Particle detectors

Questions to answer before we start to design a particle detector

- Suppose we have an accelerator that can provide us with the collisions – what exactly we want to look for?
- PHYSICS Program: list of phenomena that we wish to observe; set of questions we want to get an answer on, like
  - What is a dark matter? → want to find a particle that represents this matter, and measure its mass and quantum numbers
  - Why there are three generations of quarks and leptons? → need to search for next generations; if not found, should look at the differences that arise between models with higher number of generations and with 3 generations, and check, where is a "failure" of a model occurs
  - Why do we have a matter-antimatter asymmetry – measure violation parameter and compare to the SM value and other models…

Now physics program is in place. What is next?

- Suppose we want to measure a mass of a "supersymmetric" particle, if it exists. How? Using the simple formula:

$$m = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2}$$

- Here index i is related to the i-th decay product of this hypothetical particle

- According to this formula, we need to measure all momenta and energies of the particles that originated in the decay

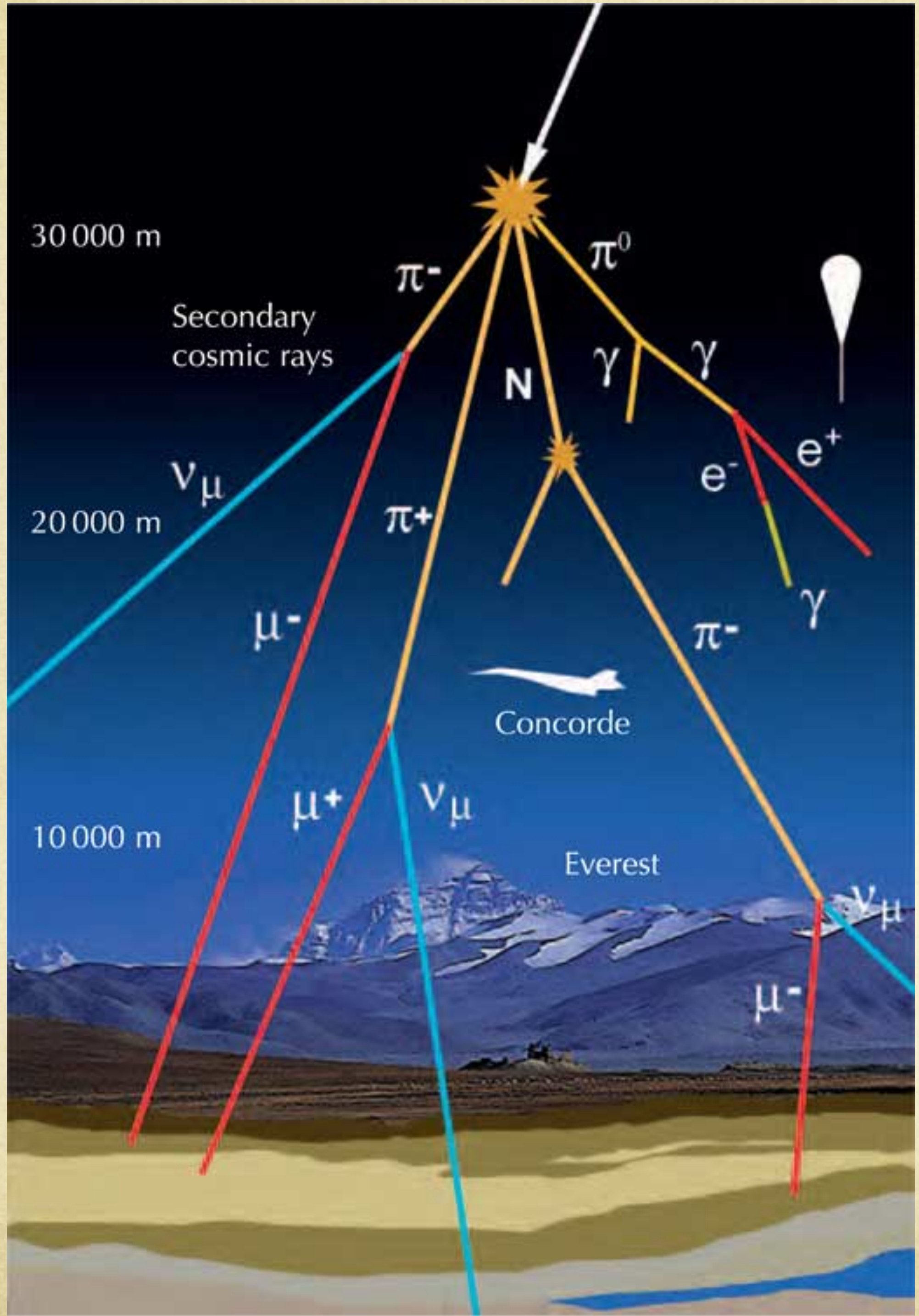
- Also need to know what kind or particle was produced in the decay – is that a muon or electron or b-quark – need IDENTIFICATION

Requirements to particle detectors

- Must be able to measure
  - spatial location
    - trajectory in an EM field → momentum
    - distance between production and decay point → lifetime
  - energy
    - momentum + energy → mass
  - flight times
    - momentum/energy + flight time → mass

The cloud chamber

- 1911 C. T. R. Wilson (1927 Nobel Prize)
  - the first tracking detector (tracking=many spatial measurements per particle)
- Principle of operation:
  - an air volume is saturated with water vapor
  - pressure lowered to generate super-saturated air
  - charge particles cause saturation of vapor into small droplets → can be observed as a “track”
  - photographs allow longer inspection



What we can see with the cloud chamber?

- Mostly muons from cosmic rays interactions with atmospheric nucleons
- Cosmic rays are energetic particles come from outer space traveling near the speed of light. Before the development of particle accelerators, cosmic rays provided physicists with their only sources of high-energy particles to study.
- The origin of the highest energy cosmic rays is one of the outstanding puzzles in astrophysics.

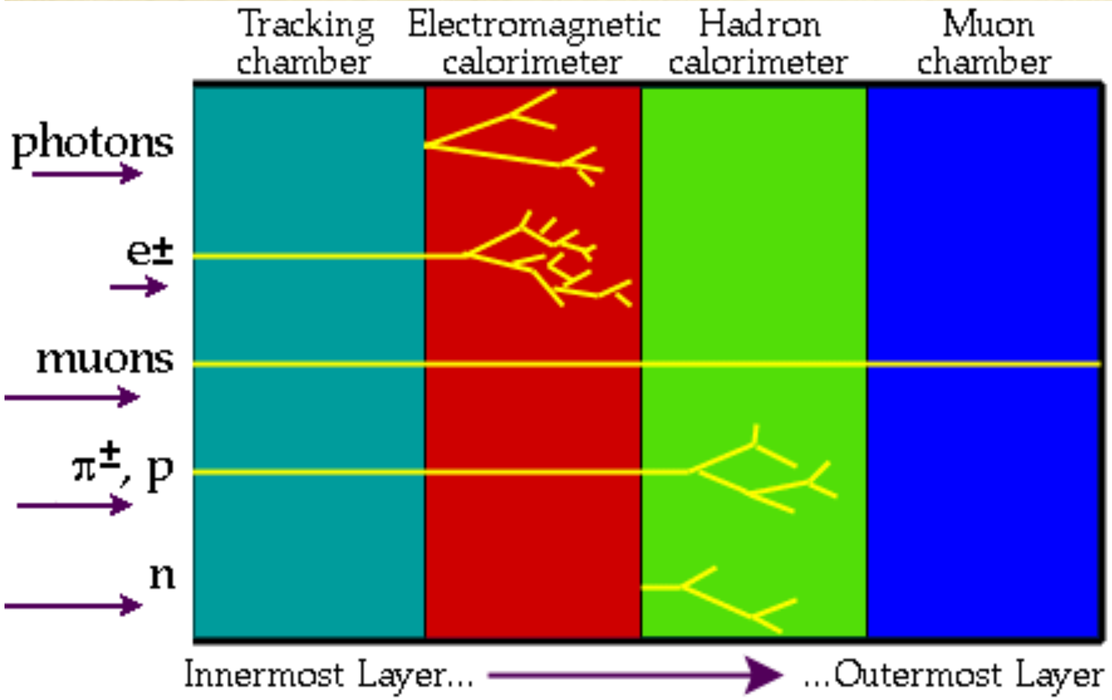
The cloud chamber

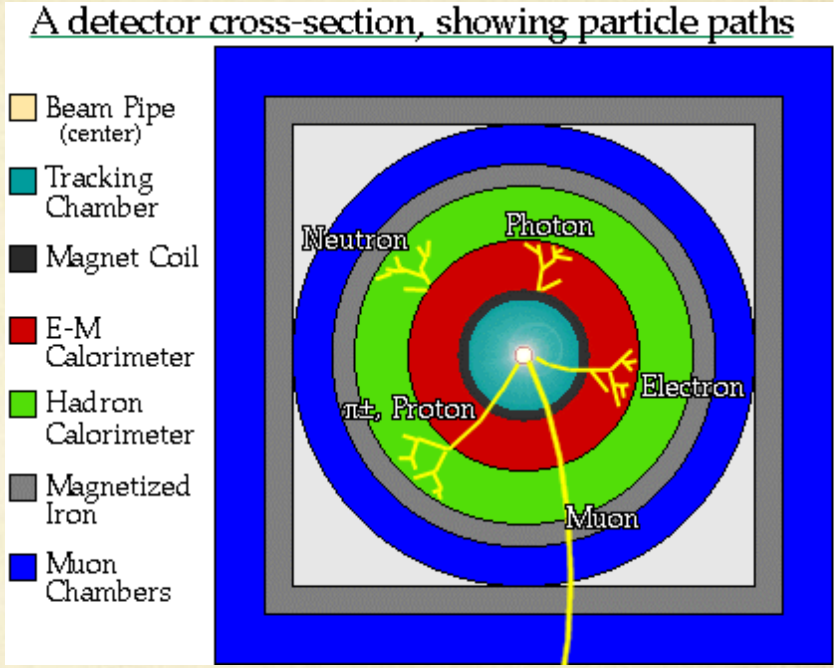
- Properties:
  - detected particles: charged particles (electrons, α,...)
  - sensitivity: single particles
  - spatial resolution: very good
  - dynamic range: good
    - as particle slows down, droplets occur closer to each other
    - if placed inside a magnet, can observe curled trajectories
  - speed: limited (need time to recover the super-saturated state)

Multipurpose detectors

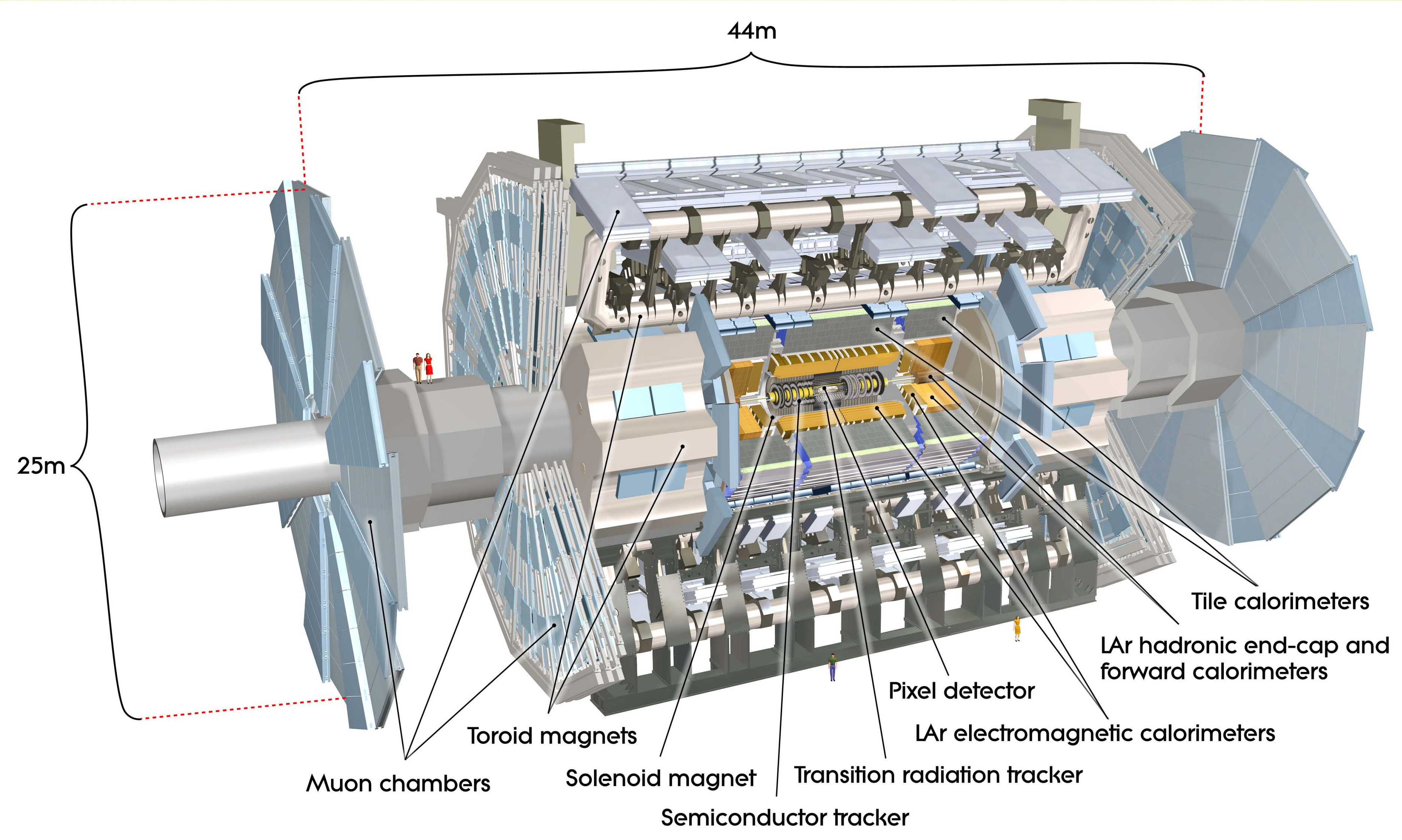
- Today people usually combine several types of various detectors in a single apparatus
  - goal: provide measurement of a variety of particle characteristics (energy, momentum, flight time) for a variety of particle types (electrons, photons, pions, protons) in (almost) all possible directions
  - also include "triggering system" (fast recognition of interesting events) and "data acquisition" (collection and recording of selected measurements)
- Confusingly enough, these setups are also called detectors (and groups of individual detecting elements of the same type are called "detector subsystems")

Generic HEP detector



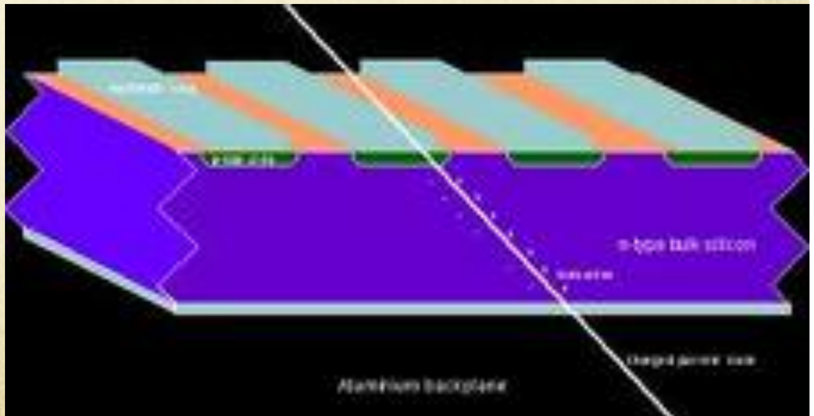


ATLAS detector

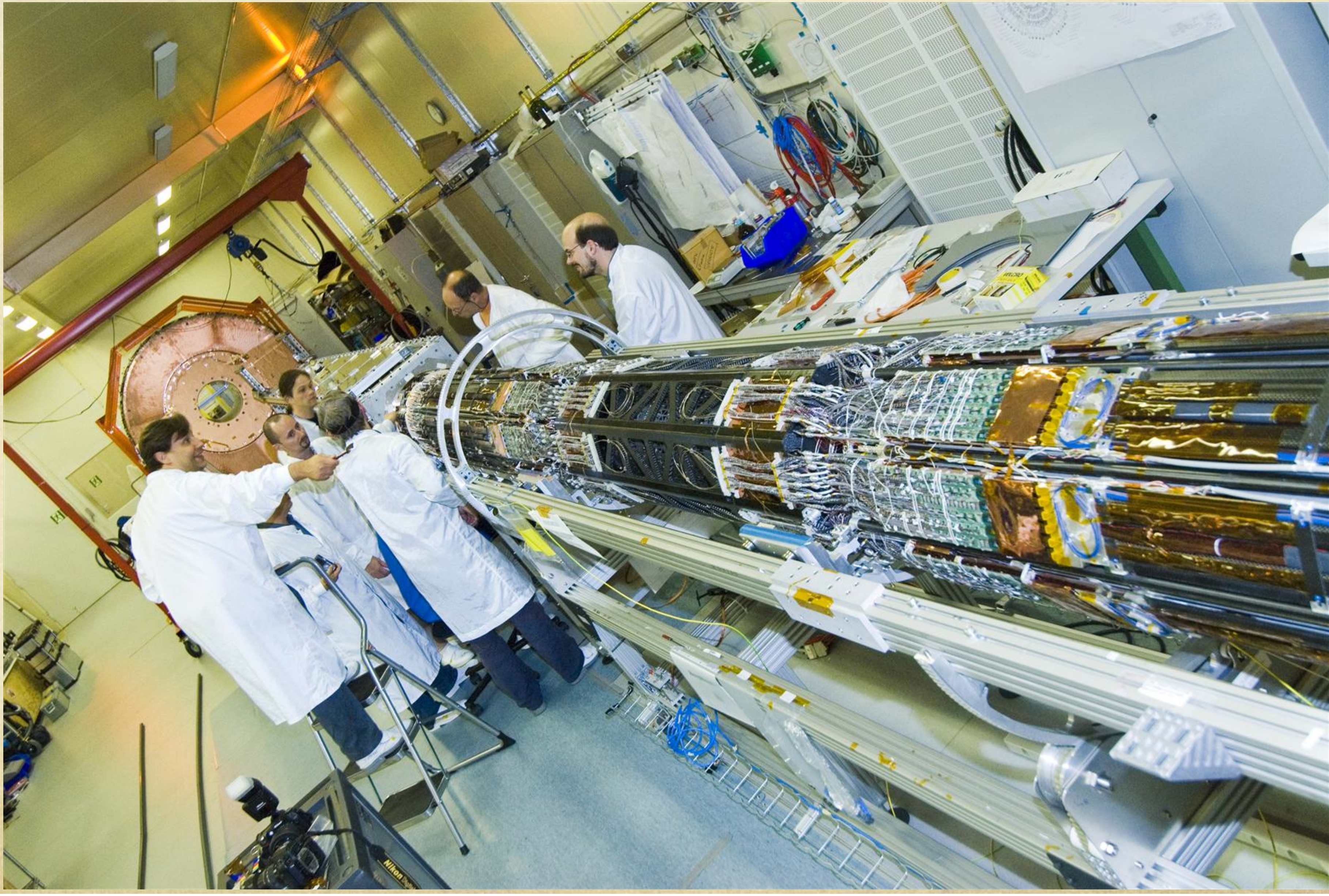


Tracking detectors

- A charged track ionizes the gas
  - 10–40 primary ion-electron pairs
  - multiplication ×3–4 due to secondary ionization
  - as electrons travel towards cathode, their velocity increases
    - electrons cause an avalanche of ionization (exponential increase)
- The same principle (ionization + avalanche) works for solid state tracking detectors
  - dense medium → large ionization
  - more compact → put closer to the interaction point
  - very good spatial resolution

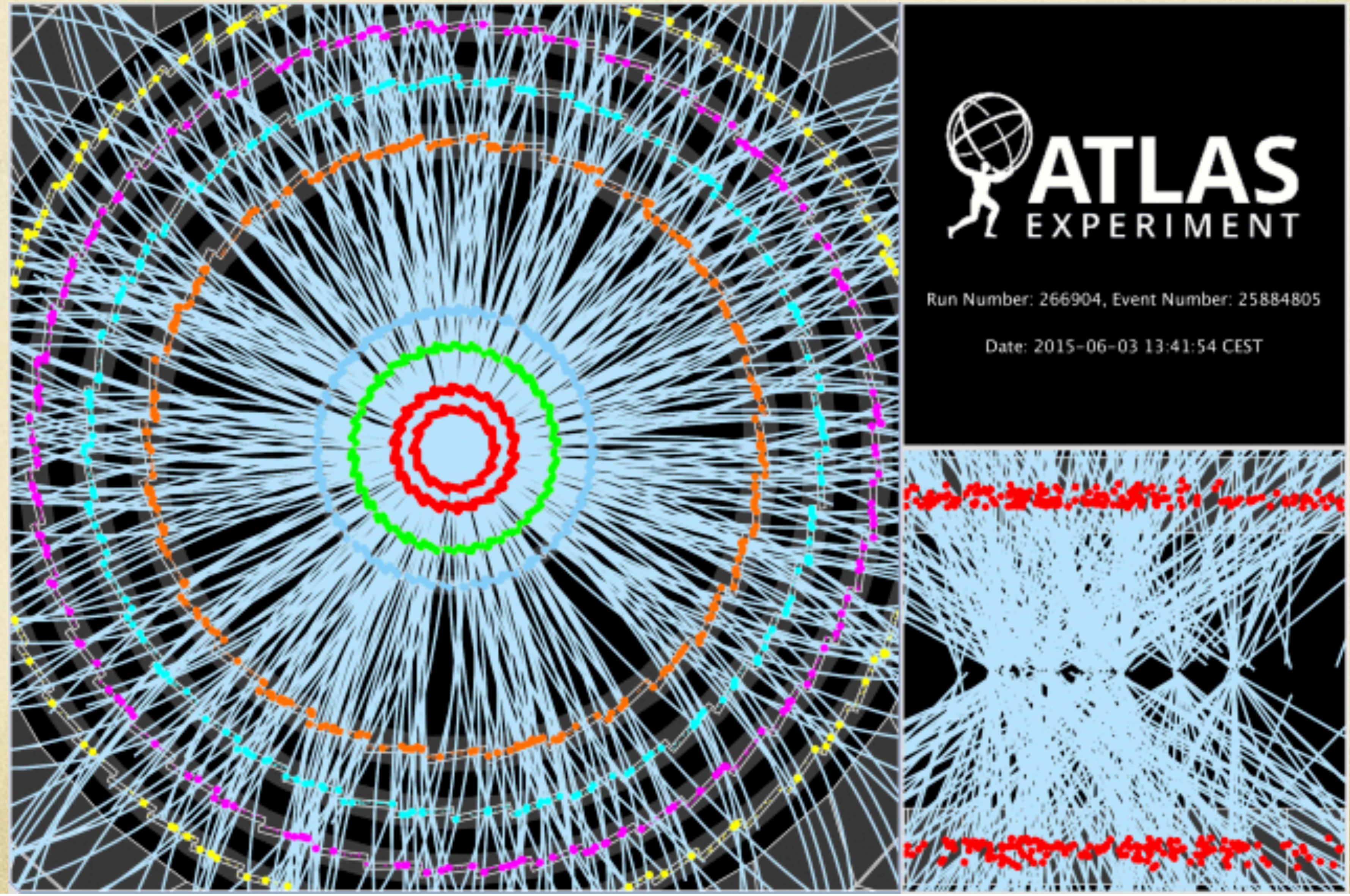


Pixel Detector

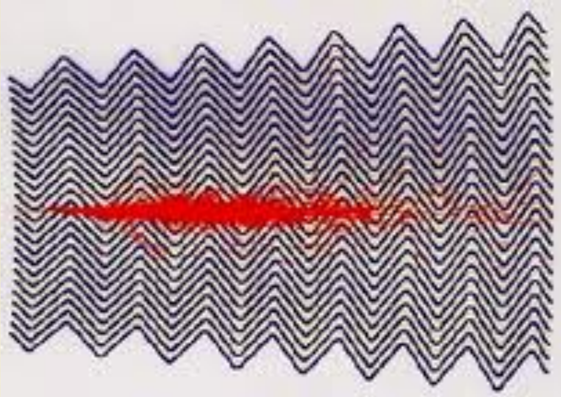


Results from Tracking

- Event recorded by the ATLAS detector on June 3, 2015

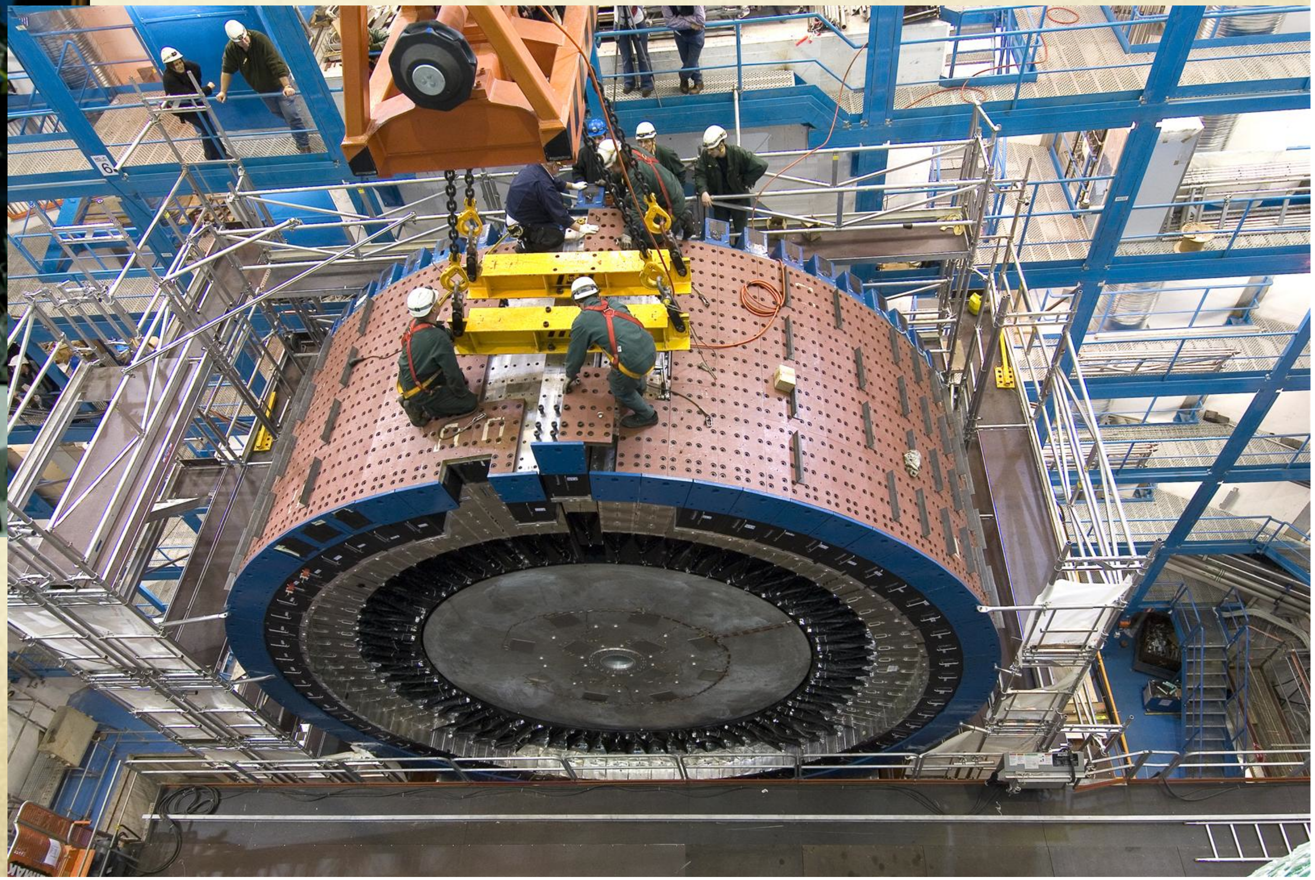


Calorimetry



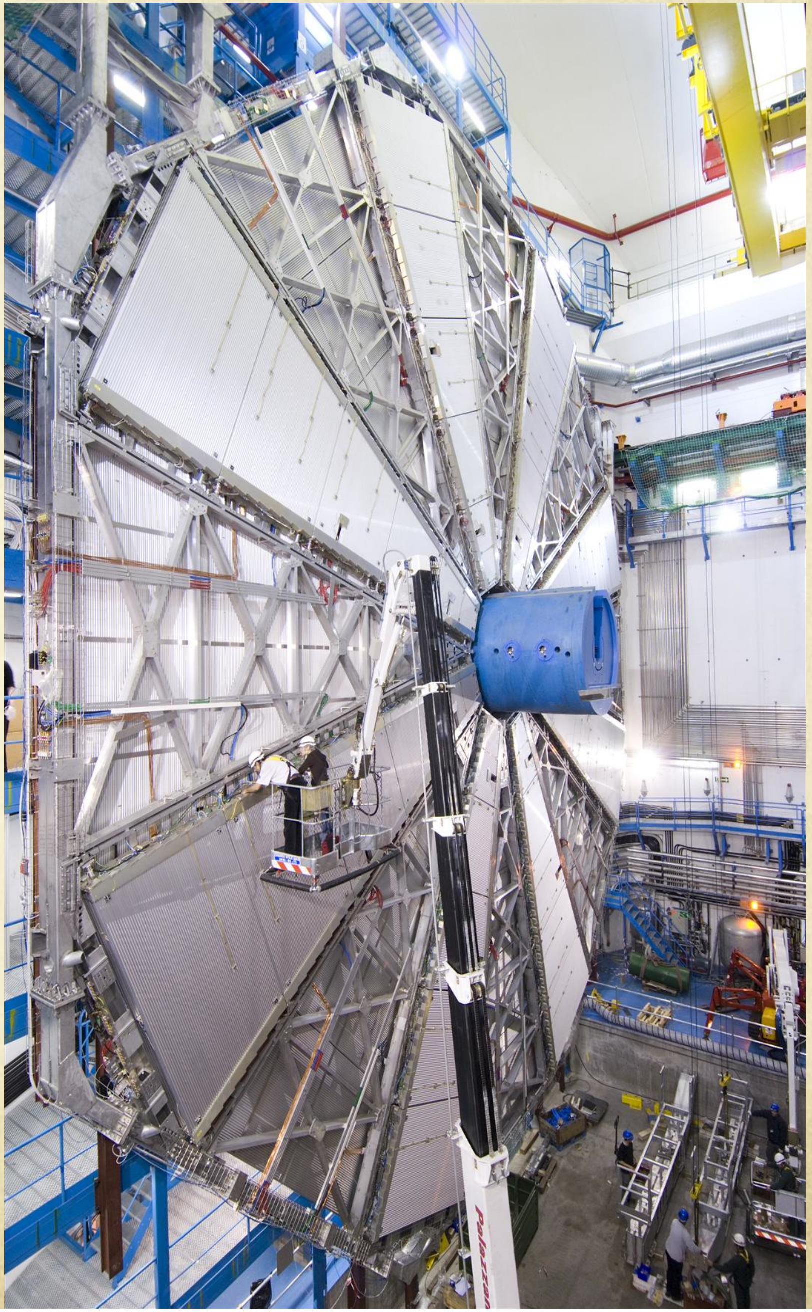
- The idea: measure energy by its total absorption
  - also measure location
  - the method is destructive: particle is stopped
  - detector response proportional to particle energy
- As particles traverse material, they interact producing a bunch of secondary particles (“shower”)
- It works for all particles: charged and neutral
- Two types of calorimeters
  - Electromagnetic – identifies photons and electrons and measures their energies
  - Hadron – identifies products of quarks – jets of hadrons originated from quarks; also measures energies of these jets
- Type of calorimeter depends only on the material inside it.

ATLAS Calorimeter



Muon detection

- Muons are charged particles, so using tracking detectors to detect them
  - Calorimetry does not work – muons only leave small energy in the calorimeter (said to be "minimum ionization particles")
  - Muons are detected outside calorimeters and additional shielding, where all other particles (except neutrinos) have already been stopped
  - As this is far away from the interaction point, use gas detectors

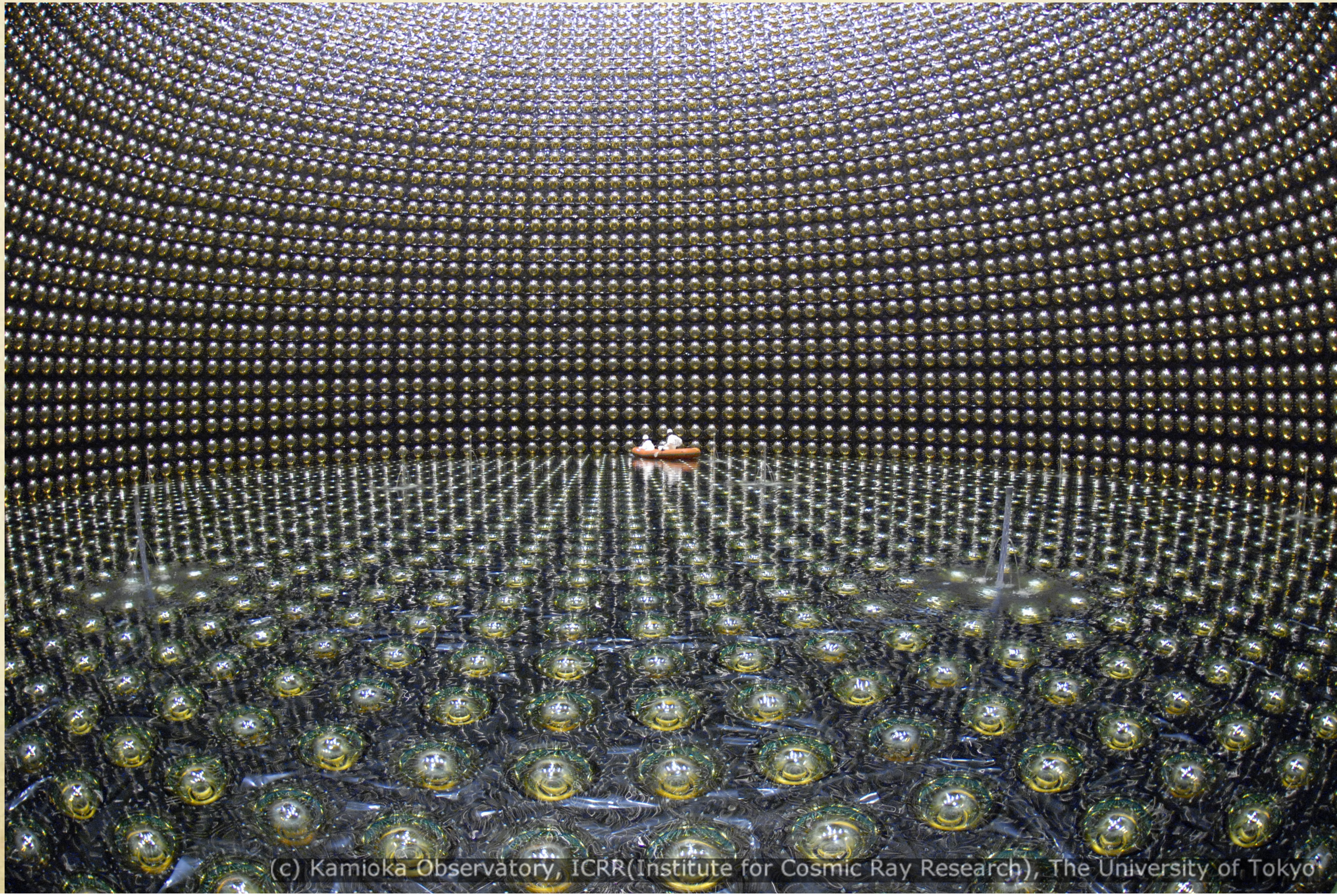


Detection of neutrinos

- In dedicated neutrino experiments, rely on their interaction with material
  - interaction probability extremely low → need huge volumes of working medium
- In accelerator experiments, detecting neutrinos is impractical – rely on momentum conservation
  - hadron colliders: the initial momentum component along the (anti)proton beam direction is unknown

SuperKamiokande: neutrino detector

- Tank of water (50,000 tons) with 11000 photomultipliers



Conclusions

- Particle detectors follow simple principles
  - detectors interact with particles
  - most interactions are electromagnetic
  - crucial to figure out which detector goes where
- Three main ideas
  - track charged particles and then stop them
  - stop neutral particles
  - finally find the muons which are left