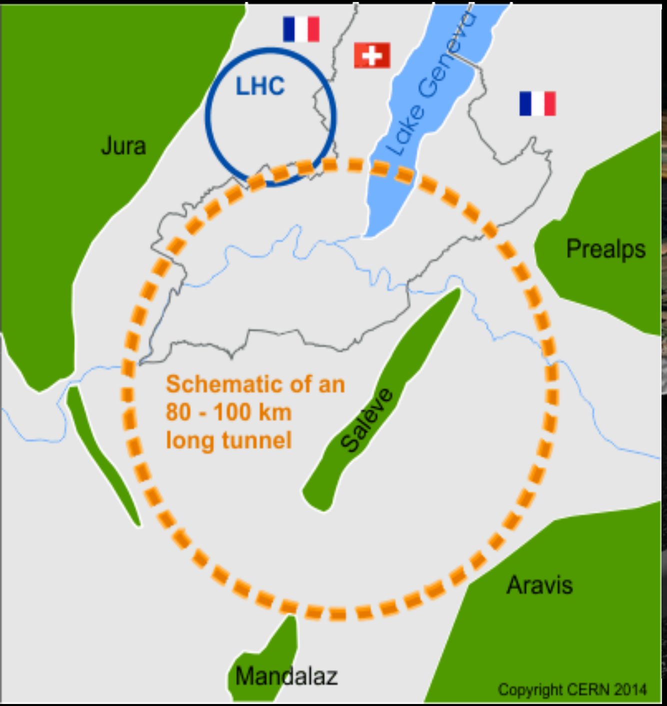
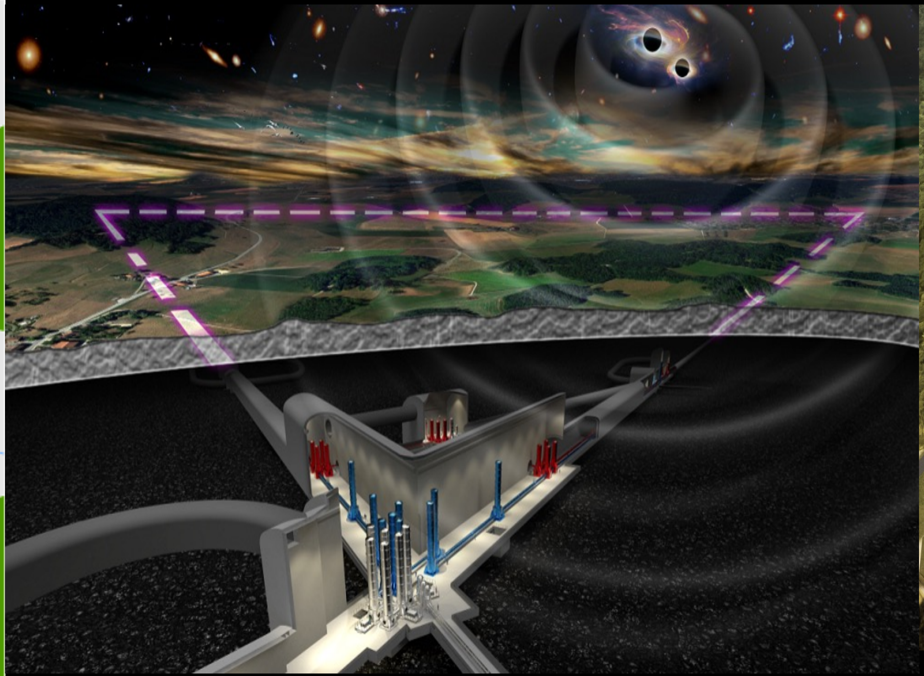
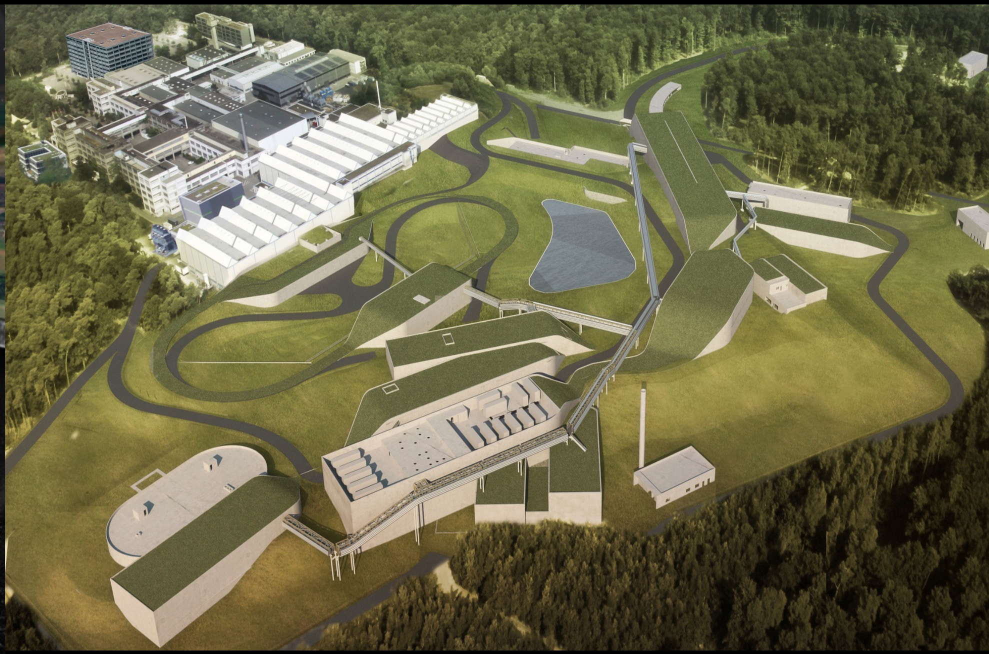
The Great Questions in Fundamental Physics and the Detector Technology Challenges to Address them via the ECFA Detector Roadmap



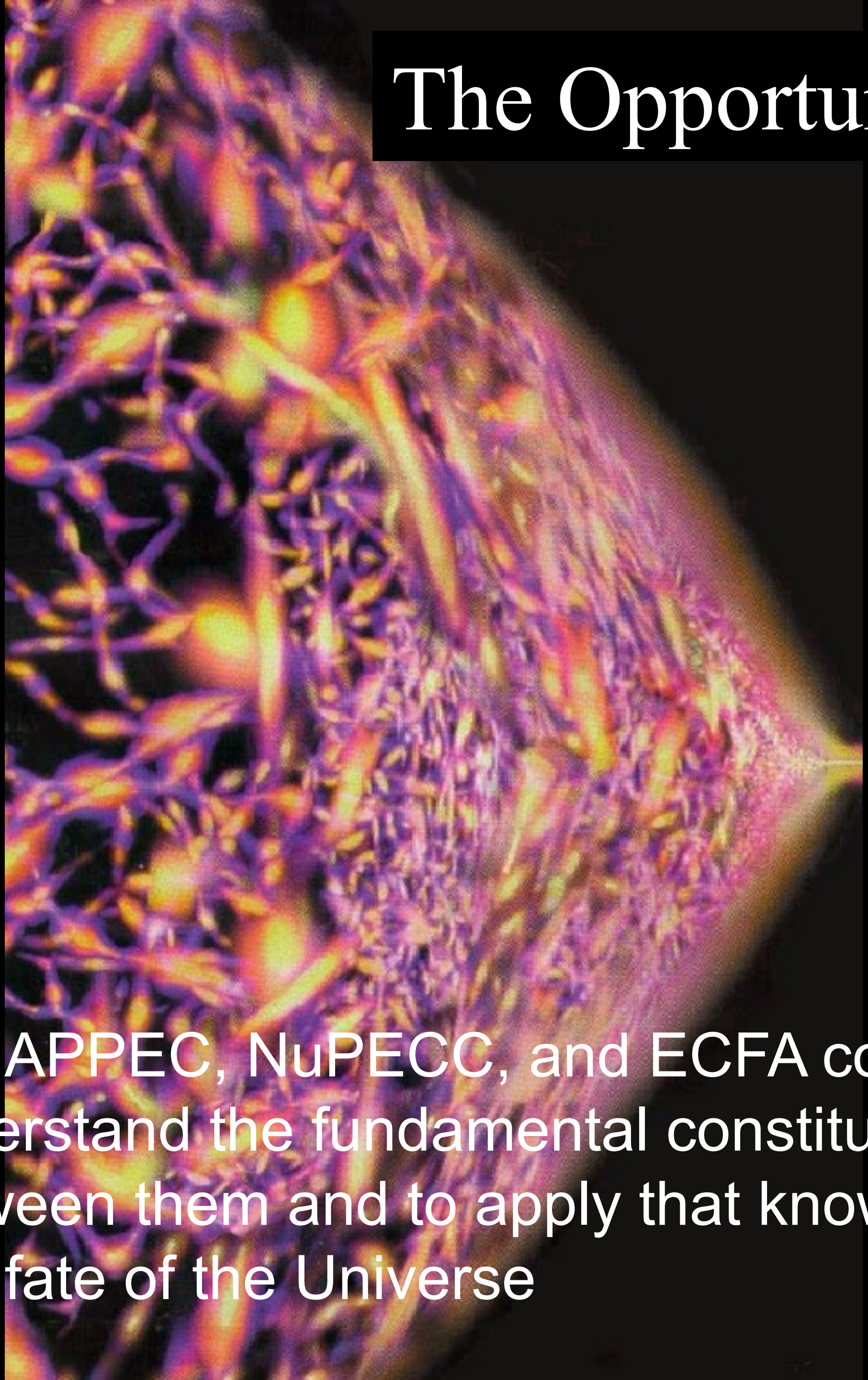




Frontier Detectors for Frontier Physics
15th Pisa meeting on advanced detectors

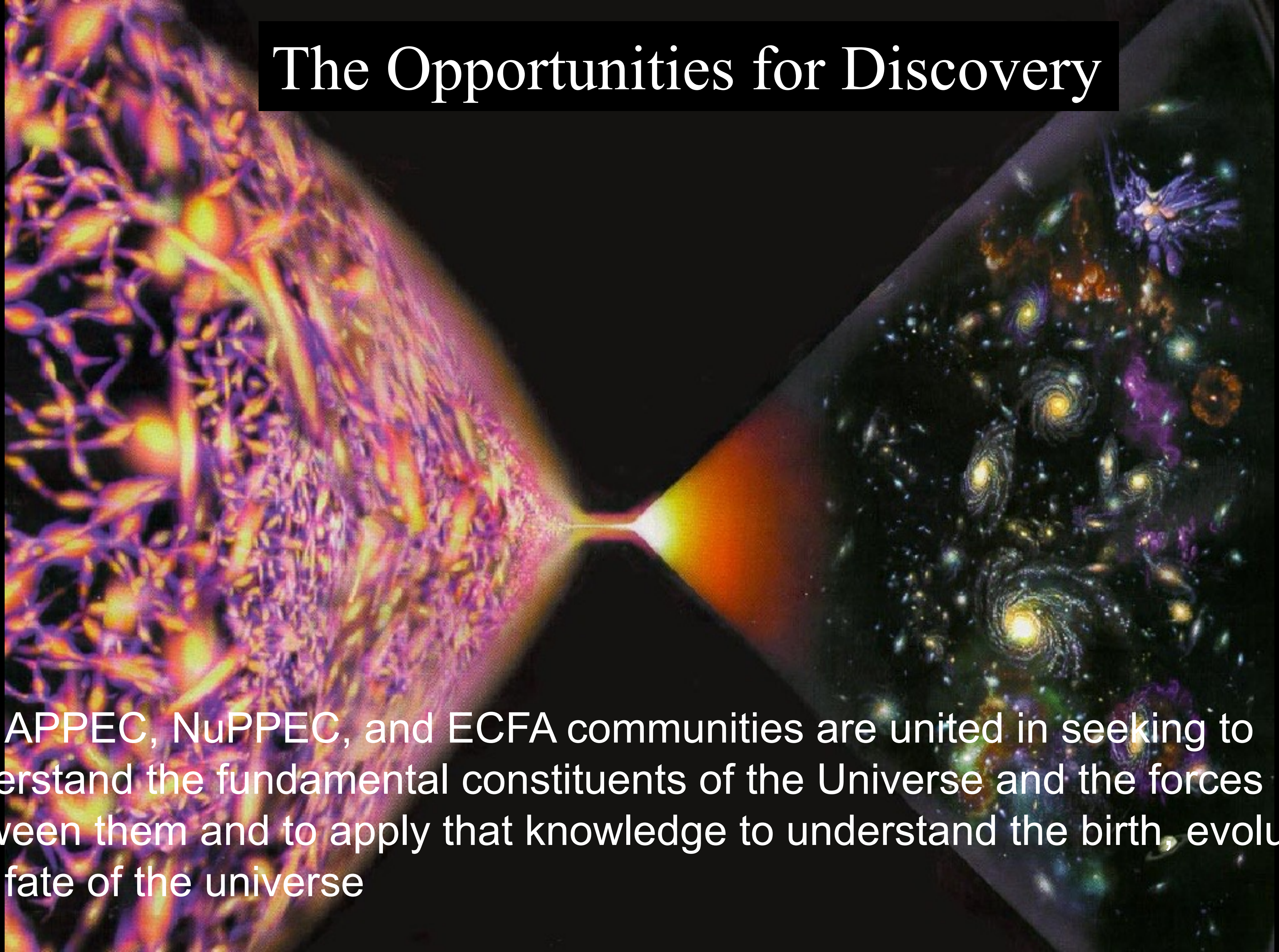
Ian Shipsey, Co-coordinator, ECFA Detector R&D Roadmap & Chair, ICFA IID Panel
Oxford University

The Opportunities for Discovery



The APPEC, NuPECC, and ECFA communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the Universe

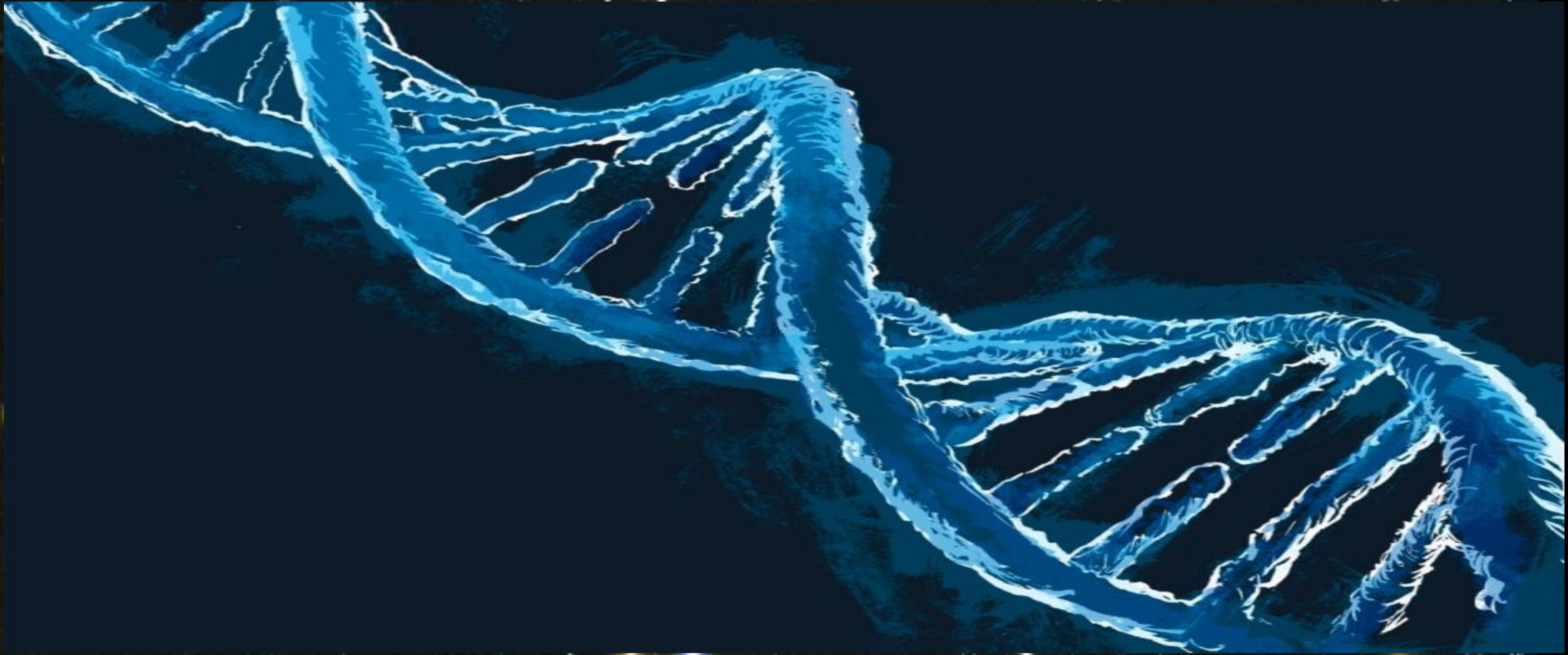
The Opportunities for Discovery



The APPEC, NuPPEC, and ECFA communities are united in seeking to understand the fundamental constituents of the Universe and the forces between them and to apply that knowledge to understand the birth, evolution and fate of the universe

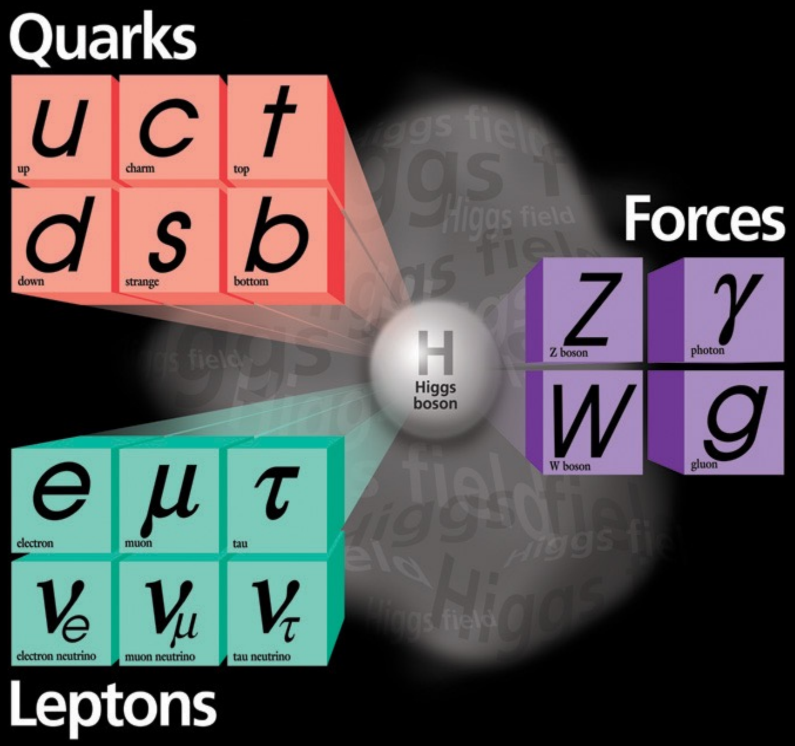
BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Our communities have revolutionized human understanding of the Universe – its underlying code, structure and evolution

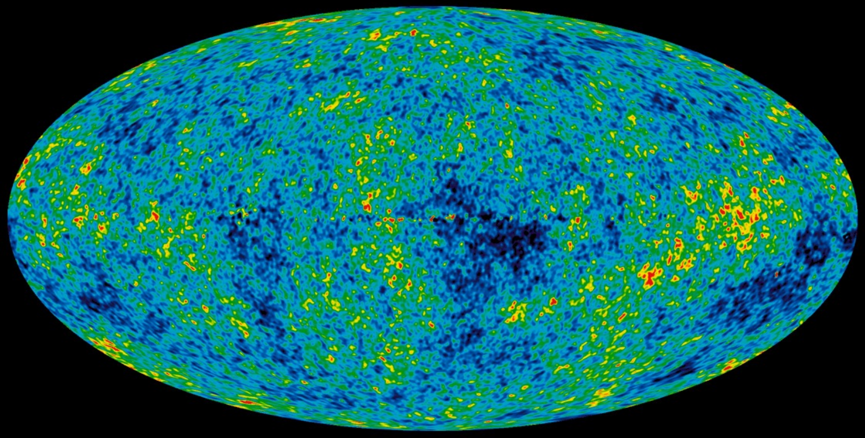


BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

Particle Standard Model



Cosmology Standard Model



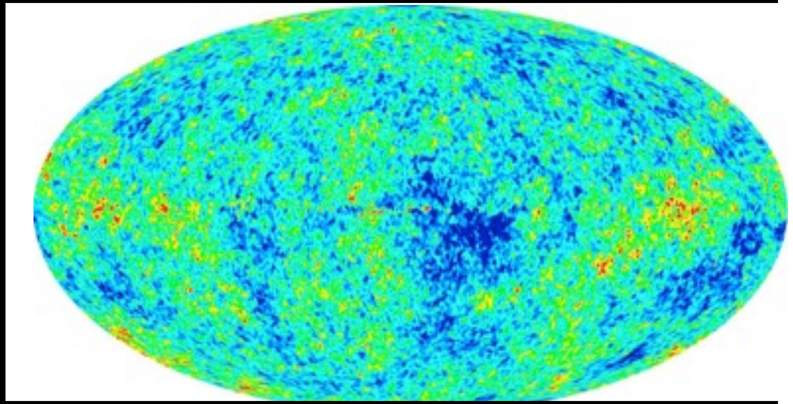
Λ_{CDM}

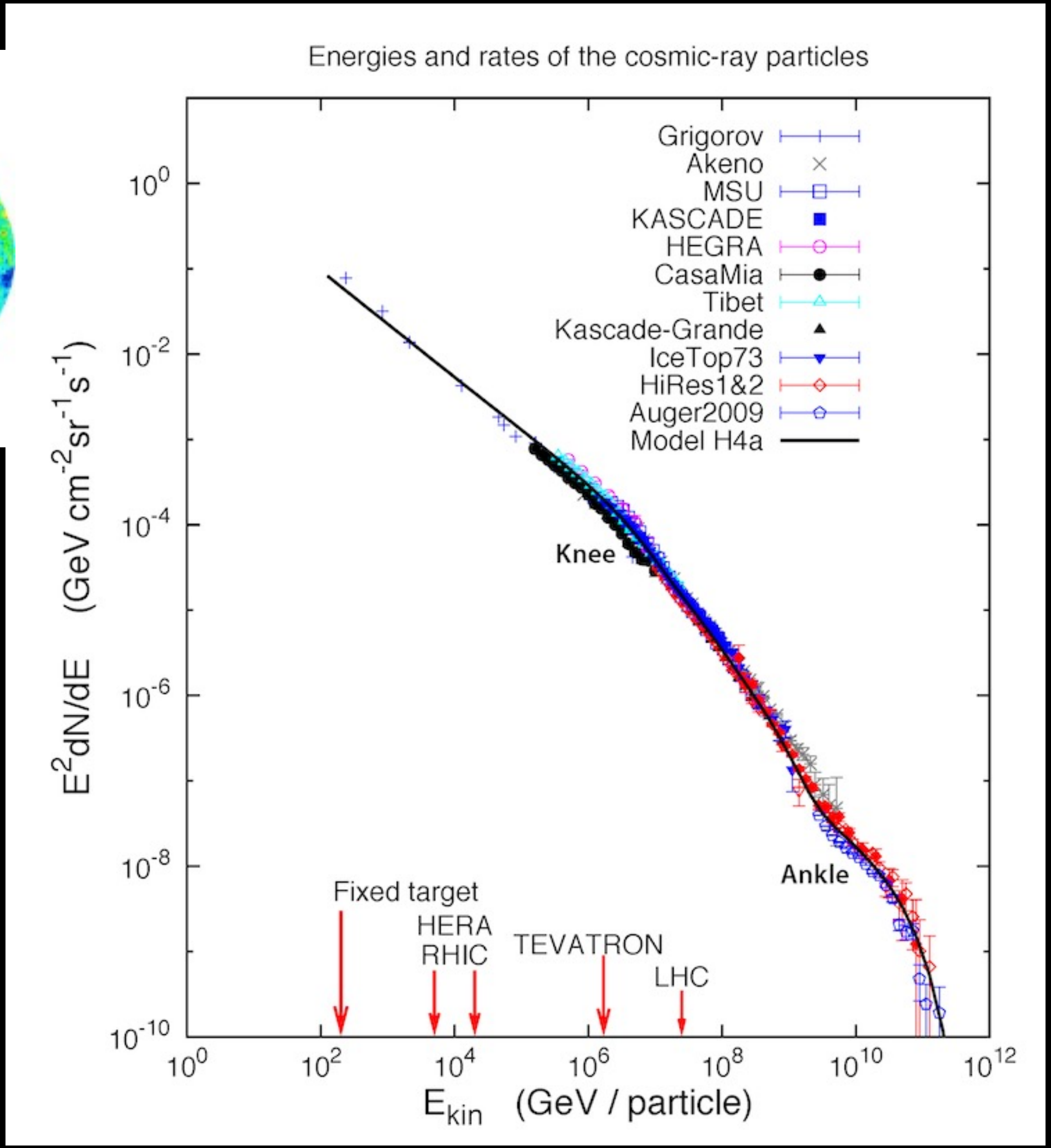
……enabled by instrumentation

APPEC
ECFA
NuPECC

Our APPEC/ECFA/NuPECC scope is broad and we deploy many tools; accelerator, non-accelerator, astrophysical & cosmological observations all have a critical role to play

Detect & Measure over 24 orders of magnitude

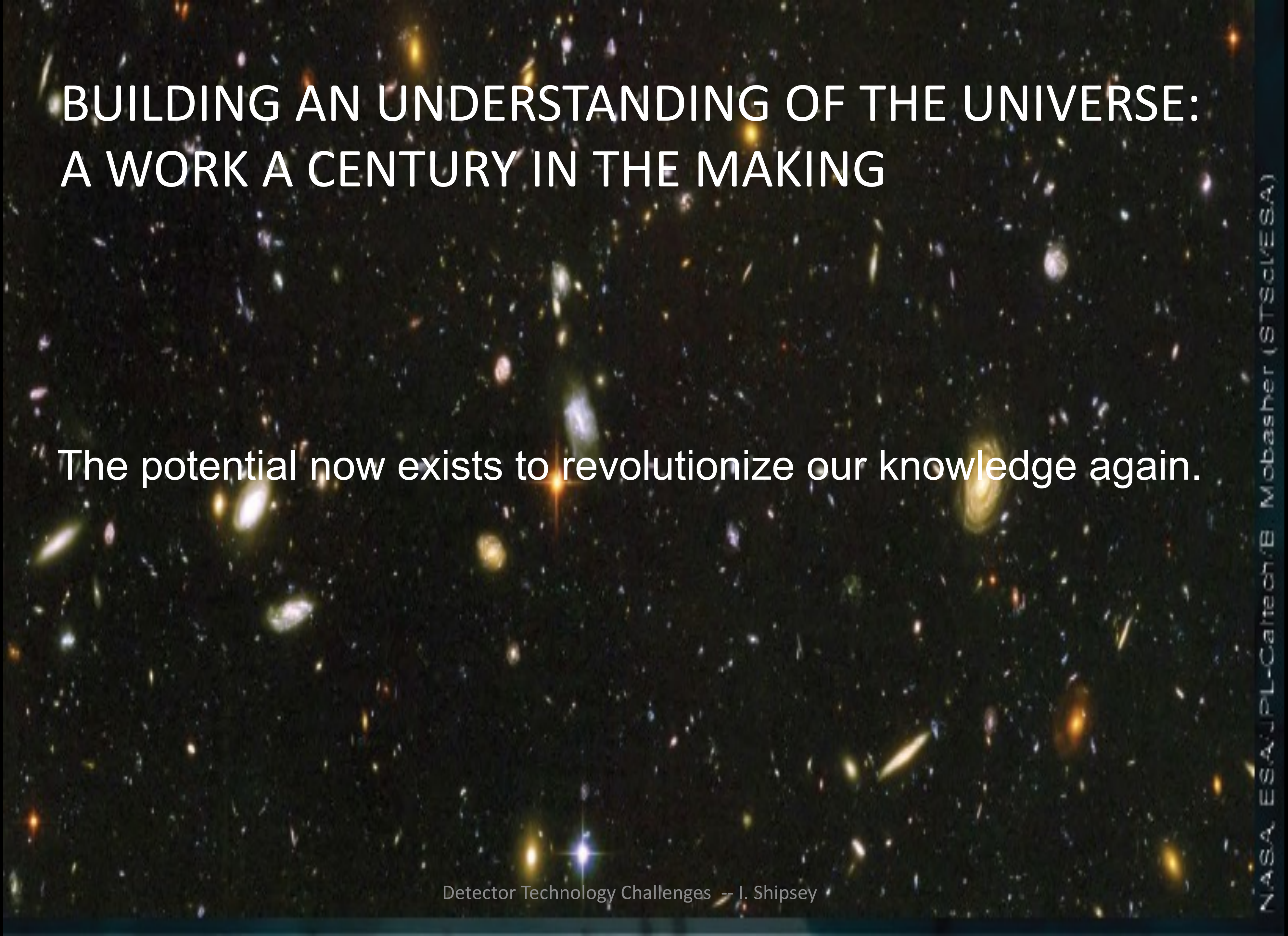




A Rich Spectrum of Technologies Developed by our Community

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

The potential now exists to revolutionize our knowledge again.



Opportunities for Discovery

Many mysteries to date go unanswered including:

The mystery of the Higgs boson

The mystery of Neutrinos

The mystery of Dark Matter

The [redacted] mystery of Dark Energy

The mystery of quarks and charged leptons

The mystery of Matter – anti-Matter asymmetry

The mystery of the Hierarchy Problem

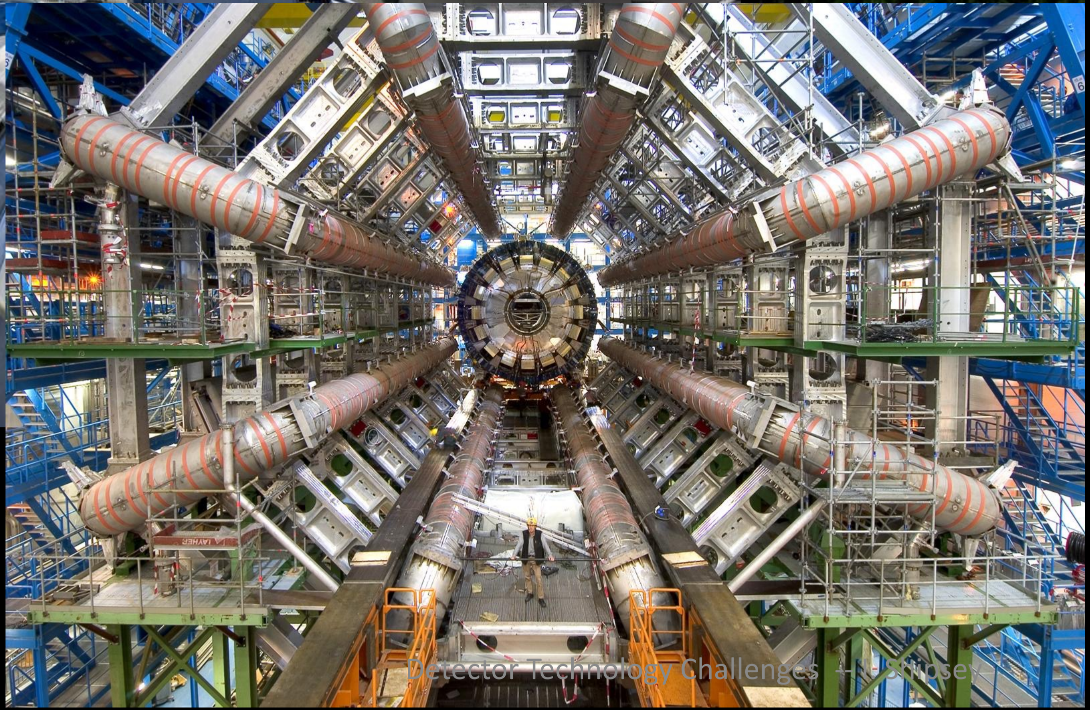
The mystery of the Families of Particles

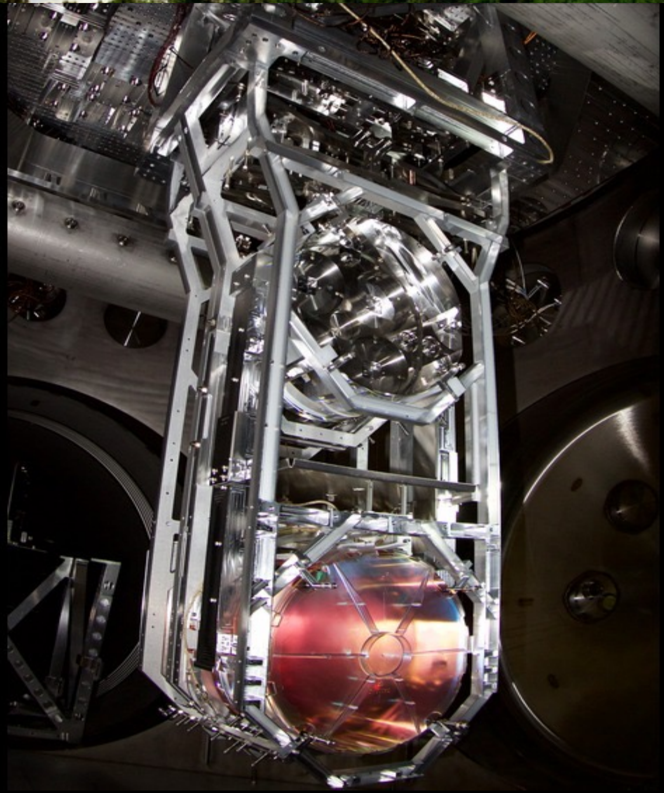
The mystery of Inflation

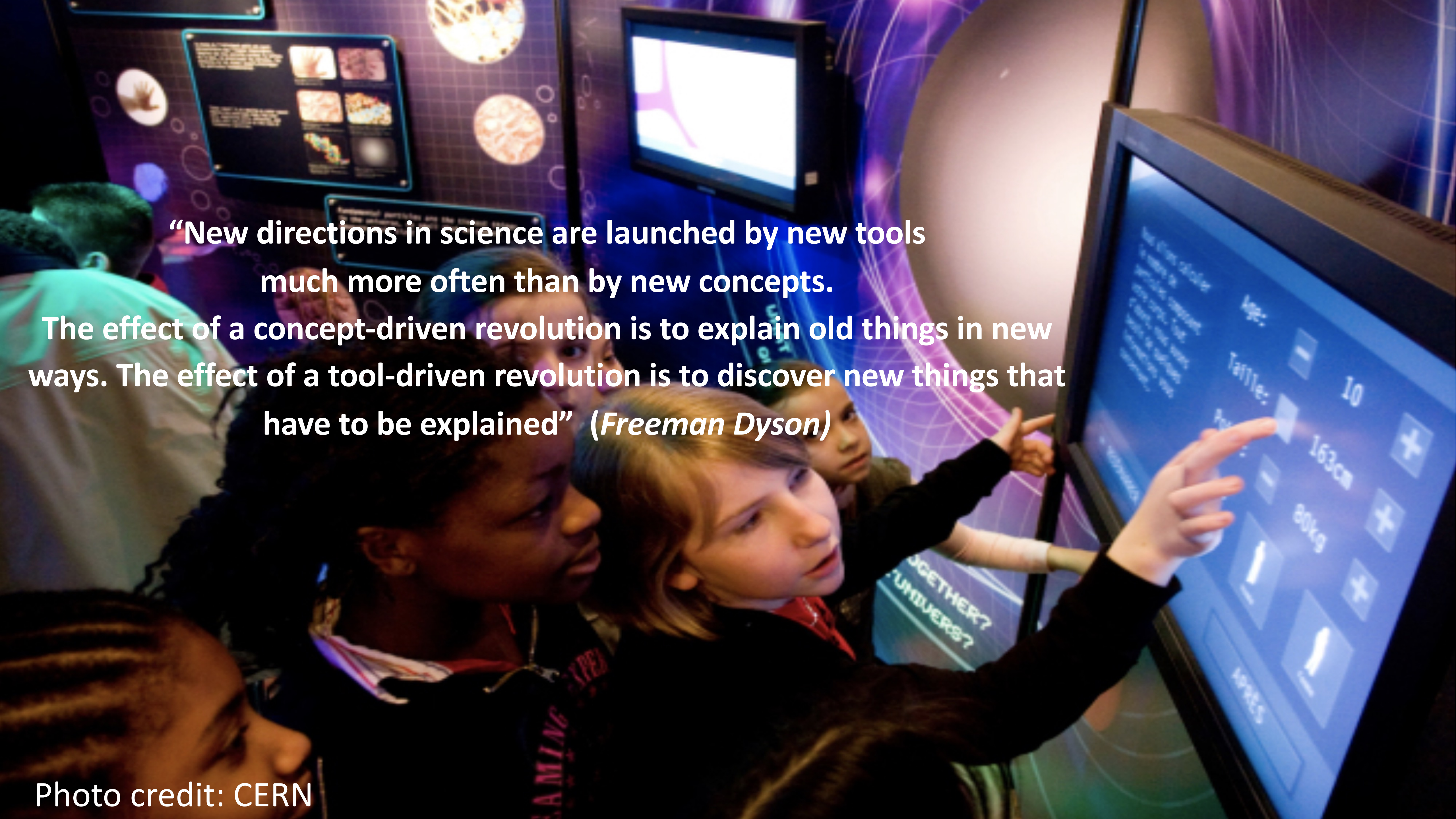
The mystery of Gravity

We are very much in a data driven era !

The gestation time to realize the tools and the experiments e.g. LHC & LIGO are decades long! For the most ambitious future experiments e.g FCCee/hh & Einstein Telescope to take the data and seize the opportunities for discovery, we must develop the tools (instrumentation and facilities) we need NOW.







“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)*

Photo credit: CERN

"Measure what is measurable, and make measurable what is not so" (*Galileo Galilei*)

Photo credit: CERN

Discoveries in particle physics

Based on an original slide by S.C.C. Ting

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN (1960)	π N interactions	
AGS BNL (1960)	π N interactions	
FNAL Batavia (1970)	Neutrino Physics	
SLAC Spear (1970)	ep, QED	
ISR CERN (1980)	pp	
PETRA DESY (1980)	top quark	
Super Kamiokande (2000)	Proton Decay	
Telescopes (2000)	SN Cosmology	

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AGS BNL (1960)	π N interactions	Two kinds of neutrinos Time reversal non-symmetry charm quark
FNAL Batavia (1970)	Neutrino Physics	bottom quark top quark
SLAC Spear (1970)	ep, QED	Partons, charm quark tau lepton
ISR CERN (1980)	pp	Increasing pp cross section
PETRA DESY (1980)	top quark	Gluon
Super Kamiokande (2000)	Proton Decay	Neutrino oscillations
Telescopes (2000)	SN Cosmology	Curvature of the universe Dark energy

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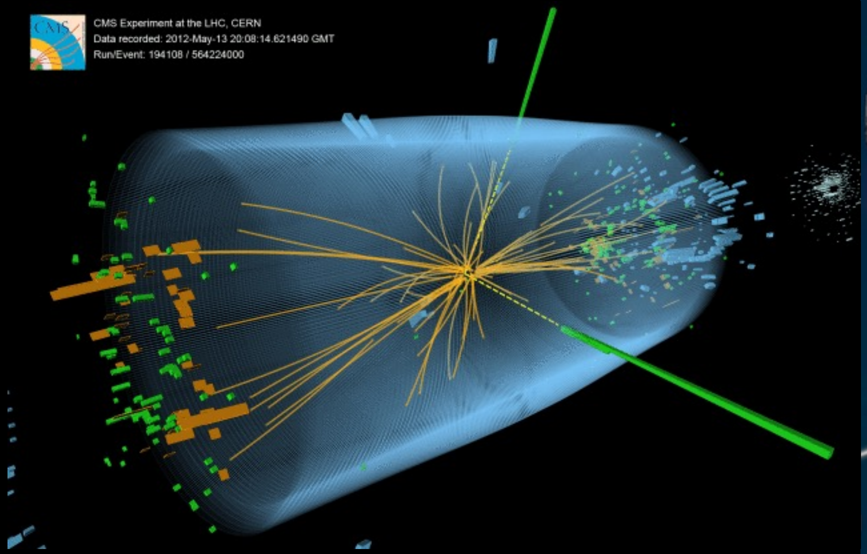
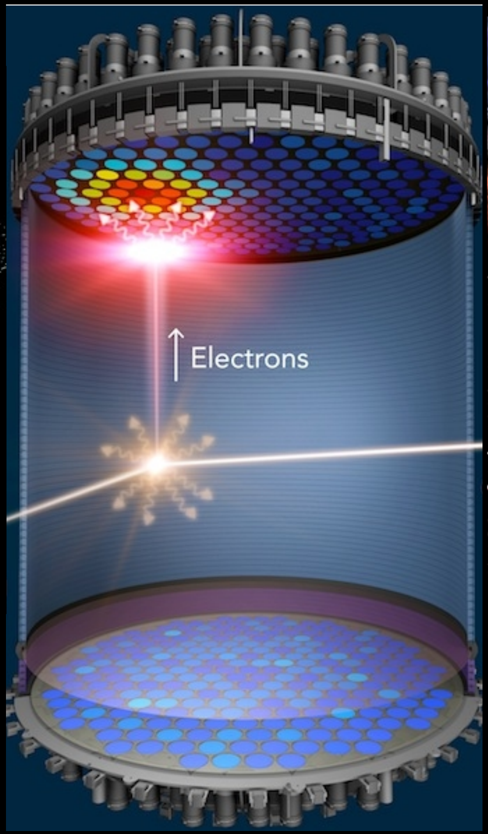
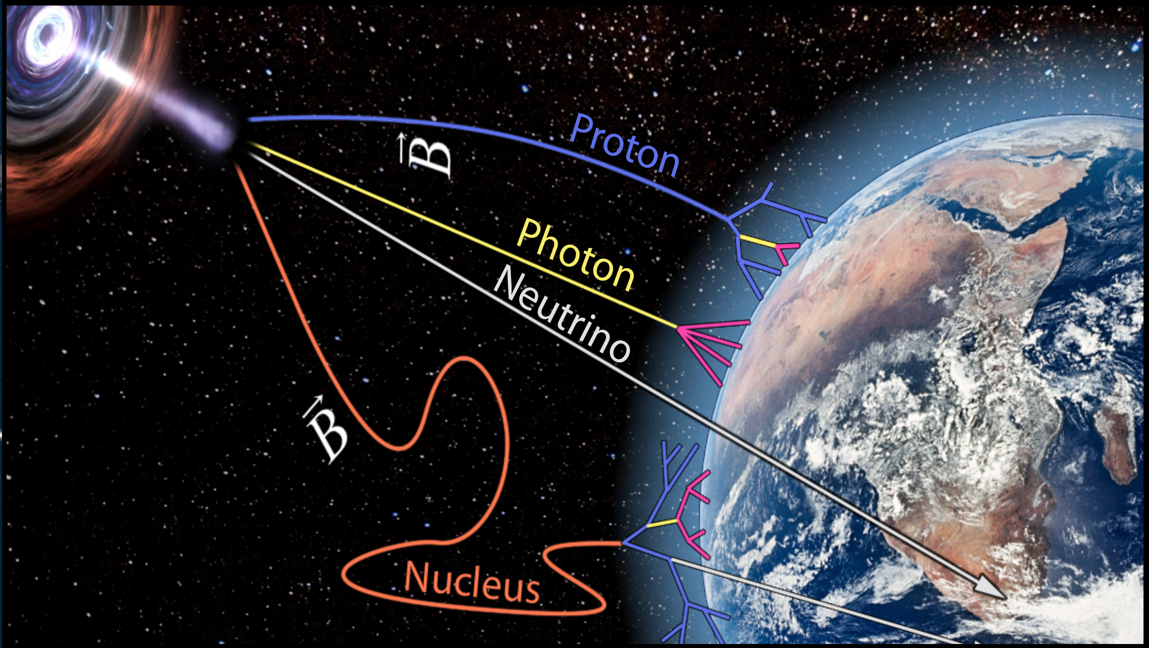
precision instruments are key to discovery when exploring new territory

Our Technologies: synergy & broad applicability

- The technologies we develop are broadly applicable across PP NP and APP & synergistically developed

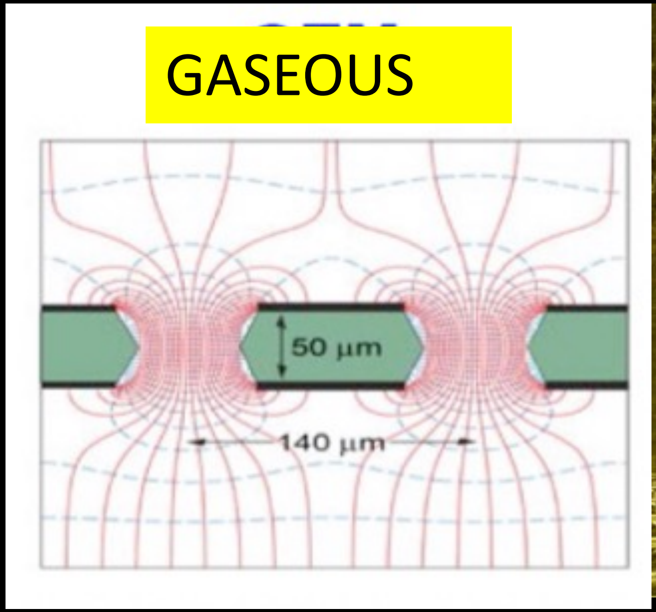


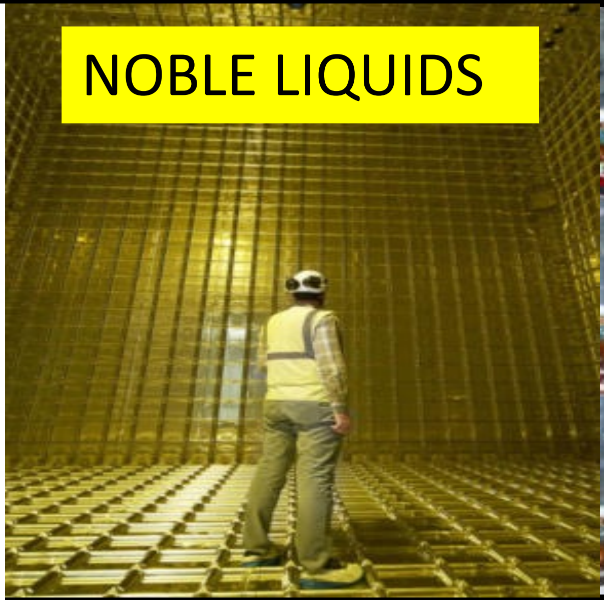


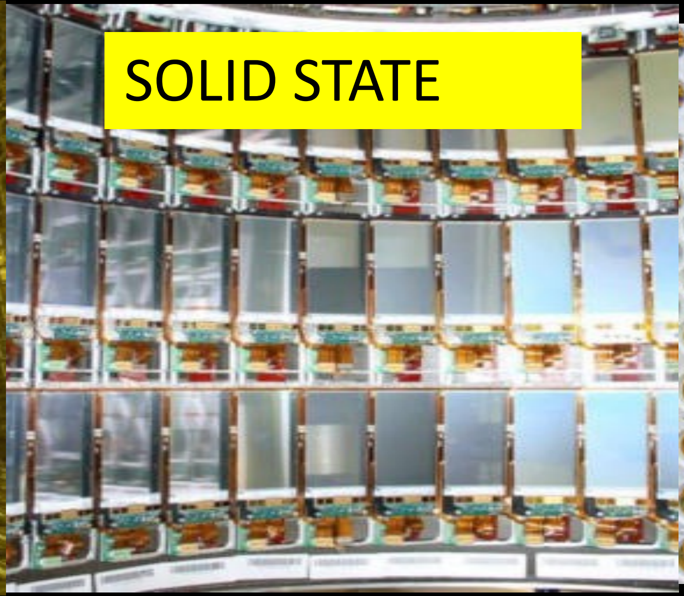


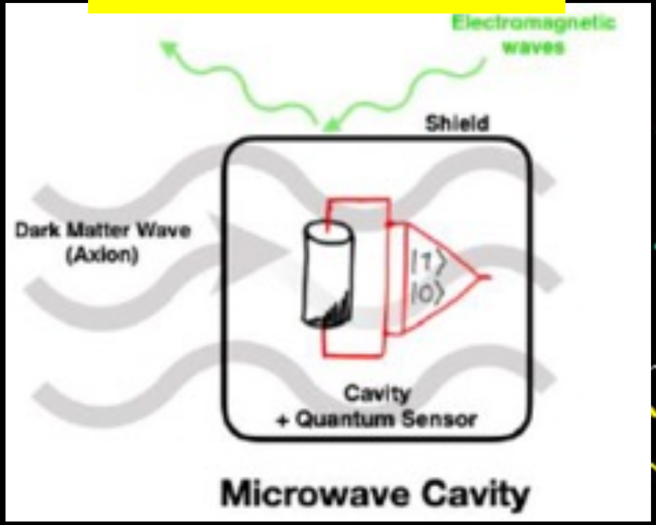
- In addition LIGO detects gravitational waves & certain quantum technologies are sensitive to dark matter waves

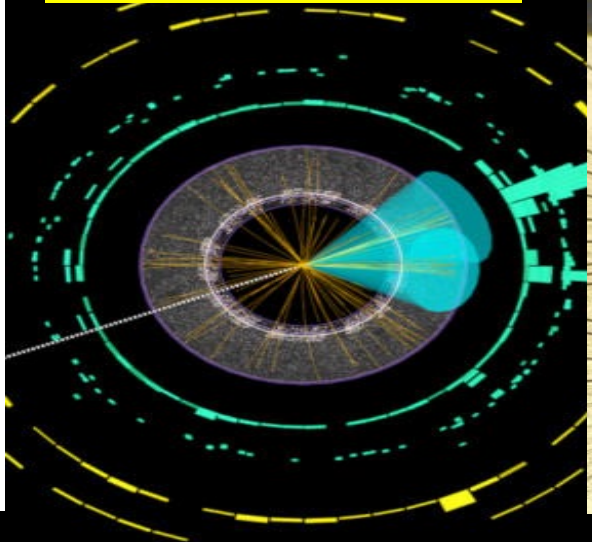
Technology Classification for the ECFA R&D Roadmap

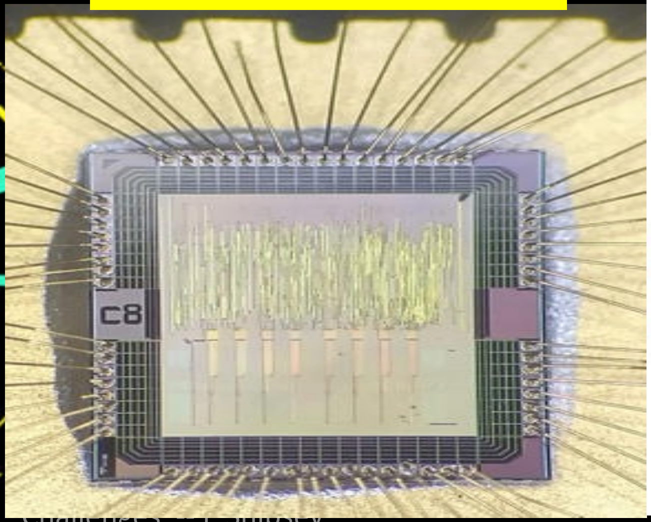


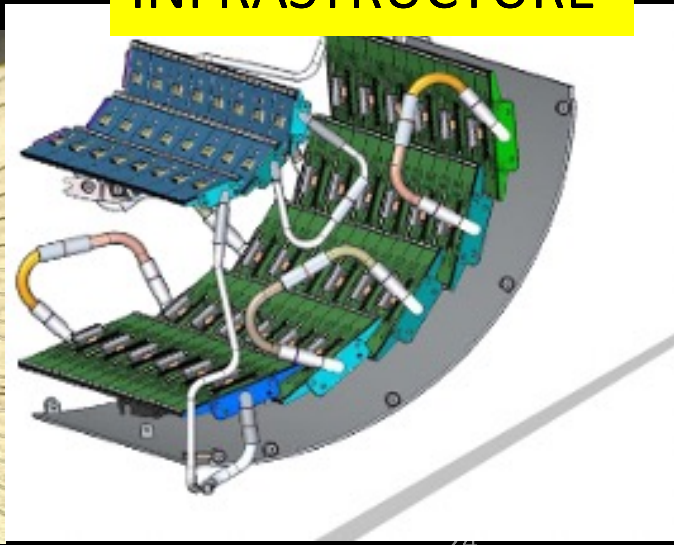








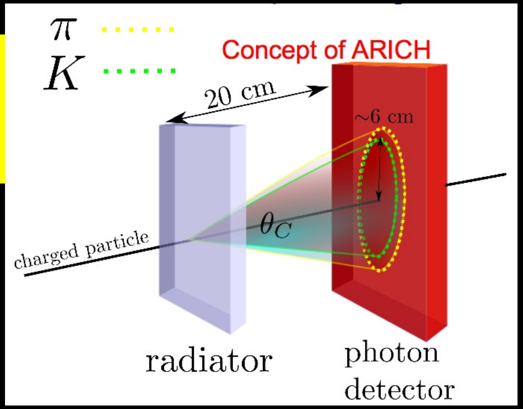


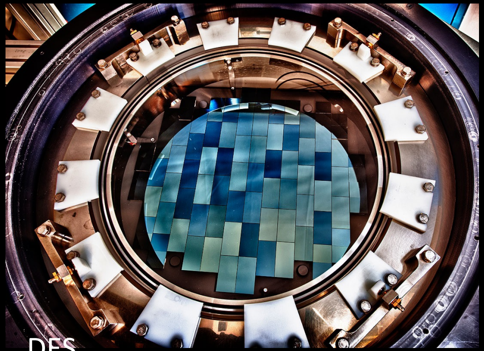


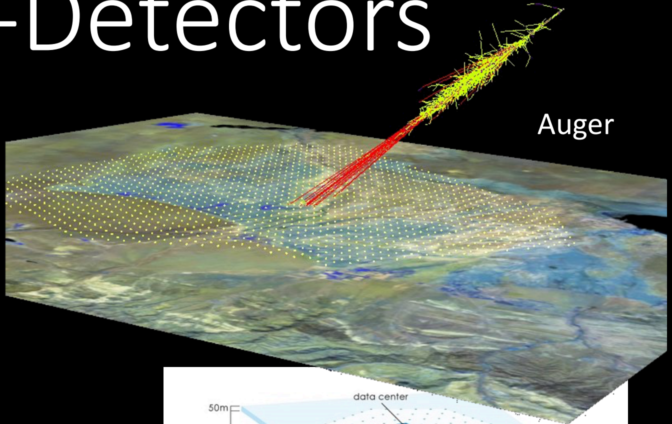
The Broad Reach of Photo-Detectors

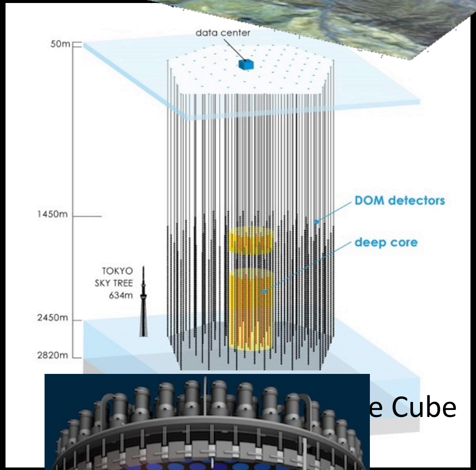
BELLE-II

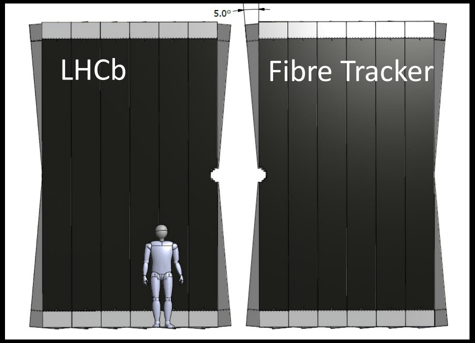
Example: Photodetectors





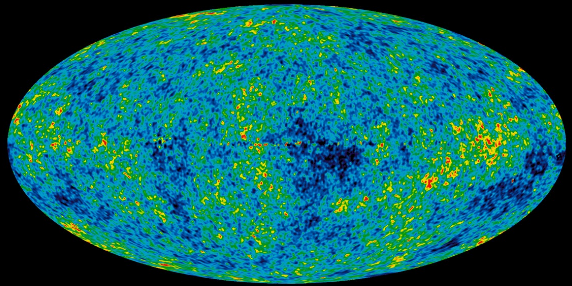


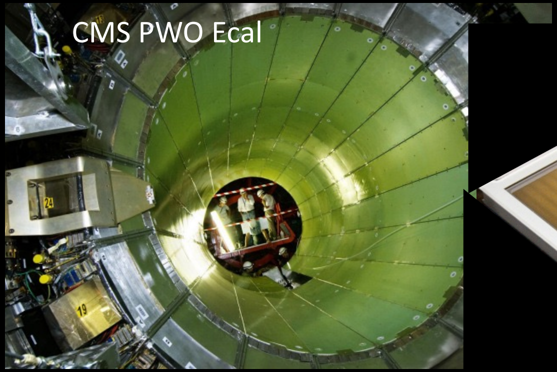


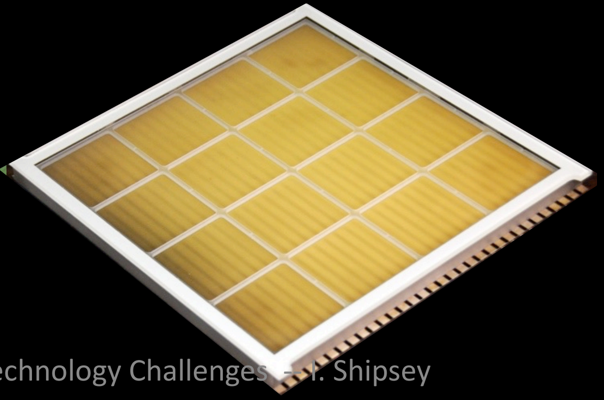


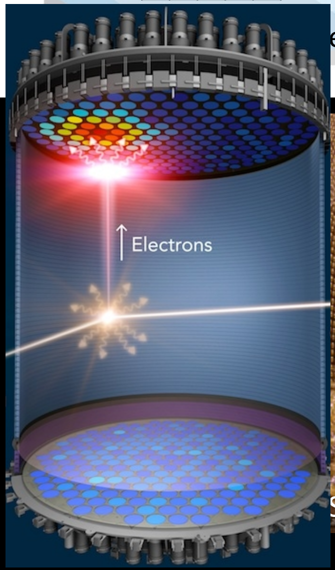
Photon detection is ubiquitous over wide range of wavelengths & signal times

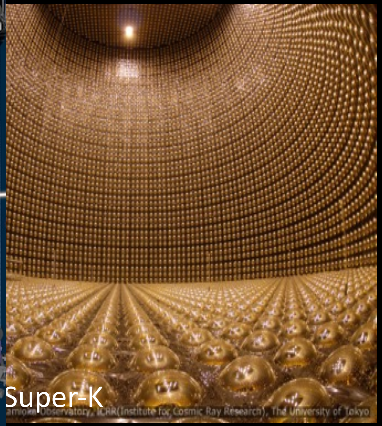
Challenge: Development of large-area devices, radiopure, cryogenic stability and high QE within appropriate wavelength sensitive window









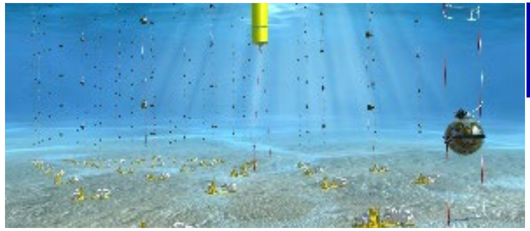


APPEC Flagship Research Infrastructures

This is not a closed, but dynamic list…

Photo-sensors play a crucial role in enabling the science objectives in each of these infrastructures

[construction KM3NeT 2020-2026]



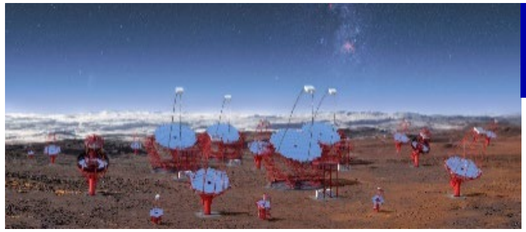
ESFRI

HE Neutrinos

[construction AugerPrime 2019-2023]

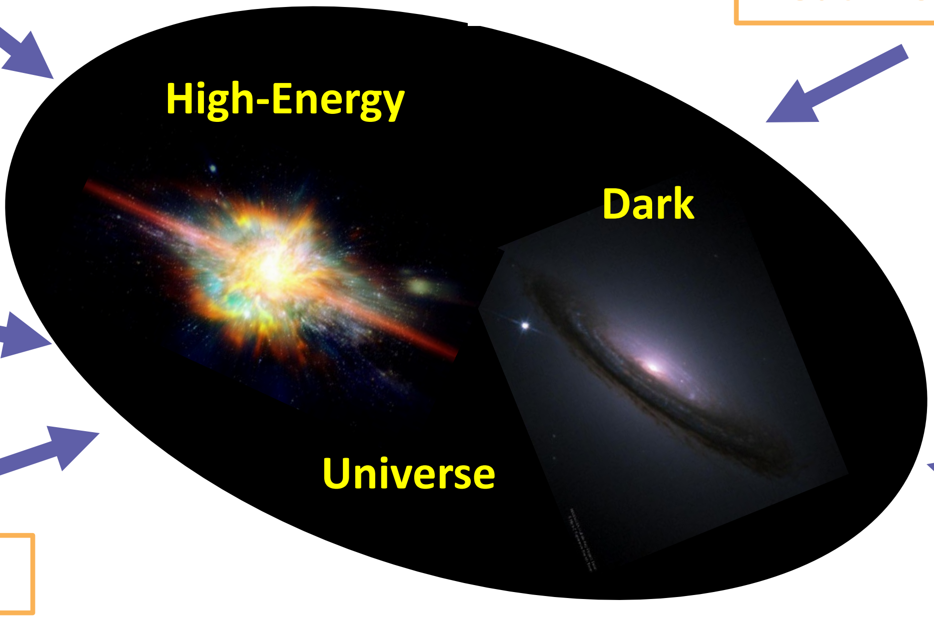
HE Cosmic Rays

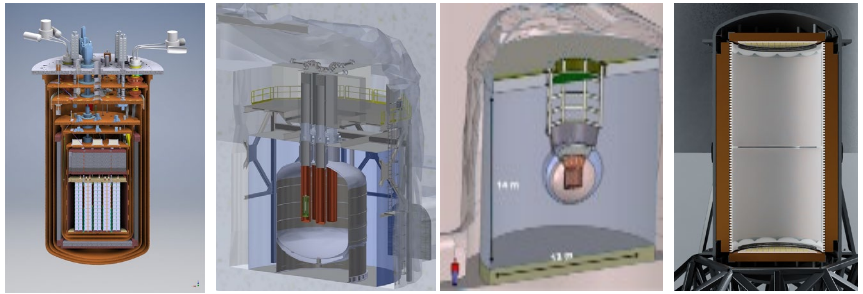
[construction CTA 2021-



ESFRI

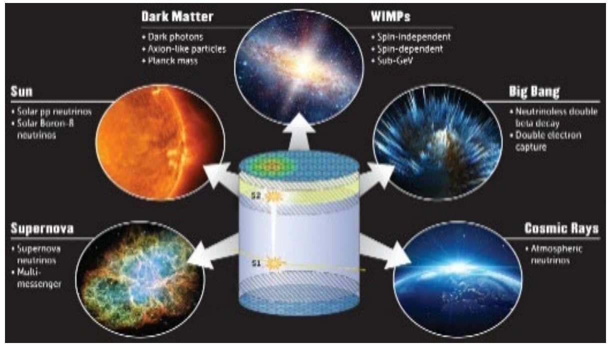
HE Gamma rays





[construction LEGEND-1000 2023-

Neutrino Properties



[construction DARWIN 2024-

Dark Matter

Modified from a slide by Andreas Haungs

High Energy Gamma-Rays Future

Detector R&D, Technical Challenges, Synergies

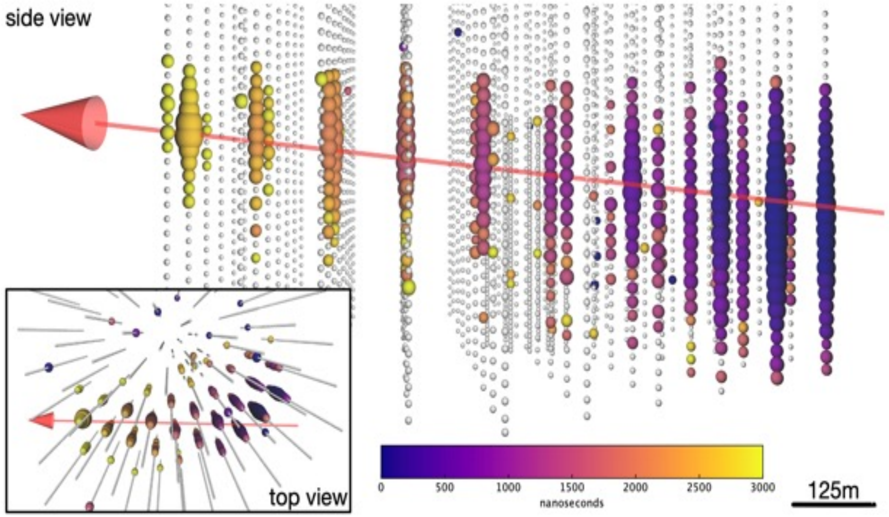
Silicon PMTs for photon and particle detection
Improving Blue-UV (Cherenkov) sensitivity, time resolution, dynamic range, ++
Fast digitisation at the detector
Common requirements with Dark Matter and DUNE (neutrino oscillation experiment)

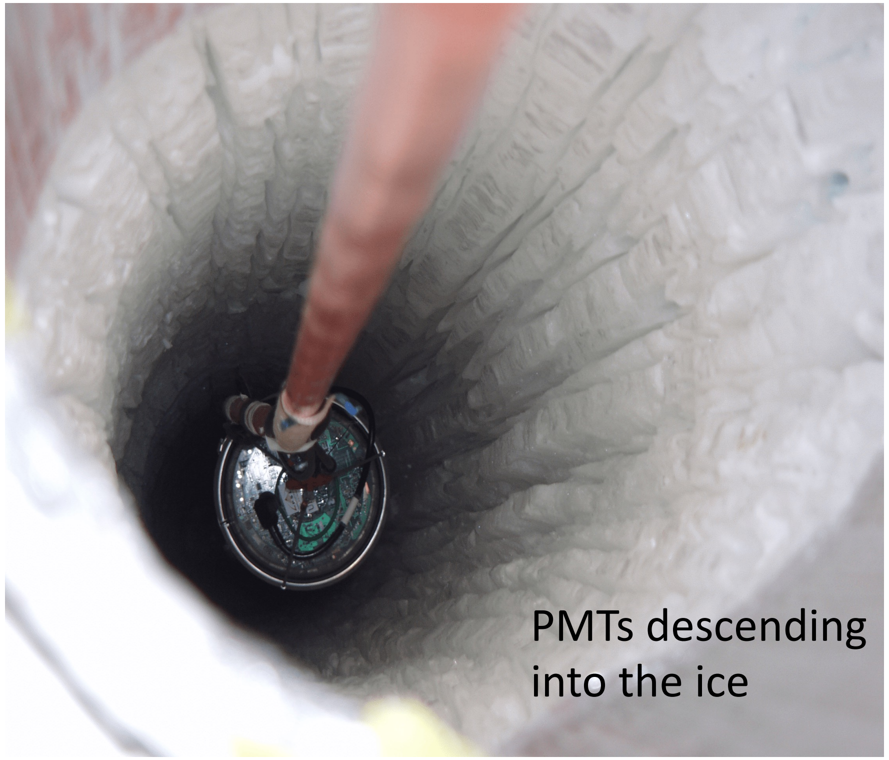
CTA

Event classification -> machine learning becoming important synergy with many fields

Photomultipliers

Ice Cube High Energy Neutrinos

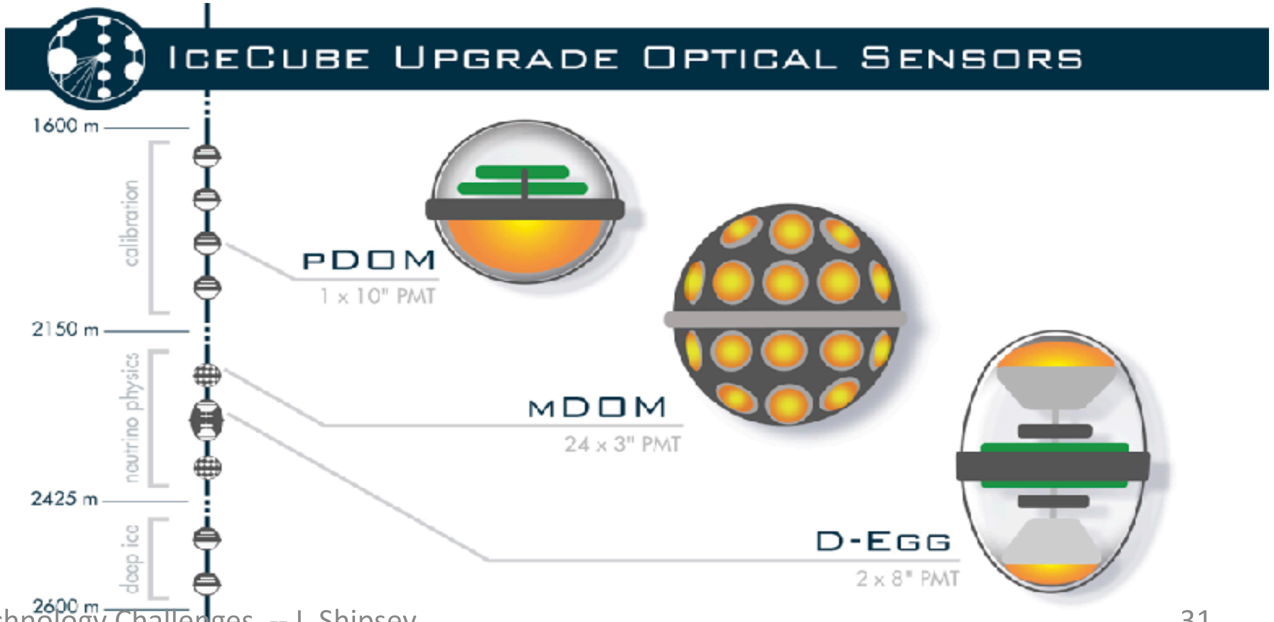




PMTs descending into the ice

Ice-Cube Gen2

- Increase the annual rate of observed cosmic neutrinos by a factor of ten
- Detect sources five times fainter than its predecessor
- (Addition of a radio array, IceCube-Gen2 will extend the energy range by several orders of magnitude)
- Planned for 2033



NOW

mDOM
(production starting)

24 x 3'' PMTs
Diameter 36 cm

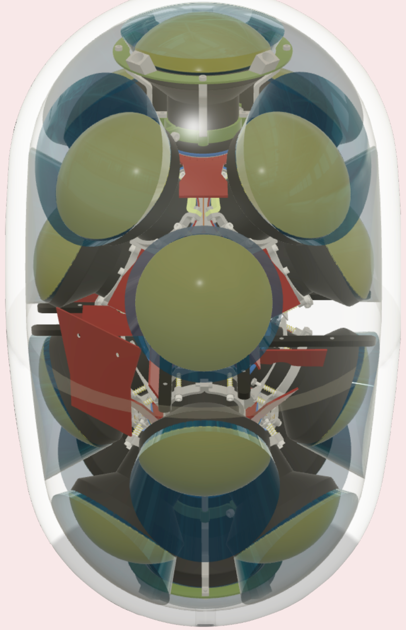
Developed by KM3NET

D-Egg
(production completed)

2 x 8'' HQE PMTs
Diameter 30 cm

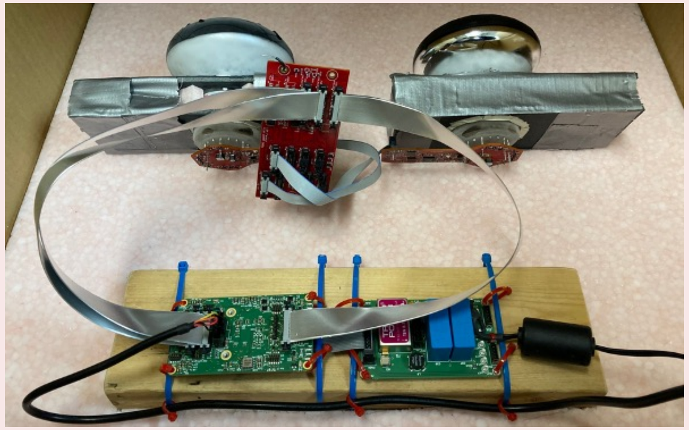
FUTURE

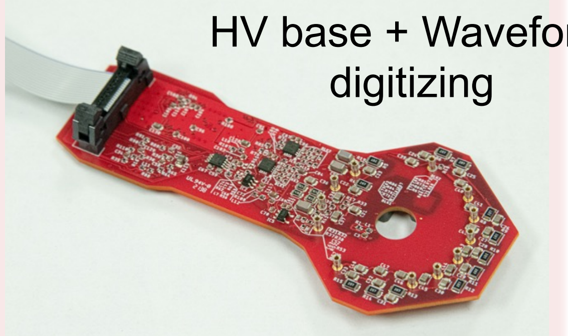
Candidate Design for Gen2



18 (16) x 4'' PMTs
Diameter 32 (31) cm

In-module electronics end-to-end testing

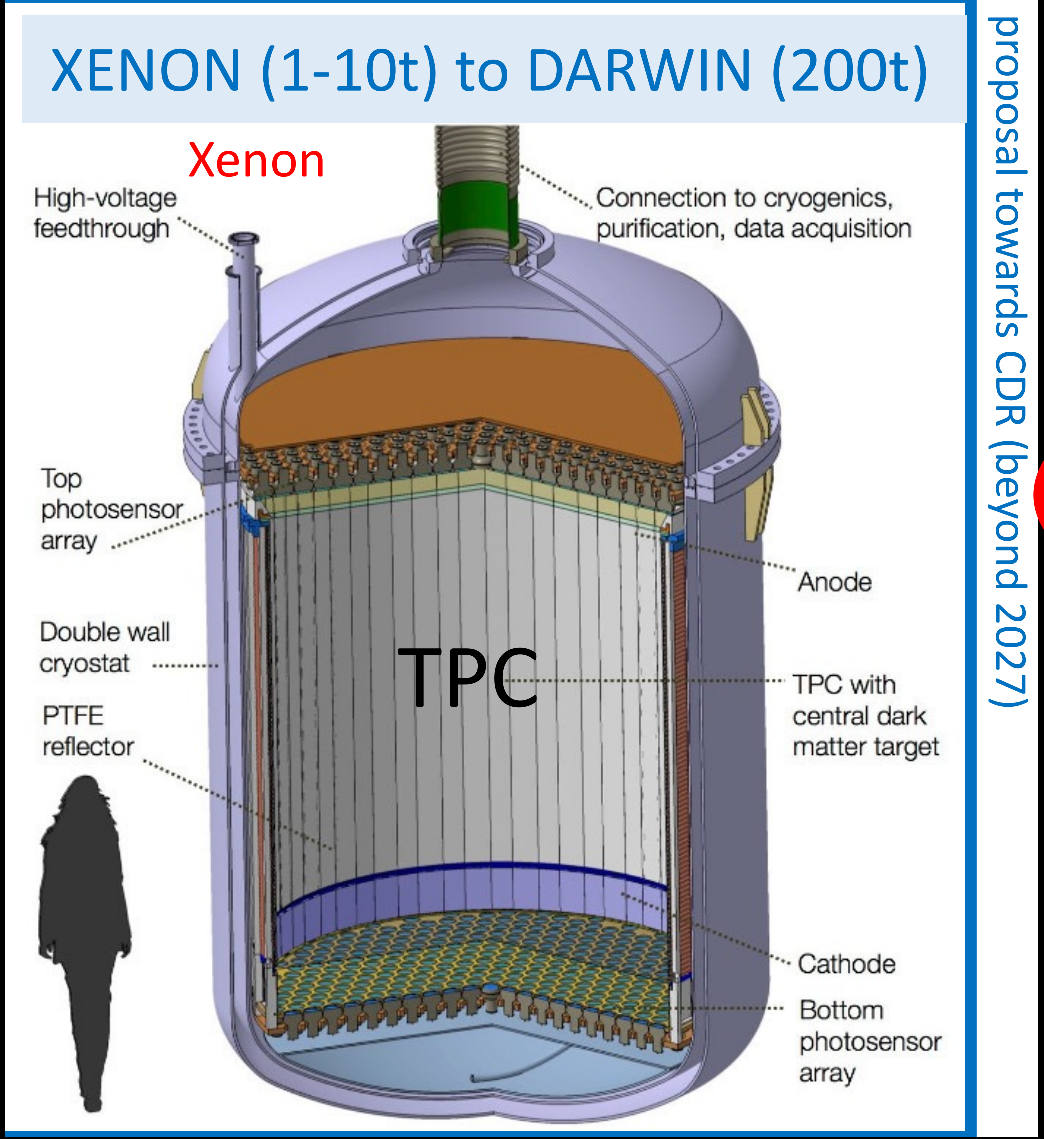




HV base + Waveform digitizing

- Evolved from mDOM & D-Egg designs
- In-module DAQ (similar to IceCube DOM)

Dark Matter Generation 3 (beyond 2027)



Detector R&D challenges ?

TPC design

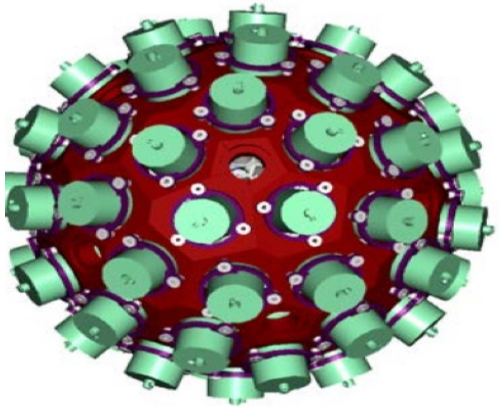
Low material Cryostat design

choice of radio-pure photosensor technology to avoid giving false positives (PMTs (baseline) SiliconPMTs & other options under evaluation)

Purity of the liquid Xenon target – large distillation columns

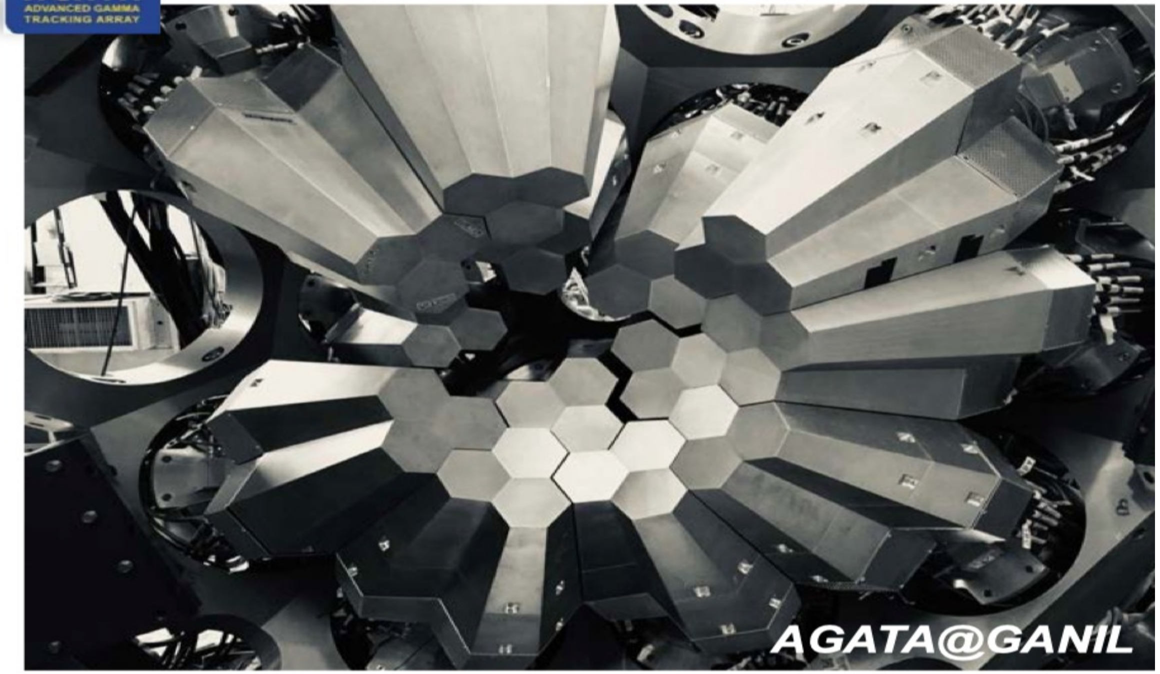
Radio-pure circulation - storage and recuperation of large amounts of xenon

AGATA: THE ultimate γ-ray spectrometer



- 180 (60 triple-clusters) 36-fold segmented crystals
- Amount of germanium: 362 kg
- Solid angle coverage: 82 %
- Singles rate >50 kHz
- Efficiency: 43% (M_{γ}=1) , 28% (M_{γ}=30)
- Peak/Total: 58% (M_{γ}=1), 49% (M_{γ}=30)
- Angular Resolution: ~1°

NuPECC LRP 2017 priority



AGATA White Book : W. Korten et al, Eur. Phys. J. A (2020) 56:137

The project timeline is to complete the array by 2030

Combination of:

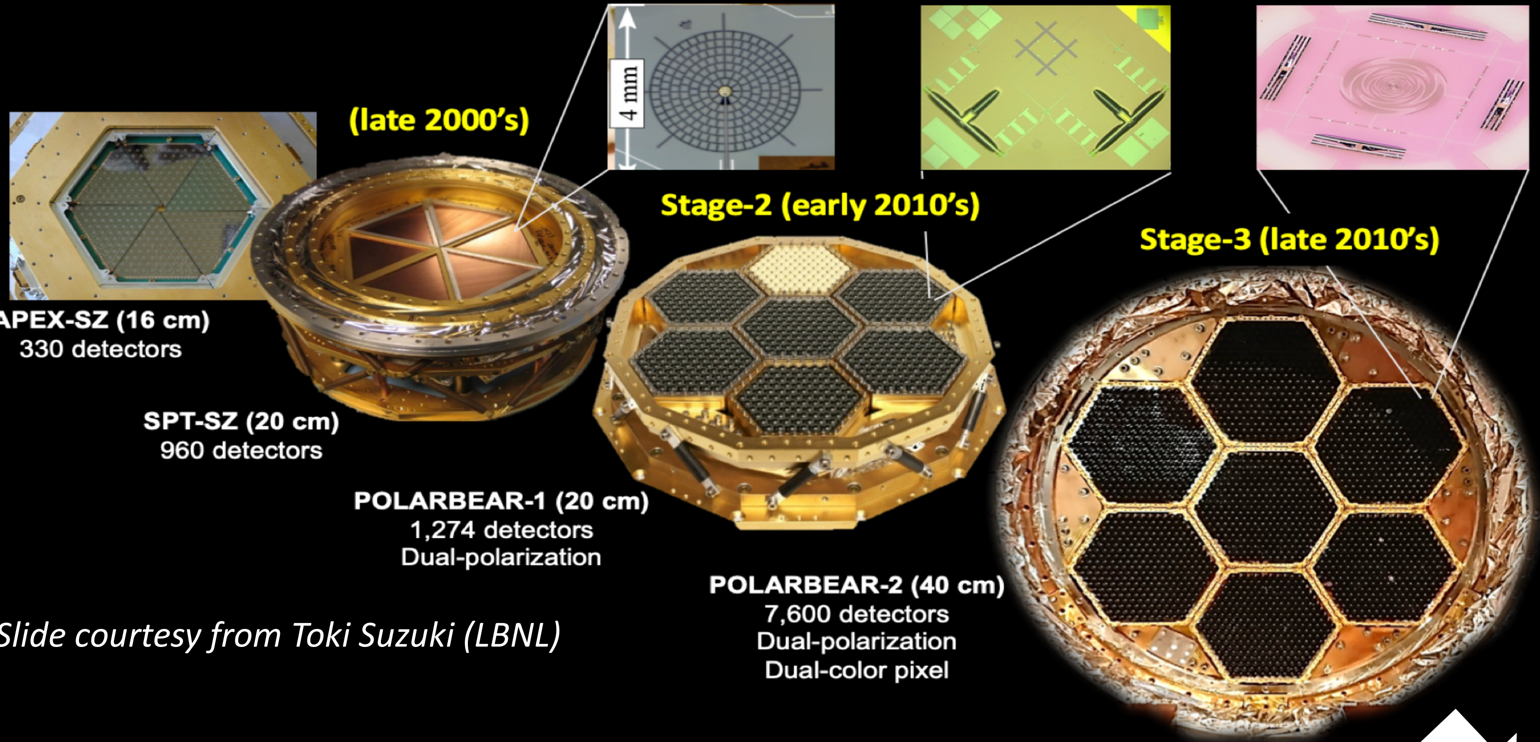
- ❑ segmented detector
- ❑ pulse-shape analysis
- ❑ tracking the γ rays
- ❑ digital electronics

Courtesy of E. Clement

Slide credit: Marek.Lewitowicz

Cosmic Microwave Background experiments

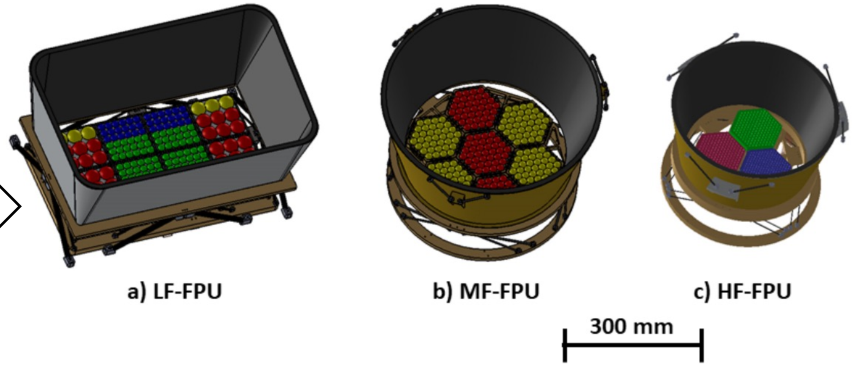
Next-generation CMB experiments are designed to probe for inflationary B-modes.

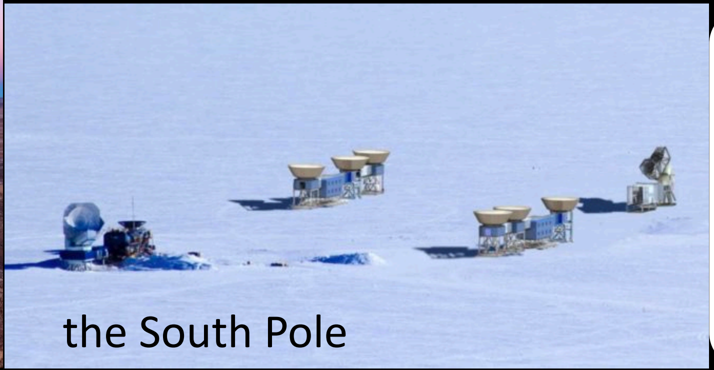


Slide courtesy from Toki Suzuki (LBNL)

LiteBIRD

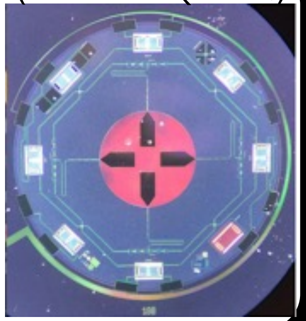
- ISAS/JAXA L-class satellite
- Launch in late 2020s
- 4508 TES bolometers at 100 mK
- Detector and readout R&D with space tech. quality control is in progress





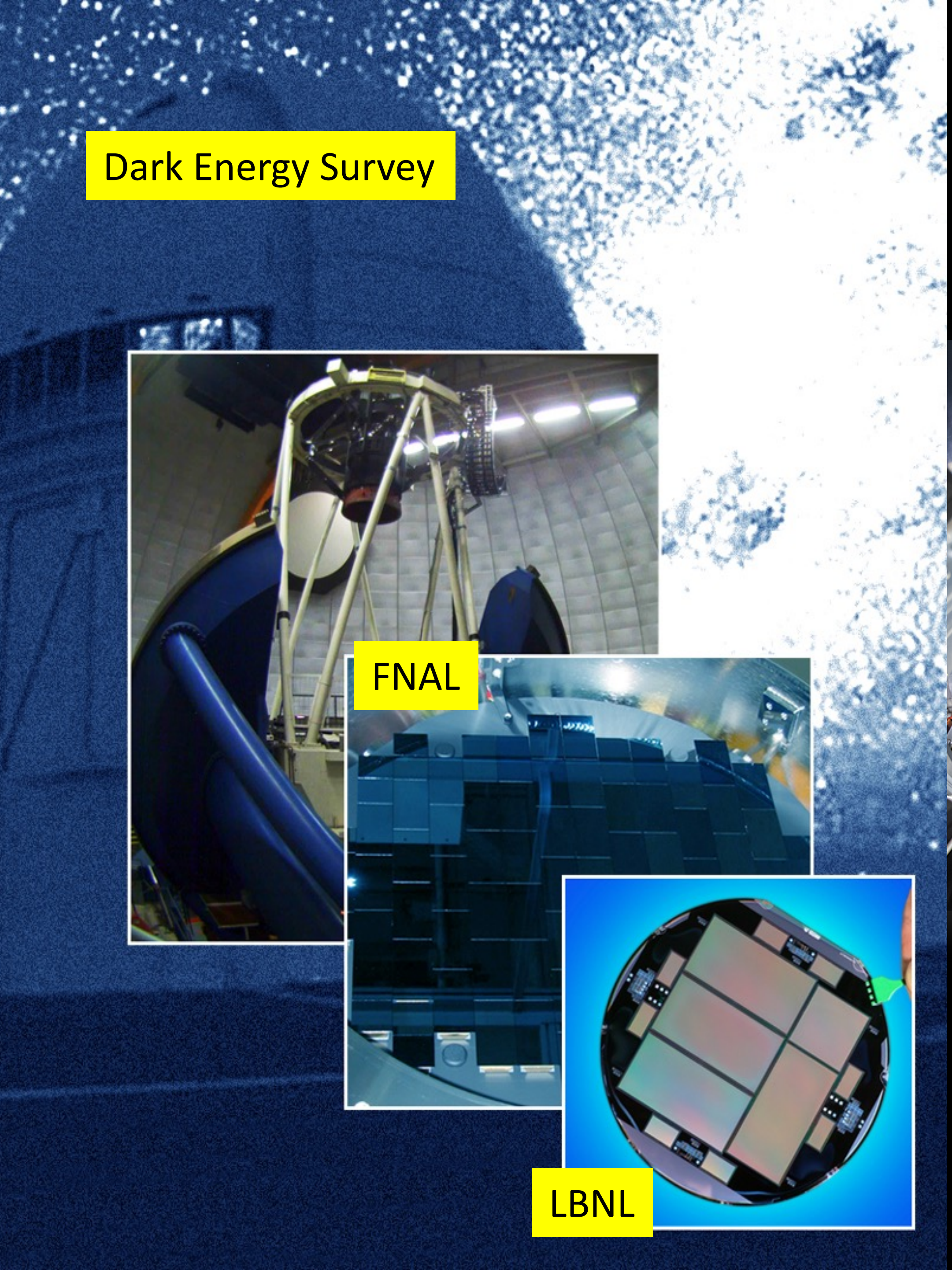
CMB-S4

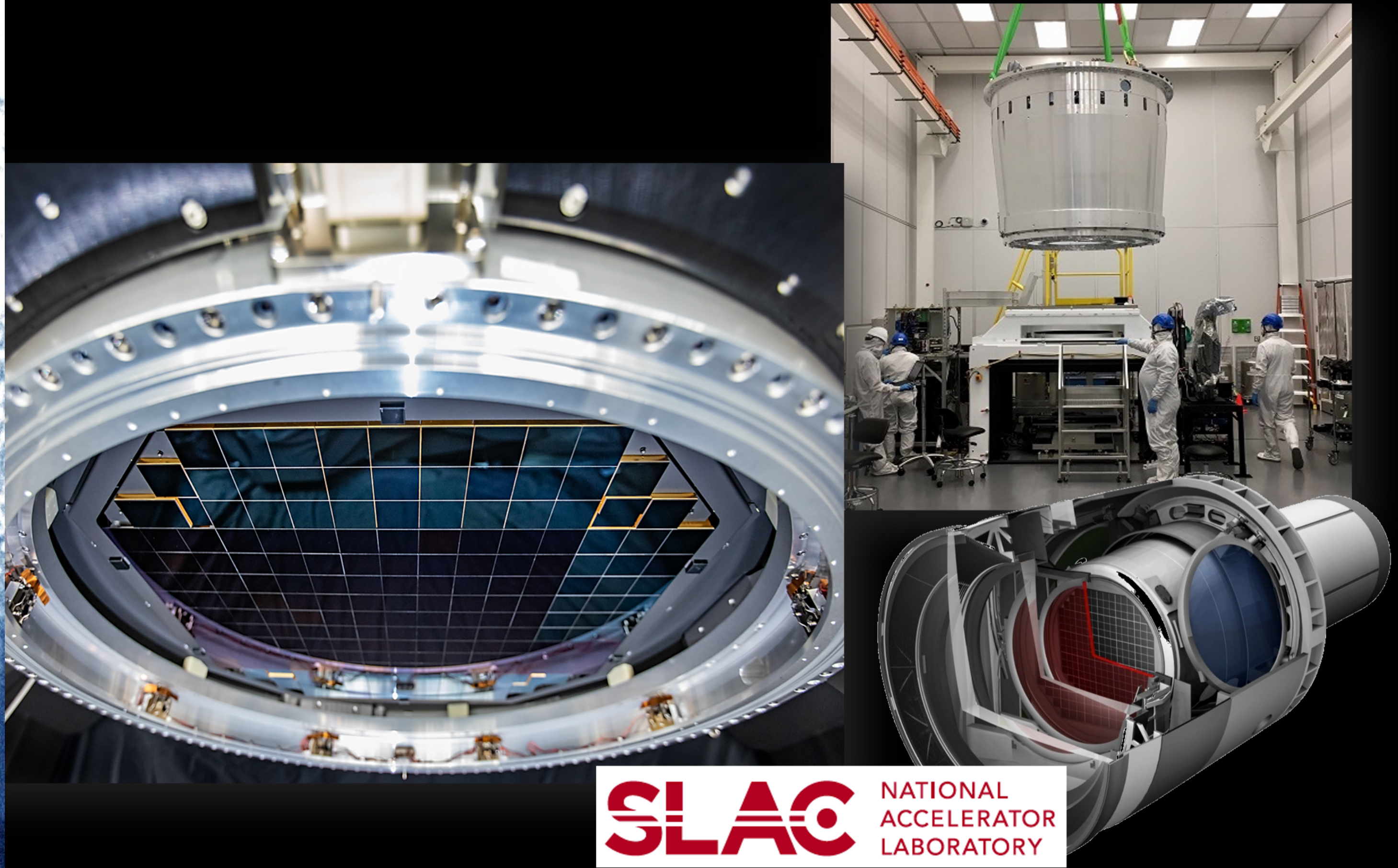
Dichroic detector (LBNL/SeeQC Inc.)



- Ground-based telescope array
- Start observing in late 2020s
- 5×10^5 TES bolometers at 100 mK
- State of art tech. and need mass production

World's Biggest Digital Camera (3200 Mpix) LSSTCam commissioning at SLAC, first light Chile, 2024

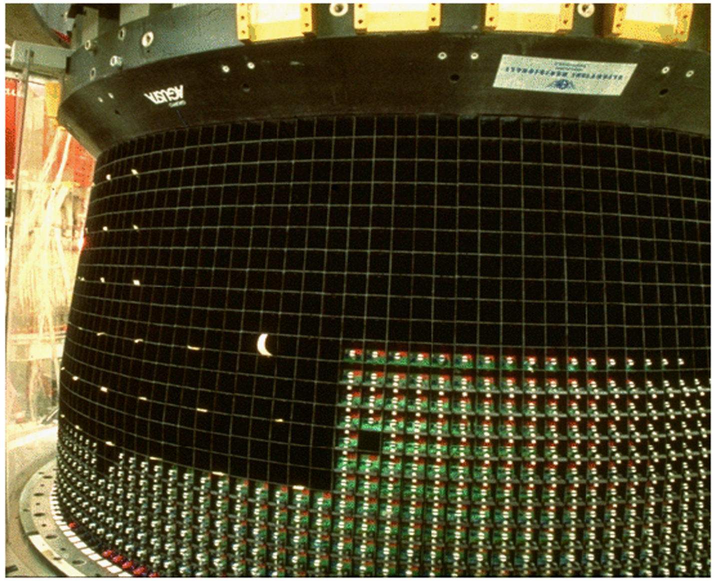


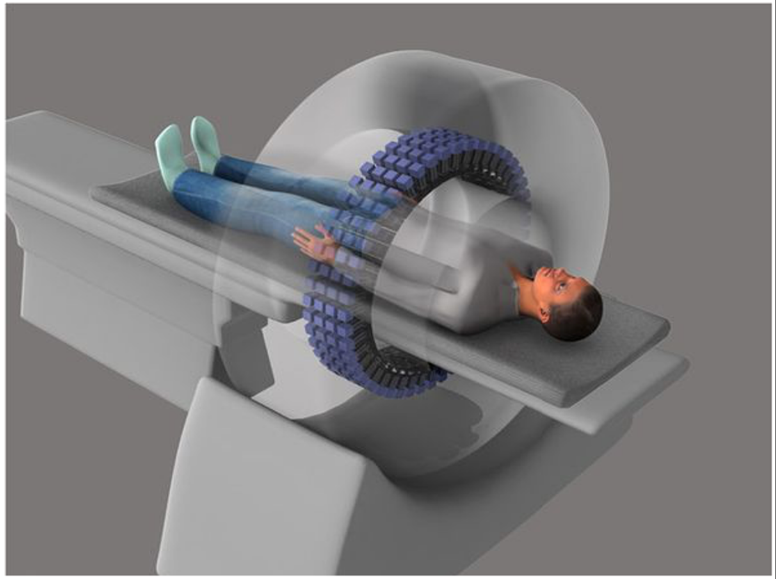


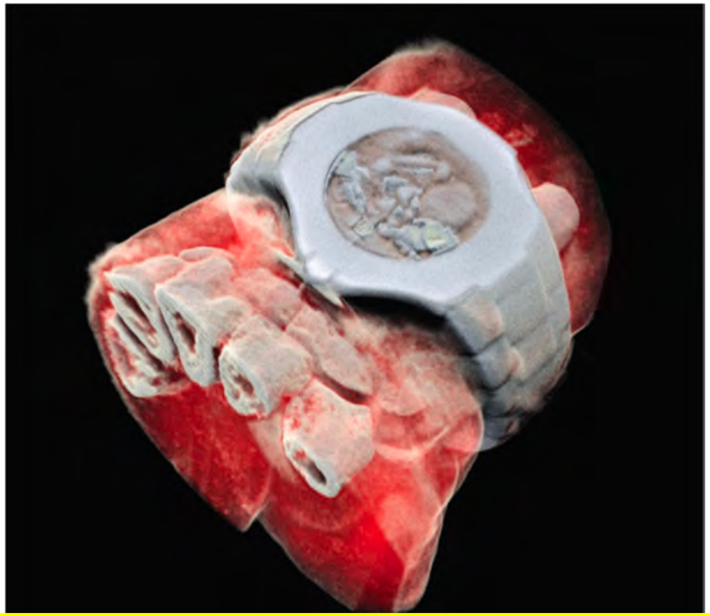
Challenge: red-sensitive CCDs to advance ground-based optical astronomy
Using techniques developed for silicon sensors for particle physics @ LBNL enabled development of thick red-sensitive CCDs for optical astronomy

Connections to other disciplines: Benefits to Society

The development of the manufacturing process of BGO crystals for the calorimeter of the L3 experiment at the LEP collider at CERN has contributed significantly to the advancement of Positron Emission Tomography (PET) scanners





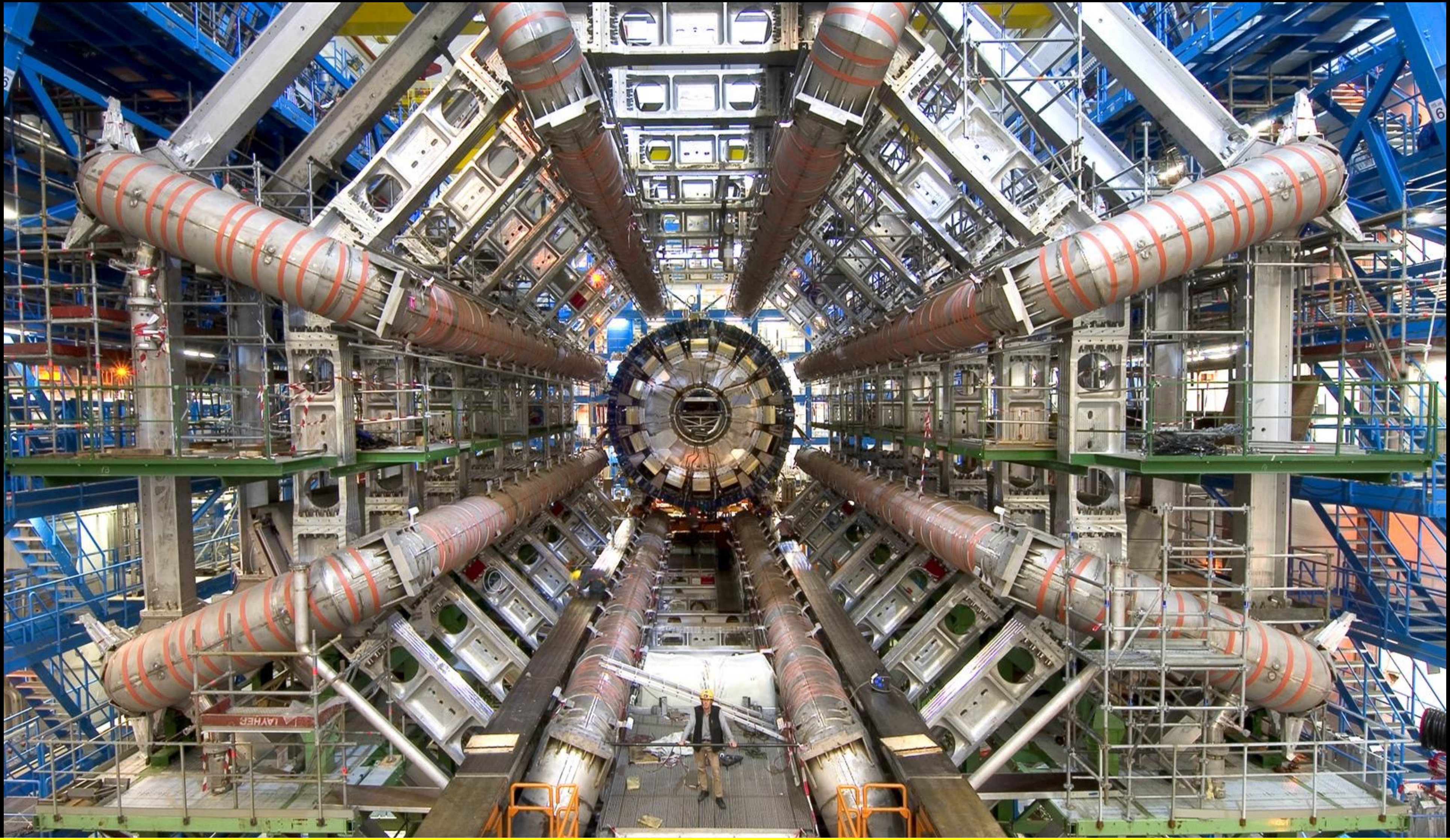


(photo credit: CERN and S.R. Cherry/U.C. Davis)

The development of large-area hybrid pixel detectors for high energy physics experiments led to the realization of the potential of this new technology to provide noise-hit-free single-photon counting impactful for development of sophisticated integrated circuits with timing. The circuit is being used in medical imaging, X-ray science, materials analysis, space dosimetry and climate studies among others

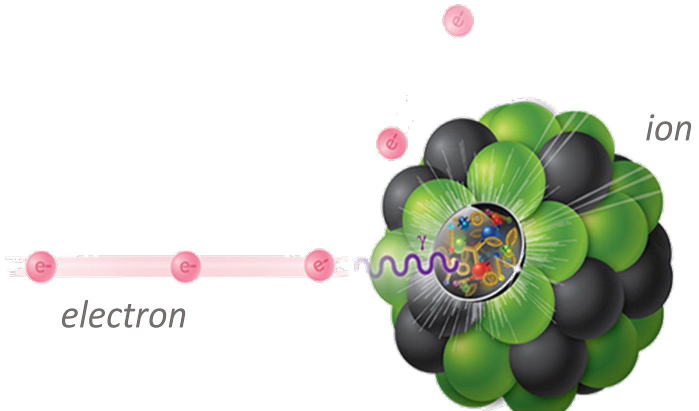
The ECFA detector R&D roadmap will lead to the development of new technologies that hold the promise to be as broadly applicable and equally transformative.

Instrumentation is the great enabler of science……..

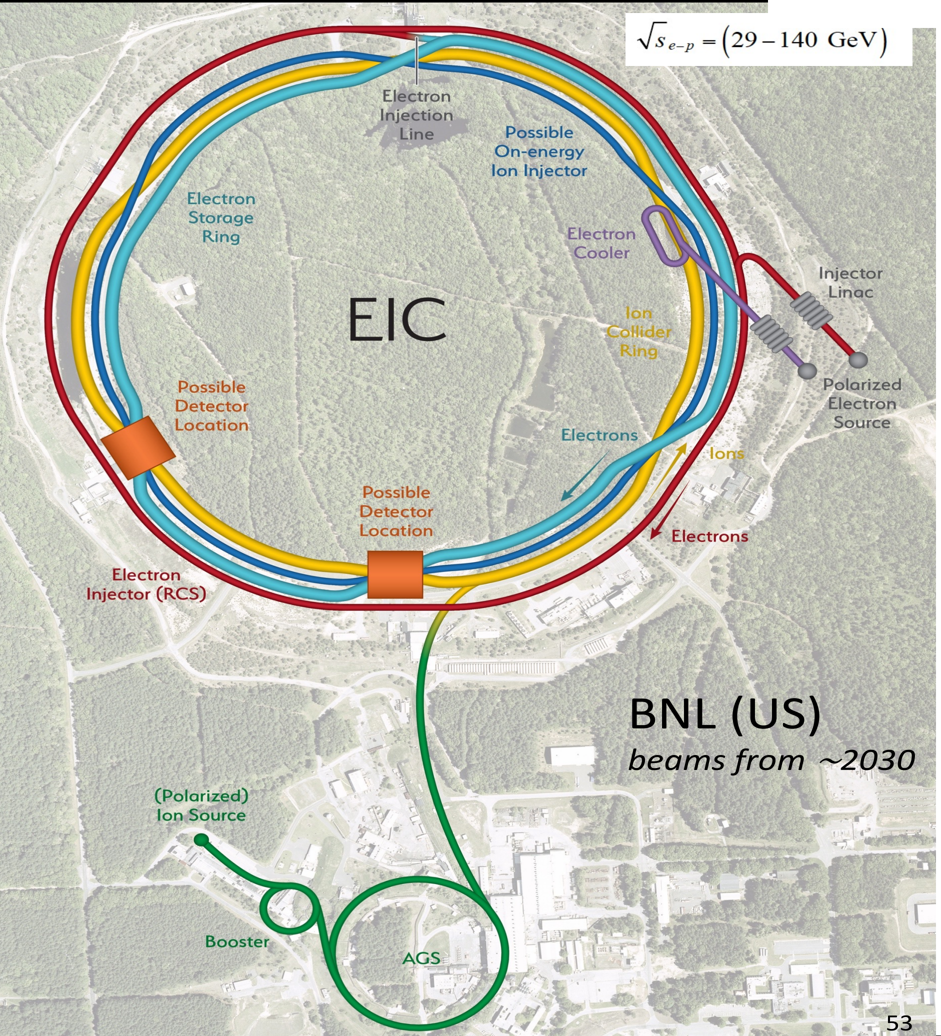


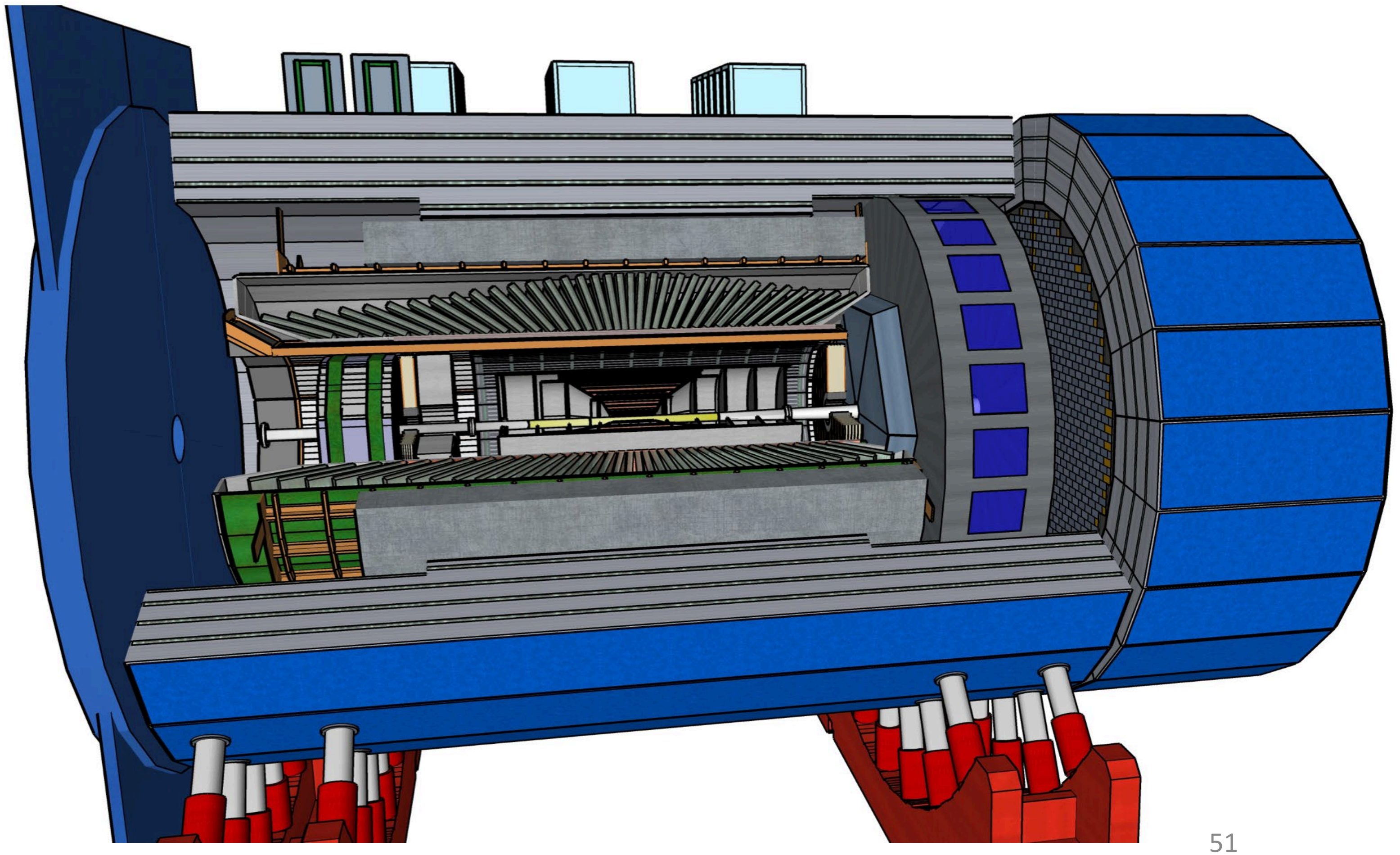
In many experiments many classes of detector technology are necessary working in synchronous harmony to reveal the mysteries of nature

Electron Ion Collider @ BNL beams from ~2030 concurrent operations with HL-LHC for a decade & mutual interest to NP & PP



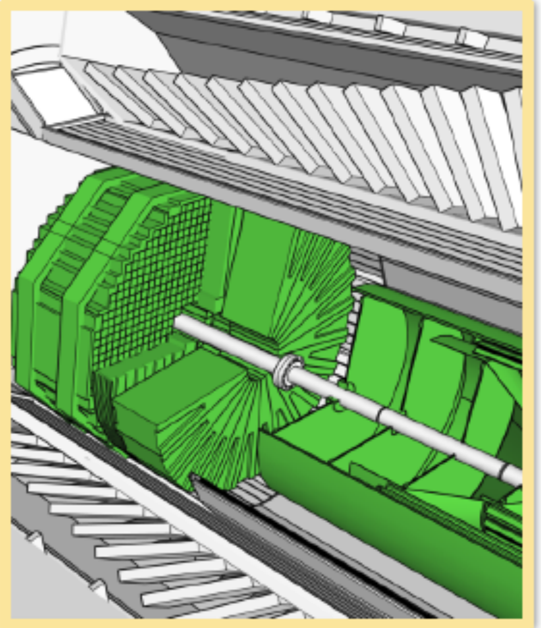
EIC Comprehensive Chromodynamics Experiment





The ECCE Reference Technologies

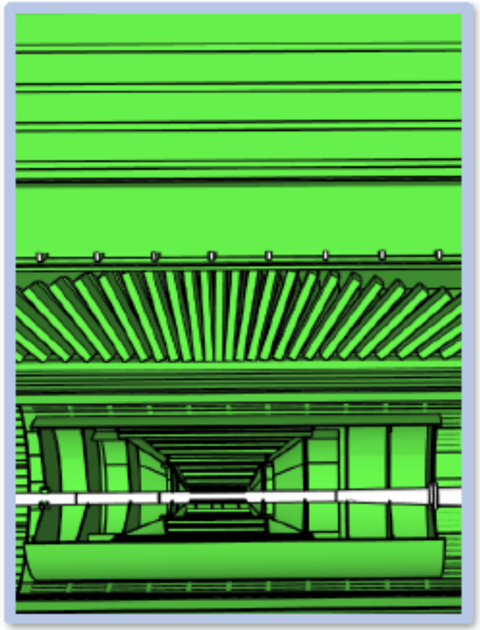
Most technologies in common with the LHC/HL-LHC & RHIC:
silicon, gaseous, photo, particle identification, calorimetry



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



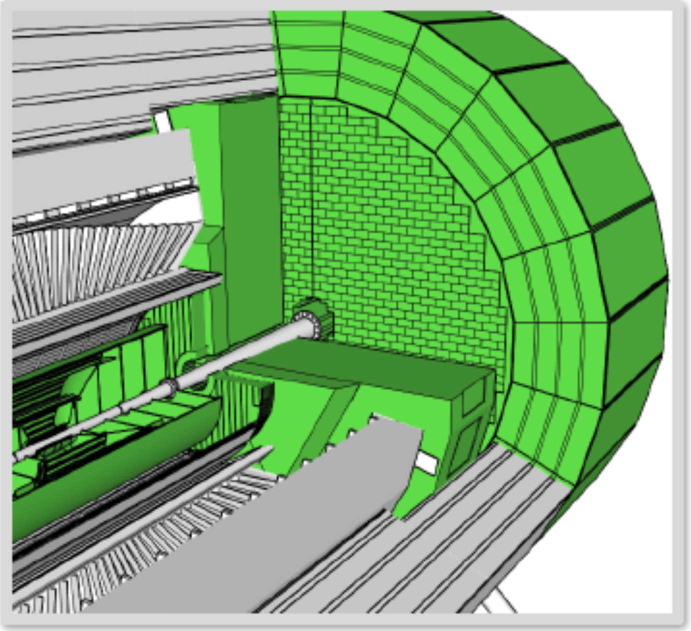
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

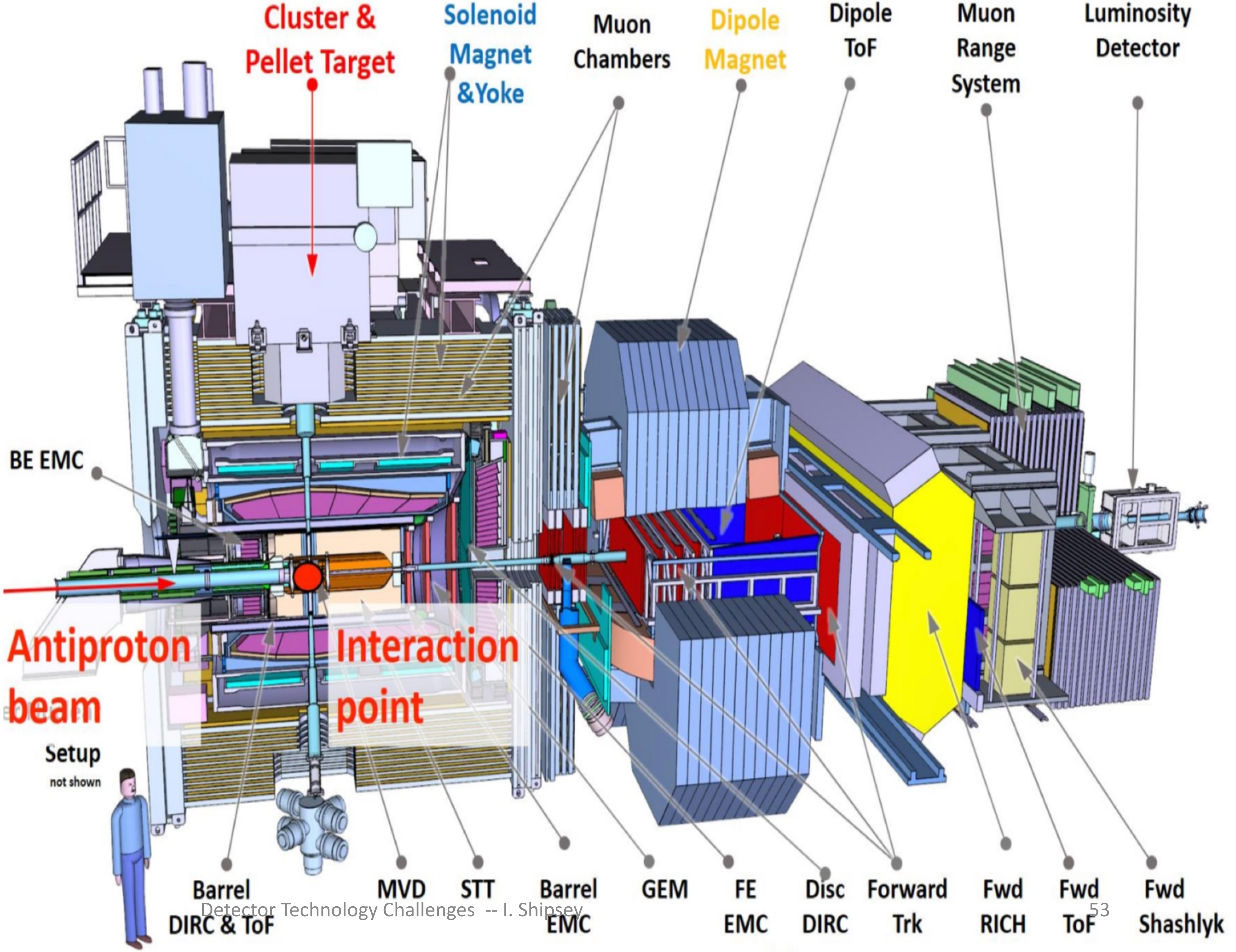
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
-
-

NP & PP working side by side immensely synergistic

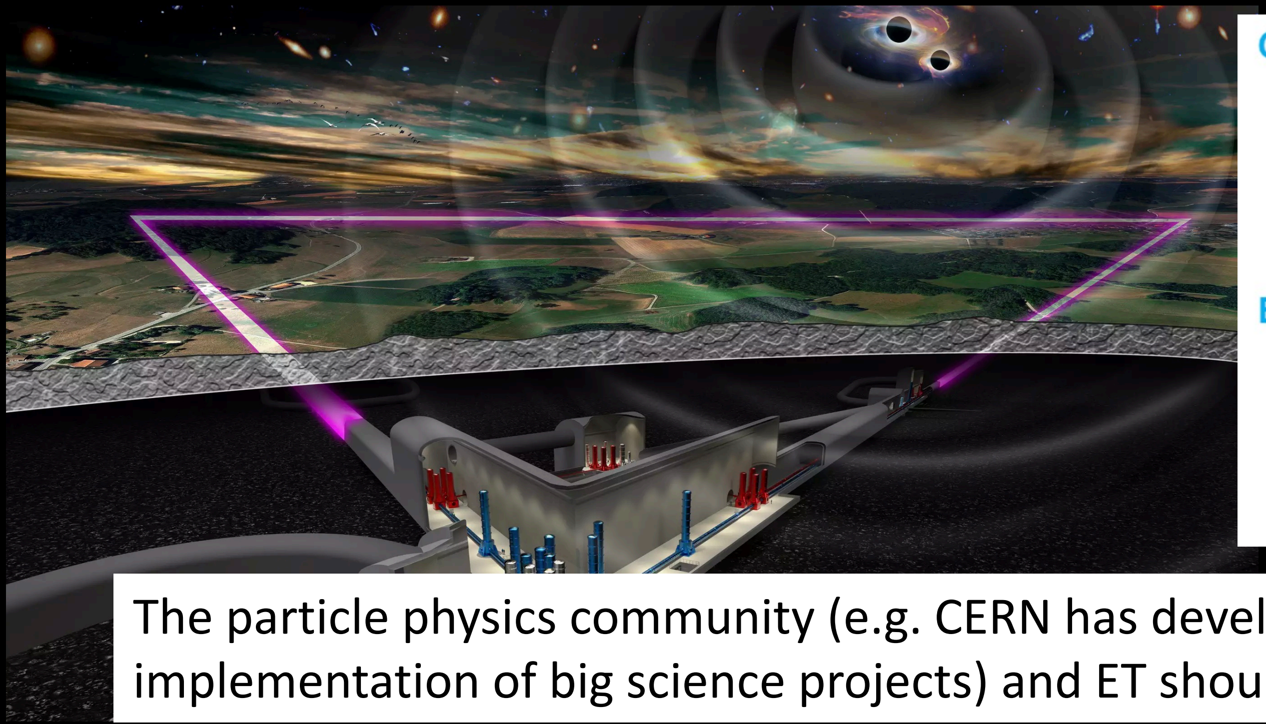
PANDA@ FAIR



Technologies in common with particle physics: Silicon, gaseous, photo, particle identification, Calorimetry

Also applies to CBM experiment @FAIR

Gravitational Waves / Future Einstein Telescope



GW and European HEP community

LIGO and Virgo are CERN-recognized experiments

MOU between CERN – INFN – Nikhef on instrumentation for Einstein Telescope

Interactions have started on R&D for vacuum instrumentation

Examples for joint R&D on instrumentation

Underground construction

Vacuum beam-tube construction, cleaning & bake out procedure

Cryogenics, controls

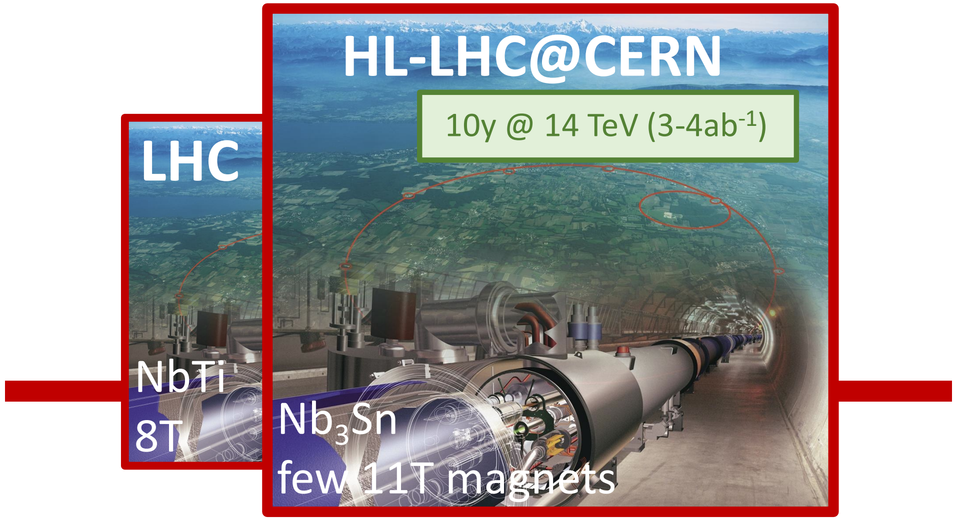
The particle physics community (e.g. CERN has developed vast experience in governance and implementation of big science projects) and ET should build on this.

Technology:
Laser power and squeezed states
Reduce Seismic (Newtonian) noise ➔ underground; long tunnels
Reduce thermal noise in suspension and test masses
➔ cryogenics to cool the mirrors

ET Pathfinder

Current flagship (27km)

impressive programme up to 2040



ep-option with HL-LHC: LHeC

10y @ 1.2 TeV (1ab^{-1})

updated CDR 2007.14491

Only 4% of the collisions that we plan to collect at the LHC has so far been recorded LHC Run 3 then HL-LHC will be immensely exciting enabled by an ambitious accelerator and detector upgrade program that is very far advanced.

Future flagship at the energy & precision frontier

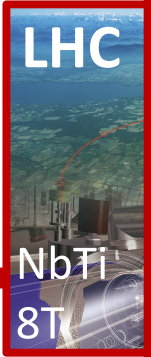
Current flagship (27km)

impressive programme up to 2040

Future Circular Collider (FCC)

big sister future ambition (100km), beyond 2040

attractive combination of precision & energy frontier



ep-option with HL-LHC: LHeC

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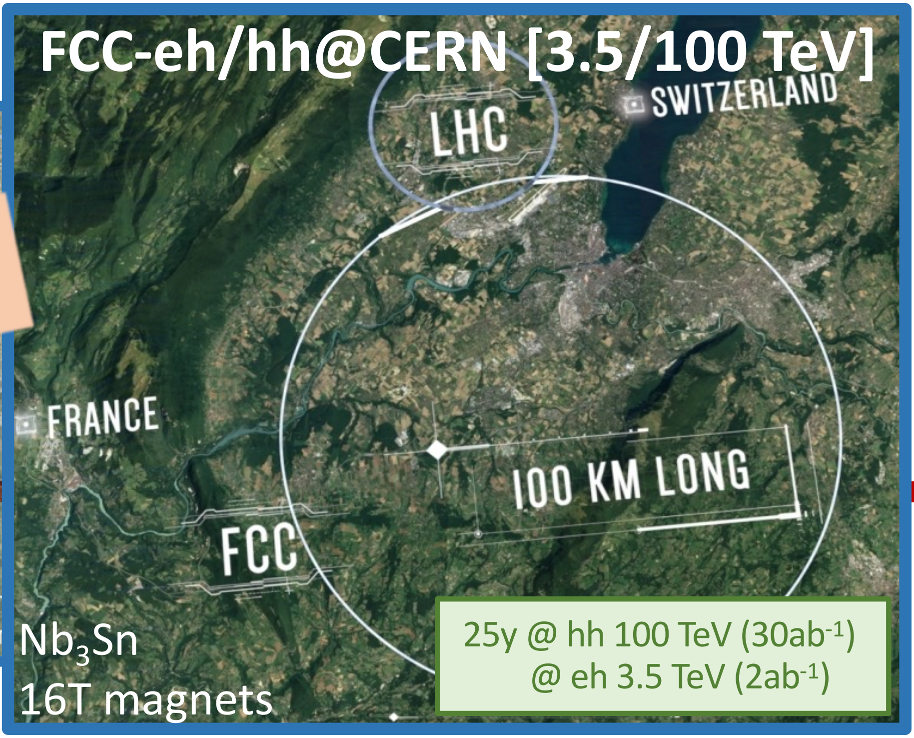
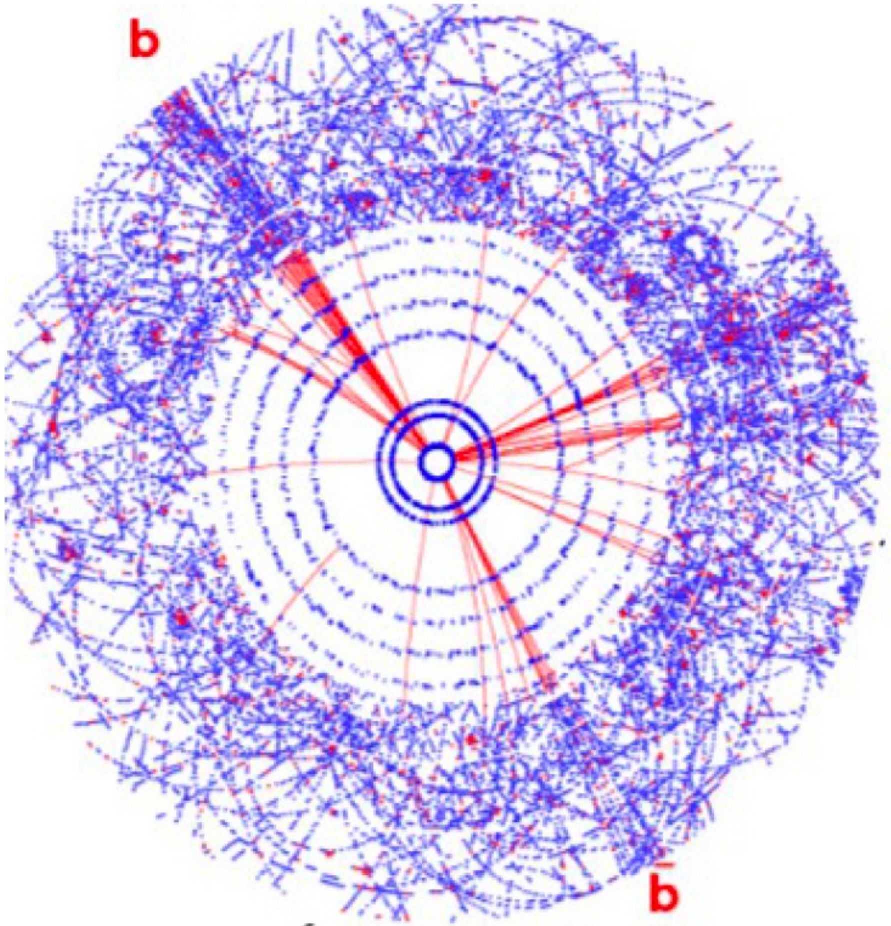


numbers assume 2 IPs for each collider (only one for FCC-eh)

by around 2026, verify if it is feasible to plan for success
(techn. & adm. & financially & global governance)

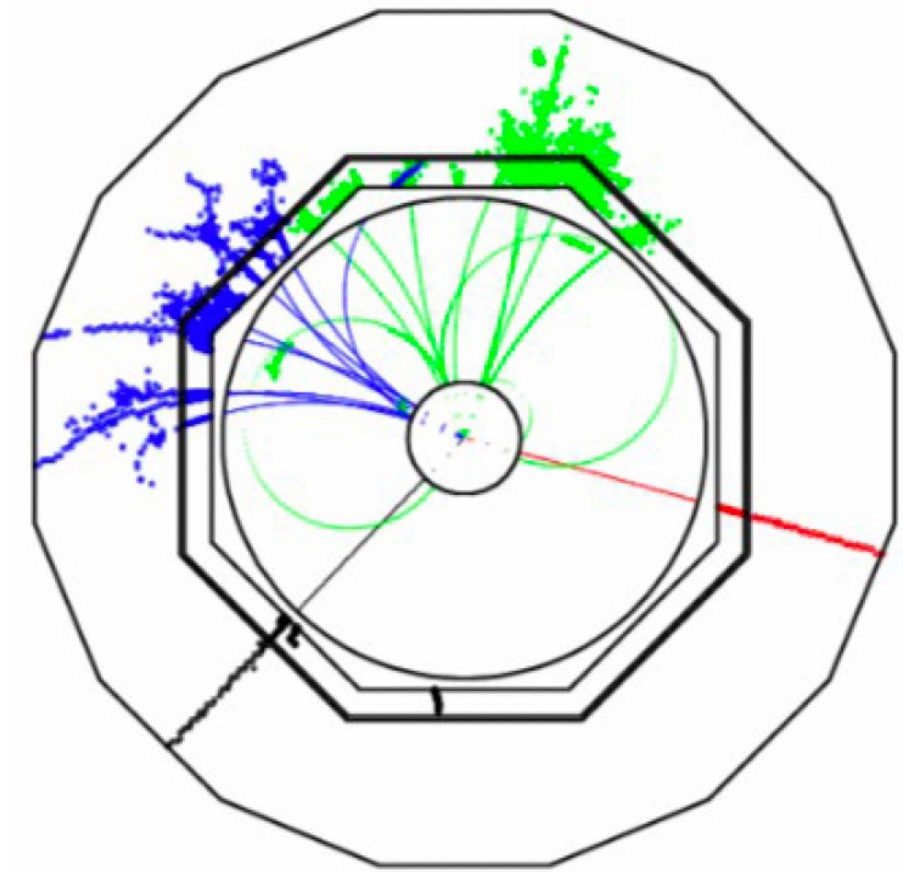
potential alternatives pursued @ CERN: CLIC & muon collider

Hadron –hadron collisions LH/HL-LHC➔ FCC-hh

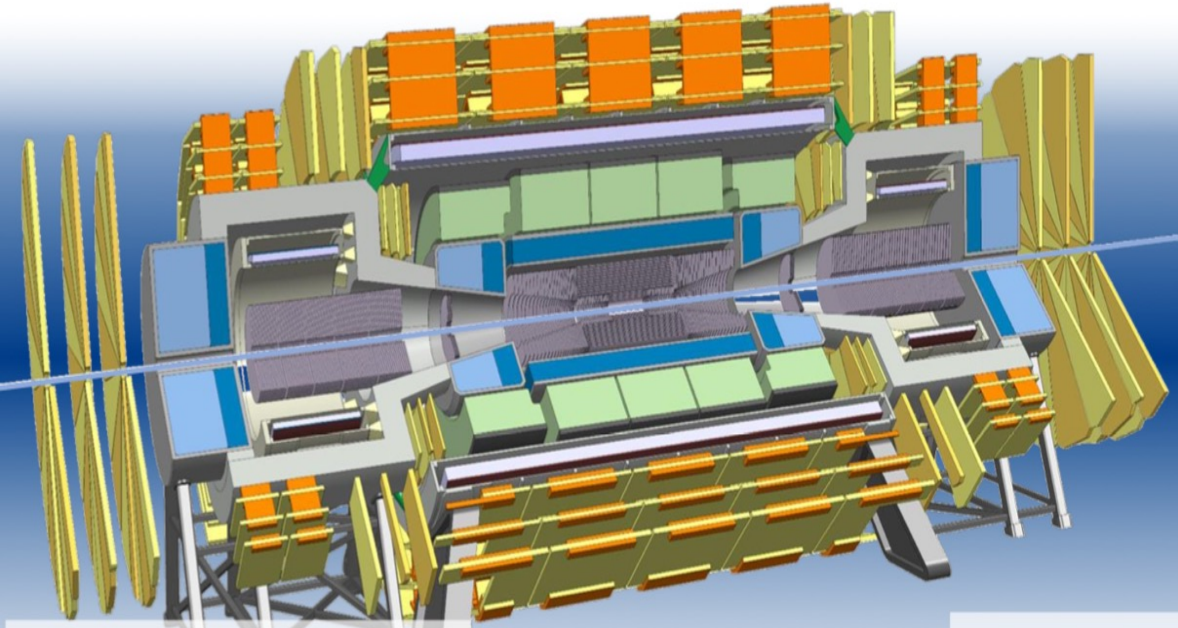


- Busy events
- Require hardware and software triggers
- High radiation levels

Electron-positron collisions LEP ➔ FCC-ee



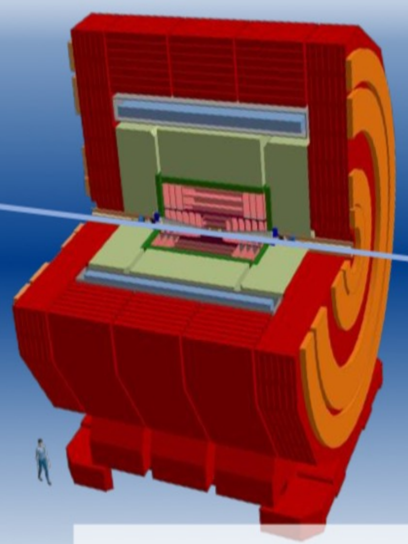
- Simple Events
- No trigger
- Full event reconstruction
- Modest radiation levels



FCChh, *HE-LHC, …*

hh collisions

e$^+$e$^-$ collisions



CLIC, *FCCee, ILC, CEPC,…*

- **Large dimensions (50m)**
- **High radiation Level (up to 2.8 x10^{17}neq/cm2; 90MGy @10 year)**
- Central solenoid (10m) 4T, Forward solenoids 4T
- Silicon tracker **Tracker Radius 1.6m, Length 32m**
  radiation damage is a concern

One of the many challenges: radiation hardness. Radiation levels go well beyond what any currently available microelectronics can survive ($\lesssim$ MGy) and few sensor technologies can cope beyond ~10^{16} n_{eq}/cm^2

➔ Detector R&D essential

- Standard dimensions
- Low radiation Level, Radiation level NIEL (<4×10^{10} neq cm^{-2}/yr); TID (<200Gy/yr)
- Magnet 4T, 2T
- Silicon tracker
  - **unprecedented spatial resolution (1-5 μm point resolution)**
  - **very low material budget (0.1X%)** Dissipated power (vertex) (<50mW/cm^2)
- Barrel fine grained calorimeter
- Compact Forward calorimeter

➔ Detector R&D essential

20 Years

- The technologies developed for the LHC took >20 years to research, develop and build

- These grew out of technologies developed for earlier rounds of experiments at earlier accelerators SppbarS, SPS, & LEP @ CERN, the Tevatron @ Fermilab and other facilities worldwide in the 1960-1990s.

- The technologies for the HL- LHC began to be developed around 2008, the R&D, build, install and commission will be completed in 2029

- The technology R&D for experiments that commence operation in the 2030s, 2040s & 2050s and beyond e.g. FCC-ee/FCC-hh is either underway already or must begin now

Most recent European Strategies

the large … … the connection … … the small

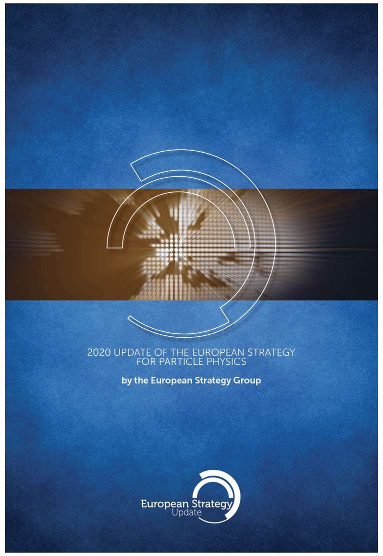
weblink

2017-2026 European Astroparticle Physics Strategy

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

weblink



2020 Update of the European Particle Physics Strategy

Are community driven strategies outlining our ambition to address compelling open questions

Guidance for funding authorities to develop resource-loaded research programmes

Update of the European Strategy for Particle Physics

the update of the European Strategy for Particle Physics, recognizing the primacy of instrumentation, called on the community via ECFA to define a global detector R&D roadmap

*C. The **success of particle physics experiments relies on innovative instrumentation and state-of-the-art infrastructures.** To prepare and realise future experimental research programmes, the community must **maintain a strong focus on instrumentation. Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities**. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a **global detector R&D roadmap** that **should be used to support proposals at the European and national levels.***

Organised by ECFA, a roadmap should be developed by the community to balance the detector R&D efforts in Europe, taking into account progress with emerging technologies in adjacent fields. The roadmap should identify and describe a diversified detector R&D portfolio that has the largest potential to enhance the performance of the particle physics programme in the near and long term. …

Most recent European Strategies

the large …

weblink

2017-2026 European Astroparticle Physics Strategy

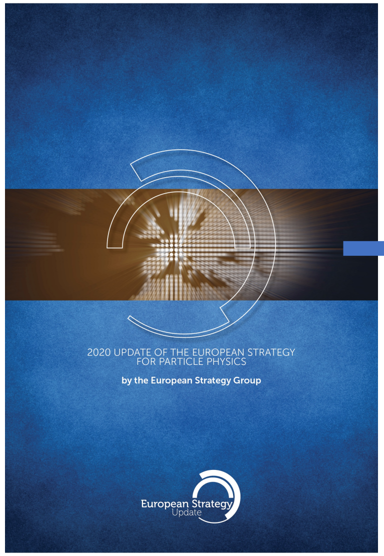
… the connection …

weblink

Long Range Plan 2017 Perspectives in Nuclear Physics

… the small

weblink



2020 Update of the European Particle Physics Strategy

ECFA Detector R&D Roadmap

ECFA Detector R&D Roadmap

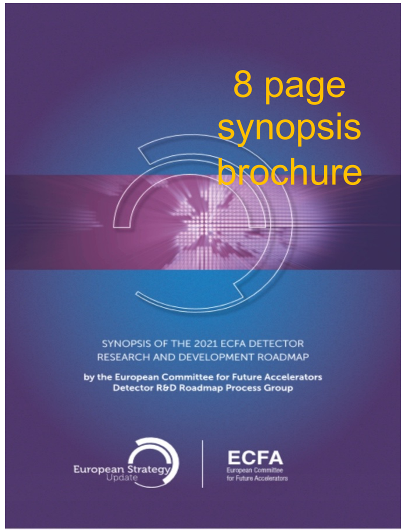
- Given the future physics programme, identify **the main technology R&D to be met so that detectors ar not the limiting factor for the timeline.**
- Detector context considered:

- Full exploitation of LHC
- Long baseline neutrinos
- Detectors for future Higgs-EW-Top factories (in all manifestations)
- Long term vision for 100 TeV hadron collider

- Future muon colliders
- Accelerator setup for rare decays/dark matter
- Experiments for precision QCD
- Non accelerator experiments (reactor neutrinos, double beta decay, dark matter)

Process organised by Panel and nine Task Forces with input sessions and open symposia with wide community consultation (1359 registrants)

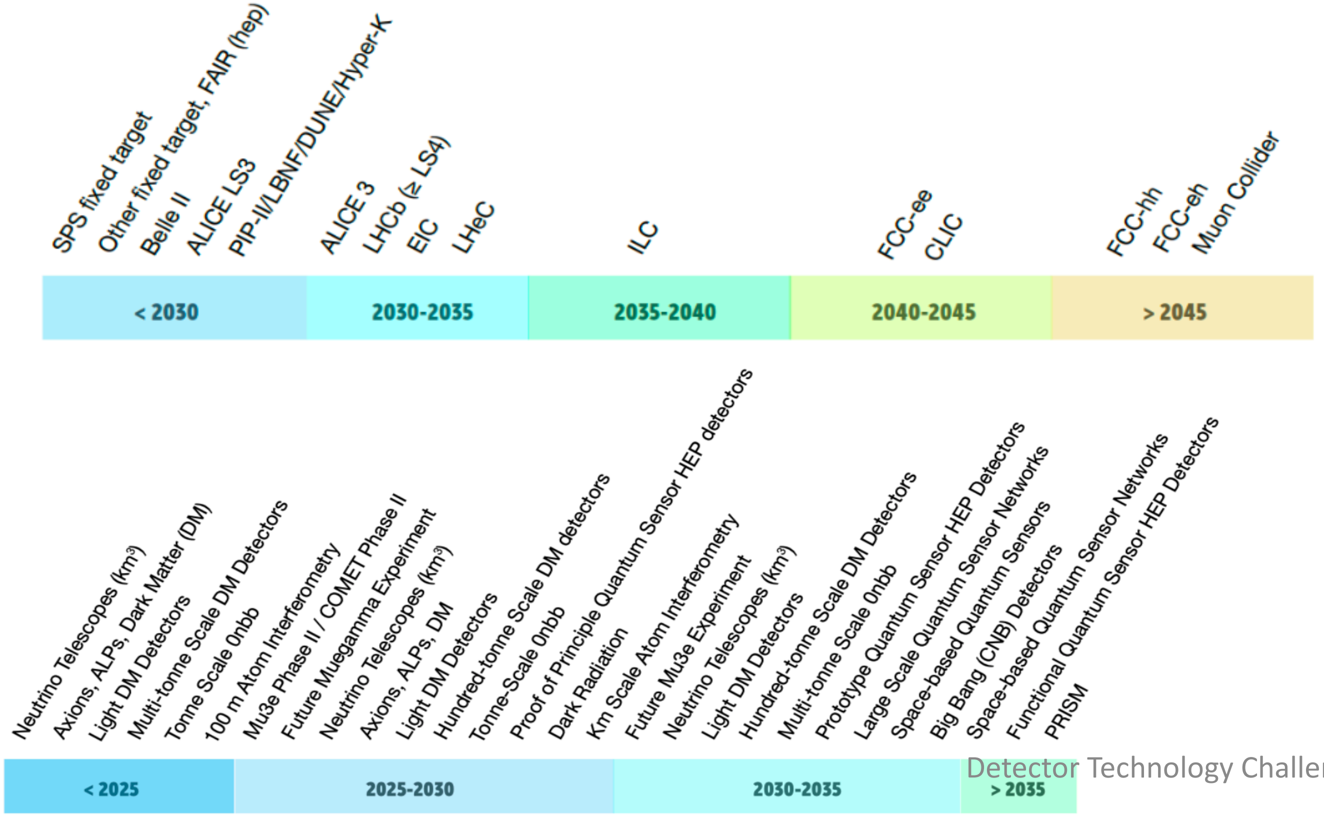
Main Document published (approval by RECFA at 19/11/21) and 8 page synopsis brochure prepared for less specialised audience

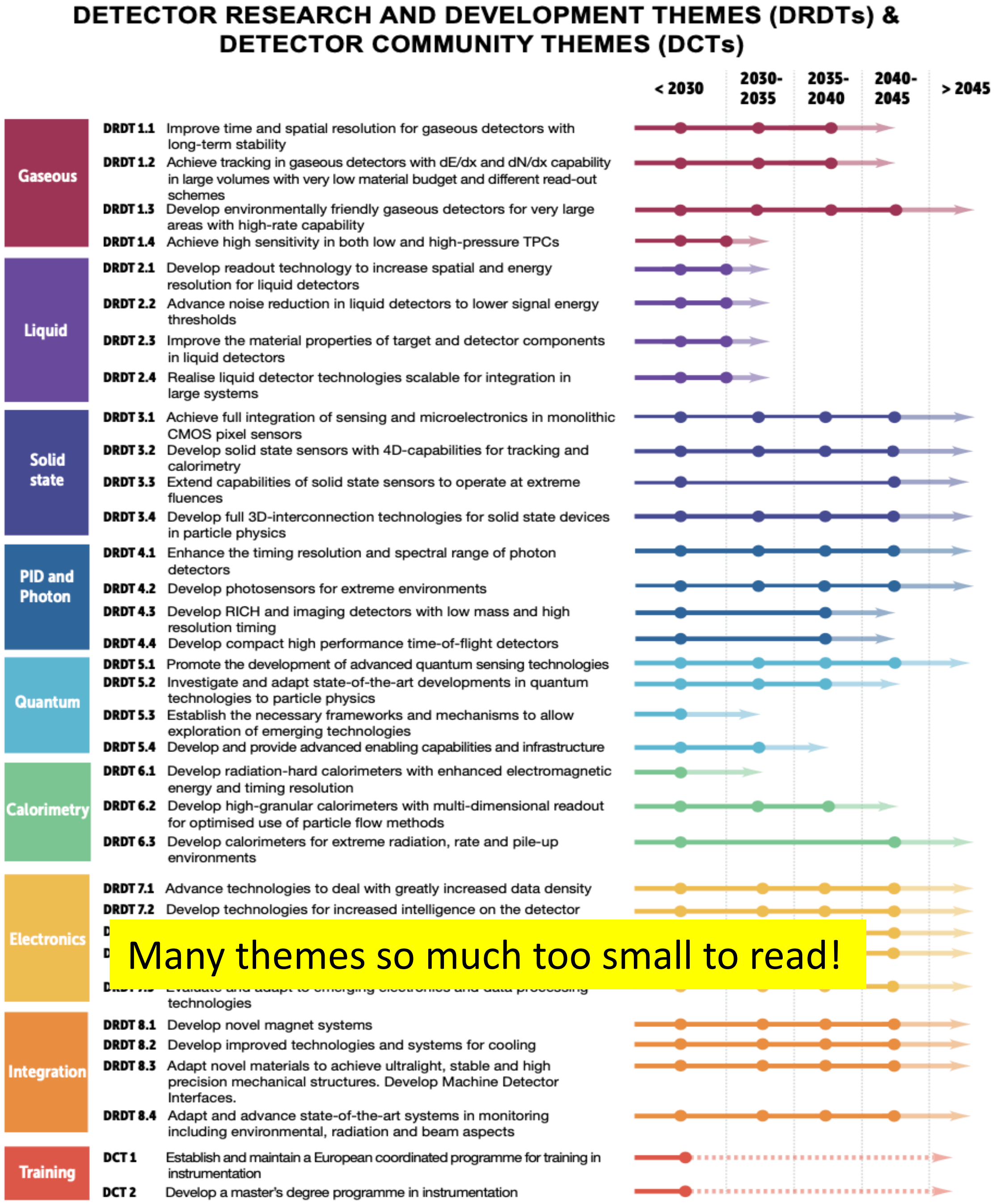


ECFA Detector R&D Roadmap Panel web pages at: https://indico.cern.ch/e/ECFADetectorRDRoadmap
Documents CERN-ESU-017: 10.17181/CERN.XDPL.W2EX

Roadmap Document Structure

Within each Task Force (one for each technology area + training) the aim is to propose a time ordered detector R&D programme by Detector Research and Development Themes (DRDT) in terms of **capabilities not currently achievable**.

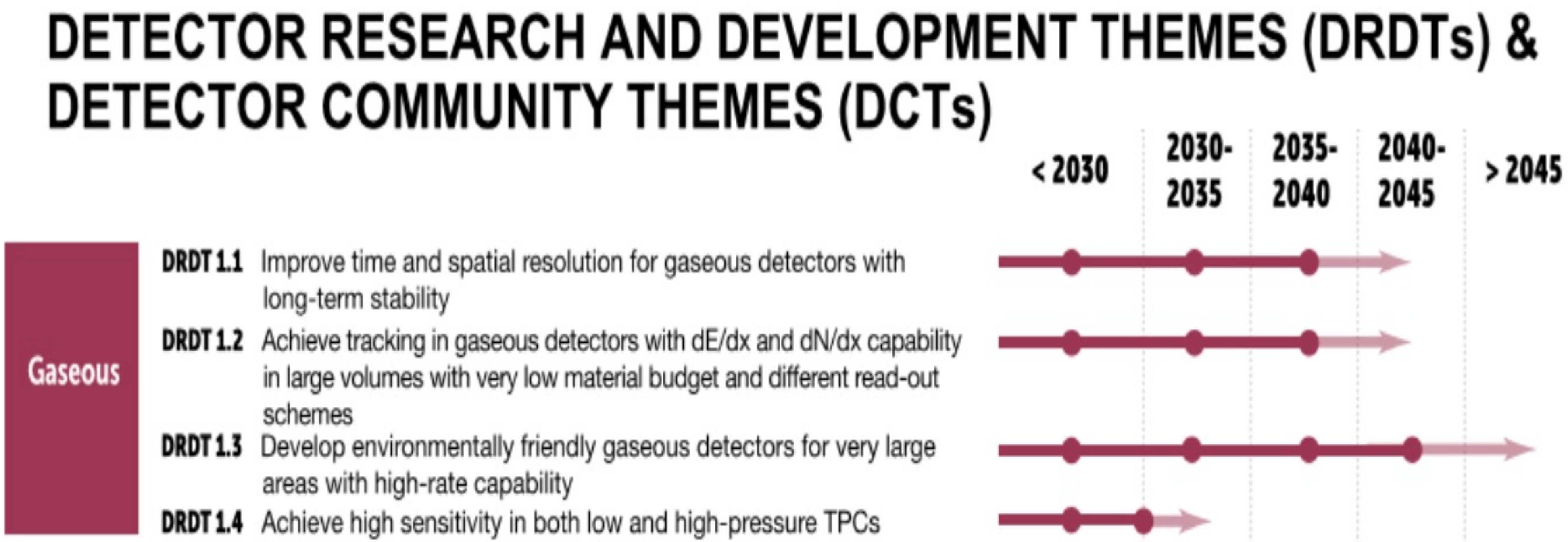


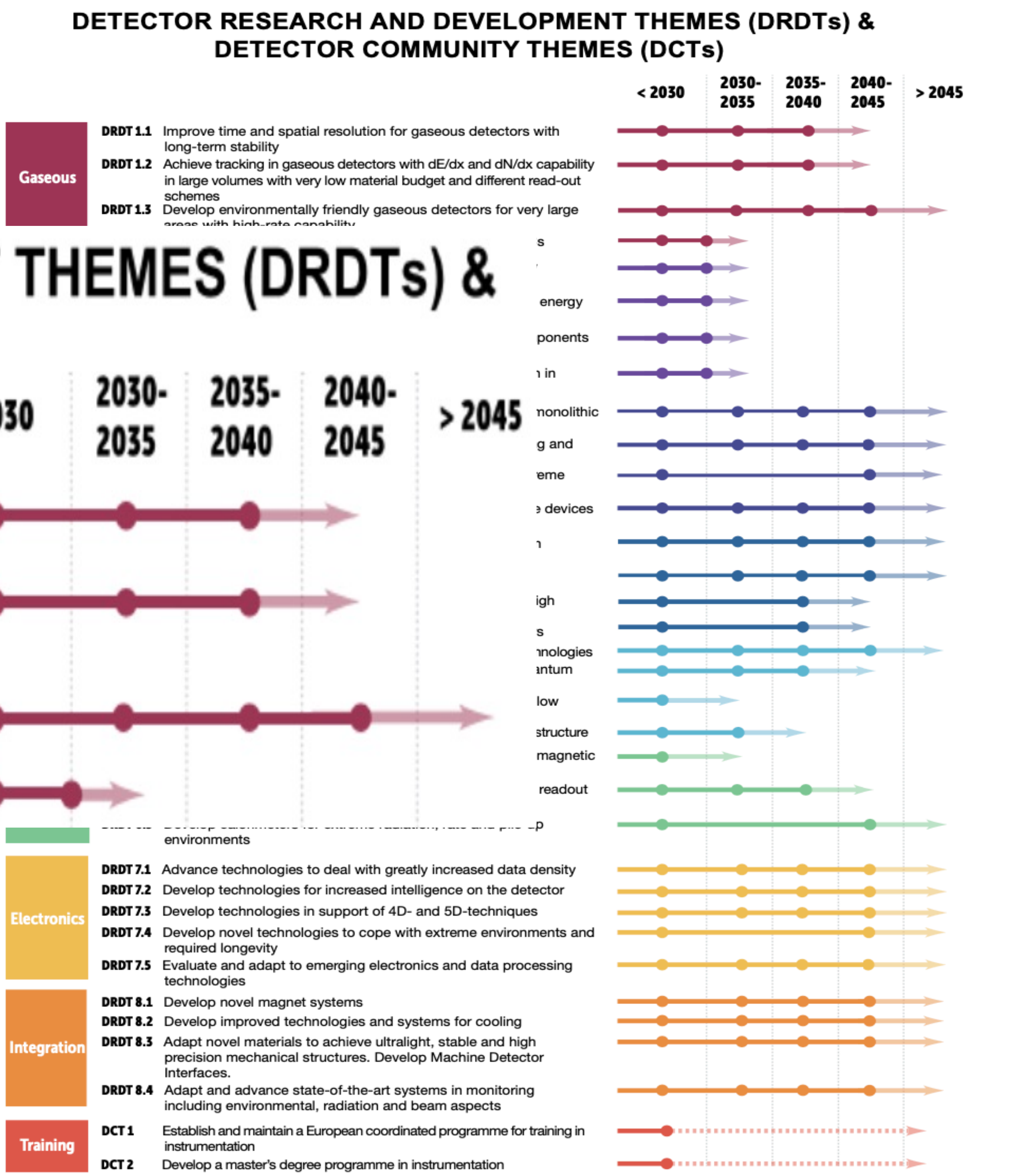


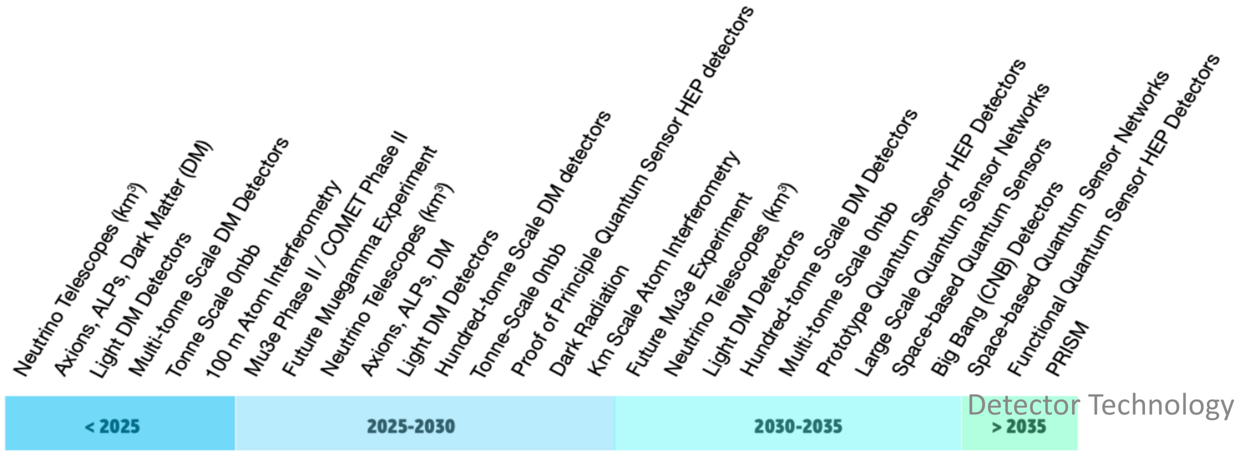
Many themes so much too small to read!

Roadmap Document Structure

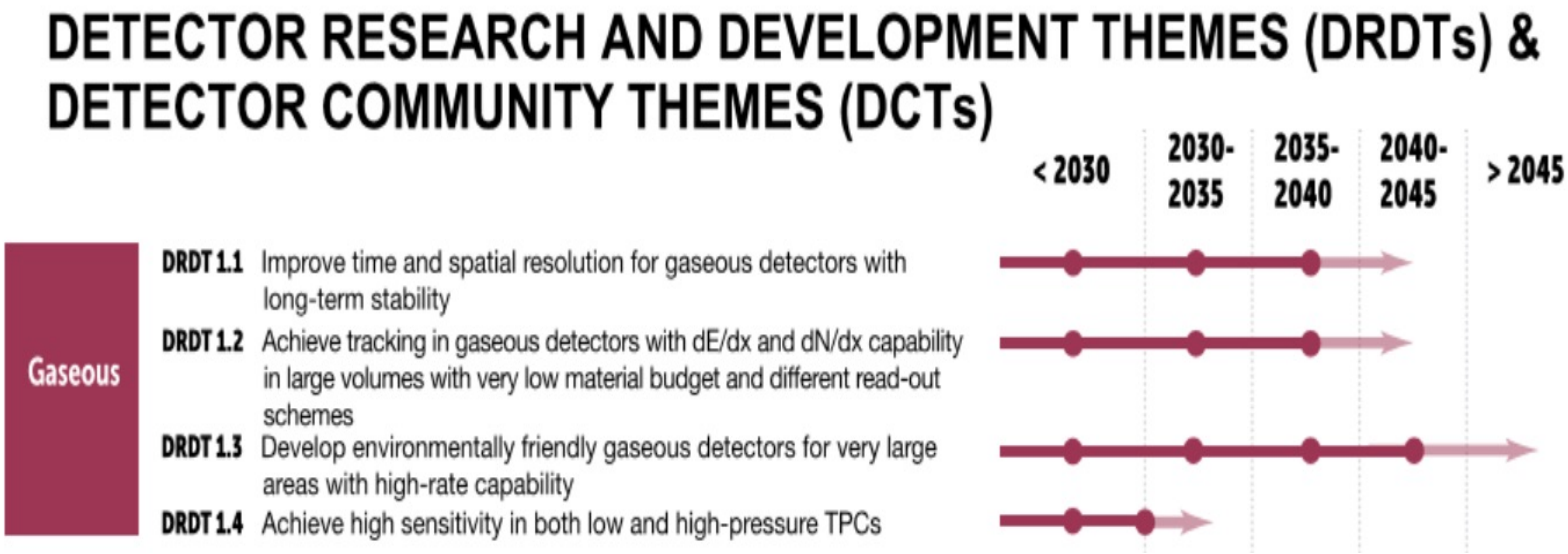
Within each Task Force the aim is to propose a time ordered detector R&D programme by

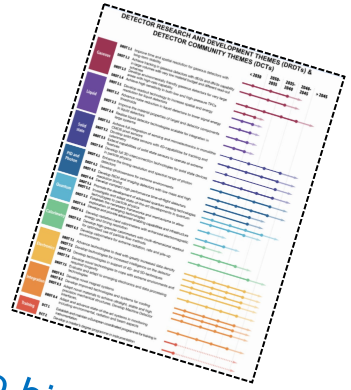






Gaseous detectors





To highlight the most important drivers for research in each technology area

To not limit a feasible start date of a future facility

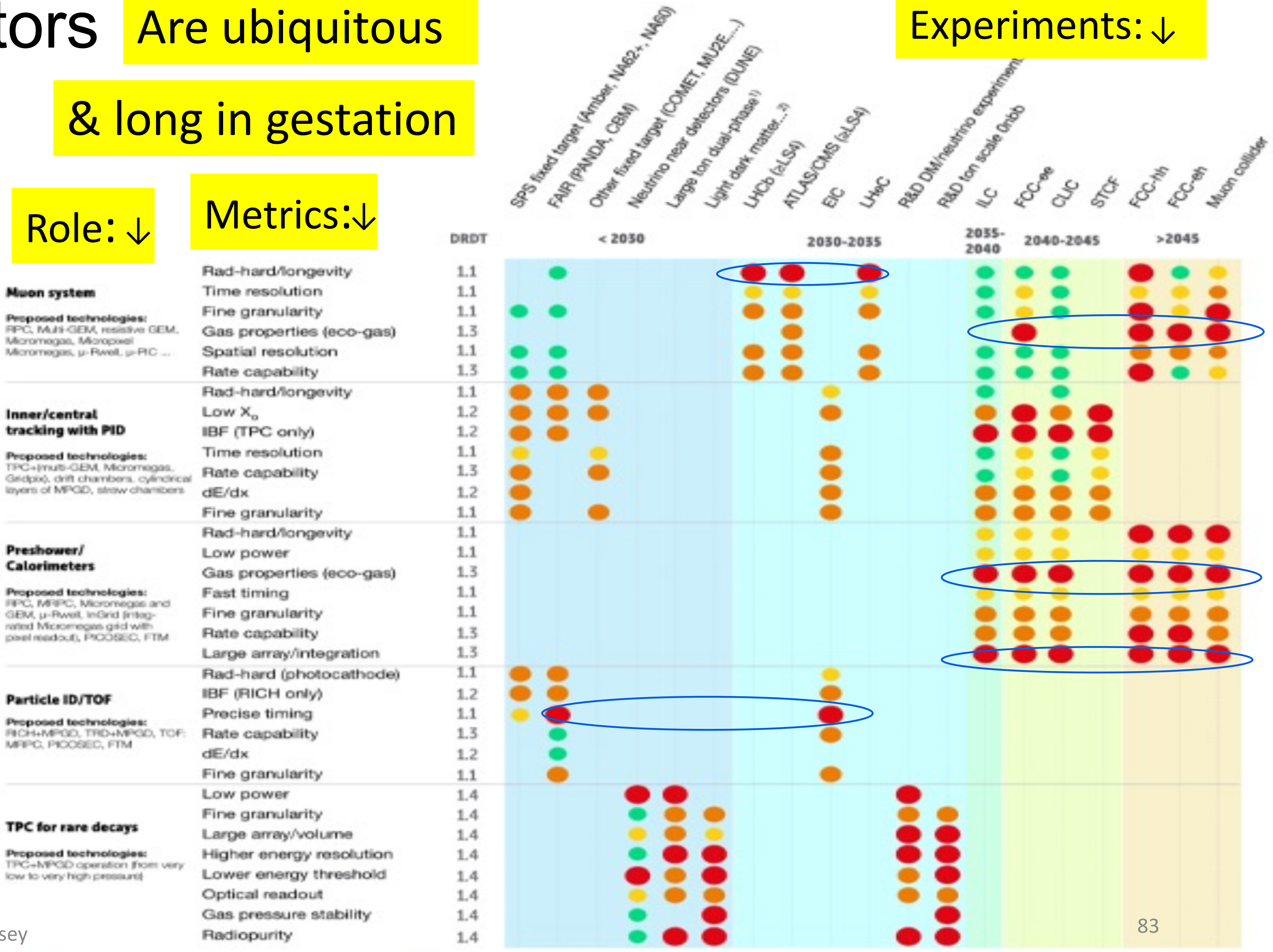
- The faded region indicates the typical time needed between the completion of the R&D phase and the readiness of an experiment at a given facility.
- Stepping stones are shown to represent the R&D needs of facilities intermediate in time.
- It should be emphasised that the future beyond the end of the arrows is simply not yet defined, not that there is an expectation that R&D for the further future beyond that point will not be needed.

Gaseous detectors

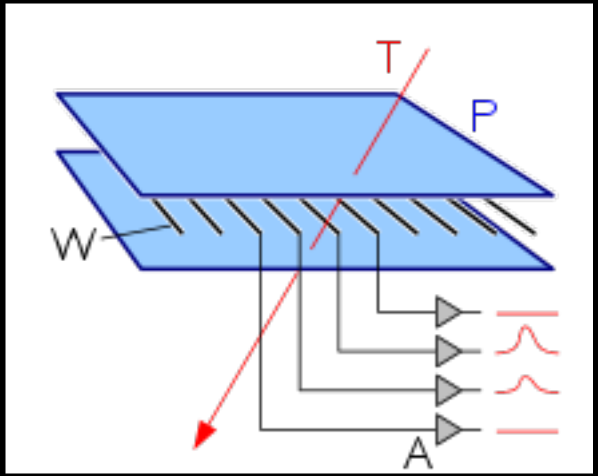
Are ubiquitous

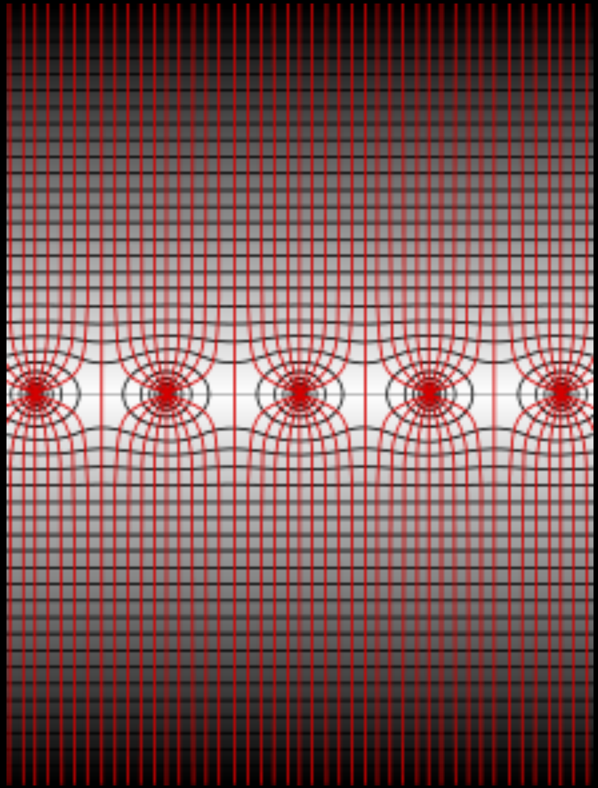
& long in gestation

- **Detector Readiness Matrices of each Task Force chapter** focus on the extent to which the R&D topic is *mission critical* to the programme rather than the intensity of R&D required
  - Must happen or main physics goals cannot be met
  - Important to meet physics goals
  - Desirable to enhance physics reach
  - R&D need being met

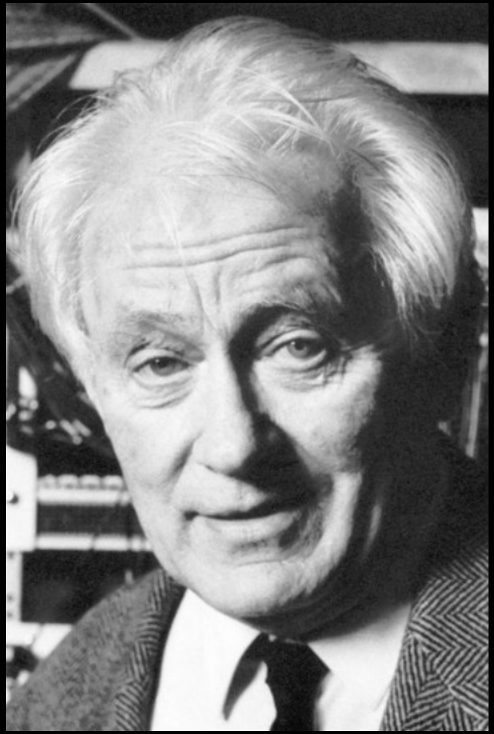


Gaseous Detectors
Multiwire Proportional Chamber
1960’s



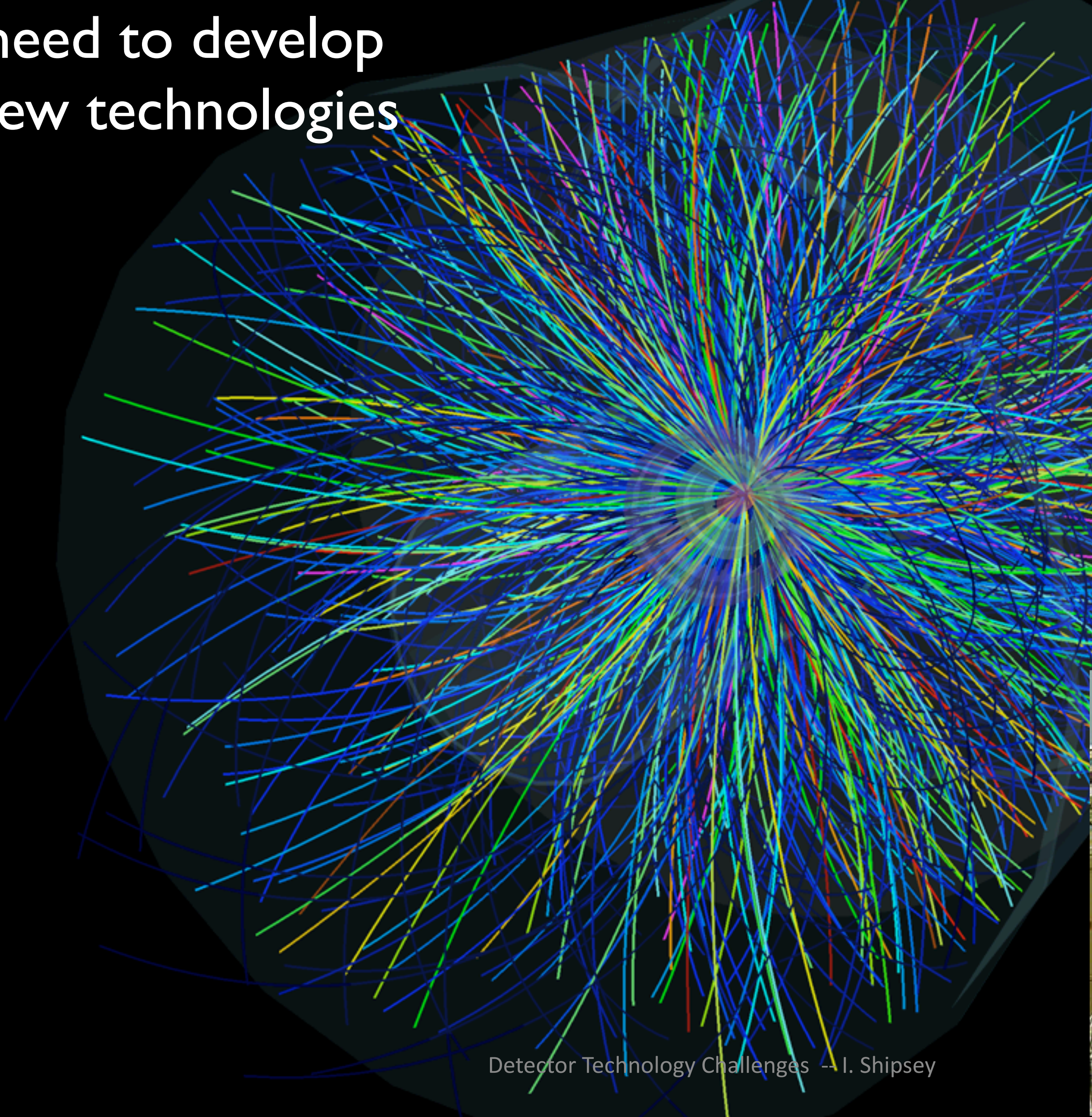


The Nobel Prize in Physics 1992 was awarded to Georges Charpak "for his invention and development of particle detectors, in particular the multiwire proportional chamber."



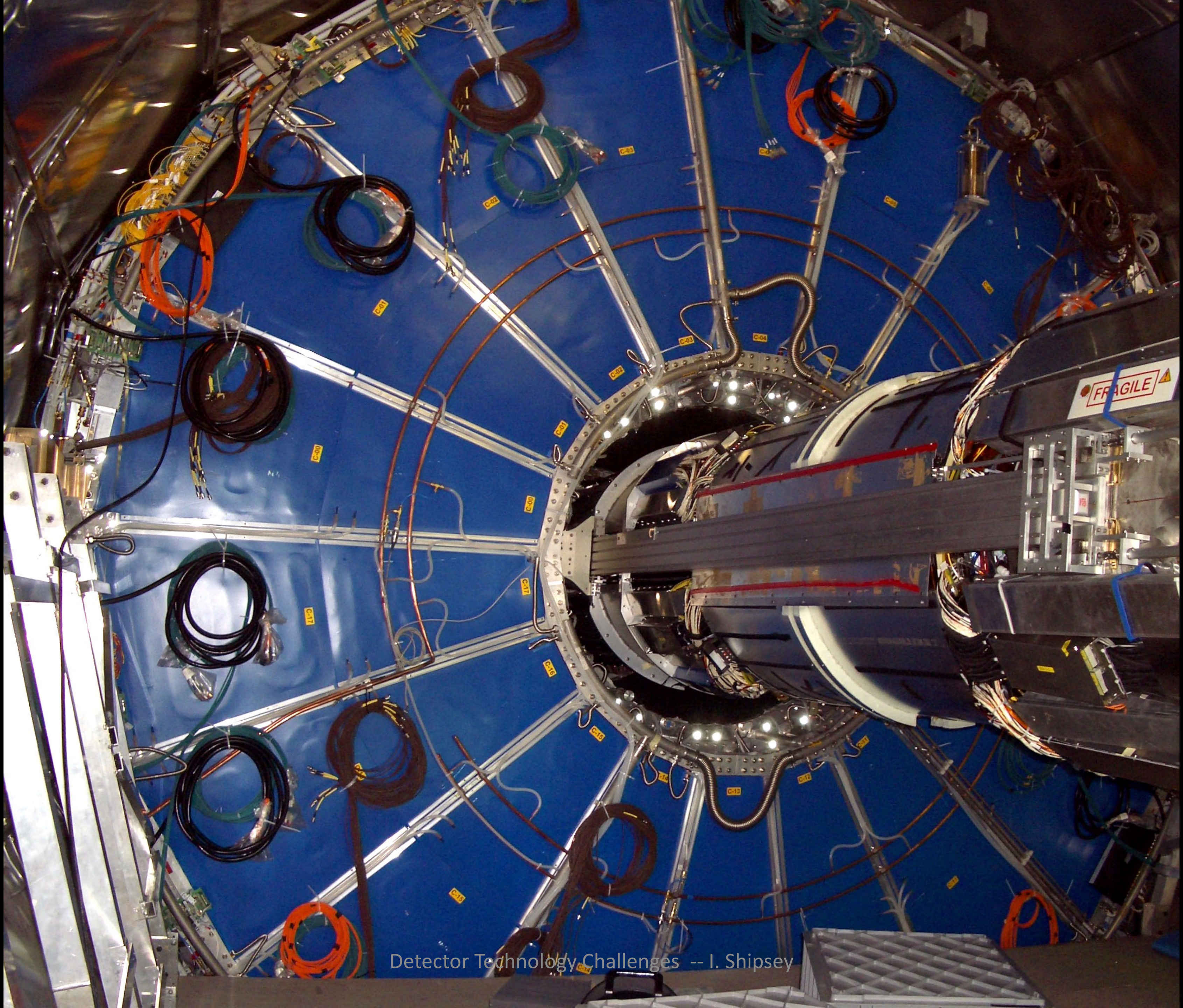
need to develop
new technologies

1970s



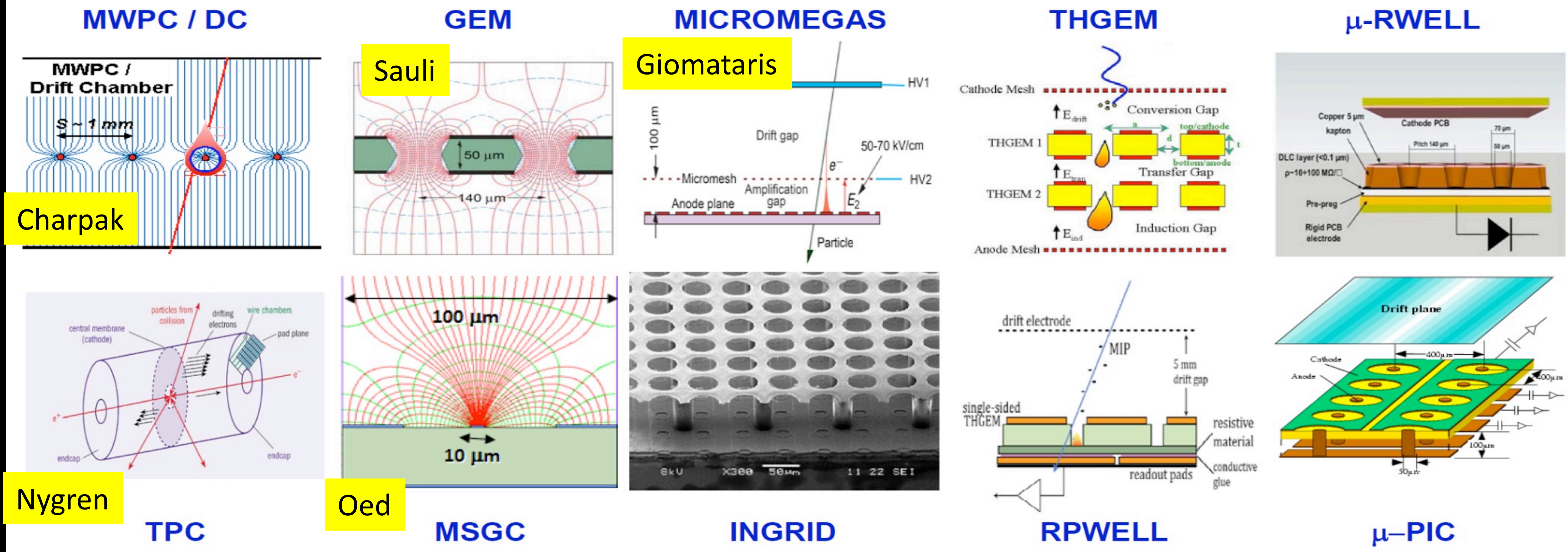
TPC

ALICE
TPC
2010



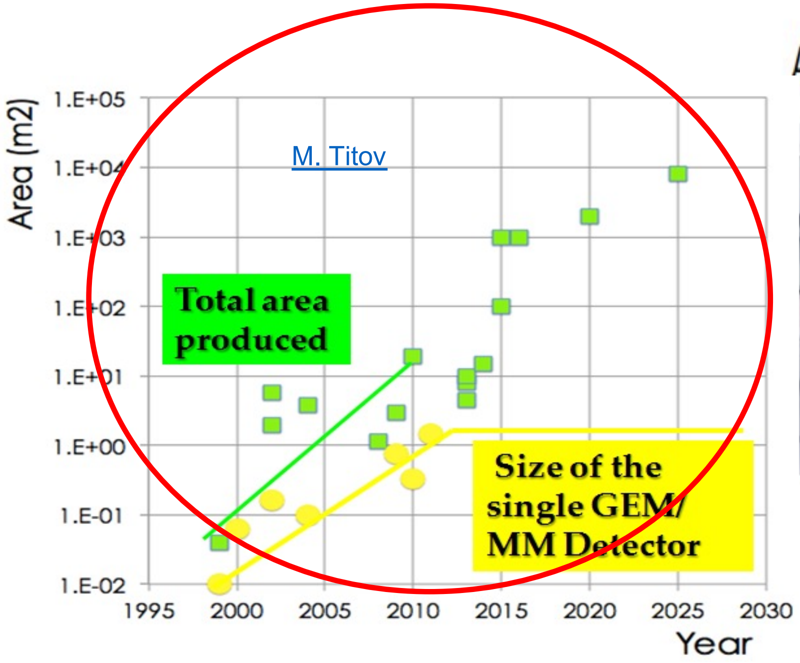
Evolution over 50 years

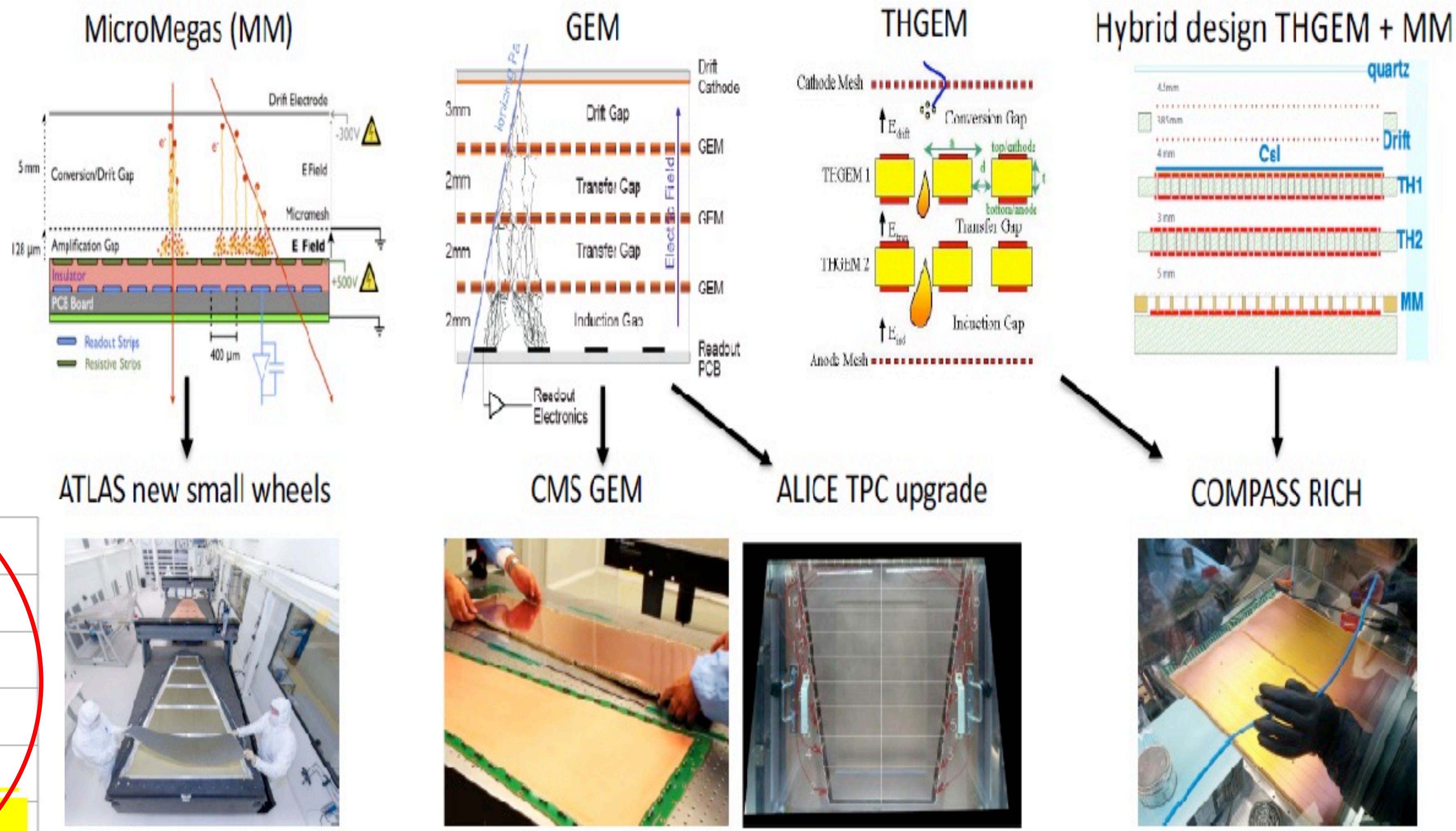
- Gaseous detectors: from Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors
- Primary choice for large-area coverage with low material budget



Gaseous detectors: MPGD area increasing dramatically

- **Upgrades to a number of systems used at the LHC** for tracking, muon spectroscopy and triggering have **taken advantage of the renaissance in gaseous detectors** (*esp* MPGDs)
- **New generation of TPCs use MPGD-based readout**: e.g. ALICE Upgrade, T2K, ILC, CepC



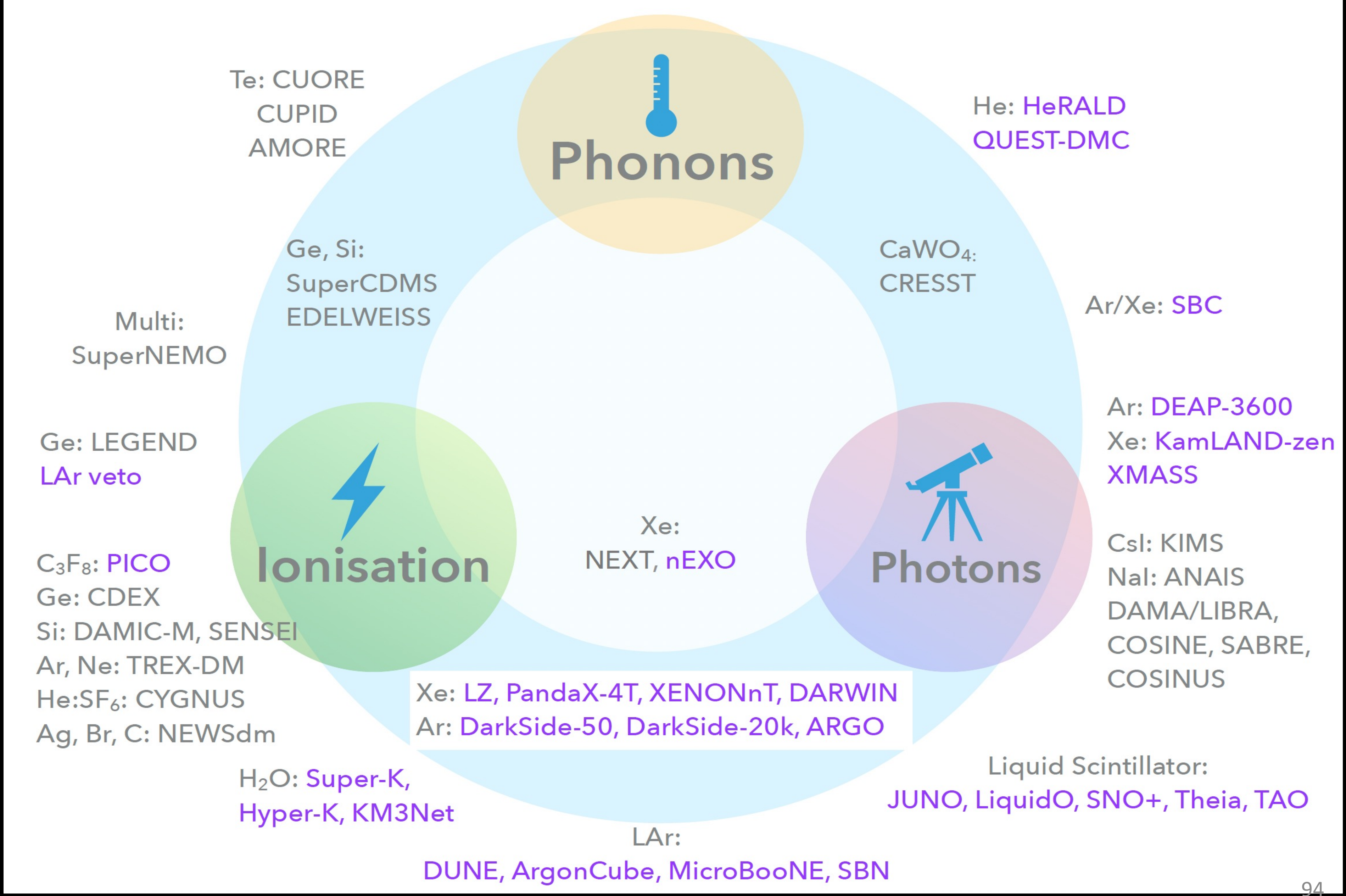


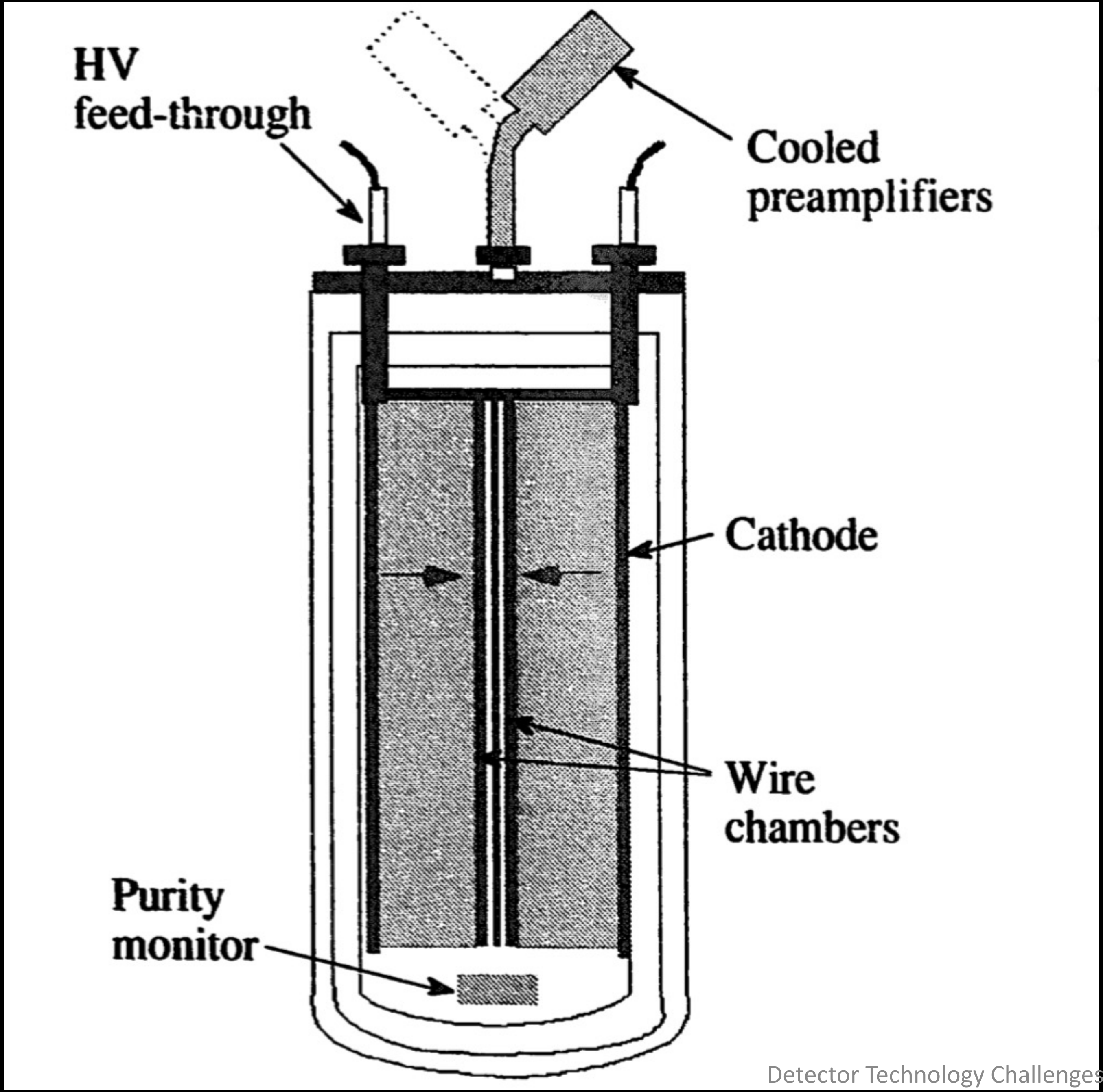
From widely used MWPC to widely used MPGD has taken 50 years

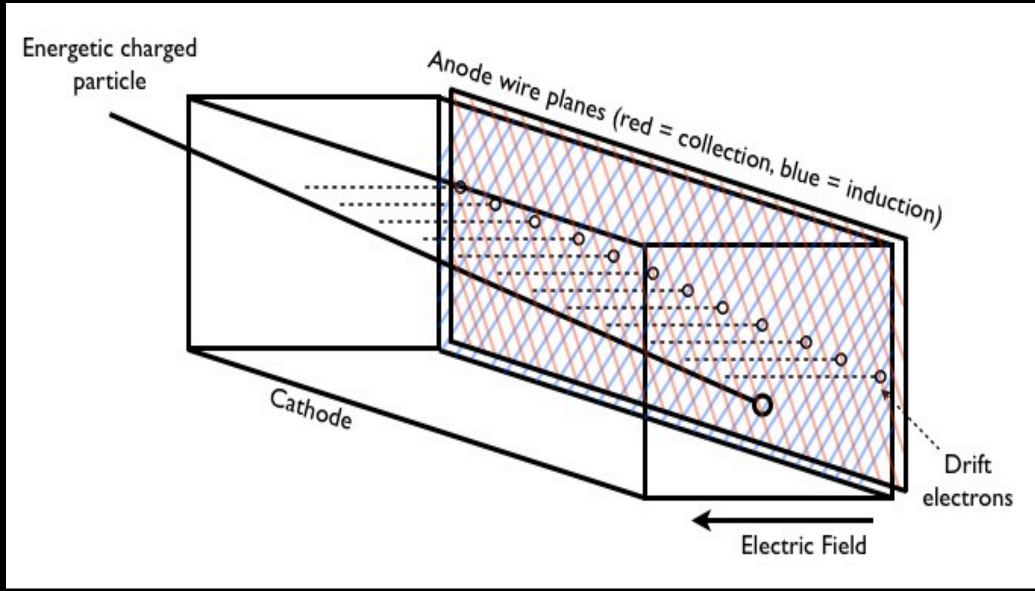
Liquid detectors

- Several large-scale and many small-scale experiments running or foreseen with liquid detectors
- for neutrino oscillation physics @ accelerators
- Neutrino nature Dirac or Majorana?
- Dark matter searches,

Modified from L. Baudis



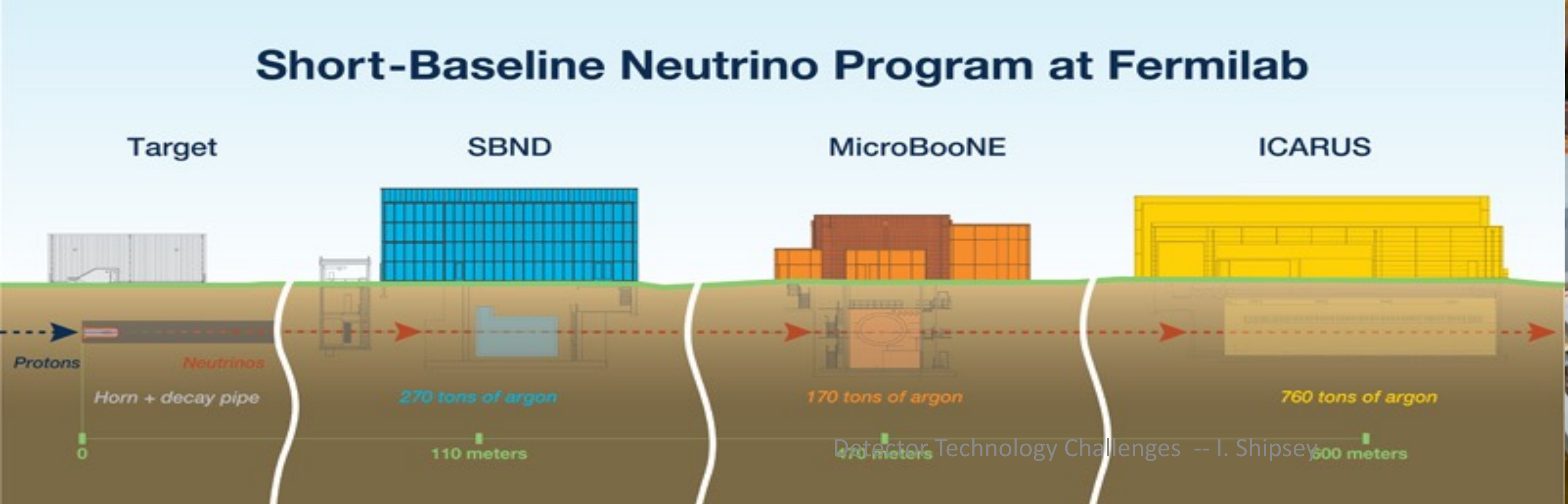


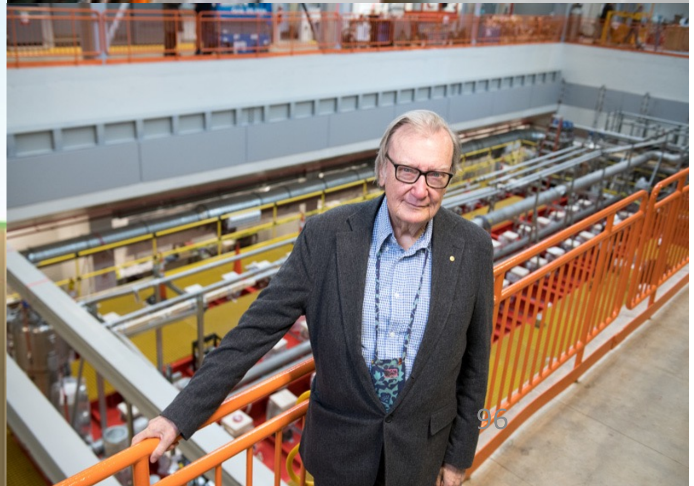


Liquid Argon TPC
1977
Rubbia

2021
Rubbia

Credit: FNAL





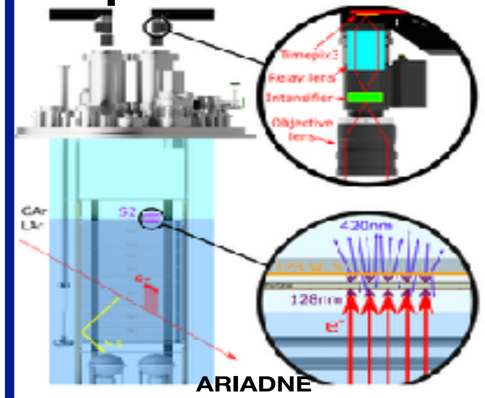
Detector R&D for neutrino experiments

Liquid Argon TPC
(DUNE)

Current:
- ➡ Cryogenics and purification
- ➡ HV and uniform E-field
- ➡ Microphysics and calibration
- ➡ Event reconstruction

Future:
- ➡ Increase charge/light collection
- ➡ Doping (light)
- ➡ ...

Optical readout

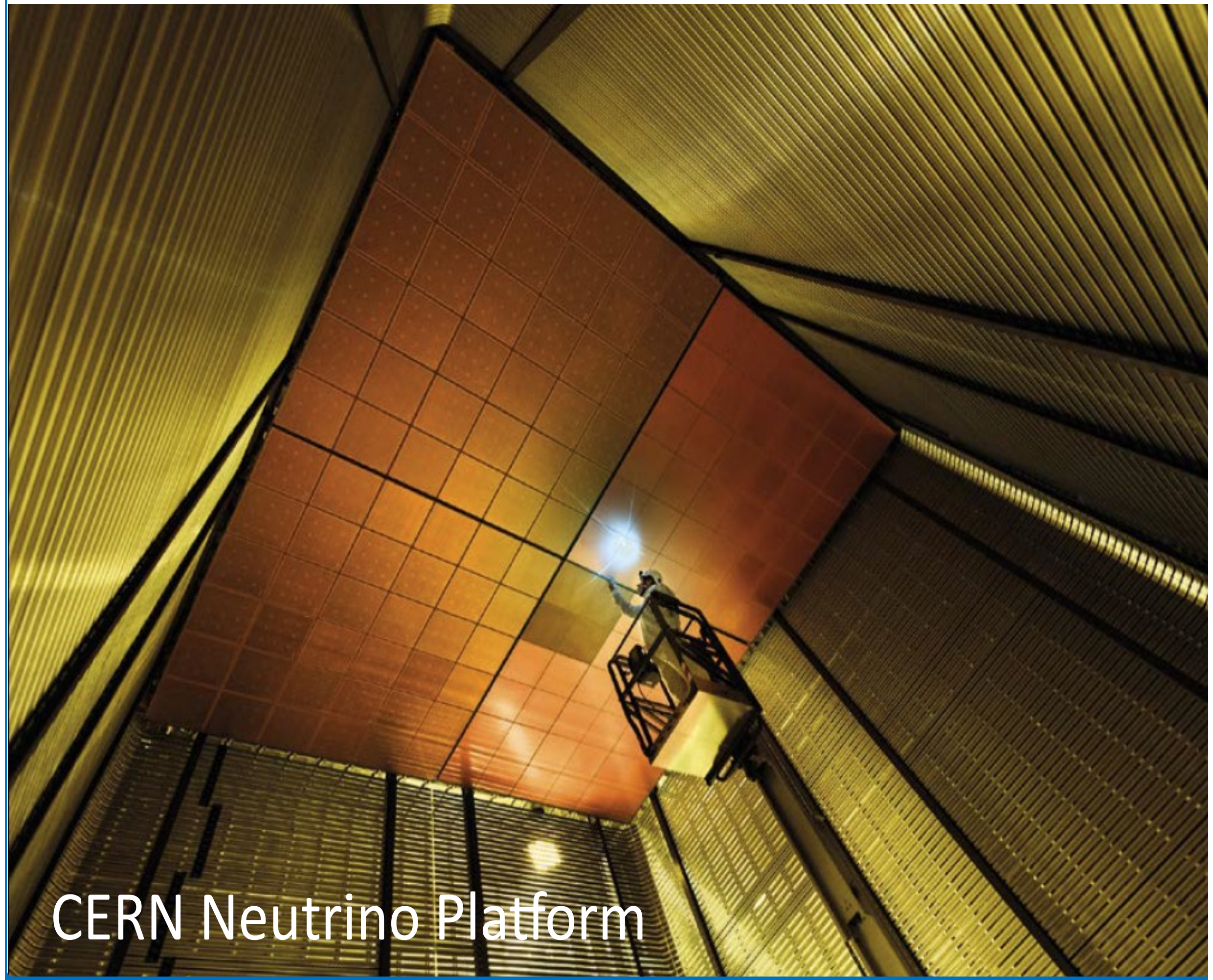


Pixel readout

Dual Q-γ readout

DUNE @ LBNF

Prototype dual-phase Liquid-Argon TPC

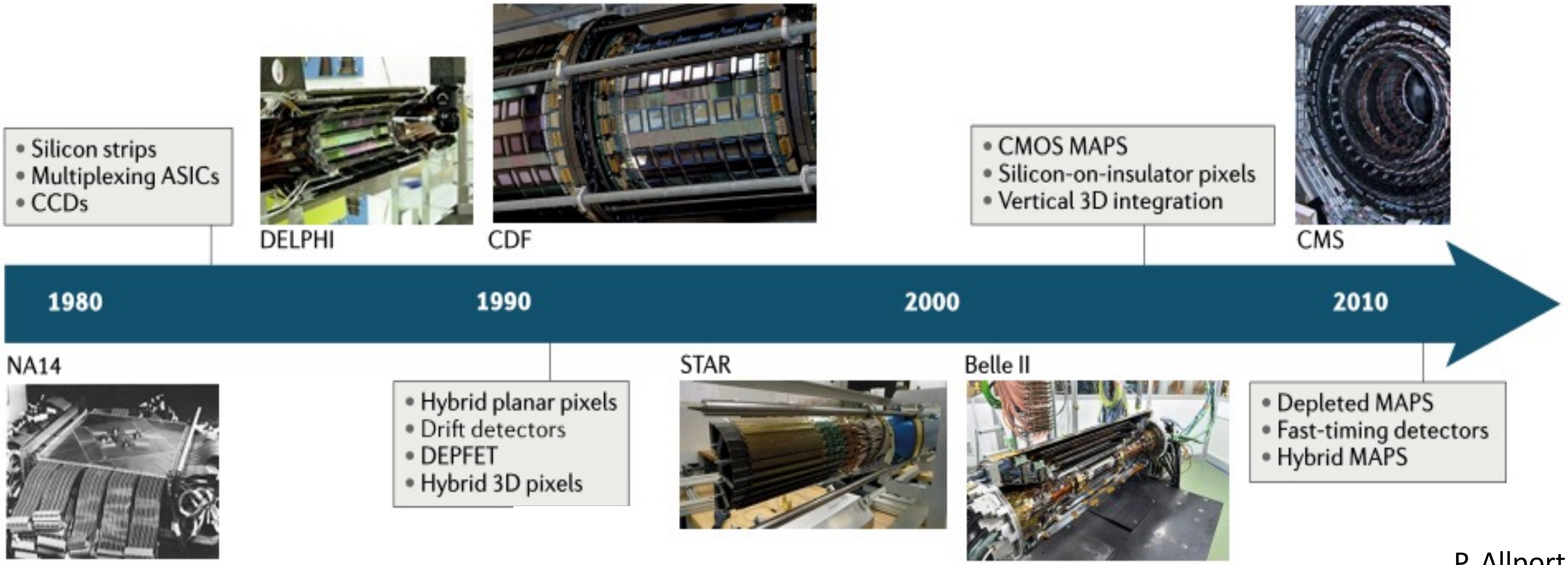


Solid State Detectors


(© ALICE collaboration)

Solid State Detectors

Many different silicon detector technologies for **particle tracking** have been developed over the last four decades:



P. Allport

Remarkable: every decade the instrumented areas have increased by a factor of 10 while the numbers of channels in the largest arrays have increased by a factor of 100

- Solid state detectors now more radiation hard and now also used for **calorimetry and time-of-flight**
- **But improved precision, radiation hardness and timing are needed**

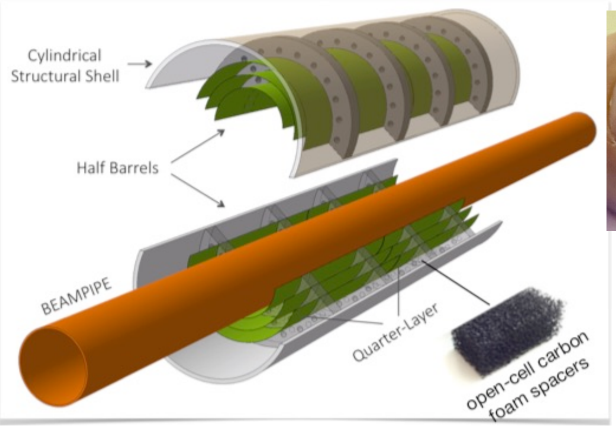
CMOS MAPS

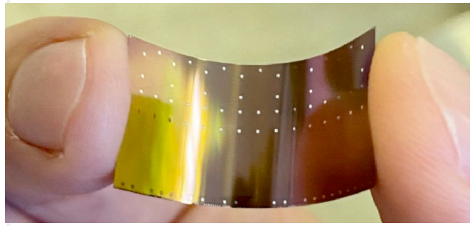
- Monolithic sensors combining sensing and readout elements
- Example: For FCC-ee vertex detector targeting spatial resolution per layer of ≤ 3μm and $X/X_0 \leq 0.05\%$, essential to have low power. Plus radiation-hardness up to $8\times10^{17} n_{eq}/cm^2$ for pp-collider.

CMOS MAPS for ALICE ITS3 (Run 4):

(LOI: CERN-LHCC-2019-018, M. Mager)

- Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 μm), air flow cooling
- Very low mass (IB), < 0.02-0.04% per layer





50μm pixel, waferscale

Slide credit Susanne Kuehn

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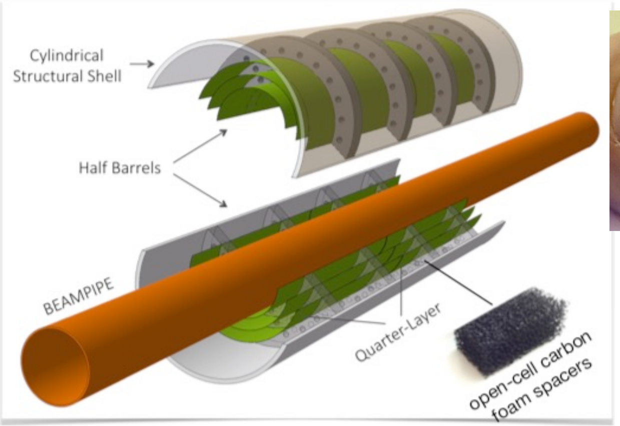

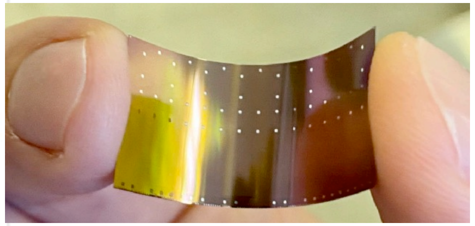

MIMOSA @ EUDET BeamTest
Telescope → 3 μm track resolution achieved

50μm pixel, waferscale

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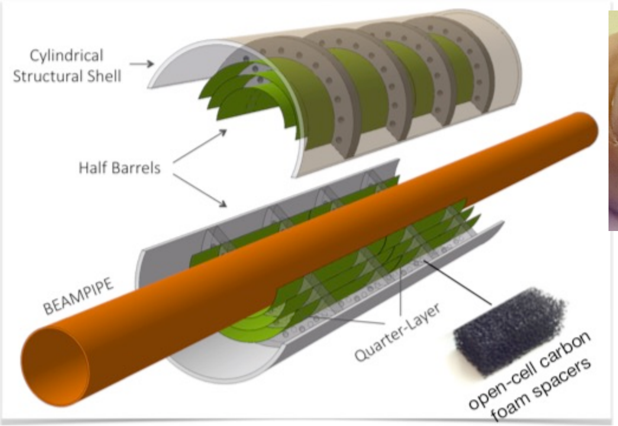

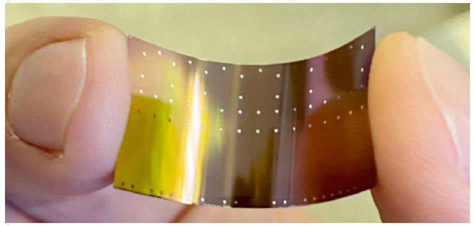

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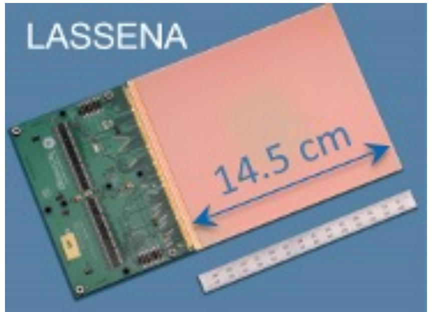
Large area: stitching
INMAPS process



Courtesy of N. Guerrini, STFC
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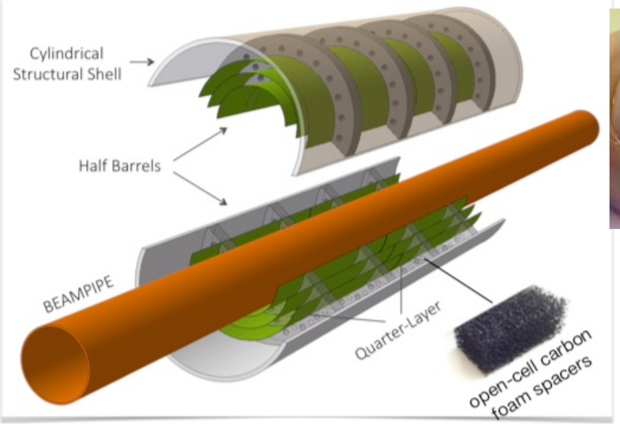
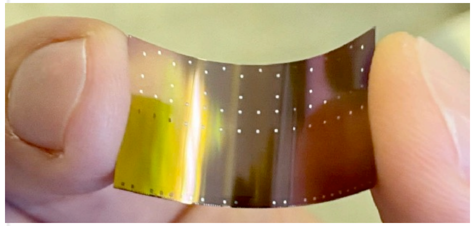
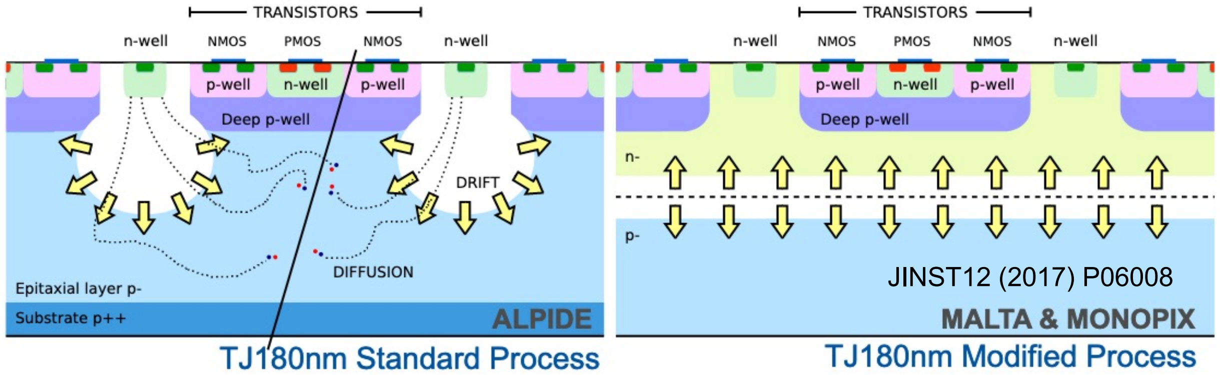




Radiation hardness of MAPS: From ALPIDE to MALTA/Monopix with modified Tower Jazz 180 nm process



→ Up to 97% efficiency after fluence of $1\times10^{15} n_{eq}/cm^2$ H. Pernegger

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Telescope → 3 μm track resolution achieved

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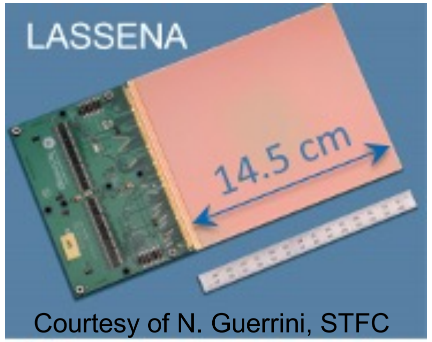

Courtesy of N. Guerrini, STFC
50μm pixel, waferscale

Slide credit Susanne Kuehn

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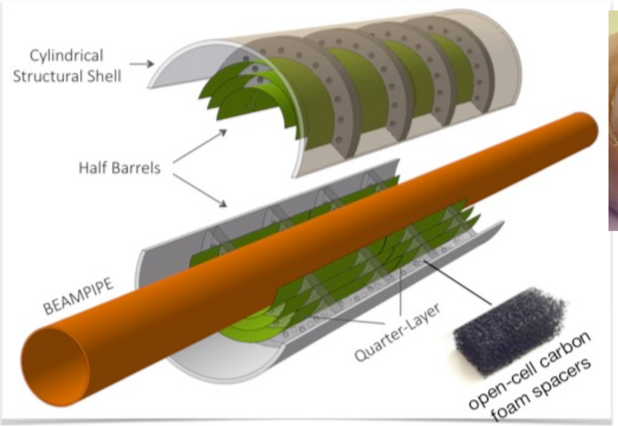

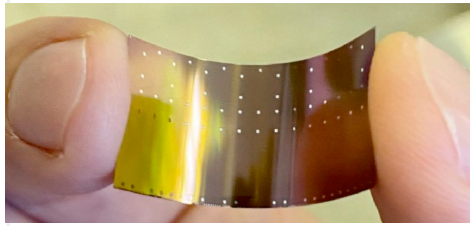

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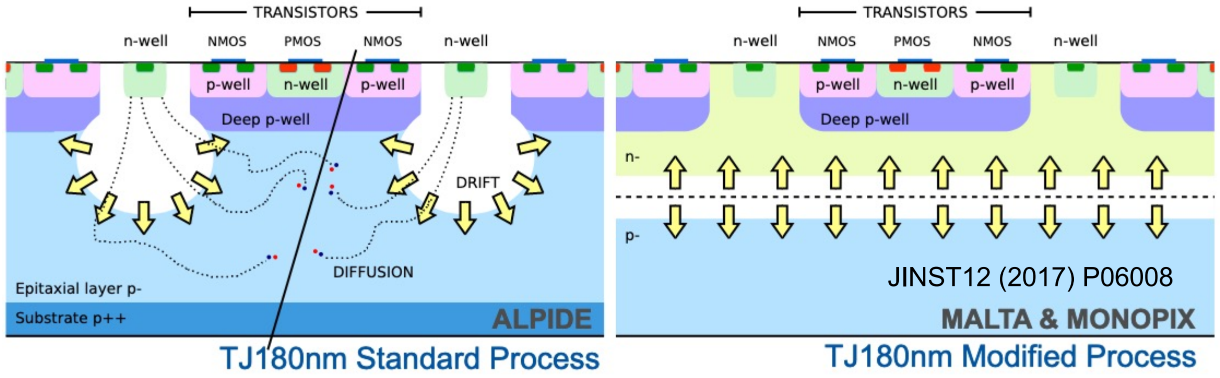

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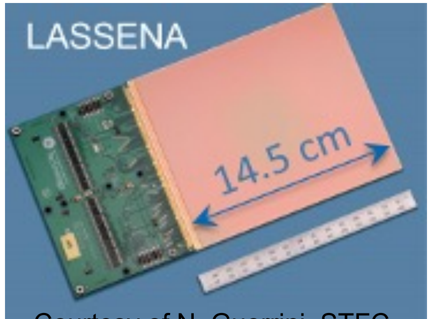


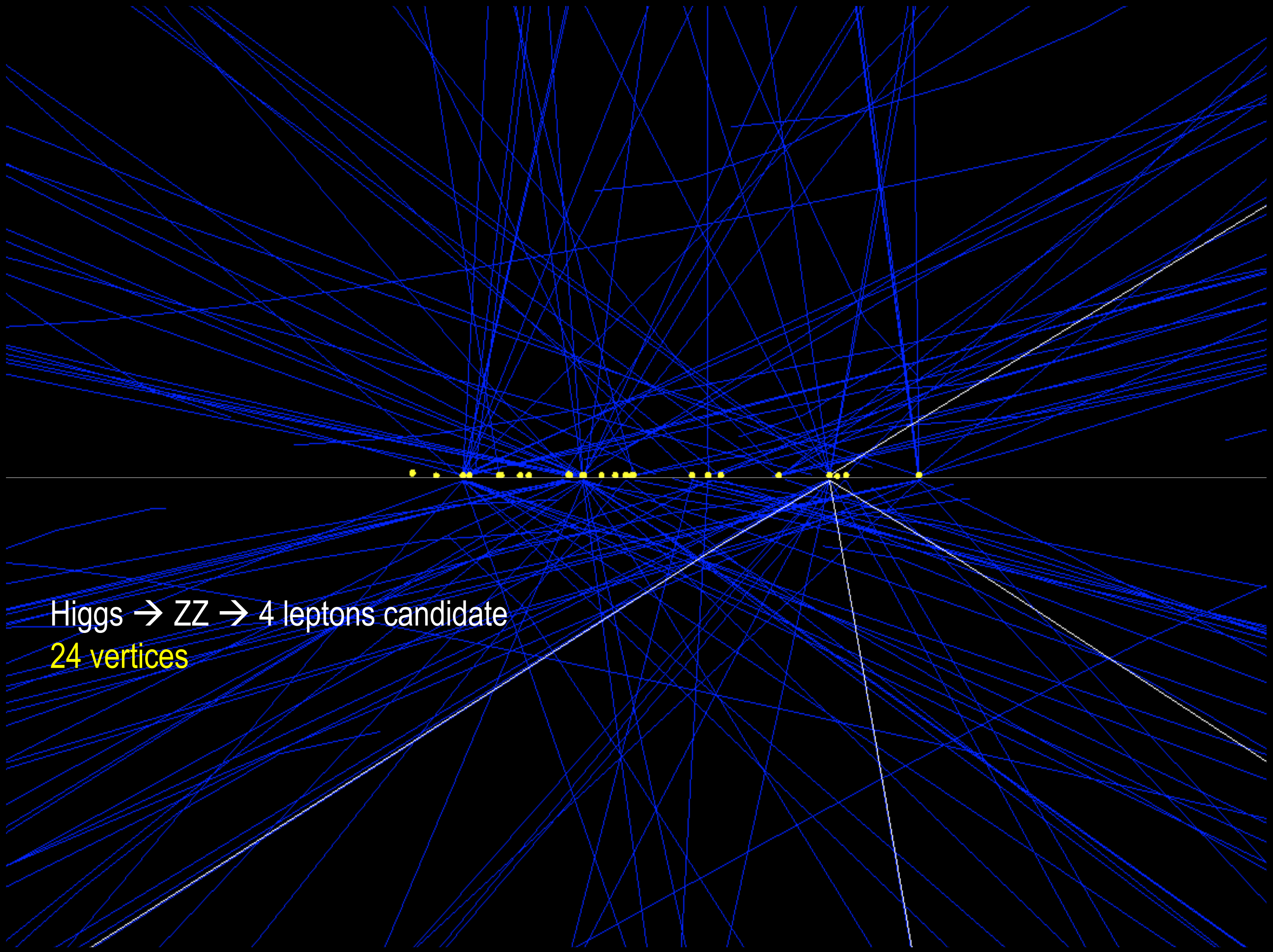
Courtesy of N. Guerrini, STFC

50μm pixel, waferscale

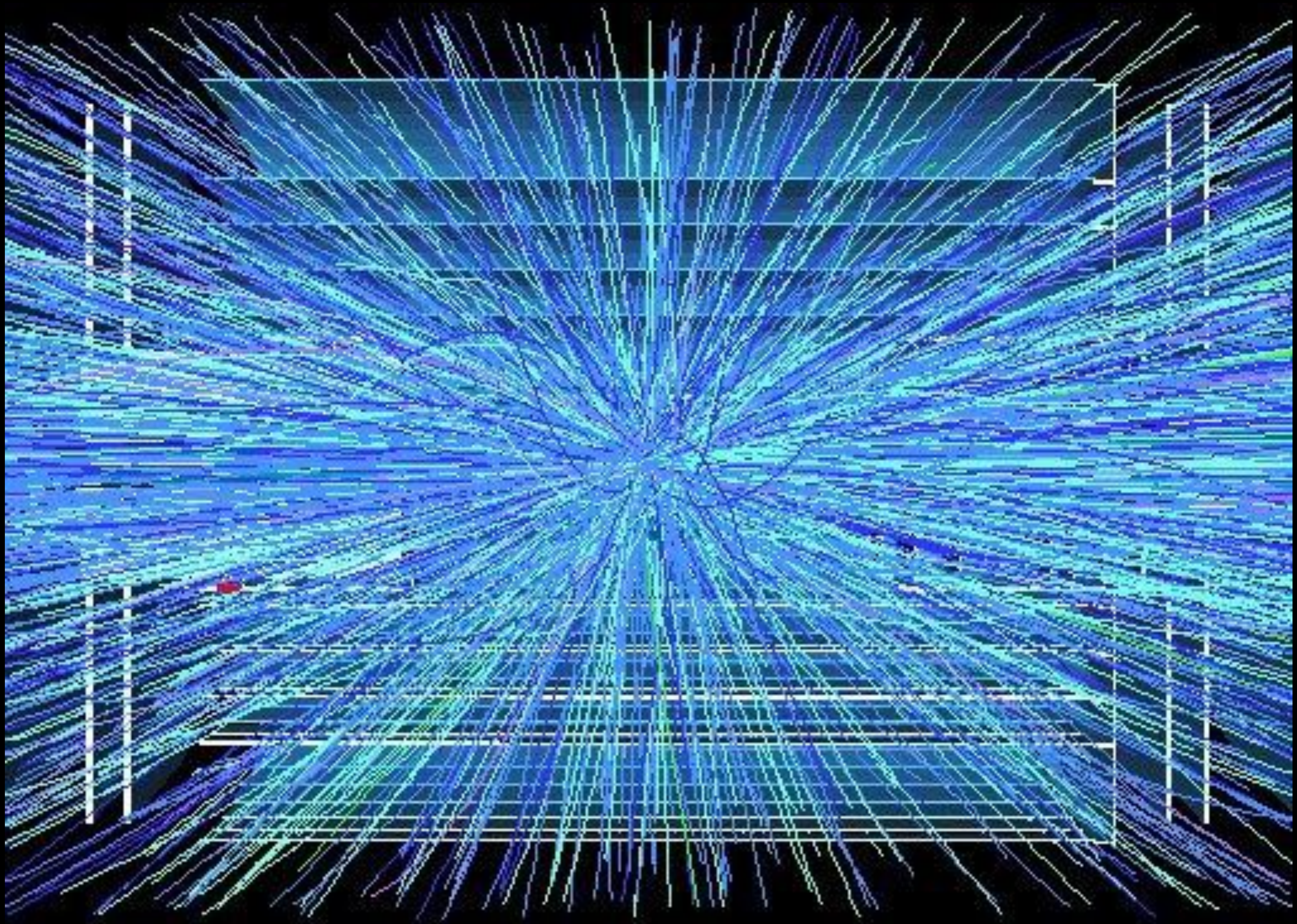
To achieve higher radiation hardness:
Hybrid technologies with thin, 3D-structures (columns/trenches) silicon and/or high bandgap materials (e.g. diamond) are mostly considered for really high radiation environments.

Slide credit Susanne Kuehn

Collisions at the LHC



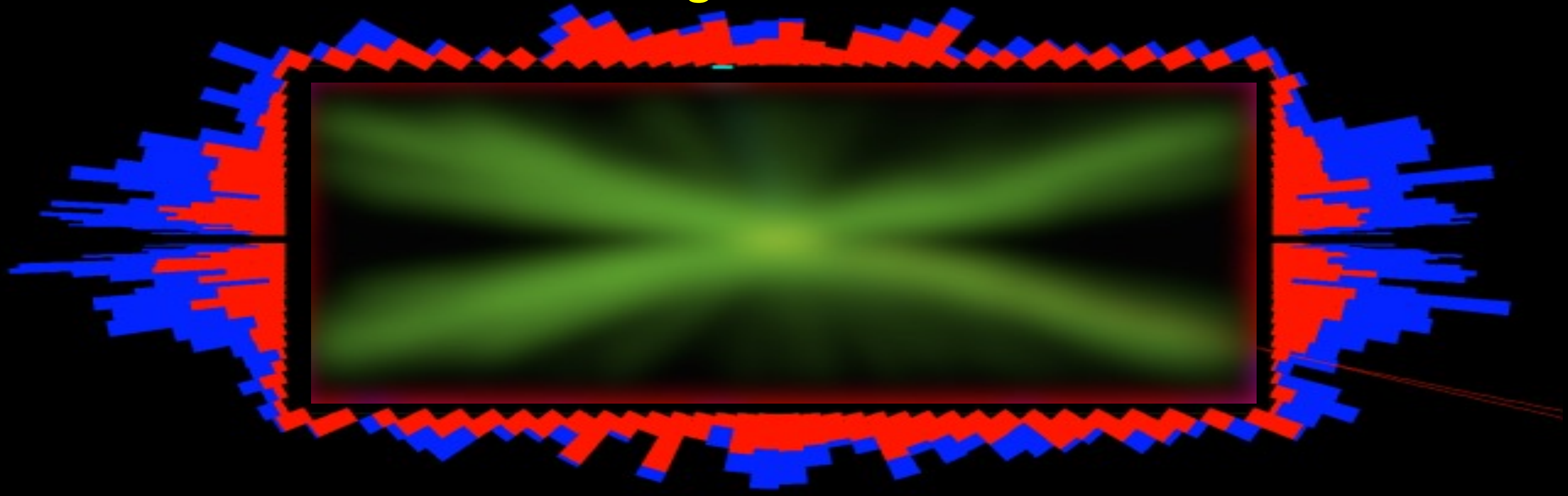
Collisions at the HL-LHC (~2029)



Event reconstruction challenges at HL-LHC

- High Luminosity → large data set, large pileup, high radiation dose

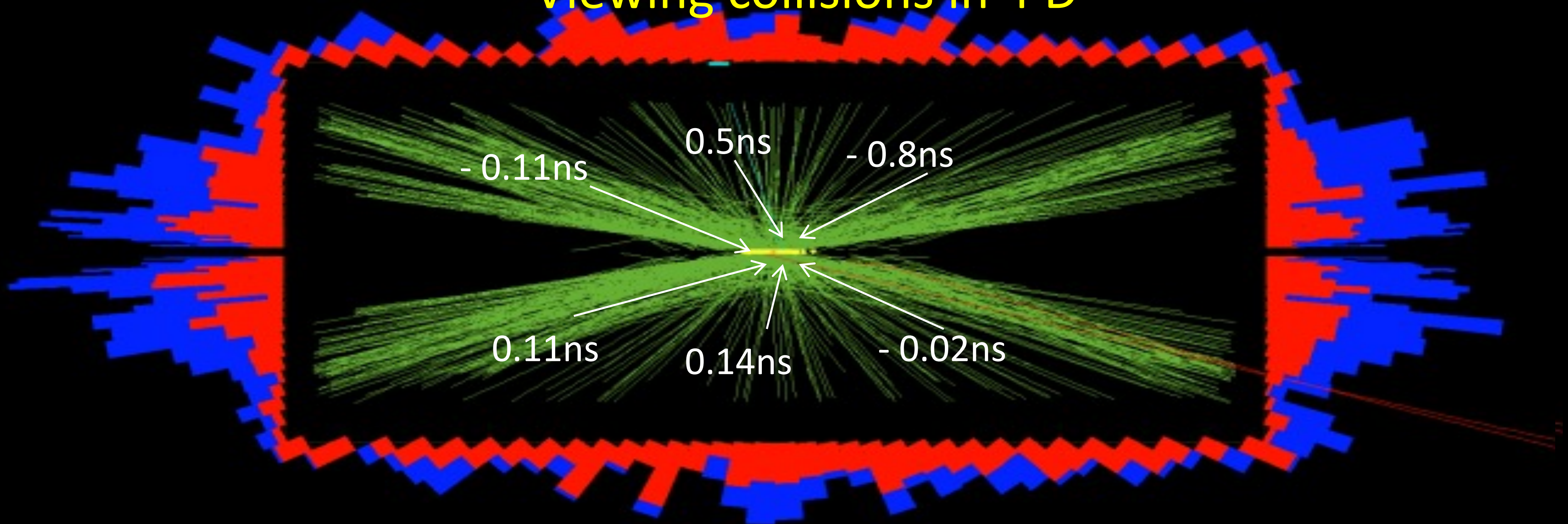
Viewing collisions in 3 D



Event reconstruction challenges at HL-LHC

- High Luminosity → large data set, large pileup, high radiation dose

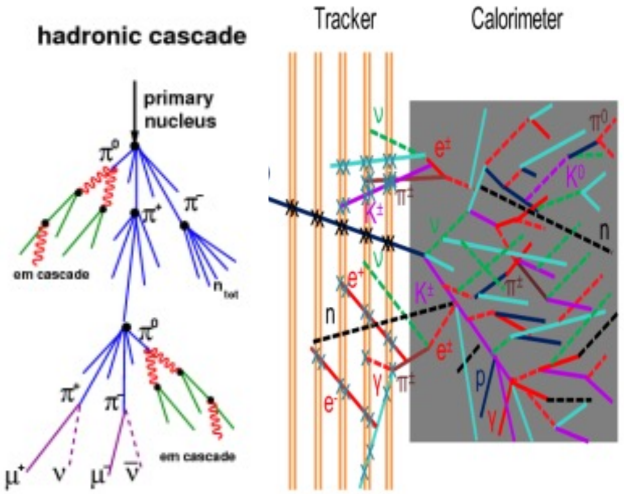
Viewing collisions in 4 D



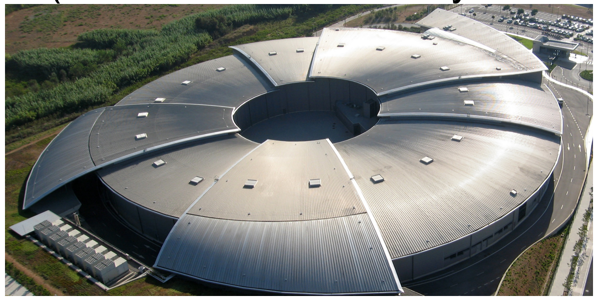
- For HL-LHC, this is enabled by new precision timing detectors → LGADs and SiPMTs
- Experience gained will be crucial for future high energy hadron colliders

LGAD and timing beyond HEP

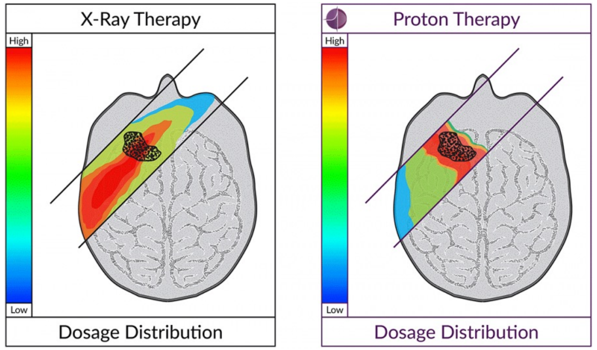
Space Applications
(Time resolved tracking)



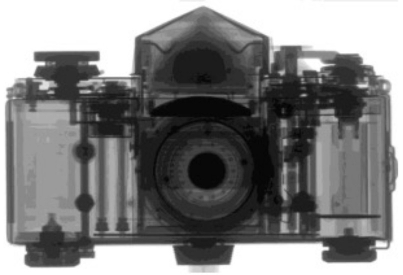
Synchrotron Applications
(LGAD tailored for X-ray detection)



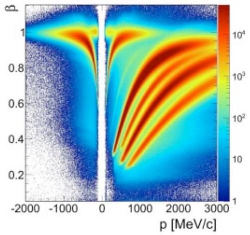
Medical Physics
(4D tracking, X-ray detection...)

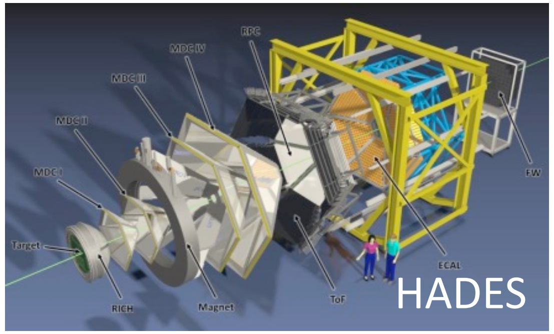


Neutron Imaging
(Combining timing LGAD with a conversion layer)



Nuclear Physics
(Particle identification)





Details at various recent workshops:

RD50 Workshops
TREDi workshops
VERTEX
Vienna conference
Etc…

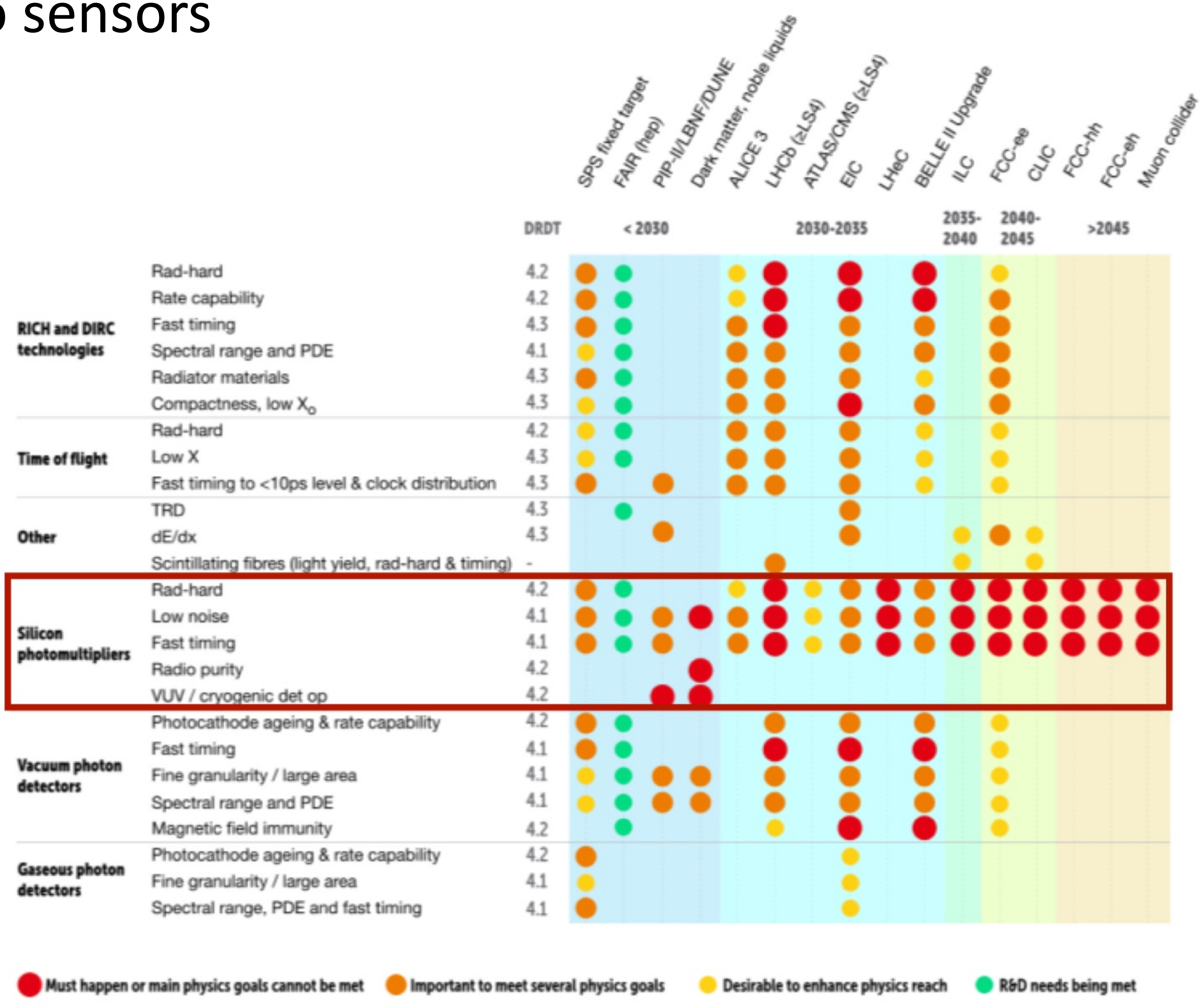
Slide credit: Giulio Pellegrini

Particle Identification and Photo sensors

Where do we stand?

- Naturally radiation hardness is at the core of the R&D for the next generation of colliders

- SiPM is the most active field but still a lot to be done, urgency is on the VUV and fast timing sensors

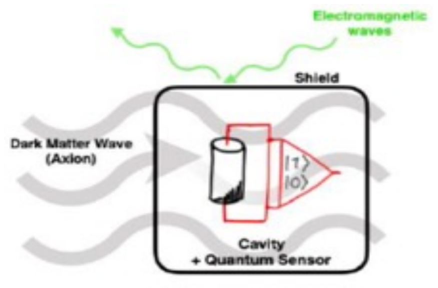


Slide credit: Matthieu Heller

Quantum and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated**: clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, …
- Several initiatives started at CERN, DESY, FNAL, US, UK, …

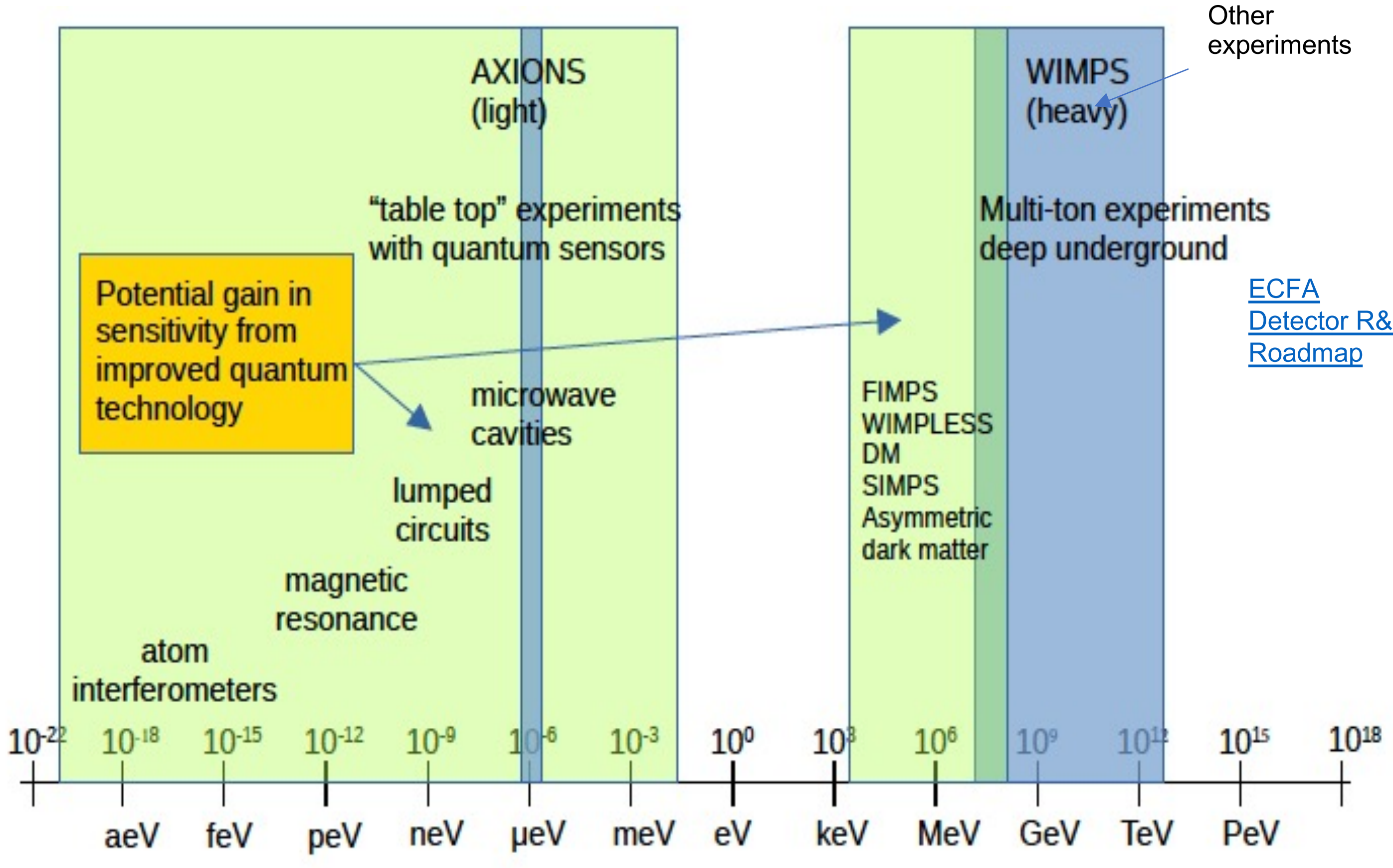
QUANTUM TECHNOLOGY INITIATIVE



Microwave Cavity

S. Golawa

Example: potential mass ranges that quantum sensing approaches open up for Axion searches



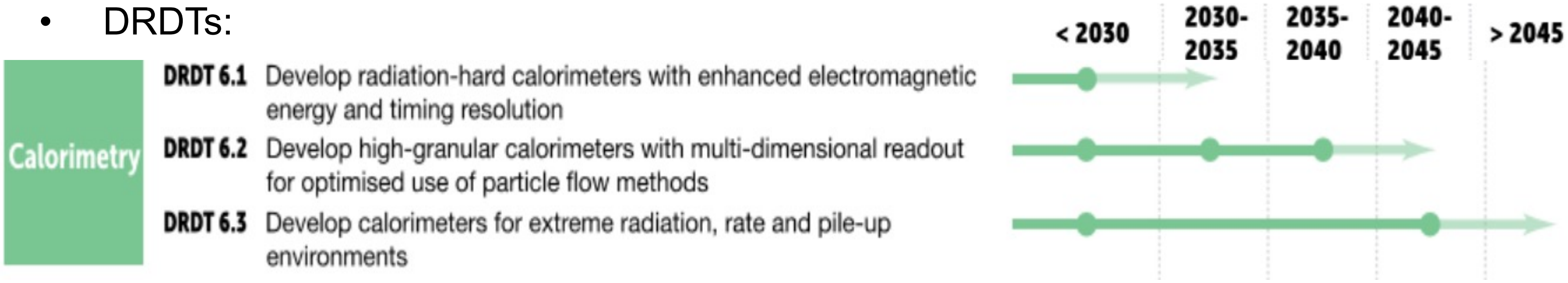
Axion mass range

ECFA Detector R&D Roadmap

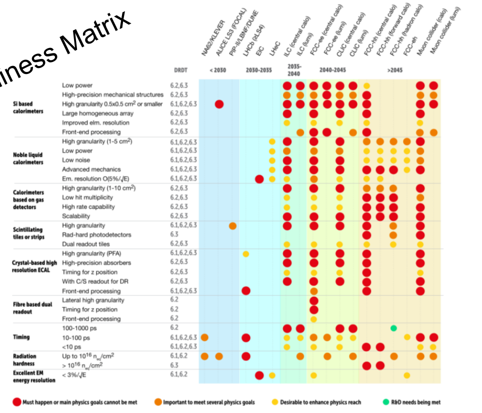
Blue: now
Light green: with quantum

Calorimetry

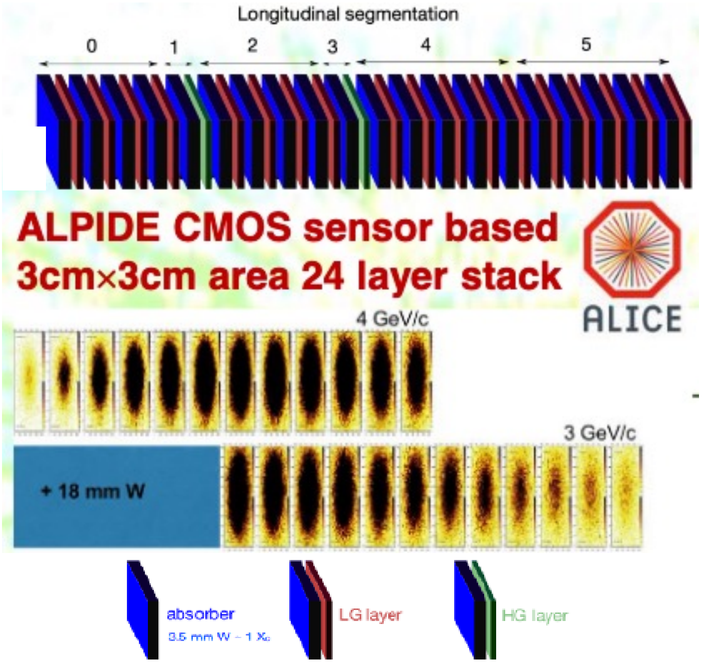
- **R&D in calorimetry has a particularly long lead-time** due to the duration of the stage for experiment specific final prototyping, procurement, production, assembly, commissioning and installation
- DRDTs:



full Detector Readiness Matrix in spare slides



ALICE FoCAL



DRDT 6.1: The enhanced electromagnetic energy and timing resolution most relevant in next decade for upgrades of ALICE and LHCb.

Example: MAPS based SiW ECALs

Good energy resolution

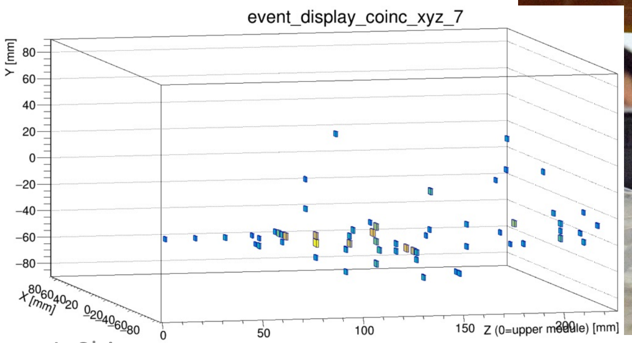
T. Peitzmann, H. Yokoyama: "Test beam performance of a digital pixel calorimeter", T. Rogoschinski: "Simulation of a SiW pixel calorimeter": TIPP 26/5/21

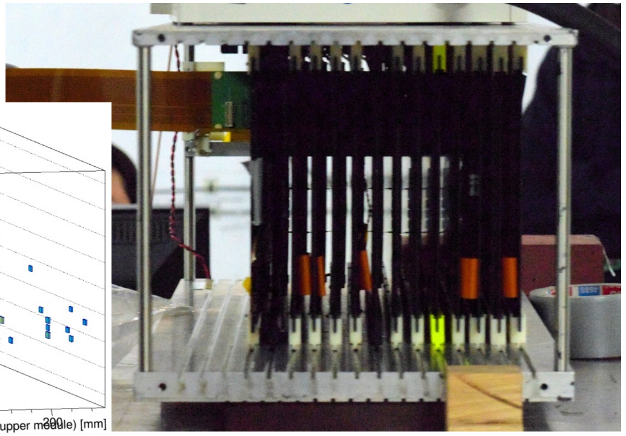
CALICE

Integrated front-end and digital electronics
15 layers with 15360 channels
2.1 mm (x11) and 4.2 mm (x3) tungsten

Culmination of 10 years of prototyping

https://aitanatop.ific.uv.es/aitanatop/siwecal-tb2021/





Slide credit: Susanne Kuehn

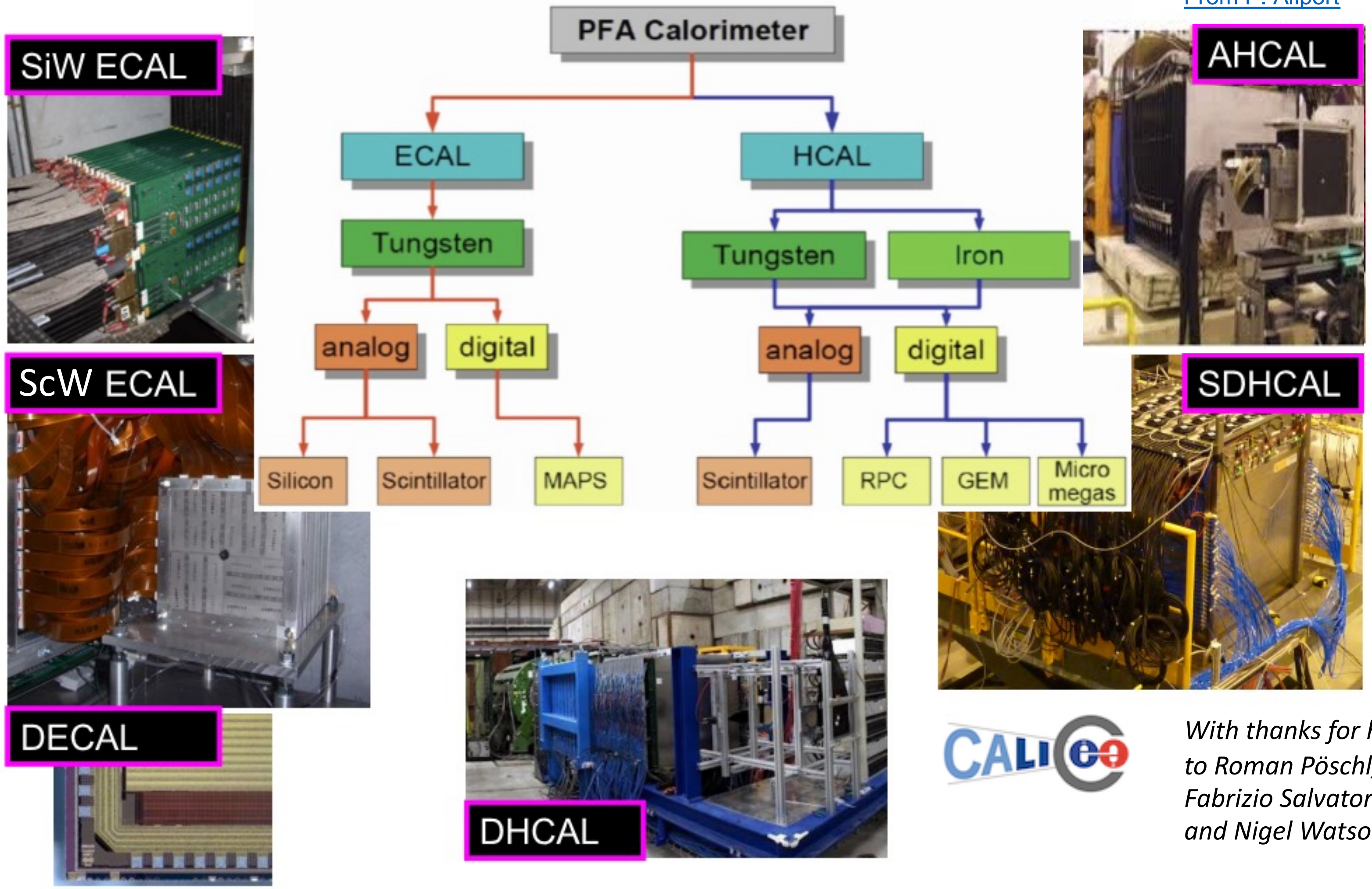
Calorimetry

DRDT 6.2: Particle Flow based on high granularity calorimeters particularly important for e^+e^- Higgs-EW-top factories.
Separation of signals by charged and neutral particles in highly granular calorimeters.

[From P. Allport]

Options are:

- **Dual-readout** (e.g. DREAM/RD52 Collaboration) f_{EM} from absorber with combined scintillator parallel plates for non-relativistic (hadronic) component and Cherenkov for relativistic (EM) component (PMMA fibres);
- High granularity **LAr/LKr**: LAr proven technique but high granularity challenging;
- Finely segmented **crystals**;
- **Particle Flow based "tracking calorimeter"** concept with very fine sense element segmentation for precise reconstruction of each particle within the jet. Up to ~100M channels and 10000 m^2 active elements



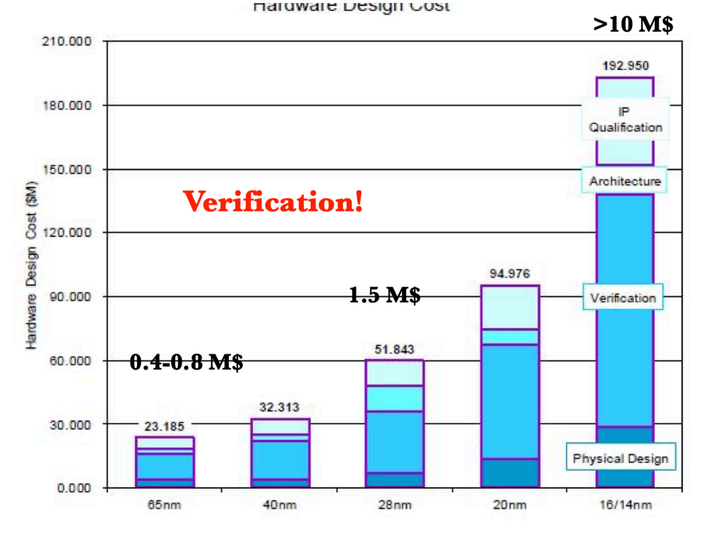
With thanks for help to Roman Pöschl, Fabrizio Salvatore and Nigel Watson

DRDT 6.3: Extreme radiation hardness and pile-up rejection critical for FCC-hh in particular

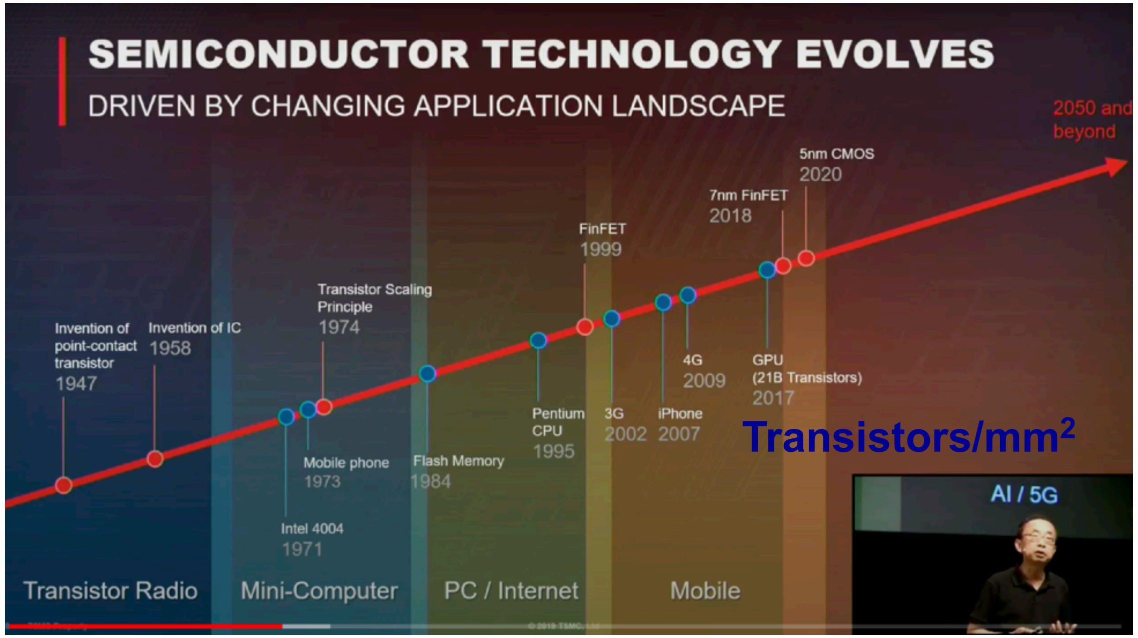
Slide credit: Susanne Kuehn

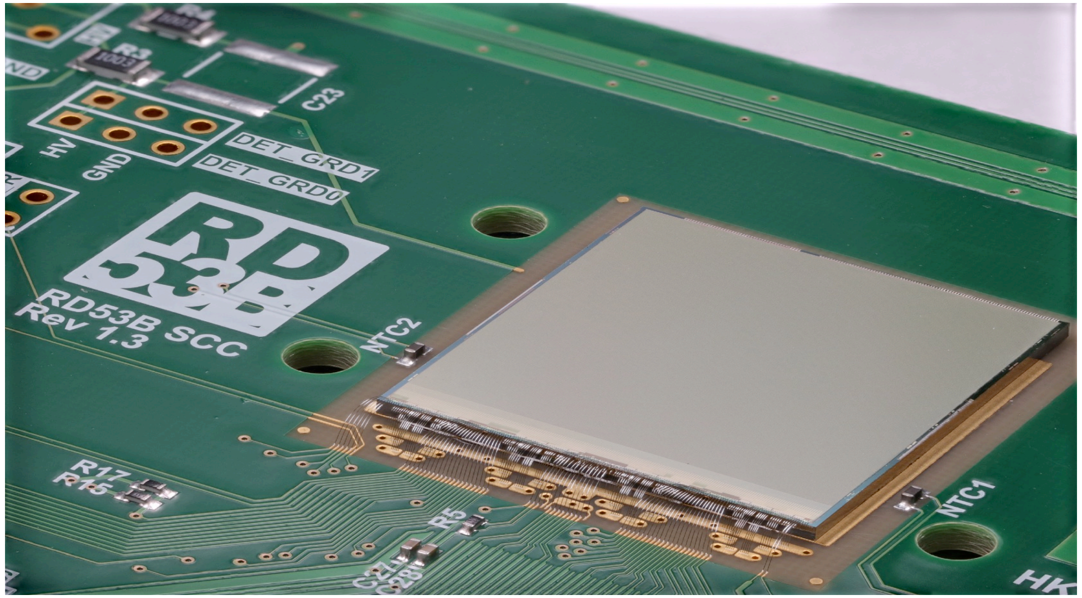
Electronics

- Main challenges on electronics: high granularity and resolution, precision timing, etc. imply a cost in processing and eventually power → need latest advances in **high-speed links and microelectronics.**
- However very specific need for PP in terms of, e.g., radiation hardness.
- Call for a **change of approach** from the past with **increased coordination** around Europe



A. Rivetti, TF7 symposium



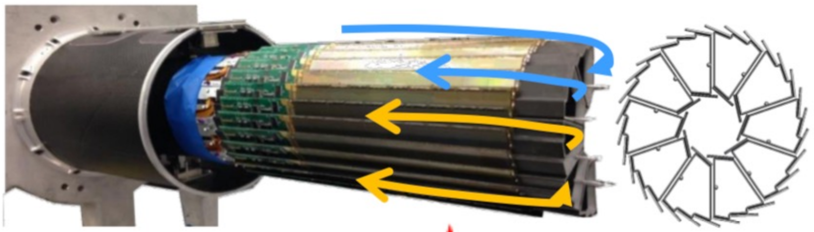


Integration

Designing and building ultra thin si sensor vertex detectors and cooling them with air/gas

AIR COOLING

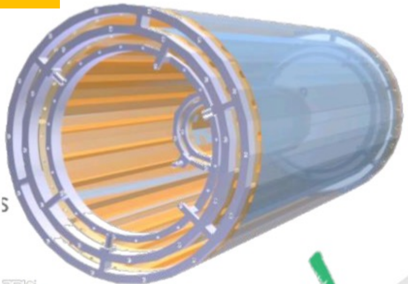
Air Flow

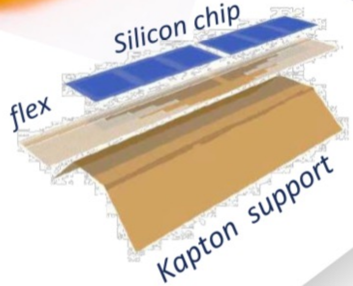


STAR HFT

in operation @LBNL

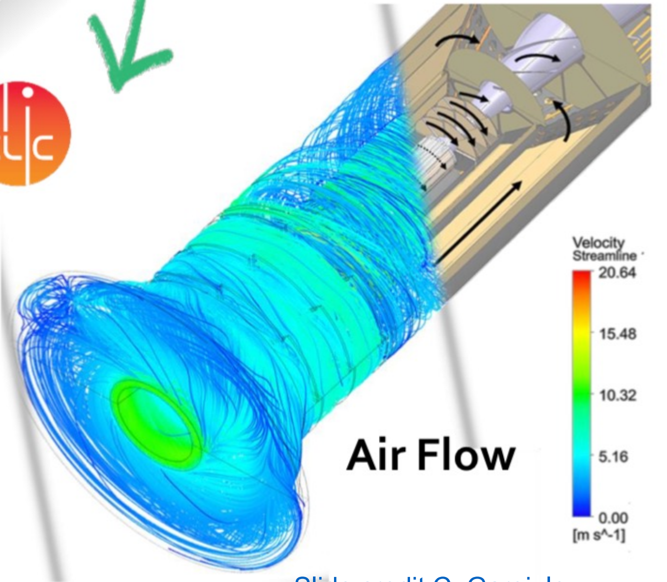
Helium gas cooling





Mu3e PSI

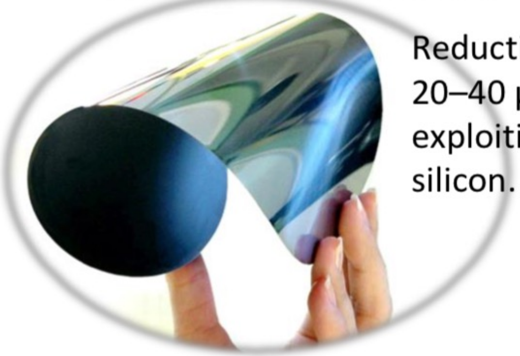
R&D



Slide credit C. Gargiulo

Curved Silicon sensors

ALICE



Reduction of thickness to about 20–40 µm open possibility of exploiting the flexible nature of silicon.

R&D

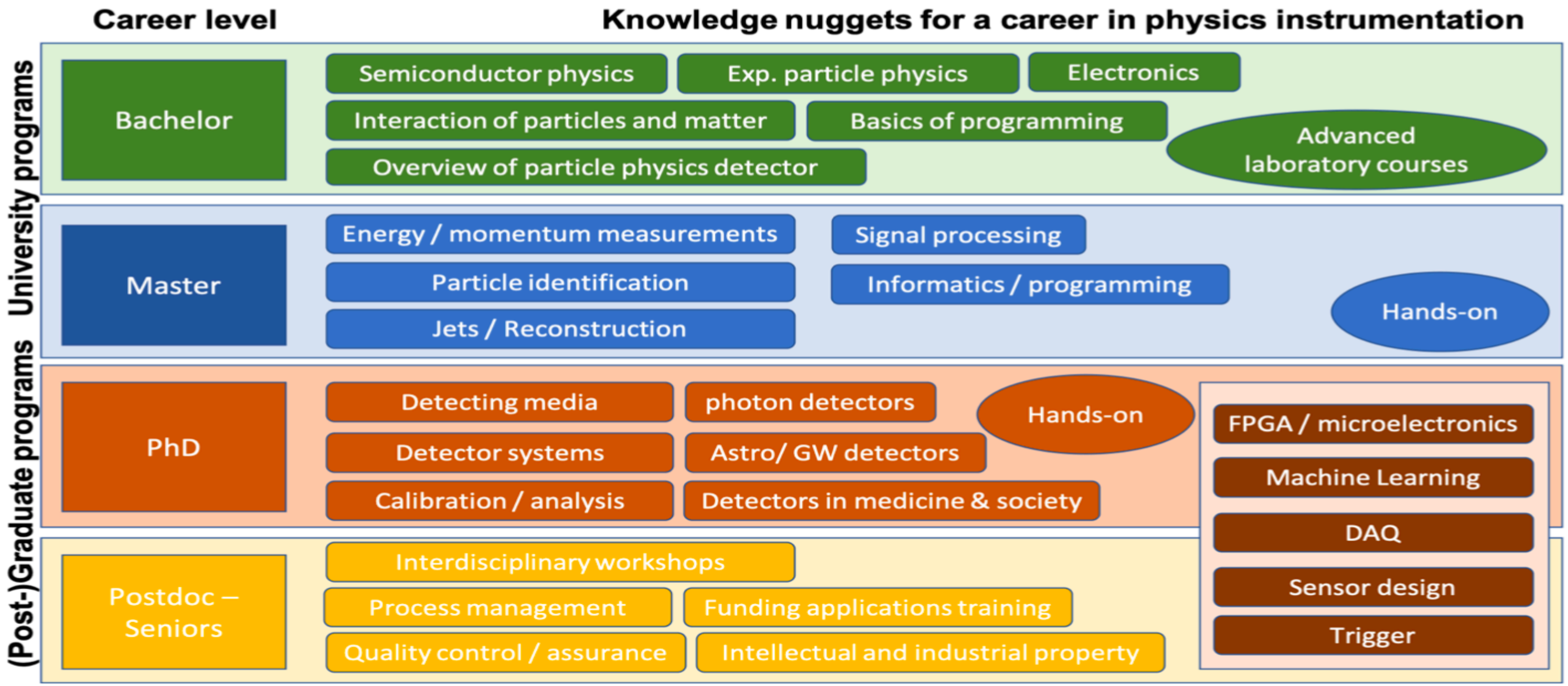
→ The design of new vertex detectors at lepton colliders will have to cope with unprecedented requirements on material budget and dimensional stability.

Reduction of material before the sensor → new sensor technologies & air/gas cooling to meet both thermal and structural vibration requirements

Training

Training	**DCT 1**	Establish and maintain a European coordinated programme for training in instrumentation
	DCT 2	Develop a master's degree programme in instrumentation

- Training for a career in physics instrumentation is a key element (especially given the timescale of the projects).
- Specific recommendation for the development of an education programme in instrumentation



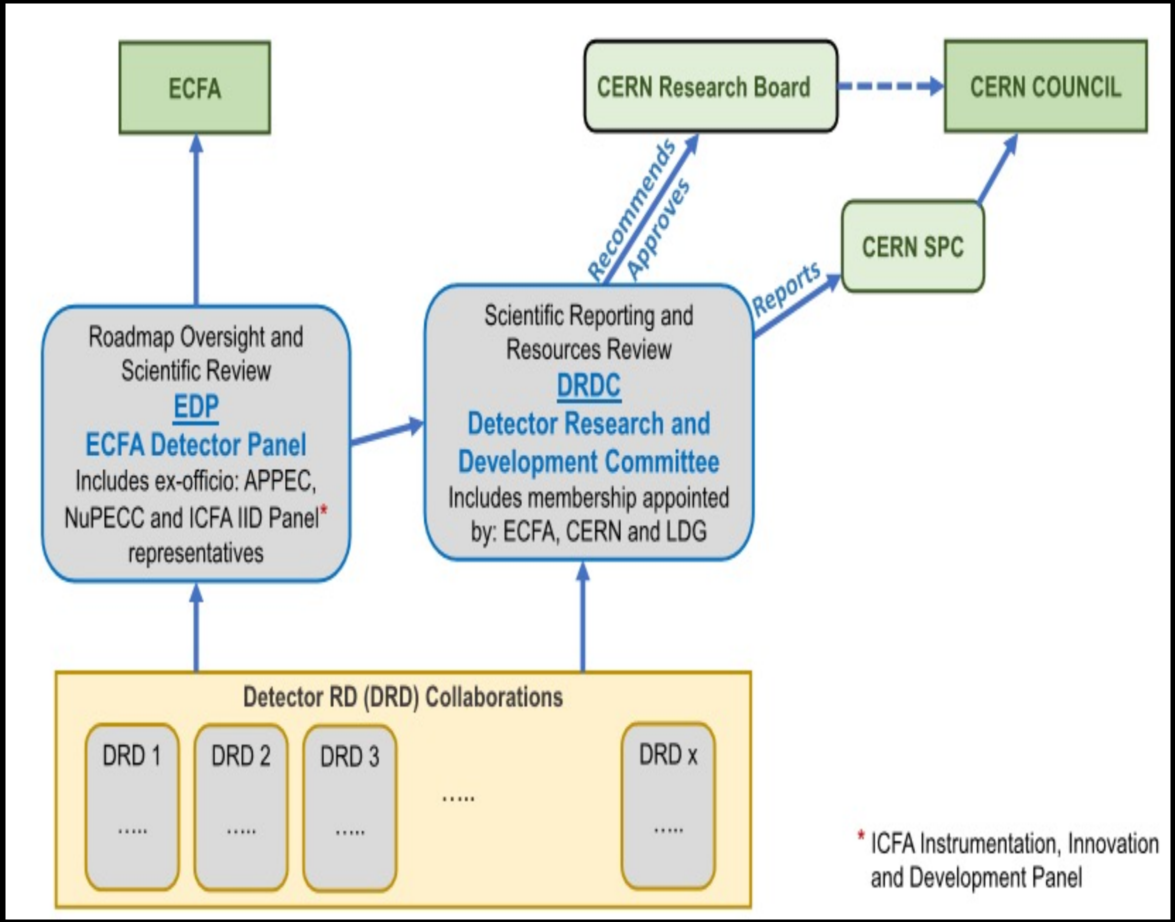
Roadmap Implementation Plan

- Next step: ECFA was mandated by Council in December 2021 to work out an implementation plan (*in close collaboration with the SPC, funding agencies & relevant research organisations in Europe and beyond)*

- Work ongoing

  - First implementation plan proposed

  - Discussions with CERN Council and Funding Agencies have started



Proposed structure:

- Establish new Detector R&D (DRD) Collaborations at CERN (one for each detector technology)
- Oversight and reviews by ECFA and CERN Committees

General Strategic Recommendations

GSR 1 - Supporting R&D facilities

It is recommended that the structures to provide Europe-wide coordinated infrastructure in the areas of: test beams, large scale generic prototyping and irradiation be consolidated and enhanced to meet the needs of next generation experiments with adequate centralised investment to avoid less cost-effective, more widely distributed, solutions, and to maintain a network structure for existing distributed facilities, e.g. for irradiation

Testbeams, irradiation, and large scale prototyping facilities

GSR 2 - Engineering support for detector R&D

In response to ever more integrated detector concepts, requiring holistic design approaches and large component counts, the R&D should be supported with adequate mechanical and electronics engineering resources, to bring in expertise in state-of-the-art microelectronics as well as advanced materials and manufacturing techniques, to tackle generic integration challenges, and to maintain scalability of production and quality control from the earliest stages.

ASIC Design, advanced mechanics

GSR 3 - Specific software for instrumentation

Across DRDTs and through adequate capital investments, the availability to the community of state-of-the-art R&D-specific software packages must be maintained and continuously updated. The expert development of these packages - for core software frameworks, but also for commonly used simulation and reconstruction tools - should continue to be highly recognised and valued and the community effort to support these needs to be organised at a European level.

GEANT4, Pandora, key4HEP

GSR 4 - International coordination and organisation of R&D activities

With a view to creating a vibrant ecosystem for R&D, connecting and involving all partners, there is a need to refresh the CERN RD programme structure and encourage new programmes for next generation detectors, where CERN and the other national laboratories can assist as major catalysers for these. It is also recommended to revisit and streamline the process of creating and reviewing these programmes, with an extended framework to help share the associated load and increase involvement, while enhancing the visibility of the detector R&D community and easing communication with neighbouring disciplines, for example in cooperation with the ICFA Instrumentation Panel.

R&D collaborations

GSR 5 - Distributed R&D activities with centralised facilities

Establish in the relevant R&D areas a distributed yet connected and supportive tier-ed system for R&D efforts across Europe. Keeping in mind the growing complexity, the specialisation required, the learning curve and the increased cost, consider more focused investment for those themes where leverage can be reached through centralisation at large institutions, while addressing the challenge that distributed resources remain accessible to researchers across Europe and through them also be available to help provide enhanced training opportunities.

Distributed Detector Laboratory

GSR 6 - Establish long-term strategic funding programmes

Establish, additional to short-term funding programmes for the early proof of principle phase of R&D, also long-term strategic funding programmes to sustain both research and development of the multi-decade DRDTs in order for the technology to mature and to be able to deliver the experimental requirements. Beyond capital investments of single funding agencies, international collaboration and support at the EU level should be established. In general, the cost for R&D has increased, which further strengthens the vital need to make concerted investments.

Enhanced Funding

GSR 7 – "Blue-sky" R&D

It is essential that adequate resources be provided to support more speculative R&D which can be riskier in terms of immediate benefits but can bring significant and potentially transformational returns if successful both to particle physics: unlocking new physics may only be possible by unlocking novel technologies in instrumentation, and to society. Innovative instrumentation research is one of the defining characteristics of the field of particle physics. "Blue-sky" developments in particle physics have often been of broader application and had immense societal benefit. Examples include: the development of the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and X-ray imaging for photon science.

From the candle to the light bulb

GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts

Innovation in instrumentation is essential to make progress in particle physics, and R&D experts are essential for innovation. It is recommended that ECFA, with the involvement and support of its Detector R&D Panel, continues the study of recognition with a view to consolidate the route to an adequate number of positions with a sustained career in instrumentation R&D to realise the strategic aspirations expressed in the EPPSU. It is suggested that ECFA should explore mechanisms to develop concrete proposals in this area and to find mechanisms to follow up on these in terms of their implementation. Consideration needs to be given to creating sufficiently attractive remuneration packages to retain those with key skills which typically command much higher salaries outside academic research. It should be emphasised that, in parallel, society benefits from the training particle physics provides because the knowledge and skills acquired are in high demand by industries in high-technology economies.

Recruiting, salaries, permanence, recognition

GSR 9 - Industrial partnerships

It is recommended to identify promising areas for close collaboration between academic and industrial partners, to create international frameworks for exchange on academic and industrial trends, drivers and needs, and to establish strategic and resources-loaded cooperation schemes on a European scale to intensify the collaboration with industry, in particular for developments in solid state sensors and micro-electronics.

Innovation

GSR 10 – Open Science

It is recommended that the concept of Open Science be explicitly supported in the context of instrumentation, taking account of the constraints of commercial confidentiality where these apply due to partnerships with industry. Specifically, for publicly-funded research the default, wherever possible, should be open access publication of results and it is proposed that the Sponsoring Consortium for Open Access Publishing in Particle Physics (SCOAP^3) should explore ensuring similar access is available to instrumentation journals (including for conference proceedings) as to other particle physics publications.

Open Access publications

Roadmap Conclusions

Requested by the EPPSU, ECFA set up a Roadmap process with broad community consultation

- Ensure that detector development with its long time scales does not become the limiting factor for the future projects envisaged by the European Strategy

A matrix structure is laid out, displaying synergies between concurrent and subsequent projects

- complemented by general strategic recommendations to strengthen the field

Discussions towards the implementation are on-going

- R&D collaborations, and the Roadmap Task Forces, anchored at CERN
- Reviews by EDP and a new DRDC
- Discussions with funding agencies in progress

The roadmap should be updated together with the European Strategy

- Review process will provide direct input

"The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark" *(Michelangelo)*

Aim high or we will not realize the potential of our field, discovery will be stalled and we betray ourselves and the next generation.

Photo credit: Michael Hoch/CERN

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