Beyond the Horizon:
Bikash Sinha
and the thermodynamics of the Little Bang

Bulletin for the CERN Community CERN

Bikash Sinha (1945 – 2023)

21 NOVEMBER, 2023

Bikash Sinha at CERN

Bikash Sinha, influential Indian scientist and pioneer in quark–gluon plasma and the early Universe, passed away on 11 August at the age of 78. As one of the ALICE experiment's early visionaries and architects, his impact on heavy-ion physics is unmistakable.

While Bikash's passing leaves an undeniable void, his legacy is a vibrant and thriving team, primed to continue his journey. We will always remember him for his charismatic personality, great kindness, openness and generosity. We honour his memory and, with our deepest condolences, extend our sympathy to his family.

https://home.cern/news/obituary/physics/bikash-sinha-1945-2023

CERNCOURIER | Reporting on international high-energy physics

Physics ▾ | Technology ▾ | Community ▾ | In focus | Magazine

March 2008

CULTURE AND HISTORY | OPINION

An Indian dream come true

13 March 2008

In the 1970s, India was still a spectator in the world theatre of high science. Individuals who migrated to other parts of the world sometimes excelled. In India, people were proud of them but remained convinced that such feats could not be accomplished back home. In the 1980s, however, there was a major paradigm shift in our mind set. We began to dream of competing with the world from India.

By the beginning of the 21st century, India was no longer a spectator but a significant player on the world stage. The glamour of individual excellence had been replaced by the wisdom of collective effort. We had turned mature and ambitious. What I have presented is a chronicle of that evolution. I am proud and grateful to be a witness and indeed a participant in this evolving panorama.

https://cerncourier.com/a/viewpoint-an-indian-dream-come-true/

CERNCOURIER | Reporting on international high-energy physics

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March 2008

CULTURE AND HISTORY | OPINION

An Indian dream come true

13 March 2008

Development of large-scale physics experiments in India:

- VECC room temperature cyclotron
- **VECC superconducting cyclotron**
- VECC Medical cyclotron
- CERN – India collaborations
- Joining ALICE at CERN: detectors, electronics, human resource development
- ALICE: PMD, Muon Arm, MANAS chip, etc. etc.
- STAR at BNL
- Joining FAIR

https://cerncourier.com/a/viewpoint-an-indian-dream-come-true/

National Meet on "India at the Large Hadron Collider"

The Department of Atomic Energy and the Department of Science & Technology, Government of India organized a National Meet on 'India at LHC' in which experts involved in construction of the Large Hadron Collider at CERN, in various experiments and discovery of Higgs Boson interacted with the Scientists, Researchers, Students, Media and enthusiasts etc. The interaction of experts with audience was very informative. India's role in CERN with future direction of high energy experiments was talked.

August 2012

- **Prof Bikash Sinha, Homi Bhabha Professor, DAE**
- Dr. T. Ramasami, Secretary, Department of Science & Technology (DST)
- Dr. R.K. Sinha, Chairman, AEC and Secretary, Department of Atomic Energy (DAE)
- Prof. V.S. Ramamurthy, Director, NIAS, Bangalore
- Dr. R. Chidambaram, Principal Scientific Advisor to Government of India

India becomes Associate Member State of CERN

January 2017

Official notification that India has ratified the Association Agreement with CERN today

Bikash Sinha:
Along the lines of European nations coming together to establish CERN, he opined that the SAARC countries could also think of jointly establishing research facilities in this part of the world.

ENHANCED COLLABORATION BETWEEN CERN AND INDIA

CERN Bulletin

20 July 2009

On Monday 22 June, Bikash Sinha, Director of the SAHA Institute of Nuclear Physics (SINP) and the Variable Energy Cyclotron Centre (VECC) in Kolkata, India and Rolf Heuer, CERN Director-General, signed new protocols to the long standing agreement between the Indian Atomic Energy Commission and CERN. This provides a framework for collaboration in low energy nuclear physics between SAHA and VECC and the ISOLDE experiment at CERN.

SINP and VECC Director Bikash Sinha and CERN Director-General Rolf Heuer signing the ISOLDE Protocols.

This was an important day for INDIA-CERN relations, which will certainly lead to many forefront technical developments and exciting new scientific results.

MACROCOSMOS, MICROCOSMOS, ACCELERATOR AND PHILOSOPHY

9 – 13 May 2022

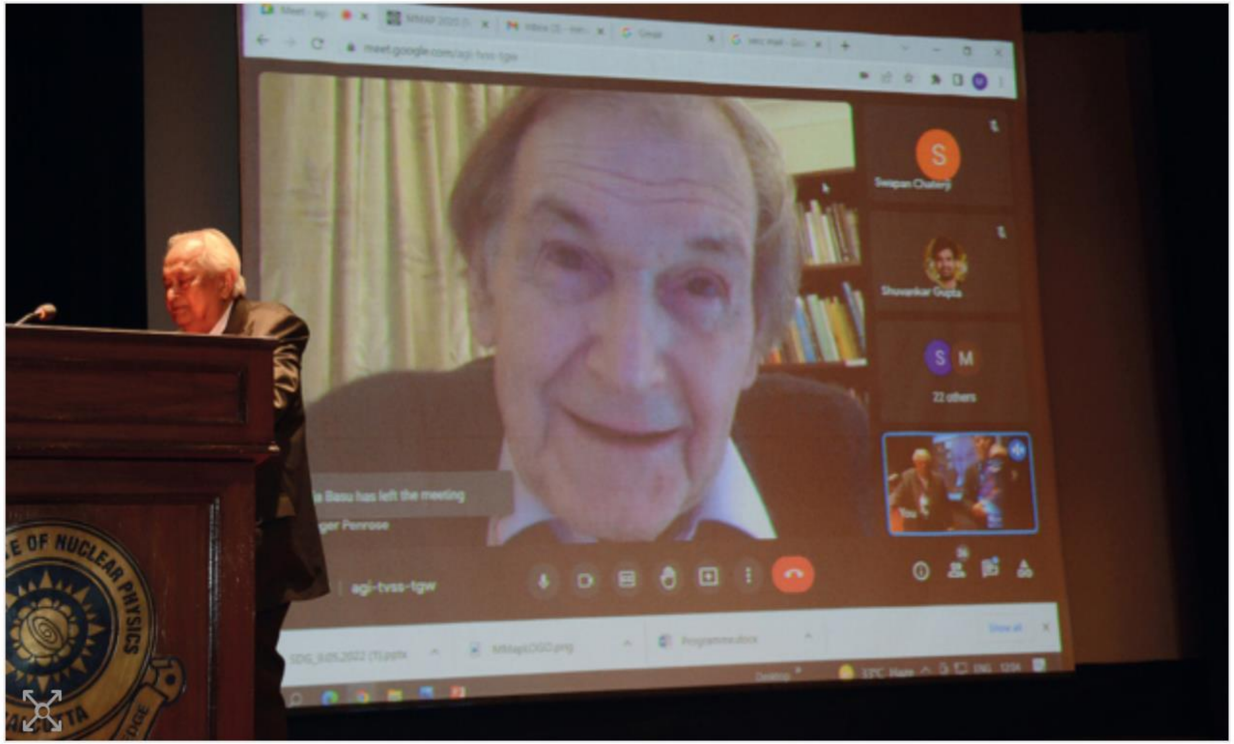
CULTURE AND HISTORY | MEETING REPORT

A carnival of ideas in Kolkata

CERNCOURIER

5 July 2023

Bikash Sinha *VECC Kolkata.*



Time and space Bikash Sinha introducing a talk by Roger Penrose at MMAP 2020, which was held in May 2022. Credit: VECC

.. combined the voyage from the microcosmos of elementary particles to the macrocosmos of our universe up to the horizon and beyond with accelerator physics and philosophy through the medium of poetry and songs, as inspired by the Indian poet Rabindranath Tagore and the creative giant Satyajit Ray.

A carnival of ideas, a mixture of low- to high-energy physics on the one hand and the cosmology of the creation of the universe on the other

Phases of Nuclear Matter

Physics Letters B
Volume 128, Issues 1–2, 18 August 1983, Pages 91-94

Universal signals of a quark-gluon plasma

Bikash Sinha

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https://doi.org/10.1016/0370-2693(83)90080-1

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Abstract

It is shown that the ratio of the production rates $(\gamma\mu^+\mu^-)$ and $(\pi^{0,\pm}\mu^+\mu^-)$ from a quark-gluon plasma is independent of the space-time evolution of the plasma fireball and thus universal signals of the quark phase.

VOLUME 73, NUMBER 18 PHYSICAL REVIEW LETTERS 31 OCTOBER 1994

Single Photons from S + Au Collisions at the CERN Super Proton Synchrotron and the Quark-Hadron Phase Transition

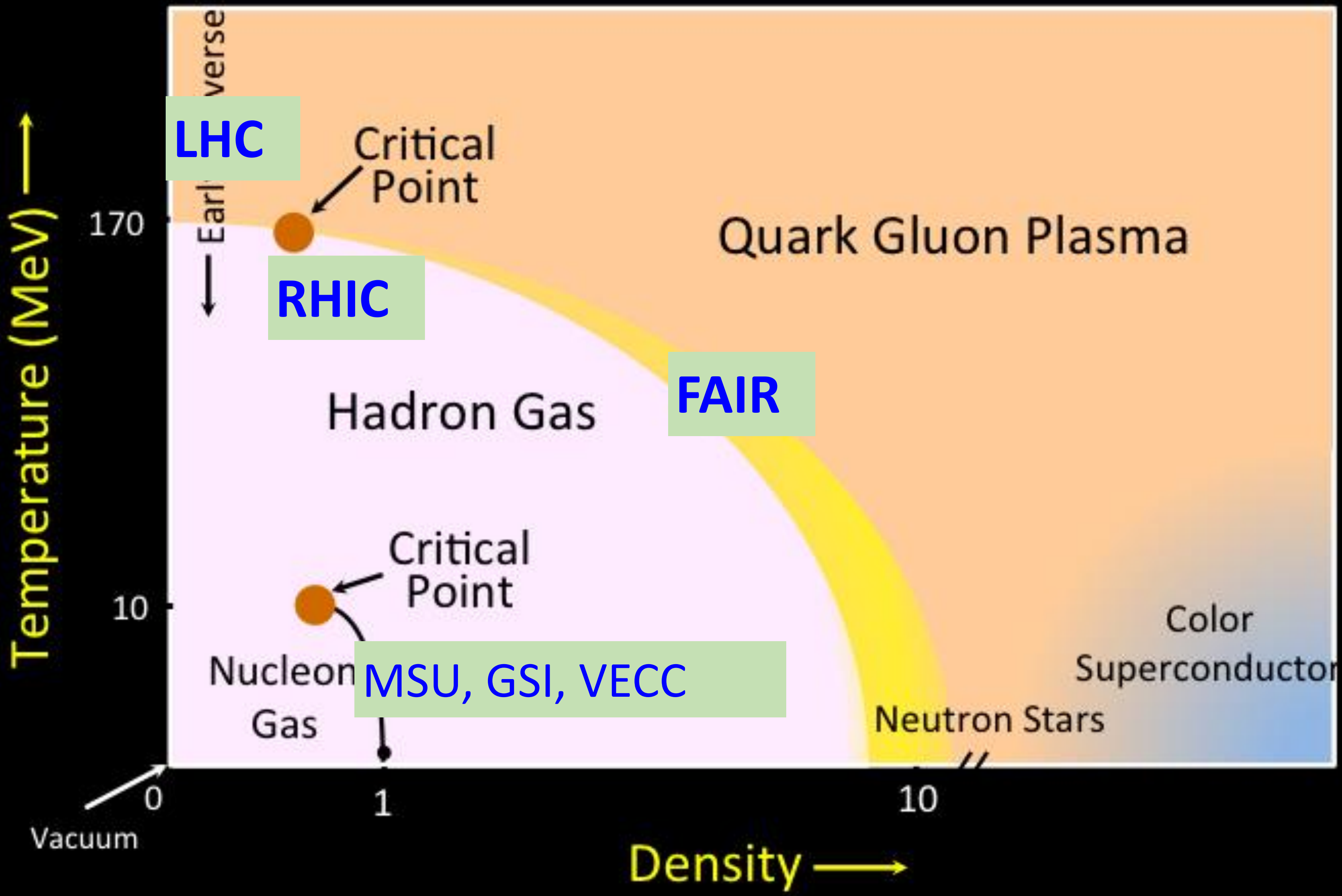
Dinesh Kumar Srivastava*
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064 India

Bikash Sinha
Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Calcutta 700 064 India
and Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Calcutta 700 064 India

(Received 29 April 1994)

The preliminary results for the single-photon spectrum obtained by the WA80 collaboration are analyzed. The data are well described by a scenario where a thermalized quark-gluon plasma is formed initially, which expands, cools, hadronizes, and undergoes a freeze-out. It is also seen that the data do not seem to favor the scenario where the matter is initially formed in a hot hadronic phase, which cools and undergoes freeze-out and does not involve a phase transition.

PACS numbers: 25.75.+r, 12.38.Mh, 24.85.+p



1 eV is roughly 11605 Kelvin

Legend has it ….

that …..

ICPAQGP

Mumbai 1988

Legend has it ….

that …..

ICPAQGP

Mumbai 1988

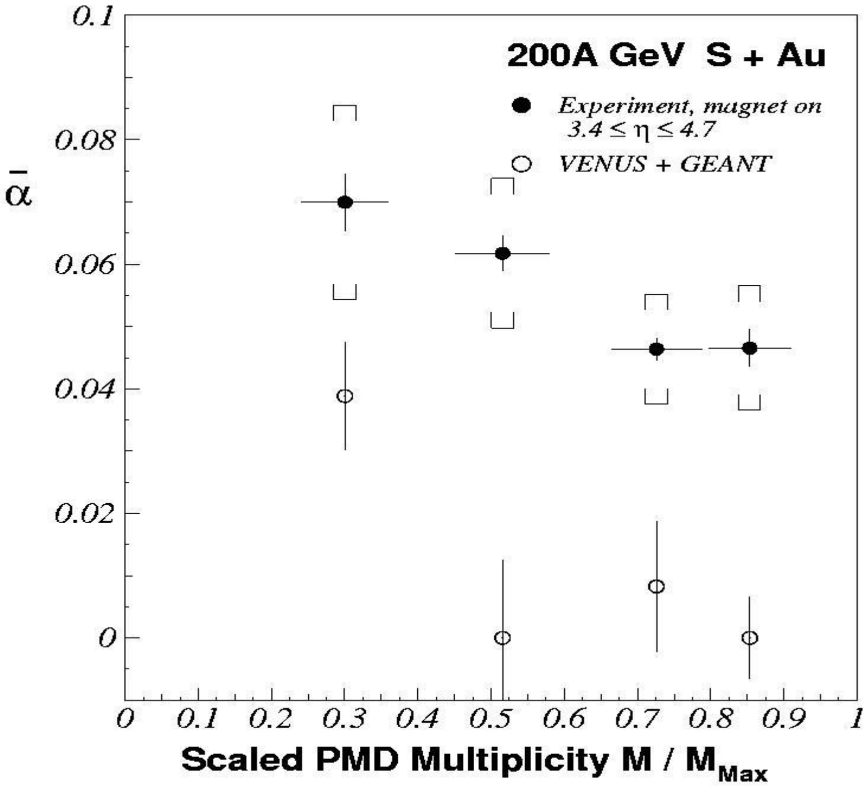
PMD in WA93 Experiment (1990-92)

Building blocks of PMD

Scintillator pads with wavelength shifting fibres using image intensifi CCD camera systems readout

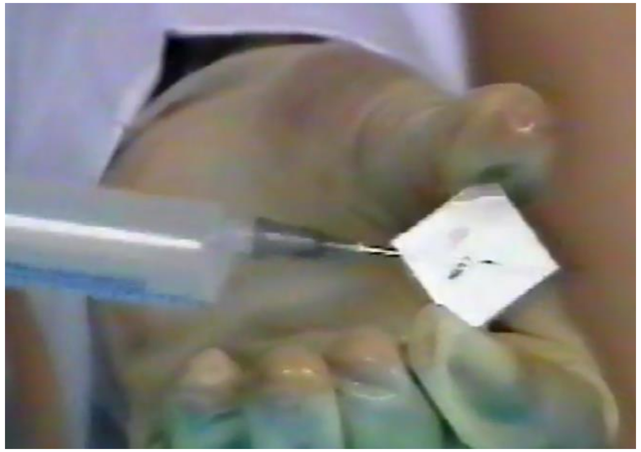
8000 pads covering an area of $3m^2$

First observation of Collective Flow at CERN SPS
Phys. Lett. B403 (1997) 390



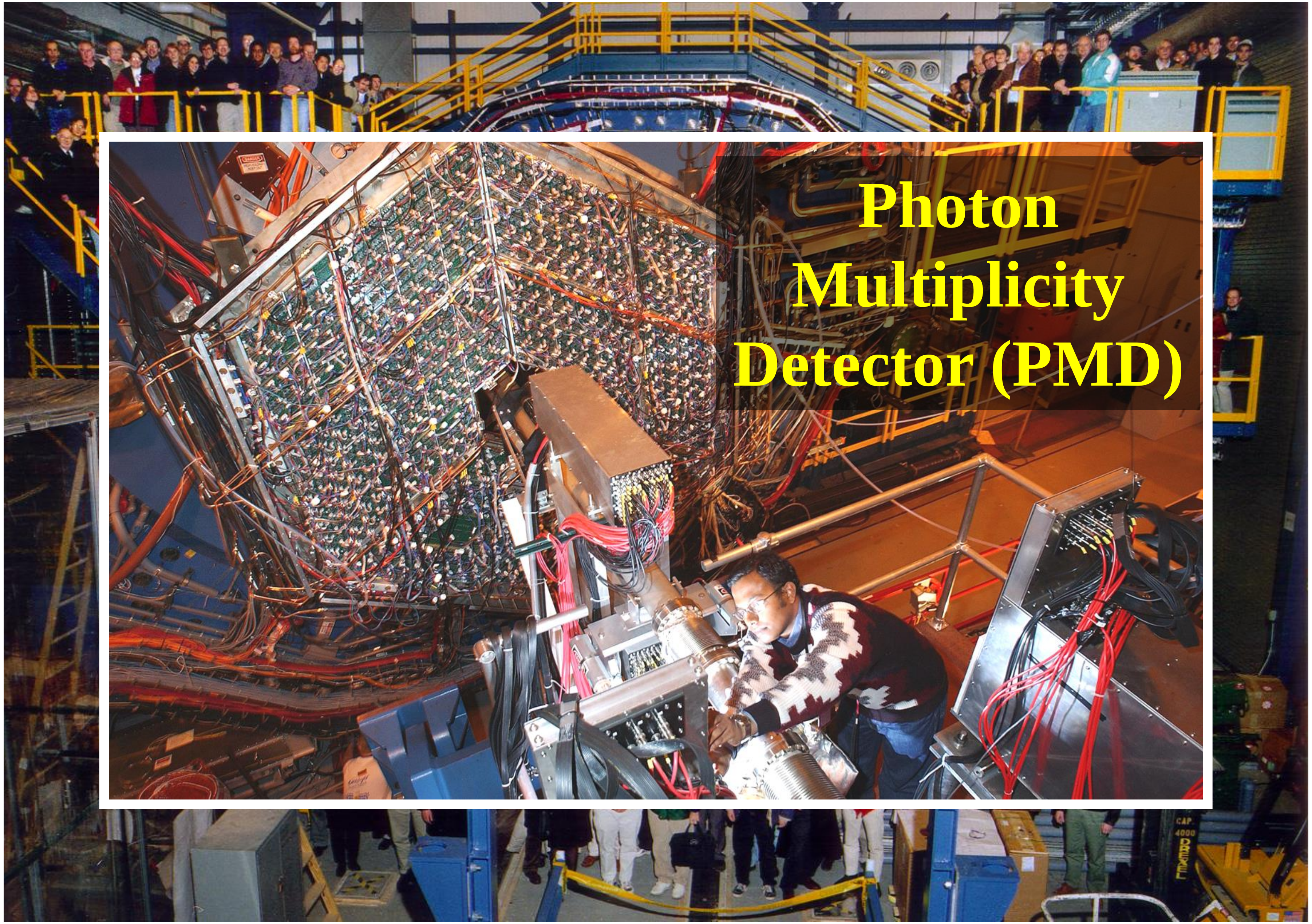
PMD in WA98 Experiment at CERN

(data taking: 1993 – 1996)



Photograph showing the WA98-PMD at VECC

STAR experiment at RHIC, BNL



India in ALICE

Photon Multiplicity Detector (PMD)

Muon Tracking Chamber

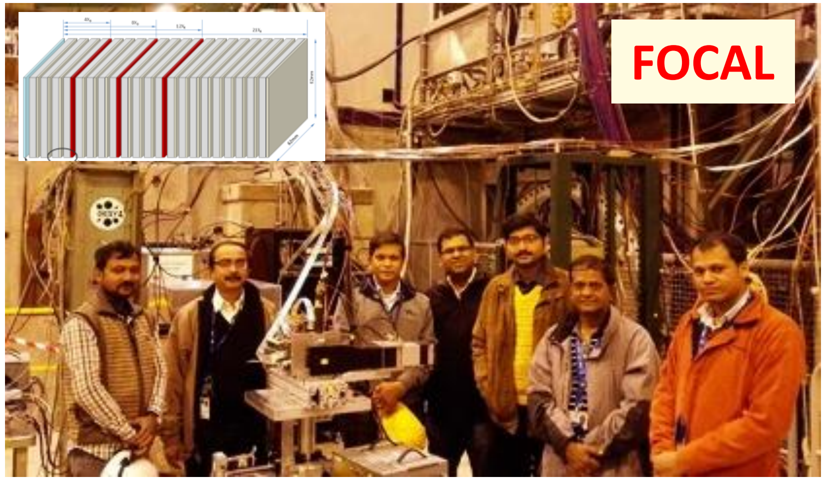
MANAS: Multiplexed ANAlog Signal Processor

First large-scale production of ASIC in India

Common Readout Unit (CRU):

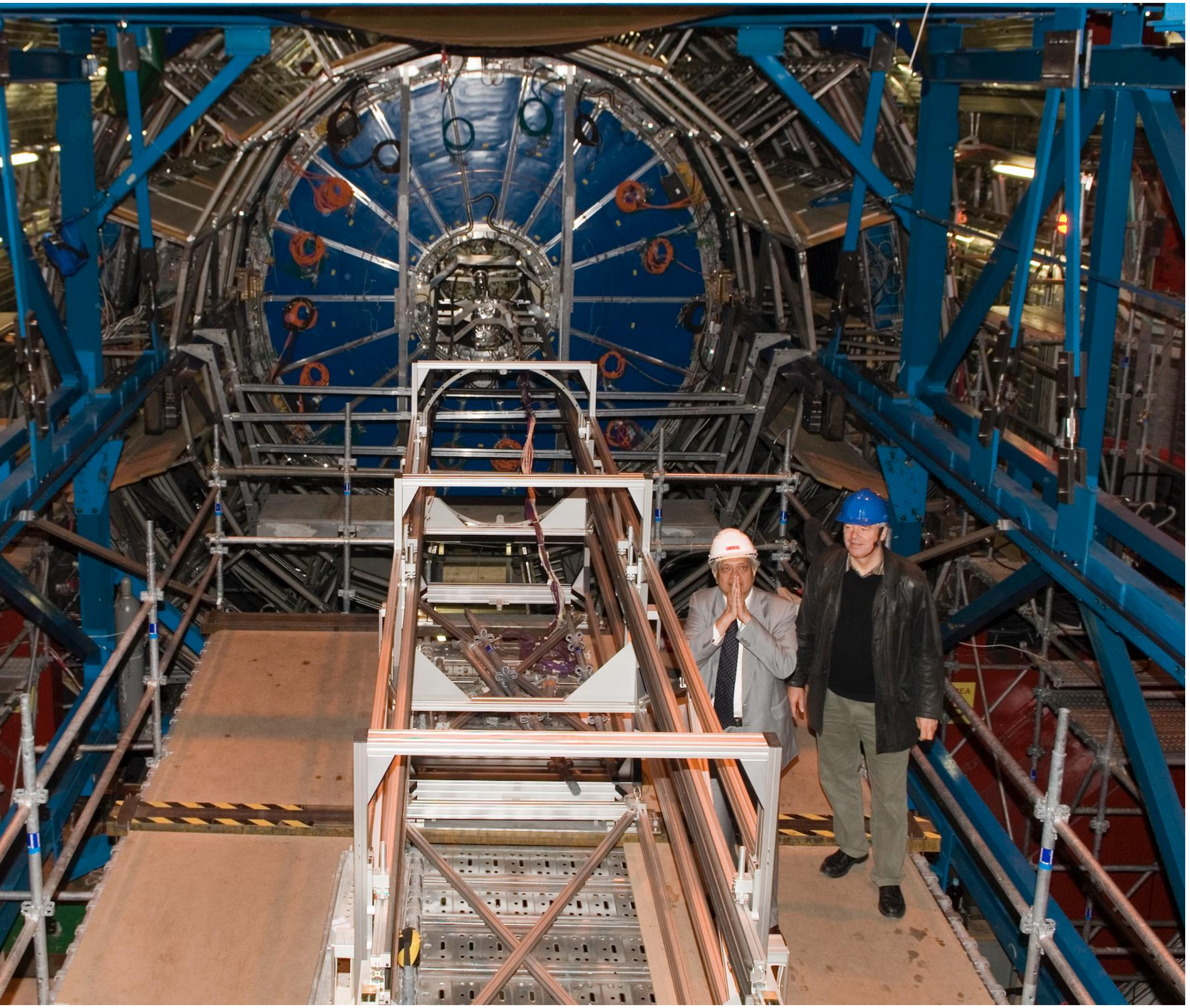
performs data concentration, reconstruction and multiplexing.

Silicon-Tungsten Calorimeter

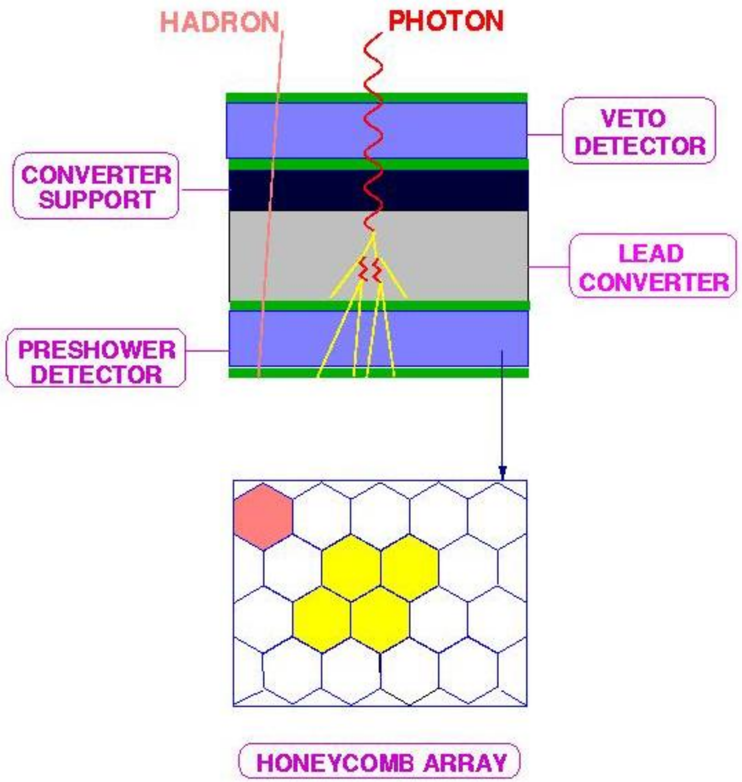


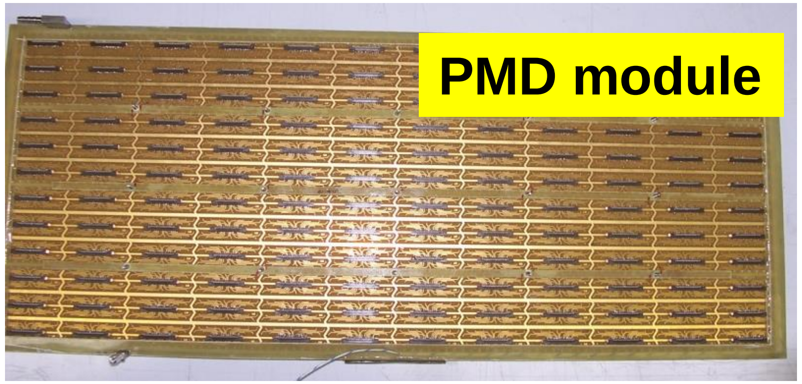
New Upgrade

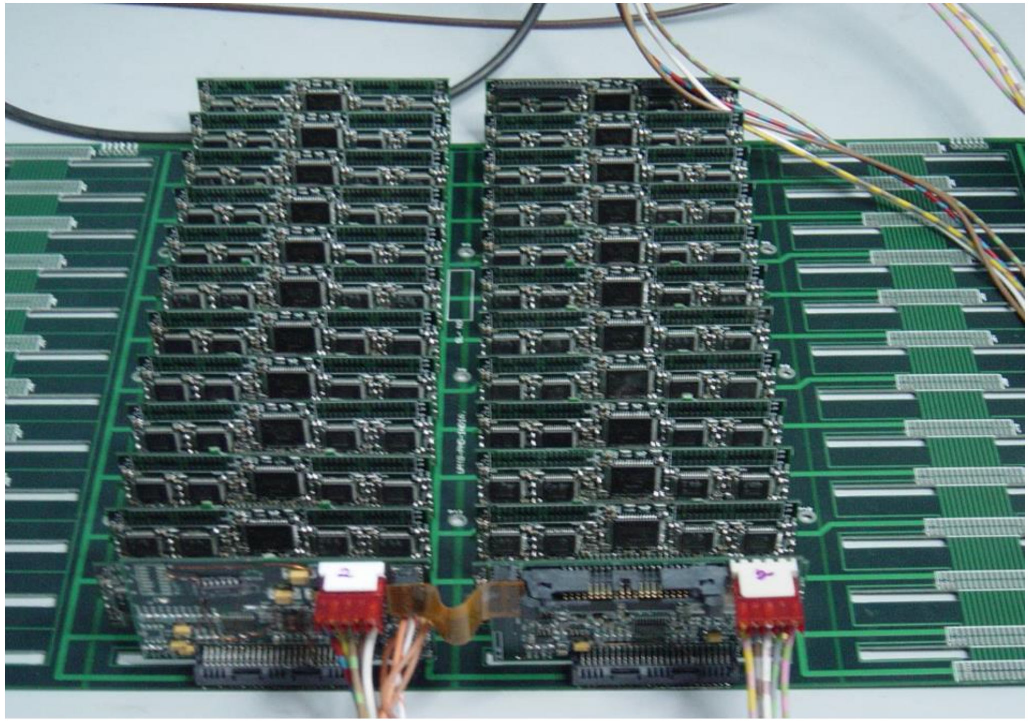
LHC GRID Computing

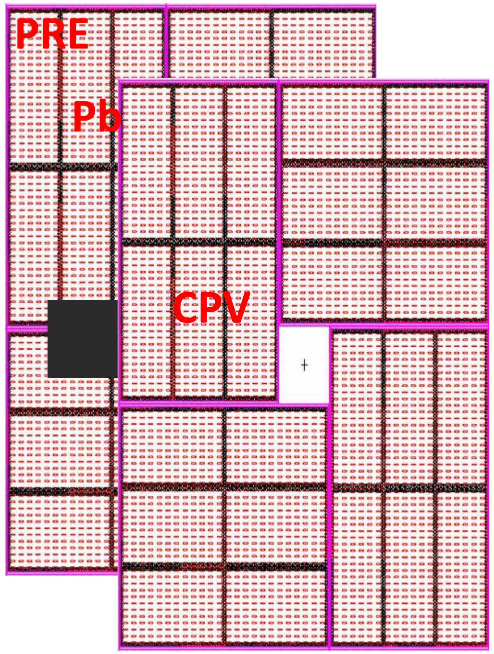


ALICE-PMD

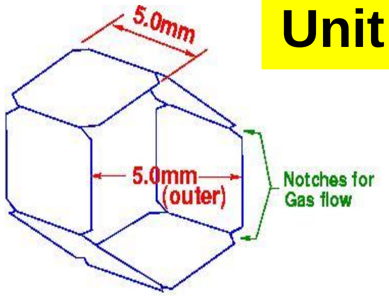




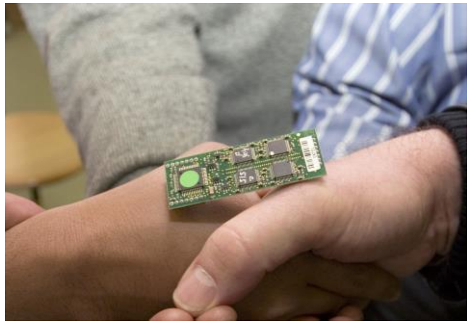




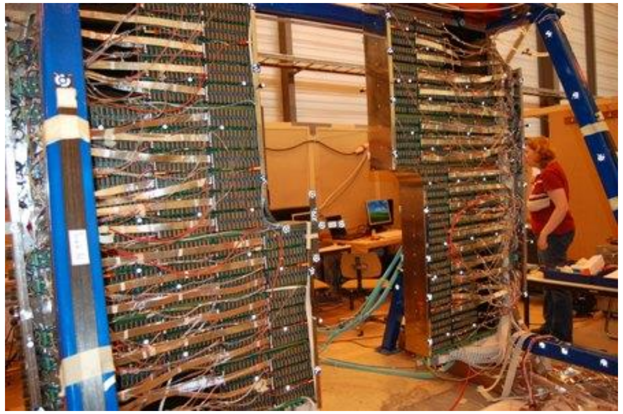
Unit cell

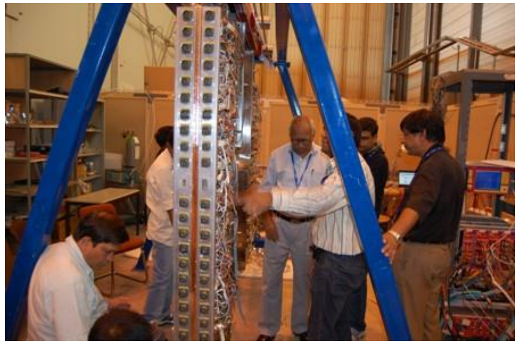


Readout
16 channel MANAS chips



Installation Pictures-PMD





<u>Lot of efforts went in:</u>

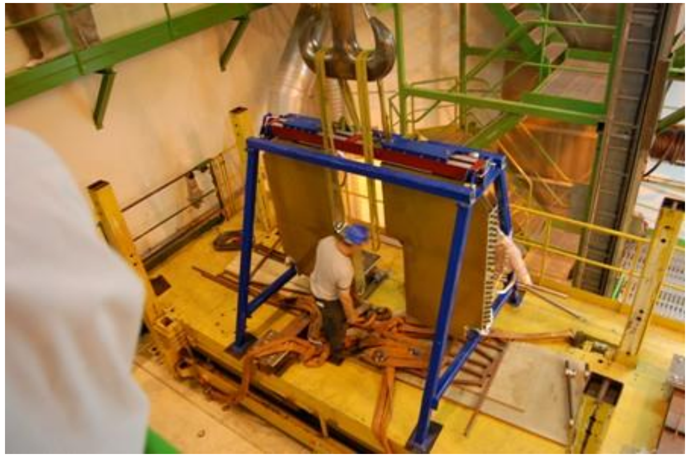
- Module fabrication
- Seasoning and conditioning
- Testing
- Integration and testing with electronics and readout
- Installation and commissioning

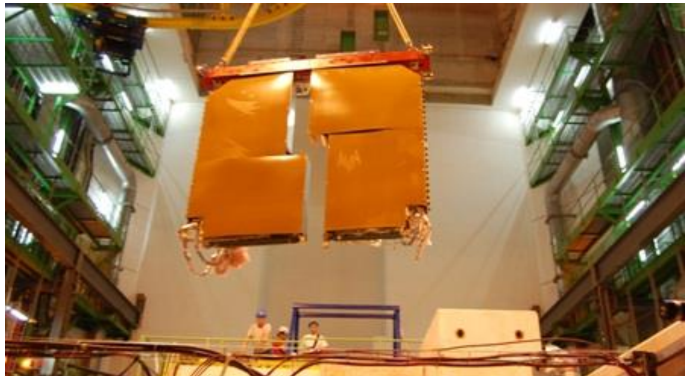
……

Commissioning of PMD in ALICE Cavern (P2)







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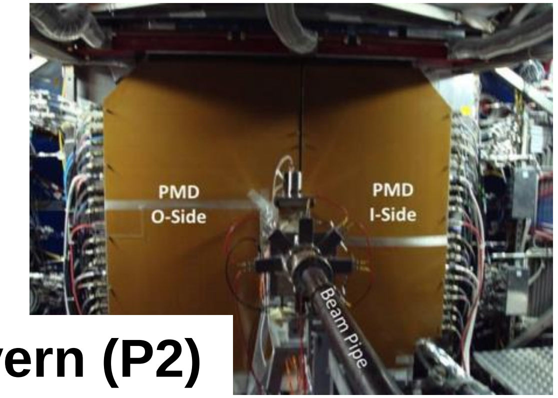
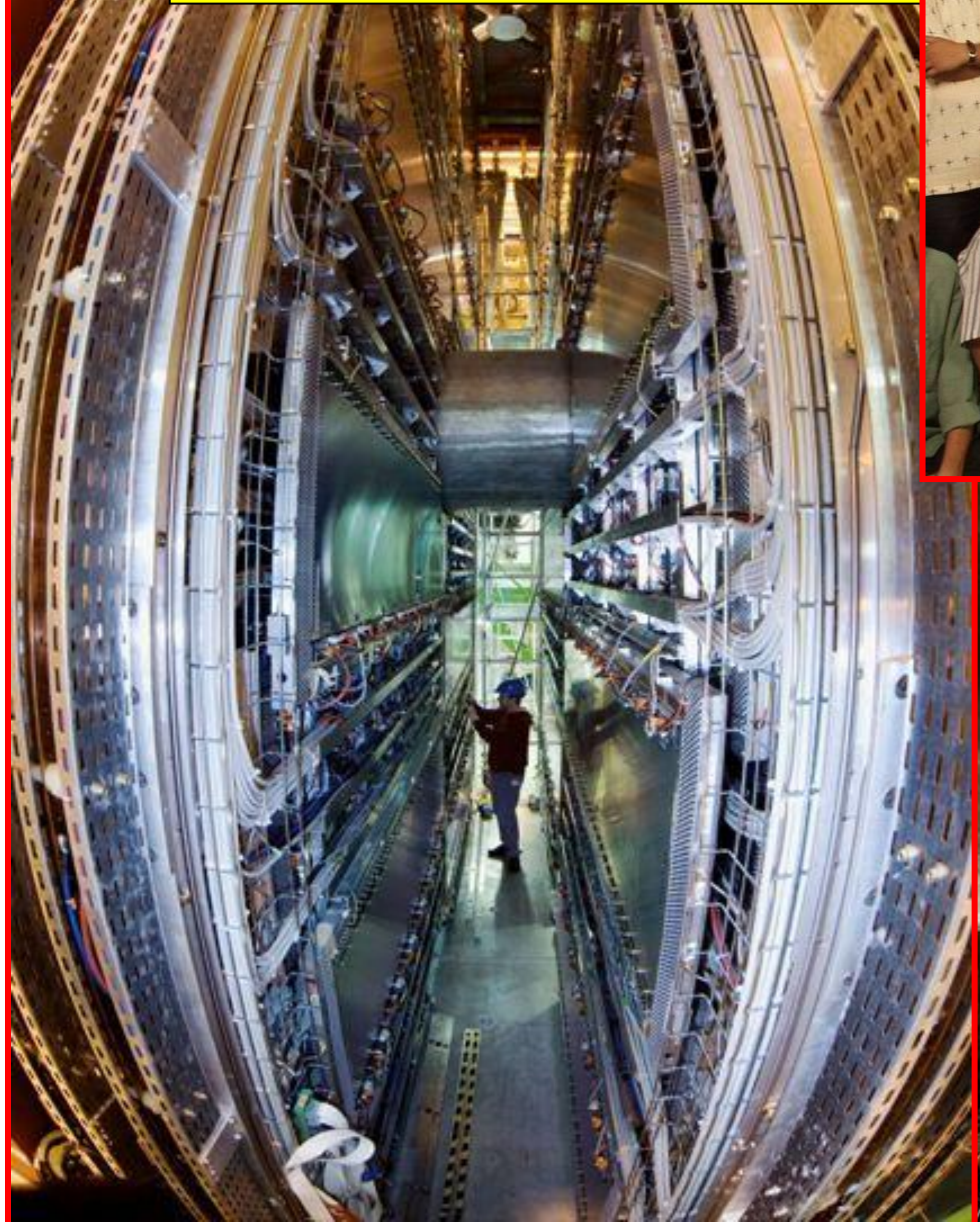
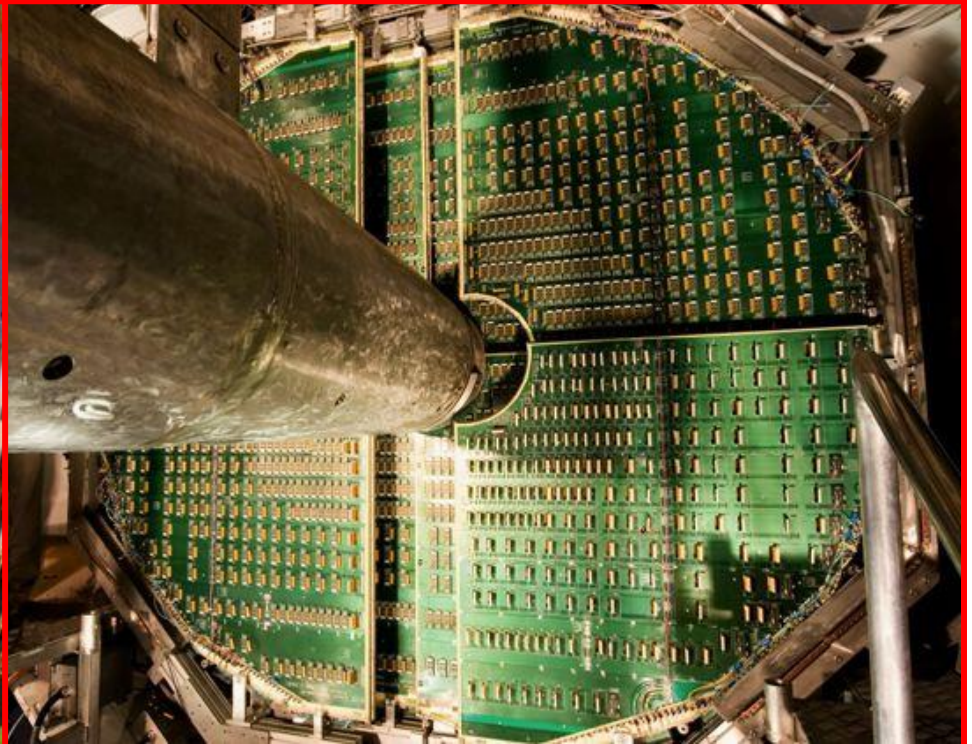
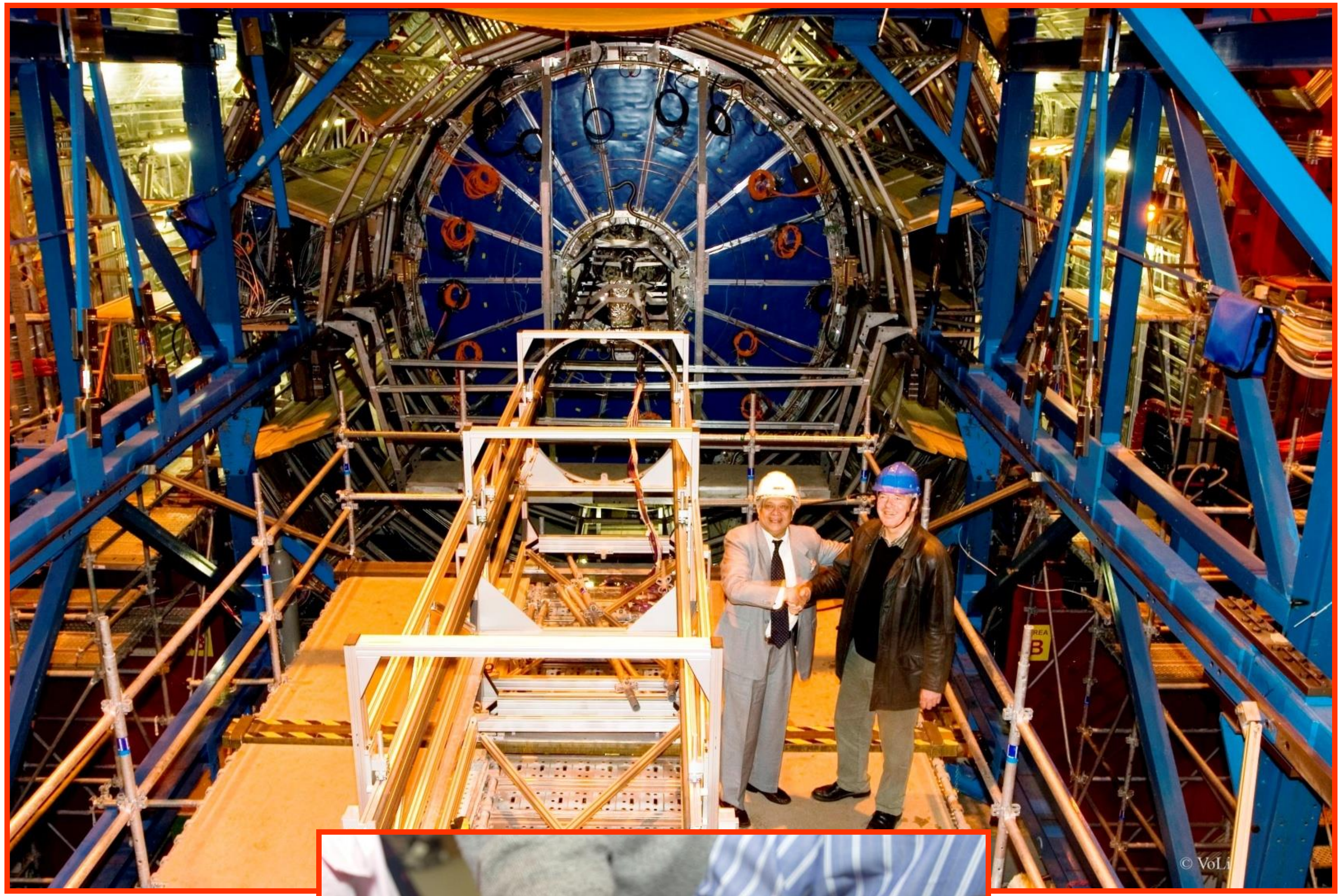


Muon Chambers

~ 100 m^2, > 10^6 channels

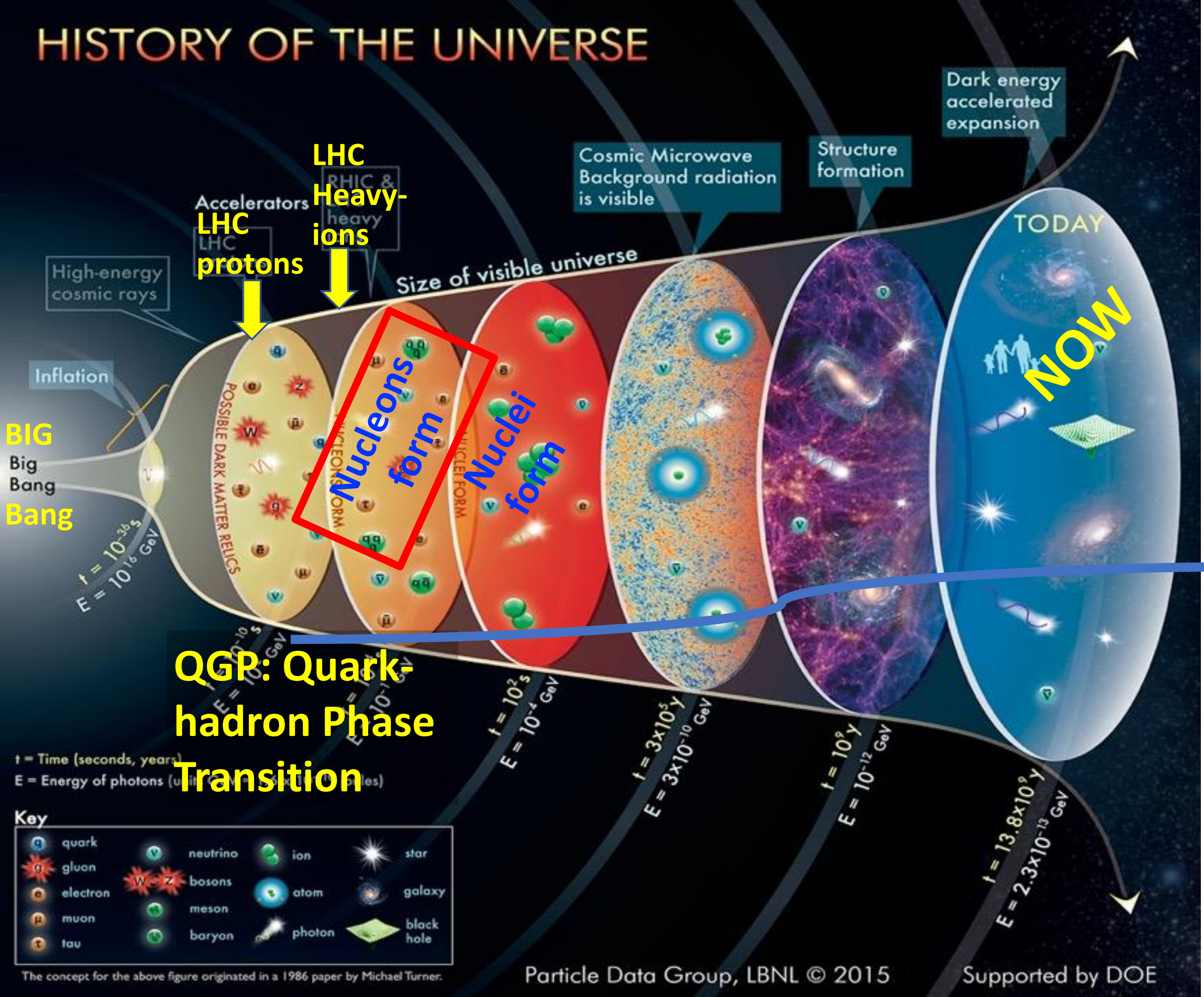


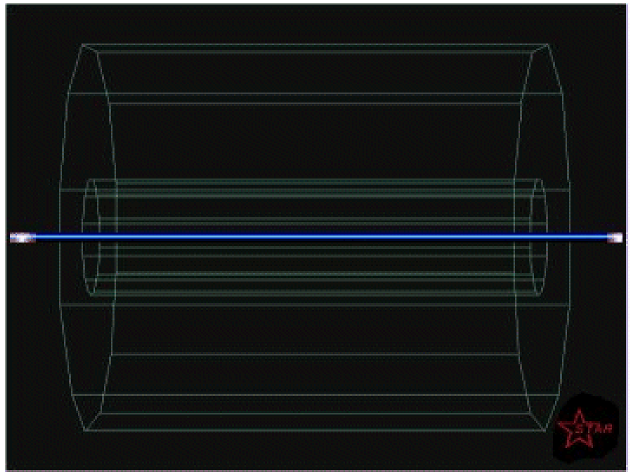




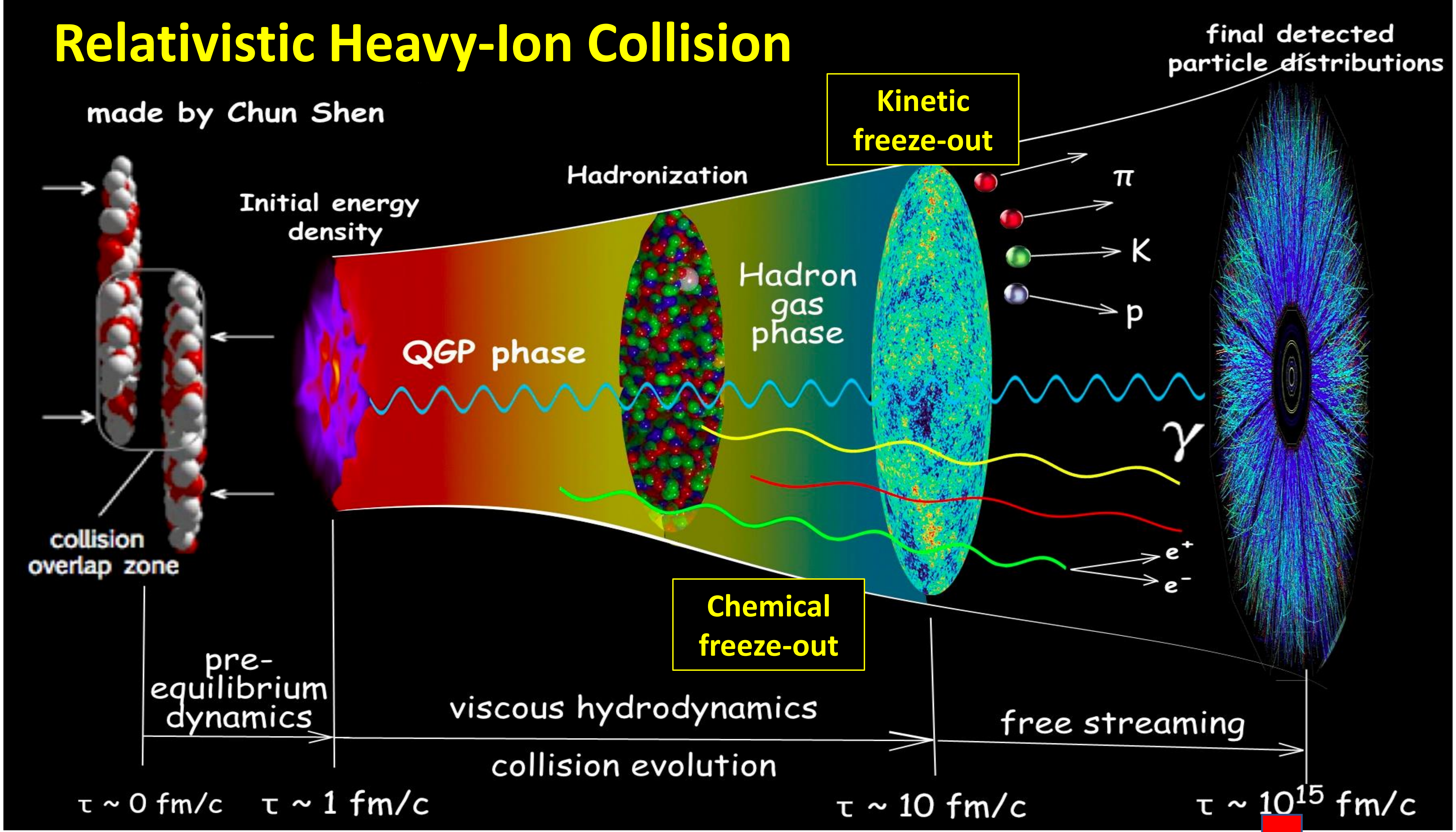
MANAS Chip

Indian Delegates in the ALICE experiment for the LHC Inauguration





Accelerators (LHC)



Initial State Fluctuations

Thermal Fluctuations

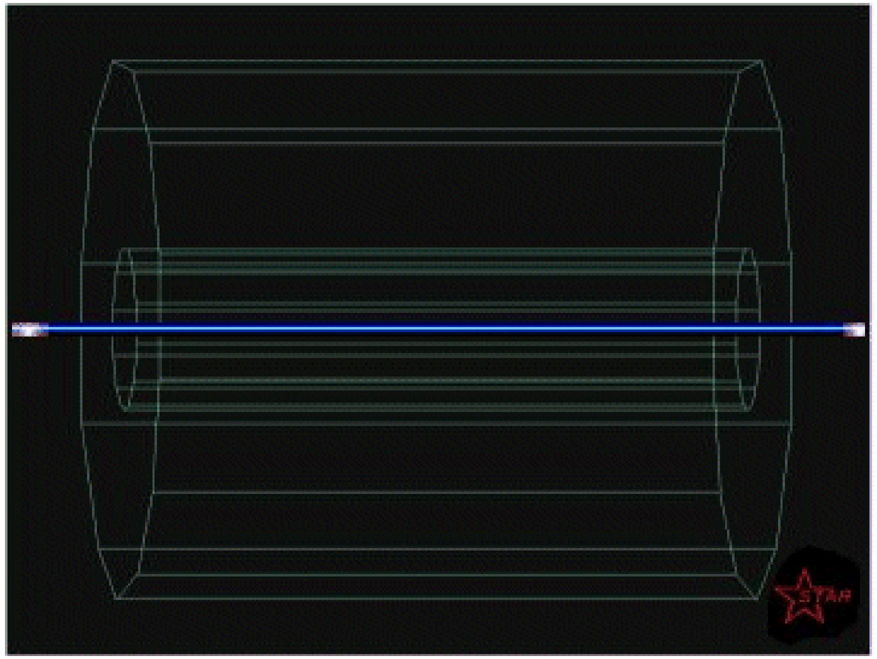
Hadronization

Measurement

(Spectra,

Fluctuation-Correlation, ….)

Thermodynamics of the 'Little Bang'



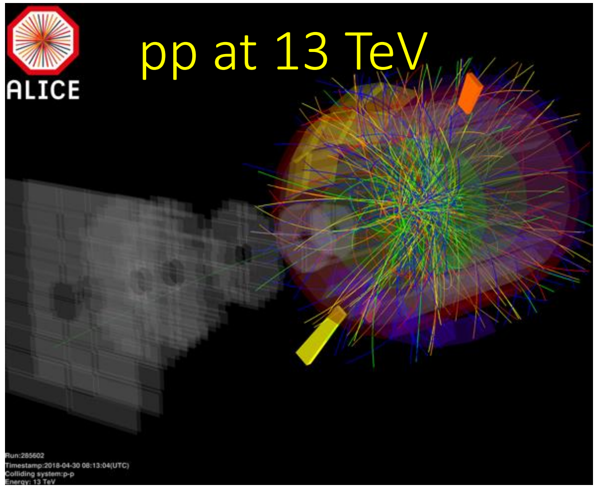
Thermodynamics deals with the study of energy, the conversion of energy between different forms and the ability of energy to do work.

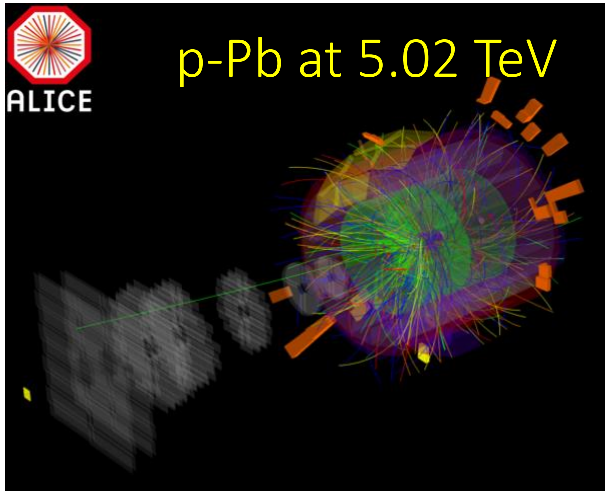
Zeroth law of thermodynamics: if two systems are in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

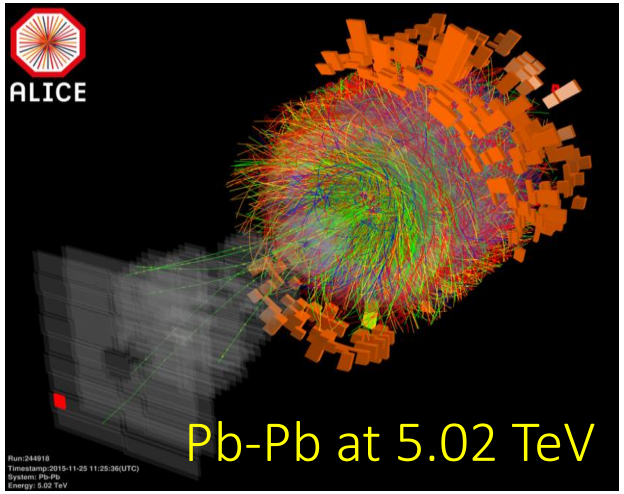
First Law of Thermodynamics is the '*law of conservation of energy*'. Energy can neither be created nor destroyed; it can just be converted from one form to another.

Second Law of Thermodynamics: The total change in entropy of a system plus its surroundings will always increase for a spontaneous process. Entropy is defined as the "measure of disorder or randomness of a system".

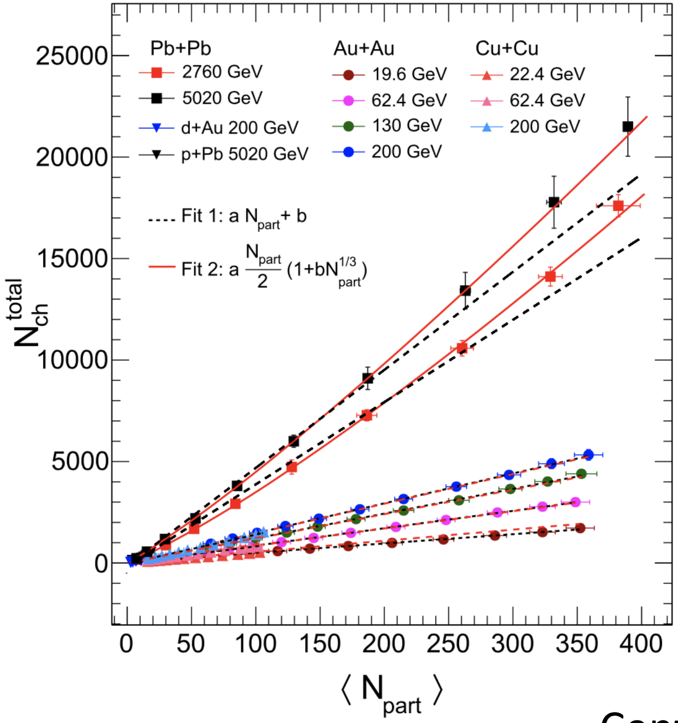
Applicability of thermodynamics



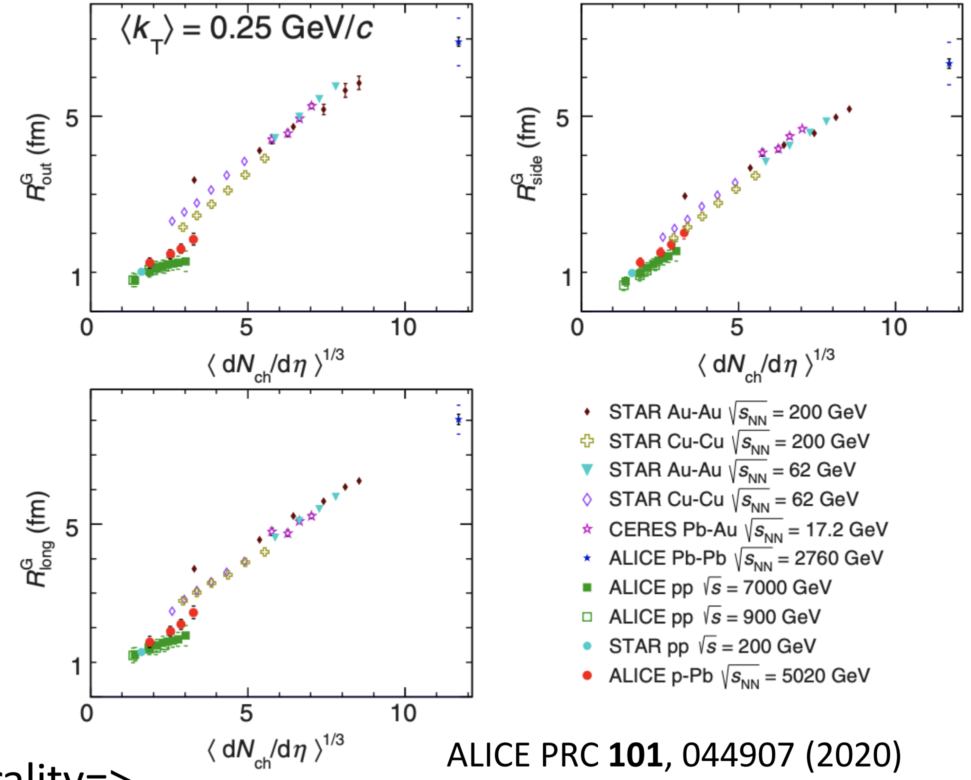




S. Basu *et al*, *JPG*. **48** 025103 (2021)



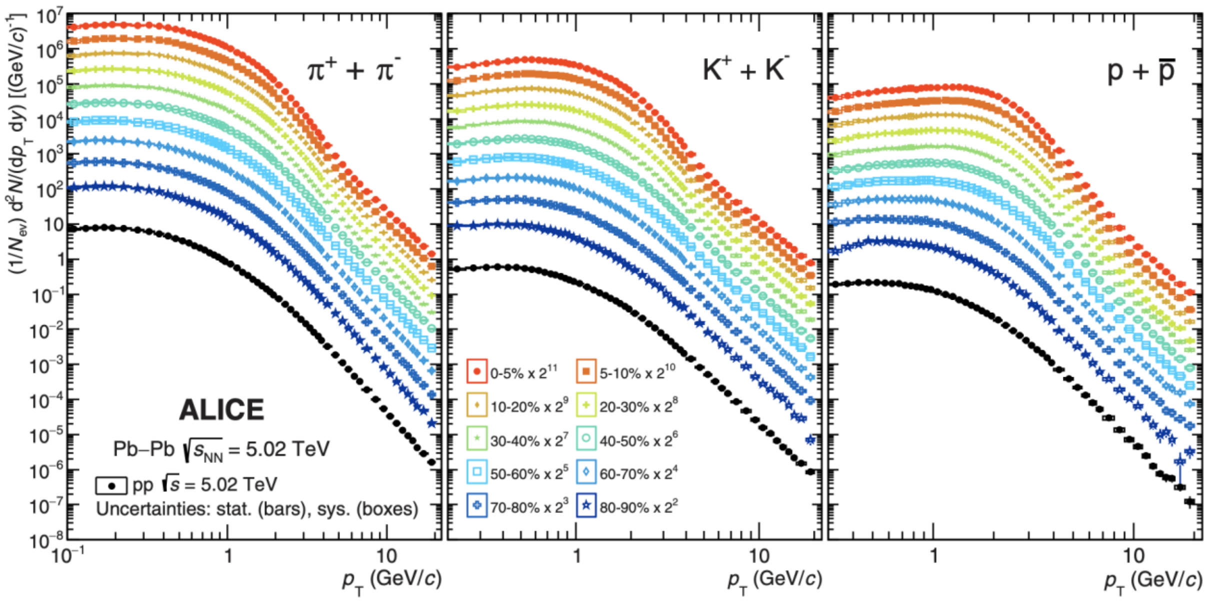
Centrality=>



ALICE PRC **101**, 044907 (2020)

- **Growth in the number of produced particles as well as volume** as a function of centrality and collision energy (keeping *N/V* roughly constant)
- **Success of hydrodynamic calculations** in explaining a large number of experimental results

Evidence for the production of thermal systems (I)



Boltzmann-Gibbs Blast-Wave model:

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

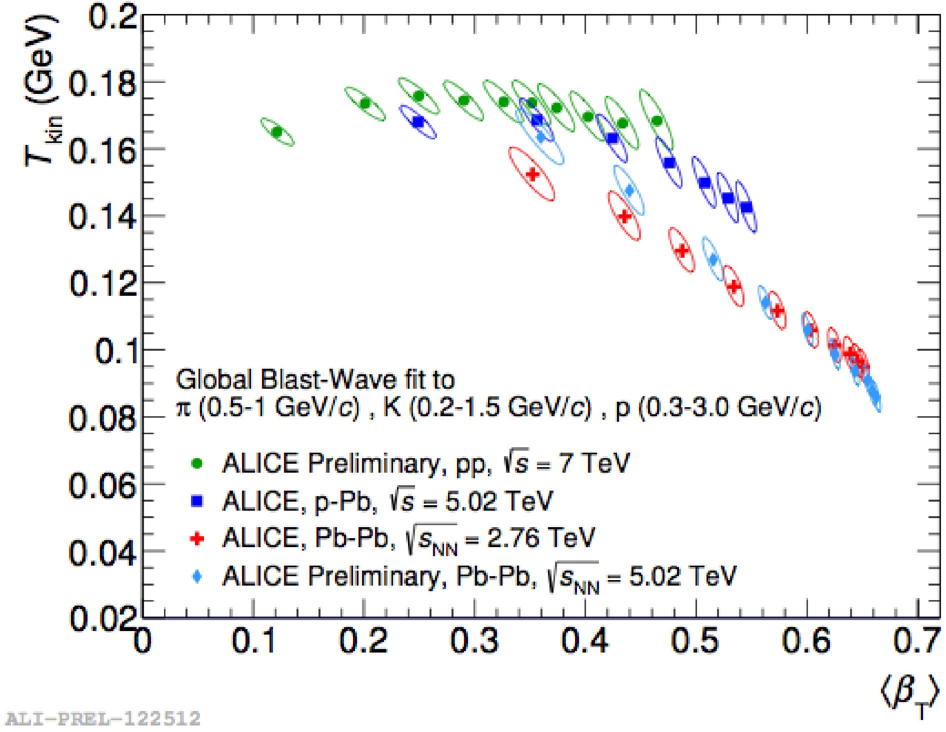
$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{kin}}\right) r\, dr.$$

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

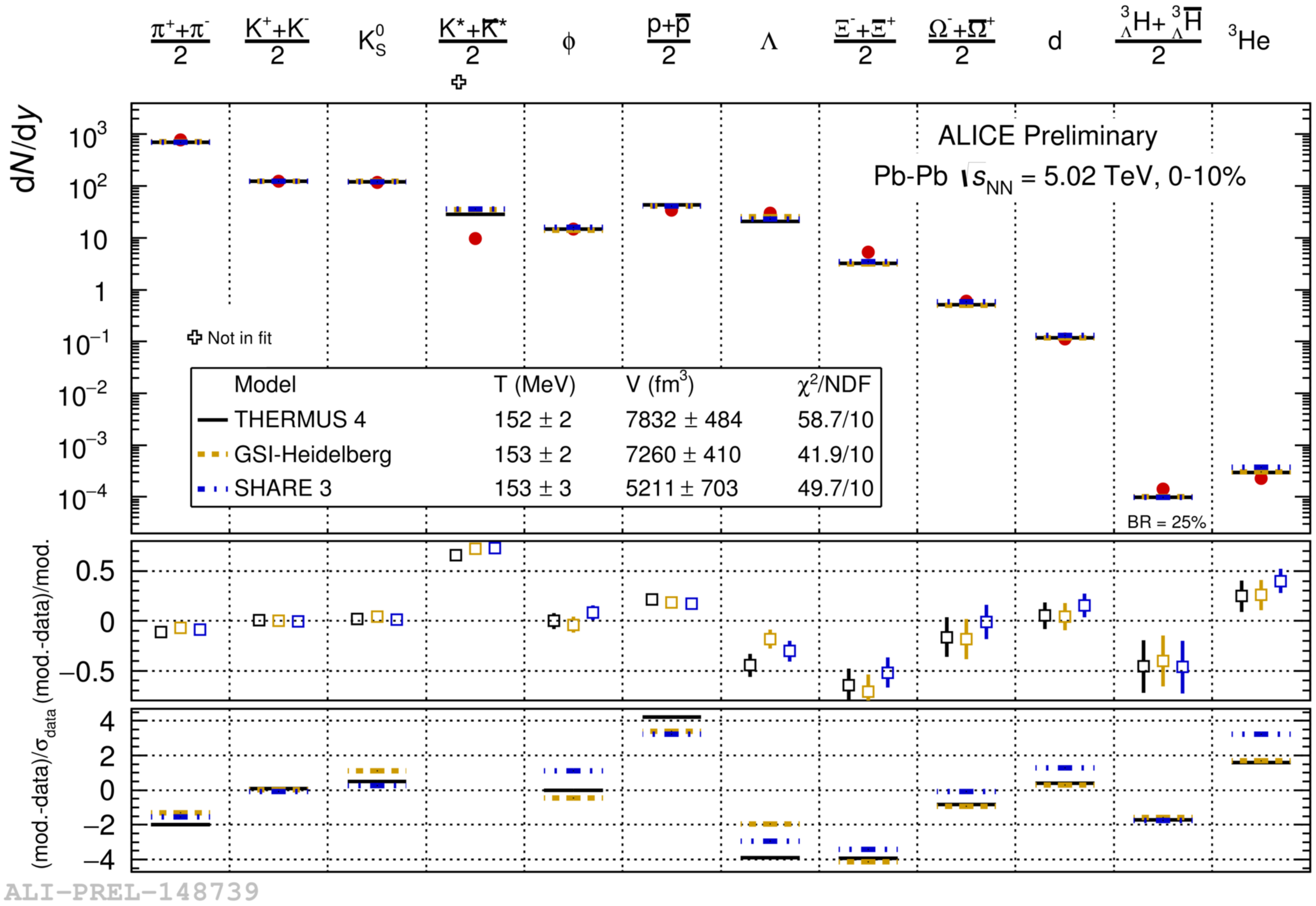
Evolution of Kinetic freeze-out temperature T_{kin} and radial flow velocity $\langle \beta_T \rangle$



- $\langle \beta_T \rangle$ 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



Model	T (MeV)	V (fm^3)	χ^2/NDF
THERMUS 4	152 ± 2	7832 ± 484	58.7/10
GSI-Heidelberg	153 ± 2	7260 ± 410	41.9/10
SHARE 3	153 ± 3	5211 ± 703	49.7/10

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

=>

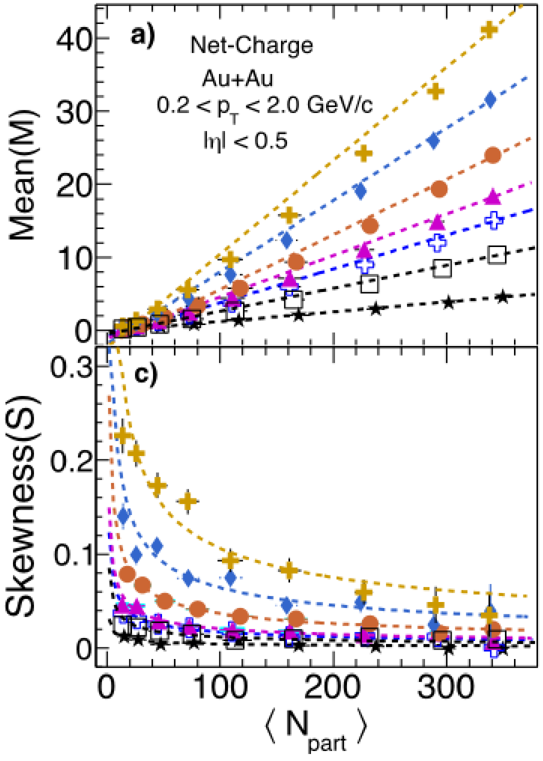
Hadrons are produced in apparent chemical equilibrium in Pb-Pb collisions at LHC.

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

Lattice meets experiment: fluctuation of conserved quantities

Thermodynamic Susceptibility ⟷ Moments of the conserved charge distributions

Distribution and moments of conserved charges



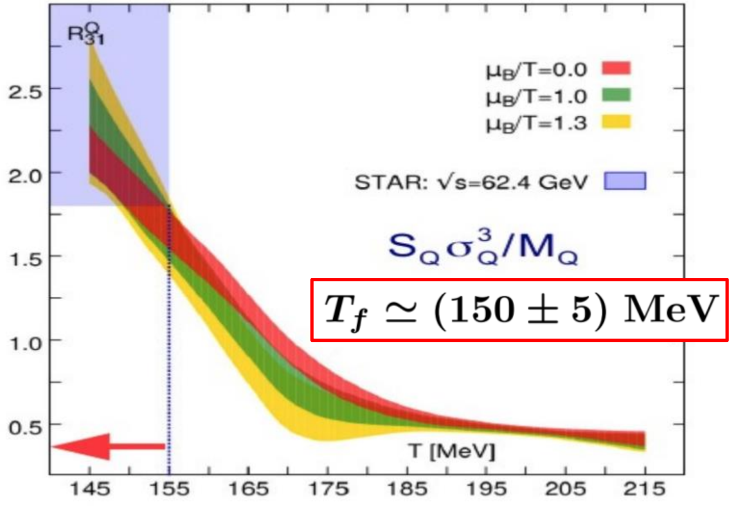
STAR: PRL 113 (2014)
Nihar R. Sahoo, TN

Chemical freezeout parameters are similar to what had been obtained from particle ratios

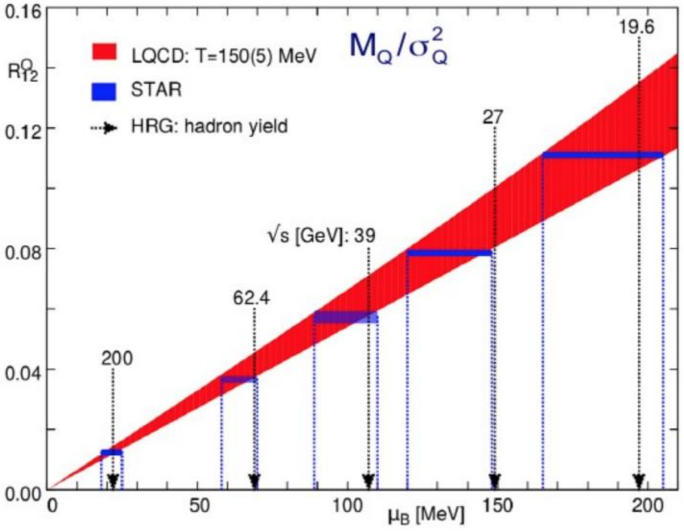
Extraction of Freezeout temperature and chemical potential

- $R_{12} = M/\sigma^2$ μ_B/T → Baryometer
- $R_{31} = S\sigma^3/M$ T → Thermometer

Chemical Freezeout temperature

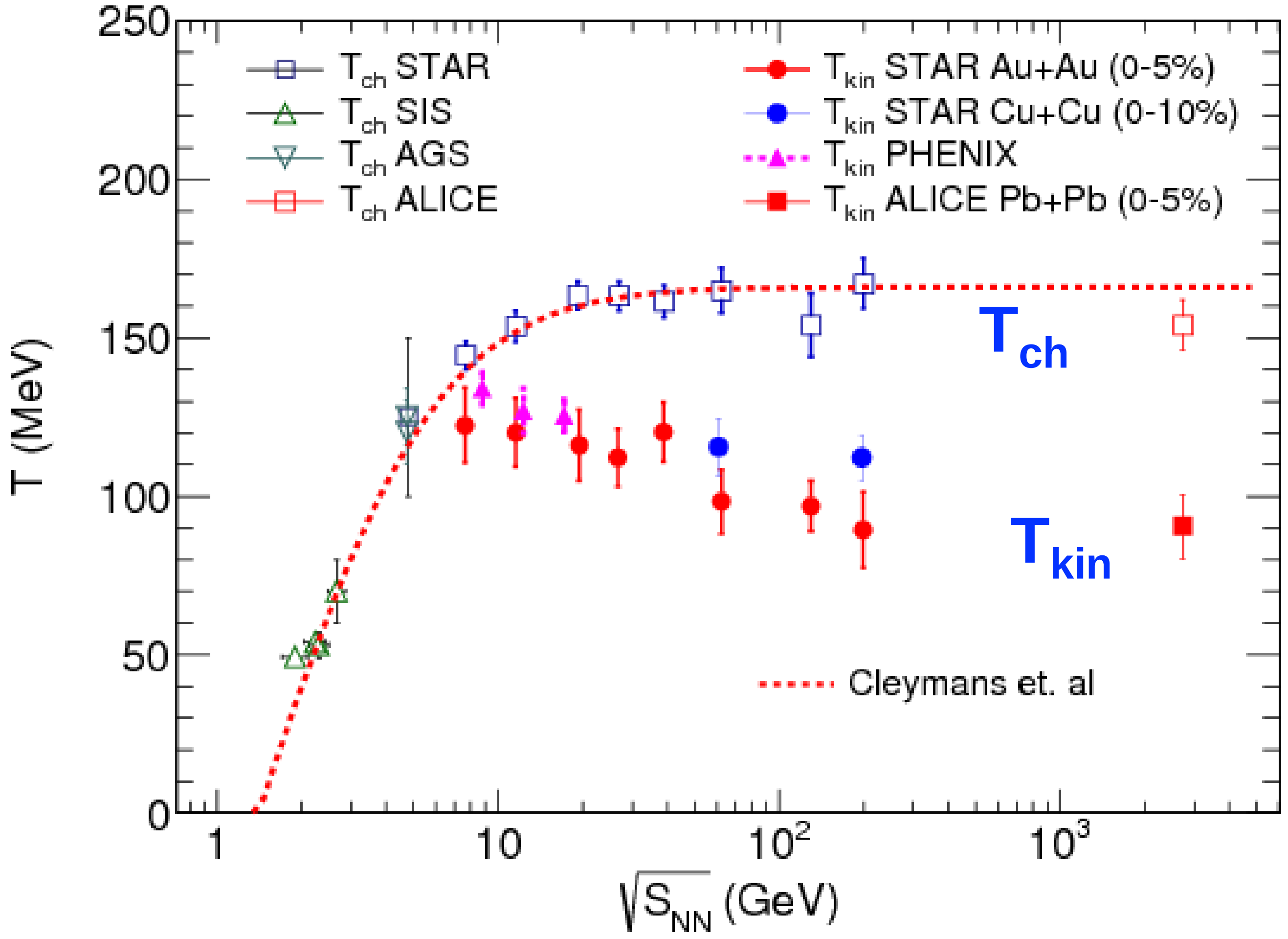


Freezeout chemical potential



Chemical and kinetic freeze-out temperatures

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

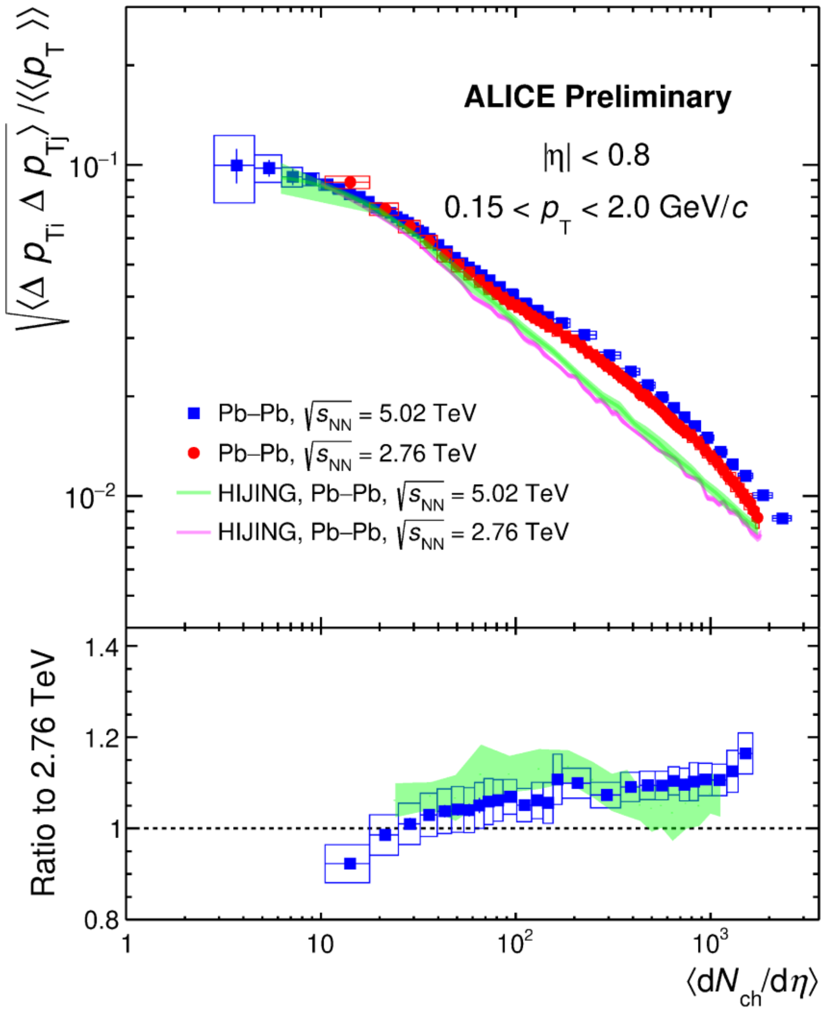


Sumit Basu et al. PRC 94 (2016) 044901
ALICE Collaboration PRD 88 (2013) 044910
STAR Collaboration PRC 79 (2009) 034909
Cleymans et al. PRC 73 (2006) 034905

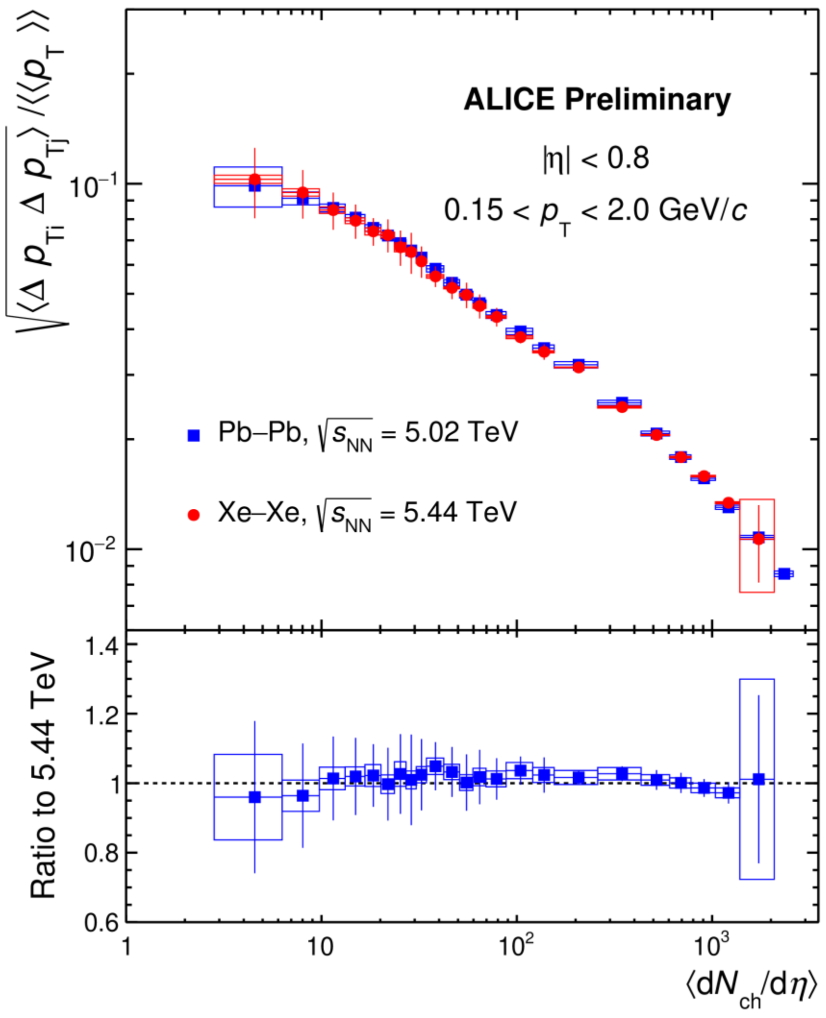
The difference between **T_{kin} and T_{ch}** increases with the increase of collision energy.

Fluctuations of mean p_T

- results from fluctuations of the energy of the fluid when the hydrodynamic expansion starts.
- $\langle p_T \rangle$ is a proxy to the system temperature => measure of **temperature fluctuations ⇒ heat capacity**.



ALI-PREL-526955



ALI-PREL-526499

ALICE Preliminary

$$\langle \Delta p_i \Delta p_j \rangle = \left\langle \frac{\sum_{i,j\neq i}(p_i - \langle p_T \rangle)(p_j - \langle p_T \rangle)}{N_{ch}(N_{ch}-1)} \right\rangle$$

Scaled variance: $\sqrt{\langle \Delta p_{Ti} \Delta p_{Tj} \rangle} / \langle \langle p_T \rangle \rangle$

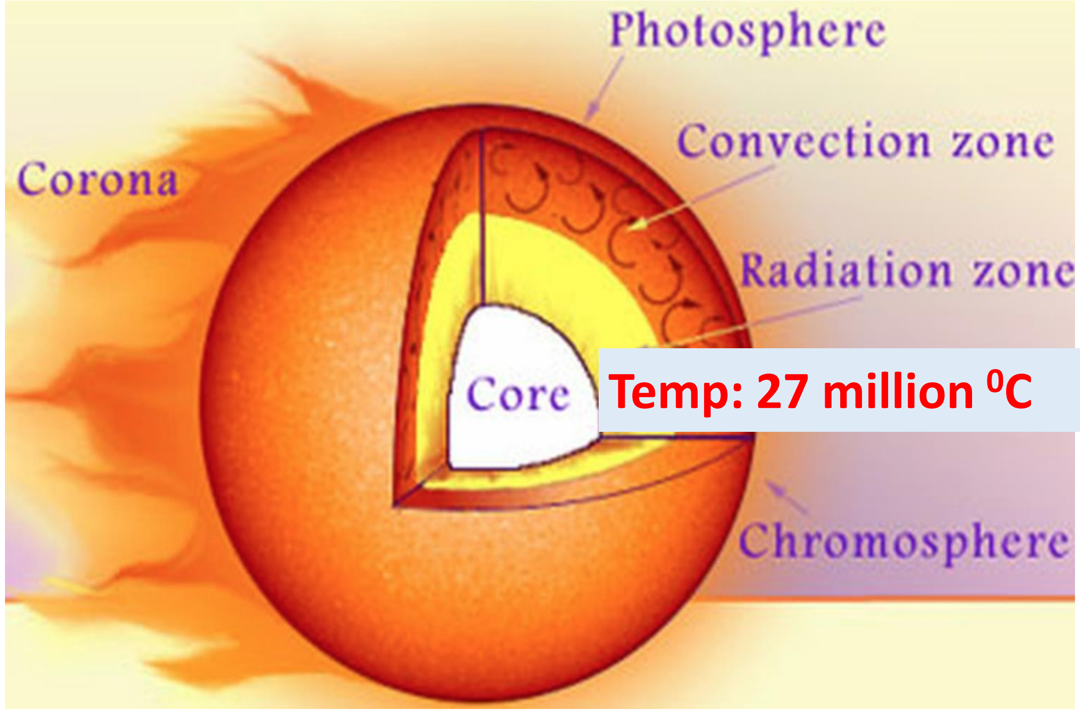
- Fluctuations decrease with increasing multiplicity and increase w/t beam energy.

Tulika Tripathy
Swati Saha
Bushra Ali

Photon Spectra and Effective temperature of the medium

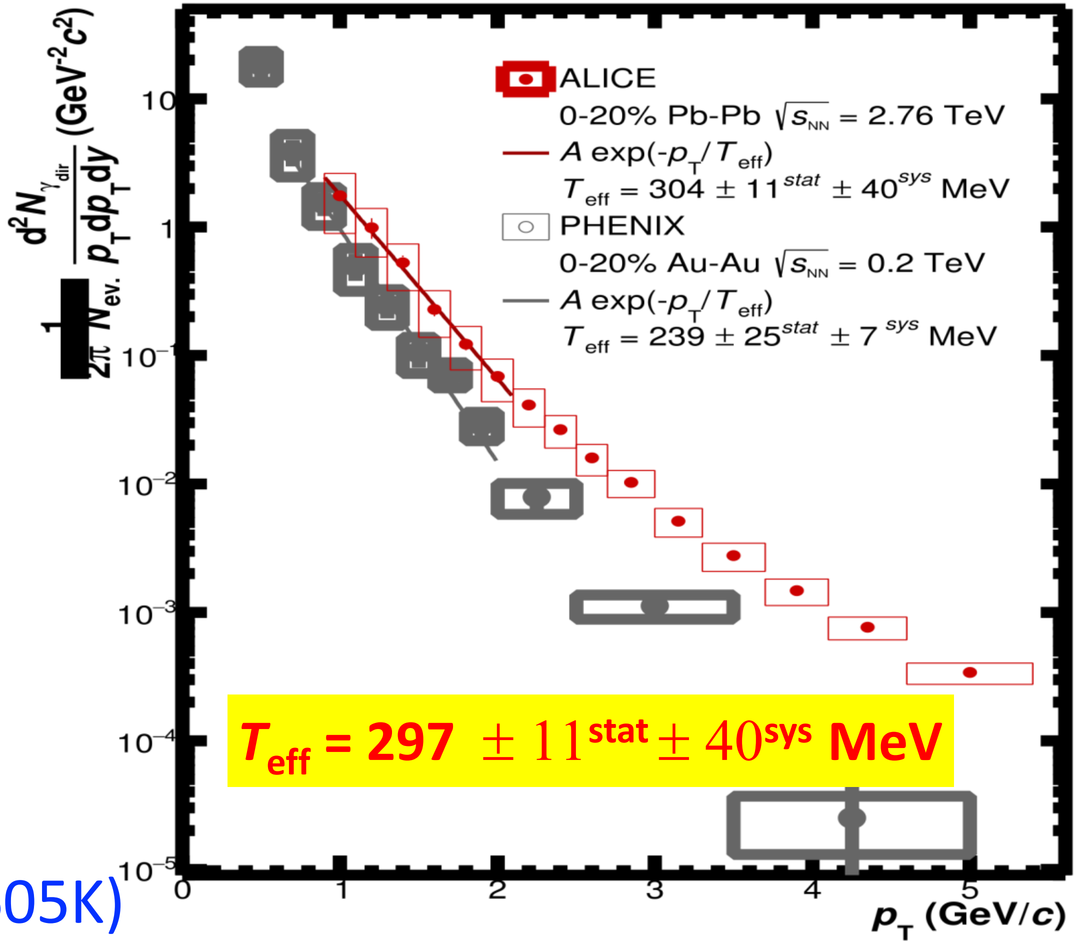
- Photons do not interact via the nuclear force → transparent to the medium
- Photons are emitted in all stages and are unaffected by the medium.

Core of the Sun:



Temp: 27 million ^{0}C

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



$T_{eff} = 297 \pm 11^{stat} \pm 40^{sys}$ MeV

(1eV=11605K)

T_{eff} = 3 million-million deg

LARGEST EVER TEMPERATURE REACHED IN THE LAB ….

Equation of State

Isothermal compressibility

Isothermal compressibility expresses how a system's volume responds to a change in the applied pressure.

$$k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

Expected behavior of k_T at the critical point (T_c):

$$k_T \propto \left(\frac{T - T_C}{T_C}\right)^{-\gamma} \propto \epsilon^{-\gamma}$$

Critical behavior → power law scaling of isothermal compressibility (k_T) → increase by an order of magnitude close to the QCD critical point (CP).

Heat capacity

Heat capacity is a response function which expresses how much a system's temperature changes when heat is transferred to it, or equivalently how much δE is needed to obtain a given δT.

- **Heat capacity:**

$$C = \left(\frac{\partial E}{\partial T}\right)_v$$

Specific Heat: the amount of energy per unit mass needed to change its temperature by one unit (for example by one deg C). This amount is directly proportional to mass, so it is expressed per unit mass.

Multiplicity Fluctuations => Isothermal compressibility (k_T)

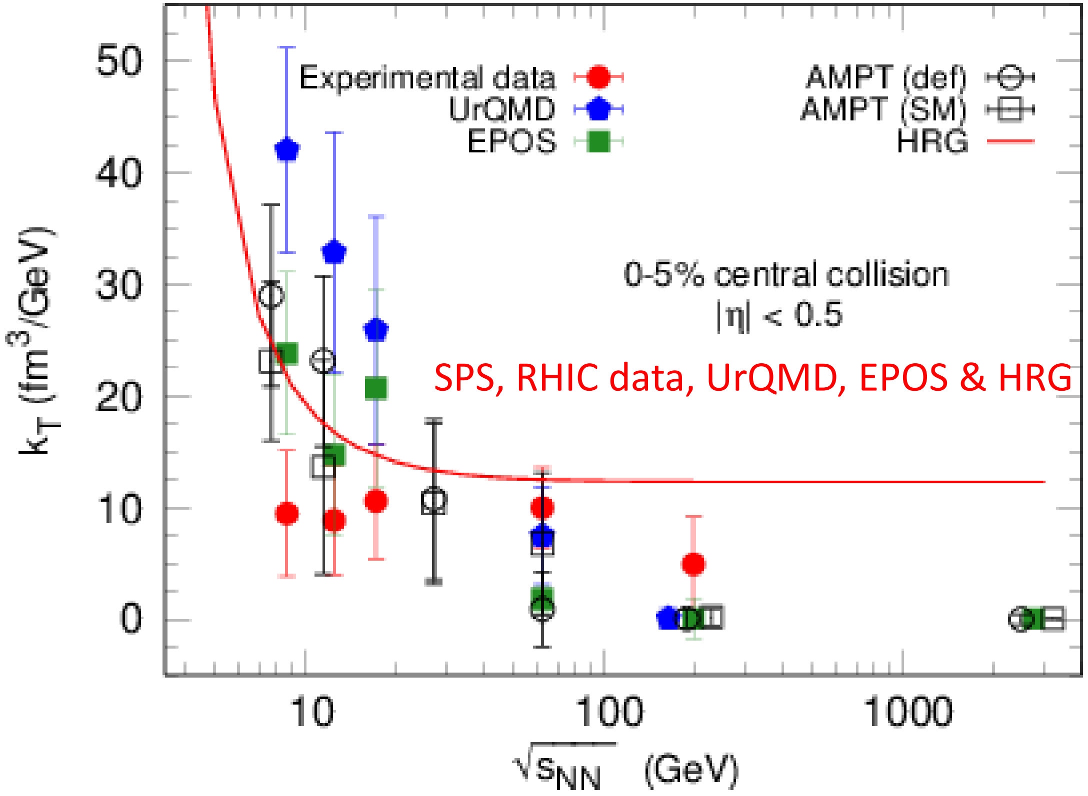
$$k_T = \frac{\sigma^2}{< N >^2} \frac{V}{k_B T}$$

[*S. Mrowczynski, Phys. Lett. B 430 (1998) 9*]

$$\omega_{ch} = \frac{k_B T \langle N_{ch} \rangle}{V} k_T$$

Basic Idea: Measure event-by-event fluctuations of particle multiplicity. Measure the variance of these fluctuations to assess the isothermal compressibility.

k_T vs collision energy

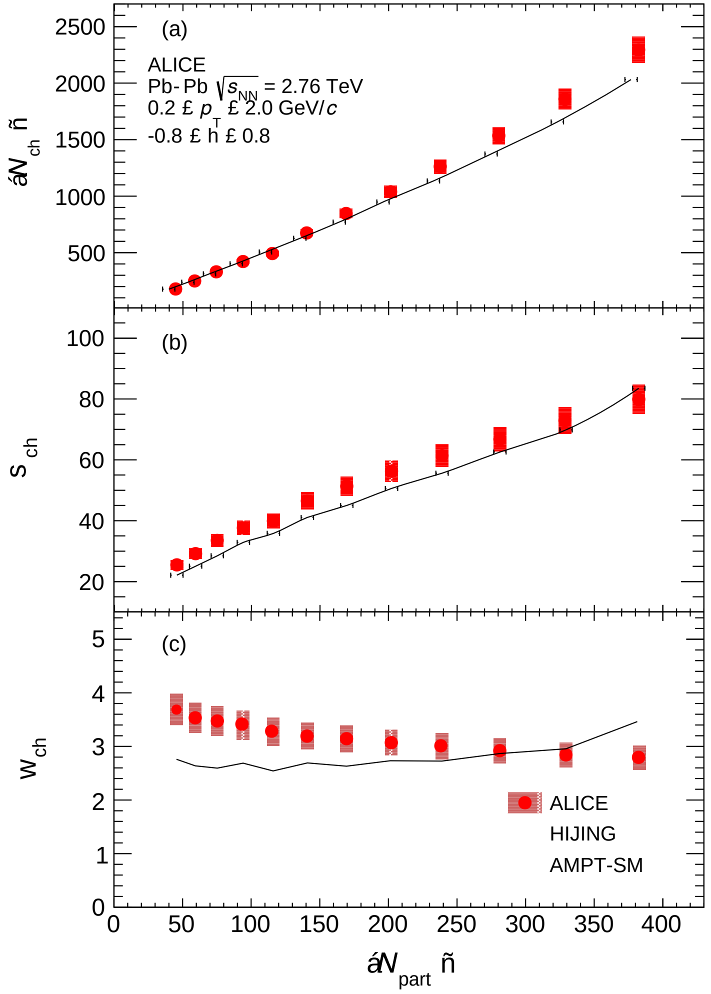


- M. Mukherjee, S. Basu, TN et al. Phys.Lett. B784 (2018) 1-5
- A. Khuntia, R. Sahoo, TN et al. Phys. Rev. C 100, 014910 (2019

Multiplicity fluctuations in Pb–Pb@2.76 TeV

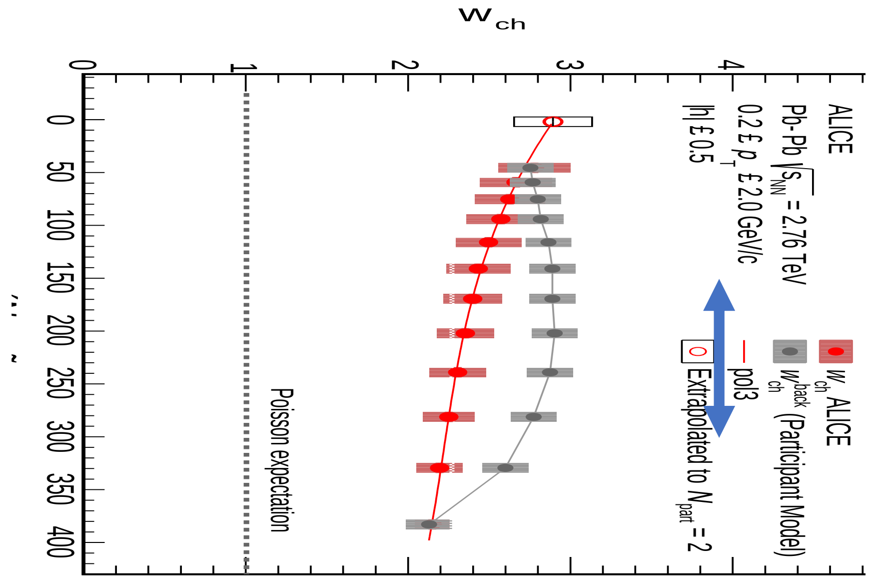
ALICE Collaboration

ALICE: Eur. Phys. J. C (2021) 81:1012



Background to the measured fluctuations:

- **Poisson expectation**: For an ideal gas, the number fluctuations are described by the Poisson distribution. ω_{ch} = 1, independent of multiplicity.
- **Scaled Variance from Participant Model**



For central collisions:

- T_{ch} = 0.156 ± 0.002 GeV
- Volume= 5330 ± 505 fm^3
- $\langle N_{ch} \rangle$ = 1410 ± 47 (*syst*)

- Fluctuations above the Poisson estimation gives, ω_{ch} = 1.15 ± 0.06

=> k_T=27.9 ± 3.18 fm^3/GeV.

Maitreyee Mukherjee, Sumit Basu

This result serves as a conservative upper limit of *kT* until various contributions to the background are properly understood and evaluated.

Estimates of the specific heat (c_V)

Phys.Rev. C94 (2016)
Sumit Basu, S. Chatterjee, R. Chatterjee, B. Nandi TN

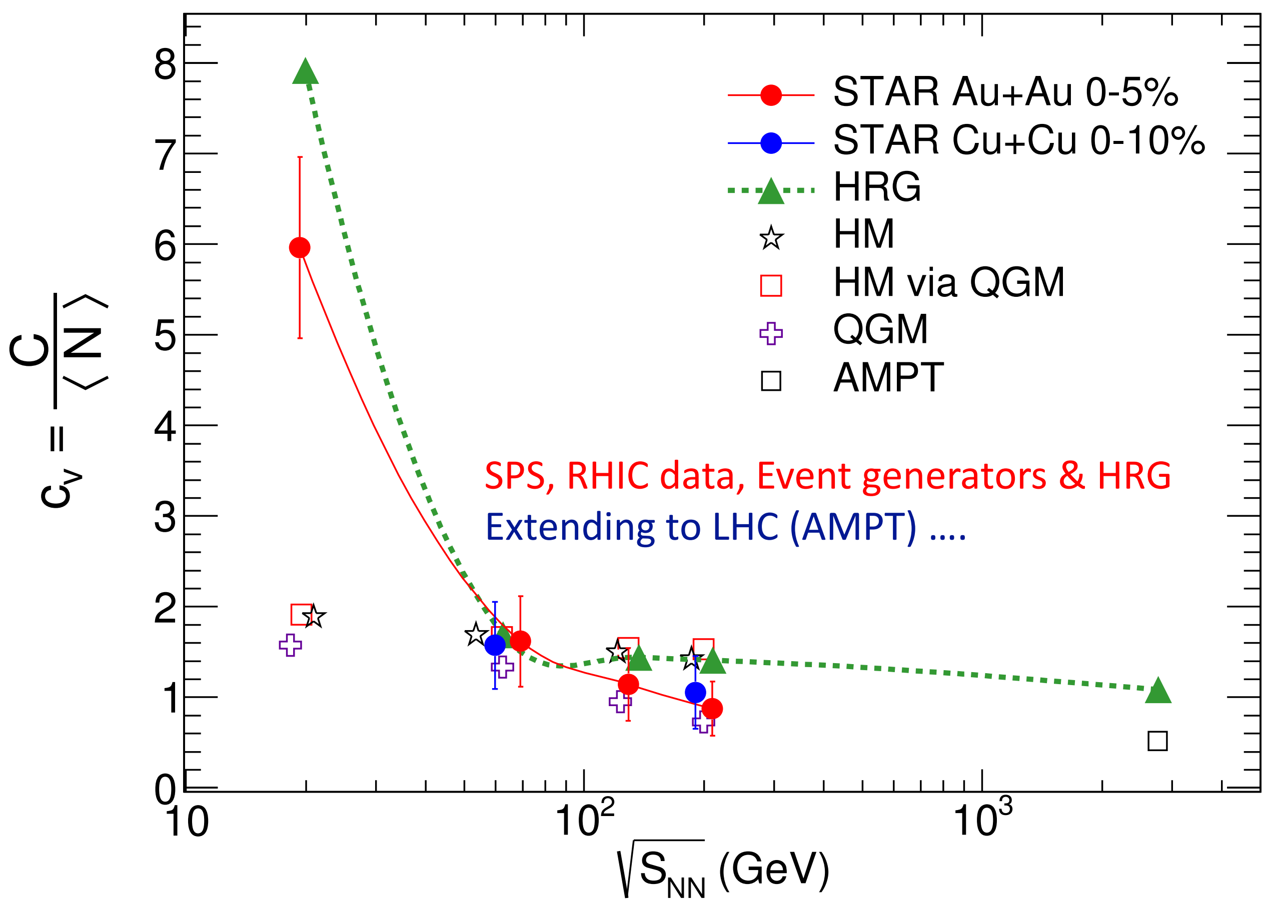
Heat capacity:

$$C = \left(\frac{\partial E}{\partial T}\right)_v \quad \Rightarrow \quad \frac{1}{C} = \frac{(\langle T^2\rangle - \langle T\rangle^2)}{\langle T\rangle^2}$$

T_{eff} has contributions from thermal (T_{kin}) and collective motion in the transverse direction ($\langle \beta_T \rangle$): radial flow

$$\frac{1}{C} = \frac{(\Delta T_{\rm eff}^{dyn})^2}{\langle T_{\rm kin}\rangle^2}.$$

Basic Idea: Measure event-by-event fluctuations of system temperatures. Measure the variance of these fluctuations to assess the heat capacity

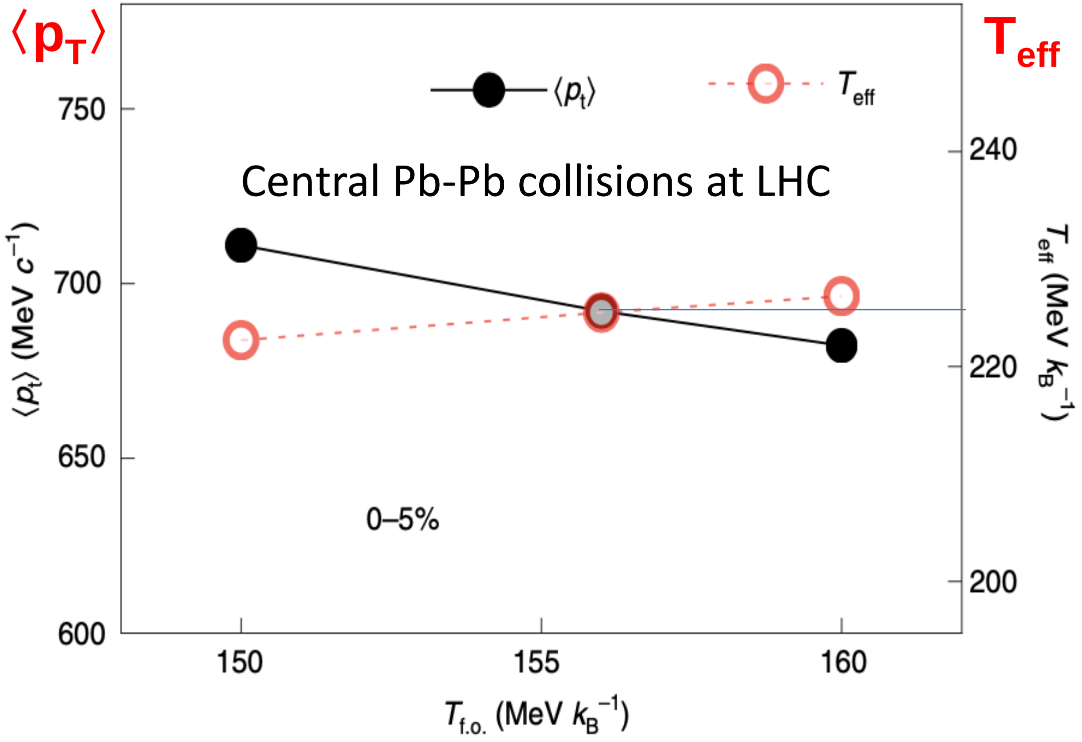


Specific heat: $c_V = \frac{C}{\langle N \rangle} = \frac{C}{VT^3}$

Estimate c_V at kinetic freezeout temperature

Thermodynamics of hot strong-interaction

Nature Physics Letters 2020
Gardim, Giacalone, Luzum and Ollitraut



Variation of ⟨p_T⟩ and T_{eff} as a function of the freeze-out temperature in ideal hydrodynamic simulations ….

QGP, modelled as a massless ideal gas with Boltzmann statistics, has a particle density $n = gT^3/\pi^2$

From experimental data, $g \approx 30$
=> This large number shows that the colour degrees of freedom are active.

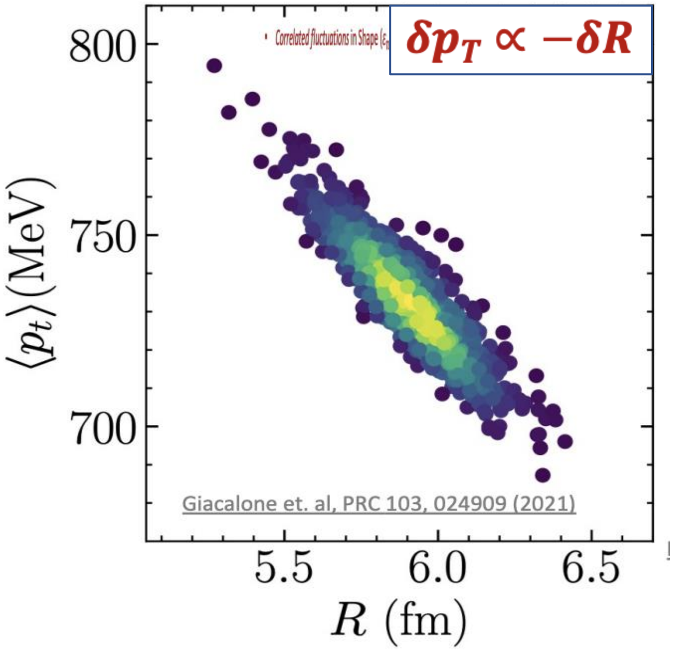
Entropy density:

$$s(T_{\rm eff}) = \frac{1}{V_{\rm eff}} \frac{S}{N_{\rm ch}} \frac{dN_{\rm ch}}{dy}$$

$$s(T_{\rm eff}) = 20 \pm 5\,{\rm fm}^{-3}$$

$$s(T_{\rm eff})/T_{\rm eff}^3 = 14 \pm 3.5$$

Accessing precursor stage of QGP formation

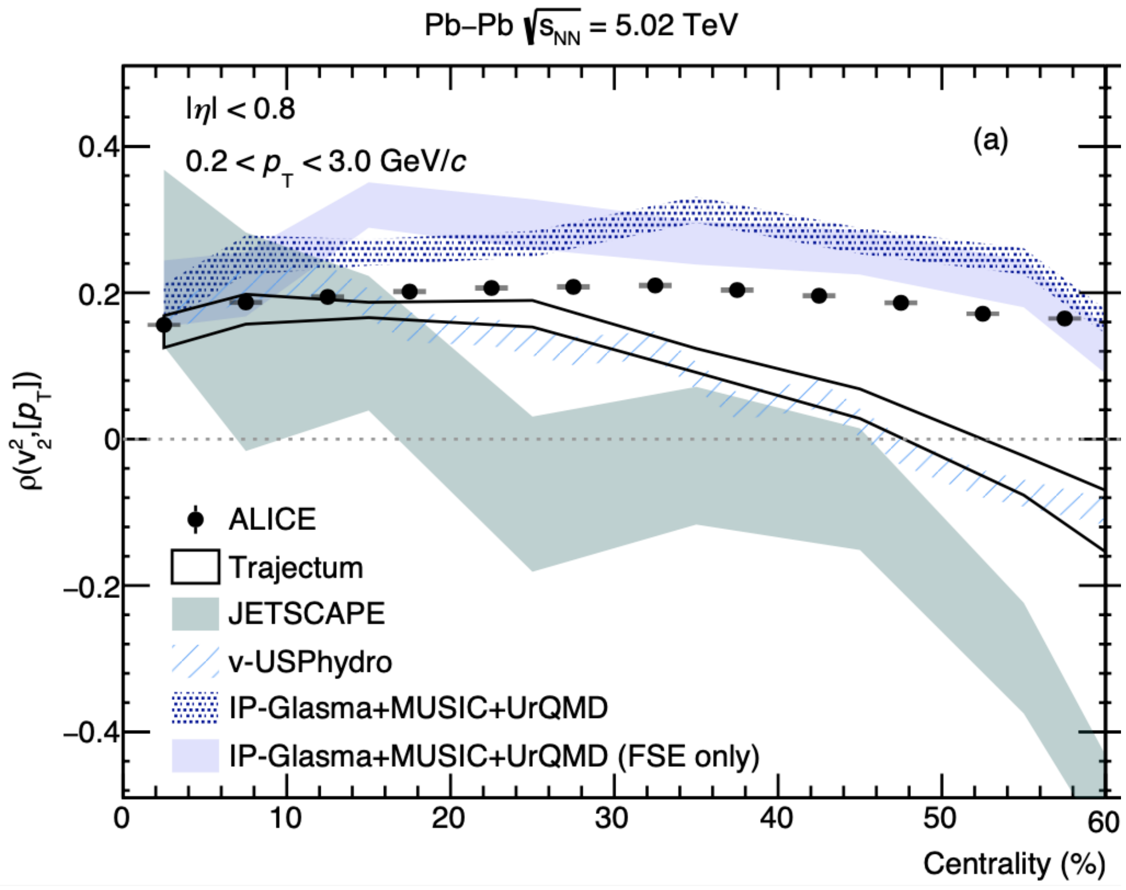


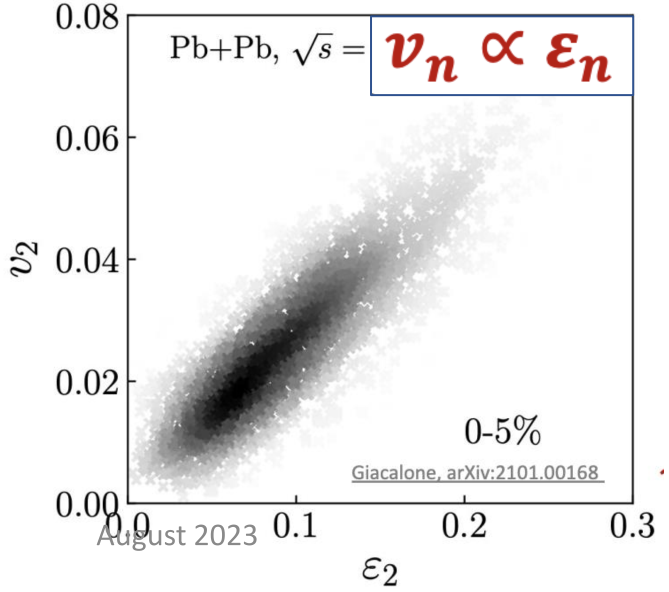
=> v_n - mean-p_T correlations

(i) Constrain the initial state, and
(ii) nuclear deformation.

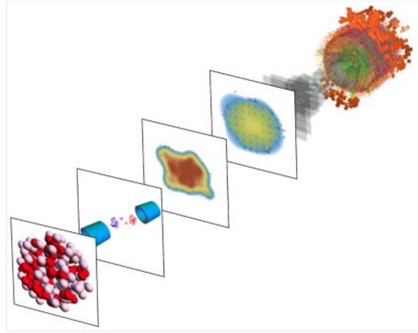
PRL **131**, 202302

ALICE collaboration, PLB 834 (2022) 13793



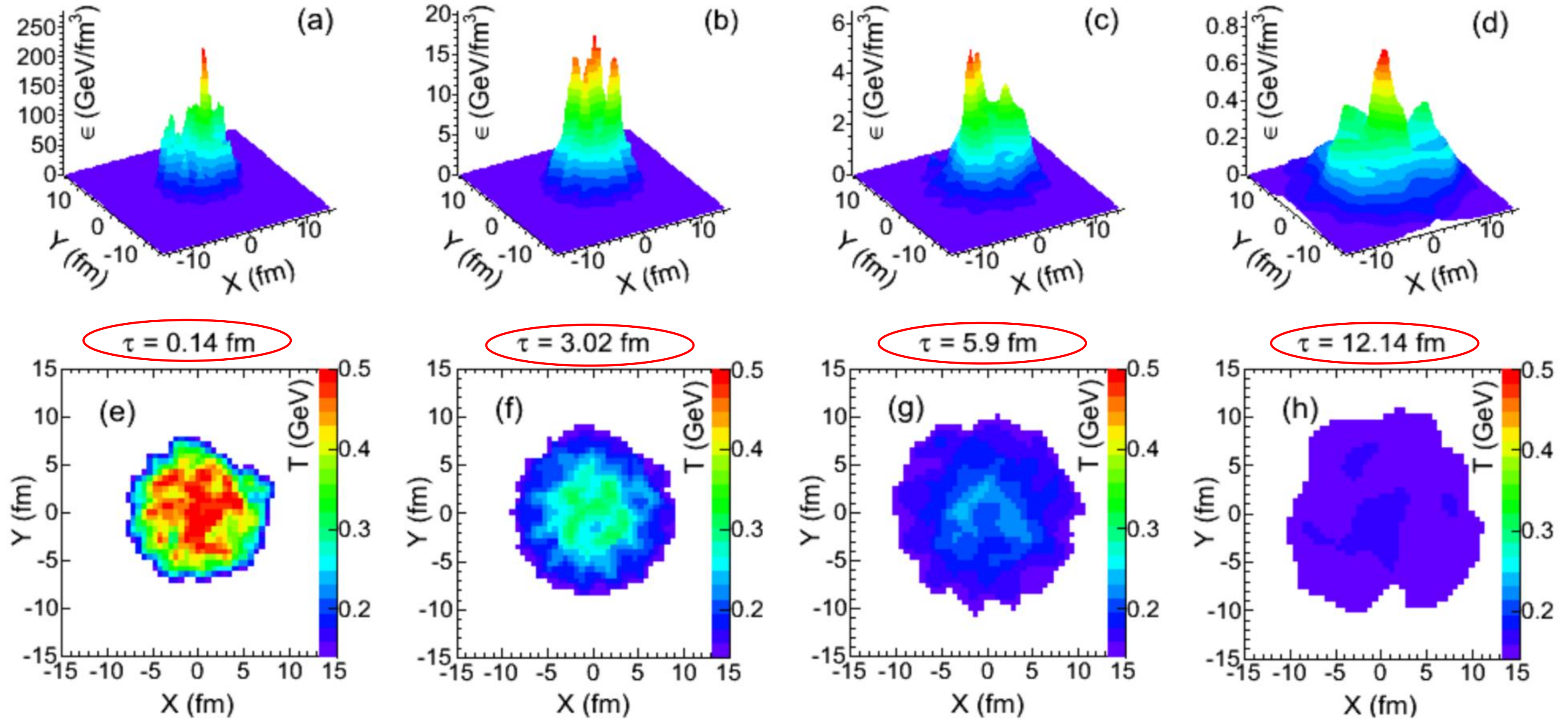


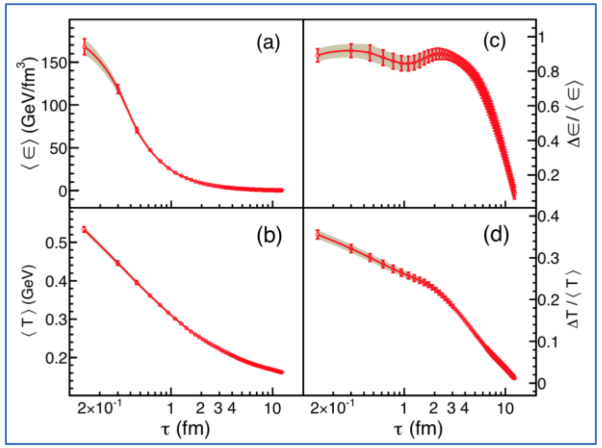
Thick-skinned: Using heavy-ion collisions at the LHC, scientists determine the thickness of neutron "skin" in lead-208 nuclei



Hydrodynamic simulation of central Pb-Pb at 2.76 TeV

arXiv:1504.04502 [nucl-ex]
Sumit Basu, TN et al.

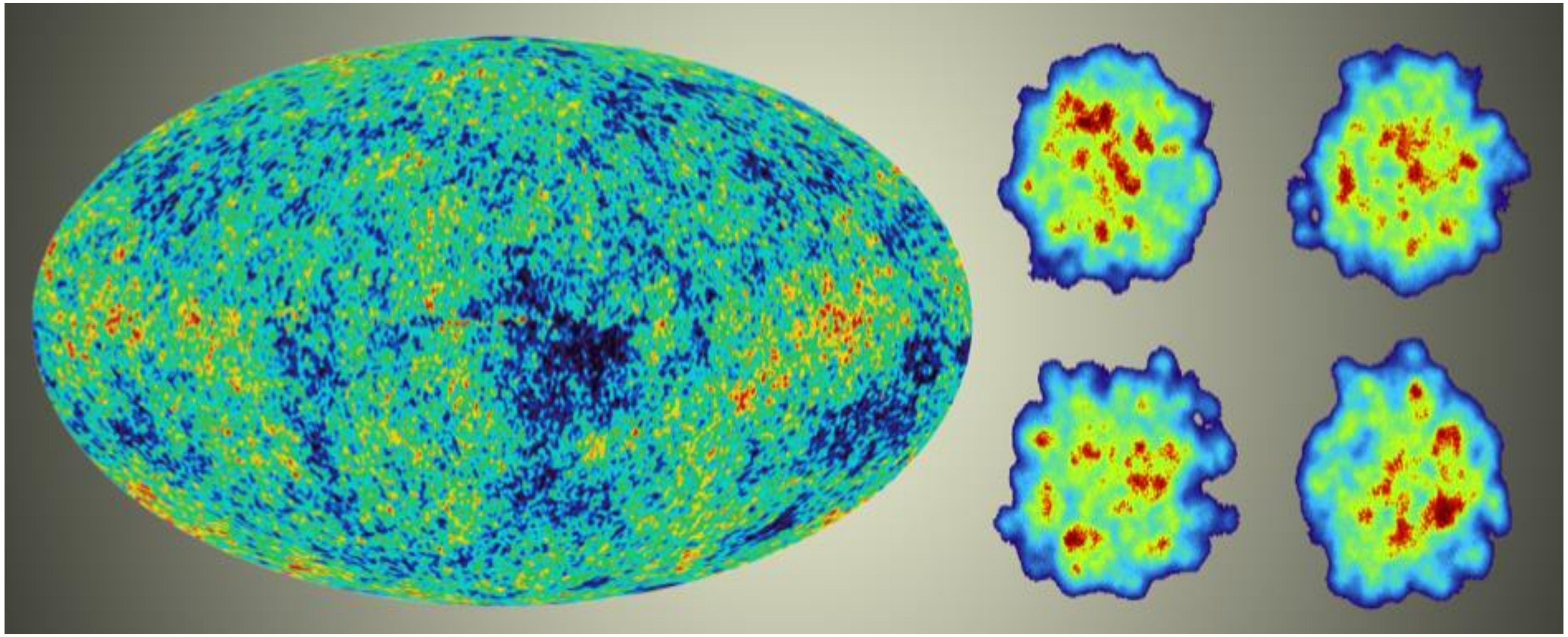




Evolution of Energy Density and temperature

Fluctuations in the Little Bang

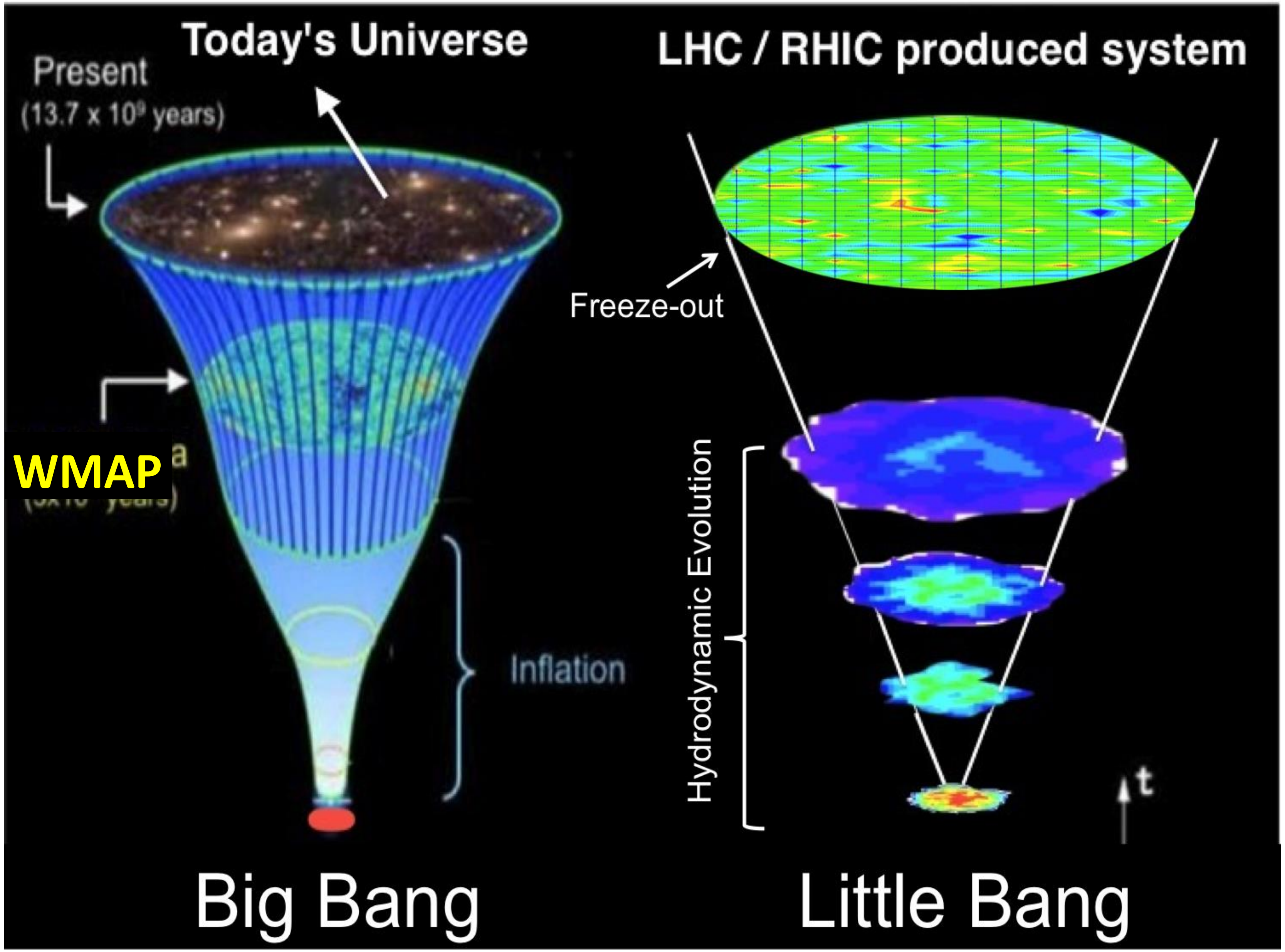
Uli Heinz, arXiv:1304.3634v1 [nucl-th] 11 Apr 2013



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 the Little Bangs



High Energy Accelerator:

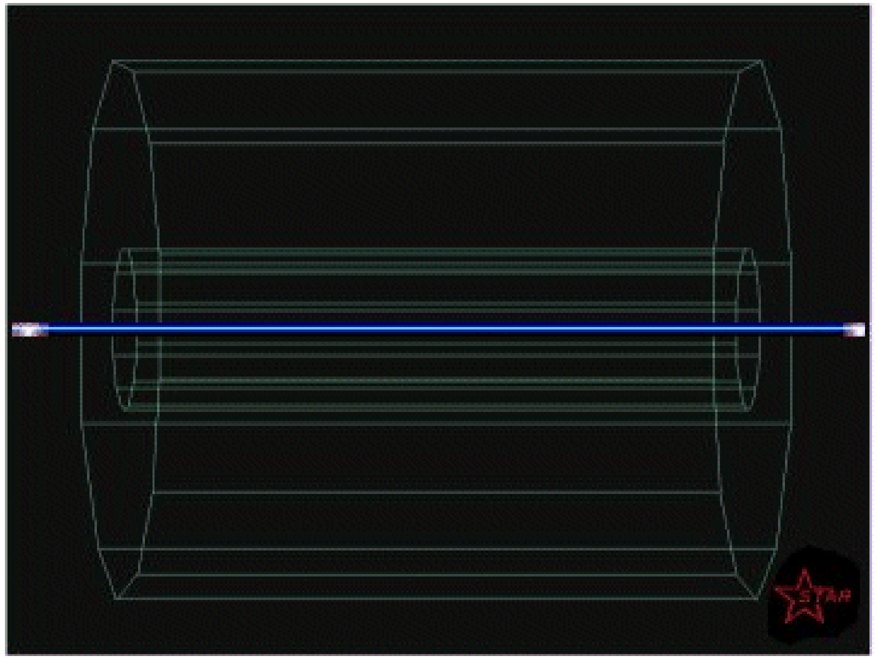
Heavy-ion Collisions:

Billions of Events (Little Bangs)

Event-by-event Fluctuations

One HUGE Event

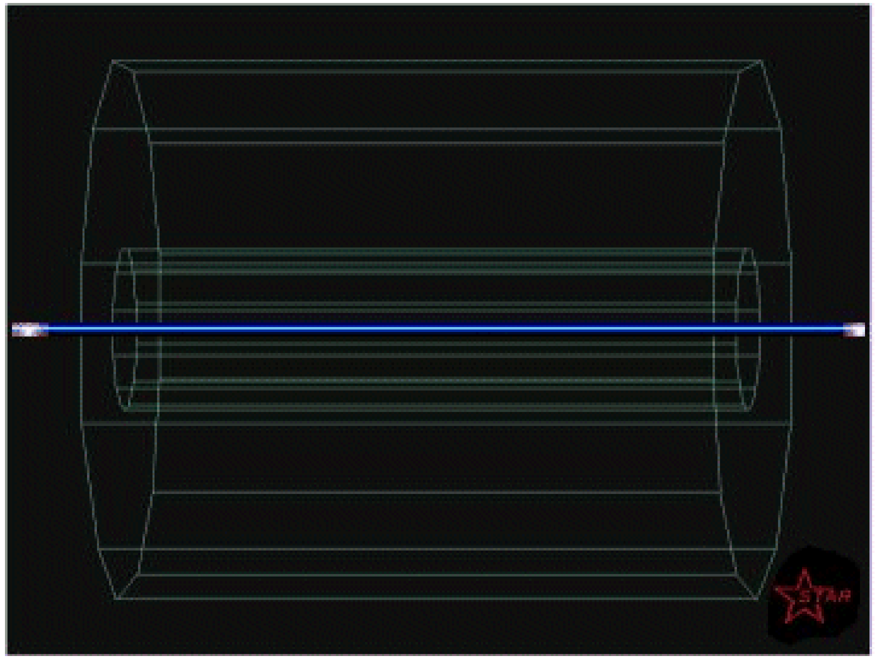
Thermodynamics of the 'Little Bang'



With President Pranab Mukherjee in 2014:

Thermodynamics with the 'Little Bang'

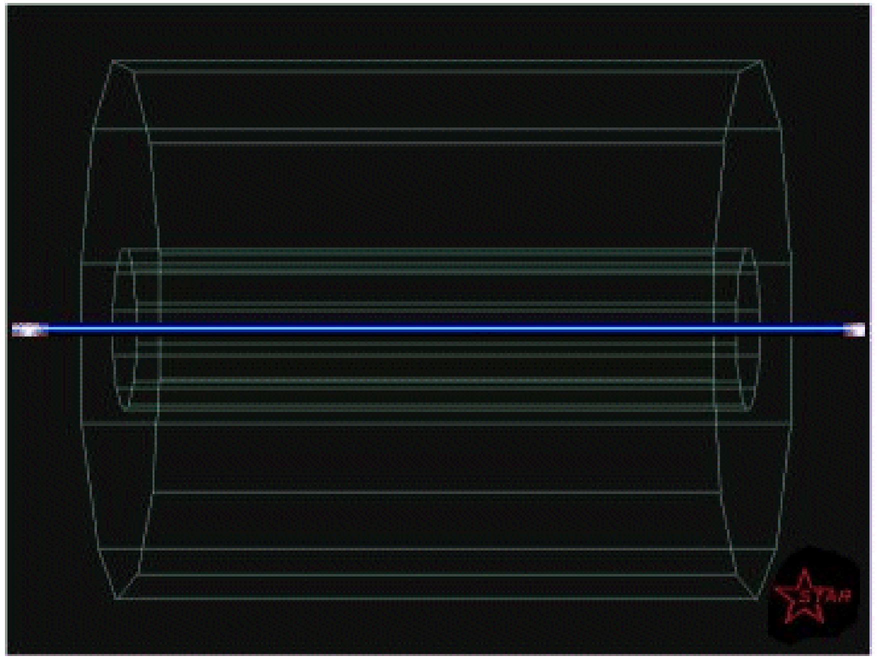
Thermodynamics of the 'Little Bang'

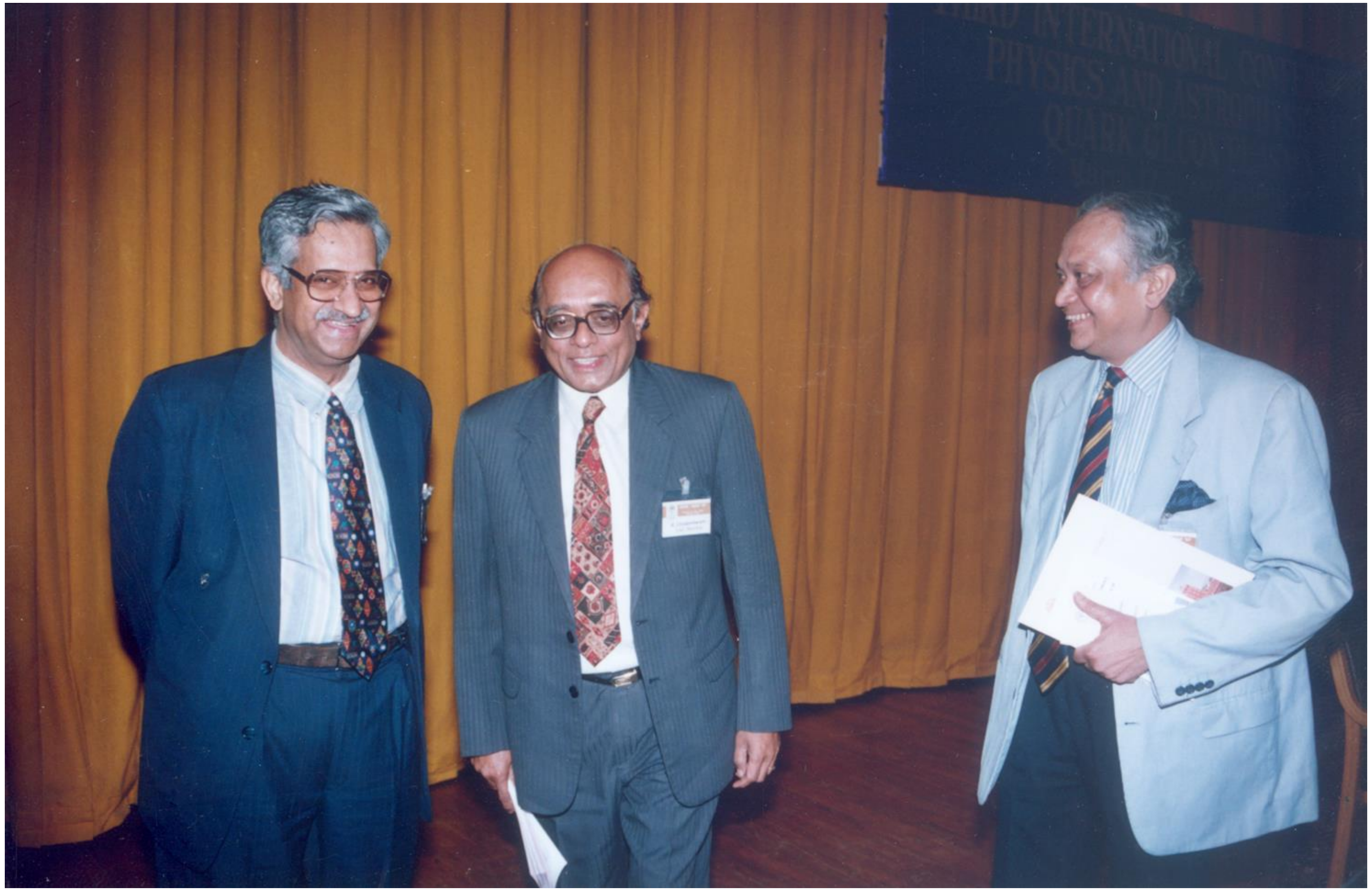


With West Bengal Chief Minister:

Thermodynamics with the 'Little Bang'

Thermodynamics of the 'Little Bang'

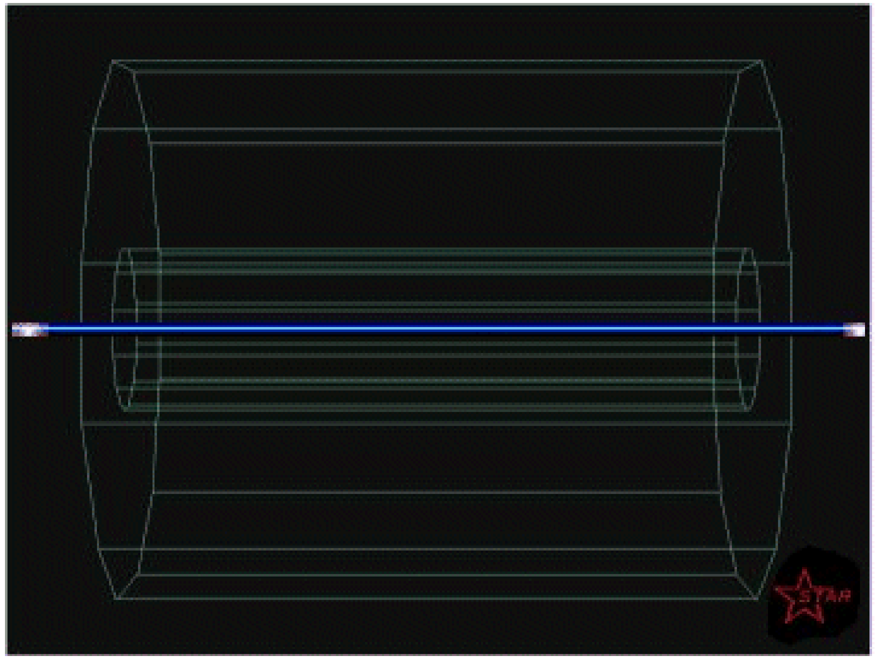




Science administration:

Thermodynamics with the 'Little Bang'

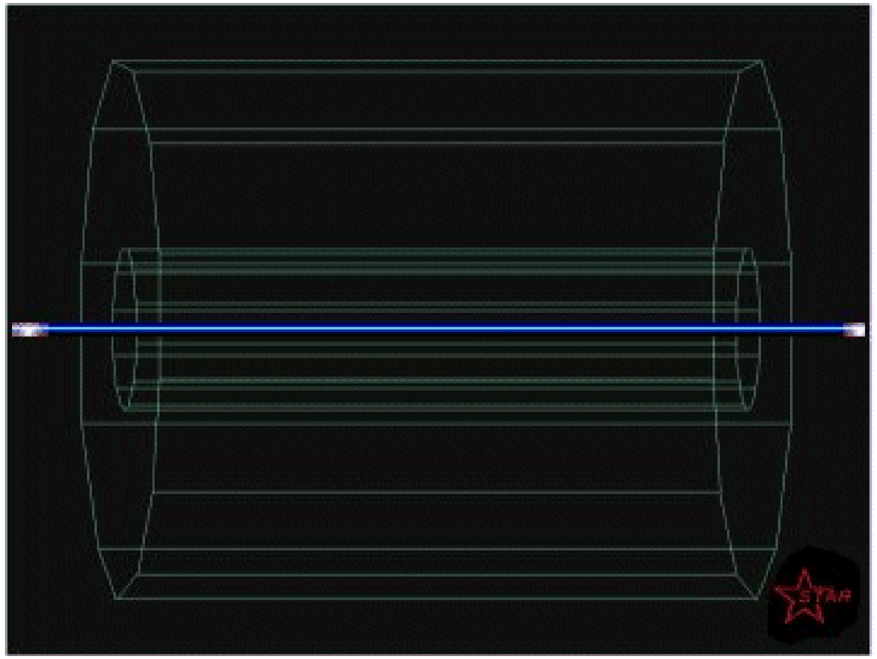
Thermodynamics of the 'Little Bang'



Close friends in the right places:

Thermodynamics with the 'Little Bang'

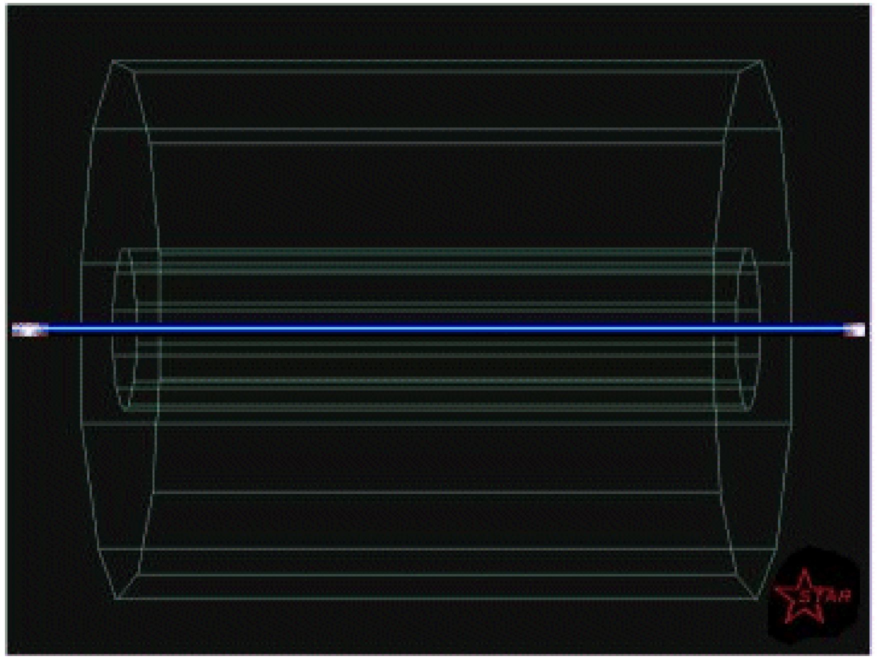
Thermodynamics of the 'Little Bang'

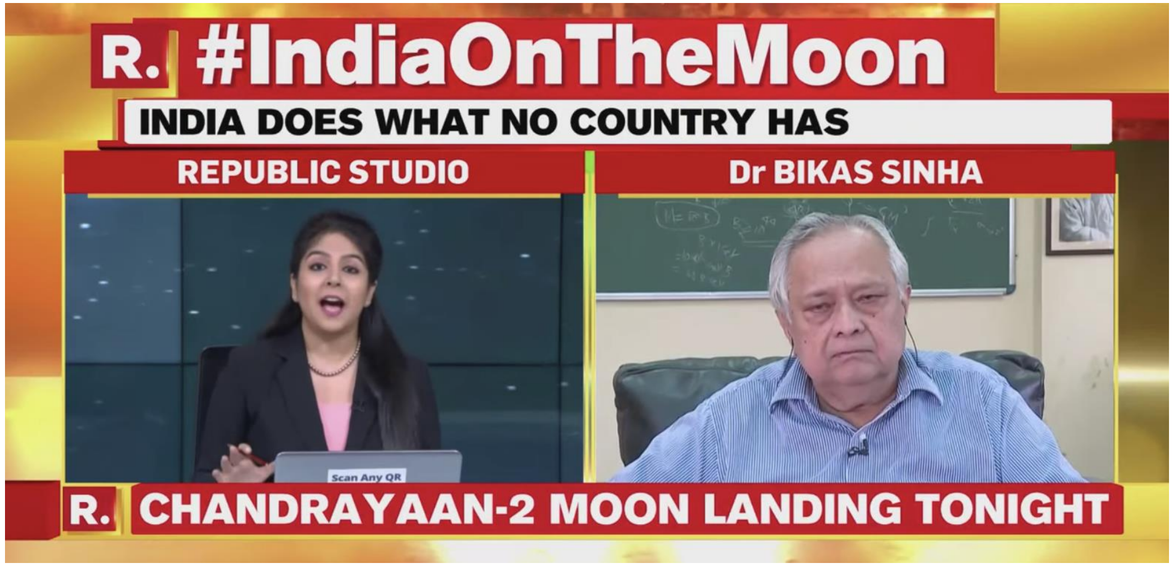


Guiding us to do what is right

Thermodynamics with the 'Little Bang'

Thermodynamics of the 'Little Bang'

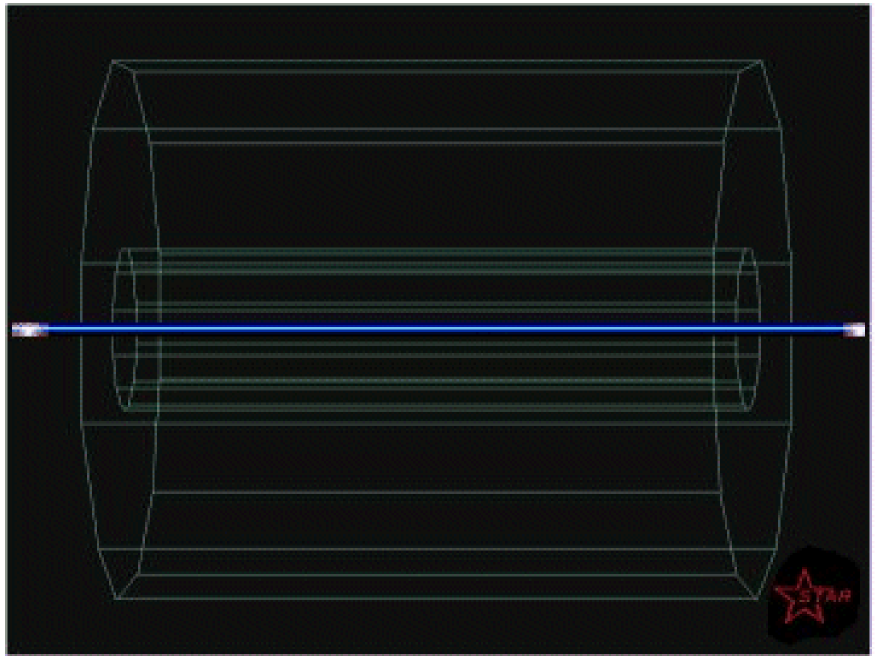


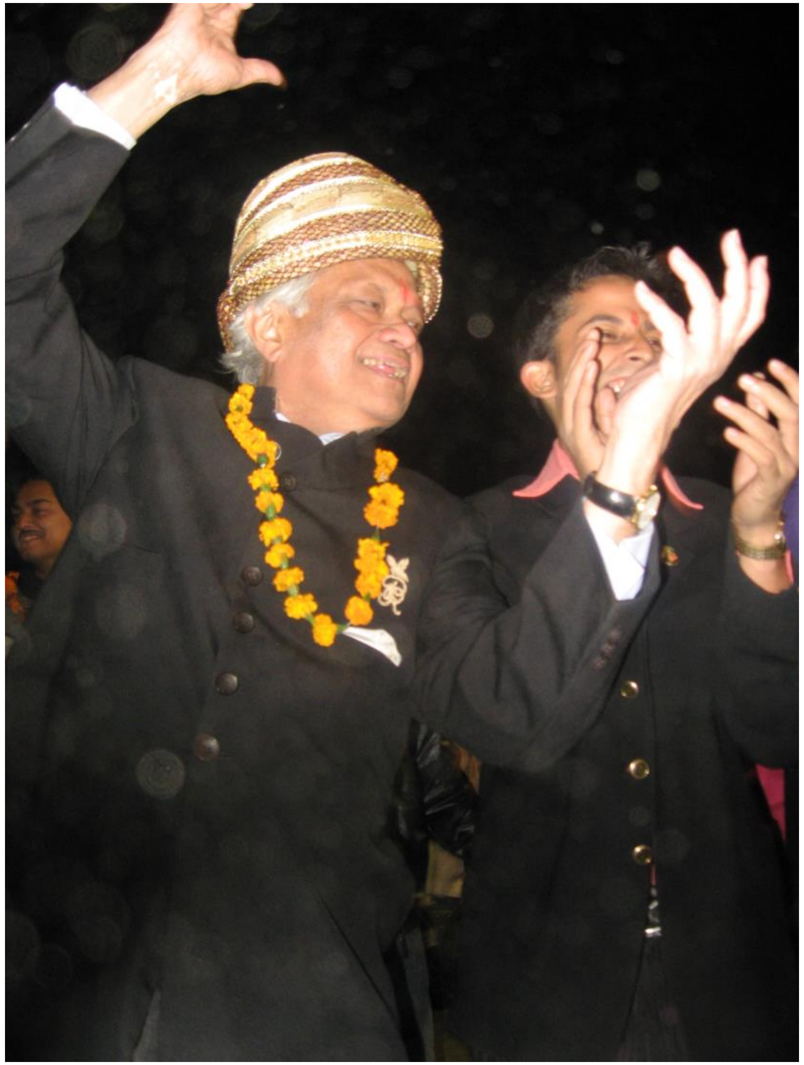


Often facing the media:

Thermodynamics with the 'Little Bang'

Thermodynamics of the 'Little Bang'





In perfect harmony (at Quark Matter 2008)

Thermodynamics with the 'Little Bang'

Thousands of stars blink away forever.

In the backdrop,

Nataraj is alone and silent.

नित्याय त्रिगुणात्मने पुरजिते कात्यायनी-श्रेयसे
सत्यायादिकुटुंबिने मुनिमनः प्रत्यक्ष-चिन्मूर्तये ।
मायासृष्ट-जगत्त्रयाय सकलाम्नायान्त-संचारिणे
सायं ताण्डव-संभ्रमाय जटिने सेयं नतिश्शंभवे ॥ ५६ ॥

"O Omnipresent, the embodiment of all virtues, the creator of this cosmic universe, the king of dancers, who dances the *Ananda Tandava* in the twilight, I salute thee."

(Source: sloka No. 56, Sivanandalahiri by Sri Adi Sankara)