QCD and Modern Theoretical Nuclear Physics

Strong interactions generate the energy in stars

Strong interactions generate the masses of nucleons and therefore the visible mass of the universe

Control the interactions of particles at the highest energies

Quarks and gluons combine together to make various forms of matter:
Some imagined and some not

Many manifestations of QCD are can be computed with precision.
Some cannot at present

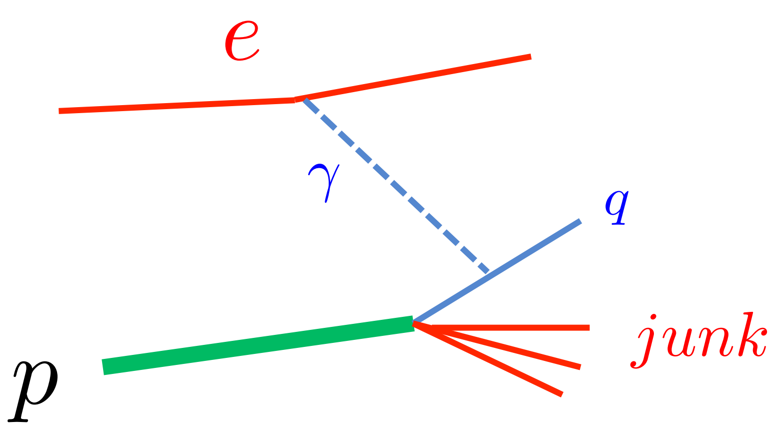
This talk outlines forefront areas where there is much to be learned

QCD is the theory of interactions of quarks and gluons
Quarks have color charge, fractional electric charge, and fractional baryon number.

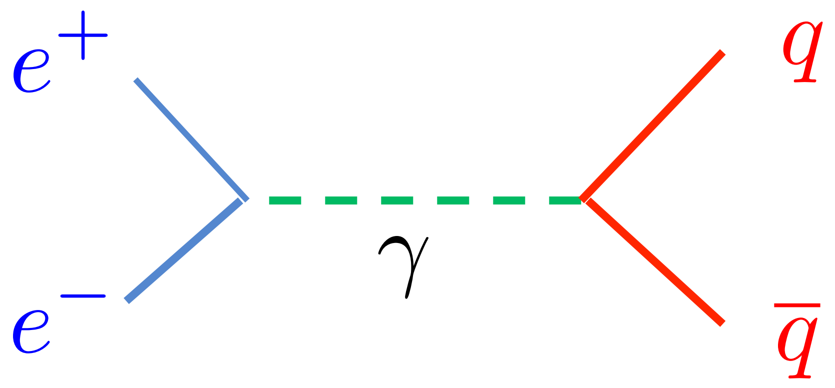
For light mass quarks:

Quark	Charge	Baryon Number
up	2/3	1/3
down	-1/3	1/3
strange	-1/3	1/3

Their existence was argued as a simple way to explain the spectroscopy of light hadrons. They were observed in the electromagnetic scattering of electrons on nucleons at the Stanford Linear Accelerator Center



Quarks in very high energy electron-positron collisions



Quarks always end up bound into mesons and nucleons before they get to detectors. There has never been a fractionally charged quark ever seen. This property of strong interactions is called confinement. It is caused because QCD predicts a long range liner force between quarks. This force is caused by a spin one colored particle, the gluon. QCD is a theory of the interactions of quarks and gluons

Color for quarks was proposed to solve the problem associated with the symmetry of the quark wavefunction for the nucleon, and the value of the cross section in electron-positron annihilation

The Gluon:

Generates the singular long range force that confined quarks into hadrons

Spin 1

8 color charges

Gluon is confined

Quarks and Gluons are described by Quantum Chromodynamics

In the equations of motion for QCD, gluons are massless.

If quarks have very small masses (a few MeV), a good description of mesons and baryons results.

The mass of the nucleon is two orders of magnitude larger than the mass of its constituents.

The gluon is a fundamental particle that is responsible for 99% of the visible mass of the universe.

We understand very little of its properties

Lattice Gauge Theory:

Path integral formulation of quantum mechanics:

$$\int [dq]\ e^{iS}$$

where

$$S = \int dt\ L[q(t)]$$

In quantum field theory, the coordinates are the quantum fields describing particles at each point in space. If we discretize space and time, then the path integral is a very large, but finite dimensional integral.

But it is oscillating and very hard to compute

$$q = \phi(t_i, \vec{x_i})$$

Rotate to Euclidean space

$$\int [dq] \; e^{-S}$$

Is a representation for

$$Tr \; e^{-\beta H} \qquad \text{when} \qquad \beta \to \infty$$

(For finite beta one is computing thermal properties)

Is used to compute correlation functions such as

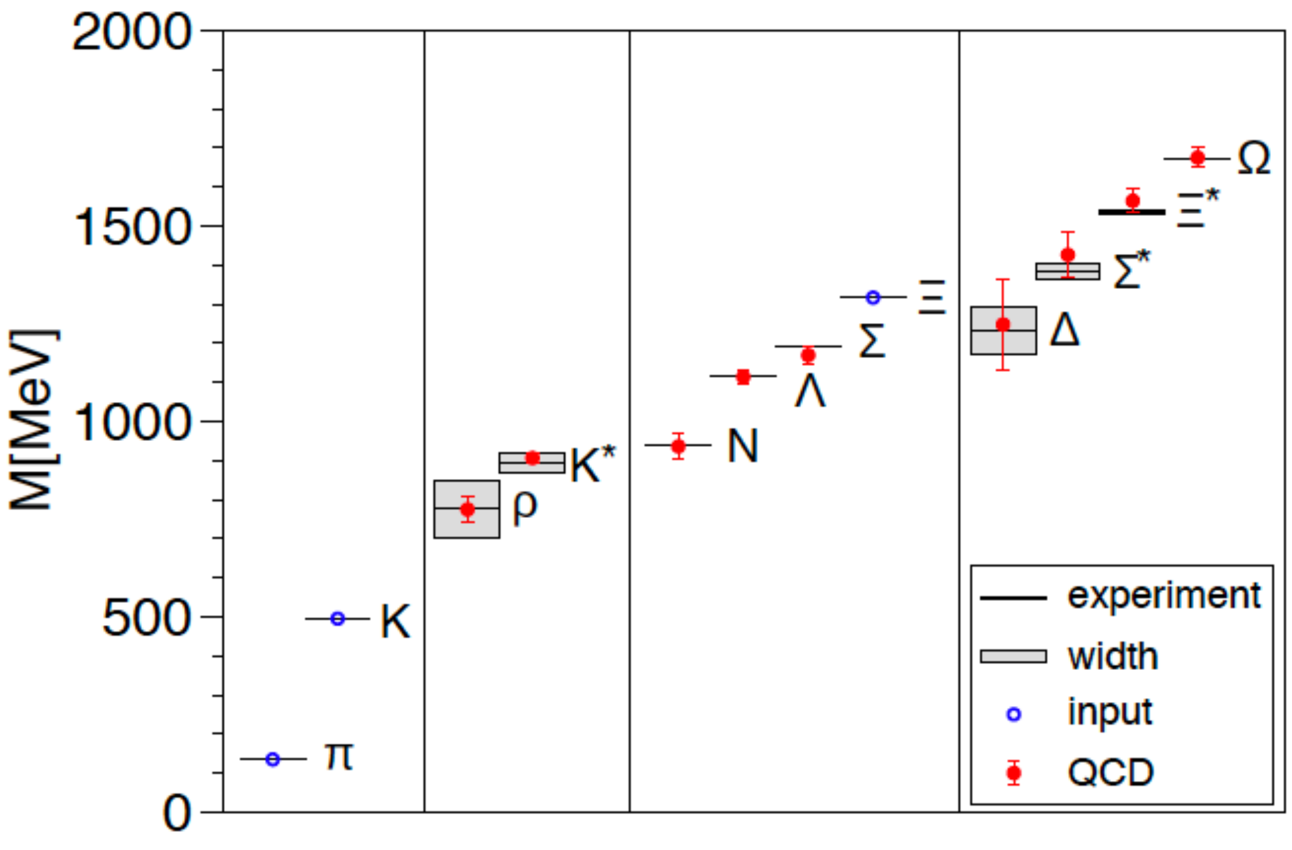
$$< q(t)q(0) >= \sum_n | < 0|q(t)q(0)|n > |^2 e^{-E_n t}$$

In the limit of large t, this projects onto the lowest energy intermediate state:

$$< q(t)q(0) >= | < 0|q(0)|n > |^2 e^{-Et}$$

E is the energy it takes to make the state of lowest energy from the ground state with the operator q

Non-oscillatory integrals can be computed using Monte-Carlo methods
Can compute energy an wavefunctions of lowest energy states (Creutz)
Spectroscopy of QCD is now a precision science:



Fodor et. al 2009

USQCD

e.g., Proton Structure Deliverables

- Quantities with currently quantifiable uncertainties and goals

Quantity	Current uncertainty	Uncertainty Goal	Impact/Target
g_A	5%	3%→1%	Benchmark of LQCD; Neutrino-nucleus X-secs V_{ud} given high enough precision
L_u, L_d	~20%	5%	Understanding the spin of the proton
g_S, g_T	20%, 7%	10%, 3%	Ultracold neutron experimental searches for BSM interactions in neutron decay
$a_{\pi\pi}^{(I=2)}$	1%	✓	More precise than experiment/phenomenology
$\langle N\|\bar{s}s\|N\rangle$	25%	10%	Input for dark matter direct detection experiments; mu2e conversion
$\langle x\rangle$	~15%	5%	Aim for ab initio input to PDFs (USQCD goal)
$\langle r^2\rangle_p$	~10%	2%	Impact proton radius puzzle
L_1, L_{1A}	20%	5%	pp fusion; next generation neutrino detectors

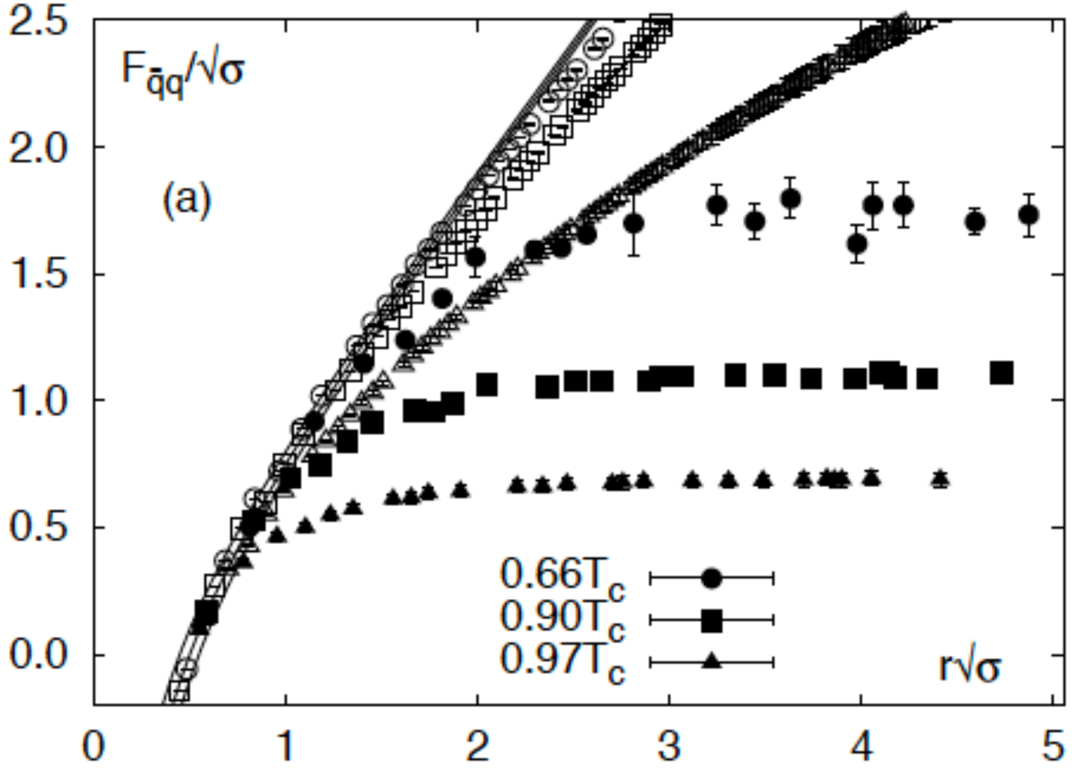
- Most goals achievable achievable in 2021 timeframe

Wide variety of hadron observable are being computed to greater precisions.

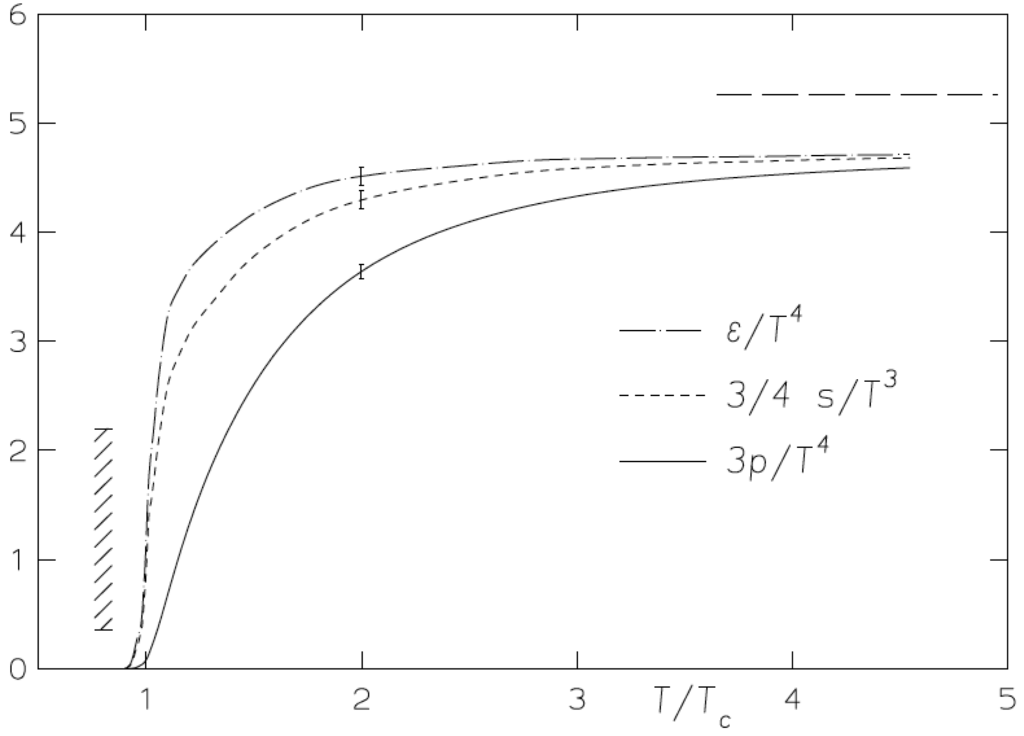
Some of intrinsic interest, some for other applications

One of the first exploratory computations done using lattice gauge theory is QCD at finite temperature.
(Great uncertainty at finite density since at finite baryon density, the path integral remains oscillatory)

First results from Creutz showed that in QCD with only gluons, the force is linear.
At high temperature there is a confinement-deconfinement phase transition where confinement disappears



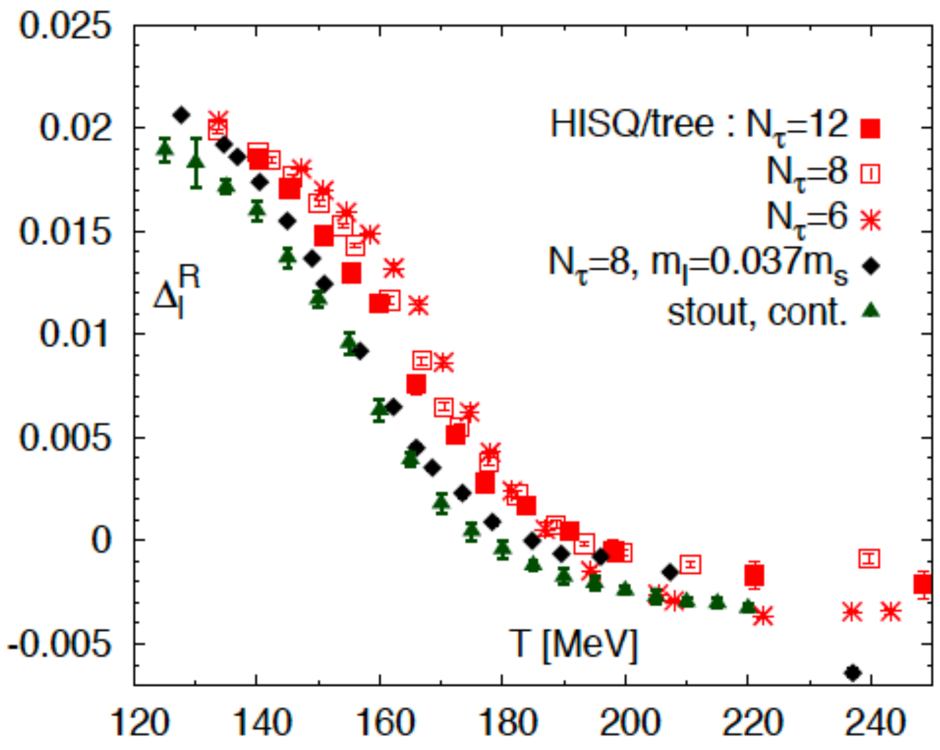
Potential energy between quarks: Open symbols for QCD without quarks at low temperatures; Solid symbols at with quarks at various temperatures (Karsch et al)



Energy density, pressure and entropy density tend to ideal gas of quarks and gluons at high temperature

Chiral Symmetry Restoration:

In equations of motion for QCD, up and down quark masses are very small, a few MeV. In real world, constituent masses of quarks are of the order of the typical QCD scale, 300 MeV A chiral symmetry protects these masses, and achieving constituent masses requires the symmetry is broken. This is accomplished by generating a chiral condensate. At high temperatures, this condensate evaporates, and quarks become small mass.



Chiral condensate as a function of temperatures for increasingly refined lattice computations

Formation of the condensate breaks a chiral symmetry. A low mass pseudo-scalar boson, the pion results

Future Directions with Much Larger Machines:

SciDAC Scientific Discovery through Advanced Computing

ECP EXASCALE COMPUTING PROJECT

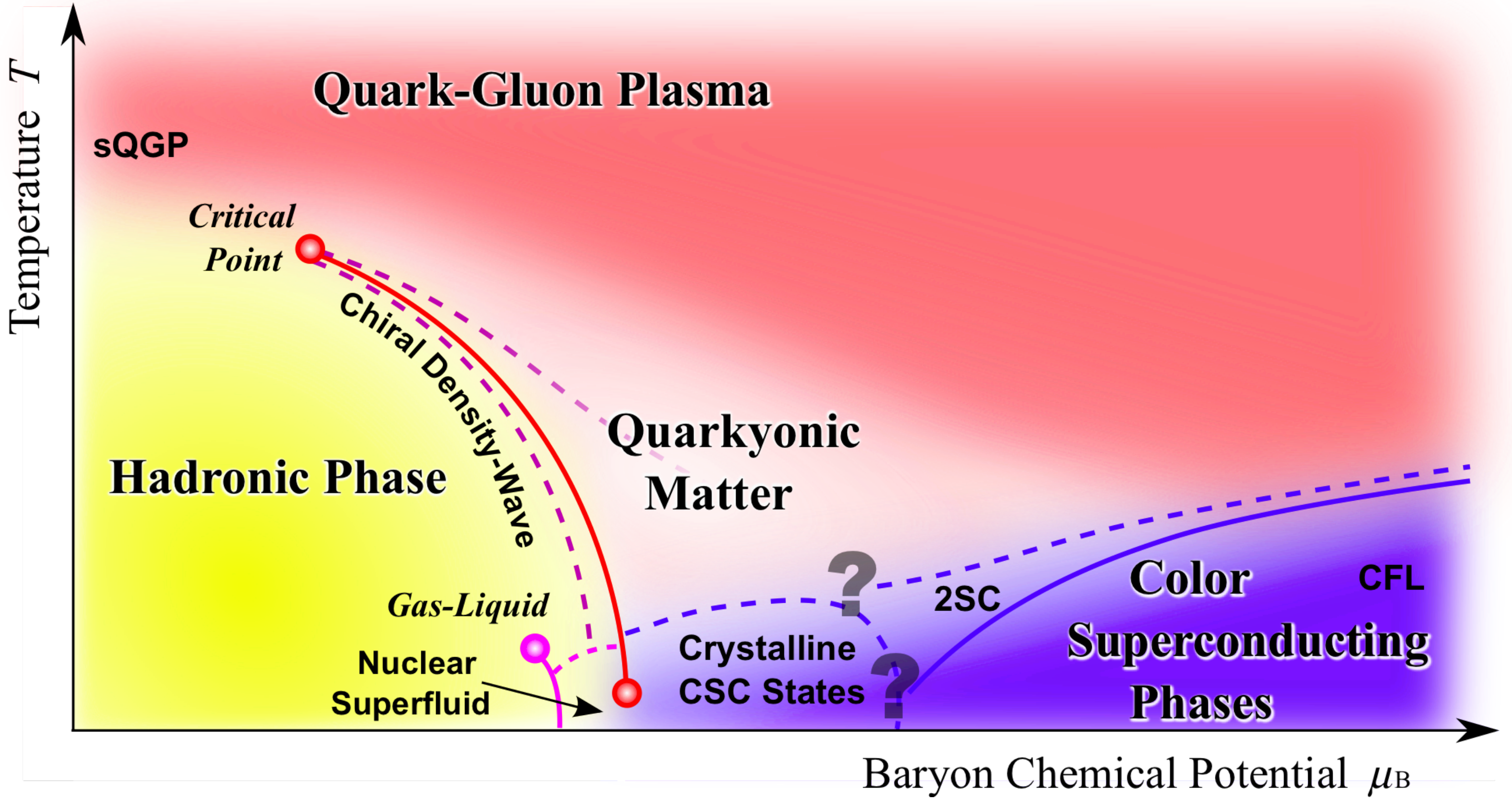
Precision matrix elements for hadronic and semi-hadronic processes
Structure functions, Imaging

Mystery of why the binding energy of nuclear matter is so small: In QCD it is naturally of order of the proton mass but is really 15 MeV?
Nucleon Forces?
Binding energy of nuclei?

Quantum computing?
Example: Fourier transformation
NlnN for N values
For p qbits (p 2 component states),

$$N = 2^p$$

Ordinary computing: $p\ 2^p$ Quantum computing p^2



Our understanding of properties of matter at high energy densities is now quite involved:

Hadronic Phase:
Quarks and gluons confined into hadrons

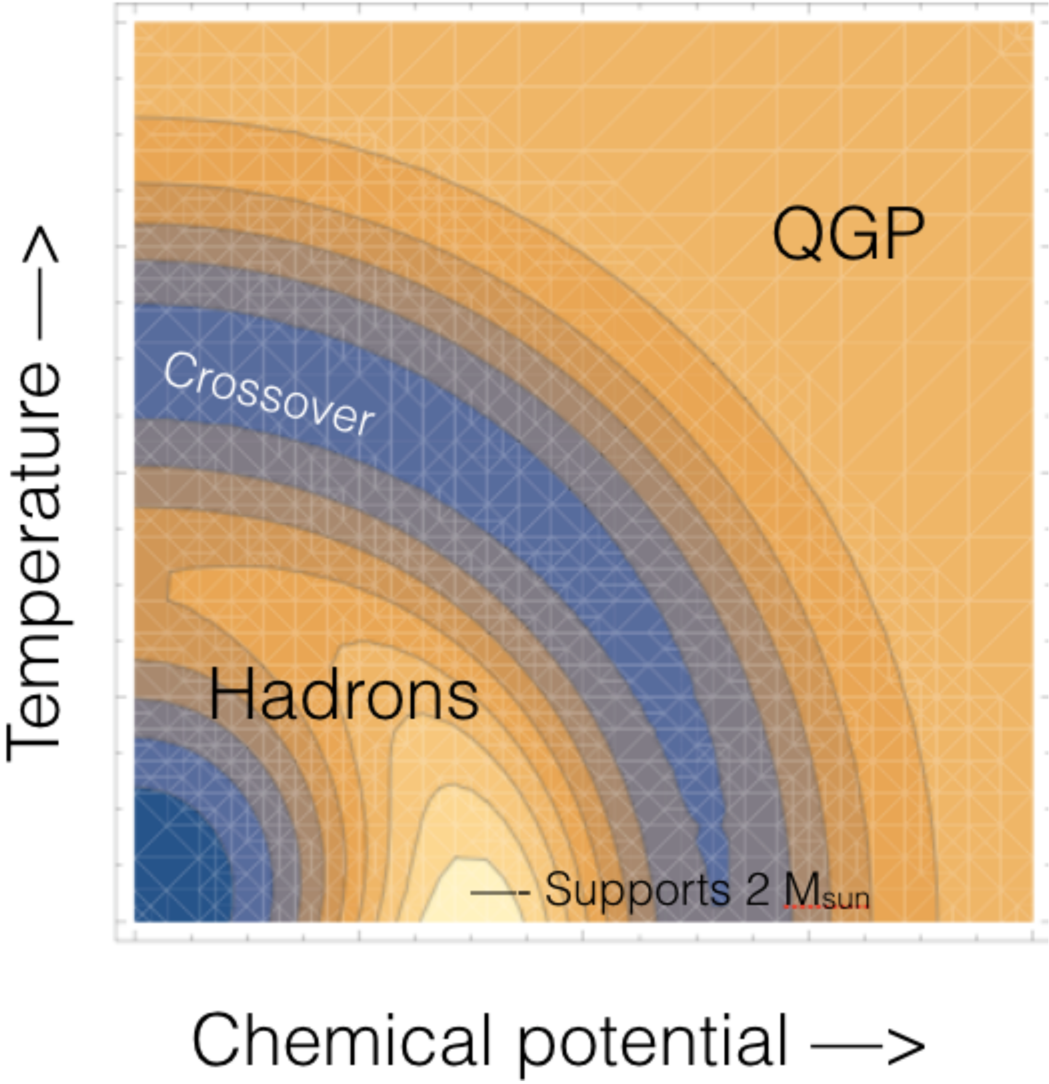
Quark Gluon Plasma:
Deconfined massless quarks and gluons

Quarkyonic Matter:
Fermis gass with quarks massless and deconfined in the Fermi Sea, but confinement of mesons and Fermi surface baryons

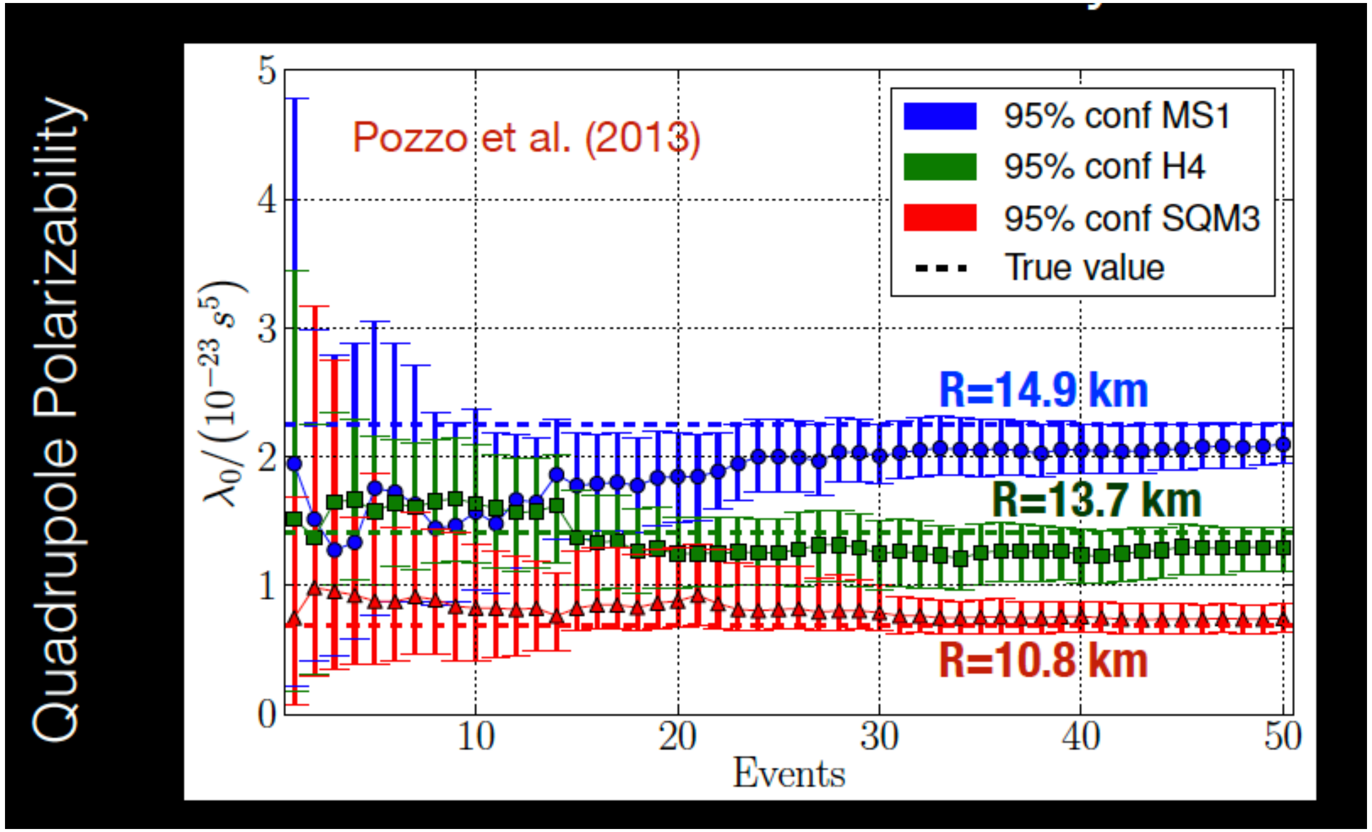
Color Superconductivity:
Qarks bound into Cooper pairs at Fermi Surface

Difficult to compute at finite density because unlike the case at zero baryon density: the path integral which one needs to compute is of various signs, and there is no good existing Monte Carlo Method

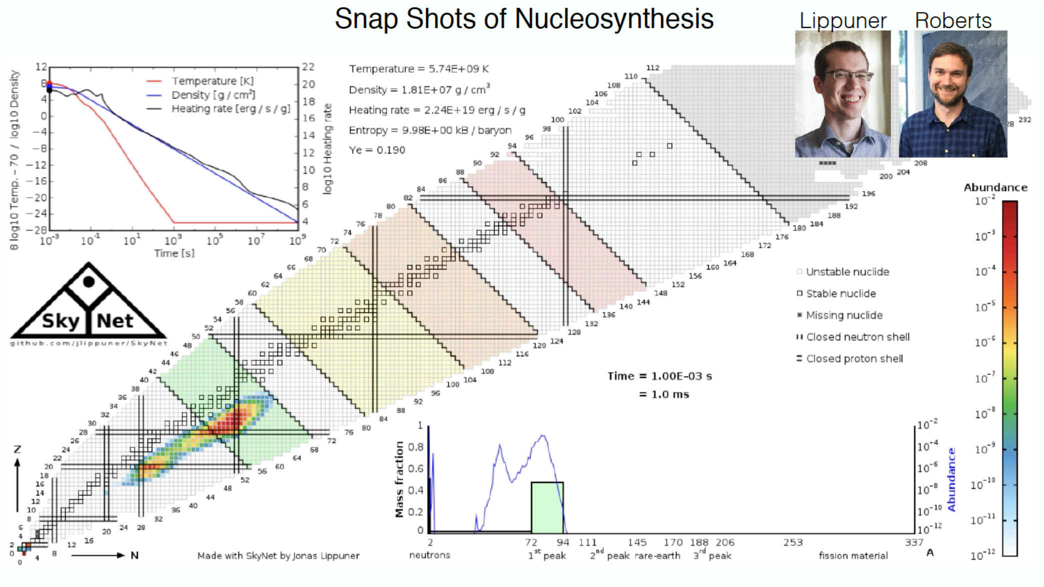
A variety of machines at FAIR, BNL and DUBNA can study the high density region

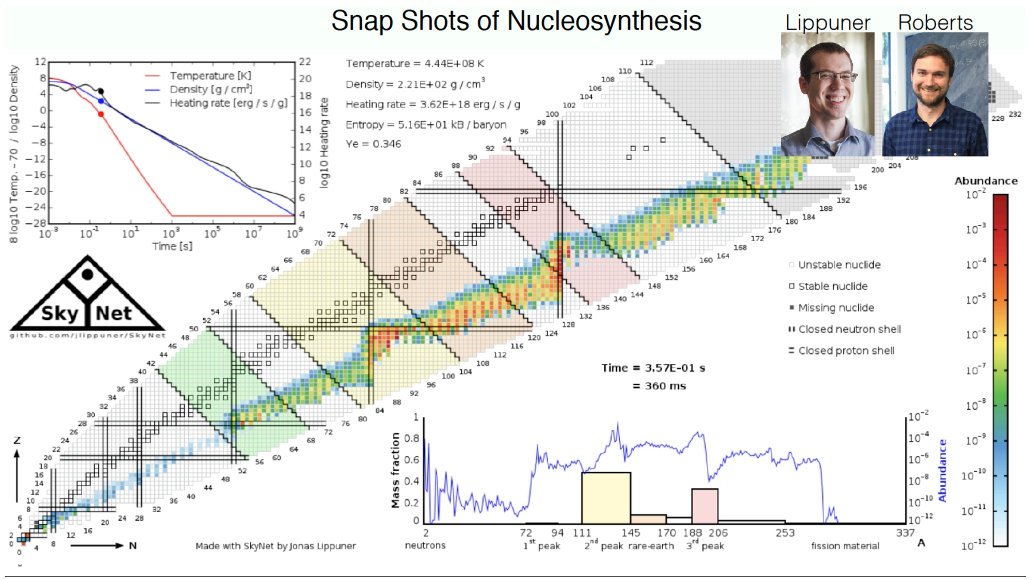


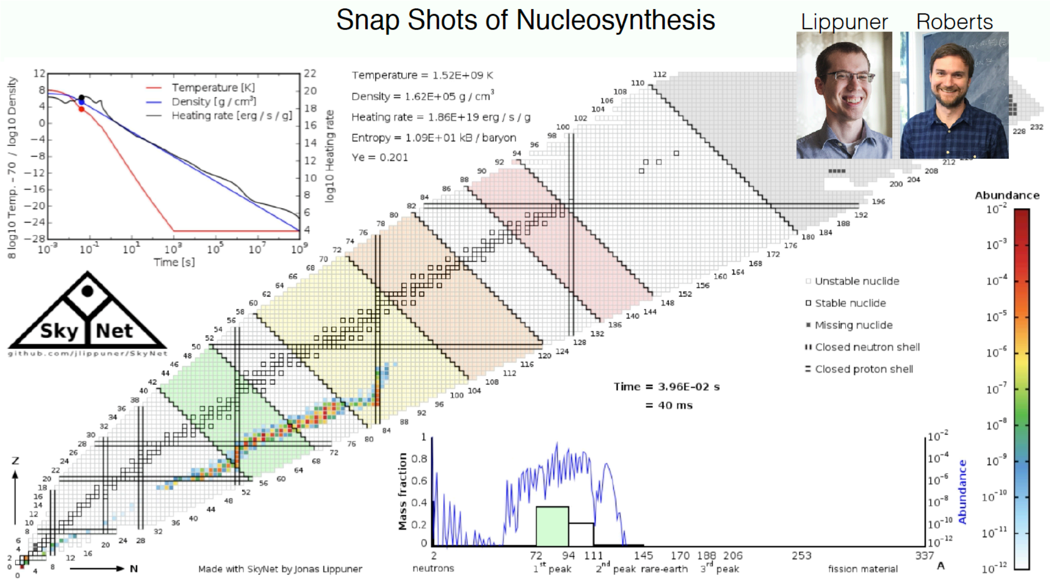
Constraint for measured masses of neutron stars: Sound velocity at some baryon density must exceed 1/3 (blue is low sound velocity, yellow higher)

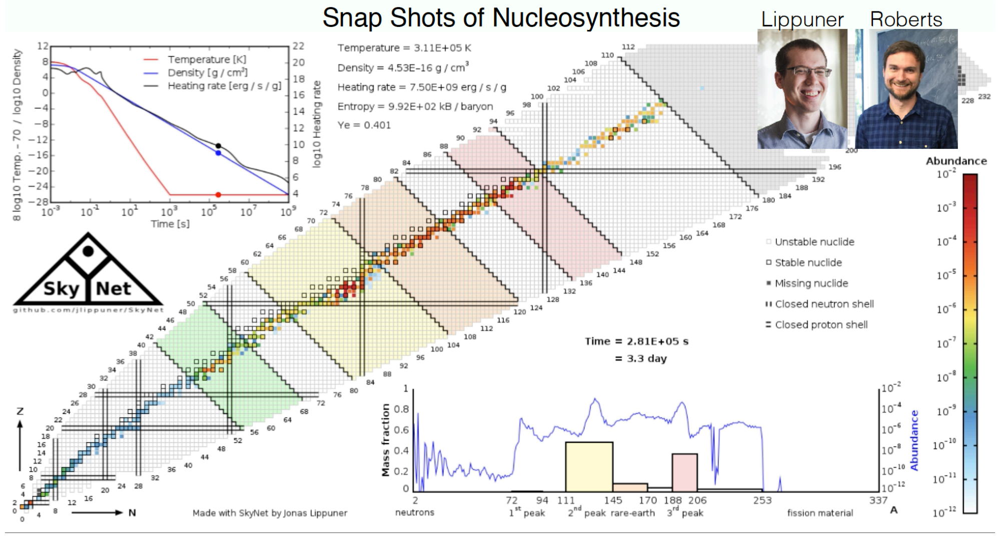


Measurements of quadrupole polarizability of gravitational radiation measured in neutron star collisions will give radii of neutron stars in collisions: This will imply strong constraint on the equation of state of high density matter



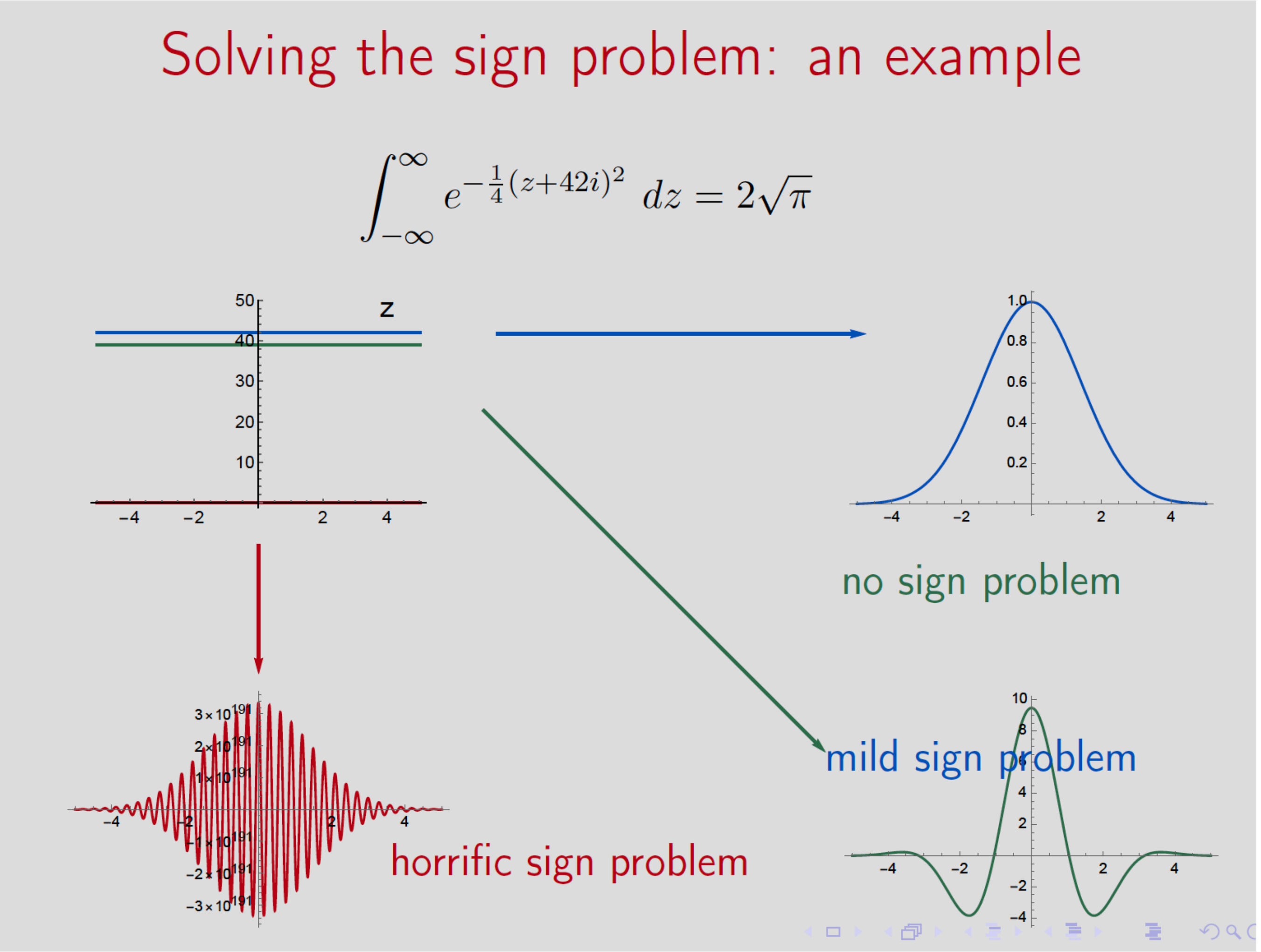






Ordinary supernova could never account for abundances of heavy nuclei (explosion begins with lighter elements); Neutron star collisions can do this since begin with heavier more neutron rich matter; Correctly predicts observed light seen from collisions

For problems in real time or finite density systems:
Path integral is oscillating



Basar

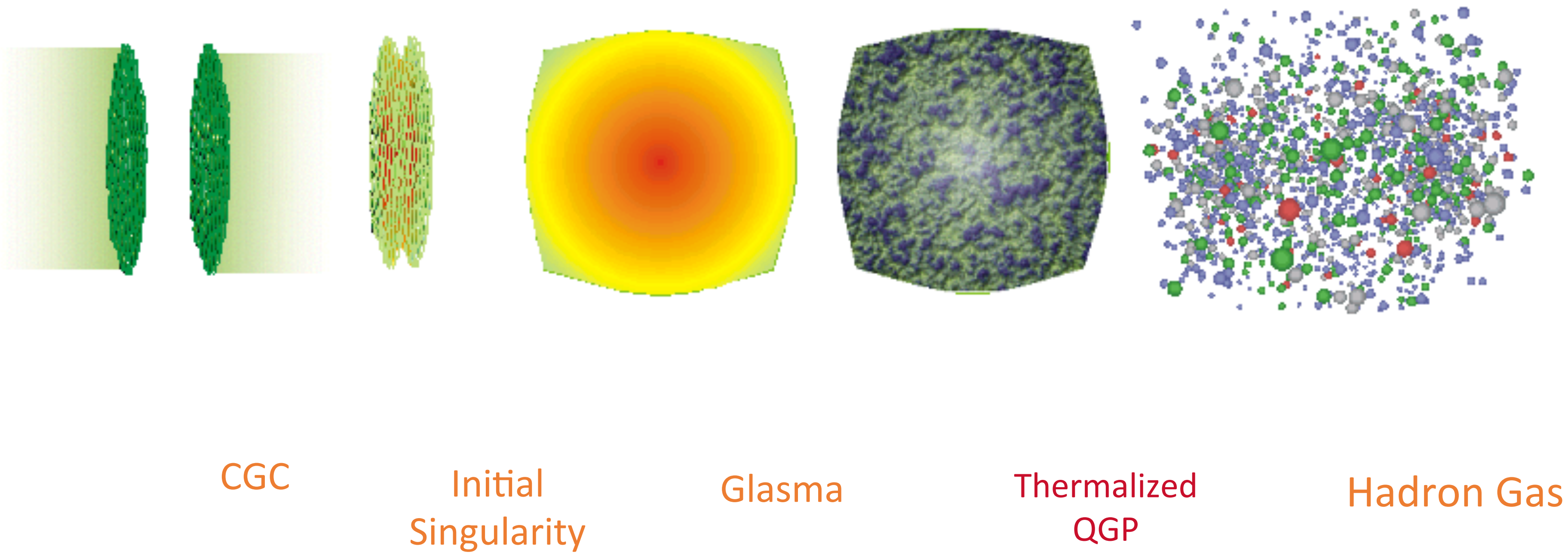
Solved by looking for stationary phase points in complex plane of fields

Progress in understanding how to do this using Monte Carlo techniques

Need to find the contour in the complex field space and evaluate integral along contour using stochastic methods

Alexandru, Basar, Bedaque and Ridgway

Properties of Matter at Very High Energy Density:

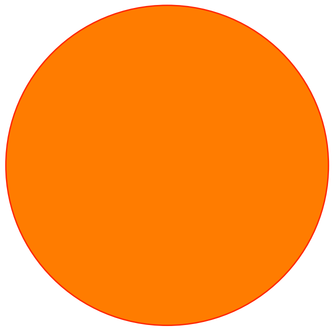


Heavy Ion Collision at RHIC and LHC are successfully probing properties of Quark Gluon Plasma

Other forms of matter such as Color Glass Condensate and Glasma play important role in such collisions and might be studied in an electron-ion collider

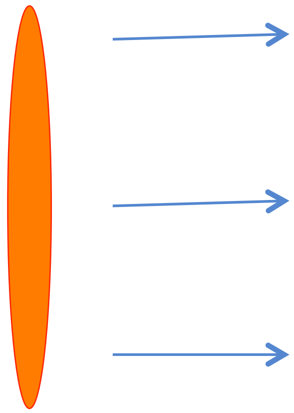
Controls properties of highest energy cosmic ray interactions

Making Quark Gluon Matter in Heavy Ion Collisions

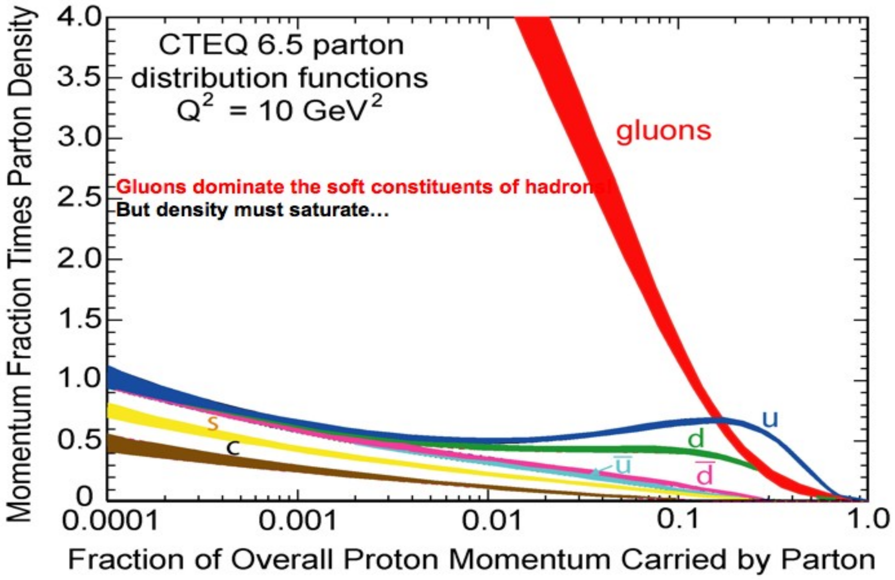


Hadron at rest

The part of the wavefunction of an ultra-relativistic nucleus responsible for high energy scattering is Lorentz contracted down to some typical QCD size scale ~ 1 Fm



A relativistic hadron with high momentum is composed of many gluon and quark constituents with much lower momentum along its directions of motion. The lowest momentum constituents are what make the longitudinal size of the hadron



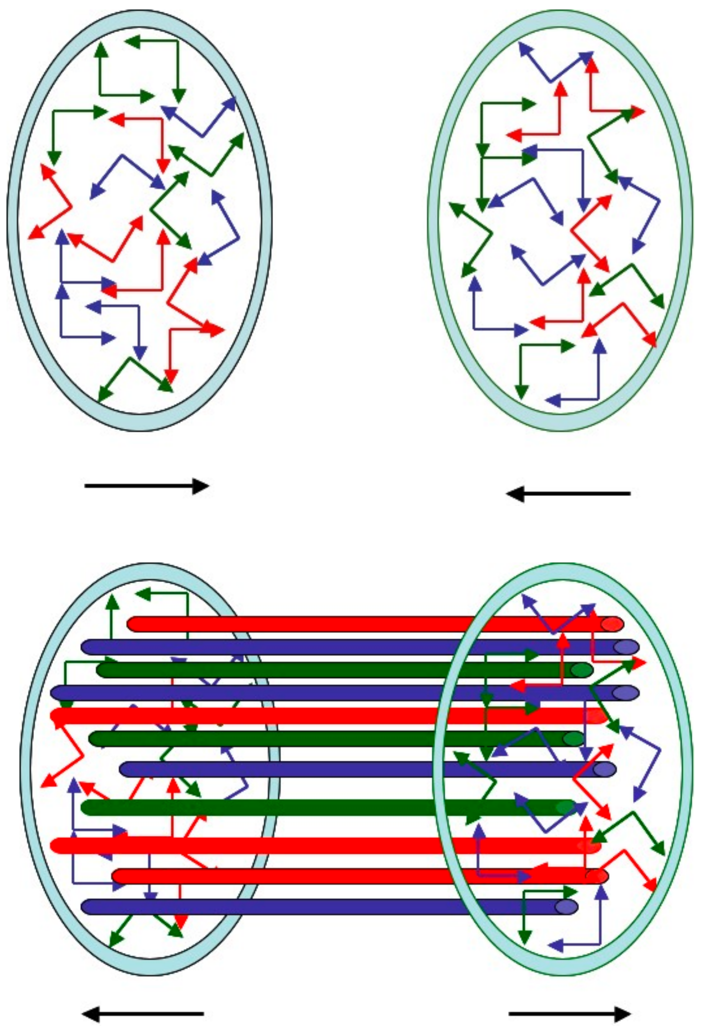
Color Glass Condensate:

Made from colored particles such as gluons and quarks
Condensate because the density of gluons is high and the gluons are highly coherent
Glass because Lorentz time dilation of the sources that generate the Color Glass Condensate slows time scales. Glasses are liquids that evolve so slowly they are for many purposes solids. CGC is mathematically like a spin glass.
McLerran-Venugopalan

Glasma:

Matter produced after the collision singularity that is initially longitudinal color electric and color magnetic fields. These fields evaporate into gluons which undergo a turbulent cascade to eventually make a thermalized Quark Gluon Plasma. Because of the coherence, the Glasma is a strongly interacting Quark Gluon Plasma
Kovner, McLerran, Weigert

(Ideas built from saturation observations of by Gribov, Levin, Ryskin; Mueller and Qiu)



Before the collision, the CGC color electric and color magnetic fields are perpendicular to direction of motion. They are analogous to high fields of an electromagnetically charged, ultrarelativistic particle

The collision dusts the colliding sheets with color electric and magnetic charges, and makes strong but weakly coupled longitudinal color fields

It is believed the Glasma thermalizes by turbulent interactions of classical fields, possibly with Bose condensation. Bose condensations issue is not fully resolved

Blaizot, Liao, Gelis Venugopalan, Berges, Schlichting, Eppelbaium, Morre, Kurkela, Greiner, Xu, Zhao, Zhuang

Hydrodynamic evolution of thermalized QGP is fairly well understood as evolution of an almost perfect fluid.

Summary:

QCD is a rich theory with many unexpected properties

It is now possible to compute many object with precision

Many others await new developments

There is a fundamental particle, the gluon, that is responsible for this wide variety of phenomenon

It’s properties are not understood.

Its role in mass generation and confinement is tangible and accessible