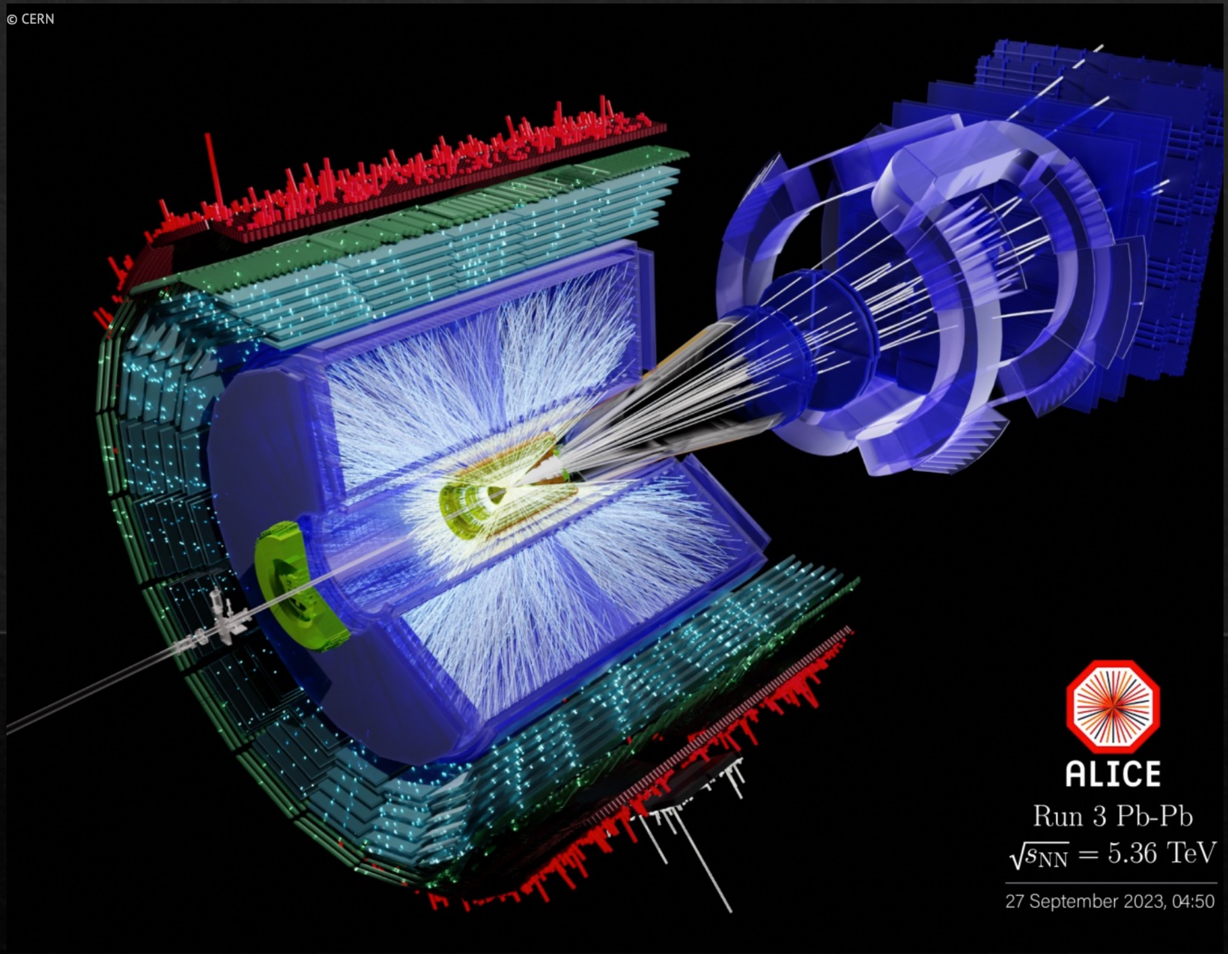
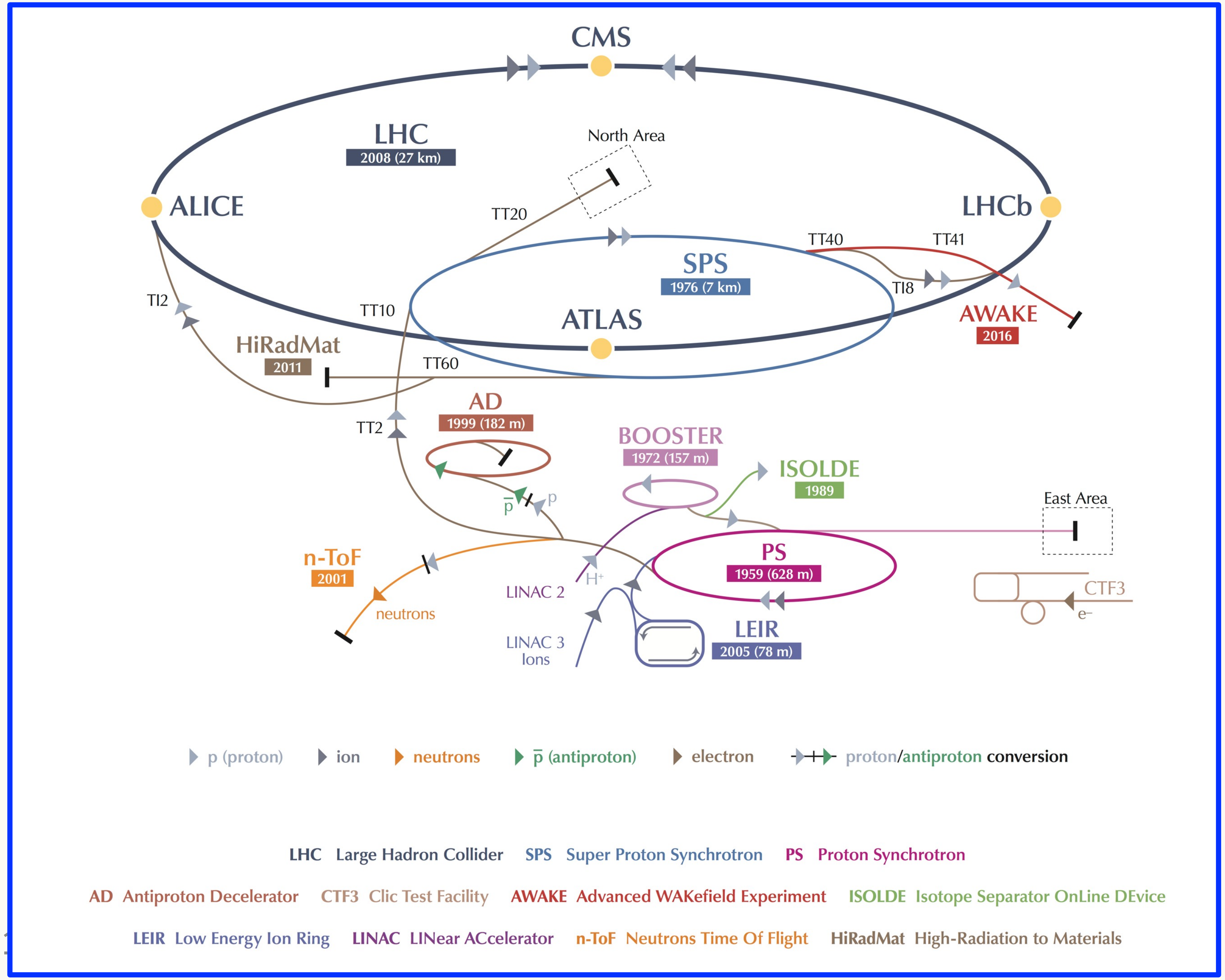


Heavy-ion Physics and the ALICE Experiment

Tapan Nayak
25 March 2024

CERN

CERN Accelerator complex



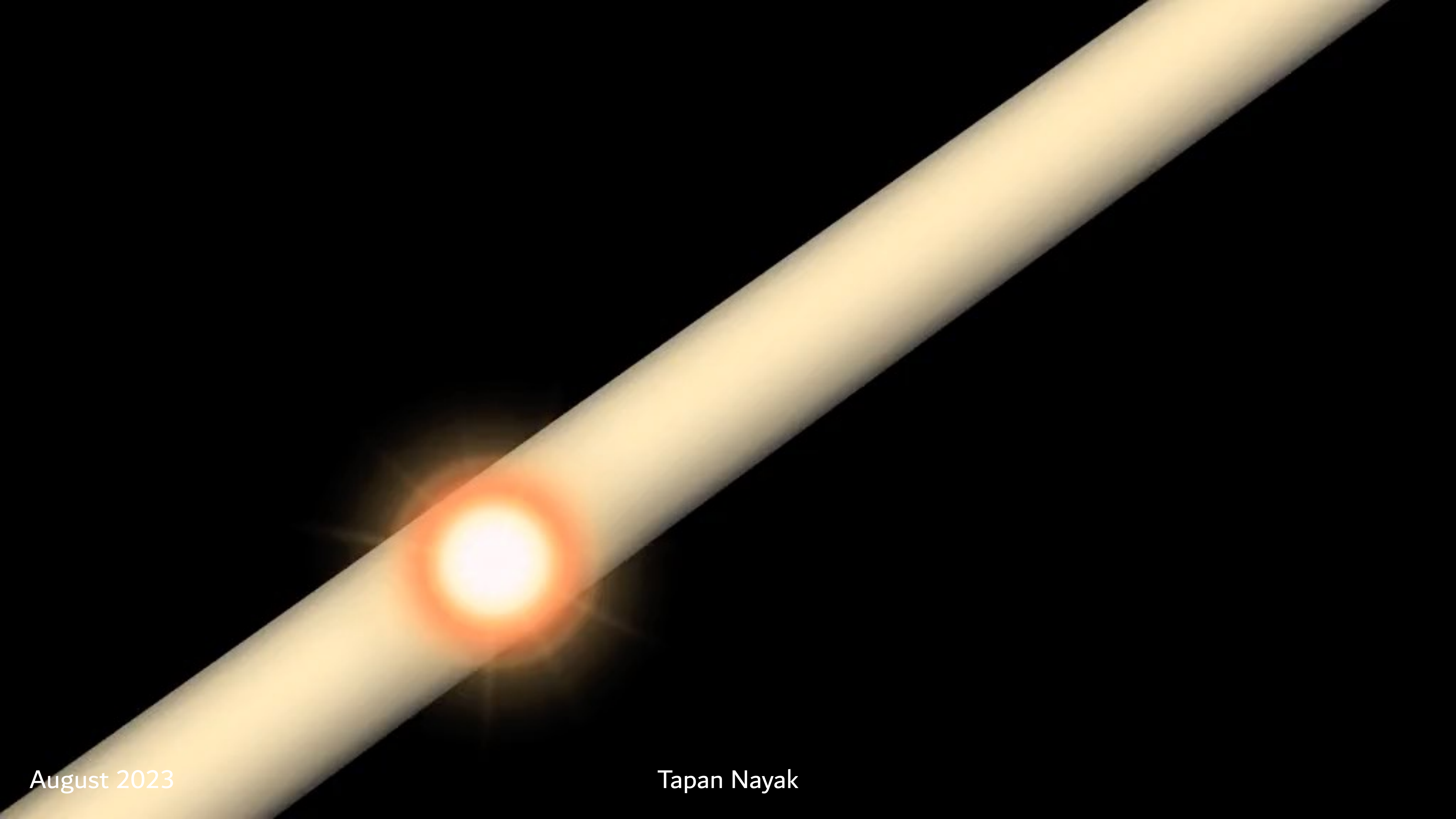
Large Hadron Collider (LHC):

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?

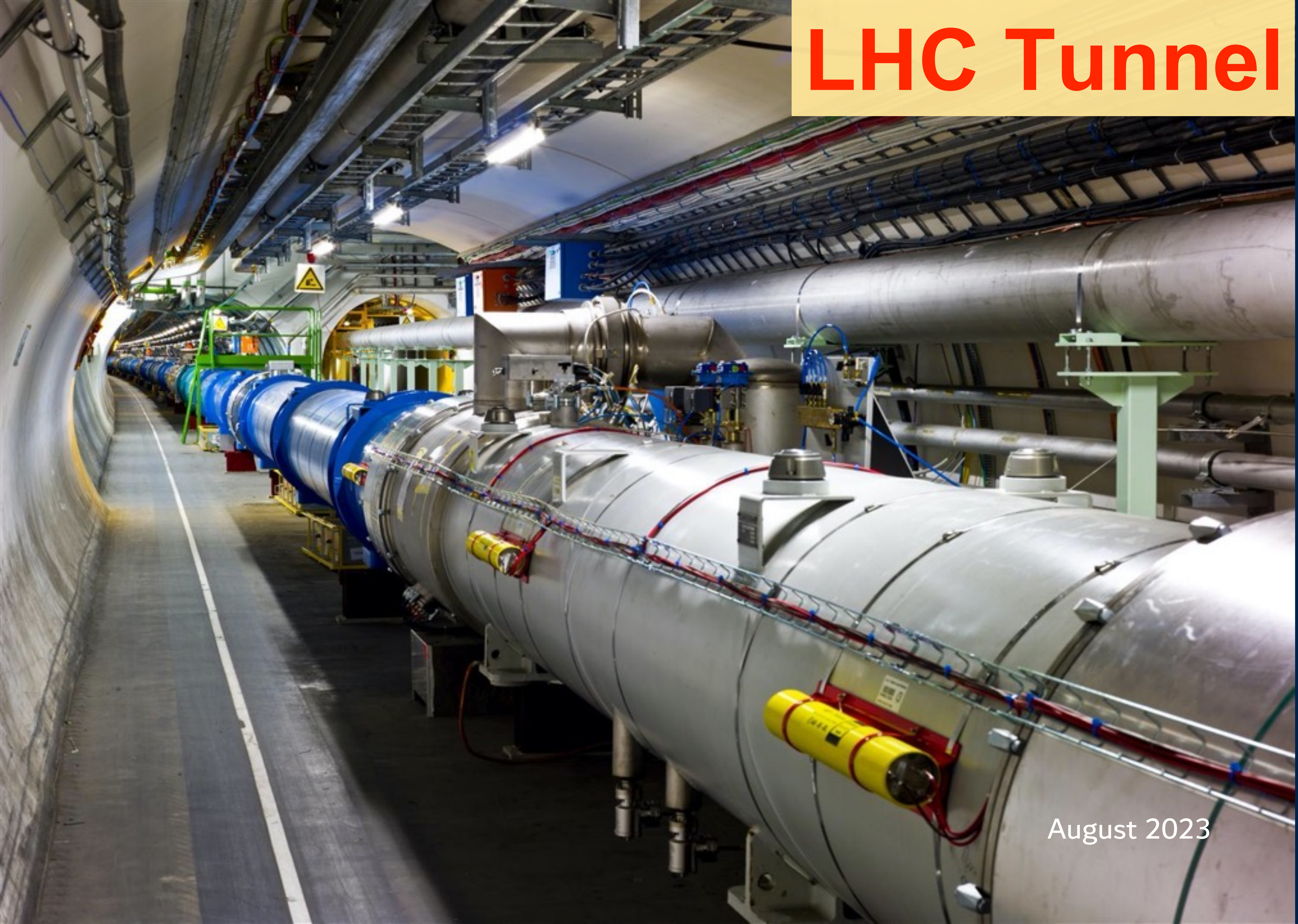


Colliding protons (14 TeV),
Lead ions (5.5 TeV)

World's Most Powerful Accelerator:
The Large Hadron Collider

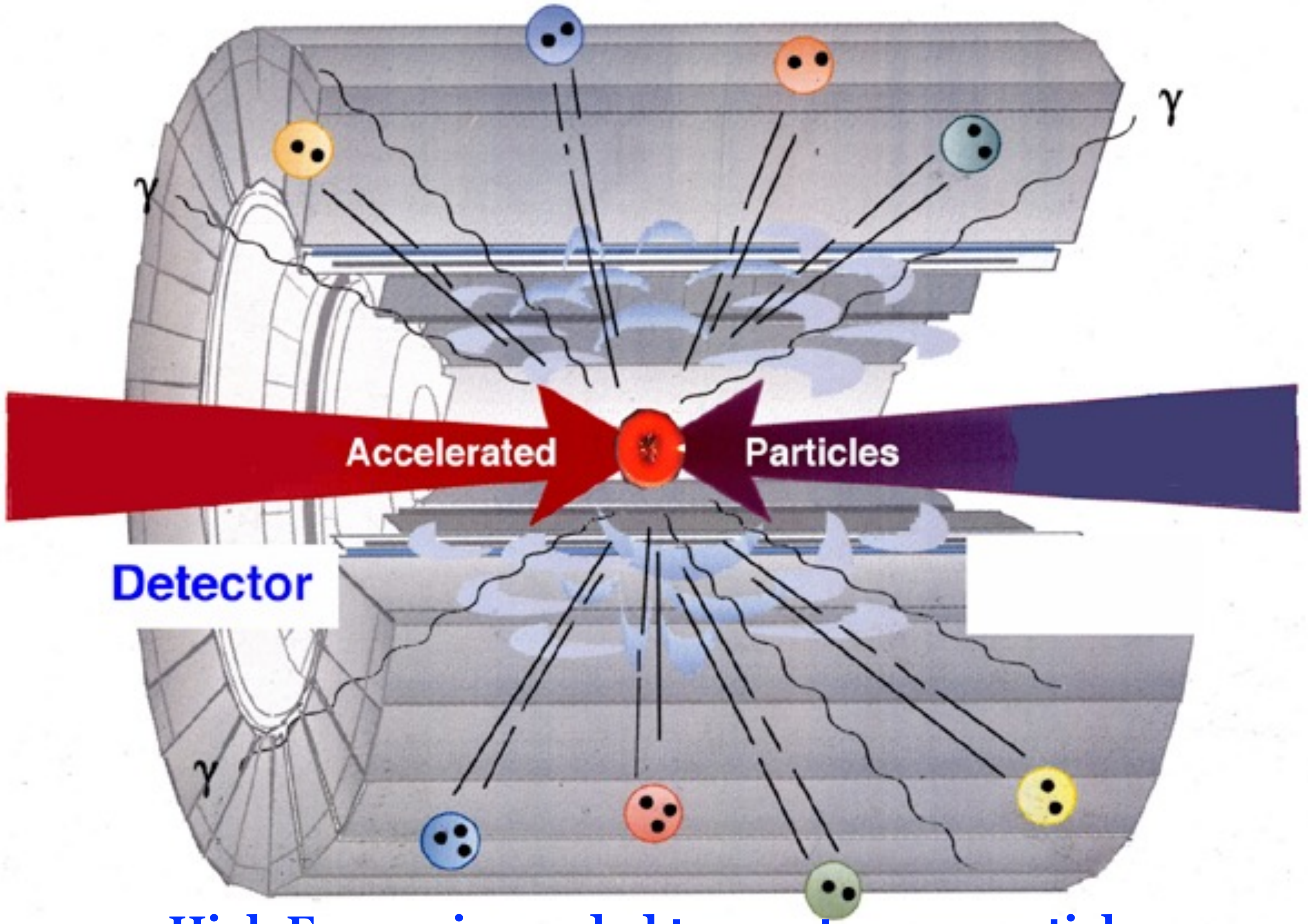

Colliding protons (14 TeV),
Lead ions (5.5 TeV)
CERN
World's Most Powerful Accelerator:
The Large Hadron Collider
Jura mountains
Lake Geneva
CMS
LHCb
ATLAS
ALICE

LHC Tunnel



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:

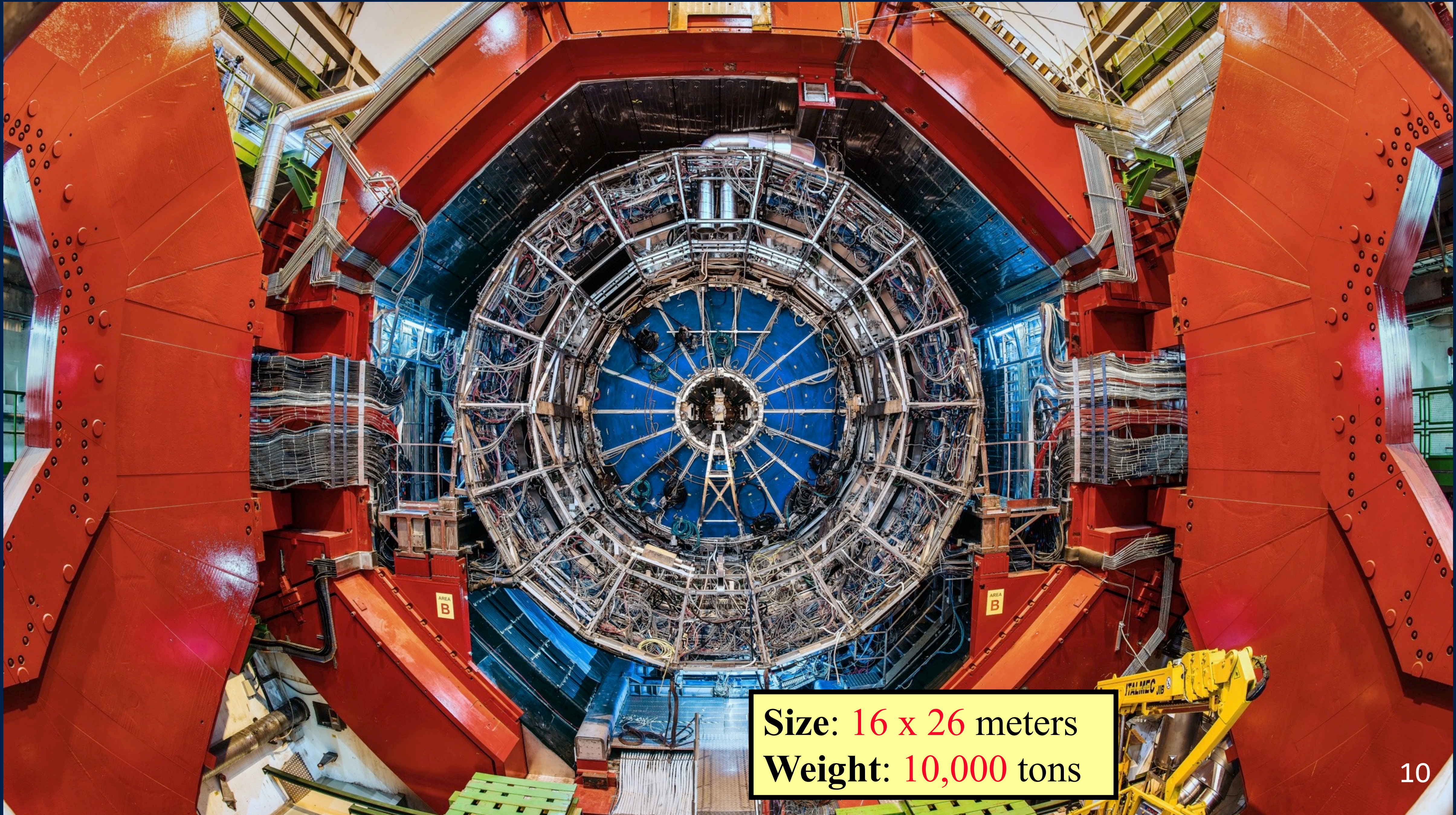
COLLIDER

$$E = mc^2$$

EXPERIMENTS

ALICE at Point-2 of the LHC

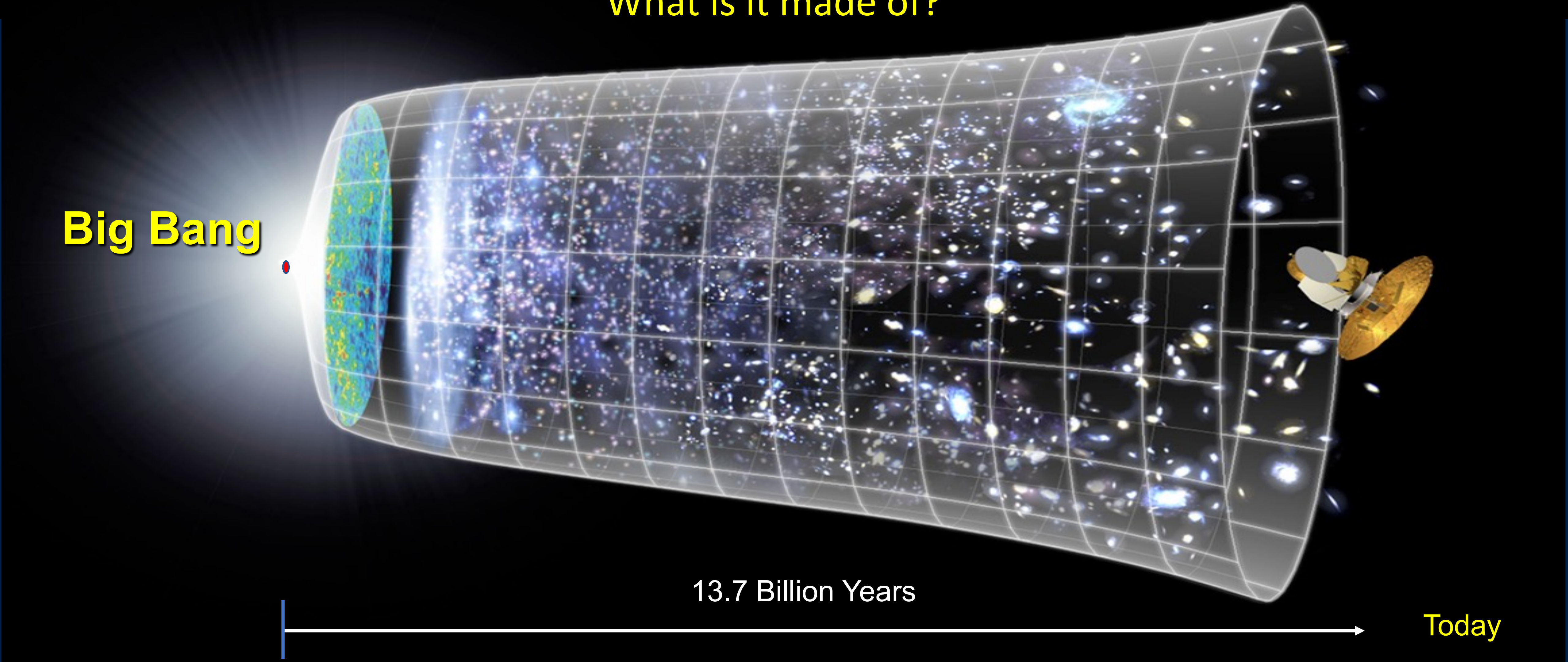
ALICE at Point-2 of the LHC

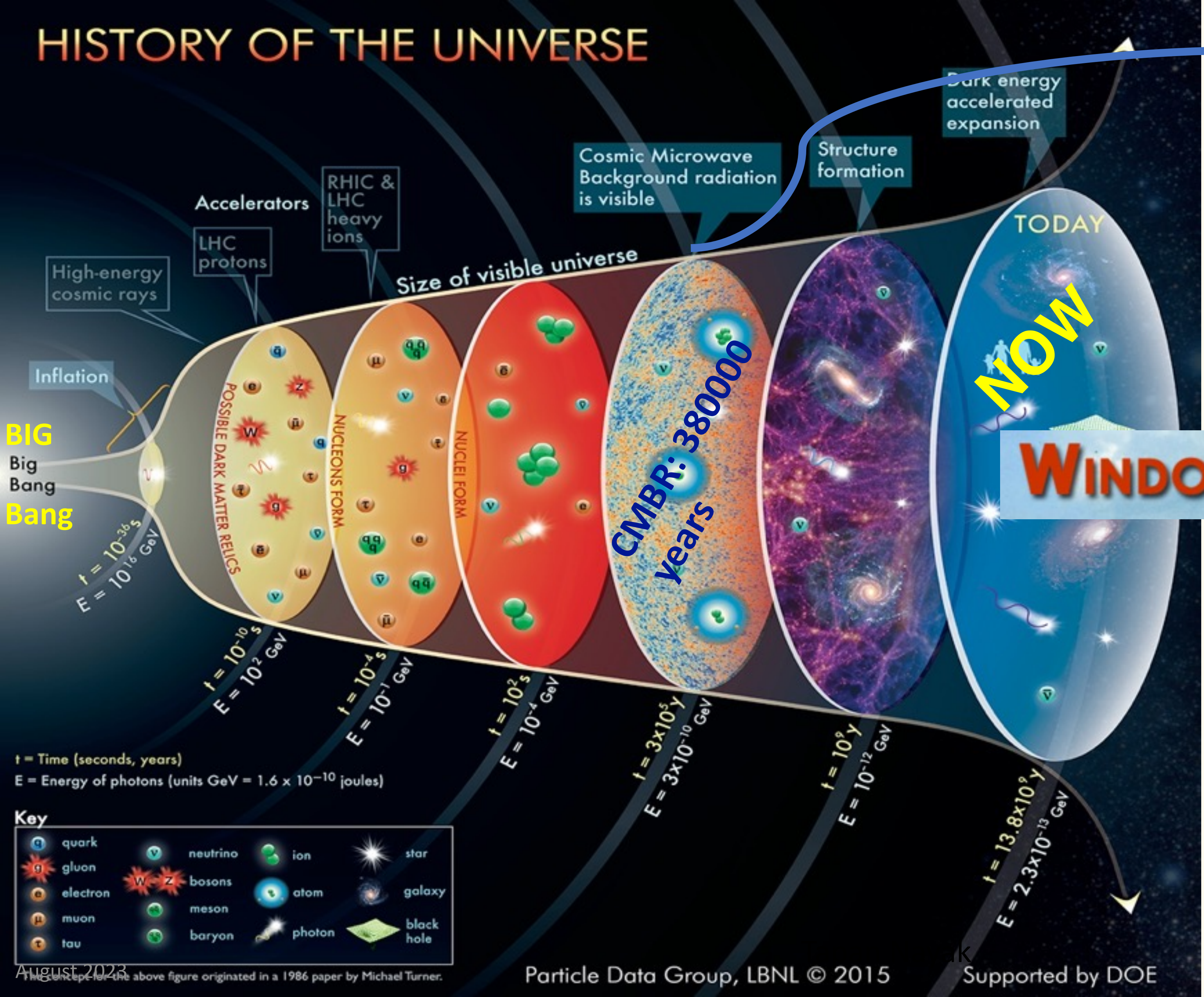


Size: 16 x 26 meters
Weight: 10,000 tons

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

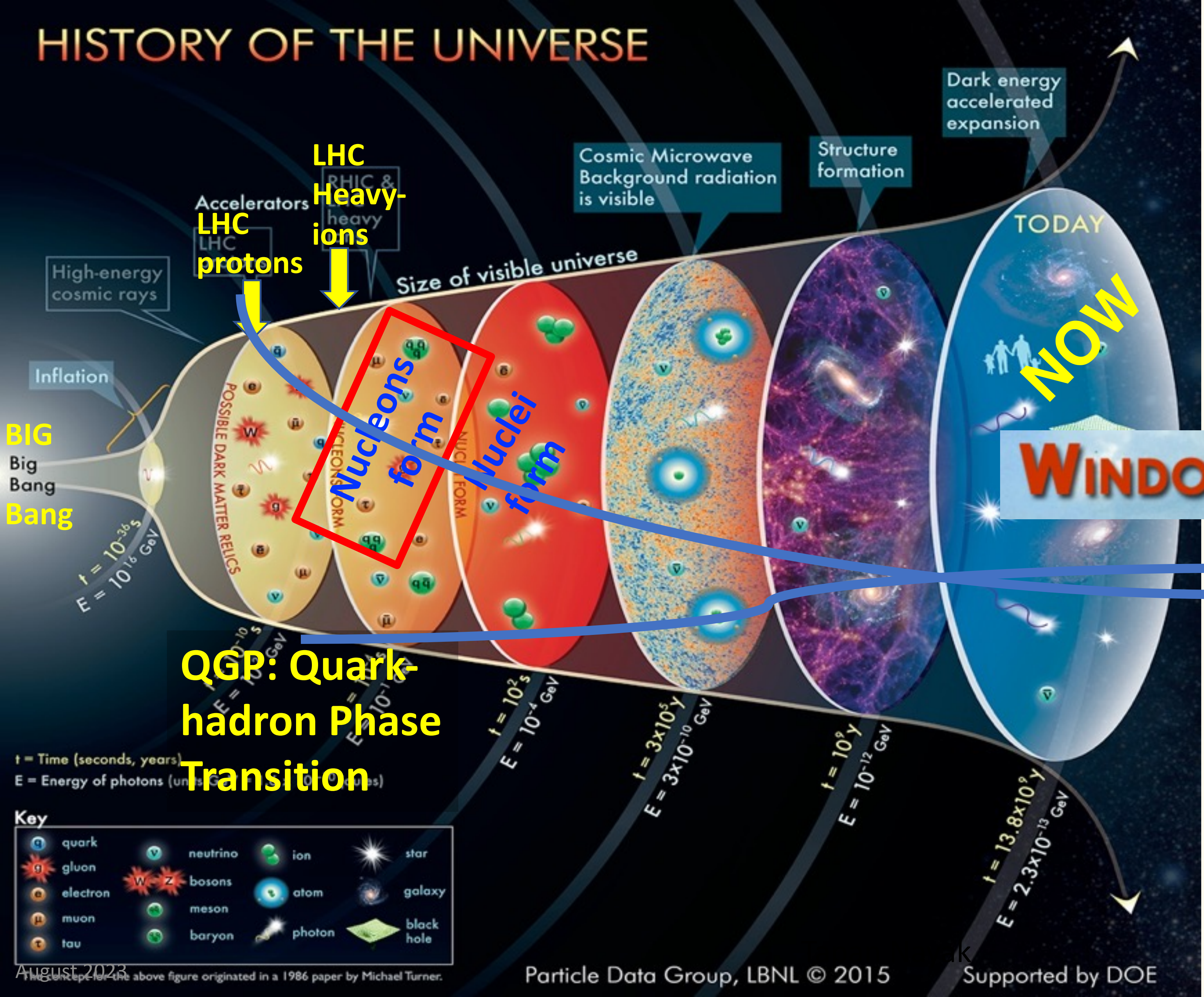
What is it made of?





Astrophysical Probes

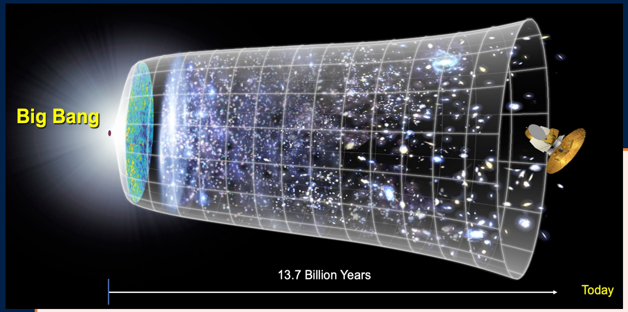
Takes us back to 380,000 years after the Big Bang



WINDOWS ON THE UNIVERSE

Accelerators (LHC)

Takes us back to within few Microseconds of the Big Bang



Big Bang Timeline

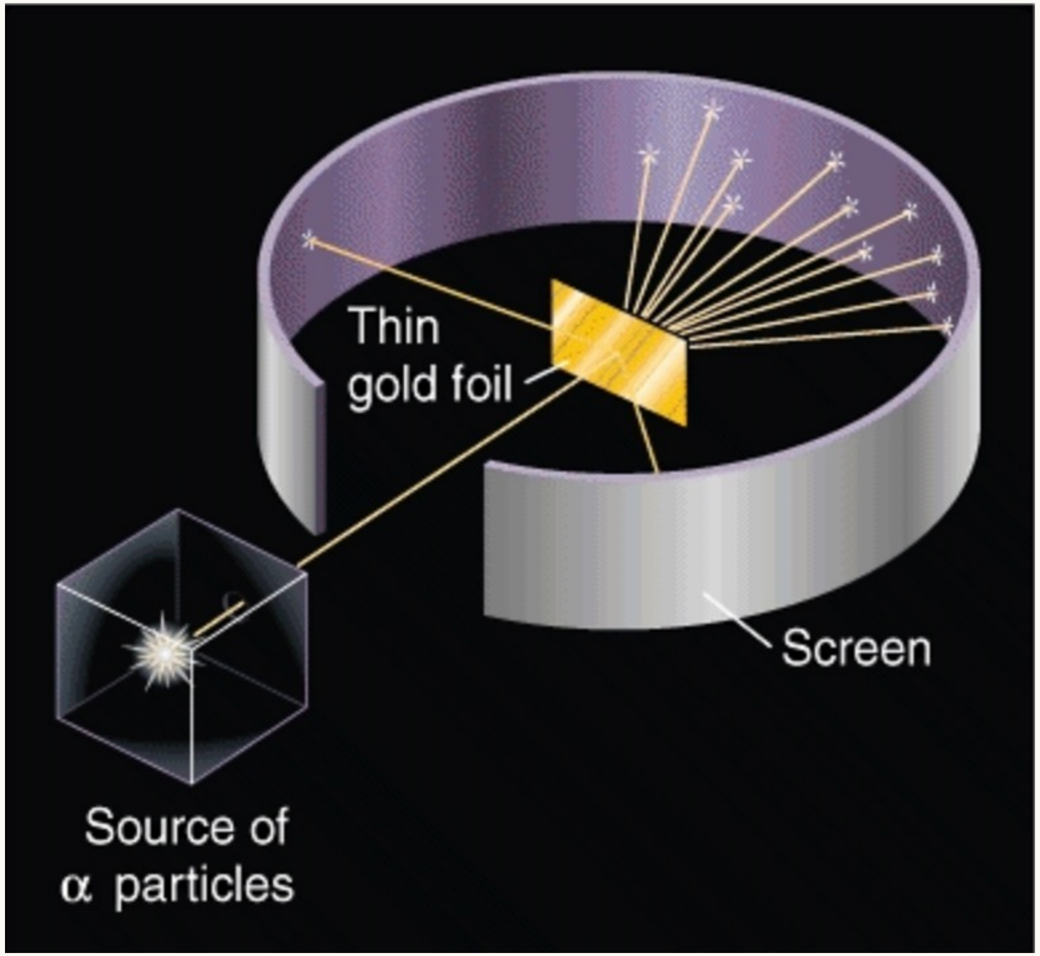
	Time Since Big Bang	Temp (GeV) (1eV=11605K)	Characterization
Big Bang	< 10^{-43} sec	~infinity	**All four forces (Gravity, Strong, Electromagnetic, and Weak) are united**
Quantum Gravity Era	~ 10^{-43} sec	10^{19}	**Gravity separates** (Planck scale). Strong, EM, and Weak forces are still united. This is the first instance of symmetry breaking among the forces.
Grand Unification Epoch	~ 10^{-35} sec	10^{14}	**Strong force separates. EM & weak forces united.**
Electroweak Epoch	~10^{-11} sec	100	**Electromagnetic and weak forces split**
Quark Epoch (quark-gluon plasma)	~10^{-6} sec	0.2	**Phase transition from a system of quarks and gluons (QGP) to hadronic matter.**
Nucleosynthesis	~ 3 mins	10^{-4}	Protons and neutrons combine to form nuclei
Galaxy formation	379,000 yrs		
Present Universe	13.7 billion yrs	10^{-13}	

Solving the mysteries of the Universe through the exploration of the Sub-atomic world.

What are the Elementary Constituents of Matter?

What are the forces that control their behaviour at the most basic level?

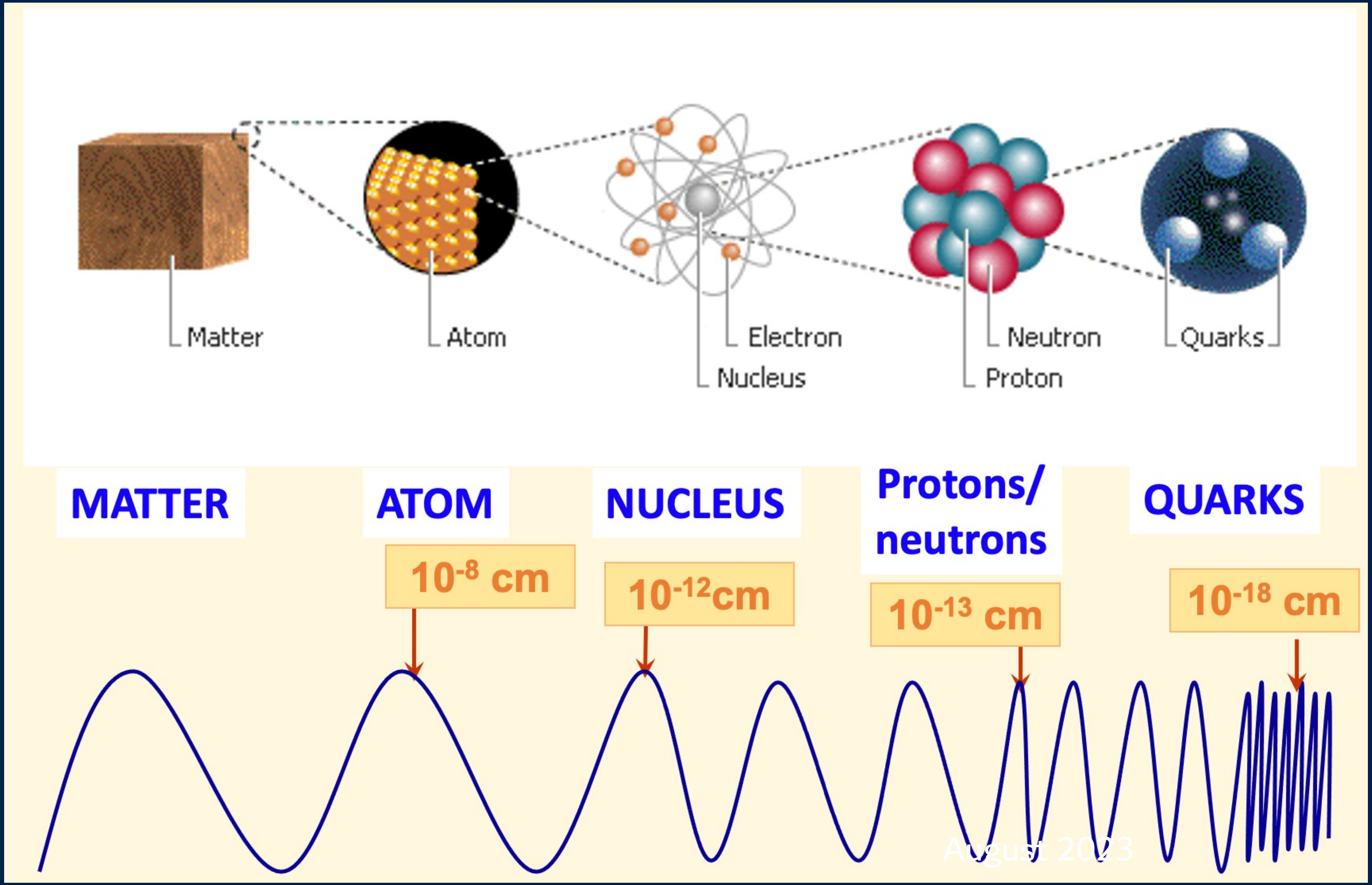
1911: The Rutherford gold foil experiment



Discovery of the 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.

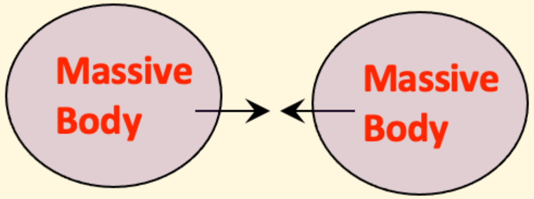
Structure of matter



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

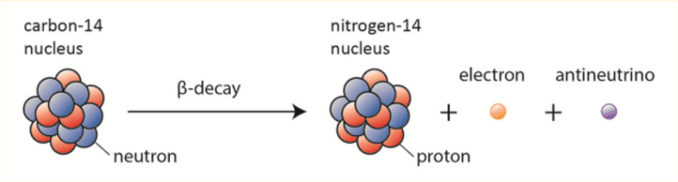
Fundamental forces of nature

Gravitational force



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

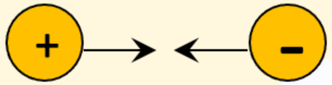
Weak force



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**

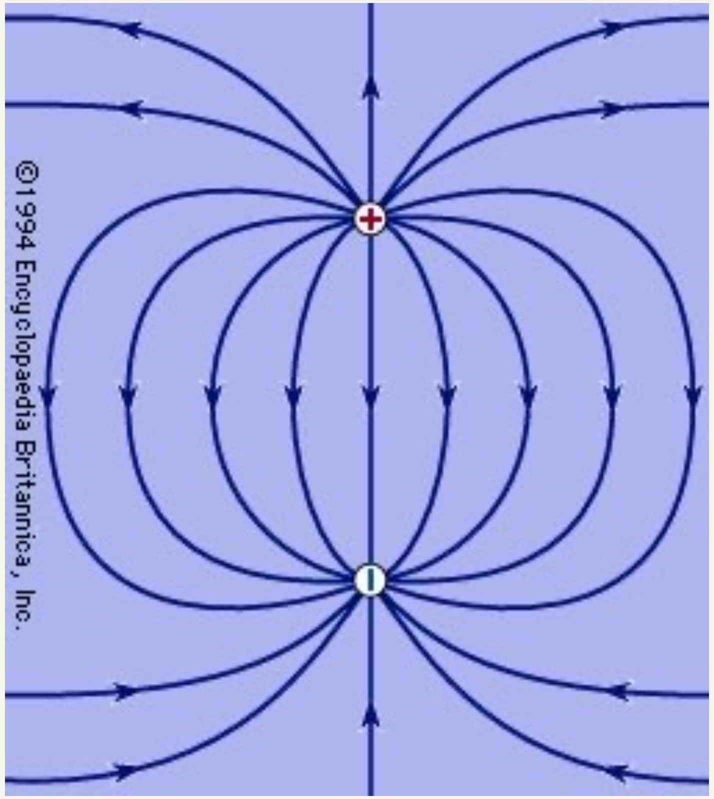
Strong force

Holds the atomic nucleus,

Binds quarks together

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

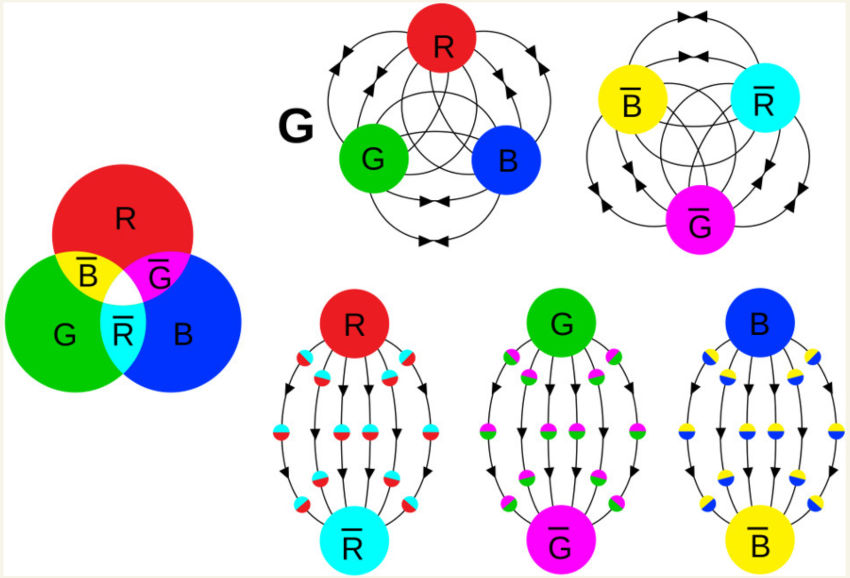
Electromagnetic interaction



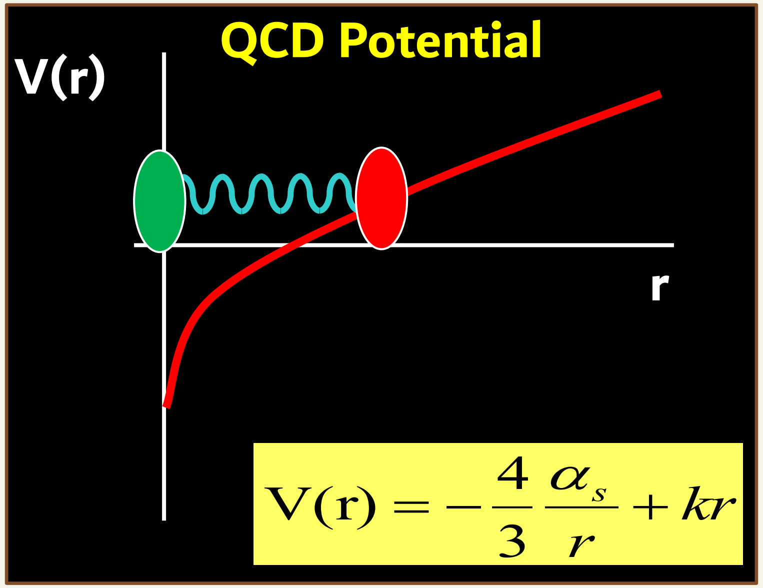
Electric field lines near equal but opposite charges

The electromagnetic force exhibits electromagnetic fields such as electric fields, magnetic fields and light

Strong interaction

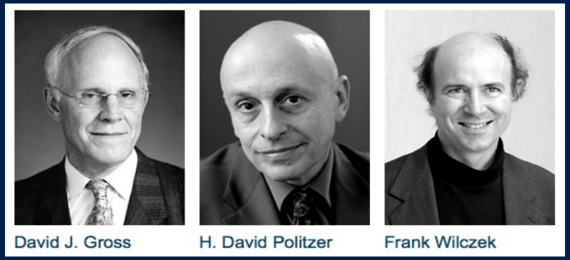


Color force in QCD



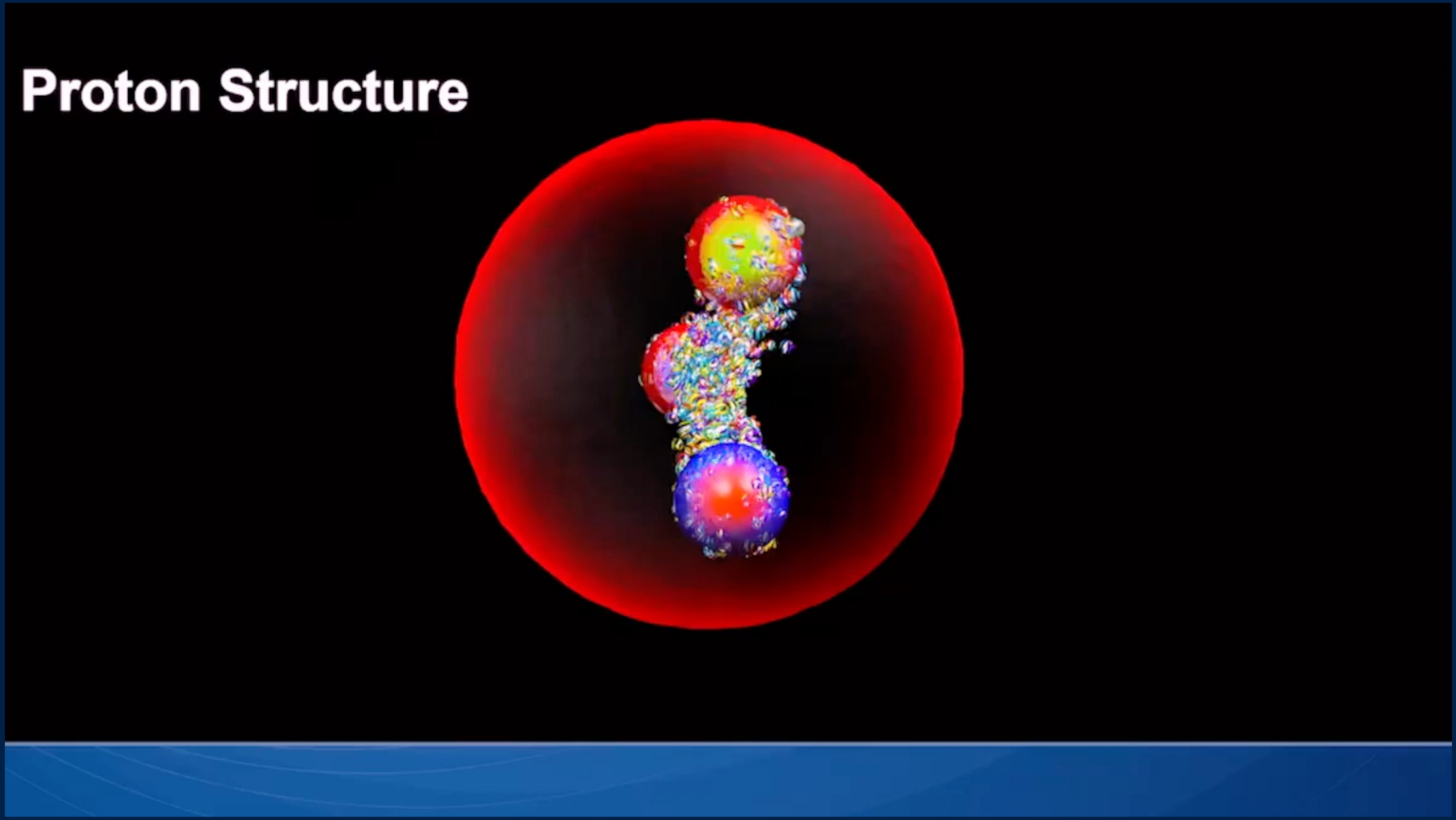
Lockdown: QUARK Confinement and Asymptotic Freedom

Nobel Prize 2004



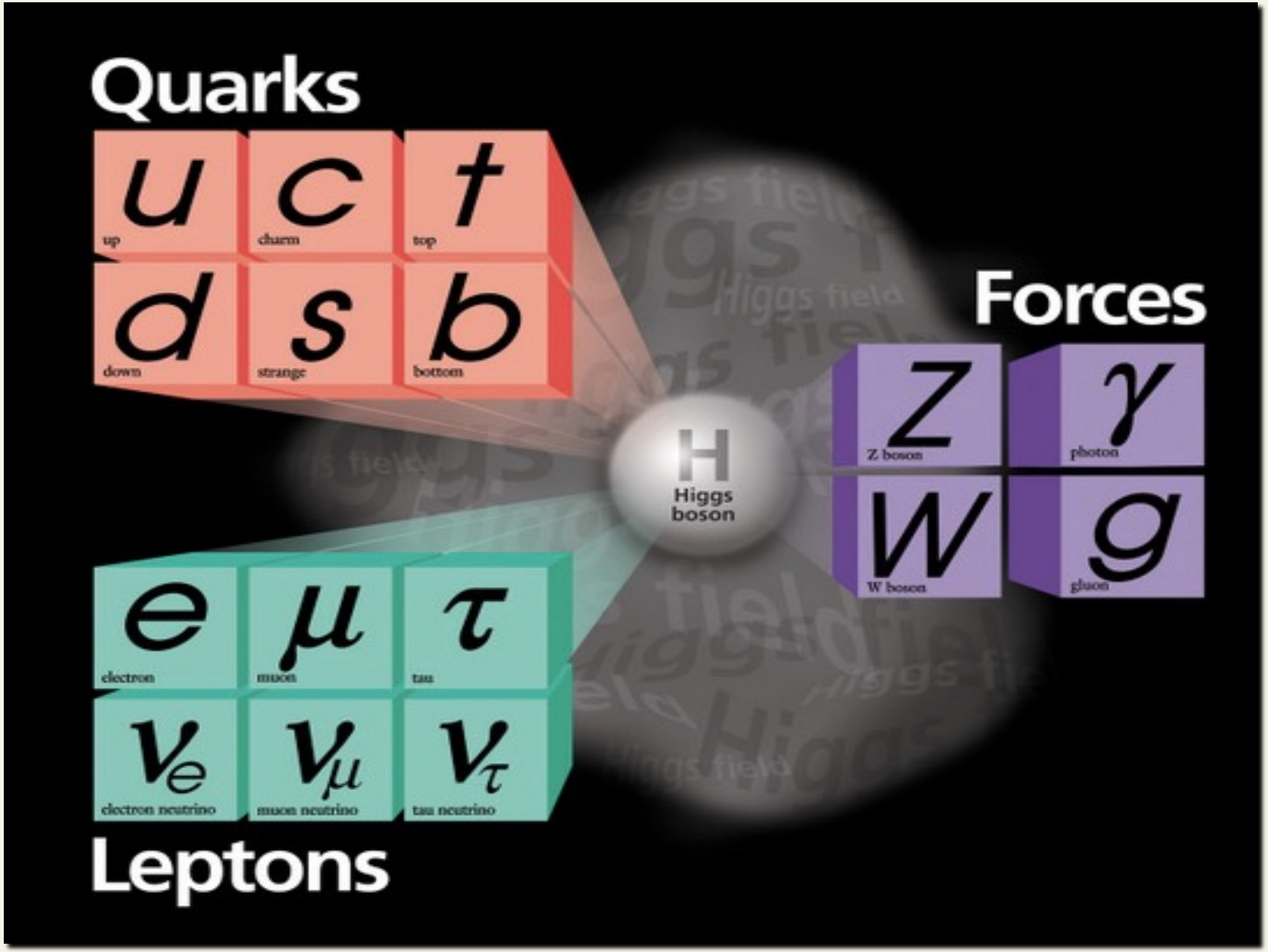
1973: asymptotic freedom
D.J. Gross, F. Wilczek, H.D. Politzer

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



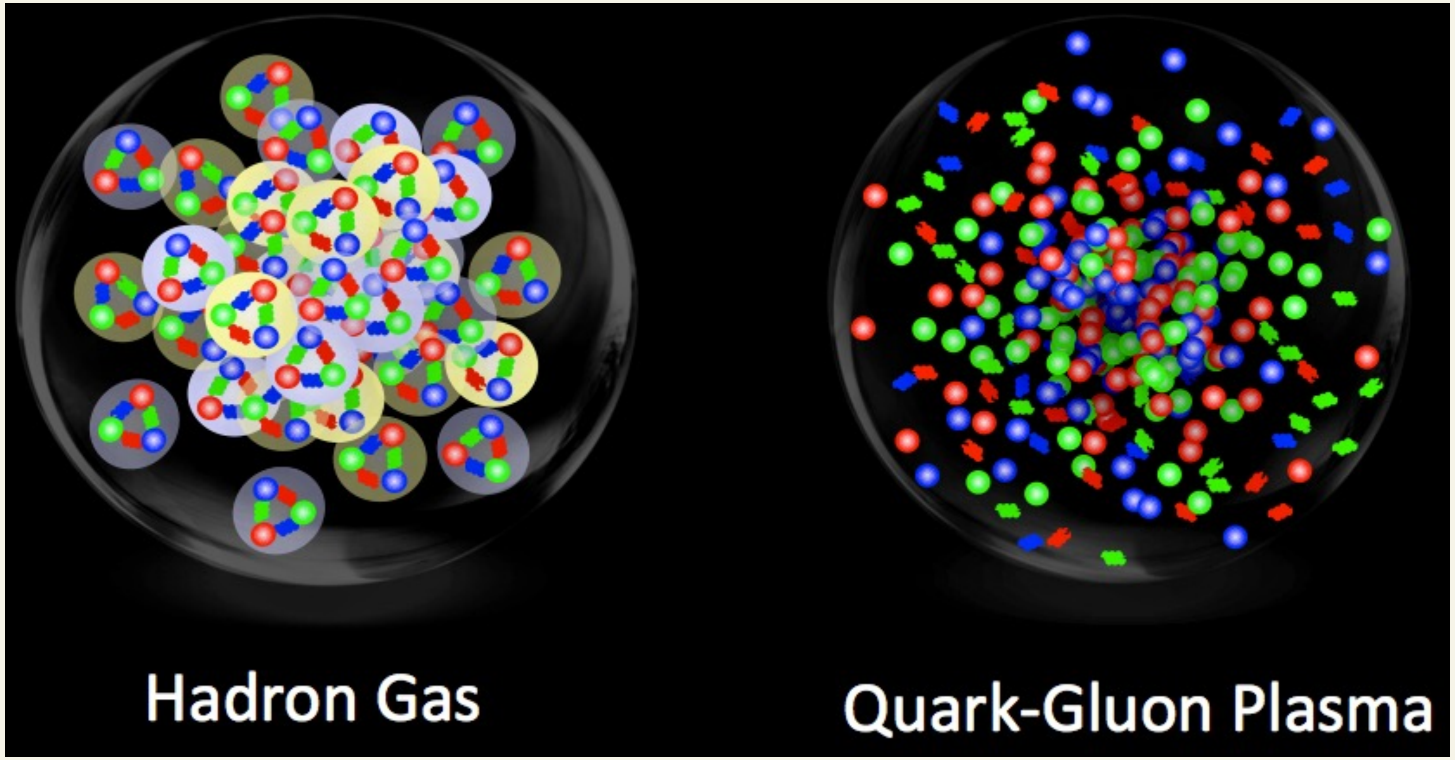
QCD: Quantum Chromodynamics

Fundamental constituents of matter



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

Quark Gluon Plasma (QGP)



T. D. Lee 1974

Hadron gas =>

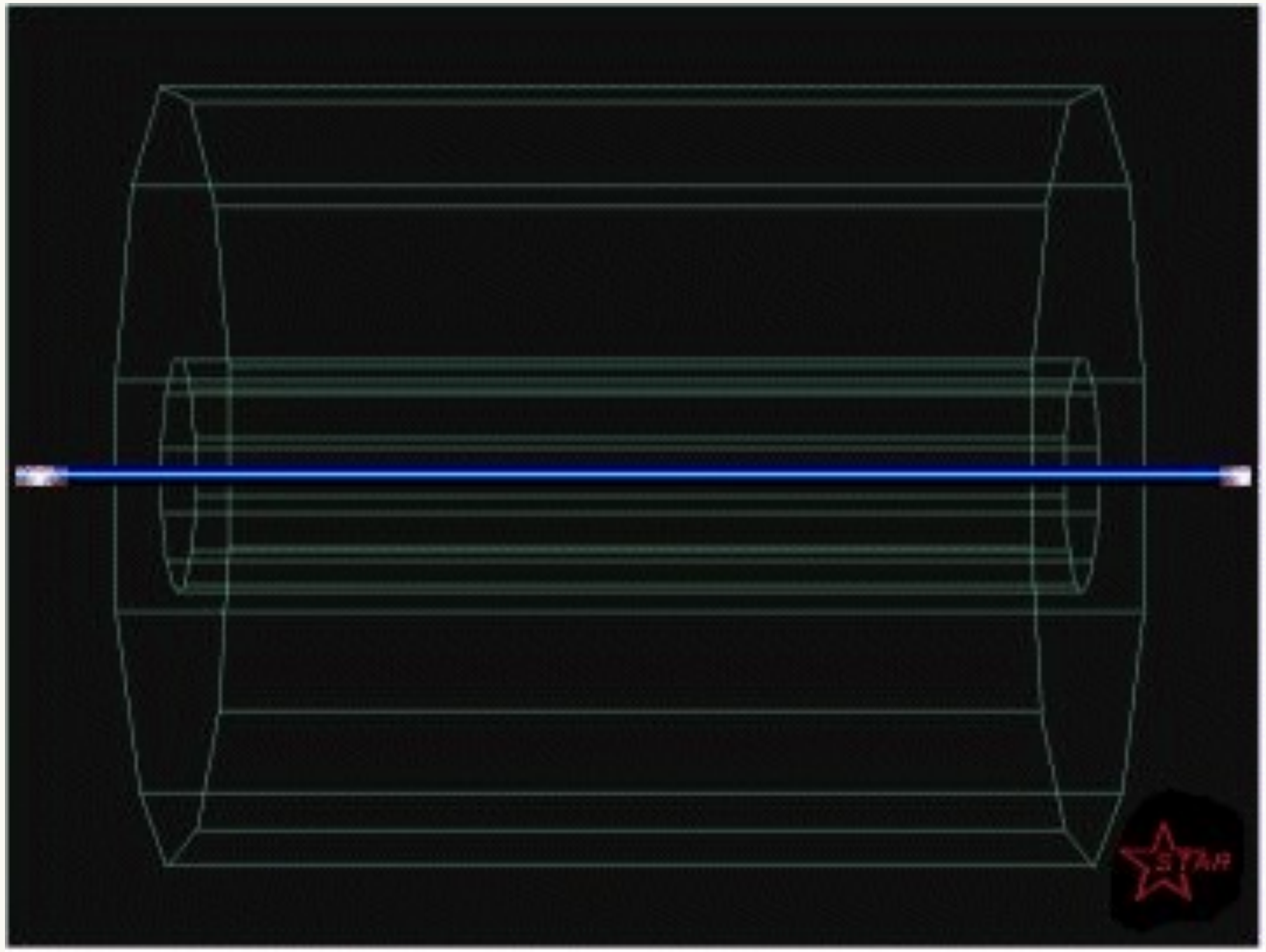
- Heat up to very high temperature
- Apply extremely high pressure

=> 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.

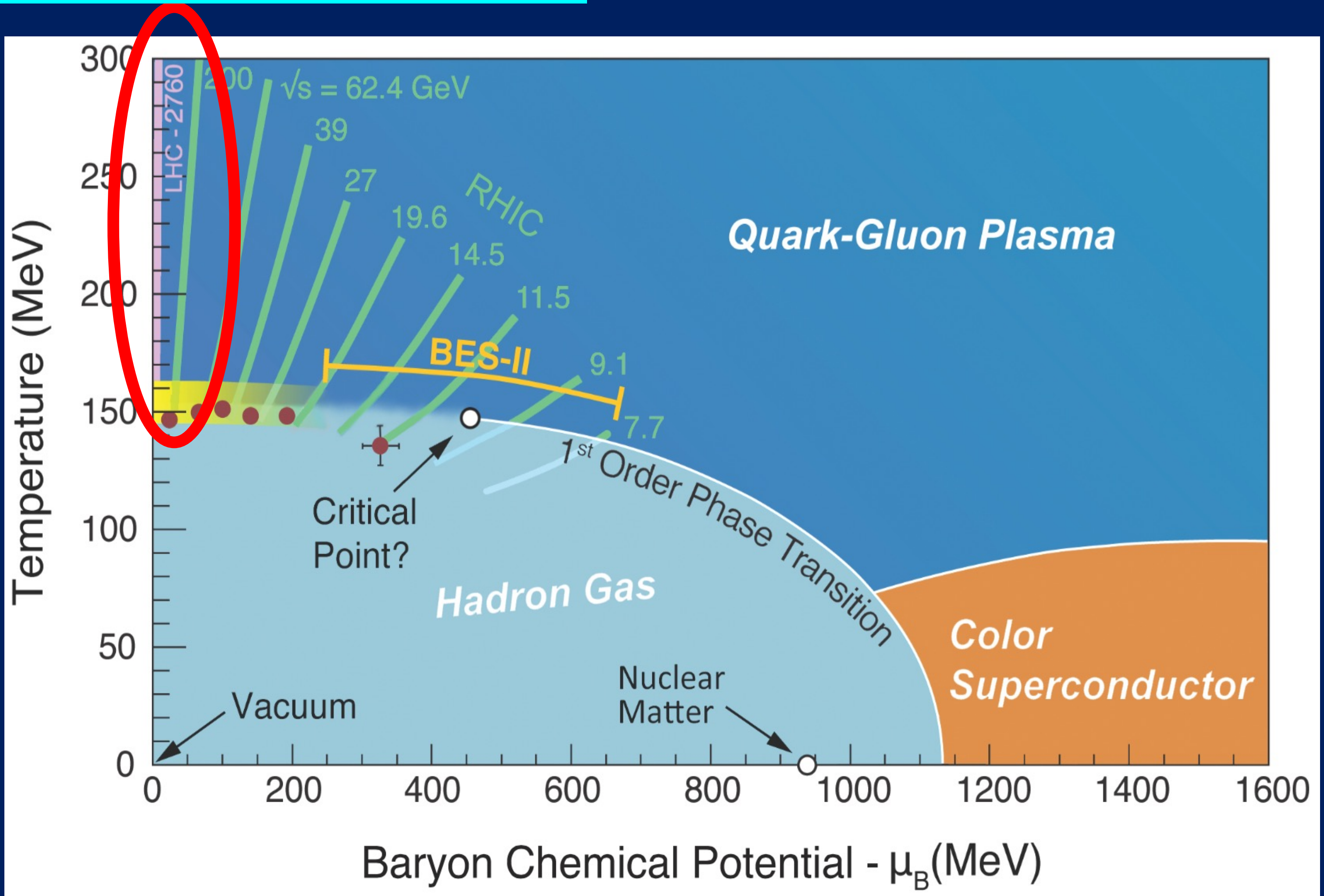
Heavy-ion collisions: Creating the Quark-Gluon Plasma

- 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***



The QCD Phase Diagram

The high-energy frontier



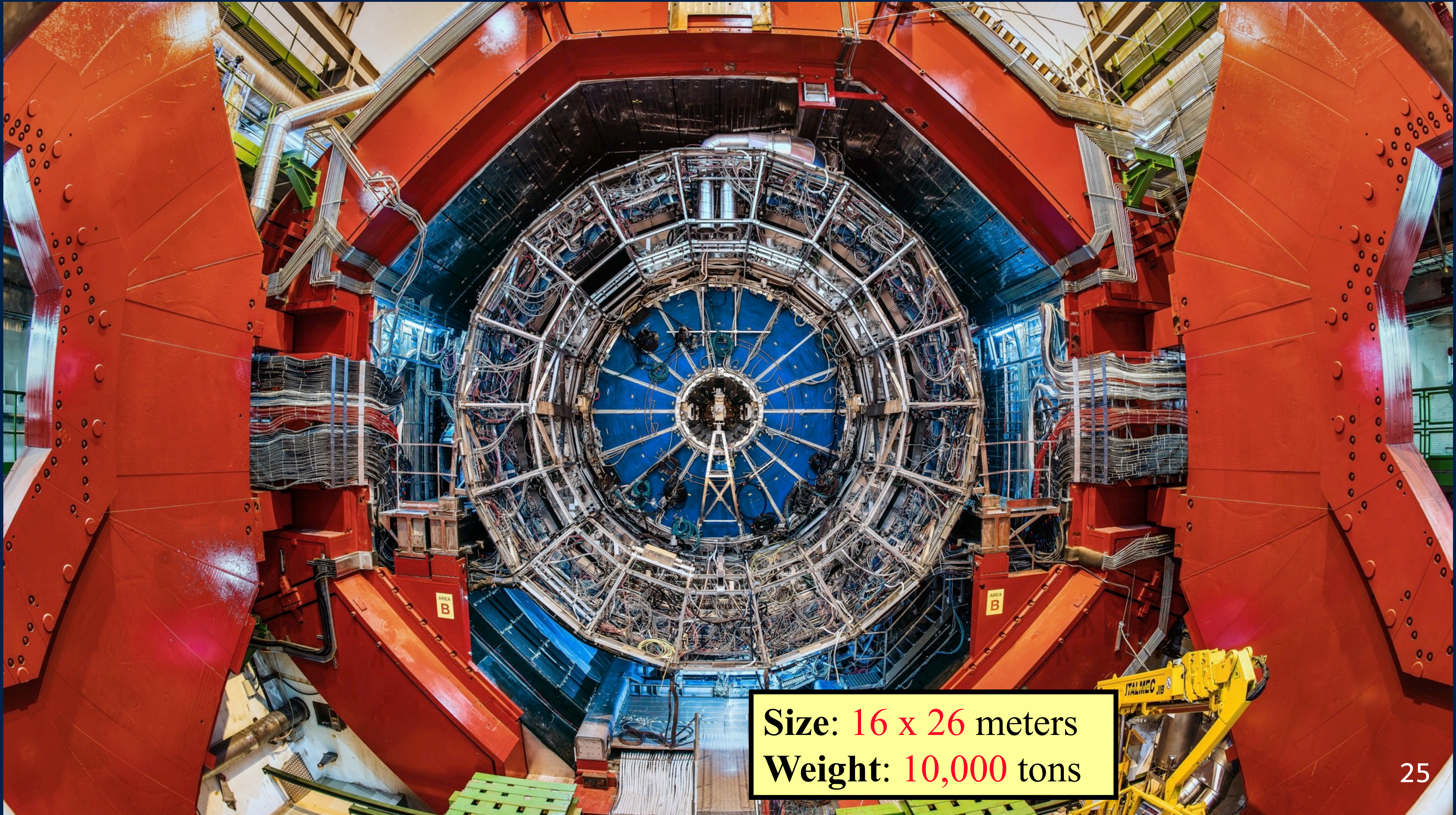
Present Facilities:

- RHIC Top Energies:
  - STAR
  - PHENIX
- CERN LHC
  - ALICE
  - ATLAS
  - CMS
  - LHCb

Future:

- LHC Run 3+4
- LHC Run 5+6 (ALICE 3)
- RHIC (sPHENIX)
- FCC at CERN?

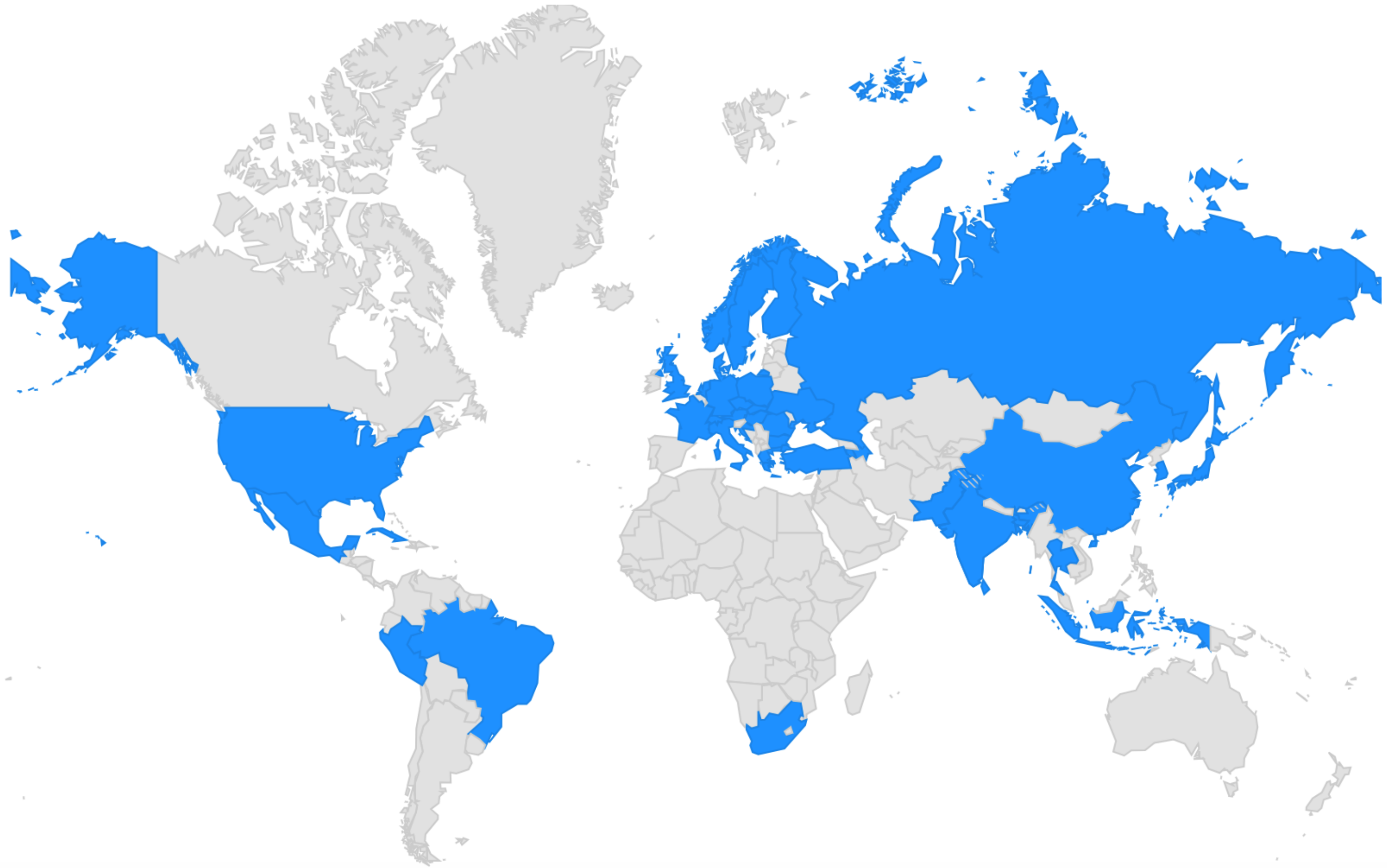
ALICE at Point-2 of the LHC



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

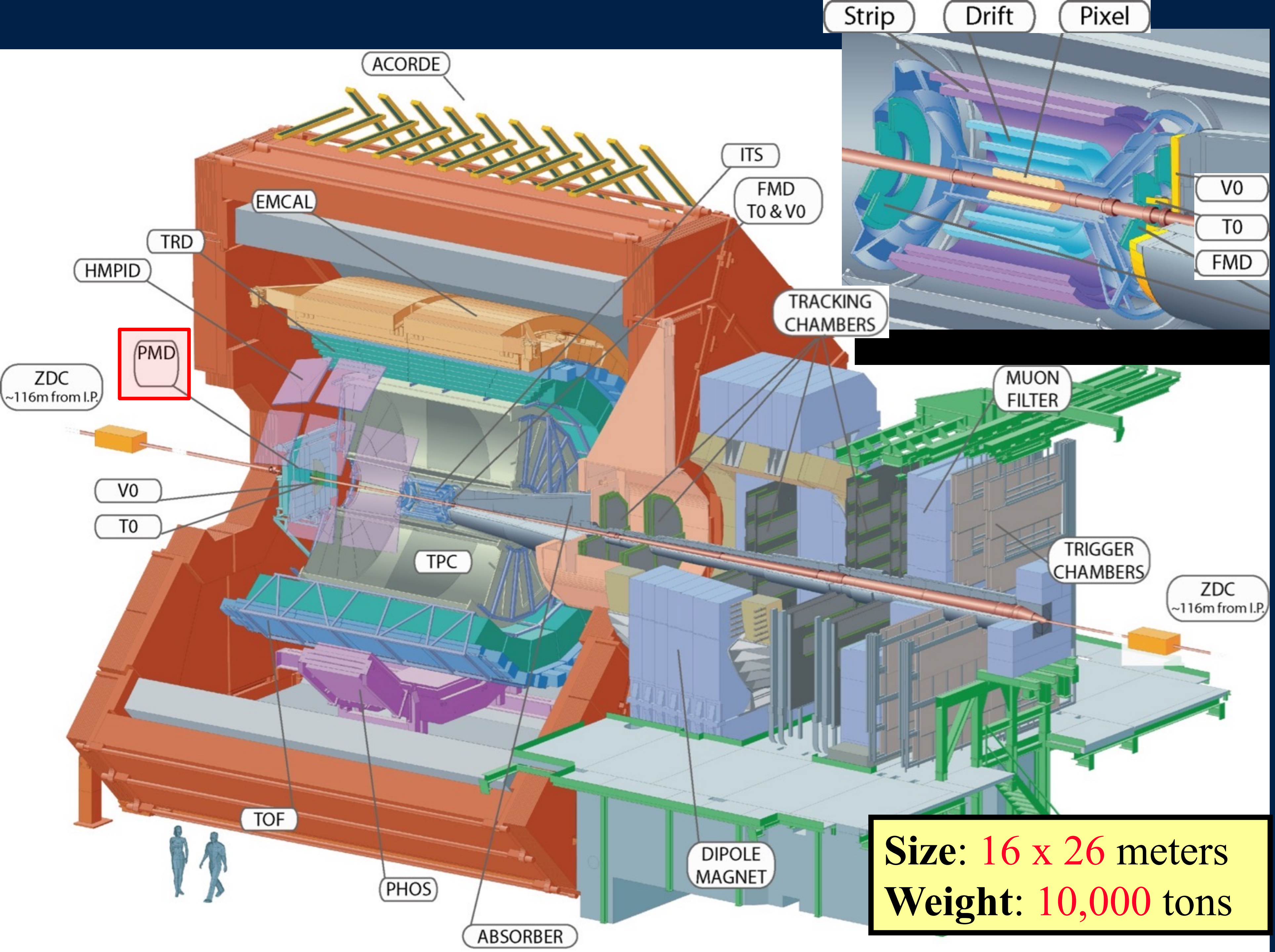
ALICE Collaboration

40 countries, 169 institutes, 1975 members



https://alice-collaboration.web.cern.ch/

ALICE
Run 1 & 2



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

CENTRAL BARREL

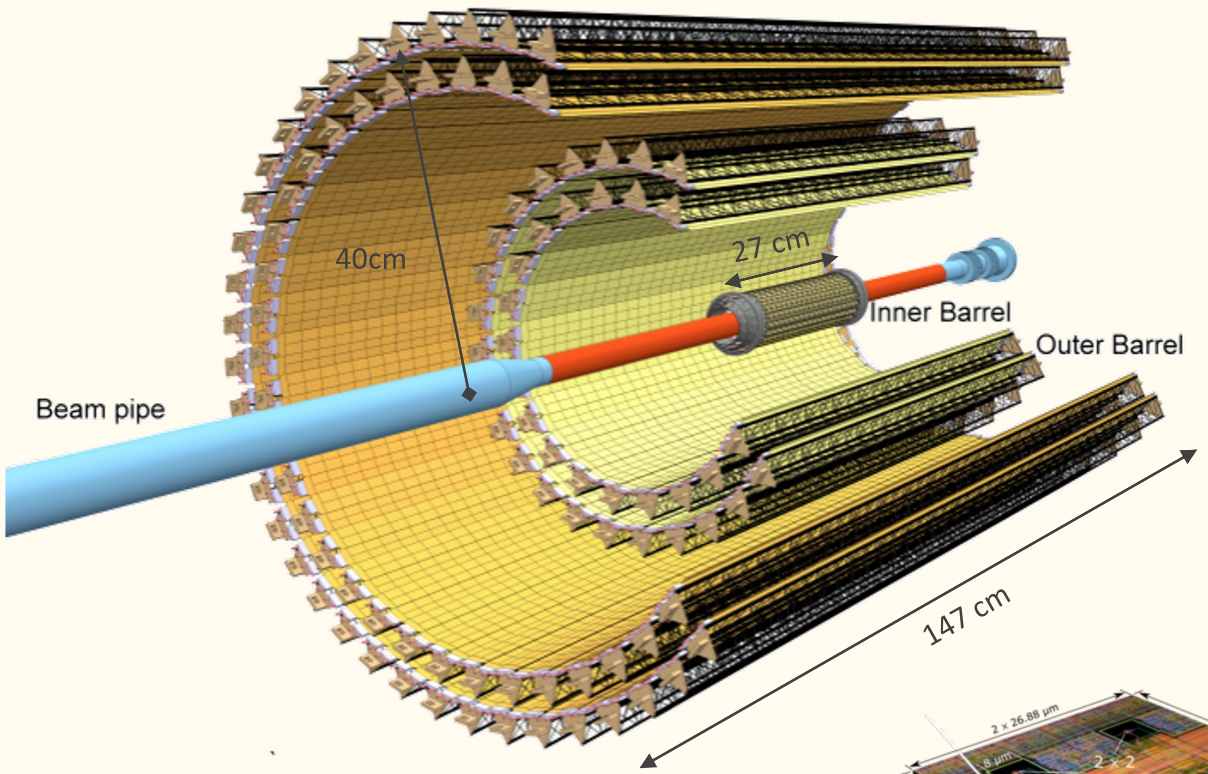
- Acceptance: |η|<0.9
- B=0.5 T
- **ITS:** High precision vertexing and centrality
- **ITS+TPC+TOF**: charged track reconstruction, PID
- **TRD:** electron ID
- **EMCAL:** calorimeter

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

SPECIAL detectors:

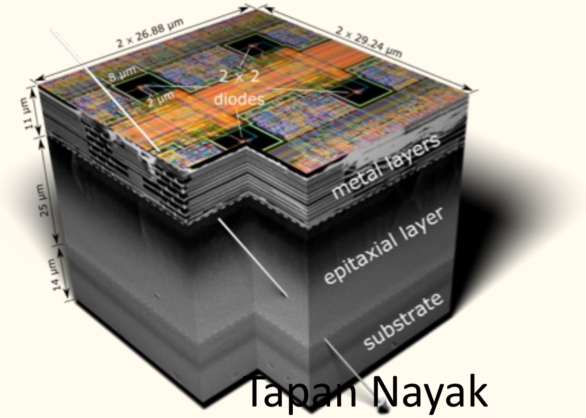
- V0
- FMD
- PMD
- ADC
- ZDC

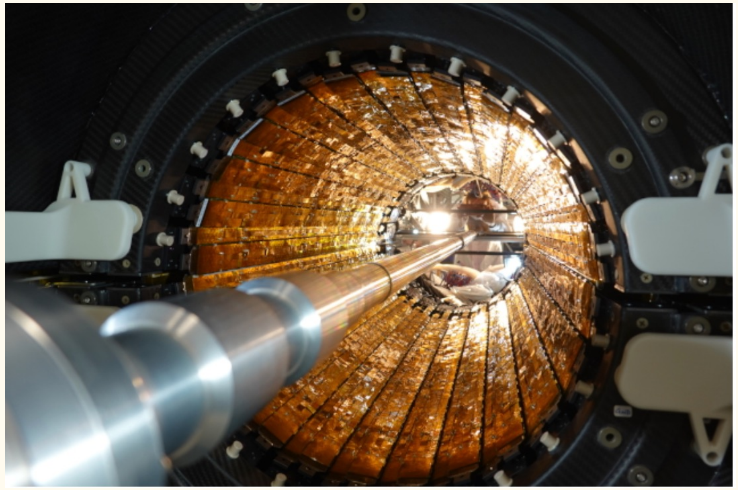
New Inner Tracking System (ITS)

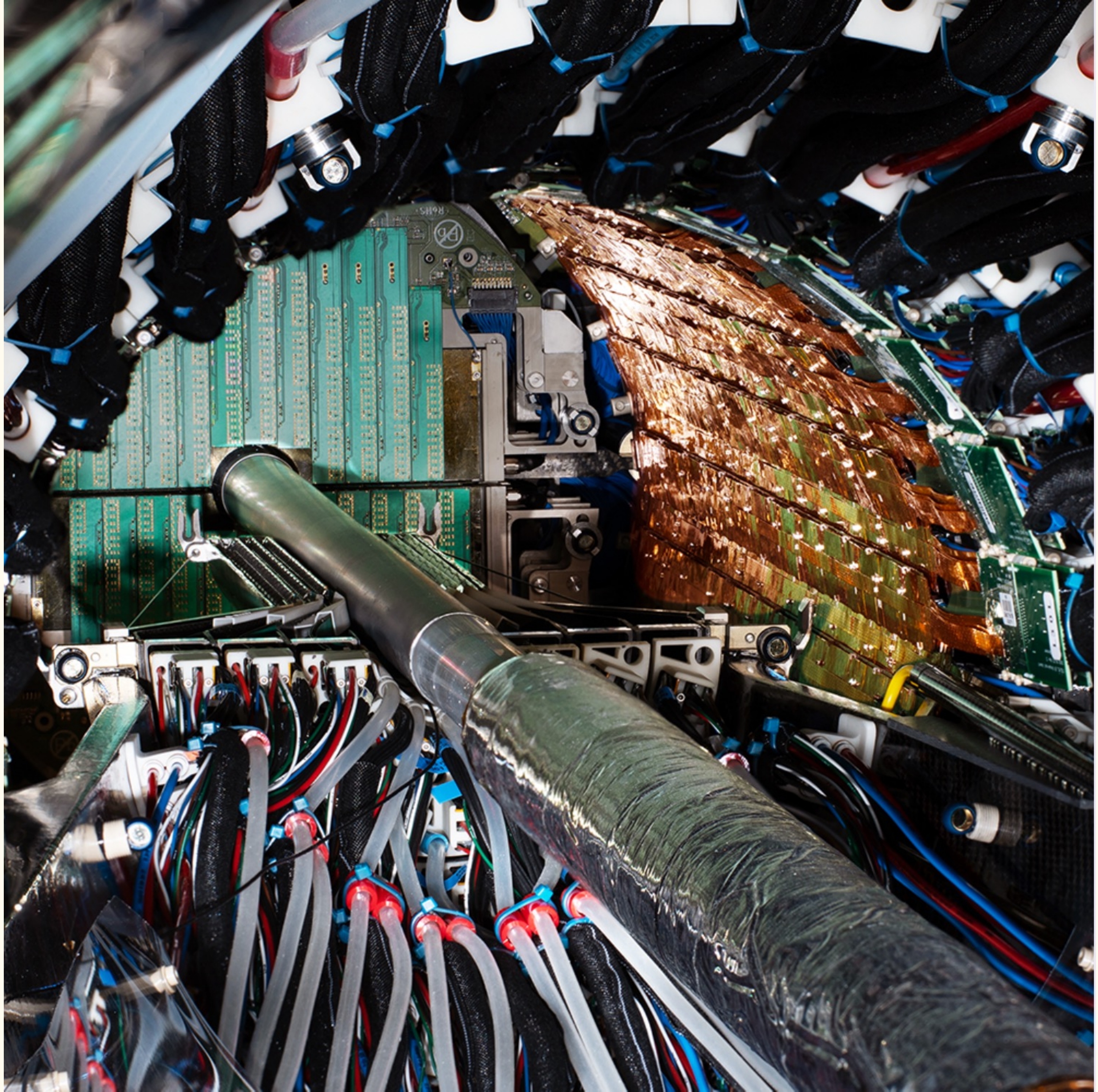


- 7-layer geometry (23 – 400mm), $|\eta| \leq 1.5$)
- 10 m^2 active silicon area (**12.5 G-pixels**)
- Pixel pitch 28 x 28 μm^2
- Spatial resolution ~5μm
- Power density < 40mW / cm^2
- Material thickness: ~0.3% / layer (IB)
- Maximum particle rate: 100 MHz / cm^2

Based on CMOS Monolithic Active Pixel Sensors (MAPS)





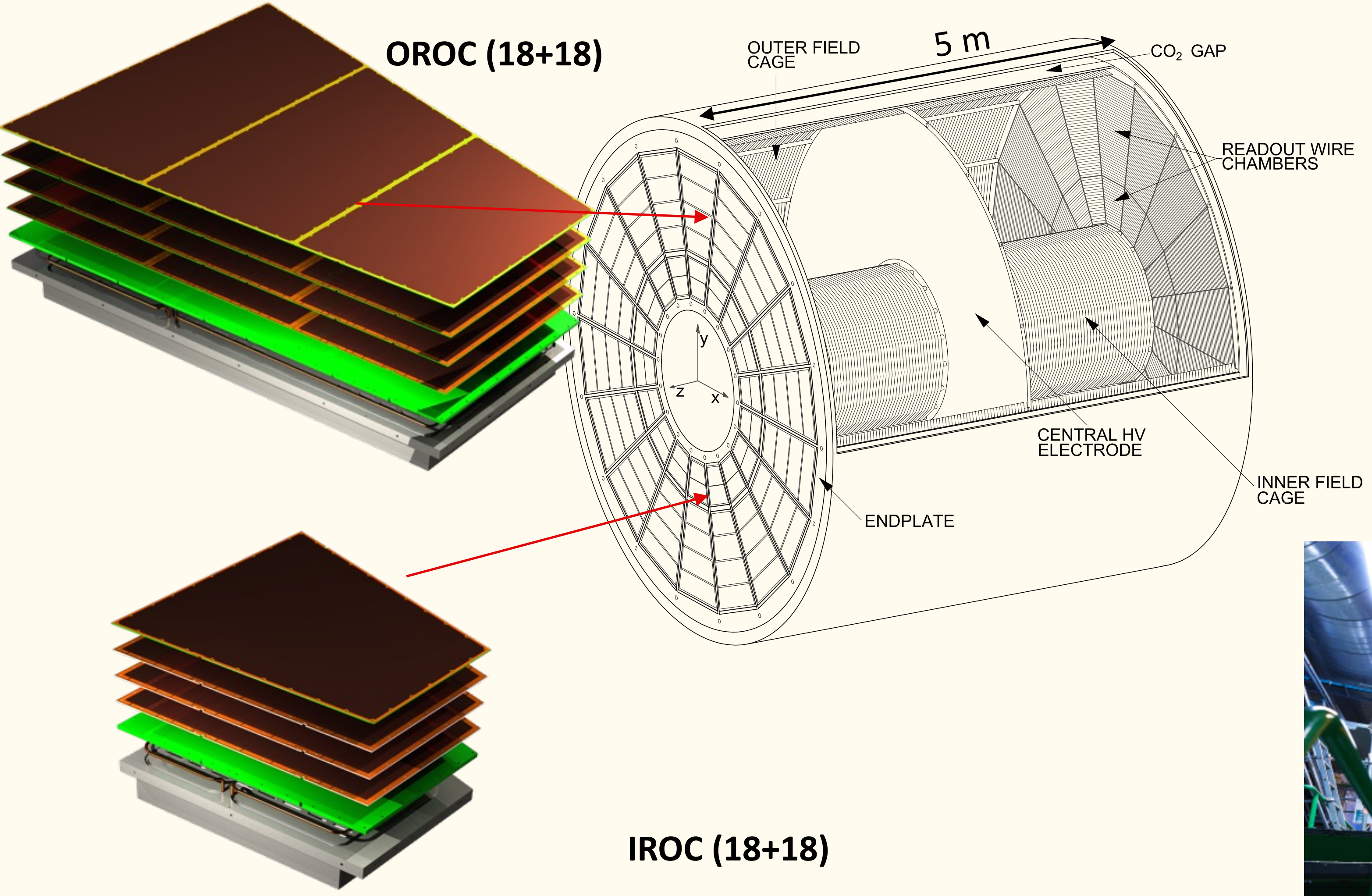


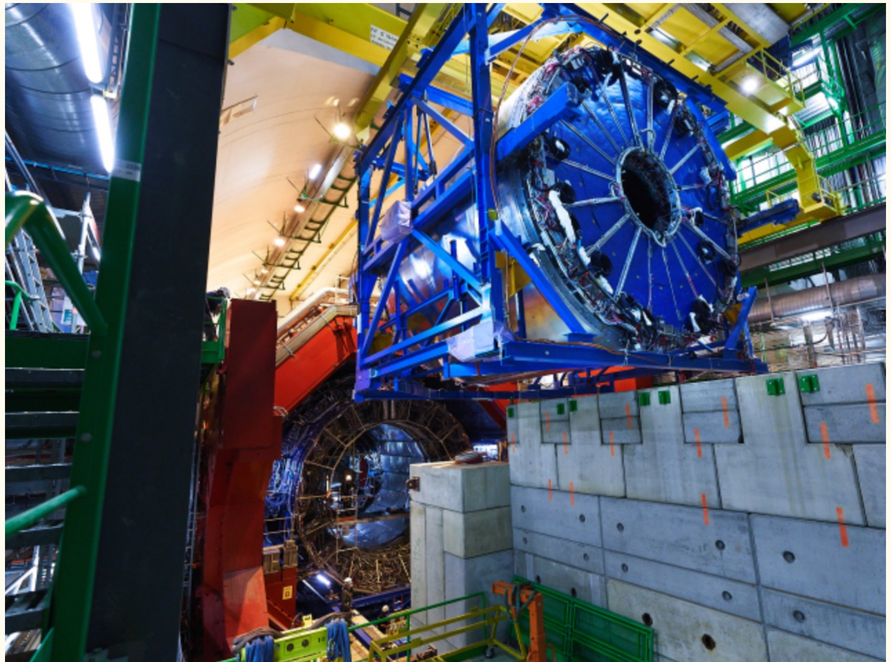
The inner (left, middle) and outer (gold colour) barrels of ALICE's state-of-the-art **Inner Tracking system (ITS)** along with the new **Muon Forward Tracker (MFT)** (green panel).

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

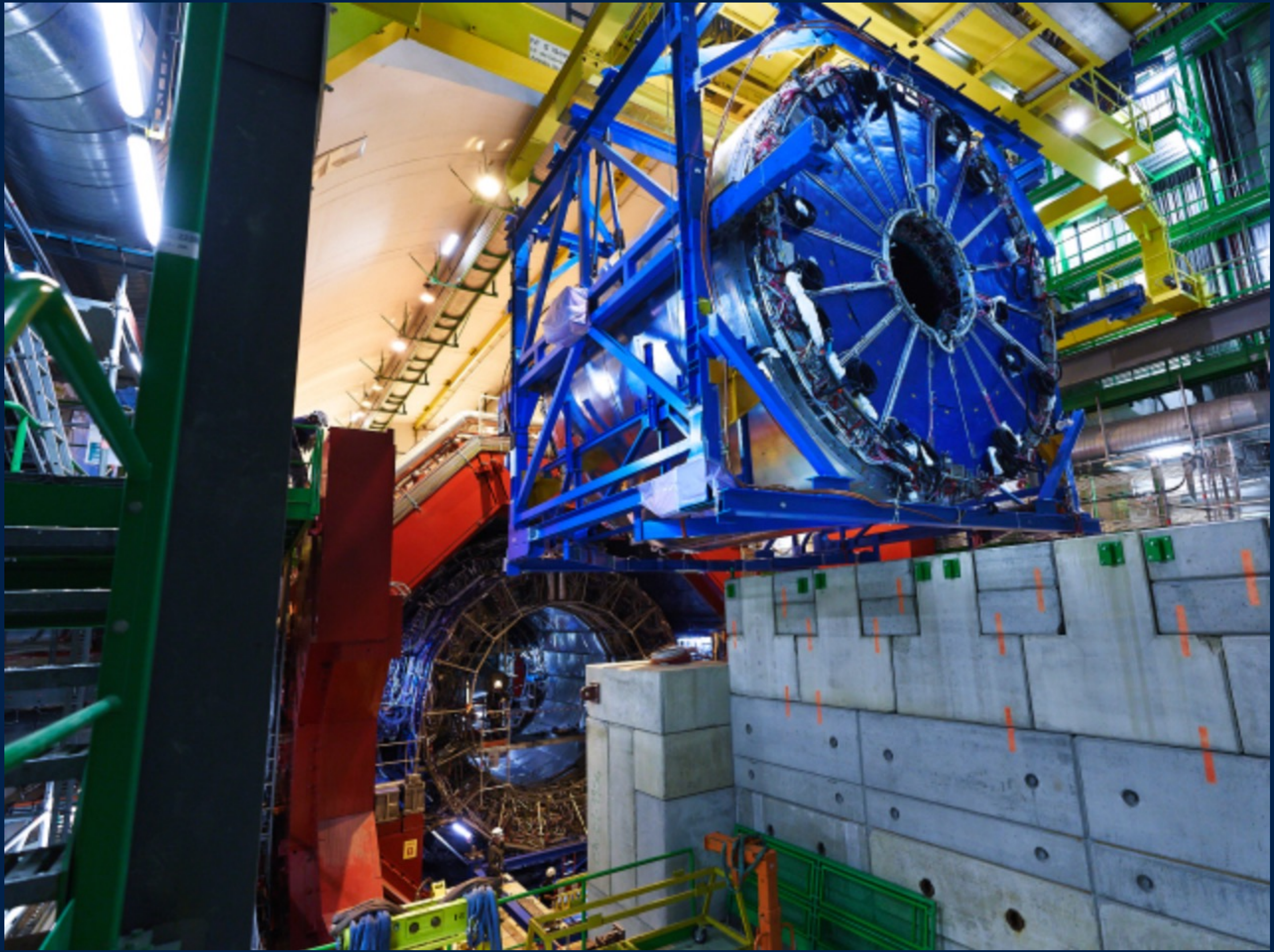
https://cerncourier.com/a/alice-tracks-new-territory/

Time Projection Chamber (TPC) with GEM detectors



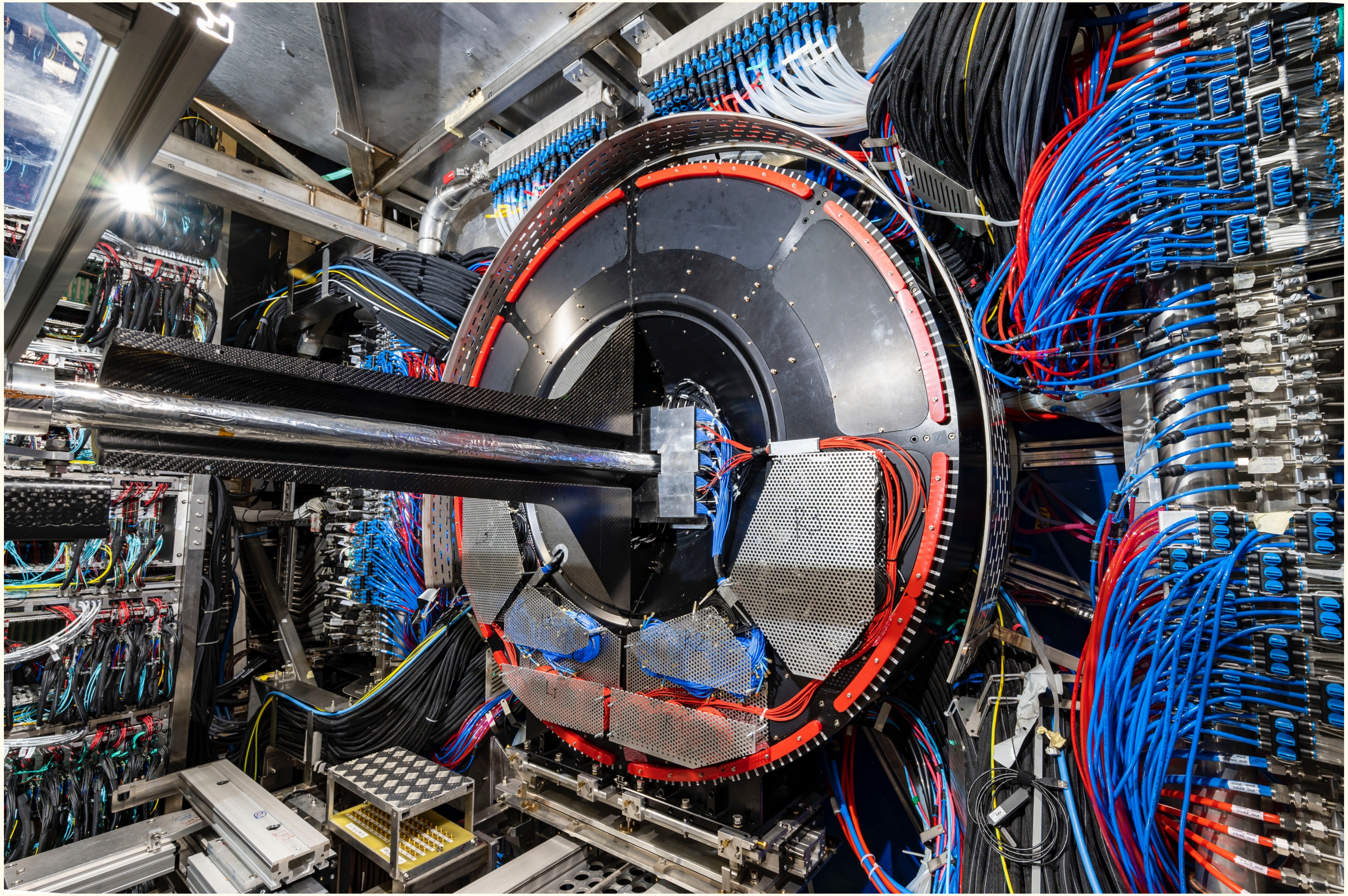


TPC installation



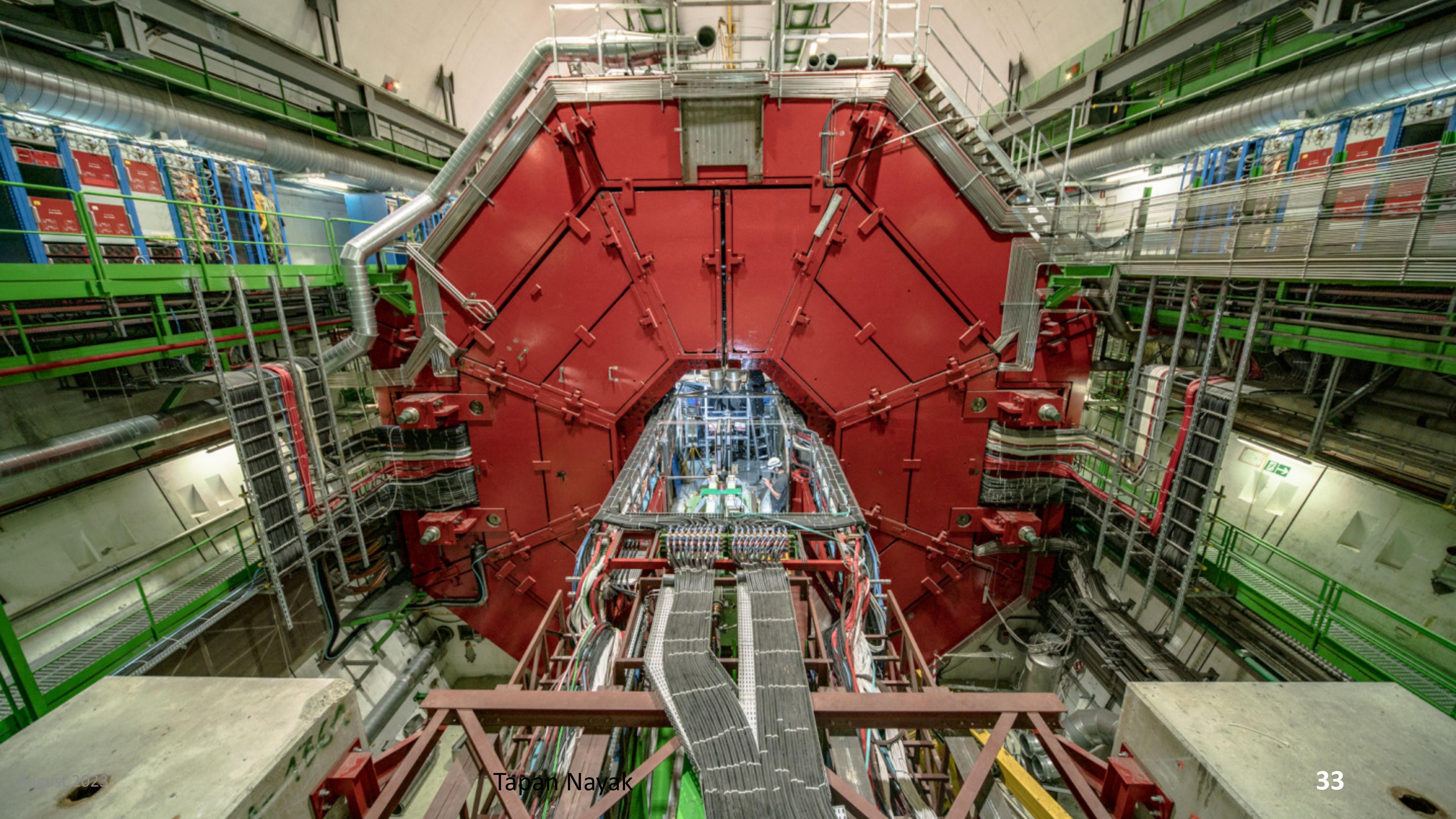
https://videos.cern.ch/record/2729677

Fast Interaction Trigger (FIT)

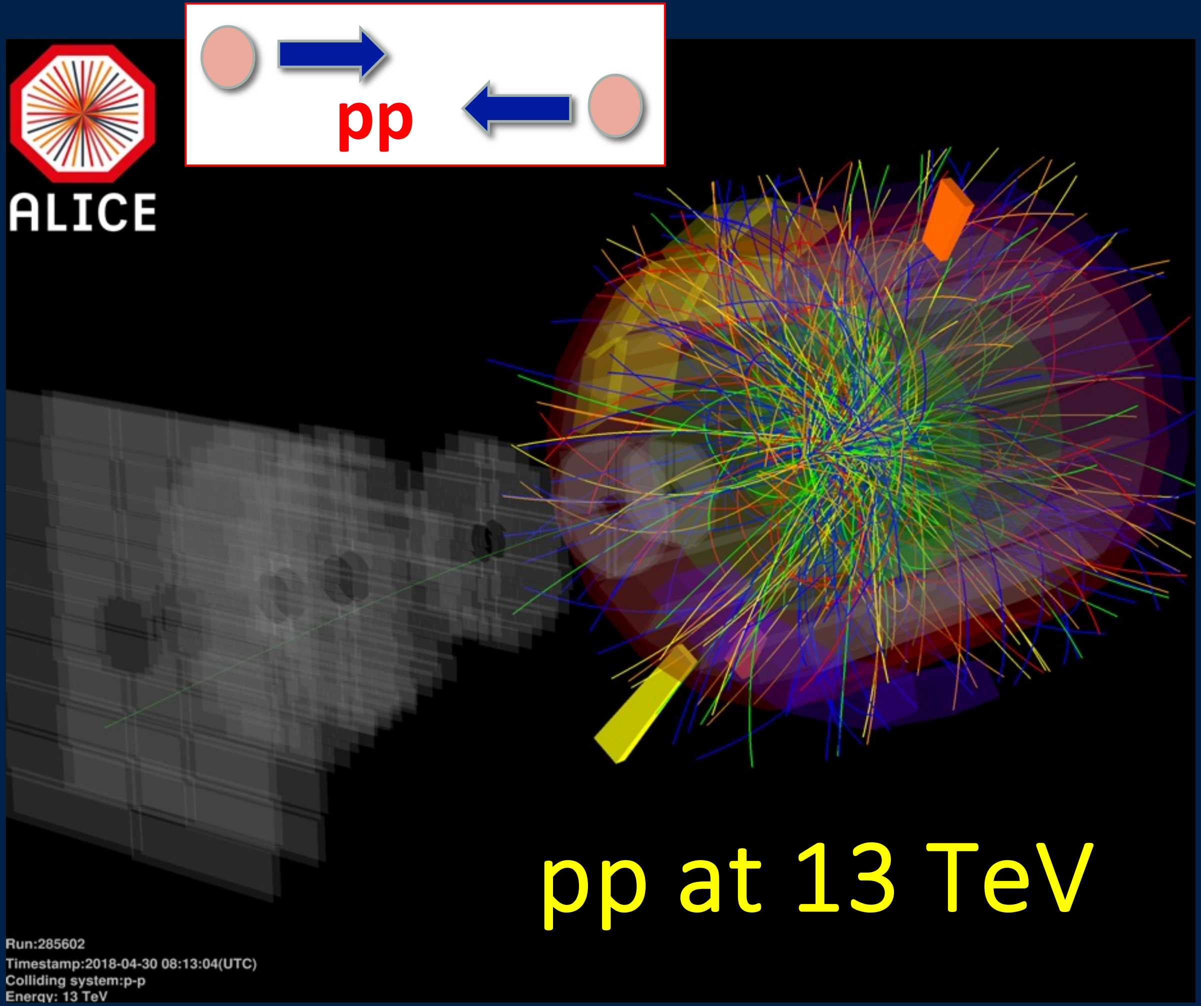


FIT is the

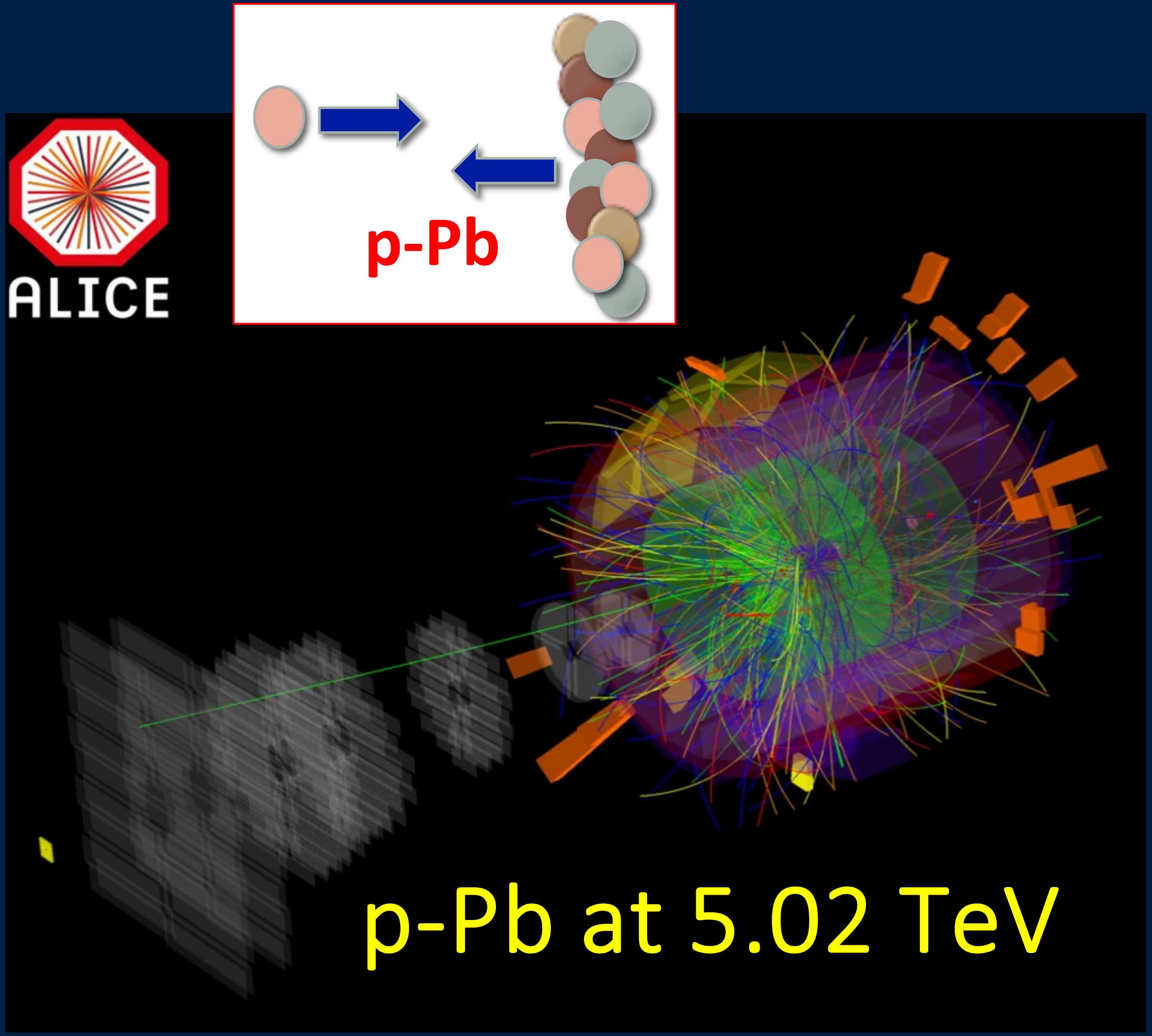
- fastest trigger,
- Online luminometer,
- initial indicator of the vertex position, and
- The forward multiplicity counter for ALICE.

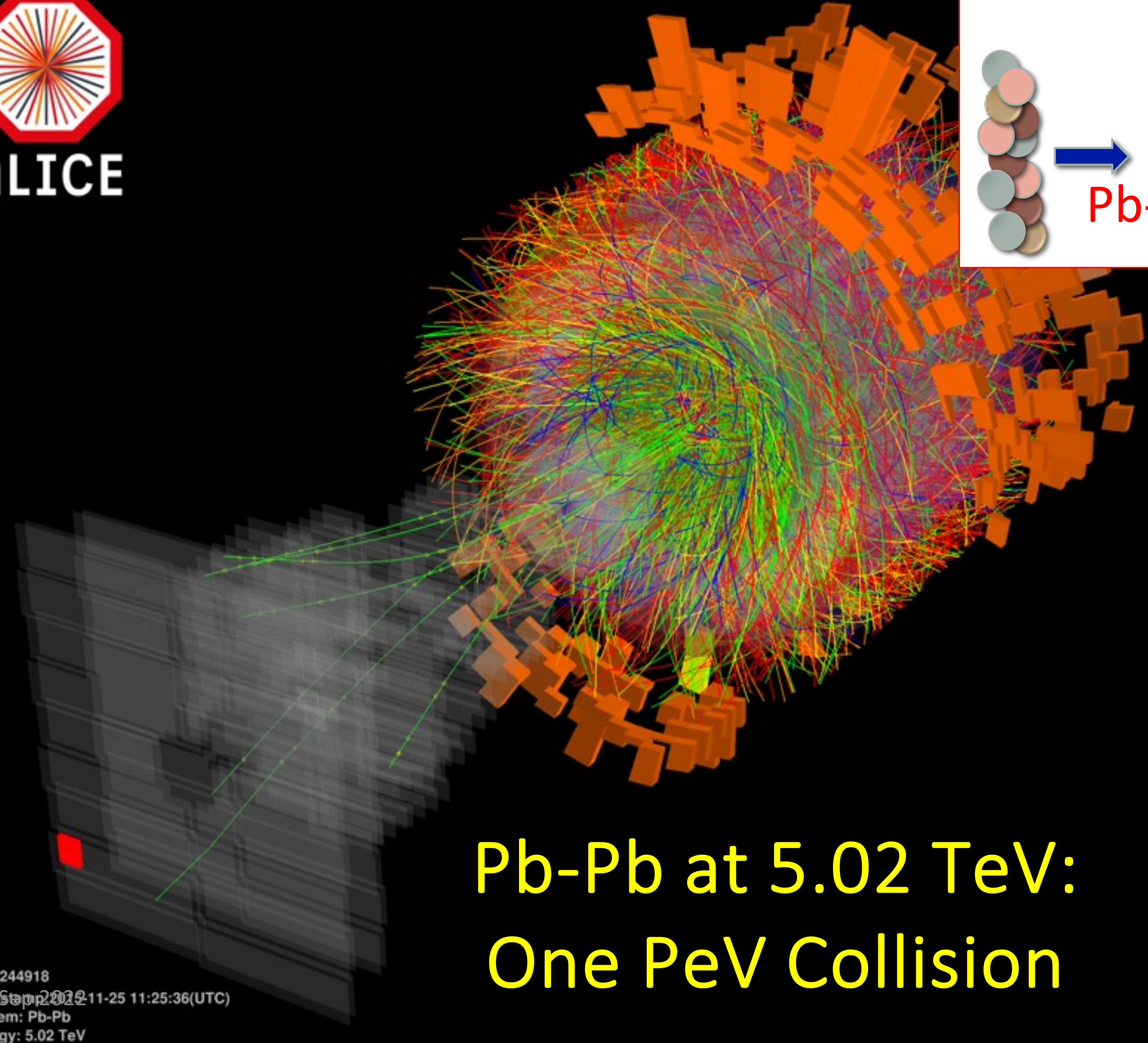


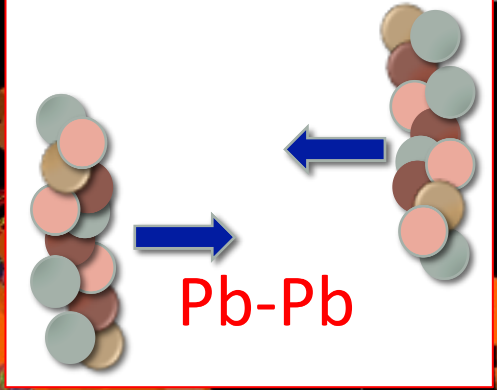
- Test of pQCD calculations from cross section measurements
- High multiplicity pp: what's the behaviour?
- Provide reference for p-Pb and Pb-Pb collisions

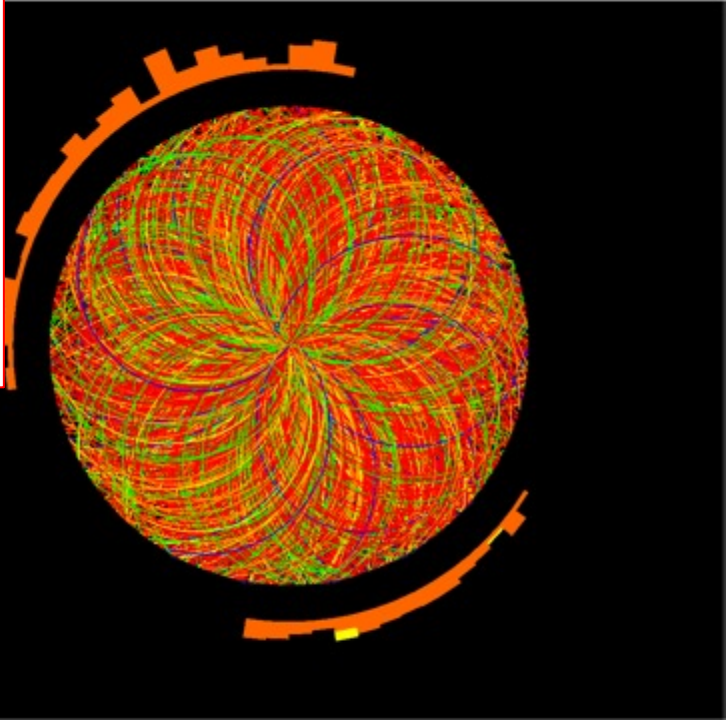


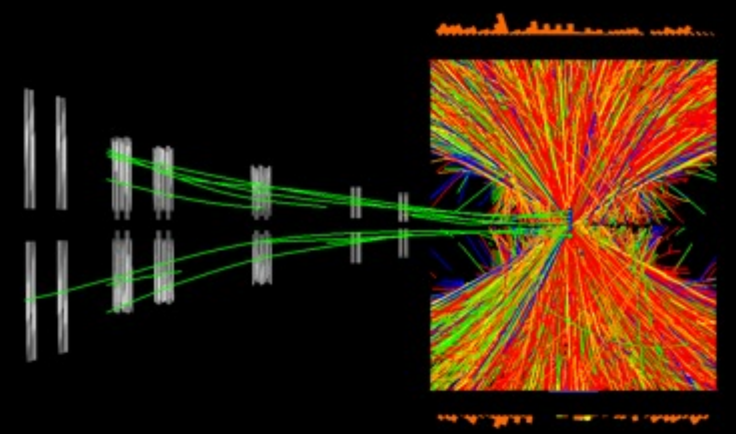
- Intermediary reference
- Address cold nuclear matter effects in initial and final states





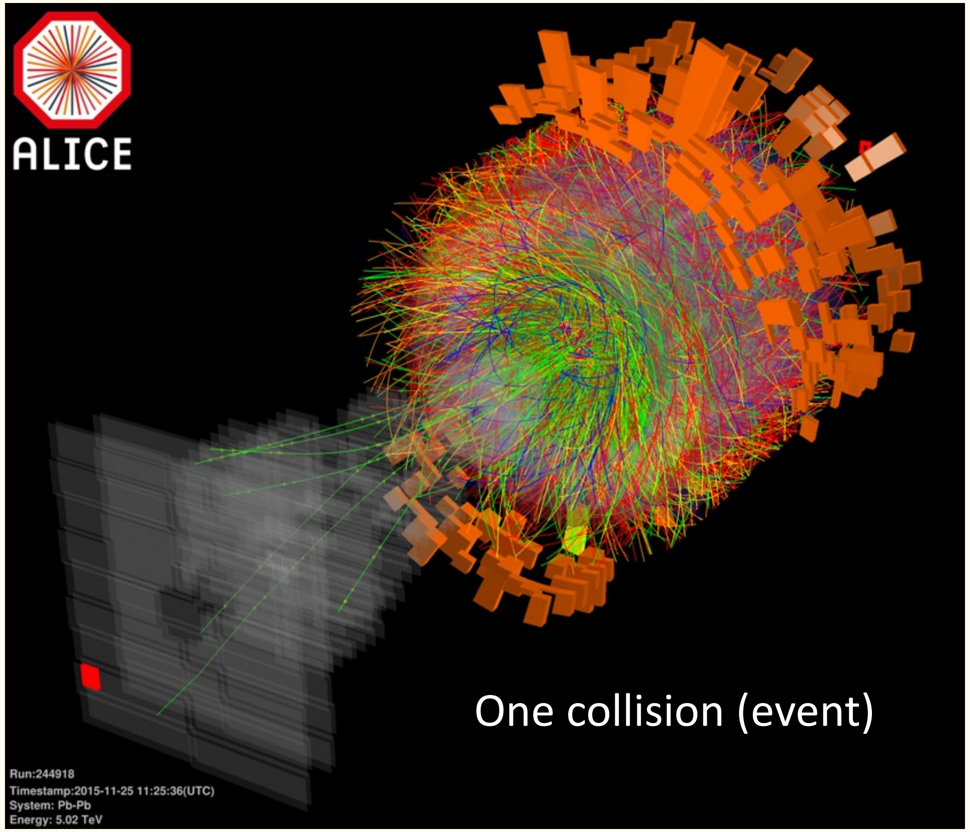






Pb-Pb at 5.02 TeV: One PeV Collision

Reconstructing the collision



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.

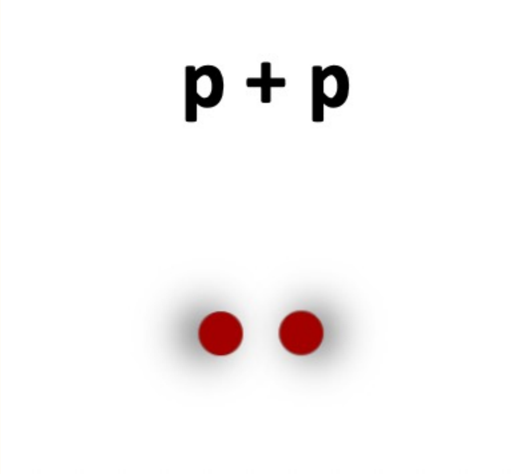
=> Offline: Event reconstruction:

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

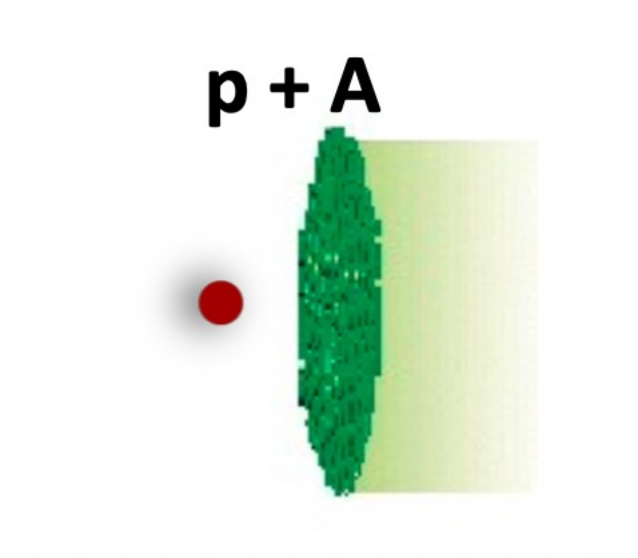
- The data flow from ALICE during Run2 was about 4 GB/second
- The data expected during next run (Run3) will be 3 TB/second

Dialing in various physics phenomena

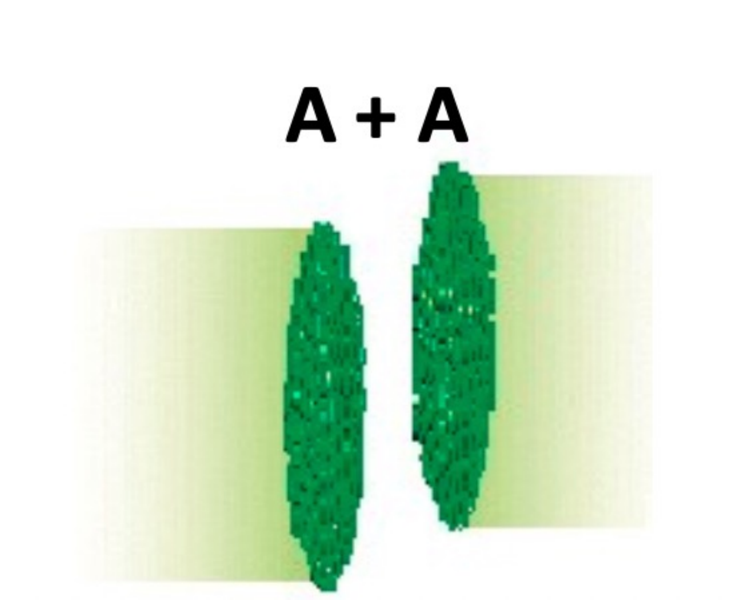
Collision system and Collision centrality



”vacuum” reference
+
high multiplicity pp collisions
to look for onset of QGP formation



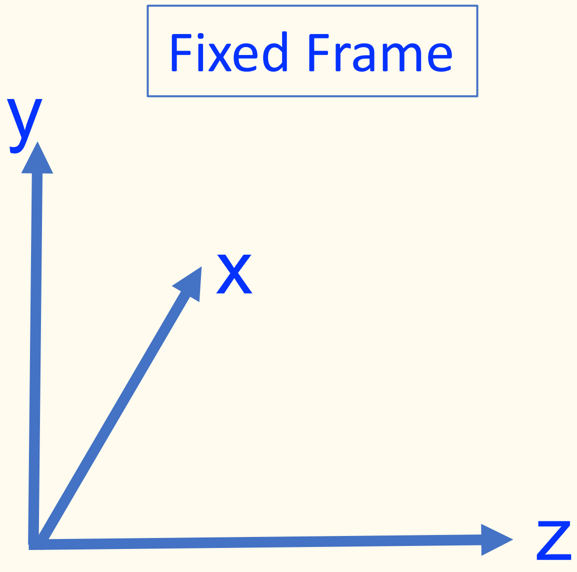
Cold nuclear matter
initial state effects
shadowing and gluon saturation

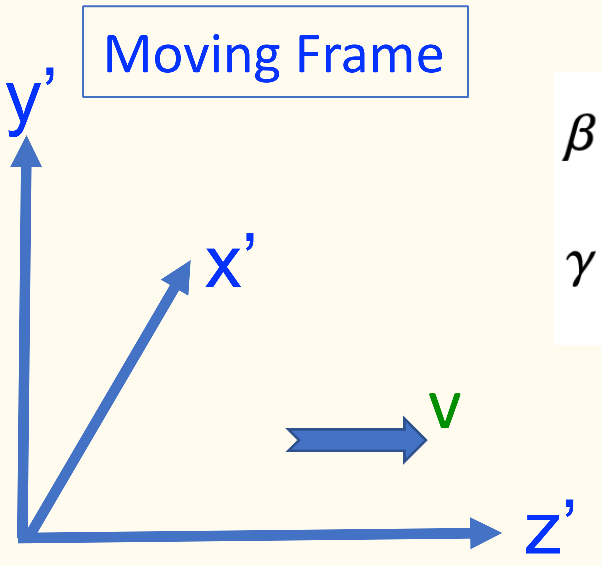


Formation of
Hot and dense matter

Centrality:
Level of overlap of the colliding
Lorentz contracted nuclei

Special theory of Relativity: Lorentz Transformation





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

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

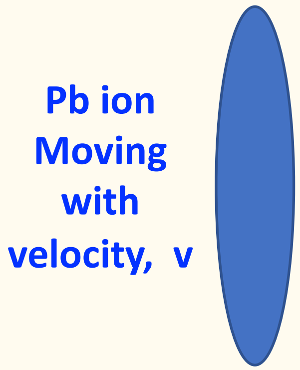
Transformation with velocity, v, along the z-axis.

- 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)

$L' = \gamma L$

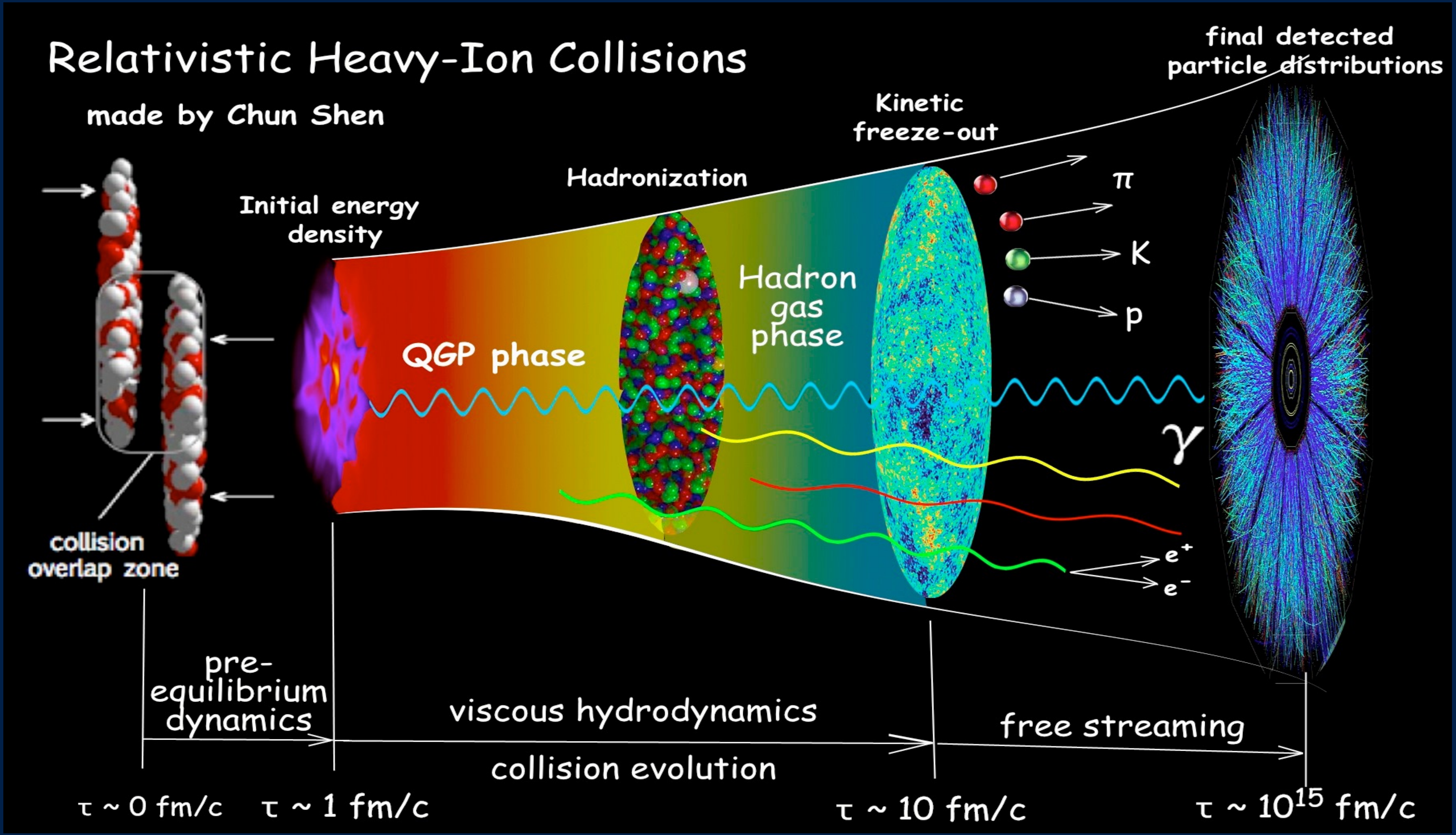
$L = L'/\gamma$

Radius of Pb ion: L
(~ 7fm)



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.



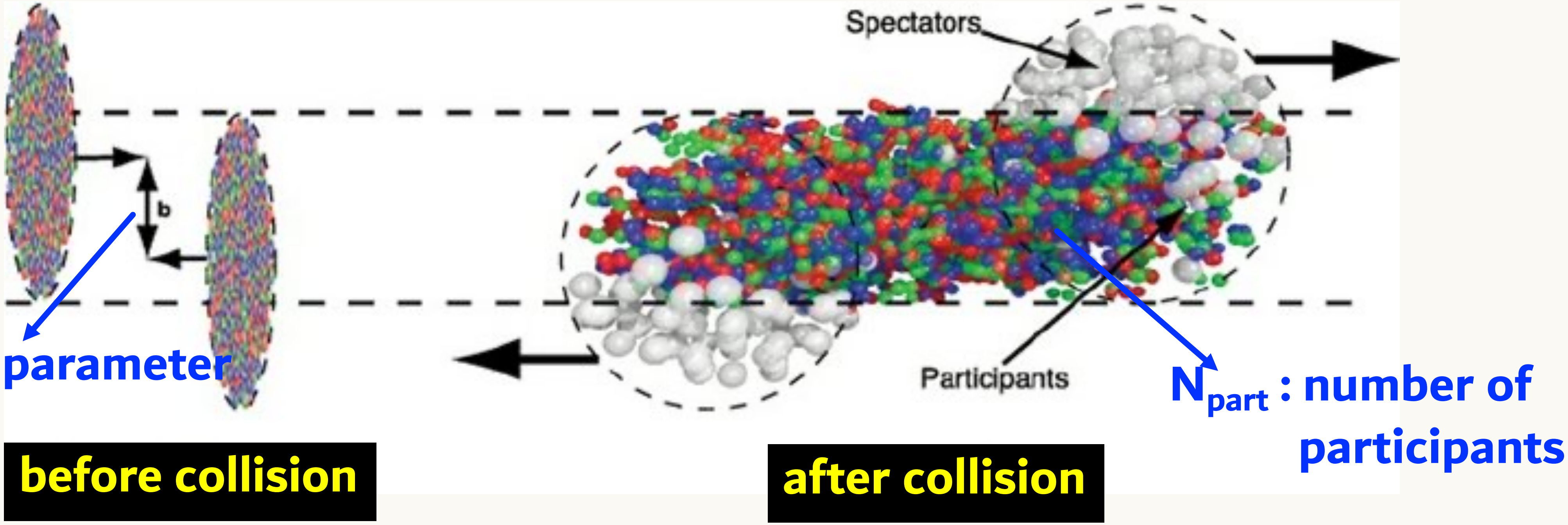
Initial State Fluctuations

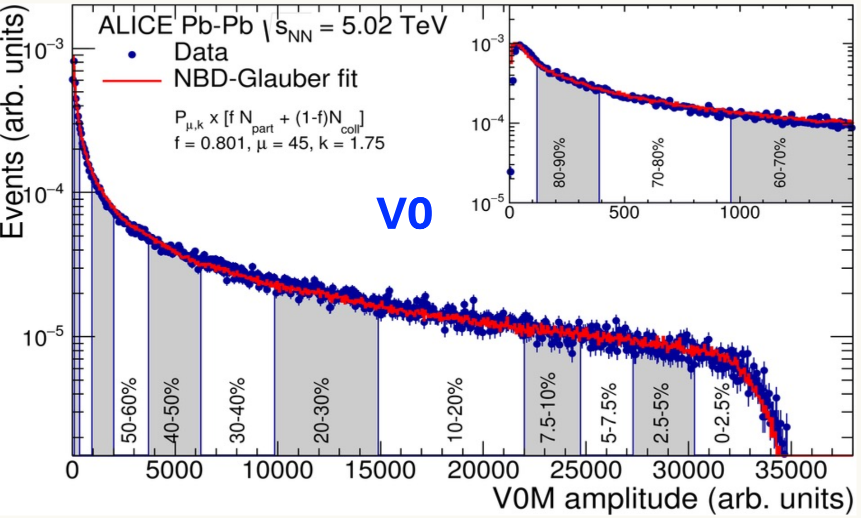
Thermal Fluctuations

Hadronization

Measurement

Centrality in heavy-ion collisions:

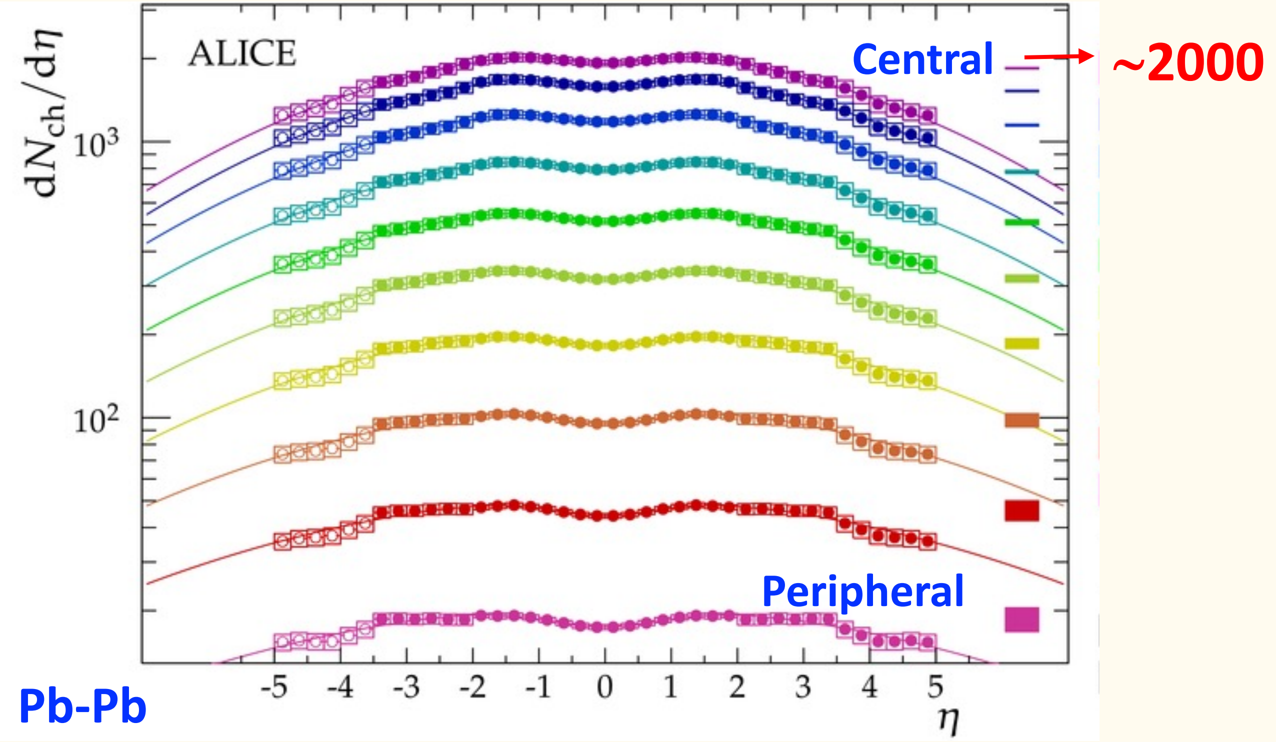


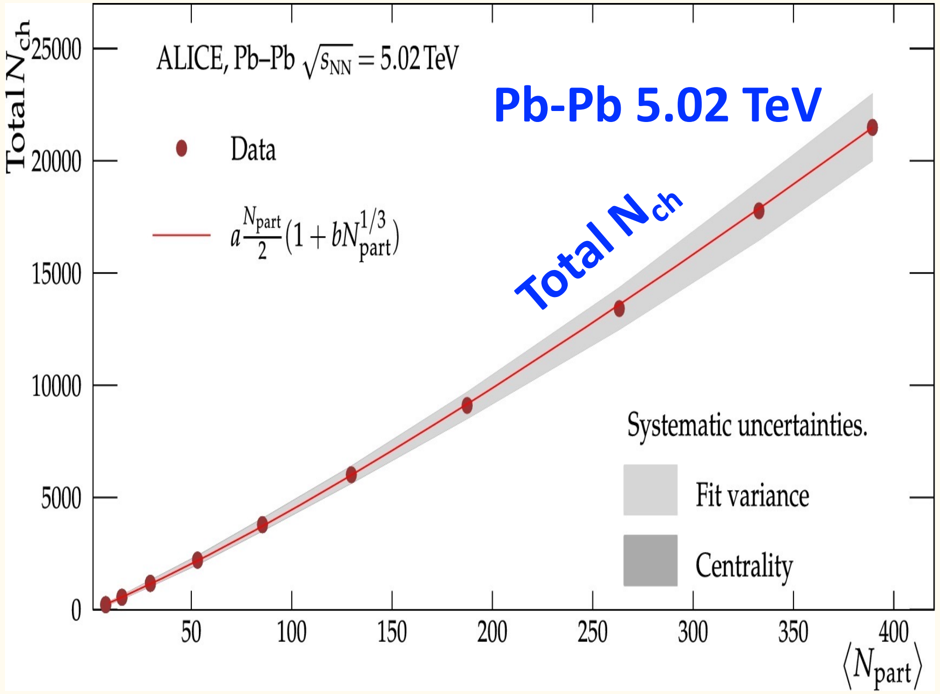


b: impact parameter, For Pb-Pb collisions, maximum of b ~ 14 fm

Central collision, b ~ 0
Peripheral collision: b > 10 fm

Charged particle multiplicity





Number of charged particles in one collision:

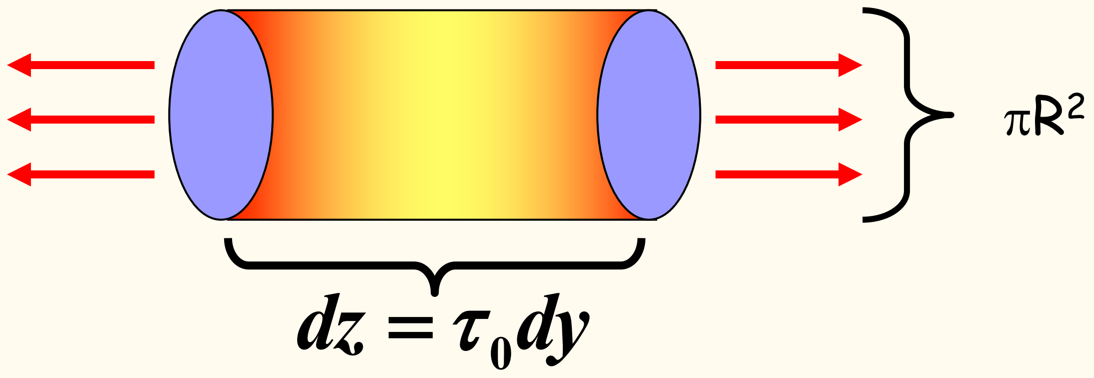
- Central collisions: 21400 ± 1300
- Peripheral collisions: 230 ± 38

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

LARGE NUMBER OF PRODUCED PARTICLES

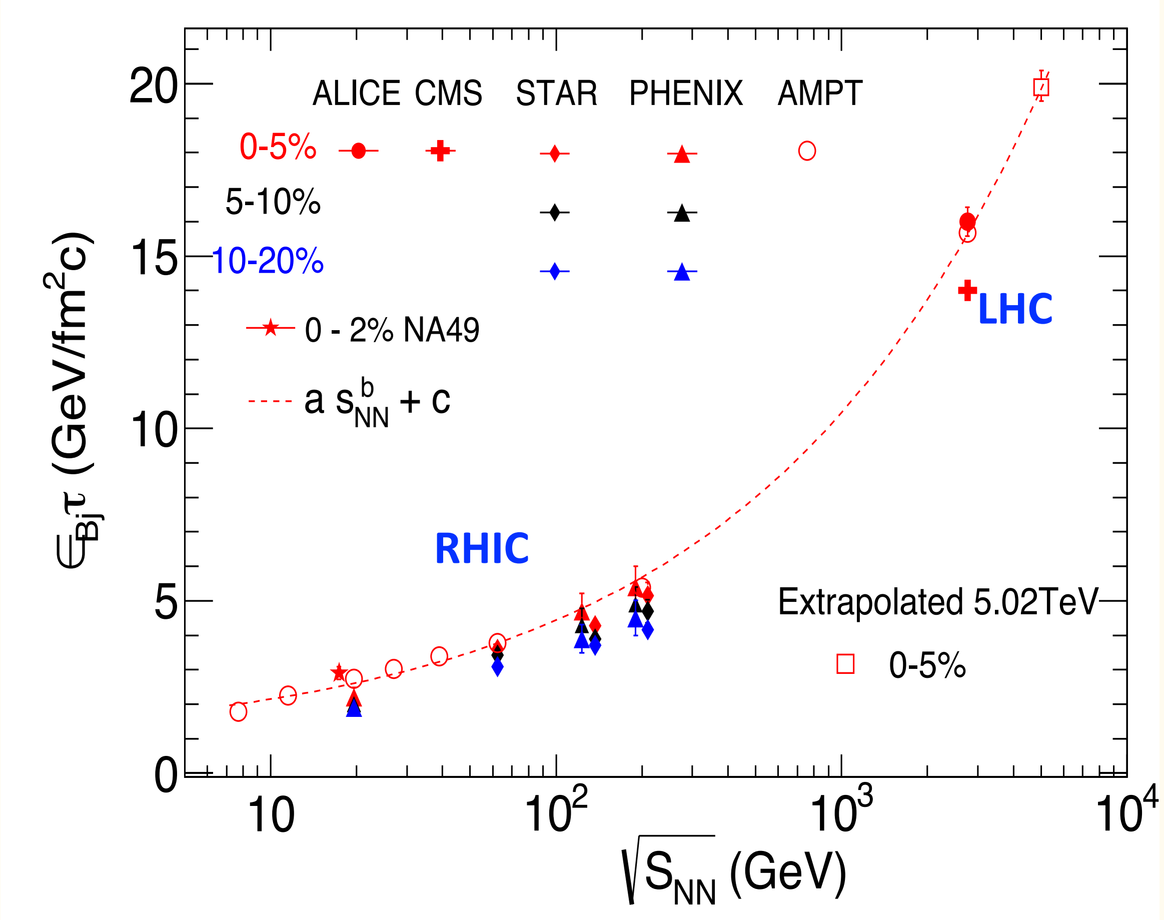
Particle density & Energy density

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



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

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



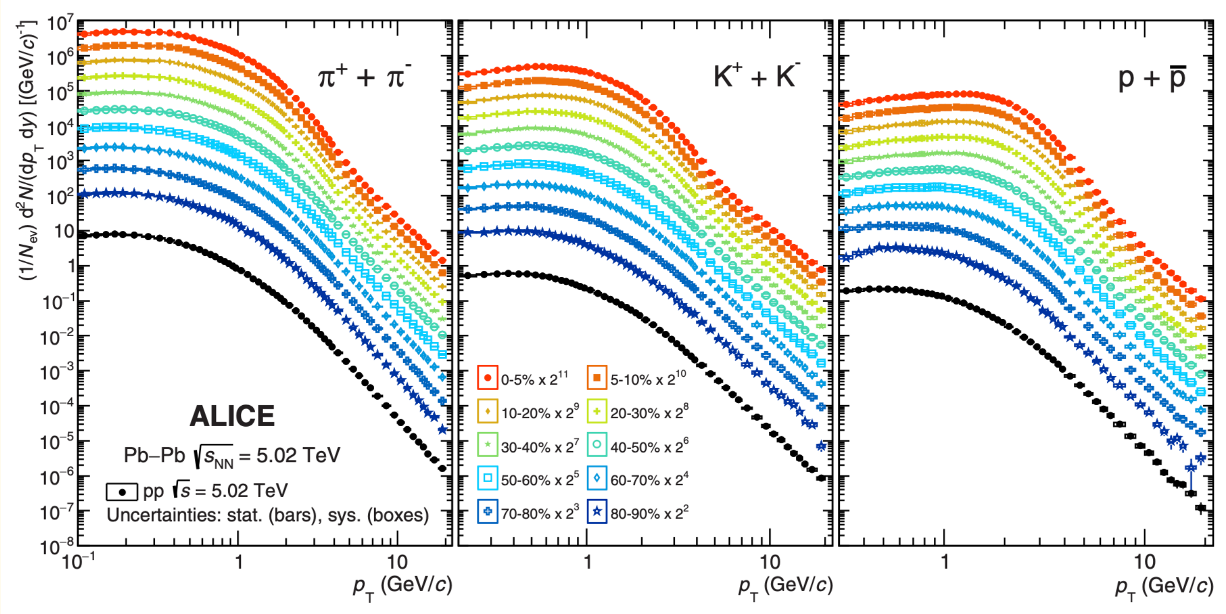
$\varepsilon.\tau \sim 16$ GeV/fm^{2}c

LARGEST ENERGY DENSITIES EVER ACHIEVED ….

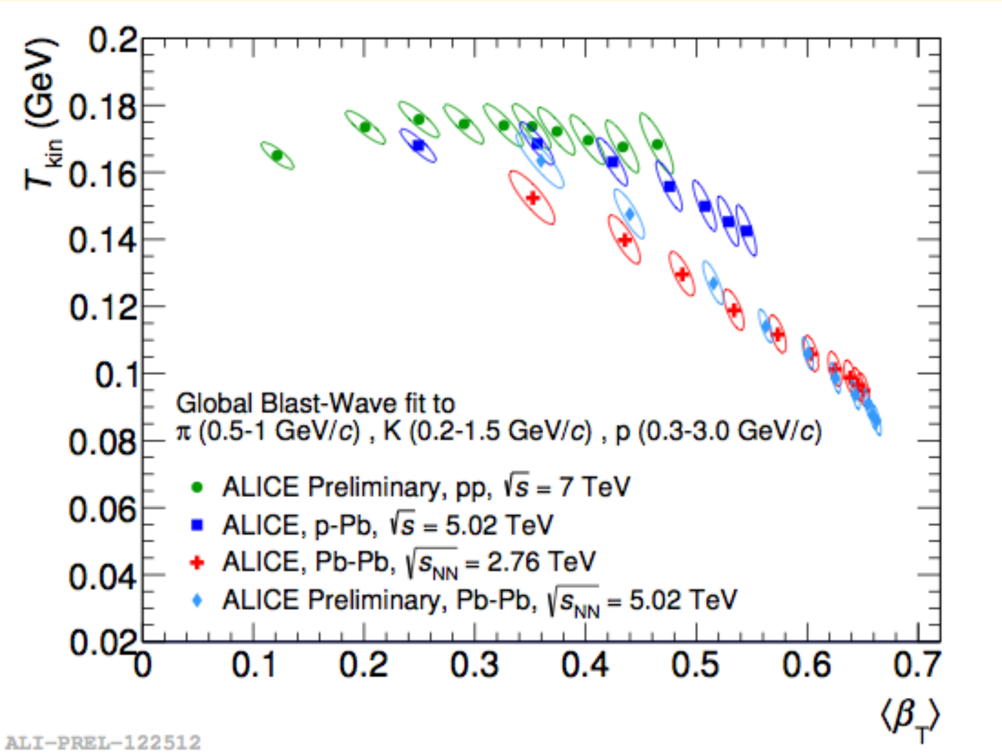
S. Basu et al. PRC 93 (2016) 064902
R. Sahoo et al. Adv. in HEP, Vol. 2015

Evidence for the production of thermal systems (I)

Particle spectra



Evolution of Kinetic freeze-out temperature T_{kin} and radial flow velocity $\langle \beta_T \rangle$



Boltzmann-Gibbs Blast-Wave model:

- Particle production from a thermalized source + a radial flow boost.
- Thermodynamic model with 3 parameters: T_{kin}, $\langle \beta_T \rangle$, and n (velocity profile).

$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{kin}}\right) r\, dr.$$

The velocity profile ρ is given by

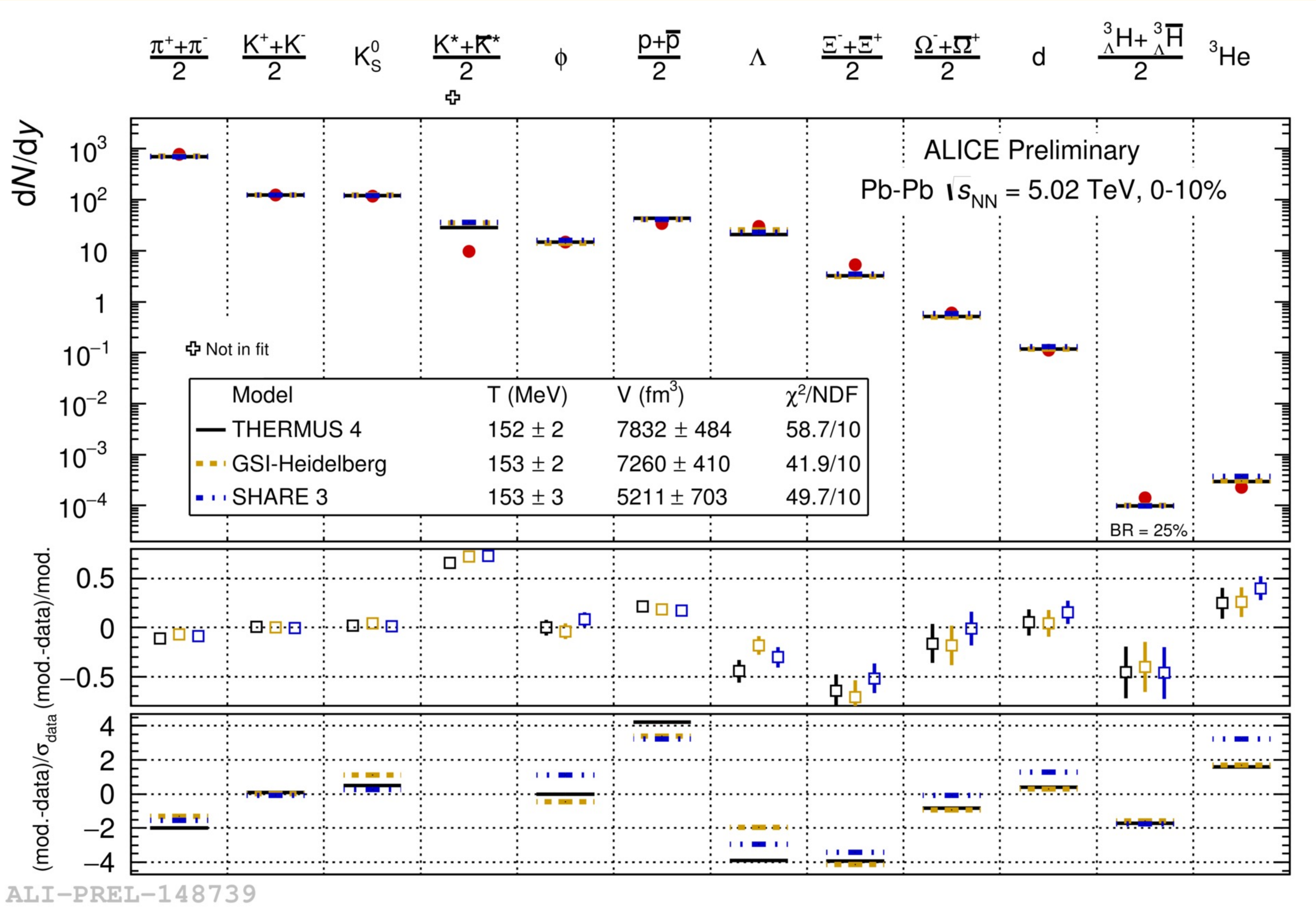
$$\rho = \tanh^{-1} \beta_T = \tanh^{-1}\left[\left(\frac{r}{R}\right)^n \beta_s\right],$$

n changes from peripheral to central (0.7 to 2.4 and is the source of radial flow fluctuation

- $\langle \beta_T \rangle$ increases with centrality
- Similar evolution of fit parameters for pp and p-Pb
- Thermalization in pp?
- At similar multiplicities, $\langle \beta_T \rangle$ is larger for smaller systems

Evidence for the production of thermal systems (II)

Particle yields in Pb-Pb at 5.02 TeV



Thermal models:

- At Chemical freeze-out => Particle yields get fixed.
- Abundance by thermodynamic equilibrium:

$$\frac{dN}{dy} \propto \exp\left(\frac{-m}{T_{chem}}\right)$$

Particle yields are well described by statistical models

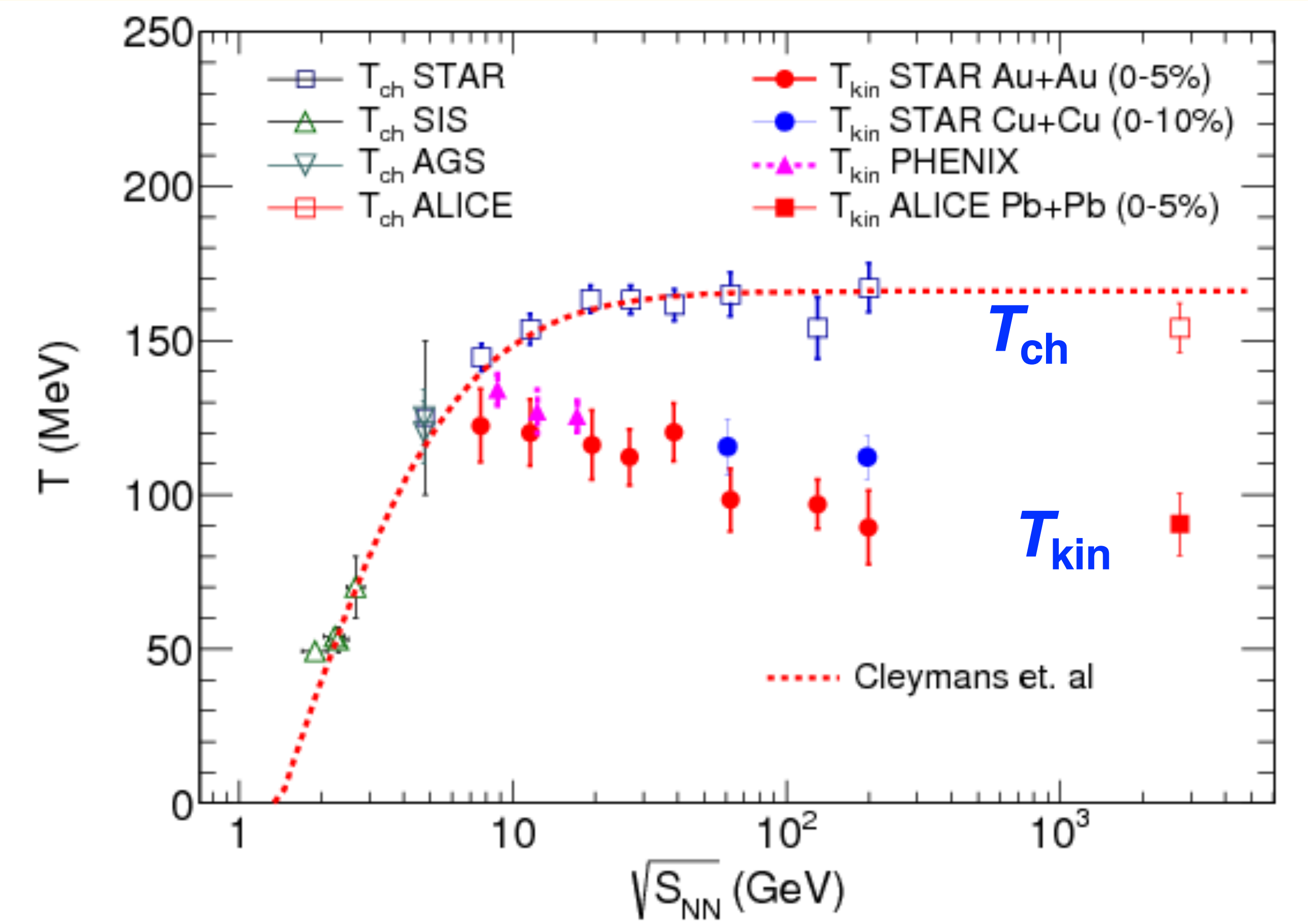
=>

Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC.

T_{ch} (Chemical freeze-out temperature) ~153 MeV

Chemical and kinetic freeze-out temperatures

Collision energy dependence of T_{kin} and T_{ch}

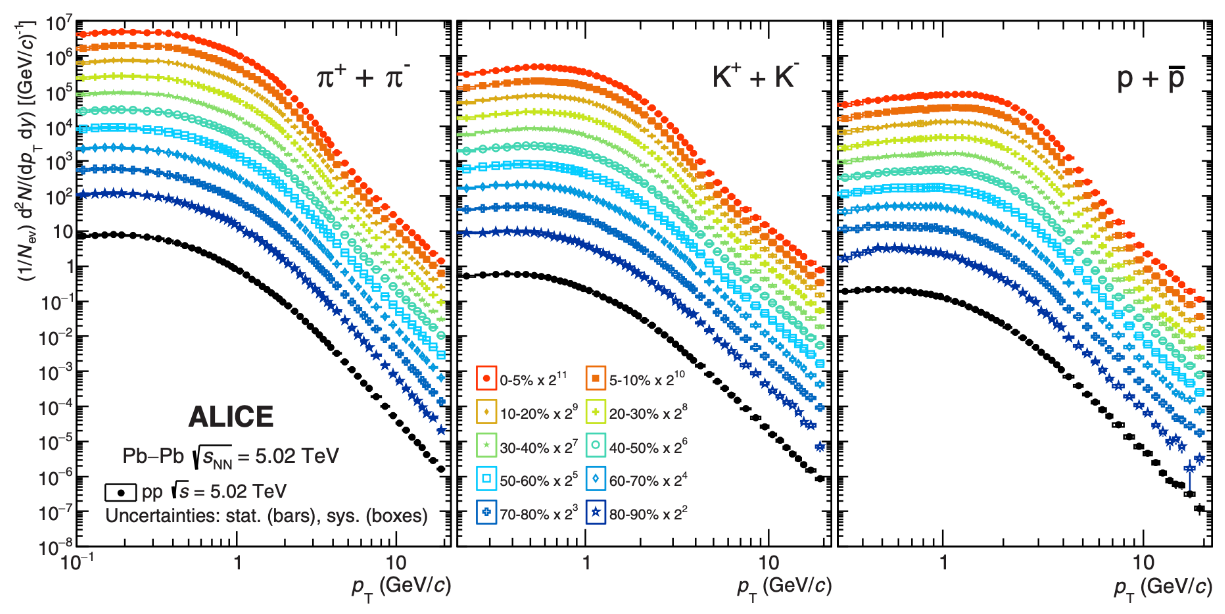


Sumit Basu et al. PRC 94 (2016) 044901
ALICE Collaboration PRD 88 (2013) 044910
STAR Collaboration PRC 79 (2009) 034909
Cleymans et al. PRC 73 (2006) 034905

The difference between T_{kin} **and** T_{ch} increases with the increase of collision energy.

Evidence for the production of thermal systems (I)

Particle spectra



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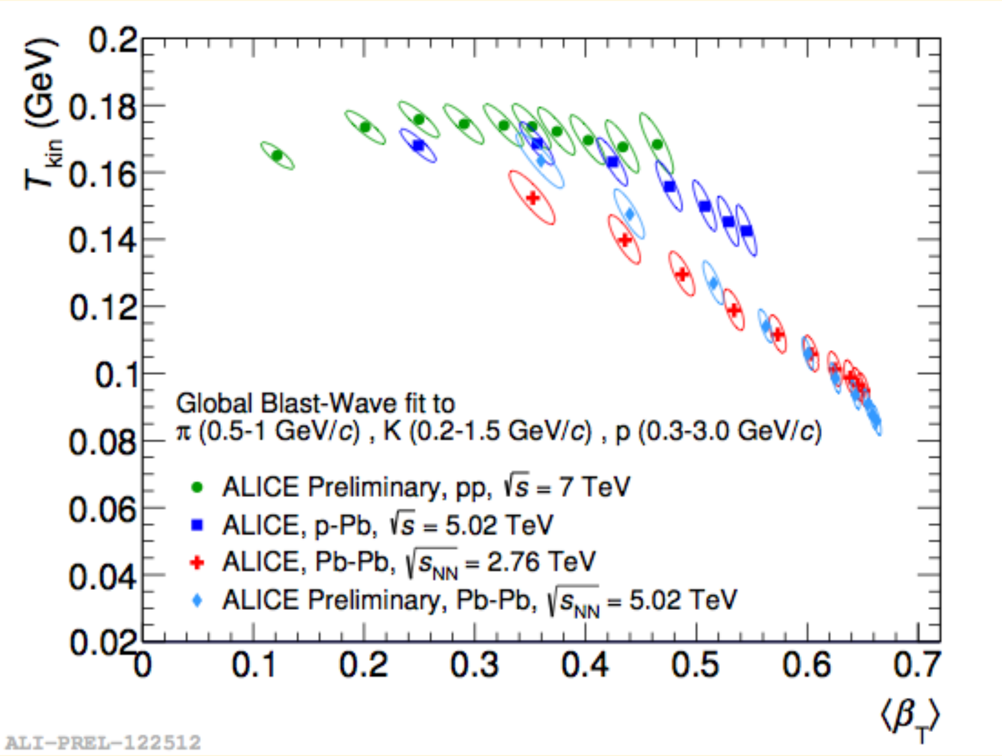

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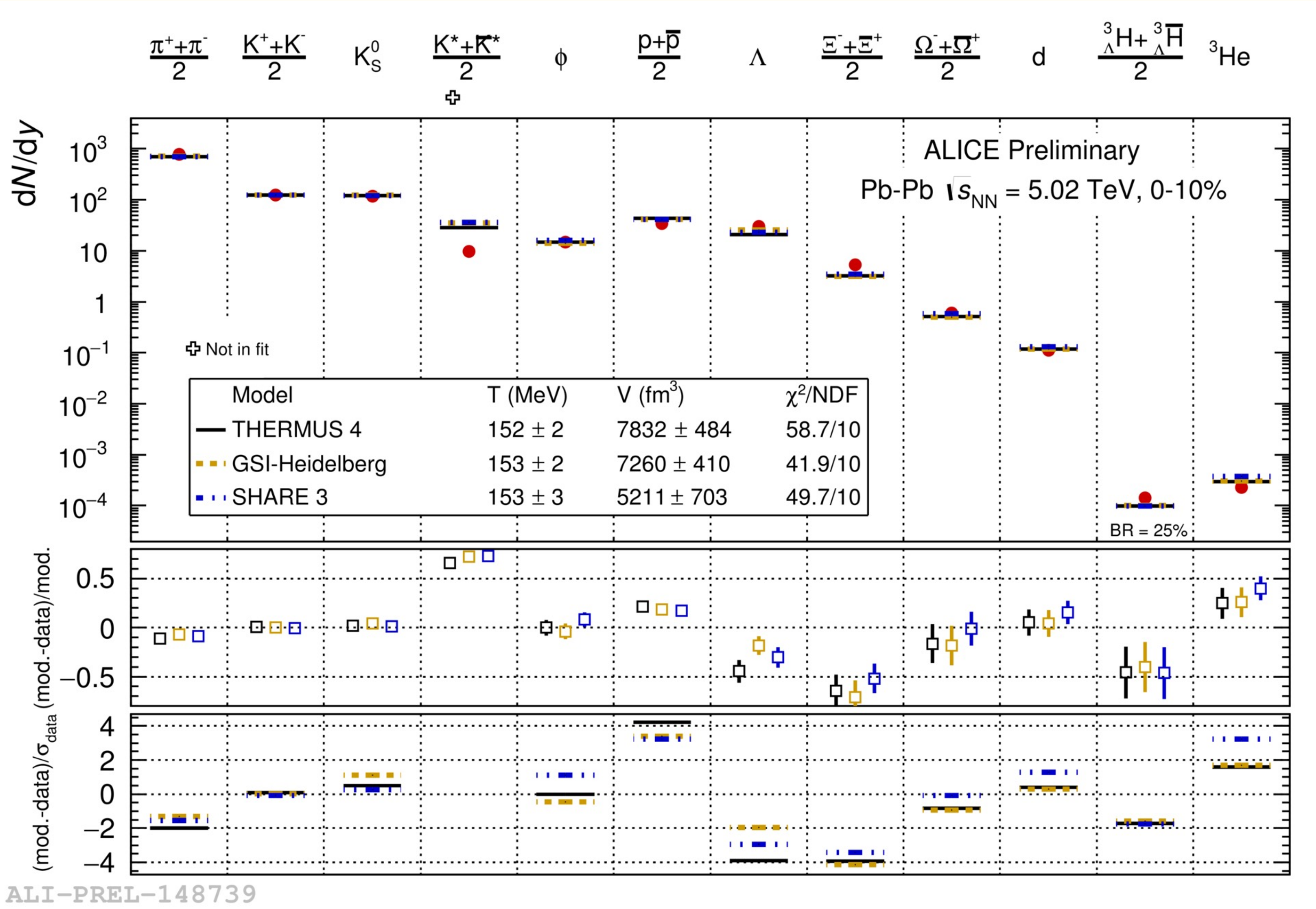

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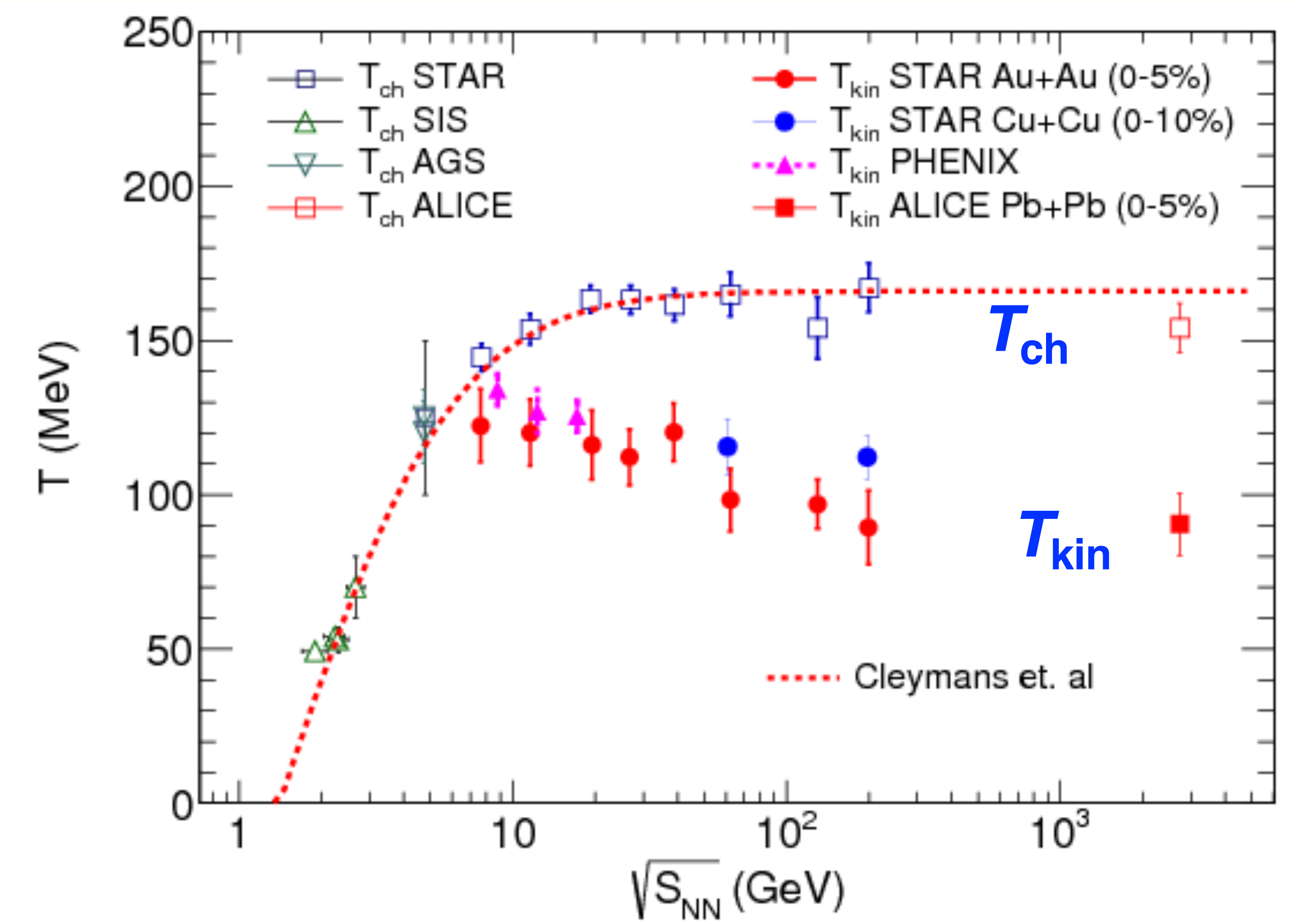

Sumit Basu et al. PRC 94 (2016) 044901
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STAR Collaboration PRC 79 (2009) 034909
Cleymans et al. PRC 73 (2006) 034905

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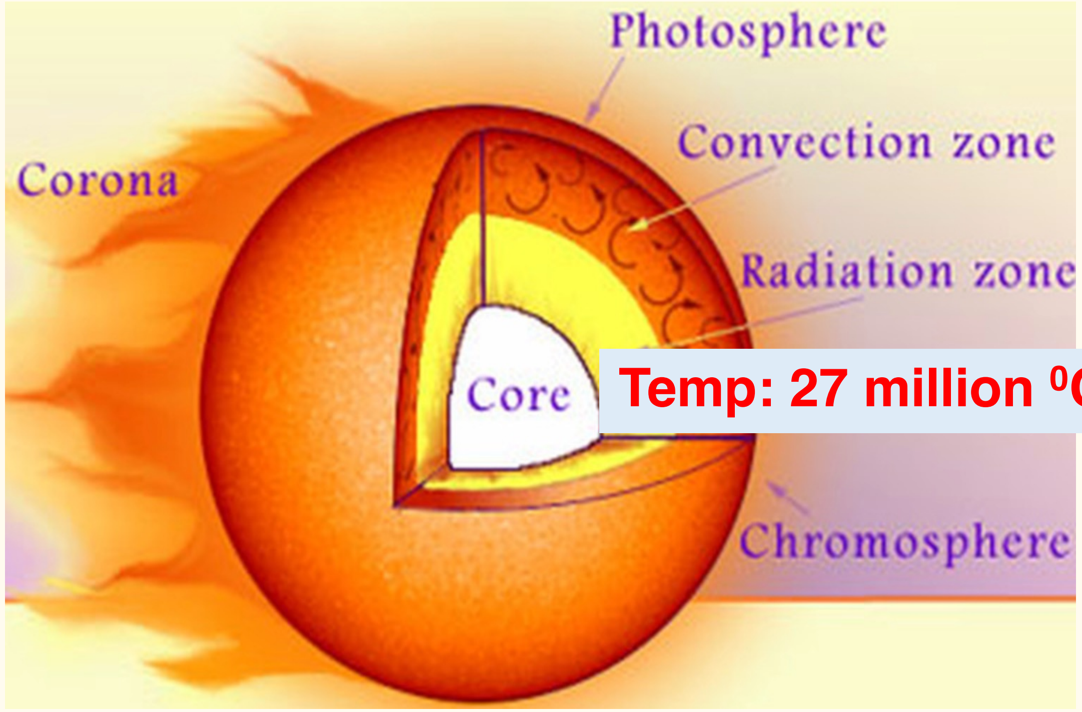
Photon Spectra and QGP temperature

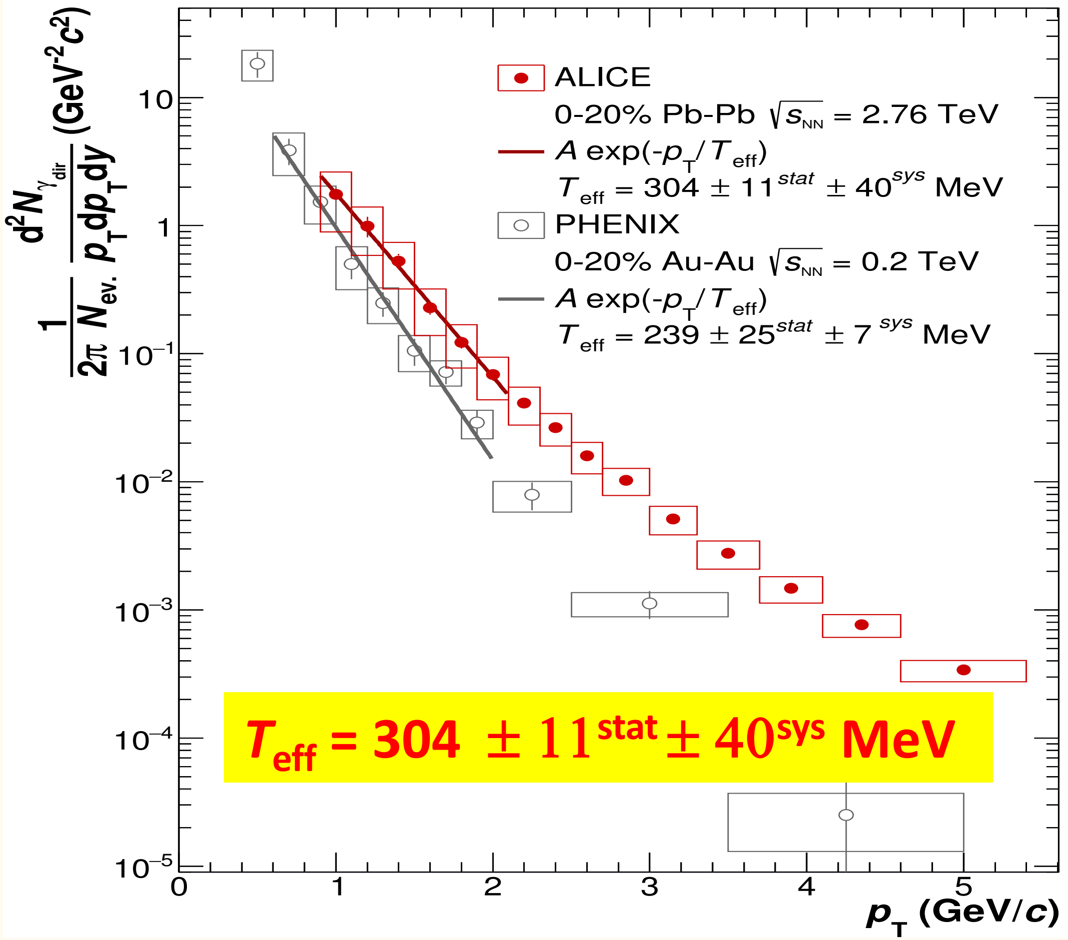
- Photons do not interact via the nuclear force → transparent to the medium
- Photons are emitted in all stages and are unaffected by the medium.

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

Core of the Sun:



Temp: 27 million ^{0}C



T_{eff} = 304 ± 11^{stat} ± 40^{sys} MeV

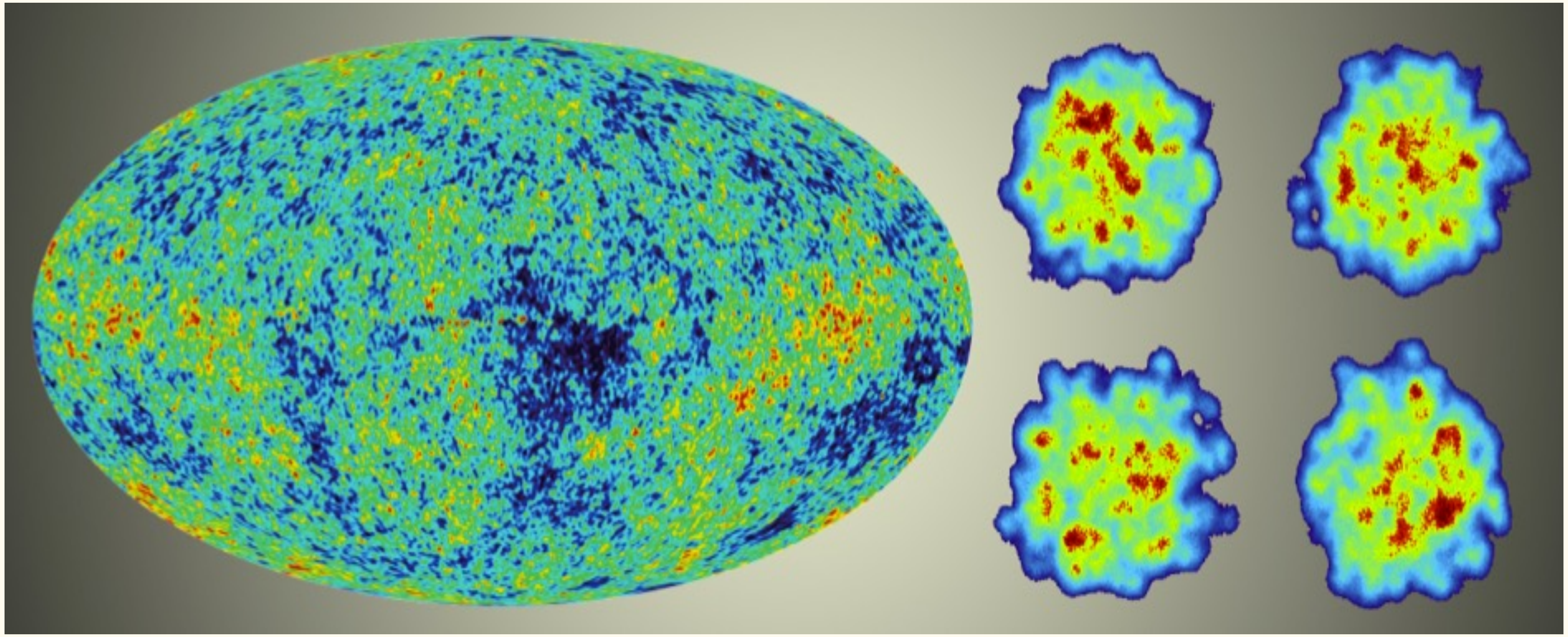
(1eV=11605K)

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

LARGEST EVER TEMPERATURE REACHED IN THE LAB ….

Fluctuations in the Little Bang

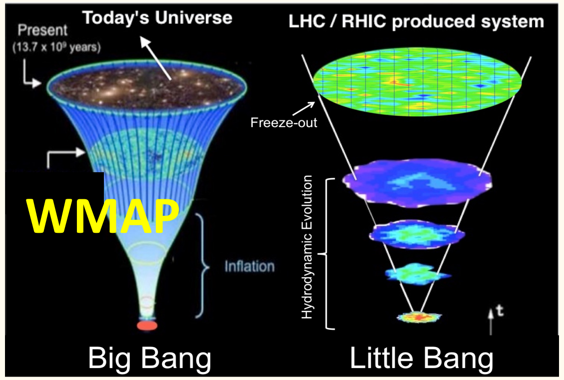
Uli Heinz, arXiv:1304.3634v1 [nucl-th] 11 Apr 2013



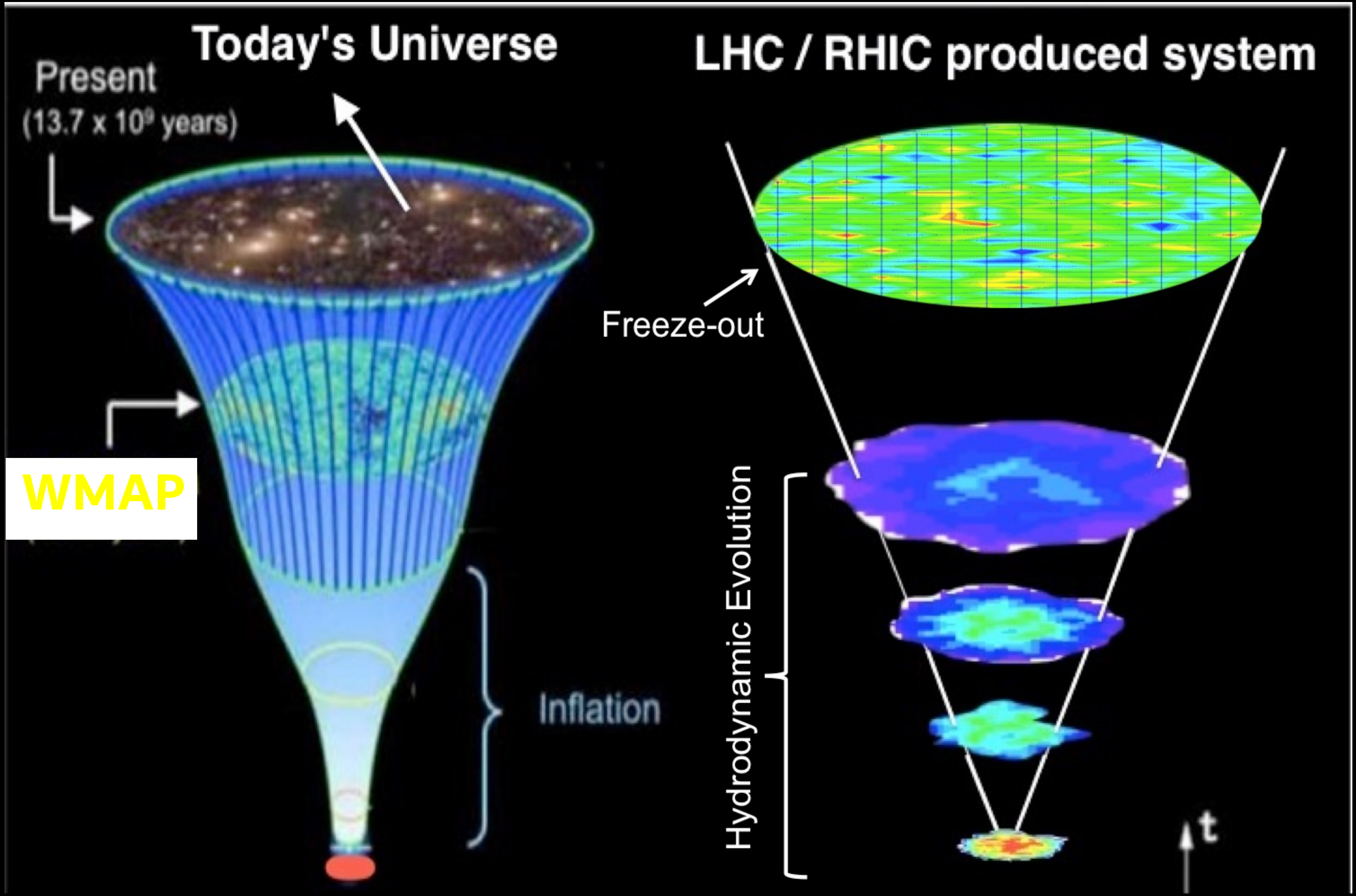
WMAP

Heavy-ion Collisions

- 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



Big Bang

Little Bang

High Energy Accelerator:

Heavy-ion Collisions:

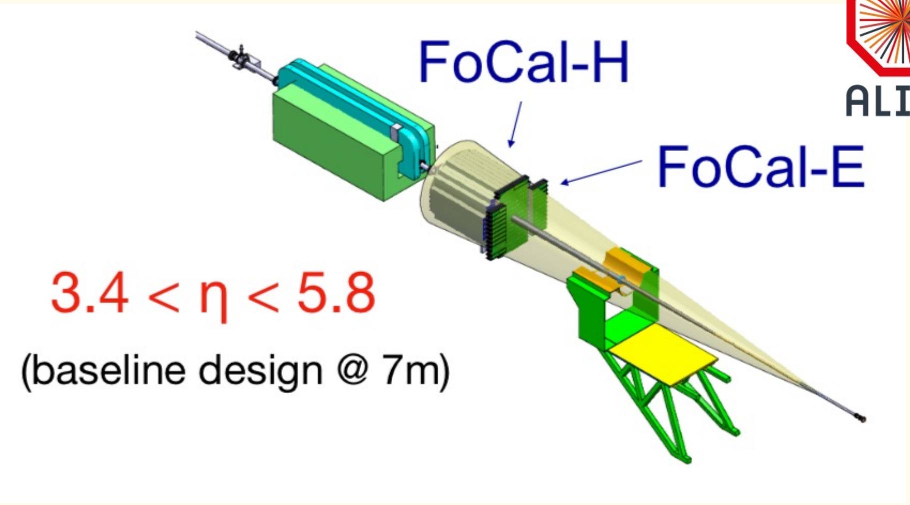
Billions of Events (Little Bangs)

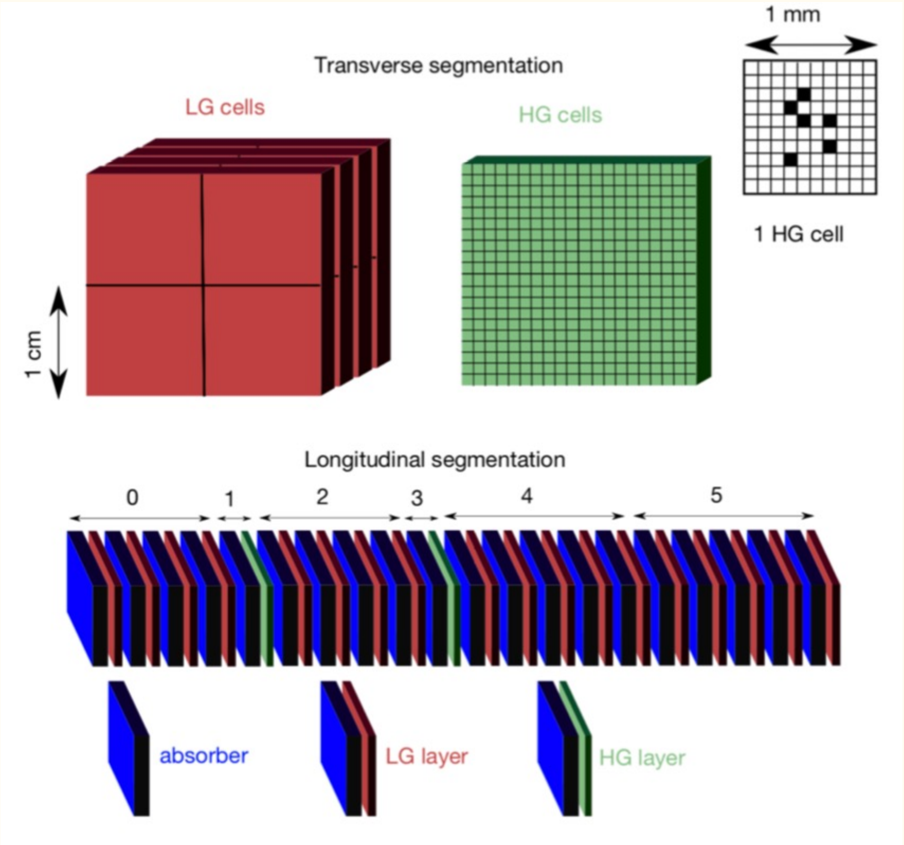
One HUGE Event

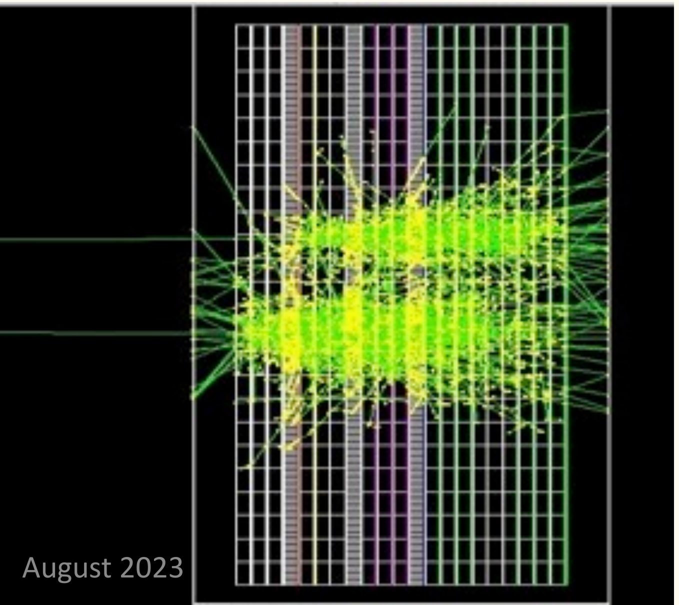
ALICE upgrade: FOCAL

- **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)

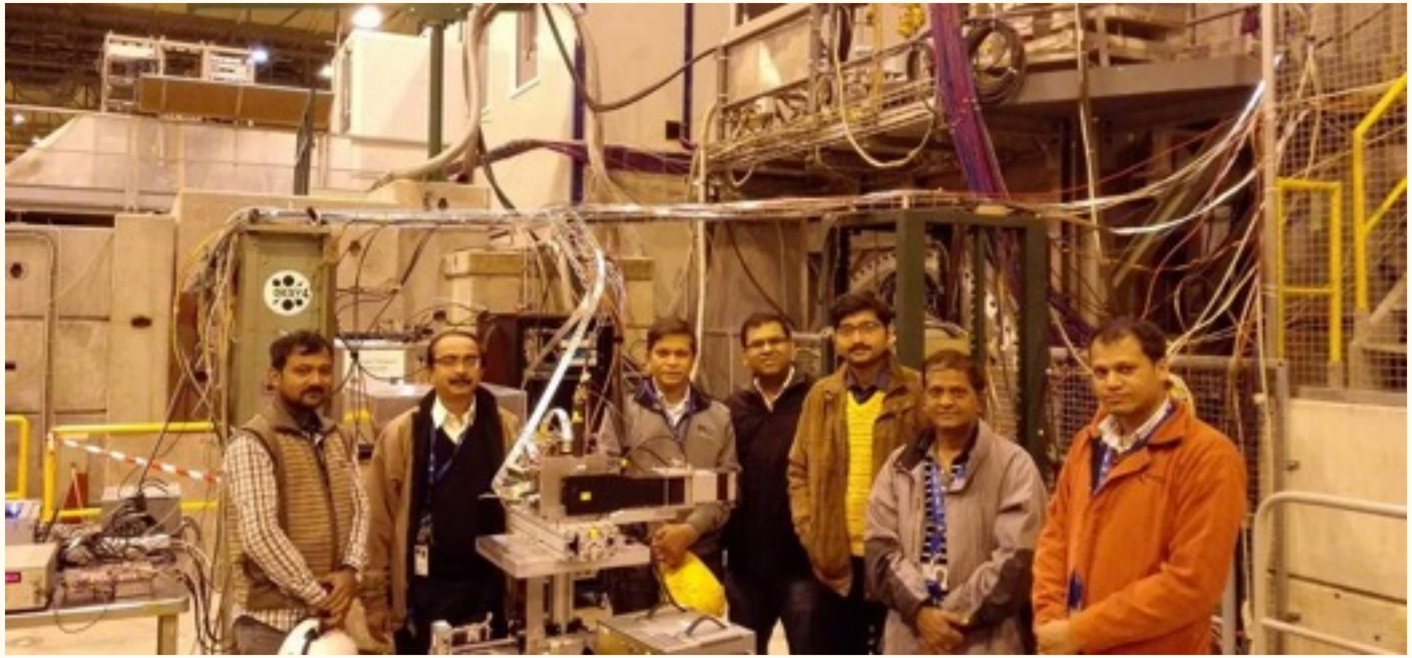


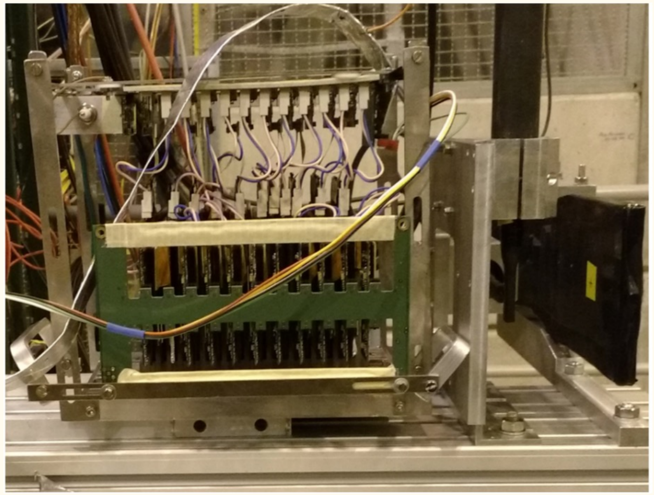


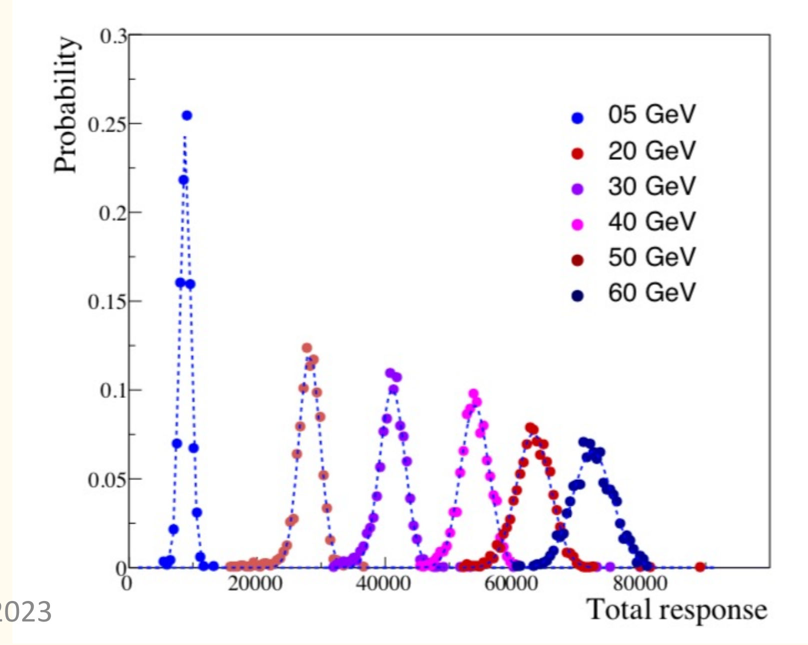


Simulation of a pi0 decaying to two photons

Silicon- Tungsten Calorimeter: 2015 test beam at CERN

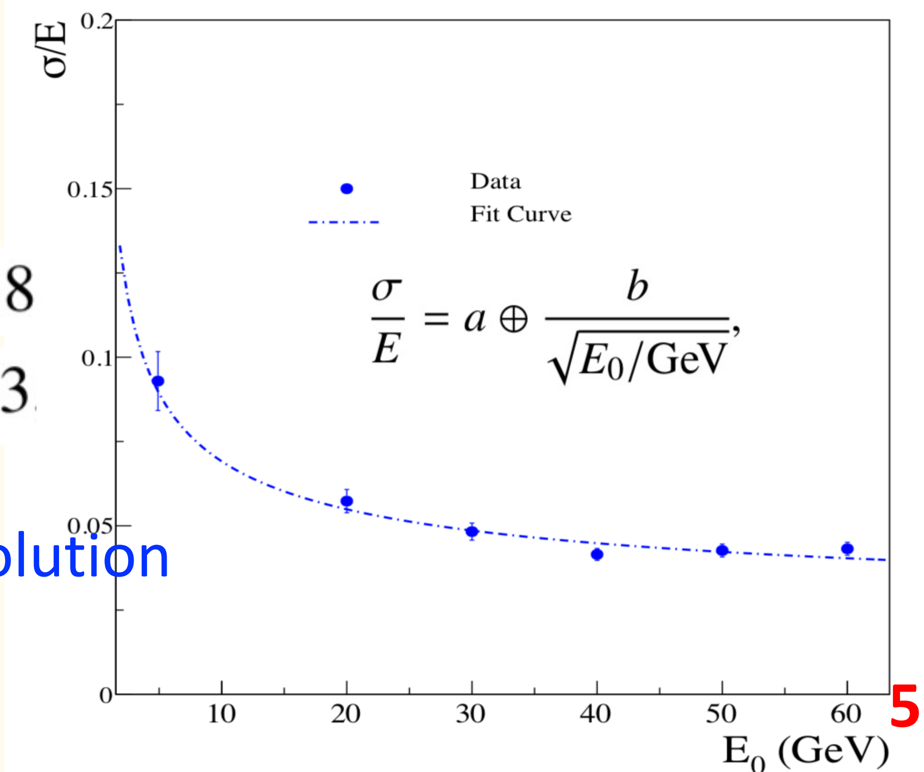






$$a = 0.020 \pm 0.0038$$

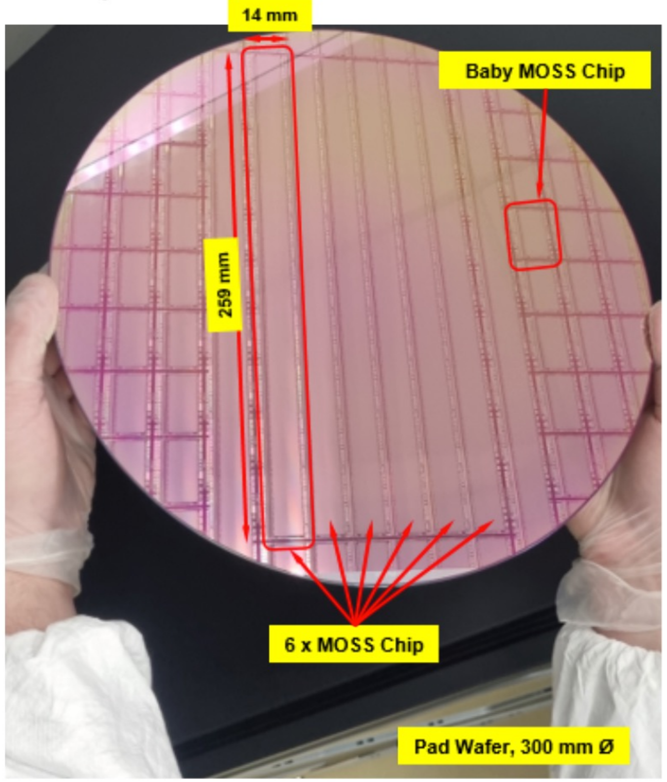
$$b = 0.1536 \pm 0.023$$

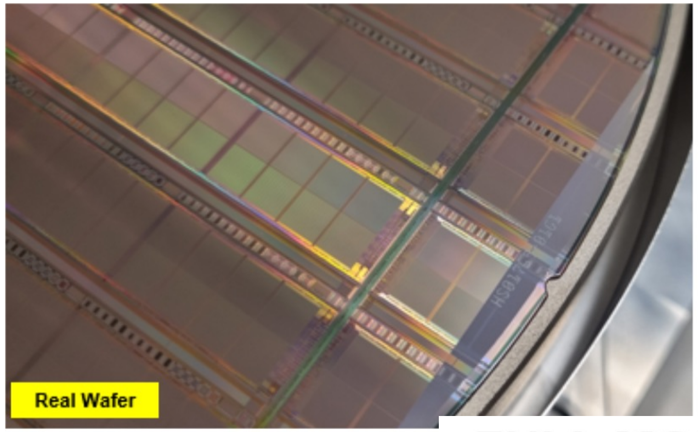


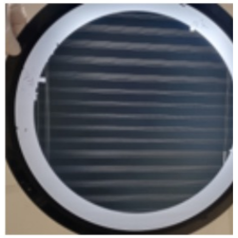
Excellent energy resolution

ITS 3

MOSS (Monolithic Stitched Sensor) CHIP Wafer

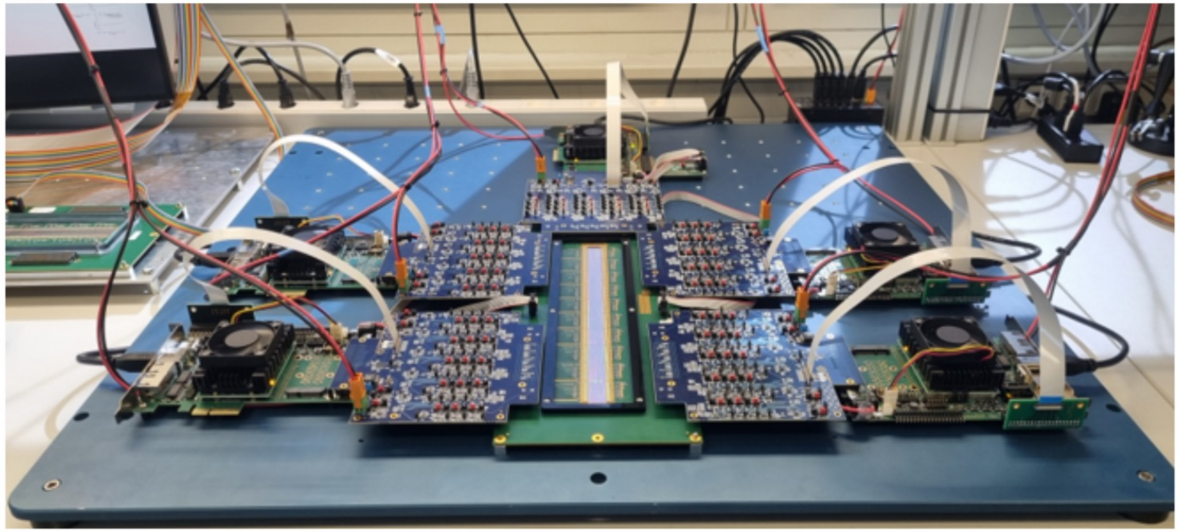






Diced Wafer

FULL MOSS CHIP TEST SYSTEM



Tapan Nayak

European Particle Physics Strategy Update recommends full exploitation of the LHC, including the heavy-ion programme

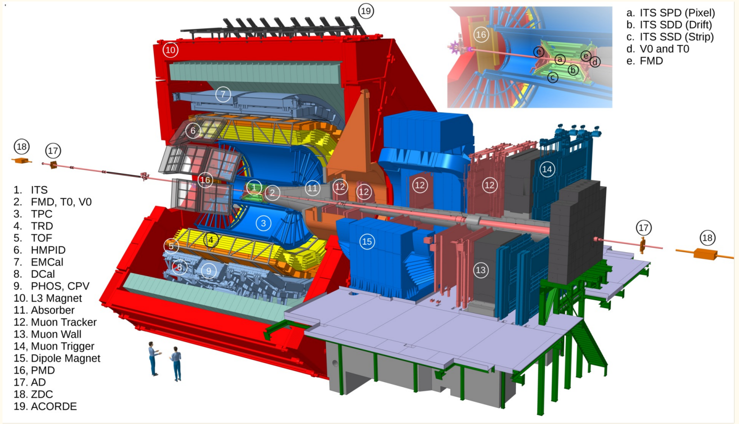
ALICE

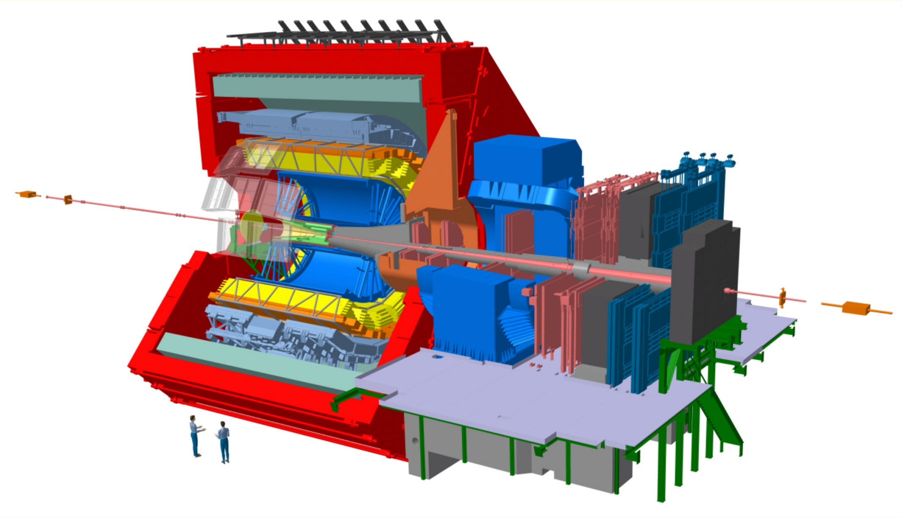
ALICE Present and Future

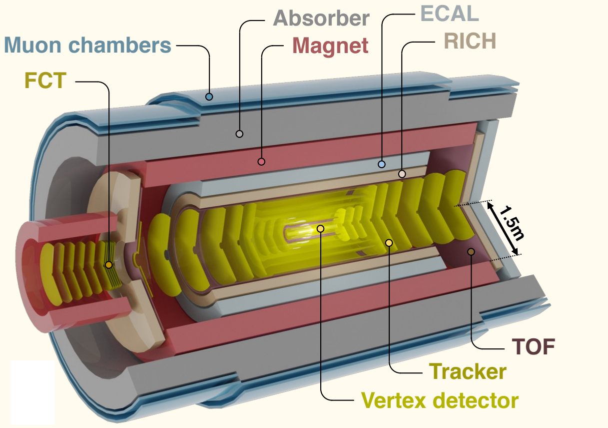
2010-2012		2015-2018		2022-2025		2029-2032		2035-2037		
Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5	LS5	Run 6

ALICE 1 → **Phase I Upgrade** → **ALICE 2** → **Phase IIb Upgrade** → **ALICE 3**

TPC, ITS, FMD, FIT
O2 (online-offline)..



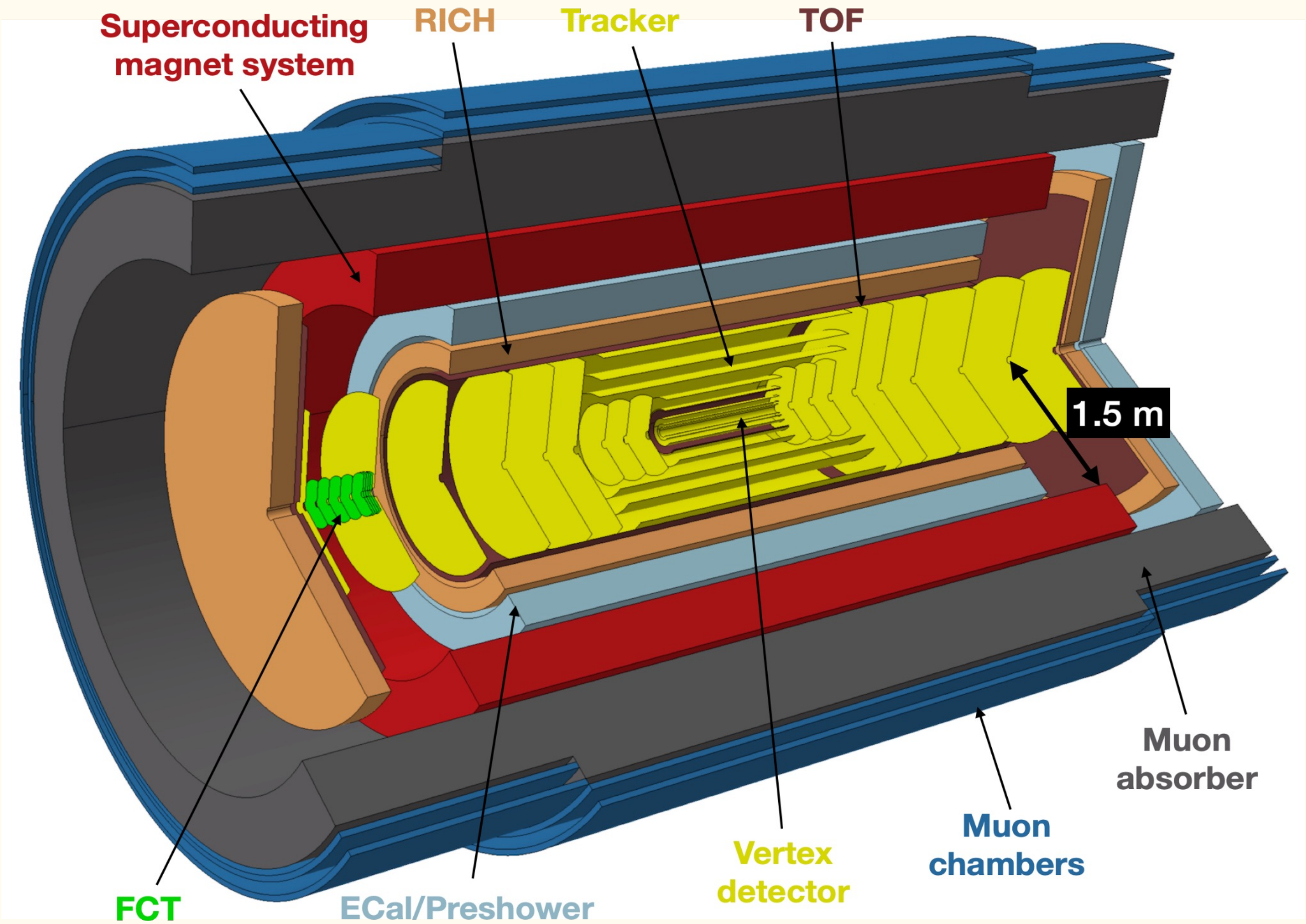




ALICE 3: a compact, next-generation multipurpose detector as a follow-up to the present ALICE experiment.

A “New ALICE 3” for LHC Run-5 (from 2035)

https://arxiv.org/abs/1902.01211



CMOS imaging technologies: high-precision spatial and time resolution

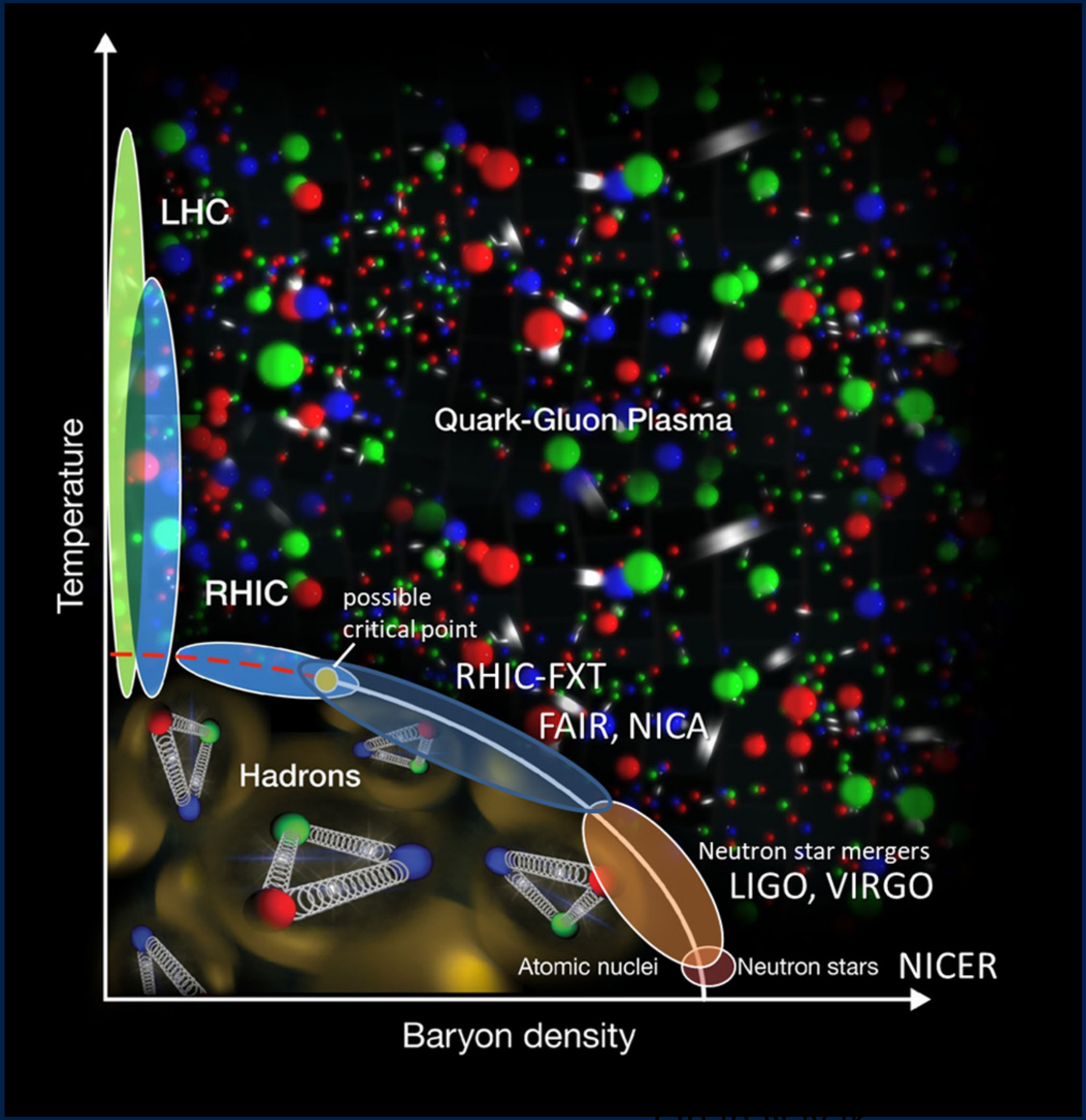
LHC Run-5:

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

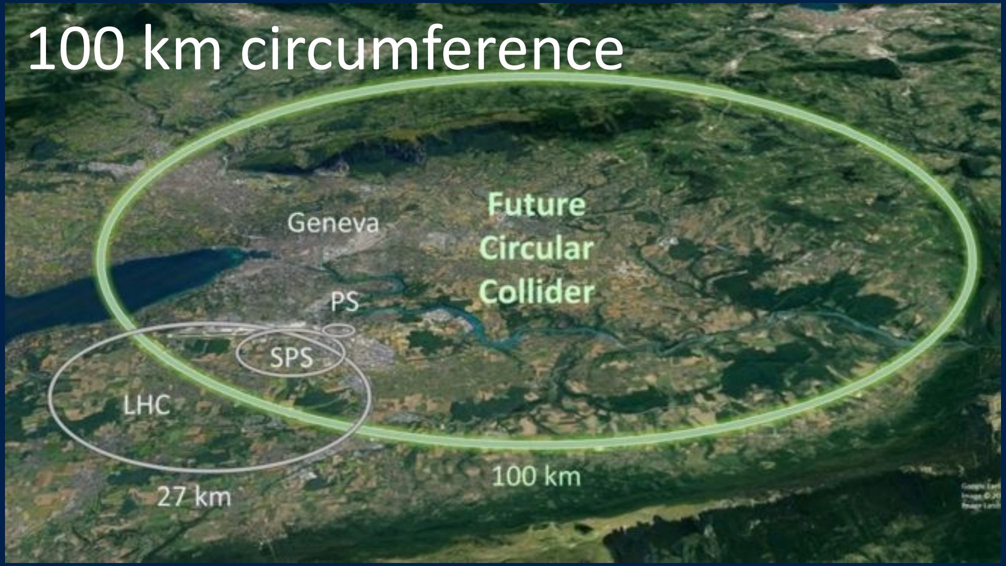
Low p_T down to ~20 MeV/c

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

Recreating the Big Bang conditions at CERN



Future Circular Collider at CERN



https://home.cern/science/accelerators/future-circular-collider