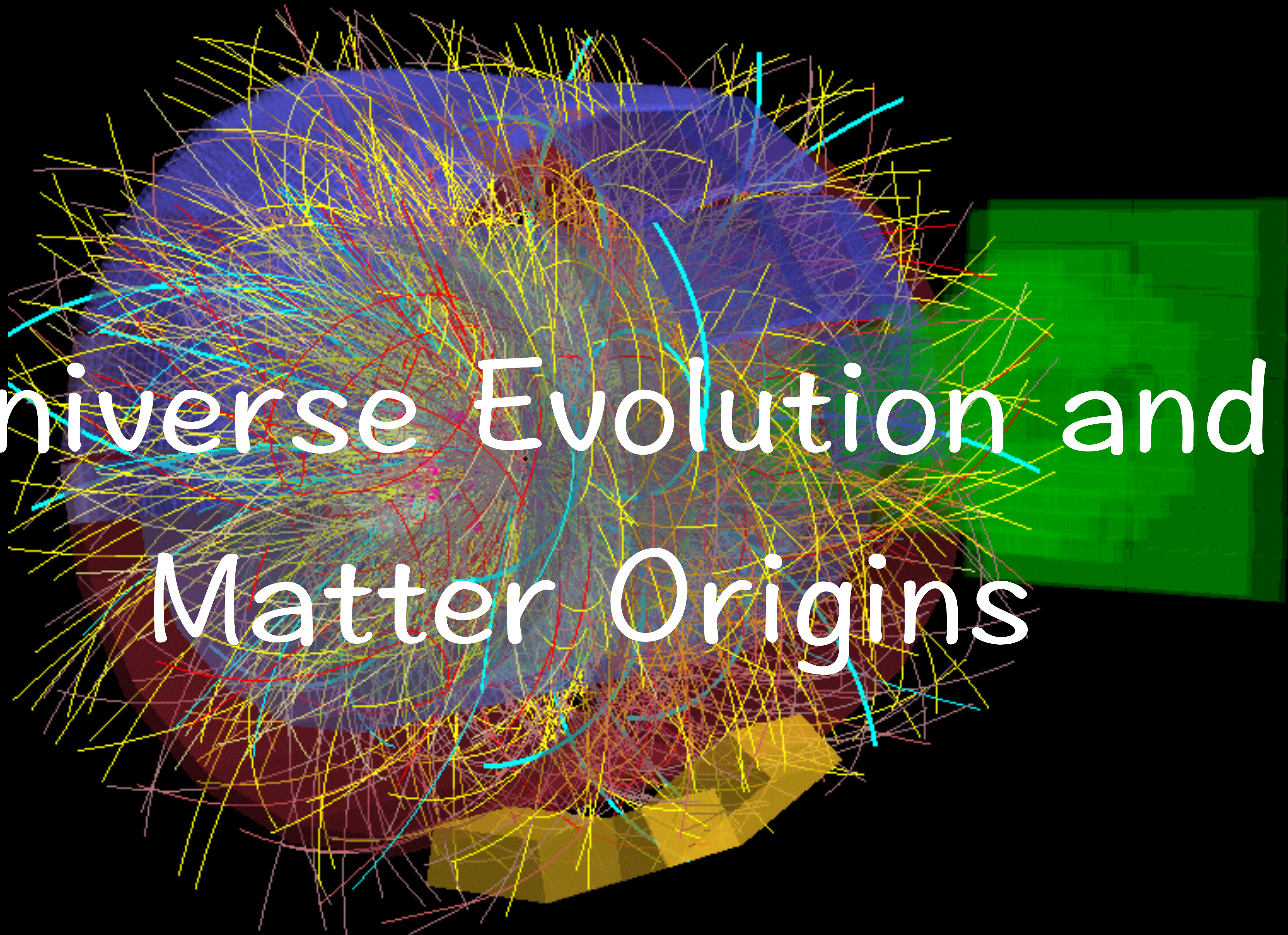
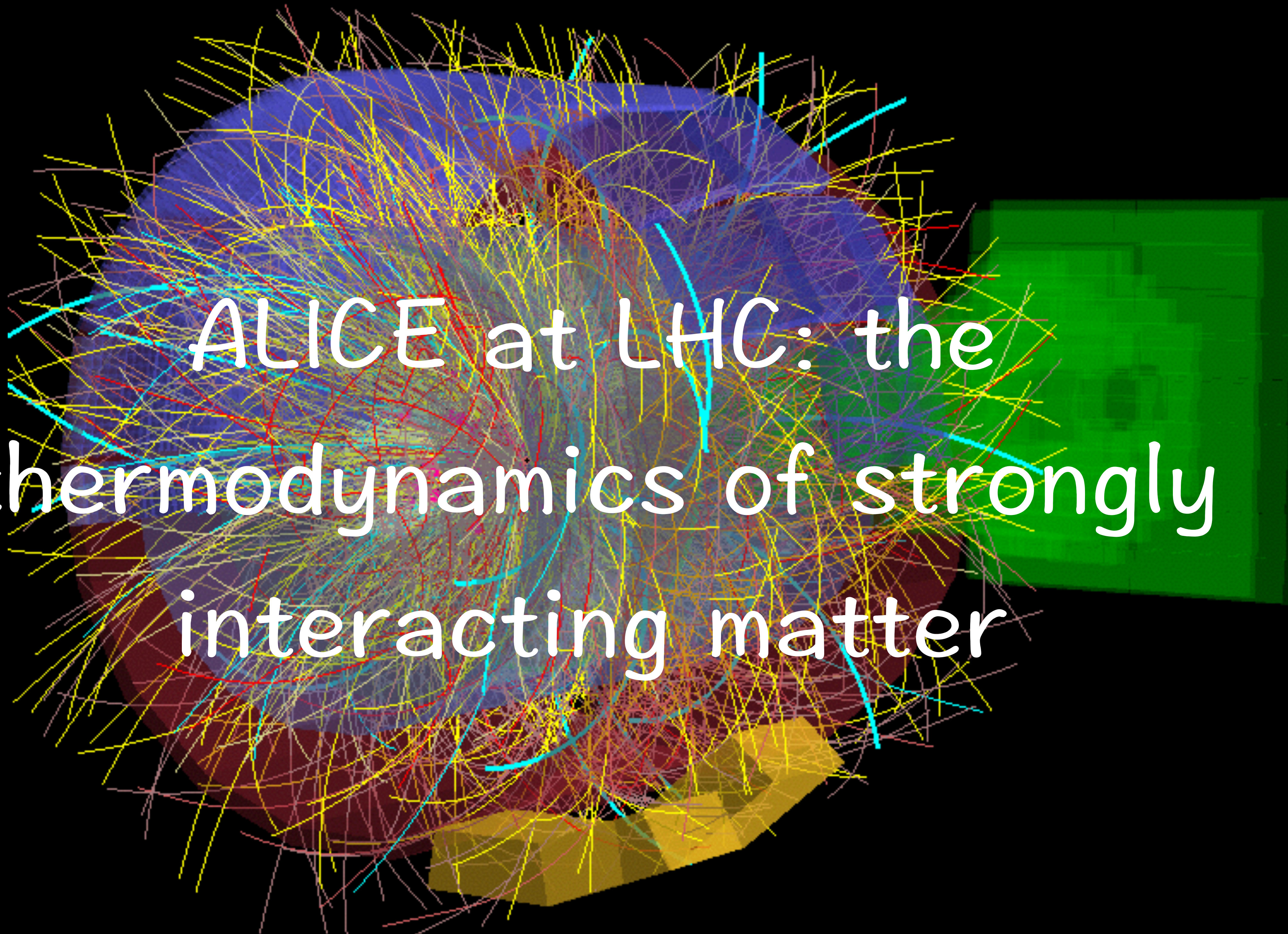
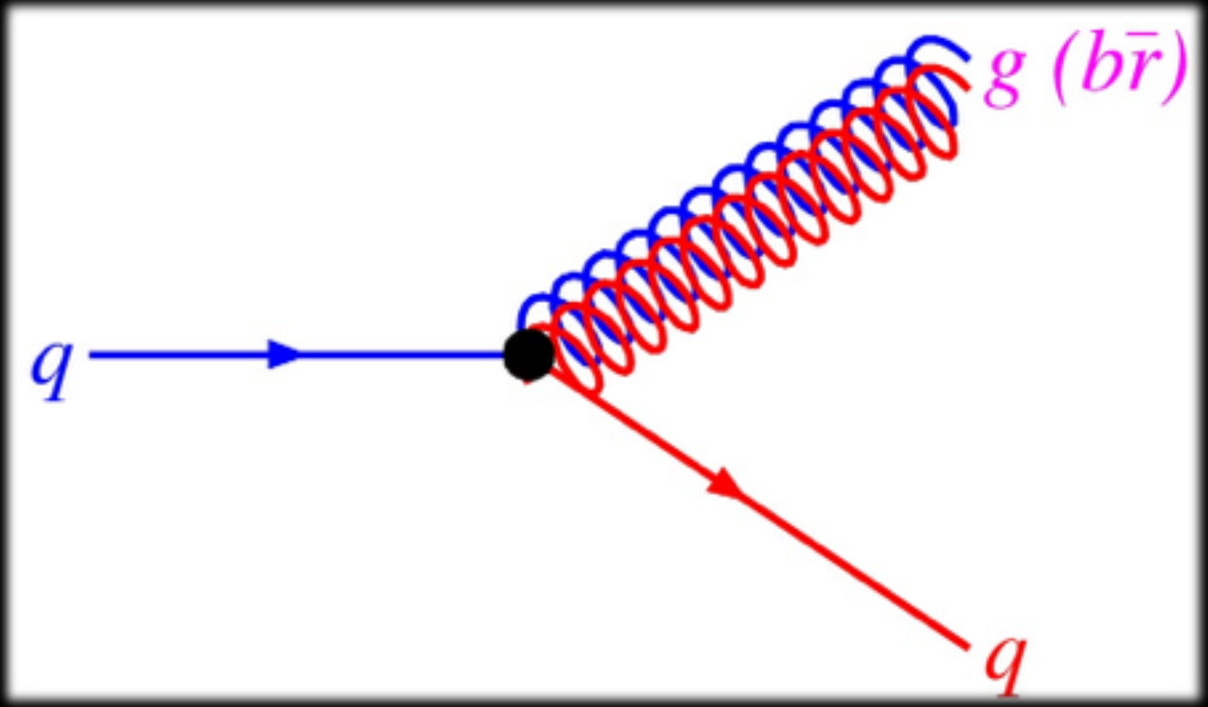


Universe Evolution and Matter Origins

ALICE at LHC: the thermodynamics of strongly interacting matter

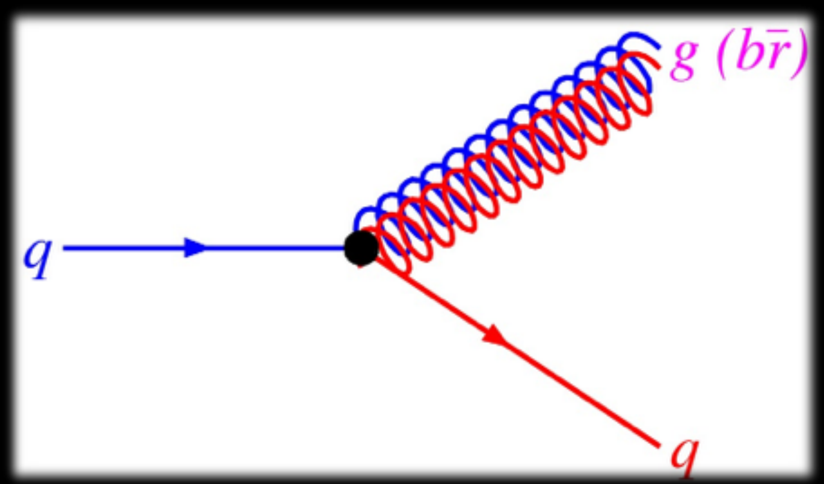


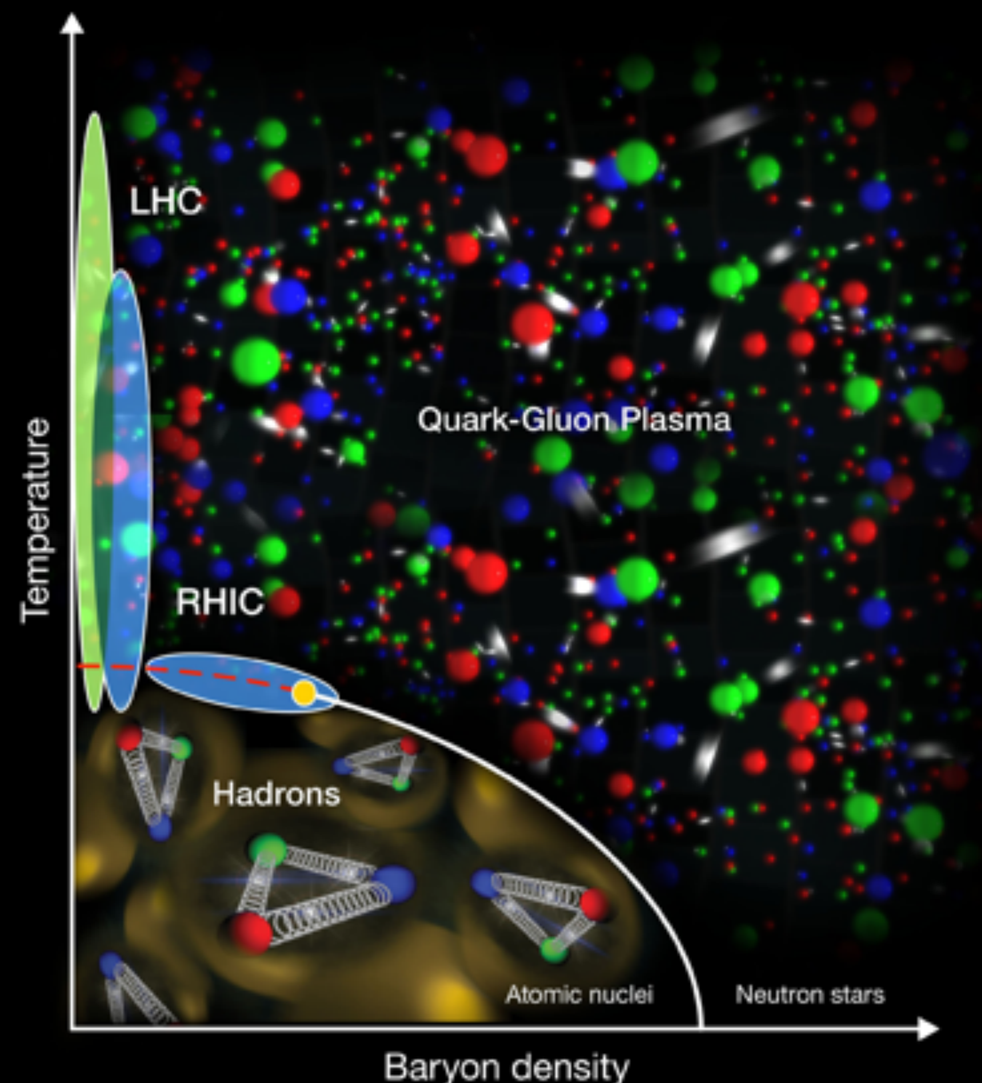
Thermodynamics of strongly interacting matter*



* many interacting constituents

Thermodynamics of strongly interaction matter





How does the complexity of matter emerge from the dynamics of the strong interaction

What are the ultimate constituents of matter ?

What are the basic forces among them ?

What are the possible states of matter ?

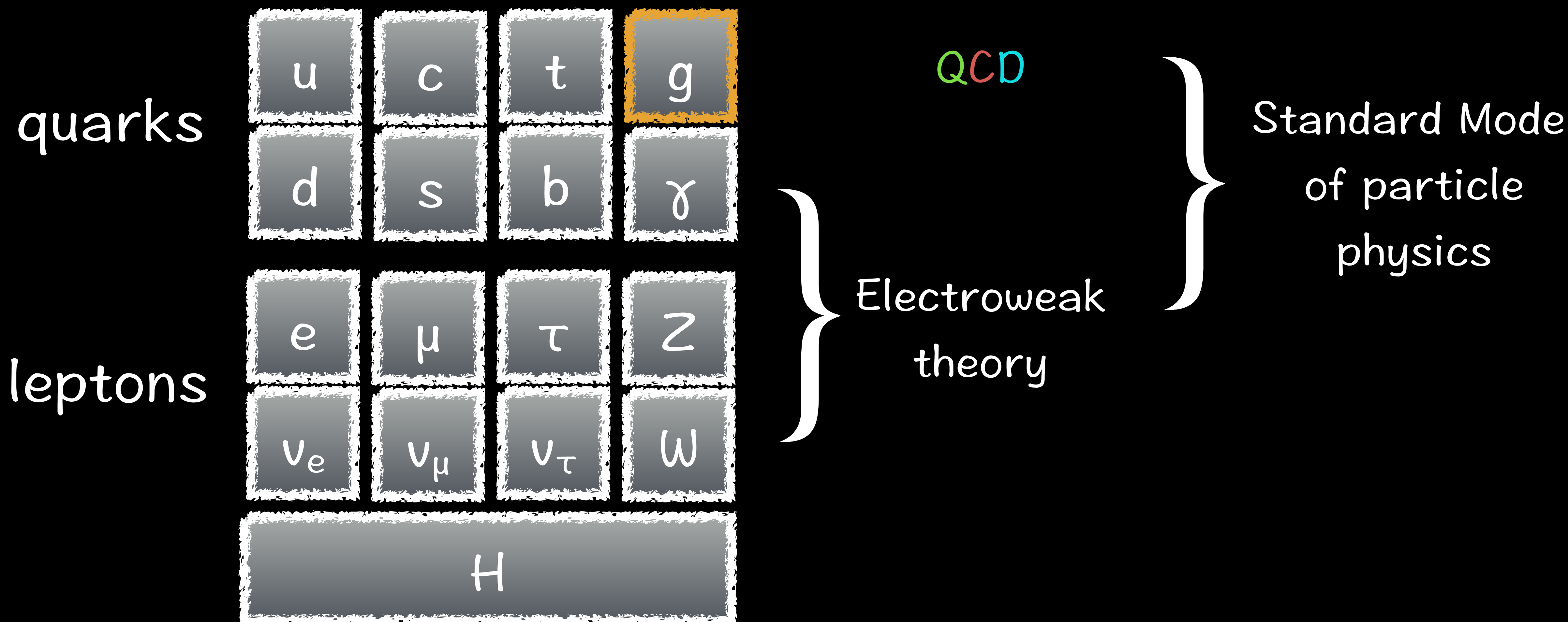
How do transition between these states occur ?

What are the ultimate constituents of matter ?

quarks	u	c	t
	d	s	b
leptons	e	μ	τ
	ν_e	ν_μ	ν_τ

- basic constituents without individual physical existence
- hadrons are the single particle states in the physical vacuum

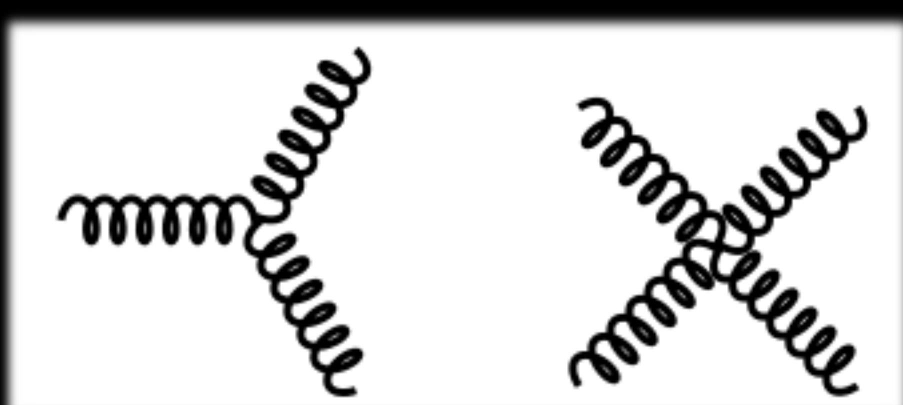
- ☑ What are the ultimate **constituents** of matter ?
- ☑ What are the basic **forces** among them ?

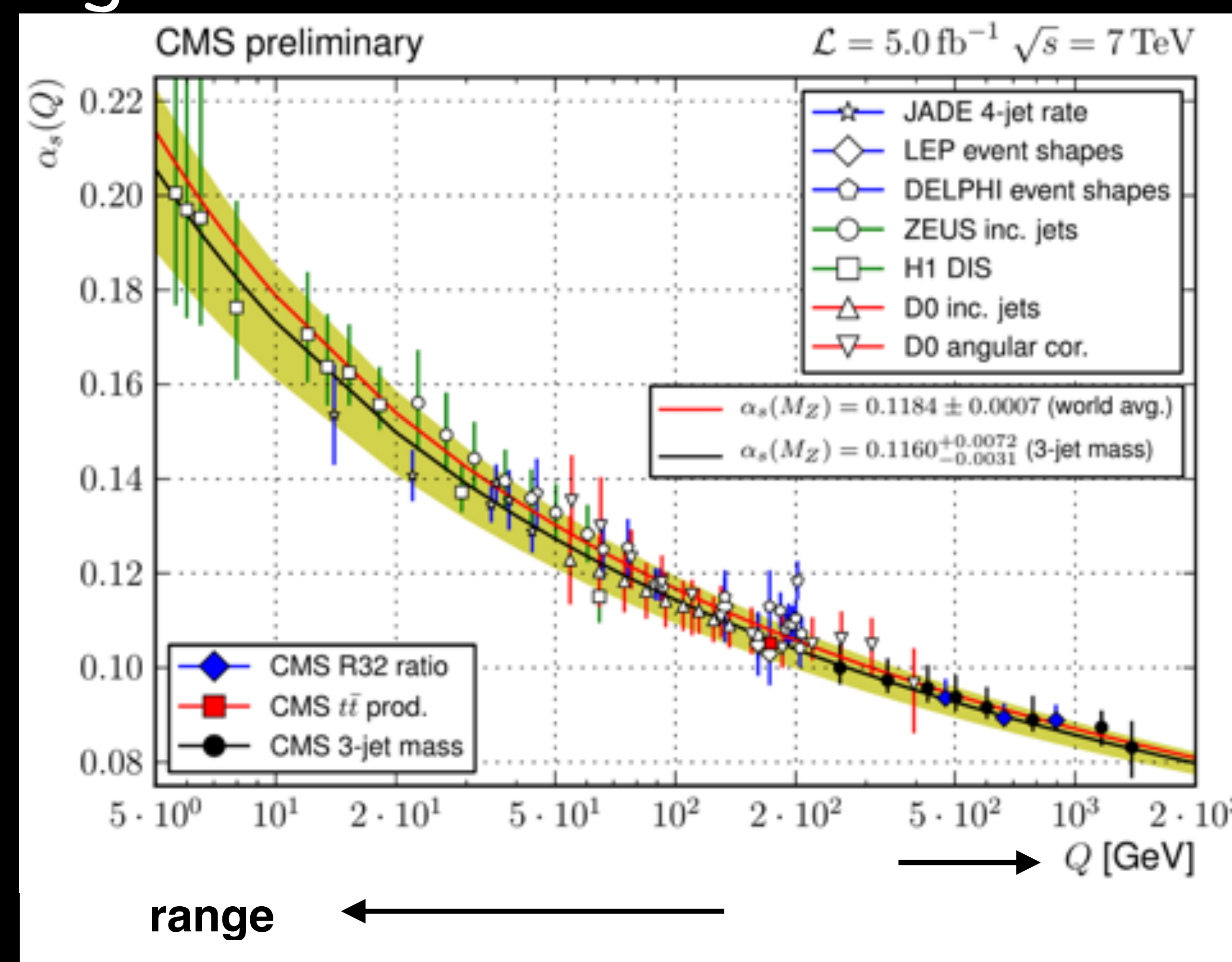


- gluon mediates the strong interaction
- color is the intrinsic charge
- quarks confined inside colorless space Λ ~ 1 fm

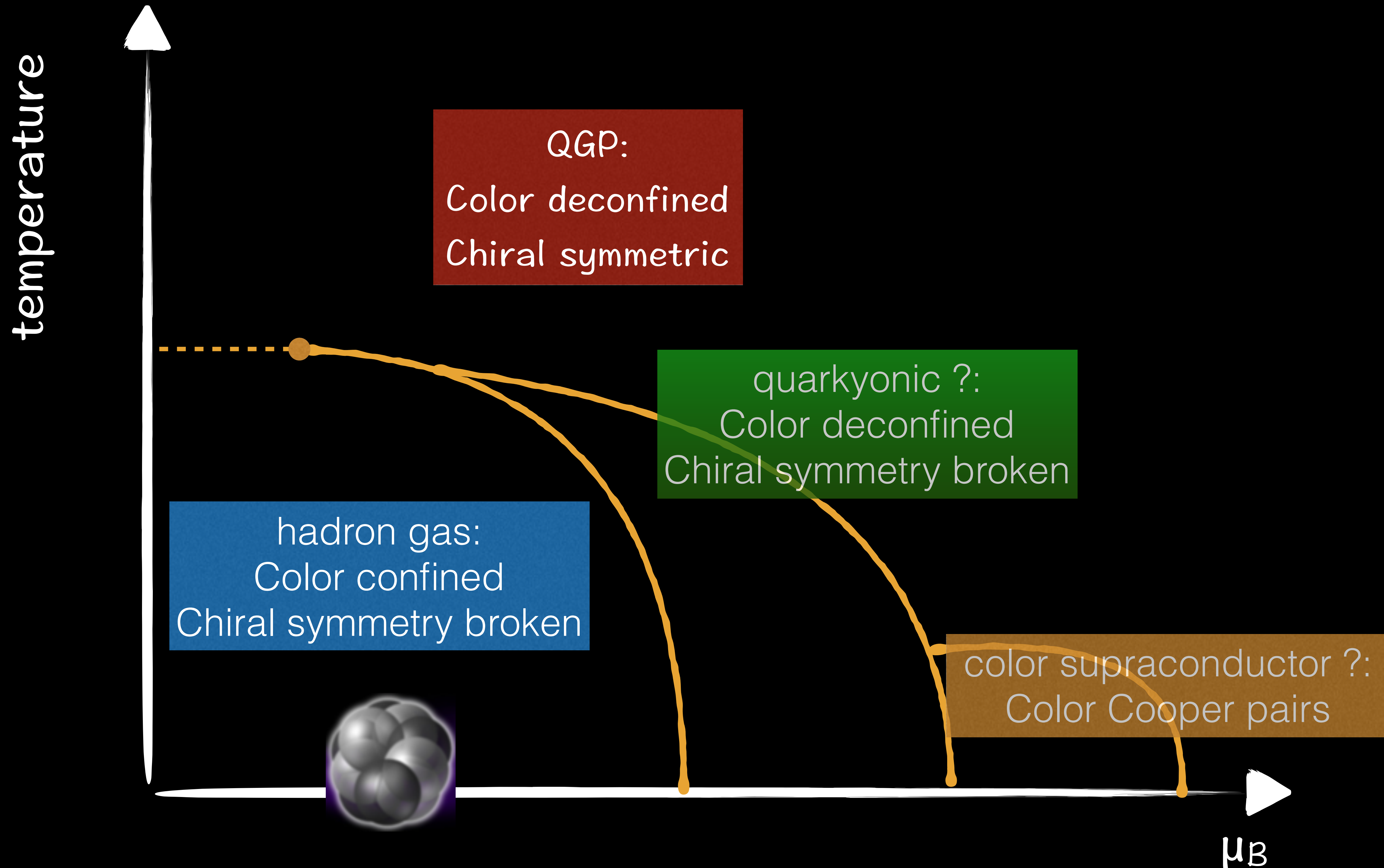
QCD: A quantum field theory

- matter fields: 6 s=1/2 quarks
- interaction fields: 8 massless gauge vector g
- 3 colors : non abelian SU(3) gauge group
- degrees of freedom change with Q^2

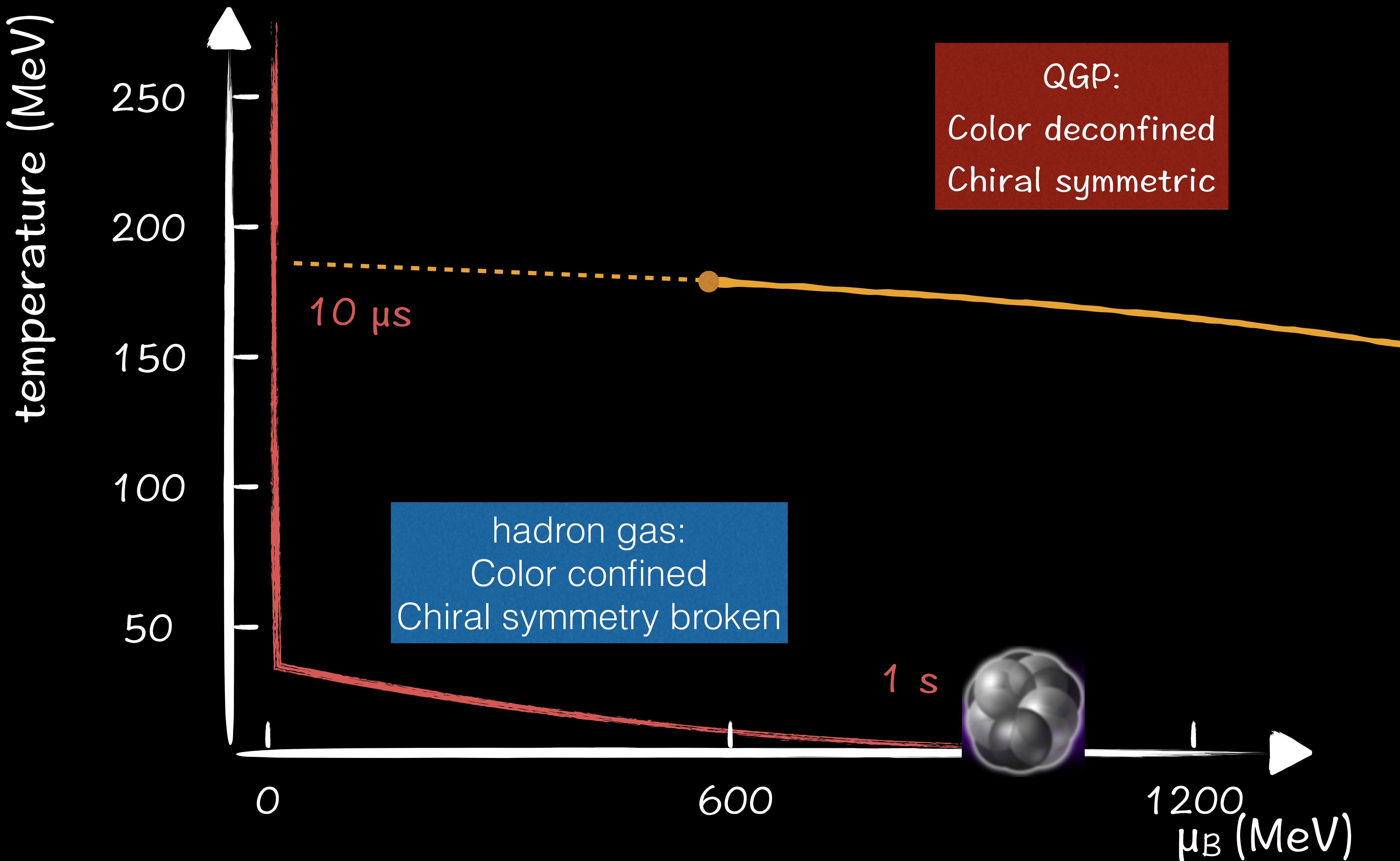




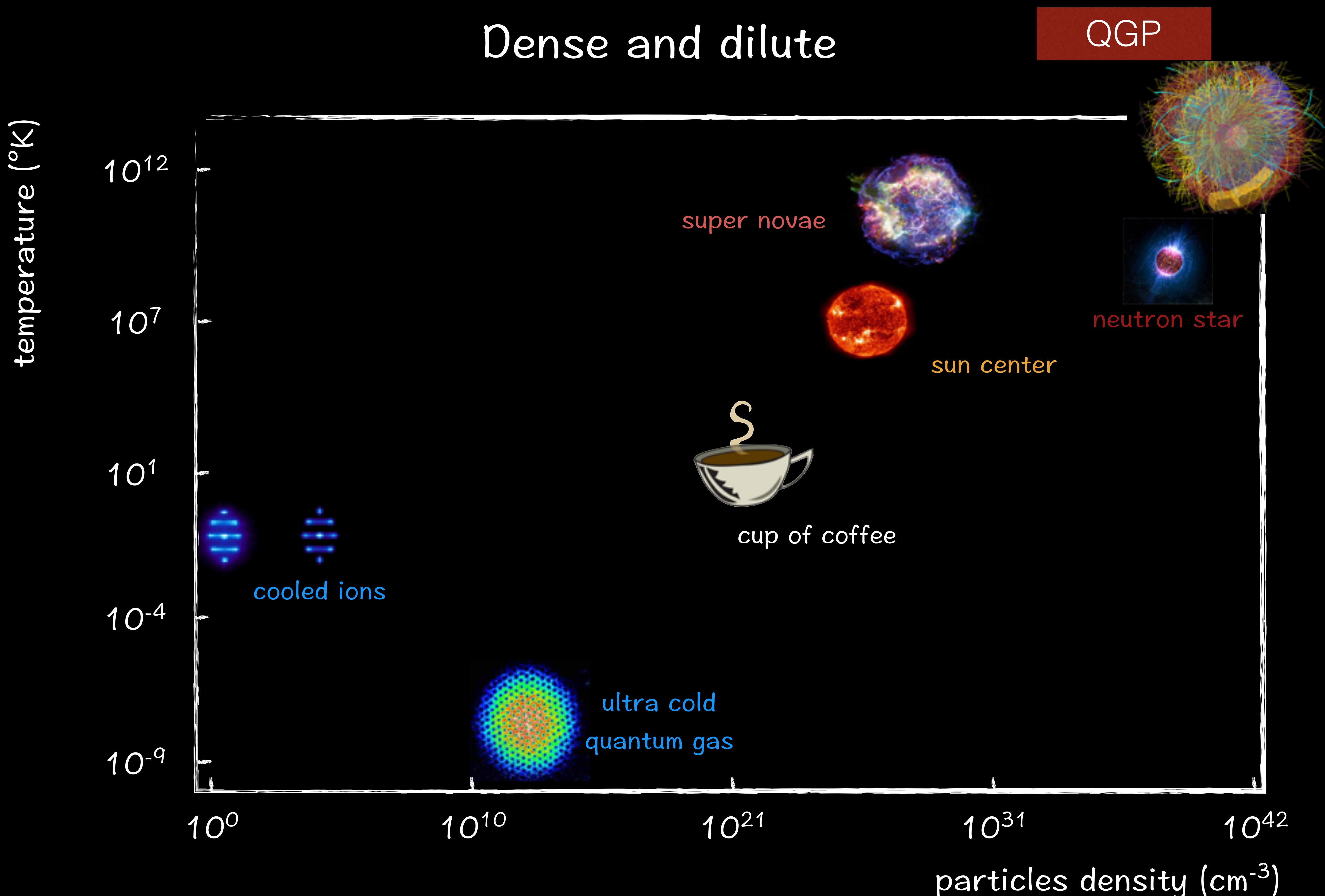
QCD: A rich phenomenology



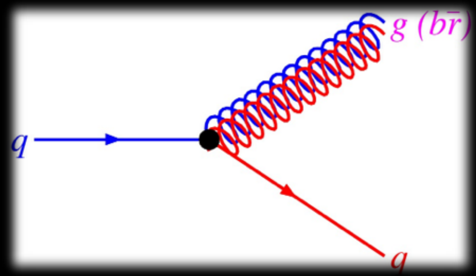
Evolution of early universe



Hot and cold
Dense and dilute

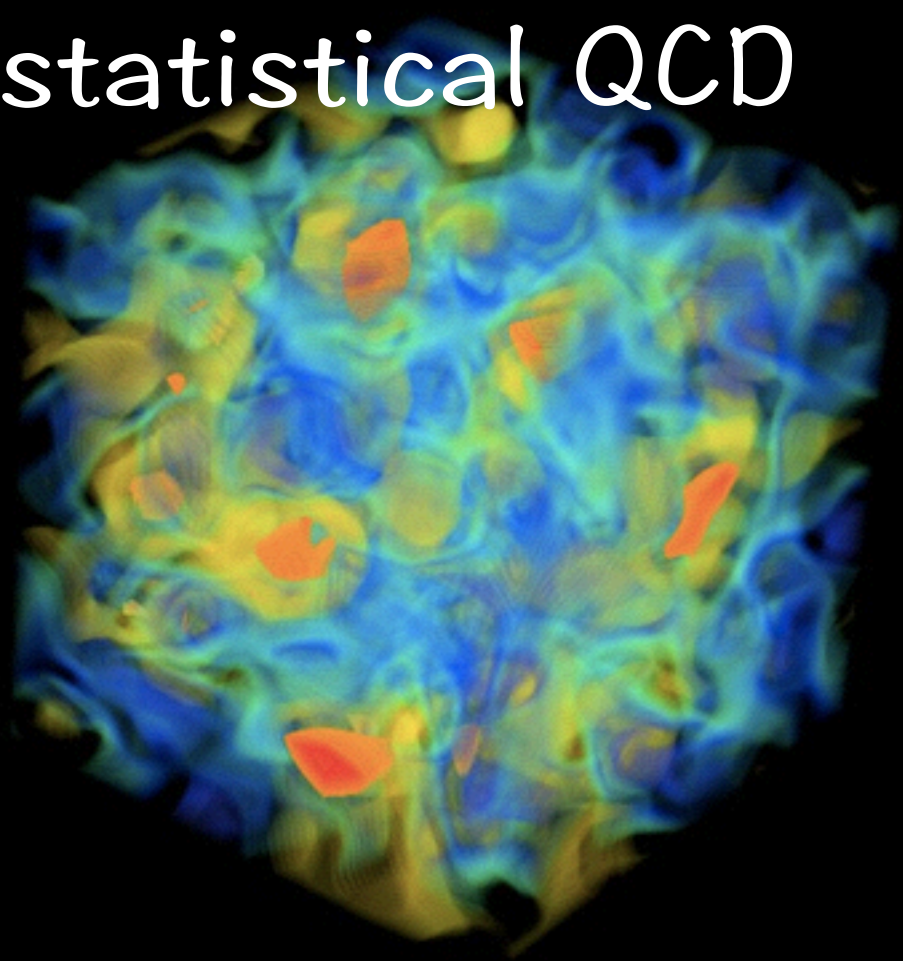


- ☑ What are the ultimate **constituents** of matter ?
- ☑ What are the basic **forces** among them ?
- What are the possible **states** of matter ?
- How do **transition** between these states occur ?

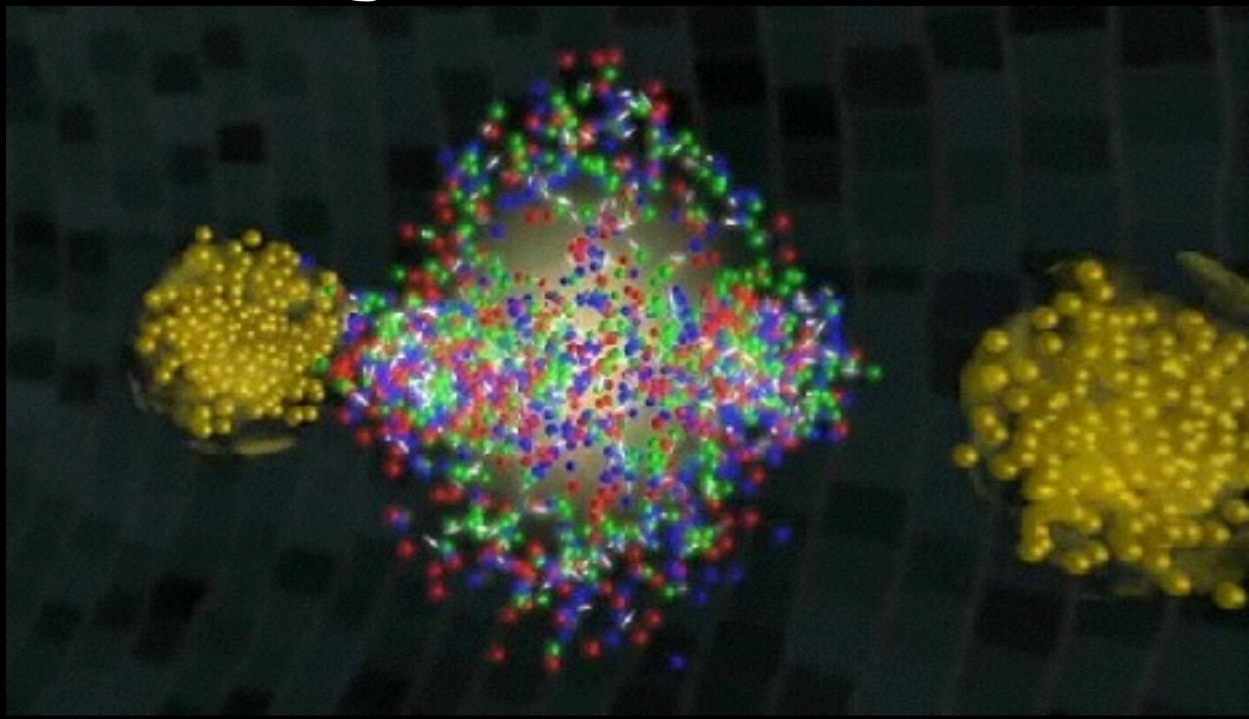


Thermodynamics of strongly interaction matter

statistical QCD



heavy-ion collisions



What are the possible states of matter ?

How do transition between these states occur ?

?

1 nucleon/m^3 → 10^{44} nucleon/m^3 → 10^{50} nucleon/m^3

- Short range aspect of dense matter makes confinement disappear
- A state of matter where basic constituents are quarks

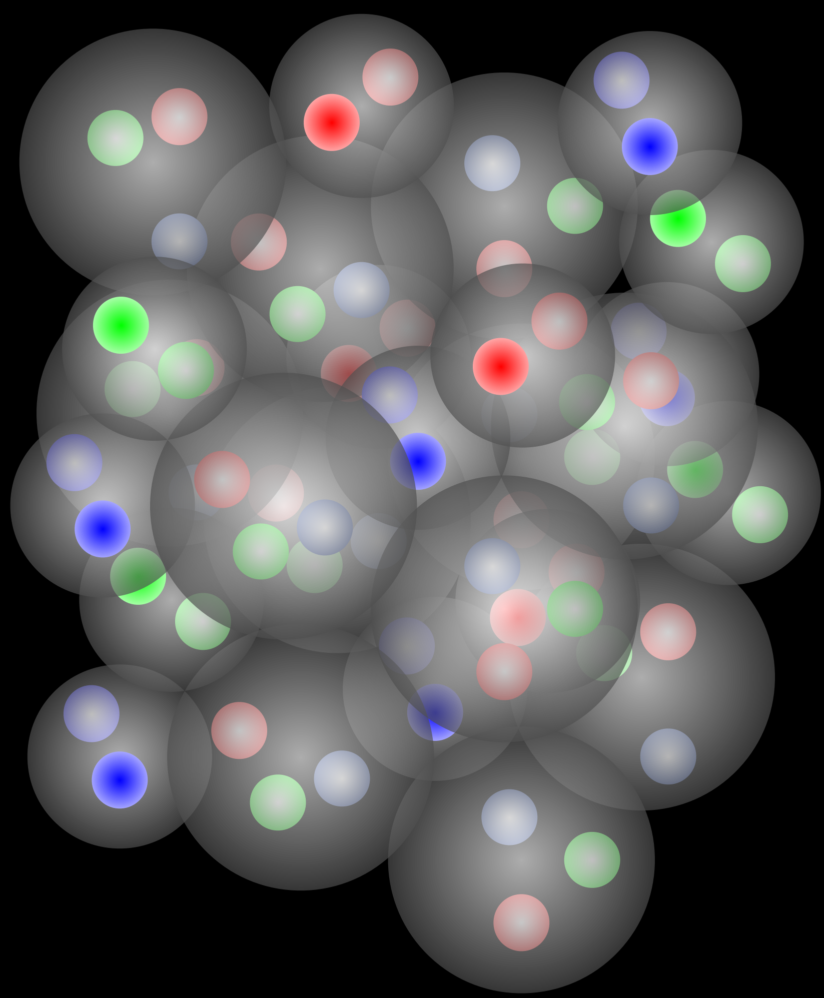
Quark Gluon Plasma

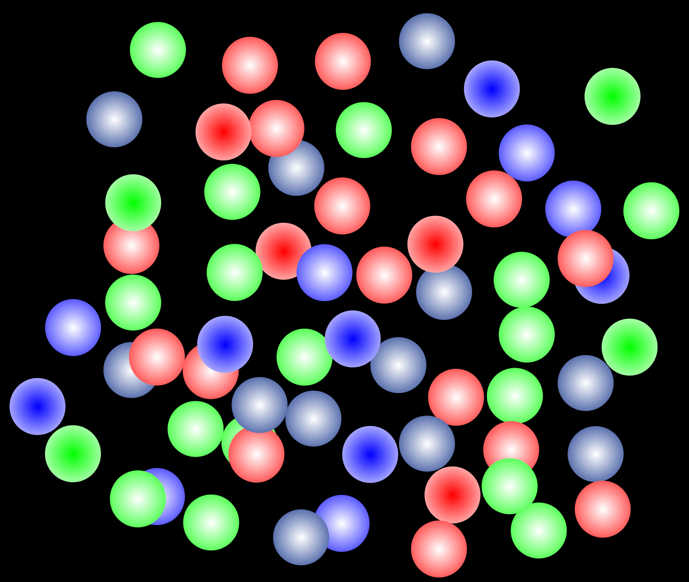
The fundamental questions about extreme matter

- What are the properties, are symmetries restored ?
- Can one measure T_H ?
- Transport parameters and EOS ?
- Nature of microscopic excitations and qp ?
- Is QGP a strongly coupled liquid ?

Quark Gluon Plasma 1

macroscopic system of unbound color charges



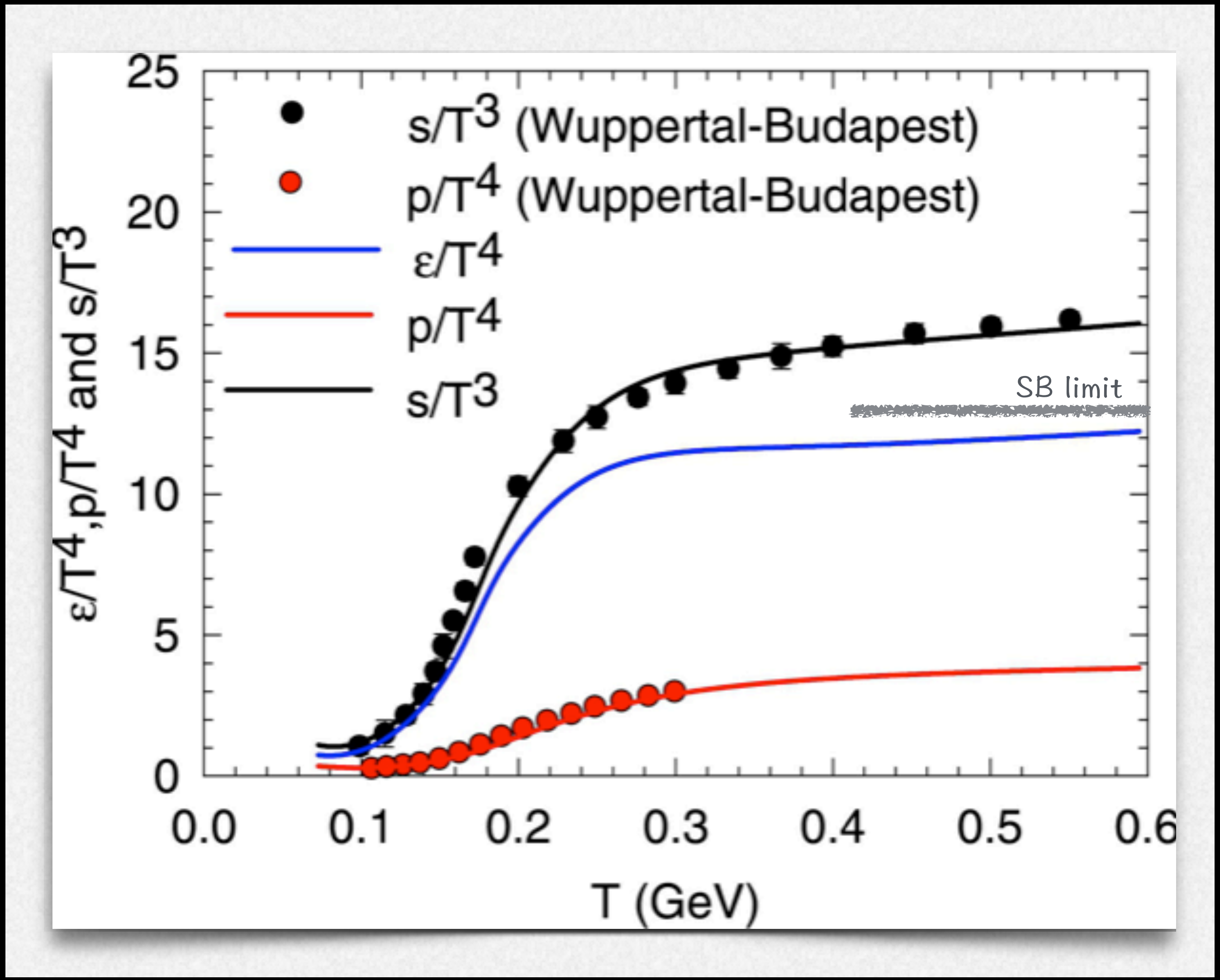


confined (color insulator) → deconfined (color conductor)

transition = collective effect with phase transition

Statistical QCD 1

macroscopic system of unbound color charges



Z_3 symmetry broken, confined hadronic state, few dof → Z_3 symmetry restored, deconfined plasma, many dof (??)

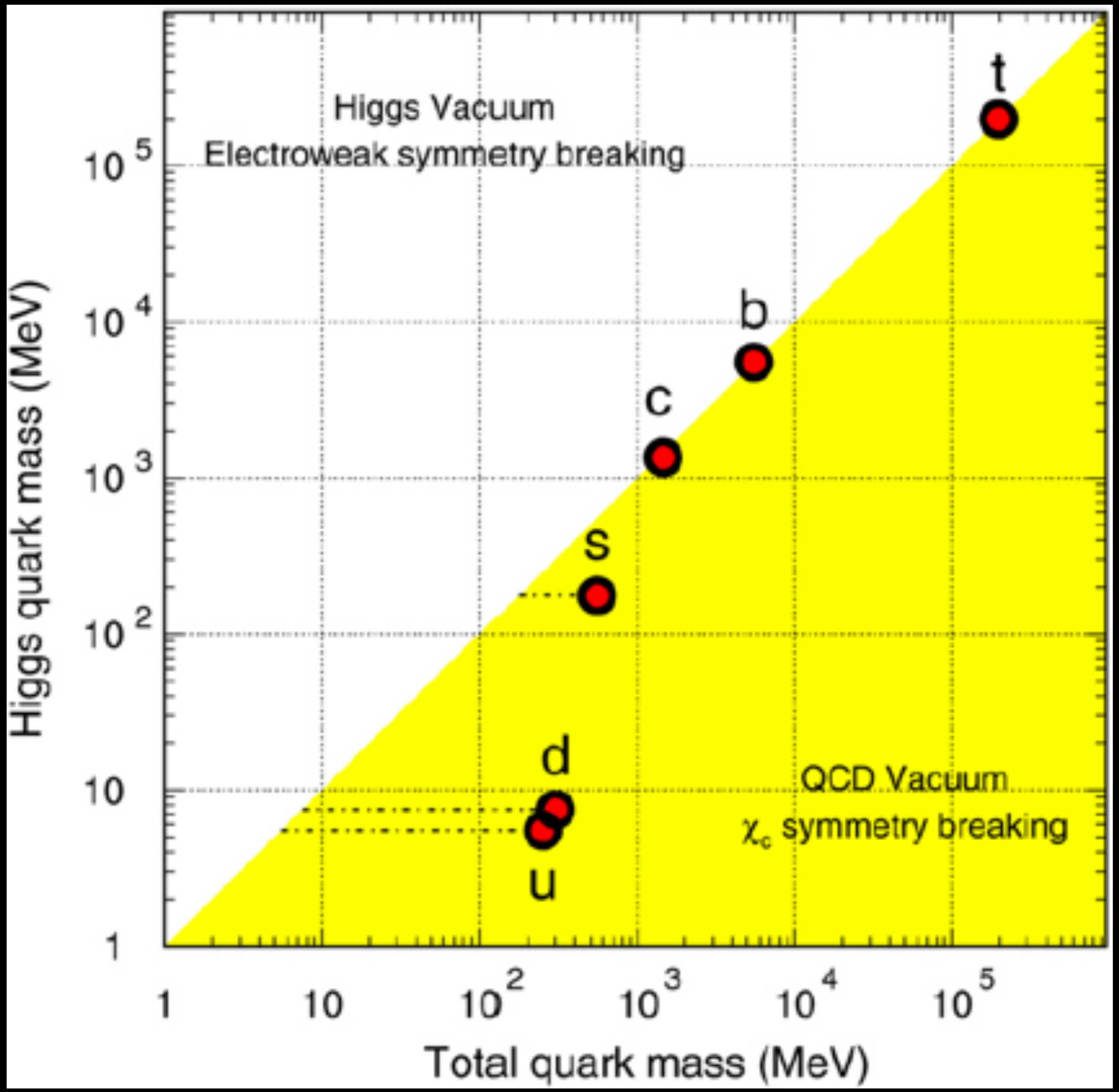
$T_H \sim 170$ MeV

Quark Gluon Plasma 2

macroscopic system of ~ massless quarks

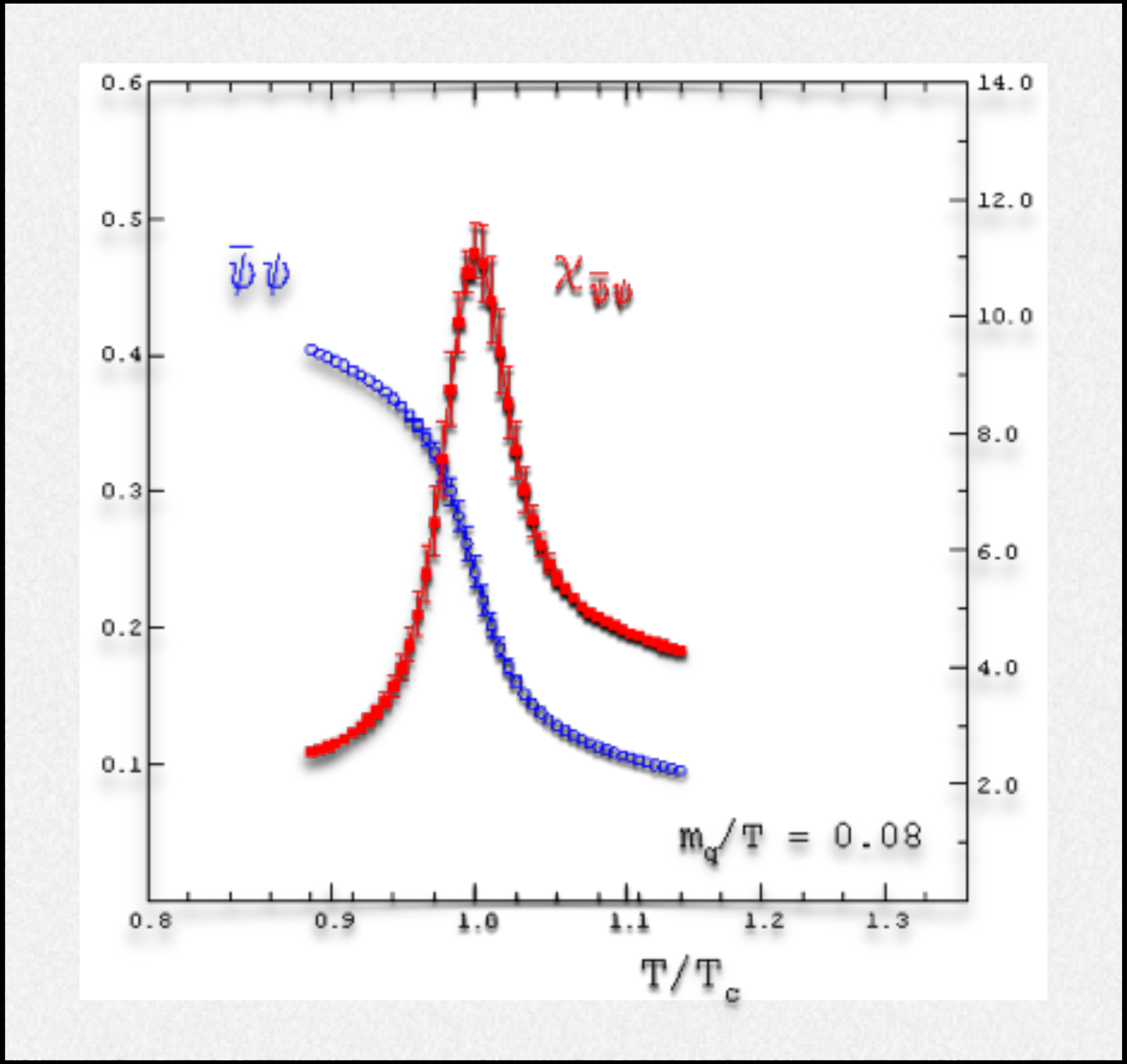
effective q mass generated through EW symmetry breaking (Higgs mass)

constituent q mass generated through confinement (spontaneous χ_c symmetry breaking)



Statistical QCD 2

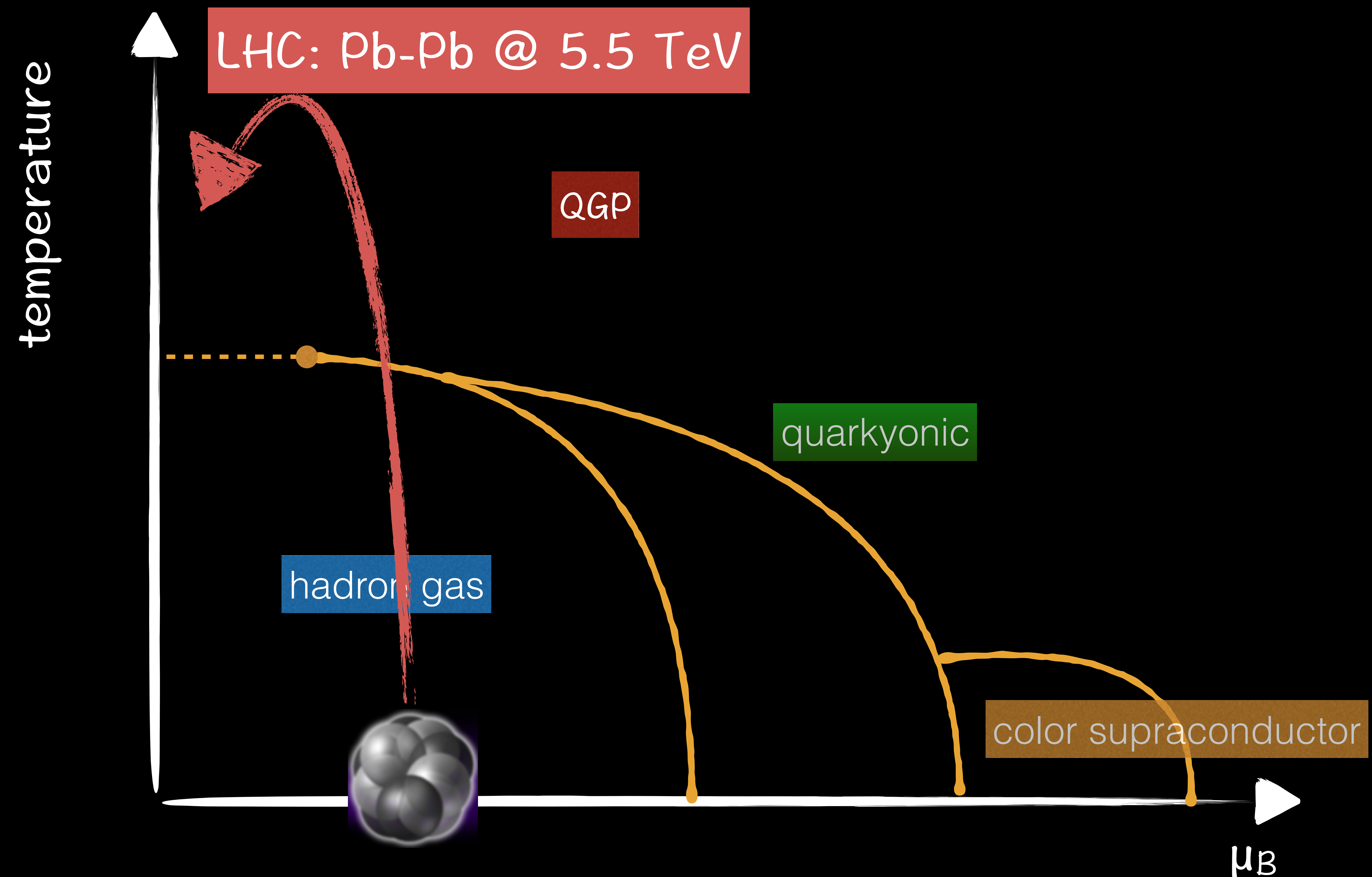
macroscopic system of ~ massless quarks



X symmetry broken, constituent mass → X symmetry restored, effective mass

T_H ~ 170 MeV

Heavy-ion collisions 1 explore the nuclear matter phase diagram

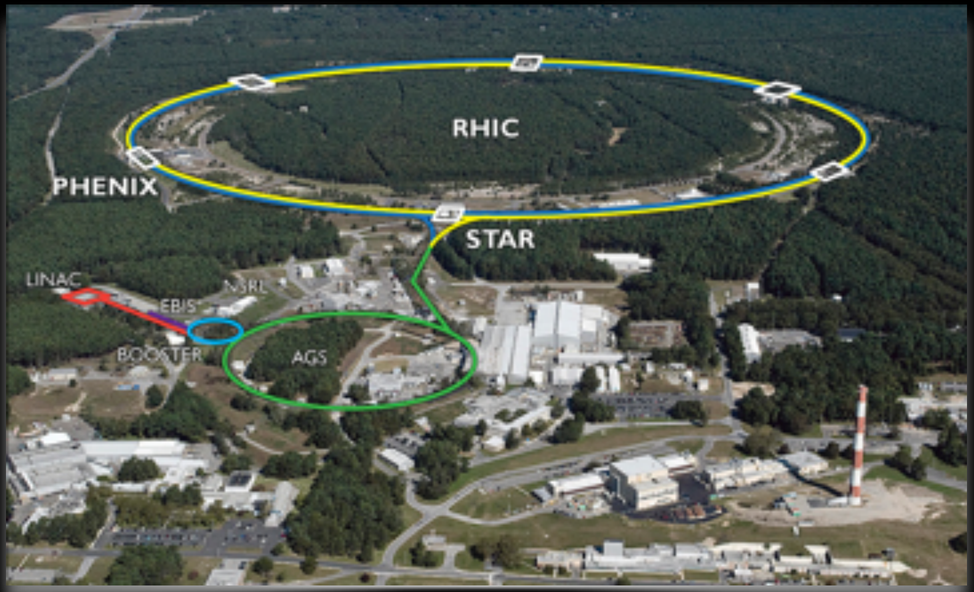


Heavy-ion collisions 2

$\sqrt{s_{NN}}$ = 5500 GeV

Why do we need collider energies to test properties of dense QCD matter which arise on typical scales T = 170 MeV ?

$\sqrt{s_{NN}}$ = 200 GeV

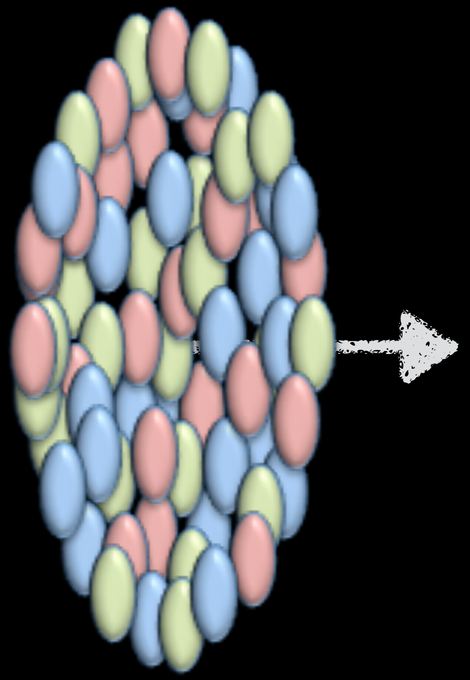


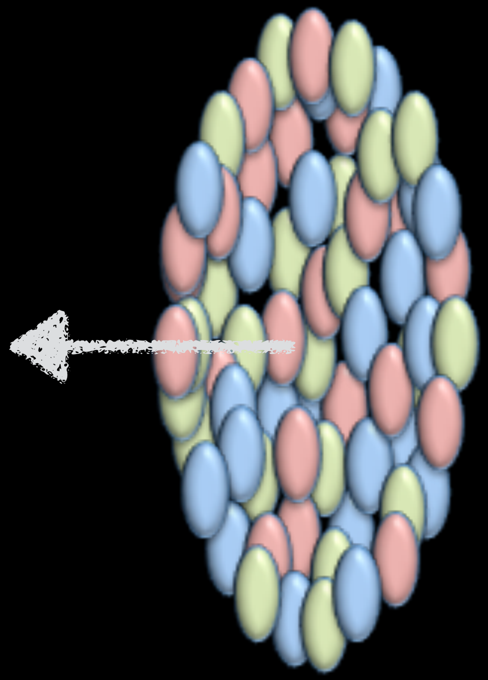
Heavy-ion collisions 2 Why do we need collider energies?

- Denser initial state (15 GeV/fm^3)
- Longer life time (10 fm/c)
- Bigger spatial extension (300 fm^3)
- Stronger collective phenomena
- Richer variety of hard probes
- Larger per event statistics

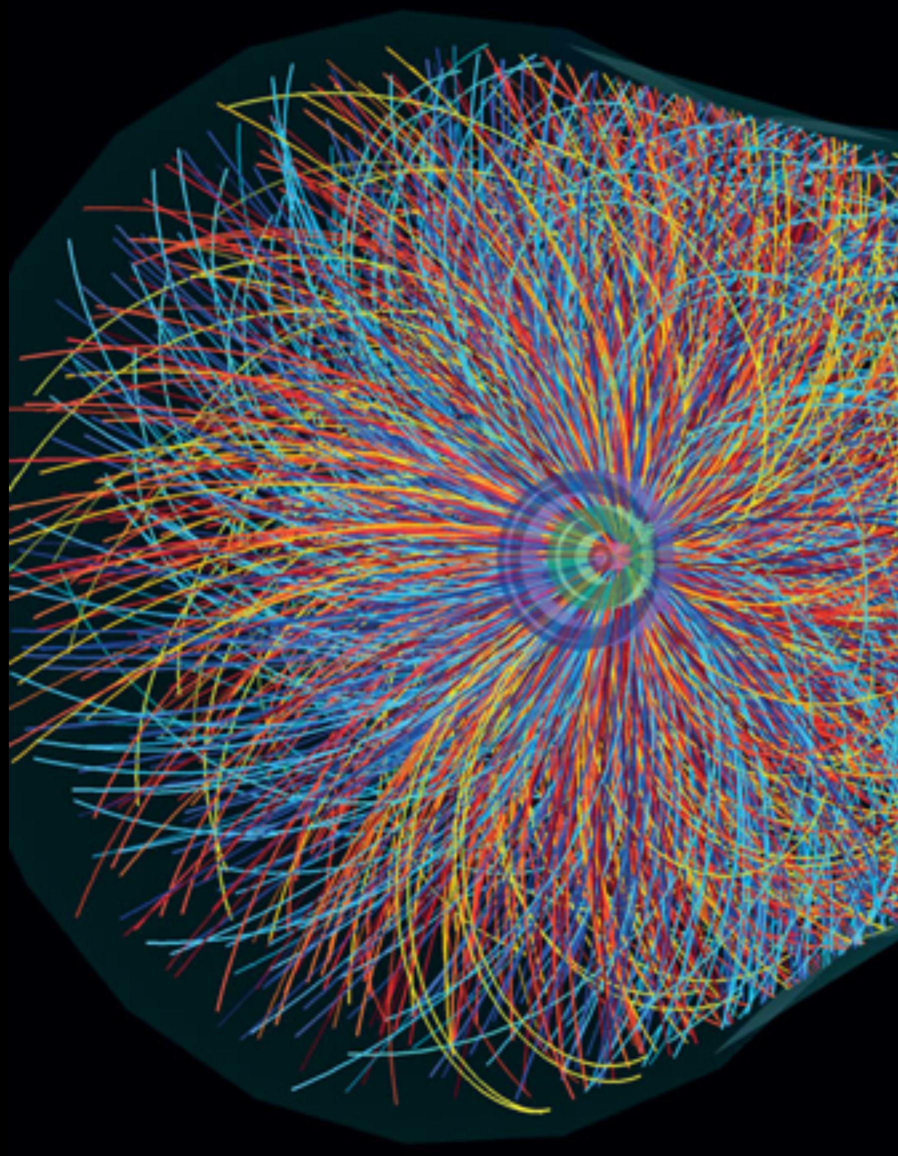
At present achievable temperatures, QGP has the properties of a liquid (α_S not small)

Heavy-ion collisions 3 Collision dynamics





QGP

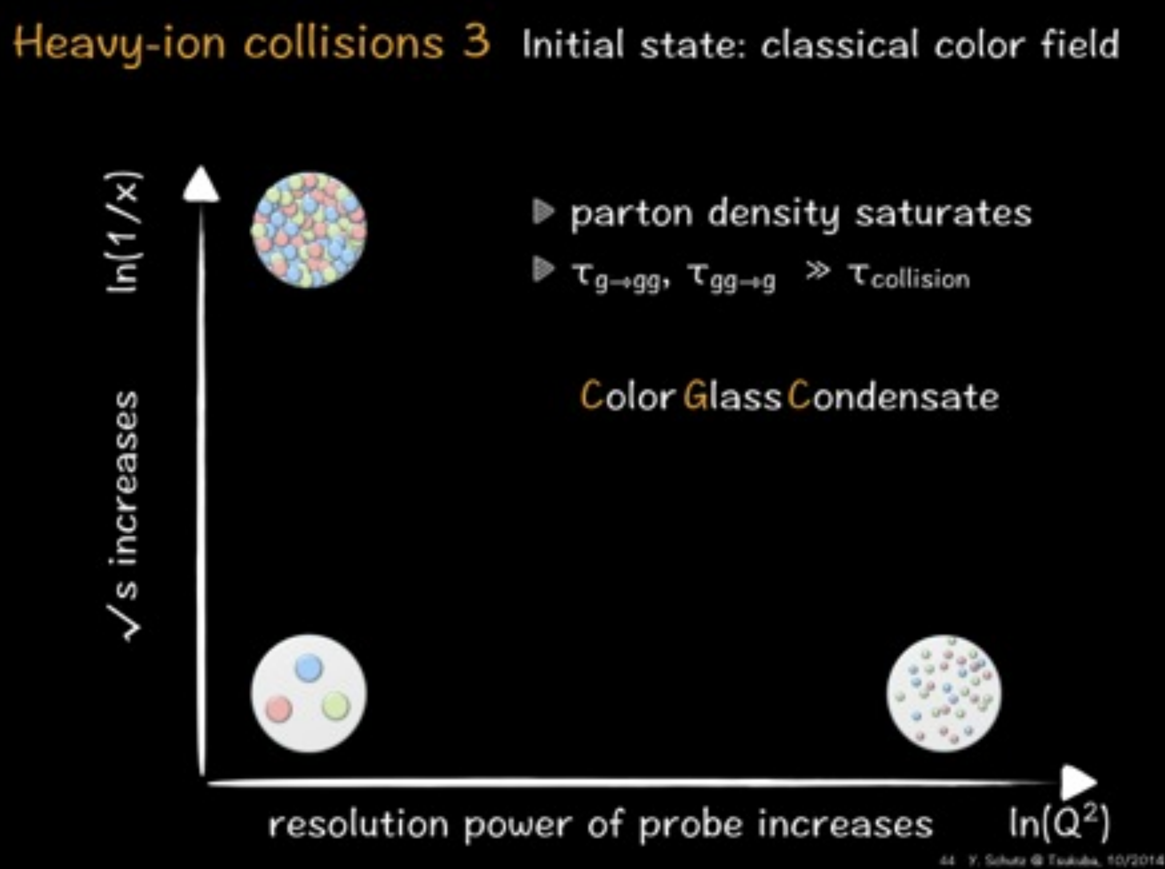


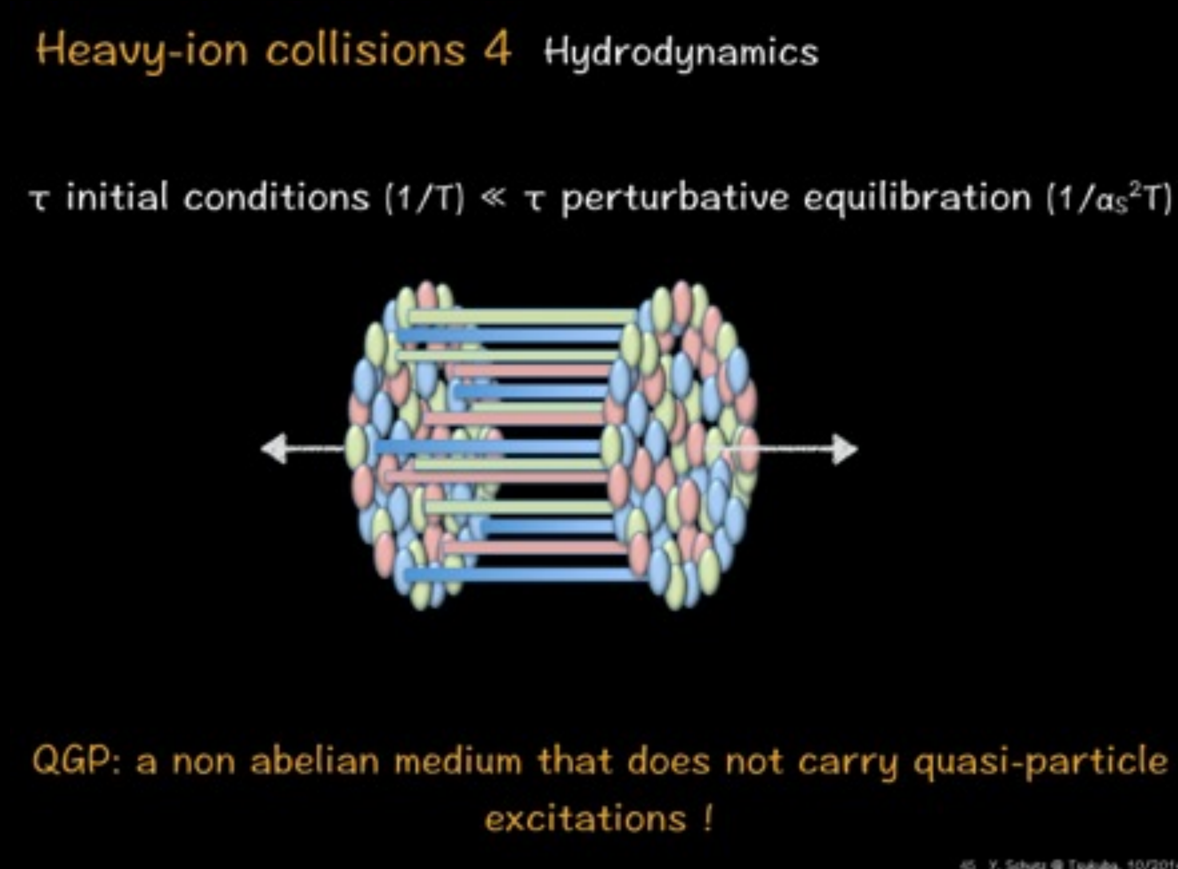
Initial state: classical color field (?)

equilibration - hydrodynamics - hadronization

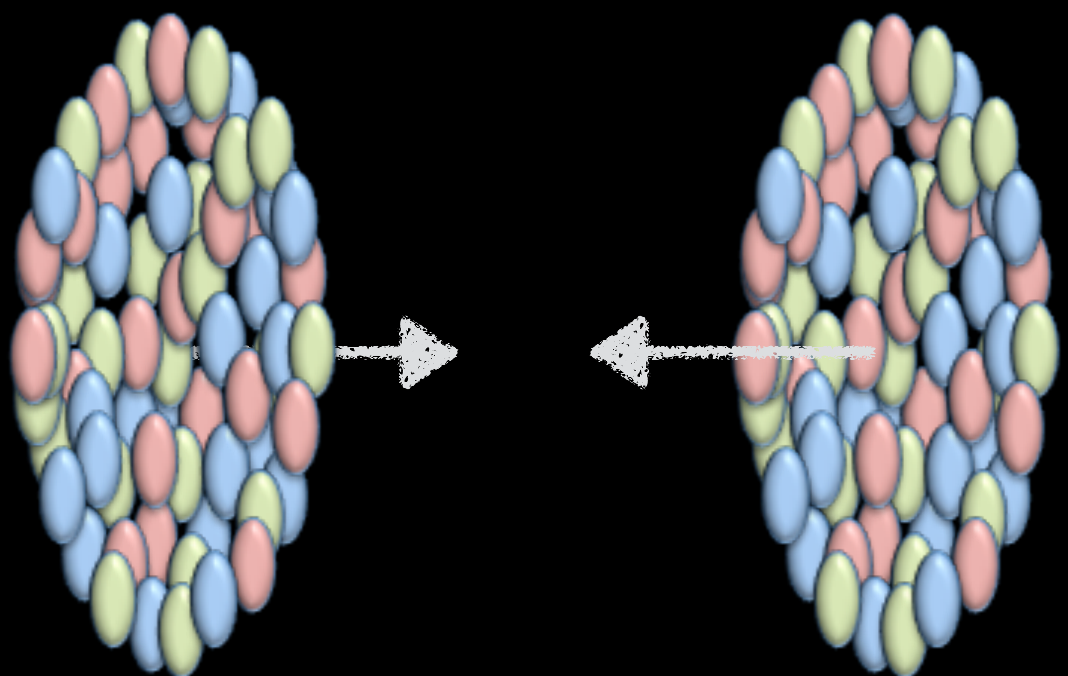
Final hadronic state

Heavy-ion collisions 3 The initial state dynamics

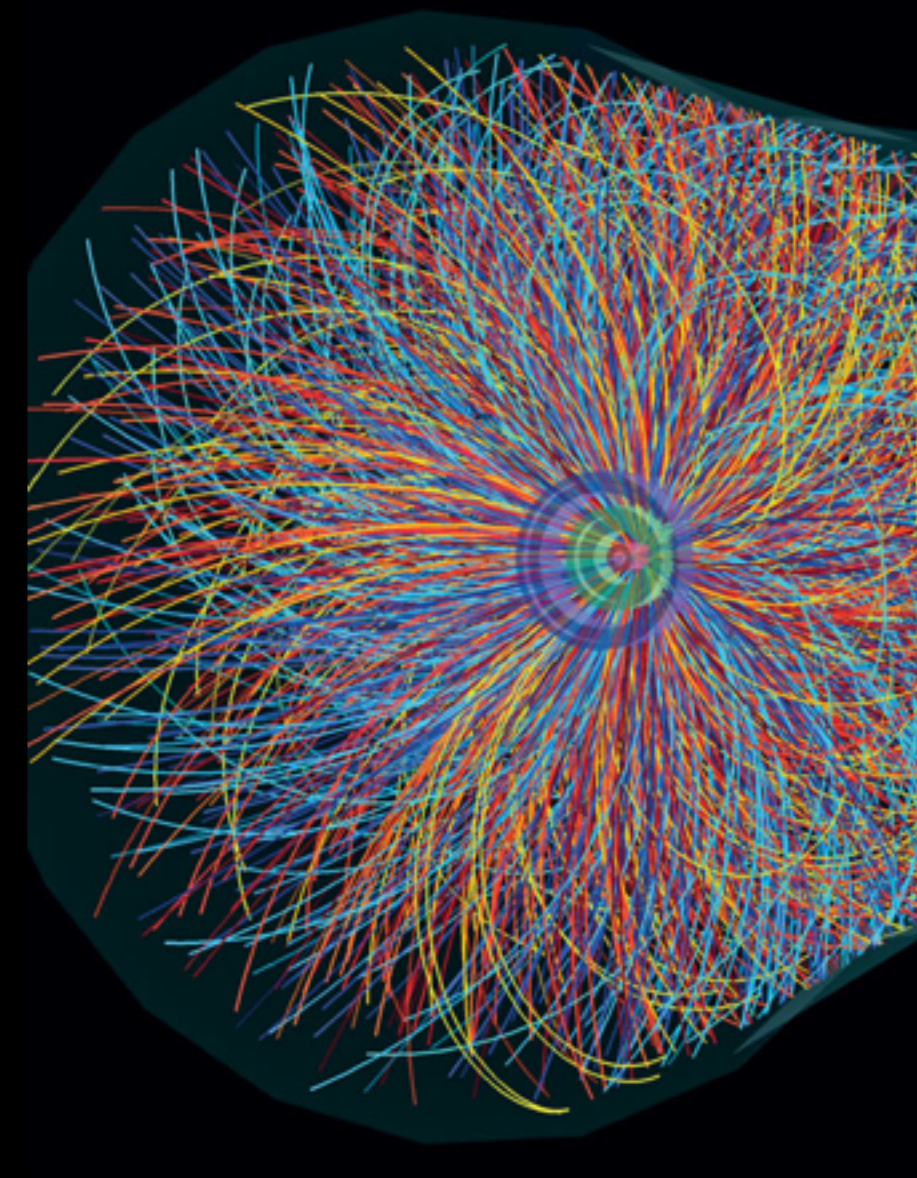




Heavy-ion collisions 3 Collision dynamics



QGP



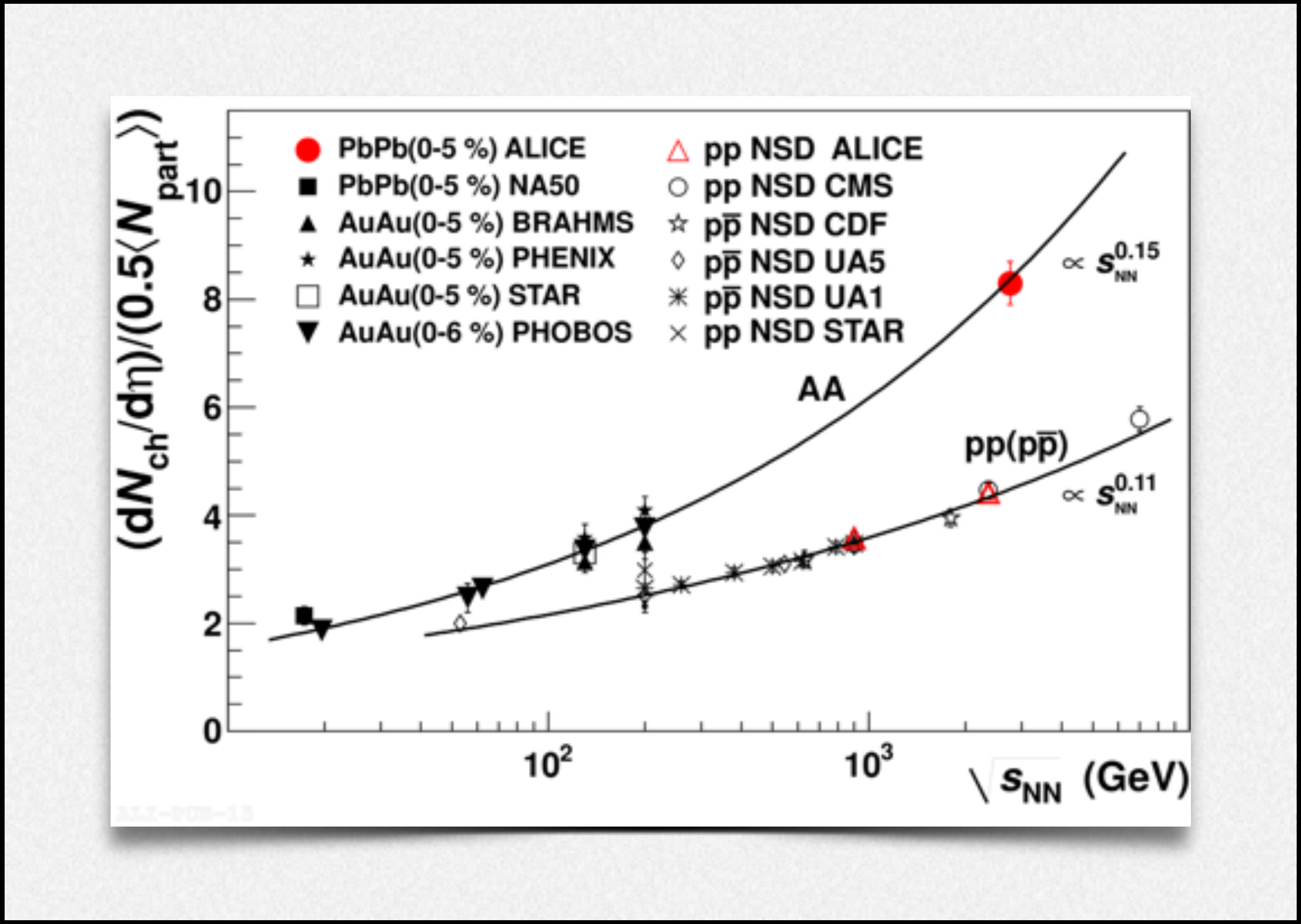
Initial state: classical color field (?)

equilibration - hydrodynamics - hadronization

Final hadronic state

Heavy-ion collisions 5 Final State

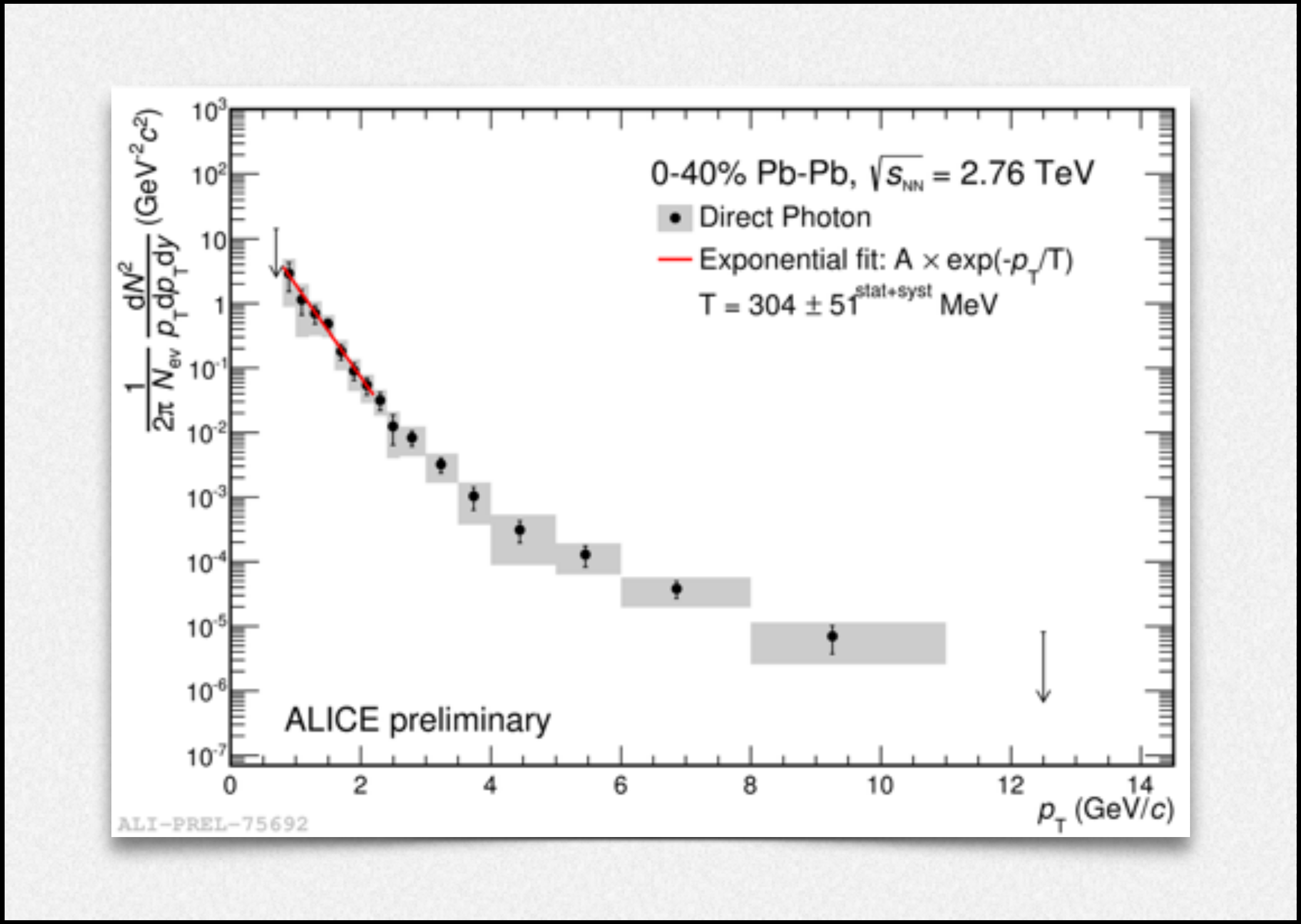
Thermodynamic properties through hadronic radiation at T_H



- Denser initial state (15 GeV/fm^3)

Heavy-ion collisions 5 Final State

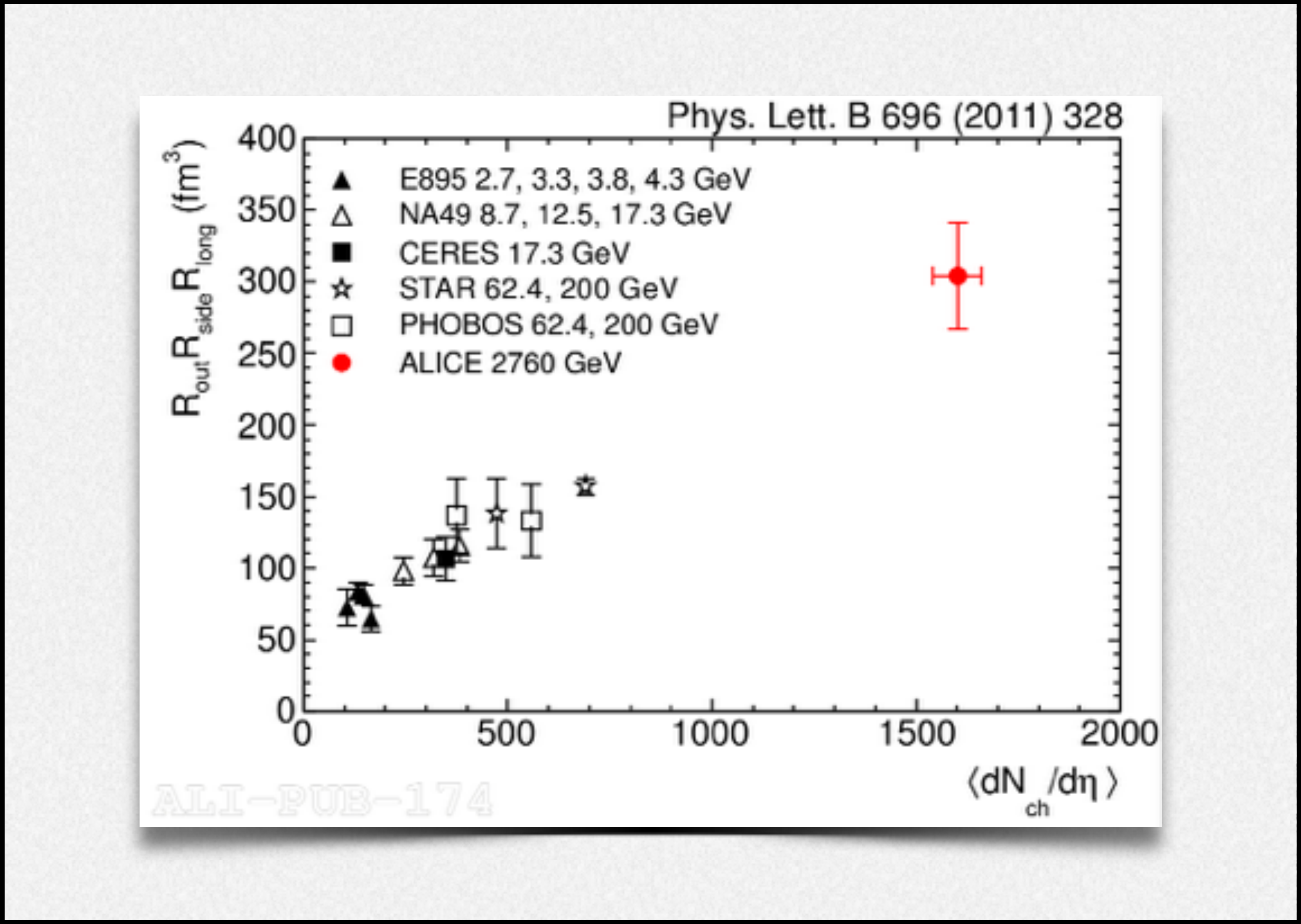
Thermodynamic properties through EM radiation



- Hotter initial condition (T > 304 MeV)

Heavy-ion collisions 5 Final State

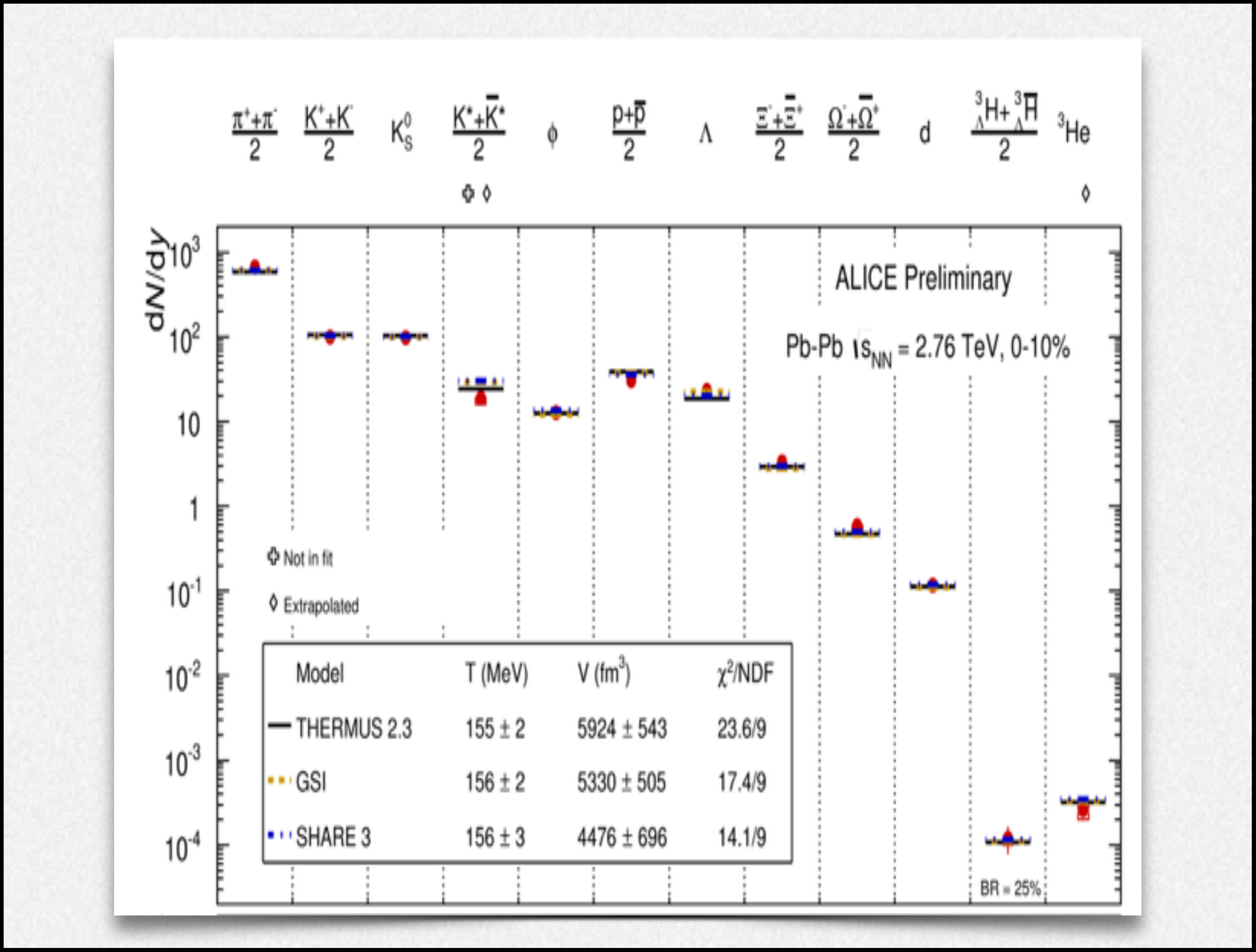
Thermodynamic properties through hadronic radiation at T_H



- Longer life time (10 fm/c)
- Bigger spatial extension (300 fm^3)

Heavy-ion collisions 5 Final State

Thermodynamic properties through hadronic radiation at T_H



- Hadronisation temperature T_H ~ 155 MeV
- Universal (e^+e^-, pp, AA) hadron production mechanism ?

Heavy-ion collisions 4 Hydrodynamics

Hydro Dynamics of QGP !

- E-p conservation
- 2nd law of thermodynamics
- properties of matter … calculable from first principles

Heavy-ion collisions 4 Hydrodynamics

initial conditions	hydro evolution	hadronisation
density, geometry, size, fluctuations	almost linear time evolution	non-linear mapping of fluctuations

collision time →

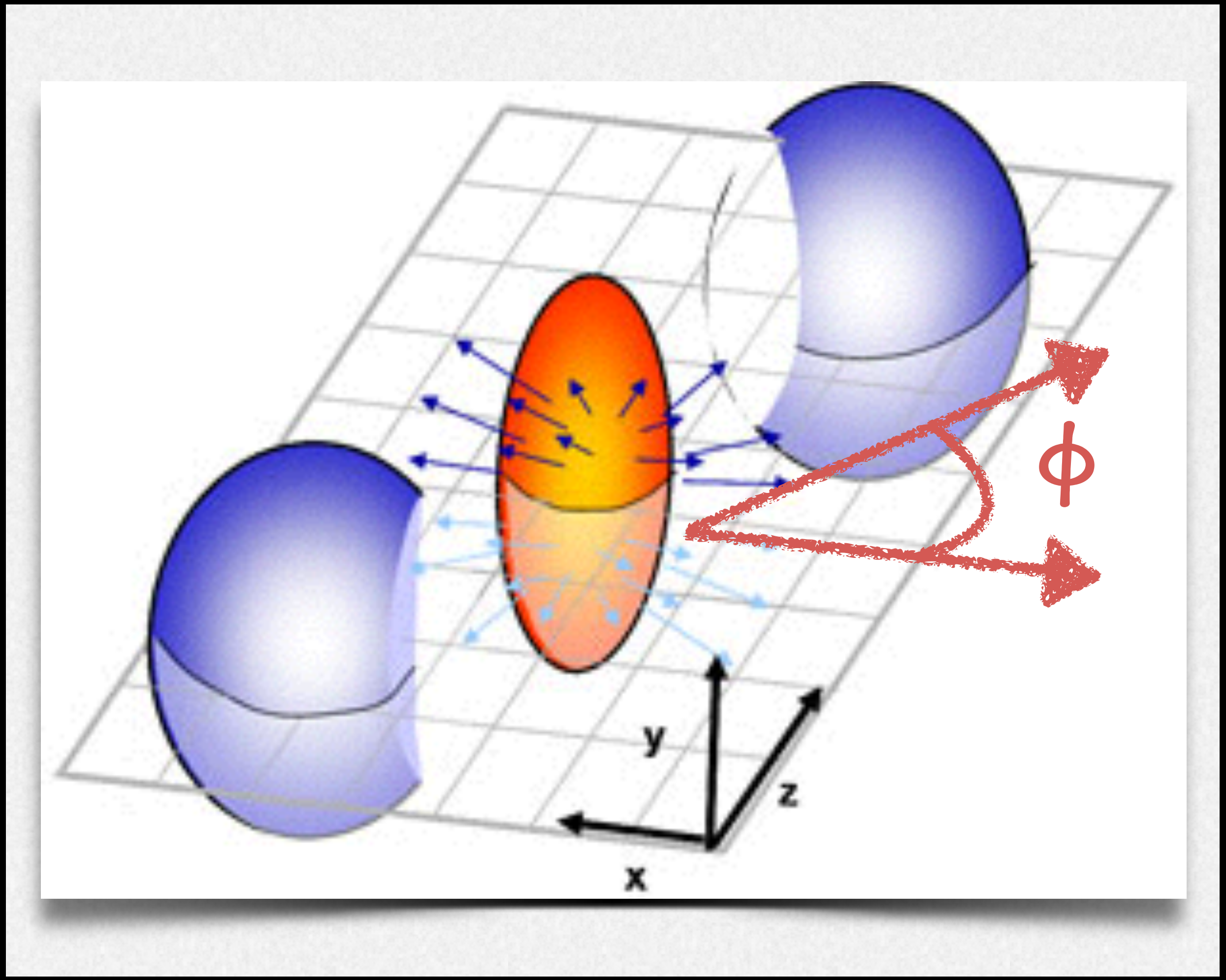
IC (IS) ? —Hydro→ FS (data)

Heavy-ion collisions 4 Hydrodynamics

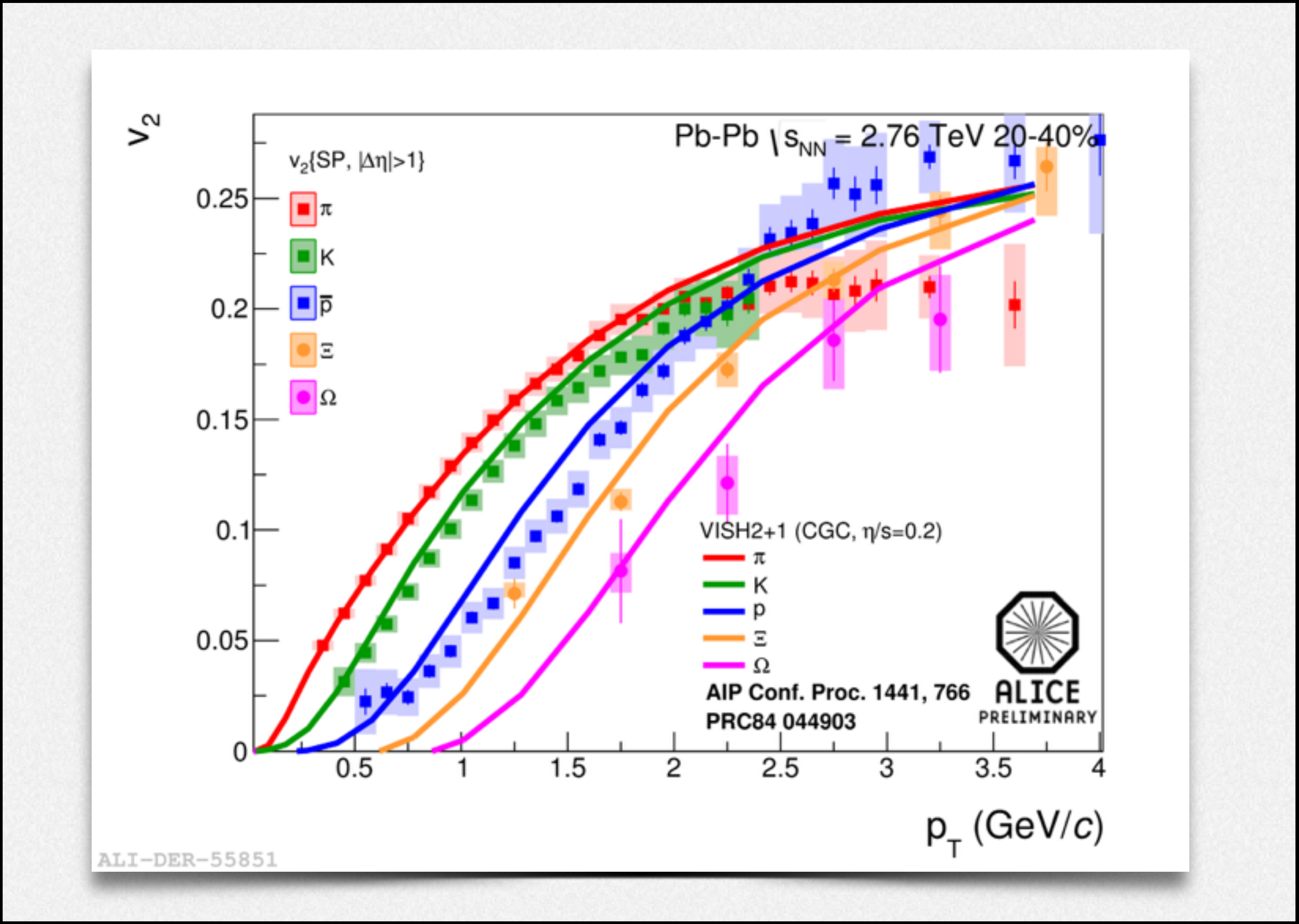
ε_2 : overlap geometry (impact parameter)

liquid + minimal shear viscosity

v_2 : mapped into momentum space



Heavy-ion collisions 4 Collectivity in action



Heavy-ion collisions 4 Hydrodynamics

initial conditions	hydro evolution	hadronisation
density, geometry, size, fluctuations	almost linear time evolution	non-linear mapping of fluctuations

→ collision time

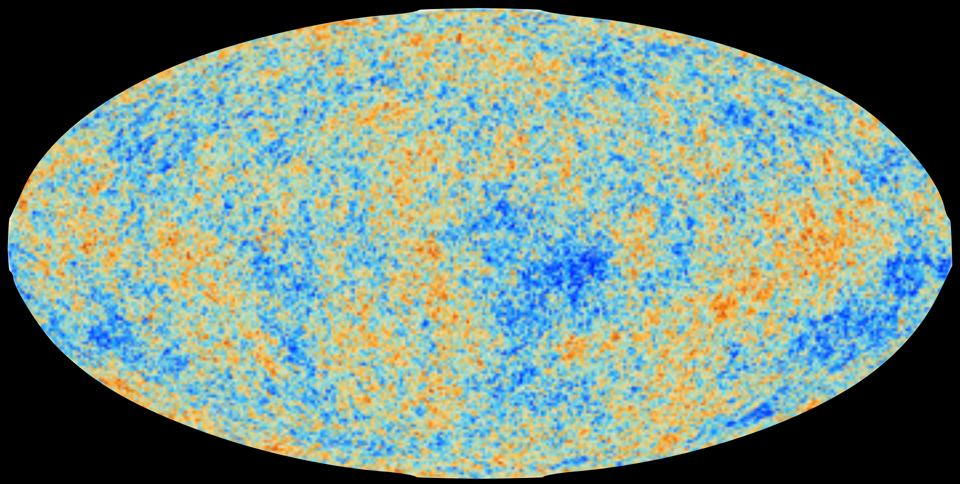
Hydro*

IC (IS) ? ← FS (data)

* Need to control initial conditions

a parte

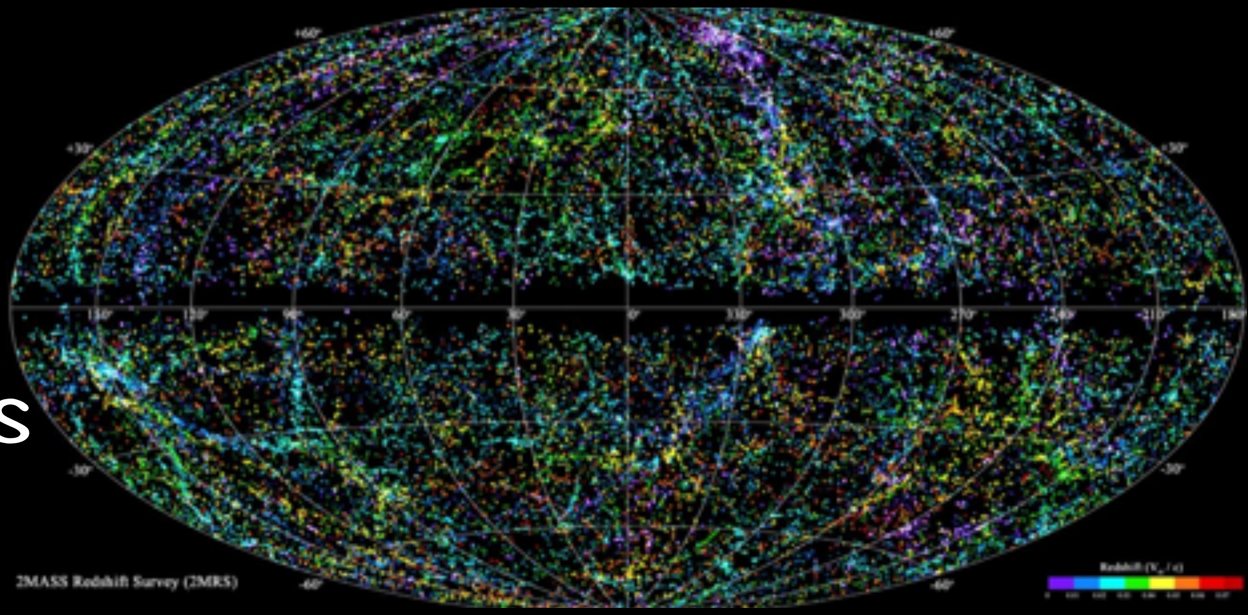
CMB - Big Bang - Universe

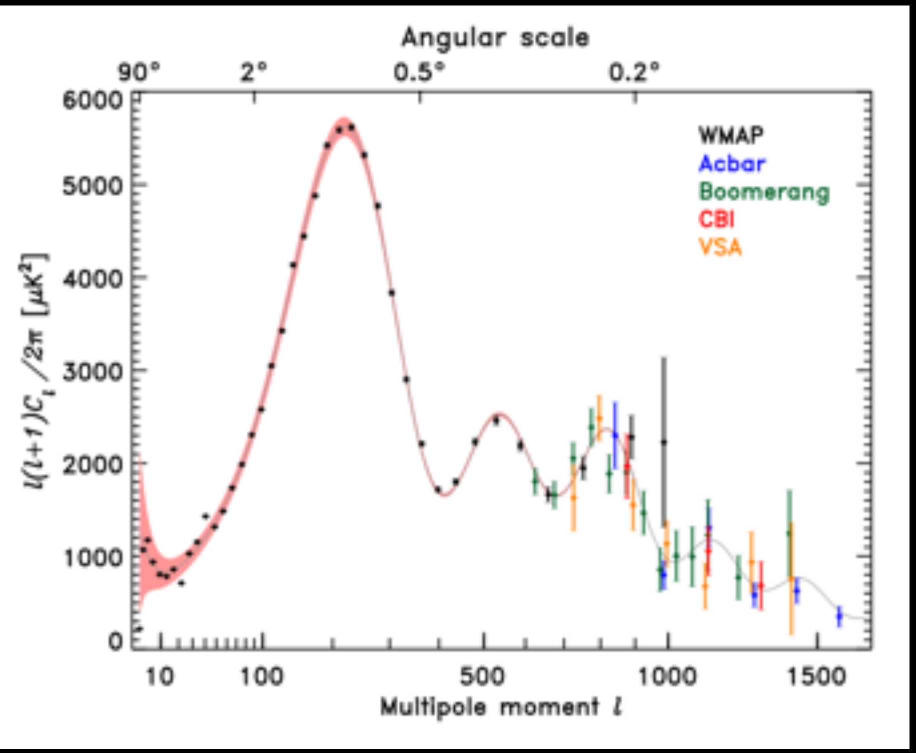


BB Model

+

parameters





a parte

CMB - Big Bang - Universe

CMB	Big Bang model	Today's Universe
isotropy, curvature, fluctuations	almost linear time evolution	non-linear mapping of fluctuations

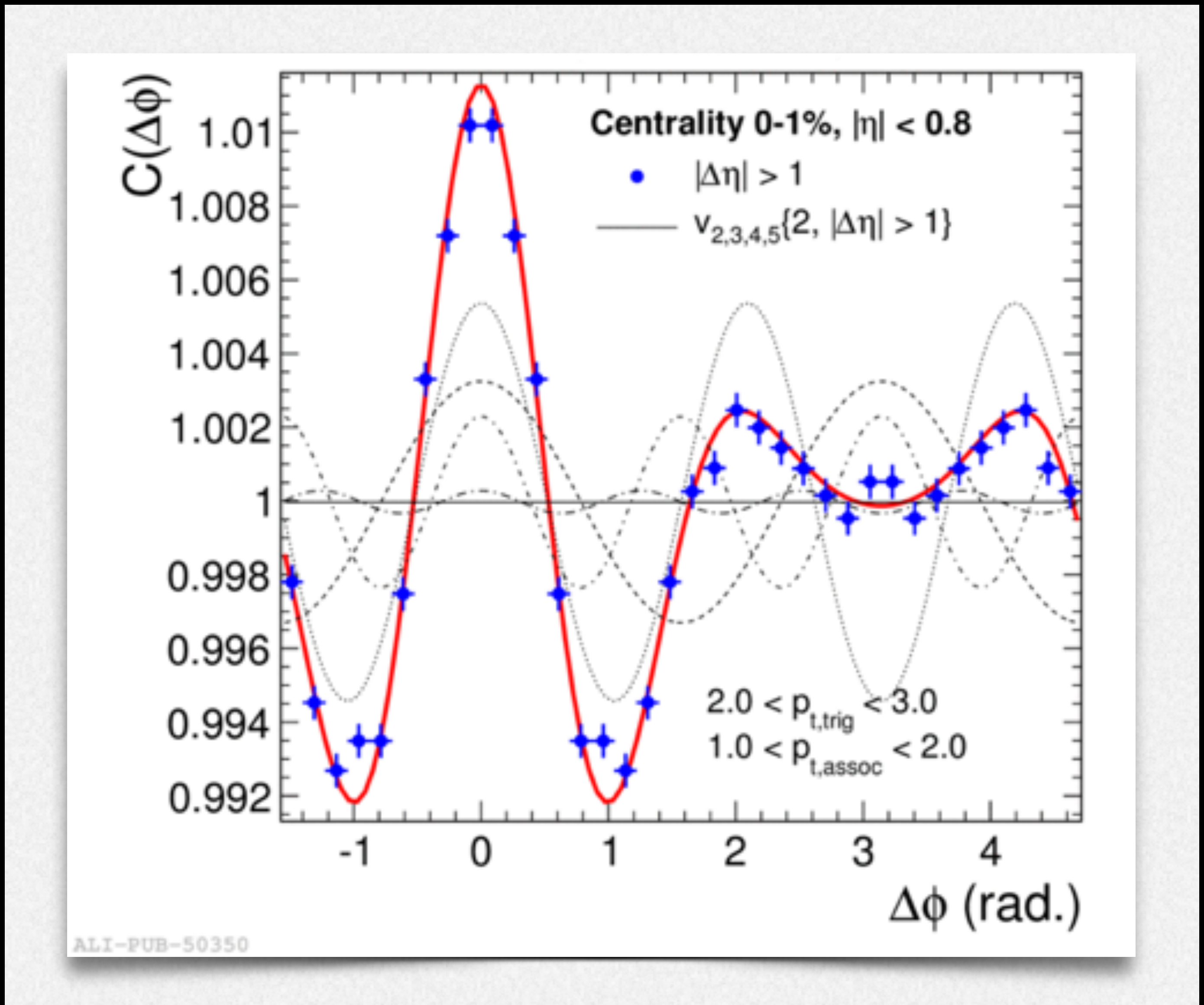
Big Bang time

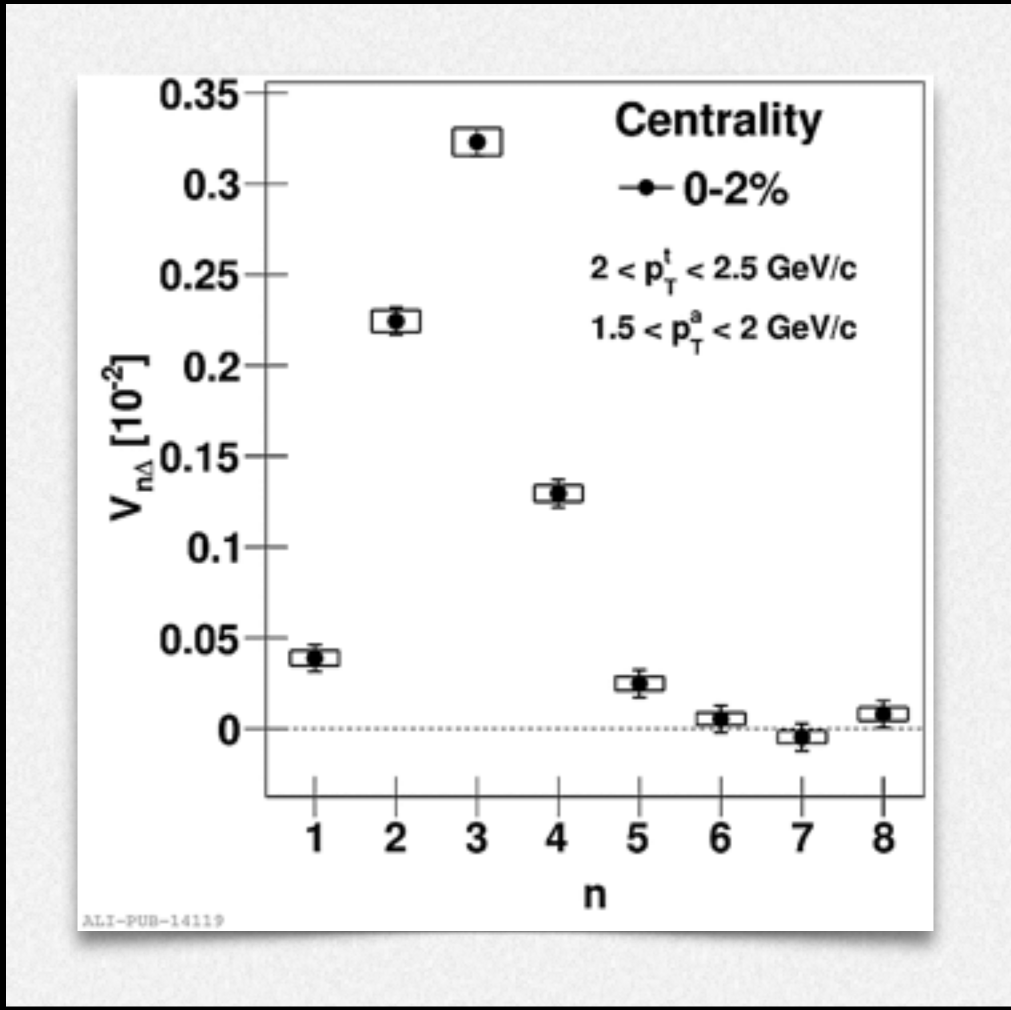
BB model*

IC (IS) → FS (data)

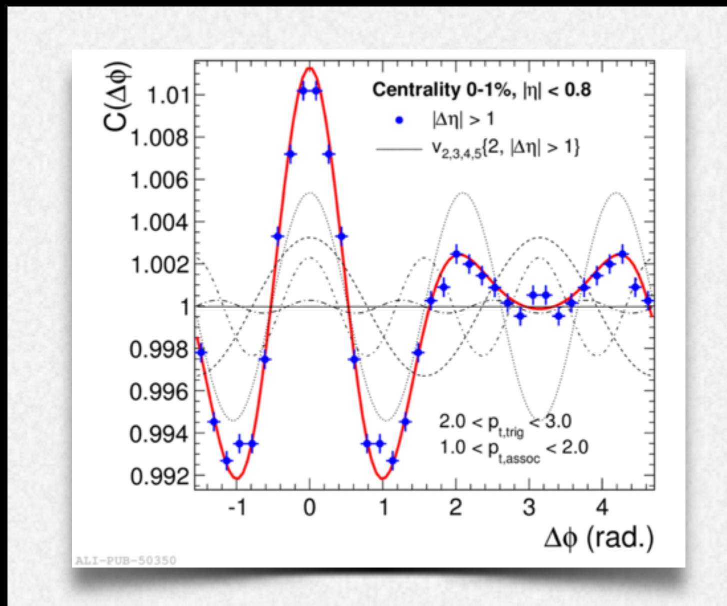
* a priori knowledge of initial conditions

Heavy-ion collisions 4 Hydrodynamics

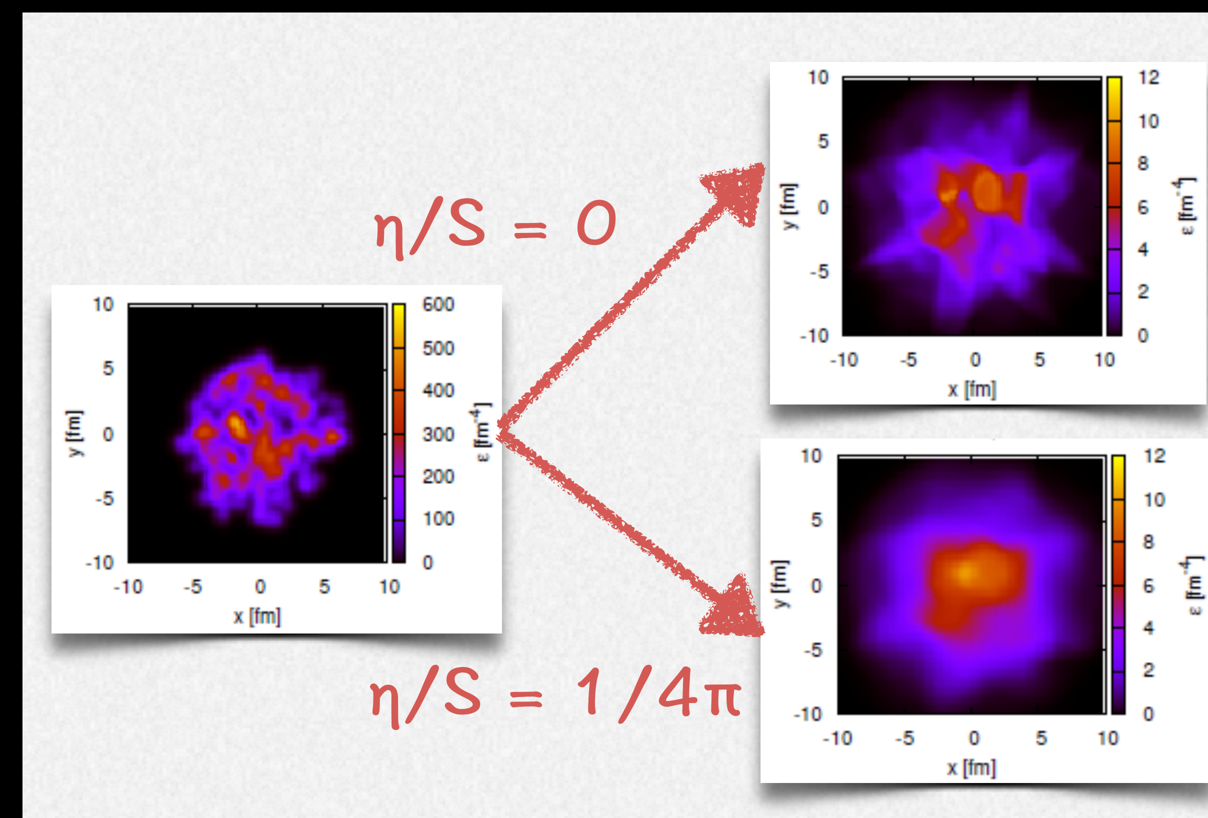




Heavy-ion collisions 4 Hydrodynamics



fluctuation damping ↔ sound attenuation length



ε_n : density/geometry fluctuations

liquid + minimal shear viscosity ($\Gamma = \eta/sT$)

v_n : mapped into momentum space

To conclude

To conclude: QGP

- is a strongly coupled plasma
- has a very short mean free path
- exhibits a high degree of collectivity and flows
- absorbs a significant fraction of high-energy partons
- ...

Fluid hydrodynamics in small systems

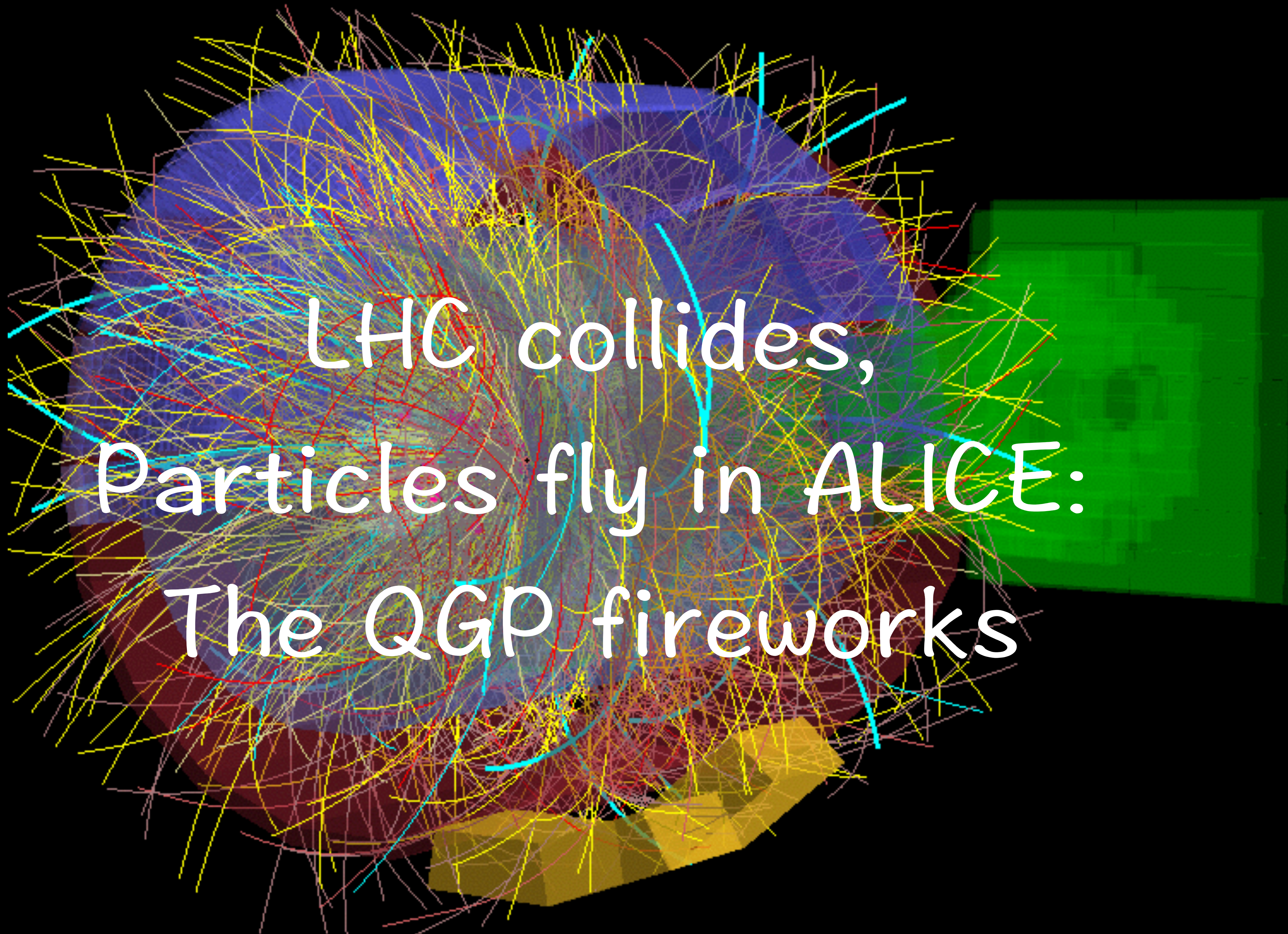
Hard probes (p_T, $m_T \gg T$) : QGP at high resolution scale

- How do high p_T q, g, Q propagate in the QGP
- Do they flow with the medium
- q recombination a possible hadronization mechanism
- Color screening probed with quarkonia states
- ...

The Quark-Gluon Plasma, a nearly perfect fluid

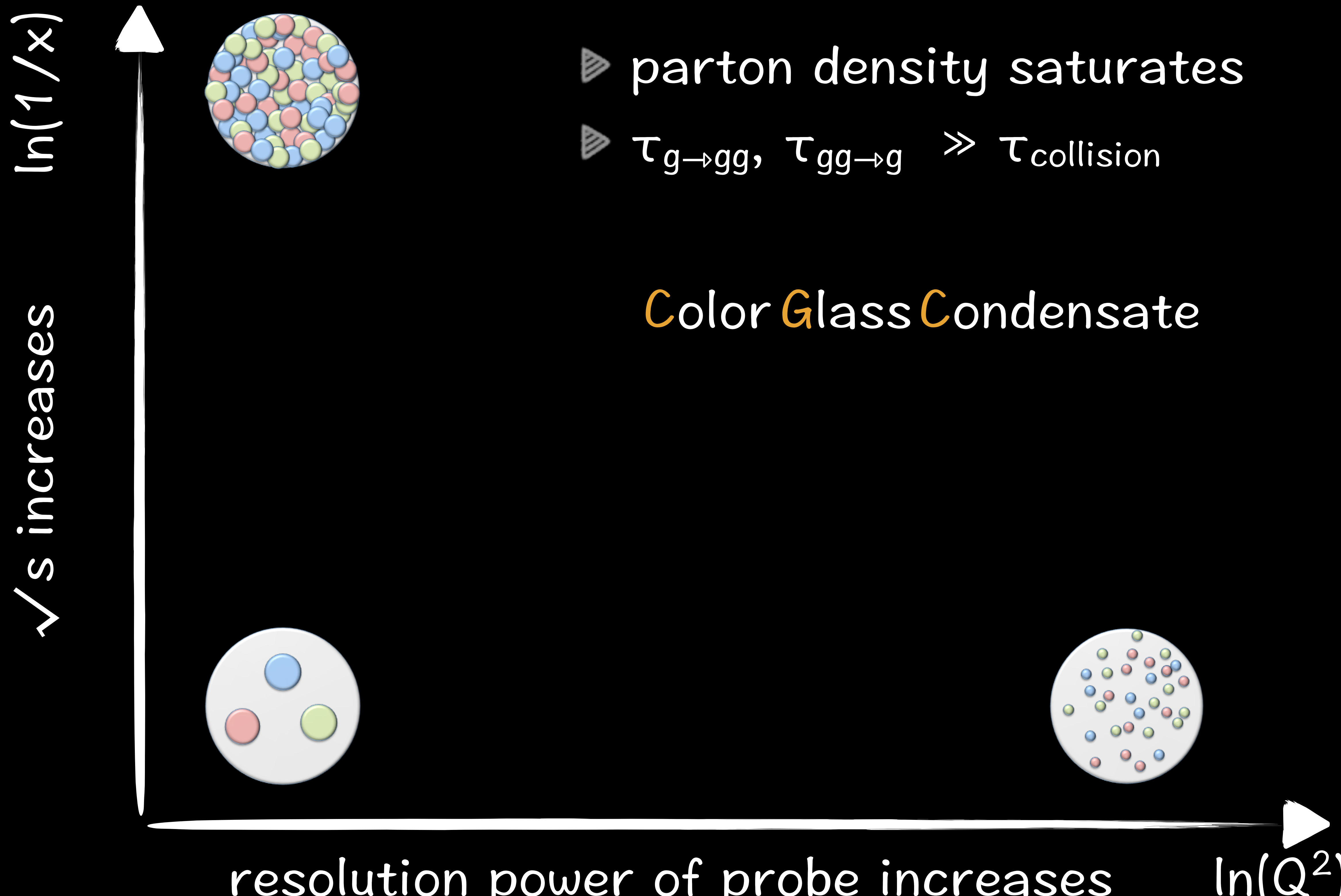
■ L. Cifarelli[1], L.P. Csernai[2] and H. Stöcker[3] - DOI: 10.1051/epn/2012206
■ [1] Dipartimento di Fisica, Universita di Bologna, 40126 Bologna, Italy;
■ [2] Department of Physics and Technology, University of Bergen, 5007 Bergen, Norway;
■ [3] GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany

We are living in interesting times, where the World's largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.



LHC collides,
Particles fly in ALICE:
The QGP fireworks

Heavy-ion collisions 3 Initial state: classical color field

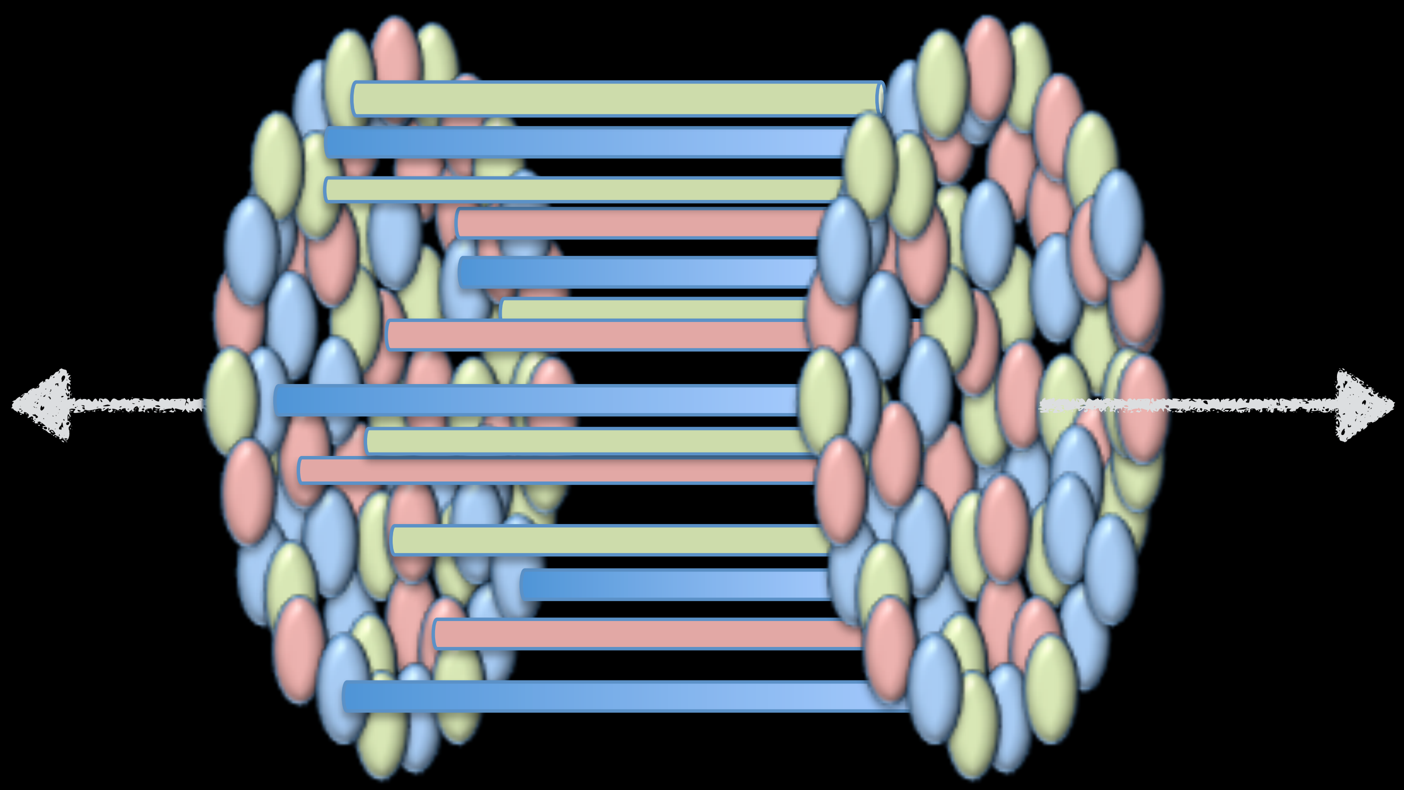


- parton density saturates
- $\tau_{g \to gg}, \tau_{gg \to g} \gg \tau_{collision}$

Color Glass Condensate

Heavy-ion collisions 4 Hydrodynamics

τ initial conditions $(1/T) \ll \tau$ perturbative equilibration $(1/\alpha_S^2 T)$



QGP: a non abelian medium that does not carry quasi-particle excitations !

Heavy-ion collisions 4 Hydrodynamics

Will come back later !

Back to Hydro Dynamics of QGP !