Heavy Ion collisions at RHIC and LHC and cosmological implications

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Corfu TR33 meeting on “Particles and the Universe”
17-21 September 2012, Corfu, Greece
Outline

I Introduction
   A. The QCD phase transition
   B. The QCD Phase transition and the early universe
   C. Neutron stars/Quark stars
   D. The QCD phase transition and Heavy Ion collisions: Set the questions to answer

II A historical tour and latest hot news on selected physics items:
   A. Direct thermal photons
   B. Flow, strangeness
   C. Jet quenching
   D. Quarkonia

III Conclusions and Outlook
I Introduction

- The QCD phase transition
Initial idea: create matter at extreme conditions of high density colliding heavy ions

By heating and/or compressing

High Energy Heavy ion collisions?

Interior of neutron stars - Quark stars?

A search that started at the Bevalac, Berkeley (1970-), moving to Brookhaven Lab (1988-) and to CERN (1989-)

Sonia Kabana, “Heavy Ion Collisions at RHIC and LHC and cosmological implications”, 17-21 Sept. 2012, Corfu, Greece
**Physics goals: Mapping out the phases of QCD**

Experimental program of Heavy Ion Collisions of last ~25 years aims to:

- Study QCD matter under extreme conditions of densities and Temperatures
- Reproduce a phase transition of the early universe at $10^{-6}$ sec after the Big Bang, between hadrons and quarks and gluons (Quark-Gluon-Plasma)

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**Lattice QCD**

An energy scan from below potential $T_c$ (SPS, RHIC BES, future accelerators) up to well above $T_c$ (LHC) can reveal the nature of the phase diagram of QCD

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QCD on the lattice predicts a cross over at zero net baryon density and $T$(characteristic) of $\sim$160-180 MeV energy density $\sim$0.6-1GeV/fm$^3$


**Historical note:** Hagedorn predicted a limiting $T$(lim)$\sim$175 MeV

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QGP seen from Jura

- A skier (quark?) is confined inside snow patches (hadrons?)
- the skier can move further... a new phase develops
- a skier (quark?) can move freely over long distances...

L. Maiani, CERN 2000
The QCD phase transition and the early universe
The little Bang

$1\text{fm/c} \sim 3 \times 10^{-24}\text{s}$
A little bang in STAR

(100 AGeV) Au → (100 AGeV) Au

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Big bang vs little bang

Similarities:  
- Expansion  
- chemical freeze out (nucleosynthesis : hadrosynthesis),  
- thermal freeze out happens after chemical freeze out  
  (Cosmic Microwave Background : hadron pT spectra)  
- initial state quantum fluctuations leave imprints in the final state

Differences:  
- Expansion rates differ by many orders of magnitude.  
  Expansion is in 3d (not 4d).  
  Expansion is driven by pressure gradients (not gravity).  
- Time scale in fm/c (not in billions of years)  
- Distances measured in fm (not light years)
The path of the early universe through the (T, μB) plane

- Path of early universe right after the QCD phase transition.
- Early universe undergoes a QCD phase transition or cross over
- The “big annihilation” starts at around 35 MeV
- High energy heavy ion experiments measure antimatter/matter ratios near 1 at T(chem fr out)=170 MeV

The path of the early universe and the phase transition

Temperature [MeV] vs. Baryon chemical potential [MeV]

- Quark Gluon Plasma
- Chirally symmetric phase
- Hadron Gas
- Chirally broken phase
- Color superconducting phases
- First order phase transition
- Crossover

J. Schaffner-Bielich, arXiv: 1105.0339
Consequences of a path of early universe through 1st order QCD phase transition


- Assuming a baryon asymmetry before QCD phase transition -> Early universe undergoes a 1st order transition at mb/T~1

- Some consequences: a strong suppression of Grav. Waves (GW) with frequencies above 10^-8 Hz and the production of GW in bubble collisions and turbulences during the phase transition.
The effective number of degrees of freedom

D. Schwarz, arXiv:0303574

The effective number of degrees of freedom \( g_\epsilon(T) = \epsilon(T)/(\pi^2/30T^4) \).

Change of degrees of freedom:
- Electroweak transition 100-200 GeV
- QCD transition 150-180 MeV
- \( e^+e^- \) annihilation at ~170 keV

Could QCD relics be CDM candidates?
Neutron stars/ Quark stars
Neutron stars

Neutron stars have density that can be much higher than nuclear density -> possibility of a quark core

Strange quark matter: true state of matter? (E Witten) -> Strange quark stars

S. Weissenborn et al, arXiv:1102.2869

Pulsar PSR J1614-2230 with a mass of 1.97+0.04 Solar masses, could be a strange star with stable strange quark matter if effects of strong coupling and color-superconductivity are taken into account.

Hybrid stars (with quark core and hadronic outer layer) have masses below hadronic and pure quark stars
Do stable quark stars matter for Omega(matter) ?

Quark core - hadronic layer - H layer

Large range of possible masses from 1.8 to 375 solar masses for radii from 9 to 1200 km

Such objects maybe candidates for Dark Matter, if formed without affecting nucleosynthesis and CMB

For large masses (more than few solar masses) difficult to detect with grav. lensing


<table>
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<th>$H$</th>
<th>Radius of dark 'star' (km)</th>
<th>Mass of dark 'star' (solar masses)</th>
<th>$N_B$ ($N_B(sun)$)</th>
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<td>1.801</td>
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The QCD phase transition and Heavy Ion collisions: Set the questions to answer
Set the Questions:

Is there a dense hot matter of quarks and gluons build and which are its characteristics?

Is local thermalization achieved?

Is there a phase transition and if yes which is the order, or is it a cross over?

Which are the critical parameters?

Is this state weakly or strongly interacting?

Is there a critical point?
II A historical tour of selected physics results:

1. Direct thermal photons
Direct photon excess in min bias Au+Au at 200 GeV

Direct photons in p+p described by NLO

Direct photon excess in min. bias Au+Au at 200 GeV over p+p at 200 GeV below pT ~2.5 GeV

Exponential spectrum in Au+Au - consistent with thermal below pT ~2.5 GeV with inverse slope $220 \pm 20$ MeV

$\Rightarrow$ T(init) from hydrodynamic models : $300-600$ MeV, depending on thermalization time

Critical d+Au check : No exponential excess in d+Au

Direct thermal photons firmly established for the first time !

BNL press release, 15 Feb 2010 : 'Perfect' Liquid Hot Enough to be Quark Soup

..collisions of gold ions ...have created matter at a temperature of about 4 trillion degrees Celsius ... about 250,000 times hotter than the center of the Sun. This temperature is higher than the temperature needed to melt protons and neutrons into a plasma of quarks and gluons.

Thermalization seems to be achieved
Latest news: $T$ from direct photons at the LHC

**RHIC result backed by LHC**

* Exponential fit for $p_T < 2.2$ GeV/$c$
  
  inv. slope $T = 304 \pm 51$ MeV
  
  for 0–40% Pb–Pb at $\sqrt{s} = 2.76$ TeV

* PHENIX: $T = 221 \pm 19 \pm 19$ MeV
  
  for 0–20% Au–Au at $\sqrt{s} = 200$ GeV

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**K. Safarik, ALICE, QM2012**

* $p_T < 2$ GeV/$c$
  
  ~20% excess of direct photons

* $p_T > 4$ GeV/$c$
  
  agreement with $N_{coll}$-scaled NLO
2. Flow, strangeness
Flow coefficients $v_n$, $n=1,2,3...$

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\phi - \Phi_n)] \]

\[ v_n = \langle \cos[n(\phi - \Phi_n)] \rangle \]

* Initial shape of the interaction region ($v_2$ - elliptic flow)
* Initial spatial fluctuations of interacting nucleons (higher order $v_n$)
Flow and shear viscosity

Shear viscosity estimates based on flow measurements
RHIC: the perfect liquid (see talk by U Heinz)

\( \eta/s \) (Au+Au 200 GeV RHIC) = 0.16
\( \eta/s \) (Pb+Pb 2.76 TeV LHC) = 0.20

U. Heinz, arXiv:1106.6350 and references therein

Lower limit from AdS/CFT: \( 1/4\pi = 0.0796 \)

\( v_2 \) of several identified hadrons,
STAR \( \sqrt{s} = 200 \) GeV Au+Au and ALICE Pb+Pb 2.76 TeV

Model with \( \eta/s = 0.20 \) (for LHC)

VISHNU: hybrid code = Viscous Israel-Stewart Hydrodynamics in 2+1 dimensions and UrQMD
T fluctuations in CMBR and $v_n$ in sQGP

P Sorensen, STAR, QM2011

Analogous to the Power Spectrum extracted from the Cosmic Microwave Background Radiation

P. Staig et al, arXiv:1008.3139 [nucl-th]
A. Adare [PHENIX], arXiv:1105:3928
Strangeness
* Strangeness enhancement was first discovered at the AGS at BNL, then at SPS at CERN

* Expect to measure strangeness enhancement with increasing energy, and jumping up above Tc

* However, measurement showed strangeness enhancement increasing with decreasing energy from SPS to AGS! (opposite to expectation)

This was later established through the SPS (NA49, NA61) energy scan, and the last 3 years with the RHIC low energy scan (K+/pi+ “horn”, M. Gazdzicki, NA49). However the maximum is not seen in the K-/pi- ratio.

However: the data points have each one a different muB!
The baryochemical potential is like salt for hadronic systems. Therefore, in order to measure a unique curve of $T$ at freeze-out as a function of $\varepsilon_{\text{init}}$ in hadronic particle systems, one has to use the same conditions, with the same $\mu_B$, the simplest one being $\mu_B=0$. 


The baryochemical potential is like salt for hadronic systems.
The strangeness enhancement is not a primary signature of the phase transition, but it grows and saturates following the Temperature at \( \mu_B=0 \).

The increase and saturation of the T at \( \mu_B=0 \) near 1 GeV/fm\(^3\) can be interpreted as onset of a phase transition at \( \mu_B=0 \).
3. Jet quenching
Jet quenching

We compare A+A to expectations from p+p, using the “nuclear modification factor” $R_{AA}$ defined as:

$$R_{AA}(p_T) = \frac{\text{Yield} (A + A)}{\text{Yield} (p + p) \times \langle N_{coll} \rangle}$$

$N_{coll}$: Average number of NN collisions in AA collision

Suppression of jets in AuAu: $R_{AA} < 1$

Quarks are expected to exhibit different radiative energy loss depending on their mass (D.Kharzeev et al. Phys Letter B. 519:1999)

Partons interact with the medium and loose energy through eg gluon radiation
Latest news:
RAA suppression at the LHC

G Roland, CMS, QM2012

Sonia Kabana, "Heavy Ion Collisions at RHIC and LHC and cosmological implications", 17-21 Sept. 2012, Corfu, Greece
RAA compared to models for energy loss allows for an estimate of gluon density $dN/dy(gluon)$

Here as an example we get (GLV model):

- $dN/dy(g) = 400$ for SPS
- $dN/dy(g) = 1400$ for RHIC
- $dN/dy(g) = 2000 - 4000$ for LHC

To estimate with confidence $dN/dy(g)$, we should understand the mechanism of jet quenching via studies of its dependence from $p_T$, energy, event plane, path length, centrality, quark mass etc.
4. Quarkonia
Quarkonia


Quarkonia: Thermometer of QGP through hierarchy of T(dissociation)

Many effects play a role like dissociation in QGP, cold matter absorption, recombination/coalescence from c, cbar, feeding
ccbar
Collision energy dependence of J/Psi

**RHIC vs LHC**

- J/Psi in forward y in ALICE less suppressed than J/Psi in forward rapidity in RHIC
  - hint to recombination of J/Psi at the LHC

**RHIC vs SPS**

- J/Psi at ycm is compatible between RHIC and SPS

Energy dependence: To compare J/Ψ at RHIC, SPS and LHC the
- CNM effects must be estimated with p+A/d+A,
- one can look also ratio to open charm,
- use same feeding corrections,
- look also with x axis parameter that includes both the **energy and centrality dependence** like the initial energy density.
The J/Psi RHIC-SPS-comparison -puzzle R Arnaldi

R Arnaldi, D Frawley, Trento 25-29 may 2009

- Divide out cold nuclear matter effects using not model but data (d+Au, p=Au)
- Plot as a function of dN/deta|eta=0 takes into account differences in energy in contrast to N_part.
- Cold nuclear matter absorbtion effect up to dN/deta|eta=0 = 300
- Suppression of J/Psi above 300

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bbar
Y suppression was discovered in 2011 at same time at RHIC and LHC

**STAR, QM2011**

- First measurement of Y(1S+2S+3S) suppression at RHIC.
- RAA of most central point is in agreement with only Y(1S) surviving

**CMS**

Indication of suppression of Y(2S+3S) with respect to Y(1S) (2010 data)
Clear hierarchy in RAA of different quarkonium states

Expected in terms of binding energy

If confirmed (using p+A, feeding corrections, etc) is an outstanding discovery for the Heavy Ion field
III Conclusions and outlook
Back to the Questions:

Is there a dense hot matter of quarks and gluons build?

Yes: Temperature:
\[ T(\text{init}) \text{ from direct gammas}=230, 300-600 \text{ MeV (models) at SPS and RHIC} > T_c \]
Increasing with energy, up to the raw measurement of 300 MeV at LHC > T_c
\[ T(\text{chemical freeze out}) \sim T_c \]

\[ T(\text{init}) \text{ via quarkonia (needs p+A)}: \]
\[ T_{\text{dissoc of } Y(1S)} > 450 \text{ MeV, } T_{\text{dissoc of } Y(2S)} > 245 \text{ MeV (P. Petreczky) in} \]
agreement with direct thermal photon measurement of \( T \)

Energy density:
\[ \epsilon(\text{Bjorken at } \tau=1\text{fm/c})= 3, 5, 16 \text{ GeV/fm}^3 \text{ at SPS, RHIC, LHC.} \]
At RHIC and LHC thermalization happens earlier than 1 fm/c and energy density is much higher (hydro models).

Density (not yet settled):
\[ dN/dy(\text{gluon}) \text{ through jet quenching is ongoing work.} \]
As an example GLV: \[ dN/dy=400,1400,2000-4000 \text{ at SPS, RHIC, LHC} \]

\( v_2 \) scaling with the number of constituent quarks (not yet settled)
Is local thermalization achieved?

Yes: Thermal direct photons at low pT measured
Hydrodynamic behaviour.
Thermal model fits to the hadron ratios (is not a direct evidence for initial
thermalization)

Is there a phase transition and if yes which is the order, or is it a cross over?

Quarkonia suppression in QGP, jet quenching, thermal direct photons, T vs energy density: signs of
a new phase.
Furthermore the energy scan has found that QGP signatures found at high energy are switched off
at low energies.
(Nr of Constituent Quark scaling, quenching, T(chem. freeze out) falls below its limiting value.)
More data and analysis are needed and forthcoming.

Which are the critical parameters?

“Critical Bjorken energy density” from (T vs $\varepsilon_{Bj}$) around 0.5-1 GeV/fm$^3$, corresponding to sqrt(s)
around 10 GeV (muB=0 case included) and Tc~160-200 MeV --> motivated building new colliders
NICA and FAIR and the Beam Energy Scan at SPS and RHIC

Is this state weakly or strongly interacting?

It is strongly interacting: sQGP
v2, shear viscosity: $\eta/s=0.07-043$ (LHC)
This is backed up by theory asymptotically free only at very large T/Tc.

Is there a critical point?

Not yet established, SPS and RHIC are on their way to look.
Conclusions and outlook

Heavy Ion Collisions: After 25 years of searches for the QGP in 2012 we arrived at a culmination point with long awaited results.

In the next few years new data will allow to establish these results and add them possible new discoveries at:

* high energy and low muB (RHIC,LHC)
* low energies and high muB (Beam Energy Scans RHIC, SPS and the new colliders NICA and FAIR)

to map out the QCD phase transition

Cosmology:

The QCD phase transition and the early universe- possible consequences (Gravitational waves)

Neutron stars/quark stars ongoing theoretical and experimental work may allow to study the QCD phase diagram and set constraints (dark stars, dark QCD relics?)
Thank you very much for your attention
Collision energy dependence of “jet quenching”:
 at which energy is it “switched off”?

RAA falls below 1 below 39 GeV

S. Milov, J. Solana, STAR, BES, QM2012
Outlook

* LHC : p+A data, A+A data
  Precision studies of the characteristics of the sQGP
  Full LHC energy measurements at \( \sqrt{s} = 5 \) TeV
  Upgrades of LHC experiment and collider.

* RHIC short term: new upgrades for highly improved Heavy Flavour and quarkonia measurements.
* RHIC long term: BES II higher statistics for low energy scan, fixed target, eA

* NICA in Dubna, FAIR at GSI Germany: new facilities to measure the low energy regime of Heavy Ion collisions
First observation ever of anti-$^4$He


- First measurement ever of 18 anti-$^4$He based on TPC+TOF+HLT
- Consistent with thermal & coalescence model expectation

Sets the background for observation of antimatter in space
Number of constituent quarks scaling

* Scaling with the number of constituent quarks (NCQ) observed. This is in agreement with quark coalescence as dominant production mechanism of hadrons at the highest RHIC energies.

* $\phi$ meson $v_2$ deviates from other particles $\sim 2\sigma$ at the highest $p_T$ data in 7.7 and 11.5 GeV $\rightarrow$ NCQ scaling is broken at 11.5 GeV and below. More data are needed at these energies for clear conclusion.

* NCQ scaling is broken for particles minus antiparticles at low energies.
Cold Nuclear Matter effects with d+Au

Milov, Solana, QM2012

* Cold Nuclear Matter effects on jet quenching need to be taken into account at all energies

* p+A will be taken in LHC this year (end 2012)
Similar suppression of hadrons and jets

**Left plots:** charged hadrons

**Right plots:** reconstructed jets

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T\(_{\text{init}}\) SPS, RHIC, LHC

* SPS: measurement not firmly established. T\(_{\text{dir} \gamma}\)~200-300 MeV (model fit), at muB~200 MeV

* RHIC:
  First clear measurement of T\(_{\text{RHIC}}\)=221\(\pm\)19\(\pm\)19 MeV (measurement)
  \(\Rightarrow\) T\(_{\text{RHIC}}\)~300-600 MeV (model fit) at muB~20 MeV

* LHC:
  Highest measured temperature: T\(_{\text{LHC}}\)=304\(\pm\)51 MeV at muB~1 MeV

* SPS, RHIC, LHC: T\(_{\text{chem. freeze out}}\)~170 MeV is similar to T\(_c\)

  * Low pT photons exhibit thermal spectrum, suggesting thermalization of their source

  * The initial T at SPS, RHIC, LHC is higher than T\(_c\)

  * The initial T rises with collision energy from SPS to RHIC to LHC
Estimating the total strange to light quarks ratio

It has been observed that thermal models can describe the ratios of final state hadrons produced in A+A, e+e- and pp(ppbar) successfully.

P. Braun Munzinger, J. Stachel et al
F. Becattini, C. Redlich, J. Cleymans et al
S. Kabana, P. Minkowski
J. Rafelski, J. Letessier, A. Tounsi
Etc. (however results vary depending on free parameters gamma(s,q))

A T near 170-180 MeV has been found for SPS and RHIC: near Tc (lattice)

These models can be used to estimate the total strange/non strange newly produced quark ratio, namely the strangeness suppression factor (Wroblefski factor)

$$\lambda_S = \frac{\langle s\bar{s} \rangle}{0.5(\langle u\bar{u} \rangle + \langle d\bar{d} \rangle)}$$

Sonia Kabana, “Heavy Ion Collisions at RHIC and LHC and cosmological implications”, 17-21 Sept. 2012, Corfu, Greece
Goal: Map out the QCD phase diagram searching for the onset of QGP signals and a possible critical point

Observables

Search for the onset of QGP signals:
Scaling of $v_2$ pT dependence with nr of quarks
Flow coefficients vs energy
Quarkonia suppression
Strangeness to light hadrons (K/π) Energy dependence
Signature for softening of EOS $v_1, v_2...$

Search for fluctuations near a critical point:

RHIC beam energy scan with Au+Au and Cu+Cu (STAR, PHENIX) started with a test run in 2008/09
sqrt(s)= 7.7, 11.5, 19.6, 22.4, 27, 39, (62, 130, 200) GeV

arXiv:1007.2613
At which collision energy is the onset of $R_{AA}$ suppression?

$R_{AA}$ suppressed also at 39 GeV

$R_{AA}$ at 62 GeV approaches value of $R_{AA}$ in 200 GeV at high $p_T$

No Suppression in Cu+Cu at 22.4 GeV


M Purschke, PHENIX, QM2011

Au+Au

Cu+Cu
Search for fluctuations of the K/\pi ratio in BES

- No strong energy dependence of $K/\pi$ fluctuations in central 0-5% Au + Au collisions at $\sqrt{s} = 7.7, 11.5, 39, 200$ GeV observed in STAR data.

- Difference between STAR and NA49 may be due to different (pT,y) acceptance, or particle identification - issue to be clarified.

STAR TPC+TOF

$\pi$: 0.2 < p_T < 1.4 GeV/c

$K$: 0.2 < p_T < 1.4 GeV/c

Terence Tarnowsky, STAR, QM2011
M Mitrovski, HEP2011

NA49, PRC79 (2009) 044910
At which energy is the onset of J/Psi suppression?

C da Silva, PHENIX, QM2011

Same detector, rapidity range and centrality
No p+p reference for 62 and 39 GeV
J/Psi suppression similar at these energies within errors
However cold nuclear matter effects are expected to be different
At which energy brakes the scaling of $v_2$ with the nr of constituent quarks?

M Mitrovski, STAR, HEP2011

$Au + Au, \sqrt{s_{NN}} = 200\ \text{GeV}$

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<tr>
<th>$v_2/n_q$</th>
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<td>0.15</td>
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<td>0.10</td>
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<td>0.05</td>
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0-80% most central

$Au+Au$ (0-80%), $\eta$-sub EP

-11.5 GeV

NCQ scaling seems to be broken for particles and antiparticles at lower energies (7, 7, 11.5 GeV)

The phi meson does not follow the trend of other mesons at 11.5 GeV

A. Schmah, STAR, QM2011
Outlook
- near term

Several major upgrades by STAR and PHENIX:

PHENIX: new silicon vertex detector commissioned with +p, took Au+Au data in 2011

STAR: new silicon vertex detector under construction designed to reach a DCA resolution of ~30 microns (Heavy Flavour Tracker). Data taking 2014.

Myon Telescope, later: forward instrumentation

Physics capabilities of HFT

![Graph showing anisotropy parameter $v_2$ as a function of transverse momentum $p_T$. The graph includes data for 200 GeV Au+Au Collisions and hydro charged hadrons, along with theoretical curves.]
Outlook - long term

PHENIX -> sPHENIX: hadronic calorimeter at ycm

STAR -> eSTAR (optimization for e+A collisions): Hcal and a new tracker for the e
Flow

- spatial anisotropy $\Rightarrow$ momentum anisotropy

Fourier decomposition of the momentum space particle distributions in the x-y plane

$v_2$ is the 2nd harmonic Fourier coefficient

The $v_2$ for hadrons:
- scales with nr of constituent quarks suggesting partonic degrees of freedom of their source and
- is consistent with low viscosity (hydro, AdS/CFT)

How is $v_2$ for direct thermal photons?
\( v_3 \) disentangles initial state and \( \eta/s \)

Stefan Bathe for PHENIX, QM2011

**\( v_2 \) described by Glauber and CGC**

**\( v_3 \) described only by**

\[ \eta/s = 1/4\pi \]

Two models

\[ \eta/s = 2/4\pi \]
Which is the path-length dependence of $dE/dx$?

$\nu_2$ not explained by pQCD (even with fluctuations & saturation)

$\nu_2$ explained by cubic path length dependence (like AdS/CFT)

While $R_{AA}$ explained by both models

$\nu_2$ data favors $dE/dx \sim l^3$ (like AdS/CFT)

Theory calculations:
Wicks et al., NPA784, 426
Marquet, Renk, PLB685, 270
Drees, Feng, Jia, PRC71, 034909
Jia, Wei, arXiv:1005.0645
**J/ψ in p+p and Cu+Cu 200 GeV**

- $R_{AA}(p_T>5 \text{ GeV/c}) = 1.4 \pm 0.4 \pm 0.2$
- Consistent with no suppression at high $p_T$
- Inconsistent with AdS/CFT+Hydro and “heavy resonance” models
- Two component model+$J/\psi$ form. time+$B$ feed down describes the trend well


R. Rapp, X. Zhao, nucl-th/0806.1239
Analysis of d+Au data of run 2009 in terms of $\sigma_{\text{abs}}$ to account for all nuclear matter effects

- $\sigma_{\text{abs}}$ increases from midrapidity to forward rapidity
- Agreement of J/Psi $R_{AA}/R_{AA}(\text{Cold Nuclear Matter})$ at $y=0$ and $y=1.75$
R Arnaldi, D Frawley, Trento 25-29 may 2009

- Divide out cold nuclear matter effects using not model but data (d+Au, p=Au)
- Plot as a function of dN/deta|eta=0 takes into account differences in energy in contrast to N_part.

--> Cold nuclear matter absorption effect up to dN/deta|eta=0 = 300

--> Suppression of J/Psi above 300


60% of all J/Psi comes from direct J/ψ. While 30% of all J/Psi come from χ_c and 10% ψ'.

χ_c and ψ' T(dissociation) ~ T_c, while J/Psi T(dissociation)~ 2.1 T_c

--> suppression of J/Psi observed, maybe due to χ_c and ψ' dissociation
--> directly produced J/Psi may not be suppressed at RHIC
--> expect more suppression at LHC due to direct J/Psi dissociation (but must account for c,cbar coalescence-> J/Psi)
What can we learn from the $K/\pi$ ratio energy dependence?

- New STAR data on $K/\pi$ are in agreement with previous SPS measurements.
- Maximum of $K^+/\pi^+$ ratio near $\sqrt{s}=7$ GeV, not seen in the $K^-/\pi^-$ in A+A, neither in p+p.
v2 BES
Extraction of Tc from data comparing to lattice
Press release LBNL June 2011

S Gupta, Lepton Photon 2011

First estimate of Tc at $\mu_B=0$, from comparison of data (at nonzero $\mu_B$) to lattice:

$T_c = 175 \pm 7$ MeV

Sourendu Gupta, et al., Science 332,1525 (2011)
arXiv:1105.3934

$k$ = kurtosis
$S$ = skewness
Ratio $k/\sigma S$ is independent of Volume
Evolving from "STAR into eSTAR"

ToF: π, K identification, t₀, electron
ECal: electrons and photons
GCT: a compact tracker with enhanced electron capability
Combine high-threshold (gas) Cherenkov with TPC(-like) tracking
HCal: W powder, spaghetti cal

GCT: LOI toward multi-institution R&D effort
HCal: R&D proposal

Simulations ahead: eSTAR task force formed

Presented to EIC Generic Detector R&D Panel

STAR Science for the Decade – QM2011 – Carl Gagliardi

Sonia Kabana, “Heavy Ion Collisions at RHIC and LHC and cosmological implications”, 17-21 Sept. 2012, Corfu, Greece
The Heavy Flavour Tracker

The STAR collaboration has proposed a new silicon vertex detector composed by:

- The existing **SSD**: a single layer of double-sided silicon strips detector located at a radius of 22 cm from the beam axis.
- **IST**: 1 intermediate layer of single sided strips: it aimed to guide tracks from the SSD through PIXEL detector. It is composed by 24 liquid cooled ladders equipped with 6 silicon strip-pad sensors.
- **PIXEL** detector: The goal of this detector is to measure with great accuracy the track pointing resolution and to find secondary decays. It is made by 2 layers of 18.4 μm x 18.4 μm CMOS Active Pixel sensors.

E. Anderssen et al., A Heavy Flavor Tracker for STAR (http://rnc.lbl.gov/hft/docs/hft_final_submission_version.pdf)


<table>
<thead>
<tr>
<th>Detector</th>
<th>Radius (cm)</th>
<th>Technology</th>
<th>Si thickness (μm)</th>
<th>Hit resolution ( R/\phi - Z ) (μm - μm)</th>
<th>Material Budget in radiation length ( X_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSD</td>
<td>23</td>
<td>double sided strips</td>
<td>300</td>
<td>30 - 857</td>
<td>1%</td>
</tr>
<tr>
<td>IST</td>
<td>14</td>
<td>Si Strip Pad sensors</td>
<td>300</td>
<td>170 - 1700</td>
<td>1.2%</td>
</tr>
<tr>
<td>PIXEL</td>
<td>2.5, 8</td>
<td>Active Pixels</td>
<td>50</td>
<td>8.6 - 8.6</td>
<td>0.37%</td>
</tr>
</tbody>
</table>
The Pixel Detector for Inner Detector Upgrades

TPC – Time Projection Chamber
HFT – Heavy Flavor Tracker
- SSD – Silicon Strip Detector
  - \( r = 22 \text{ cm} \)
- IST – Inner Silicon Tracker
  - \( r = 14 \text{ cm} \)
- PXL – Pixel Detector
  - \( r = 2.5, 8 \text{ cm} \)

Leo Greiner, NSD M3 April 11, 2011

We track inward from the TPC with graded resolution:

<table>
<thead>
<tr>
<th>Detector</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC</td>
<td>~1mm</td>
</tr>
<tr>
<td>SSD</td>
<td>~300( \mu \text{m} )</td>
</tr>
<tr>
<td>IST</td>
<td>~250( \mu \text{m} )</td>
</tr>
<tr>
<td>PXL</td>
<td>&lt;30( \mu \text{m} )</td>
</tr>
</tbody>
</table>

vertex

PXL:
High granularity (~20 microns pixel pitch)
Short integration time (<200 microsec)
thin sensors (50 microns, 0.37% X₀)
Relativistic Heavy Ion Collider

RHIC site in BNL on Long Island, USA

RHIC has been exploring nuclear matter at extreme conditions over the last decade 2000-2011

4 experiments:
STAR PHENIX
BRAHMS PHOBOS

Colliding systems:
p↑+p↑, d+Au, Cu+Cu, Au+Au
Energies A+A:
\( \sqrt{s_{NN}} = 62, 130, 200 \text{ GeV} \)
and low energy scan
7.7, 11.5, 19.6, 22.4, 27, 39 GeV
STAR and PHENIX detectors at RHIC

STAR detectors cover midrapidity, full azimuthal angle coverage

- TPC
- Em cal
- TOF

PHENIX detectors at RHIC

- Central Magnet
- South Inner Magnet
- North Inner Magnet
- ZDC South
- ZDC North

1.2<|y|<2.2 \( \Delta \Phi = 2\pi \)

|y|<0.35 \( \Delta \Phi = 2\times\pi/2 \)

Subatech, "Heavy Ion Collisions at RHIC and LHC and cosmological implications", 17-21 Sept. 2012, Corfu, Greece
Direct photon elliptic flow in min bias Au+Au at 200 GeV

What we expect from theory?

- Expected $v_2$ of prompt photons depends on emission time:
  - Small at early time (flow not build up), larger at later time (like hadrons)

**Theory calculation:**
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

**PHENIX measurement:**
- Large direct photon $v_2$ observed at low $p_T$, where thermal photons dominate (~0.15 at $p_T\sim2.5$ GeV)
- $v_2 \rightarrow 0$ at high $p_T$ where prompt photons dominate

Models underpredict direct photon $v_2$

Challenge to theorists
BIG BANG

LITTLE BANG

WMAP:
Temperature
Fluctuations of the
Cosmic Microwave Background.

LHC Heavy Ions:
Event-by-Event FLUCTUATIONS of:
- Conserved Quantities (Net Charge, Net baryon number ....)
- Mean pT, Temperature ........
B and C quenching measured in MB Au+Au at 200 GeV

Sakaguchi, PHENIX, QM2012
Quenching of beauty measured via J/Psi and b-jets

Note: centrality for b-measurements is different than for charged hadrons
Quenching of charm and beauty

* The RAA of Charm and Beauty are both suppressed at RHIC and LHC.
* Puzzle at RHIC since few years: (b+c) -> e suppression is similar to that of charged hadrons (STAR, PHENIX).

![Graph showing D0 RAA vs p_T for Au+Au collisions at 200 GeV y10+y11 with 0-80% and 0-10% centrality, and M.He 0-80% and M.He 0-5% centrality.](image)

G Roland, CMS, QM2012

Note: the centrality for b-measurements is different than for charged hadrons.

X. Dong STAR QM2012

* The RAA of D0 at RHIC (STAR) is suppressed after p_T=3 GeV, and is similar to the RAA of charged hadrons at pT~6 GeV.

Sonia Kabana, “Heavy Ion Collisions at RHIC and LHC and cosmological implications”,
17-21 Sept. 2012, Corfu, Greece
First measure of Y suppression in Au+Au at 200 GeV

Rosi Reed, STAR, flash talk, poster QM2011

- $\Upsilon(1S+2S+3S)$ suppression at central collisions
- Similar suppression with high $p_T$ J/$\psi$
- First measurement of $\Upsilon$ suppression at RHIC
- RAAN at most central point is in agreement with only $\Upsilon(1S)$ surviving
- Statistical uncertainty will be improved by factors 2 to 3 for Au+Au 2011 and p+p 2009 respectively

Energy dependence of Y suppression:
Pb+Pb at the LHC: $Y(2S+3S)/Y(1S)$ suppression observed (CMS, QM2011)
Does the J/ψ flow?

Zebo Tang, STAR, QM2011

- J/ψ 20-60%
- φ 0-80%
- charged hadrons 20-60%

- J/ψ v2 ~ 0 up to pT ~ 8 GeV/c in mid-central 20-60%
- Disfavors coalescence from thermalized charm quarks at RHIC
Collision energy dependence of RAA
Nuclear modification factor $R_{AA}$ at RHIC vs LHC

M Purschke, PHENIX, QM2011

- $R_{AA}$ measured up to $p_T = 20$ GeV/c in central Au+Au
- $R_{AA}$ (of $\pi^0$, $\eta$, $\omega$) $\approx 0.2$ in central Au+Au at high $p_T (>5$ GeV)
- The $R_{AA}$ looks very similar between RHIC and LHC
- No suppression for direct gammas below $p_T$ 13 GeV
Which is the mass dependence of E loss?
RAA of electrons from heavy flavour decays

Similar result in STAR, PRL 98 (207) 192301, erratum 2011

**Which is the mass dependence of E loss?**

RAA of electrons from heavy flavour decays

Similar result in STAR, PRL 98 (207) 192301, erratum 2011

*Is the suppression of $R_{AuAu}$ coming from cold nuclear matter effects?* - New preliminary d+Au data from PHENIX shows that **this is not the case**

* RAA of open c,b -> e in Cu+Cu 0-20% and periph. Au+Au shows little suppression (not shown)

**Mesons and NonPhotonicElectrons (NPE) from heavy flavour decays exhibit similar suppression**

→ **mass dependence of energy loss not as expected from models for radiative de/dx**

**Challenge to the theory**

Adding collisional dE/dx improves the agreement with data

--->

**Need to disentangle charm and beauty**

Sonia Kabana, "Heavy Ion Collisions at RHIC and LHC and cosmological implications"

17-21 Sept. 2012, Corfu, Greece
Disentangling beauty and charm

Confidence level contours for the nuclear modification factor $R_{AA}$ for beauty and charm are determined from $R_{AA}$ of NPE (Phenix) and the $B/(C+B)$ measurement from $e$-$h$ and $e$-$D0$ correlations for $pT>5$ GeV (STAR).

![Graph showing $R_{AA}$ vs $p_T$ for beauty and charm correlations.]

Contribution of electrons from beauty become ~50% at ~5 GeV $p_T$ in $p+p$ collisions

$R_{AA}(e_B) < 1$ even if $R_{AA}(e_D) = 0$ --> Beauty and Charm are both suppressed in Au+Au

Measurements of $B$ and $C$ in Au+Au are crucial --> Silicon detectors upgrades STAR and PHENIX

I: (M. Djordjevic et al, PLB 632, 81, 2006) radiative energy loss with initial $g$ density $dN/dy(g)=1000$. This model is excluded by the data.

II: (Adil, Vitev, PLB649, 139, 2007) collisional dissociation of $D$ and $B$ mesons in the QGP causes suppression of $R_{AA}$.

III: (van Hees et al, PRC73, 034913, 2006) Large elastic scattering cross section associated with resonance states of $D$ and $B$ mesons in the QGP.

Set the Questions to answer:

Is there a dense hot matter of quarks and gluons build?

Is local thermalization achieved?

Is there a phase transition or cross over?

If phase transition, which are the critical parameters? (Tc)

If phase transition, which is the order of the transition?

Is this state weakly or strongly interacting?

Which are the characteristics of this state? (T, density, energy density, viscosity, pressure, lifetime, volume, freeze out conditions)

Is there a critical point?

Which is the phase diagram of QCD?
$\nu_3$ disentangles initial state and $\eta/s$

$\nu_2$ described by Glauber and CGC

$\nu_3$ described only by Glauber

AdS/CFT predicts $\eta/s = 1/4\pi$

Lappi, Venugopalan, PRC74, 054905
Drescher, Nara, PRC76, 041903
Historical Milestones of the search for the QCD phase transition

1988-89 AGS BNL and SPS CERN:
Discovery that strangeness is enhanced over pions in Si+Au and Au+Au collisions at $\sqrt{s}(NN)=1-5$ GeV
K/$\pi$, $\Lambda/\pi$ enhancement in A+A over p+A

2000 CERN press release:
Discovery of a new state of matter in A+A collisions at $\sqrt{s}(NN)=17, 19$ GeV
$\chi_c, \Psi', J/\Psi$ suppression,
$T(\text{direct } \gamma) \approx 200-300$ MeV (model fit),
Strangeness enhancement including Omegas, Xis,
$T(\text{chem. fr. out}) \approx 170$ MeV is located near $T_c$

2003 BNL press release:
Discovery of jet quenching in Au+Au at $\sqrt{s}(NN) = 200$ GeV, large elliptic flow
Discovery of a strongly interacting QGP (sQGP)
sQGP found consistent with a perfect liquid
Applications of AdS/CFT duality on sQGP
Marks a new era in QCD studies

J/Psi suppression, NA50 Coll.

STAR

Sonia Kabana, “Heavy Ion Collisions at RHIC and LHC and cosmological implications”, 17-21 Sept. 2012, Corfu, Greece
Historical Milestones of the search for the QCD phase transition

Which are the critical parameters of the phase transition?:
Several observables where suggestive of an onset of the QCD phase transition at energy lower than top SPS (19 GeV) energy, possibly with $\varepsilon_{(\text{Bjorken})} \sim 1 \text{ GeV/fm}^3$, motivating a low energy scan.

Low energy scan SPS (1999-), RHIC (2009-):
Study onset of transition, search for a possible critical point (as yet inconclusive and ongoing) and map out the QCD phase diagram.

2010: first PbPb collisions at the LHC!
2011: large data sample collected
Jet quenching, Quarkonia suppression

$\varepsilon(B) \sim 16 \text{ GeV/fm}^3$

2010/11: RHIC upgrades accomplished
lead to largest data sample ever taken at RHIC (a billion Au+Au events) with highly enhanced identification capabilities due to new detectors
-> since 2009 a “new RHIC collider and experiments”

2011: Y suppression discovered at RHIC and LHC
Signatures of the Quark Gluon Plasma

A. “Internal” Signatures originating “from the QGP itself”:

Direct photons from QGP $\rightarrow T(QGP)$
Strangeness enhancement (Mueller, Rafelski 1981) $\rightarrow K/\pi$
$U,d,s$ yields for $T(\text{freeze out})$ or $p_T$ slopes (Van Hove, H Stoecker et al) $\rightarrow$ plateau vs energy at $T_c \rightarrow e_{\text{init}}(\text{crit}), \sqrt{\text{s}}(\text{“crit”})$
Multiquark states from QGP (Greiner et al) $\rightarrow$ ‘small QGP-lumps’
Critical fluctuations near the critical point, $T_c \rightarrow K/\pi, <p_T>$, etc
Hadronic mass/width changes (Pisarski 1982) $\rightarrow$ rho etc

B. “External” Signatures of high $p_T$ probes altered by the QGP:

Charmonia suppression (Satz, Matsui 1987) $\rightarrow T(\text{dissociation})$ of $c\bar{c}, b\bar{b}$
Jet quenching (J D Bjorken 1982) $\rightarrow$ medium density

--> Goal is to achieve a combination of many signatures
ATLAS, 0-1% central Pb+Pb, pT integrated $v_n$

Result for LHC (preliminary): 

$$0.07 \leq \frac{\eta}{s} \leq 0.43$$

- A simultaneous fit of $v_2-\nu_6$ gives a preferred extracted $\eta/s$ for each initial condition
- Range of results quantifies uncertainty

(Also see U Heinz et al) for $v_n$ fits
Quenching of open charm and beauty

The RAA of Charm and Beauty are both suppressed at RHIC and LHC.

* Puzzle at RHIC since few years: (b+c) -> e suppression is similar to that of charged hadrons (STAR, PHENIX).

* The RAA of D0 at RHIC (STAR) is suppressed after pT=3 GeV, and is similar to the RAA of charged hadrons at pT~6 GeV.

* The RAA of D0 at LHC (ALICE) is suppressed and is similar to the RAA of charged hadrons at high pT.
J/ψ produced by recombination of thermalized c-quarks should have non-zero elliptic flow
– measurements give a hint for non-zero $v2$
– qualitative agreement with transport models, including regeneration
– complementary to indications obtained from J/ψ RAA studies
The J/Ψ puzzle at RHIC

J/Ψ at forward y in Au+Au, PHENIX, arXiv:1103.6269
C da Silva, PHENIX, QM2011

- Suppression doesn’t increase with local density
  \[ R_{AA} (|y|<0.35) > R_{AA} (1.2<|y|<2.2) \]
  \[ R_{AA} (RHIC, |y|<0.35) \approx R_{AA} (SPS) \]

- Data on J/Ψ Psi in forward rapidity 1.2-y-2.2 show larger J/Ψ suppression at forward y with respect to midrapidity
- If J/Ψ from ψ' and χ_c decays is fully suppressed, RAA drops to 0.6
- PHENIX has measured the y-dependance of R(dAu) and R(CP) of J/Ψ in d+Au (arXiv:1010.1246).
J/ψ in A+A, \( p_T \) and Npart dependence

* Suppression in central collisions at high \( p_T \)
* Low \( p_T \) (Phenix data in blue) is more suppressed
  RAA systematically higher at high \( p_T \)

- \( J/\psi \) \( v_2 \) ~ 0 up to \( p_T \) ~ 8 GeV/c in mid-central 20-60%
- Disfavors coalescence from thermalized charm quarks at RHIC
\( J/\psi \) suppression and coalescence

\( J/\psi \) suppression at low \( p_T \) maybe from excited stats (\( \psi', \chi_\psi \))


60\% of all J/Psi comes from direct \( J/\psi \). (30\% of all J/Psi come from \( \chi_c \) and 10\% \( \psi' \))

\( \chi_c \) and \( \psi' \) T(dissociation) \( \sim T_c \), while \( J/\psi \) T(dissociation) \( \sim 2 T_c \)

Suppression of J/Psi observed, maybe due to \( \chi_c \) and \( \psi' \) dissociation

Directly produced J/Psi may not be suppressed at SPS and RHIC

One can then expect more suppression at LHC due to direct J/Psi dissociation (but must account for possible c,cbar coalescence-> J/Psi)

\textbf{J/Psi assumed completely suppressed and resurrected by c,cbar “coalescence”}

A Andronic et al, Phys Lett B 652 2007, p 259

- \textbf{J/Psi is assumed to be completely suppressed at RHIC}
- \textbf{R_AA(J/Psi) is then estimated for the process of c, cbar coalescence to J/Psi, within a thermal model}
  \( \rightarrow \) This estimate can describe \( R_{AA}(J/Psi) \) at RHIC
  \( \rightarrow \) It predicts a great enhancement of \( R_{AA}(J/Psi) \) at LHC
J/Psi in A+A, $p_T$ and Npart dependence

K Safarik, ALICE, QM2012

**Low $p_T$ is less suppressed**

**RAA of J/Psi smaller at low $p_T$, in central collisions ->**

**Indication of J/Psi regeneration at LHC at low $p_T$?**

At low $p_T \sim 50\%$ J/ψ from recombination
Gravitational waves may allow to distinguish between types of phase transition

Upper plot: Cross over case comparing to inflation and kination (assuming a long period of domination of kinetic energy of a scalar field).

Lower plot: Gravitational Waves emanating from bubble collisions and turbulences during a 1st order QCD phase transition

Comparison to sensitivity of experiments: SKA (Square Kilometer Array), PPTA (Parks Pulsar Timing Array), LISA (Laser Interferometer Space Antenna)

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\( \Psi'' \), \( J/\Psi \) suppression, \( T(\text{direct } \gamma)\sim 335 \text{ MeV}, T(\text{chem. fr. out})\sim 170 \text{ MeV near } T_c \)

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2010: first PbPb at the LHC !
Discovery of Y suppression in 2011 at RHIC and LHC
Hierarchy of b\bar{b} and c\bar{c} suppression patterns (2012, LHC)