Lecture #1 Start

Heavy Ion Experiment

What is it all about…

Artwork by Sarah Szabo

National Nuclear Physics Summer School 2016

Jamie Nagle
University of Colorado

Lecture Philosophy

- Less is more.. (i.e. not comprehensive by any means)
- Keep It Simple Stupid (KISS) principle…
- Even the experts often miss the big questions…
- Take away goals…

  - an appreciation for the science
  - excitement of the field
  - some details on experimental methods
  - open questions and opportunities for discovery by young people such as yourselves

Let me know if there are specific things you want to hear

Simplest Goals

Emergent Phenomena…

Collectivity…

What is the underlying origin?

For this flock of birds, it is all short range interactions (amazing!)

Emergent Phenomena

Connection from the QCD Lagrangian to phenomena of confinement and asymptotic freedom was fundamental

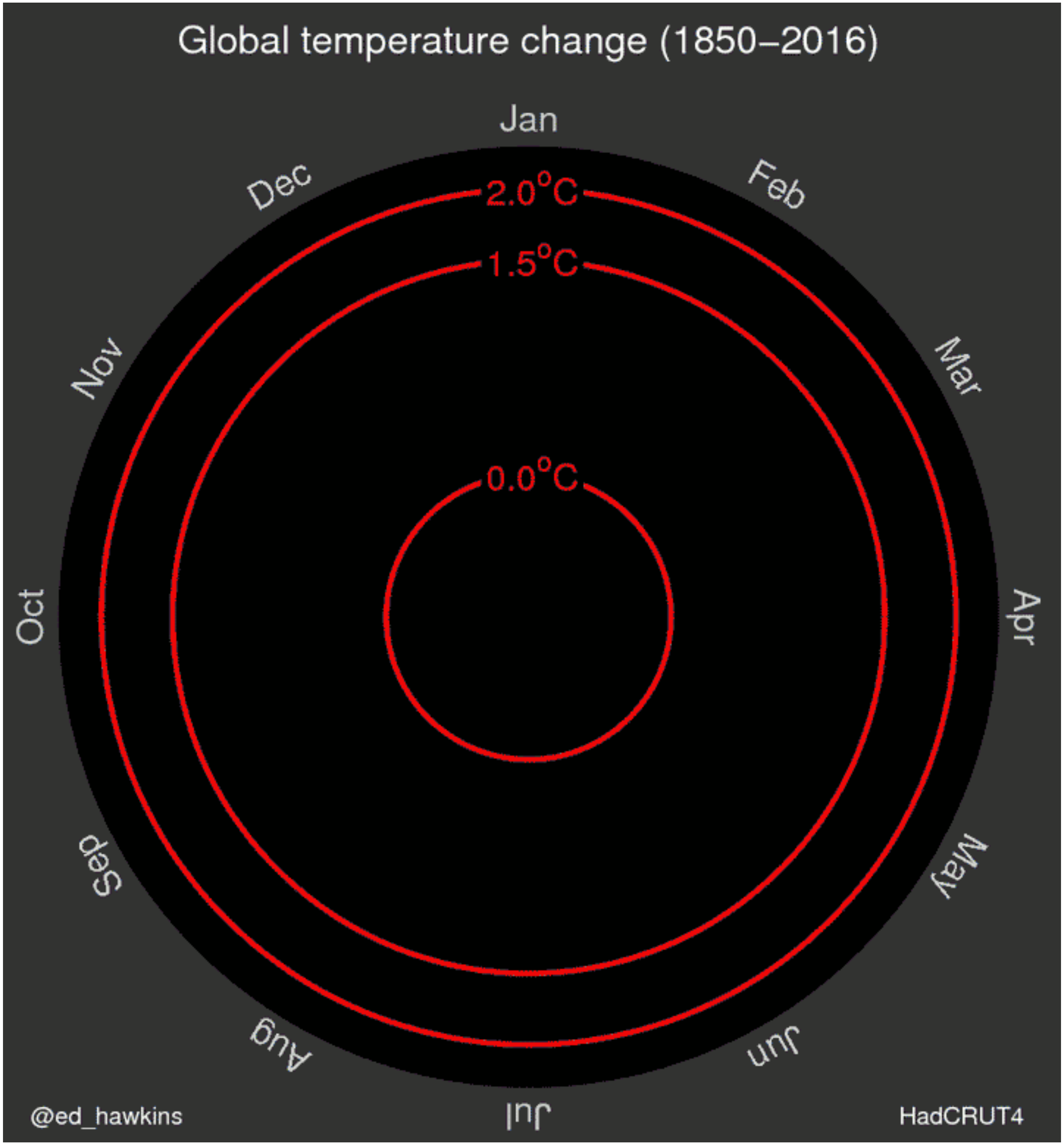
Connection from QCD to the emergent phenomena of near perfect fluidity of the Quark-Gluon Plasma is just as fundamental

Perfect fluidity tells us the nature of the QGP, more importantly we need to reconcile:

Most important discovery in field: perfect fluid

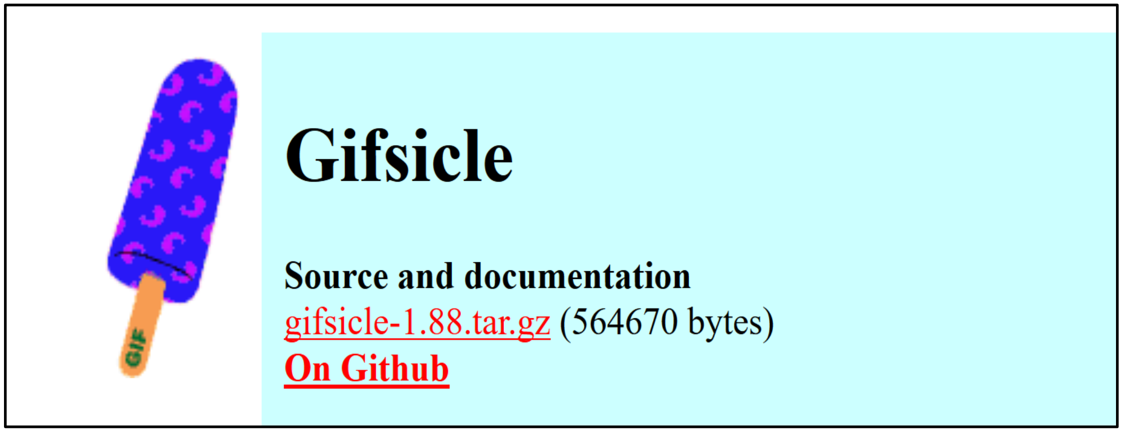
&

Crucial part of QCD: weak coupling at short distances


Global temperature change (1850–2016)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2.0°C
1.5°C
0.0°C
@ed_hawkins
HadCRUT4

Easy Tools

https://www.lcdf.org/gifsicle/



Wild animations are distracting, but key visualizations stick with people.
Make your own!

Create your own ideas and borrow only selectively. The more important the talk, the more important it is to show your thoughts…

http://arohatgi.info/WebPlotDigitizer/app/

Data thief programs allow you to choose which data sets to show, re-fit your model, etc.

Side note to students…

1) Data visualization is very important

2) Leads to breakthroughs via more intuitive and physical picture

3) Most talks only get across 2-3 items that a given audience member will recall later

A Brief History of Time (in Heavy Ions)

A long time ago in a galaxy far,
far away....

History can be boring,
though often early in a new field that is when
the most basic questions are discussed openly.
Later people often focus
too much on the latest details.

Annual Review Articles of Relevance Here…

Hard-Scattering Results in Heavy-Ion Collisions at the LHC
Annual Review of Nuclear and Particle Science
Vol. 64: 383-411 (Volume publication date October 2014)
First published online as a Review in Advance on August 1, 2014
DOI: 10.1146/annurev-nucl-102912-144532
Edwin Norbeck,[1,*] Karel Šafařík,[2] and Peter A. Steinberg[3]

Collective Flow and Viscosity in Relativistic Heavy-Ion Collisions
Annual Review of Nuclear and Particle Science
Vol. 63: 123-151 (Volume publication date October 2013)
First published online as a Review in Advance on June 13, 2013
DOI: 10.1146/annurev-nucl-102212-170540
Ulrich Heinz[1] and Raimond Snellings[2]

Lattice QCD Thermodynamics with Physical Quark Masses
Annual Review of Nuclear and Particle Science
Vol. 65: 379-402 (Volume publication date October 2015)
First published online as a Review in Advance on July 30, 2015
DOI: 10.1146/annurev-nucl-102014-022157
R.A. Soltz,[1] C. DeTar,[2] F. Karsch,[3,4] Swagato Mukherjee,[3] and P. Vranas[1]

Topology, Magnetic Field, and Strongly Interacting Matter
Annual Review of Nuclear and Particle Science
Vol. 65: 193-214 (Volume publication date October 2015)
First published online as a Review in Advance on June 5, 2015
DOI: 10.1146/annurev-nucl-102313-025420
Dmitri E. Kharzeev[1,2]

First Results from Pb+Pb Collisions at the LHC
Annual Review of Nuclear and Particle Science
Vol. 62: 361-386 (Volume publication date November 2012)
First published online as a Review in Advance on July 20, 2012
DOI: 10.1146/annurev-nucl-102711-094910
Berndt Müller,[1] Jürgen Schukraft,[2] and Bolesław Wysłouch[3]

The Color Glass Condensate
Annual Review of Nuclear and Particle Science
Vol. 60: 463-489 (Volume publication date November 2010)
DOI: 10.1146/annurev.nucl.010909.083629
Francois Gelis,[1] Edmond Iancu,[1] Jamal Jalilian-Marian,[2] and Raju Venugopalan[3]

From Gauge-String Duality to Strong Interactions:A Pedestrian's Guide
Annual Review of Nuclear and Particle Science
Vol. 59: 145-168 (Volume publication date November 2009)
First published online as a Review in Advance on June 3, 2009
DOI: 10.1146/annurev.nucl.010909.083602
Steven S. Gubser[1] and Andreas Karch[2]

Coalescence Models for Hadron Formation from Quark-Gluon Plasma
Annual Review of Nuclear and Particle Science
Vol. 58: 177-205 (Volume publication date November 2008)
DOI: 10.1146/annurev.nucl.58.110707.171134
Rainer Fries,[1,2] Vincenzo Greco,[3,4] and Paul Sorensen[5]

What Do Electromagnetic Plasmas Tell Us about the Quark-Gluon Plasma?
Annual Review of Nuclear and Particle Science
Vol. 57: 61-94 (Volume publication date November 2007)
First published online as a Review in Advance on April 4, 2007
DOI: 10.1146/annurev.nucl.57.090506.123124
Stanisław Mrówczyński[1] and Markus H. Thoma[2]

Viscosity, Black Holes, and Quantum Field Theory
Annual Review of Nuclear and Particle Science
Vol. 57: 95-118 (Volume publication date November 2007)
First published online as a Review in Advance on April 20, 2007
DOI: 10.1146/annurev.nucl.57.090506.123120
Dam T. Son[1] and Andrei O. Starinets[2]

Glauber Modeling in High-Energy Nuclear Collisions
Annual Review of Nuclear and Particle Science
Vol. 57: 205-243 (Volume publication date November 2007)
First published online as a Review in Advance on May 9, 2007
DOI: 10.1146/annurev.nucl.57.090506.123020
Michael L. Miller,[1] Klaus Reygers,[2] Stephen J Sanders,[3] and Peter Steinberg[4]

Results from the Relativistic Heavy Ion Collider
Annual Review of Nuclear and Particle Science
Vol. 56: 93-135 (Volume publication date November 2006)
First published online as a Review in Advance on May 17, 2006
DOI: 10.1146/annurev.nucl.56.080805.140556
Berndt Müller
Department of Physics, Duke University, Durham, North Carolina 27708; email: muller@phy.duke.edu
James L. Nagle

Phase Transitions in the Early and Present Universe
Annual Review of Nuclear and Particle Science
Vol. 56: 441-500 (Volume publication date November 2006)
First published online as a Review in Advance on August 2, 2006
DOI: 10.1146/annurev.nucl.56.080805.140539
D. Boyanovsky,[1,2,3] H.J. de Vega,[3,2,1] and D.J. Schwarz[4]

DIRECT PHOTON PRODUCTION IN RELATIVISTIC HEAVY-ION COLLISIONS
Annual Review of Nuclear and Particle Science
Vol. 55: 517-554 (Volume publication date December 2005)
DOI: 10.1146/annurev.nucl.53.041002.110533
Paul Stankus

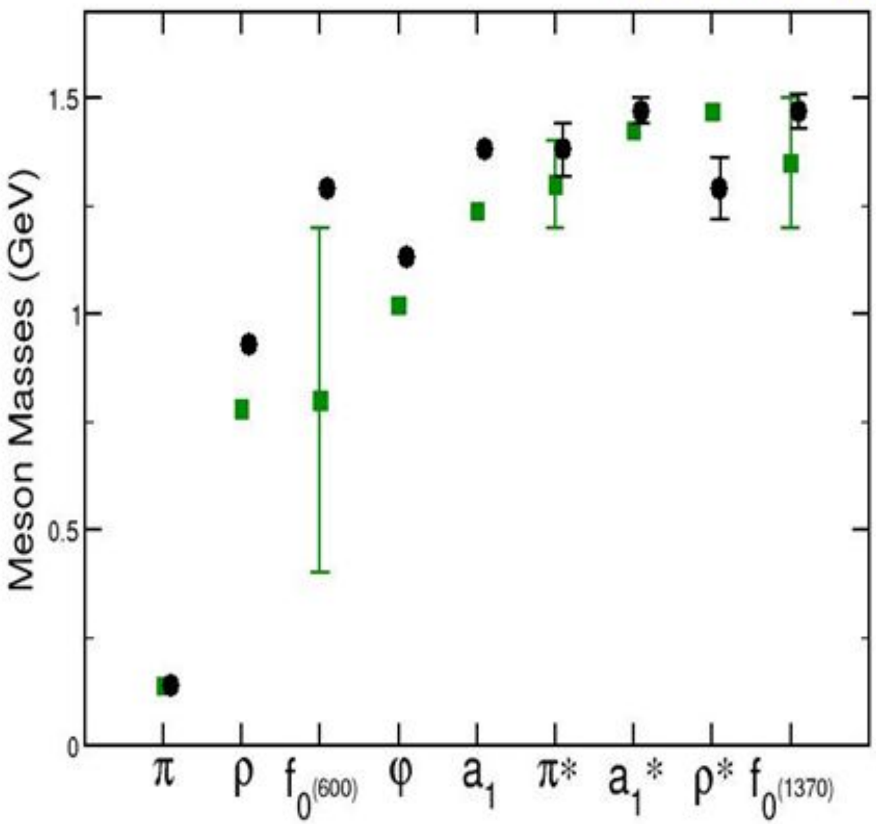
Hydrodynamic Models for Heavy Ion Collisions
Annual Review of Nuclear and Particle Science
Vol. 56: 163-206 (Volume publication date November 2006)
First published online as a Review in Advance on June 5, 2006
DOI: 10.1146/annurev.nucl.54.070103.181236
P. Huovinen
Department of Physics, University of Virginia, Charlottesville, Virginia 22904 and Helsinki Institute of Physics, University of Helsinki, FIN-00014, Finland; email: ph4h@virginia.edu
P.V. Ruuskanen

FEMTOSCOPY IN RELATIVISTIC HEAVY ION COLLISIONS: Two Decades of Progress
Annual Review of Nuclear and Particle Science
Vol. 55: 357-402 (Volume publication date December 2005)
DOI: 10.1146/annurev.nucl.55.090704.151533
Michael Annan Lisa
Department of Physics, The Ohio State University, Columbus, Ohio 43210; email: lisa@mps.ohio-state.edu
Scott Pratt

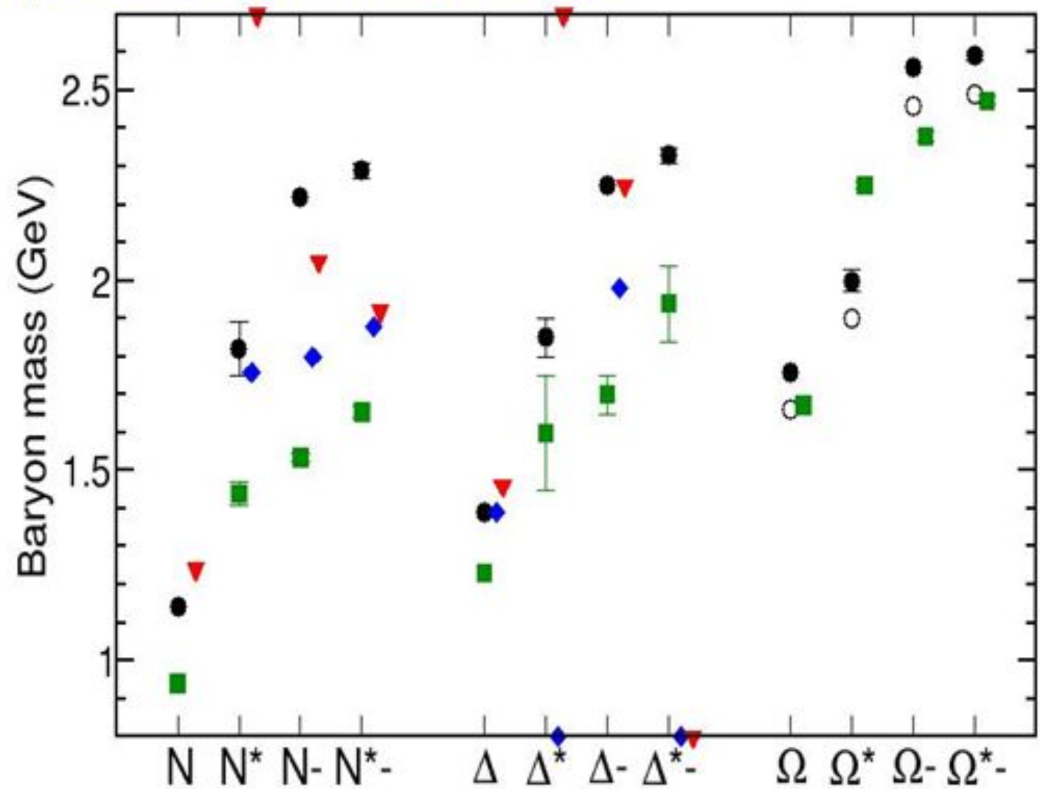
LATTICE QCD AT FINITE TEMPERATURE
Annual Review of Nuclear and Particle Science
Vol. 53: 163-198 (Volume publication date December 2003)
DOI: 10.1146/annurev.nucl.53.041002.110609
E. Laermann[1] and O. Philipsen[2]

Start in 1950s → Hadron Zoo

Mesons



Baryons



- More and more hadrons being discovered.
- Too many to be fundamental particles?
- Hadrons are strings (interesting history).

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

R. Hagedorn

CERN - Geneva

ABSTRACT

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp\left(\frac{m}{T_o}\right).$$

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.

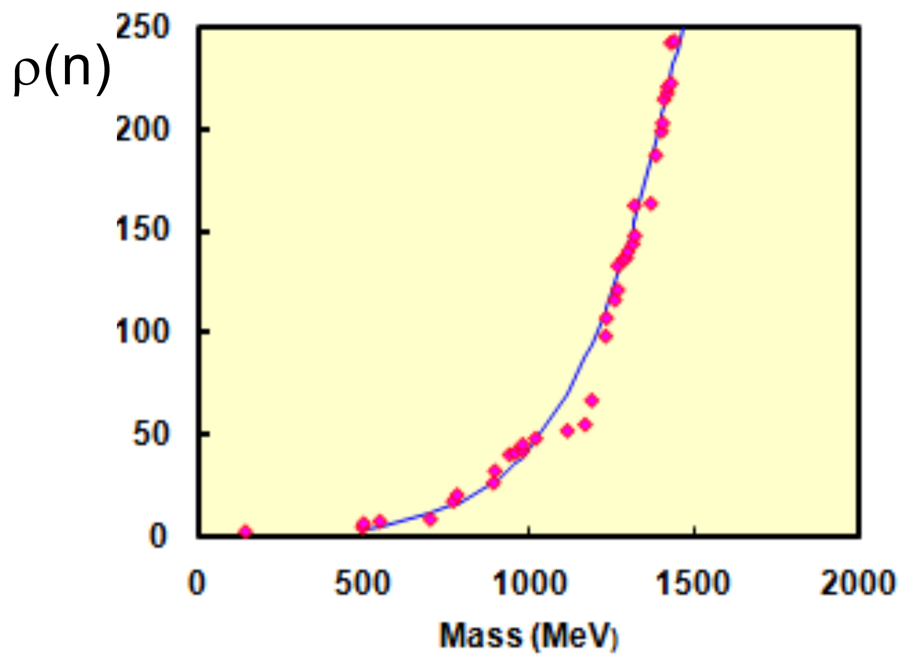
Another consequence is the prediction that the elastic amplitude $A(s,t)$ should decrease as $\sim \exp(-p_\perp / 2T_o)$ for any non-zero fixed scattering angle and $s \to \infty$.

For astrophysics the present theory puts some doubt on the neutron-star model for the interior of collapsing stars; at the same time it suggests a straightforward improvement.

http://cds.cern.ch/record/346206

Circa 1965 Hagedorn observed that these hadrons had an exponentially increasing density of states ρ(n)

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp\left(\frac{m}{T_o}\right).$$



Modern era compilation from PDG by Zajc

STATISTICAL THERMODYNAMICS OF STRONG INTERACTIONS AT HIGH ENERGIES

R. Hagedorn

CERN - Geneva

ABSTRACT

In this statistical-thermodynamical approach to strong interactions at high energies it is assumed that higher and higher resonances of strongly interacting particles occur and take part in the thermodynamics as if they were particles. For $m \to \infty$ these objects are themselves very similar to those which shall be described by this thermodynamics. Expressed in a slogan: "We describe by thermodynamics fire-balls which consist of fire-balls, which consist of fire-balls, which ...". This principle, which could be called "asymptotic bootstrap", leads to a self-consistency requirement for the asymptotic form of the mass spectrum. The equation following from this requirement has only a solution if the mass spectrum grows exponentially:

$$\rho(m) \xrightarrow[m \to \infty]{} \text{const.} m^{-5/2} \exp\left(\frac{m}{T_o}\right).$$

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions. It should - via a Maxwell-Boltzmann law - govern the transversal momentum distribution in all high energy collisions of hadrons (including e.m. form factors, etc.). There is experimental evidence for that, and then T_o is about 158 MeV ($\approx 10^{12}$ °K). With this value of T_o the asymptotic mass spectrum of our theory has a good chance to be the correct extrapolation of the experimentally known spectrum.

Another consequence is the prediction that the elastic amplitude $A(s,t)$ should decrease as $\sim \exp(-p_\perp/2T_o)$ for any non-zero

Think about adding more and more energy to a system…

- Excite more states
- Give states more energy, i.e. a higher Temperature

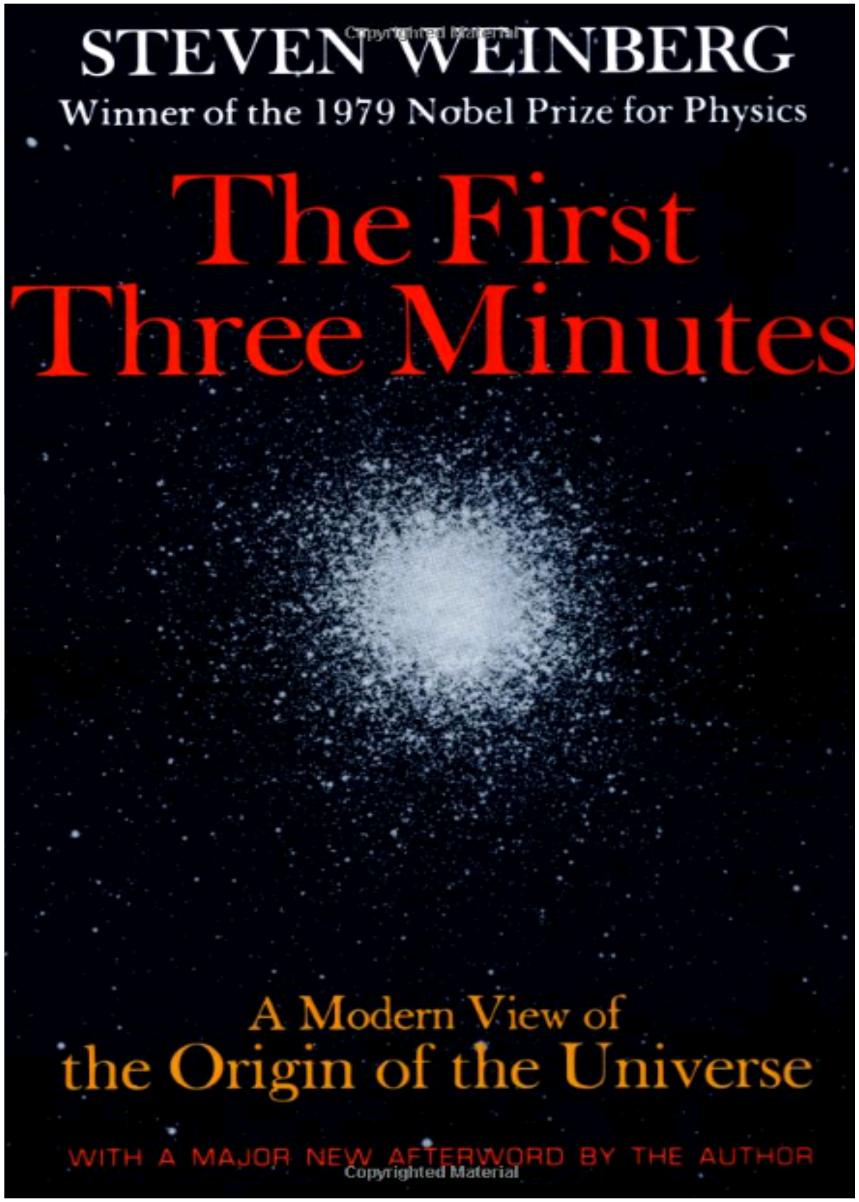
Equiparition Theorem

With exponentially increasing number of states, all the energy goes in to equally exciting these states, and not more energy per state.

T_o is a remarkable quantity: the partition function corresponding to the above $\rho(m)$ diverges for $T \to T_o^-$. T_o is therefore the highest possible temperature for strong interactions.

"**Ultimate Temperature** in the Early Universe"

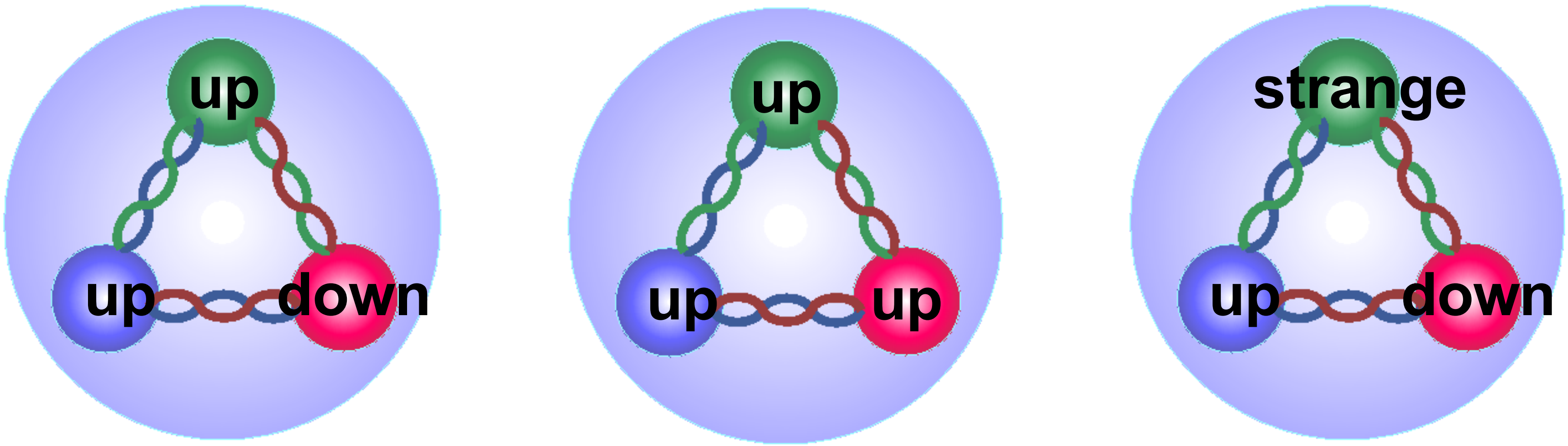
K. Huang & S. Weinberg, Phys Rev Lett 25, 1970.



"…a veil, obscuring our view of the very beginning"

Steven Weinberg, *The First Three Minutes* (1977).

Quark Model



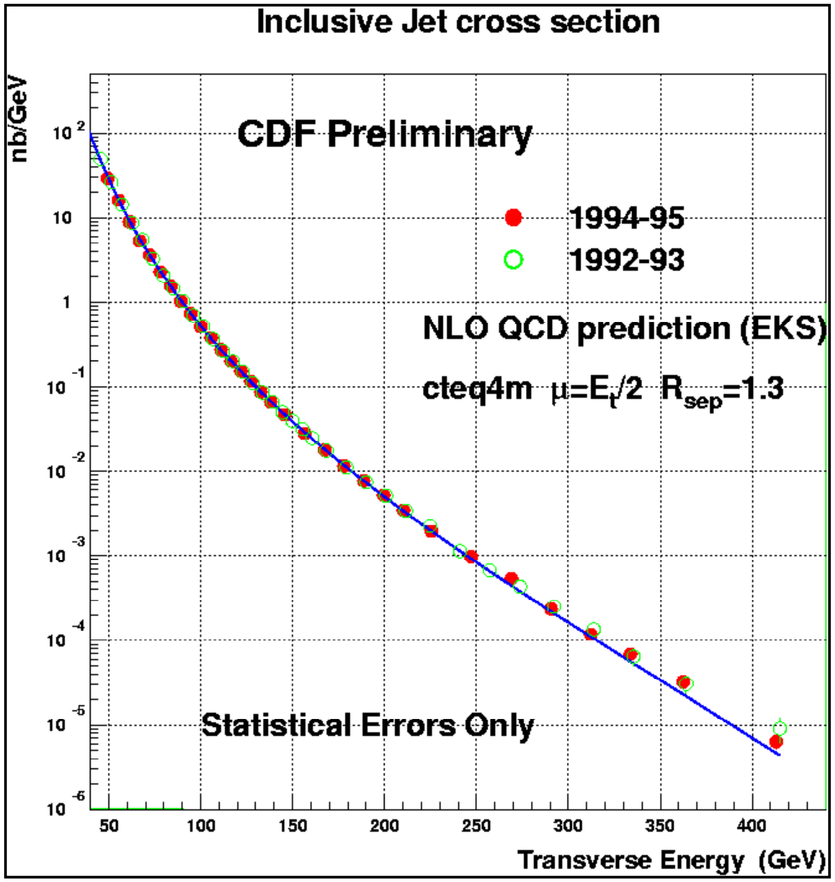
Proton **Δ++** **Λ**

New degrees of freedom inside hadrons.

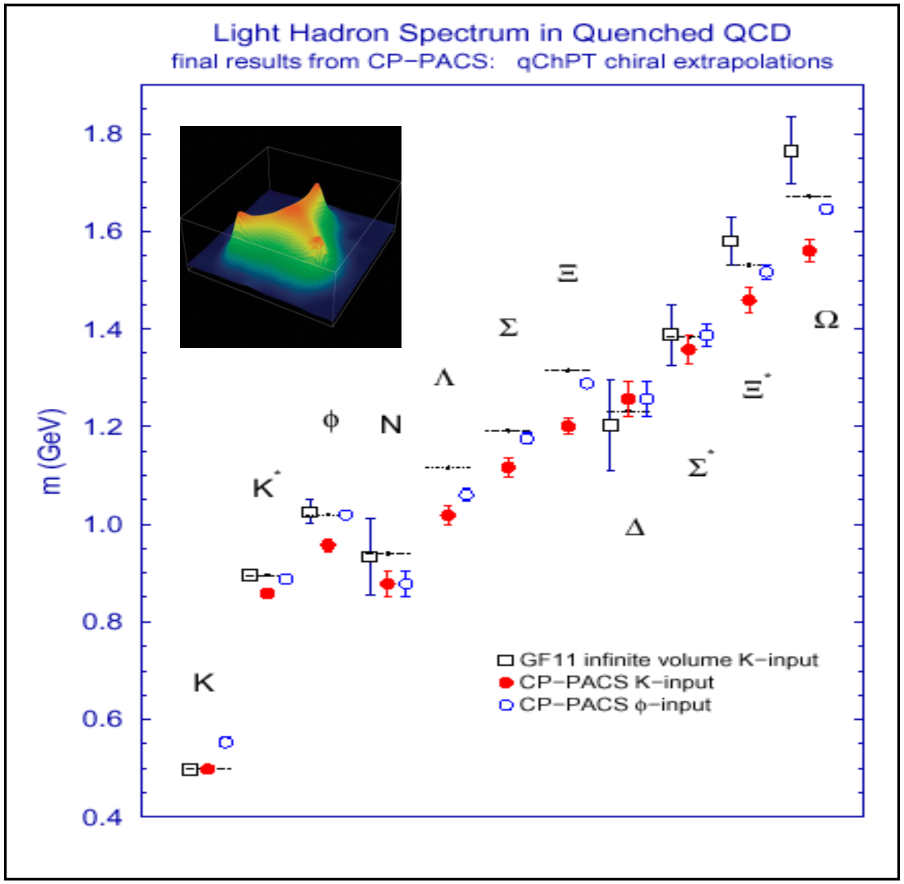
Rapidly people started to think about *Quark Matter* as being relevant at these very high temperatures.

We have strong evidence that QCD is the correct theory of the strong interaction

Perturbative Calculations



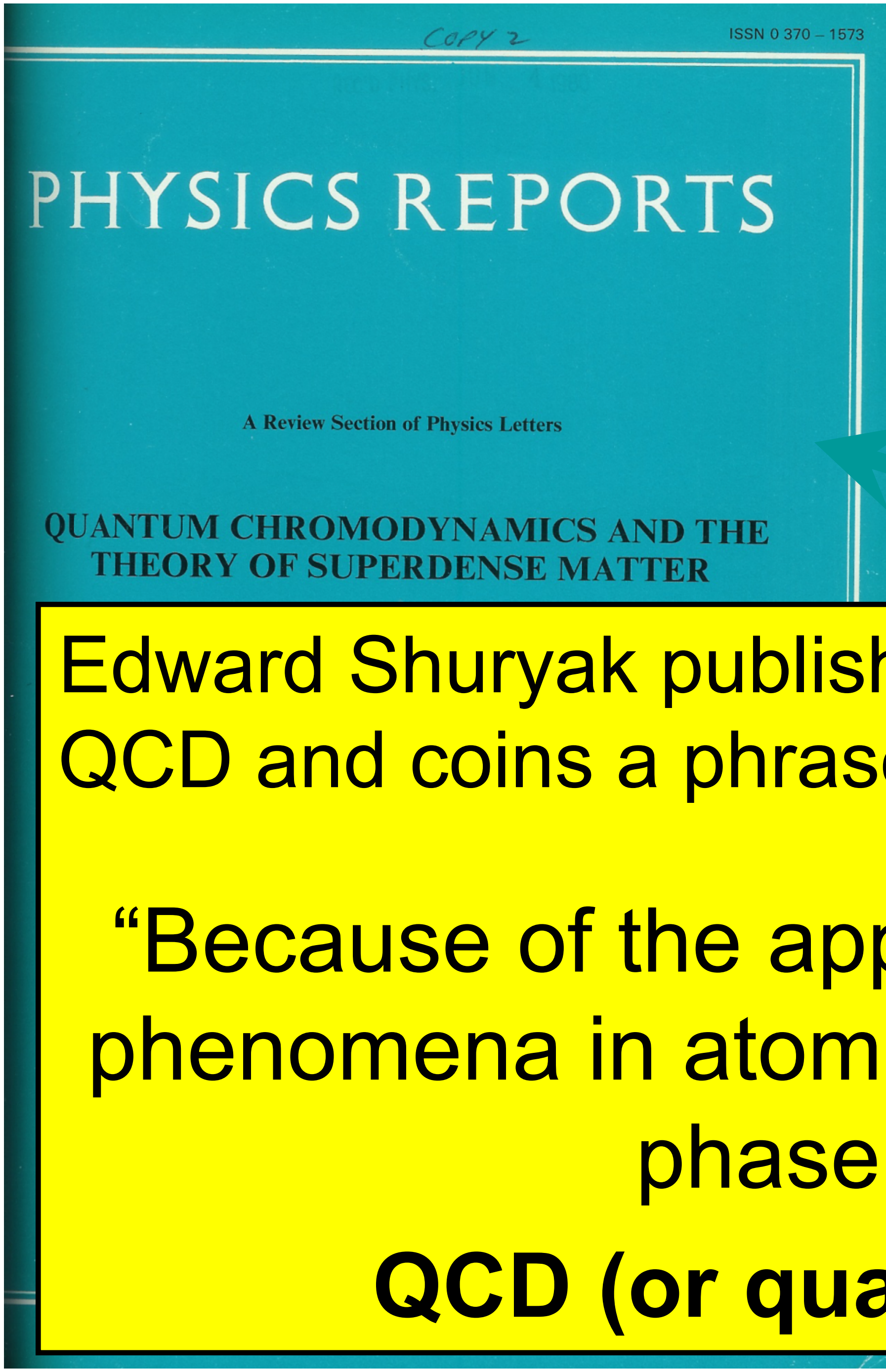
Lattice Calculations

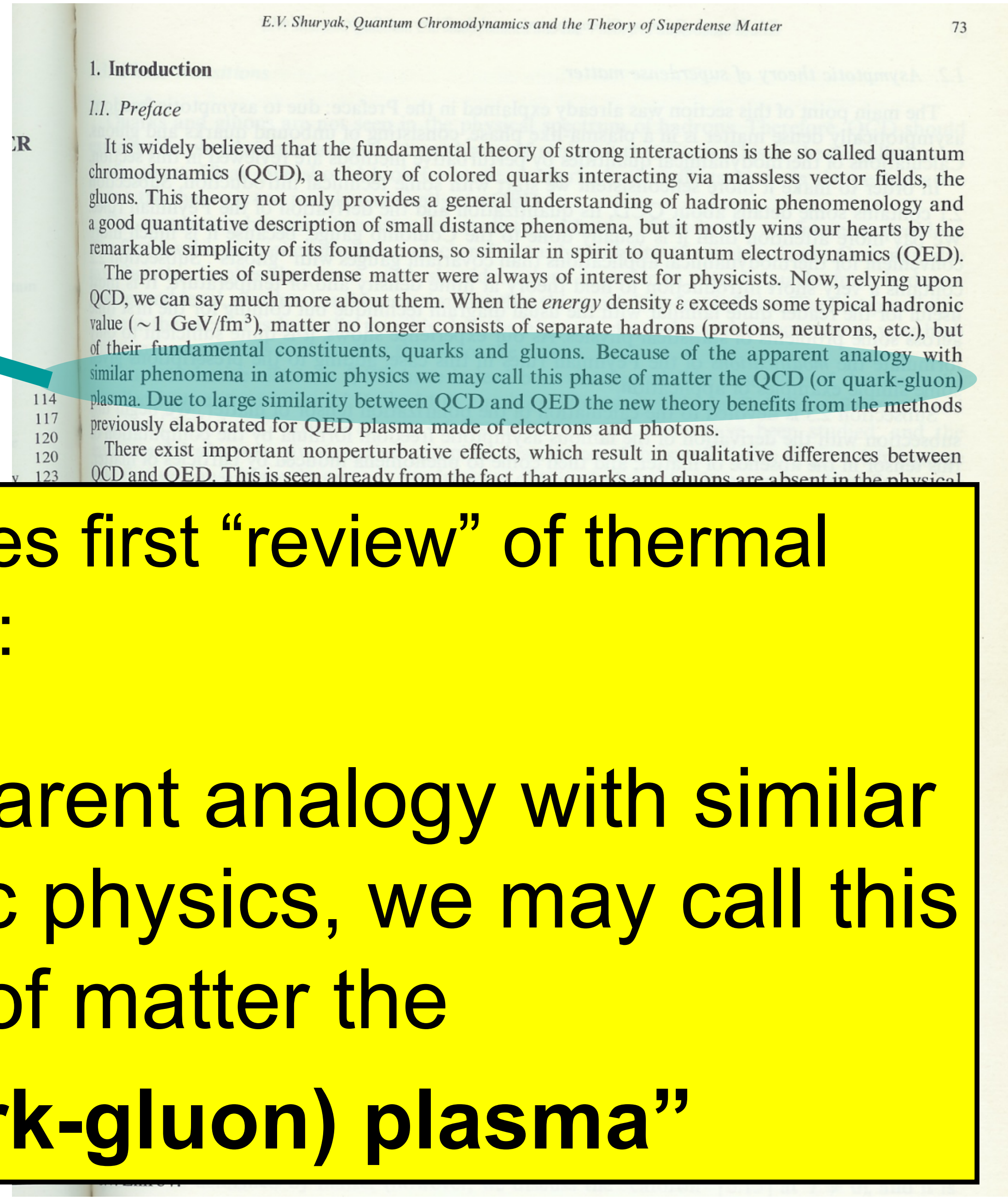


The field is about understanding
emergent phenomena from QCD,
just like condensed matter physics from QED.

Quark-Gluon Plasma

Birth of a Name




E.V. Shuryak, Quantum Chromodynamics and the Theory of Superdense Matter 73

1. Introduction

1.1. Preface

It is widely believed that the fundamental theory of strong interactions is the so called quantum chromodynamics (QCD), a theory of colored quarks interacting via massless vector fields, the gluons. This theory not only provides a general understanding of hadronic phenomenology and a good quantitative description of small distance phenomena, but it mostly wins our hearts by the remarkable simplicity of its foundations, so similar in spirit to quantum electrodynamics (QED).

The properties of superdense matter were always of interest for physicists. Now, relying upon QCD, we can say much more about them. When the *energy* density ε exceeds some typical hadronic value (~1 GeV/fm^3), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma. Due to large similarity between QCD and QED the new theory benefits from the methods previously elaborated for QED plasma made of electrons and photons.

There exist important nonperturbative effects, which result in qualitative differences between QCD and QED. This is seen already from the fact that quarks and gluons are absent in the physical

Edward Shuryak publishes first "review" of thermal QCD and coins a phrase:

"Because of the apparent analogy with similar phenomena in atomic physics, we may call this phase of matter the

QCD (or quark-gluon) plasma"

Melting the Hadrons

Can we melt the hadrons and liberate these quark and gluon degrees of freedom?

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

Energy density for “g” massless d.o.f.

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

Hadronic Matter: quarks and gluons confined
For T ~ 200 MeV, 3 pions with spin=0

$$= \ 2 \ 8_{g} + \frac{7}{8} \ 2_{s} \ \ 2_{a} \ \ 2_{f} \ \ 3_{c} \ \ \frac{{}^{2}}{30} T^{4}$$

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

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

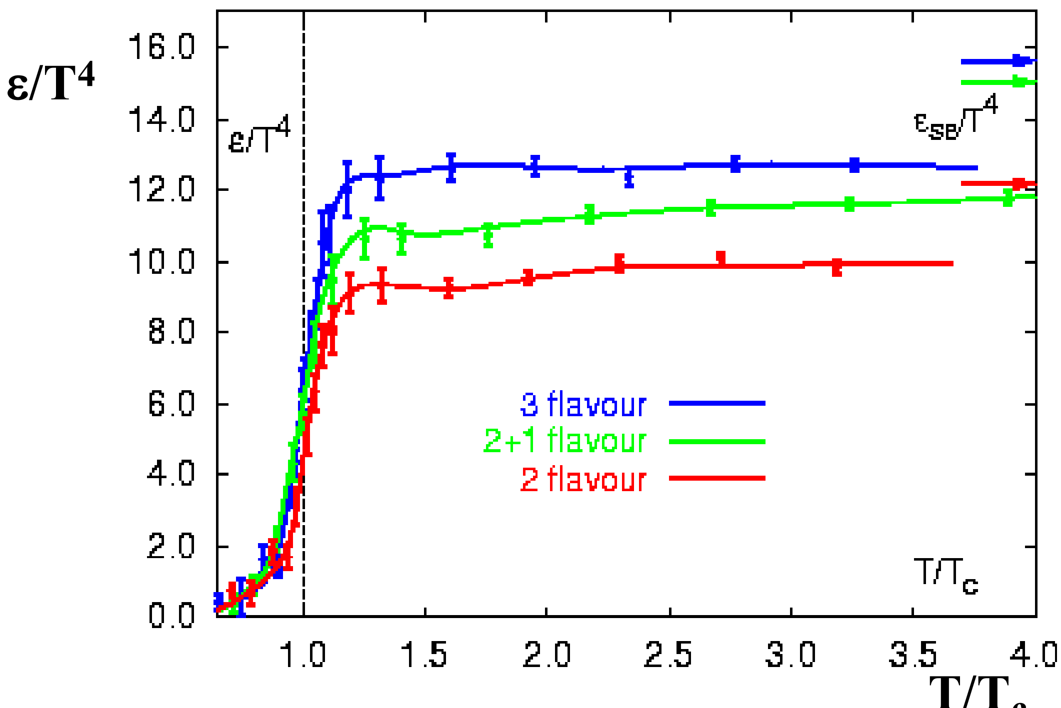
37 !

No Limiting Temperature

Lattice QCD calculations indicate that as one increases the energy input, it is very hard to move the temperature above approximately 170 MeV.

However, eventually the temperature does exceed the "limiting temperature" with a rapid jump in the effective degrees of freedom!

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



(F. Karsch, hep-lat/0106019)

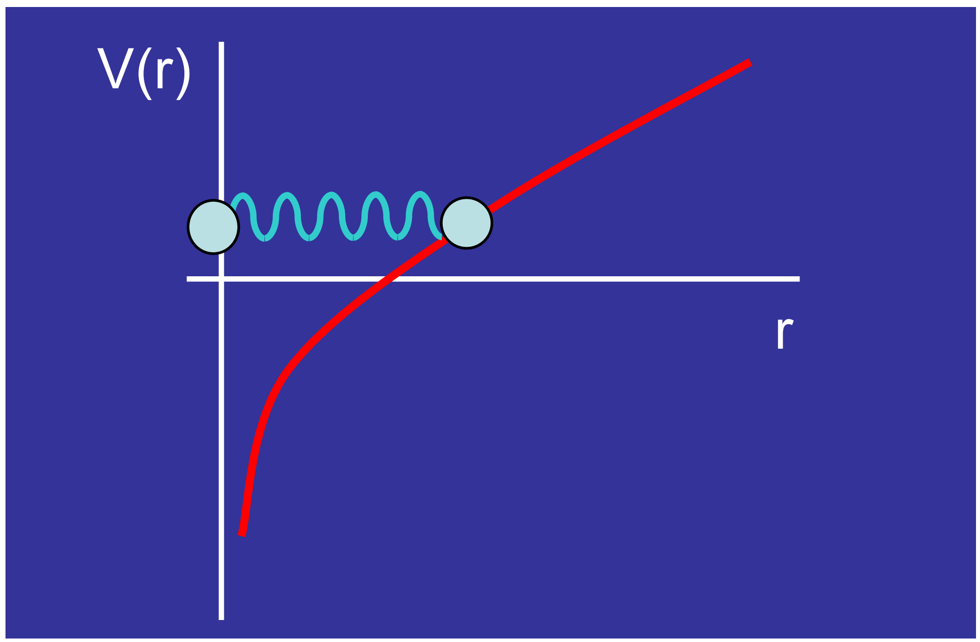
Question: why only 2 or 3 flavors?

Free Quarks?

No one has ever seen a free quark.

$$V = \frac{4}{3}\frac{s}{r} + kr$$

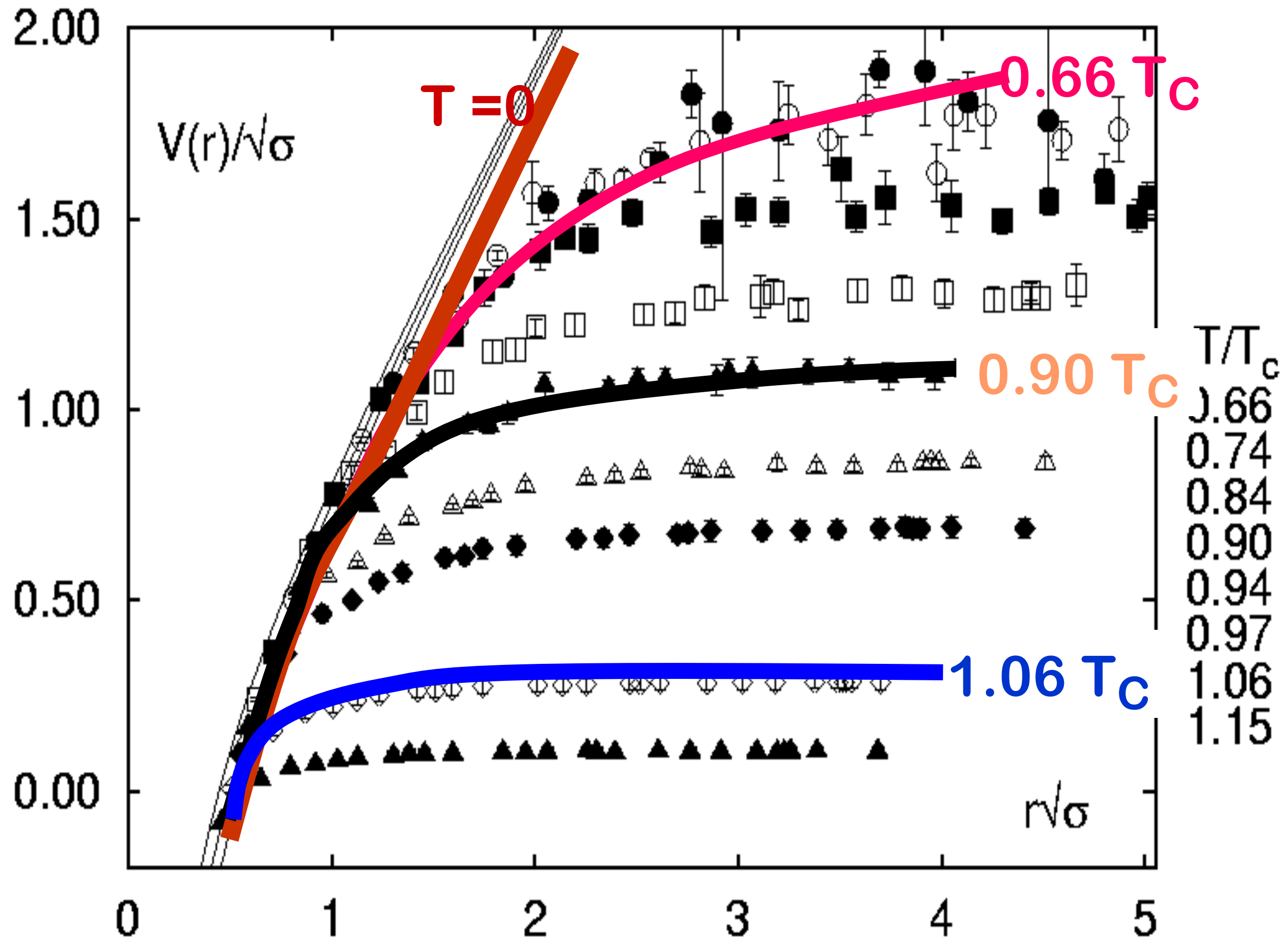
"Coulomb" "Confining"



QCD is a "confining" gauge theory.

Lattice Thermodynamics

Lattice QCD (for heavy quarks as a test) show a screening of the long range confining potential gradually as one passes the transition temperature.

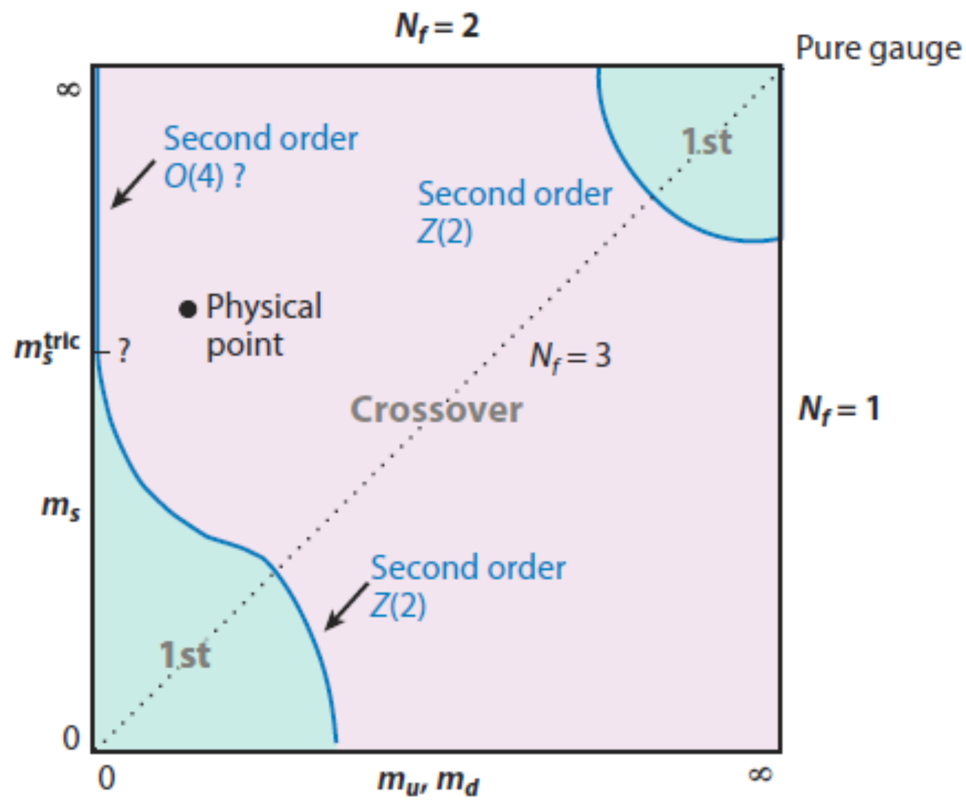


F. Karsch, hep-ph/0103314

Transition Order?

Pisarski and Wilczek, Phys.Rev.D ('84)

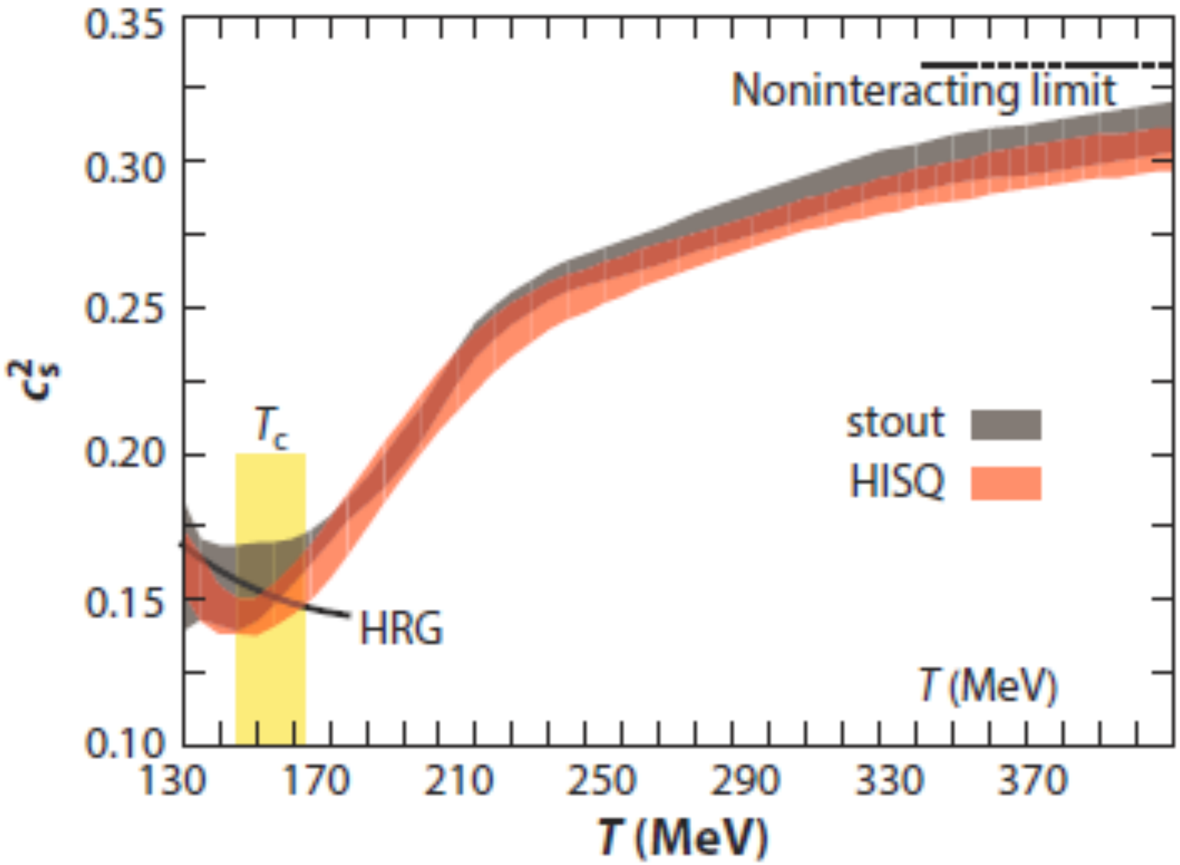
- $N_f = 2$ ($m_s = \infty$, $m_{u,d} = 0$)
  2nd order (O(4) universality)
- $N_f = 3$ ($m_s = 0$, $m_{u,d} = 0$)
  1st order (fluctuation/instanton induced)
- $N_f = 2+1$ ($m_s >> m_{u,d} \neq 0$)
  1st order or crossover



Recent lattice QCD results for a realistic strange quark mass indicate a smooth cross over transition for zero net baryon density.

This has substantial implications.

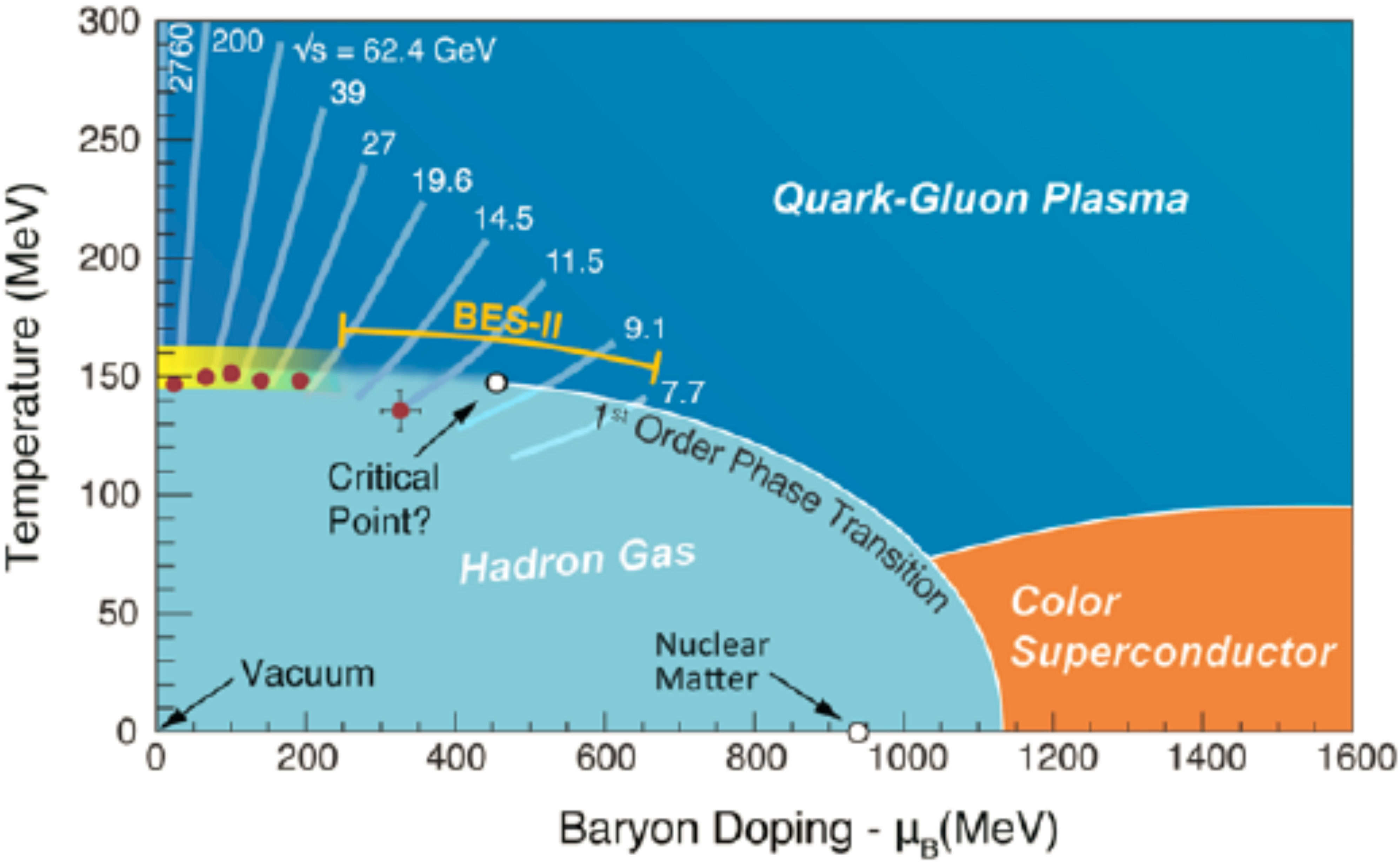
Speed of Sound



Speed of sound drops near transition ("soft point in EoS") and actually goes to zero in first order transition.

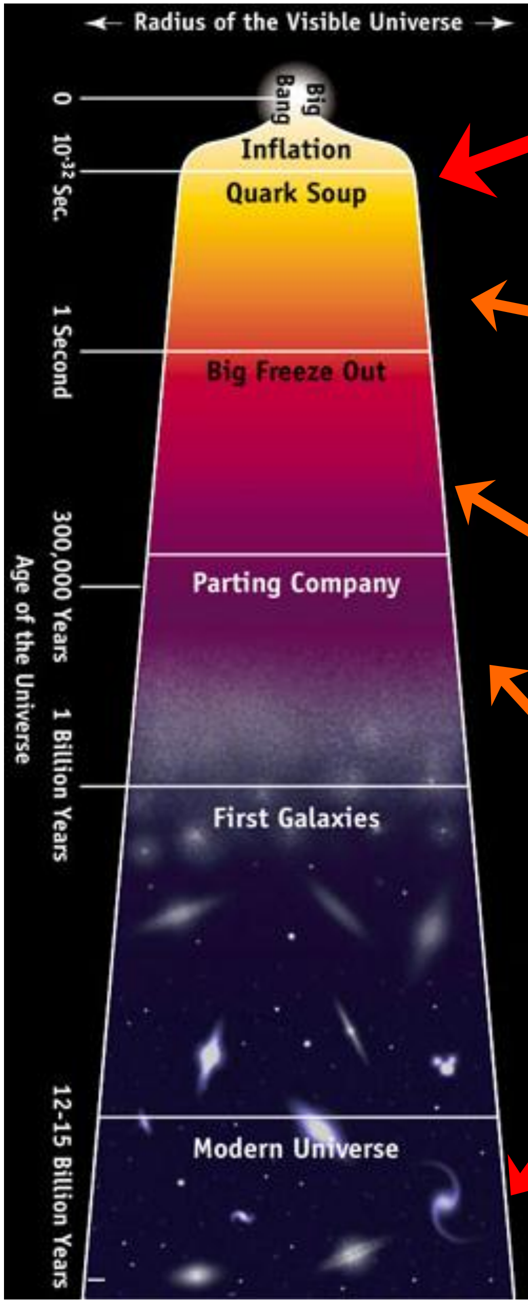
Sound wave transmits energy. In true mixed phase, all energy is absorbed into rearranging constituents.

Phase Diagram of Nuclear Matter



QGP
and
Cosmology

Brief History of Time



Too hot for quarks to bind!!!

Standard Model (N/P) Physics

Quark Gluon Plasma

Too hot for nuclei to bind

Nuclear/Particle (N/P) Physics

Hadron Gas

Nucleosynthesis builds nuclei up to He

Nuclear Force…Nuclear Physics

Universe too hot for electrons to bind

E-M…Atomic (Plasma) Physics

E/M Plasma

Today's Cold Universe

Gravity…Newtonian/General Relativity

Solid Liquid Gas

Annu. Rev. Nucl. Part. Sci. 2006. 56:441–500
doi: 10.1146/annurev.nucl.56.080805.140539

First published online as a Review in Advance on August 2, 2006

Phase Transitions in the Early and Present Universe

D. Boyanovsky,[1,2,3] H.J. de Vega,[3,2,1] and D.J. Schwarz[4]

Quark nuggets and strangelets

Inhomogeneous nucleosynthesis

Cold dark matter clumps

Damping of gravitational waves at the QCD transition

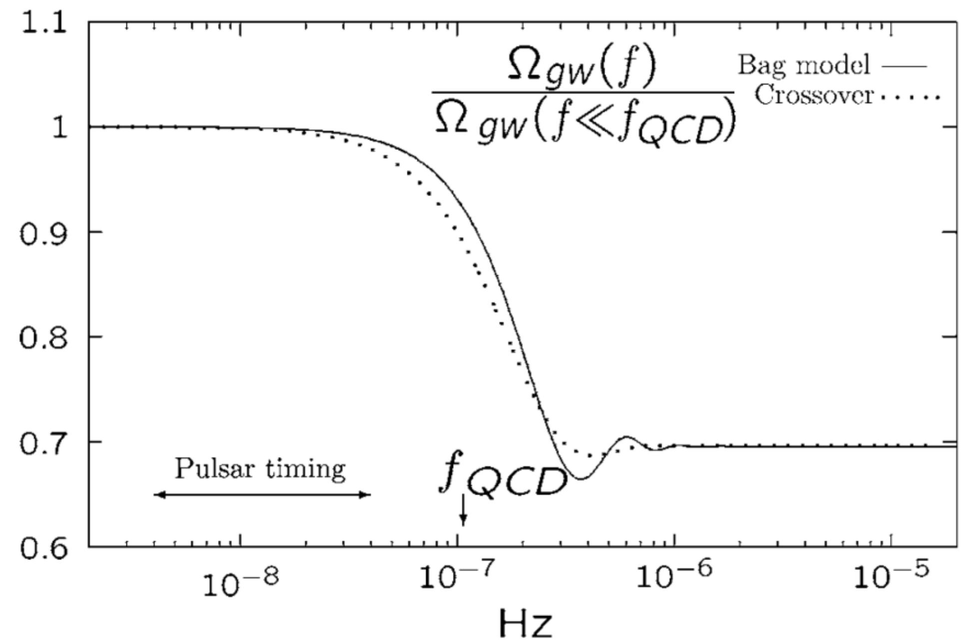


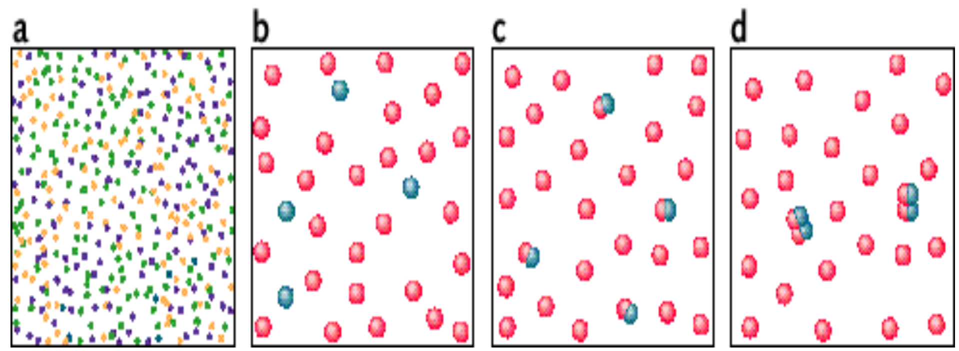
Figure 11 The modification of the energy density, per logarithmic frequency interval, of primordial gravitational waves from the QCD transition. Figure taken from Reference 107.

Supercooling and Bubbles

If the plasma-to-hadrons transition were strongly first order, bubble formation could lead to an inhomogeneous early universe, thus impacting big bang nucleosynthesis (BBN).

Are the bubbles too small and close together such that diffusion before nucleosynthesis erases the inhomogeneities? (200 MeV to 2 MeV)

This line of investigation was quite active when the dark matter issue raised questions about the implied baryon content in the universe from BBN.

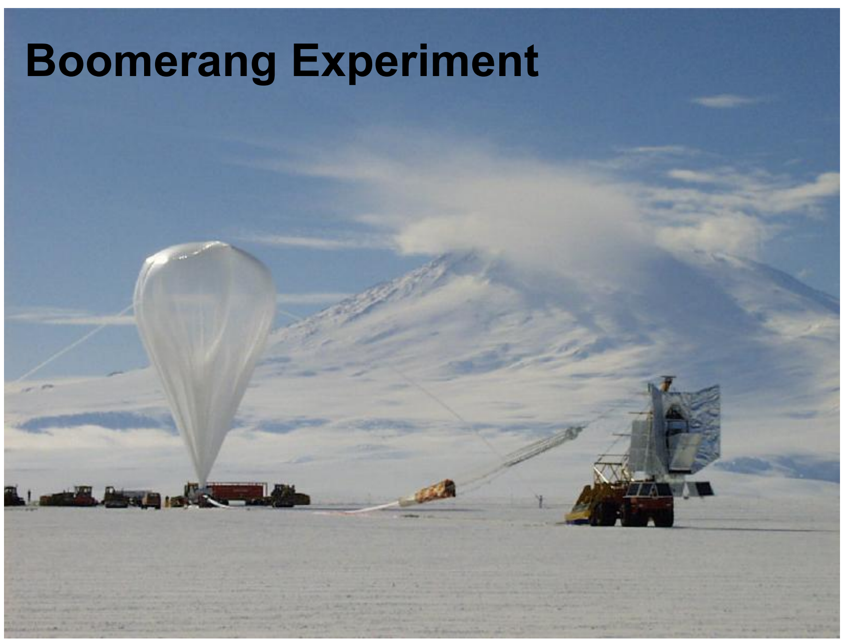


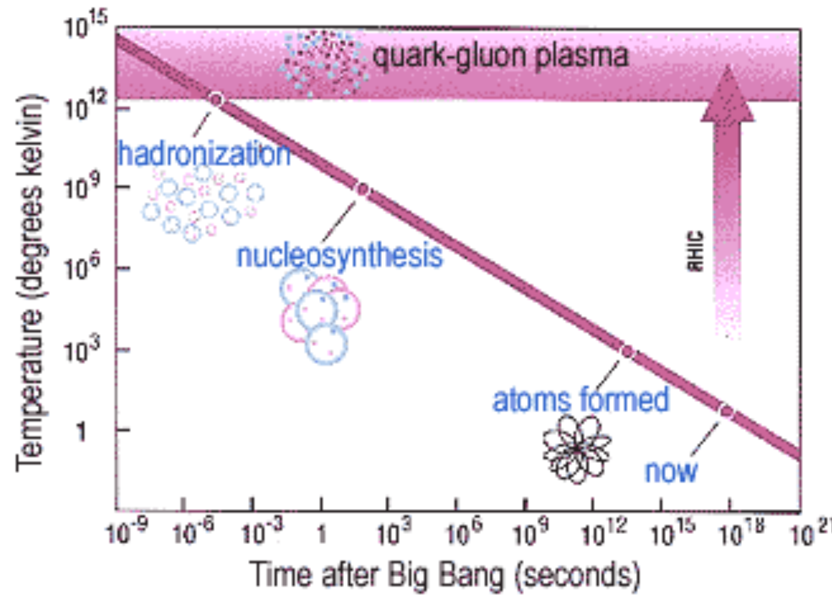
No BBN Problem

Physics Today, July 2001: Cosmic Microwave Background Observations

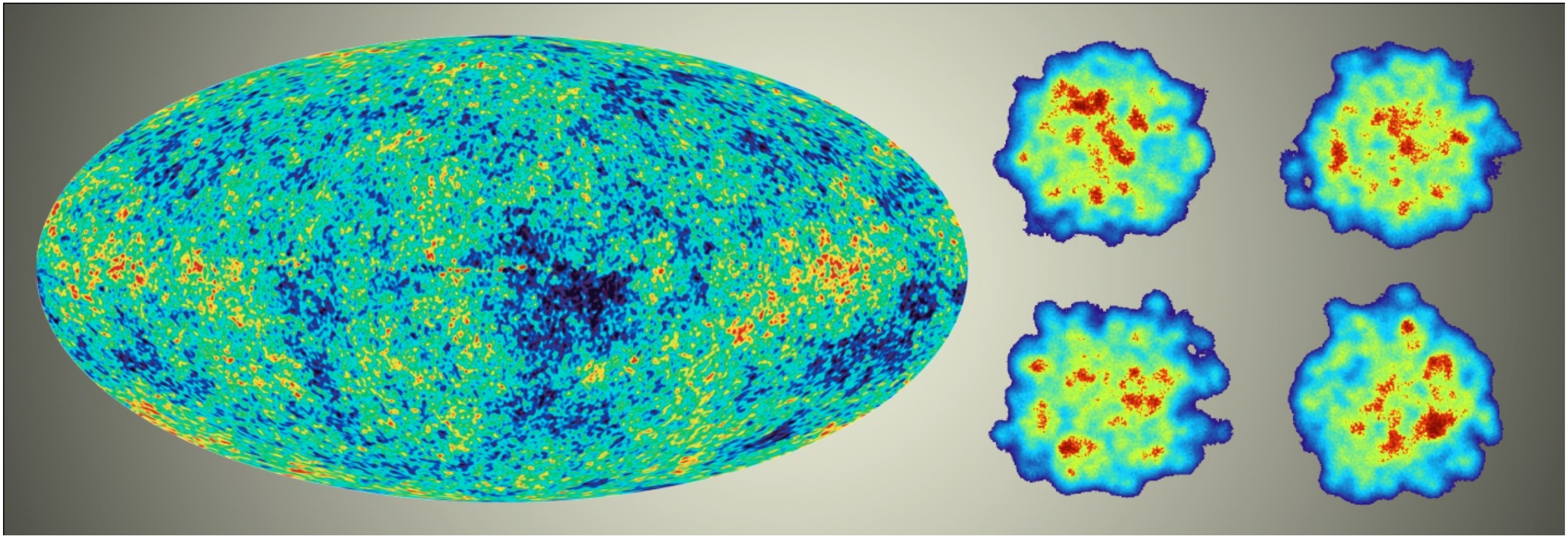
"The value deduced from the second harmonic in the acoustic oscillations for W_B=0.042 ± 0.008 (cosmic baryon mass density) is in very good agreement with the value one gets by applying the theoretical details of primordial big bang nucleosynthesis to the observations of cosmic abundances of deuterium."

In addition, Lattice QCD now confirms a smooth cross over transition.





Big Bang versus Little Bangs



Universe Case:

Fluctuations pre-inflation…
and not impacted by QGP

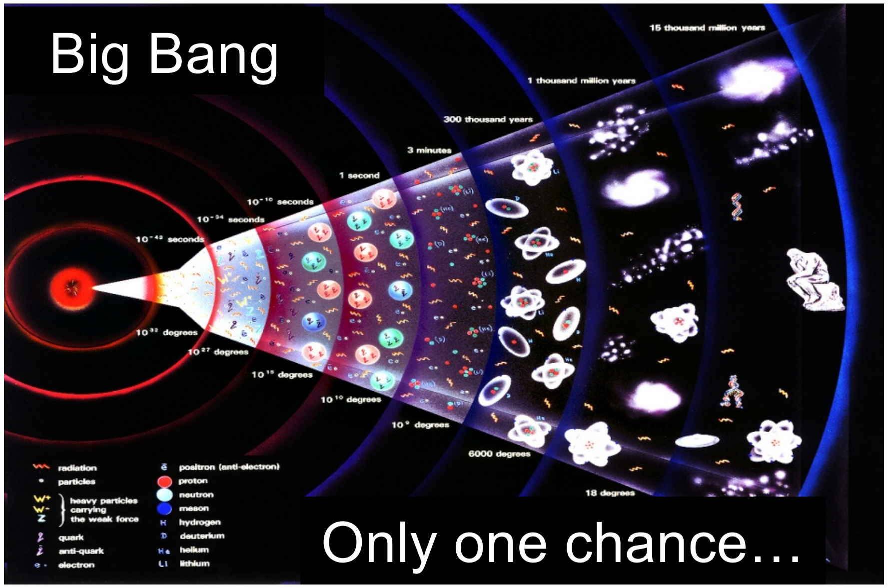
Heavy Ion Case:

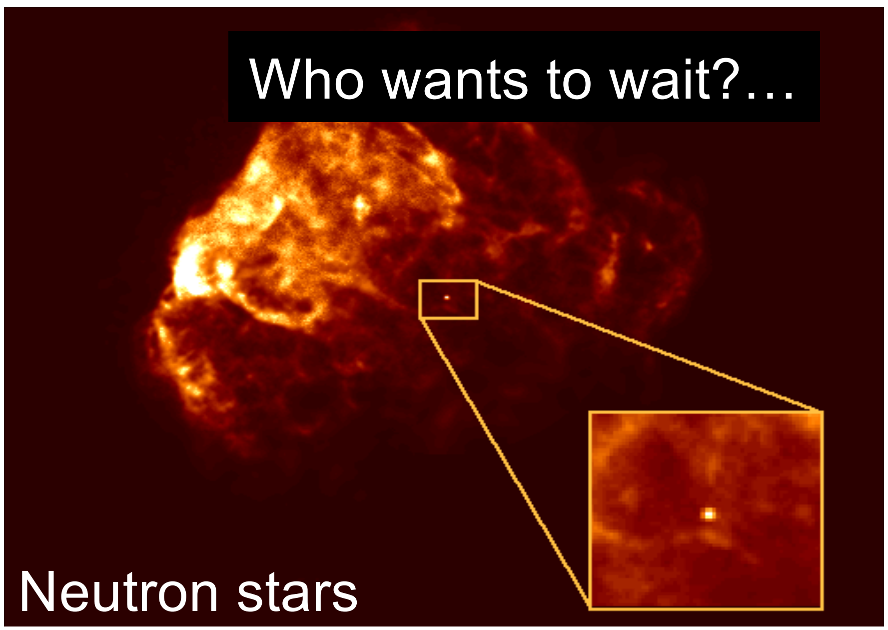
QGP initial
condition
fluctuations

Study structures that survive to understand earlier epoch

Heavy Ion Experiments

How to Access This Physics?





Neutron star mergers… maybe the waiting is over

http://science.energy.gov/~/media/np/nsac/pdf/201603/Weinstein_LIGO_20160323.pdf

Heavy Ion Machine History

Bevalac-LBL and SIS-GSI fixed target
max. **2.2 GeV**

1992 Au-Au

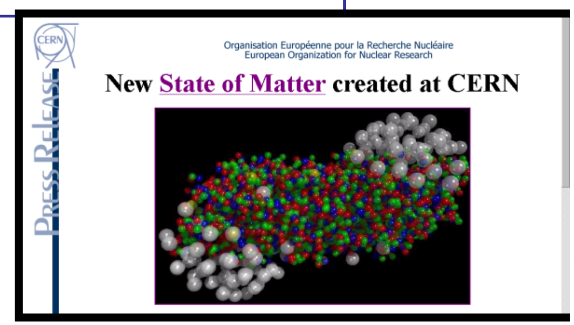
AGS-BNL fixed target
max. **4.8 GeV**

E864/941, E802/859/866/917, E814/877, E858/878, E810/891, E896, E910 …

1994 Pb-Pb

SPS-CERN fixed target
max. **17.3 GeV**

NA35/49, NA44, NA38/50/51, NA45, NA52, NA57, WA80/98, WA97, …

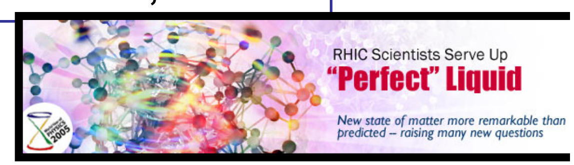


TEVATRON-FNAL (fixed target p-A)
max. **38.7 GeV**

2000 Au-Au

RHIC-BNL collider
max. **200.0 GeV**

BRAHMS, PHENIX, PHOBOS, STAR



2010 Pb-Pb

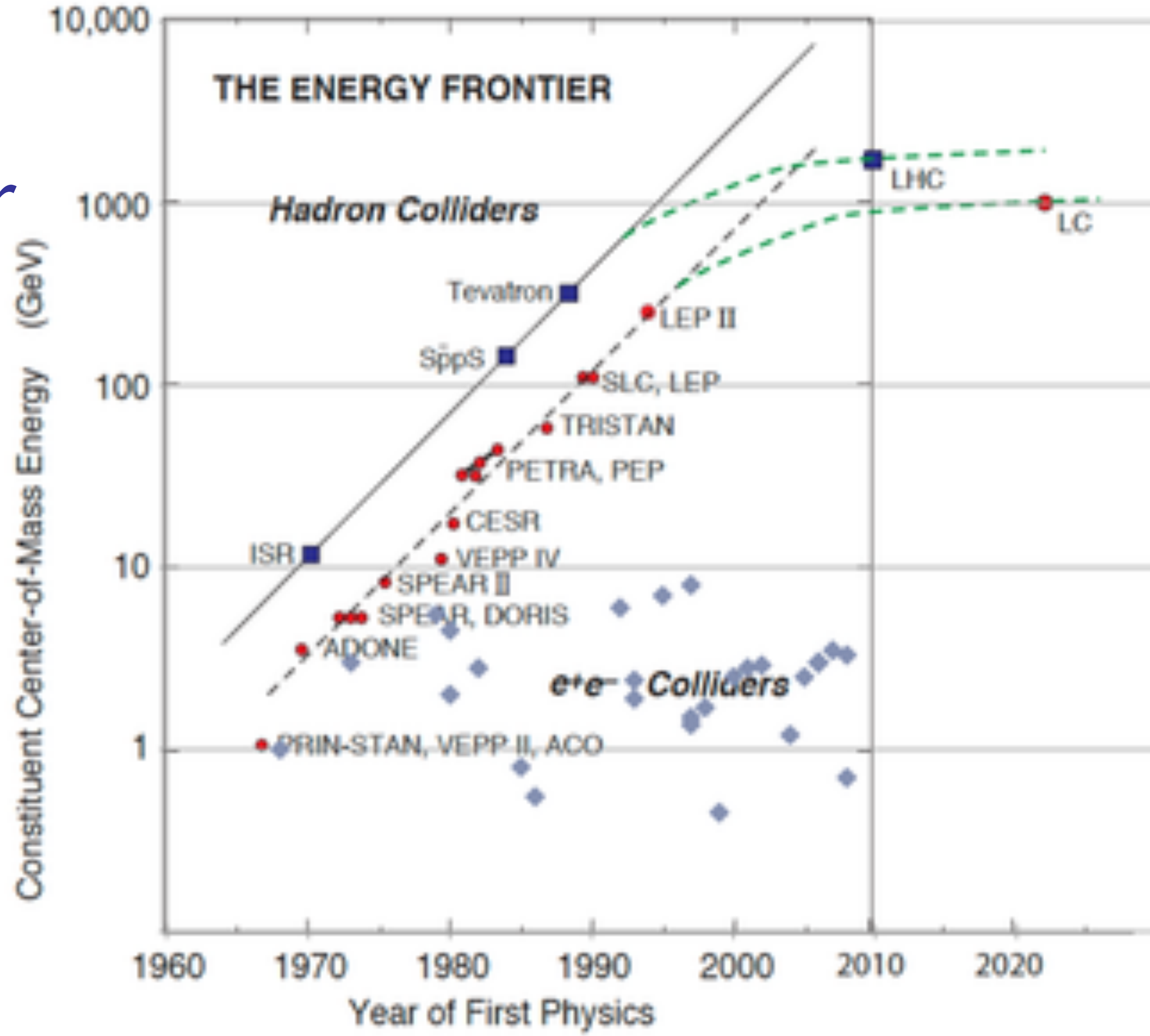
LHC-CERN collider
max. **2760.0 GeV**

ALICE, ATLAS, CMS, LHCb (pA)

Particle Physics

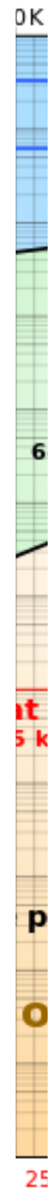
the energy frontier

Machine with highest energy for point-like interactions dominates the world!

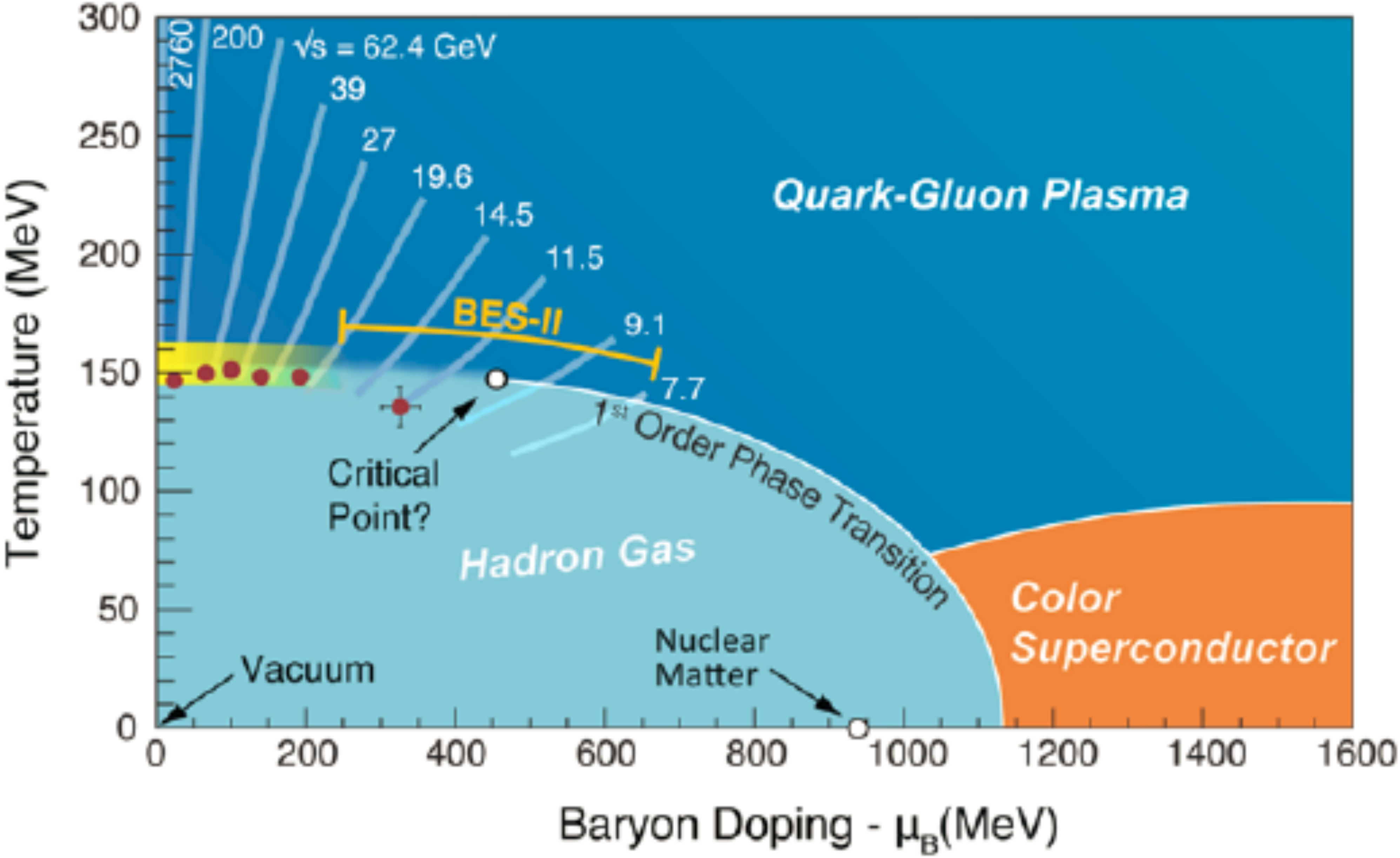


Nuclear Physics – studying a state of matter (thermodynamics, many-body physics) and how that emerges from underlying QCD theory

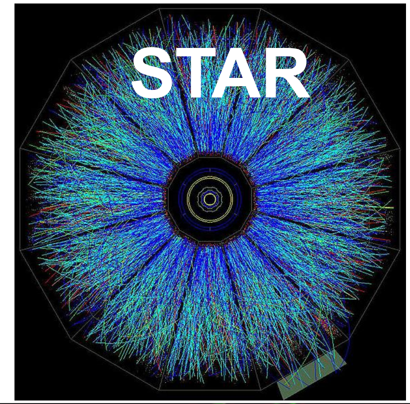
Think of mapping out a phase diagram with only one temperature?

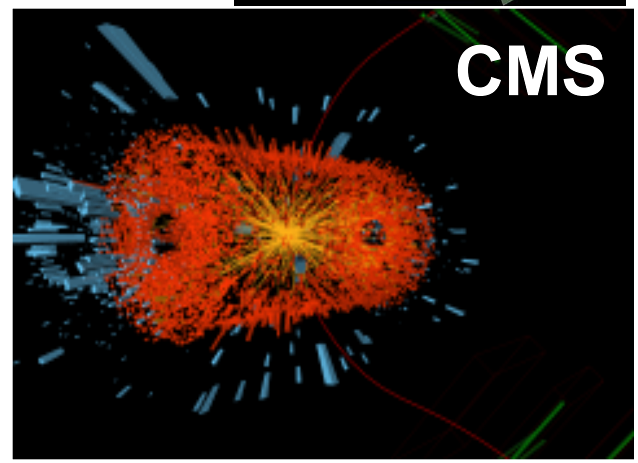


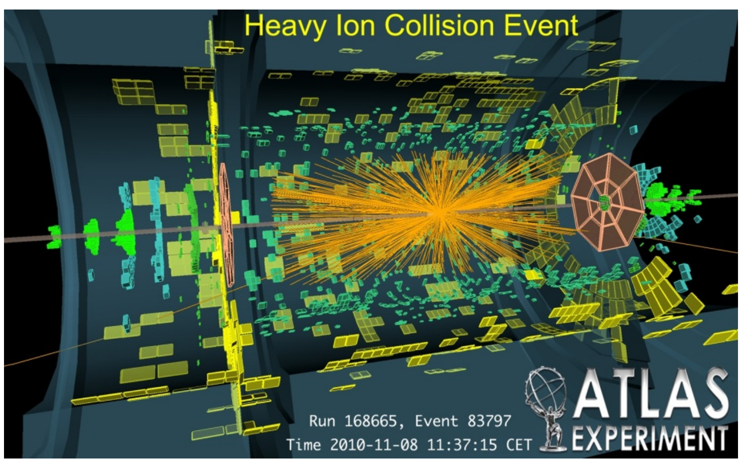
Phase Diagram of Nuclear Matter

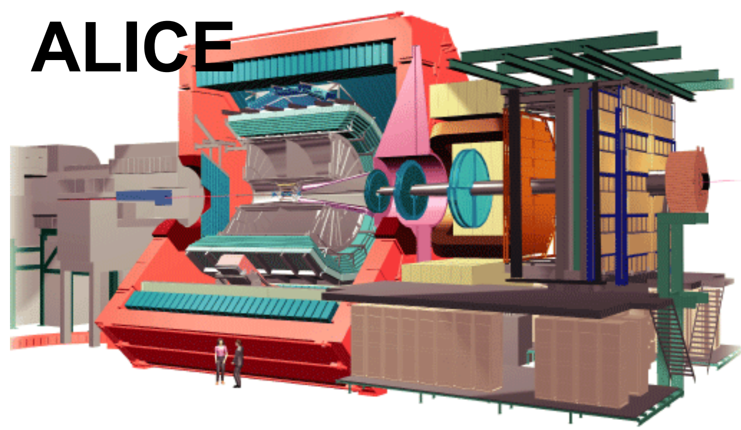


Experimental Tools





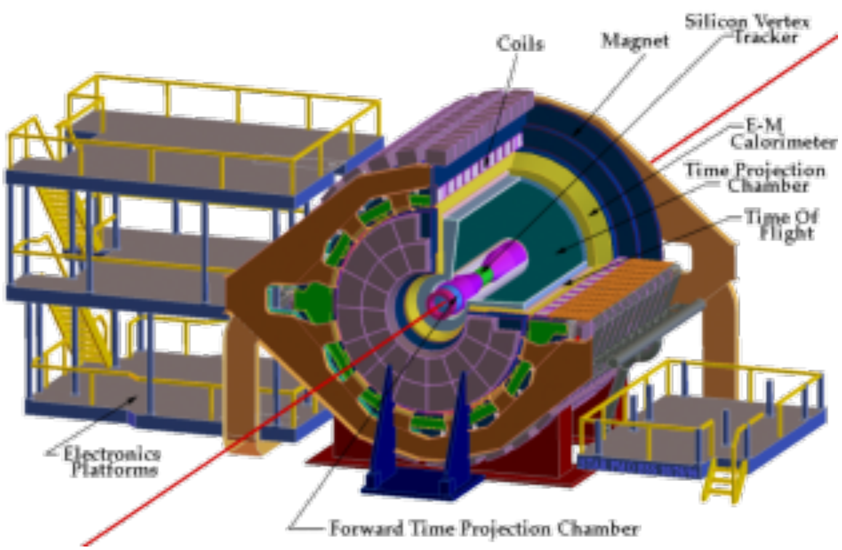




STAR

Hadronic Observables over a Large Acceptance
Event-by-Event Capabilities

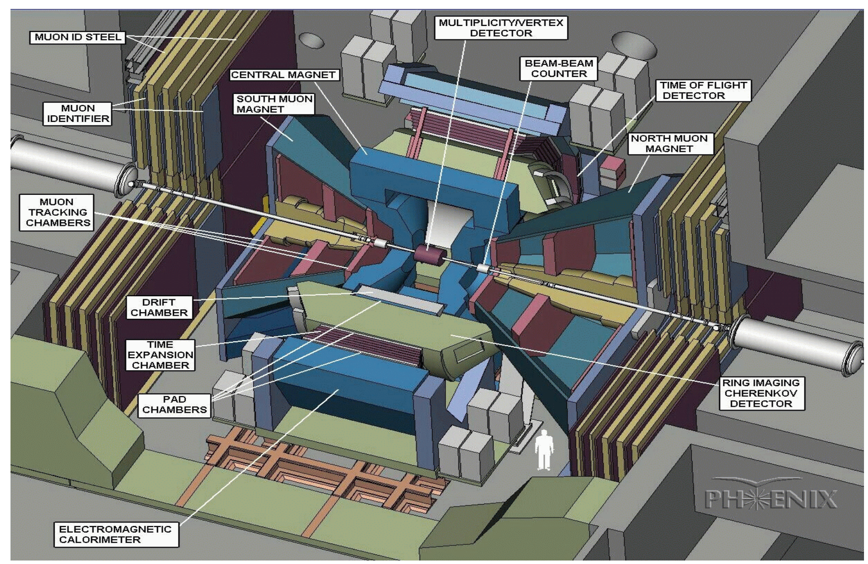
Solenoidal magnetic field
Large coverage Time-Projection Chamber
Silicon Tracking, RICH, EMC, TOF



PHENIX

Electrons, Muons, Photons and Hadrons Measurement Capabilities
Focus on Rare Probes: J/ψ, high-p_T

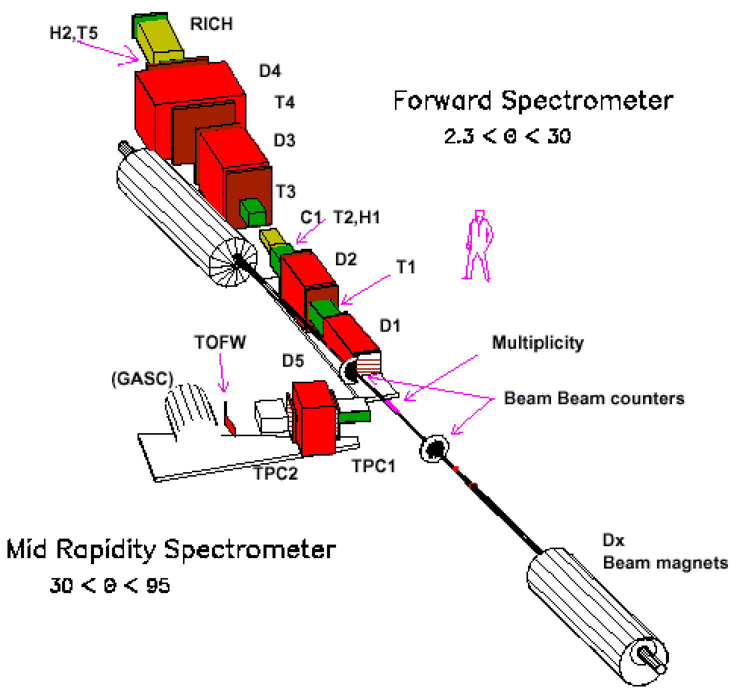
Two central spectrometers with tracking and electron/photon PID
Two forward muon spectrometers



BRAHMS

Hadron PID over broad rapidity acceptance

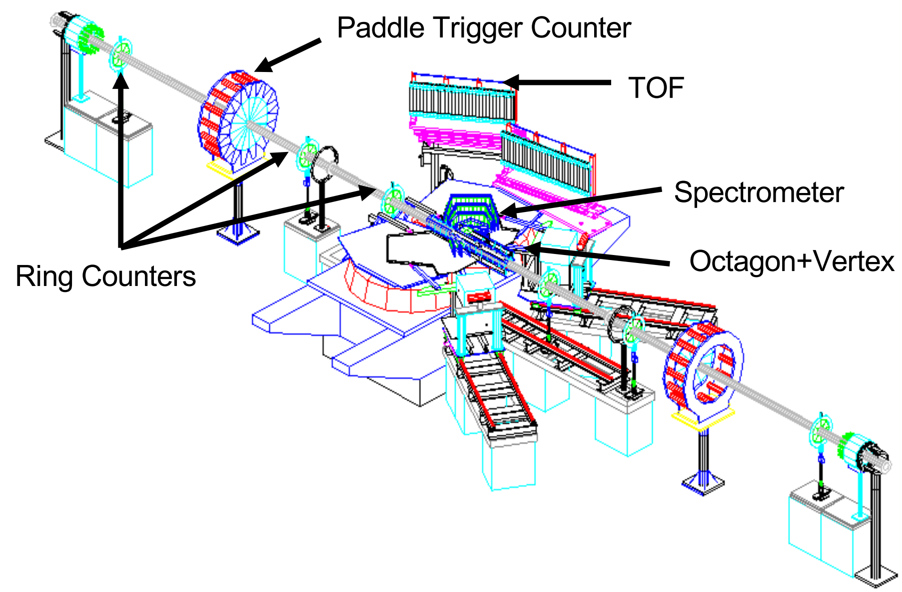
Two conventional beam line spectrometers
Magnets, Tracking Chambers, TOF, RICH



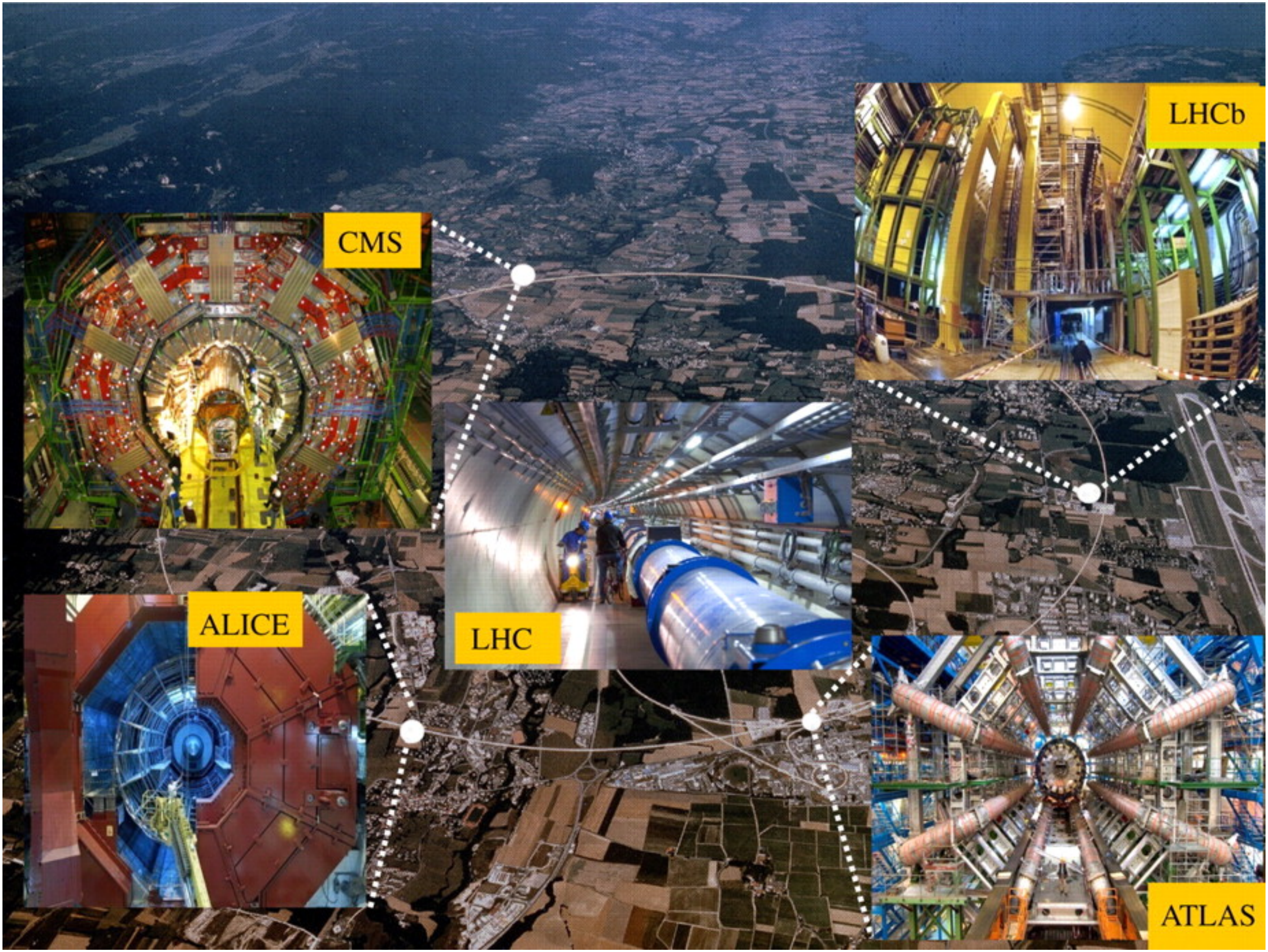
PHOBOS

Charged Hadrons in Central Spectrometer
Nearly 4π coverage multiplicity counters

Silicon Multiplicity Rings
Magnetic field, Silicon Strips, TOF

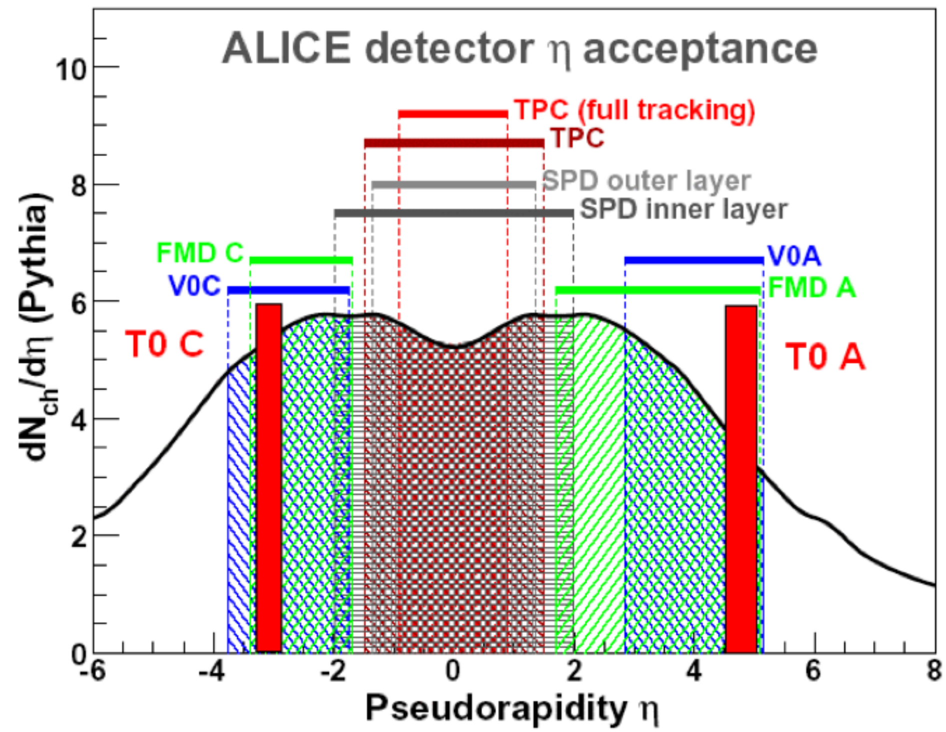


Biggest contributions – intellectually independent thinking!


LHCb
CMS
LHC
ALICE
ATLAS

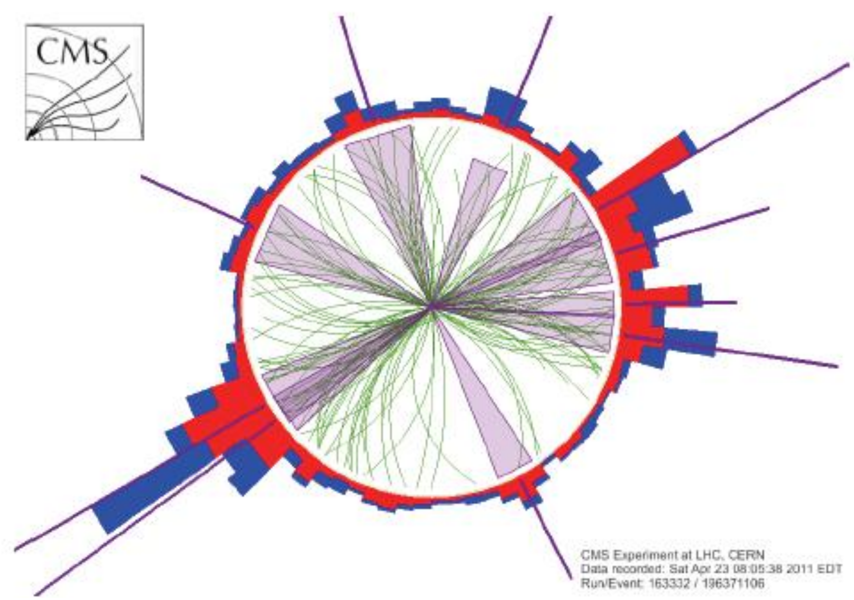
ALICE – dedicated heavy ion detector

Key advantages – particle identification, focused 1000+ people



ATLAS & CMS –

full calorimetry, tracking, *different approaches and analysis philosophies*



Collision Dynamics

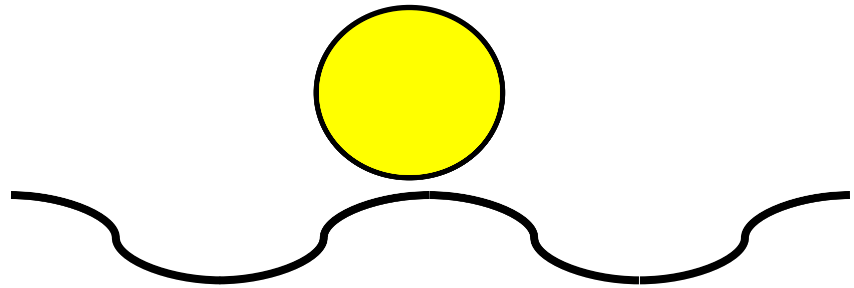
Structure of the Proton

See the whole proton

Momentum transfer

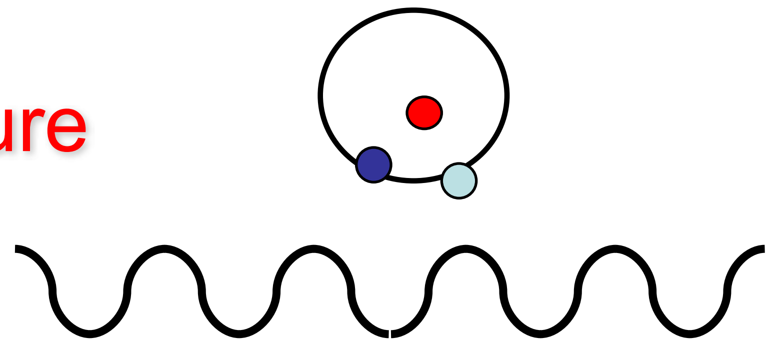
Q^2 = 0.1 GeV^2

Wavelength λ = h/p



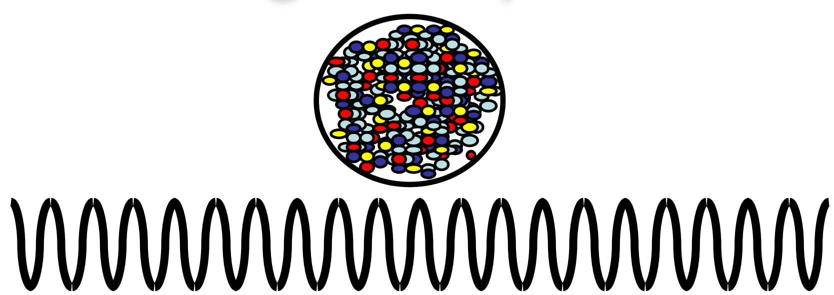
See the quark substructure

Q^2 = 1.0 GeV^2



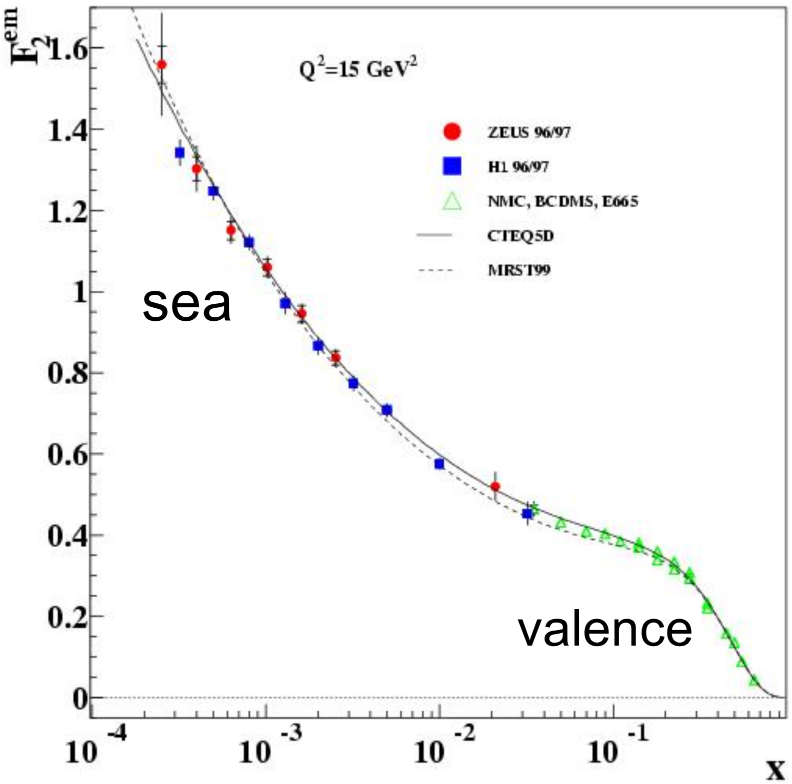
See many partons (quarks and gluons)

Q^2 = 20.0 GeV^2

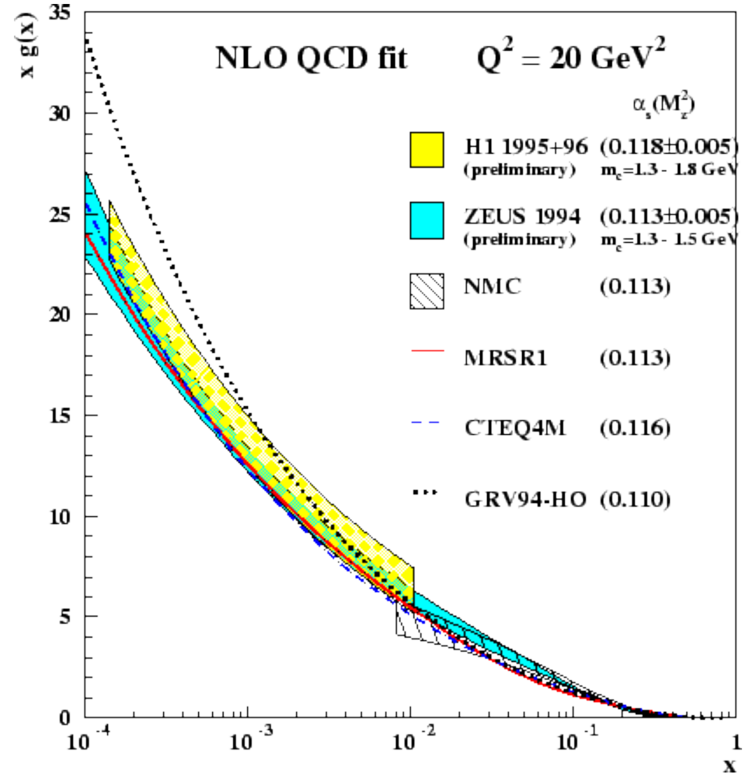


Parton Distribution Functions

Quarks



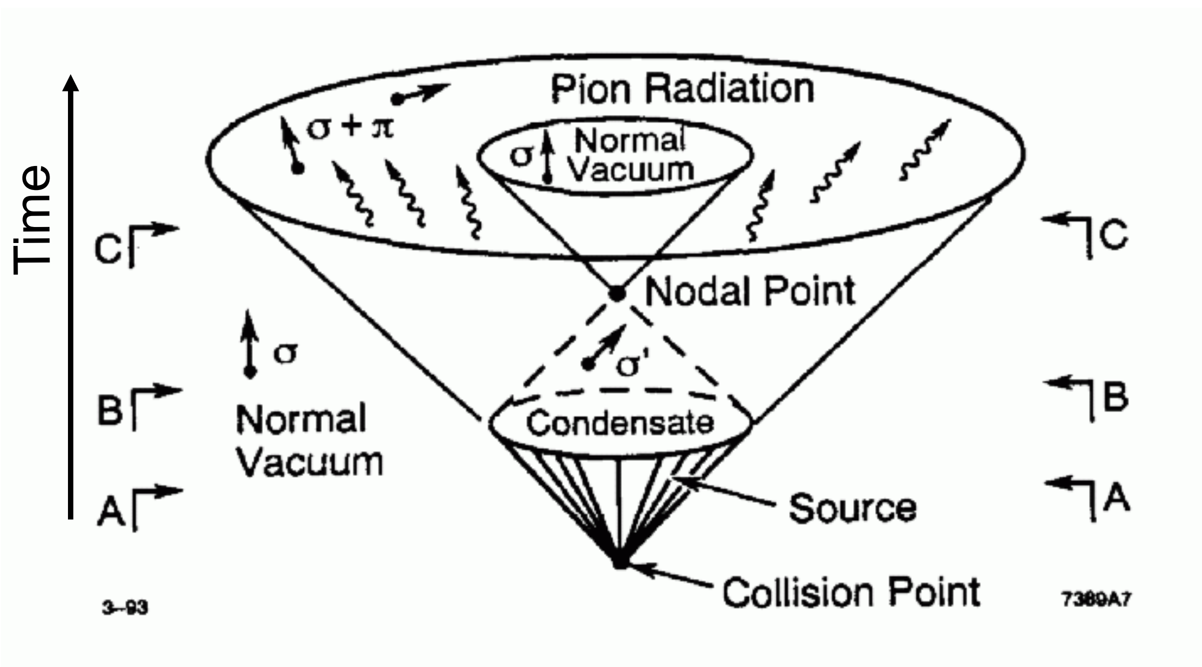
Gluons



- Structure functions rise rapidly at low-x
- More rapid for gluons than quarks
- Watch out for side-by-side plots with different vertical scales (left 1.7 and right 30!)

QGP in Proton+Proton Reactions?

Bjorken speculated that in the "interiors of large fireballs produced in very high-energy pp collisions, vacuum states of the strong interactions are produced with anomalous chiral order parameters."



http://www-minimax.fnal.gov/

"Baked Alaska"

Fermi (1950)

"High Energy Nuclear Events", Prog. Theor. Phys. 5, 570 (1950)

Groundwork for statistical approach to particle production in strong interactions:

"Since the interactions of the pion field are *strong*, we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws."

241.

HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several π–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

Landau (1955)

Significant extension of Fermi's approach

Considers fundamental roles of

- Hydrodynamic evolution
- Entropy

"The defects of Fermi's theory arise mainly because the expansion of the compound system is not correctly taken into account…(The) expansion of the system can be considered on the basis of relativistic hydrodynamics."

88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

1. Introduction

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of 10^9 eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume V in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume V in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, μ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume V will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \qquad (1.1)$$

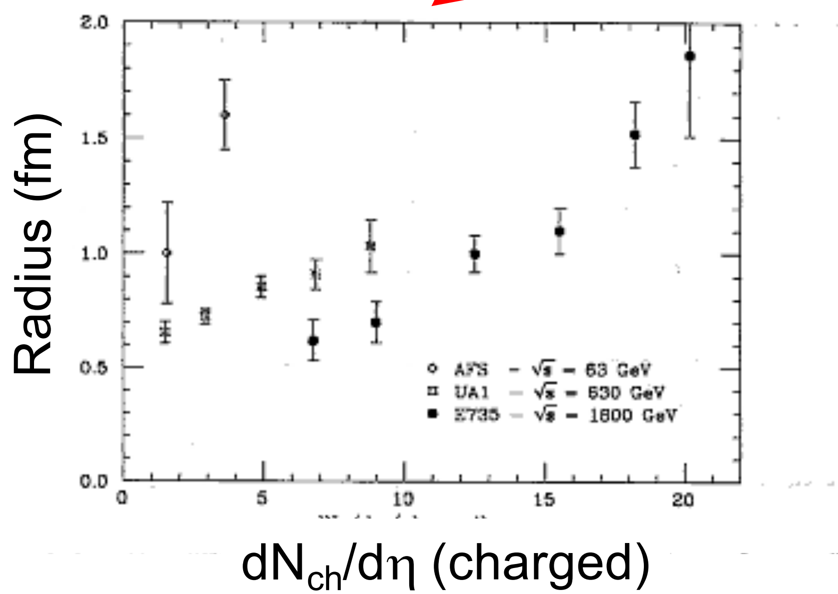
where M is the mass of a nucleon and E' the nucleon energy in the centre of mass system.

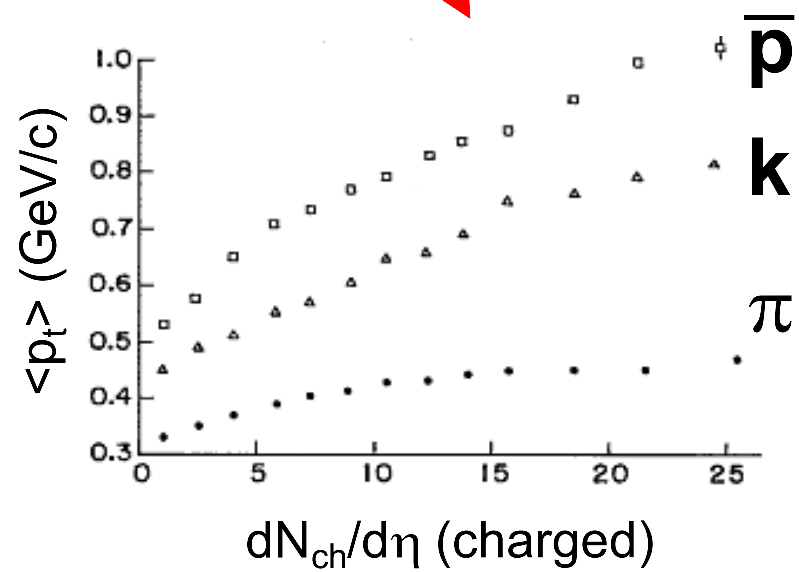
(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume V at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, 56, 309 (1955).
S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, 3, 15 (1956).

QGP Signatures?

Experiments (E735, UA1, others) observe substantially larger source volumes in high multiplicity pp (ppbar) events via particle correlations and boosted p_t spectra.





VOLUME 67, NUMBER 12 PHYSICAL REVIEW LETTERS 16 SEPTEMBER 1991

Transverse Baryon Flow as Possible Evidence for a Quark-Gluon-Plasma Phase

Péter Lévai[a] and Berndt Müller
Department of Physics, Duke University, Durham, North Carolina 27706
(Received 13 March 1991)

Why Heavy Ions?

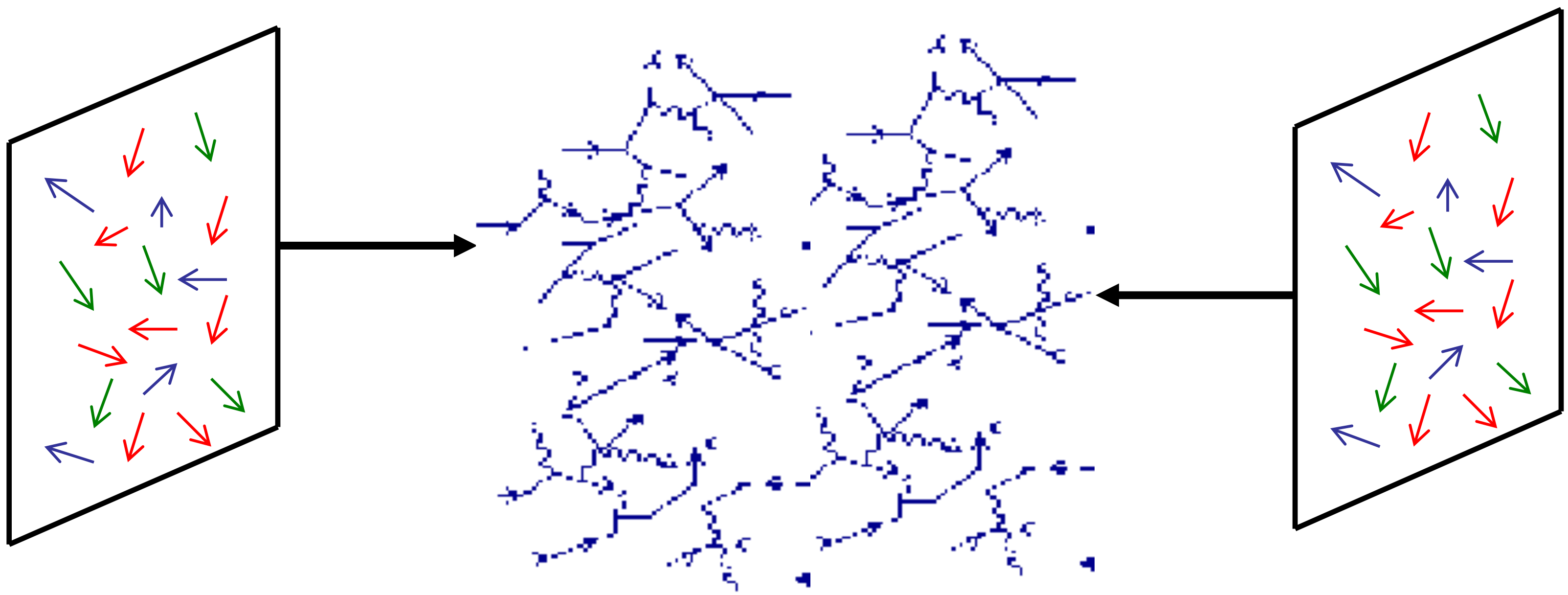
- High energy density may be achieved in proton-proton collisions, but the partonic re-interaction time scale is only of order 1-3 fm/c

- It is difficult to select events with different geometries and avoid autocorrelations

- We will see that probes with long paths through the medium are key observables

- We should not rule out p+p reactions, but rather study the similarities and differences with A+A reactions -- spoiler alert: this is a big issue

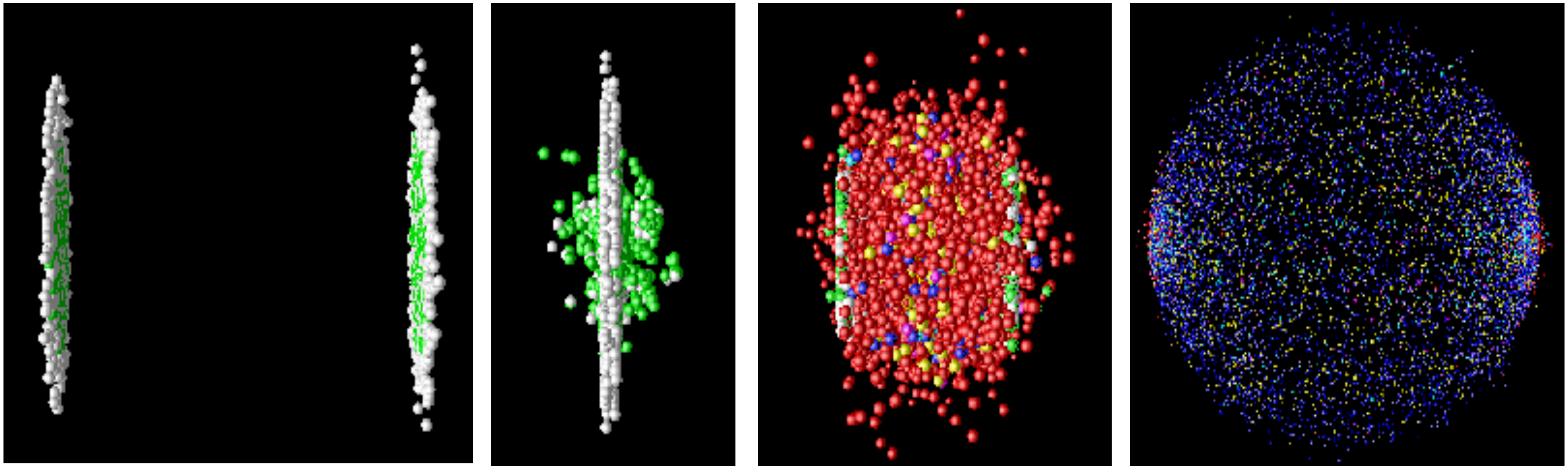
RHIC and LHC = Gluon Colliders



20,000 gluons, quarks, and antiquarks
are made physical in the laboratory !

What is the nature of this ensemble of partons?
New emergent phenomena?

Heavy Ion Time Evolution



1. Initial Nuclei Collide
2. Partons are Freed from Nuclear Wavefunction
3. Partons interact and potentially form a Quark-Gluon Plasma
4. System expands and cools off
5. System Hadronizes and further Re-Scatters
6. Hadrons and Leptons stream towards our detectors

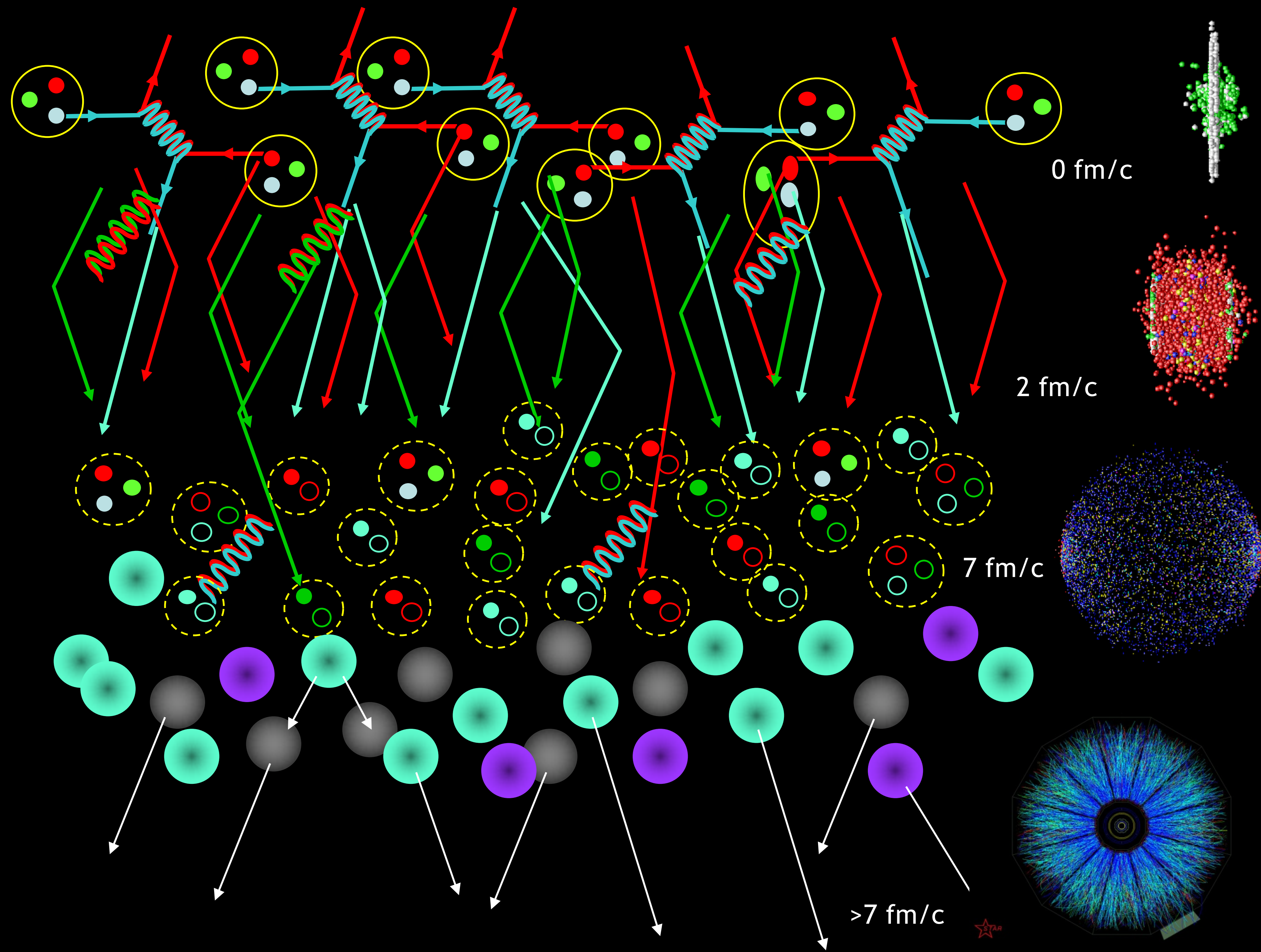
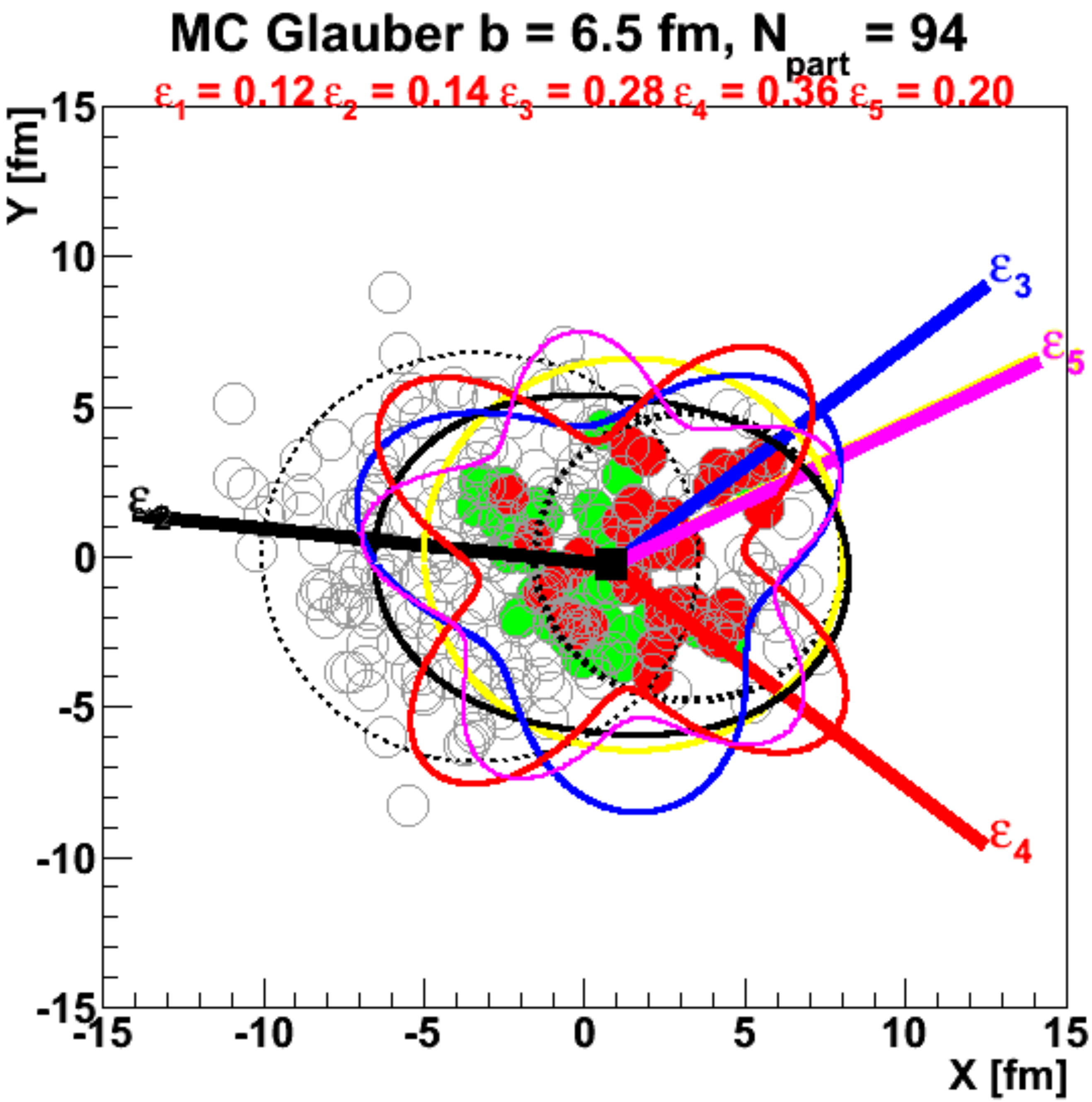


Diagram from Peter Steinberg

Initial Conditions

Monte Carlo

Glauber Model and Characterization



https://tglaubermc.hepforge.org/

TGlauberMC is

- Home
- Subversion
- Tracker
- Wiki

TGlauberMC: A ROOT-based implementation of the PHOBOS Glauber Monte Carlo

Authors: Burak Alver (MIT), Mark Baker (BNL), Constantin Loizides (MIT), Peter Steinberg (BNL)
Brookhaven National Laboratory (BNL) & Massachusetts Institute of Technology (MIT)

"Glauber" models are used to calculate geometric quantities in the initial state of heavy ion collisions, such as impact parameter, number of participating nucleons and initial eccentricity. The four RHIC experiments have different methods for Glauber Model calculations, leading to similar results for various geometric observables. In this document, we describe an implementation of the Monte Carlo based Glauber Model calculation used by the PHOBOS experiment. The assumptions that go in the calculation are described. A user's guide, arXiv:0805.4411, is provided for running various calculations.

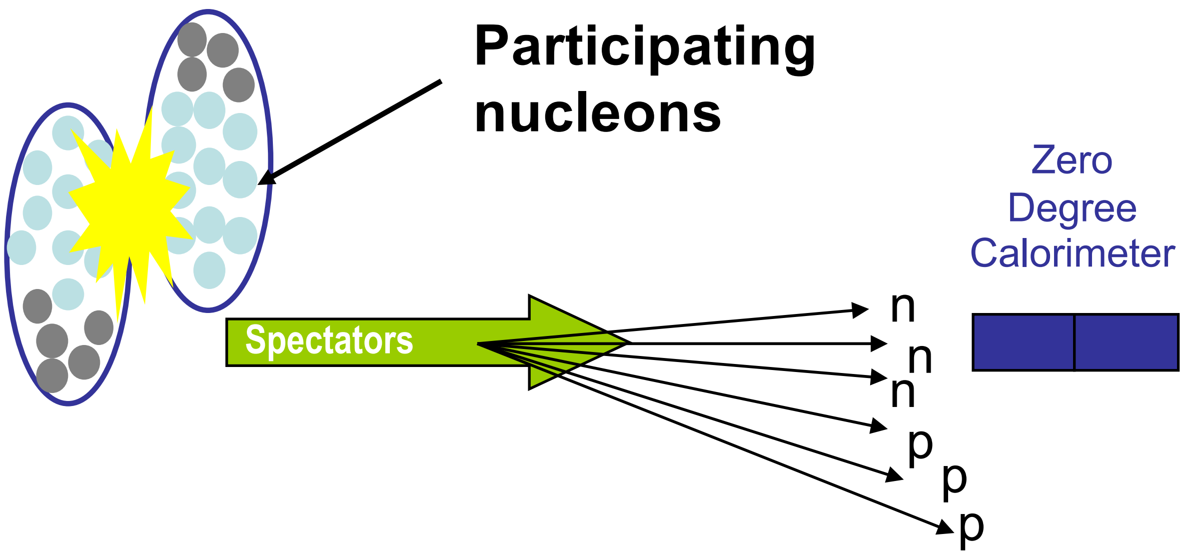
An **improved version (v2)** by C. Loizides (LBNL), J. Nagle (Colorado U.), P. Steinberg (BNL) is described in arXiv:1408.2549, which includes tritium, Helium-3, and Uranium, as well as the treatment of deformed nuclei and Glauber-Gribov fluctuations of the proton in p+A collisions.

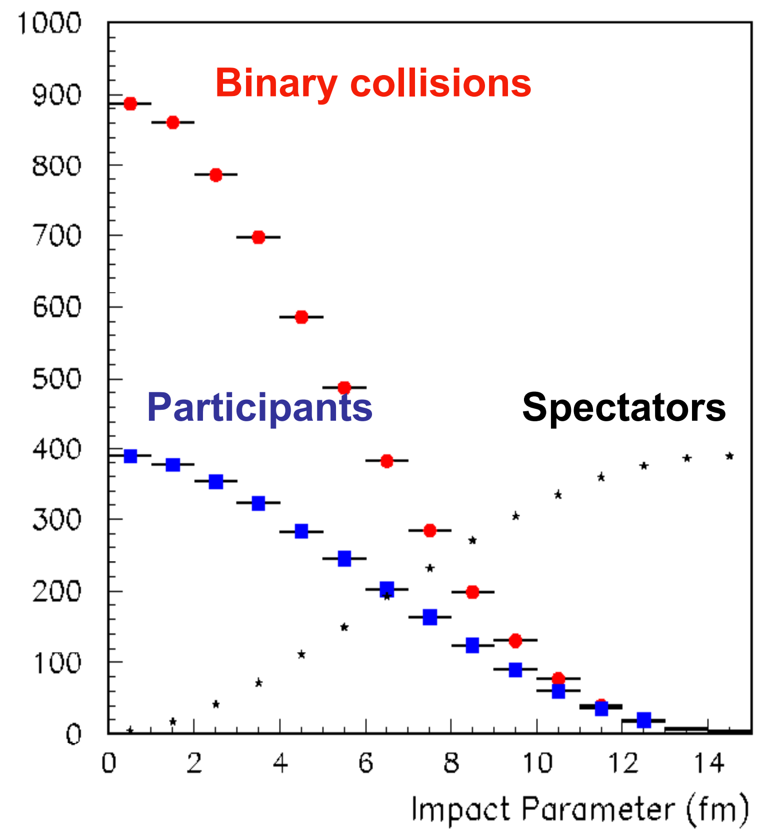
For the latest release see the TGlauberMC downloads page.

Click here to contact the authors with questions.

Collision Characterization

The impact parameter determines the number of nucleons that participate in the collision.





Participants = 2 x 197 - Spectators

Glauber Modeling in High-Energy Nuclear Collisions
Annual Review of Nuclear and Particle Science
Vol. 57: 205-243 (Volume publication date November 2007)
First published online as a Review in Advance on May 9, 2007
DOI: 10.1146/annurev.nucl.57.090506.123020

Michael L. Miller,[1] Klaus Reygers,[2] Stephen J. Sanders,[3] and Peter Steinberg[4]

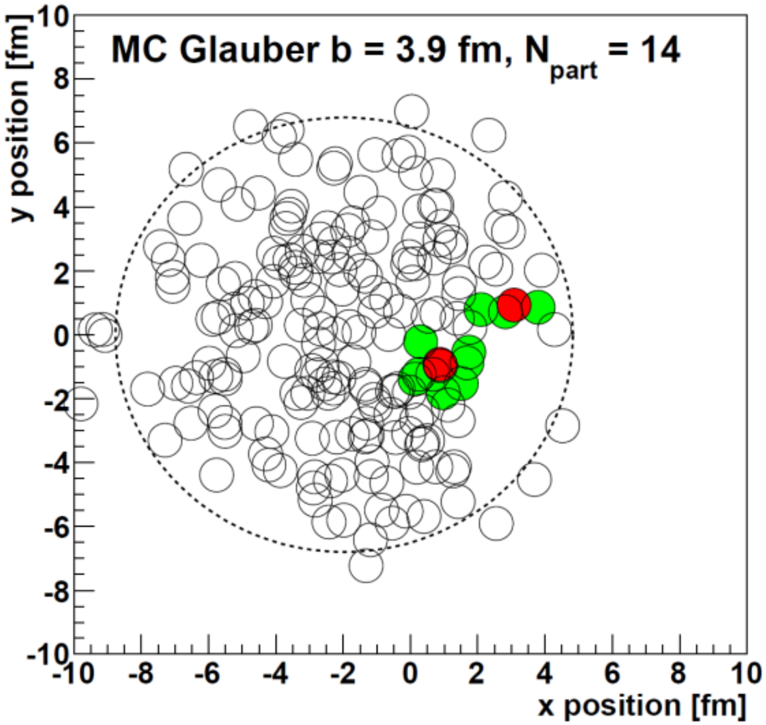
Relate experimental observables to averages from the Monte Carlo Glauber.

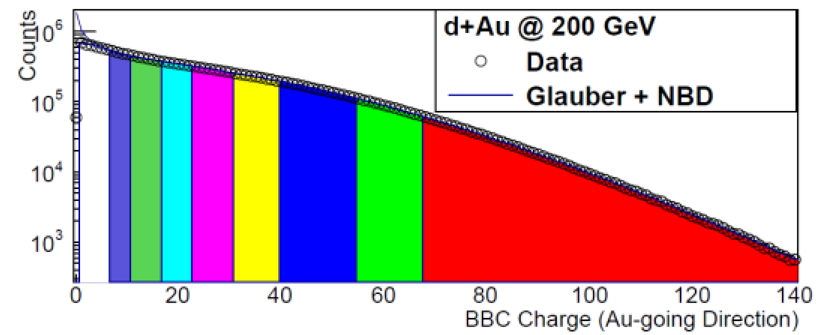
Ncoll (binary collisions), Npart (participants), Nspec (spectators) b (impact parameter), elliptical shape, orientation, overlap area,..

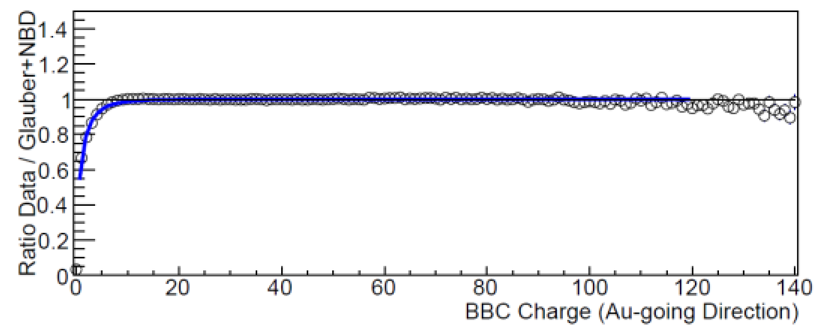
$$\varepsilon_n = \frac{\sqrt{\langle r^2 cos(n\phi)\rangle^2 + \langle r^2 sin(n\phi)\rangle^2}}{\langle r^2\rangle}$$

$$S = 4\pi\sqrt{\langle x^2\rangle\langle y^2\rangle - \langle xy\rangle^2}$$

ALICE Centrality Paper – good resource
http://arxiv.org/abs/1301.4361

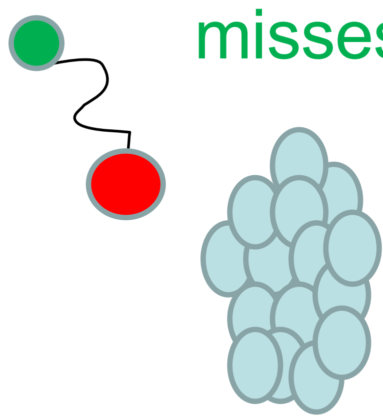


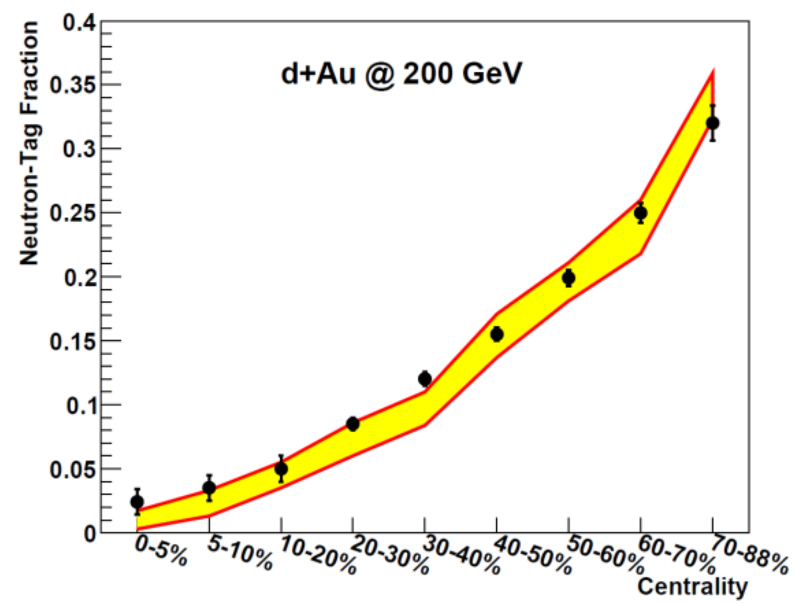




d+Au

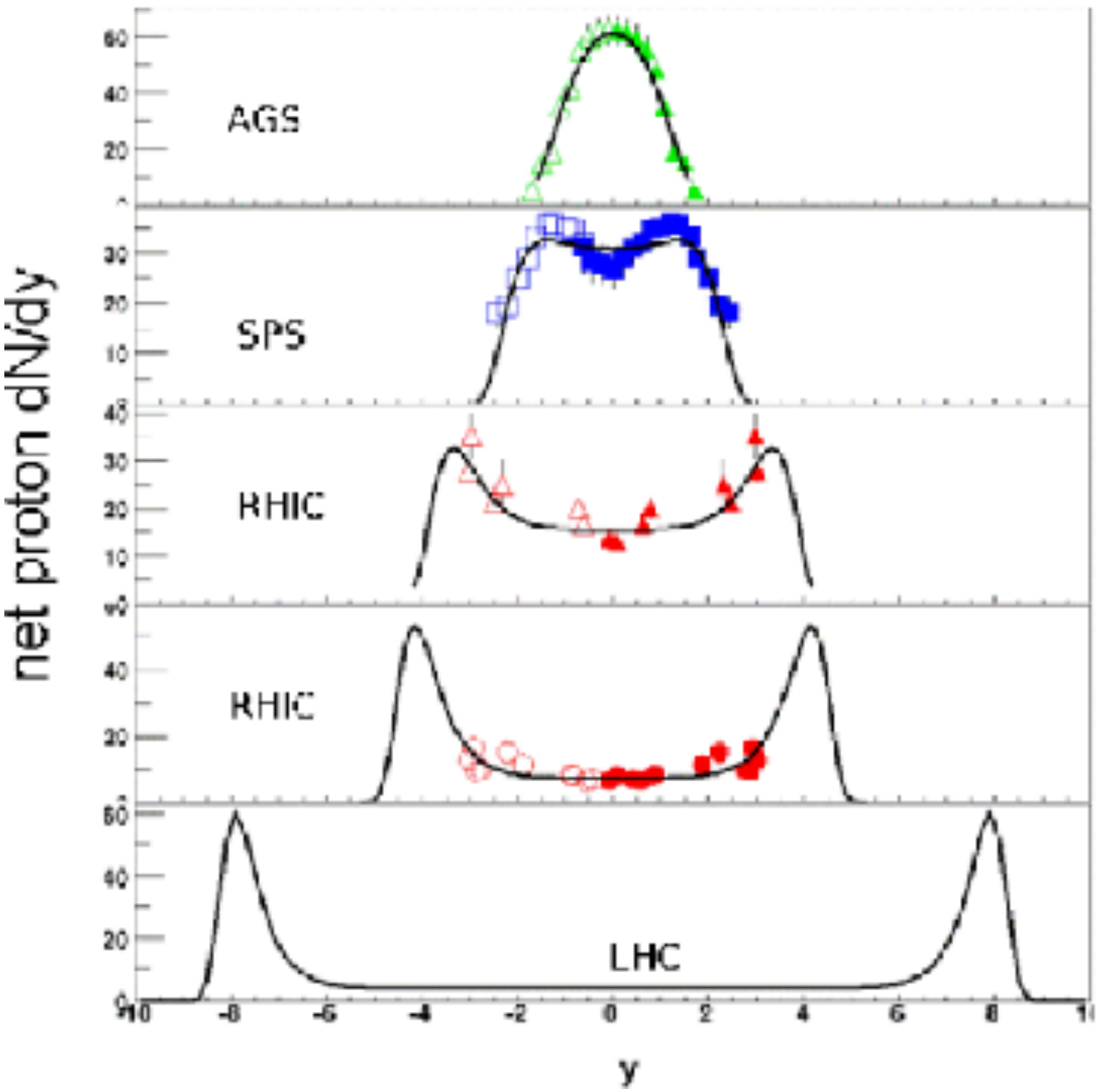
Sometimes the neutron misses





http://journals.aps.org/prc/abstract/10.1103/PhysRevC.90.034902

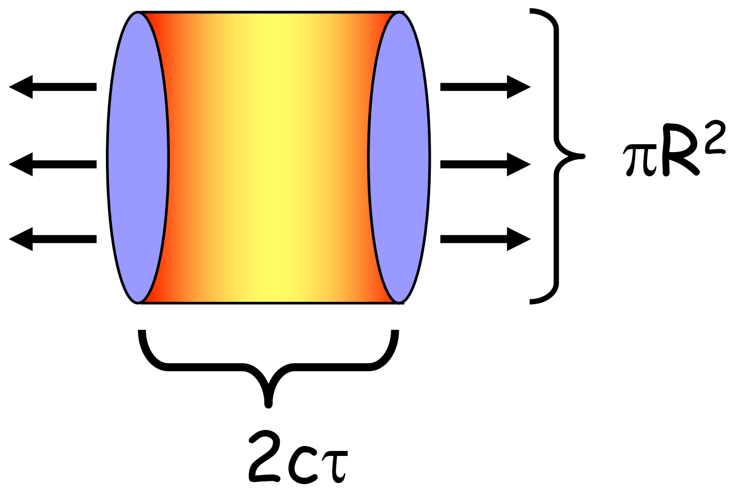
How much energy goes into QGP?



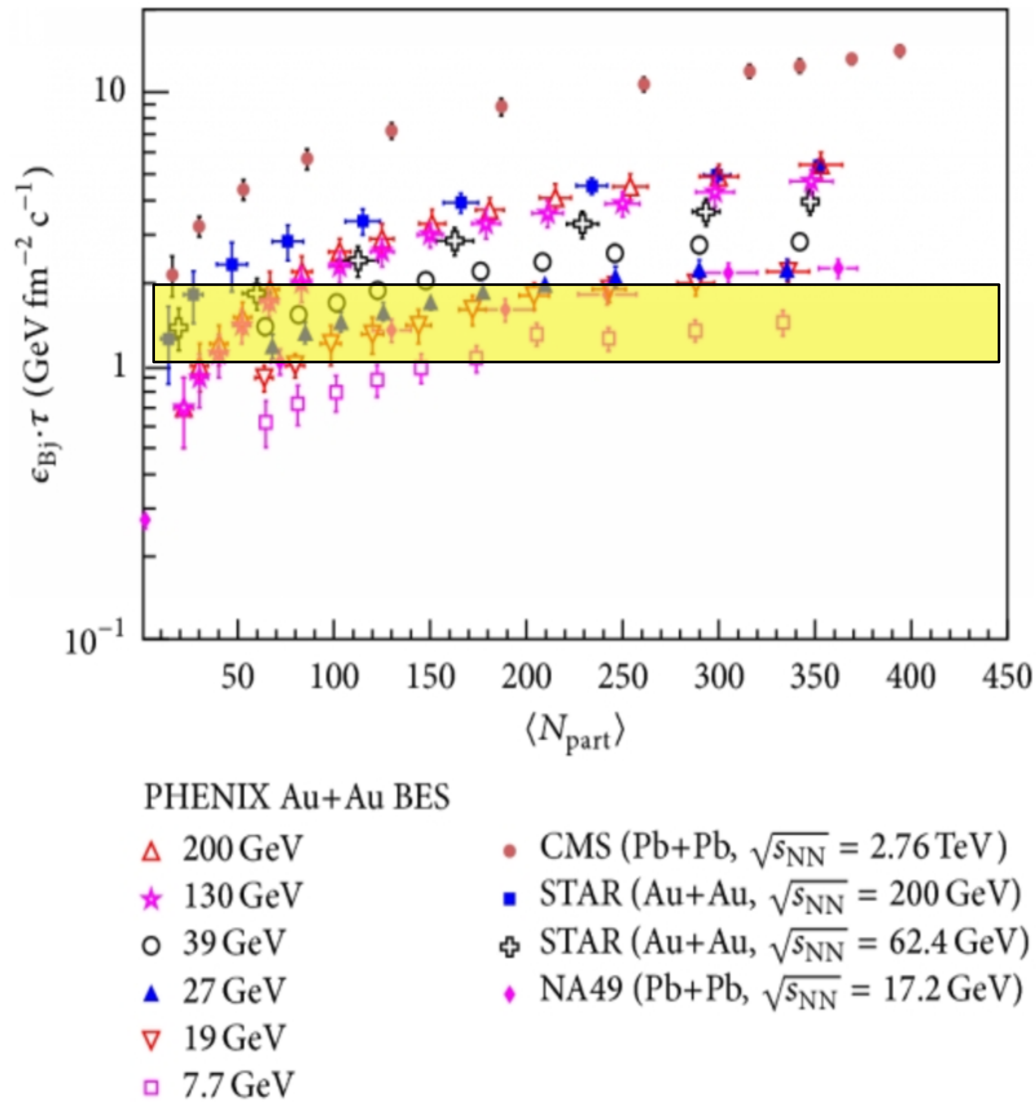
At RHIC out of a maximum energy of 39.4 TeV in central Gold+Gold reactions, **26 TeV** is made available for heating the system.

Bjorken Energy Density

$$_{Bj} = \frac{1}{R^2}\frac{1}{2c} \quad 2\frac{dE_T}{dy}$$



10 GeV/fm³



Early energy density
well above expected
QGP transition

* Side note about errata or lack thereof…

Collision Dynamic Summary

- Depositing majority of kinetic energy into new medium

- Energy density appears above phase transition value

- Energy is distributed into particle production statistically

- No sharp global feature distinct from smaller hadron collisions, but instead gradual changes