Heavy-ions physics at collider energies
– Lecture I –

France-Asia Particle Physics School

Les Houches, 23-25 Sept. 2008

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Plan of lectures

1st

- Introduction
  - High-energy nucleus-nucleus collisions physics programme:
    confinement, chiral symmetry, early Universe thermodyn., low-x QCD ...
  - Colliders & Experiments: RHIC(Au-Au@200 GeV), LHC(PbPb@5.5 TeV)
- Study of many-body QCD (thermo)dynamics:
  - Soft probes:
    (1) $dN_{ch}/d\eta \Rightarrow$ Colour-Glass-Condensate – gluon $xG_A(x,Q^2)$
    (2) Low p_T π/K/p spectra $\Rightarrow$ QCD Equation-of-State

2nd

    (3) Elliptic flow $\Rightarrow$ QCD medium viscosity, AdS/CFT test-bed
  - Hard probes:
    (1) "Jet quenching" $\Rightarrow$ Parton density, $\langle\hat{q}\rangle$ transport coefficient
    (2) Direct (thermal) photons $\Rightarrow$ QCD critical temperature (T_{crit})
    (3) Quarkonia suppression $\Rightarrow$ QCD critical ε_{crit} , T_{crit}

6 big HEP questions for the LHC

☞ "Mass generation" problem: What is the origin of elementary particle masses ? Higgs mechanism ? other physics ?

☞ "Flavour" problem: Why so many types of matter particles ? Origin of baryon asymmetry in the Universe ?

☞ "Hierarchy", "fine tuning" problem: Why large (10^{16} !) difference between EW & gravity (Planck) scales ? strings ? extra-dims ?

☞ "Dark matter" problem: ~1/4 matter in universe invisible. SUSY ?

☞ "QCD in non-perturbative regime" : Why quark confinement ? HE hadronic cross-sections ? Gauge-String duality (AdS/CFT) ?

☞ "Highest-energy cosmic-rays" : Sources/nature of CRs at 10^{20} eV?

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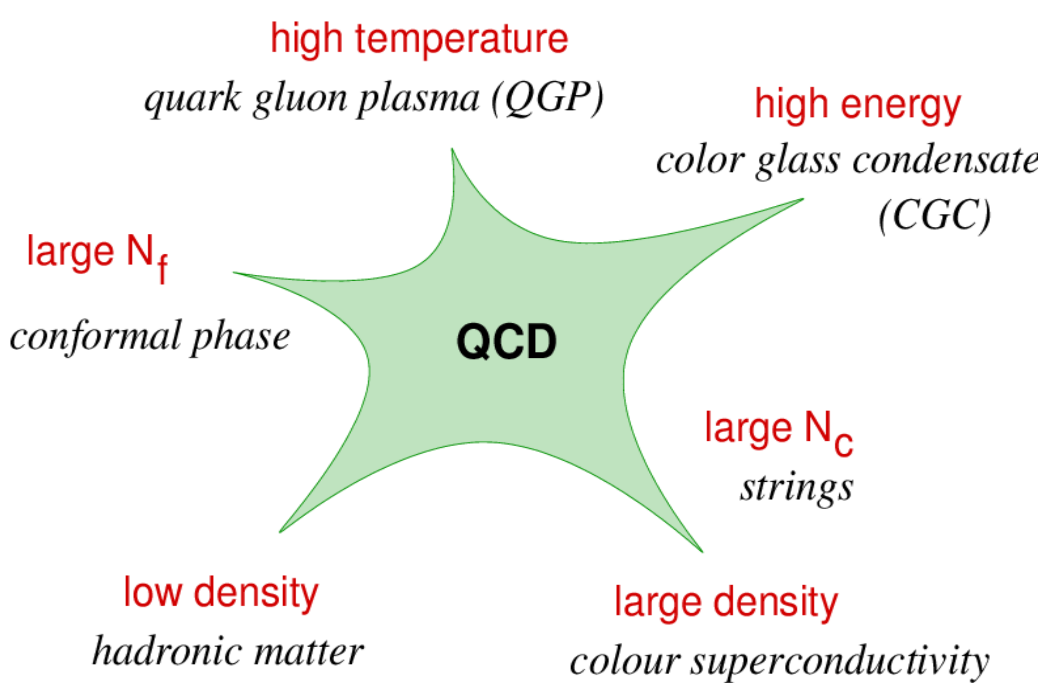
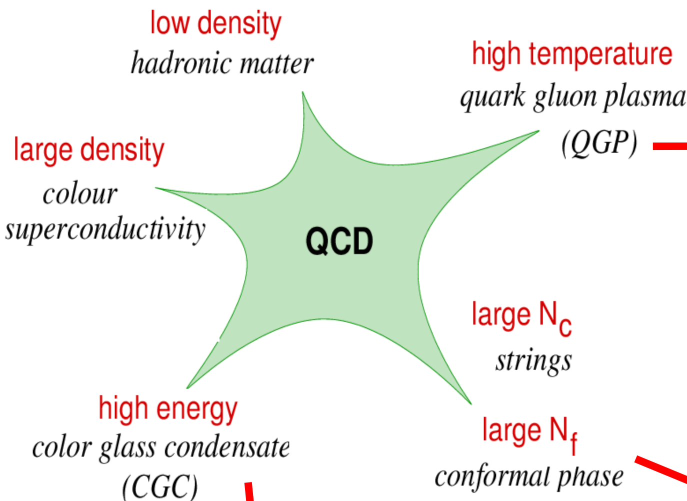
The many facets of QCD

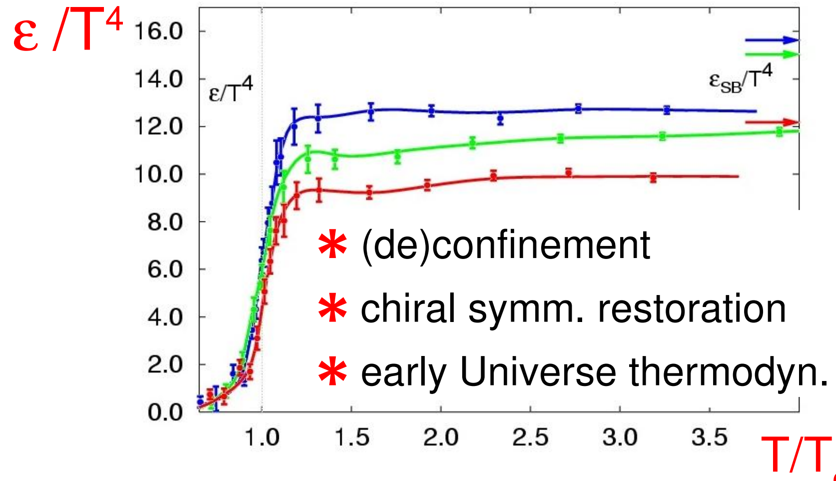
- QCD is a QFT with very rich dynamical content: asymptotic freedom, confinement, (approx.) χ-symmetry, non-trivial vacuum, $U_A(1)$ anomaly...
- The only sector of the SM whose collective behaviour can be studied in the lab: phase transition(s), thermalization of fundamental fields, ...
- QCD has a very diverse many-body phenomenology at various limits:



QCD matter: physics menu & theoretical tools

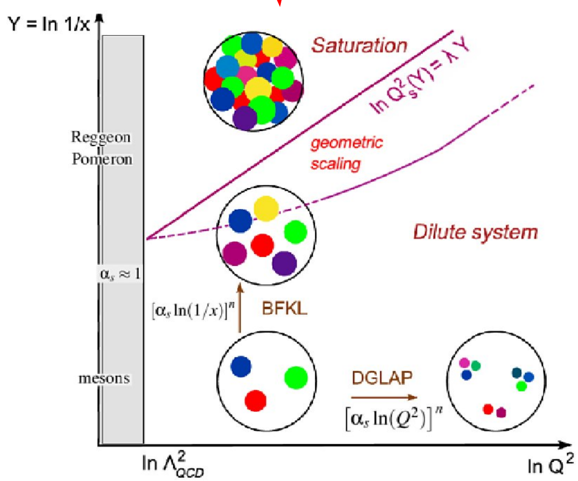


- Lattice QCD at high-T: **QGP**



* (de)confinement
* chiral symm. restoration
* early Universe thermodyn.

- High-density QCD at small-x: **CGC**

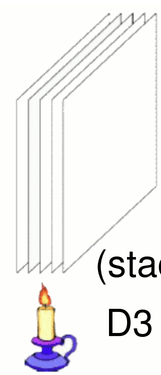


- Gauge-gravity duality: **AdS/QCD**

$$\mathcal{L} = \frac{1}{2g_{\rm YM}^2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu}) + i\mathrm{Tr}(\bar\psi\gamma^\mu D_\mu\psi) \Longleftrightarrow ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2}d\Omega_5^2$$

$\mathcal{N} = 4$

SU(N_c)



(stack of 4 D3 branes)

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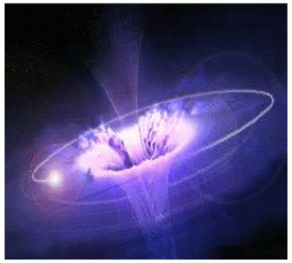
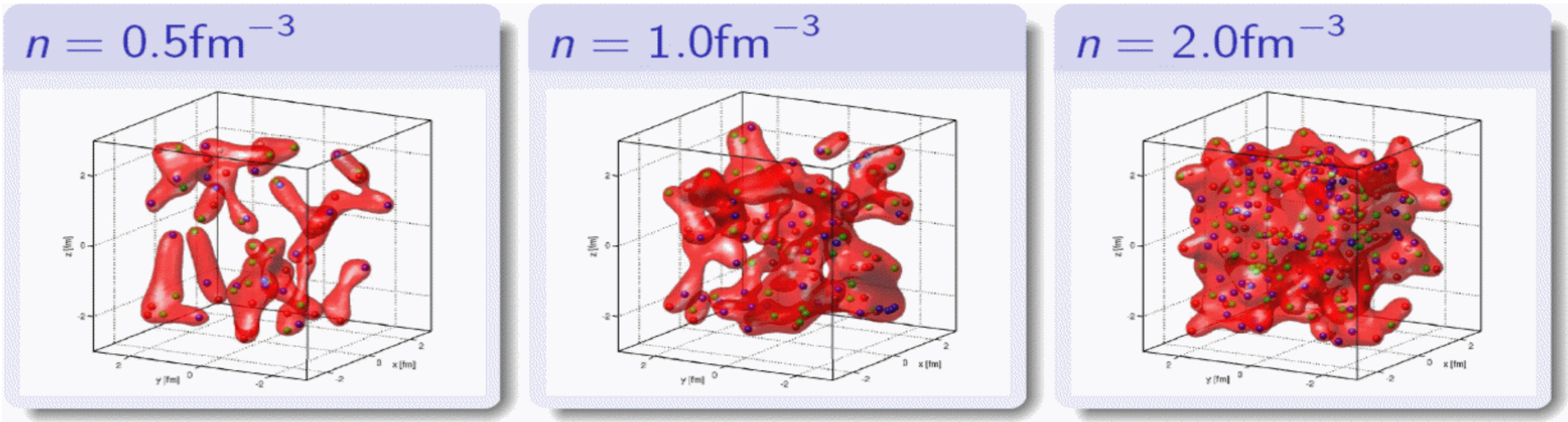


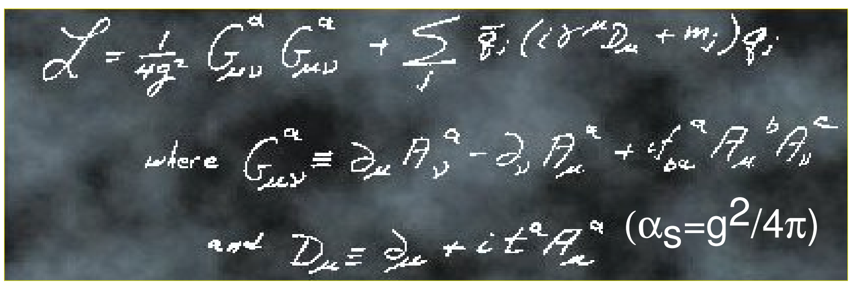
BH in 5-Dims.

Thermal gauge theory = black hole in anti de-Sitter space

Quark-Gluon-Plasma: color deconfinement

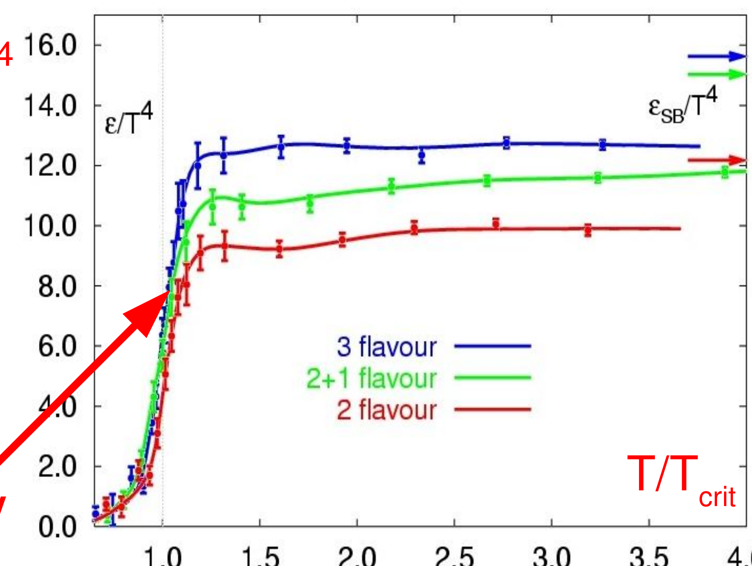


QCD Equation-of-State: ε=f(T)



$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

ε / T^4



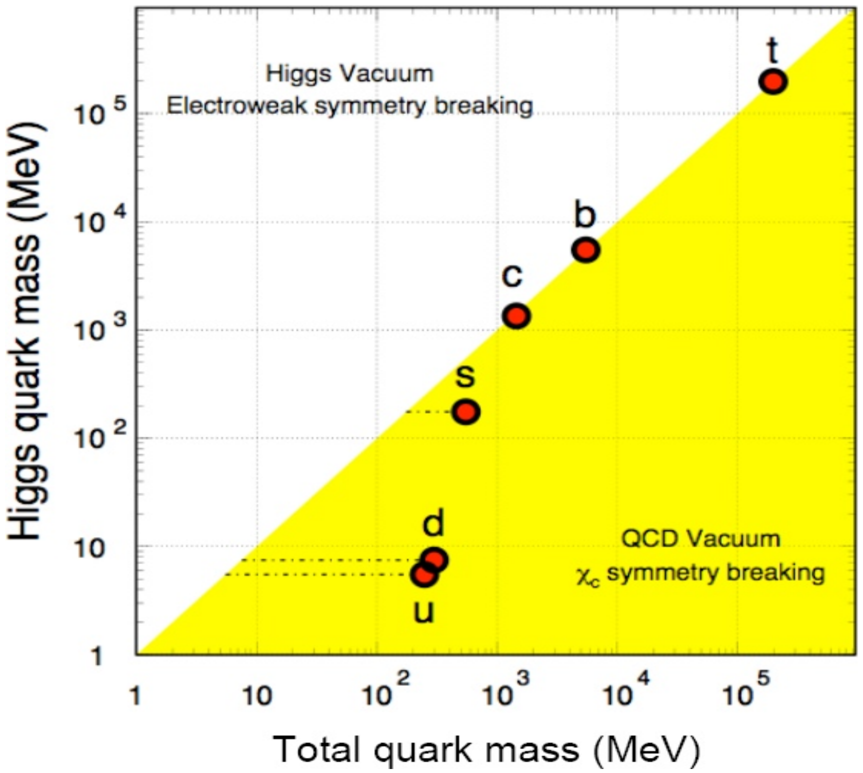
T/T_{crit}

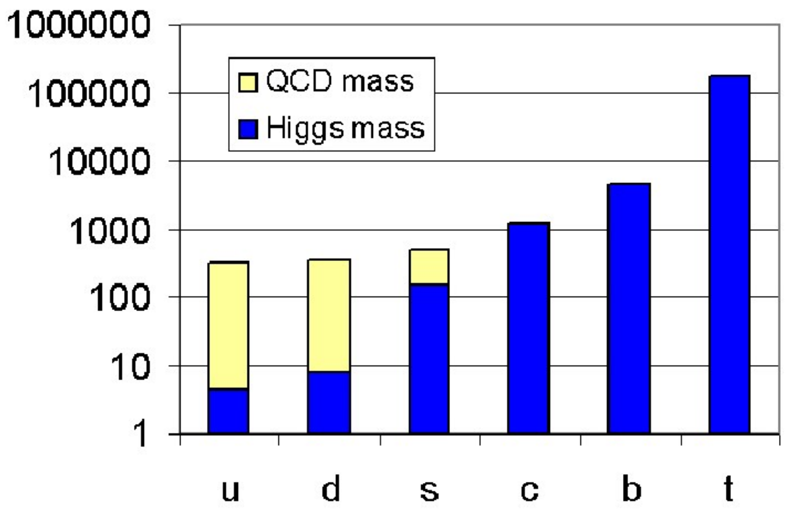
- Quarks&gluons liberated @ $T_{crit} \sim 190$ MeV

$\varepsilon_{crit} \propto T^4 \sim 1\ \mathrm{GeV/fm}^3$

χ-symmetry = origin of (visible) mass

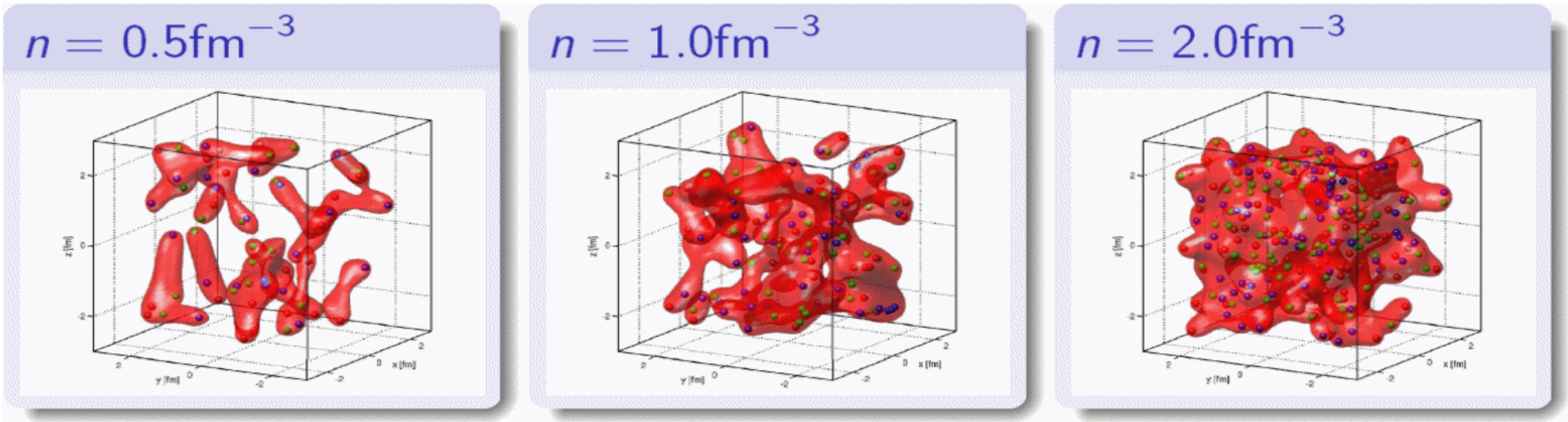
- QCD (= χ-symm breaking) not (!) Higgs (= EWK-symm breaking) is truly responsible for the origin of (baryon) mass (~4% of all Universe):





- ~98% of the (light-quarks) mass generated dynamically (gluons) in the QCD confining potential

Quark-Gluon-Plasma: χ-symmetry restoration



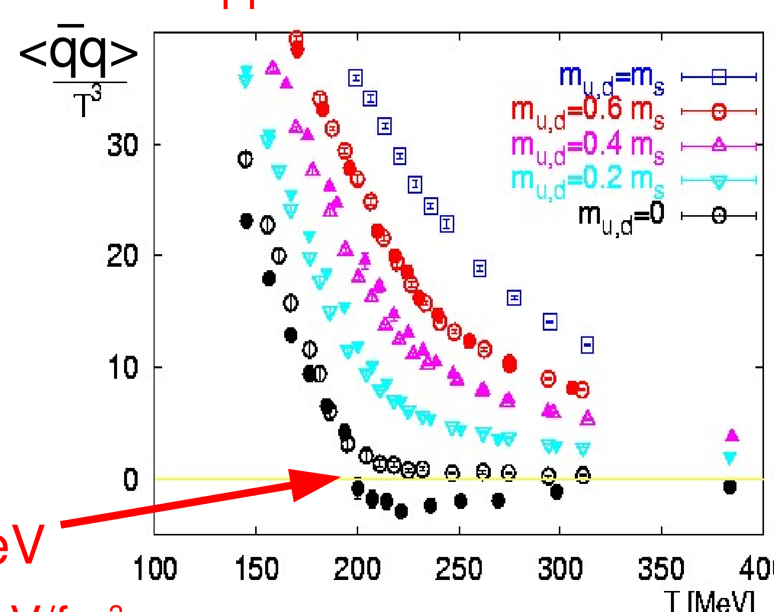
$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$ $(\alpha_S = g^2/4\pi)$

$\alpha_S(Q^2) \sim 1/\ln(Q^2/\Lambda^2)$, $\Lambda \sim 200$ MeV

qq-condensate vs. T



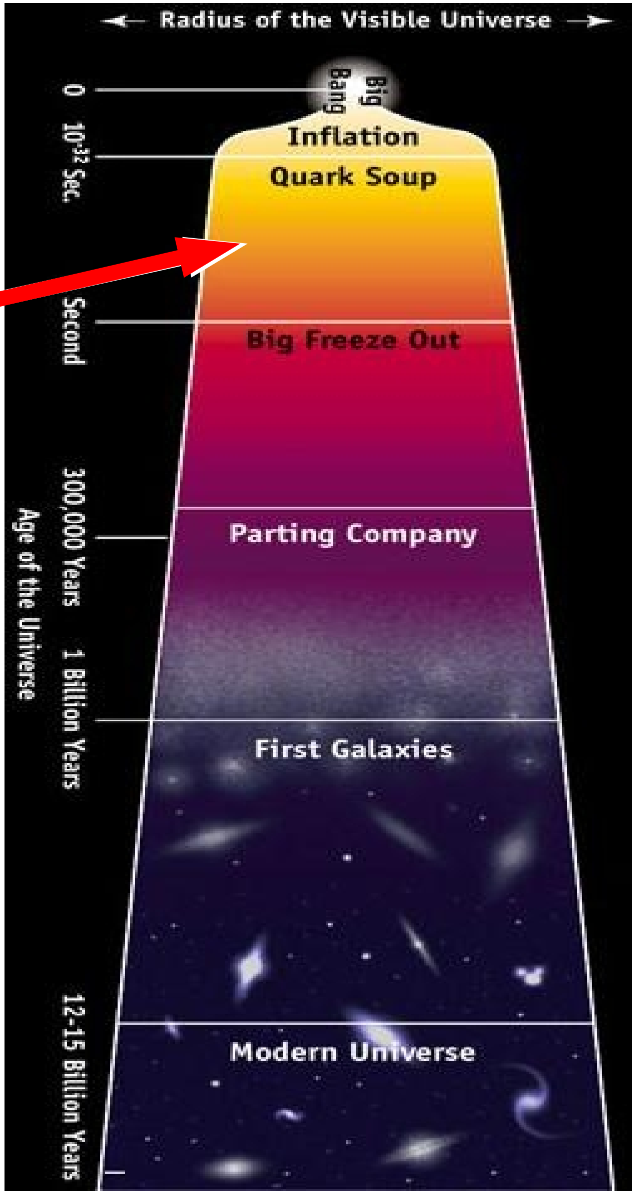
- Quarks become massless @ T_{crit}~190 MeV

$\varepsilon_{crit} \propto T^4$~1 GeV/fm³

QCD transition in the primordial Universe

- The Quark-Gluon-Plasma was already produced ~13.7 Gyears ago ...

a few micro-secs after Big-Bang

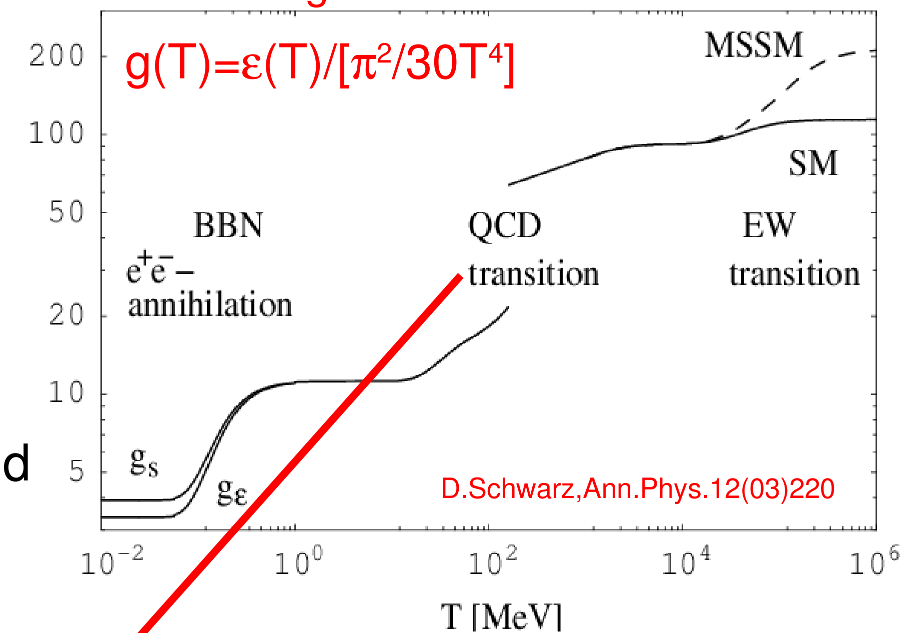


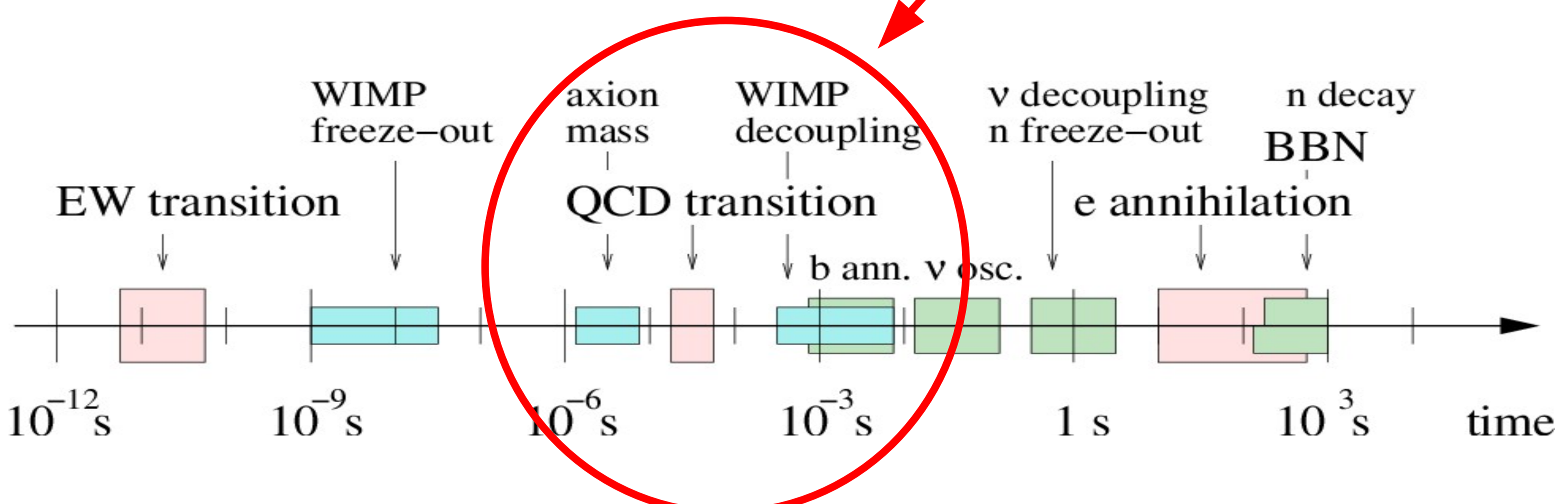
QCD transition in the primordial Universe

- Most important event between EW (or SUSY) transition and Big-Bang Nucleosynthesis:

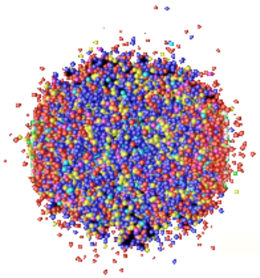
- QCD phase-transition = background for many Dark-Matter relic densities

effective degrees of freedom vs T

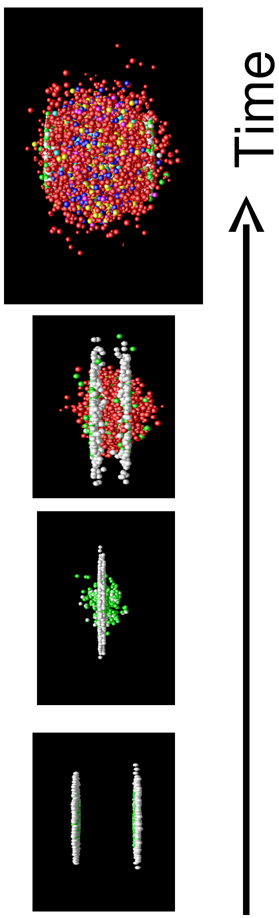


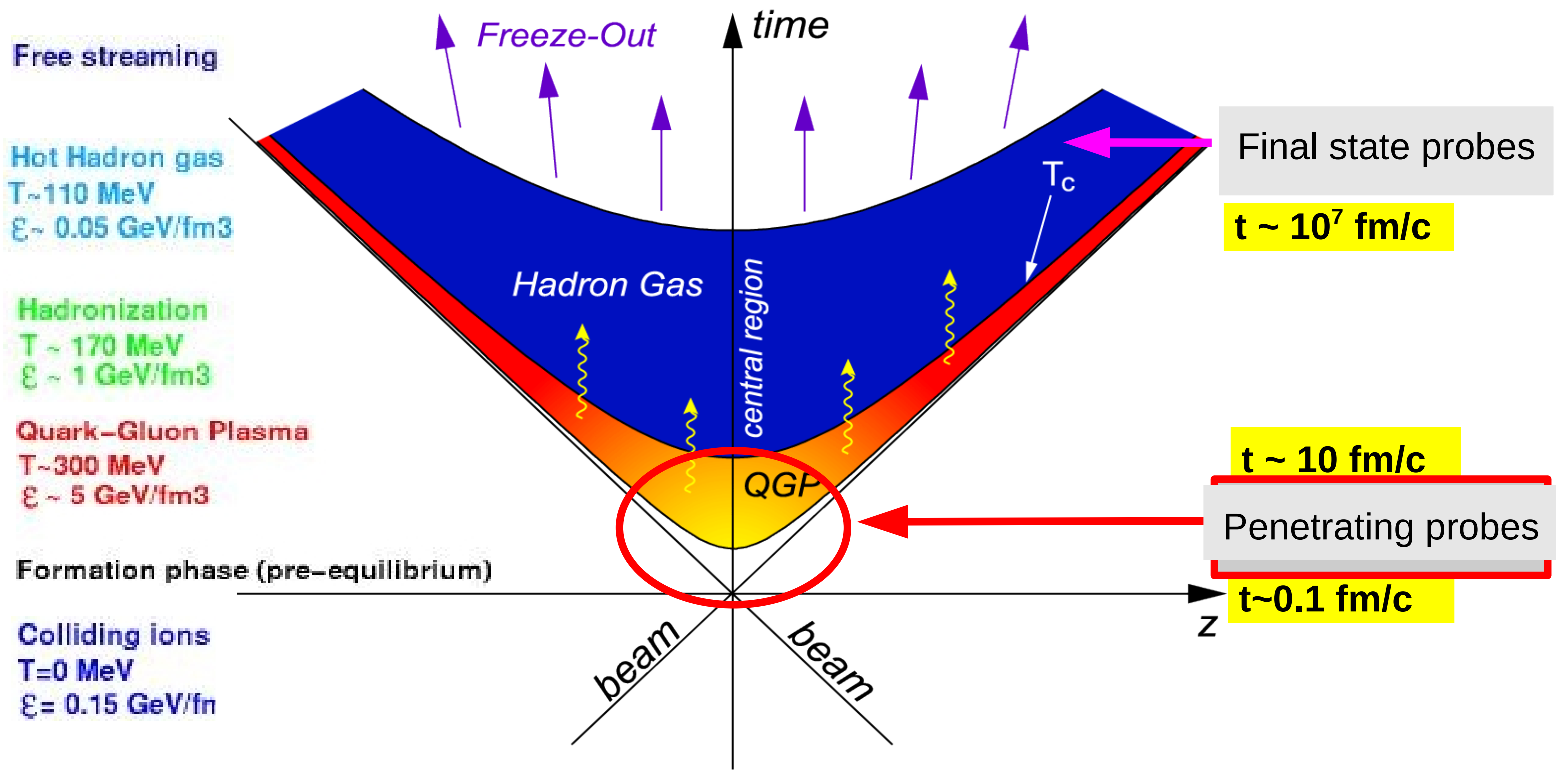


The "Little Bang" in the lab.



- High-energy nucleus-nucleus collisions: fixed-target ($\sqrt{s}$=20 GeV, SPS) or colliders ($\sqrt{s}$=200 GeV, RHIC; $\sqrt{s}$=5.5 TeV, LHC)
- Expanding QGP: volume~$\mathcal{O}(10^3$ fm$^3)$ for times ~ 0.1-10 fm/c
- Collision dynamics: Diff. observables sensitive to diff. reaction stages

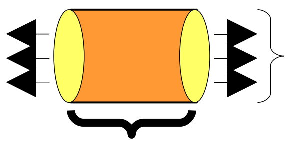




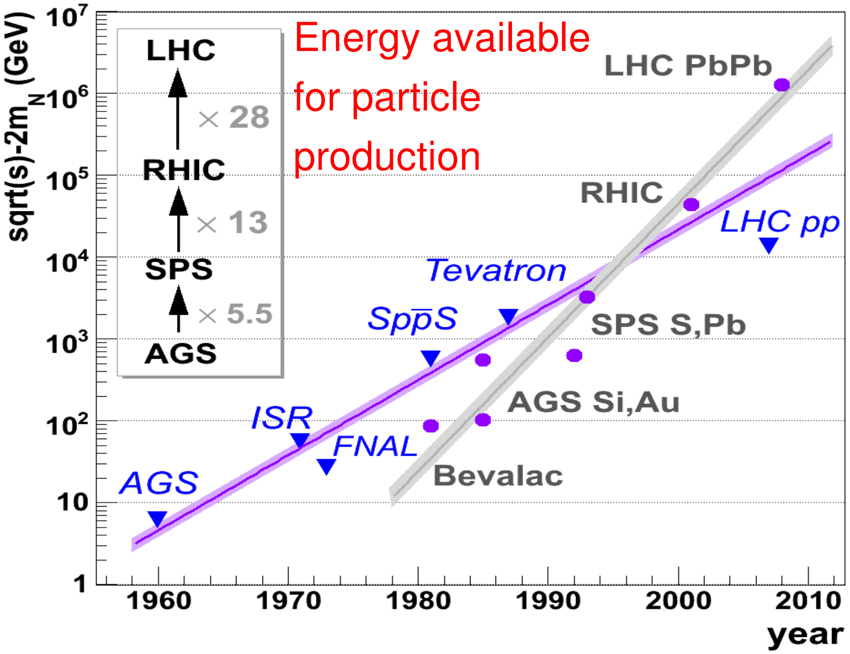
Energy densities in A-A collisions

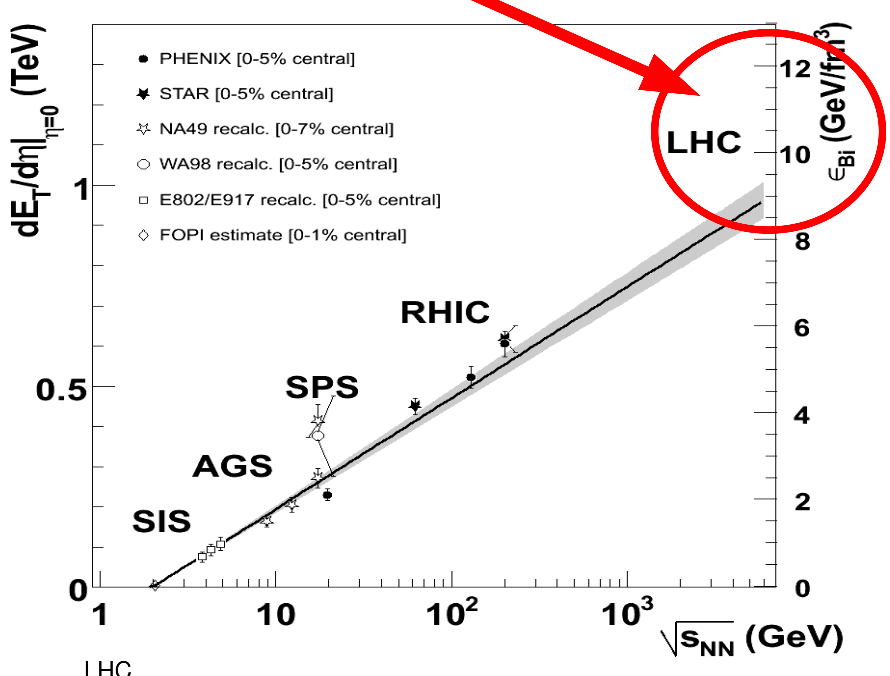
- T.D. Lee [Rev. Mod. Phys. 47 (75) 267]: *"In HEP we've concentrated on experiments in which we distribute a higher & higher amount of energy into a region with smaller & smaller dimensions. In order to study the question of 'vacuum' (...) we should investigate 'bulk' phenomena by distributing high energy over a relatively large volume."*
- Energy density: "Bjorken estimate" (longitudinally expanding plasma):

$$\epsilon_{Bj} = \frac{dE_T}{dy}\frac{1}{\tau_0 \pi R^2}$$



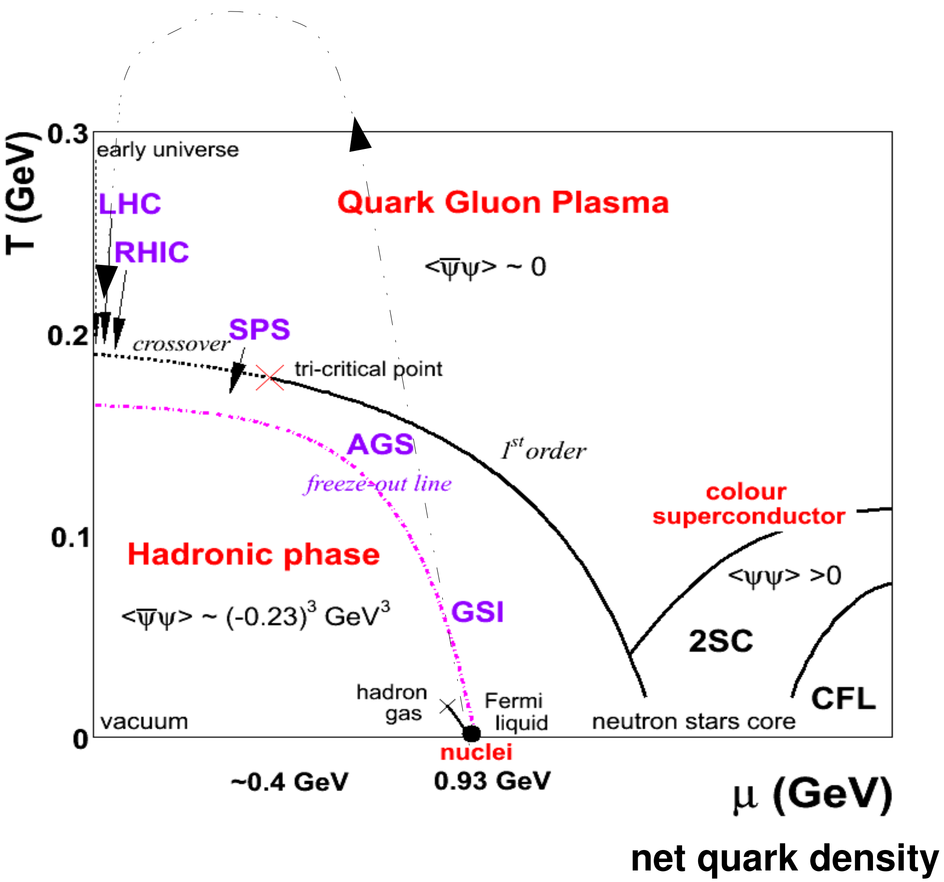
τ_0~ 1 fm/c >> τ_{cross} = 2R/γc ~5·10^{-3} fm/c



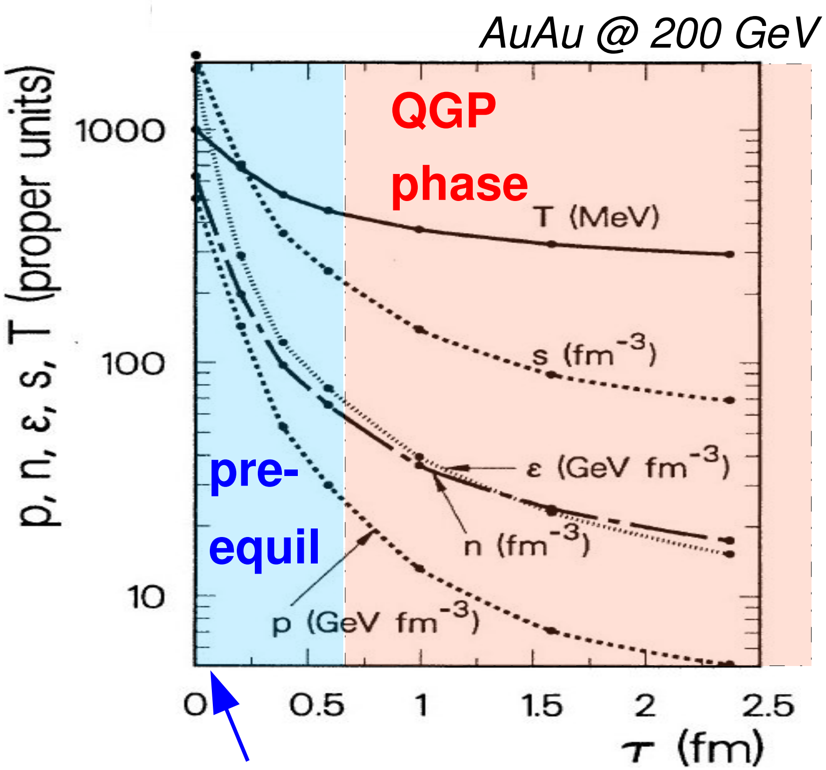


Dynamical exploration of QCD phase diagram

- A-A collisions follow a trajectory along the QCD phase diagram



- Time evolution of longitudinally expanding system: $\varepsilon \sim 1/\tau^{4/3}$, $T \sim 1/\tau^{1/3}$, ...

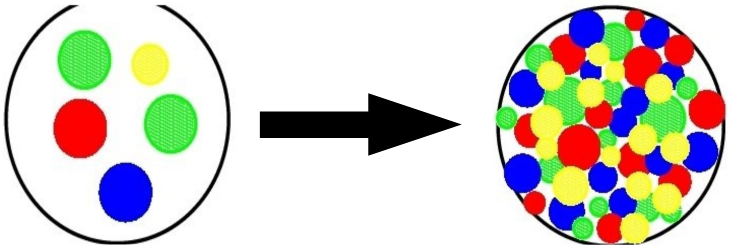


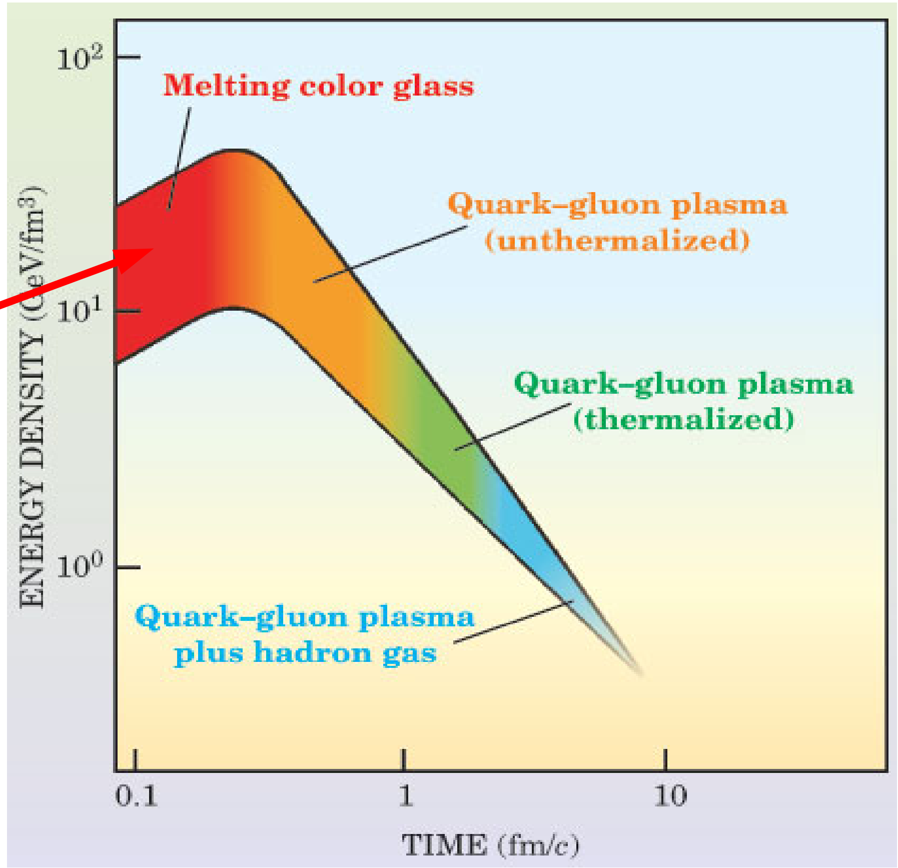
$\tau_{cross} = 2R/\gamma \sim 0.1$ fm/c (RHIC)
~ 0.004 fm/c (LHC)

- Hydrodynamics needed to extract information on medium properties.

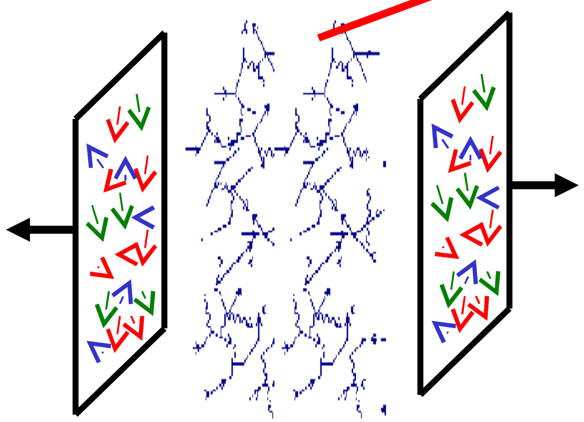
Initial nucleus: Saturated gluon system

- Nucleus at high-energy = Color-Glass-Condensate (CGC) system ...





"sheets" of CGC collide

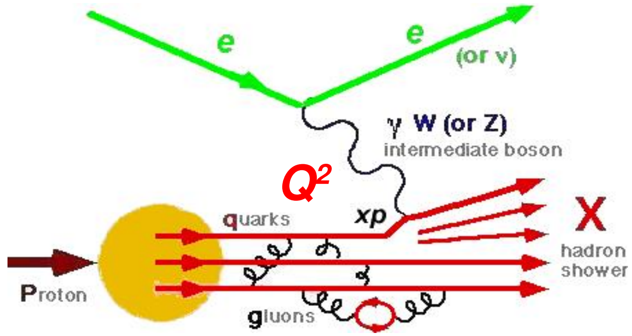


gluons released

So, what is the Color-Glass-Condensate ... ?

Hadron structure at low-x

- DIS *e*-p collisions probe partonic distributions in the proton:



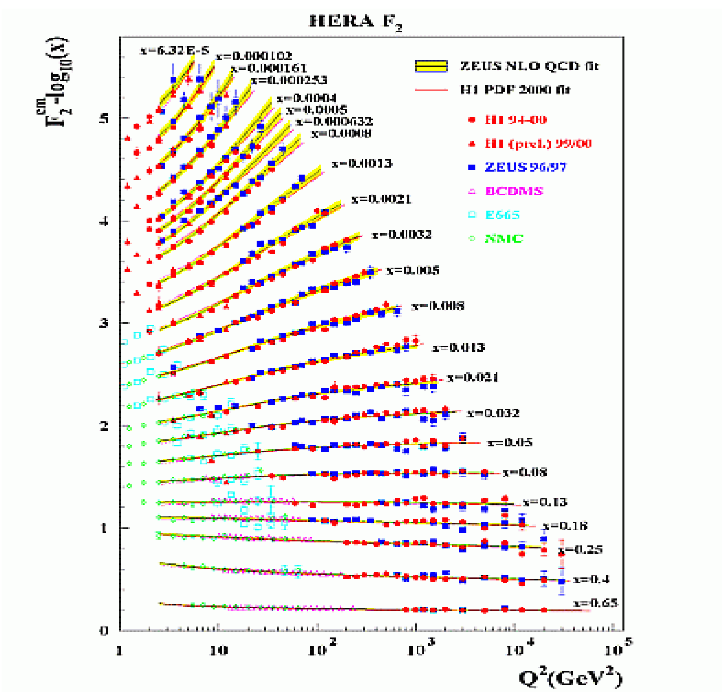
Q^2 = "resolving power"

Bjorken x = momentum fraction carried by parton

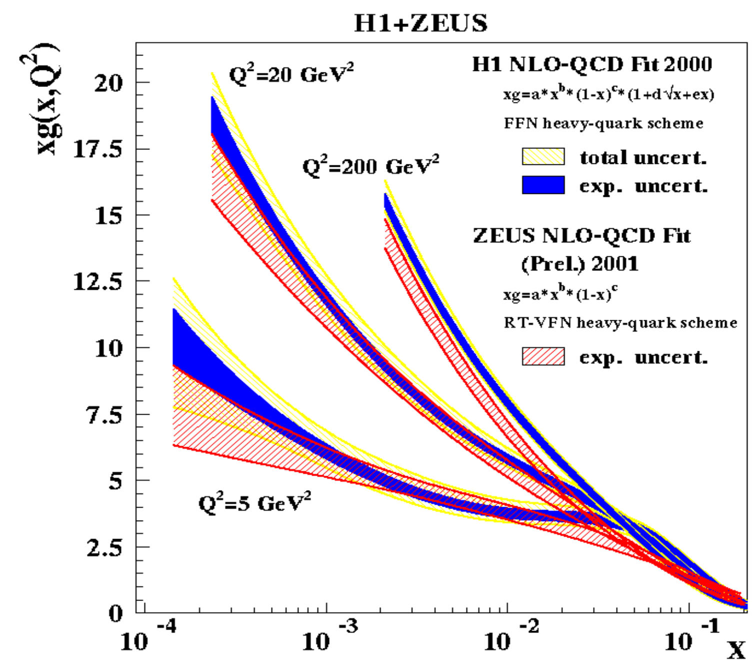
$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[2xy^2F_1 + 2(1-y)F_2\right]$$

F_1,F_2 = proton structure functions, (y = inelasticity).

- HERA: strong rise of low-x $F_2(x,Q^2) \propto$ sea-quarks, $\partial \ln F_2/\partial \ln Q^2 \propto$ gluons



$\Rightarrow$



Color Glass Condensate: gluon saturation

- PDF evolution controlled by QCD "radiation" equations:

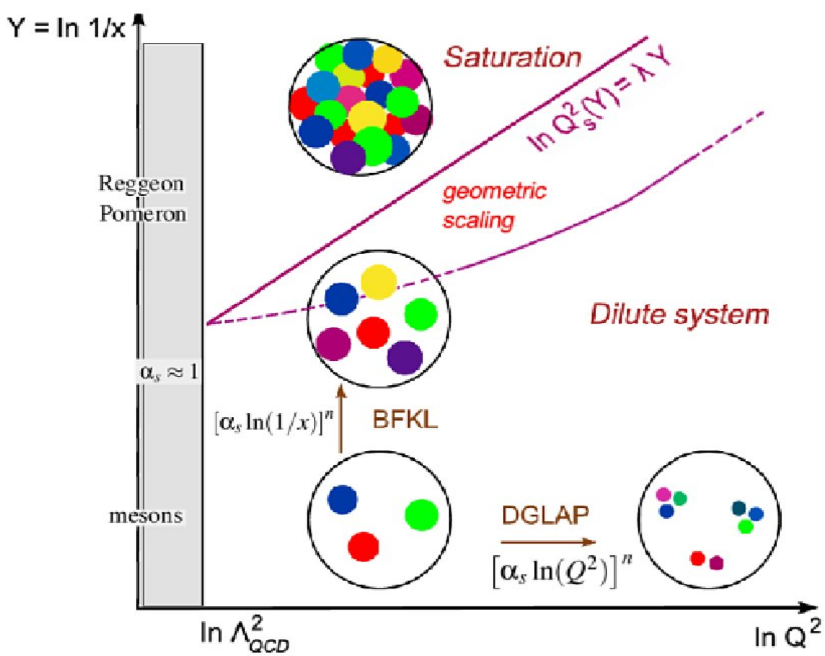
Q^2 - DGLAP: $F_2(Q^2) \sim \alpha_s \ln(Q^2/Q_0^2)^n$, $Q_0^2 \sim 1$ GeV^2

x - BFKL: $F_2(x) \sim \alpha_s \ln(1/x)^n$

Linear eqs. cannot work at high densities: Unitarity violated (even for $Q^2 \gg \Lambda^2$), factorization theorems break down.

- Onset of non-linear QCD below "saturation scale" (Q_s) when gluons start to overlap: $gg \to g$

$$Q_s^2 \sim \alpha_s \frac{xG_A(x, Q_s^2)}{\pi R_A^2}$$



- Nucleus (larger parton tranverse density) amplifies saturation effects:

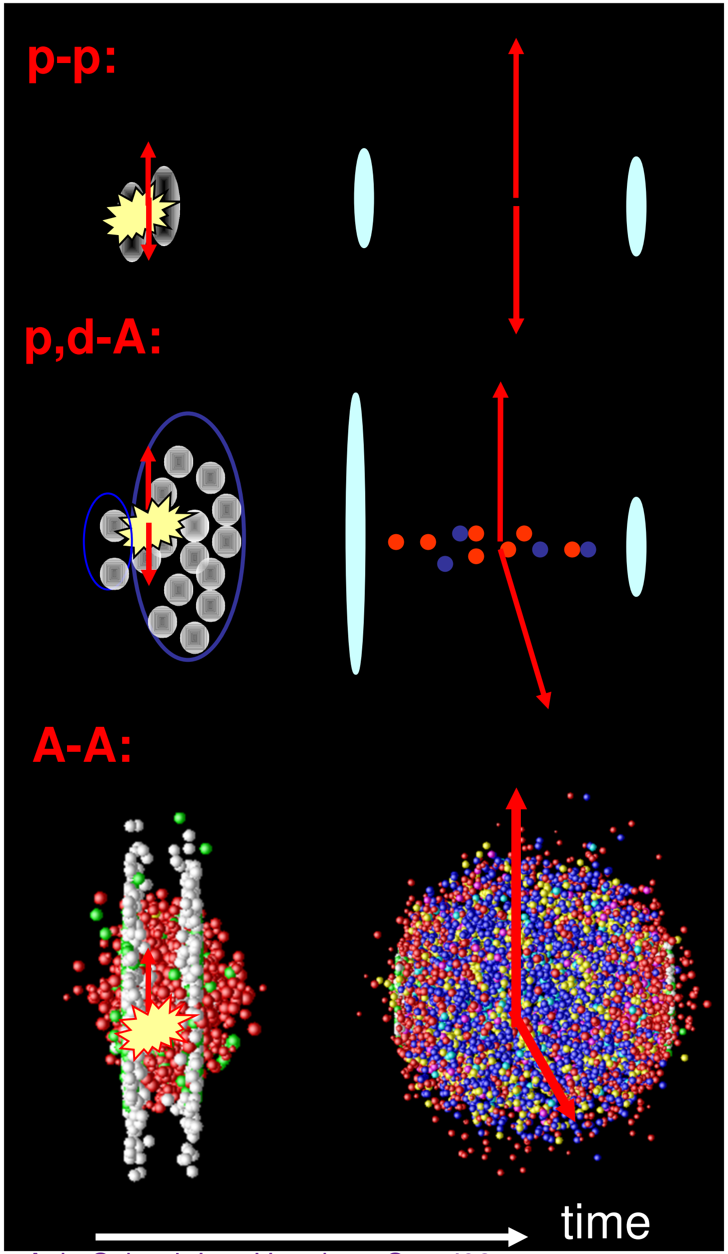
$$Q_s^2 \sim A^{1/3} \sim 6$$

$Q_s^2 \sim 1$ GeV^2 (HERA,p)

$Q_s^2 \sim 2$ GeV^2 (e)RHIC (Au), 5 GeV^2 (LHC,Pb)

Heavy-Ion Colliders & Experiments

Systematic experimental approach

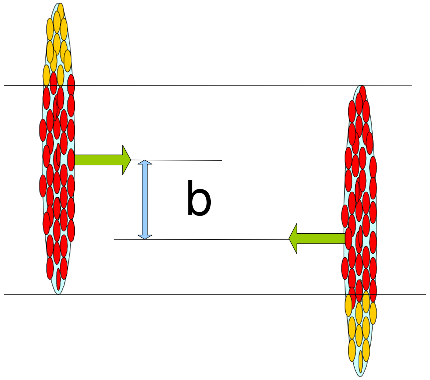


- In heavy-ions physics we need to measure:

p-p = "QCD vacuum" (reference)

p,d-A = "cold QCD medium" (control)

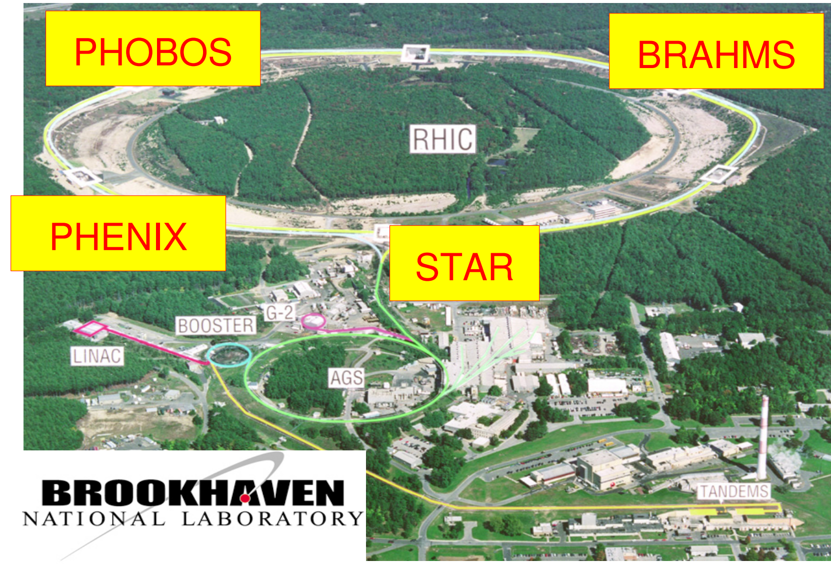
A-A = "hot & dense QCD matter"



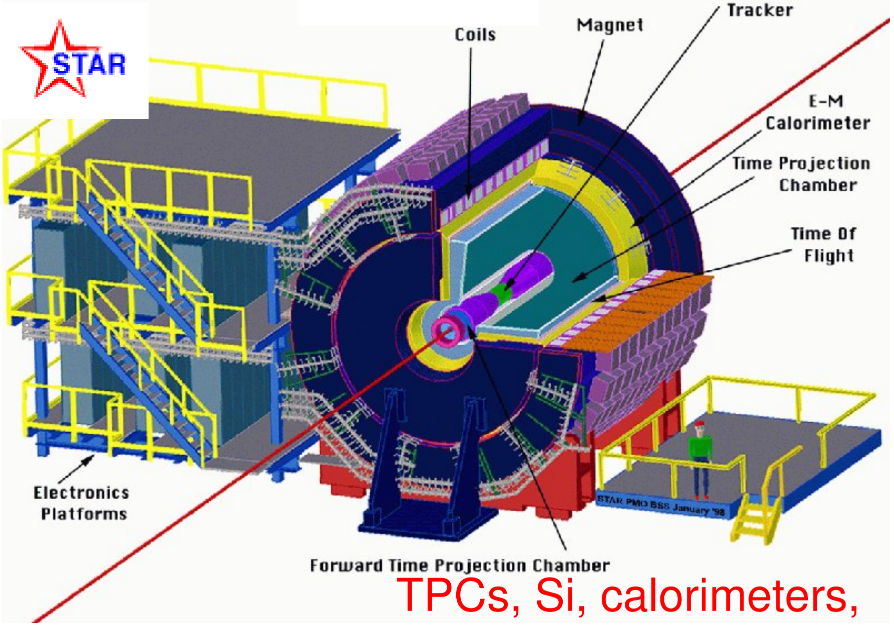
Volume of plasma can be selected varying impact parameter b

Relativistic Heavy-Ion Collider (RHIC) @ BNL

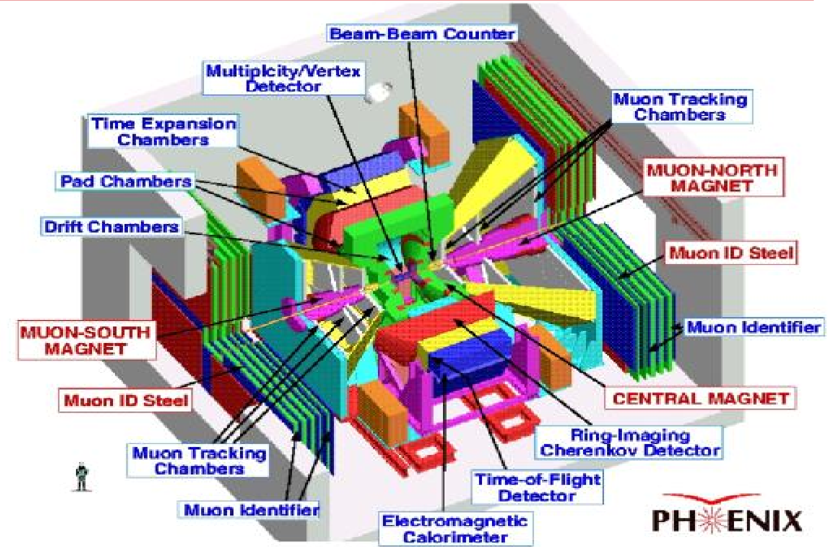
- Specifications:
  - 3.83 km circumference
  - 2 independent rings:
    - 120 bunches/ring
    - 106 ns crossing time
  - A+A collisions @ $\sqrt{s_{NN}}$ = 200 GeV
  - Luminosity: $2\cdot10^{26}$ cm^{-2} s^{-1} (~1.4 kHz)
  - p+p @ $\sqrt{s}_{max}$ = 500 GeV
  - p,d+A @ $\sqrt{s}_{max}$ = 200 GeV
- 4 experiments:
  - **BRAHMS, PHENIX, PHOBOS, STAR**
- Runs 1 - 7 (2000 2008):
  - Au+Au,Cu+Cu @ 22, 62, 200 GeV
  - d+Au @ 200 GeV
  - p+p (polarized) @ 22, 62, 200 GeV



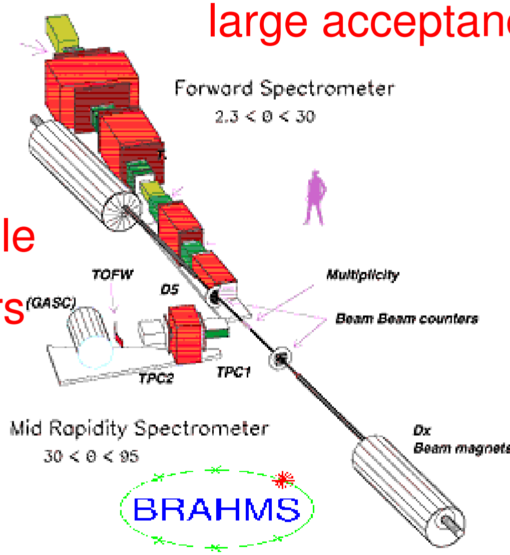
RHIC experiments



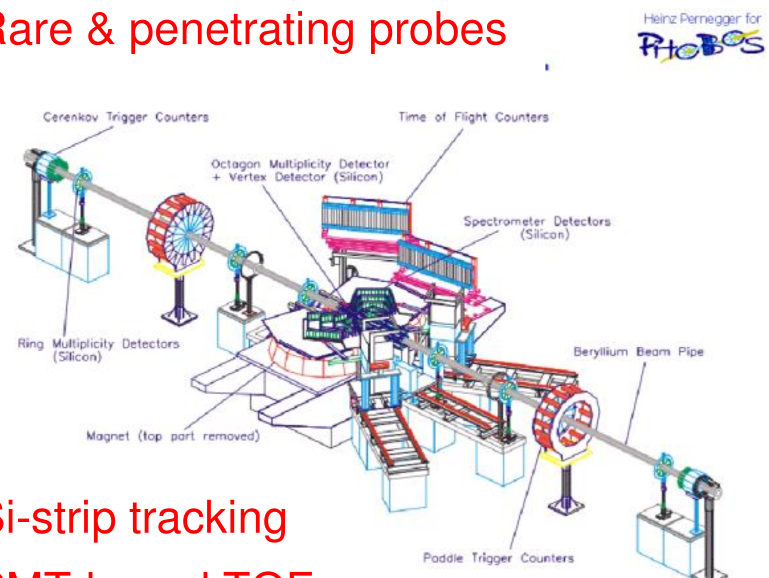
TPCs, Si, calorimeters,
large acceptance



Hadrons, e,μ,γ. High-rate DAQ.
Rare & penetrating probes



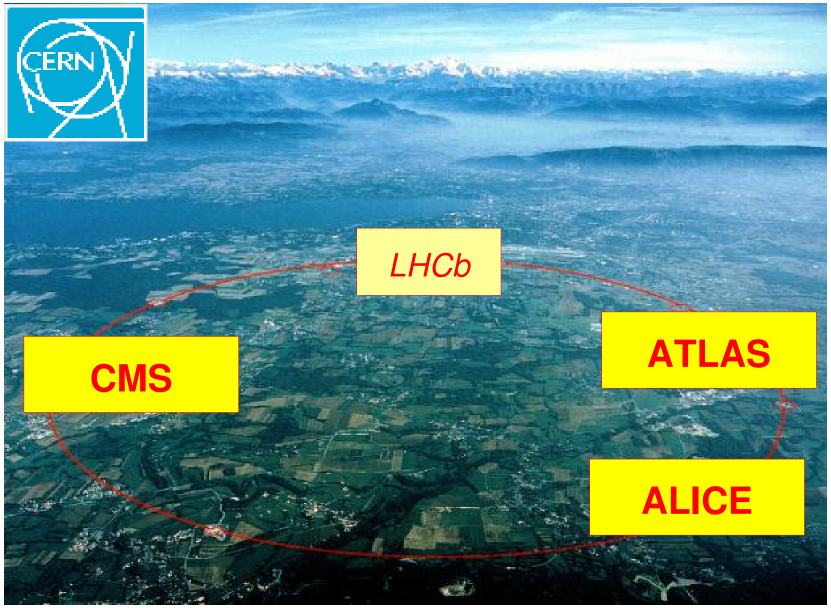
2 magn. dipole spectrometers in “fix-target” config.



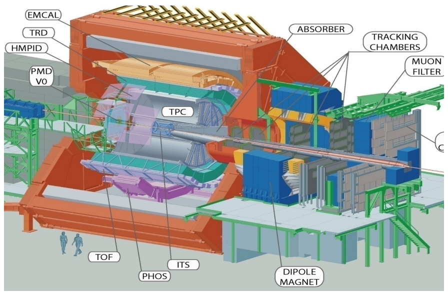
Si-strip tracking
PMT-based TOF

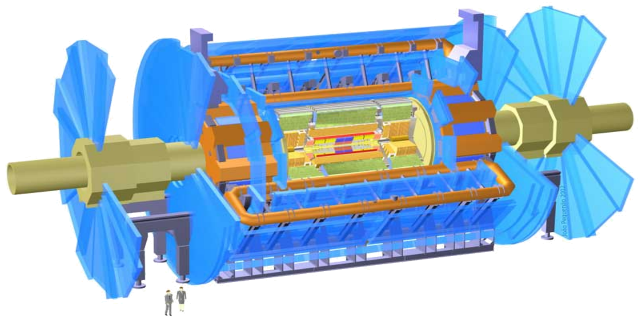
Large Hadron Collider (LHC) @ CERN

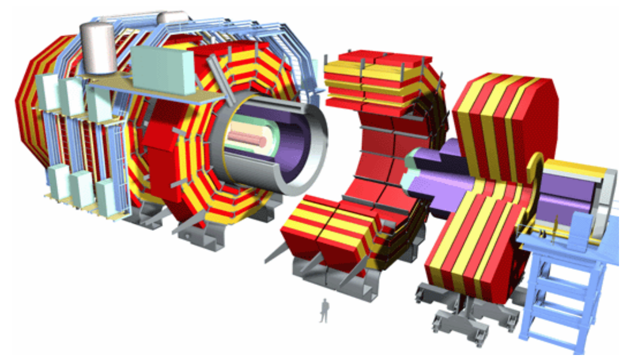
- Specifications:
  - 1 ring: 26.66 km circumference
    - 8.33 T superconducting coils
    - 25 ns crossing time
  - Pb-Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV
  - Lumi: 10^{27} cm^{-2} s^{-1} (~3 kHz, 1mo.)
  - p-p collisions @ $\sqrt{s_{NN}}$ = 14 TeV
  - Lumi: 10^{34} cm^{-2} s^{-1} (~400 Mhz, 8 mo.)
  - p,d-Pb @ $\sqrt{s_{NN}}$ = 8.8 TeV
- 3 experiments:
  ALICE, ATLAS, CMS
- Run planning:
  - p-p @10,14 TeV (2008,2009, ...)
  - Pb-Pb @ 5.5 TeV (2009, 2010)
  - p-Pb @ 8.8 TeV (2011?)



LHC heavy-ion experiments







ALICE: dedicated HI experiment

People: largest community (~1000)

$|\eta|<1$: Tracking (TPC+ITS+TRD)

Calorimetry (EMCal, PHOS)

$\eta=2.5\text{-}4$: Muon spectrometer.

0.5 T solenoid magnet

Strongest capabilities:

low-p_T, light-quark PID, ...

ATLAS & CMS: multipurpose (pp+HI) program

People: ~50/2000 (ATLAS), ~120/2500 (CMS)

$|\eta|< 2.5$: Tracking, muons

$|\eta|< 5$: EM/HAD Calorimetry

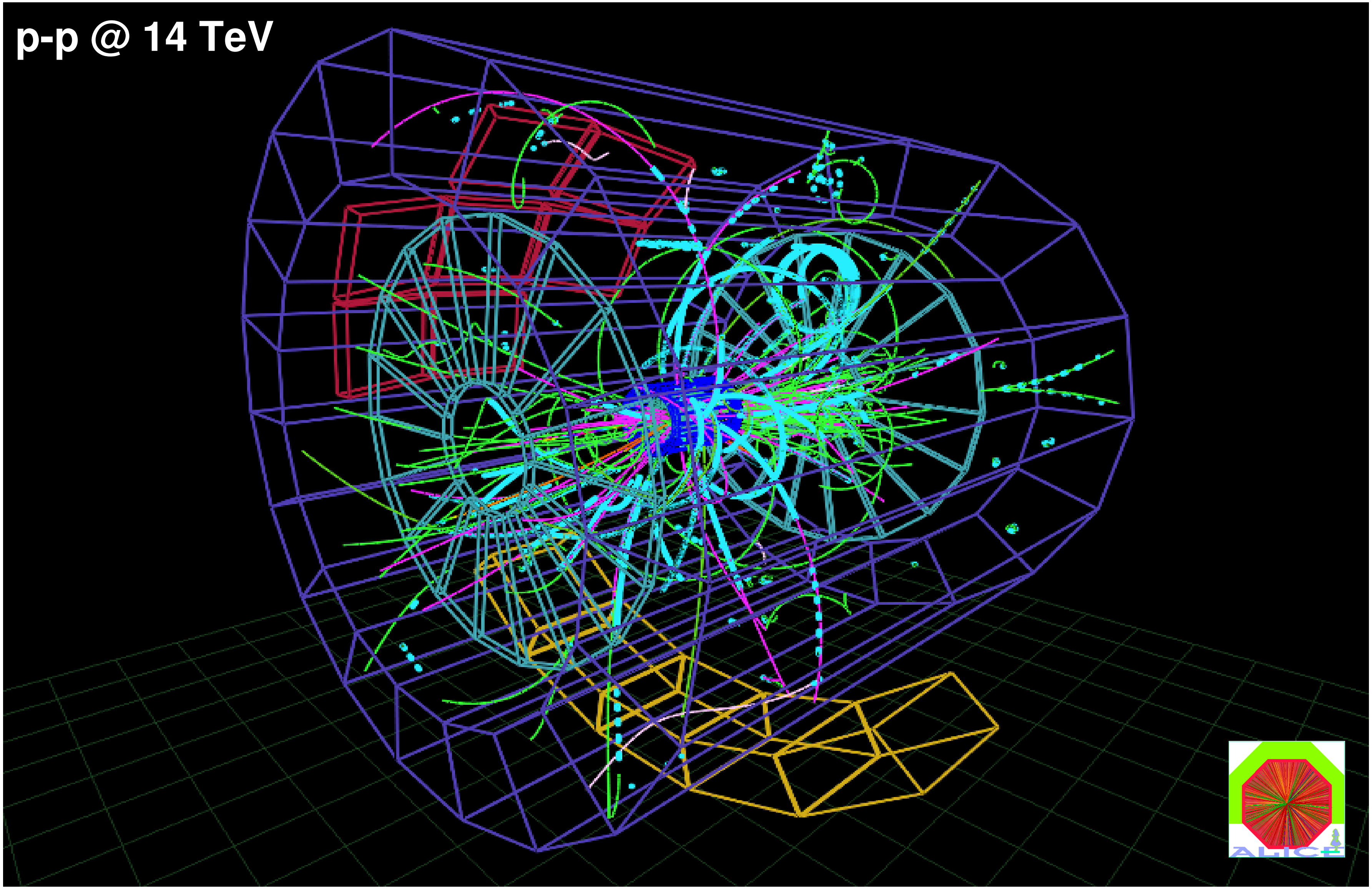
$\eta=5\text{-}6.6$: Forward calorimetry (CMS)

4 T (CMS), 2 T (ATLAS) mag. field

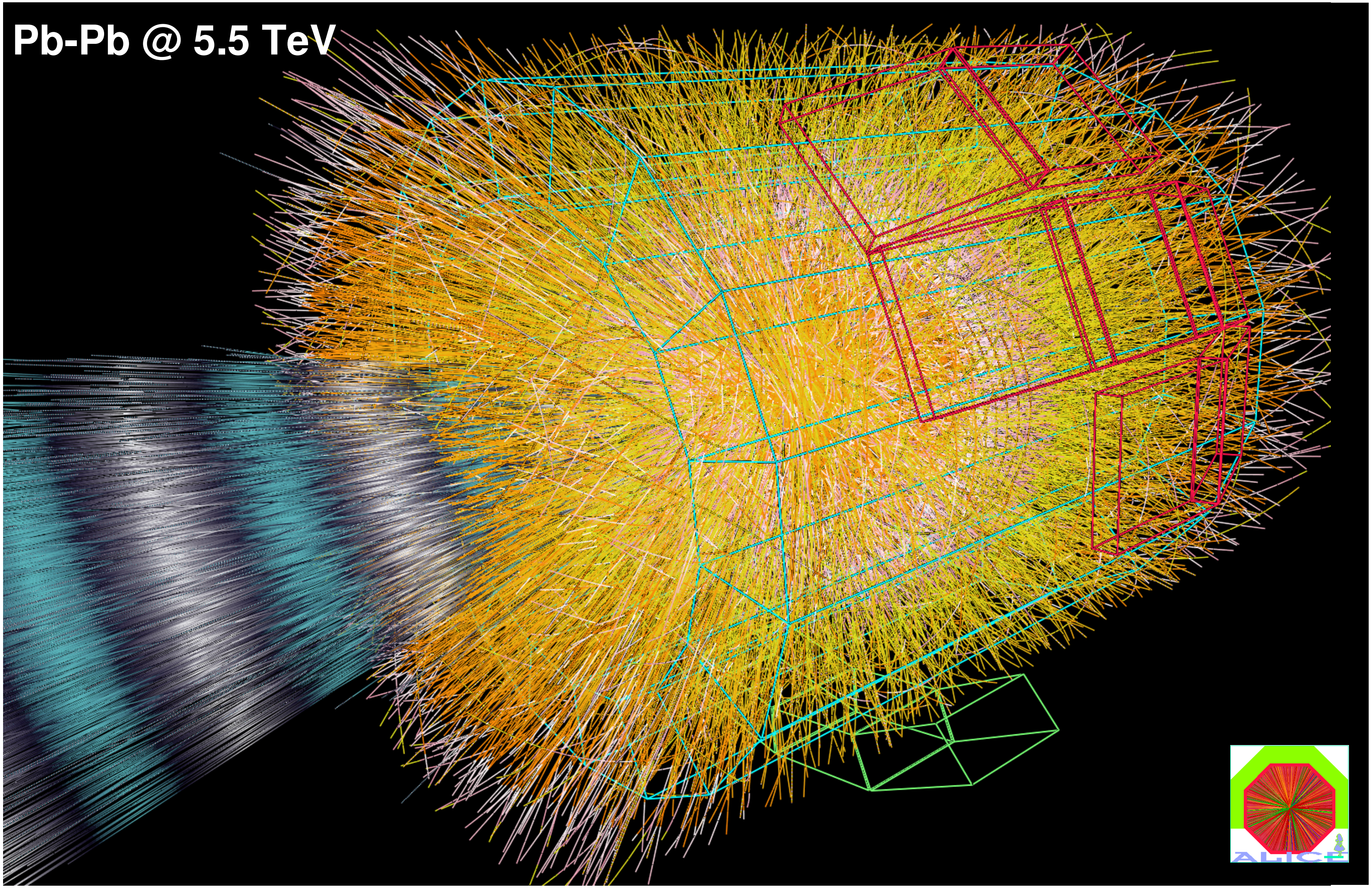
Strongest capabilities:

hard-probes, full jet reco, heavy-Q jet PID

ALICE event display: p-p @ 14 TeV



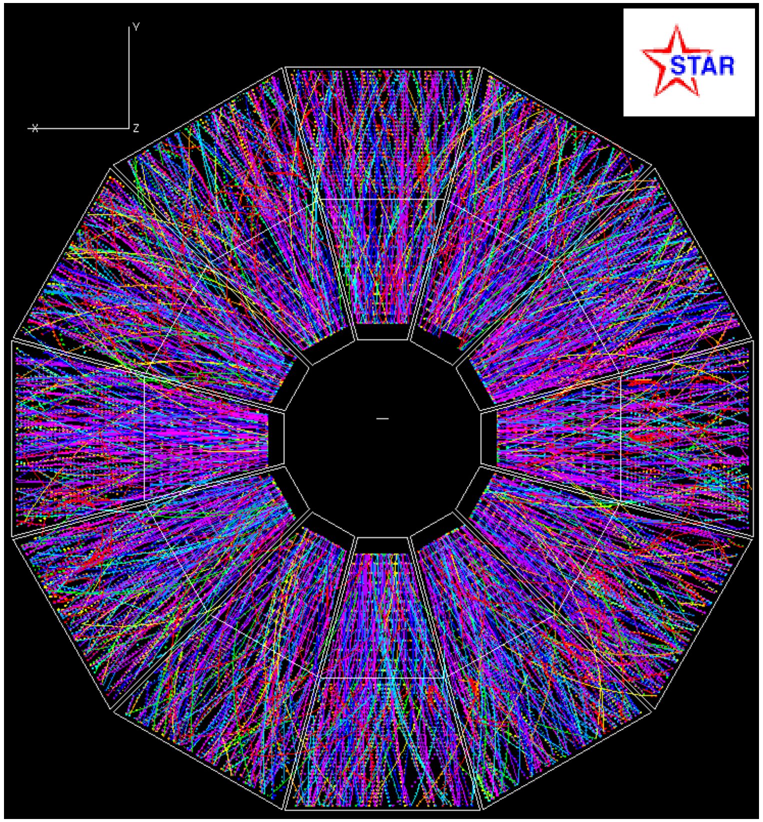
ALICE event display: Pb-Pb @ 5.5 TeV

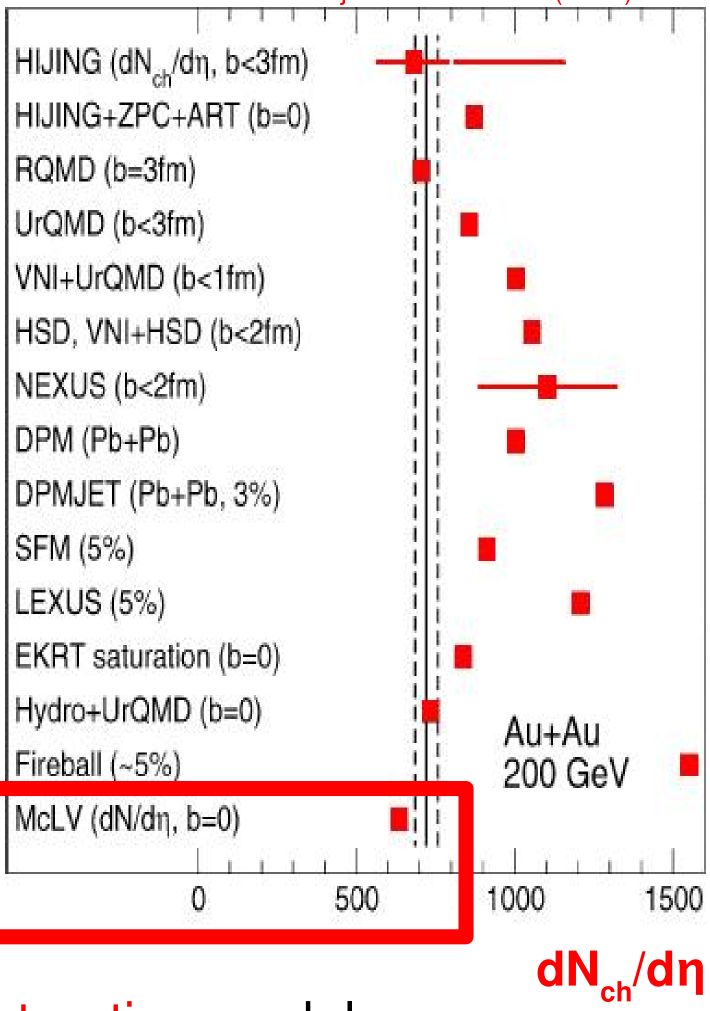


Soft QGP probes (I): Total hadron multiplicity

Total AA hadron multiplicity (RHIC)

- AuAu (200 GeV) 0-5% central collisions:





~650 charged hadrons per unit rapidity at y=0

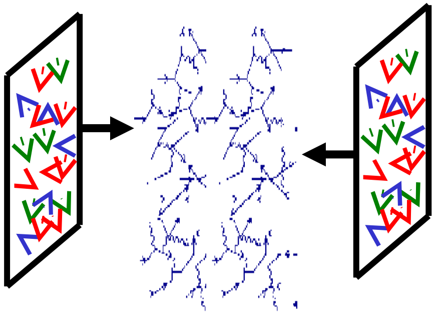
- "Reduced" multiplicity predicted by gluon saturation models.

(reduced initial parton flux: gg→g)

Total PbPb hadron multiplicity (LHC)

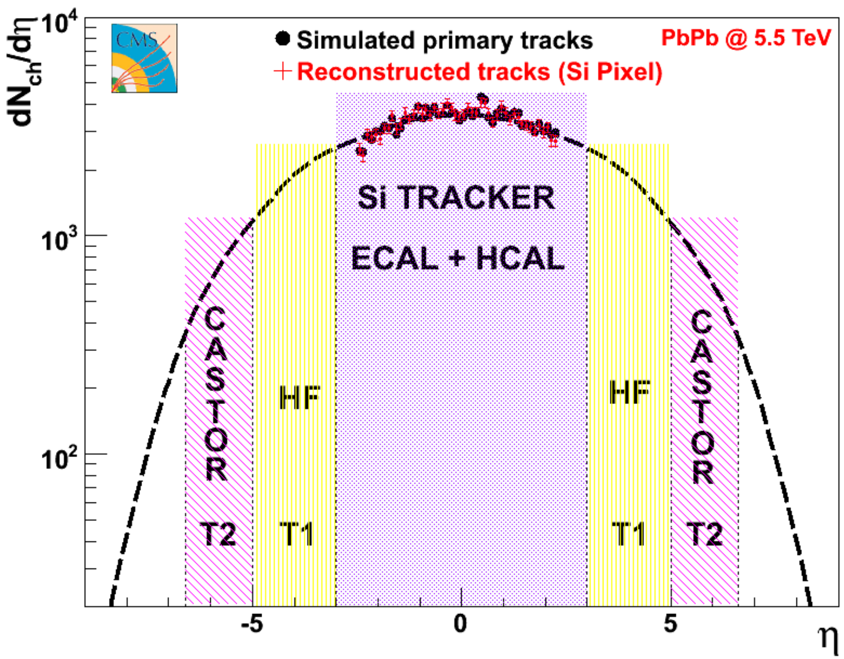
- Final A+A multiplicity ∝ Initial number of released gluons :

CGC: $$\frac{dN}{d^2b\,d\eta} \propto \frac{1}{\alpha_s(Q_s^2)} Q_s^2 \propto xG(x,Q_s^2)\cdot A^{1/3}$$



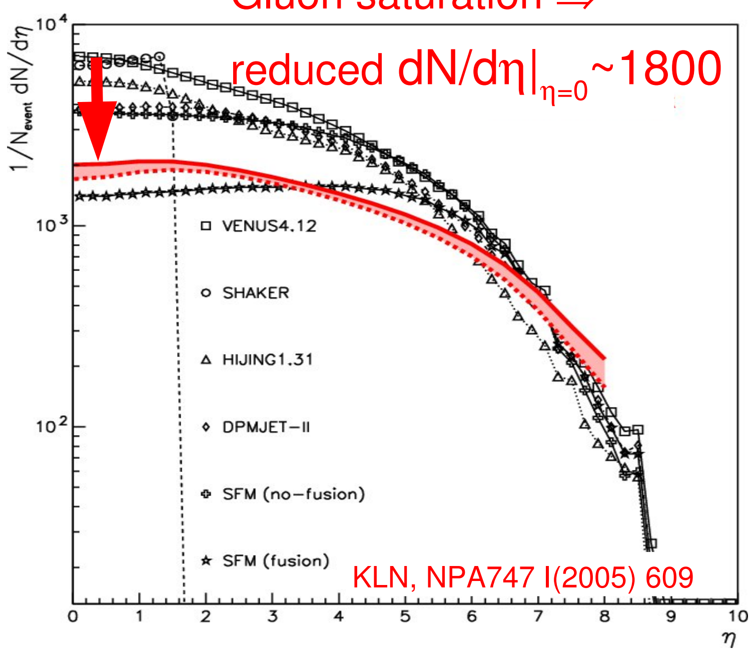
+ “local parton-hadron duality” (*1 gluon = 1 final hadron*)

- $dN_{ch}/d\eta$ ($|\eta|<2.5$) measured e.g. via hit counting in Si pixels:



Gluon saturation ⇒

reduced $dN/d\eta|_{\eta=0}$~1800

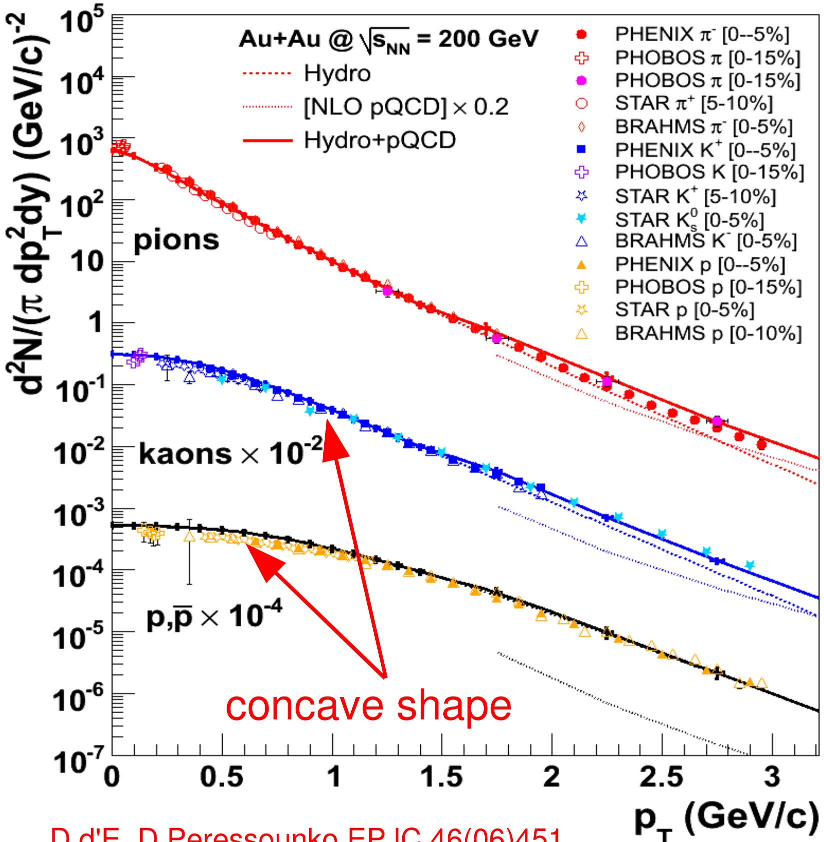


KLN, NPA747 I(2005) 609

Soft QGP probes (II):
Soft hadron spectra

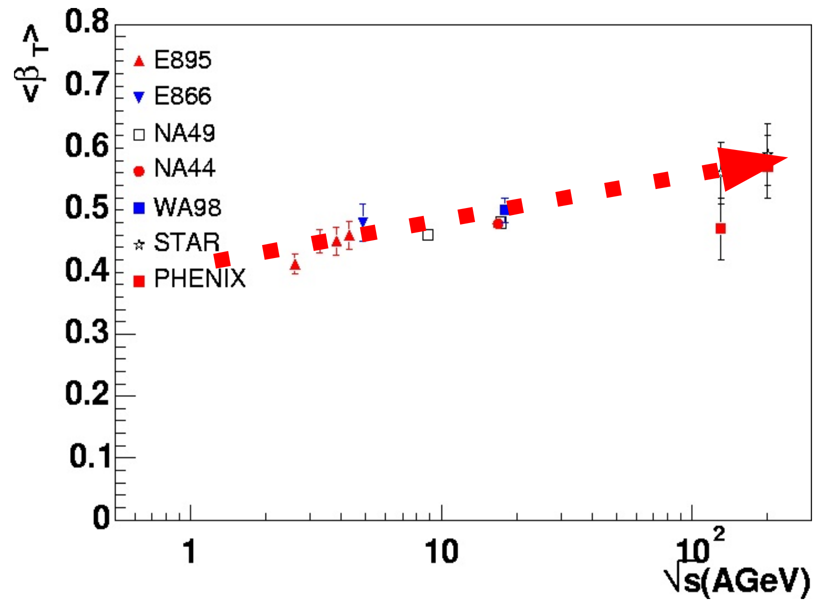
Soft hadron spectra (RHIC)

- Single hadron ($\pi^\pm$, $K^\pm$, p, pbar) p_T spectra up to ~2 GeV/c boosted for increasing centrality, with a (mass-dependent) collective radial flow:



D.d'E, D.Peressounko EPJC 46(06)451

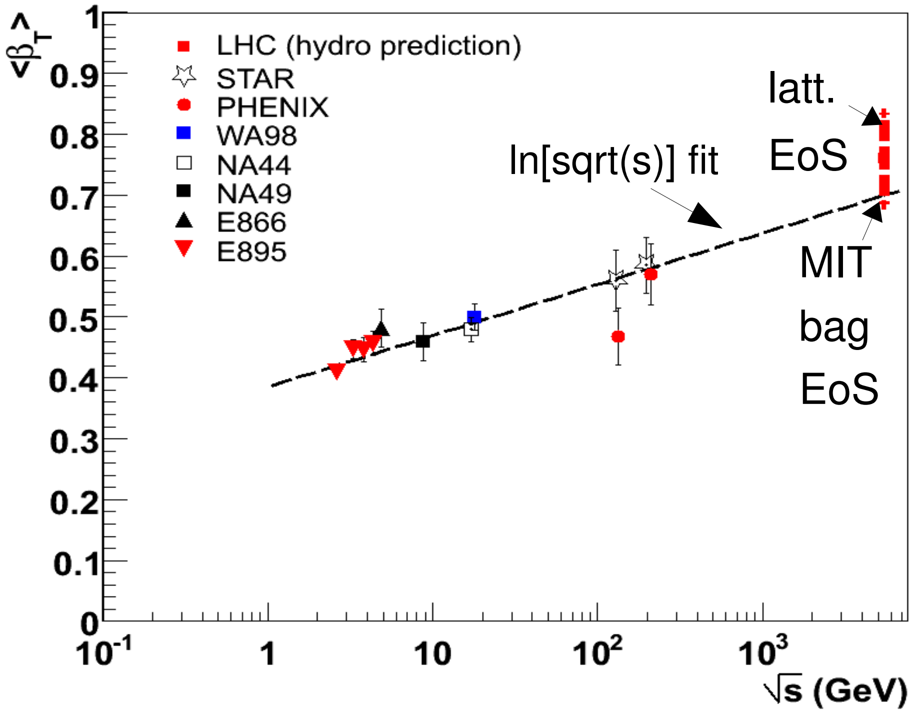
Strong radial collective flow built-up at freeze-out: $<\beta_T> \approx 0.6$



- "Explosive" behaviour reproduced by hydrodynamics calculations with QGP Eq.-of-State (ε~30 GeV/fm^3) & fast thermalization times (τ~0.6 fm/c)

Soft hadron spectra (LHC)

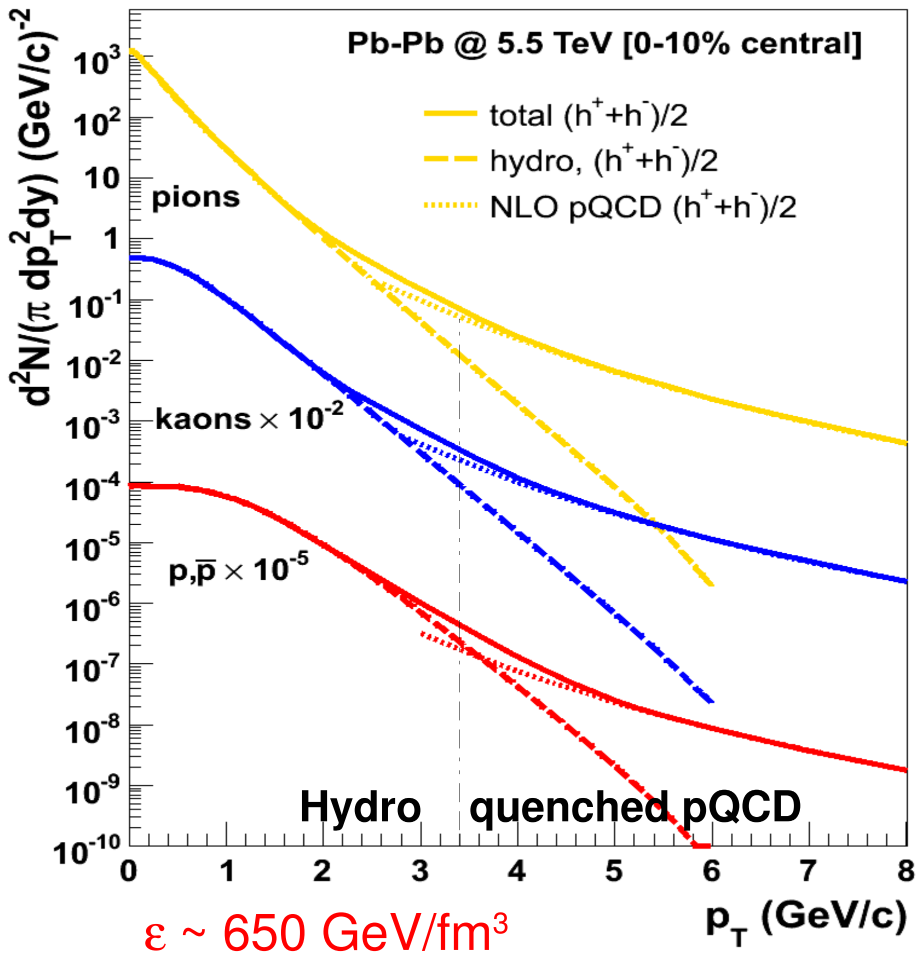
- Collective expansion velocity of inclusive hadrons: $\langle\beta_T\rangle \approx 0.75$



Arleo-Dd'E-Peressounko JPG 35 (08)054001

- Single hadron ($\pi^\pm$, $K^\pm$, p,p) p_T spectra

Pb-Pb @ 5.5 TeV (central, <b>~3 fm):



$\varepsilon \sim 650$ GeV/fm^3

$\tau \sim 0.1$ fm/c

Plan of lectures: tomorrow ...

1^{st}

- Introduction
  - High-energy nucleus-nucleus collisions physics programme:
    confinement, chiral symmetry, early Universe thermodyn., low-x QCD ...
  - Colliders & Experiments: RHIC(Au-Au@200 GeV), LHC(PbPb@5.5 TeV)
- Study of many-body QCD (thermo)dynamics:
  - Soft probes:
    (1) $dN_{ch}/d\eta \Rightarrow$ Colour-Glass-Condensate – gluon $xG_A(x,Q^2)$
    (2) Low p_T π/K/p spectra $\Rightarrow$ QCD Equation-of-State

2^{nd}

    (3) Elliptic flow $\Rightarrow$ QCD medium viscosity, AdS/CFT test-bed
  - Hard probes:
    (1) "Jet quenching" $\Rightarrow$ Parton density, $\langle\hat{q}\rangle$ transport coefficient
    (2) Direct (thermal) photons $\Rightarrow$ QCD critical temperature (T_{crit})
    (3) Quarkonia suppression $\Rightarrow$ QCD critical ε_{crit} , T_{crit}

Backup slides

LHC: new frontier for QGP/CGC studies

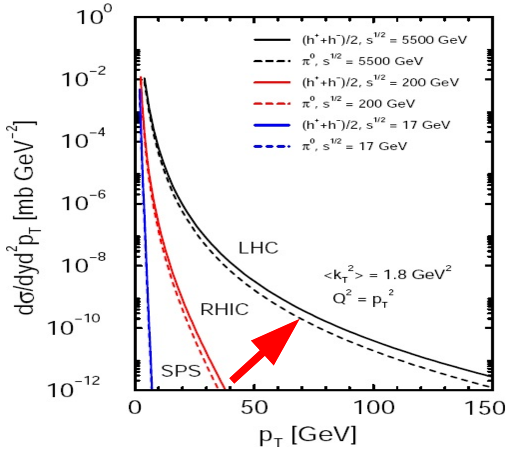
- Produced quark-gluon matter:

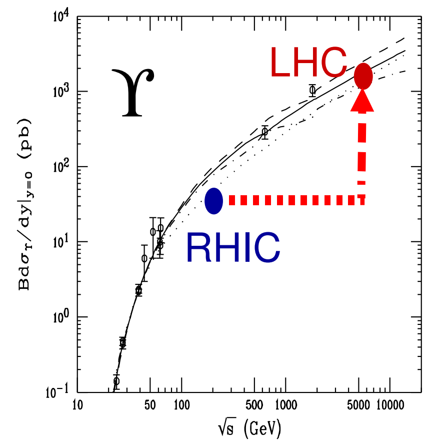
  hotter, denser, bigger, longer-lived

	SPS	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	17	200	5500	X 28
dN_{ch}/dy	500	850	1500-3000	x 2-3
τ^0_{QGP} (fm/c)	1	0.2	0.1	faster
T/T_c	1.1	1.9	3.0-4.2	hotter
ε (GeV/fm^3)	3	5	15-60	denser
τ_{QGP} (fm/c)	≤2	2-4	≥10	longer
τ_f (fm/c)	~5	~10	~20	
V_f(fm^3)	few 10^3	few 10^4	few 10^5	bigger

- Very large pQCD cross-sections

  ("tomographic" probes of QCD medium)





$x=2p_T/\sqrt{s}\sim10^{-4}$-$10^{-5}$ ~ 30-45 times

smaller than @ RHIC. Q_s^2 ~ ×3 larger