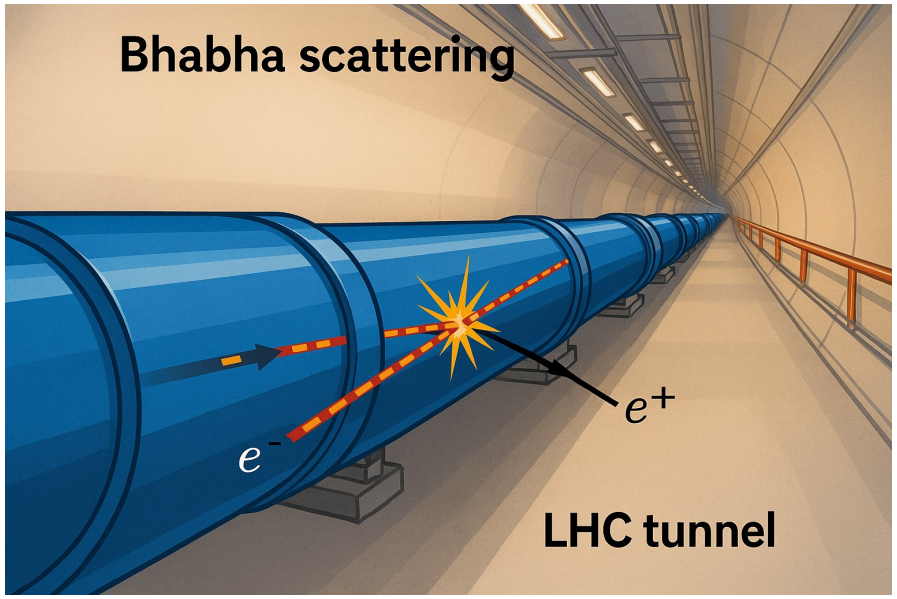
Recreating microsecond old universe conditions in the laboratory - science and societal benefits

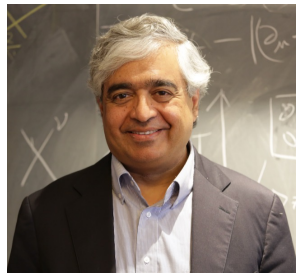
Bedanga Mohanty

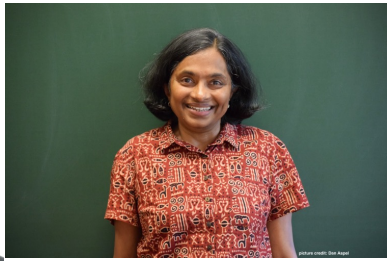
12th Annual Homi Bhabha Memorial Public Lecture

IISER Pune, 7th November 2025

Homi Bhabha Lecture

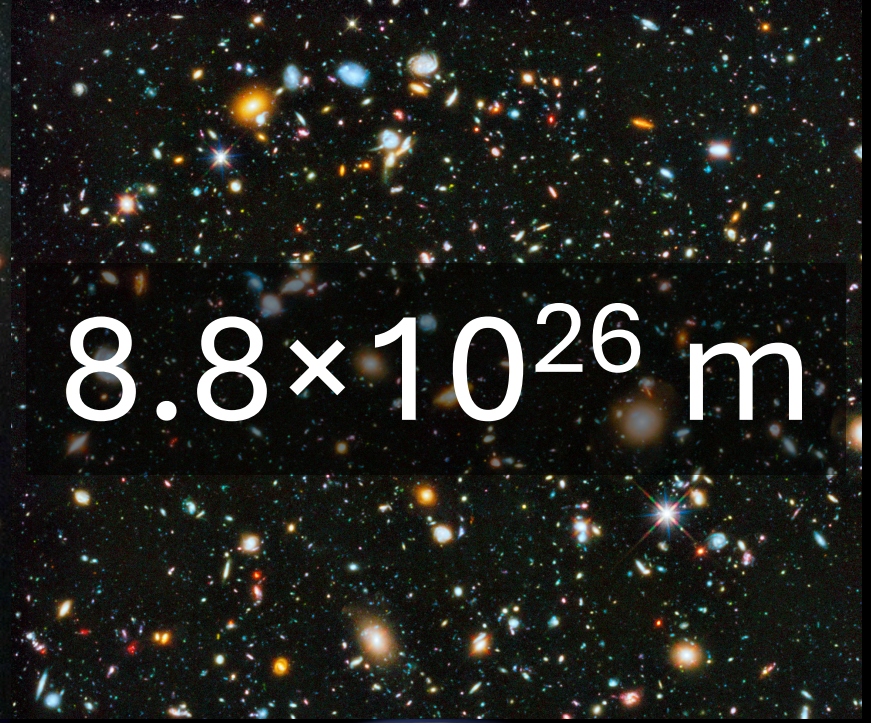




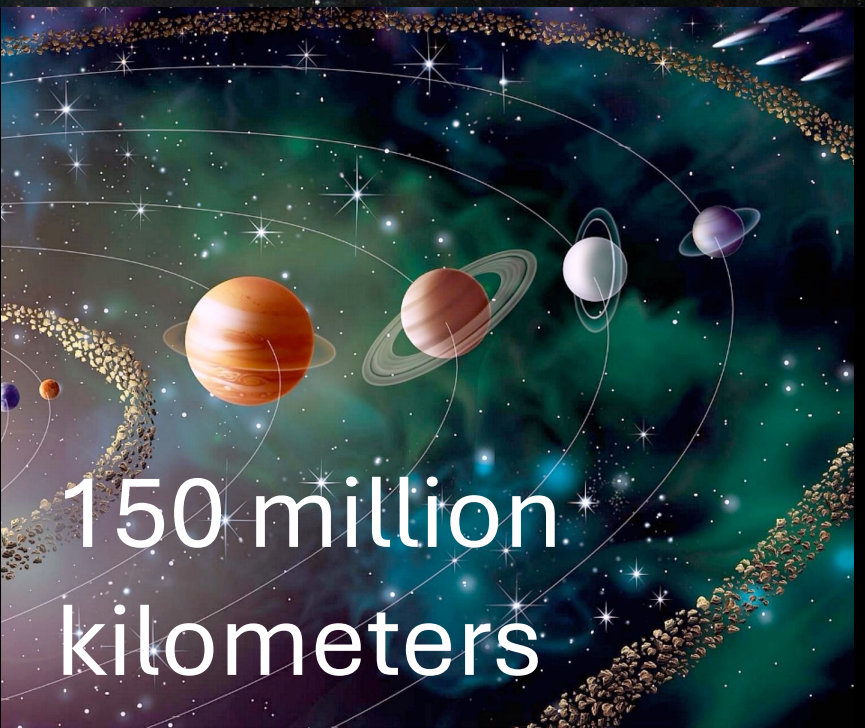


Context	LHC Process	Relation to Bhabha Scattering	Purpose
LEP (historical)	$e^+e^- \to e^+e^-$	Original Bhabha process	Luminosity calibration
LHC UPCs	$\gamma\gamma \to e^+e^-$	Crossing-symmetric to Bhabha	QED tests, luminosity
pp collisions	QED/EW lepton pair production	Includes same diagrams	Background modelling
Simulation frameworks	Matrix element libraries	Derived from Bhabha QED vertex	Event generation

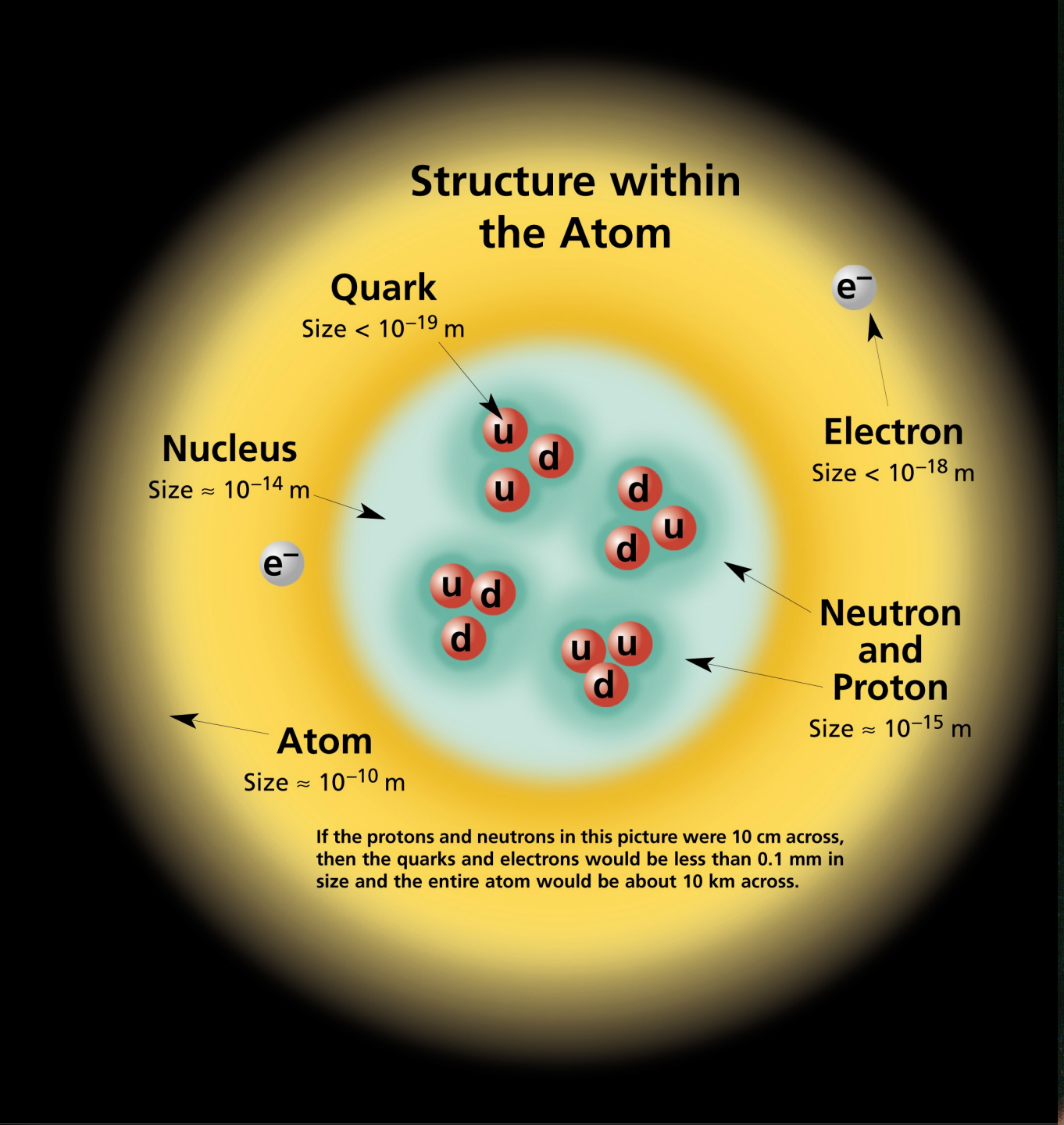
Honored to deliver this year's lecture



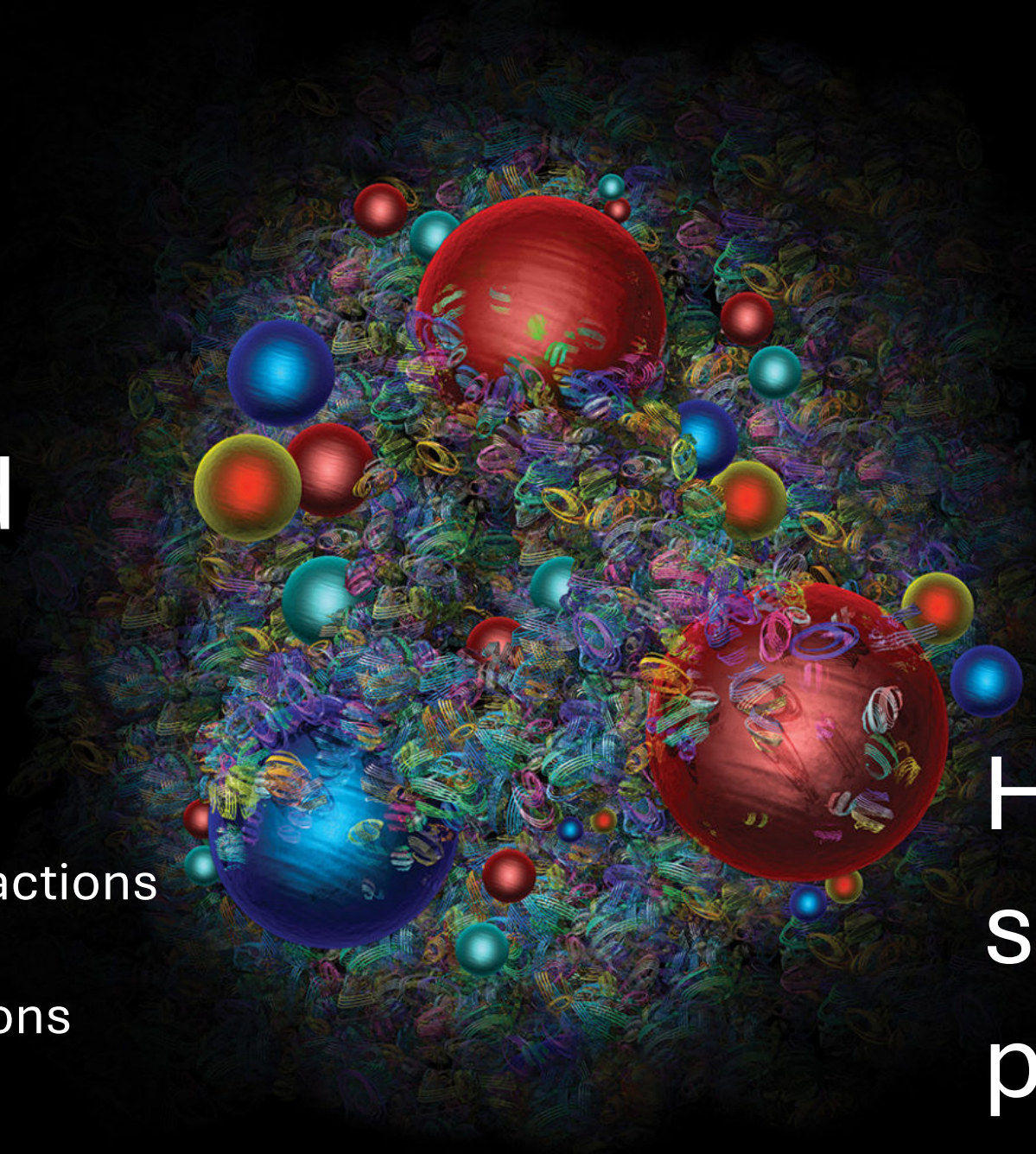
Universe is Big !



What are the basic building blocks ?


Structure within the Atom
Quark
Size < 10^{-19} m
e^-
Electron
Size < 10^{-18} m
Nucleus
Size ≈ 10^{-14} m
u
d
u
d
d
u
e^-
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Building blocks: electrons, quarks and gluons



No free quarks and gluons in nature

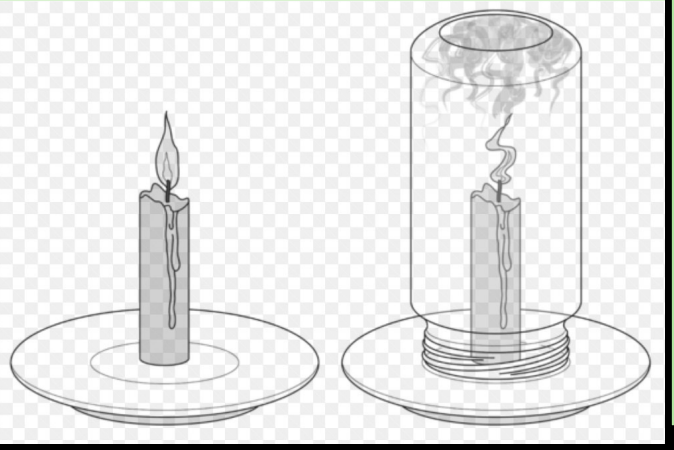
Strong interactions
Electromagnetic interactions
Weak interactions
Gravitational interactions

How to study the properties ?

CERN: A graphic impression and gluons inside the proton

Hydrogen burns

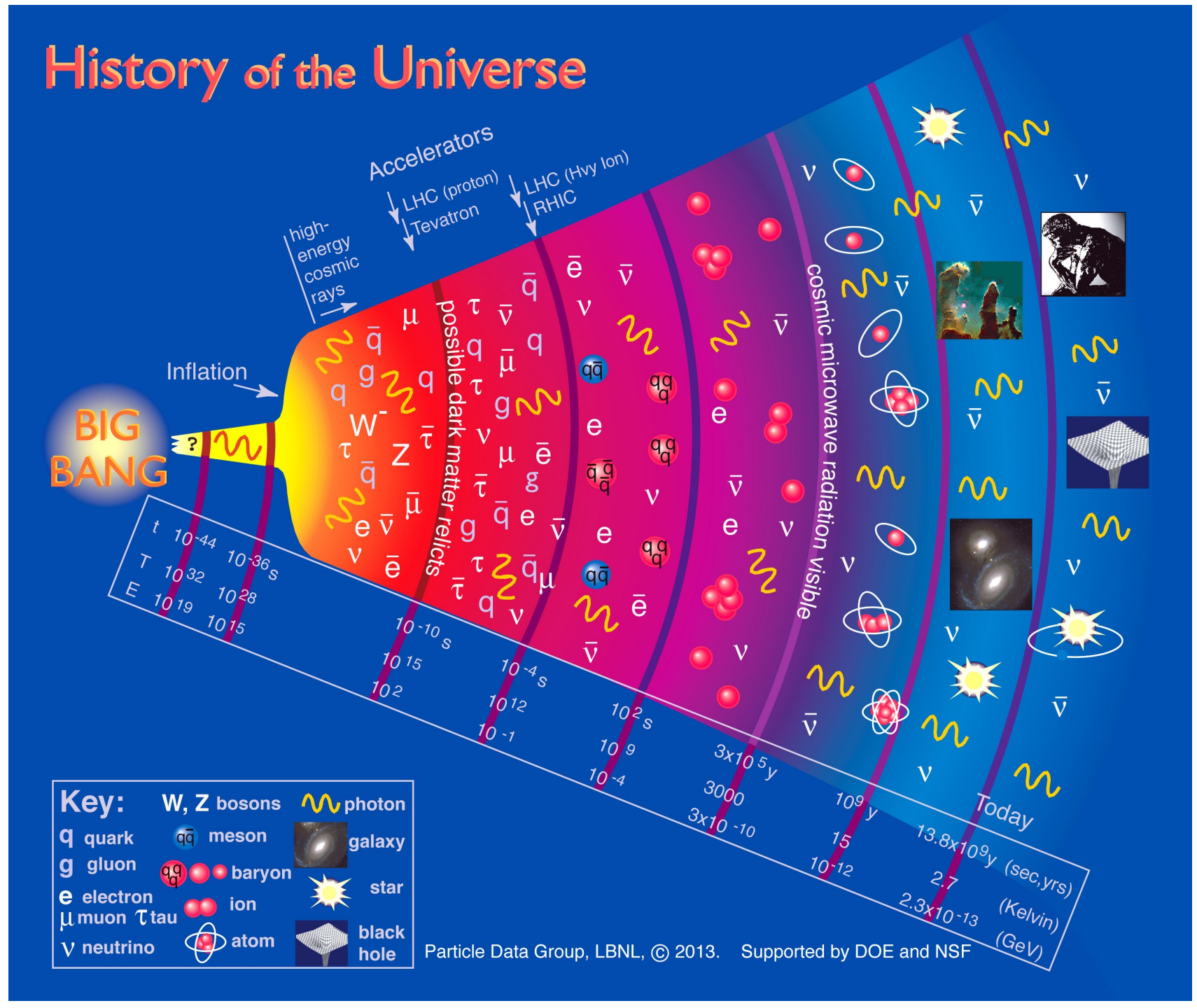
Oxygen supports burning

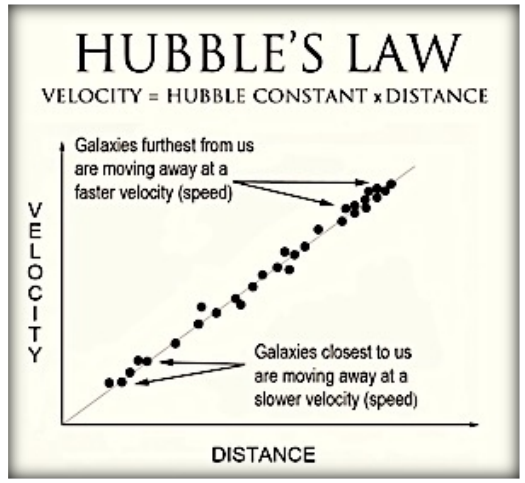


Free system of quarks and gluons needed to study properties.

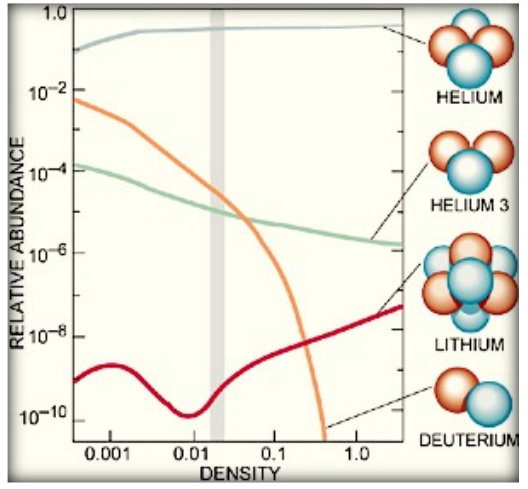
Were quarks and gluons ever free?

Big Bang Model

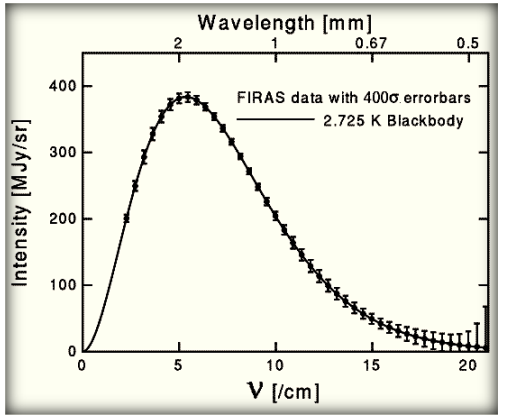




Expanding Universe

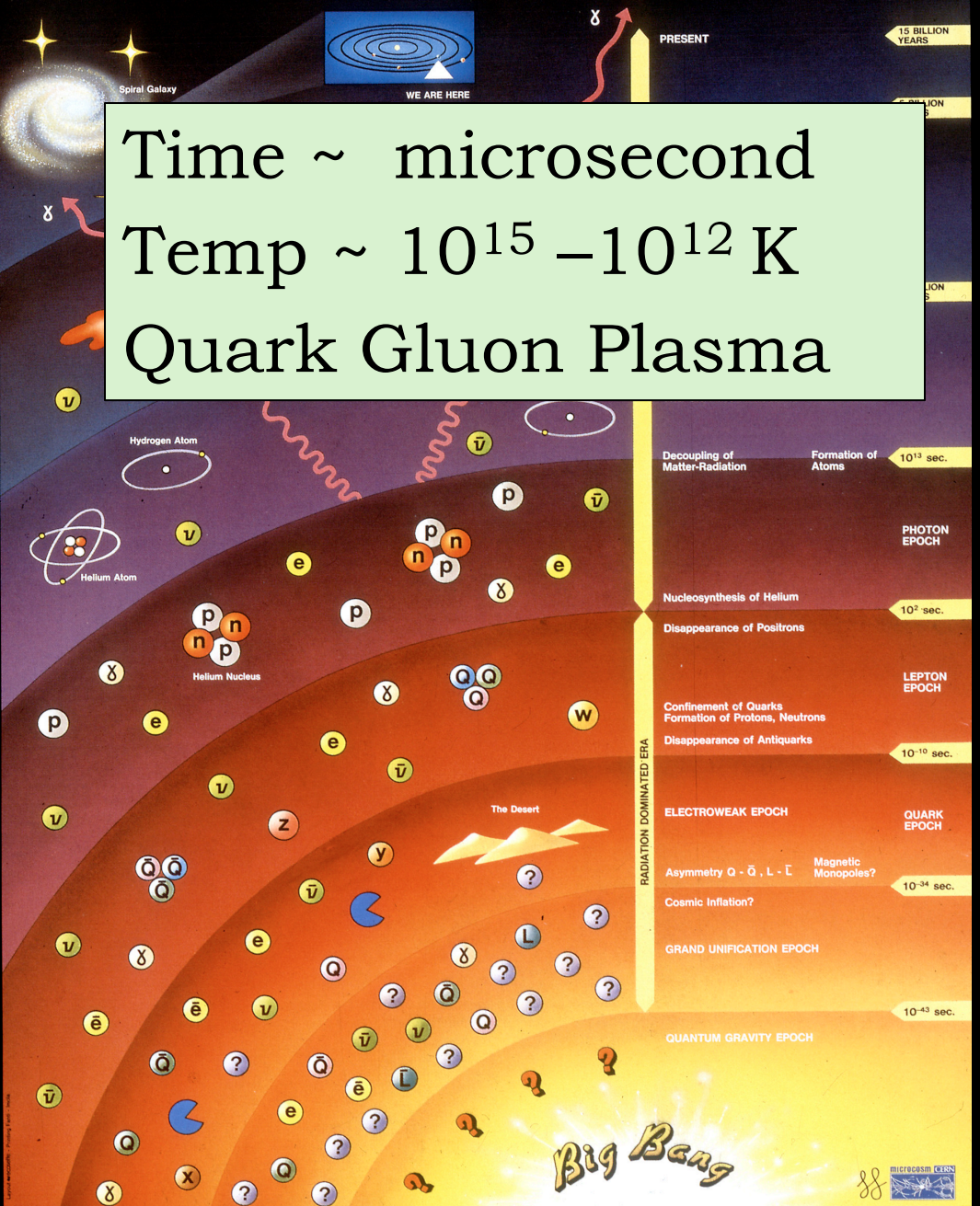


Nuclei Abundances



CMBR

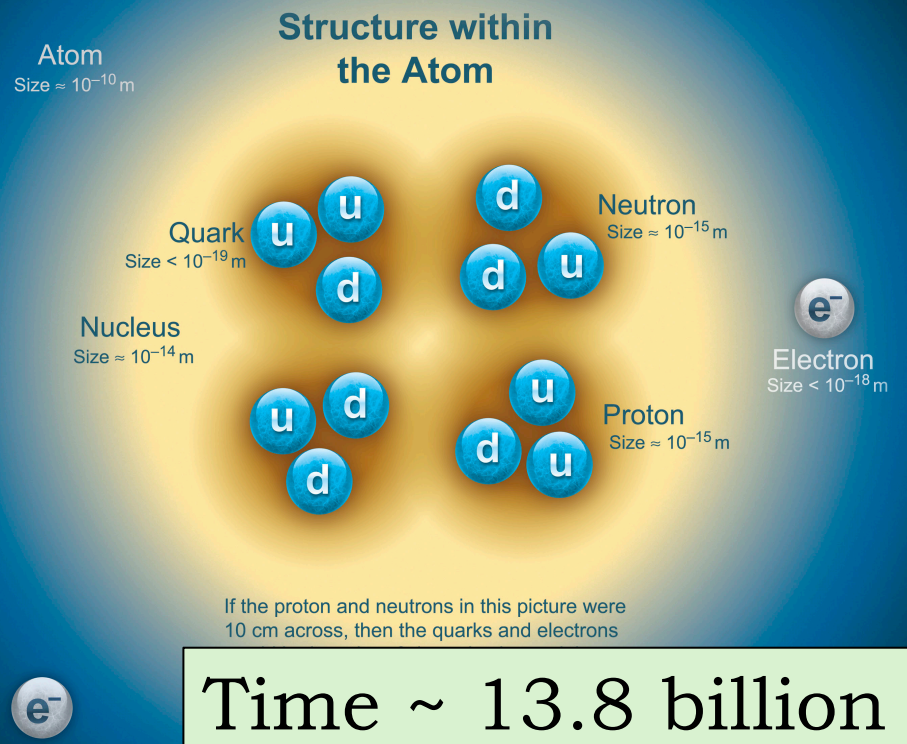
History of the Universe



Time ~ microsecond

Temp ~ 10^{15} –10^{12} K

Quark Gluon Plasma



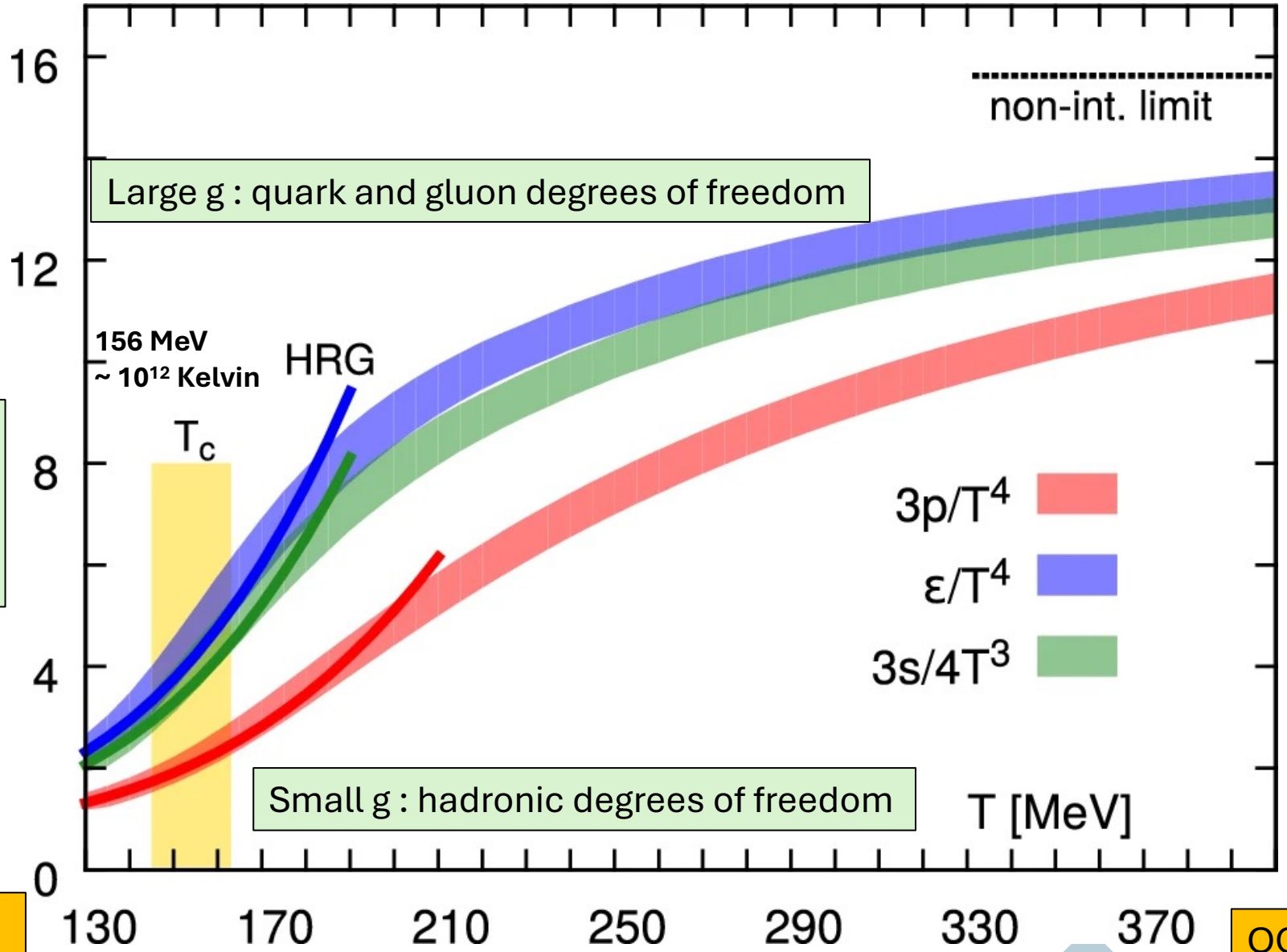
Time ~ 13.8 billion years

Temperature ~ 2.7 K

Quarks confined

No free quarks in nature

$$\varepsilon = g\frac{\pi^2}{30}T^4$$



Theory: QCD

Hadronic Phase (confined)

QGP Phase (deconfined)

HotQCD Collaboration: Phys. Rev. D 90, 094503 (2014)

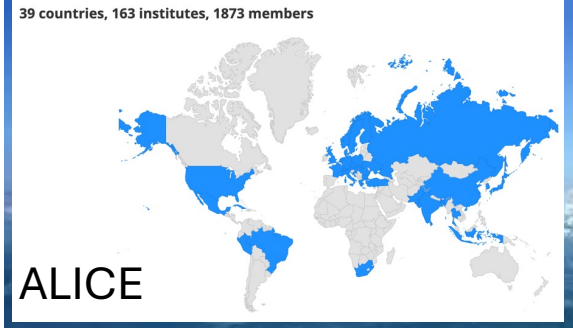
STAR is composed of 75 institutes from 14 countries, with a total of 731 collaborators.

World map with STAR institutions marked - Blue = STAR institutions (council seat), violet = affialated institutes

https://www.bnl.gov/rhic/

RELATIVISTIC HEAVY ION COLLIDER

https://home.web.cern.ch/science/accelerators/large-hadron-collider



LARGE HADRON COLLIDER

Goal # 1 : Reach temperatures ~ **10^{12} Kelvin** mimicking the early Universe conditions.
Goal # 2 : Form a **free system of quarks and gluons** – fundamental constituents of visible matter.
Goal # 3 : Study the **properties of quarks and gluons -** the building blocks of matter.

Indian contributions to LHC activities

Accelerator and Computing

Corrector Magnets (616 MCDO & 1146 MCS)

Quench Heater Power Supply (QHPS) HDS units 5500

Local protection units (LPU) 1435

Figure 2: Dipole magnet (red) and dipole vacuum chamber installed in TL2 at CERN

Precision Magnet Positioning System PMPS 7080

- Expert support for SC Dipole magnet measurements 100 Man years
- Support for LHC hardware commissioning 20 Man years. (16 Man years completed)

High voltage test set-up for nQHPS

nQPSRacks ready for installation

Determination of excessive frosting in cryogenic subsystem & re-evaluation of safety valve size etc.

Contributions to LINAC 4 project

100kV solid state modulator for LINAC 4 at SM18 hall at CERN. Design, developed and Commissioned by RRCAT.

We received four 1MW klystrons and 1MW circulators ... RF waveguide components for our projects on SNS/RRCAT and ADS/ LEHIPA at ... CERN klystron and ... at 1MW peak power ... RRCAT.

Two Cu coated SS WR 2300 waveguide power ... developed by ... were installed in ... LINAC 4 tunnel at CERN.

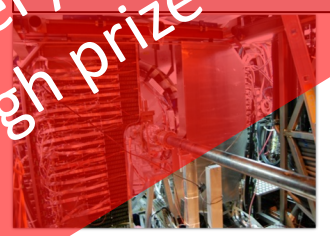
CMS Tier-2 Centre at TIFR, Mumbai

1996 : AEC (Atomic Energy Commission) agrees to take part in the construction of the LHC and to contribute to the CMS and ALICE experiments and to the LHC Computing Grid with Tier-2 centres in Mumbai and Kolkata.

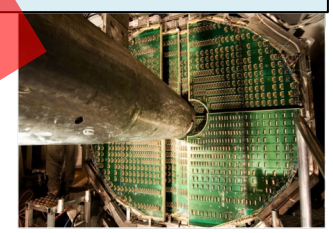
Table 1: Major Indian Contributions to LHC.

	Details of Indian Contributions	Qty
1	50000 litres Liquid Nitrogen tanks.	
2	Superconducting corrector magnets Sextpole (MCS) Decapole and Octupole (MCO)	 1146 616
3	Precision Magnet Positioning System (PMPS) Jacks	7080
4	Quench Heater Power Supplies QHPS	5500
5	Integration of QPS units into racks	6200
6	Control Electronics for circuit breakers of energy extraction system	70
7	Local protection units (LPU)	1435
8	SC Dipole magnet tests/measurements, expert support in Man years	100
9	Manpower for Commissioning LHC Hardware, like, Cryogenics, Controls Power converters, Protection systems.	20 Man years
10	Data management software upgrade, Data analysis software projects.	In all about 41 Man years
11	Development of JMT-II software	
12	Software development-slow control of Industrial Systems of LHC	
13	Design and calculations for Vacuum system for beam dump line	
14	Analysis of cryo-line jumper and magnet connections	

Detectors and electronics



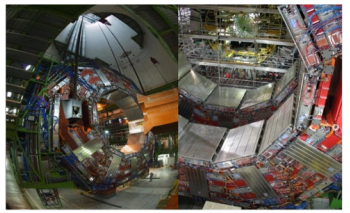
ALICE Photon Multiplicity Detector (PMD)



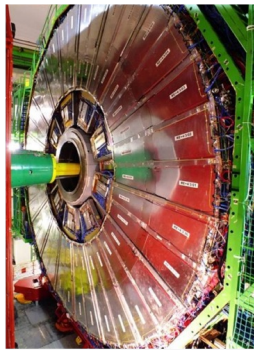
Station-2 of ALICE Muon Spectrometer

MANAS: 16 channel Amplifier, shaper, track and hold for ALICE

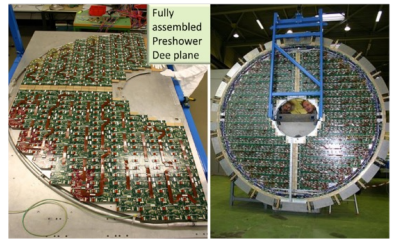
Silicon-Tungsten Calorimeter



CMS: Outer rings of HO



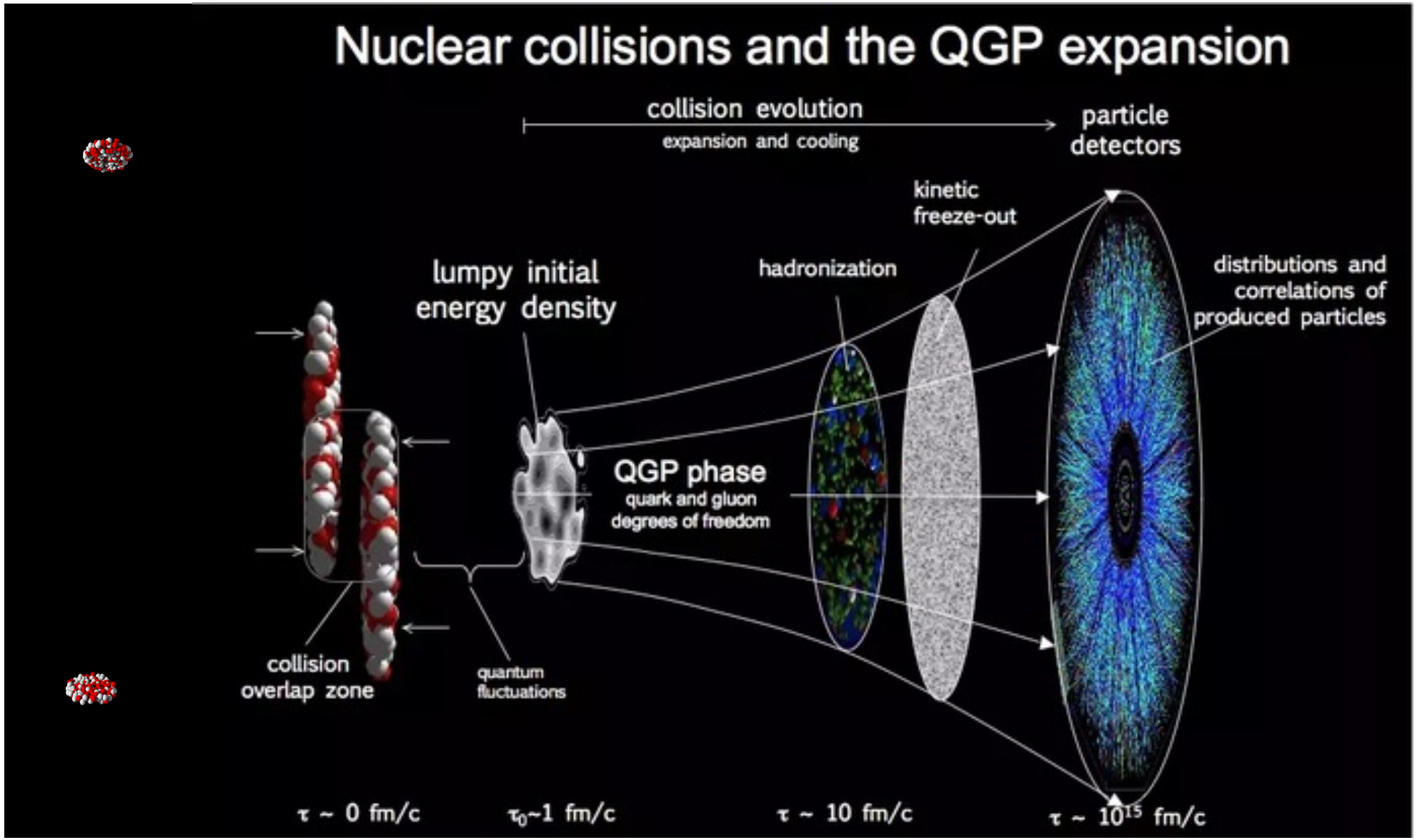
CMS:RPC fully installed



2002: India was granted Observer status to the CERN Council.
2017: India Associate Member.

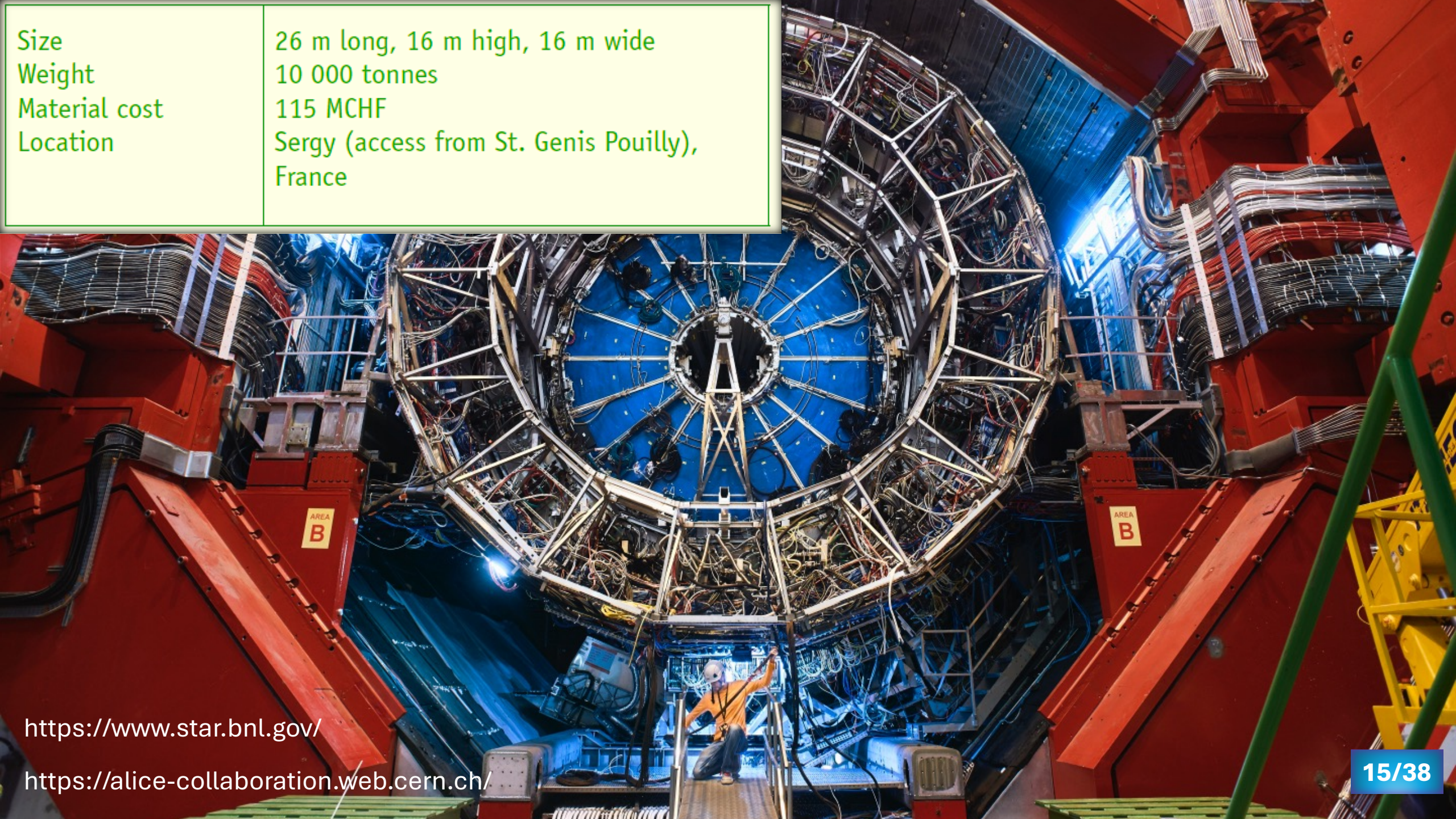
Time for rich science harvest – already one noble prize – discovery of Higgs Boson and all four experiments received the Breakthrough prize in fundamental physics – 2025.

Little Bang Model



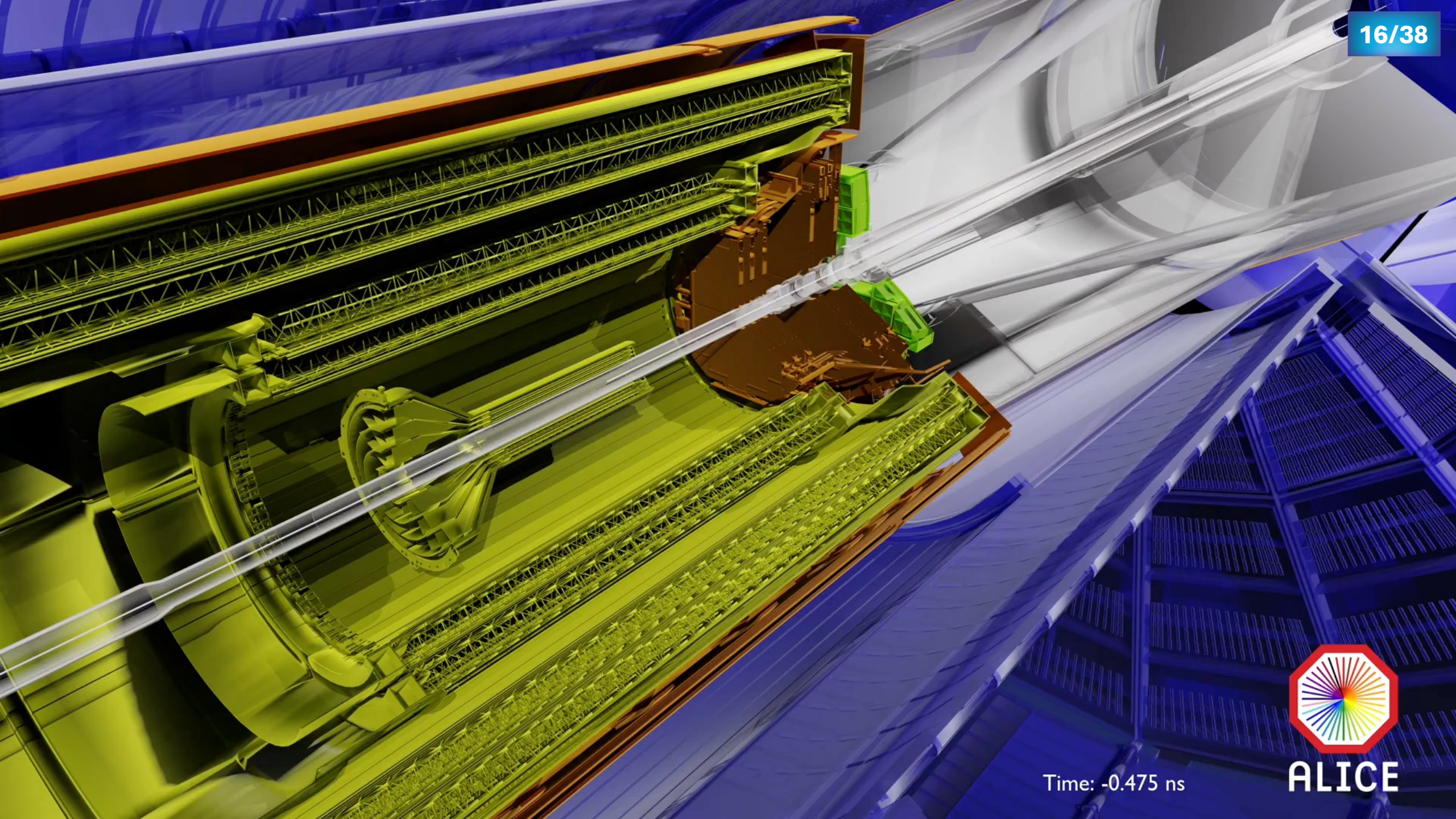
Zepto-scale system

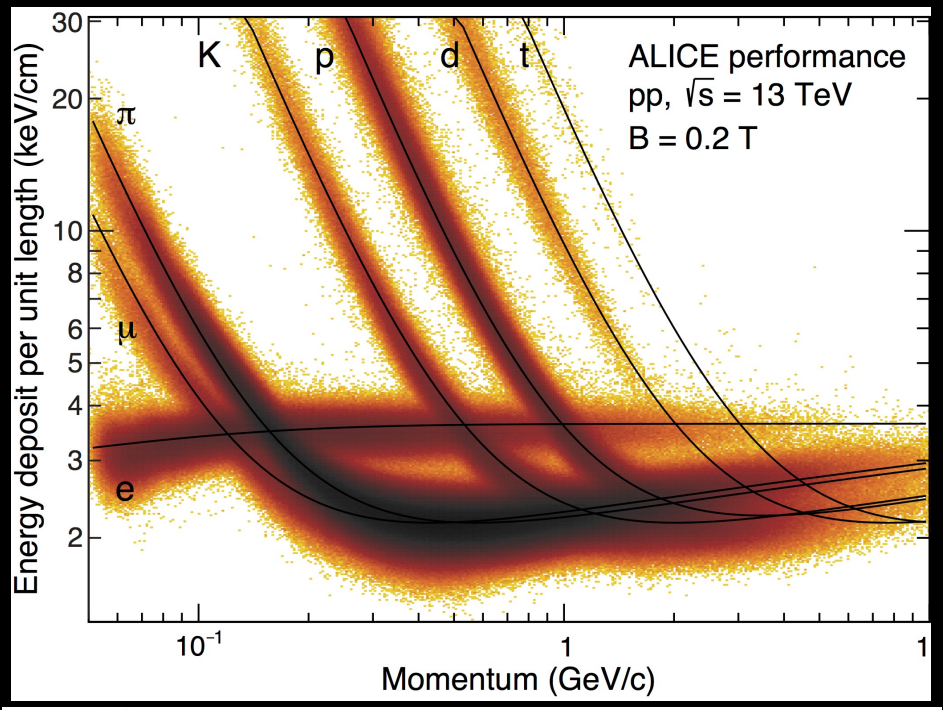
Size	26 m long, 16 m high, 16 m wide
Weight	10 000 tonnes
Material cost	115 MCHF
Location	Sergy (access from St. Genis Pouilly), France

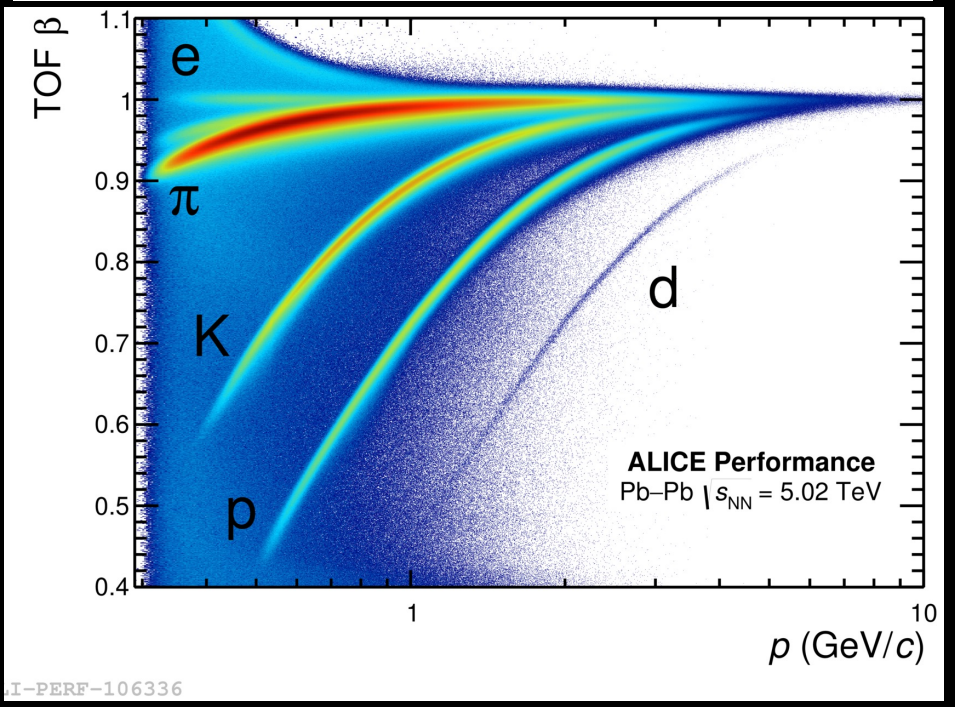


https://www.star.bnl.gov/

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


Time: -0.475 ns
ALICE



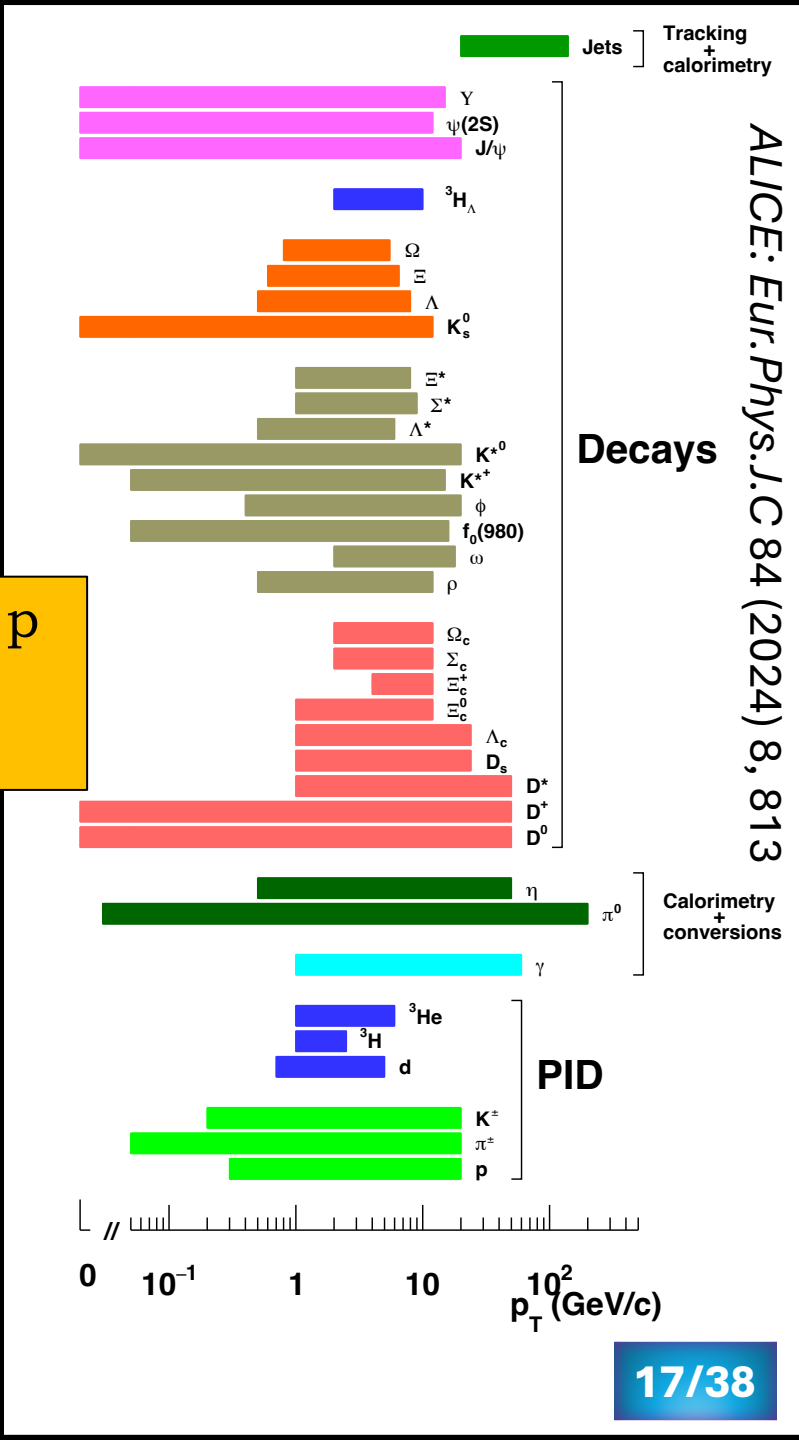


Ionization energy loss:
- $< dE/dx > \sim A / \beta^2$
$= A (1 + m^2/ p^2)$

5 charged particles: e, μ, π, K, p
2 neutral particles: n, γ
Neutrinos undetected

$$m = \sqrt{\left(\sum_i E^i\right)^2 - \left(\sum_i \vec{p}^{\,i}\right)^2}$$

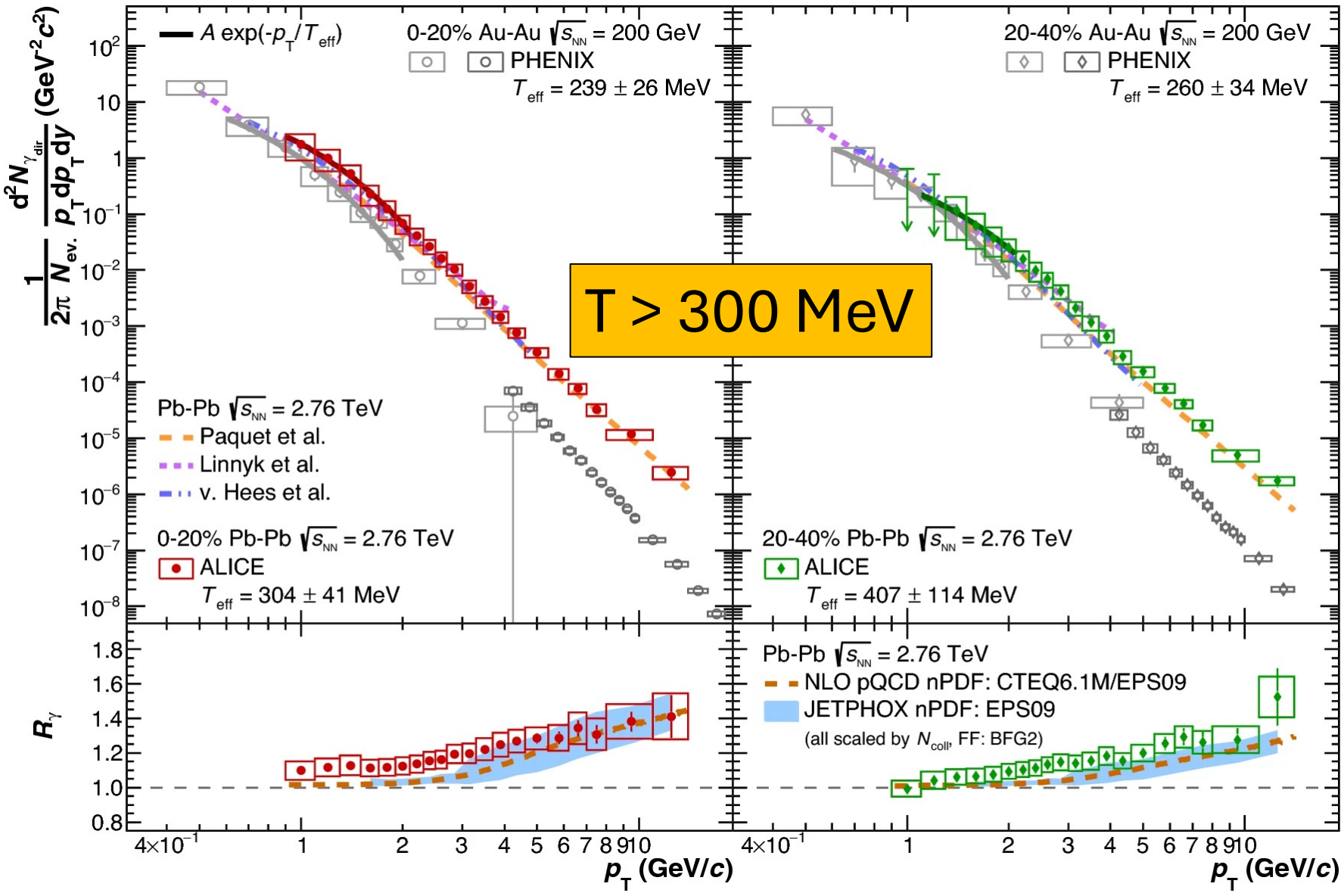
Time of flight:
$< \tau > = L / \beta$
$= L \ (1 + m^2/ p^2)^{1/2}$

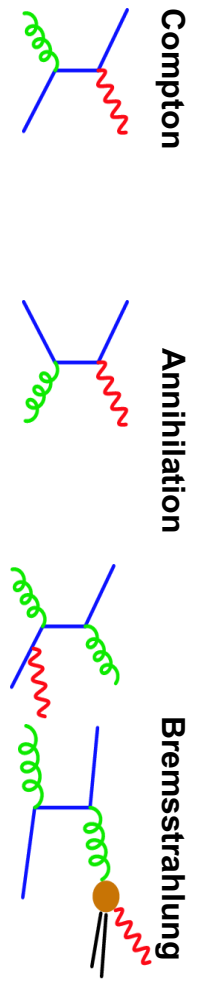


1 MeV ~ 10^{10} Kelvin

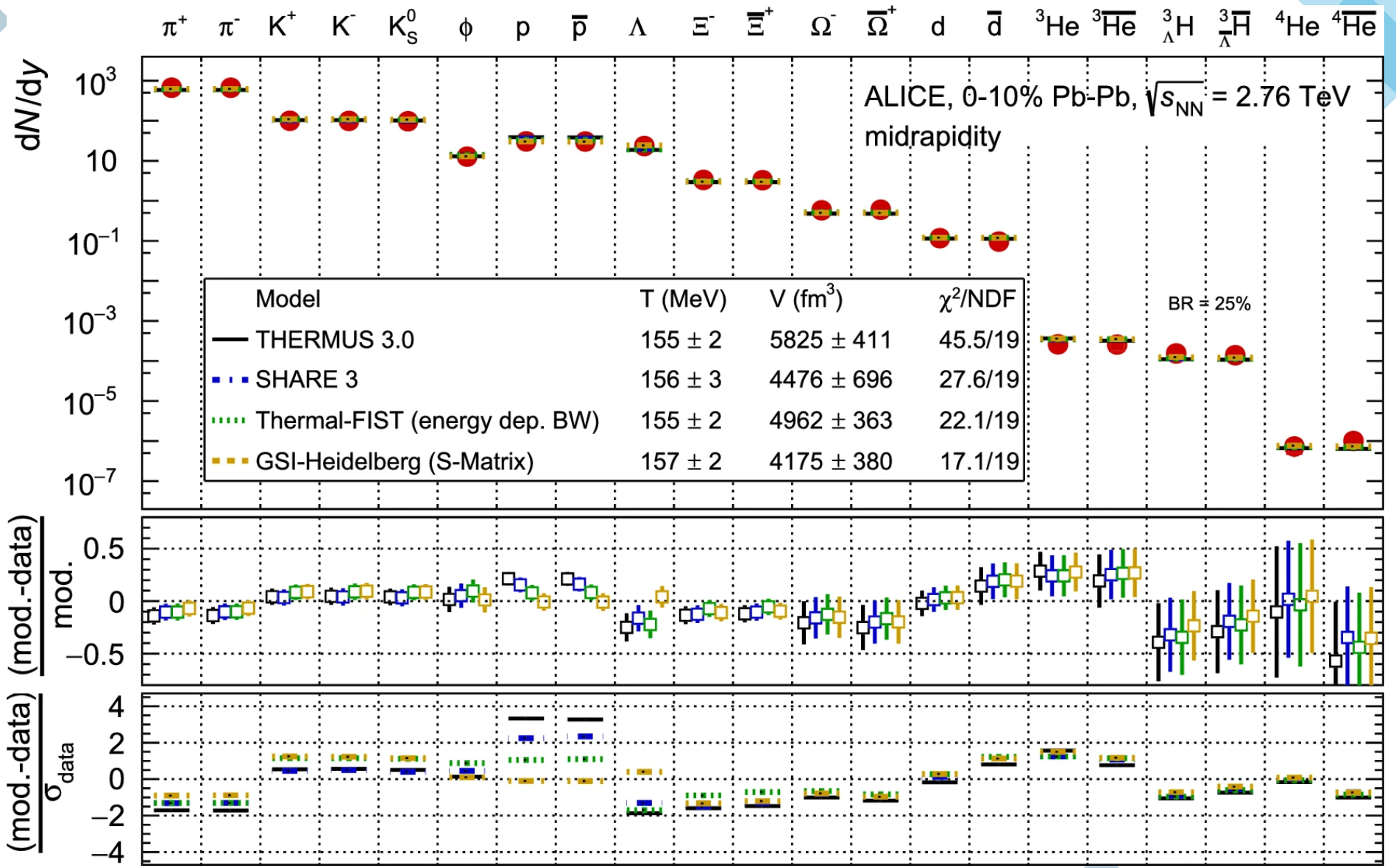
$$d^2 N_{\gamma_{\rm dir}} / (p_{\rm T}\, {\rm d}p_{\rm T}\, {\rm d}y) \propto e^{-p_{\rm T}/T_{\rm eff}}$$

ALICE: Eur.Phys.J.C 84 (2024) 8, 813





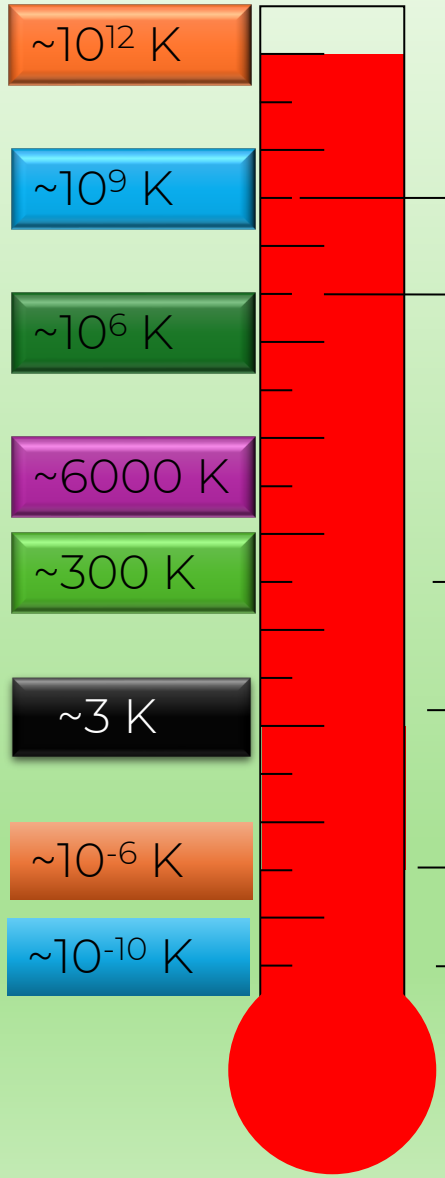
$$n = \frac{1}{V}\frac{\partial(T \ln Z)}{\partial \mu} = \frac{V T . m_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left(e^{\beta k \mu_i}\right) K_2\left(\frac{k m_i}{T}\right)$$



ALICE: Eur.Phys.J.C 84 (2024) 8, 813

T ~ 156 MeV

PERSPECTIVE ON THE TEMPERATURE



Nucleus-Nucleus collisions ~ 600 MeV

Neutron Star Thermonuclear Explosion

(Terrestrial Nuclear explosions)

Solar Interior

Solar Surface

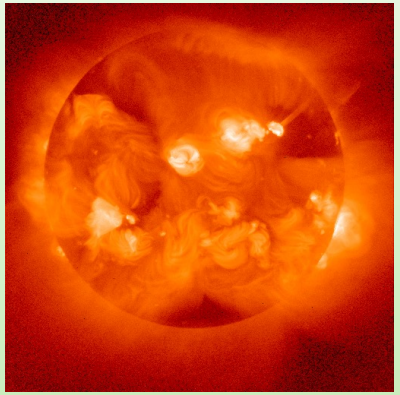
Room Temperature ~ **1/40 eV**

Cosmic Microwave Background

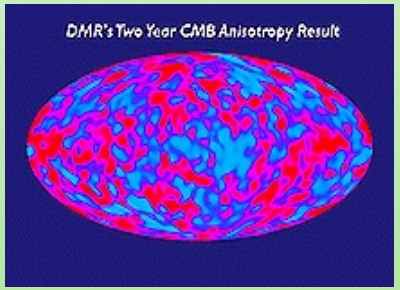
Trapped Ions

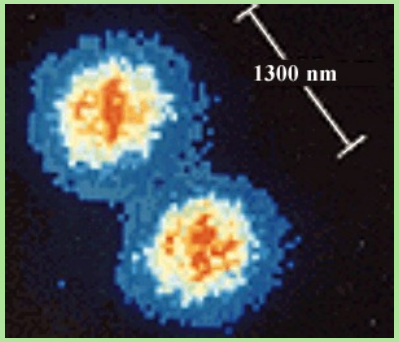
Rhodium metal spin cooling (2000)

(Low-T World Record!)



Highest temperatures on Earth





WHO
CERN, LARGE HADRON COLLIDER

WHAT
5X10^12 DEGREE(S) KELVIN

WHERE
SWITZERLAND

WHEN
13 AUGUST 2012

On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

Highest artificial temperature

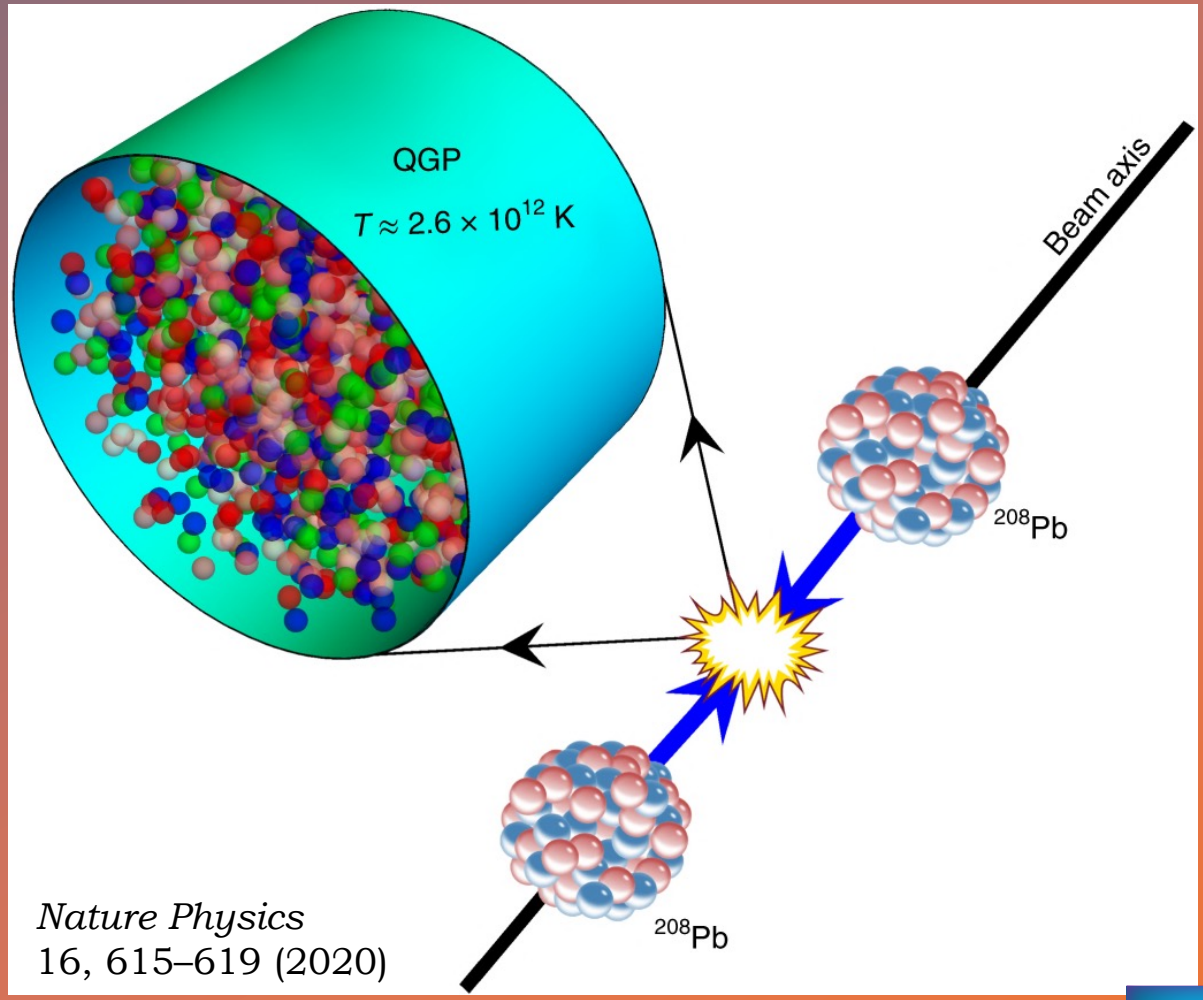
https://www.guinnessworldrecords.com/world-records/highest-man-made-temperature

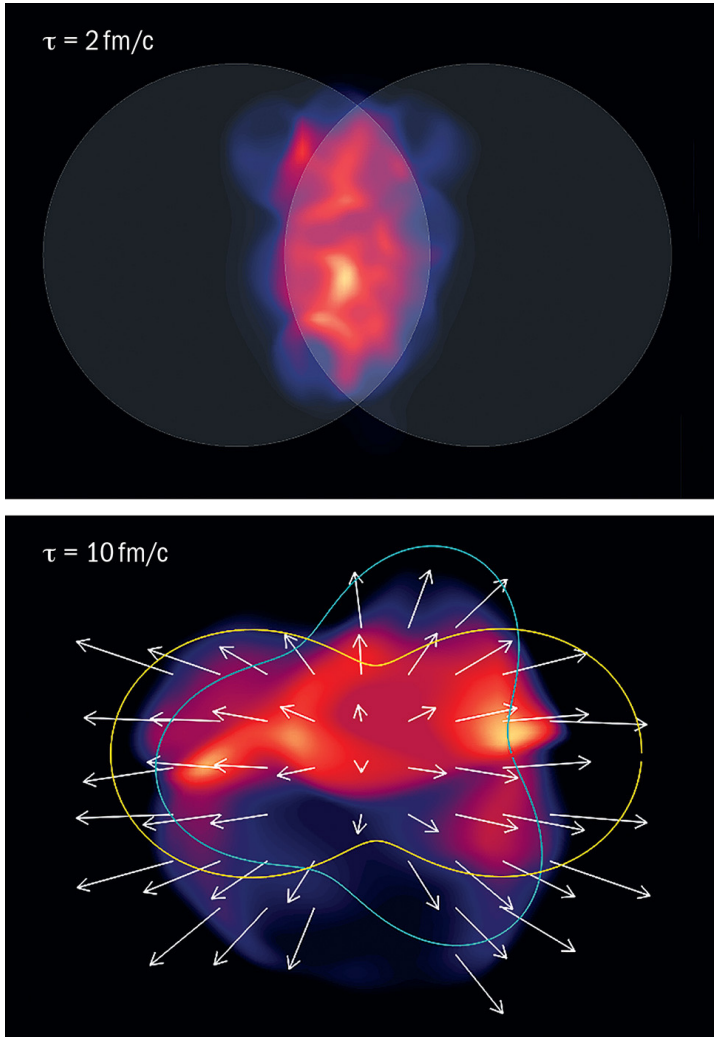
Conclusion # 1

Largest temperatures recorded in laboratory.

Mimics the microsecond old Universe conditions.

Quark Gluon Plasma formed.

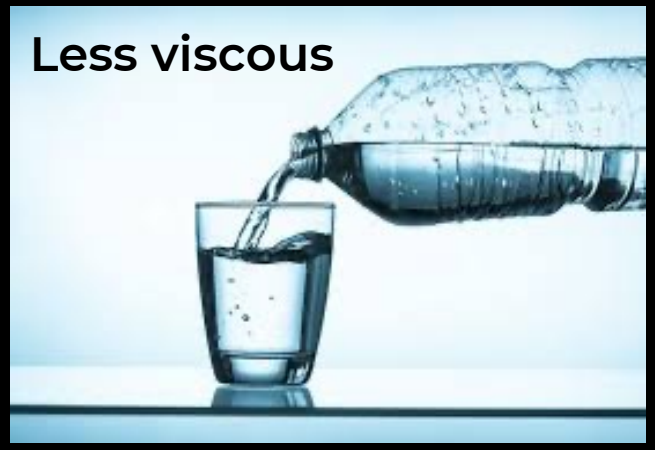




An illustration of the evolving energy density of the QGP created in a noncentral collision. Credit: MUSIC arXiv:1209.6330

What is the Viscosity of Quark Gluon Plasma ?

VISCOSITY : RESISTANCE TO FLOW



Dilute gas, $\eta = (1/3)\, npl.$
Uncertainty principle $pl \gtrsim \hbar$.
Entropy density, $s \sim k_B n$,
Lower bound to $\eta/s \gtrsim \frac{\hbar}{k_B}$.

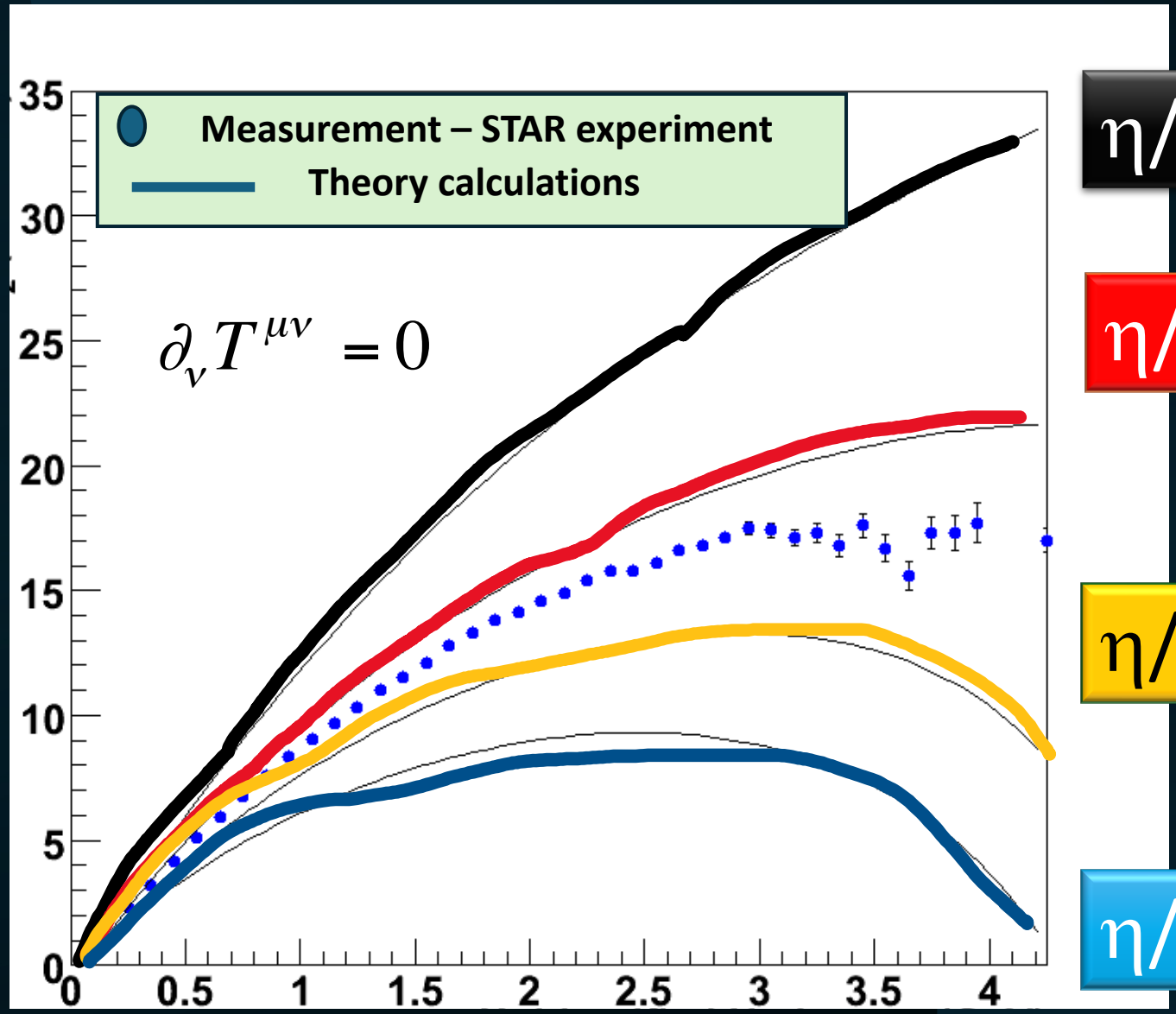
Kovtun, Son, and Starinets
(KSS bound) $\eta/s \geq \frac{\hbar}{4\pi k_B} = 1/4\pi$.

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun, D. T. Son, and A. O. Starinets
Phys. Rev. Lett. **94**, 111601 – Published 22 March 2005

Natural principles kinematic viscosity $\eta/s \geq 1/4\pi$.

FLOW AND RESISTANCE TO FLOW - VISCOSITY



$\eta/s \sim 0$

Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?

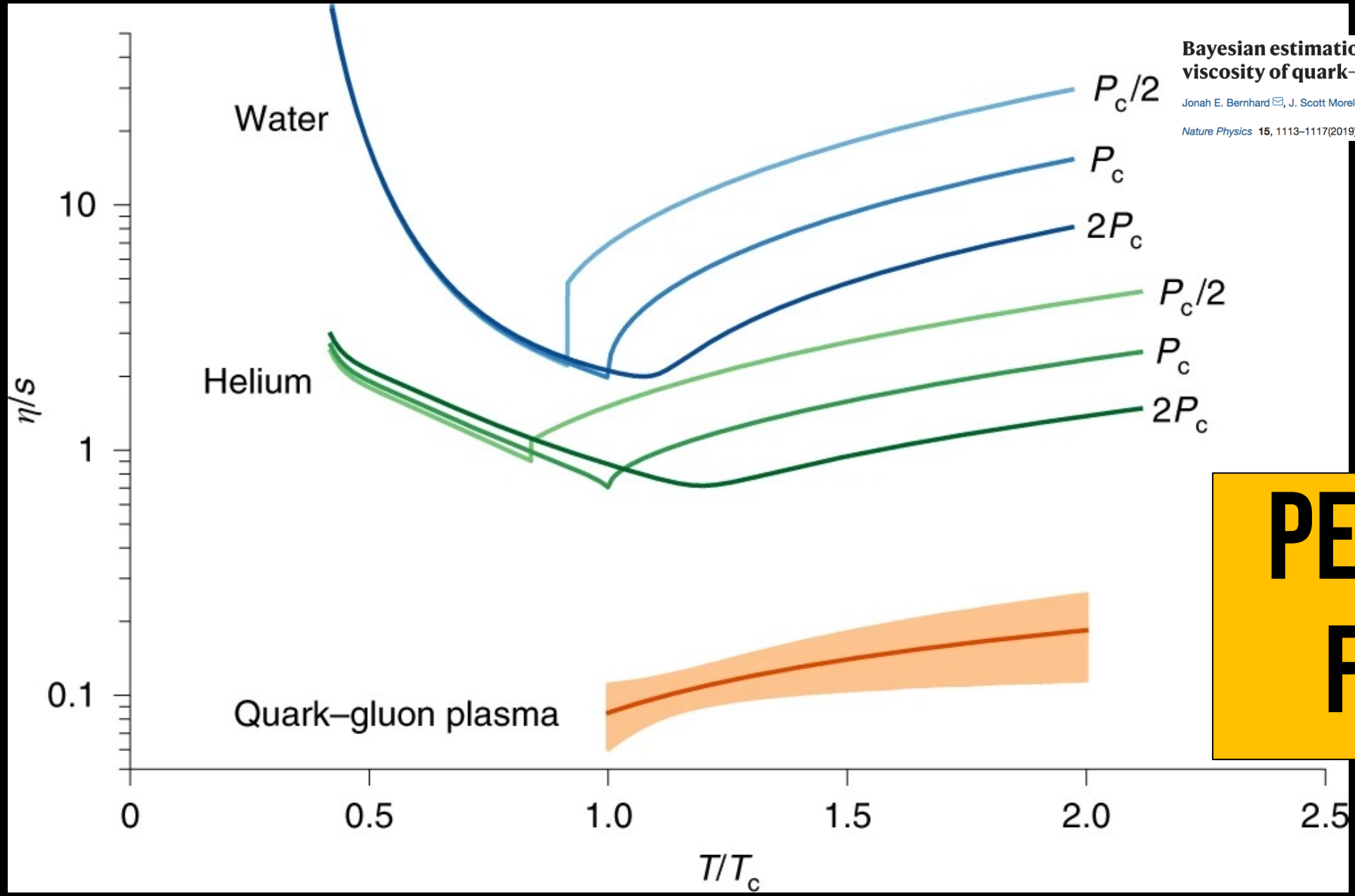
Paul Romatschke and Ulrike Romatschke
Phys. Rev. Lett. **99**, 172301 – Published 24 October 2007

$\eta/s = 1/4\pi \sim (1/20)$Water

$\eta/s = 2/4\pi \sim (1/10)$Water

$\eta/s = 3/4\pi \sim (1/6)$Water

Kinematic viscosity



Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma

Jonah E. Bernhard ✉, J. Scott Moreland & Steffen A. Bass

Nature Physics **15**, 1113–1117(2019) | Cite this article

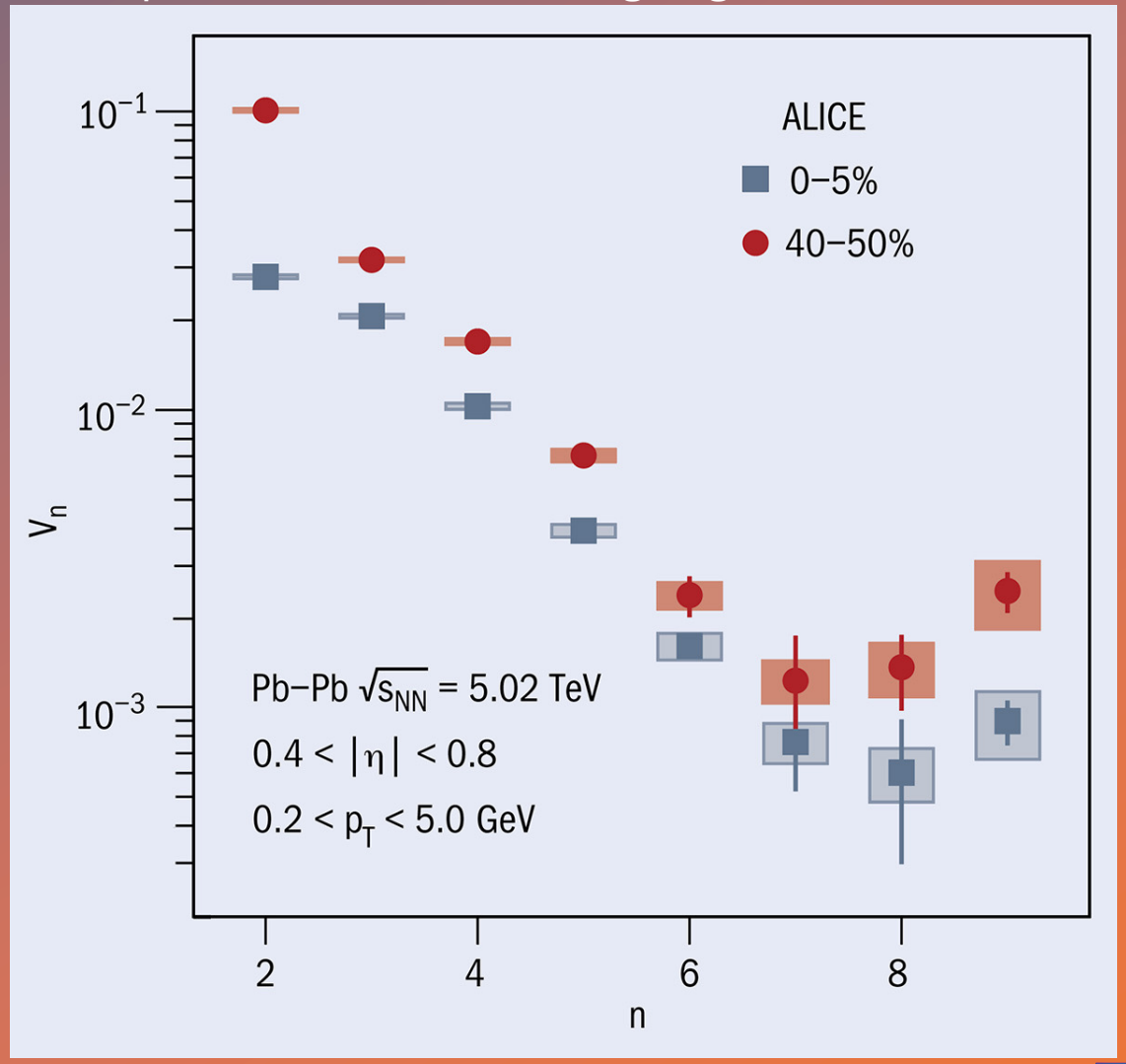
PERFECT FLUID

Normalized temperature

Conclusion #2

Plasma of Quarks and Gluons, building blocks of visible matter, at 10^{12}K is a perfect fluid.

https://cerncourier.com/a/going-with-the-flow/

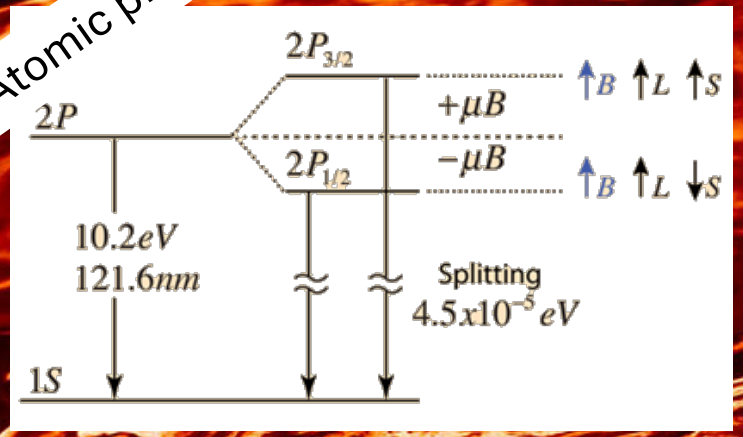


Flow

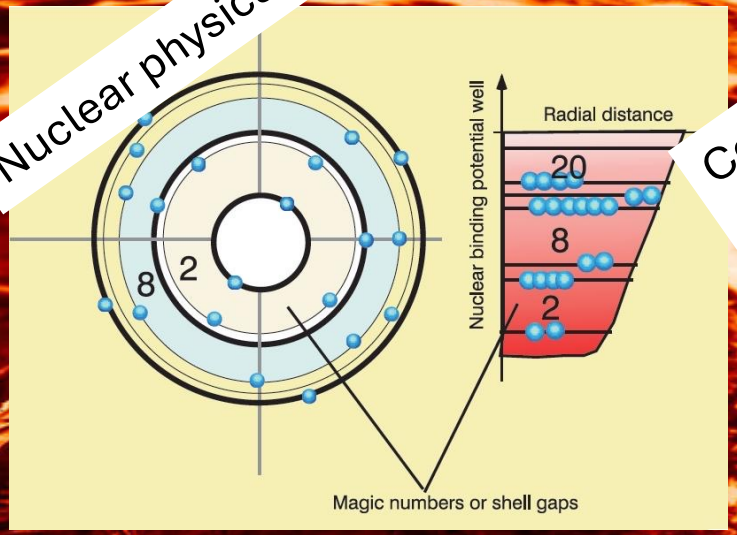
Order

Spin-orbital angular momentum interactions

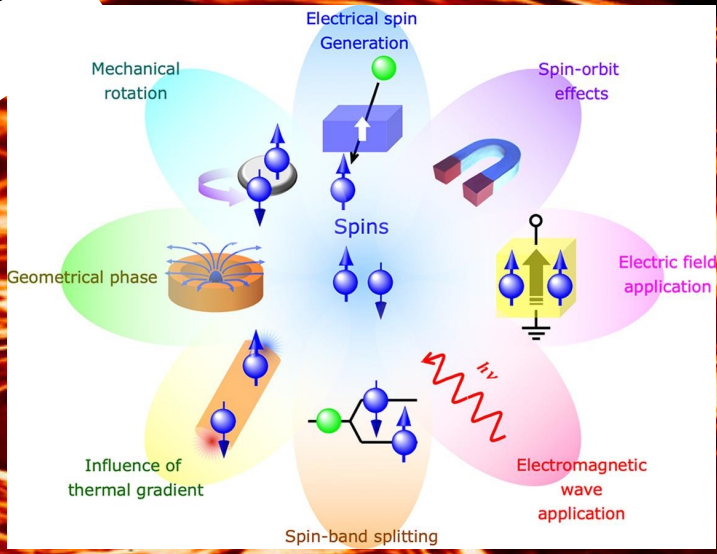
Atomic physics

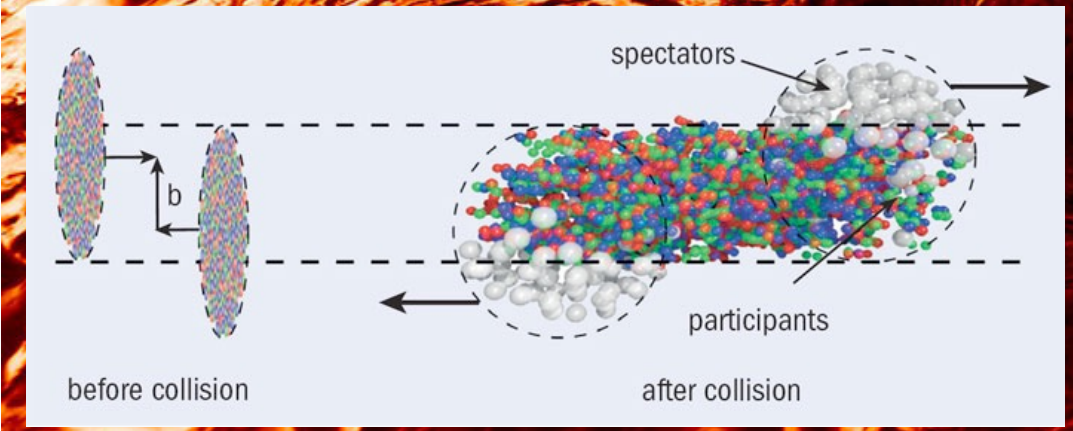


Nuclear physics



Condensed matter physics





$$L = r \times p \sim bA\sqrt{s_{NN}} \sim 10^4\,\hbar$$

$$\omega = \frac{1}{2}\nabla \times v \qquad \omega_y = \frac{1}{2}(\nabla \times v)_y \approx \frac{1}{2}\frac{dv_z}{dy}$$

Large Angular Momentum

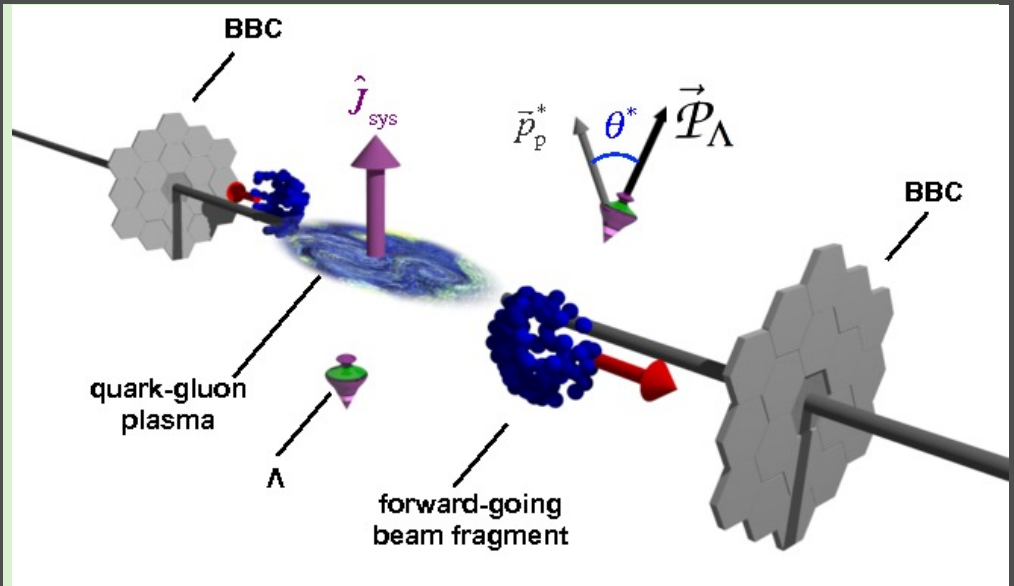
➔

Spin-orbit interactions

➔

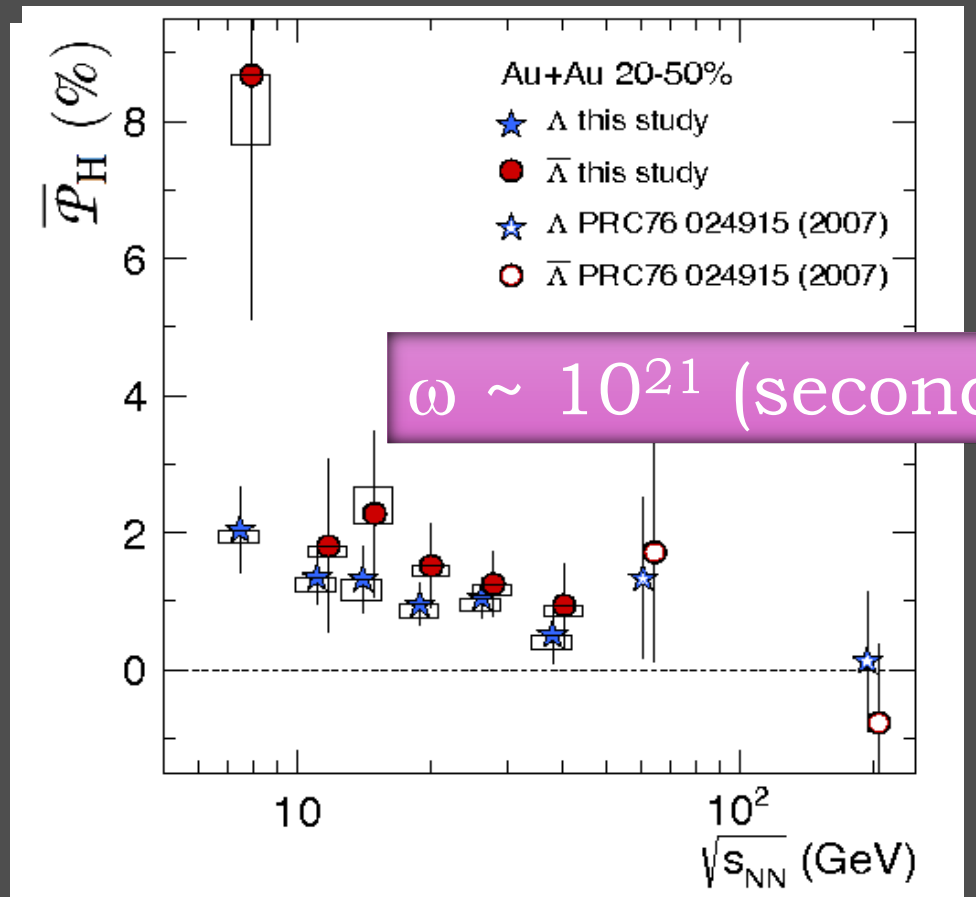
Polarization / Vorticity

Measuring Polarization



$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$

$$\omega = k_B T \left(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\overline{\Lambda}'}\right)/\hbar$$



$\omega \sim 10^{21}$ (second)$^{-1}$

Published: 03 August 2017

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration

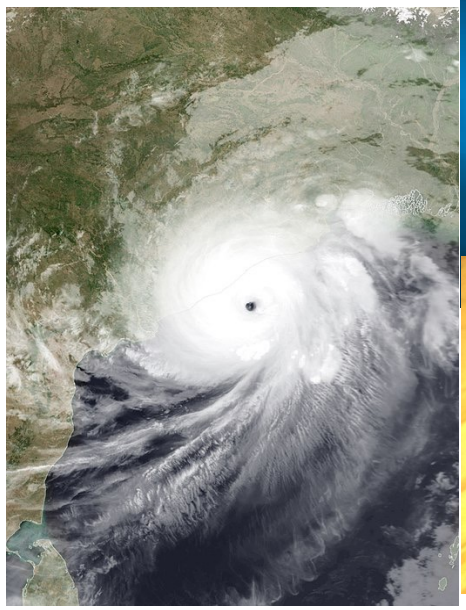
Nature **548**, 62–65(2017) | Cite this article

Perspective on vorticity

vorticity $\boxed{\boldsymbol{\omega} = \operatorname{curl} \mathbf{u}}$

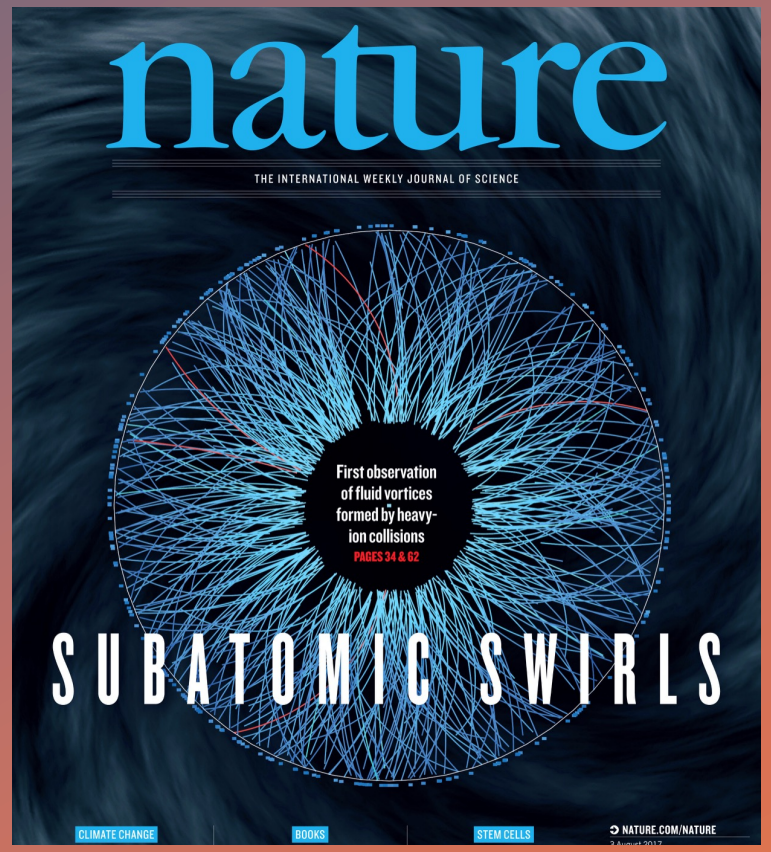
Several fluids < 10^3 $(second)^{-1}$

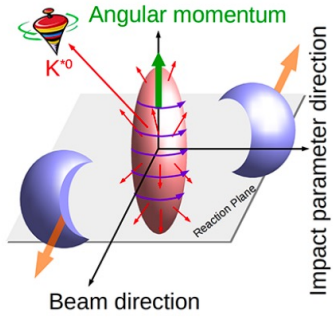
QGP ~ 10^{21} $(second)^{-1}$



Conclusion # 3

Plasma of Quarks and Gluons, building blocks of visible matter, at 10^{12}K is a highly vortical fluid.





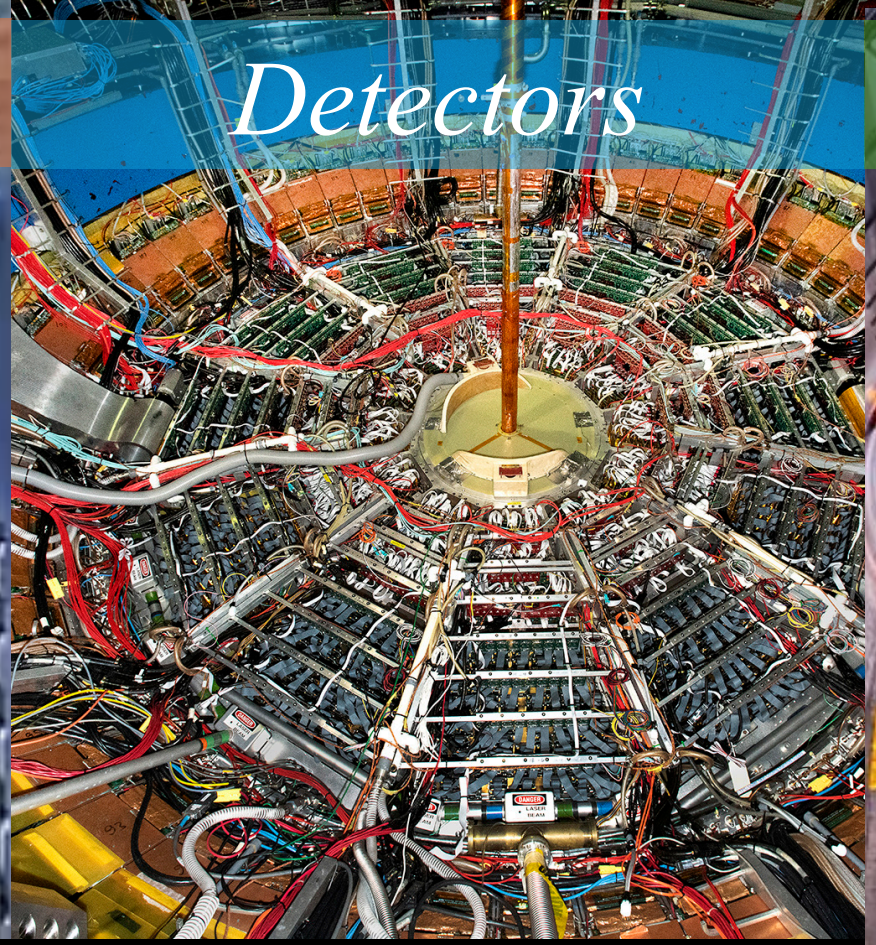
EDITORS' SUGGESTION

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya *et al.* (The ALICE Collaboration)

Phys. Rev. Lett. **125**, 012301 (2020)

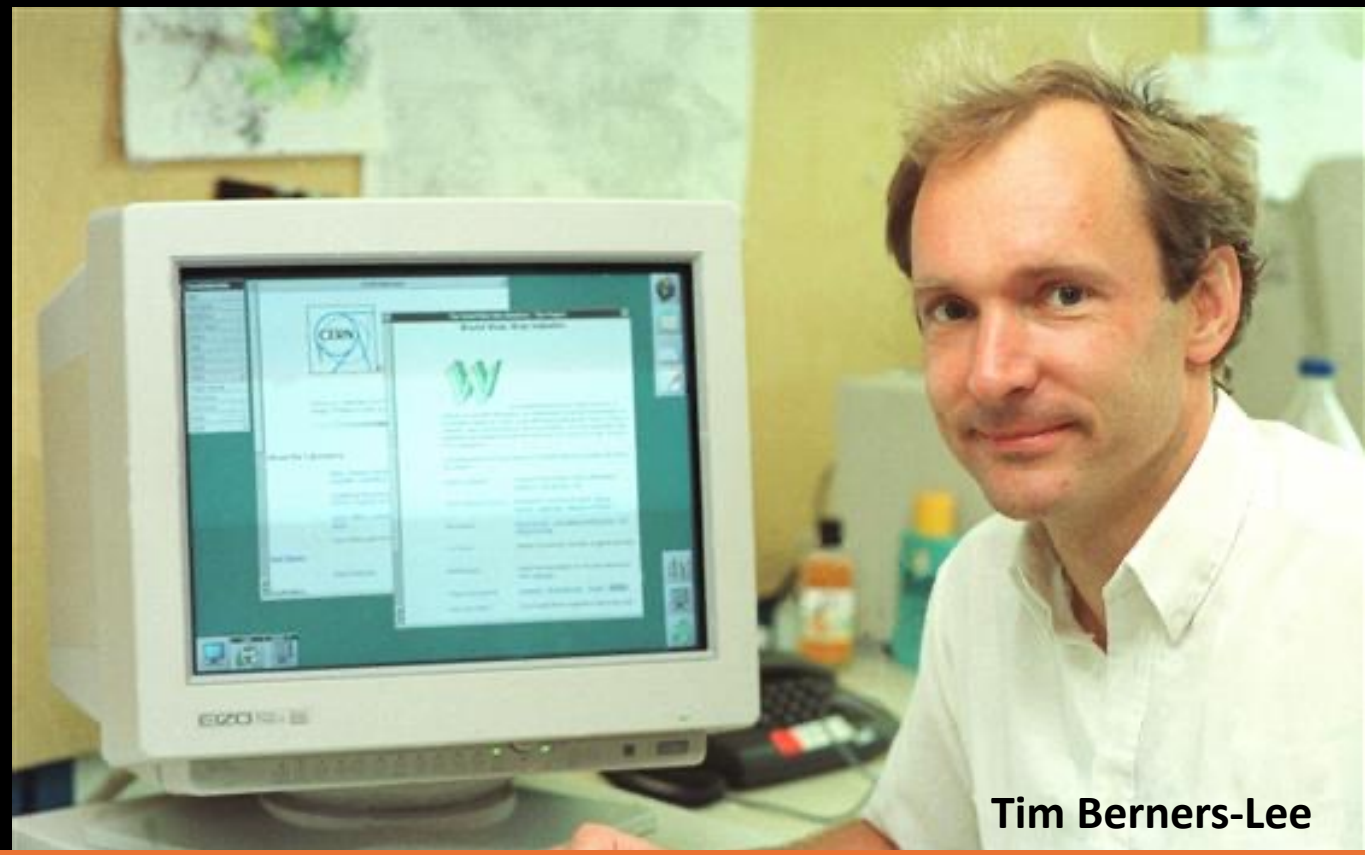


EACH OF THE ASPECT HAS SOCIETAL APPLICATIONS

COMPUTING: THE WORLD WIDE WEB

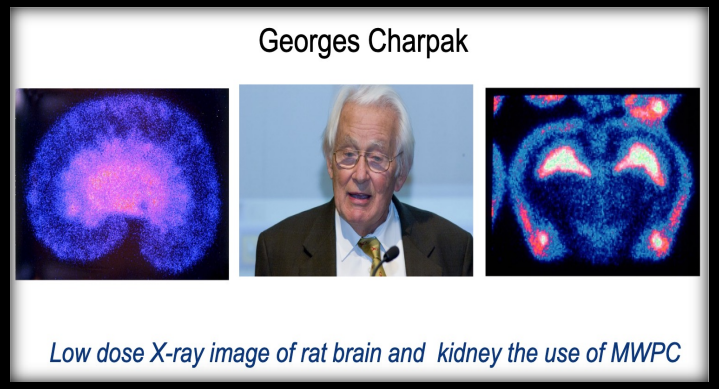
1) 1989 www@CERN

2)1993 CERN places World Wide Web technology in the public domain, donating it to the world.

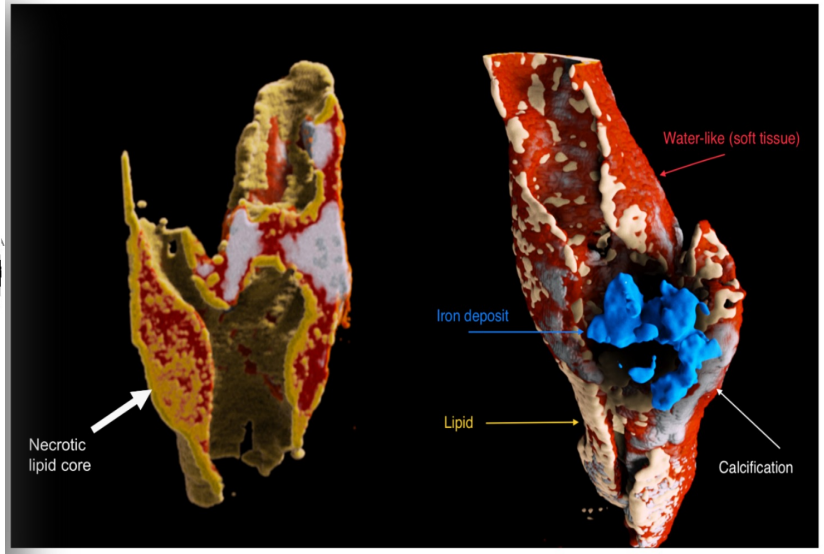


Few other technological advances in history have more profoundly affected the global economy and societal interactions than the Web.

DETECTORS AS DIAGNOSTIC INSTRUMENTATION

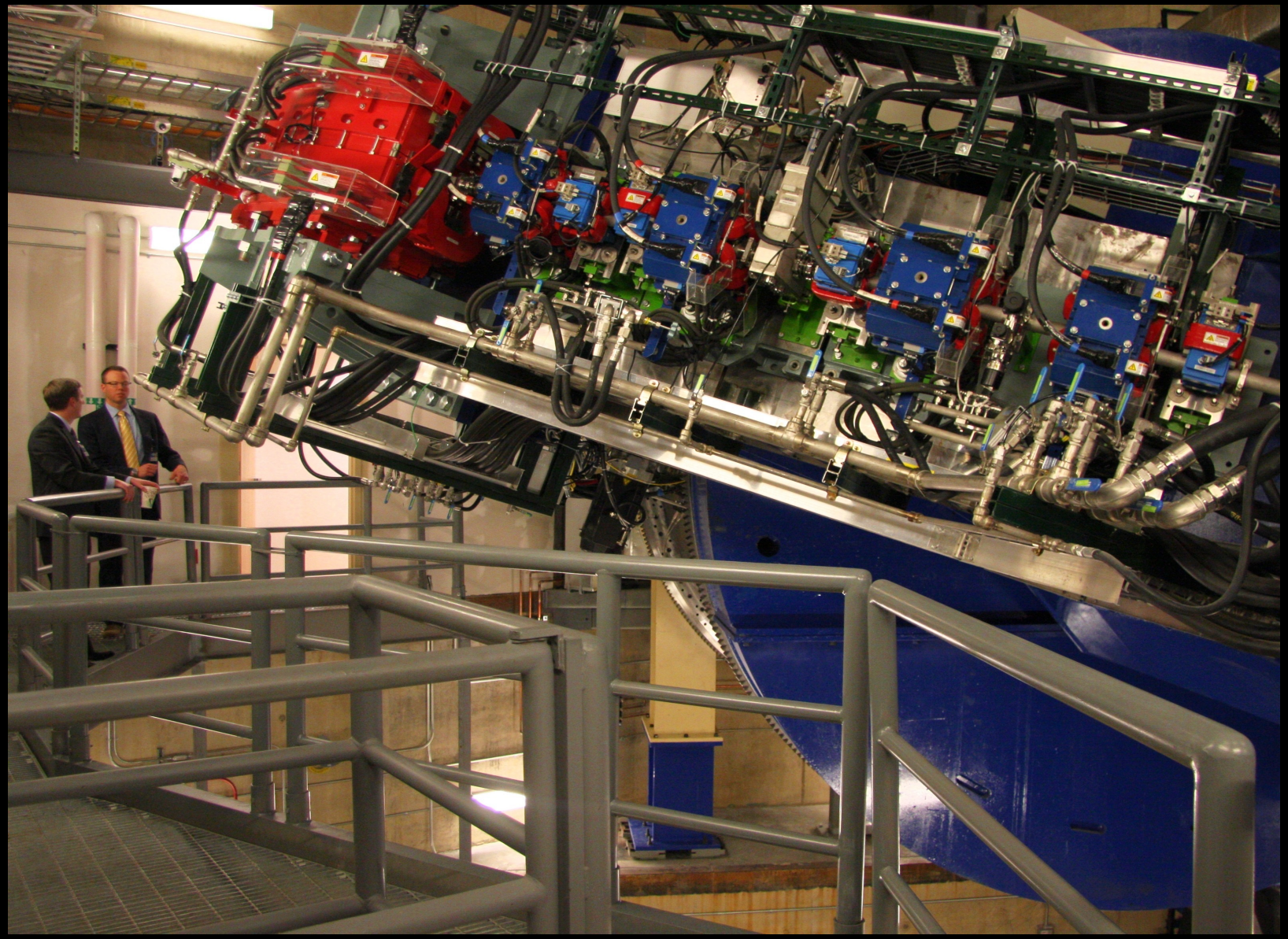


Imaging done in 1968. Nobel Prize 1992 - "for his invention and development of particle detectors, in particular the multiwire proportional chamber."



Particle detectors first developed for particle physics are now ubiquitous in medical imaging.

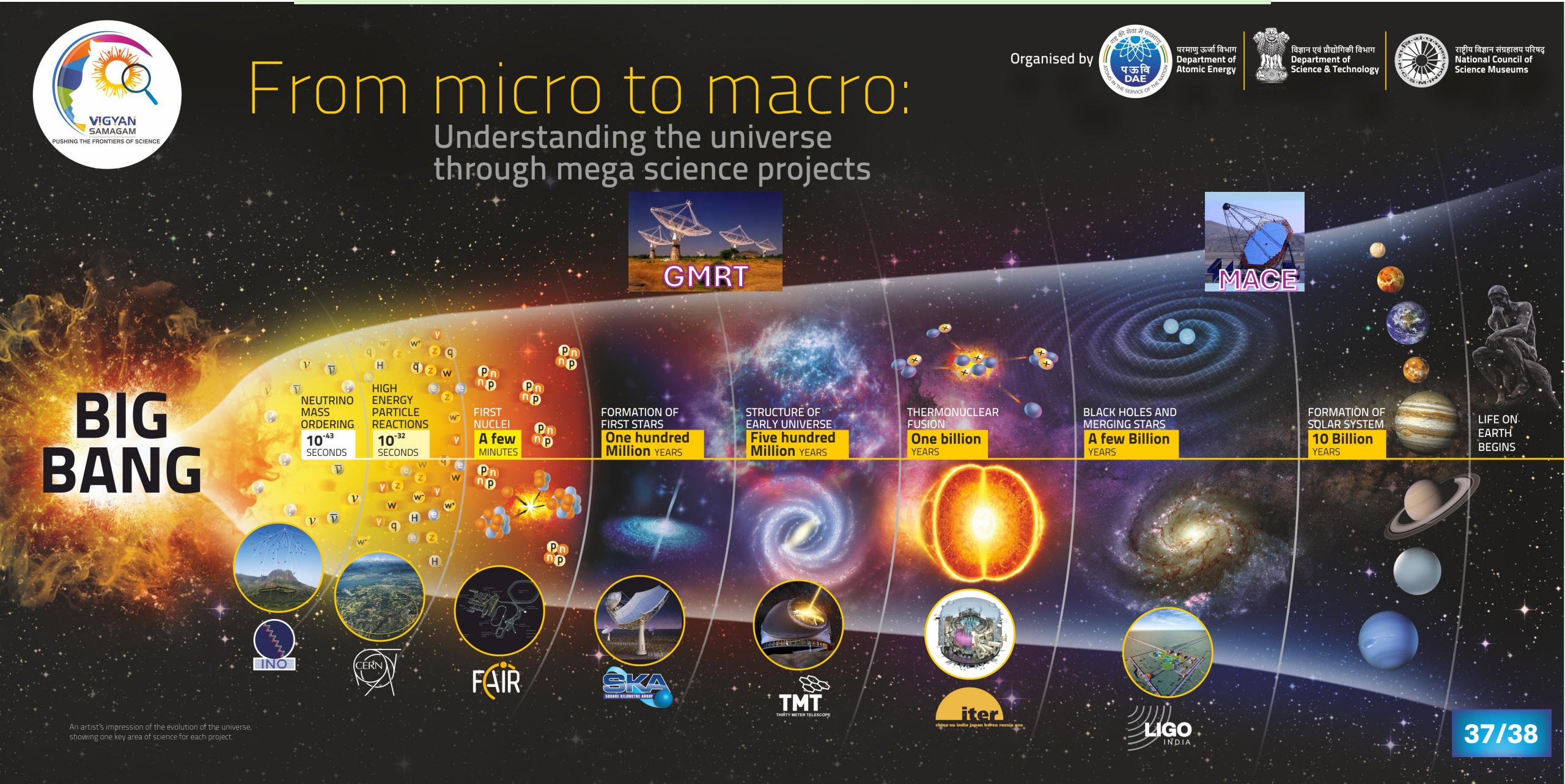
Accelerators: Radiotherapy



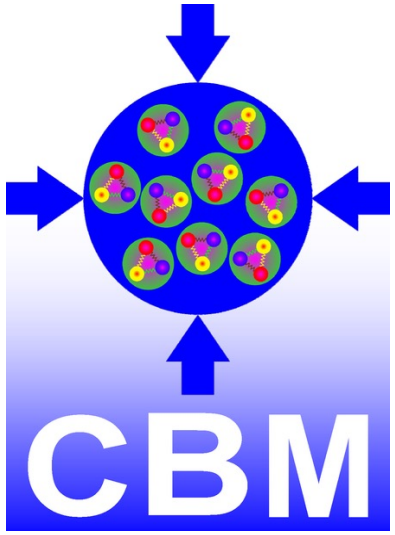
Marie Curie – First woman to received Nobel Prize – Birthday – 7th November
Happy International Medical Physics Day

Our quest to know more about nature, leads to building things that are at the forefront of cutting-edge technology. This technology has widespread applications in society.

Mega Sciences: Opportunities



Acknowledgements



IISER Pune Physics Department

Acknowledgements

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