Unveiling our Universe at the CERN Large Hadron Collider



CERN is the world's biggest laboratory for nuclear and particle physics

Goal: to understand the most fundamental particles and laws of the Universe

Tapan Nayak

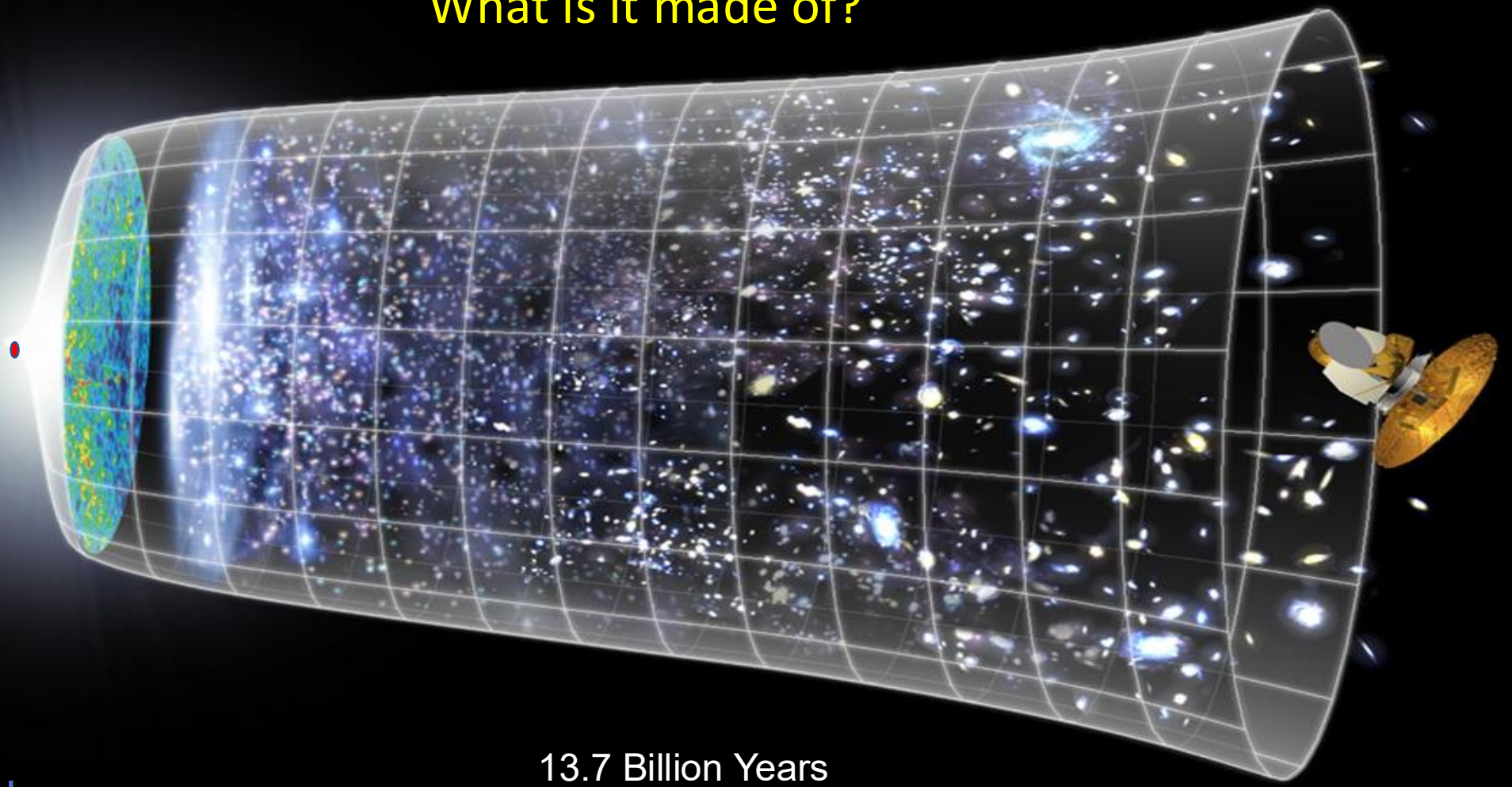
19 Nov 2026

Four pillars underpin CERN's mission



Our Universe ..... How did it start?

What is it made of?



Tracing the evolution of the Universe

ALICE

Accelerators

Recreating the early Universe, microseconds after the Big Bang



Quarks and electrons

Protons and neutrons form

Light nuclei form

Cosmic Microwave Background

Star and Galaxy Formation

Today

Big Bang

Quark-Gluon Plasma

Telescopes

Exploring the Universe from CMB to first galaxies

Time after the Big Bang

~ 1 microsecond

~ 10 microseconds

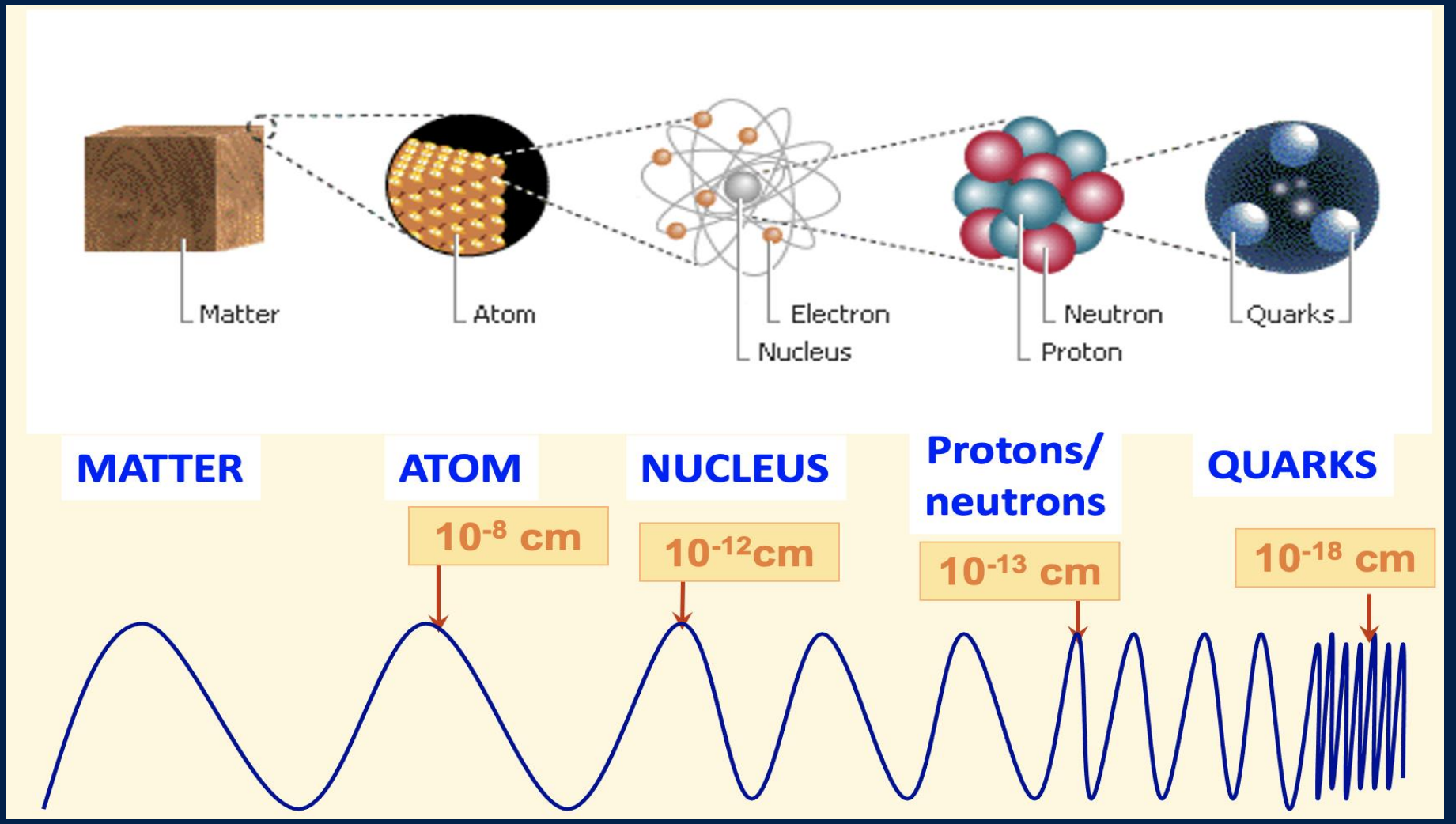
~ 3 min

380,000 years

~ 1 billion years

13.8 billion years

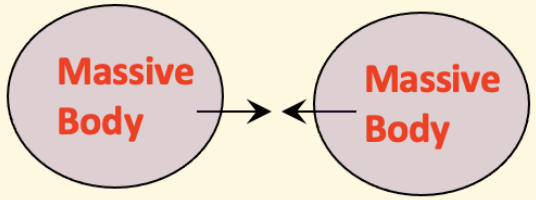
Structure of matter



$$\lambda = \frac{h}{p}$$

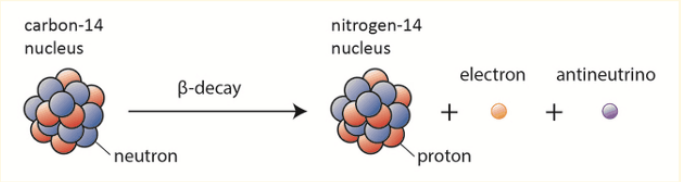
Fundamental forces of nature

Gravitational force



- Attractive
- Between two massive bodies
- Weak in nature (weakest force)
- Very long range (almost infinite)

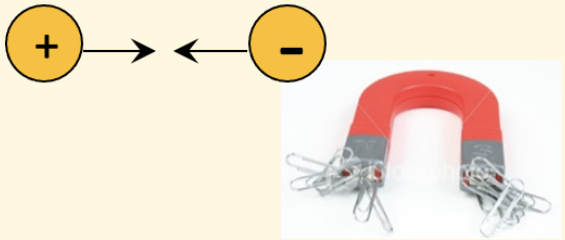
Weak force



Example: beta decay

- Weak in nature
- Short range
- Between fundamental particles

Electromagnetic force



- Between electric or magnetic charges
- stronger force with long range
- Attractive or Repulsive

Strong force

Holds the atomic nucleus,

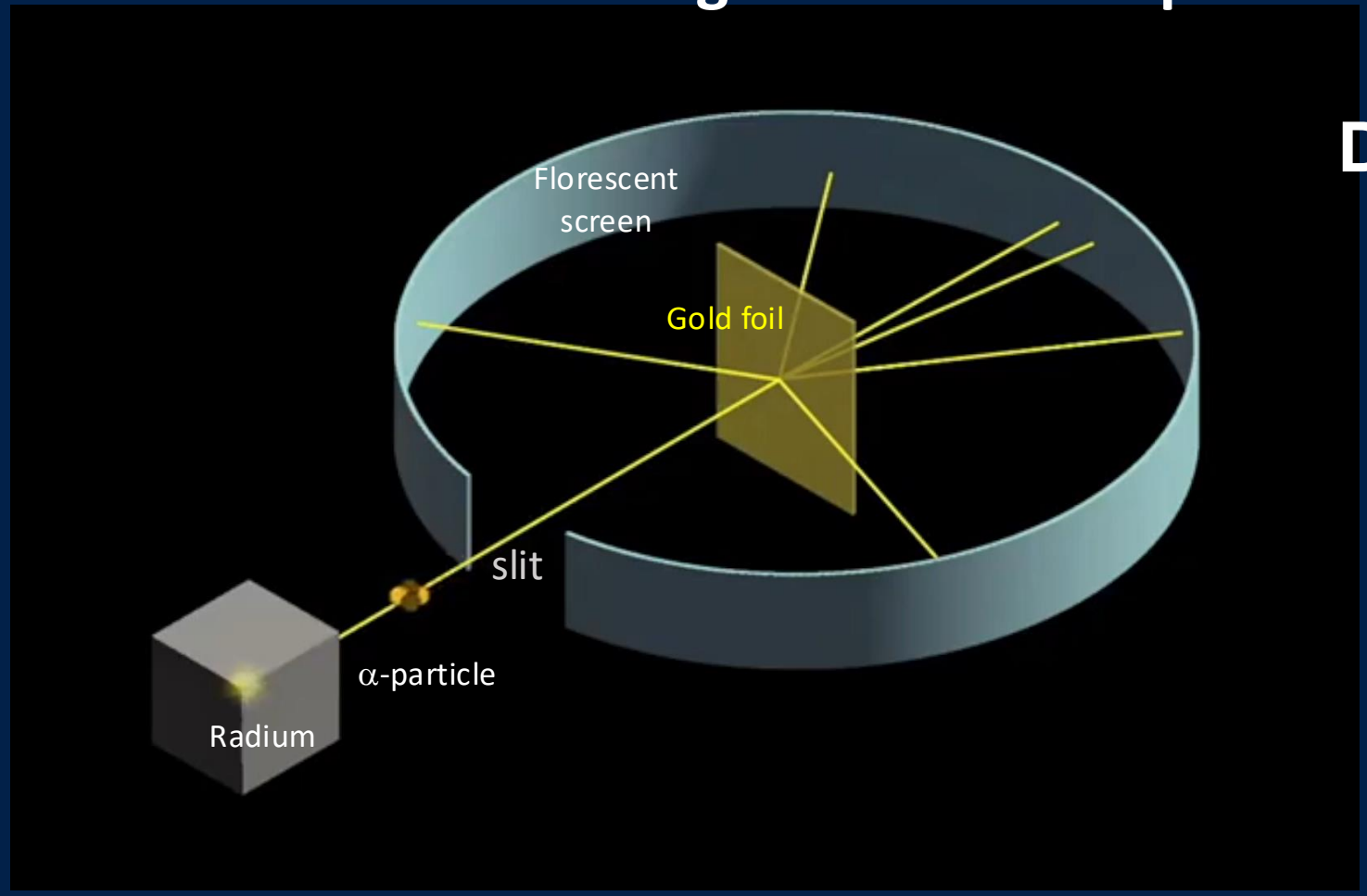
Binds quarks together

- Strongest and short range 10^{-13} cm
- Basically attractive

1911: The Rutherford gold foil experiment

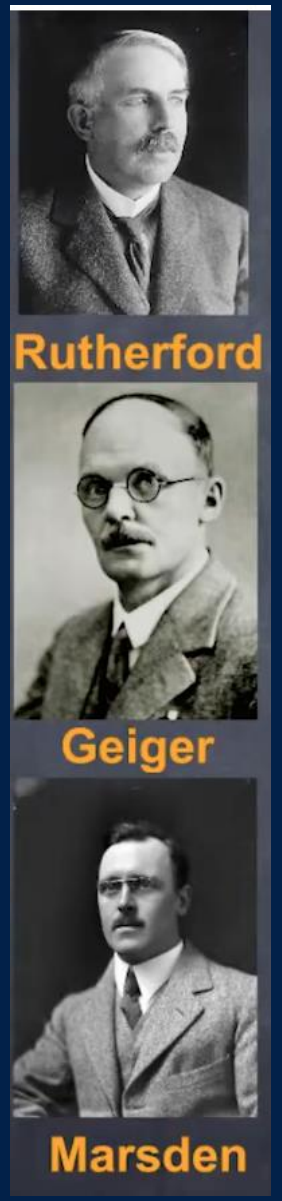
Rutherford - Geiger–Marsden experiment, 1909

Elastic scattering experiment

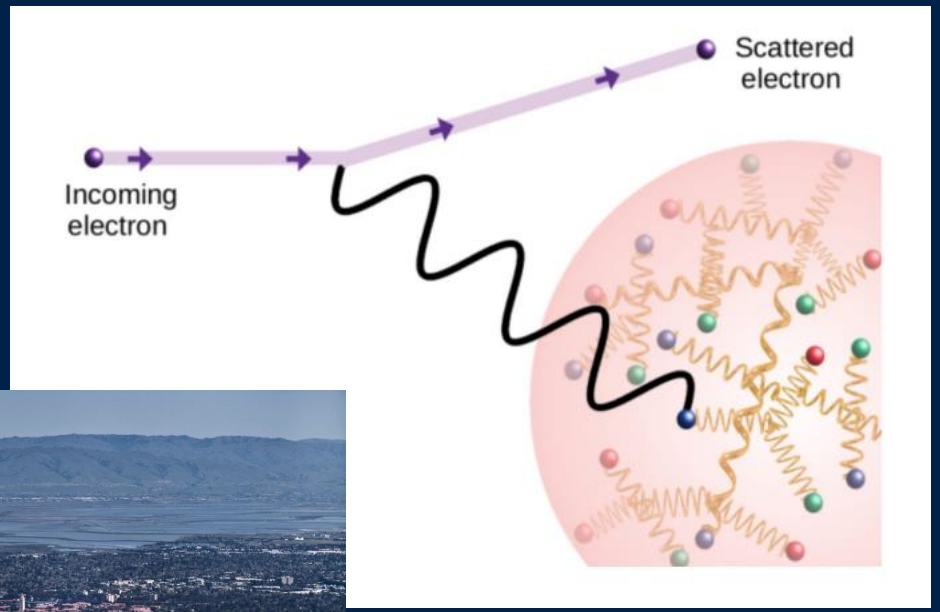


Discovery of nucleus

In 1911: Earnest Rutherford postulated that atoms have their positive charge concentrated in a very small nucleus, and thereby pioneered the Rutherford model, or planetary model of the atom, through his discovery and interpretation of the Rutherford scattering in his gold foil experiment.

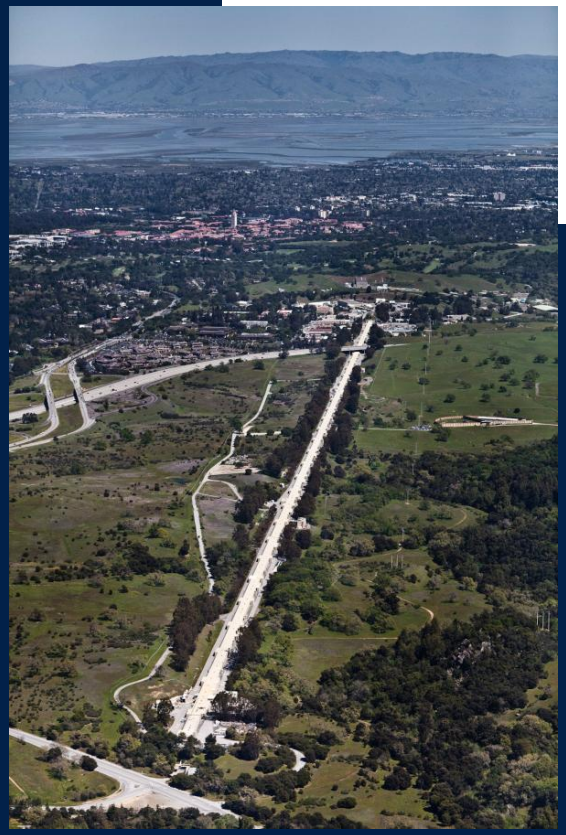


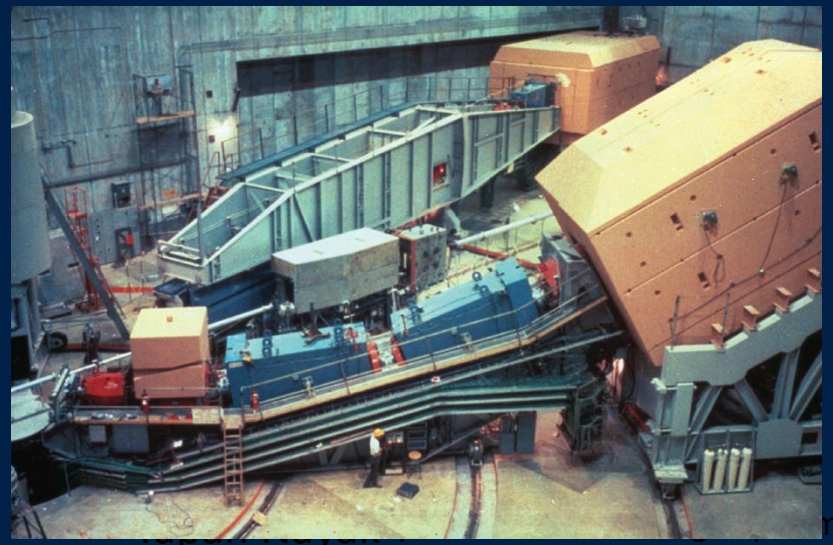
1967-72: SLAC-MIT Deep Inelastic Experiment



Discovery of quarks

- SLAC experiments showed: scattering inconsistent with a smooth charge distribution.
- The proton isn't a smooth ball of charge - it's made up of discrete point-like constituents – quarks.
- Data exhibited scaling behaviour (Bjorken scaling), predicted by Feynman's parton model.
- **Kendall, Friedman & Taylor - Nobel Prize in Physics, 1990.**





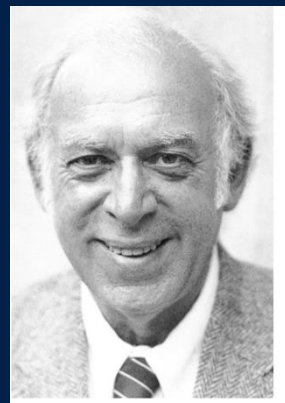


Photo: Donna Coveney, MIT.
Nobel Foundation archive
Jerome I. Friedman

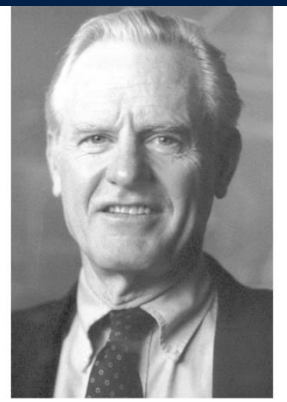


Photo from the Nobel Foundation archive.
Henry W. Kendall

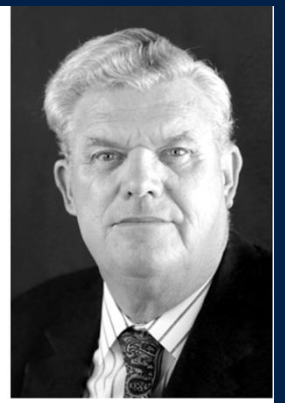
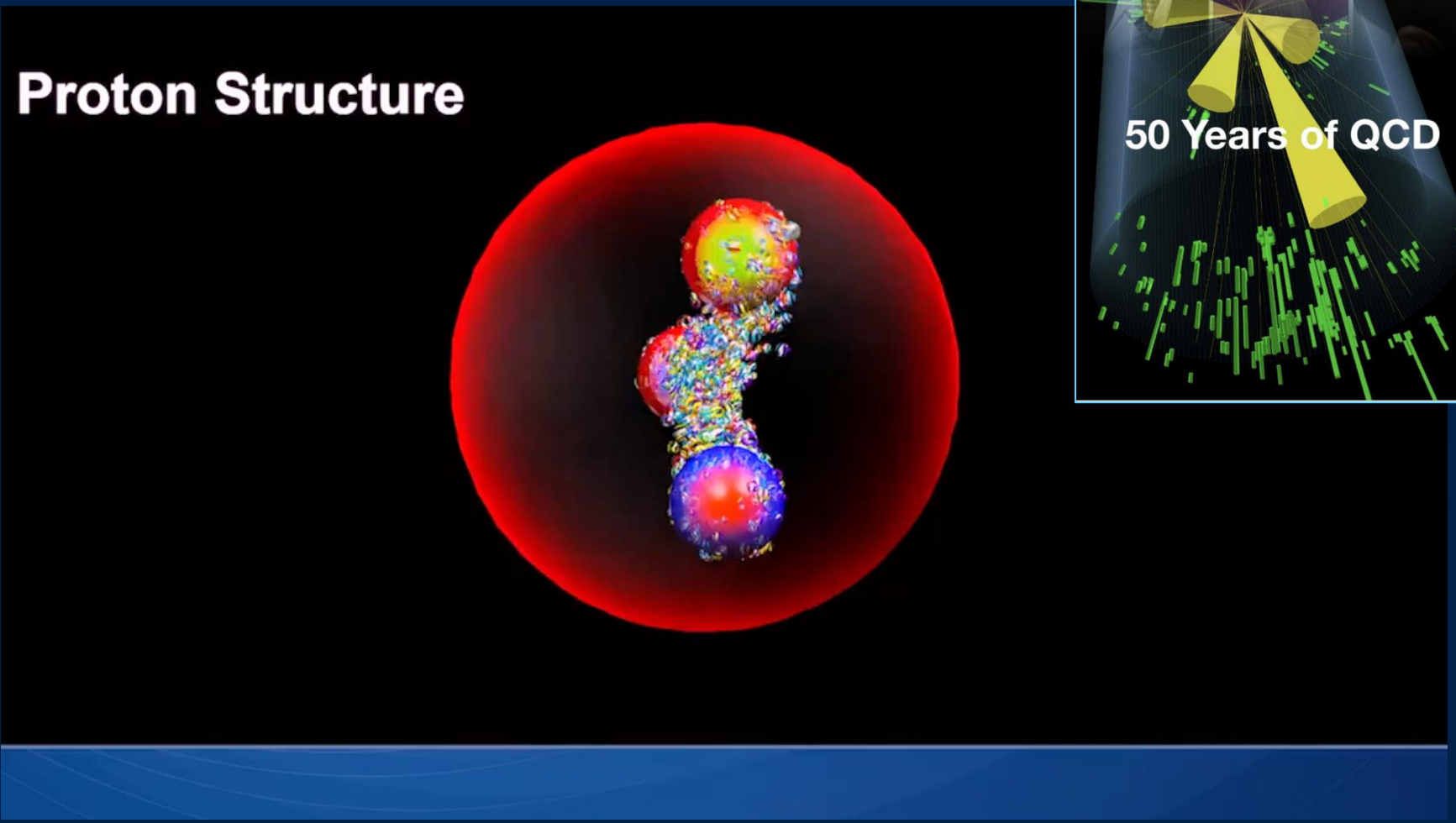


Photo: T. Nakashima
Richard E. Taylor
Prize share: 1/3

1973-75: Quark confinement & Asymptotic freedom



1973: asymptotic freedom
D.J. Gross, F. Wilczek, H.D. Politzer

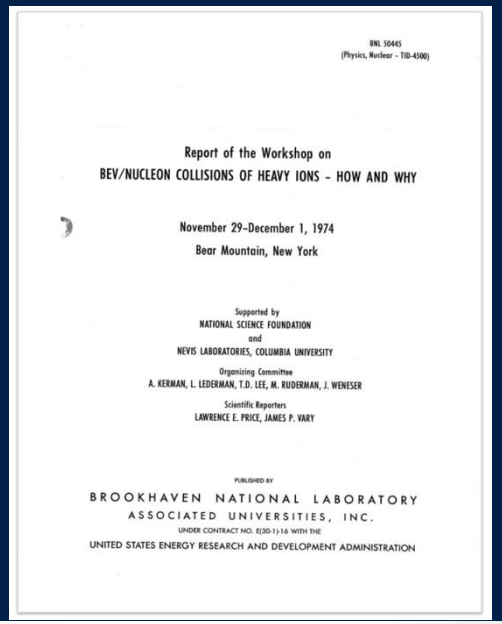
1975: asymptotic QCD and deconfinement
N. Cabibbo and G. Parisi;
J. Collins and M. Perry

Nobel Prize 2004



1974: Bear Mountain Workshop: 29 Nov – 1 Dec

"GeV/nucleon Collisions of Heavy Ions: How and Why"



BNL 50445
(Physics, Nuclear - TID-4500)

Report of the Workshop on
BEV/NUCLEON COLLISIONS OF HEAVY IONS - HOW AND WHY

November 29-December 1, 1974
Bear Mountain, New York

Supported by
NATIONAL SCIENCE FOUNDATION
and
NEVIS LABORATORIES, COLUMBIA UNIVERSITY

Organizing Committee
A. KERMAN, L. LEDERMAN, T.D. LEE, M. RUDERMAN, J. WENESER

Scientific Reporters
LAWRENCE E. PRICE, JAMES P. VARY

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UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Organized by: A. Kerman, Leon Lederman, T.D. Lee, M. Ruderman, J. Weneser

T.D. Lee:
"It would be intriguing to explore new phenomena by distributing high energy or high nuclear matter over a relatively large volume."



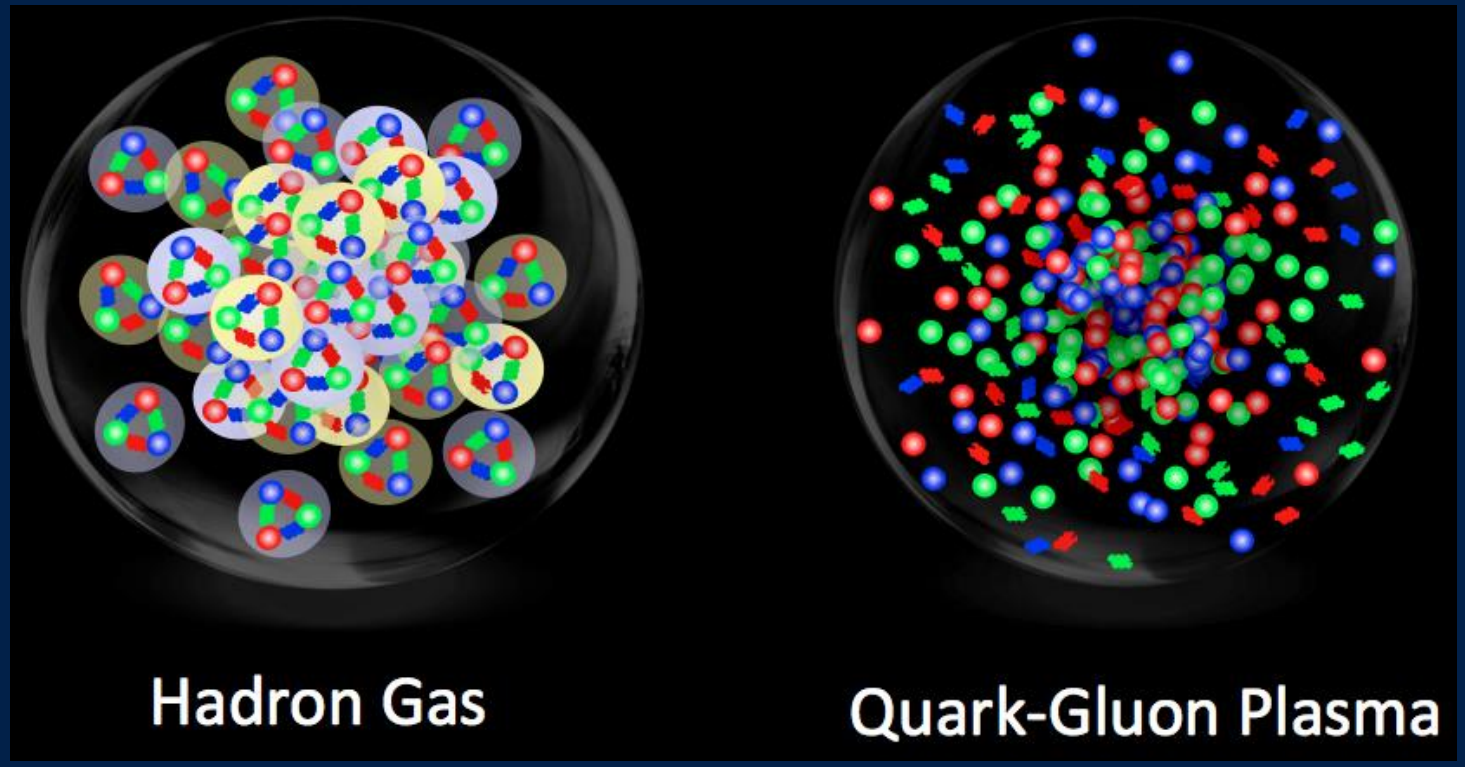
Anticipated the formation of a **quark–gluon plasma** and marked one of the earliest coordinated efforts to connect **nuclear physics with QCD**, bridging the transition from hadron studies to modern high-energy nuclear science.

1975:

- **J.C. Collins and M.J. Perry 1975**: "Superdense Matter: Neutrons or Asymptotically Free Quarks?"
  first mention of a deconfined transition in dense matter (quark soup)

- **Cabbibo and Parisi 1975**: "Exponential hadronic spectrum and quark liberation"
  interpreted the existence of the Hagedorn limiting temperature as a signal of a second-order phase transition between the hadronic and quark–gluon phases of matter.

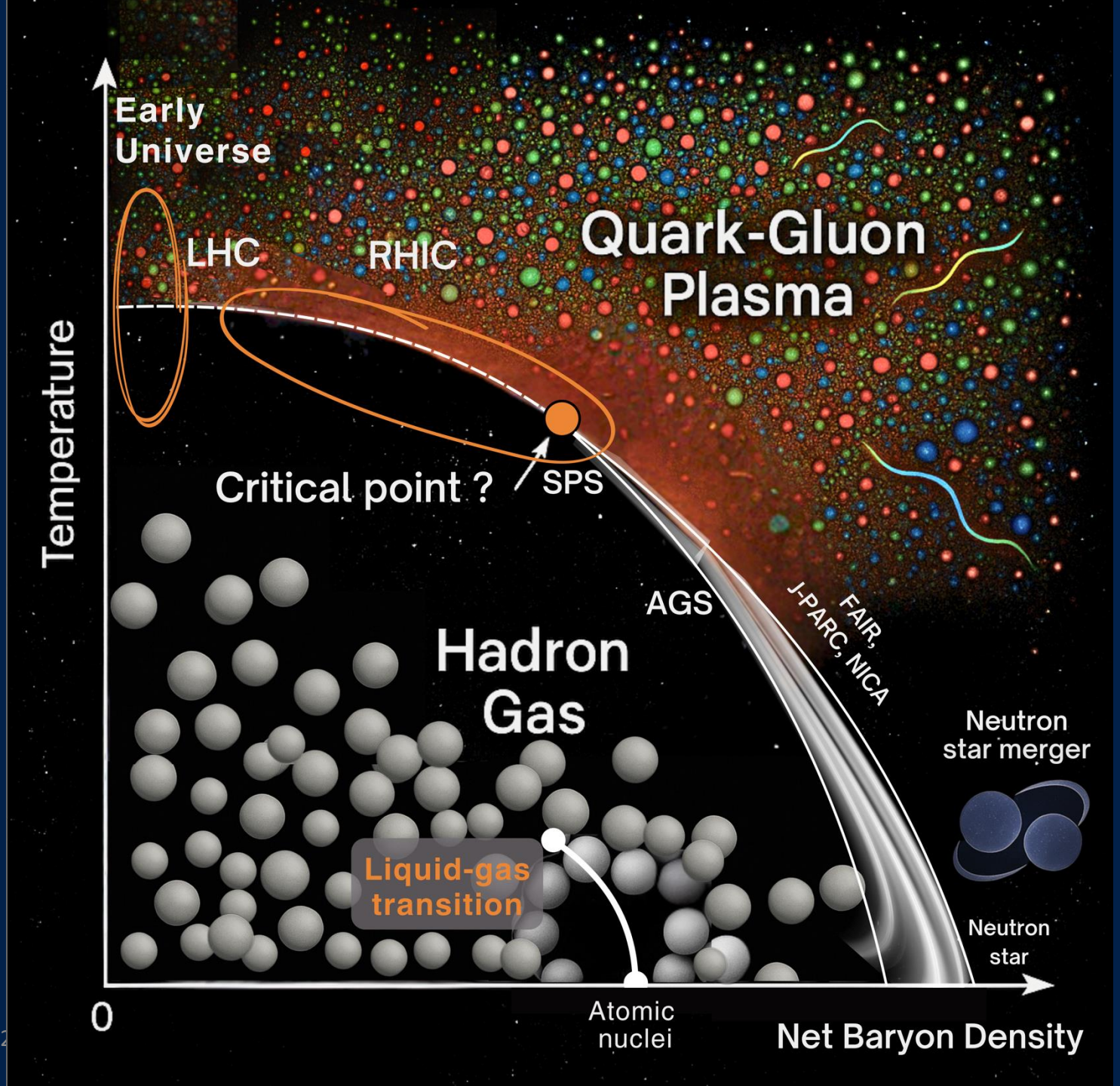
Quark-Gluon Plasma (QGP)



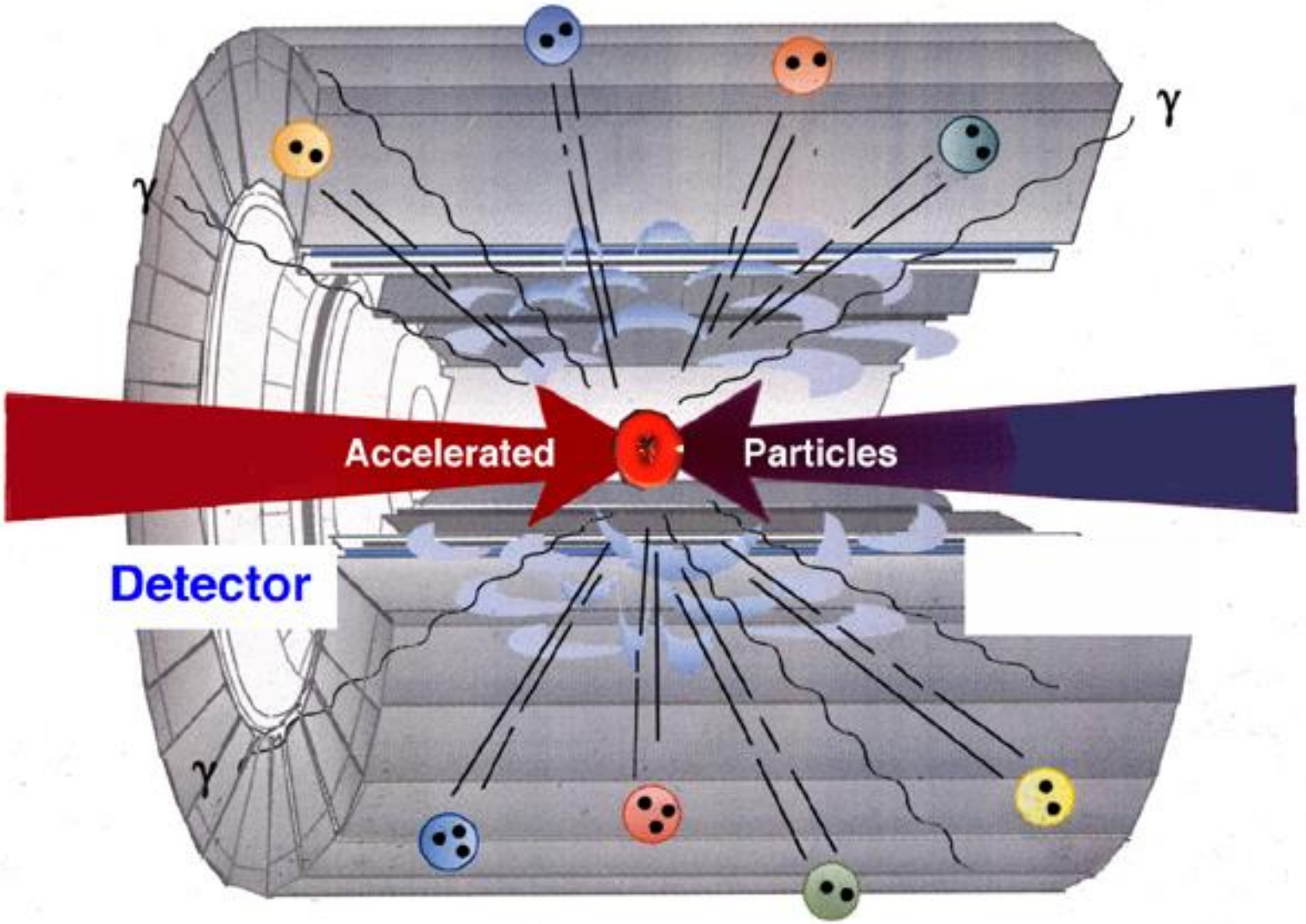
Hadron gas =>
- Heat up to very high temperature
- Apply extremely high pressure

=> the boundaries disappear forming a system of free quarks and gluons

Quark Gluon Plasma (QGP): (locally) thermally equilibrated state of matter in which quarks and gluons are deconfined from hadrons, so that color degrees of freedom become manifest over nuclear, rather than merely nucleonic, volumes.



QCD Phase Diagram



High Energy is needed to create new particles

Need High Energy Accelerator:

COLLIDER

$$E = mc^2$$

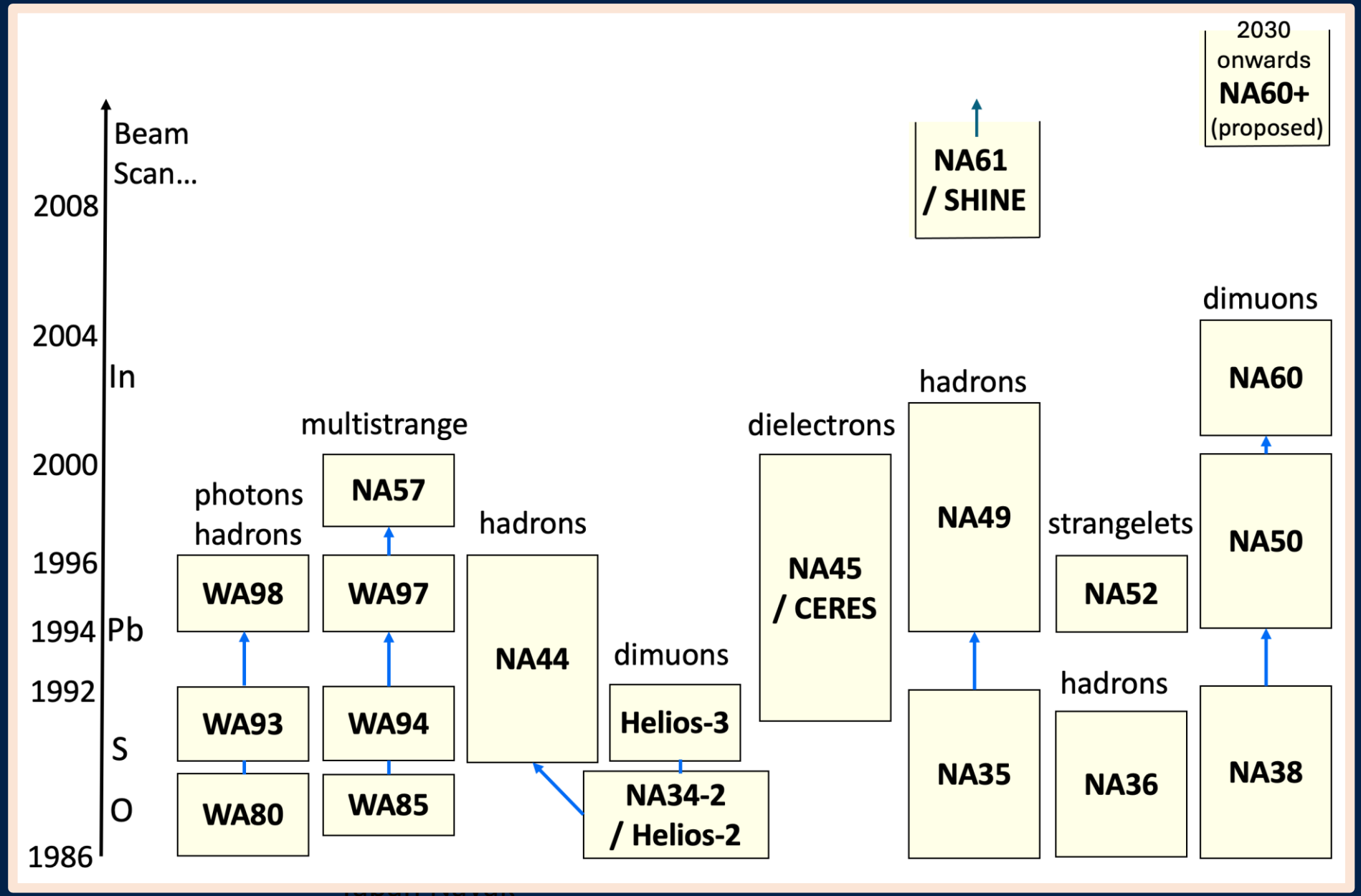
EXPERIMENTS

Heavy-ion collisions



- Take a high-mass atom: like Pb
- Take away the electron => Ion (***Heavy-ion***)
- ***Accelerate the Ion*** to almost the speed of light
- ***Collide the Ions => Create the Little Bang***
- Study the aftermath by specialized detector systems which surround the collision point **=> *Experiment***

Experiments at the CERN - SPS



2000: New State of Matter created at CERN

C

SPECIAL SEMINAR

TITLE : A New State of Matter:
Results from the CERN Lead-Beam Programme
TIME : Thursday 10 February at 09.30 hrs
PLACE : Council Chamber, bldg 503

ABSTRACT

This special seminar aims at an assessment of the results from the heavy ion programme with lead ion beams at CERN which was started in 1994. A series of talks will cover the essential experimental findings and their interpretation in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma.

Ulrich Heinz (CERN)
Making Quark-Gluon Matter in Relativistic Nuclear Collisions

Louis Kluberg (IN^2P^3)
The J/ψ suppression pattern observed in Pb-Pb collisions ions: a signature for the production of a new state of matter.

Johanna Stachel (University of Heidelberg)
Virtual and real photons radiated by the cooling and hadronizing fireball.

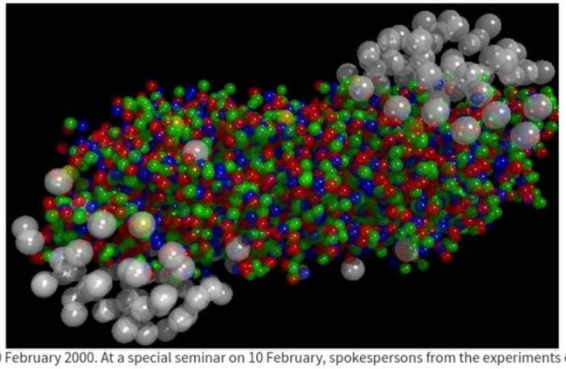
Reinhard Stock (University of Frankfurt)
Hadron Signals of the Little Bang.

Emanuele Quercigh (CERN)
Strange signals of a new state of matter from nuclear collisions at SPS.

Luciano Maiani (Director General, CERN)
Summary.

New State of Matter created at CERN

10 FEBRUARY, 2000



Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Geneva, 10 February 2000. At a special seminar on 10 February, spokespersons from the experiments on CERN[1]'s Heavy Ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

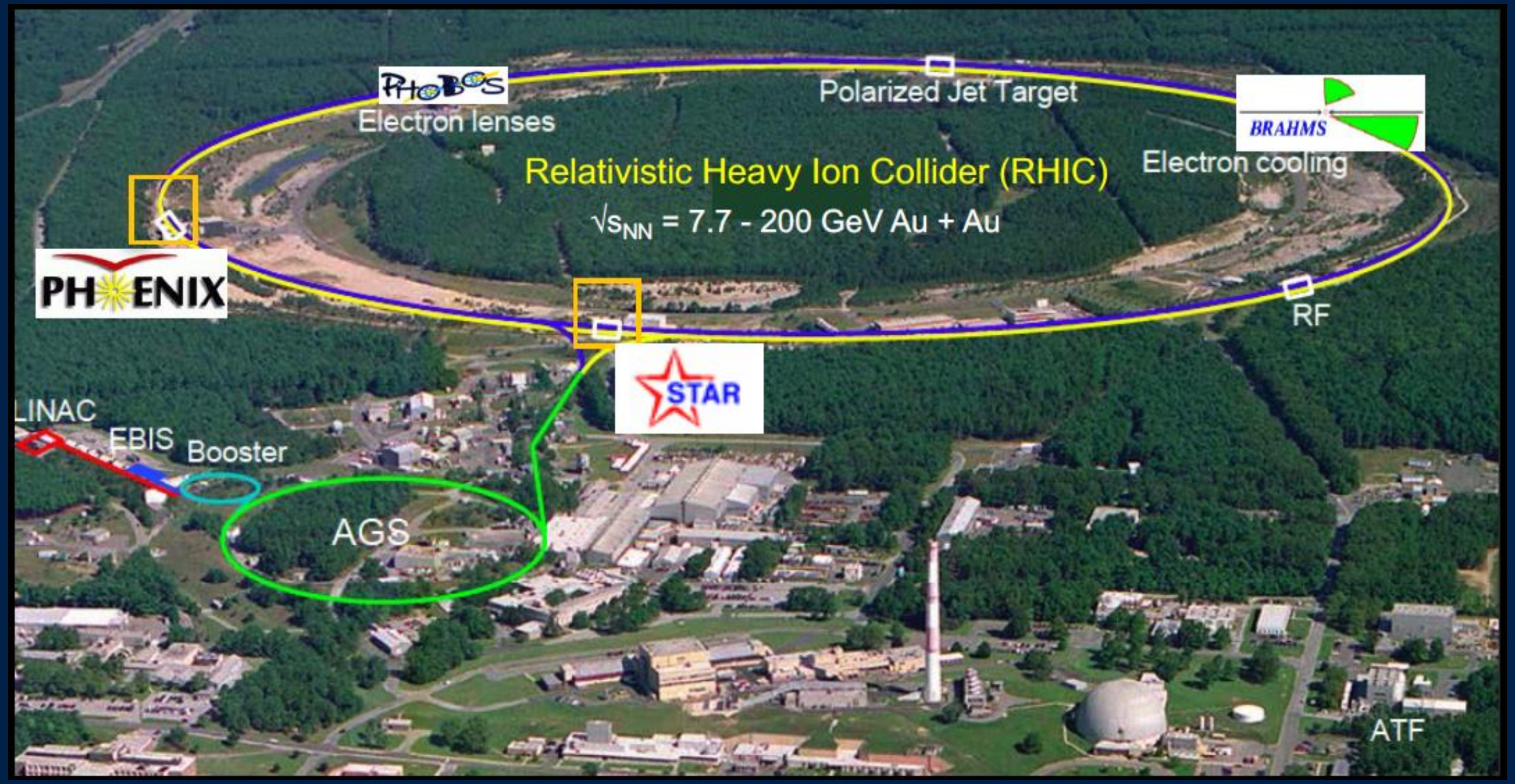
Professor Luciano Maiani, CERN Director General, said *"The combined data coming from the seven experiments on CERN's Heavy Ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN's Large Hadron Collider."*

First Signals of deconfinement

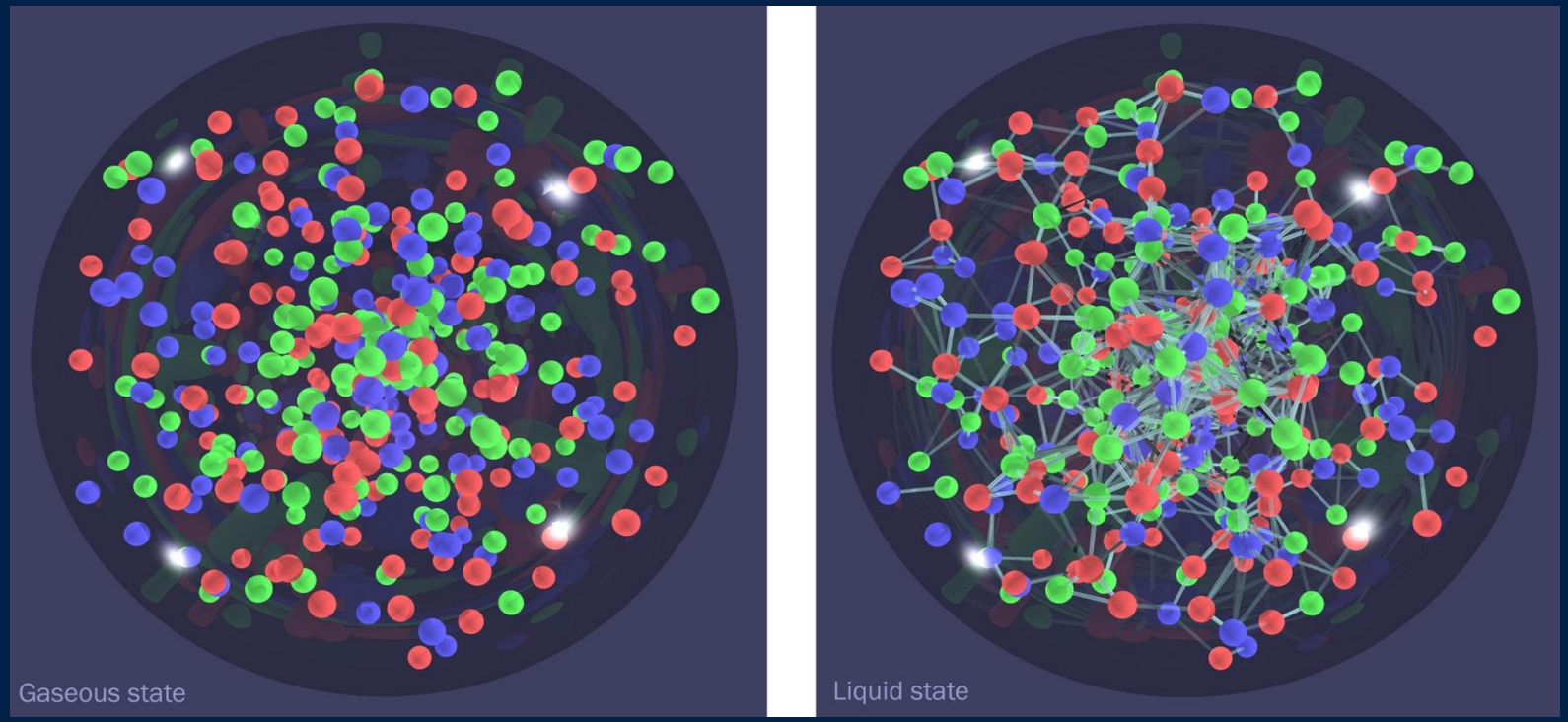
The experimental findings from the SPS had been interpreted in terms of the creation of a new state of matter at about 20 times the energy density inside atomic nuclei. It also suggested the evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stage.

Luciano Maiani, CERN Director General during that time, noted that "the challenge now passes to the **Relativistic Heavy Ion Collider (RHIC)** at the Brookhaven National Laboratory and later to CERN's **Large Hadron Collider (LHC)**".

The RHIC complex at BNL



2005: RHIC scientists serve up ‘Perfect’ liquid



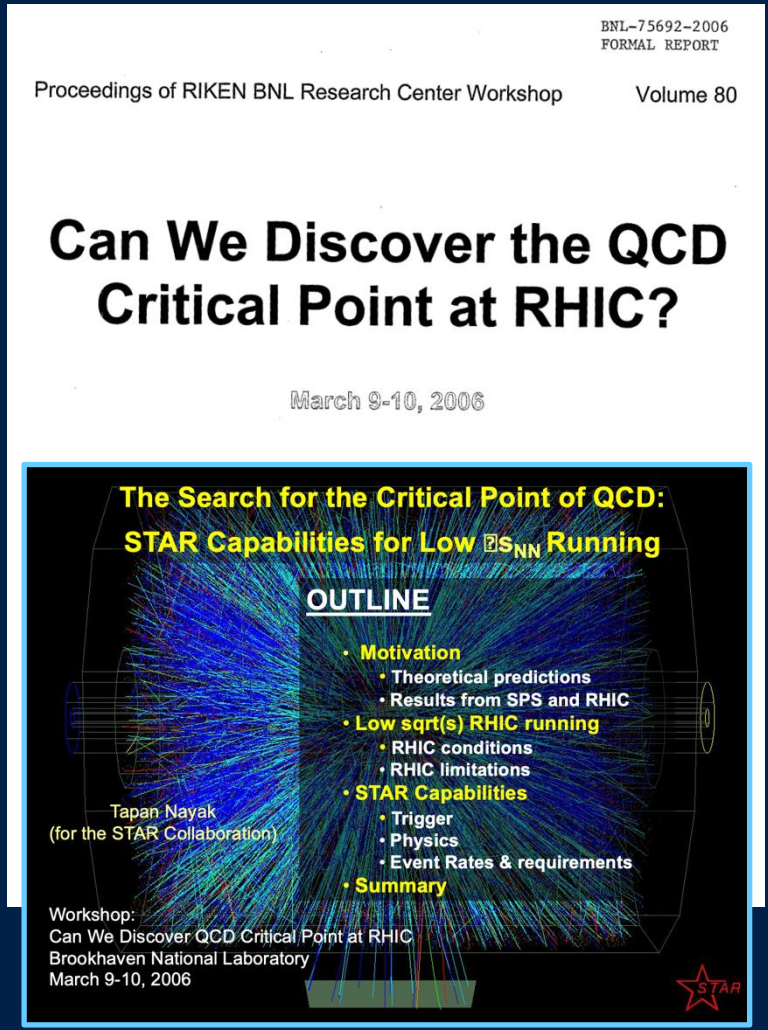
Gaseous QGP

QGP liquid state

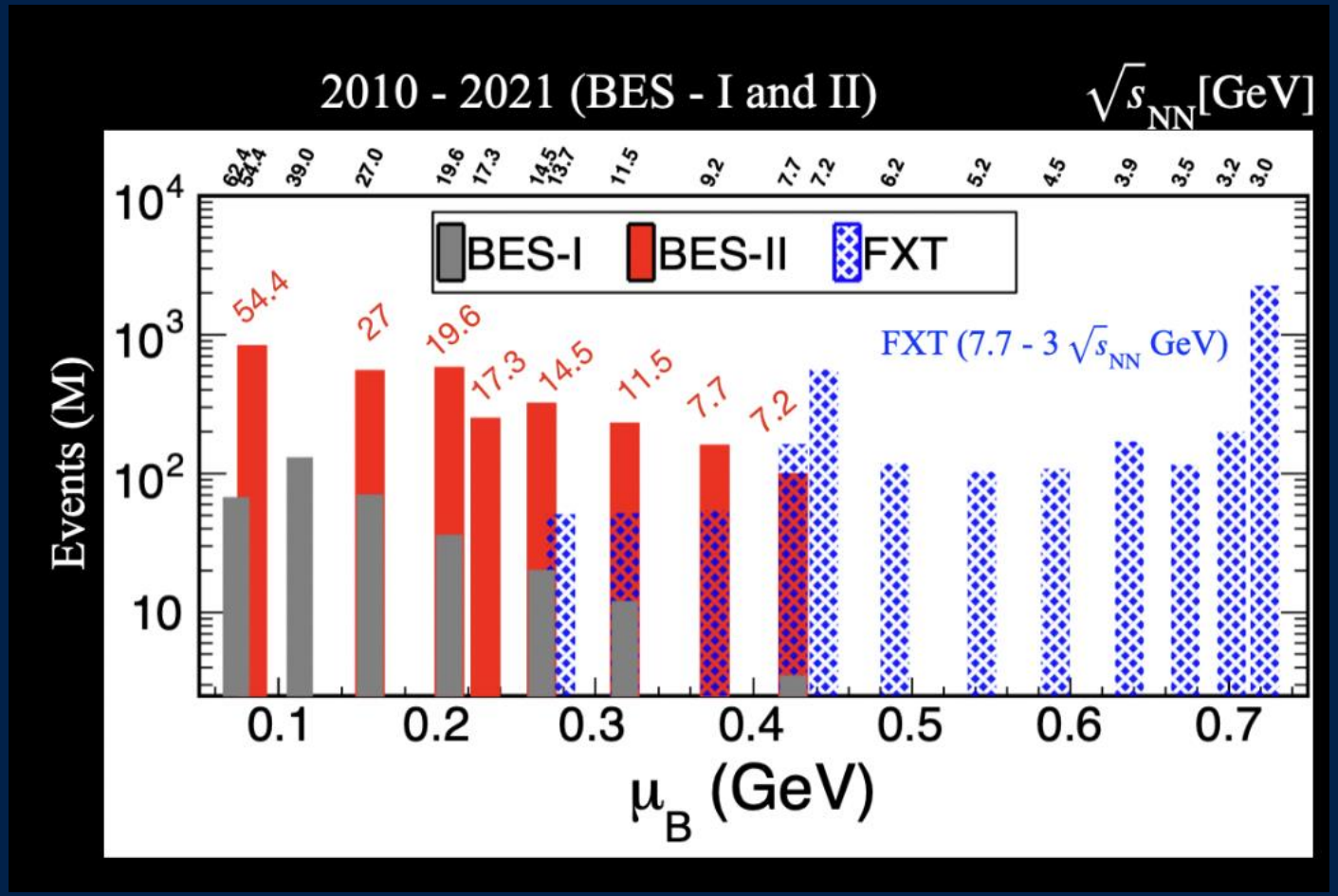
The green "force lines" and collective motion show the much higher degree of interaction and flow among the quarks in what is now being described as a nearly "perfect" liquid.

- RHIC collaborations announced the creation of the quark-gluon plasma - a strongly interacting, nearly perfect liquid of quarks and gluons.
- The QGP shows collective flow, early thermalization, and energy loss of partons through jet quenching.
- Unlike a weakly interacting gas, the matter behaves as a strongly coupled liquid with extremely low viscosity, representing the most perfect fluid ever observed.

2006: Can We Discover the QCD Critical Point at RHIC?



2010 – 2021: RHIC Beam Energy Scan



RHIC Beam Energy Scan: mapping the QCD phase diagram and searching for signals of a critical point.

Tapan Nayak

Colliding protons (14 TeV),
Lead ions (5.5 TeV)

World's Most Powerful Accelerator:

The Large Hadron Collider



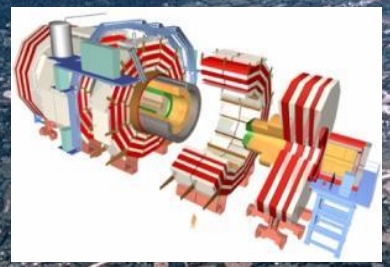
Colliding protons (14 TeV),
Lead ions (5.5 TeV)

World's Most Powerful Accelerator:

The Large Hadron Collider

Jura mountains

Lake Geneva

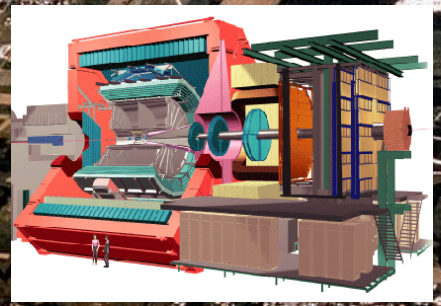


CMS

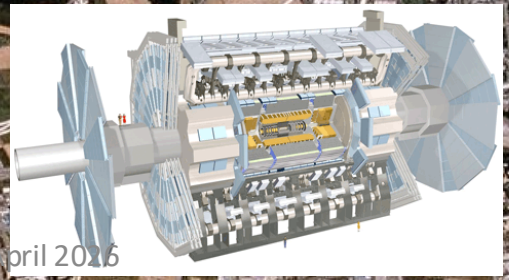


LHCb

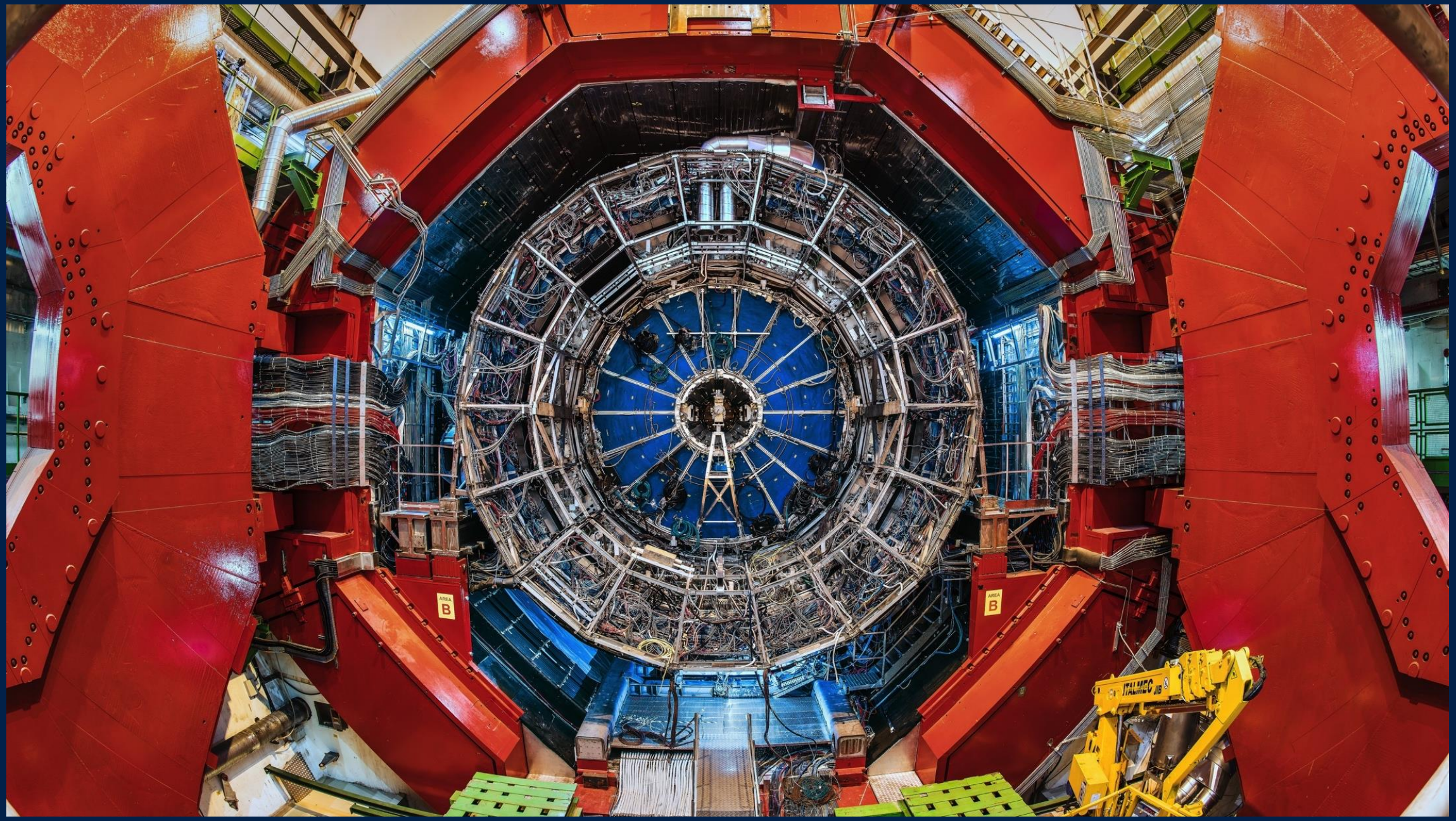
ATLAS



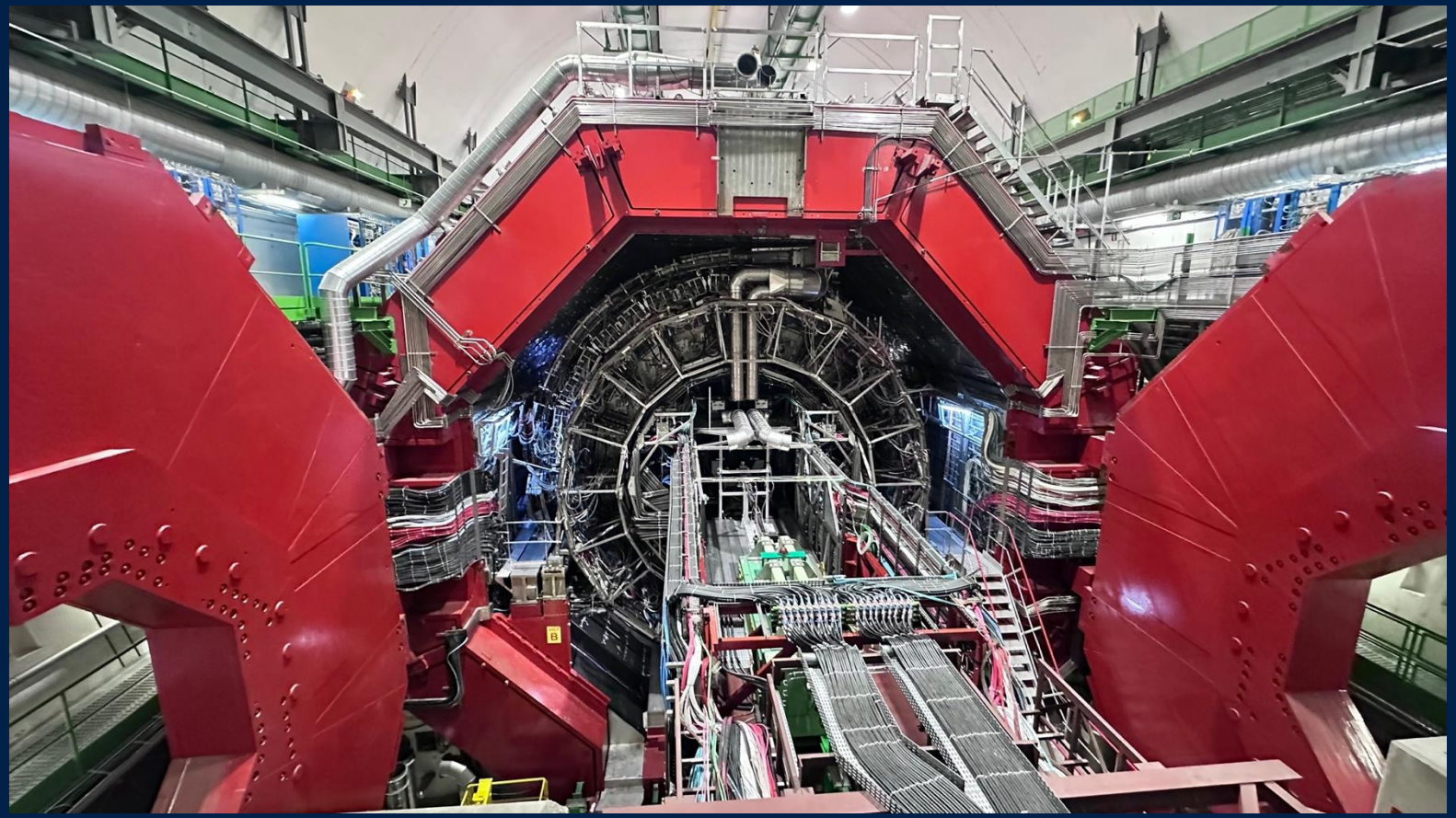
ALICE



ALICE at Point-2 of LHC



ALICE at Point-2 of LHC



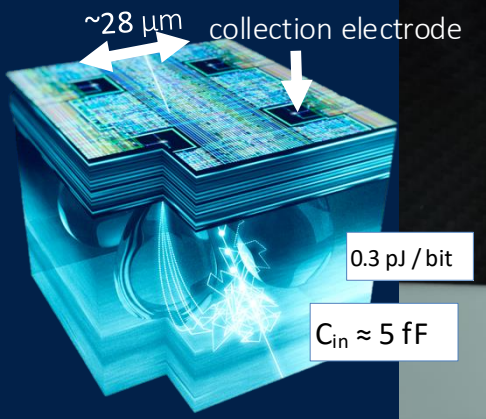
ALICE timeline

- 1992: Expression of interest
- 1996: Technical Proposal
- 1997: ALICE approval
- 2000 – 2007: construction
- 2002 – early 2008: Installation
- 2009 – 2018: physics data taking
- 2019 - 2021: phase I upgrades
- 2022 – 2033: physics data taking
- 2034 – 2035: phase IIb upgrades
- 2036 – 2041: physics data taking

Inner Tracking System (ITS2)

7 layers, 10 m^2 silicon

based on MAPS, 12.5 G pixels



0.3 pJ / bit

$C_{in} \approx 5$ fF

Q_{in} (MIP) ≈ 1300 e ⇨ V ≈ 40mV

0.36% X_0 per layer

pixel size:

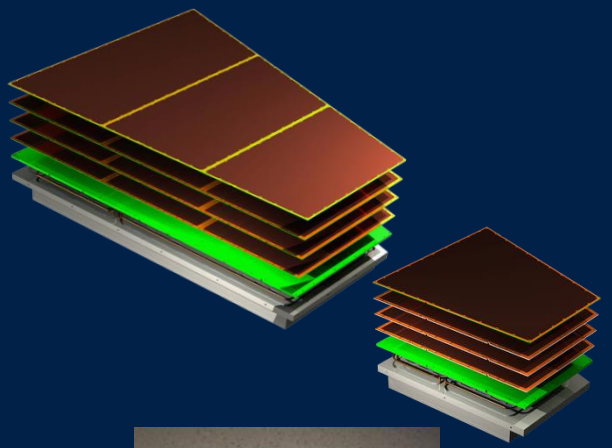
30 x 30 μm^2

beam pipe radius: 18mm

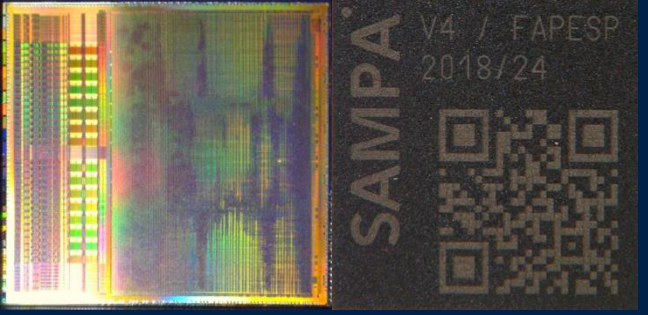
3x higher pointing resolution

TPC: Time Projection Chamber

with GEM detectors







SAMPA chip

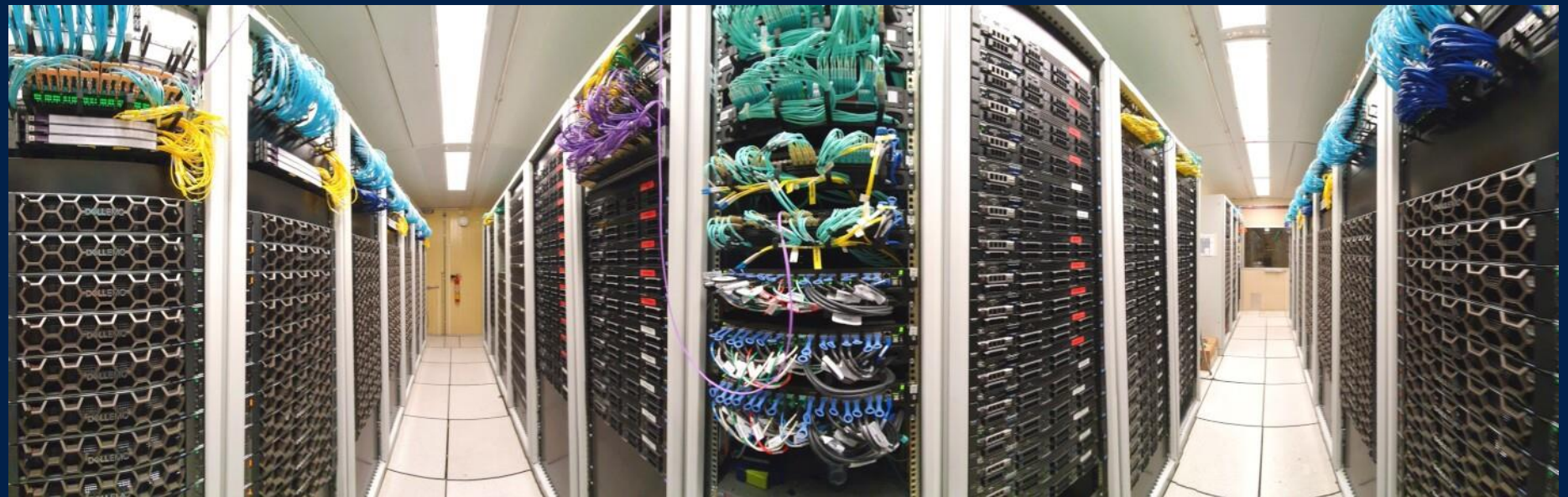
ALICE computing: 3.6 TeraBytes/s raw data —> up to 170 GBytes/s to disk

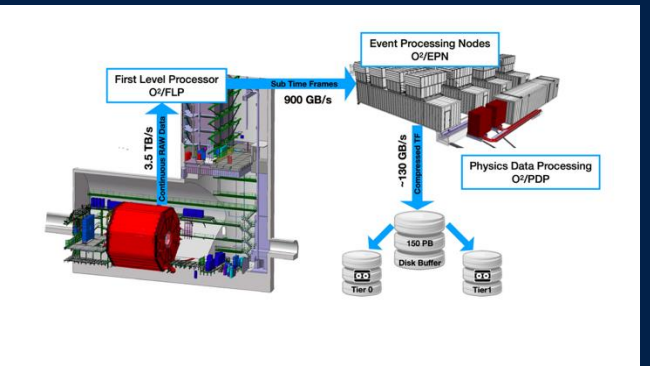
350 EPN servers
50k CPUs
2800 AMD GPUs
150 PetaBytes disk





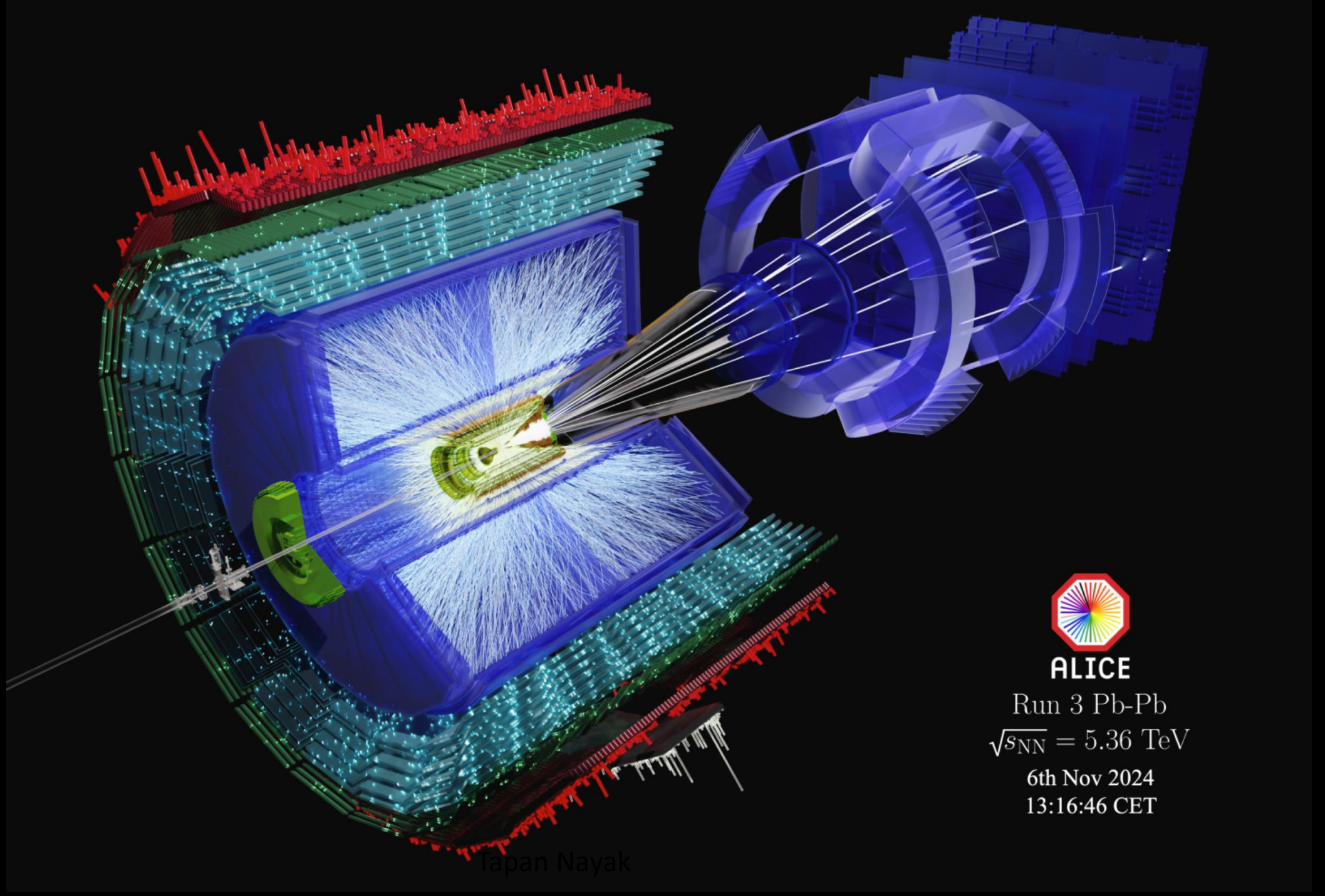
common readout unit
(world's largest FPGA)





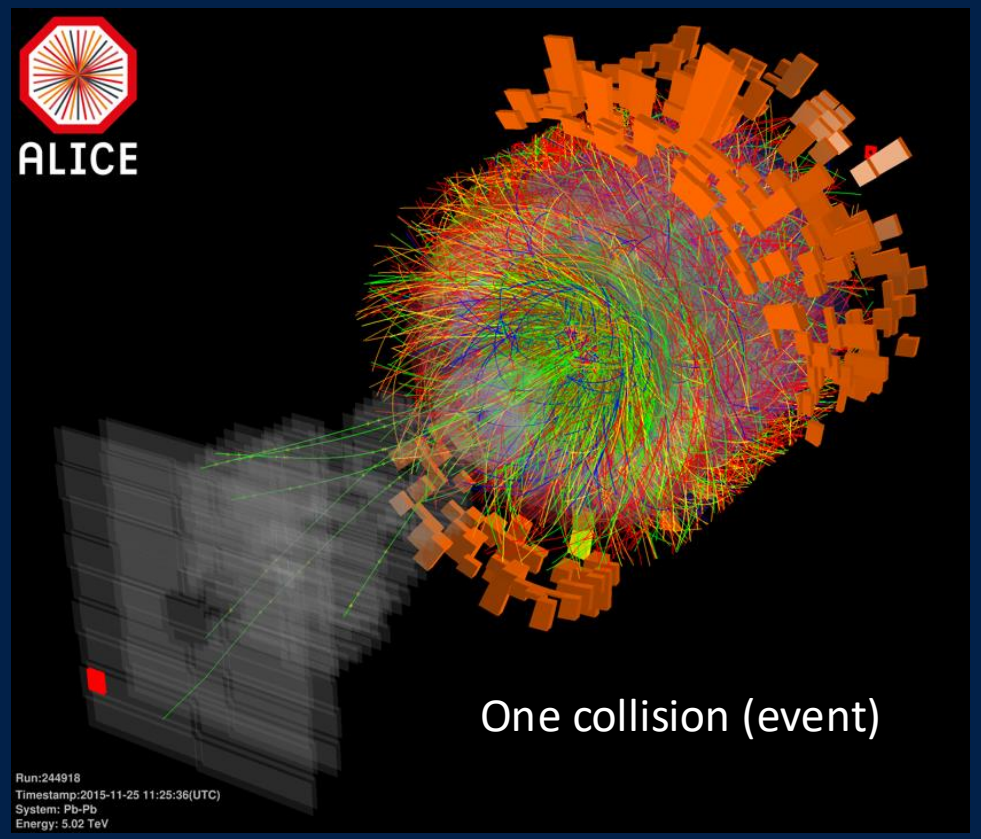
ALICE 实验控制中心




ALICE
Run 3 Pb-Pb
$\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
6th Nov 2024
13:16:46 CET

Tapan Nayak

Reconstructing the collision



One collision (event)

What has just happened?

- What particles were created?
- Where were they produced?
- What were the parent particles?

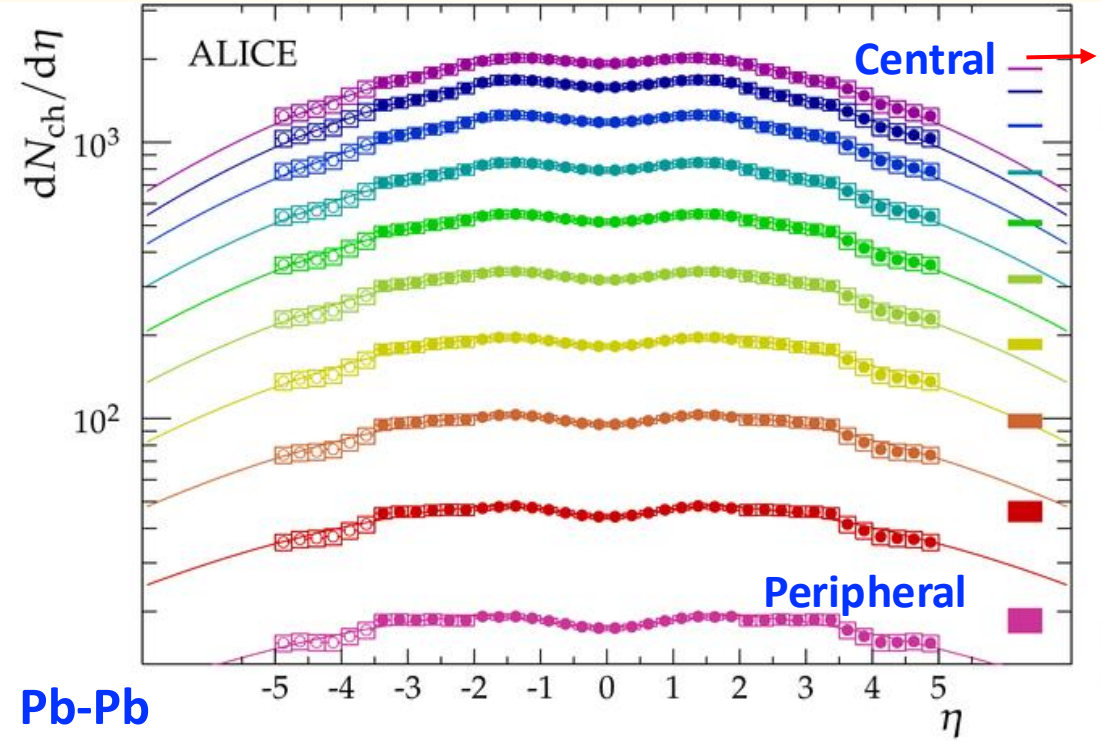
=> Online (live):

- Online data quality monitoring and calibrations.
- Using Triggers to keep events of interest and sends to storage.

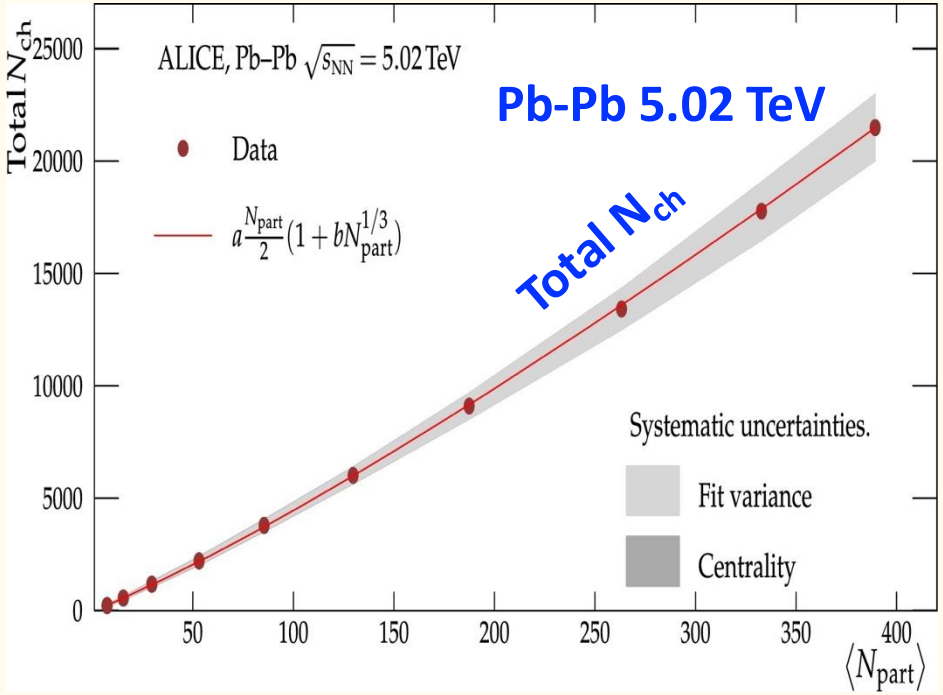
=> Offline: Event reconstruction:

- Vertexing
- Tracking
- Particle identification of each of the tracks

Charged particle multiplicity



~2000



Number of charged particles in one collision:

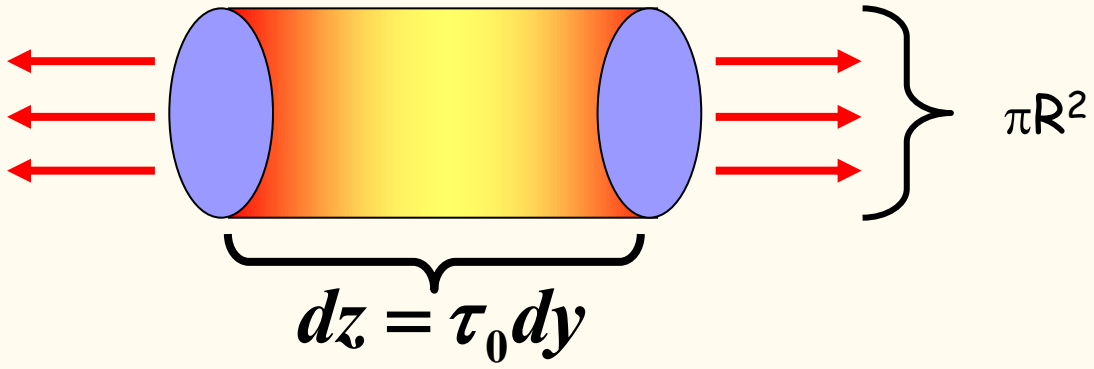
- Central collisions: 21400 ± 1300
- Peripheral collisions: 230 ± 38

Phys.Lett. B 772 (2017) 567577
Phys. Rev. Lett. 116 (2016) 222302

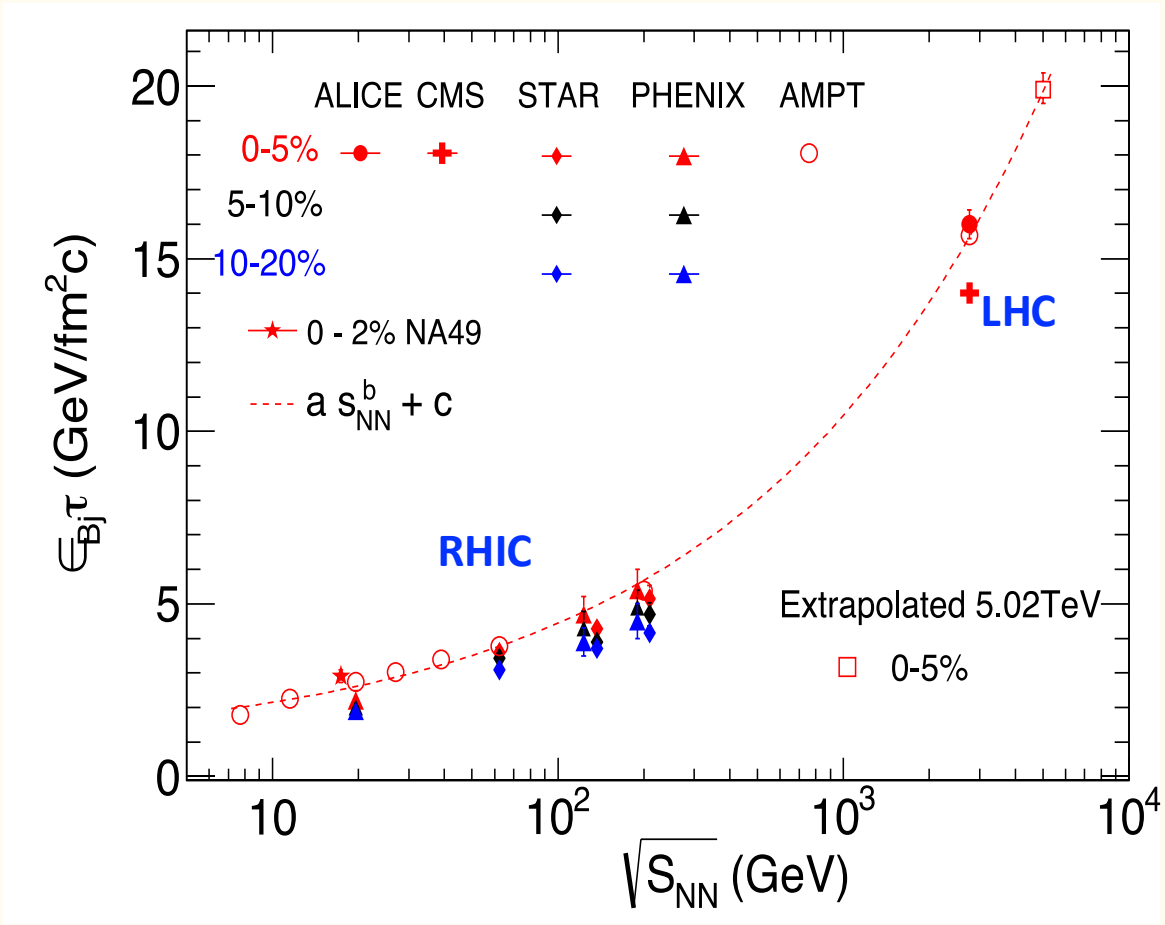
LARGE NUMBER OF PRODUCED PARTICLES

Particle density & Energy density

J. D. Bjorken, Phys. Rev. D 27, 140 (1983).



$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy} \approx \frac{1}{\pi R^2 \tau} < m_T > \frac{3}{2}\frac{dN_{ch}}{d\eta}$$



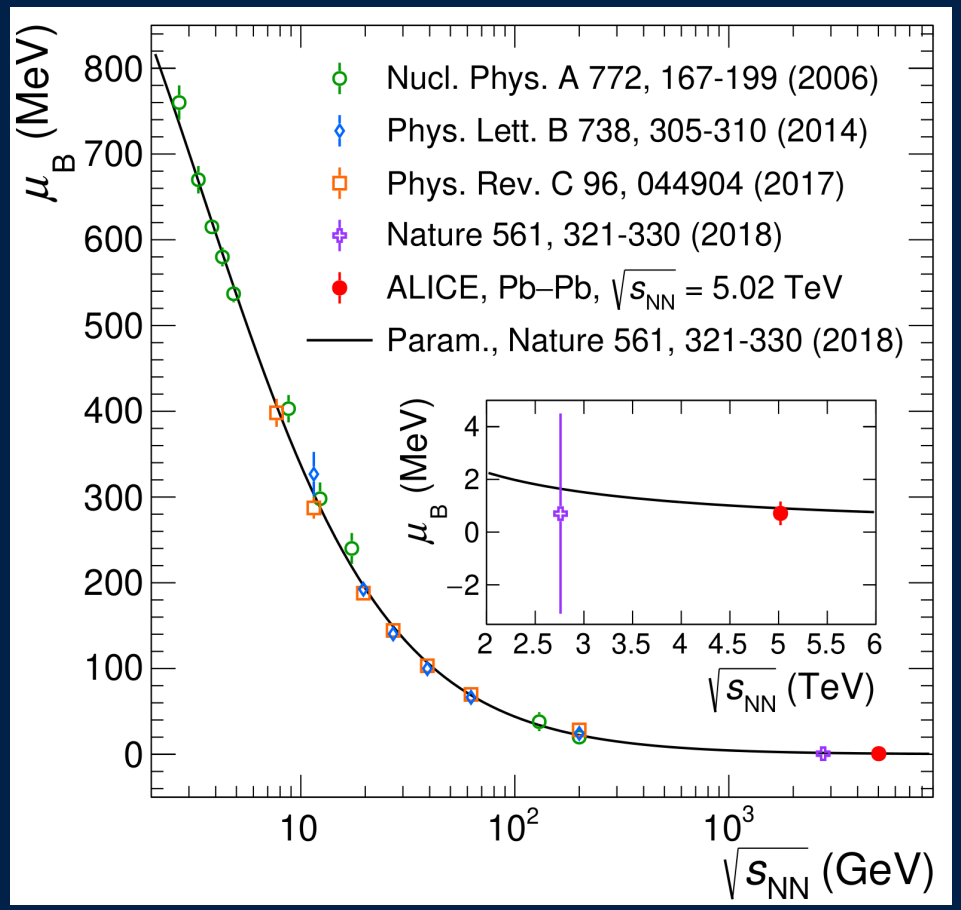
ε.τ ~ 16 GeV/fm²c

LARGEST ENERGY DENSITIES EVER ACHIEVED ….

S. Basu et al. PRC 93 (2016) 064902
R. Sahoo et al. Adv. in HEP, Vol. 2015

Balancing matter and anti-matter: obtaining μ_B

ALICE: Phys. Rev. Lett. 133 (2024) 092301



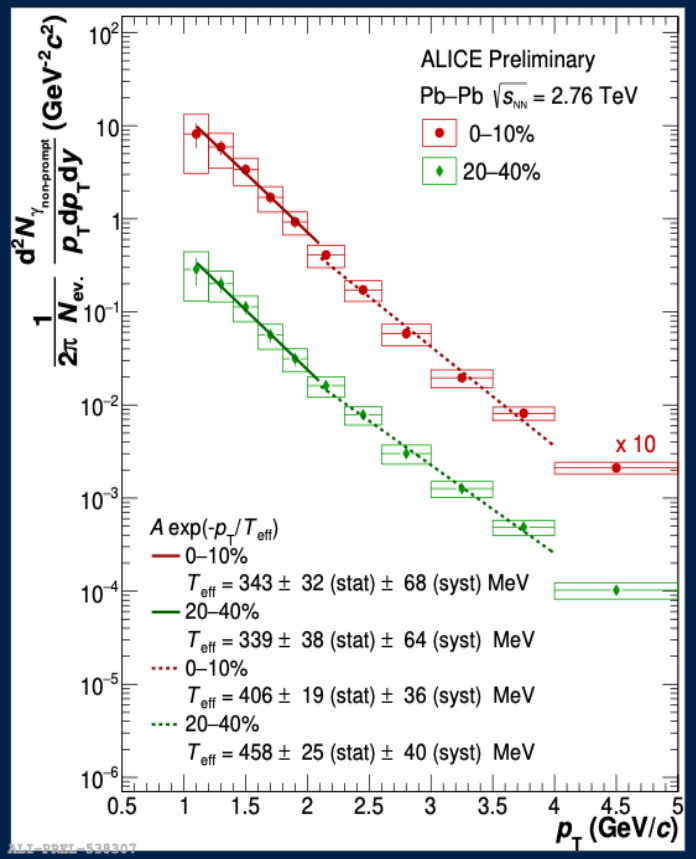
- The collision starts with matter only, carrying a large amount of baryon number from the lead nuclei.
- During the collision process, incoming lead nuclei interact while penetrating each other. The valence quarks that carry most of the baryon number are at large rapidities (close to the beam direction).
- The **resulting extreme energy density converts gluons into quark–antiquark pairs in equal numbers**, forming a nearly matter–antimatter–symmetric quark–gluon plasma.
- A small fraction of the incoming baryon number is stopped and transported to mid-rapidity, leaving most baryons moving forward and creating only a tiny matter–antimatter imbalance.

The medium created in lead–lead collisions at the LHC is nearly electrically neutral and baryon-number-free at mid-rapidity!

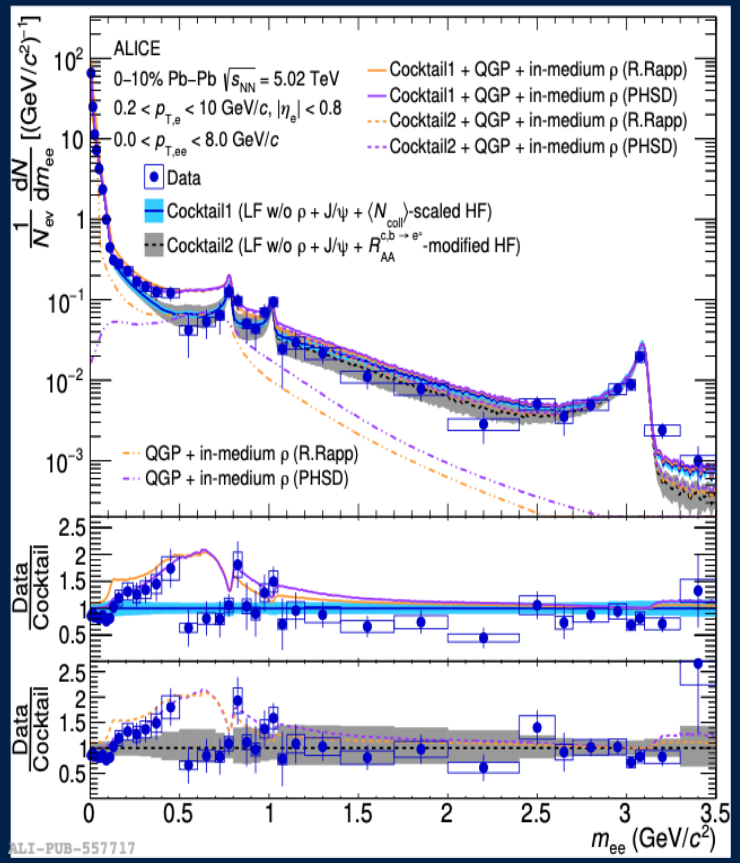
Tapan Nayak

Taking temperature: photons and dileptons

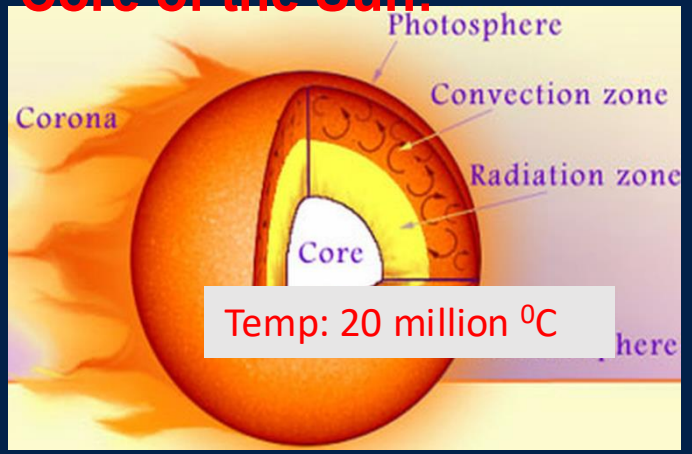
Direct photon excess spectrum



Dielectron mass spectrum



Core of the Sun:



Apparent (blue-shifted) temperature T ≈ 340 MeV

(1eV=11605K)

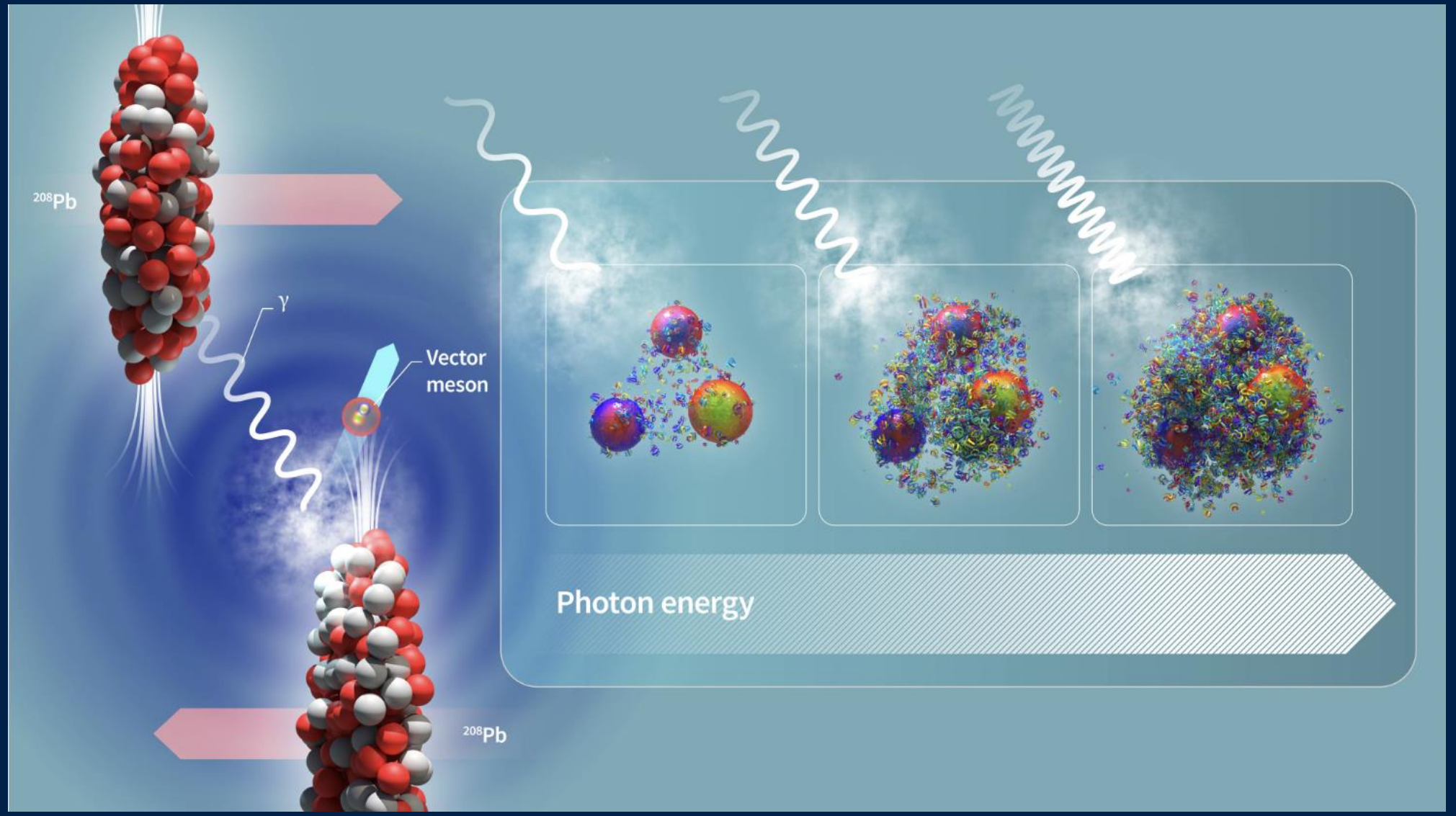
T_{eff} = 4 trillion Kelvin

Largest ever temperature reached in the lab ….

- Electromagnetic radiation **(real) photons** and **dielectrons (virtual photons)** measure the temperature of the QGP
- Challenging measurement: large background from hadronic decays

Shining light into the nucleus to probe its structure

Ultra-peripheral Collision

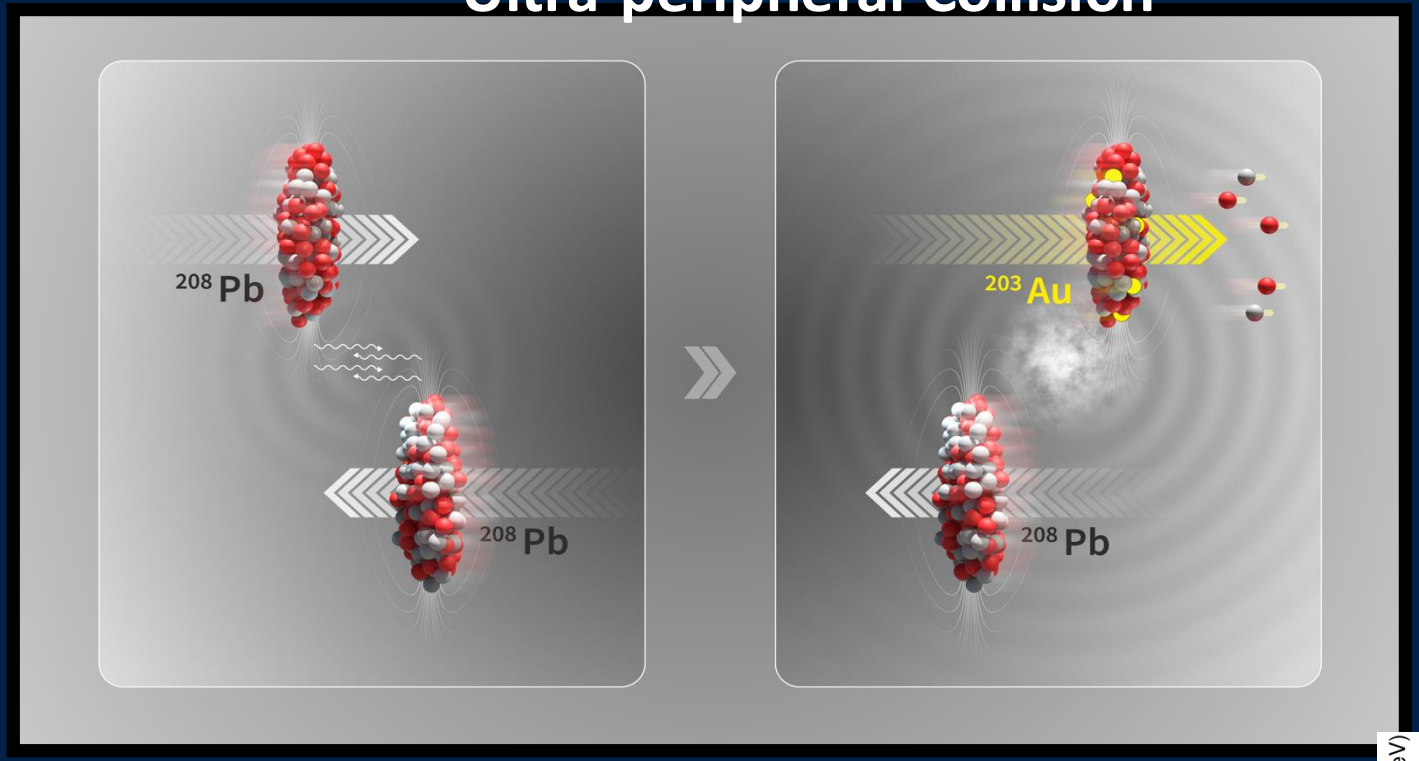


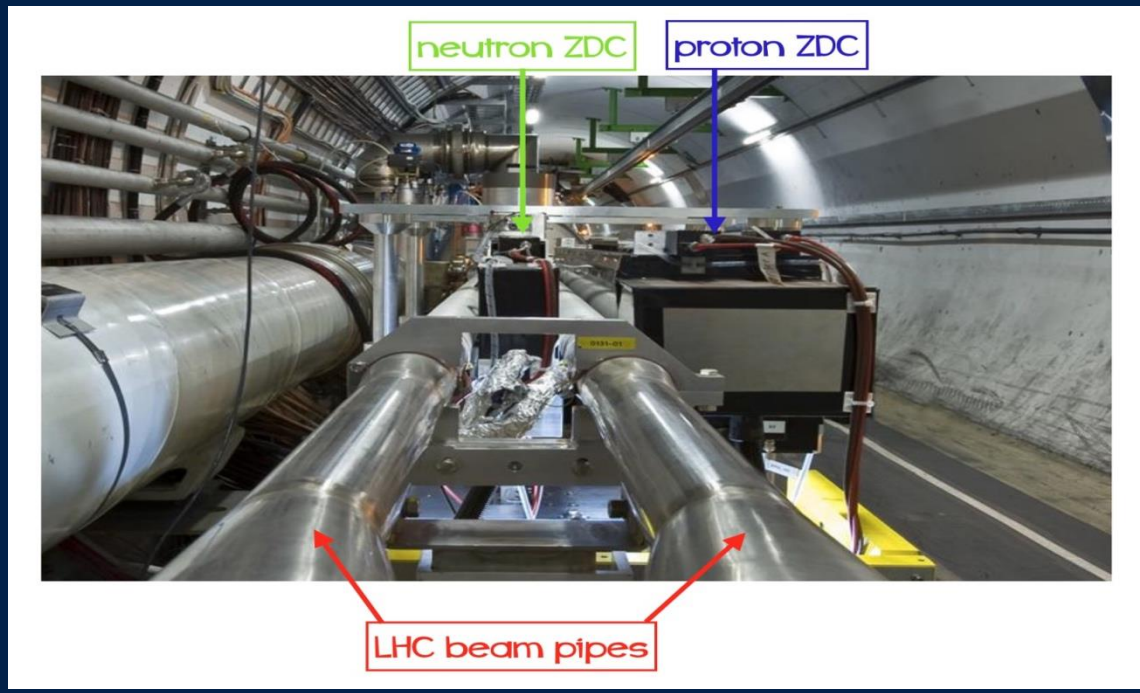
When the two beams at the LHC pass by close to each other without colliding, one of the beams may emit a photon of very high energy that strikes the other beam.

This can result in photon-nucleus, photon-proton, and even photon—photon collisions.

Turning lead into gold

Ultra-peripheral Collision

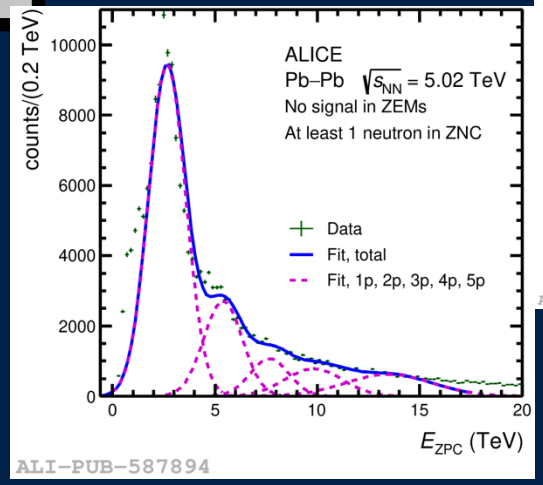


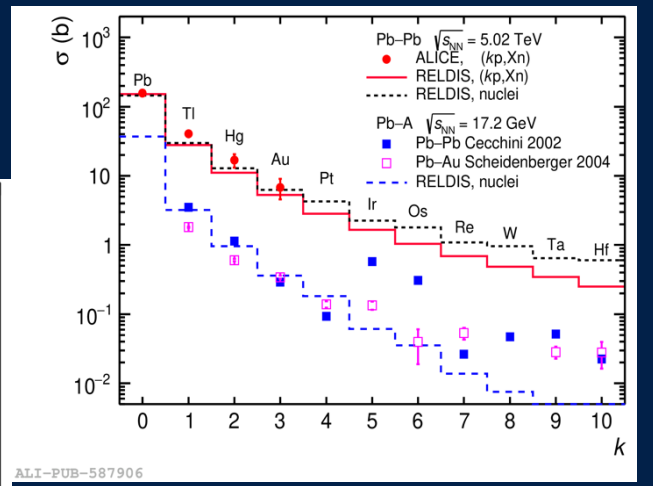


Proton emission cross-sections in UPC:

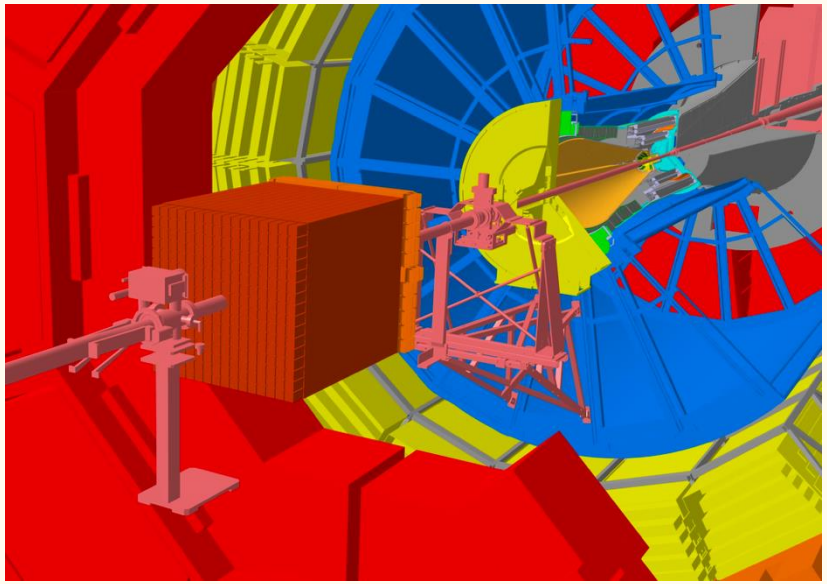
- Production of Pb, Ti, Hg, and Au isotopes determined from 0p, 1p, 2p, 3p emission cross-sections.

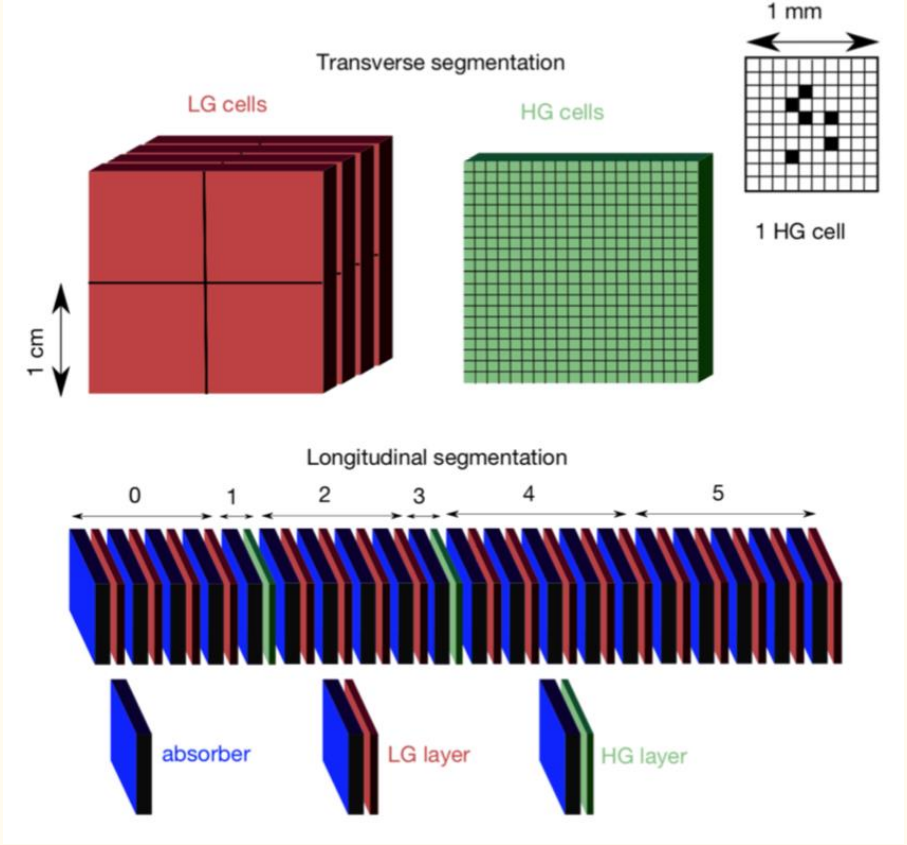
- ALICE estimates that about 1.6×10^{-11} g of gold isotopes were produced at the LHC in the four experiments from 2010 - 2018.

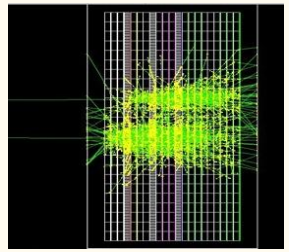




LS3 upgrade: FoCal







- **FoCal-E**: electromagnetic section with tungsten converters: 18 silicon pad layers, and two ultra-fine pixel layers,
- **FoCal-H**: hadronic section of copper and scintillating fibres.

- Initial State: Low-x Gluon Saturation
- Initial State: Nuclear PDFs
- Jet quenching, flow, and correlations …

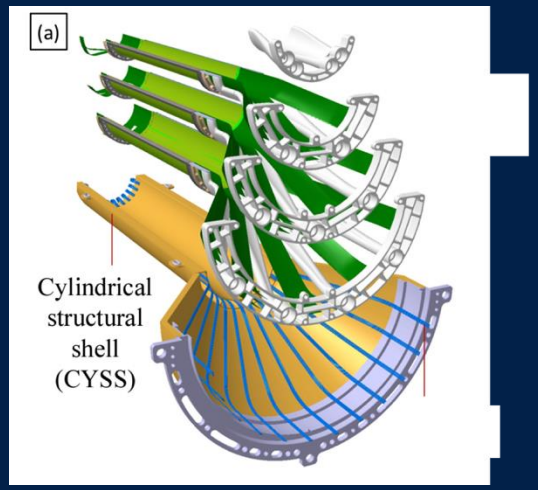
Measure forward production of:

- Isolated direct photons
- π^0
- Jets
- UPC J/ψ

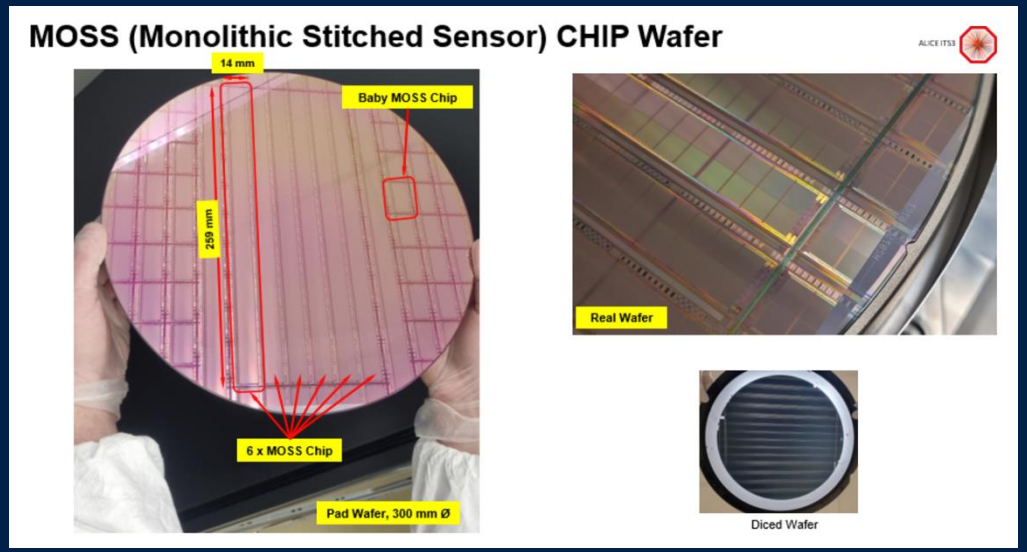


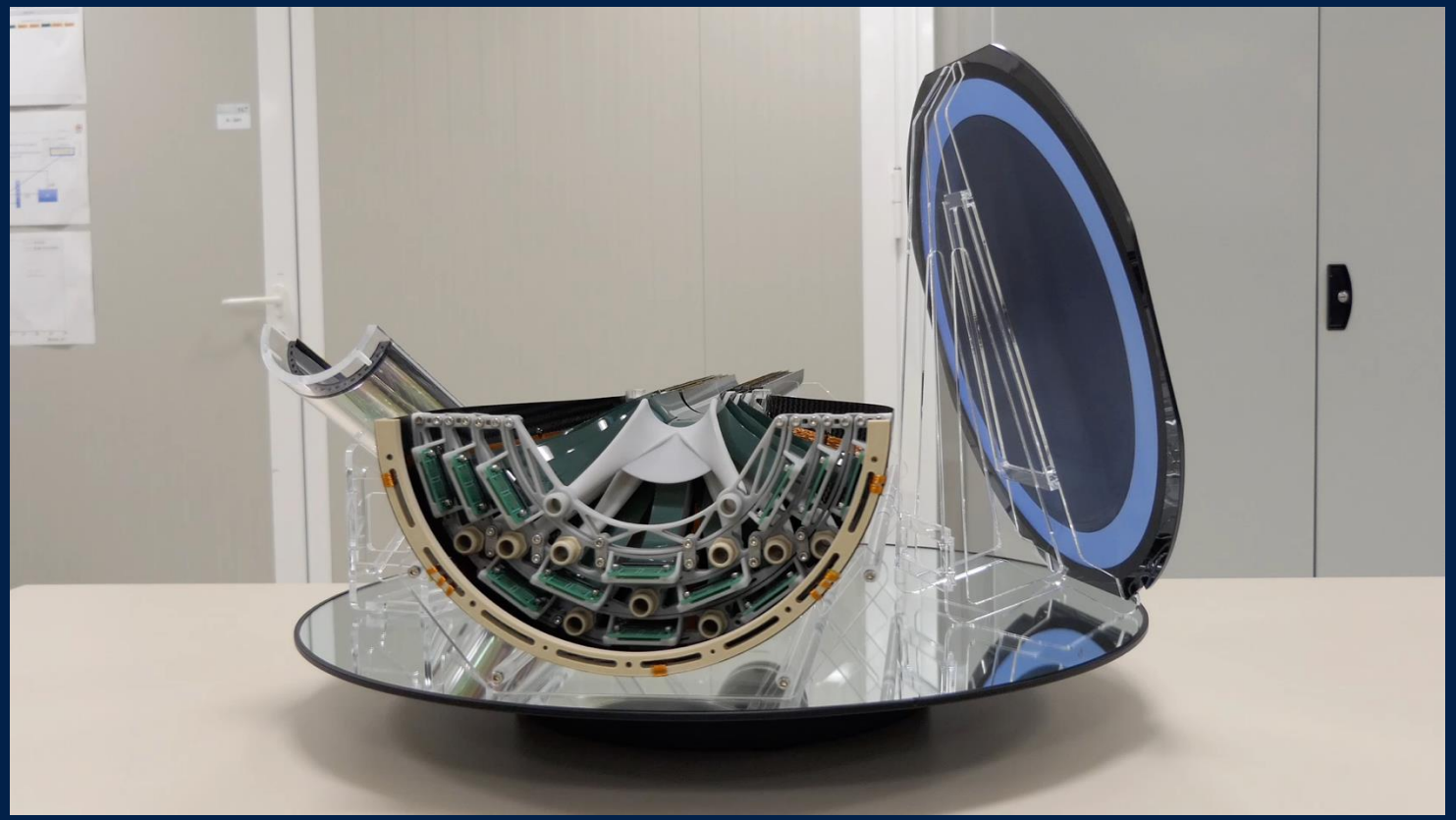
Tapan Nayak

ITS 3: ultra-light, fully cylindrical silicon tracking layers



- Replace inner 3 tracking layers
- Large-area sensors, curved around beam pipe, carbon foam support
- Improved pointing resolution for
  - Heavy flavour reconstruction
  - Di-lepton measurements

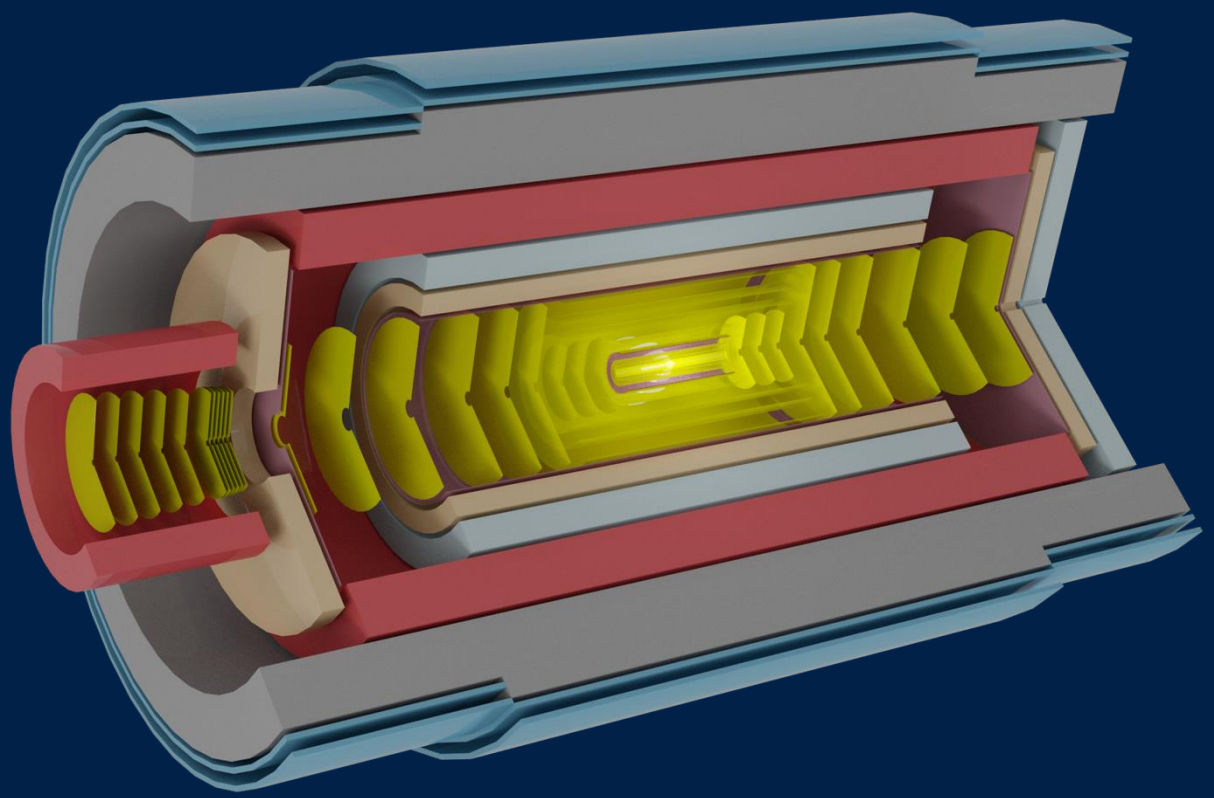




Next generation heavy-ion experiment: ALICE 3

UNDER PREPARATION FOR 2035

ALICE 3



Novel detector concept

- Compact, lightweight all-pixel tracker
- Retractable vertex detector → **first layer only ~5 mm from the beam**

A new frontier for pixel detectors

- **~2.5 µm spatial resolution**
- **~60 m² of silicon pixels**

❖ **Particle Identification over large acceptance: muons, electrons, hadrons, photons**

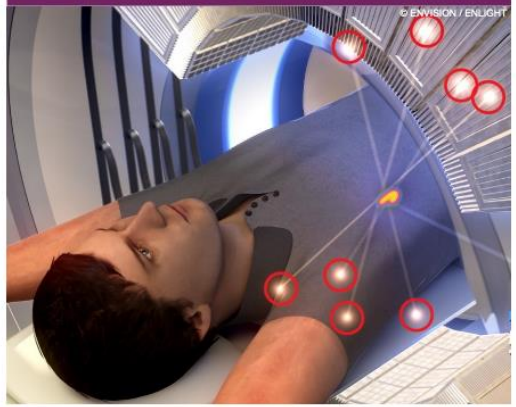
❖ **Fast readout and online processing**

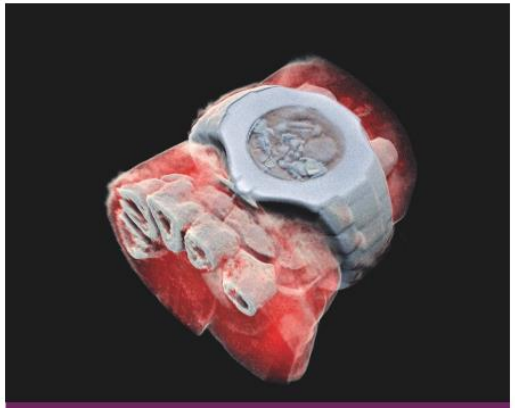
CERN's technological innovations have important applications in medicine and healthcare



Accelerator technologies are applied in cancer radiotherapy with protons, ions and electrons.

Technologies applied at CERN are also used in PET, for medical imaging and diagnostics.





Pixel detector technologies are used for high resolution

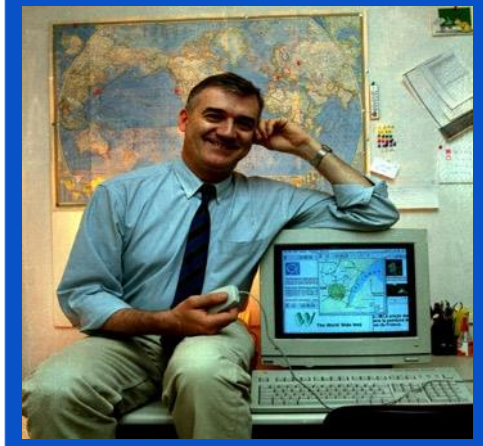
3D colour X-ray imaging.

CERN produces innovative radioisotopes for nuclear medicine research.



The World Wide Web (www)

The WWW

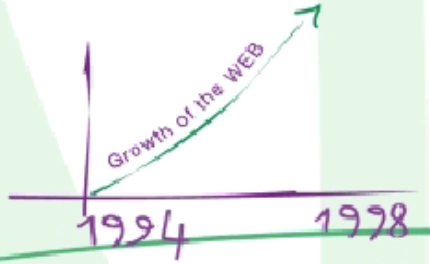


EUROPEAN LABORATORY FOR PARTICLE PHYSICS

World-Wide Web :

Invented at CERN

Everyone knows the World-Wide Web, but not everyone knows that it was invented at CERN. Conceived to give particle physicists easy access to their data wherever they happened to be, the Web has grown into a telecommunications revolution.



What is the Web ?

But what is the Web ? In short, it is a world of information at the click of a mouse. To use it, you need a computer, a connection to the Internet, and a browser programme. When you run your browser, it displays a page of information which might be held on your own computer or fetched from somewhere else, you needn't know or even care where it comes from. Certain words, phrases, or images are highlighted, and clicking on them causes the browser to go off and find another page, which probably contains more highlighted items, and so on. The Web knows no geographical boundaries. For example, starting from the CERN 'Welcome page' in Switzerland, your next click might take you to the other side of the world. All the information seems to be in the little box in front of you, and in a sense it is. When you click on a piece of highlighted text your browser connects to another computer, asks it for the requested information, and displays it on your screen. You are then free to browse the new page at leisure, the computers have finished their 'conversation'.

How did it start ?

It all began in 1989, when Tim Berners-Lee proposed a distributed information system for CERN based on hypertext. By hiding network addresses behind highlighted items on the screen, information could be linked between several computers. This system became the Web, with the world as its library.



Tim Berners-Lee, CERN March 1989, May 1990

Examples of technologies developed at CERN
WWW, of course! But there are many more....

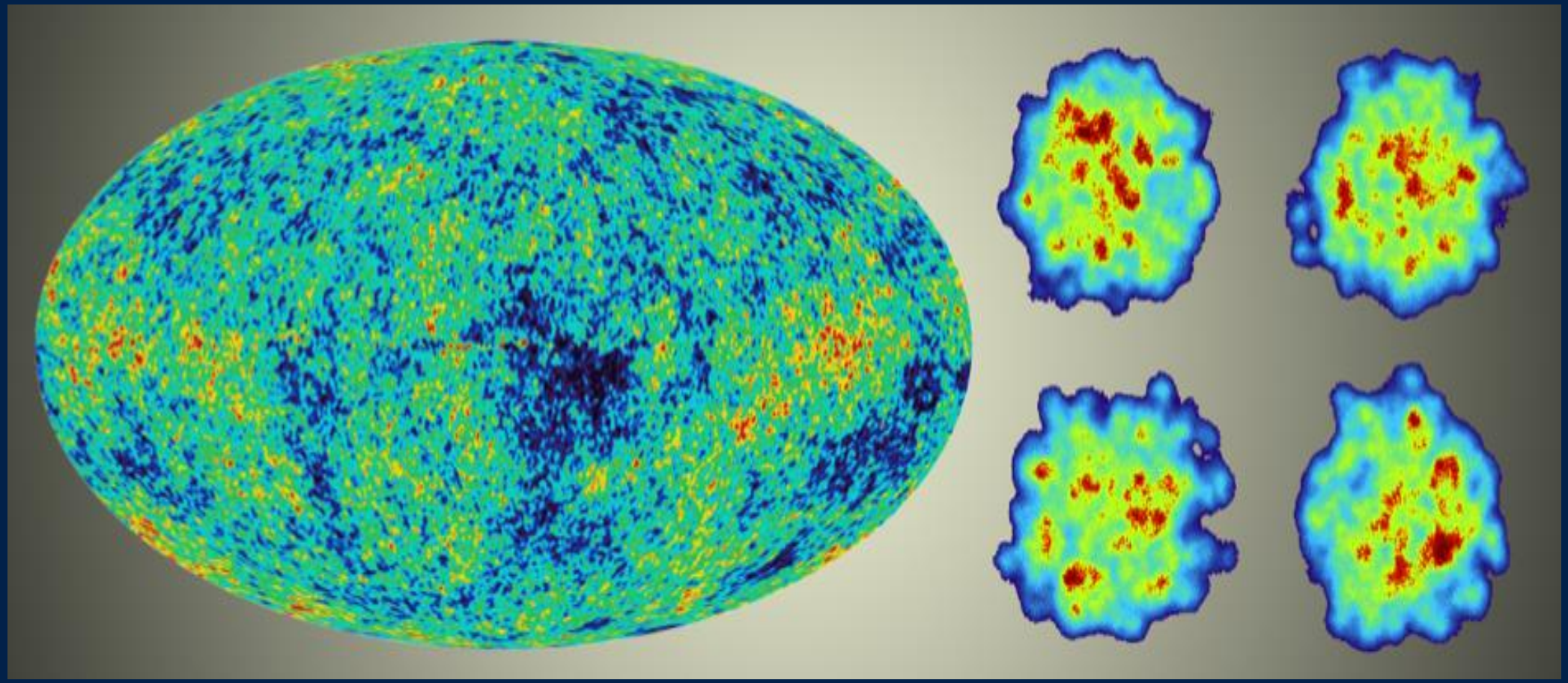




Frank Beck and Bent Stumpe, engineers from CERN, developed a transparent touch screen in the early 1970s.

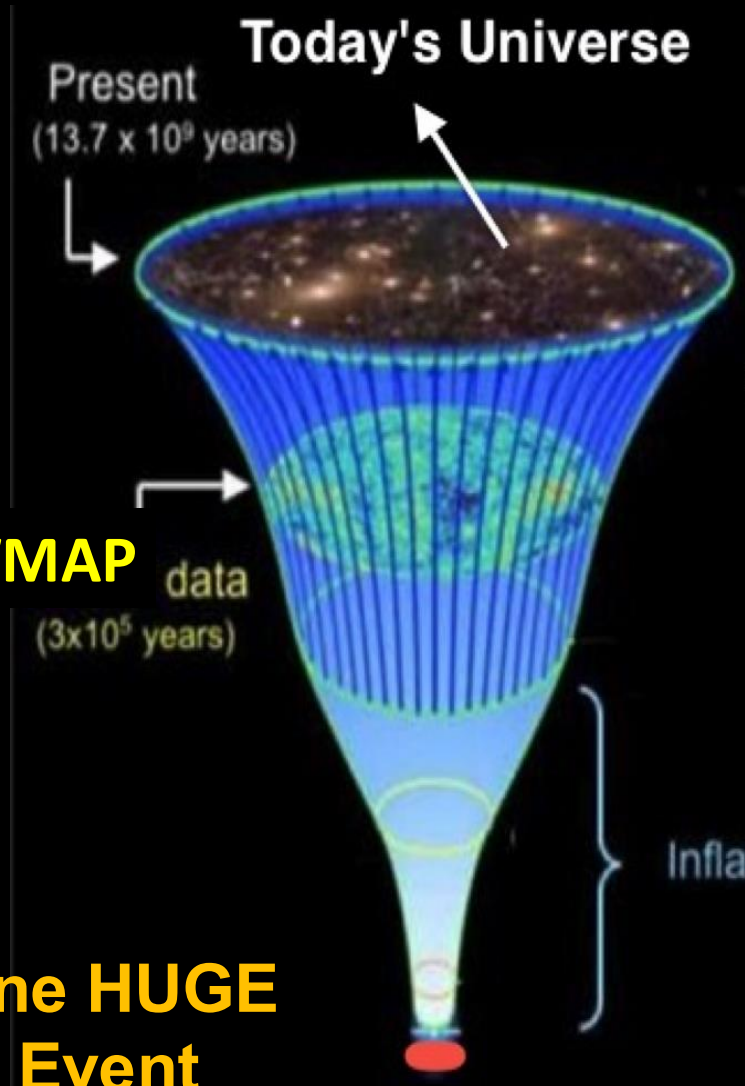
It was manufactured by CERN and put to use in 1973

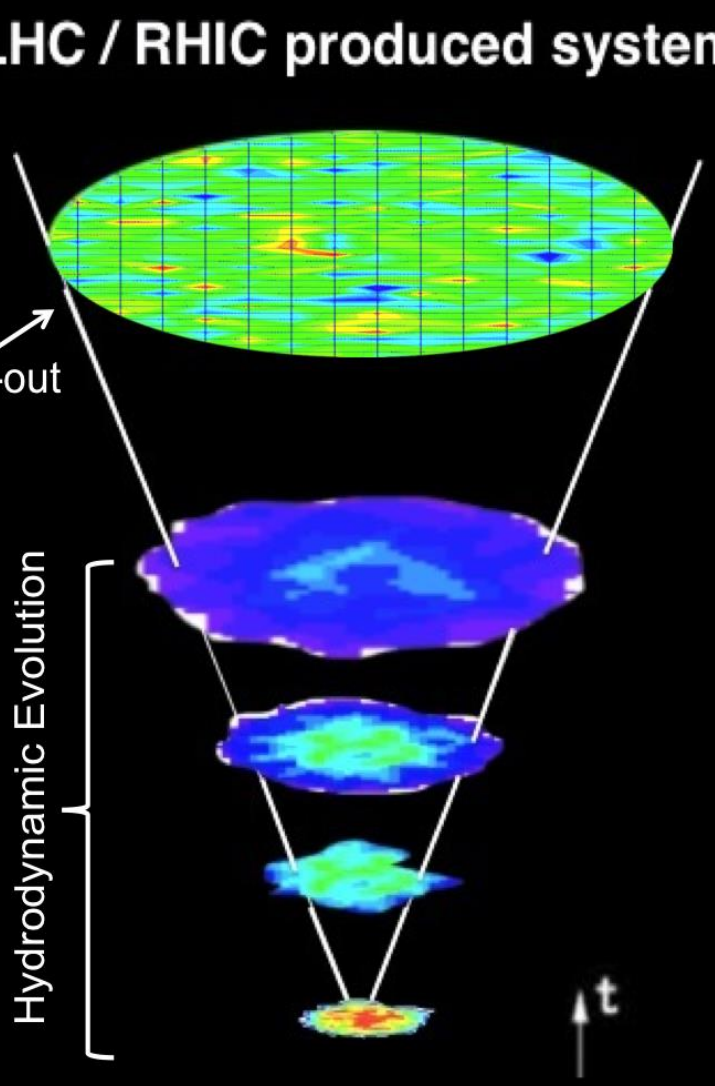
Fluctuations in the Little Bang



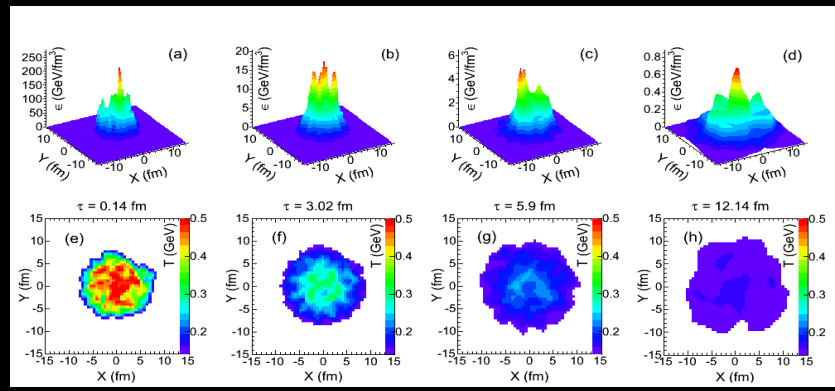
- Hadrons detected by the experiment are mostly emitted at the freeze-out
- Similar to the CMBR which carry information at the surface of last scattering in the Universe, these hadrons may provide information about the earlier stages (hadronization) of the reaction in heavy-ion collision.

The Big Bang… and Little Bangs





Smashing nuclei => Billions of Little Bangs

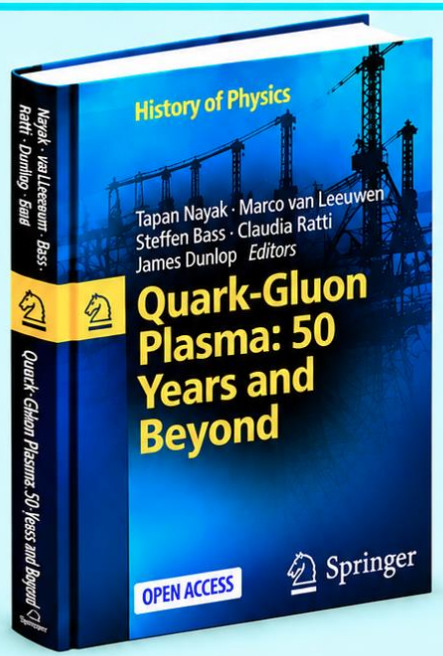


Sumit Basu

One HUGE Event

Big Bang

Little Bang

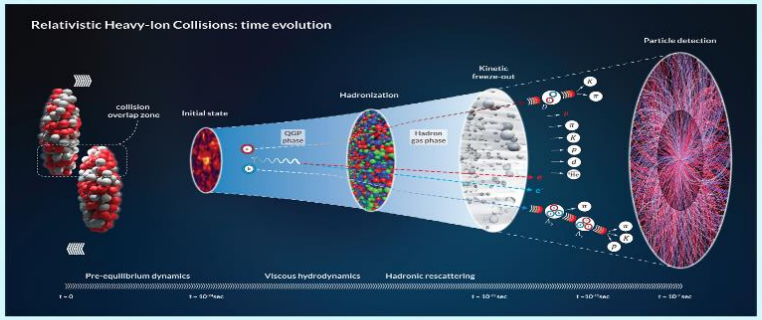


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What was the Universe like just after the Big Bang?

The answer takes us to **quark-gluon plasma (QGP)** — an extremely hot and dense state of matter that filled the Universe in its earliest moments.

Quark-Gluon Plasma: 50 Years and Beyond tells this extraordinary story of **research and discovery**, and how scientists recreate this state of matter in **high-energy nuclear collisions** at laboratories worldwide.

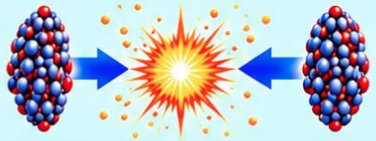


Contributions from leading researchers around the world

Personal recollections

Topical reviews

50 years of discovery



View the book on Springer

Springer

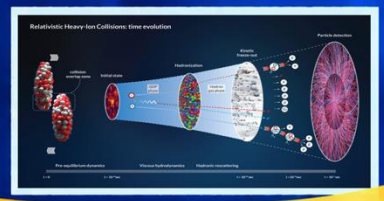


Quark-Gluon Plasma: 50 Years and Beyond

Editors Tapan Nayak · Marco van Leeuwen
Steffen Bass · Claudia Ratti · James Dunlop

What was the Universe like just after the Big Bang?

The answer: quark-gluon plasma — the extremely hot and dense state of matter that filled the early Universe. The book traces its story from early research to the latest developments.



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