Prof. P C Mahanta Memorial Lecture

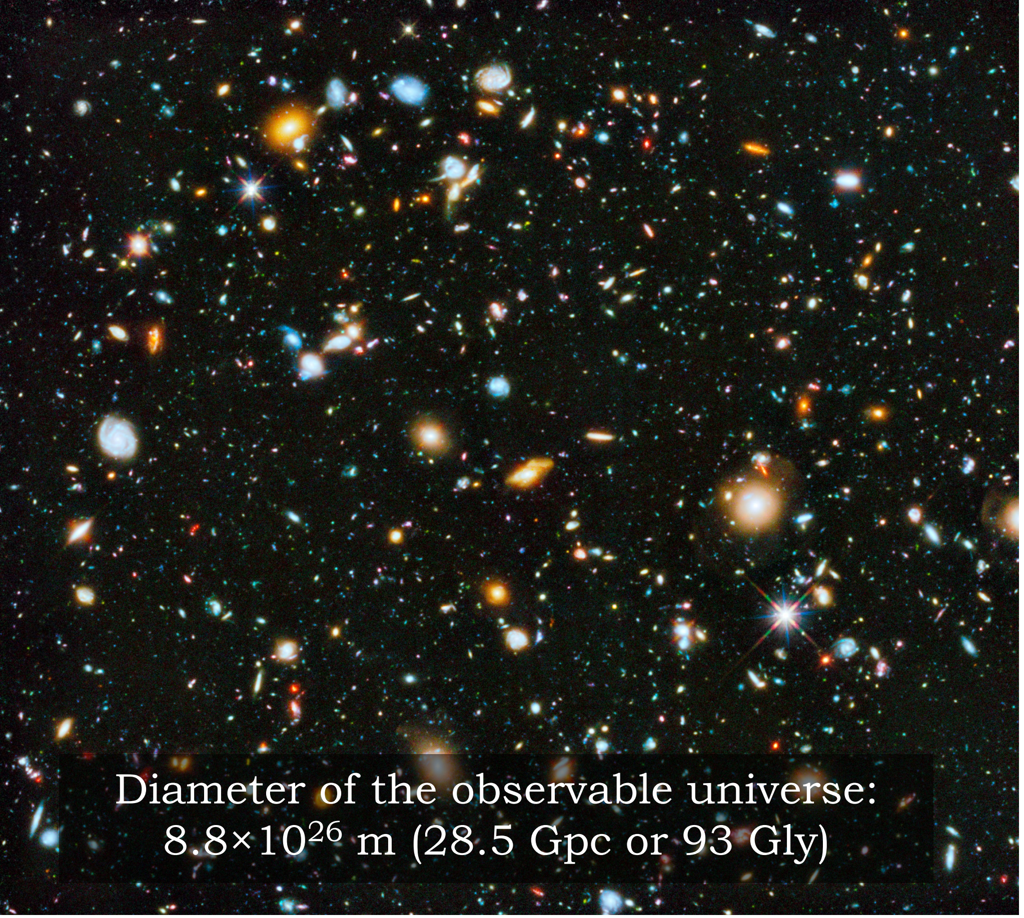
Recreating microsecond old Universe conditions in the Laboratory

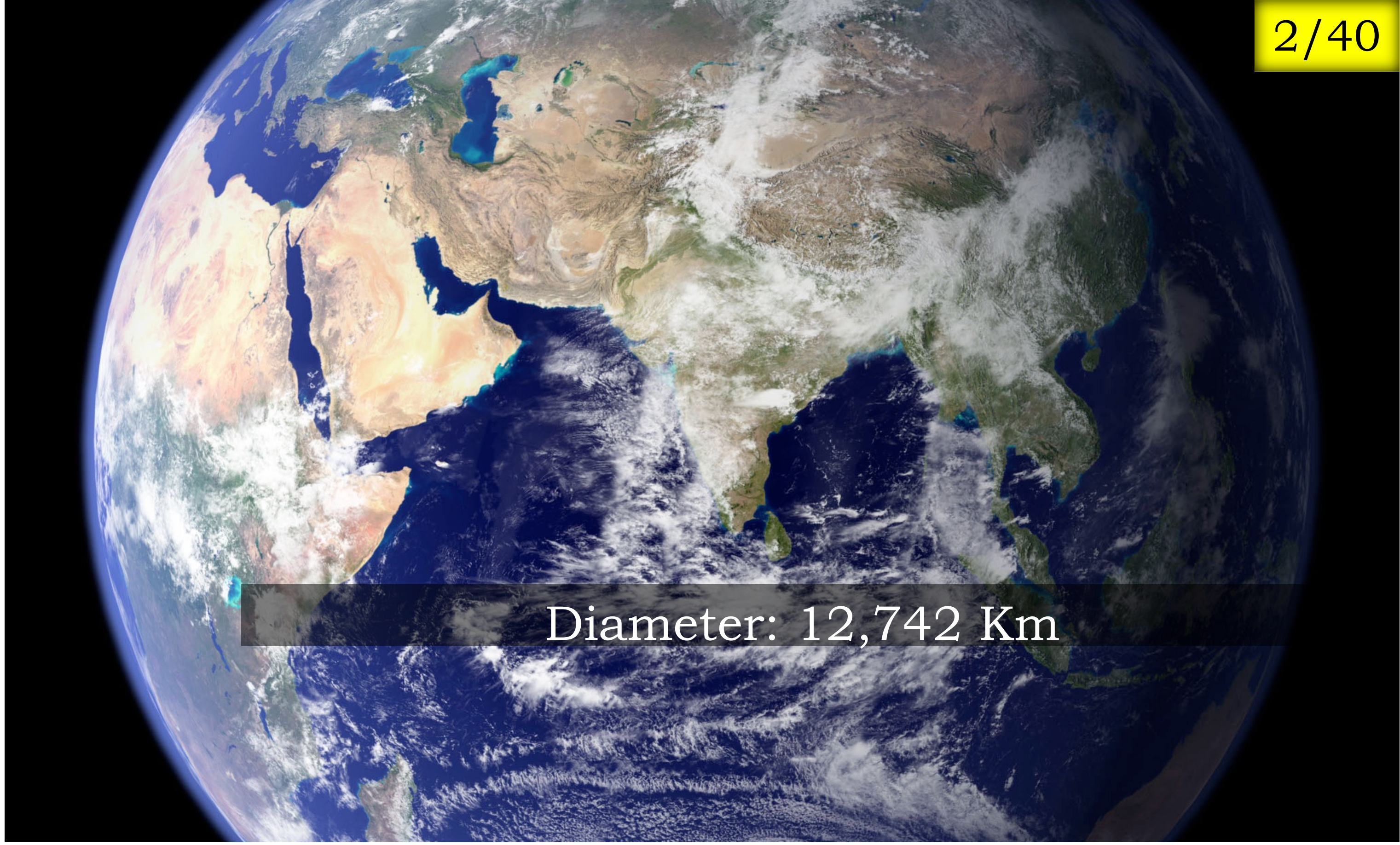
Bedanga Mohanty

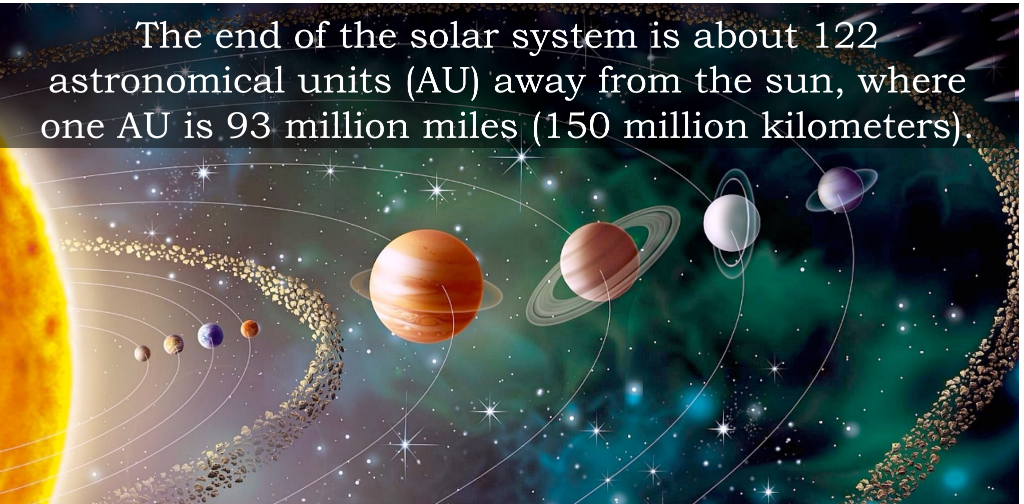
NISER

Gauhati University

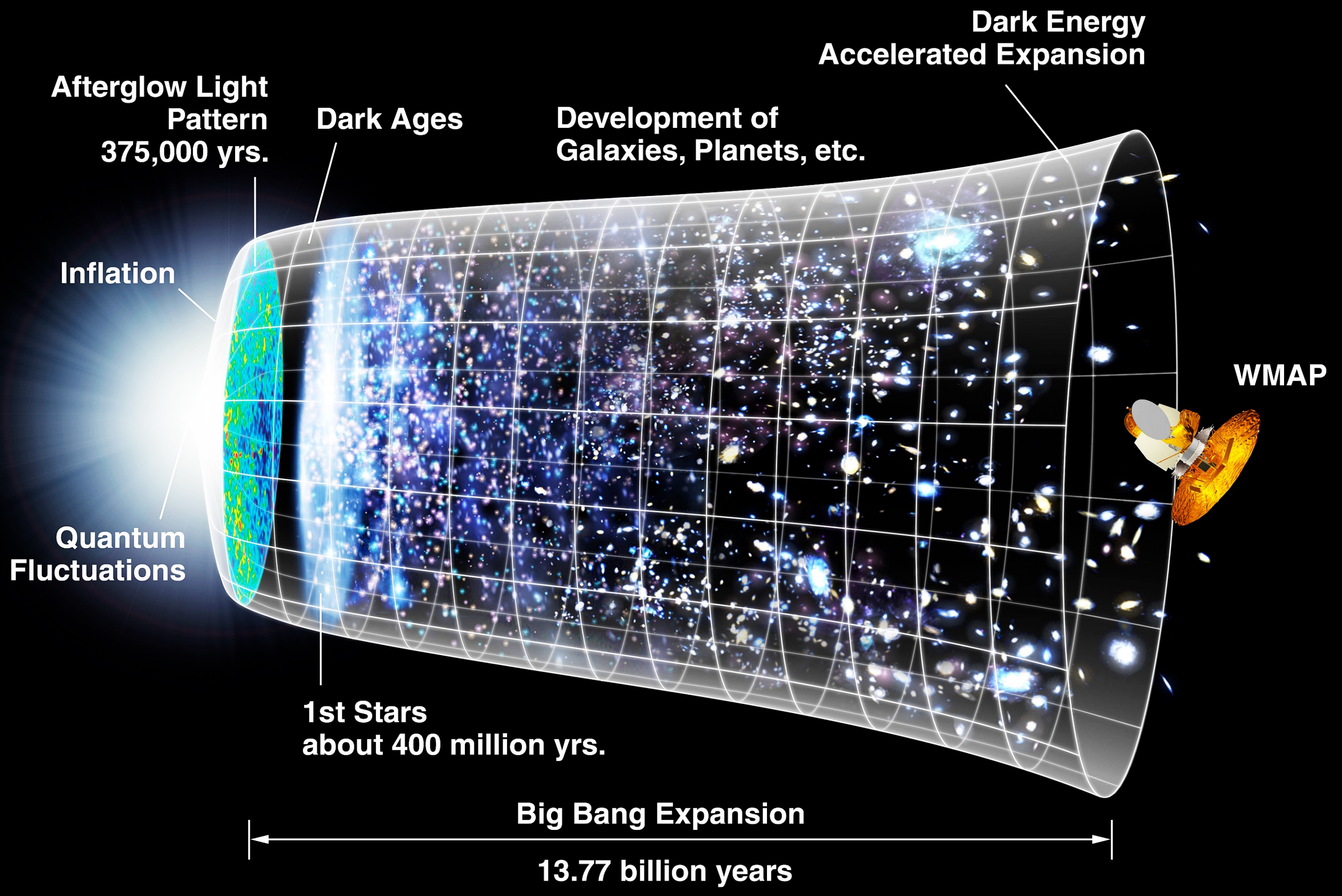
8th March 2022


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).

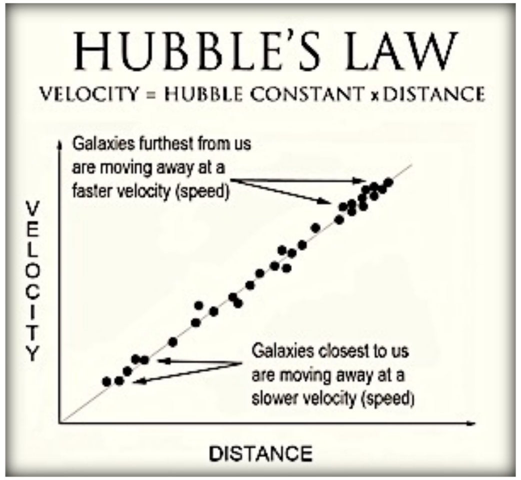

Universe is BIG !
Brahmaputra ~ 3800 KM

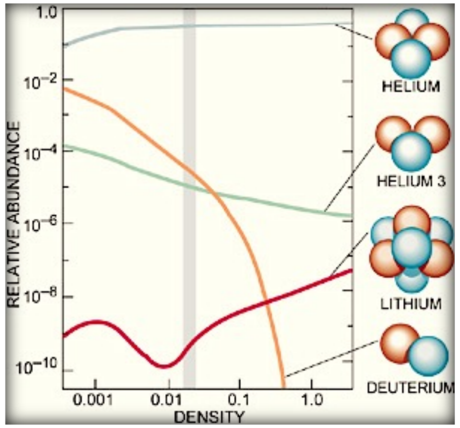


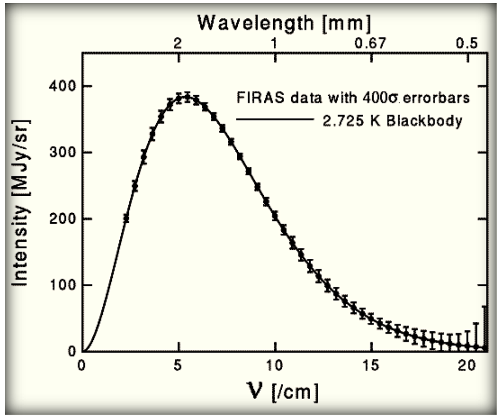
Success of Big Bang Model (George Gamow – 1948)

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

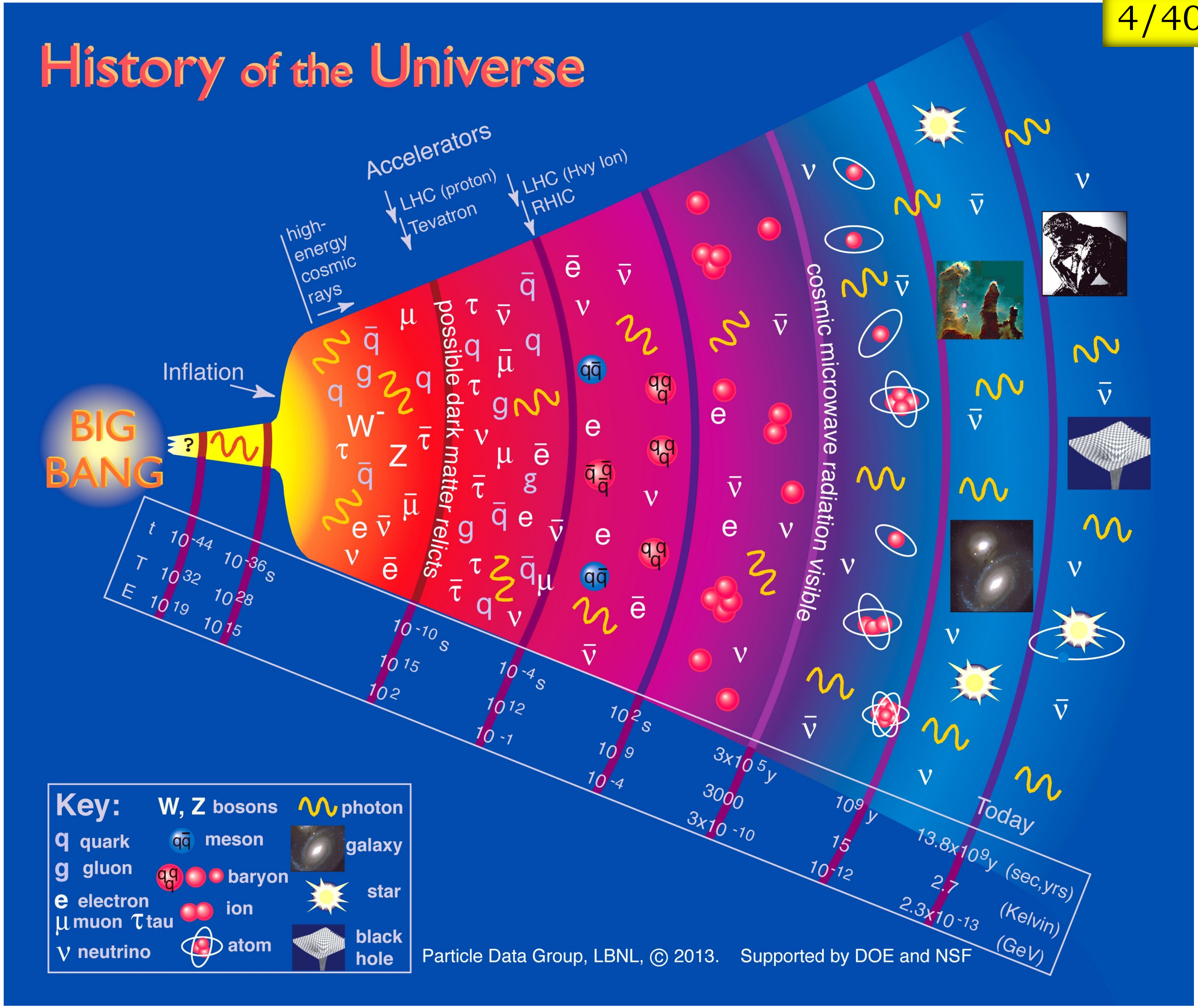
NASA/WMAP Science Team



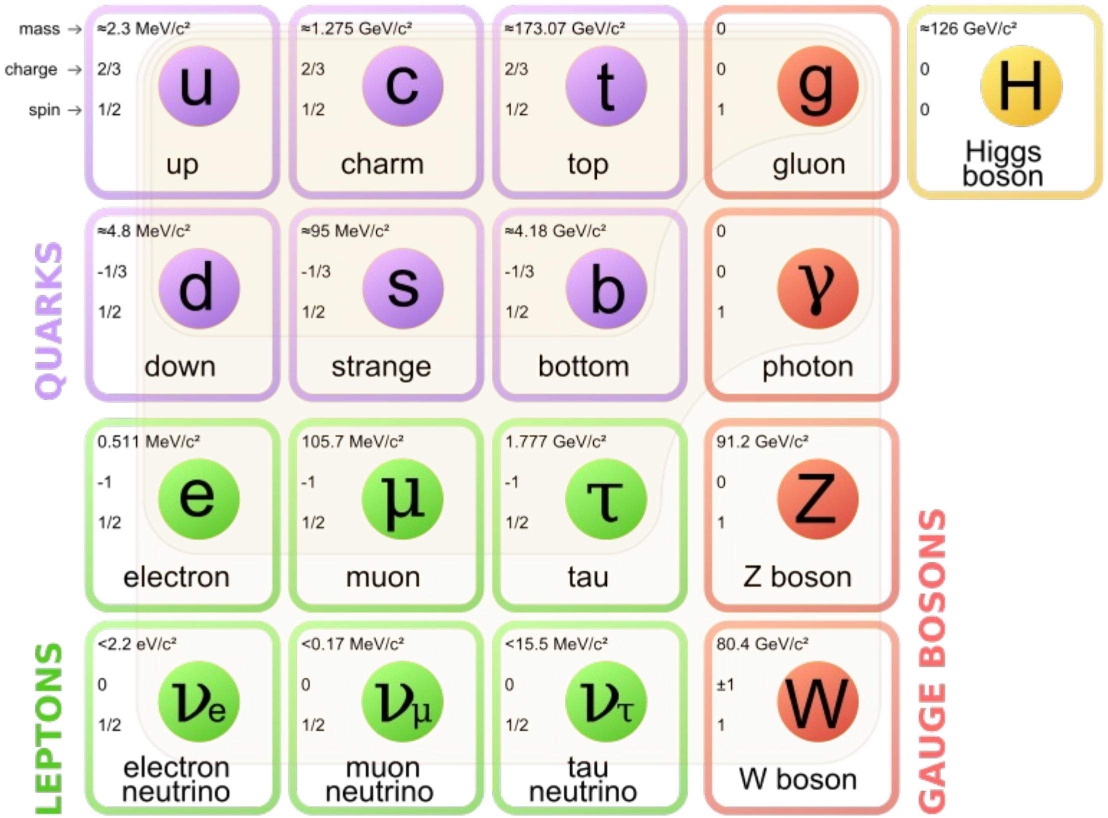


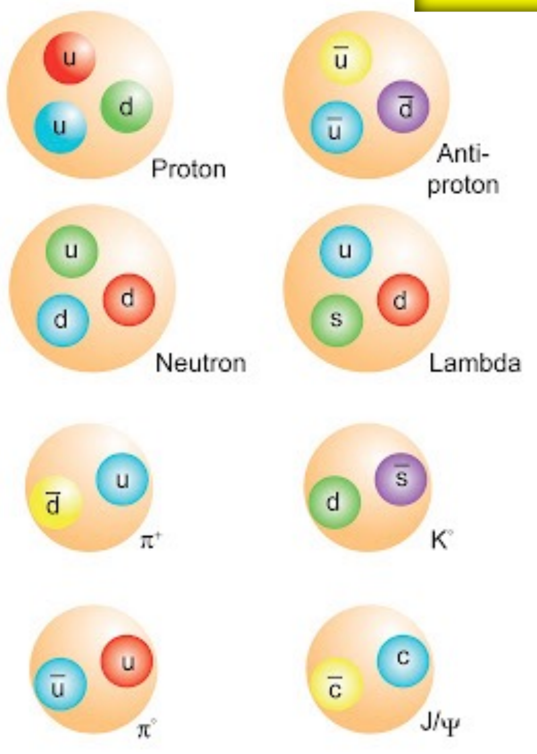


Microsecond Old Universe



Fundamental constituents and forces





1 MeV/c² = 1.79 x 10^{-30} **kg**

1 MeV ~ 10^{10} **Kelvin**

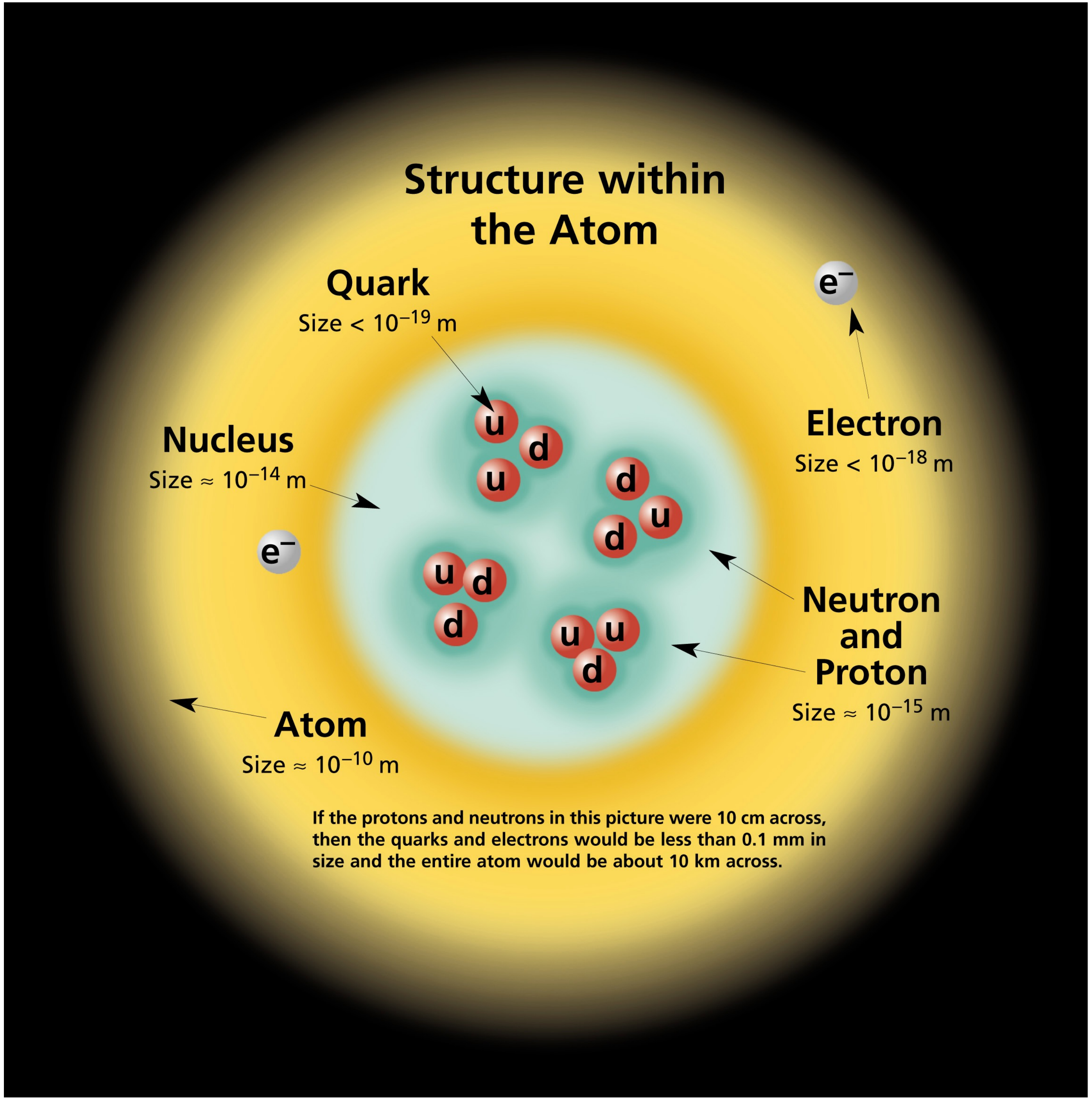
Atom ~ 10^{-10} m
Nucleus ~ 10^{-14} m
Quarks < 10^{-19} m

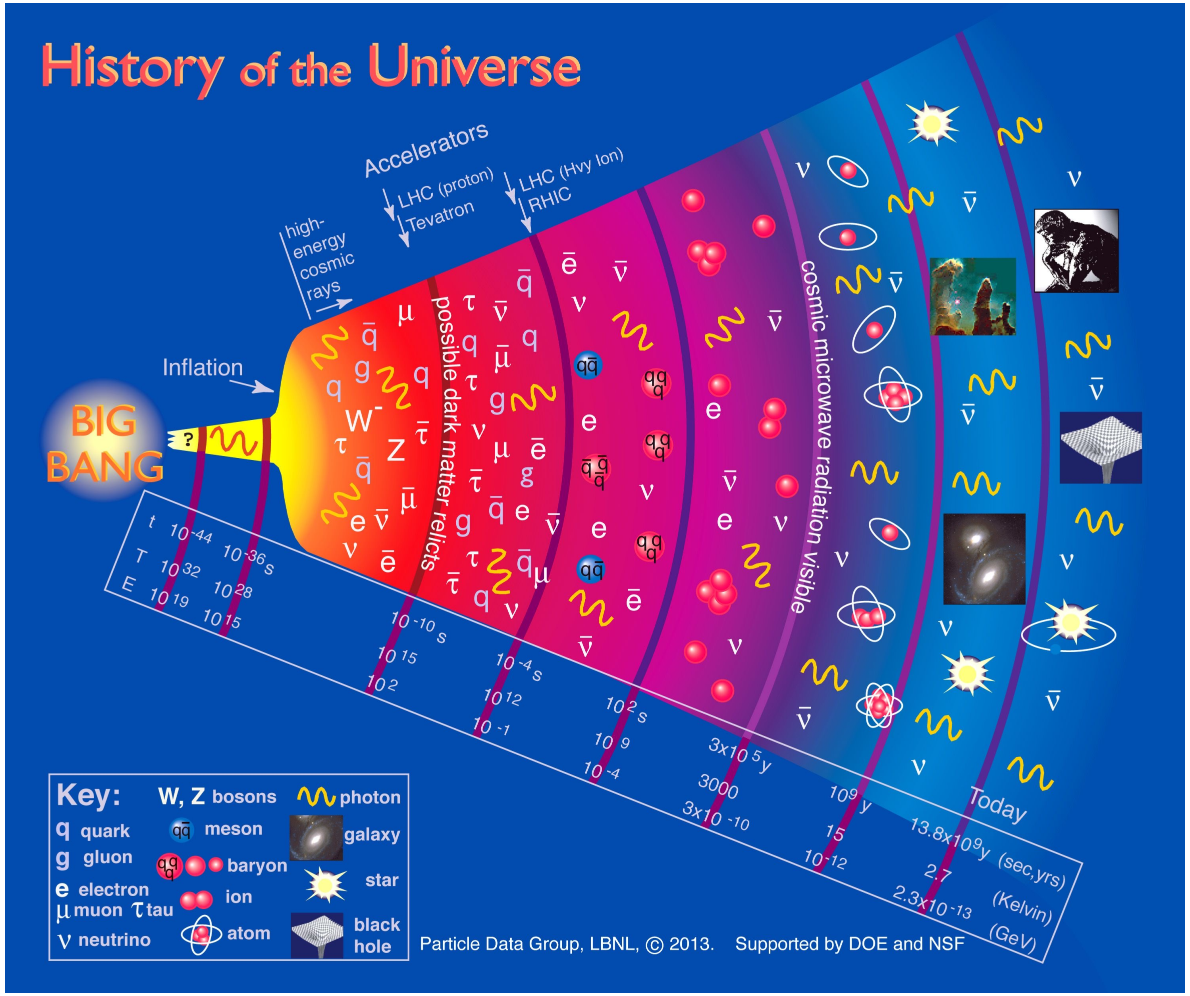
PROPERTIES OF THE INTERACTIONS

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: $3{\times}10^{-17}$ m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Atom

Quark and gluons not free

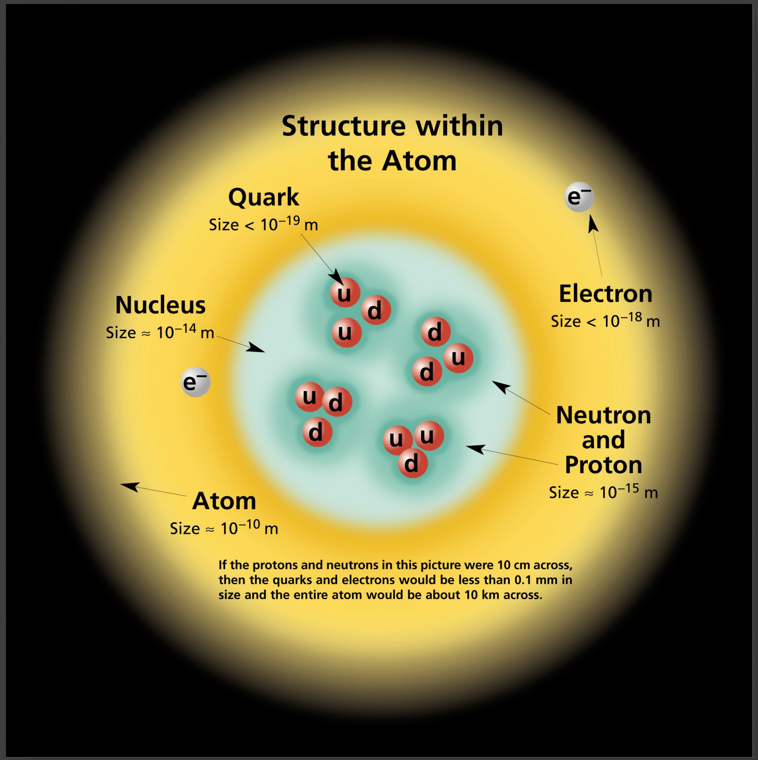




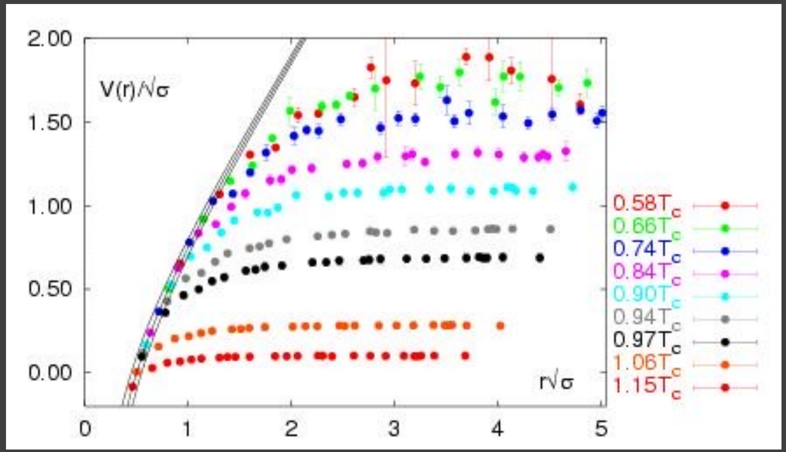
https://physicsworld.com/a/neutron-stars-may-contain-free-quarks/

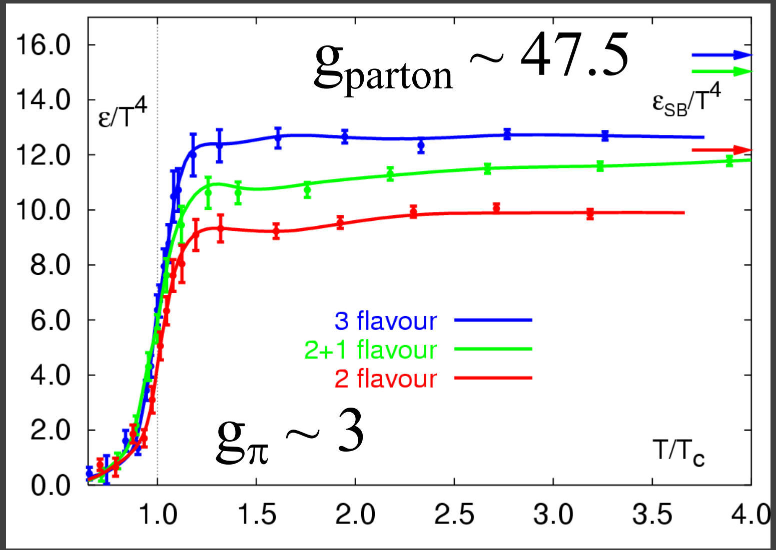
Universe: Free state of quarks and gluons

Temperatures - 10^{12-15} Kelvin or densities - 10^{18} kg/m^3



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





~ 154 MeV (10^{12} K)

$\varepsilon/T^4 \sim g\,(\pi^2/30)$

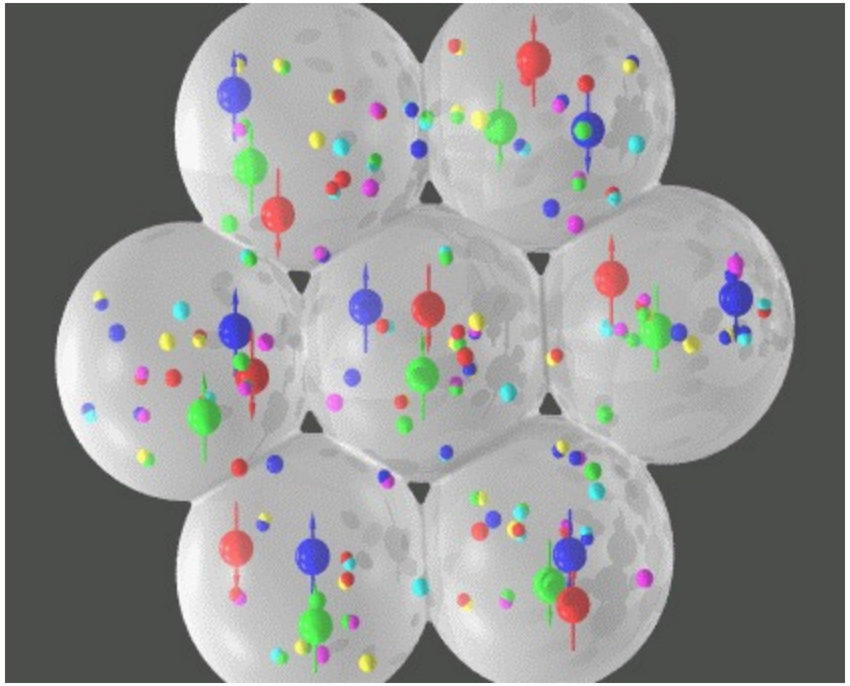
Matter at extremely high temperature→ QGP

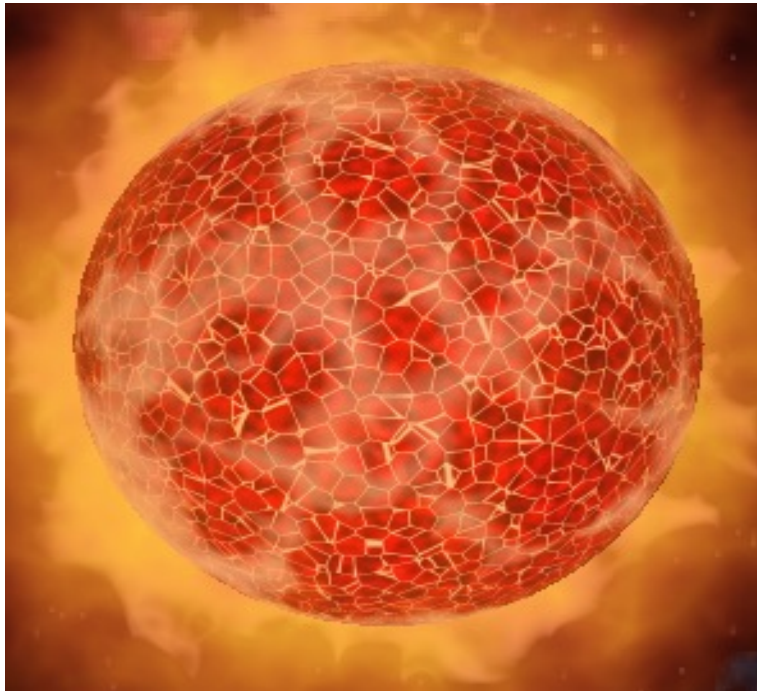
F. Karsch, Prog. Theor. Phys. Suppl. 153, 106 (2004)

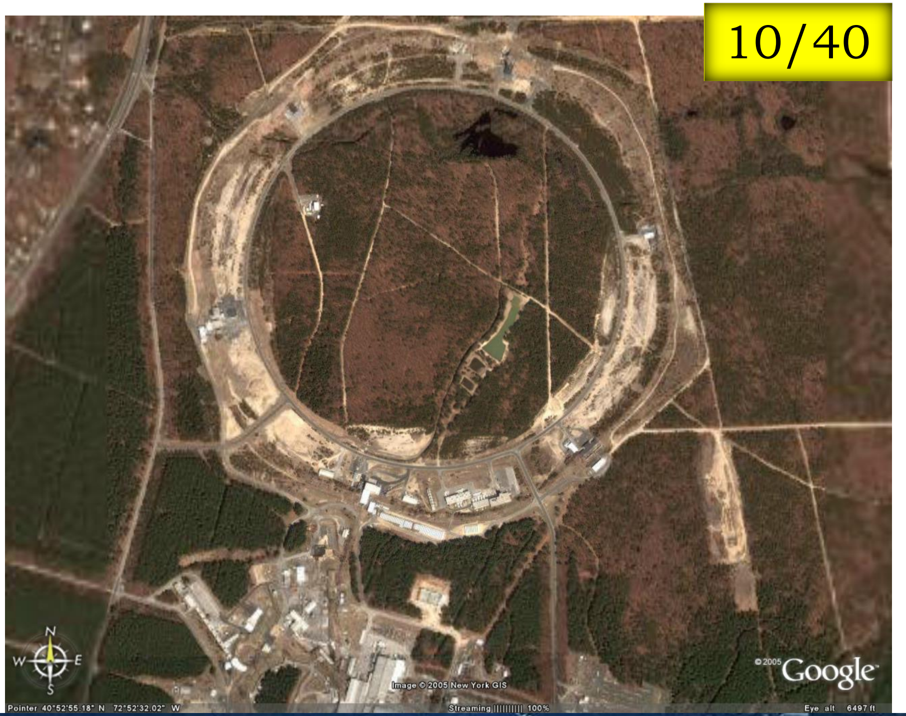
Theoretical support for little Bang

Properties of fundamental constituents we are made

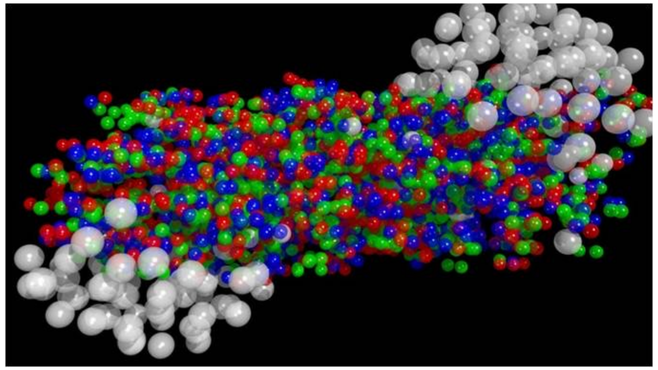
Free system of quarks and gluons needed to study properties – Viscosity, conductivity, diffusion co-efficient, opacity etc







One trillion Kelvin !



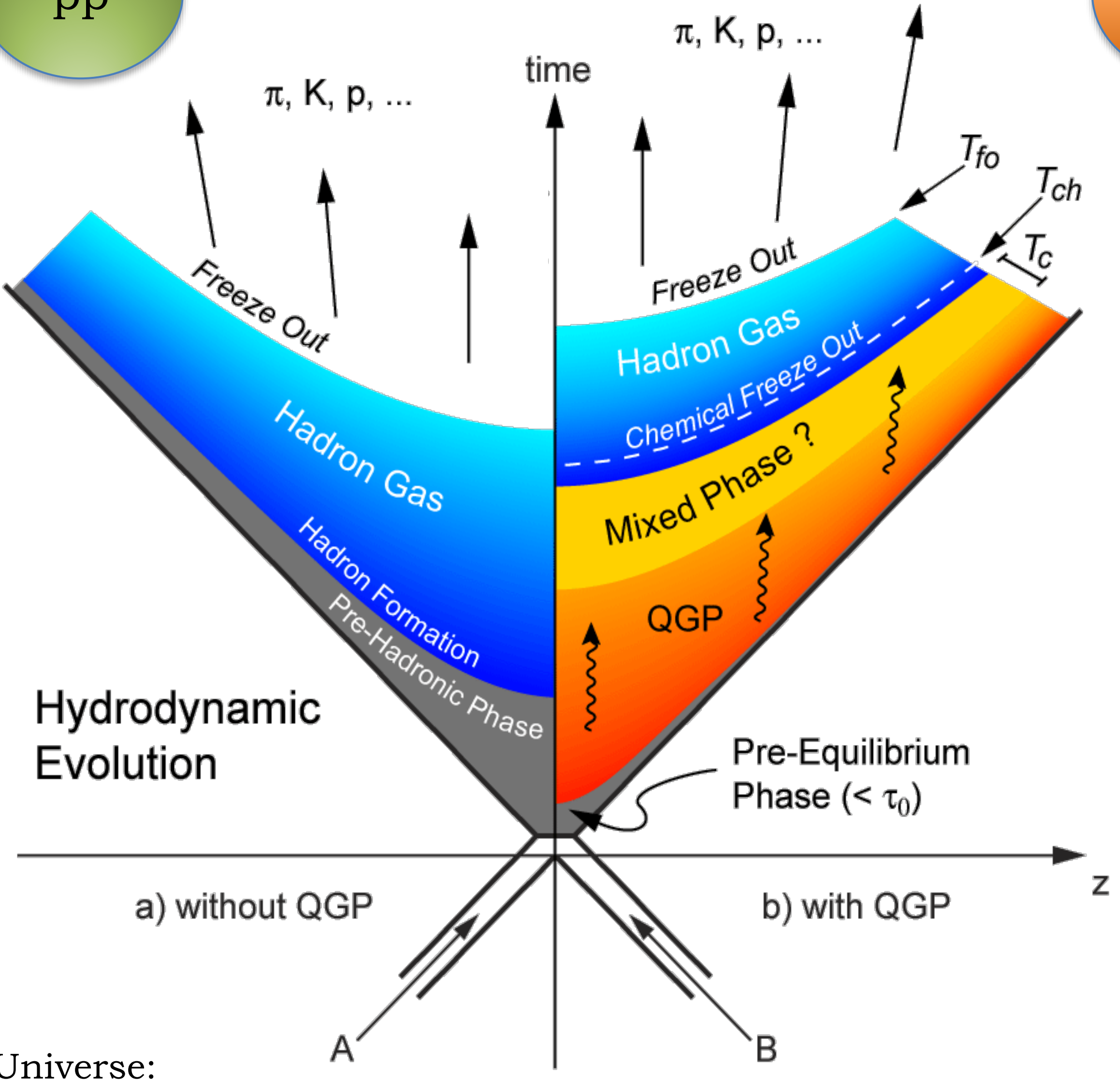
Relativistic Heavy Ion Collider
And
Large Hadron Collider

Quark Gluon Plasma – Heavy Ion Collisions

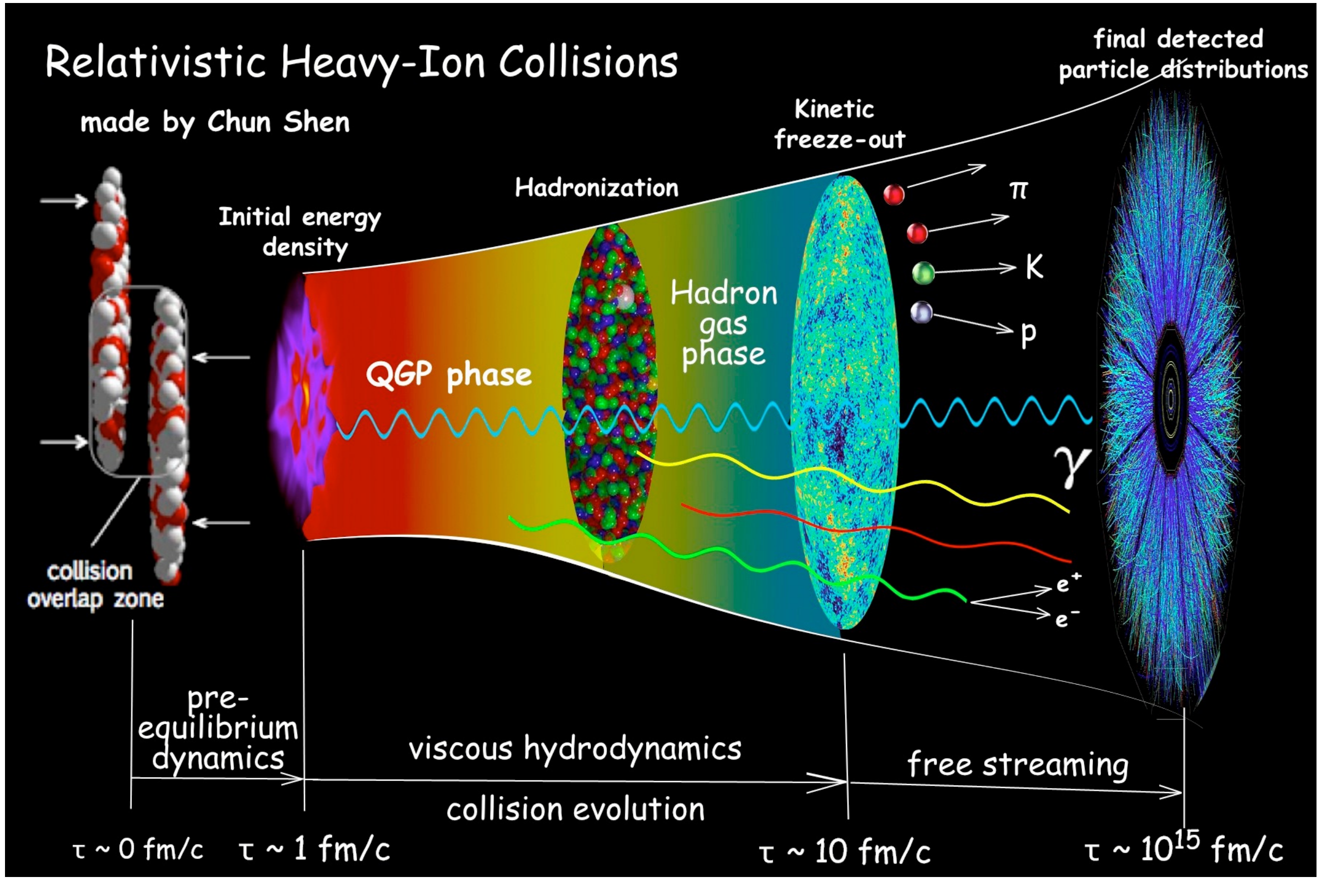
J. D. Bjorken Physical Review D 27 (1983) 140

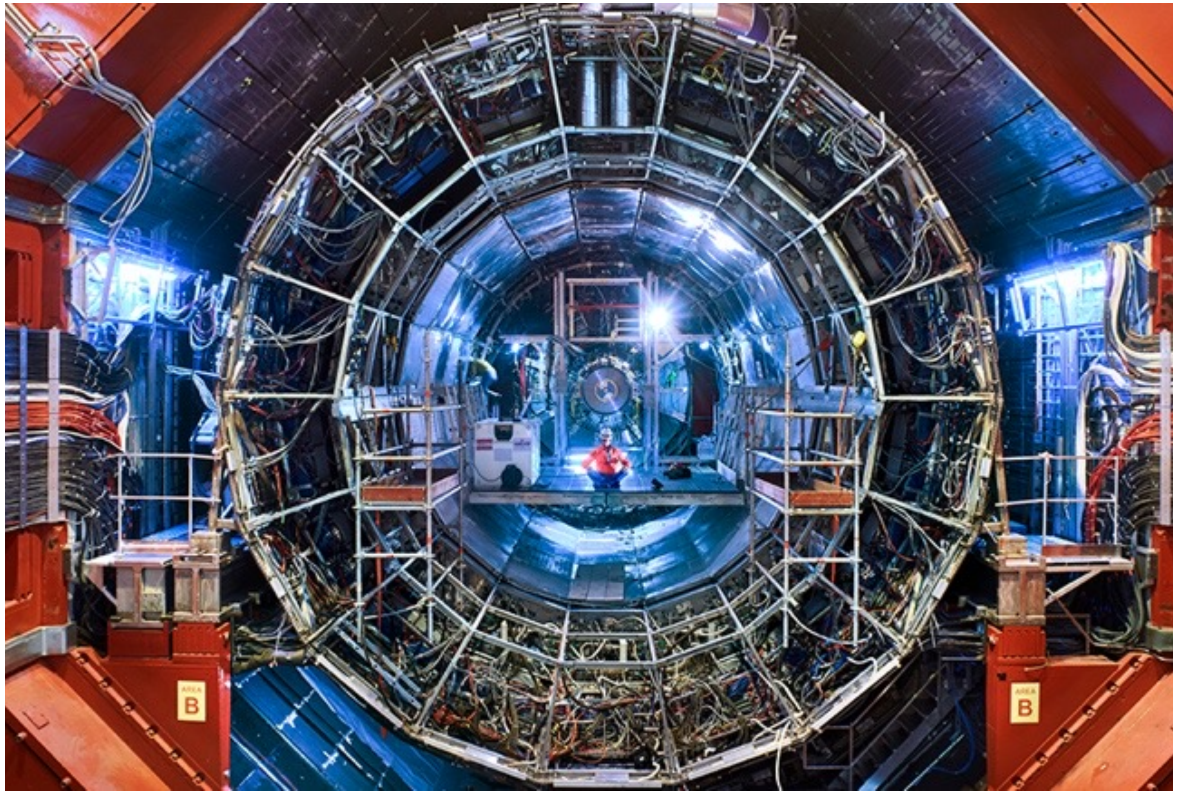
pp

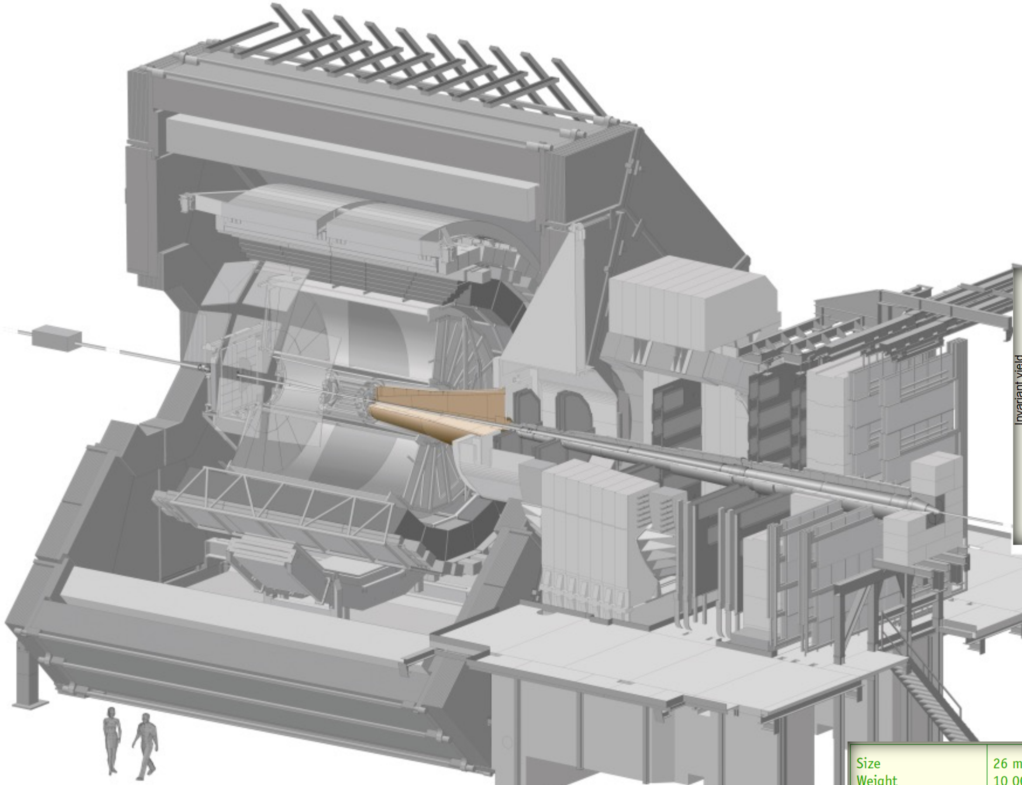
AA

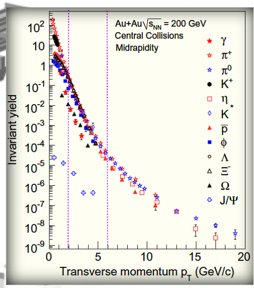


Universe:
QCD Phase Transition: T ~ 200MeV
EW Phase Transition: T ~ 150 GeV
GUT Phase Transition: T ~10^{16} GeV









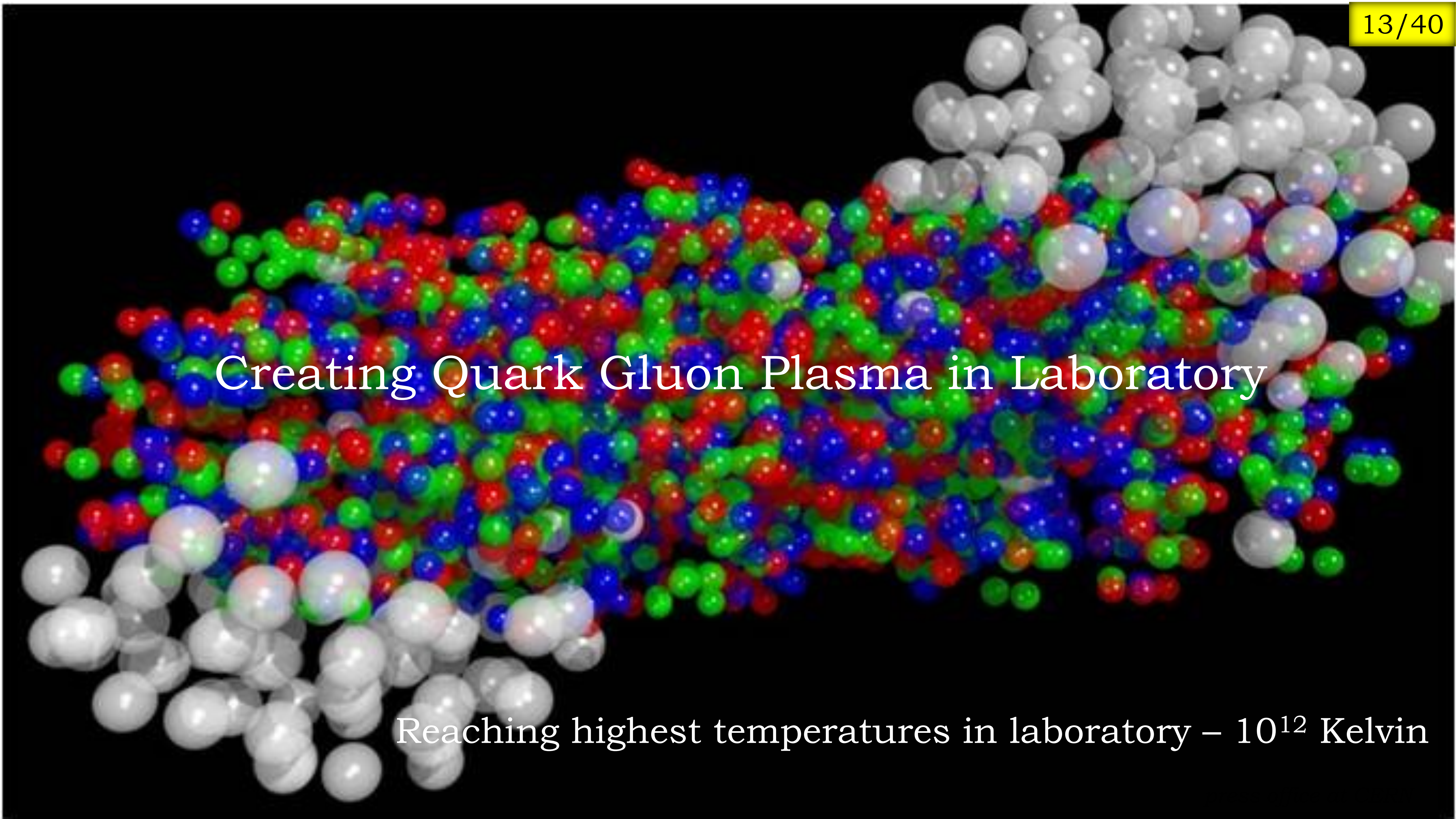
Size	26 m long, 16 m high, 16 m wide
Weight	10 000 tonnes
Material cost	115 MCHF
Location	Sergy (access from St. Genis Pouilly), France

Typical Detector

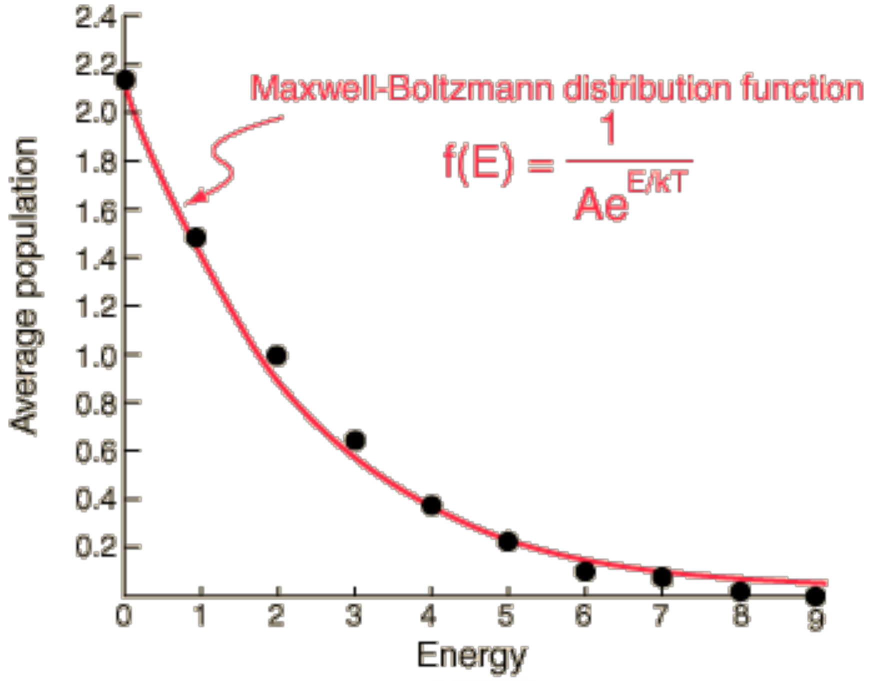
- QGP: Femto-Scale in time and space

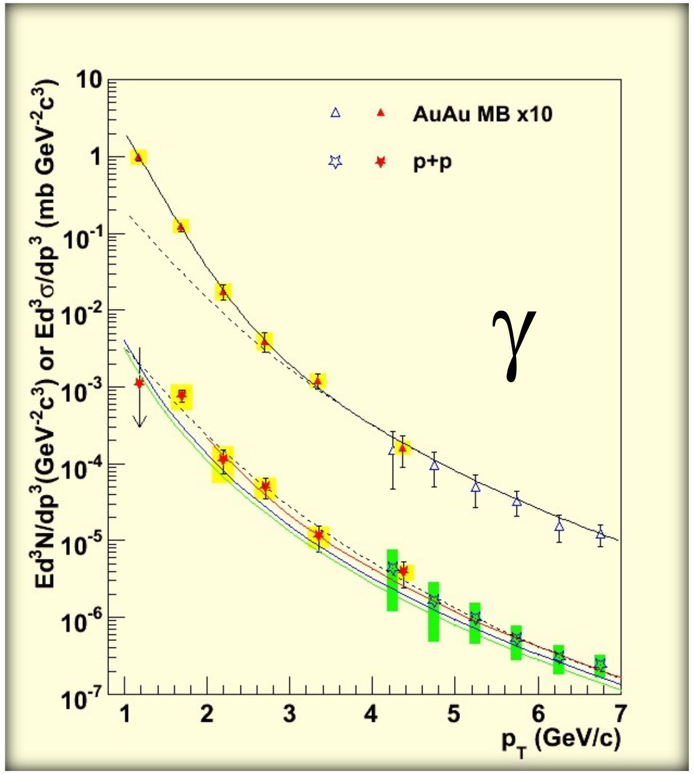
TOF data analysis GU played a leading role

Creating Quark Gluon Plasma in Laboratory



Reaching highest temperatures in laboratory – 10^{12} Kelvin





Measuring Temperature

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

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

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

Perspective on the Temperature

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

~10^{12} K

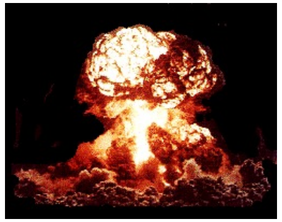
Nucleus-Nucleus collisions

~ 150 MeV

~10^{9} K

Neutron Star Thermonuclear Explosion

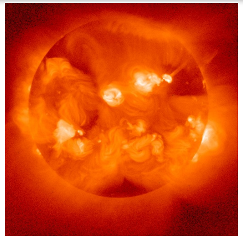
(Terrestrial Nuclear explosions)



~10^{6} K

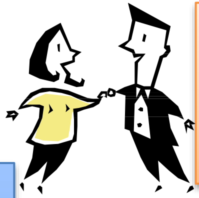
Solar Interior

Solar Surface



~6000 K

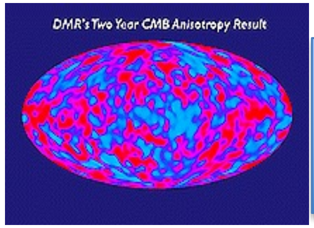
~300 K



Room Temperature

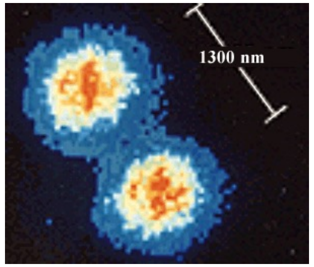
~ 1/40 eV

~3 K



Cosmic Microwave Background

~10^{-6} K



Trapped Ions

~10^{-10} K

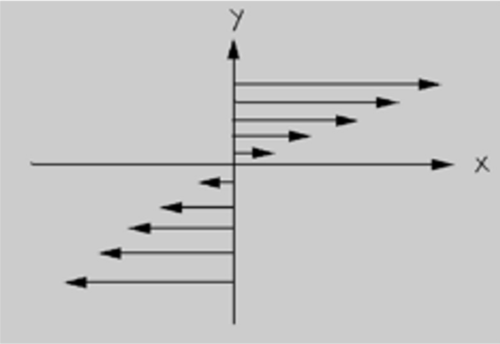
Rhodium metal spin cooling (2000)

(Low-T World Record!)

QGP | Perfect Fluid

Viscosity: resistance to flow

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



Divide by density – kinematic viscosity
Compare across different fluids

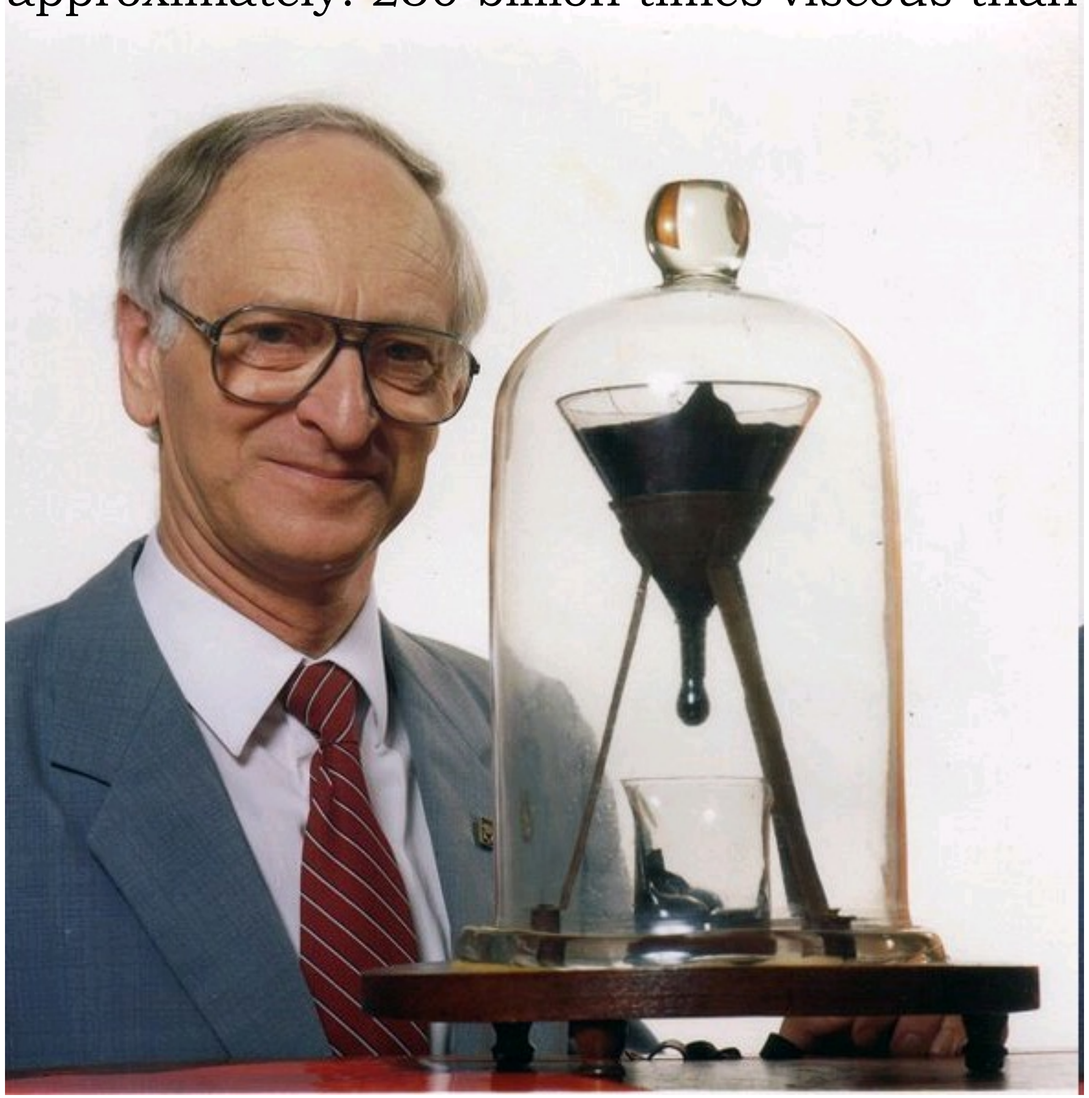
Dilute gas, η = (1/3) *npl.*
Uncertainty principle pl $\gtrsim \hbar$.
Entropy density, $s \sim k_B n$,
Lower bound to $\eta/s \gtrsim \frac{\hbar}{k_B}$.

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

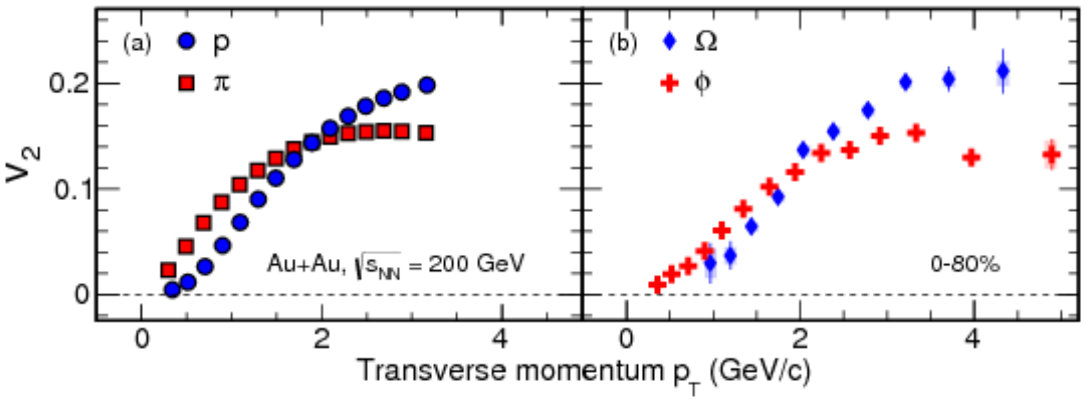
Pitch approximately: 230 billion times viscous than water



Wiki

(1927-present) 8 drops

Flow



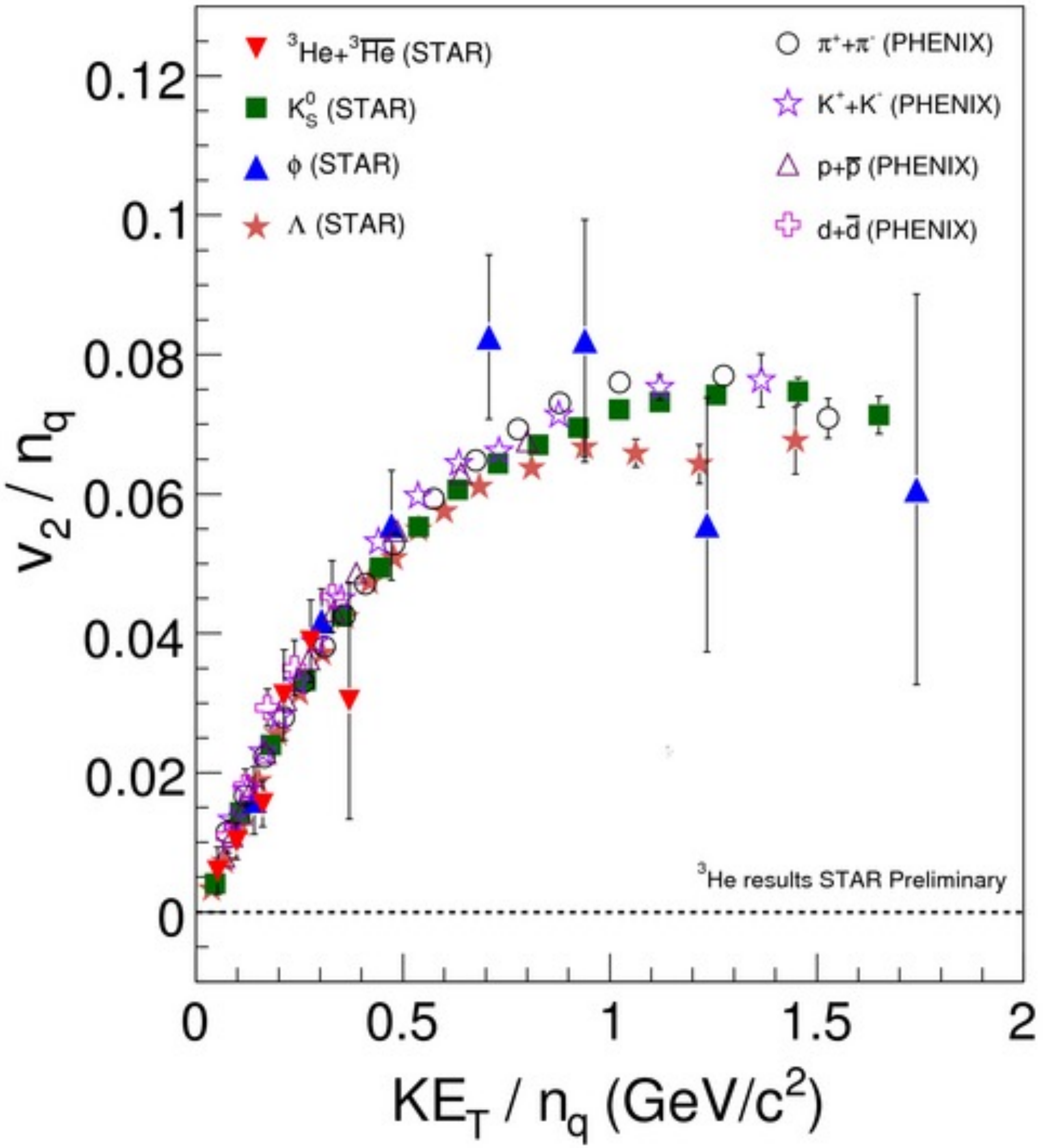
Momentum

$$v_2 = \langle \cos 2\varphi \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

PRL **116,** 062301 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

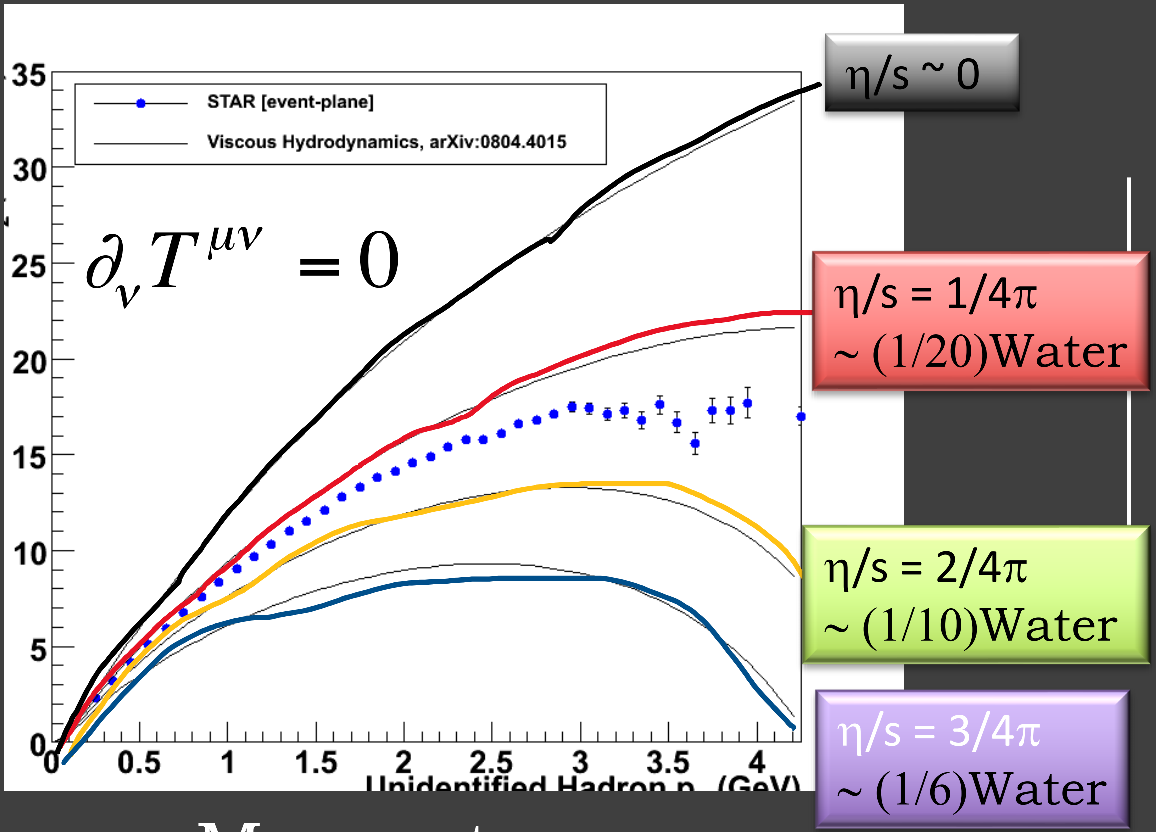
Centrality and Transverse Momentum Dependence of Elliptic Flow of Multistrange Hadrons and ϕ Meson in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

Evidence of partonic flow



n_q – 3 for baryons and 2 for mesons

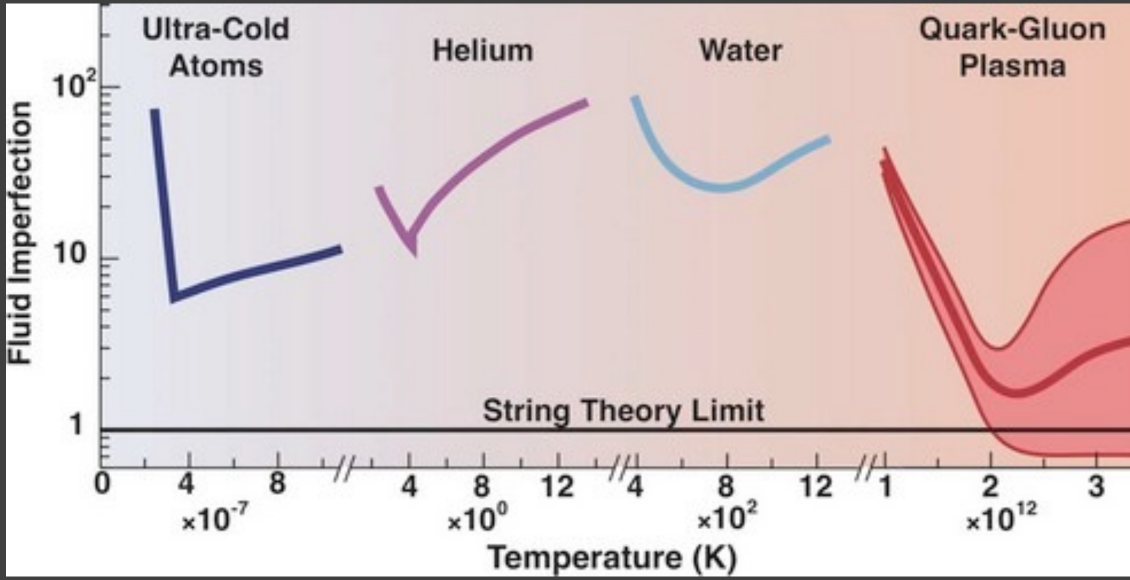
Flow



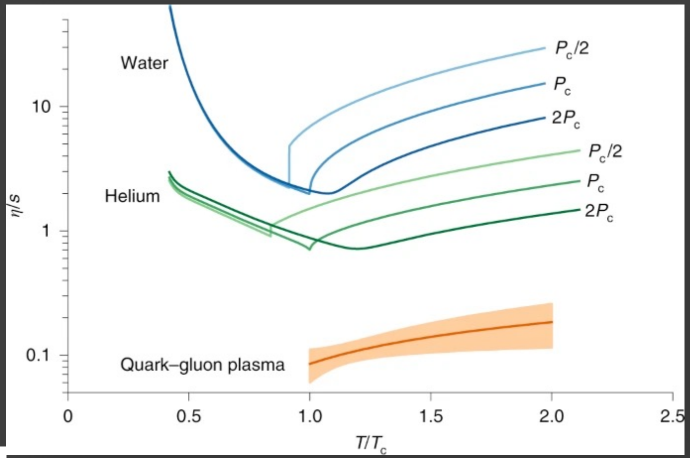
Momentum

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



Perfect Fluid

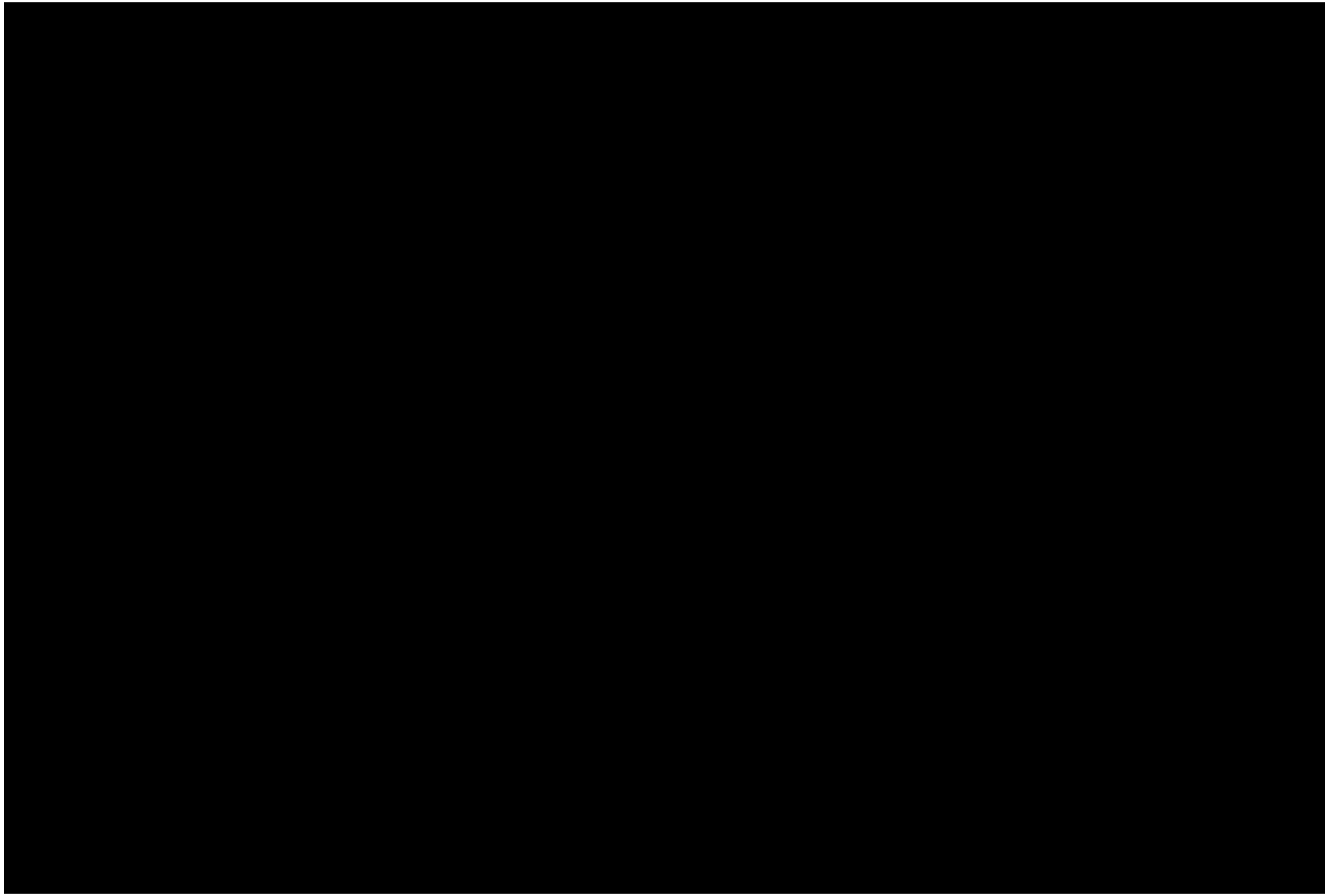


Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma

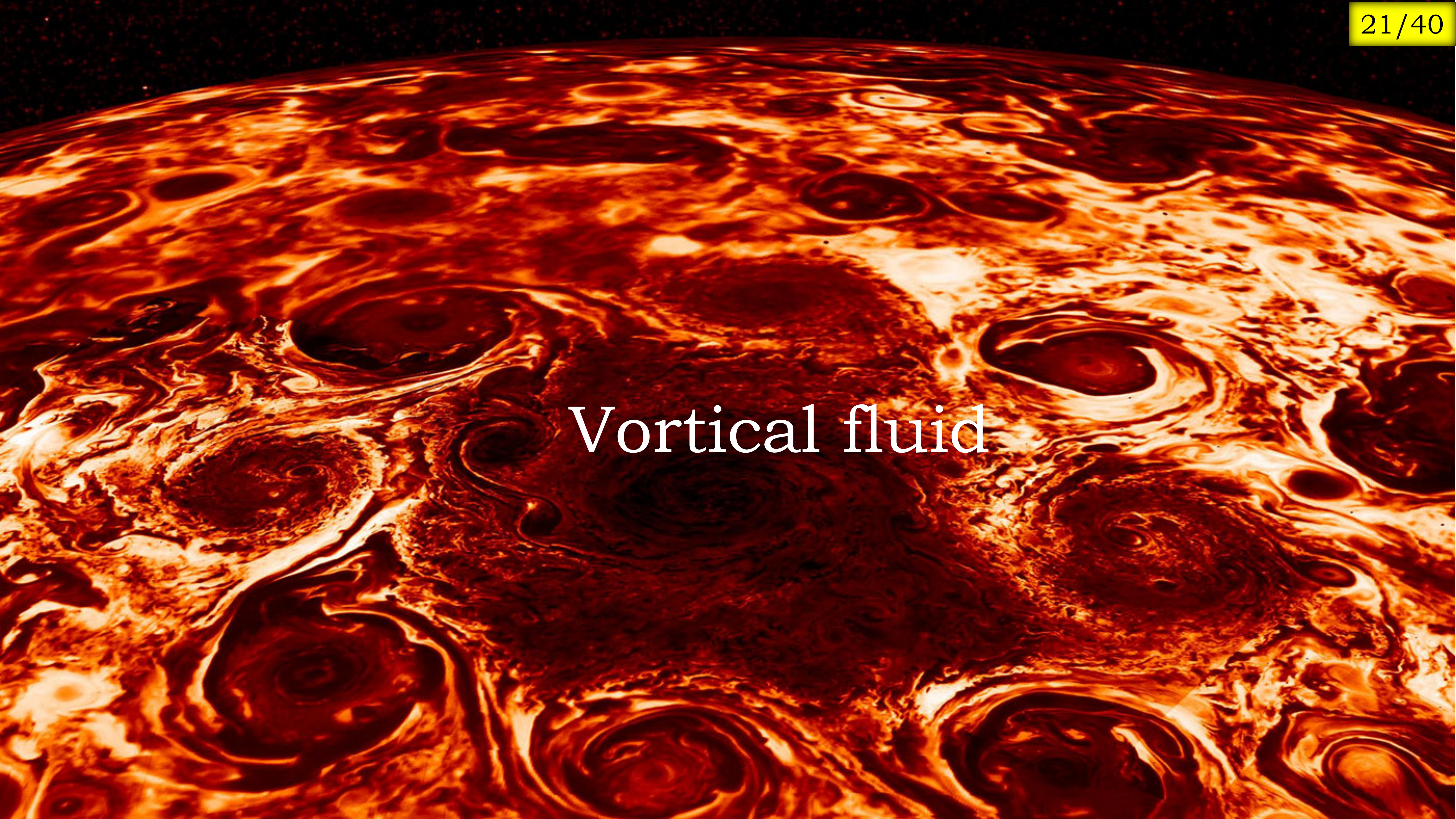
Jonah E. Bernhard, J. Scott Moreland & Steffen A. Bass

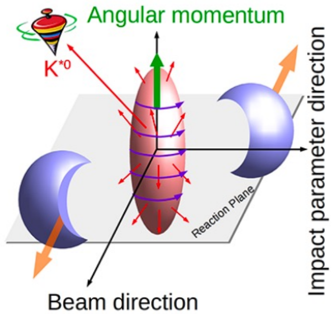
Nature Physics 15, 1113–1117(2019) | Cite this article

Perfect Fluid



Vortical fluid





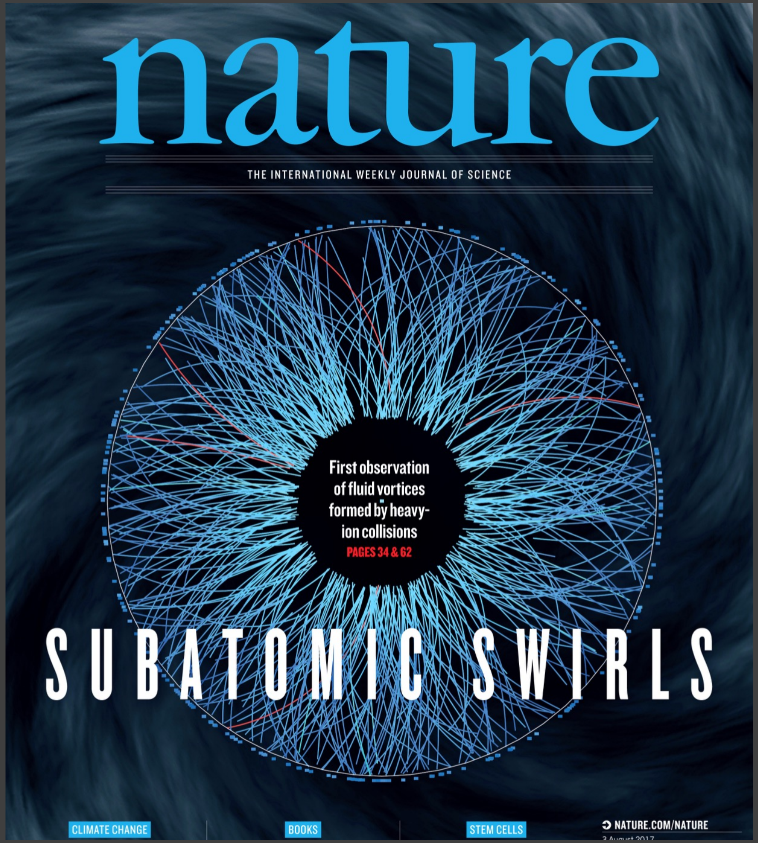
EDITORS' SUGGESTION

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

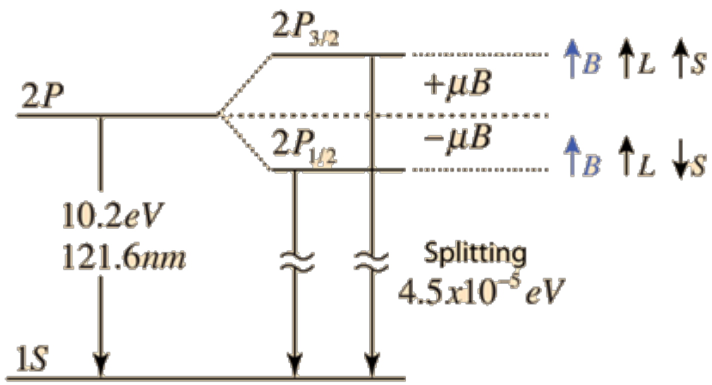
The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

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

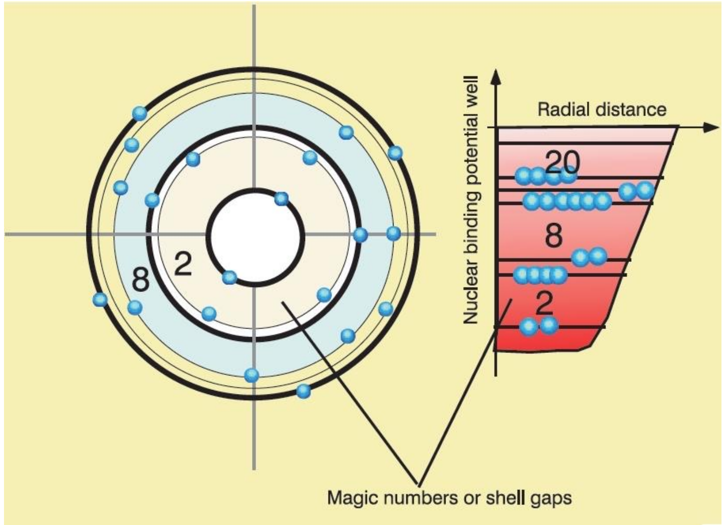
Phys. Rev. Lett. **125**, 012301 (2020)



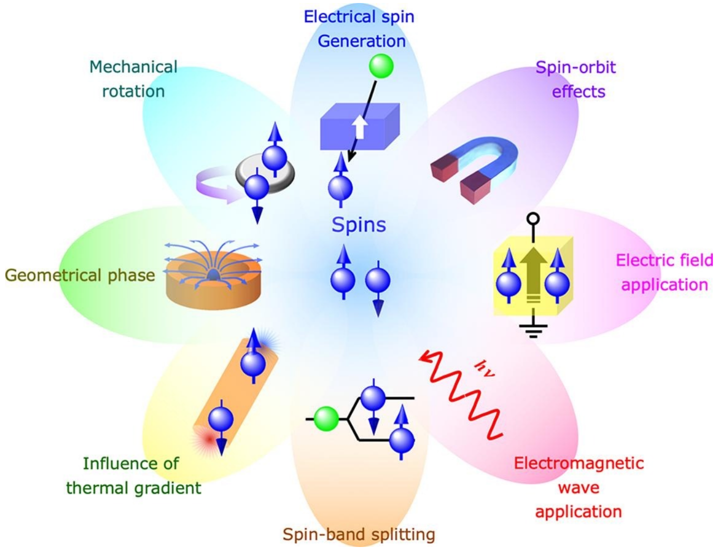
Evidence for Spin-orbit interactions



Atomic Physics



Nuclear Physics

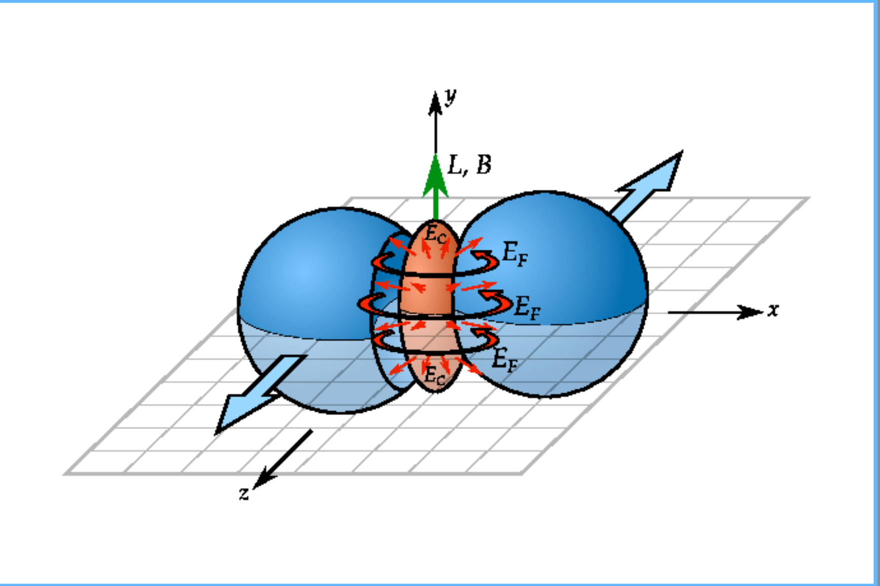


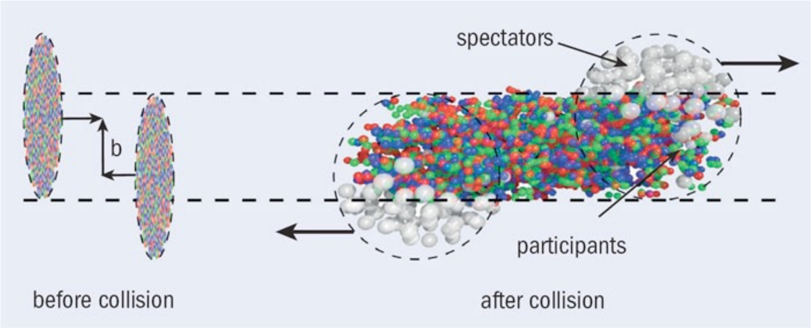
Material Sciences

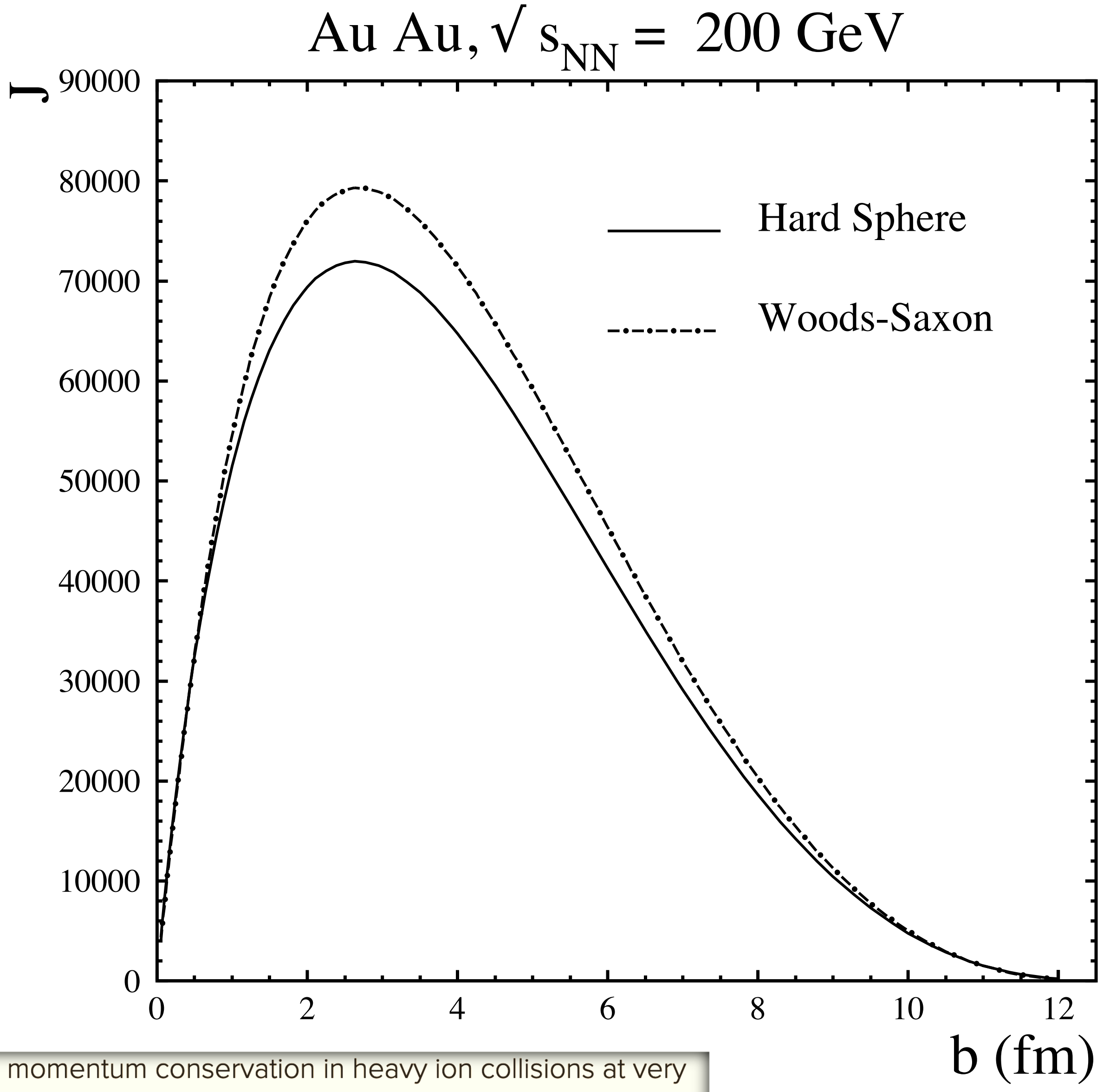
Wiki

Spin-orbit interactions

Large Angular Momentum





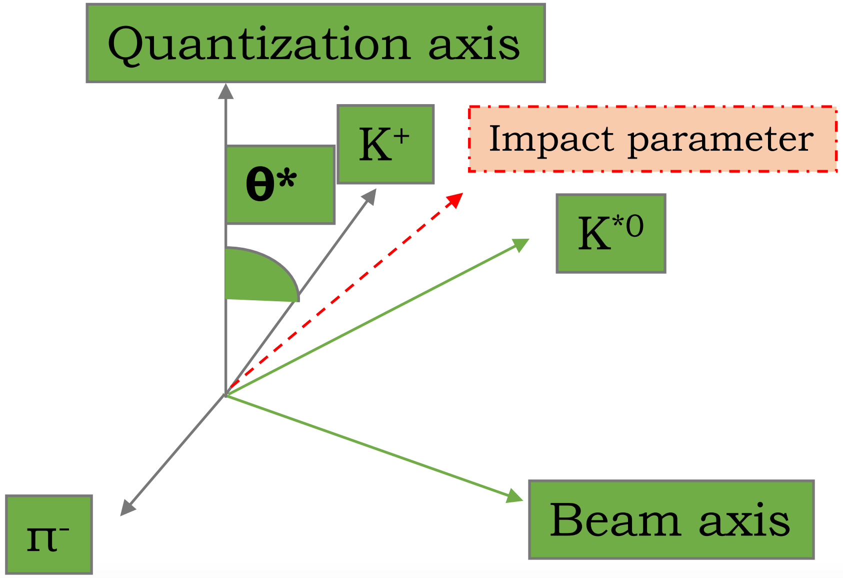


Angular momentum conservation in heavy ion collisions at very high energy

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

Angular distribution of vector mesons

K^{*0} Vector meson
- Mass – 896 MeV/c^2
- Lifetime – 4 fm/c
- Spin 1
- Decays to K^+ and π^- (B.R – 66%)
- Quark content $(d,\bar{s})$



K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta d\phi} = \langle \theta, \phi, \lambda_1, \lambda_2 | M \rho M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

$$= \sum_{\lambda_V} \sum_{\lambda_{V'}} \langle \theta, \phi, \lambda_1, \lambda_2 | M | \lambda_V \rangle \langle \lambda_V | \rho | \lambda_{V'} \rangle \langle \lambda_{V'} | M^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

λ = Helicities
ρ = spin density matrix
M = Decay amplitude

Quantization axis
- Normal to production plane (Momentum of vector meson and beam axis)
- Normal to reaction plane (Impact parameter and beam axis)

Angular distribution of vector mesons

In terms of spherical harmonics

$$\frac{dN}{dcos\theta d\phi} = |C|^2 \times \sum_{m_1,m_2} Y^*_{1,m_1}(\theta,\phi) Y_{1,m_2}(\theta,\phi) \rho_{m_1,m_2}$$

Integrating over azimuthal angle

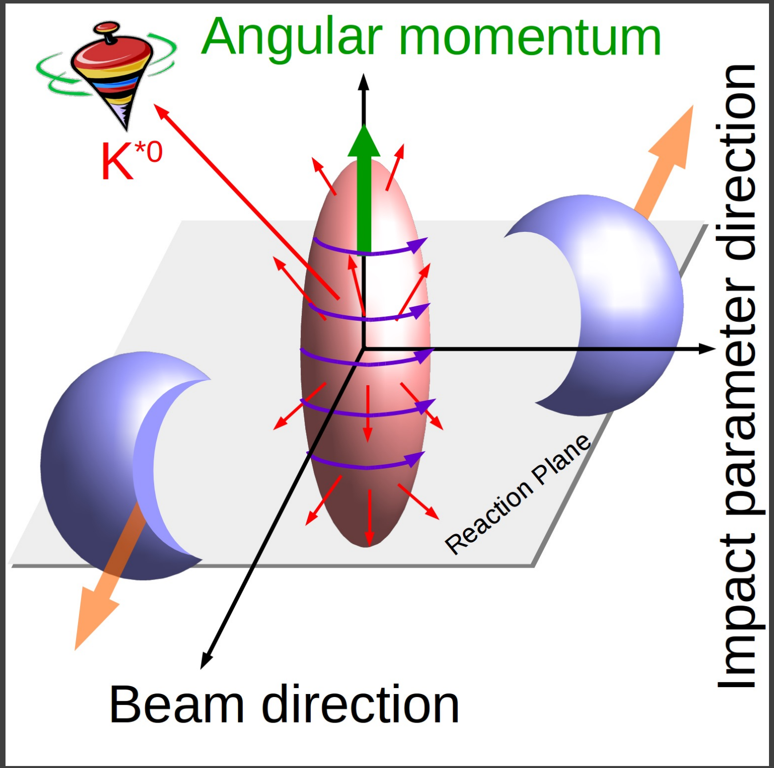
$$\frac{dN}{dcos\theta} = |C|^2 \times \frac{3}{8\pi}\left[sin^2\theta\rho_{-1,-1} + 2cos^2\theta\rho_{0,0} + sin^2\theta\rho_{1,1}\right] \times 2\pi$$
$$= |C|^2 \times \frac{3}{4}\left[sin^2\theta\left(\rho_{-1,-1} + \rho_{1,1}\right) + 2cos^2\theta\rho_{0,0}\right]$$

Normalized spin density matrix – Trace = 1

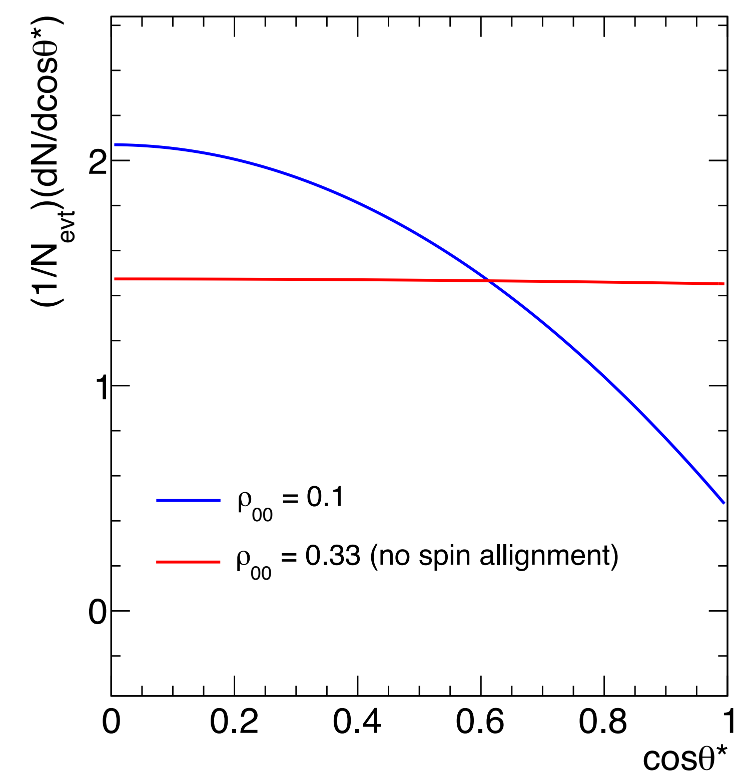
$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\left(3\rho_{0,0} - 1\right)\right]$$

ρ_{00}: Probability vector meson is in spin state = 0

$\rho_{00} = 1/3$ → No spin alignment

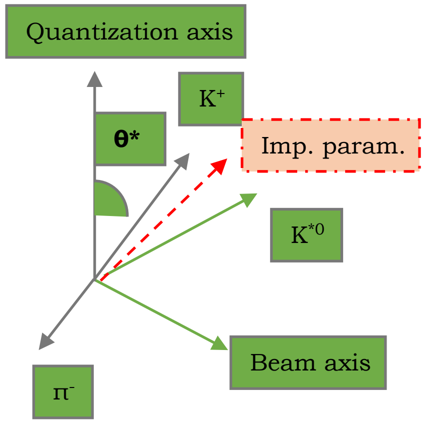


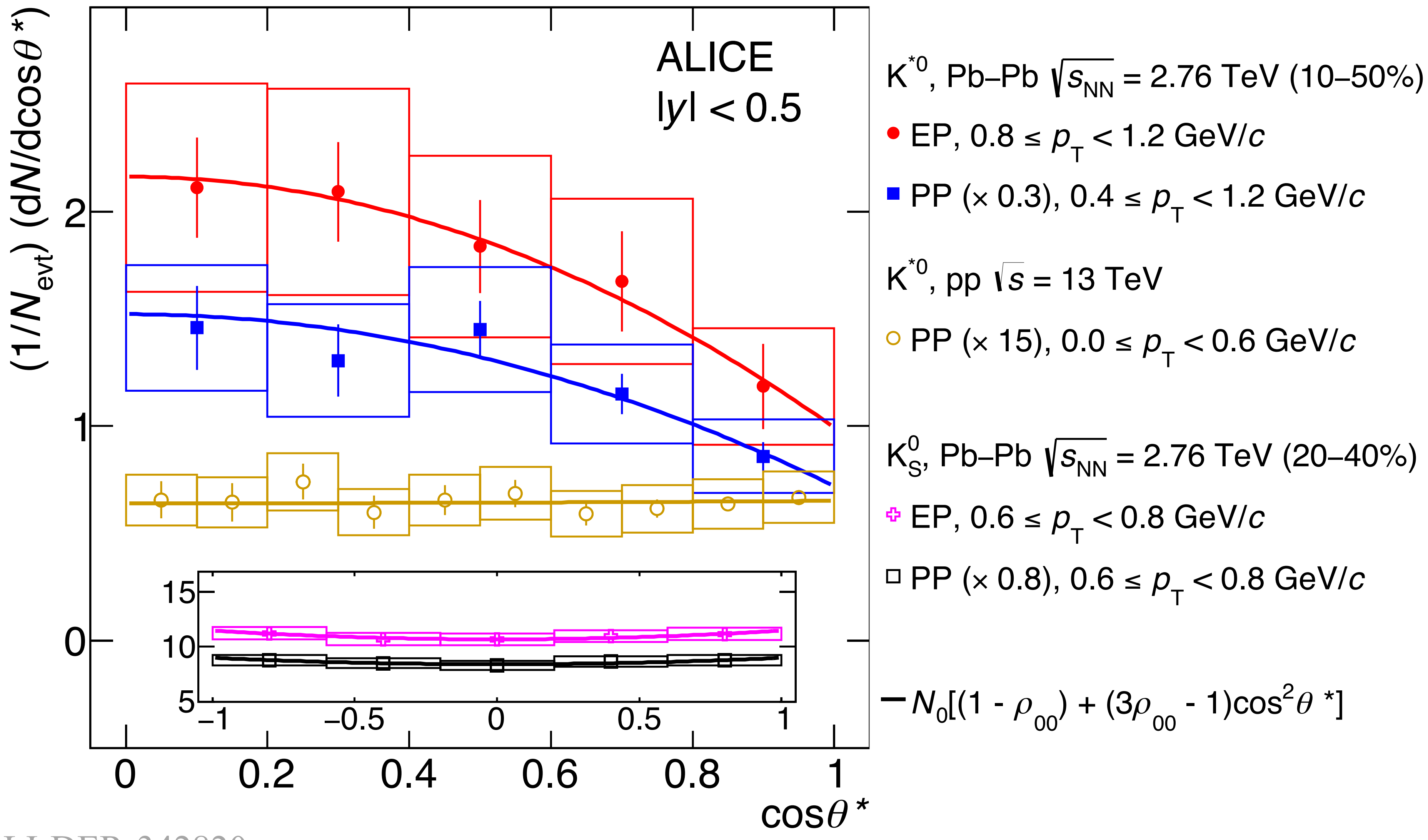
$$\frac{dN}{dcos\theta} = N_0 \left[1 - \rho_{0,0} + cos^2\theta \left(3\rho_{0,0} - 1\right)\right]$$



Finding spin-orbit interactions in QCD matter

Angular distribution of vector mesons





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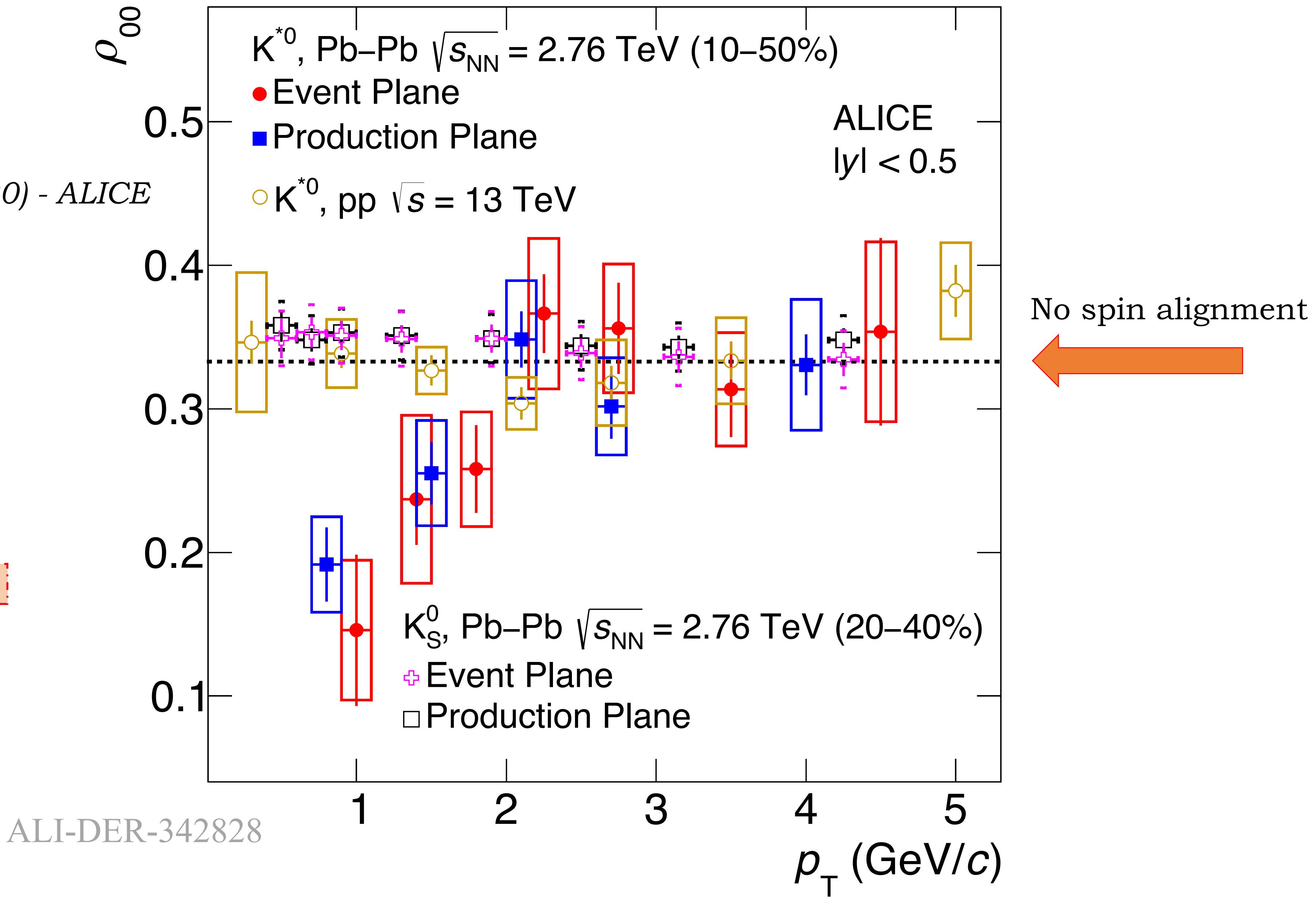
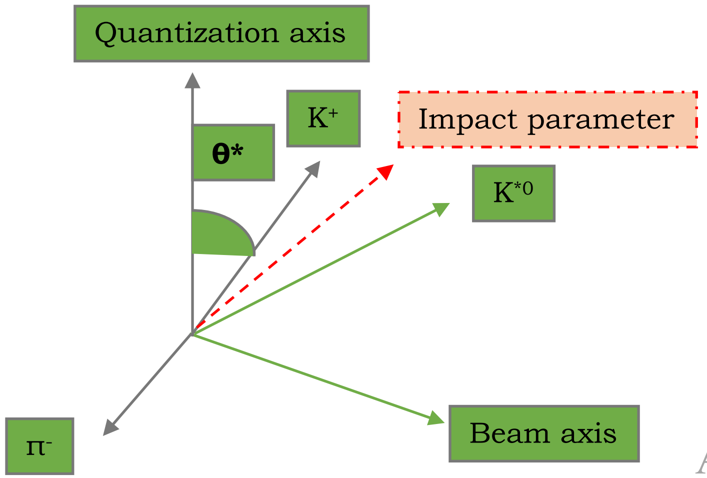
Phys. Rev. Lett. 125, 012301 (2020) - ALICE

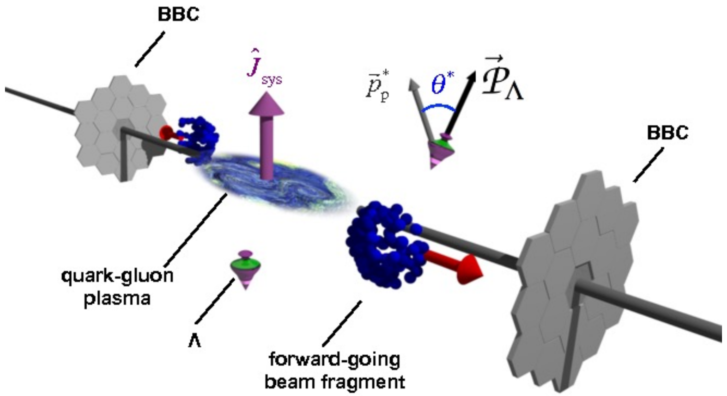
Spin alignment of vector mesons

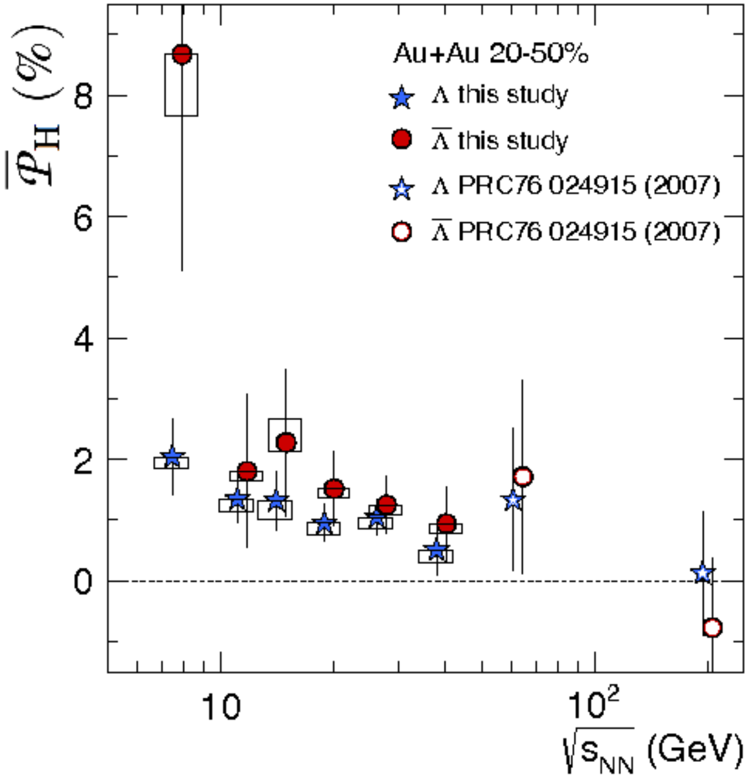
Phys. Rev. Lett. 125, 012301 (2020) - ALICE

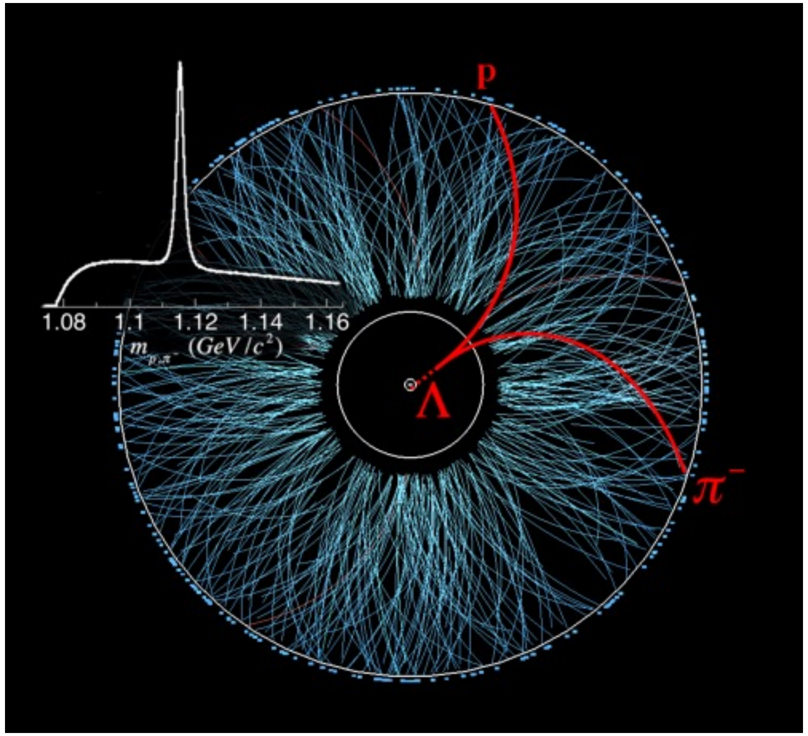




$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{\mathcal{P}}_H| \cos\theta^*\right)$$







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

Published: 03 August 2017

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration

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

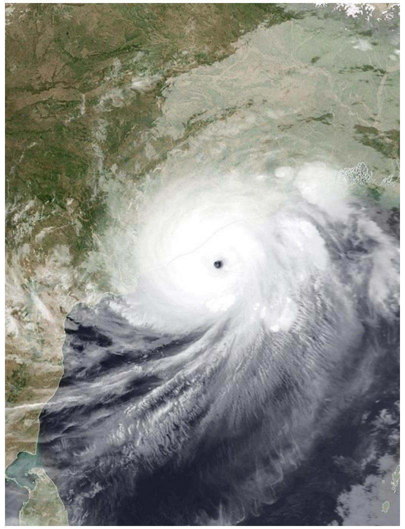
Most vortical fluid

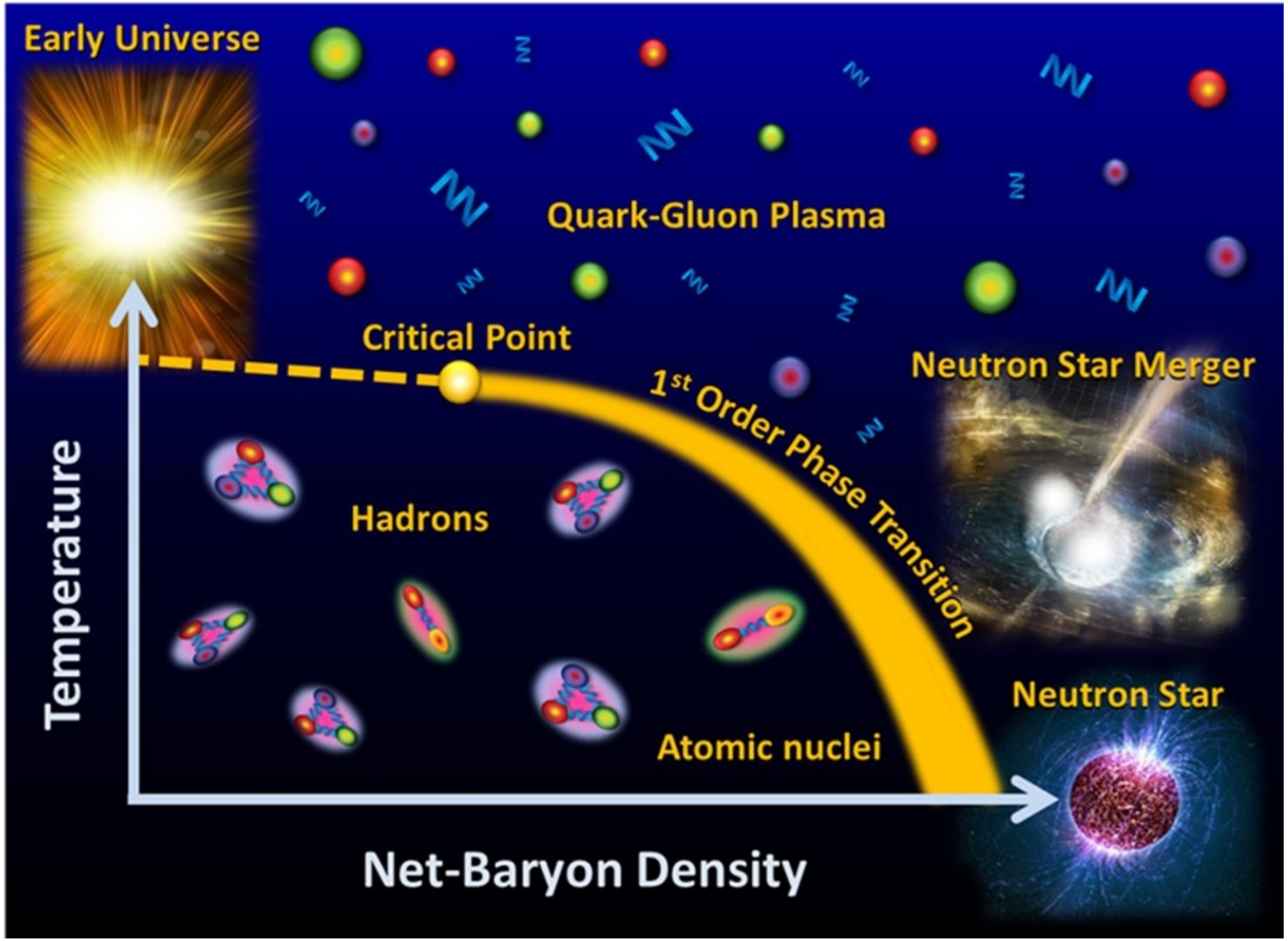
10^{21} (second)$^{-1}$

Perspective on vorticity

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

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





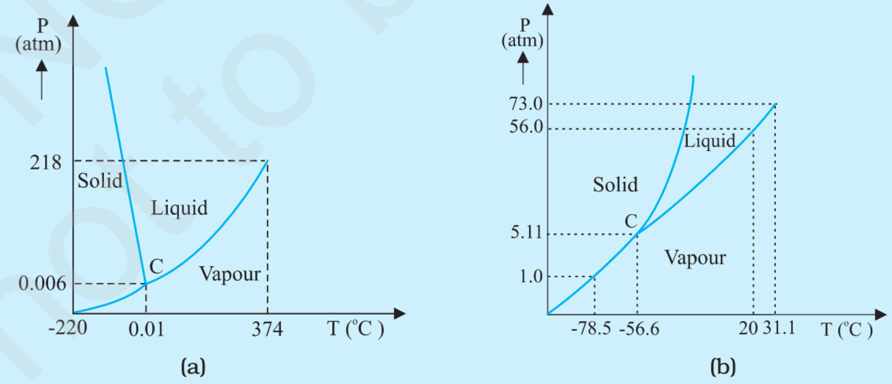
Phase diagram of strong interactions

Changing two nuclei collision energies

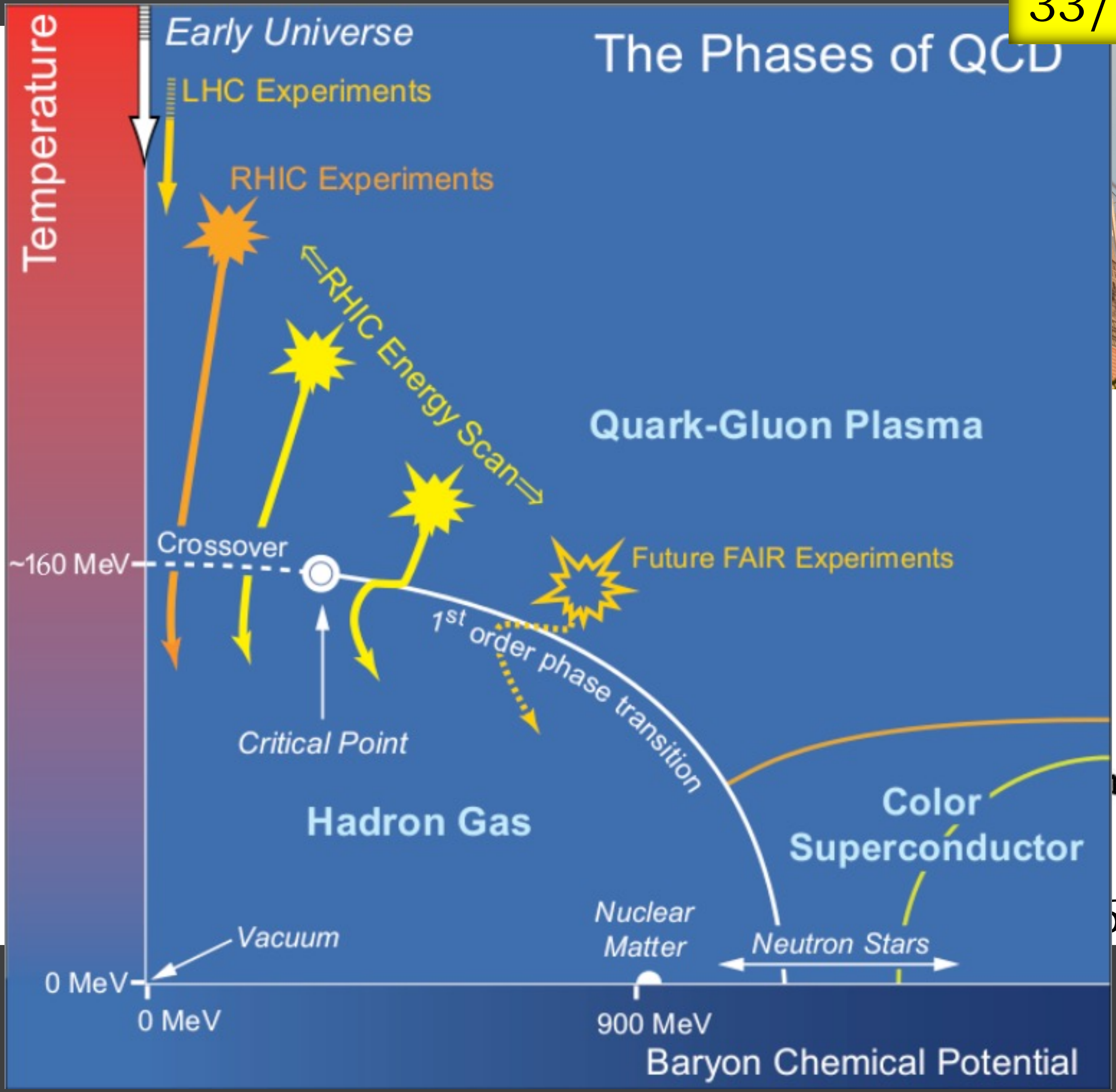
Phase Diagram

Triple Point

The temperature of a substance remains constant during its change of state (phase change). A graph between the temperature T and the Pressure P of the substance is called a phase diagram or $P-T$ diagram. The following figure shows the phase diagram of water and CO_2. Such a phase diagram divides the $P-T$ plane into a solid-region, the vapour-region and the liquid-region. The regions are separated by the curves such as sublimation curve (BO), **fusion curve** (AO) and **vaporisation curve** (CO). The points on **sublimation curve** represent states in which solid and vapour phases coexist. The point on the sublimation curve BO represent states in which the solid and vapour phases co-exist. Points on the fusion curve AO represent states in which solid and liquid phase coexist. Points on the vapourisation curve CO represent states in which the liquid and vapour phases coexist. The temperature and pressure at which the fusion curve, the vaporisation curve and the sublimation curve meet and all the three phases of a substance coexist is called the **triple point** of the substance. For example the triple point of water is represented by the temperature 273.16 K and pressure 6.1110^{-3} *Pa*.



Pressure-temperature phase diagrams for (a) water and (b) CO_2 (not to the scale).



G.Parisi

2021

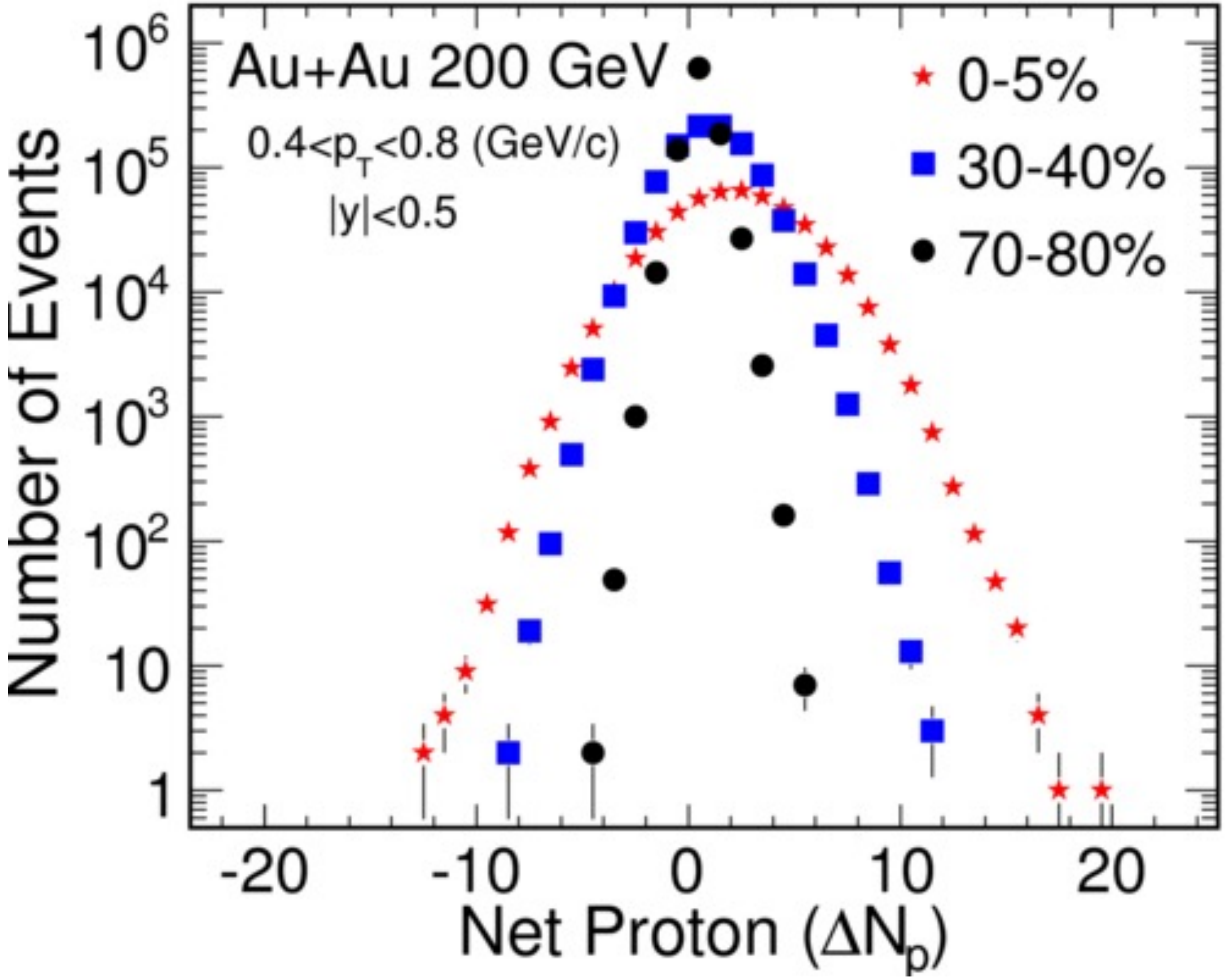
"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

Critical Point

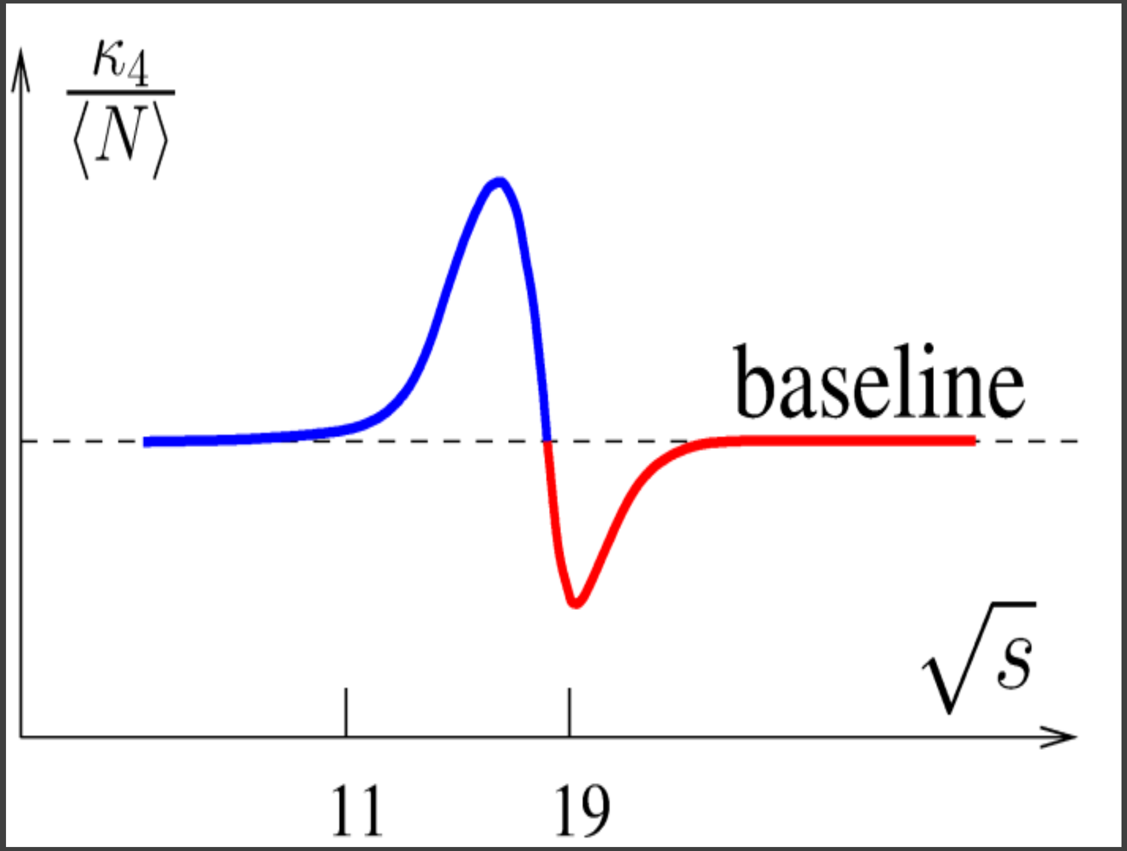
Fluctuations and susceptibility

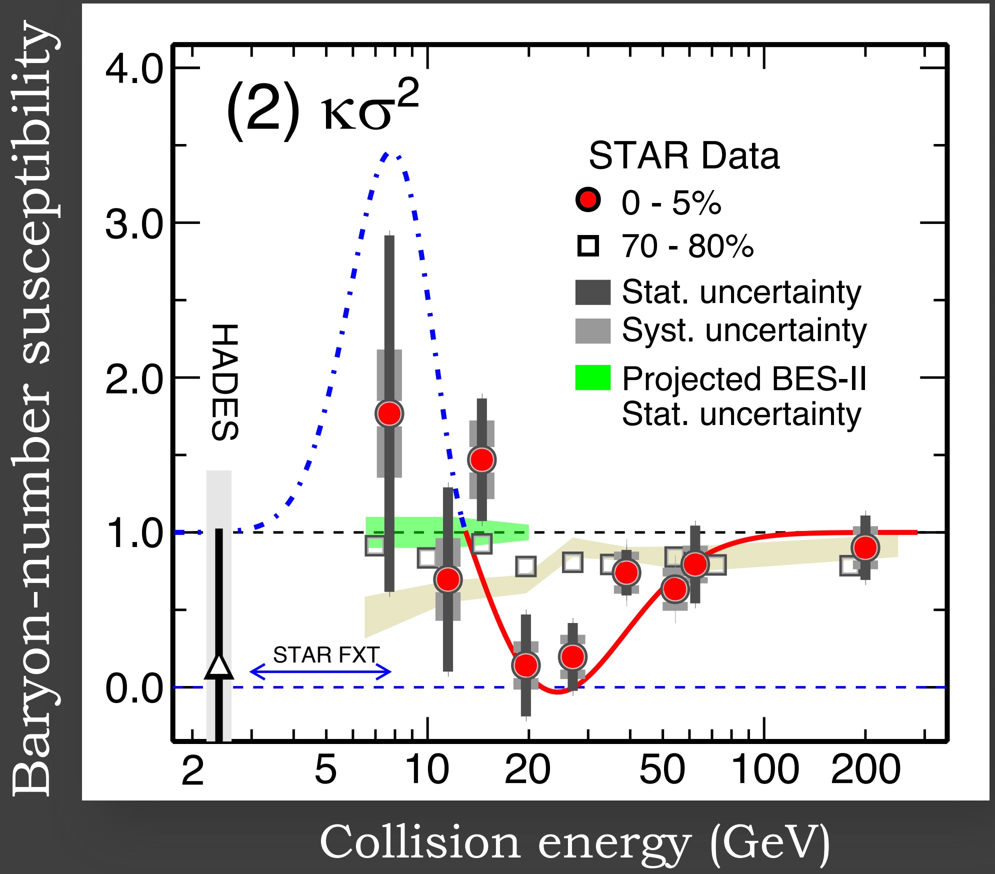
$$\langle(\delta N)^2\rangle \approx \xi^2,\ \langle(\delta N)^3\rangle \approx \xi^{4.5},\ \langle(\delta N)^4\rangle \approx \xi^7$$

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$



R. Gavai and S. Gupta Phys.Lett.B 696 (2011) 459-463
STAR: *Phys.Rev.Lett.* 105 (2010) 022302
Science 332 (2011) 1525-1528





M. Stephanov, ***PRL107***, 052301(2011)

STAR Collaboration, ***PRL (2021)***

Critical point of QCD

WILCZEK'S UNIVERSE

Cracking the Secret of Matter's Phases

New research sheds light on the behavior of liquids and gases under extreme conditions.

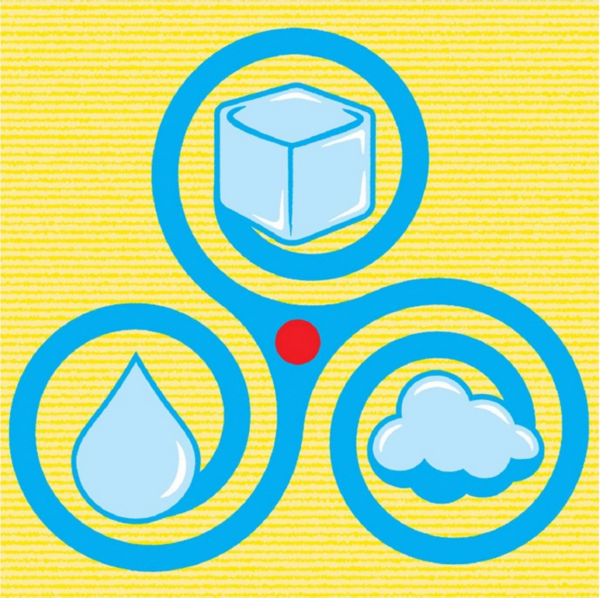
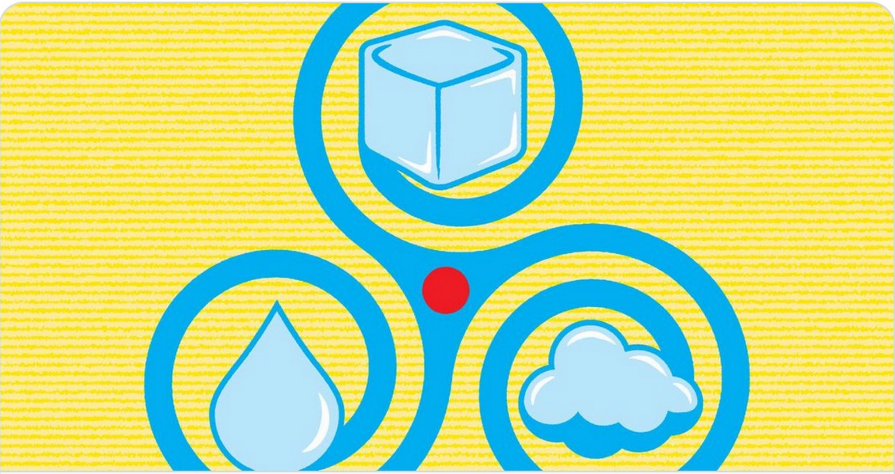


ILLUSTRATION: TOMASZ WALENTA

By Frank Wilczek
July 29, 2021 1:55 pm ET

WSJ Science @WSJscience

The fact that matter has different phases - solid, liquid, gas - is profoundly strange, writes physicist Frank Wilczek in his latest for WSJ. New research is cracking these phases' secrets.



wsj.com
Cracking the Secret of Matter's Phases
New research sheds light on the behavior of liquids and gases under extreme conditions.

In the early 1990s, Krishna Rajagopal and I predicted that there would be a critical point— around 10 trillion degrees—where the distinction between nuclear and quark matter fades away. That point's existence could be confirmed, we proposed, by observing fluctuations in the fireballs that have nearly the critical temperature and pressure.

Experimenters at Brookhaven have reported hints of just such behavior. They are now analyzing a much bigger data set to nail it down (or not). If all goes well, they'll have demonstrated that deep ideas invented to understand problems in physical chemistry and thermal engineering continue to be useful far beyond their down-to-earth origins.

Summary so far .....

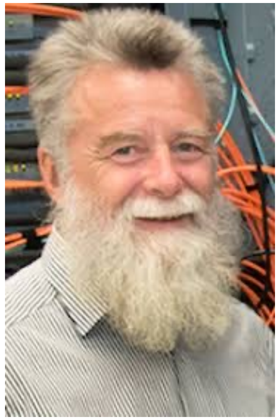
- Microsecond old Universe matter recreated in Laboratory. System of de-confined quarks and gluons formed. Matter of quarks and gluons created at Temperatures ~ 10^{12} degree kelvin
- The de-confined quarks and gluons (fundamental constituent of any visible matter) exhibits the property of perfect fluidity with high degree of Vorticity
- Phase Diagram of Strong Interactions being laid out.
- Exciting experimental results on critical point and phase boundary. Susceptibility has a non-monotonic variation with beam energy.

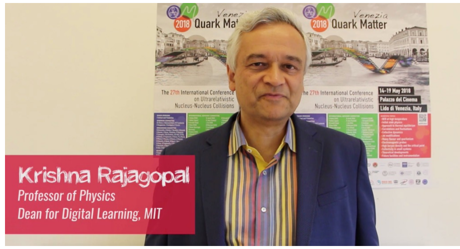
Mega Sciences

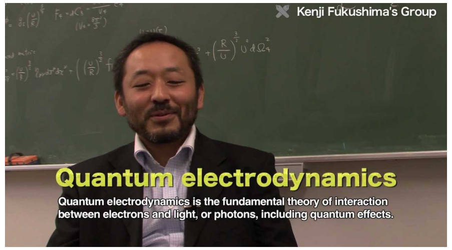
Come join !

"I do not know what I may appear to the world; but myself I seem to have been only like a boy playing on the Sea shore and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me." - Attributed to Sir Isaac Newton (1642 – 1727)

ALICE







STAR

CBM

राष्ट्रीय विज्ञान शिक्षा एवं अनुसंधान संस्थान
NISER
विद्ययाऽमृतमश्नुते

राष्ट्र की सेवा में परमाणु
प उ वि
DAE
ATOMS IN THE SERVICE OF THE NATION

Department of Science & Technology, Government of India
सत्यमेव जयते

Acknowledgements

Important contributions from GU group

To the young students and faculty of the University …

Prof. C. V.Raman:

"Youth is the most glorious time of all. I have said elsewhere that most of the great discoveries in Science have been made by young people. It is not the experience or wisdom that old age brings, but the freshness of outlook, the indomitable desire to achieve, which is the characteristic of youth, that makes discoveries possible. It is this that makes life worthwhile. If only you realise this and realise that here I am, I am still young, let me see what I can do, that all discoveries become possible."

Thank you