An introduction to Instrumentation

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Disclaimers

- This is a twisted view of instrumentation from the eyes of a particle physicist
- I've spent my whole career working for LHC experiments
- 25 minutes is not enough to cover everything, apologies if I left out your favourite detector / technology
- I'm looking forward to learning from you!

What is instrumentation?

An instrument can be many things…

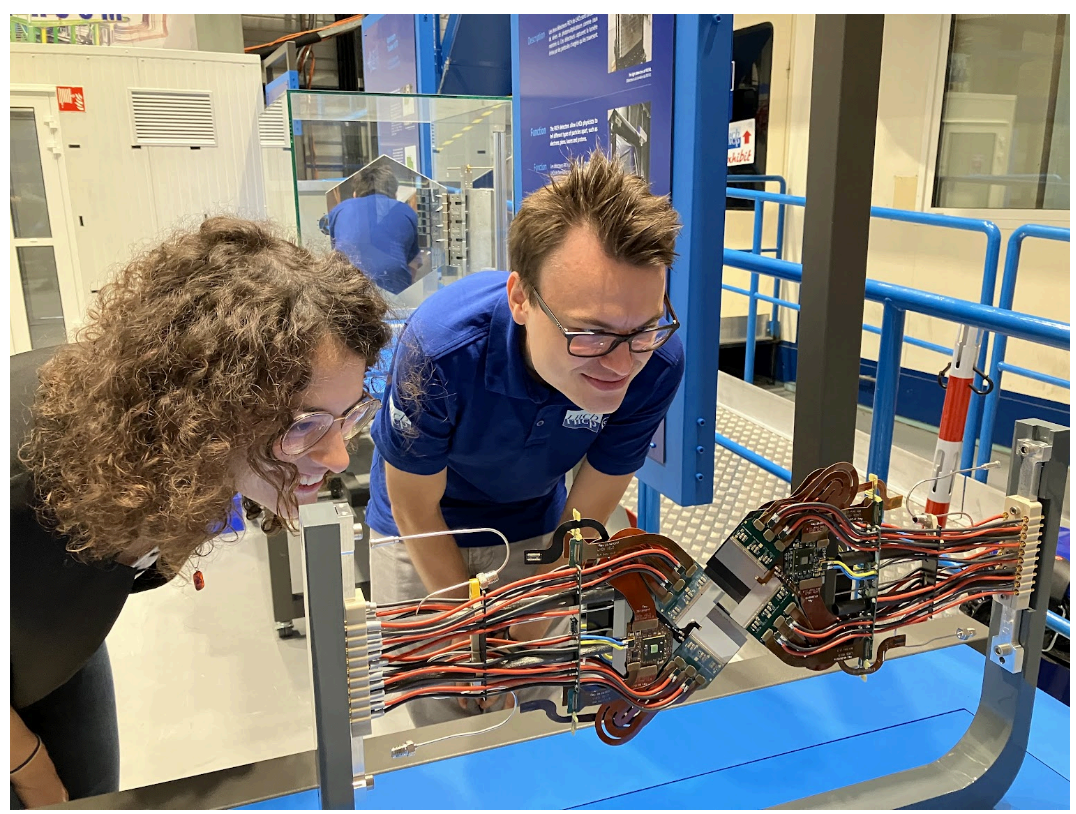
Instrumentation 101

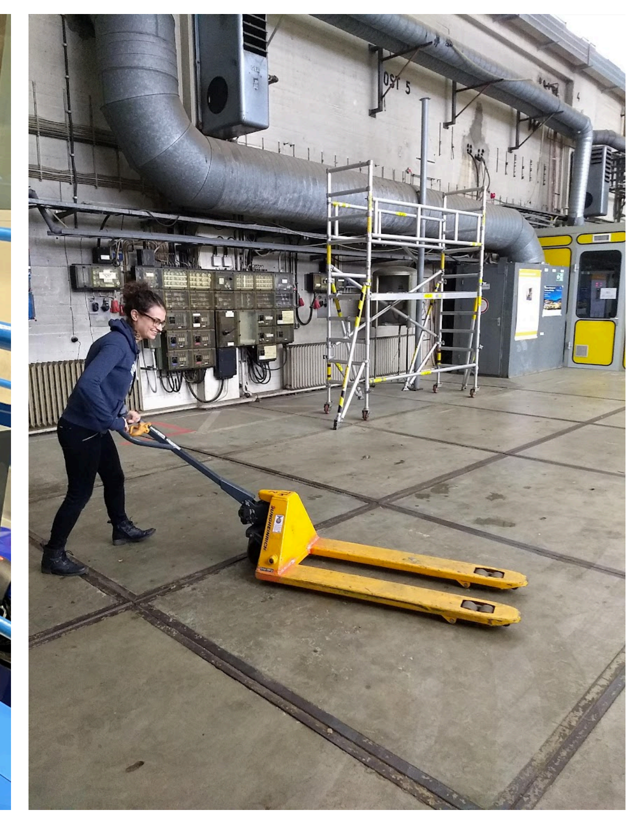
Experiment: A test under controlled conditions that is made to demonstrate a known truth, examine the validity of a hypothesis, or determine the efficacy of something previously untried.

Instrumentation: a collective term for measuring instruments that are used for indicating, measuring and recording physical quantities.

Wikipedia definitions

But it's also a lot of fun!



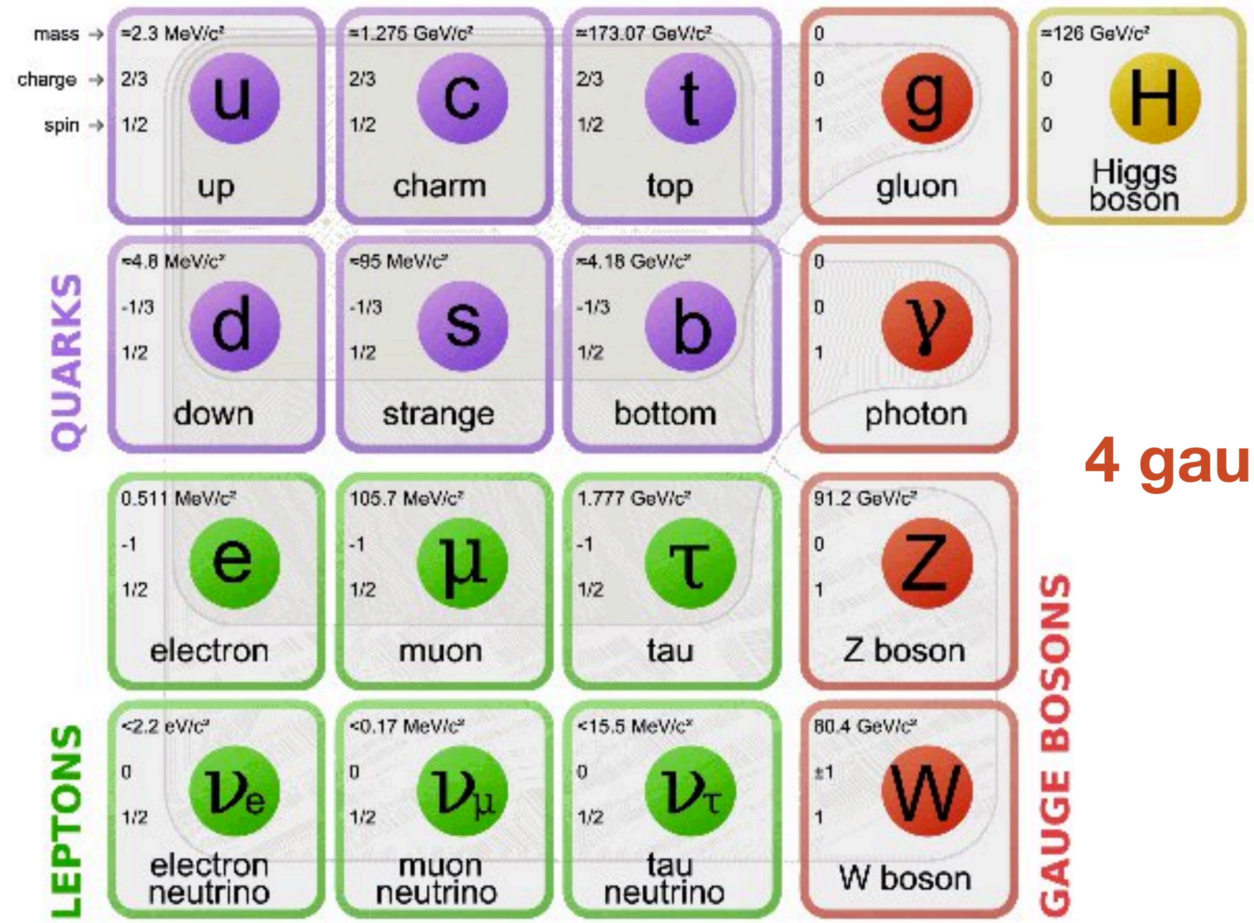


Let’s start here

Let’s start here

Is it a particle zoo?

6 types of quarks

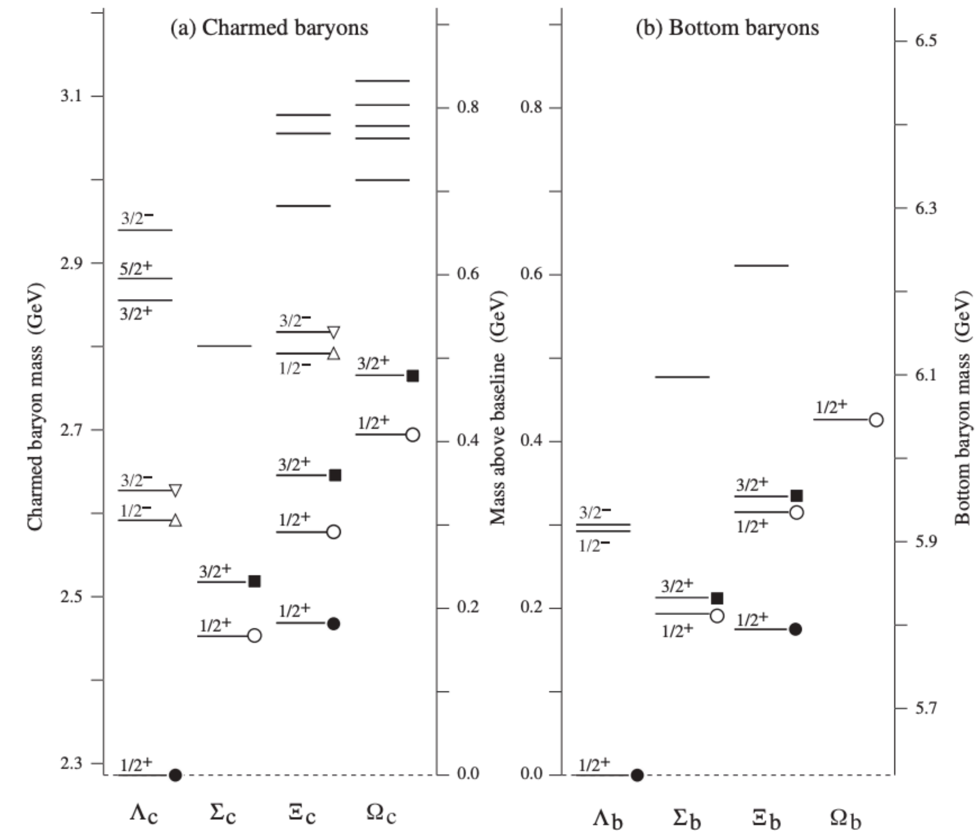


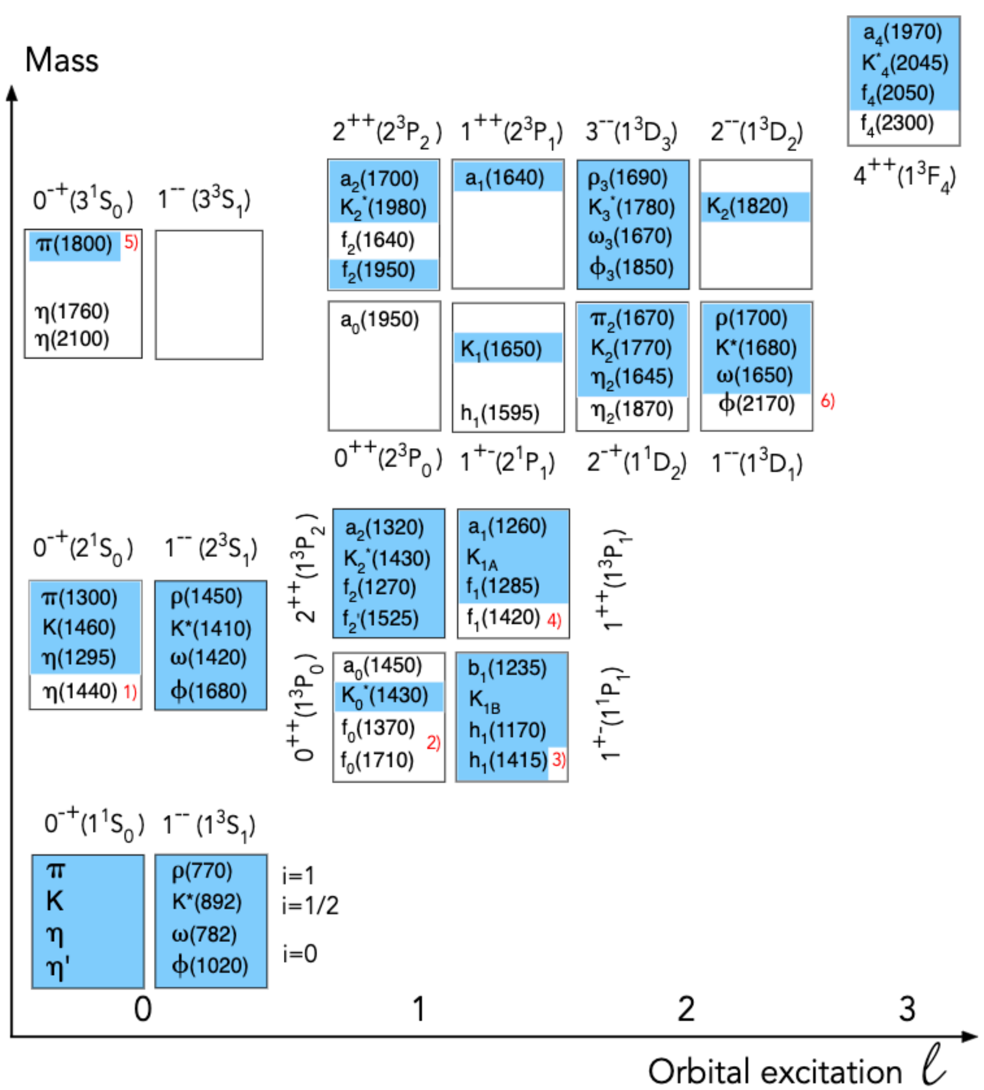
4 gauge bosons + 1 scalar

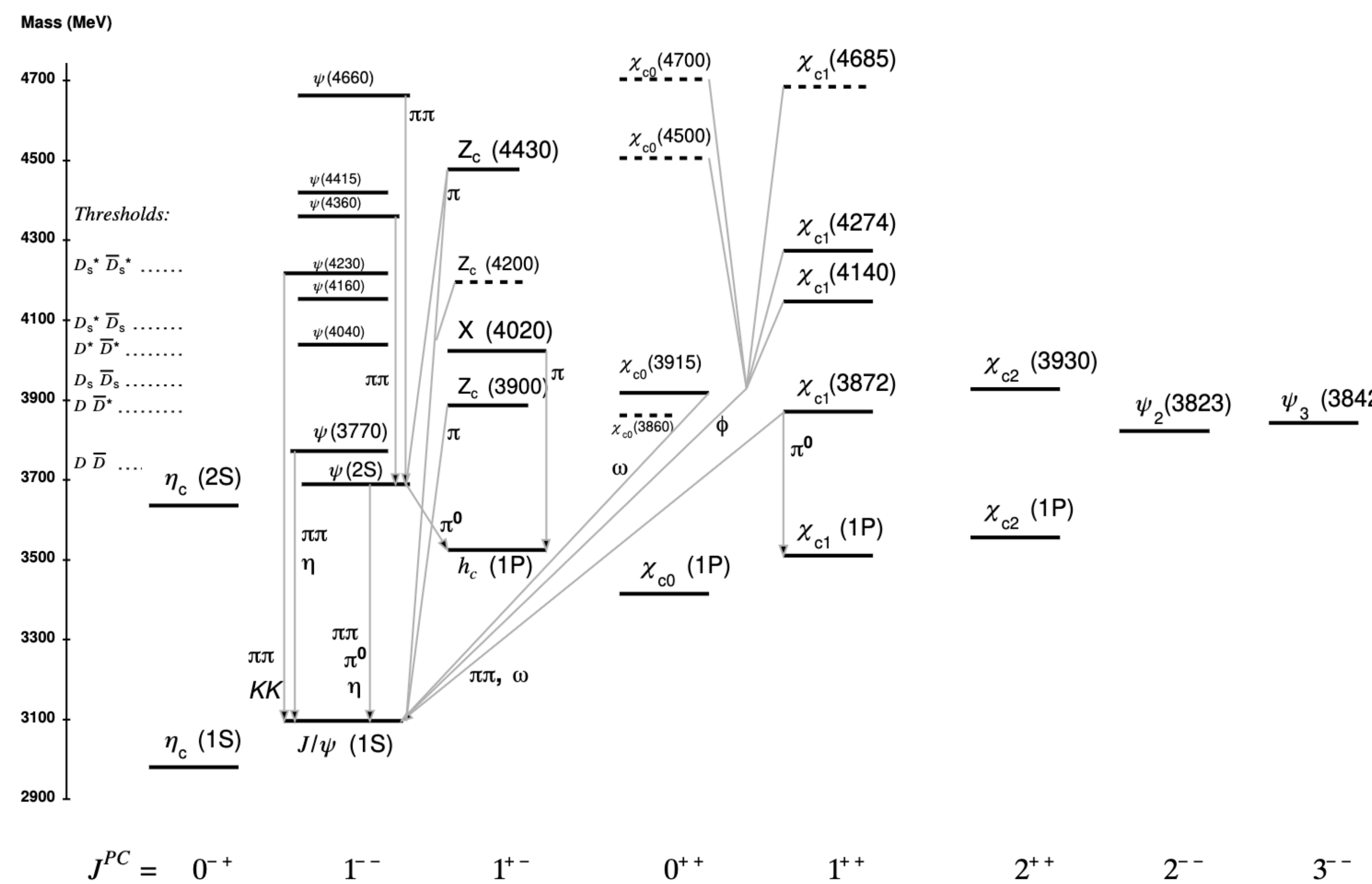
3 charged and 3 neutral leptons

Or a particle jungle?

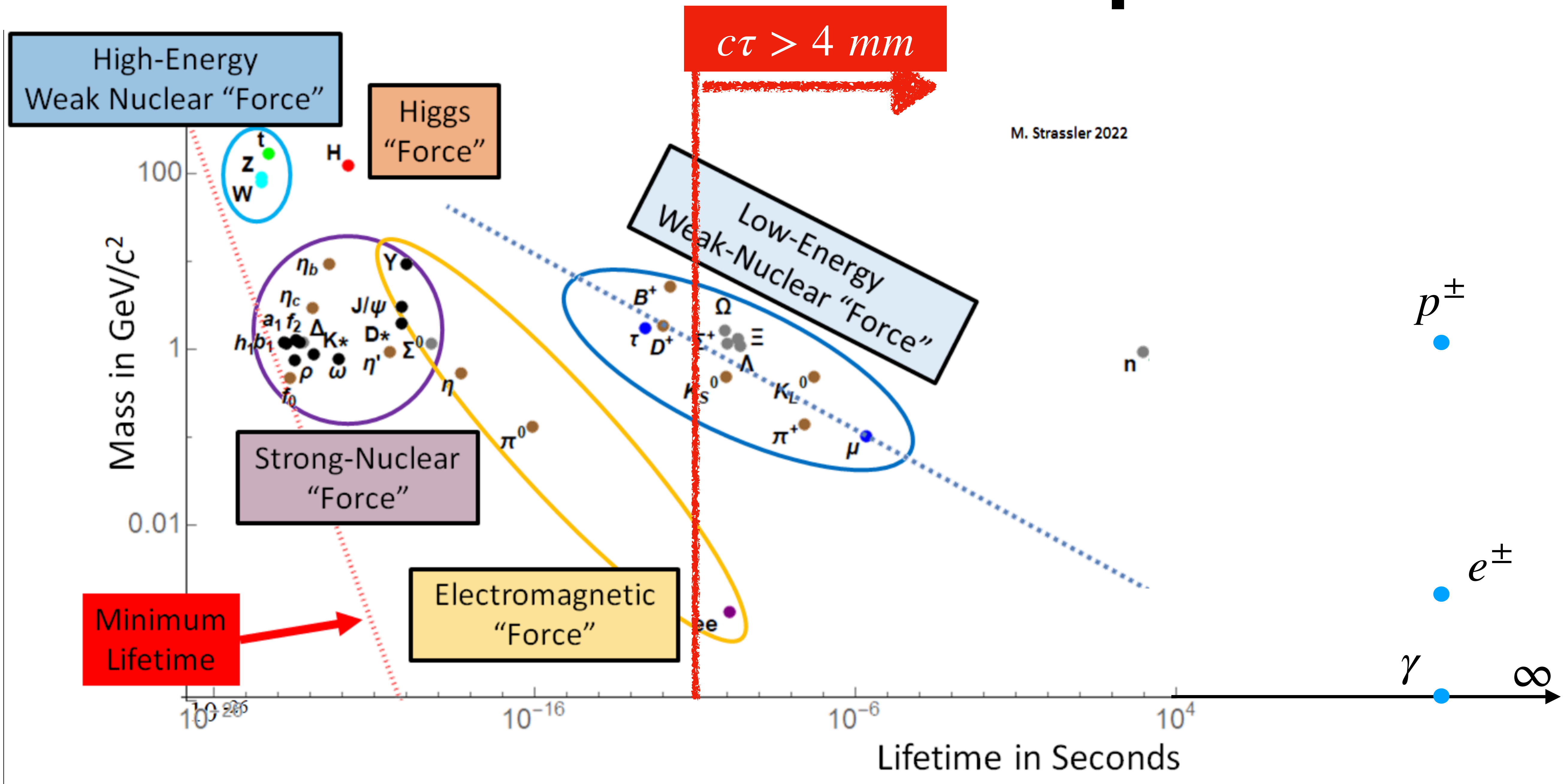
- Thanks to the strong interaction: More than 200 mesons + baryons have been found
- + a few exotics (tetraquarks & pentaquarks)
- + the yet un-observed ones!







And the domesticated particles?



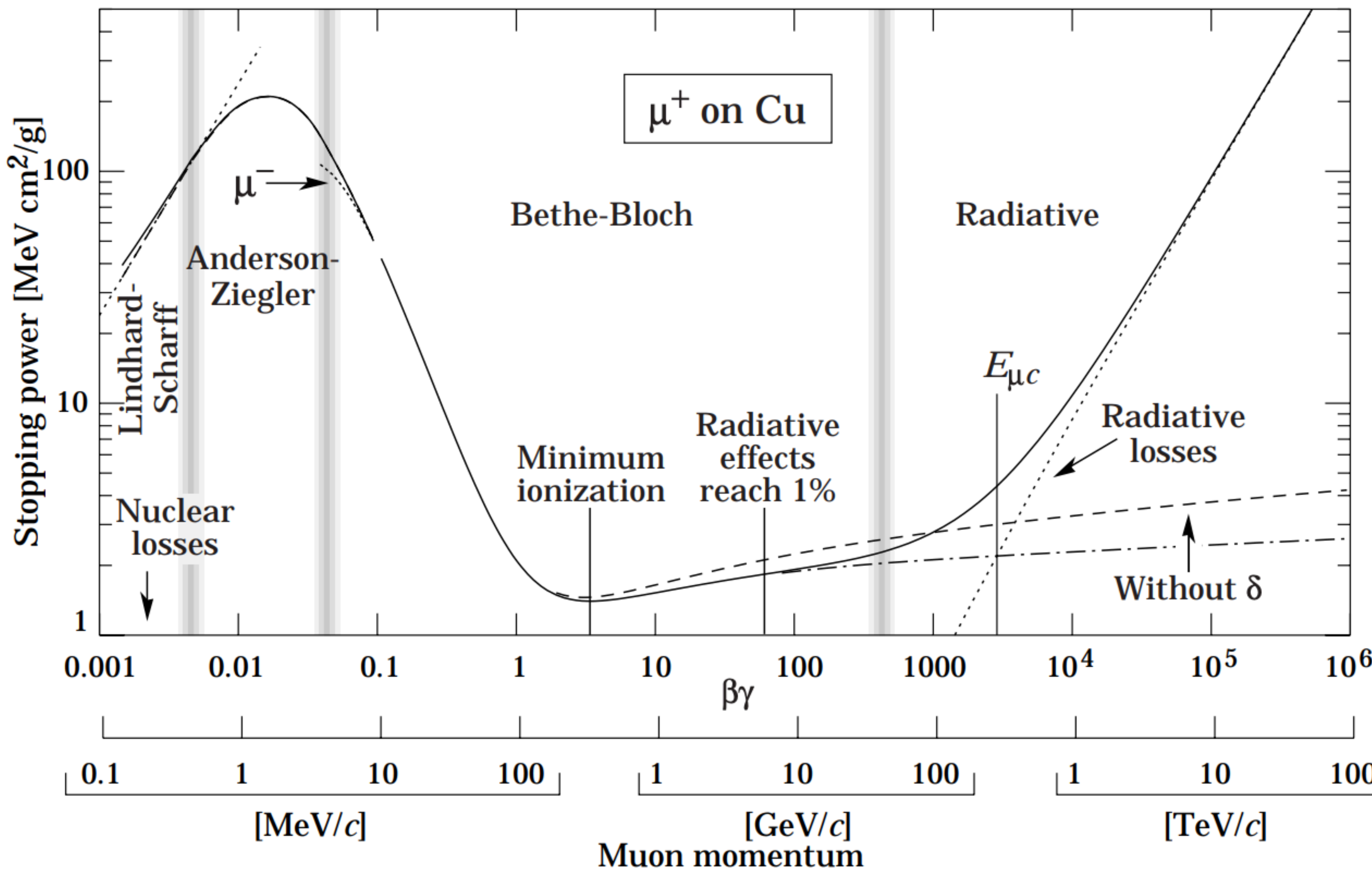
- Among all the observed particles, only ~13 can travel more than a few mm before decaying: $e^{\pm}, \mu^{\pm}, \gamma, \pi^{\pm}, K^{\pm}, p^{\pm}, K^{0}, n$
- Closest detectors to a p-p collision can reach 2 mm

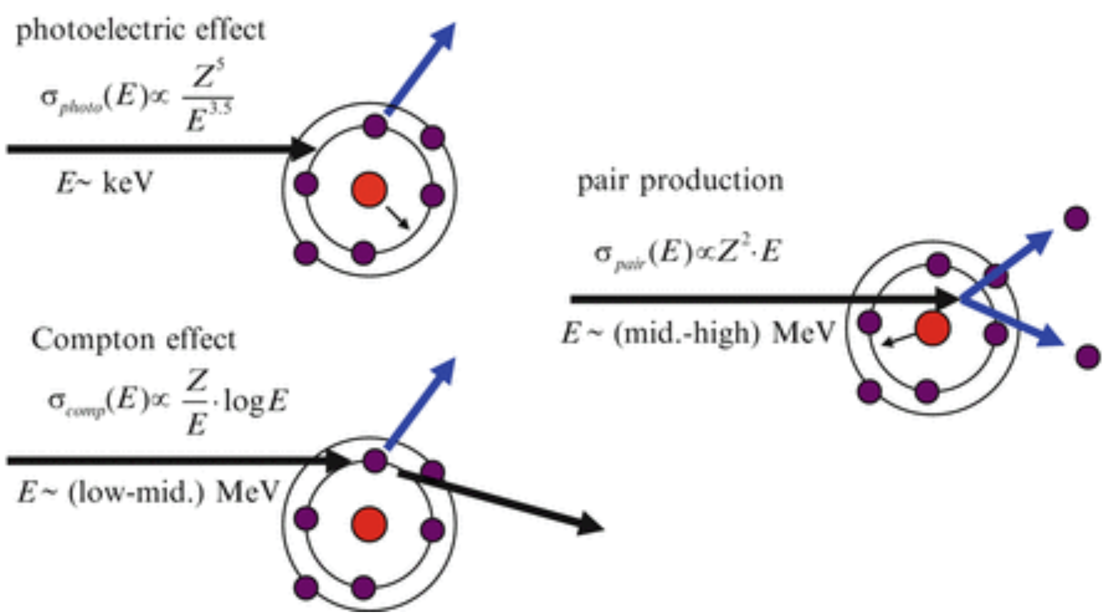
*Particle detectors rely on detecting these particles, **measuring their properties** and using conservation laws to reconstruct their "lost" parents*

It's all about material interaction

We need a "visible" signal from the passage of particles through our detector material

- **Charged particles:** ionisation, Cherenkov, Bremsstrahlung → continuous energy loss in medium
- **Photons:** photo-electric effect, Compton scattering, pair production → instantaneous full energy loss
- **Hadrons:** nuclear interactions
- **Neutrinos:** weak interactions





Bethe-Bloch

$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

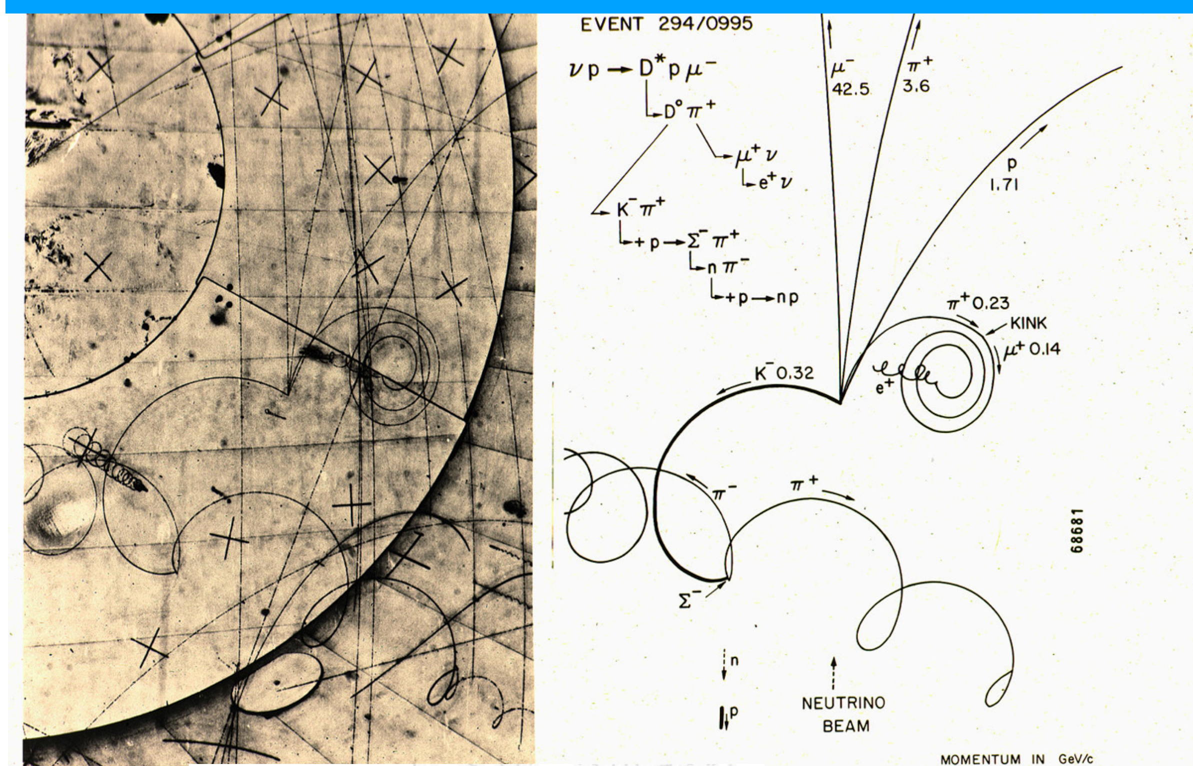
Tracking 101

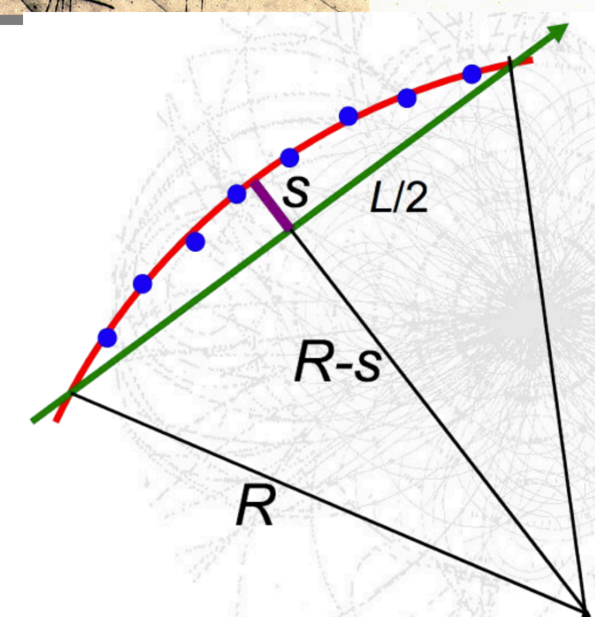
- The trick for charged particles: make them bend!

$$\frac{d\vec{p}}{dt} = q\vec{\beta} \times \overrightarrow{B} \ldots \rightarrow p[GeV] = 0.3B[T]\rho[m]$$

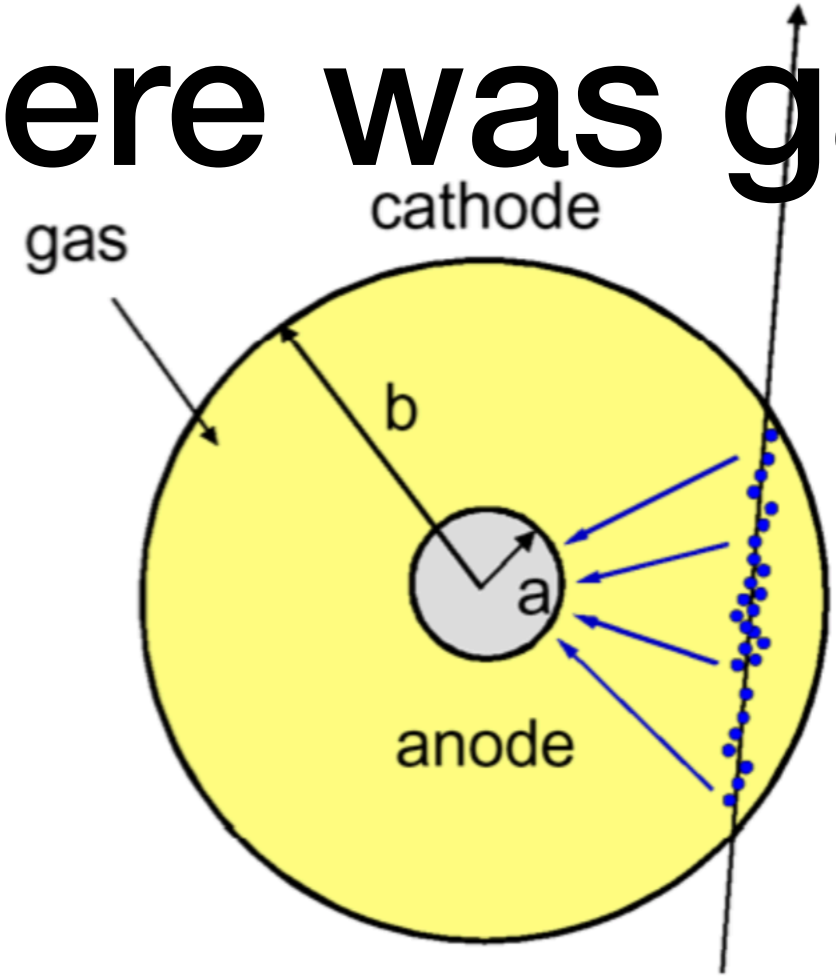
- Having the measurement of β and p $\rightarrow$ particle mass & charge
- Measuring the curvature under B-field gives access to momentum - **tracking**
- And can lead us back to the interaction vertices
- Momentum resolution: $\frac{\sigma p_T}{p_T} \sim \frac{\sigma_y p_T}{\sqrt{n}BL^2}$
- Good measurement:
    - High B-field, lever arm, number of hits
    - Good single-hit resolution, not too high p_T (low bending)

Production and decay of a charmed meson state in the Big European Bubble Chamber





In the beginning, there was gas

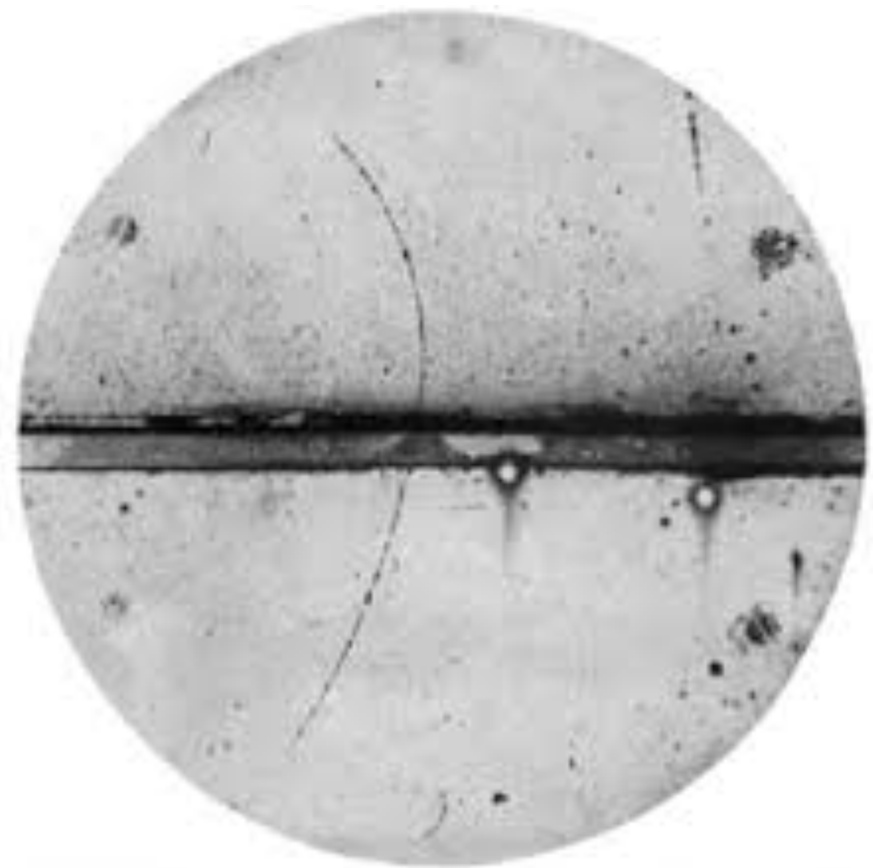


Principle of operation

- Particle traverses a gas volume (gas choice very important!) ionising it
- Created electron/ion pairs drift in electric field that we apply
- Towards collection anode/cathode → generated current

Some properties

- Large coverage, good position resolution & low material budget
- Low yield of created pairs → Require internal amplification
- Long collection time due to ion tail → can be handed by filtering electronics



And then came Semiconductors!

Solid-state sensors:

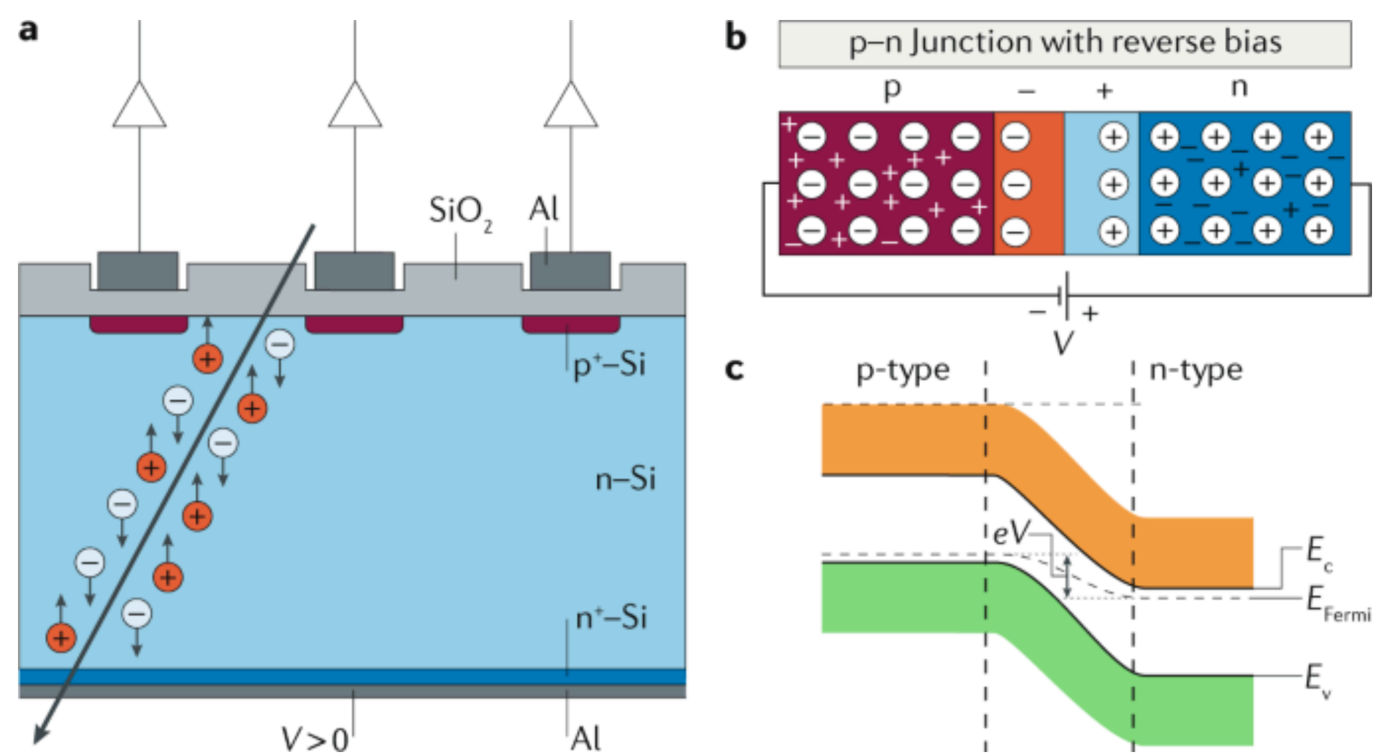
- Semiconductors like Silicon, Germanium and Diamond
- Two sides, one negative charge carriers/electrons (n-type) and one with positive carriers/holes (p-type)
- Put them together (p-n junction) → intermediate region without carriers (depletion region)
- Apply some voltage; forward bias - large current / **reverse bias → low transient current (our preference in HEP!)**

Principle of operation:

- When a particle passes through, it generates electron - hole pairs
- Again, carriers drift due to the electric field
- Signal generation according to **Shockley - Ramo** theorem

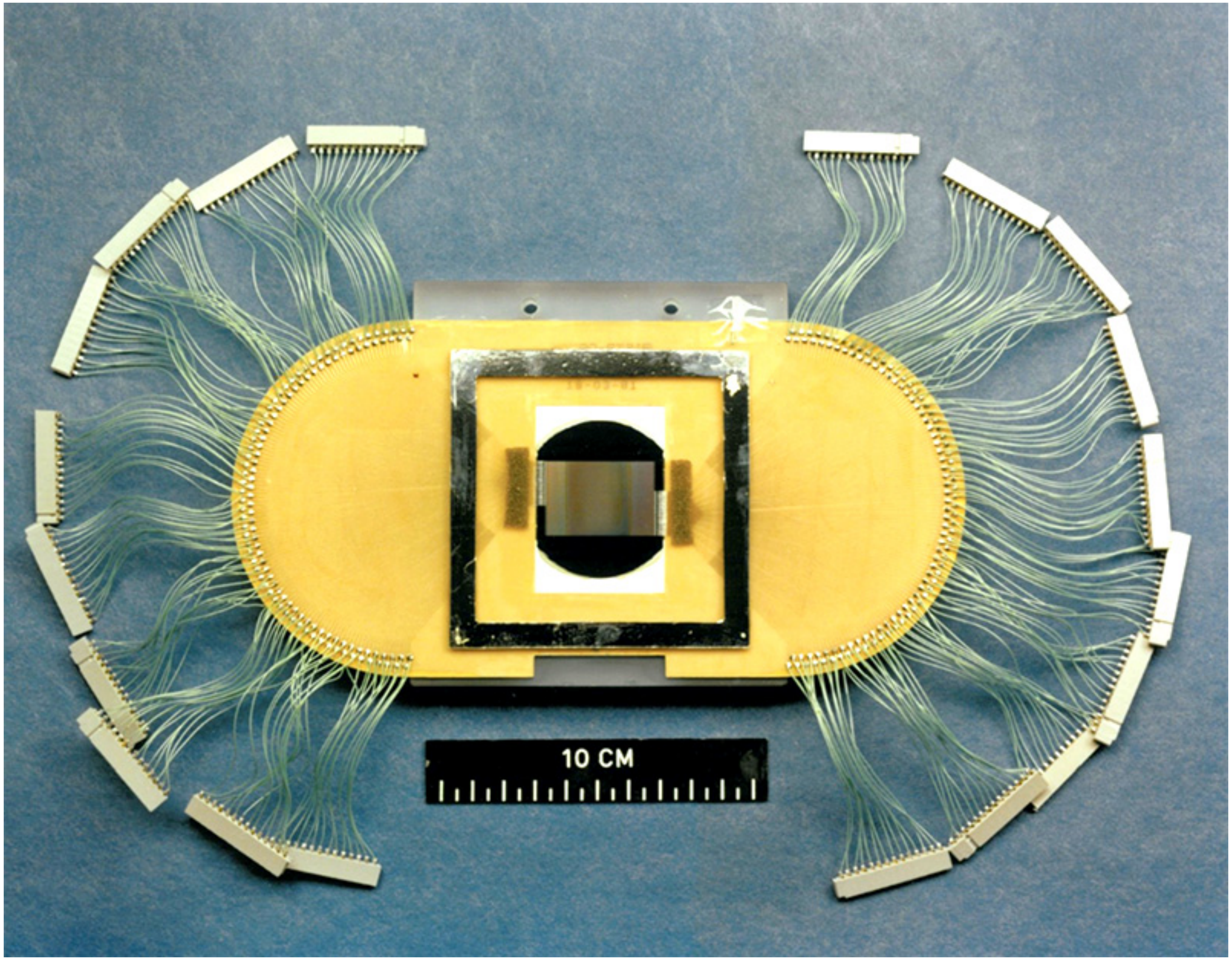
Some properties:

- High yield of created pairs -> No/little internal amplification
- O(μm) segmentation & short (O(ns-ps)) signals -> can withstand very high particle rates
- Radiation hard
- Expensive & difficult to manufacture



And then came Semiconductors!

First usage of a silicon sensor in HEP at 1983 - NA11/NA32 experiment @ CERN



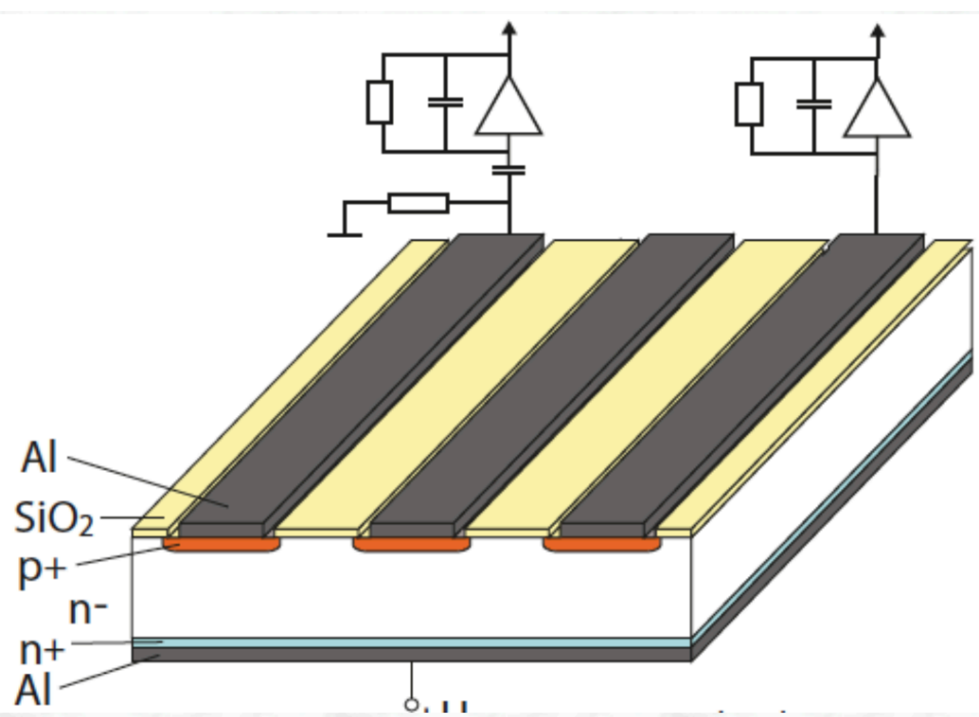
Since then: making silicon sensors stronger, faster, better… and smaller

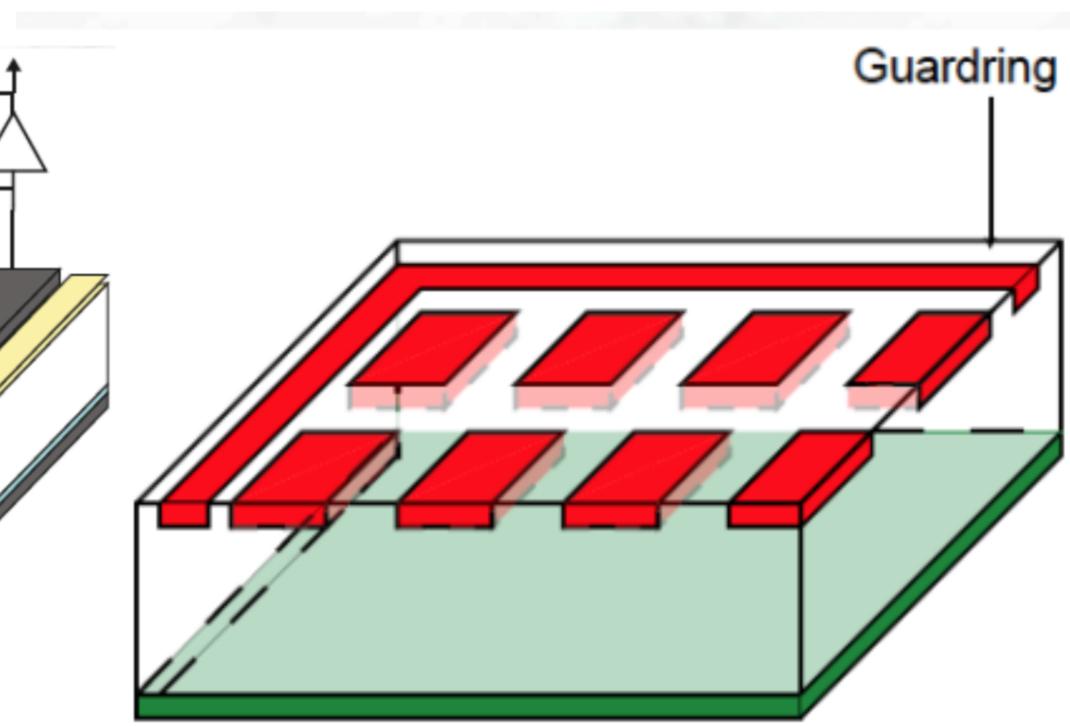
A few considerations to make a silicon tracker

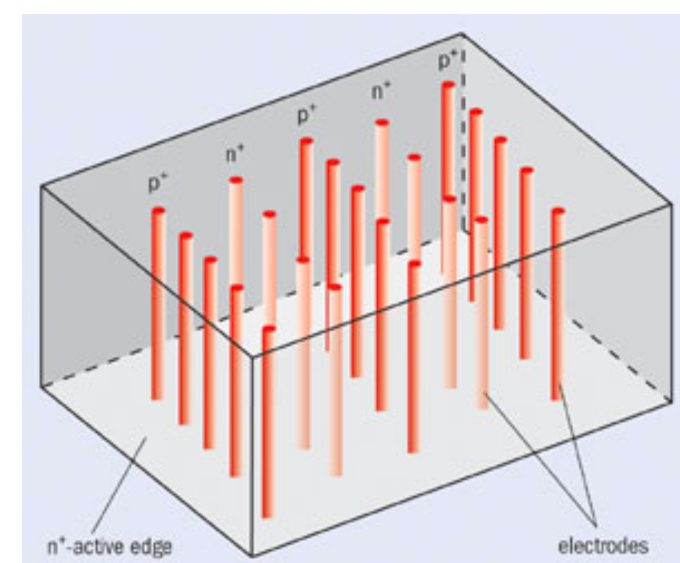
Strips and pixels

- Strips: 2-D tracking, can be recovered by smart detector design choices (tilting/overlapping layers)
- Pixels: full 3-D tracking, but large amount of read-out channels, high power consumption
- Usual compromise in HEP: pixels in the innermost layers, strips in the larger outermost area

More about trackers on Thiziri's talk







Silicon for timing

Using time information in instrumentation is not new: Time of flight for particle identification has been used for many years!

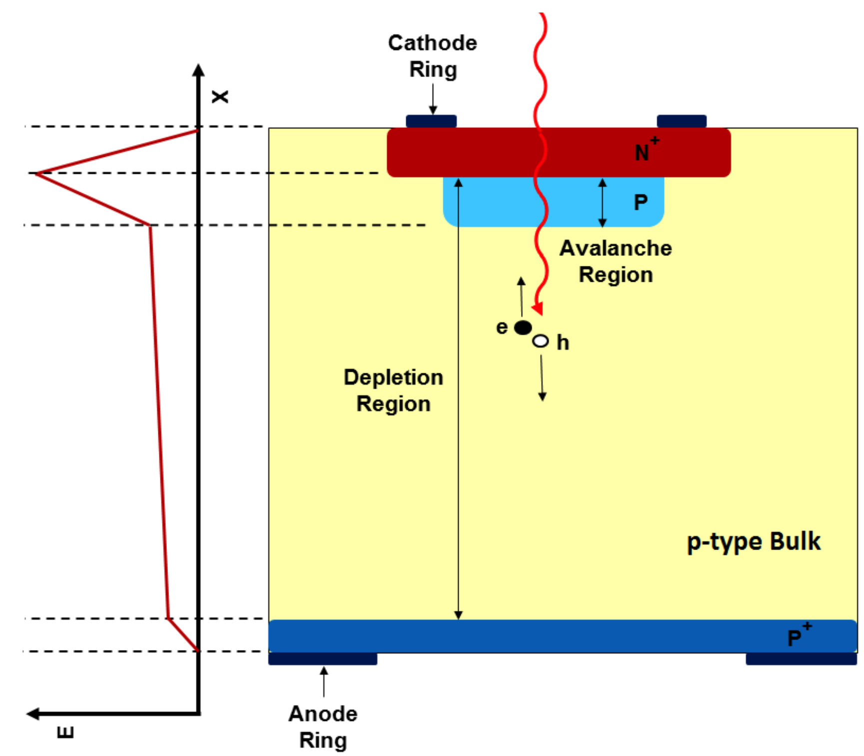
But, tracking traditionally done in **3-D**

However a paradigm shift is coming:

- LHC experiments are planning an increase in luminosity, which means more busy, complicated events
- Spatial resolution of trackers may no longer be as efficient in separating interactions and correctly performing the pattern recognition
- Explore usage of timing information, which is completely orthogonal : **4-D tracking**

What ingredients do we need (for a typical LHC environment)?

- O(10-100ps) time resolution
- Fast readout & radiation hardness
- Various technologies, more emerging:
  - LGADs: very good time resolution, poor spatial resolution: separate layers for time and position needed
  - AC/TI LGADs, Timespot: 4-D sensors (time & spatial info together), extensive R&D ongoing



Marko will give us more details on timing detectors

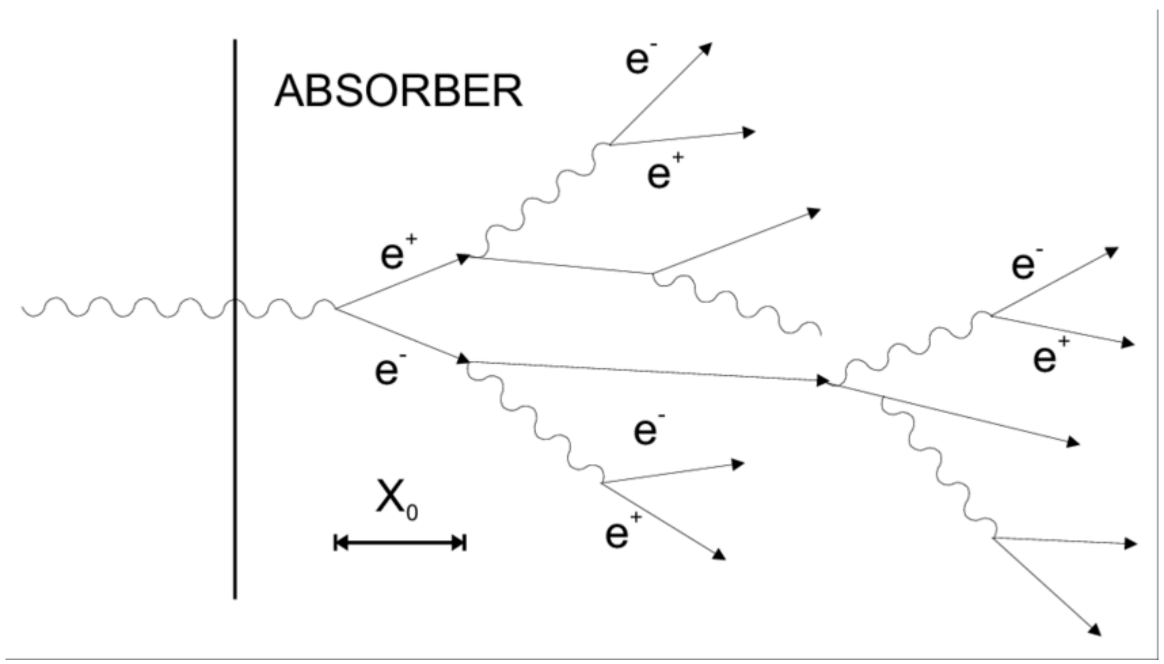
Calorimetry

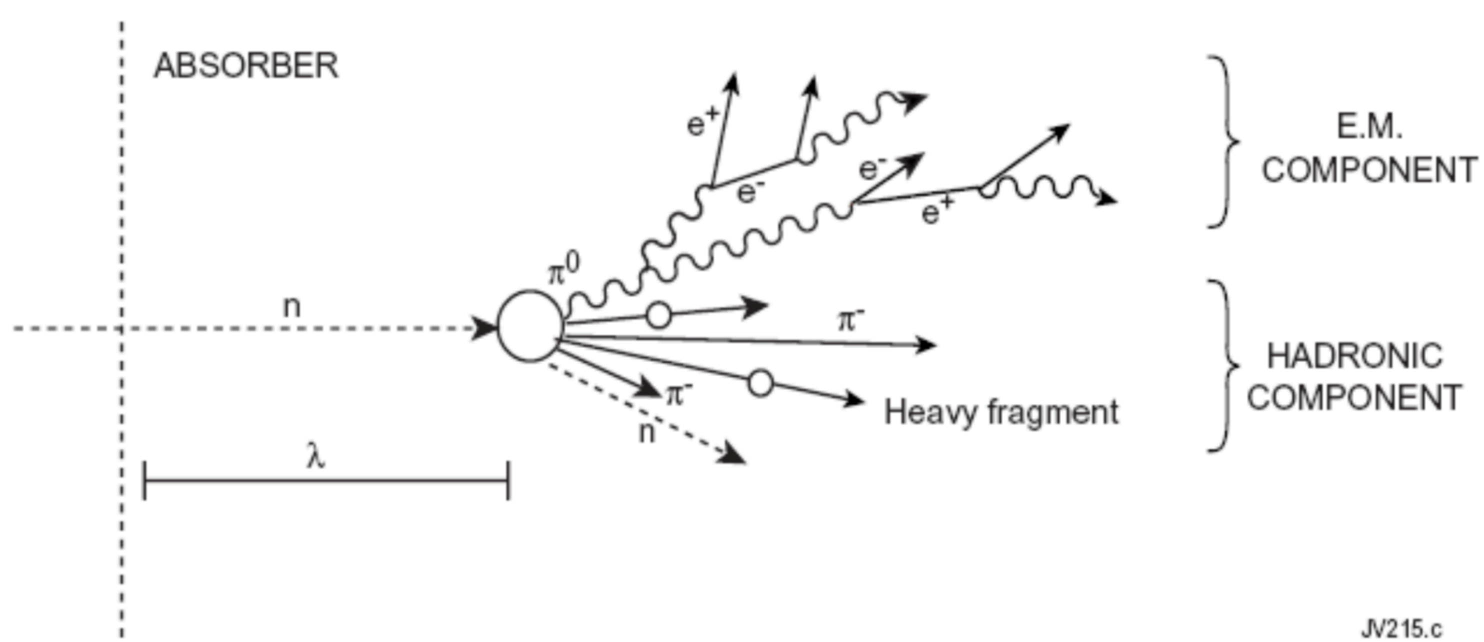
Measuring energy

- Up to now, we've measured the momentum of only charged particles - what about neutrals?
- We can take advantage of electromagnetic and hadronic cascades /showers in thick "absorber" materials →**Calorimeters!**
- Destructive measurement → original particle is **lost** (only muons and neutrinos can survive)
- Measuring the shower size gives the original particle energy

EM showers:
- Produced by electrons and photons
- Sequence of pair production & Brem.
- Shower size described by radiation length X_0

Hadronic showers:
- Produced by hadrons (strong interactions)
- Contains EM component
- Shower size described by interaction length λ_{int}

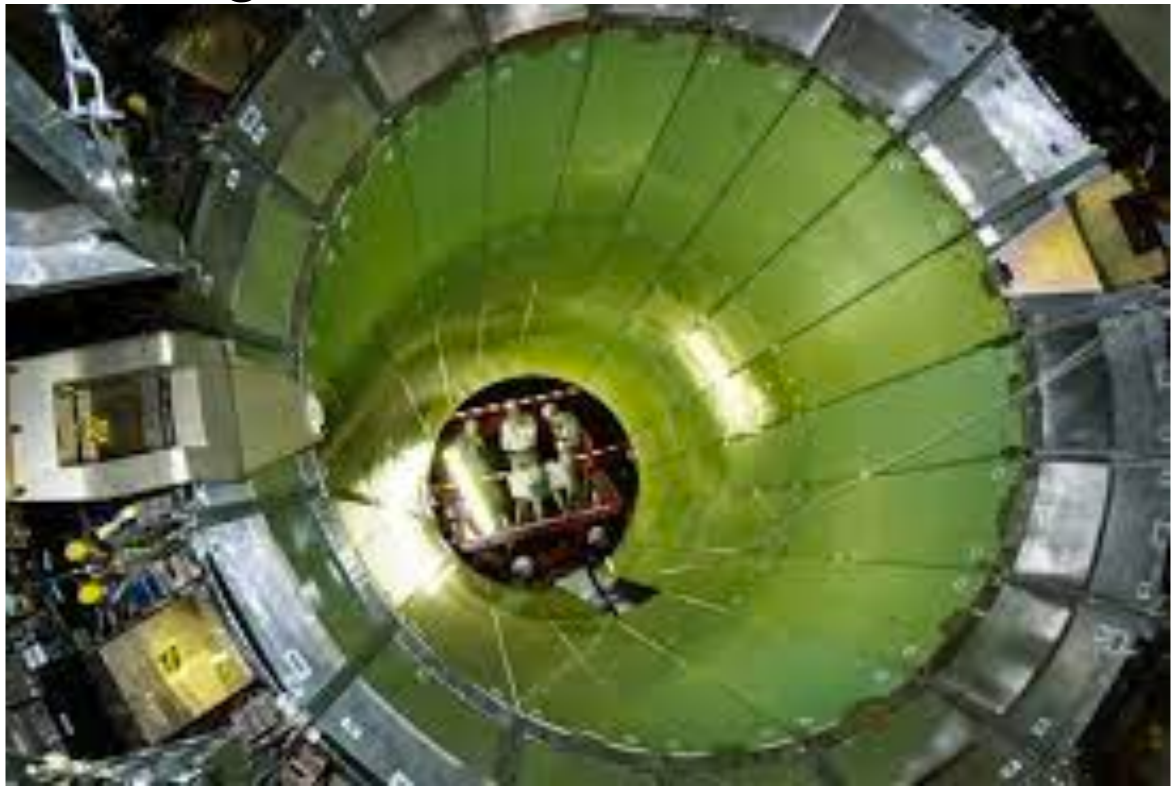




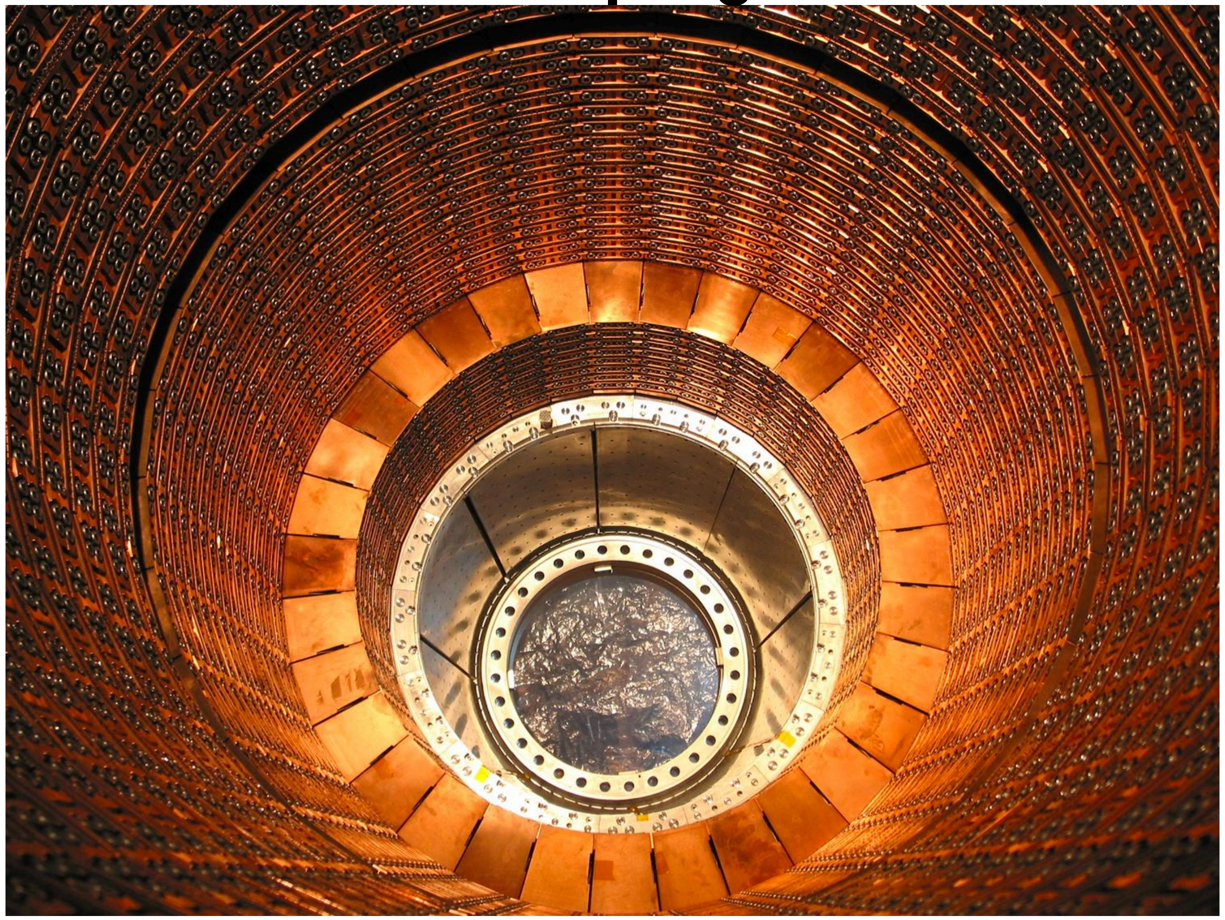
Calorimeters

- Homogeneous calorimeters:
  - Active medium (the material that records the showers) also acts as absorber (the material that helps develop the shower)
  - Excellent energy resolution
  - But no longitudinal information on shower development

CMS homogeneous PbWO4 EM calorimeter



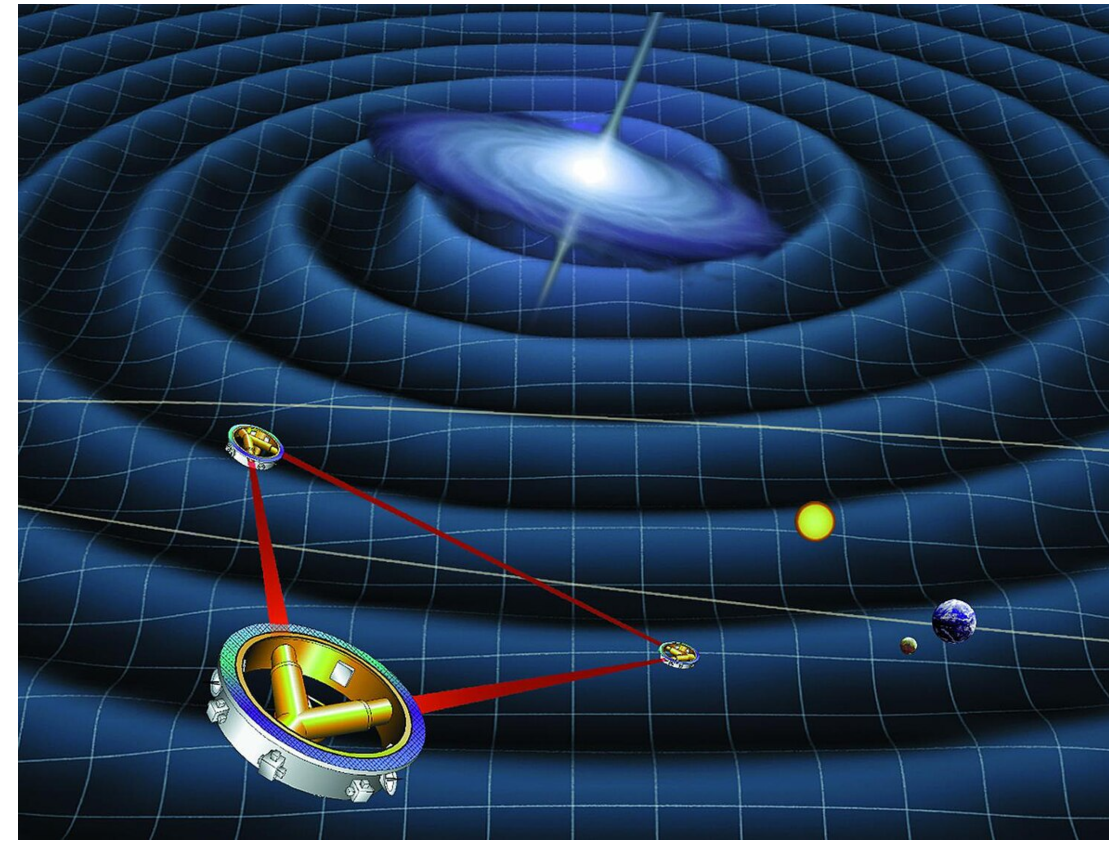
ATLAS LAr EM sampling calorimeter



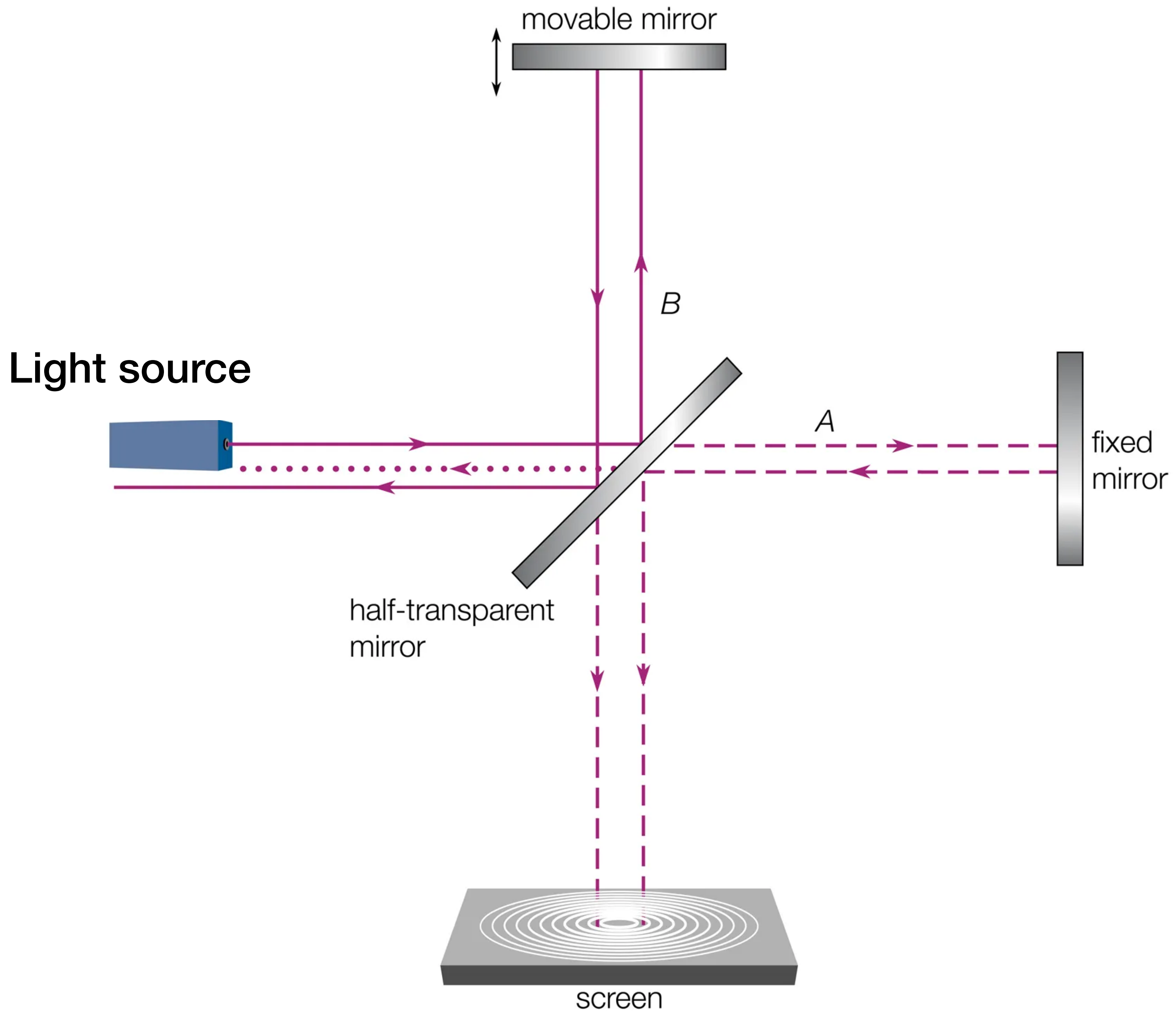
- Sampling calorimeters:
  - Active medium separate from the absorber (usually placed in alternating layers)
  - Some energy is always lost in the absorber → limited energy resolution
  - But, information on longitudinal shower development

More about calorimetry on Christian's talk

And now, let's take a little trip



A word on interferometers

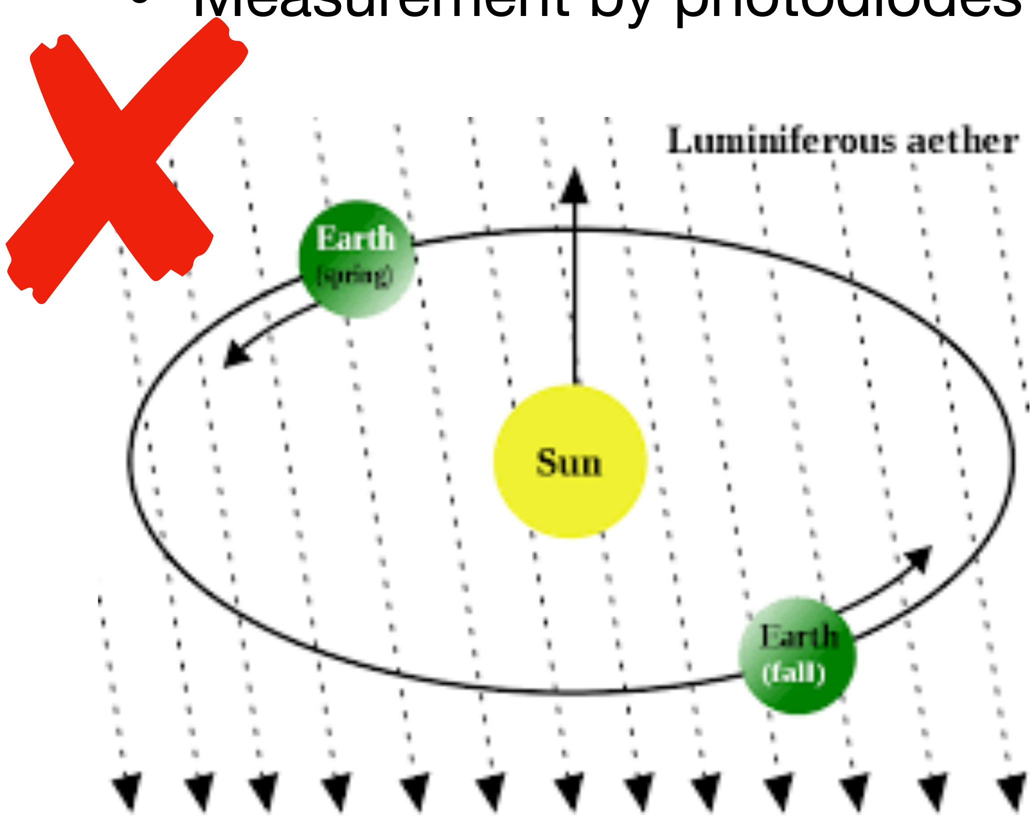


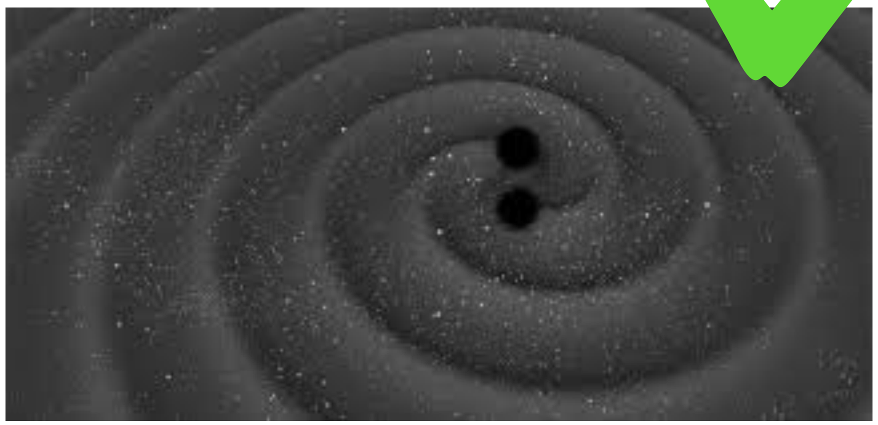
Some highlights

- Was used in 1887 to disprove luminiferous aether (a proposed medium for light propagation)
  - Light source: oil lamp
  - Arm length: 1.3 m , path length after reflections 11 m
  - Measurement by telescope

- Was used in 2015 from LIGO and VIRGO experiments to prove the existence of gravitational waves
  - Light source: laser
  - Arm length: 4 km , after reflection 1200 km!
  - Measurement by photodiodes

we will hear more about future uses in gravitational wave detection in Maxime’s talk

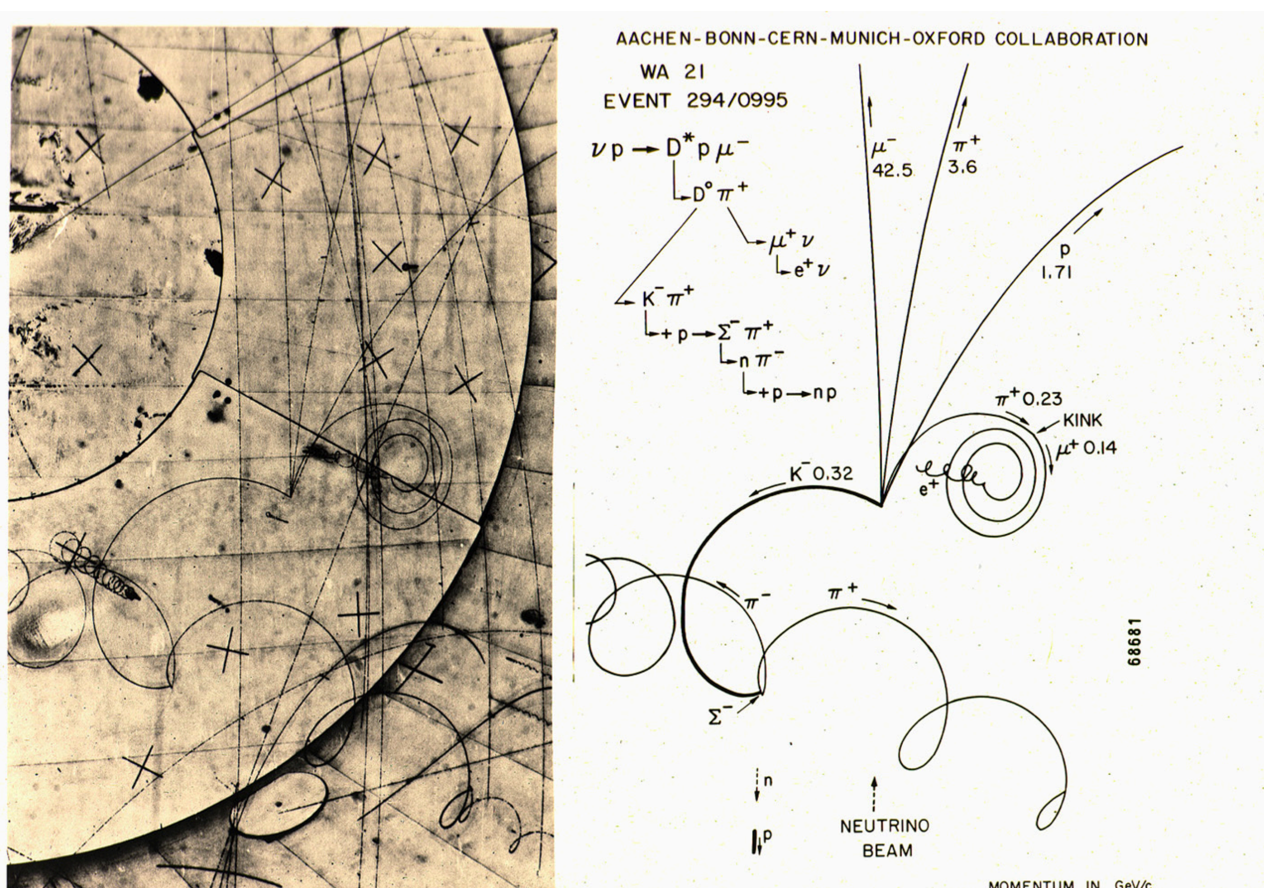




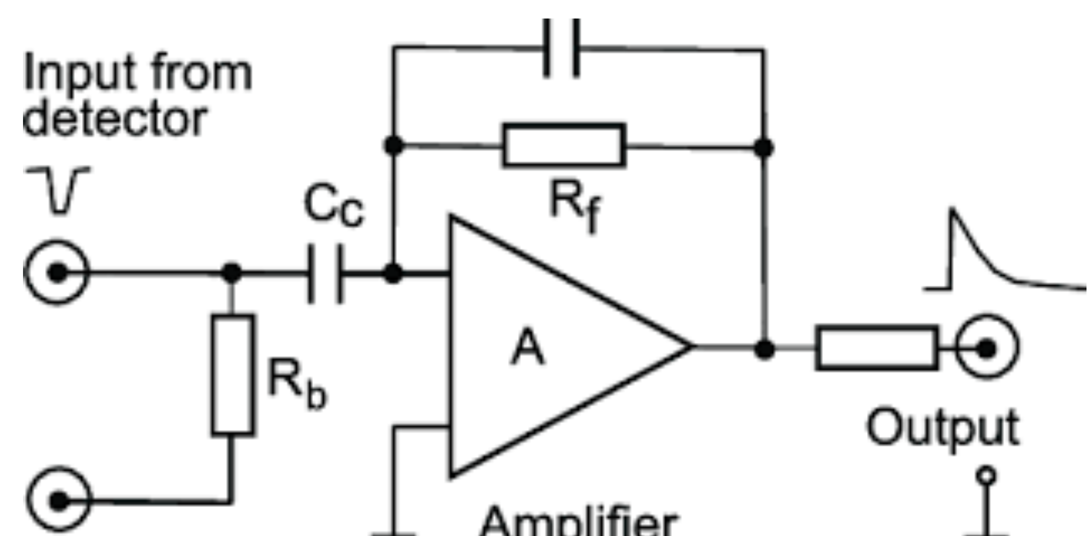
And what to do with all these signals?

First of all, record it

- **In the bubble-chamber era: Photographic methods**
  - Quite precise but…
  - Very low rate ~ few HZ → can't operate in a modern collider!
  - Automation of data analysis is hard

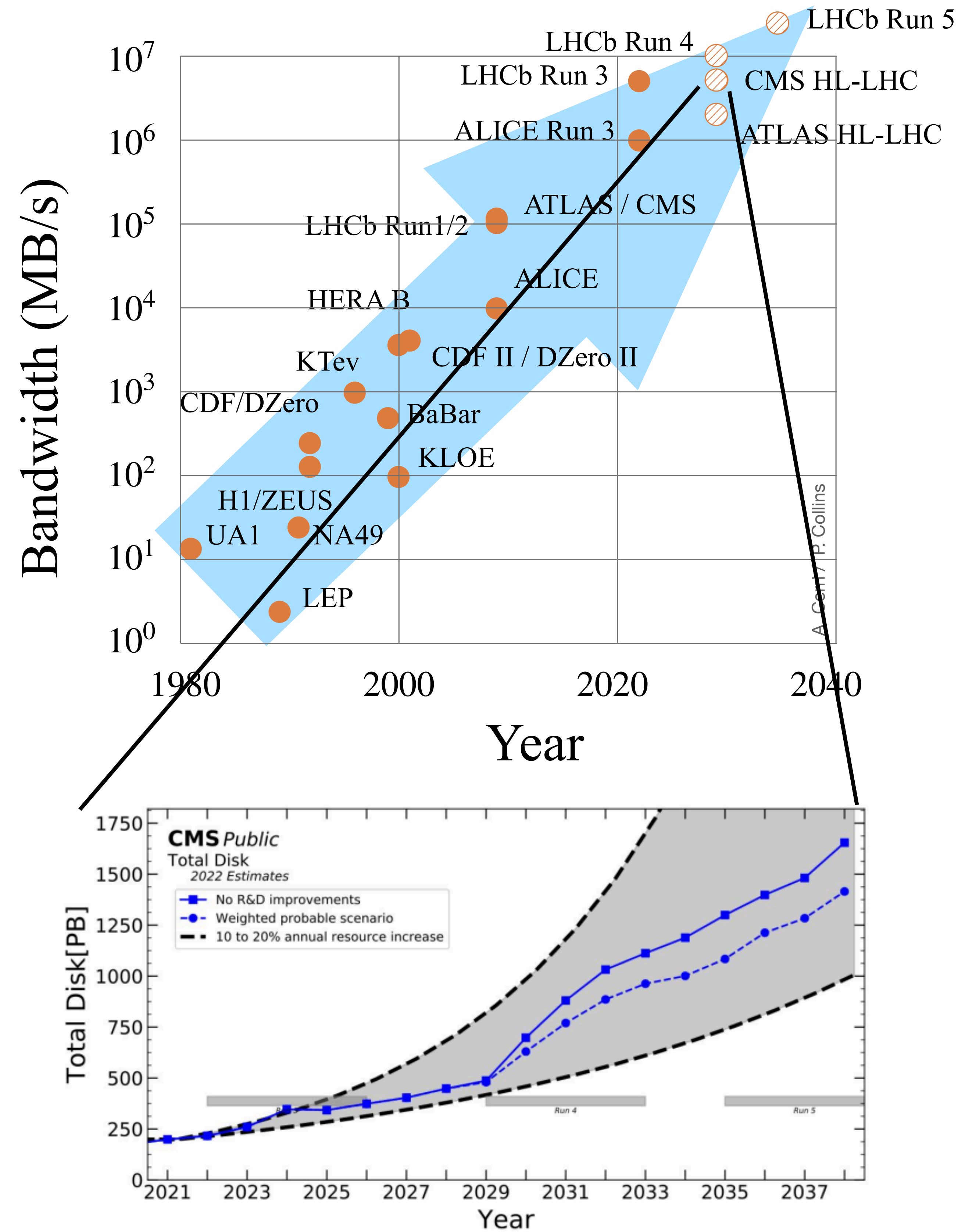


- **Today: Integrated electronics (ASICs)**
  - Allow us to go down to O(MHz) rates
  - What we get: electronic signals, usually digital
  - A wide variety of circuits for position, energy and time measurement
  - Same requirements as the active material (radiation hard, compact & not too power consuming)

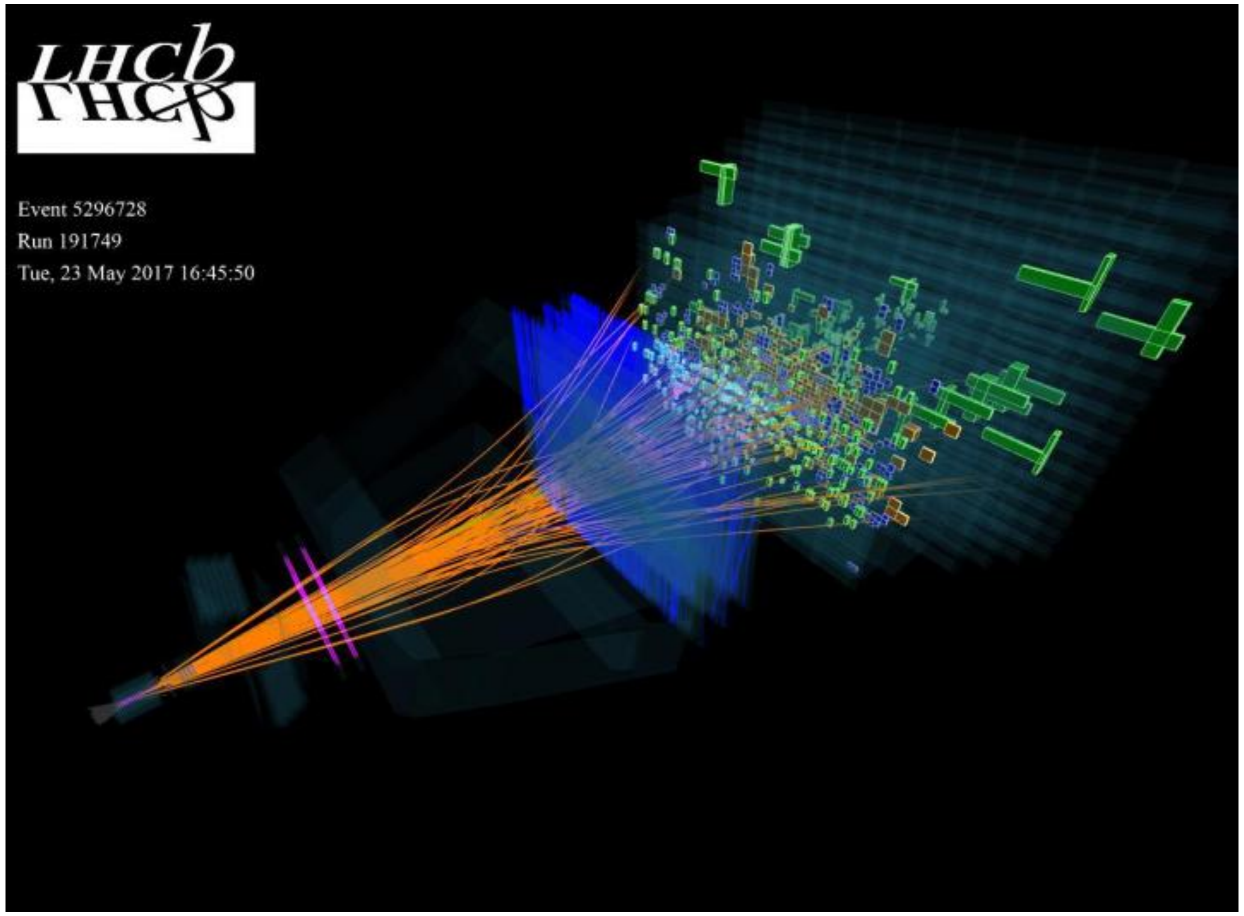


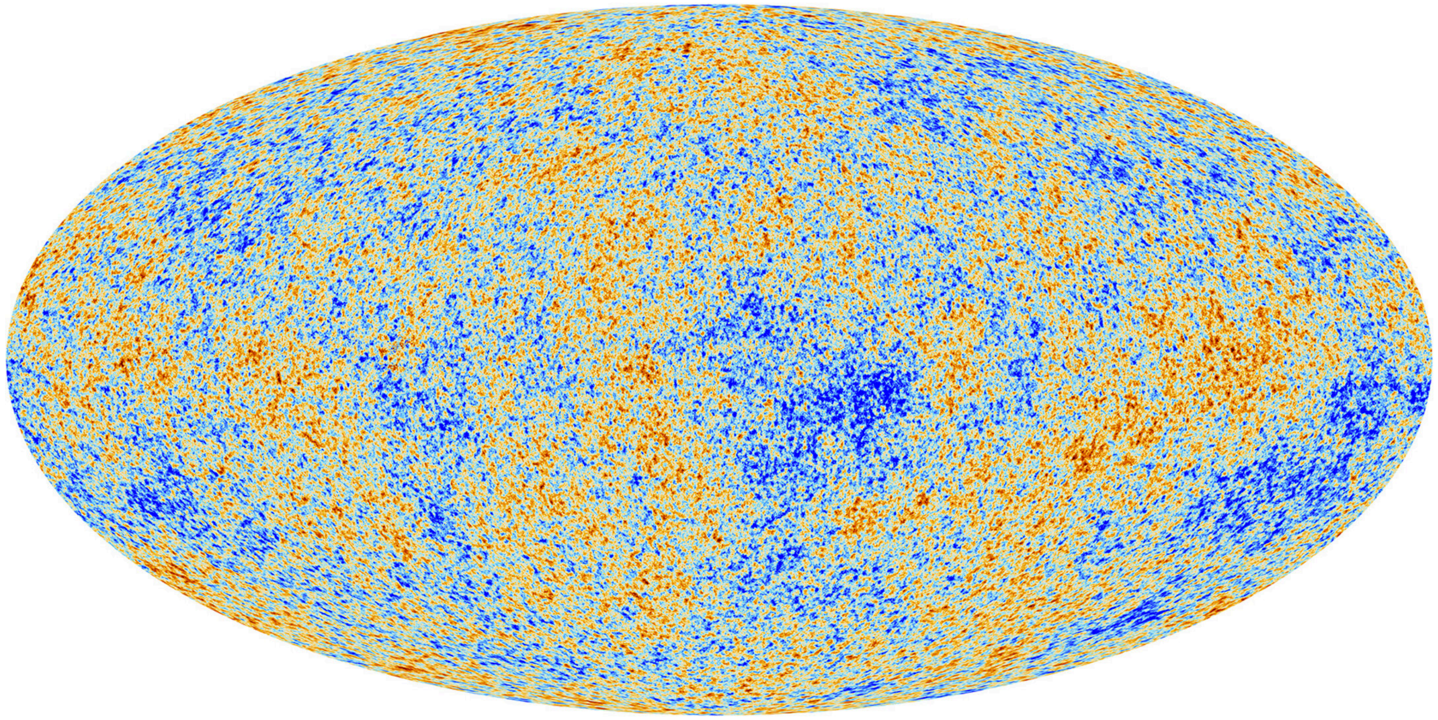
Then, process it…

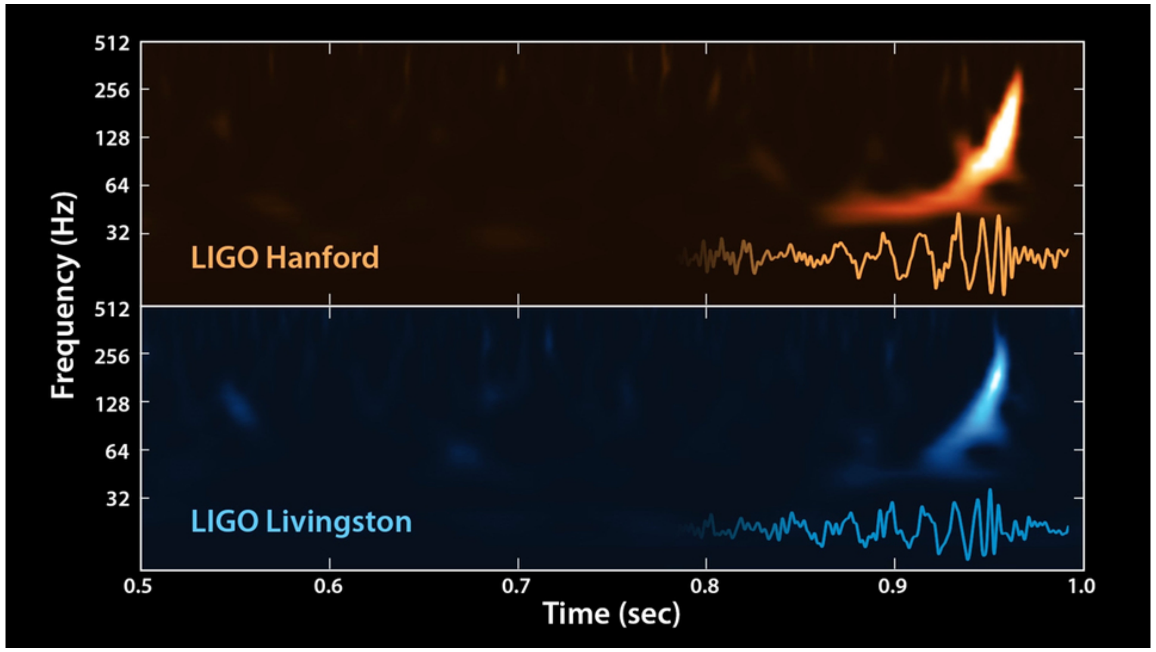
- Technological breakthroughs in material and electronics have improved signal yields and detection times → we're at the picosecond era!
- At the same time, demand for precision is increasing
- Many experiments need to process TB of data every second!
- Traditionally, this has been handled by fast electronics making decisions based on topical signals - **Triggers**
- However, new strategies are now emerging:
  - **Software triggering** based on heterogeneous architectures (GPUs, FPGAs)
  - **Machine-learning** developments for topological event reconstruction, faster simulation and inclusive selections



In the end







These images are thanks to the instruments, and you!

Credits

- I. Wingerter's CERN summer school lectures
- EDIT 2020 Lectures on detectors
- Wikipedia
- And more…

Backup

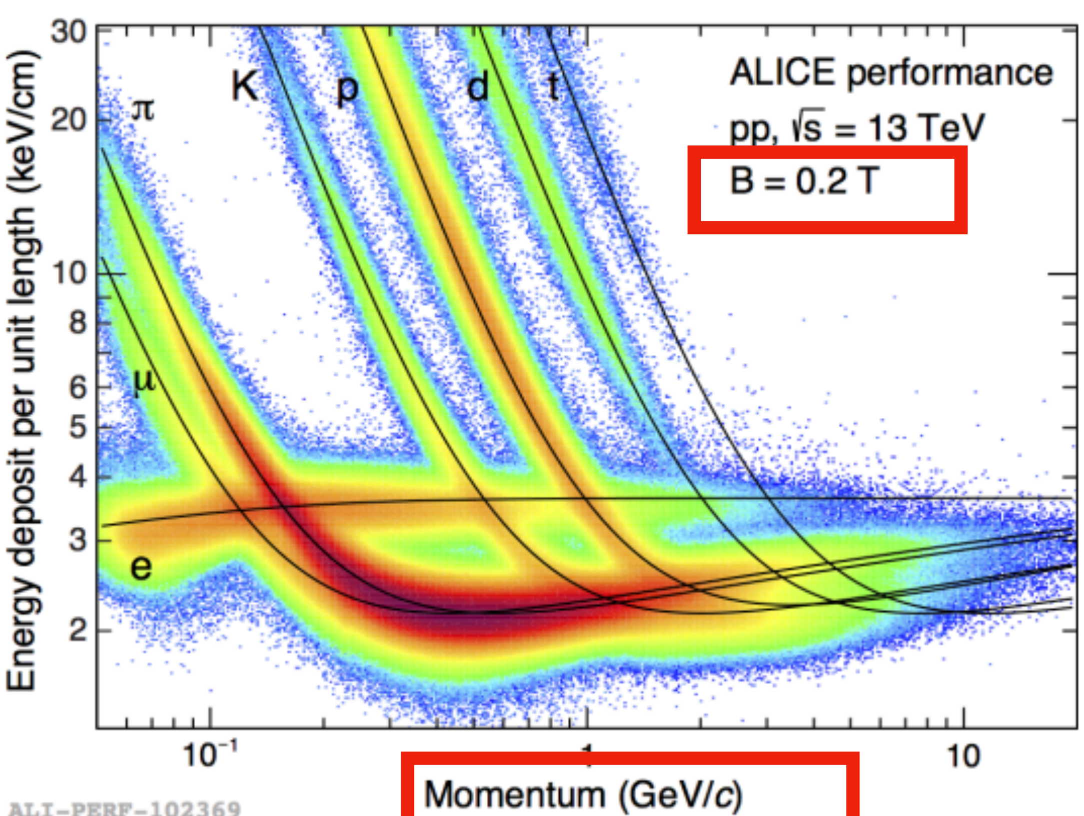
Hello, I love you, will you tell me your name?

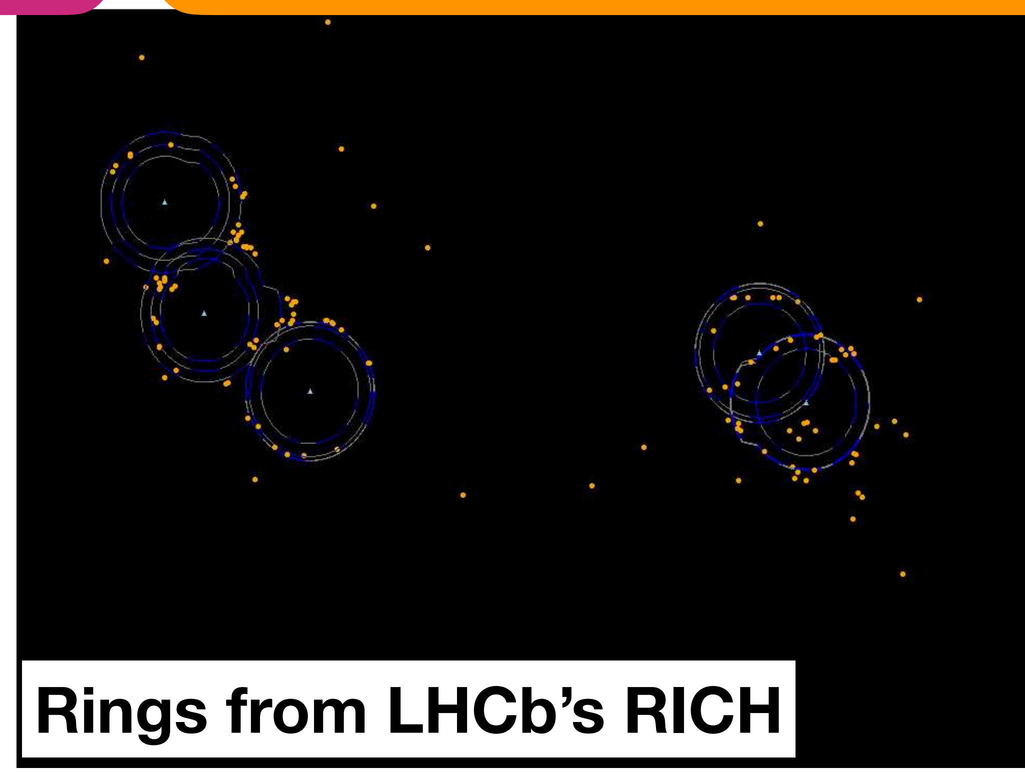
We measured p … And what about β ?

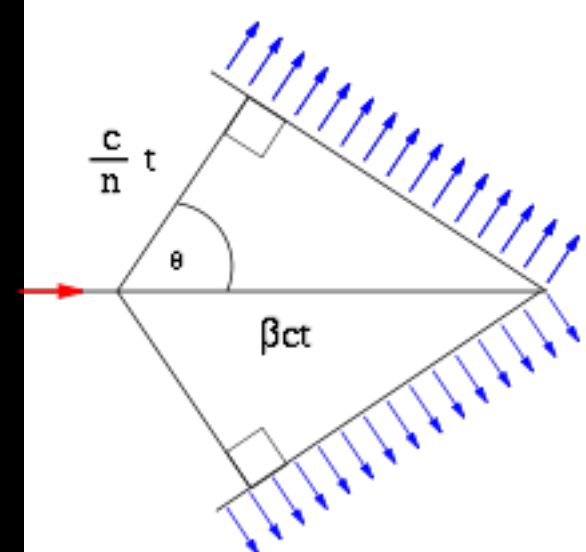
- **Measuring the energy loss $\frac{dE}{dx}$**
  - Remember the Bethe-Bloch?
  - Excellent for $p \leq 1$ GeV/c
  - Multi-wire proportional chambers, Time-projection chambers

- **Cherenkov radiation**
  - Radiation from charged particle crossing medium at speed greater than speed of light within the medium
  - Emission angle reversely proportional to β
  - PID for 1 - 100 GeV/c

ALICE's TPC PID power





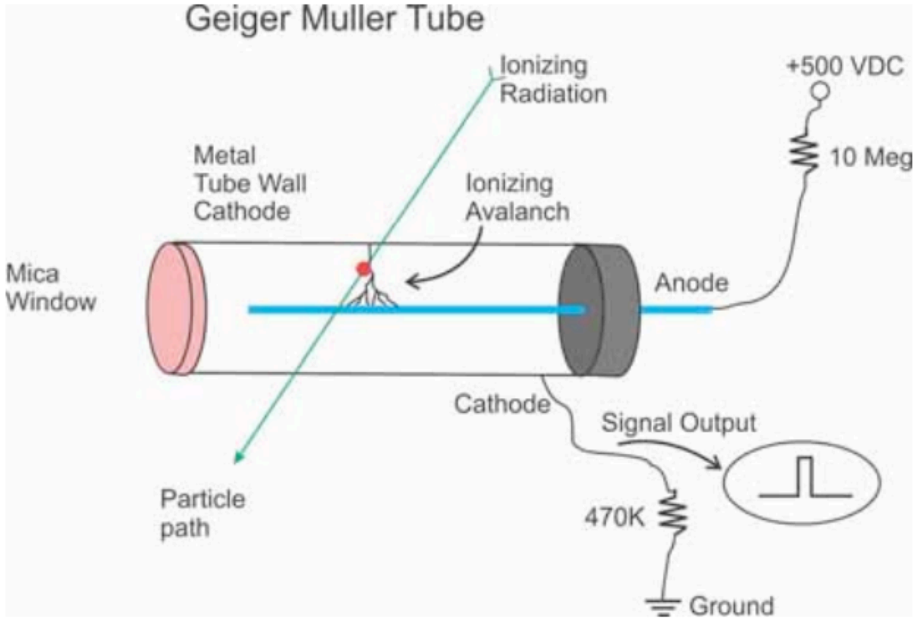


- + Direct measurement with Time-of-Flight (TOF)
- +Transition Radiation

Gas detectors

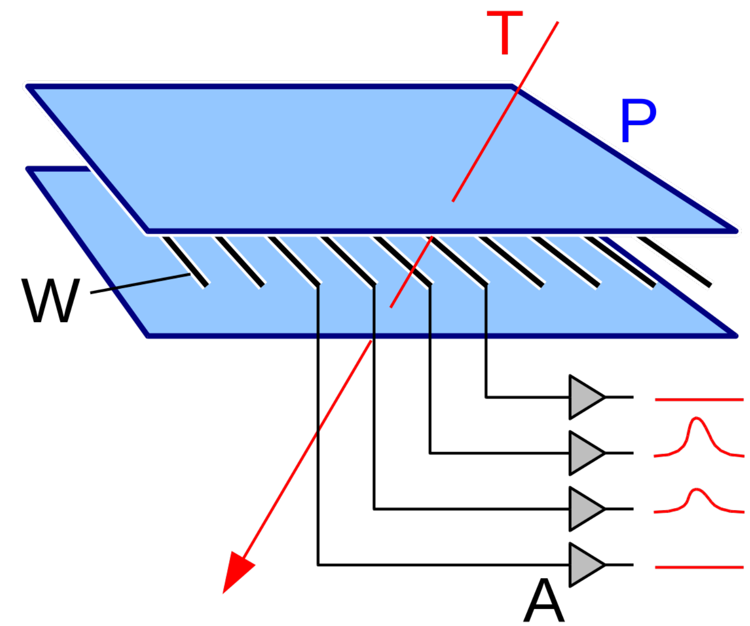
First generation: the good-old single-wire:

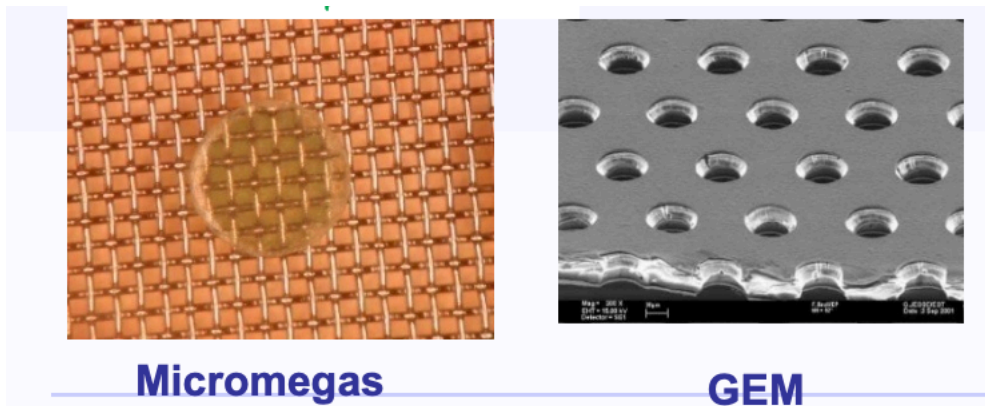
- Geiger-Muller tube: high voltage → avalanche, saturation of charge (no particle ID). First electrical signal from a particle!
- Also single-wire proportional & ionisation counters



Adding some more wires makes all the difference

- **Multi-Wire Proportional Counter (MWPC):** spacial resolution achieved by combining signals from all wires - revolutionised data collection rate
- Adaptations: thin gap, resistive plate and drift chambers
- **Time Projection Chamber (TPC):**
  - full 3-D reconstruction, x-y from wires and segmented cathode of MWPC
  - z = vdrift x tdrift from drift time
  - Not only gases, but also liquid scintillators!
- New generation of **MicroPattern** gaseous detectors (MicroMegas, GEMs) → higher segmentation & rates

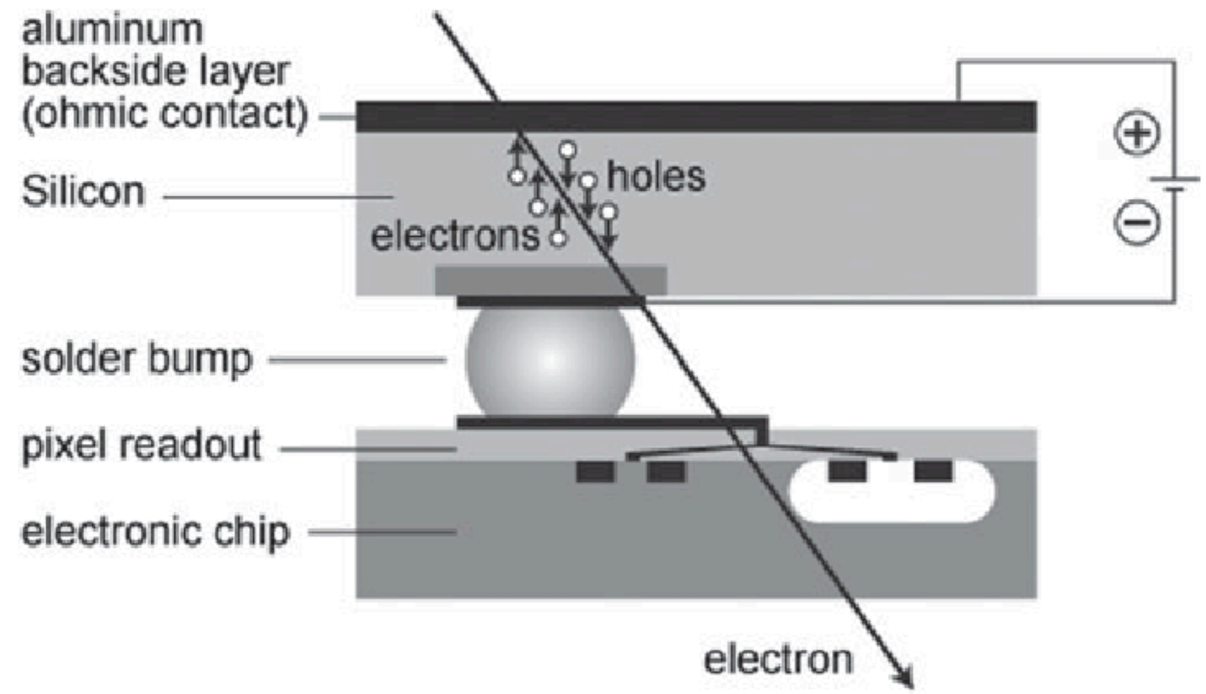




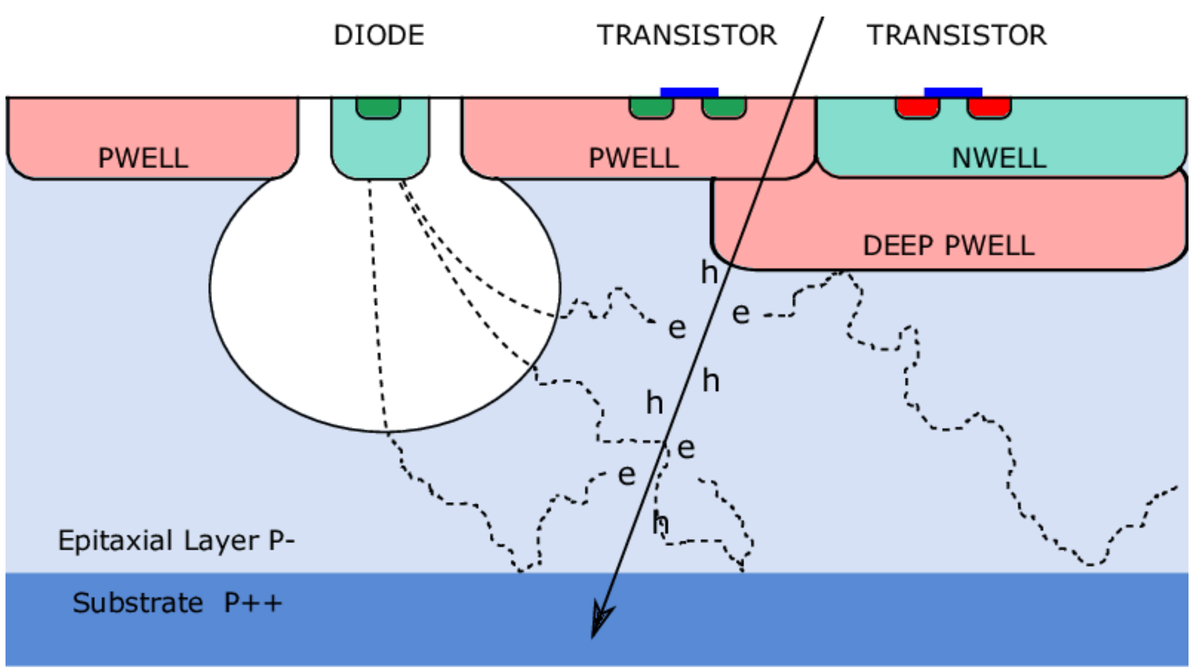
A few more considerations to make a tracker

Hybrid or monolithic?

- **Hybdrid sensors:** typical connection of sensor to front-end electronics chip through wire and bump-bonds
  - Radiation hard, fast timing
  - difficult and expensive (and you might have to do thousands of them!)



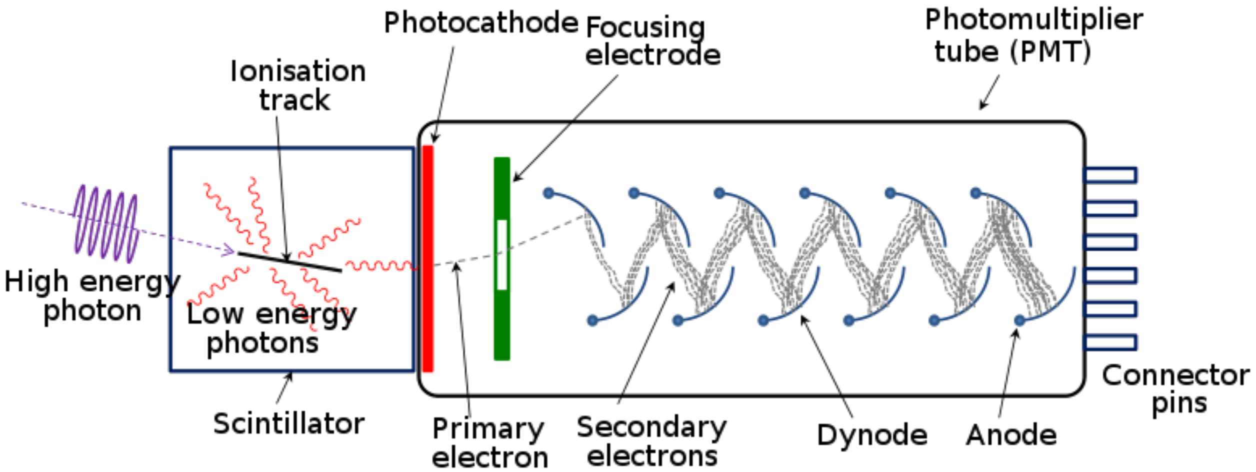
- **CMOS technology:** integrate signal-processing circuits on sensor substrate (sensor & electronics become one)!
  - Cheap, easy to produce and assemble
  - Radiation hardness & timing being worked on



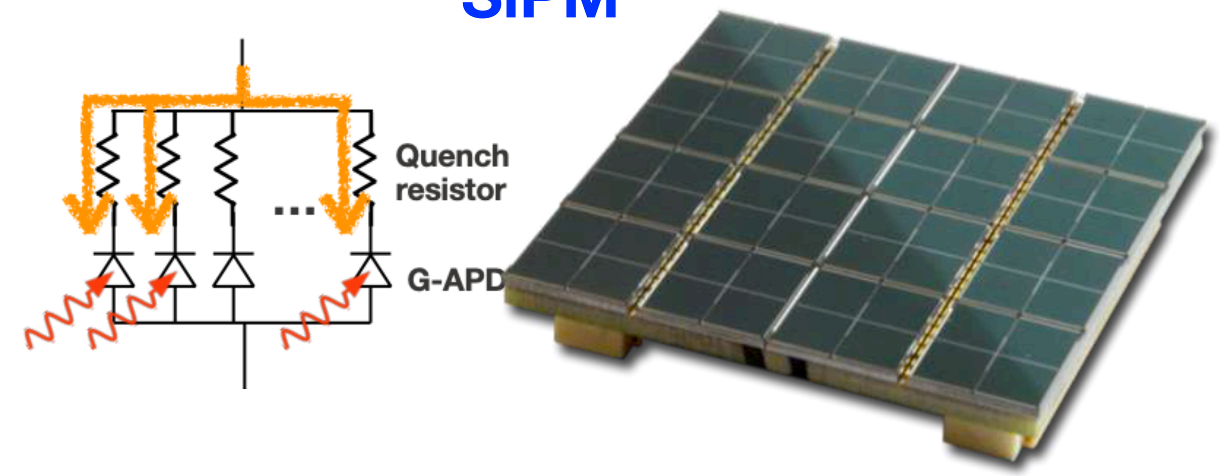
Photodetectors

- Primary high energy photon → primary electron
- Electrons accelerated in electric field through a dynode chain producing more electrons → internal amplification!
- Important properties: gain, quantum efficiency, spectral range, single photon detection…

PMT tube



SiPM



Can be vacuum

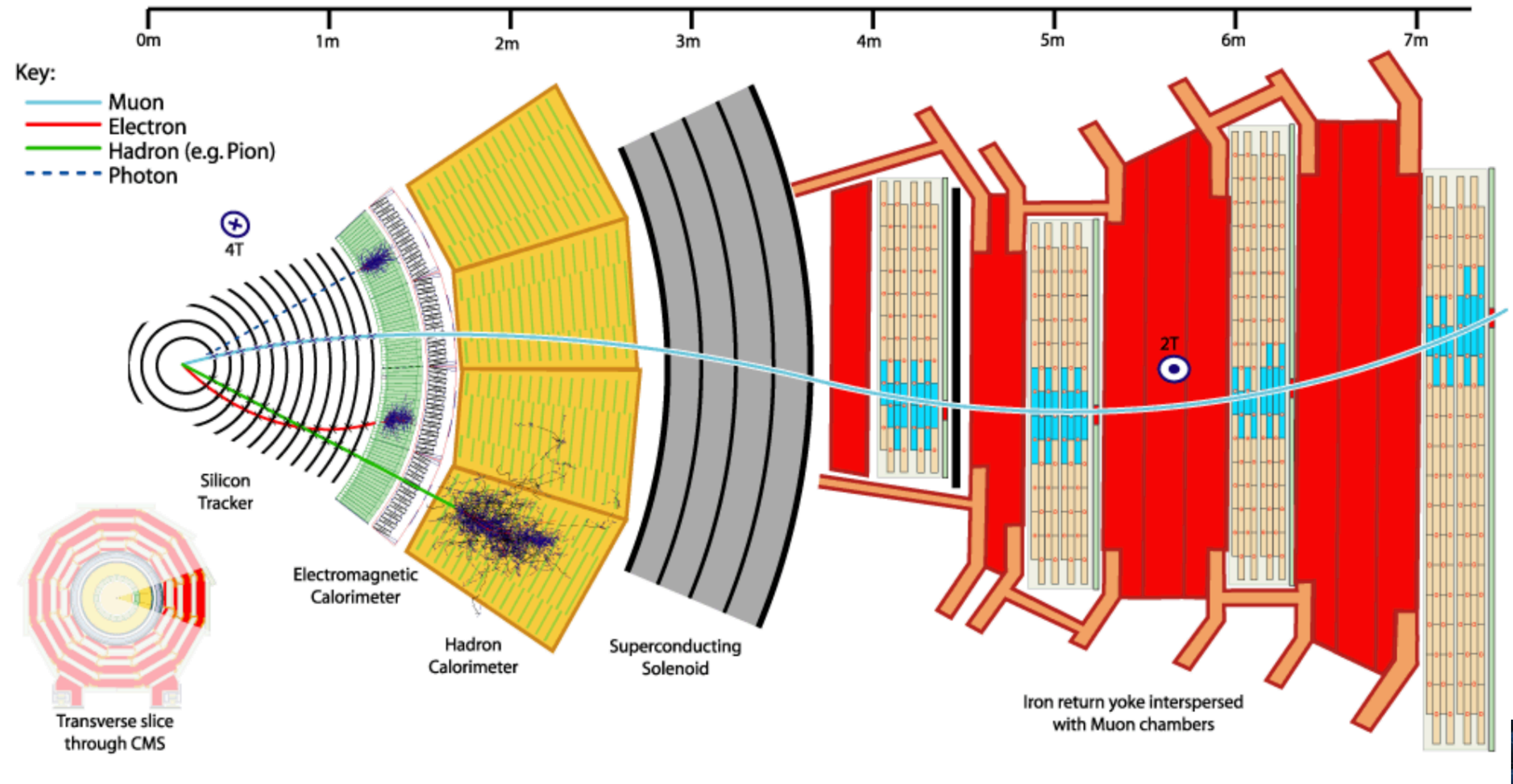
- Old technology, but still used in many experiments
- Quantum efficiency ~ 20-30% @ 400 nm
- High gain, low noise, good timing, radiation hard
- Segmenting the anode readout can give position sensitivity (MAPMTS)
- Some disadvantages: bulky, sensitive to magnetic field (and expensive)

Or solid state photodetectors

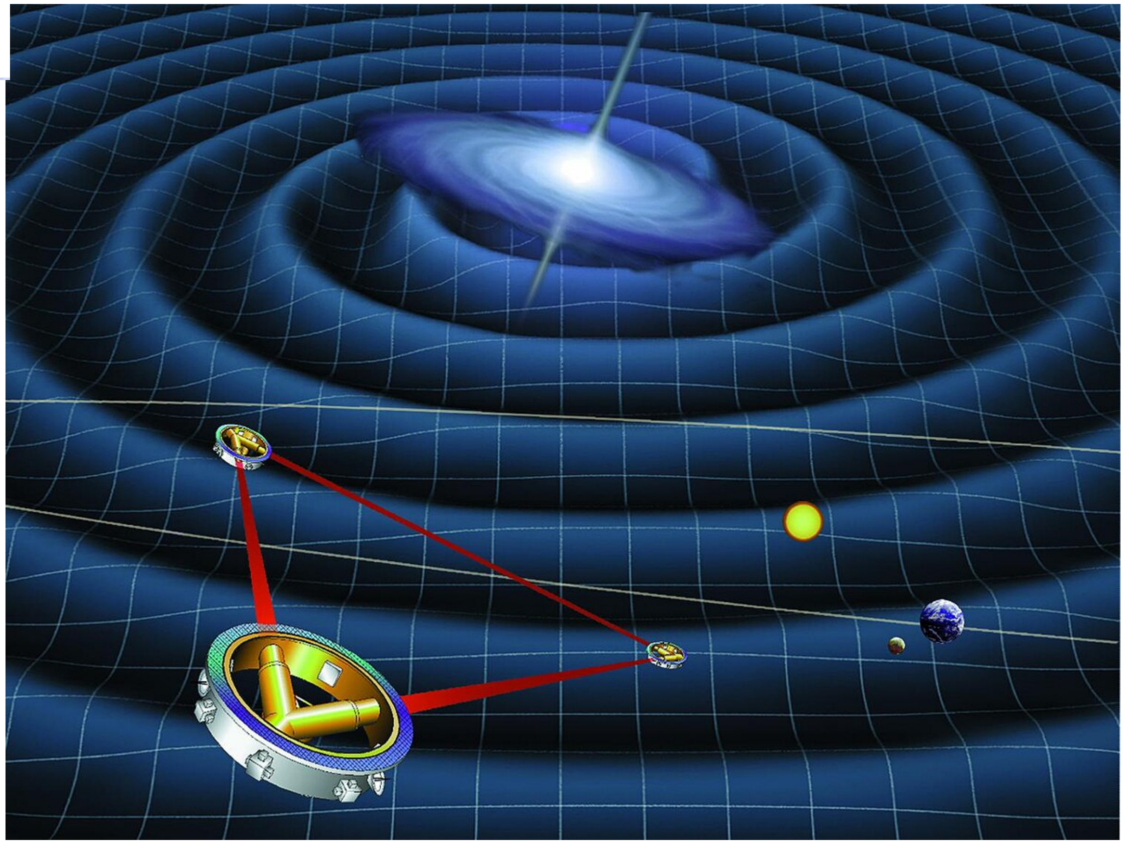
- Photon induces electron-hole pairs → photocurrent
- Quantum efficiency ~ 100 %
- Originally no internal gain (**photo-diode**)
- Can be induced by operating at high reverse voltage → **Avalanche Photo-Diode (APD)**
- Even higher gain by connecting in parallel many APDs together → **Silicon Photomultipliers (SiPMs)**

Putting everything together

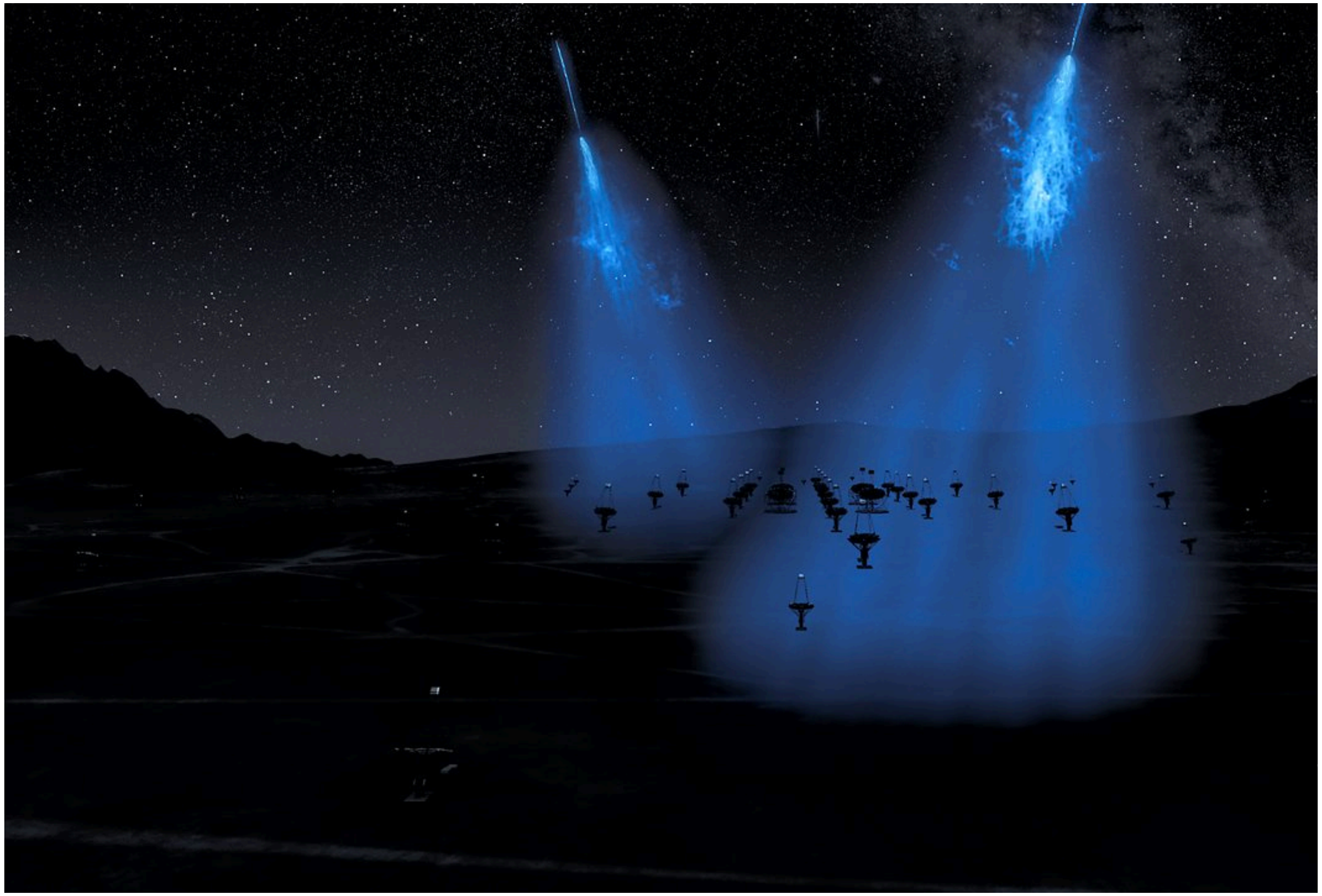
CMS experiment @ CERN

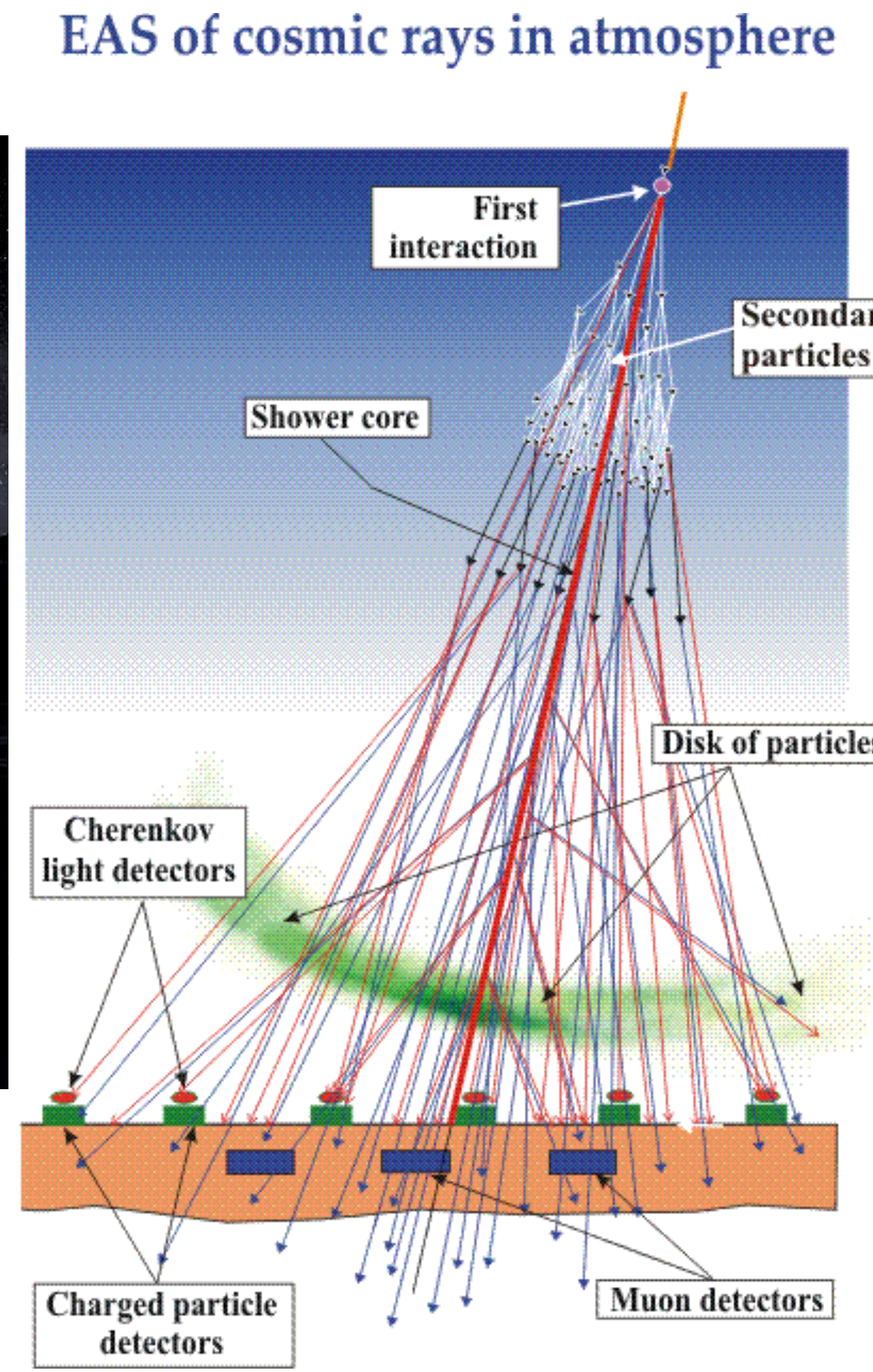


LISA in Space



And giant ones





Earth's atmosphere acts as a giant absorber for cosmic rays

X0 & $\lambda_{int} \sim 2000$ x LAr , but, we have a lot of air!

Atmospheric and ground-based detectors measure the shower, similar to calorimeters!