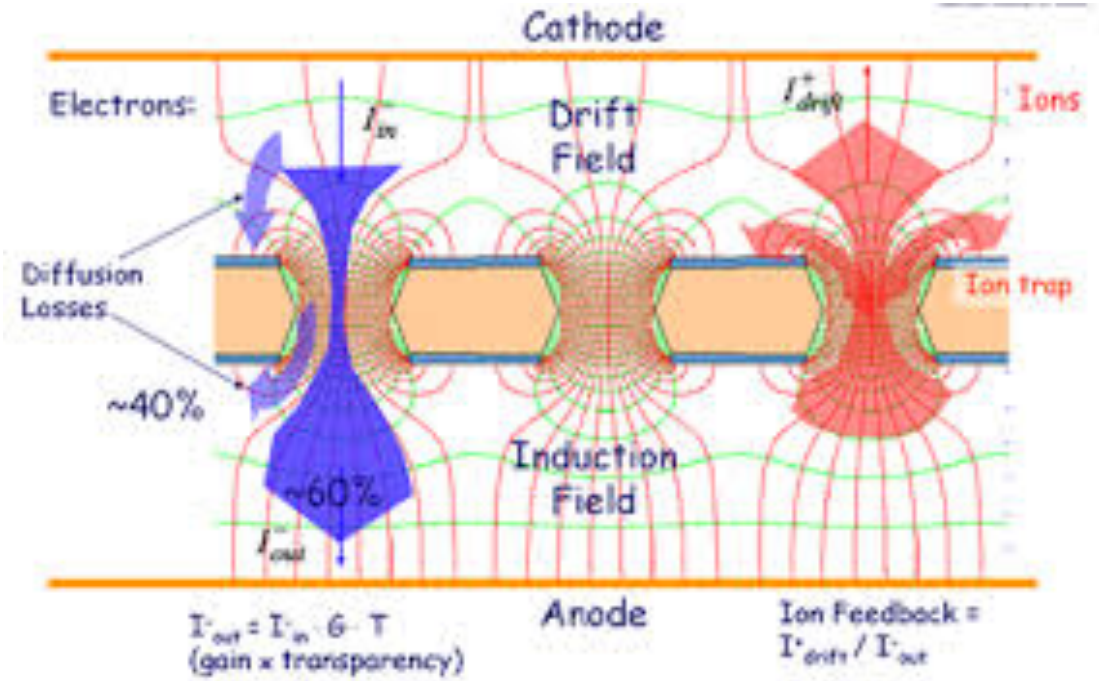
- These are MWPC's miniaturized (by ~factor of 10), with gas gaps of ~2 – 10 mm.
- *Electrodes are formed by lithography on insulator or semiconductor surfaces* (i.e., no wires). Pitch ~100 – 200 microns.
- Strips or pixels
- *Low dead time* (ion drift distance to cathode is short).
- Many varieties, to *optimize against aging and for different conditions*.
- Examples (these both include an amplification structure): **Micromegas** and **GEM**

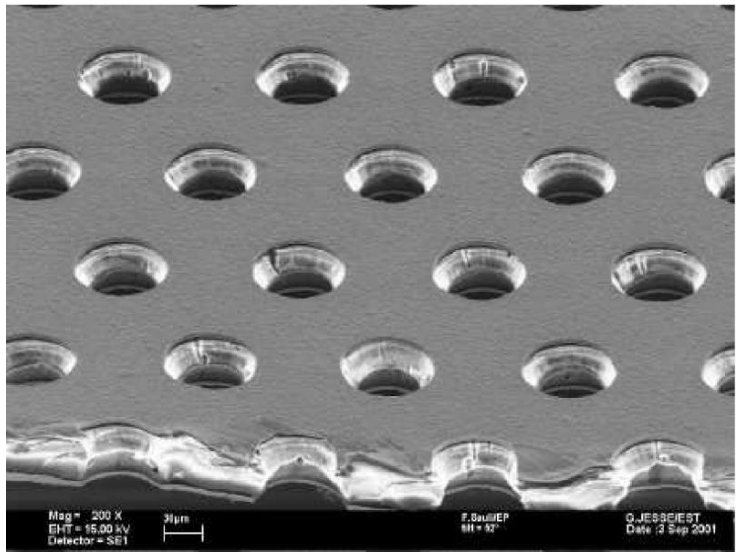
Improvement in rate capability: capable of ~10^6 Hz/mm^2

Improvement in granularity: capable of ~30 μm spatial resolution

Gas electron multiplier (GEM)*

Also include ***a conversion gap***, plus ***a multiplication region*** produced by a thin insulating Kapton foil coated with metal film on both sides, and containing ~50 μm holes on a ~100 μm pitch. Different potentials on the films produce charge multiplication in the holes. ***Gain ~10^5*** on electrons for cascaded arrays. Short gap restricts breakdown.



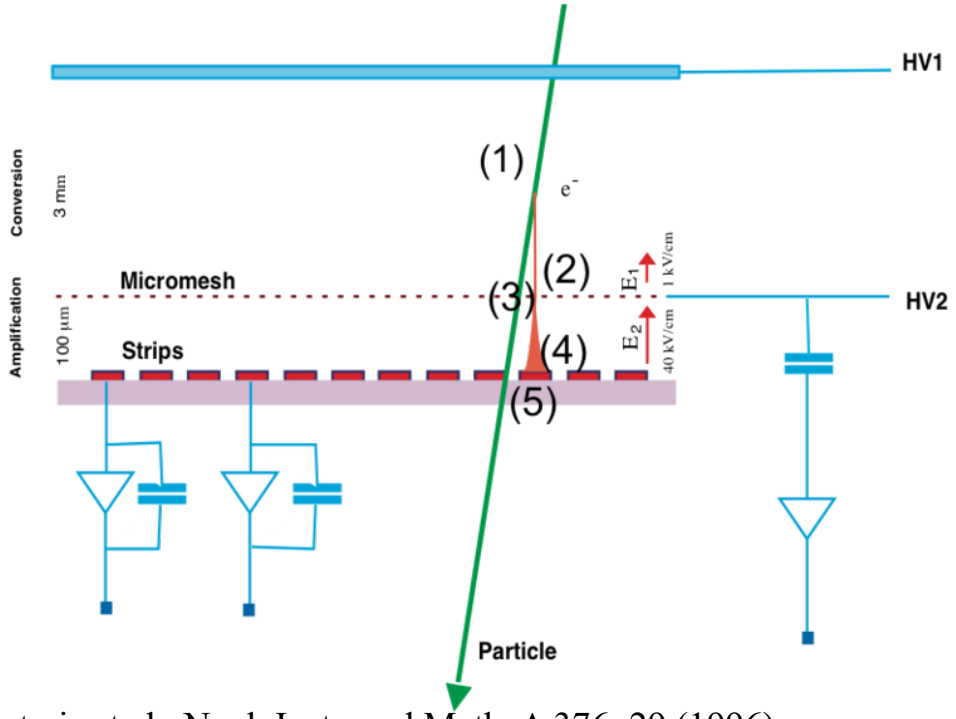


GEM technology is also proposed for the ILC TPC.

* F. Sauli, Nucl. Instr. Meth. A A 386: 531 (1997)

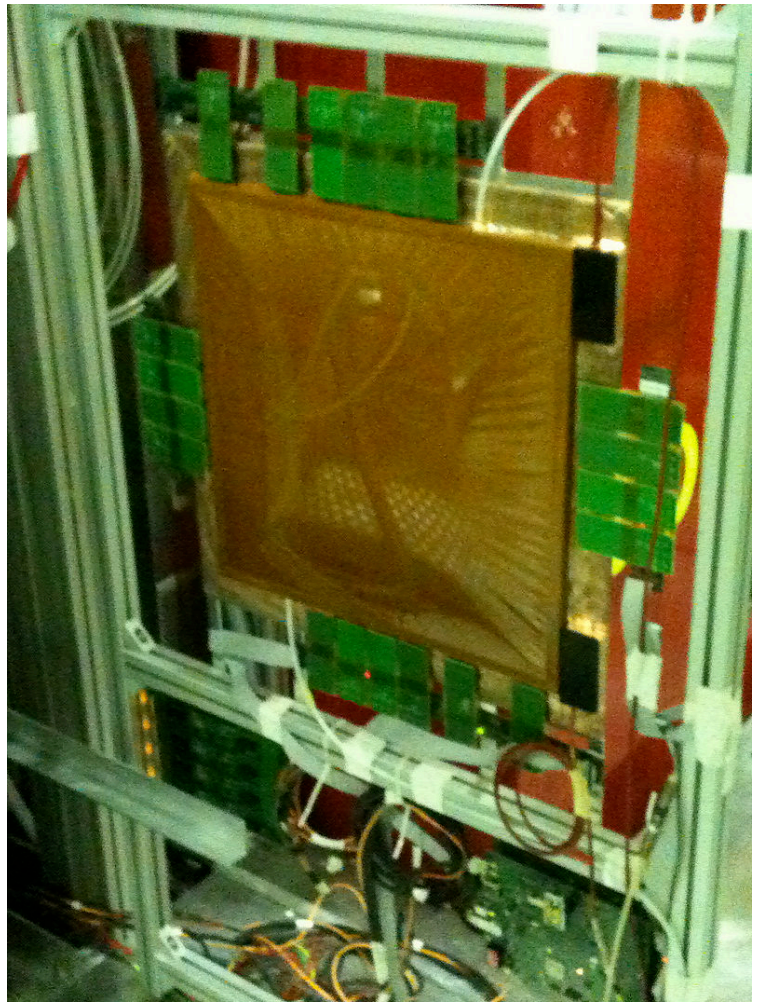
Micro-Mesh Gas Structure (Micromegas)*

- Primary electrons are produced in the ionization process in a ***2-5mm conversion gap***, then drift to a ***50-100 μm multiplication gap***, bordered by a cathode mesh and anode readout structure.
- High E field (~100 kV/cm) in the multiplication gap provides ***gain ~10^5*** on electrons.
- Ions are collected in the near cathode, so ***timing precision and rate capability are good***.



* Y. Giomataris et al., Nucl. Instr. and Meth. A 376: 29 (1996).

Micromegas is operating in the COMPASS Experiment...

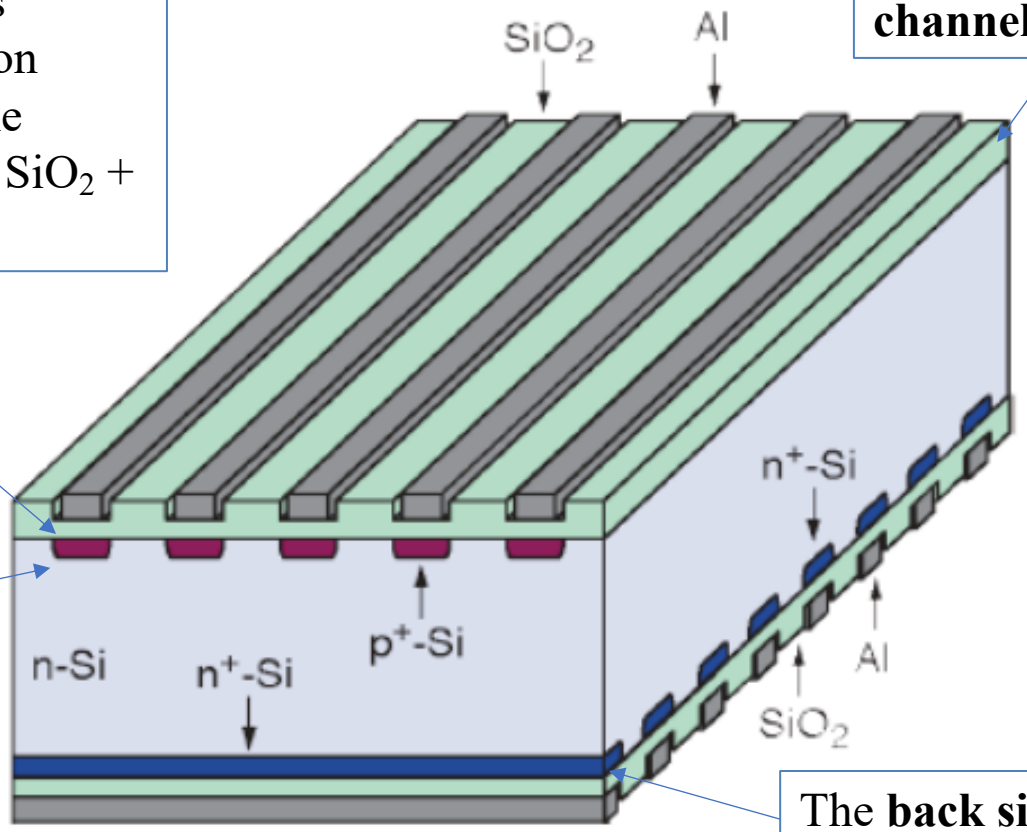


...and has been proposed for a "Micromegas TPC" at the International Linear Collider (ILC)

Silicon Pixel and Strip Detectors: replace the ionization medium (gas) with semiconductor, for the ultimate precision

In modern detectors, typically signal routed to read-out electronics is capacitively induced on **metal electrodes**. The capacitor dielectric is SiO_2 + Si_3N_4.

SiO_2 grows naturally on wafer surface, and electrically **isolates channels.**

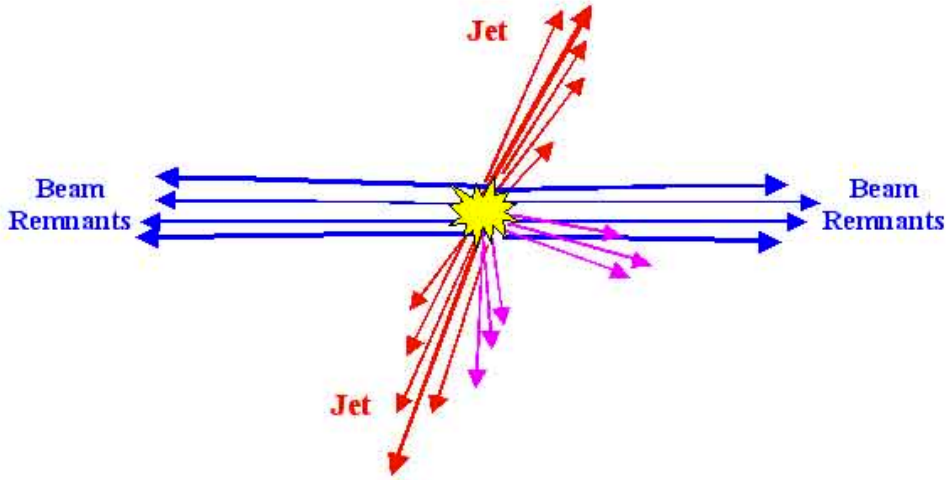


The pn junction is at the interface of the bulk with these **implanted strips** ("p^+" means $10^{18} \geq n_{dopant}/cm^3 >> 10^{13}$). Under *reverse bias*, the region depleted of free carriers grows from the junction toward the n^+ side ("back side").

The **back side also takes an implant, which** can be segmented (in "double sided detectors") or not.

Calorimetry: Measurement of Energy, Missing Energy, and Particle ID

Calorimetric method: ***total absorption of the energy*** of a particle, in material bulk, then measurement of the deposited energy. The particle is destroyed in the process.



Applies to ***neutral and charged*** particles.

Role of the calorimeter:

- precision measurement of the four-vectors of individual particles and jets
- measurement of mass peaks
- measurement of energy flow, to recognize missing energy
- identification of jet substructure
- rejection of pileup (multiple overlapping interactions during a single beam crossing)

Measurement principles use

- atomic and molecular excitation (ionization, scintillation)
- collective effects in the medium (Cherenkov light, phonons)
- heat deposition (transition from superconducting to normal)

In addition to measuring energy, ***the calorimeter can provide full information on the track 4-vector as well as fast input to a detector trigger.***

Very different physics for detection of electromagnetically showering particles (electrons, positrons, photons) versus strongly interacting (i.e. hadronic) particles (pions, kaons, protons, neutrons)

Electromagnetic calorimetry

Principle of detection: Energy loss (dE/dx). Here is what dominates the process:

- for showering particles with energy ~ MeV
  - for photons - photoelectric and Compton
  - for charged particles – ionization and excitation

} These do not produce a shower / avalanche

- for showering particles with energy $\gtrsim$ 100 MeV
  - for photons – pair production
  - for charged particles – bremsstrahlung

} These DO produce a shower / avalanche

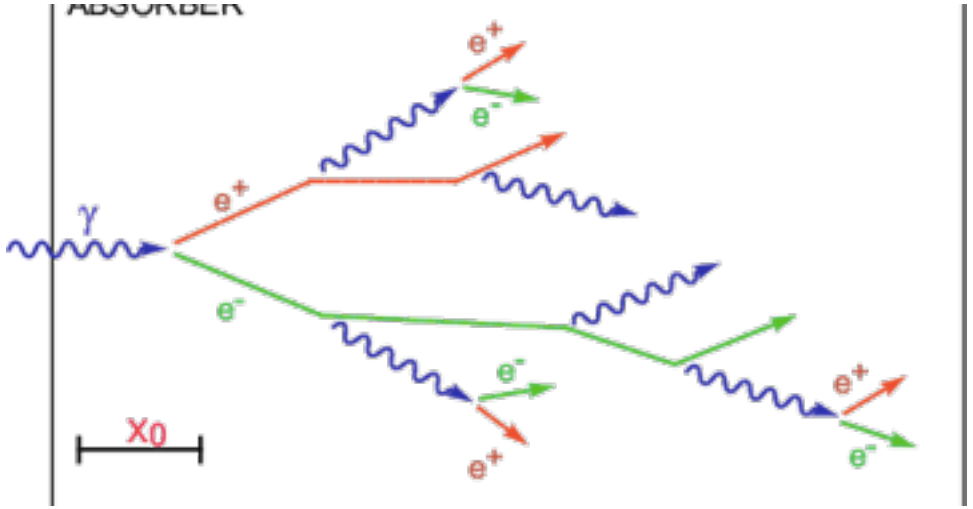
Recall **that radiation length X_0** characterizes the loss rate:

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

Think of X_0 as "the typical distance the electron travels before it brems, or the typical distance the photon travels before it converts to a pair."

Typically the **depth *t*** of an EM calorimeter is indicated in units of radiation lengths:

$$t = \frac{x}{X_0}$$



In a simplified model of the shower, ***the # shower particles at depth t*** is:

$$N(t) = 2^t$$

If the primary incident particle has energy E_0, the ***energy of each particle in generation t*** is:

$$E(t) = E_0 2^{-t}$$

The ***shower stops when***

$$E_0 / N < E_c$$

where E_c is a critical energy at which Compton/photoelectric/ionization begin to dominate (depends on the material).

Thus:

$$E_c = E_0 2^{-t_{\max}}$$

And the ***position of the shower maximum*** is

$$t_{\max} = \frac{\ln(E_0 / E_c)}{\ln 2}$$

Thus: in designing, **the thickness of the calorimeter should go as ln E_0.**

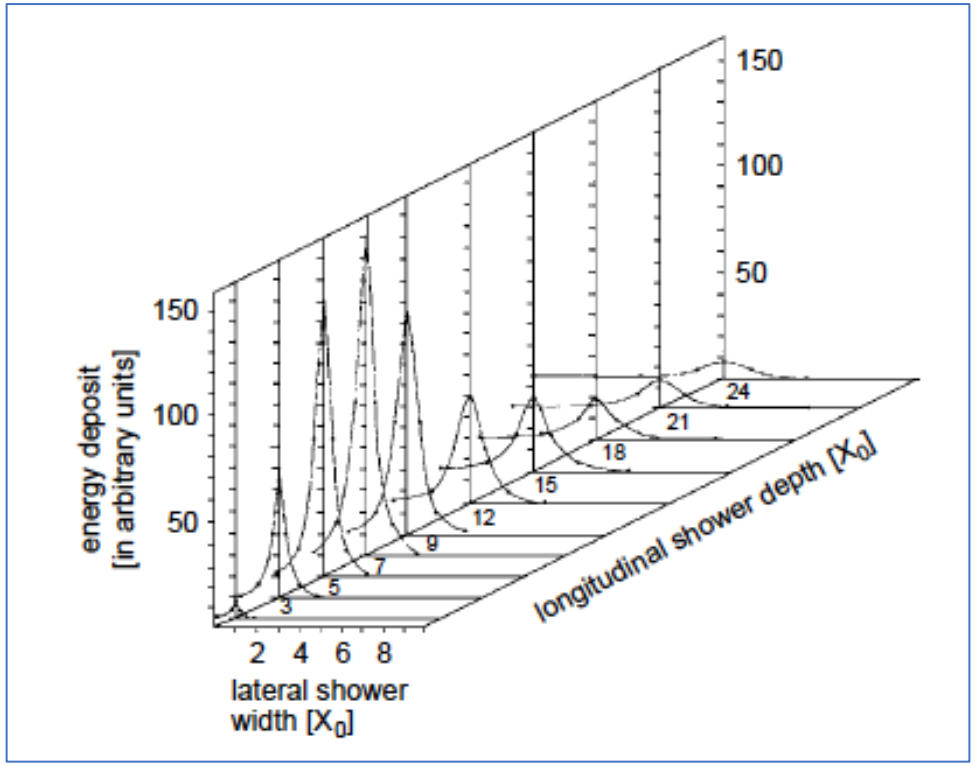
Note: below E_c, production of electrons and positrons stops within 1 X_0, but photons continue to penetrate a further 7-9 X_0. **To fully contain a shower, the calorimeter should have depth ~ 16 X_0.**

The actual formation of the shower is more complicated than this but can be well modeled using Monte Carlo, as:

$$\frac{dE}{dt} = E_0 \cdot b \cdot \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

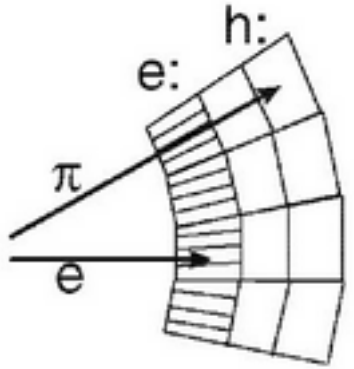
where

$$\Gamma(g) = \int_0^\infty e^{-x} x^{g-1} dx$$



(In dense media, the development of the shower is modified by the Landau-Pomeranchuk-Migdal (LPM) effect, a quantum mechanical effect which suppresses production of low energy photons. This must be considered at modern experiments such as those at the LHC.)

The **cascade is narrow (Opening angle $\langle\theta^2\rangle \sim \gamma^2$** due to brem and pairs, and **increases** with depth due to multiple scattering of electrons, $\langle\theta\rangle \sim 1/E_e$.) Because showers broaden as they develop, calorimeters use projective geometry:



About ***95% of a shower is contained within a cylinder about the axis, of radius $2R_M$***, where

$$R_M = \frac{21\ \text{MeV}}{E_c} X_0[\text{g/cm}^2] \qquad \text{is the Moliere radius.}$$

The ***resolution of a calorimeter is approximately equal to the non-containment fraction***. Thus 5% non-containment translates to about 5% resolution.

The shower profiles have long tails: increasing the collection from 90% to 99% requires an order of magnitude more mass.

The energy deposited in the medium is due to the ionization losses of the charged particles $\propto$ # of electrons and positrons.

To detect this energy, 2 processes are needed:

1) The energy is transferred from the particle to the medium – ***"the particle is absorbed"***
2) ***The energy is read out*** - detected

Two options for EM calorimeter configuration:

- ***homogeneous:*** the absorber and the detector are combined
- ***sampling***: the absorber and the detector are distinct

Homogeneous calorimeters – the full volume of the detector can absorb the energy and transmit it to readout

Measurement principle is any of these:

- detection of *scintillation* light (medium is scintillating crystals or liquid noble gas)
- collection of *ionization* (medium is liquid noble gas)
- generation of *Cherenkov* light (medium is heavy transparent crystal or lead glass)

The most important features of the calorimeter are the position and energy resolutions for photons and electrons.

Energy resolution:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

crystal non-uniformity ($c < 1\%$)
electronics noise (b~100's of MeV)
photoelectron statistics (a~3%-5%)

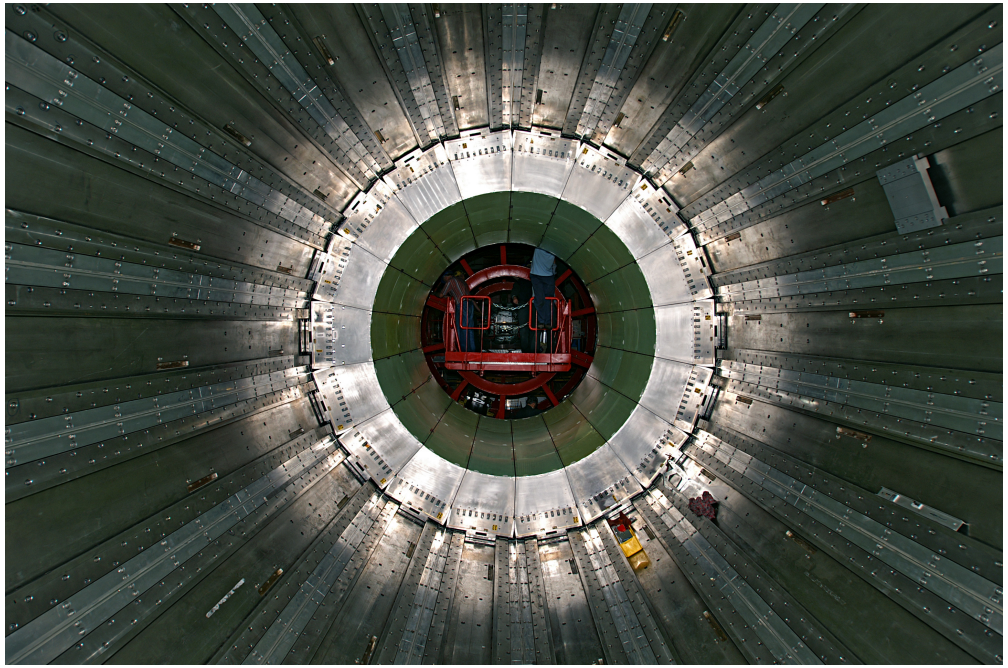
Notice: the resolution improves with increasing energy.

Example homogeneous calorimeter types:

1) **Crystal** calorimeters -best resolution at this time: $\sigma_E/E \sim 1\%$

(Lead glass calorimeters – less expensive than crystals, but lower Cherenkov light production increases resolution to $\sim 5\%/\sqrt{E}$)

2) **Ionization** calorimeters – often using noble liquids: liquid argon (LAr) is abundant, inexpensive, obtainable with high purity, radiation hard



CMS Ecal: 80k $PbWO_4$ (lead tungstate) *crystals*, mounted inside 4T solenoid: ***Strengths:*** short radiation length, small Moliere radius, fast scintillation emission, high radiation hardness. ***Challenge:*** low light output.

ATLAS LAr EM Calorimeter *(ionization principle)*

Calorimeter position resolution is taken from the corrected center of gravity of the energy deposition. Approximately,

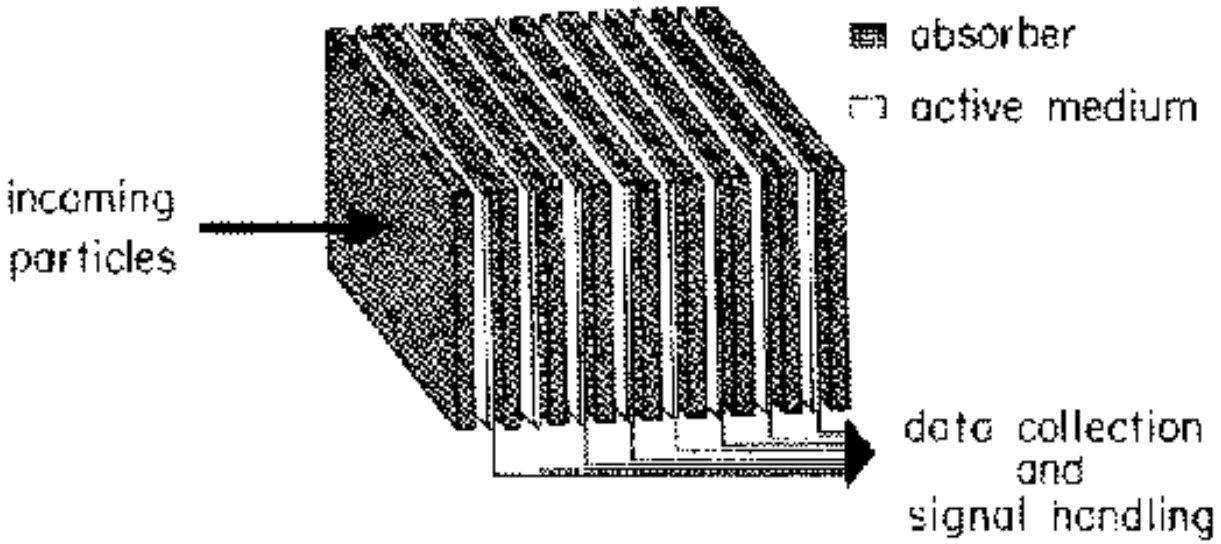
$$\sigma_{longitudinal-position} \sim \frac{R_M}{\sqrt{E / E_c}} \sim \text{few mm for } \mathrm{E}_\gamma = 1 \text{ GeV with crystals}$$

$$\sigma(\theta) \sim \frac{\text{few mrad}}{\sqrt{E}}$$

Sampling calorimeters – longitudinal stack of absorbers separated by thin counters

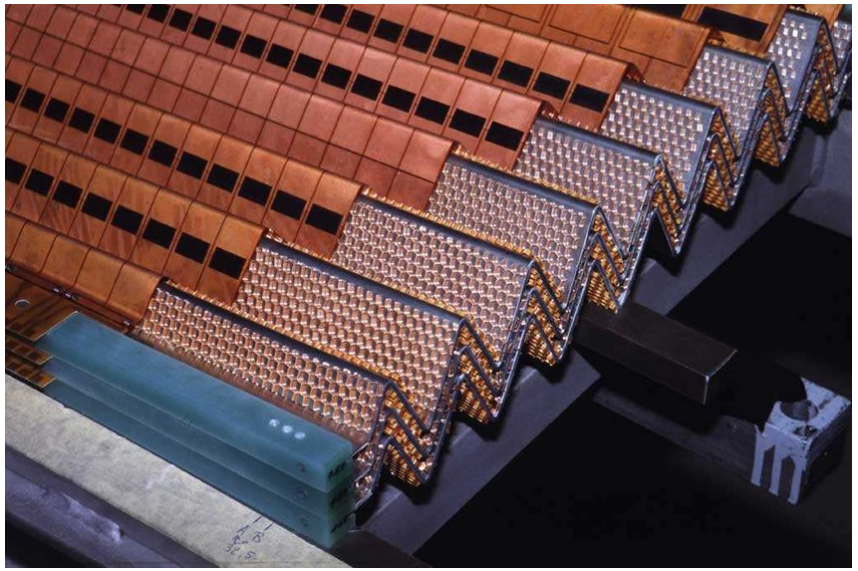
- ***Typical sensors***: gas-filled ionization chambers, cryogenic noble gases (LAr, LXe) as ionization chambers, warm liquids, scintillators
- ***Typical absorbers***: U, Fe, W, Cu, should be > 2 cm thick

- *Advantage:* each material can be separately optimized
- *Disadvantage:* contribution to resolution from sampling fluctuations (minimized in dense materials: typically ~8% in LAr @ 1 GeV).



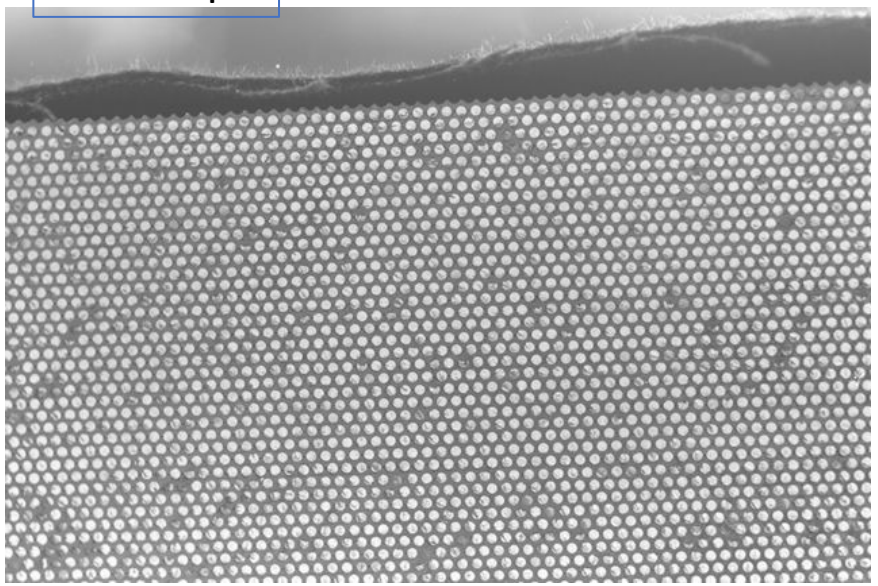
Sampling calorimeters, continued

Layers can be planes, or more complicated. To avoid "cracks" (gaps between adjacent towers): see the ***accordion*** chamber...



...and the ***spaghetti*** calorimeter, in which the counters are fibers embedded in the absorber...

KLOE Exp.



...and more geometries: shashlik-calorimeter, tile-calorimeter....

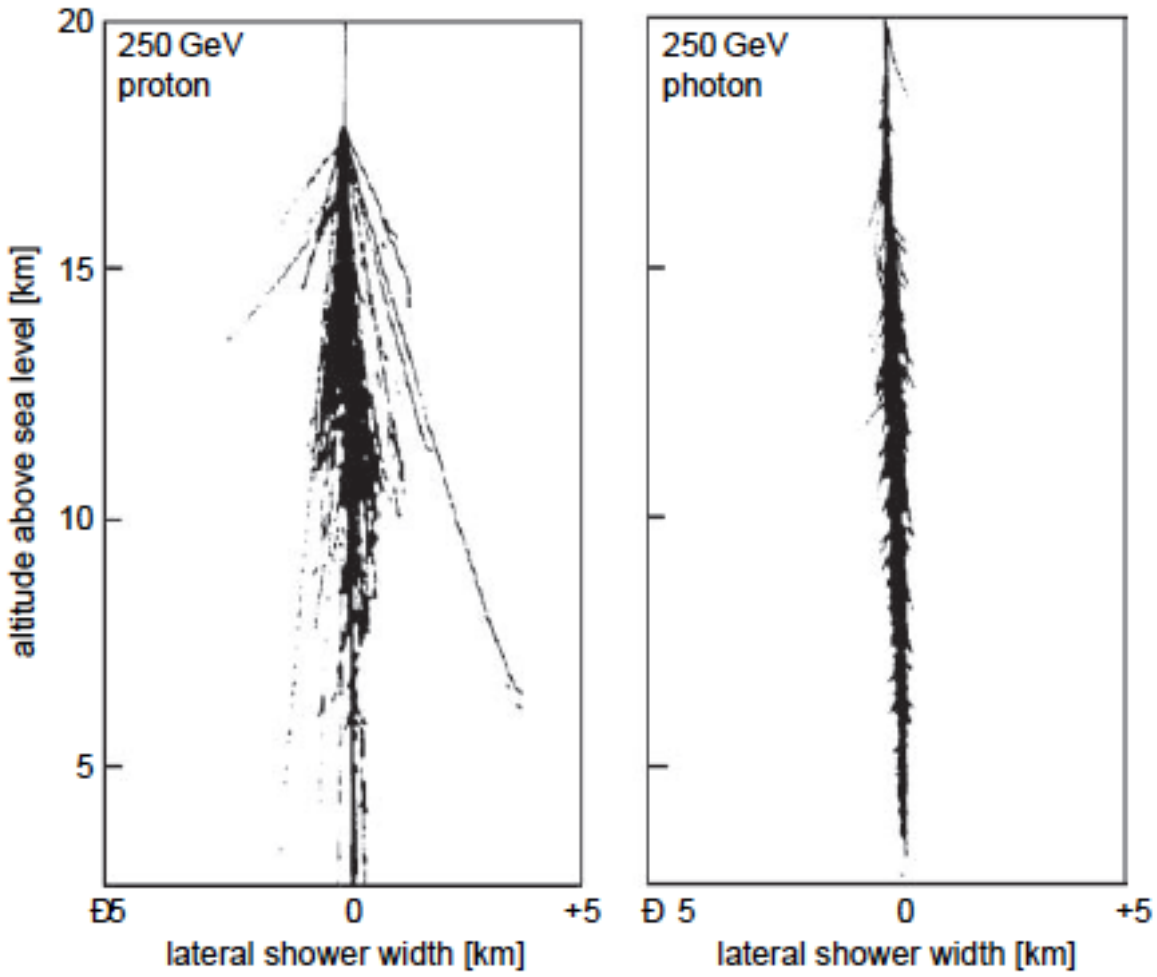
Hadronic calorimetry – to measure the energy of non-showering particles

- Similar geometries, but the ***longitudinal shower development is determined by nuclear interactions***
- Showers include pions, kaons, nucleons
- Characterized by the ***nuclear interaction length***:

$$\lambda_I \sim 35\left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right]A^{1/3}$$

This is longer than X_0 for most materials.

- Hadronic showers are broader than EM showers due to large transverse momentum transfers in nuclear interactions. Compare simulated air showers of equal-energy proton and photon.



How is the hadron energy dissipated in the absorber?

- 1/3 of the hadrons produced are $\boldsymbol{\pi^0}$**.** These decay quickly to photons, producing EM showers.

- Another 30%-40% of the hadron energy is dissipated invisibly as **broken nuclear bonds or production of stable neutrals** (neutrons, K_L^0).

- ***ONLY the EM energy dissipated by charged particles is recorded by any calorimeter***, so the **hadron signal is smaller than the EM calorimeter signal, for the same particle energy.** ***Up to 40% of the non-EM energy may be "invisible"*** – binding energy of nucleons released in nuclear reactions – with large event-to-event fluctuations.

- Large fluctuations in hadron shower development (i.e. fluctuations in number of π^0's) leads to ***worse resolution than in EM calorimeter***

- ***Hadron calorimeters are intrinsically nonlinear with energy*** – the average EM fraction (called "e") increases with energy.

- The response of the calorimeter to the non-EM fraction (called "h") is constant with energy. Thus:

$$\frac{e}{h} > 1$$

"Compensation" is a technique to recover information on the invisible energy, i.e. to achieve $\frac{e}{h} \to 1$

Only sampling calorimeters can be compensated.

Compensation methods:

- *suppress the EM response* (e.g. choose high-Z absorber material)
- *boost the non-EM response* (choose an absorber containing hydrogen; incoming neutrons recoil on the protons, which then contribute to the signal)
- *"offline compensation"* – determine the energy sharing between EM and hadronic components on an event-by-event basis through analysis of event characteristics (shower shape, composition) – this is "Dual REadout Method" (DREAM) calorimetry.
- uranium absorber – *fission materials liberate additional energy*

ZEUS (uranium/scintillator) achieved $\frac{\sigma}{E} \sim \frac{35\%}{\sqrt{E}}$. ATLAS (non-compensating) "Tile" calorimeter achieves $\frac{\sigma}{E} \sim \frac{42\%}{\sqrt{E}}$

Calorimetry applications outside the realm of particle accelerators:

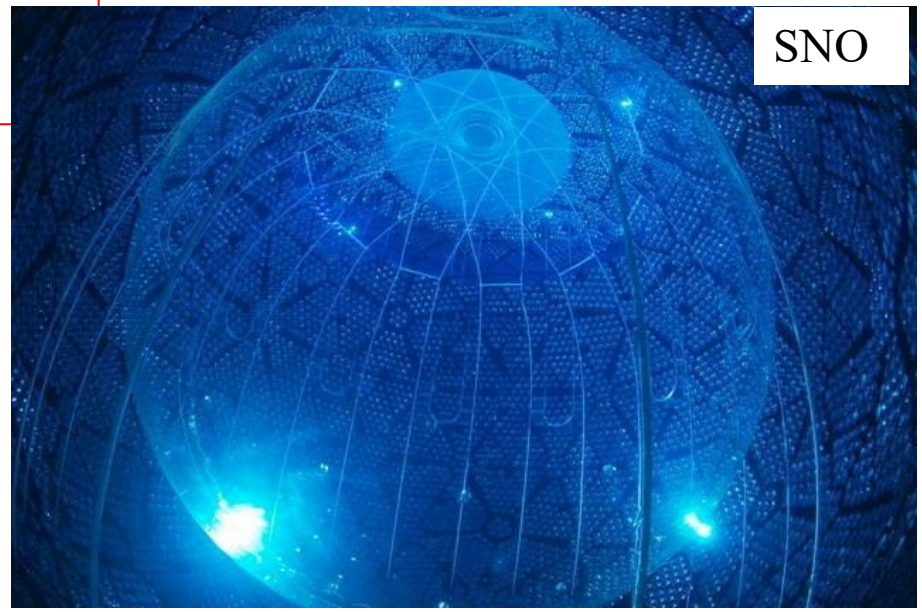
- energy measurements of *extensive cosmic ray showers induced in the atmosphere*: detect scintillation or Cherenkov light (Pierre Auger, HiRes Fly's Eye).

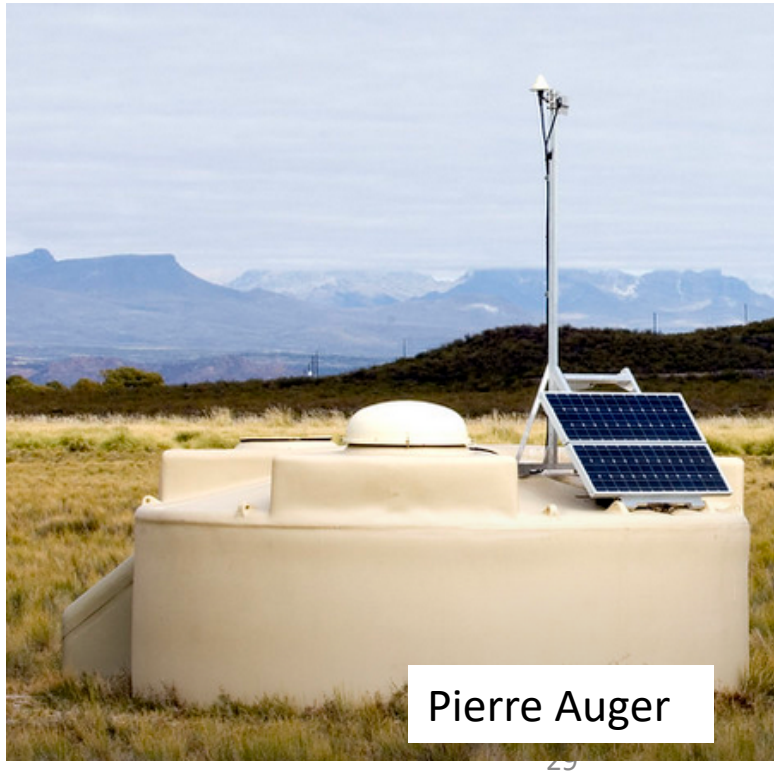
- energy measurements of cosmic neutrinos or muons: *"neutrino telescopes" employing photo detectors in a matrix of absorber deep underground or in the sea* (Kamiokande, IceCube, SNO).

- detection of *extremely low energy particles* (e.g. hypothesized WIMPs). This requires cryogenic operation to suppress thermal noise.

Phonons provide a signal in the μeV to meV range, detectable with classical calorimetry via energy deposition in an absorber (CRESST detectors, CYGNUS, DRIFT)


CRESST


SNO


Pierre Auger