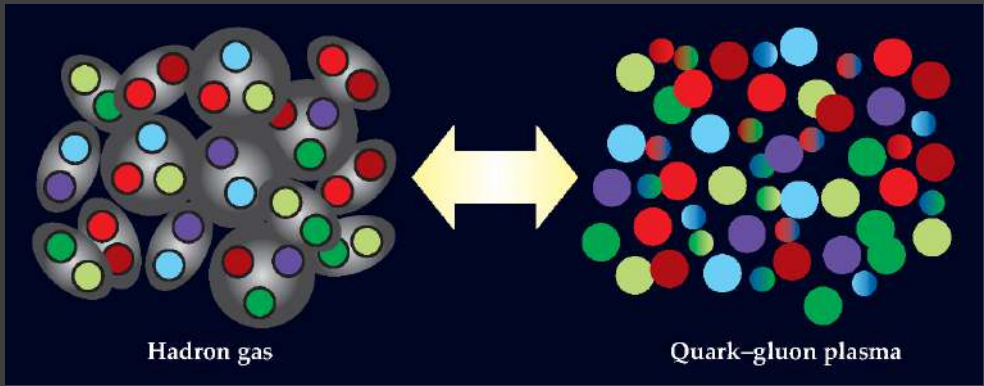
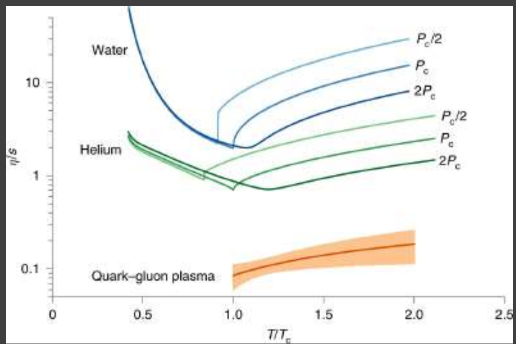
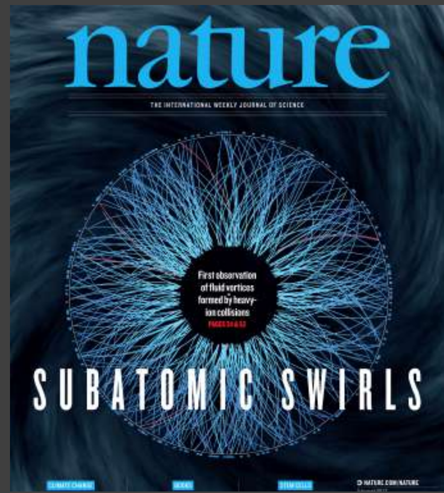
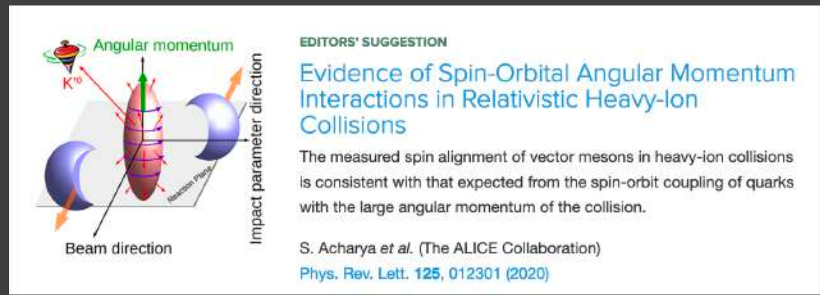
Physics Today **63**, 5, 39 (2010)





Nature Physics, 15, 1113 (2019)

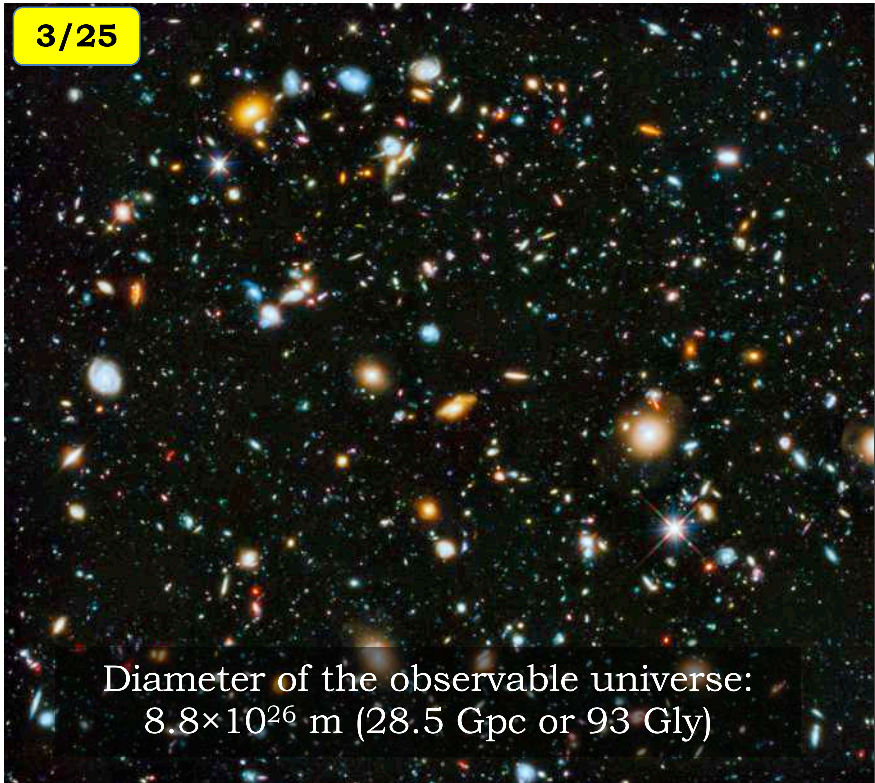




Quark-Gluon Plasma: the perfect and most vortical fluid

Bedanga Mohanty, NISER

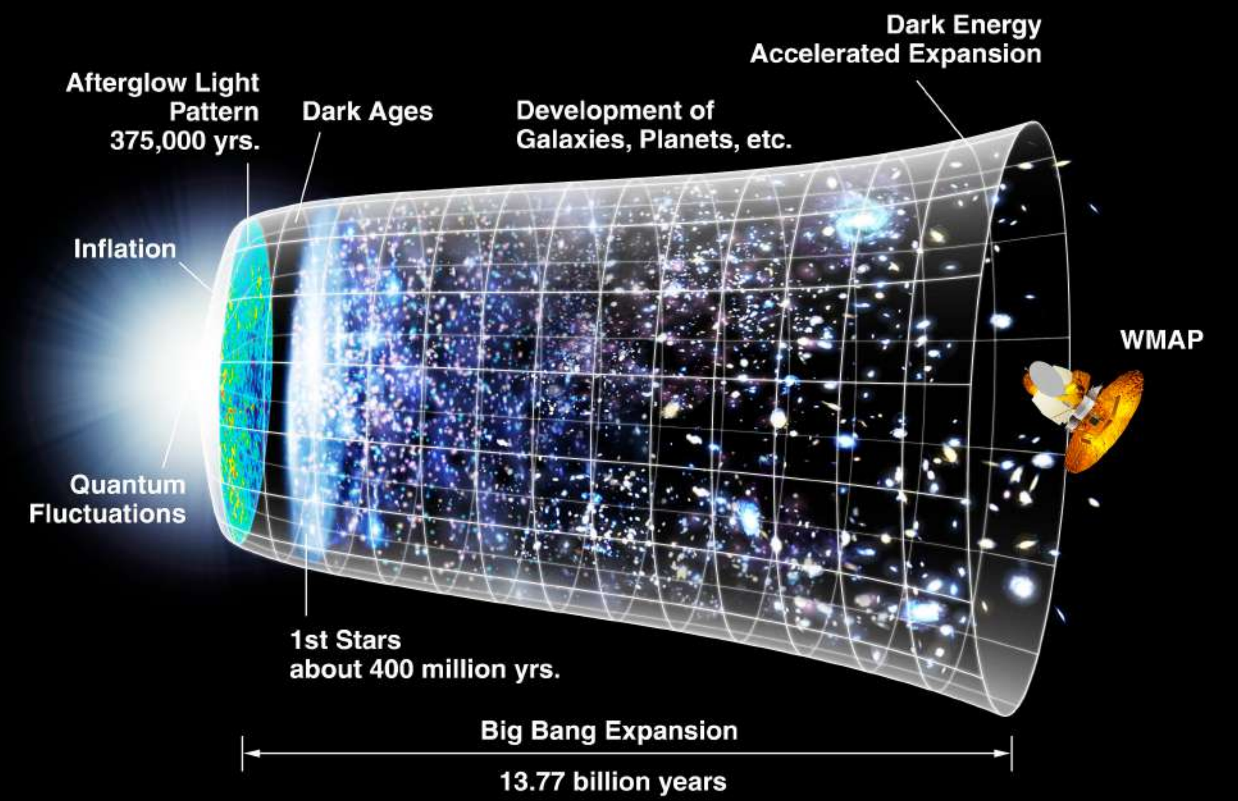
Young minds wondering about the Universe!



Universe is BIG !

The end of the solar system is about 122 astronomical units (AU) away from the sun, where one AU is 93 million miles (150 million kilometers).

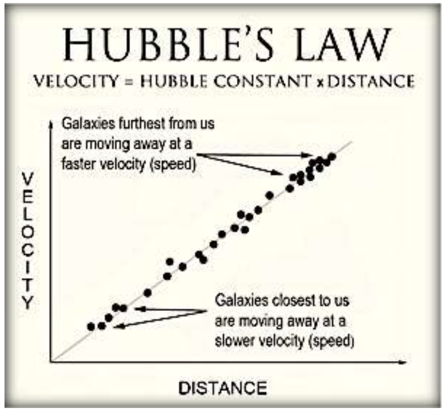
Images: internet

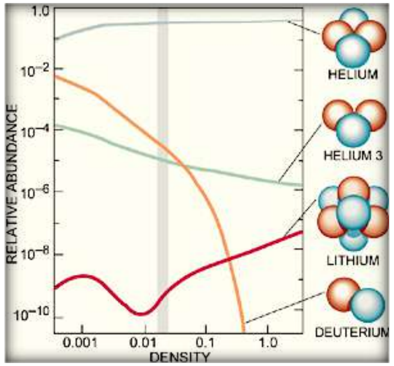


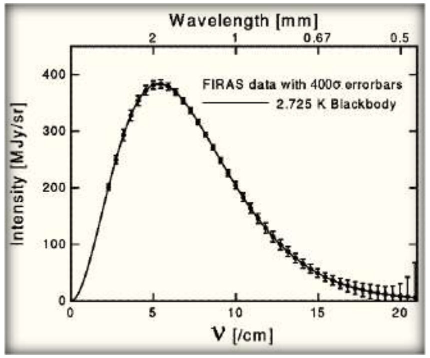
Success of Big Bang Model (George Gamow – 1948)

- ❖ Observational verification of expansion
- ❖ Predicted & observed abundances of light elements
- ❖ Discovery of the Cosmic Microwave Background

NASA/WMAP Science Team





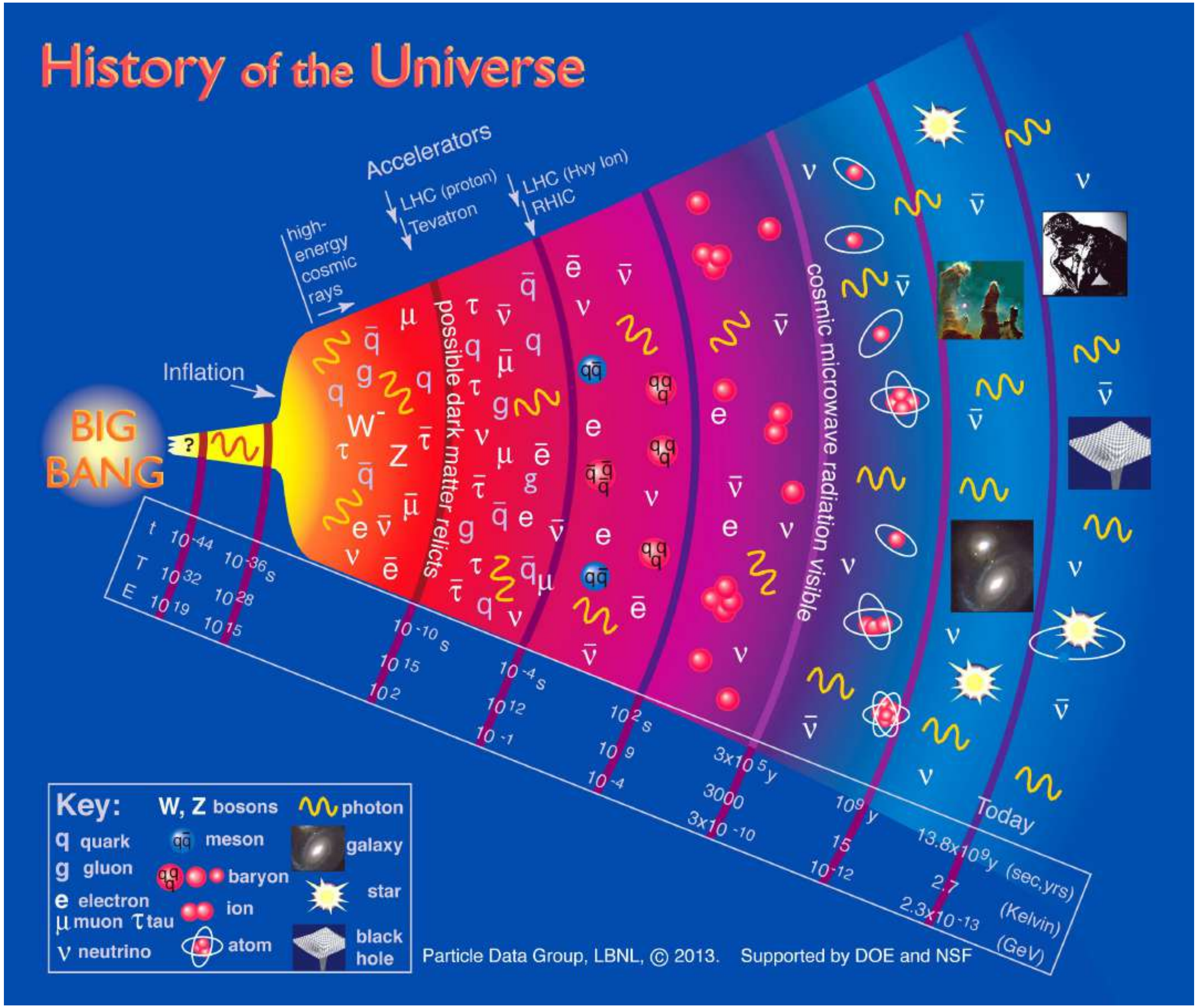


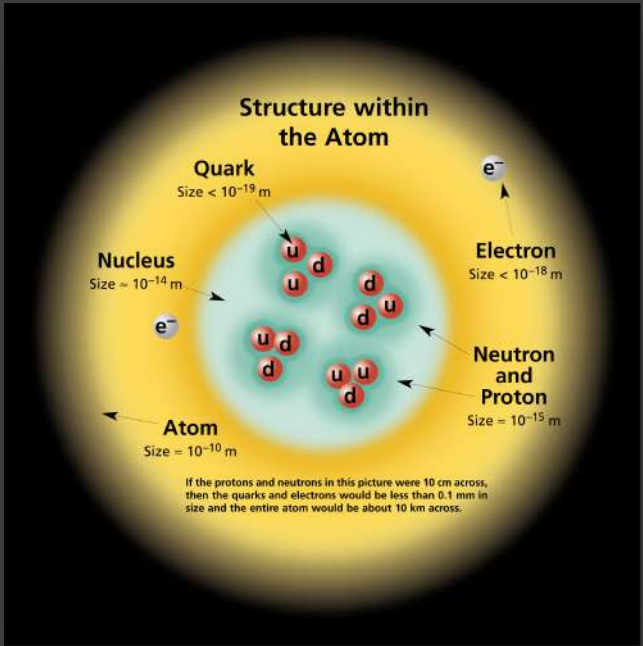
Evolution of Universe

Quark Gluon Plasma

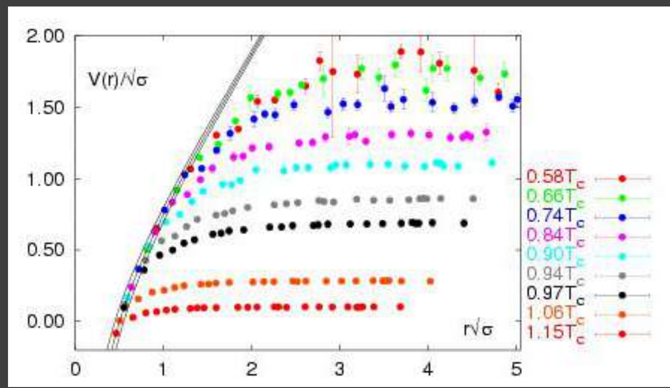
Time ~ µs

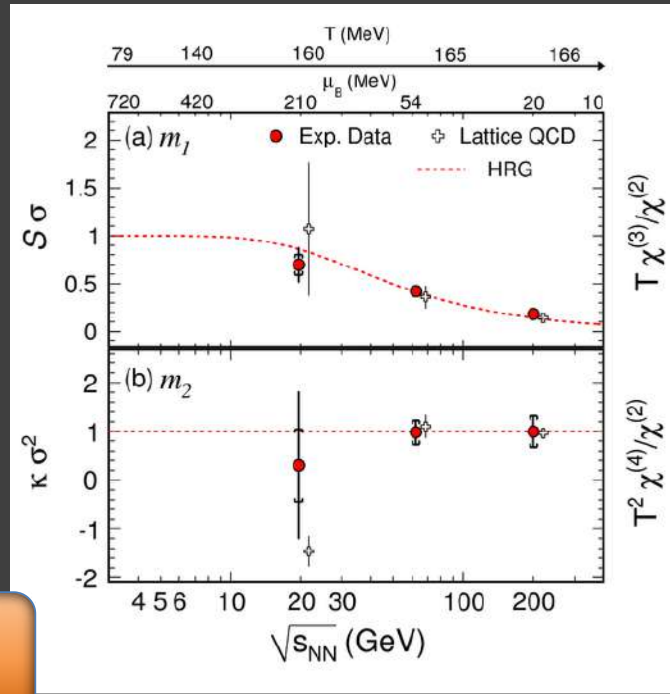
Temp ~ $10^{15} - 10^{12}$ K





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





~ 170 MeV (10^{12} K)

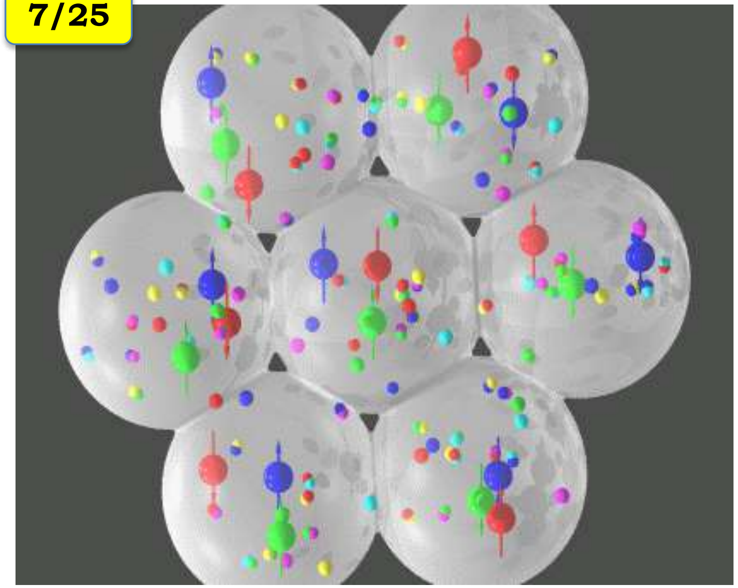
Science AAAS

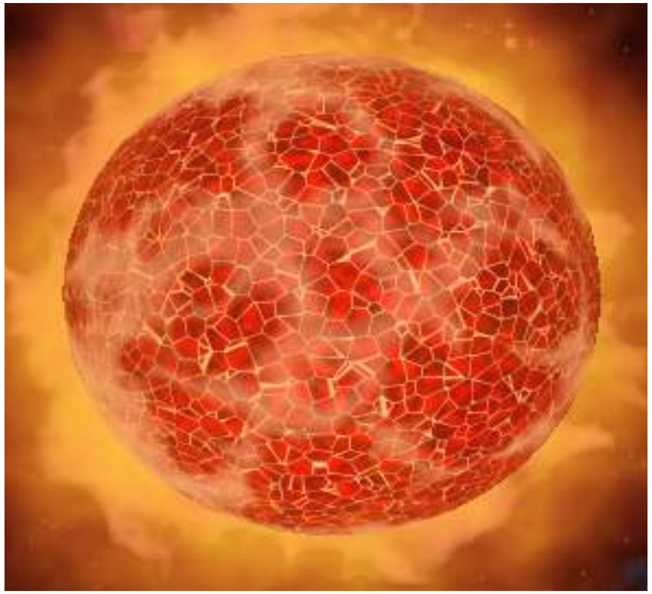
"Scale for the Phase Diagram of Quantum Chromodynamics"

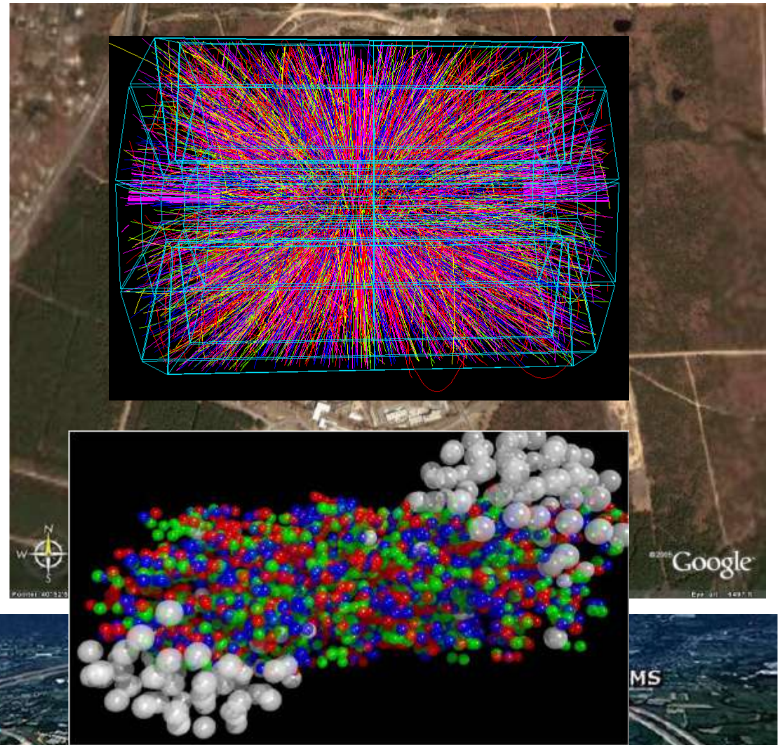
Science*, *332, 1525(2011)

Matter at extremely high temperature→ QGP

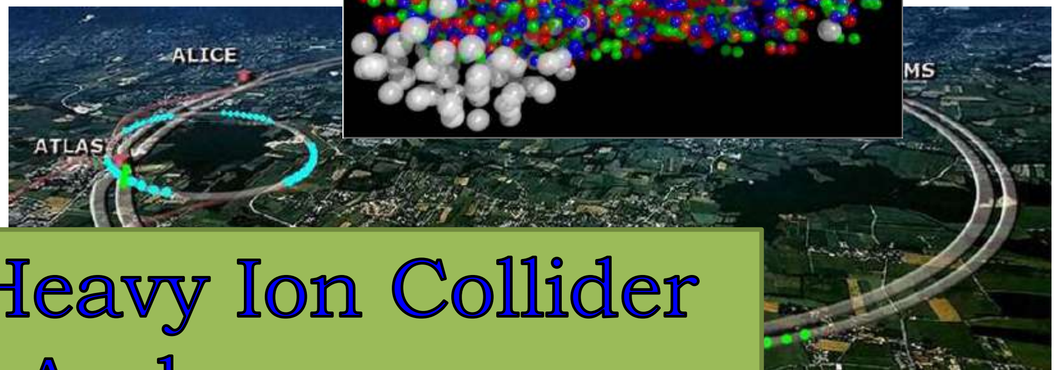
Theoretical support for QGP







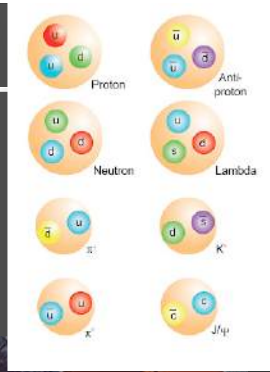
One trillion Kelvin !

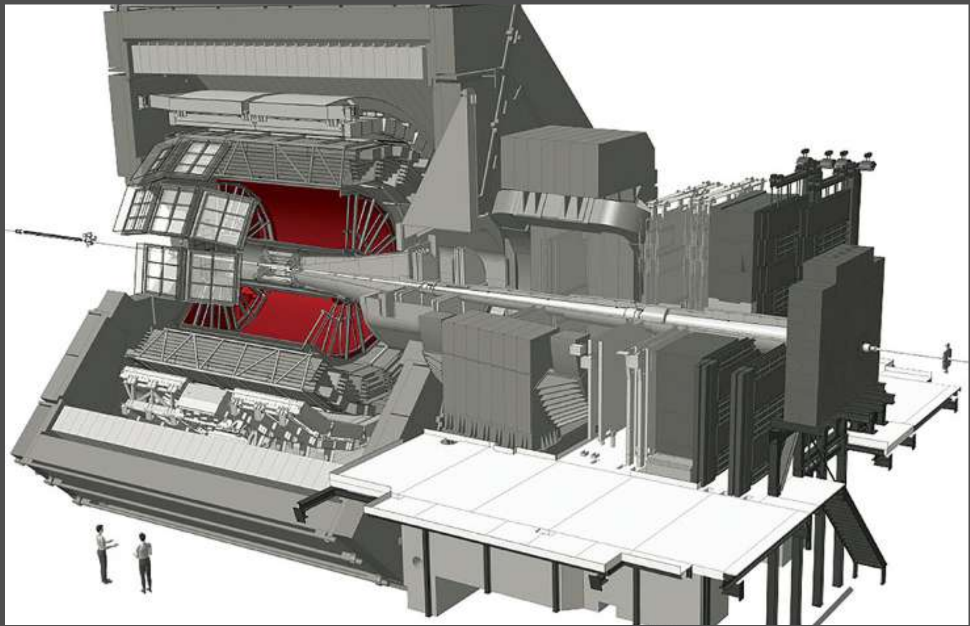


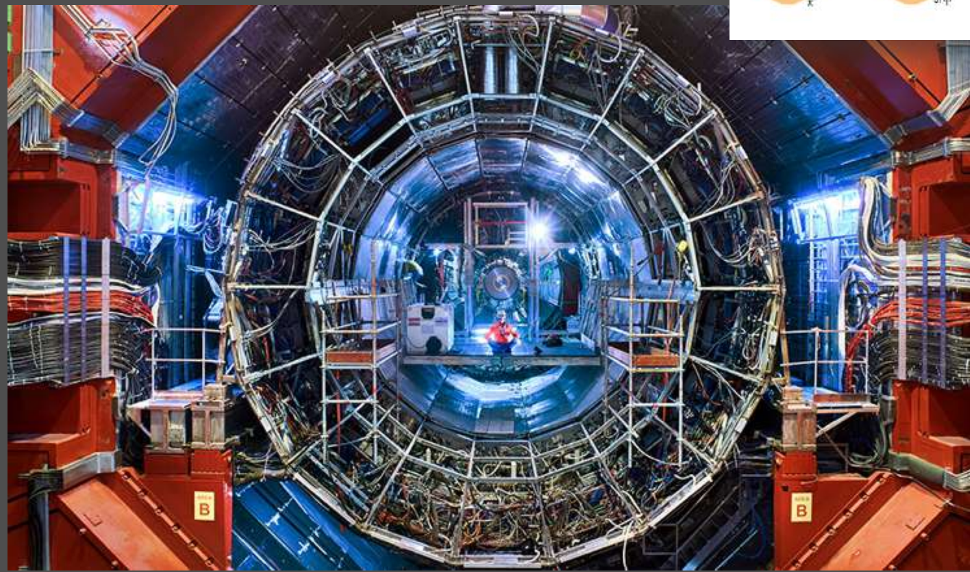
Relativistic Heavy Ion Collider
And
Large Hadron Collider

QGP: Femto-Scale
in time and space

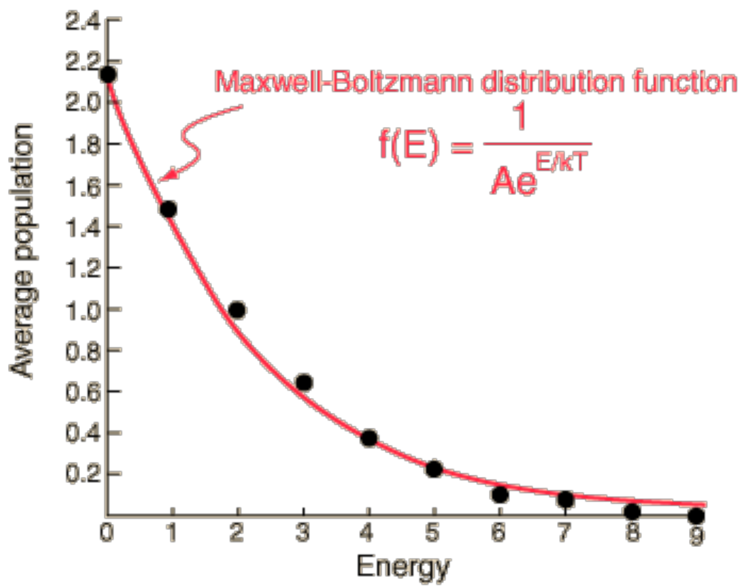
Typical Detector

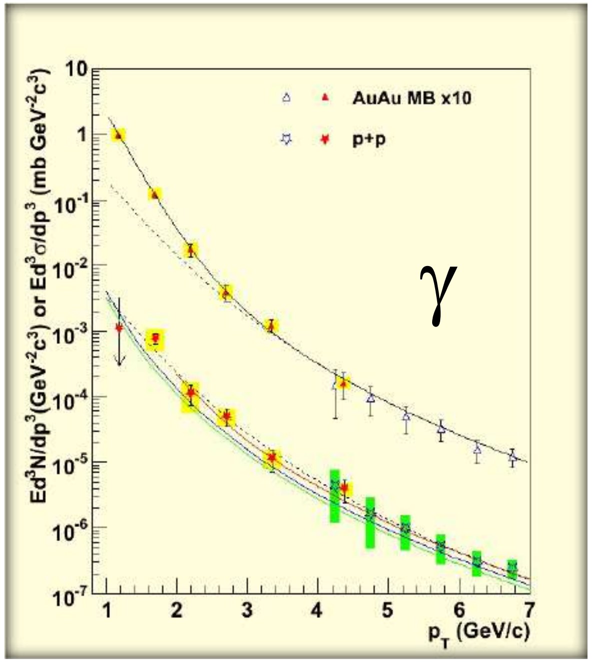






Particle Physics + Nuclear Physics + Condensed Matter Physics + Engineering Science + Detector Physics
Analysis of data also requires knowledge of Statistical, Thermal, Relativistic kinematic Computational, QCD and QED physics.





Measuring Temperature

Inverse slope provides temperature
300 – 600 MeV ~ 10^{12} K
Quark Gluon Plasma

Perspective on the Temperature

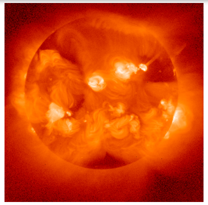
~10^{12} K — Nucleus-Nucleus collisions — **~ 150 MeV**

~10^{9} K — Neutron Star Thermonuclear Explosion

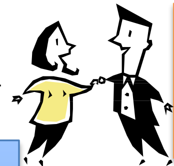
(Terrestrial Nuclear explosions)

~10^{6} K — Solar Interior

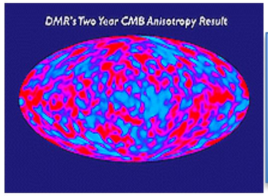
~6000 K — Solar Surface



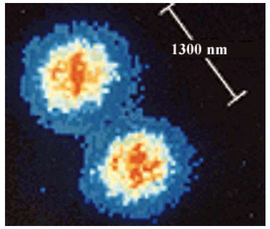
~300 K — Room Temperature **~ 1/40 eV**



~3 K — Cosmic Microwave Background

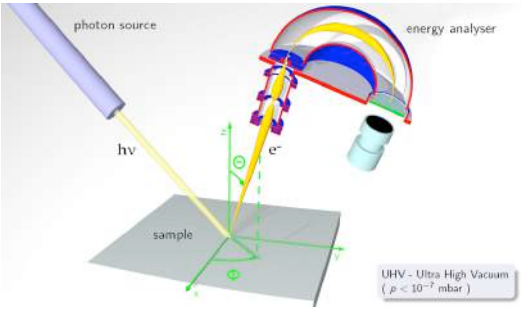


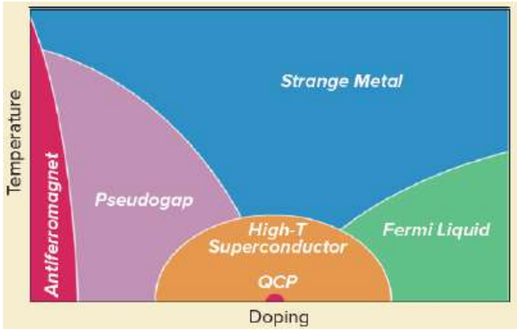
~10^{-6} K — Trapped Ions

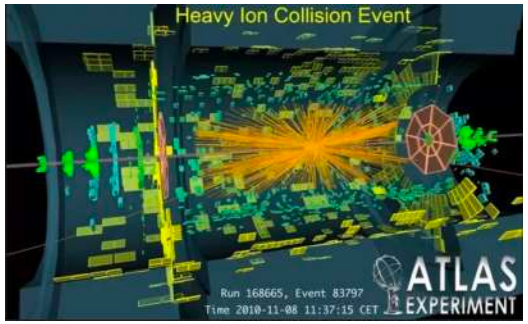


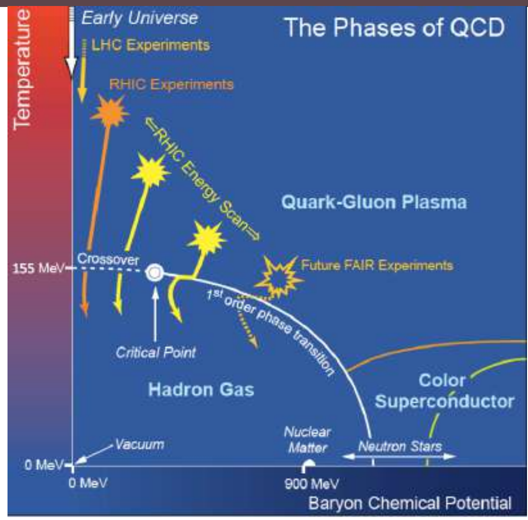
~10^{-10} K — Rhodium metal spin cooling (2000)

(Low-T World Record!)







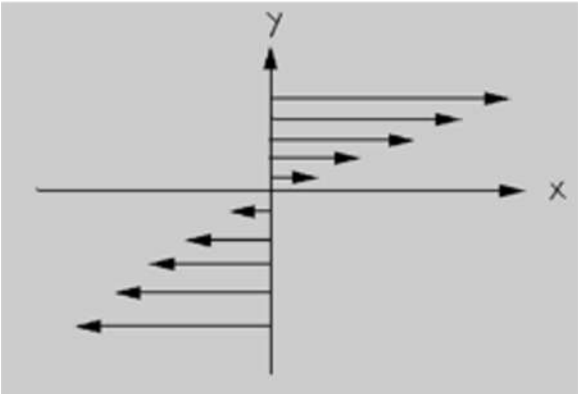


Baryon doping

Emergent properties of matter

Viscosity: resistance to flow

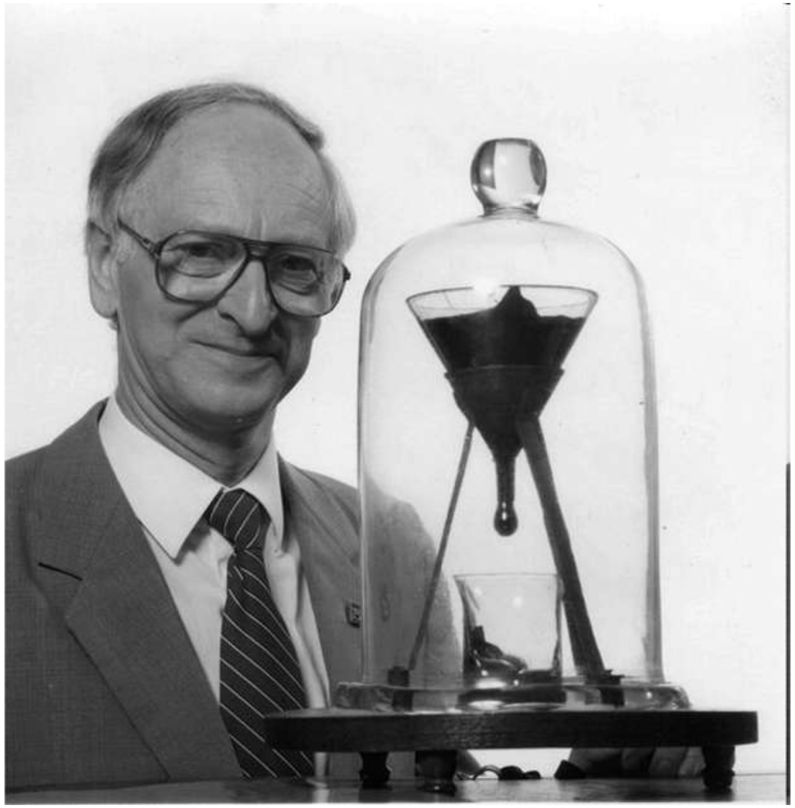
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



Dilute gas, η = (1/3) *npl.*
Uncertainty principle pl ≳ *ħ*.
Entropy density, *s* ~ $k_B n$,
Lower bound to η/s ≳ $\frac{\hbar}{k_B}$.

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

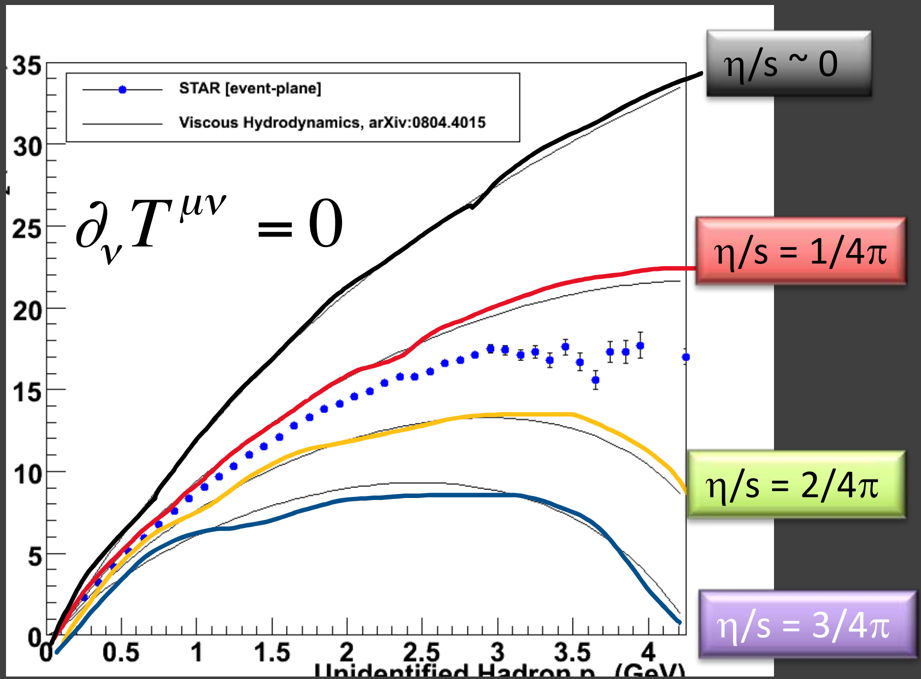
Pitch approximately
230 billion times viscous than water.



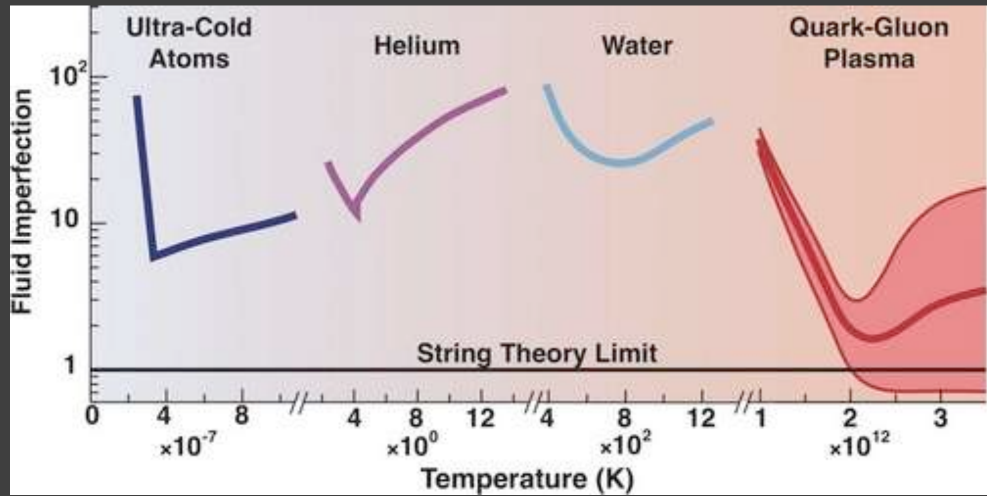
(1927-present) 8 drops

Wiki

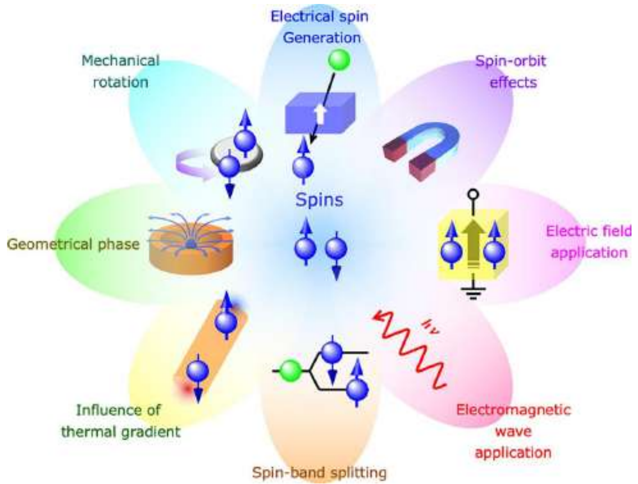
Flow



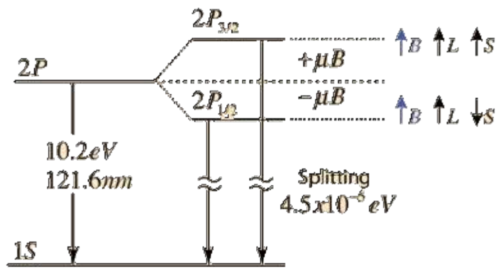
Momentum



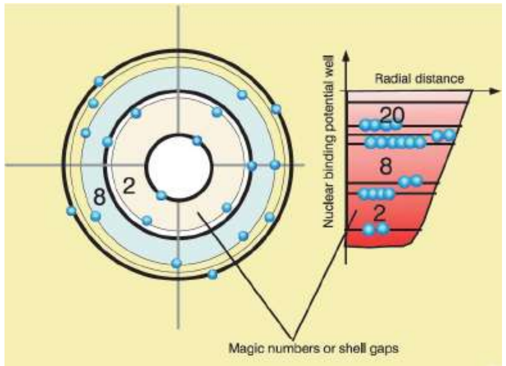
Perfect Fluid



Material Science



Atomic Physics



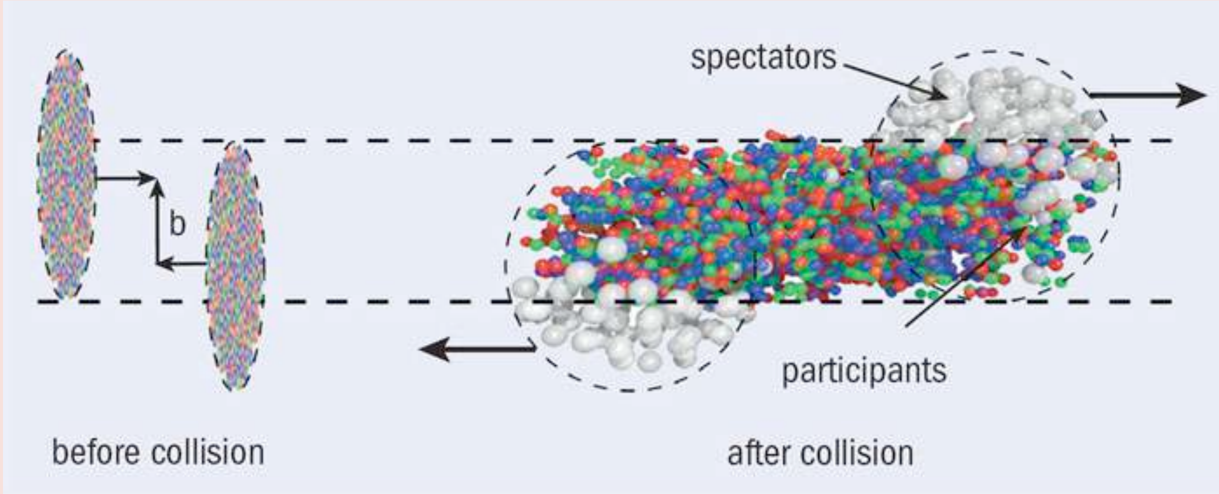
Nuclear Physics

Spin-orbit interactions

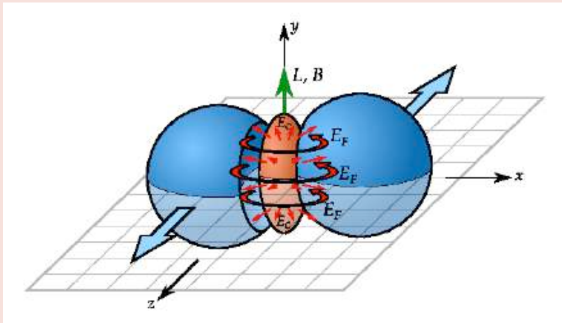
L.S

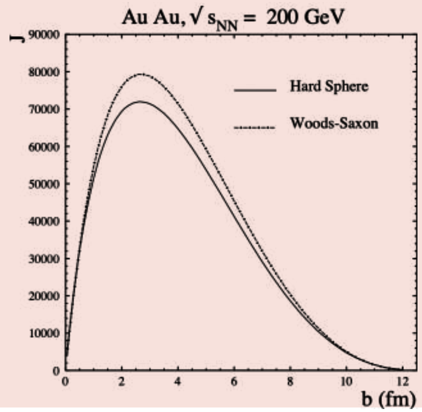
Images: internet

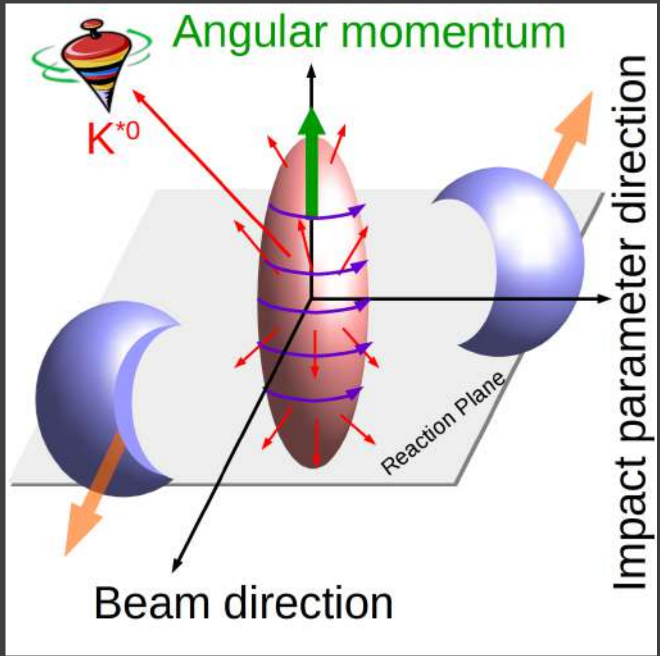
Large Angular Momentum



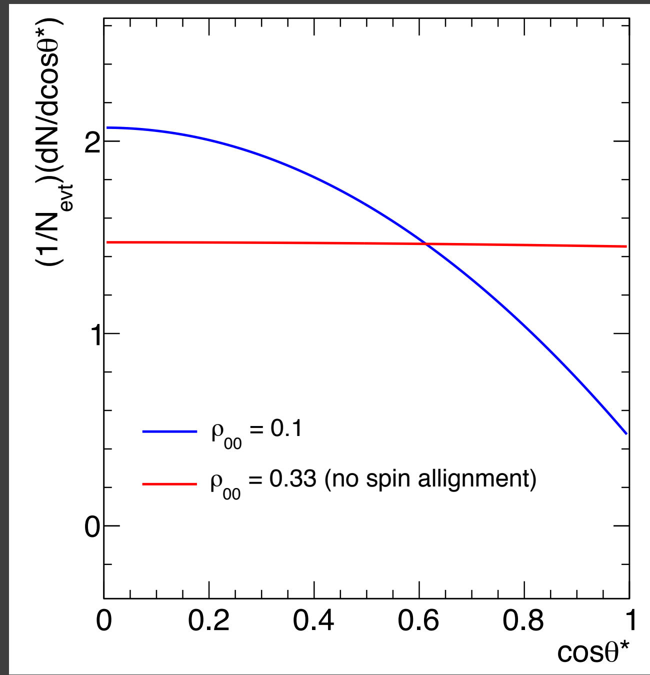
L ~ 10^5 $\hbar$





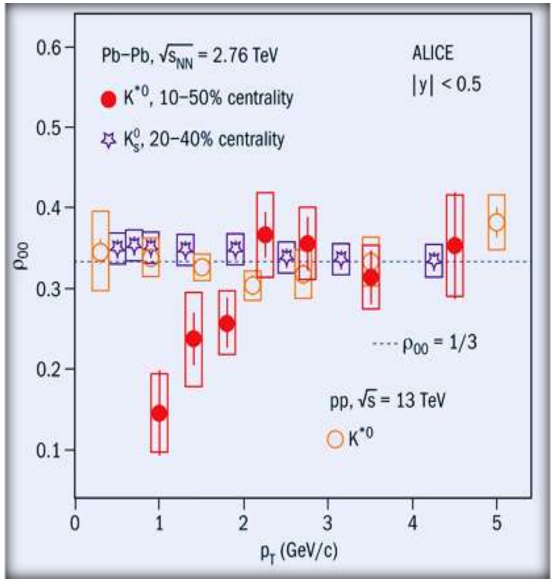


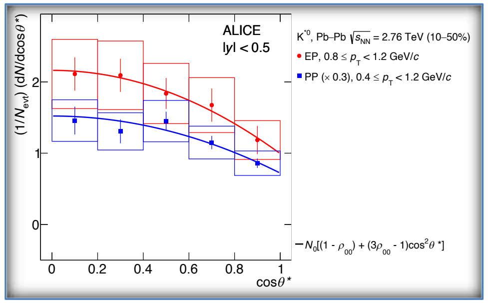
$$\frac{dN}{dcos\theta} = N_0 \left[1 - \rho_{0,0} + cos^2\theta \left(3\rho_{0,0} - 1\right)\right]$$

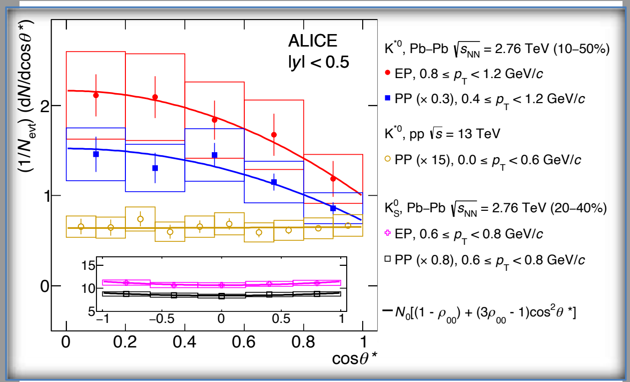


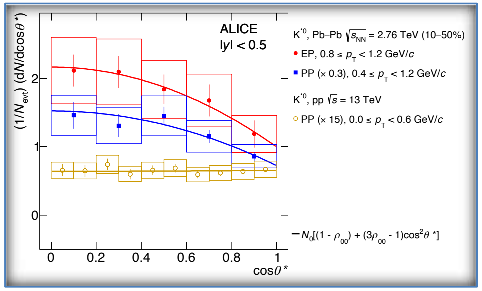
Finding spin-orbit interactions in QCD matter

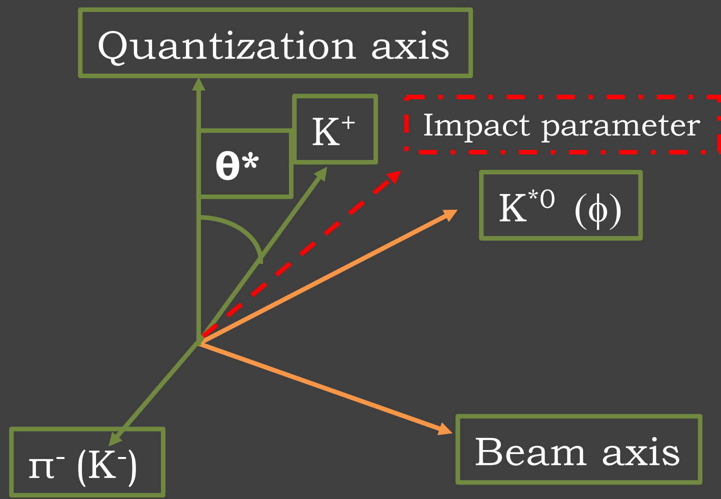
Angular distribution of vector mesons



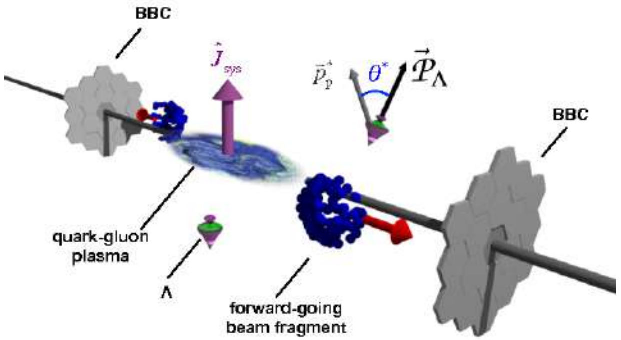


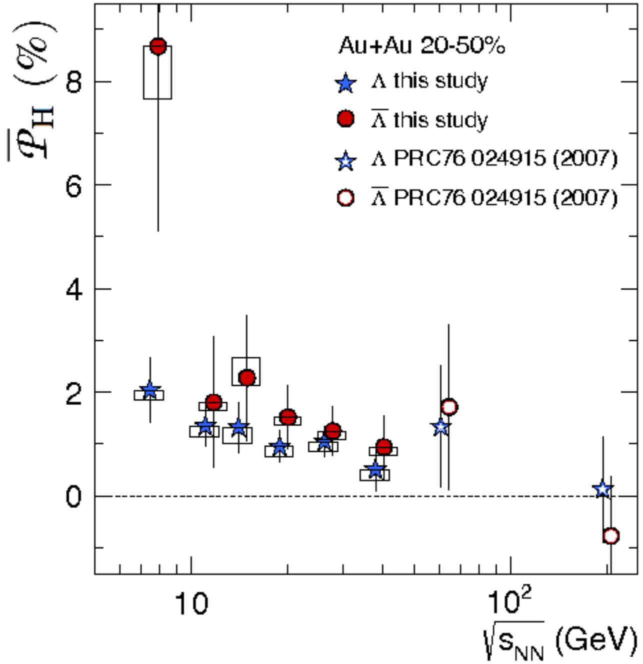


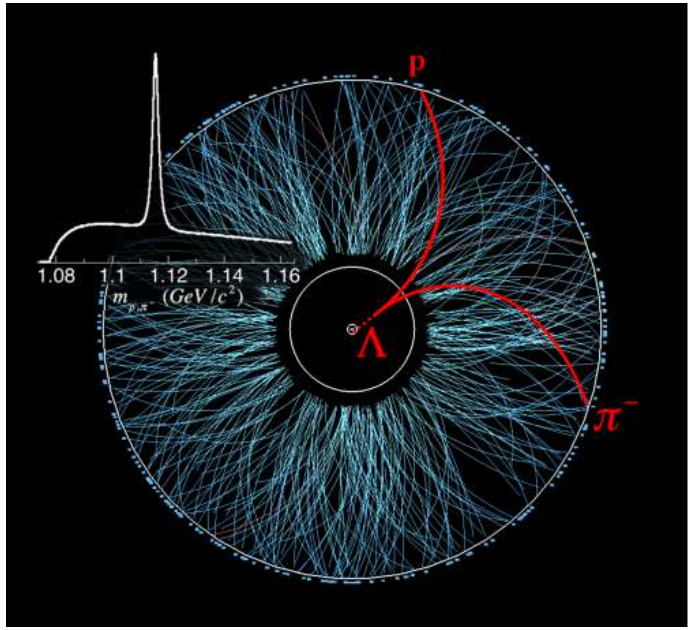




$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$







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

Most vortical fluid

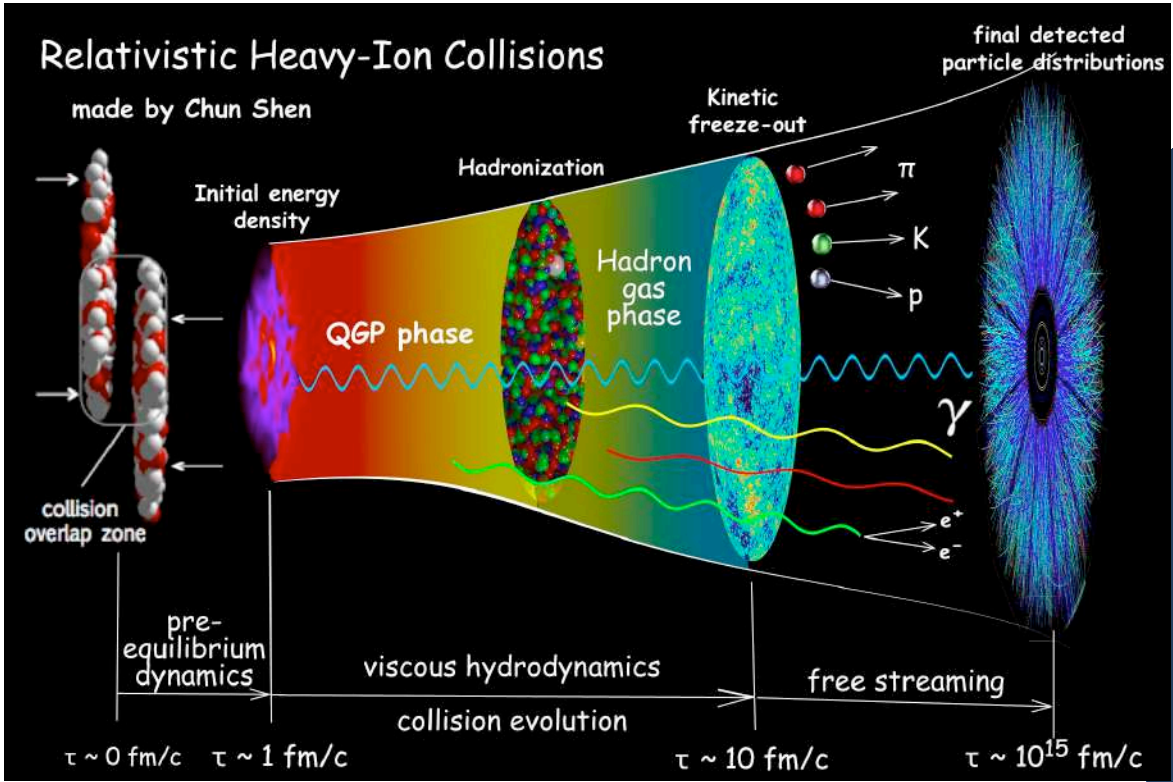
10^{21} (second)$^{-1}$

Perspective on vorticity

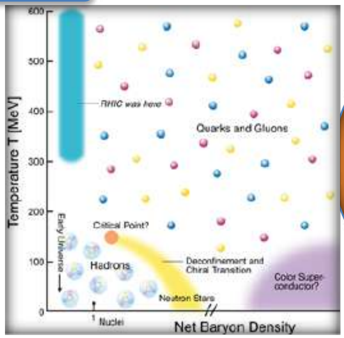
vorticity $\boxed{\boldsymbol{\omega} = \operatorname{curl} \mathbf{u}}$

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

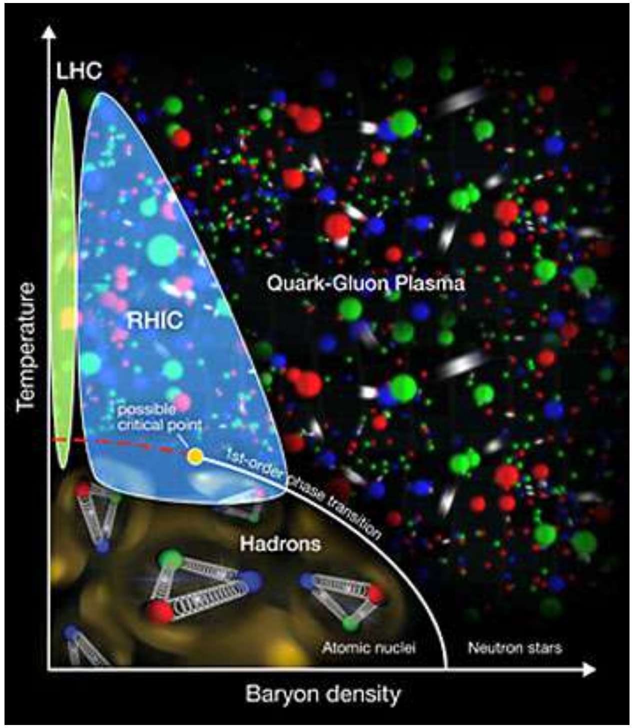
Images: internet

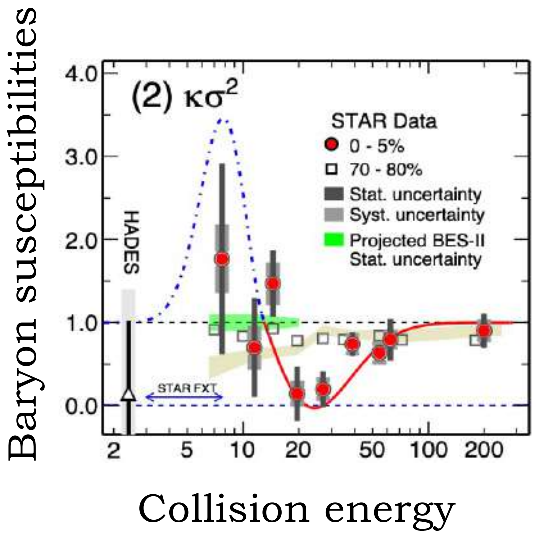


We understand the evolution after mini-Bang

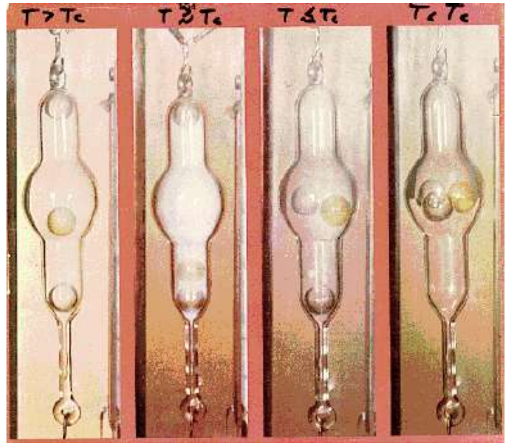


Quark Gluon Plasma: Perfect fluid and most vortical



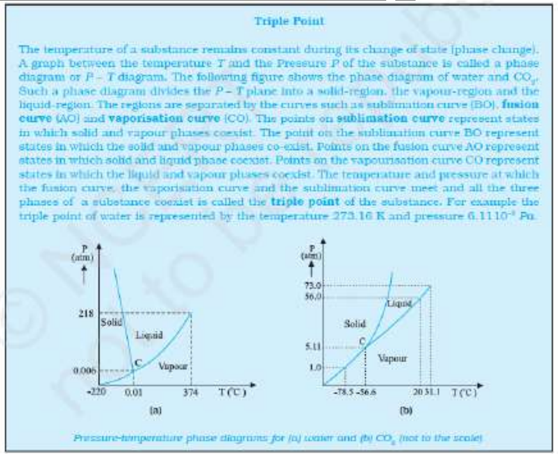


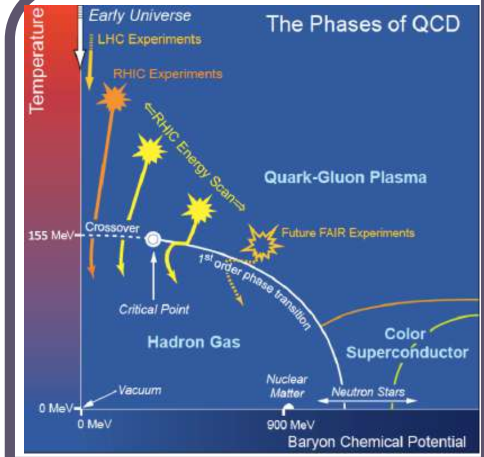
Critical opalescence



Miles to go before we sleep …


Phase diagram of matter on the way to textbooks

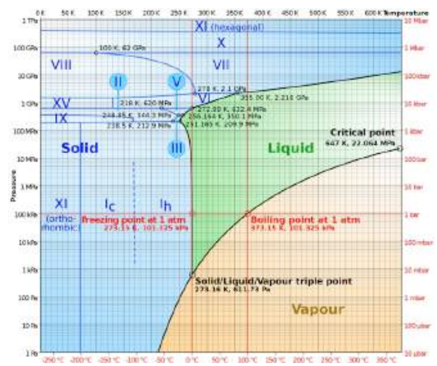




QCD

√

QED



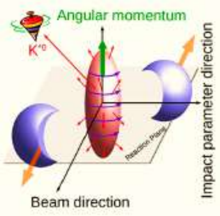
Chapter – 11
Thermal Properties of Matter
NCERT - Book

Mega Sciences

Come join !

Thank you

References



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)

Angular momentum conservation in heavy ion collisions at very high energy

F. Becattini, F. Piccinini, and J. Rizzo
Phys. Rev. C **77**, 024906 – Published 21 February 2008

Published: 03 August 2017

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration

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

Centrality and Transverse Momentum Dependence of Elliptic Flow of Multistrange Hadrons and ϕ Meson in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}}=200$ GeV

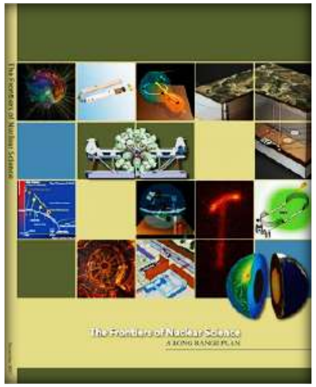
L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. **116**, 062301 – Published 10 February 2016

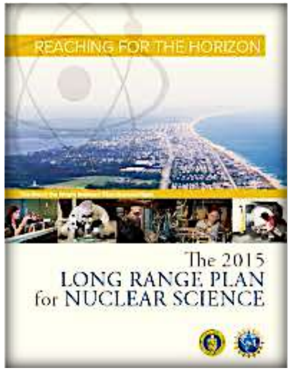
RESEARCH ARTICLE

Scale for the Phase Diagram of Quantum Chromodynamics

Sourendu Gupta[1], Xiaofeng Luo[2,3], Bedangadas Mohanty[4,*], Hans Georg Ritter[3], Nu Xu[5,3]
+ See all authors and affiliations

Science 24 Jun 2011:
Vol. 332, Issue 6037, pp. 1525-1528
DOI: 10.1126/science.1204621





PC: Dr. Sutanu Roy, SMS

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

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

Enhanced Production of Direct Photons in $\mathrm{Au}+\mathrm{Au}$ Collisions at $\sqrt{s_{NN}}=200$ GeV and Implications for the Initial Temperature

A. Adare *et al.* (PHENIX Collaboration)
Phys. Rev. Lett. **104**, 132301 – Published 29 March 2010

Energy Dependence of Moments of Net-Proton Multiplicity Distributions at RHIC

L. Adamczyk *et al.* (STAR Collaboration)
Phys. Rev. Lett. **112**, 032302 – Published 23 January 2014

VIEWPOINT

Taking the temperature of extreme matter

Charles Gale
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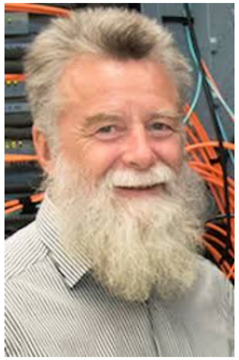
ALICE



STAR

CBM

राष्ट्रीय विज्ञान शिक्षा एवं अनुसंधान संस्थान

NISER

विद्ययाऽमृतमश्नुते

Acknowledgements

राष्ट्र की सेवा में परमाणु

प ऊ वि

DAE

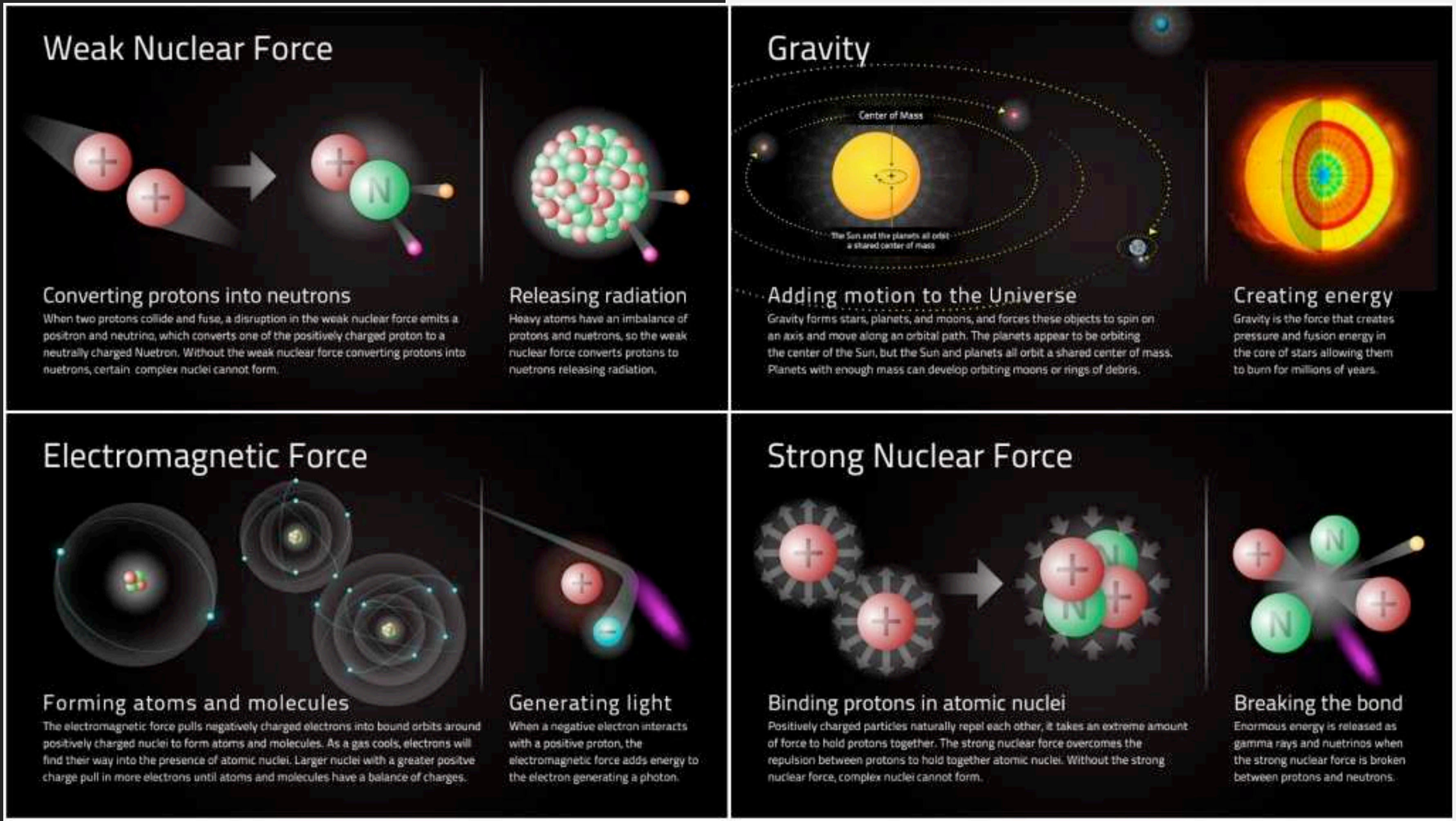
ATOMS IN THE SERVICE OF THE NATION

Department of Science & Technology, Government of India

सत्यमेव जयते

Back up

https://www.facebook.com/553426615/videos/pcb.10157580367111616/10157580353876616

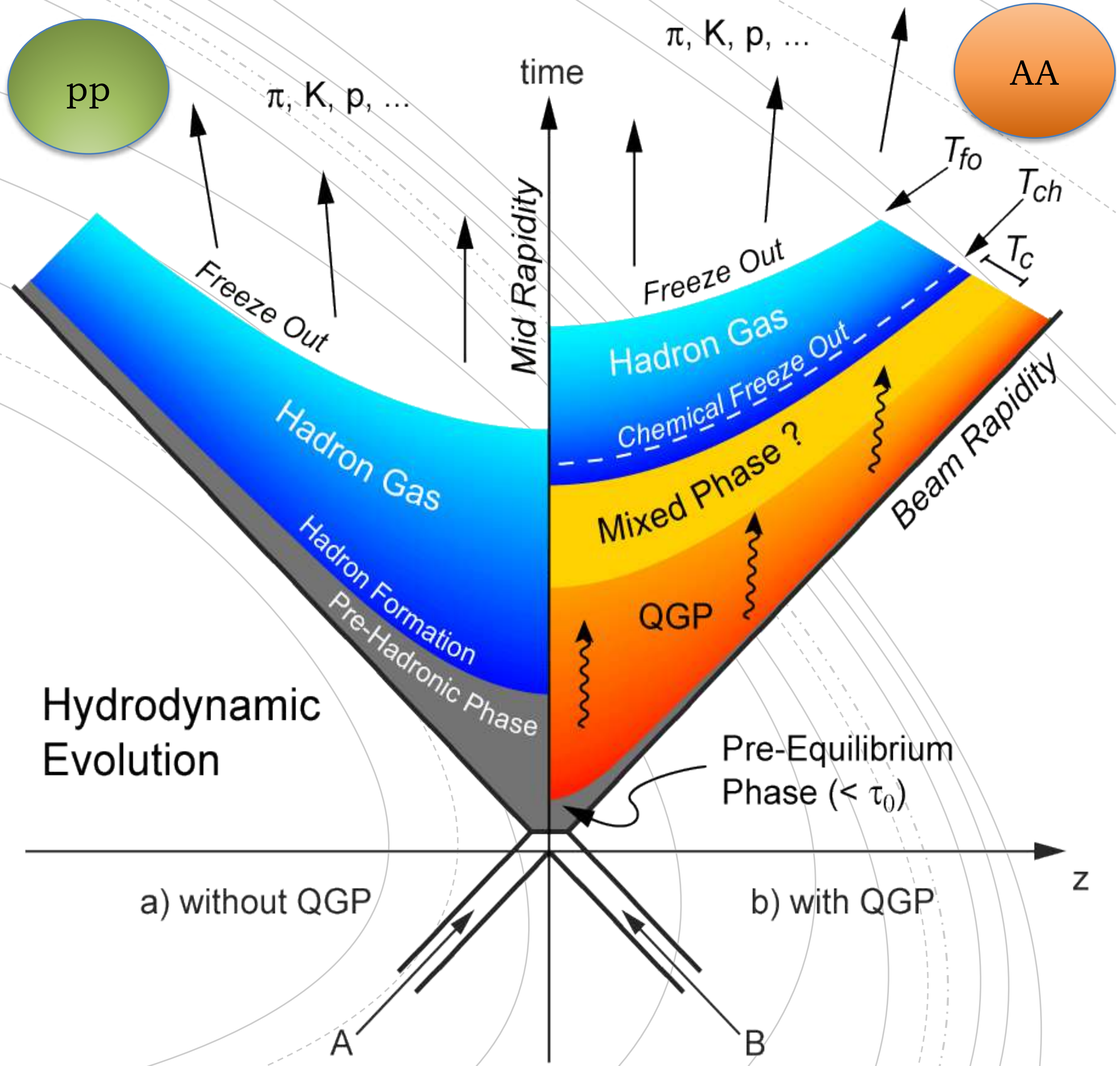


Fundamental Interactions

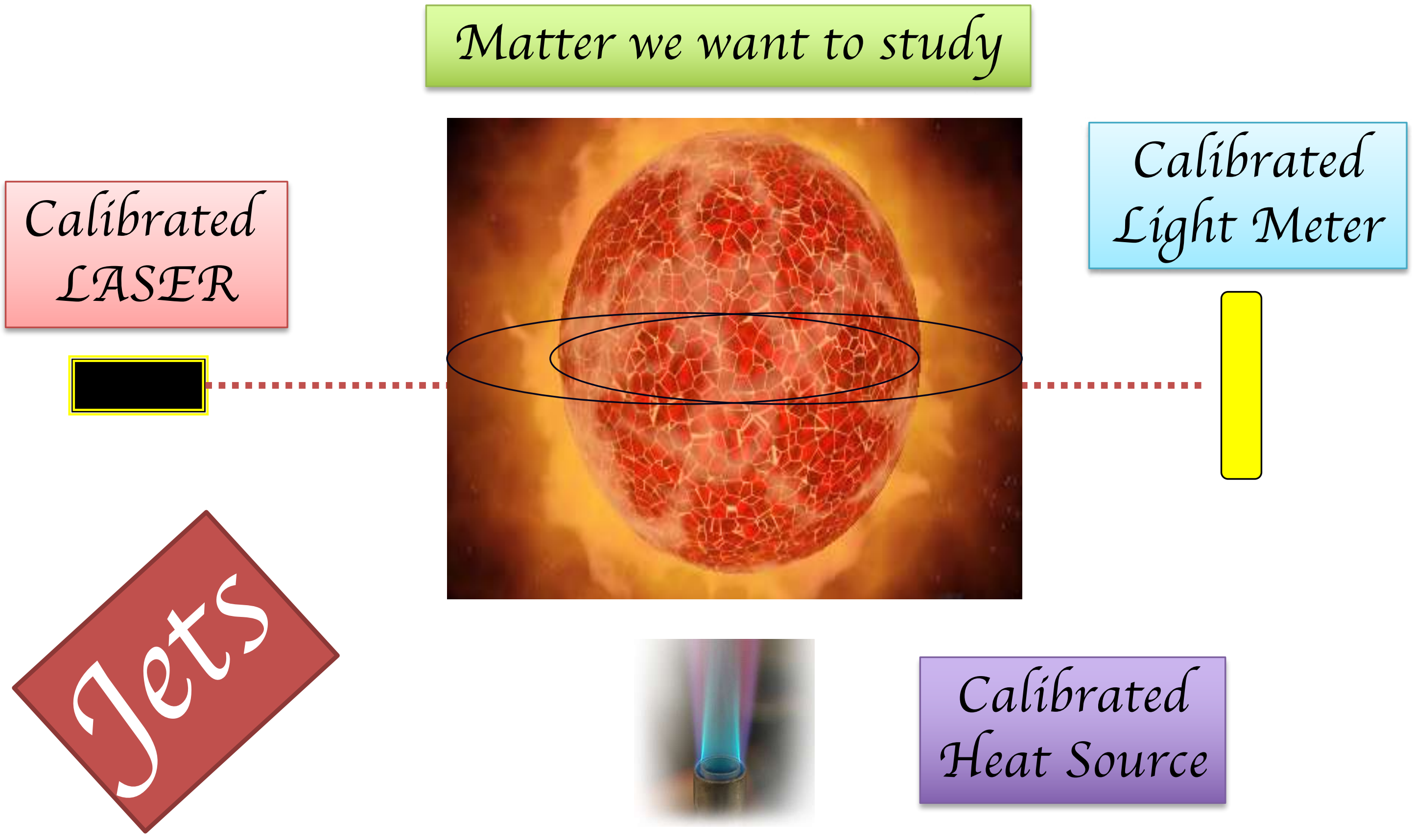
J. D. Bjorken Physical Review D 27 (1983) 140

Space – Time evolution of heavy-ion collisions

Universe:
QCD Phase Transition: T ~ 200MeV
EW Phase Transition: T ~ 150 GeV
GUT Phase Transition: T ~10^{16} GeV

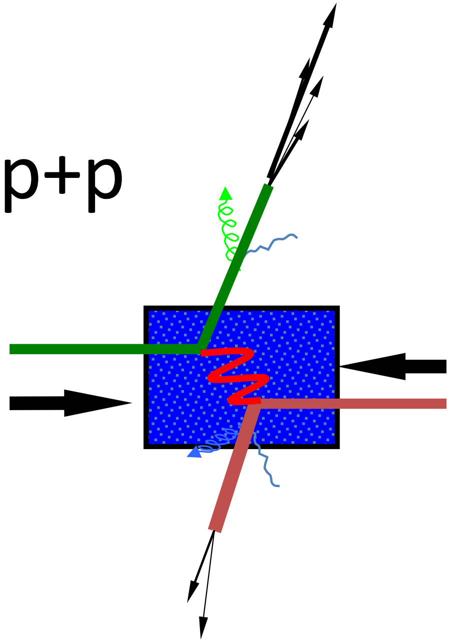


Opacity


Matter we want to study
Calibrated LASER
Calibrated Light Meter
Jets
Calibrated Heat Source

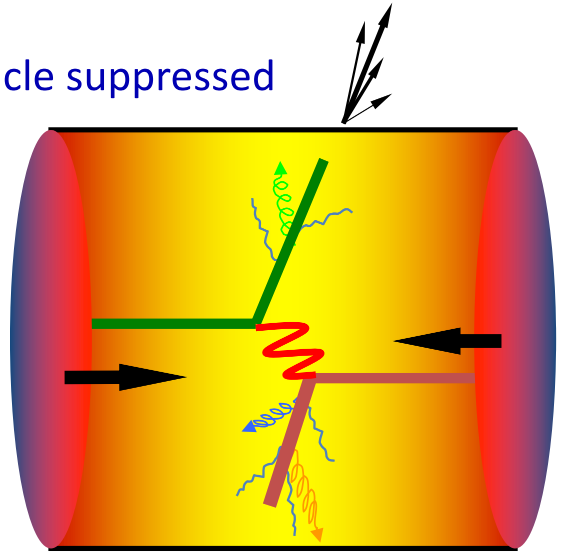
Quenching of Jets

p+p



A+A

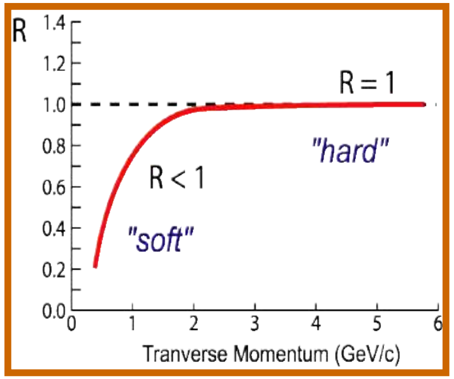
leading particle suppressed



back-to-back jets disappear

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

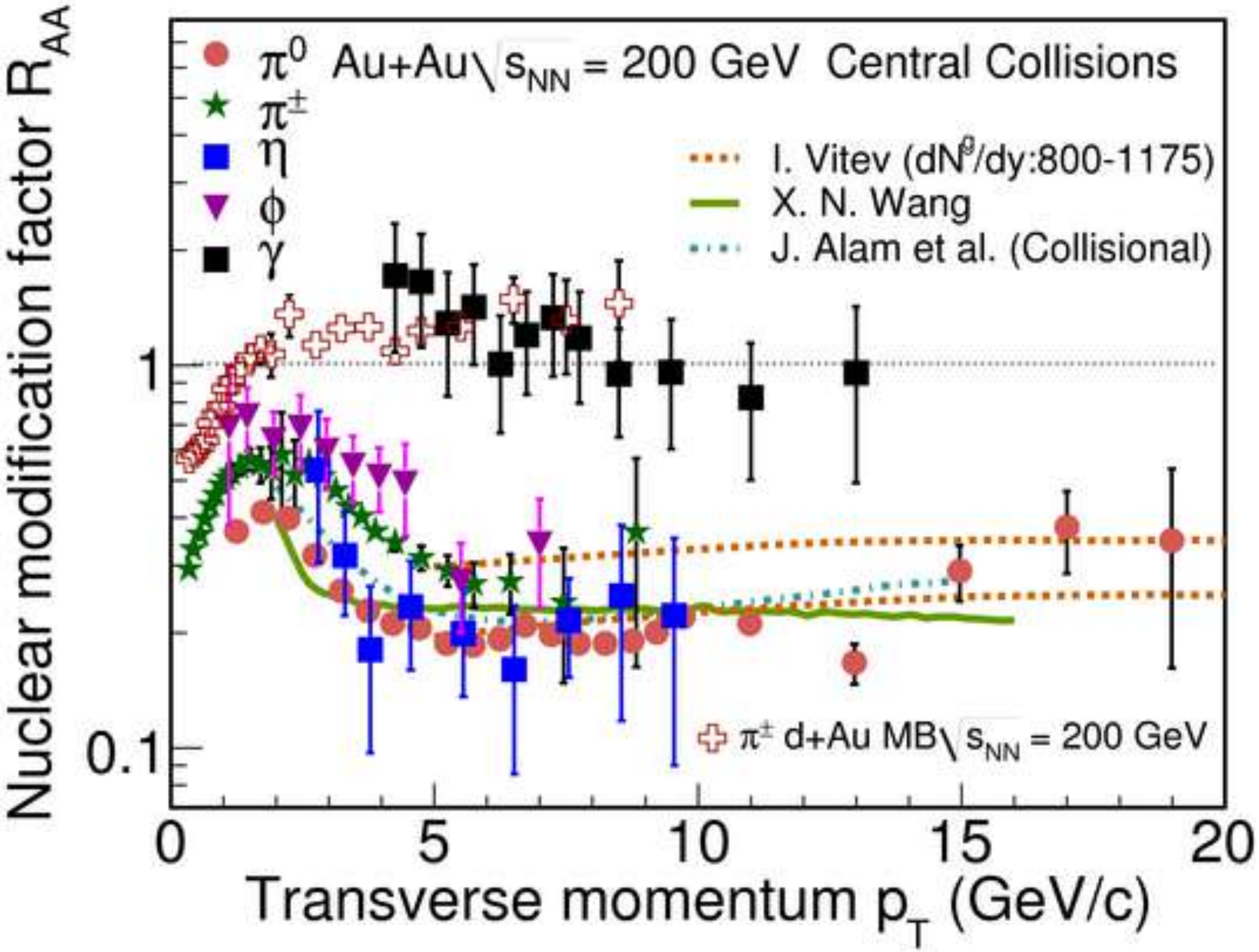


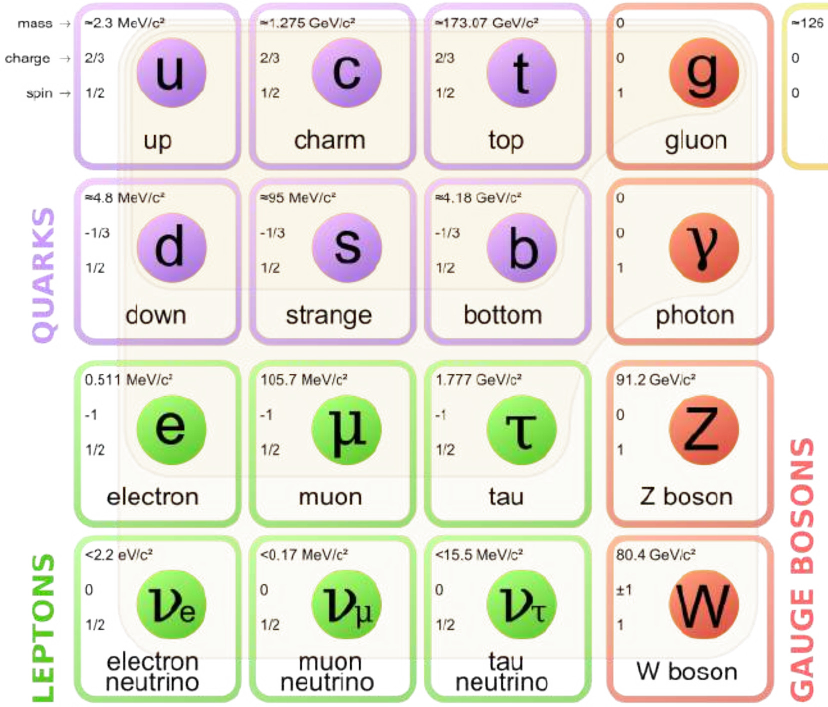
High p_T hadron production suppressed

Experimental evidence of Quenching of Jets ≡ *Energy loss of quarks and gluons in dense medium*

1) Photons are not suppressed
2) No suppression in d+Au collisions

$\varepsilon_{initial} > \varepsilon_C$ (Lattice)





PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Standard Model