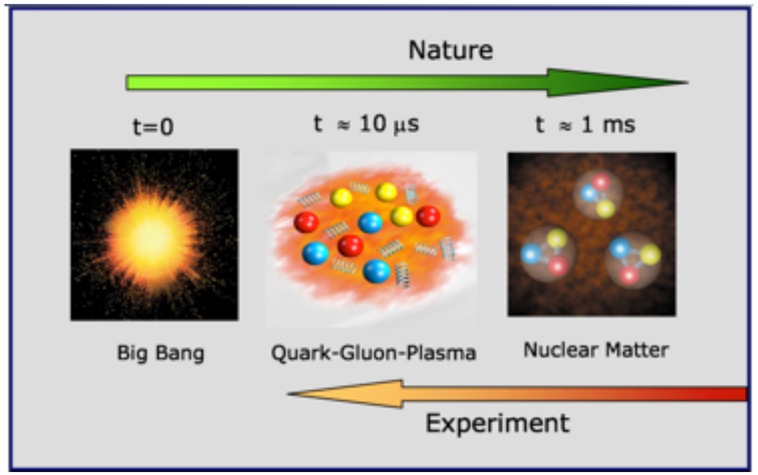
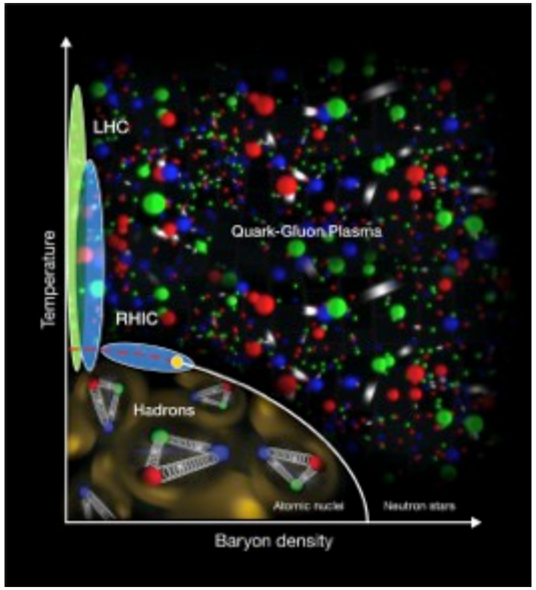
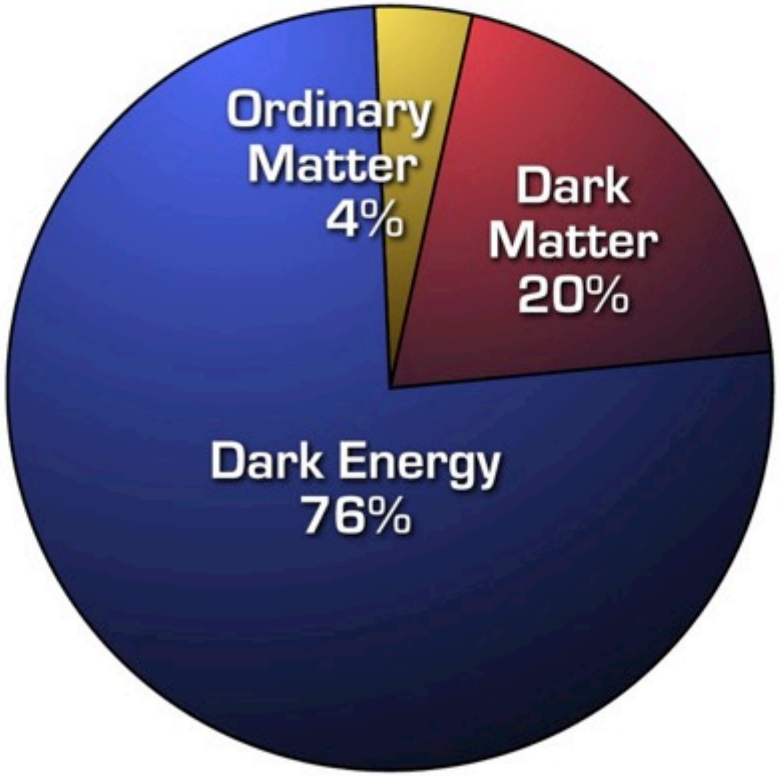
De-confined State of Quarks and Gluons – Quark Gluon Plasma

Bedanga Mohanty
National Institute of Science Education and Research Bhubaneswar





Universe: Ordinary Matter

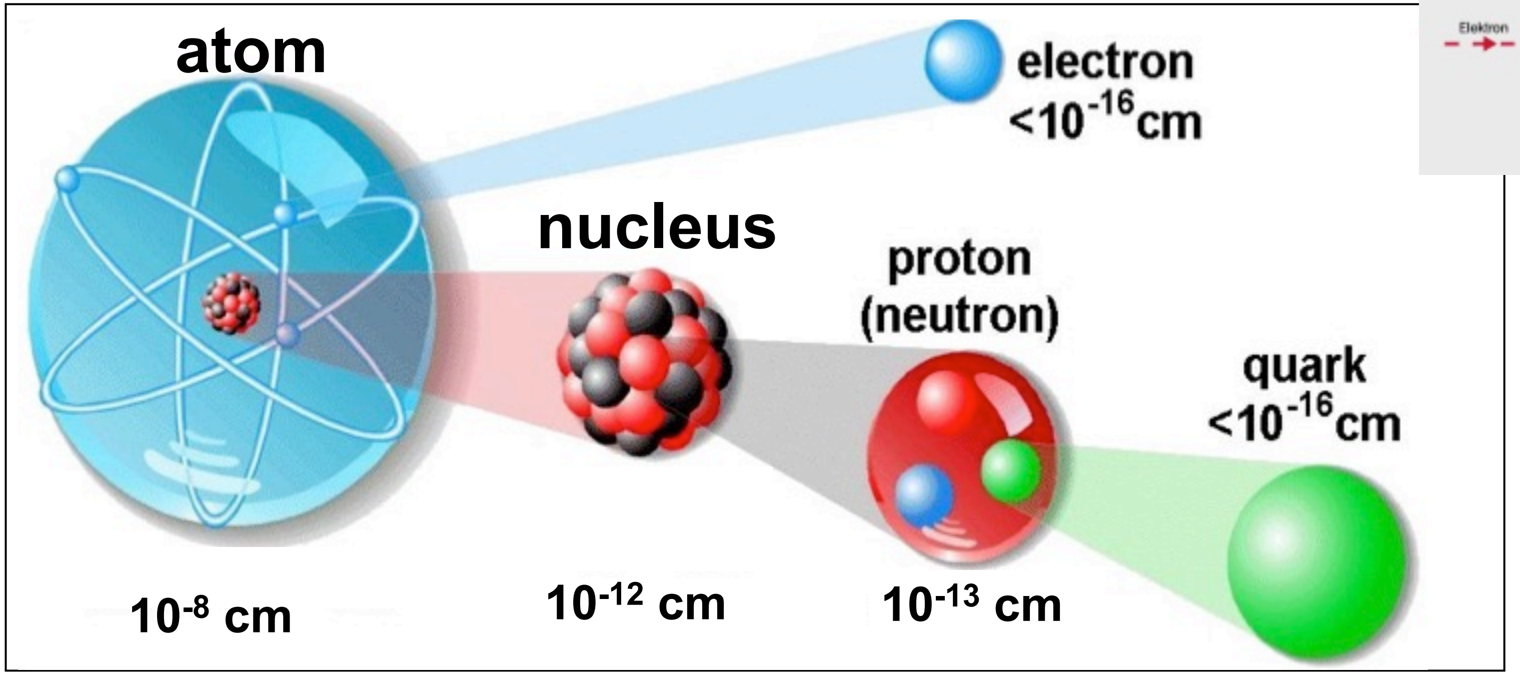


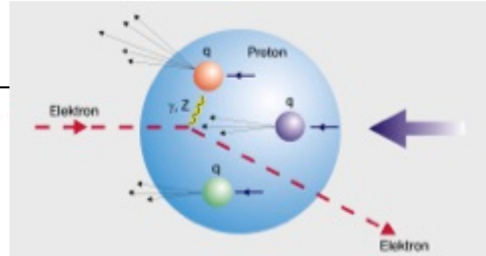
Do we know about the properties of the fundamental constituents that make the ordinary matter

http://www.euclid.caltech.edu/image/euclid2011-001a

Fundamental Constituents of Ordinary Matter

~1900 ~1910 ~1940 1970





ETH Zurich, Institute for Particle Physics.

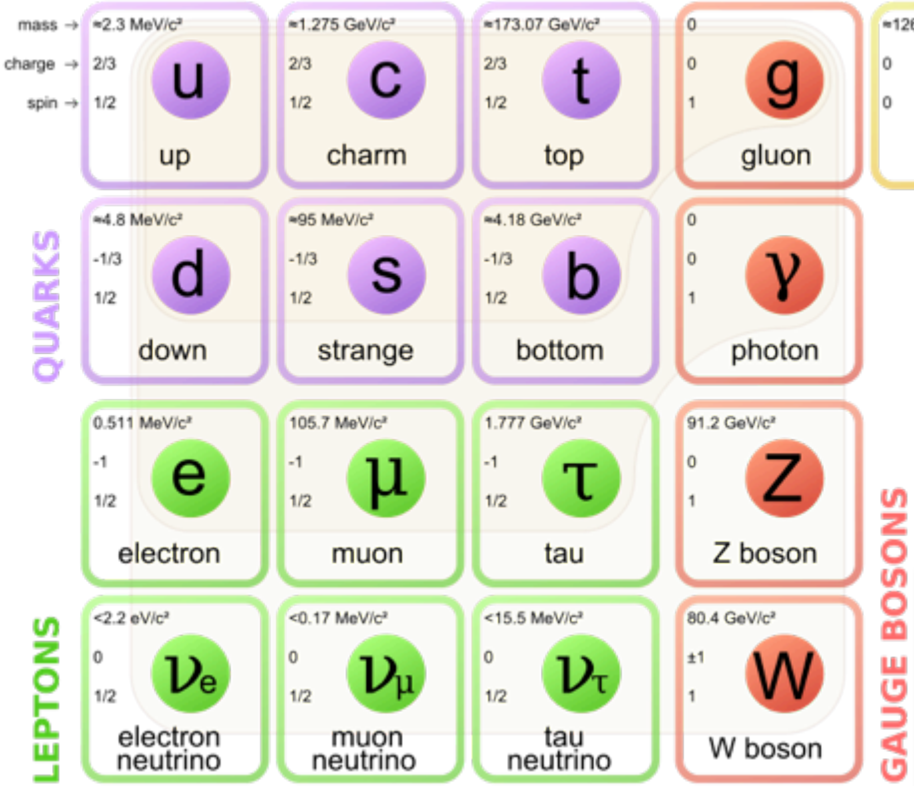
$$\lambda = h/p$$

$$f = E/h$$

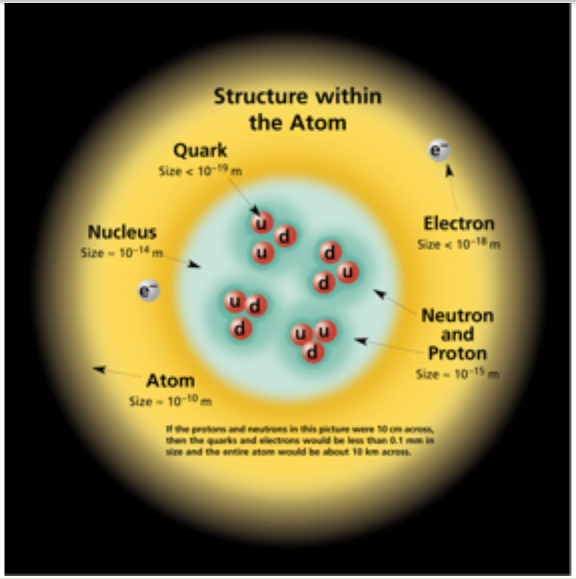
De-Broglie equation

Higher the momentum smaller the distance scale we probe

Standard Model: Ultimate Constituents



particleadventure.org

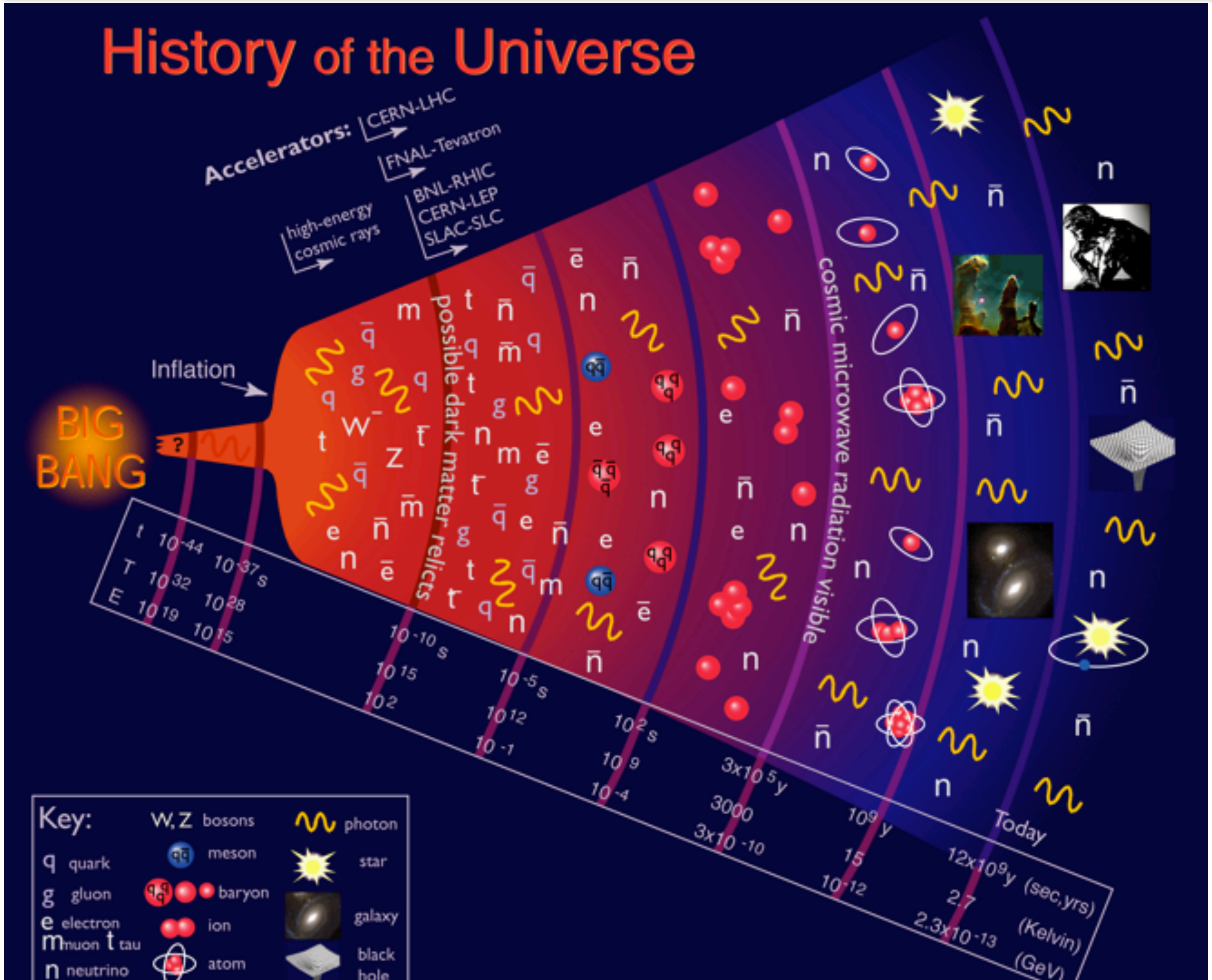


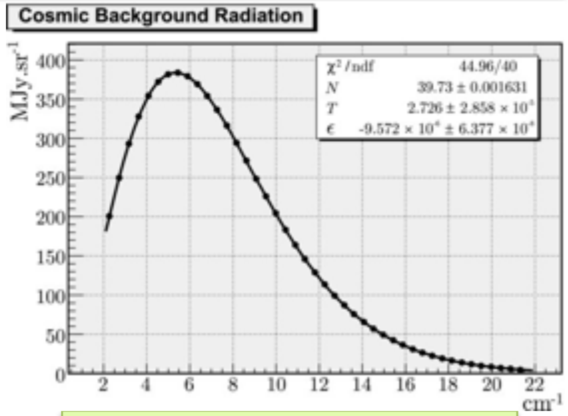
Fundamental constituents of visible matter are confined inside hadrons. No free quark seen.

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	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Primordial Matter in Early Universe

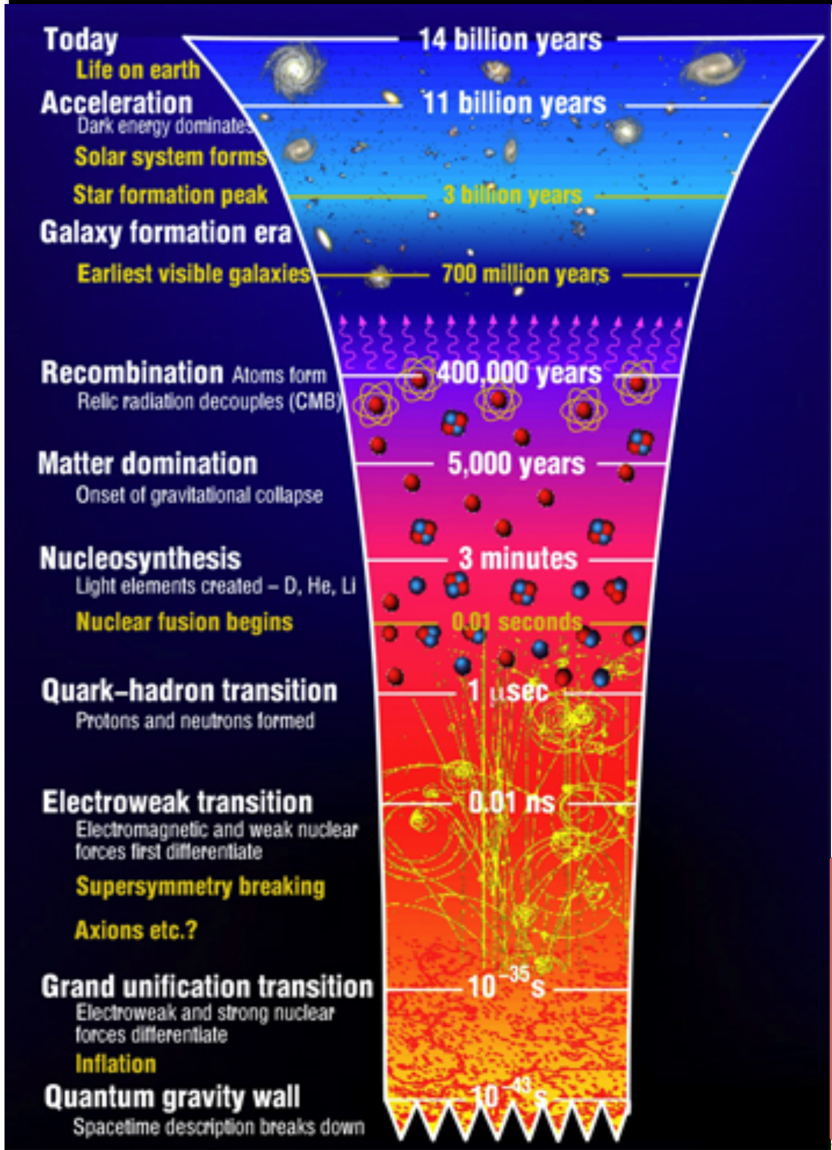


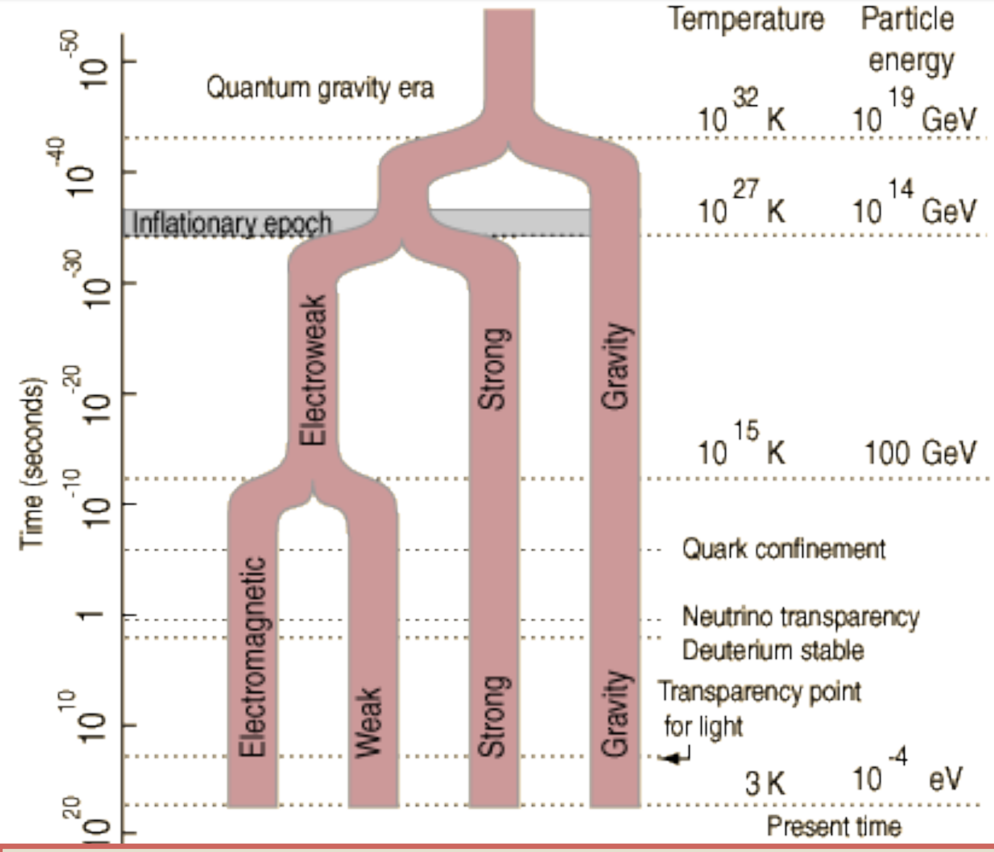


Micro-second old Universe had this primordial matter

As the universe cooled, they were confined and have remained that way since

QCD Transition in Early Universe





Universe:

QCD Phase Transition: T ~ 200 MeV

Electroweak Phase Transition: T ~ 150 GeV

GUT phase Transition: T ~ 10^{16} GeV

QCD Transition the only one possible to study in Laboratory

How to Create Primordial Matter

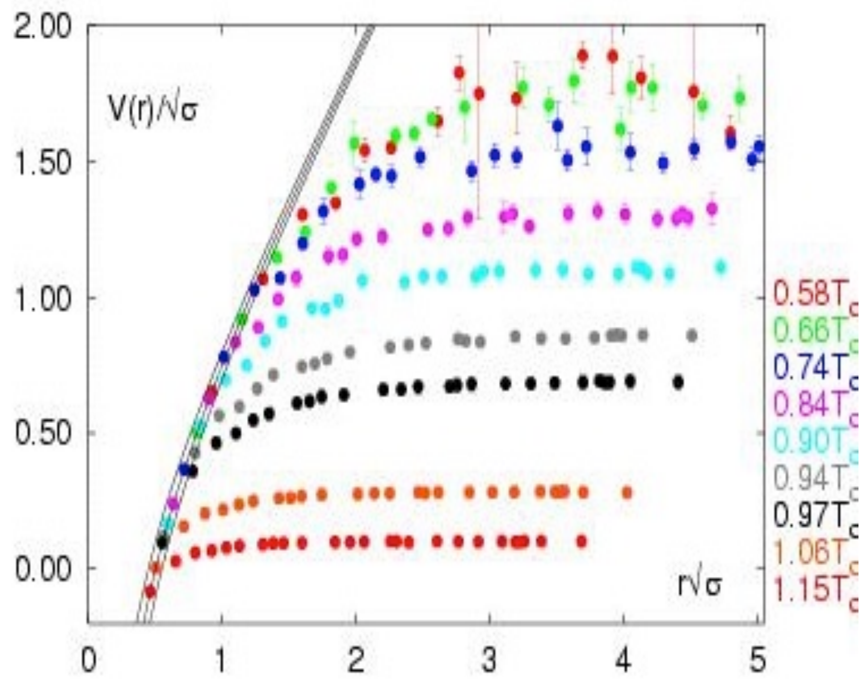
Hadrons are composite objects made of quarks and gluons.

QCD is a "confining" gauge theory, with an effective potential:

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

"Coulomb" "Confining"

Karsch et al



No one has ever seen a free quark.

Matter at high temperature or energy density can be de-confined

Quantum Chromodynamics

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

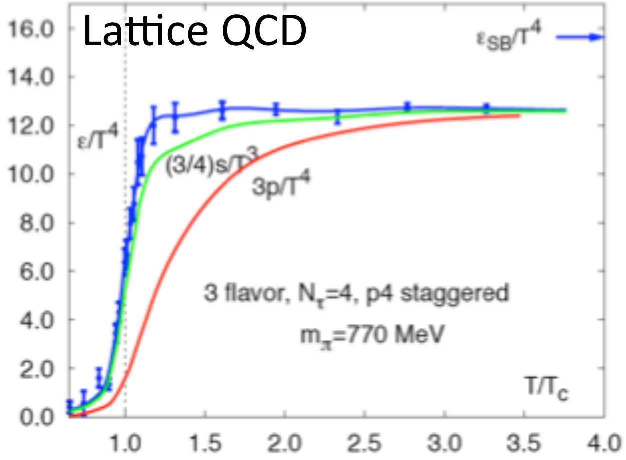
Energy density for "g" massless d.o.f.

$$\varepsilon = 3\cdot\frac{\pi^2}{30}T^4$$

Hadronic Matter:
3 π with spin=0

$$\varepsilon = 37\cdot\frac{\pi^2}{30}T^4$$

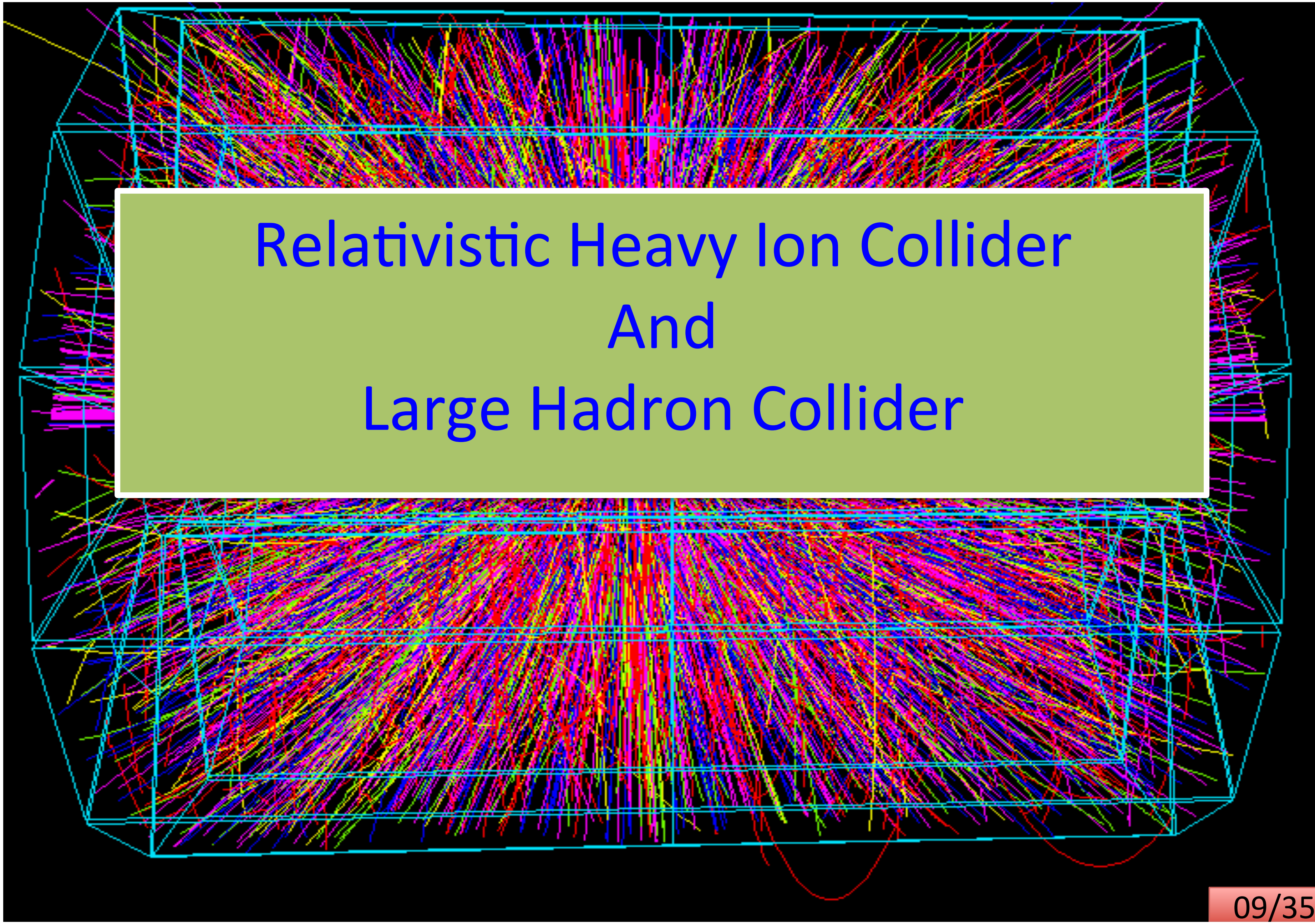
Quark Gluon Plasma:
8 gluons;
2 quark flavors, antiquarks, 2 spins, 3 colors



Matter at high temperature or energy density can be de-confined

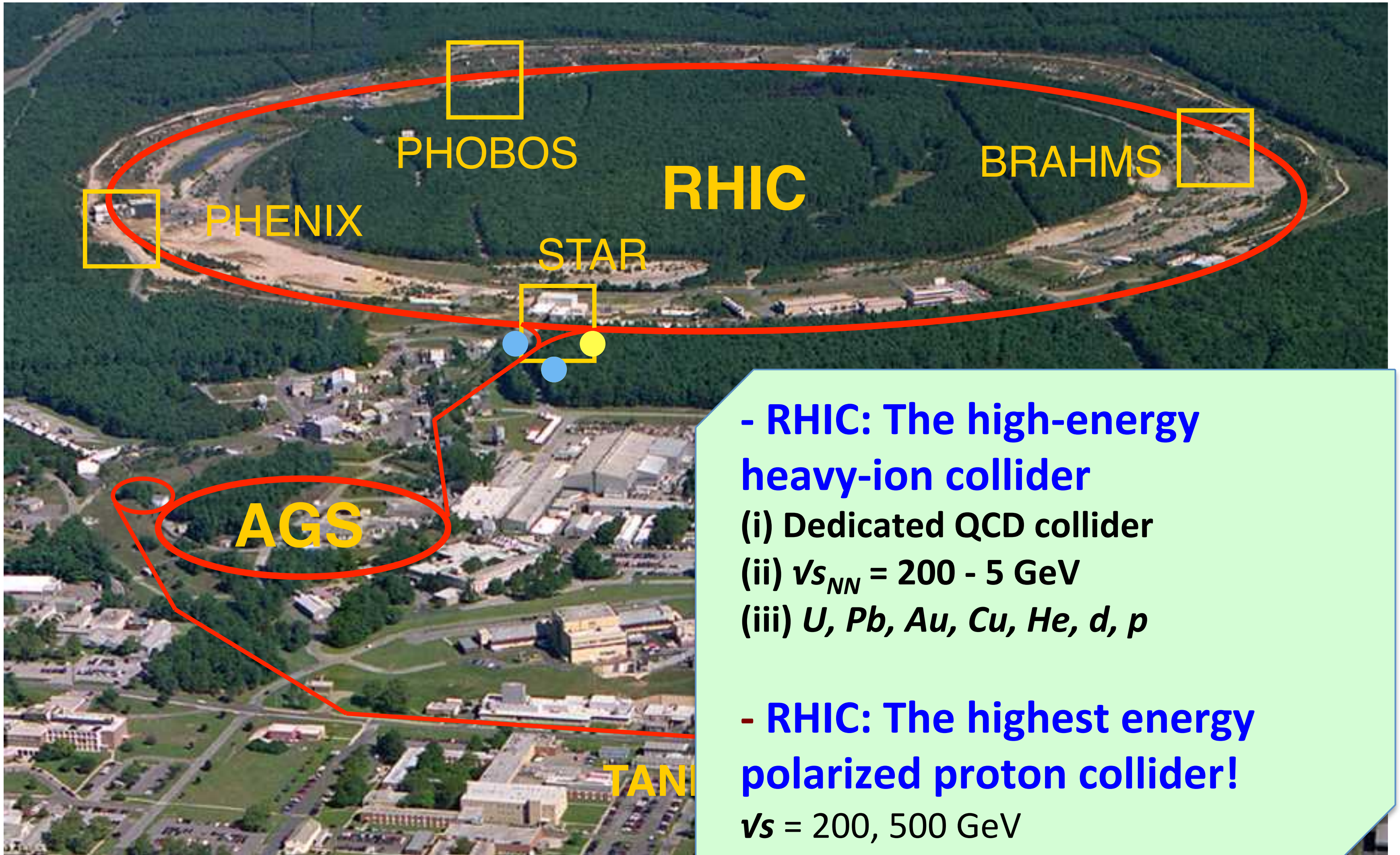
$T_c \sim 170$ MeV

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



Relativistic Heavy Ion Collider
And
Large Hadron Collider

Relativistic Heavy Ion Collider



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

(iii) *U, Pb, Au, Cu, He, d, p*

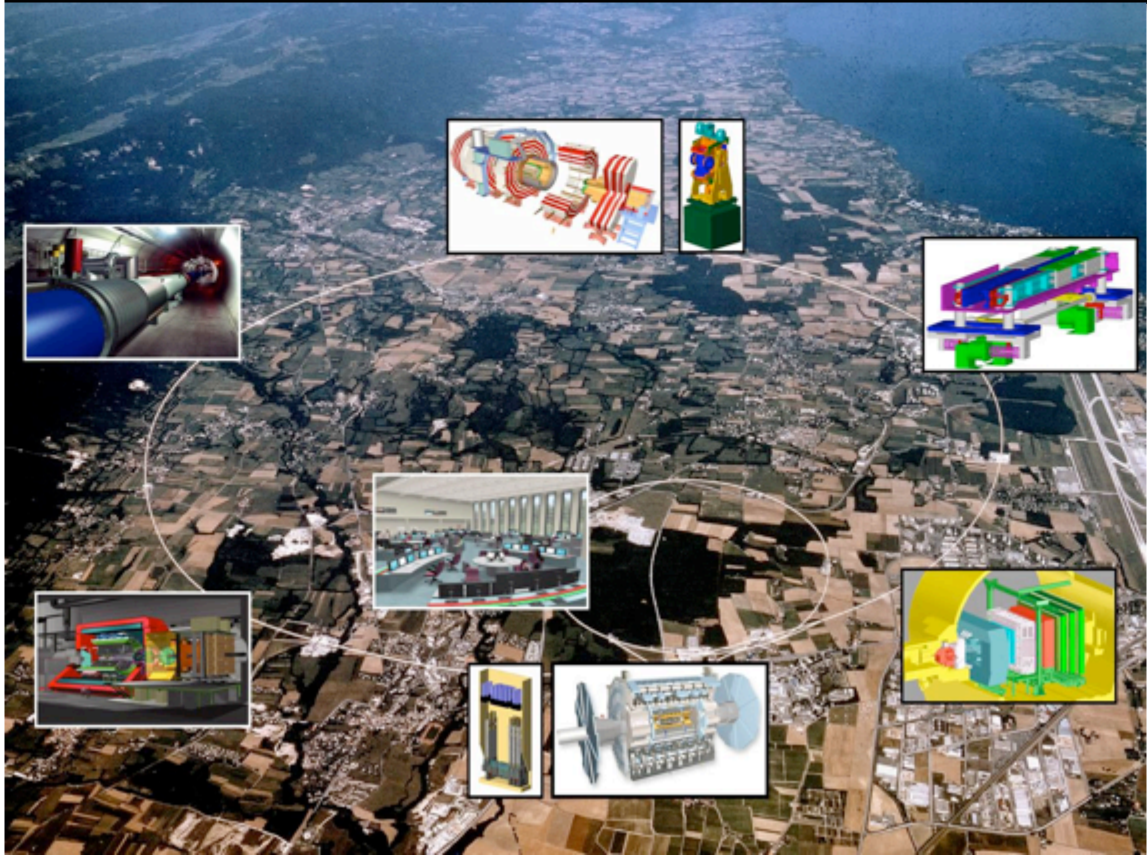
- RHIC: The highest energy polarized proton collider!

$\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

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

Large Hadron Collider



- ✧ Produces matter with temperature more than 100,000 times the temperature of Sun
- ✧ Data recorded will fill around 100,000 dual layer DVDs every year

- ✧ Largest particle accelerator: Circumference is 26.659 Km.
- ✧ Worlds Coldest place: 9300 magnets at -271.3°C (1.9 K) – Colder than outer space
- ✧ Worlds Loneliest place: Internal pressure 10^{-13} atm. 10 times less than the pressure on moon
- ✧ Fastest Race track: Trillions of protons race 11245 times a second with speed 99.9999991% speed of light

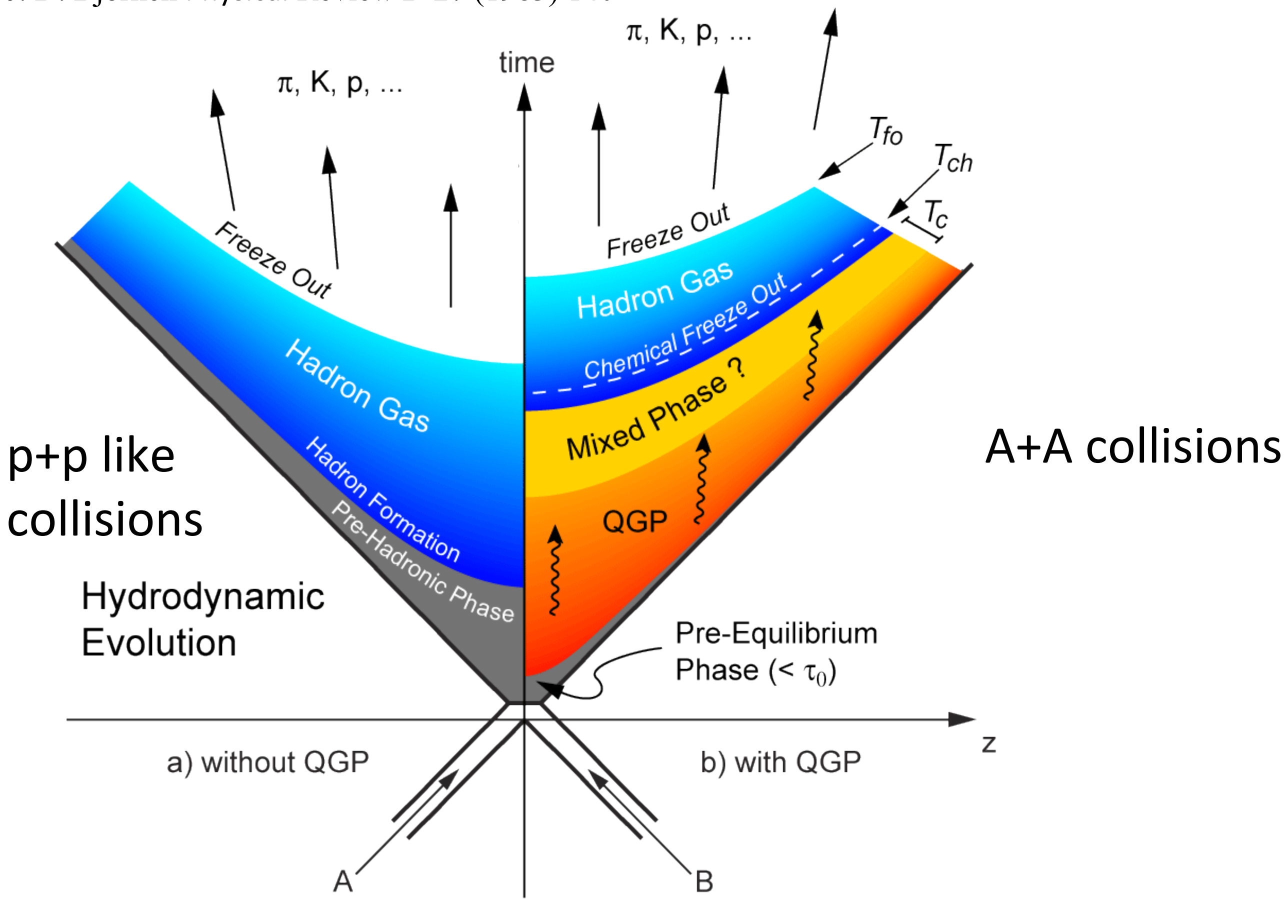
http://home.cern/topics/large-hadron-collider

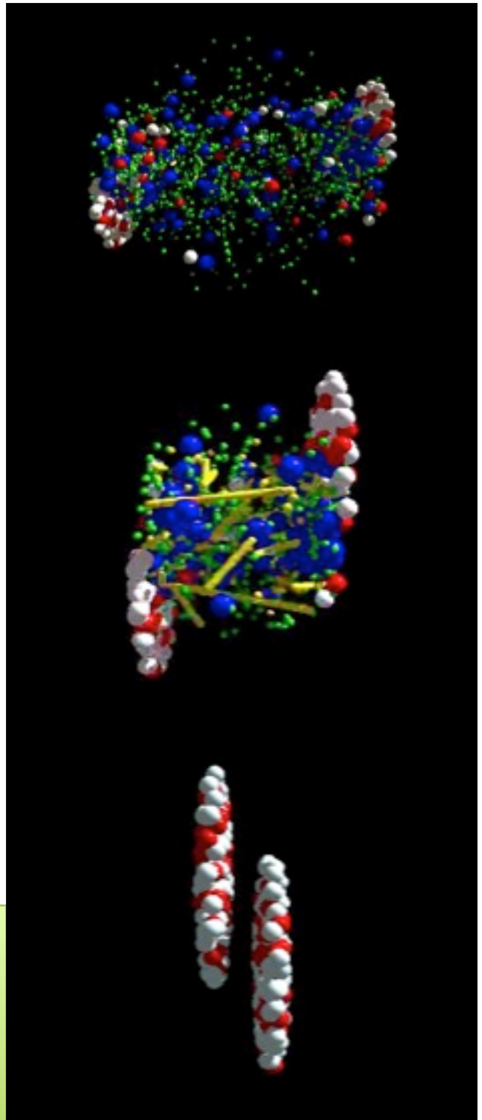
The CMS magnet system contains about 10 000 t of iron, which is more iron than in the Eiffel Tower

The Sun never sets for such experiments

Heavy-Ion Collisions – QCD Transition

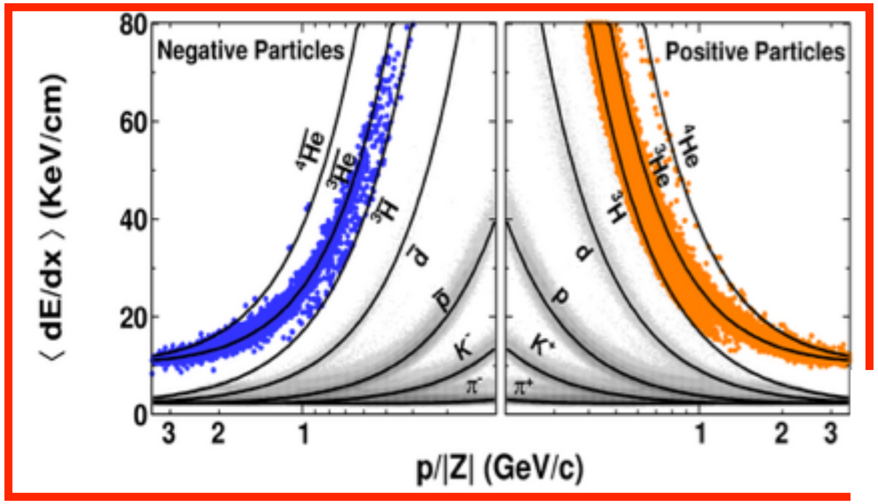
J. D. Bjorken Physical Review D 27 (1983) 140





Colliding two nuclei - create the QCD transition Confined (hadrons) -- De-confined (quarks & gluons) in laboratory

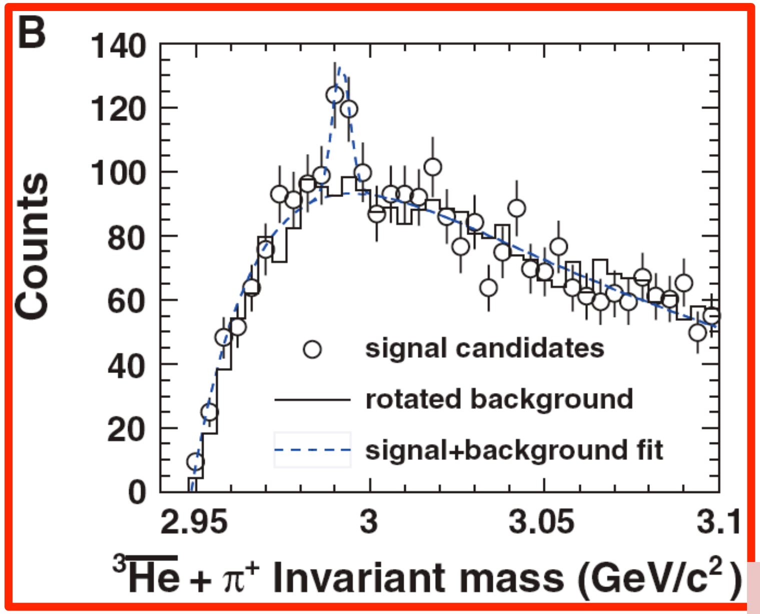
Heaviest Anti-Nuclei

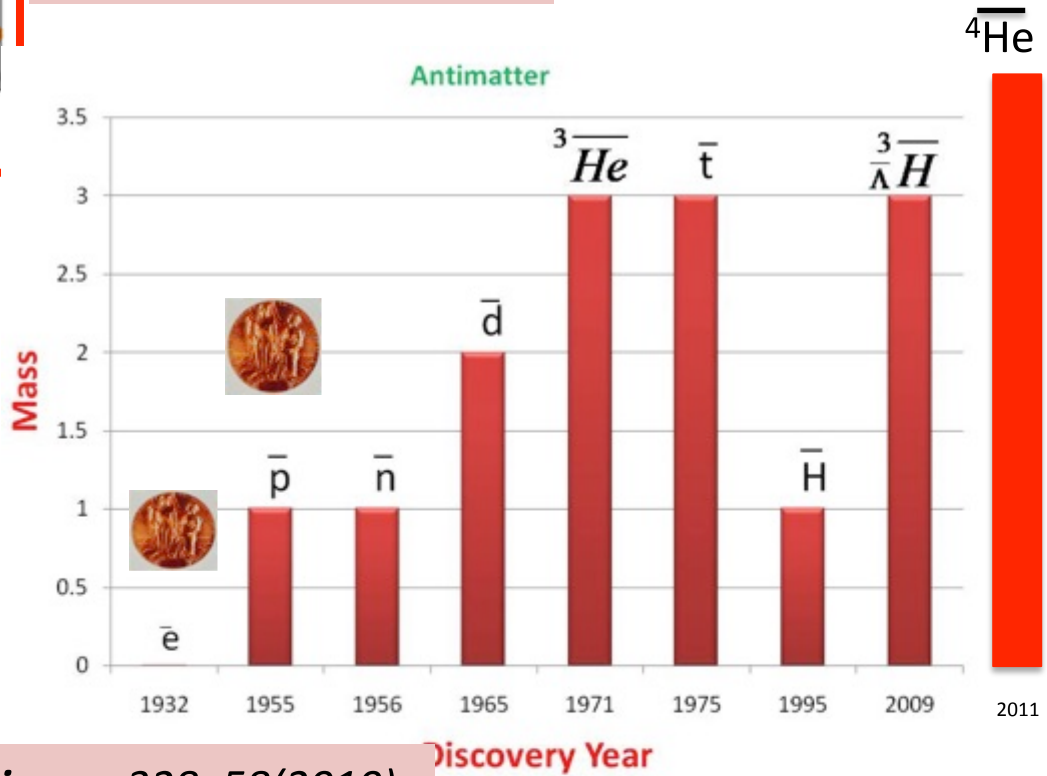


Ionization energy loss:
- < dE/dx > ~ A / β^2
= A (1 + **m²**/ p²)

5 kind of charged Particles and two Neutral particles

Nature, *473, 353(2011).*





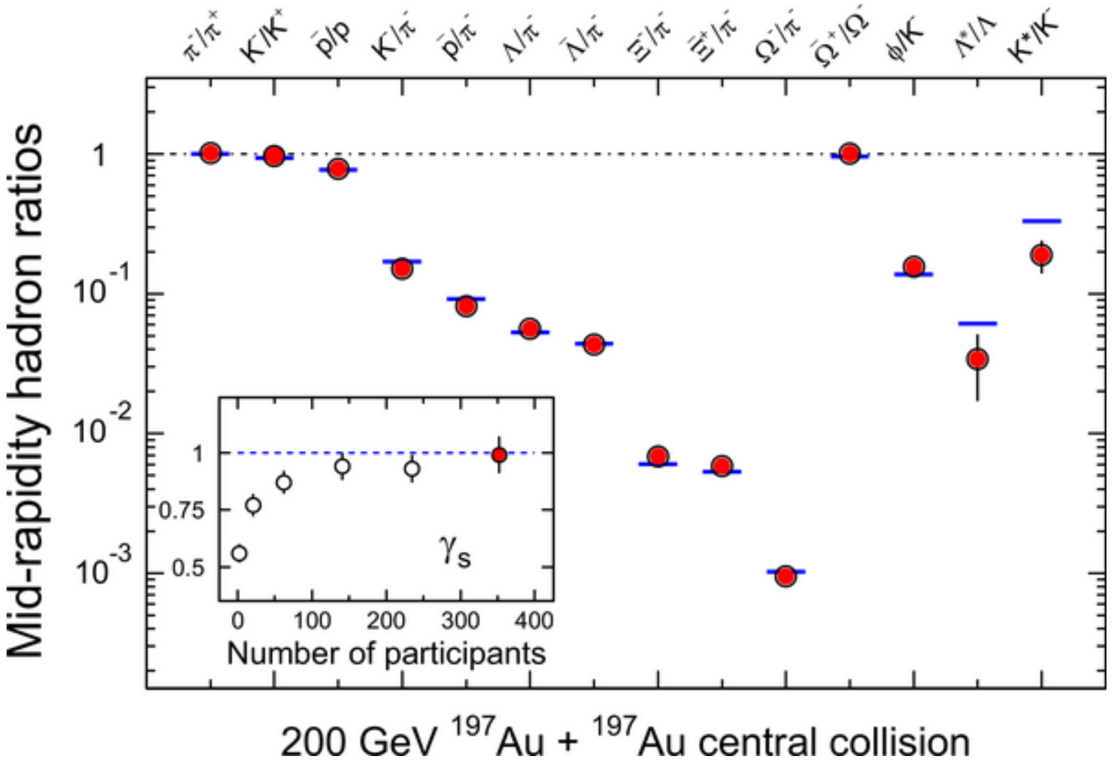
Science, *328, 58(2010)*

$M^2 = E^2 - p^2$

Louis Pasteur: *"In the field of observation, chance only favours those minds which have been prepared"*

Particle Production – Thermalized Source

STAR: NPA



T_{ch} = 163 ± 4 MeV
μ_B = 24 ± 4 MeV

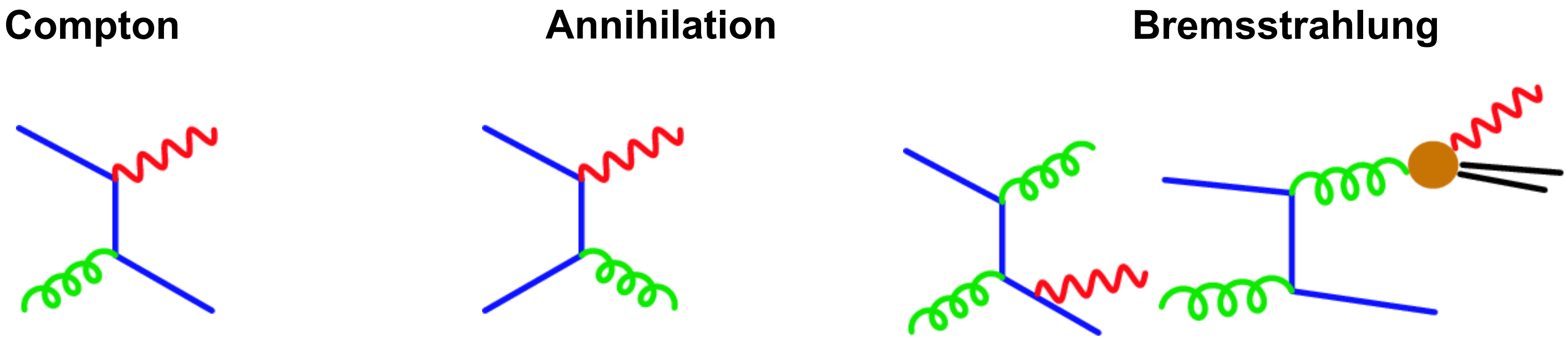
$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{V.T.m_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

Statistical Model with Grand Canonical Ensemble.
Incorporates the various conservation laws.
Assumes thermal and chemical equilibrium.

In central collisions, the system is thermalized at RHIC

Did we form Primordial Matter

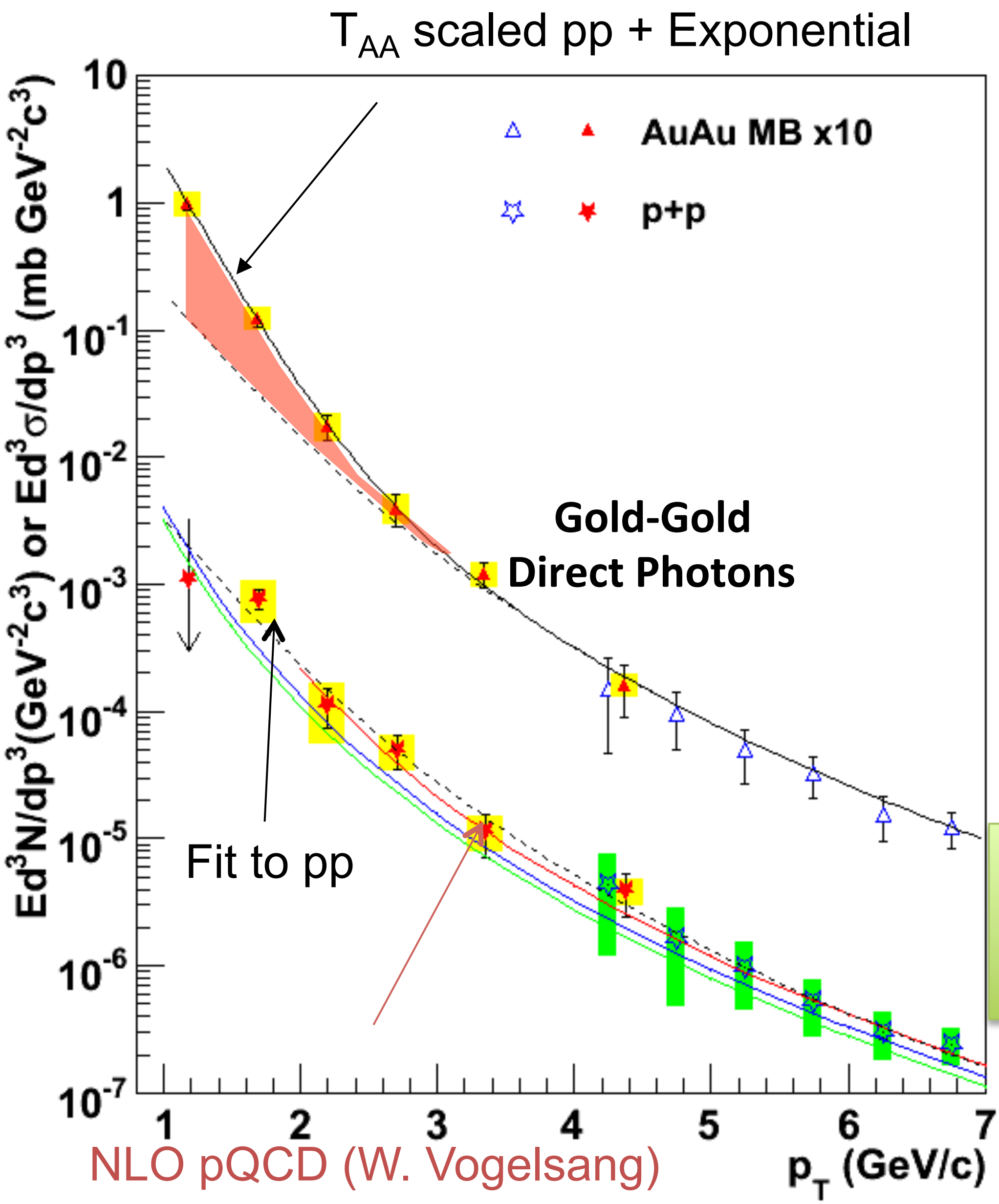
If there is system of free quarks and gluons – Photons can be produced through:



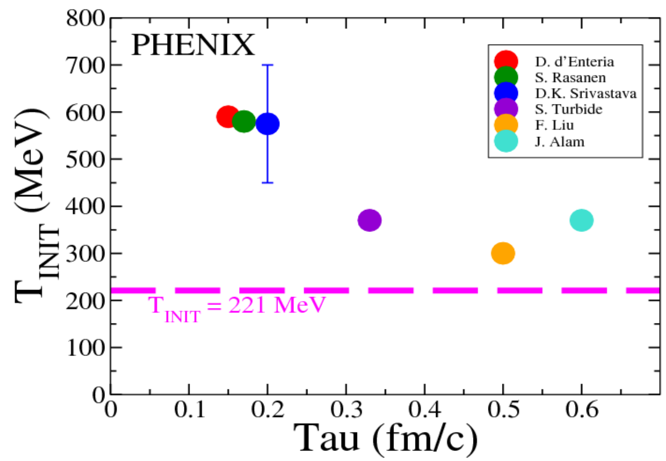
In a hydrodynamic picture: Slope of momentum distribution of these photons

$$T_{eff} = T_{th} + \frac{1}{2} m v_r^2$$

Did we form the Primordial Matter



T_i = 300-600 MeV



$T_{initial} > T_C$ (QCD)

Deconfined state of quarks
And Gluons

Proton-Proton
Direct Photons

Perspective of Temperature

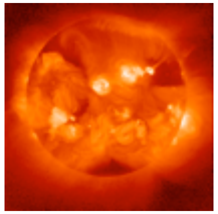
~10^{12} K — Nucleus-Nucleus collisions — ~ 120 MeV

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

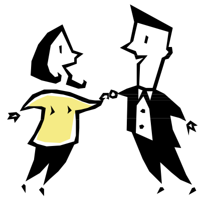
(Terrestrial Nuclear explosions)

~10^{6} K — Solar Interior

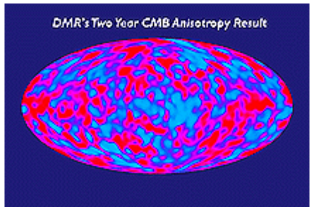
~6000 K — Solar Surface



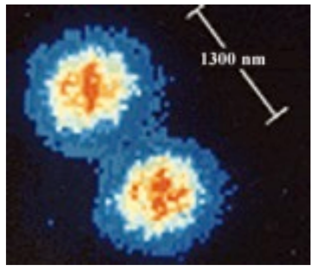
~300 K — Room Temperature ~ 1/40 eV



~3 K — Cosmic Microwave Background



~10^{-6} K — Trapped Ions

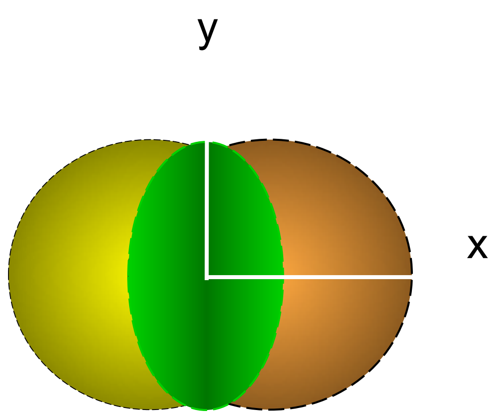


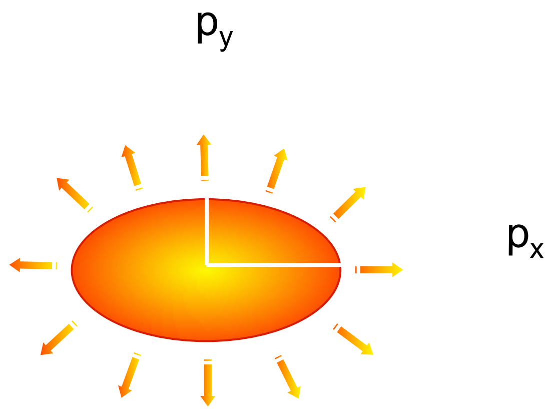
~10^{-10} K — Rhodium metal spin cooling (2000)

(Low-T World Record!)

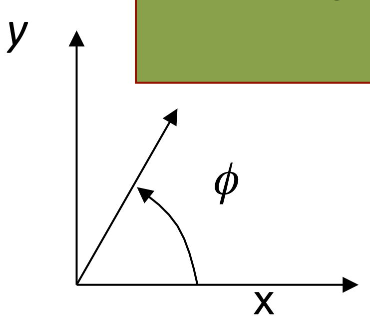
Collectivity

coordinate-space-anisotropy ⇨ momentum-space-anisotropy





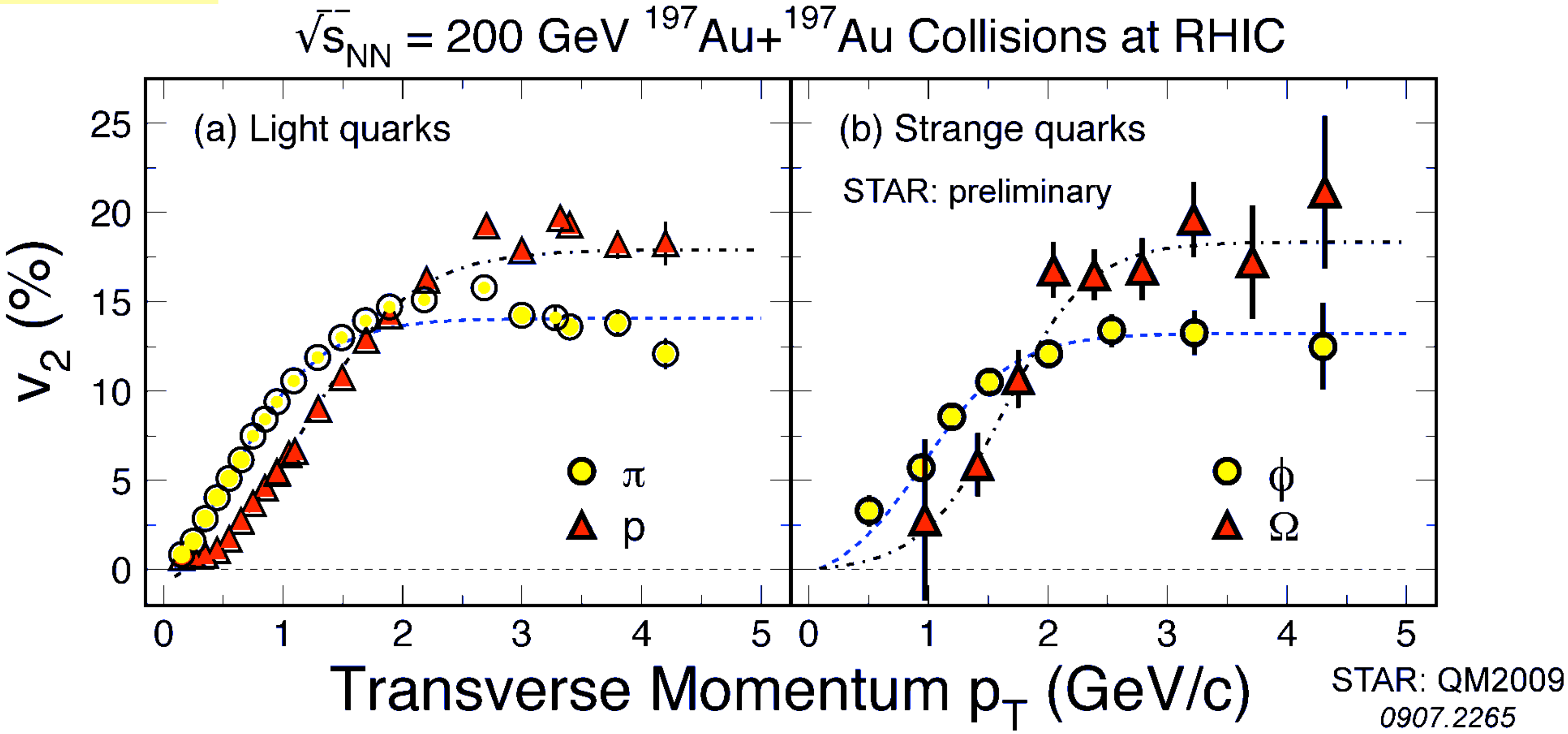
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$



Strong Collectivity

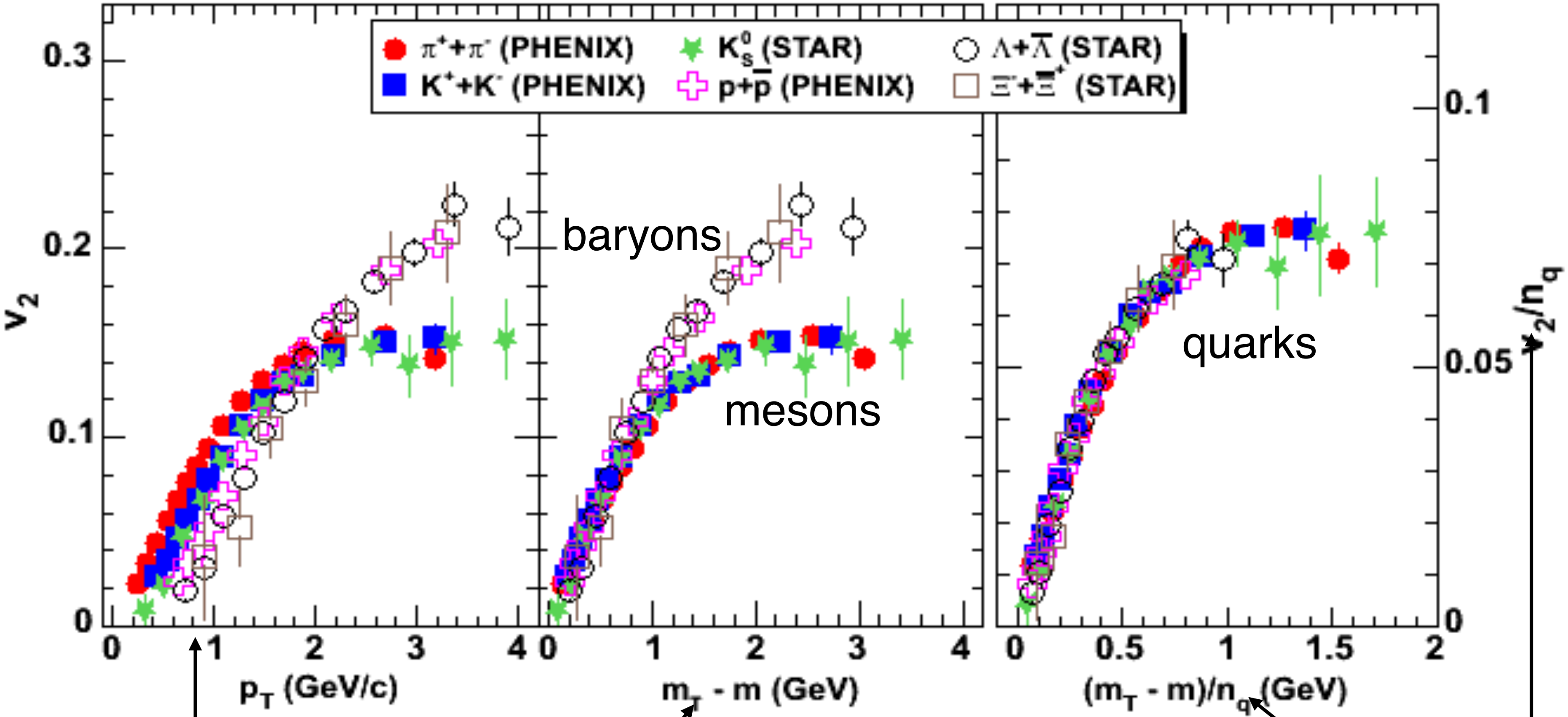
$v_n = \langle \cos n\phi \rangle$

STAR PRL : 2016



Low p_T : Heavier hadrons have lower v_2 (~ hydrodynamic pattern)
High p_T : Collectivity grouped along baryon-meson lines
(~ Hadronization by partonic recombination)
All p_T : Collectivity similar for hadrons with strange and light quark
(~ developed at partonic stage)

Partonic Collectivity



particle mass dependence

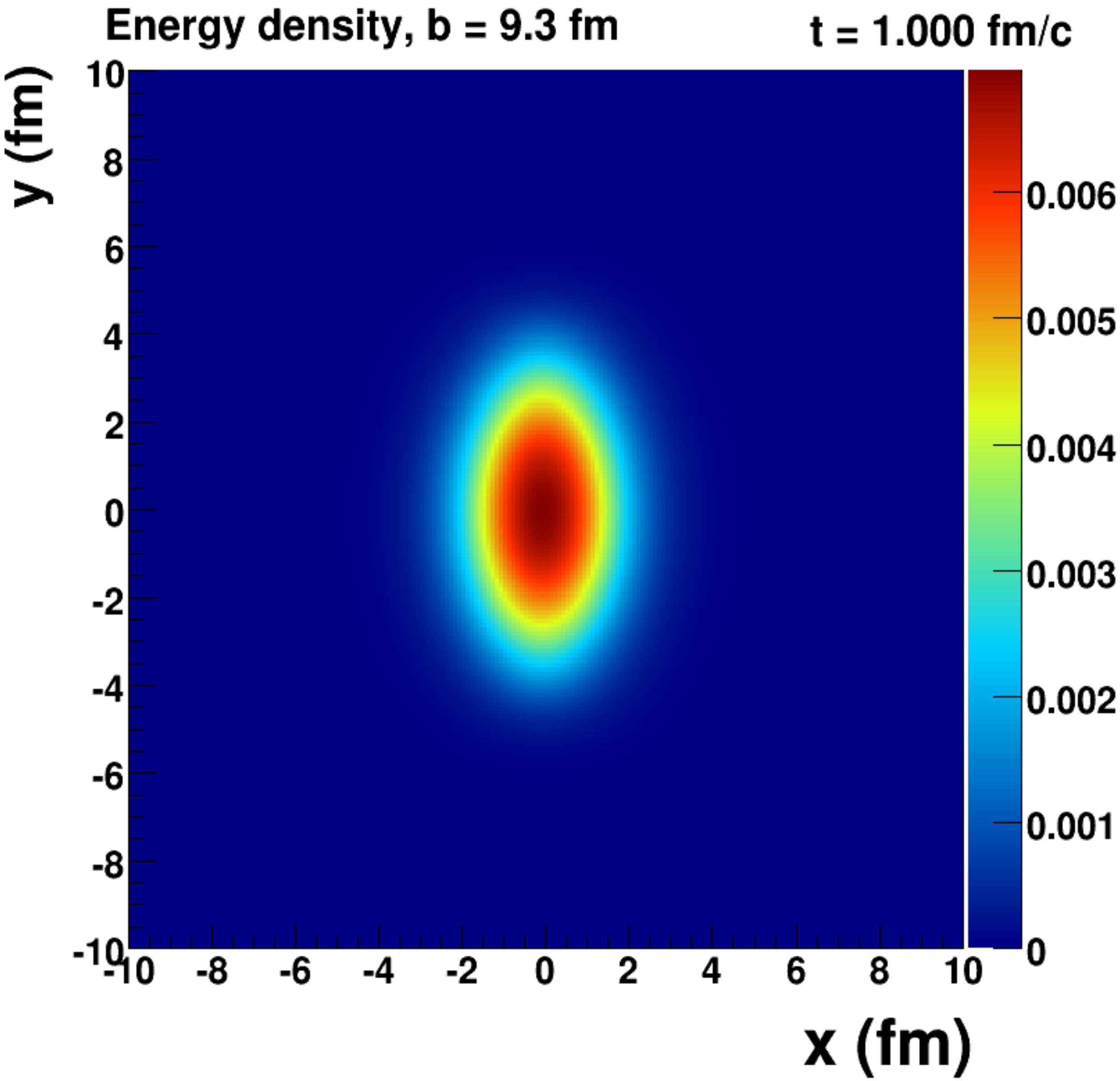
plotted vs. trans. kinetic energy

both axes scaled by number of constituent quarks

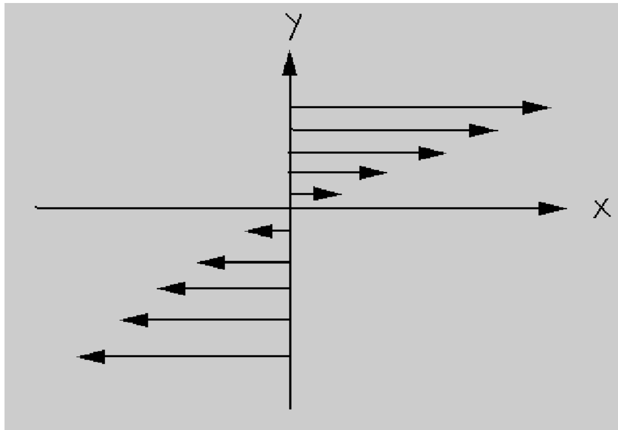
n_q = 2 for mesons
n_q = 3 for baryons

recombination of quarks
quarks have v_2 before hadronization

Properties of QGP



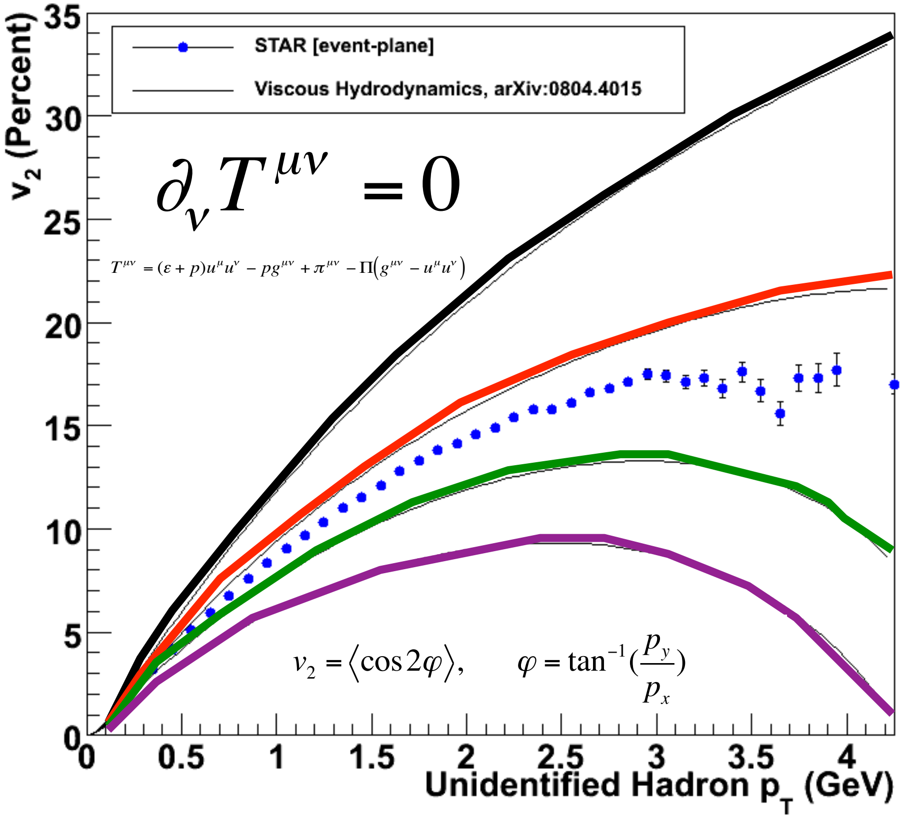
$$\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$$

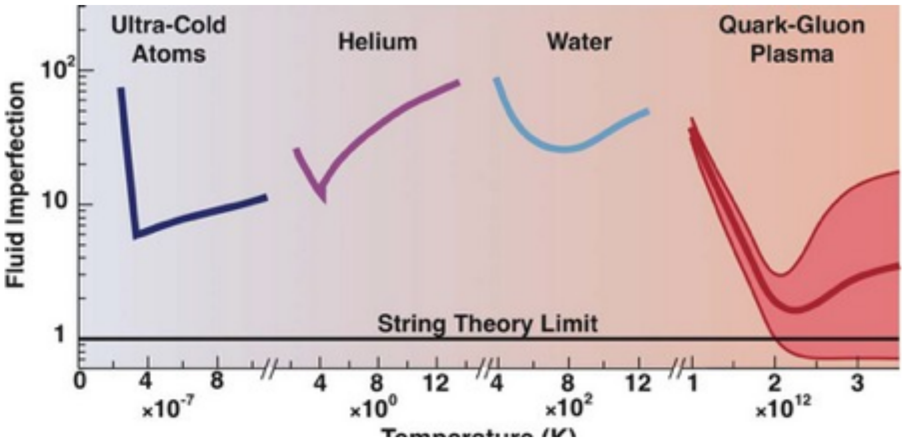


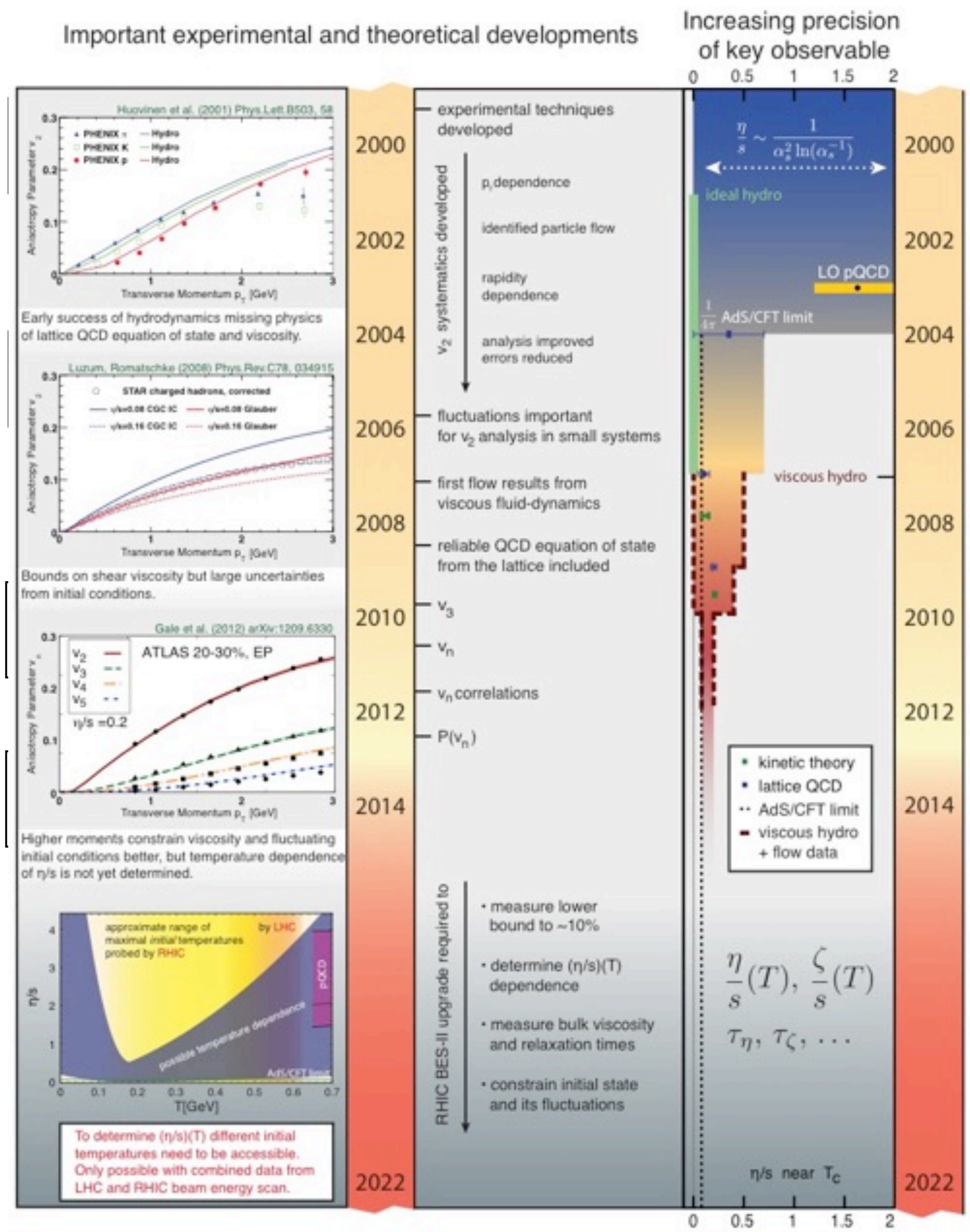
$$v_n = \langle \cos n\phi \rangle$$

Viscosity:
Resistance to Flow

Viscosity

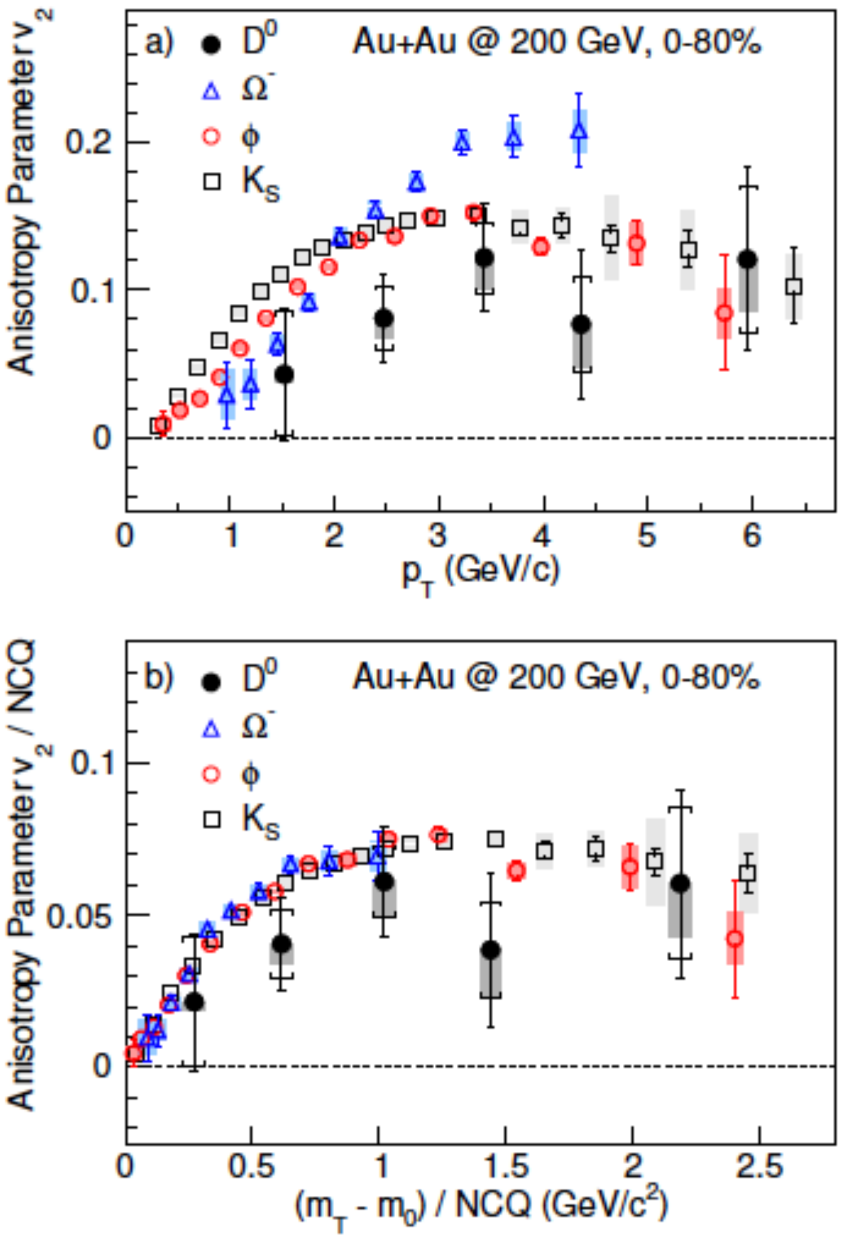






Perfect Fluid

Collectivity : Heavy Quarks



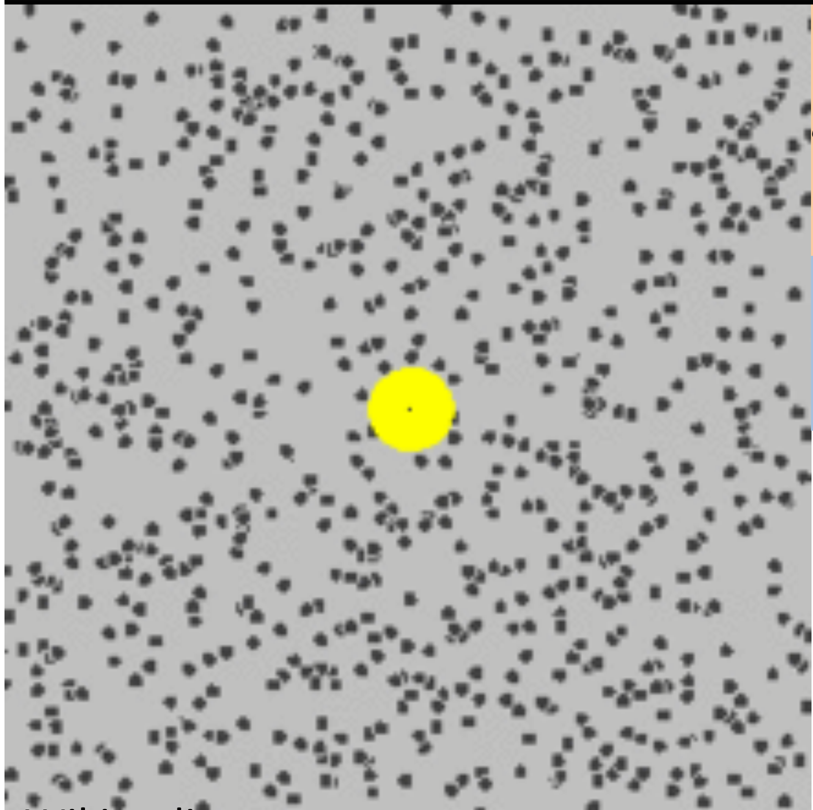
Charm flow is smaller compared to light flavor particles.

Indicates charm quark is not fully thermalized and does not flow completely with the medium

Charm quarks initially produced, their ropagation in QGP medium is analogous to Brownian Motion in molecular physics

STAR PRL : 2016 (to be submitted)

Properties of QGP



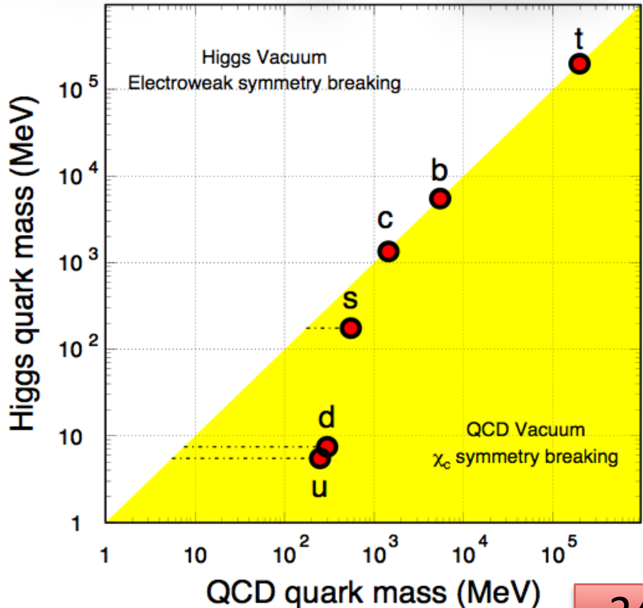
Wikipedia

Brownian motion of a big particle (dust particle) that collides with a large set of smaller particles (molecules of a gas)

Served as definitive confirmation that atoms and molecules actually exist.

Einstein's theory

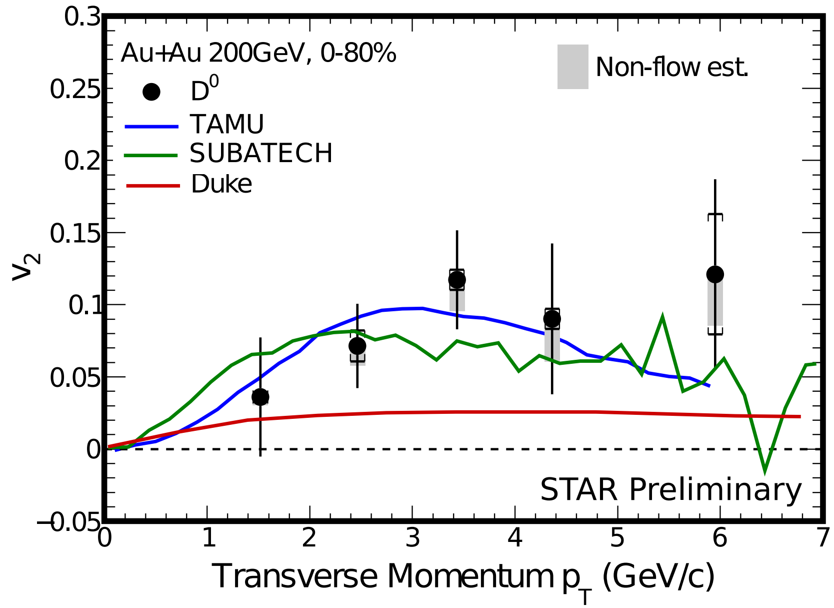
$$\frac{\overline{x^2}}{2t} = D = \mu k_B T = \frac{\mu RT}{N} = \frac{RT}{6\pi\eta r N}.$$

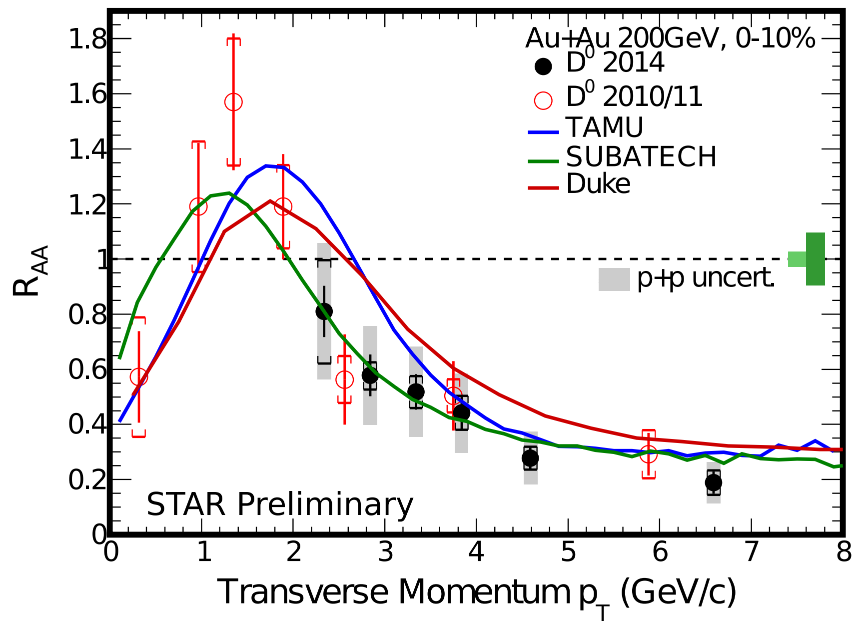


Brownian Motion of Heavy Quarks in a bath of light partons

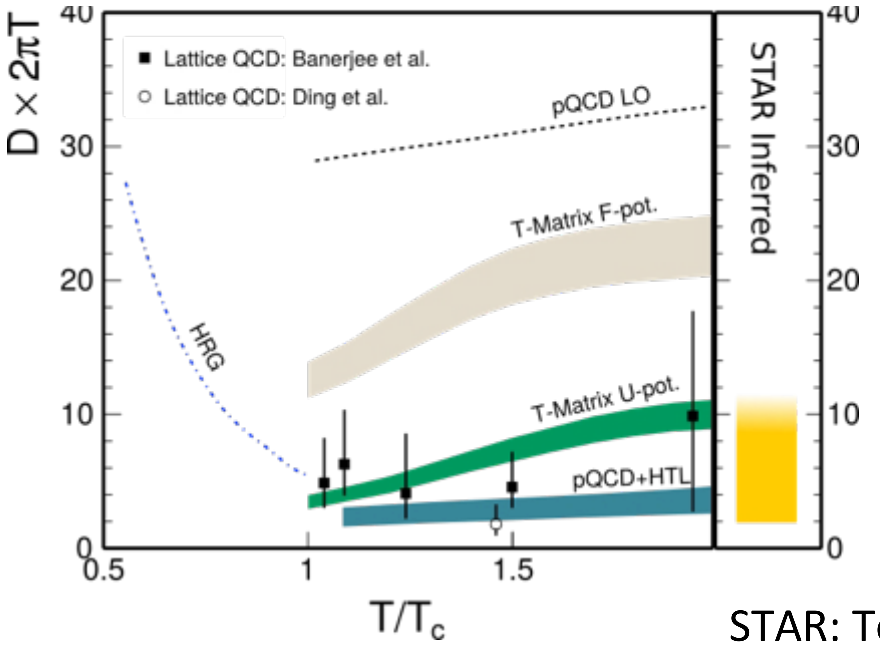
Diffusion: Measure of mobility

Diffusion Co-efficient





STAR: QM2015

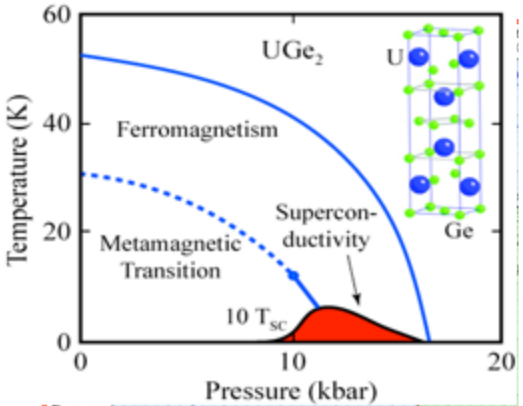


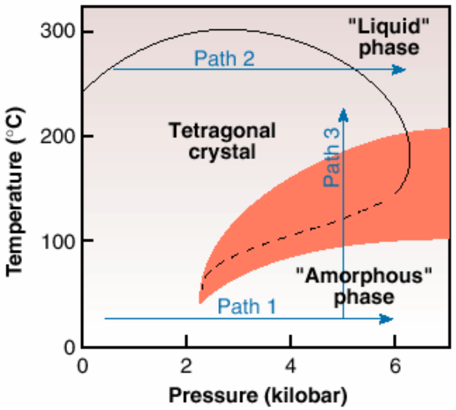
The Diffusion co-efficient times 2π T is observed to be between 1 – 10 and consistent with Lattice QCD calculations

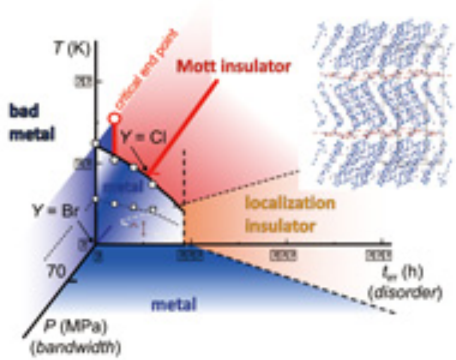
D. Banerjee, S. Datta, R. Gavai, and P. Majumdar, Phys. Rev. D85 , 014510 (2012).

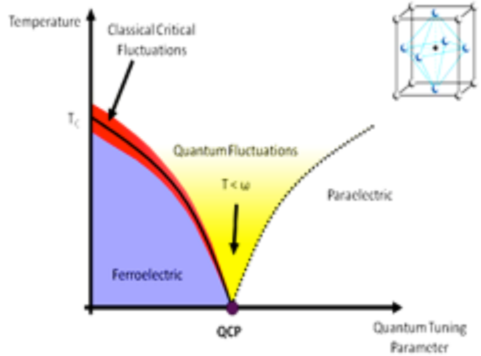
STAR: To be submitted to PRL

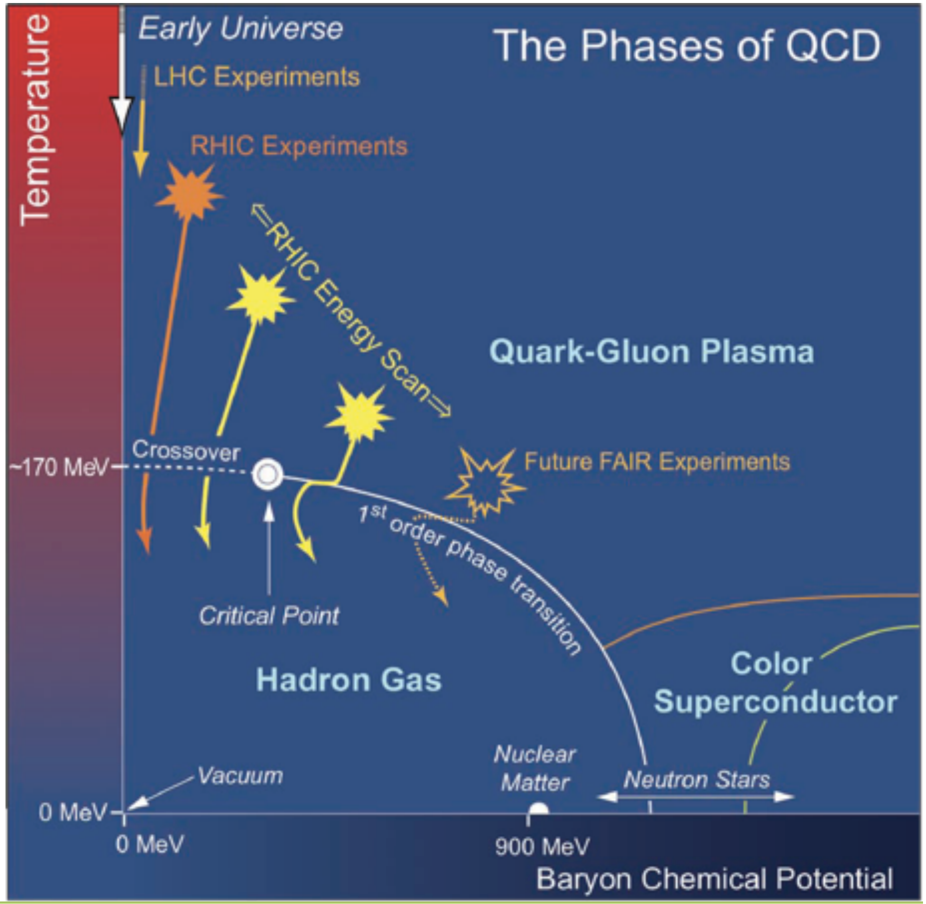
Phase diagram of QCD matter











Phase diagram of Water
Electromagnetic interaction
Precisely known

http://www1.lsbu.ac.uk/water/water_phase_diagram.html

Phase diagram of strong interactions
Largely still a conjecture

NSAC Long range plan

Many

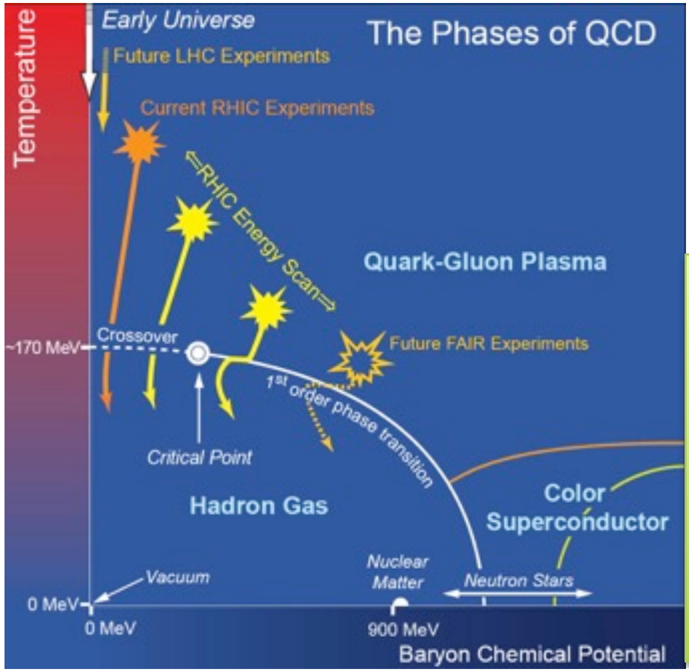
Unique

Experimental access to the Phase diagram of QCD

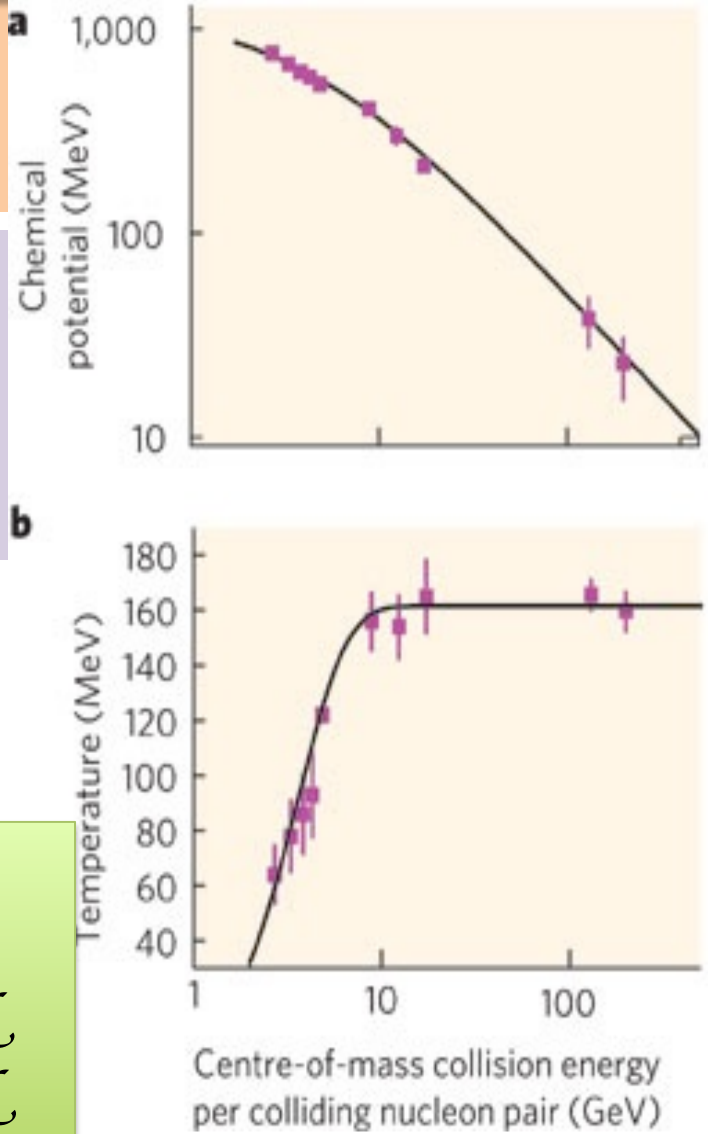
Physical systems undergo phase transitions when external parameters such as the temperature (T) or a chemical potential (μ) are tuned.

Conserved Quantities:

- Baryon Number ~ μ_B
- Electric Charge ~ μ_Q ~ small
- Strangeness ~ μ_S ~ small

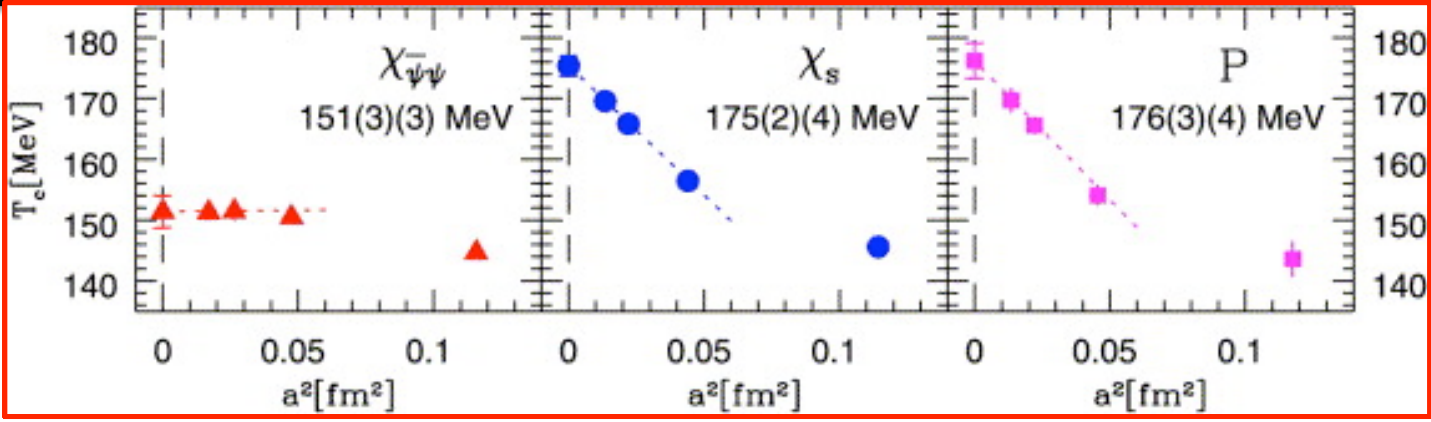


Varying beam energy varies Temperature and Baryon Chemical Potential



P. Braun-Munzinger, J. Stachel
Nature 448:302-309,2007

QCD Phase Structure ~ Transition Temperature

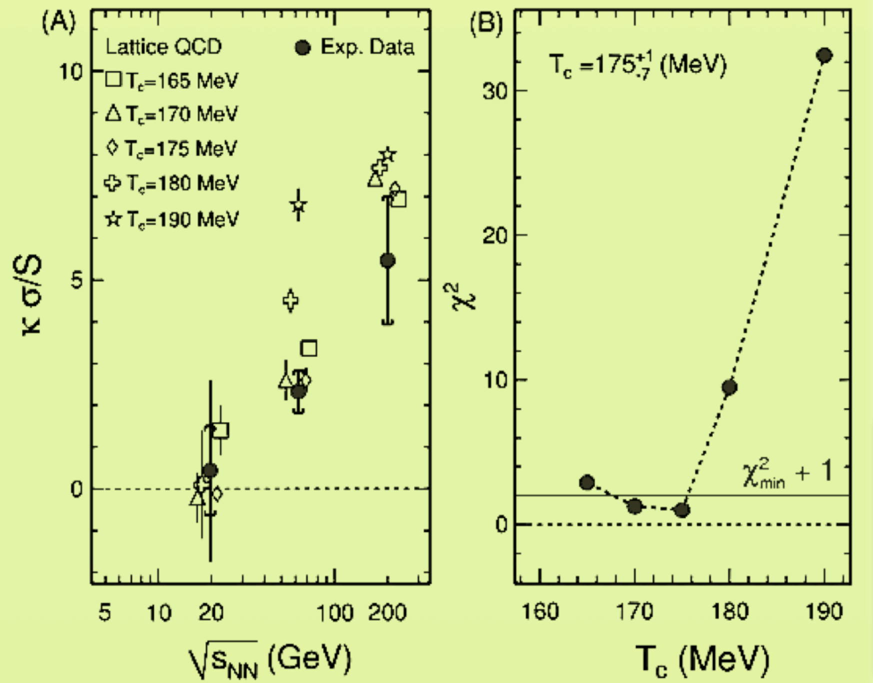


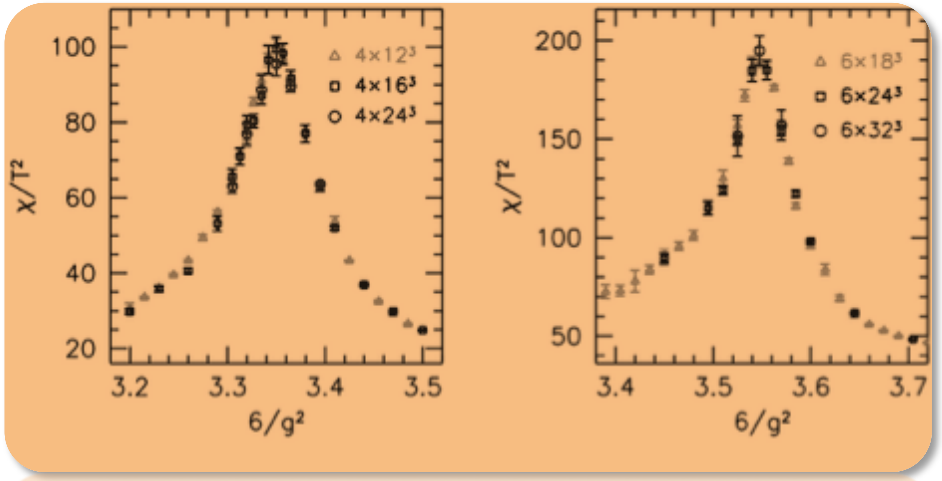
PRD85 (2012) 054503

NPA 830 (2009) 805c

Nature443:675-678,2006

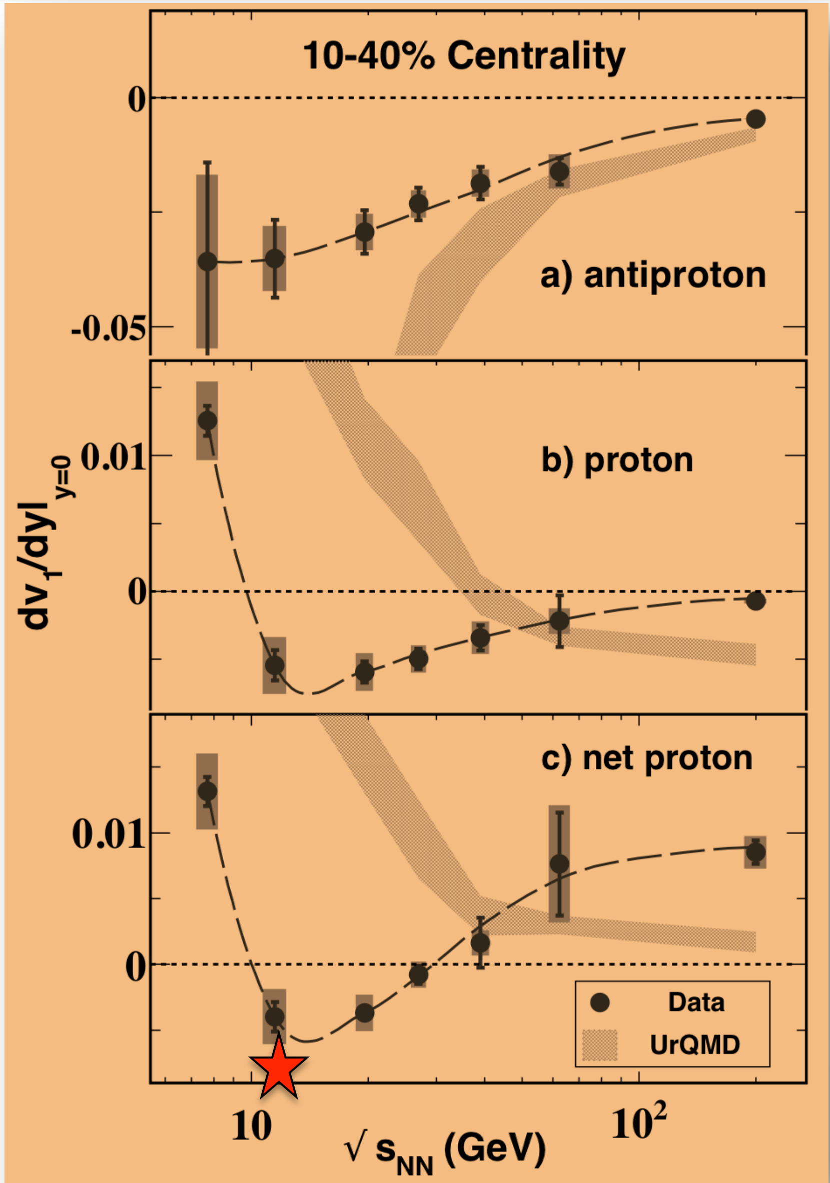
Science 332 (2011) 1525-1528

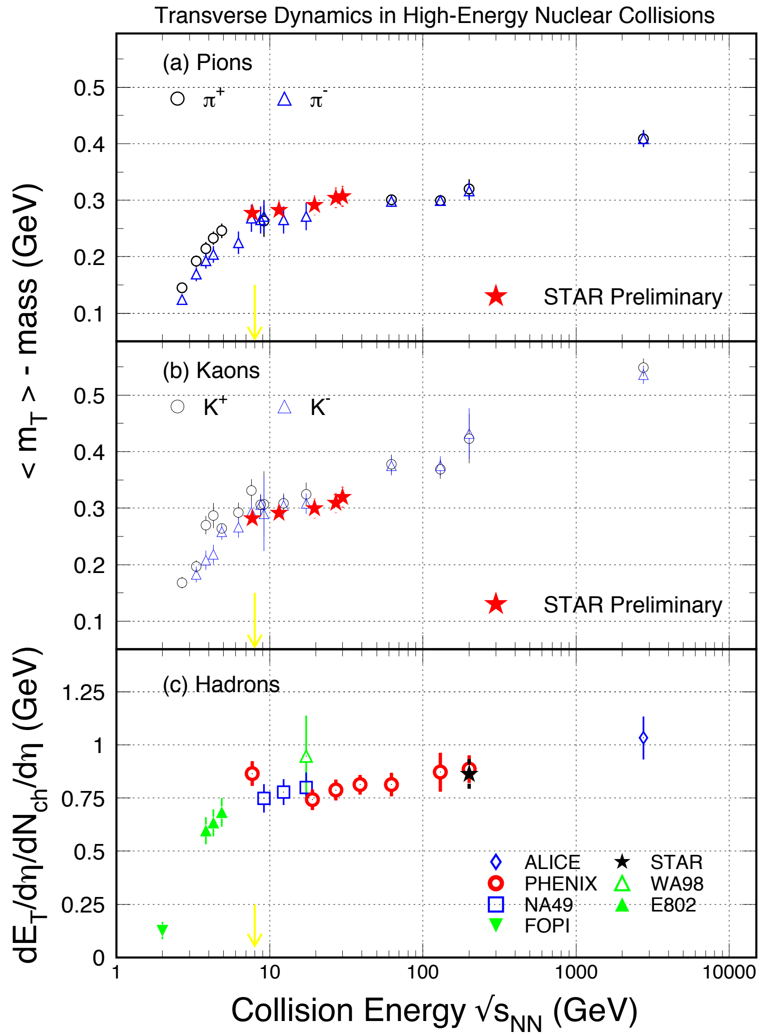




Transition temperature and Cross Over established at zero baryon chemical potential

Experimental Result: 1st Order PT

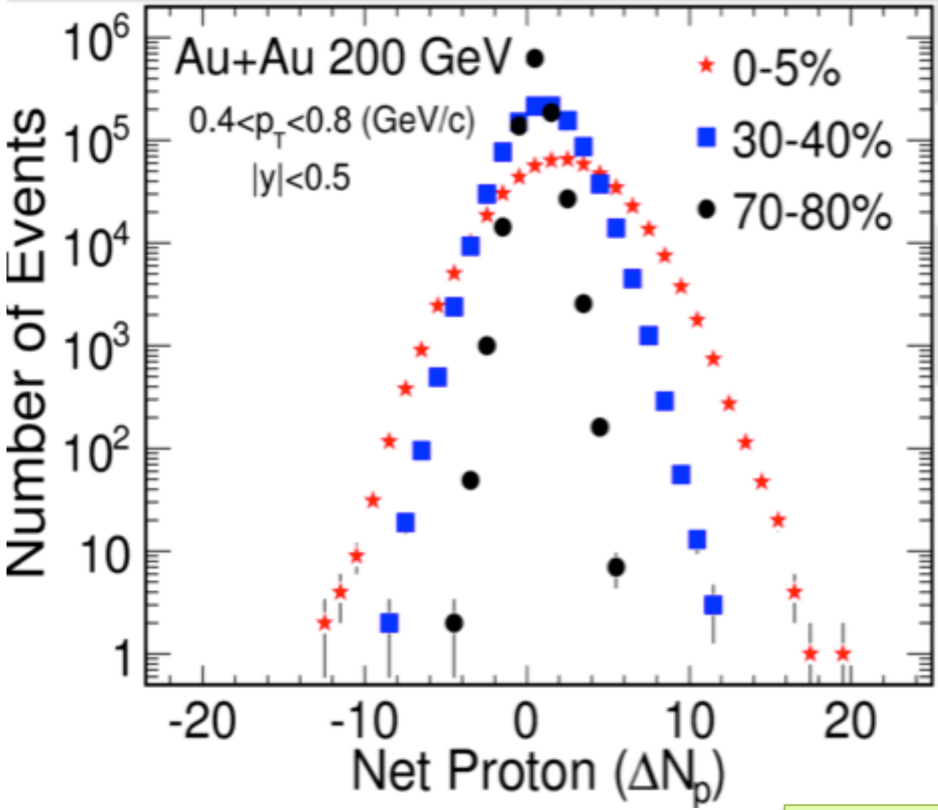




STAR: Physical Review Letters 2014

Observations consistent with 1st order Phase transition expectations

Experiment and Theory Link



Shape of distribution ~ correlations

Moments relates to Correlation length (ξ):
Study phase transition and Critical Point

$< (\delta N)^2 > \sim \xi^2$

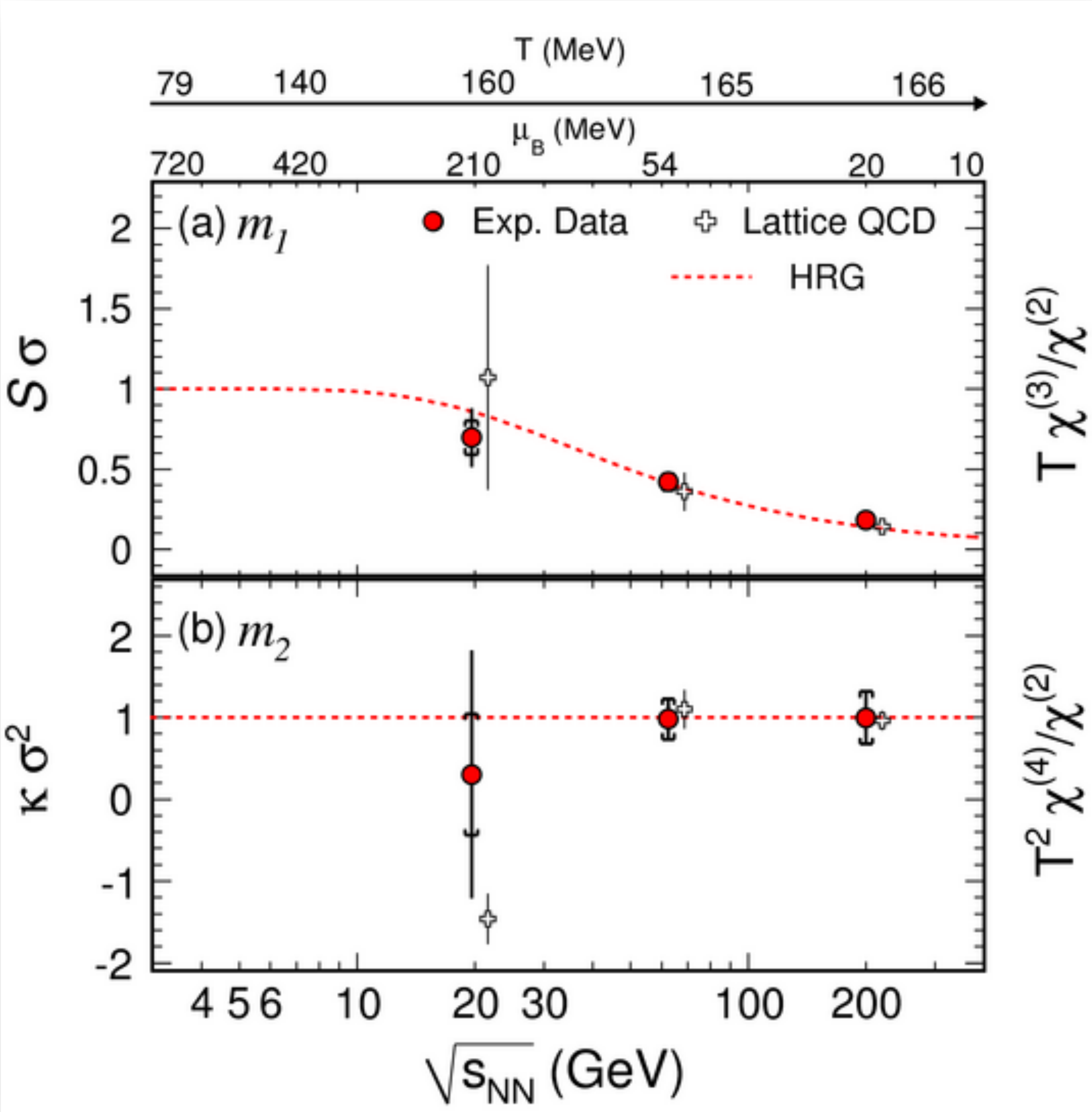
$< (\delta N)^3 > \sim \xi^{4.5}$

$< (\delta N)^4 > - 3 < (\delta N)^2 >^2 \sim \xi^7$

STAR: Physical Review Letters 2010& 2014
M. Stephanov: Physical Review Letters 2009;2011
S. Gupta and R. Gavai : Physics Letters B 2011
M. Cheng .. F. Karsch ..: Physical Review D 2009

Moments relates to Susceptibility (χ) :
Study Bulk properties of QCD matter
Kurtosis x Variance $\sim \chi^{(4)} / [\chi^{(2)} T^2]$
Skewness x Sigma $\sim [\chi^{(3)} T] / [\chi^{(2)} T^2]$

Data and QCD (Non-Zero T) 1st Comparison



1st comparison of high energy nuclear collision data to 1st principle QCD calculations

Confirms formation of QGP

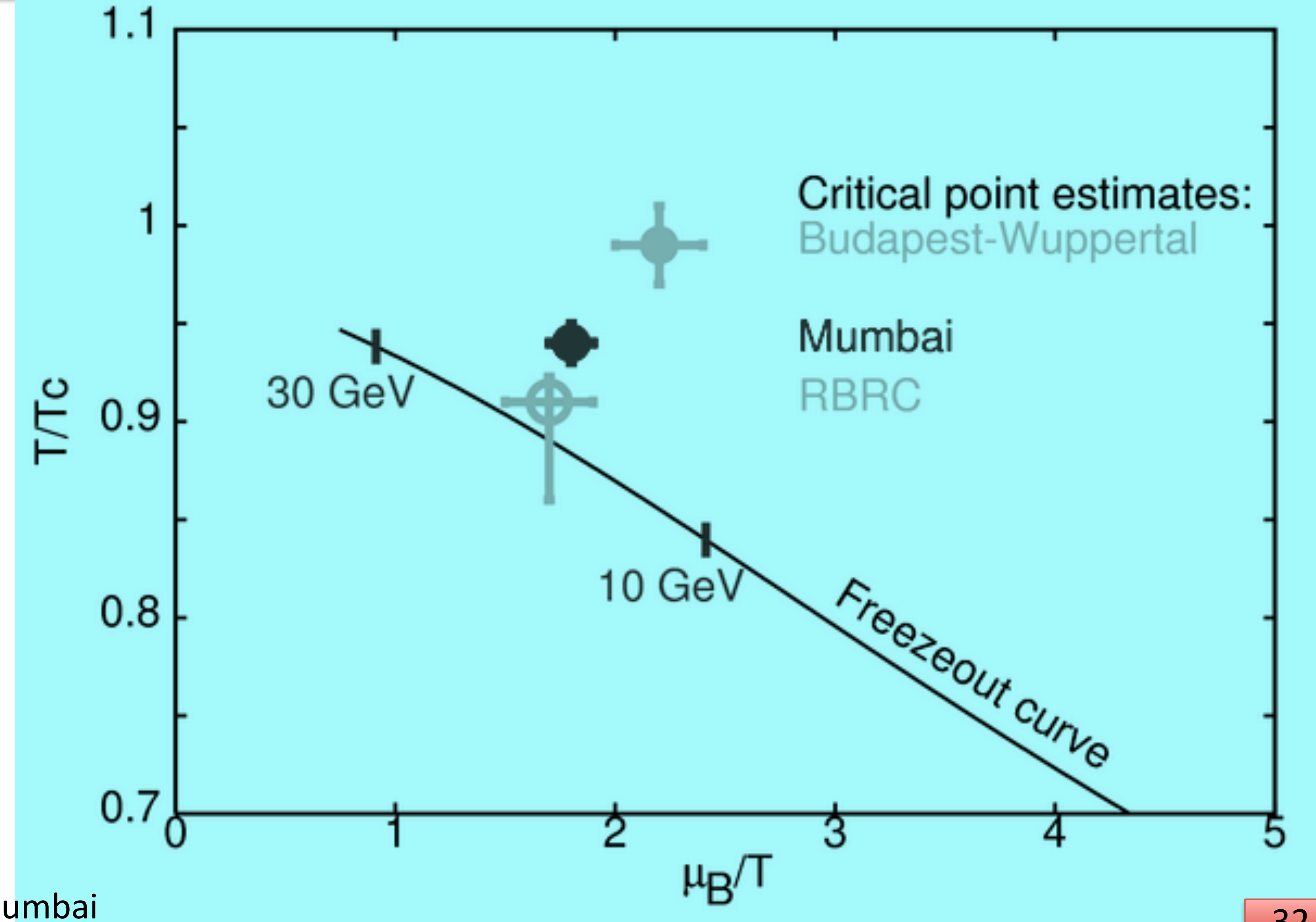
Quark-Hadron transition is a cross over

Science
AAAS

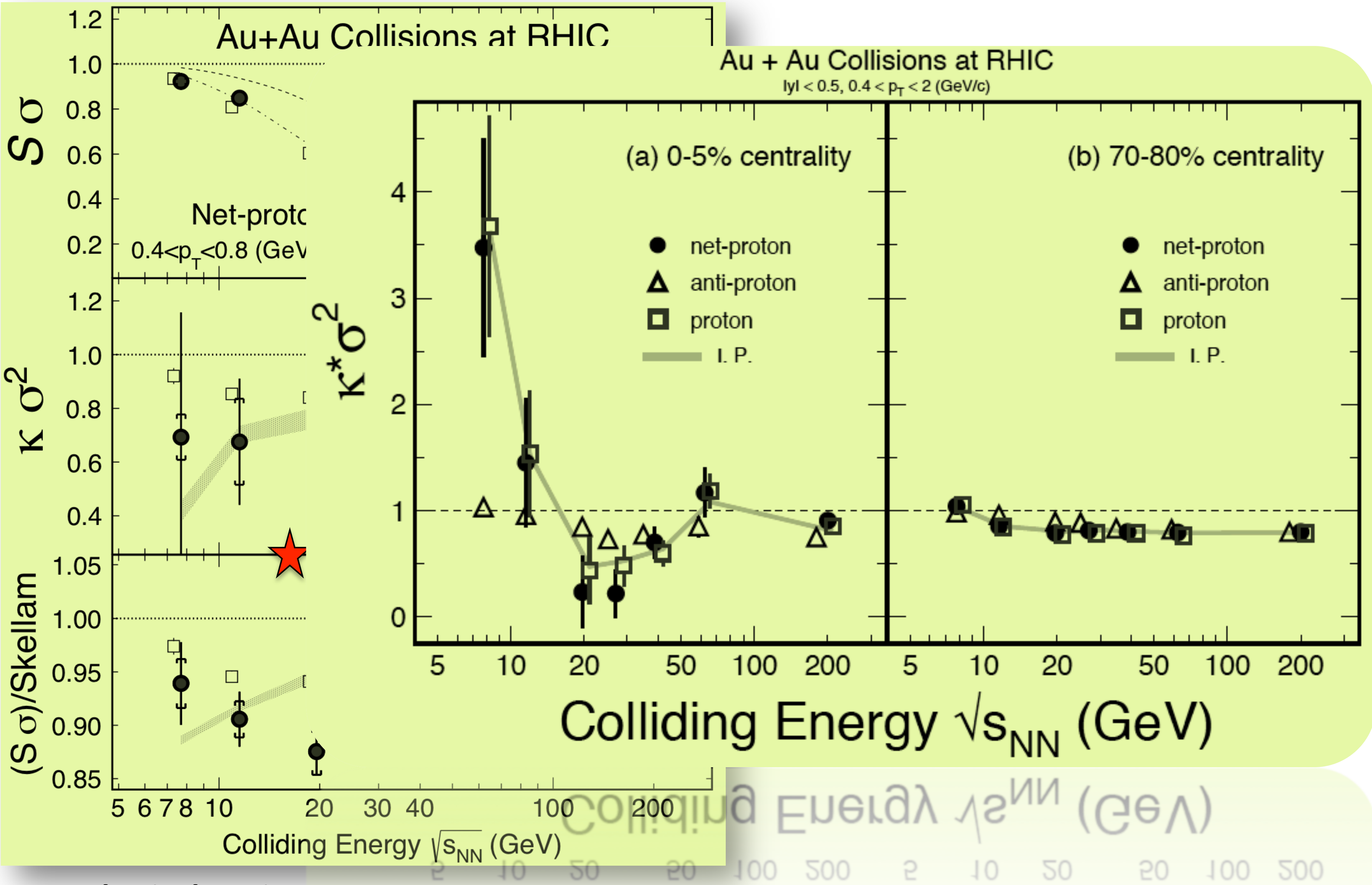
"Scale for the Phase Diagram of Quantum Chromodynamics"

Science, 332, 1525(2011)

Critical Point and First Order Phase Transition



Experimental Result: Critical Point



STAR: Physical Review Letters 2014

Summary

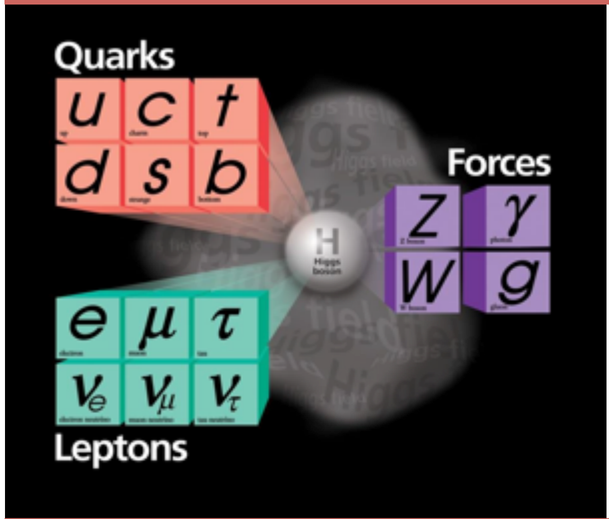
QCD phase transition and primordial matter created in Laboratory. System of de-confined quarks and gluons formed.

The system of fundamental constituent of any visible matter exhibits the property of perfect fluidity with high degree of opacity. The heavy quarks exhibit Brownian motion in a thermal bath of light partons.

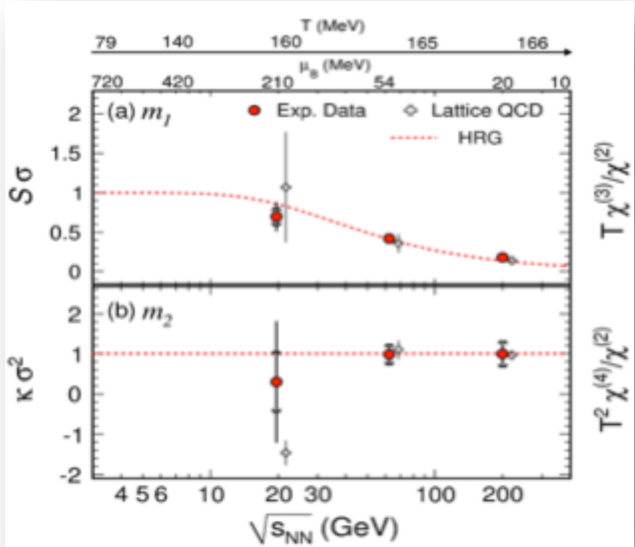
Phase Diagram of Strong Interactions being laid out. Transition temperature and order of phase transition established at zero baryon chemical point. Exciting experimental results on critical point and phase boundary. Susceptibility has a non-monotonic variation with beam energy.

QCD in 21st Century

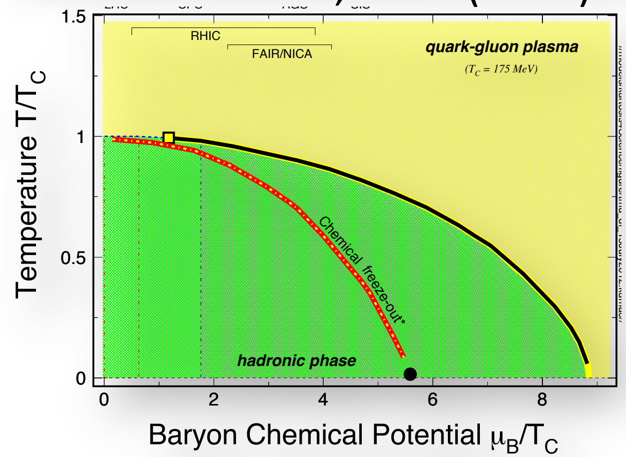
Standard Model & Origin of Mass



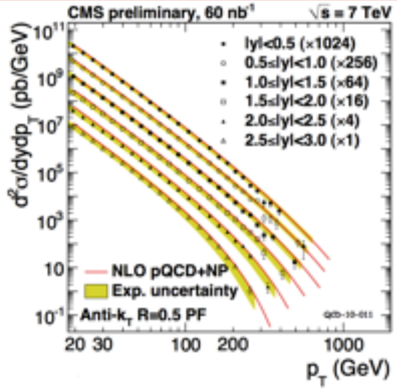
Test of QCD
Non-perturbative T>0
&
Phase structure of QCD
Phase diagram



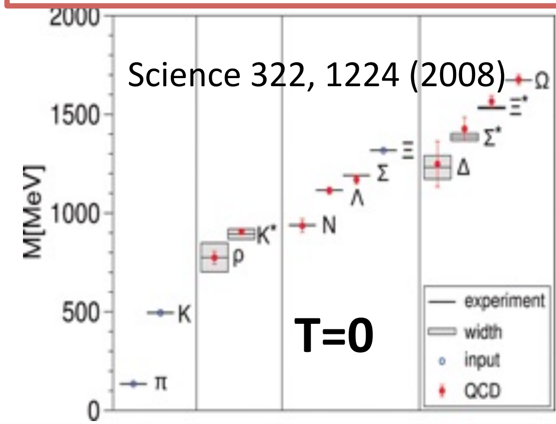
Science 332, 1525 (2011)



Test of QCD, Short distance scales, perturbative regime



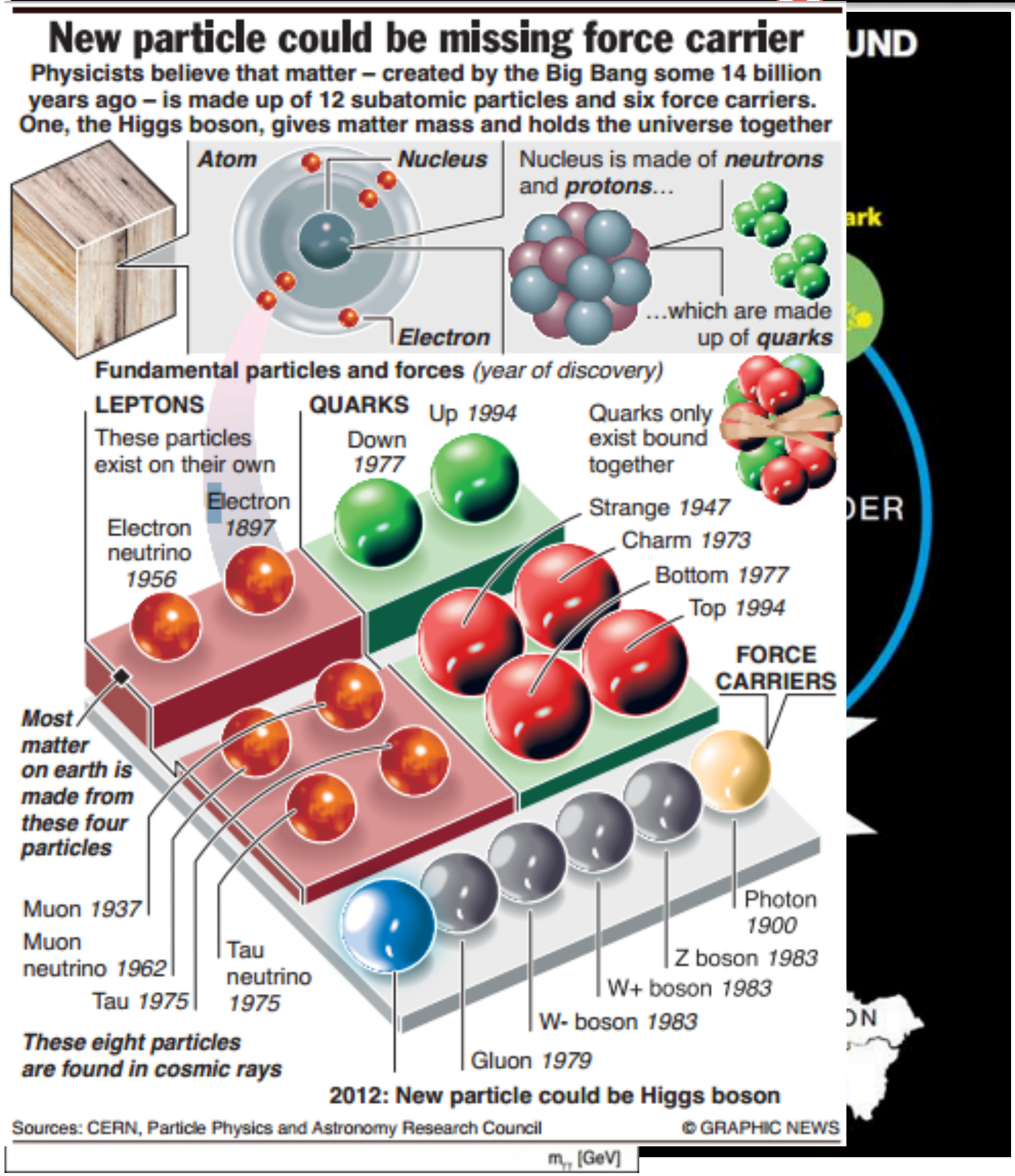
Test of QCD, Long distance scales, Non-perturbative regime

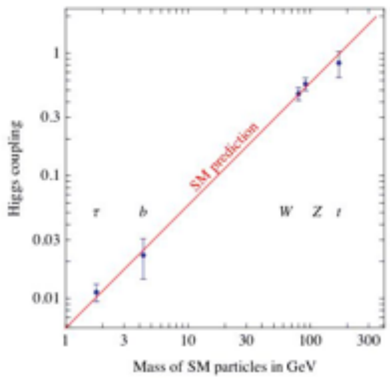


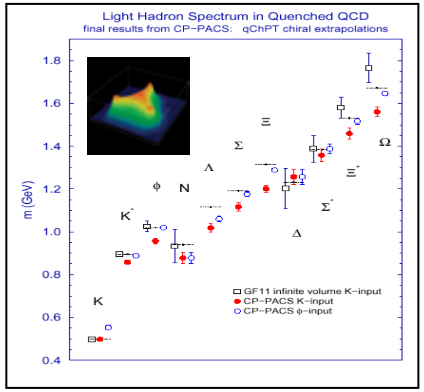
Towards a complete test of QCD as a theory

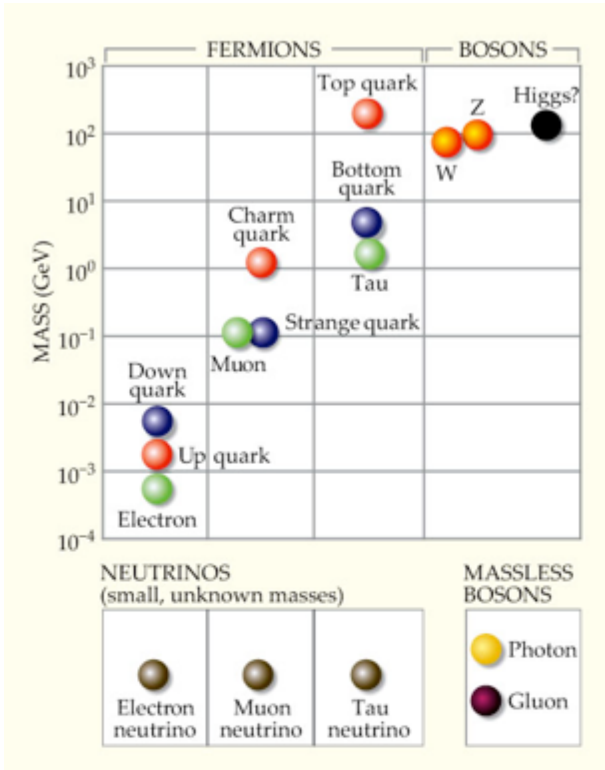
Back Up

Origin of Mass



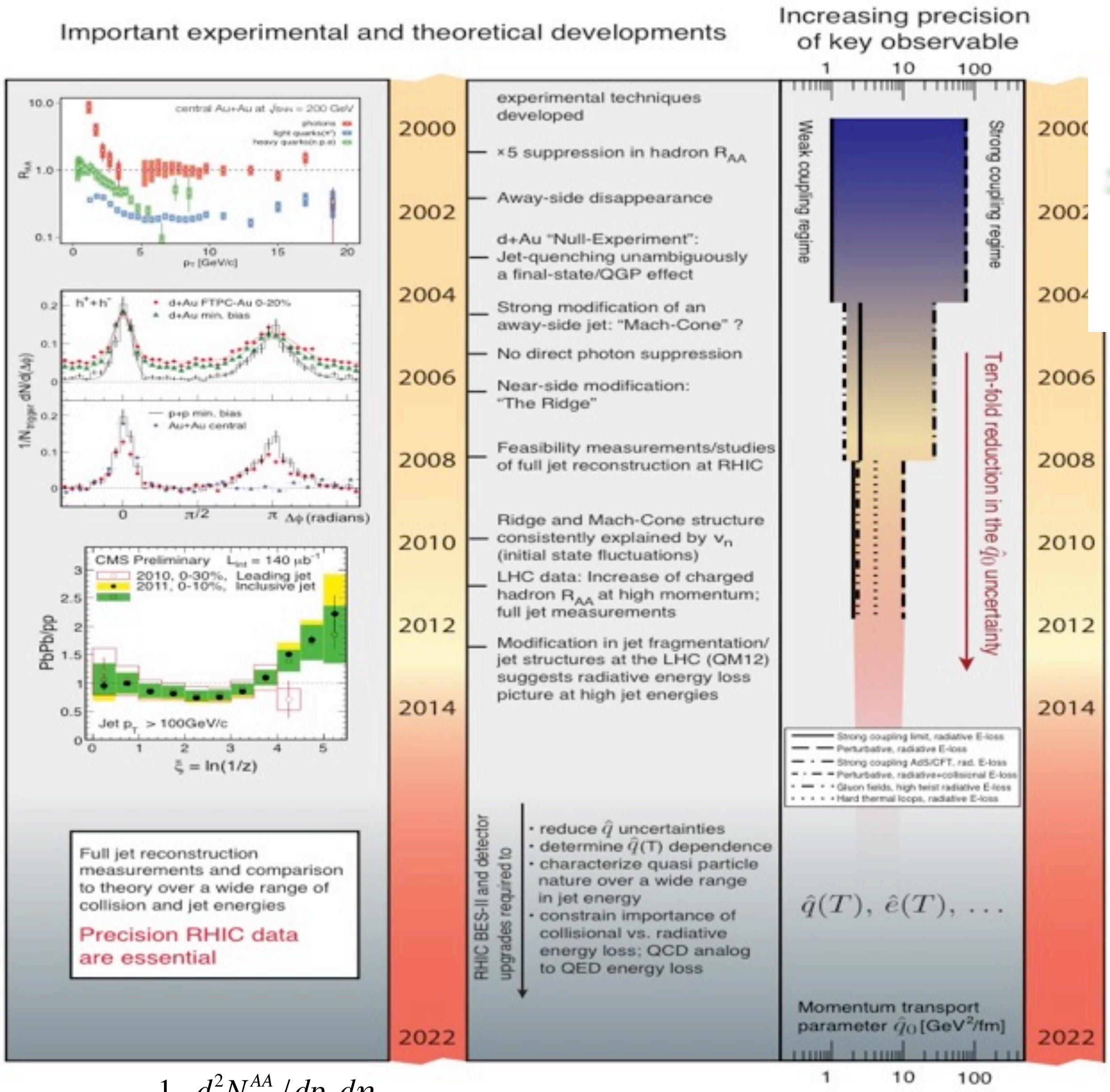


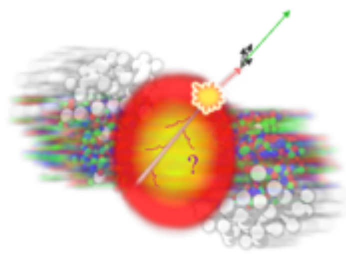


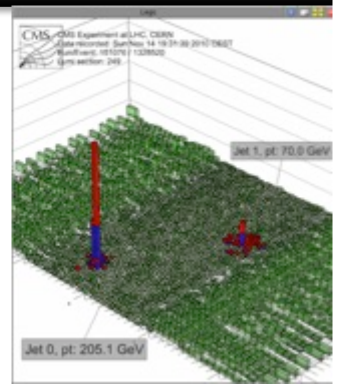


Large Hadron Collider contribution to science.

Opacity







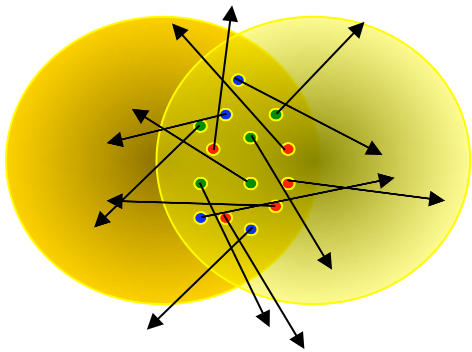
$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{d^2N^{AA}/dp_T d\eta}{d^2\sigma^{NN}/dp_T d\eta}$$

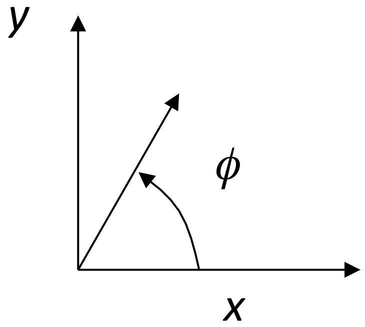
Jets Quenched

The shear viscosity to entropy density ratio is found to lie between (1-2)/4π and that reflecting the stopping power was observed to be between 2-10 GeV²/fm.

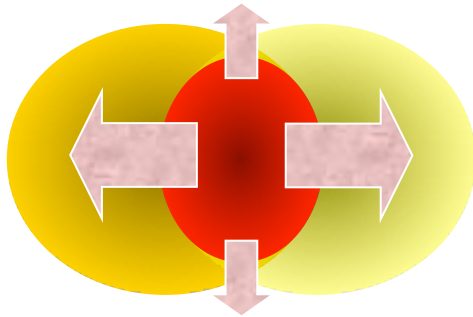
Collectivity

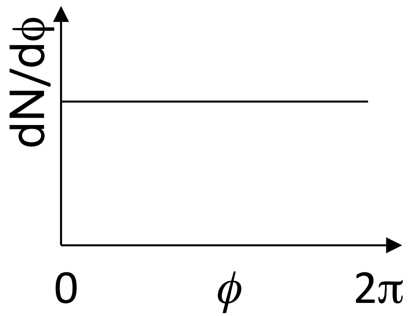
Initial spatial anisotropy

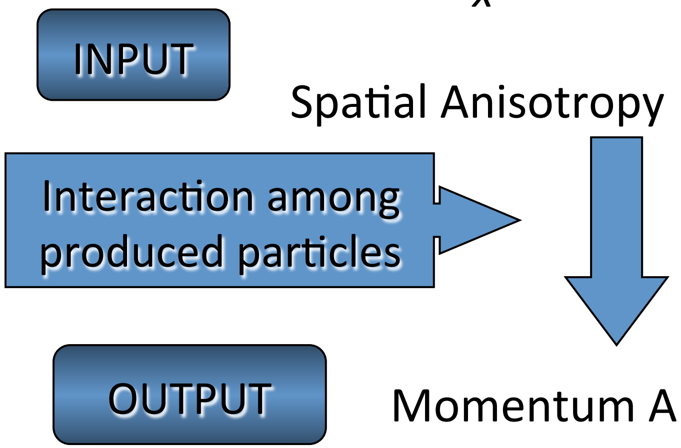




Pressure gradient

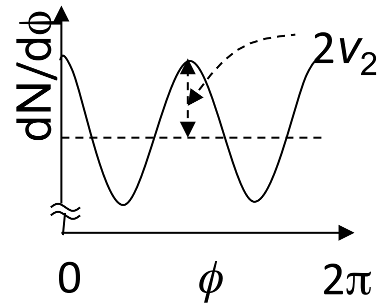






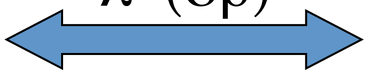
Spatial Anisotropy

Momentum Anisotropy



$$\varepsilon_x = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

$\lambda = (\sigma\rho)^{-1}$



$c_s^2 = dP/d\varepsilon$

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

Free streaming

$v_2 = 0$