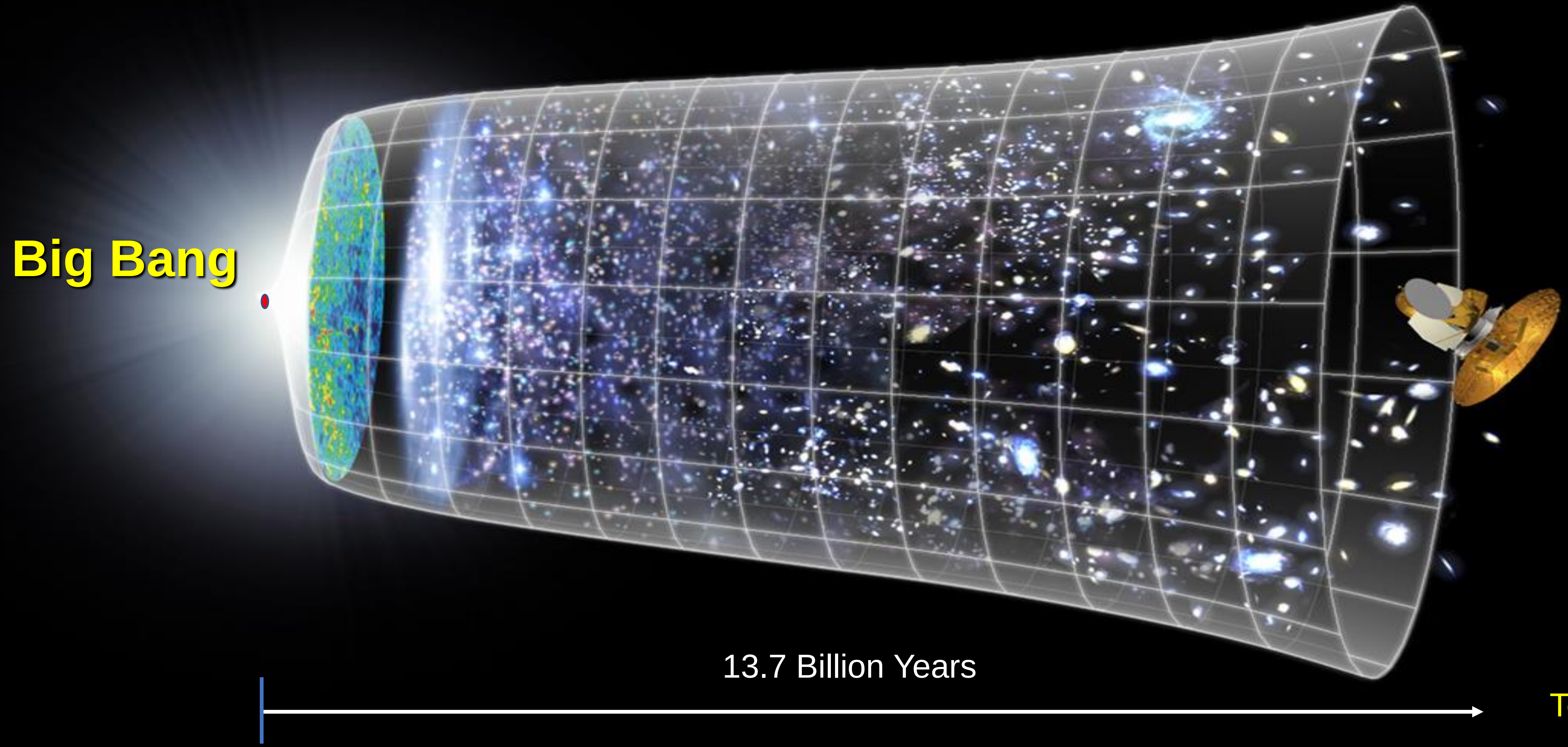
Introduction to heavy-ion physics and the ALICE experiment

Tapan Nayak

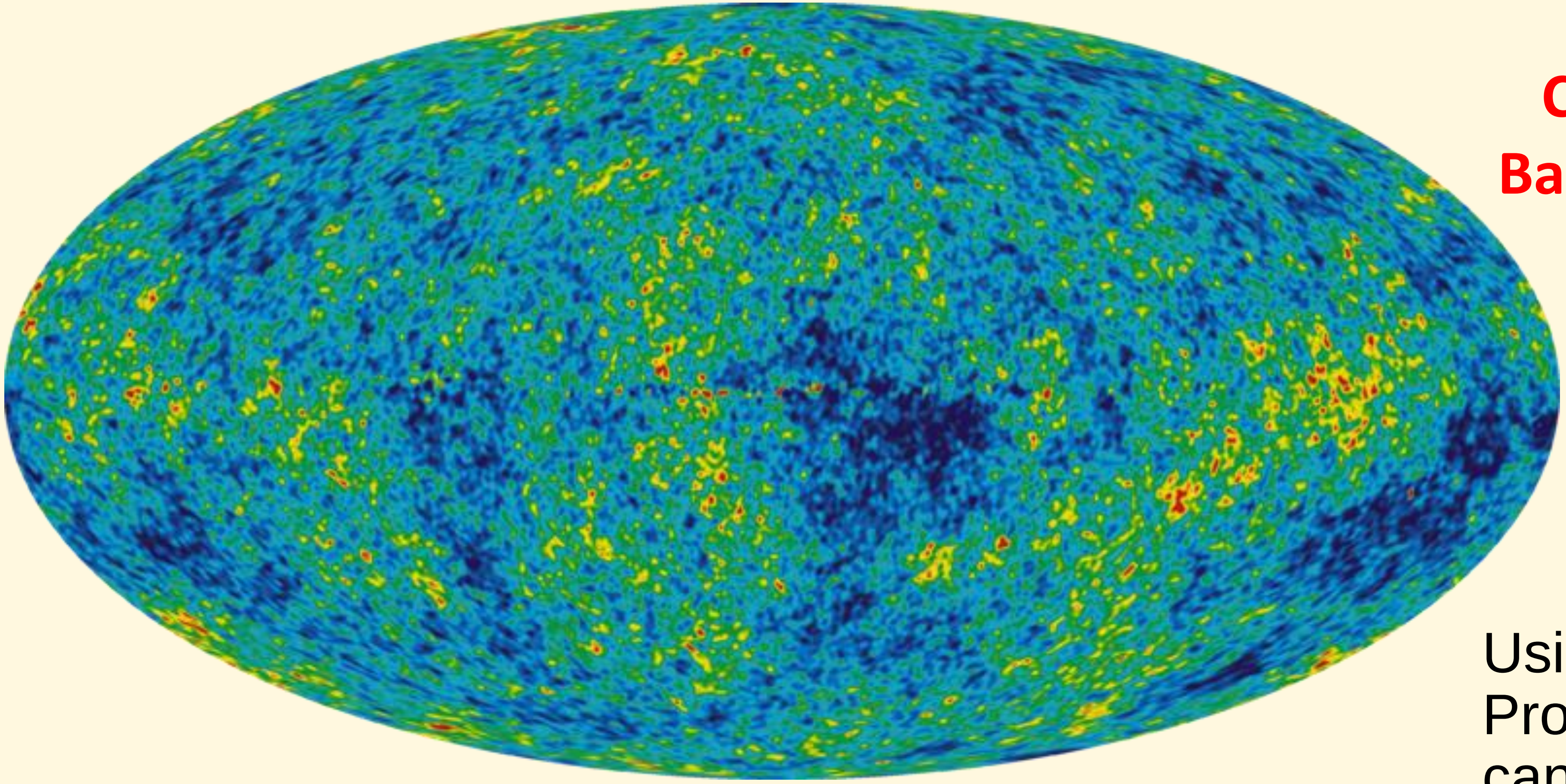
16 February 2021

Our Universe ….. How did it start?

What is it made of?



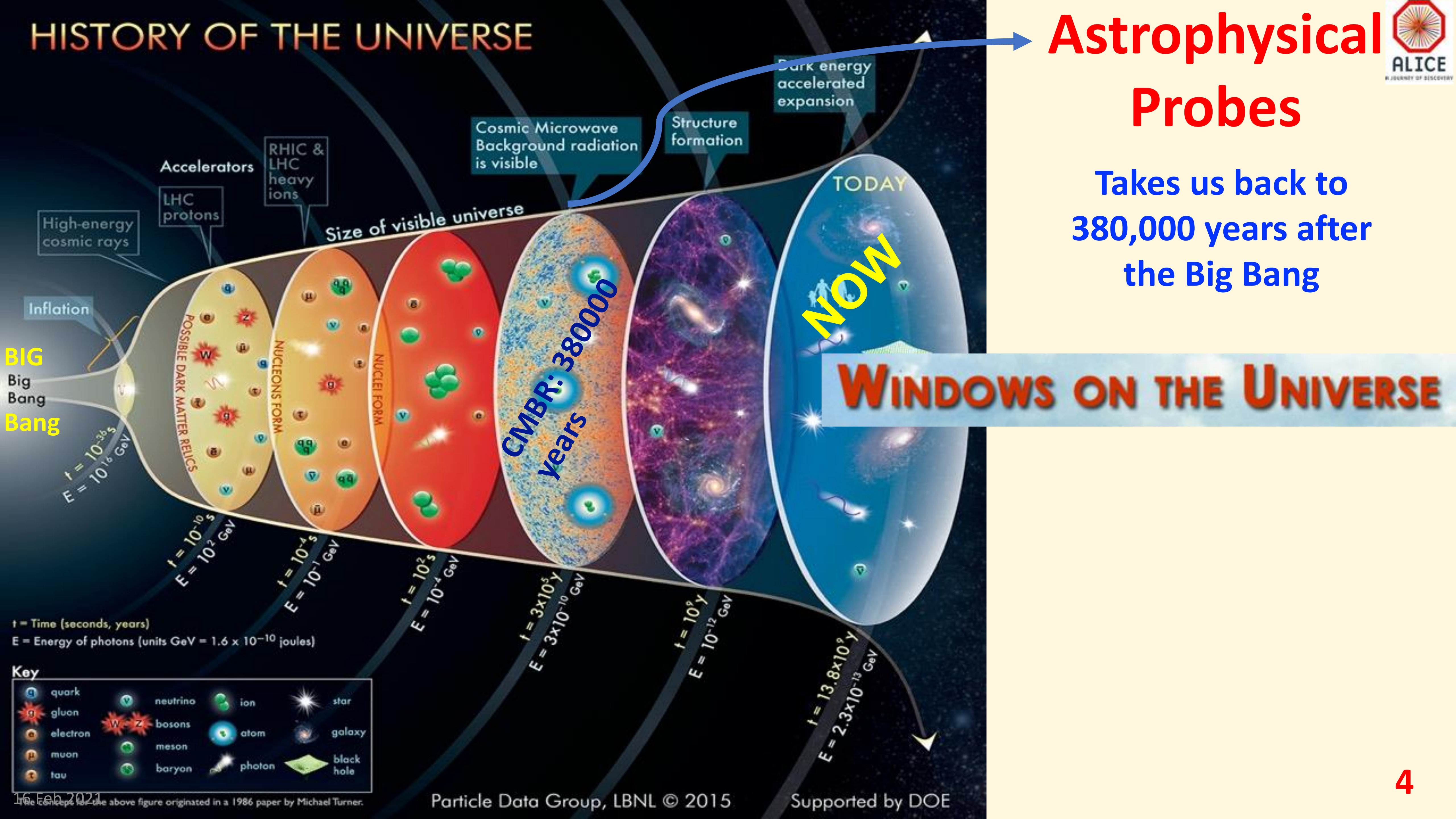
Astronomical probes



Cosmic Microwave Background Radiation (CMBR)

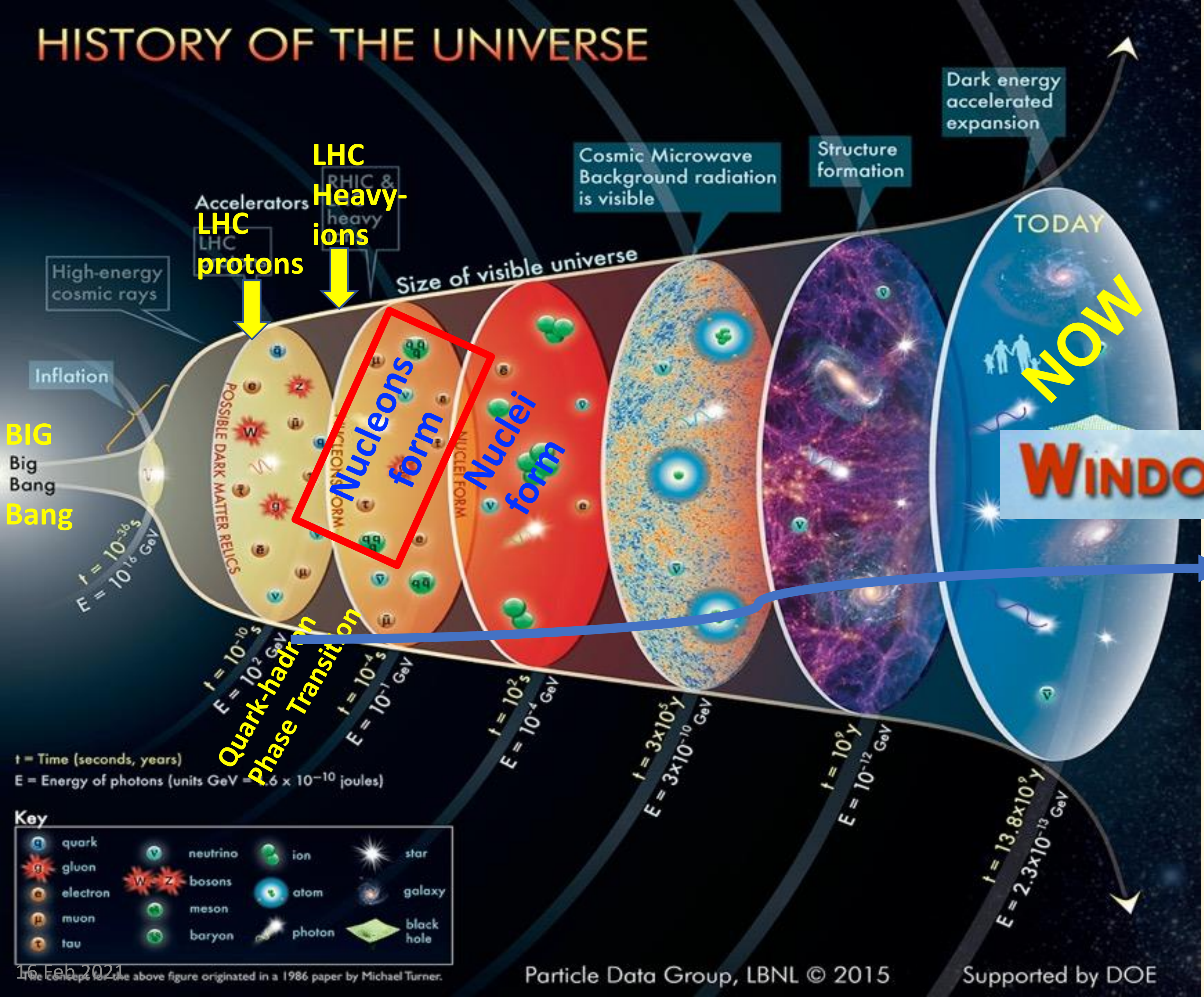
Using Astronomical Probes: The closest we can go to the Big Bang is 380,000 years from the beginning ….

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

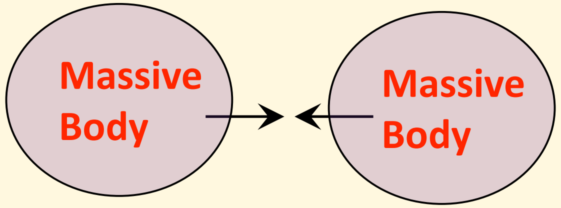
Accelerators (LHC)

Takes us back to within few Microseconds of the Big Bang

- Quark Gluon Plasma

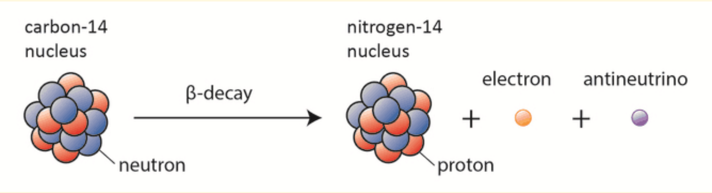
Fundamental forces of nature

Gravitational force



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

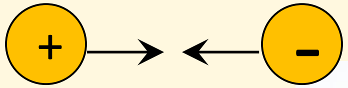
Weak force



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

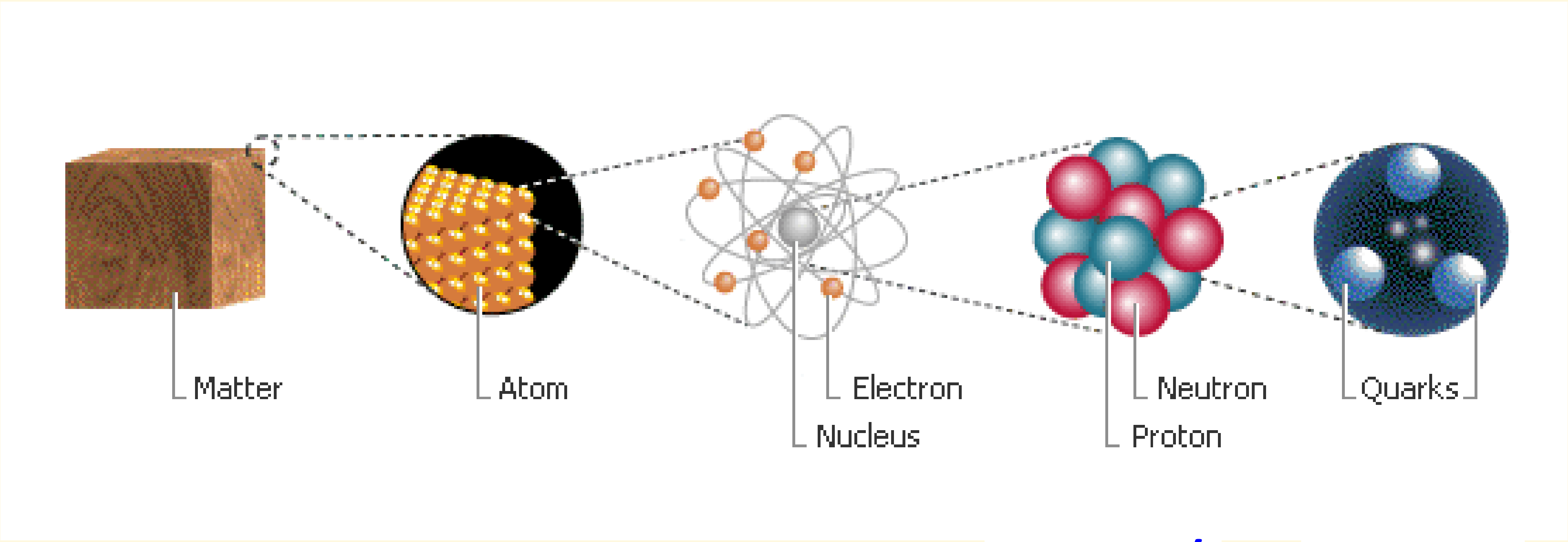
Strong force

Holds the atomic nucleus,

Binds quarks together

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

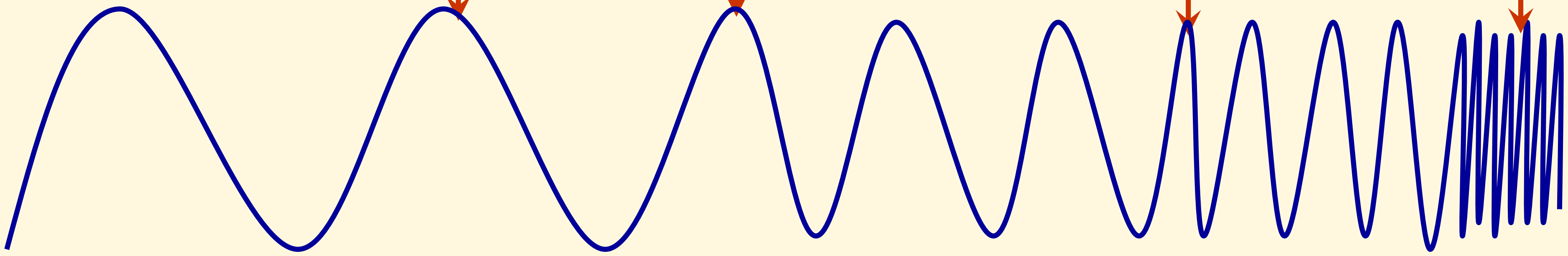
Structure of matter



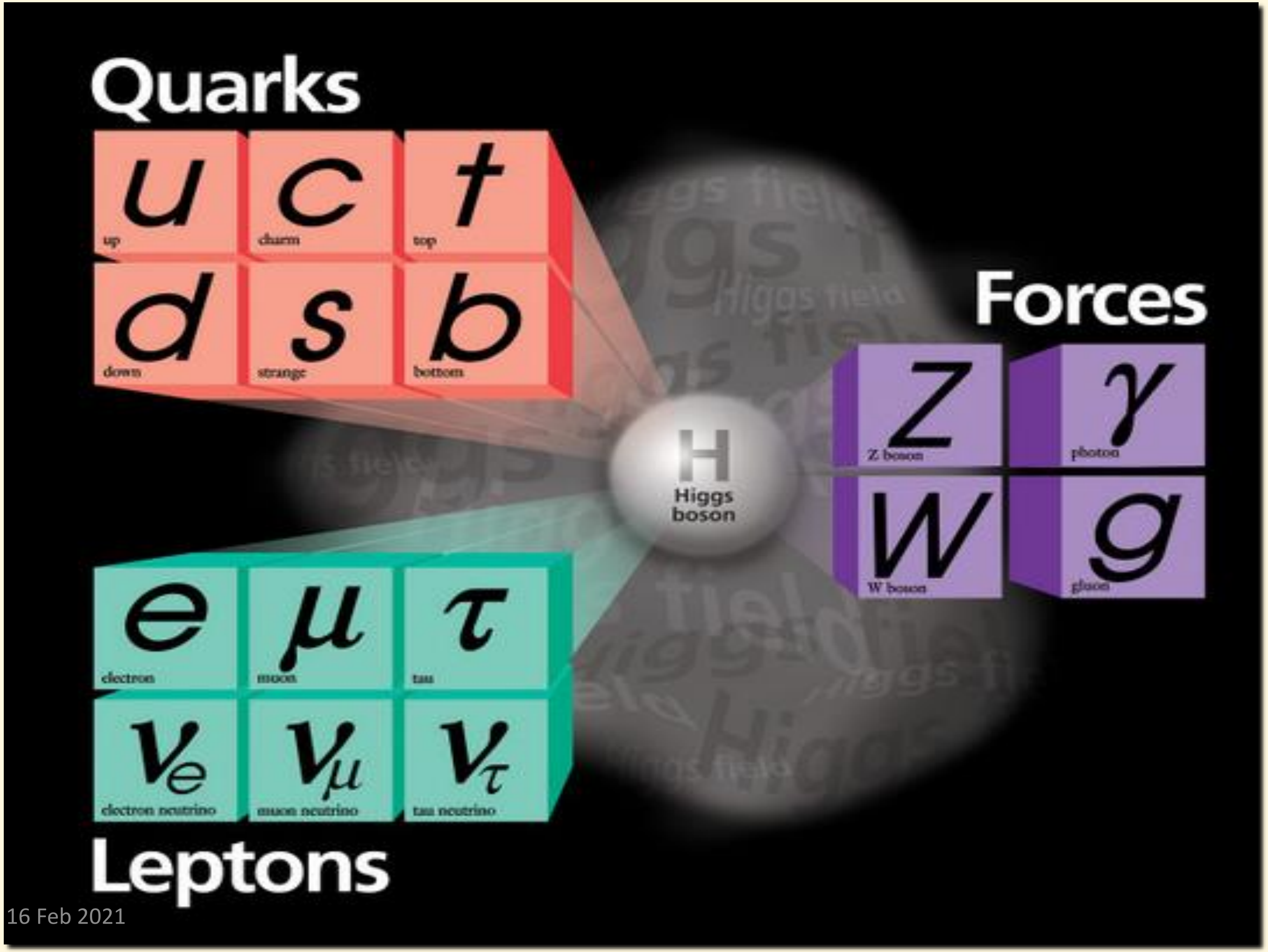
MATTER | **ATOM** | **NUCLEUS** | **Protons/ neutrons** | **QUARKS**

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

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



Fundamental constituents of matter



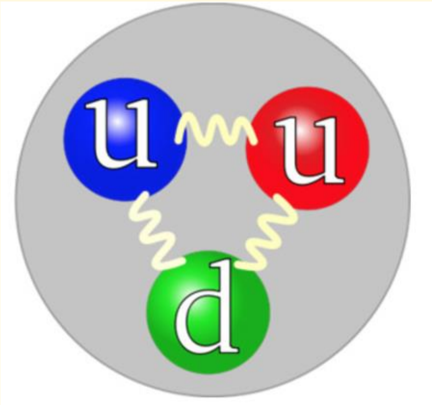
Higgs particle is responsible for **giving mass** to all particles.

Lockdown: Quark confinement

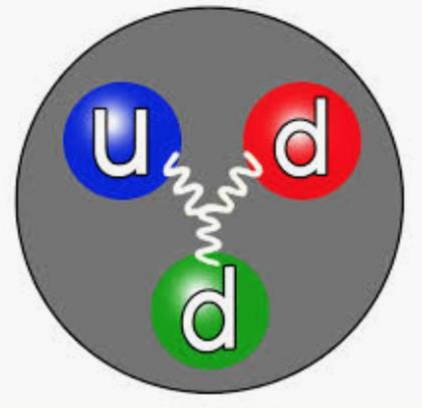
No one has ever seen a free quark

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

Proton



Neutron



Coloued quarks attract one another by exchanging gluons, of which there are eight types. Gluons are massless, have spin 1, travel at the speed of light, and carry both a color and a different anticolor.

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.

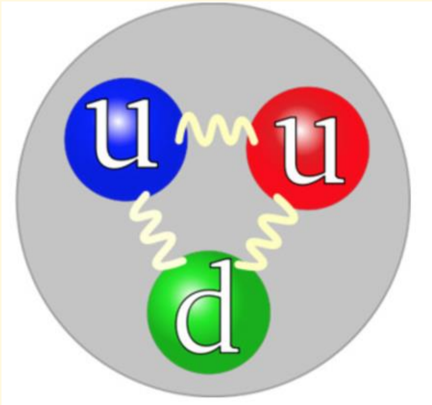
Lockdown: Quark confinement

No one has ever seen a free quark

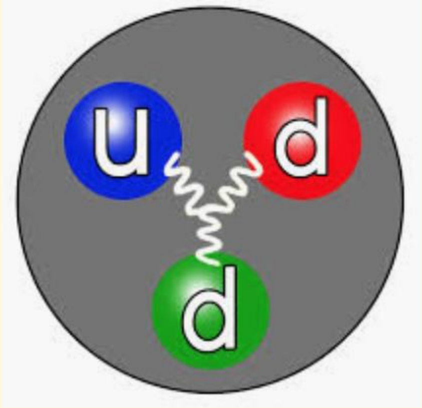
- **Asymptotic freedom:** q-q interactions become weaker as the inter-quark distance becomes shorter.

  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



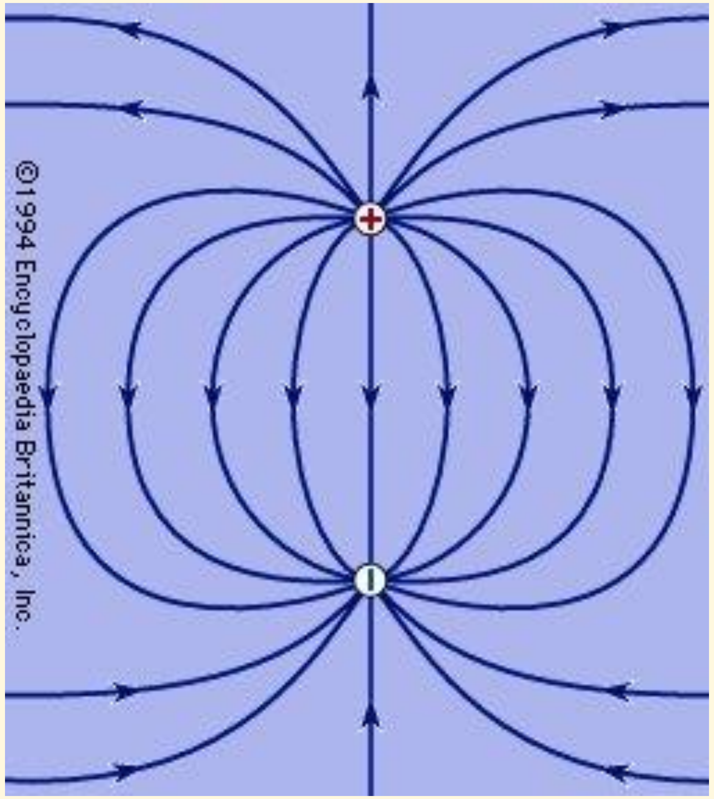
Neutron



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

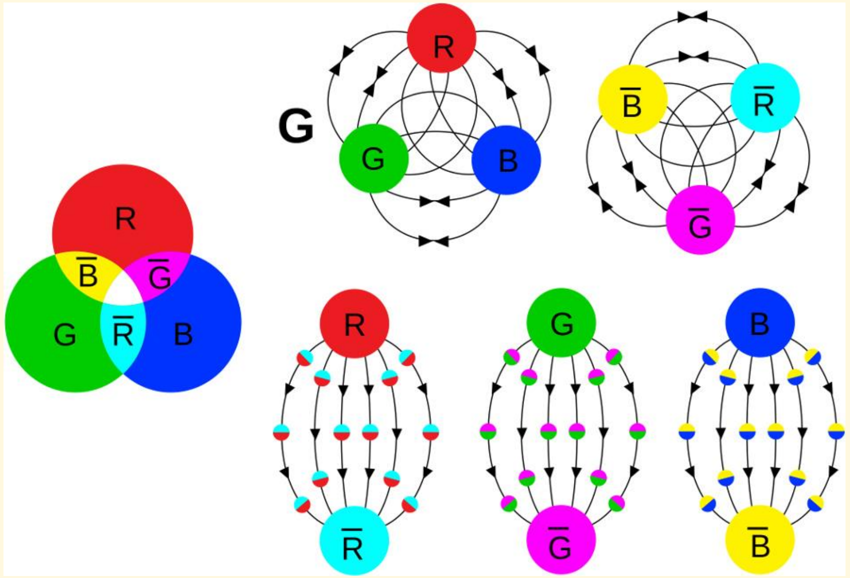
Electromagnetic interaction

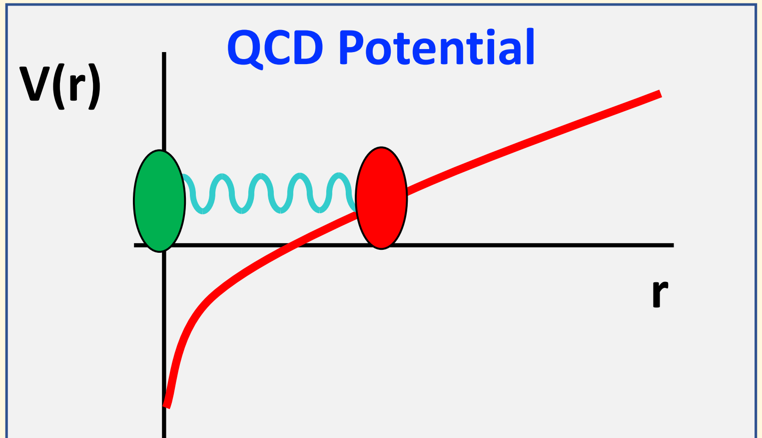


Electric field lines near equal but opposite charges

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

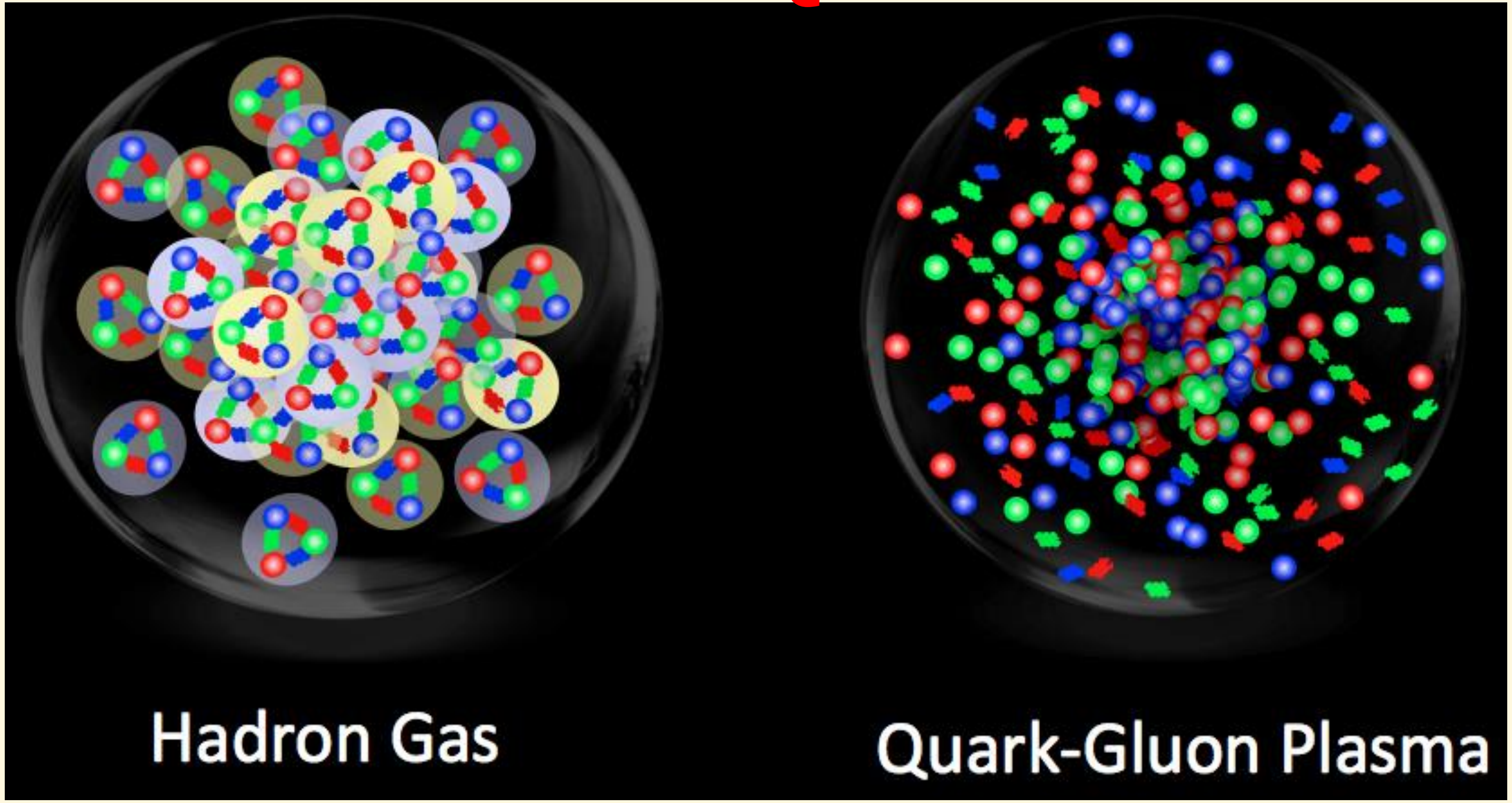
Color force in QCD





$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

Deconfinement => Quark Gluon Plasma



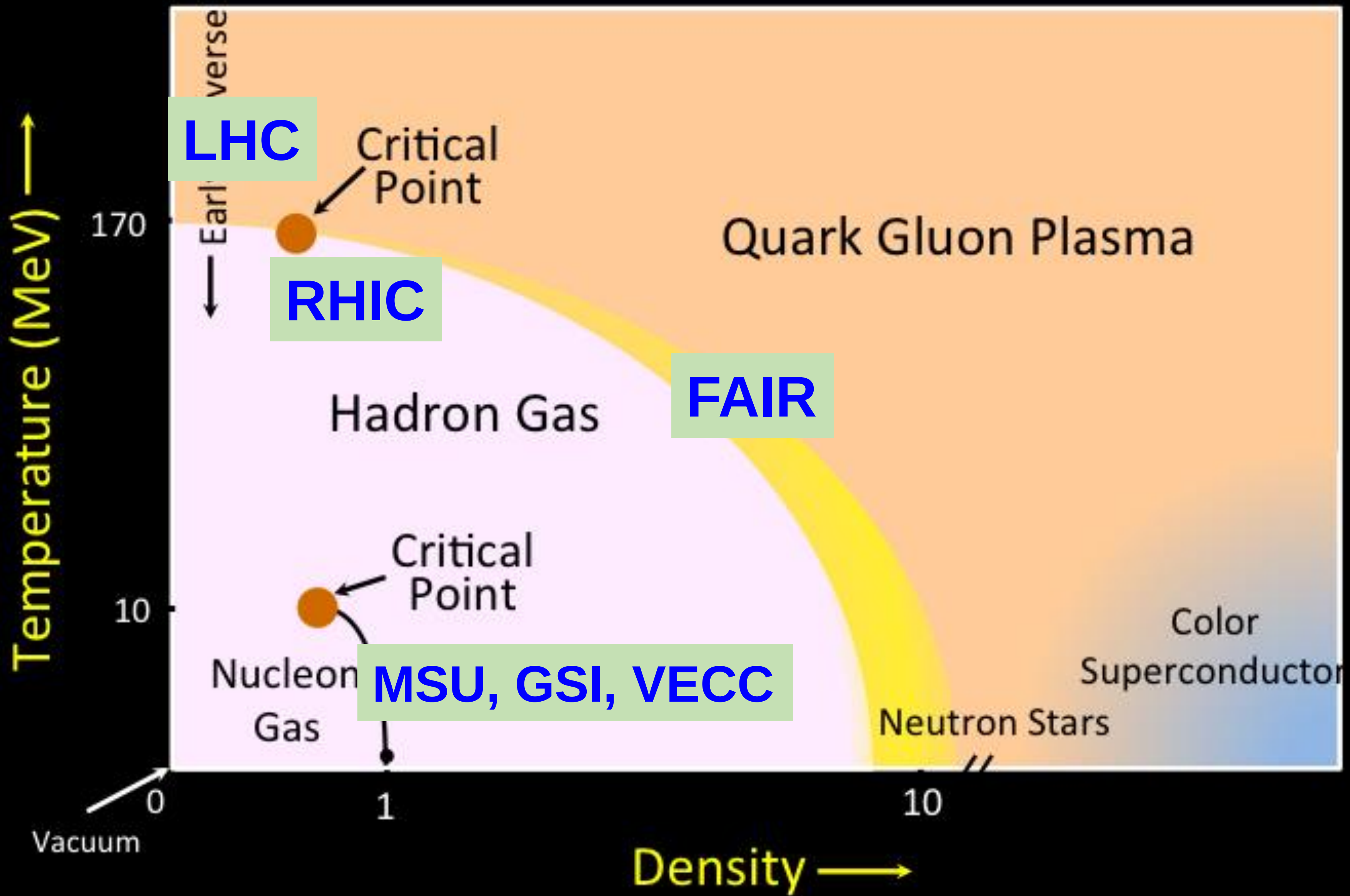
Hadron gas =>

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

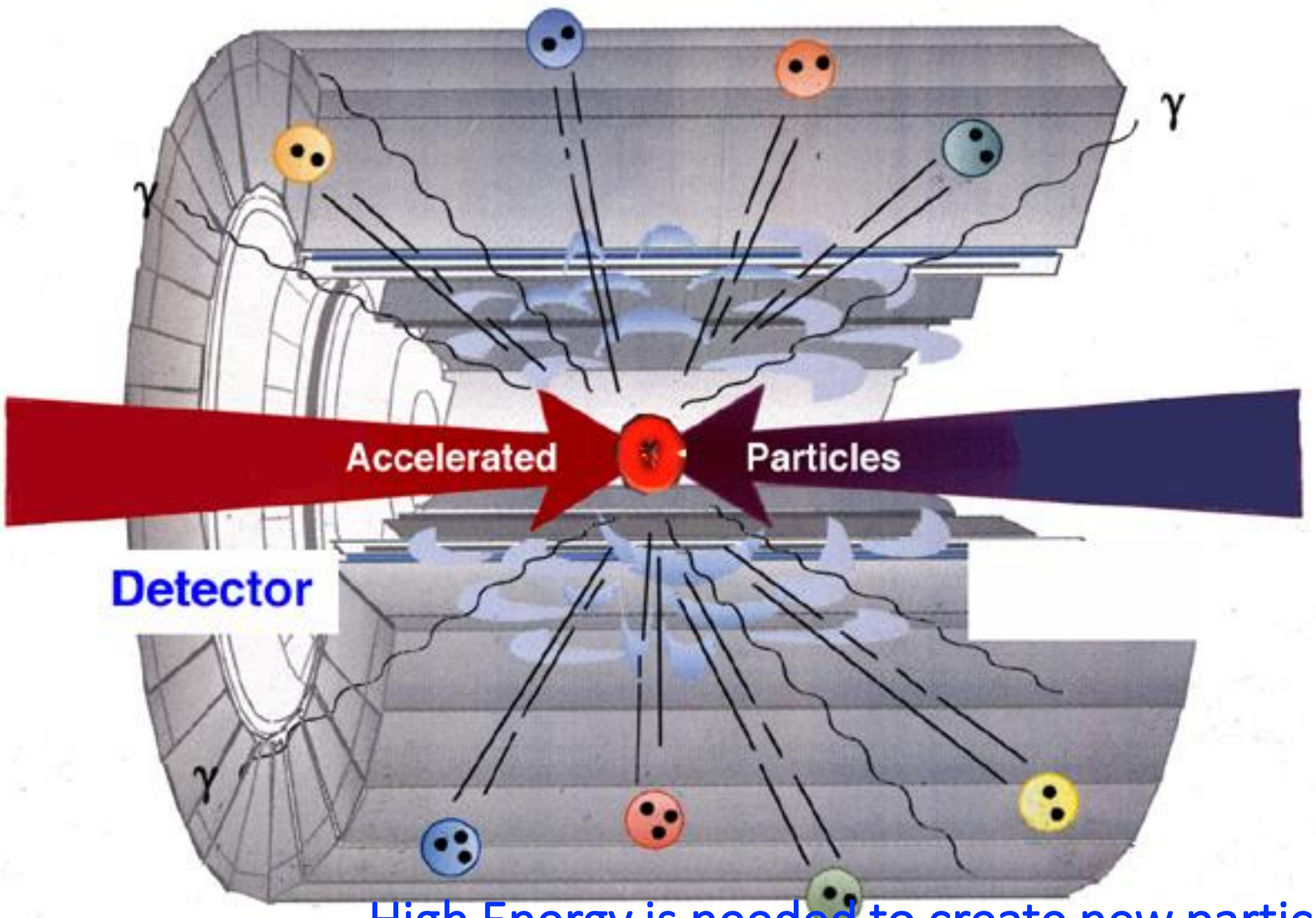
=> the boundaries disappear forming a system of free quarks and gluons

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



High Energy is needed to create new particles

Need High Energy Accelerator:

COLLIDER

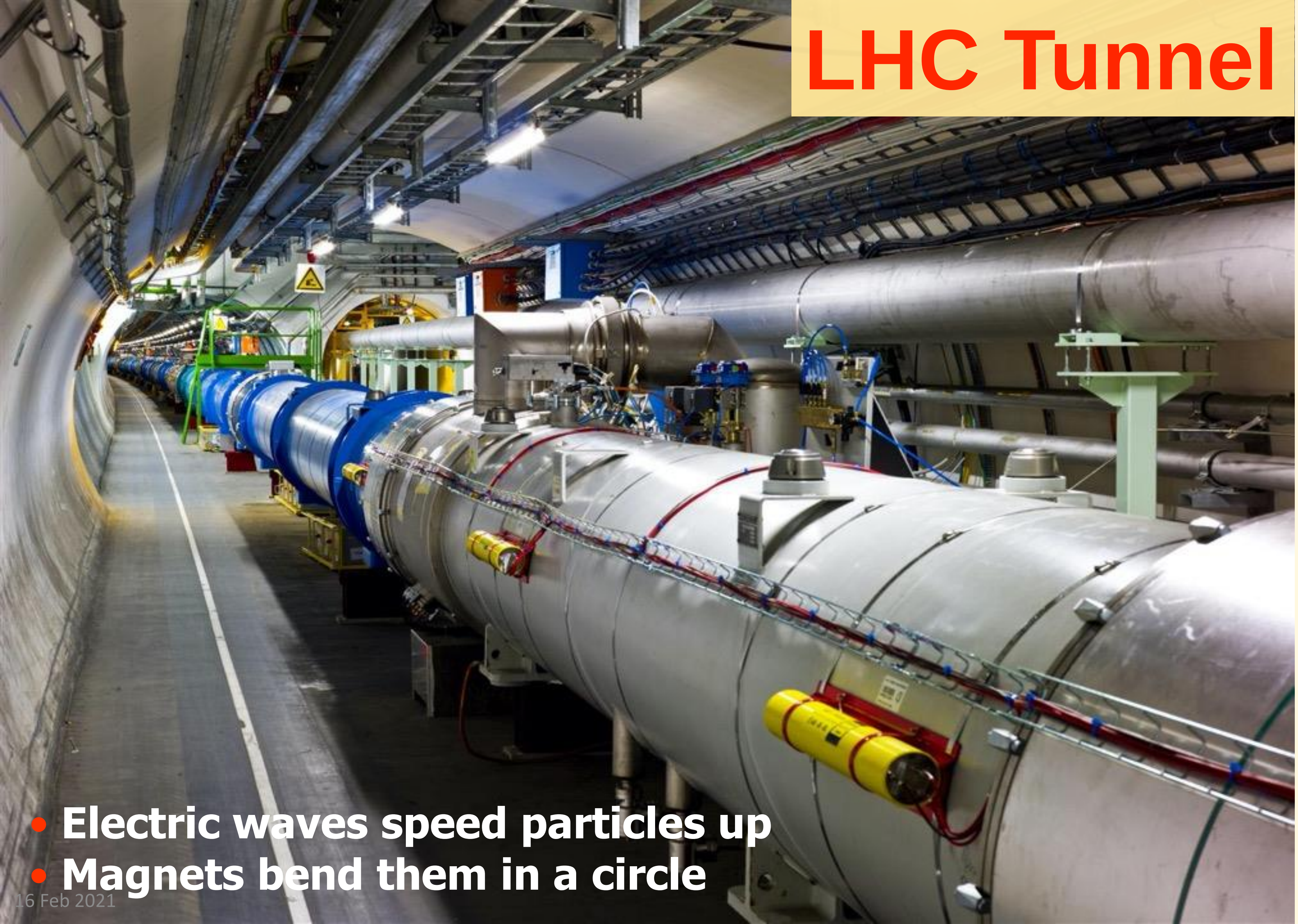
$$E = mc^2$$


CERN
“Science without borders”

World's Most Powerful Accelerator: The Large Hadron Collider

27 km circumference
~ 100 m underground
Design Energy:
14 TeV (pp), 5.5 TeV (Pb-Pb)

LHC Tunnel



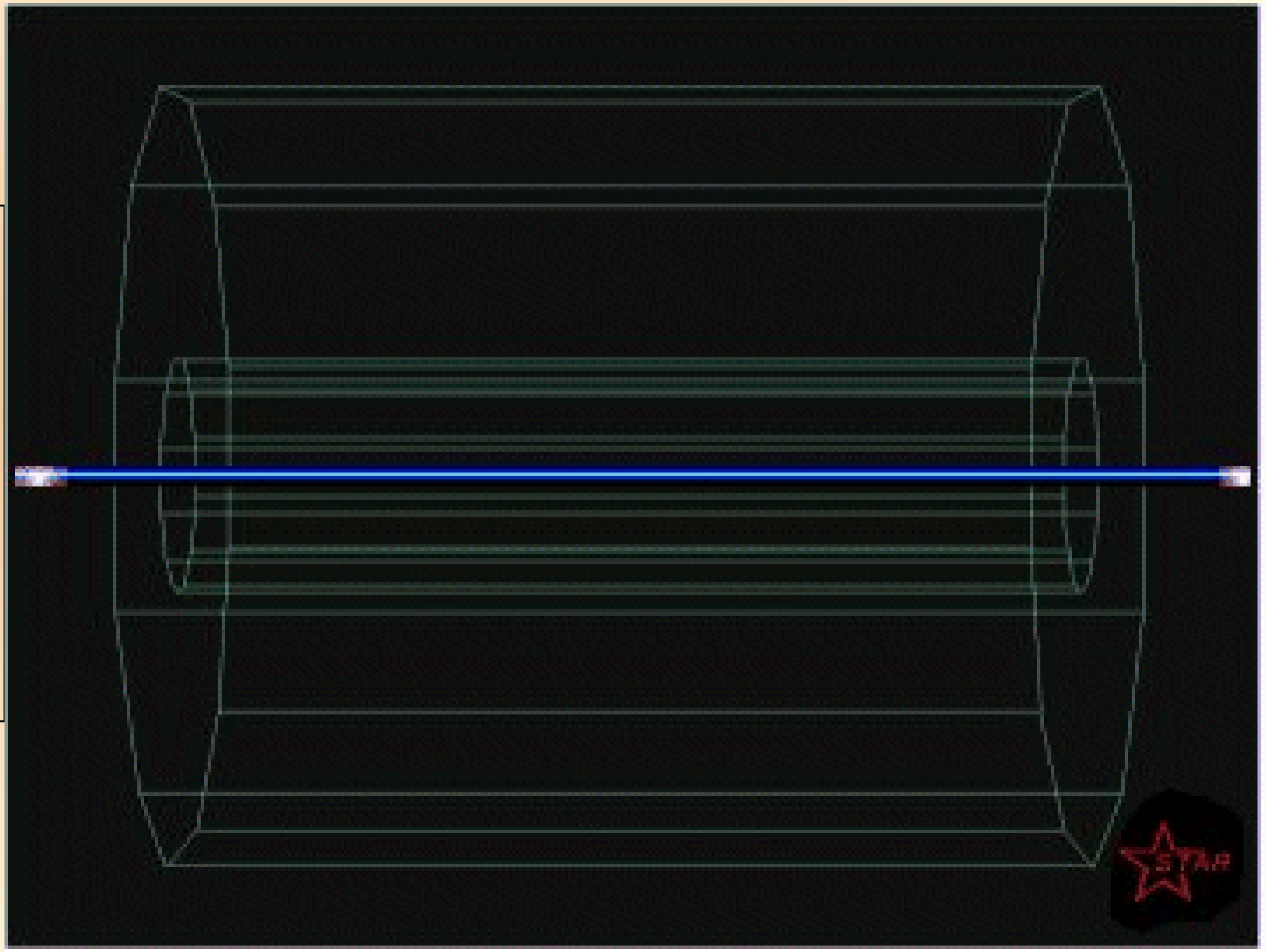
- **Electric waves speed particles up**
- **Magnets bend them in a circle**

27km tunnel:

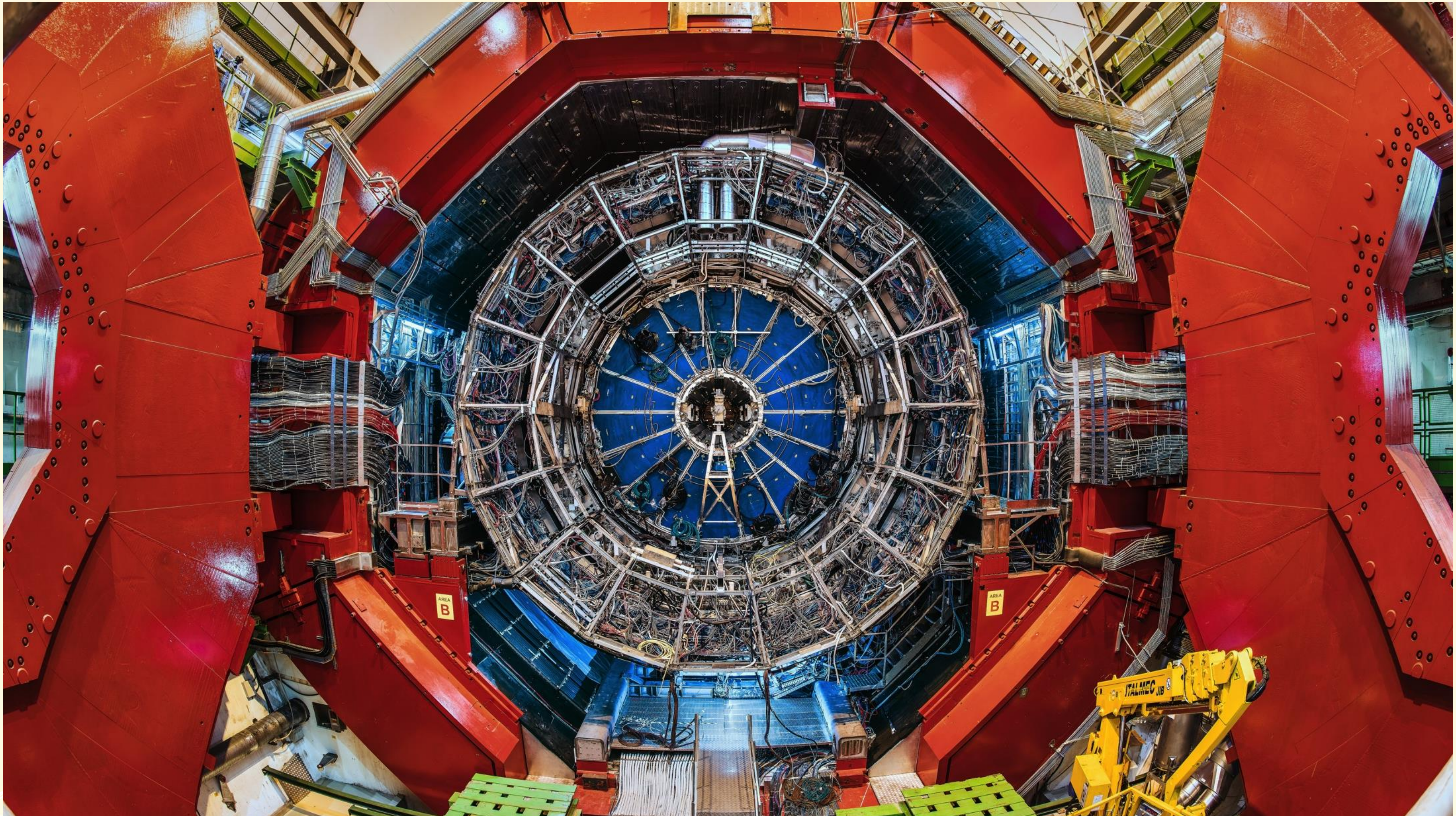
- 50-150m below ground
- Two beams circulating in opposite directions
- Total of 9300 magnets: beams controlled by 1800 superconducting magnets (up to 8T)

Heavy-ion collisions: Creating the QGP state

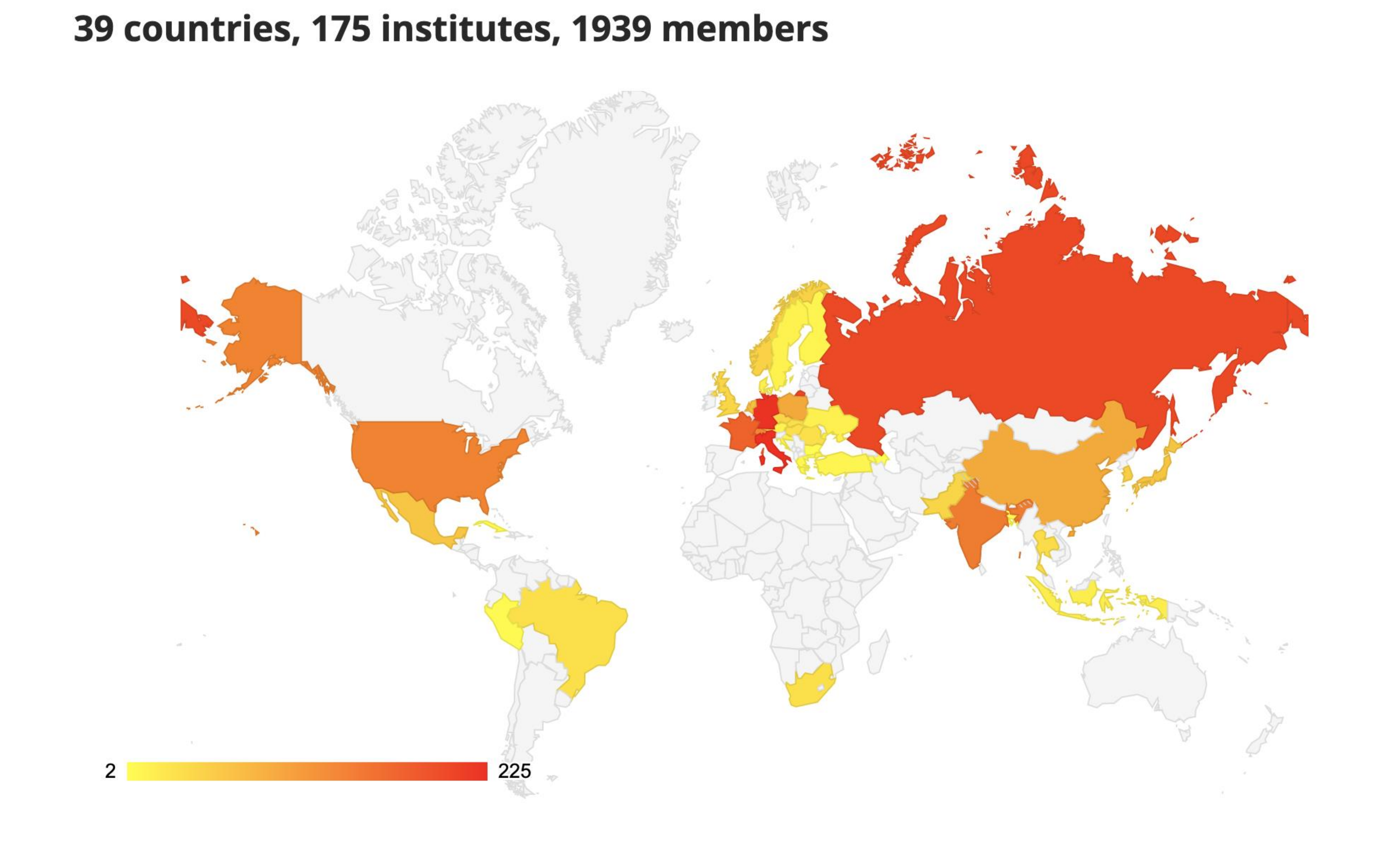
- Take a high-mass atom like Au or Pb
- Take away the electron => Ion (***Heavy-ion***)
- ***Accelerate the Ion*** to almost the speed of light
- ***Collide the Ions => Create the Little Bang***
- Study the aftermath by specialized detector systems which surround the collision point ***=> Experiment***



ALICE at Point-2 of the LHC

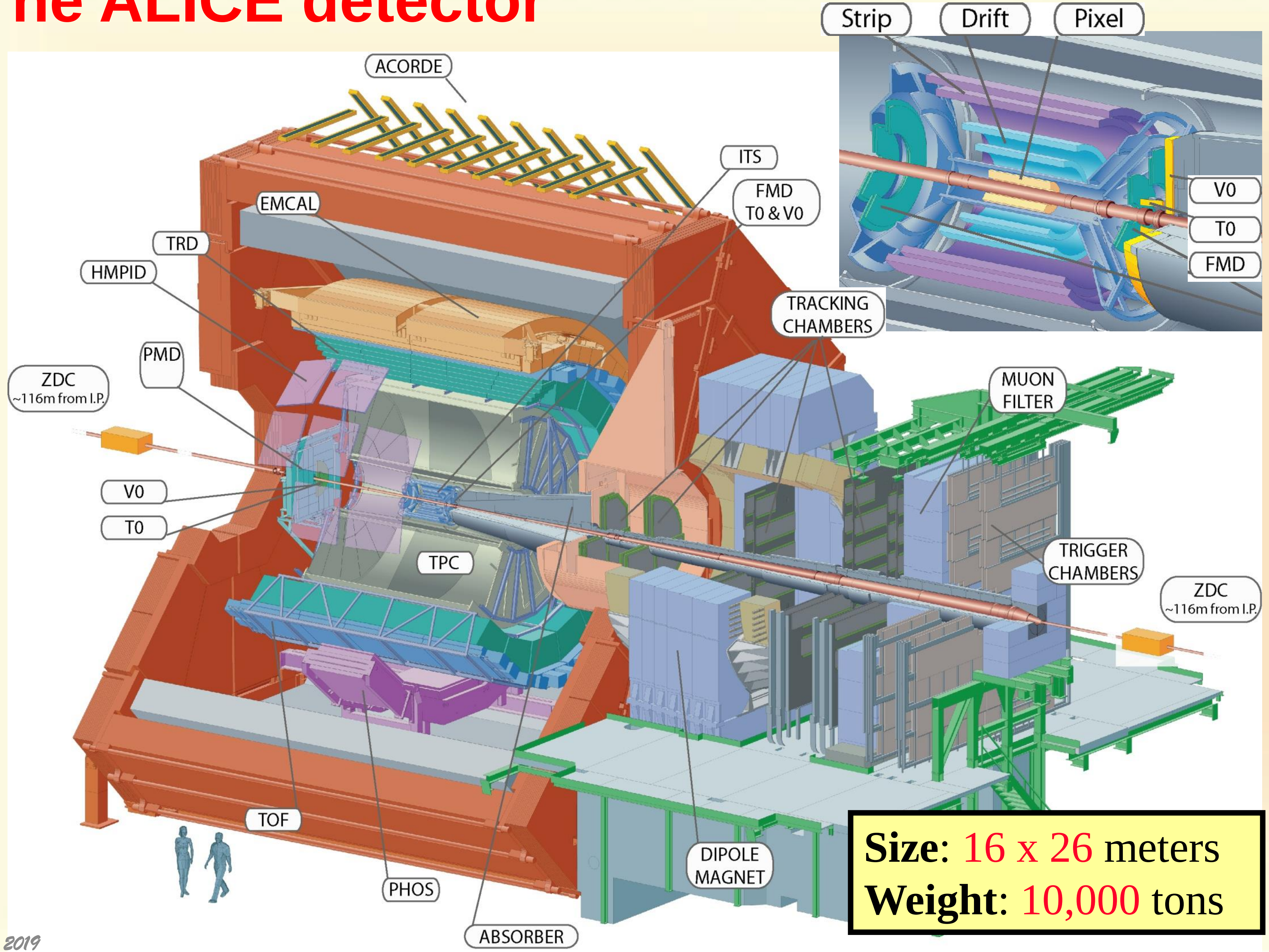


ALICE Collaboration



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

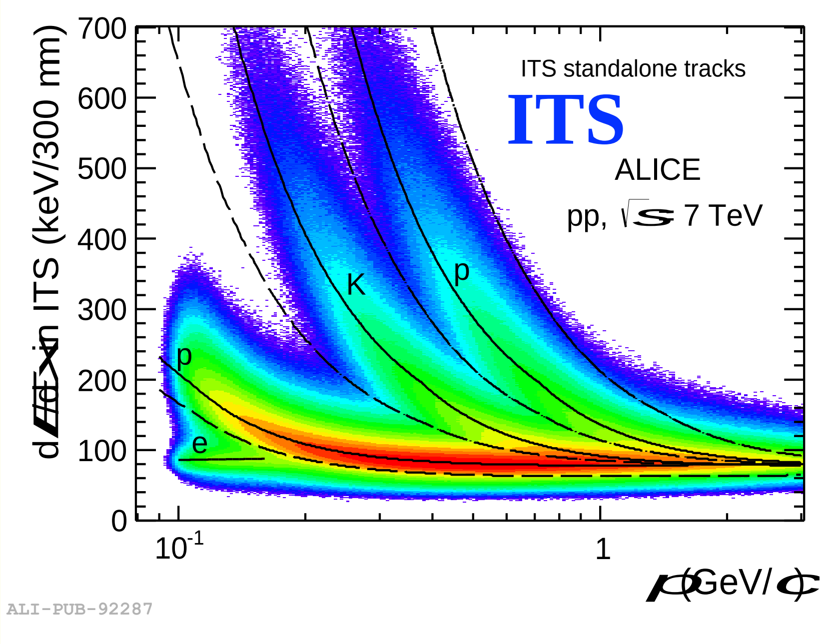
Muon Arm:
$-4<\eta<-2.5$

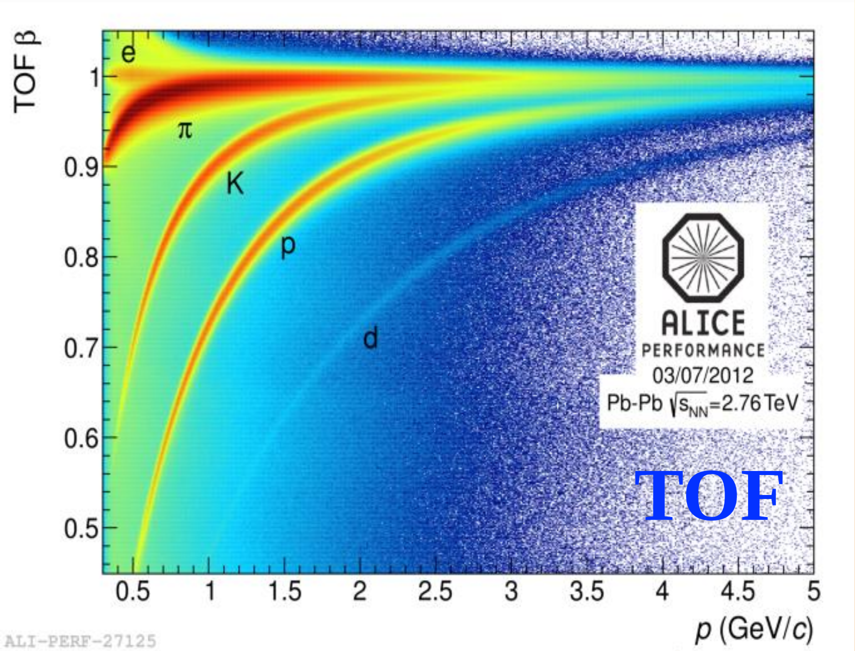
SPECIAL detectors:

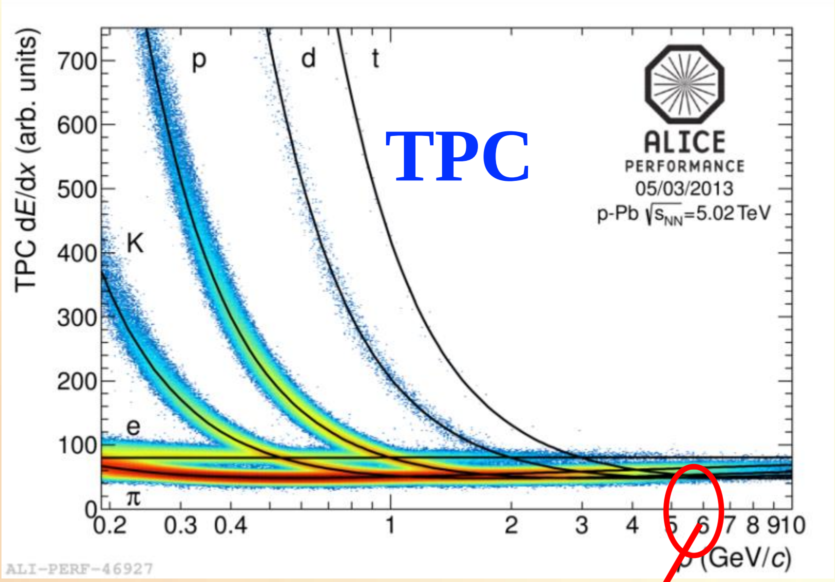
- V0
- FMD
- PMD
- ADC
- ZDC

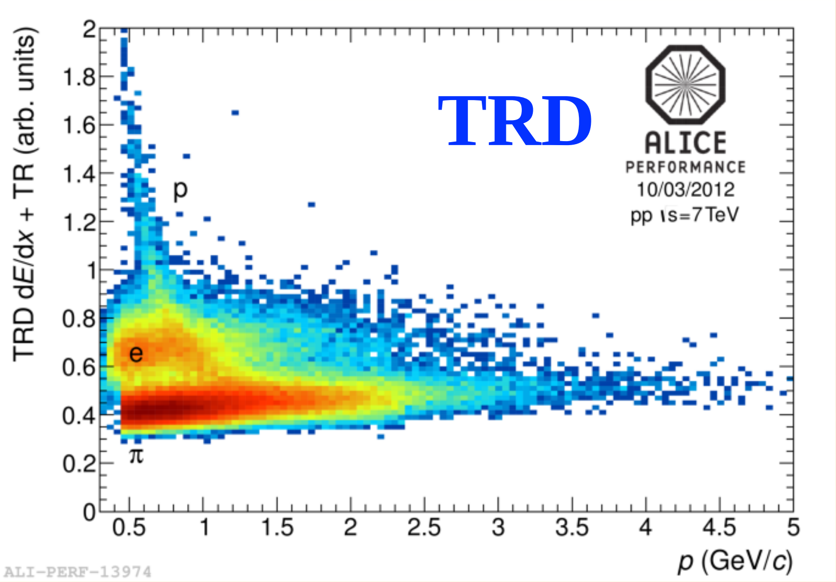
Size: 16 x 26 meters
Weight: 10,000 tons

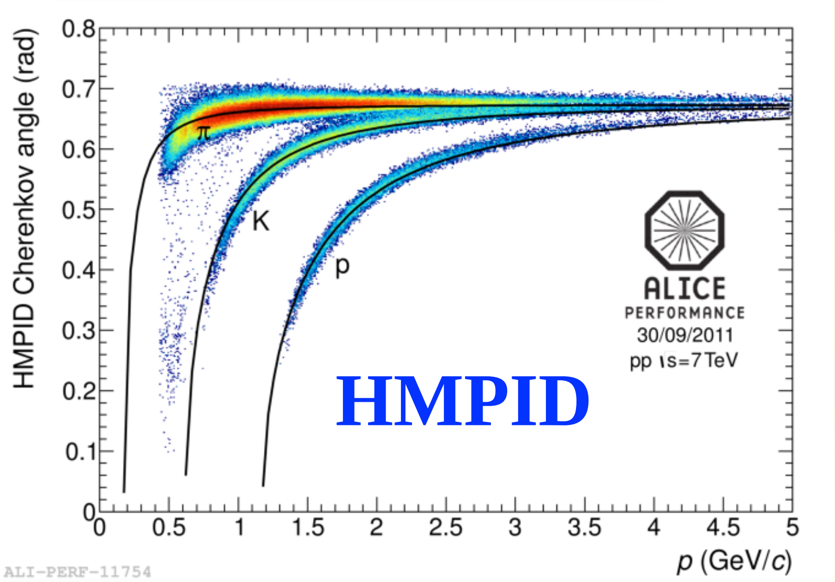
ALICE performance

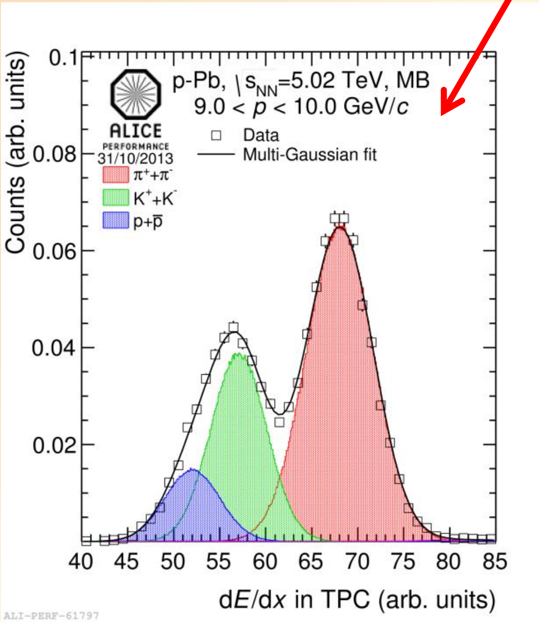




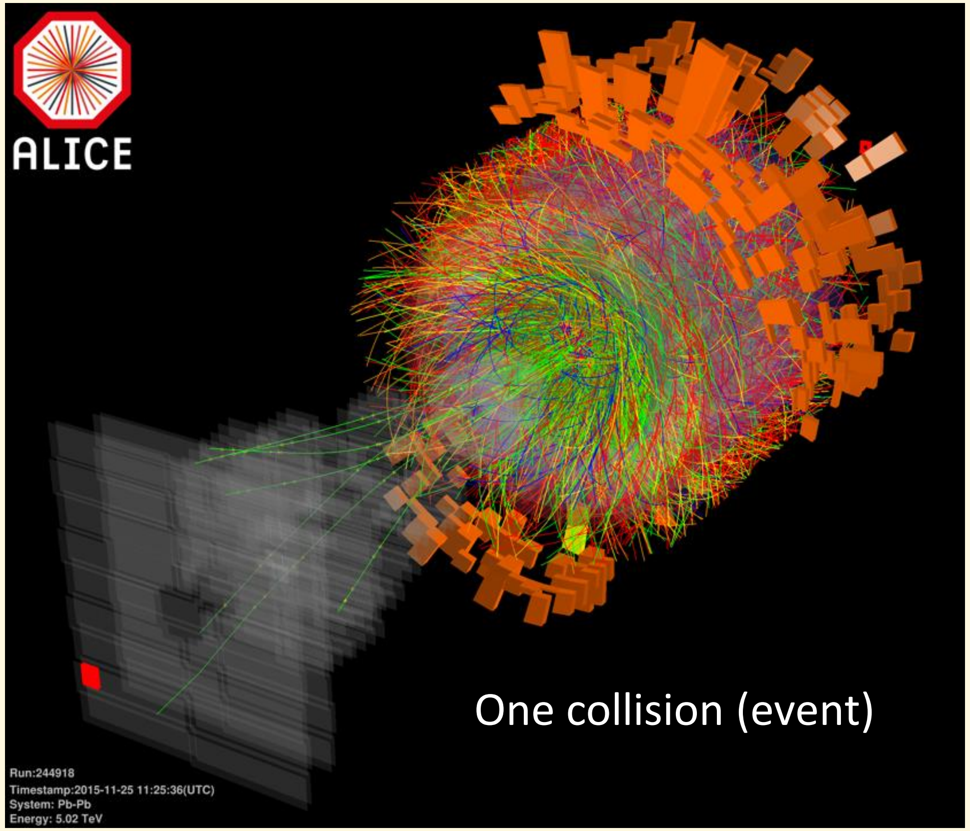








Reconstructing the collision



What has just happened?

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

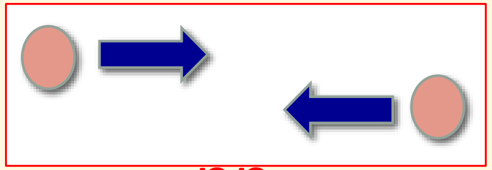
=> Online (live):

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

=> Offline: Event reconstruction:

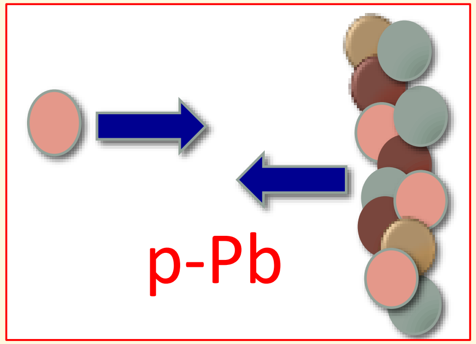
- Vertexing
- Tracking
- Particle identification of each of the tracks

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

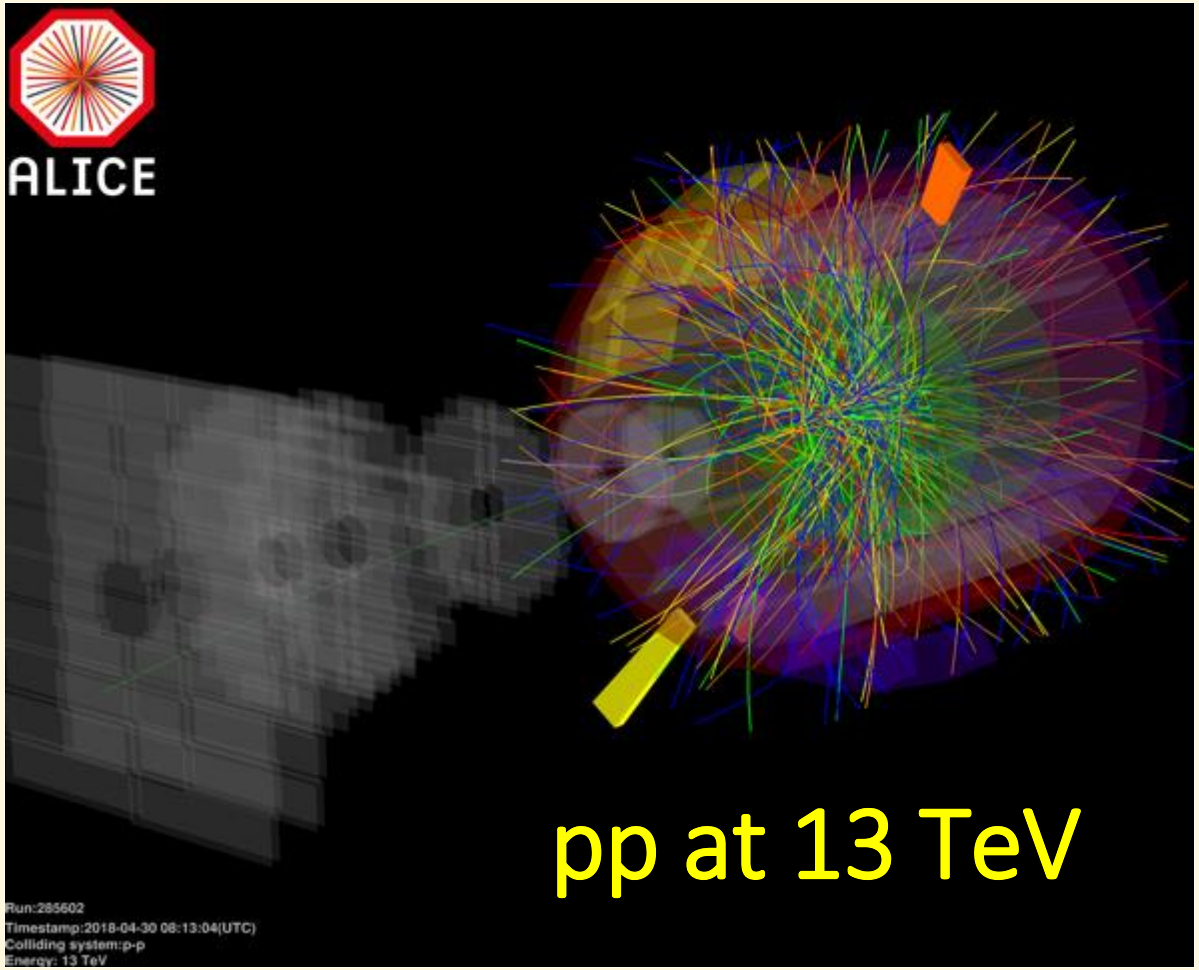


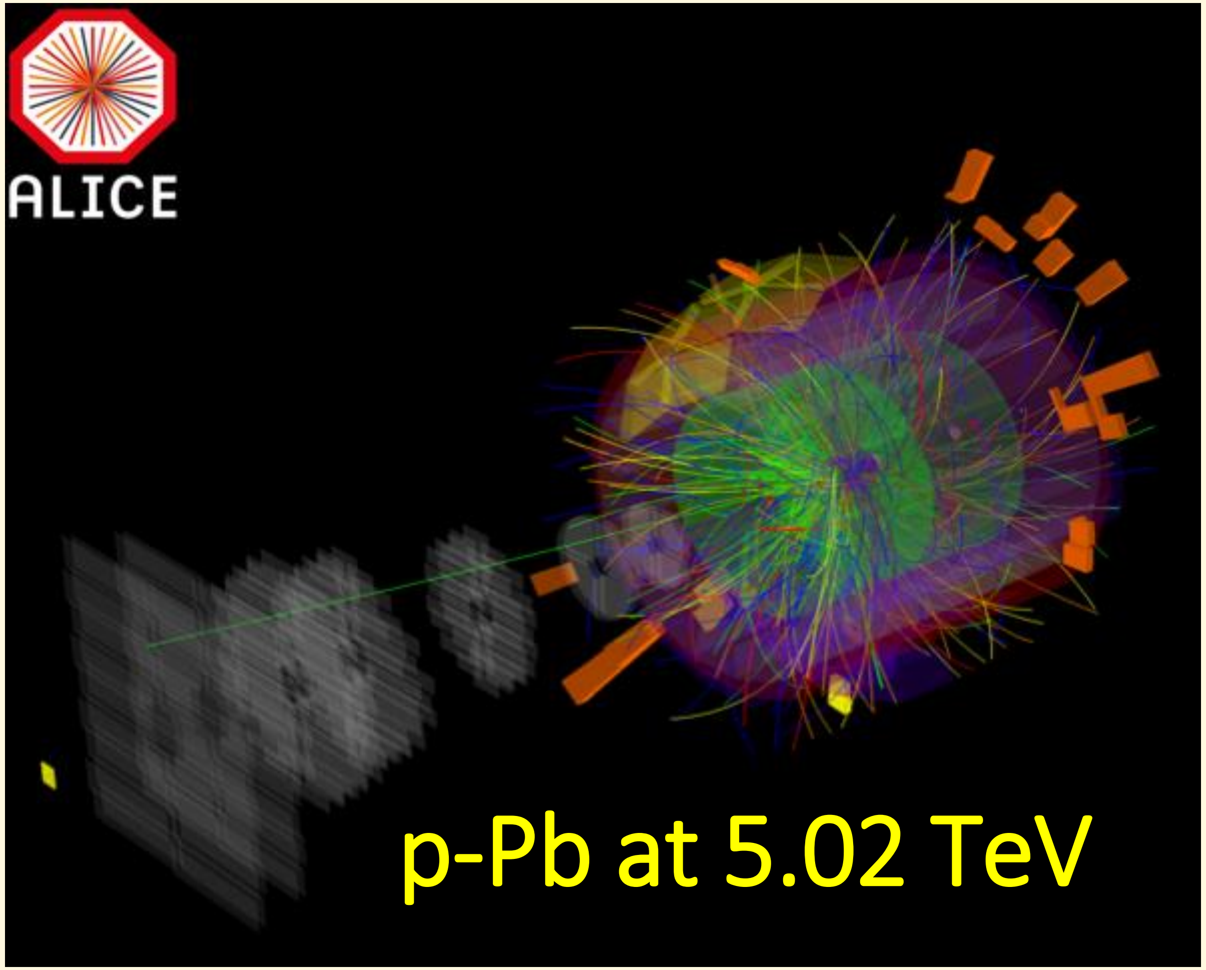
pp

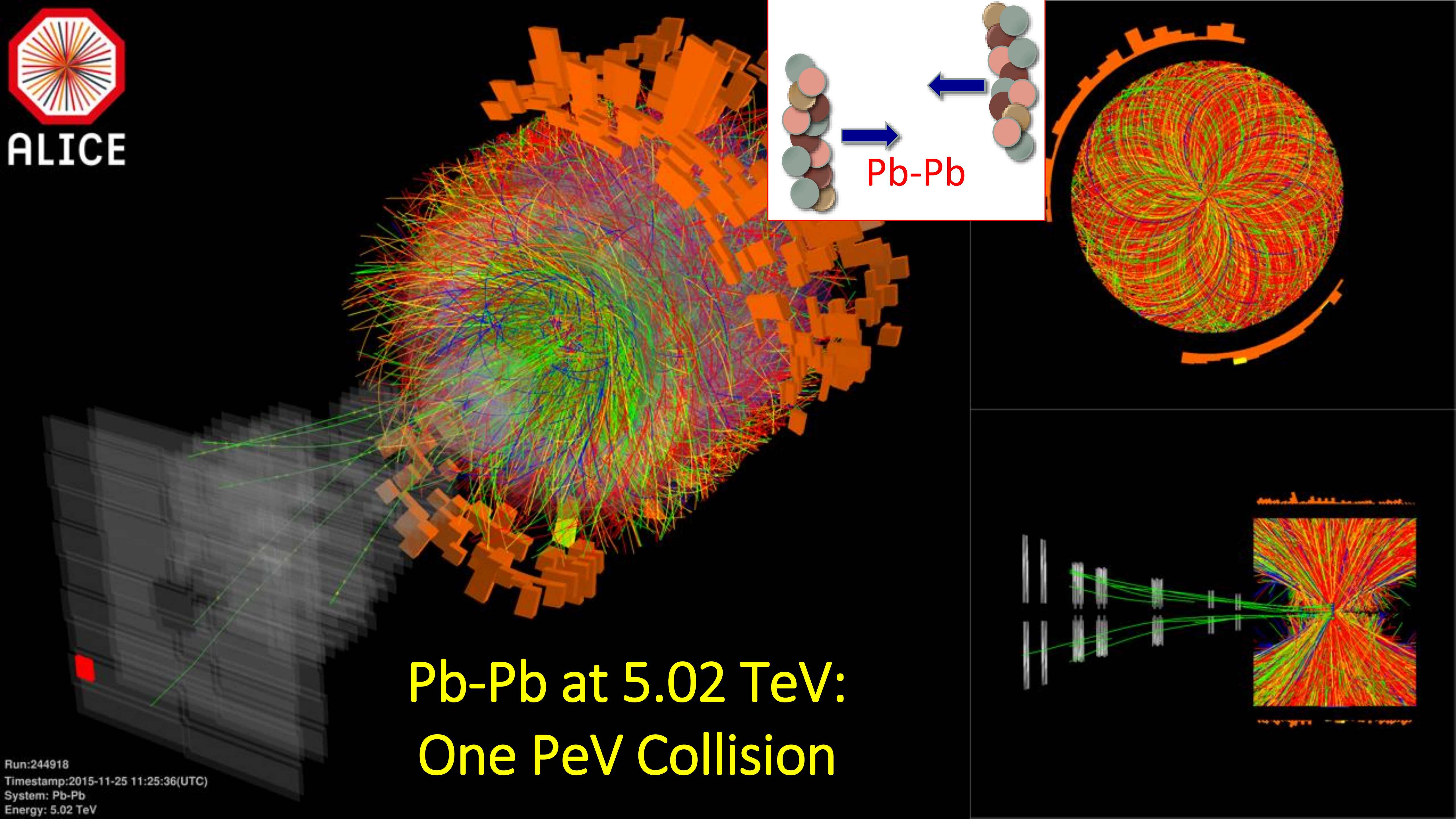
- Test of pQCD calculations from cross section measurements
- Provide reference for p-Pb and Pb-Pb collisions
- High multiplicity pp: what's the behaviour?

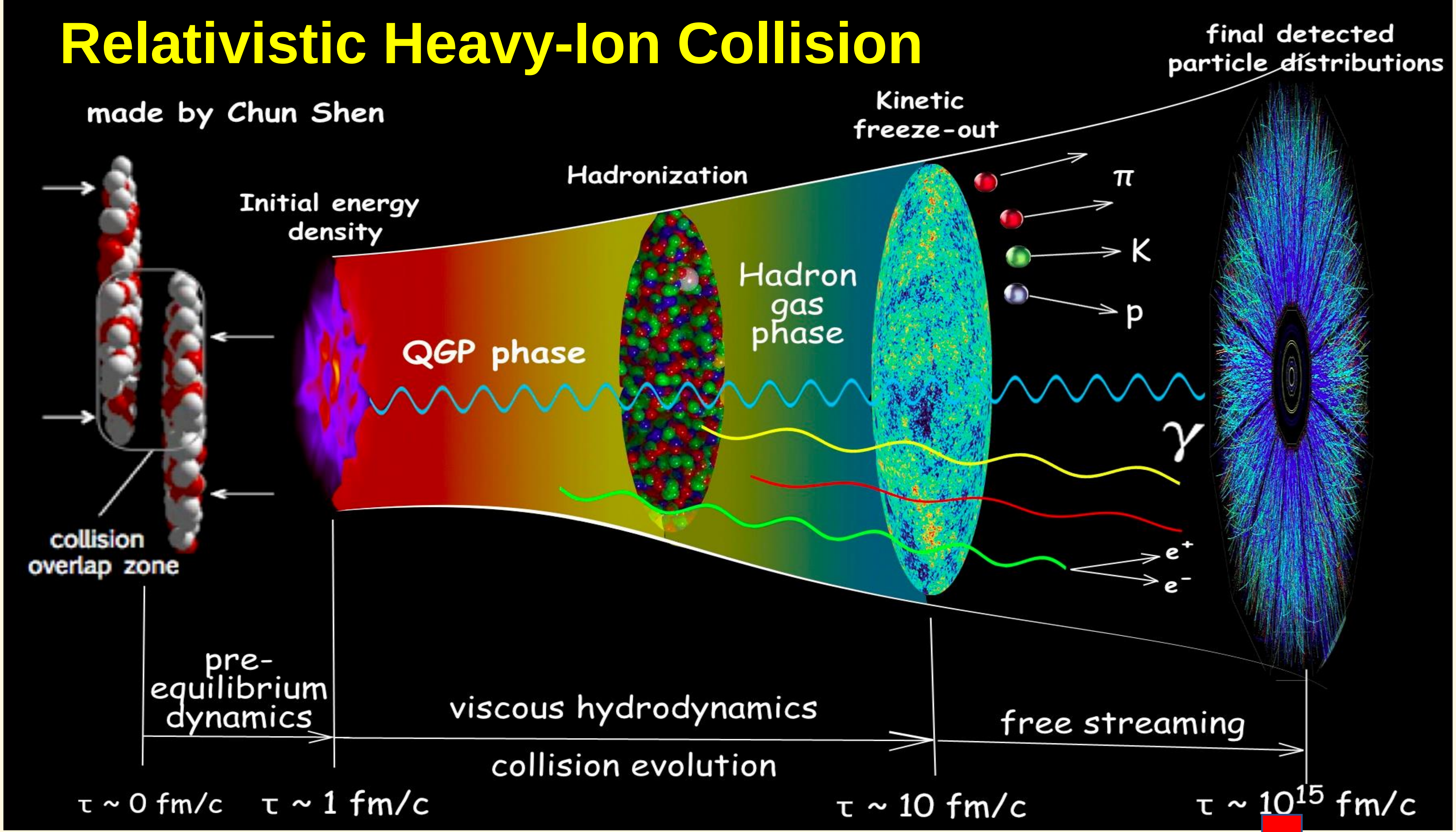


- Intermediary reference
- Address cold nuclear matter effects in initial and final states






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



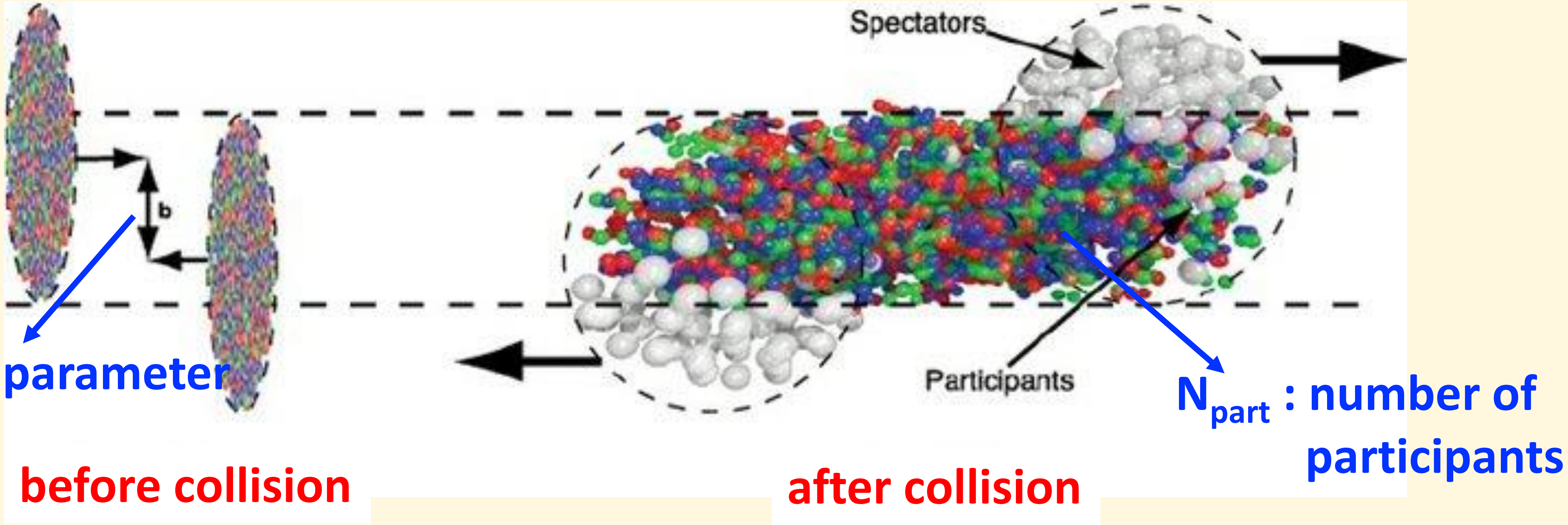
Initial State Fluctuations

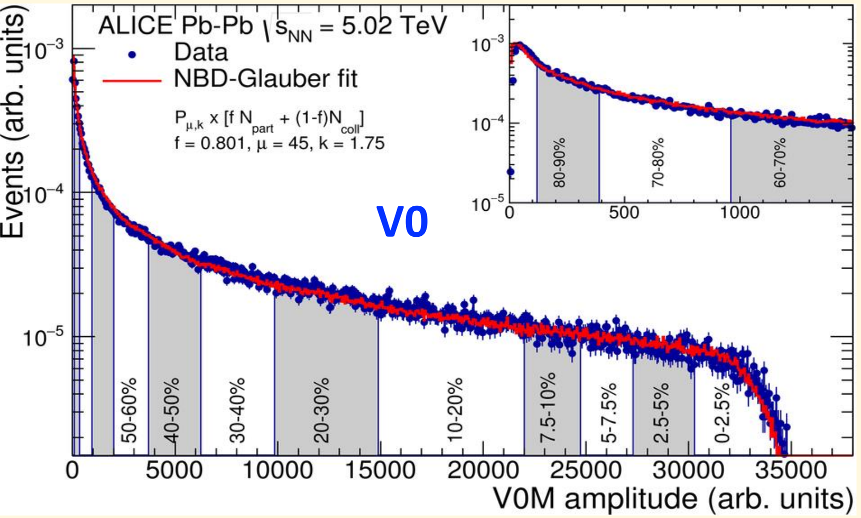
Thermal Fluctuations

Hadronization

Measurement

Centrality in heavy-ion collisions:

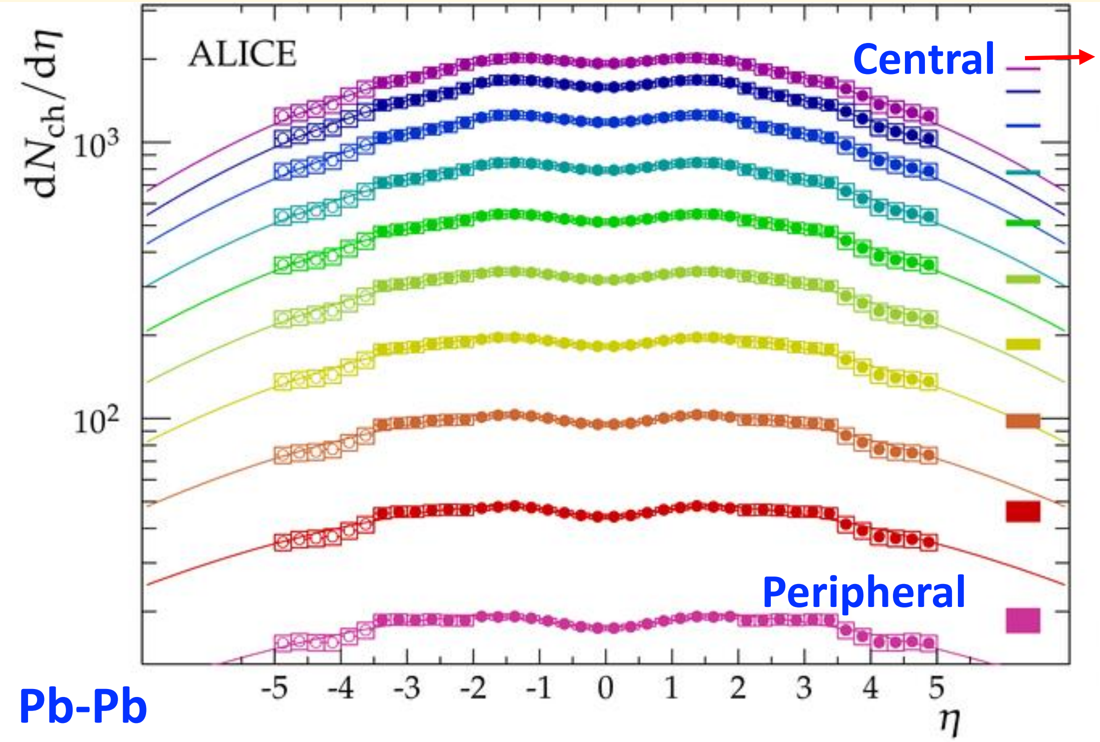


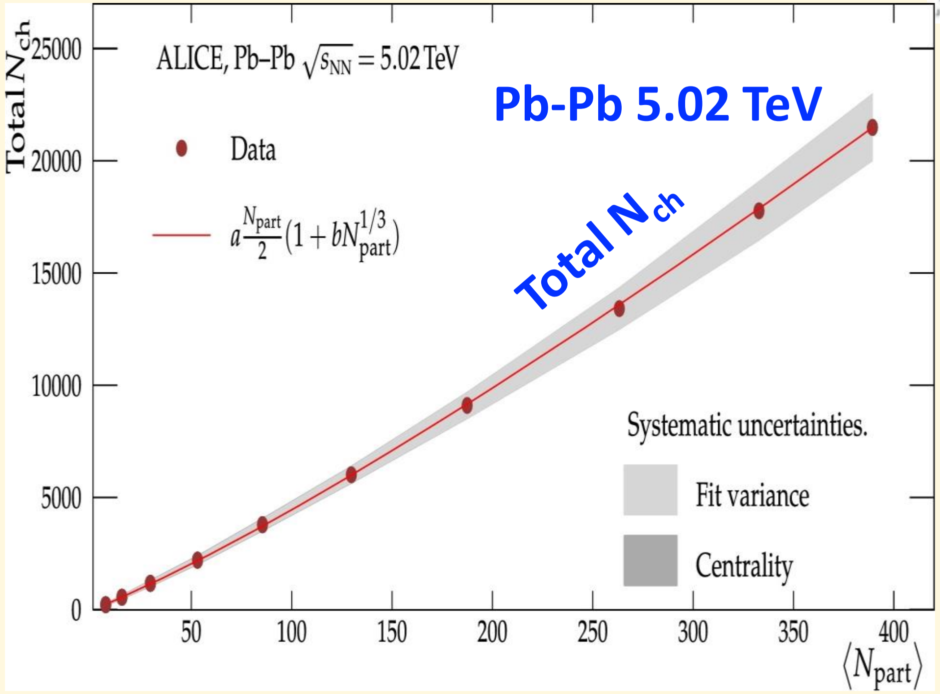


b: impact parameter, For Pb-Pb collisions, maximum of b ~ 14 fm

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

Charged particle multiplicity





Number of charged particles in one collision:

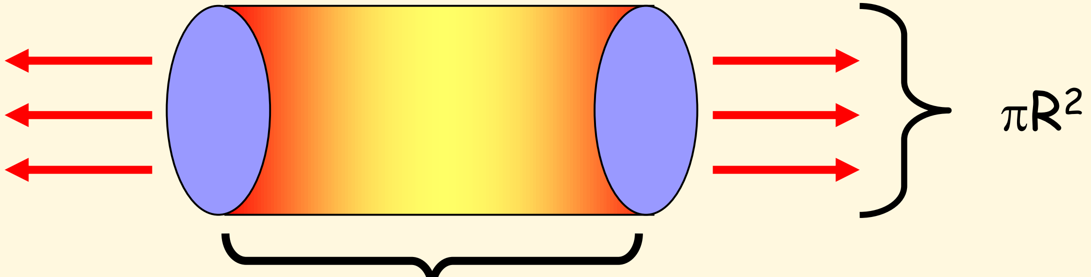
- Central collisions: 21400 ± 1300
- Peripheral collisions: 230 ± 38

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

VERY LARGE NUMBER OF PRODUCED PARTICLES

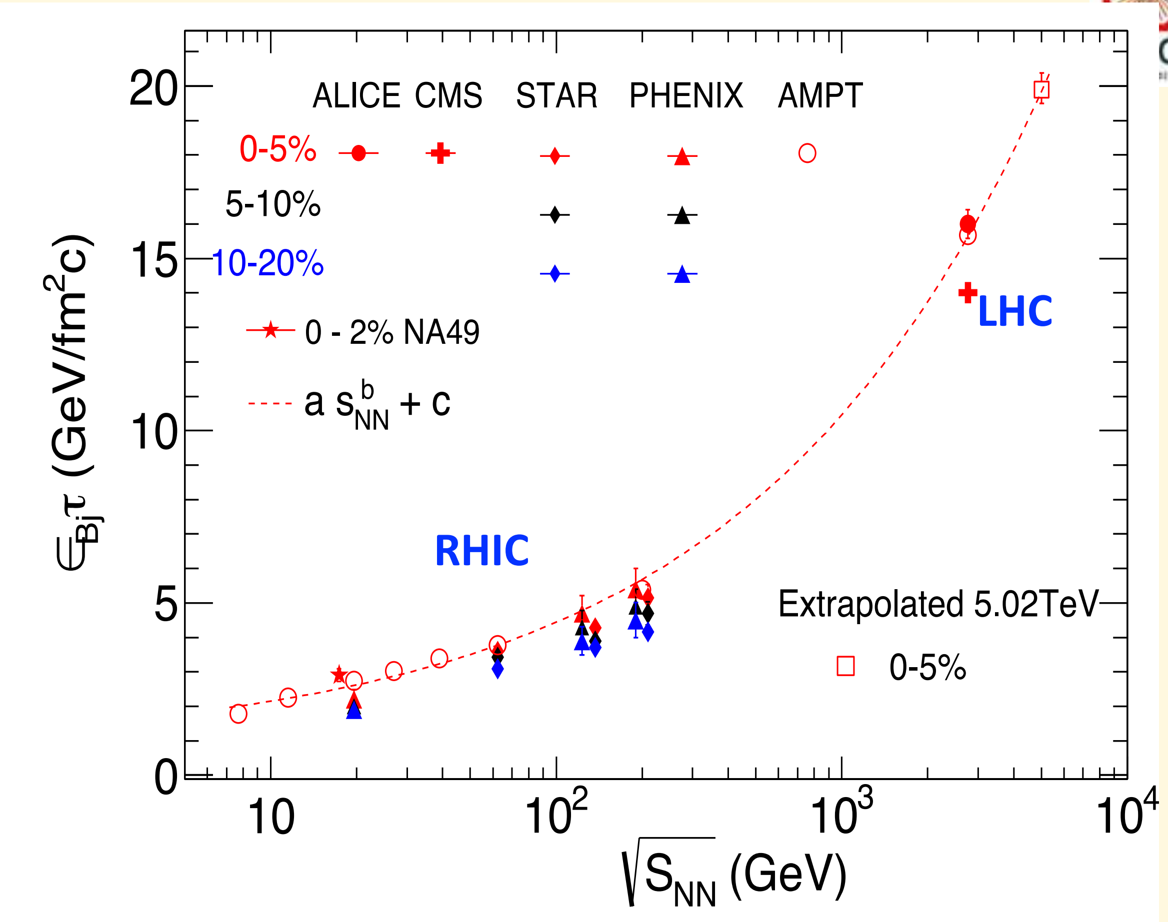
Particle density & Energy density

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



$$dz = \tau_0 dy$$

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



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

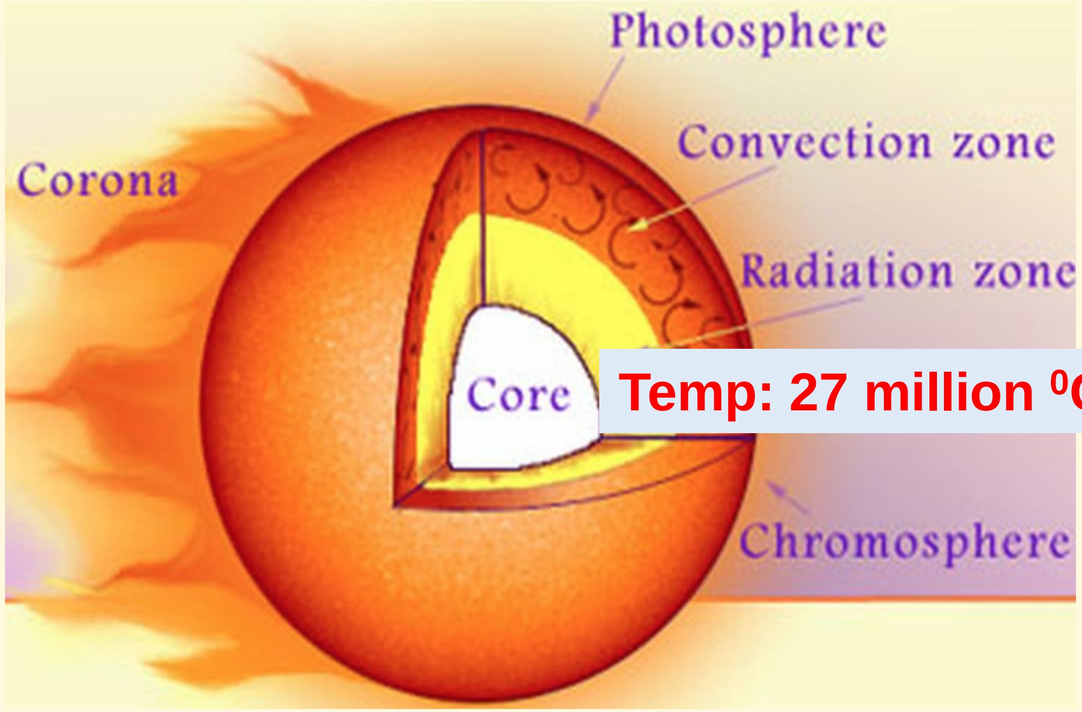
LARGEST ENERGY DENSITIES EVER ACHIEVED ....

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

Photon Spectra and QGP temperature

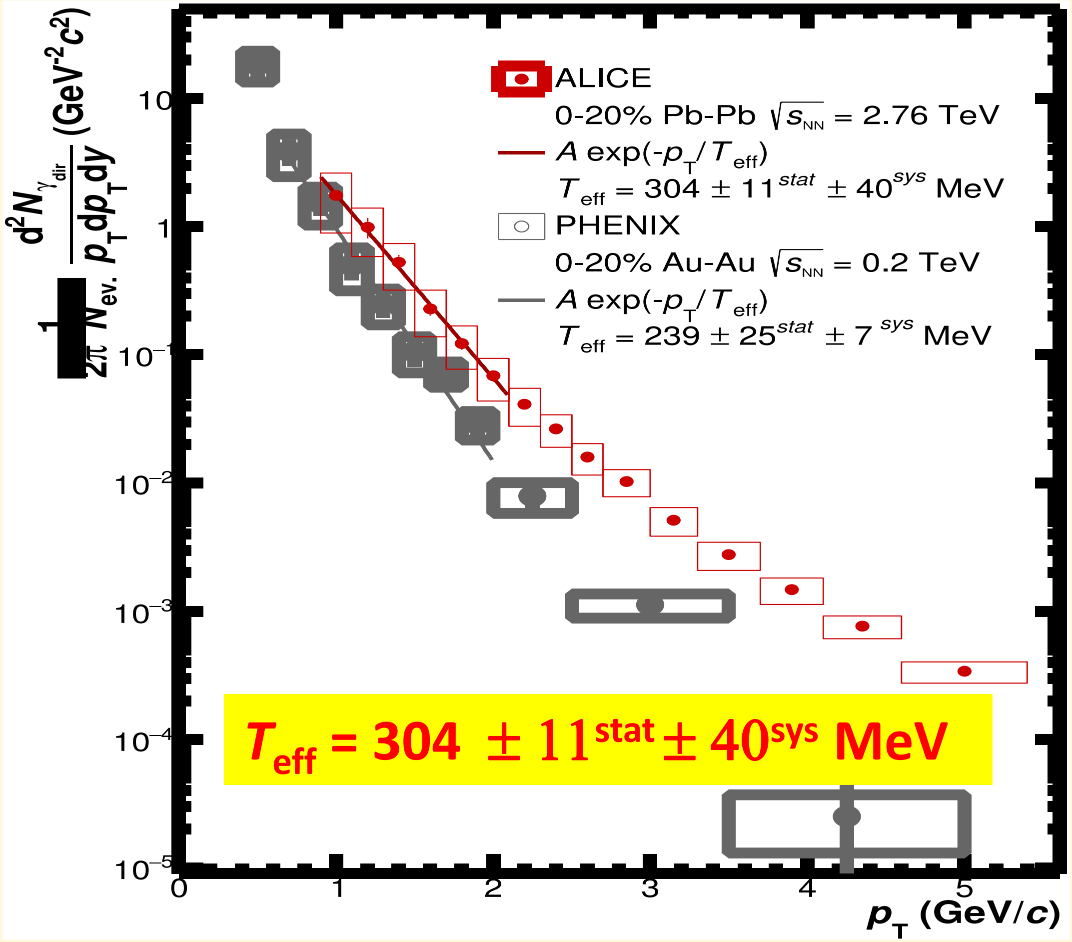
- Photons do not interact via the nuclear force → transparent to the medium
- Photons are emitted in all stages and are unaffected by the medium.

Core of the Sun:



Temp: 27 million ^{0}C

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



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

(1eV=11605K)

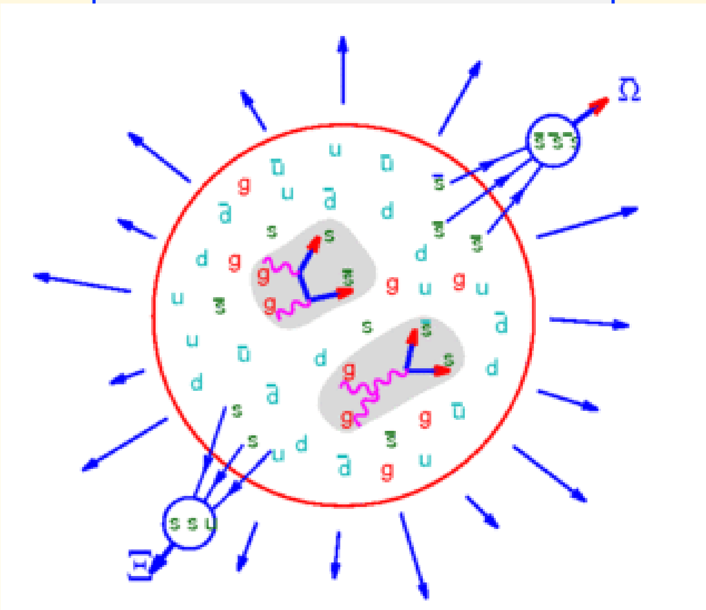
T_{eff} = 3,527,920 million deg

LARGEST EVER TEMPERATURE REACHED IN THE LAB ….

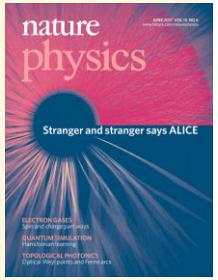
Strangeness enhancement

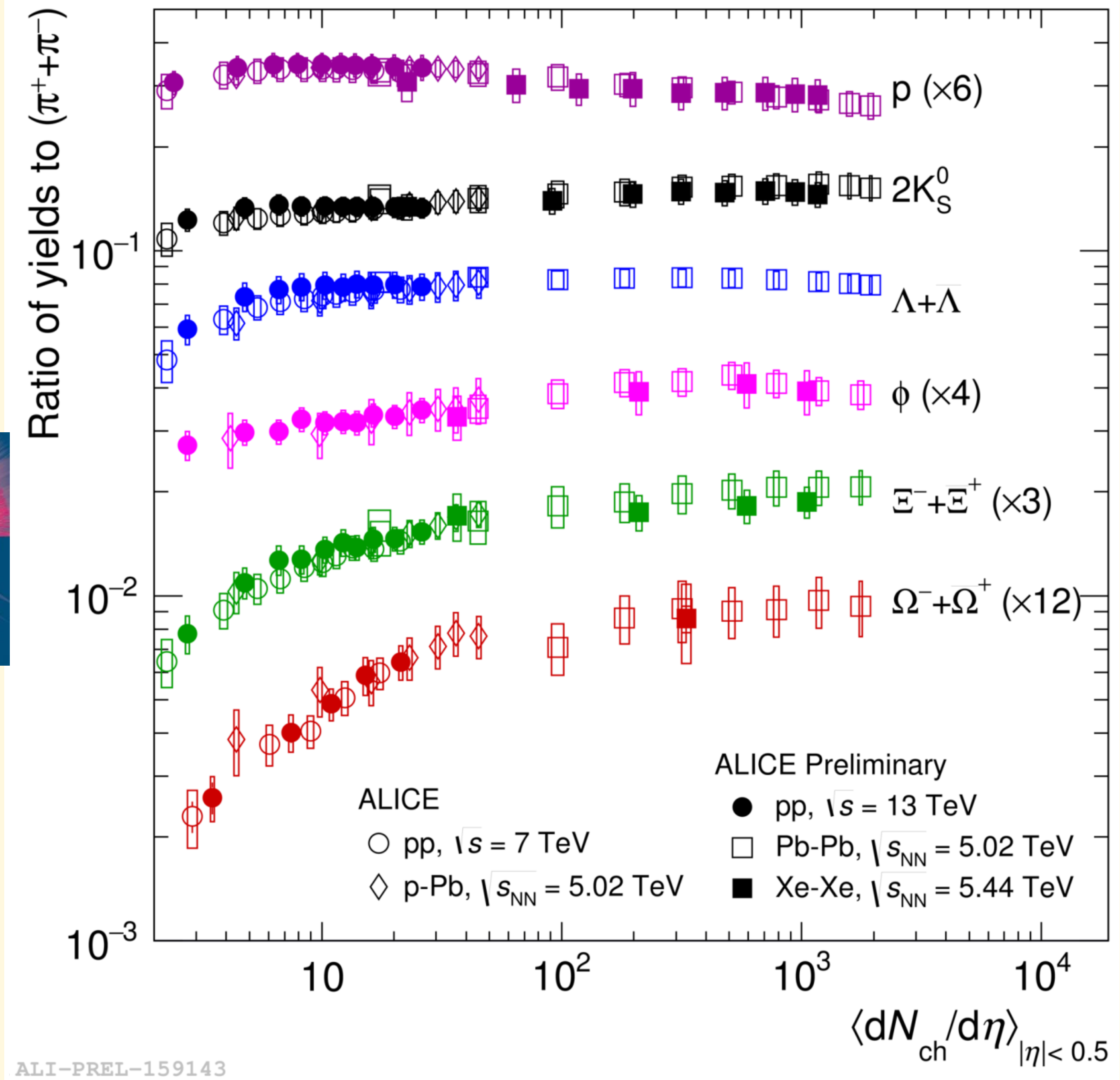
Ordinary nuclear matter is composed of *u*, *d* quarks. Strange quarks are produced in the collision

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



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



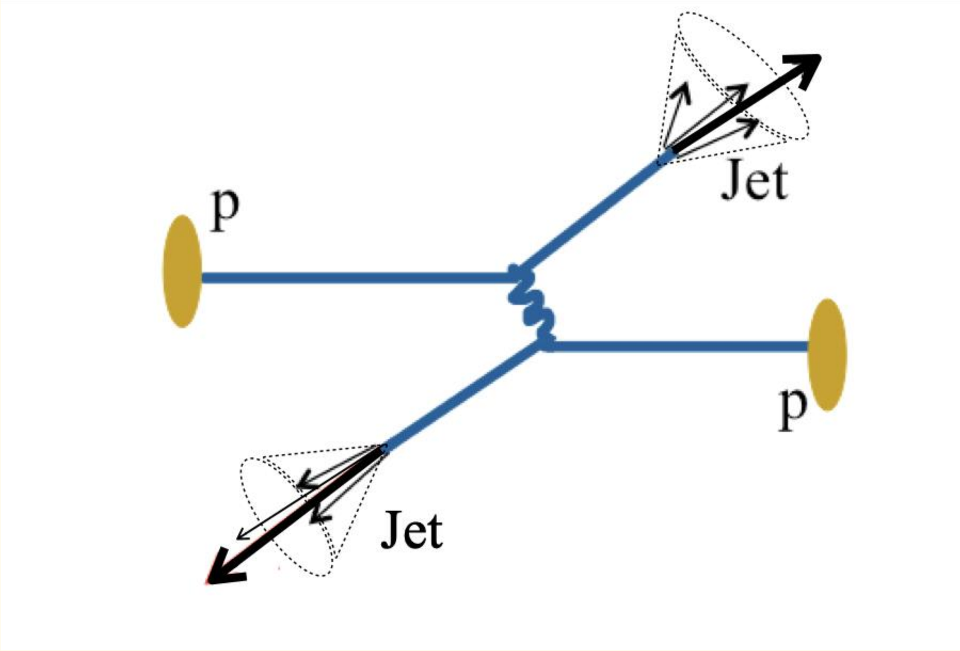


S = 0
S = 1
S = 1
S = 0
S = 2
S = 3

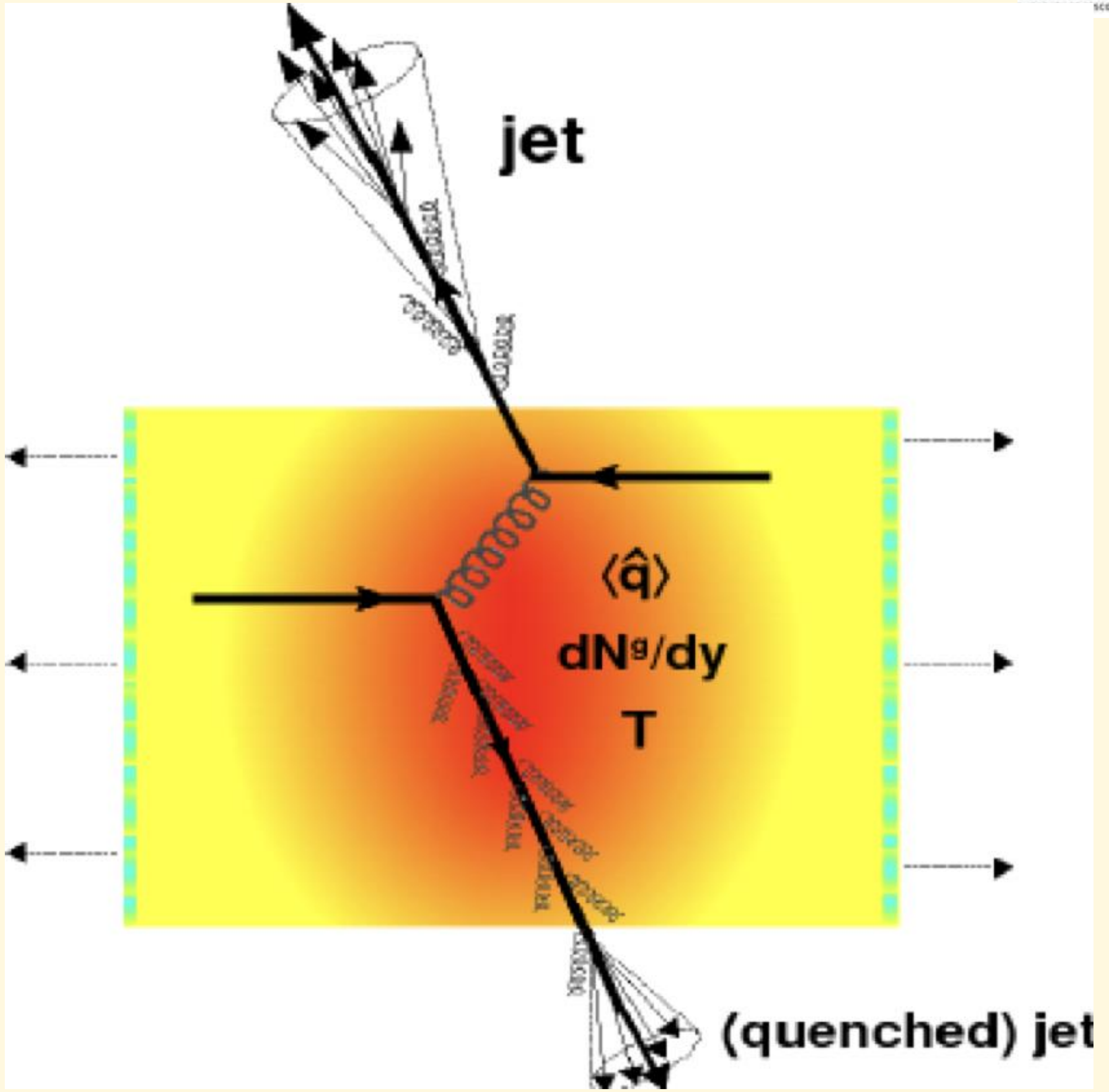
The enhanced production of strangeness relative to u and d quarks => formation of QGP matter.

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)

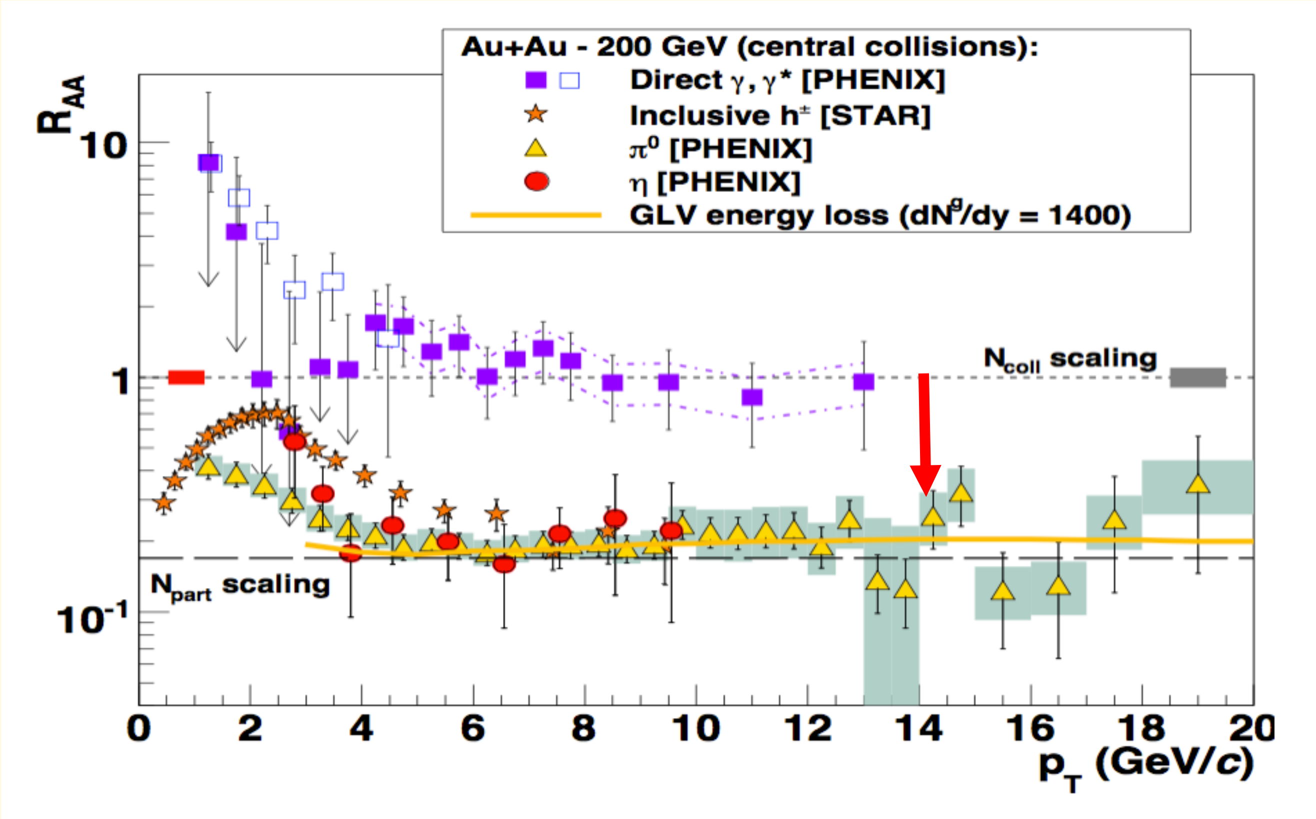
Evidence of Jet-quenching

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

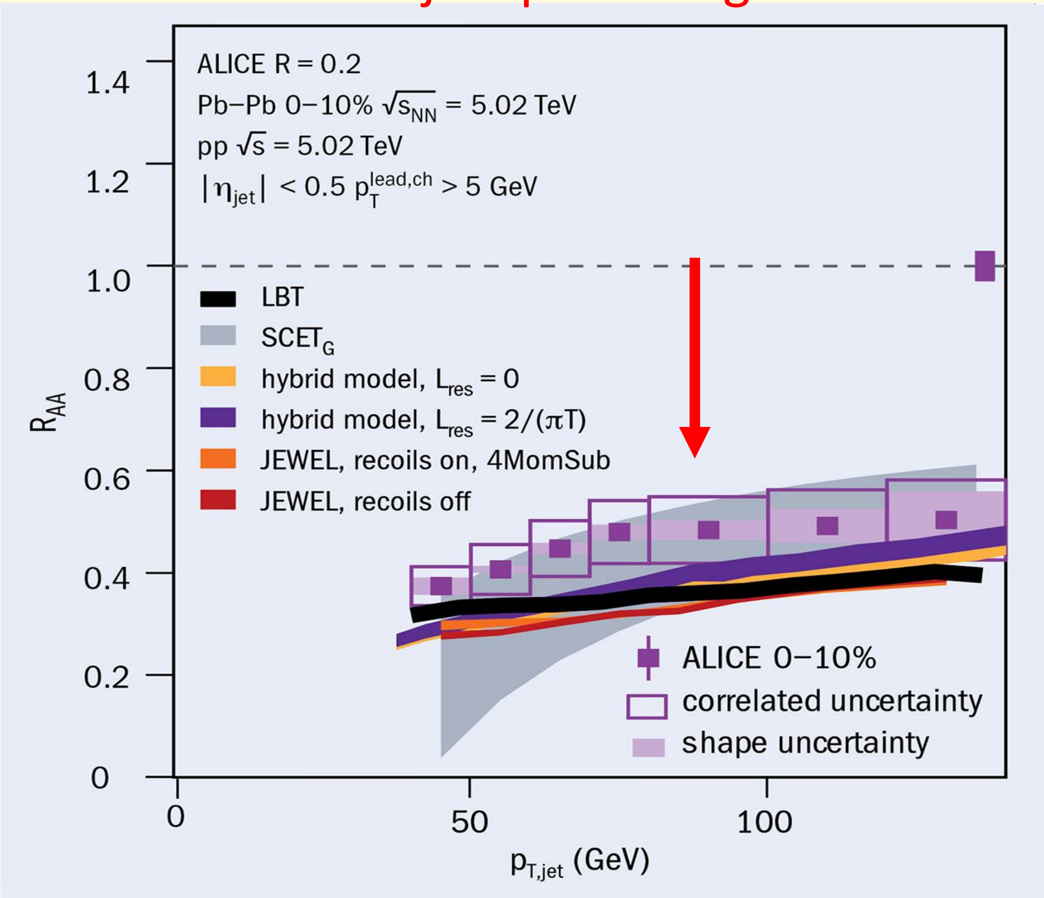
$R_{AA} = 1$: No jet suppression jet-quenching

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

First evidence of jet-quenching at RHIC



Confirmation of jet-quenching at LHC



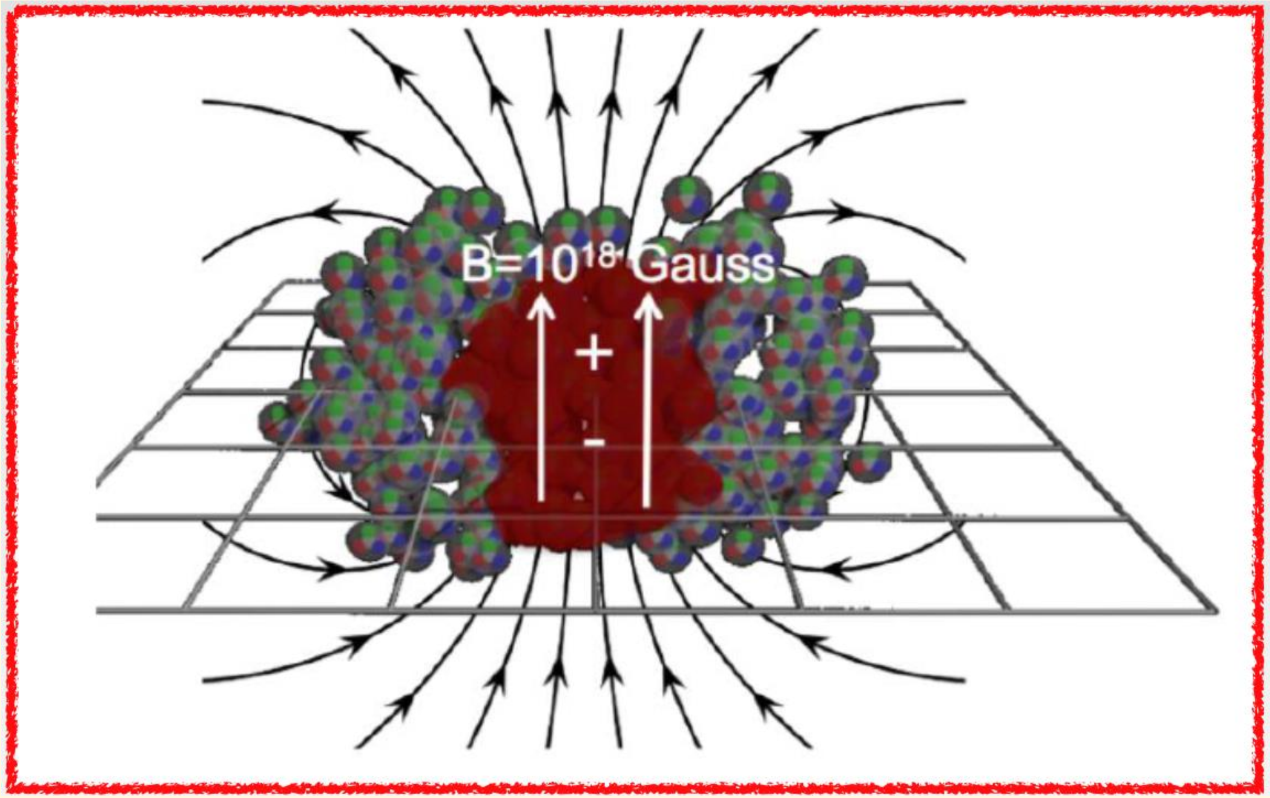
ALICE Collab. 2020 *Phys. Rev. C* **101** 034911.

Jet-quenching => QGP formation

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.

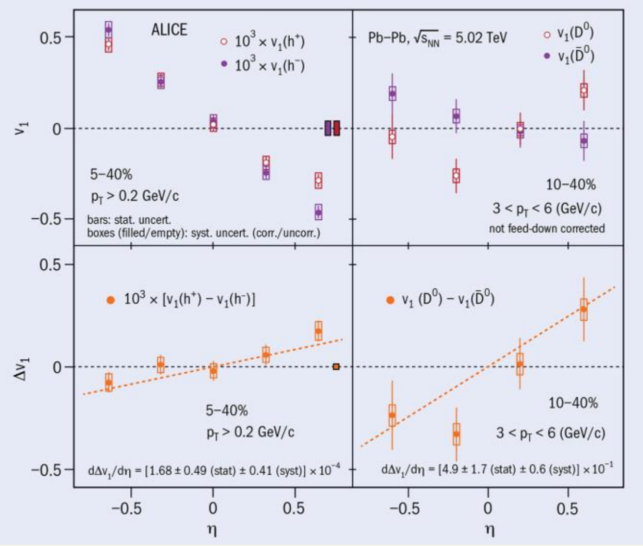
Earth's magnetic field: 10^{-5} Tesla.
LHC magnets: 8.3 Tesla
Magnestar (type of neutron star): 10^{10} Tesla



Probing the extreme electromagnetic fields:

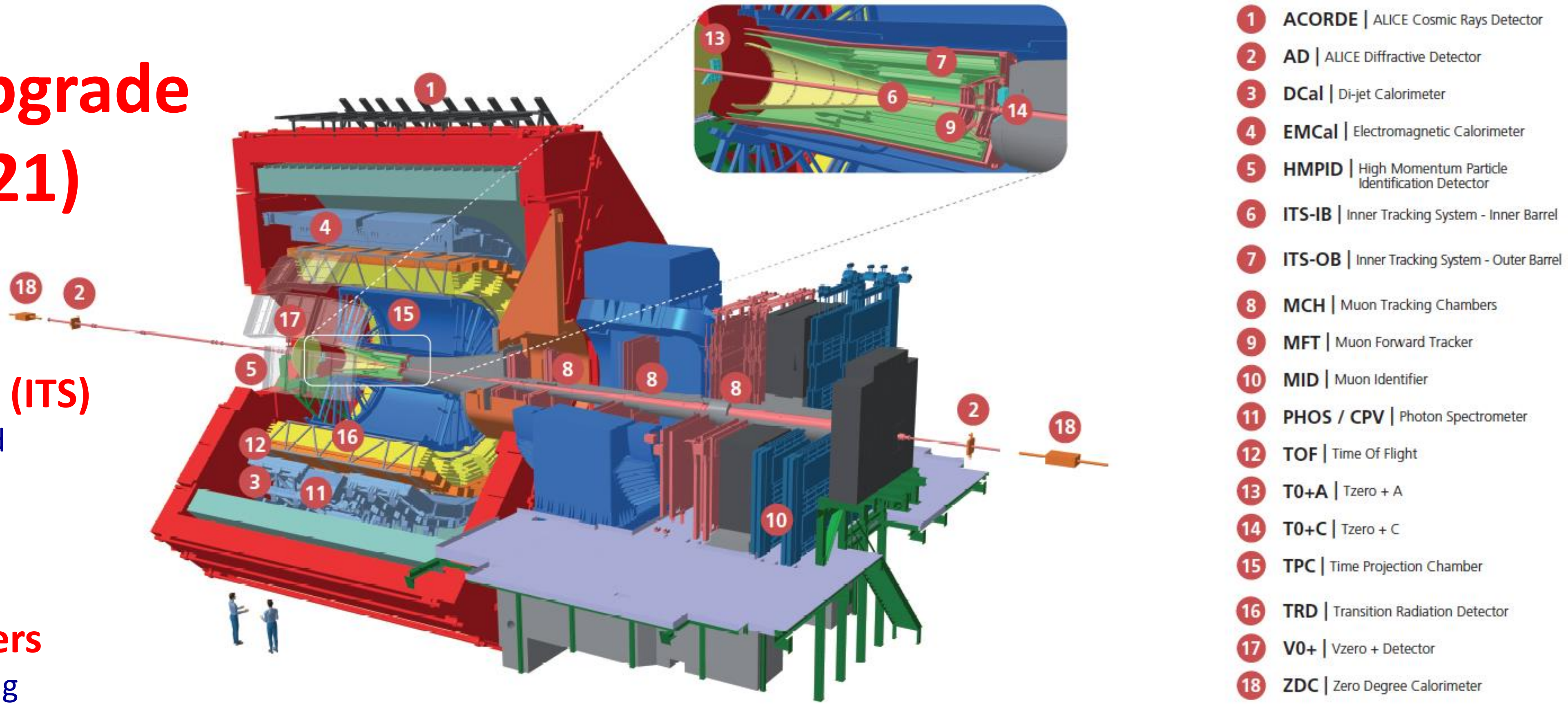
The strong magnetic field affects the evolution of the QGP. Chiral phenomena such as the chiral magnetic effect gets induced by the strong fields.

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



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

ALICE LS2 Upgrade (2019-2021)



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

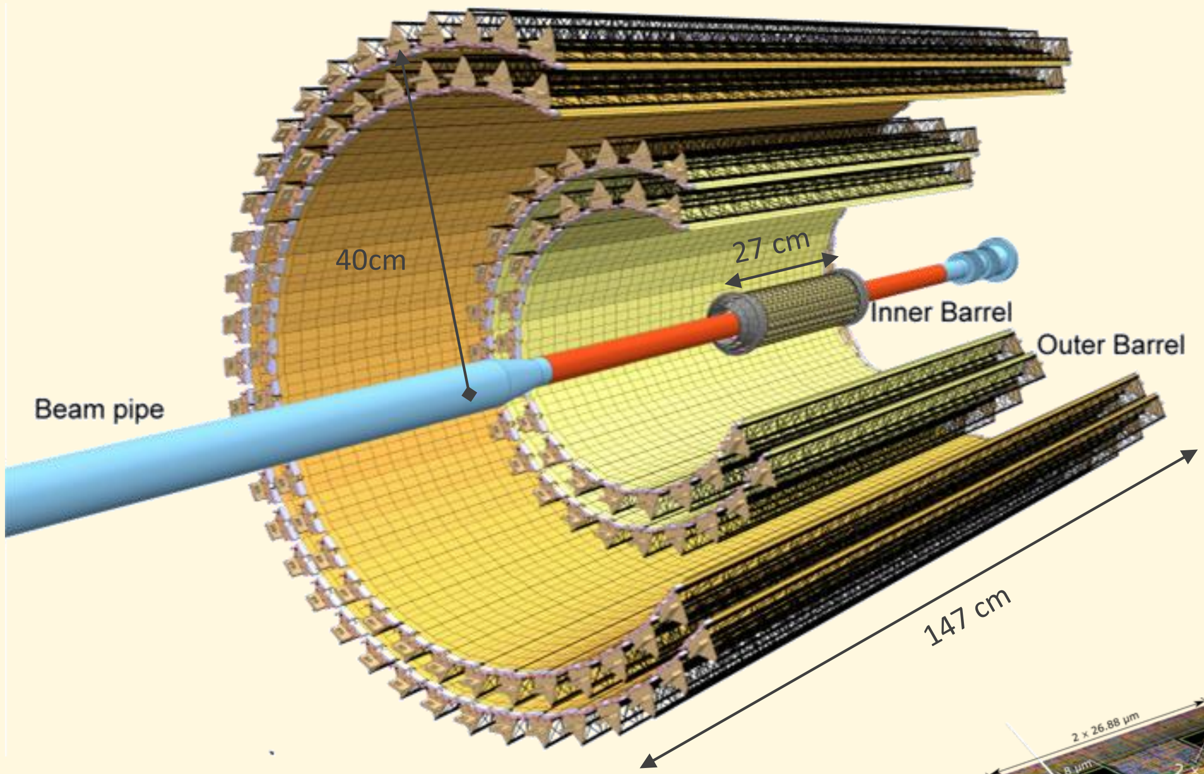
New Trigger Detectors (FIT, AD)

- + centrality, event plane

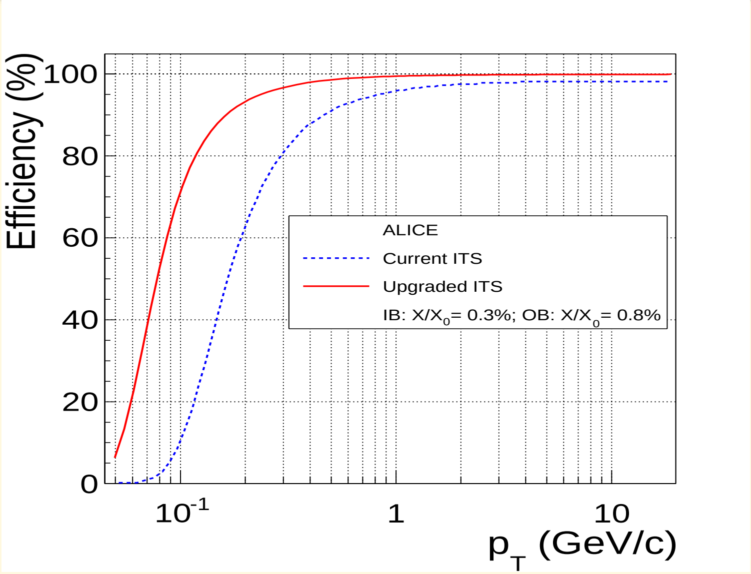
New Central Trigger Processor (CTP)

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

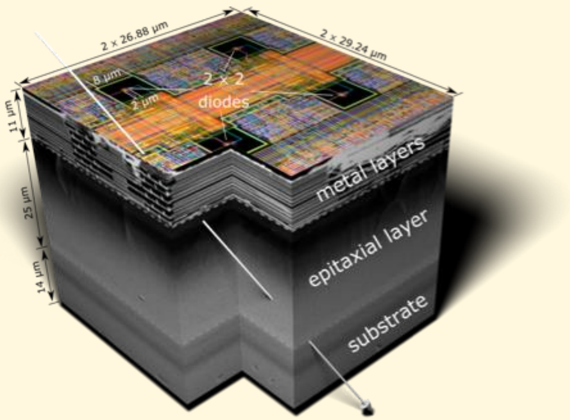
ITS Upgrade



- 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

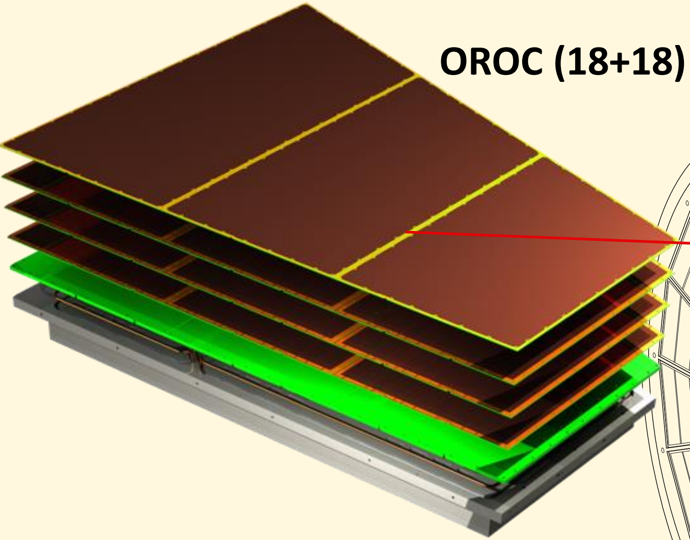


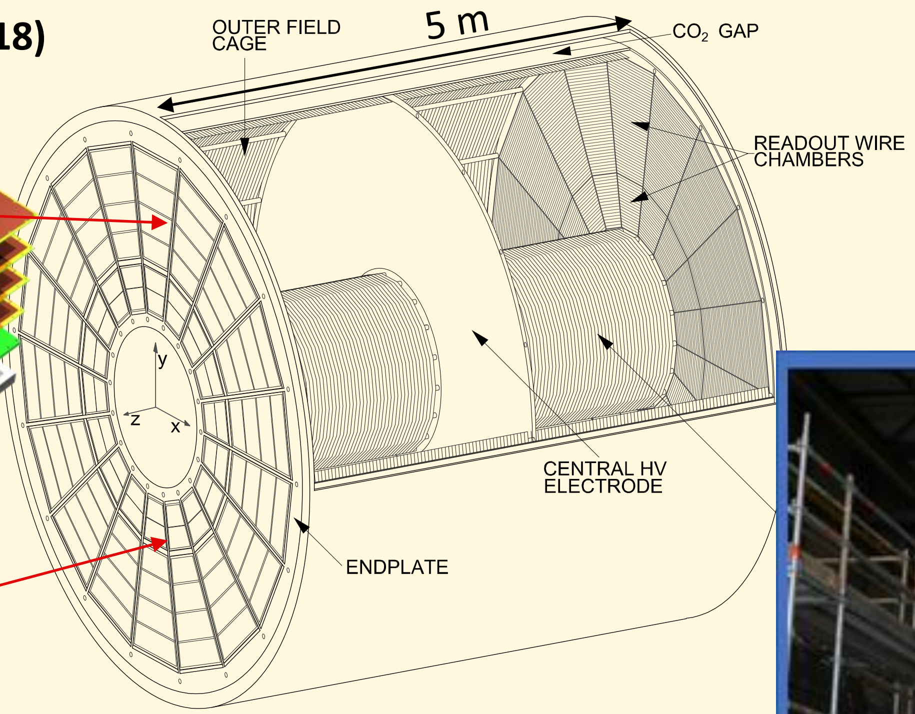
Based on CMOS Monolithic Active Pixel Sensors (MAPS)

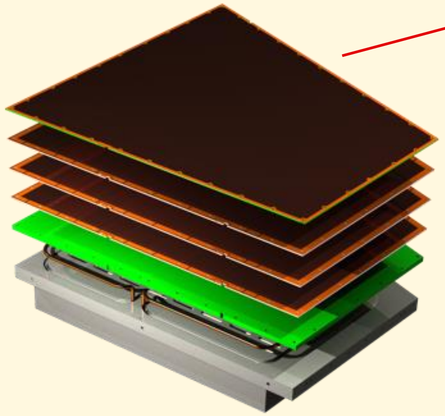


TPC Upgrade with GEMs

OROC (18+18)







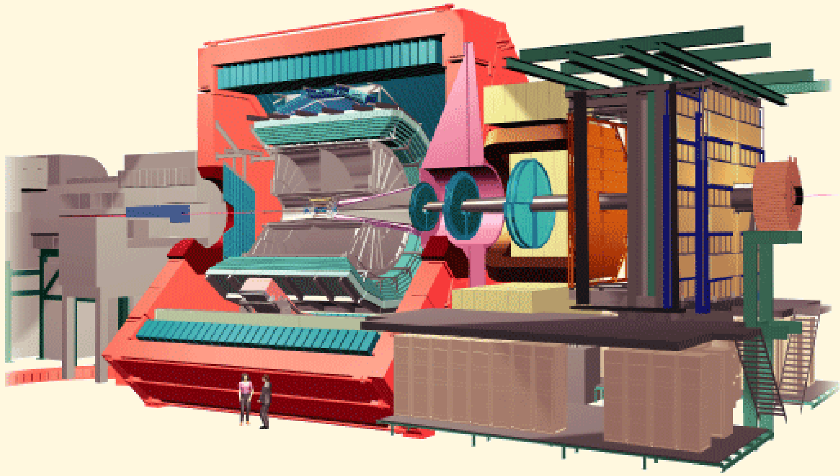
IROC (18+18)

Time Projection Chamber (TPC)

Read-out Architecture

	Before LS2	RUN3
Luminosity	10^{27} cm^{-2} s^{-1}	**6 x 10^{27} cm^{-2} s^{-1}**
Collision rate	8 kHz (PbPb)	**50 kHz (PbPb)**
Max Readout rate	500 Hz (PbPb)	**PbPb: 50 kHz** **pp & pPb: 200 kHz**

- Several detectors will have continuous readout to address pileup and avoid trigger-generated dead-time.
- Online/Offline (O2) Facility: to reduce recorded data volume by doing the online reconstruction.
- Common Readout Unit (CRU) of O2: tasked to perform data concentration, reconstruction and multiplexing.



50 kHz (70 MB/event)
3.3 TB/s

Online
Offline
(O2)

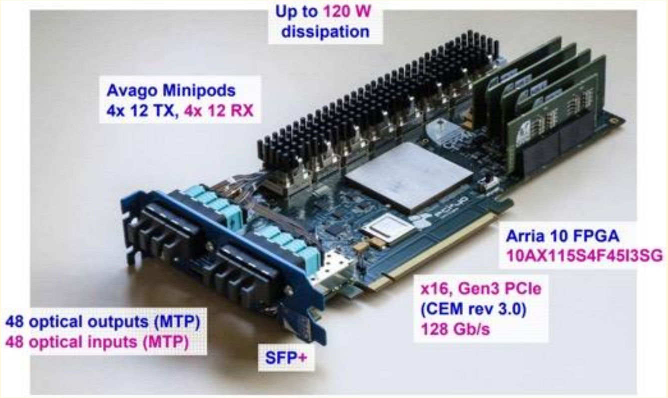
CRU

50 kHz (1.5 MB/event)

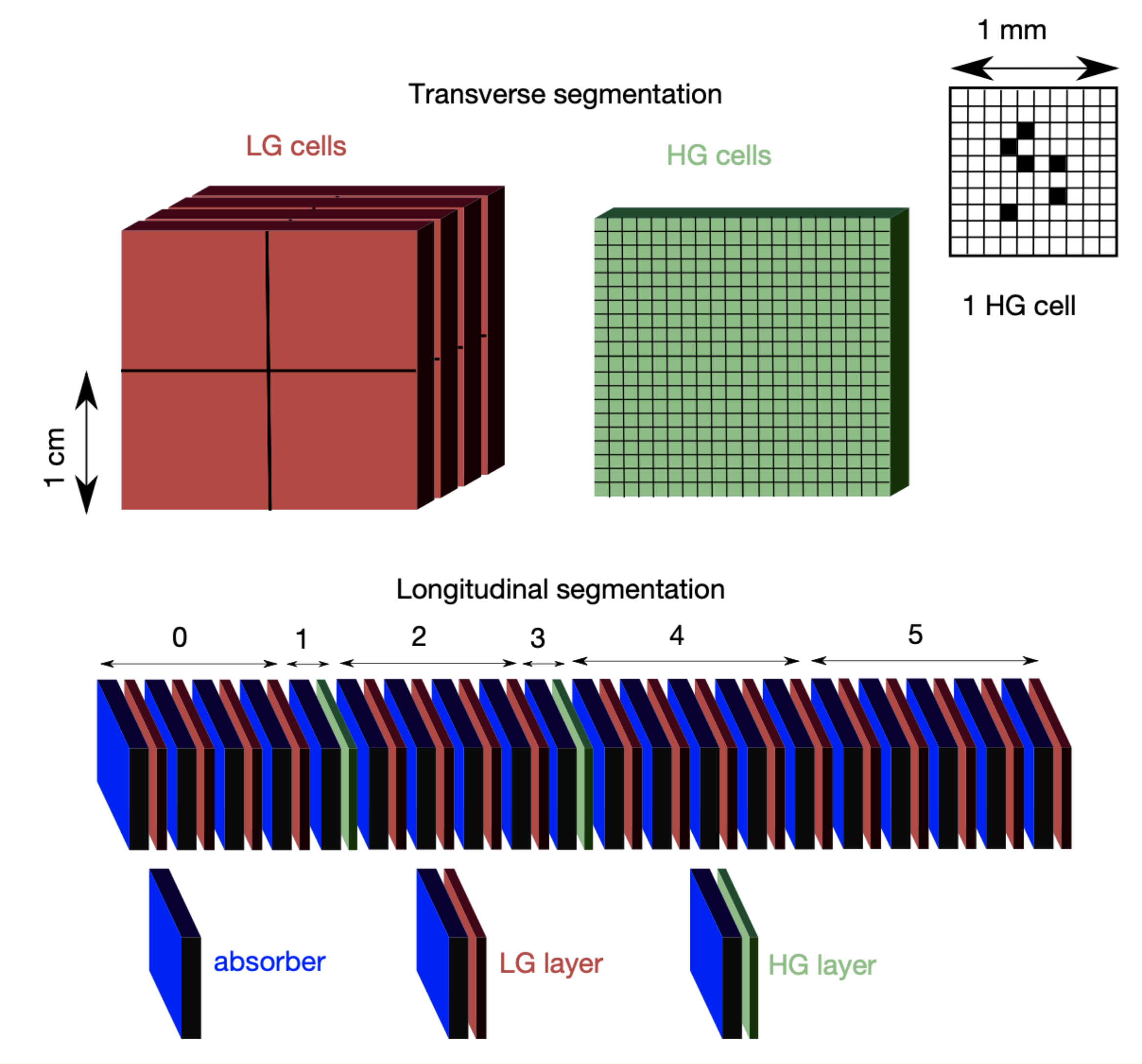
Storage

90 GB/s (peak)

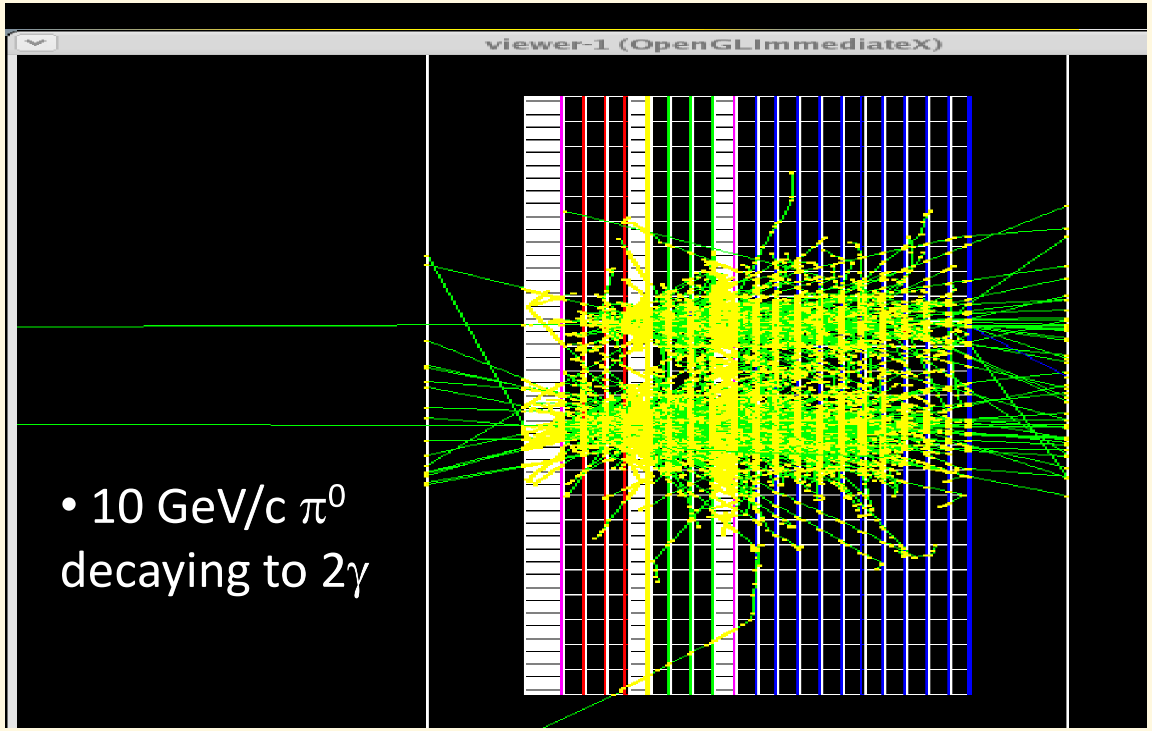
CRU FPGA Board:



A Forward Calorimeter (FoCal)



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

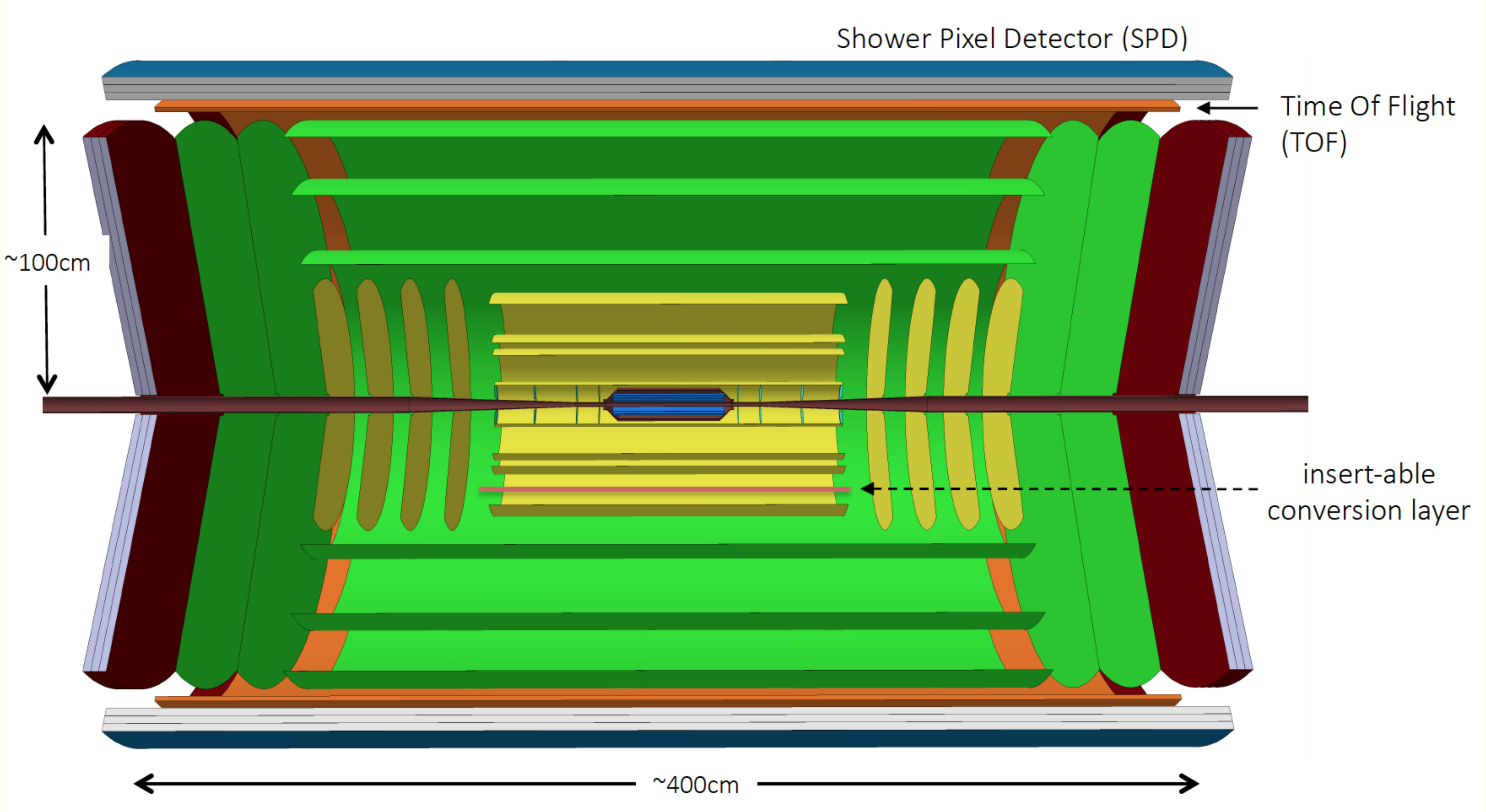


Large Hadron Collider: Timeline (tentative)

From 2040: FUTURE CIRCULAR COLLIDER

A "New ALICE 3" from LHC Run-5 (2032 ..)

https://arxiv.org/abs/1902.01211



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

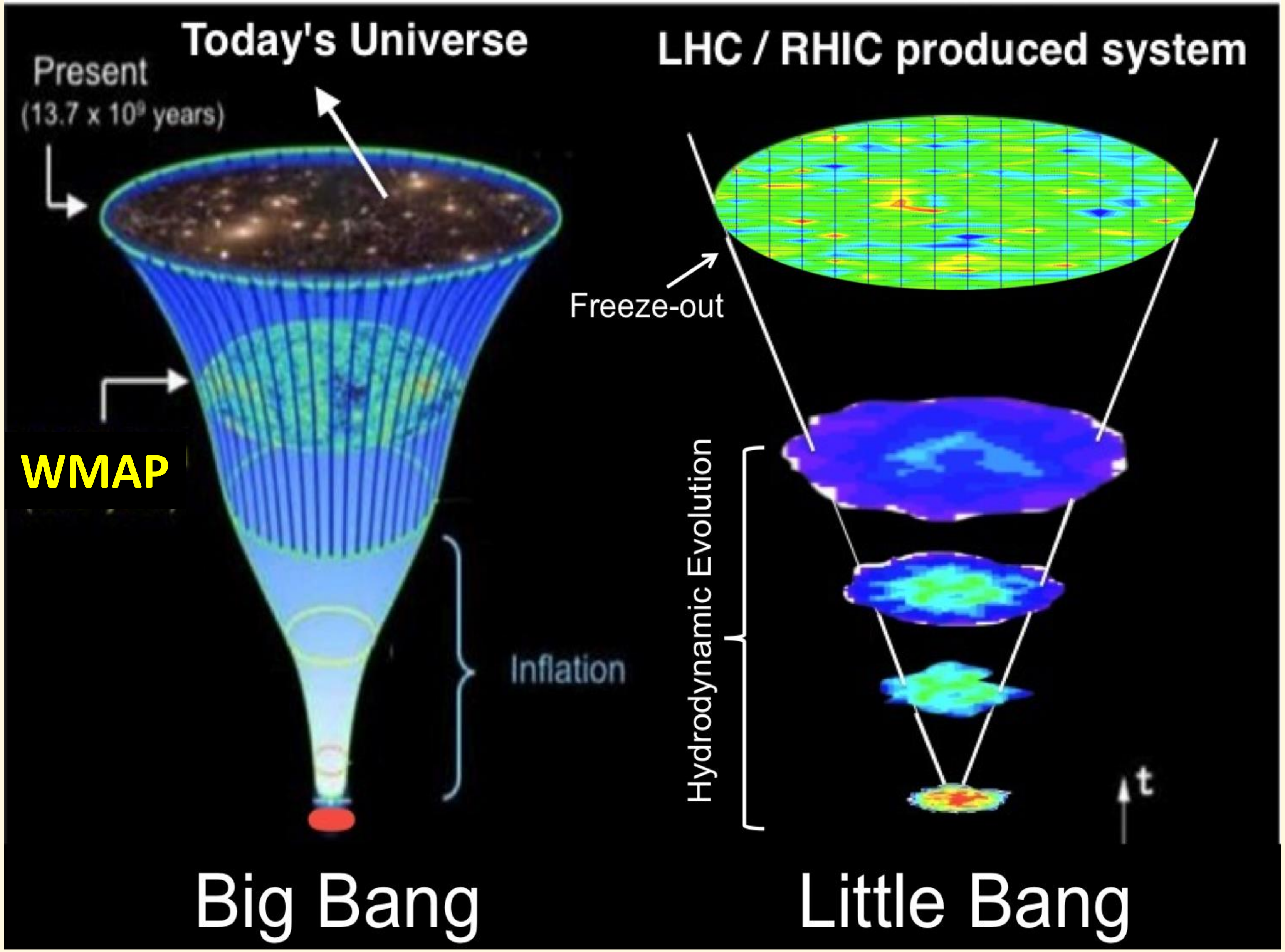
CMOS imaging technologies: high-precision spatial and time resolution

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

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