The hottest matter on earth: what its made of, how its formed, and how it flows

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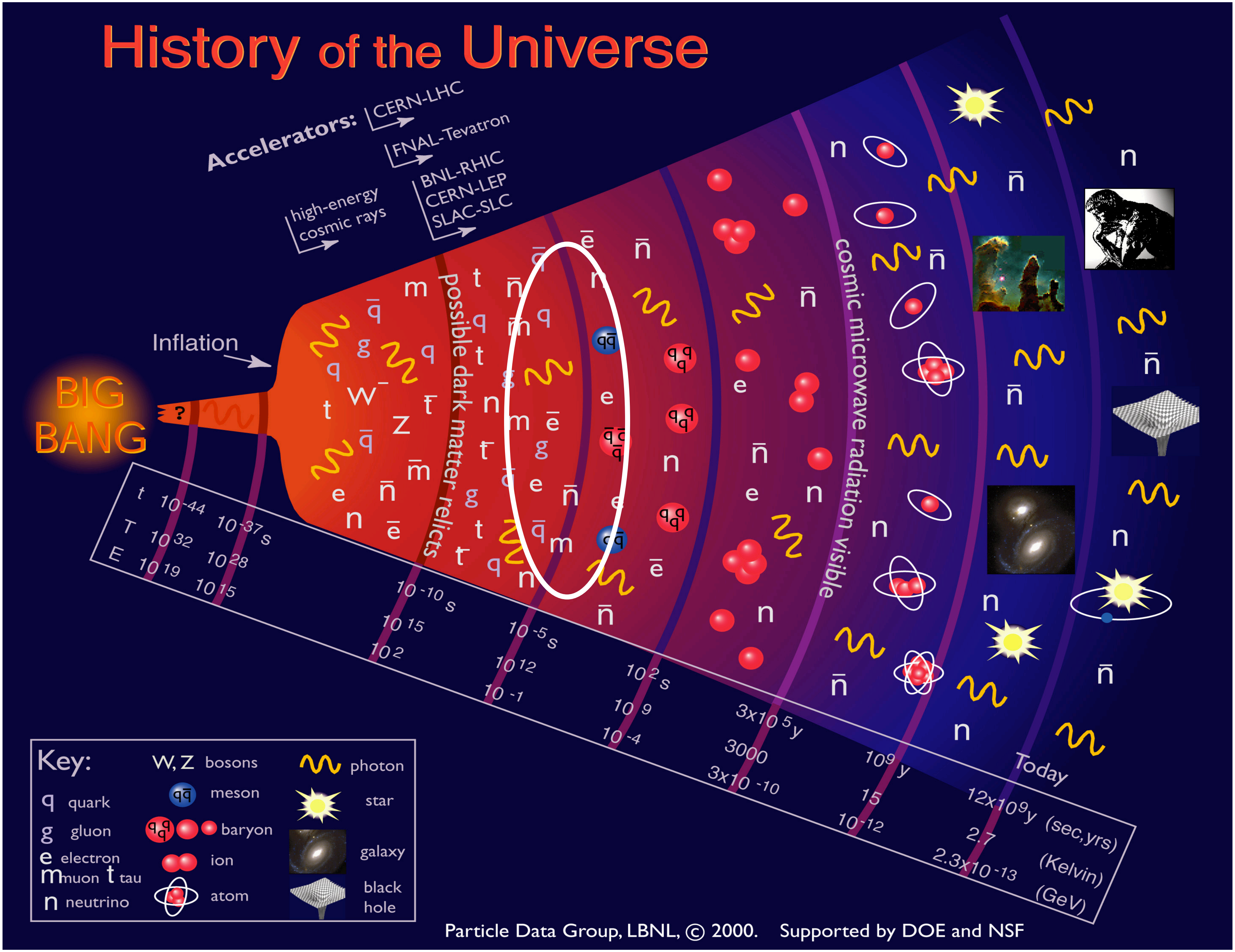
Brookhaven National Laboratory

UCT lectures, February 2012

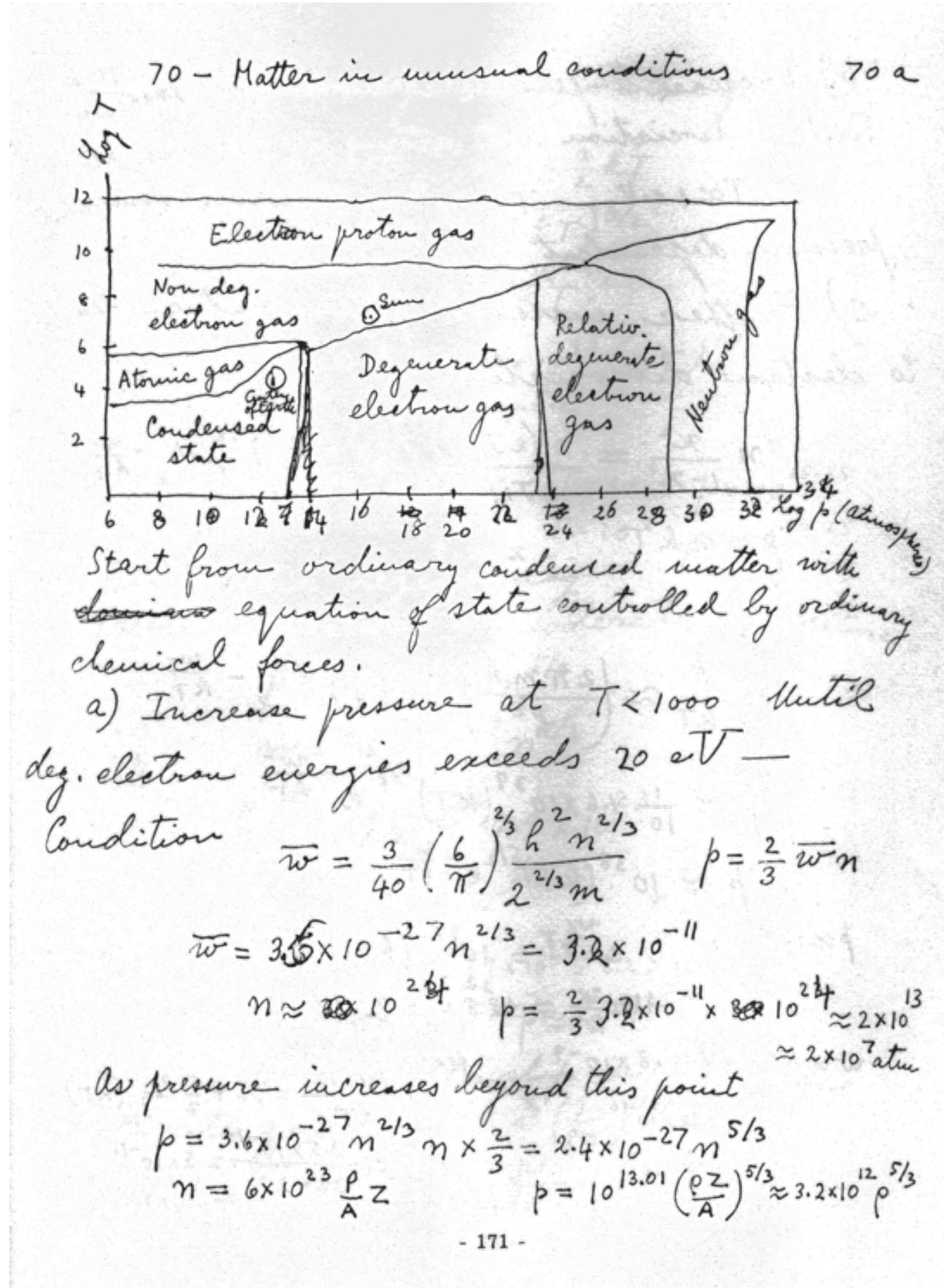
Outline of lectures

- **Lecture I: QCD and the Quark-Gluon Plasma**
- **Lecture II: Gluon Saturation and the Color Glass Condensate**
- **Lecture III: Quantum field theory in strong fields. Factorization and the Glasma**
- **Lecture IV: Quantum field theory in strong fields. Instabilities and the spectrum of initial quantum fluctuations**
- **Lecture V: Quantum field theory in strong fields. Decoherence, hydrodynamics, Bose-Einstein Condensation and thermalization**
- **Lecture VI: Future prospects: RHIC, LHC and the EIC**


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

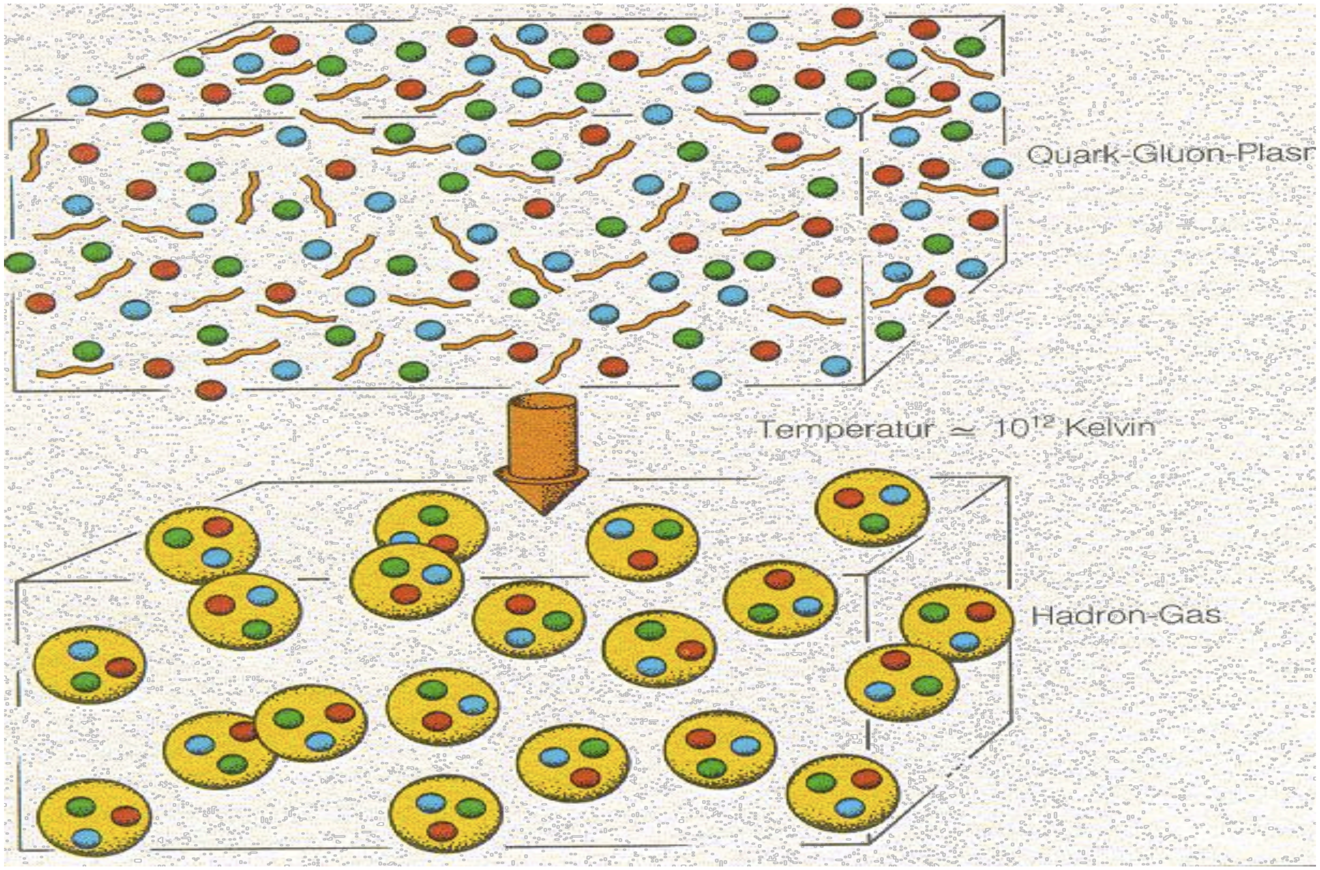

What happens to matter when it is heated up to temperatures 100,000 times hotter than the center of the sun?
center of sun 15,000,000 Celsius (27,000,000 Fahrenheit)

Matter in unusual conditions



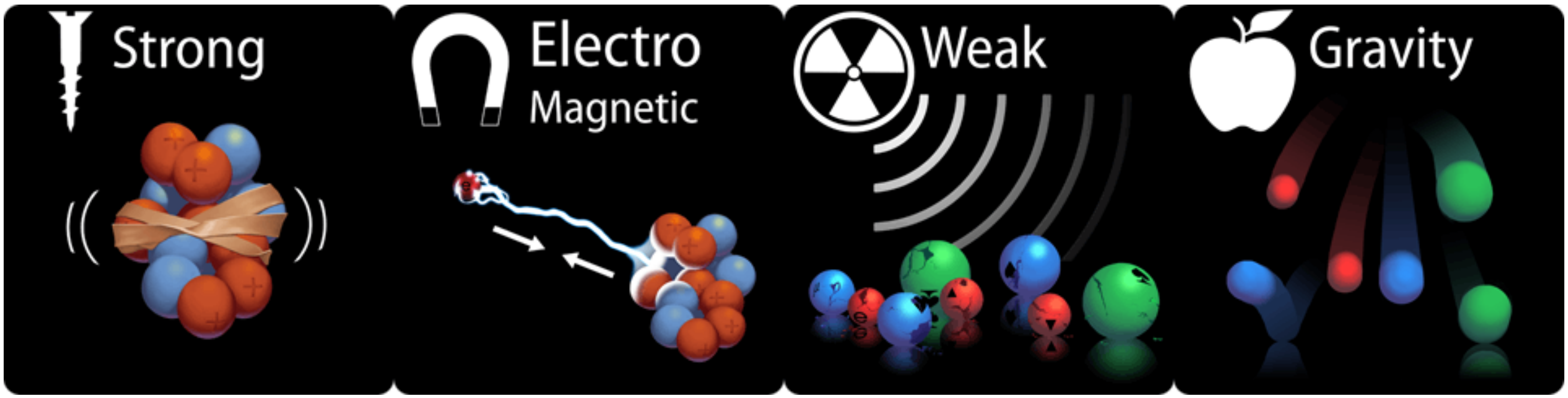
E. Fermi: “ Notes on Thermodynamics and Statistics ” (1953)

Universe evolved from Quarks & Gluons to Hadrons



How did this happen ?
Is there a phase transition (vapor to liquid) transition ?

QCD-Theory of the Strong Force

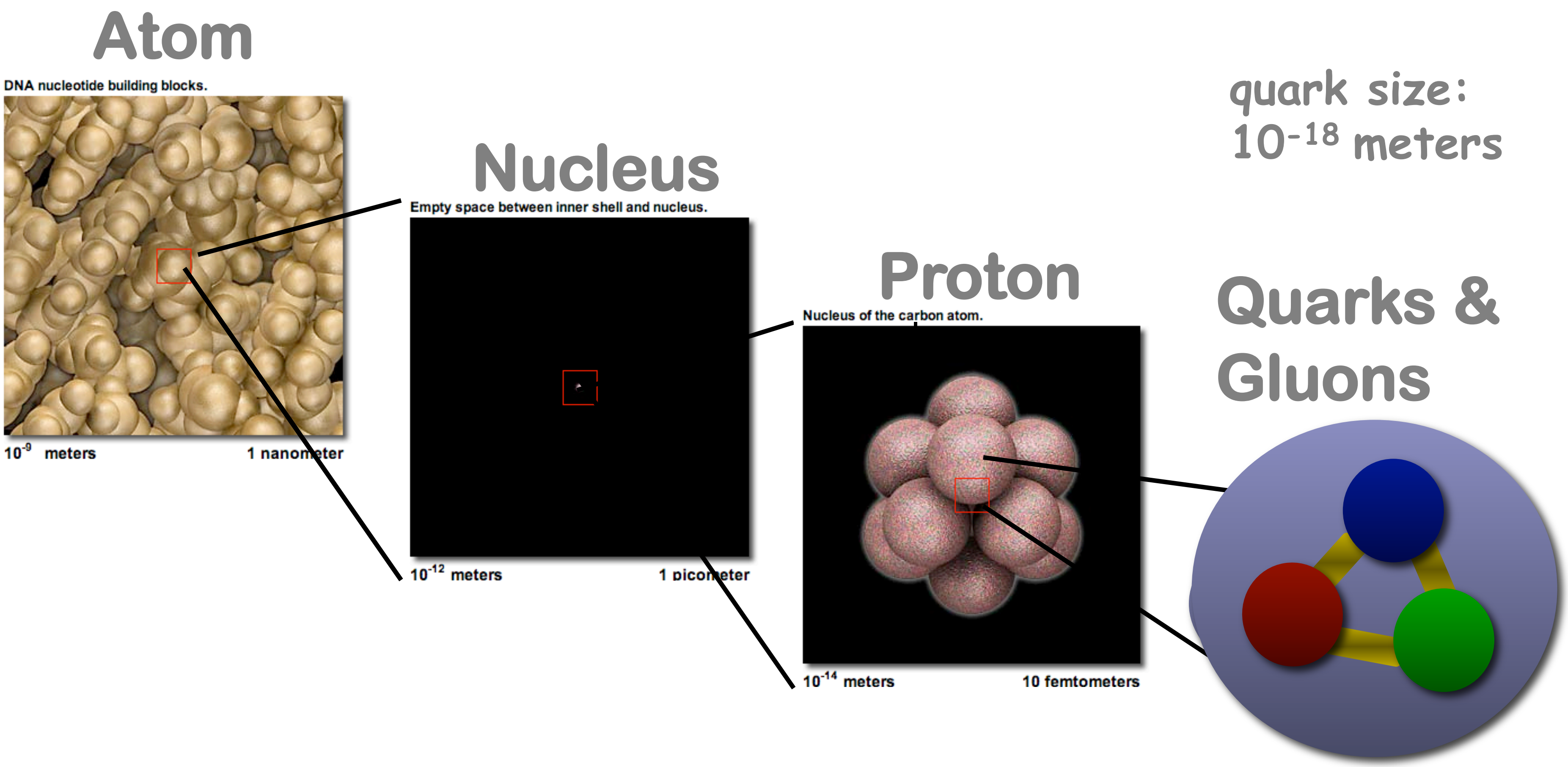


Relative strength	1	10^{-2}	10^{-6}	10^{-38}
Interaction range	10^{-15}	∞	10^{-15}	∞

2004 Nobel Prize in Physics

What does the strong force act on?

Quarks & Gluons: elementary, fundamental constituents of 99 % of visible matter in the universe.



Quantum Chromodynamics (QCD): fundamental theory of the strong force

QCD: theory of the strong interaction

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} + \sum_f \bar{q}^a_f (i\gamma^\mu D_\mu - m_f) q^a_f$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$

$$D_\mu = \partial_\mu - i g A^a_\mu \frac{\lambda^a}{2}$$

Gluon fields

Quark fields

Symmetries of QCD Lagrangian:

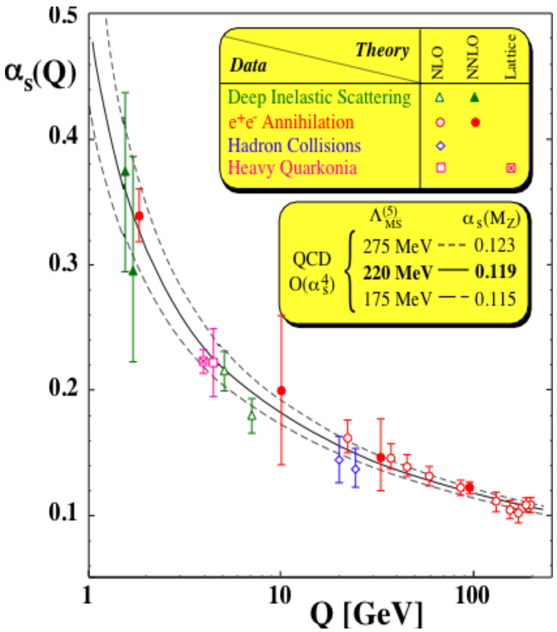
$$\underbrace{SU(3)_c}_{\text{i}} \times \underbrace{SU(3)_L \times SU(3)_R}_{\text{ii}} \times \underbrace{U(1)_A \times U(1)_B}_{\text{iii}}$$

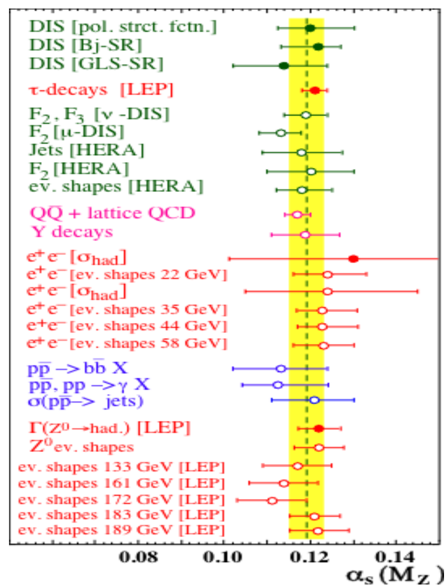
- **i) Gauge "color" symmetry: unbroken but confined**
- **ii) Global "chiral" symmetry: exact for massless quarks**
- **iii) Baryon number and axial charge (m=0) are conserved**
- **iv) Scale invariance:** $\psi(x) \longrightarrow \lambda^{3/2}\psi(\lambda x)\ ;\ A^a_\mu(x) \longrightarrow \lambda\, A^a_\mu(\lambda x)$
- **v) Discrete C,P & T symmetries**

Chiral, Axial, Scale and (in principle) P & T are broken by Vacuum / Quantum effects

QCD: asymptotic freedom

Gross,Wilczek, Politzer





Coupling grows weaker with increasing momentum transfer (shorter distances)

$$\alpha_S(Q^2) = \frac{12\pi}{(11\,N_c - 2\,n_f)\ln\left(\frac{Q^2}{\Lambda^2_{\rm QCD}}\right)}\left[1 - \frac{6(153-19n_f)}{(11N_c-2n_f)^2}\frac{\ln(\ln(Q^2/\Lambda^2_{\rm QCD}))}{\ln(Q^2/\Lambda^2_{\rm QCD})}\right] + \cdots$$

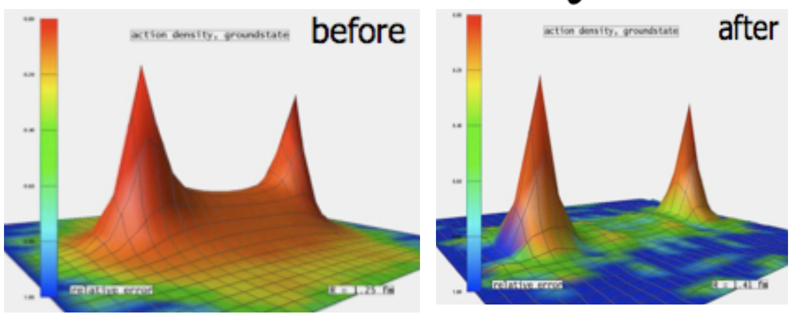
Super-dense and Super-hot QCD matter
is a weakly coupled gas of quarks and gluons
-- analytical computations feasible

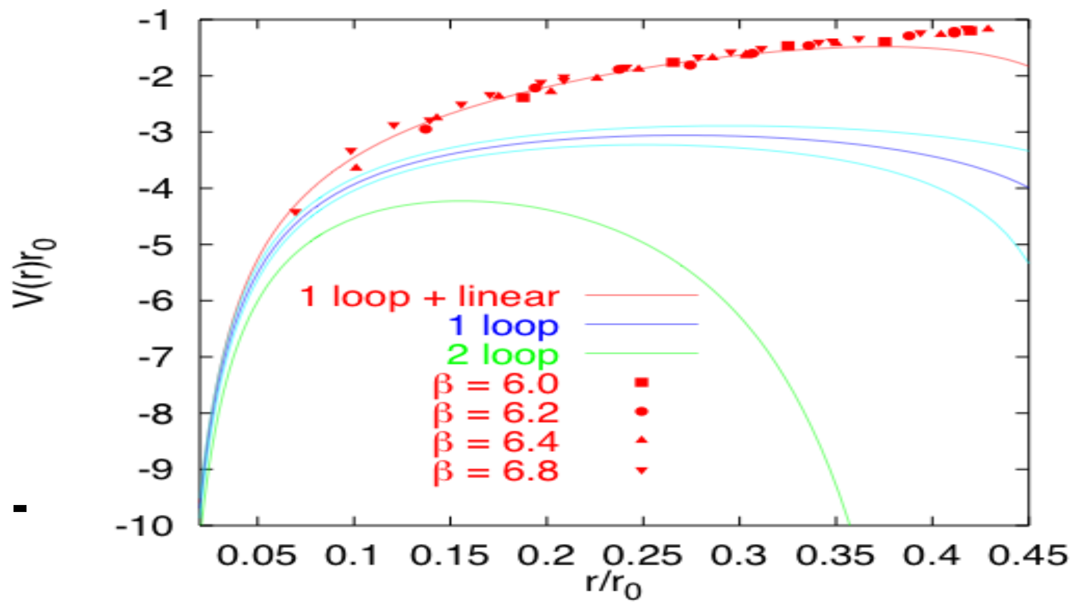
Cabibo-Parisi; Collins-Perry

QCD: Infrared Slavery

$$V(r) = \sigma r - \frac{e}{r}$$

$\sigma = 425\ \mathrm{MeV}^2\ ;\ e \approx 0.5$





Potential between static quark-anti-quark pair grows linearly at large distances -
intuitive picture of confinement

QCD matter is strongly interacting at low Temp. and Density
- static properties computed using lattice methods

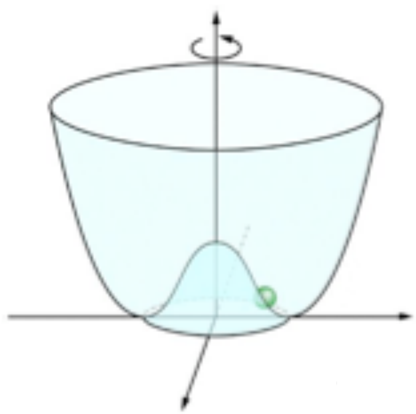
QCD: Chiral symmetry breaking

Chiral basis :  $q_L = \frac{1}{2}(1-\gamma_5)q, \quad q_R = \frac{1}{2}(1+\gamma_5)q$ 

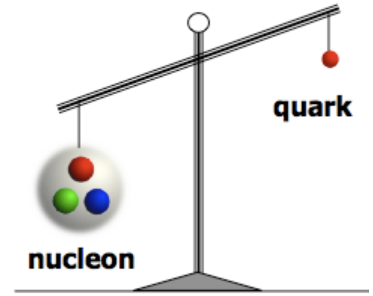
QCD Lagrangian : $\mathcal{L}_{cl} = \mathcal{L}_{cl}(q_L, A) + \mathcal{L}_{cl}(q_R, A)$

Quantum QCD vacuum:

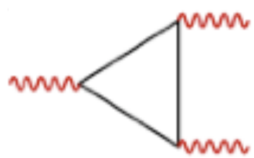
Chiral condensate: spontaneously generate mass via Nambu-Goldstone mechanism



$$\longrightarrow \langle \bar{q}_R q_L \rangle \neq 0$$

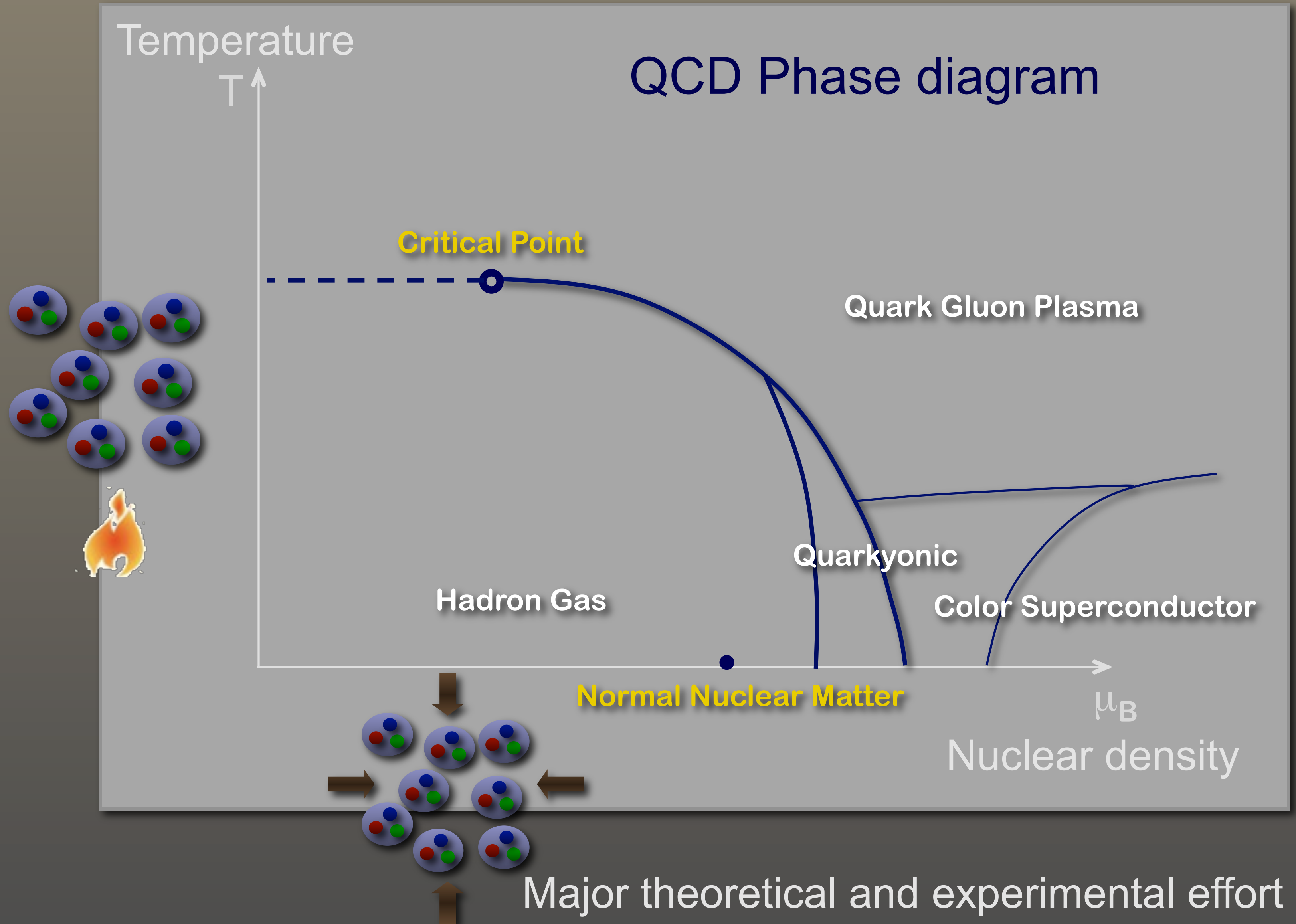


m_q ~ 10 MeV ; m_N ~ 1 GeV

Axial anomaly:  **Quantum violation of $U(1)_A$** $\partial_\mu J^\mu_A = -2n_f \frac{\alpha_S}{8\pi} F^{\mu\nu,a}\tilde{F}^a_{\mu\nu}$

Chiral symmetry restoration at large T: $\langle \bar{q} q \rangle \longrightarrow 0$

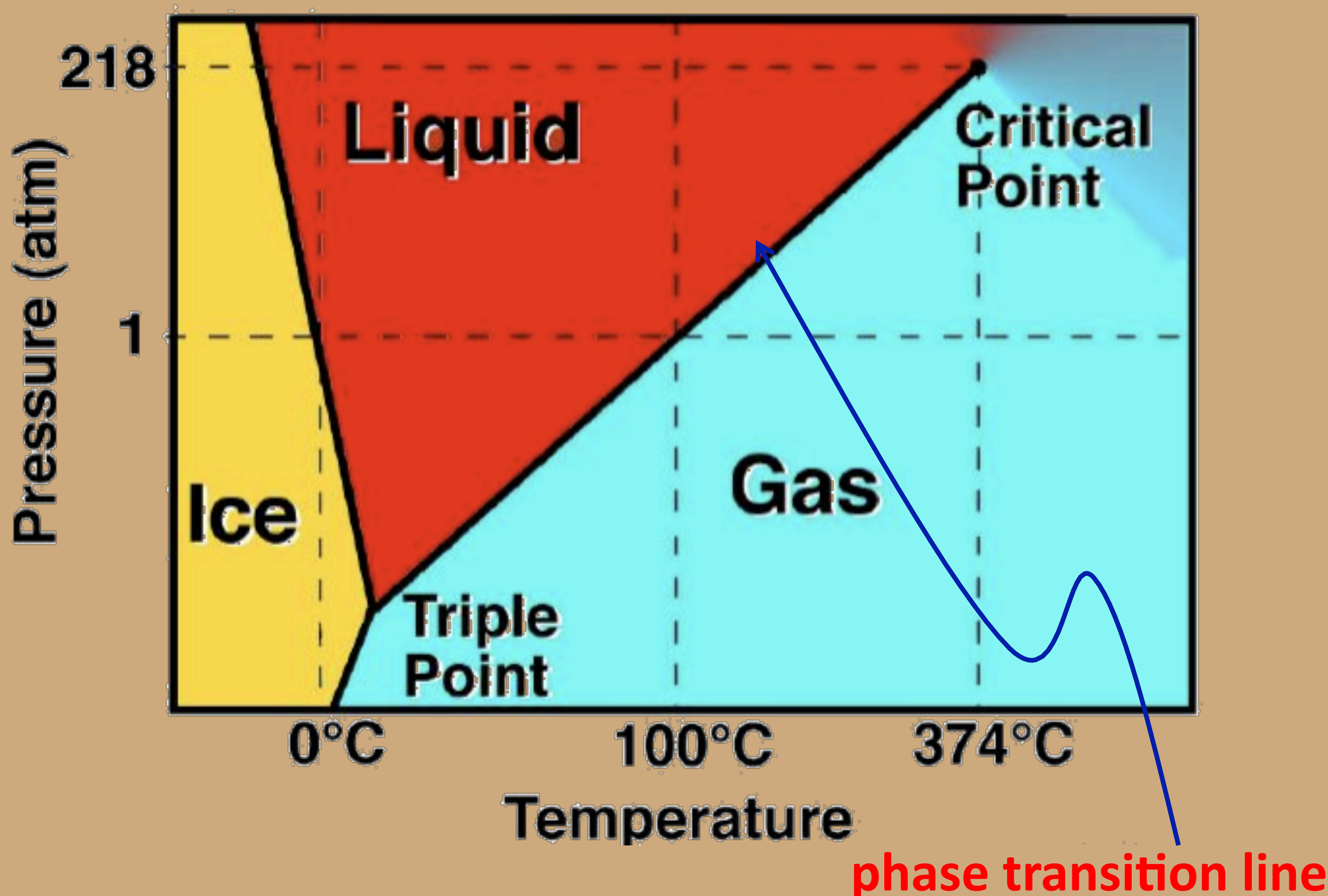
phase diagram of nuclear matter



Major theoretical and experimental effort to map and explore this rich phase structure.

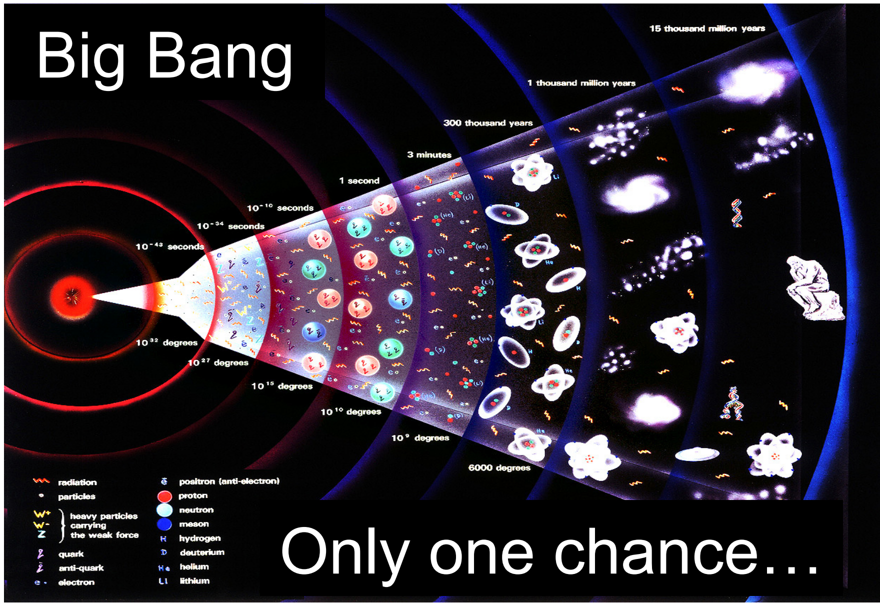
Phase Diagram of Water

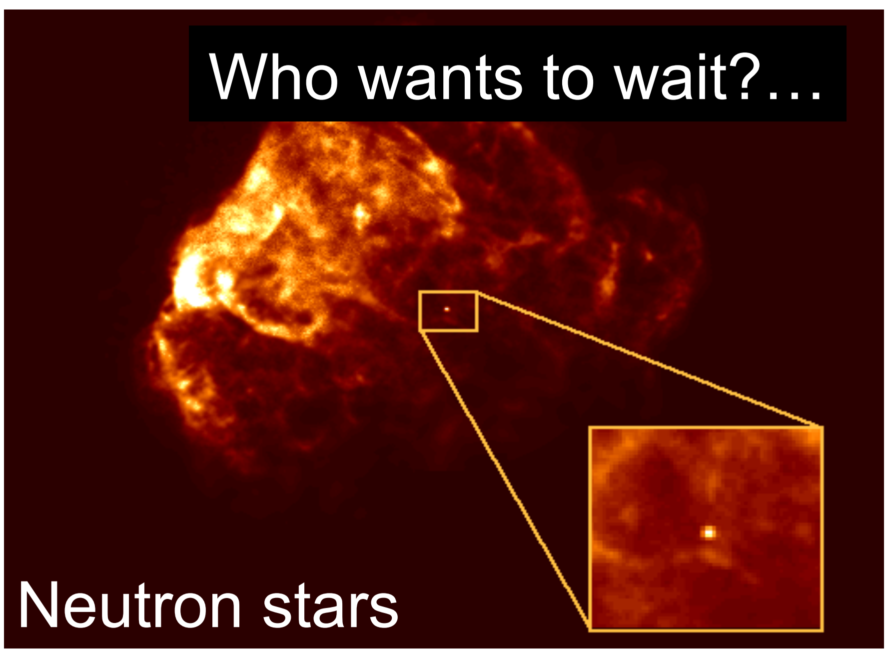
Physicists' way of mapping the phase that will exist for a given pressure and temperature

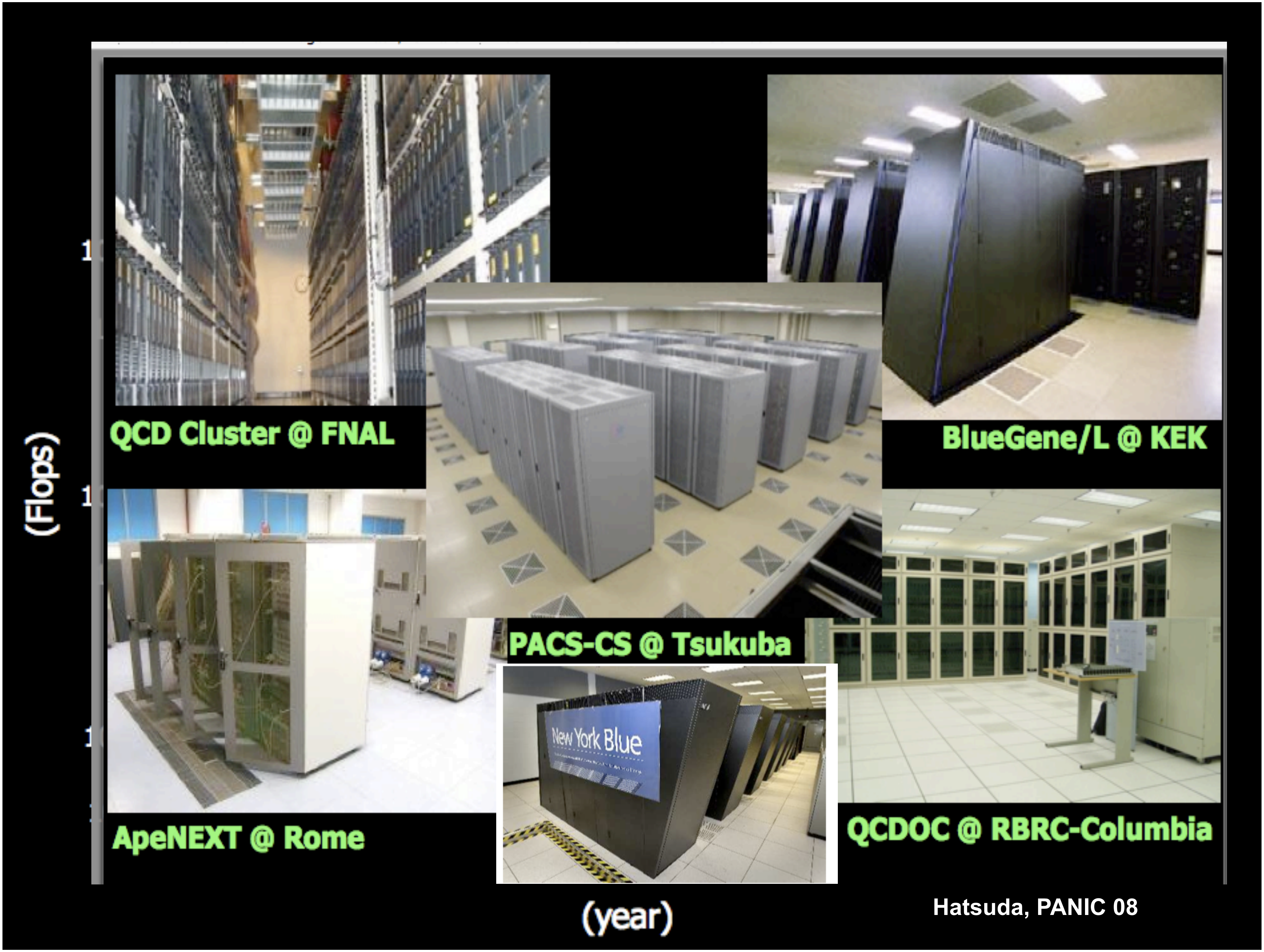


Where to study QCD matter ?

Peter Steinberg

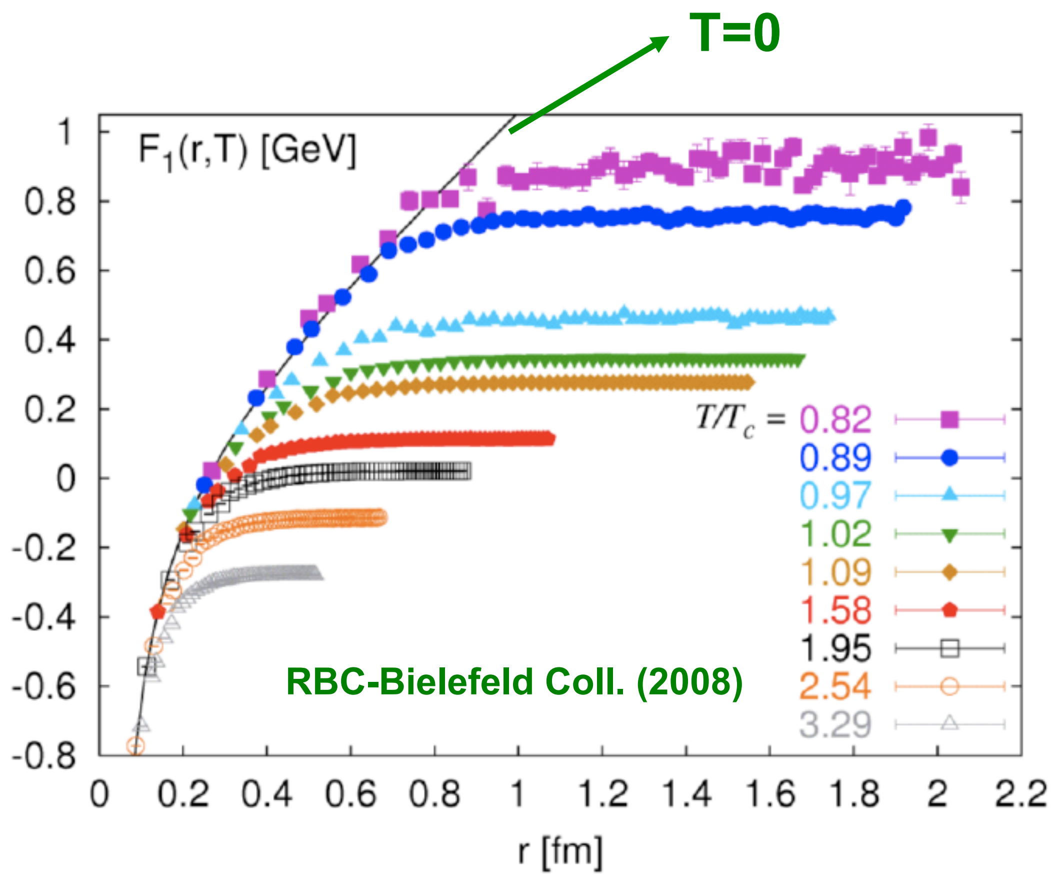





QCD Cluster @ FNAL
BlueGene/L @ KEK
PACS-CS @ Tsukuba
ApeNEXT @ Rome
New York Blue
QCDOC @ RBRC-Columbia
(Flops)
(year)
Hatsuda, PANIC 08

Lattice QCD at finite T:

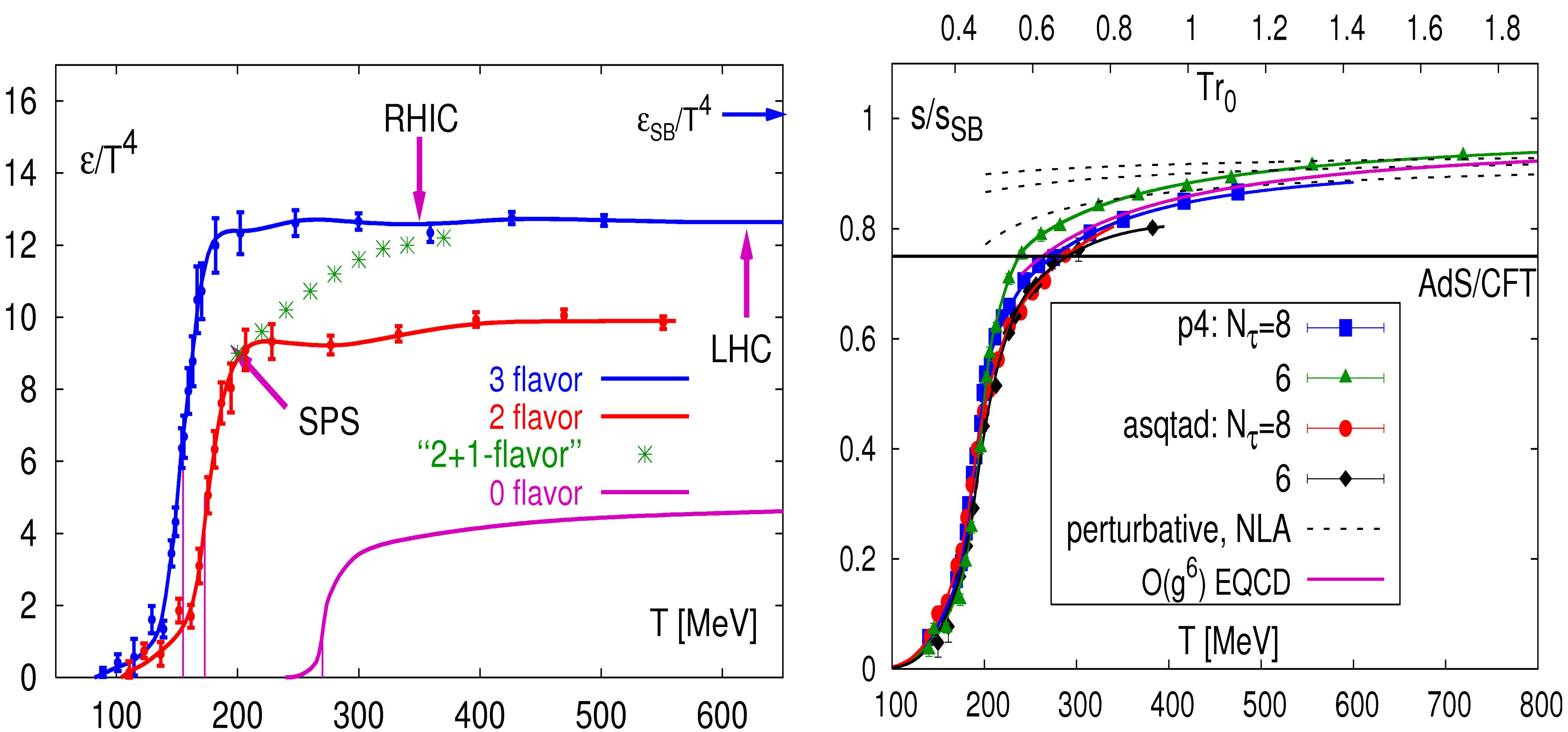
Plasma screens potential between heavy quarks



Suppression of heavy quarks suggested as possible signature of Quark-Gluon formation - Matsui, Satz 1986

QCD at finite T:

Lattice results for Energy & Entropy Density

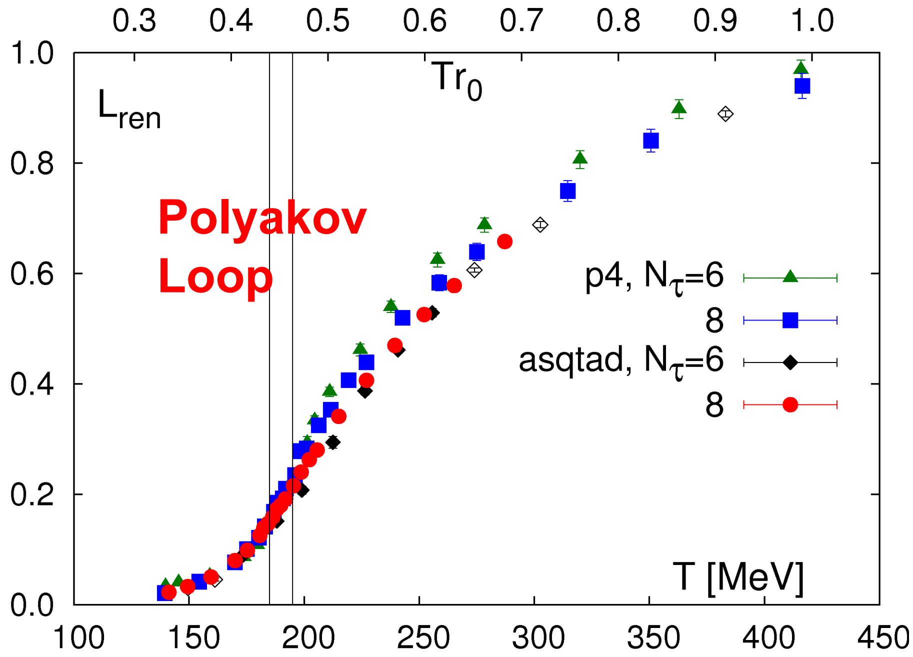


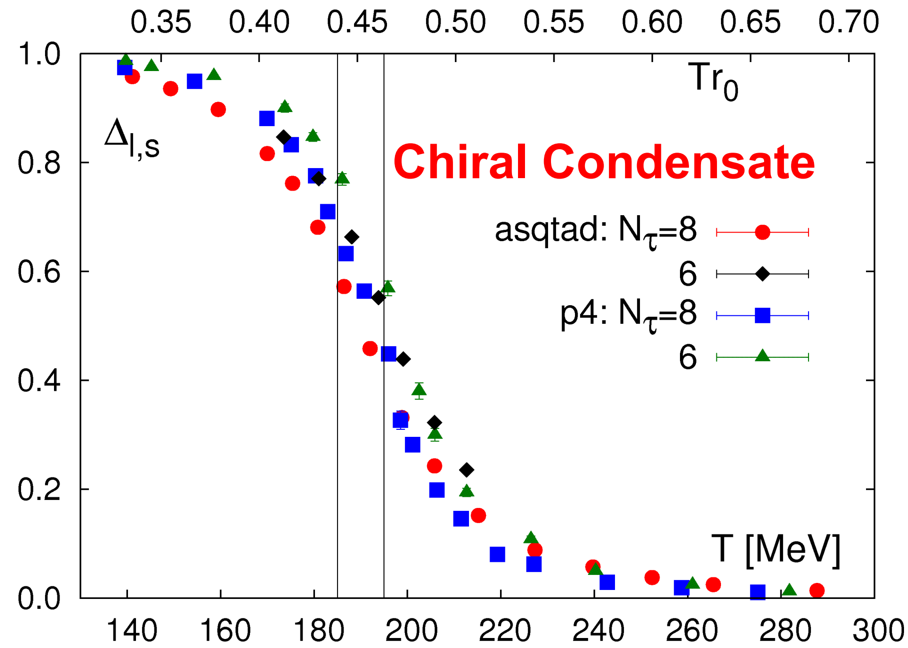
Rapid rise at T ~ 170 MeV

Petreczky, Quark Matter 2009

QCD at finite T:

Lattice results for Confinement and Chiral Symmetry





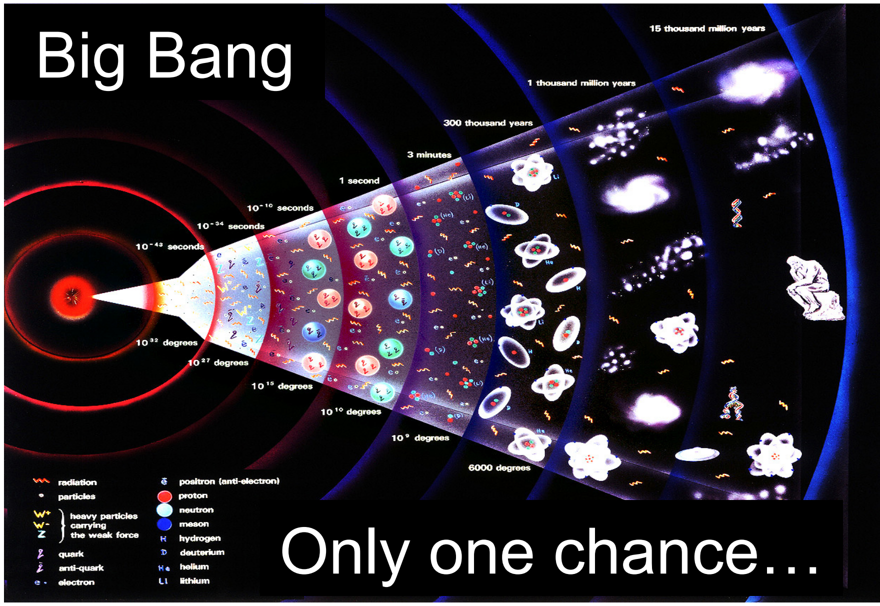
Rapid change in same T interval corresponding to rapid change in Energy and Entropy densities

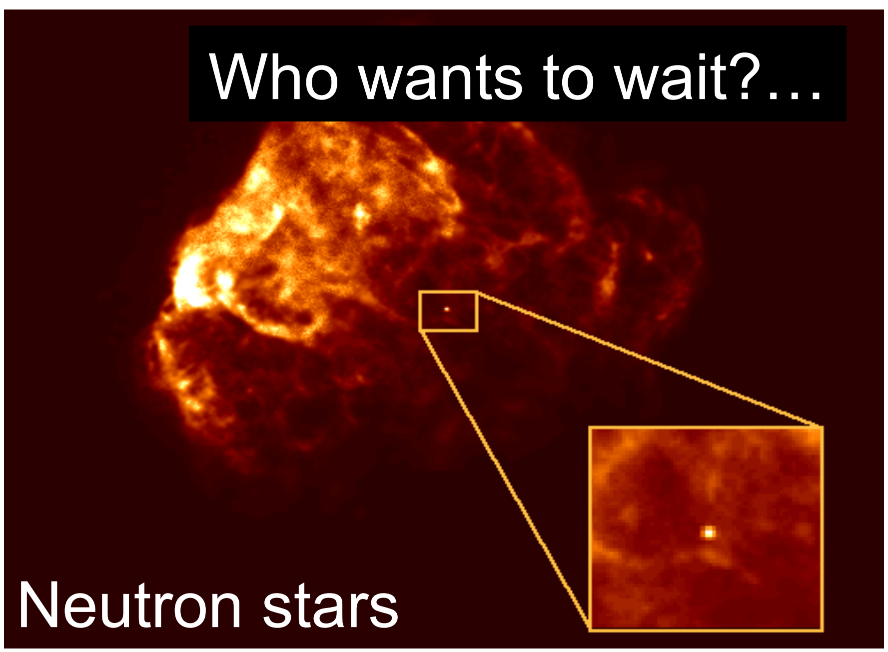
Bazavov et al, (HotQCD Coll.) arXiv:0903.4379

Finite T transition is a crossover Aoki et al, Nature 443 (06) 675

Where to study QCD matter ?

Peter Steinberg



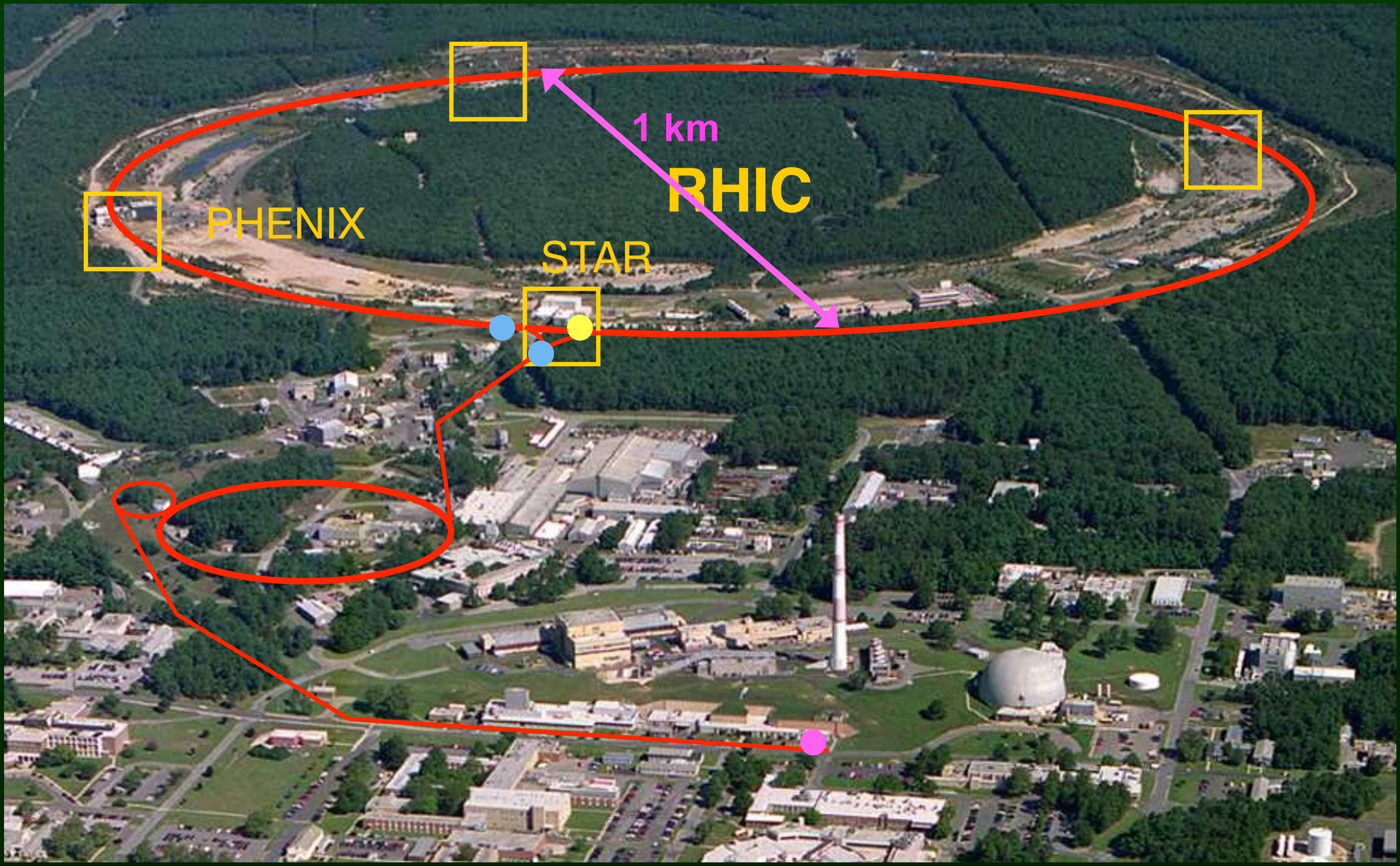


Heavy Ion Experiments

Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV

The place to look for quark-gluon plasma

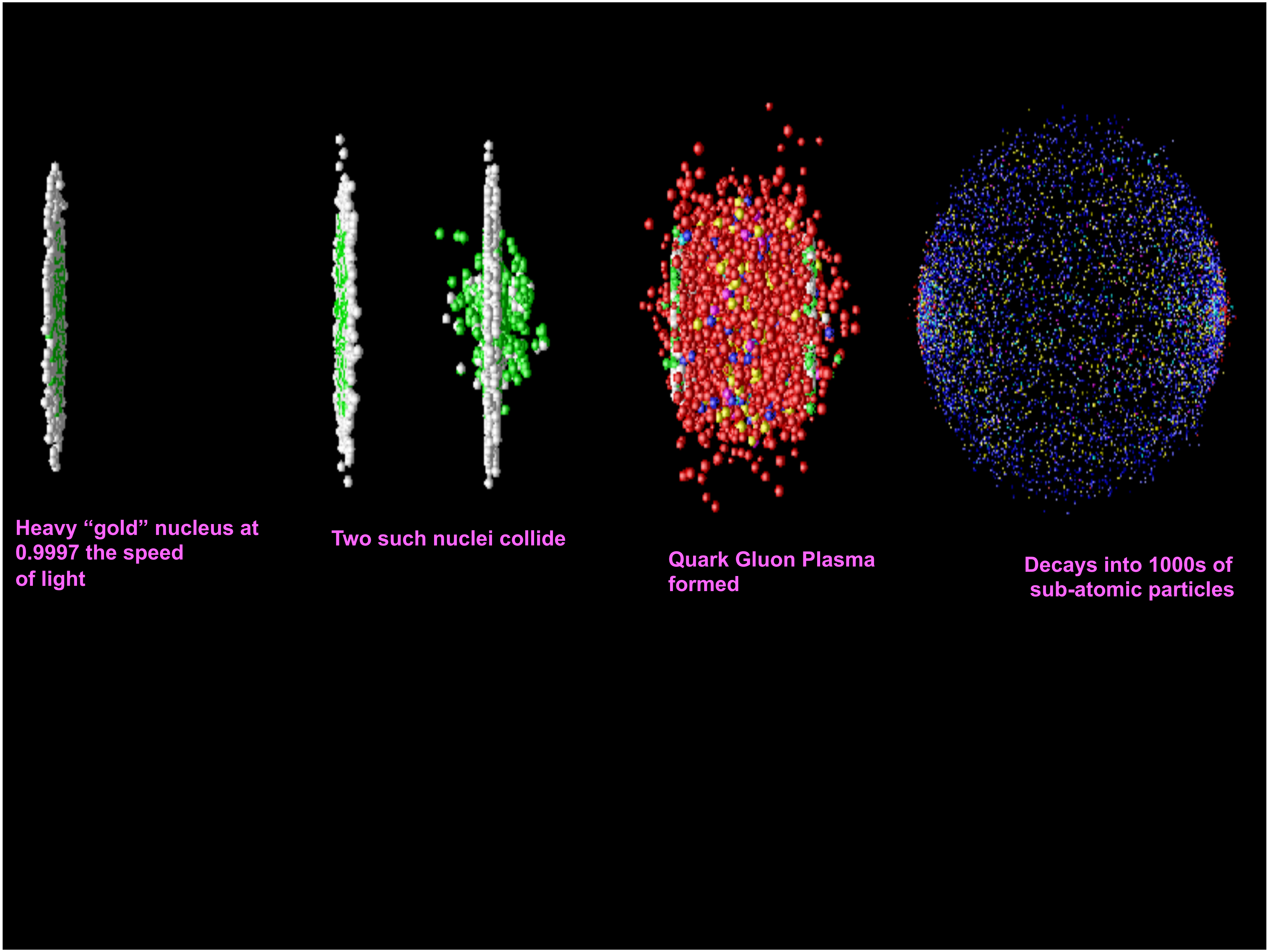
Relativistic Heavy Ion Collider RHIC @ BNL



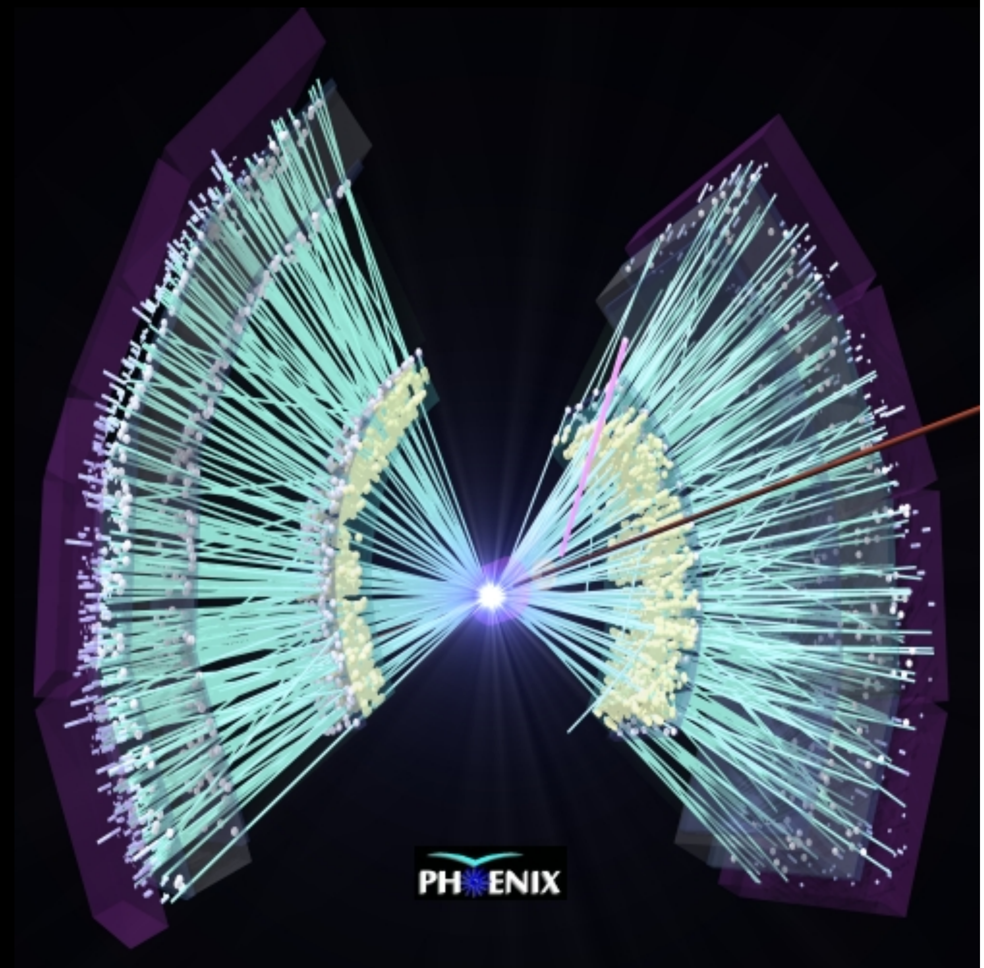
3 km ring

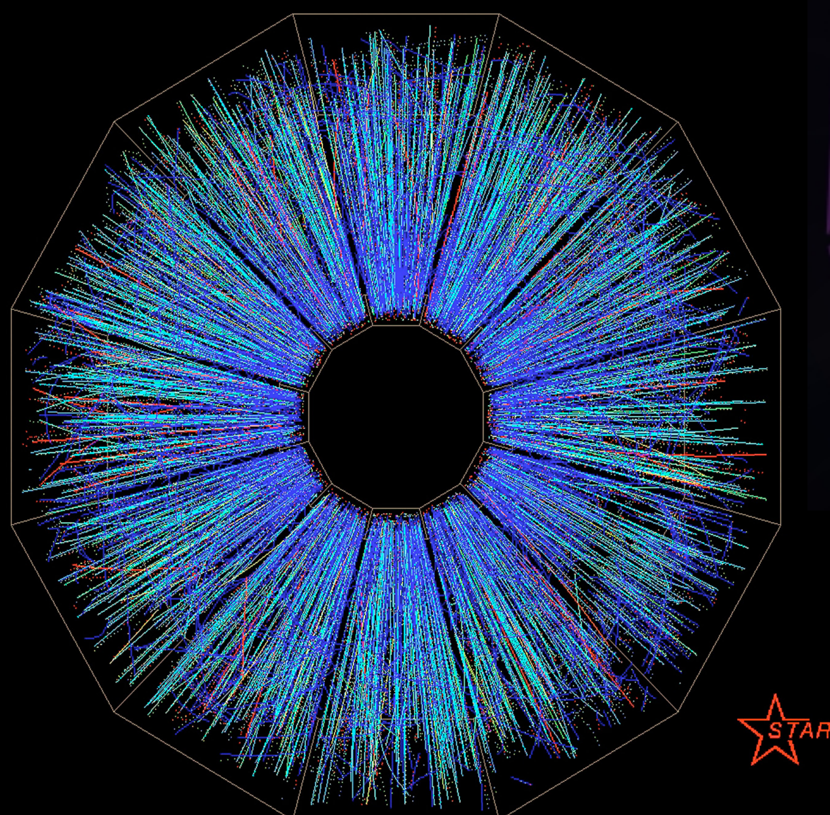
animation by Mike Lisa

major international enterprise: thousands of scientists and engineers


Heavy “gold” nucleus at
0.9997 the speed
of light
Two such nuclei collide
Quark Gluon Plasma
formed
Decays into 1000s of
sub-atomic particles

We cannot determine if a QGP was produced by observing it directly - its lifetime is too short (~ 10^{-23} seconds…)





but studying the detailed structure behind these images, RHIC scientists conclude the QGP was a nearly perfect fluid

BBC NEWS | Science/Nature | Early Universe was 'liquid-like'

http://news.bbc.co.uk/2/hi/science/nature/4462209.stm

rhic bbc

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Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

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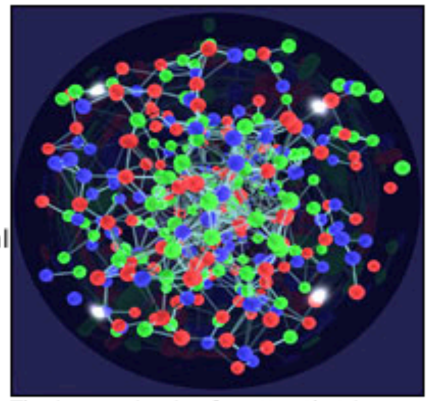
Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.



The impression is of matter that is more strongly interacting than predicted

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The researchers, at the US Brookhaven National Laboratory, say these particles were seen to behave as an almost perfect "liquid".

The work is expected to help scientists explain the conditions that existed just milliseconds after the Big Bang.

The details, presented to the American Physical Society in Florida, will be published across a number of papers in the journal Nuclear Physics A.

> **People like me, who use model calculations, are already so excited about the data because we believe they have actually found the elusive state known as the quark-gluon plasma**
>
> Asst Prof Steffen Bass, Duke University

They summarise the work of four collaborative experiments - dubbed Brahms, Phenix, Phobos and Star - which have been running on Brookhaven's

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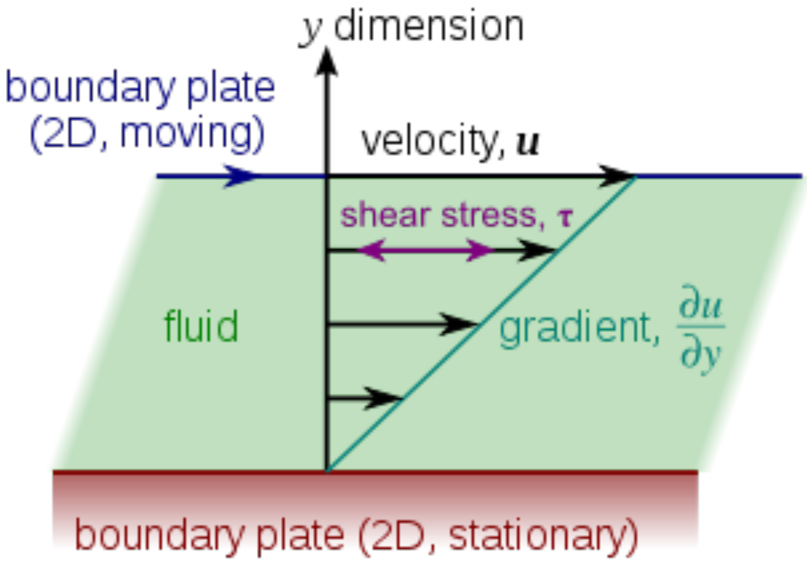
Viscosity

- **Introduced by Claude Navier in 1822 (Navier Stokes equation)**



Pitch tar: viscosity 230 billion times that of water

$$\frac{F}{A} = \eta \frac{\partial u_x}{\partial y}$$

A (nearly) perfect fluid

"Bjorken Hydrodynamics" for relativistic fluids

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

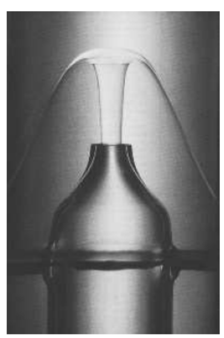
Viscous term smaller than ideal term for

$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} \equiv \frac{\eta}{s}\frac{1}{\tau T} << 1$$

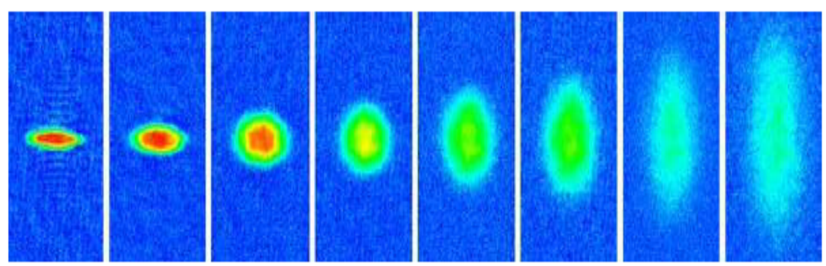
From kinetic theory

$$\frac{\eta}{s} \sim \frac{\hbar}{k_B}\frac{\tau_{\mathrm{relax.}}}{\tau_{\mathrm{quant.}}}$$

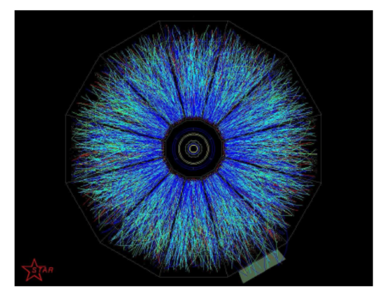
H_2O



^4He



^6Li



sQGP

A (nearly) perfect fluid

"Bjorken Hydrodynamics"

$$\frac{d\varepsilon}{d\tau} = -\frac{\left(\varepsilon + P - \frac{4}{3}\frac{\eta}{\tau}\right)}{\tau}$$

Viscous term smaller than ideal term for

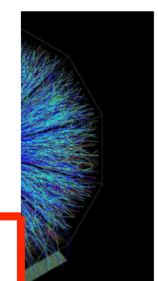
$$\frac{\eta}{\varepsilon + P}\frac{1}{\tau} \equiv \frac{\eta}{s}\frac{1}{\tau T} << 1$$

AdS/CFT:

$$\frac{\eta}{s} \geq \frac{\hbar}{k_B}\frac{1}{4\pi}$$

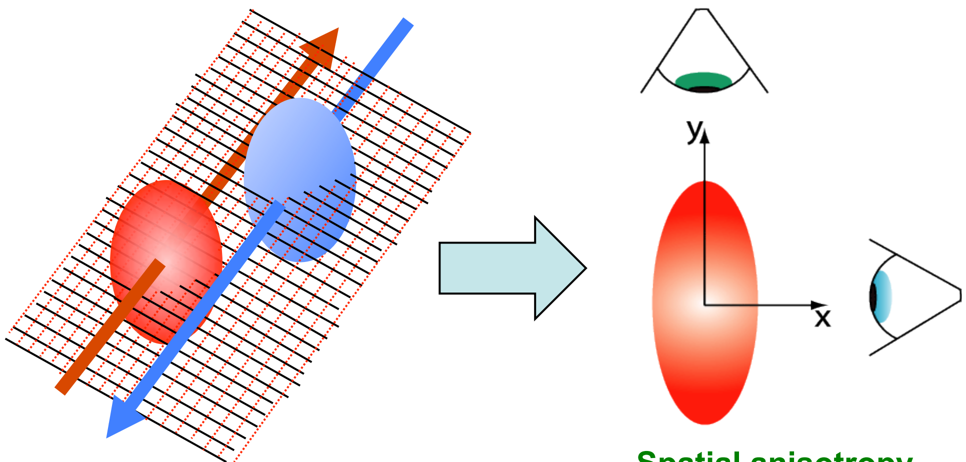
H$_2$O

Fluid	$T\ [K]$	$\eta\ [Pa \cdot s]$	$\eta/n\ [\hbar]$	$\eta/s\ [\hbar/k_B]$
H_20	370	2.9×10^{-4}	85	8.2
^4He	2	1.2×10^{-6}	0.5	1.9
$^6Li\ (\lvert a_s \rvert \simeq \infty)$	23×10^{-6}	$\leq 1.7 \times 10^{-15}$	≤ 1	≤ 0.5
QGP	2×10^{12}	$\leq 5 \times 10^{11}$	-	≤ 0.4



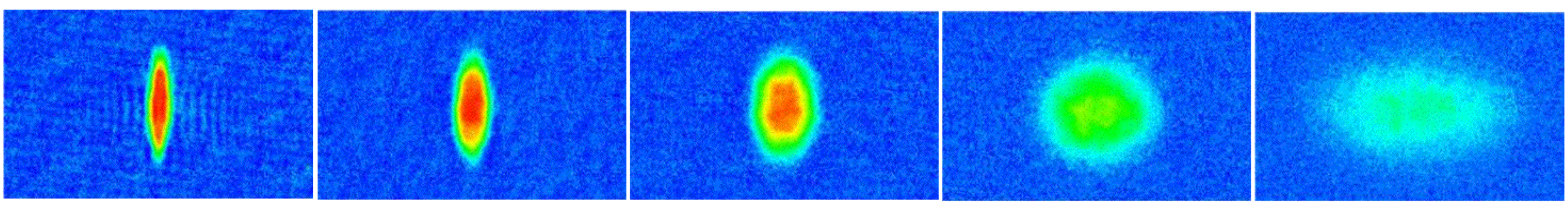
GP

Strong flow = (nearly) ideal hydrodynamics



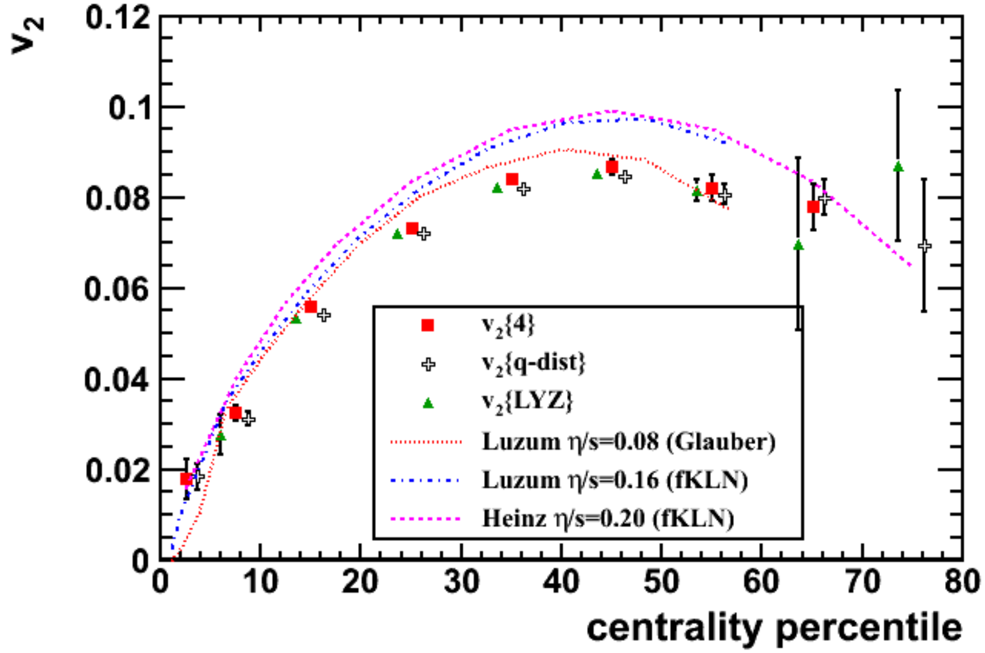
$$\frac{dN}{dy\,p_\perp dp_\perp d\phi} = \frac{1}{2\pi}\frac{dN}{dy\,p_\perp dp_\perp}\left(1 + 2\,v_2(p_\perp)\cos 2(\phi - \Psi_{\rm RP}) + \cdots\right)$$

Spatial anisotropy

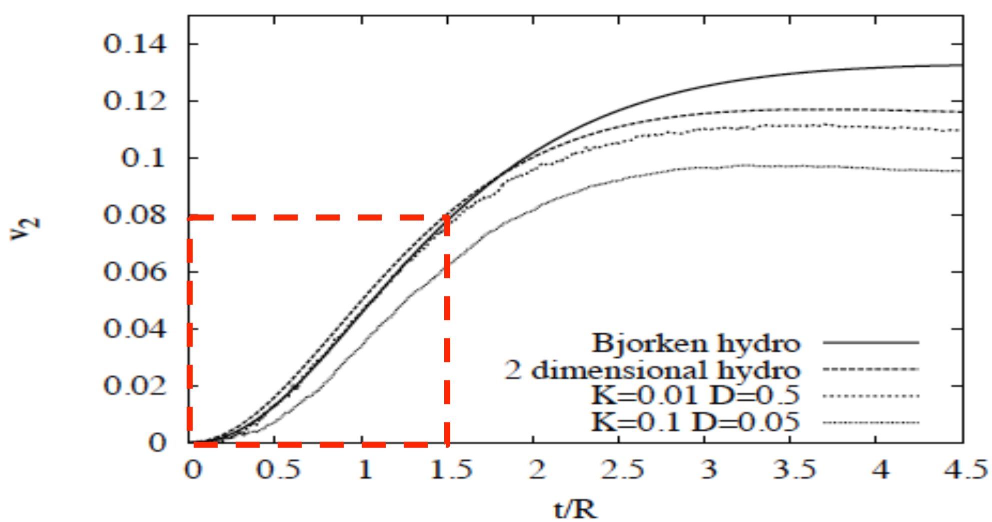


v_2 measures how efficiently hot matter converts spatial anisotropies to momentum anisotropy
– most efficient way is hydrodynamics

Strong flow = (nearly) ideal hydrodynamics



v_2 at LHC in agreement with (slightly) viscous relativistic hydrodynamics

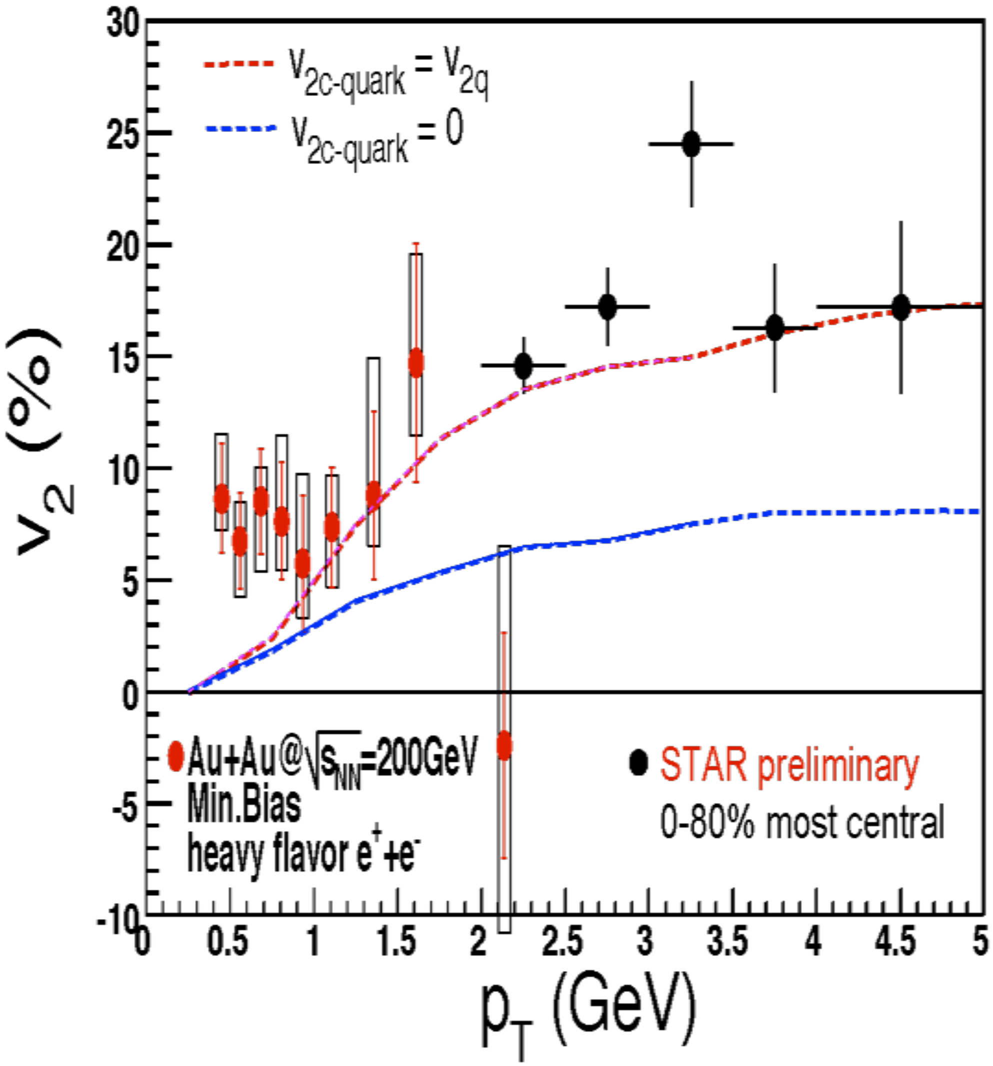


Takes a long time ~ R/c_S

to build up v_2

Flow must set in very early (≤ 1 fm)

Even heavy quarks (charm & beauty flow)



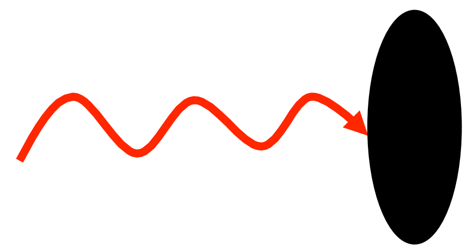
AdS/CFT and the KSS bound

AdS/CFT conjecture: Maldacena

"Holographic Duality between strongly coupled N=4 supersymmetric Yang-Mills theory at large coupling and Nc & classical 10 dimensional gravity in the background of D3 branes

KSS bound: Kovtun,Son,Starinets

Classical absorption cross-section of a graviton with energy ω on a black brane



$$\sigma(\omega) = \frac{8\pi G}{\omega} \int dt d\mathbf{x}\, e^{i\omega t} \langle [T_{xy}(t,\mathbf{x}), T_{xy}(0,0)] \rangle$$

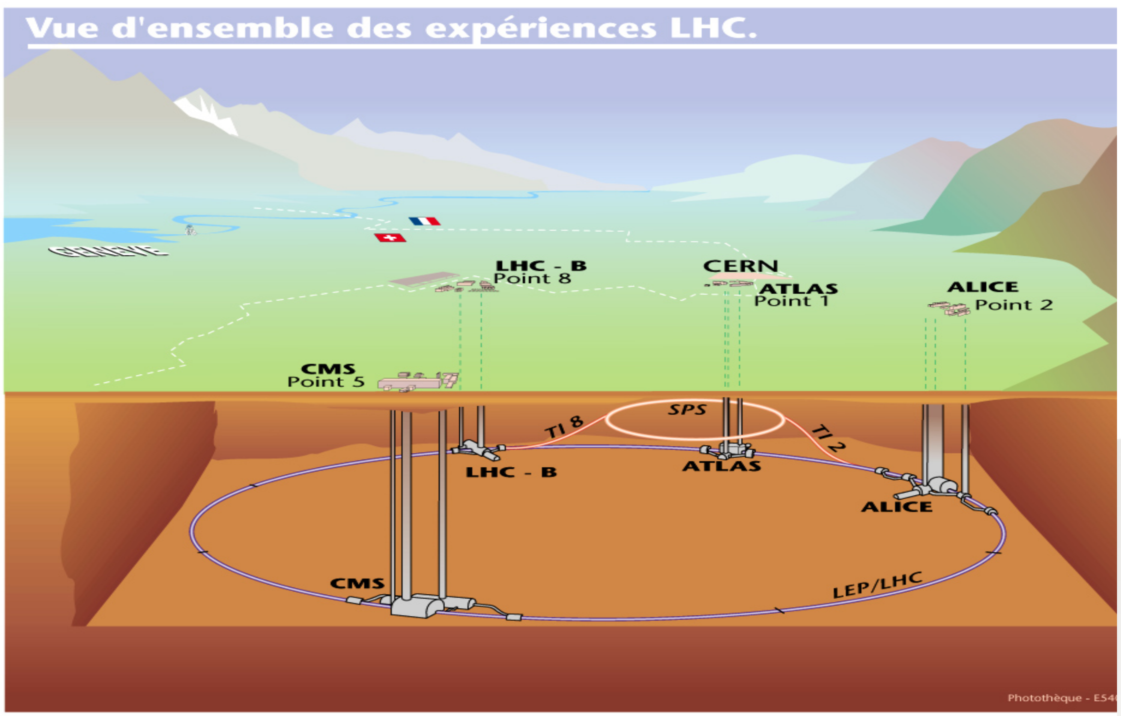
From Kubo: $\eta = \frac{\sigma(0)}{16\pi G}$

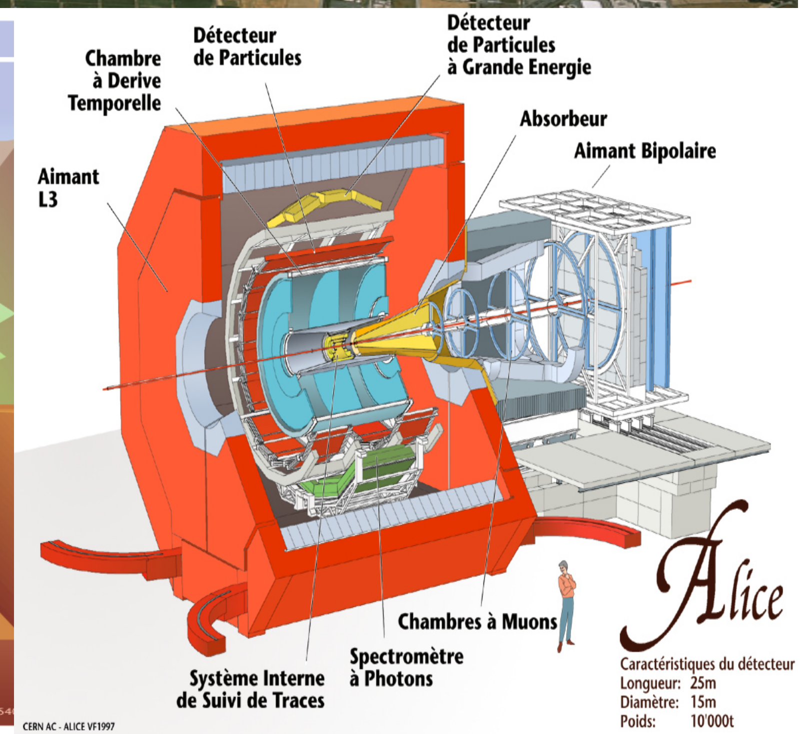
From Beckenstein: $s = \frac{a}{4G}$

where a= area of black brane

Theorem: $\sigma(0) = a$

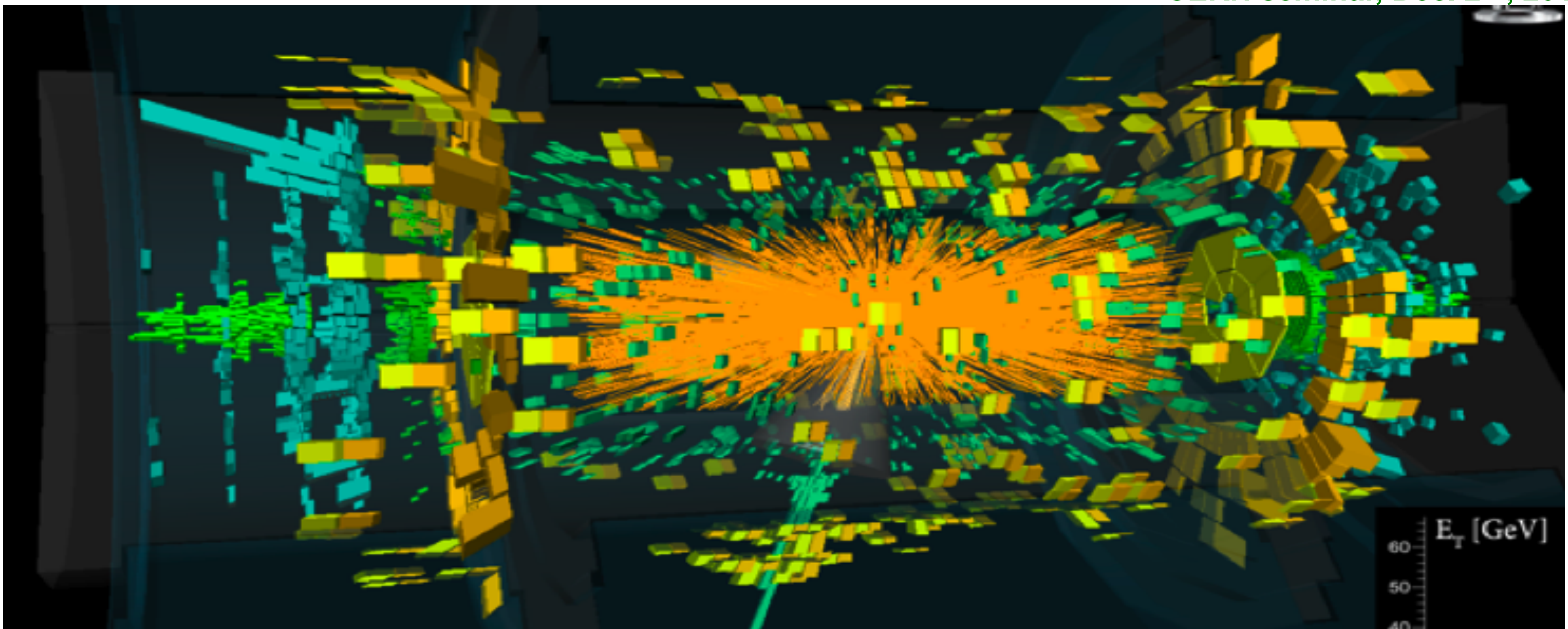
Putting it all together: $\frac{\eta}{s} \geq \frac{\hbar}{k_B} \frac{1}{4\pi}$

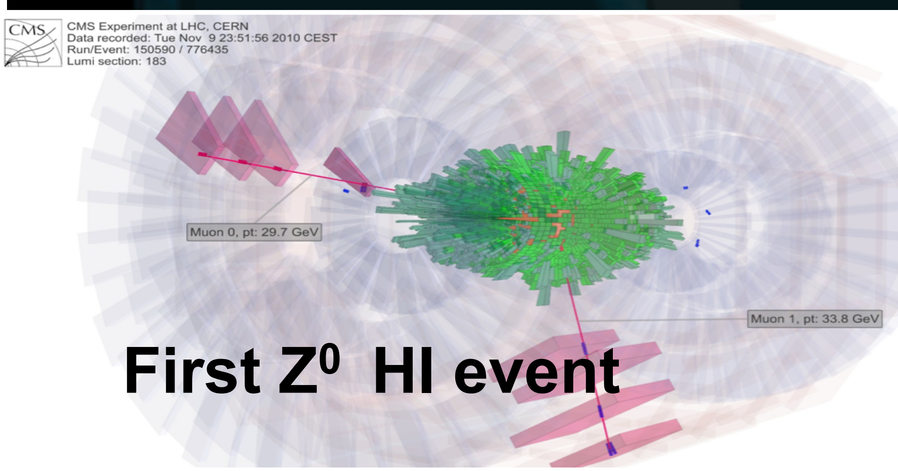

Vue d'ensemble des expériences LHC.
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

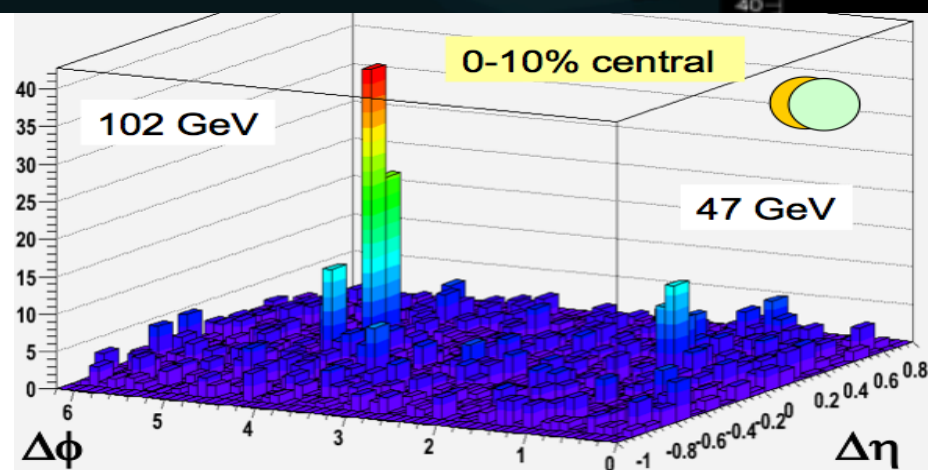

Chambre
à Derive
Temporelle
Détecteur
de Particules
Détecteur
de Particules
à Grande Energie
Absorbeur
Aimant Bipolaire
Aimant
L3
Chambres à Muons
Spectromètre
à Photons
Système Interne
de Suivi de Traces
CERN AC - ALICE VF1997
Alice
Caractéristiques du détecteur
Longueur: 25m
Diamètre: 15m
Poids: 10'000t

A contemporary view

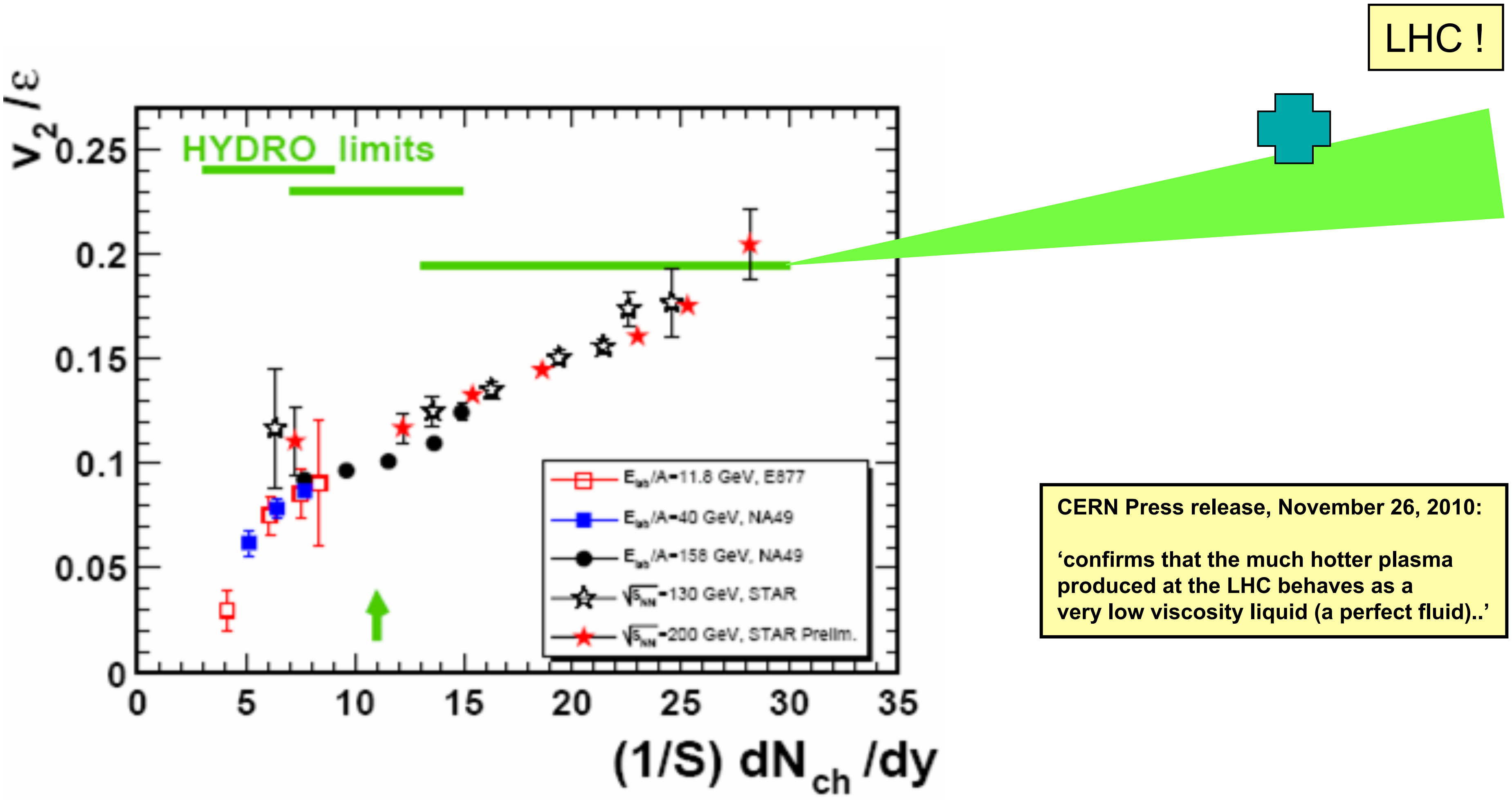
CERN seminar, Dec. 2nd, 2010







Strong flow = (nearly) ideal hydrodynamics

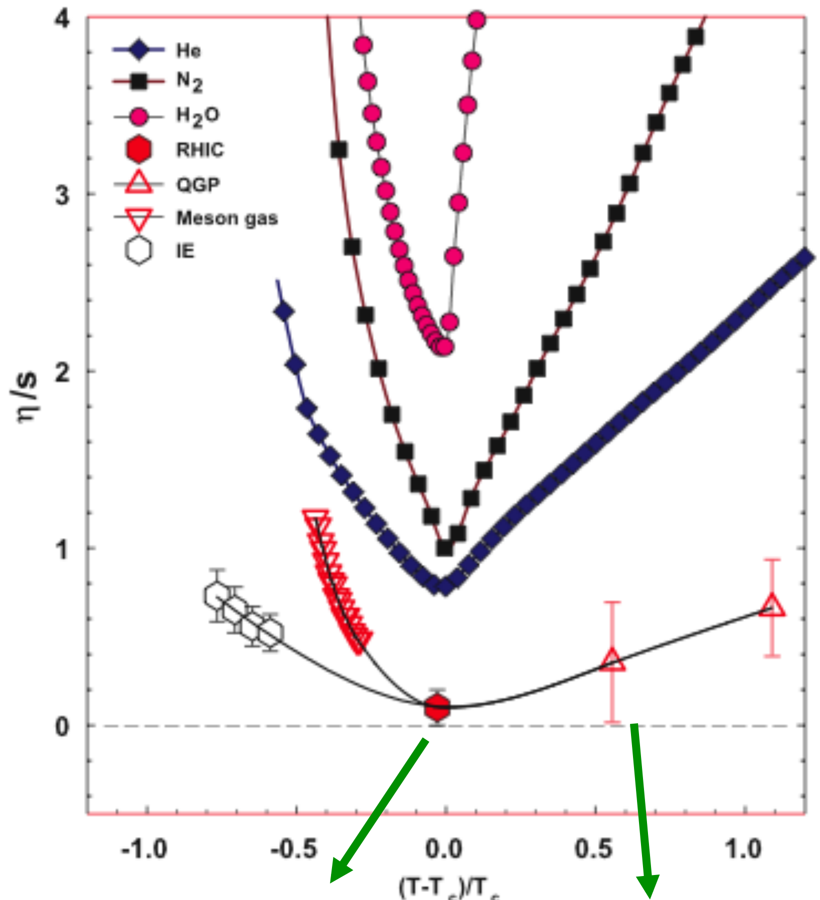


CERN Press release, November 26, 2010:

'confirms that the much hotter plasma produced at the LHC behaves as a very low viscosity liquid (a perfect fluid)..'

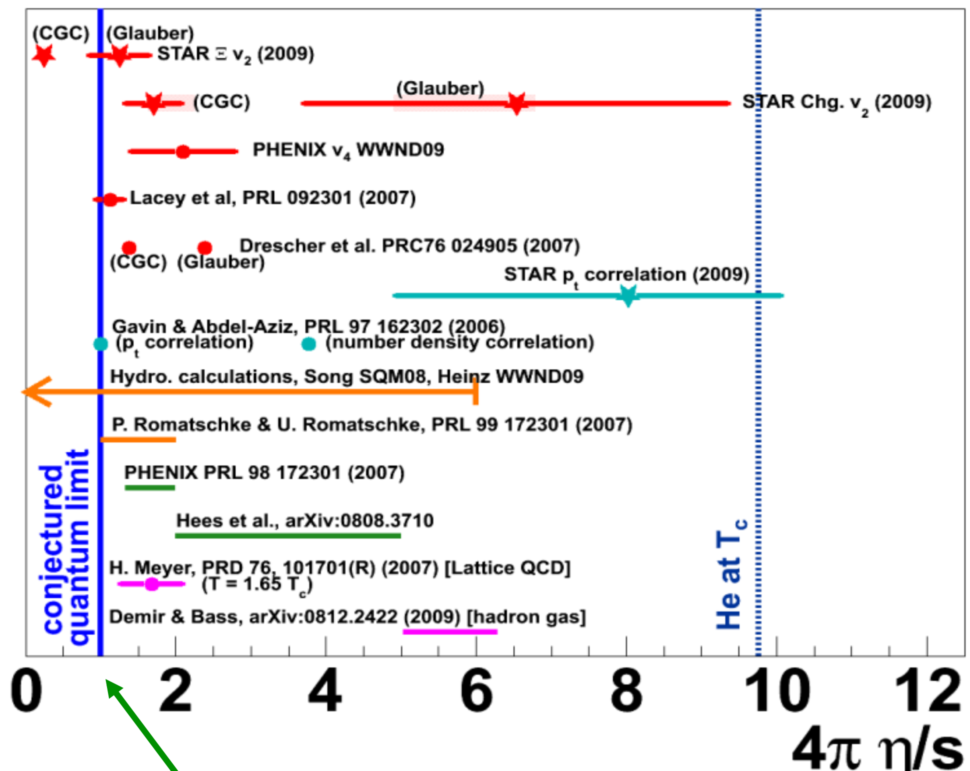
v_2 at RHIC and the LHC is large

Dissipation in the QGP relative to other fluids



Lacey, nucl-ex/0608046

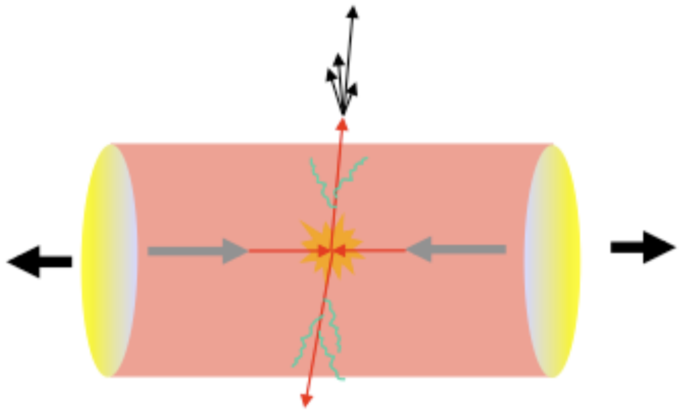
Lattice data: Nakamura, Sakai, PRL94 (2005)

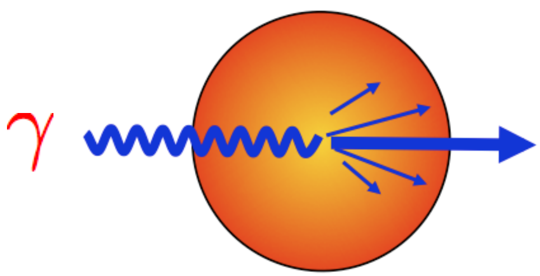


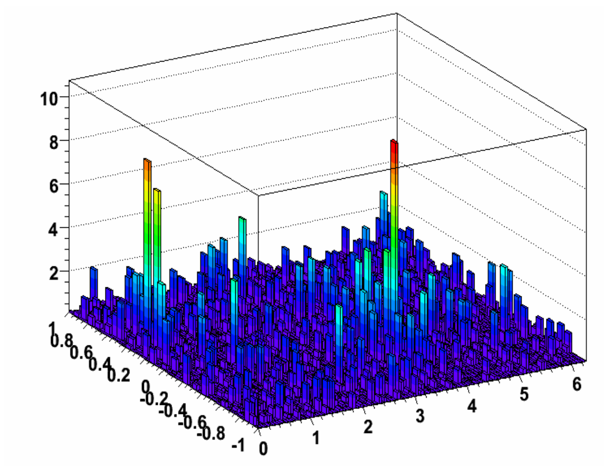
RHIC estimates close to conjectured universal lower bound of $\eta/s = 1/4\pi$ (based on the AdS/CFT correspondence)

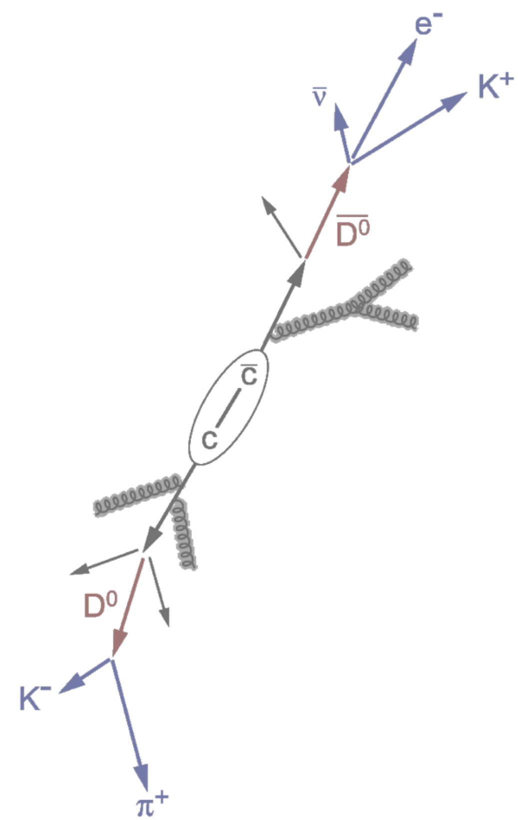
Kovtun, Son, Starinets

Hard Probes of the sQGP



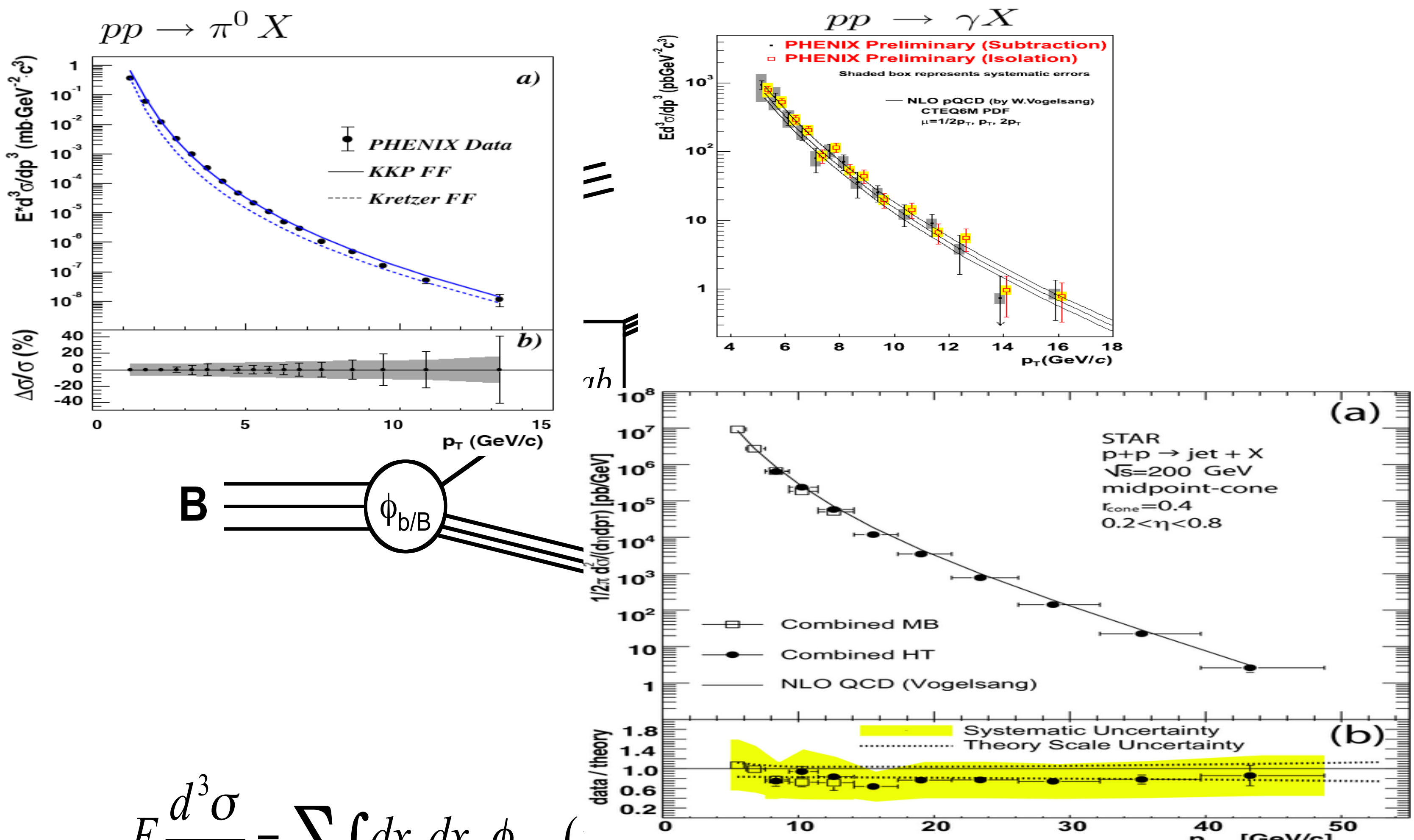






High p_T (>> T) hadrons, heavy mesons (charm and beauty), J/ψ and Upsilon, hard photons and JETS…

The pp Benchmark for Heavy Ion Collisions

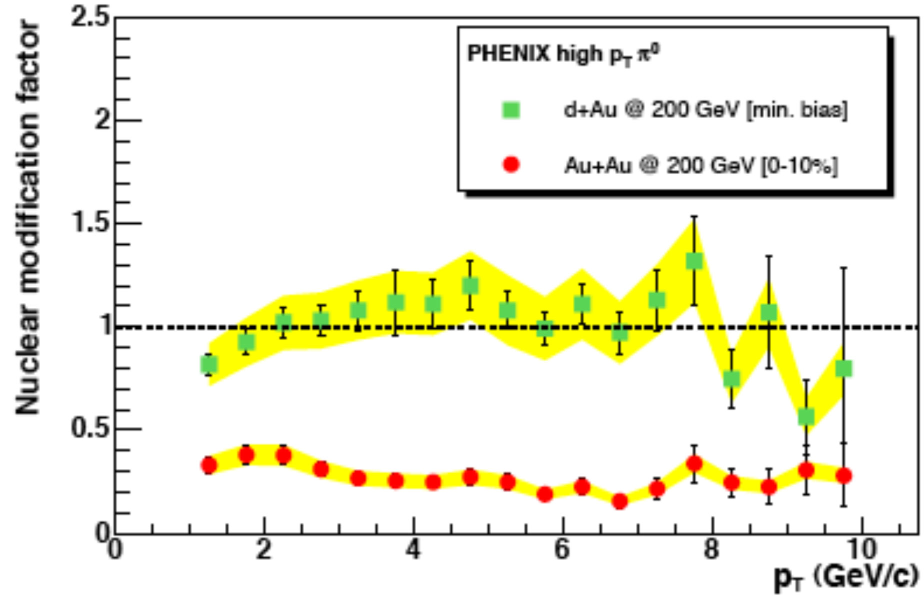


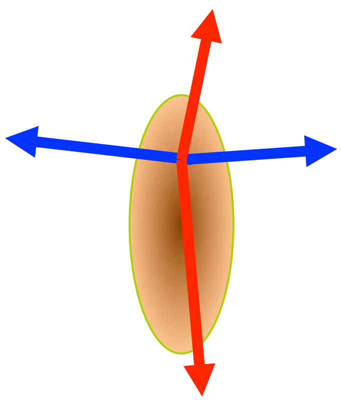
$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(\ldots$$

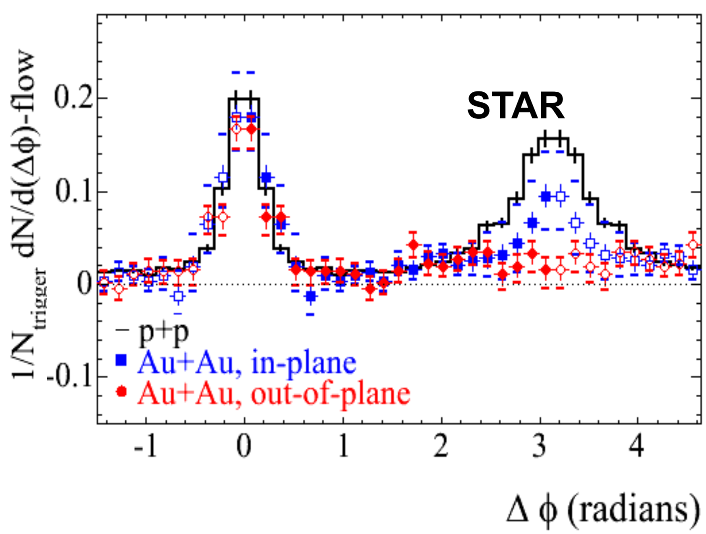
pQCD works exceptionally well!

Hard probes are modified by strongly interacting medium

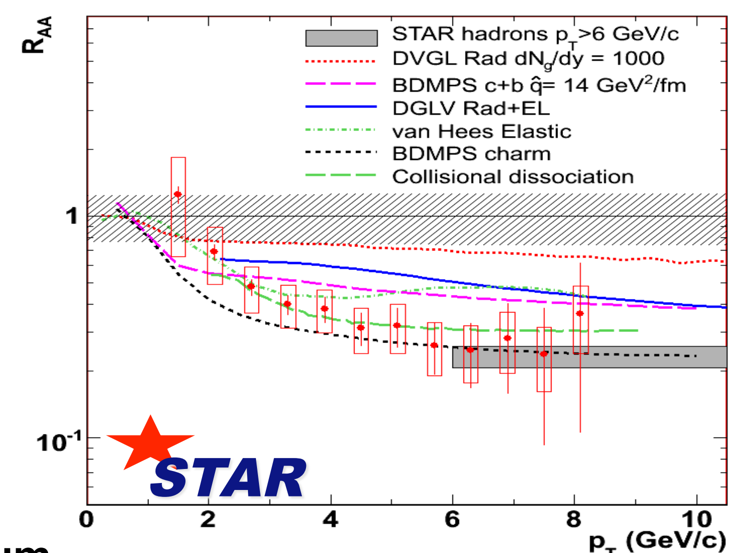
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$





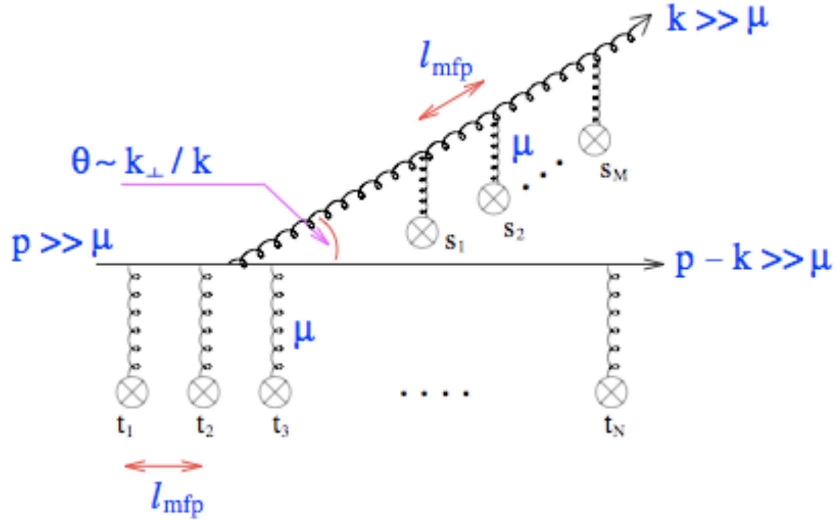


Energy loss dependent on parton path length in medium



Heavy quarks suppressed just as much as light quarks!

Energy loss in hot QCD matter

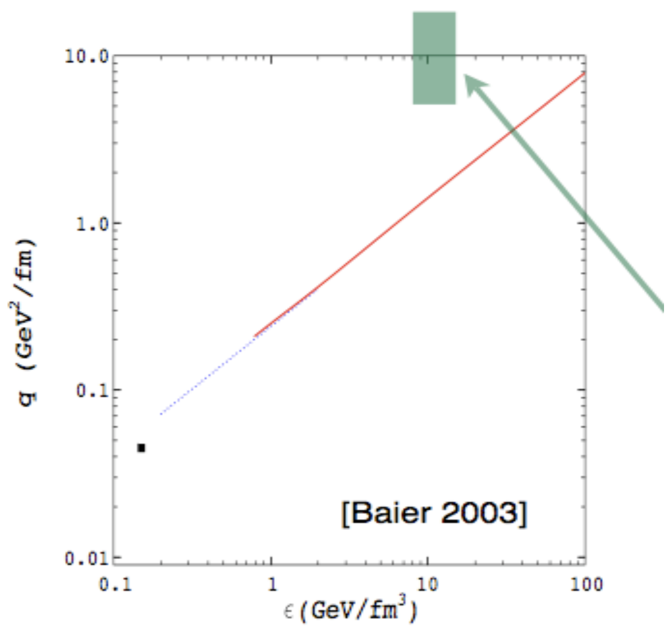


Bjorken
Gyulassy-Wang
Baier,Dokshitzer,Mueller,Peigne,Schiff
Zakharov

$$-\frac{dE}{dz} = \frac{\alpha_S N_c}{4}\, p_\perp^2 \; ; \; p_\perp^2 = \hat{q}\, L$$

$$\hat{q}_{\text{ideal gas}} \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq 2\epsilon^{3/4}$$

Characterizes properties of hot medium

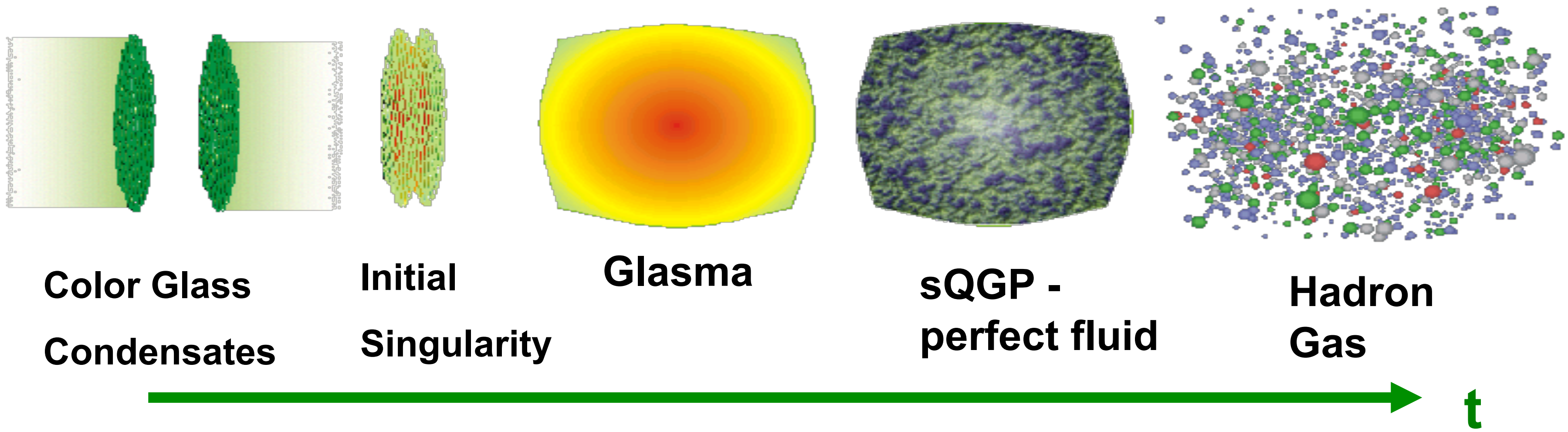


Detailed model estimates all over the place

$$\hat{q} = 1.5 - 19\ \mathrm{GeV}^2/\mathrm{fm}$$

Significantly higher than ideal gas!

Standard model of HI Collisions




QGP