

Nature Physics, 15, 1113 (2019)



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)

Quark-Gluon Plasma: the perfect and most vortical fluid

Bedanga Mohanty, NISER

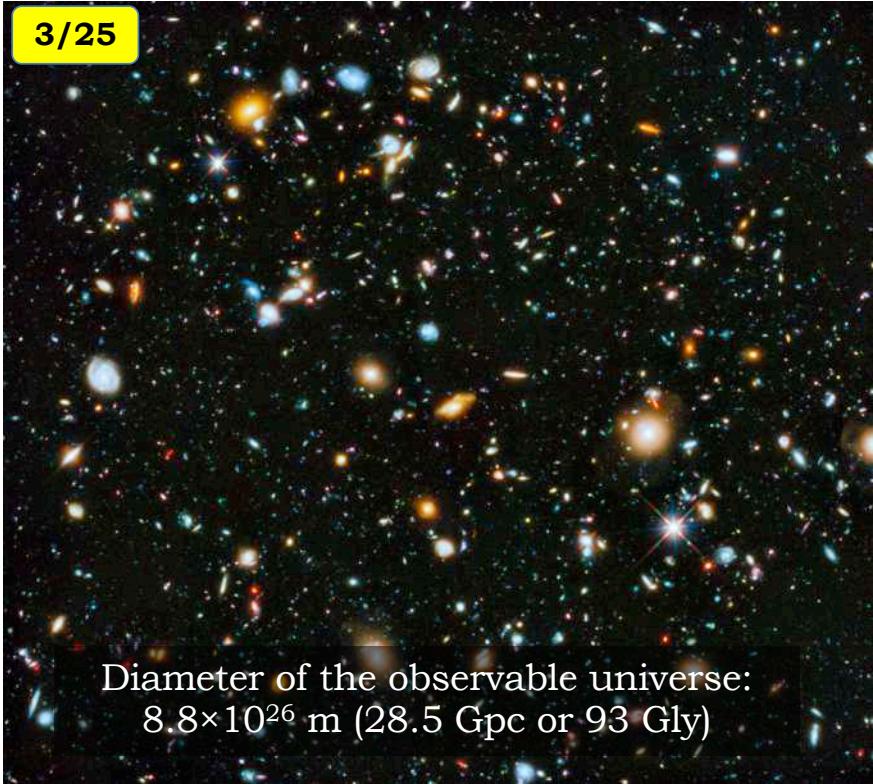
2/25



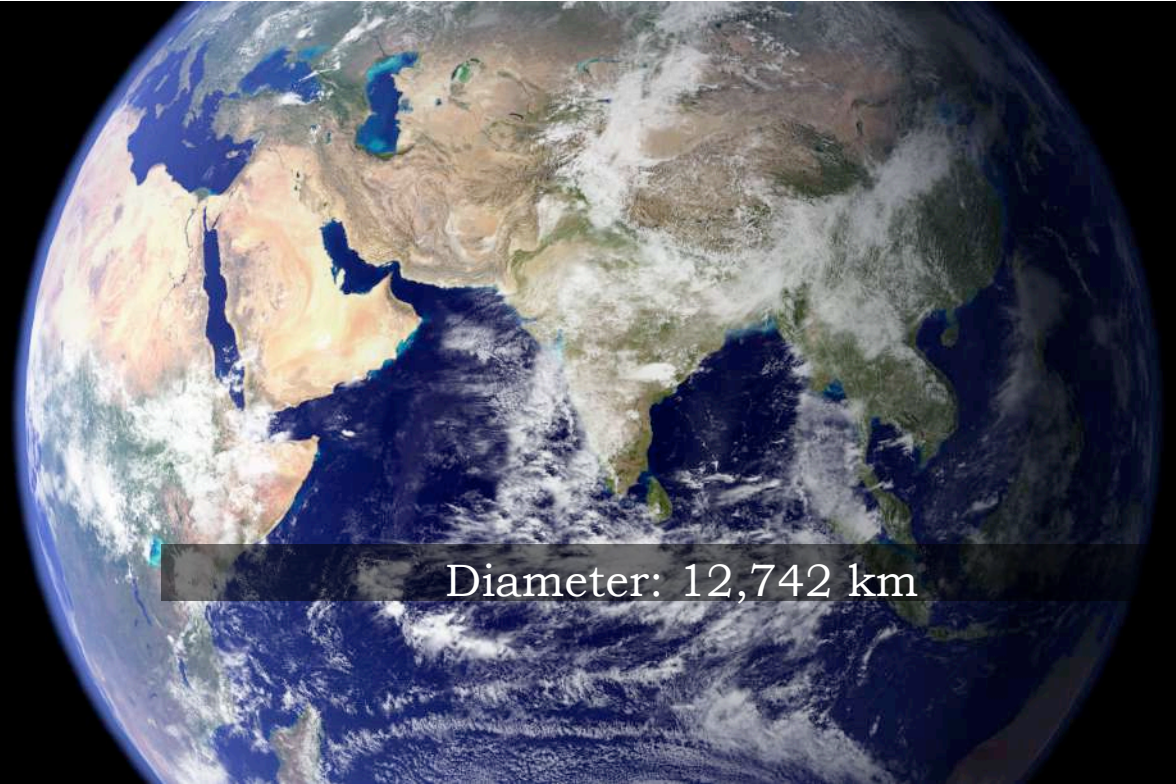
Young minds
wondering about
the Universe!



3/25



Diameter of the observable universe:
 8.8×10^{26} m (28.5 Gpc or 93 Gly)



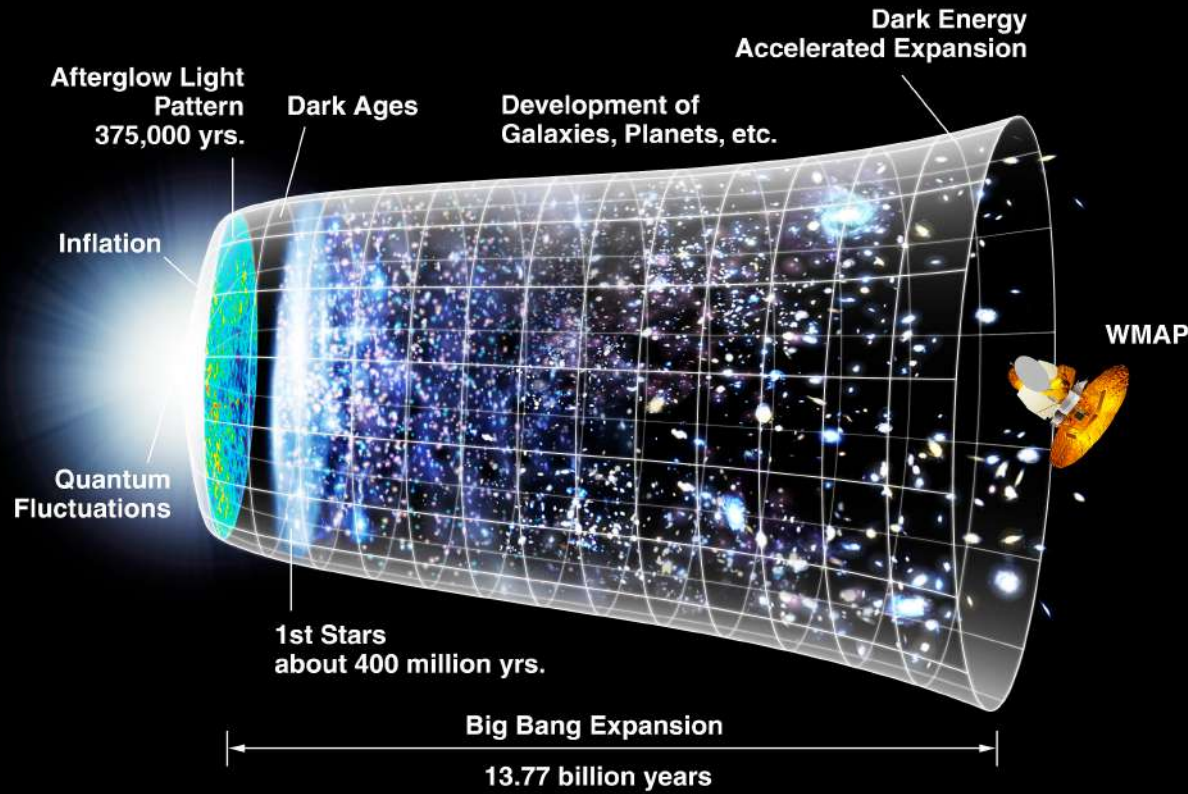
Diameter: 12,742 km



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).

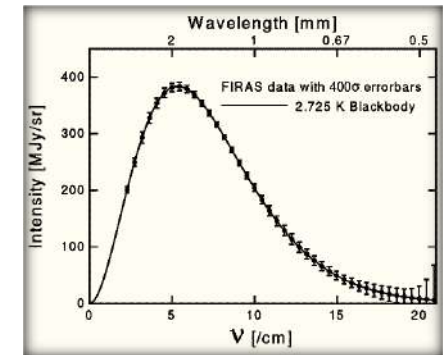
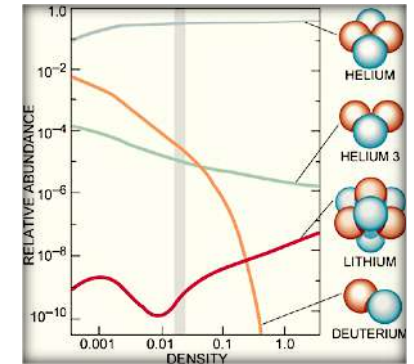
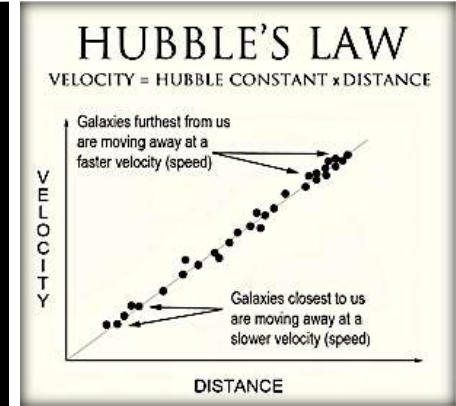
Universe is BIG !

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



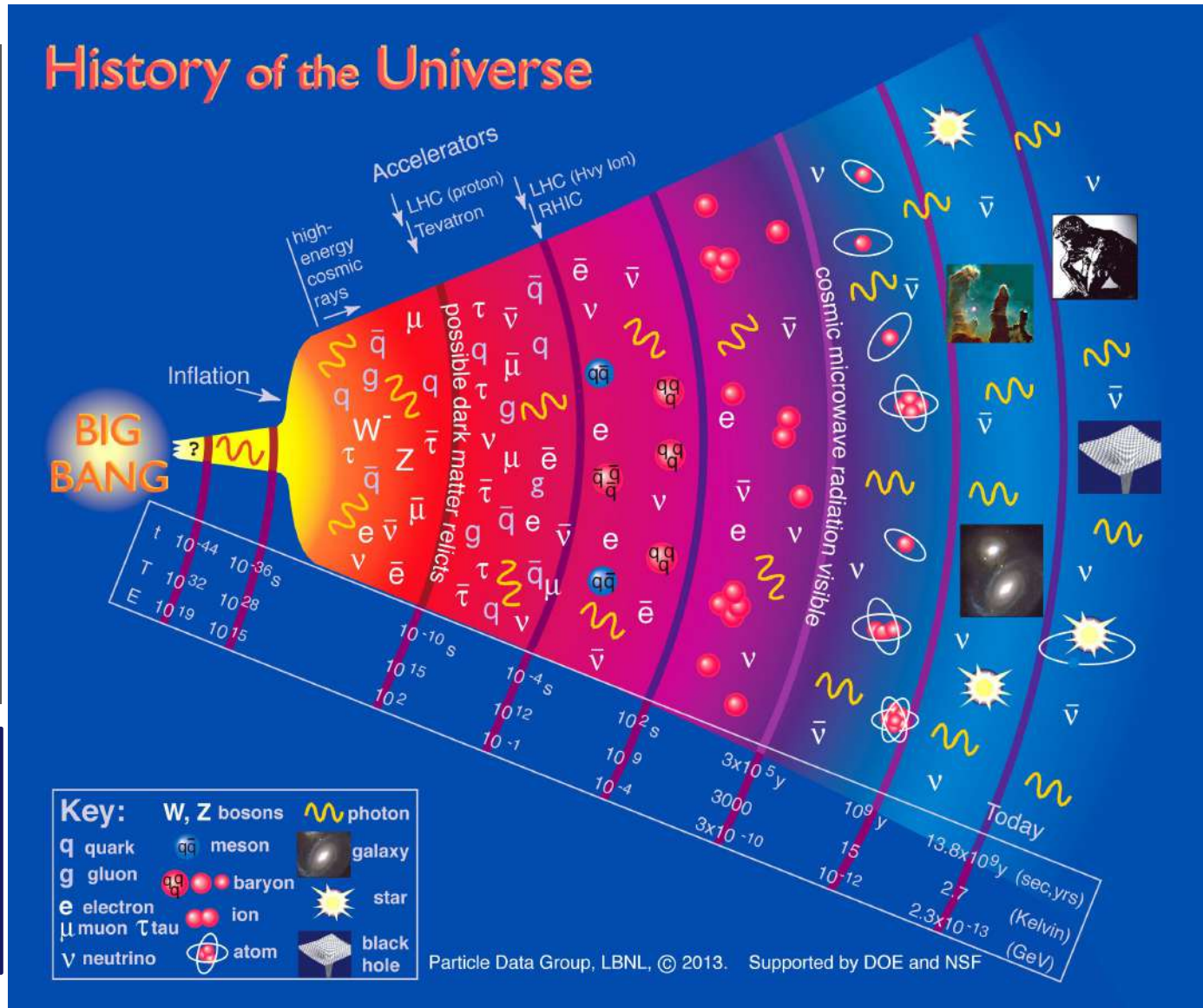
Evolution of Universe

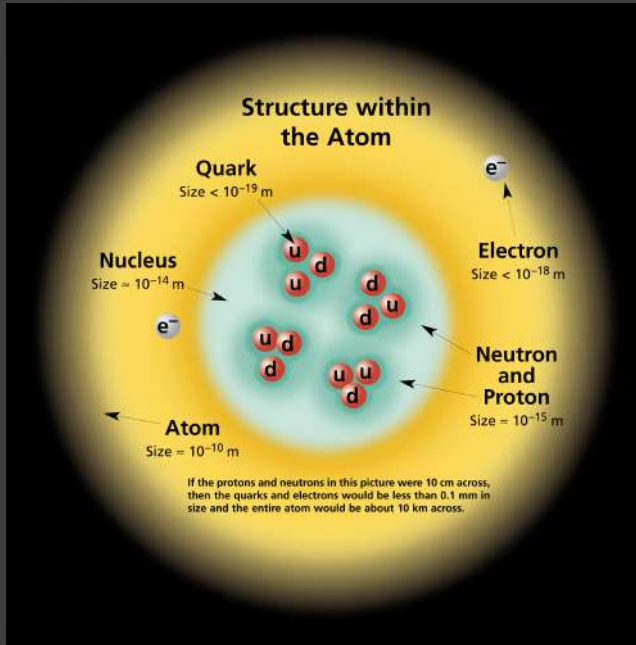
Quark
Gluon
Plasma

Time ~ μs

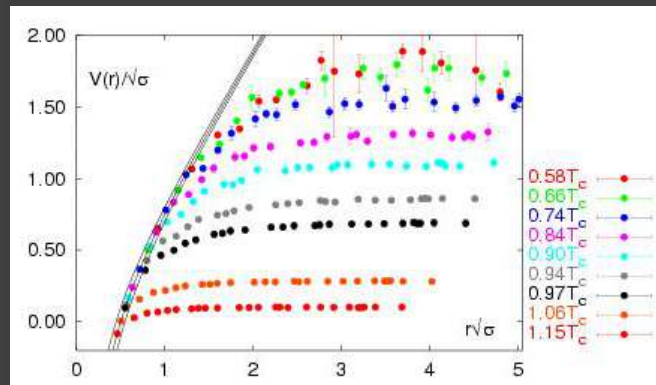
Temp ~ $10^{15} - 10^{12} \text{ K}$

History of the Universe

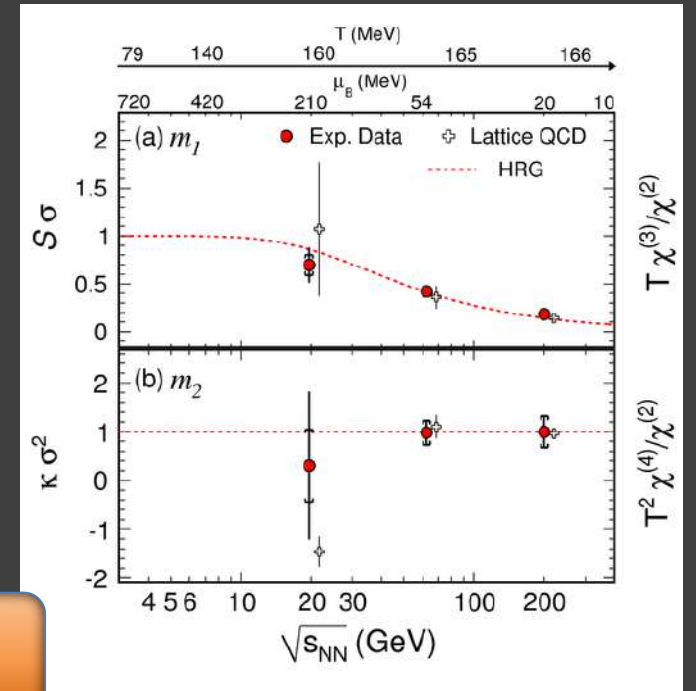




$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$



~ 170 MeV (10^{12} K)



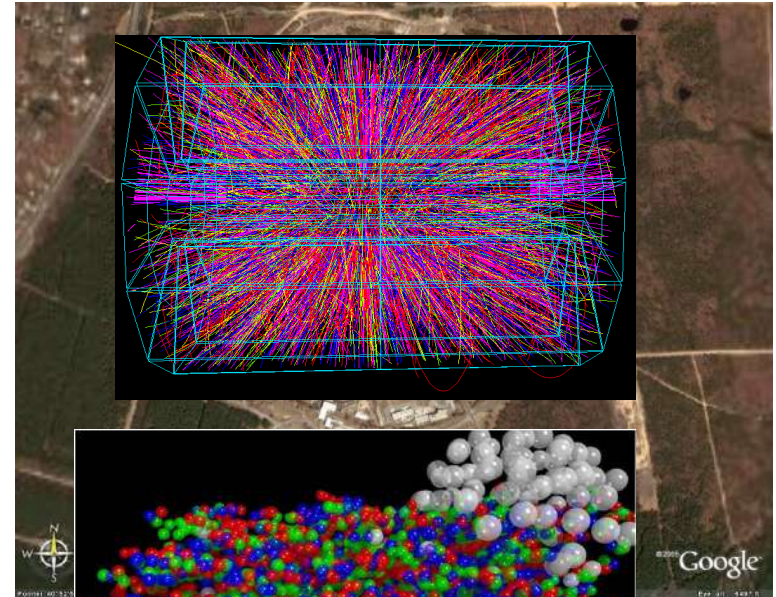
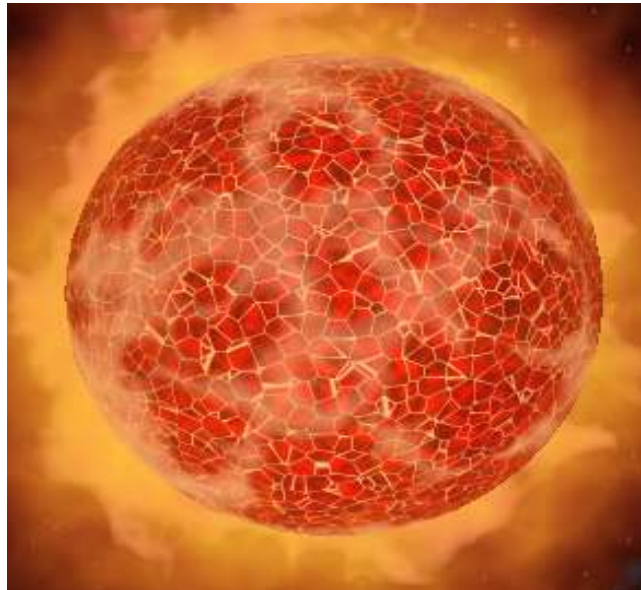
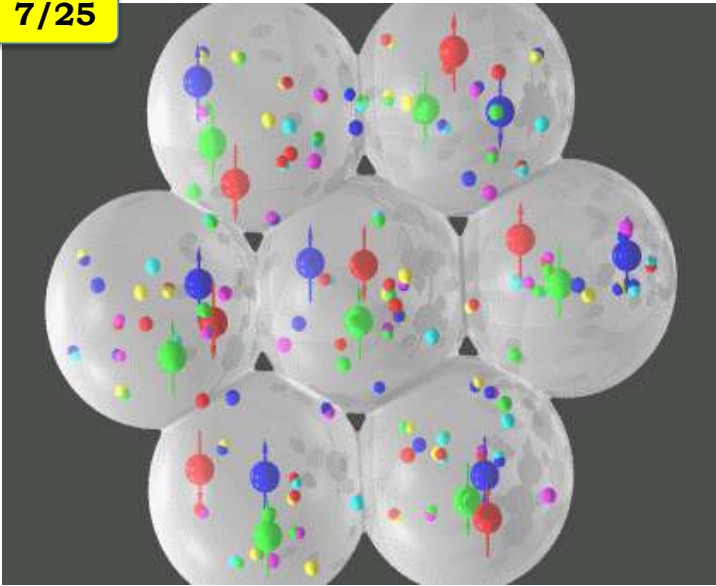
Matter at extremely high temperature \rightarrow QGP

Science
AAAS

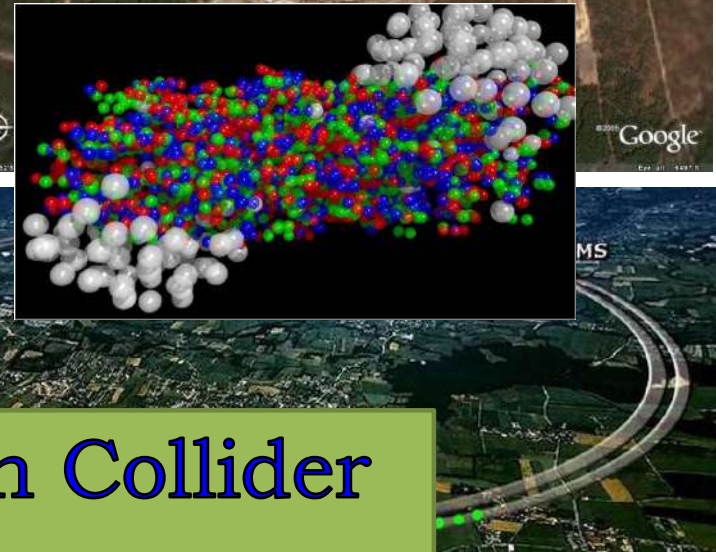
"Scale for the Phase Diagram of
Quantum Chromodynamics"

Science, 332, 1525(2011)

Theoretical support for QGP



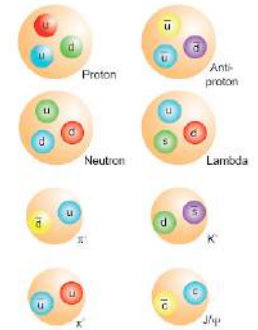
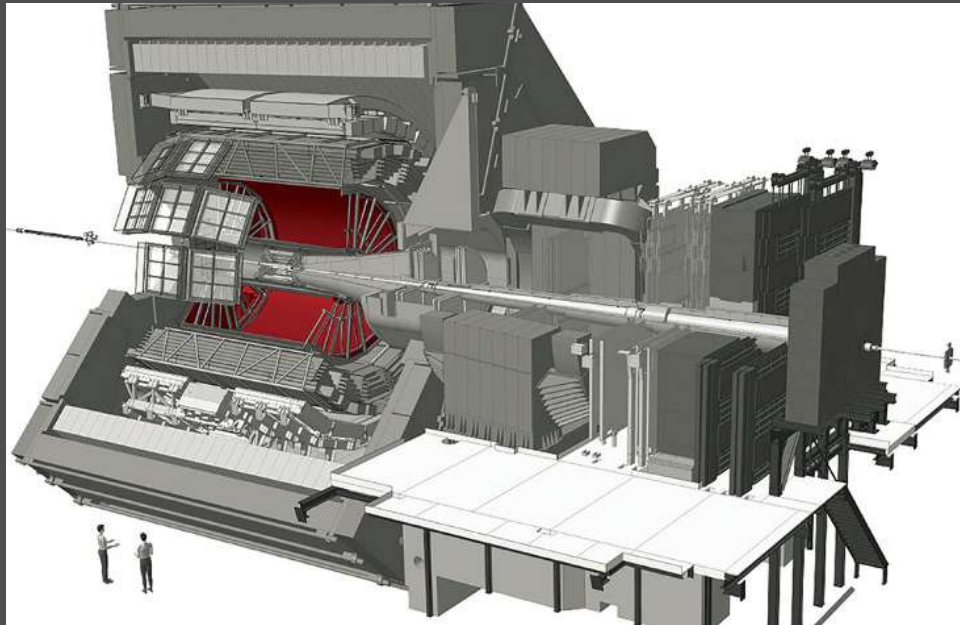
One trillion Kelvin !



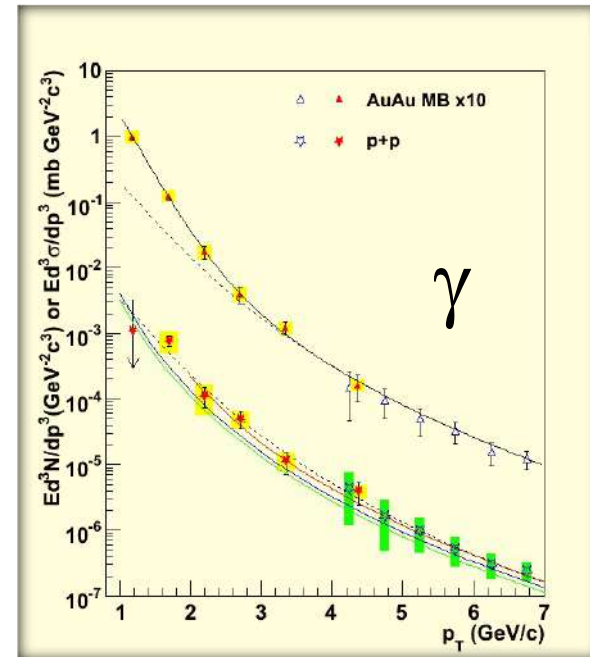
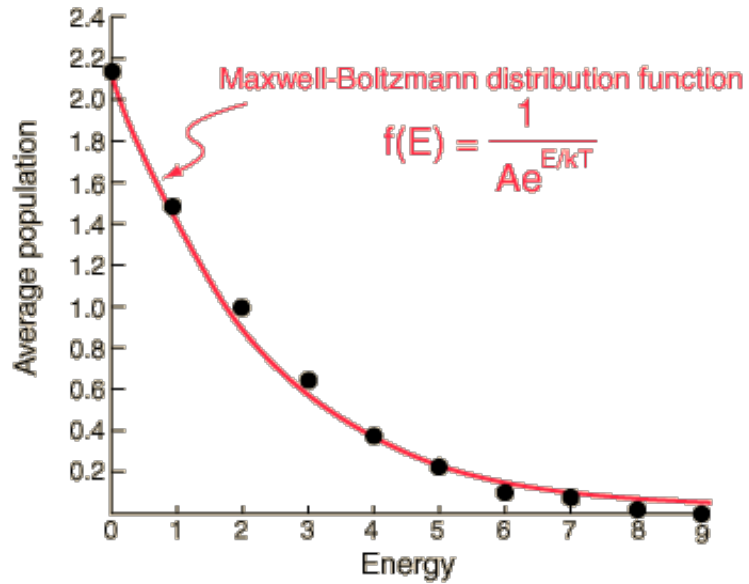
Relativistic Heavy Ion Collider And Large Hadron Collider

QGP: Femto-Scale
in time and space

Typical Detector



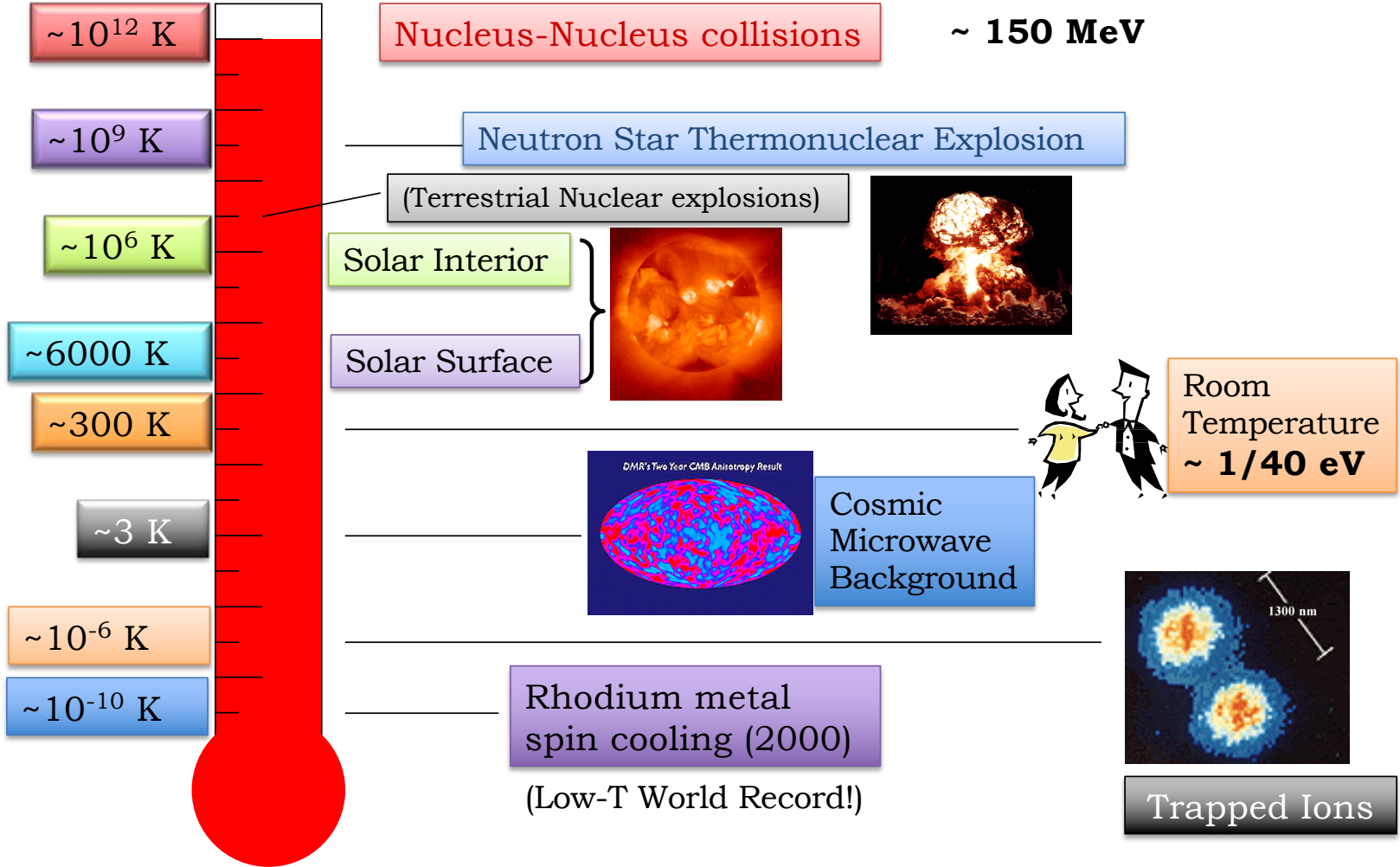
Particle Physics + Nuclear Physics + Condensed Matter Physics + Engineering Science + Detector Physics
Analysis of data also requires knowledge of Statistical, Thermal, Relativistic kinematic Computational, QCD and QED physics.

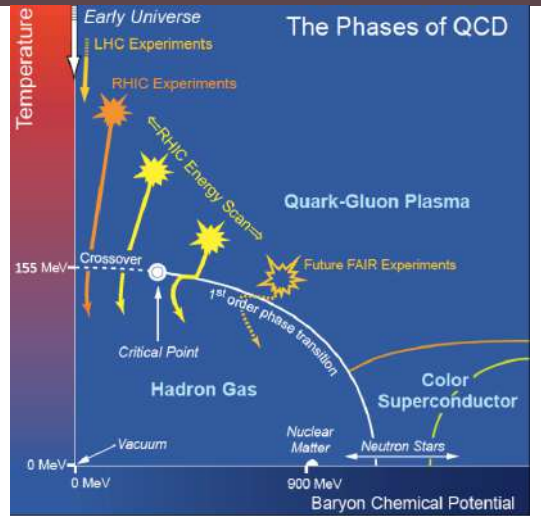
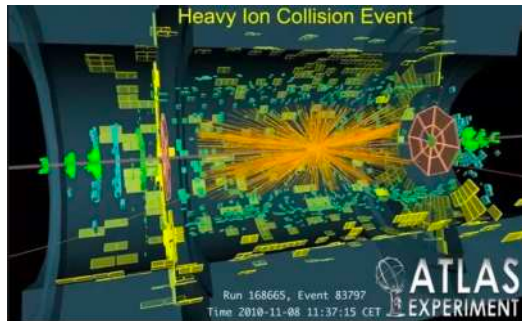
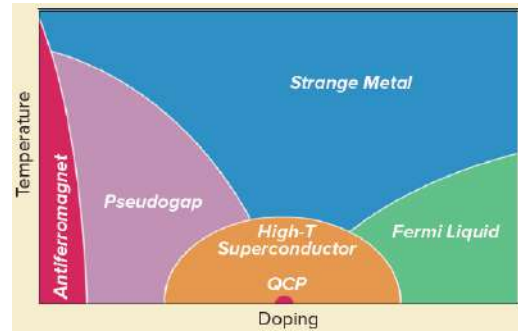
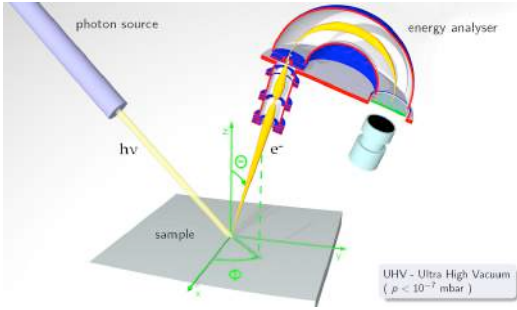


Measuring Temperature

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

Perspective on the Temperature



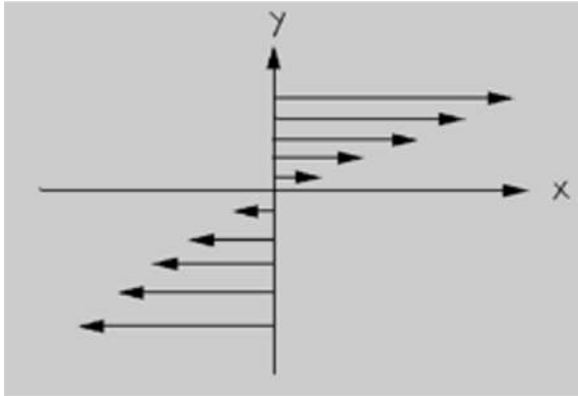


Baryon doping

Emergent properties of matter

Viscosity: resistance to flow

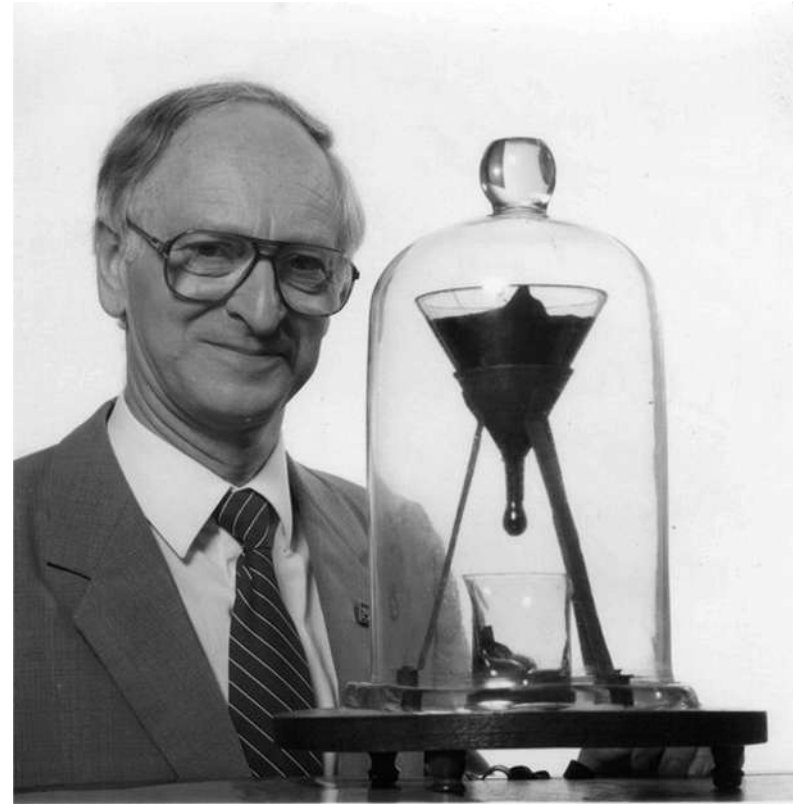
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$



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) $\eta/s \geq \frac{\hbar}{4\pi k_B} = 1/4\pi$.

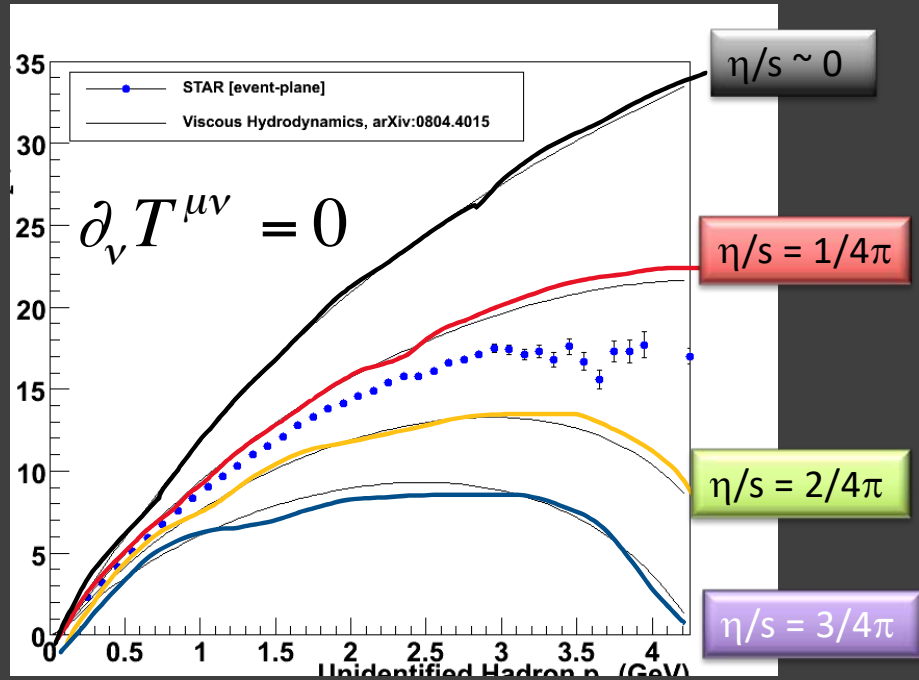
Pitch approximately
 230 billion times viscous than water.



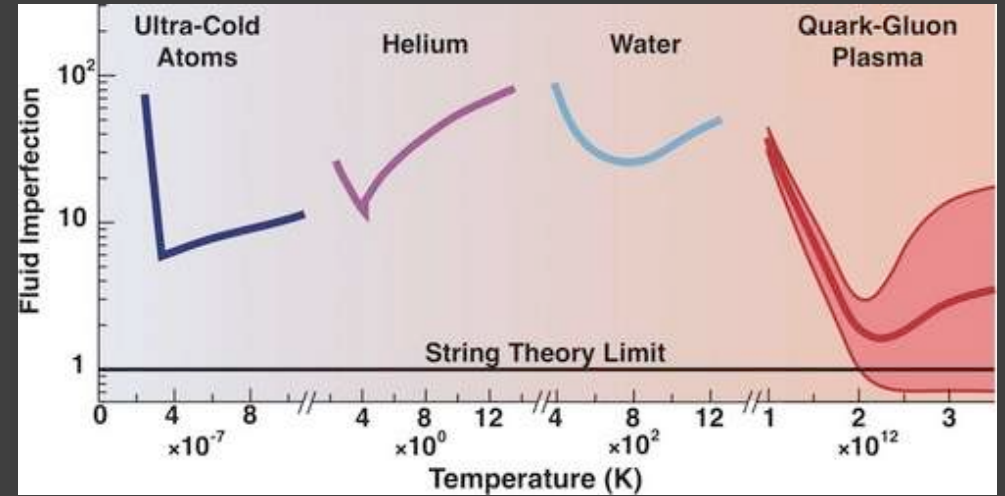
(1927-present) 8 drops

Wiki

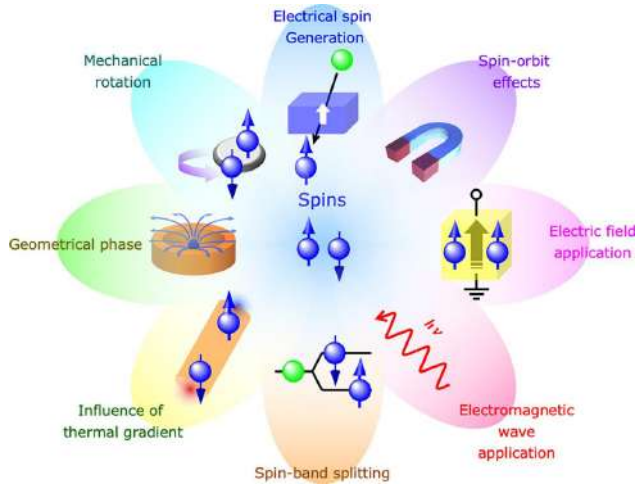
FLOW



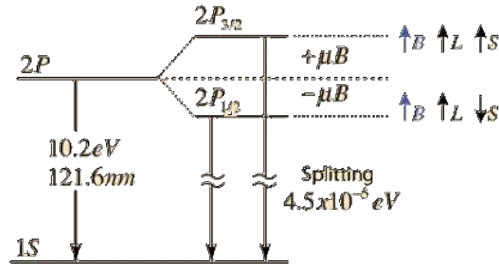
Momentum



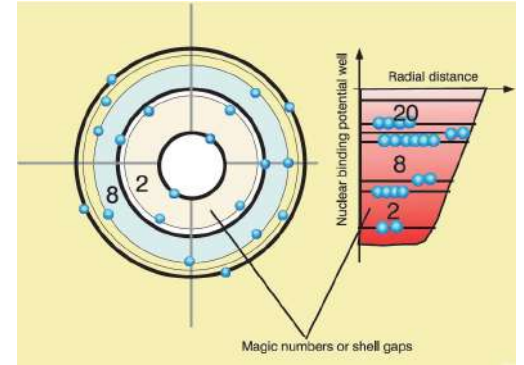
Perfect Fluid



Material Science



Atomic Physics

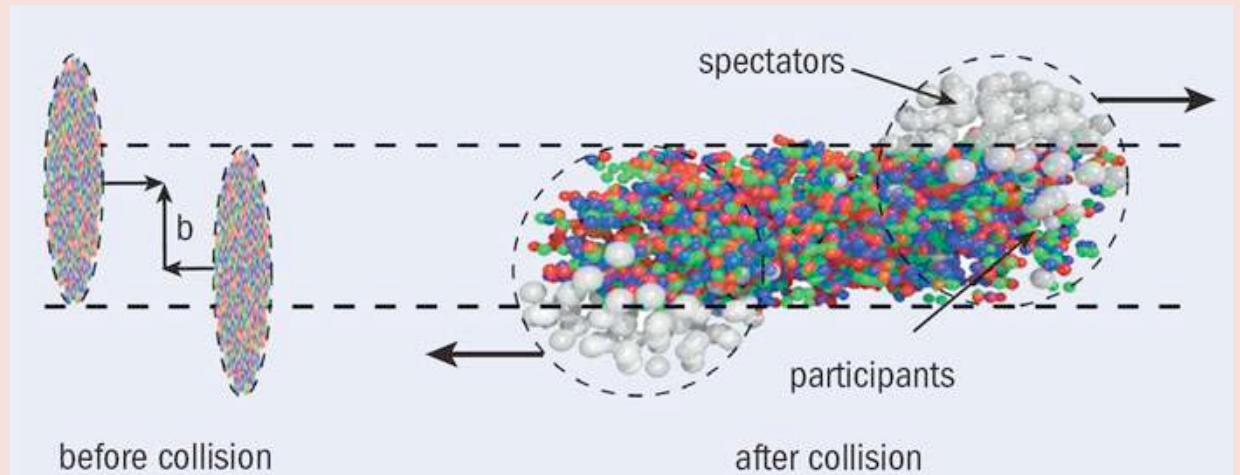


Nuclear Physics

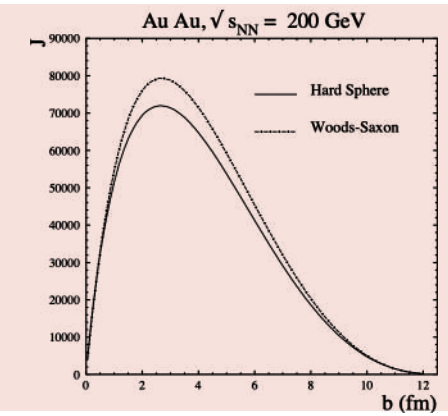
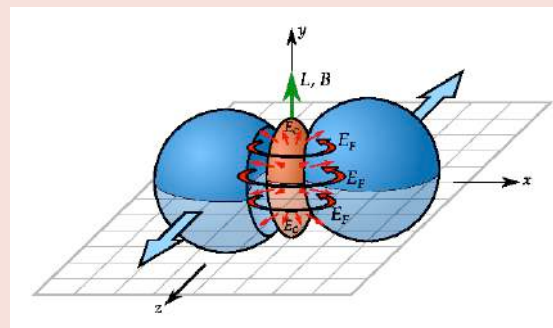
Spin-orbit interactions

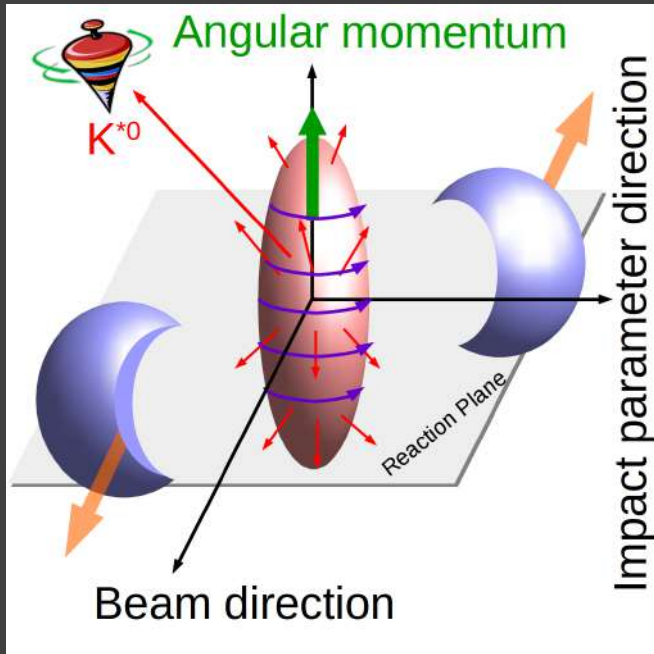
L.S

Large Angular Momentum

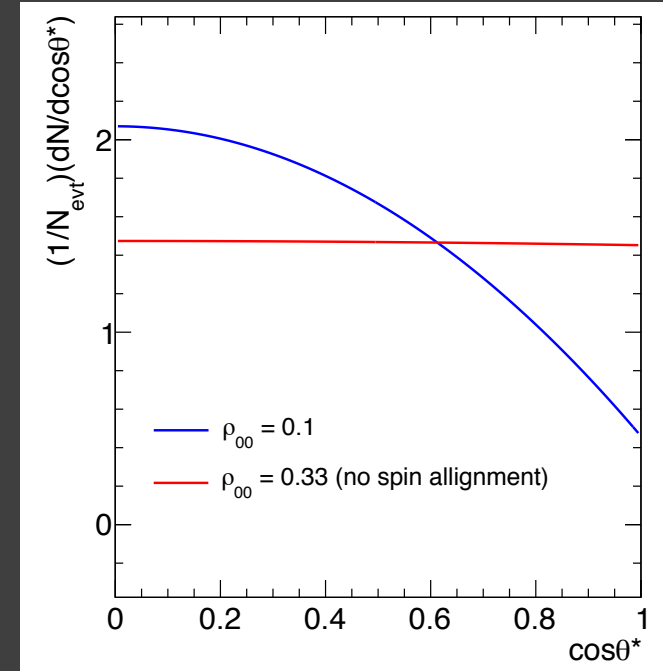


$$L \sim 10^5 \hbar$$

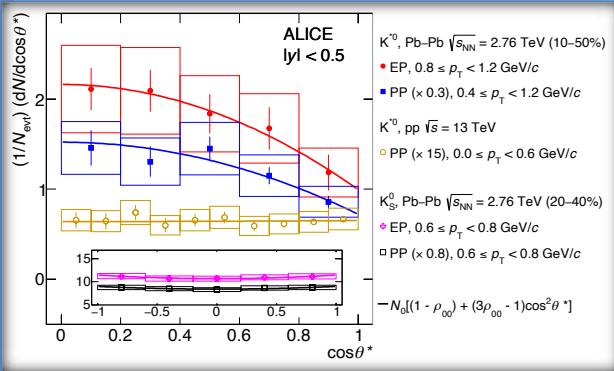
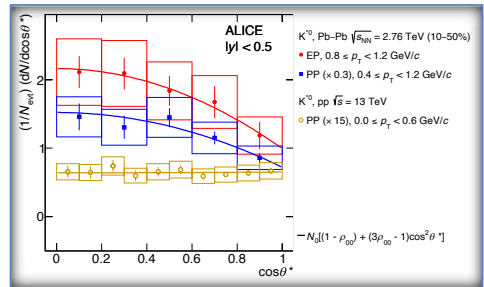
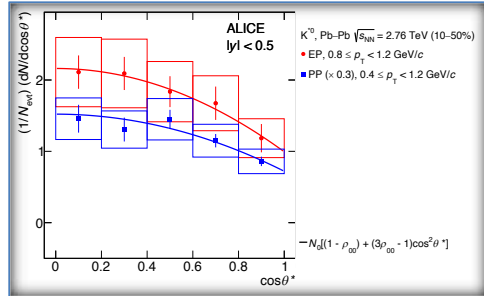
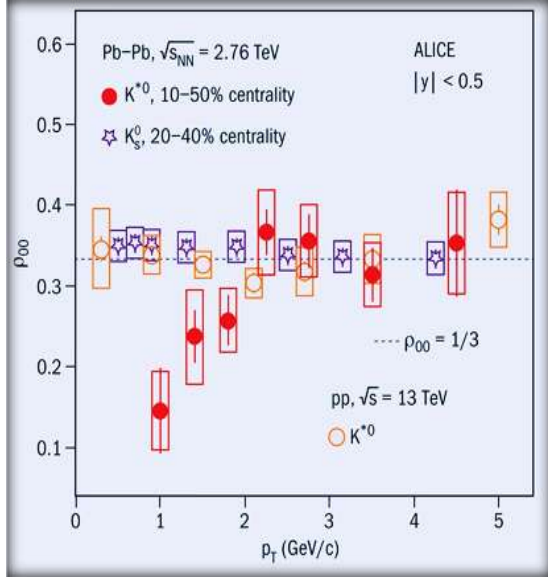




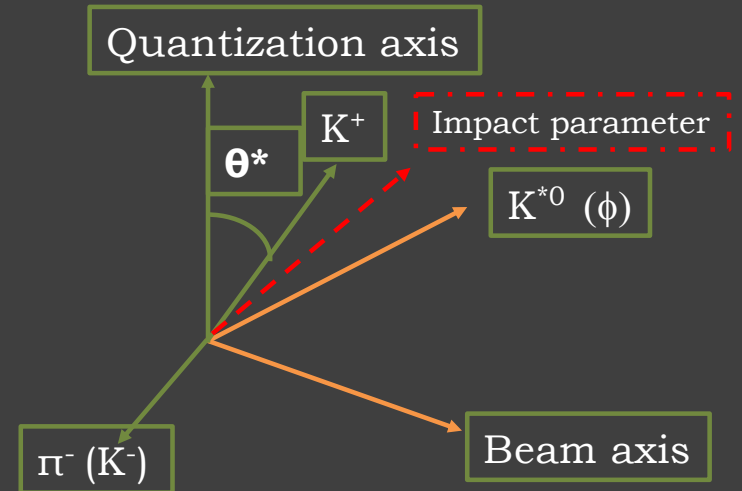
$$\frac{dN}{d\cos\theta} = N_0 [1 - \rho_{0,0} + \cos^2\theta (3\rho_{0,0} - 1)]$$



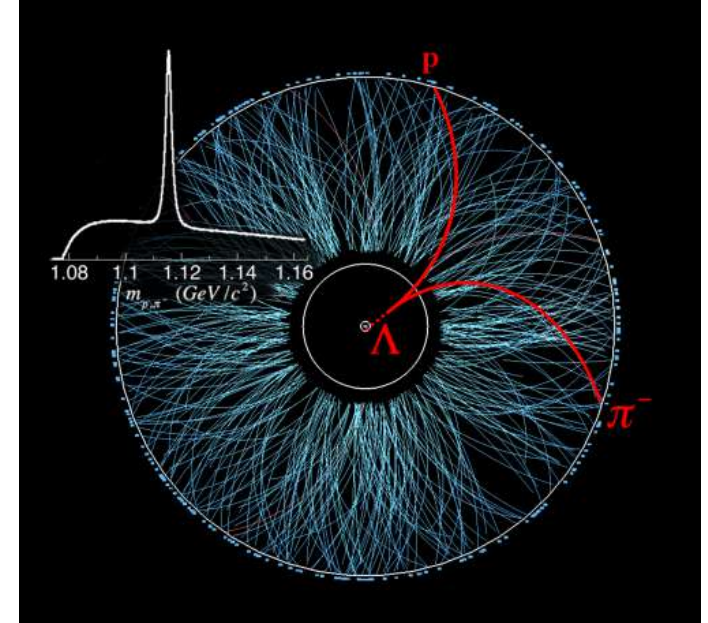
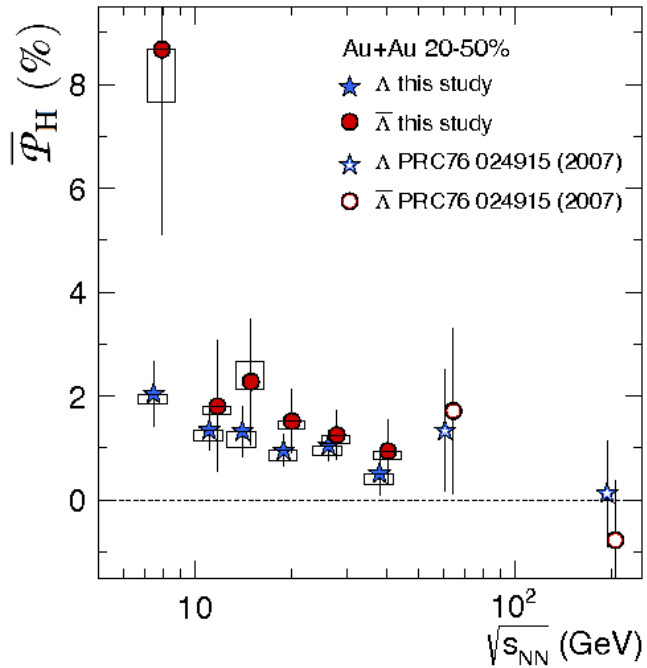
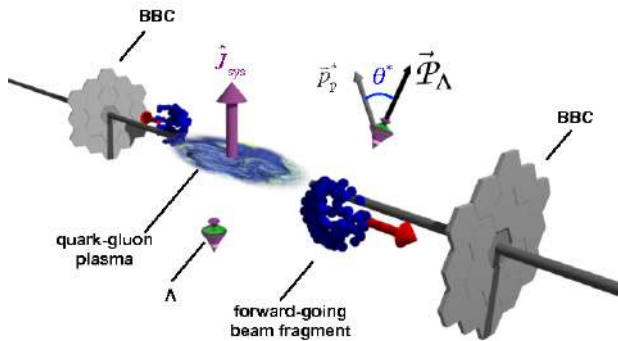
Finding spin-orbit interactions in
QCD matter



Angular distribution of vector mesons



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



$$\omega = k_B T (\bar{P}_{\Lambda'} + \bar{P}_{\bar{\Lambda}'}) / \hbar$$

Most vortical fluid

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

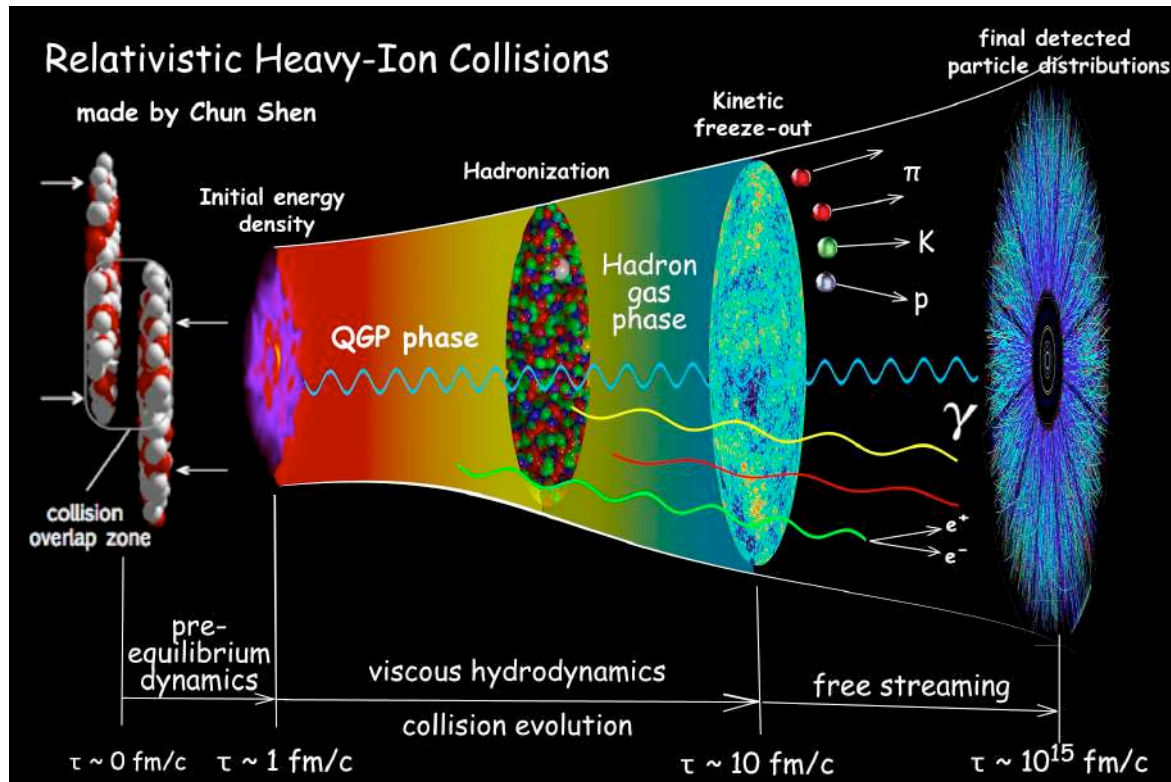
Perspective on vorticity



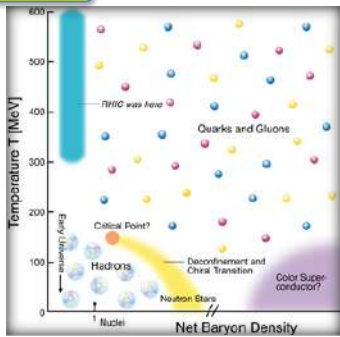
vorticity $\boldsymbol{\omega} = \text{curl } \mathbf{u}$

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

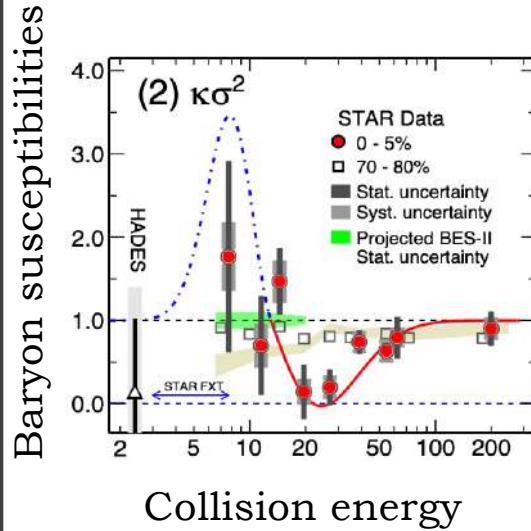
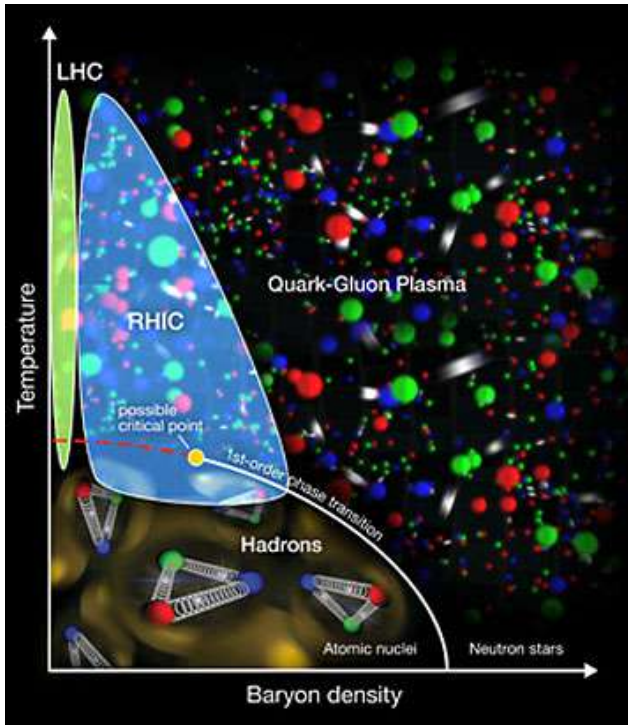




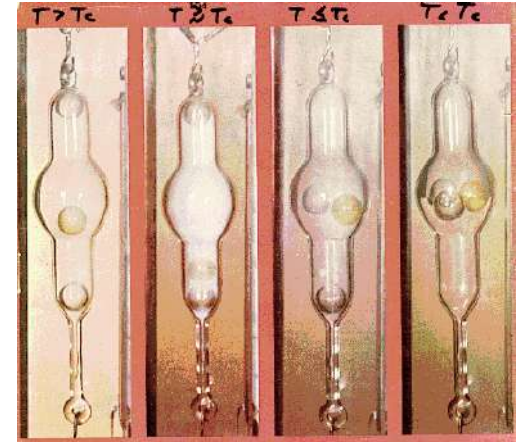
We understand
the evolution
after mini-Bang



Quark
Gluon
Plasma:
Perfect fluid
and most
vortical



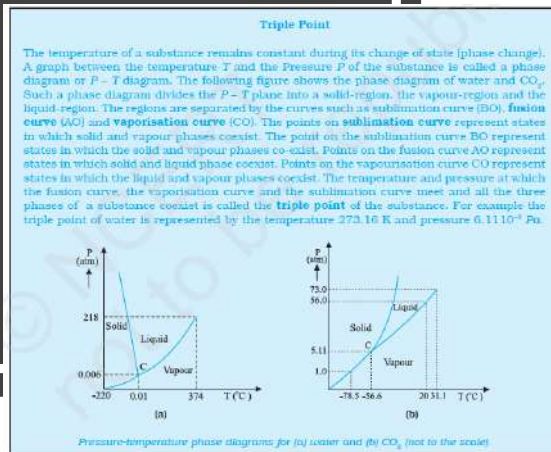
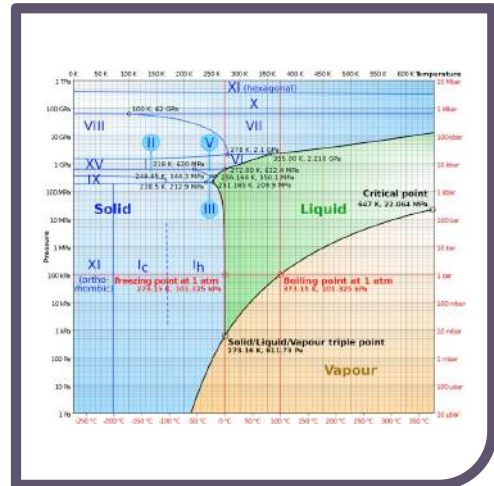
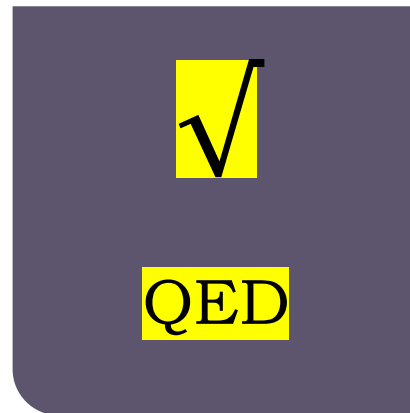
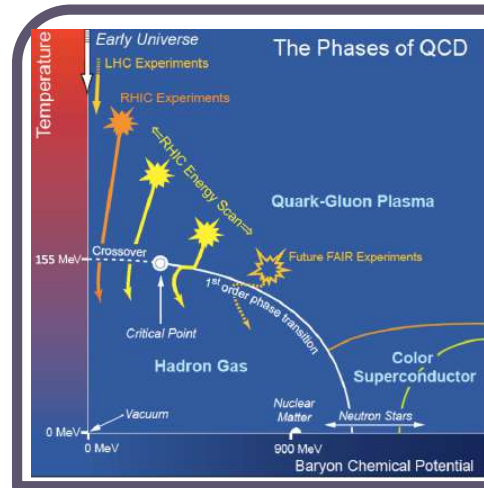
Critical opalescence



Miles to go before we
sleep ...



Phase diagram of matter on the way to textbooks



Chapter - 11
 Thermal Properties of Matter
 NCERT - Book

Mega Sciences

Come join !

From micro to macro:
Understanding the universe through mega science projects

Organised by

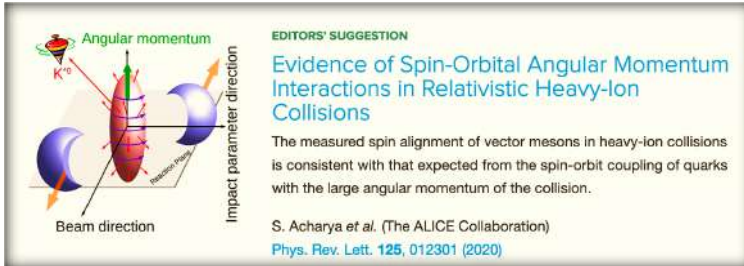
BIG BANG

Event	Time Scale	Associated Project
NEUTRINO MASS ORDERING	10 ⁻³¹ SECONDS	INO
HIGH ENERGY PARTICLE REACTIONS	10 ⁻¹² SECONDS	FAIR
FIRST NUCLEI	A few MINUTES	FAIR
FORMATION OF FIRST STARS	One hundred Million YEARS	TMT
STRUCTURE OF EARLY UNIVERSE	Five hundred Million YEARS	TMT
THERMONUCLEAR FUSION	One billion YEARS	ITER
BLACK HOLES AND MERGING STARS	A few Billion YEARS	LIGO
FORMATION OF SOLAR SYSTEM	10 Billion YEARS	LIGO
LIFE ON EARTH BEGINS	-	-

An artist's impression of the evolution of the universe showing the key areas of interest for each project.

Thank you

References



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

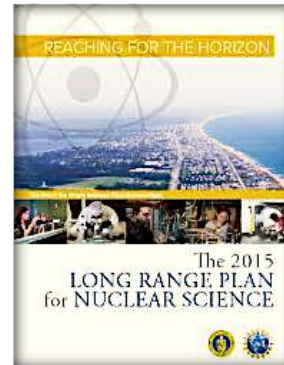
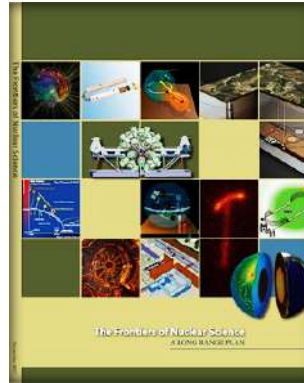
Global Λ hyperon polarization in nuclear collisions

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 Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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



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 Au + 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

RESEARCH ARTICLE

Scale for the Phase Diagram of Quantum Chromodynamics

Sourendu Gupta¹, Xiaofeng Luo^{2,3}, Bedangadas Mohanty^{4,*}, Hans Georg Ritter³, 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

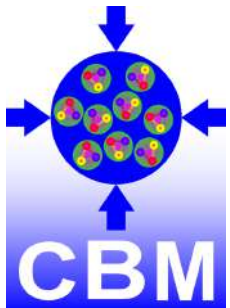
VIEWPOINT

Taking the temperature of extreme matter

Charles Gale
 Department of Physics, McGill University, Montréal, QC H3A 2T8, Canada
 March 29, 2010 • Physics 3, 28



ALICE



Acknowledgements



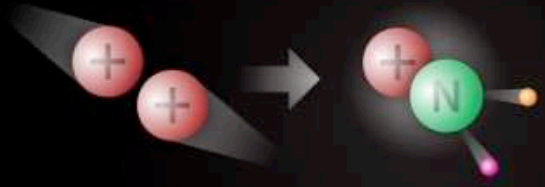
Department of Science & Technology, Government of India

सत्यमेव जयते

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

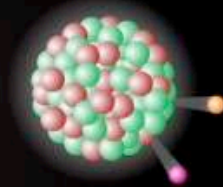
Back up

Weak Nuclear Force



Converting protons into neutrons

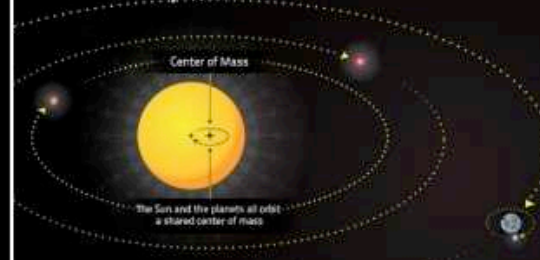
When two protons collide and fuse, a disruption in the weak nuclear force emits a positron and neutrino, which converts one of the positively charged proton to a neutrally charged Neutron. Without the weak nuclear force converting protons into neutrons, certain complex nuclei cannot form.



Releasing radiation

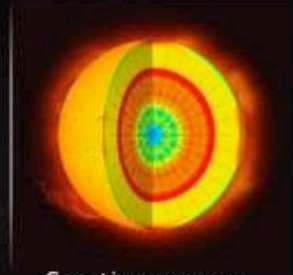
Heavy atoms have an imbalance of protons and neutrons, so the weak nuclear force converts protons to neutrons releasing radiation.

Gravity



Adding motion to the Universe

Gravity forms stars, planets, and moons, and forces these objects to spin on an axis and move along an orbital path. The planets appear to be orbiting the center of the Sun, but the Sun and planets all orbit a shared center of mass. Planets with enough mass can develop orbiting moons or rings of debris.



Creating energy

Gravity is the force that creates pressure and fusion energy in the core of stars allowing them to burn for millions of years.

Electromagnetic Force



Forming atoms and molecules

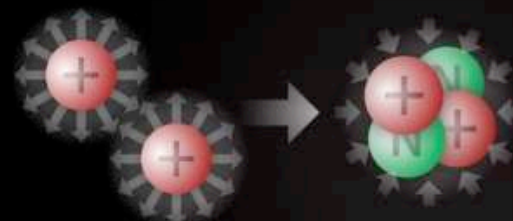
The electromagnetic force pulls negatively charged electrons into bound orbits around positively charged nuclei to form atoms and molecules. As a gas cools, electrons will find their way into the presence of atomic nuclei. Larger nuclei with a greater positive charge pull in more electrons until atoms and molecules have a balance of charges.



Generating light

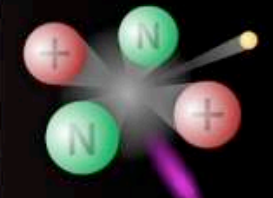
When a negative electron interacts with a positive proton, the electromagnetic force adds energy to the electron generating a photon.

Strong Nuclear Force



Binding protons in atomic nuclei

Positively charged particles naturally repel each other, it takes an extreme amount of force to hold protons together. The strong nuclear force overcomes the repulsion between protons to hold together atomic nuclei. Without the strong nuclear force, complex nuclei cannot form.



Breaking the bond

Enormous energy is released as gamma rays and neutrinos when the strong nuclear force is broken between protons and neutrons.

Fundamental Interactions

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

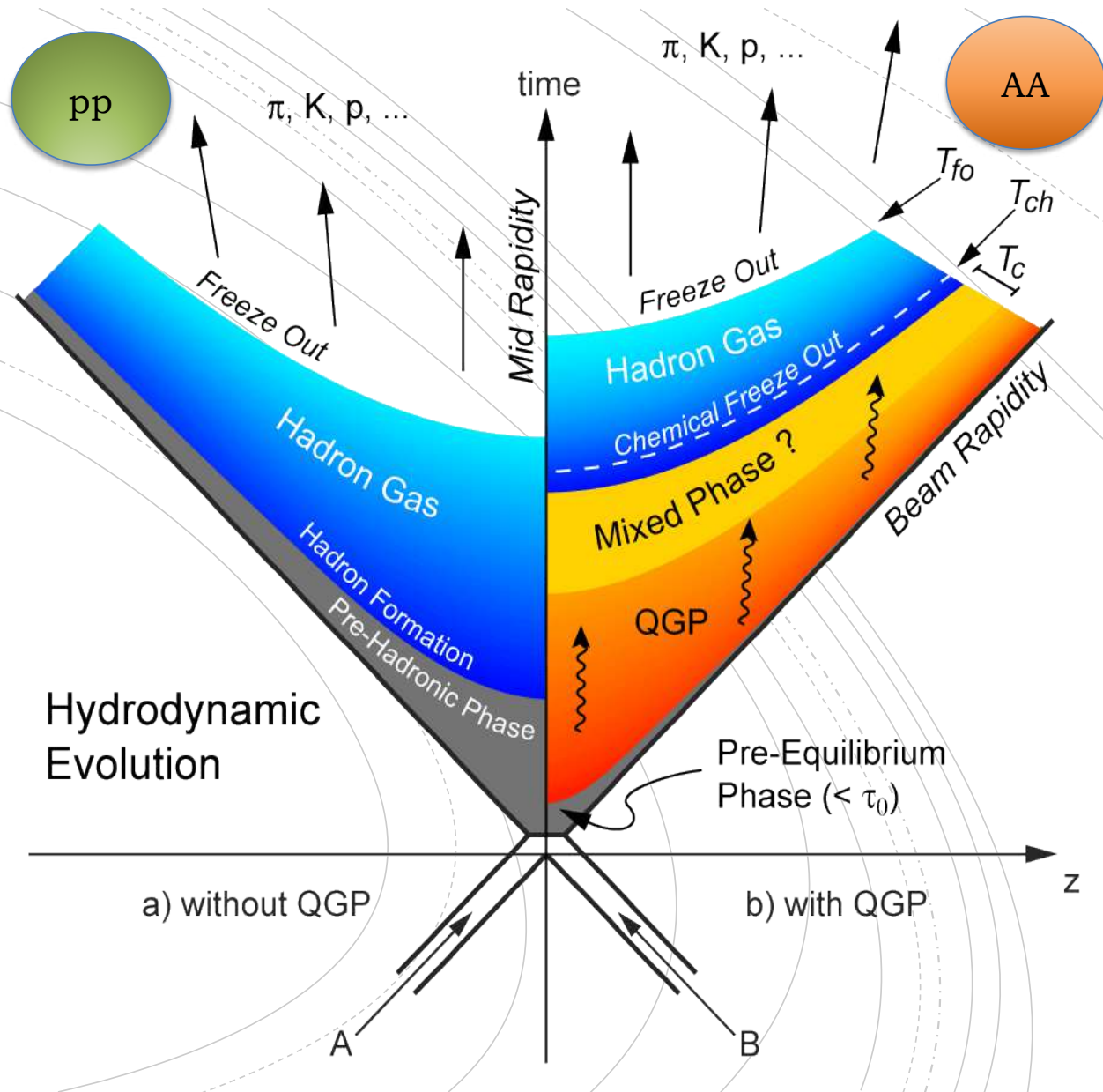
Space – Time evolution of heavy-ion collisions

Universe:

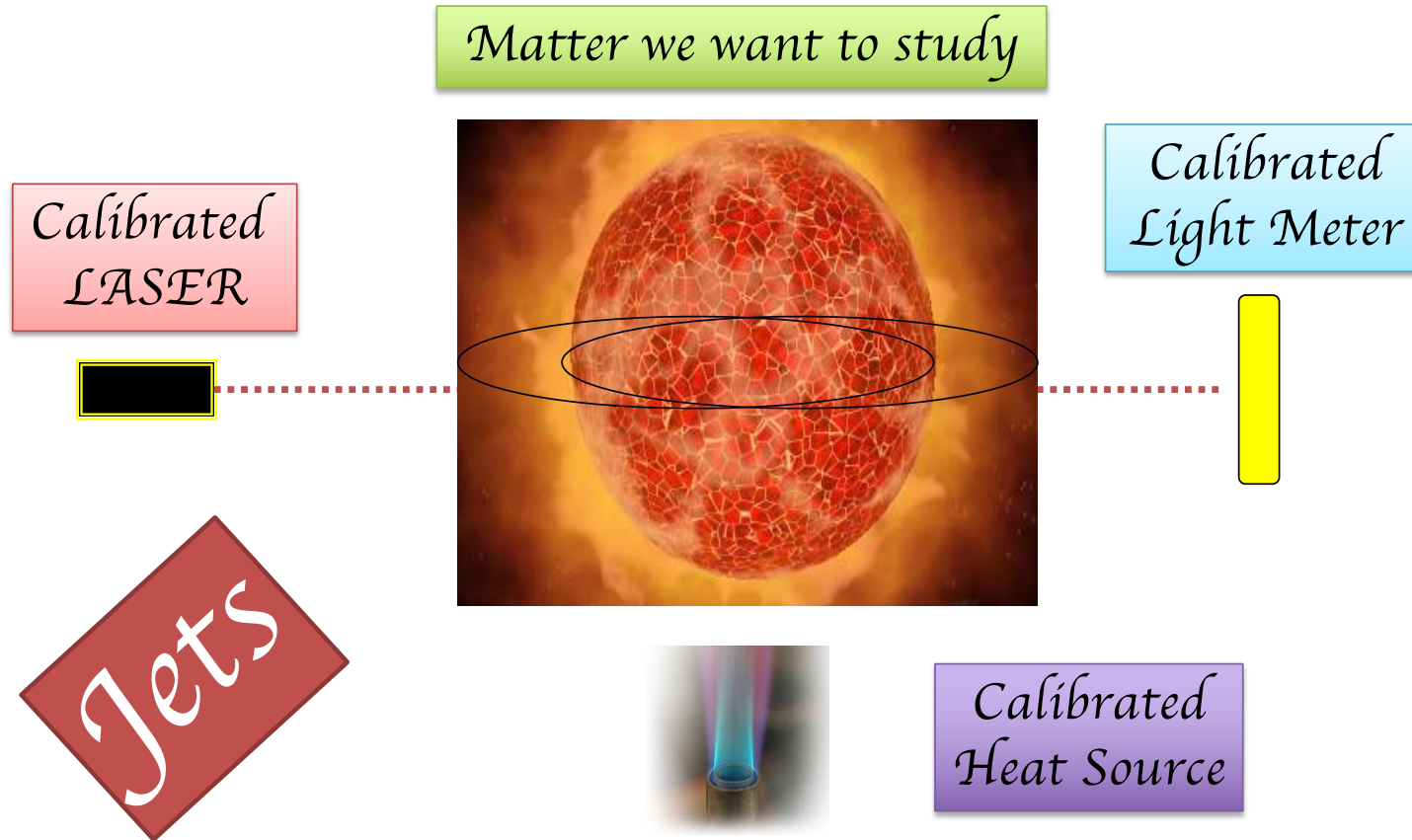
QCD Phase Transition: $T \sim 200\text{MeV}$

EW Phase Transition: $T \sim 150\text{ GeV}$

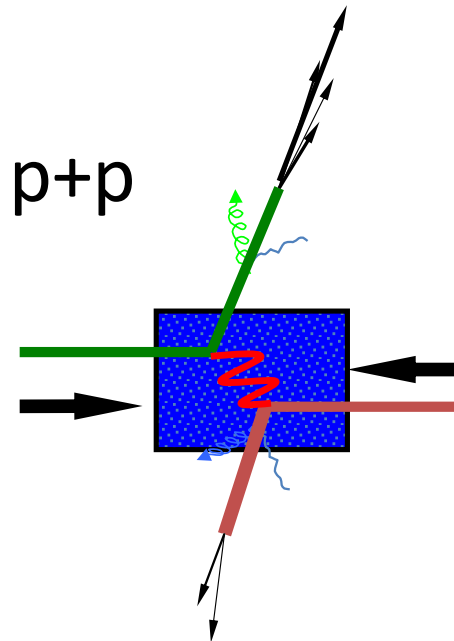
GUT Phase Transition: $T \sim 10^{16}\text{ GeV}$



Opacity

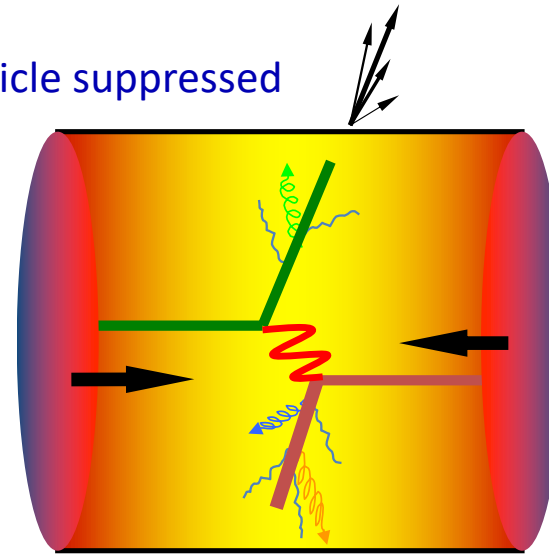


Quenching of Jets



leading particle suppressed

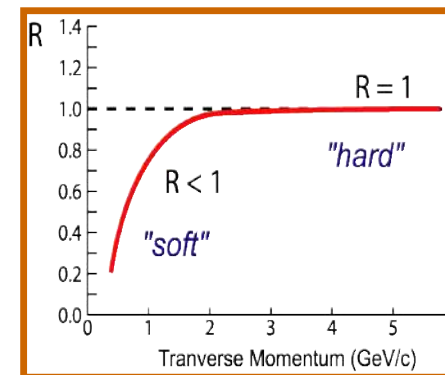
A+A



back-to-back jets disappear

Nuclear Modification Factor:

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

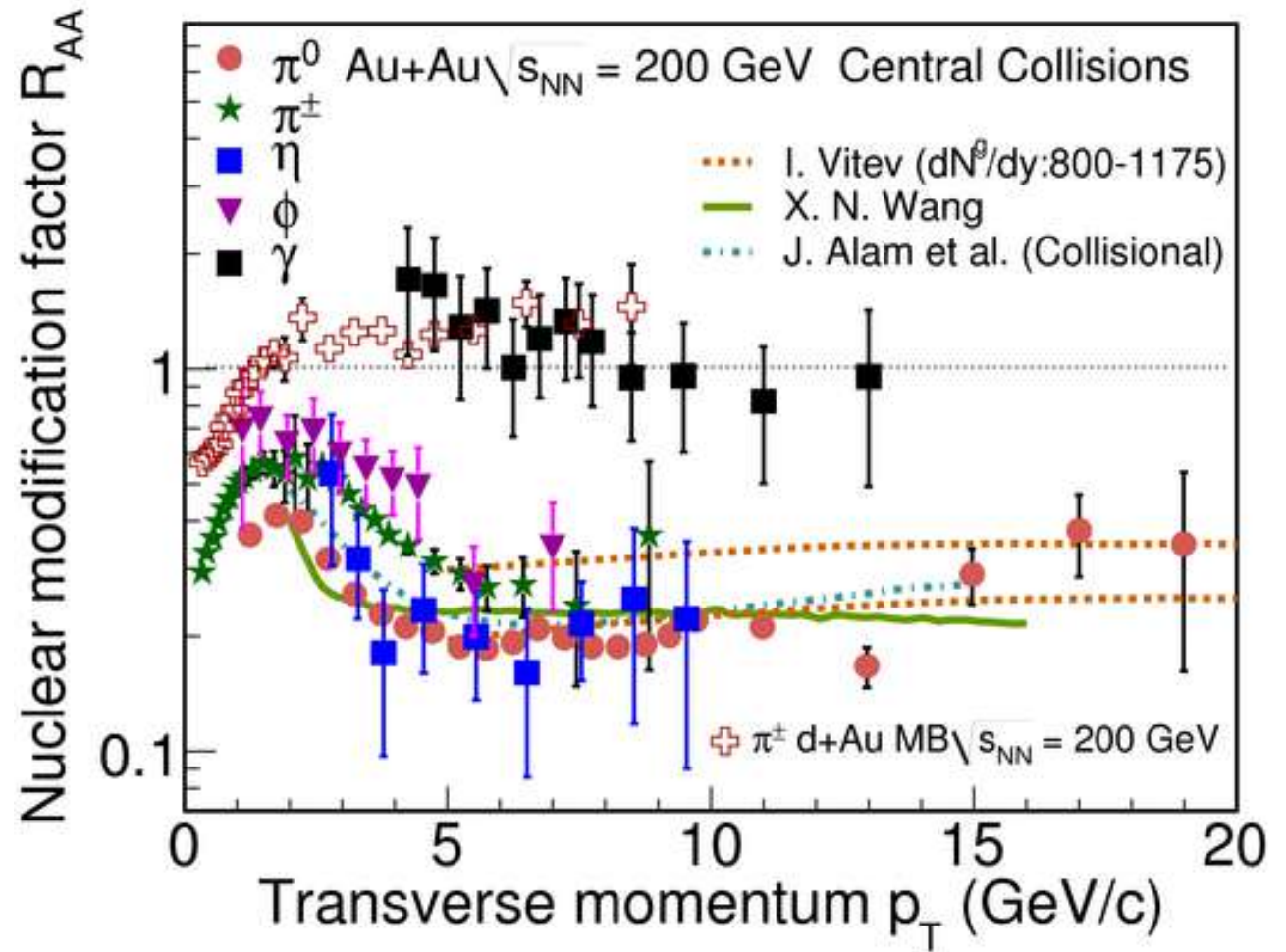


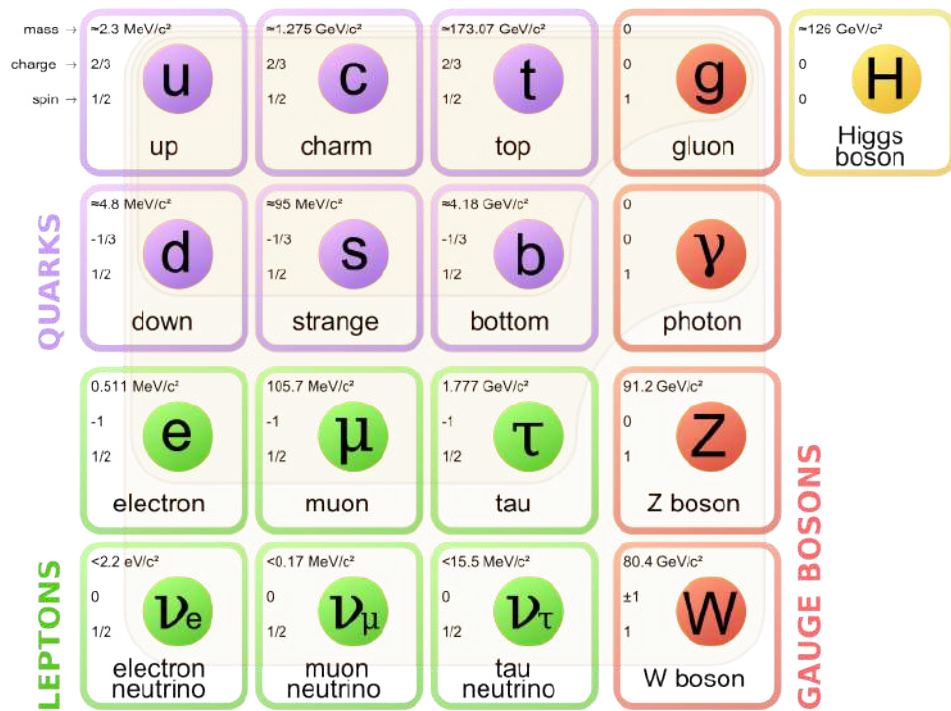
High p_T hadron production suppressed

Experimental evidence of Quenching of Jets \equiv Energy loss of quarks and gluons in dense medium

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

$\epsilon_{\text{initial}} > \epsilon_c$
(Lattice)





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

Standard Model