The perfectly fluid Quark-Gluon Plasma

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May 11th, 2006

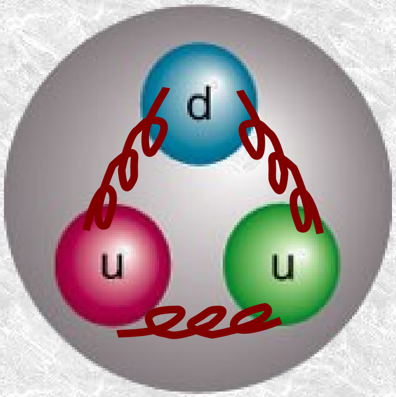
Outline

- **Introduction**
  - Deconfinement and the Quark Gluon Plasma (QGP)
  - The Quantum Chromo Dynamics (QCD) phase diagram
- **Heavy Ion collisions**
- **Hunting the QGP**
- **The "perfect fluid" created at RHIC**
  - Review of the experimental evidence
- **Probing the perfect liquid**
  - Jet tomography
- **The future**
- **Summary**

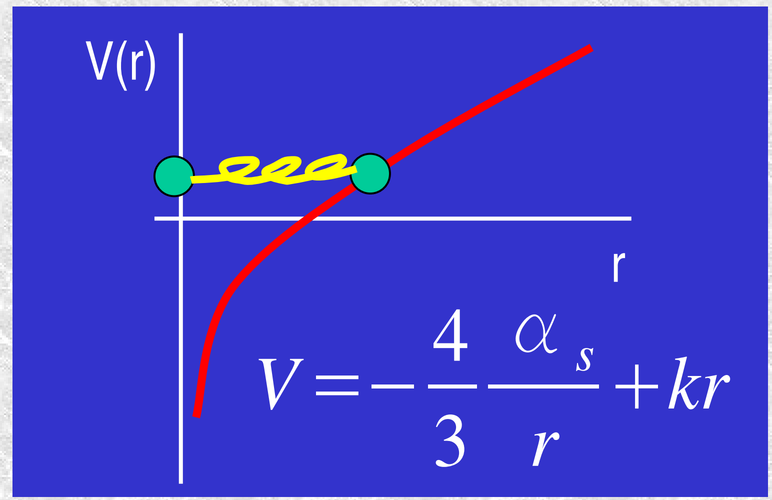
Introduction

Quarks, gluons and the Strong Interaction

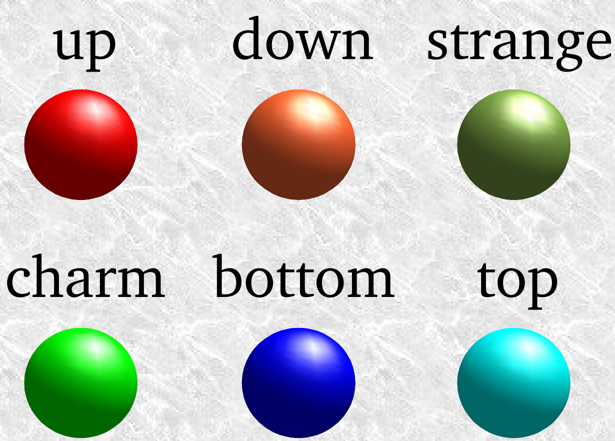
The proton is a composite object made of quarks and gluons.



No one has ever seen a free quark. QCD is a "confining" gauge theory, with an effective potential:



Quarks & gluons carry a "color charge"
Protons and hadrons are color neutral

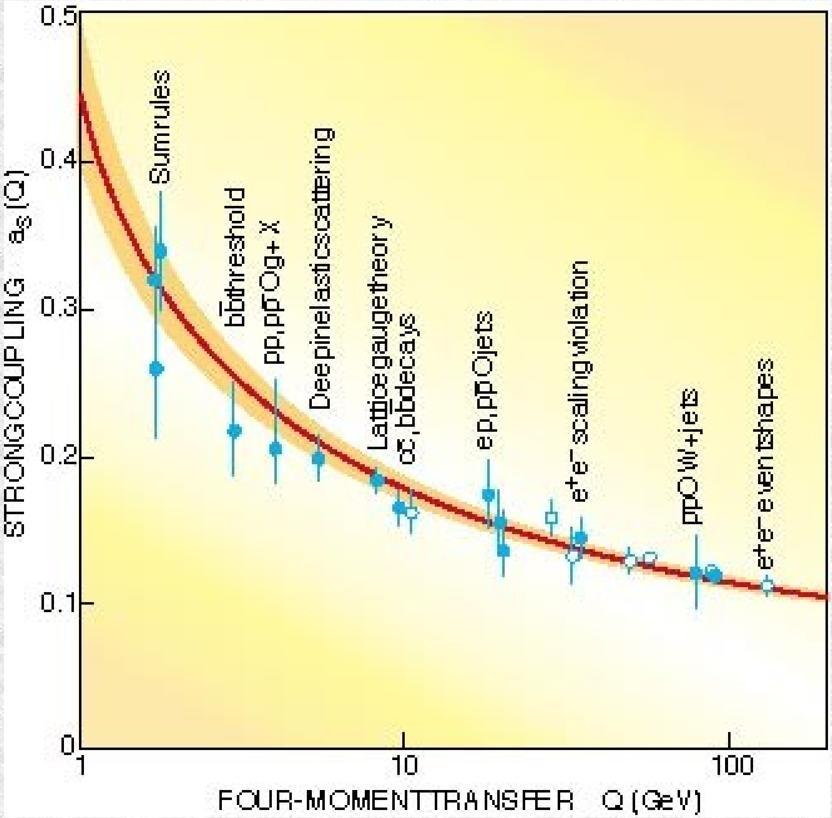


gluons – self-interacting

Asymptotic freedom in QCD

D.Gross, F.Wilczek, Phys.Rev.Lett 30, (1973)

H.Politzer, Phys.Rev.Lett. 30, (1973)



- The strong coupling constant **decreases** with momentum transfer

$$\alpha_S \xrightarrow[Q\to\infty]{} 0$$

- "if all fundamental constituents carry sufficient momentum ordinary hadronic matter will melt down into a deconfined state of quarks and gluons"
  Collins, Perry, PRL 34 (1975)

Quark-Gluon Plasma = a new state of matter made of non-confined quarks and gluons (more generally: colored degrees of freedom)

How? heating matter in Heavy Ion collisions

Melting the hadrons

- At what T_c can we liberate the quark and gluon degrees of freedom?
- Energy density of "**g**" **massless degrees of freedom** in thermal equilibrium at **zero baryon density:**

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

  - Below T_c: ultrarelativistic hadron gas – mostly π^+, π^-, π^0

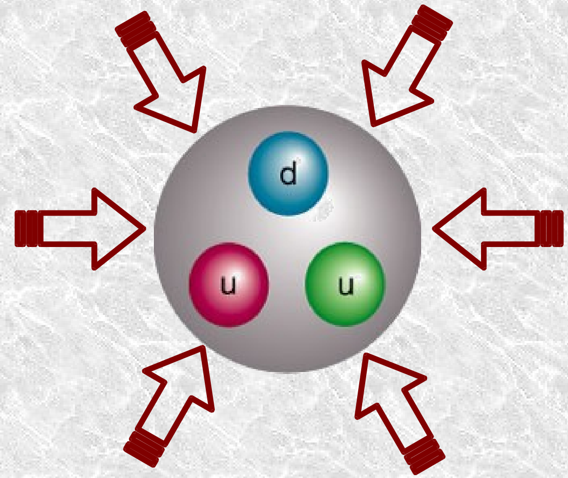
$$g_{HG} = 3$$

  - Above T_c: Quark-Gluon ideal gas (wQGP = weakly coupled QGP)

$$g_{QGP} = \underbrace{2_{hel} \cdot 8_{color}}_{\text{gluons}} + \frac{7}{8} \cdot \underbrace{2_{spin} \cdot 2_{q\bar{q}} \cdot 3_{flavor} \cdot 3_{color}}_{\text{quarks}} \approx 50$$

Melting the hadrons – bag model

- The vacuum exerts a pressure $B \approx 200\ \text{MeV}^4$ on colored particles – quarks and gluons



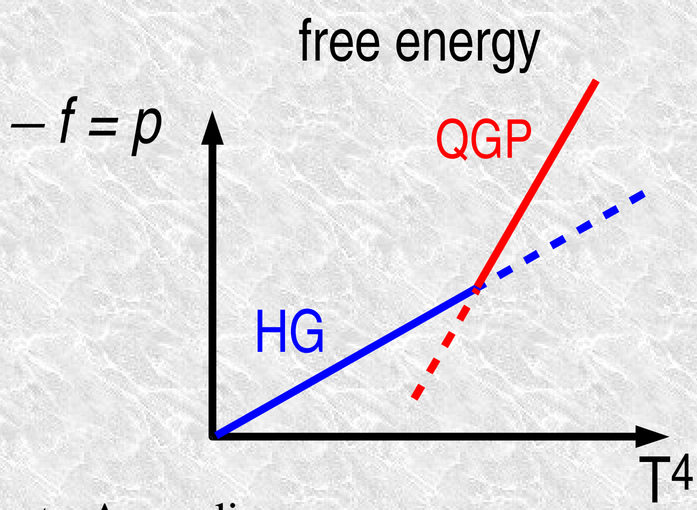
  - in the QGP phase (perfect Q&G gas)

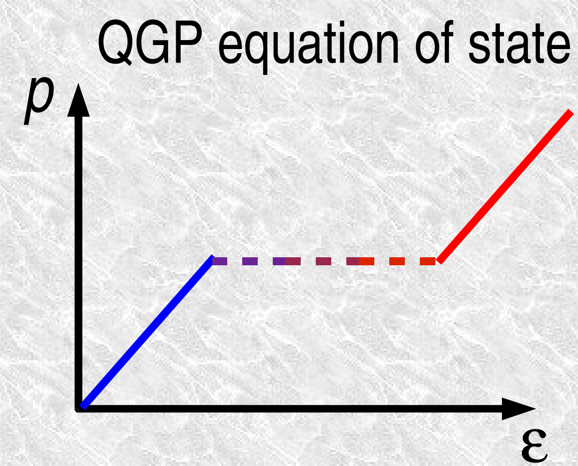
$$p_{QGP} = \frac{1}{3}\varepsilon_{QGP} - B$$

  - in the HG phase, no vacuum pressure

$$p_{HG} = \frac{1}{3}\varepsilon_{HG}$$

- Phase transition when $p_{HG} = p_{QGP} \Rightarrow$ **$T_c \approx 150$ MeV**

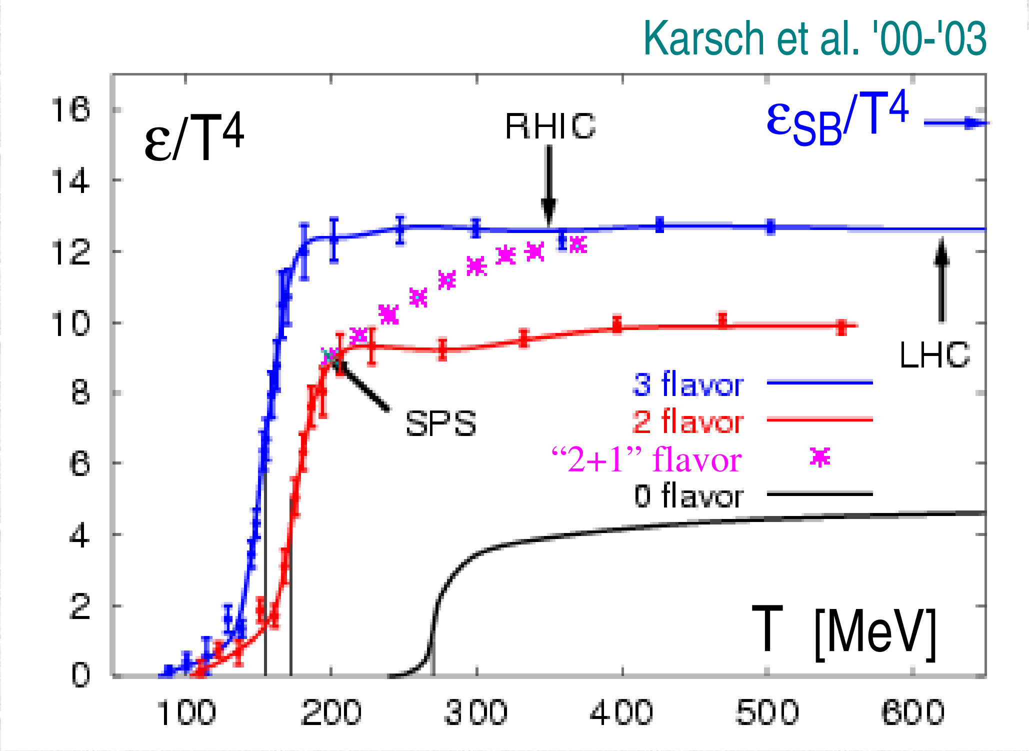




Melting the hadrons – lattice QCD

- Lattice QCD predicts a rapid cross-over to a QGP:

$$\frac{\varepsilon}{T^4} \propto g = \text{no. of degrees of freedom}$$



} 20% off the perfect QG gas:

a negligible difference?

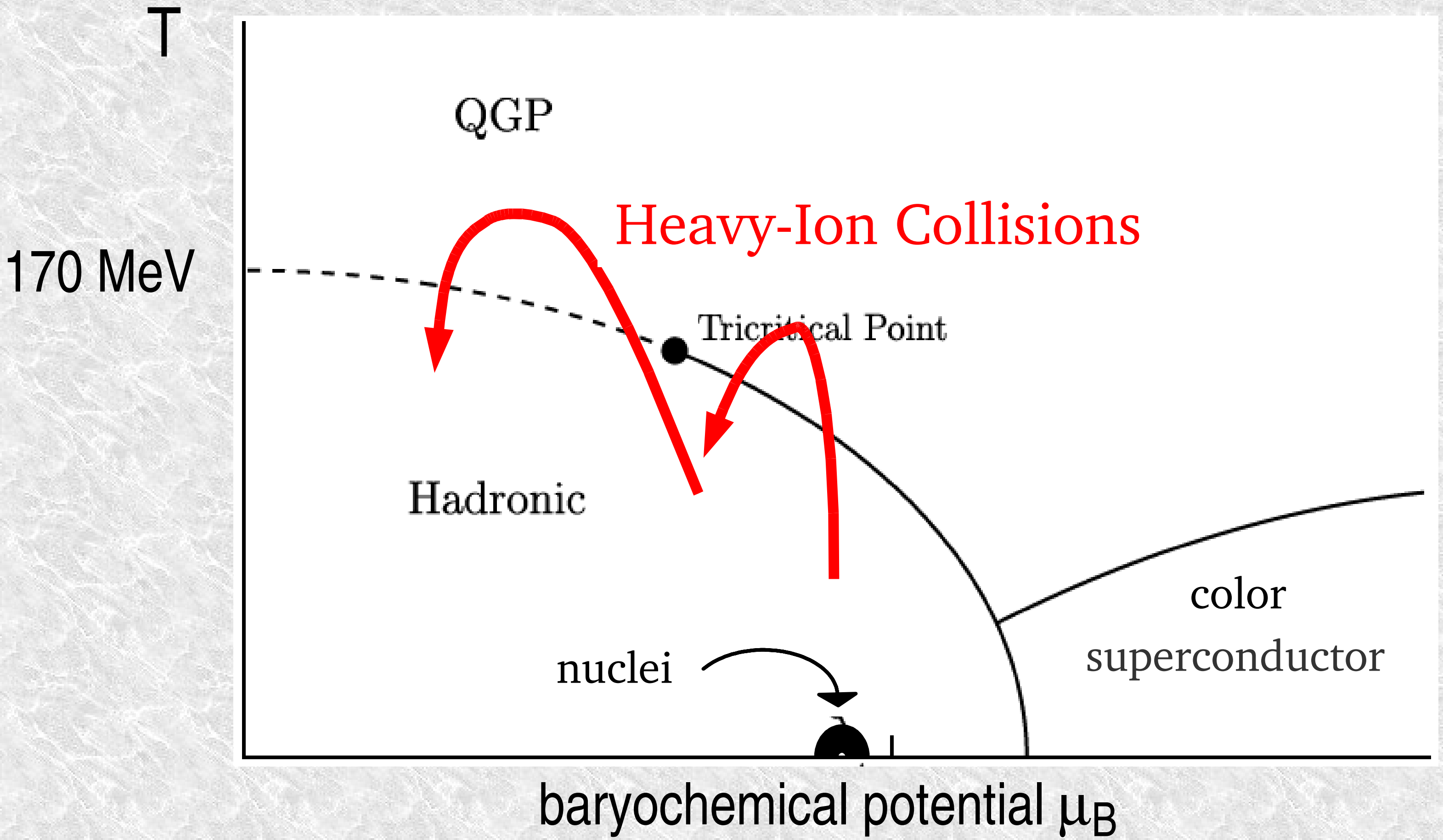
a different kind of QGP?
- Quark, gluon bound states?
- quasi-particles?

Transition temperature: $T_c \sim 170$ MeV $\varepsilon_c \sim 1$ GeV/fm^3

(remember: normal nuclear matter has ε~0.16 GeV/fm^3)

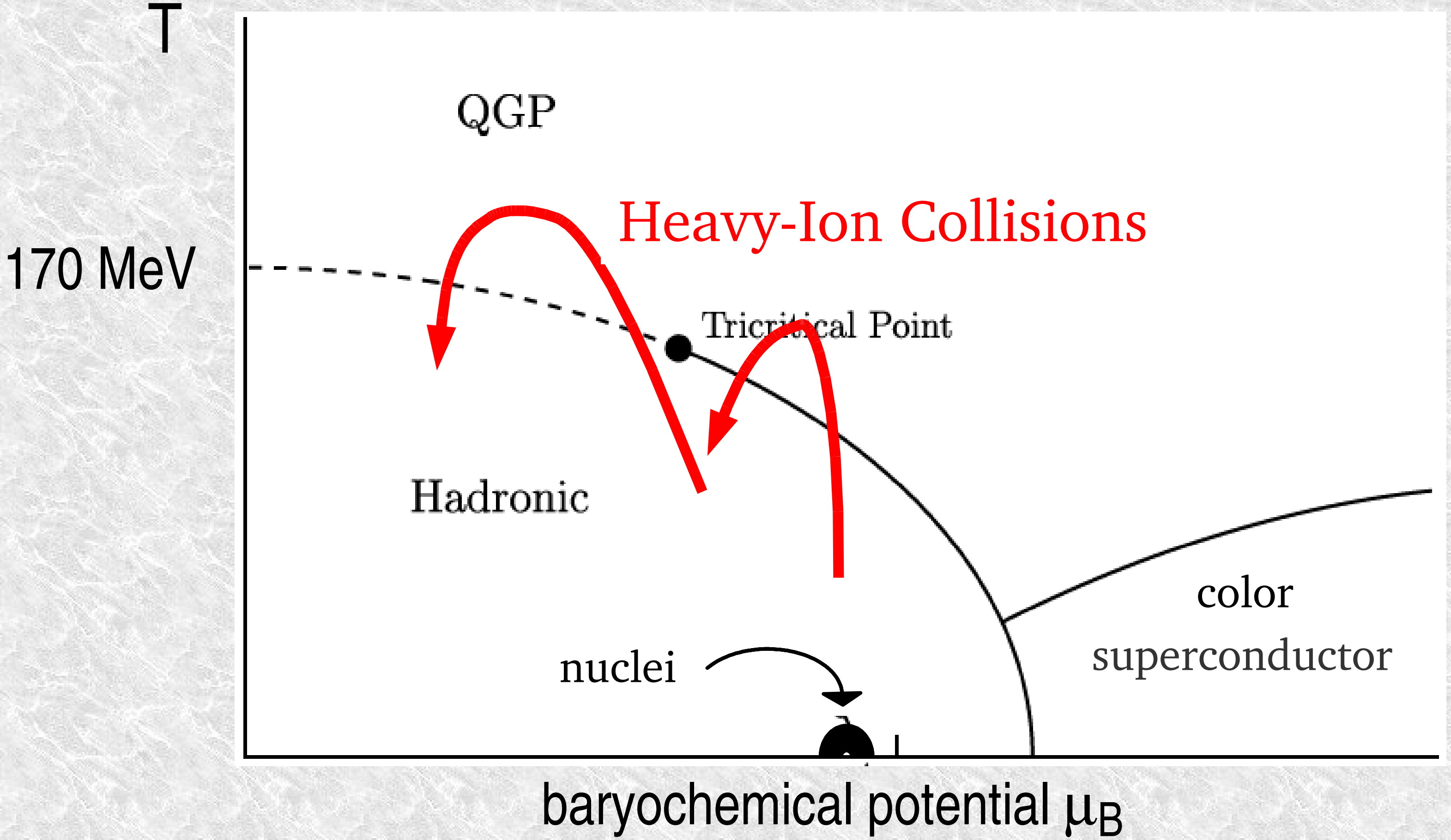
The QCD phase diagram

- Let's add an axis: μ_B = baryochemical potential ~ n_B-$n_{\bar{B}}$
- At high net baryon density, pressure from Pauli exclusion principle
  - quark-quark interactions allow for Cooper pairs to form
  - QGP becomes a color superconductor (Wilczek, Rajagopal, Son).



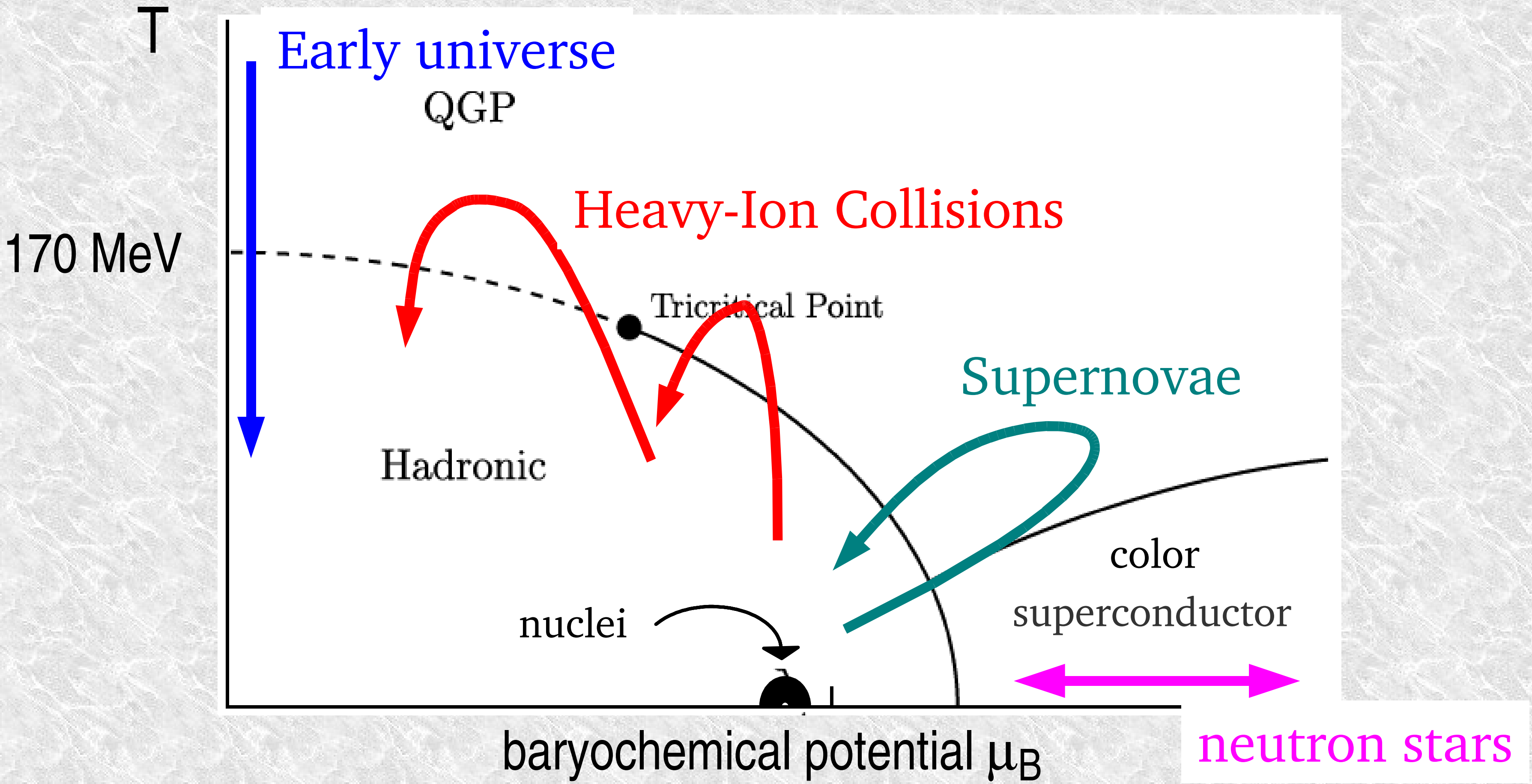
Why studying QGP & phase transition?

- **Particle physics and quantum field theory**
  - "primordial" form of QCD matter at high-T, high baryon density
  - insight into quark and gluon confinement, origin of mass
  - example of phase transition in strong self-interacting field theory



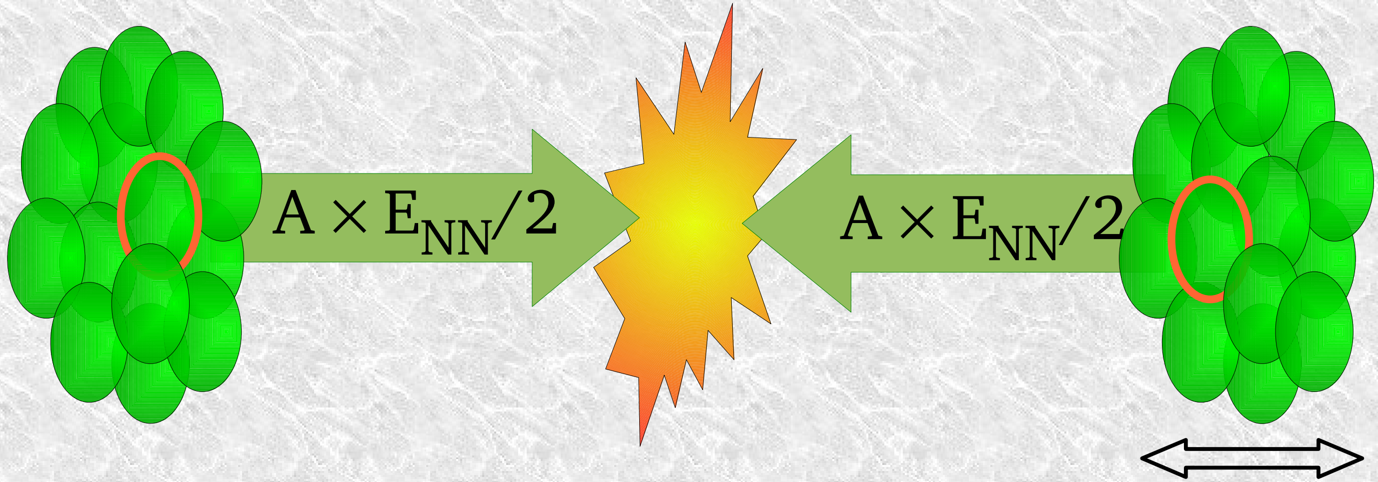
Why studying QGP & phase transition?

- **Cosmology and astrophyisics:**
  - QGP present in the very early universe (t < 10 μs)
  - Phase transition in the early universe, analyzable in the lab
  - may occur in supernovae, γ-ray burst, neutron stars



Heavy Ion Collisions

Heavy ion collisions

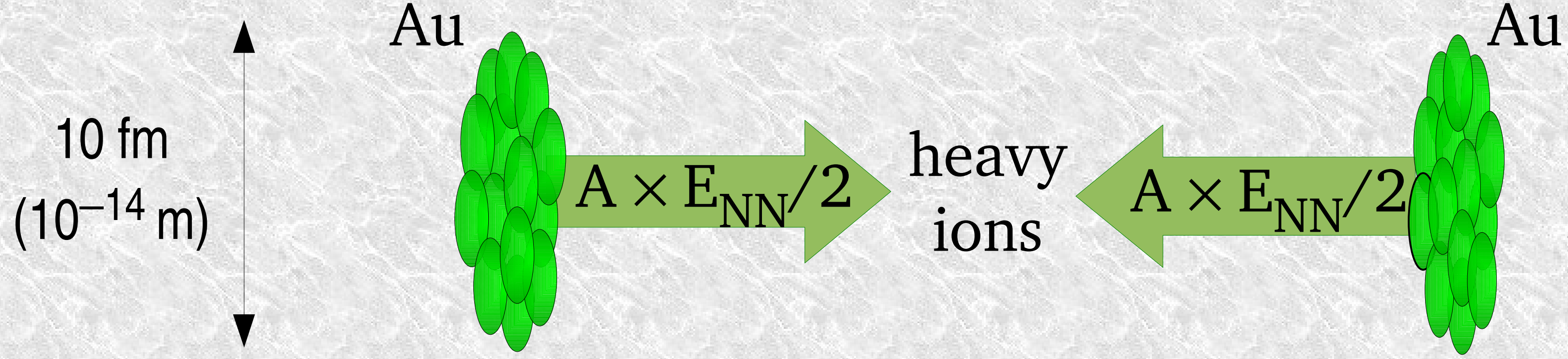


$$L = \frac{R_A}{\gamma}$$

- E_{NN} = Center-of-mass energy per nucleon pair
- nucleon-nucleon cross-section
  - E_{NN} deposited in the collision region
  - particle creation out of this energy
- Lorentz contraction

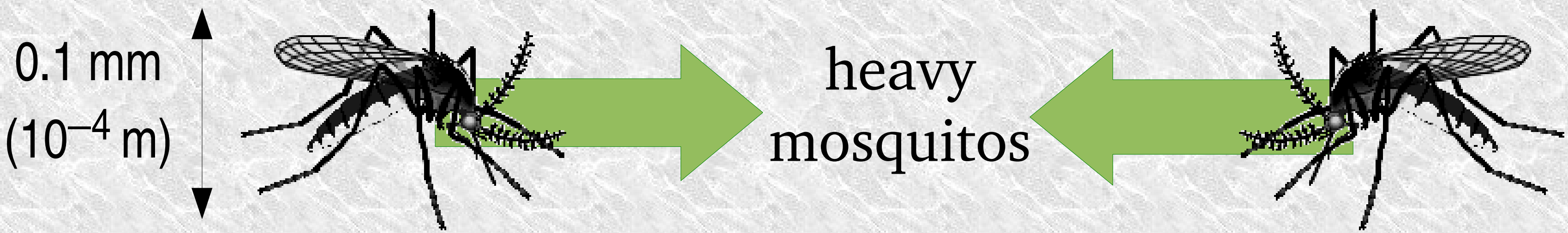
Lot of energy in a small volume V ⇒ large ε=E/V ⇒ high T

How high is the energy?



$$E = 1.6\cdot 10^{-19}\frac{J}{eV} \times 197 \times 200\,GeV = 6\ \mu J$$

@ RHIC



$$E = 2\times\frac{1}{2}\,m\,v^2 = 0.1\,g \times (30\,cm/s)^2 = 9\ \mu J$$

What's the difference? The energy density $\varepsilon = E/V$!

Heavy ion colliders

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	& In+In, S+U, p+Pb
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**	**& d+Au, p+p, Cu+Cu**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV	& p+Pb, p+p

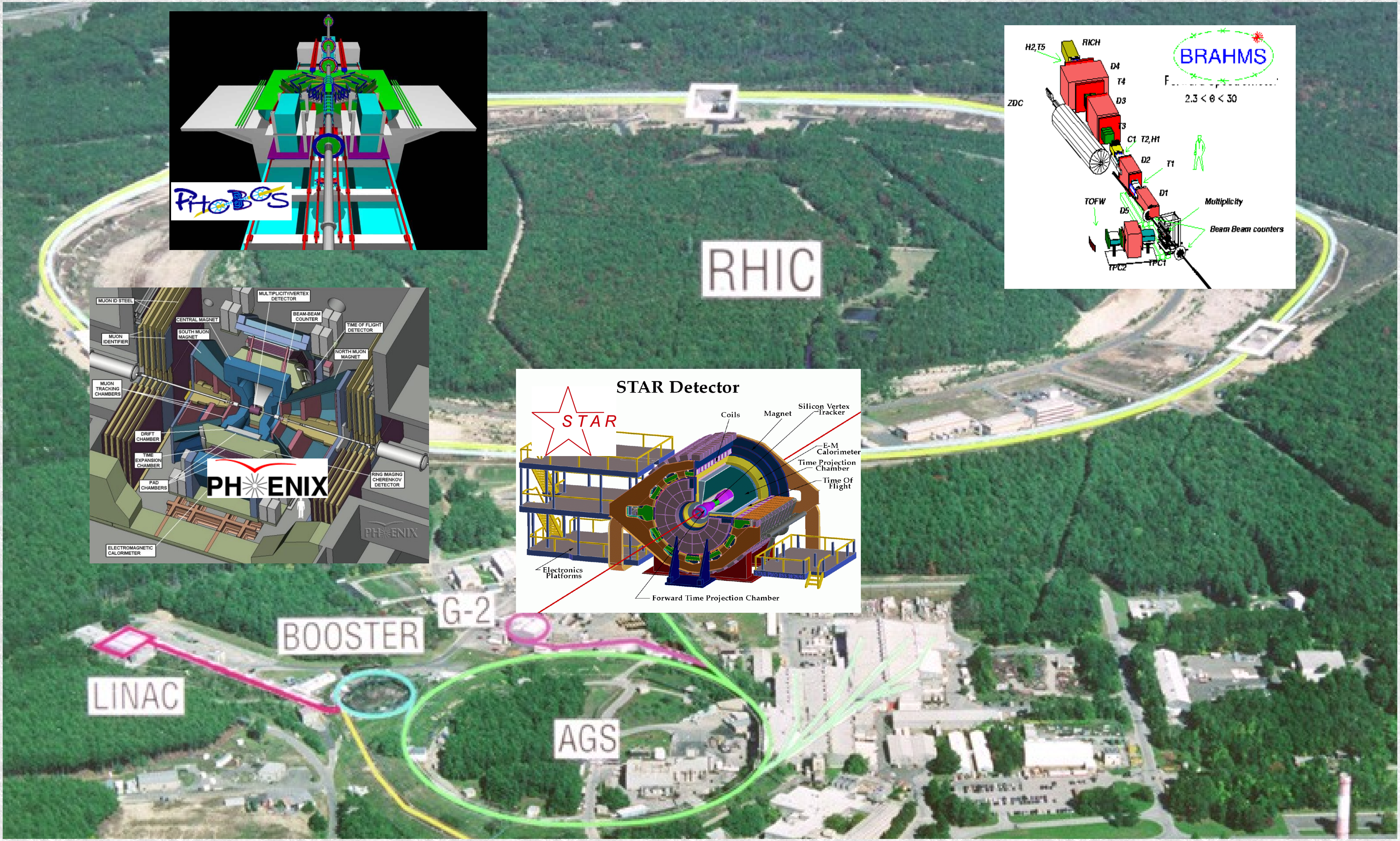
by 2008, 3 orders of magnitude in 30 years!

However, RHIC data only makes sense in context:

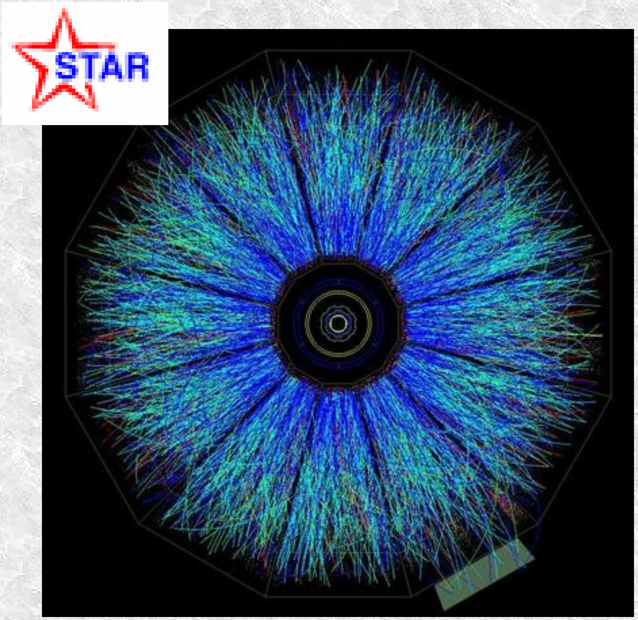
Facility	Location	System	Energy (CMS)
ISR	CERN	p+p	24-63 GeV
SPS	CERN	p+A	20 GeV
Tevatron	FNAL	p+A	13-38 GeV
LEP/LEP2	CERN	e+ + e-	91-210 GeV
UA1/UA5	CERN	pbar+p	200-900 GeV
Tevatron	FNAL	pbar+p	630-1800 GeV

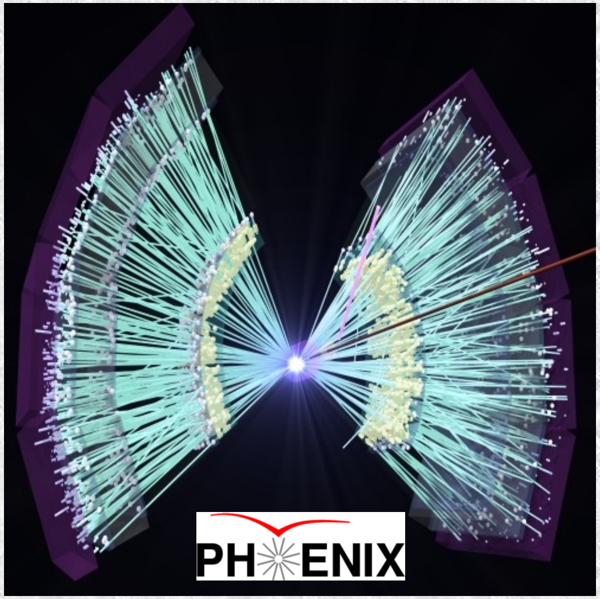
Goal is to understand strong interactions in all forms

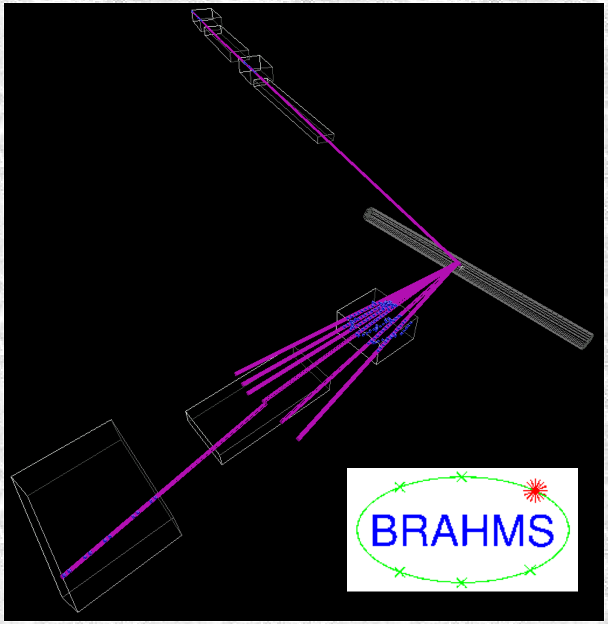
RHIC experiments @ BNL (USA)



Where is the QGP?

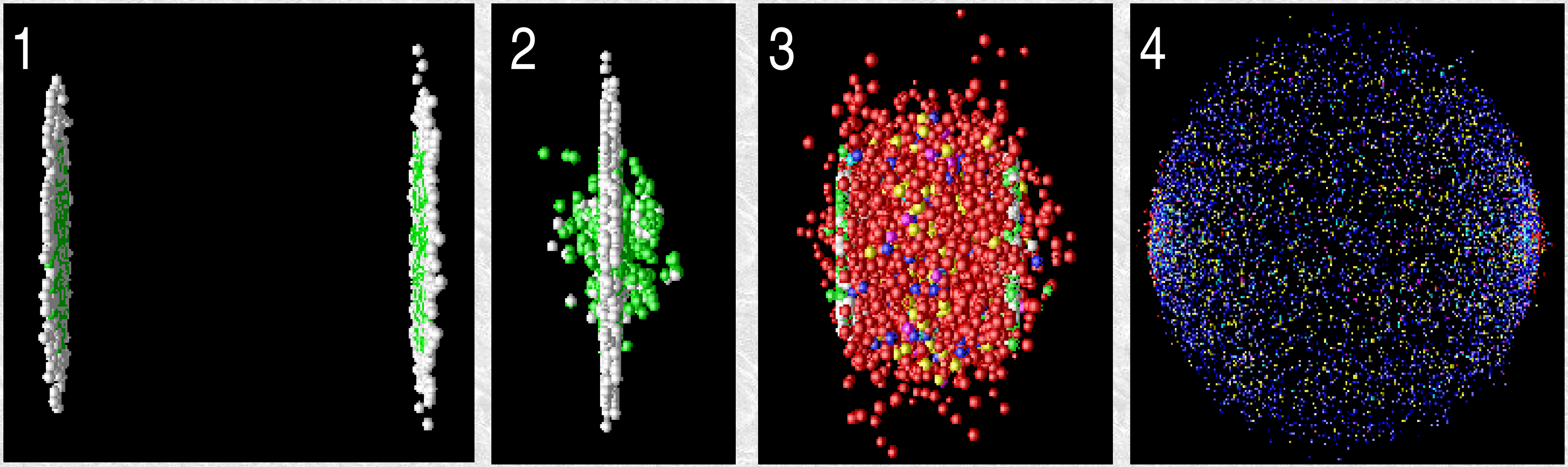






Hunting the QGP

Evolution of the collision



Colliding Nuclei

Hard collisions
Bulk partons

QGP??
Hadron gas??

Freeze-out to hadrons

Initial conditions	Initial state	Dynamics of the "fireball"	Final state

perturbative QCD (pQCD)

Color Glass Condensate (CGC)

Hydro models; Transport models

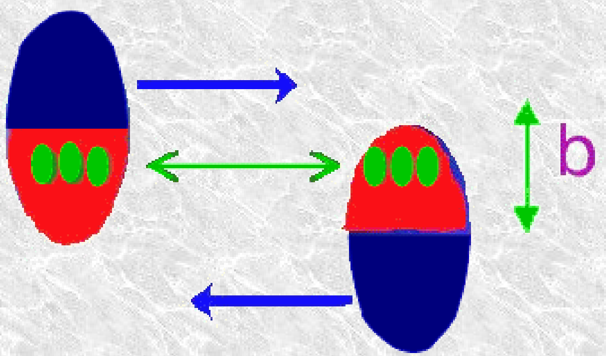
What we actually measure…

Experimental handles

Collision geometry

Participant Nucleon Number

$$N_{part}(b) = 2\int d^2s\,\tau_A(s+\tfrac{b}{2})\left\{1-e^{-\sigma\tau_A(s-\frac{b}{2})}\right\} \leq 2A$$



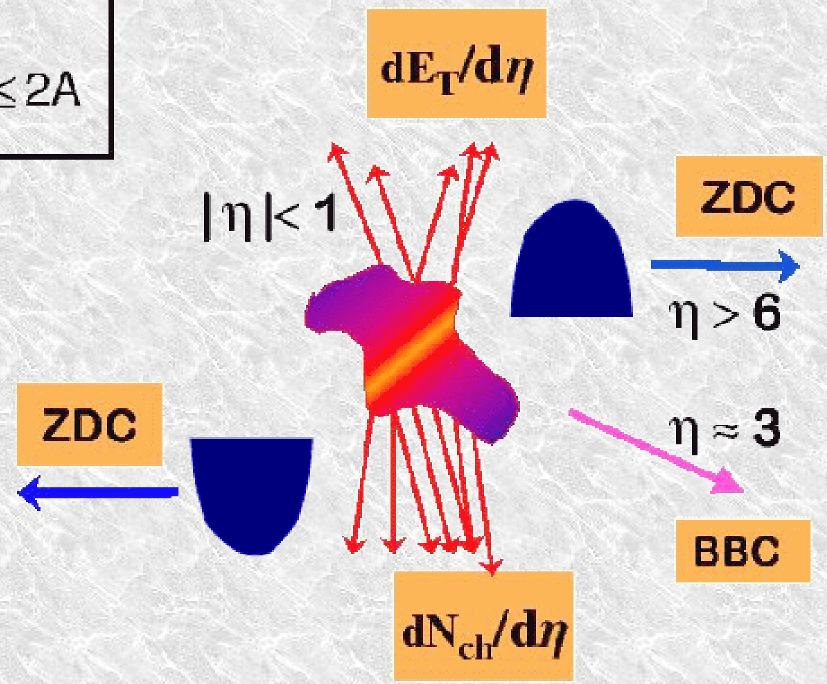
$$\tau_A(b) = \int dz\,\rho_A(z,b) \approx 2\rho_0\sqrt{R^2 - b^2}$$

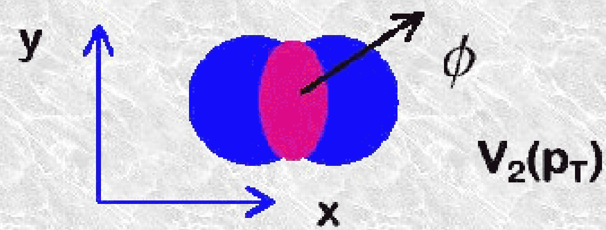
$$T_{AA}(b) = \int d^2s\,\tau_A(s+\tfrac{b}{2})\tau_A(s-\tfrac{b}{2})$$

Binary Collision Number

$$N_{coll}(b) = \sigma T_{AA}(b) \sim A^{4/3}$$

Observables

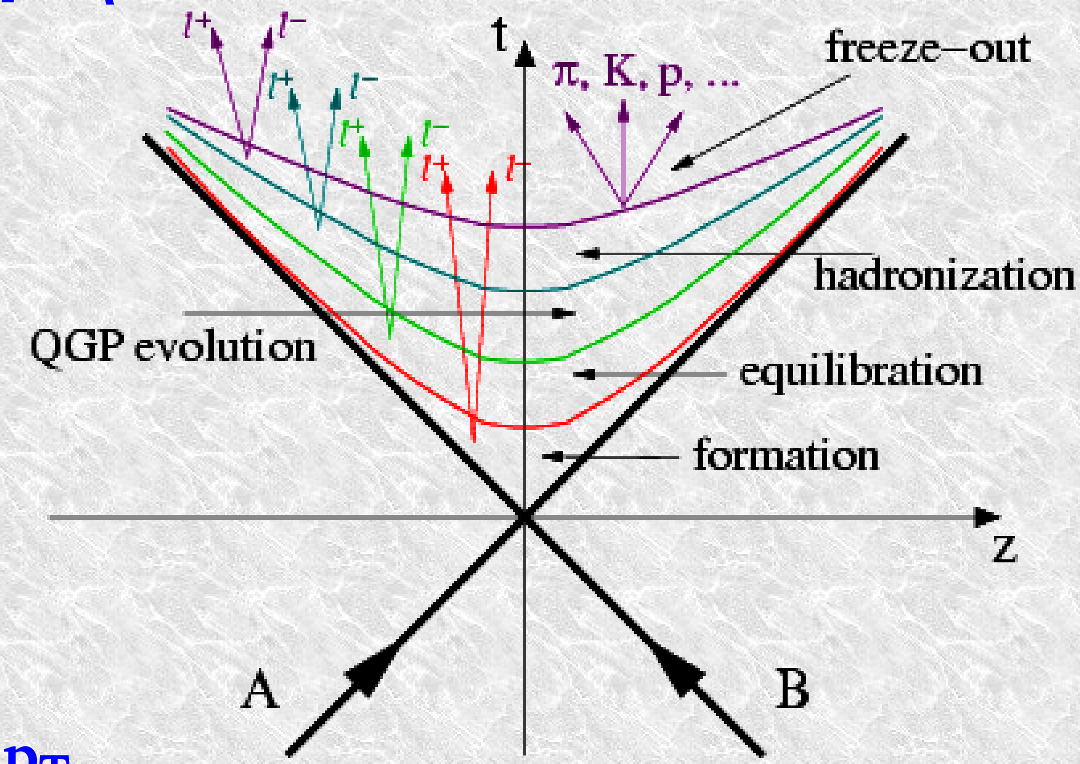




Variables: $A\,,\;\; b\,,\;\; \sqrt{s}\,,\;\; \eta = 0.5\,\ln(\tan(\theta/2))\,,\;\; p_T\,,\;\; \phi$

How to probe the created matter?

- **Global observables**
  - charged particle density $\mathbf{dN_{ch}/d\eta}$
  - transverse energy $\mathbf{dE_T/d\eta}$
  - elliptic flow $\mathbf{v_2}$
- **Soft probes (low scale)**
  - particle ratios $\mathbf{p/p, \pi^+/\pi^-, \ldots}$
  - low p_T spectra $\mathbf{dN/dp_T}$
  - elliptic flow $\mathbf{v_2(p_T)}$
- **Hard probes (large scale)**
  - high p_T hadron spectra $\mathbf{dN/dp_T}$
  - J/ψ production
  - high p_T lepton spectra



The perfect fluid observed at RHIC

The top physics story for 2005
according to the American Physical Society

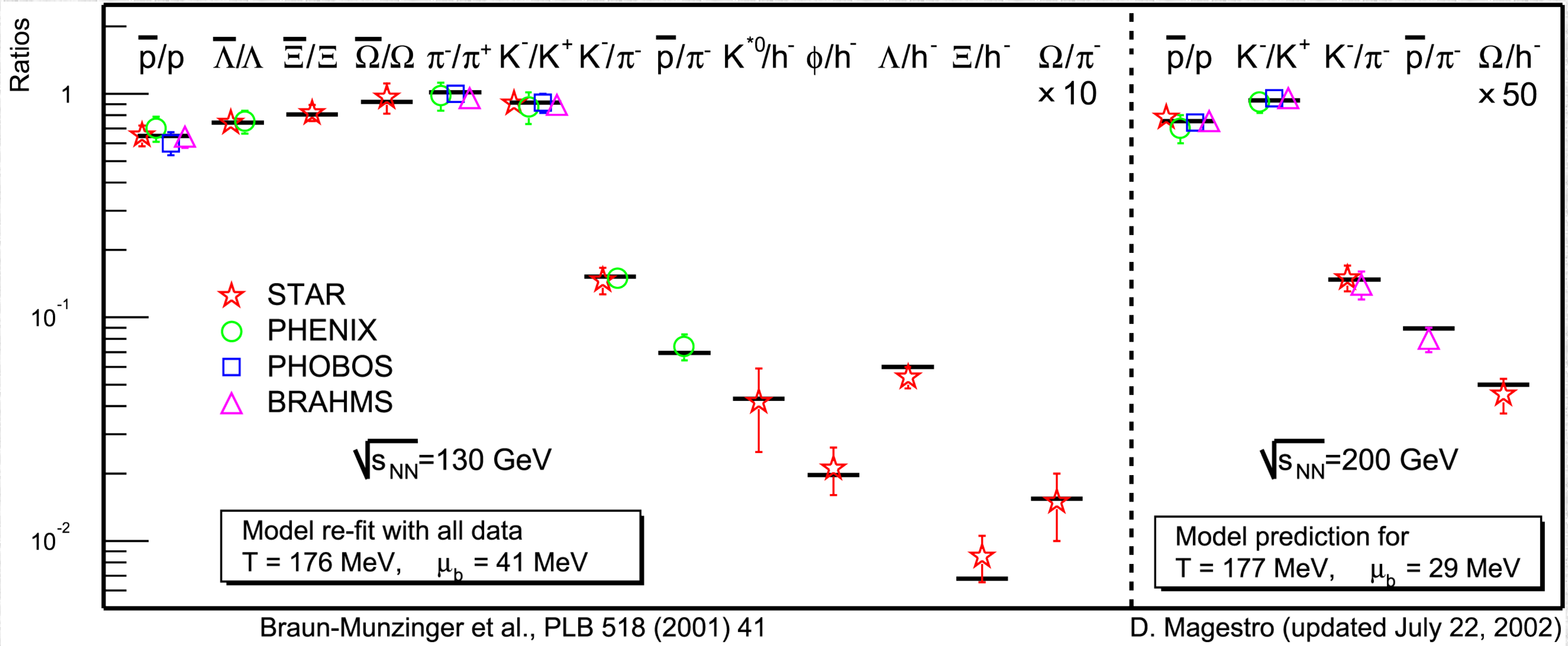
Particle ratios

$$N_i \propto g_i V \int \frac{d^3 p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

$$i = \pi^{\pm}, K^{\pm}, p, \bar{p}, \Lambda, \bar{\Lambda}, \Sigma, \Xi, \Omega, \ldots$$

T = freeze-out temperature

μ_B = baryochemical potential at freeze-out



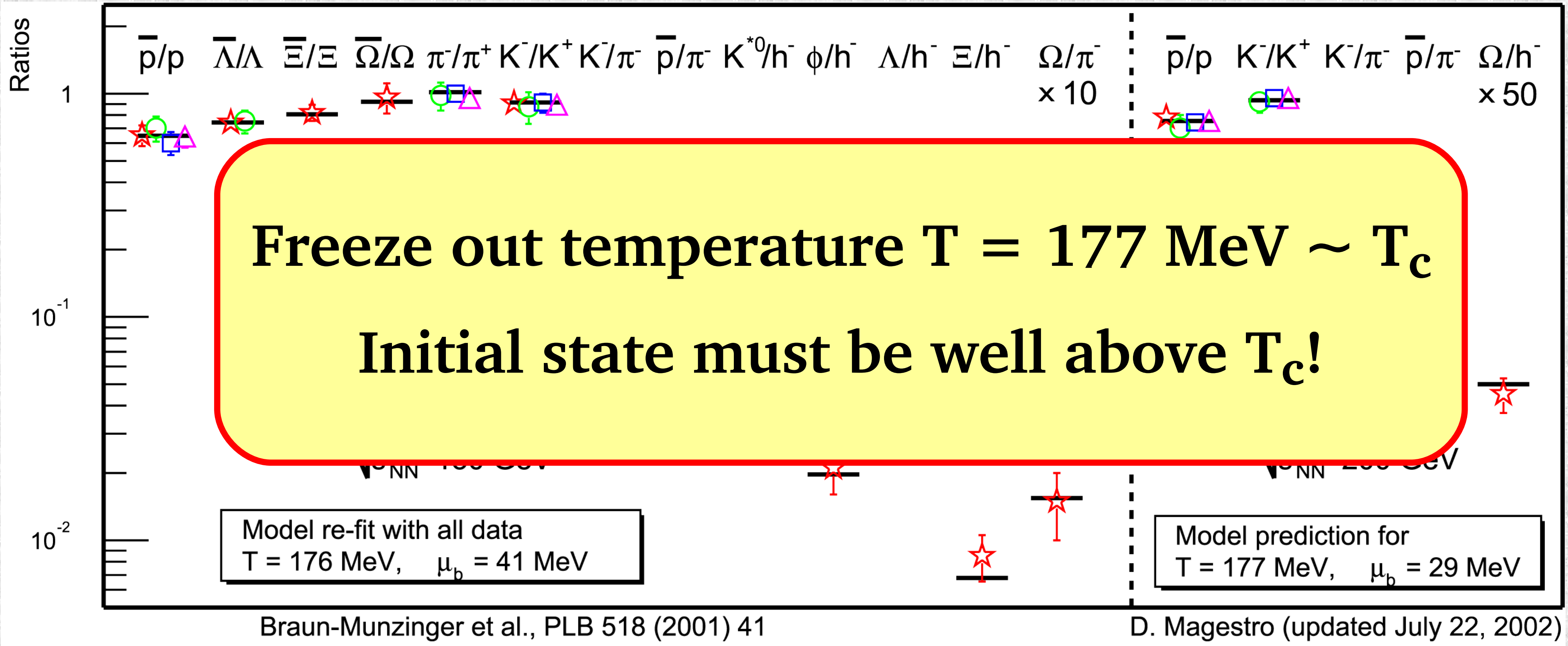
Particle ratios

$$N_i \propto g_i V \int \frac{d^3 p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

$$i = \pi^{\pm}, K^{\pm}, p, \bar{p}, \Lambda, \bar{\Lambda}, \Sigma, \Xi, \Omega, \ldots$$

T = chemical freeze-out temperature

μ_B = baryochemical potential at freeze-out



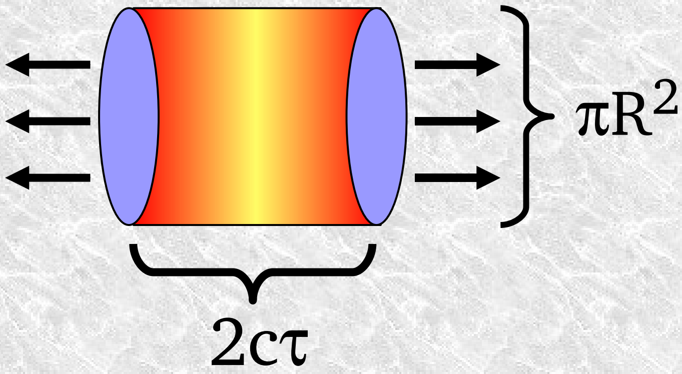
Freeze out temperature T = 177 MeV ~ T_c

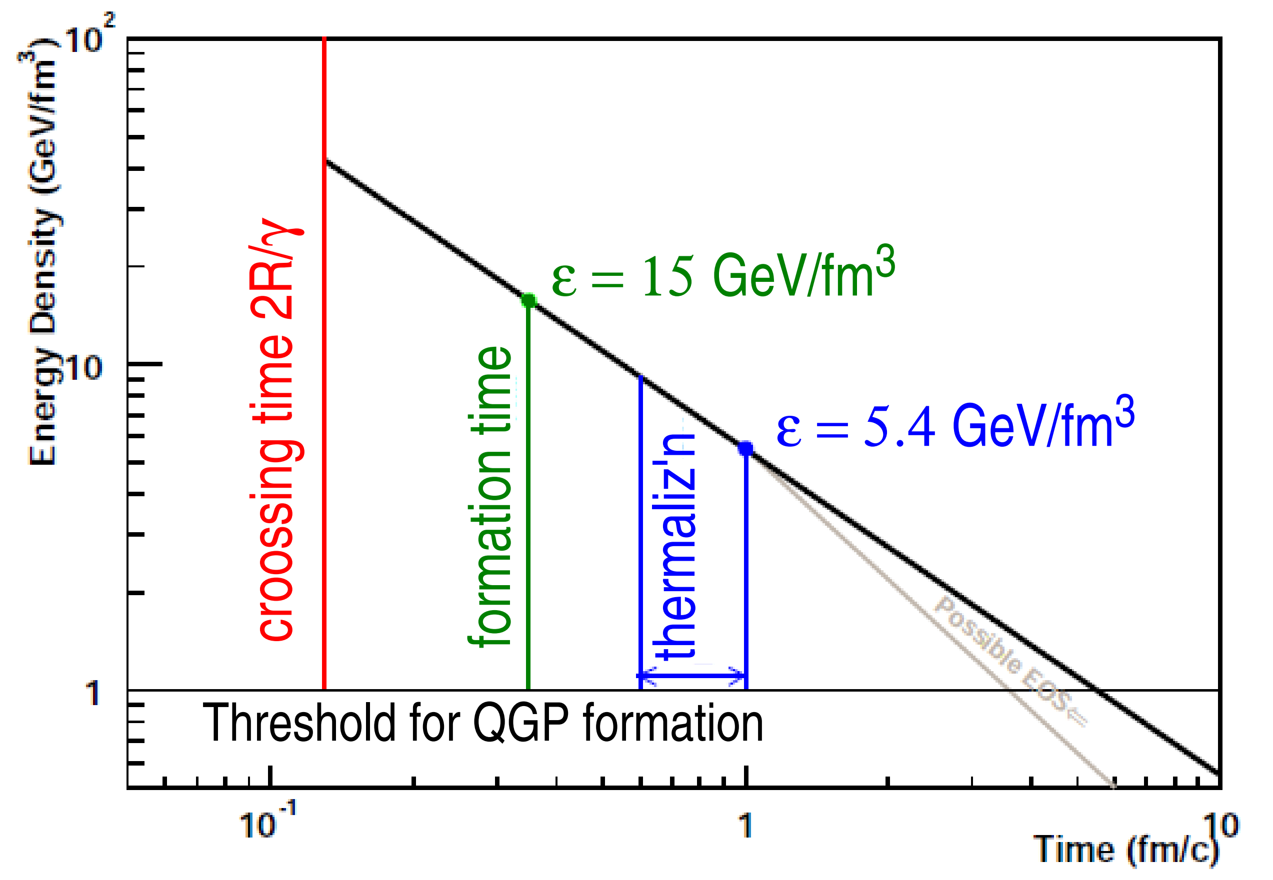
Initial state must be well above T_c!

Transverse energy density

- What about the initial state energy density ⇒ temperature?
- Bjorken's estimate:

$$\varepsilon_{Bj} = \frac{1}{\pi R^2} \frac{1}{2c\tau} \left| 2 \frac{dE_T}{dy} \right|$$





- Phenix $dE_T/d\eta = 600$ GeV ⇒ $\varepsilon_{Bj}\,\tau = 5.4 \pm 0.6$ GeV/fm² (central coll.)
- formation time: $\tau_0 \sim \hbar/\langle m_T \rangle \leq 0.35$ fm

  (final state hadrons $\langle m_T \rangle$ from PHENIX)

Conclusion 1

The initial temperature of the fireball is well above the critical temperature Tc~170 MeV for the QGP phase transition.

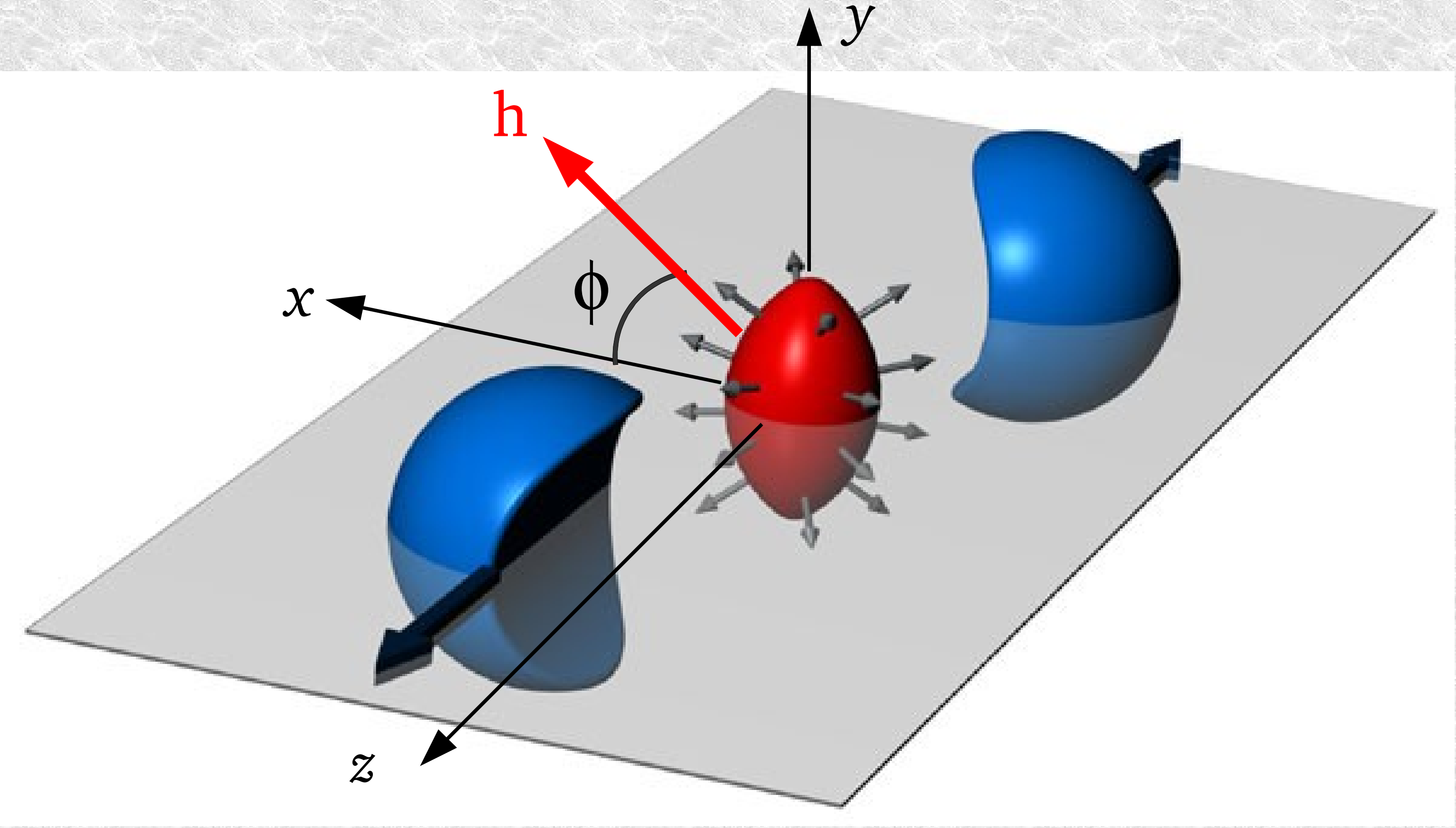
Questions

Does this system equilibrate before cooling below T_c?

Does it show collective behaviour?

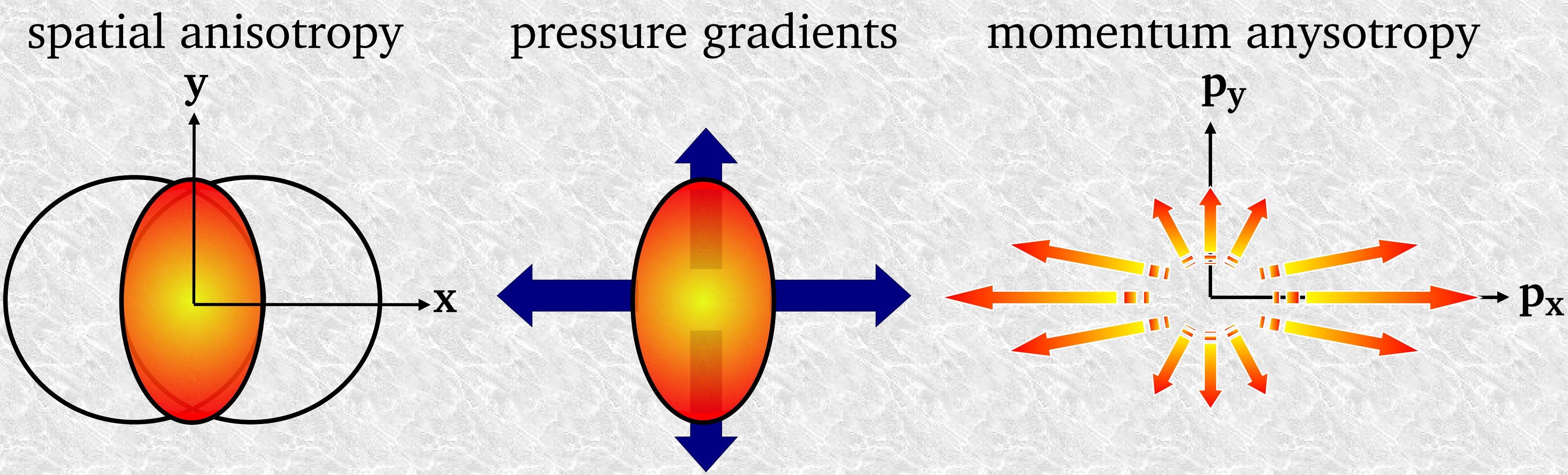
What are its constituents?

Non-central collisions



- Produced system is no more azimuthally symmetric
- Initial state geometry maps into final state angular distribution
- Nature of this mapping carries info on initial state properties

Elliptic flow

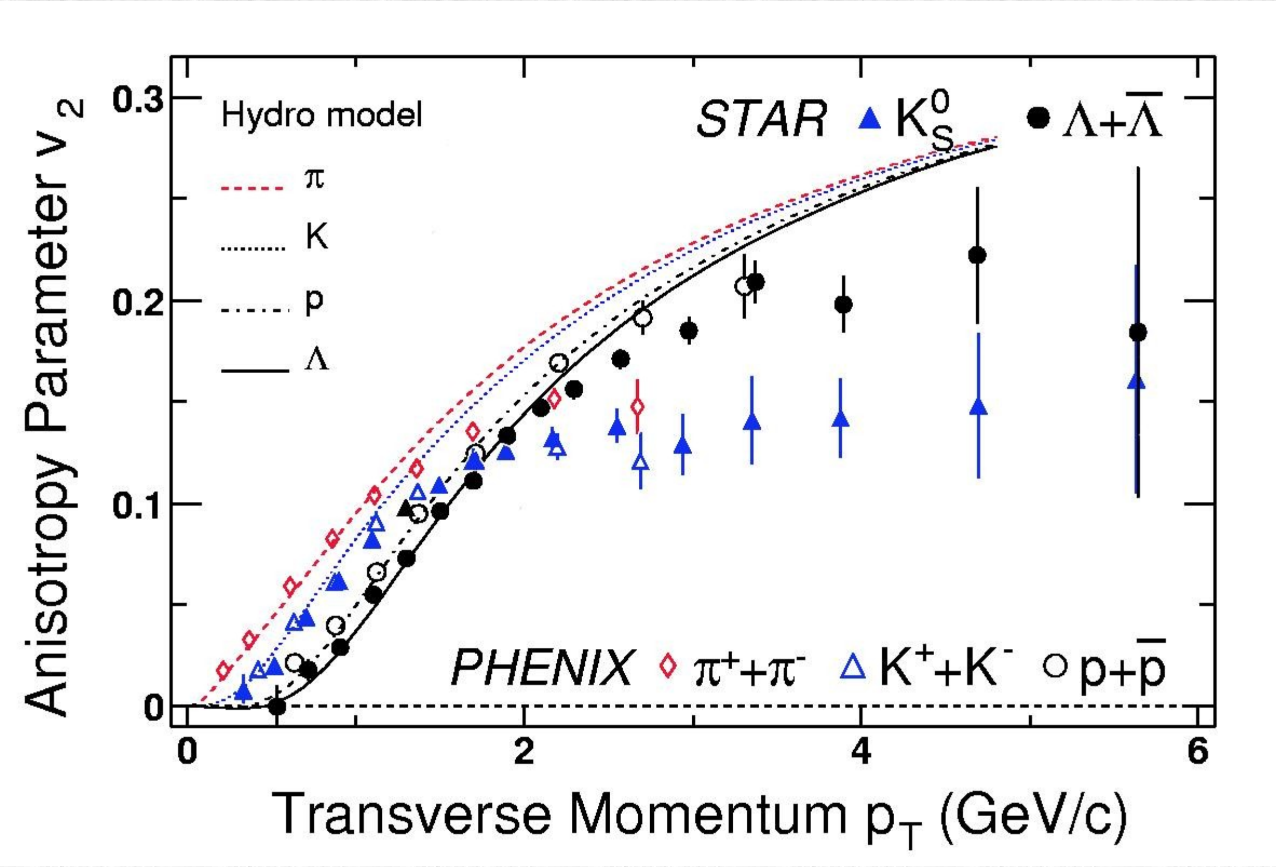


$$\frac{dN}{dp_T\, d\phi} = N_0 \left[1 + v_1(p_T)\cos(\phi) + 2\, v_2(p_T) \cos(2\phi) + \ldots \right]$$

elliptic flow

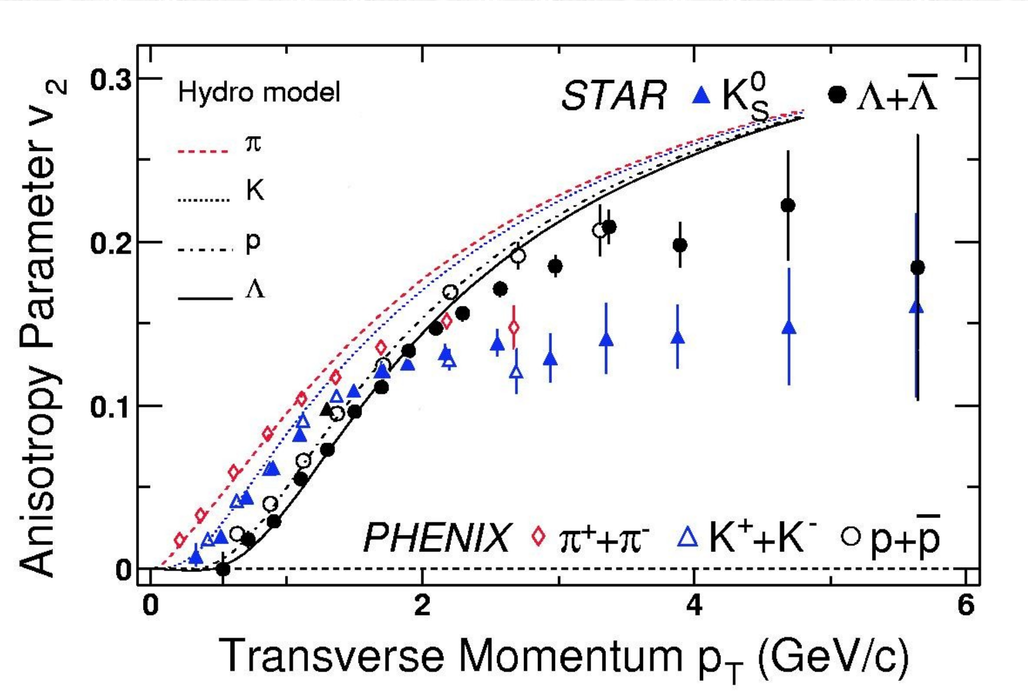
- Strong scatterings ⇒ local thermal equilibrium ⇒ pressure gradients
- Self-quenching effect – stops on short time scales
  - strong flow ⇒ rapid equilibration

Elliptic flow – experimental data

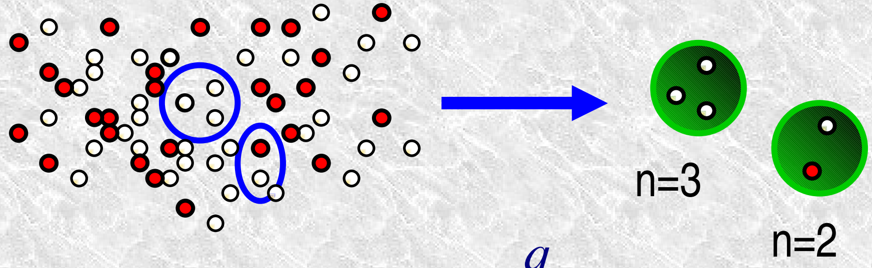


- Strong flow ⇒ rapid equilibration
- Rapid equilibration + high T >> T_c ⇒ QGP formation?
  - still we don't know the nature of the system's constituents

Elliptic flow – valence quark scaling

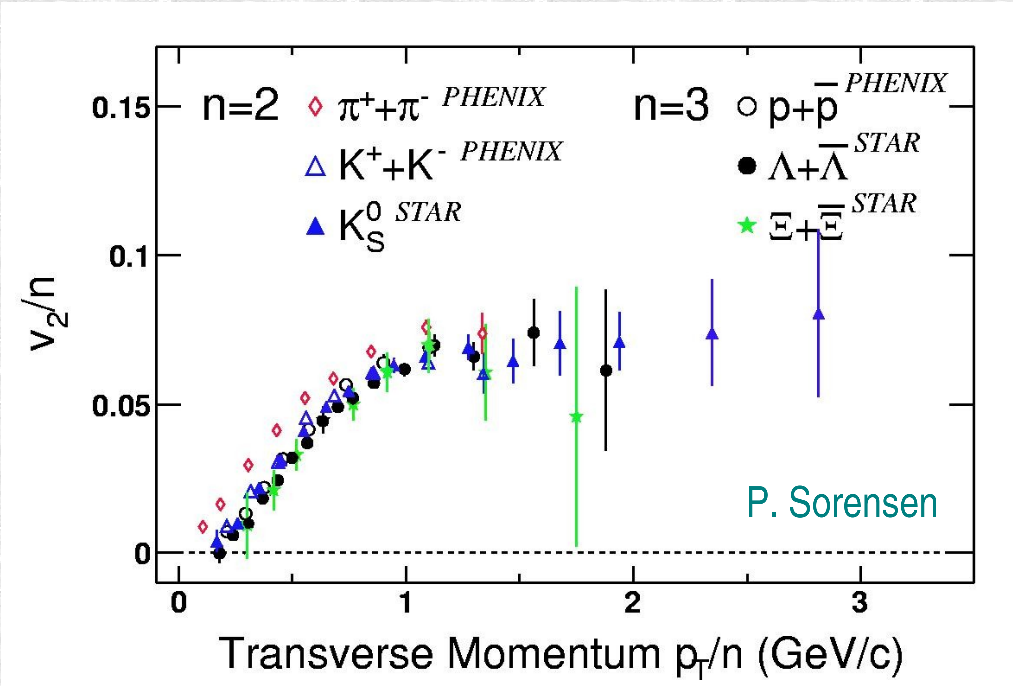


- Assume:
  - quarks are flowing with v_2^q
  - hadrons = quark recombination



- Then
$$\begin{cases} v_2 = n_q \times v_2^q \\ p_T = n_q \times p_T^q \end{cases}$$

Elliptic flow – valence quark scaling



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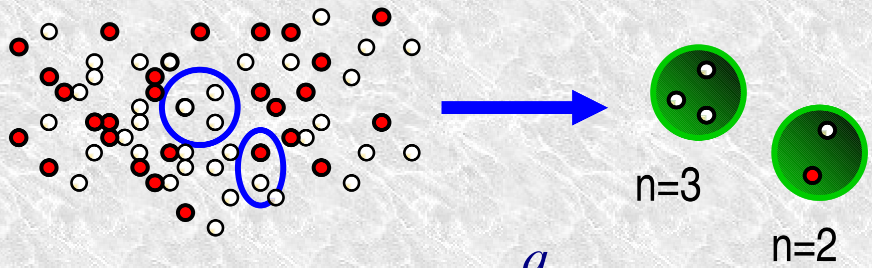


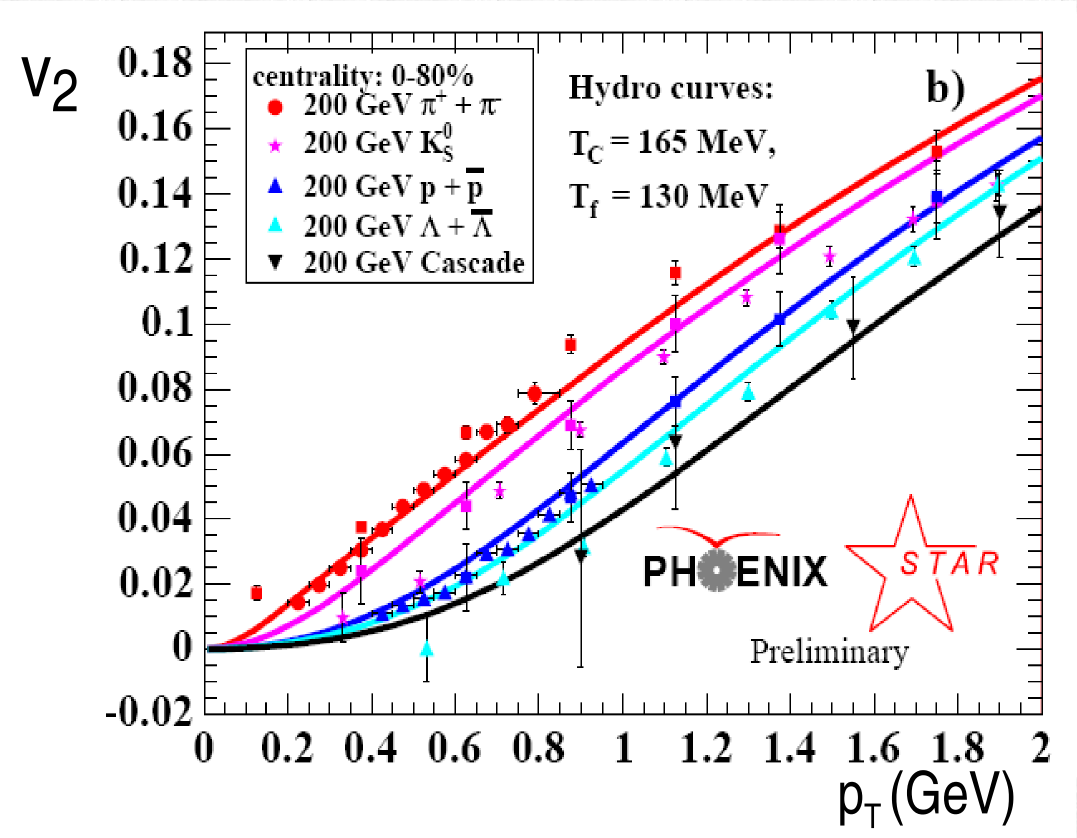
- Then $\begin{cases} v_2 = n_h \times v_2^q \\ p_T = n_h \times \langle p_T^q \rangle \end{cases}$

- Perfect scaling for all hadrons – some deviation for pions (from ρ decays)
- **The constituents of the flowing system are partons!**

High temperature $T >> T_c$
Rapid equilibration
Parton degrees of freedom

⇒ **Quark-Gluon Plasma!**

Elliptic flow – hydrodynamics



- Assume
  - local thermal equilibrium
  - small mean free path
- Conservation laws

$$\partial_\mu \left[(\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu} \right] = 0$$

$$\partial_\mu \left[s u^\mu \right] = 0$$

- Equation of state (EoS)

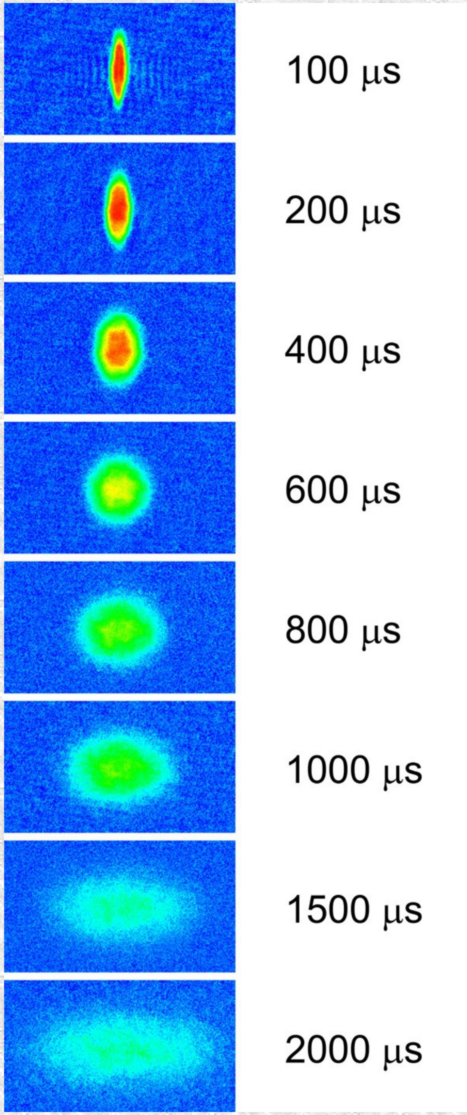
$$p = p(\varepsilon)$$

- **Hydro with QGP EoS** describes flow over a range of masses
- Thermalization time $t_0 = 0.6 - 1$ fm/c and $\varepsilon = 20$ GeV/fm^3
- Hydro = small mean free path = **strongly interacting system**!
  - not a weakly coupled gas of quark and gluons...

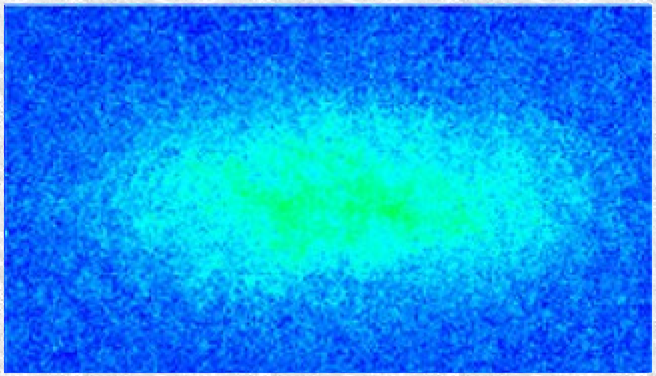
The atomic connection

- Heavy ion collisions similar to system of ultracold ^{7}Li atoms

Kinast et al., PRL 92 (2004) 150402
Bartenstein et al., PRL 92 (2004) 203201



- Atoms trapped in magnetic fields
- Tunable strength of interaction
- Open the trap ⇒ elliptic flow!
- In this experiment
  - very strong interactions
  - hydrodynamic behaviour



Conclusion 2

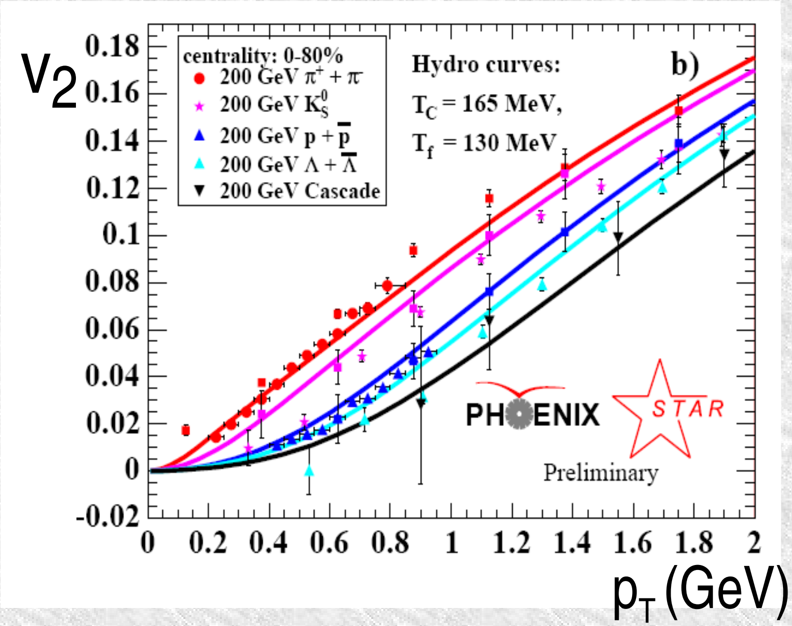
Rapid equilibration with QGP EoS,
large energy density
partonic d.o.f. with strong interactions

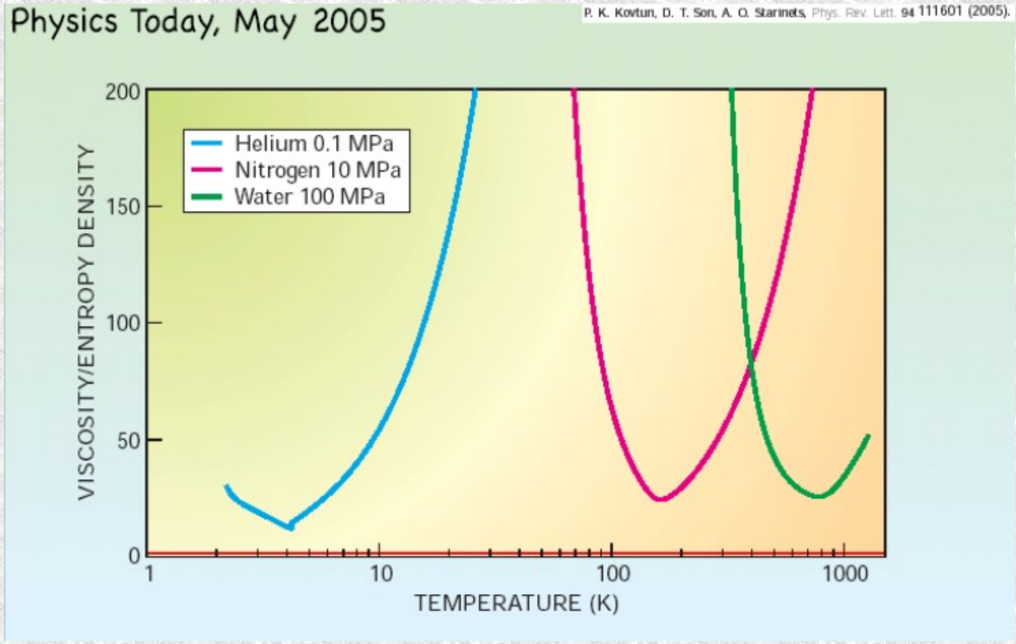
We have a sQGP!
(strongly interacting QGP)
with hydro behaviour

Like a perfect fluid?

- First time that hydro describes data **without any viscosity***!
  - Not true at SPS, not true in peripheral collisions at RHIC

*viscosity = resistance of liquid to shear forces (and hence to flow)





- Hydro equations + viscosity fit data with $\eta/s \sim 0.5$ (similar from lattice): 400 times less viscous than water, 10 times less than superfluid helium !
- Lower bound on viscosity from string theory (!!): $\eta/s > 1/4\pi$

the QGP is (nearly) a perfect fluid!

The string theory connection

- An example of strongly interacting Yang-Mills theory:
  - N=4 Supersymmetric Yang-Mills theory

N=4 SYM	← (conjectured) mathematical duality → Maldacena '97	Type IIB superstring on a $AdS_5 \times S_5$ space
strong coupling	←→	weak coupling
entropy of thermal SYM matter	←→	black-hole entropy $S/S_0 = 3/4$
	Kovtun, Son, Starinets, Policastro '02-'05	
η/s of thermal SYM matter	←→	absorption of gravitons by the black-hole $\eta/s = 1/4\pi$

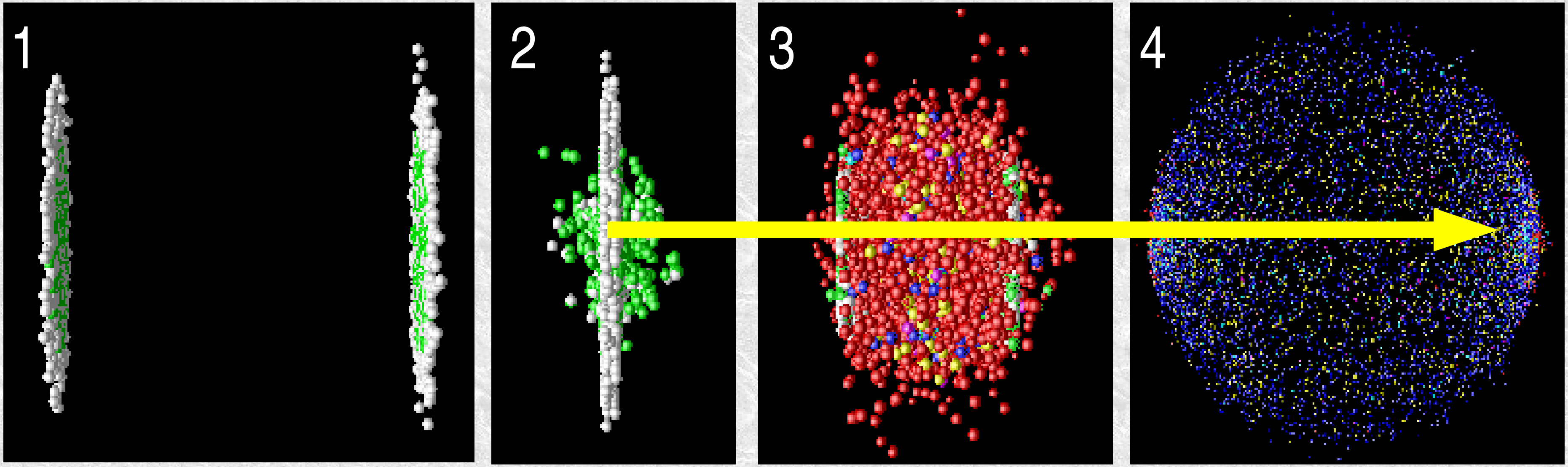
- Surprise: RHIC $\rightarrow$ sQGP shows η/s close to $1/4\pi$
  lattice QCD $\rightarrow$ sQGP has $S/S_0 \approx 0.8$

Conclusion 3

The sQGP is a nearly perfect liquid!

Probing the perfect fluid

Hard probes

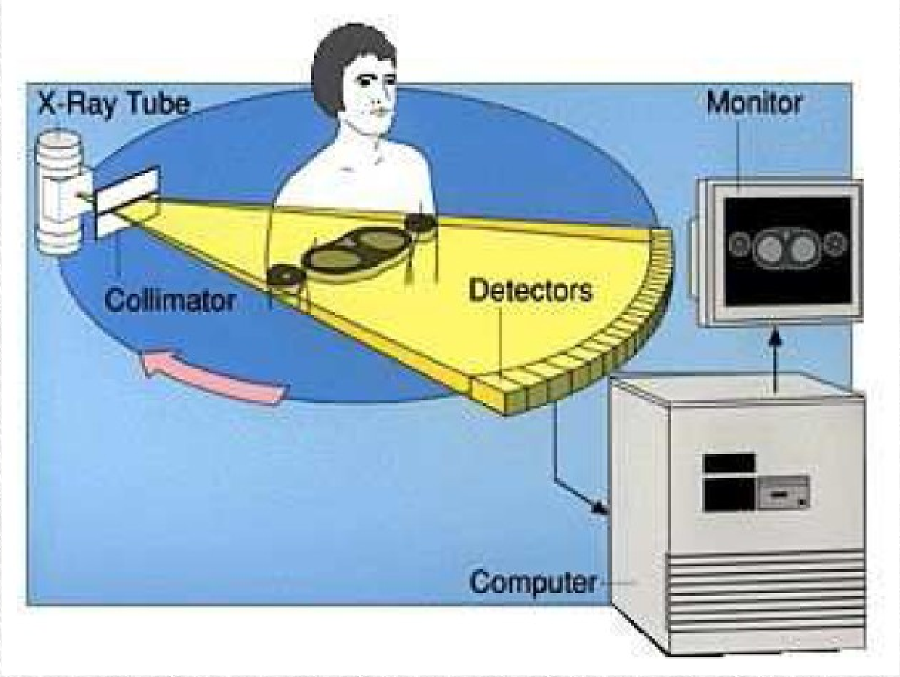


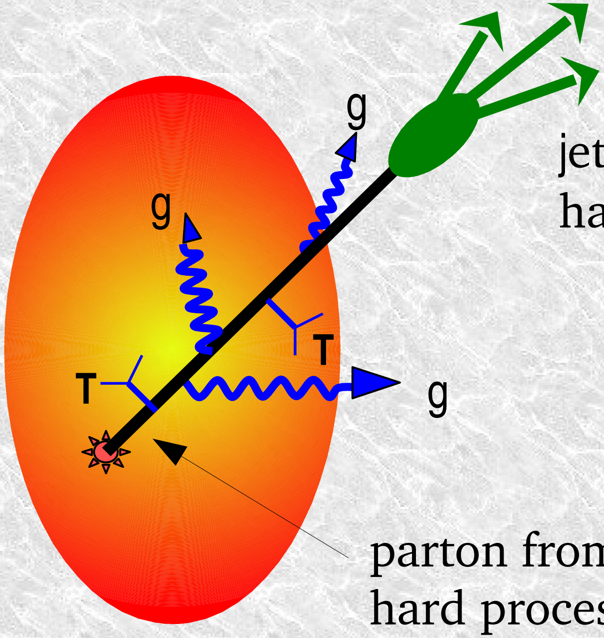
- Hard probes created at t~0.1-0.2 fm – travel through the medium
- This allows to study:
  - Response of the probe to the medium (e.g. jet tomography)
  - Response of the medium to the hard probes

Jet tomography

Review: Gyulassy, Vitev, Wang, Zhang, nucl-th/0302077
Baier,Dokshitzer, Mueller, Peigne, Schiff, Zakharov, Wiedemann, ...

- The QCD analog of Computed Axial Tomography (CAT)





Computed Axial Tomography

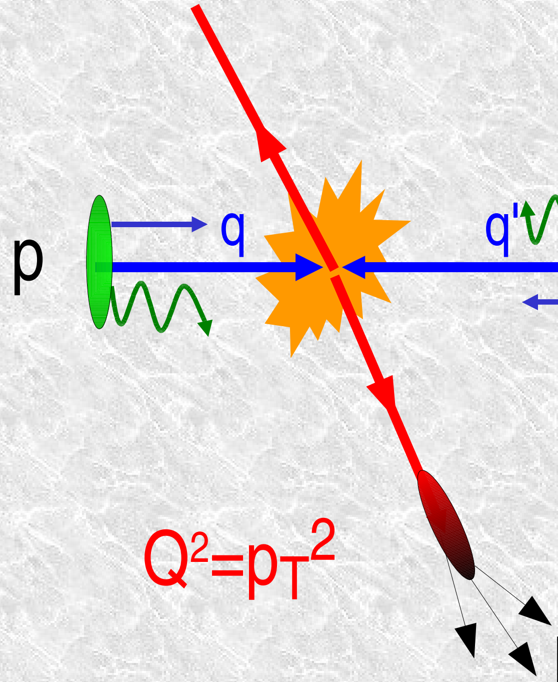
- Calibrated x-ray source
- x-ray absorption
- properties of the medium

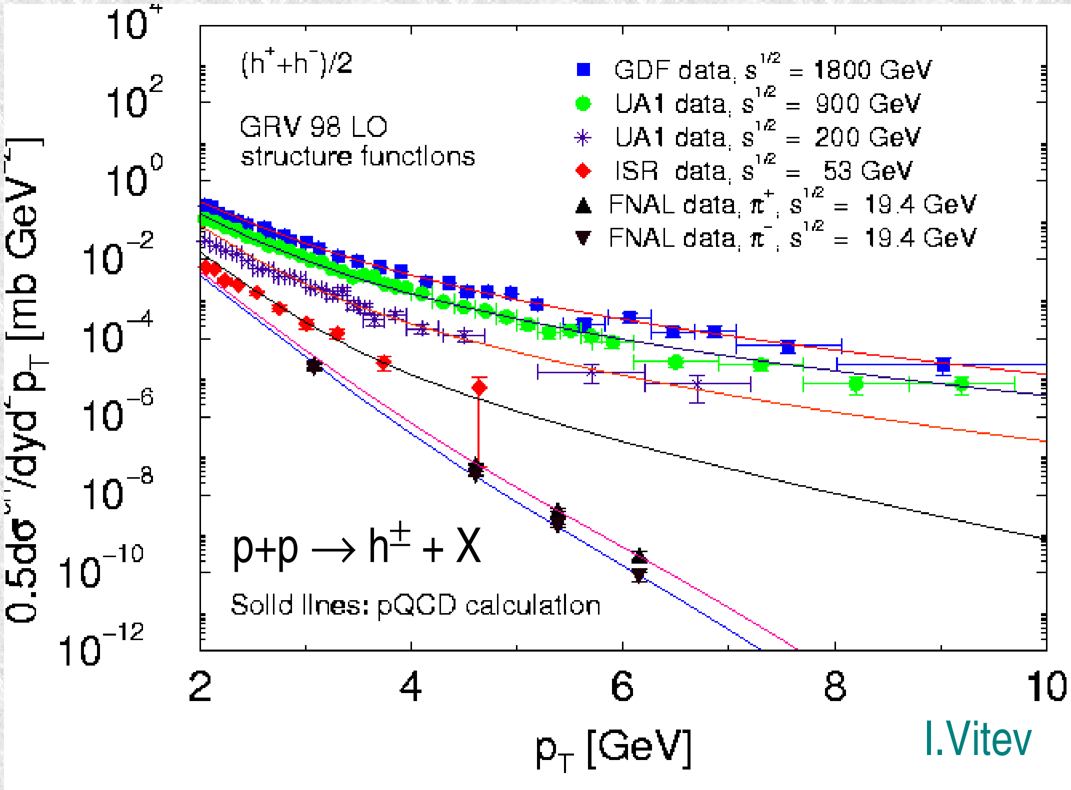
Single hadron tomography

- Calibrated hard partons source
- energy loss (gluon bremsstrahlung) computed in pQCD
- properties of the medium

Calibrated source – pQCD

- Perturbative QCD (pQCD) successful in computing hard probes
  - hard probe = observable with large momentum scale Q > 1-2 GeV
- **Example:** hadron production at large p_T in p+p collisions





Note: power-law pT spectrum
= hallmark of pQCD

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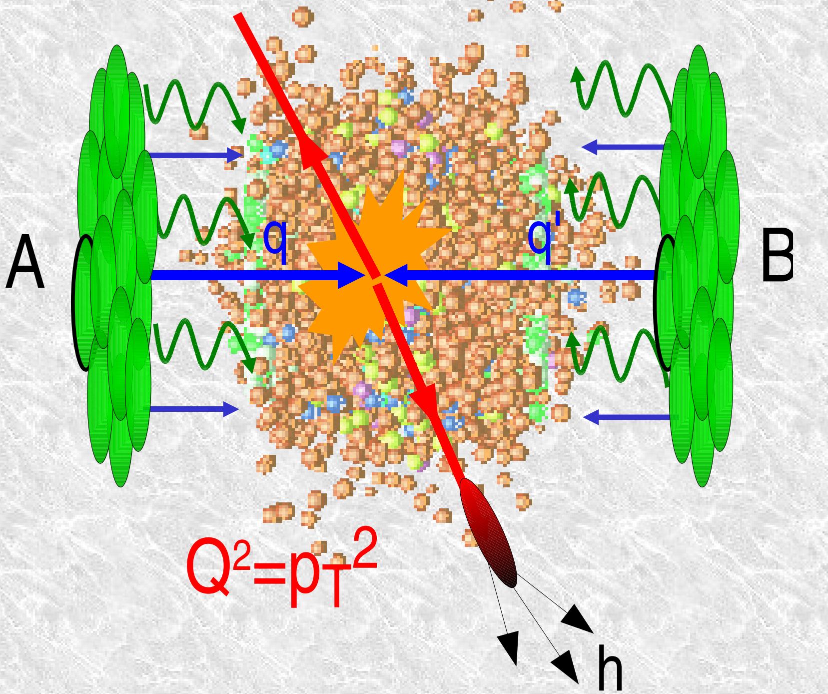
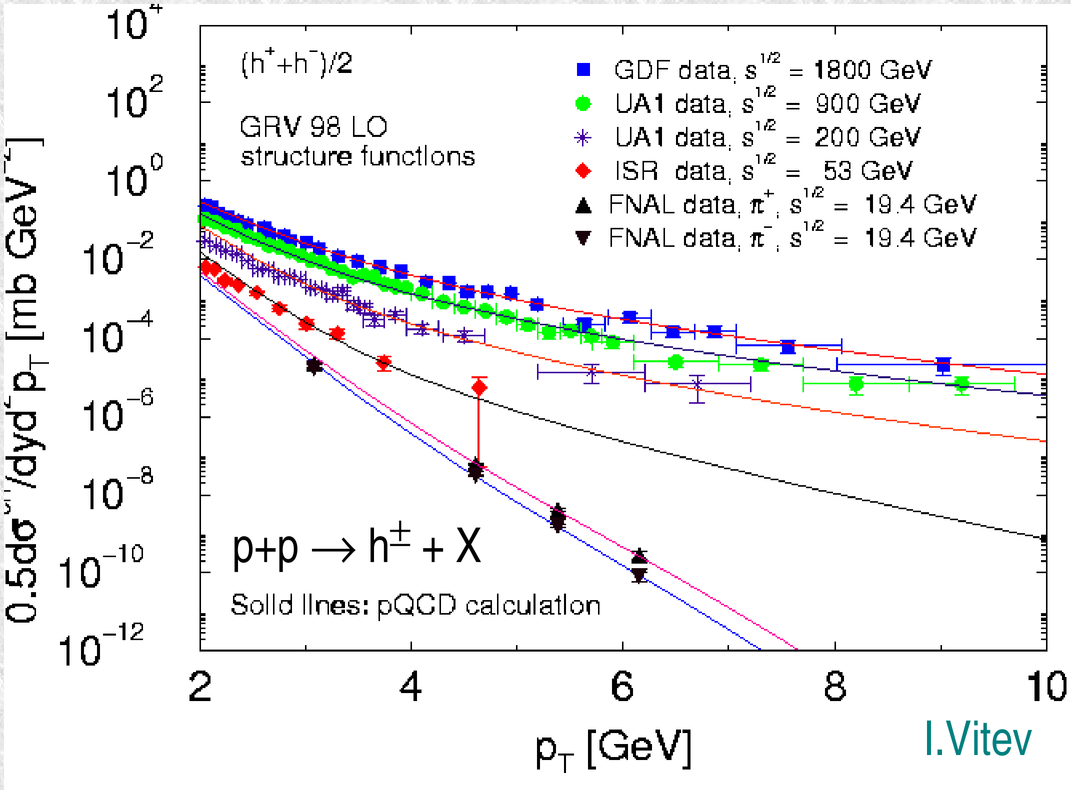
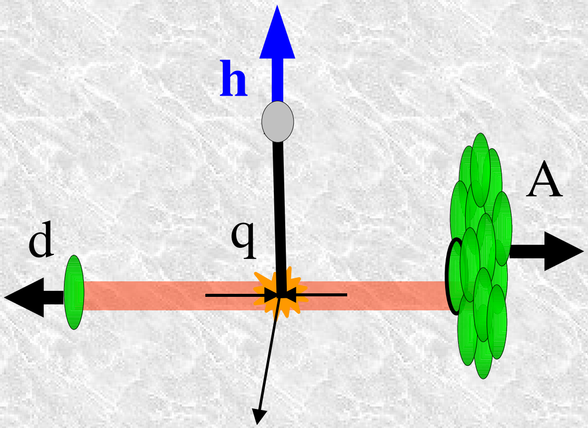


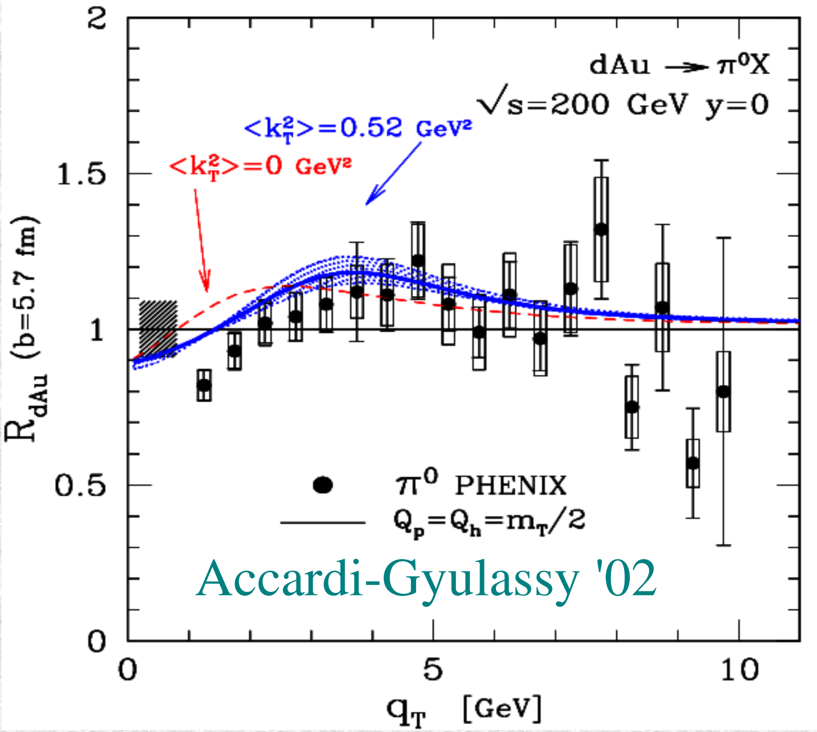


Note: power-law pT spectrum
= hallmark of pQCD

- **Nuclear effects** – QGP or intial state
  – by comparison with suitably scaled p+p baseline

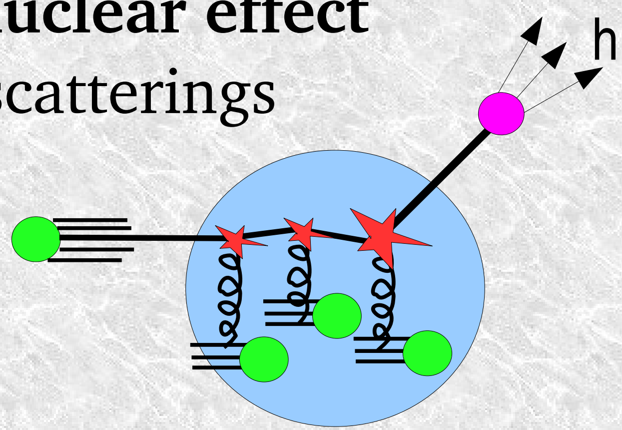
d+Au: Cronin effect



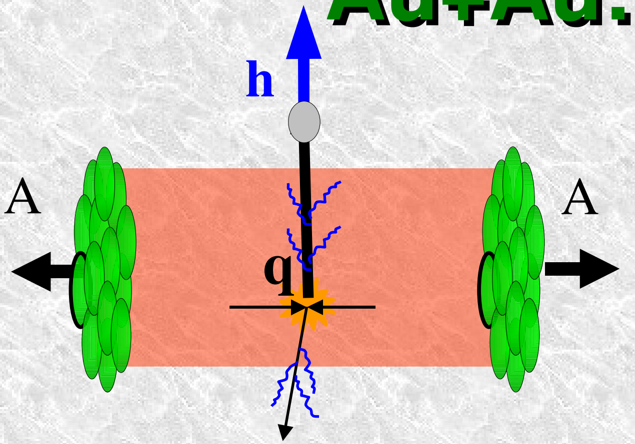


$$R_{dAu} = \frac{(d\sigma^h/d^2p_T)_{d+Au}}{N_{coll}(b)\,(d\sigma^h/d^2p_T)_{p+p}}$$

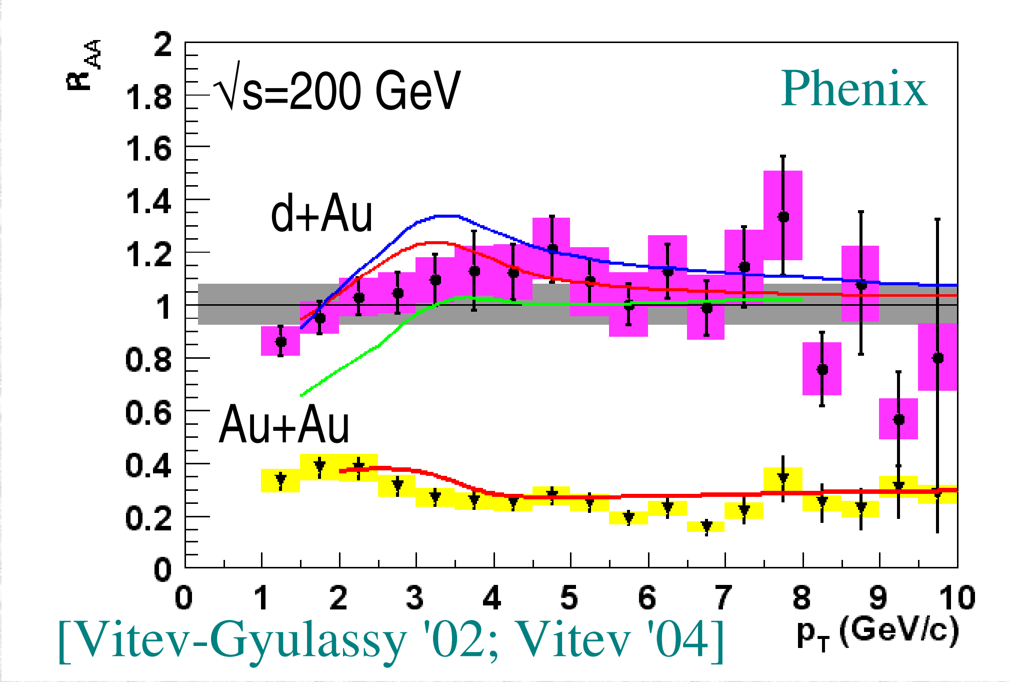
- No medium produced ⇒ **Initial state nuclear effect**
- Usually interpreted as multiple parton scatterings
  [review: Accardi, hep-ph/0212148]



Au+Au: jet quenching



$$R_{AA} = \frac{(dN^h/d^2p_T)_{A+A}}{N_{coll}(b)\,(d\sigma^h/d^2p_T)_{p+p}}$$

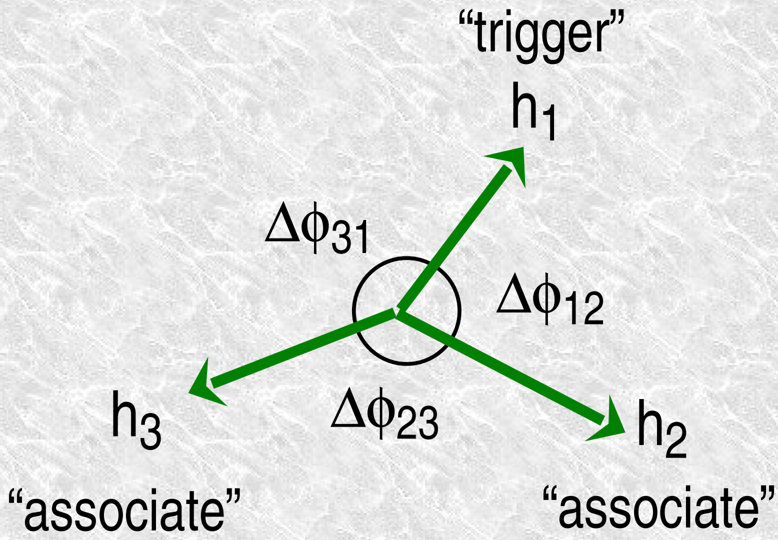


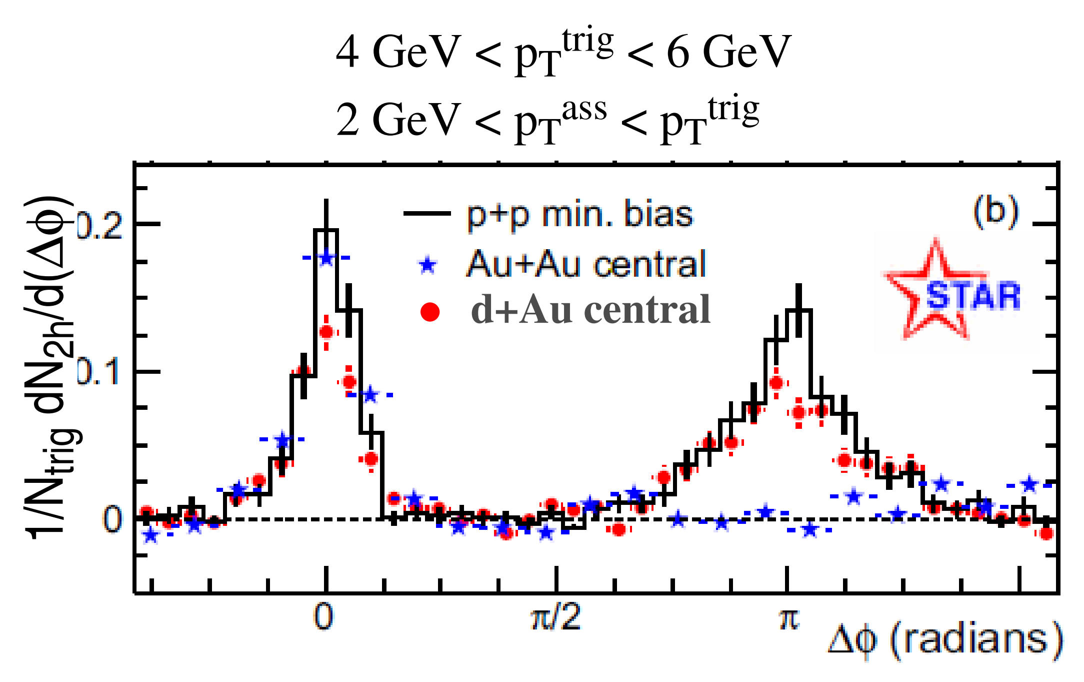
medium effect
"Jet Quenching"

- Energy loss computation requires gluon density
  $dN^g/dy = 800 - 1000 \quad \Rightarrow \quad \varepsilon \sim 14 - 20\ \mathrm{GeV/fm^3}$

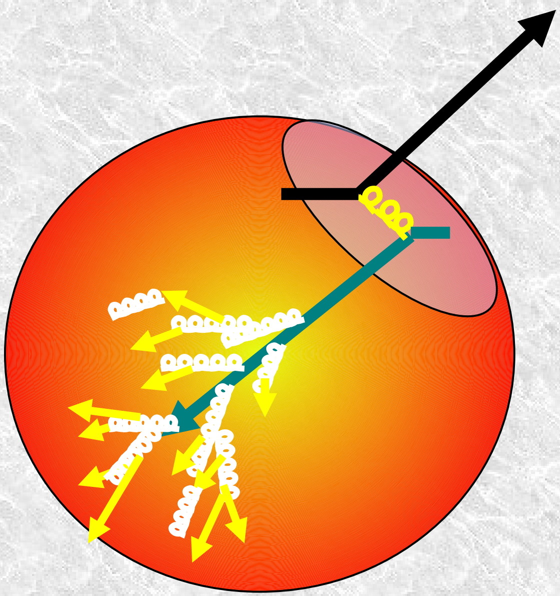
Dihadron tomography

- hadron pair distribution w.r.t. relative angle in p_T plane



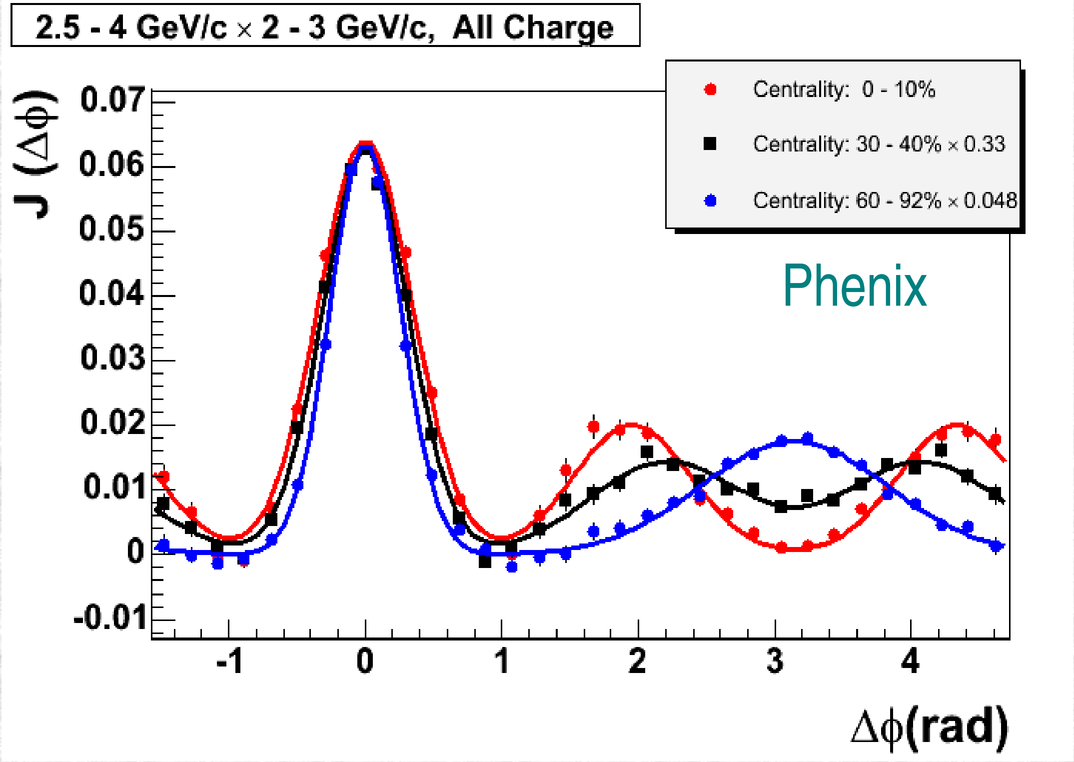


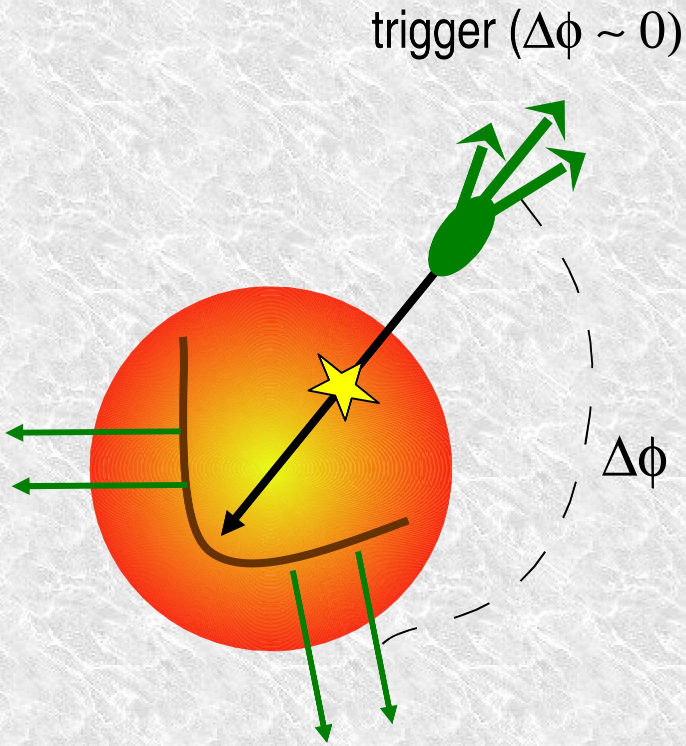
- Disappearance of the back-to-back jet
  - fireball has a very opaque core ≡ large color density
  - if parton traverses the core, it loses all its energy
  - "Surface emission"



Where does all this energy go?

- The lost energy excites collective modes of the plasma
  - Mach cones
  - Cerenkov radiation

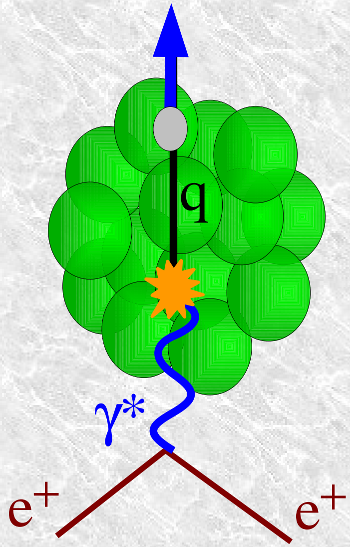


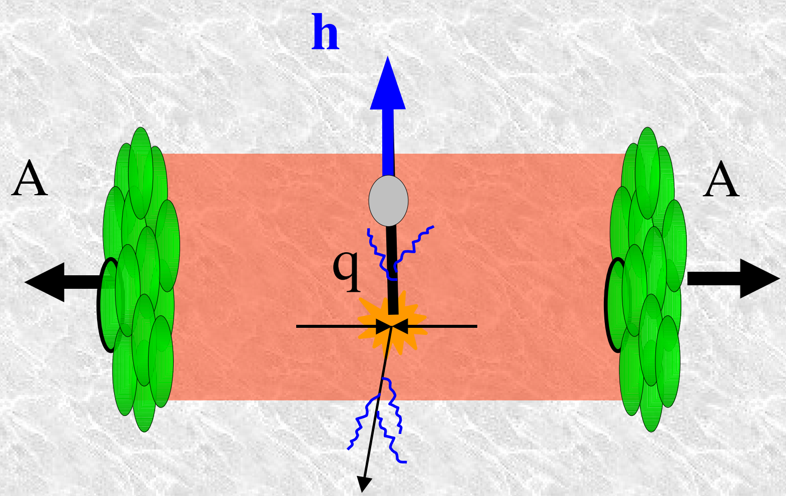


- We see the response of the medium to the hard probe

The HERMES connection

- Untested assumption in jet tomography:
  - "the partons hadronize well outside the medium" – is it true?
  - test it in nuclear Deep Inelastic Scattering (nDIS) [HERMES, JLAB]





- nDIS is a clean environment for
  (1) space-time evolution of fragmentation
  - nucleons as micro-detectors

  (2) Cold nuclear matter effects
  - quark energy loss

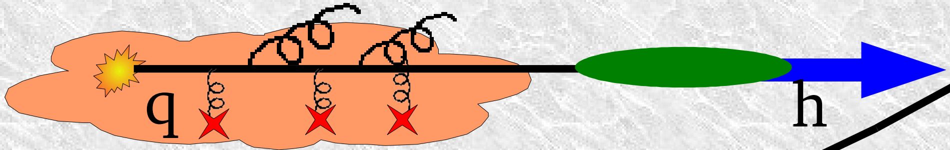
Jet-quenching in A+A

⇓

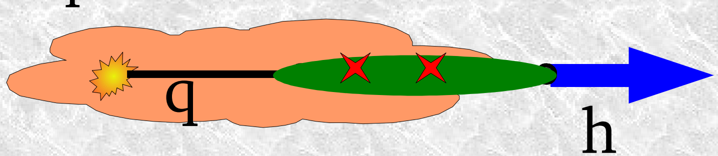
properties of hot nuclear matter

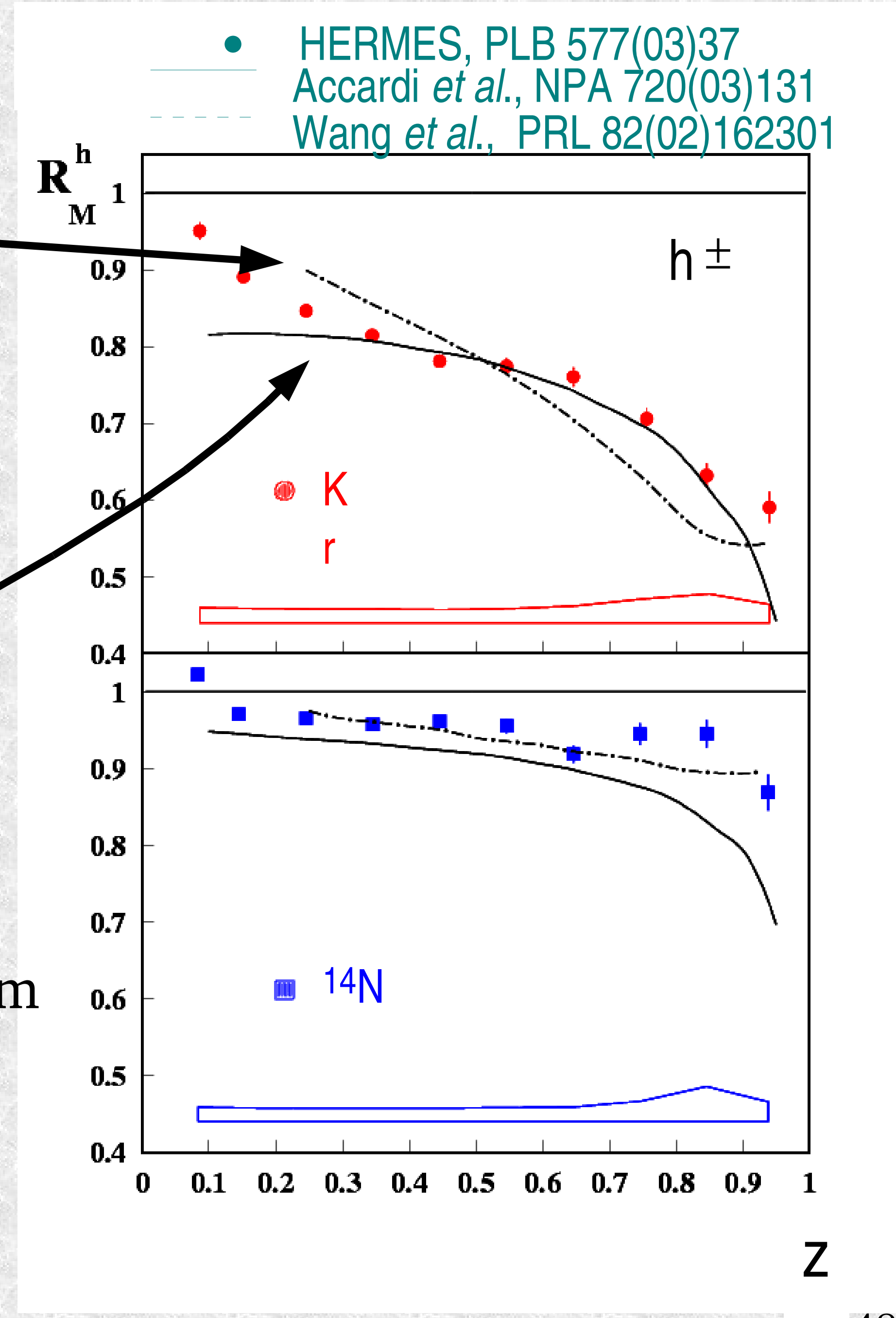
The HERMES connection

- Hadron suppression is observed on A compared to ^{2}H
- **Energy loss (gluon brehmsstrahlung)**
  [Arleo; Wang *et al.*]
  - hadronization outside the medium
  - gluon radiation off struck quark
  - "parton attenuation"



- **Hadron absorption**
  [Accardi *et al.*;
  Falter *et al.*; Kopeliovich, *et al.*]
  - color neutralization inside the medium
  - prehadron-nucleon scatterings
  - prehadron attenuation

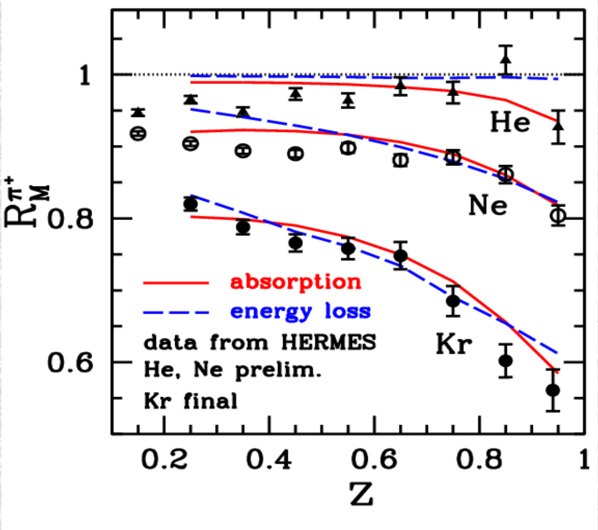




Energy loss vs. absorption

- How to distinguish energy loss from nuclear absorption?
  - Hence, in-medium vs. out-of-medium hadron formation

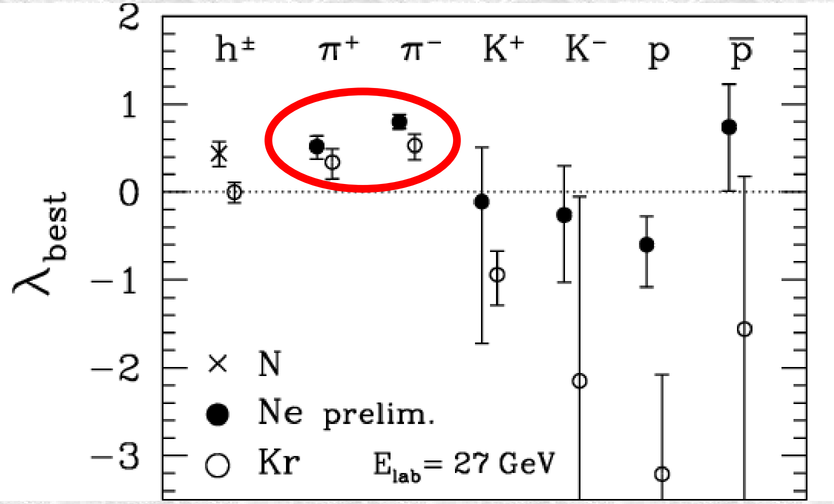
- Conventional thinking: A-dependence – wrong!
  - both give $R_M \propto A^{2/3}$
    [Accardi et al., NPA 761 (05);
    Accardi, Acta Phys. Hung. in press]



- Proposal: study scaling of R_M data
  [Accardi, nucl-th/0604041]

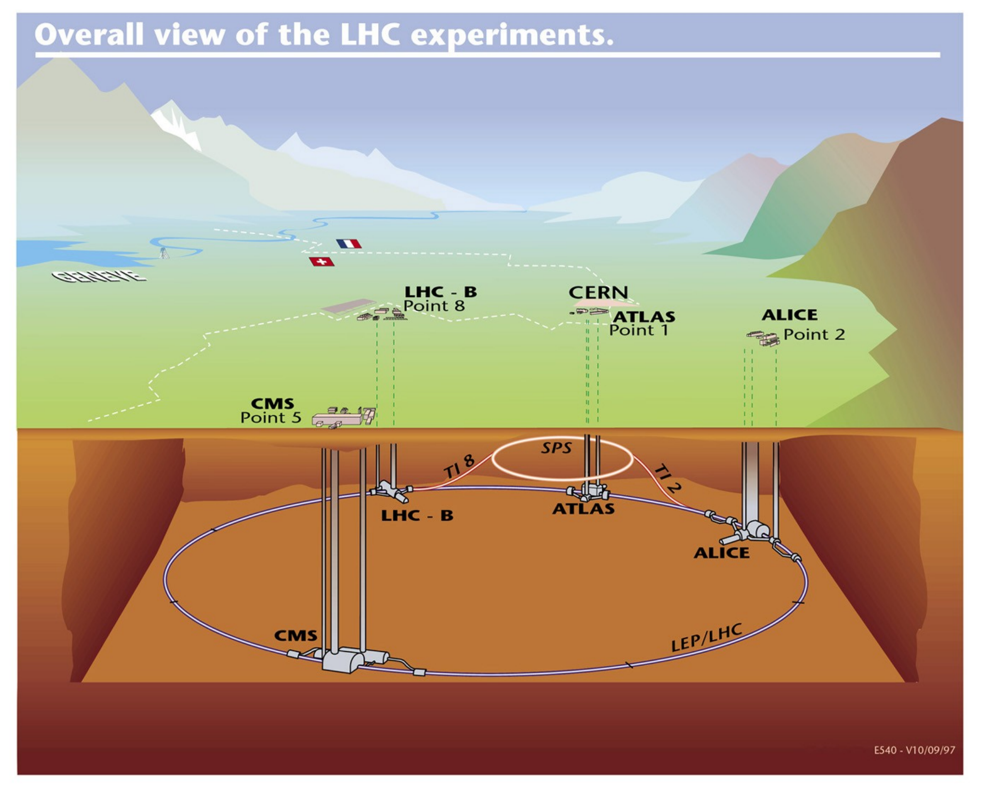
$R_M = R_M[\tau(z,\nu)]$ with $\tau = C\, z^{\lambda}\, (1-z)\, \nu$

- <u>absorption models</u>: $\lambda > 0$
  [finite formation time]
- <u>energy loss models</u>: $\lambda \lesssim 0$
  [from energy conservation]



The future

LHC – stepping up in energy

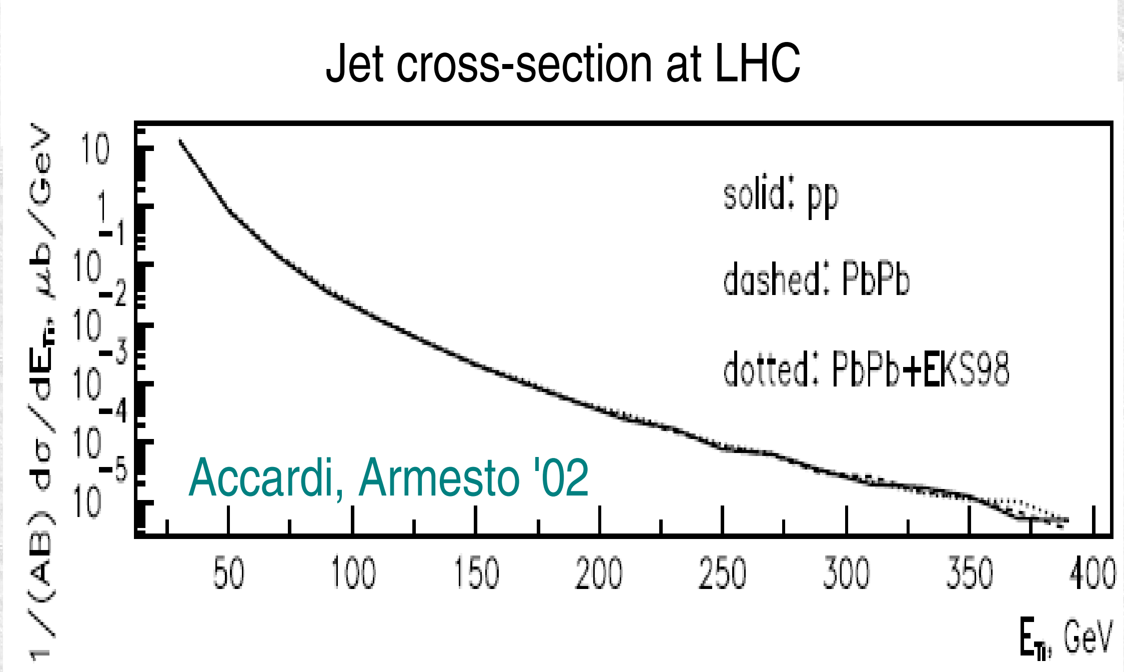


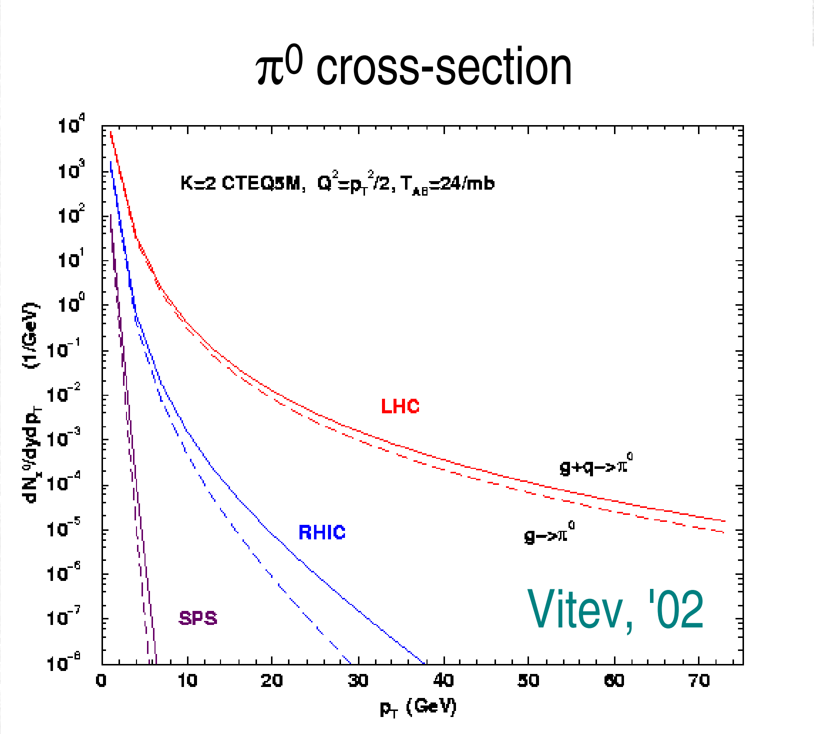
b=0 y=0	SPS	RHIC	**LHC**
$\sqrt{s}$ [GeV]	17	200	**5500**
dN_{ch}/dy	430	700	**3000**
$dN_{net\text{-}B}/dy$	30	5	**0**
T [GeV]	250	400	**800**
ε_0 [GeV/fm^3]	2.5	15	**240**
τ_0 [fm/c]	0.8	0.6	**0.2**
τ_{QGP} [fm/c]	< 2	7	**20**
dN_{glue}/dy	~300	~1000	**~3000**

- a factor 30 in $\sqrt{s}$ compared to RHIC
- **QGP: hotter, denser, longer… & weaker?**

LHC – the hard probe machine

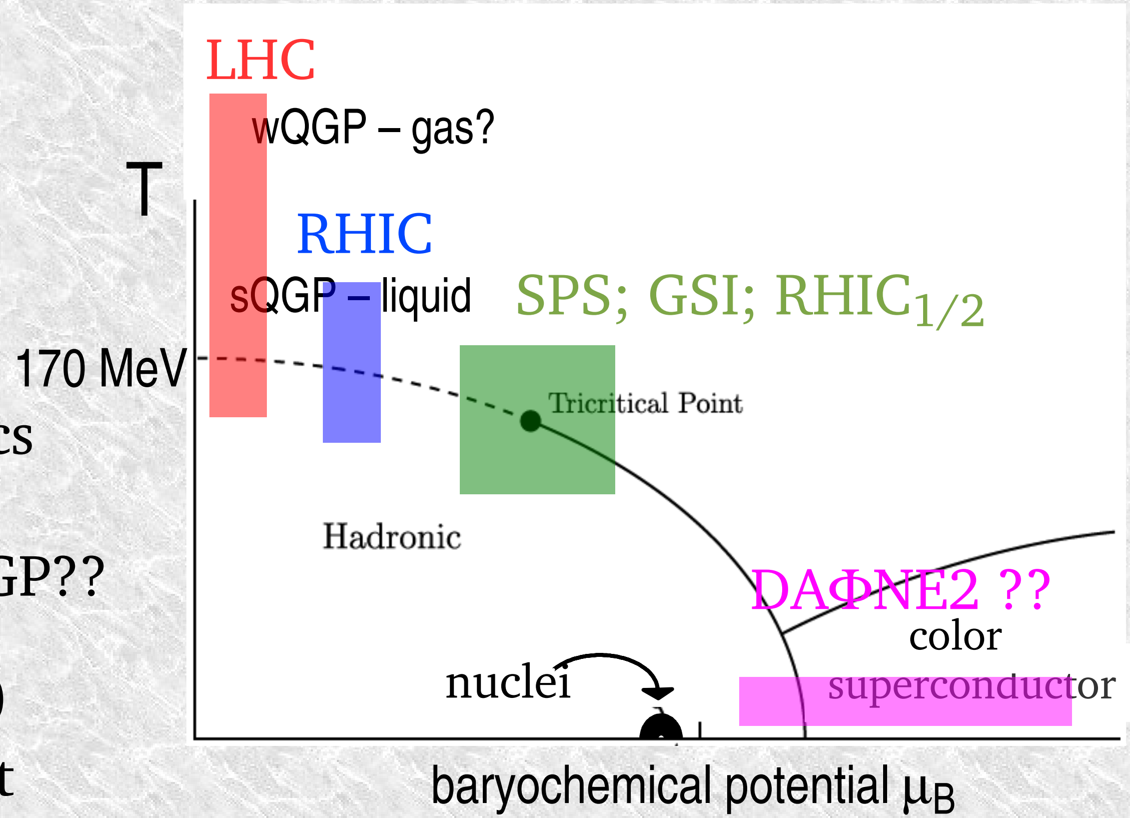
- Hard probes copiously produced
  - orders of magnitude increase in cross-section
- Jet physics in full glory
  - 1 month at nominal luminosity
  - Full reconstruction of jets with 50 GeV < E_T < 275 GeV





Where do we go from here?

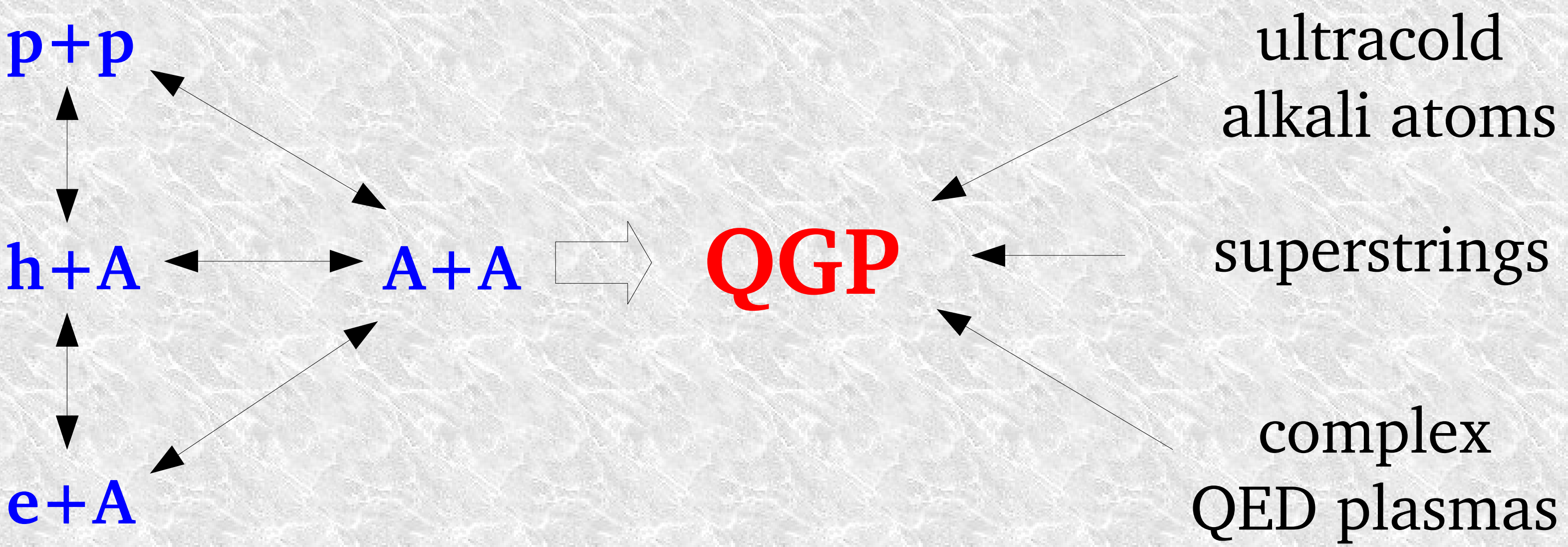
- RHIC (2000 – ....)
  - rapid cross-over
  - perfectly fluid QGP
  - strongly interacting
- LHC (> 2008)
  - truly hard probes – jet physics
  - parton saturation regime
  - accessing weakly coupled QGP??
- GSI (2014) – $RHIC_{1/2}$ (> 2010)
  - search for the tricritical point
  - building upon SPS (1980 – ....)
- DAΦNE2 ??
  - deeply bound kaonic nuclei (ppnK)
  - shrink nucleus size ⇒ 4-10 fold increase in μ_B at T=0
  - color superconductivity in the lab ??



Summary

Summary

- The quest for the QGP is over:
  - a perfectly fluid QGP has been seen at RHIC
- We are beginning to study it and marvel at its unexpected properties
- New theoretical and experimental challenges are in front of us!



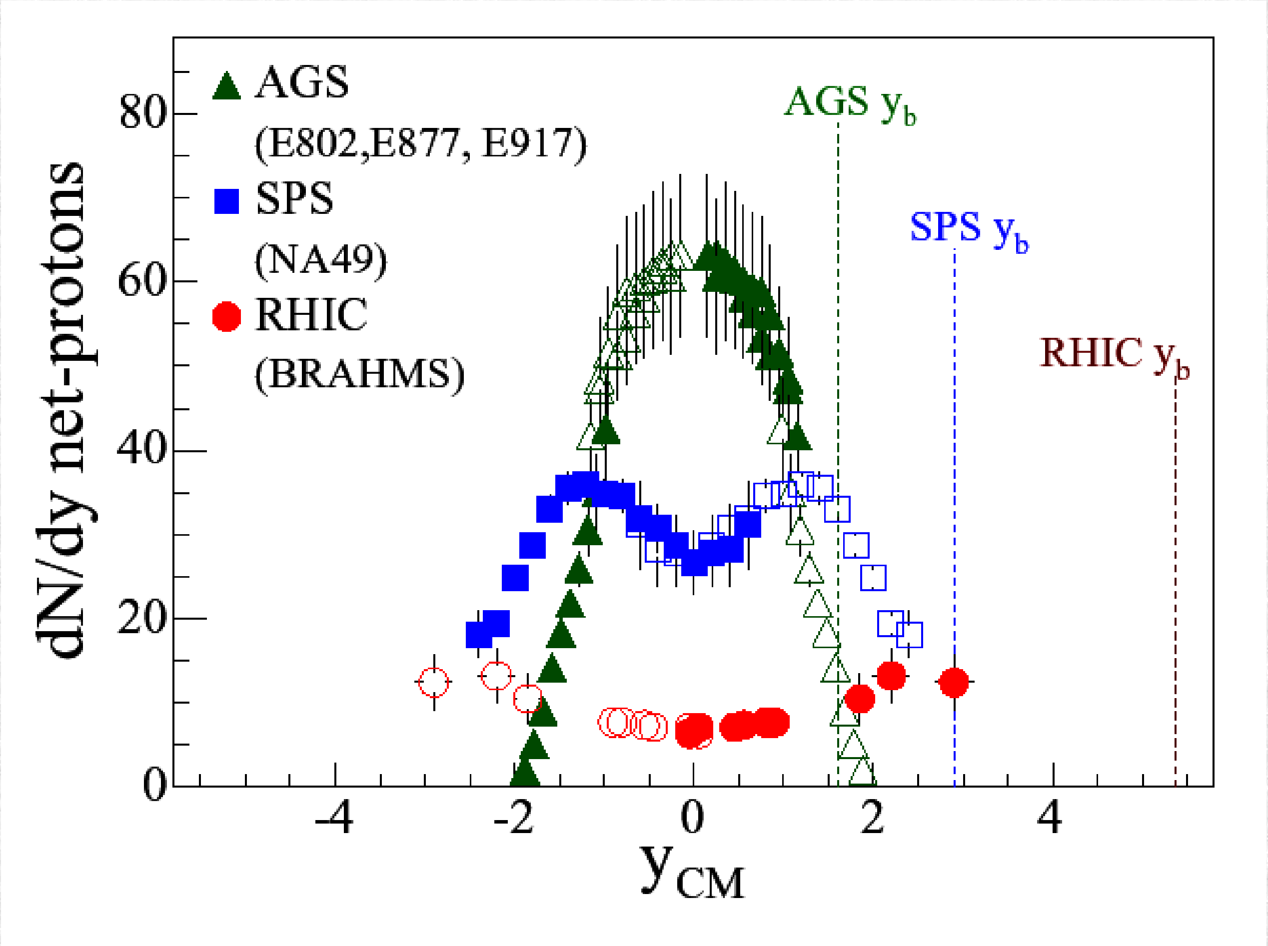
References

- RHIC collaborations “white papers”: Nucl. Phys. A 757(2005)
  - BRAHMS page 1 – PHOBOS page 28 – STAR page 102 – PHENIX, page 184
- Reviews:
  - Gyulassy, McLerran, “New forms of matter discovered at RHIC”, NPA 750(2005)30
  - Boyanowski et al., “Phase transitions in the early and the present universe”, hep-ph/0602002
  - Starinets, “Transport coefficients of strongly coupled gauge theories: insights from string theory”, nucl-th/0511073
- Entry points:
  - Proceedings of “Quark Matter 2005”, Budapest (HUN)
  - Thoma, “Complex plasmas as a model for the quark-gluon-plasma liquid”, hep-ph/0509154
  - B.Gelman et al. “Cold Strongly Coupled Atoms Make a Near-perfect Liquid”, nucl-th/0410067

Credits

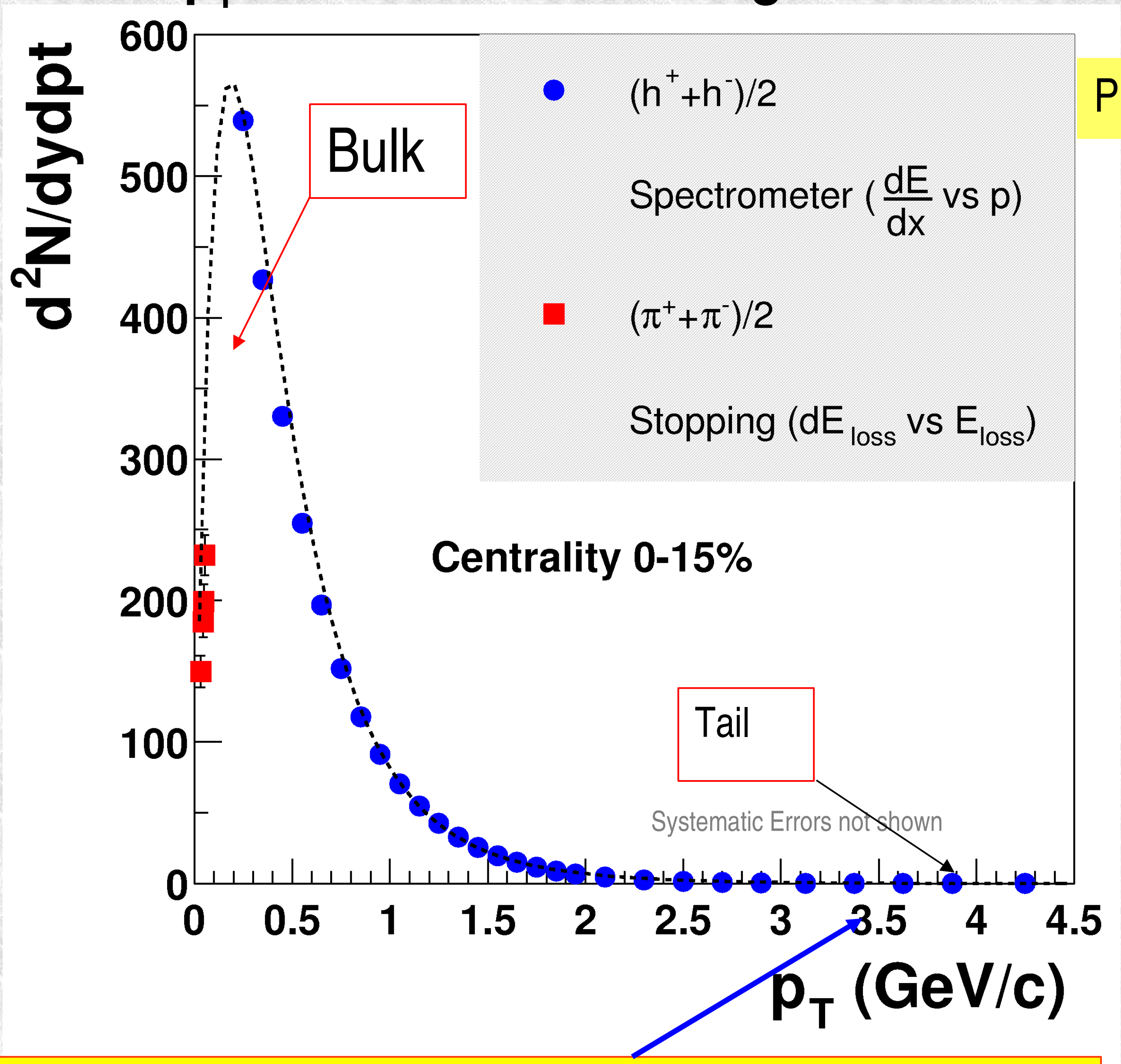
- For help and inspiration, direct or indirect, for this seminar: M.Gyulassy, J.Nagle, M.Rosati, P.Steinberg, I.Vitev

Backup Slides



AGS
(E802,E877, E917)
SPS
(NA49)
RHIC
(BRAHMS)
AGS y_b
SPS y_b
RHIC y_b
dN/dy net-protons
y_{CM}
0
20
40
60
80
-4
-2
0
2
4

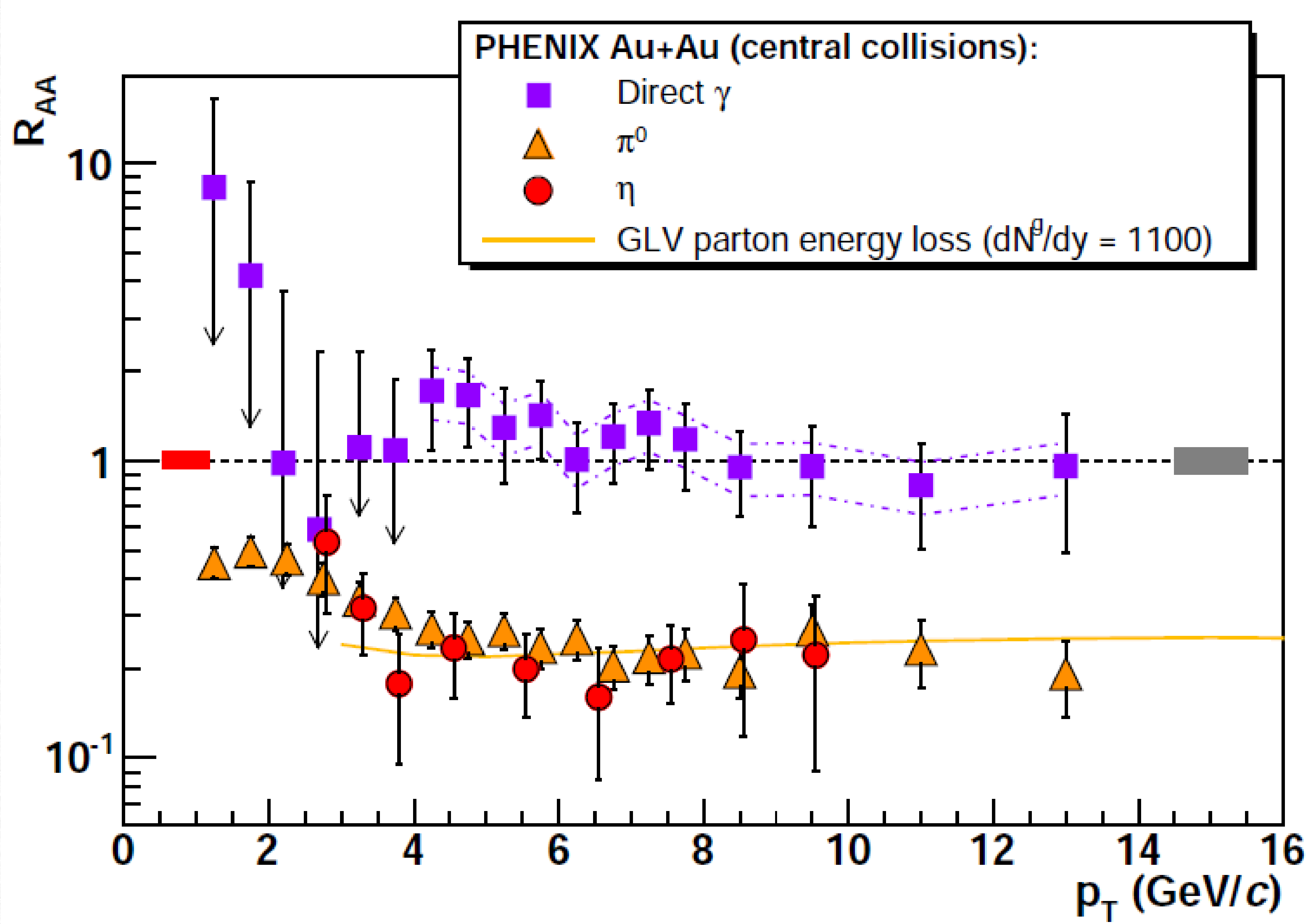
p_T Distribution of Charged Particles



Phobos Preliminary

G.Roland

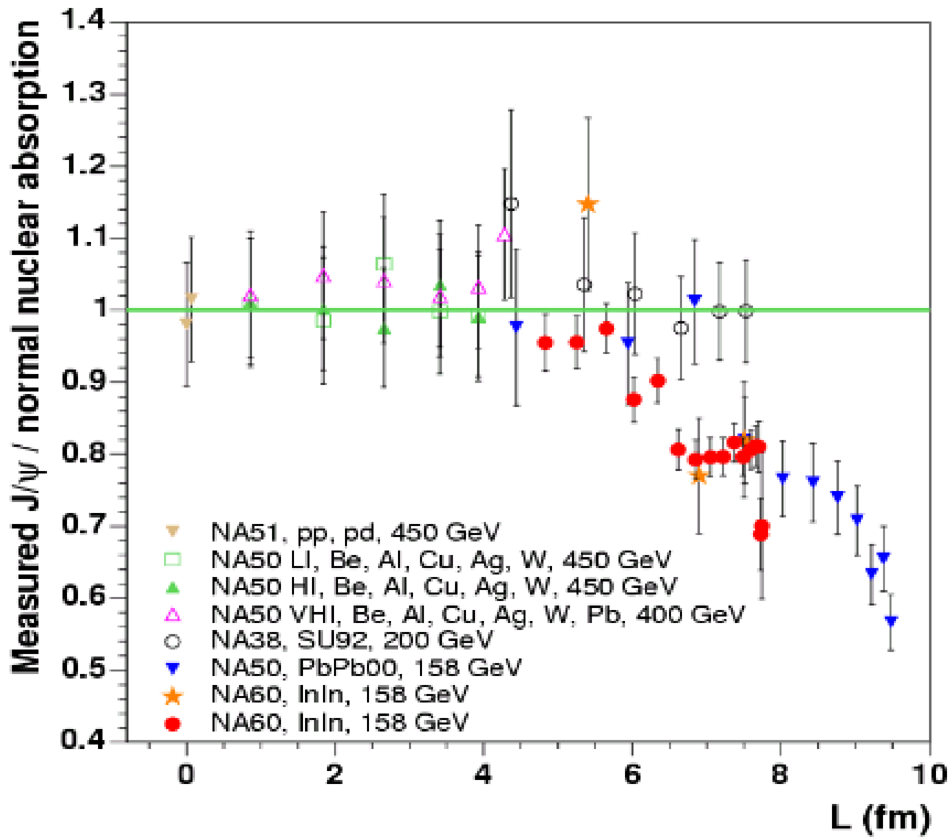
How can we use this tiny pQCD tail to wag the QGP Bulk?

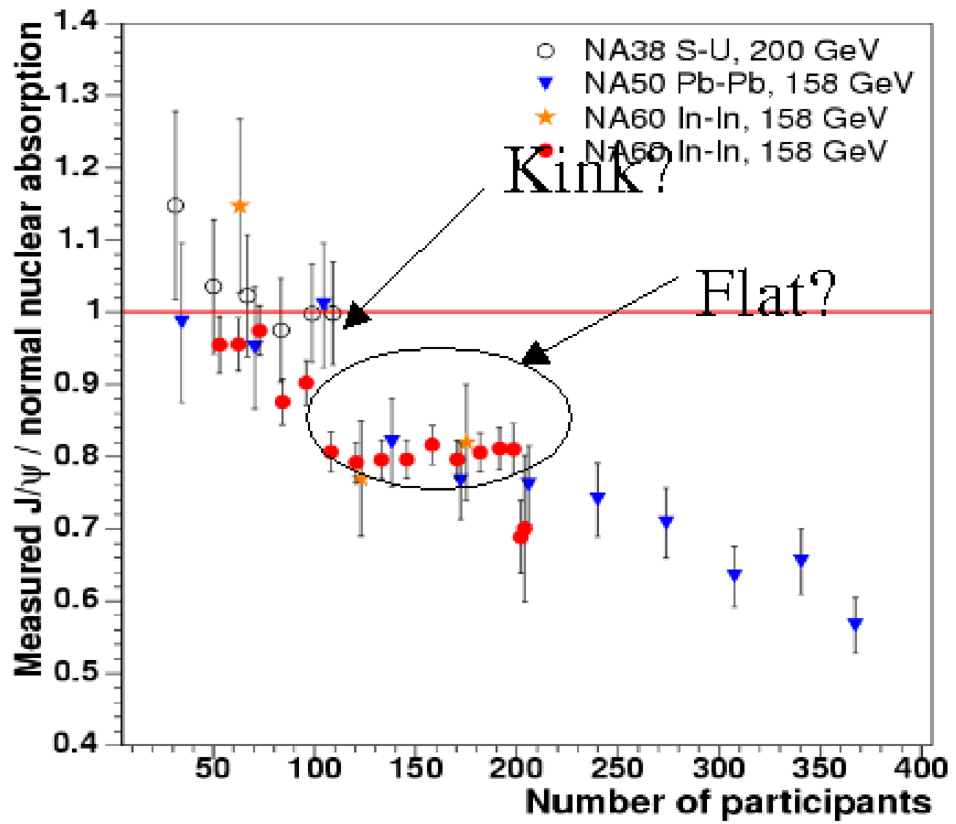


PHENIX Au+Au (central collisions):
Direct γ
π⁰
η
GLV parton energy loss (dNᵍ/dy = 1100)
R_AA
10
1
10⁻¹
0
2
4
6
8
10
12
14
16
p_T (GeV/c)

J/y suppression

Ratio of Measured/Expected

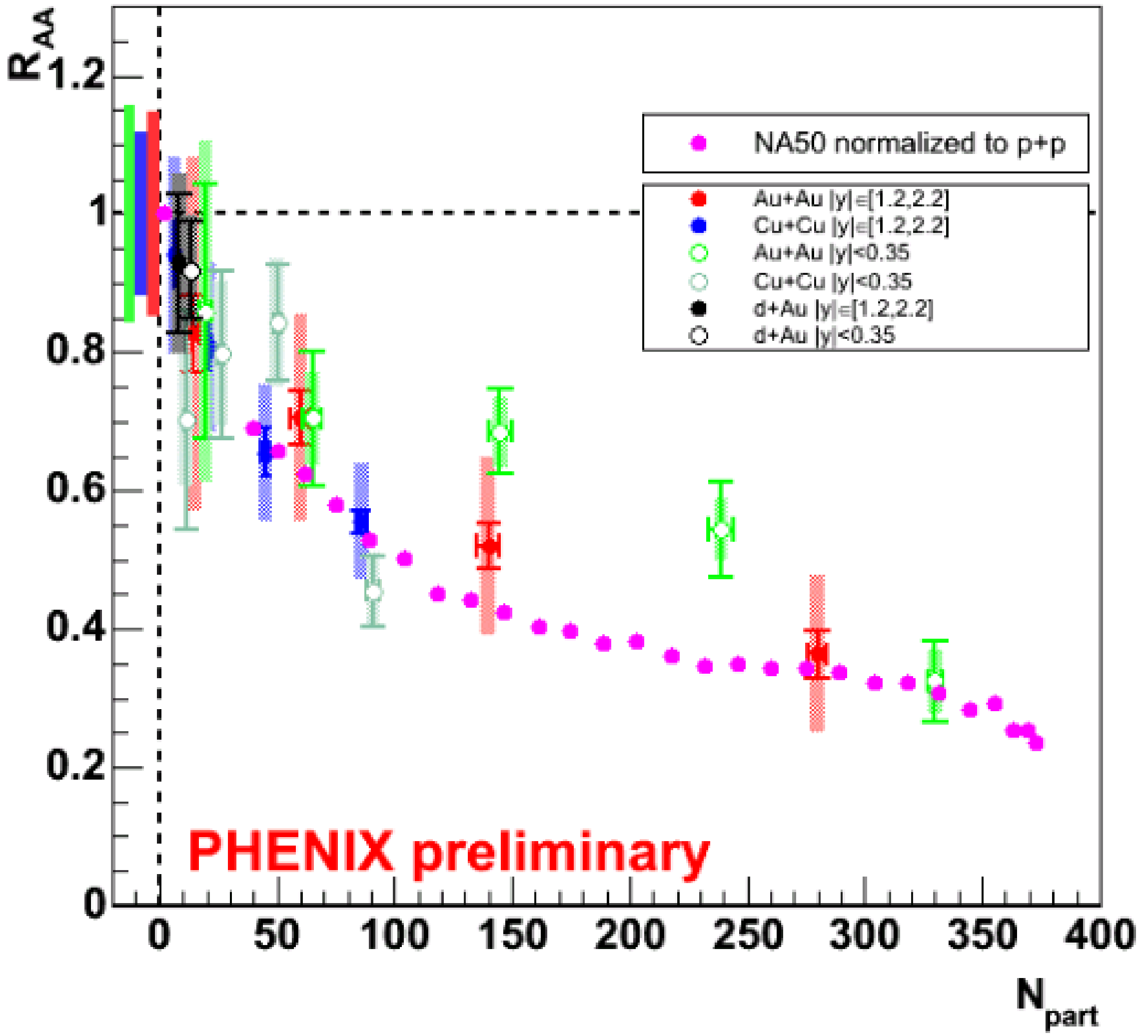




Suppression seems to scale with Npart and not L!

Comparison to SPS

J/ψ nuclear modification factor R_{AA}



A similar suppression pattern as seen by NA50!?!

Scaling with Npart?

Difference in energy and rapidity coverage.

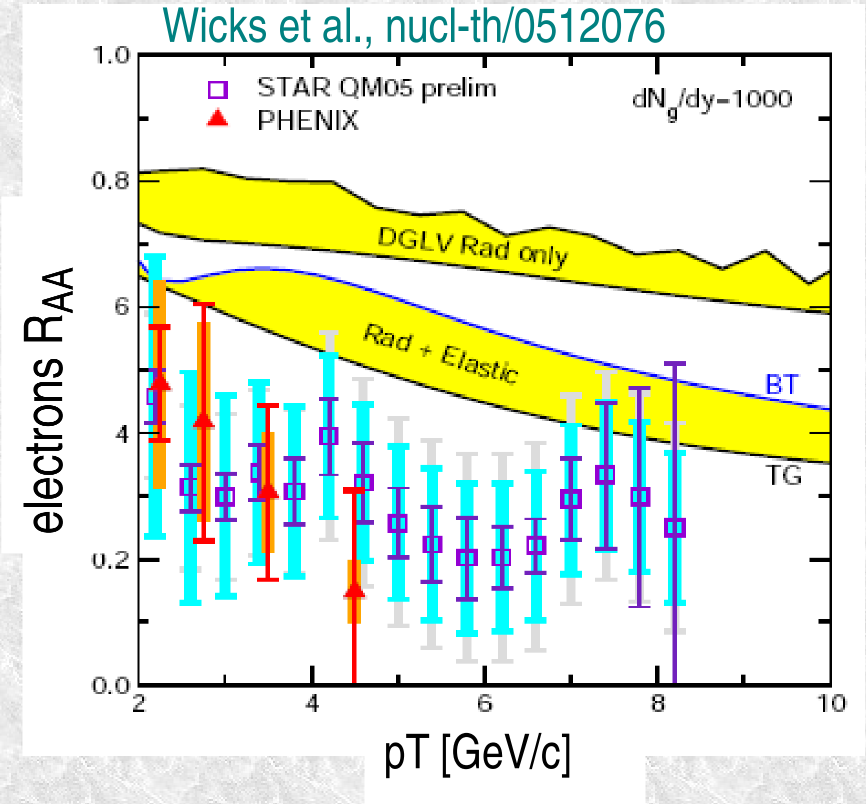
Need MUCH more statistics at RHIC?

More on energy loss

Problems with energy loss theory

- Heavy flavour puzzle at RHIC [QM2005, STAR, PHENIX, Djordjevic, Armesto]
  - single non-photonic e^- as much suppressed as p
  - e^- comes from D and B mesons $\Rightarrow c$ and b-quarks
  - NLO pQCD rates for c and b + heavy quark energy loss theory
    $\Rightarrow$ ***theory gives half of the observed suppression!***

- **"If STAR $R_{AA}(e^-)$ is confirmed, it will be a theoretical challenge to devise novel energy loss mechanisms able to explain these data." M.Djordjevic, QM2005**



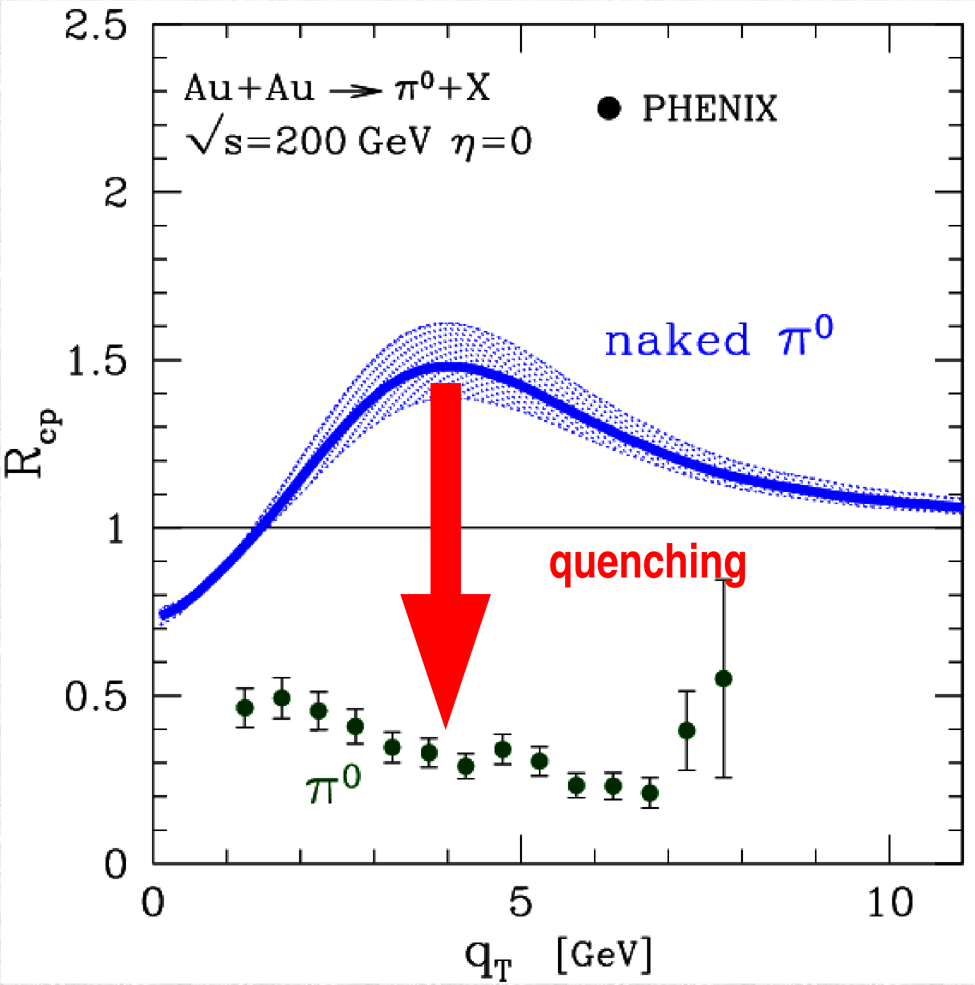
When does quenching start?

Third act: A+A collision

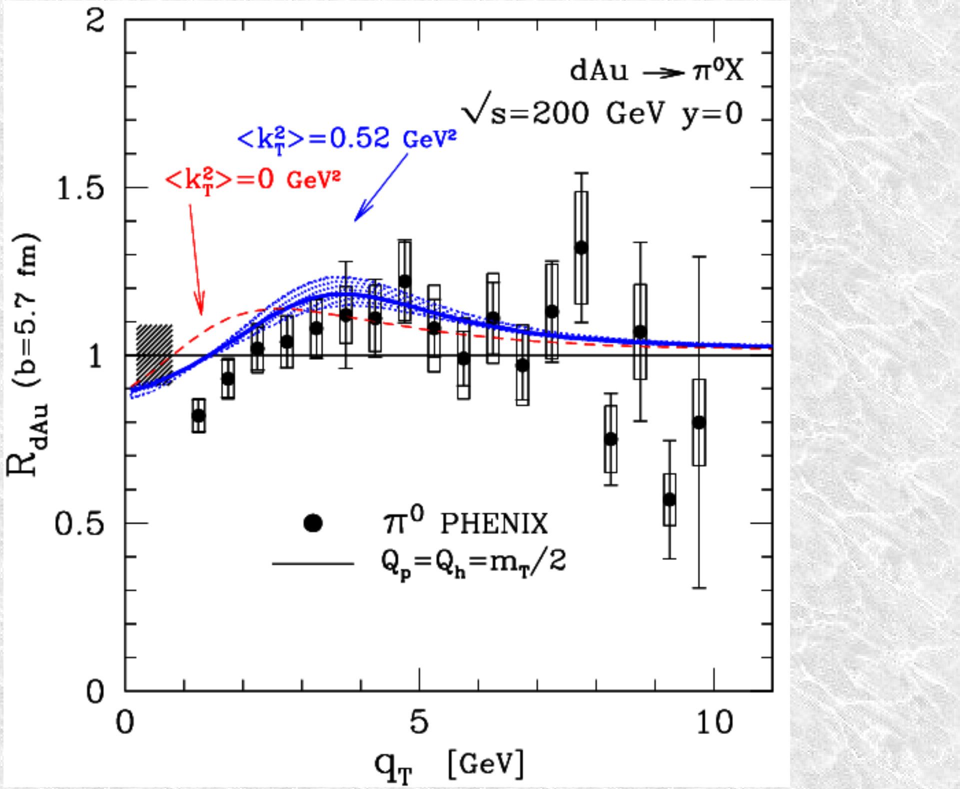
minimal extension of GE model:

$$\frac{d\sigma^h_{AB}}{d^2bd^2p_t} = \sum_i f_{i/A} \otimes \frac{d\sigma^{iB}}{d^2bd^2p_t} \otimes D_{i\to h} + \sum_j f_{j/B} \otimes \frac{d\sigma^{jA}}{d^2bd^2p_t} \otimes D_{j\to h}$$

1) Phenix π^0 - $\sqrt{s}$=200 GeV (p_0 = 1.0 GeV ± 10%)

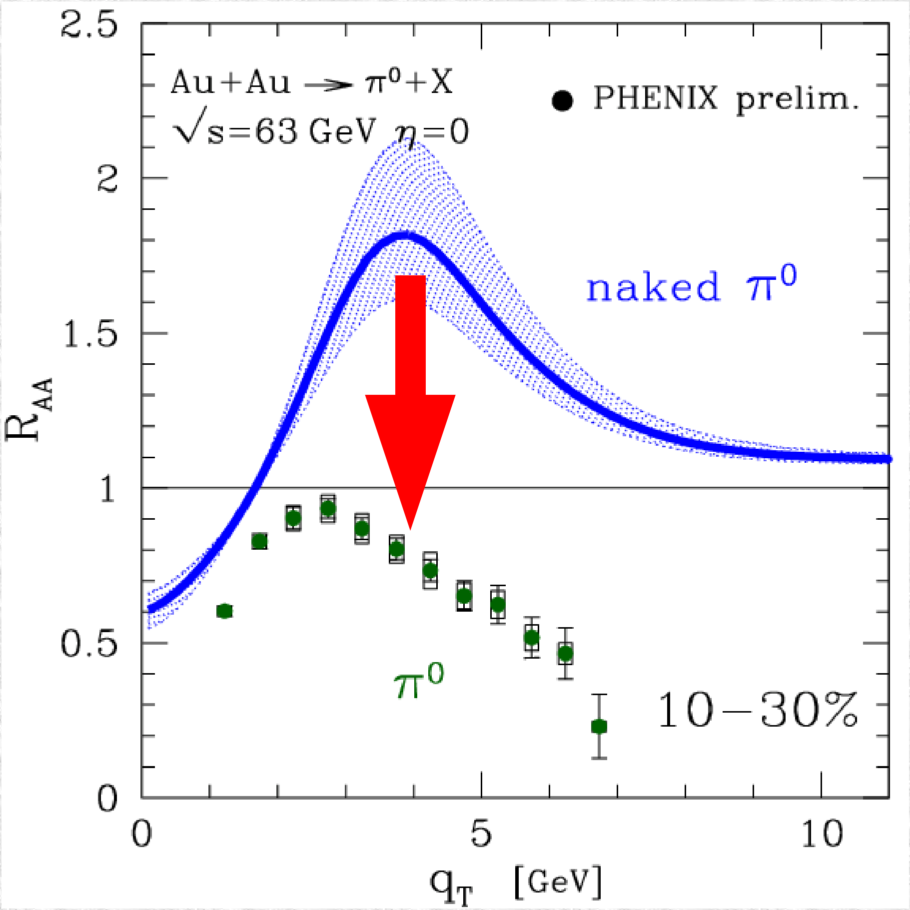


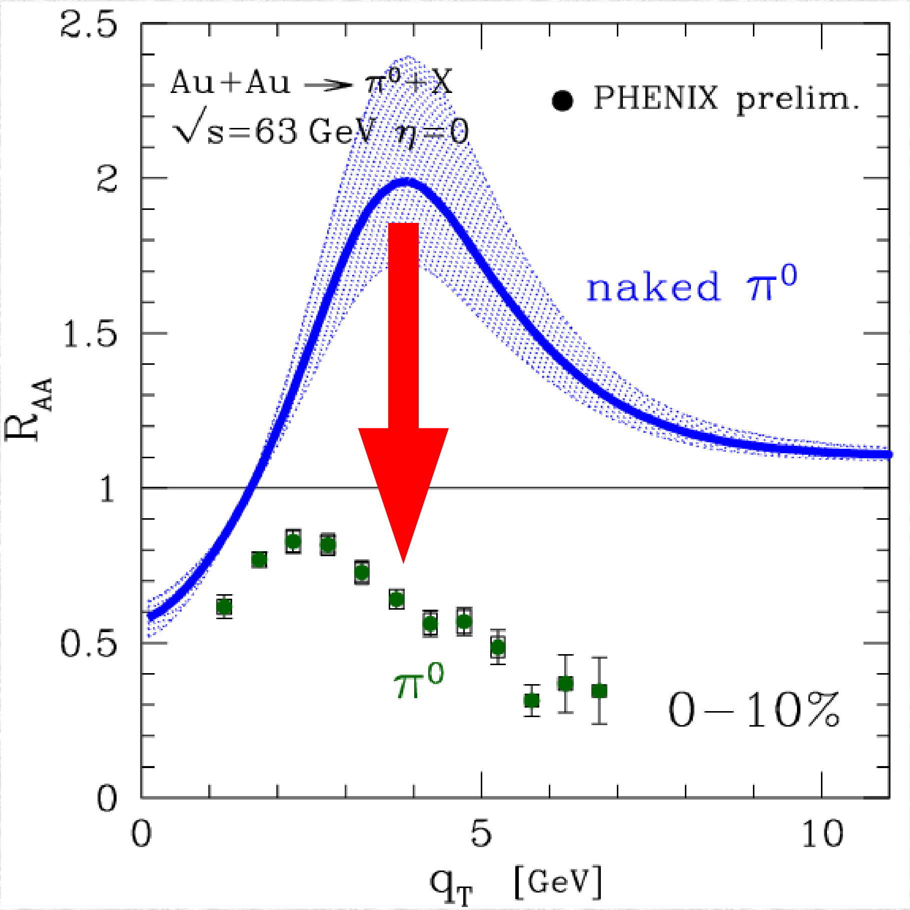
Note: existence of quenching from d+Au data alone - for magnitude we need theory computation



2) Phenix π^0 - $\sqrt{s}$=62.4 GeV (p_0 = 0.82 GeV ± 10%)

At 62 GeV we do not have data on d+Au ⇒ theory is needed





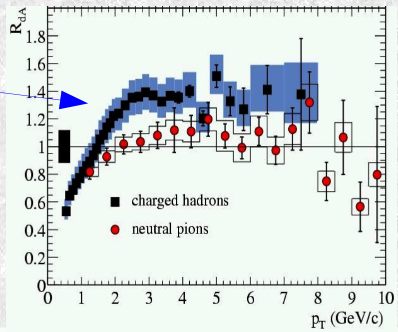
- As expected, less suppression in peripheral collisions.
- Where does quenching begin? theory vs. data is needed

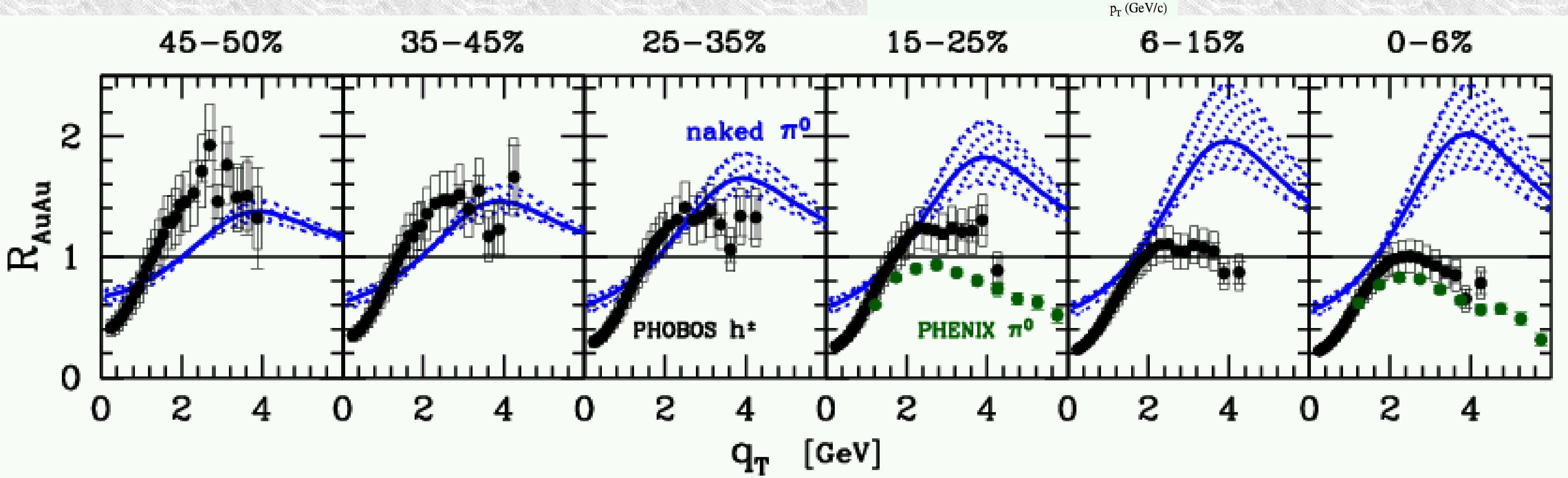
⇒ let's look at PHOBOS **h± data**

3) Phobos h± - √s=62.4 GeV

(p_0 = 0.82 GeV ± 10%)

Attention: baryon-meson anomaly
computations are for π^0's





no quenching

quenching begins

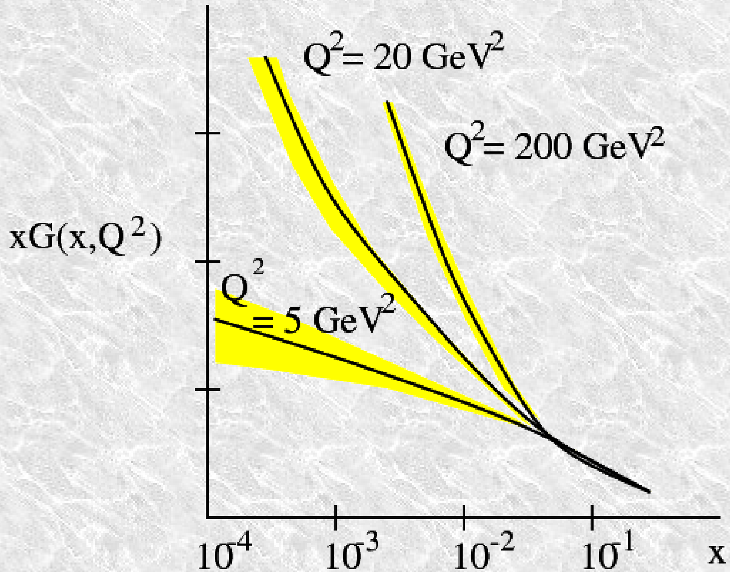
more and more quenched

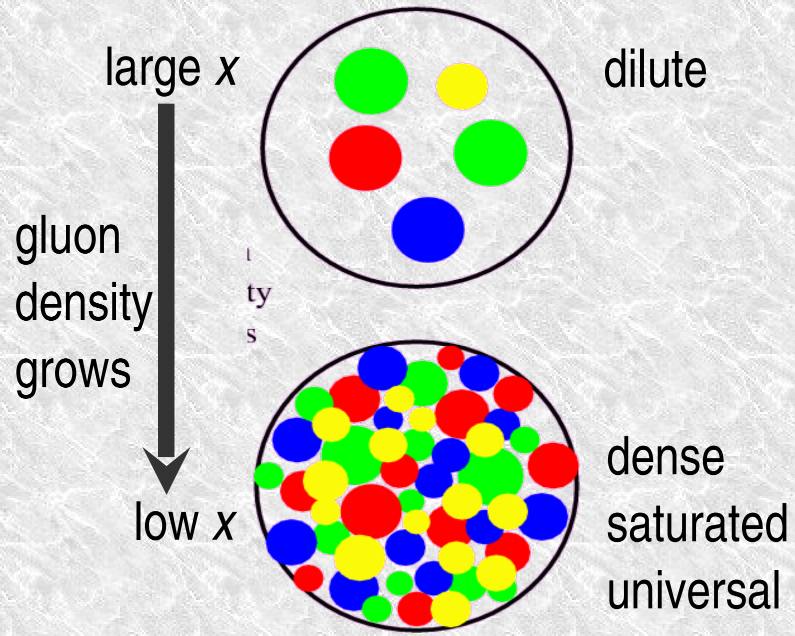
Quenching begins at around 40-45% centrality

The color glass condensate

Color Glass Condensate

- **A new form of QCD matter** – the long wavelength fabric of hadrons
  - At low energy hadron (nucleus) = valence quarks + few gluons
  - At high energy: gluon density grows ⇒ recombination &saturation





$$x = E_{\text{constituent}} / E_{\text{hadron}}$$

- From first-principles QCD – Young theory, semi-quantitative control
- **Can be made and probed in high-energy heavy-ion collisions**

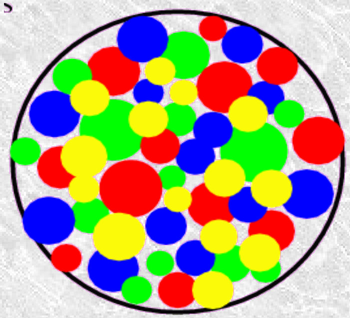
Color Glass Condensate

- **Color –** gluons have “color” in QCD.

- **Glass –** gluons at small-x:
  - generated by large-x slowly moving valence-like partons, randomly distributed in transverse plane
  - renormalization group equation: integrate out fast gluon d.o.f.
    $\Rightarrow$ universality: independent of initial hadron
  - almost frozen over the natural time scale of scattering
  - analog to spin glasses

- **Condensate –** gluons saturate below a momentum Q_s

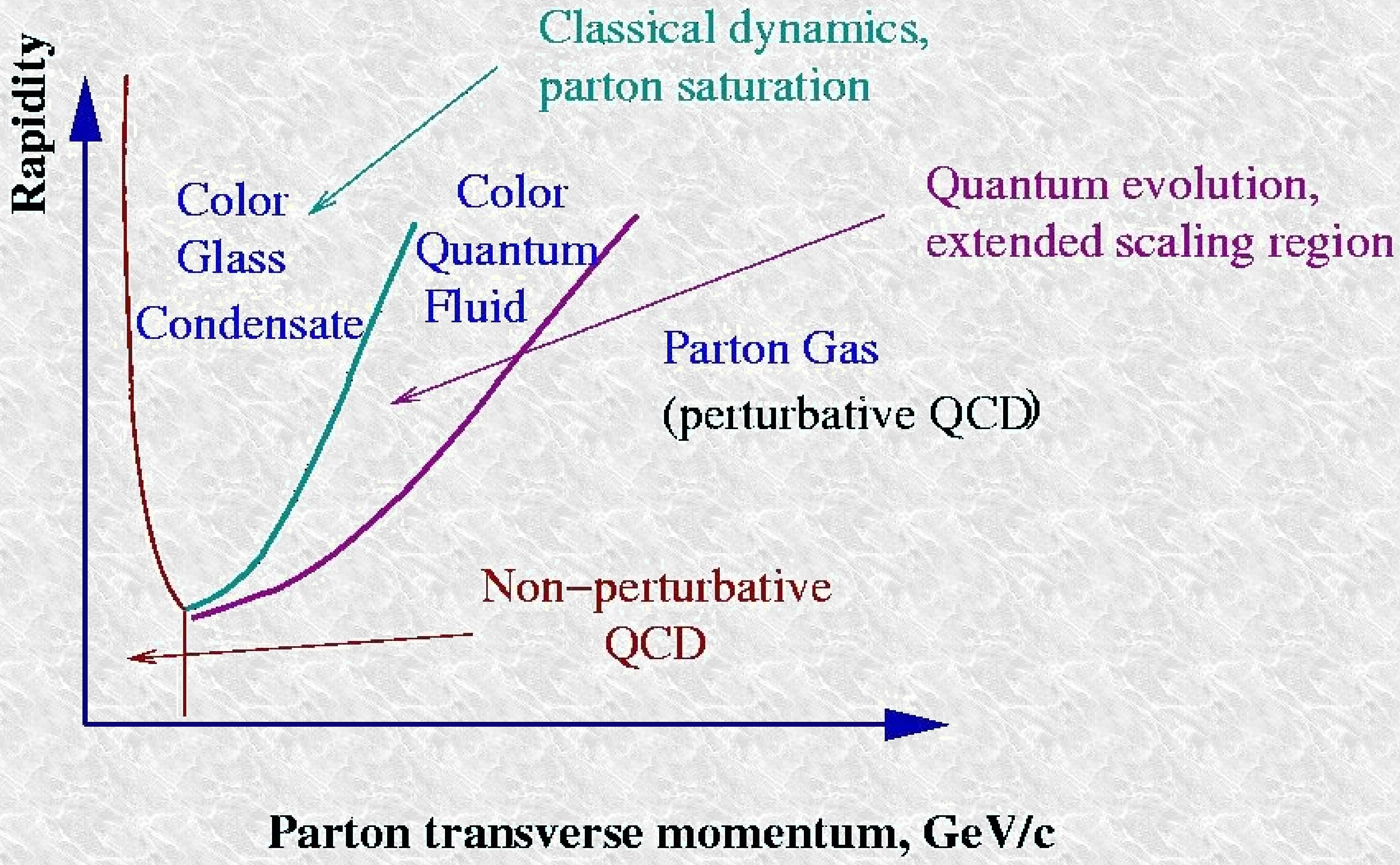
$$Q_s^2 \simeq \alpha_s \frac{A\, xG(x, Q_s)}{\pi R_A^2} \propto A^{1/3}$$



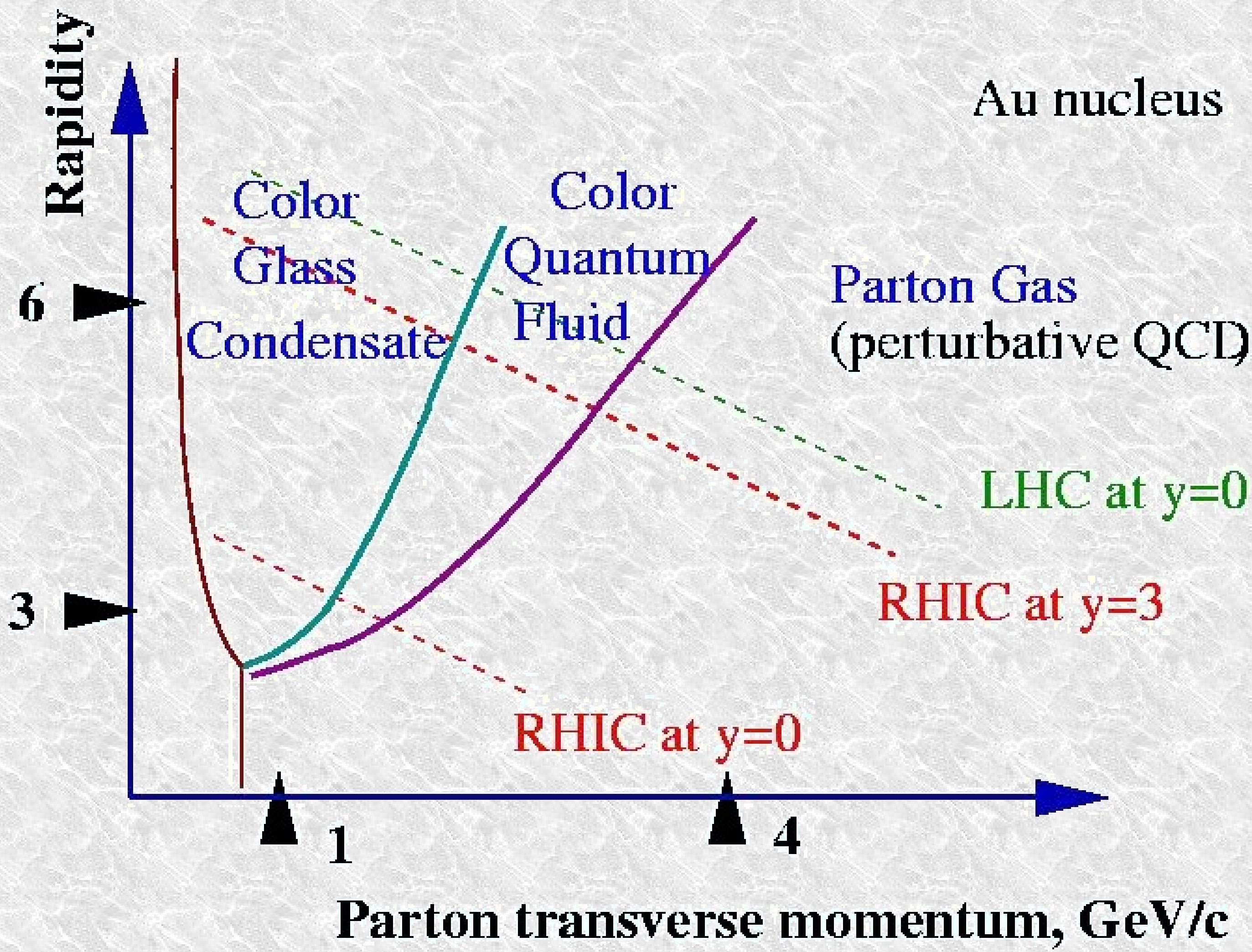
  - Coherent state with high occupancy $\sim 1/\alpha_s(Q_s)$
  - Can be better described as a field rather than point particle

Color Glass Condensate

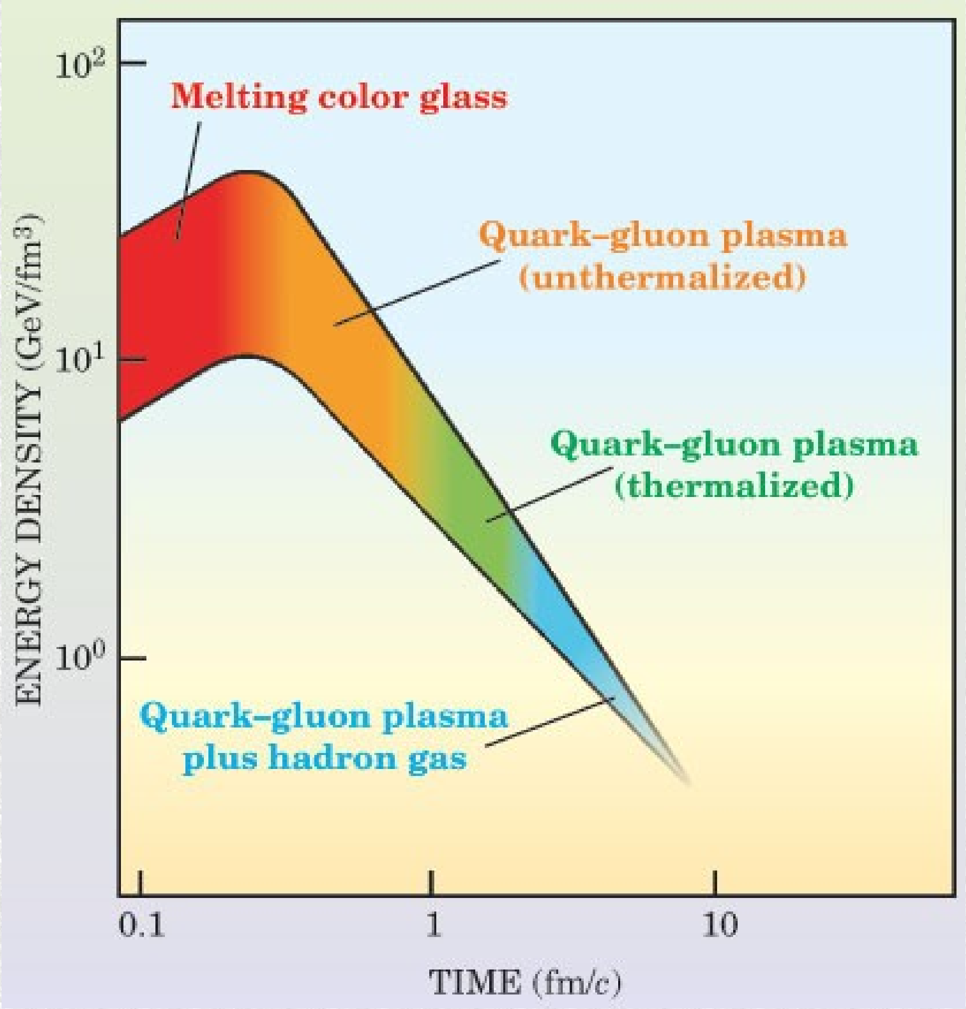
- **CGC "phase diagram"** - sketch



CGC phase diagram



- Bulk of parton production ($p_T < Q_s \sim$ 1-2 GeV) from CGC melting
- Theoretical control over initial condition for QGP evolution



L. McLerran,
T. Ludlam,
Physics Today,
October 2003

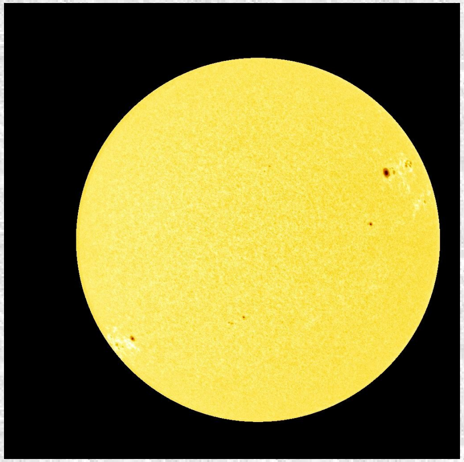
Lessons from QED plasmas

(transparencies adapted from M.Thoma's QM2005 talk)

1. Strongly Coupled Plasmas

Plasma = ionized gas, 99% of visible matter in Universe

Plasmas generated by high temperatures, electric fields, or radiation



Classifications:

2. Non-relativistic – relativistic plasmas (pair plasmas, QGP)
3. Classical – quantum plasmas (white dwarfs, QGP)
4. Ideal – strongly coupled plasmas (complex plasmas, QGP)

Coulomb coupling parameter

$$\Gamma = \frac{Q^2}{dT}$$

Q: charge of plasma particles
d: inter particle distance
T: plasma temperature

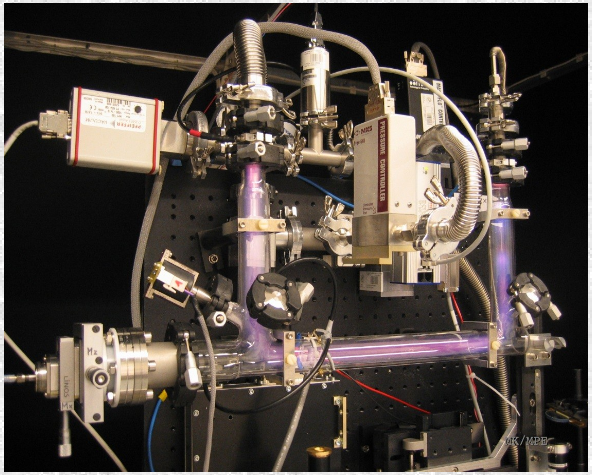
Ideal plasmas: $\Gamma << 1$ (most plasmas: $\Gamma < 10^{-3}$)

Strongly coupled plasmas: $\Gamma > O(1)$

Examples: ion component in white dwarfs, high-density plasmas at GSI

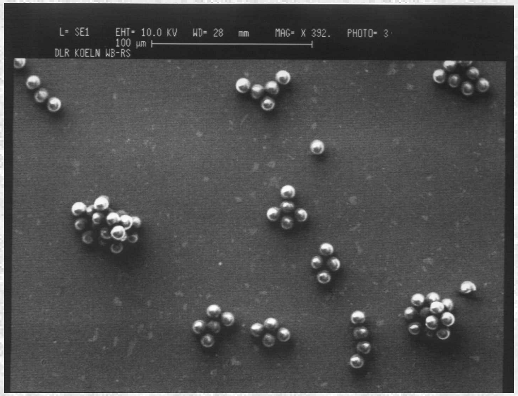
Non-perturbative description, e.g., molecular dynamics

2. Complex Plasmas



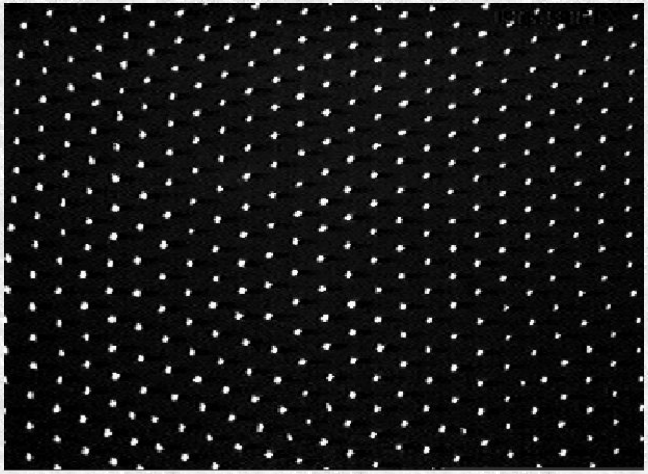
Dusty or complex plasmas = multi component plasmas with ions, electrons, neutral gas, and microparticles (dust)

E.g.: low temperature neon plasma in a dc- or rf discharge



Injection of microparticles with diameter 1 – 10 µm
- Microparticles collect electrons on surface ⇒ large negative charge: $Q = 10^3 - 10^5\, e$
- Inter particle distance about 200 µm

⇒ plasma crystal (predicted 1986, discovered 1994 at MPE)



Observation: illumination by laser sheet and recorded by CCD camera

3. Phases of the plasmas

Melting of plasma crystal by pressure reduction; less neutral gas friction; temperature increase; decrease of Coulomb coupling parameter $\Gamma = Q^2/(dT)$

long range order (crystalline phase) → short range order (liquid phase) → disordered phase (gas)

Quantitive analysis of equation of state and determination of Γ:
pair correlation function

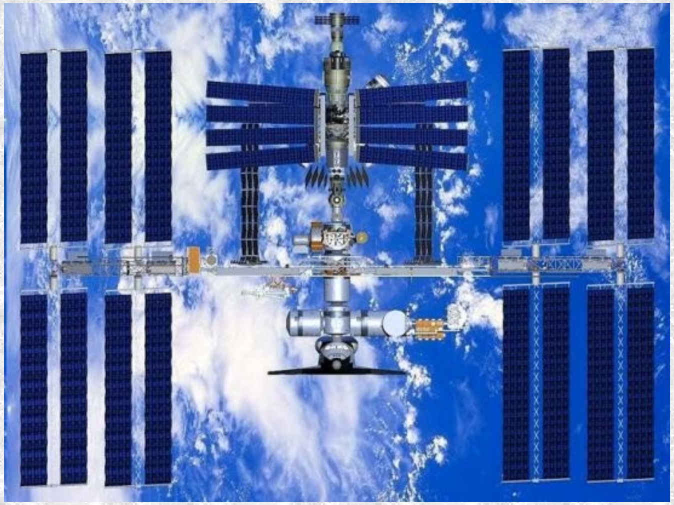
4. Collective phenomena

Mach cones induced by a laser beam have been observed

5. The fun part of this business

Gravity has strong influence on microparticles   microgravity experiments

M.Thoma !!

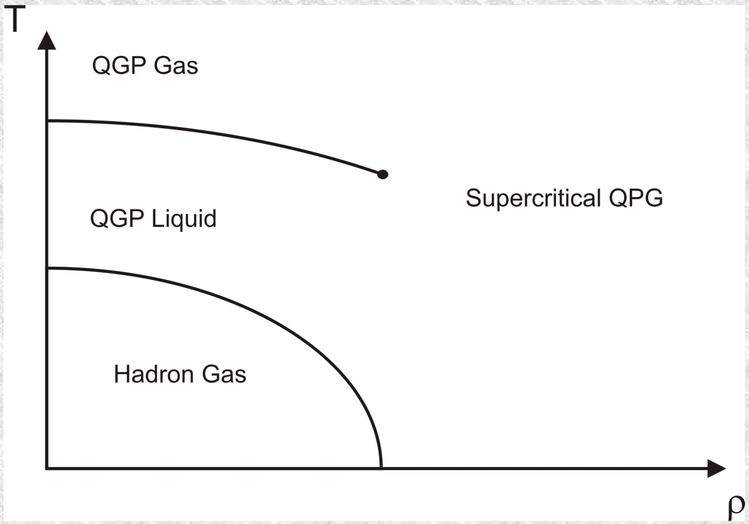


6. Applications to the Quark-Gluon Plasma

Estimate of interaction parameter $$\Gamma \simeq 2\frac{C\alpha_s}{dT}$$

$C = 4/3$ (quarks), $C = 3$ (gluons)
$T = 200$ MeV $\quad \alpha_s = 0.3 - 0.5$
$d = 0.5$ fm
Ultrarelativistic plasma: magnetic interaction as important as electric

$\Gamma = 1.5 - 6 \rightarrow$ QGP Liquid?



RHIC data (hydrodynamical description with small viscosity, fast thermalization) indicate QGP Liquid

Attractive and repulsive interaction
gas-liquid transition at a temperature of a few hundred MeV

Deeply bound kaonic nuclei

^3He ---> $^3HeK^-$ *shrinkage !!*

K^-p interaction is <u>strongly attractive</u>

2002 DEAR results

-> PRL 94, 212302 (2005)

$\rho_c \sim 4 - 10\, \rho_0$

$\Rightarrow$ *Explore cold and dense nuclear matter*

(AMD method *Dote et al. 2002)*

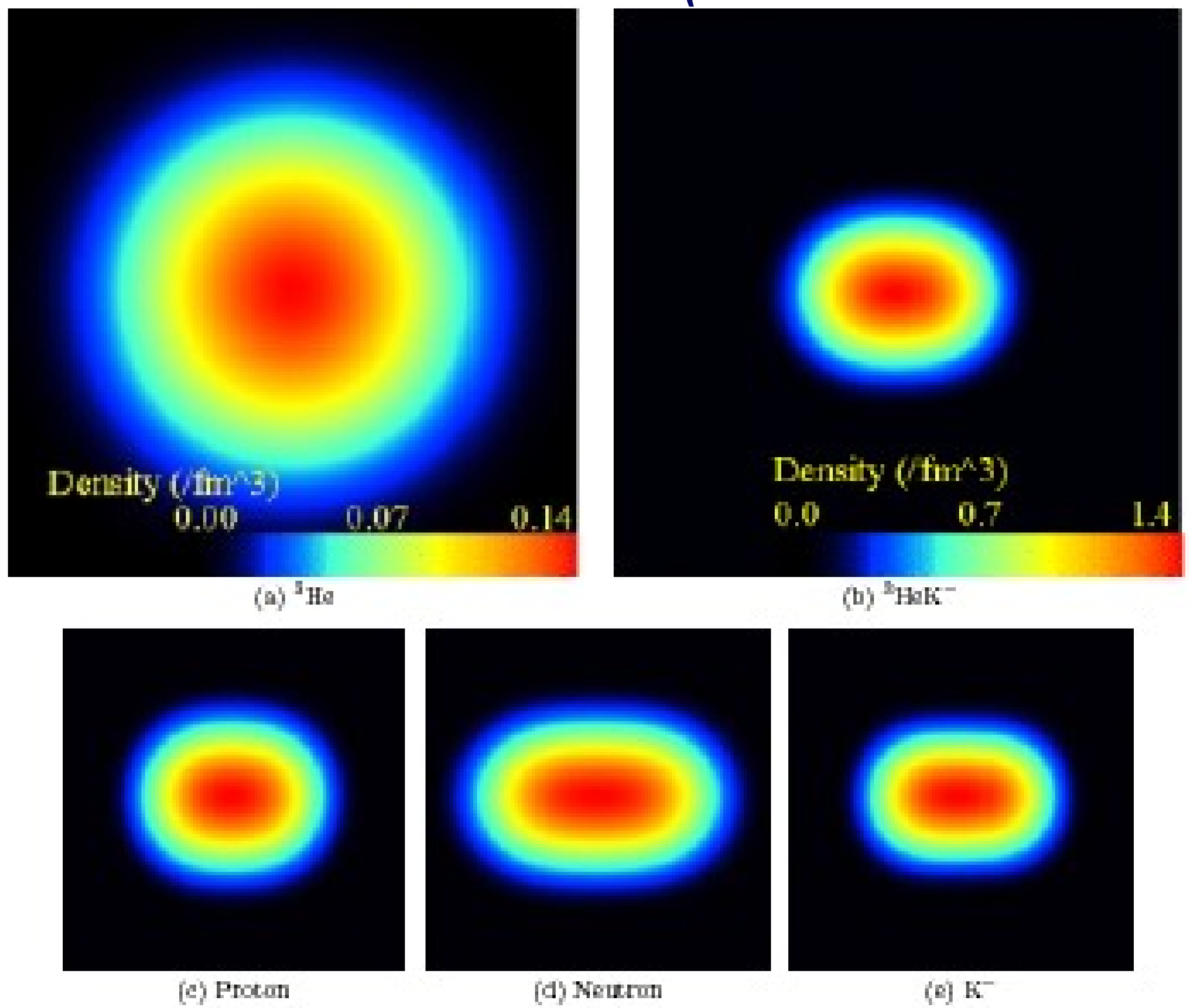


FIG. 1: Calculated density contours of ppnK$^-$. Comparison between (a) usual ^{3}He and (b) ^{3}HeK$^-$ is shown in the size of 7.5 by 7.5 fm. Individual contributions of (c) proton, (d) neutron and (e) K$^-$ are given in the size of 4.5 by 4.5 fm.

Production mechanisms of DBKNS:

1) **Stopped K^- reactions on light nuclei**, with ejection of a proton or a neutron as spectators

2) **In-flight K^- reactions:**

- Knock-out reactions (K^-, N) where one nucleon is knocked out in the formation stage;
- (K^-, π^-) reactions in proton-rich systems to produce exotic bound nuclear states on unbound systems.

3) **Protons (3.5 – 4.5 GeV) on a deuteron target** for the production of K^-pp detected in a 4π detector.

4) The identification of clusters as residual fragments ("K fragments") in **heavy ion collisions** via the invariant mass of their decay products.

Identification and study of DBKNS:

- **Formation -> missing mass**
- **Decay -> invariant mass**

  -> Spectroscopy!