Studying a new Phase of Matter - An introduction to the Quark Gluon Plasma and Relativistic Heavy Ion Physics

How to make a QGP

RHI Physics - Leicester - U.K

Helen Caines - Yale University

September 2009

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Hard physics and the QGP

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Soft and hard physics????

Soft and hard physics????

Soft physics - bulk of particles produced sit below 2 GeV/c
phenomenology needed to describe data

Hard physics - calculable via pQCD

Relativistic Heavy Ions I - Why, Where, and How

RHI Physics

Leicester - U.K

Helen Caines - Yale University

September 2009

Outline :

QCD and Asymptotic Freedom

The Quark Gluon Plasma

The Accelerators

The Experiments

A brief history of RHI

1973: Gross, Wilczek and Politzer: Asymptotic freedom of QCD

1974: Workshop on “BeV/nucleon collisions of heavy ions” at Bear Mountain, NY - turning point in bringing HI physics to the forefront as a research tool

Driving Question: “Is the vacuum a medium whose properties one can change?”

“We should investigate.... phenomena by distributing energy of high nucleon density of a relatively large volume” T.D.Lee

Note: At this point the idea of quarks as the ultimate state of matter at high energy density has not yet taken hold

A brief history of RHI - II

1975: Collins and Perry - EoS of matter needed to set upper limit on the maximum mass of a neutron star

Crucial realization: ultra-high T & baryon density corresponds to QCD asymptotic regime, no longer hadronic. State would be a weakly interacting "Quark Soup"

1978: Shuryak coined the term "Quark Gluon Plasma"

1984: SPS starts, Pb-Pb at $\sqrt{s_{NN}}$ = 9-17.3 GeV (end 2003)

1986: AGS starts, S-S up to at $\sqrt{s_{NN}}$ = 7.6 GeV (end 2000)

2000: RHIC starts, Au-Au at $\sqrt{s_{NN}}$ = 200 GeV

2010: LHC starts, Pb-Pb at $\sqrt{s_{NN}}$ = 5.5 TeV

The standard model

Quantum field theory that unifies our understanding of 3 out of the 4 fundamental forces:

electromagnetic, weak, strong

~~gravity~~ understood classically but no QFT to date

Describes interactions of quarks and leptons through exchange of force particles - gauge bosons

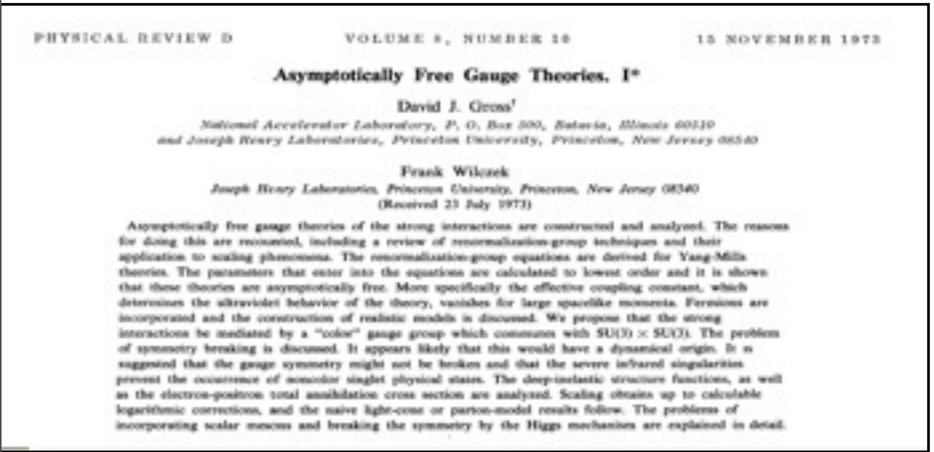
So far all experiments have been consistent with Standard model predictions

Does not describe:

All fundamental interactions - gravitation missing (+dark matter and dark energy)

Mass of the neutrinos (but simple extensions do)

QCD - Gross, Politzer, Wilczek - 1973



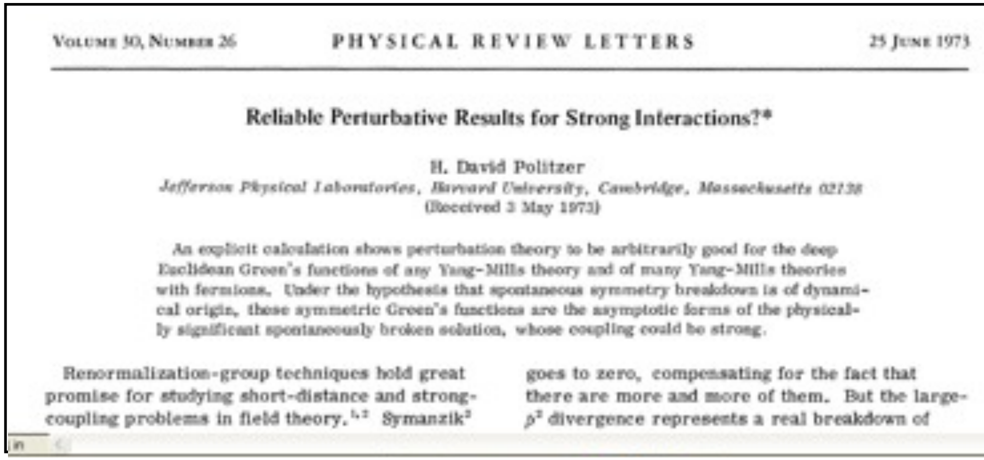
PHYSICAL REVIEW D VOLUME 8, NUMBER 10 15 NOVEMBER 1973

Asymptotically Free Gauge Theories. I*

David J. Gross[†]
National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510
and Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Frank Wilczek
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540
(Received 23 July 1973)

Asymptotically free gauge theories of the strong interactions are constructed and analyzed. The reasons for doing this are recounted, including a review of renormalization-group techniques and their application to scaling phenomena. The renormalization-group equations are derived for Yang-Mills theories. The parameters that enter into the equations are calculated to lowest order and it is shown that these theories are asymptotically free. More specifically the effective coupling constant, which determines the ultraviolet behavior of the theory, vanishes for large spacelike momenta. Fermions are incorporated and the construction of realistic models is discussed. We propose that the strong interactions be mediated by a "color" gauge group which commutes with SU(3) × SU(3). The problem of symmetry breaking is discussed. It appears likely that this would have a dynamical origin. It is suggested that the gauge symmetry might not be broken and that the severe infrared singularities prevent the occurrence of noncolor singlet physical states. The deep-inelastic structure functions, as well as the electron-positron total annihilation cross section are analyzed. Scaling obtains up to calculable logarithmic corrections, and the naive light-cone or parton-model results follow. The problems of incorporating scalar mesons and breaking the symmetry by the Higgs mechanism are explained in detail.



VOLUME 30, NUMBER 26 PHYSICAL REVIEW LETTERS 25 JUNE 1973

Reliable Perturbative Results for Strong Interactions?*

H. David Politzer
Jefferson Physical Laboratories, Harvard University, Cambridge, Massachusetts 02138
(Received 3 May 1973)

An explicit calculation shows perturbation theory to be arbitrarily good for the deep Euclidean Green's functions of any Yang-Mills theory and of many Yang-Mills theories with fermions. Under the hypothesis that spontaneous symmetry breakdown is of dynamical origin, these symmetric Green's functions are the asymptotic forms of the physically significant spontaneously broken solution, whose coupling could be strong.

Renormalization-group techniques hold great promise for studying short-distance and strong-coupling problems in field theory.[1,2] Symanzik[3] goes to zero, compensating for the fact that there are more and more of them. But the large-p^2 divergence represents a real breakdown of

Quantum Chromodynamics:

- theory of strong force
- quarks and gluons fundamental constituents
- gluons force carriers - self interacting
  (unlike photons in QED)

Quarks in the human body represent only ~2% of total mass.
Rest from strong interaction via chiral symmetry breaking

Comparing theories

QCD	QED
$\alpha_s \approx 1$	$\alpha_{em} = e^2/4\pi \approx 1/137$
Force = const	Force = $1/r^2$
3 colour charges: red, blue, green	2 charges: + , -
Gauge boson: g (8)	Gauge boson: γ (1)
Charged?: Yes	Charged?: No
self interaction	no self interaction

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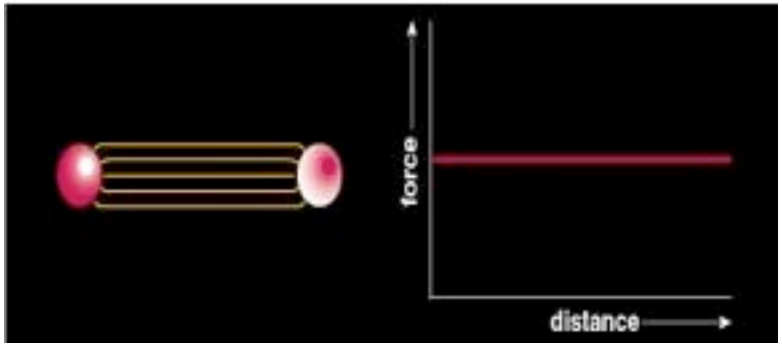

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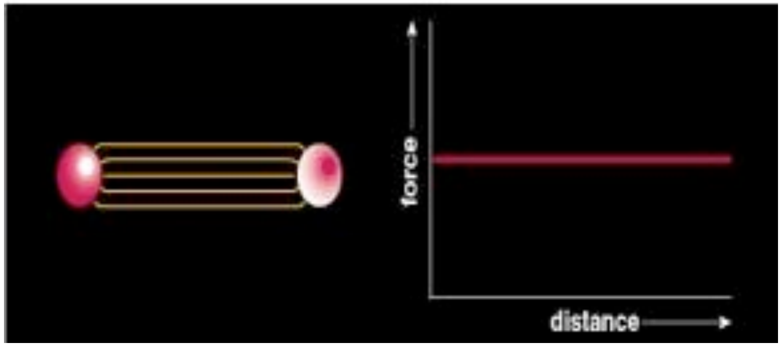

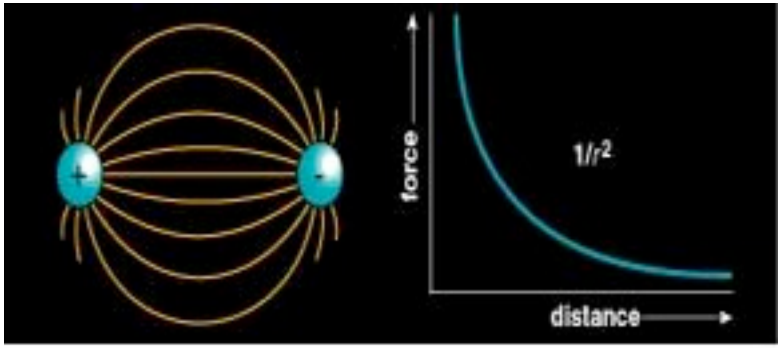

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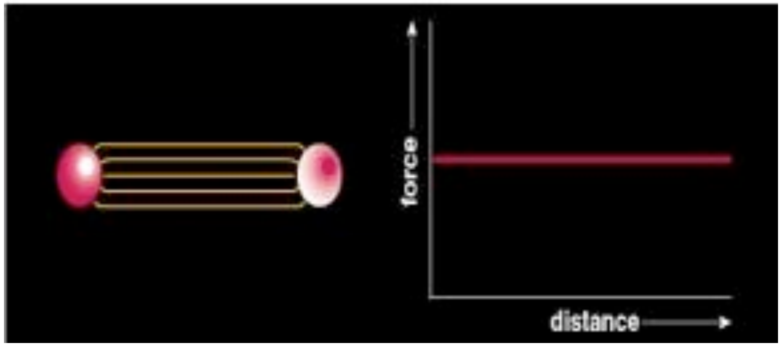
Comparing theories

<u>QCD</u>

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

$\alpha_s \approx 1$



Force = const

3 colour charges:

red, blue, green

Gauge boson: g (8)

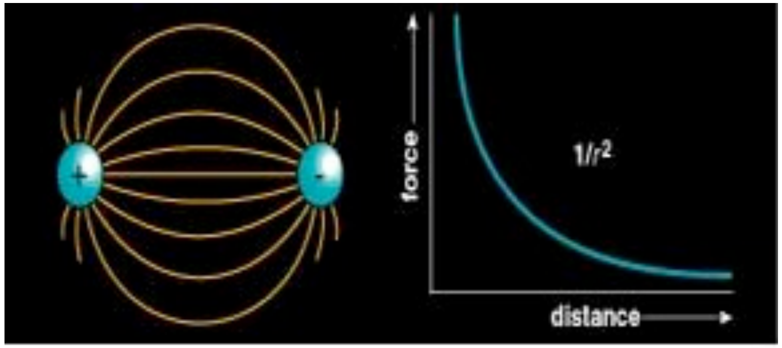
Charged?: Yes

self interaction

<u>QED</u>

$$V_{em}(r) = -\frac{q_1 q_2}{4\pi\epsilon_0 r} = -\frac{\alpha_{em}}{r}$$

$\alpha_{em} = e^2/4\pi \approx 1/137$



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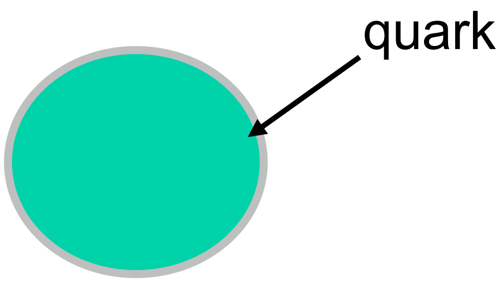
Confinement - QCD

Confinement: fundamental & crucial feature of strong interaction
force = const has significant consequences



"white" proton

Confinement - QCD

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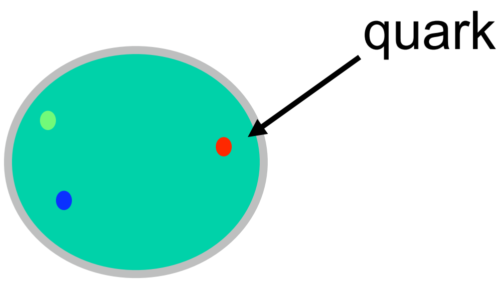

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Strong color field
Force *grows* with
separation !!!

Confinement - QCD

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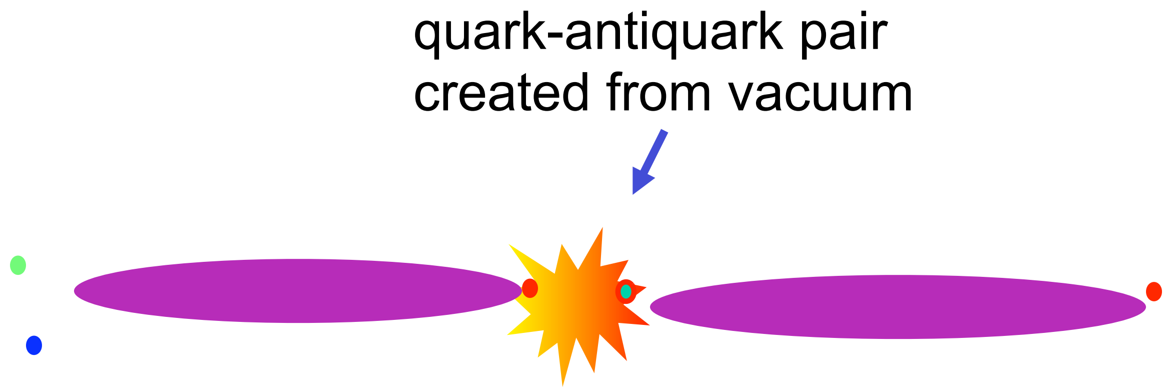

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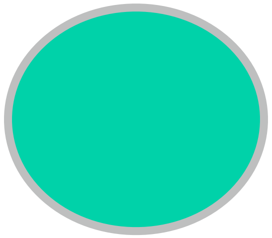
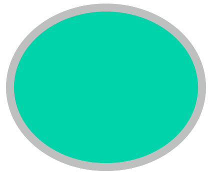


“white” proton
(confined quarks)



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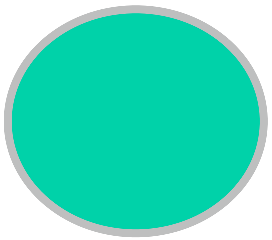

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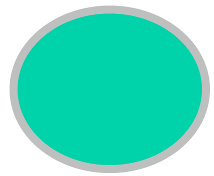
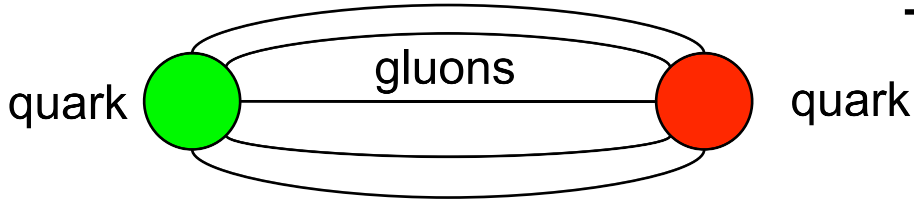


"white" π^0
(confined quarks)

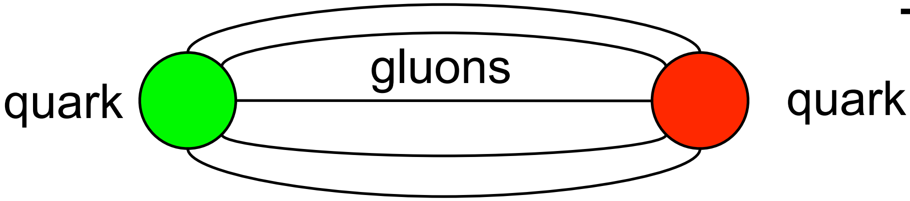
To understand the strong force and confinement: Create and study a system of deconfined colored quarks and gluons

We don't see free quarks



The size of a nucleus is $1.2A^{1/3}$ fm where A is the mass number and a fm is 10^{-15} m

We don't see free quarks



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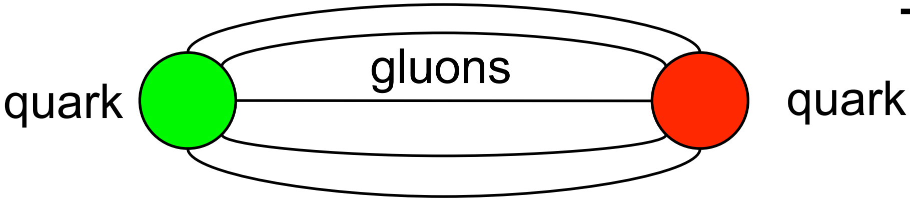
$$1\frac{GeV}{fm} = \frac{10^9 eV}{10^{-15} m} \times \frac{1.6 \times 10^{-19} J}{eV} = 1.6 \times 10^5 N$$

We don't see free quarks



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$$1\frac{GeV}{fm} = \frac{10^9 eV}{10^{-15} m} \times \frac{1.6 \times 10^{-19} J}{eV} = 1.6 \times 10^5 N$$

Compare to gravitational force at Earth's surface

$$F = 1.6 \times 10^5 N = M \times g = M \times 9.8 m/s^2$$

$$\Rightarrow \quad M = 16,300 kg$$

Quarks exert 16 metric tons of force on each other!

Asymptotic freedom

Stated Coupling Constants are “constant” 1 - not true

Runs with Q^2 (mtm transfer)
accounts for vacuum polarisation

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{[1 + (\alpha_s(\mu^2)\frac{(33-2n_f)}{12\pi})ln(Q^2/\mu^2)]}$$

$\alpha_s(\mu^2) \sim 1$!!
μ^2: renormalization scale
33: gluon contribution
n_f: # quark flavours

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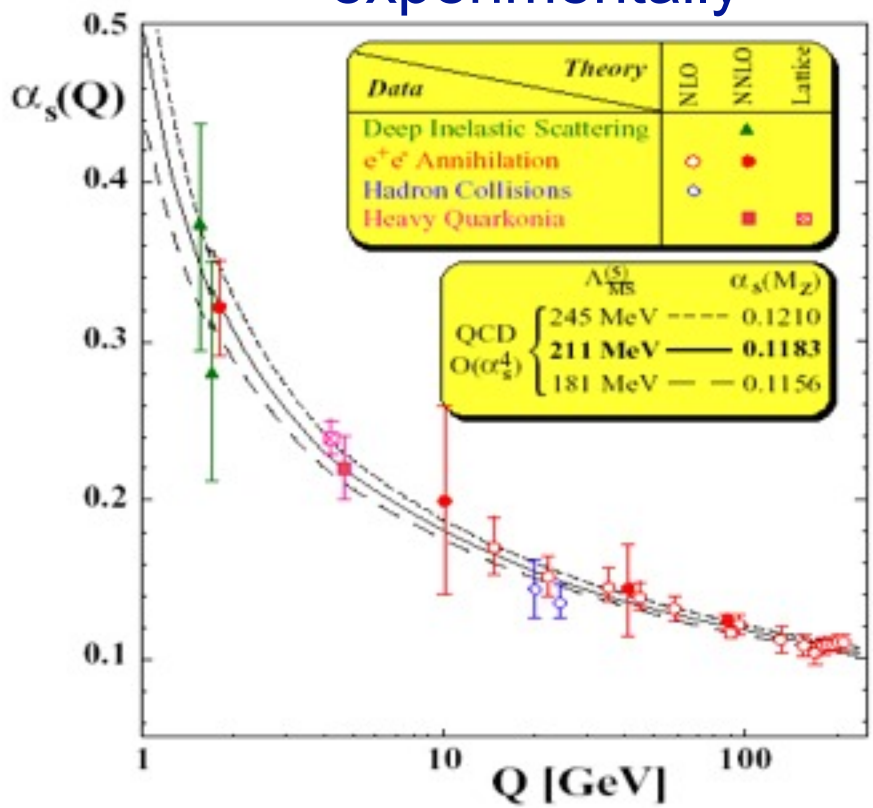
Running measured experimentally



0.2 fm 0.02 fm 0.002 fm

Asymptotic freedom

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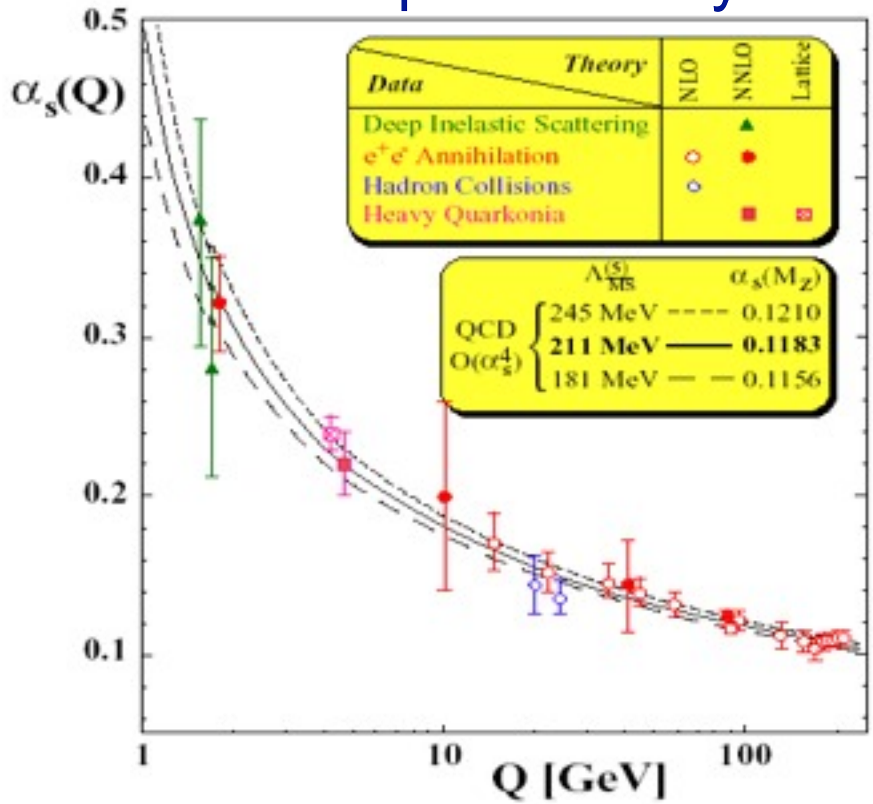
$\alpha_s(Q^2) \rightarrow 0$, as $Q \rightarrow \infty$, $r \rightarrow 0$

Coupling very weak

→ partons are essentially free

Asymptotic Freedom

Running measured experimentally



0.2 fm 0.02 fm 0.002 fm

Asymptotic freedom

Stated Coupling Constants are “constant” 1 - not true

Runs w ... red

accour ... y

$\alpha_s(Q^2) =$

$\alpha_s(\mu^2)$ ~

μ^2: renor

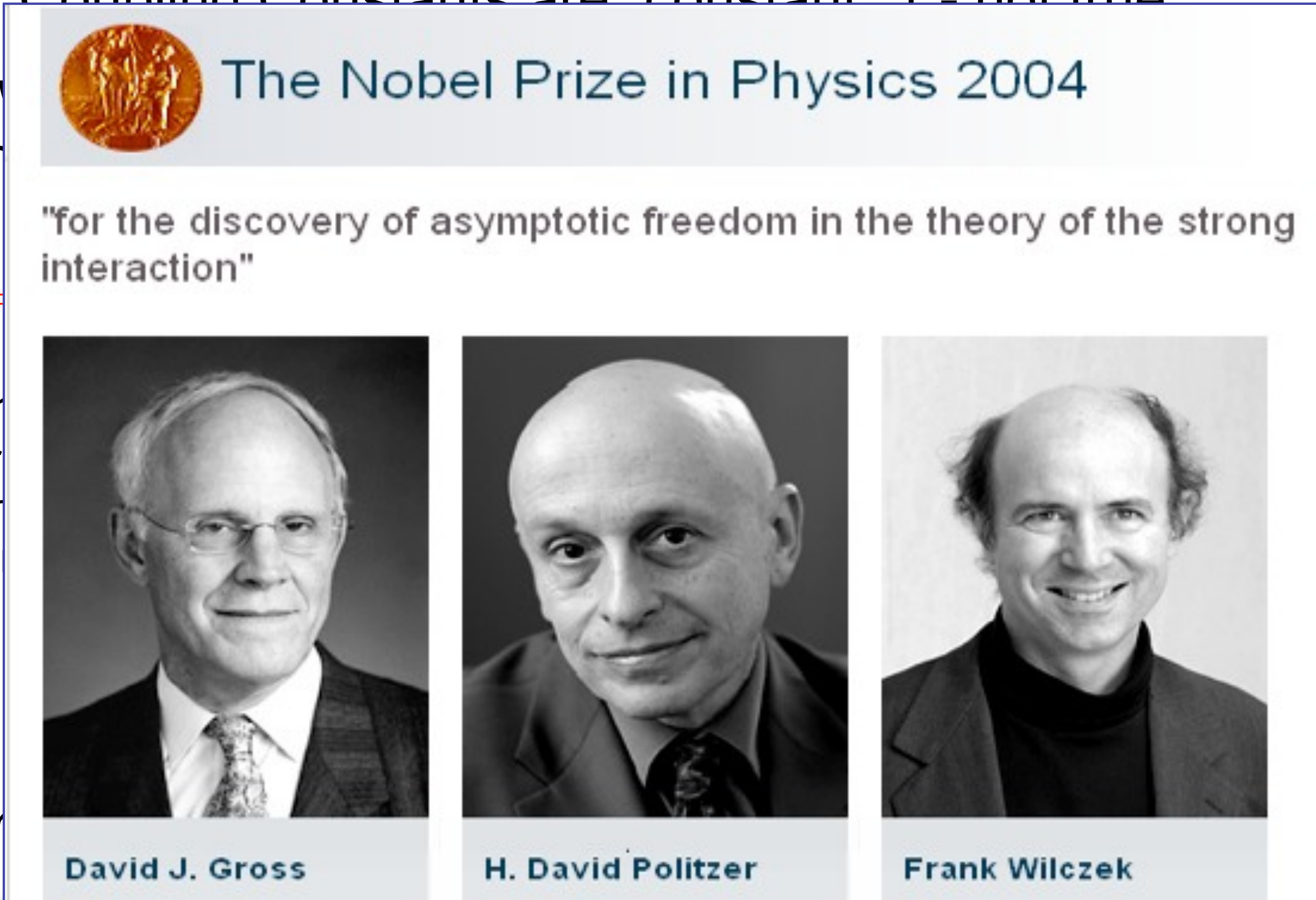
33: gluor

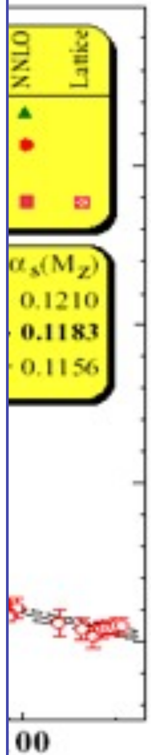
n_f: # qua

$\alpha_s(Q^2)$

Coupli

→ par

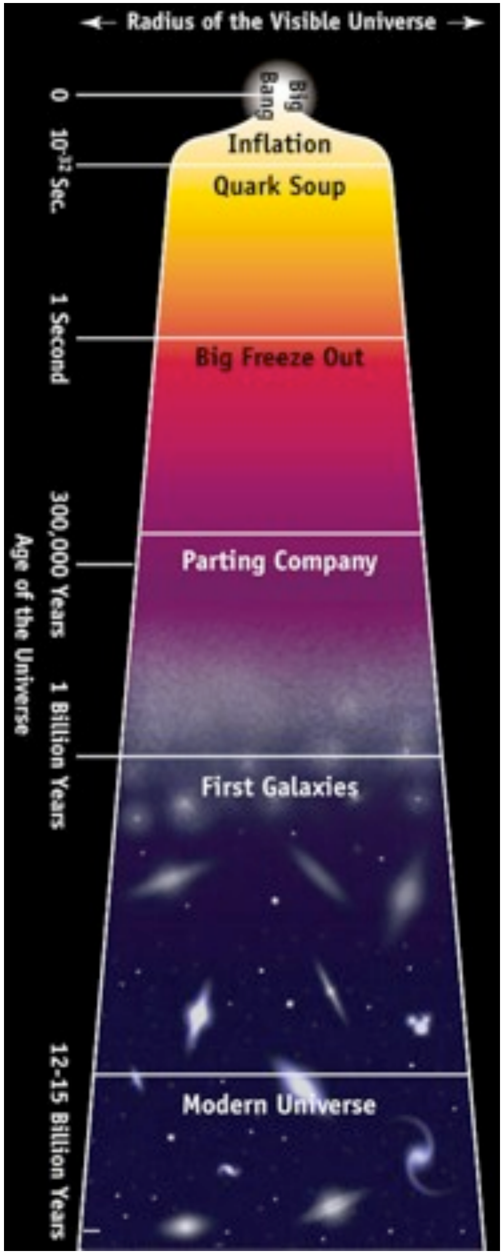




Asymptotic Freedom

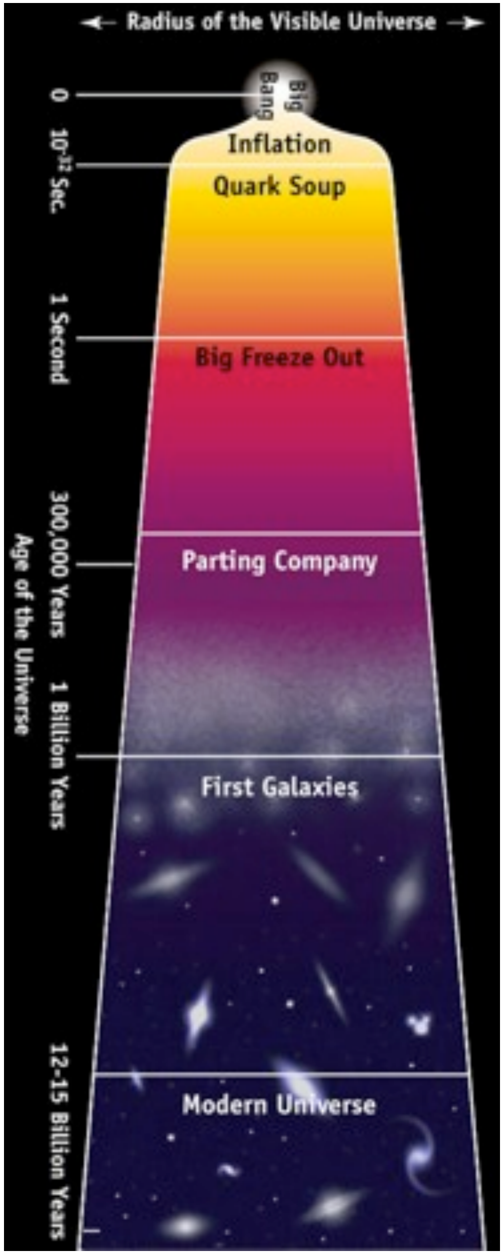
0.2 fm 0.02 fm 0.002 fm

Evolution of the universe



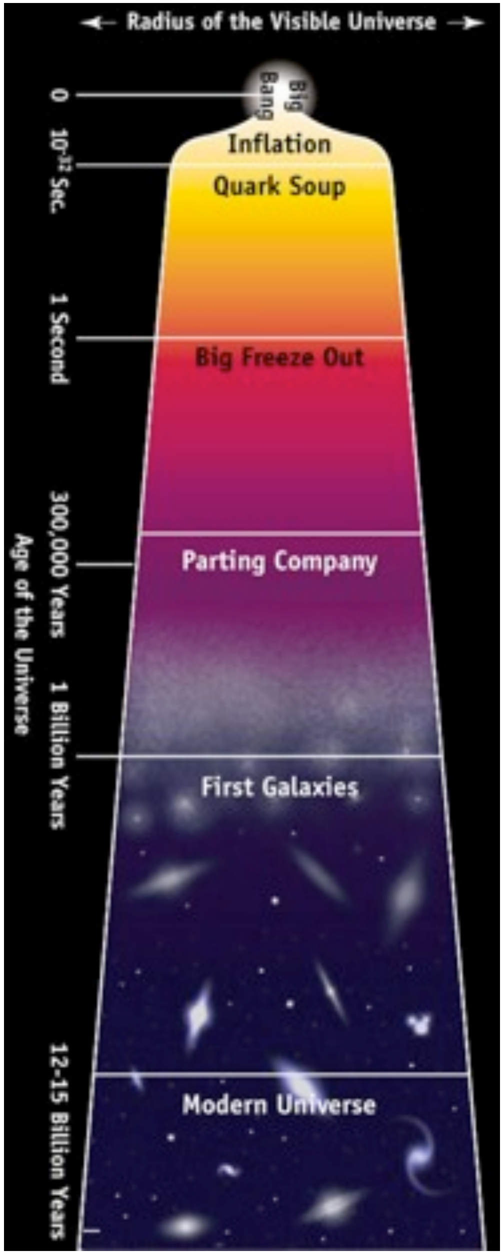
10^{-44} sec	Quantum Gravity	Unification of all 4 forces	10^{32} K
10^{-35} sec	Grand Unification	E-M/Weak = Strong forces	10^{27} K
10^{-35} sec ?	Inflation	universe exponentially expands by 10^{26}	10^{27} K
2 10^{-10} sec	Electroweak unification	E-M = weak force	10^{15} K
$2 \cdot 10^{-6}$ sec	**Proton-Antiproton pairs**	**creation of nucleons**	**10^{13} K**
6 sec	Electron-Positron pairs	creation of electrons	$6x10^{9}$ K
3 min	**Nucleosynthesis**	**light elements formed**	**10^{9} K**
10^{6} yrs	Microwave Background	recombination - transparent to photons	3000 K
10^{9} yrs ?	Galaxy formation	bulges and halos of normal galaxies form	20 K

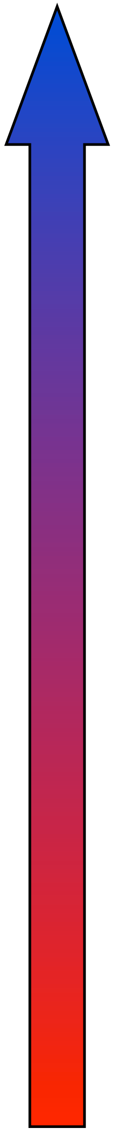
Evolution of the universe



The universe gets cooler !

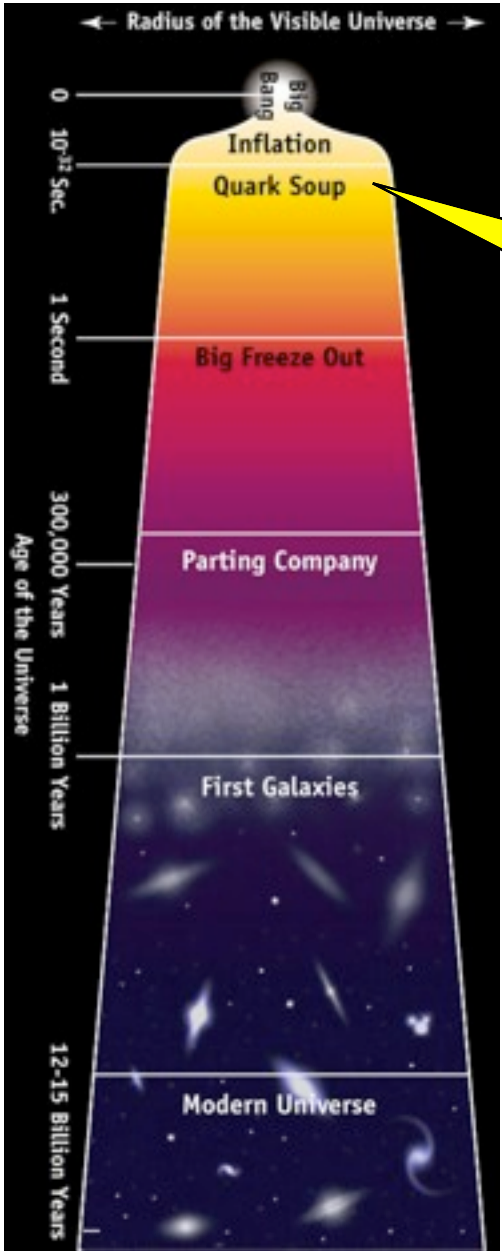
Evolution of the universe

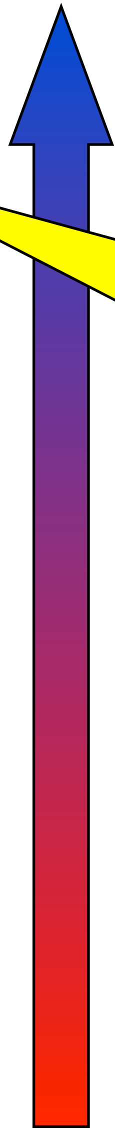




Reheating Matter ?

Evolution of the universe





Reheating Matter ?

?

Need temperatures around $1.5 \cdot 10^{12}$ K (200 MeV) far hotter than center of the sun ($\sim 2 \cdot 10^{7}$K)

Asymptotic freedom vs Debye screening

Asymptotic freedom occurs at very high Q^2

Problem: Q^2 much higher than available in the lab.

So how to create and study this new phase of matter?

Solution: Use effects of Debye screening

In the presence of many colour charges (charge density n), the short range term of the strong potential is modified:

Charges at long range ($r > r_D$) are screened

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In the presence of many colour charges (charge density n), the short range term of the strong potential is modified:

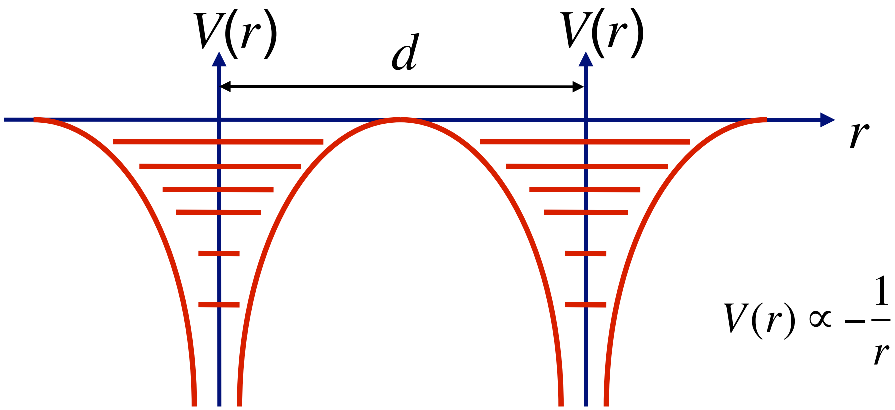
$$V_s(r) \propto \frac{1}{r} \Longrightarrow \frac{1}{r} exp[\frac{-r}{r_D}]$$

where $r_D = \frac{1}{\sqrt[3]{n}}$ is the Debye radius

Charges at long range ($r > r_D$) are screened

QED and Debye screening

$r > r_D$



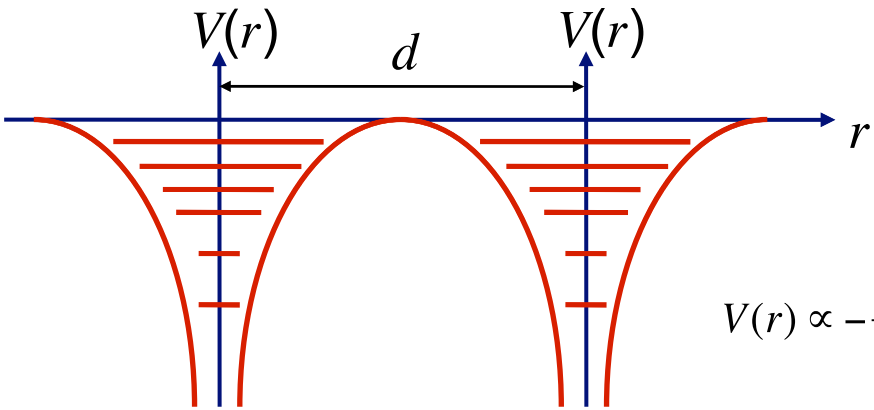
$r < r_D$

e^- separation < e^- binding radius

→ conductor

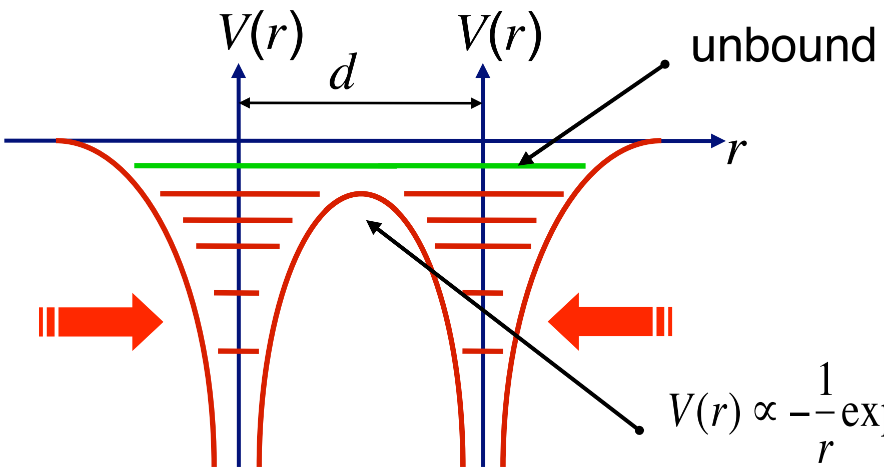
QED and Debye screening

$r > r_D$



$$V(r) \propto -\frac{1}{r}$$

$r < r_D$



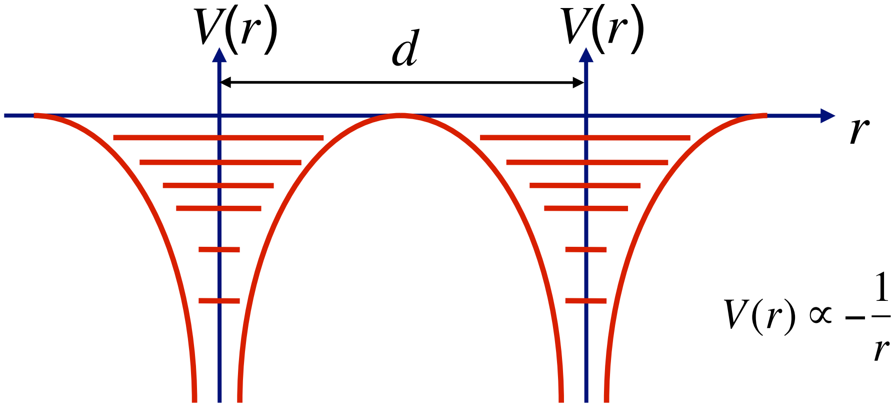
$$V(r) \propto -\frac{1}{r}\exp\left[\frac{-r}{r_D}\right]$$

e^- separation < e^- binding radius
→ conductor

This is the Mott Transition

QED and Debye screening

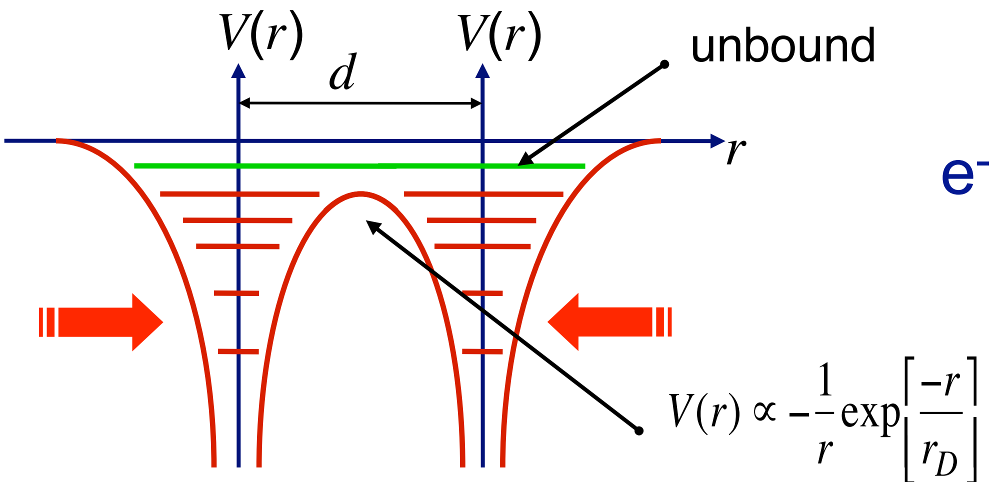
r > r$_D$



In condensed matter this leads to an interesting transition

e$^-$ separation > e$^-$ binding radius
→ insulator

r < r$_D$



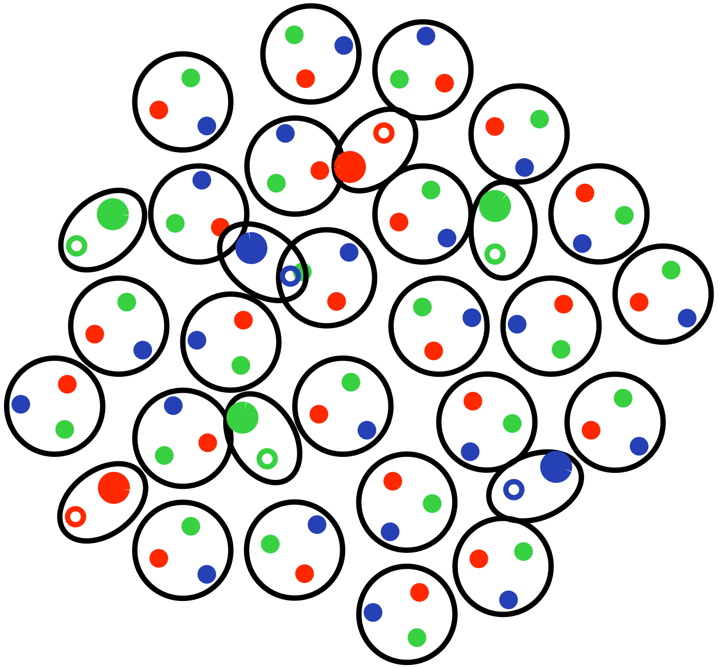
e$^-$ separation < e$^-$ binding radius
→ conductor

This is the Mott Transition

QCD and Debye screening

At low colour densities:

quarks and gluons confined into colour singlets
→ hadrons (baryons and mesons)



QCD and Debye screening

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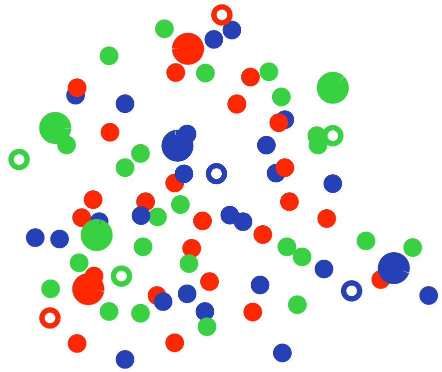


At high colour densities:

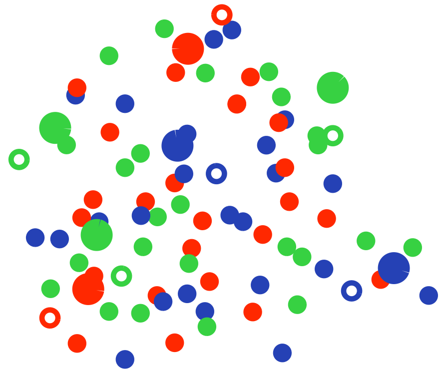
quarks and gluons unbound
Debye screening of colour charge

→ QGP - colour conductor

QCD and Debye screening

At low colour densities:

quarks and gluons confined into colour singlets
→ hadrons (baryons and mesons)



At high colour densities:

quarks and gluons unbound
Debye screening of colour charge

→ QGP - colour conductor

Can create high colour density by heating or compressing

→ QGP creation via accelerators or in neutron stars

What are the necessary conditions?

First Estimation: Phenomenological calculation

The MIT bag model (Bogolioubov (1967)) :

- Hadrons are non-interacting quarks confined within a bag.
- Quarks are massless inside "bag", infinite mass outside
- Quarks confined within the "bag" but free to move outside
- Confinement modeled by Dirac equation.

(m_{inside}~0, $M_{outside}$~infinity, θ_V = 1 inside the bag and zero outside the bag)

$$i\gamma^\mu \partial_\mu \psi - M\psi + (M - m)\theta_V \psi = 0$$

Wave function vanishes outside of bag, satisfying boundary conditions at bag surface

With bag radius = R

$$E_i = \omega_i \frac{\hbar c}{R}$$

MIT bag model

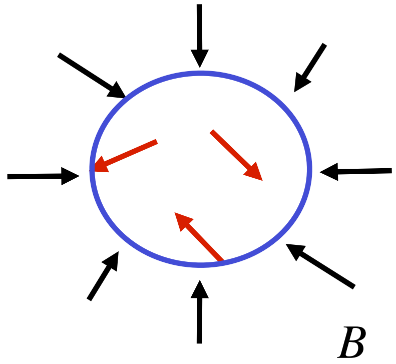
MIT group realized E-p conservation violated

Included an external "bag pressure" balances internal pressure from quarks.

e.g. nucleon ground state is 3 quarks in $1s_{1/2}$ level

To create this pressure the vacuum attributed with energy density B

$$E_i = \omega_i \frac{\hbar c}{R} + \frac{4\pi}{3} R^3 B$$



Boundary condition now:

Energy minimized with respect to R

$$B^{\frac{1}{4}} = (\Sigma_i \omega_i \frac{\hbar c}{4\pi})^{\frac{1}{4}} \frac{1}{R}$$

R=0.8 fm, 3 quarks

$B^{1/4}$ = 206 MeV/fm^3

Critical temperature from MIT bag

If μ (chemical potential) = 0 (true for massless quarks):

degeneracy factor

$$E_q = \frac{g_q V}{2\pi^2}\int_0^\infty \frac{p^3 dp}{1+e^{p/T}}$$

Fermi-Dirac distribution

$$E_g = \frac{g_g V}{2\pi^2}\int_0^\infty p^3 dp\{\frac{1}{e^{p/T}-1}\}$$

Bose-Einstein distribution

$$E_q = \frac{7}{8} g_q V \frac{\pi^2}{30} T^4$$

$$E_g = g_g V \frac{\pi^2}{30} T^4$$

$g_q = g_{\bar{q}} = N_c N_s N_f = 3x2x2 = 12$

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Total energy density is: $\epsilon_{TOT} = \epsilon_q + \epsilon_{\bar{q}} + \epsilon_g = 37\frac{\pi^2}{30}T^4$

P = 1/3 ε, $T_c = (\frac{90}{37\pi^2})^{\frac{1}{4}} B^{\frac{1}{4}}$,$B^{1/4}$ = 206 MeV/fm^3

i.e. T > T_c, the pressure in the bag overcomes the bag pressure

$T > T_c = 144$ MeV → de-confinement and QGP

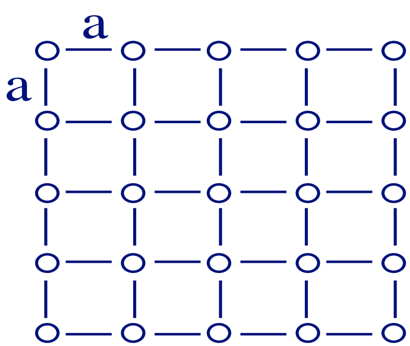
What are the necessary conditions? - II

Second estimation: Lattice QCD

At large Q^2: coupling small, perturbation theory applicable

At low Q^2 : coupling large, analytic solutions not possible,
solve numerically → Lattice QCD

$$N_s^3 \times N_\tau$$



quarks and gluons can only be placed on lattice sites

Can only travel along connectors

Better solutions:

- higher number sites
- smaller lattice spacing

Cost:

- CPU time

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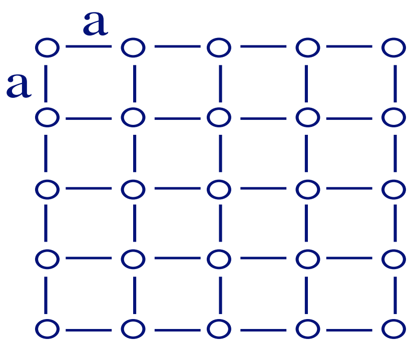

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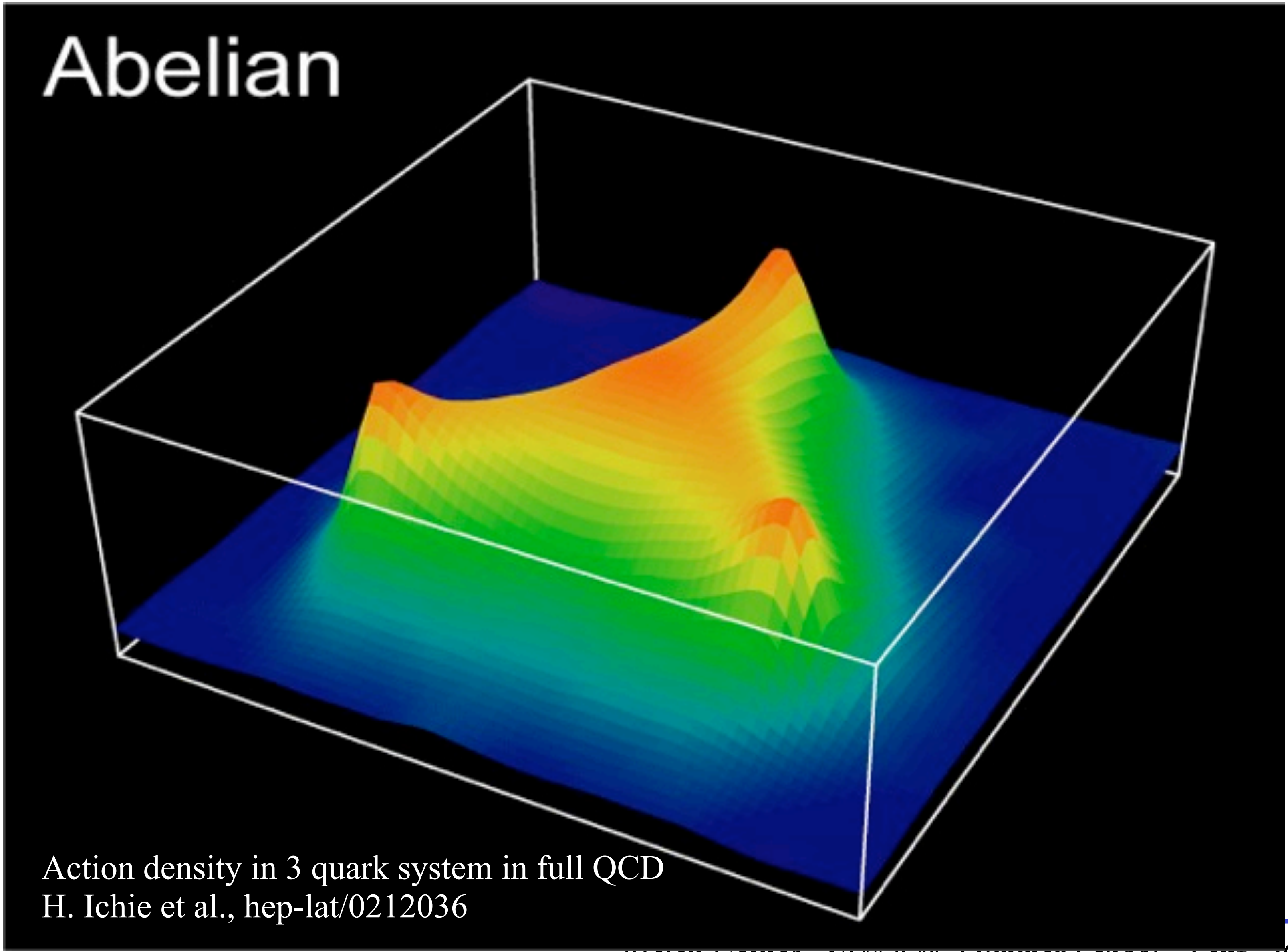
Lattice QCD making contact with experiments:

Proton mass calculated to within 2%

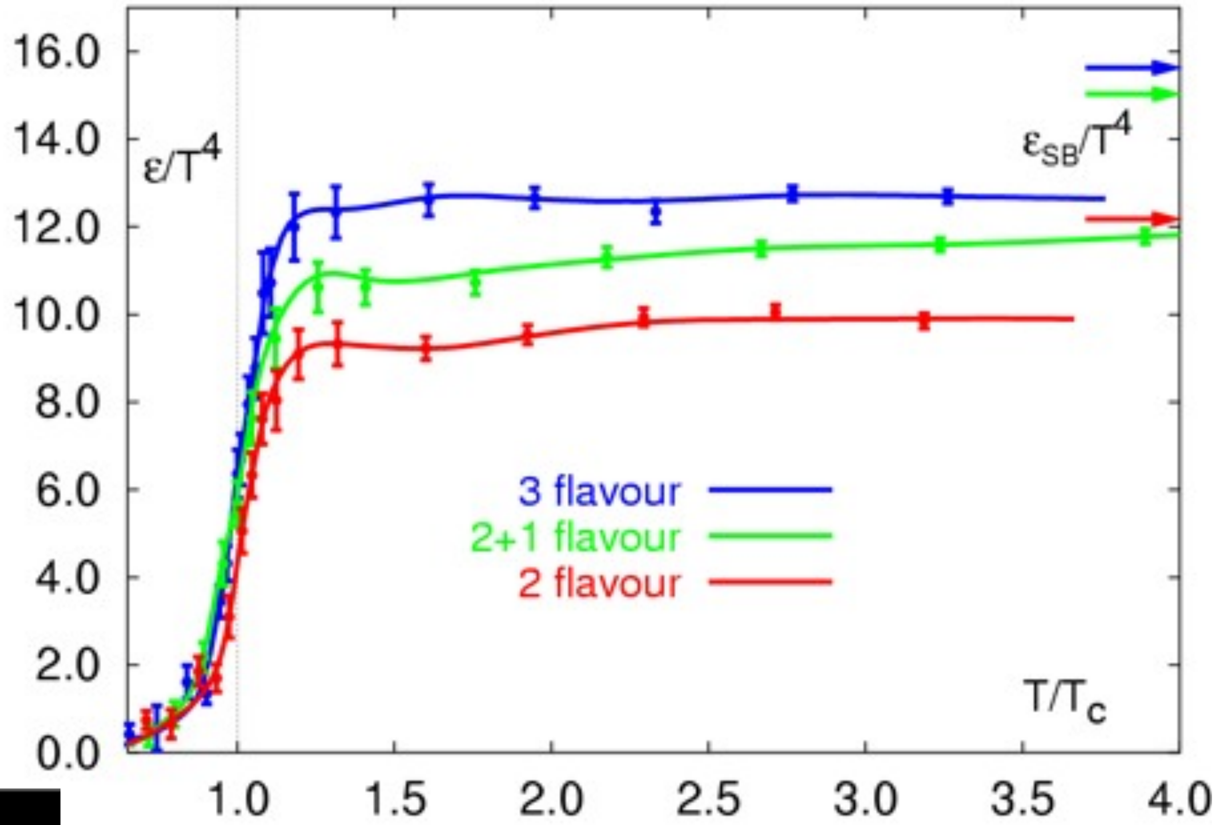
Lattice QCD at finite temperature



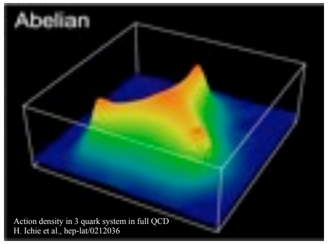
Action density in 3 quark system in full QCD
H. Ichie et al., hep-lat/0212036

Lattice QCD at finite temperature

- Coincident transitions: deconfinement and chiral symmetry restoration
- Recently extended to $\mu_B > 0$, order still unclear (1^{st}, 2^{nd}, crossover ?)



$T_C \approx 170$ MeV



F. Karsch, hep-ph/0103314

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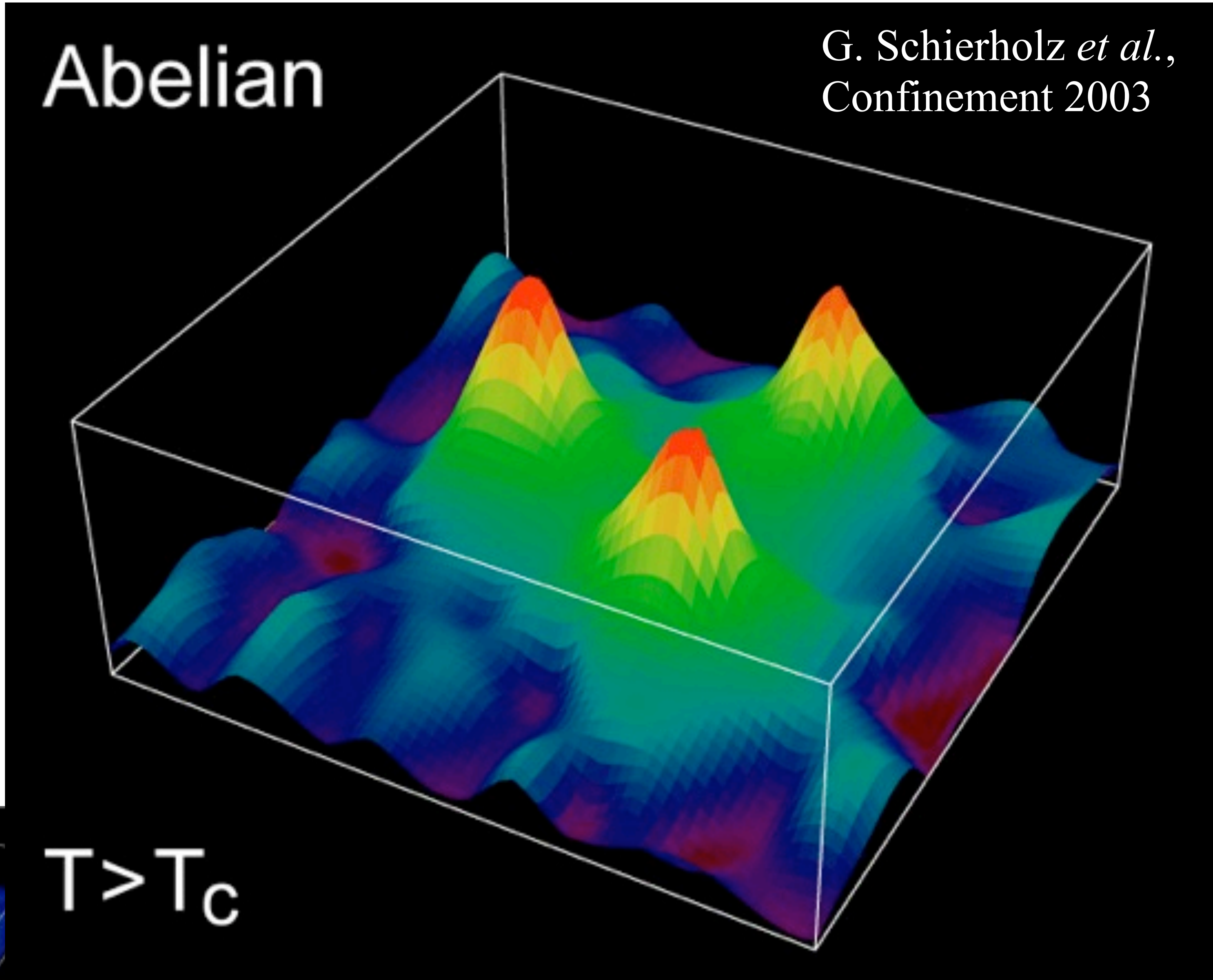
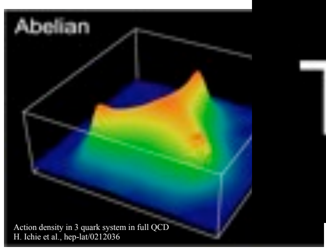
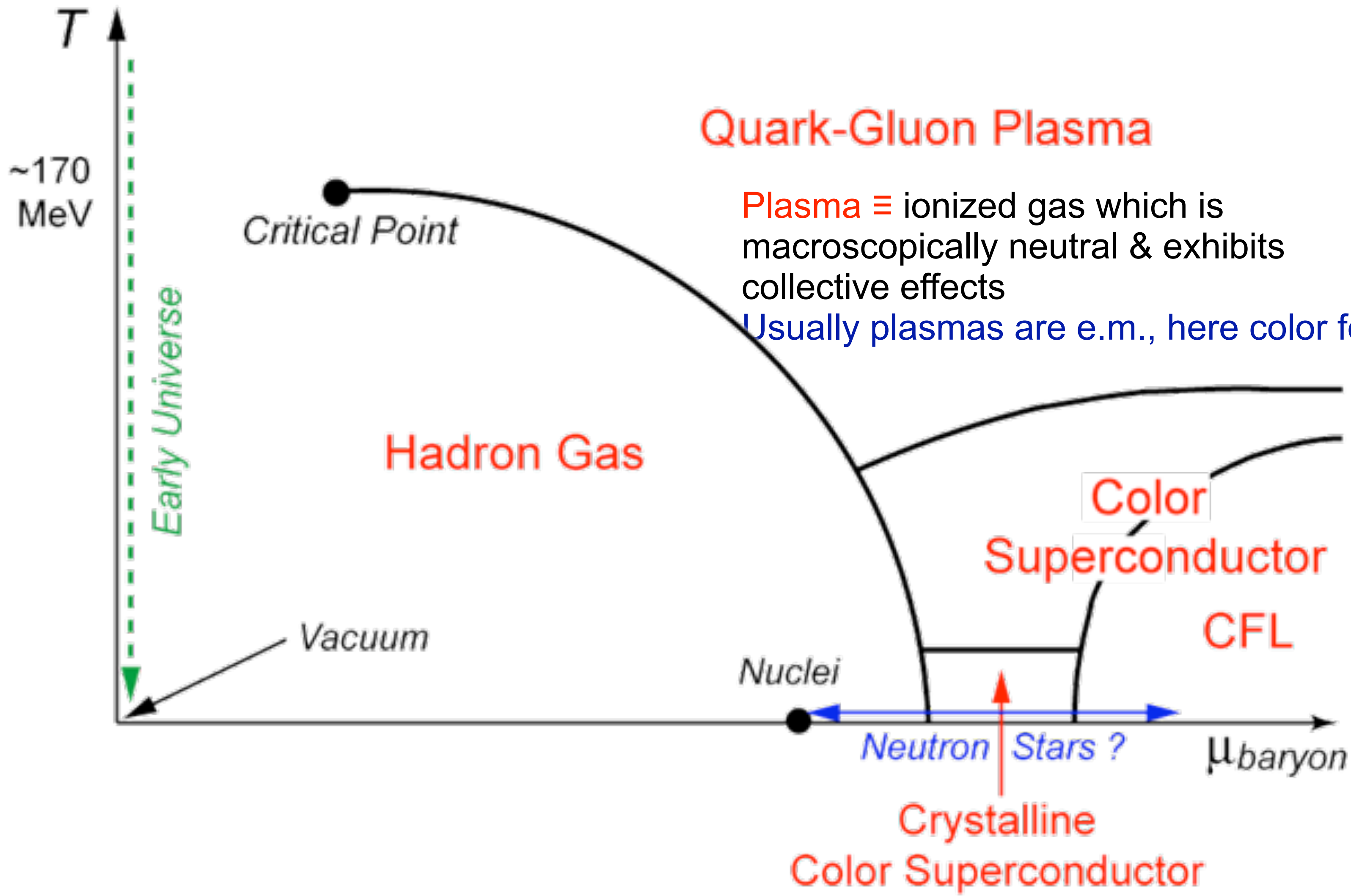




QCD phase diagram of hadronic matter



Plasma ≡ ionized gas which is macroscopically neutral & exhibits collective effects

Usually plasmas are e.m., here color forces

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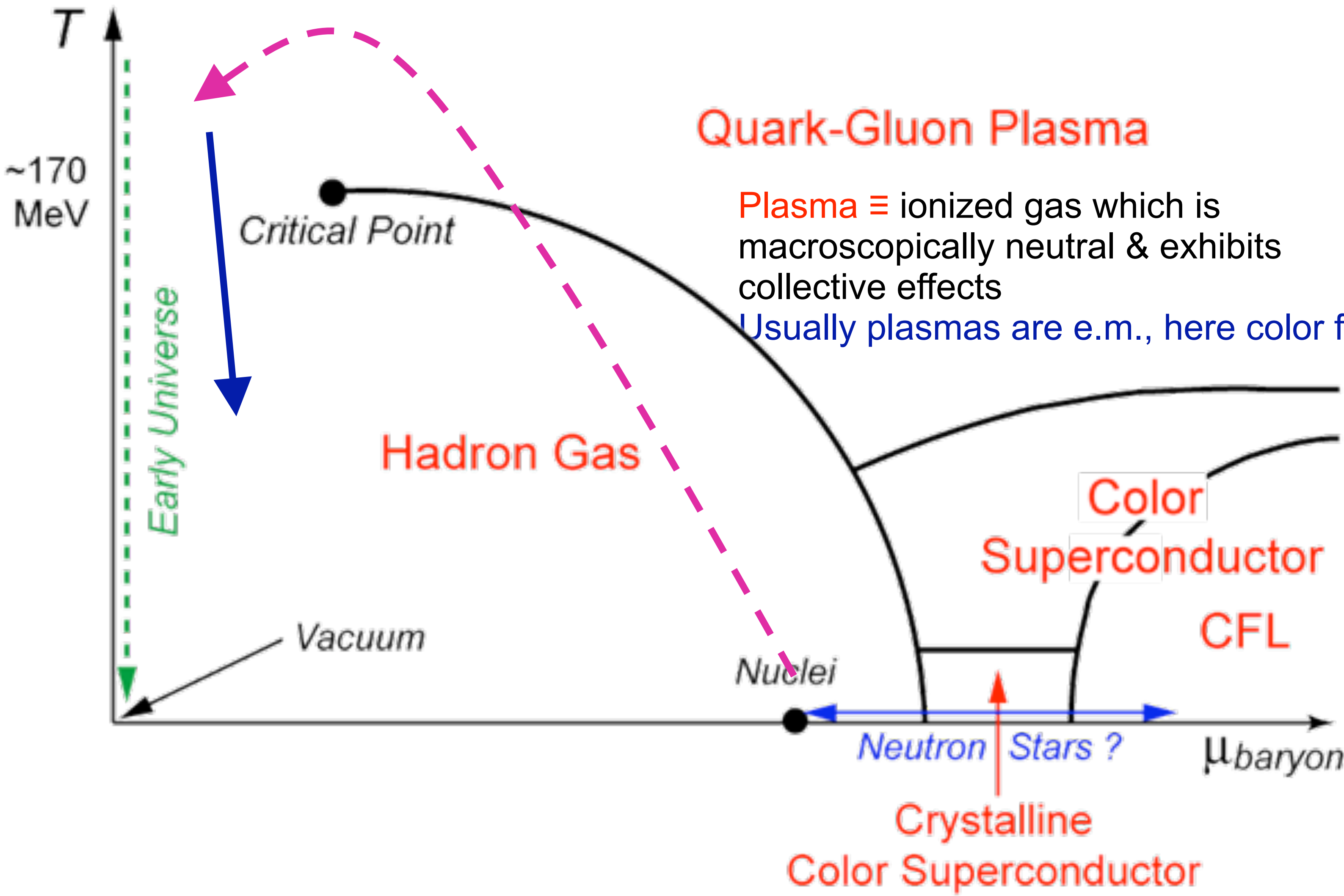

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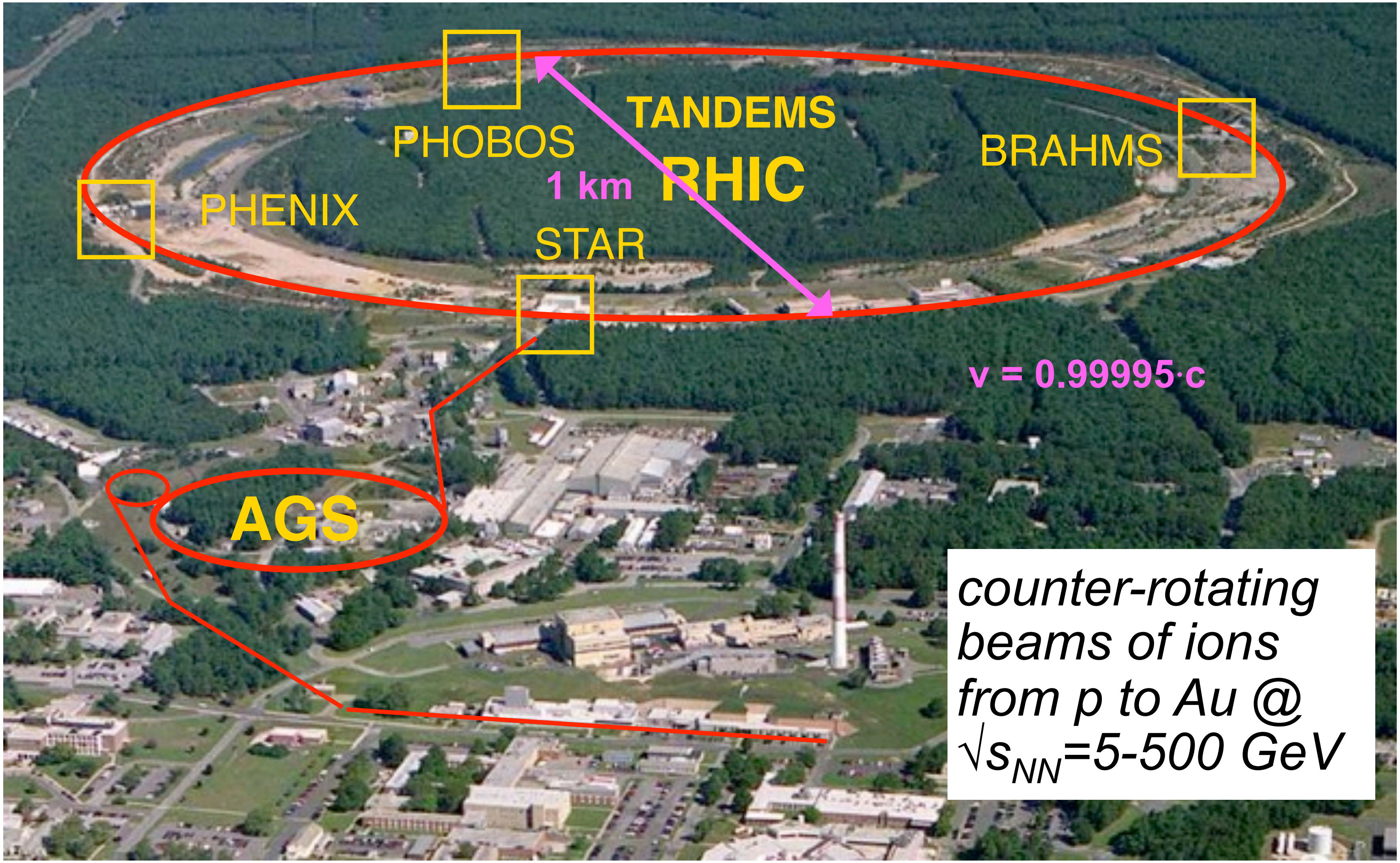
RHIC - a collider



counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

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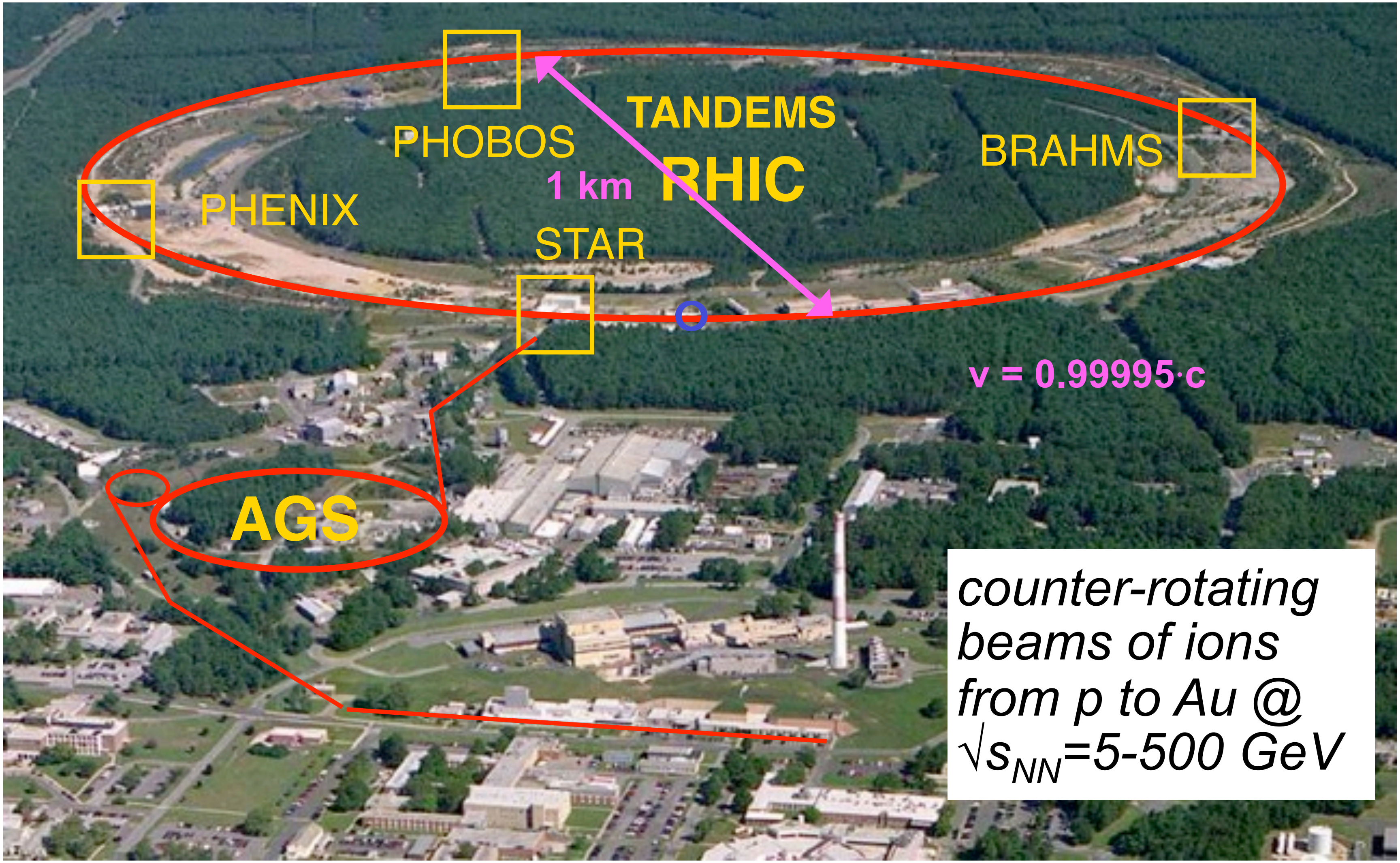

counter-rotating beams of ions from p to Au @ $\sqrt{s_{NN}}$=5-500 GeV

RHIC and the LHC

	RHIC	LHC
Start date	2001	2009
Ion	Au-Au & p-p	Pb-Pb & p-p
Max $\sqrt{s}$	200 GeV	5.5 TeV
Circumference	2.4 miles	17 miles
Depth	On surface	175 m below ground
HI Exp.	BRAHMS,PHENIX, PHOBOS, STAR	ALICE, ATLAS, CMS
Located	BNL, New York, USA	CERN, Geneva, Switzerland

What we want to measure ...

- Baseline (majority of produced particles)
  - $K^{\pm}$, $\pi^{\pm}$, π^{0}, p, $\bar{p}$
- Strangeness
  - K^{0}_{s}, K^{*}, ϕ, Λ, Ξ, Σ, Ω
- Real and Virtual Photons
  - γ
  - $\gamma^{*} \rightarrow \mu^{+}\mu^{-}$, $\gamma^{*} \rightarrow e^{+}e^{-}$
- Heavy Flavor
  - D^{0}, D^{*}, $D^{\pm}$, B
  - Λ_{c}
- Quarkonia
  - J/ψ, ψ', χ_{c}, Υ, Υ', Υ''
- Jets $\Rightarrow$ high-p_{T} hadrons in cone
- Decay channels matters too: $\rho \rightarrow e^{+}e^{-}$ versus $\rho \rightarrow \pi^{+}\pi^{-}$

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- And all that over all p_T ?
- Acceptance (ideal 4π) ?
- All centralities, multiplicities ?
- Recording every collision ?

The perfect detector?

- Momentum **p**

- magnetic field × length: B×dl
- high-pt ⇒ large B×dl ⇒ small p_T tracks curl up
- low-pt ⇒ small B×dl ⇒ high p_T tracks care straight (p_T res. lost)

- Particle ID

- γ, e ⇒ hadron blind, little material
- hadrons ⇒ PID through interaction with material

- Acceptance

- large acceptance ⇒ lots of data ⇒ slow
- small acceptance ⇒ few data ⇒ fast

- Energy

- γ, e ⇒ E.M. Calorimeter
- hadrons ⇒ Hadronic Calorimeter

- Heavy flavor ID

- secondary vertices ⇒ high precision Si detectors = material
- semileptonic decays (c, b → e + X, B → J/ψ (→ e e) + X) ⇒ hadron blind, little material

Mission impossible

Question: How to proceed with experimental design when

$$\sum \overrightarrow{(\text{Theoretical Opinion})} \approx 0\ ?$$

Hermeticity

- A key factor in collider detectors
  - Goal of essentially complete event reconstruction
  - Discovery potential of missing momentum/energy now well established
  - Of course this due to manifestation of new physics via electroweak decays
- In heavy ion physics
  - $dN_{ch}/dy \sim 1000$
  - ➡ exclusive event reconstruction "unfeasible"
  - But
    - Seeking to characterize a **state of matter**
    - Large numbers ➡ statistical sampling of phase space a valid approach

PID – long lifetime (>5 ns)

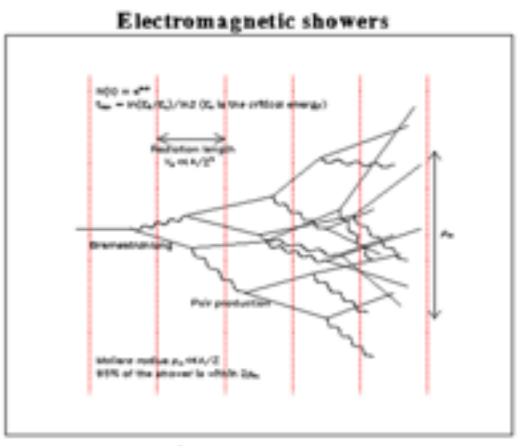
Examples: π, K, γ, p, n, …

Charge (if any!) and 4-momentum needed for PID

4-momentum from at least two of these quantities:

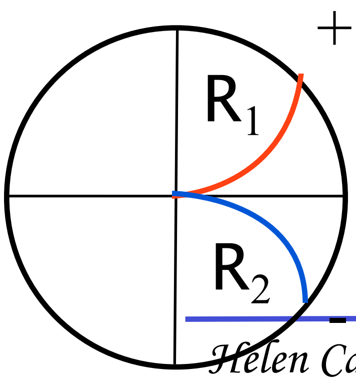
energy	3-momentum	velocity
↓	↓	↓
calorimetry	tracking	time-of-flight + pathlength or Cherenkov-effect
↓	↓	

Fully stop the particle
Convert its energy to
- light, charge…
Collect and read out

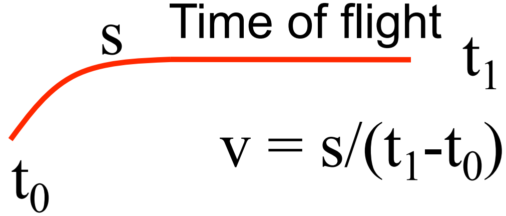


Follow path of charged particles in magnetic field – get momentum from curvature

$$p_T = (q/c) \times B \times R$$

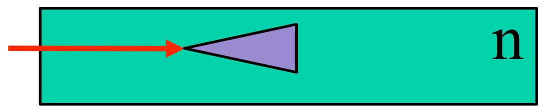


Time of flight



$$v = s/(t_1 - t_0)$$

Cherenkov



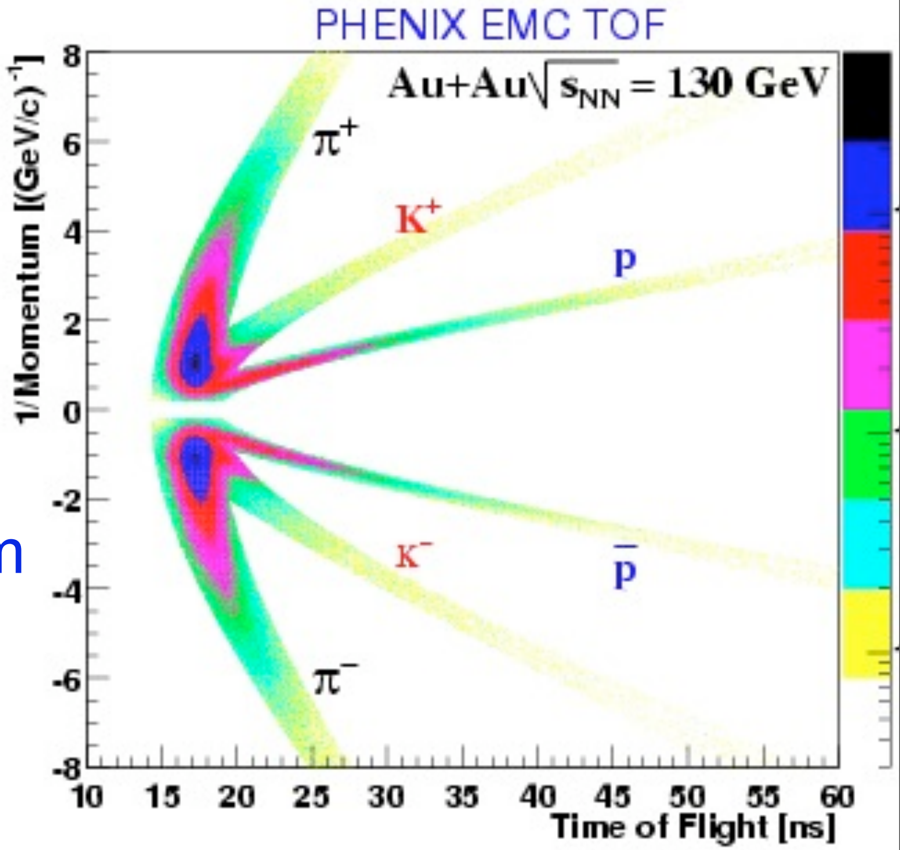
$$\cos(\alpha) = 1/\beta n$$

PID – long lifetime (>5 ns)

Why do I emphasize long lifetime? Because the detectors are fairly large, and the particle produced at the vertex has to survive until it reaches the dete

Example:
hadron identification with momentum and time-of-flight measurement

y axis: inverse of the momentum
x axis: time-of-flight



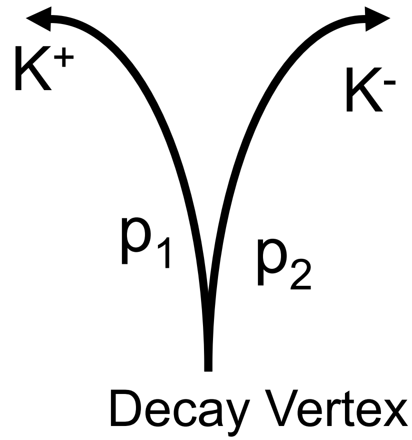
There are many more methods to identify long-lived particles

PID – short lifetime (<5 ns)

Examples: π^0, ϕ, Λ, …

Have to be reconstructed from their more stable decay products

Assume you want to measure the φ meson via its φ→KK decay by measuring both kaons and reconstructing its invariant mass



$$m^2 = (p_1 + p_2)^2$$

But what if there are more than 2 kaons in the event? Or you take a pion for a kaon? Which two go together?

S = Total - Background

Background could be like-sign pairs or pairs from different events

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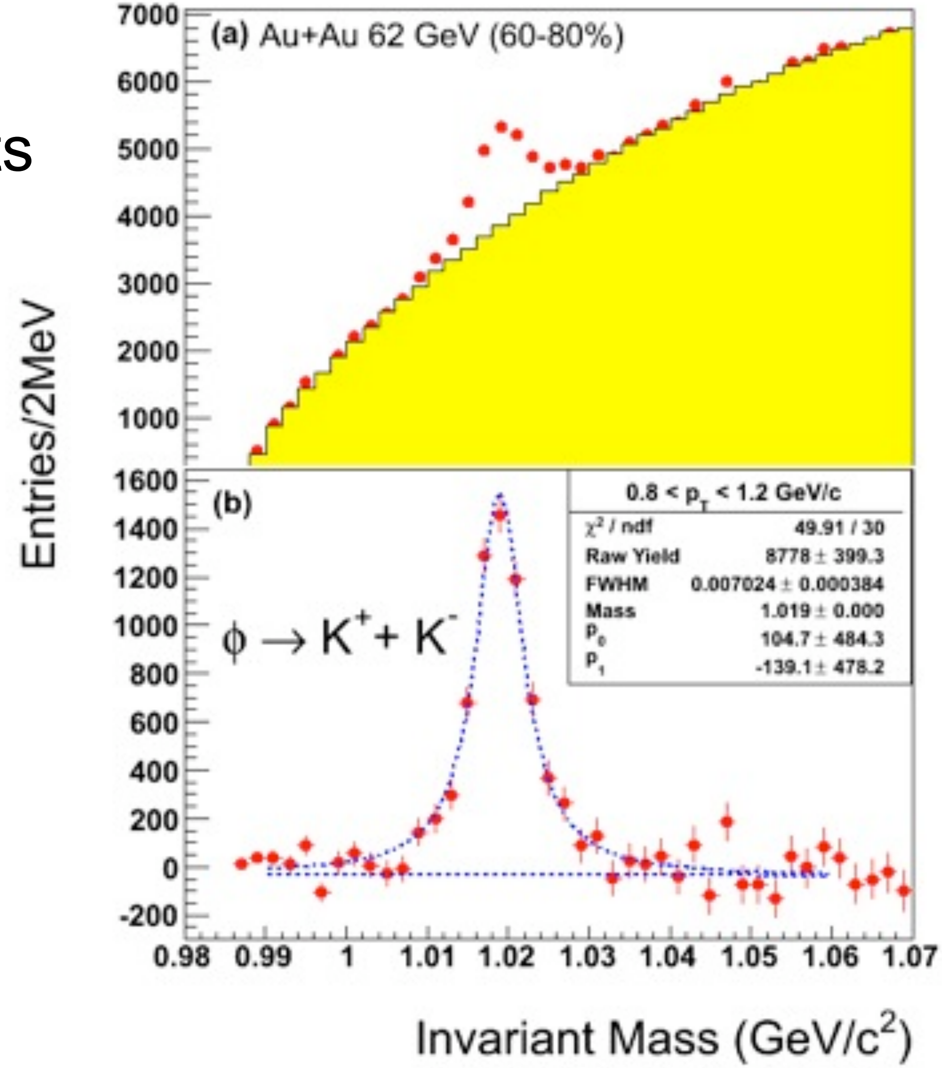
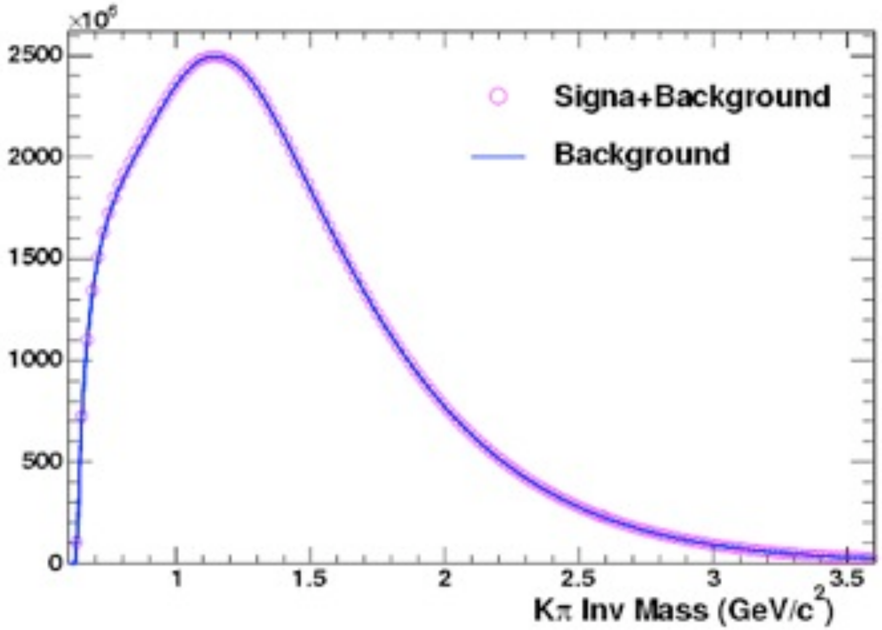
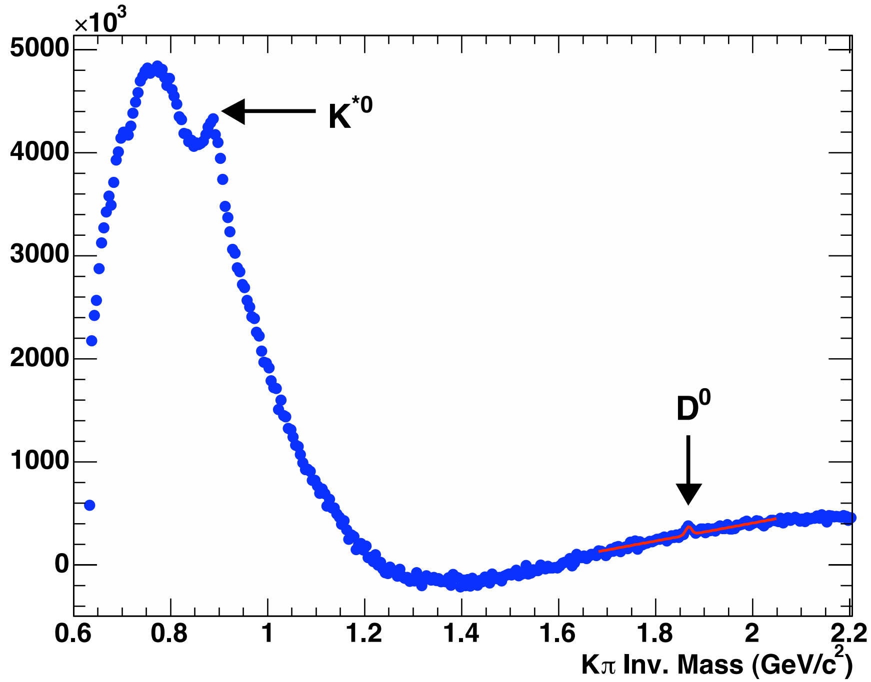


PID - very short lifetime in <1 mm

Here $D^0 \rightarrow K\,\pi$ ($c\tau$ = 123 μm)

- Brute force method
  - select K and π tracks
  - combine all pairs from same events ⇒ signal+background
  - combine all pairs from different events ⇒ background
  - subtract background from signal+background ⇒ signal





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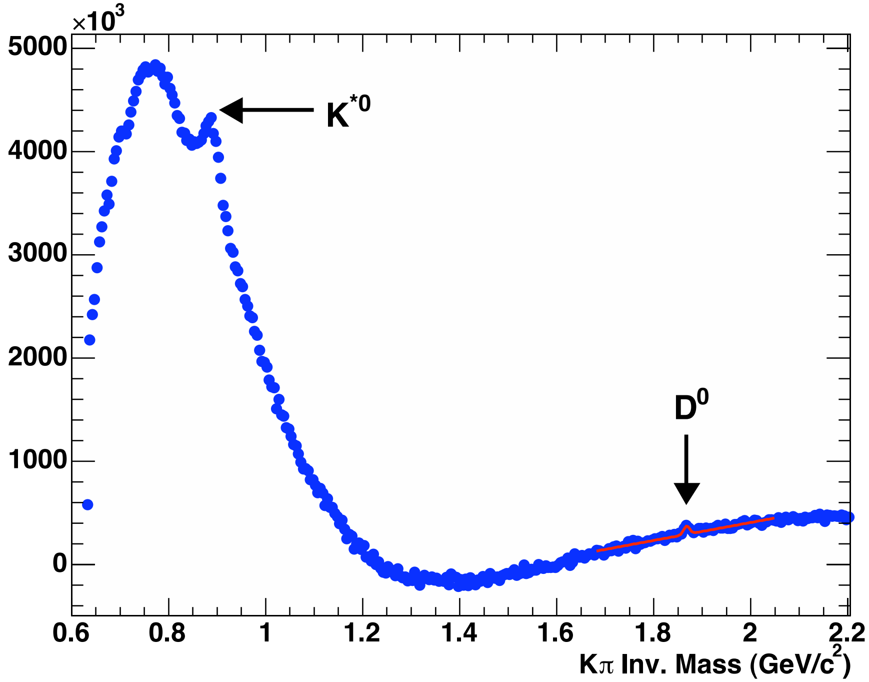
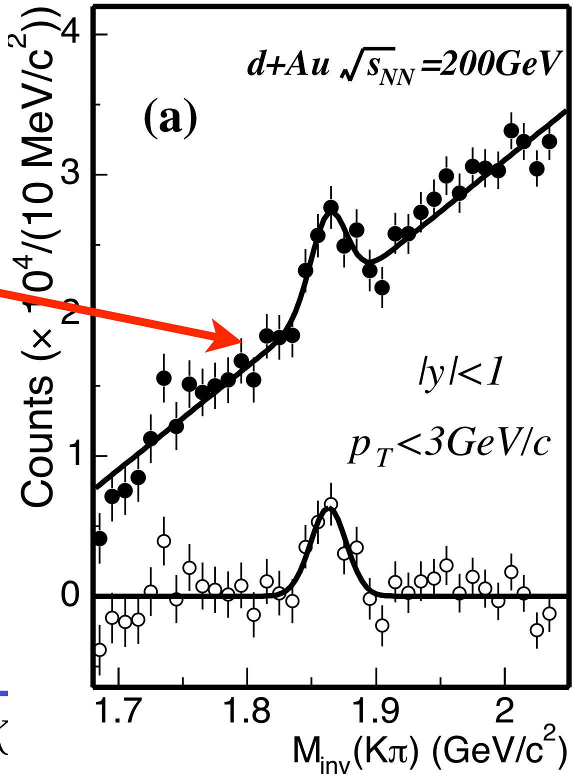


Residual background not eliminated. Needs further work to get to final spectra ....



Design guidelines for QGP detection

Big Plan:

- Consistent framework for describing most of the observed phenomena
- Avoid single-signal detectors
- "Specialized" detectors but keep considerable overlap for comparison and cross-checks
- Expect the unexpected
  - Preserve high-rate and triggering capabilities
  - Maintain flexibility as long as $'s allow

Design Questions (years of sweat, discussion, and simulations)

- What measuring techniques do you want to use?
- What technologies (detectors) fit your goals, constraints?
- Figure out how to combine them

RHIC experiments in a nutshell

BRAHMS

small experiment - 2 spectrometer arms
tiny acceptance $\Delta\phi$, $\Delta\eta$, measures p_T, has PID
movable arms $\Rightarrow$ large $\Delta\eta$ coverage

PHOBOS

small experiment - “tabletop”
(i) huge acceptance $\Delta\phi$, $\Delta\eta$, no p_T info, no PID
(ii) small acceptance $\Rightarrow$ very low - low p_T, moderate PID

PHENIX

large experiment - 2 central arms + 2 muon arms
moderate acceptance central arms: $\Delta\phi = \pi$, $\Delta\eta = \pm 0.35$
leptons (muons in forward arms), photons, hadrons

STAR

large experiment
large acceptance (barrel): $\Delta\phi = 2\pi$, $\Delta\eta = \pm 1$ + forward
hadrons, jets, leptons, photons

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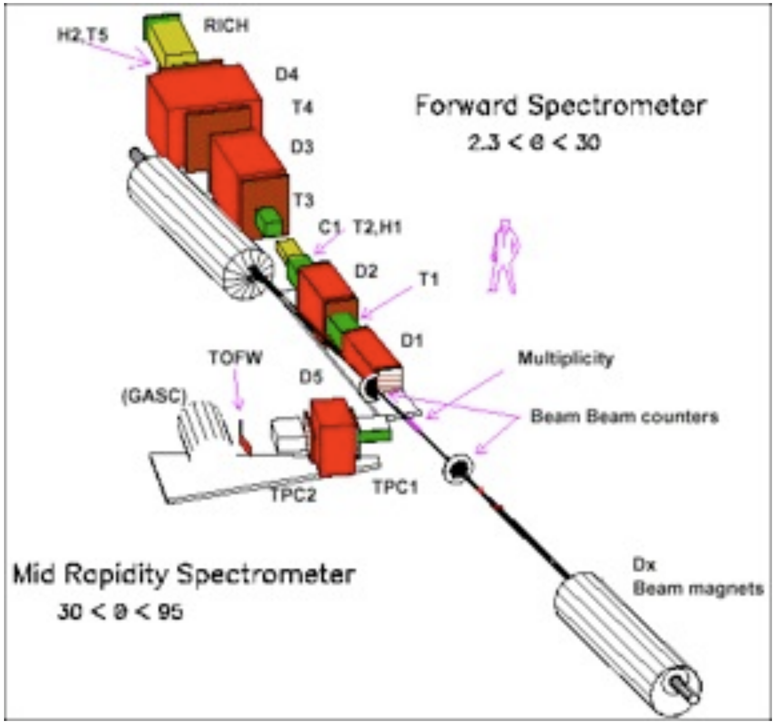
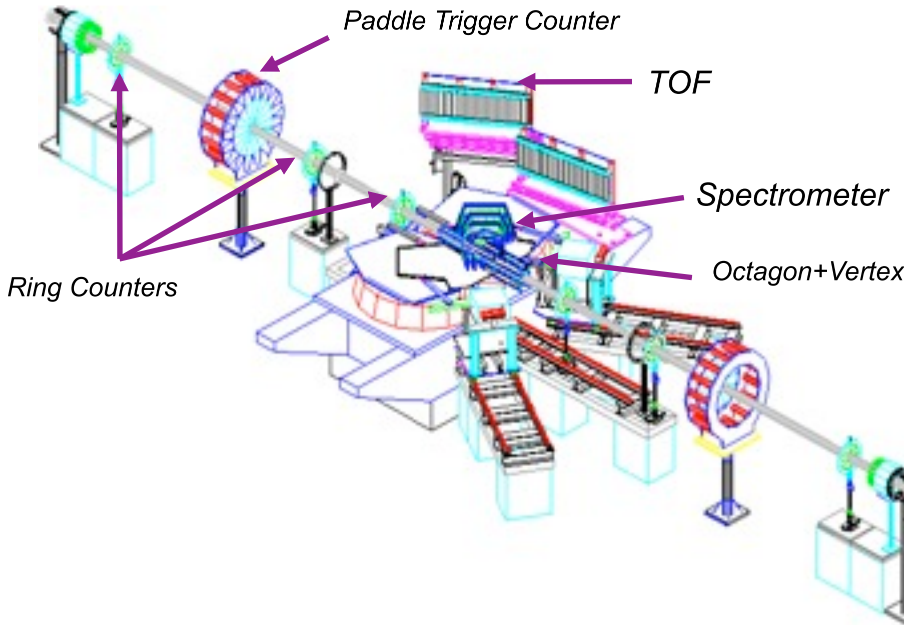
RHIC - the two "small" experiments

BRAHMS
2 "Conventional" Spectrometers
Magnets, Tracking Chambers, TOF, RICH, ~40 Participants

PHOBOS
"Table-top" 2 Arm Spectrometer
Magnet, Si μ-Strips, Si Multiplicity Rings, TOF, ~80 Participants





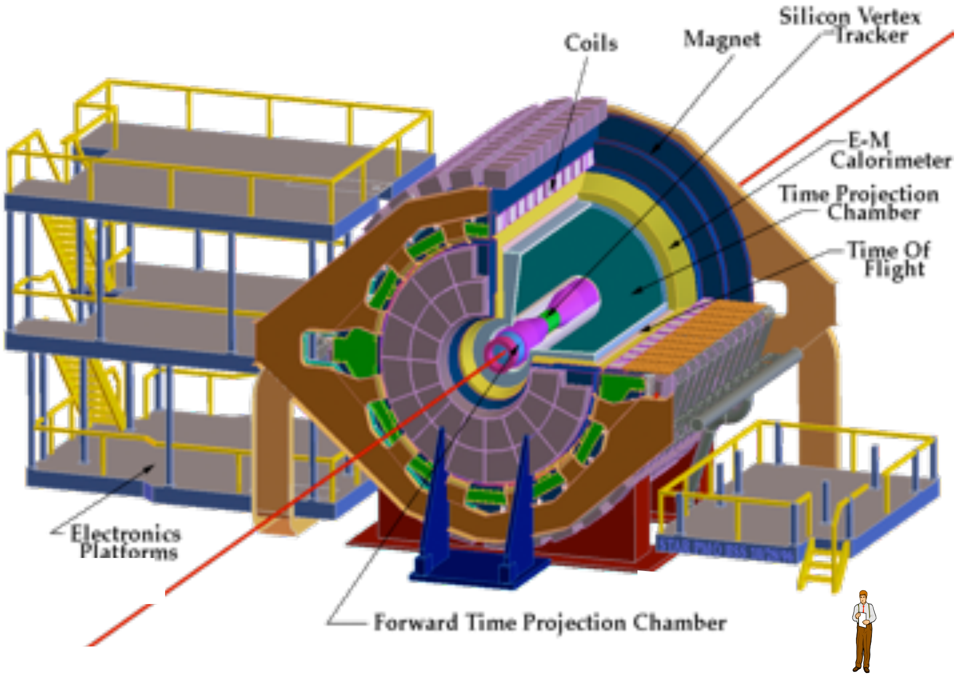
- ***Inclusive Particle Production Over Large Rapidity Range***

- ***Charged Hadrons in Select Solid Angle***
- ***Multiplicity in 4π***
- ***Particle Correlations***

RHIC - the two “large” experiments

STAR

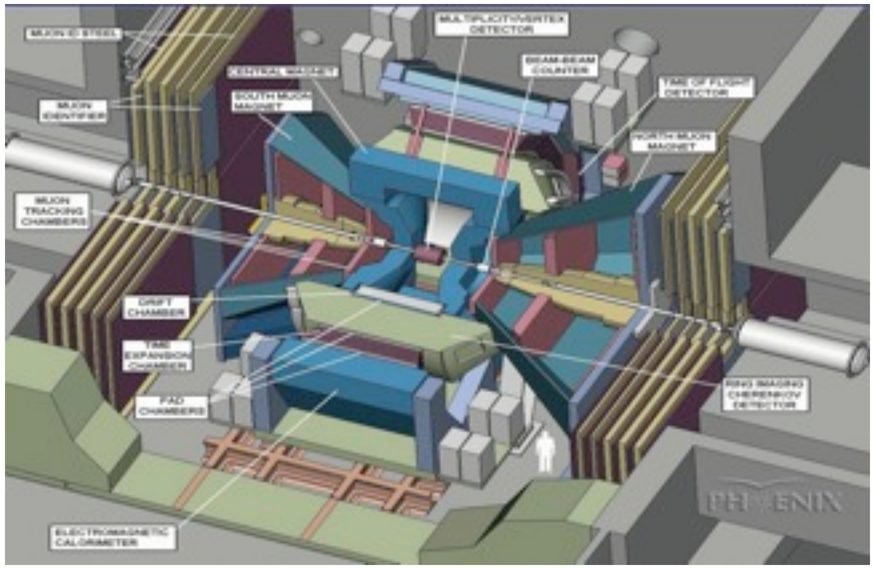
Solenoidal field
Large-Ω Tracking
TPC’s, Si-Vertex Tracking
RICH, EM Cal, TOF
~420 Participants



- **Measurements of Hadronic Observables using a Large Acceptance**
- **Event-by-Event Analyses of Hadrons and Jets, Forward physics, Leptons, Photons**

PHENIX

Axial Field
High Resolution & Rates
2 Central Arms, 2 Forward Arms
TEC, RICH, EM Cal, Si, TOF, μ-ID
~450 Participants



- **Leptons, Photons, and Hadrons in Selected Solid Angles**
- **Simultaneous Detection of Various Phase Transition Phenomena**