Heavy Ion Collisions and the study of hot and dense QCD matter

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Taller de Altas Energías 2013. Benasque


200 GeV Gold + Gold
RHIC at BNL

HIC experimental programs

- Past Programs: SIS/LBL, AGS/BNL, SPS/CERN
- Present Programs:

1) RHIC/BNL (2000-On): Au-Au @ 200 GeV (also p+p, d+Au, Ca-Ca and lower energies):
Discovery machine: First evidence for a new new, strongly interacting state of matter: a "perfect fluid"

Press release Apr '05

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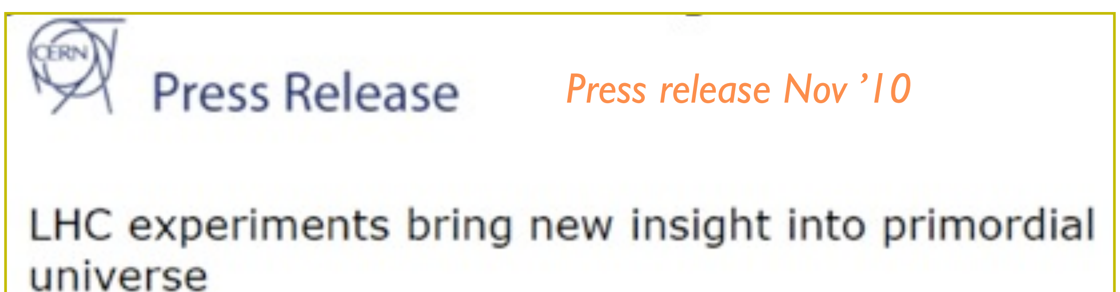
2) LHC/CERN (2010-On) : Pb-Pb @ 2.76 TeV (also p+p @ 2.76 TeV and p+Pb @ 5 TeV)

Confirmation & Precision machine: quantitative description of the thermal properties of the QGP

- 1 month of running per year starting Nov '10
- 1 dedicated experiment: ALICE (U. Santiago). CMS and ATLAS also involved in data taking/analysis
- So far, excellent accelerator and detectors performances: Data collected ~ 0.15 nb^{-1}
- 2013: p+Pb collisions @ 5 TeV (LHCb also joining!)



Press release Nov '10

Outline

⇒ Part I

- ✓ Motivation. QCD & the QCD vacuum
- ✓ QCD at high temperature or density: Quark Gluon Plasma

⇒ Part II

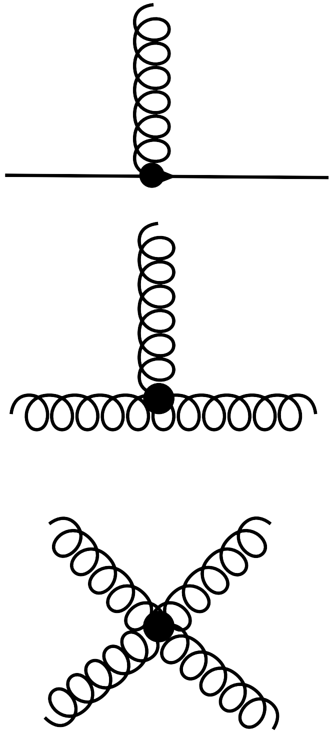
- ✓ Heavy Ion collision experiments
- ✓ Relevant findings at RHIC and the LHC

Goal of HIC experiments: Study hot and dense QCD matter

- ☛ QCD physics: understanding the QCD vacuum, confinement and chiral symmetry.
- ☛ Field theory: Emergence of macroscopic (thermal) phenomena from fundamental gauge theories
- ☛ Cosmology: Reproduce in the laboratory conditions ~10μs after the Big Bang

Microscopic theory ⇒ Quantum Chromodynamics

$$\mathcal{L}_{QCD} = \sum_{flavors} \bar{q}_f \, (i \not{D} - m_f) \, q_f - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \ldots$$



quarks $q_f^{\alpha,\,a} \rightarrow \begin{cases} \alpha = 1, \ldots 4 & \text{Lorentz index} \\ a = 1 \ldots N_c = 3 & \text{Color index} \\ f = \text{u, d, s, c, b, t} & \text{Flavor index} \end{cases}$

gluons $A^{\mu,a} \rightarrow \begin{cases} \mu = 1, \ldots 4 & \text{Lorentz index} \\ a = 1 \ldots N_c^2 - 1 = 8 & \text{Color index} \end{cases}$

Gauge symmetry: SU(N_c=3) (non-abelian)

+2/3	u (3 MeV)	c (1.2 GeV)	t (171 GeV)
-1/3	d (5 MeV)	s (105 MeV)	b (4.2 GeV)

Strong interactions are responsible for 99% of (visible) matter in the Universe

Electromagnetism

Microscopic theory: QED (p, e, γ)

$\Downarrow$

Macroscopic, collective behavior:

- Phase transitions: gas, solid, fluid, superfluid ...
- Condensed / solid state physics: Insulators, semi-conductors, ferromagnets, glasses ...
- Chemistry ... industry

Strong interactions

Microscopic theory: QCD (quarks, gluons)

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Strong interactions

Microscopic theory: QCD (quarks, gluons)

$\Downarrow$

Macroscopic, collective behavior:

- What are the phases of QCD ?

⋮

- Is a color-chemistry possible?
- Are there color-superconductors?
- Color-industry?

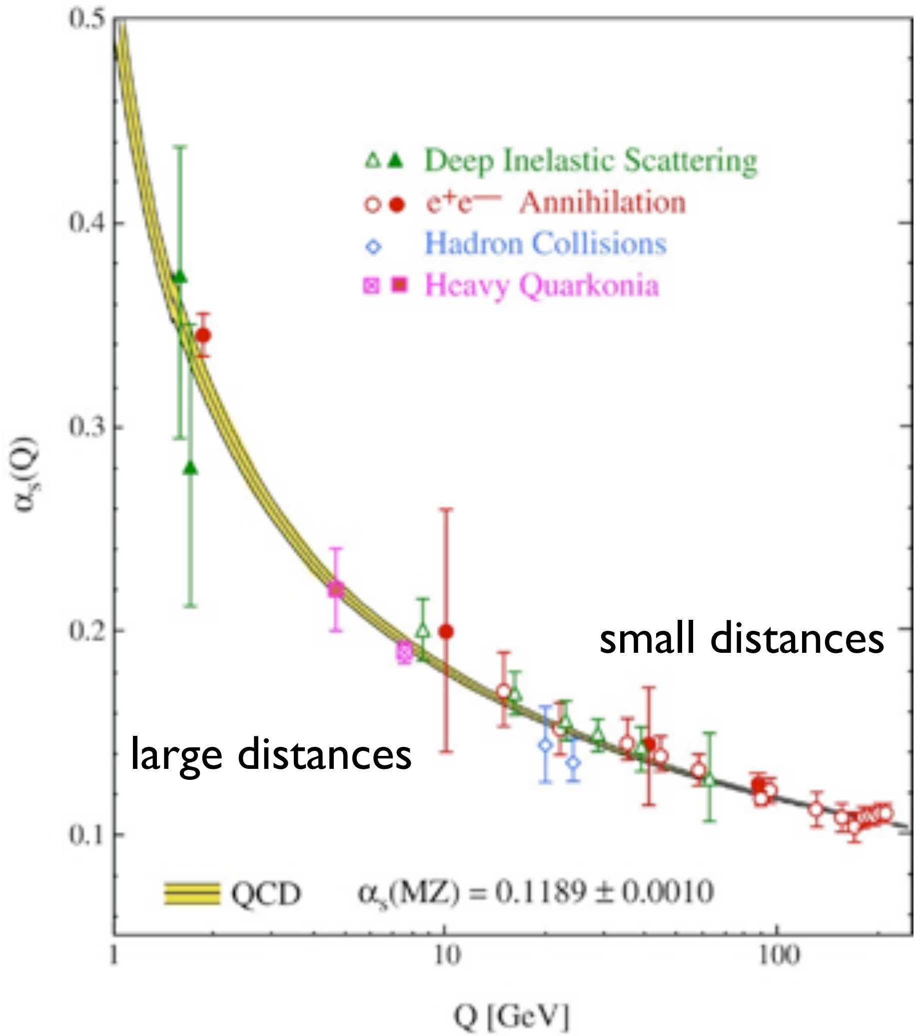
$\Downarrow$

Study of QCD matter at high density or temperature

Properties of QCD:

• **Asymptotic freedom:** The strength of the interaction is smaller at short distances

$\alpha_s = g^2/(4\pi)$



Well understood via
perturbative calculations

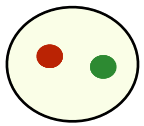
↳

$$\beta(g) = \frac{\partial g}{\partial \log(\mu)} = \frac{g^3}{(4\pi)^2}\left\{\left[\frac{1}{3} - 4\right]N_c + \frac{2}{3}N_f\right\} < 0$$

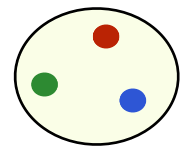
Properties of QCD:

- **Asymptotic freedom:** The strength of the interaction is smaller at short distances

- **Confinement:** Quarks and gluons are not observed as free states. They are confined in color singlet states, hadrons.



mesons ($q\bar{q}$)
$\pi,\ K,\ \rho\ldots$



baryons (qqq)
$p,\ n,\ \Lambda' s\ldots$

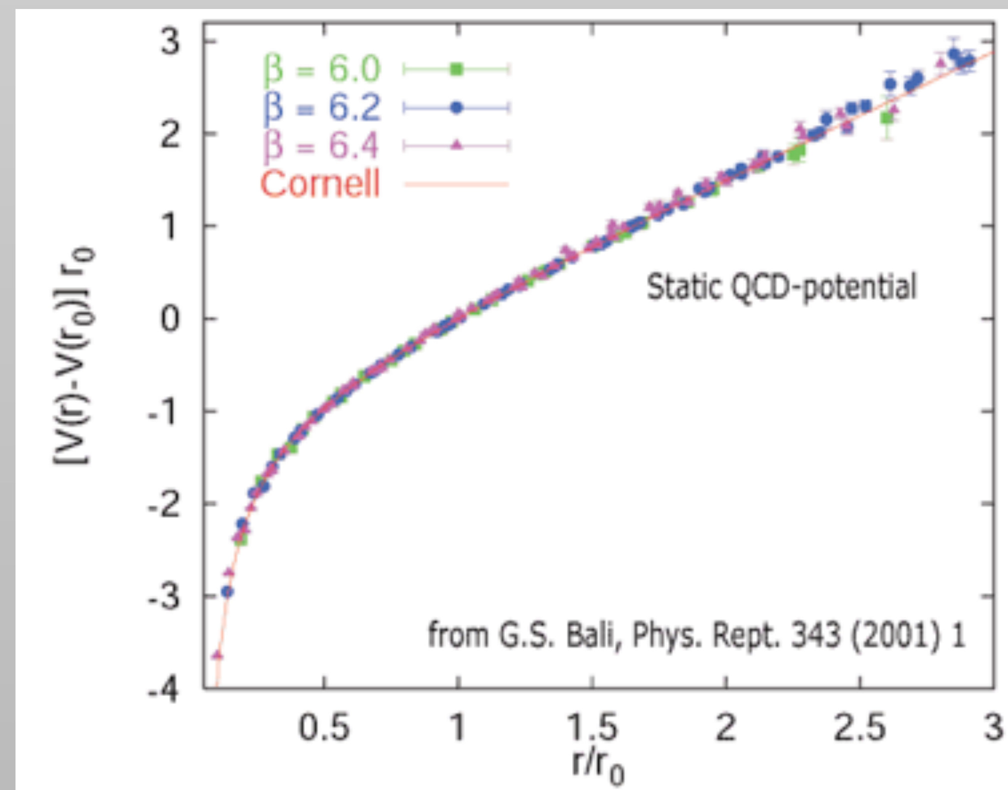
⇒Potential models:

$$V(R) = -\frac{\alpha_{eff}}{R} + K\,R$$

Coulomb Linear

⇒String tension

$$K \sim (420\,\mathrm{MeV})^2 = 900\,\mathrm{MeV\,fm}^{-1}$$



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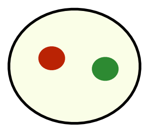

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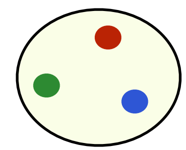
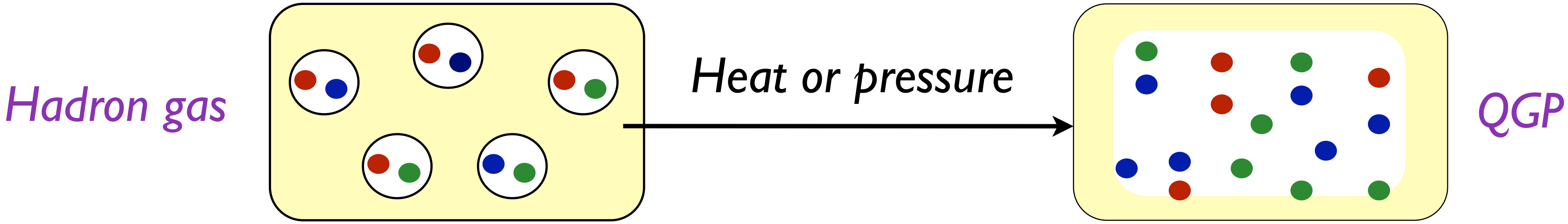


baryons (qqq)
$p, n, \Lambda' s \ldots$

☛ Would a high-temperature (density) QCD system allow (quasi)free quarks and gluons, i.e a Quark Gluon Plasma?



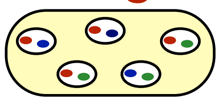
$$\text{if } T \gg \Lambda_{QCD} \quad \text{then} \quad \alpha_s(T) \ll 1$$

Hints from Lattice QCD:

- The **entropy, energy density or pressure** of a an ideal (non-interacting) gas are proportional to the # d.o.f:

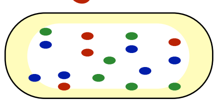
$$\left(\frac{\mathbf{s}}{T^3};\frac{\mathbf{e}}{T^4};\frac{\mathbf{p}}{T^4}\right)\propto \#\,\mathrm{d.o.f.}$$

Pion gas



$$\mathbf{d_\pi = 3} \rightarrow\ (\pi^+,\pi^-,\,\pi^{\mathbf{0}})$$

QGP



$$\mathbf{d_{q\bar{q}g} = d_g + \frac{7}{8}d_{q\bar{q}} = 2_s\cdot(N_c^2-1)+\frac{7}{8}\cdot 2_{q\bar{q}}\cdot 2_s\cdot N_f\cdot N_c = 37}\,(\text{for } N_f=2)$$

Results from Lattice QCD:

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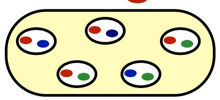
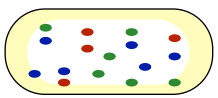


$$d_\pi = 3 \rightarrow (\pi^+, \pi^-, \pi^0)$$

QGP



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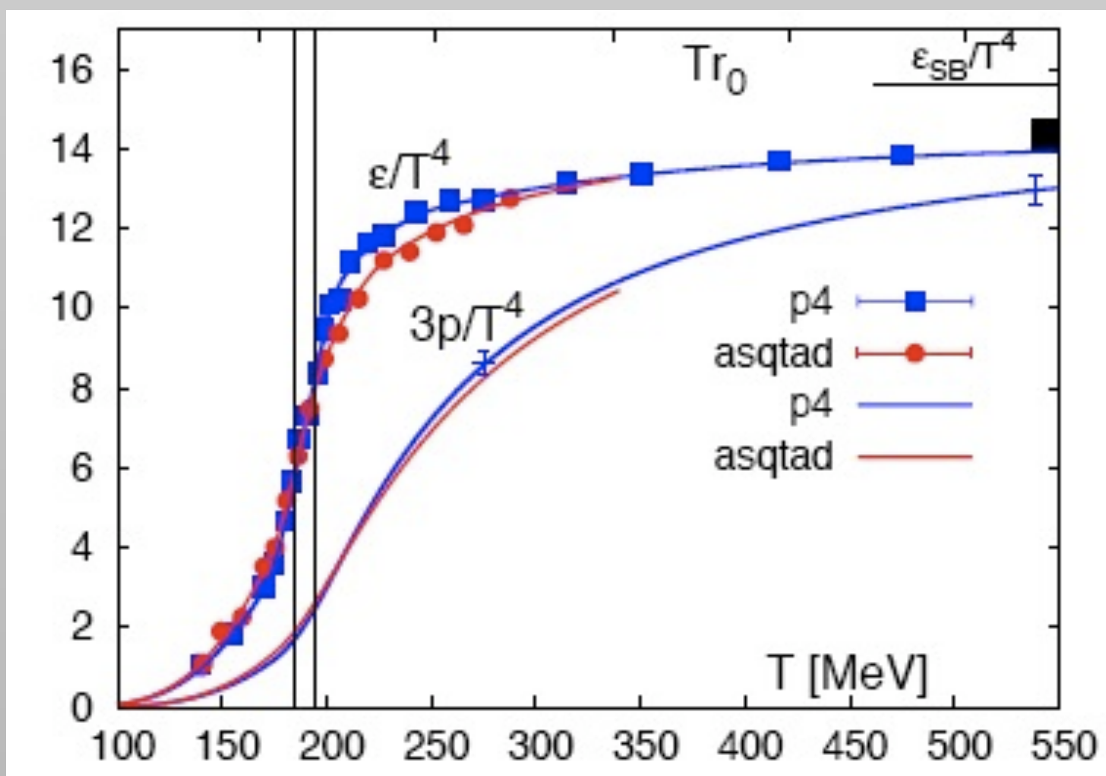
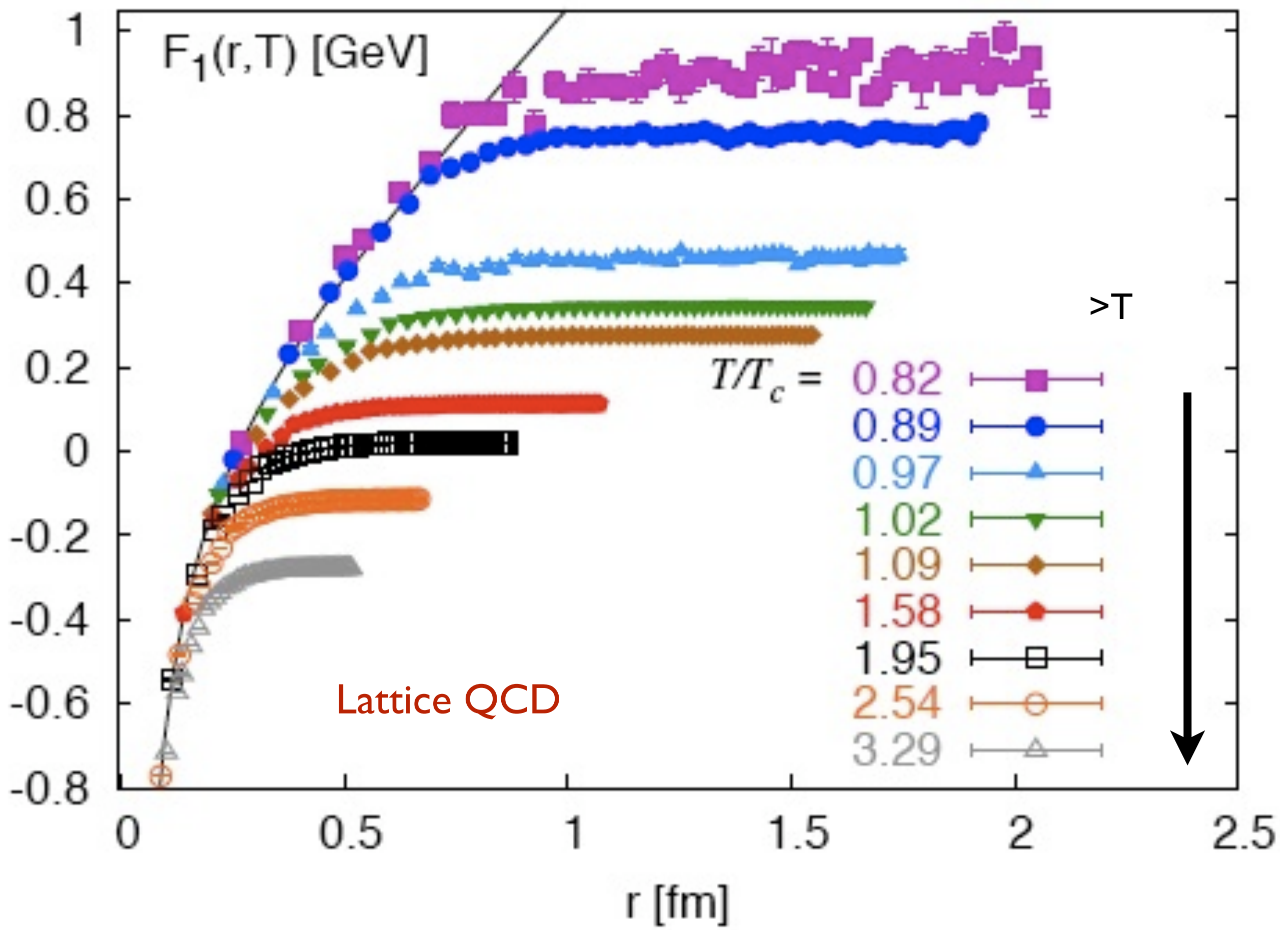


- *Explosion of degrees of freedom around T= 150 - 180 MeV*
- *Is there a phase transition around that temperature?*

Results from Lattice QCD:

- The string in potential models ¨melts¨at high temperatures :

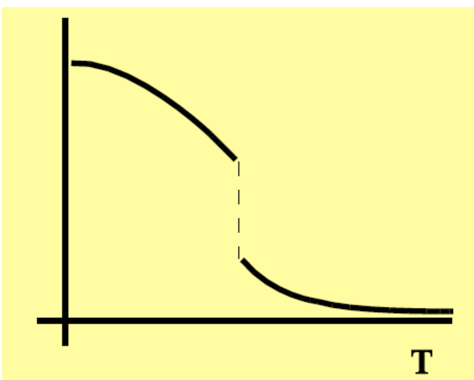


Phase diagram and broken symmetries

- Phase transitions of thermodynamical systems can be related to the restoration of broken symmetries of the system
- Phase transitions are signaled by the abrupt changes in the behaviour of the order parameter

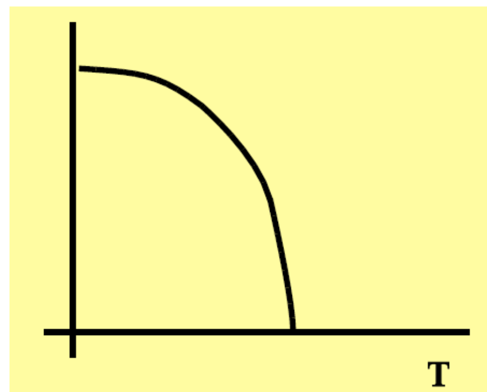
order parameter

First order: discontinuity in the order parameter



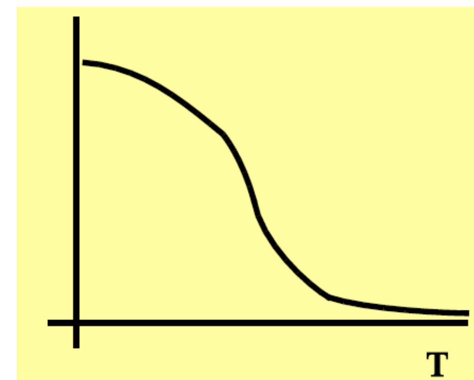
Water melting into ice (density)

Second order: discontinuity in the 1st derivative



Ferromagnets (magnetic susceptibility)

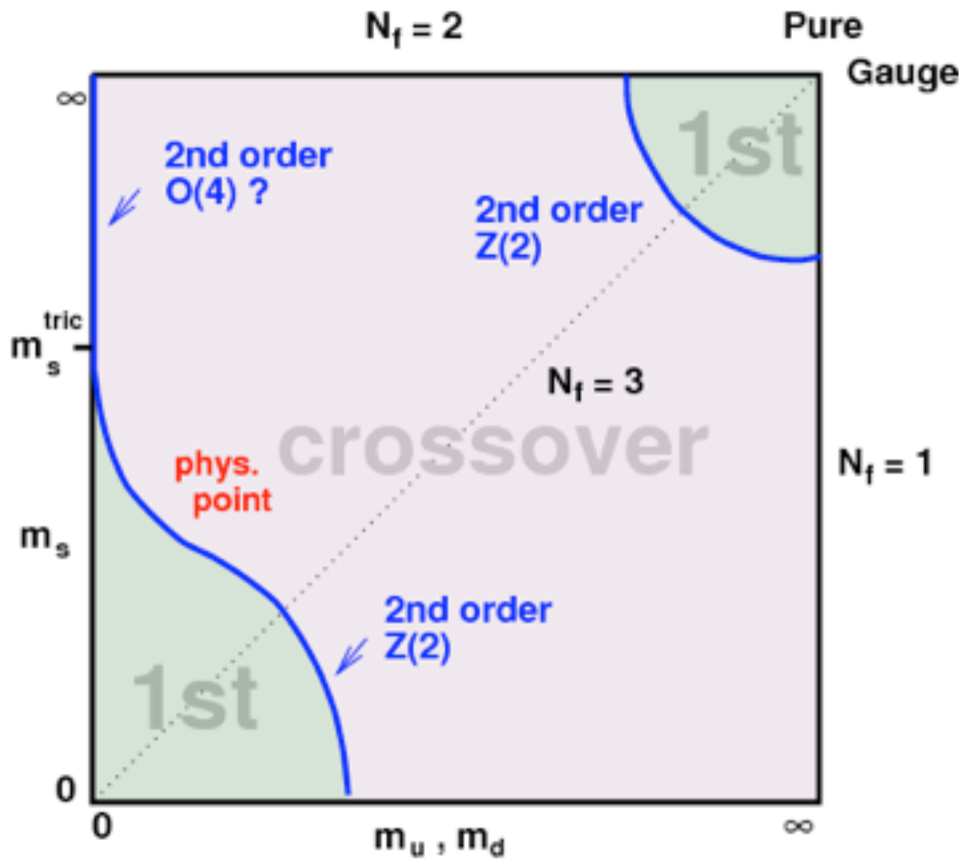
Crossover: continuous behaviour



Butter melting

Phase diagram and broken symmetries

- Phase transitions of thermodynamical systems can be related to the restoration of broken symmetries of the system
- Phase transitions are signaled by the abrupt changes in the behaviour of the order parameter
- Lattice calculations indicate that for realistic quark masses the phase transition from hadronic matter to a QGP at zero baryochemichal potential is actually a crossover



Phase diagram and broken symmetries

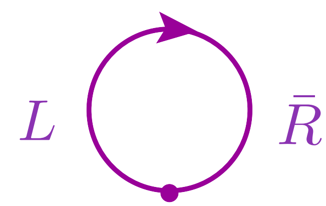
- QCD with massless quarks can be decomposed into right- and left-handed sectors

$$\mathcal{L}_{quarks} = \bar{q}_L \, i \, \not{D} \, q_L + \bar{q}_R \, i \, \not{D} \, q_R \qquad\qquad q_{L(R)} = \frac{1 \mp \gamma^5}{2} q$$

It is invariant under $SU_L(N_f) \times SU_L(N_f)$; $\begin{pmatrix} u \\ d \end{pmatrix}_{L(R)} \mapsto \exp\left[i \, \theta^a_{L(R)} \, \lambda^a \right] \begin{pmatrix} u \\ d \end{pmatrix}_{L(R)}$

⇒ Chiral symmetry is spontaneously broken in the vacuum

$$\langle 0 | \bar{q} \, q | 0 \rangle = \langle 0 | \bar{q}_L \, q_R + \bar{q}_R \, q_L | 0 \rangle \approx -(240 \, \text{MeV})^3$$



The chiral condensate can be regarded as an order parameter for the phase transition

$$\langle 0 | \bar{q} q | 0 \rangle = \begin{cases} \neq 0, & \text{for } T < T_c \\ = 0, & \text{for } T > T_c \end{cases}$$

99% of the mass of visible matter has its dynamical origin in QCD

	mass (GeV)	$\sum q_m$ (GeV)
p	$\sim$1	$2m_u + m_d \sim$0.03
π	$\sim$0.13	$m_u + m_d \sim$ 0.02

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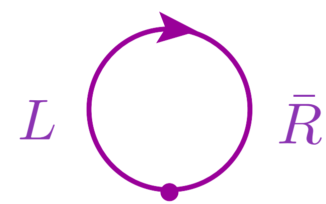

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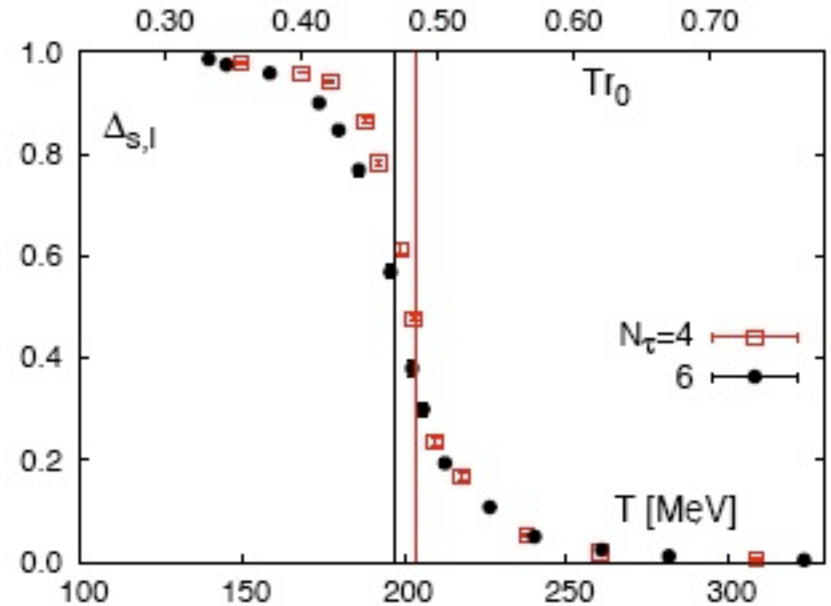
⇒ Other symmetries: Center symmetry Z(Nc) for Polyakov loops (infinitely heavy masses)

$$L(\vec{x}) = \frac{1}{N_c} \,\mathrm{tr} \exp\left[i \, g \int_0^{\frac{1}{T}} A_4(\tau, \vec{x}) \, d\tau\right] \qquad \langle 0|L(\vec{x})|0\rangle = \begin{cases} = 0, & \text{for } T < T_c \\ \neq 0, & \text{for } T > T_c \end{cases}$$

Phase diagram and broken symmetries

- The chiral symmetry (Z(Nc)) is restored (broken) above the phase transition:

$\langle q\bar{q} \rangle$



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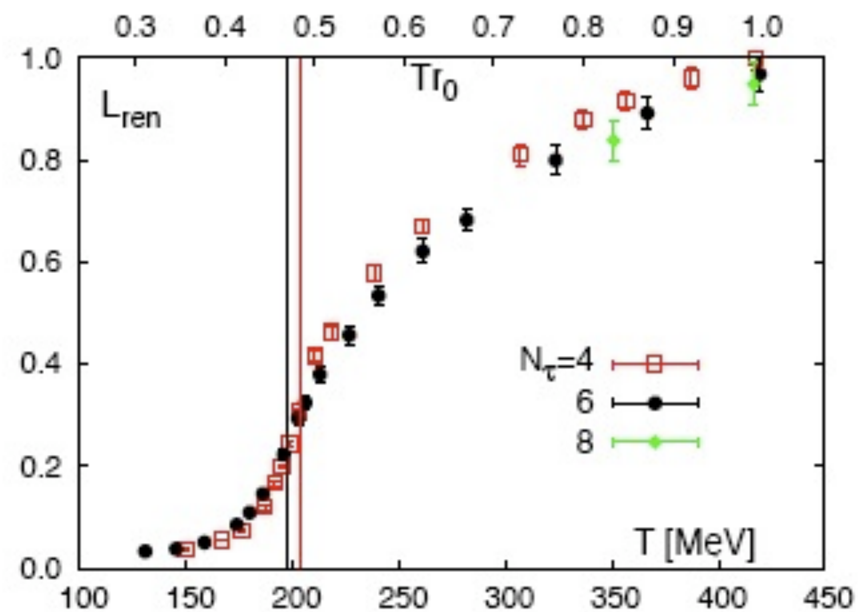
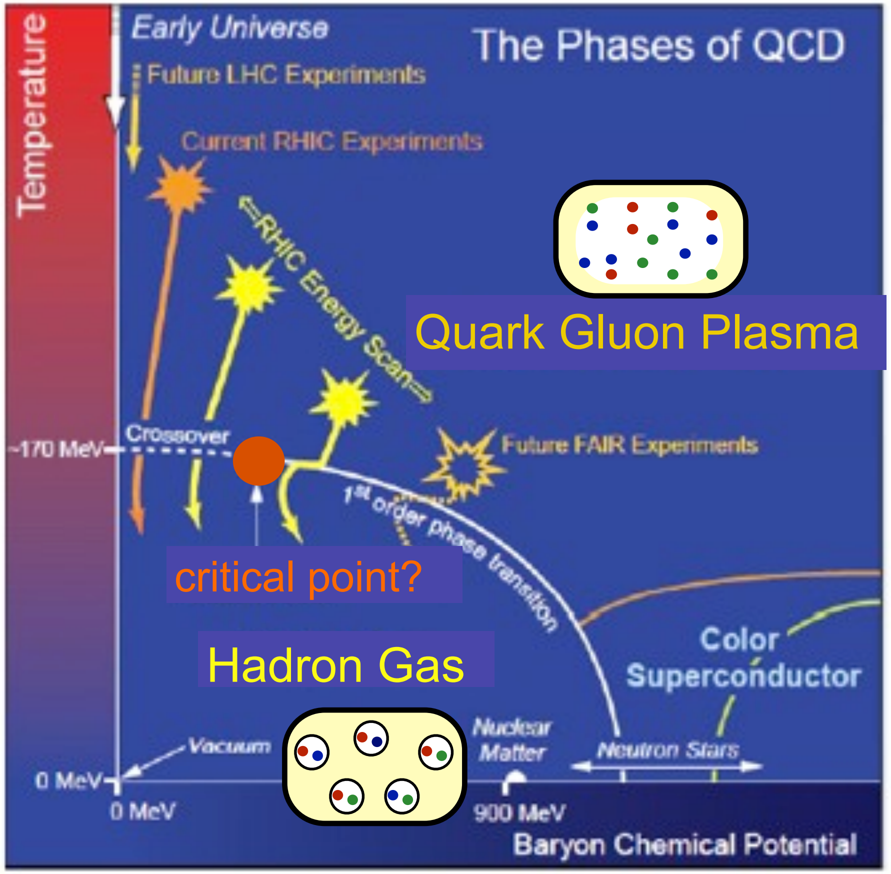


The QCD Phase diagram. A sketch



- Current understanding of phase diagram is rather speculative due to the lack of reliable theoretical tools or empiric information. Mostly based on models

- It has been suggested that the phase diagram may have a critical point where the first order phase transition happening at high baryon density ends

⇒ Part II

- ✓ Heavy Ion collision experiments
- ✓ Relevant findings at RHIC and the LHC

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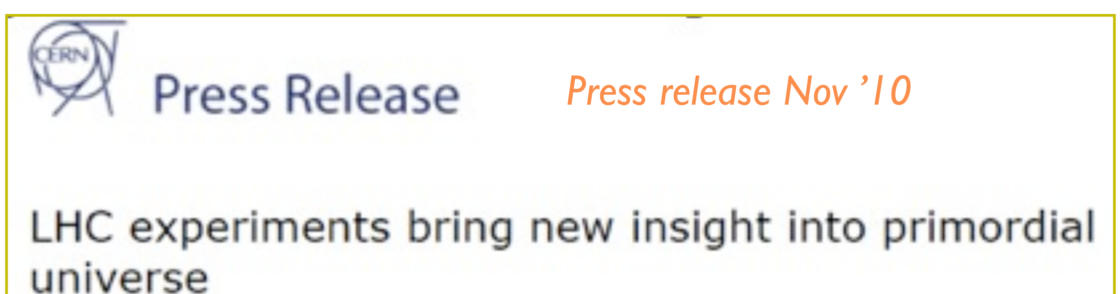
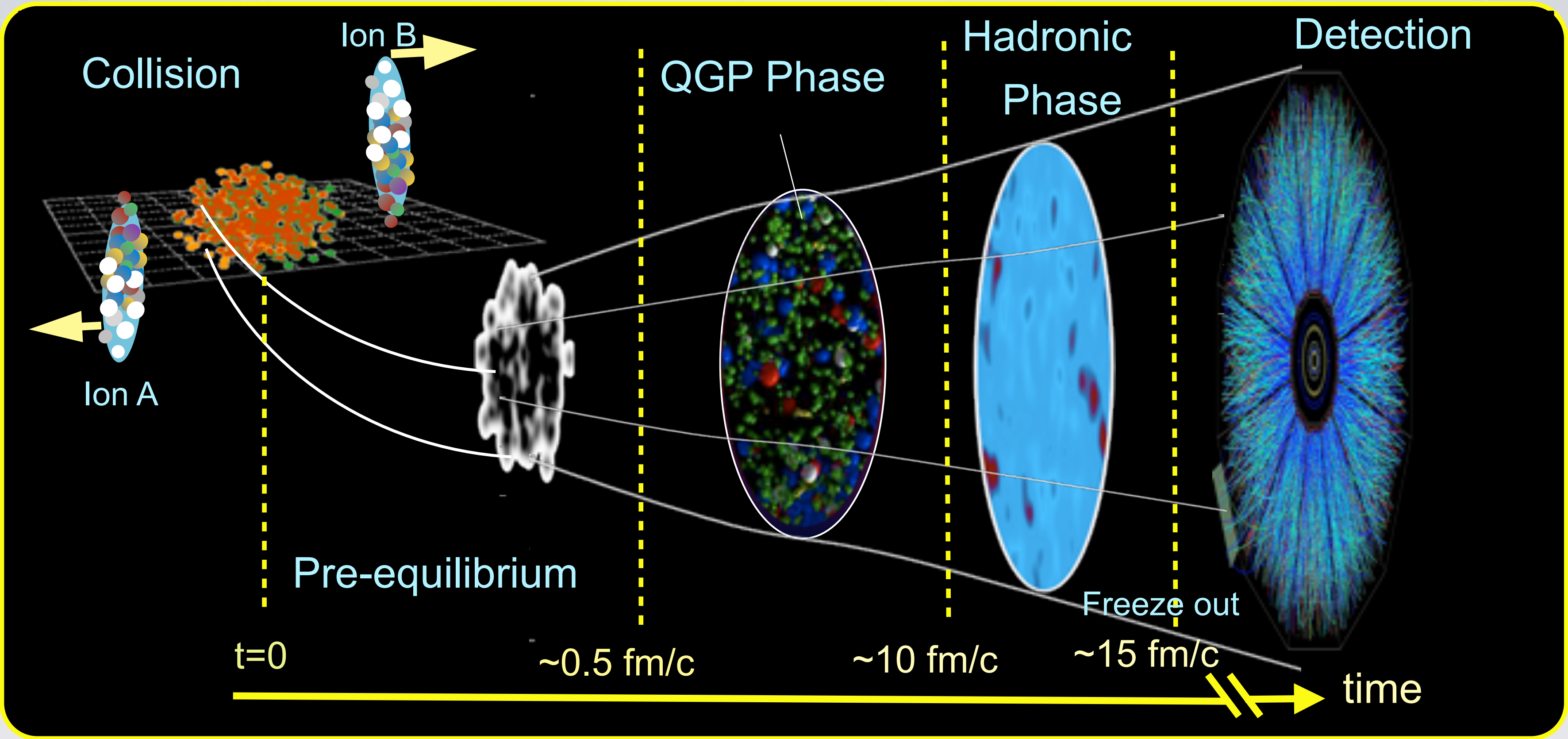
- So far, excellent accelerator and detectors performances: Data collected ~ 0.15 nb^{-1}
- 2013: p+Pb collisions @ 5 TeV (LHCb also joining!)



Press release Nov '10

Space-time picture of heavy ion collisions. The “little bang”

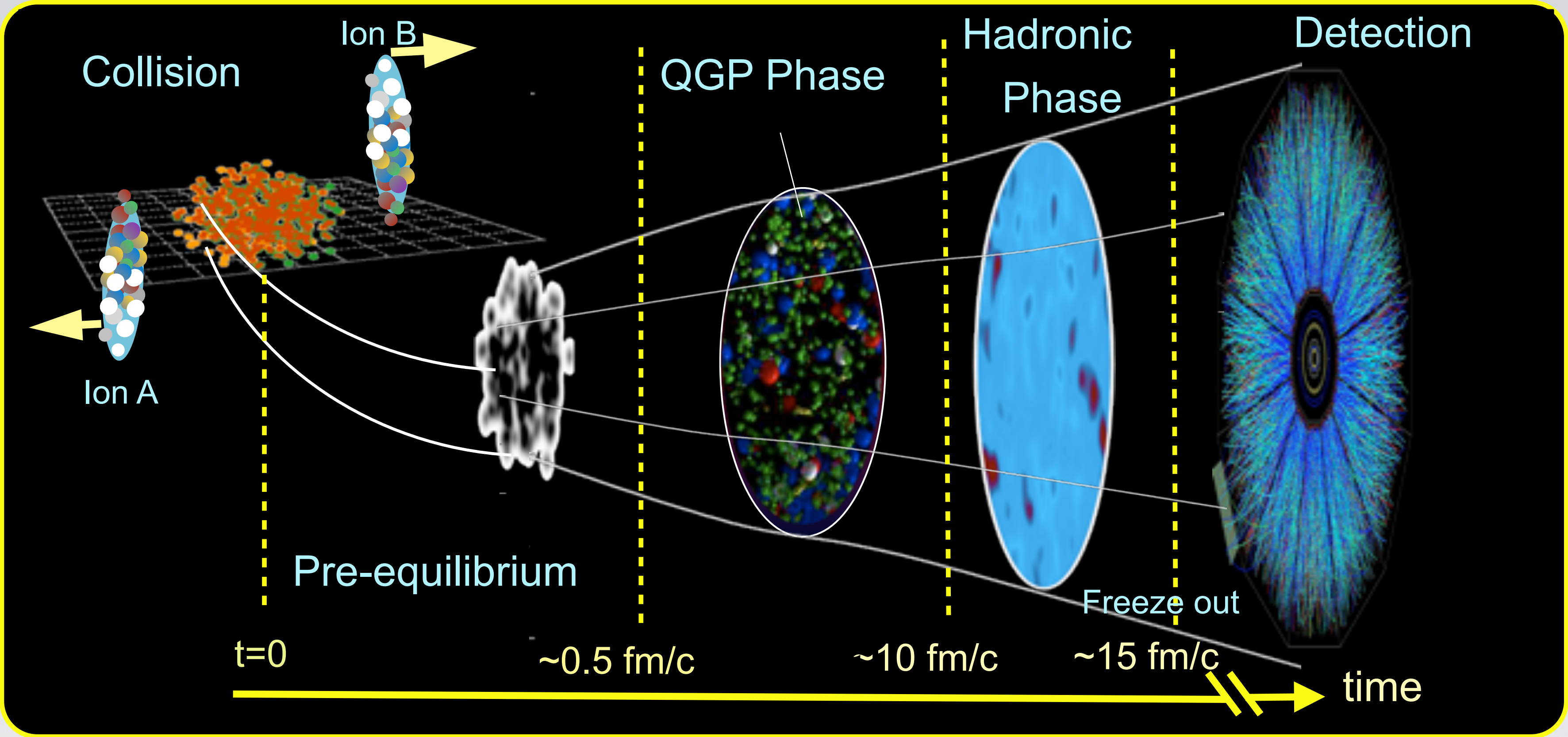


Fireball:

- ~10^{-15} meters across
- lives for ~5×10^{-23} seconds
- Typical LHC event:

- $T_{QGP} \sim 10^5 T_{sun}$ ~ 4 trillion °C
- ~15000 particles detected
(l⁺l⁻, π’s, γ’s, p’s,resonances...)

Observables



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~ 99% of detected particles

- Multiplicities
  - Initial state: Initials T, ε, μ
  - Thermal, chemical equilibrium?
  - Thermal radiation, dileptons
- Correlations (collectivity)
  - Flow, fluctuations, transport
  - Femptoscopy.
- Charge asymmetries: CP Violation

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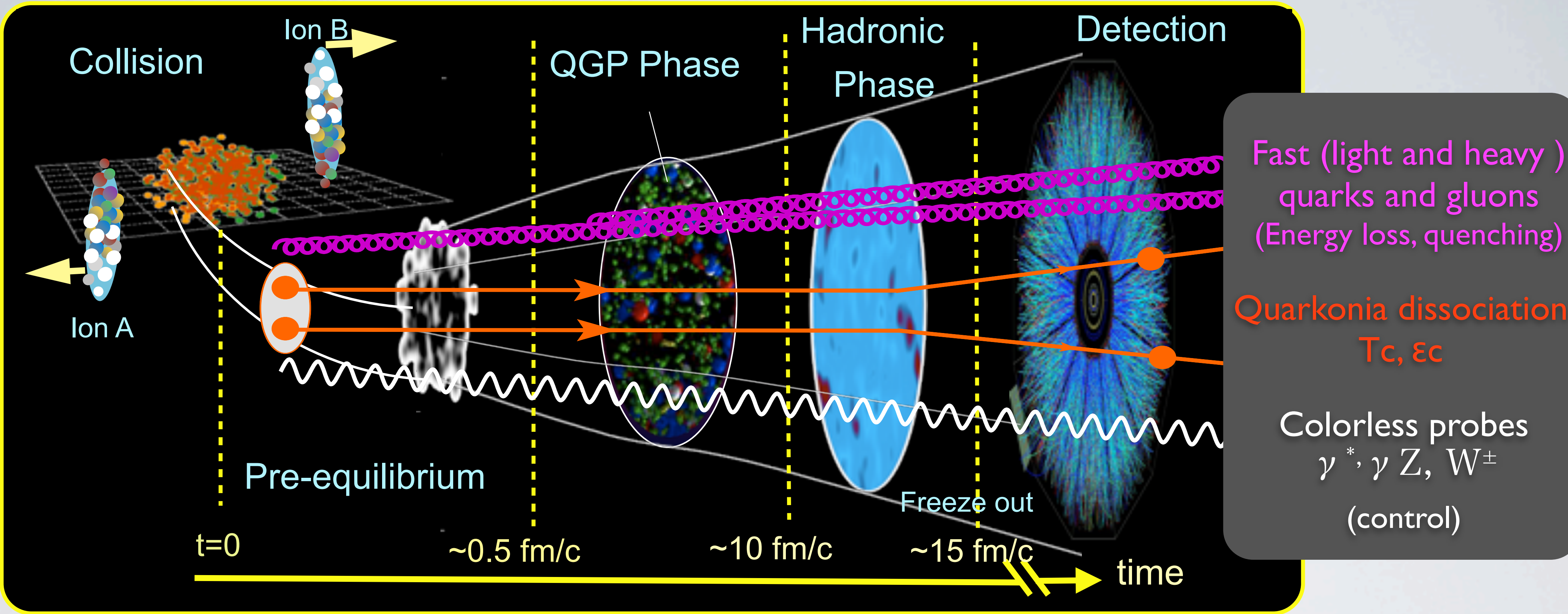

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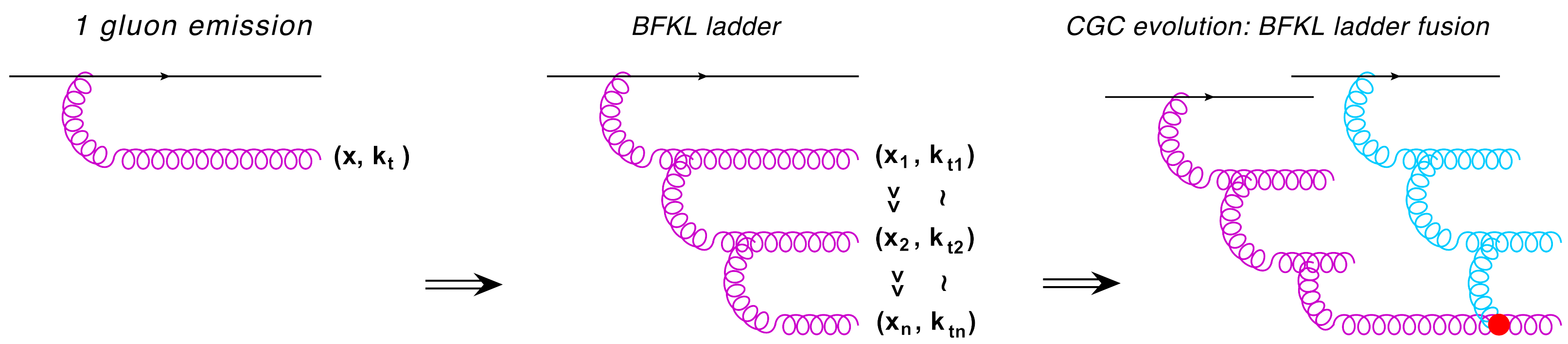
Hard Probes: p >> <p_t>,T

~ 1% of detected particles

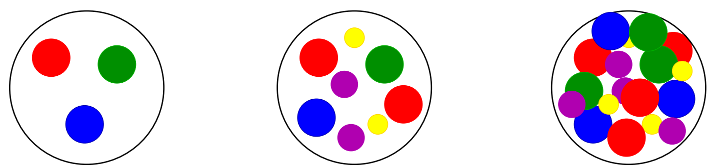
- Produced at very early times
- Medium tomography & diagnosis
- Interpretation requires "vacuum" (p+p) and "cold nuclear" (p+Pb) data at the same energy

1. Before the collision: Non-linear dynamics and saturation

- Gluon recombination processes reduce the # of gluons in the wave function before the collision



Dilute regime at low energies "BFKL"



Dense regime at high energies "BK-JIMWLK"

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})$$

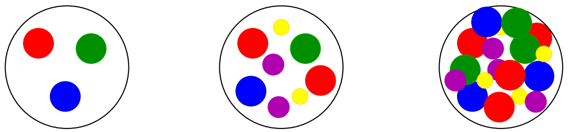
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \underbrace{\mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t})}_{\text{radiation}} - \underbrace{\phi(\mathbf{x}, \mathbf{k_t})^2}_{\text{recombination}}$$

- In the saturation regime, color fields become perturbatively strong ~ 1/g. Classical scenario

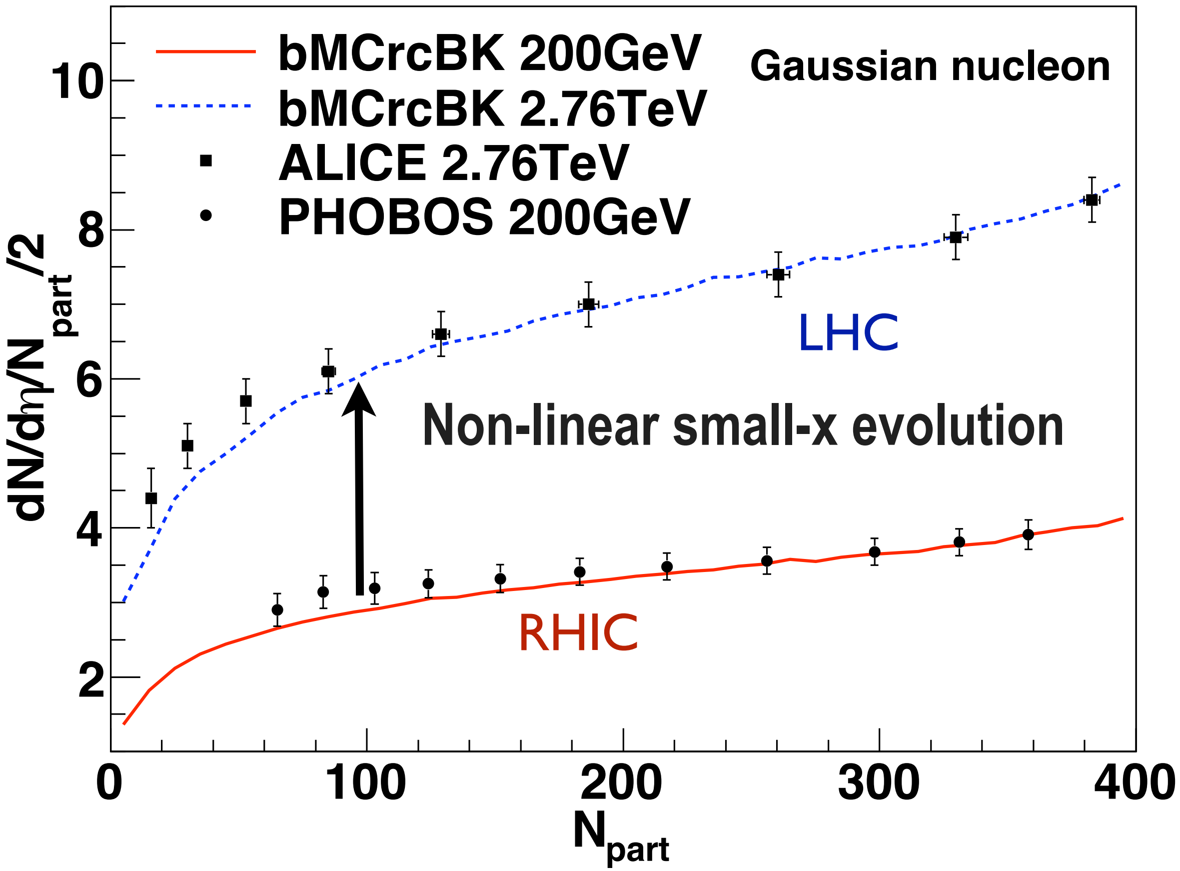
$$\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x}) \qquad \phi \propto \langle \mathbf{A}\mathbf{A}^\dagger \rangle \sim \frac{\mathbf{1}}{\alpha_\mathbf{s}} \to aa^+ \gg [a, a^\dagger] \sim 1$$

All these effects are accounted for by the Color Glass Condensate effective theory

1. Before the collision: Non-linear dynamics and saturation



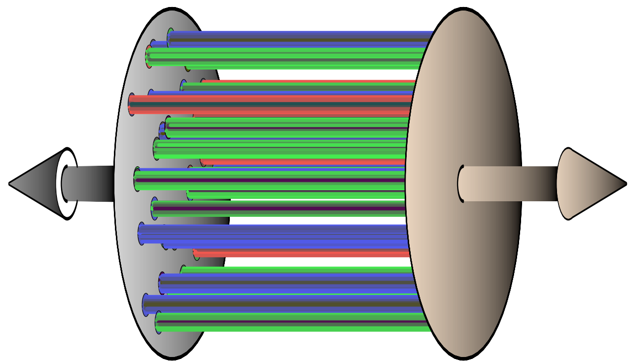
- Empiric "confirmation": RHIC and LHC total multiplicities are a lot smaller than those corresponding to a simple superposition of nucleon-nucleon collisions



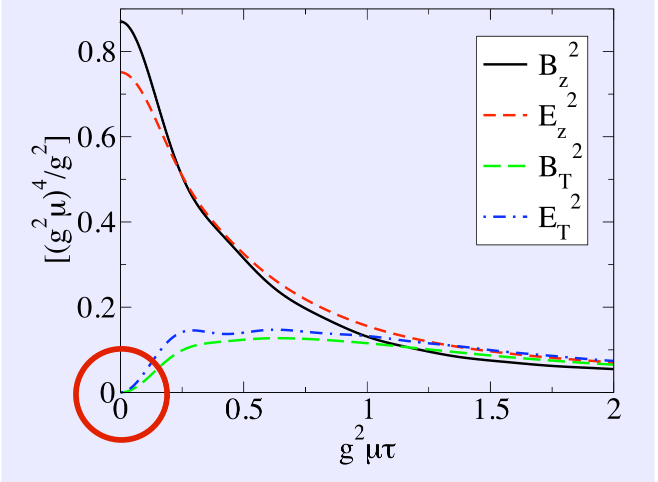
Glasma: The medium right after the collision $\tau \lesssim 1/Q_s$

Chromo electric-magnetic fields are longitudinal

$$\boldsymbol{E}^z = ig\left[\mathcal{A}_1^i, \mathcal{A}_2^i\right] \quad , \qquad \boldsymbol{B}^z = ig\epsilon^{ij}\left[\mathcal{A}_1^i, \mathcal{A}_2^j\right]$$

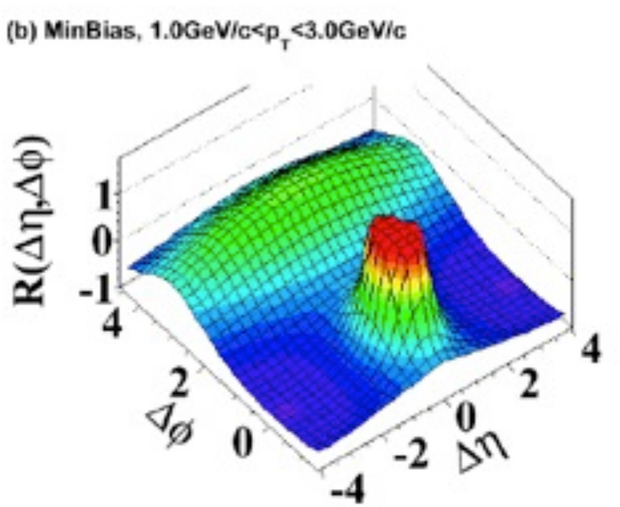


Flux tubes

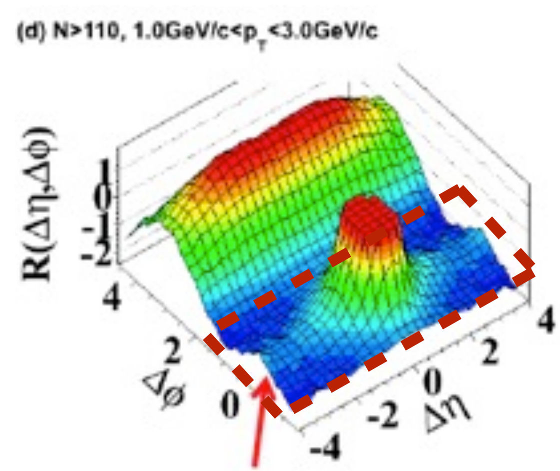


The ridge: extended in rapidity (longitudinal direction) 2-particle angular correlations correlations

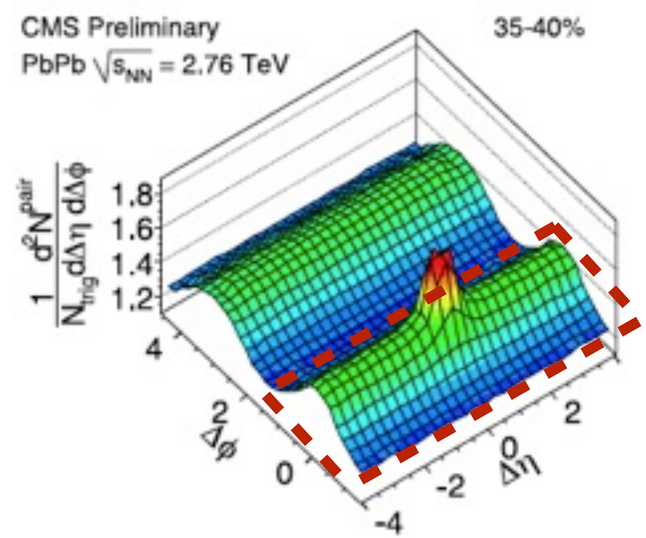
p-p min. bias



p-Pb and p-p Nch>110



Pb-Pb

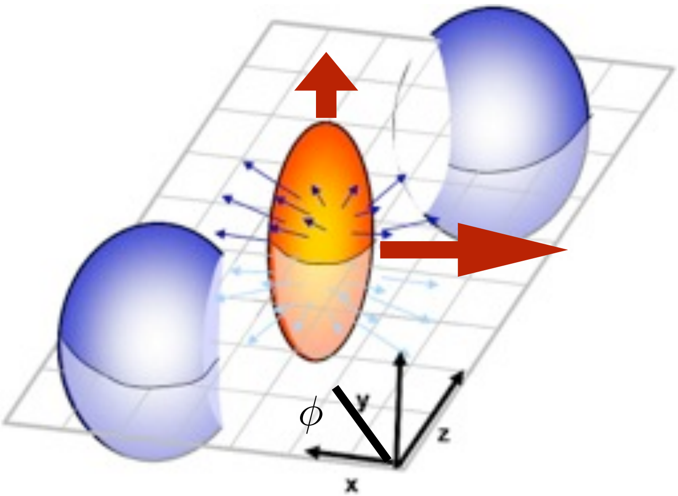


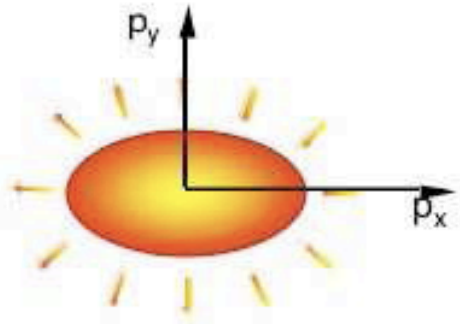
Pantha Rei: RHIC and LHC matter flow!

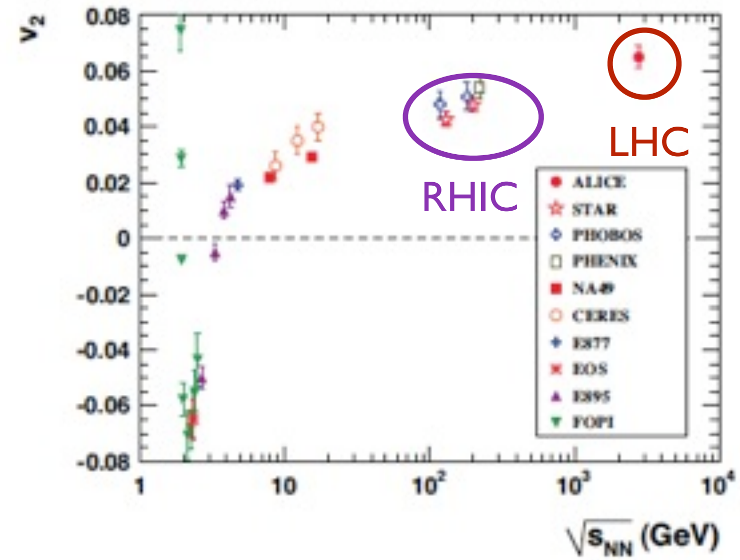
initial geometry anisotropy → Final state momentum anisotropy →

Elliptic flow

$$\frac{d\,N^h}{d^2p_t\,d\phi} \propto 1 + 2\,\mathbf{v_2(p_t)}\,\cos(2\phi) + \dots$$







Pantha Rei: RHIC and LHC matter flow!

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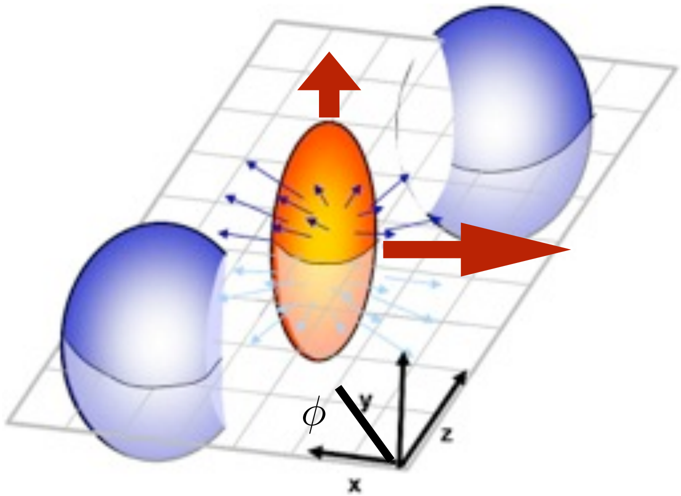
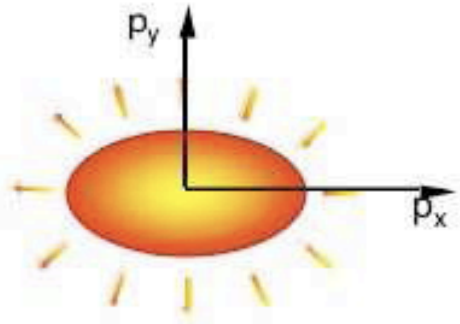
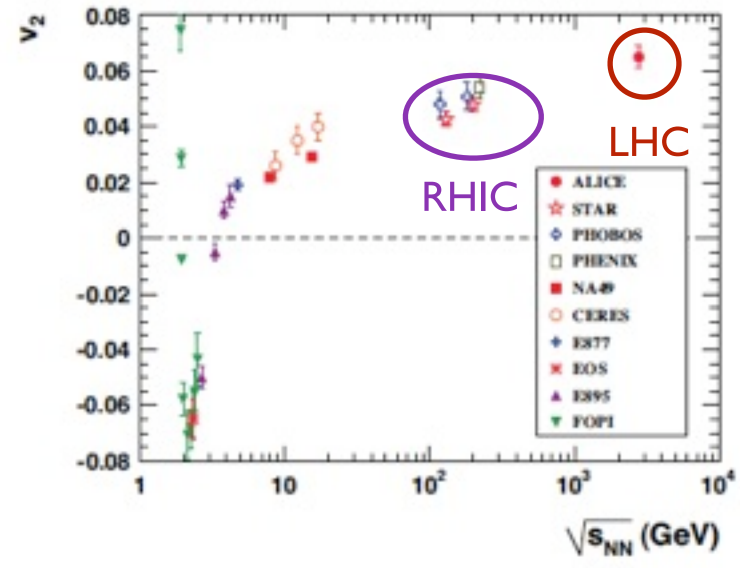
Elliptic flow







⇒ The fireball expansion is very well described by Hydrodynamics:

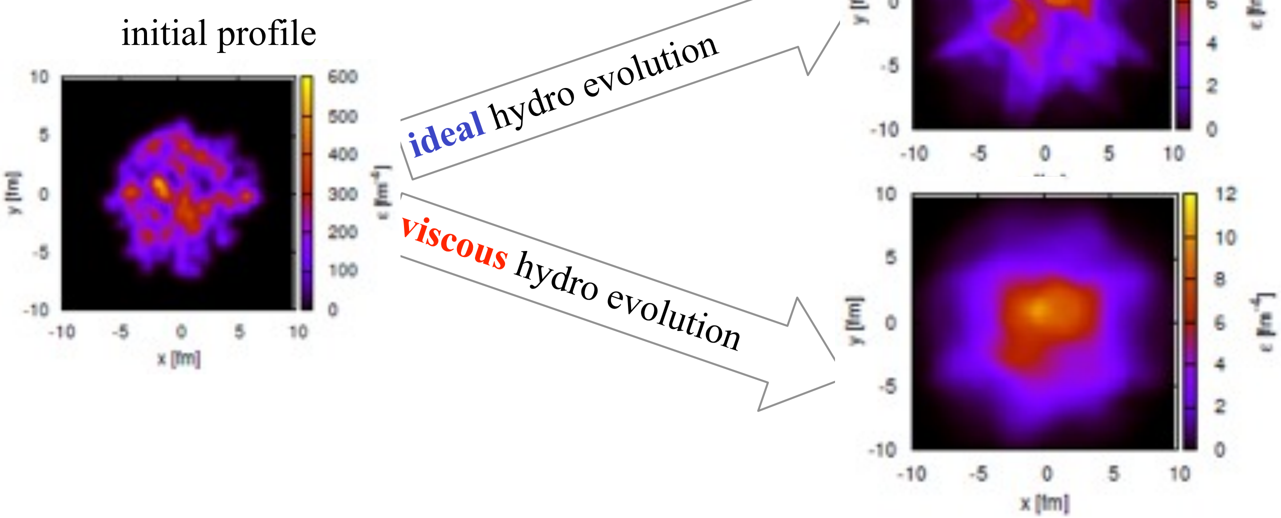
- energy-momentum + charge conservation
- local equilibrium + small mean free path
- Equation of state: e(p,T,μ)

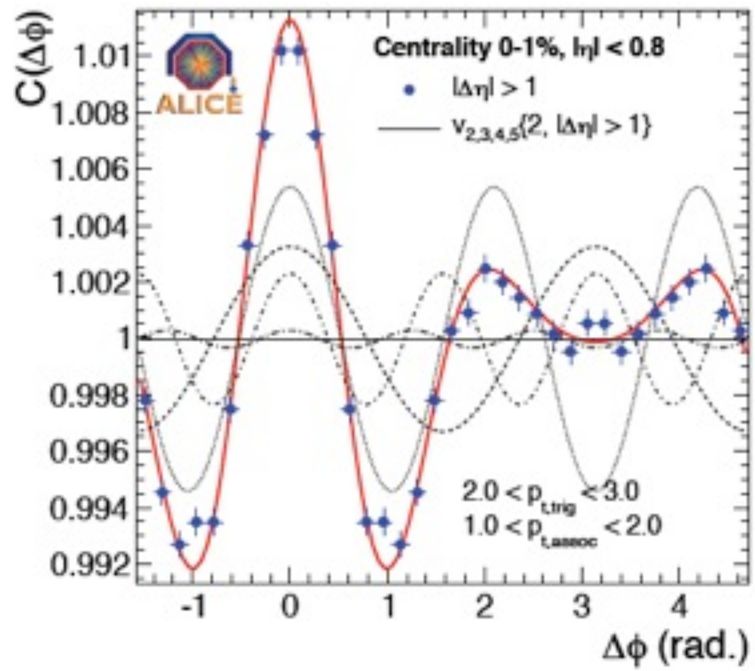
$$\partial_\mu T^{\mu\nu} = 0$$
$$\partial_\mu j^\mu_B = 0$$

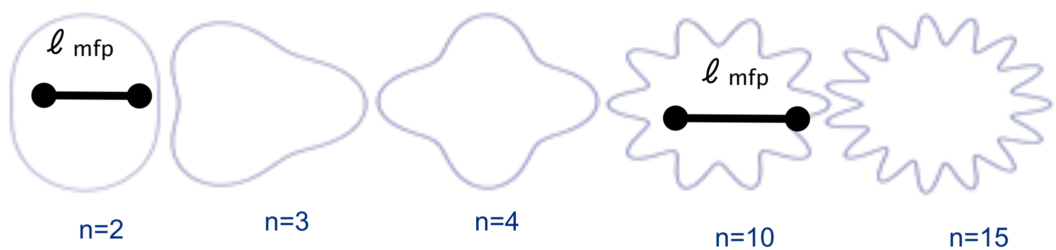
$$T^{\mu\nu} = \underbrace{[\epsilon(p,T) + p]\,u^\mu u^\nu - p\,g^{\mu\nu}}_{\text{ideal fluid}} \underbrace{+F(\nabla_\mu u^\nu; \eta; D \ldots)}_{\text{dissipative terms (viscosity...)}}$$

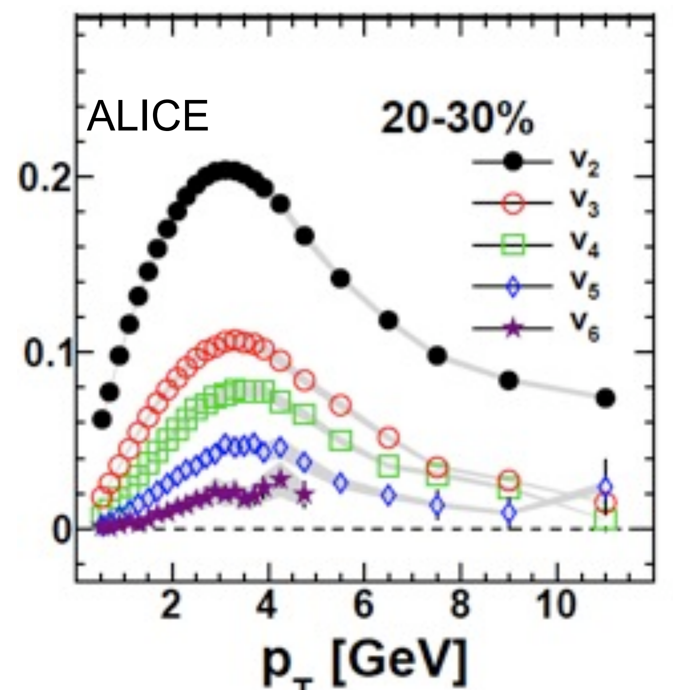
Flow: Geometry, fluctuations and higher harmonics

lumpy, fluctuating initial conditions









- Higher harmonics are more affected by dissipative effects

$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

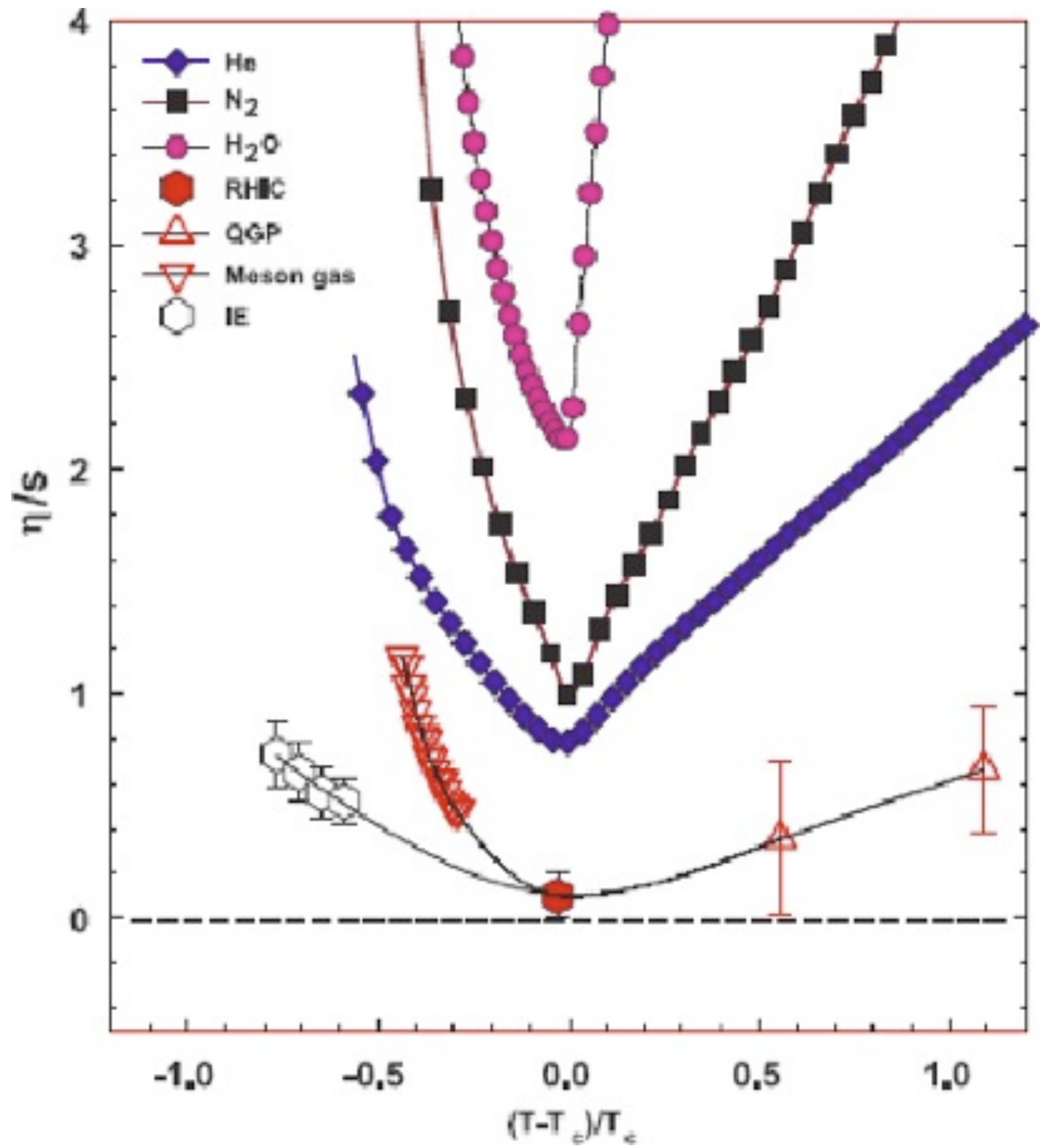
The most perfect fluid (smallest viscosity) ever measured!!

$$\eta / s \leq 5 \times (1/4\pi)$$

KKP bound derived
in the framework of the AdS/CFT
correspondence= 1/4Π

Small viscosity strongly
indicative of strong coupling
behaviour

The produced medium at RHIC
and the LHC is far from the
expected quasi-free QGP

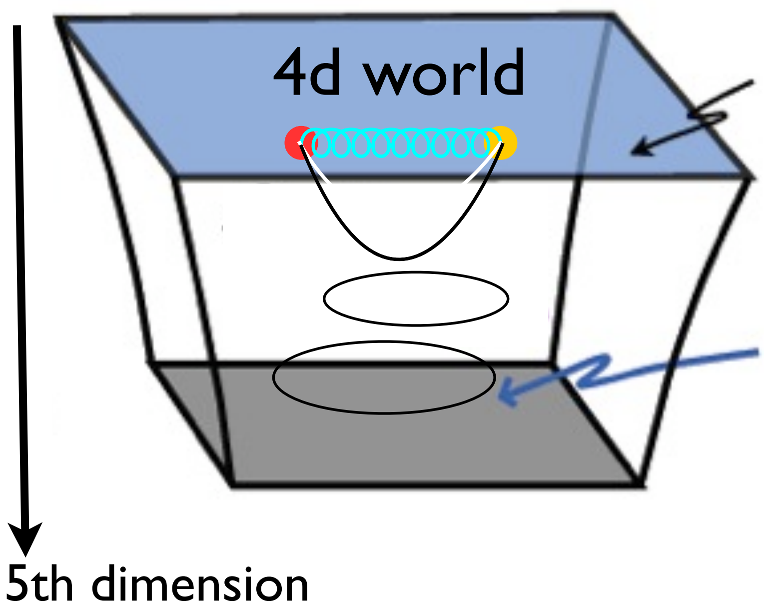


KKP bound

The String Connection (or the weird couple)

- So RHIC matter behaves like a strongly interacting system (perfect fluid, jet quenching..)
- So we need a formalism that allows to study strongly coupled systems in real-time formalism (Lattice QCD operates in imaginary time)

The Anti de Sitter / Conformal Field Theory Correspondance (AdS/CFT)



Weakly coupled supergravity in $AdS_5 \times S_5$ space ⟷ N=4 SYM in 4d

$$\lambda = g_s^2 N_c \rightarrow \infty$$

$$N_c \rightarrow \infty$$

Black brane along the fifth dimension ⟷ Finite-T system

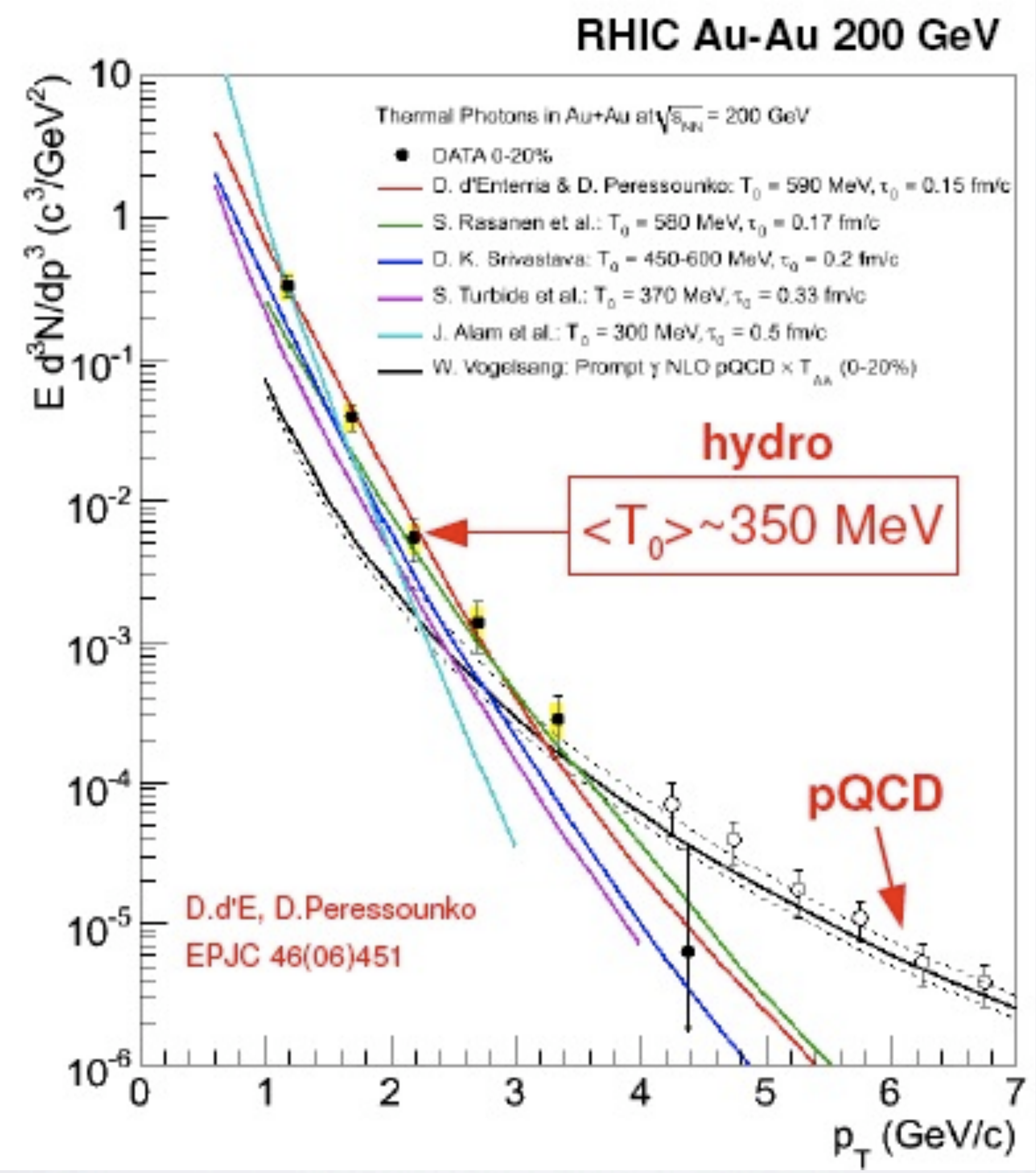
$$T = \frac{1}{\pi z_h}$$

Caveats: N=4 SYM is conformal. It is supersymmetric. It includes scalar and fermions. It has no charges in the fundamental representation (quarks)....

Used for: Studies of thermalization and onset of hydrodynamics behaviour, energy loss of soft and slow particles...

One step back: Does the medium really thermalize?

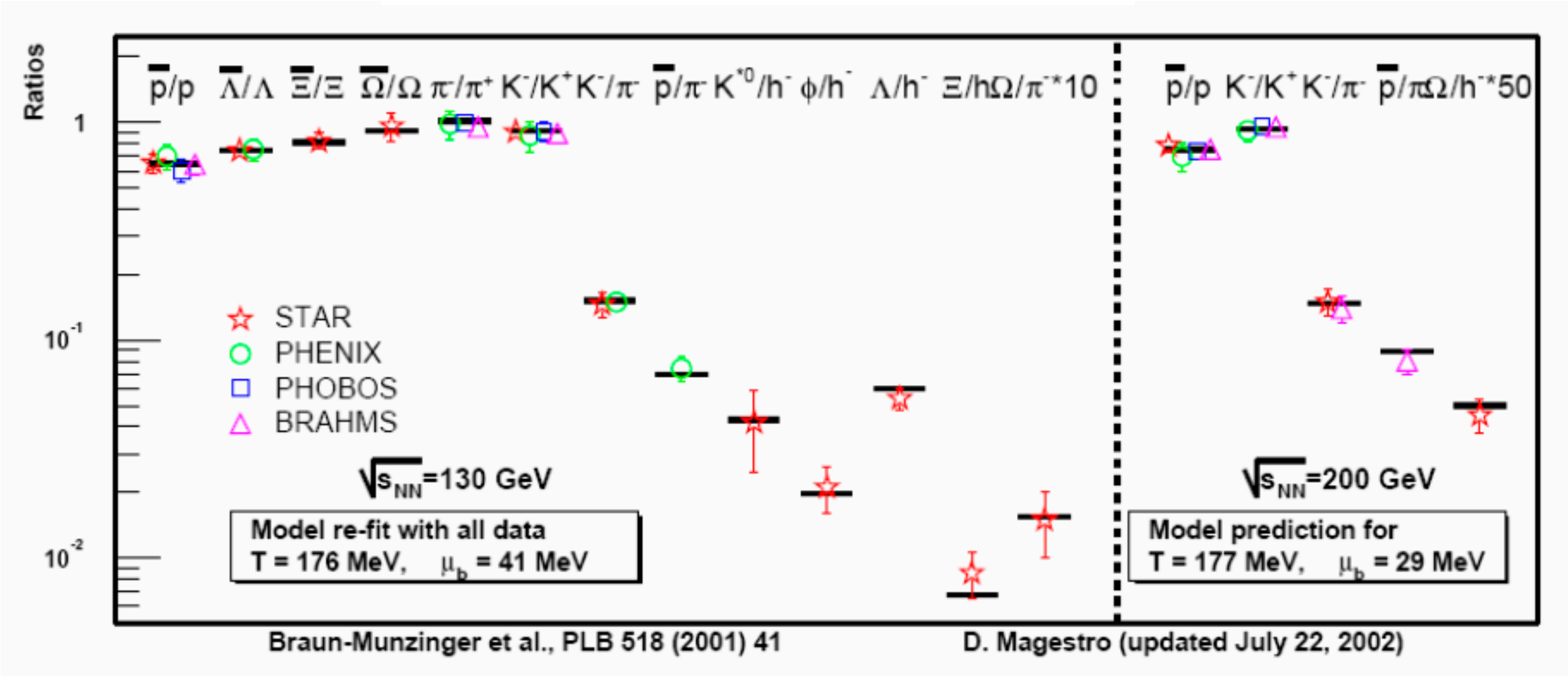
Photon spectrum: Thermal at low kt



One step back: Does the medium really thermalize?

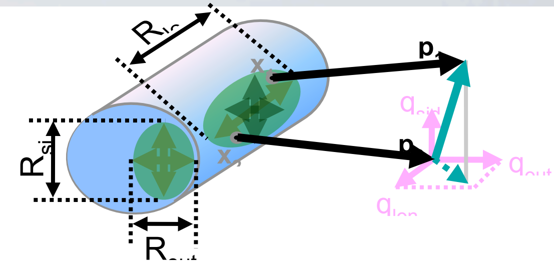
Relative abundances of different hadronic species well described in statistical models (grand canonical ensamble + chemical equilibrium)

$$N_i = V\, g_i \int \frac{d^3p}{(2\pi)^3} \frac{1}{\exp\left(\frac{E_i}{T} - \frac{\mu_i}{T}\right) - 1}$$ *for bosons*

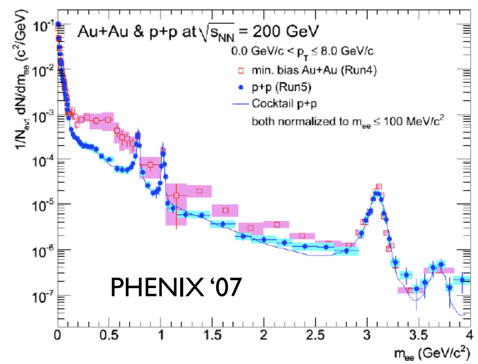


BUT: They also work in e+e- and pp(bar). Statistical nature of thermalization??

Soft sector: A lot more...

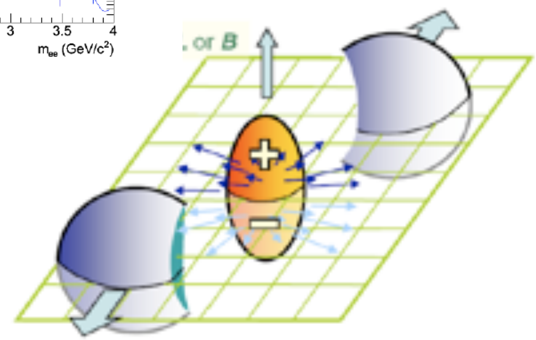


- **Femptoscopy:** Information about the dimensions of the region of particle production through
pion and kaon interferometry

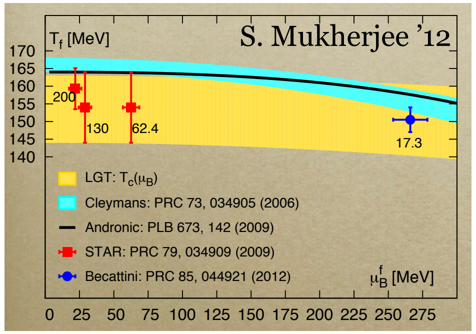


- **EM radiation:** Photon and low-mass dilepton emissions from the fireball

- **Searches for CP-Violation:** metastable domains where vacuum excitations violate parity could be created in Heavy Ion Collisions: *Another fundamental aspect of QCD probed with heavy ion collsions*



- **Fluctuations: search of the critical point:** Higher cumulants, kurtosis in particle correlations, susceptibilities...

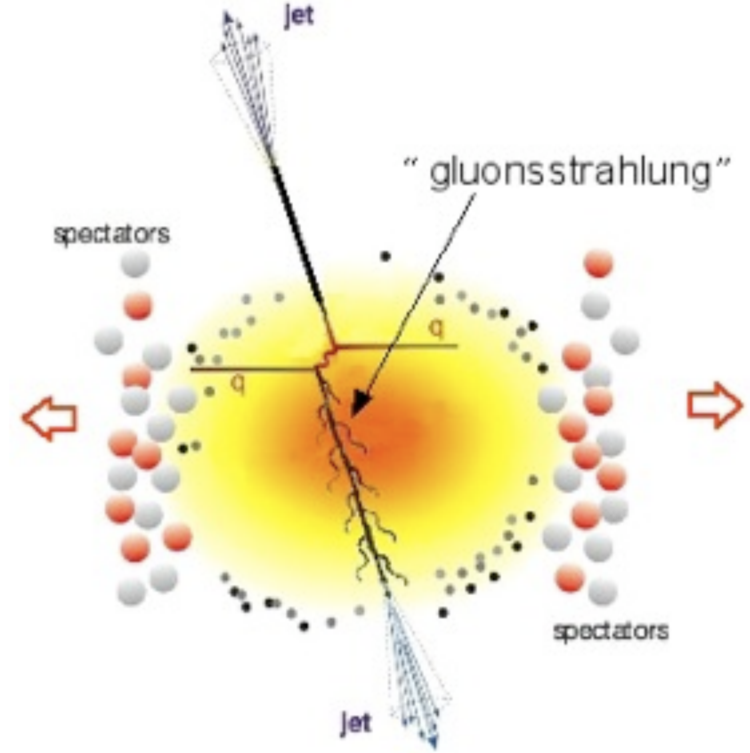


Hard Probes

- They serve as tomographic probes of the produced medium

- Their production rate is well understood in pQCD

- Main RHIC highlight: The produced medium is opaque to the propagation of colored particles



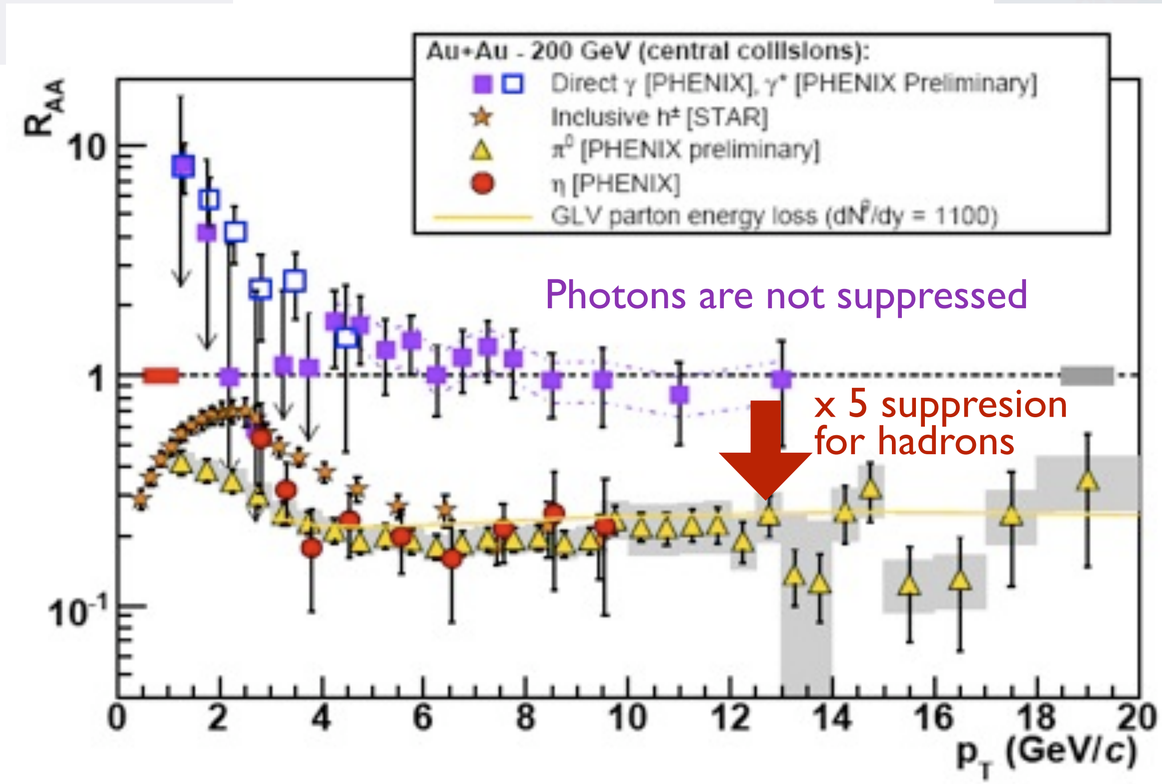
$$R_{AA}(p_T, b) = \frac{d\sigma_{AA}/dp_T d^2b}{T_{AA}(b) d\sigma_{pp}/dp_T}$$

Parton energy-loss

$$\langle \Delta E \rangle \propto \alpha_s C_R \langle \hat{\mathbf{q}} \rangle L^2$$

Transport coefficient

$$\hat{q} \simeq \text{a few GeV}^2/\text{fm}$$

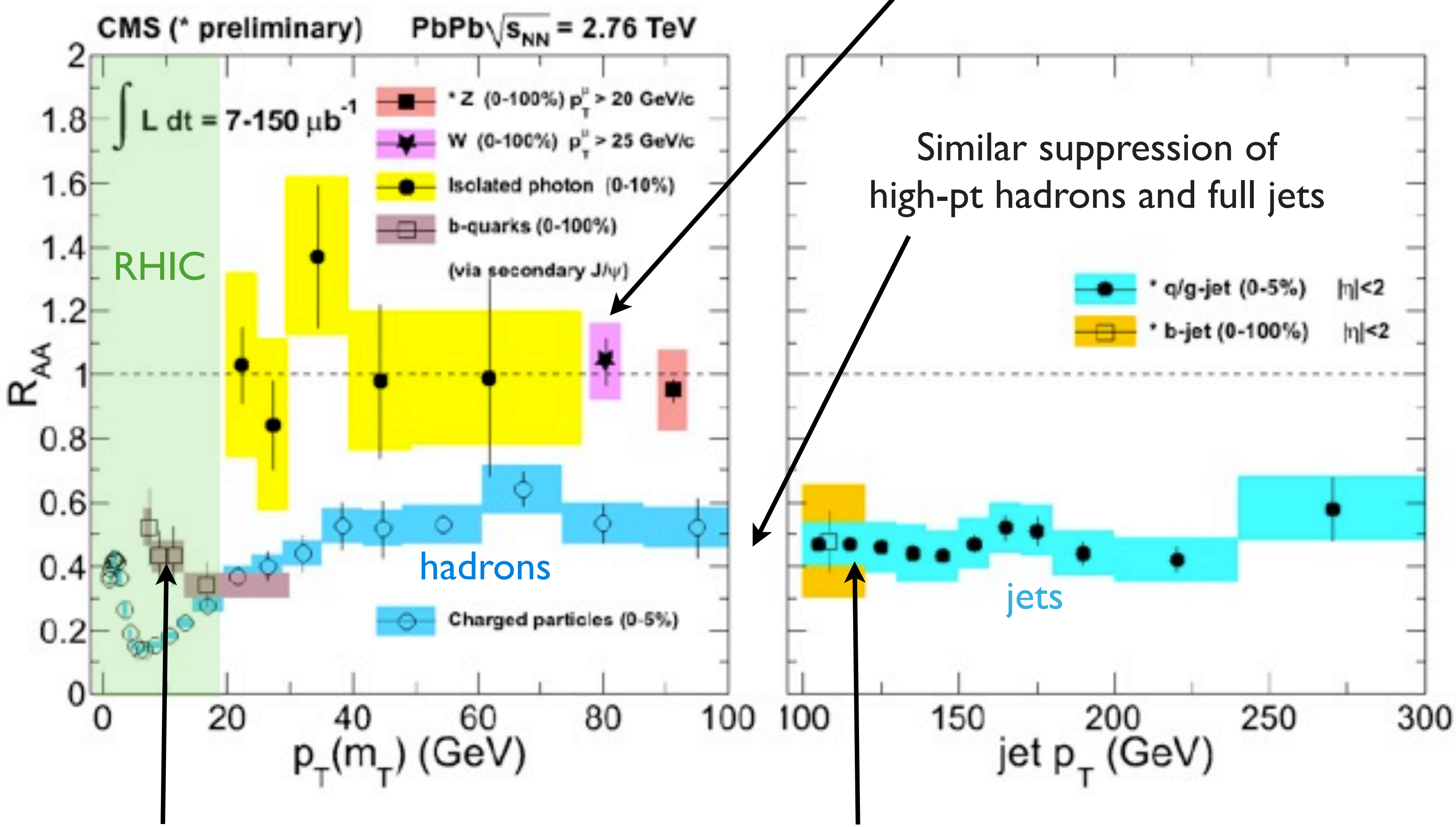


Hadron and Jet quenching at the LHC

$$R_{AA}(p_T, b) = \frac{d\sigma_{AA}/dp_T d^2b}{T_{AA}(b) d\sigma_{pp}/dp_T}$$

Confirmation of the factorization hypothesis

Colorless particles (γ, W, Z) unaffected by the medium

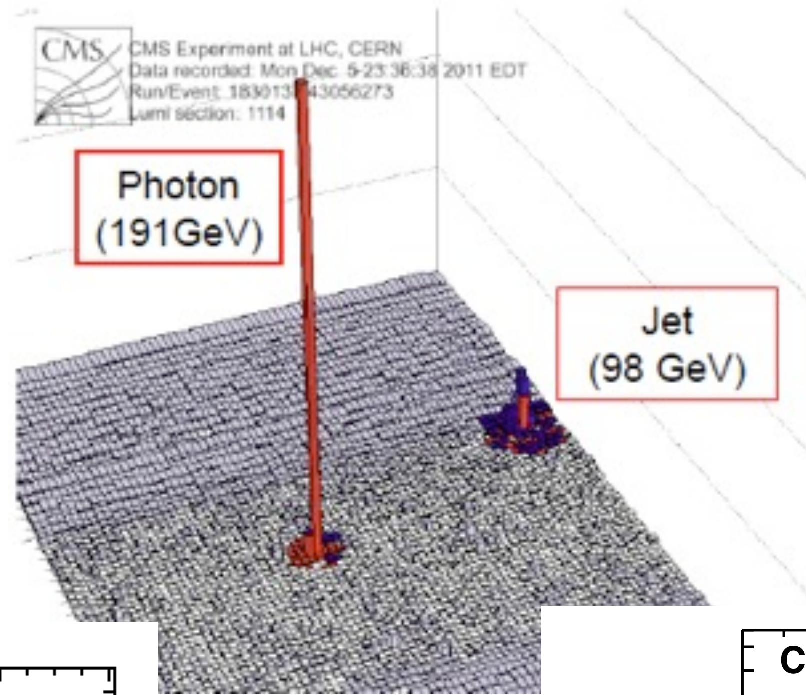


Distinct B-suppression pattern at small pt

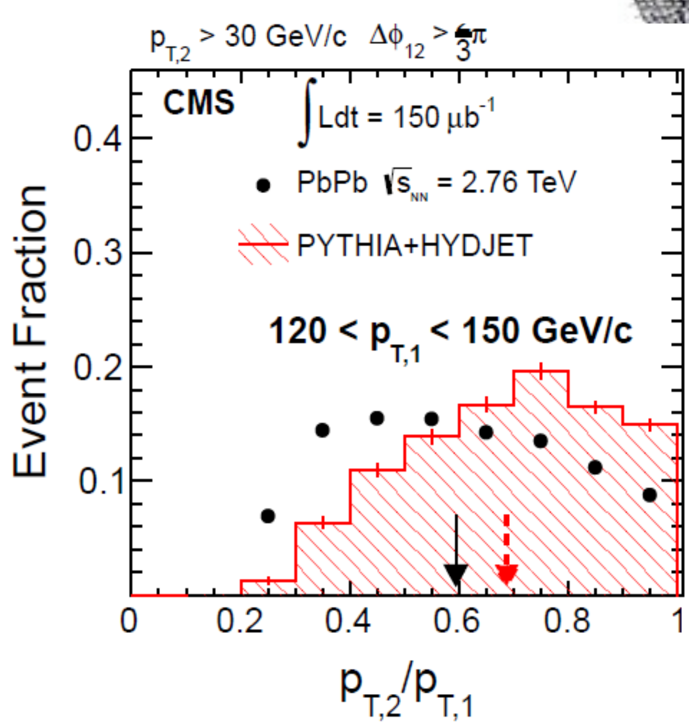
First observation of B-jet suppression

Jet Anatomy at the LHC

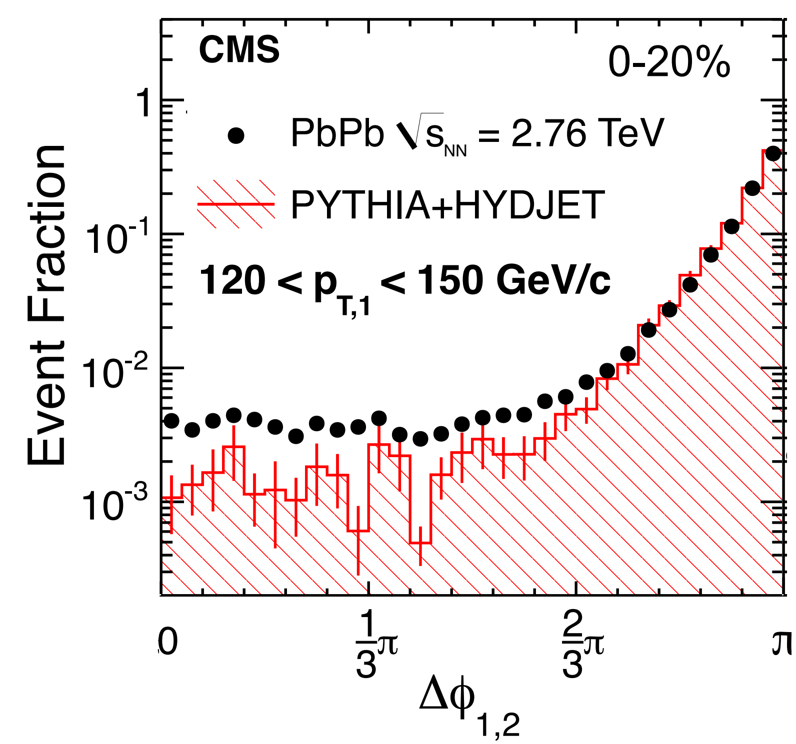
- Large fraction of pt-imbalanced pairs. Azimuthal correlation (*back-to-backness*) similar to p-p collisions
- (Hard part of) Jet fragmentation functions similar to vacuum.



momentum imbalance



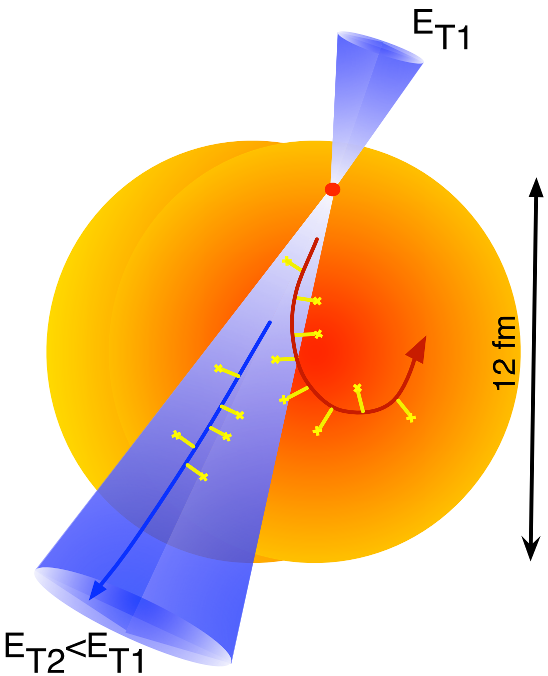
azimuthal correlation

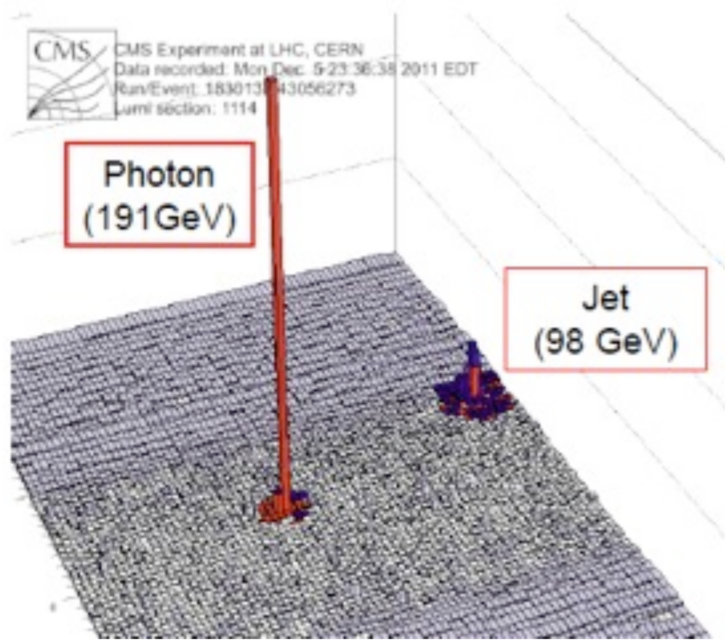


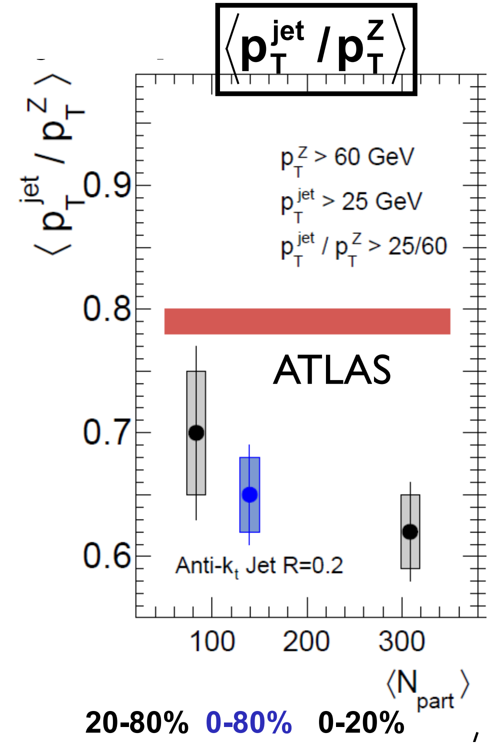
Jet Anatomy at the LHC

Dijet, photon-jet and Z-jet correlations:

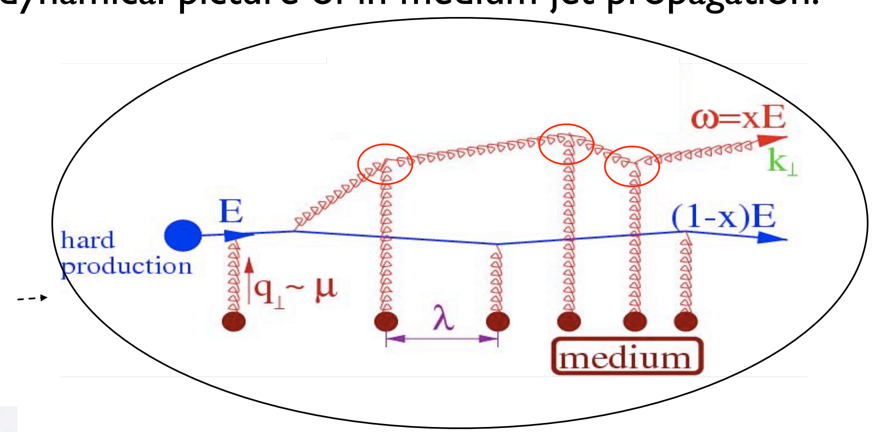
- Large fraction of pt-imbalanced pairs. Azimuthal correlation (*back-to-backness*) similar to p-p collisions
- (Hard part of) Jet fragmentation functions similar to vacuum.



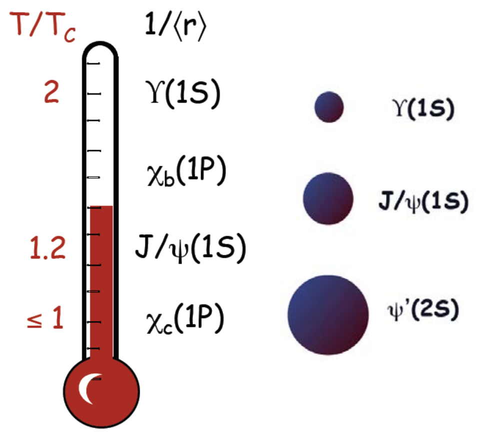


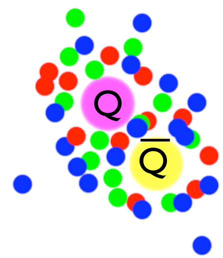


- Physical picture: soft components are transported out the jet cone by rescatterings with the medium
- Strong constraints of energy-loss models. Goal: to build a full dynamical picture of in medium jet propagation:
  - Coherence between emitters
  - Energy corrections
  - Color reconnections
  - Jet conversions
  - ...
  - Building practical MC analysis tools



Melting of Quarkonia States: A QGP Thermometer?



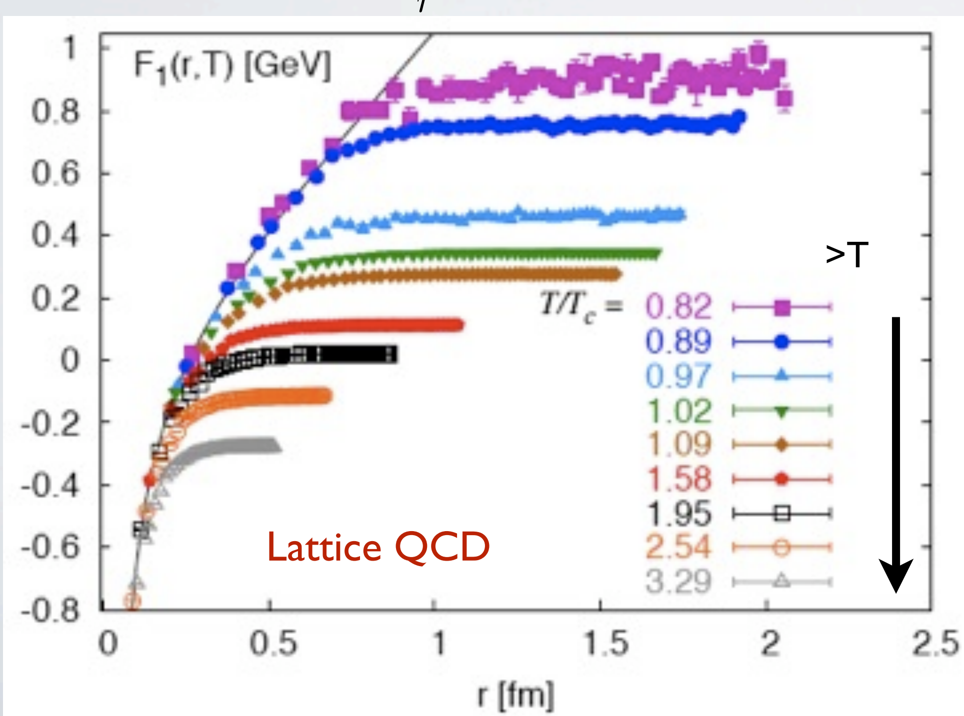


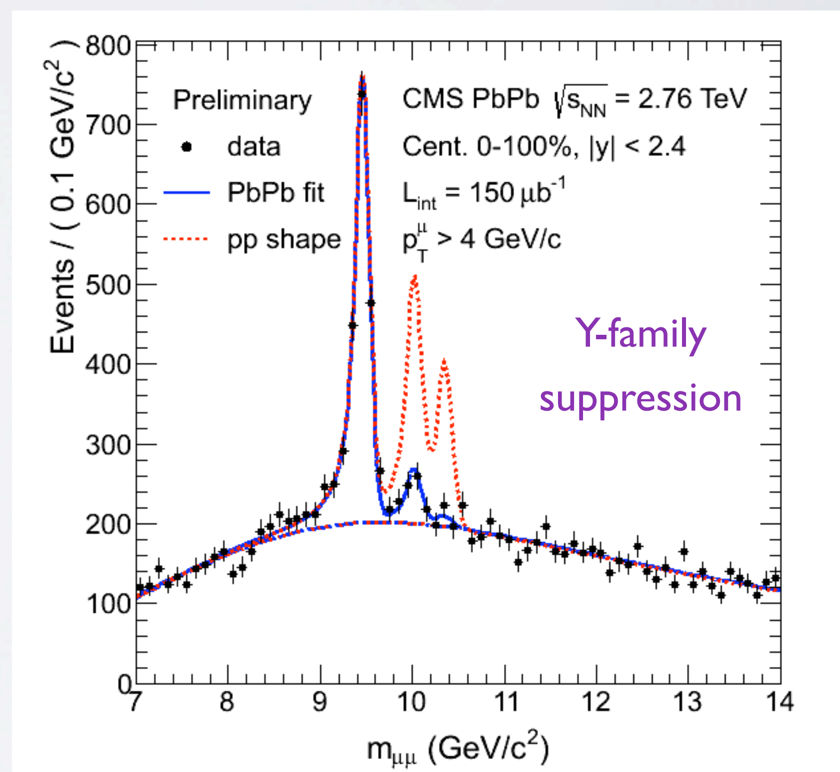
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

*From non-relativistic potential theory

- QQ (cc: J/ψ, ψ', χ$_{c...}$ and bb: Υ, Υ', χ$_{b...}$) states are expected to melt in the medium due to color screening.
- Sequential melting: QQ size~ $\dfrac{1}{E_{\rm bind}} \gtrsim r_{\rm Debye} \sim \dfrac{1}{gT}$ ~ medium resolution

$$V(r,T) \approx -\frac{\alpha_{eff}}{r} \exp[-m_D\, r] + K(T)\, r$$





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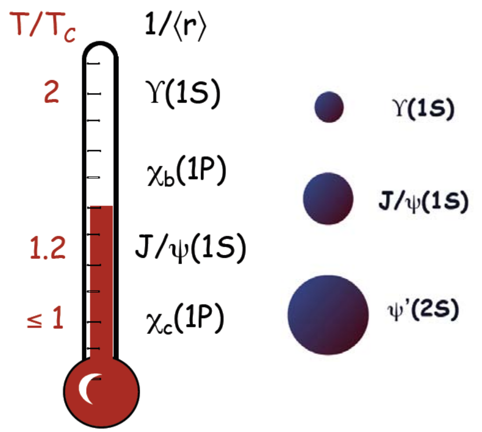

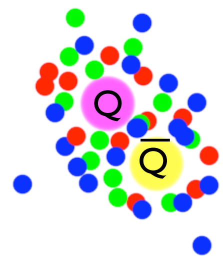

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radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

*From non-relativistic potential theory

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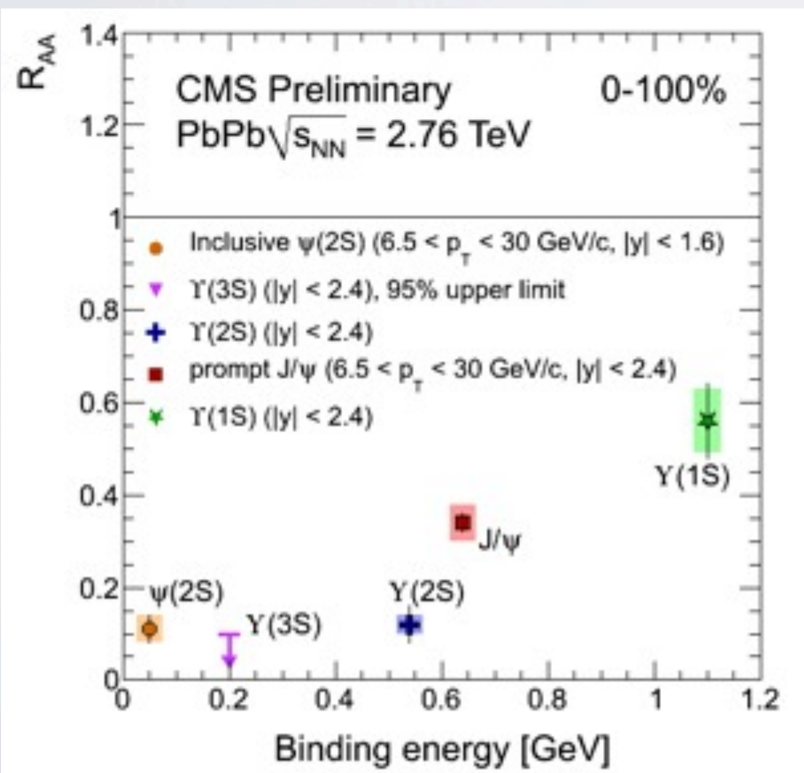


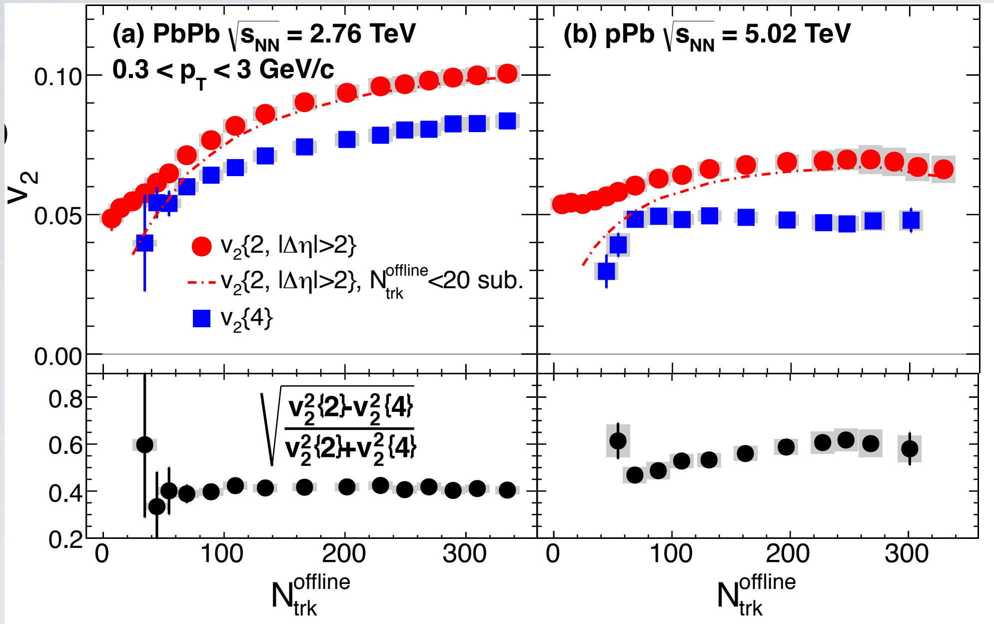
- Such a a picture starts emerging from data!!

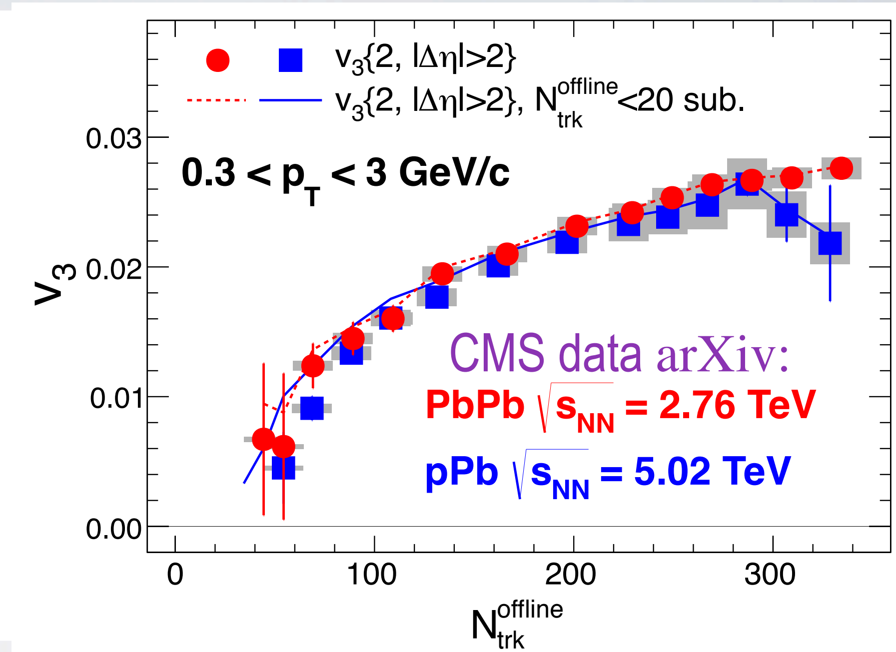
(a big) BUT!!:

- Kinematic cuts affect total yield reconstruction
- In-medium spectral functions (imaginary potential, Landau damping...) and transport not yet well understood.
- Other cold (shadowing, saturation, absorption) and hot (regeneration) effects not yet well understood
- When looked more differentially (pt-distributions, centrality dependence, flow etc) the whole picture does not quite fit yet

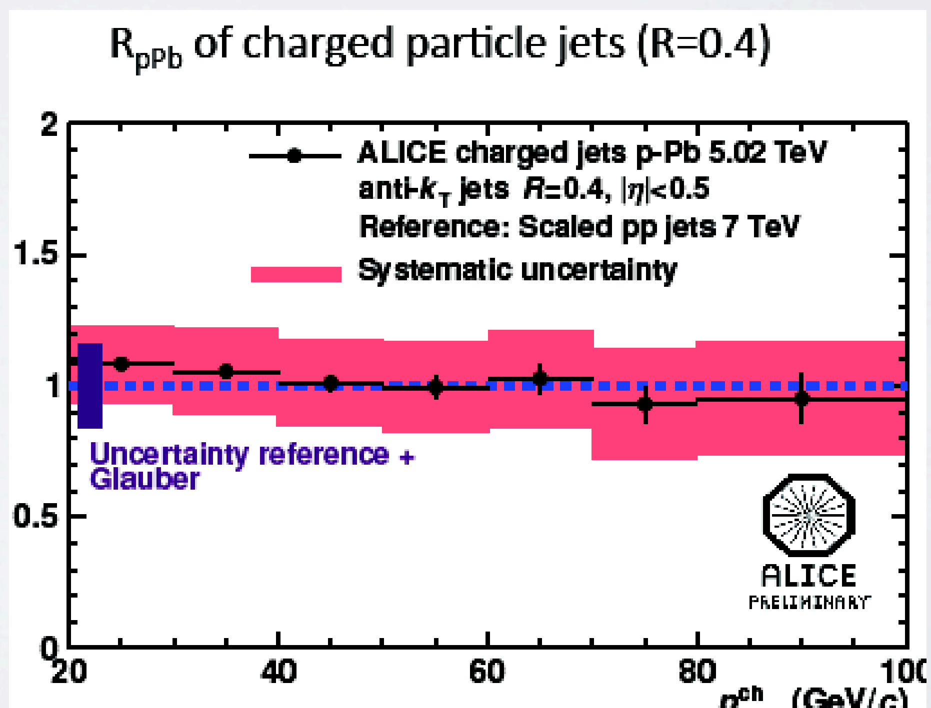
News from the p+Pb run at the LHC (2013)

The matter produced in p+Pb collisions flows!!





But it does not quench jets!!



Plans for the future

- ALICE, CMS and ATLAS at the Heavy Ion Town meeting, CERN 29 Jun 2012 *http://indico.cern.ch/event/HItownmeeting*
- ALICE, CMS and ATLAS contributions to the Preparatory Group for a European Strategy for Particle Physics

LHC:

- End of Phase0 (2010-2013).
  - 0.15 nb^{-1} in Pb-Pb coll $\sqrt{s_{NN}}$ = 5.5 TeV
  - Feb 2013: p-Pb run (5TeV, $\int dt\, L \sim 30nb$)

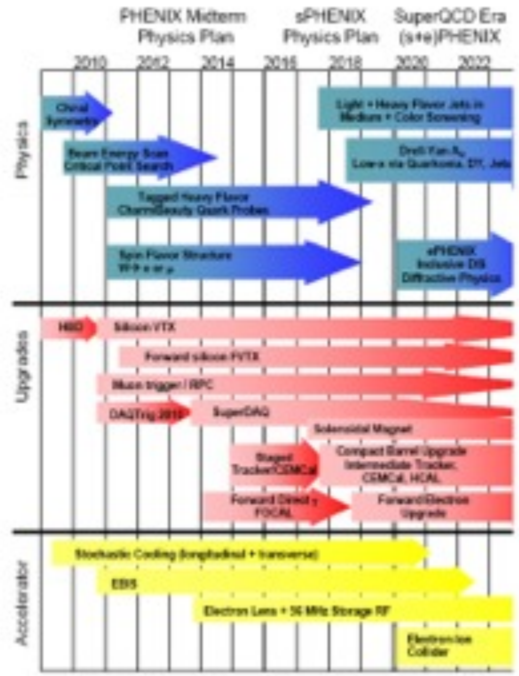
- 2013-2014: Long Shutdown 1.
  - ALICE, CMS and ATLAS detector upgrades

- Phase1 (2015-2017)
  - 1-3 nb^{-1} Pb-Pb at $\sqrt{s_{NN}}$ = 5.5 TeV
  - Reference data p-p, p-Pb $\sqrt{s_{NN}}$ = 5.5 TeV

- 2018 Long ShutDown2
  - Significant detector upgrades

- Phase2 (2019-beyond)
  - Luminosity increase to $6x10^{27} cm^{-1}s^{-1}$
  - Goal: **O(10 nb^{-1})** in Pb-Pb at $\sqrt{s_{NN}}$ = 5.5 TeV
  - Lighter nuclei

RHIC:



STAR Decadal Plan Synopsis

	Near term (Runs 11-13)	Mid-decade (Runs 14-16)	Long term (Runs 17-)
Colliding systems	p+p, A+A	p+p, A+A	p+p, p+A, A+A, e+p, e+A
Upgrades	FGT, FHC, RP, DAQ10K, Trigger	HFT, MTD, Trigger	Forward Instrum., eSTAR, Trigger
(1) Properties of sQGP	Υ, $J/\psi \to ee$, n_{ee}, v_2	Υ, $J/\psi \to \mu\mu$, Charm v_2, R_{CP}, Charm corr, Λ_c/D ratio, μ-atoms	p+A comparison
(2) Mechanism of energy loss	Jets, γ-jet, NPE	Charm, Bottom	Jets in CNM, SIDIS, c/b in CNM
(3) QCD critical point	Fluctuations, correlations, particle ratios	Focused study of critical point region	
(4) Novel symmetries	Azimuthal corr, spectral function	$e-\mu$ corr, $\mu-\mu$ corr	
(5) Exotic particles	Heavy anti-matter, glueballs		
(6) Proton spin structure	W A_L, jet and di-jet A_{LL}, intra-jet corr, $(\Lambda+\bar{\Lambda})$ D_{LL}/D_{TT}		Λ D_{LL}/D_{TT}, polarized DIS, polarized SIDIS
(7) QCD beyond collinear factorization	Forward A_N		Drell-Yan, F-F corr, polarized SIDIS
(8) Properties of initial state			Charm corr, Drell-Yan, J/ψ, F-F corr, Λ, DIS, SIDIS

- Focus on energy scan and varying initial conditions (nuclei) - Polarized target: Spin physics

Others: Planned facilities involving high-energy nuclear reactions **EIC** (Electron Ion Collider), **LHeC** (Large hadron-electron collider), **FAIR** (GSI; Facility for antiproton & ion research) would provide complementary studies.

Back up slides

Lattice QCD

• In the grand-canonical ensemble, the thermodynamical properties of a system in thermodynamical equilibrium are given by (see Karsch, Lecture Notes in Physics '02):

$$Z(T,V,\mu_i) = \mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}$$

$$P = T\frac{\partial \ln Z}{\partial V}, \quad S = \frac{\partial (T \ln Z)}{\partial T}, \quad N_i = T\frac{\partial \ln Z}{\partial \mu_i} \qquad \langle \mathcal{O} \rangle = \frac{\mathrm{Tr}\mathcal{O}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}{\mathrm{Tr}\exp\{-\frac{1}{T}(H - \sum_i \mu_i N_i)\}}$$

• With a rotation to Euclidean space -it→1/T and imposing (anti)periodic boundary conditions for (fermions) bosons,

$$Z(T,V,\mu) = \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}A^\mu \exp\{-\int_0^{1/T} dx_0 \int_V d^3x(\mathcal{L}_E - \mu\mathcal{N})\}$$

• The partition function may be computed perturbatively, or by discretization and Monte Carlo methods: lattice QCD.

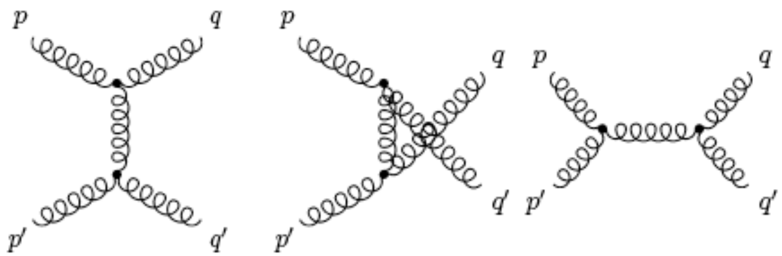
One step back: Does the medium really thermalize?

Transport models:

• Ideal hydro is the extreme version of transport for very large opacities. If thermalization/isotropization is not achieved, small deviations can be dealt with through viscous corrections, but large deviations require transport: relativistic Boltzmann equation.

$$f(\vec{p}, t, \vec{x}) \propto \frac{dN}{d^3p\, d^3x} \qquad\qquad p^\mu \partial_\mu f = -\mathcal{C}[f]$$

Collision term $C[f_p] = C_{gain} - C_{loss}$

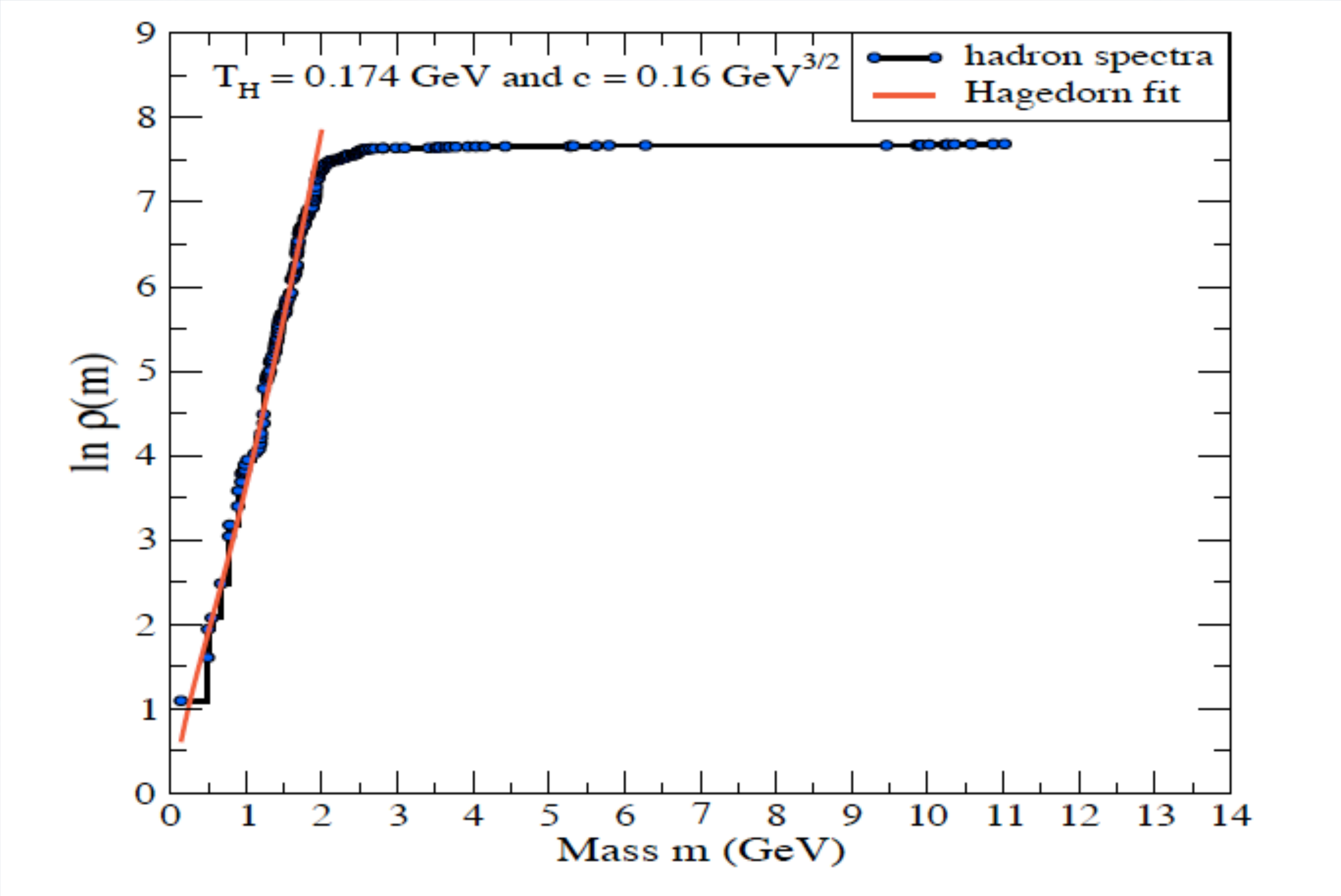


• Parton transport now includes 2↔2 and 2↔3 reactions (BAMPS)

accelerates isotropization.

• Hadron transport includes many reactions/species (AMPT, UrQMD).

Hagedorn Temperature

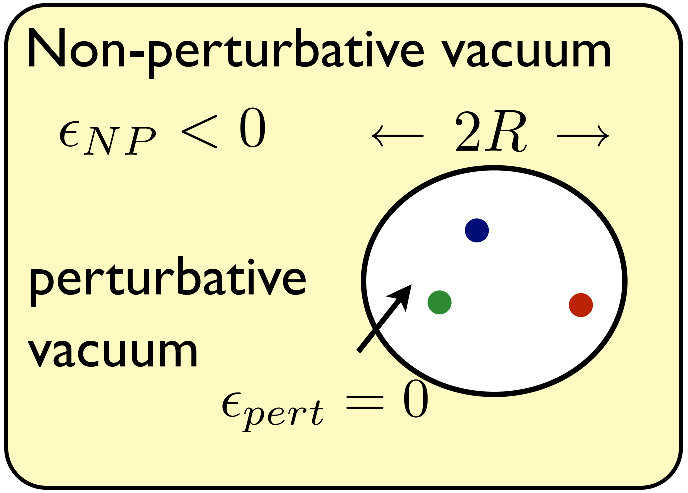


⇒Bag model: Hadrons are "droplets" of perturbative vacuum with quasi free quarks and gluons inside:

$$H_{bag} = H_{kin} + H_{bag} + \cdots \approx \frac{x}{R} + \frac{4}{3}\pi R^3 B + \ldots$$

Bag constant

$$B \sim \epsilon_{pert} - \epsilon_{Non-pert} \sim (250\,\mathrm{MeV})^4$$



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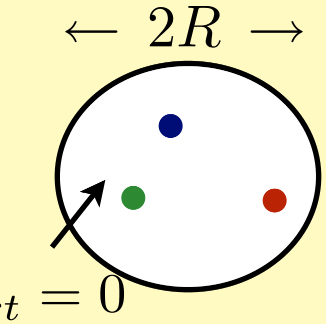
Bag constant

$$B \sim \epsilon_{pert} - \epsilon_{Non-pert} \sim (250\,\mathrm{MeV})^4$$

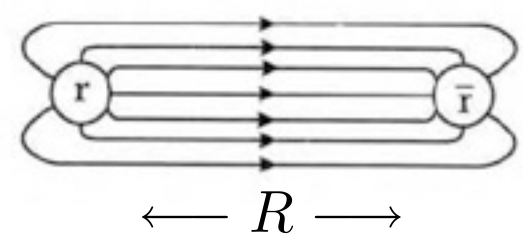
Non-perturbative vacuum

$\epsilon_{NP} < 0$



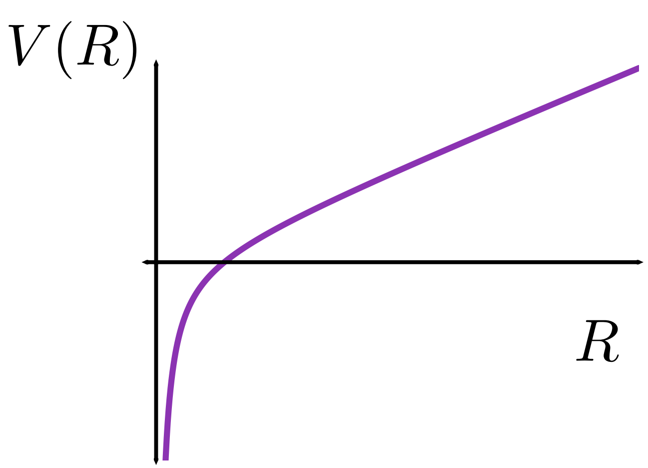
⇒ **Potential models.** Lines of color field are confined to flux tubes or strings

$$V(R) = -\frac{\alpha_{eff}}{R} + K\,R$$

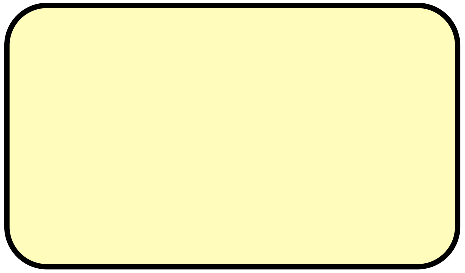


String tension:

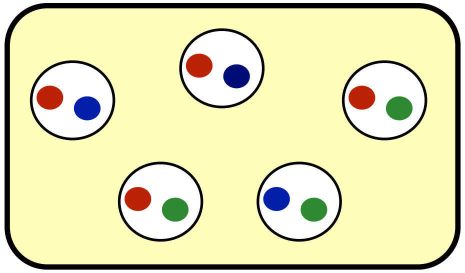
$$K \sim (420\,\mathrm{MeV})^2 = 900\,\mathrm{MeV\,fm}^{-1}$$



Vacuum at T=0



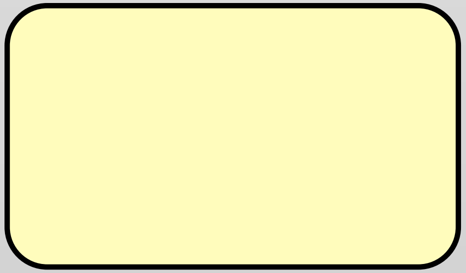
Pion Gas T>0



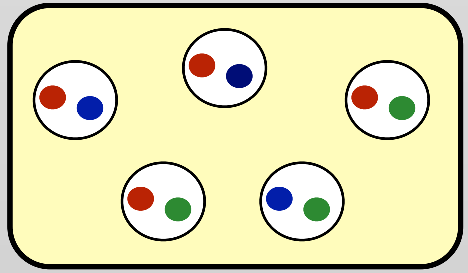
⇒ Pressure and energy density of ideal Bose (and Fermi) massless gas

Pion gas: $$p_\pi \approx d_\pi \frac{\pi^2}{90} T^4 , \quad \epsilon_\pi = 3\, p_\pi \, , \quad d_\pi = 3 \; (\pi^\pm, \pi^0)$$

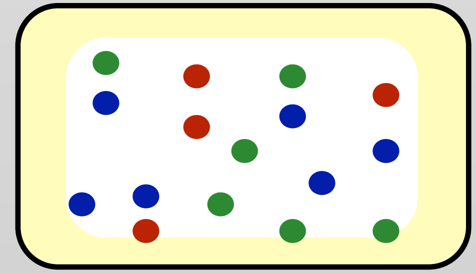
Vacuum at T=0



Pion Gas



Quark-Gluon Plasma



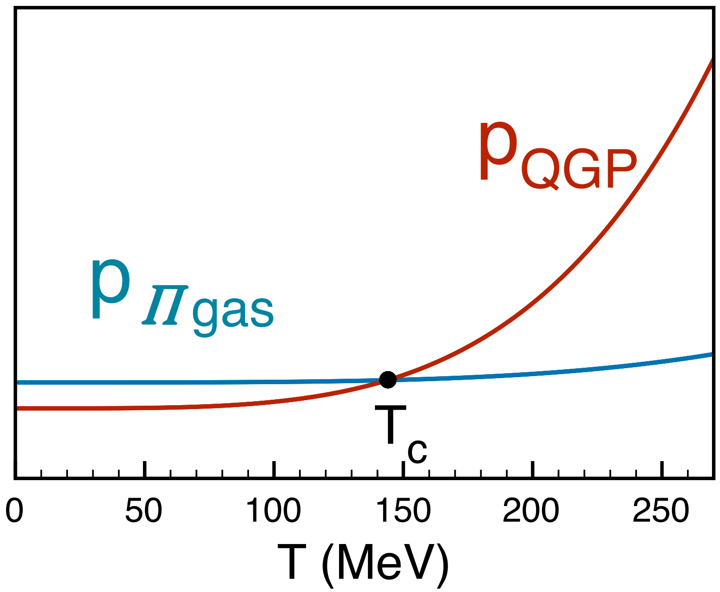
$\mathbf{d}_\pi = \mathbf{3} \rightarrow (\pi^+, \pi^-, \pi^0)$

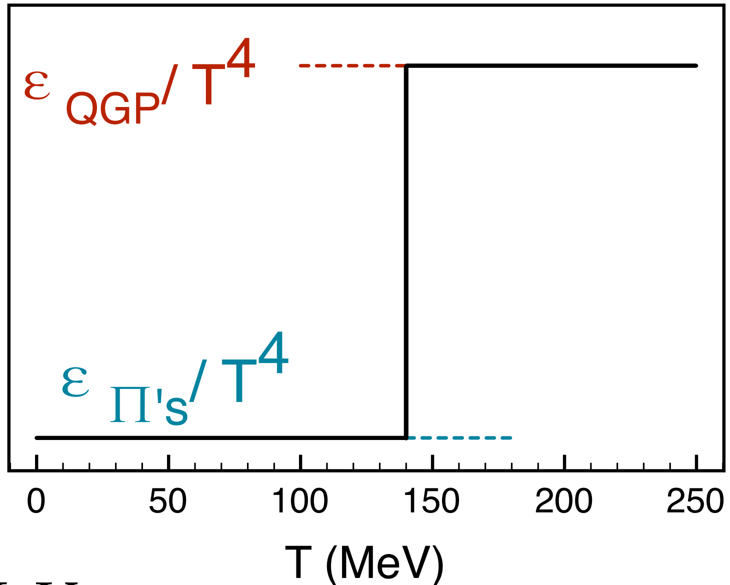
⇒ Pressure and energy density of ideal Bose (and Fermi) massless gas

Pion gas: $$p_\pi \approx d_\pi \frac{\pi^2}{90} T^4 \,, \quad \epsilon_\pi = 3\, p_\pi \,, \quad d_\pi = 3 \; (\pi^\pm, \pi^0)$$

QGP: $$p_{QGP} \approx d_{gq\bar{q}} \frac{\pi^2}{90} T^4 - B \,, \quad \epsilon_{QGP} \approx d_{gq\bar{q}} \frac{\pi^2}{30} T^4 + B$$

$$d_{gq\bar{q}} = d_g + \frac{7}{8} d_{q\bar{q}} = 2_s \cdot (N_c^2 - 1) + \frac{7}{8} \cdot 2_{q\bar{q}} \cdot 2_s \cdot N_c \cdot N_f = 37 \; (N_f = 2)$$





$$T_c \approx 140\,\mathrm{MeV}$$

Latent heat of the phase transition: $L = \epsilon_{QGP}(T_c) - \epsilon_{\pi's} \sim 4B \sim 1\mathrm{GeV\,fm}^{-3}$

Energy density of nuclear matter $\epsilon_{nm} \sim 0.15\,\mathrm{GeV\,fm}^{-3}$

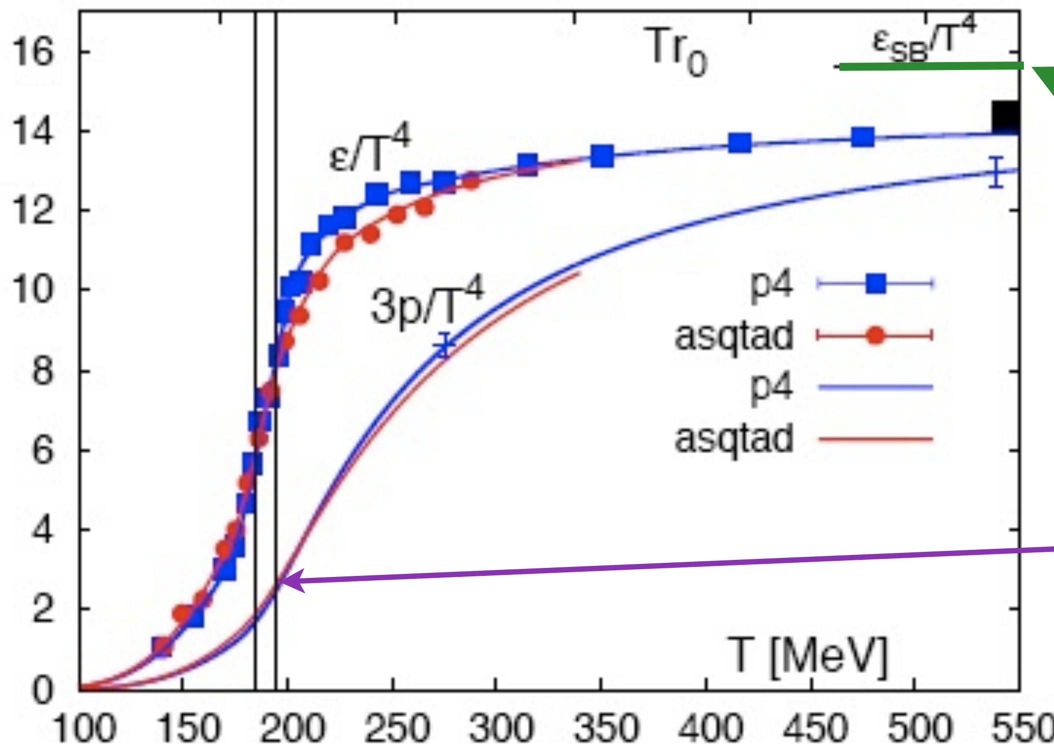
QGP $T_c^{QGP} \approx 170\,\mathrm{MeV} \sim 2 \cdot 10^{12}\,\mathrm{Kelvins}$

Sun core $T_{Sun} \sim 1.5 \cdot 10^7\,\mathrm{Kelvins}$

Córdoba $T_{\text{Córdoba}} \sim 10^3\,\mathrm{Kelvins}$

Results from Lattice QCD

Energy density & pressure



Stephan-Boltzman (ideal gas) limit

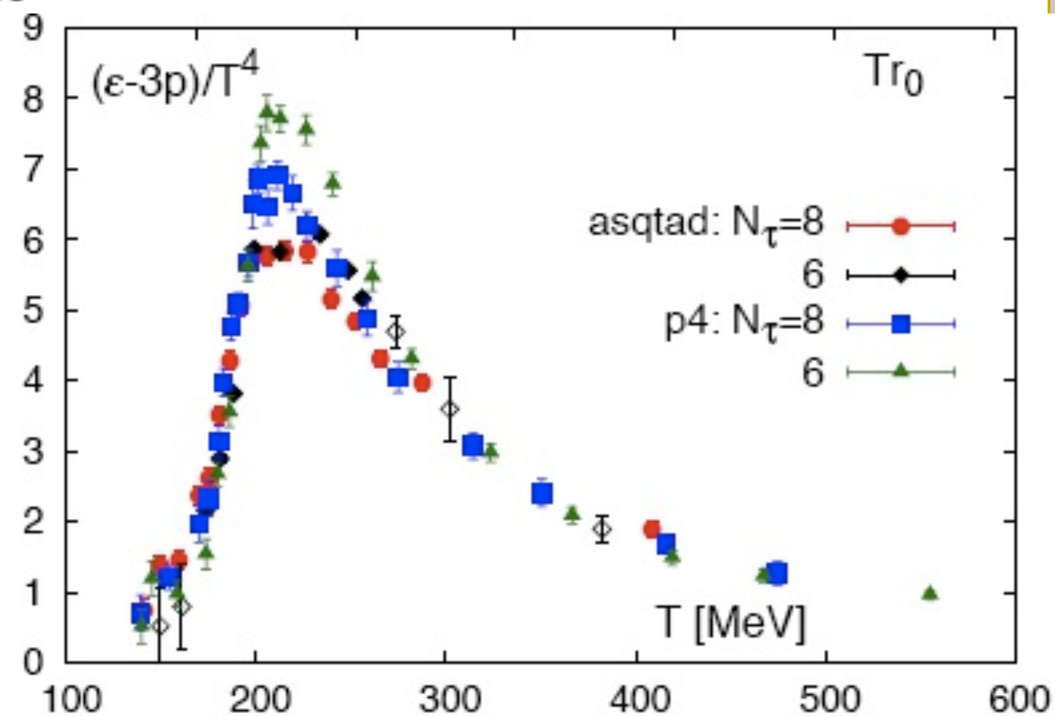
"Explosion" of degrees of freedom

$$T_c \approx 170 \div 180\,\mathrm{MeV}$$

For an ideal gas $\epsilon = 3p \sim T^4$

The "trace anomaly" $T^{\mu}_{\mu} = \epsilon - 3p$

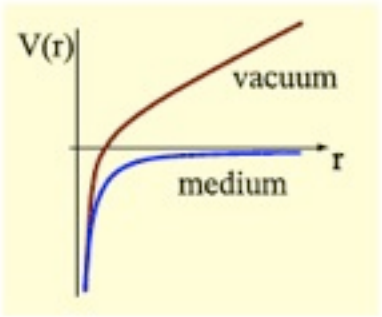
is a measure of the interaction
(and also of the degree of violation of scale symmetry)

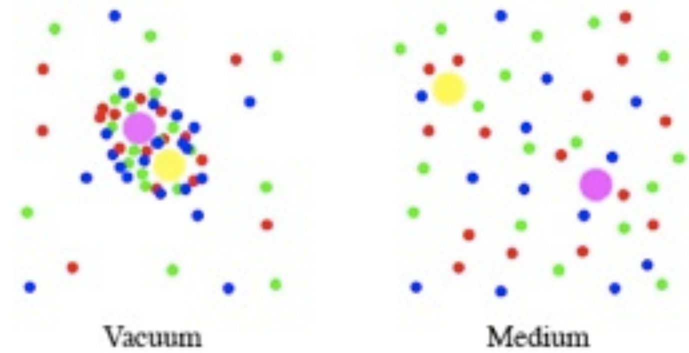


Debye screening of the heavy quark potential in the QGP phase

- The presence of free quarks and gluons around a heavy quark pair screens the interaction.

- The string tension tension goes to zero





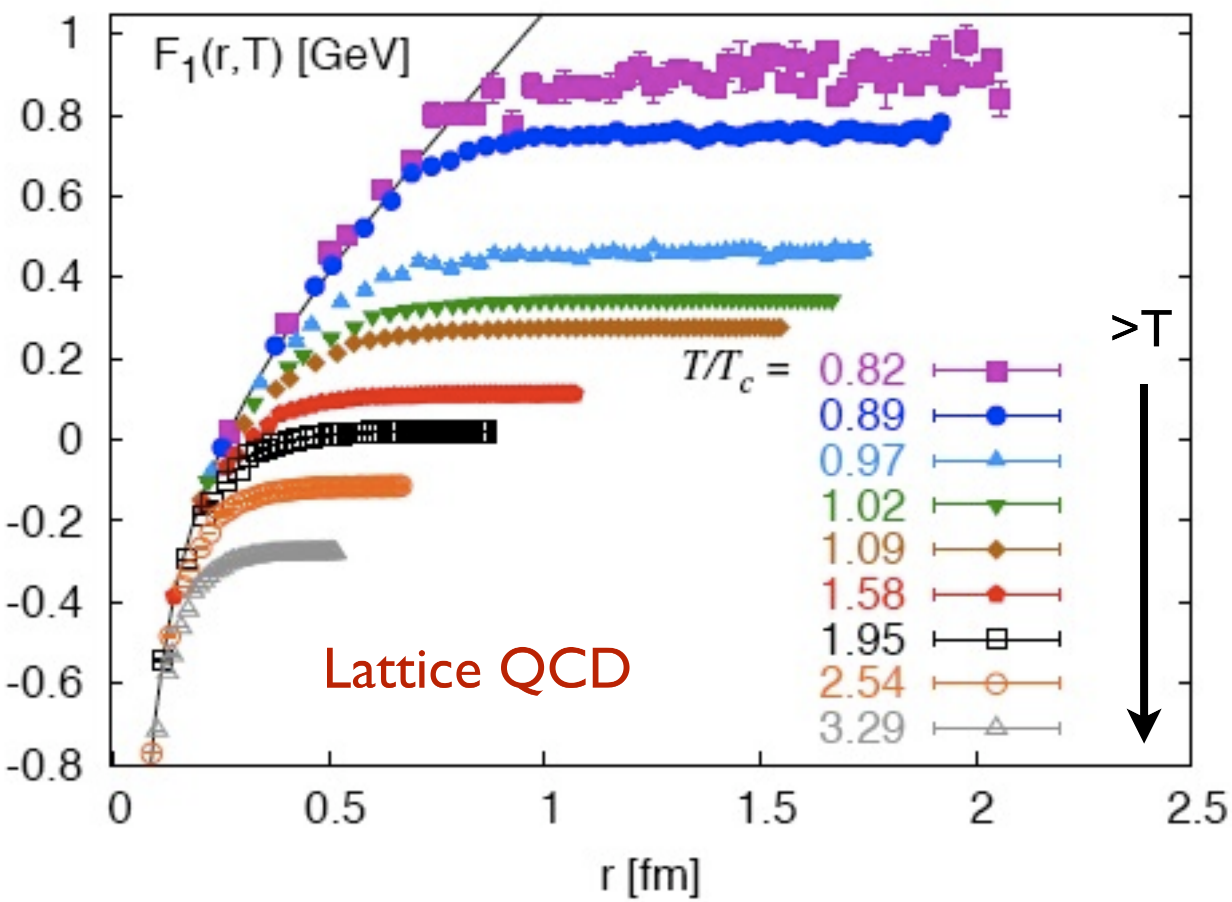
$$V(r,T) \approx -\frac{\alpha_{eff}}{r} \exp[-m_D\, r] + K(T)\, r$$

Debye mass

$$m_D^2 = \frac{N_c + \frac{1}{2} N_f}{3}\, g^2\, T^2$$

effective string tension

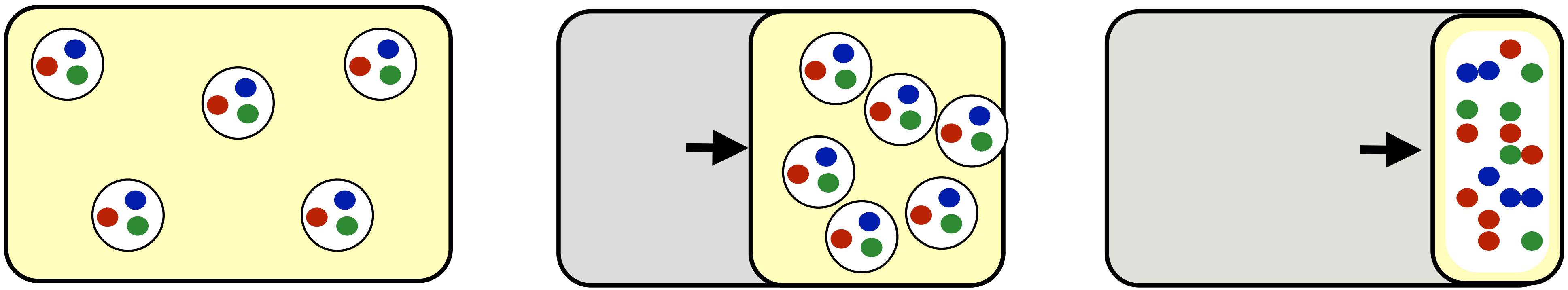
$$K(T) \to 0 \;\text{ for } T >> T_c$$



⇒Other way for the QGP: compressing nuclear matter at low temperatures

Baryon number density ~ Baryochemical potential

$$n_B = \frac{1}{3}\frac{N_q - N_{\bar{q}}}{V} = d \cdot \frac{T^3}{6}\left[\frac{\mu_B}{T} + \frac{1}{\pi^2}\left(\frac{\mu_B}{T}\right)^3\right]$$



$\mu_B < \mu_{Bc}$ $\qquad$ $\mu_B > \mu_{Bc}$

Pressure of a Fermi gas:

$$p_F = d \cdot \frac{T^4}{3}\left[\frac{7\pi^2}{120} + \frac{1}{4}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{8\pi^2}\left(\frac{\mu_B}{T}\right)^4\right]$$

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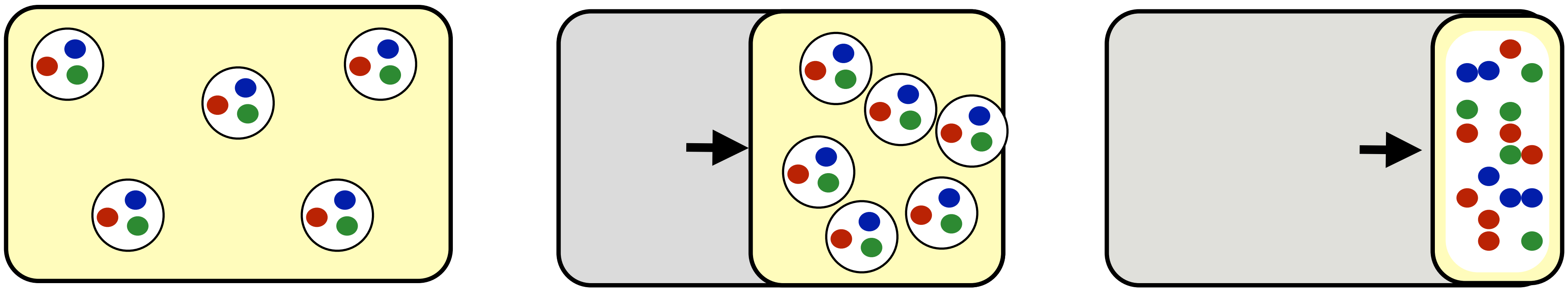

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Critical baryochemical potential for the QGP phase transition (T=0)

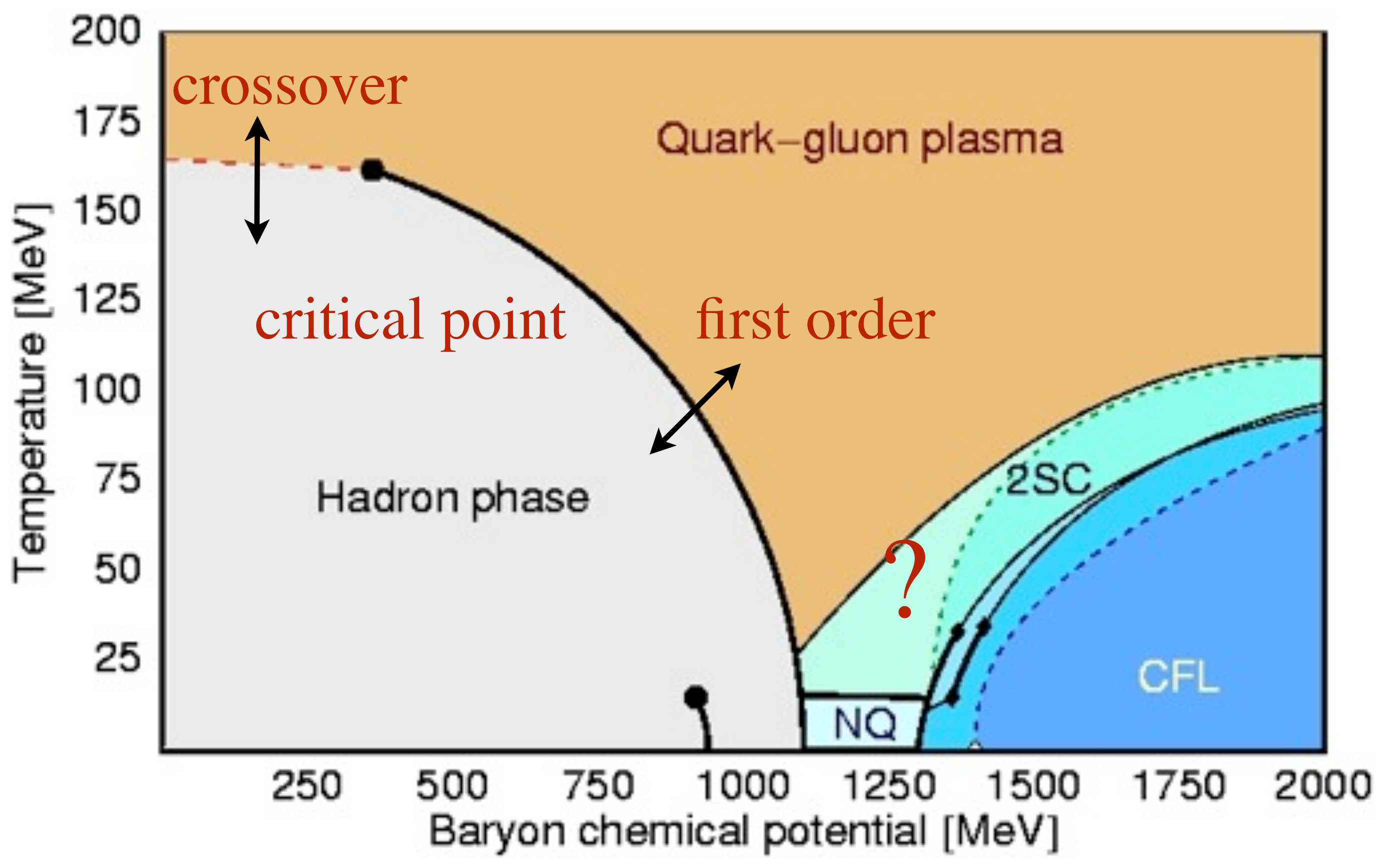
$$p_{q\bar{q}}(\mu_{Bc}) = B \implies \mu_{Bc} \approx 3\sqrt{\pi}\,B^{1/4} \approx 1.1 \;\; \mathrm{GeV}$$

Nuclear matter: $\mu_{B\,nm} \approx 0.9 \;\; \mathrm{GeV}$

Putting all together: The phase diagram of QCD

• At low the phase transition is smooth crossover between hadron gas and QGP. *More like melting butter*

• At larger the transition becomes first order. Existence of a critical point. *More like water-vapor transition*



• A number of phases, Color Superconductivity (2SC), Color Flavor Locked (CFL) ... have been proposed. Lattice methods not reliable ready in this regime ....

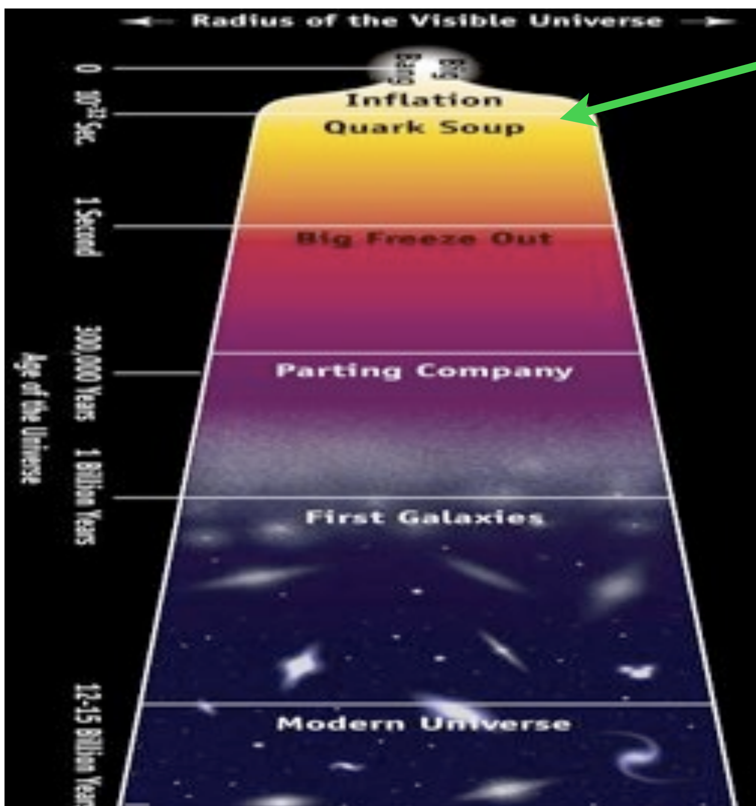
Where to find the QGP?

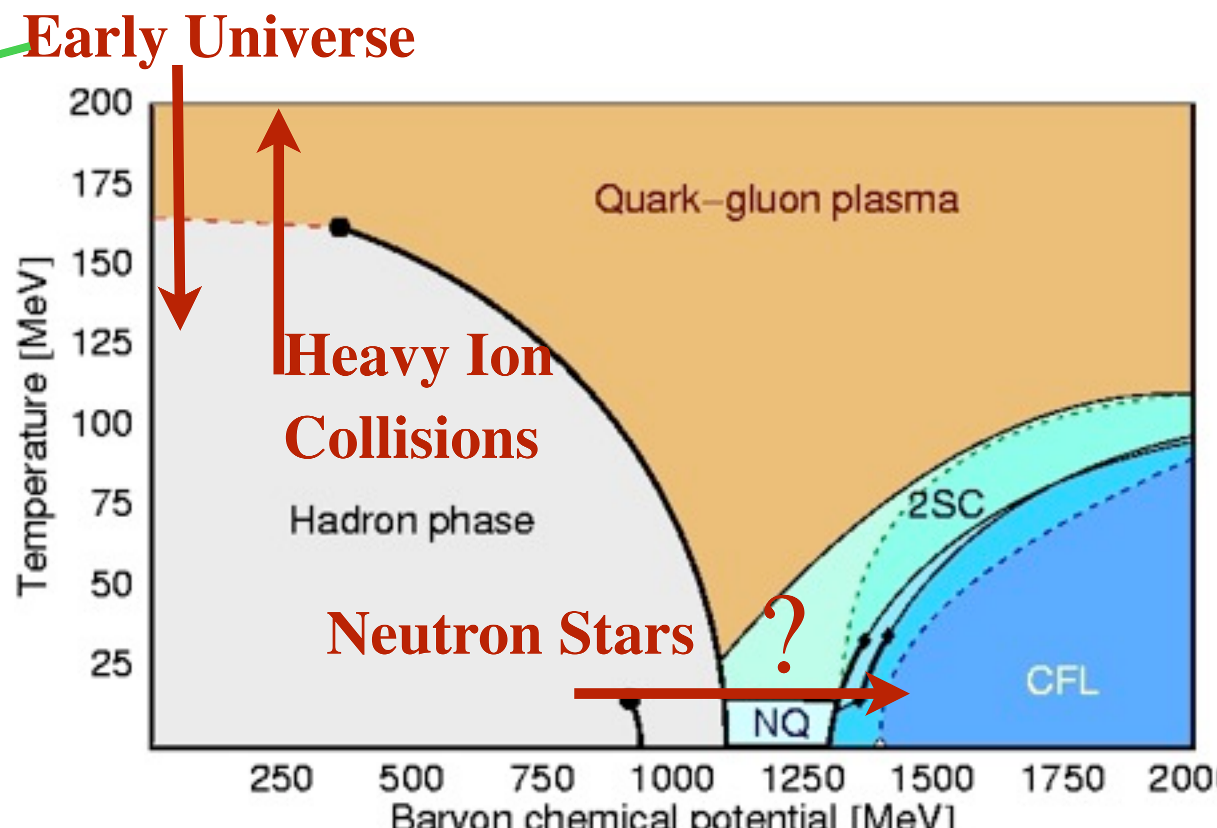
⇒Heavy ion collisions

⇒ Core of neutron stars may be composed "exotic" quark matter

$$M_{NS} \sim 1 \div 2\, M_{Sun}\,; \quad R_{NS} \sim 10\,\text{km}$$

⇒ Early Universe: The temperature of the Universe at time 10^{-4}~10^{-5} seconds was T_{univ}~ 200 MeV. It went through a phase transition from quarks and gluons to hadrons





Relativistic Heavy Ion Collider (RHIC)
Alternating Gradient Synchrotron (AGS)
@ Brookhaven National Lab (BNL)

Large Hadron Collider (LHC)
Super Proton Synchrotron (SPS)
@ CERN

	Lab	years	$\sqrt{s_{NN}}$ (GeV)	
AGS	BNL	87/99	5	
SPS	CERN	86/02	17	
RHIC	BNL	01/??	200	Au-Au, d-Au, p-p, Cu-Cu
LHC	CERN	??/??	5500	Pb-Pb, p-Pb, p-p

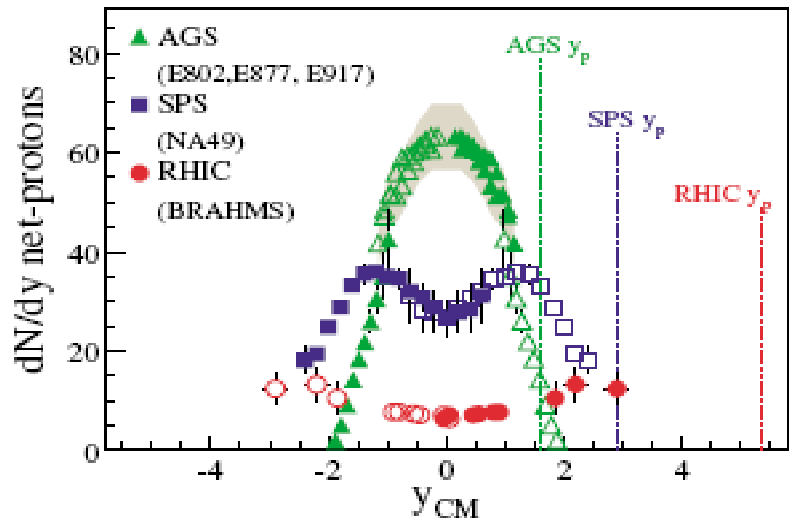
- First hints of QGP formation at SPS. More conclusice evidence obtained at RHIC
- Of the 4 big experimental collaborations at the LHC, one (ALICE) is fully dedicated to HIC. Other two (ATLAS and CMS) will perform related measurements

Locating HIC experiments on the QCD phase diagram:

- The baryon density in the midrapity region decreases with increasing collison energy

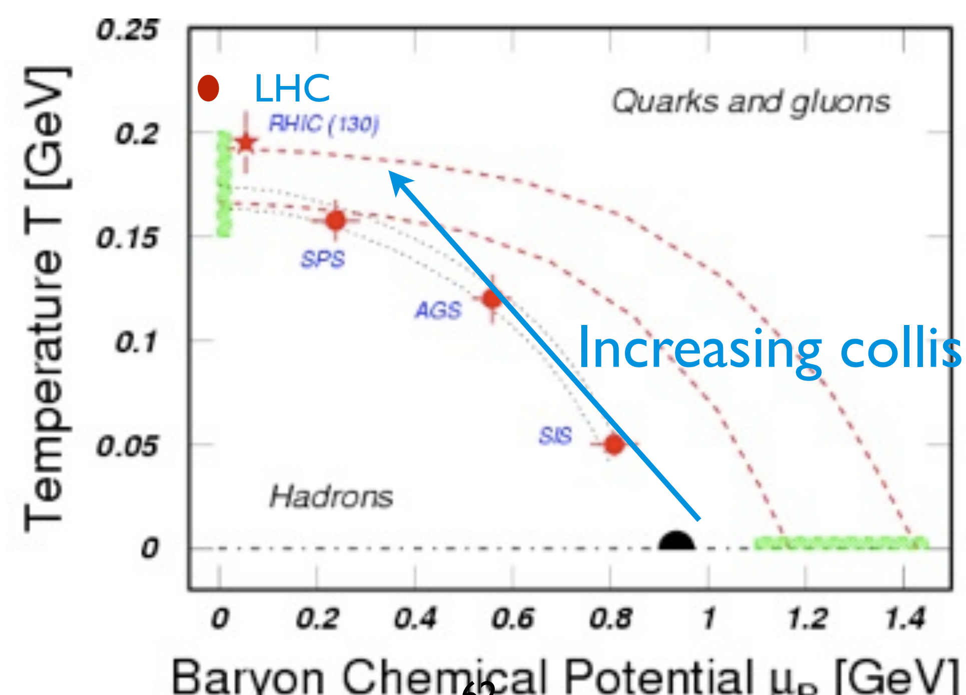
$$\eta = \ln \frac{p_0 + p_z}{p_0 - p_z}$$

High energy:
valence quarks are not
slowed down by the collison

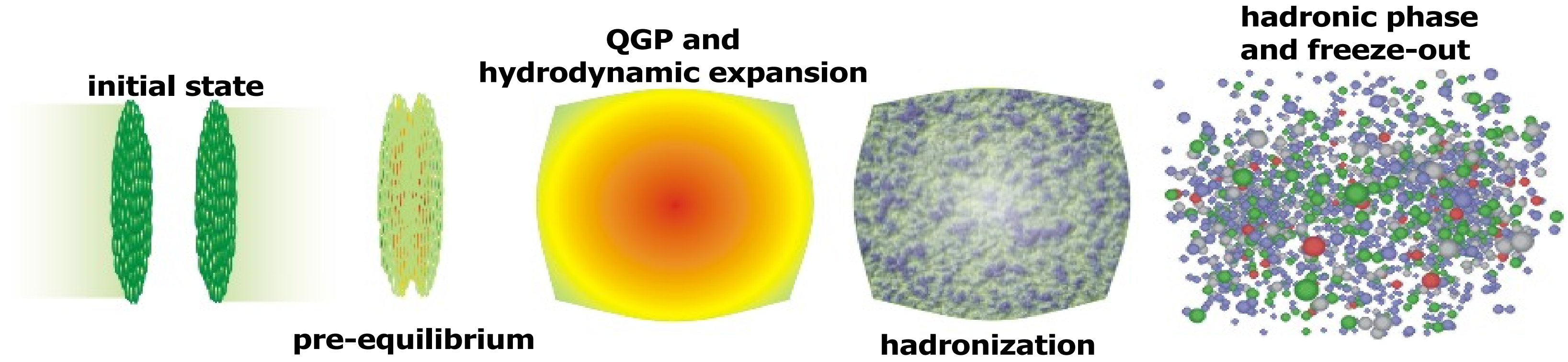


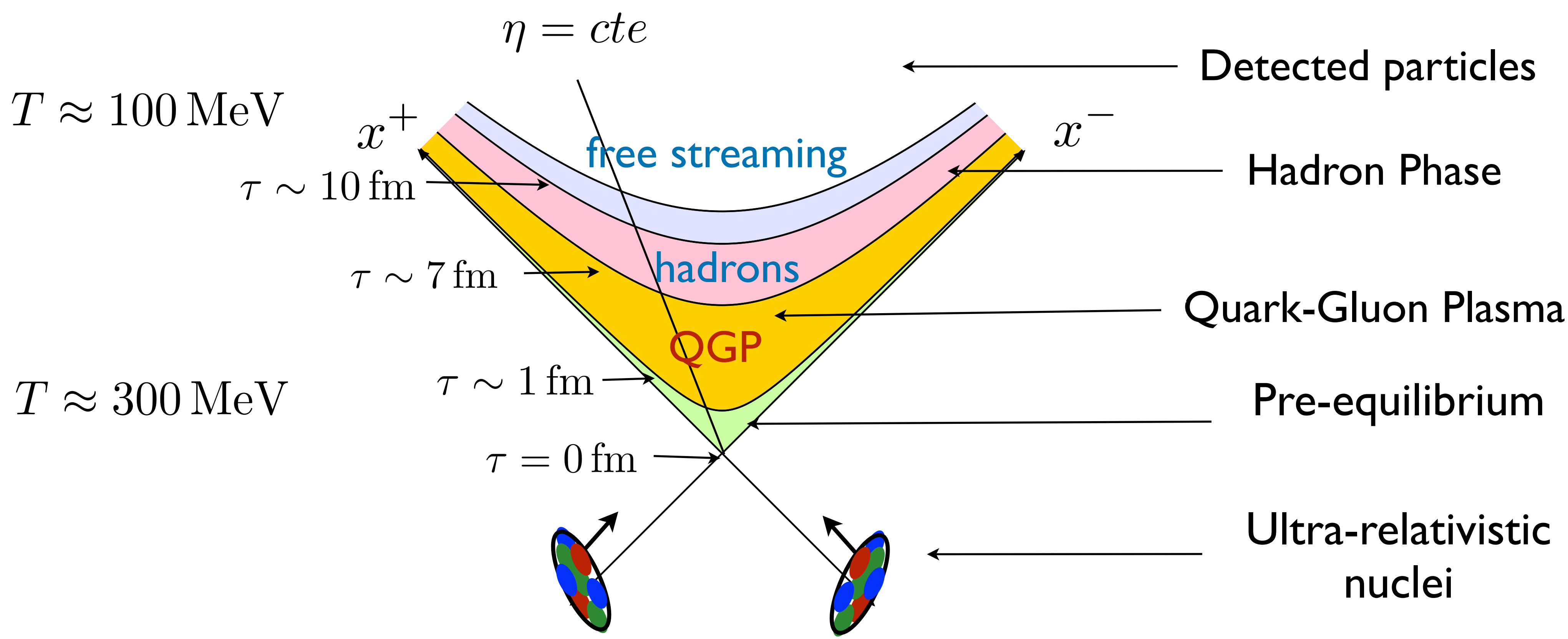
increasing collision energy

- The temperature increases with collision energy



Space-time view of heavy-ion collisions

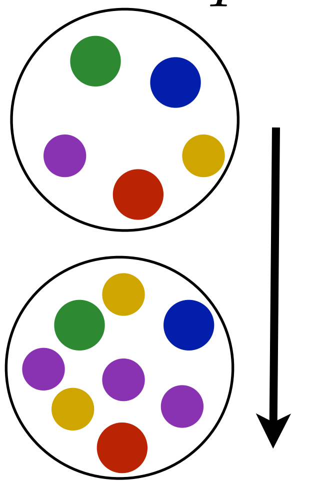




We lack of a unified description of the collision dynamics at all times

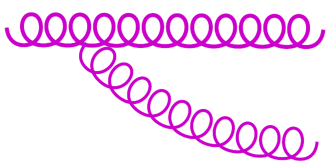
The Initial State: Color Glass Condensate & Saturation

$$Y = \ln \frac{p_0 + p_z}{p_0 - p_z}$$



ΔY

gluon radiation



p_z

$k_z = x\, p_z$

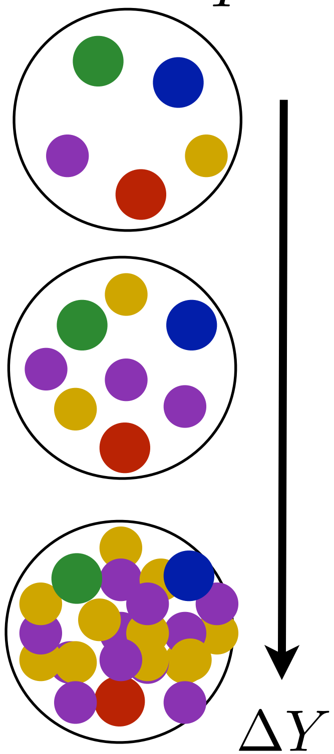
linear evolution (DGLAP, BFKL), dilute regime

$$\frac{\partial N_g}{\partial Y} \sim P\, N_g$$

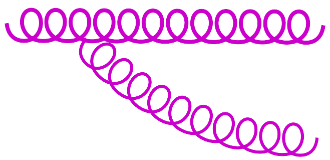
exponentially growing gluon densities

The Initial State: Color Glass Condensate & Saturation

$$Y = \ln \frac{p_0 + p_z}{p_0 - p_z}$$



gluon radiation



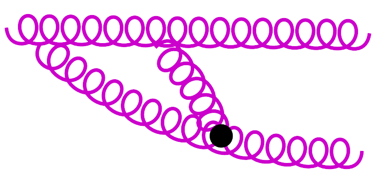
p_z

$k_z = x\, p_z$

linear evolution (DGLAP, BFKL), dilute regime

$$\frac{\partial N_g}{\partial Y} \sim P\, N_g$$

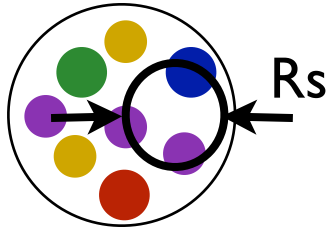
gluon recombination



Non-linear evolution (CGC), high density

$$\frac{\partial N_g}{\partial Y} \sim P\, N_g - R\, N_g^2$$

- At high energies (large rapidities, small-x), the hadron wavefunction reach saturation due to the growing importance of recombination processes



$$Q_s \sim \frac{1}{R_s} \qquad\qquad k_t < Q_s(Y)$$

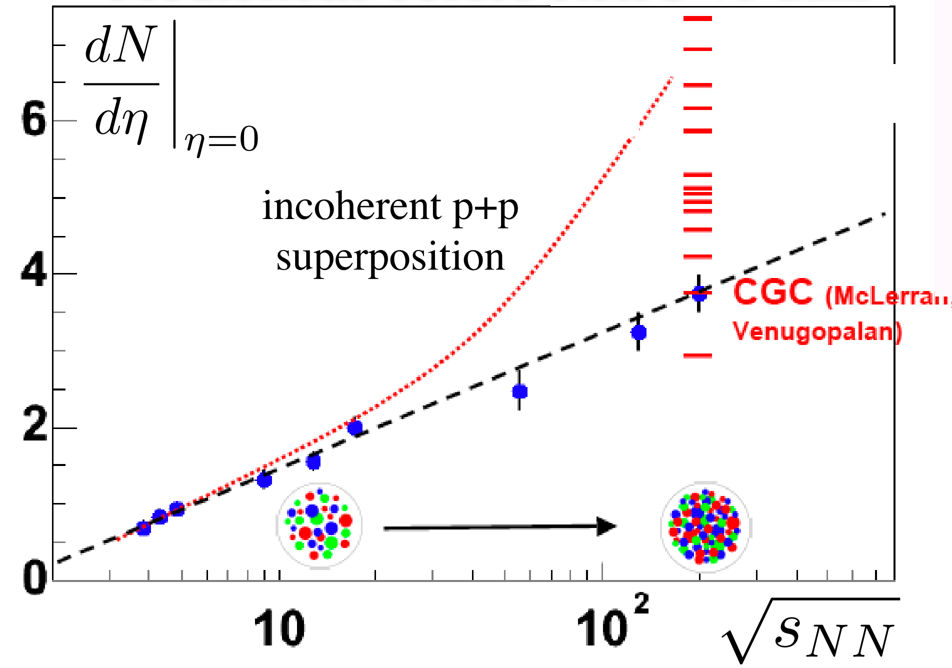
- Saturation is enhanced in nuclei (large # of gluons, even at low energies)

$$Q^2_{sA} \sim A^{1/3}\, Q^2_{sp} \quad \Rightarrow \quad A^{1/3} \sim 6 \quad \Rightarrow \quad Q^{2,\,RHIC}_{sAu} \sim 1 \div 2\, \mathrm{GeV}^2$$

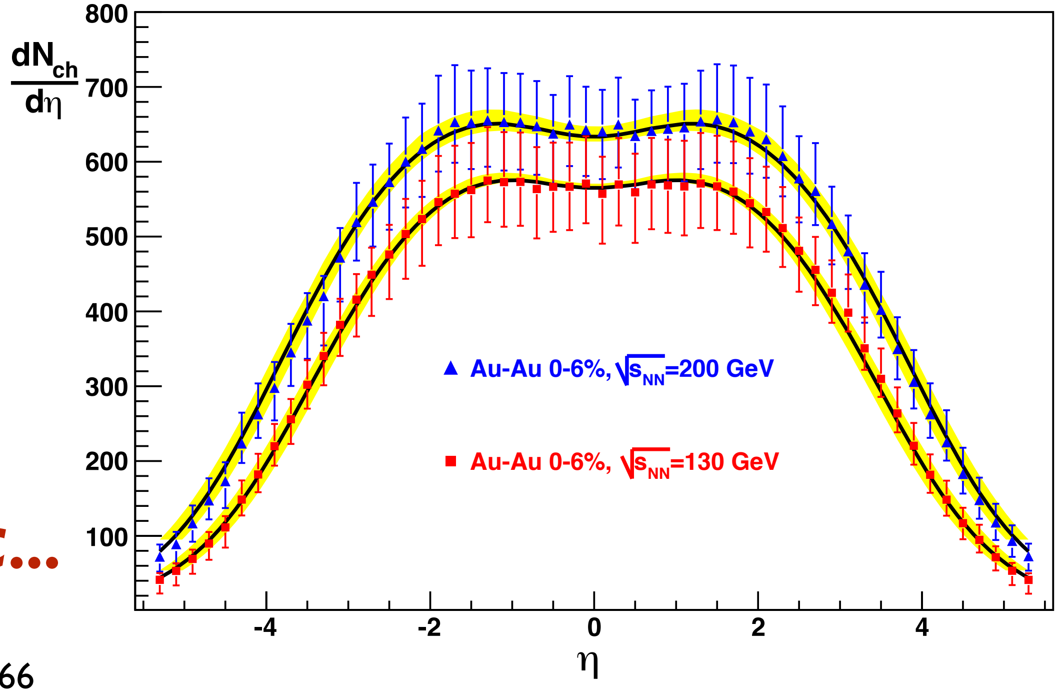
Bulk properties of RHIC matter: Multiplicities

- One expects the total # of produced hadrons to be proportional to the # of partons in the wavefuncttin of colliding nuclei
- First surprise at RHIC: Total multiplicities came out a lot smaller than predicted by simple superpositions of proton-proton collisions:

Predictions before RHIC vs data



- Saturation explanation: The flux of colliding partons (mostly gluons) is reduced due to saturation effects



- CGC predictions account the energy rapidity, centrality of the multiplicities

… CGC has been discovered at RHIC…

The success of hydrodynamics at RHIC

⇒ Hydrodynamics is an effective theory that describes the long wavelength modes of the conserved charges of the system

energy-momentum conservation: $\partial_\mu T^{\mu\nu} = 0$

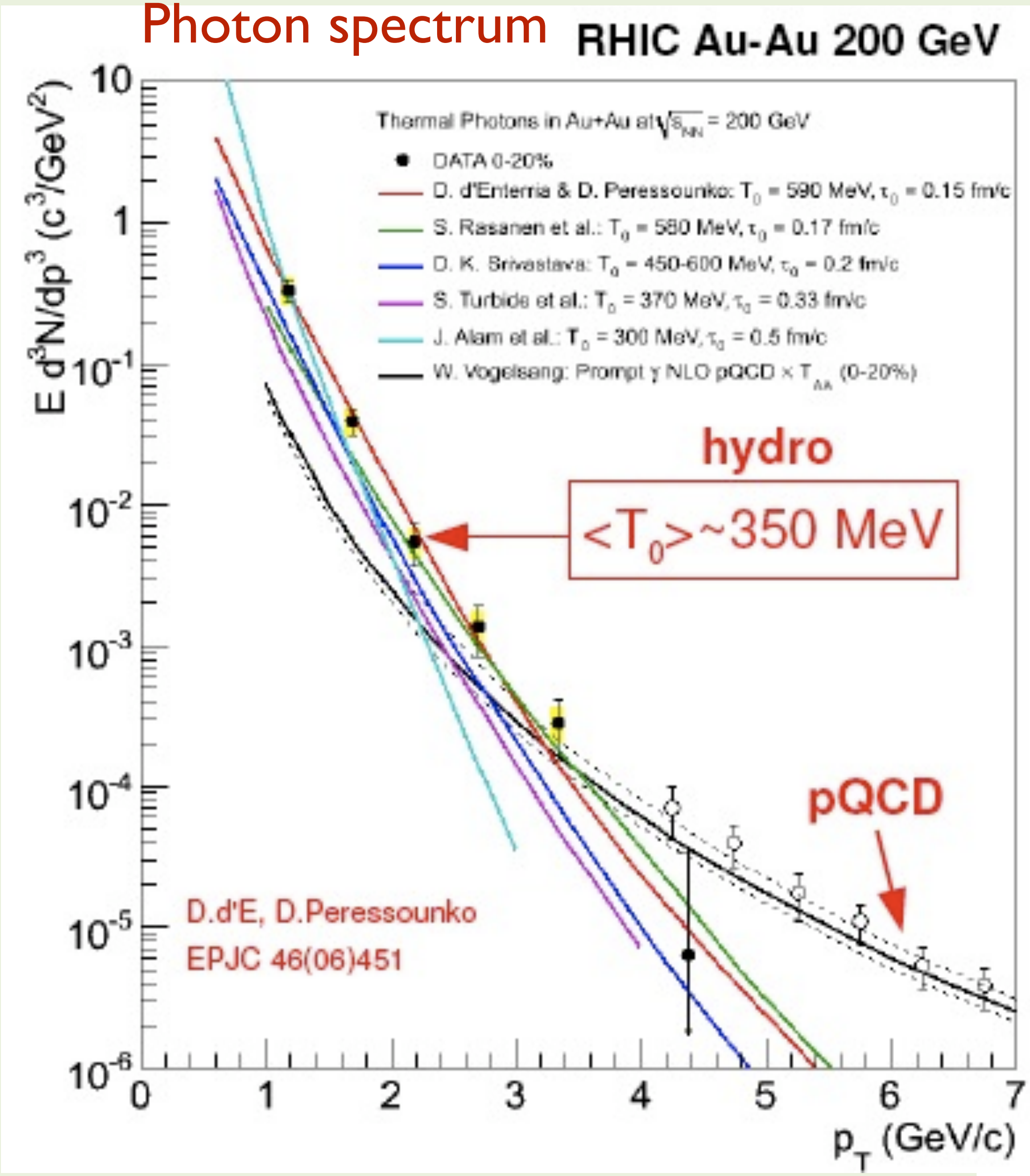
baryon number conservation: $\partial_\mu j_B^\mu = 0$

⇒It requires local equilibrium and a small mean free path: $\lambda_{mfp} \sim (\sigma\, n)^{-1} \to 0$

$$T^{\mu\nu} = \underbrace{[\epsilon(p,T) + p]\, u^\mu u^\nu - p\, g^{\mu\nu}}_{\text{ideal fluid}} \underbrace{+ F(\nabla_\mu u^\nu; \eta; D \ldots)}_{\text{dissipative terms (viscosity...)}}$$

⇒ Ideal hydro describes a lot of RHIC data!!

Photon spectrum



Input for hydro evolution:

- QGP E.oS.
- short thermalization time:

$$\tau_{therm} \sim 0.6 \div 1\,\mathrm{fm}$$

- initial energy density:

$$\epsilon_{\tau_{therm}} \sim 30\,\mathrm{GeV/fm}^3$$

hadron spectrum