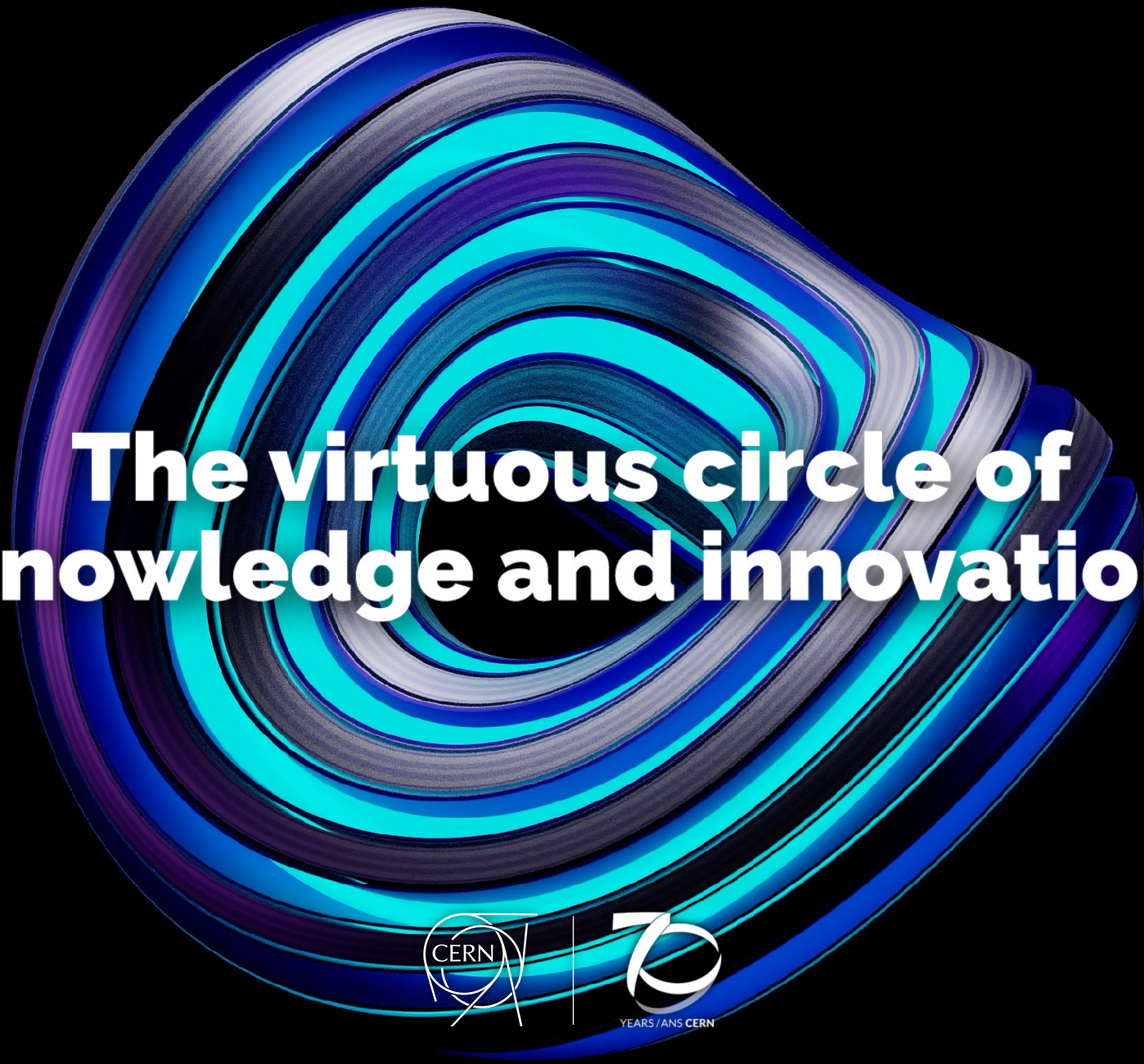

The virtuous circle of
knowledge and innovation
CERN
70
YEARS / ANS CERN

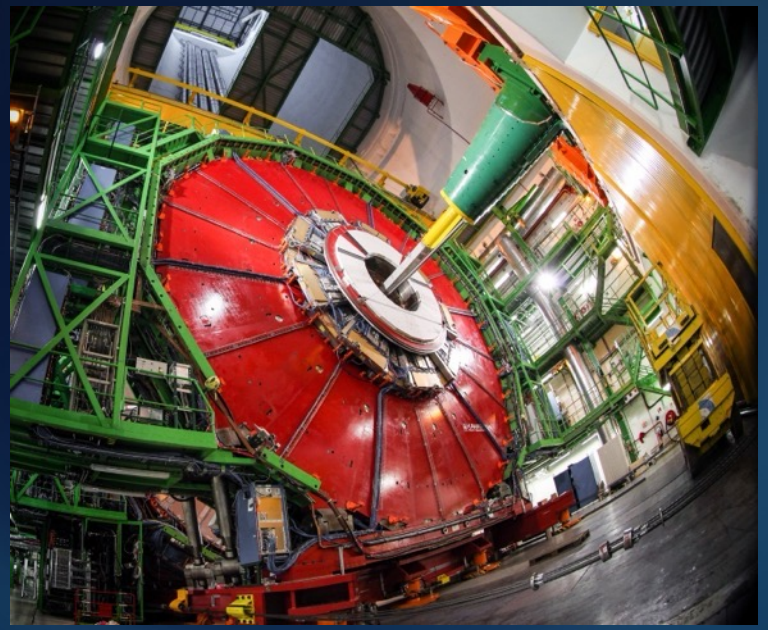
# The Virtuous Circle of Knowledge and Innovation

Host: **Paola Catapano**

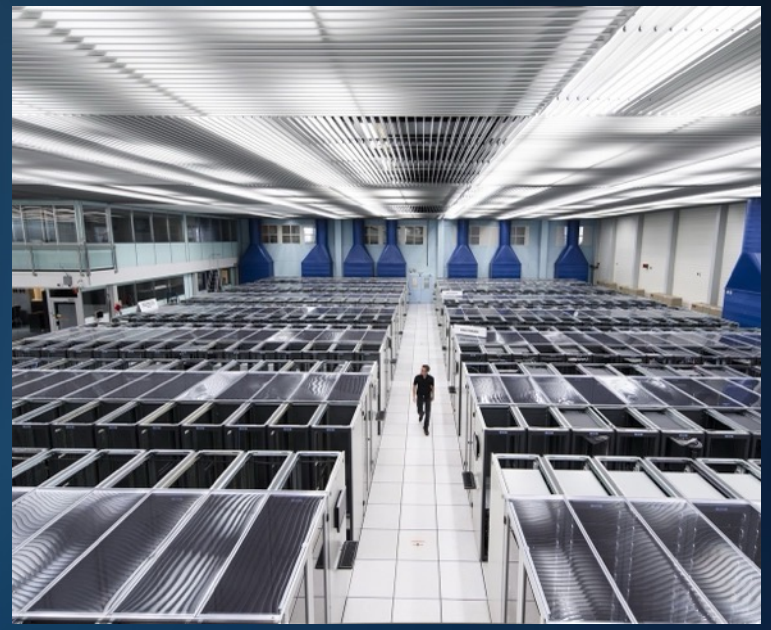
Speakers: **Alain Aspect, Tabea Arndt, Amalia Ballarino, Reinhold Bertlmann, Daniela Bortoletto, Nicolas Gisin, Michele Grossi, Jan Jakubek, Steffen Kappler, Alessandra Lombardi**

# We develop technologies in three key areas

ACCELERATORS



DETECTORS



COMPUTING

Session 1

# Advanced Particle Accelerators Powering Progress

**Alessandra Lombardi**
Senior accelerator physicist, CERN

**Amalia Ballarino**
Deputy Head of Magnets, Superconductors, and Cryostats Group, CERN

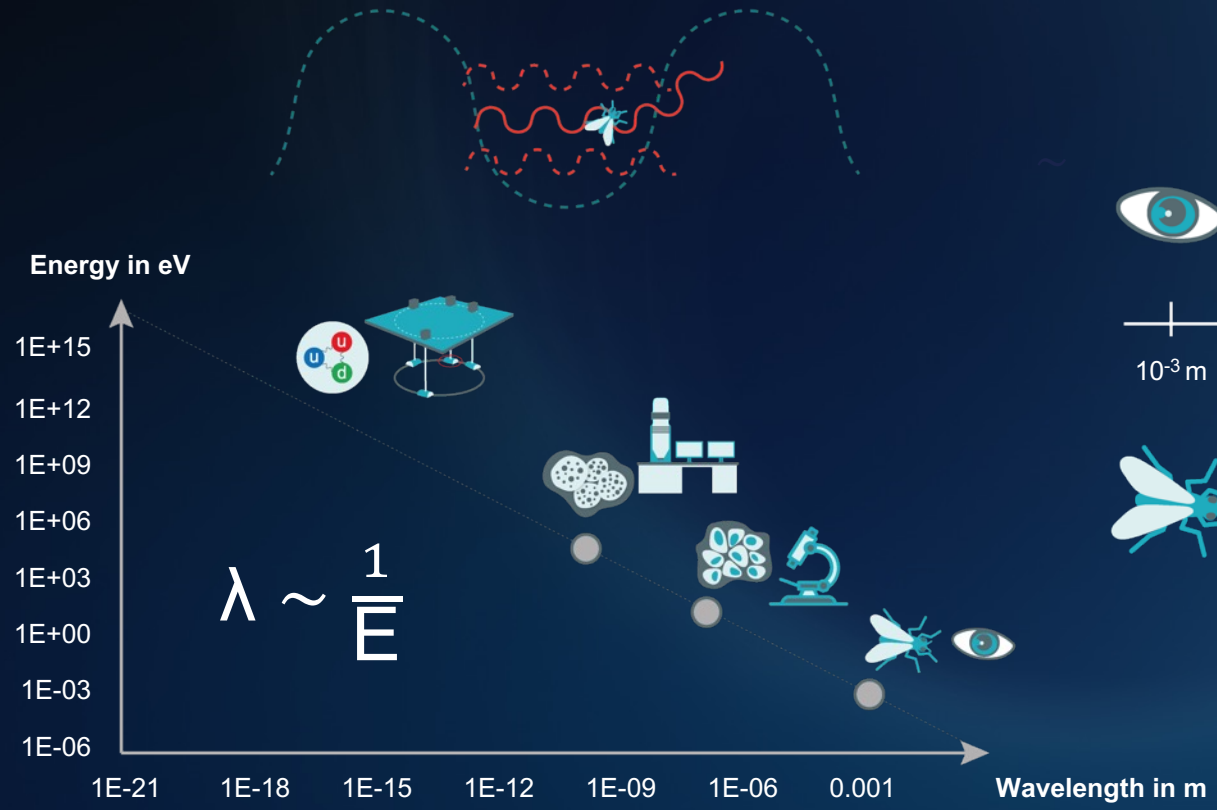
**Tabea Arndt**
Professor at the Karlsruhe Institute of Technology (KIT), Germany

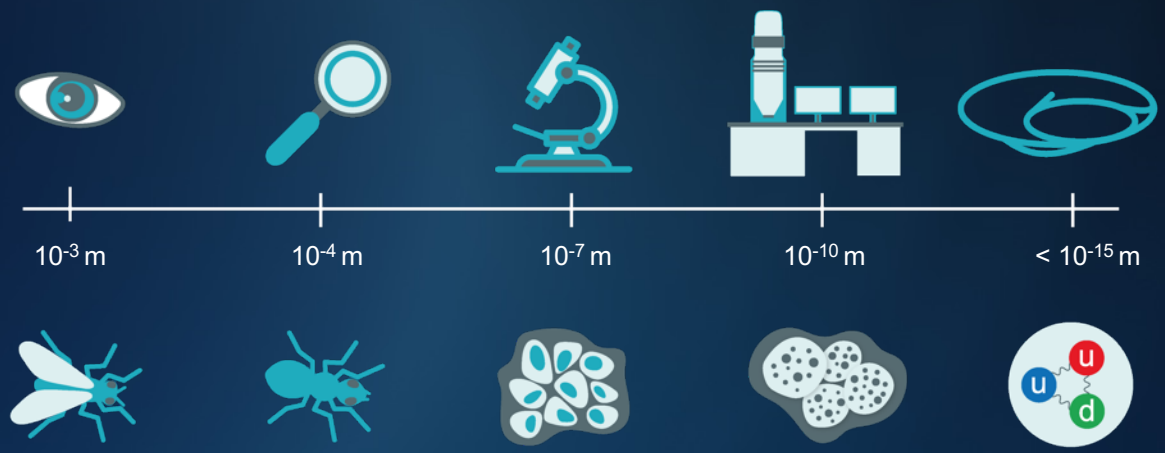
CERN | 70 YEARS / ANS CERN

# Particle Accelerators
# Probing the infinitely small

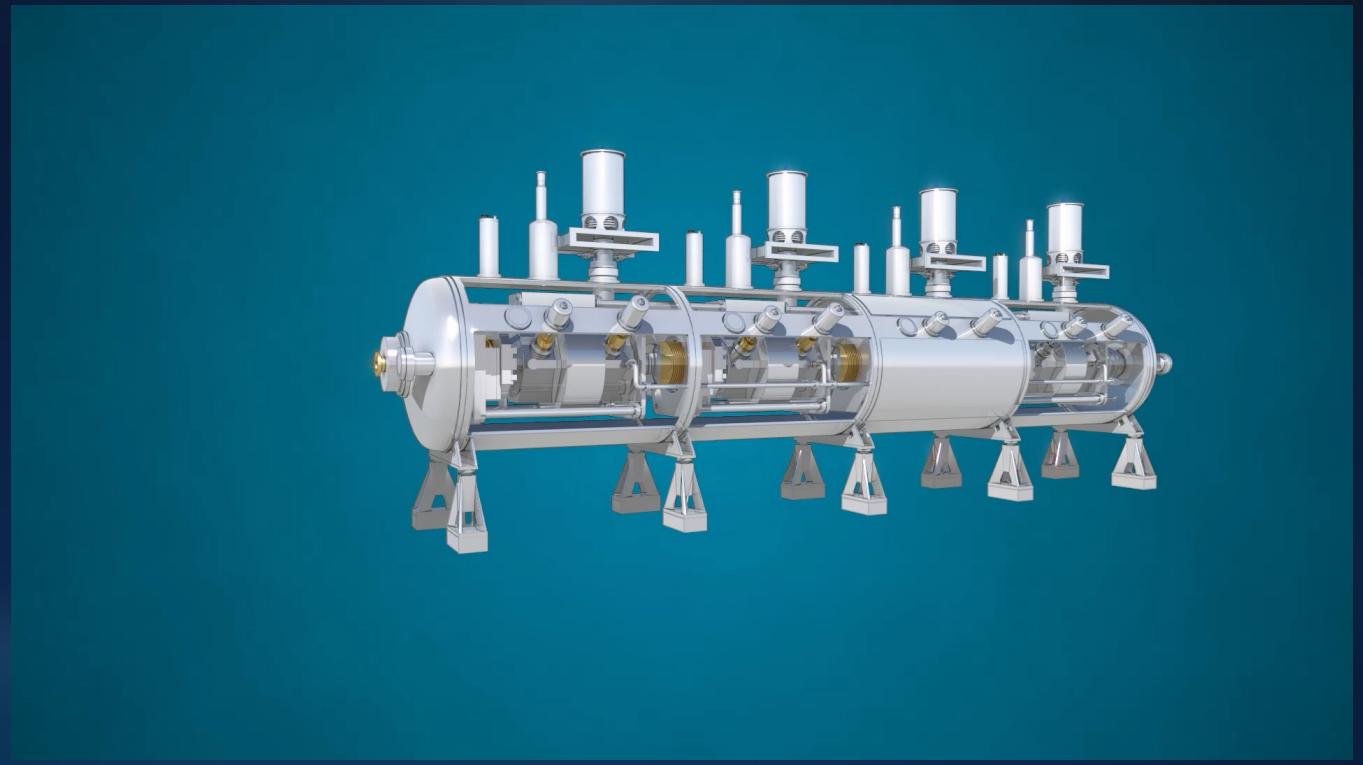
**Alessandra Lombardi**
Senior accelerator physicist, CERN

# Energy and wavelength

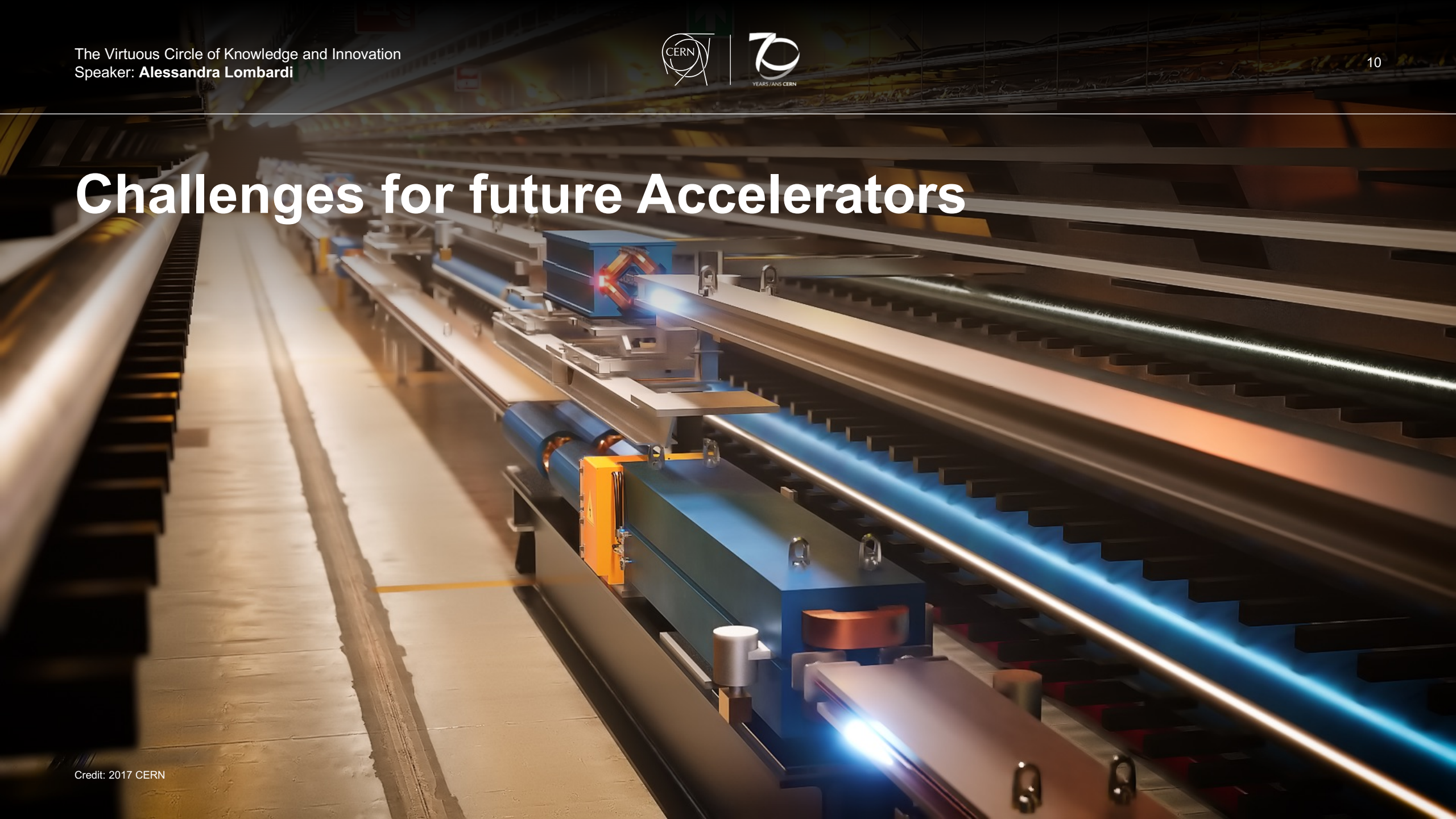


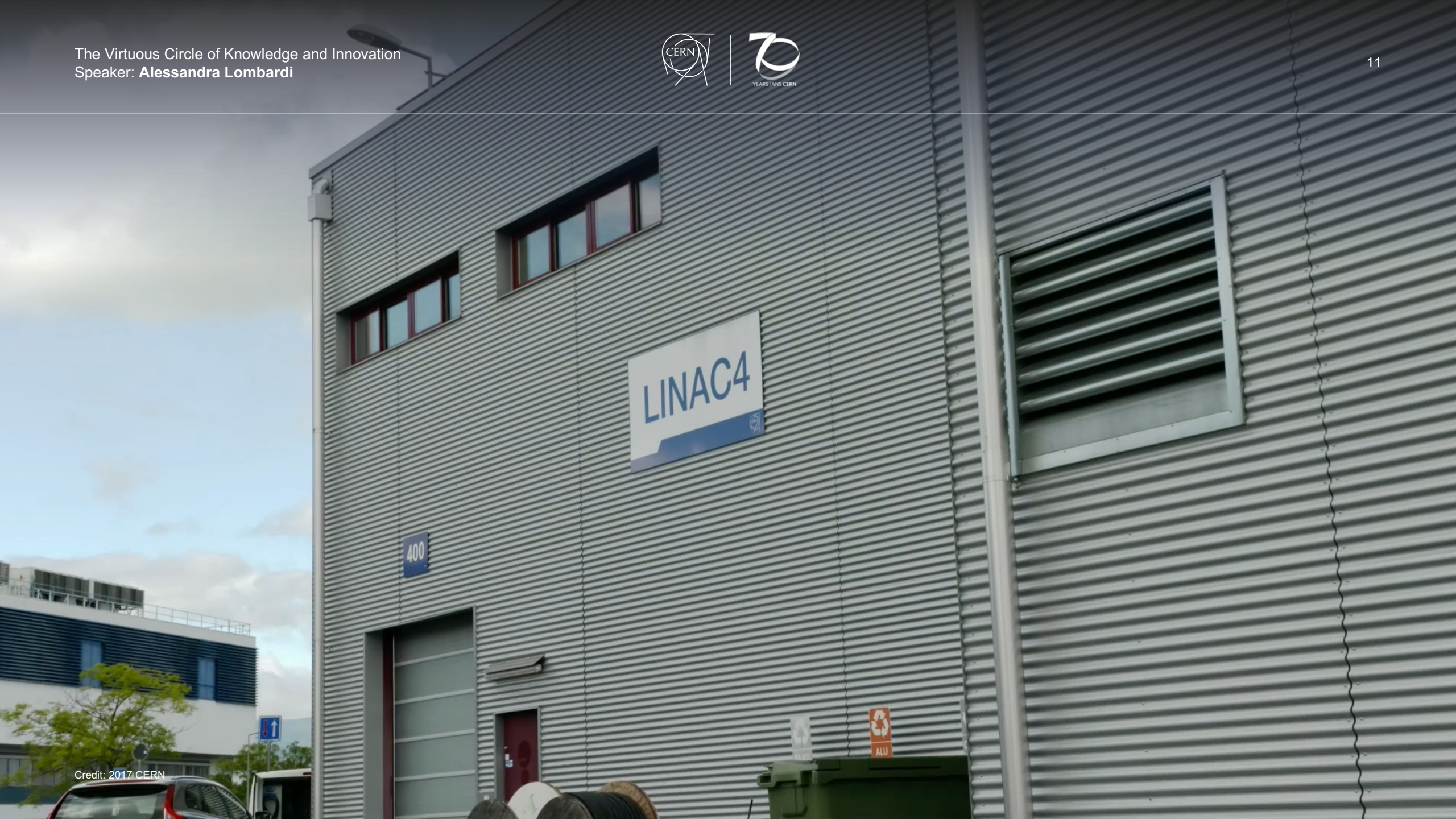
# Accelerators challenges and key technologies



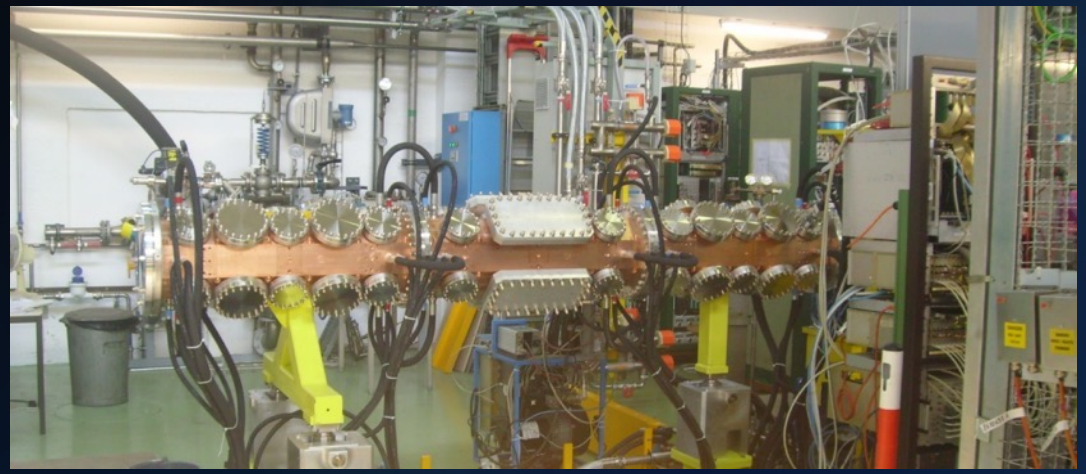
# Challenges for future Accelerators



Credit: 2017 CERN




Credit: 2017 CERN



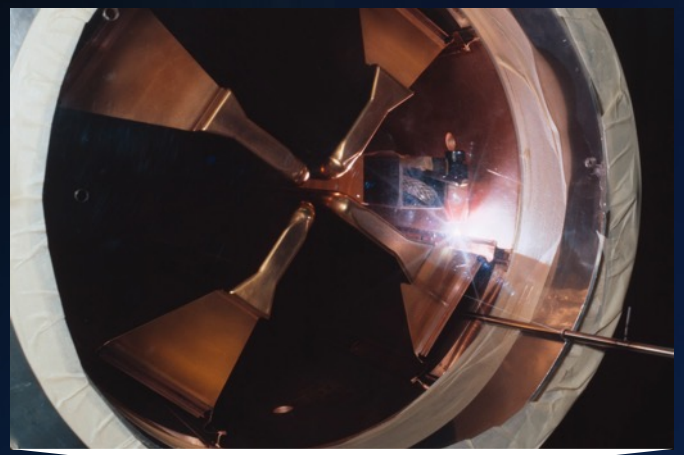
Radio Frequency Quadrupole

Drift Tube Linac

Cell-coupled DTL

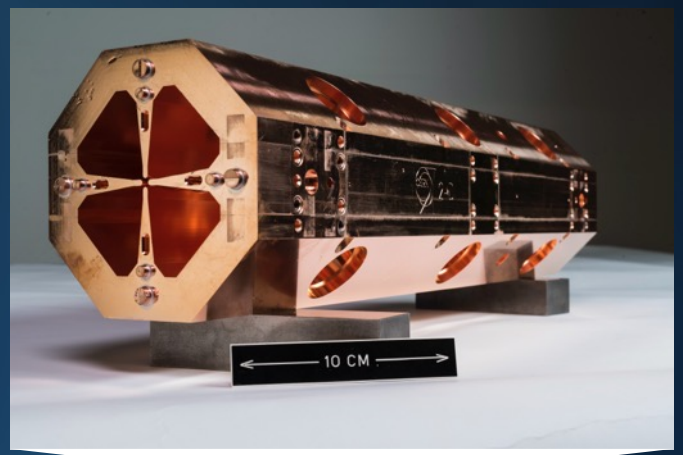
PI-mode Structure

# Path towards industrialisation



**1990 – LINAC2 RFQ2**
200 MHz
0.5 MeV /m
Weight : 900kg/m
Ext. diametre : ~45 cm
Beam current: 200 mA

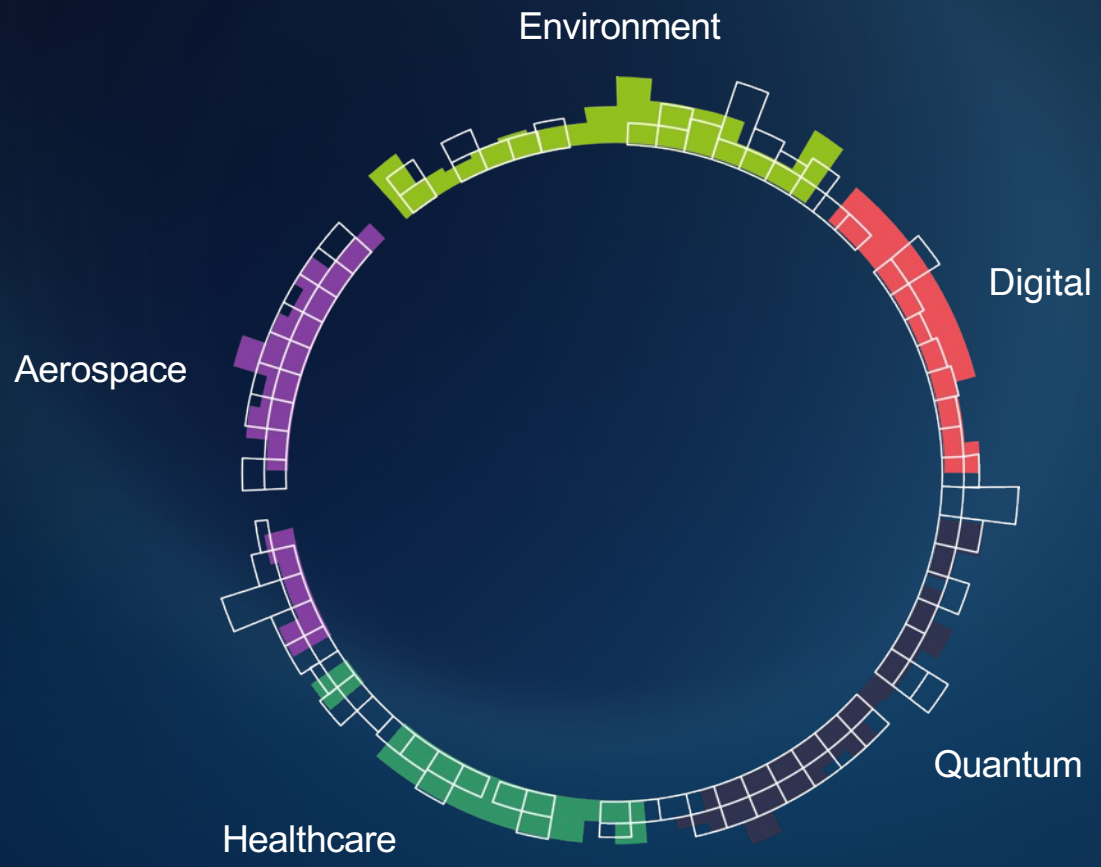
**2007 – LINAC4 RFQ**
352 MHz
1MeV/m
Weight : 400kg/m
Ext. diametre : 29 cm
Beam current : 80 mA




**2014 – HF RFQ**
750MHz
2.5MeV/m
Weight : 100 kg/m
Ext. diametre : 13 cm
Beam current : 0.1 mA

Credit: CERN

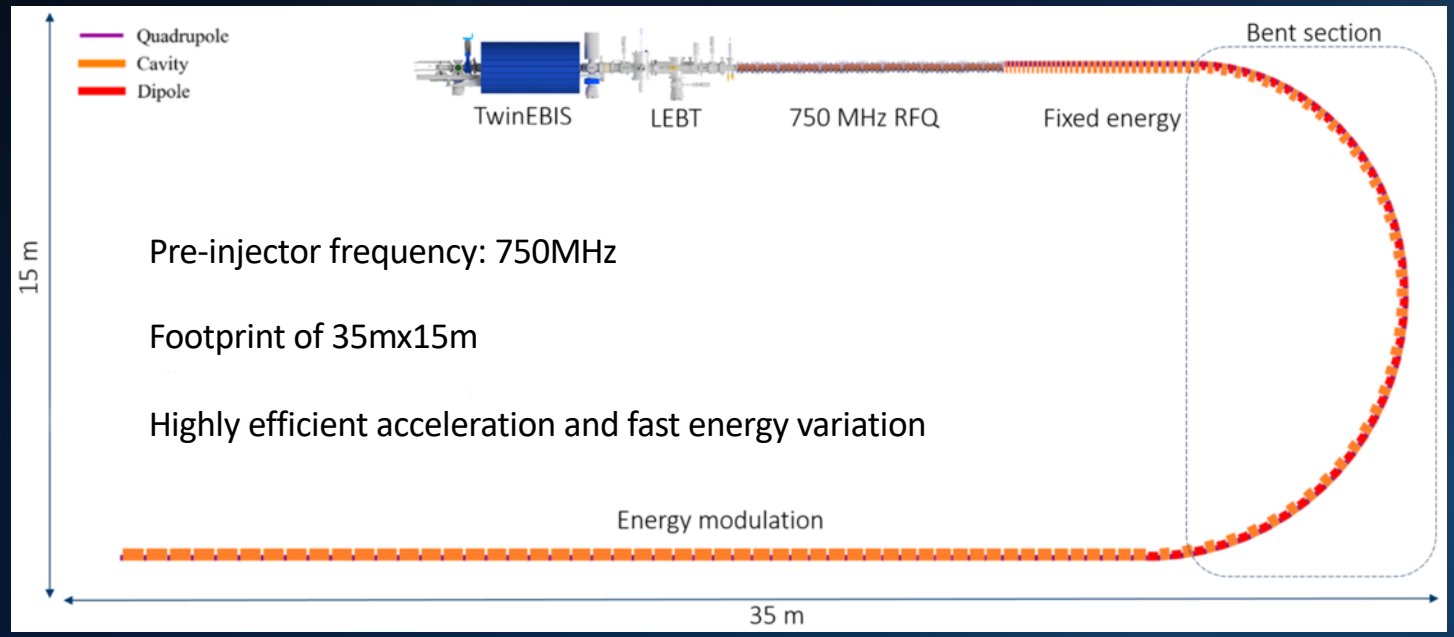
# Application of low-energy accelerators

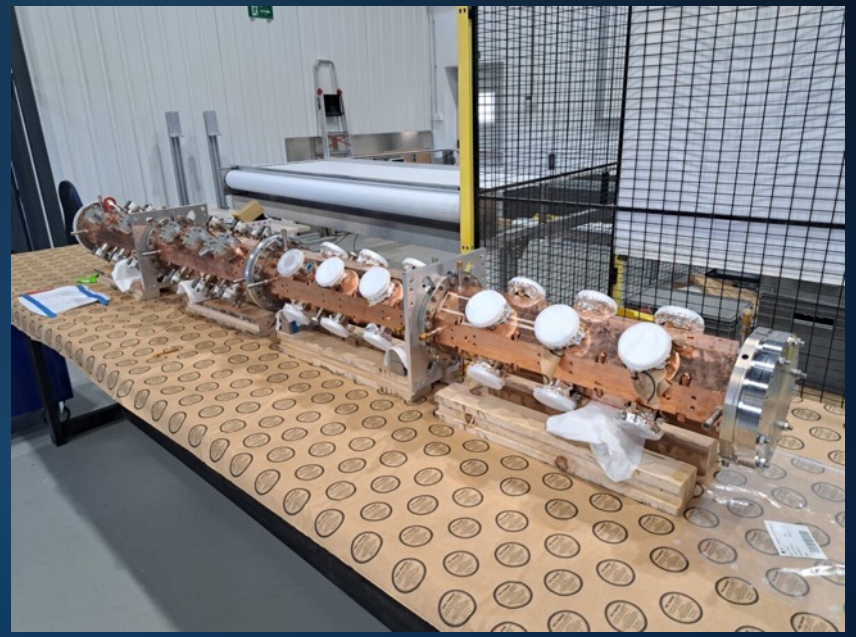


# NEXT challenge: accelerate Carbon in a LINAC

## Bent LINAC

Interlaced cavity-dipole scheme

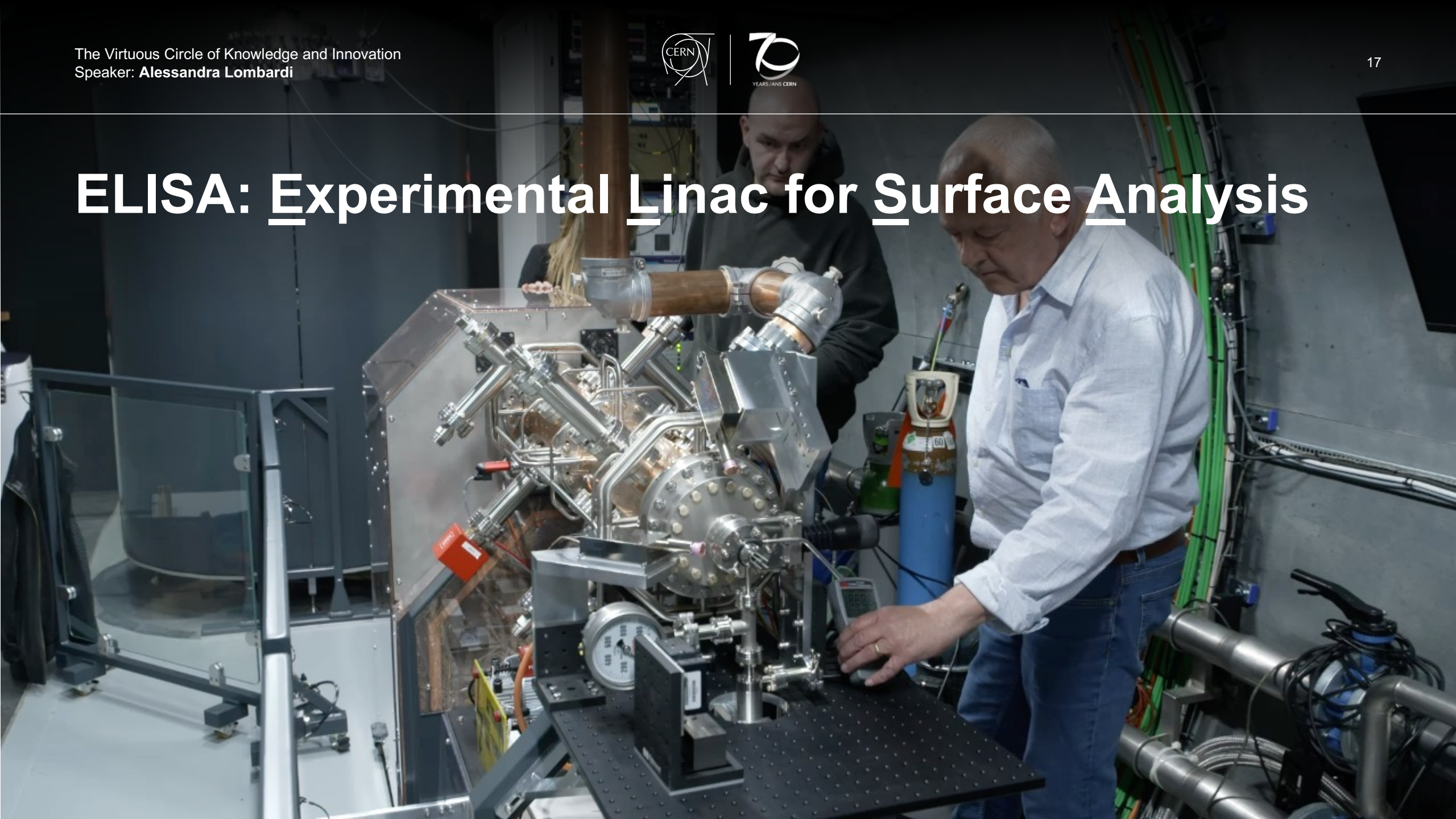


# MACHINA: accelerating art diagnostics

Credit: INFN

# ELISA: Experimental Linac for Surface Analysis

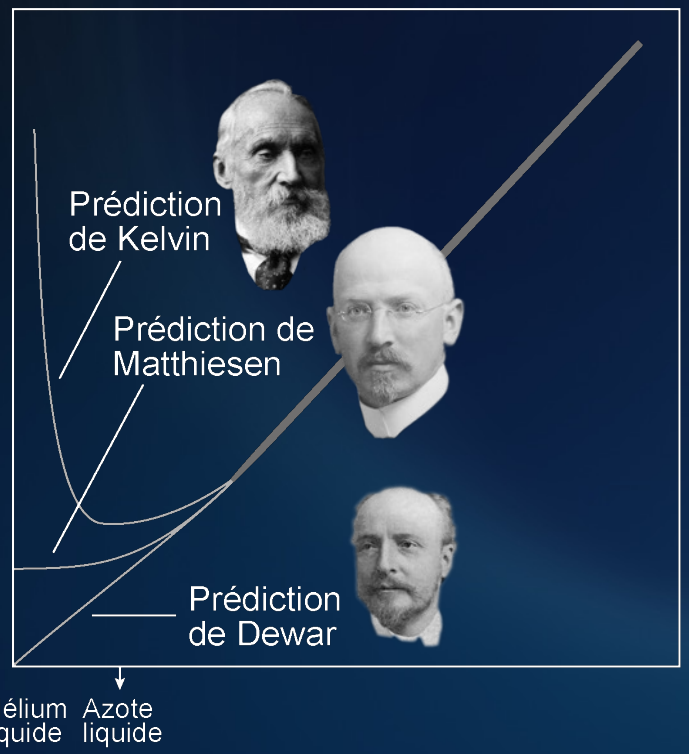


# Superconductivity

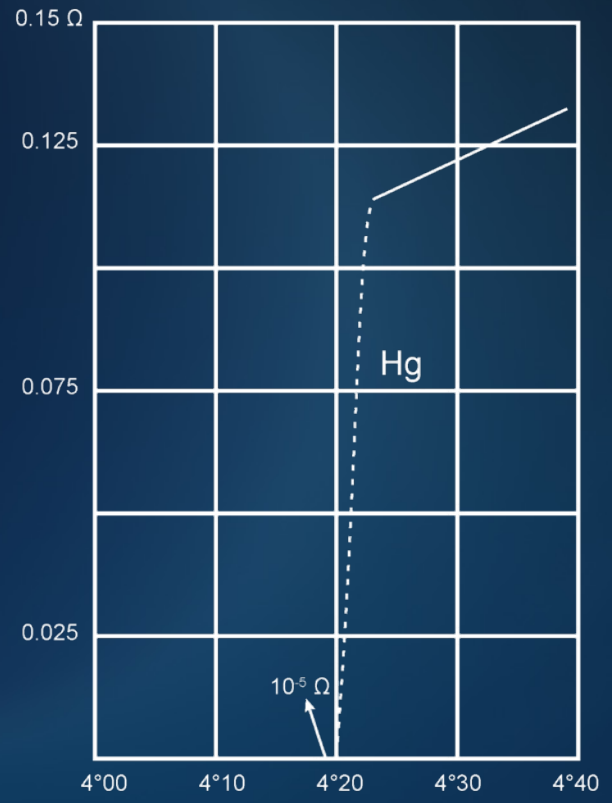
**Amalia Ballarino**
Deputy Head of Magnets, Superconductors, and Cryostats Group, CERN

# The cold war

**Predictions of the XIX century**

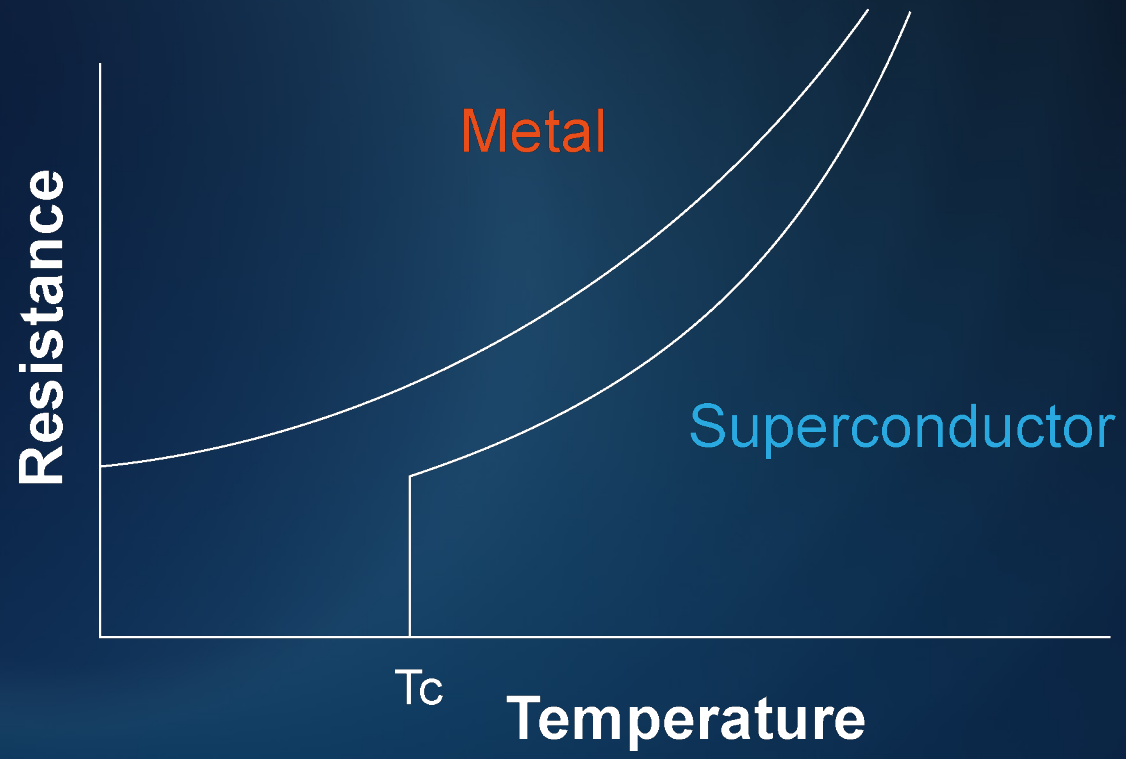



**Onnes, 1911, original plot**



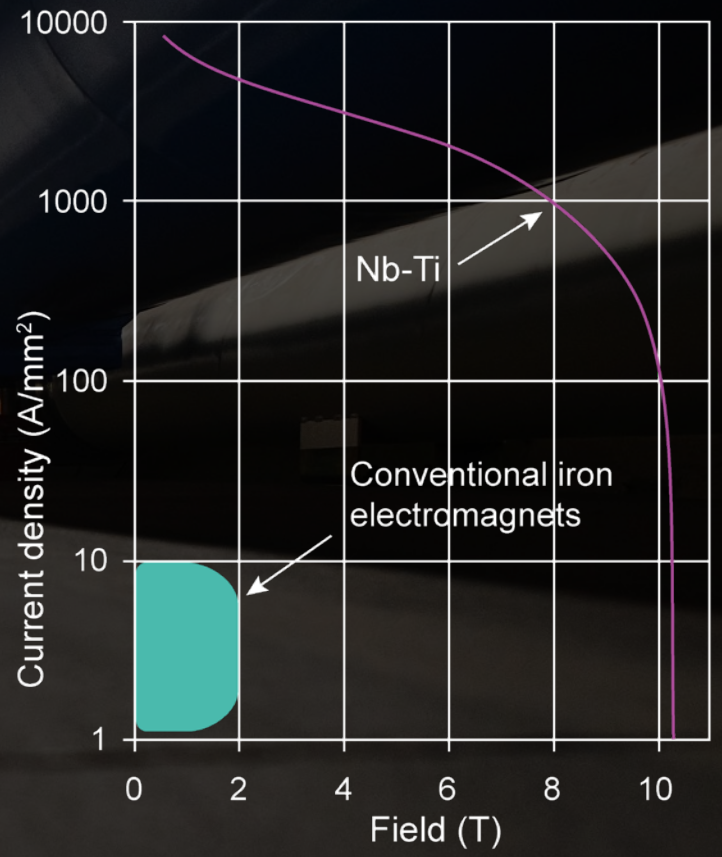

**4.2 K = - 268.95°C**
**Liquid helium**

# Superconductivity

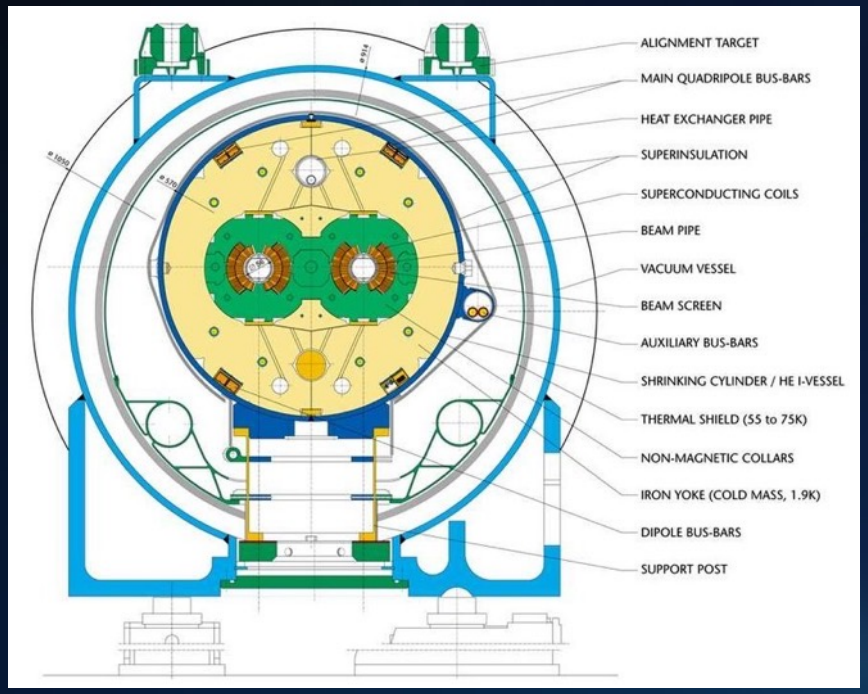



# Superconductivity for Colliders

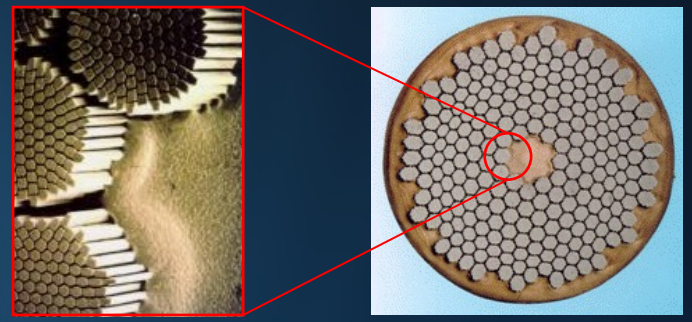
- Abolished Ohm's Law
  - No power consumption (although refrigeration power)
  - High current density
- Consequences
  - Energy savings
  - Smaller, lighter magnets
  - High magnetic fields feasible →
  - new research possibilities



# The Large Hadron Collider Magnets

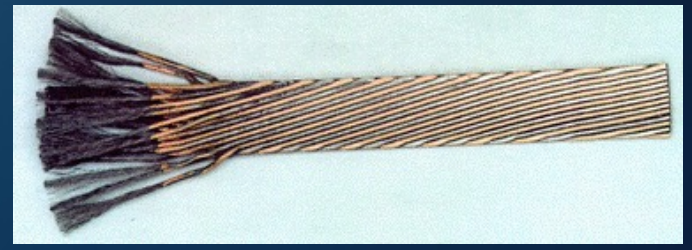



**LHC Nb-Ti wire**
**1mm**



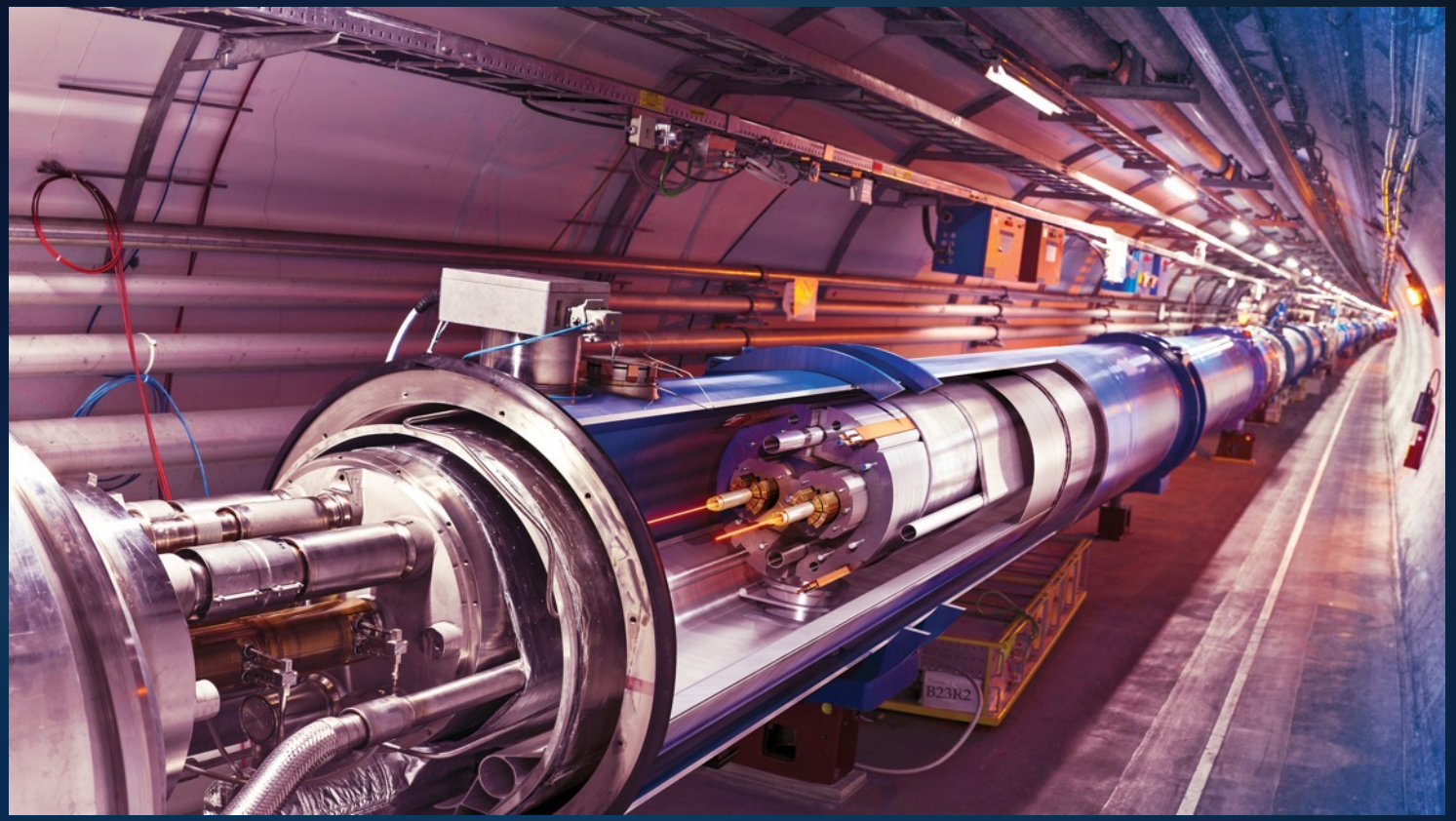
Ic(5T, 4.2 K) ~ 1000 A

**LHC Nb-Ti Cable**



**Ic(10T, 1.9 K) ~ 13000 A**

# Giant dipole electromagnets - 15 m long - 30 tons



# Superconductivity in the LHC

~ 10000 superconducting magnets

~ 1.5 Million Ampere

30 tons of superfluid helium

superfluid helium at 1.9 K (- 271.3 $^{0}$C)

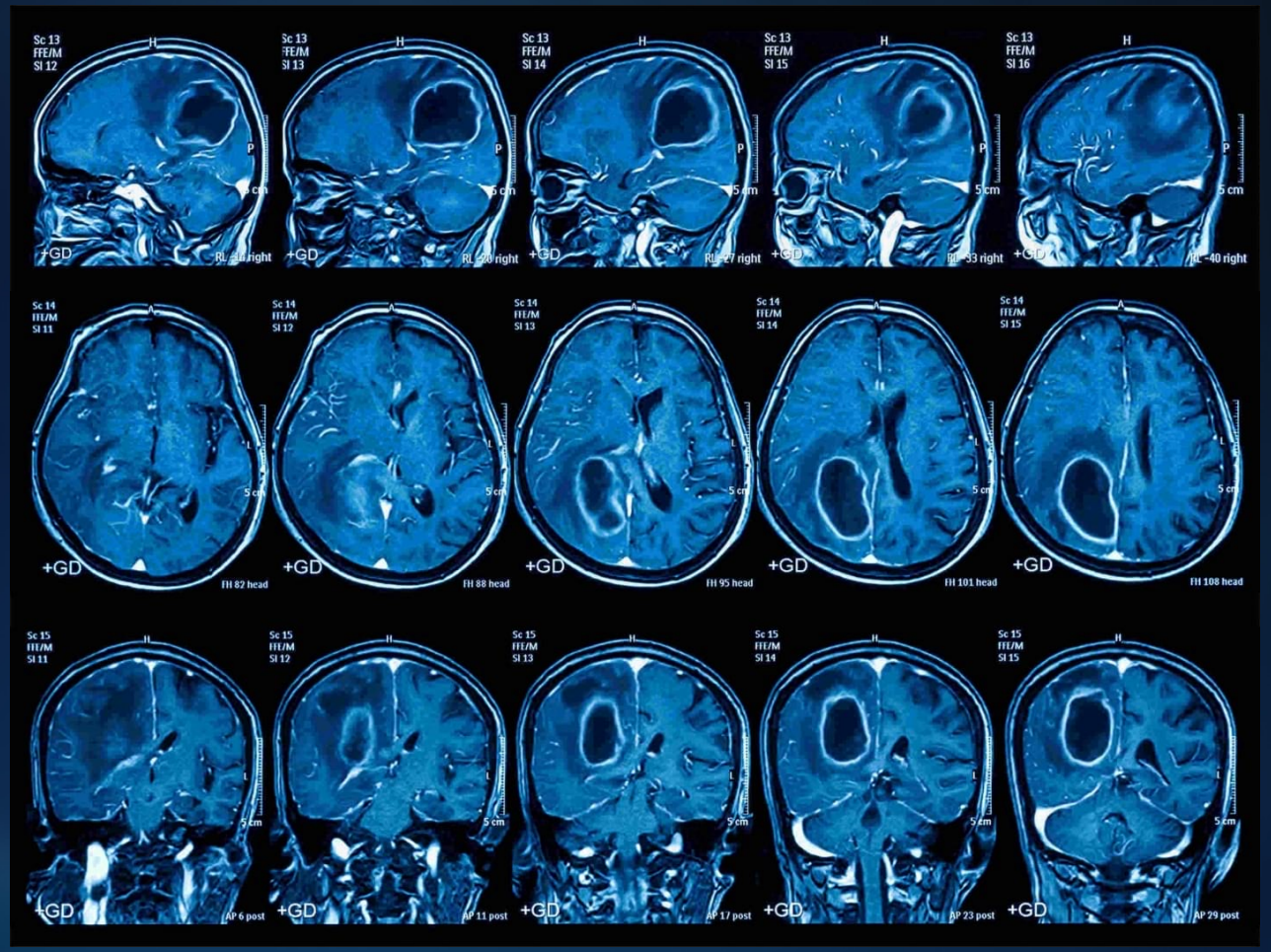
1200 tons/7600 km of Nb-Ti cables

# MRI Magnets

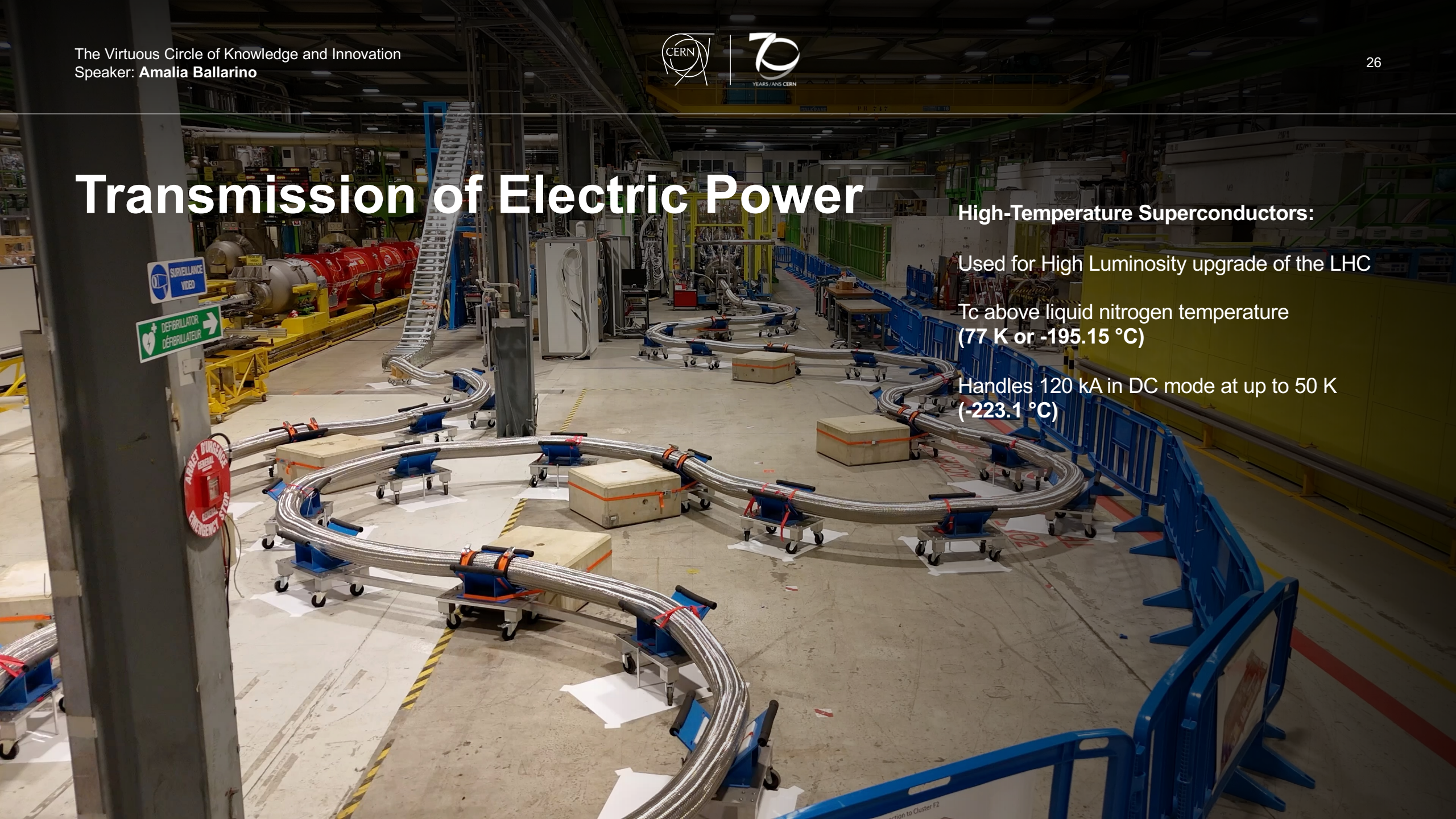
Superconducting magnets in MRI:
Non-invasive 3D anatomical imaging

MRI industry consumes ~4000 tons of Nb-Ti annually

Over 50,000 MRI scanners worldwide



# Transmission of Electric Power




**High-Temperature Superconductors:**

Used for High Luminosity upgrade of the LHC

Tc above liquid nitrogen temperature
**(77 K or -195.15 °C)**

Handles 120 kA in DC mode at up to 50 K
**(-223.1 °C)**

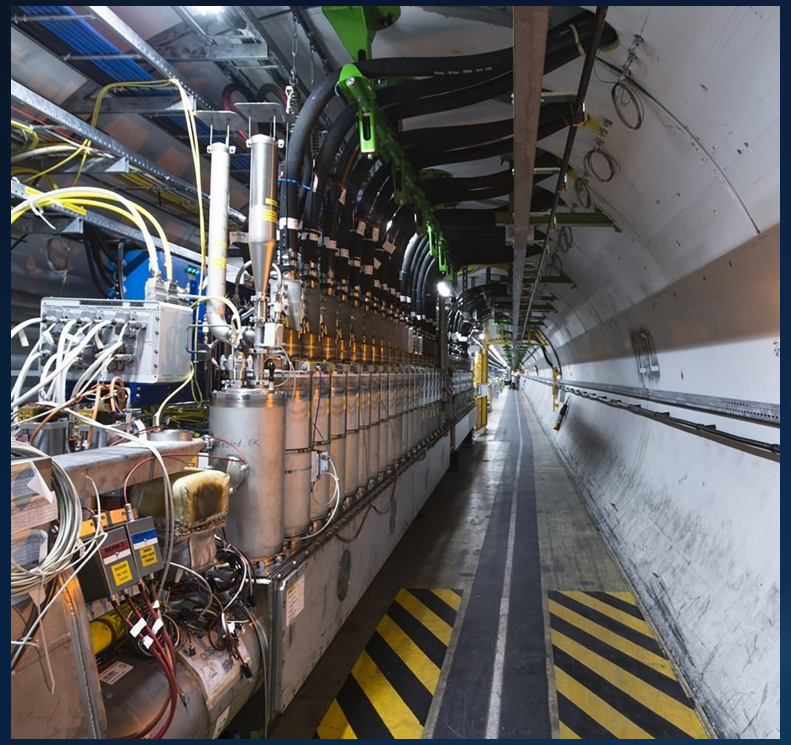
# Superconducting Technology for future low-emission aeroplanes

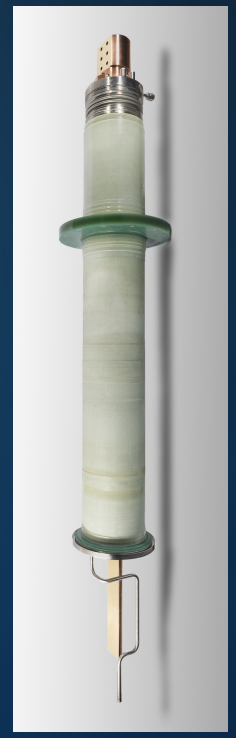
# Superconductivity – “accelerated” developments in Power Applications

**Tabea Arndt**
KIT – The Research University in Helmholz

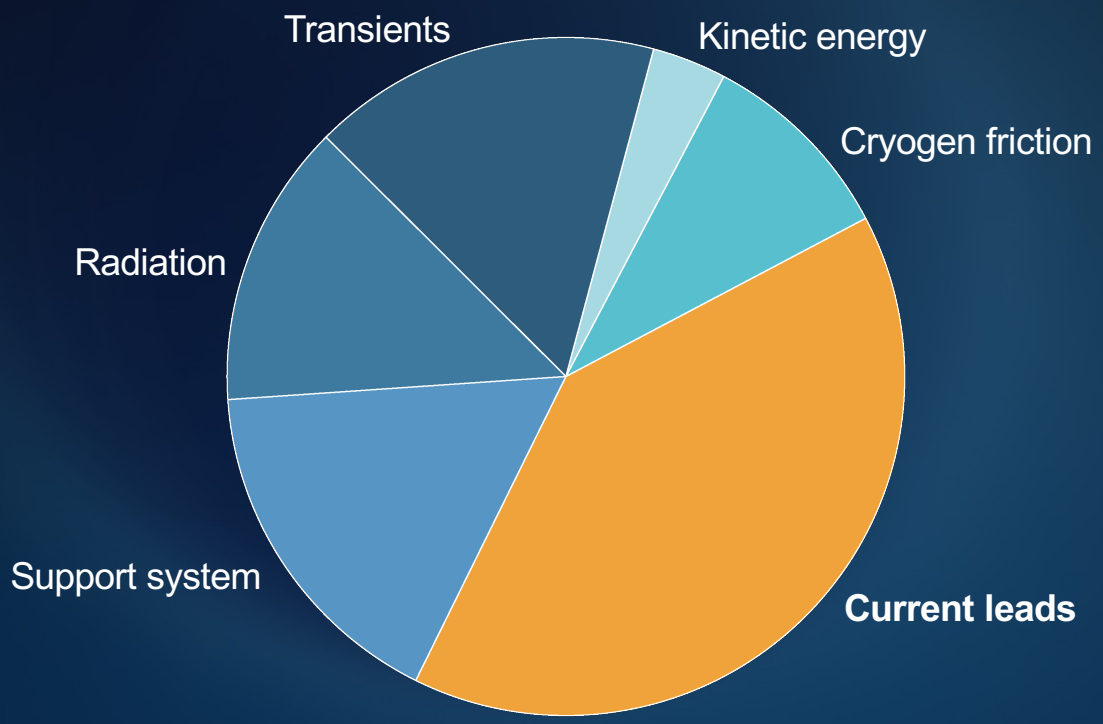
Credit: 2017 CERN

# Current leads from the LHC to Fusion And other applications



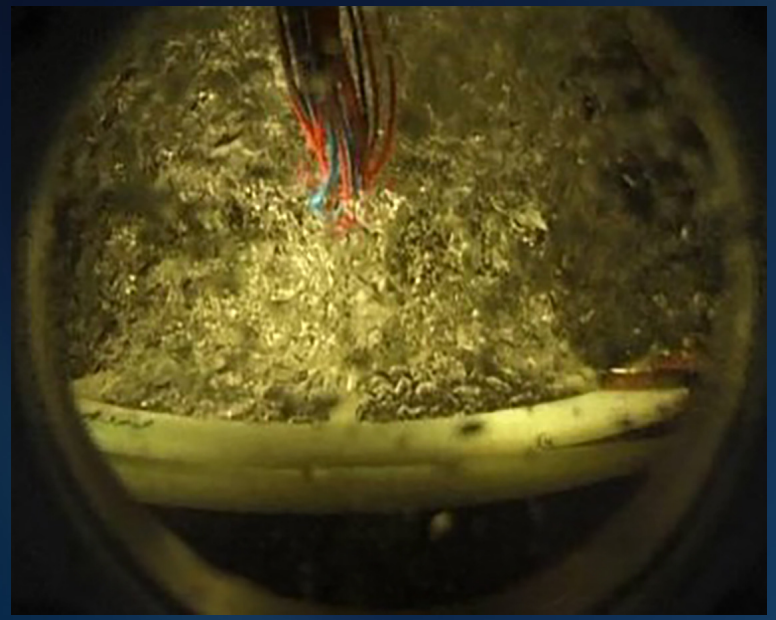
# Heat loads – (in rotating machines)




**Current leads are the major heat loads!**

# Fault current limiters

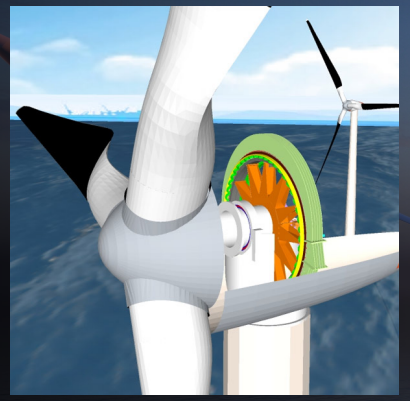
Stadtwerke Augsburg, Siemens

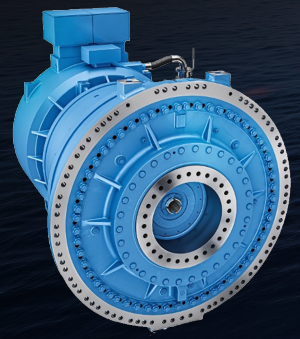


AmSC 2G-wire tested at Siemens

AmSC, Nexans, Siemens

# Windpower Generators





Credit: Shutterstock

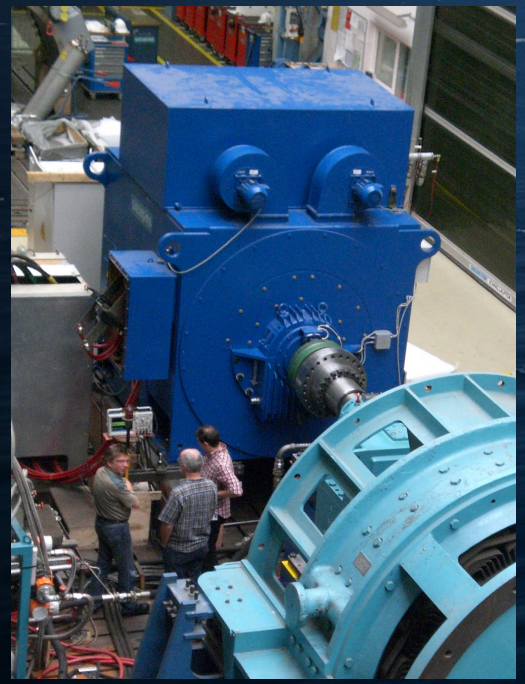
# Magnetic Billet Heaters


Zenergy, Bültmann

# Transformer

Credit: Shutterstock

# Electric ships



Siemens

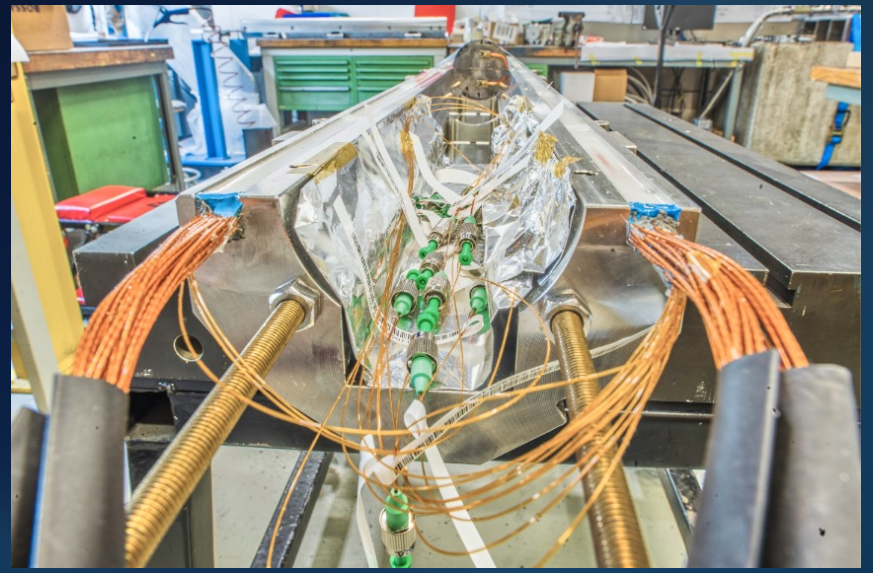

Credit: Shutterstock

# ETruck

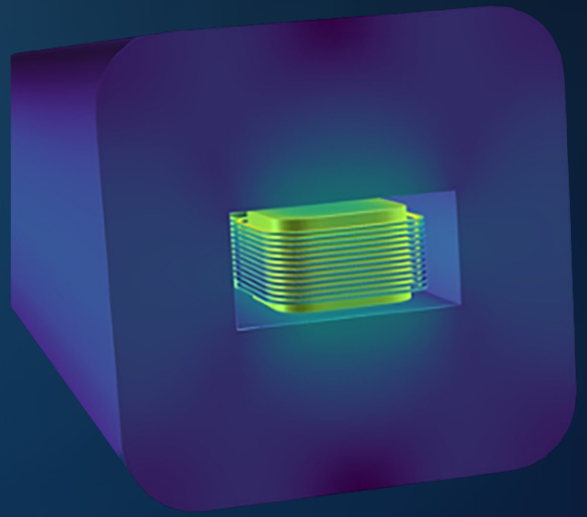

DAIMLER TRUCK
#HydrogenRecordRun
1,047 km
GenH2 TRUCK
#HydrogenRecordRun
DAIMLER TRUCK
#HydrogenRecordRun
H2

# Levitation & Transportation

# The SHiP experiment

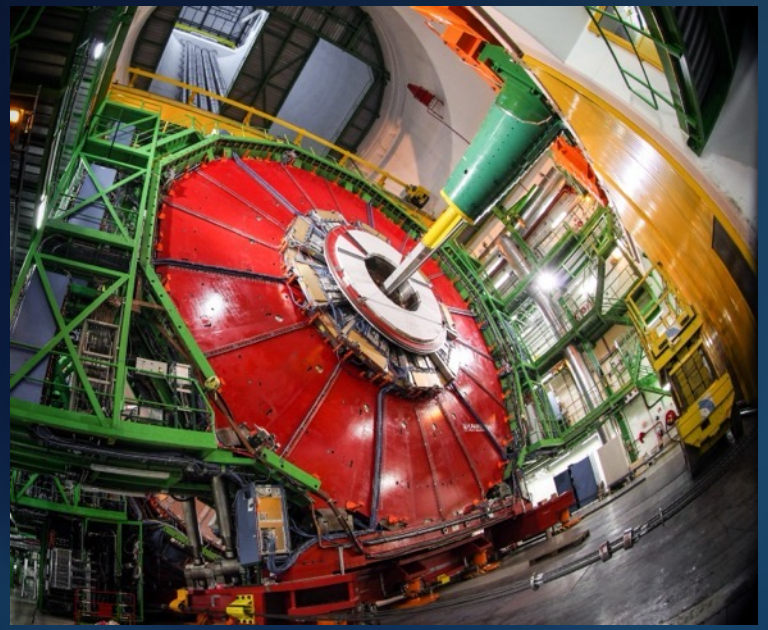


SHiP
*Search for Hidden Particles*

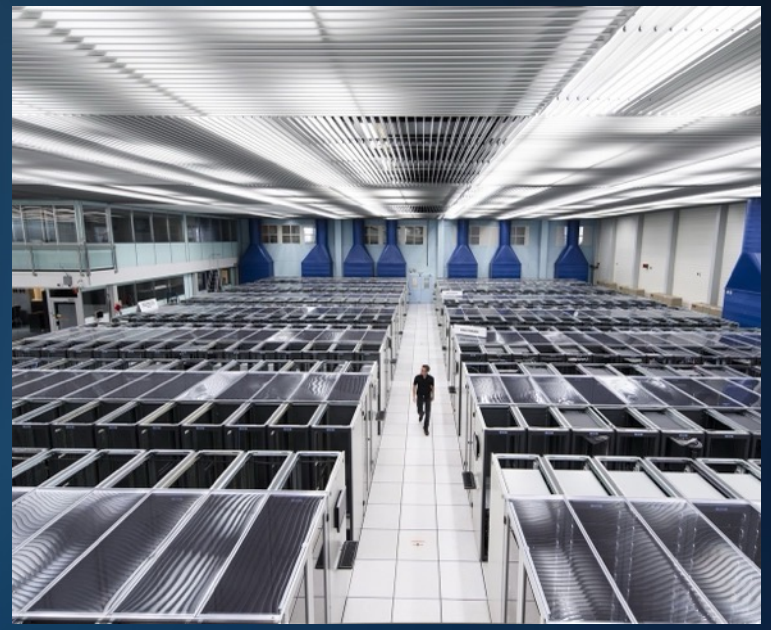


# We develop technologies in three key areas

ACCELERATORS



DETECTORS



COMPUTING

Session 2

# Particle Detectors Sensing the Invisible

**Daniela Bortoletto**
Particle Physics, University of Oxford, UK

**Steffen Kappler**
Concepts, Technology and Innovation, Siemens Healthineers

**Jan Jakubek**
Co-founder and scientific director, ADVACAM

# Particle Detectors Sensing the Invisible

**Daniela Bortoletto**
Head of Particle Physics, University of Oxford, UK

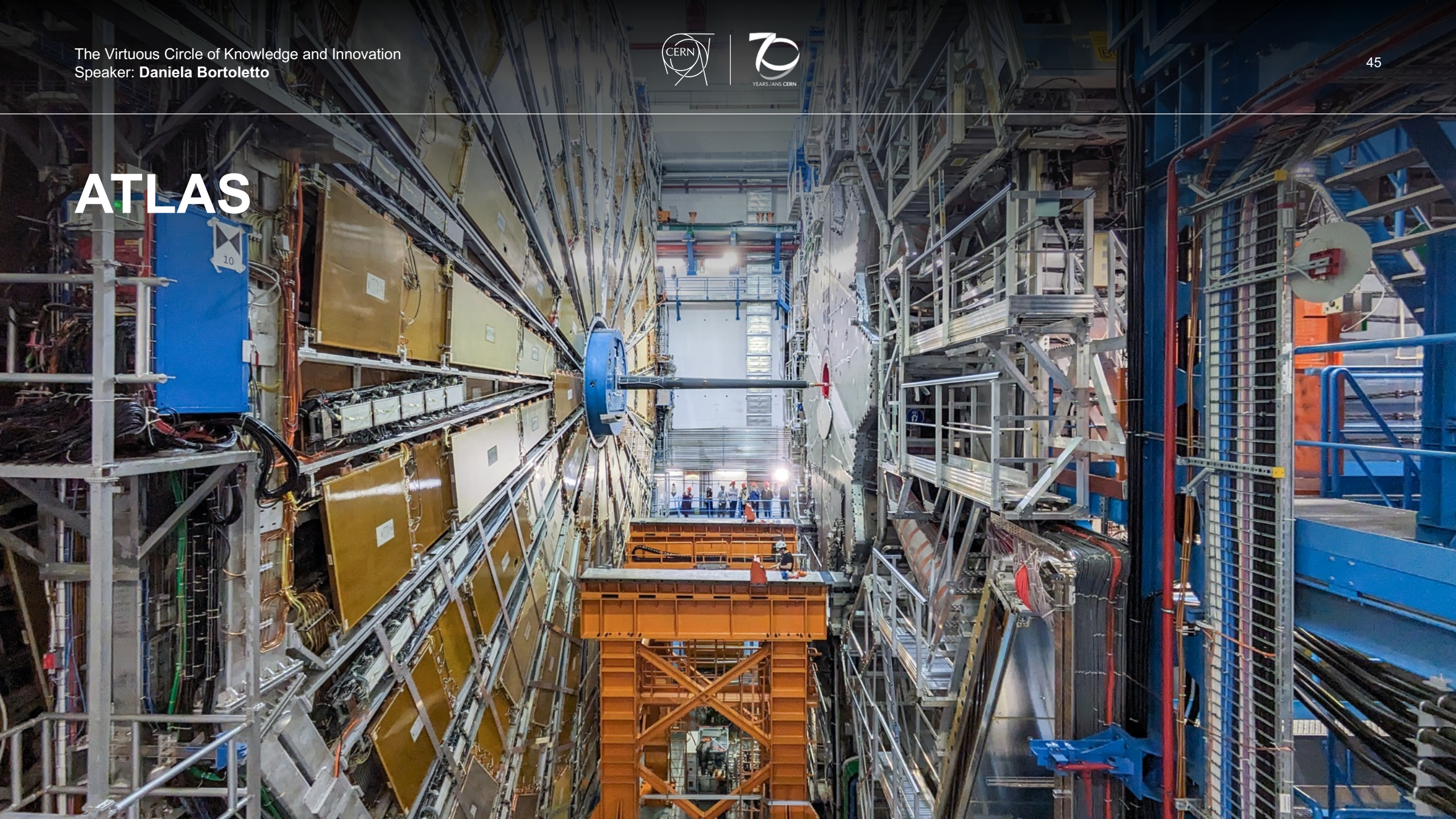

ATLAS

CMS

ALICE

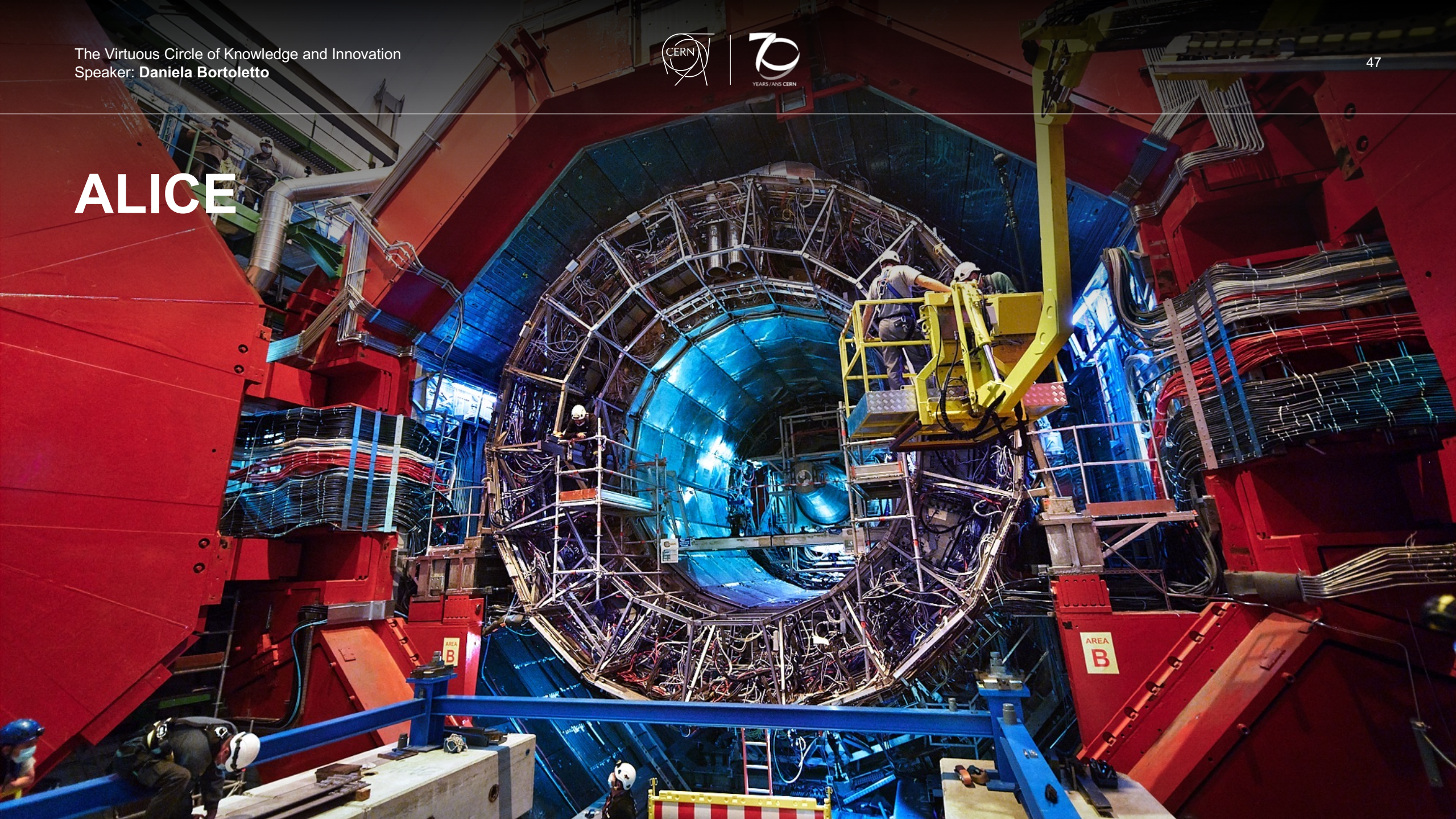
LHCb

# ATLAS



# CMS

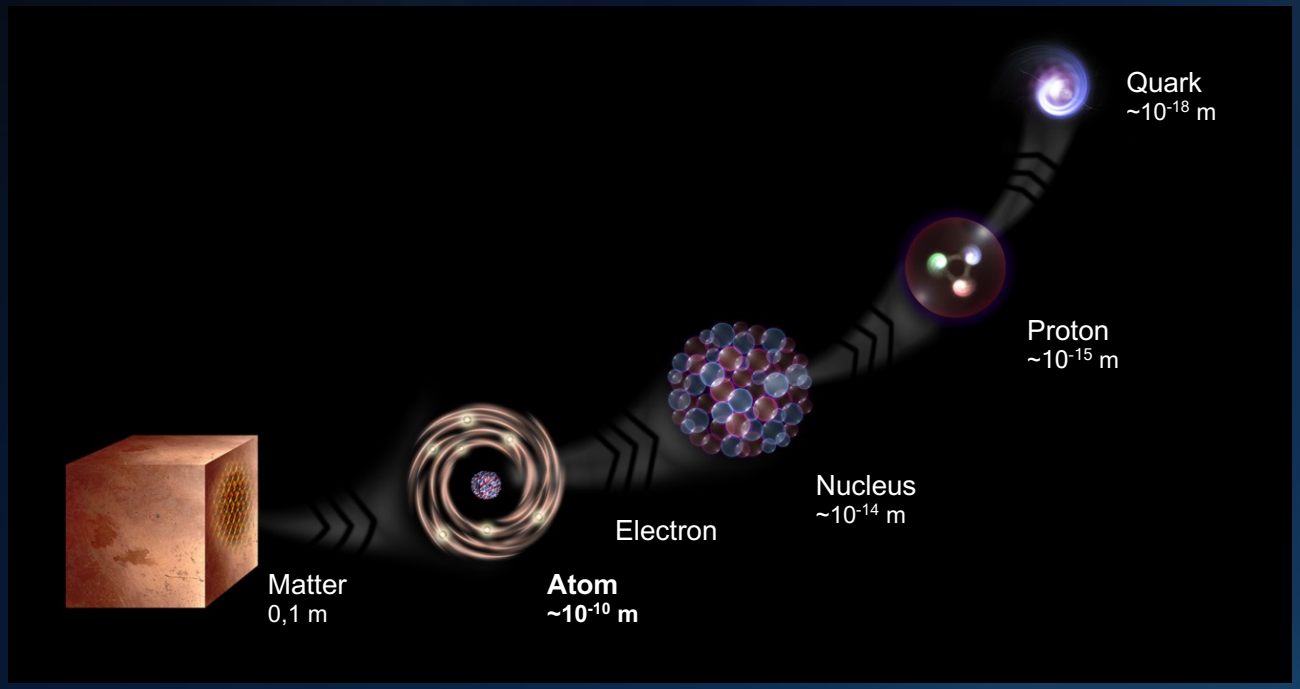
# ALICE



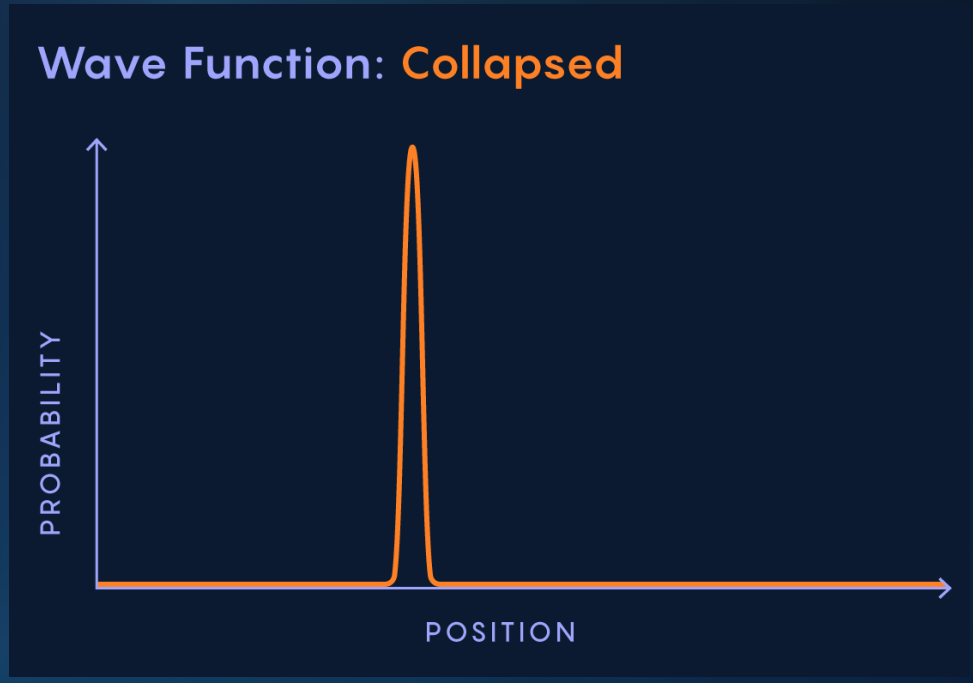
# LHCb

# Elementary Particles

Subatomic particles that are not composed by other particles




a quantum excitation of a field



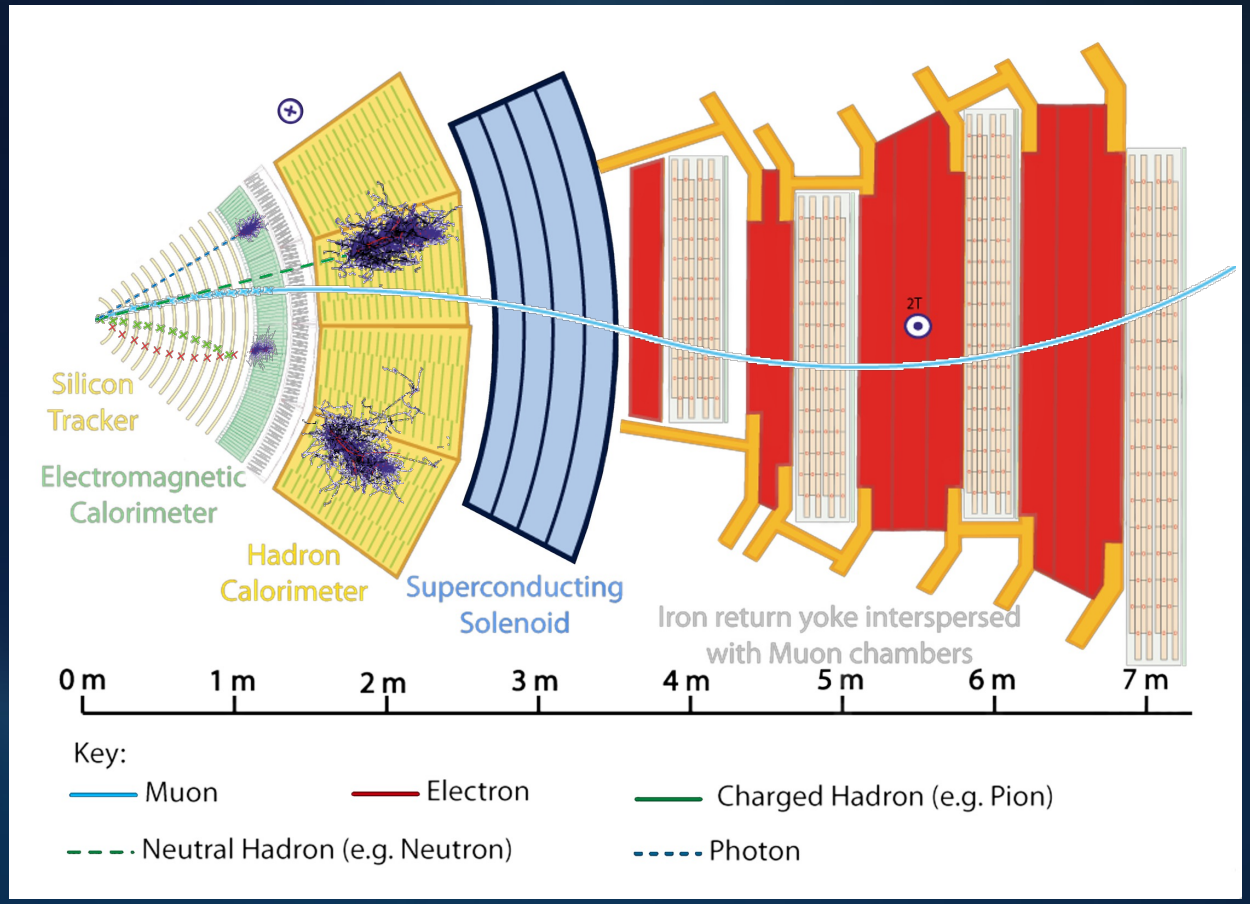

Elementary particles: quarks and electrons < $10^{-18}$ m = 0.0000000000000000001

# How do we “see” particles?

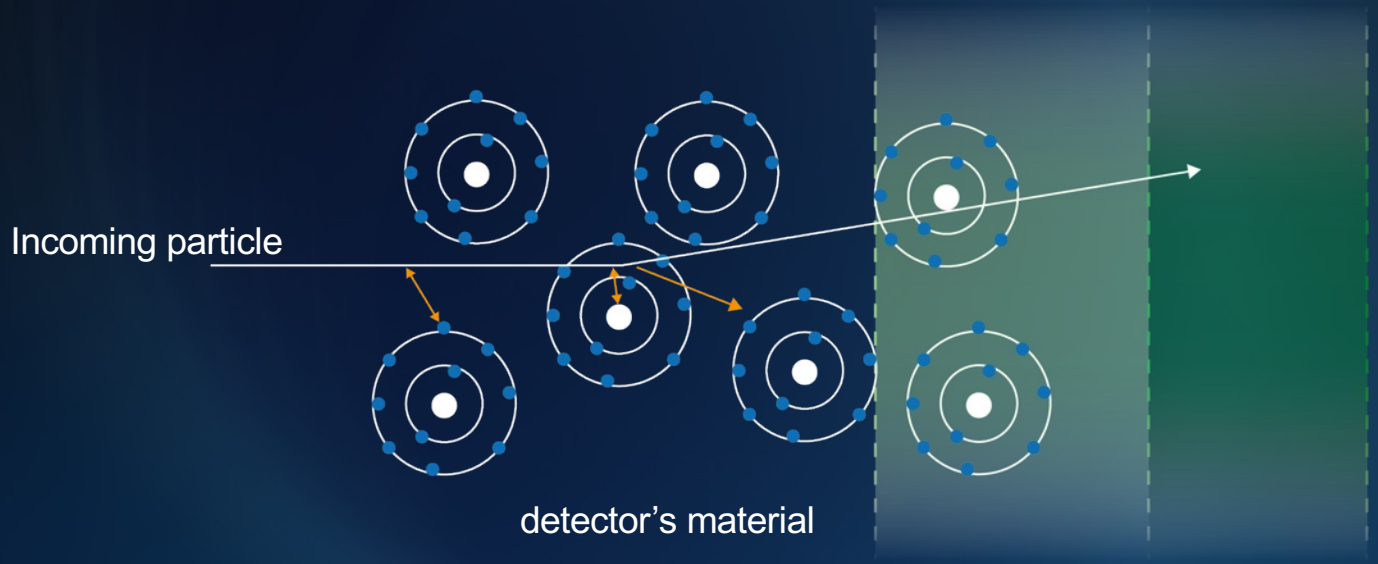
“footprint” often in the form of a charge signal or light

“stable particles”
(decay length > few cm)

electrons, muons, protons, neutrons, pions, kaons



# Interaction of particles with the detector




Interaction with the atomic electrons
atoms are excited or ionized

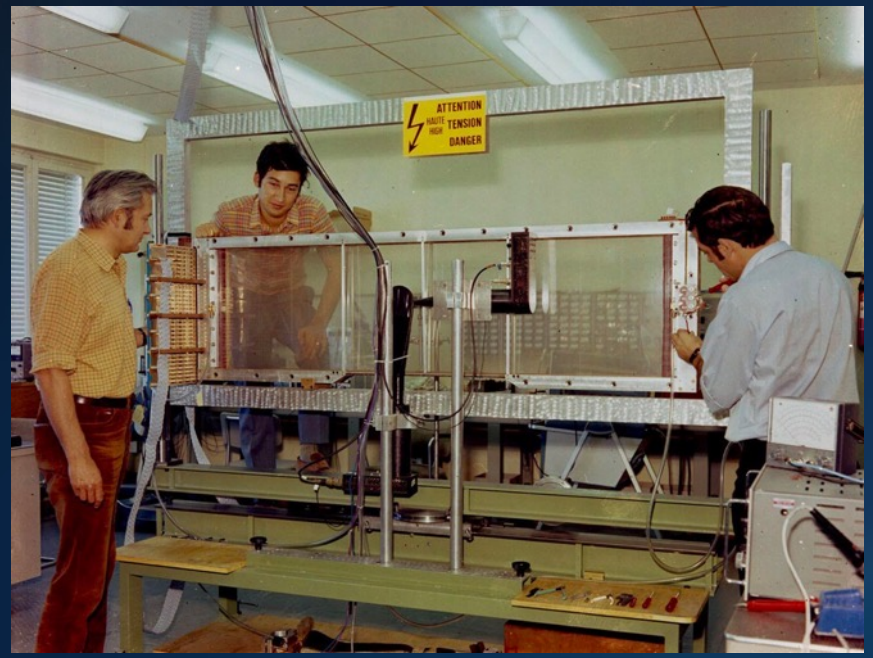
Interaction with the atomic nucleus
Bremsstrahlung photons

If particle's velocity > velocity of light
in the medium Cherenkov Radiation

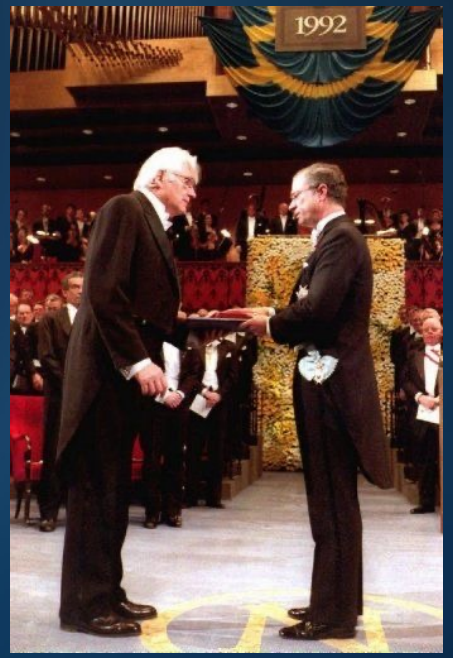
When particle crosses the boundary
between two media Transition radiation

# Georges Charpak: Revolutionizing particle detection

from “visual detectors” to “electronic detectors”




1971-1972 – Large-size Multiwire Proportional Chamber




1992 Nobel award ceremony

# Multiwire Proportional Chambers: a transformative innovation

Medical imaging and healthcare

Security and inspection

Material science and archaeology

Environmental monitoring

Industrial applications

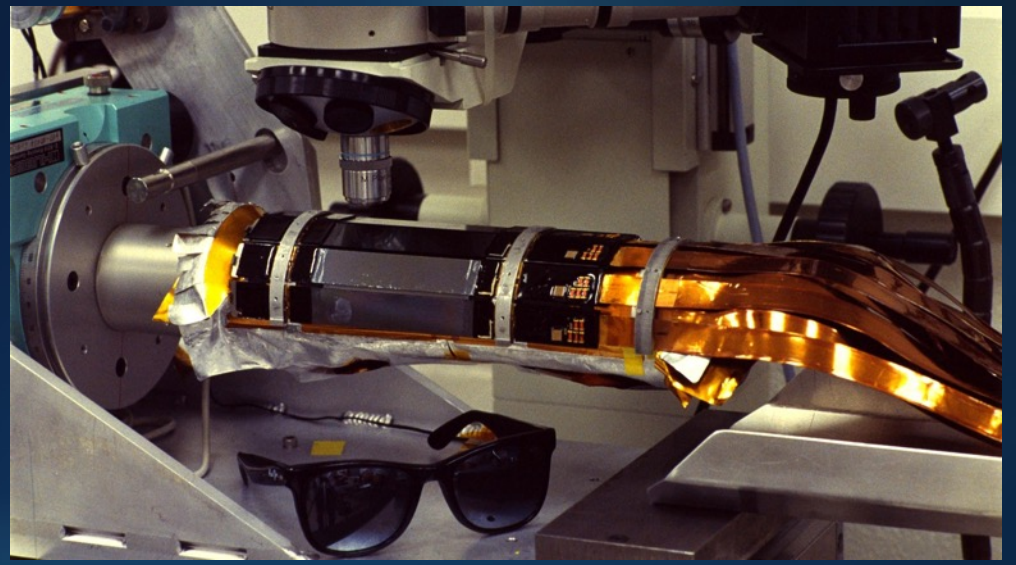
# The silicon revolution and discoveries

1980 - search for particles with charm and beauty quarks (decay length ~ 100 μm)

Silicon technology for microelectronics

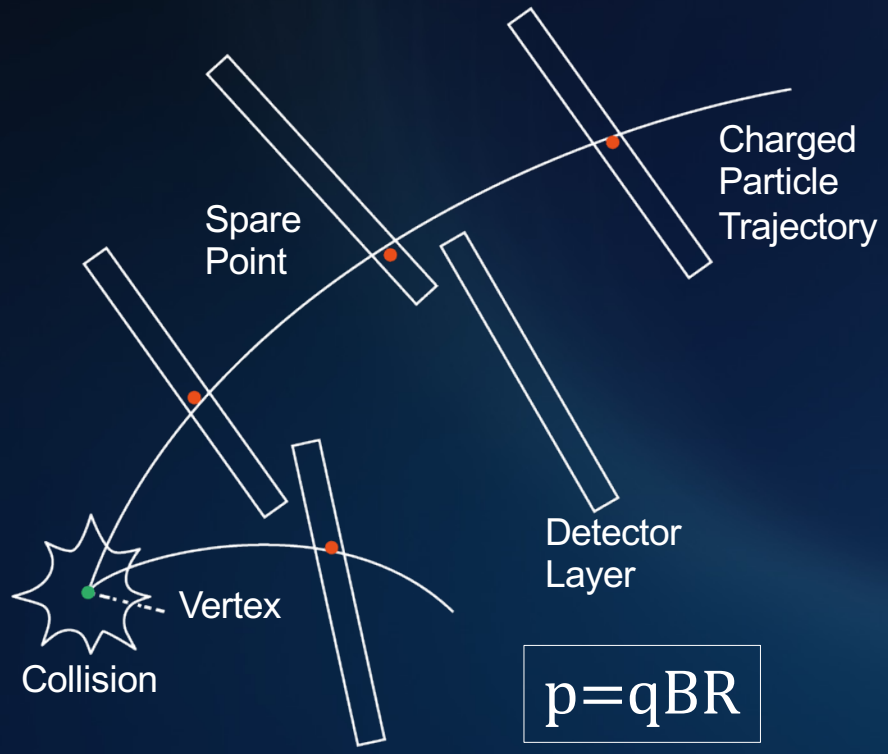
**Kemmer 1979,** KETEK
from electronics to detector fabrication

NA11- NA32: measurements of Lifetimes of particles containing c-quarks
MARK II: measurement of charm, tau, and b-lifetime

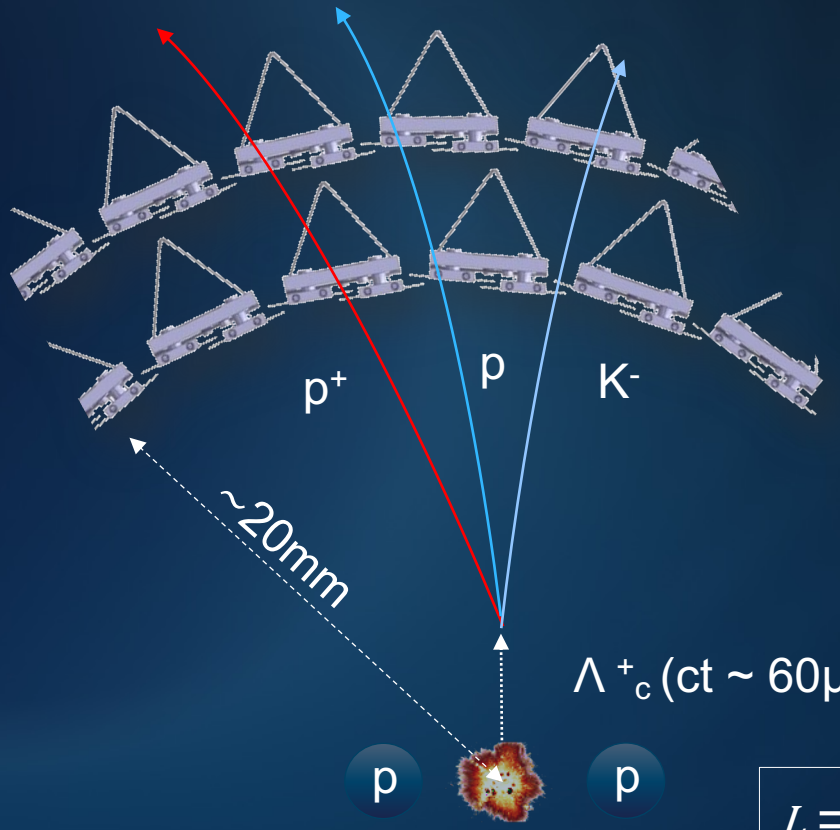


# Silicon trackers at the heart of all LHC experiments

Giant, ultra-fast and very complex 3D camera




$$p = qBR$$

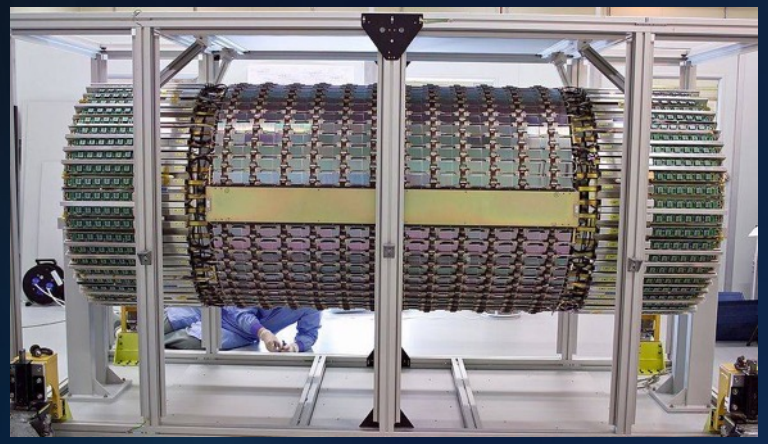


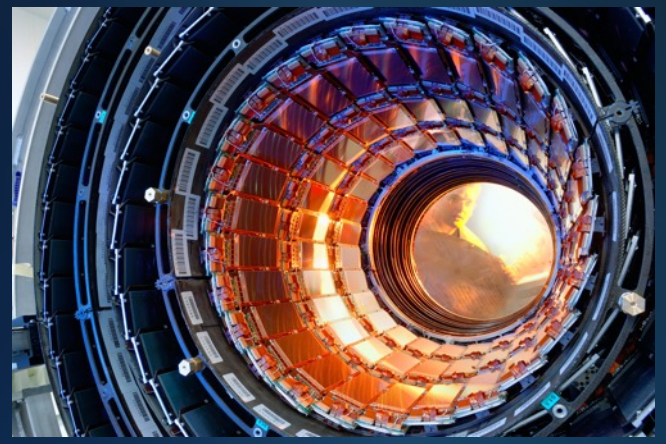

$$L = \beta\gamma c\tau$$

# Silicon trackers at the heart of all LHC experiments

Giant, ultra-fast and very complex 3D camera

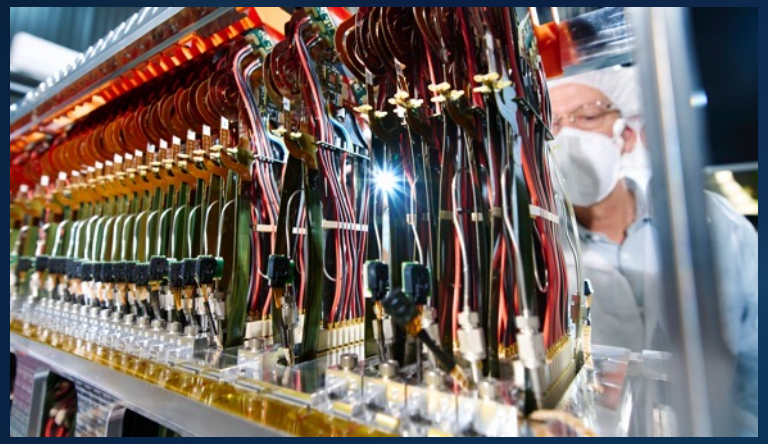
ATLAS

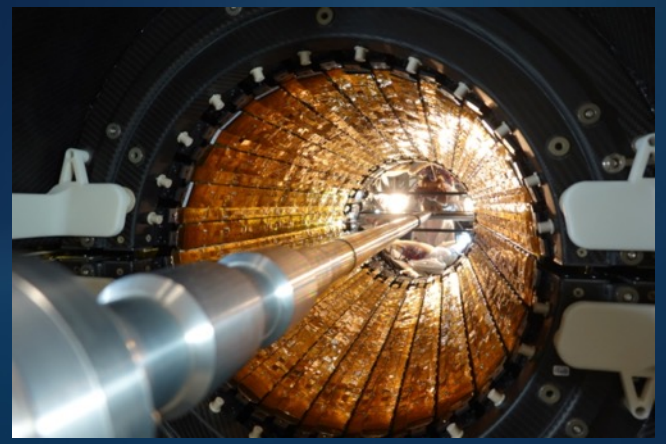




CMS

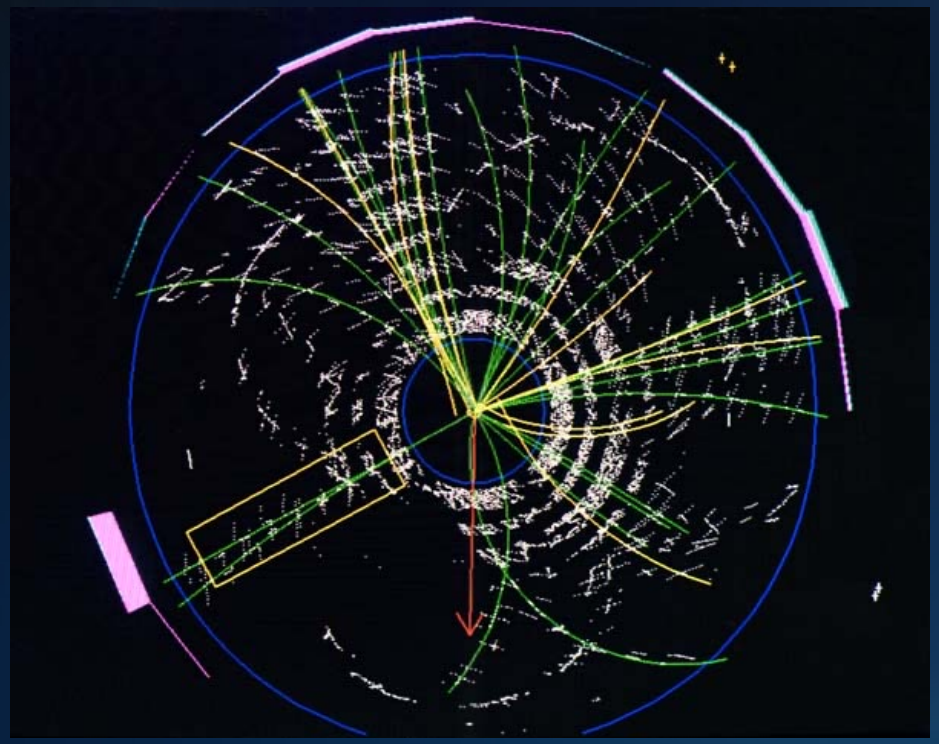
LHCb



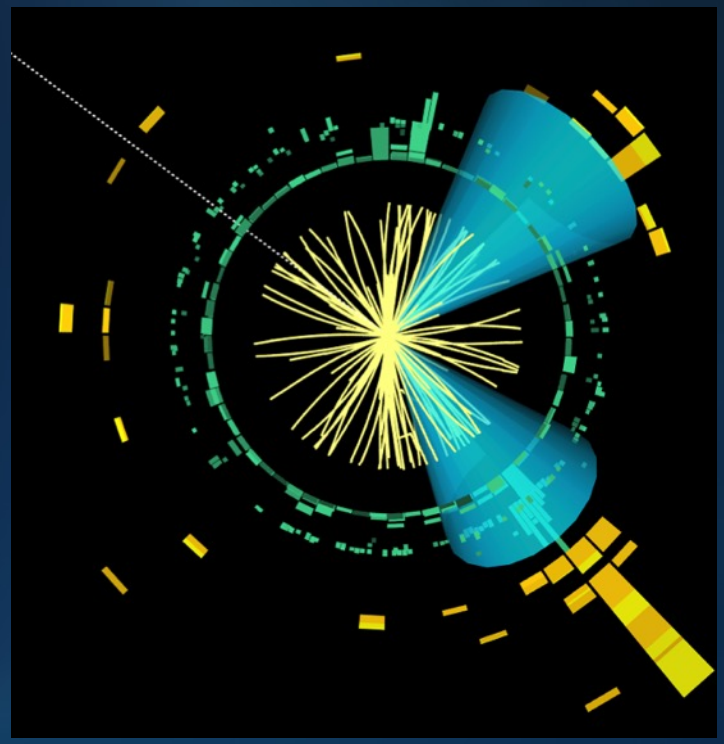


ALICE

# Silicon detectors discovery enablers

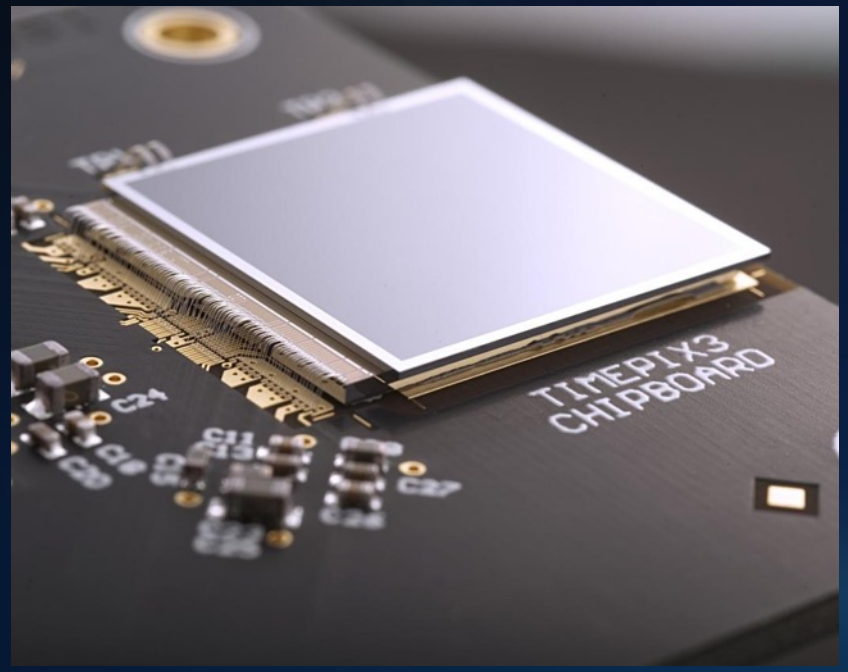


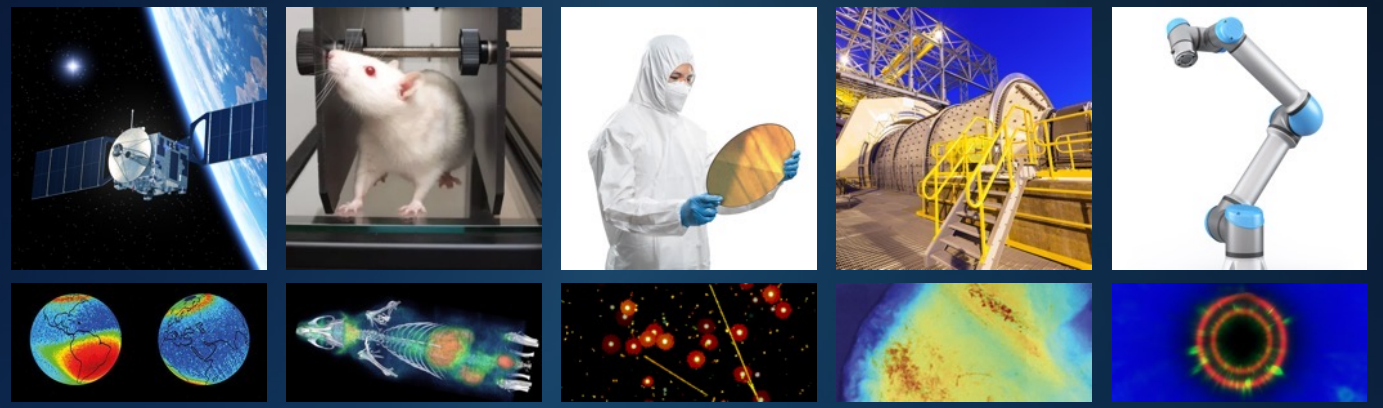
1995 - Top quark (t→Wb) discovery
**Tevatron**



2018 - Discovery of H → bb at the LHC

# From particle physics to technology and back



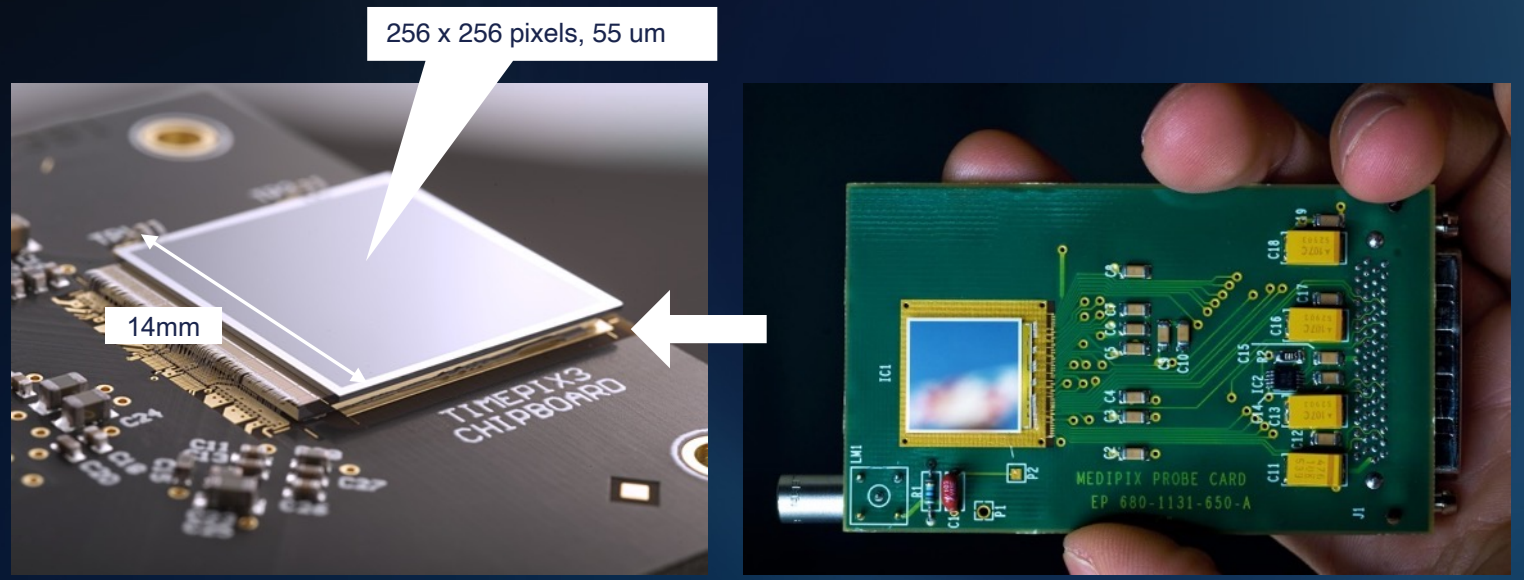
# Advanced particle accelerators and their surprising applications to society

**Jan Jakubek**
Co-founder and scientific director, ADVACAM

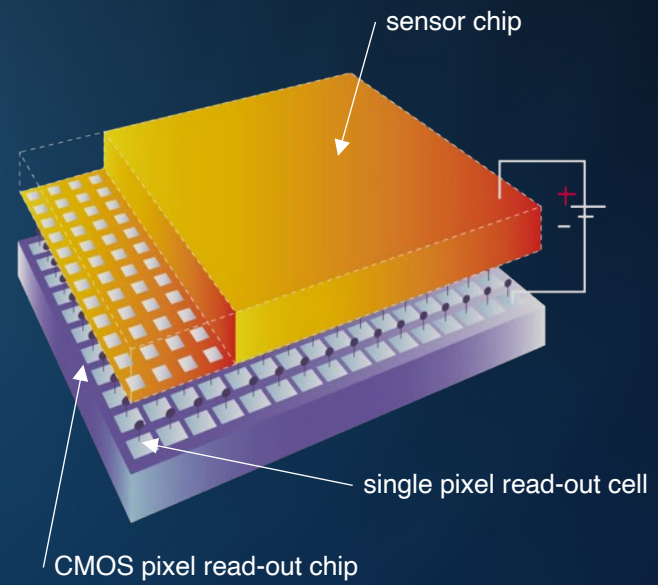
CERN | 70 YEARS / ANS CERN


Credit: CERN

# Each ionizing particle is visible!

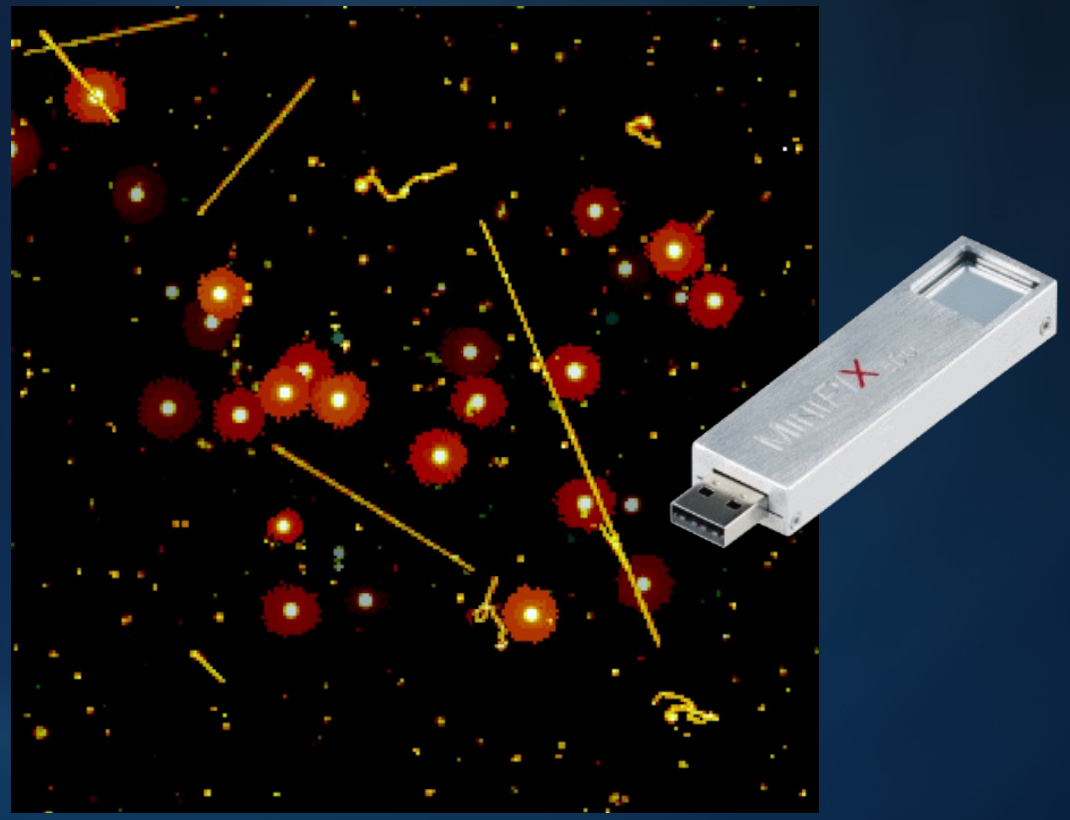



Read-out ASIC chip Timepix3



# On-line visualization of ionizing radiation

- **Each particle** type observed as **typical pattern**
- Each pixel records digitally:
  - The deposited energy
  - the number of hits or time of first interaction.



Natural radiation background in the office

# MiniPIX EDU in classrooms

MiniPIX EDU for Education, physics teaching and basic radiation experiments.


# The face mask test

### Use MiniPIX detector


### 1. Measure unused mask

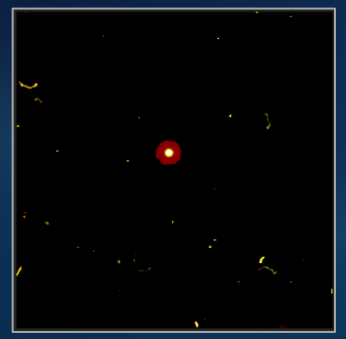
### 2. Use it for 5 min

### 3. Measure used mask

### Why?

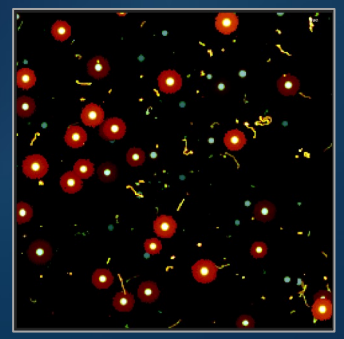
- Radon decay products are ionized
- They stick to dust and aerosols
- Mask filters them out greatly
- **Exhaled air is filtered in lungs!**

### Unused mask



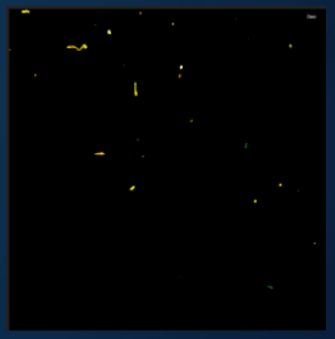
Just very small activity observed

### Used mask



Huge increase

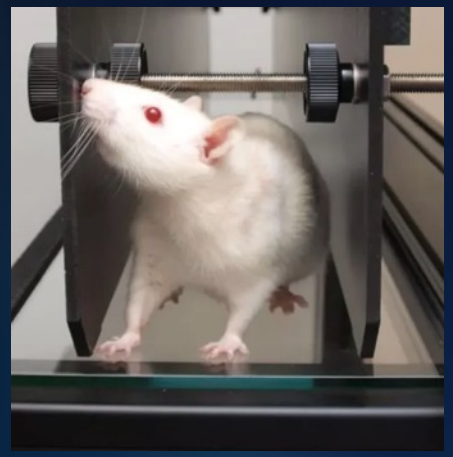
### Exhaling only



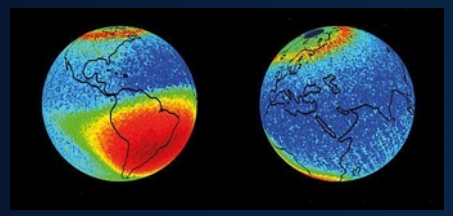
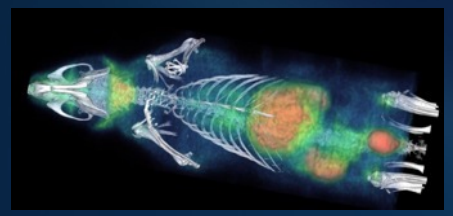
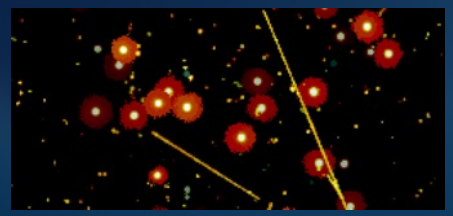
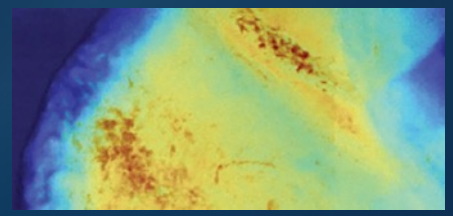
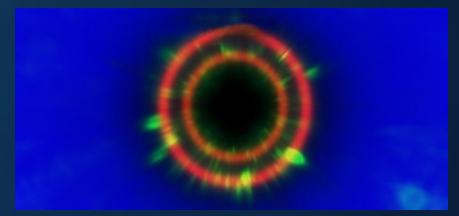
Low activity: Rest stays in lungs !!!

# Technology applications

Space | Biology | Research | Mining | Non-destructive testing

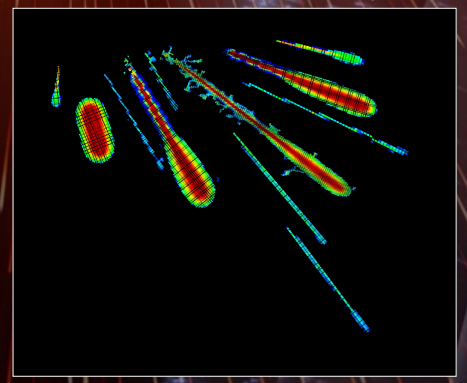


Credit: Shutterstock

Credit: ESA, Unsplah

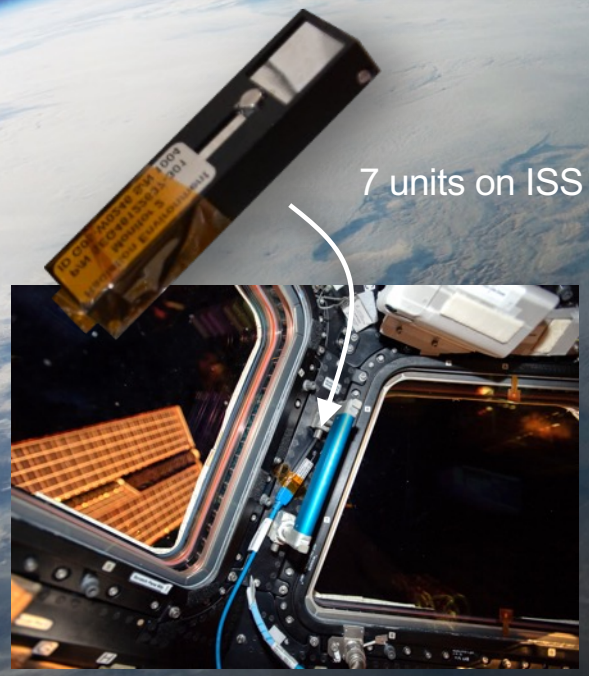
# Cosmic radiation presents a risk to biological and electronic systems



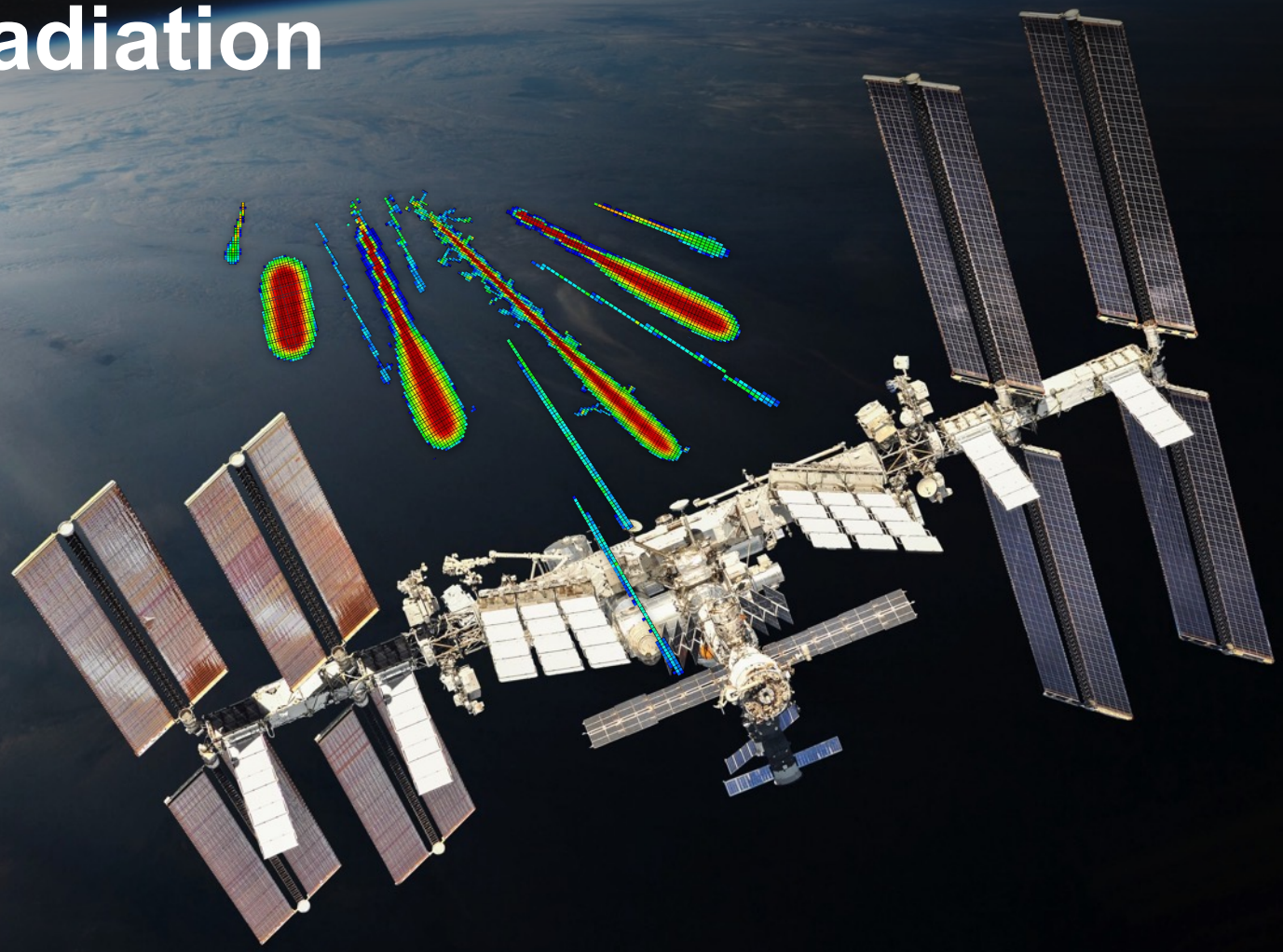
Timepix detector visualizes and recognizes each particle of cosmic radiation

Credit: ESA

# Monitor Space Radiation

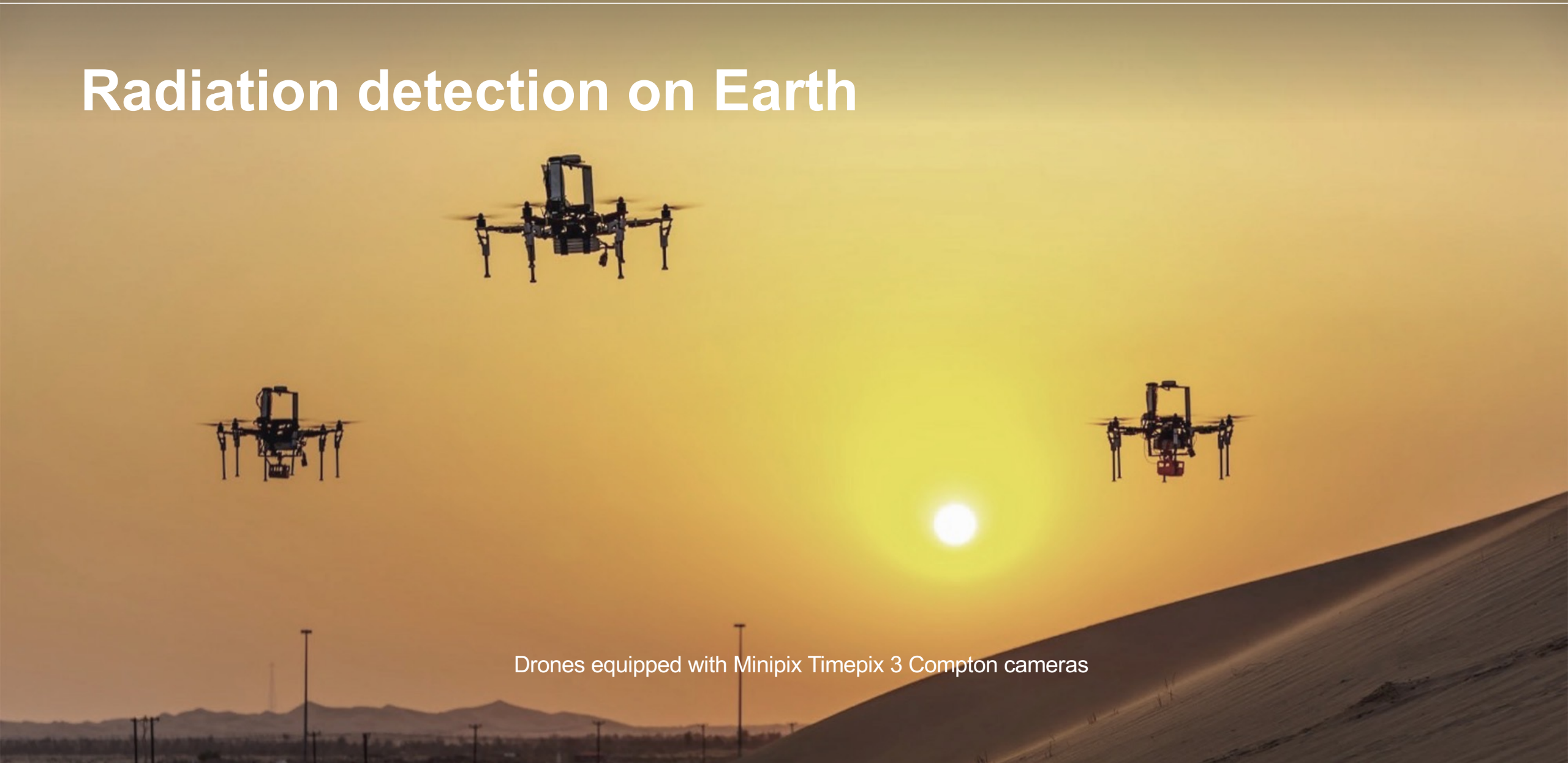



**MP1003**



Credit: Shutterstock

# Radiation detection on Earth

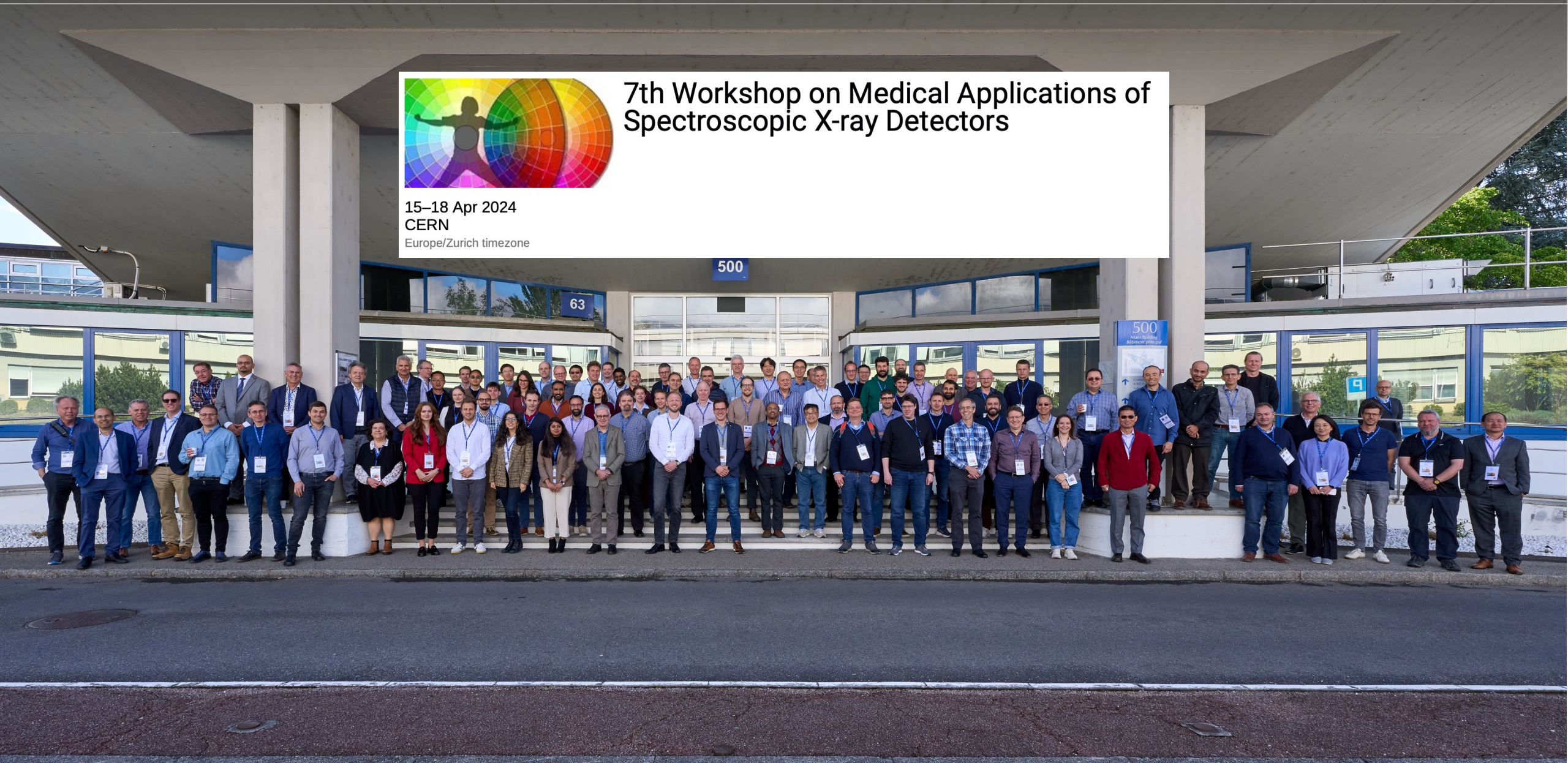


Drones equipped with Minipix Timepix 3 Compton cameras

# Radiation detection on Earth

# Medical X-ray Imaging

**Steffen Kappler**
Technology & Innovation, Siemens Healthineers

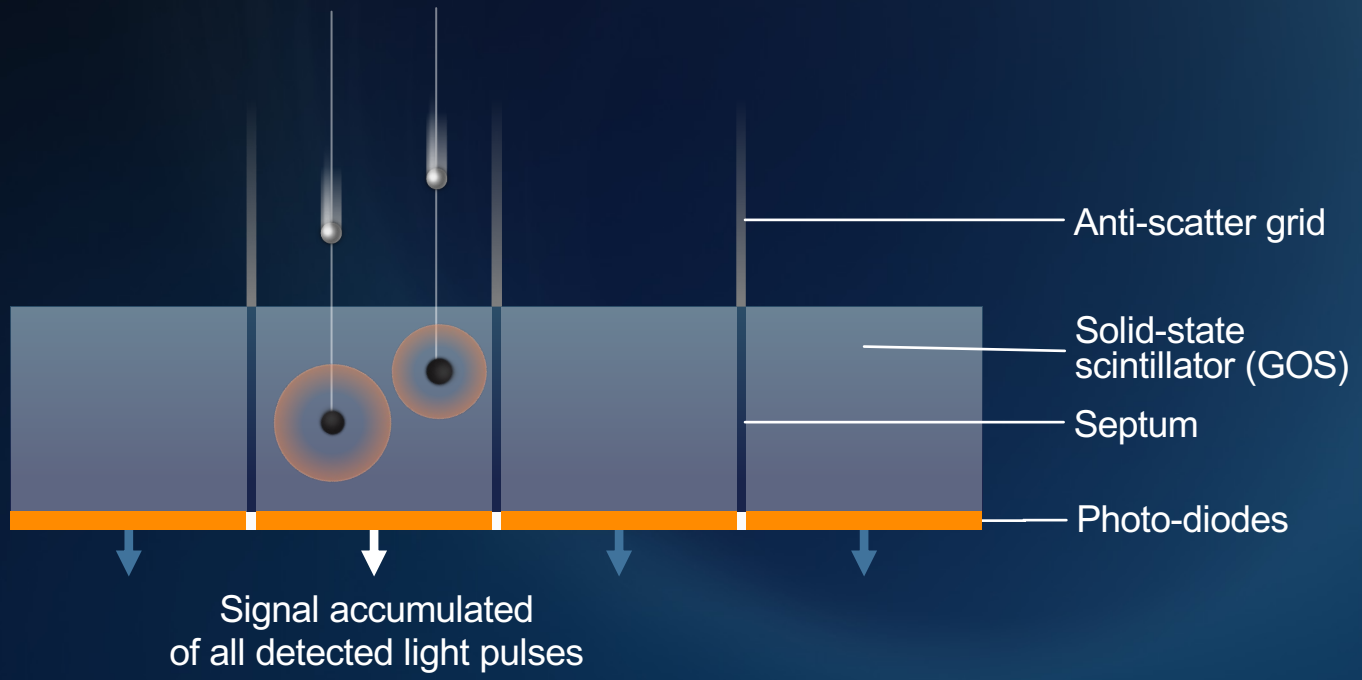

7th Workshop on Medical Applications of Spectroscopic X-ray Detectors
15–18 Apr 2024
CERN
Europe/Zurich timezone
500
63
500

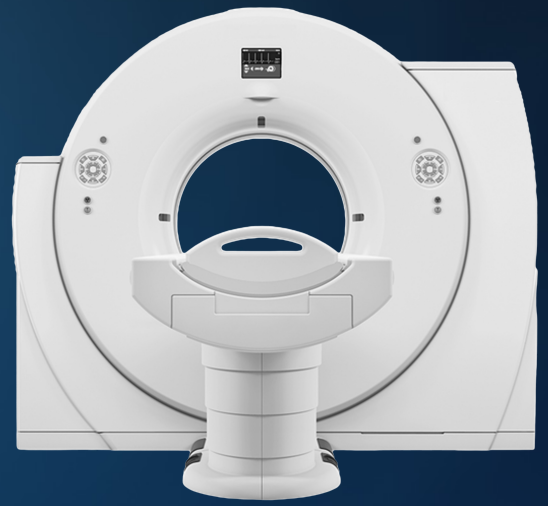
"I am convinced, that institutions like CERN play an important role for continuous innovations in medical imaging.

Communities like the Medipix Collaboration and the SpecXray Workshop are essential instruments of our society, connecting and affirming researchers in academia and industry during the maturation and commercialization processes of disruptive detector technologies for medicine."

**Steffen Kappler**

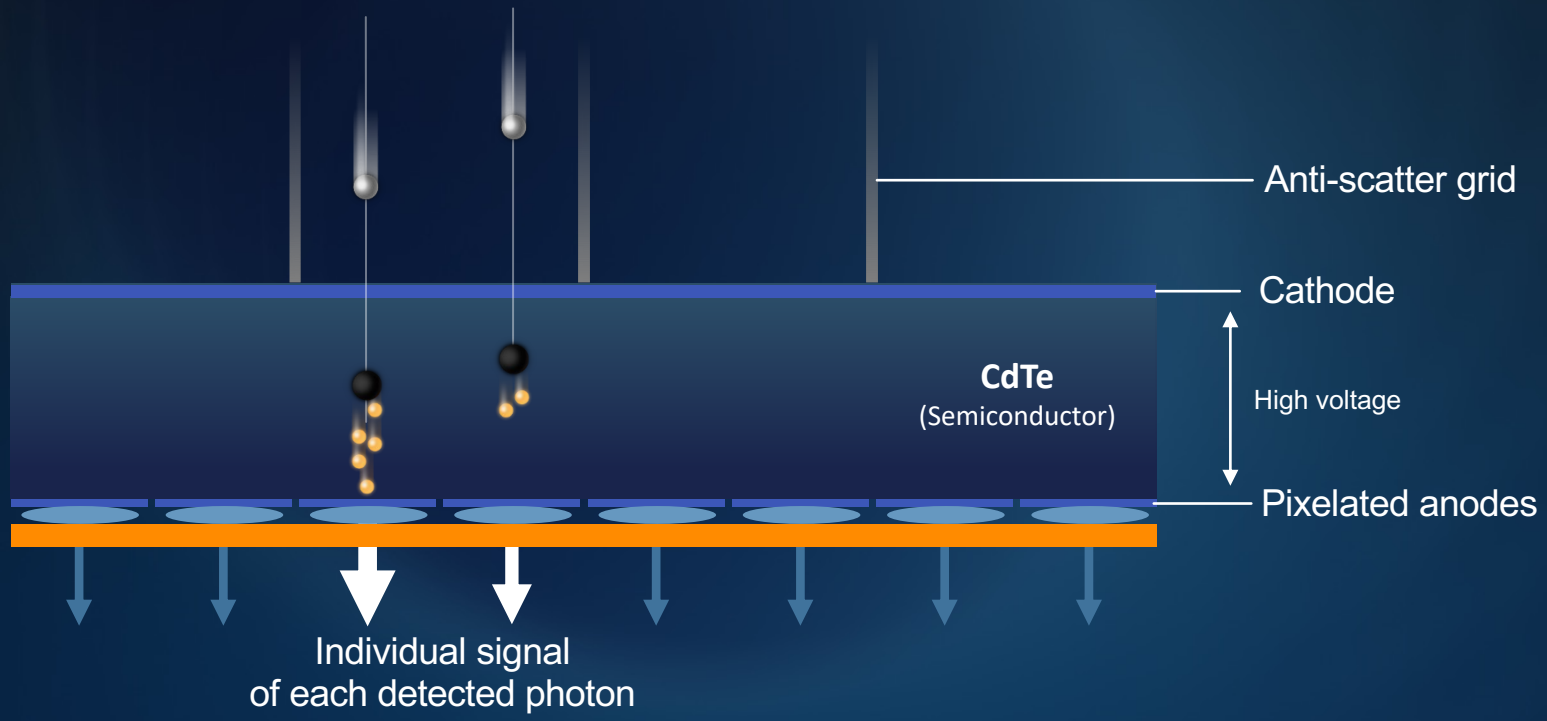
# Established Technology: Energy-integrating detectors



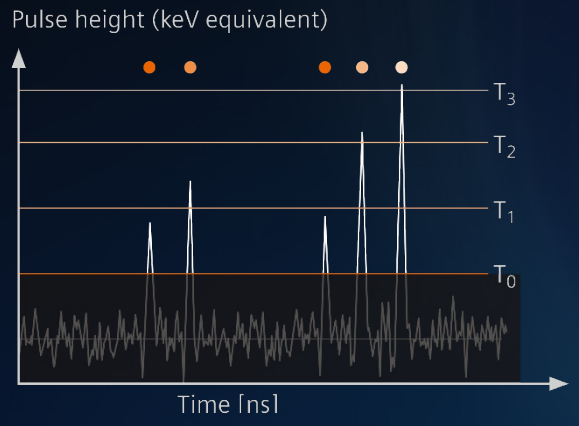
**Two-step conversion: X-rays → light → electric current**

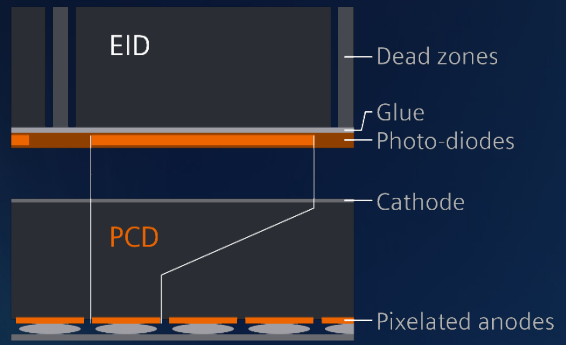
# Disruptive Technology: Photon-counting detectors

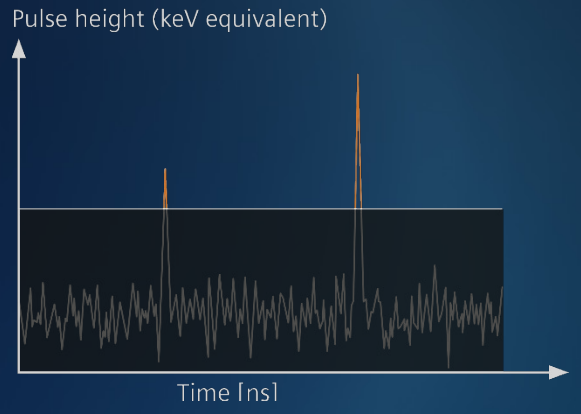


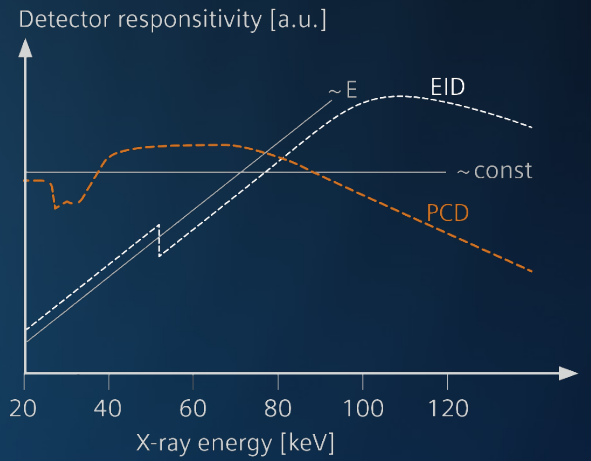

**Single-step direct conversion: X-rays → electric current**

# Benefits of photon-counting detectors



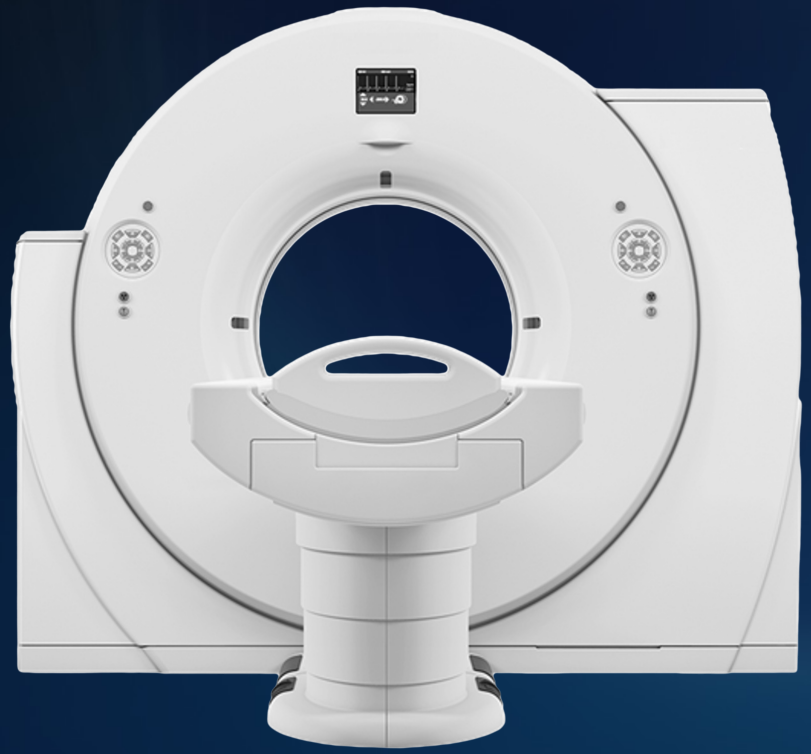

**Intrinsic spectral sensitivity**

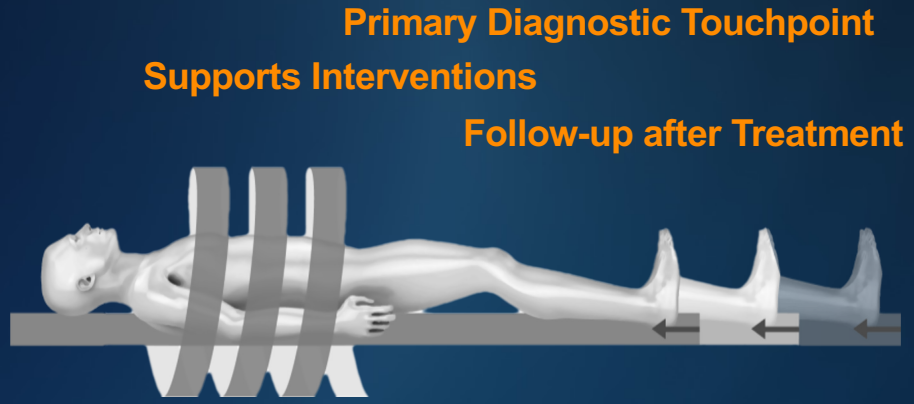
**Smaller detector pixels**

**Elimination of electronic noise**

**Equal energy contribution**

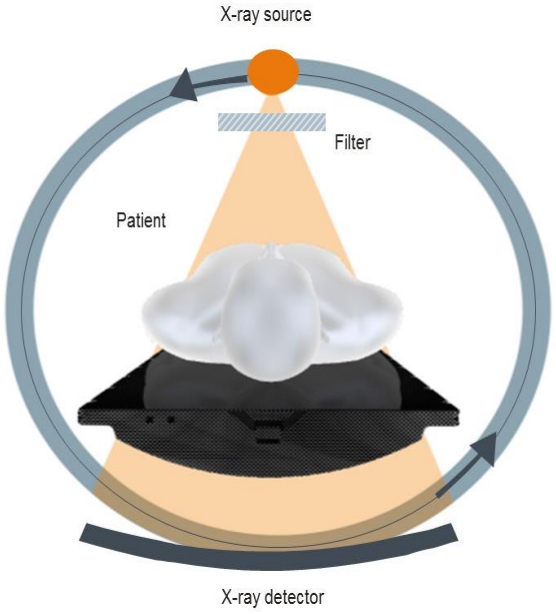
# Computed Tomography plays a central role in medical diagnostics

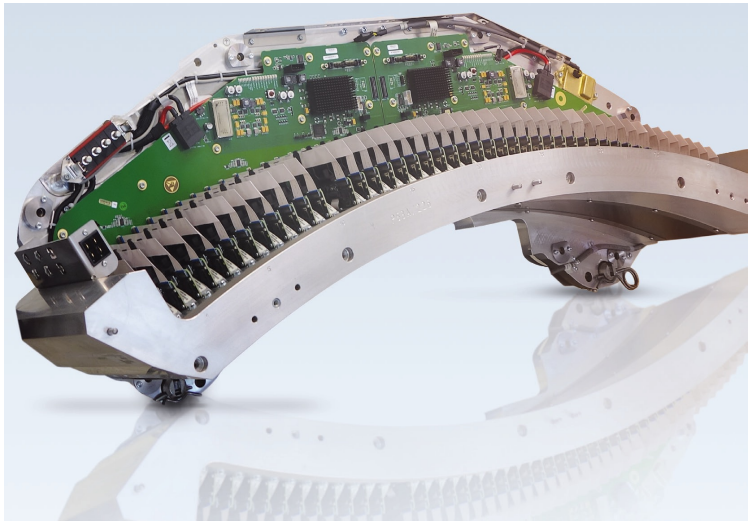


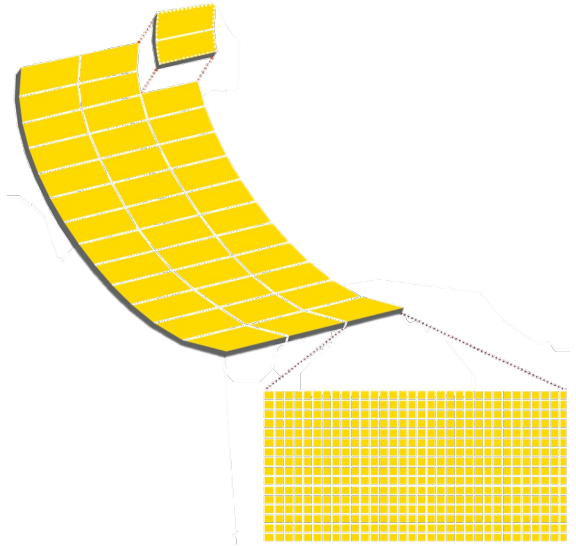



- Morphological imaging within seconds
- Functional information by spectral X-ray techniques

# X-ray tube and detector are core components of CT scanners



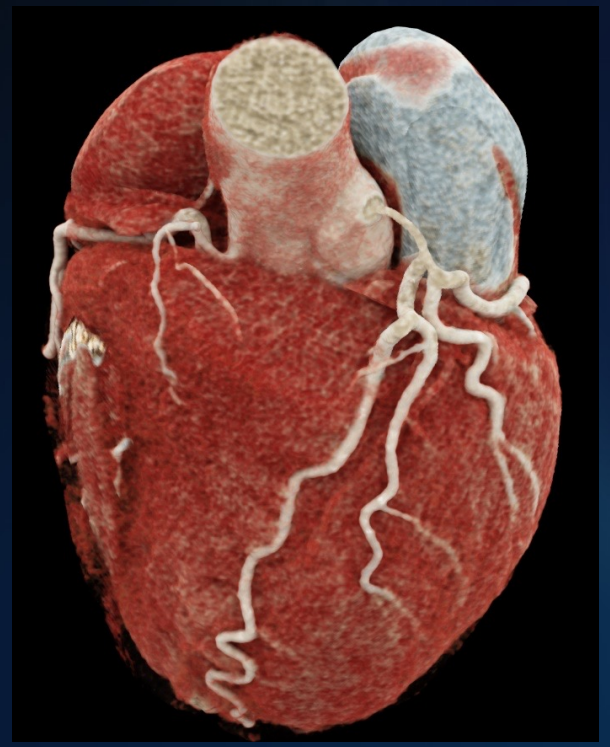





# 1st photon-counting CT by SIEMENS Healthineers


NAEOTOM Alpha®

# 1st photon-counting CT by SIEMENS Healthineers




NAEOTOM Alpha®

# 1st photon-counting CT by SIEMENS Healthineers

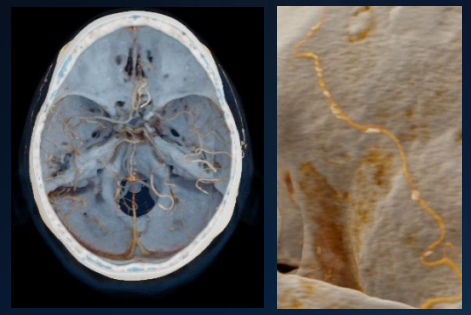

NAEOTOM Alpha®

# NAEOTOM Alpha ® – New Era of CT Imaging

Started in academia with scientific collaborations, and entered clinical routine

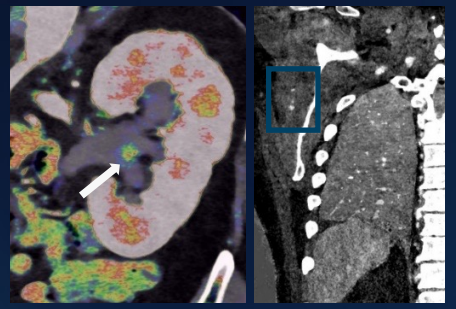
## Neurology

Make the unseen visible
and impact patient management



## Oncology

Aim for new standards
in cancer treatment

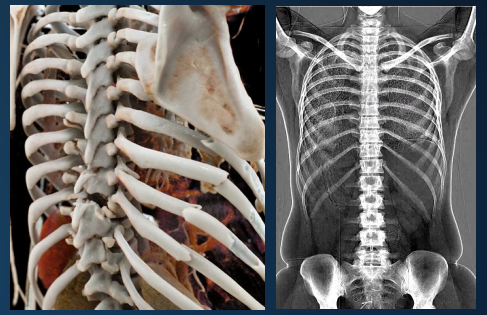


## Musculoskeletal

More details with ultra-high resolution

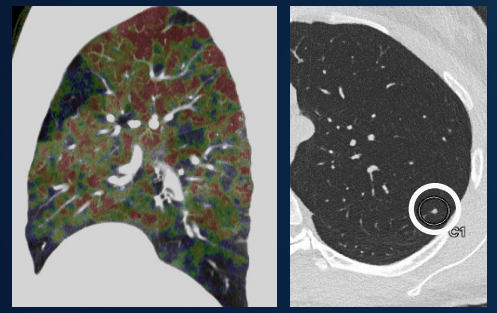
## Emergency

Aim for new standards
in Trauma and ED



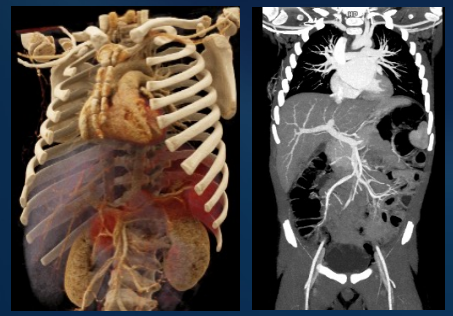
## Pulmonology

- Functional evaluation of lung diseases
at high level of detail



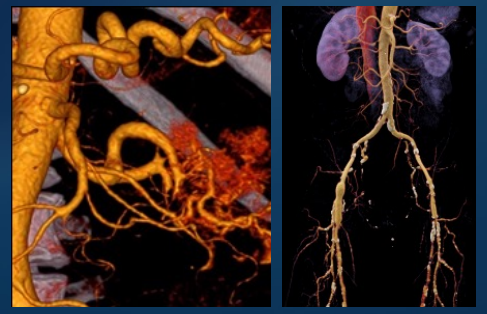
## Pediatrics

Dose efficiency and spectral
information for small patients



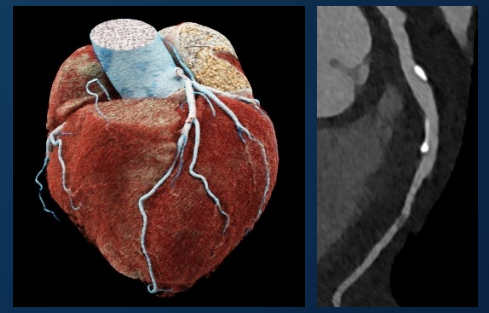
## Vascular

- High contrast at low dose



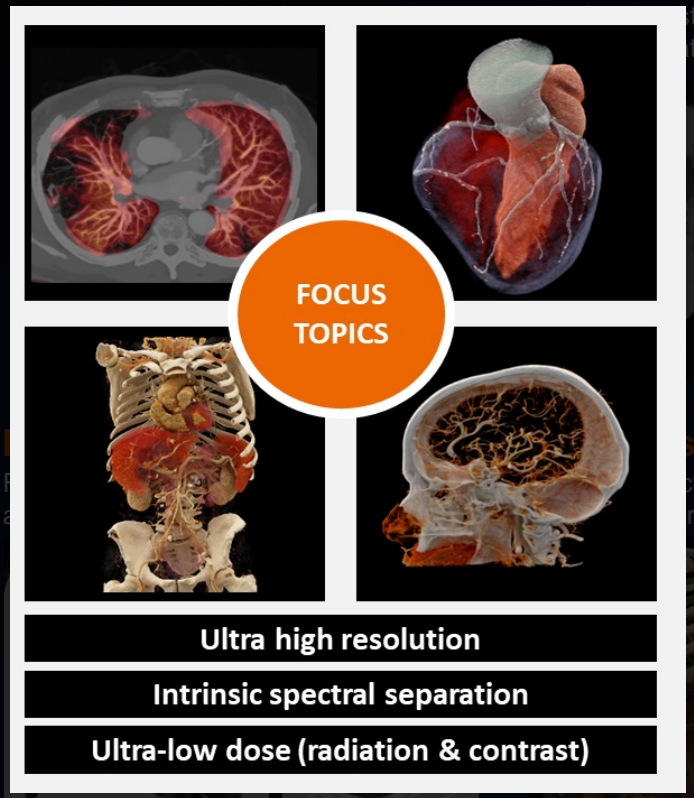
## Cardiology

Inform treatment planning
with confidence



# NAEOTOM Alpha ® – New Era of CT Imaging

Started in academia with scientific collaborations, and entered clinical routine




## Neurology

## Oncology

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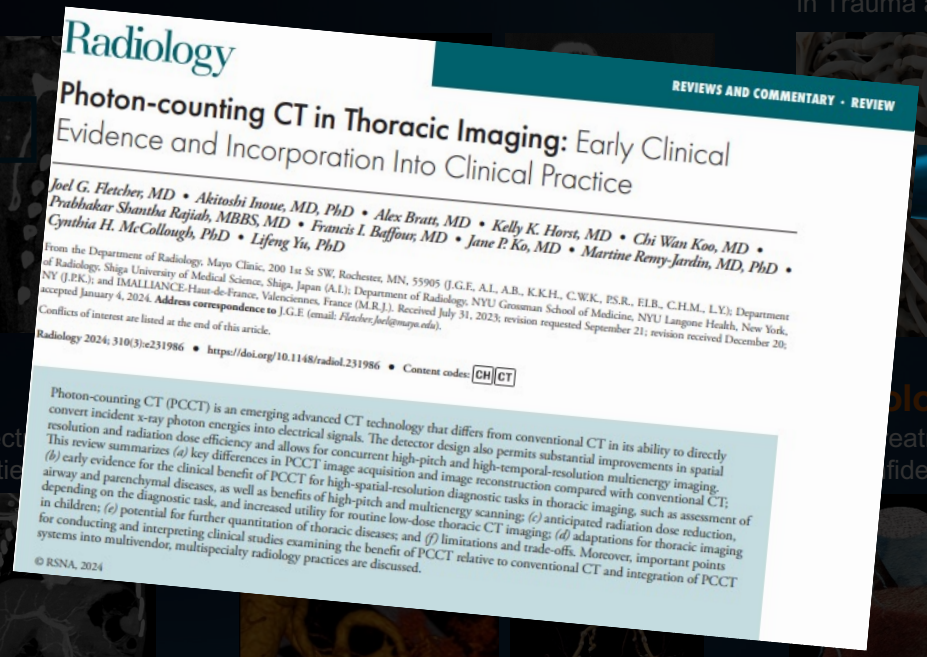
## Musculoskeletal

More details with ultra-high resolution

## Emergency

Aim for new standards
in Trauma and ED

Radiology

REVIEWS AND COMMENTARY · REVIEW

**Photon-counting CT in Thoracic Imaging:** Early Clinical Evidence and Incorporation Into Clinical Practice

*Joel G. Fletcher, MD • Akitoshi Inoue, MD, PhD • Alex Bratt, MD • Kelly K. Horst, MD • Chi Wan Koo, MD • Prabhakar Shantha Rajiah, MBBS, MD • Francis I. Baffour, MD • Jane P. Ko, MD • Martine Remy-Jardin, MD, PhD • Cynthia H. McCollough, PhD • Lifeng Yu, PhD*

From the Department of Radiology, Mayo Clinic, 200 1st St SW, Rochester, MN, 55905 (J.G.F., A.I., A.B., K.K.H., C.W.K., P.S.R., F.I.B., C.H.M., L.Y.); Department of Radiology, Shiga University of Medical Science, Shiga, Japan (A.I.); Department of Radiology, NYU Grossman School of Medicine, NYU Langone Health, New York, NY (J.P.K.); and IMALLIANCE-Haut-de-France, Valenciennes, France (M.R.J.). Received July 31, 2023; revision requested September 21; revision received December 20; accepted January 4, 2024. **Address correspondence to** J.G.F. (email: *Fletcher.Joel@mayo.edu*).

Conflicts of interest are listed at the end of this article.

**Radiology 2024; 310(3):e231986** • https://doi.org/10.1148/radiol.231986 • Content codes: CH CT

Photon-counting CT (PCCT) is an emerging advanced CT technology that differs from conventional CT in its ability to directly convert incident x-ray photon energies into electrical signals. The detector design also permits substantial improvements in spatial resolution and radiation dose efficiency and allows for concurrent high-pitch and high-temporal-resolution multienergy imaging. This review summarizes *(a)* key differences in PCCT image acquisition and image reconstruction compared with conventional CT; *(b)* early evidence for the clinical benefit of PCCT for high-spatial-resolution diagnostic tasks in thoracic imaging, such as assessment of airway and parenchymal diseases, as well as benefits of high-pitch and multienergy scanning; *(c)* anticipated radiation dose reduction, depending on the diagnostic task, and increased utility for routine low-dose thoracic CT imaging; *(d)* adaptations for thoracic imaging in children; *(e)* potential for further quantitation of thoracic diseases; and *(f)* limitations and trade-offs. Moreover, important points for conducting and interpreting clinical studies examining the benefit of PCCT relative to conventional CT and integration of PCCT systems into multivendor, multispecialty radiology practices are discussed.

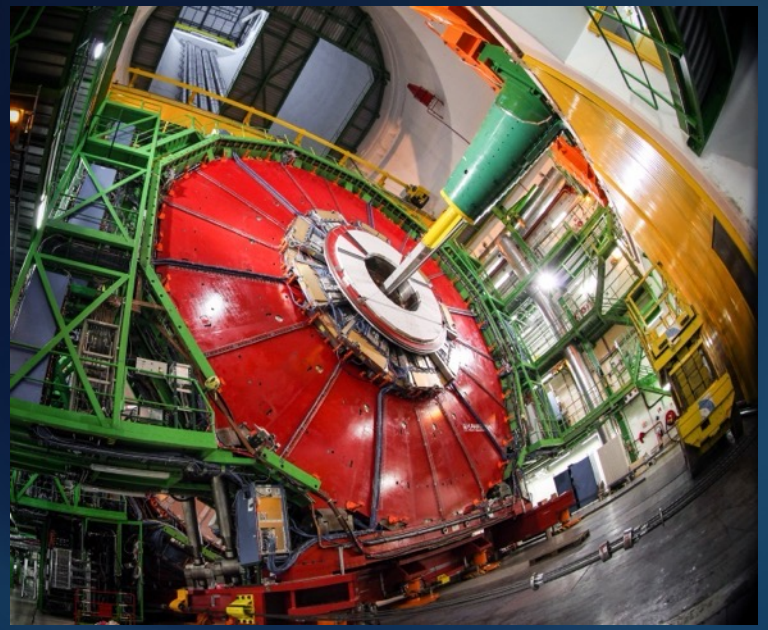


## Musculoskeletal

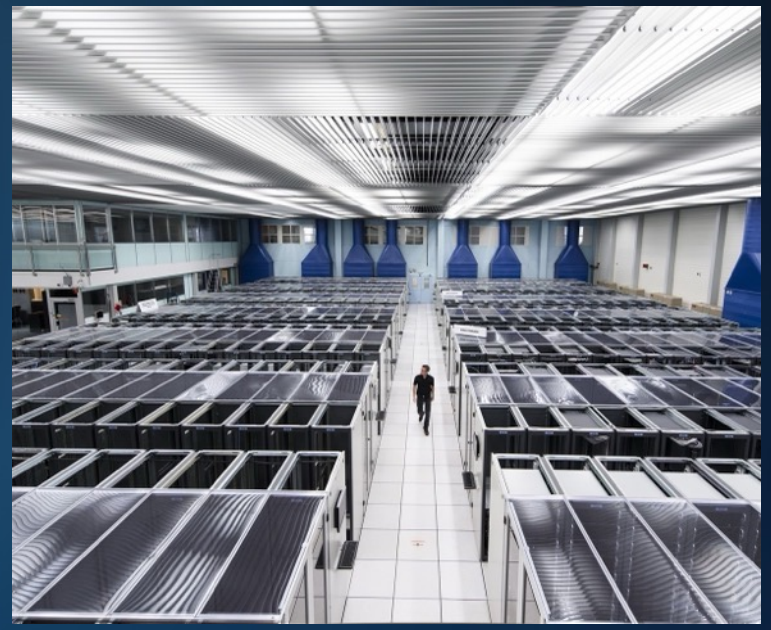
eatment planning
fidence

# We develop technologies in three key areas

ACCELERATORS



DETECTORS



COMPUTING

Session 3

# The Quantum Revolution

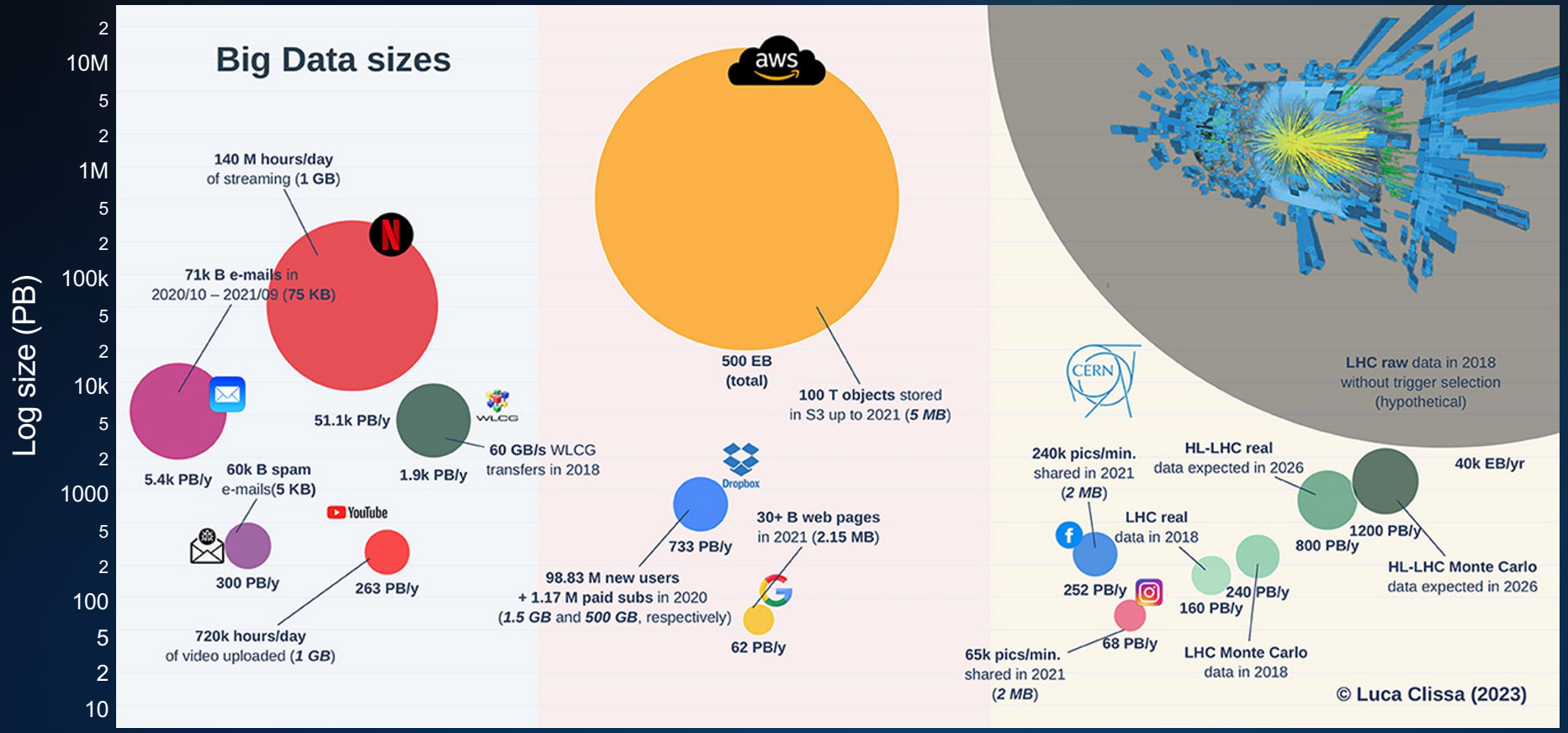

**Alain Aspect**
Nobel Prize, Physics 2022
Institut Optique / Paris Saclay University

**Reinhold Bertlmann**
Professor of Physics, University of Vienna, Austria

**Nicolas Gisin**
University of Geneva, Constructor University

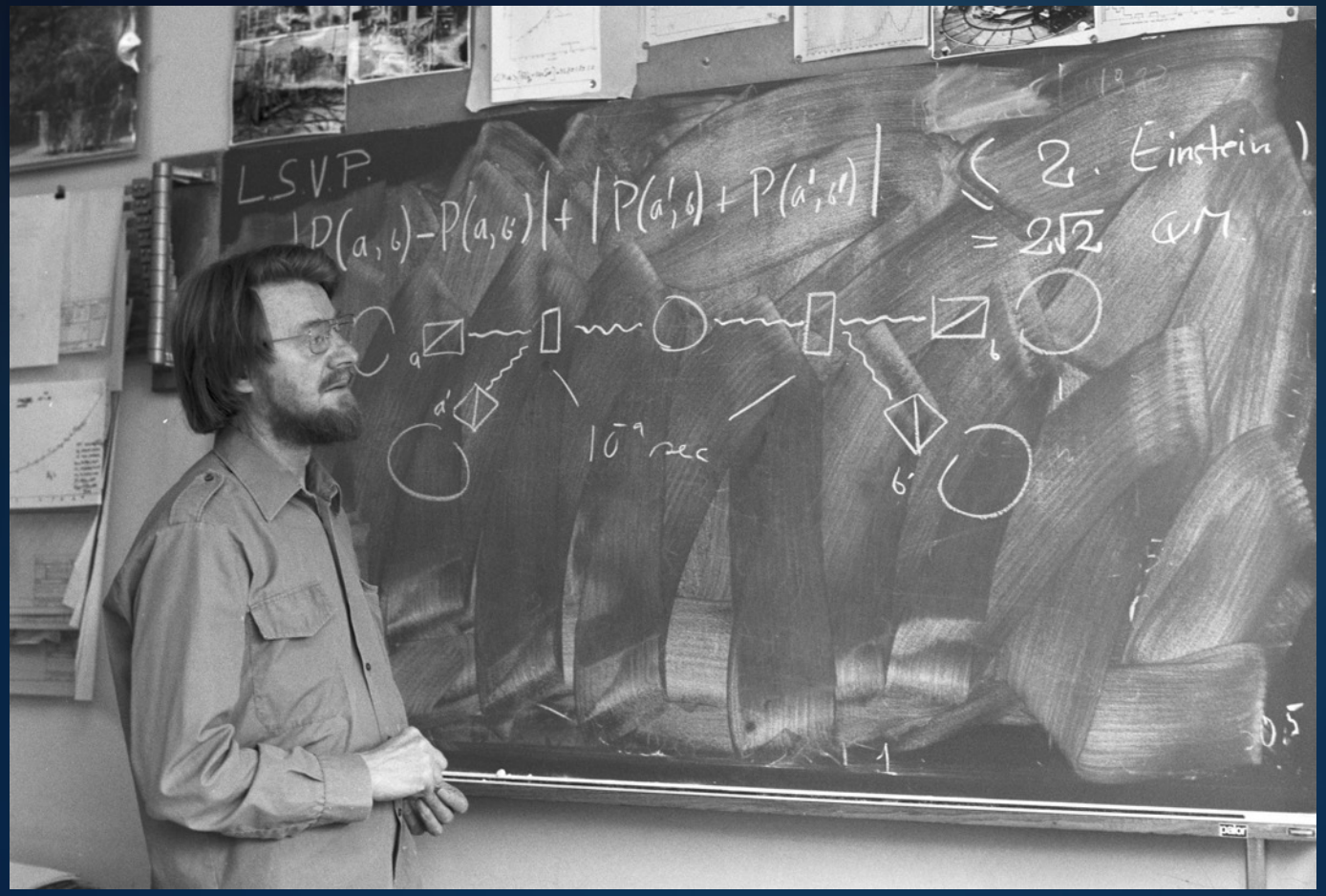
**Michele Grossi**
Quantum Algorithm Coordinator, CERN


# Big Data




A comprehensive survey of data production, storage, and streaming in science and industry

# Bell inequalities




# From Bell inequalities theorem to the Quantum Revolution

**Alain Aspect**
Nobel Prize, Physics 2022

**Reinhold Bertlmann**
Professor of Physics, University of Vienna, Austria

**Nicolas Gisin**
University of Geneva, Constructor University

# First Encounter


Nuclear Physics B177 (1981) 218–236


CERN
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SCIENTIFIQUE

## MAGIC MOMENTS

J.S. BELL and R.A. BERTLMANN[1]

*CERN, Geneva, Switzerland*

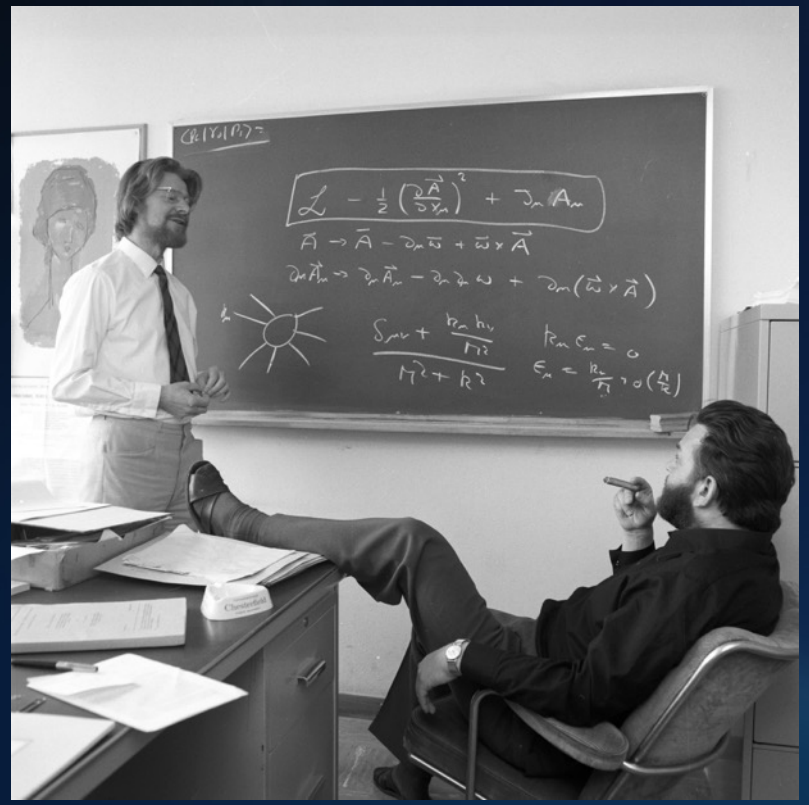
Received 30 June 1980

The moment method of Shifman, Vainshtein and Zakharov, for calculating bound-state energies in QCD, is tested in the context of potential models. For simple power-law potentials of low degree a refined version of the method works surprisingly well. The cruder version actually used by Shifman, Vainshtein and Zakharov for charmonium works less well, and the composite potentials usually envisaged for charmonium are less accurately dealt with than simple power potentials. We conjecture then that the magnitude of their confinement parameter $\phi$ has been substantially underestimated by those authors.

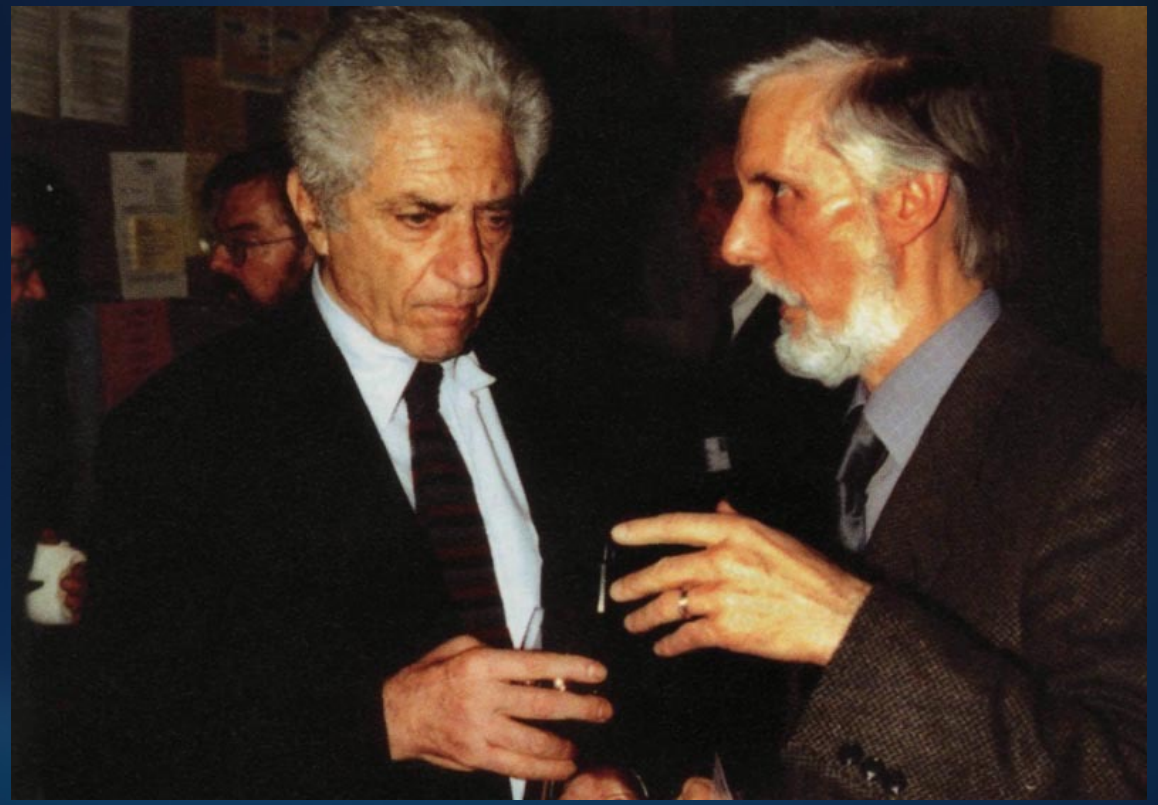
# Tea Tasting

Reinhold & John

# John Bell – Particle Physicist

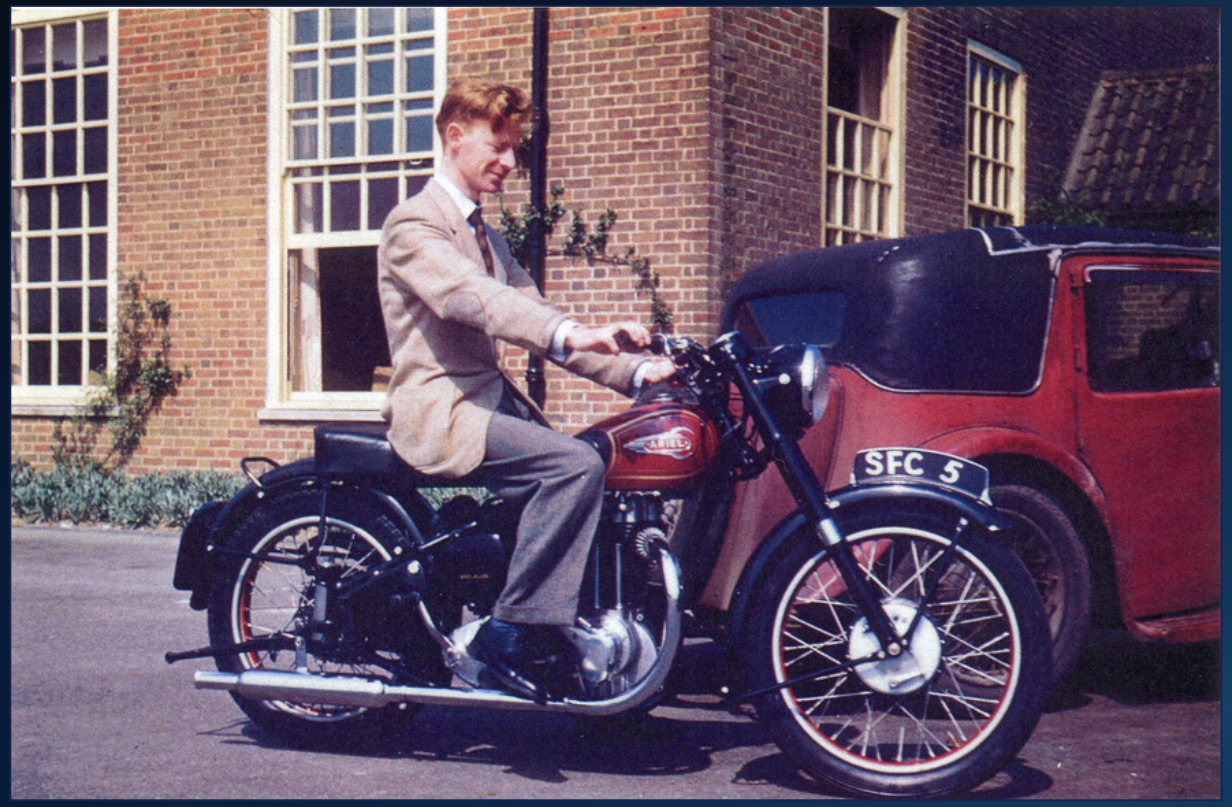


With Martinus Veltman



Bertlmann with Jack Steinberger

# John Bell – Accelerator Physicist




In 1950s at Harwell

# John Bell – Accelerator Physicist

*Particle Accelerators*
1981 Vol.11 pp.233–238
0031-2460/81/1104/0233$06.50/0



## ELECTRON COOLING IN STORAGE RINGS

J. S. BELL and M. BELL
*CERN, Geneva, Switzerland*

*(Received February 2, 1981)*

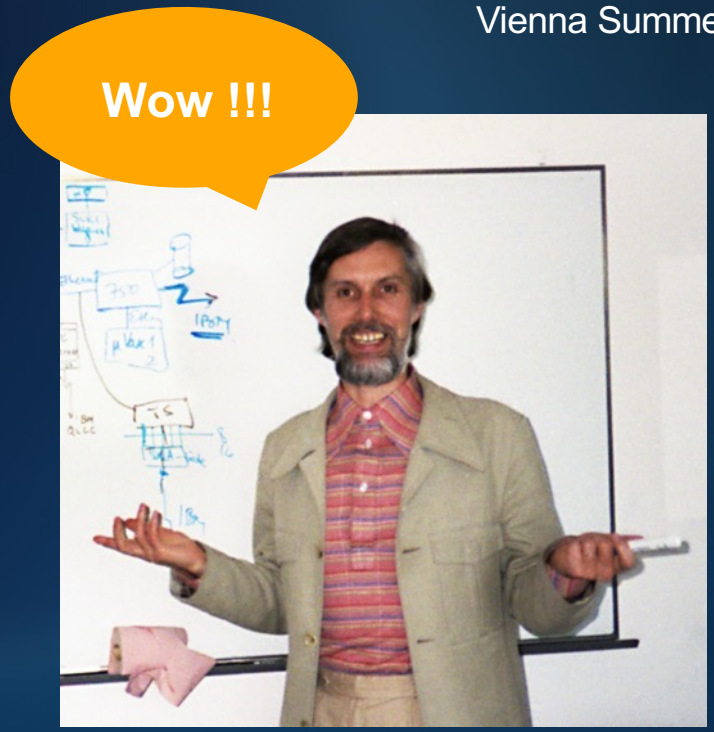
It is found that the effect of "flattening" of the electron velocity distribution is to increase the rate of cooling of small betatron oscillations by a factor of 2.4, and not by a factor of 4 as often quoted. This is when the cooler magnetic field is ignored. When it is allowed for, in the usual way, the cooling rate involves a divergent integral whose regulation depends on the details of particular cases.

With his wife Mary Bell

# Surprise

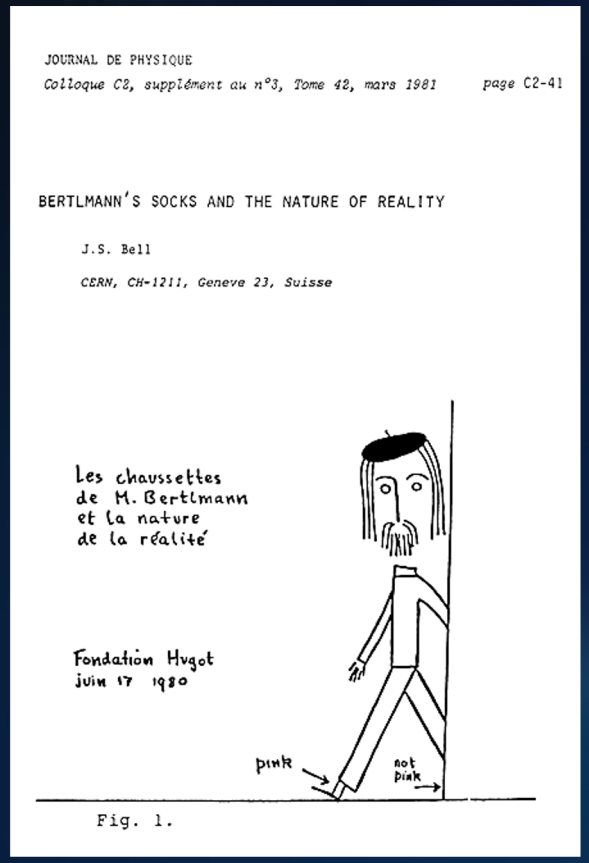

Gerhard Ecker

Out of the Blue,
Vienna Summer 1980




Reinhold A. Bertlmann

# Bertlmann's Socks



JOURNAL DE PHYSIQUE
*Colloque C2, supplément au n°3, Tome 42, mars 1981* *page C2-41*

BERTLMANN'S SOCKS AND THE NATURE OF REALITY

J.S. Bell

*CERN, CH-1211, Geneve 23, Suisse*



Fig. 1.

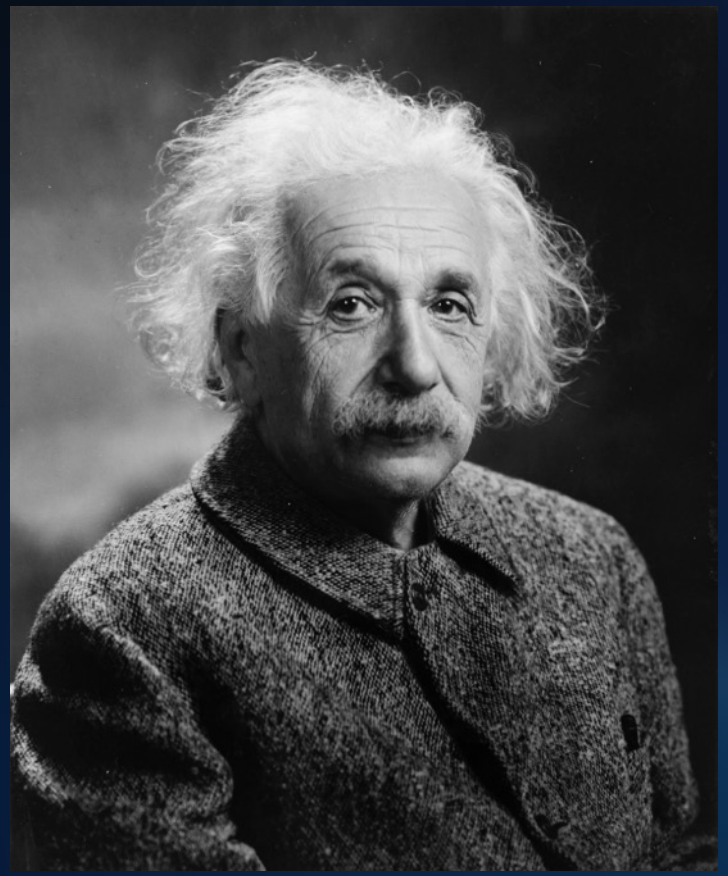
"Dr. Bertlmann likes to wear two socks of different colours. Which colour he will have on a given foot on a given day is quite unpredictable. But when you see that the first sock is pink you can be already sure that the second sock will not be pink."

"Observation of the first, and experience of Bertlmann, gives immediate information about the second."

*"And is not the EPR business just the same?..."*

No !!

# Einstein vs Bohr



# Quantum physics

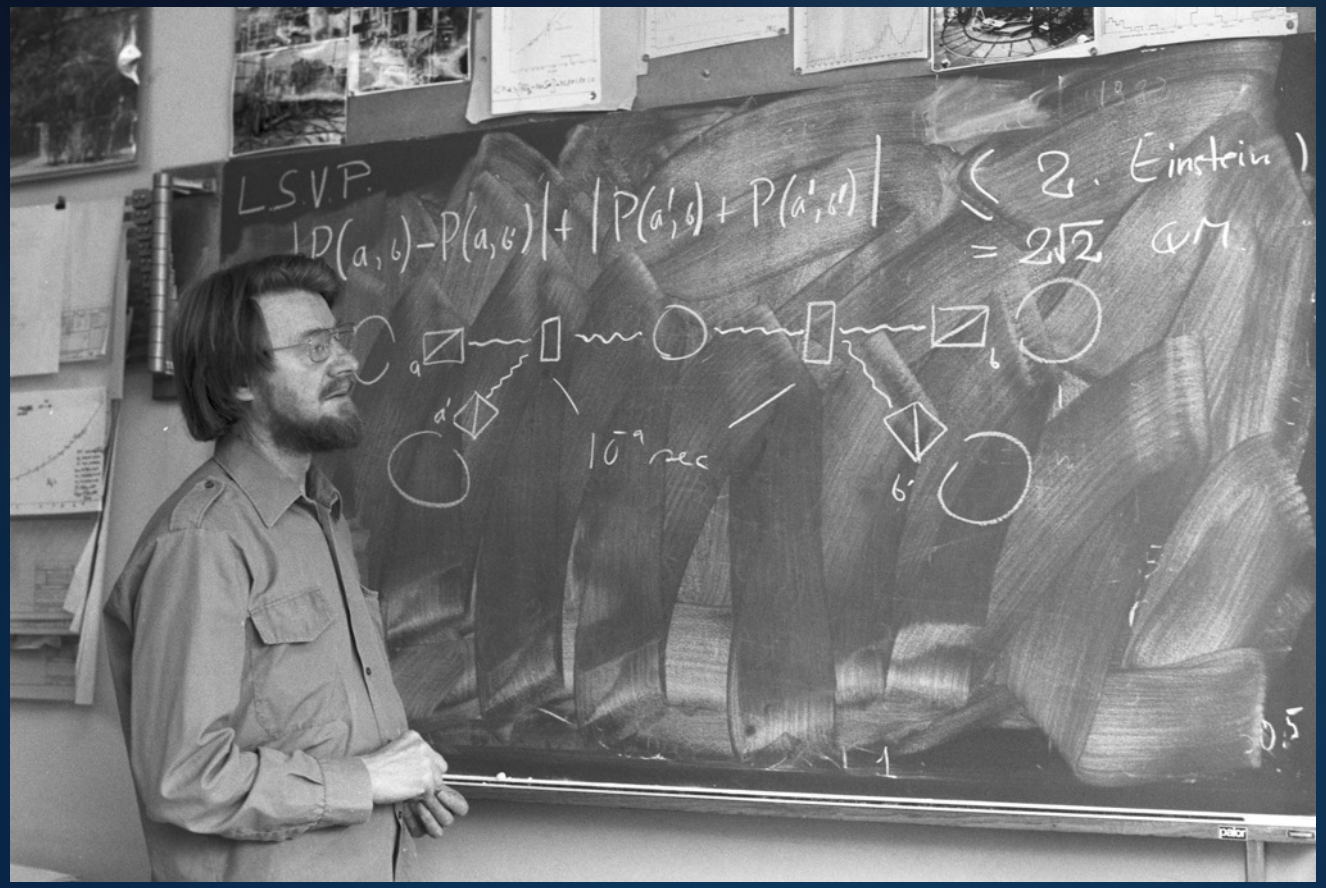
**Classic world (human experience)**

Continuos behaviour

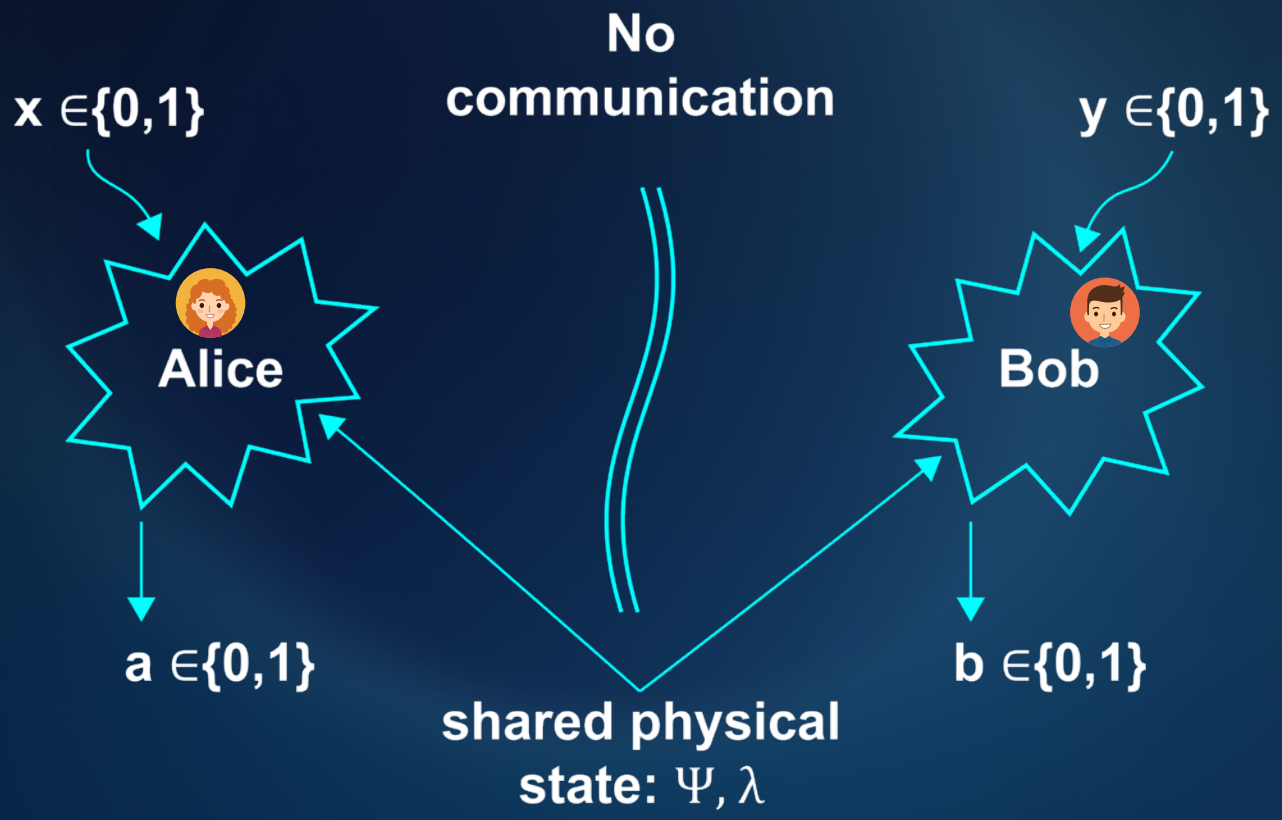
**Quantum world (micro)**

Quantum particles – wave like

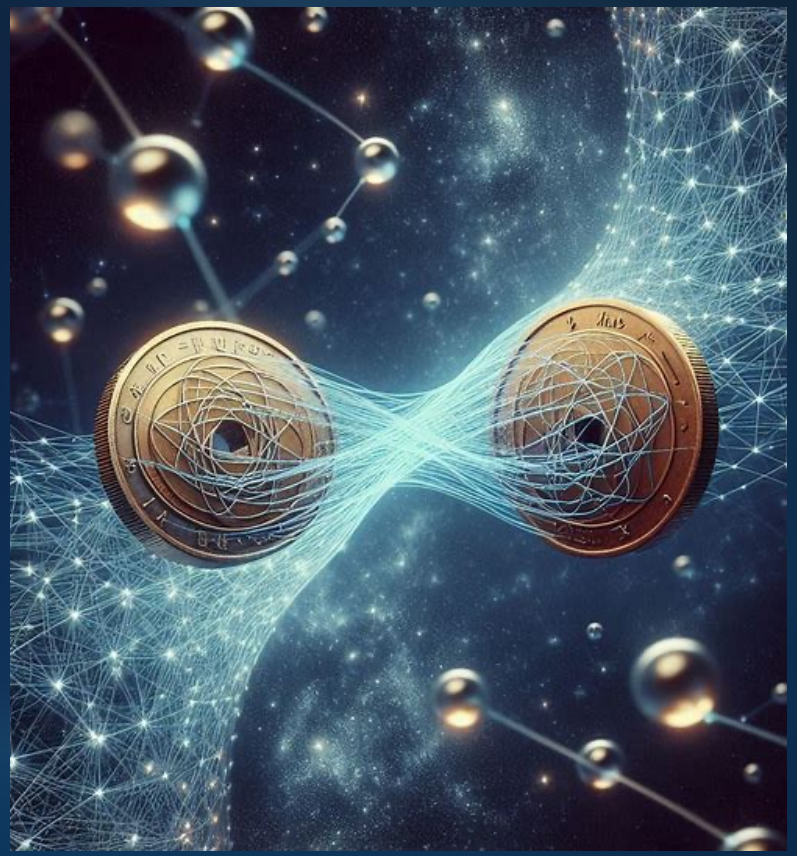
# Bell's theorem



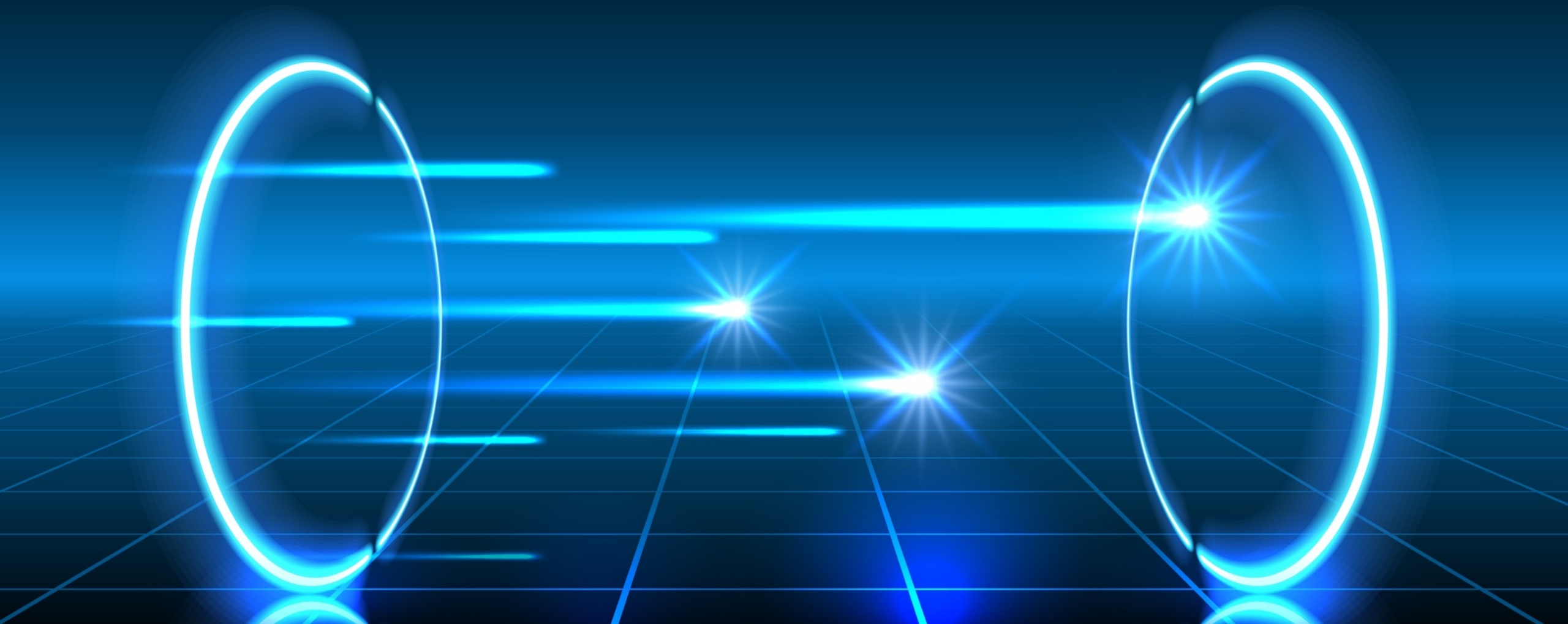
# Bell locality



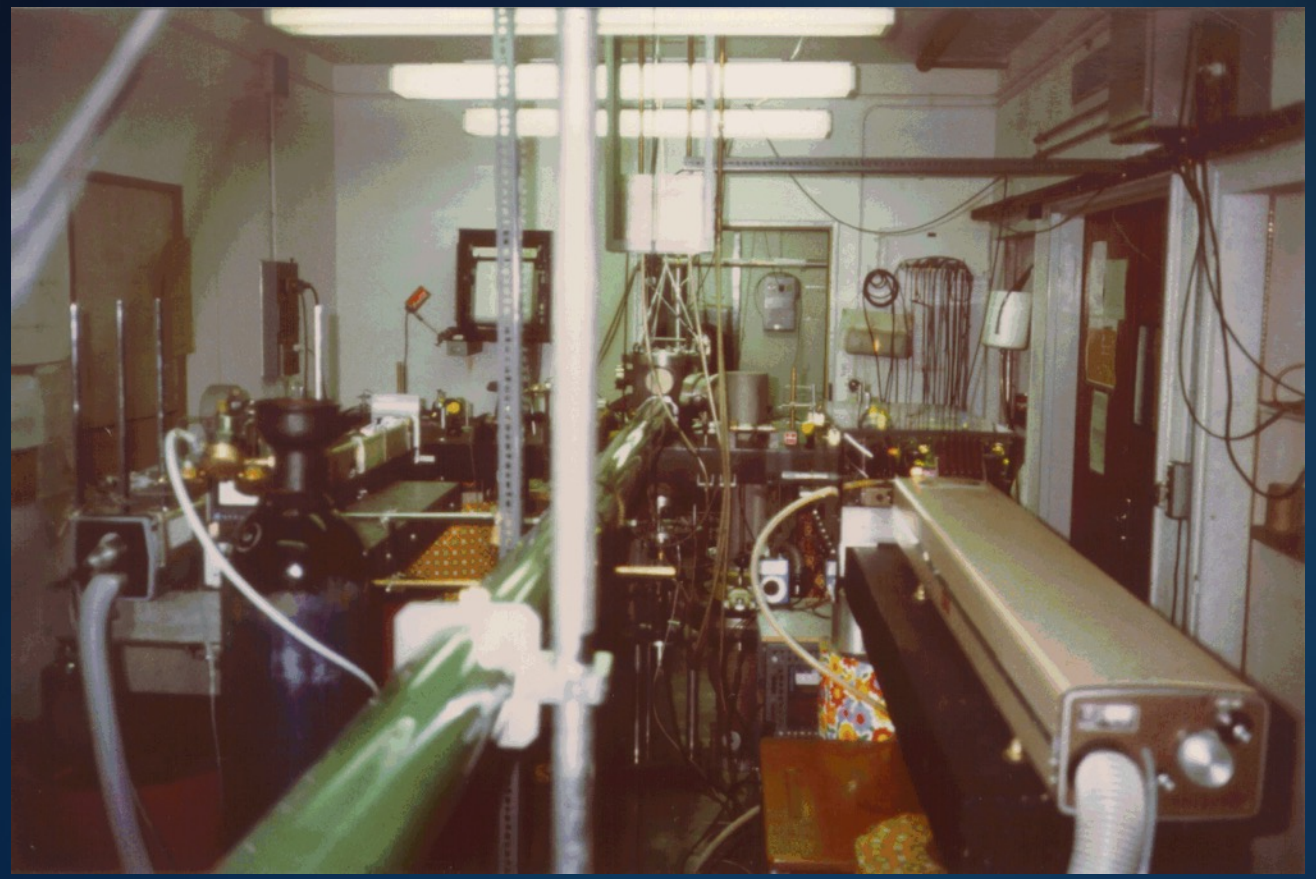
# Entanglement



# Quantum teleportation



# The curiosity lab

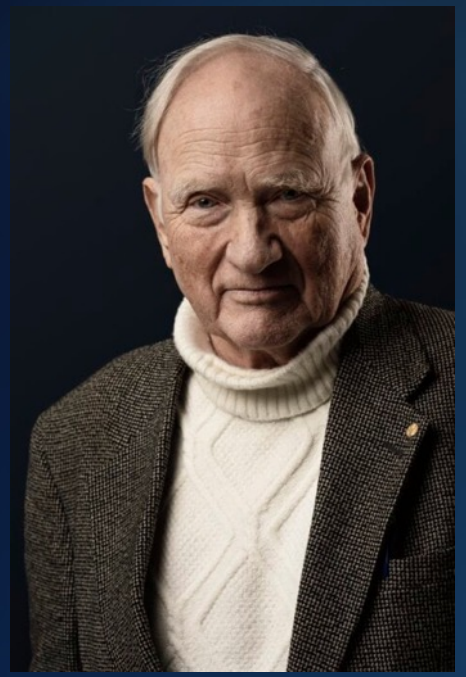


Aspect's 1982 experiment

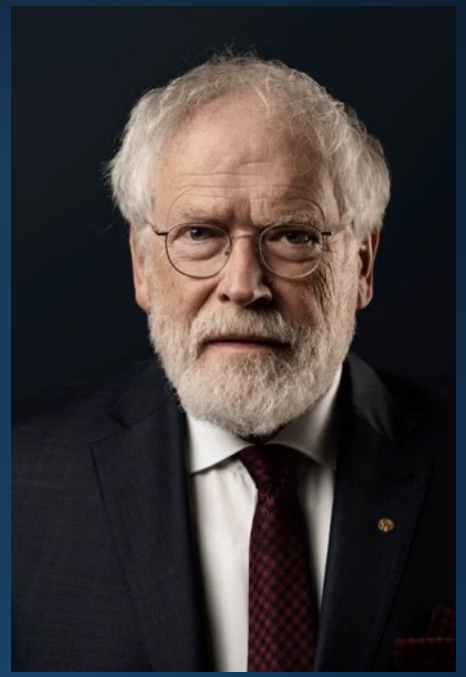
# From Bell's thought experiment to Aspect's lab

Alain Aspect developed this experiment, using a new way of exciting the atoms so they emitted entangled photons at a higher rate. He could also switch between different settings, so the system would not contain any advance information that could affect the results.

Alain Aspect



John F. Clauser



Anton Zeilinger

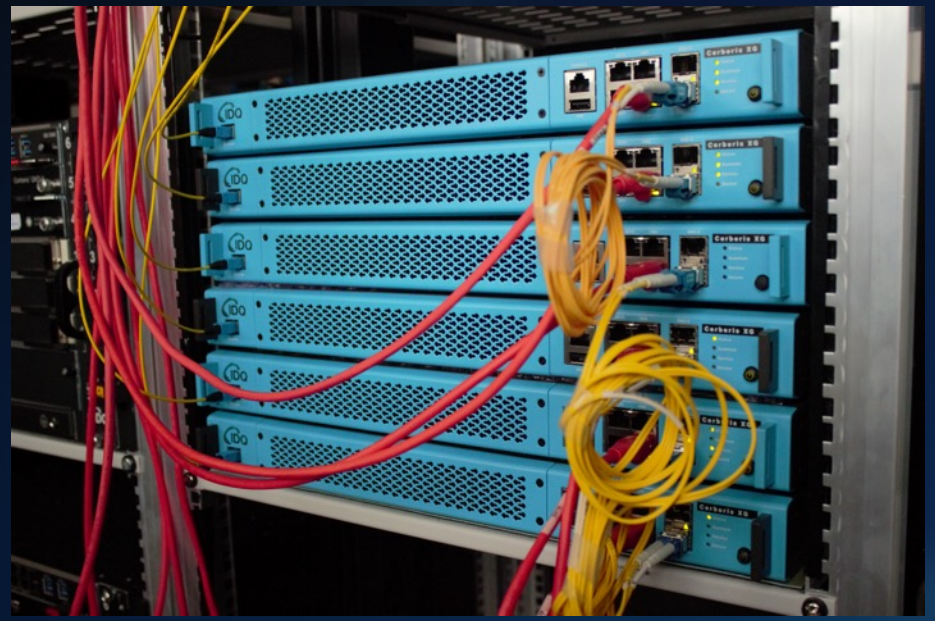
The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the **violation of Bell inequalities** and **pioneering quantum information science**"

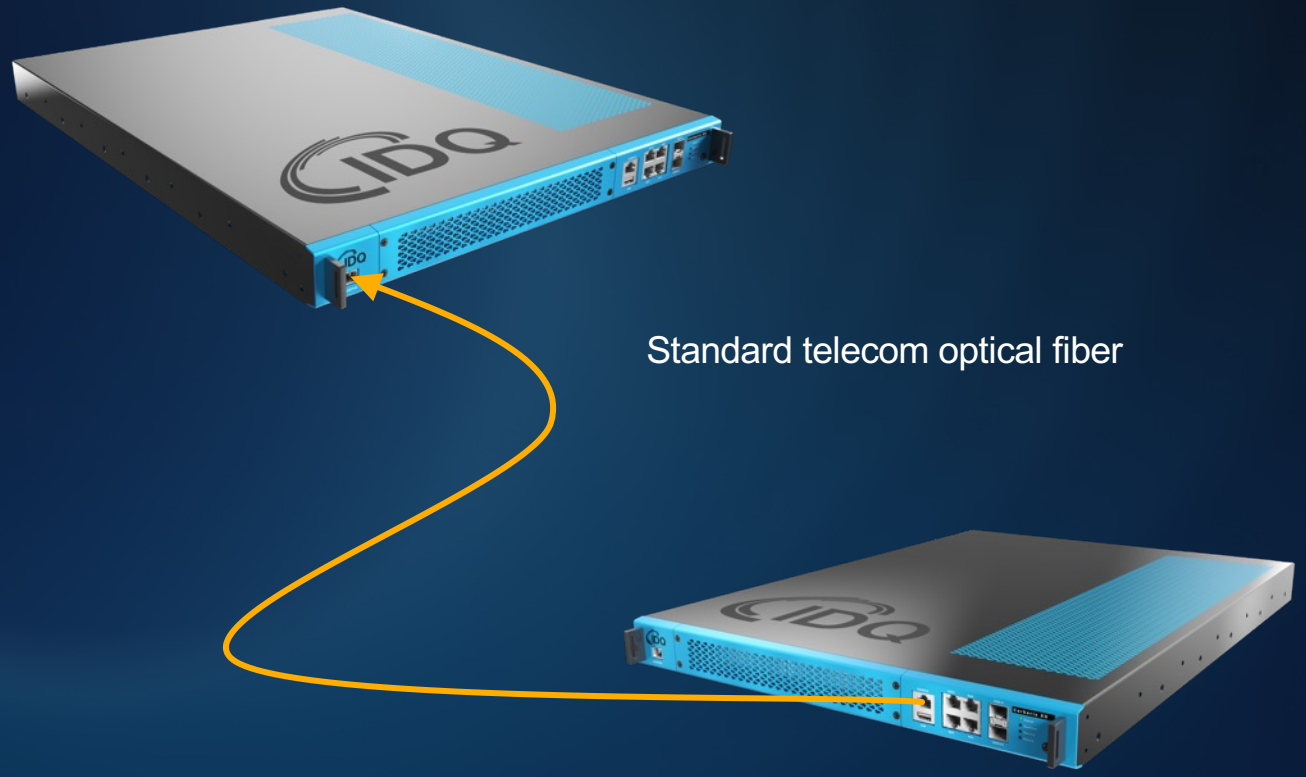
# The real-world lab: Geneva 1997

Violation of Bell inequality over 10 km

# Visit by Mary Bell during the experiment

# Quantum Key Distribution





# Sample of QKD networks

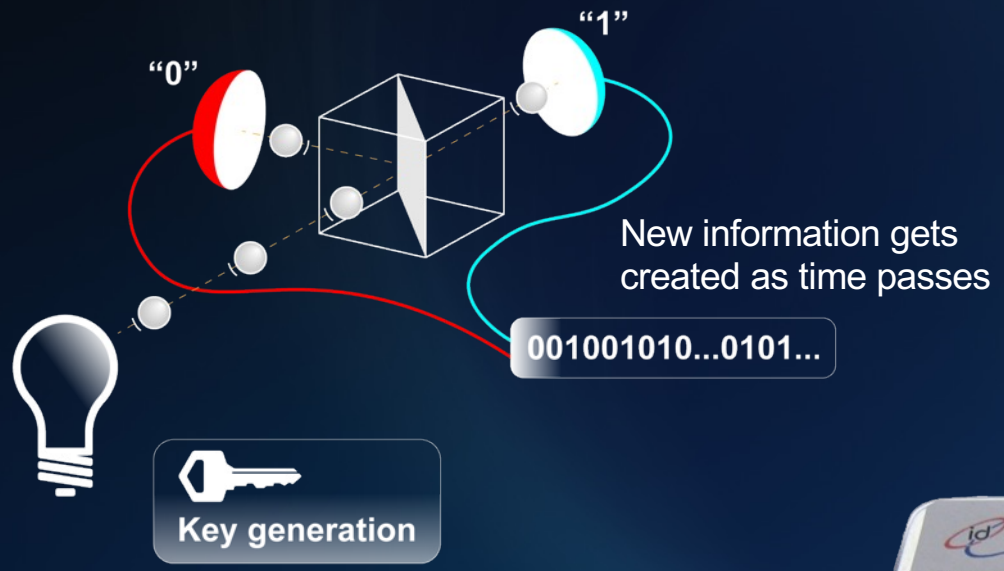

Geneva-Lausanne


Poland

South-Korea

EU Quantum
Communication Infrastructure

# Quantum Random number generator




New information gets created as time passes

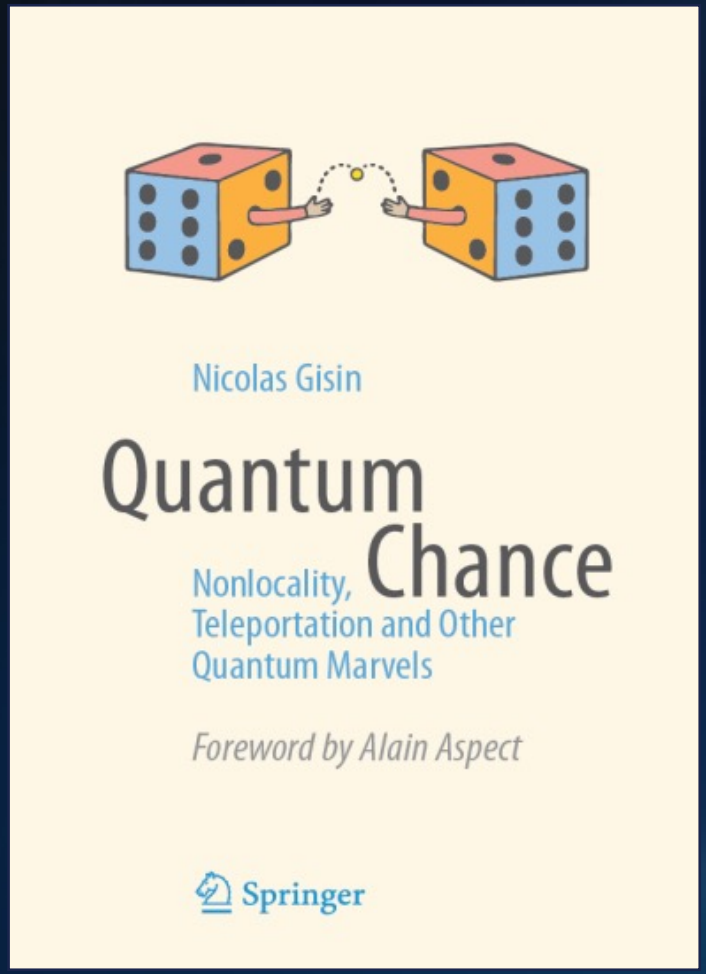

4 cm

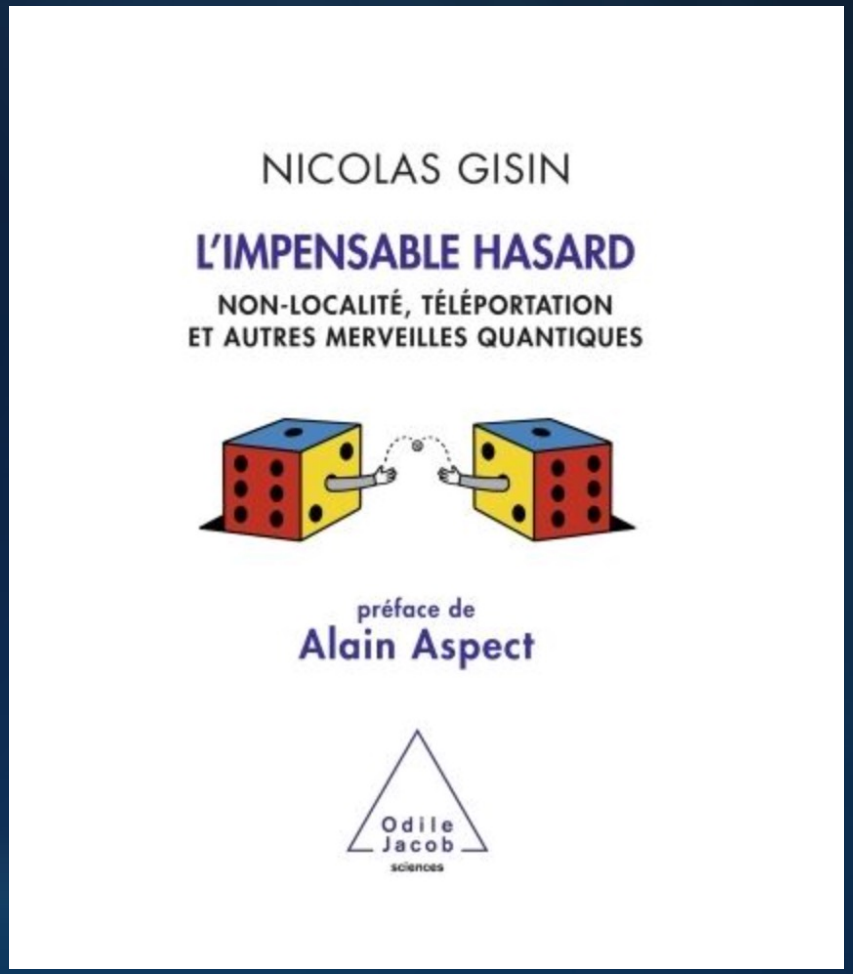

First mass application of Q technologies

mm size
μw power

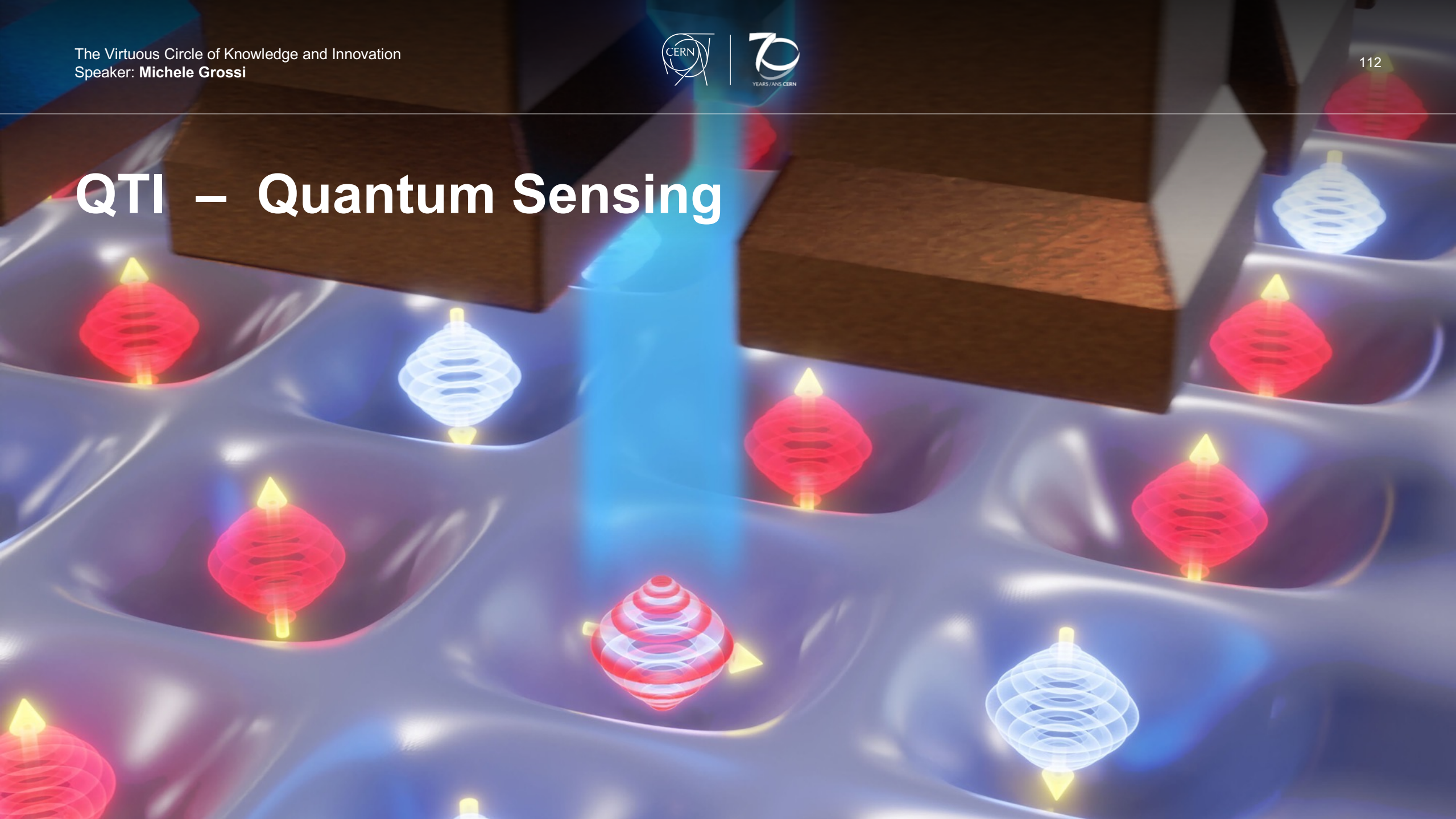
# Application of superconducting single-photon detectors to… Rockets: Ariane 6

- First space launcher using Opto-Pyrotechnics
- Main advantages:
  - immunity to electromagnetic interference,
  - simpler handling, shorter integration times,
  - mass, volume and cost reductions
- Reduced design-to-build lead times
- Enhanced safety and reliability
- First flight in 2024

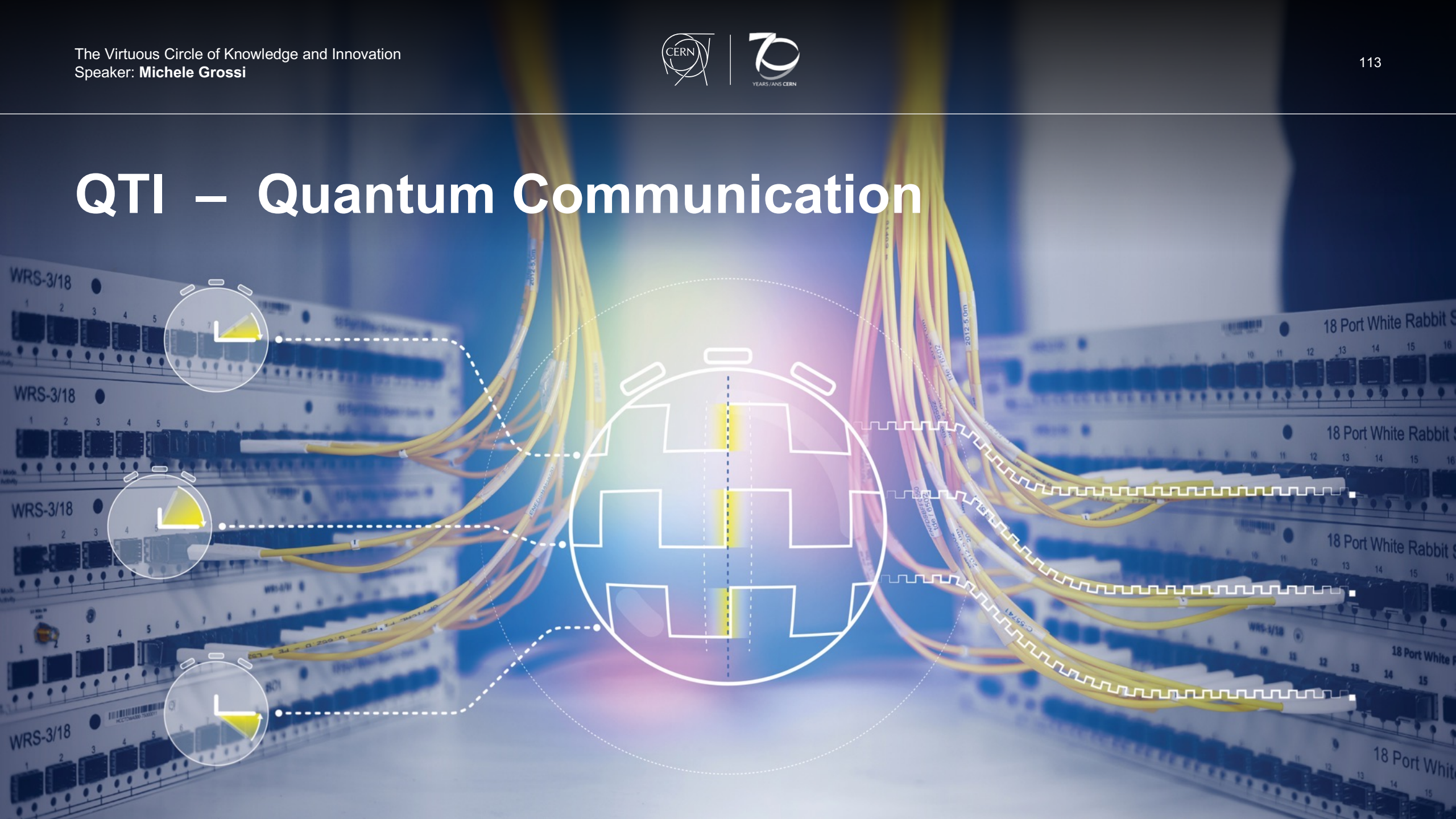

Nicolas Gisin
Quantum Chance
Nonlocality, Teleportation and Other Quantum Marvels
Foreword by Alain Aspect
Springer


NICOLAS GISIN
L'IMPENSABLE HASARD
NON-LOCALITÉ, TÉLÉPORTATION
ET AUTRES MERVEILLES QUANTIQUES
préface de
Alain Aspect
Odile Jacob
sciences

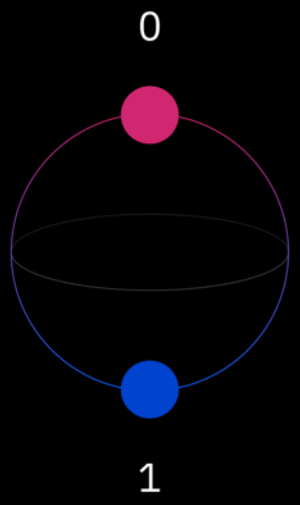
# QTI – Quantum Sensing

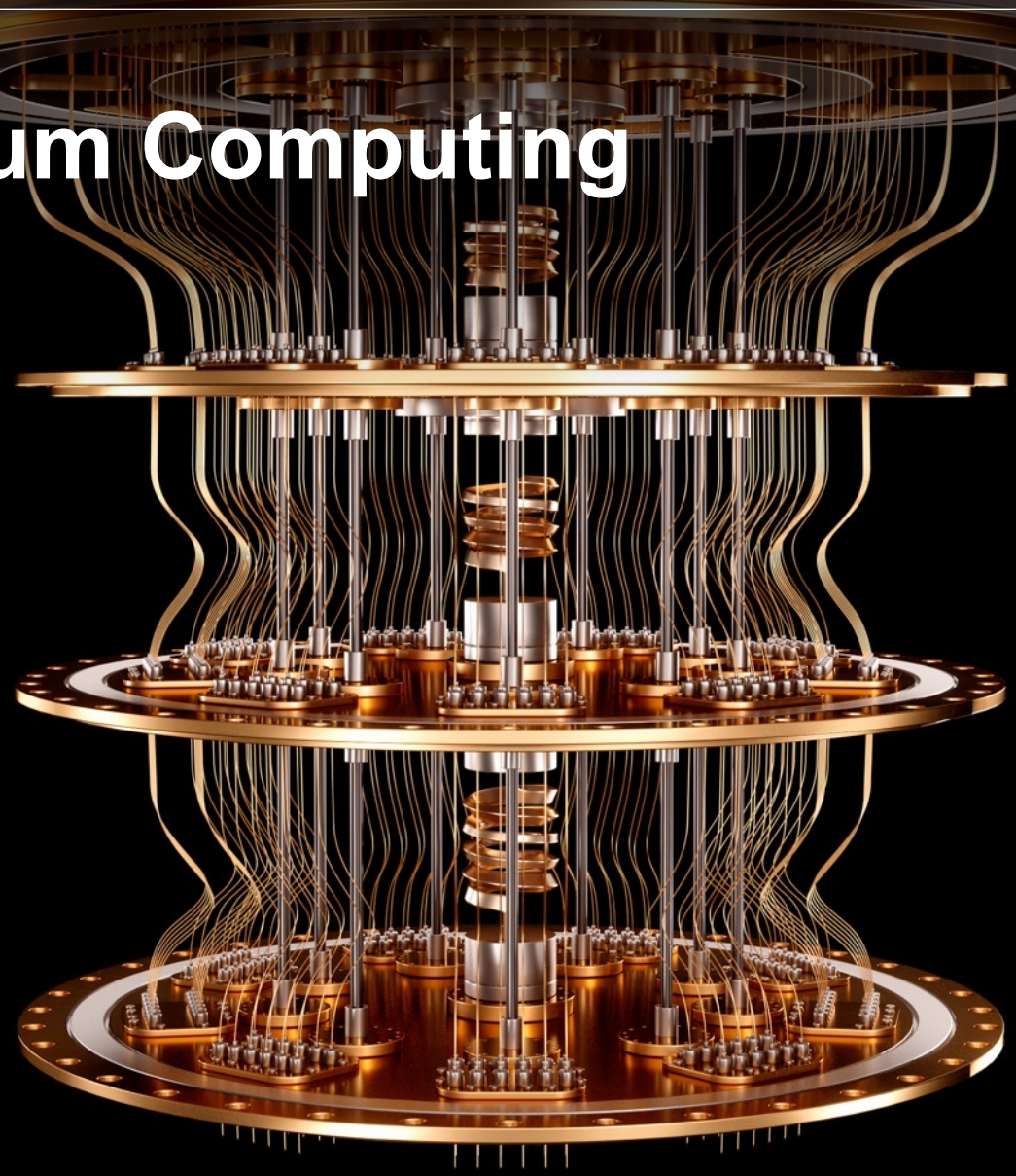


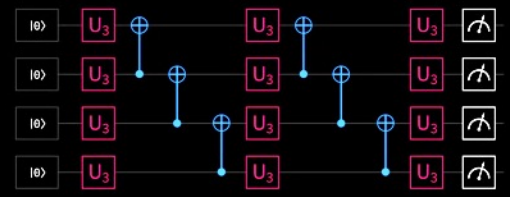
# QTI – Quantum Communication



# QTI – Quantum Computing





# John’s Confession

# The Virtuous Circle of Knowledge and Innovation

Moderated by: **Paola Catapano**

Speakers: **Alain Aspect, Tabea Arndt, Amalia Ballarino, Reinhold Bertlmann, Daniela Bortoletto, Nicolas Gisin, Michele Grossi, Jan Jakubek, Steffen Kappler, Alessandra Lombardi**

CERN | 70 YEARS / ANS CERN

**Luciano Musa**

project leader CERN70

**Ana Godinho**

Head of Communications, CERN

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SEASON 2024
CERN's 70th Anniversary

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Plus d'informations et inscription trois semaines avant chaque événement sur **visit.cern**

# Programme of Events

**Unveiling the Universe**
30 January

**From particle physics to medicine**
7 March

**The virtuous circle of knowledge and innovation**
18 April

**CERN: an extraordinary human endeavour**
As part of the Cineglobe festival
19 May

**The case of the (still) mysterious Universe**
6 June

**Exploring farther: machines for new knowledge**
4 July

1954-2024
YEARS/ANS CERN

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