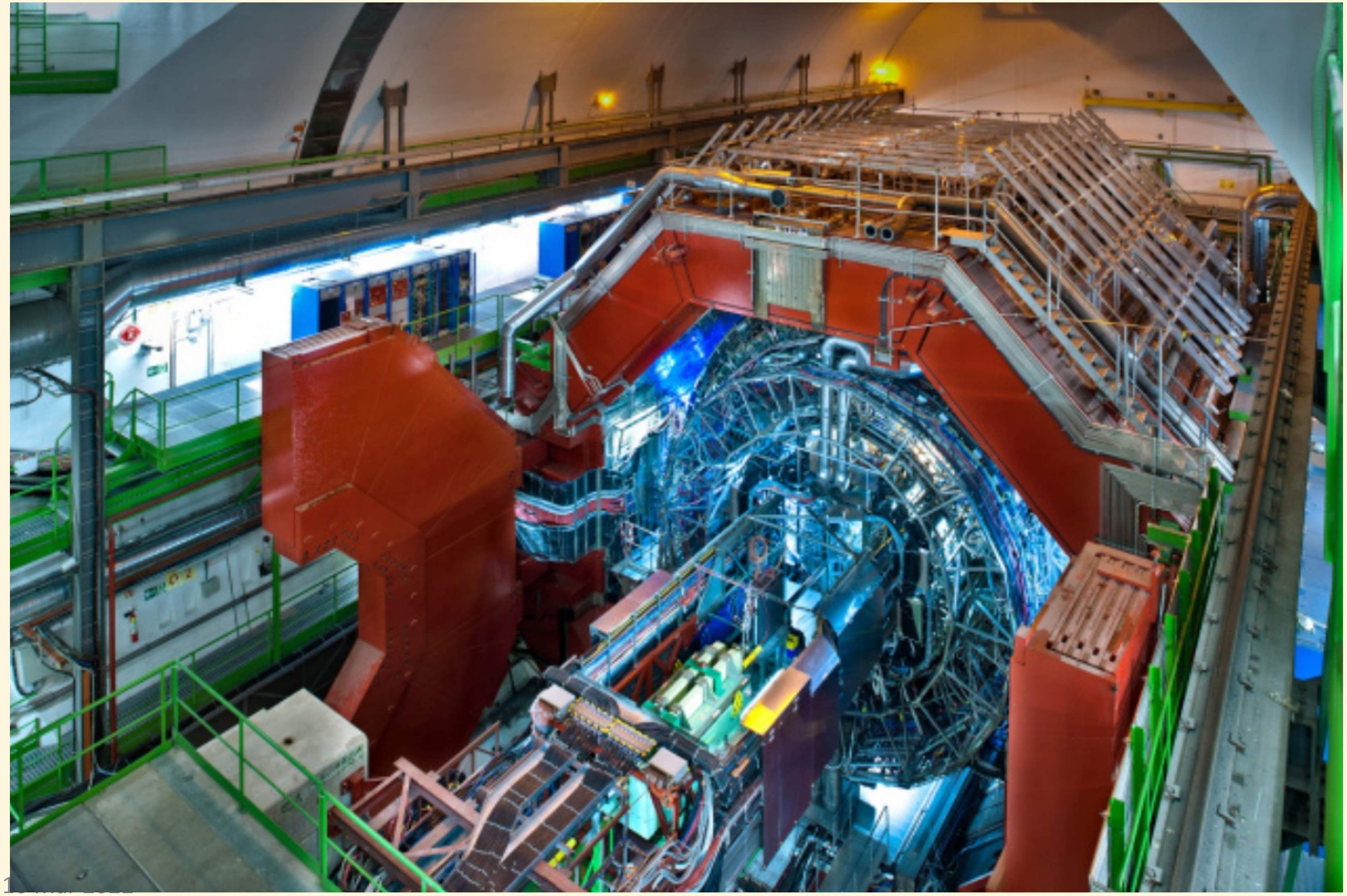
Physics of quark-gluon plasma and the ALICE experiment at CERN



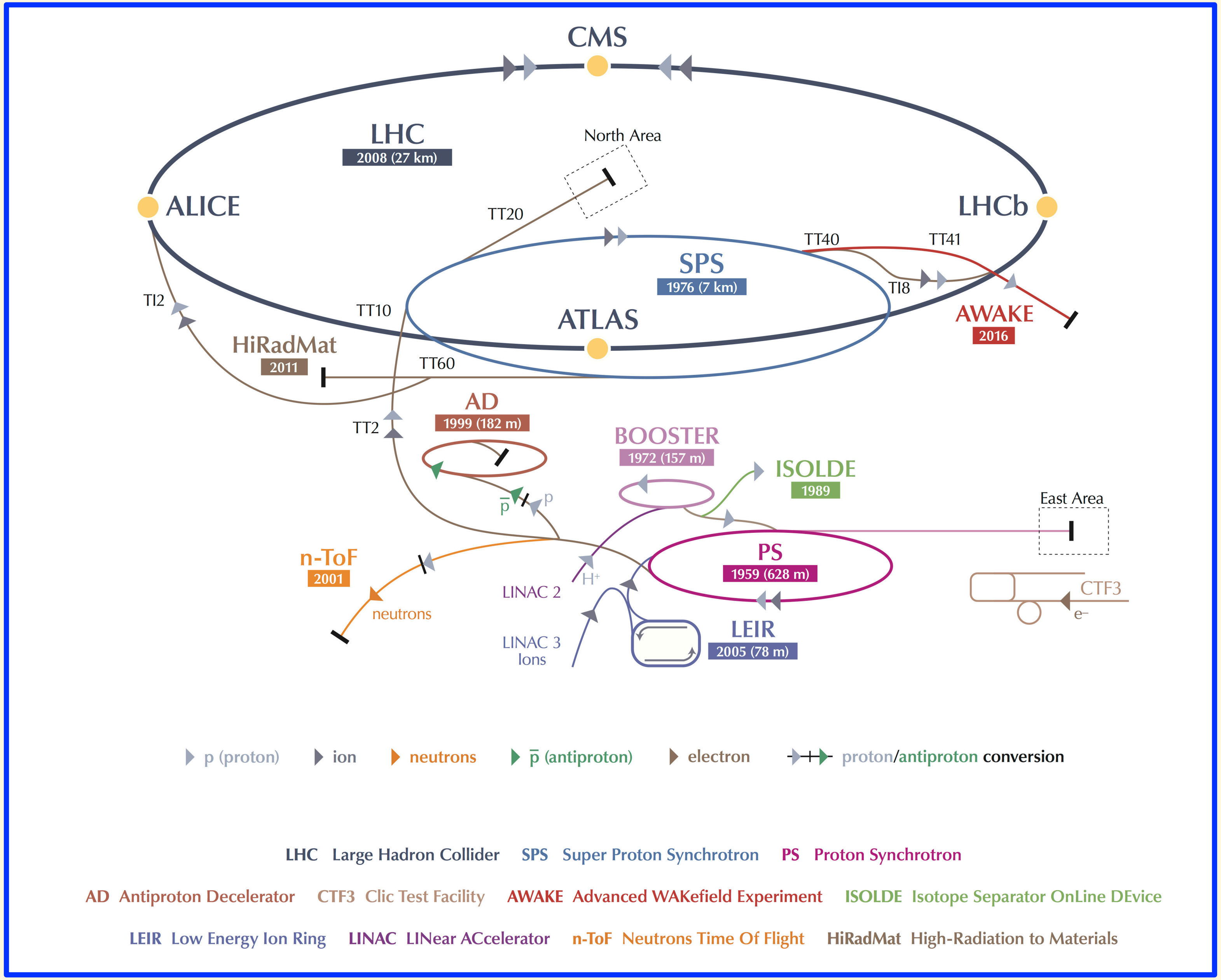
International Particle Physics Masterclasses

Tapan Nayak
10 Mar 2022

CERN

“Science without borders”

CERN Accelerator complex

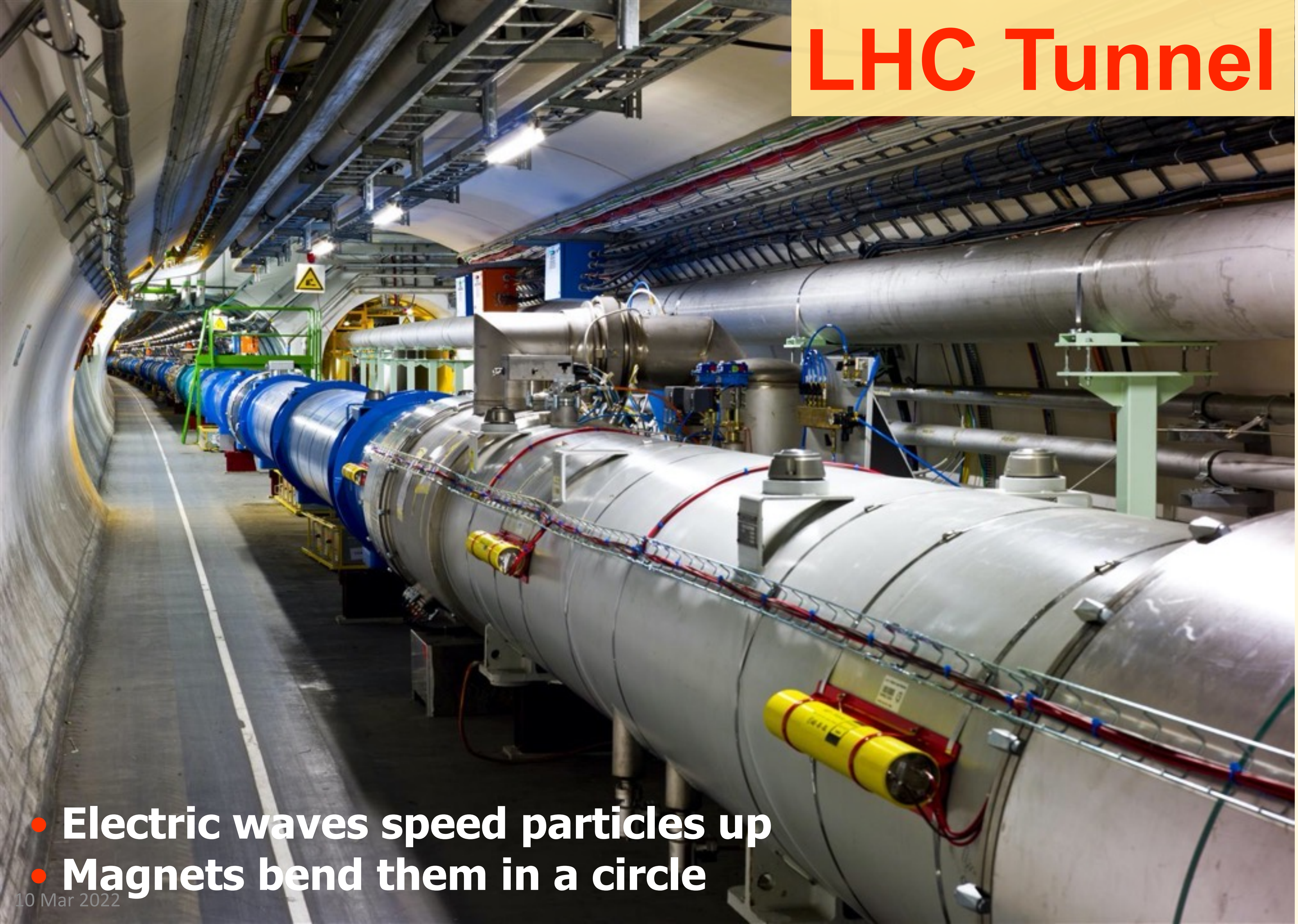


The LHC is the last ring in a complex chain of particle accelerators. The smaller machines are used in a chain to boost the particles to their final energies.

The LHC collides:
- proton on proton
- **Heavy-ions (lead on lead)**
- proton on lead
- ….

Why heavy-ions?

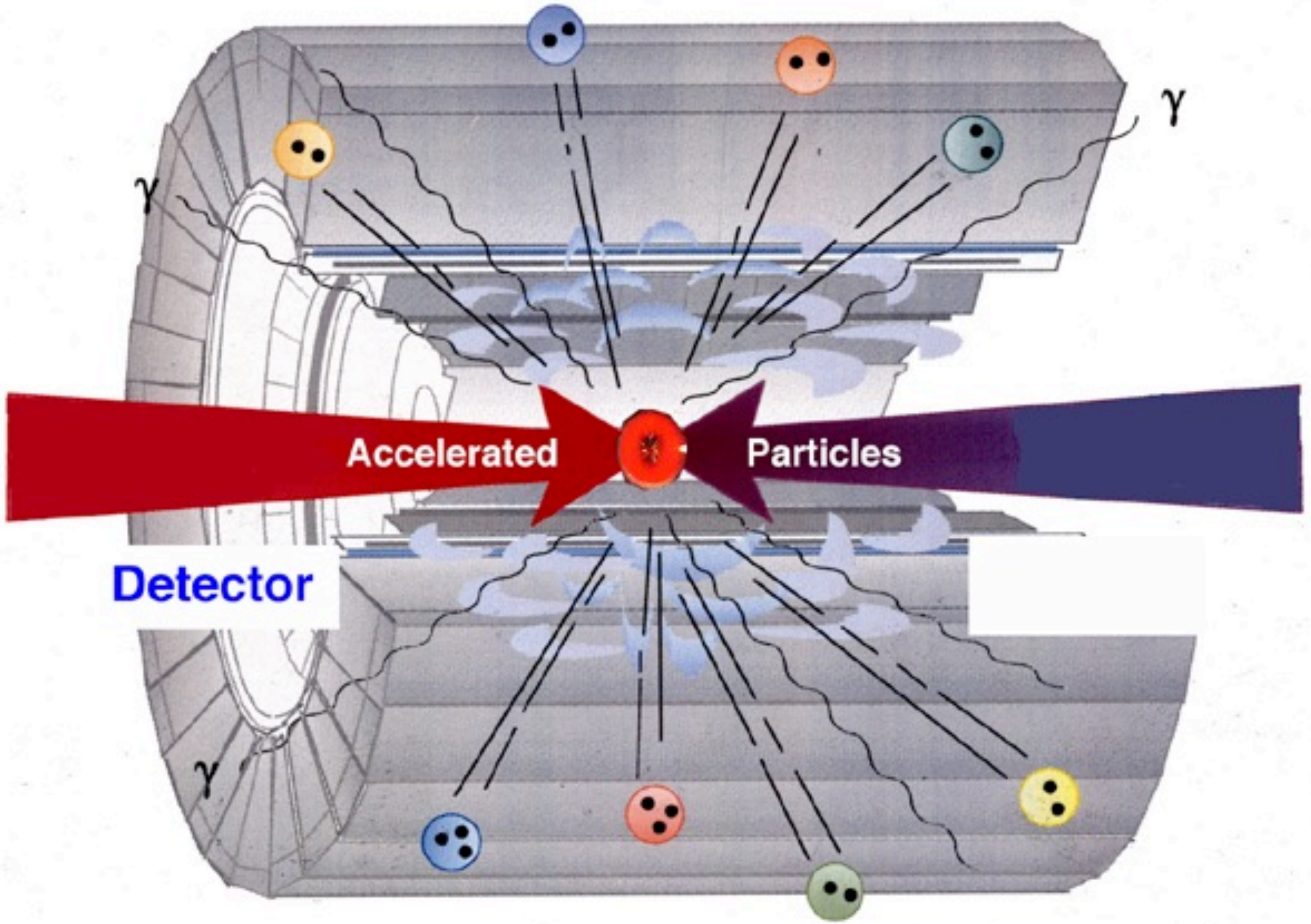
LHC Tunnel



- **Electric waves speed particles up**
- **Magnets bend them in a circle**

27km tunnel:

- 50-150m below ground
- Two beams circulating in opposite directions
- Total of 9300 magnets: beams controlled by 1800 superconducting magnets (up to 8T)



High Energy is needed to create new particles

Need High Energy Accelerator:

COLLIDER

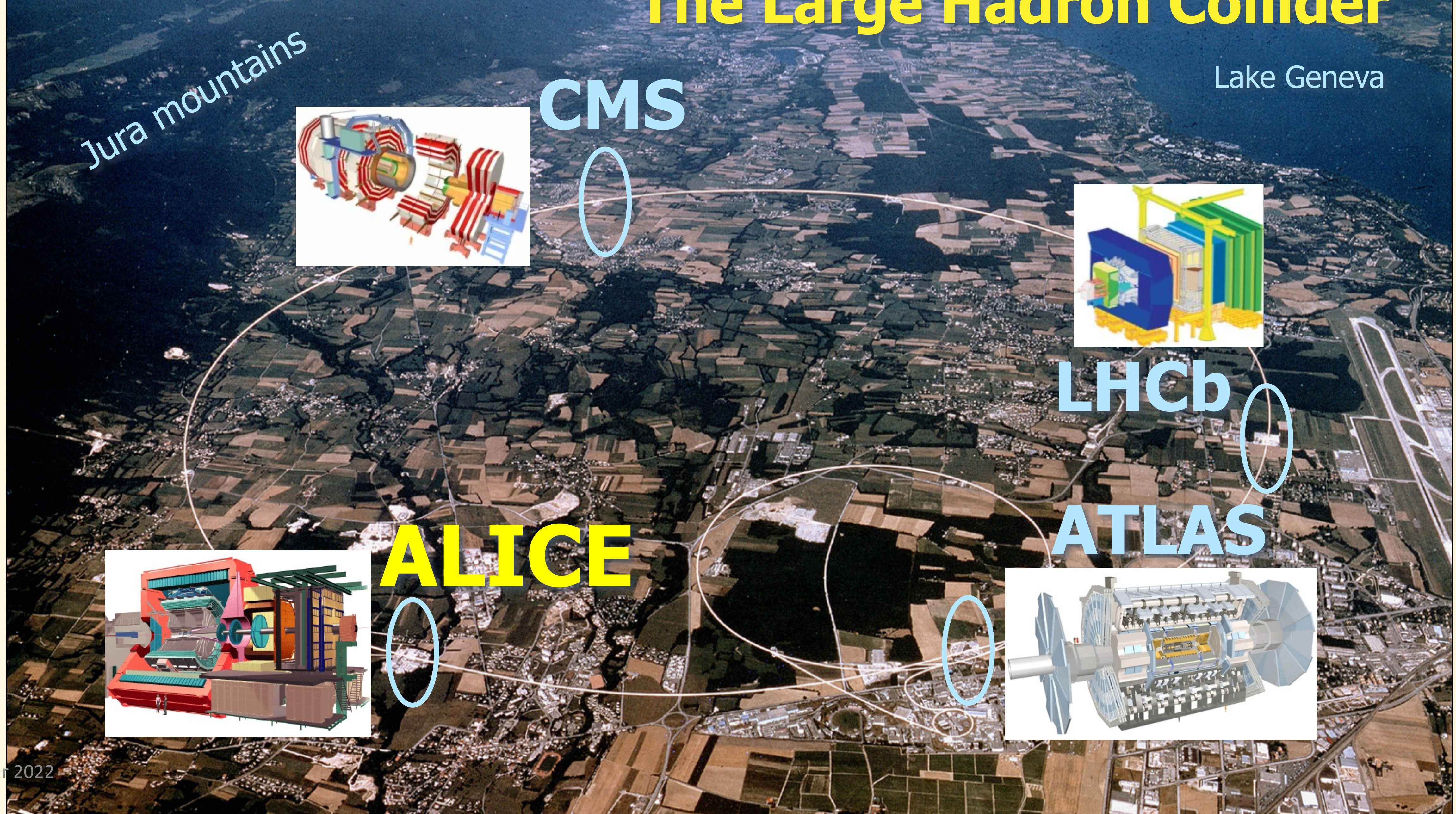
$$E = mc^2$$

EXPERIMENTS

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

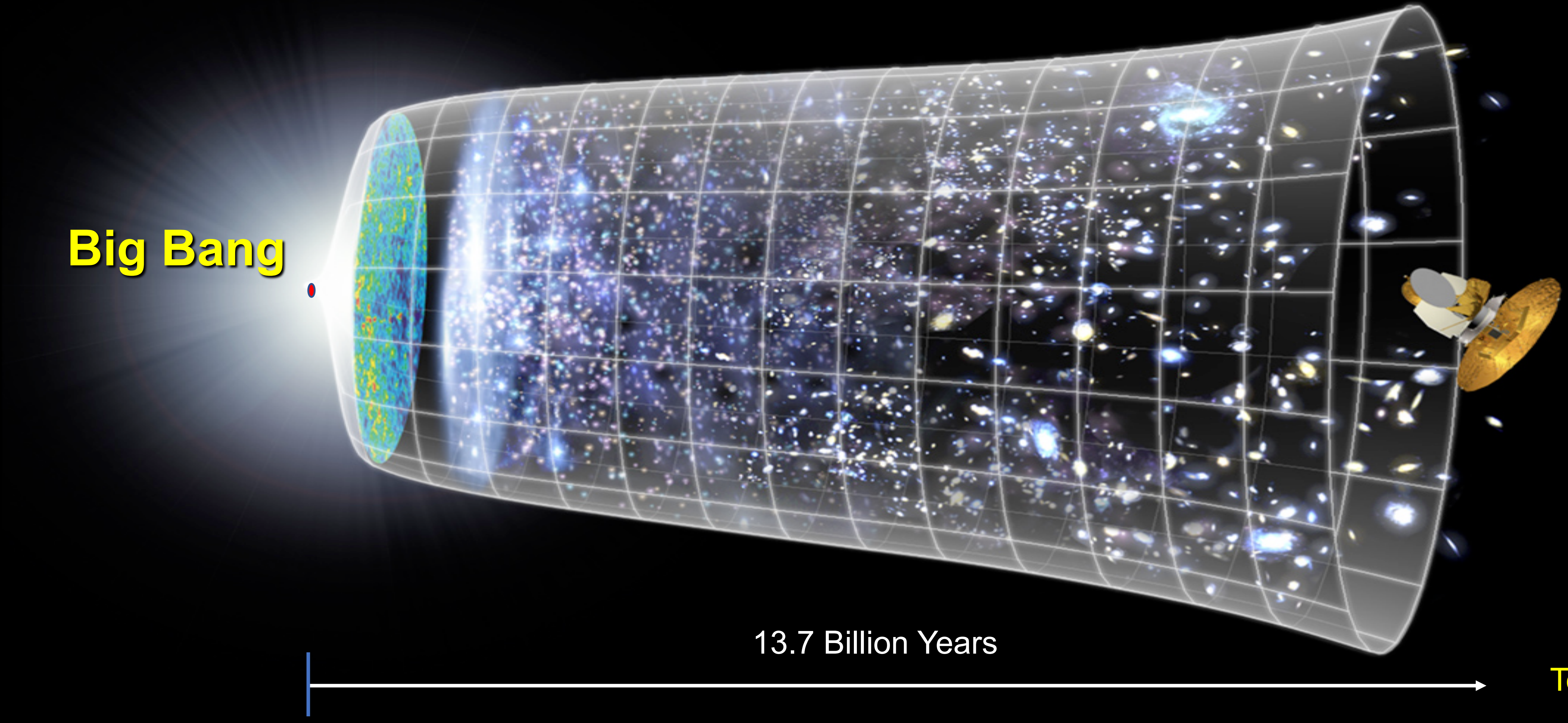
World's Most Powerful Accelerator:

The Large Hadron Collider



Our Universe ….. How did it start?

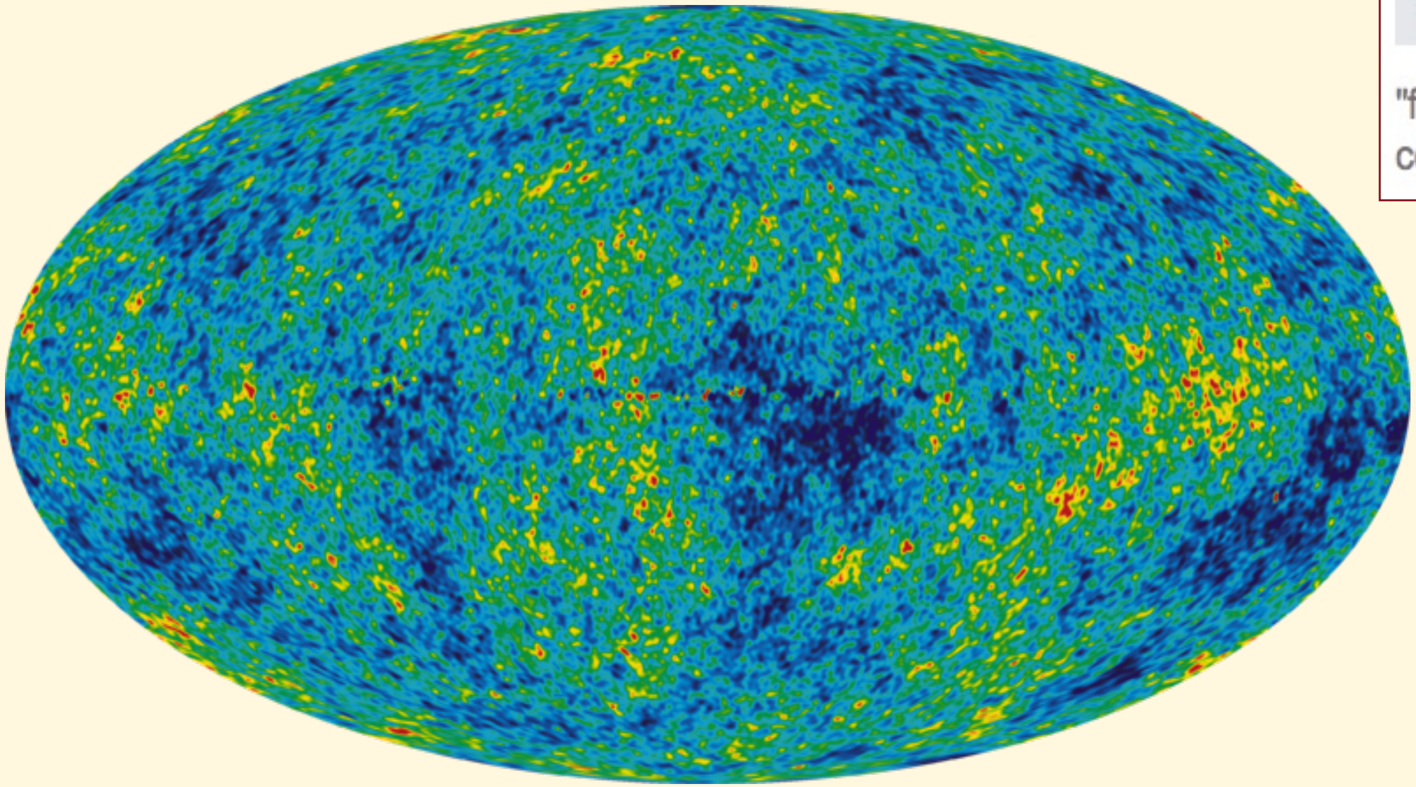
What is it made of?



Astronomical probes

Hubble telescope
James Webb Space Telescope ….

The sky picture of the infant universe created from nine years of [Wilkinson Microwave Anisotropy Probe](#) *(WMAP) data.*



The Nobel Prize in Physics 2006

George Smoot & John Mather

"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

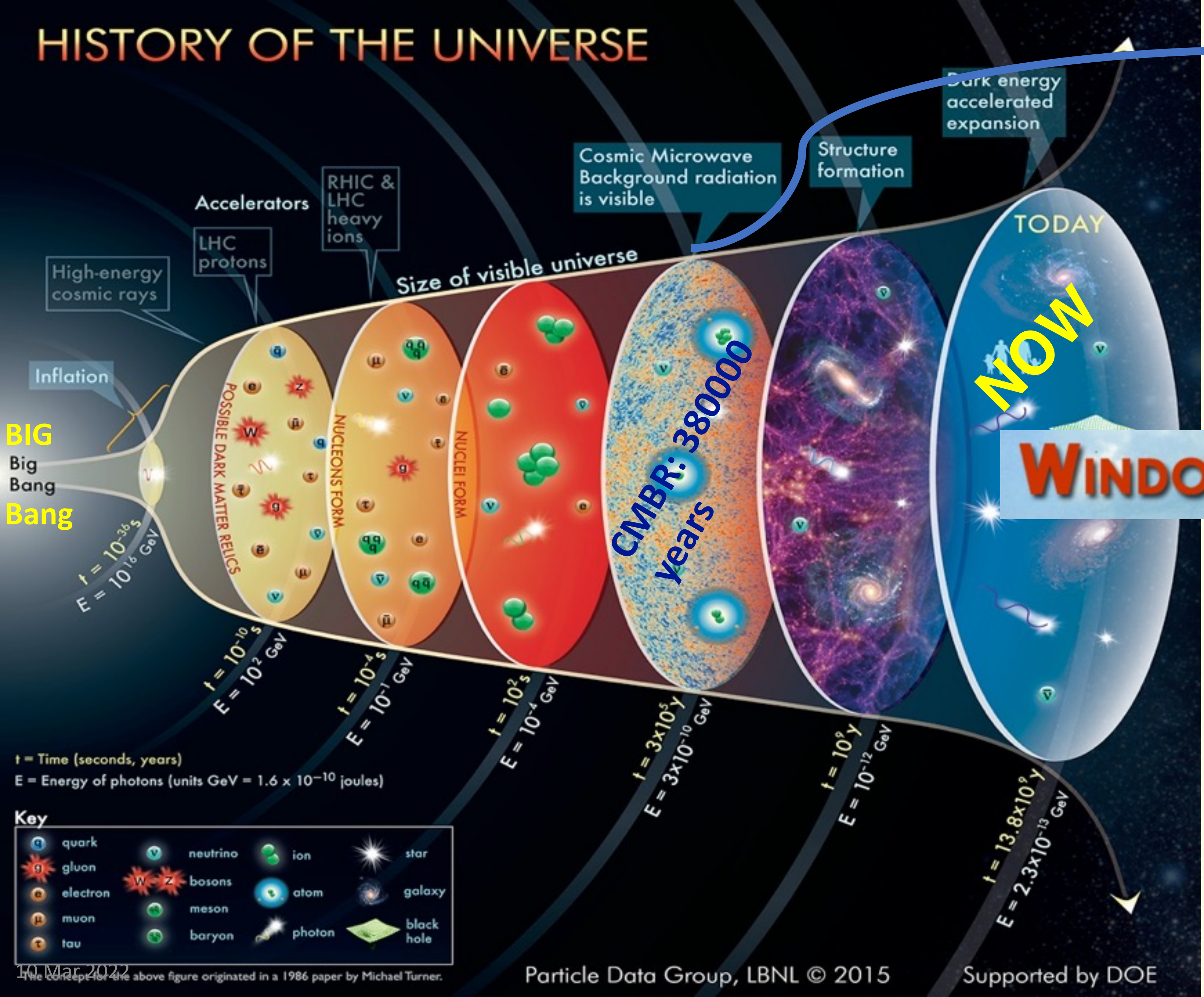
Cosmic Microwave Background Radiation (CMBR)

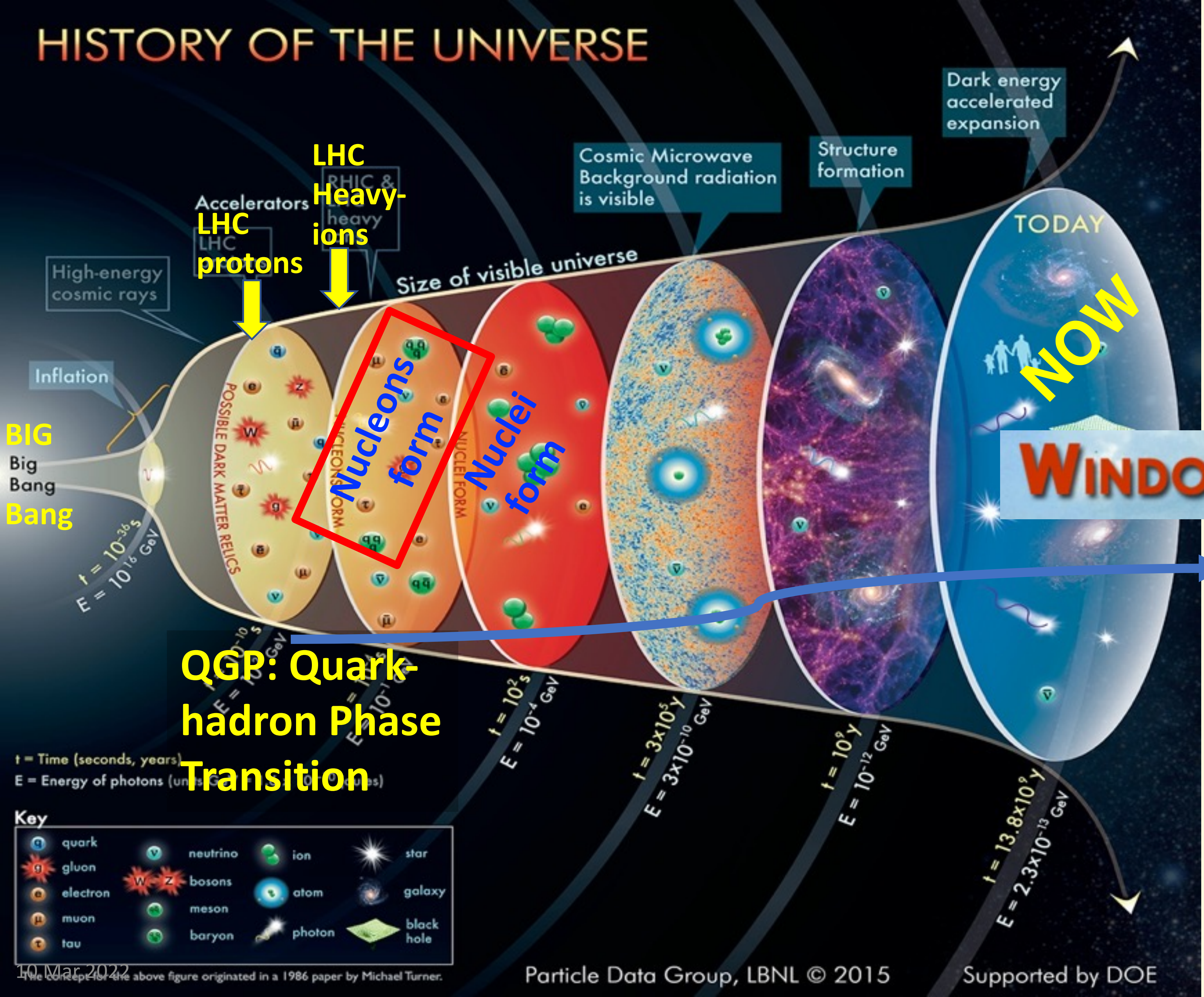
Using Astronomical Probes: The closest we can go to the Big Bang is 380,000 years from the beginning ….

Our Goal: to go to Few millionth of a second from the Big Bang

Astrophysical Probes

Takes us back to 380,000 years after the Big Bang





Windows on the Universe

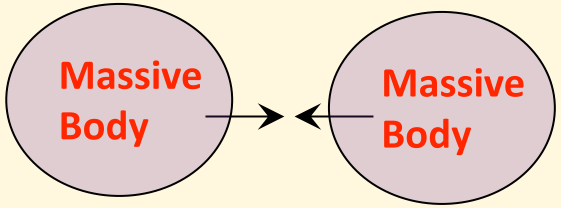
Accelerators (LHC)

Takes us back to within few Microseconds of the Big Bang

- Quark Gluon Plasma (QGP)

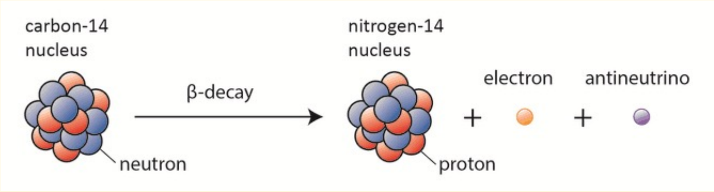
Fundamental forces of nature

Gravitational force



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

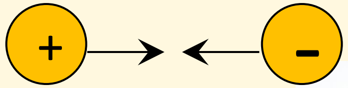
Weak force



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

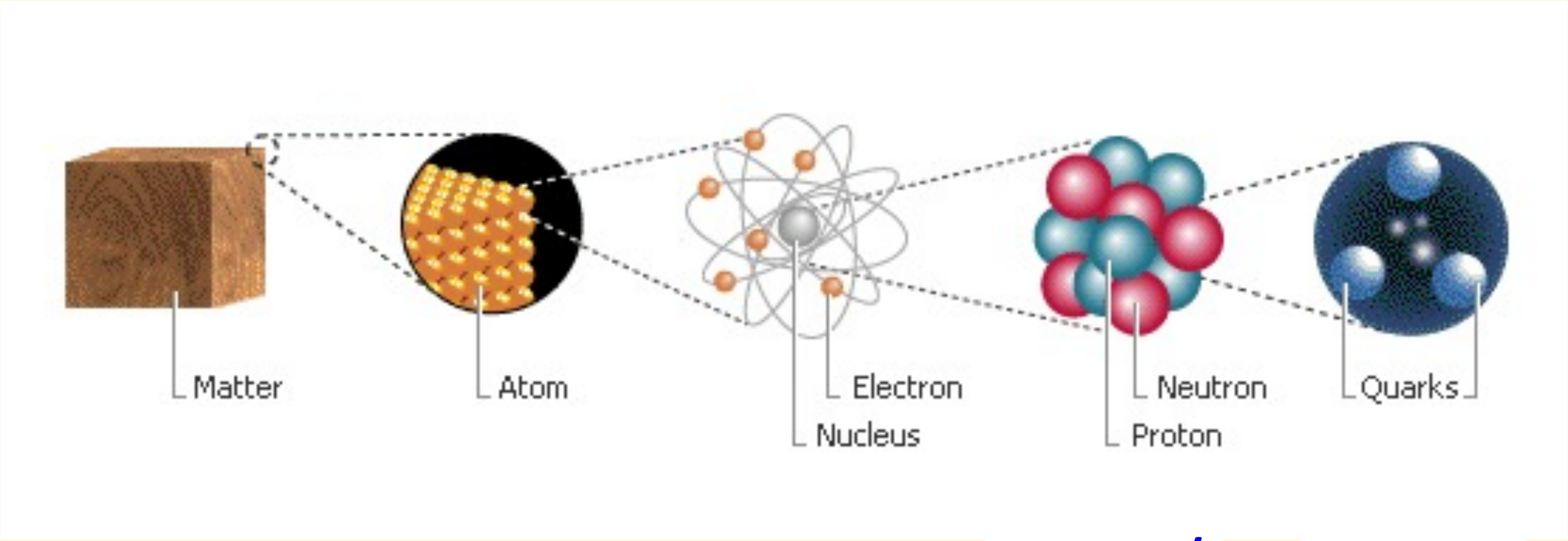
Strong force

Holds the atomic nucleus,

Binds quarks together

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

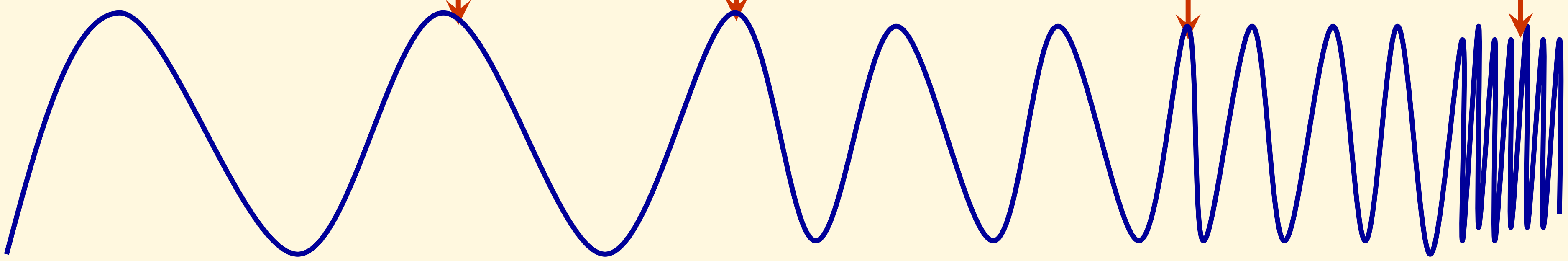
Structure of matter



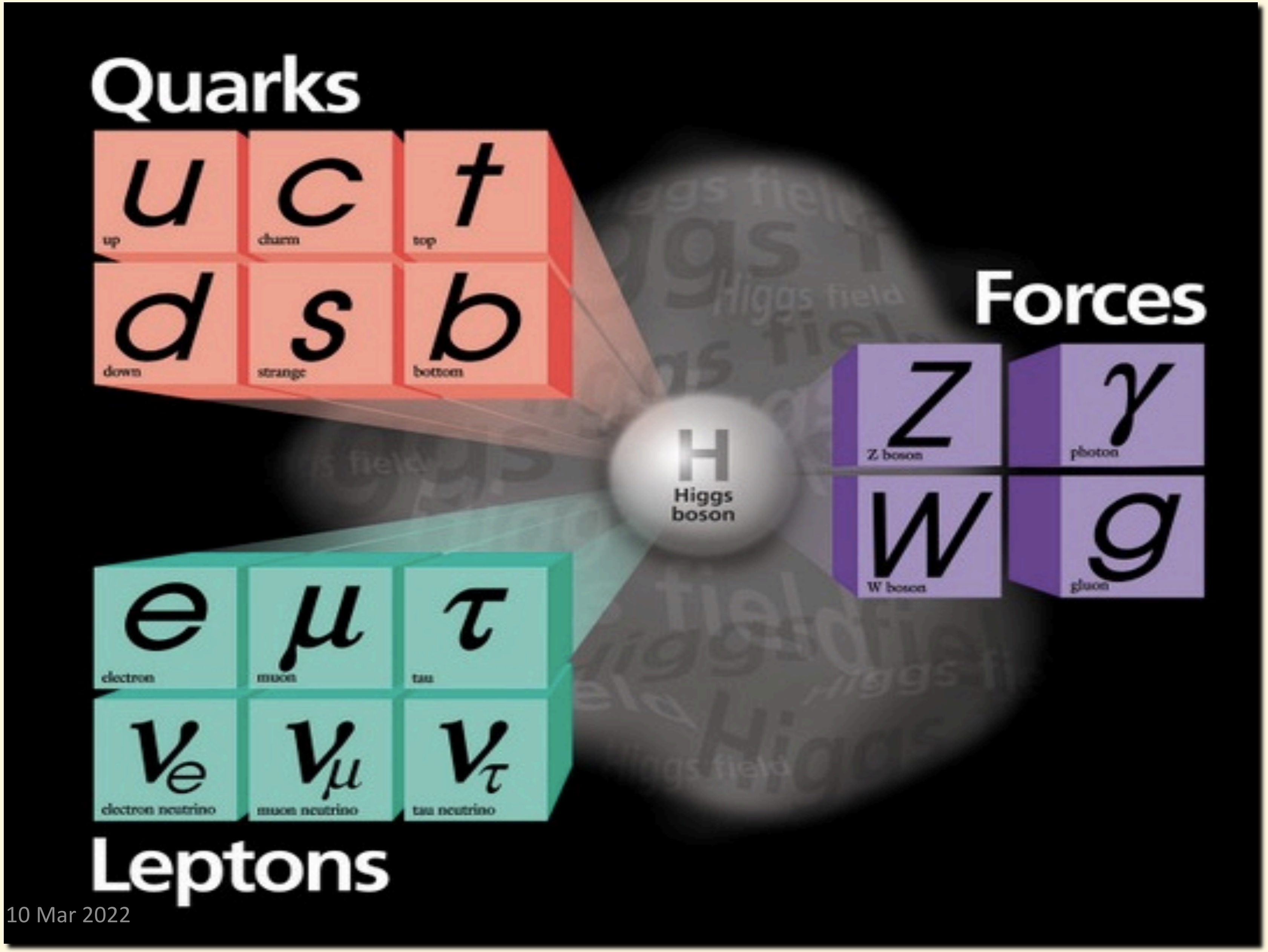
MATTER | **ATOM** | **NUCLEUS** | **Protons/ neutrons** | **QUARKS**

10^{-8} cm | 10^{-12}cm | 10^{-13} cm | 10^{-18} cm

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



Fundamental constituents of matter



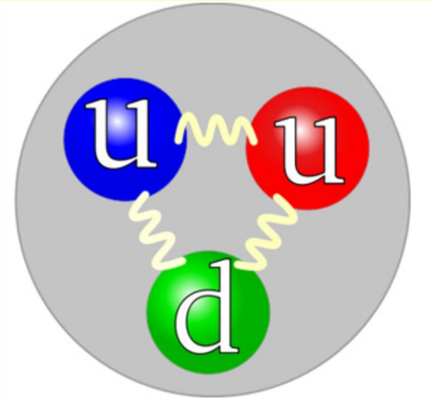
Higgs particle is responsible for **giving mass** to all particles.

Lockdown: Quark confinement

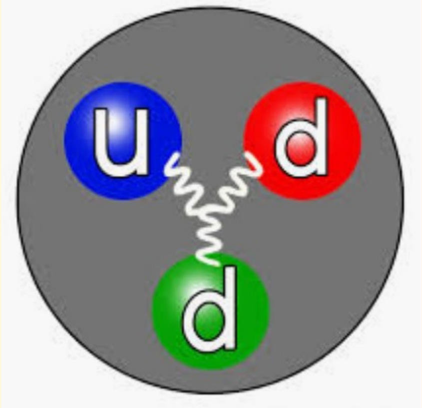
No one has ever seen a free quark

- **Quarks are locked-down within the hadrons**
  =>
  Free quarks seem not to exist, and only colorless hadrons are seen : **confinement**.

Proton



Neutron



Coloured quarks attract one another by exchanging gluon. There are eight types of gluons. Gluons are massless, have spin 1, travel at the speed of light, and carry both a color and a different anti-colour.

Colour force increases with distance, and the energy required to separate them produces quark-antiquark pairs long before they are far enough apart to observe separately.

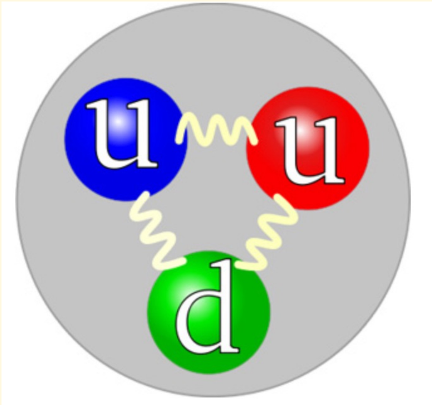
Asymptotic freedom:

No one has ever seen a free quark

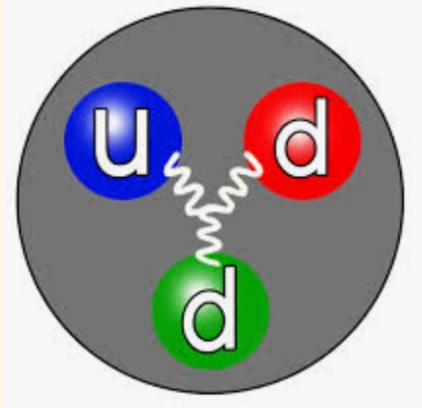
- q-q interactions become weaker as the inter-quark distance becomes shorter.

Quarks interact weakly at high energies. At low energies the interaction becomes strong, leading to the confinement of quarks and gluons within composite hadrons.

Proton



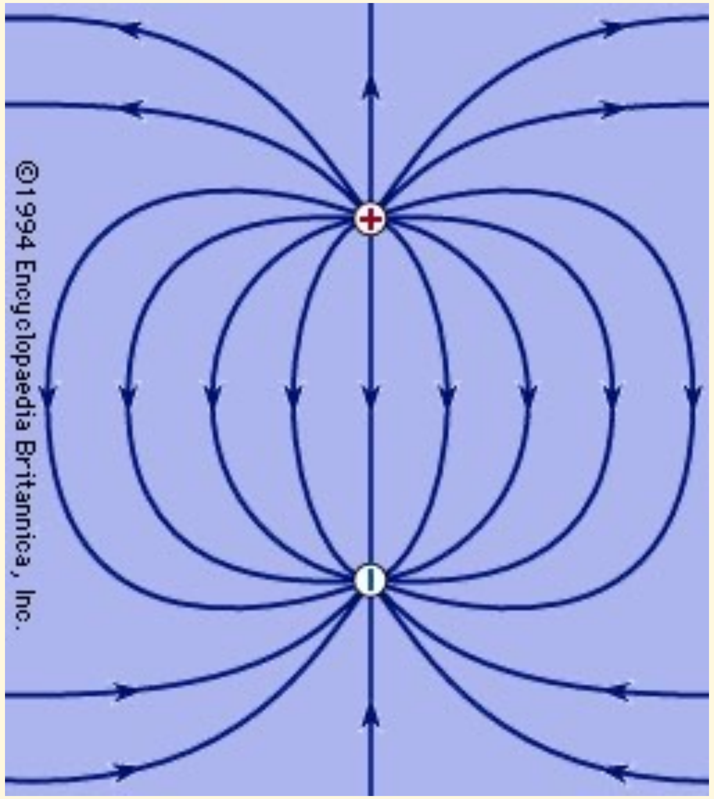
Neutron



Nobel Prize 2004

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

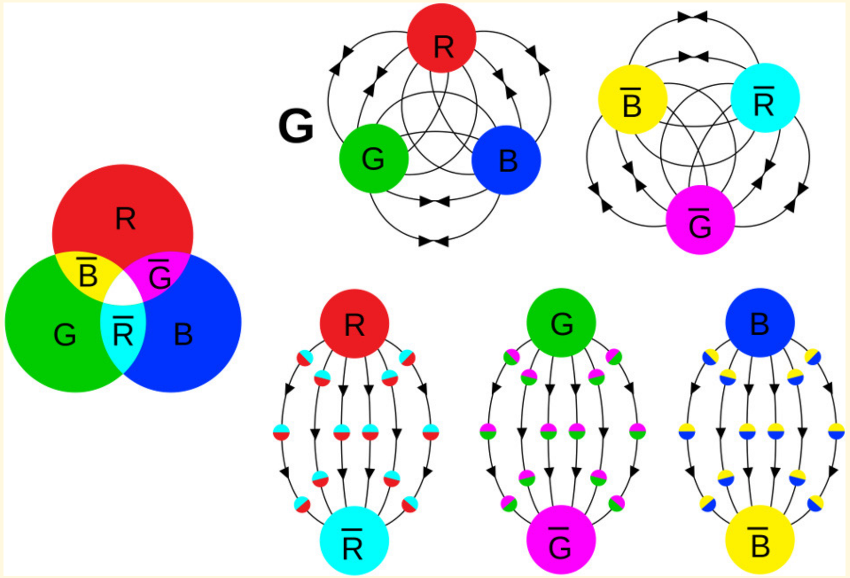
Electromagnetic interaction

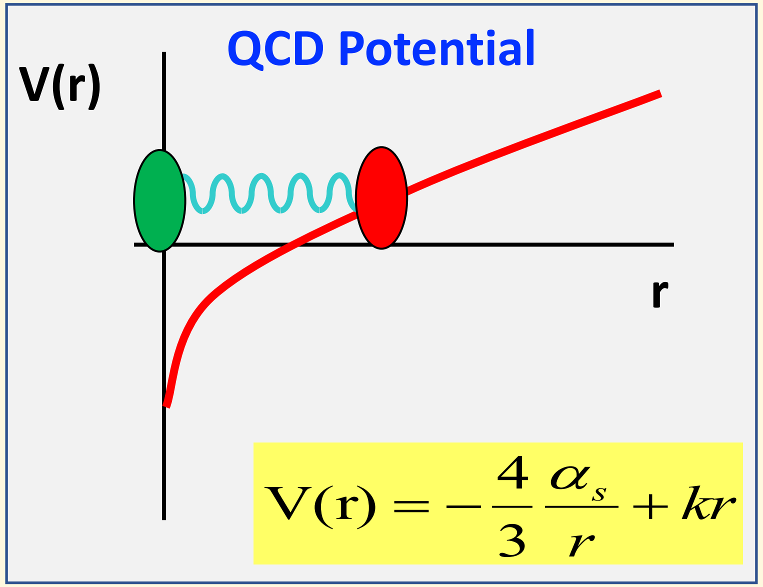


Electric field lines near equal but opposite charges

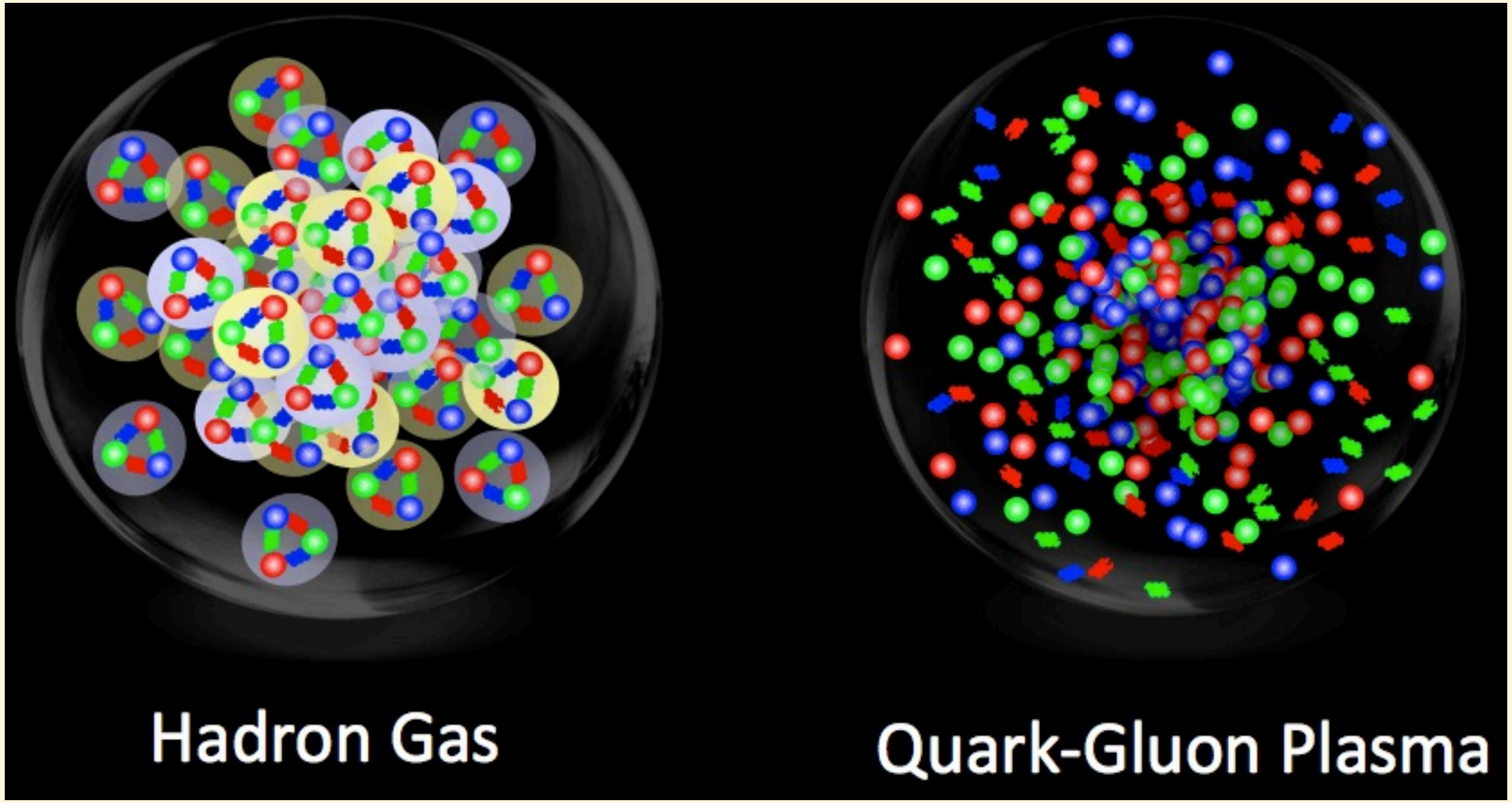
The electromagnetic force exhibits electromagnetic fields such as electric and magnetic fields.

Color force in QCD





Deconfinement => Quark Gluon Plasma



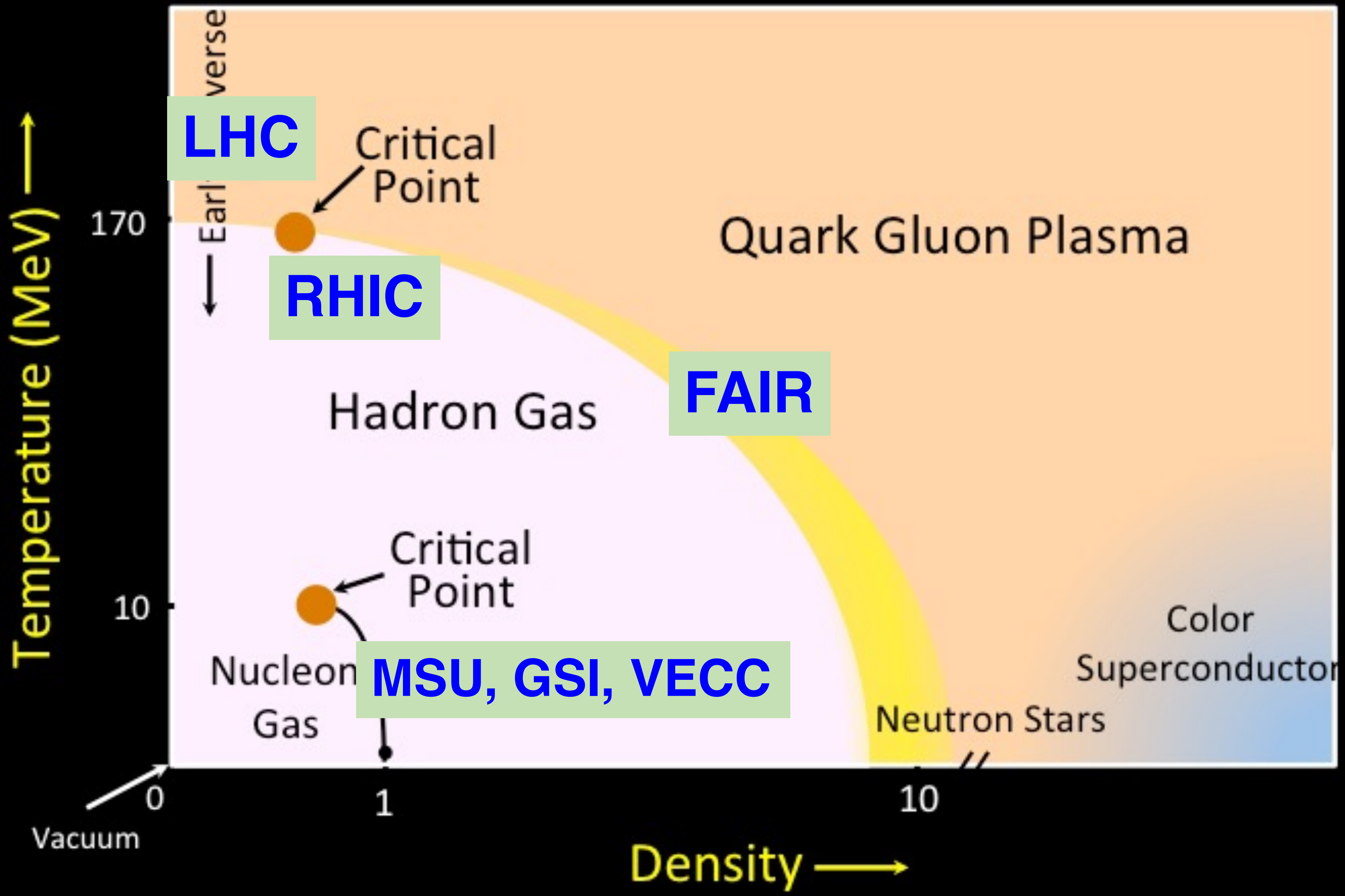
Hadron gas =>

- 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.

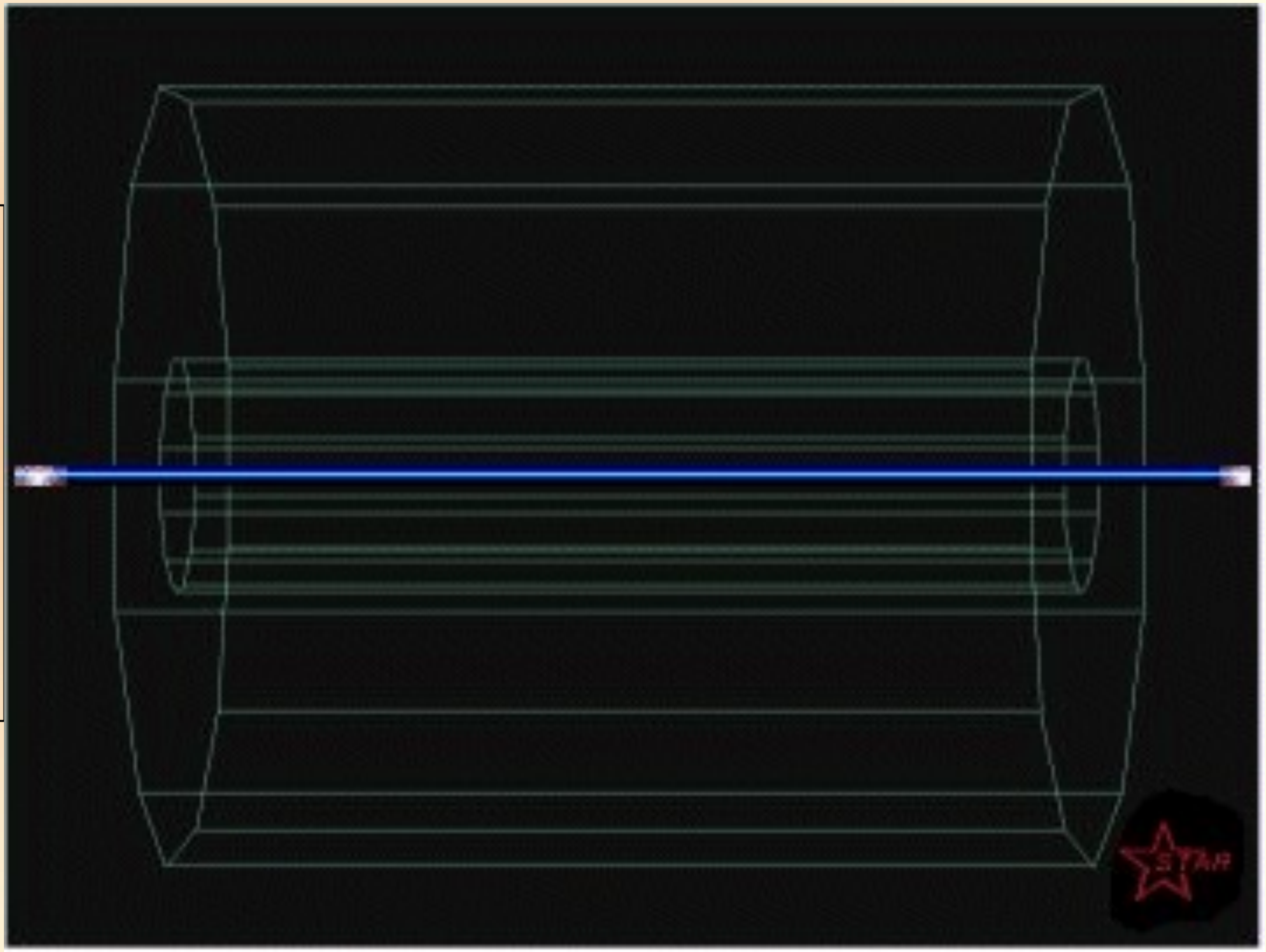
Phases of Nuclear Matter



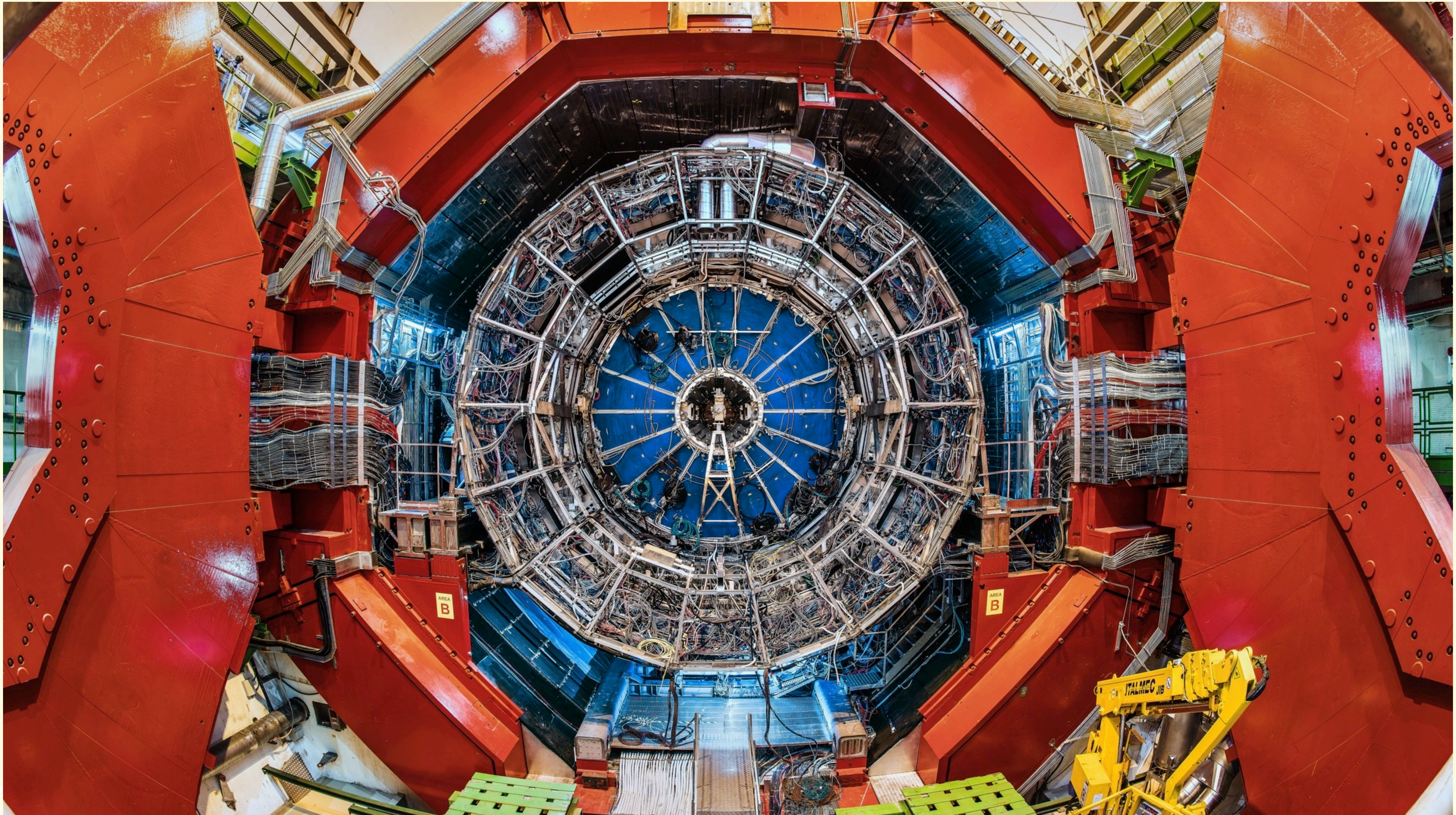
1 eV is roughly 11605 Kelvin

Heavy-ion collisions: Creating the QGP state

- Take a high-mass atom like Au or 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***

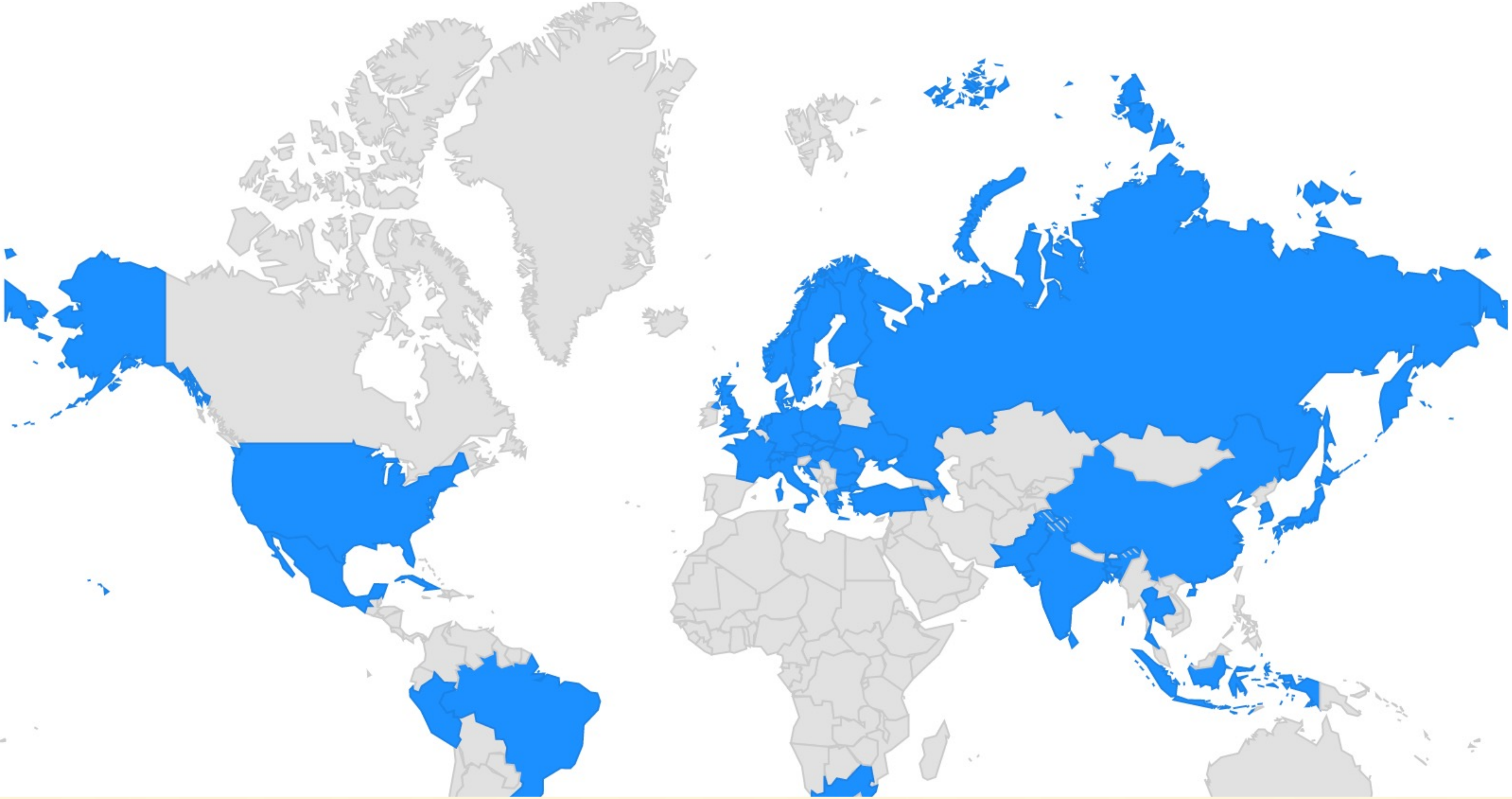


ALICE at Point-2 of the LHC



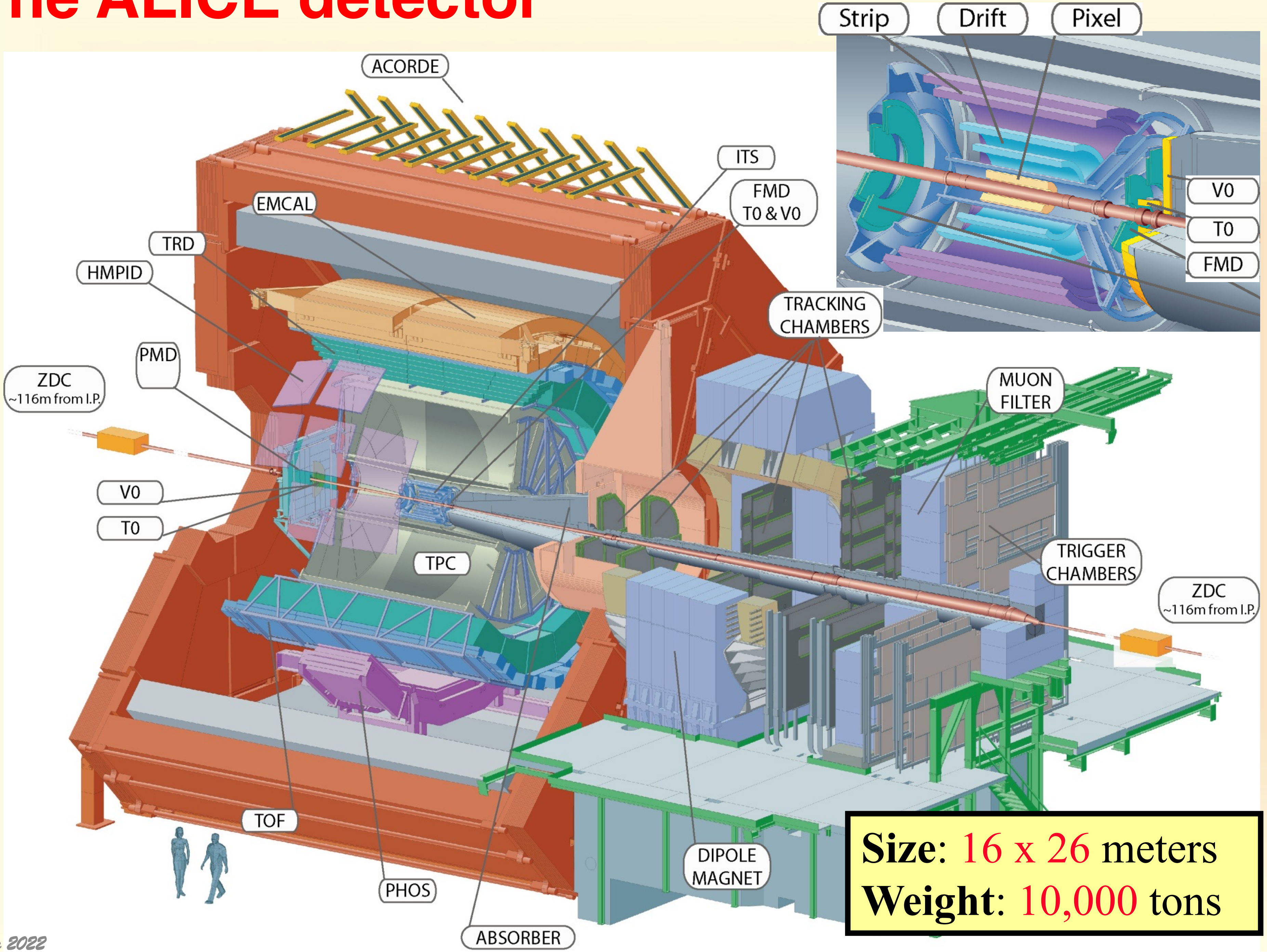
ALICE Collaboration

40 countries, 172 institutes, 1964 members



The ALICE detector

Till 2018



CENTRAL BARREL

- Acceptance: $|\eta|<0.9$
- B=0.5 T
- **ITS:** High precision vertexing and centrality
- **ITS+TPC+TOF**: charged track reconstruction, PID
- **TRD:** electron ID
- **EMCAL:** calorimeter

Muon Arm:
$-4<\eta<-2.5$

SPECIAL detectors:

- V0
- FMD
- PMD
- ADC
- ZDC

Size: 16 x 26 meters
Weight: 10,000 tons

India in ALICE

ALICE

Photon Multiplicity Detector (PMD)

Muon Tracking Chamber and MFT

MANAS: Multiplexed ANAl og Signal Processor

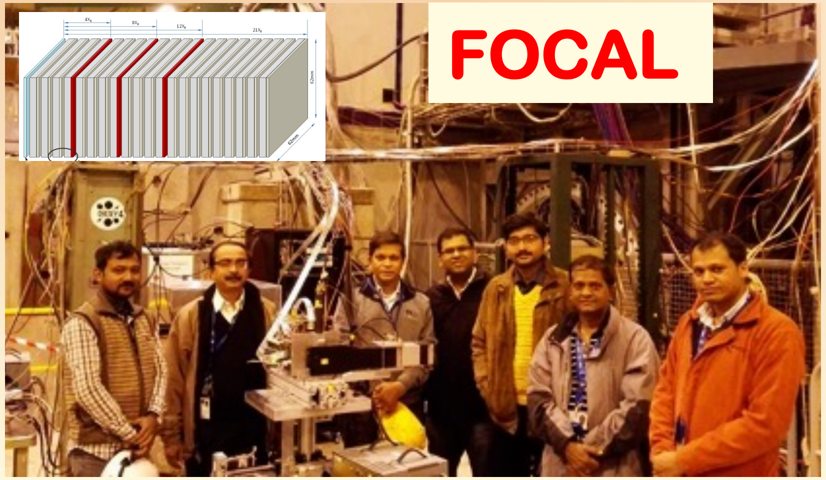
First large scale production of ASIC in India

Common Readout Unit (CRU):

ALICE LS2 Upgrade

Performs data concentration, reconstruction and multiplexing.

Silicon-Tungsten Calorimeter



FOCAL

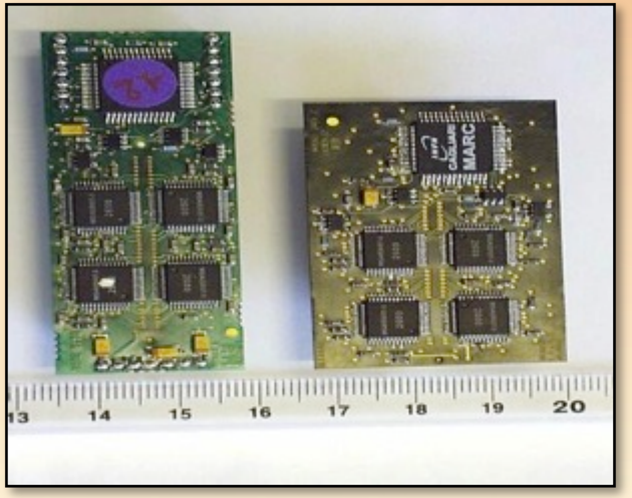
LHC GRID Computing

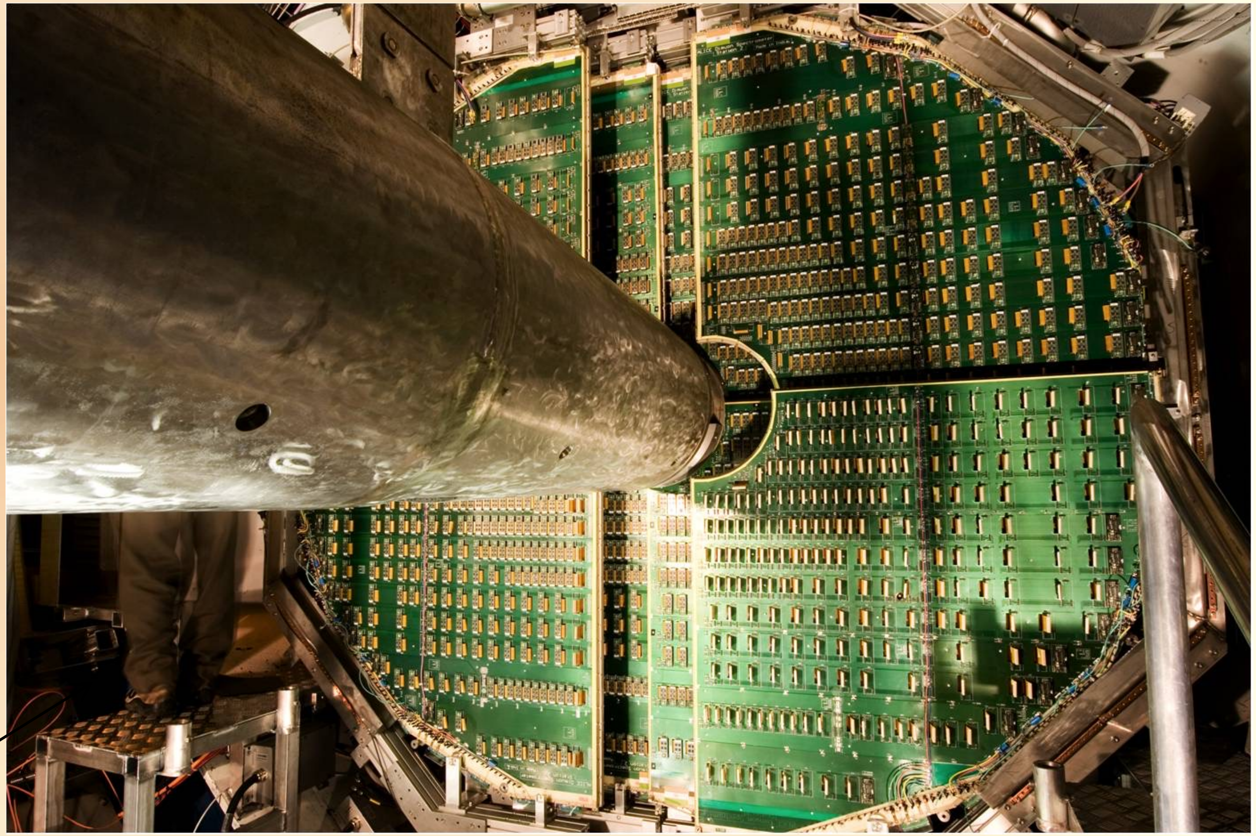
Muon Tracking Chambers

Collaboration France, India, Italy, Russia:

- 5 stations of two Cathode Pad Chambers ~ 100 m^2
- 1.1×10^6 channels, occupancy < 5%   (in Pb+Pb)
  → Read out at 1 kHz
- Chamber thickness ~ 3% X0
- Beam test results for the spatial resolution : 50 μm for a required resolution < 100 μm

Station 2 of the Muon Tracking Chamber



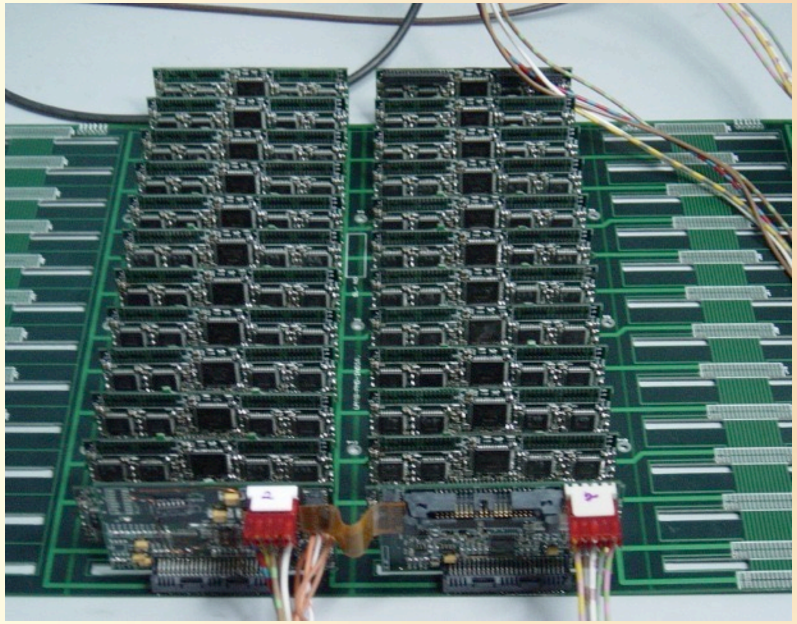


- **MANAS electronics chip: 16-channel Amplifier, shaper, track-and-hold**
- **MANU board: Reads 1.1 million pads of tracking chambers of ALICE**

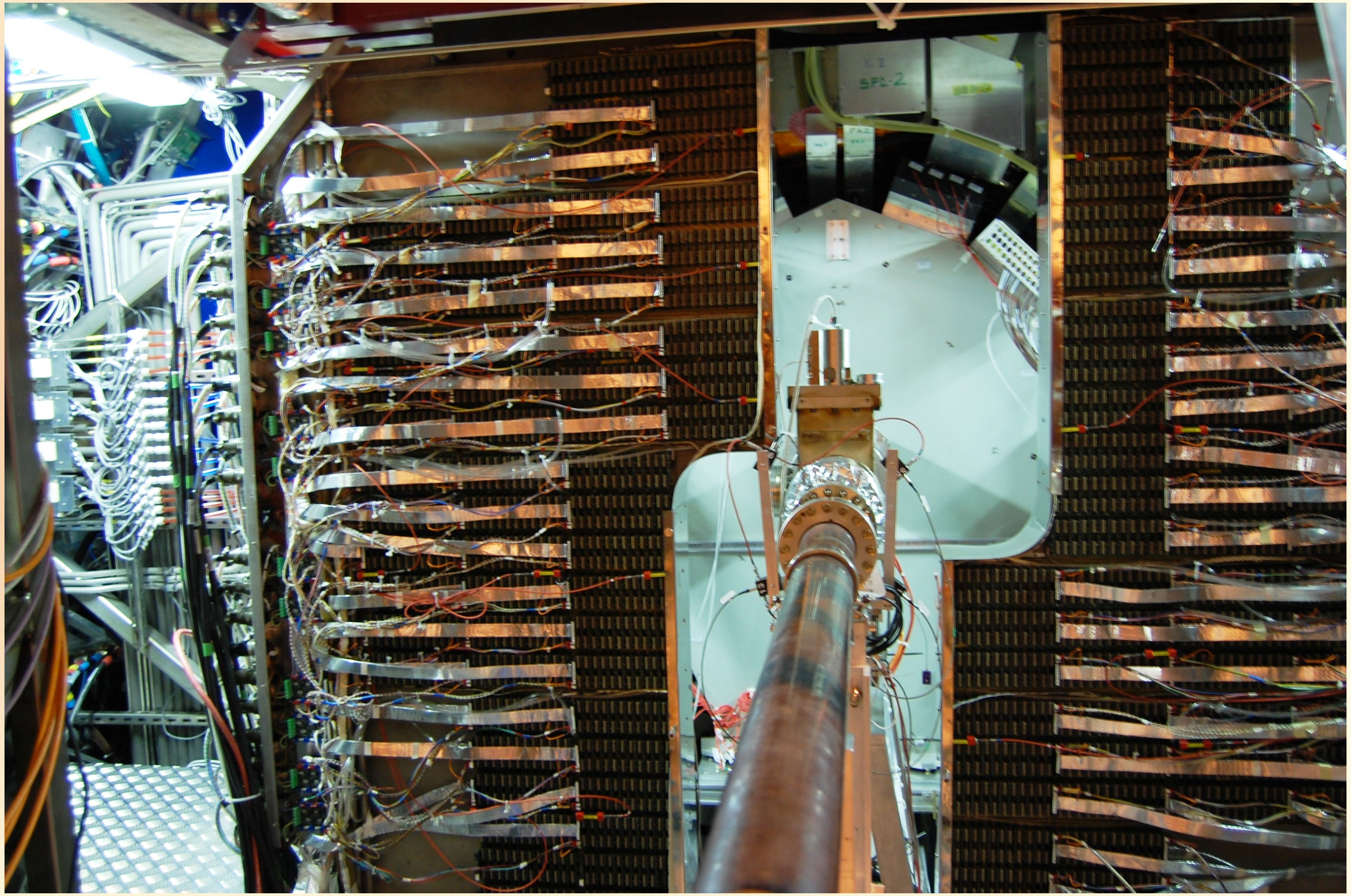
PMD: Photon Multiplicity Detector

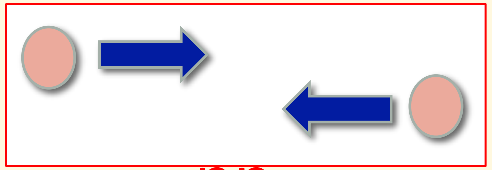
100 % Indian effort: from conception to commissioning (Design, Fabrication, Installation, Detector Control, and DAQ)

48 Modules with 221,184 gas cells:



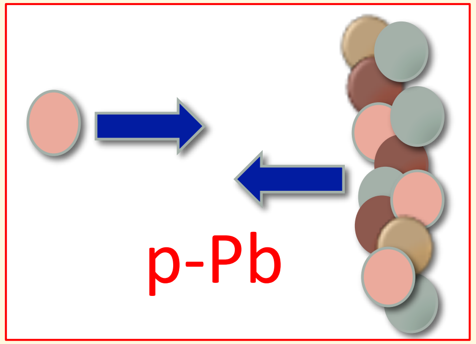
PMD in the ALICE cavern



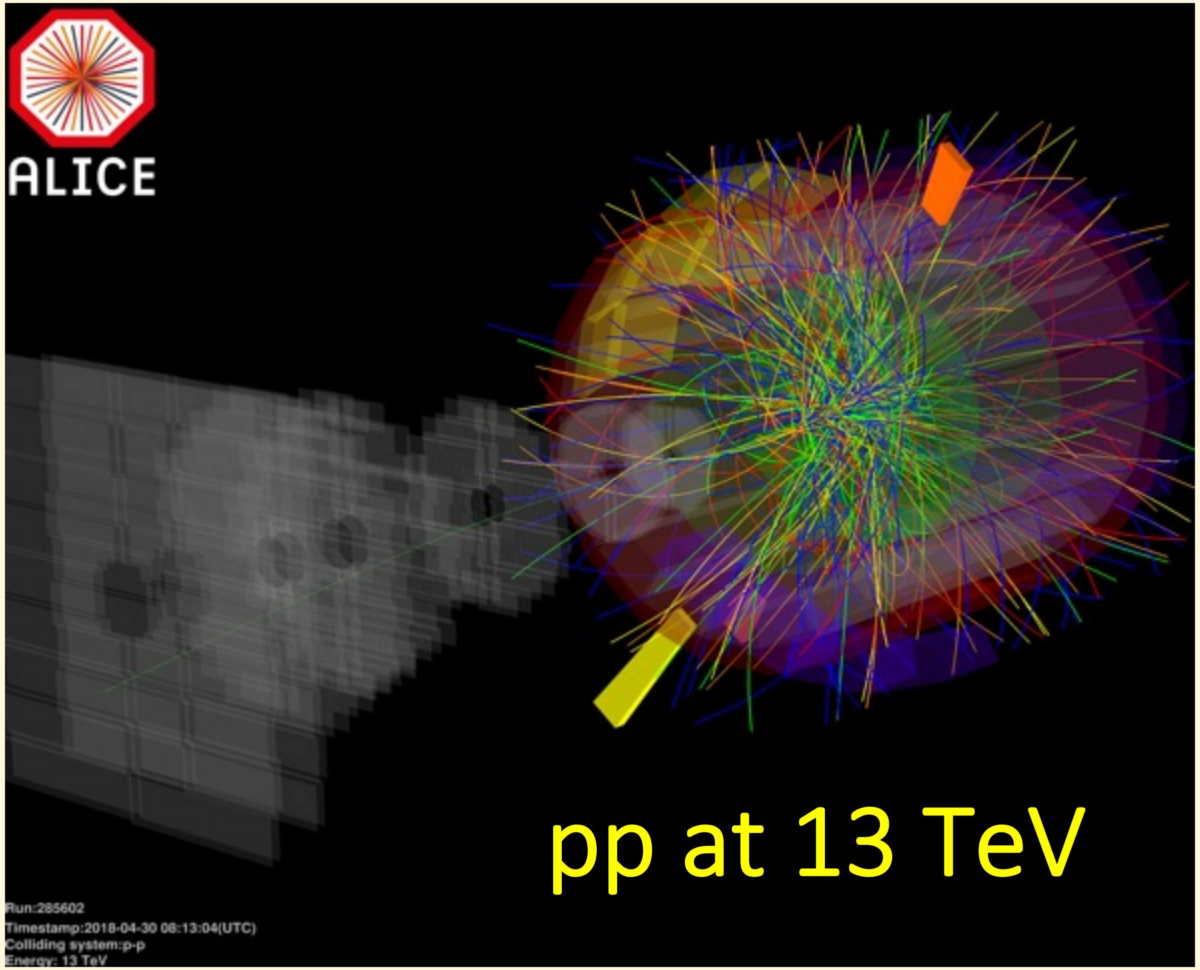


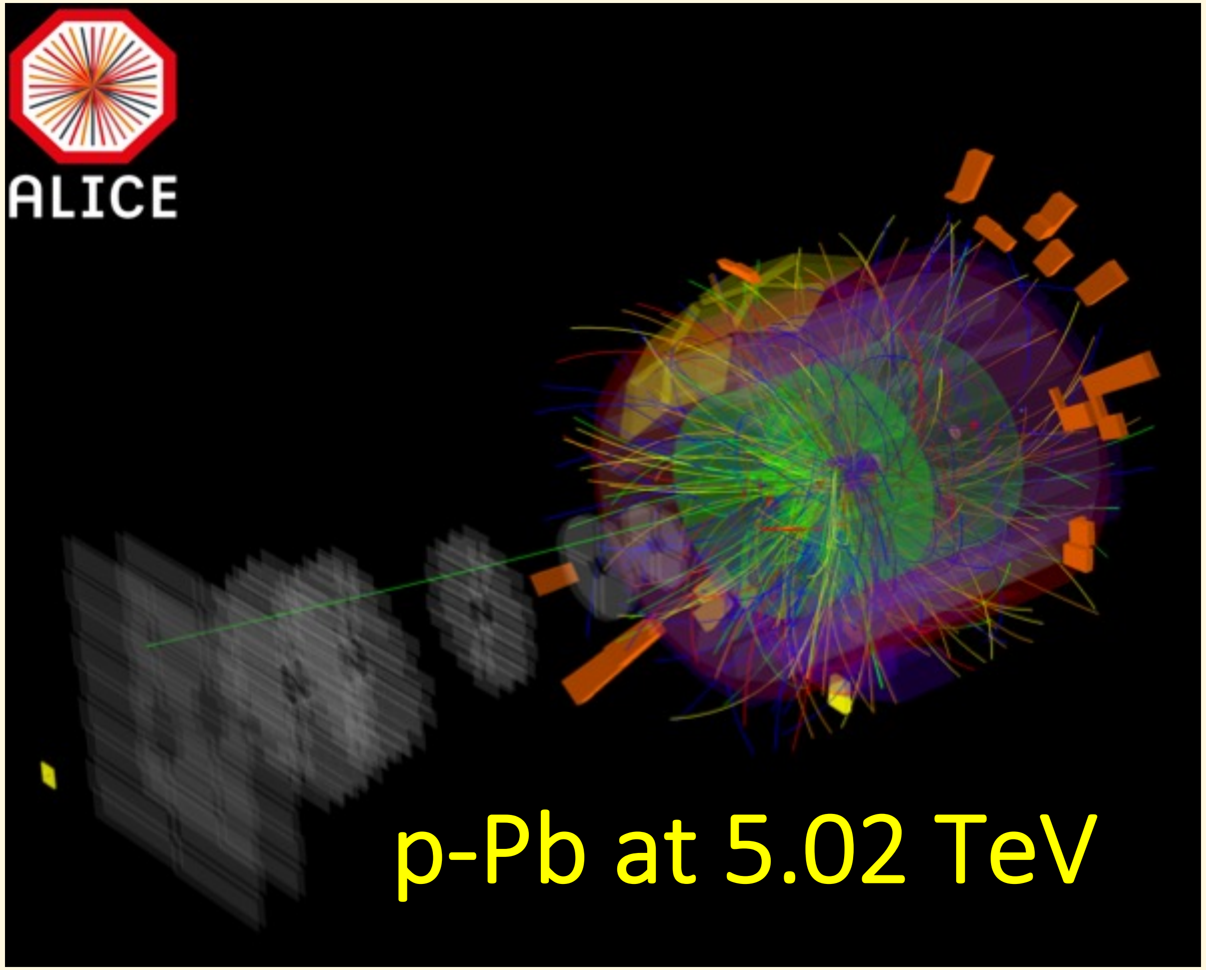
pp

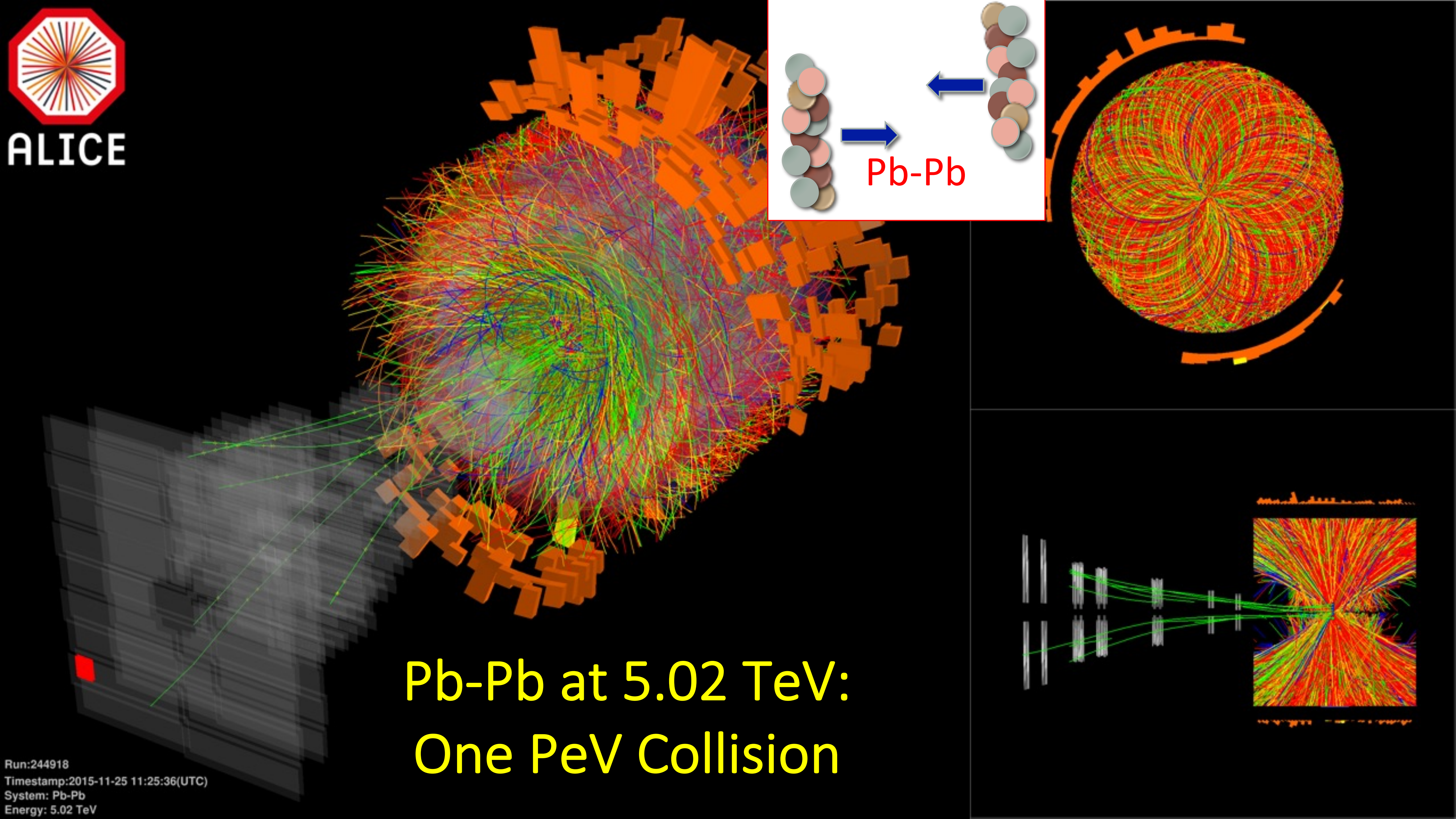
- Test of pQCD calculations from cross section measurements
- Provide reference for p-Pb and Pb-Pb collisions
- High multiplicity pp: what's the behaviour?



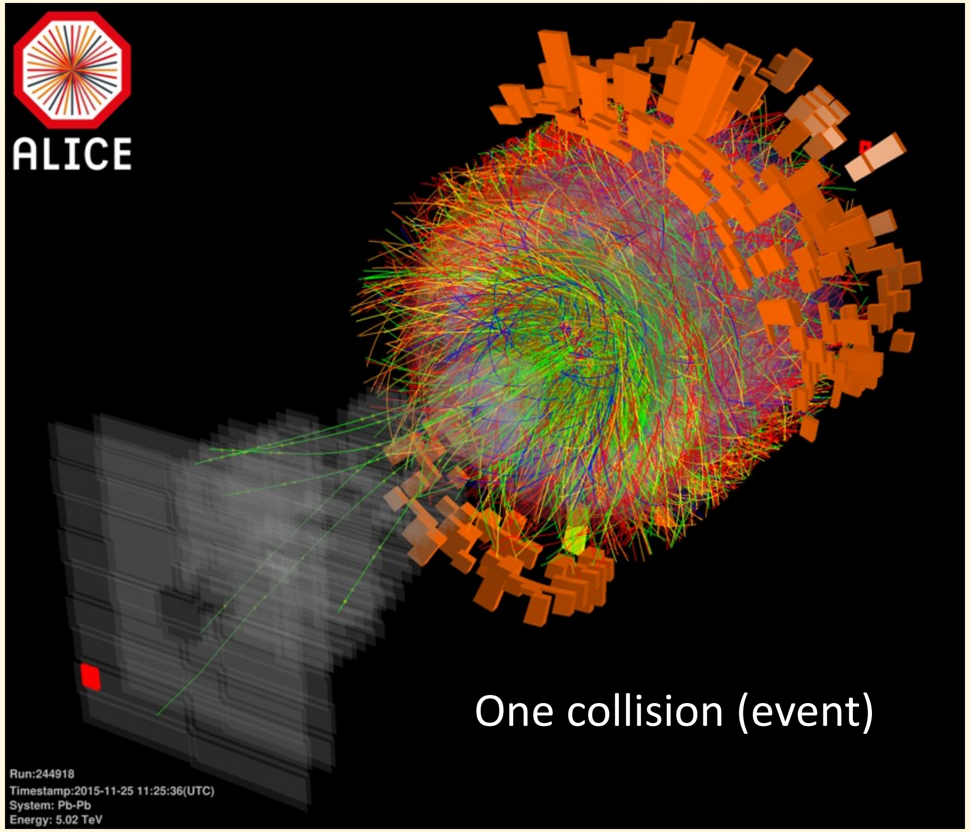
- Intermediary reference
- Address cold nuclear matter effects in initial and final states






ALICE
Pb-Pb
Pb-Pb at 5.02 TeV:
One PeV Collision
Run:244918
Timestamp:2015-11-25 11:25:36(UTC)
System: Pb-Pb
Energy: 5.02 TeV

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):

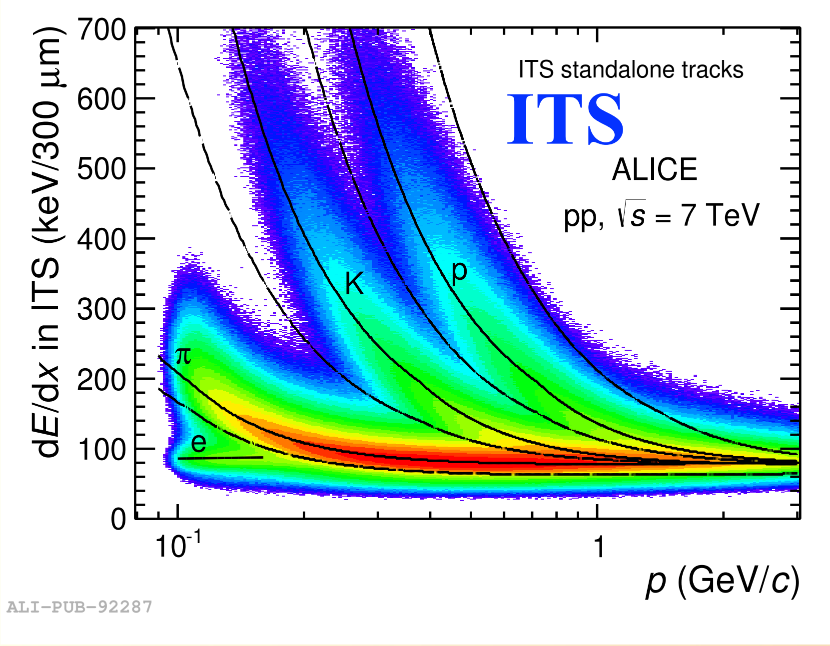
- Online data quality monitoring, calibrations.
- Using Triggers to keep events of interest and sends to storage.

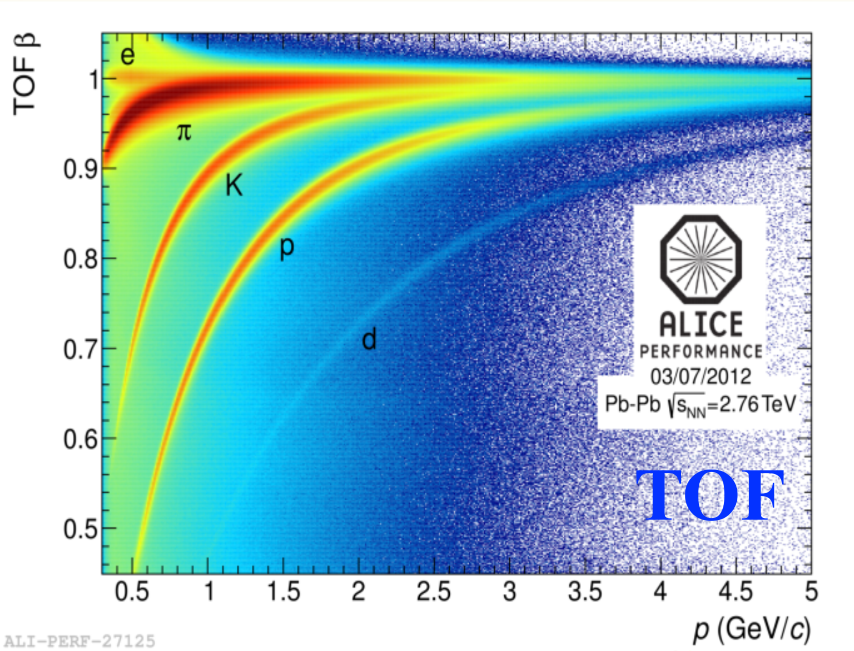
=> Offline: Event reconstruction:

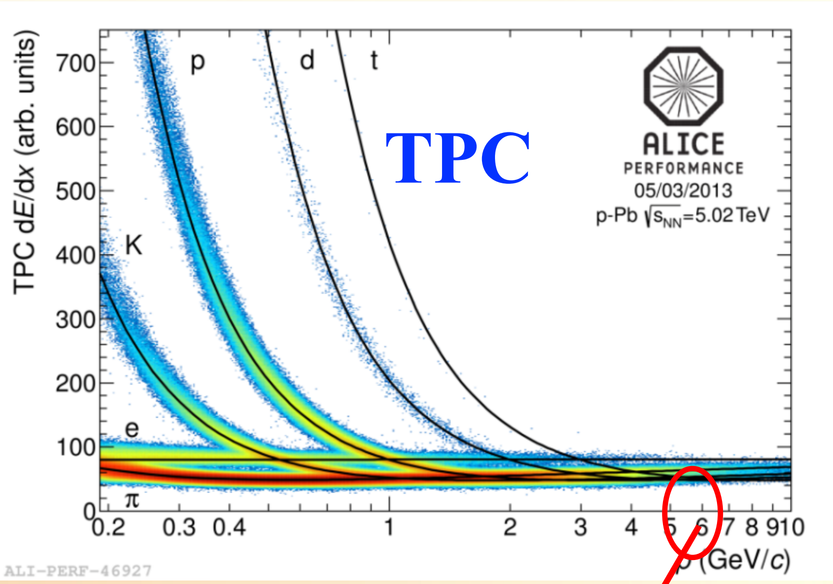
- Vertexing
- Tracking
- Particle identification of each of the tracks

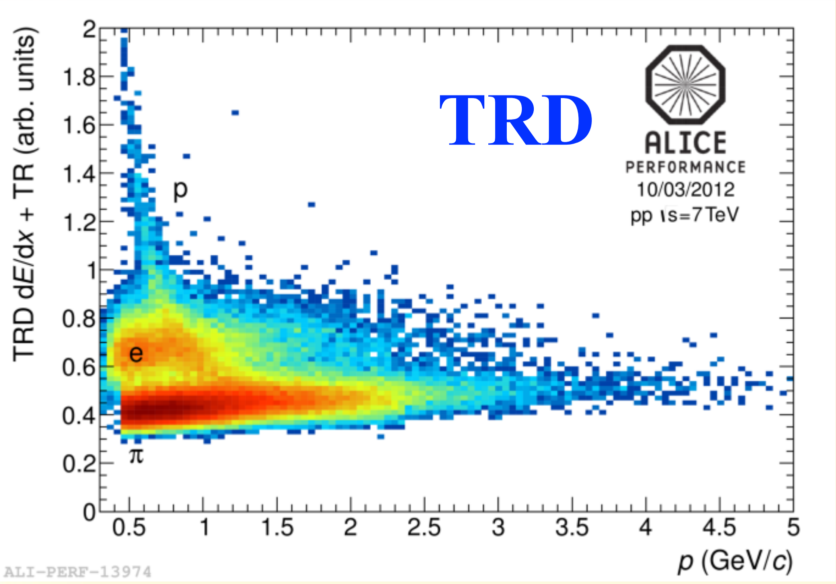
- The data flow from ALICE during Run2 was about 4 GB/second
- The data expected during next run (Run3) will be 3 TB/second

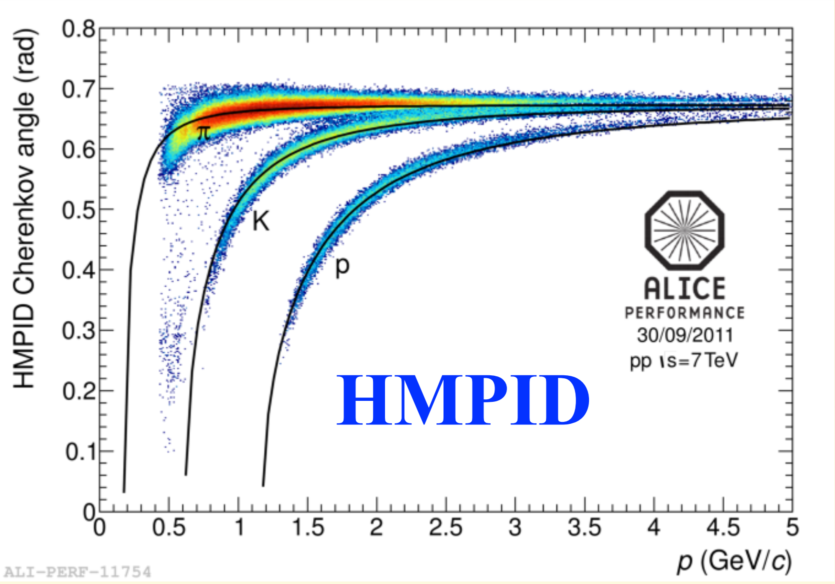
ALICE performance

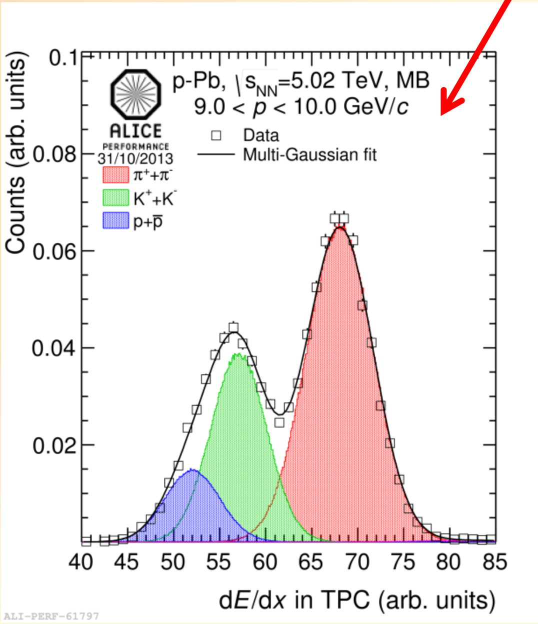




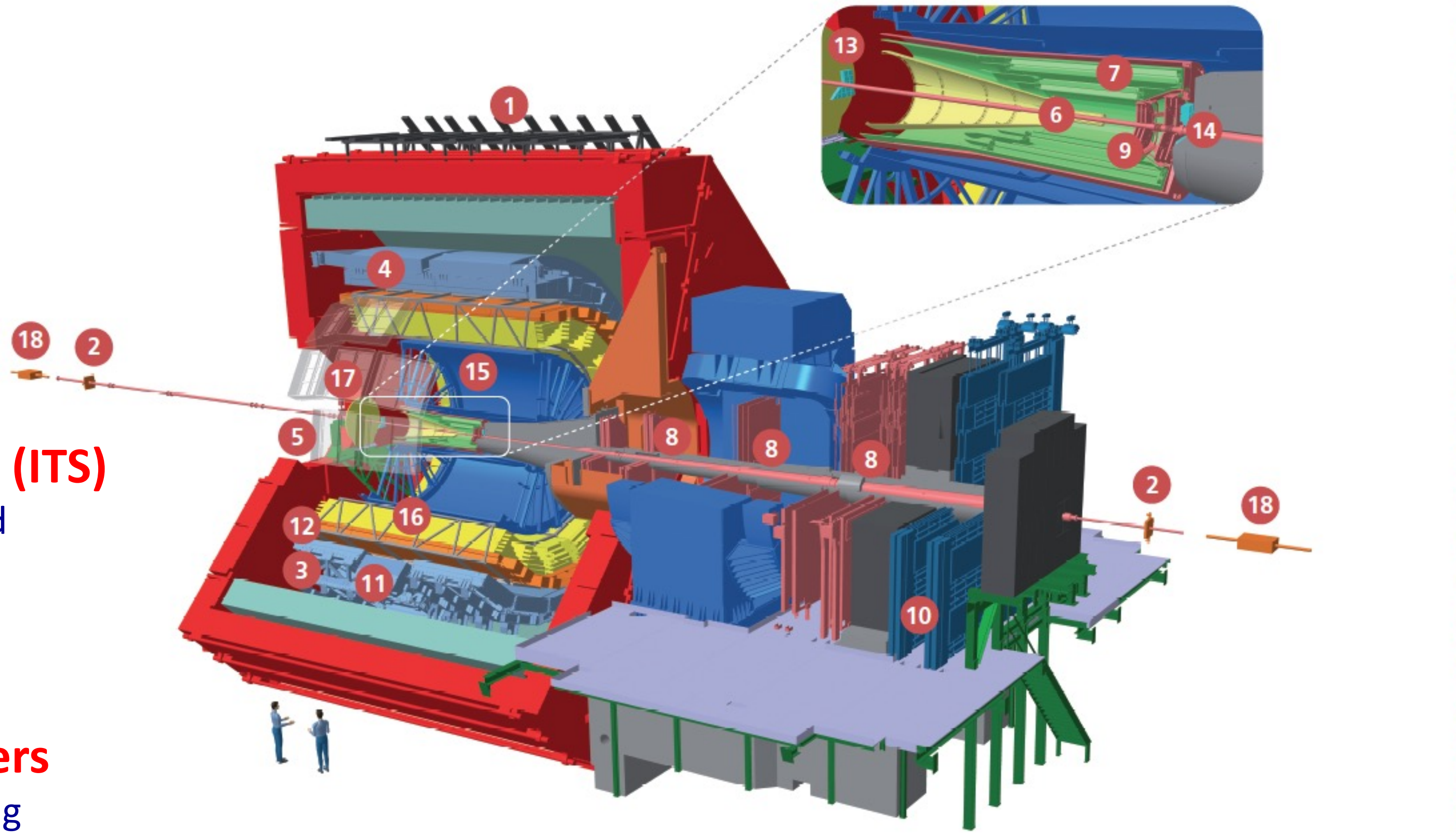








ALICE in (2022)



New Inner Tacking System (ITS)

- MAPS technology: improved resolution
- Less material,
- Faster readout

New TPC Readout Chambers

- New readout chambers using 4-GEM technology
- New electronics for continuous readout (SAMPA)

New Forward Muon Tracker (MFT)

- Vertex tracker at forward rapidity

Muon Arm

- New electronics (SAMPA)
- New electronics for Muon Trigger

Online Offline (O2) system

- new computing facility
- on line tracking & data compression
- 50kHz Pb-Pb event rate

Common Projects:

Common Readout Unit (CRU)
SAMPA common FE chip

New Trigger Detectors (FIT, AD)

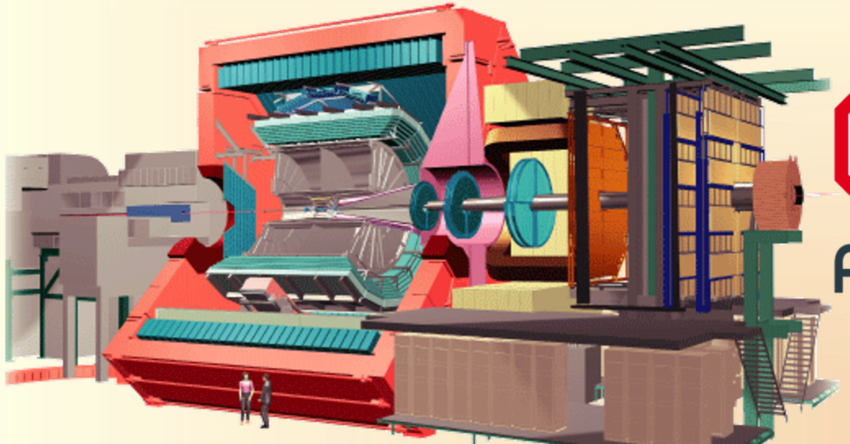
- + centrality, event plane

New Central Trigger Processor (CTP)

Upgraded readout for TOF, TRD, PHOS, EMCAL, CPV, HMPID

Common Readout Unit (CRU) in Run3

3: The total data volume from the front-end cards of the detectors will e significantly, reaching a sustained data throughput of up to 3 TB/s. The computing model is designed for a maximal reduction in the data volume



Pb-Pb 5.5 TeV

50 kHz (70 MB/event)
Total ~3 TB/s

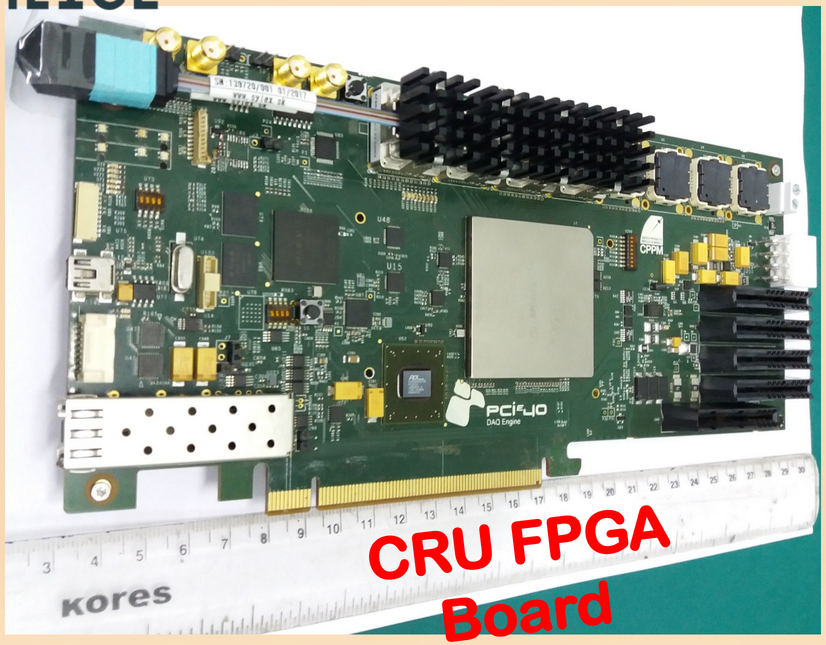
Online
Offline
(O^2)

CRU

50 kHz (1.5 MB/event)

Storage

90 GB/s (peak)



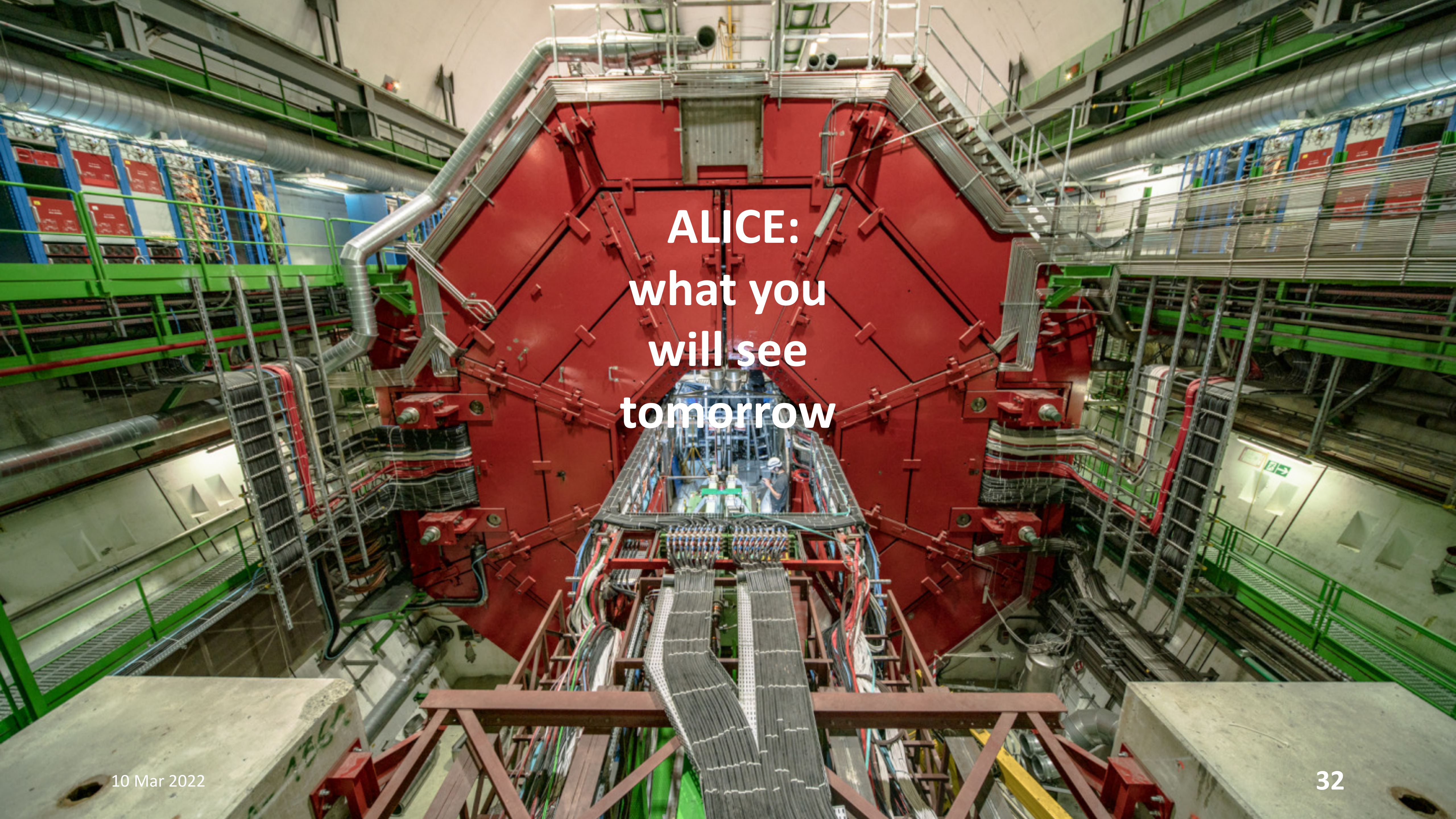
CRU is tasked to perform online data concentration, reconstruction and multiplexing.

This makes CRU one of the most important components of ALICE.

India's Contribution:

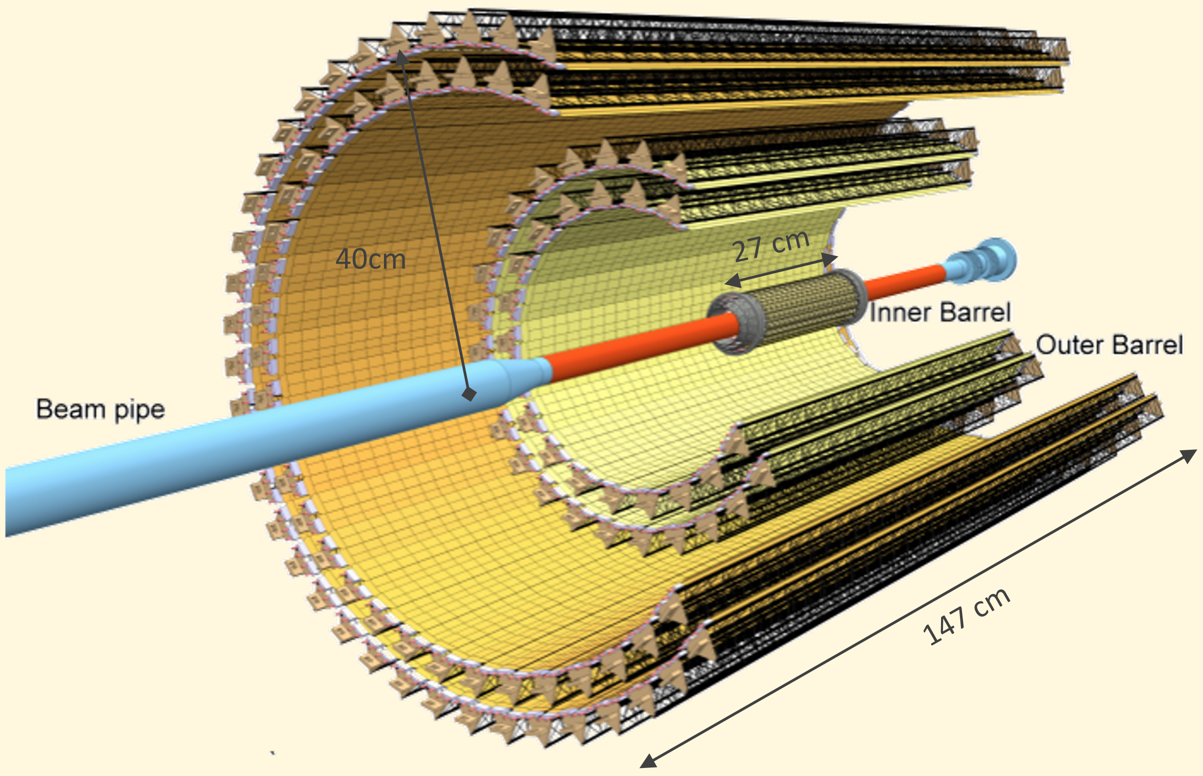
400 CRU boards for TPC

Indian scientists and engineers have contributed to the design, prototyping and testing of the CRU over the last five years in collaboration with CERN, Wigner Institute, and CPPM, Marseille.



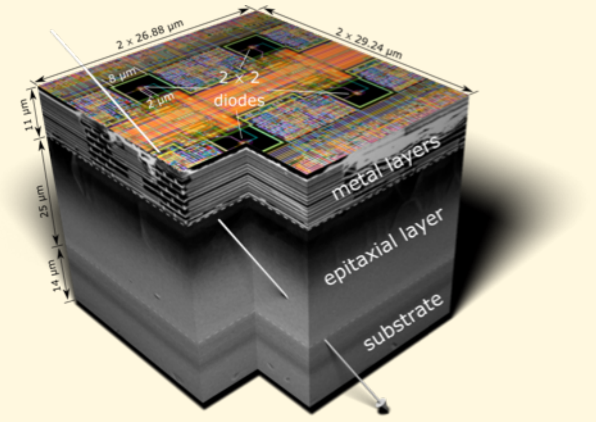
ALICE: what you will see tomorrow

New Inner Tracking System (ITS)



- 7-layer geometry (23 – 400mm), $|\eta| \leq 1.5$)
- 10 m^2 active silicon area (**12.5 G-pixels**)
- Pixel pitch 28 x 28 μm^2
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Material thickness: ~0.3% / layer (IB)
- Maximum particle rate: 100 MHz / cm^2

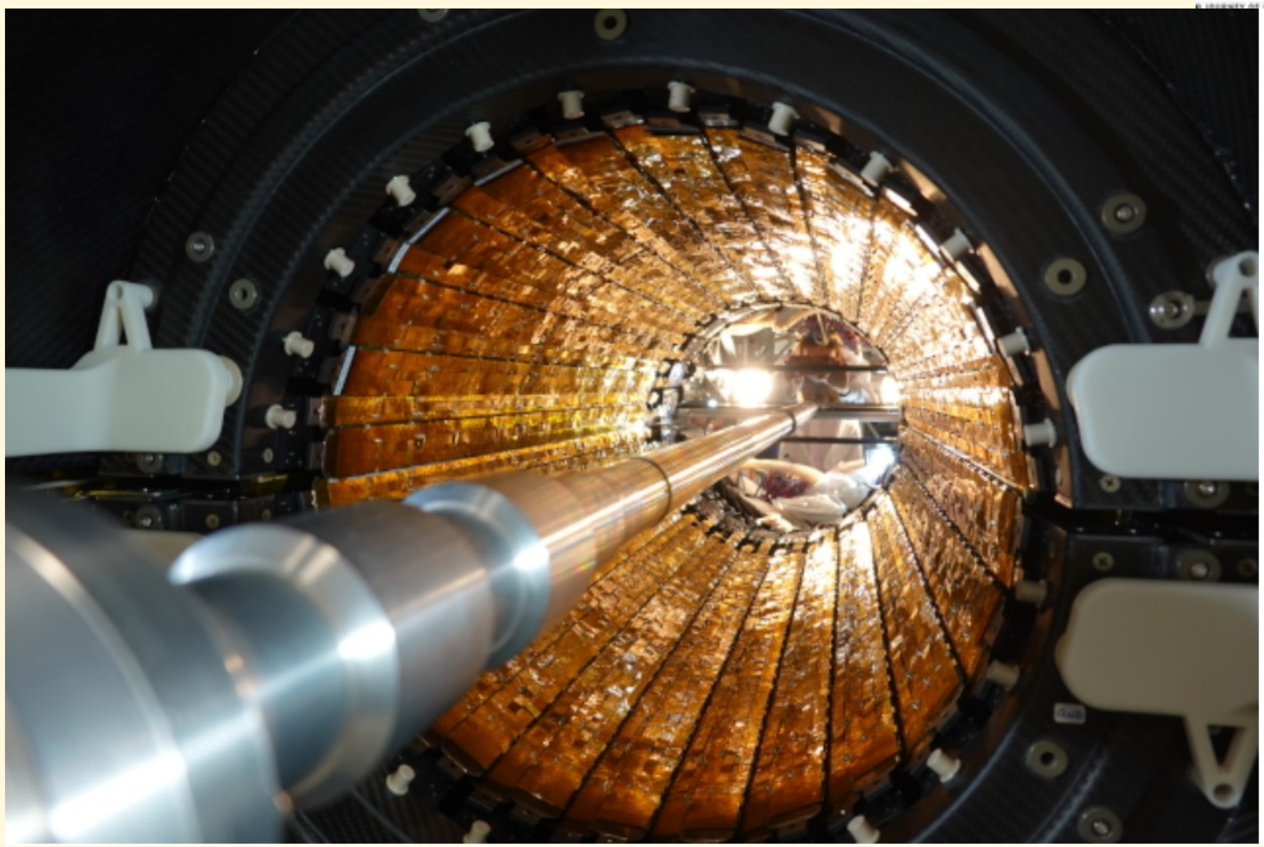
Based on CMOS Monolithic Active Pixel Sensors (MAPS)



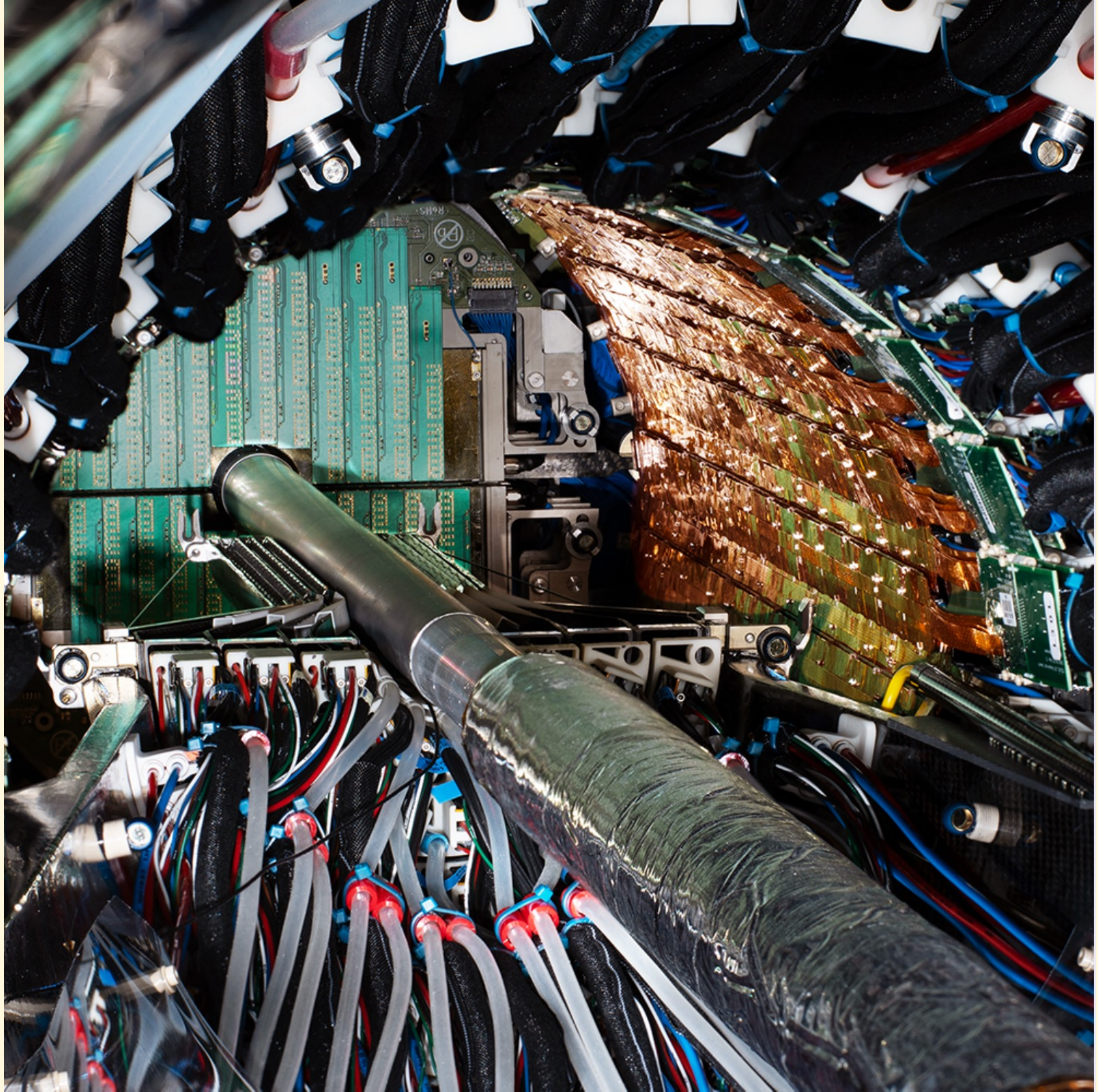
ITS inner

$10\ m^2$ active silicon area (**12.5 G-pixels**)

ITS outer



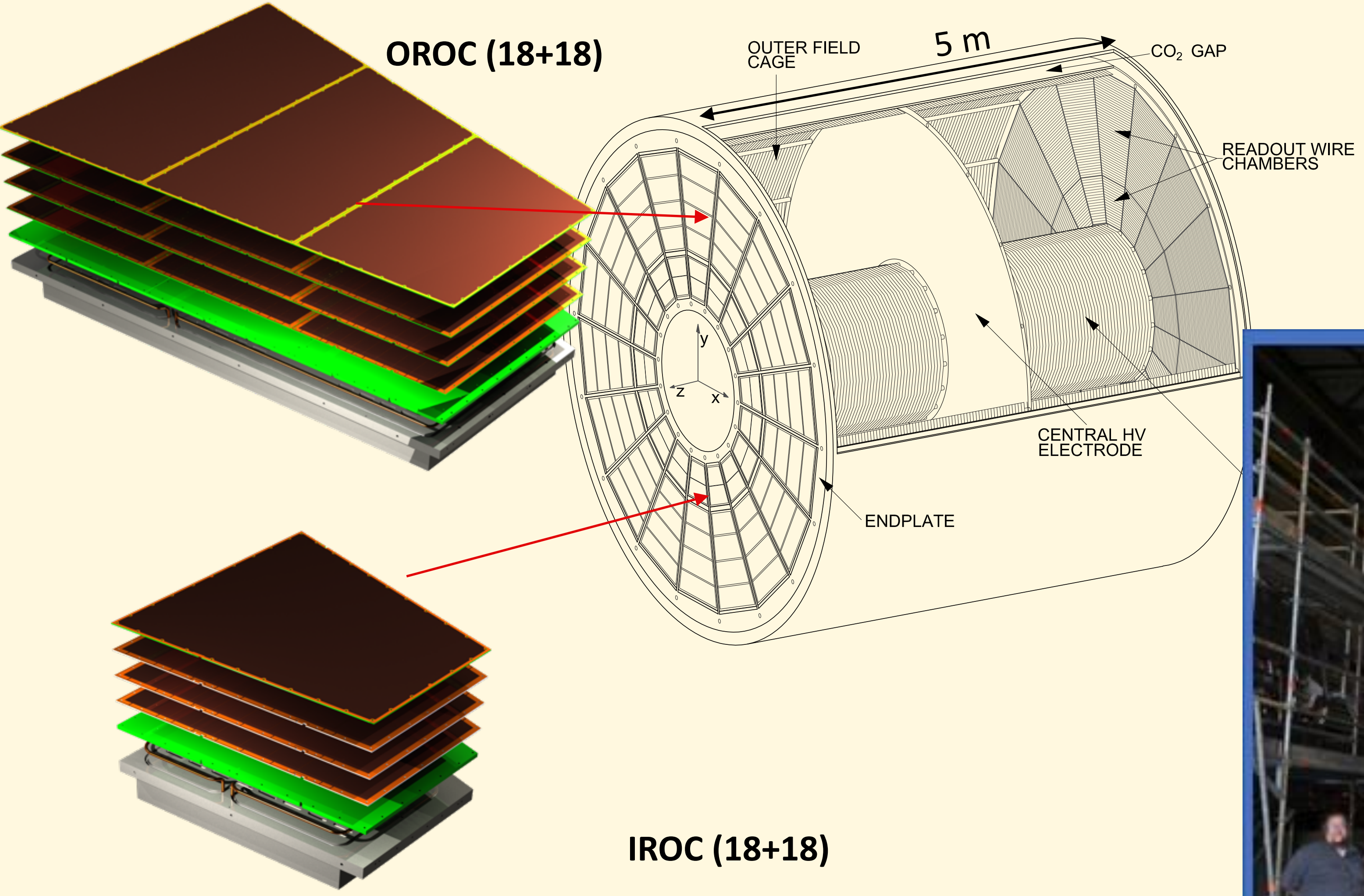
- In recent years, CMOS image pixel sensors have been widely used in digital cameras and smartphones. The ALICE ITS uses the same technology for detecting particles.
- In contrast to consumer applications, it is significantly larger: $10 m^2$ surface area (more than the sensors of 25000 cameras), and contains 12.5 billion pixels, a thousand times more than most consumer devices.
- On top of it, it takes 50000 pictures a second.



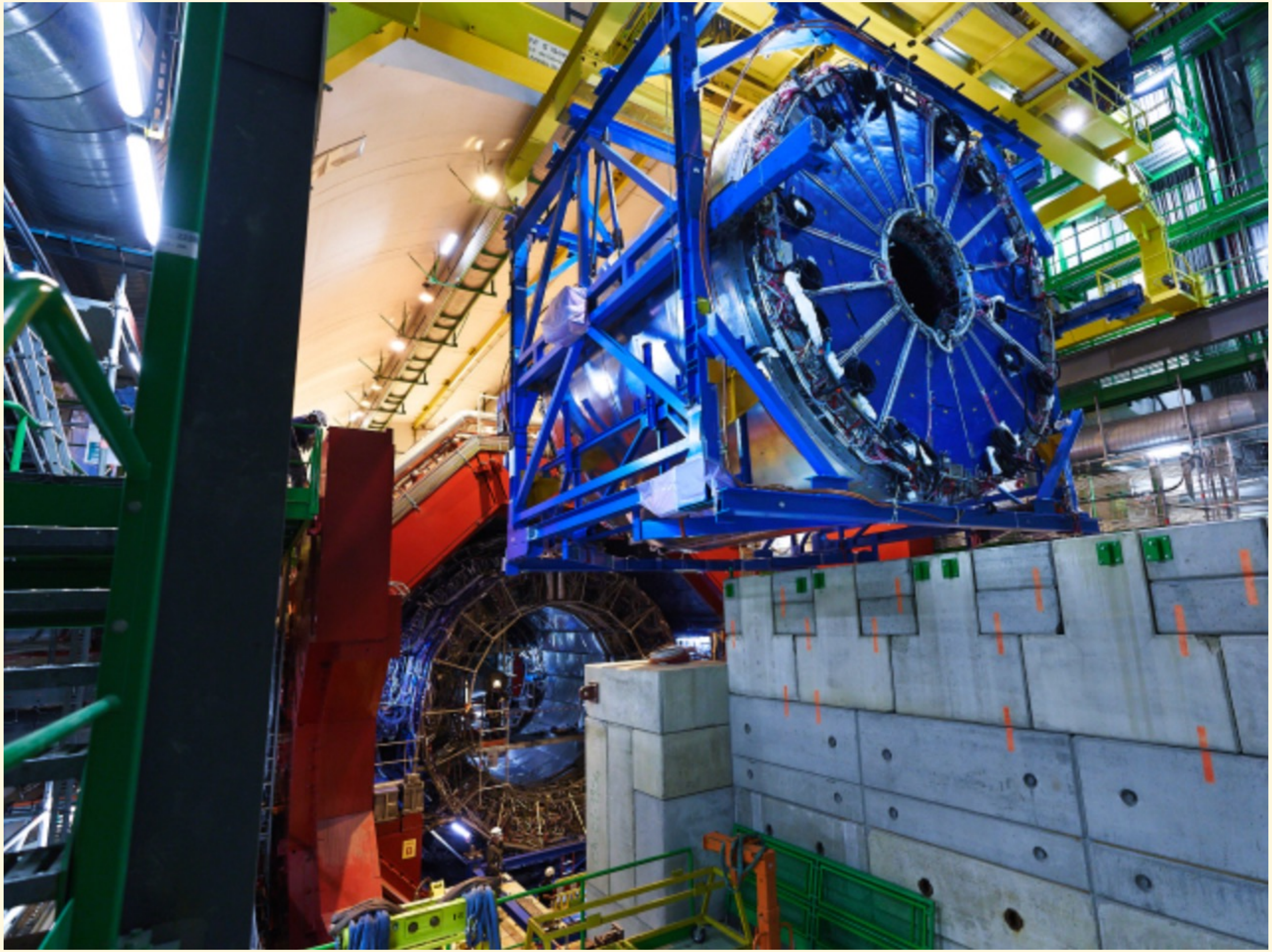
The inner (left, middle) and outer (gold colour) barrels of ALICE's state-of-the-art **Inner Tracking system (ITS)** along with the new **Muon Forward Tracker (MFT)** (green panel).

https://cerncourier.com/a/alice-tracks-new-territory/

Time Projection Chamber (TPC) with GEM detectors

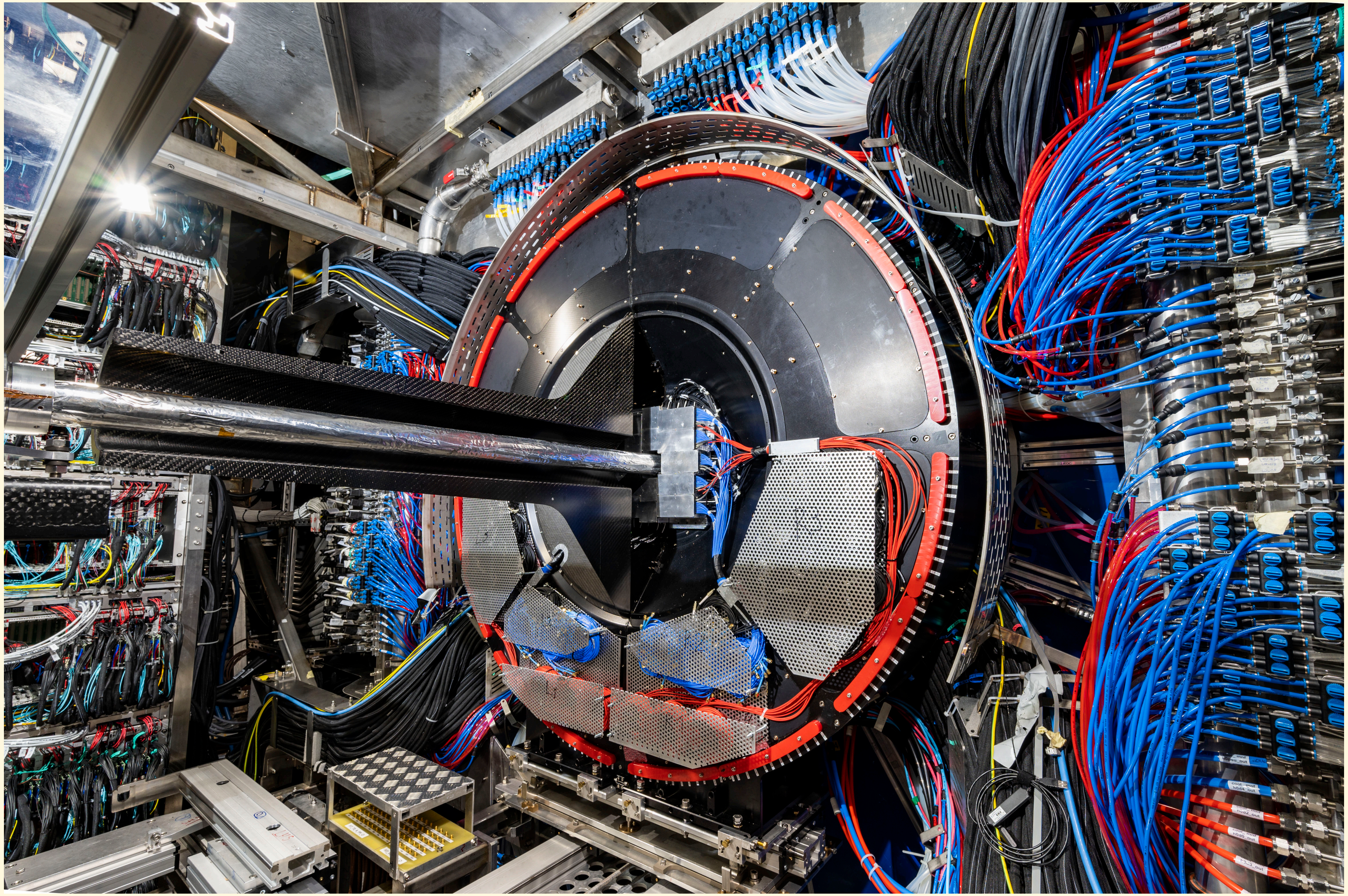


TPC installation



https://videos.cern.ch/record/2729677

Fast Interaction Trigger (FIT)

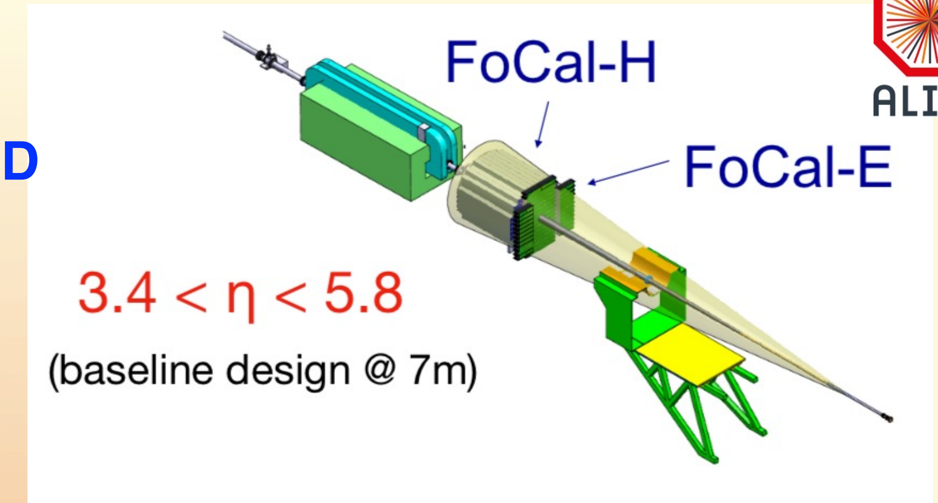


FIT is the

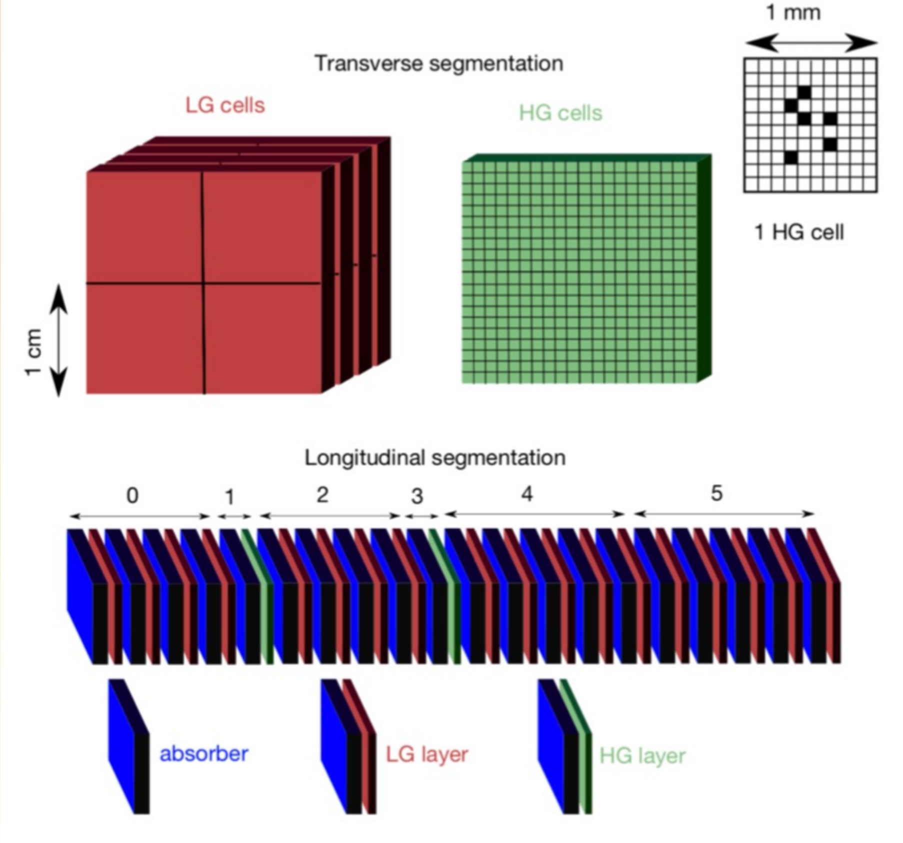
- fastest trigger,
- Online luminometer,
- initial indicator of the vertex position, and
- The forward multiplicity counter for ALICE.

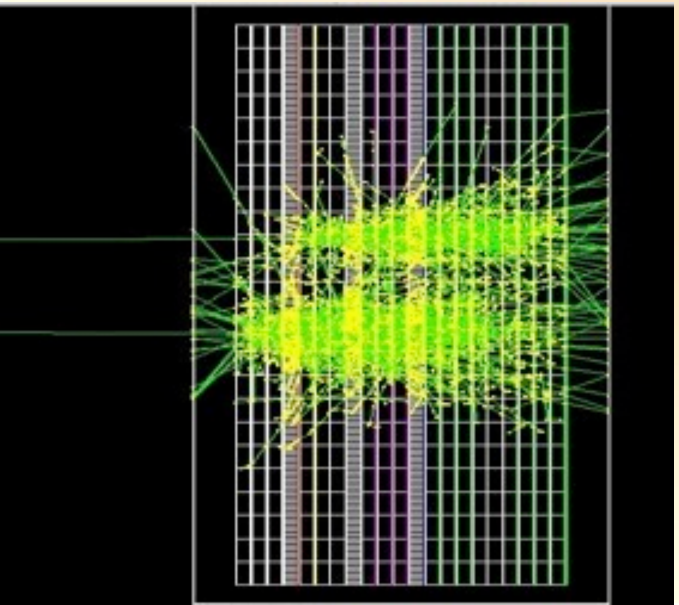
ALICE upgrade: FOCAL

2008: First Proposal from India as a replacement for PMD



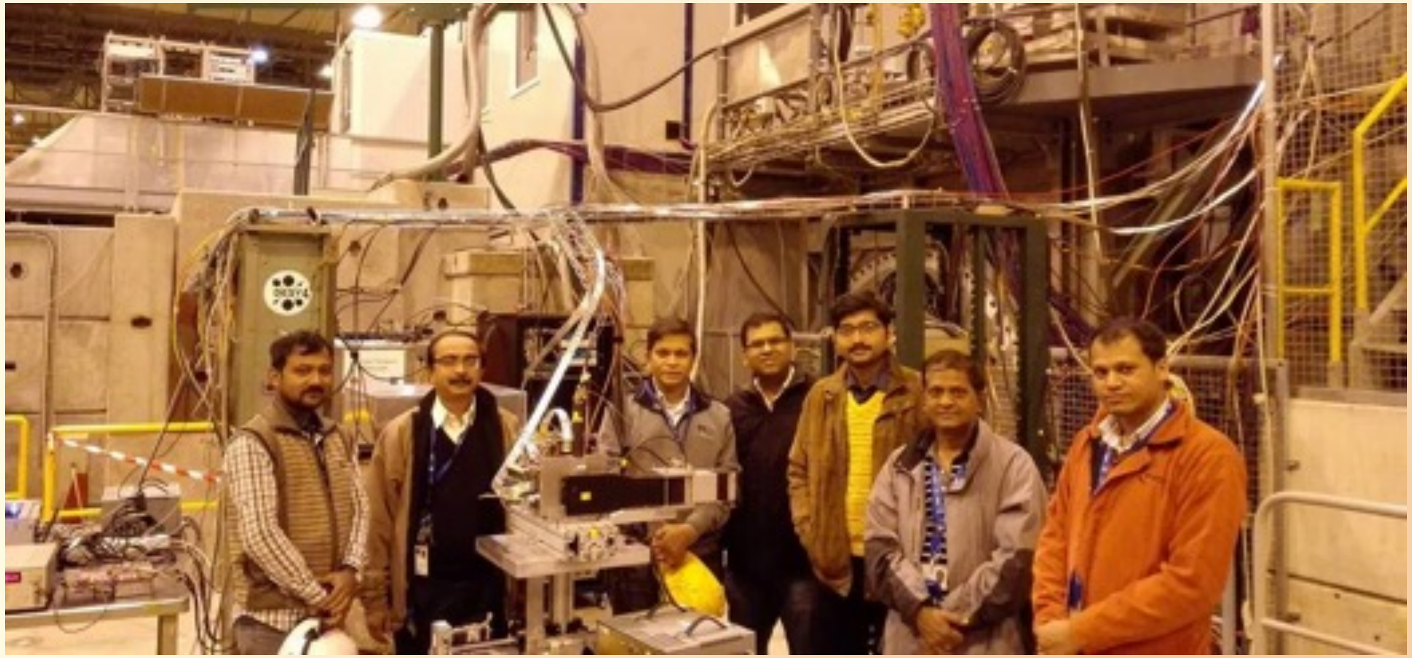
- **Physics:**
  - Initial State: Low-x Gluon Saturation
  - Initial State: Nuclear PDFs
  - Jet quenching, flow and correlations …
- **Detector R&D done in India**
- **All components from India:**
  - High resolution Silicon Pad Detector
  - Readout chips (MANAS, AnuIndra, AnuSanskar)

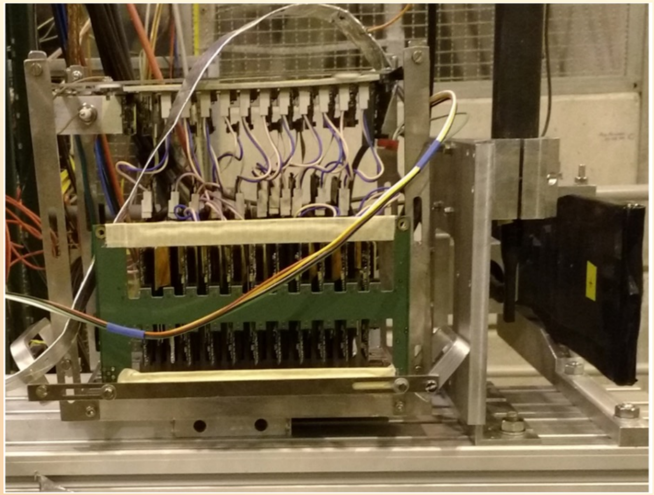


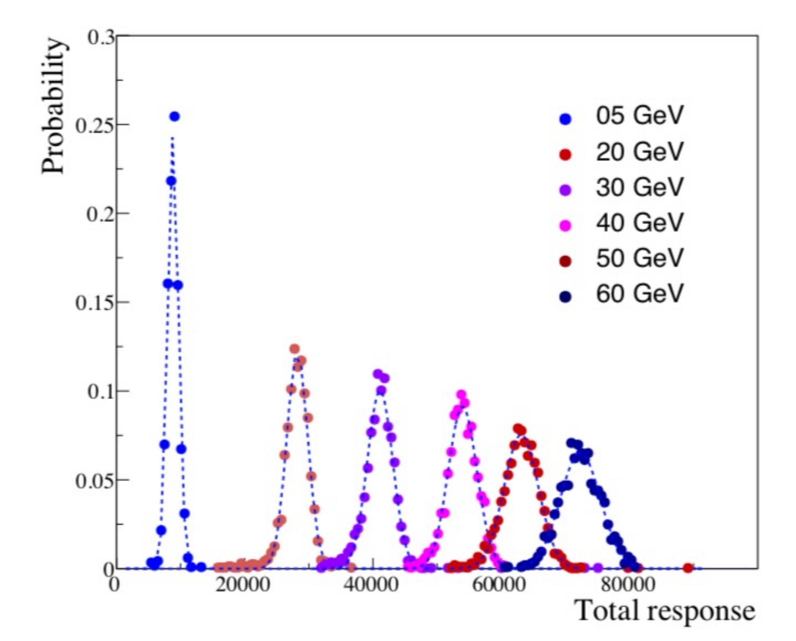


Simulation of a pi0 decaying to two photons

Silicon- Tungsten Calorimeter: 2015 test beam at CERN

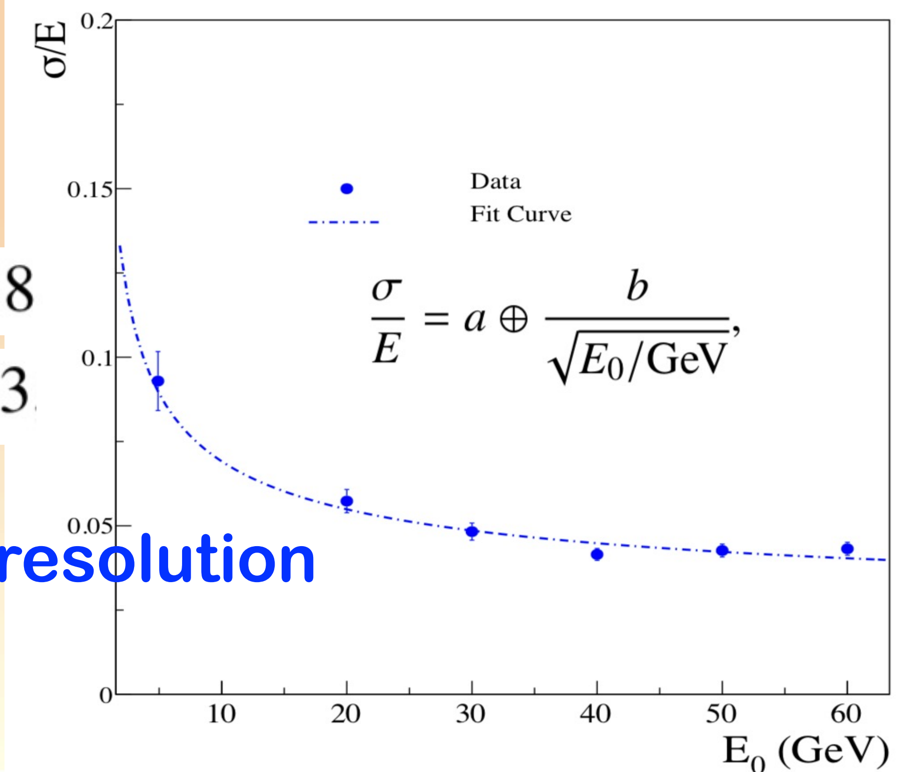






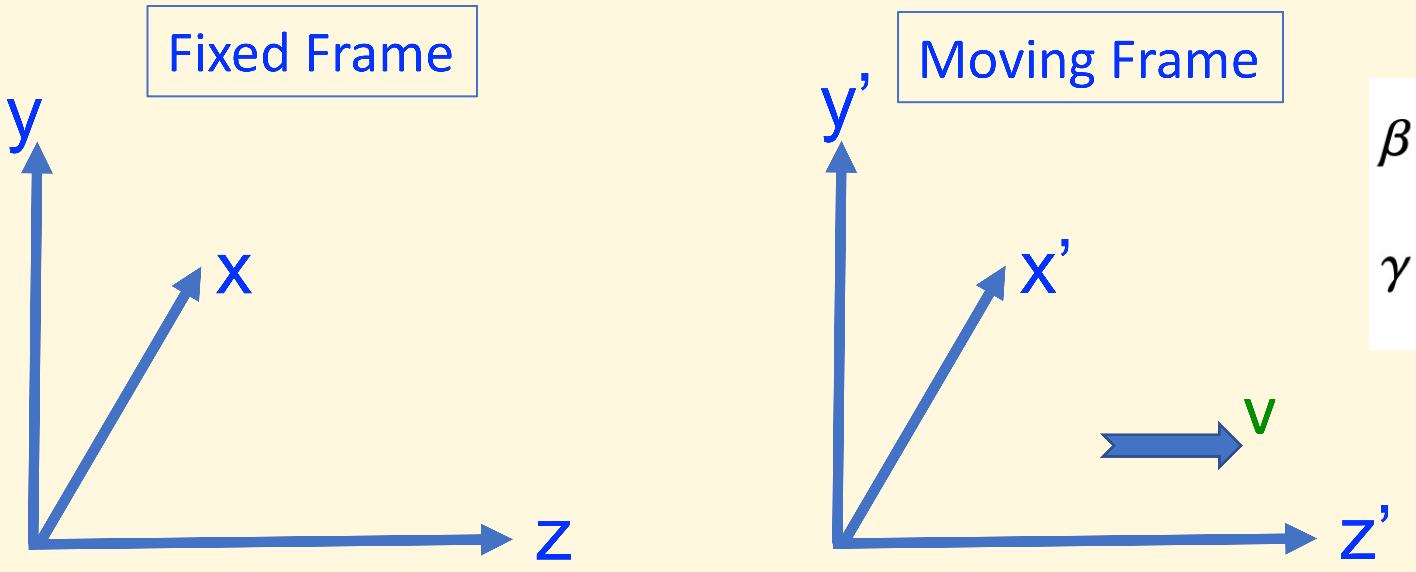
$$a = 0.020 \pm 0.0038$$

$$b = 0.1536 \pm 0.023$$



Excellent energy resolution

Special theory of Relativity: Lorentz Transformation



$$\beta = \frac{v}{c}$$

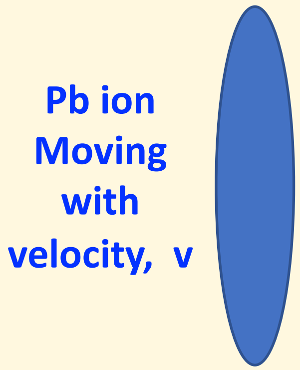
$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$x' = x$$
$$y' = y$$
$$z' = \gamma \cdot (z - vt)$$
$$t' = \gamma \cdot (t - \frac{vz}{c^2})$$

Transformation with velocity, v, along the z-axis.

- In moving frame an object has always the same length (it is invariant !)
- From fixed frame moving objects appear contracted by a factor γ (Lorentz contraction)

Radius of Pb ion: L
(~ 7fm)



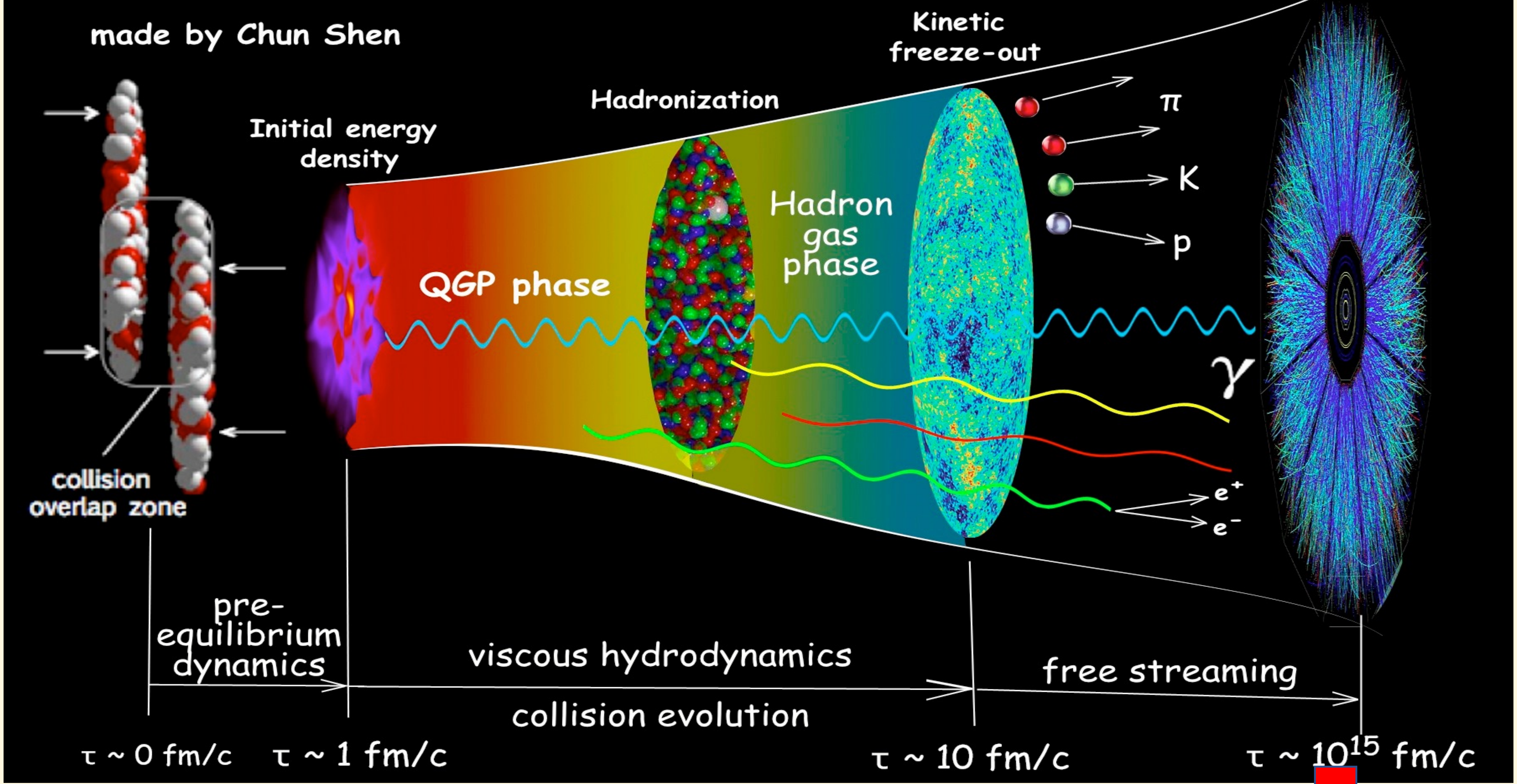
$L' = \gamma L$

$L = L'/\gamma$

For v = 0.999999991 c
$\gamma = 7453.$

Length (radius) along z-axis appear contracted by 7453 times.
Only the longitudinal direction gets contracted – not the transverse ones.

Relativistic Heavy-Ion Collision



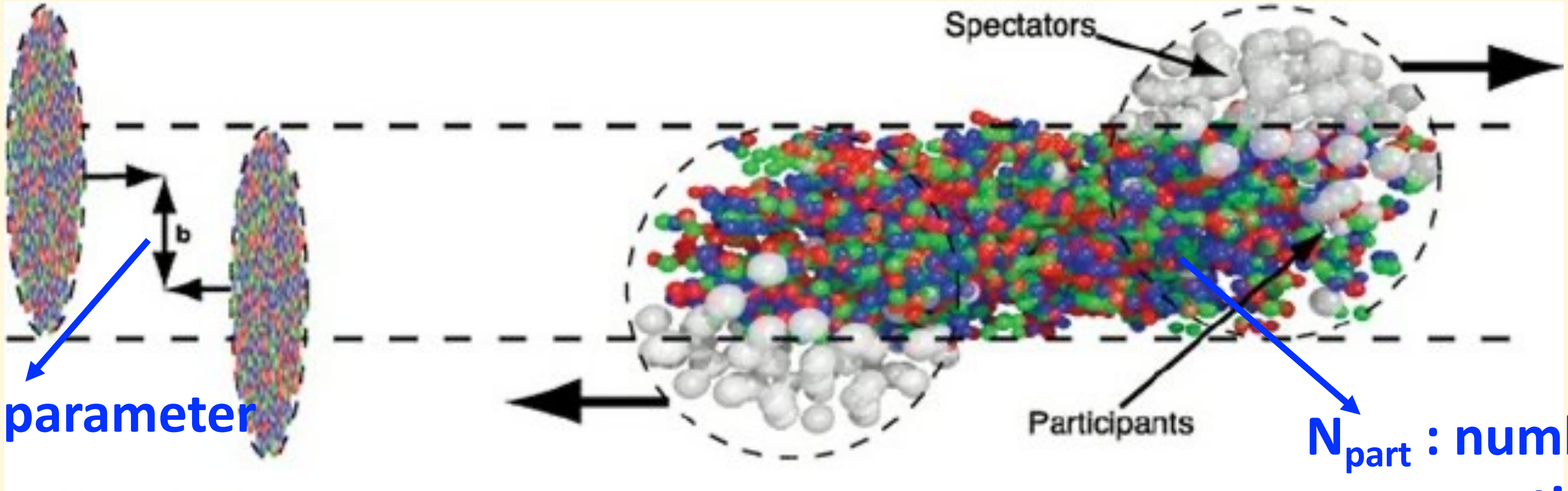
Initial State Fluctuations

Thermal Fluctuations

Hadronization

Measurement

Centrality in heavy-ion collisions:

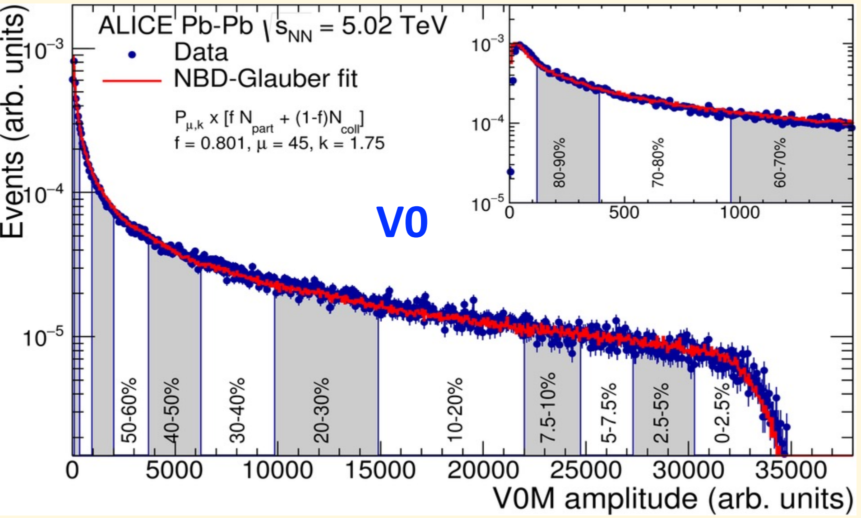


b : impact parameter

N_{part} : number of participants

before collision

after collision

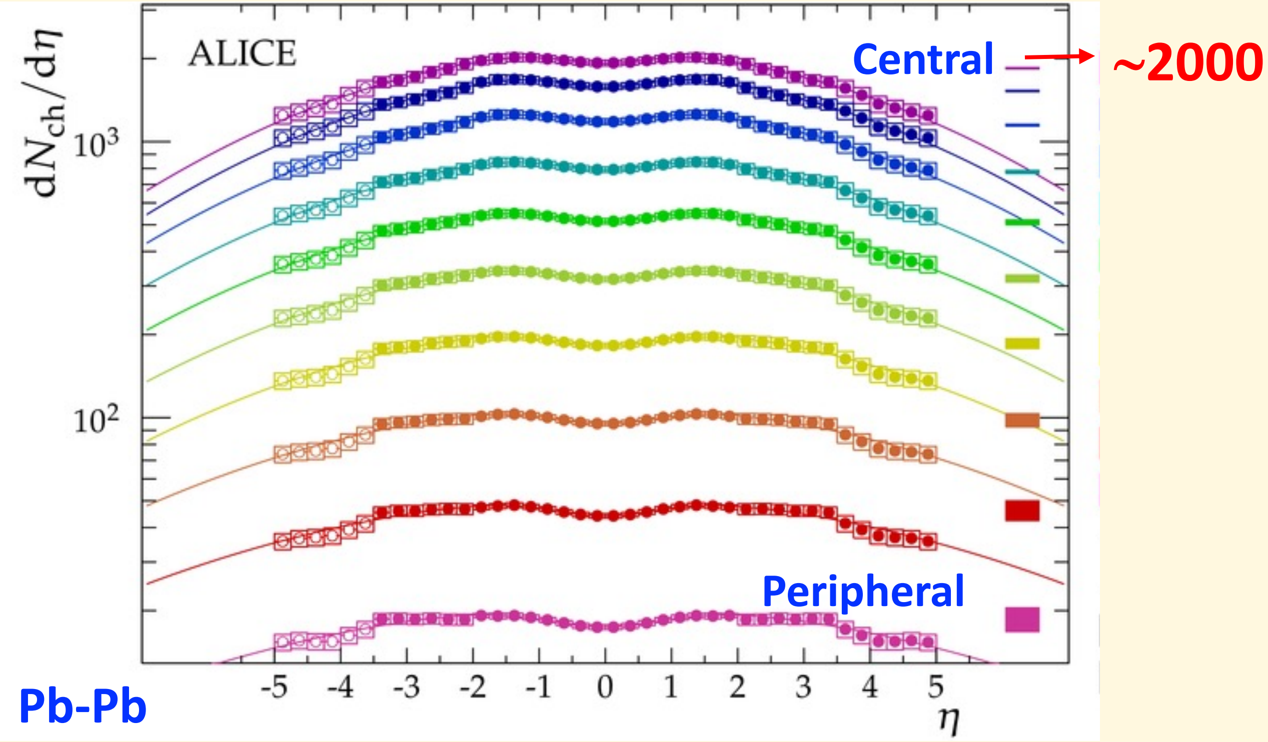


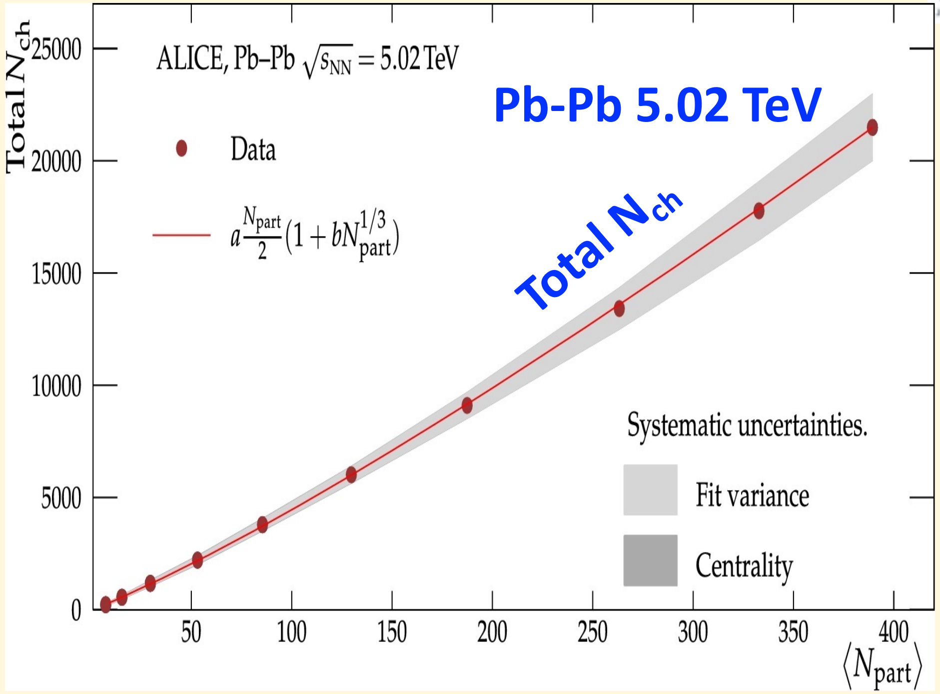
b: impact parameter,   For Pb-Pb collisions, maximum of b ~ 14 fm

Central collision, b ~ 0

Peripheral collision: b > 10 fm

Charged particle multiplicity





Number of charged particles in one collision:

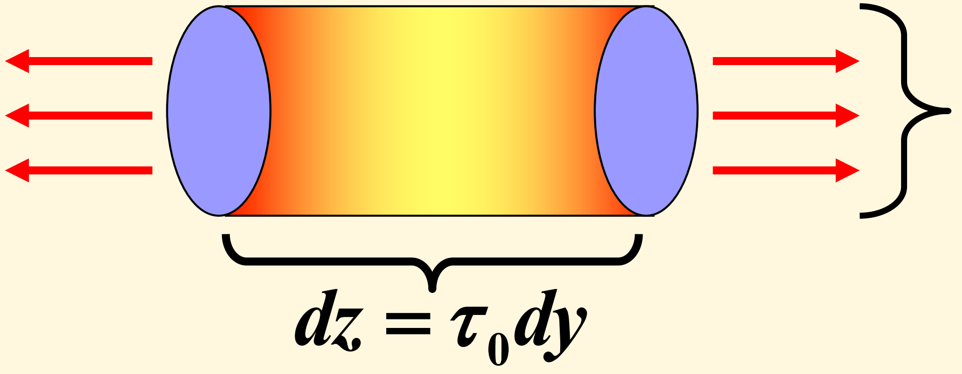
- Central collisions: 21400 ± 1300
- Peripheral collisions: 230 ± 38

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

VERY LARGE NUMBER OF PRODUCED PARTICLES

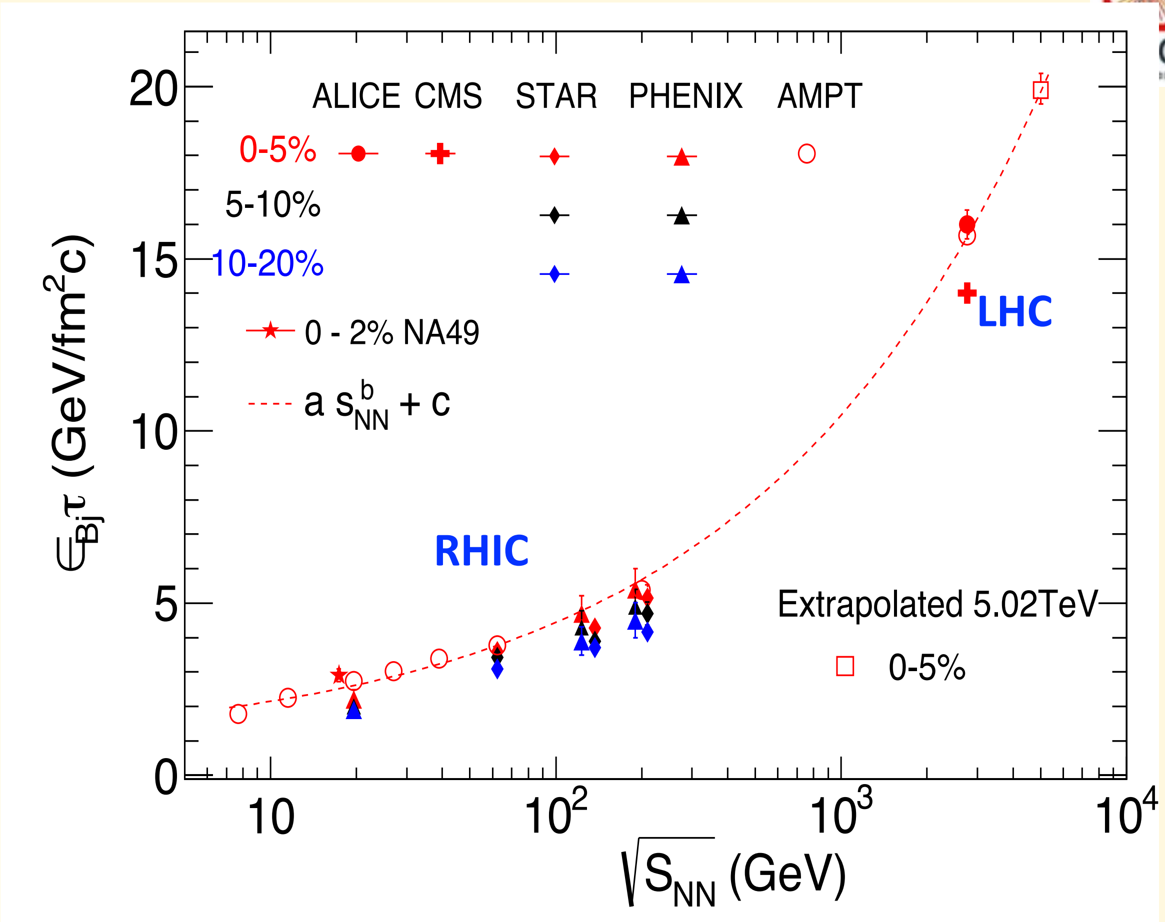
Particle density & Energy density

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



$$\varepsilon_{Bj}(\tau) = \frac{1}{\pi R^2 \tau}\frac{dE_T}{dy}$$

$$\approx \frac{1}{\pi R^2 \tau} < m_T > \frac{3}{2}\frac{dN_{ch}}{d\eta}$$



$\varepsilon.\tau \sim 16$ GeV/fm^{2}c

LARGEST ENERGY DENSITIES EVER ACHIEVED ….

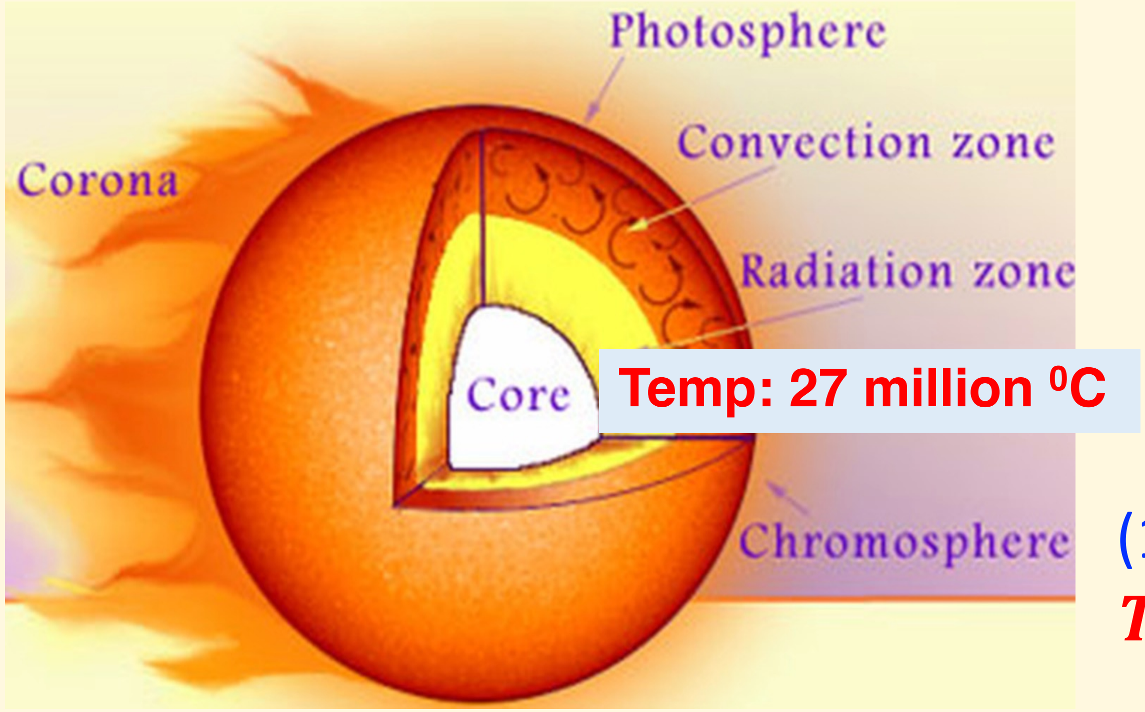
S. Basu et al. PRC 93 (2016) 064902
R. Sahoo et al. Adv. in HEP, Vol. 2015

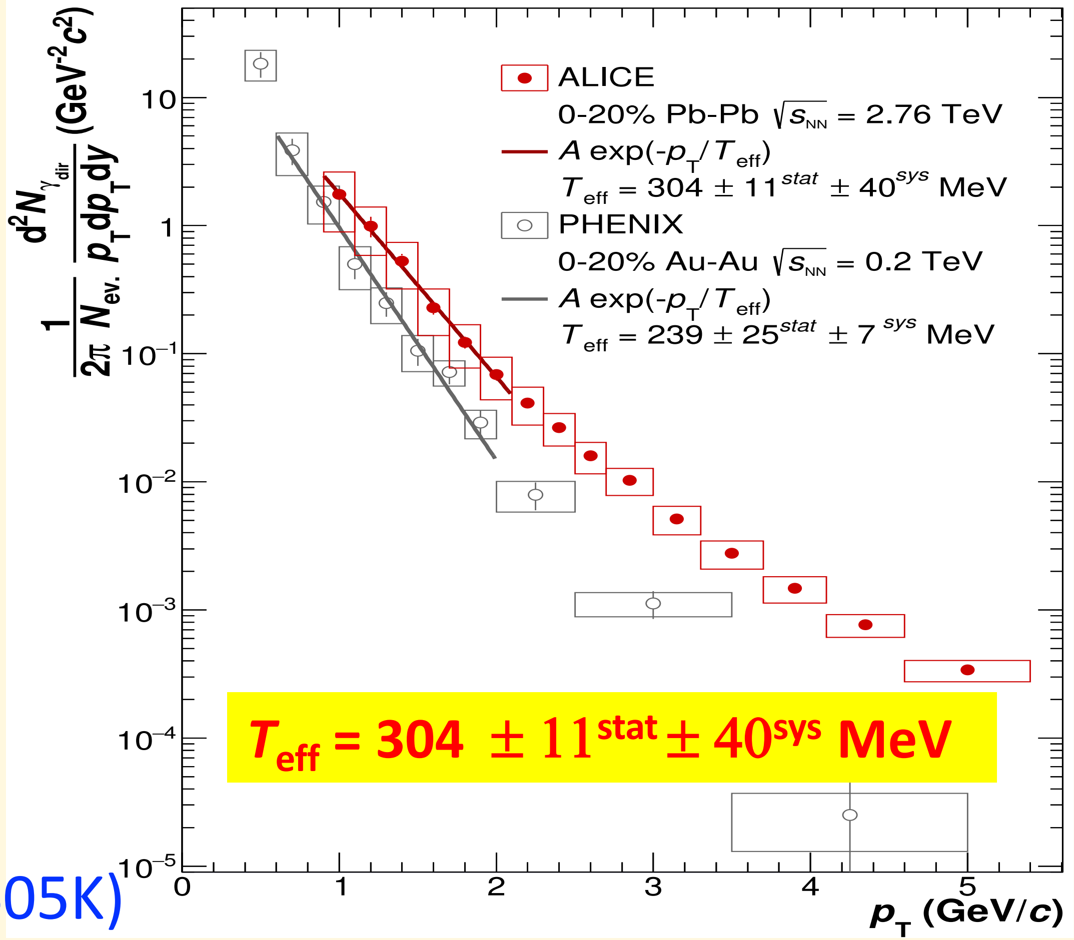
Photon Spectra and QGP temperature

[Phys. Lett. B 754 (2016) 235-248]

- Photons do not interact via the nuclear force → transparent to the medium
- Photons are emitted in all stages and are unaffected by the medium.

Core of the Sun:





(1eV=11605K)

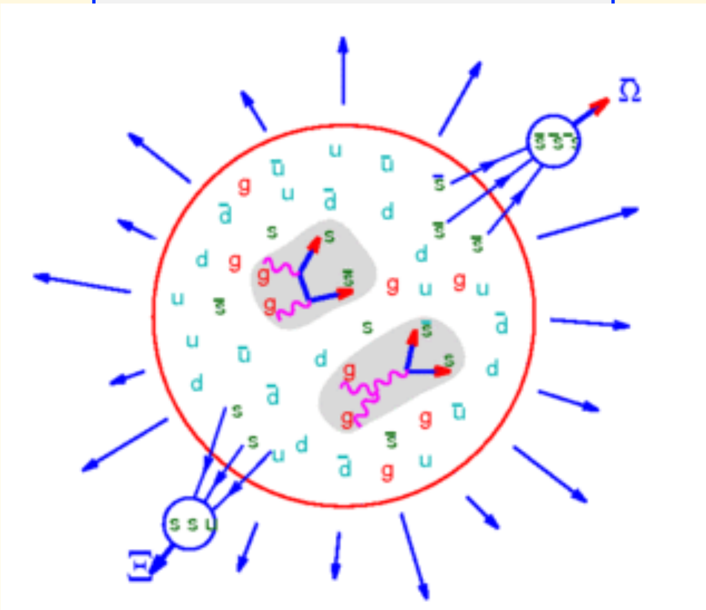
T_{eff} = 3,527,920 million deg

LARGEST EVER TEMPERATURE REACHED IN THE LAB ....

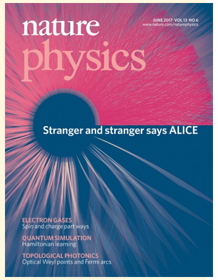
Strangeness enhancement

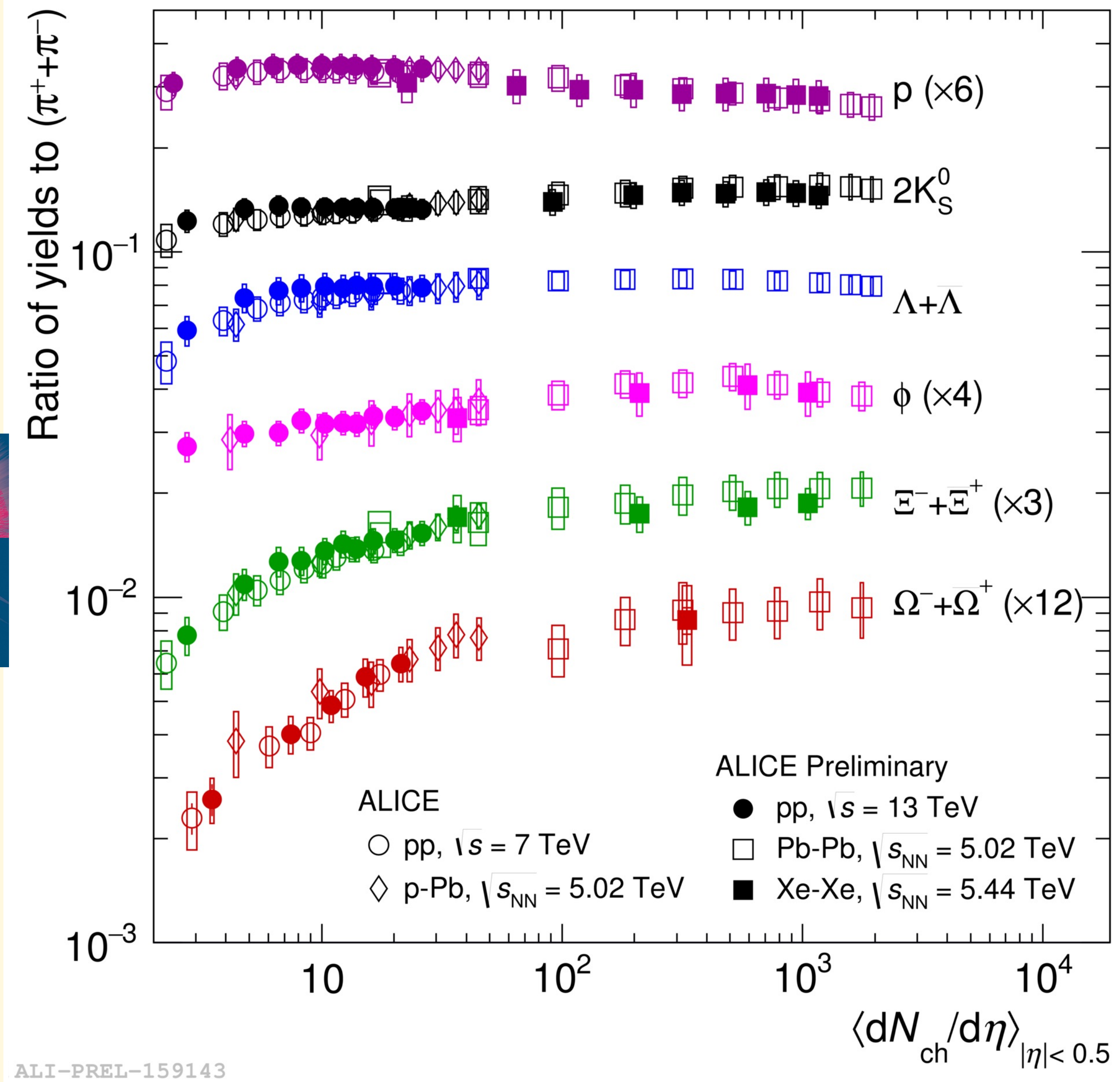
Ordinary nuclear matter is composed of *u*, *d* quarks. Strange quarks are produced in the collision

$$m_{u,d,s} < \Lambda_{QCD} < m_{c,b,t}$$



J. Rafelski and B. Müller, PRL48, 1066 (1982)
P. Koch, B. Müller, J. Rafelski, Phys. Rep. 142, 167 (1986)

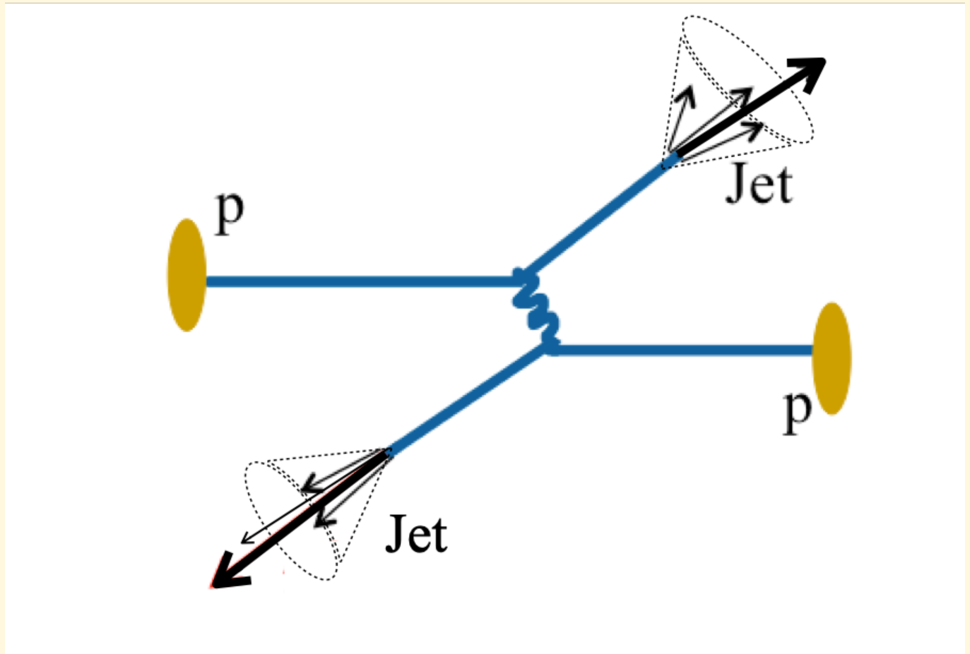




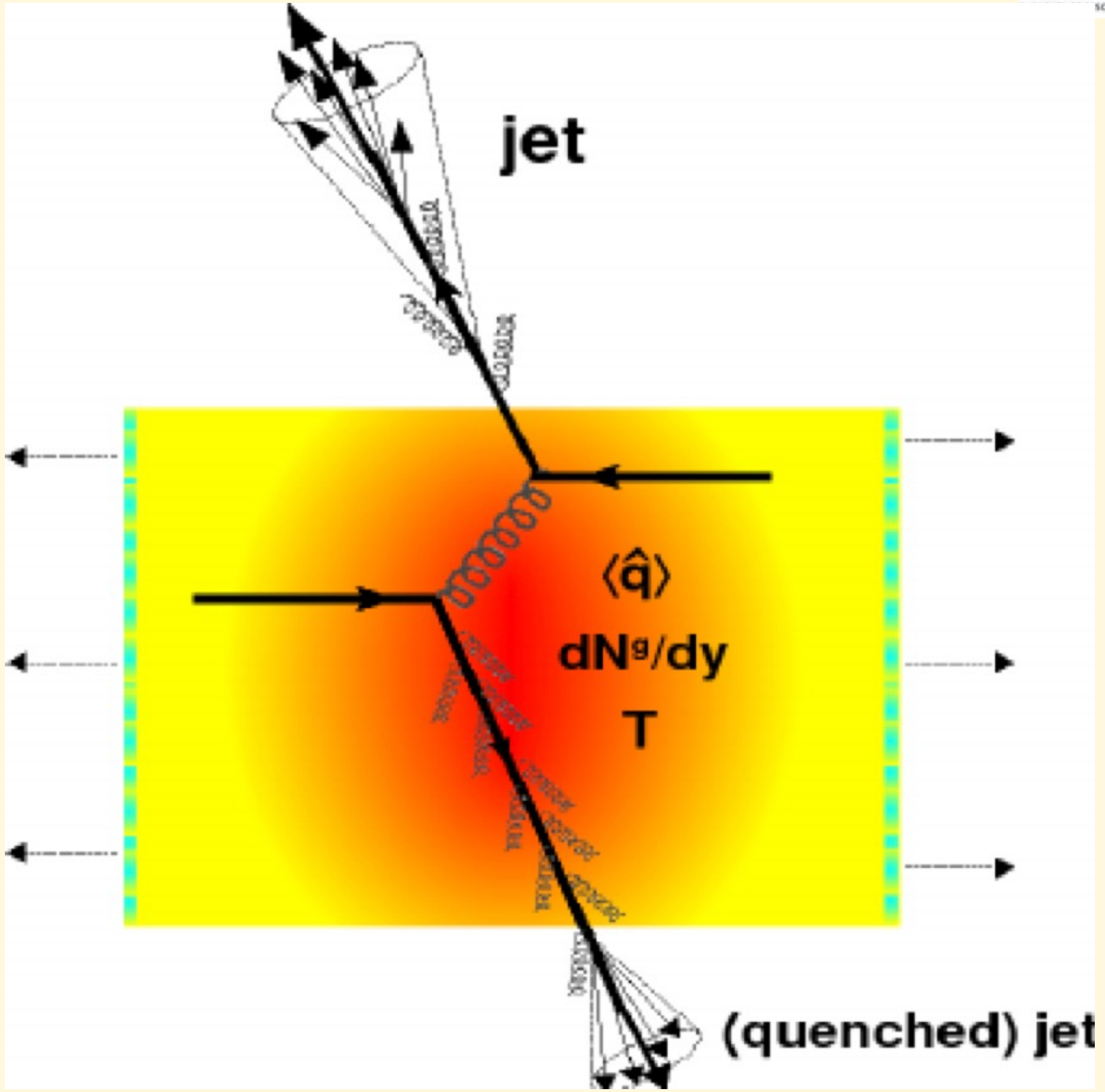
The enhanced production of strangeness relative to u and d quarks => formation of QGP matter.

Jet-quenching in Quark Gluon Plasma

Jet is a collimated spay of hadrons fragmented from a high energetic parton.



Back-to-back jets in p+p collision (vacuum)



Jet-quenching: Consequence of parton energy loss in the QGP (due to gluon radiation)

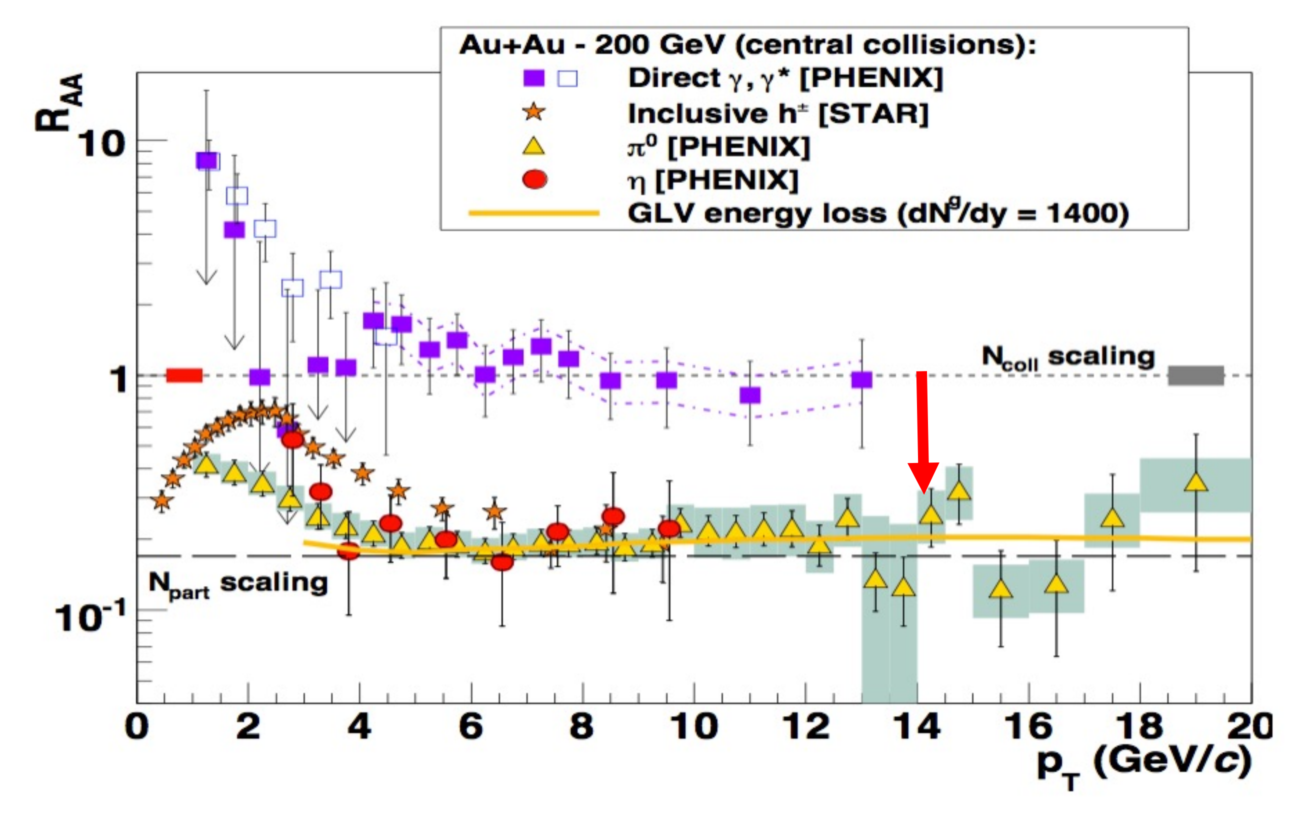
Evidence of Jet-quenching

$$R_{AA} = \frac{\text{Yield in A + A}}{\text{Normalized Yield in p + p}}$$

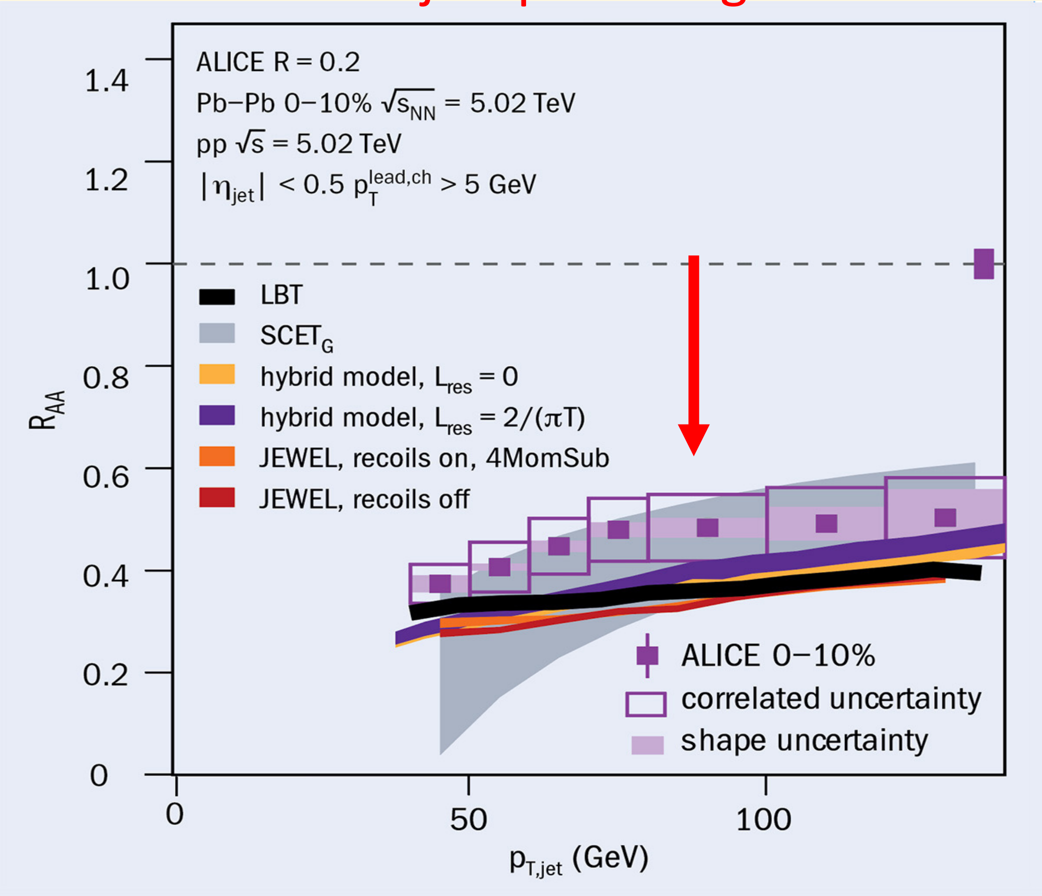
$R_{AA} = 1$: No jet suppression jet-quenching

$R_{AA} < 1$: jet-quenching

First evidence of jet-quenching at RHIC



Confirmation of jet-quenching at LHC



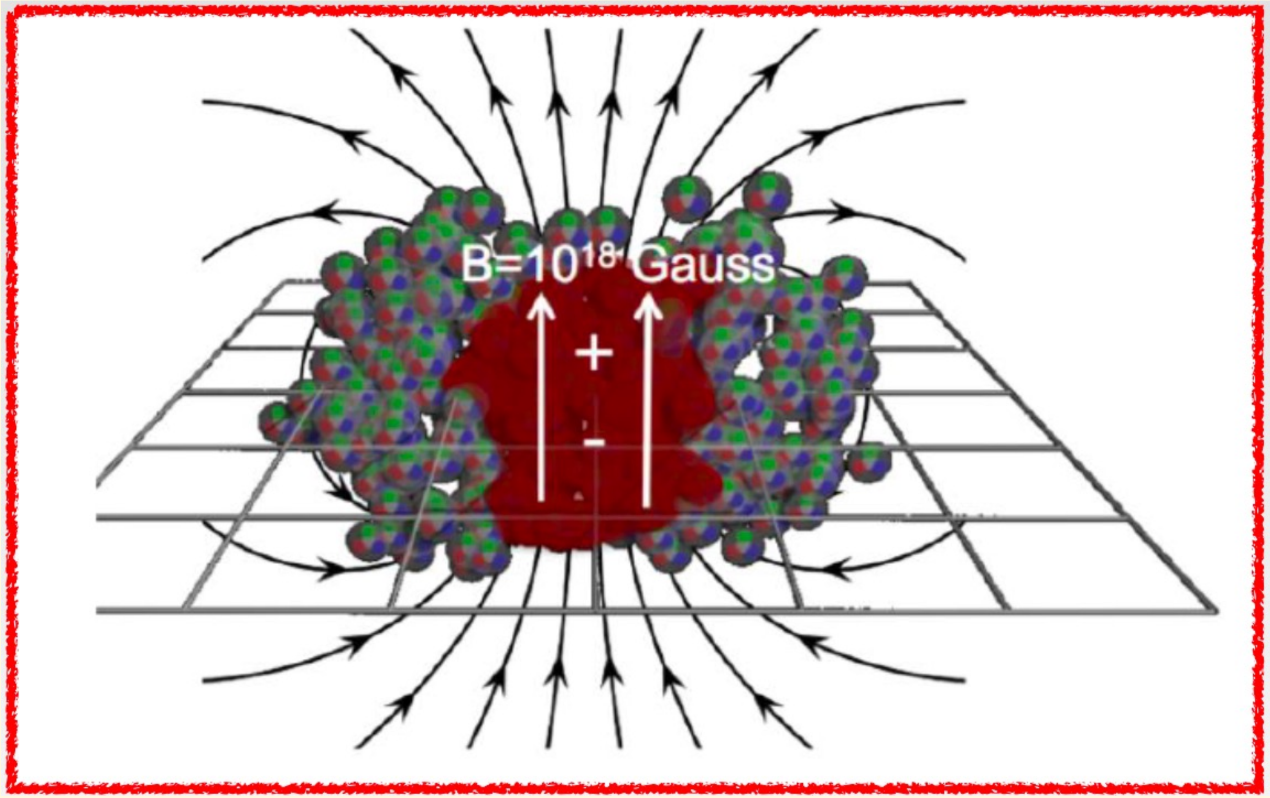
Jet-quenching => QGP formation

ALICE Collab. 2020 *Phys. Rev. C* **101** 034911.

Generation of enormous magnetic field: 10^{14} Tesla

Two colliding nuclei generate two electric currents in opposite directions, and produce a magnetic field perpendicular to the reaction plane. The non-central collisions generate enormous magnetic field of 10^{14} Tesla by the movement of the spectator protons.

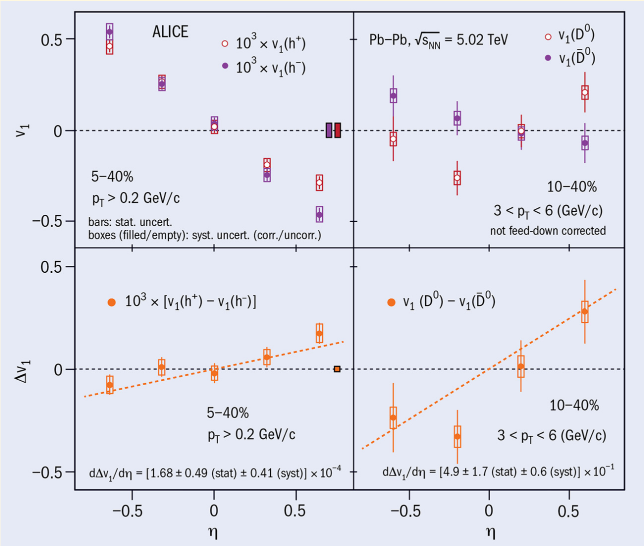
Earth's magnetic field: 10^{-5} Tesla.
LHC magnets: 8.3 Tesla
Magnestar (type of neutron star): 10^{10} Tesla



Probing the extreme electromagnetic fields:

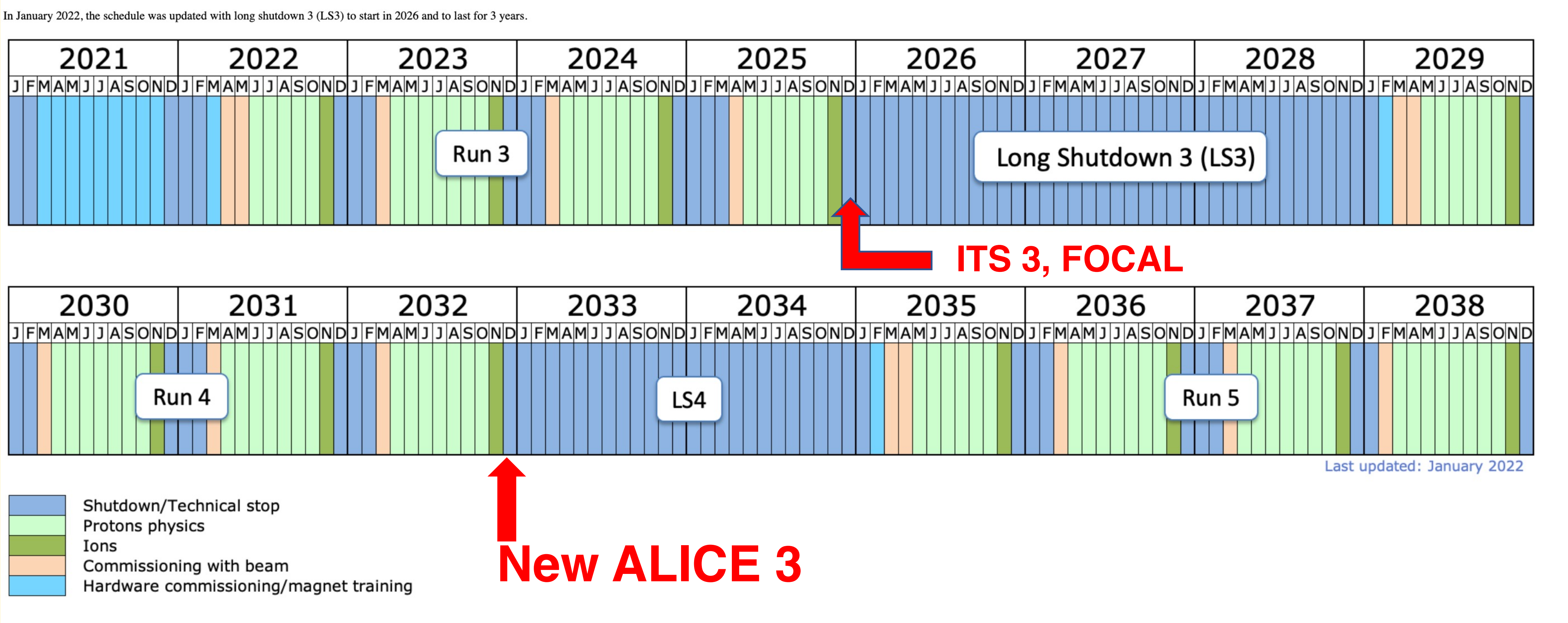
The strong magnetic field affects the evolution of the QGP. Chiral phenomena such as the chiral magnetic effect gets induced by the strong fields.

=> Compare the directed flow of charged particles (u,d quarks) to D mesons (charm quarks)



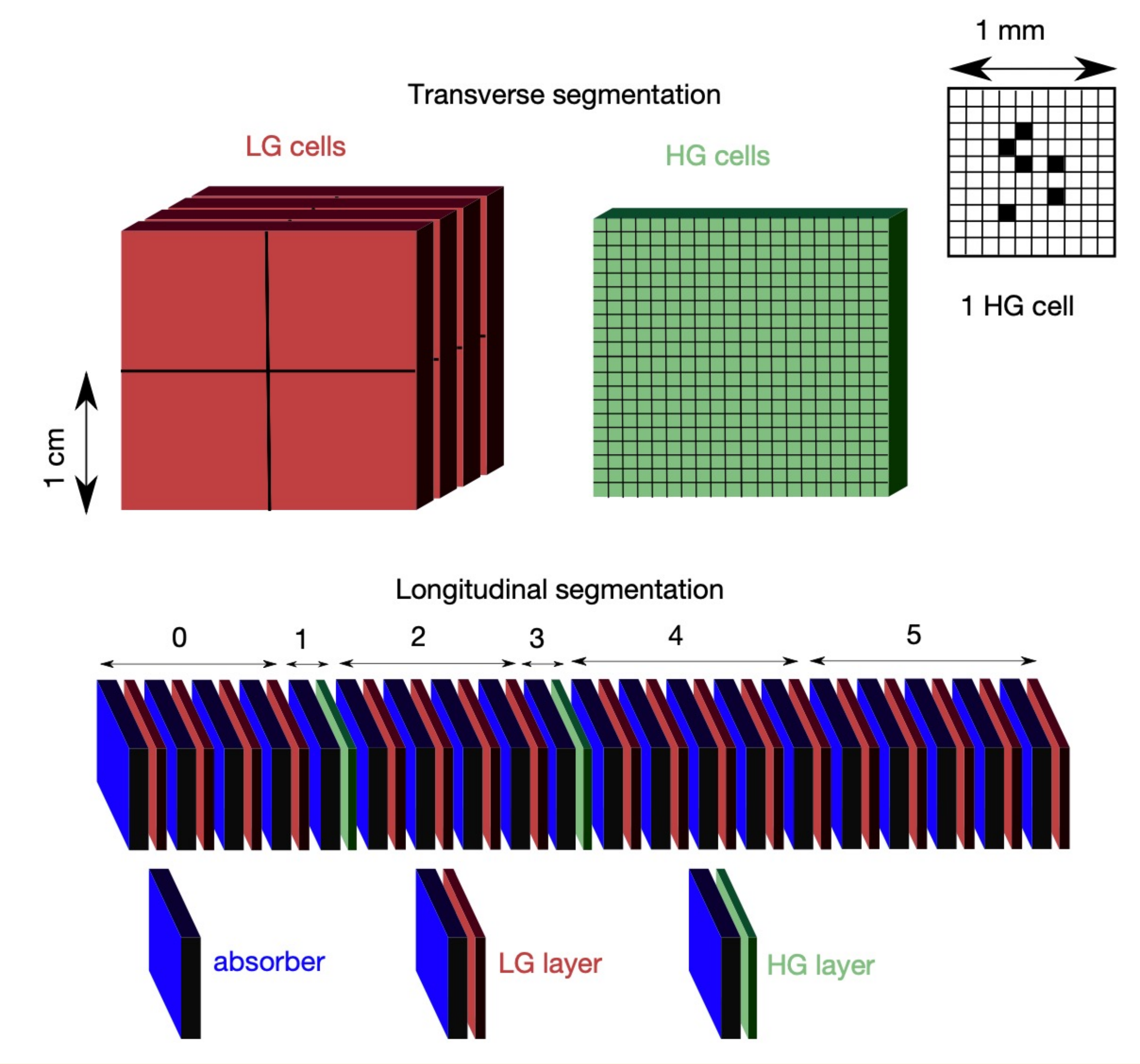
https://cerncourier.com/a/alice-probes-extreme-electromagnetic-fields/

Large Hadron Collider: Schedule (Jan 2022)

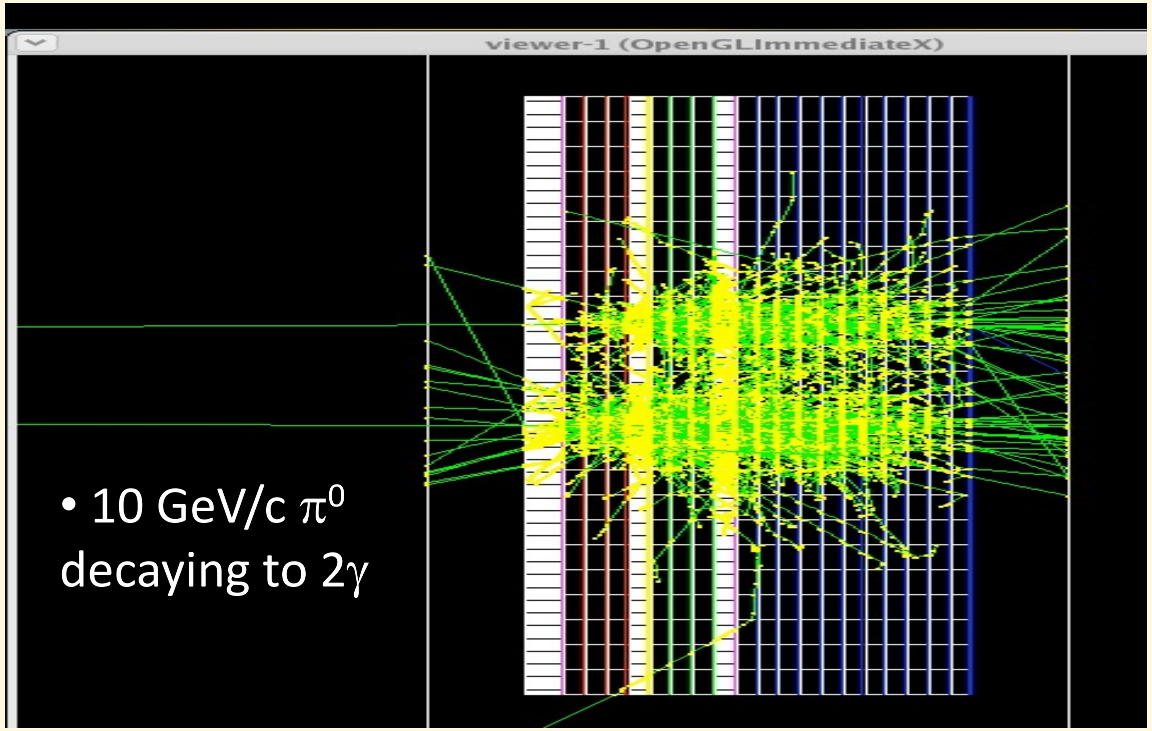


A Forward Calorimeter (FoCal) for LHC Run 4

(2029 onwards ….)



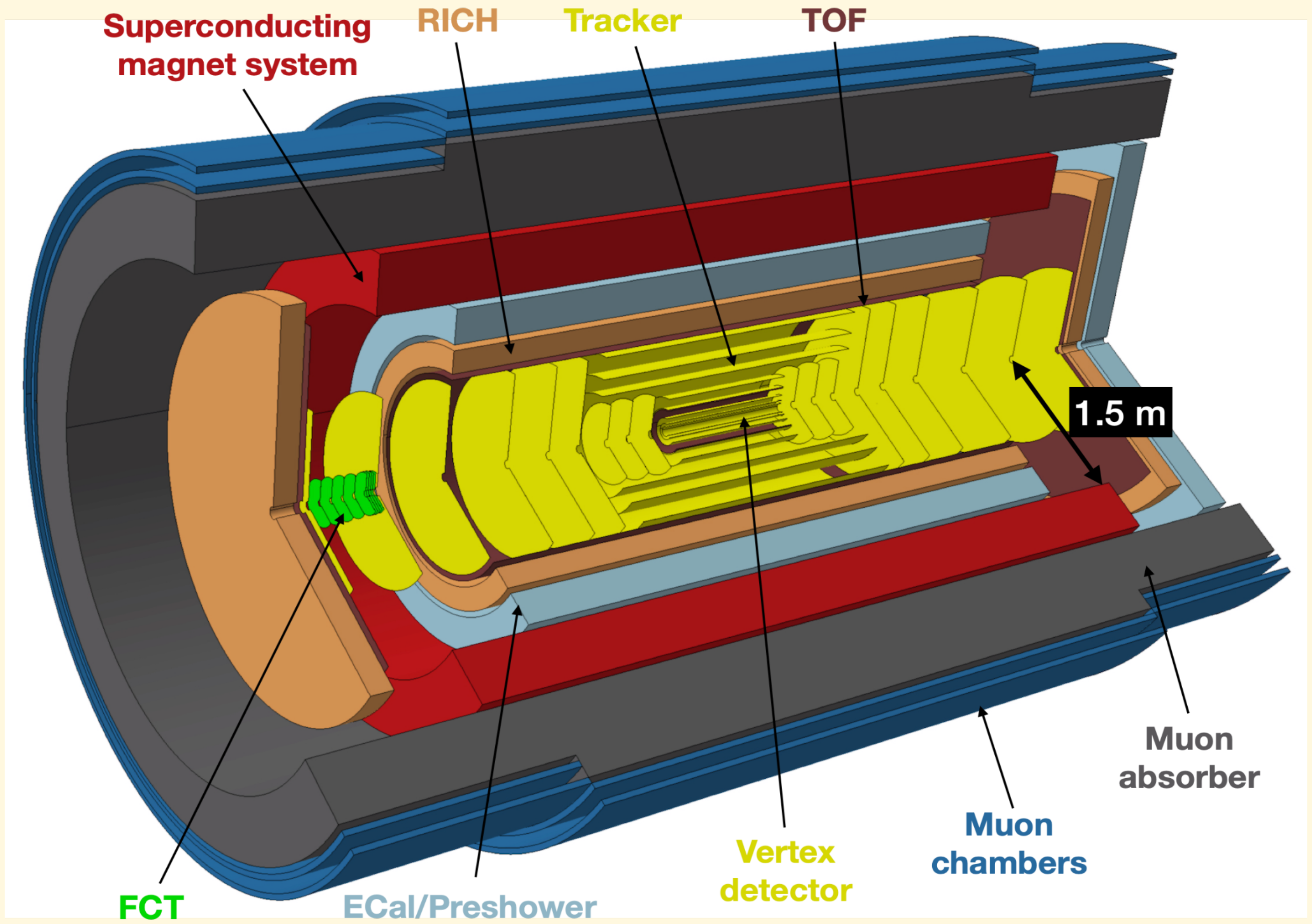
- ✓ Sensivite Medium:
  - Silicon Pad: 1 cm^2
  - Silicon Pixel: 1 mm^2
- ✓ Absorber: Tungsten



A "New ALICE 3" for LHC Run-5

https://arxiv.org/abs/1902.01211

(2035 onwards ….)



CMOS imaging technologies: high-precision spatial and time resolution

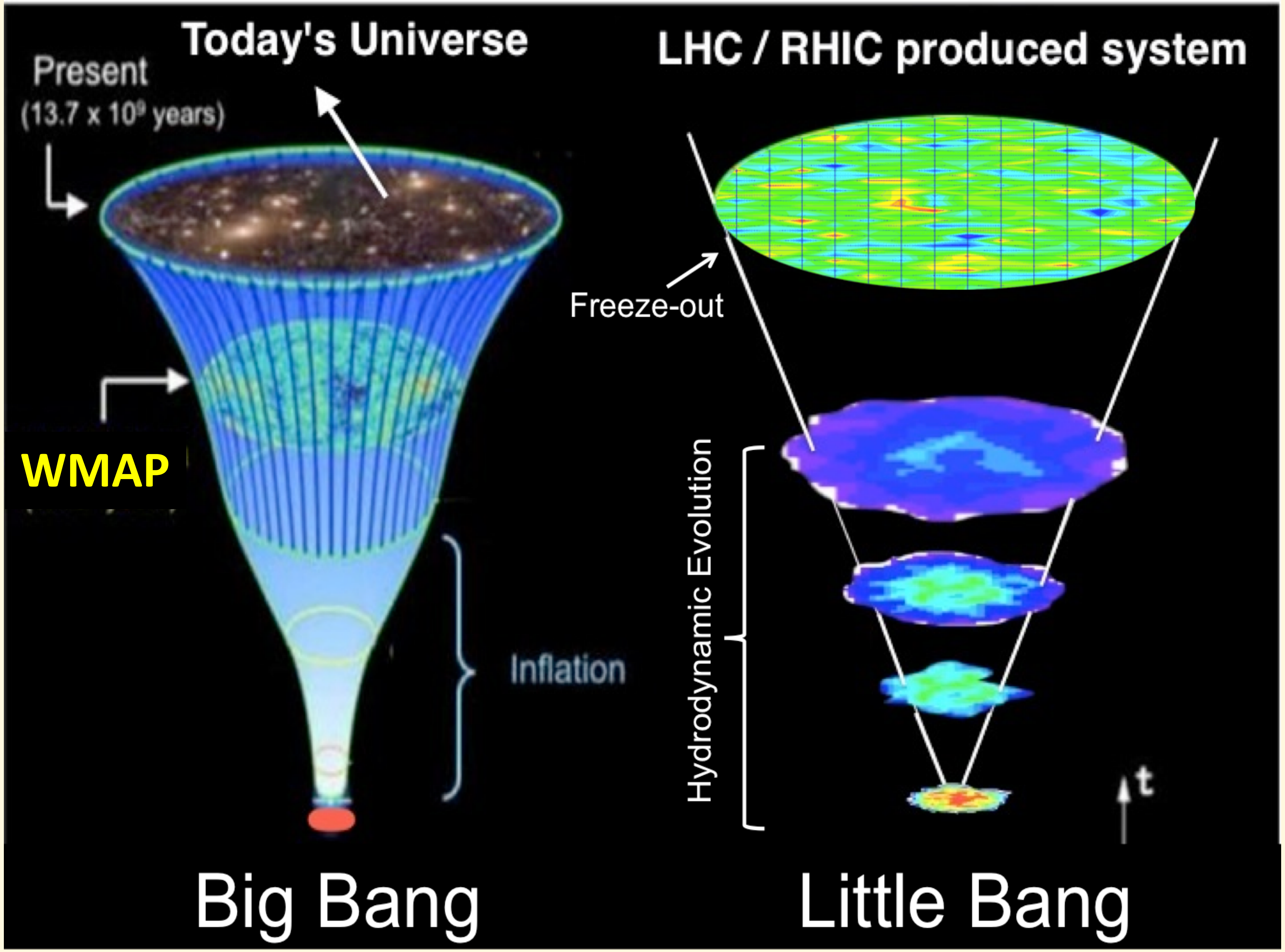
LHC Run-5:

- Tracker: ~10 tracking barrel layers
- Hadron ID: TOF with outer silicon layers
- Electron ID: pre-shower
- Conversion photons

Low p_T down to ~20 MeV/c

Extended rapidity coverage: up to 8 rapidity units + FoCal (Forward Calorimeters)

The Big Bang and Little Bangs



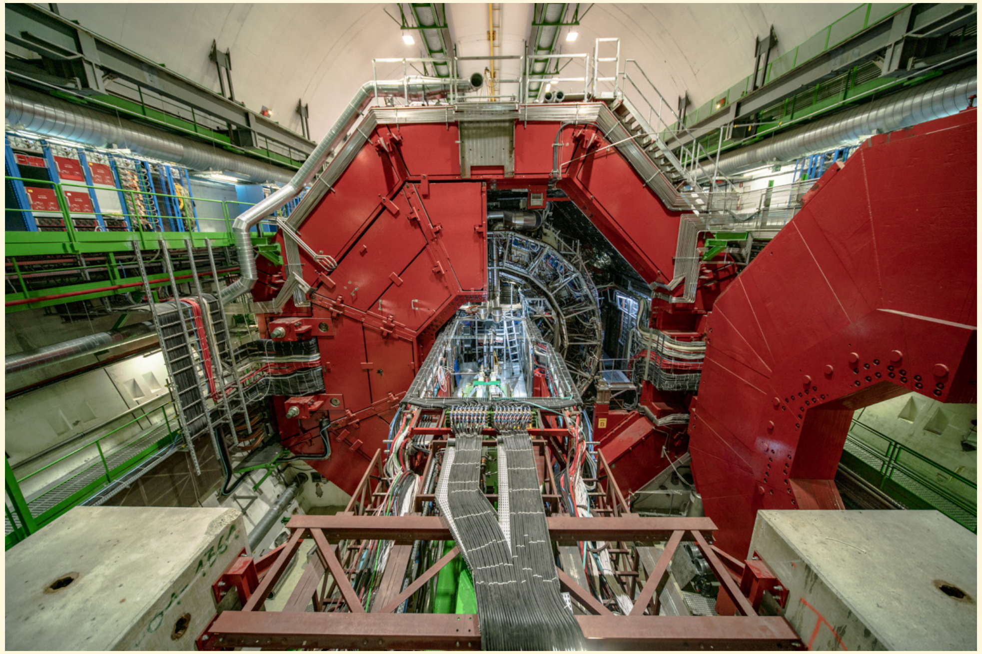
High Energy Accelerator:

Heavy-ion Collisions:

Billions of Events (Little Bangs)

Event-by-event Fluctuations

One HUGE Event



Recreating the Big Bang conditions at the LHC