Technological challenges of particle physics experiments

Open Symposium – Update of the European Strategy for Particle Physics

Granada, May 13, 2019

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INFN and University, Pisa

Disclaimer

- Lots of input from the community, but views expressed are my own.
  - And even more so are the provocations.

- Parallel session on detector R&D will be essential to discuss and reach clear conclusions

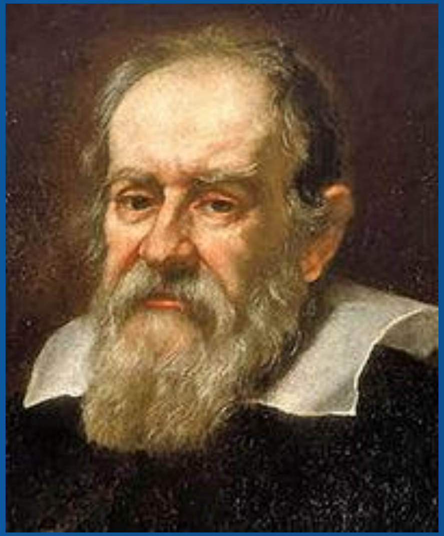
Tool-driven revolutions

The importance of detector development

Measurements and discoveries

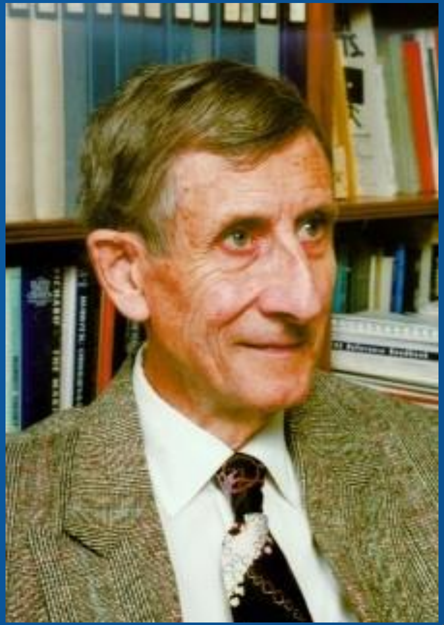
Galileo Galilei

- Measure what can be measured, and make measurable what cannot be measured.



Freeman Dyson

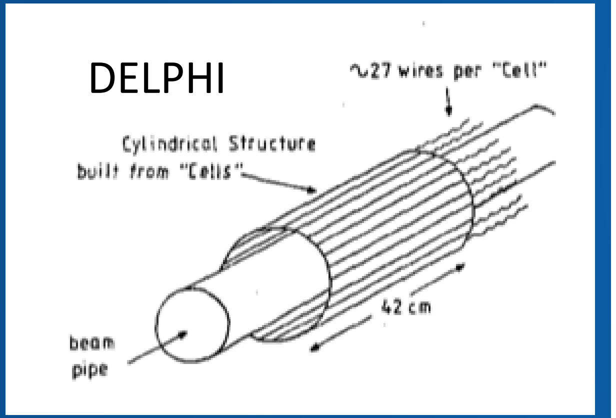
- The effect of a concept-driven revolution is to explain old things in new ways.
- The effect of a tool-driven revolution is to discover new things that have to be explained.

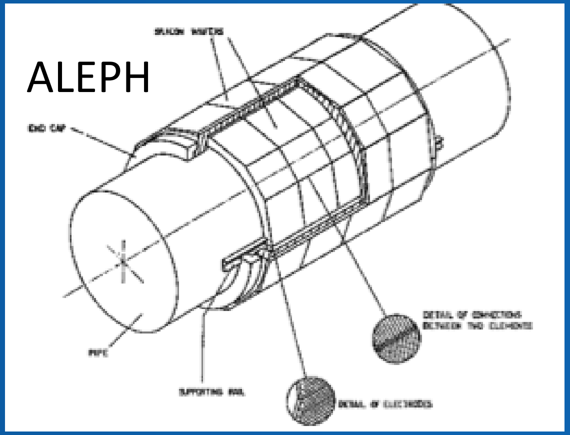


Two examples of enabling technologies

Silicon Vertex Detectors @ LEP

- At the time of TDRs, silicon detectors where still in development (1983)

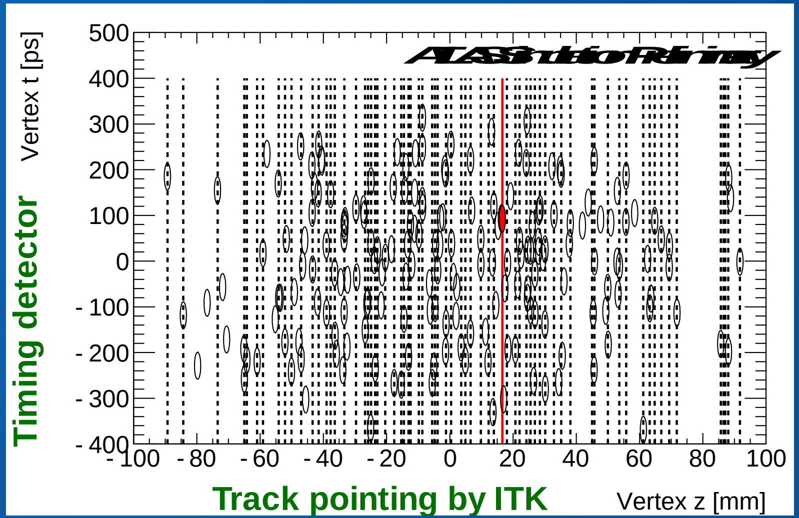




- They have enabled secondary vertices and a large fraction of LEP physics

Timing Detectors @ HL-LHC

- Timing Detectors where not included in initial ATLAS/CMS upgrade projects (2015)
- Hopefully will provide powerful tool to reduce pileup and increase effective luminosity



Detector R&D questions

Focus

- Generic
- Guided

Coordination

- Distributed
- Centralized

Human factor

- Recruiting
- Training
- Recognition

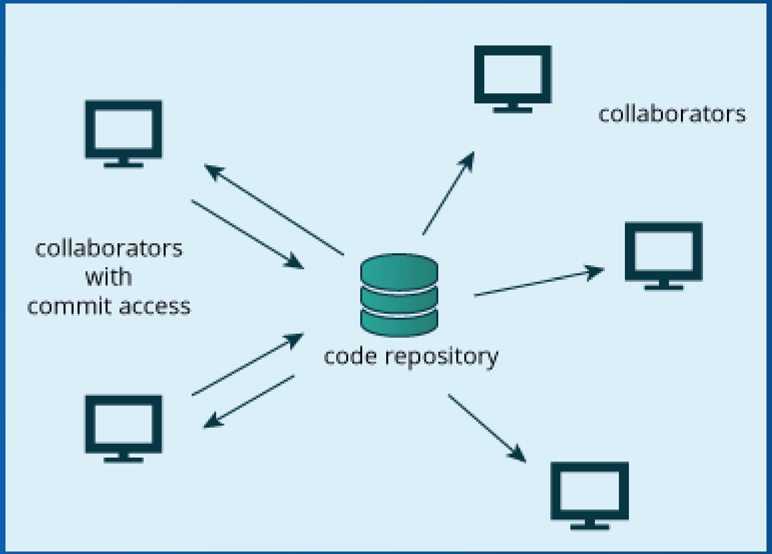
R&D Focus

- 70-20-10 guideline:
  - 70% on NOW – current detectors
  - 20% on NEXT – future detectors
  - 10% on HORIZON – blue sky R&D
- NOW and NEXT should be driven by well defined or prospective requirement
- HORIZON should be driven by technology and what's possible
  - Need more connection to other fields
- % of what resources ? Money, time

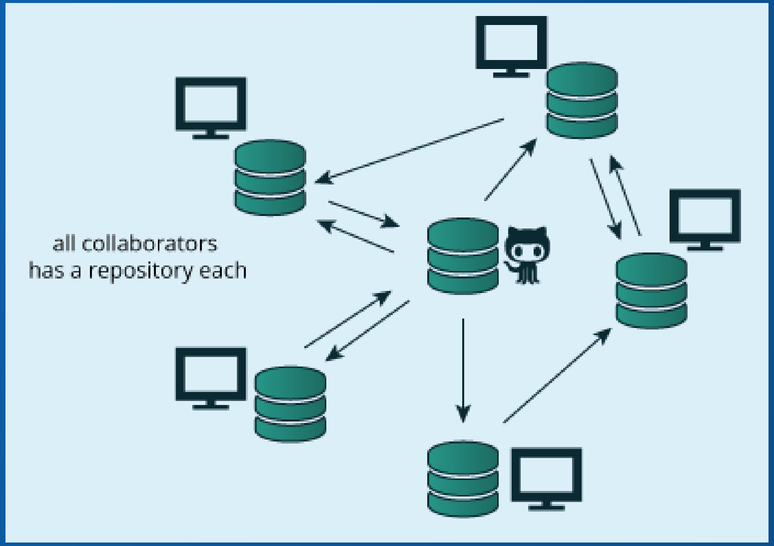
R&D Coordination

- Expertise is distributed in many institutions
- git model
  - Distributed effort, but with full information exchange
  - Essential to have flexible collaboration network
- Coordination in large labs important for
  - Ideas exchange
  - Technical support
  - Synergy and optimization
  - Data repository
  - Tools

Centralized



Distributed (git)



CERN RD Projects

- Good examples of coordination towards common goals
- RD42 – Diamond detectors
- RD50 – Silicon radiation hard devices
- RD51 – Micropattern gas detectors
- RD53 – Pixel readout chip for ATLAS and CMS
- ...and several others in the past
- In general, large collaborations of interacting institutes.
- Good model, but
  - Focus can be lost and people just "keep going"
    - regular reassessment important.
  - Resources always a problem – especially people.
- CERN is central, but support needed from other labs and agencies

Humans

- The current career model just doesn't work very well
  - Except for very few geniuses, one cannot be expert and innovative simultaneously in physics analysis, detectors, computing, teaching, outreach….
- Recruiting: if you fail discovering new physics you can start develop a new detector
  - Essential to attract brilliant young physicists to detector R&D
- Training: go in the lab and get that piece of hardware to work
  - Education and expertise transfer necessary to maintain knowledge and capabilities
- Career: this guy only knows about detectors, should we really hire him/her ?
  - Career opportunities for detector physicists must be greatly strengthened and kept open in a systematic way

Humans

- The current career model ~~just doesn't work very well~~ **is broken**
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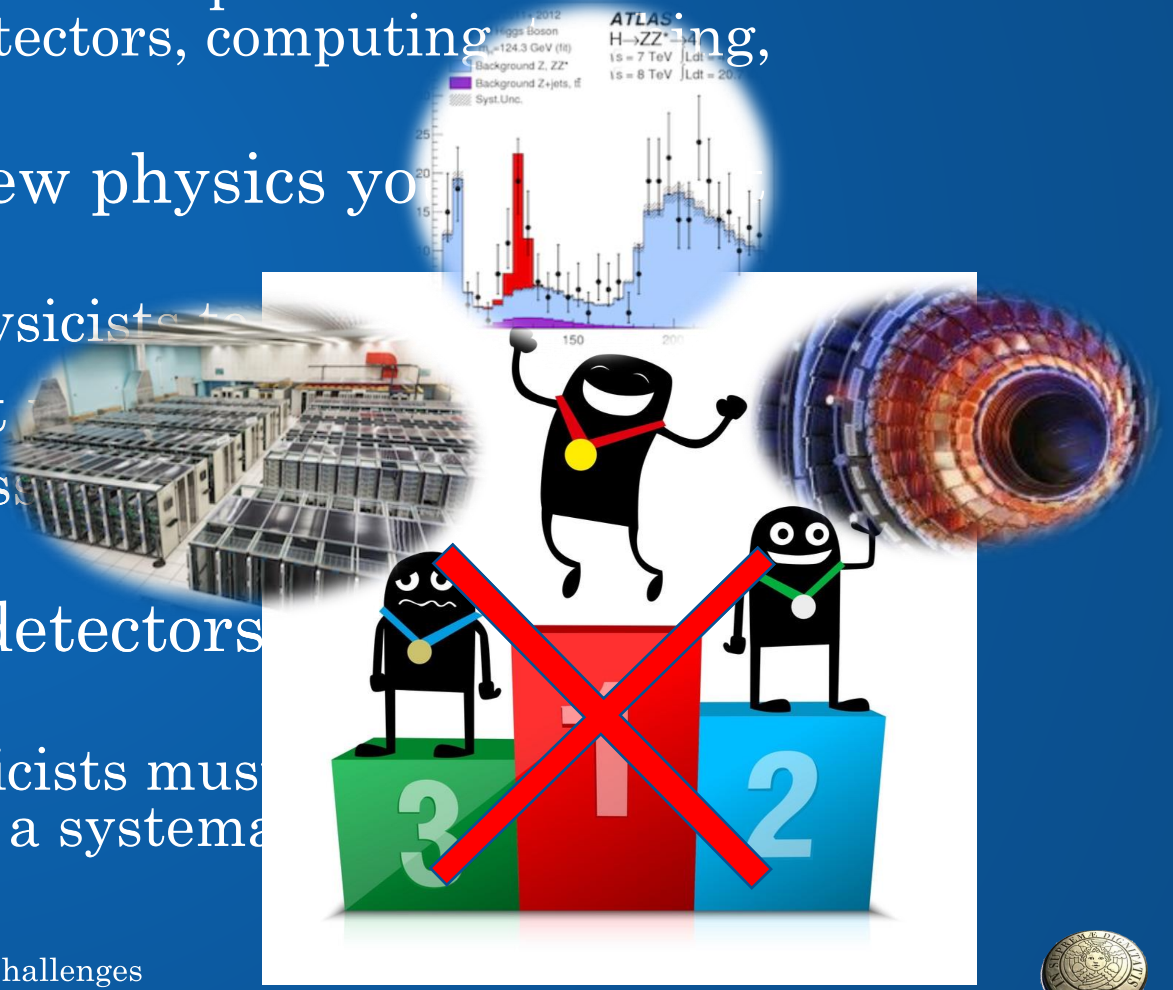
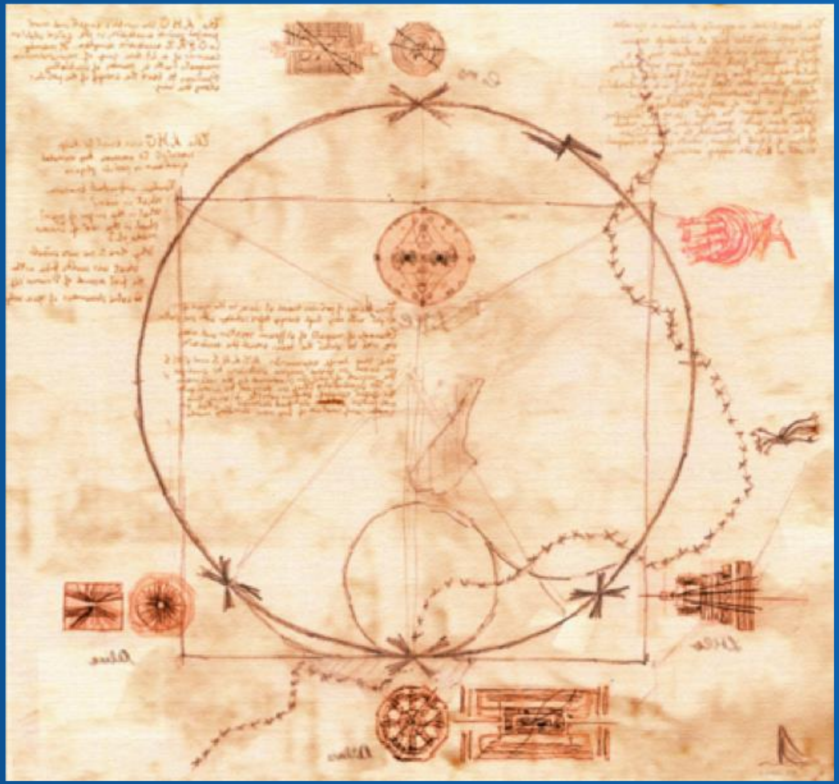
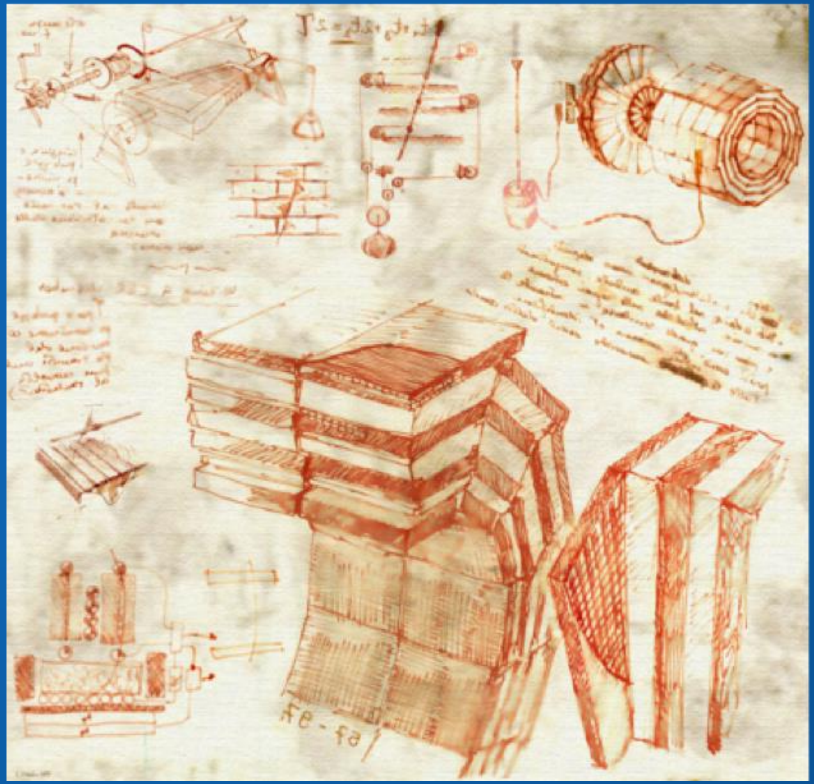


Long R&D Process

- New findings for Leonardo's anniversary

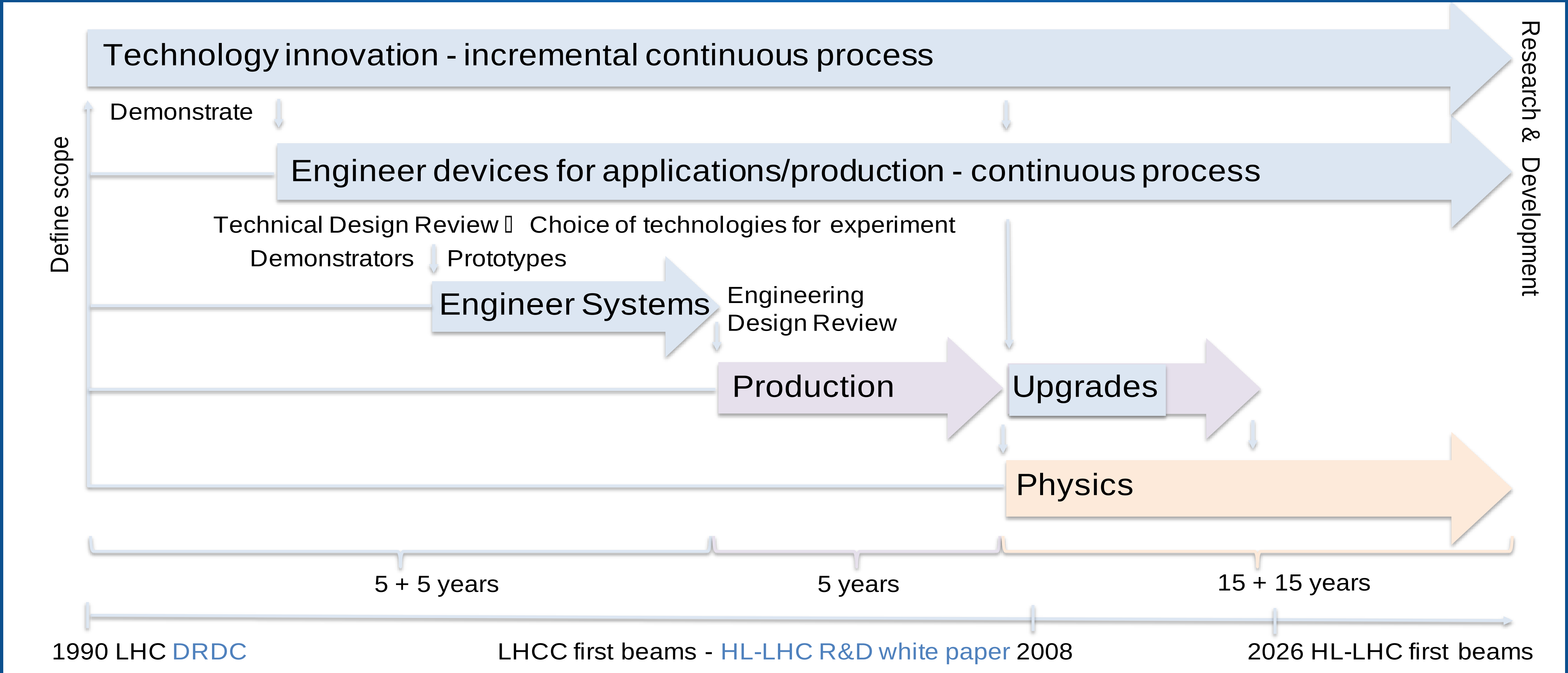




(c) S.Cittolin

Long R&D Process

D.Contardo, parallel session



Technology

- It's a long long long time to market. For instance
  - CMOS image sensor invented in the early '90
  - CMOS MAPS for charged particles started around 1999

- Technology tracking and connection with industry
  - HEP is not driving the technology, but can develop new ideas and innovative applications
  - Need to go beyond the client-supplier model – for the most part we are small clients
  - Develop more collaboration mechanisms between scientists and industry
- Technology transfer and societal impact
  - Strive to look outside our niche (ATTRACT example)
- → Good discussion points for the parallel session

Technological challenges

A personal view trying to identify challenges

Looking more at future than current programs

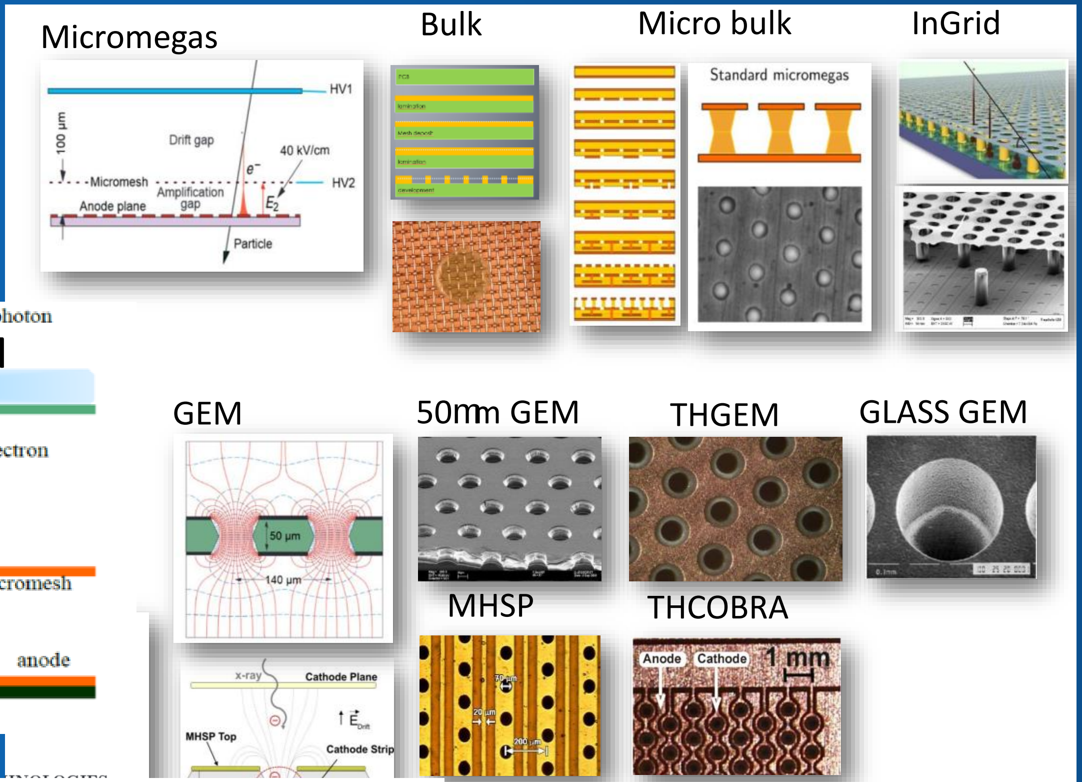
Different environments

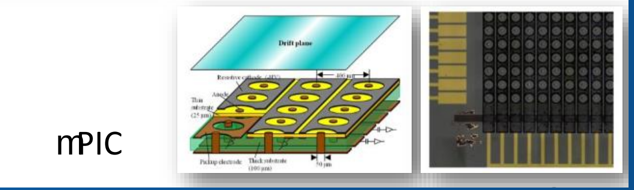
- Colliders and fixed target
  - Hadron / lepton / lepton-hadron collider detectors
  - Fixed target experiments
- Elusive particles
  - Accelerator neutrinos near and far detector
  - Reactor neutrinos
  - Low energy high sensitivity ($0\nu 2\beta$, g-2, EDM, …)
- Astro-particle and cosmology
  - Dark matter detectors
  - Cosmic rays (charged, gamma)
  - Cosmic neutrinos
  - Gravitational waves
  - Satellite experiments

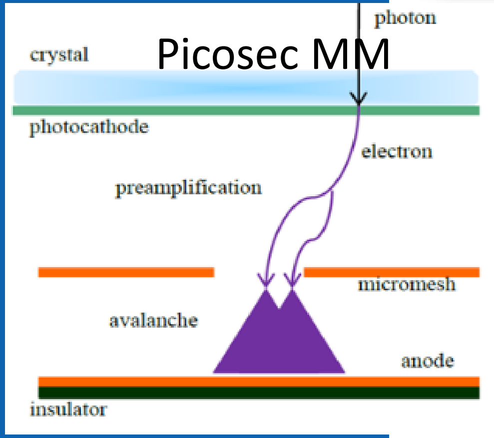
- Extremely different requirements
- Many possible synergies based on technology development
- More cross-field communication is important

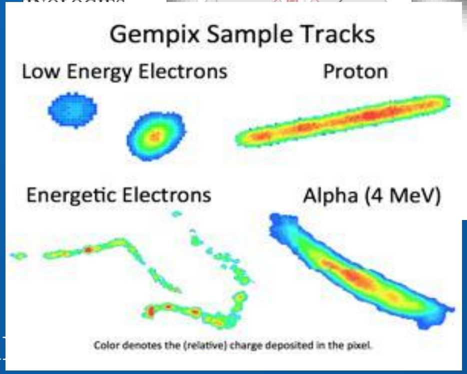
Micro Pattern Gas Detectors

- Very active field. Good coordination through RD51
- Future directions:
  - Resistive materials and architectures
  - Fast and precise timing
  - New materials and technologies
  - Hybrid detectors
- Challenges
  - Granularity
  - Time resolution
  - Large area, Large volume
- Reliability of industrial production still to be optimized for large surfaces
- Many applications, for instance treatment plans



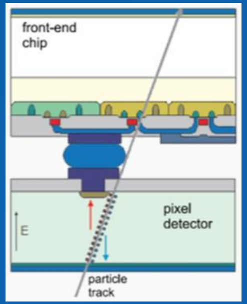


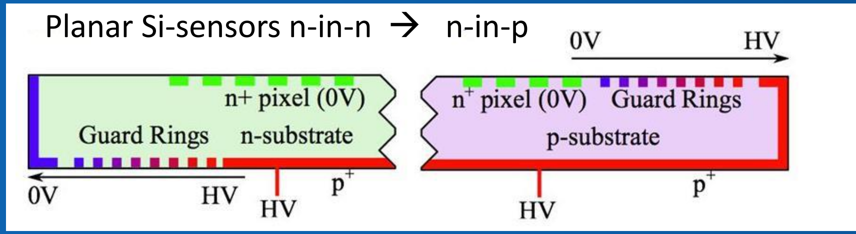


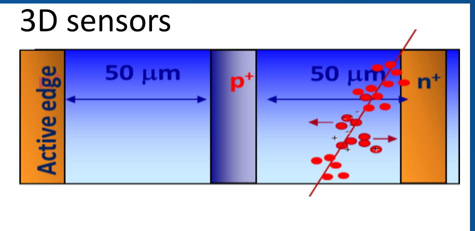


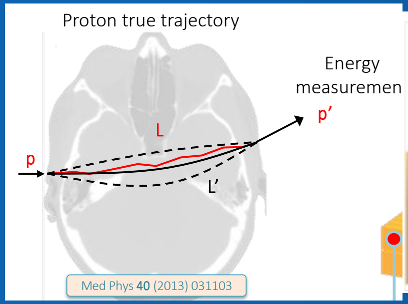
Tracking with Silicon

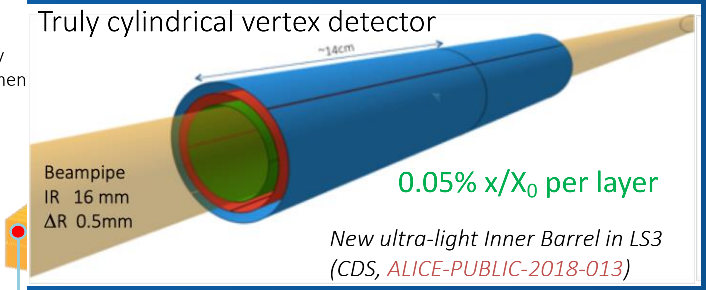
- Great successes of silicon sensors
- Main challenges:
  - Granularity
  - Speed
  - Reduced material
  - Radiation resistance
- Large effort in many directions
- Smart detectors → measure direction
- CMOS MAPS most active development
  - Interesting for applications like proton radiography
  - Can be thinned to become flexible
  - Can be stitched to cover large area

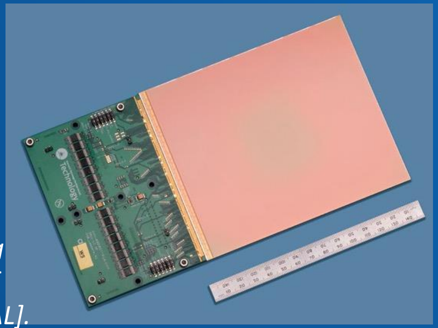




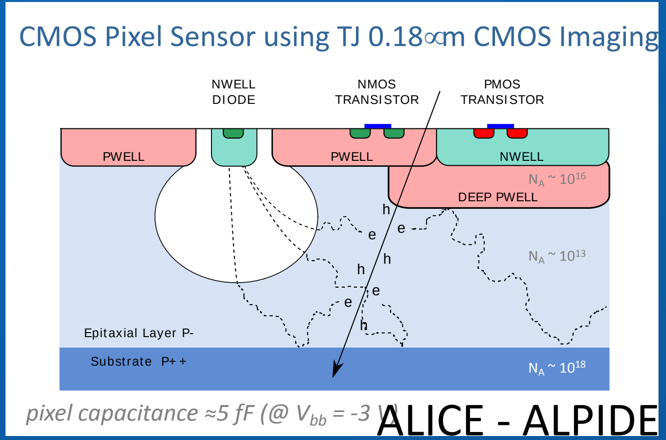


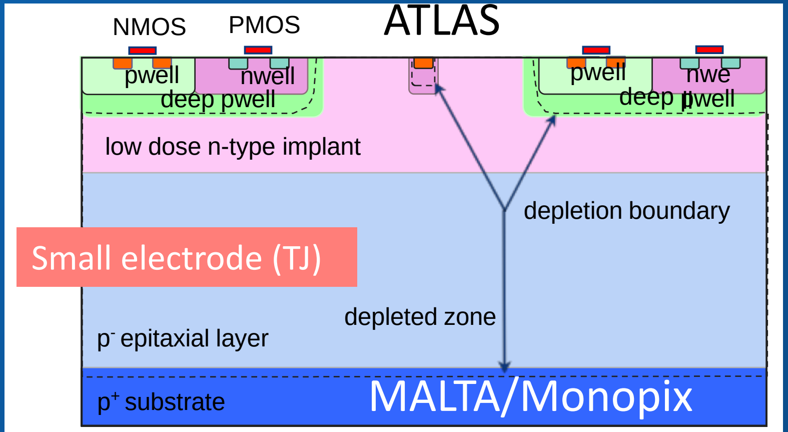






Wafer-scale stitched imaging sensor with an active area of 140x140 mm [N. Guerrini, RAL].

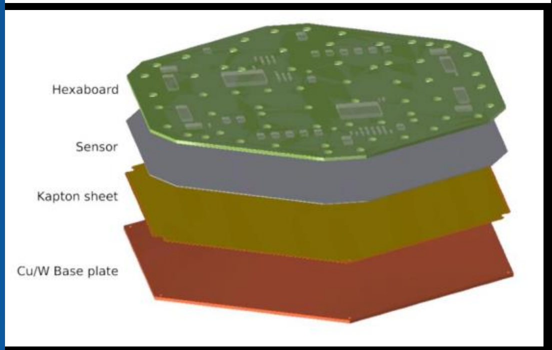


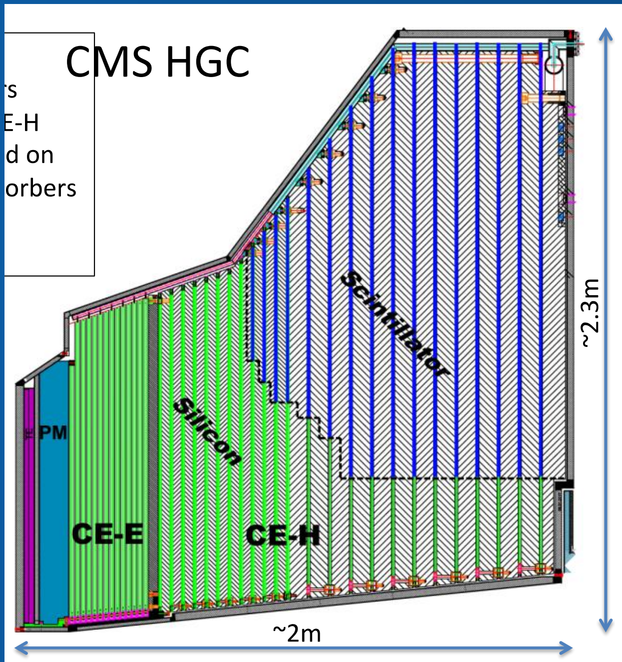


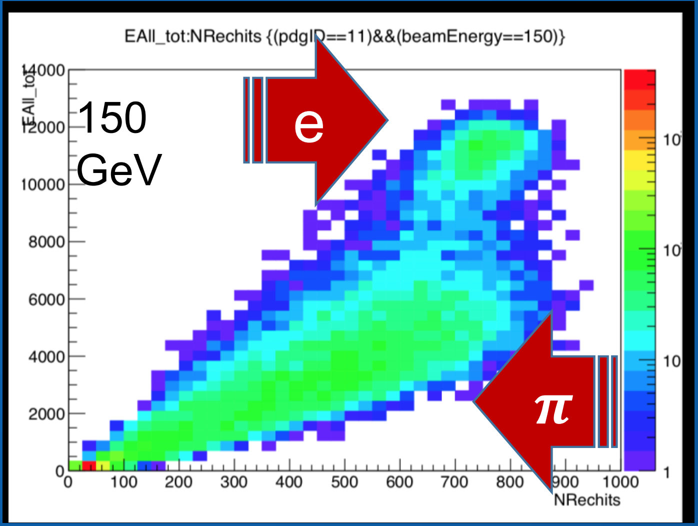
Calorimetry

- Many techniques, depending on application
  - Crystal - Ultimate resolution, especially for low energy
  - Scintillator (sampling)
  - Liquid Noble Gas - Intrinsic rad hardness
  - Particle flow calorimetry
    - Silicon-tungsten 5D measurement
- Challenges:
  - Photon detection
  - High granularity
  - Large volumes and mass
  - Possibility of dual readout

Silicon sampling calorimeter

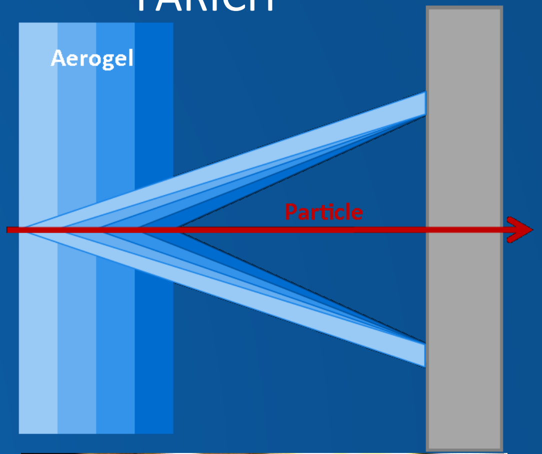


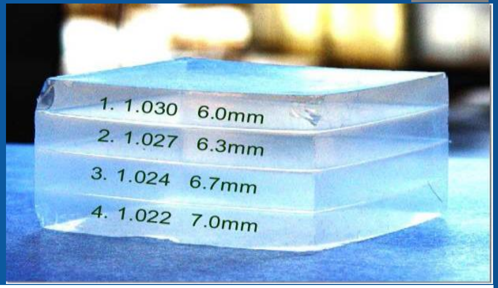


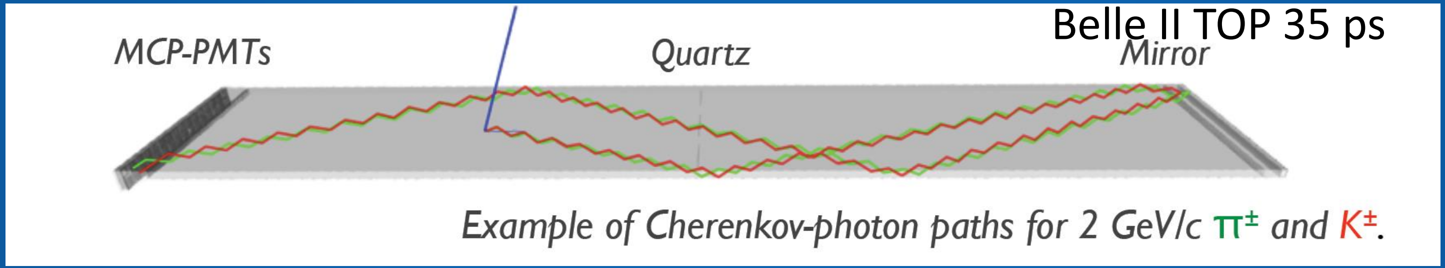


Particle Identification

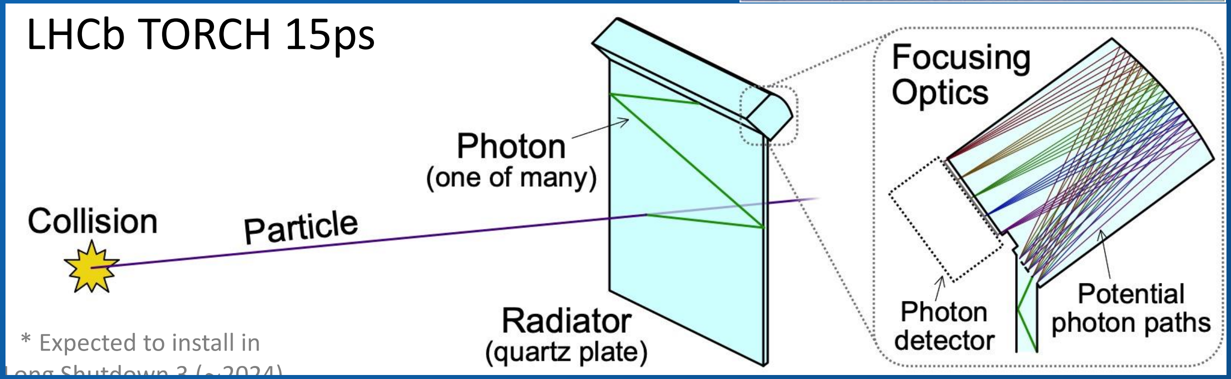
- Crucial element for flavour physics
- RICH, Focusing Aerogel RICH
- Time of Propagation Counter, TORCH (timing)





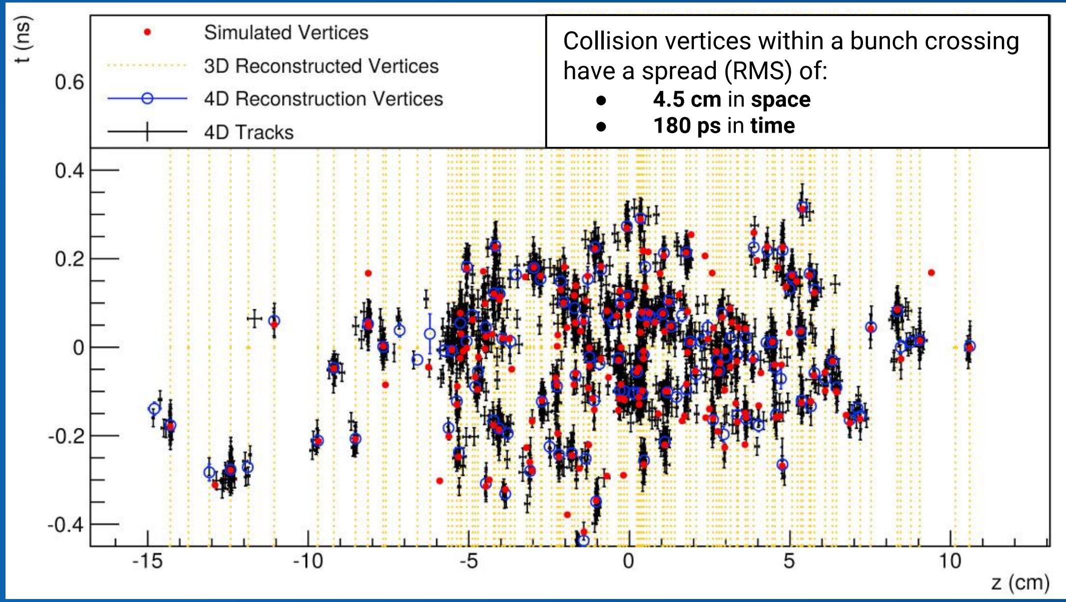


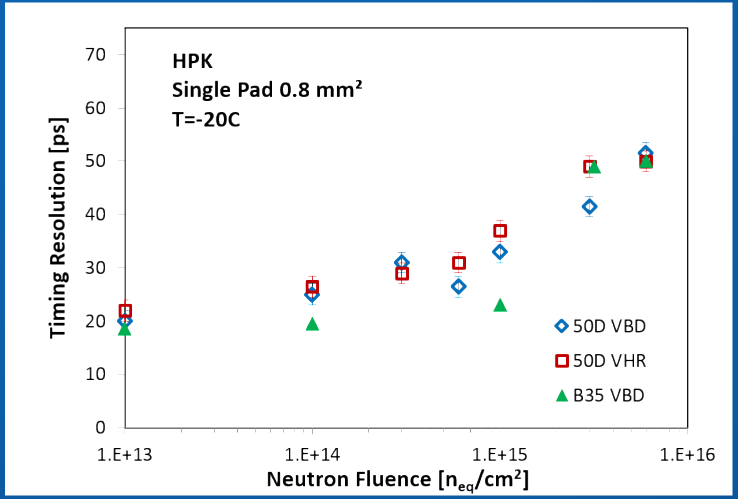
- Challenges
  - Timing resolution
  - Quartz polishing
  - Mechanical system

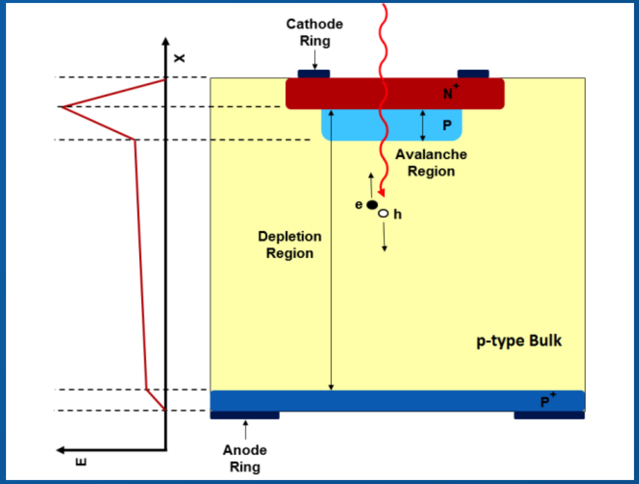


Timing

- Fast development of precise timing sensors
  - Reconstruction in calorimeter
  - Time of flight and time of propagation (PID applications)
  - Pileup rejection in HL-LHC
- Low Gain Avalanche Device:
  - 30 ps possible
- Challenges:
  - Radiation hardness
  - System aspects of timing







Electronics

- Crucial role in all systems
  - ASIC – engineering bottleneck
  - FPGAs – COTS or custom boards
  - Firmware – pervasive and often critical
  - High speed links and optoelectronics
- Challenges:
  - Industry-driven technology
  - Expertise critical mass required
  - Cross-experiment collaboration mandatory
  - Huge cost of engineering runs
- Comments:
  - Scaling is not stopping any time soon
  - No longer your dad's transistors, maybe other uses
  - Interconnect and Through Silicon Vias next frontier

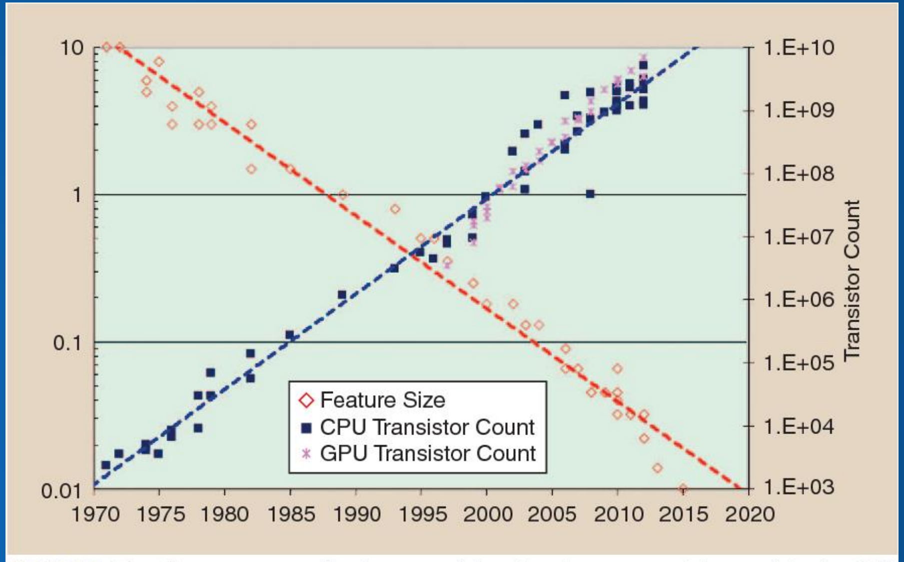
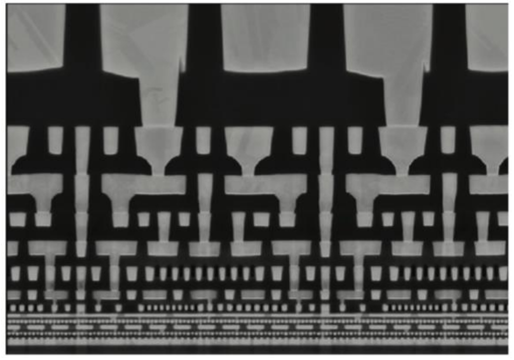
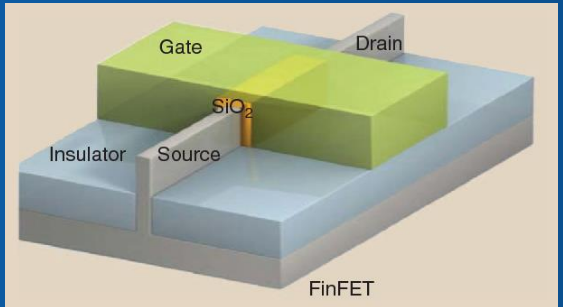
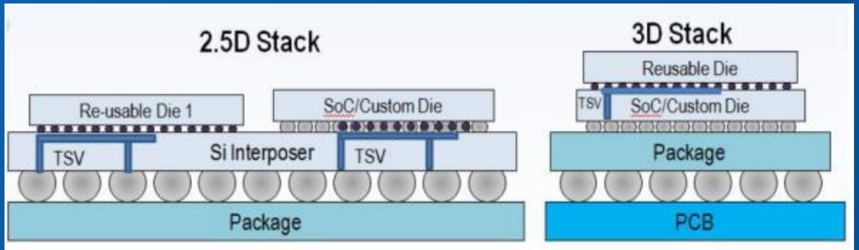


FIGURE 2. The silicon process technology trend showing the exponential growth in the CPU/


A 14 nm FINFET process metal stack

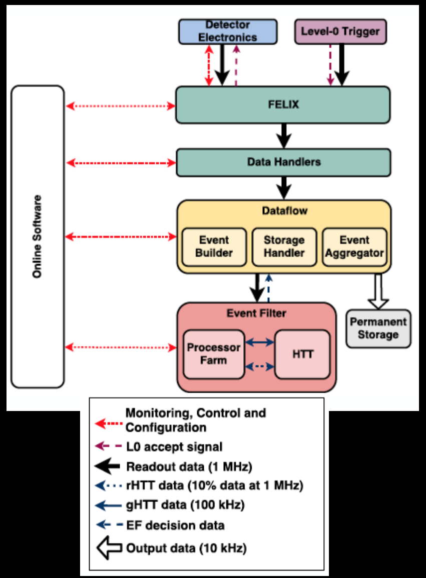




Trigger and DAQ

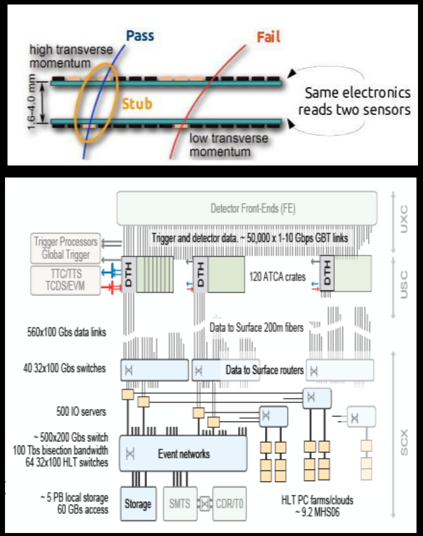
- Critical for high luminosity accelerators
- Delicate compromise between physics and bandwidth
- Challenges
  - Best use of technology evolution
  - Use special feature of detector and hardware acceleration (AM, FPGA, GPUs)
  - How to handle non standard physics
    - Long lived particles
    - Magnetic monopoles
    - ….

ATLAS



Minimize data flow bandwidth by using multiple trigger levels and regional readout (RoI)

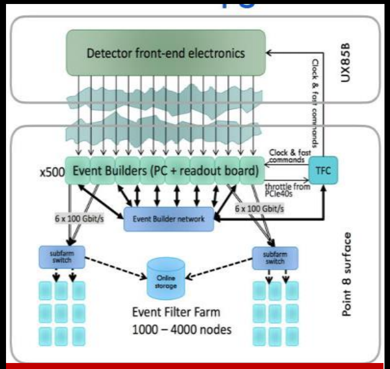
CMS



Allow large data flow bandwidth. Invest in scalable commercial network and processing systems

LHCb

40 MHz trigger-less DAQ



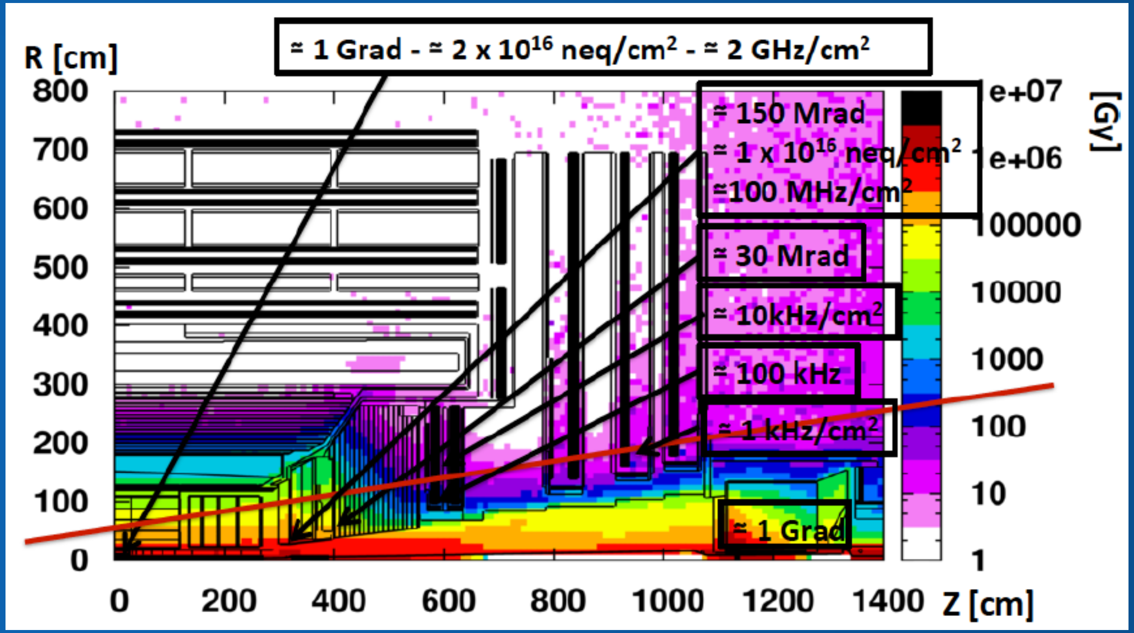
Massive use of data links

Real time align&calib
Expand physics program by not saving the raw data.

7/9/2018 Daniela Bortoletto, ICHEP 2018 Seoul

Radiation

- Radiation resistance considerations are omni-present in detectors
- Huge progress in identifying materials and design techniques
- Next accelerators might increase the radiation level by more than a factor 10-100
  - FCC
  - Muon collider
- Solutions are not in hand today



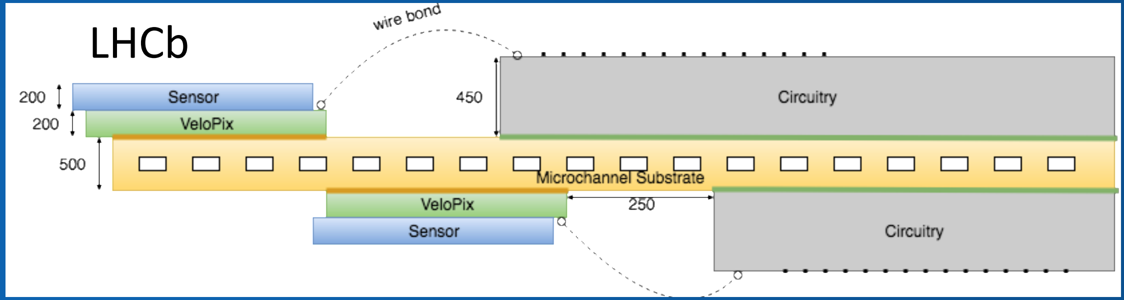
1. **Increasing radiation levels**
   - **Semiconductor detectors will be exposed to hadron fluences equivalent to more than 10^{16} n_{eq}/cm^2 (HL-LHC) and more than 7×10^{17} n_{eq}/cm^2 (FCC)**
     ➔ detectors used now at LHC cannot operate after such irradiation
2. **New requirement and new detector technologies**
   - New requirements or opportunities lead to new technologies (e.g. HV-CMOS, LGAD,…) which need to be evaluated and optimized in terms of radiation hardness

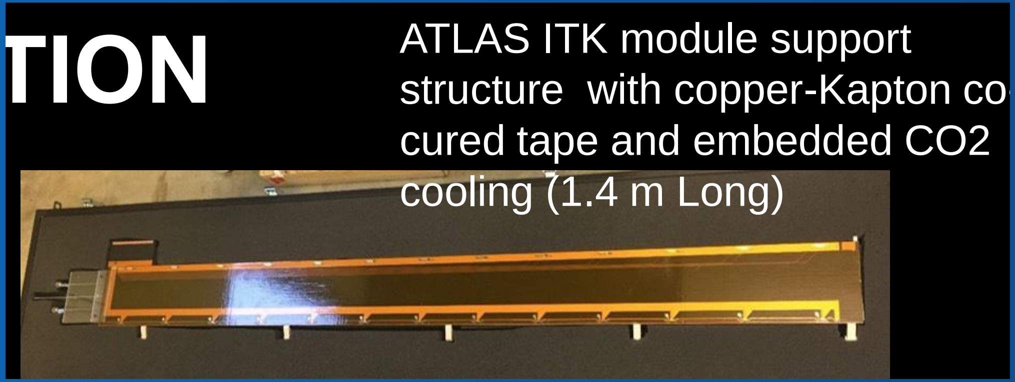
G.Casse and M.Moll, RD50 Status Report

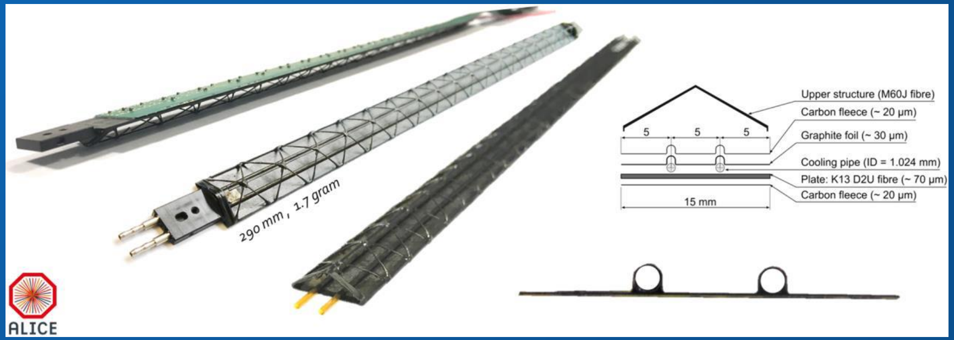
Detector systems

Many challenges

- Mechanical support
  - Material reduction, Advanced materials
  - Non conventional uses of materials
  - Mechanical stability
- Cooling
  - Dual phase, microchannels
- Cables and power distribution
  - Energy efficiency, Serial powering
  - Cable plant and material
  - Wireless transmission
- Experiment magnets
  - New Superconductive materials
  - What if we can have higher fields ?
- Project management, engineering support



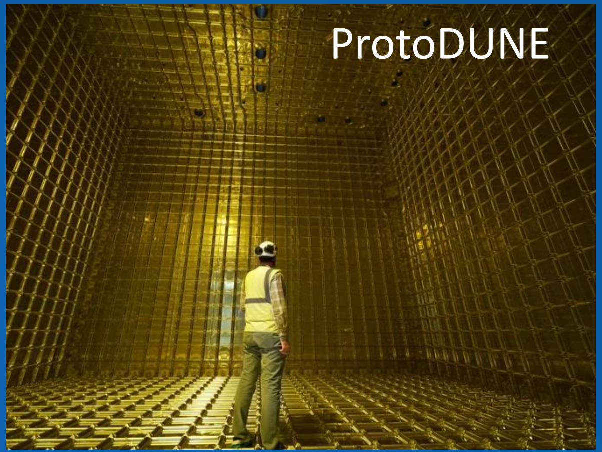


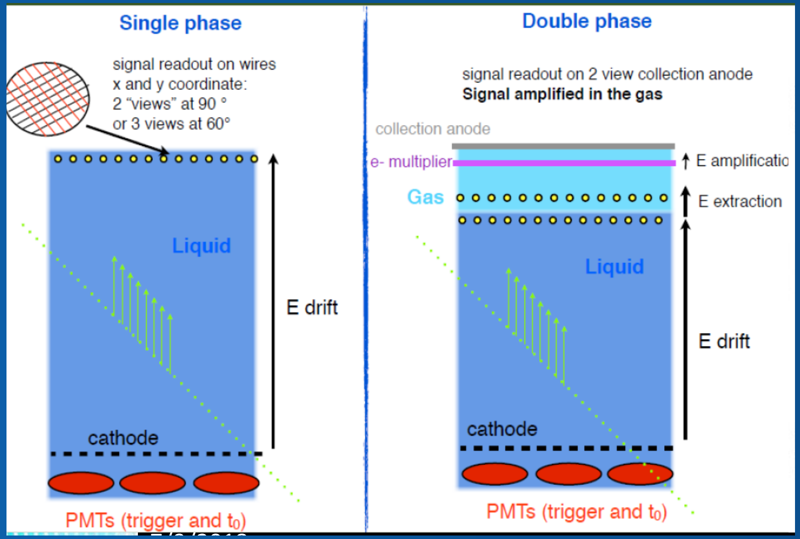


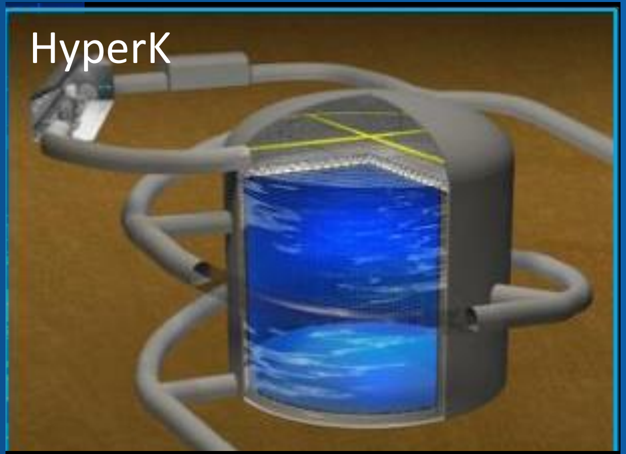
Neutrinos

#126, #131

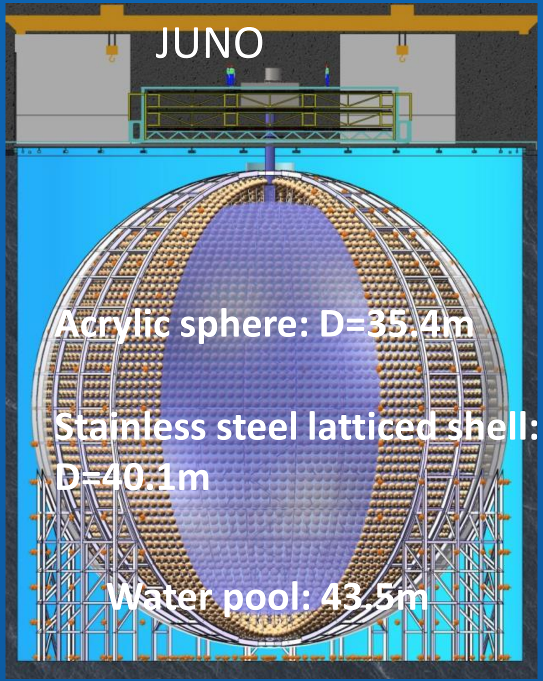
- Near, far, and reactor detectors
- Water vs scintillator vs Liquid gas
- Challenges: large mass, radio purity, photomultipliers / photodetectors
- Example the technological breakthrough from industry
  - Insulation technique from naval industry



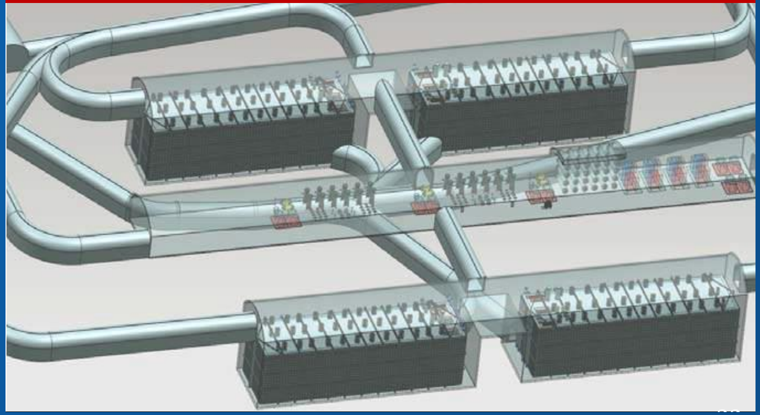




- 260 kton ultrapure water
- 190 kton fiducial mass: 10×SK



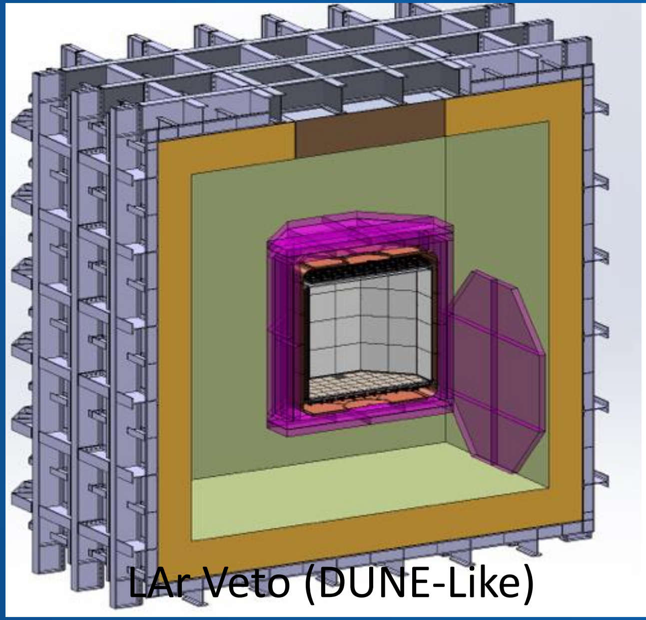
40 kton Liquid Argon Time Projection Chamber (LArTPC) DUNE

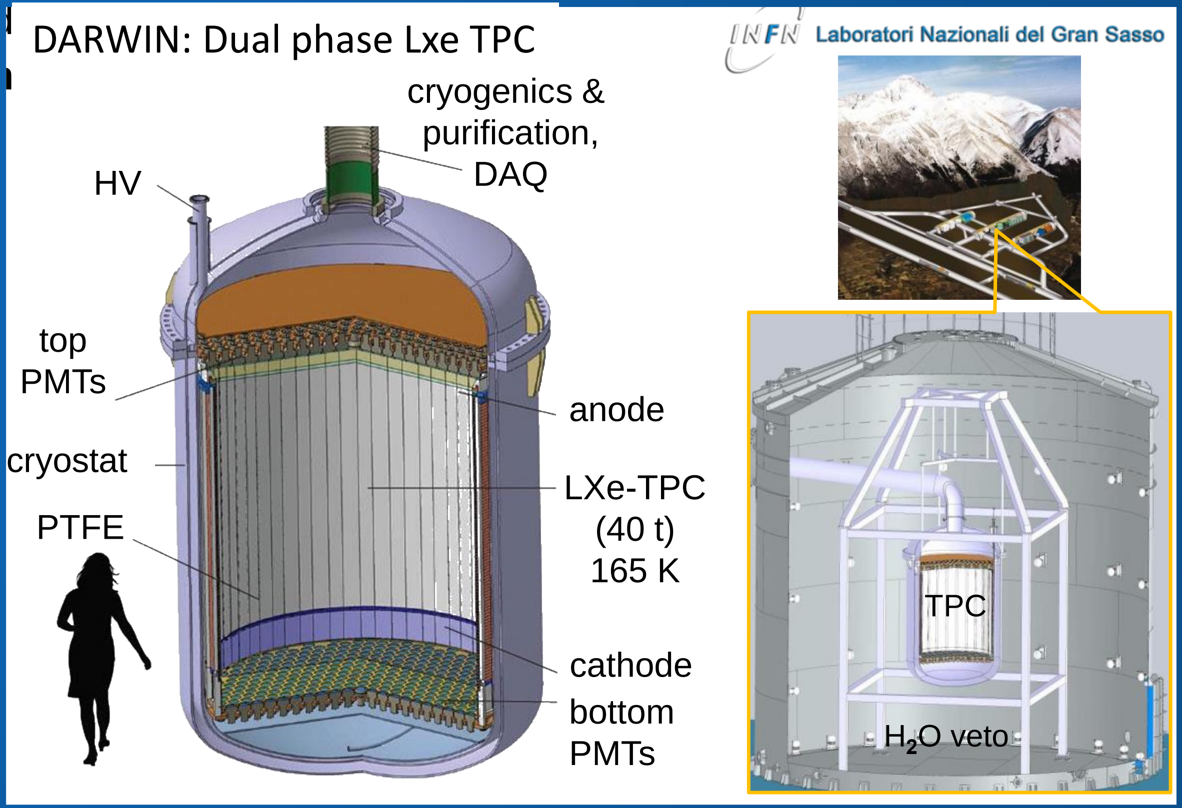


Dark Matter and known unknowns

- Large mass total adsorption.
- Challenges
  - Active Shielding for Background rejection
  - Mass, Radio purity,
  - Photo detectors

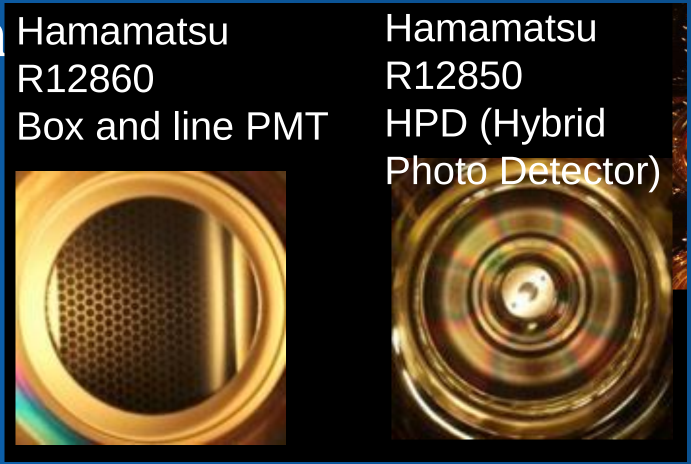
- Large cryogenic infrastructure
- Large mass of LAr(depleted) /Lxe
- Dual phase operation

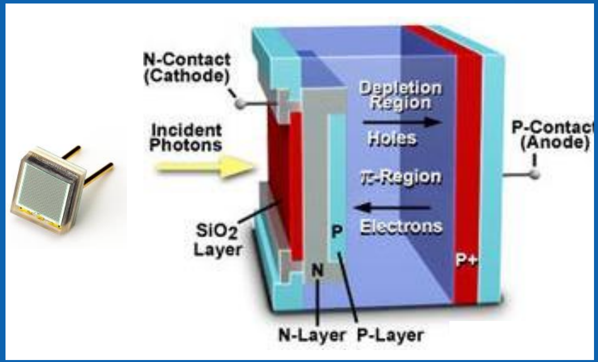


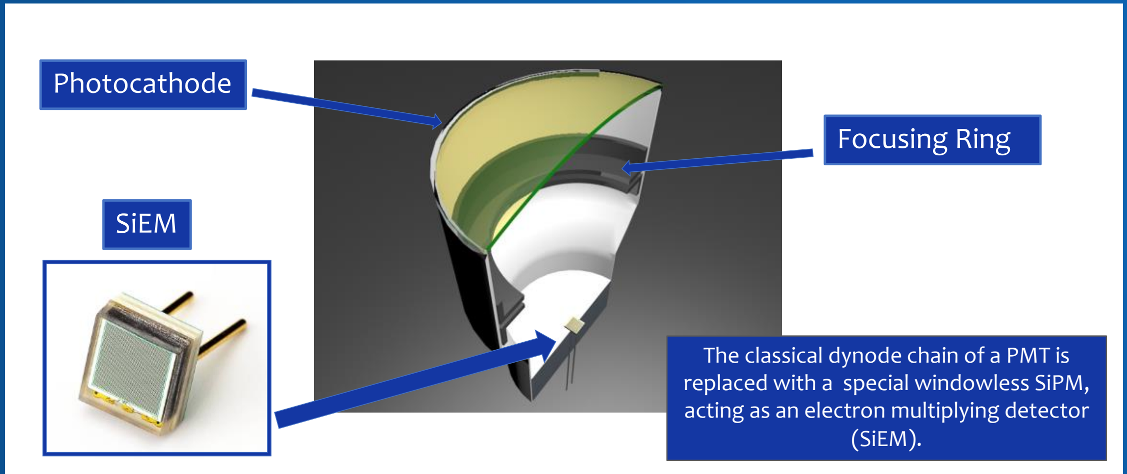


Photon detectors

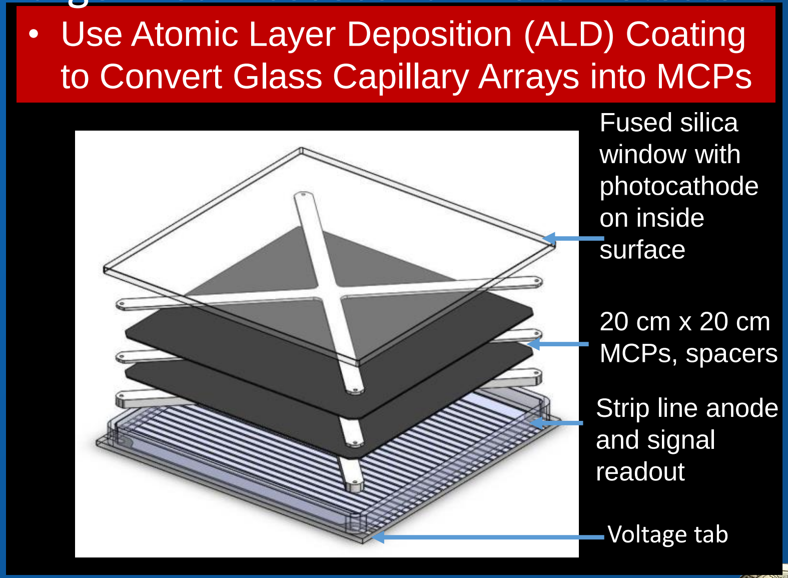
- Photon detection is key to many detection system
- PMT, APD, SiPM, LAPPD, VacuumSiPMTube
- Challenges:
  - Quantum efficiency
  - Spectral response
  - Speed
  - Noise







Large Area Picosecond Photo Detectors



Gravitational Waves

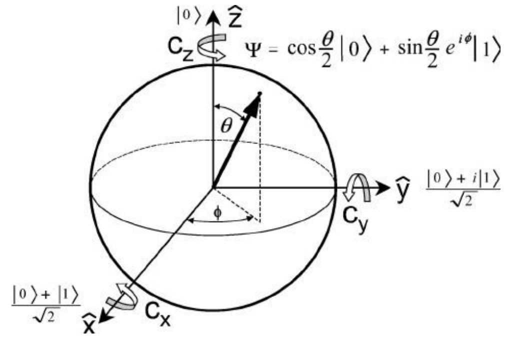
- Observation of GW opens new challenging field
  - Ten binary black holes and a binary neutron star coalescences so far
  - Huge coordination effort for multi-messenger astronomy
- Einstein telescope is the next ambitious project to increase sensitivity
- Strong synergies with HEP
  - Underground facilities
  - Vacuum technology
  - Cryogenics
  - Controls and automation
  - Electronics and DAQ
  - Computing
  - Governance of world-wide efforts

Quantum mechanics

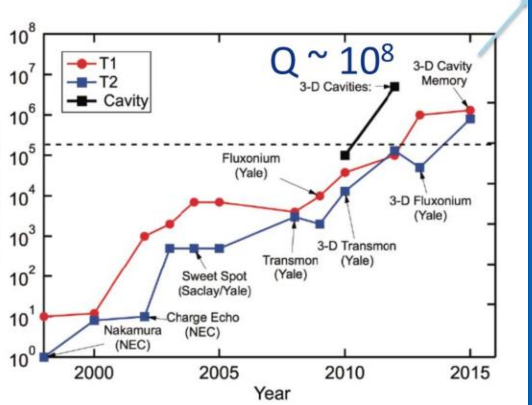
- Use of quantum coherence effect in sensors is becoming reality
  - Go beyond fundamental limits in sensitivity → Axions, Dark Matter
  - Exploration of unknown unknowns
- Connection with condensed matter physics
- Technology from HEP can be helpful to quantum physics
  - Hi Q in RF cavities to improve coherence time of QUbits
- Also: quantum dots for 0v2β

a bit can take two values "0" and "1"

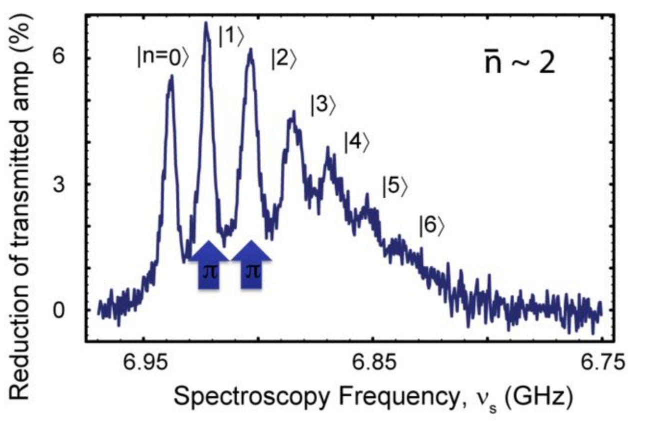
qubit: represented by the surface of the sphere with all possible combinations of state "0" and "1".

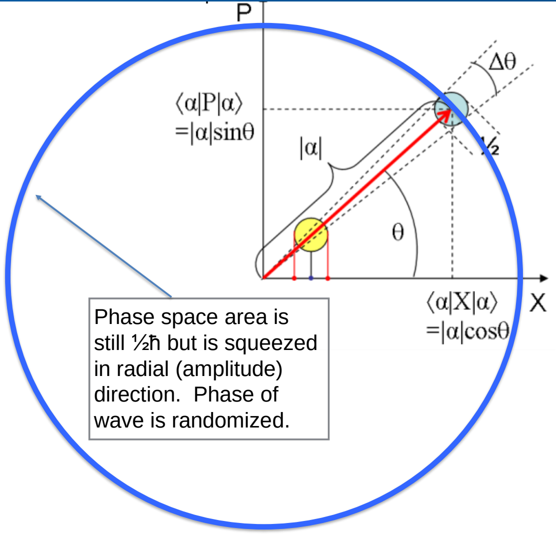


- Quantum non demolition measurement can do much better in counting photons
- Excite cavity with axion and then count photons with QND



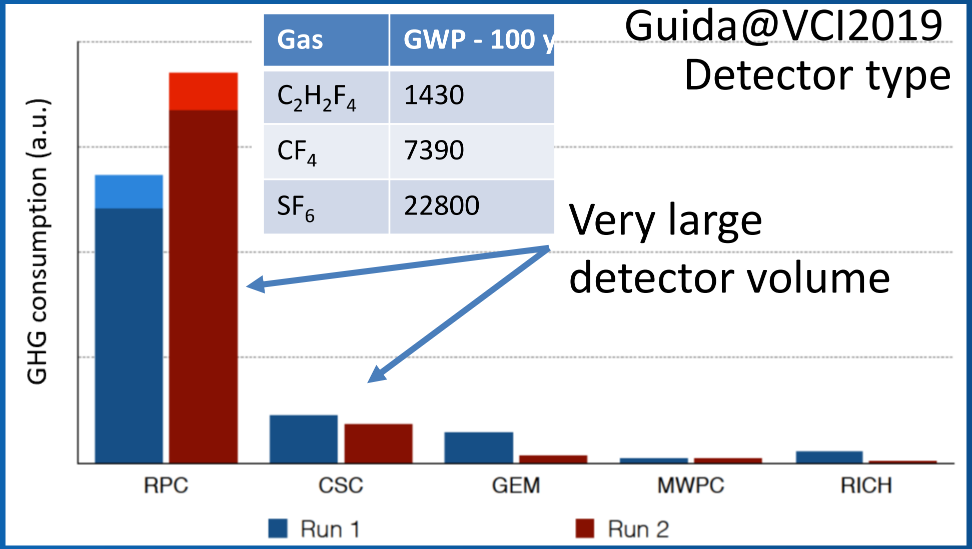
M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)





Environmental impact

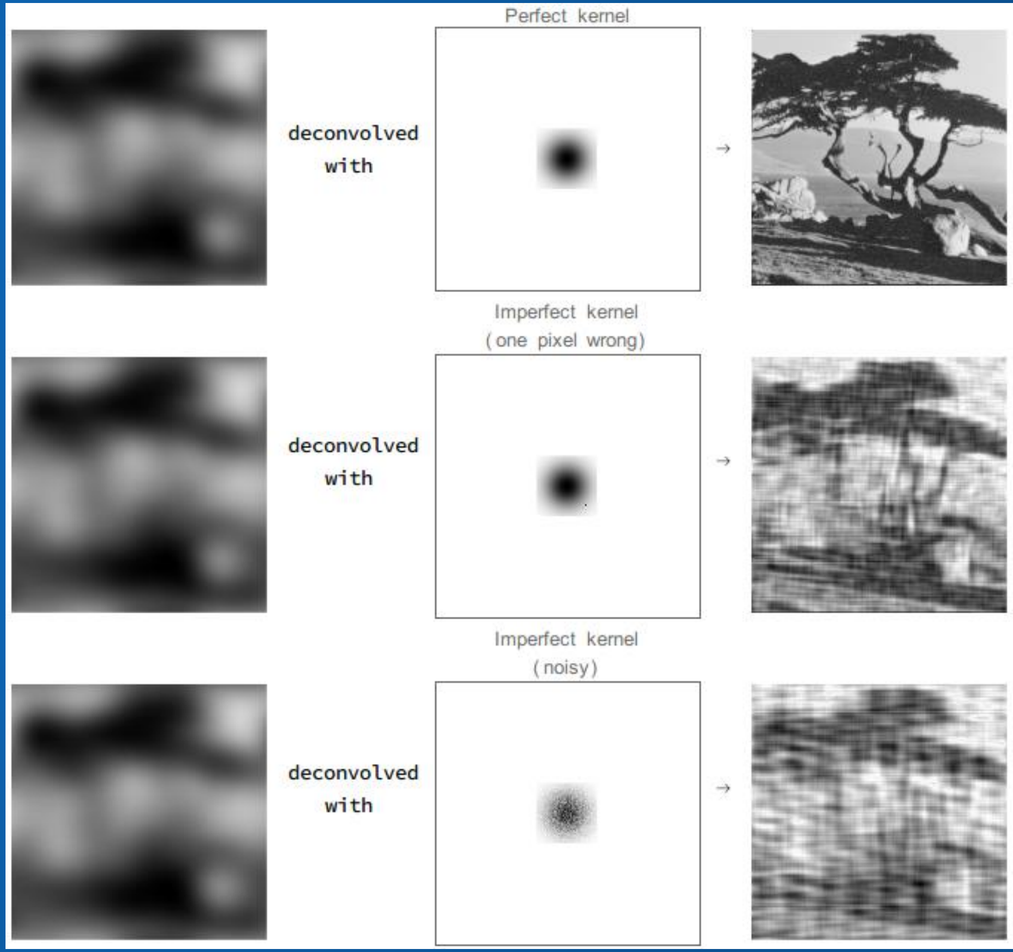
- More attention to enviromental impact of HEP experiments and activities is needed
- Alternative gases with reduced GWP
- Radioactive waste control and reduction
- Energy efficiency and carbon footprint of operation
  - Including buildings, meetings and travel



The importance of simulation

- Simulation is essential for the detector design process
  - Indispensable for detector and system optimization.
  - Can avoid costly mistakes and save huge amounts of money.
- Simulations are also used to deconvolve detector response from actual measurement to access the underlining physics
  - Done in many different ways, more or less explicitly
  - Accuracy is of paramount importance
  - Artifact creation and interpretation mistakes can be very damaging

Example from image processing



Summary and take away message

- Tool-driven revolutions: detector are our tools
- 70-20-10 model: need to support also blue sky R&D. It's a long process.
- git model: distributed, but with strong coordination
- We are only human and need to eat: jobs in detector R&D.
- Directions: there are many promising developments.
- Grow stronger bi-directional connections with industry and society.
- Invest in the people and in the murky future

Some references

- A.Marchioro – CERN Seminar May 3, 2019
- ESPPU submissions (#)
- VCI2019 - The 15th Vienna Conference on Instrumentation
- ICHEP 2018: International Conference on High Energy Physics (especially D.Bortoletto's talk)
- PM2018 - 14th Pisa Meeting on Advanced Detectors
- EPSHEP-2017 – EPS Conference on HEP 2017