QCD

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IGFAE - Santiago de Compostela

TAE (Taller de Altas Energias) - Workshop on High Energy Physics
Benasque September 2022

[Two lectures on selected topics]

Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
An ERC Advanced Grant 2019 · 2024
erc
European Research Council
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IGFAE
Instituto Galego de Física de Altas Enerxías
USC
XUNTA DE GALICIA
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Outline

Lecture 1: QCD at colliders - *“gluon multiplication”*

- Jets
- Parton Distribution Functions

Lecture 2: Hot and dense QCD

- The structure of matter in extraordinary conditions of temperature and density

Afternoon - two cases revealing quantum coherence

QCD and collectivity

Standard Model built/discovered looking for the **highest possible degree of simplicity**

All particle content and interactions of the Standard Model discovered using this principle
— greatest success of the reductionistic approach in Physics

Also very successful — **Complex systems with emerging behavior**

[Strongly-coupling many body systems; quantum entanglement with many d.o.f…]

Region of transition — largely unknown

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments

Best available tool to study the first levels of complexity

Equilibrium AND non-equilibrium dynamics

[This animation was done before LHC started]

An apparently simple lagrangian hides a plethora of **emerging**

[This animation was done before LHC started]

Nucleus-nucleus collisions provide optimal conditions for these QCD studies - extended object in the transverse plane

QCD

QCD is the theory of strong interactions.

⇒ It describes interactions between hadrons (p, π, ...)

- Asymptotic states.
- *Normal* conditions of temperature and density.
- Nuclear matter (us).
- Colorless objects.

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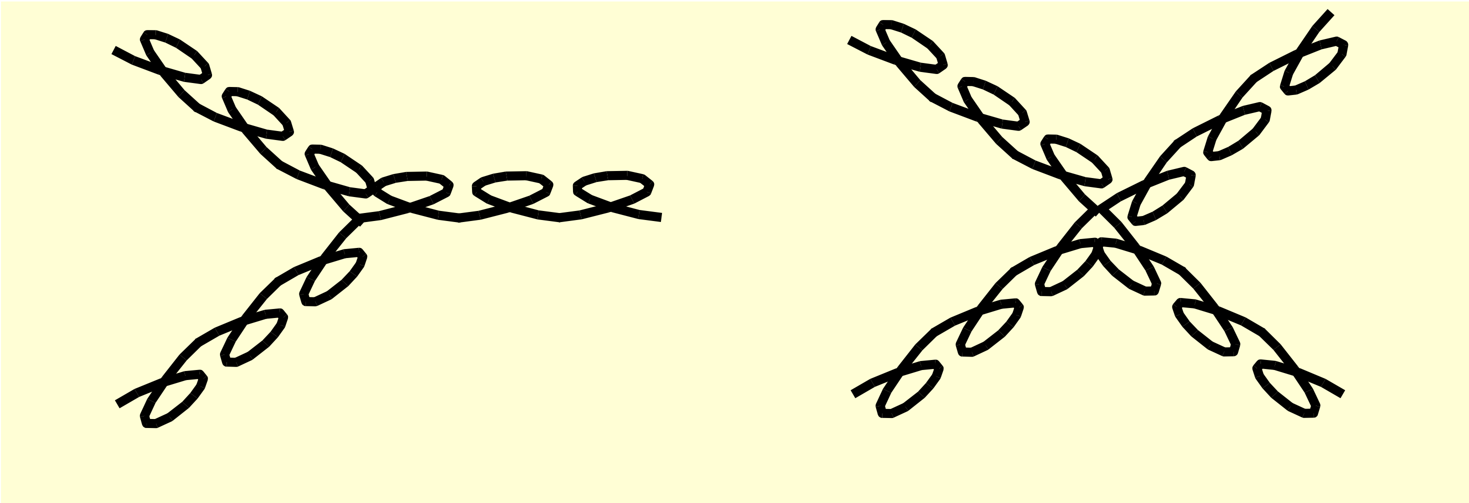
⇒ Quarks and gluons in the Lagrangian

- Fundamental particles.

charge=+2/3	u ($\sim$5 MeV)	c ($\sim$1.5 GeV)	t ($\sim$175 GeV)
charge=-1/3	d ($\sim$10 MeV)	s ($\sim$100 MeV)	b ($\sim$5 GeV)

- Colorful objects. color = charge of QCD $\longrightarrow$ vector
  Similar to QED, but gluons can interact among themselves



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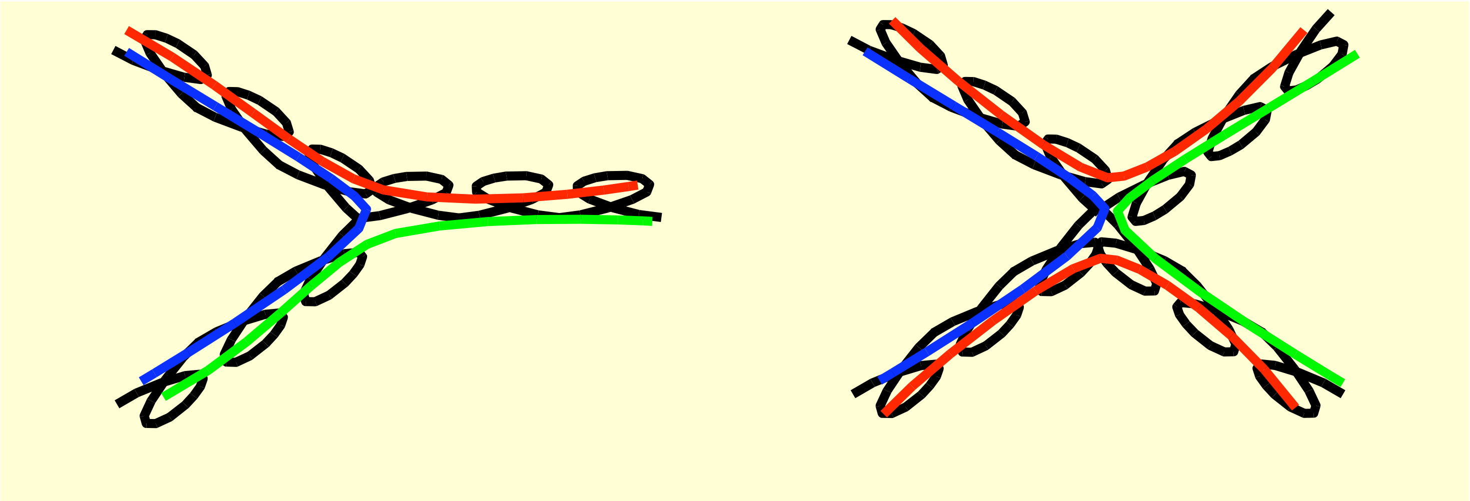

- Gluons carry color charge $\longrightarrow$ This changes everything...

QCD

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$\Rightarrow$ No free quarks and gluons: Confinement.

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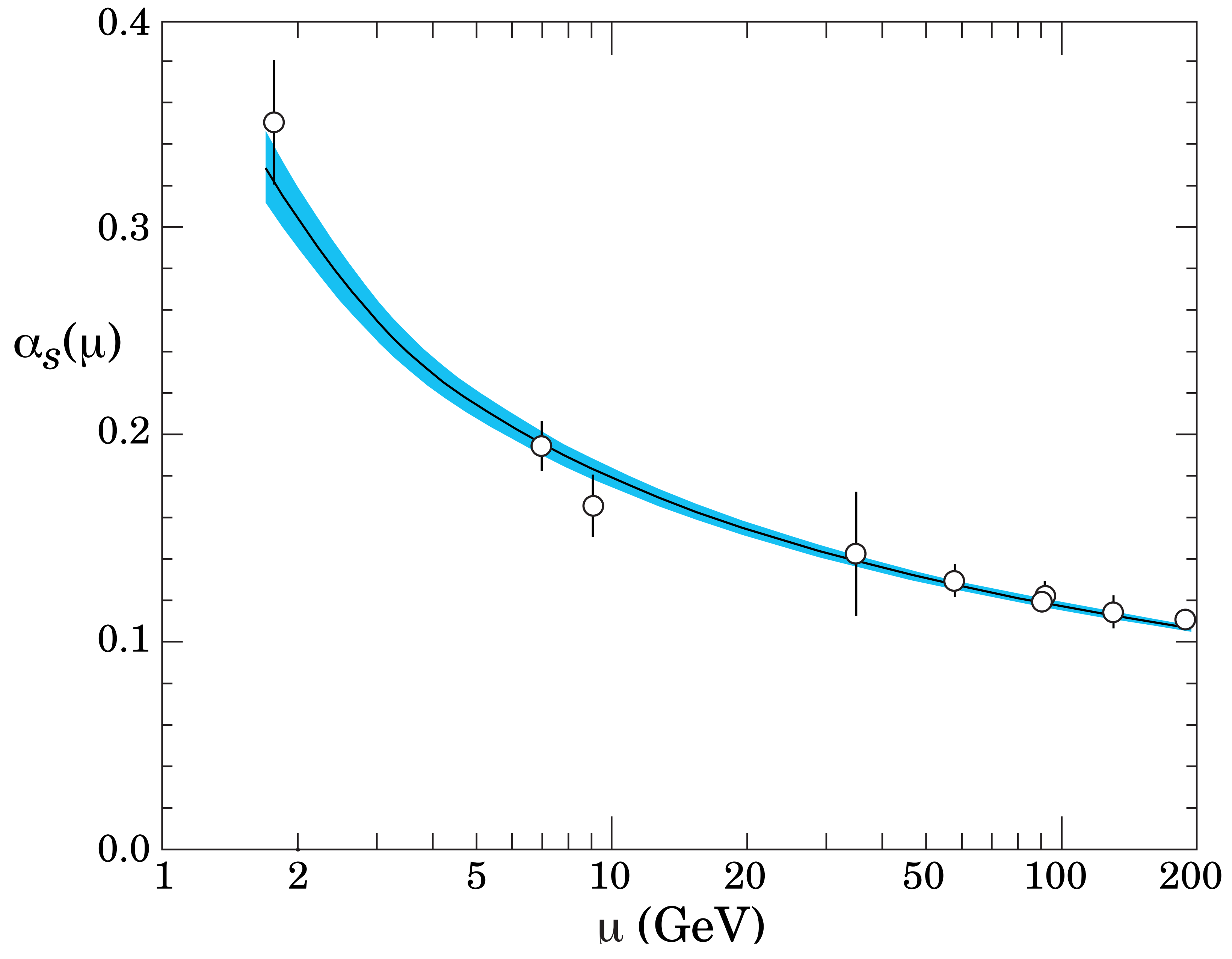
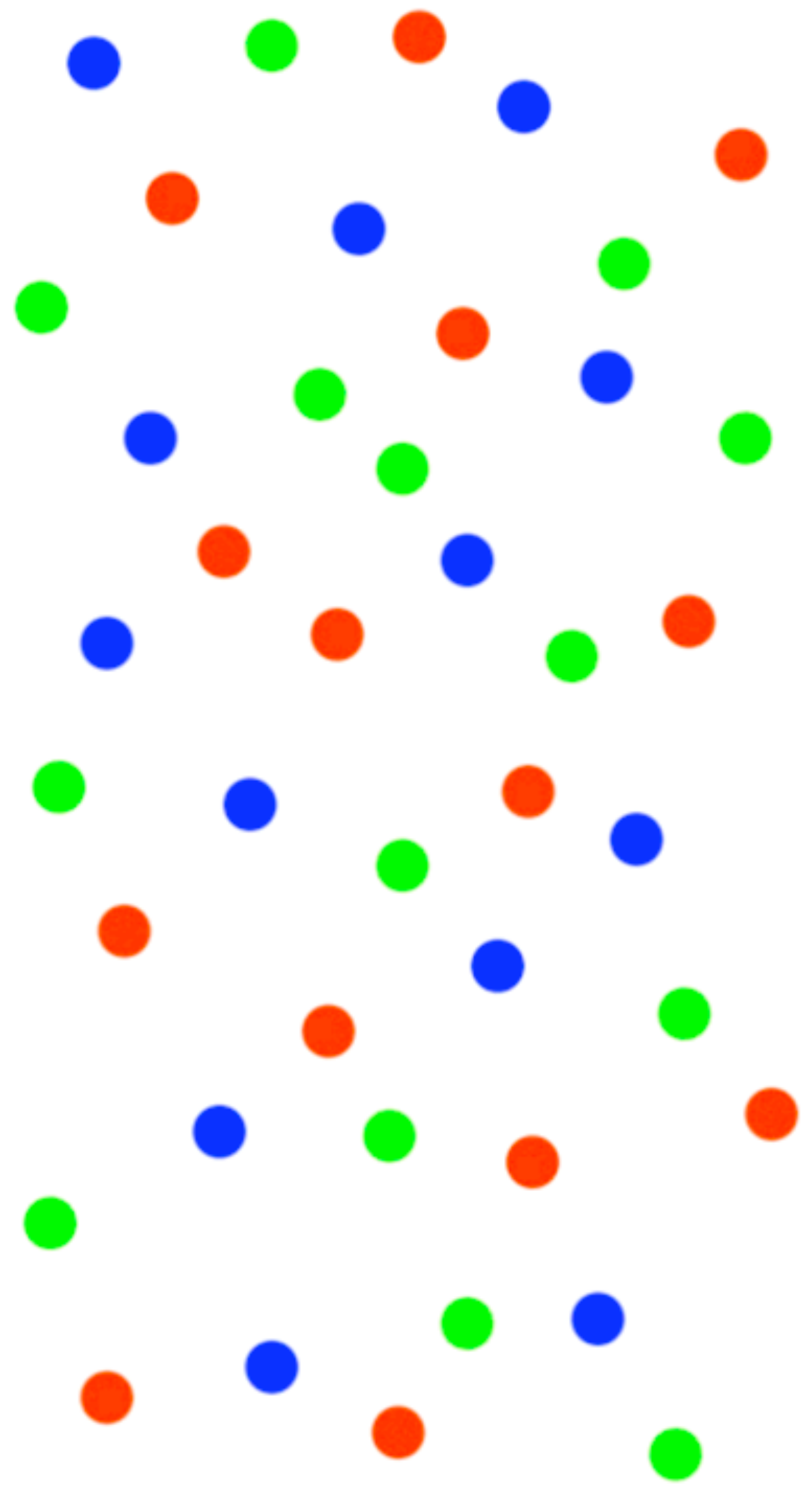
⇒ No free quarks and gluons: Confinement.

⇒ Strength smaller at smaller distances: Asymptotic freedom.



Picture

⇒ In quantum field theory, vacuum is a medium which can screen charge. (quarks or gluons disturb vacuum).



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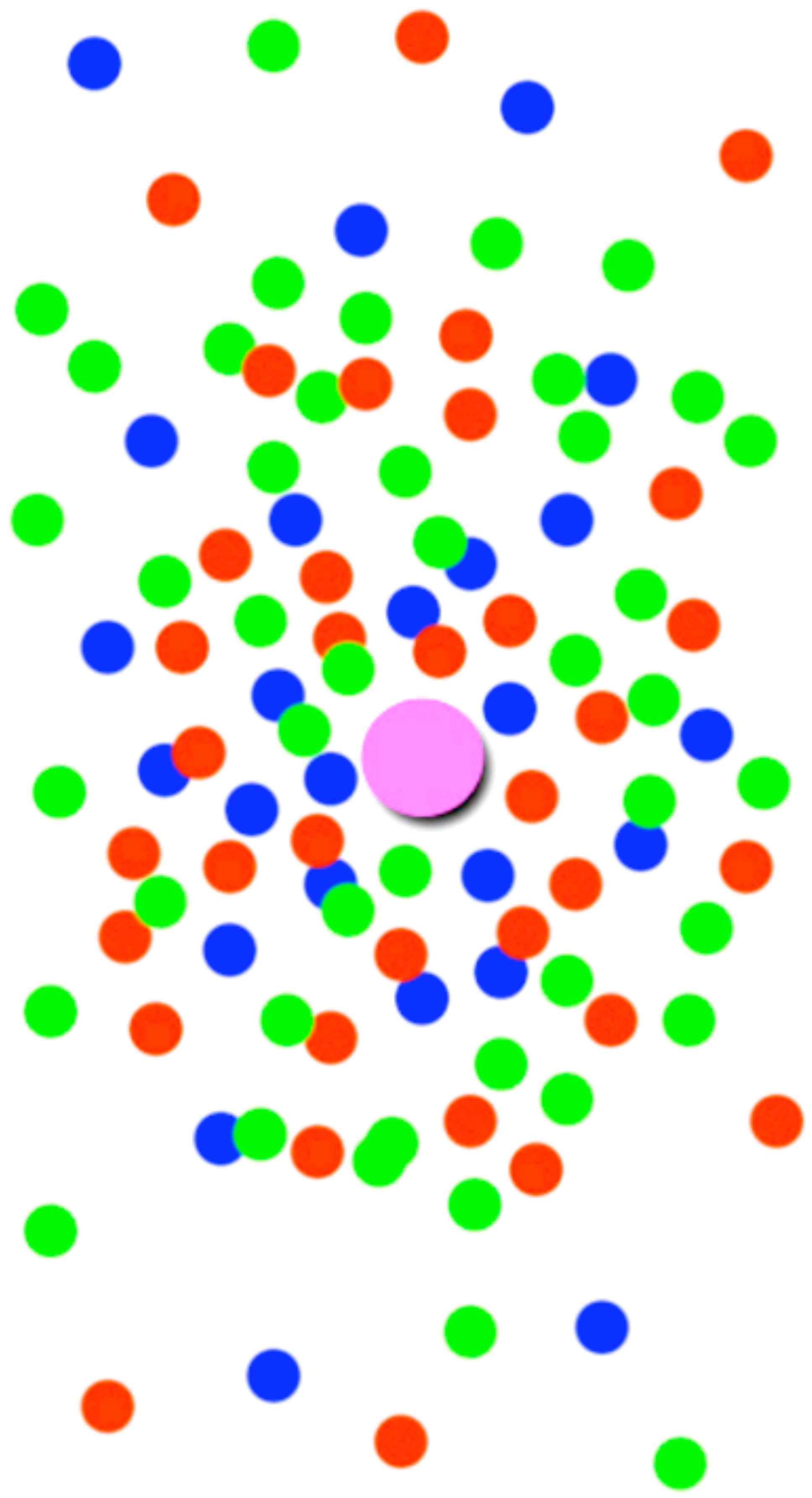
⇒ confinement $\Longrightarrow$ isolated quarks (gluons) = infinite energy



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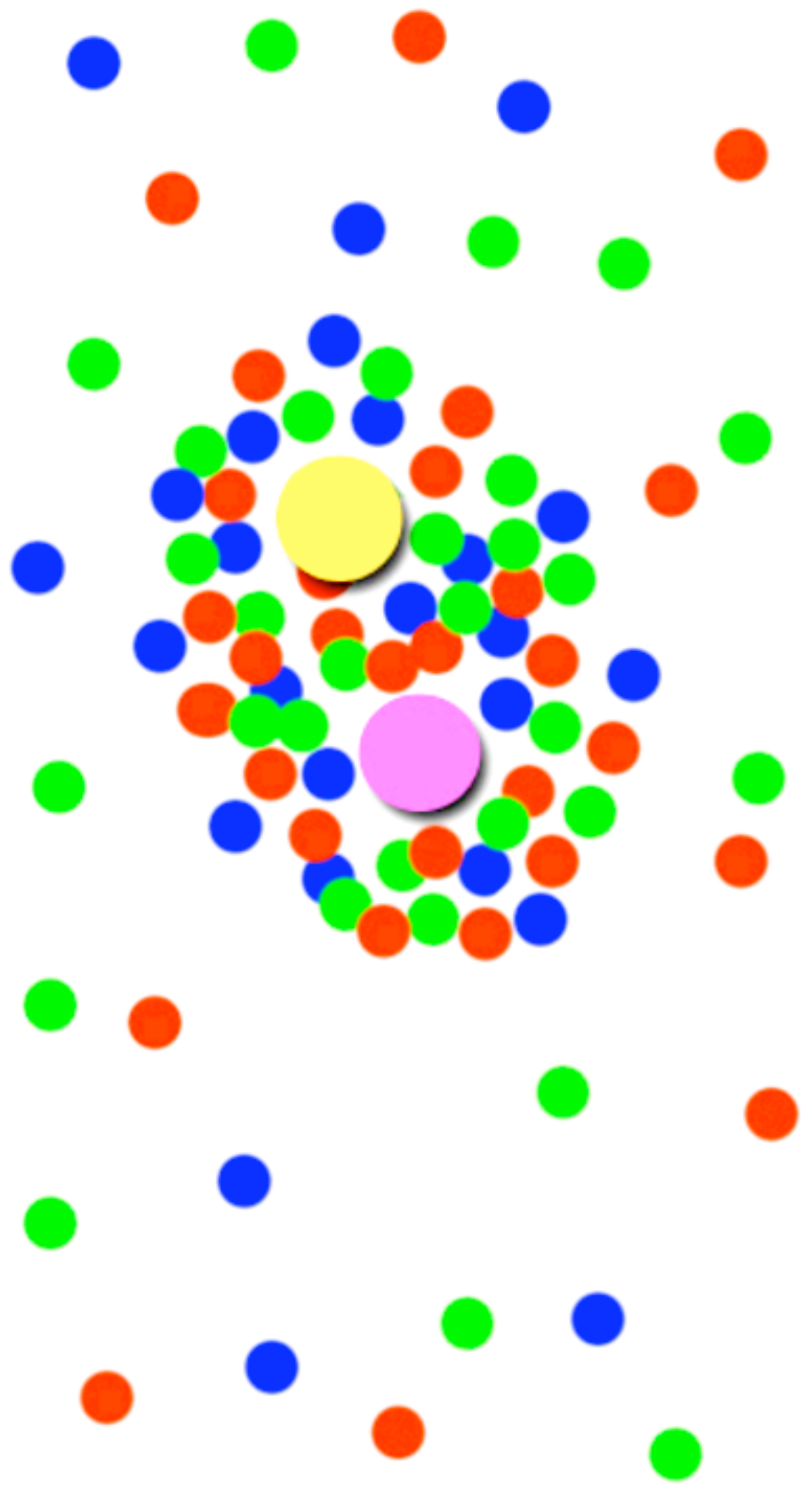
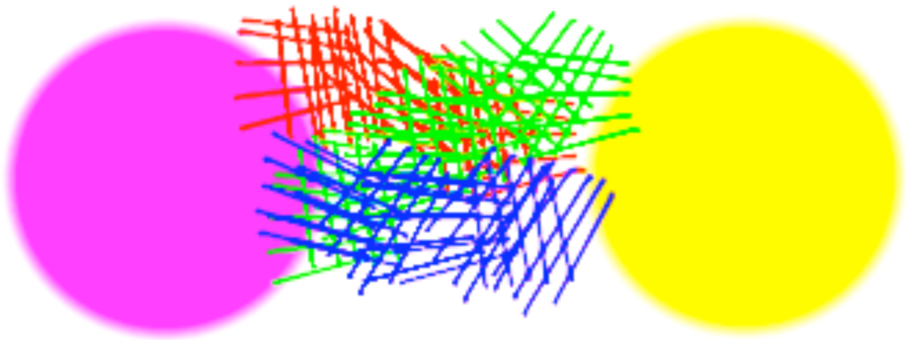
- ⇛ masses:

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



String picture

A way of visualizing a meson $\longrightarrow$ a $q\bar{q}$ pair join together by a string



$\Rightarrow$ Colorless object

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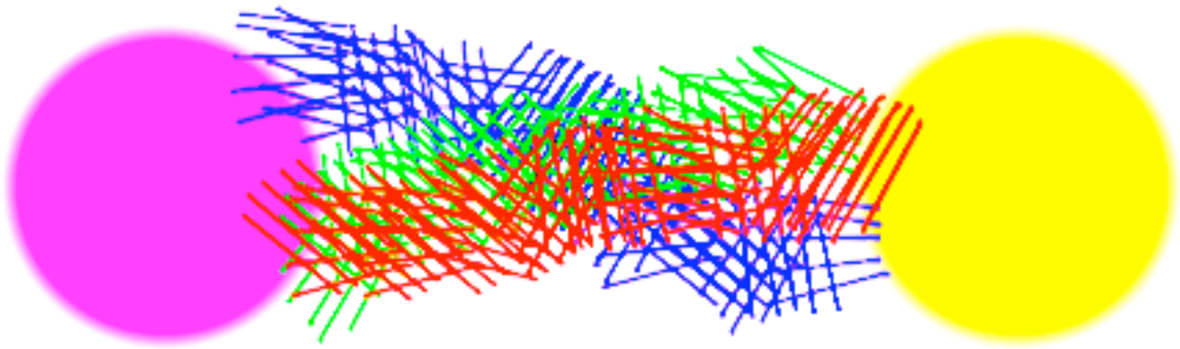

⇛ Colorless object

⇛ The potential between a $q\bar{q}$ pair at separation r is

$$V(r) = -\frac{A(r)}{r} + Kr$$

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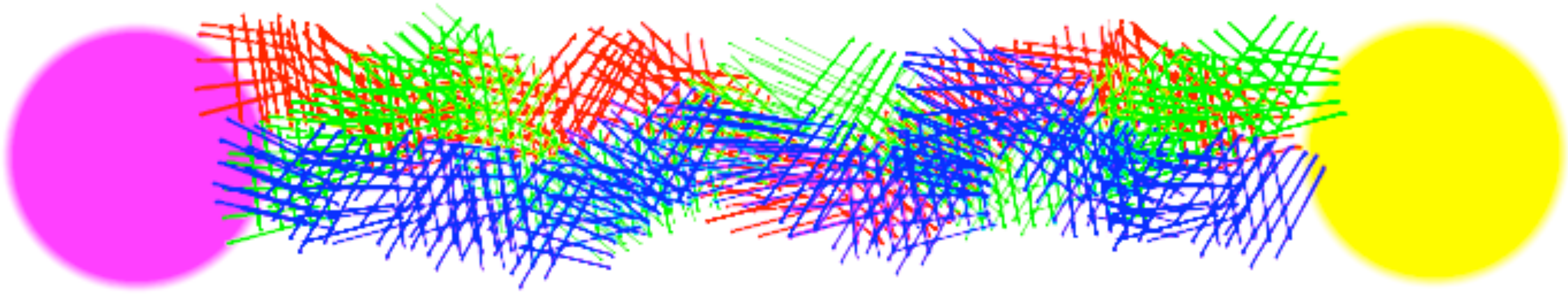

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- $\Rightarrow$ When the energy is larger than $m_q + m_{\bar{q}}$ a $q\bar{q}$ pair breaks the string and forms two different hadrons.

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⇛ In the limit $m_q \to \infty$ the string cannot break (infinite energy)

Chiral symmetry

In the absence of quark masses the QCD Lagrangian splits into two independent quark sectors

$$\mathcal{L}_{\rm QCD} = \mathcal{L}_{\rm gluons} + i\bar{q}_L\gamma^\mu D_\mu q_L + i\bar{q}_R\gamma^\mu D_\mu q_R$$

⇛ For two flavors $(i = u, d)$ $\mathcal{L}_{\rm QCD}$ is symmetric under $SU(2)_L \times SU(2)_R$

⇛ However, this symmetry is not observed

Solution: the vacuum $|0\rangle$ is not invariant

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \longrightarrow \quad \text{chiral condensate}$$

⇛ Symmetry breaking

Golstone's theorem $\Longrightarrow$ massless bosons associated: pions

So, **properties of the QCD vacuum**

- Confinement
- Chiral symmetry breaking

Is there a regime where these symmetries are restored?

QCD phase diagram

Free quarks and gluons?

Asymptotic freedom: Quarks and gluons interact weakly at

@ Small distances — **increase density**

@ Large momentum — **increase temperatures**

QCD phase diagram

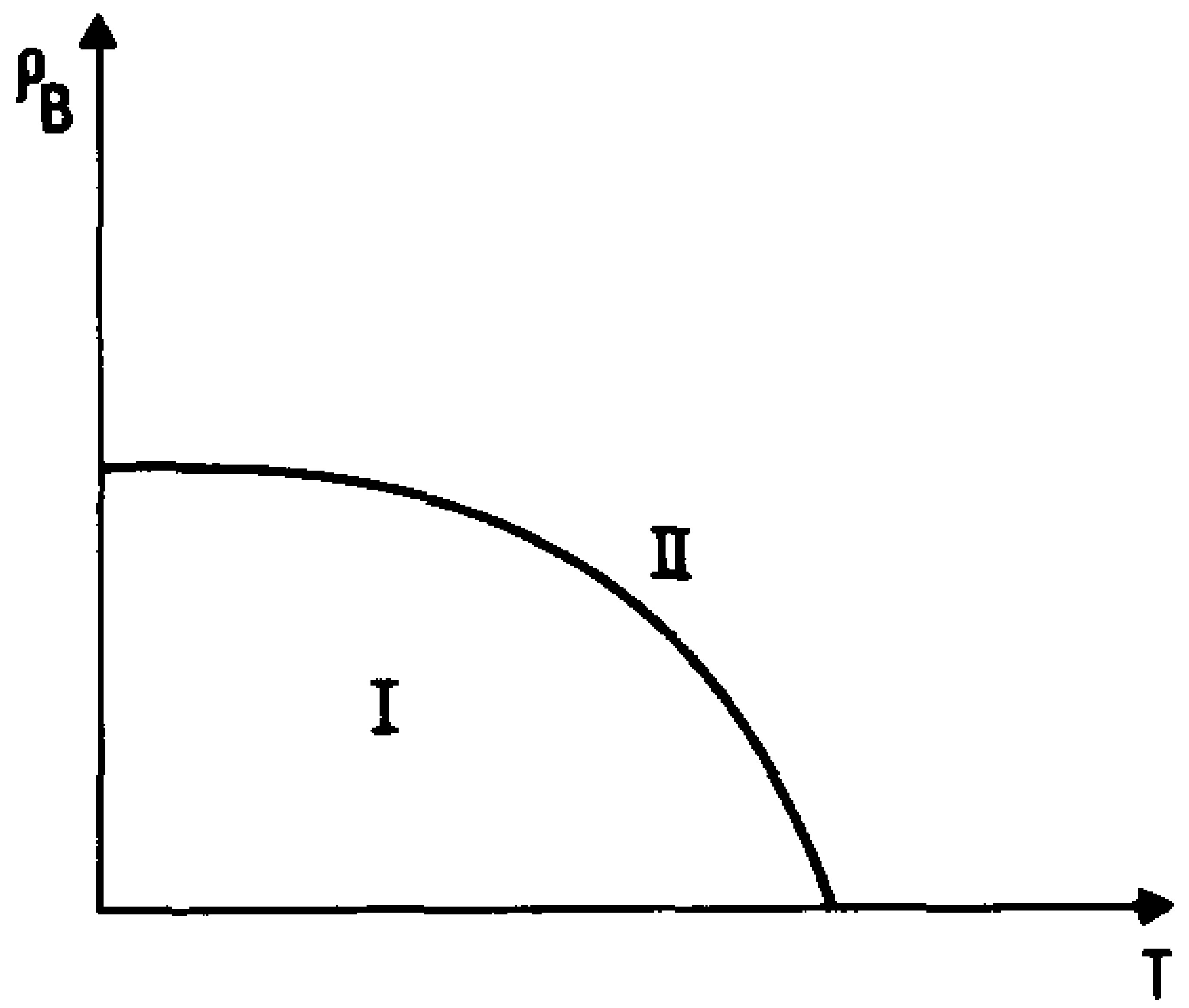
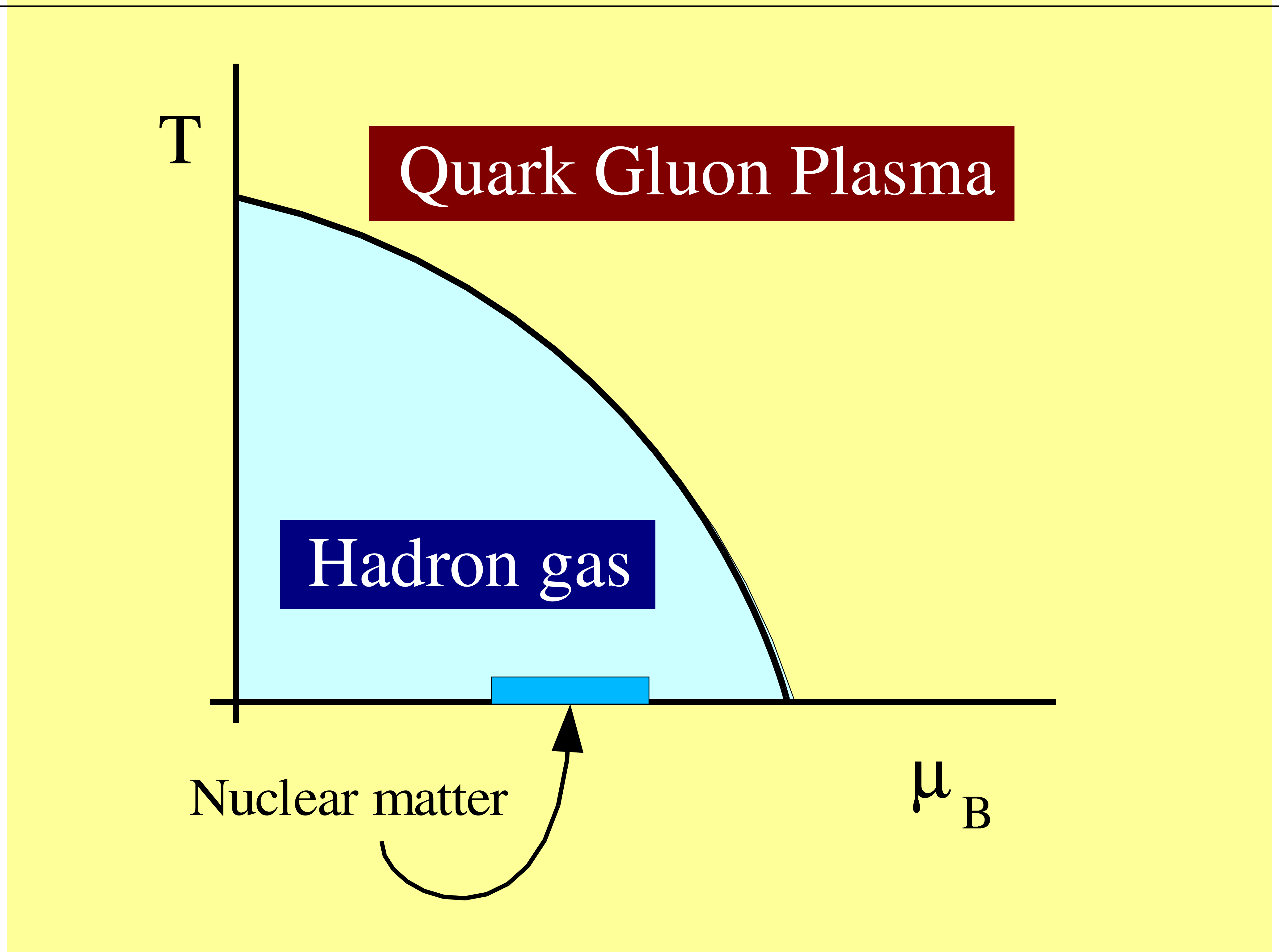


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

[Cabibbo and Parisi 1975]

QCD phase diagram



⇒ First lattice calculation found a first order phase transition

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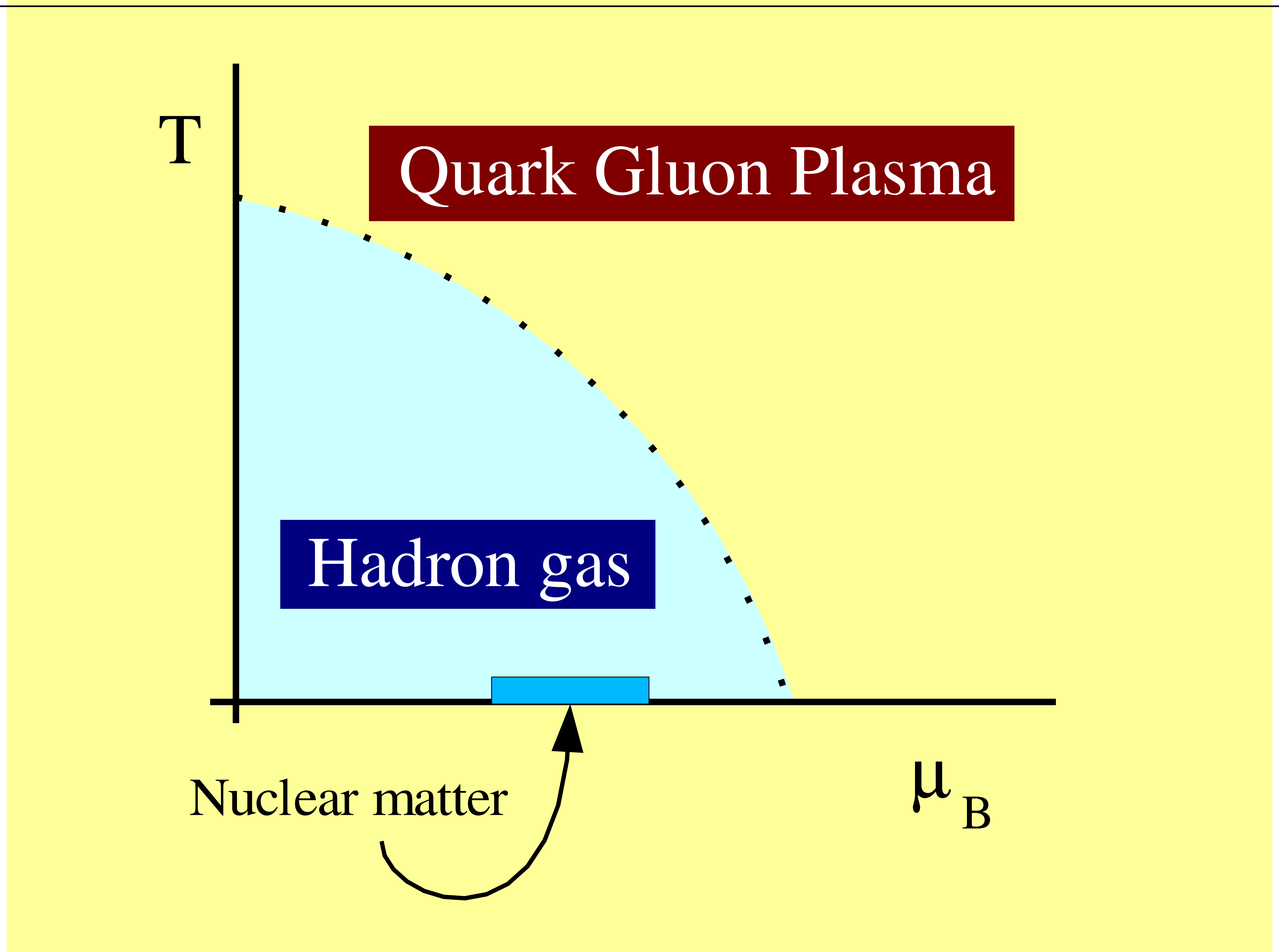

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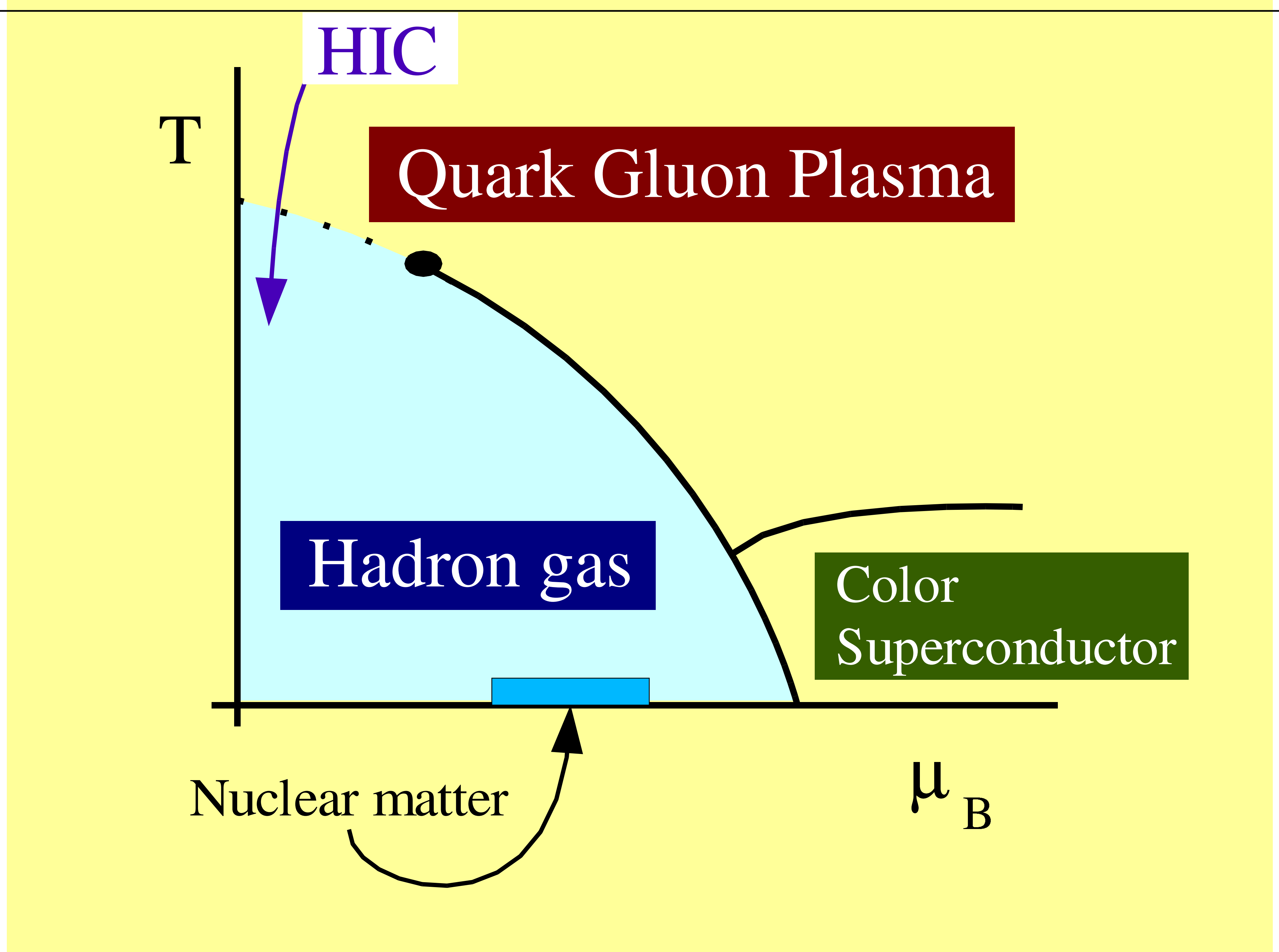

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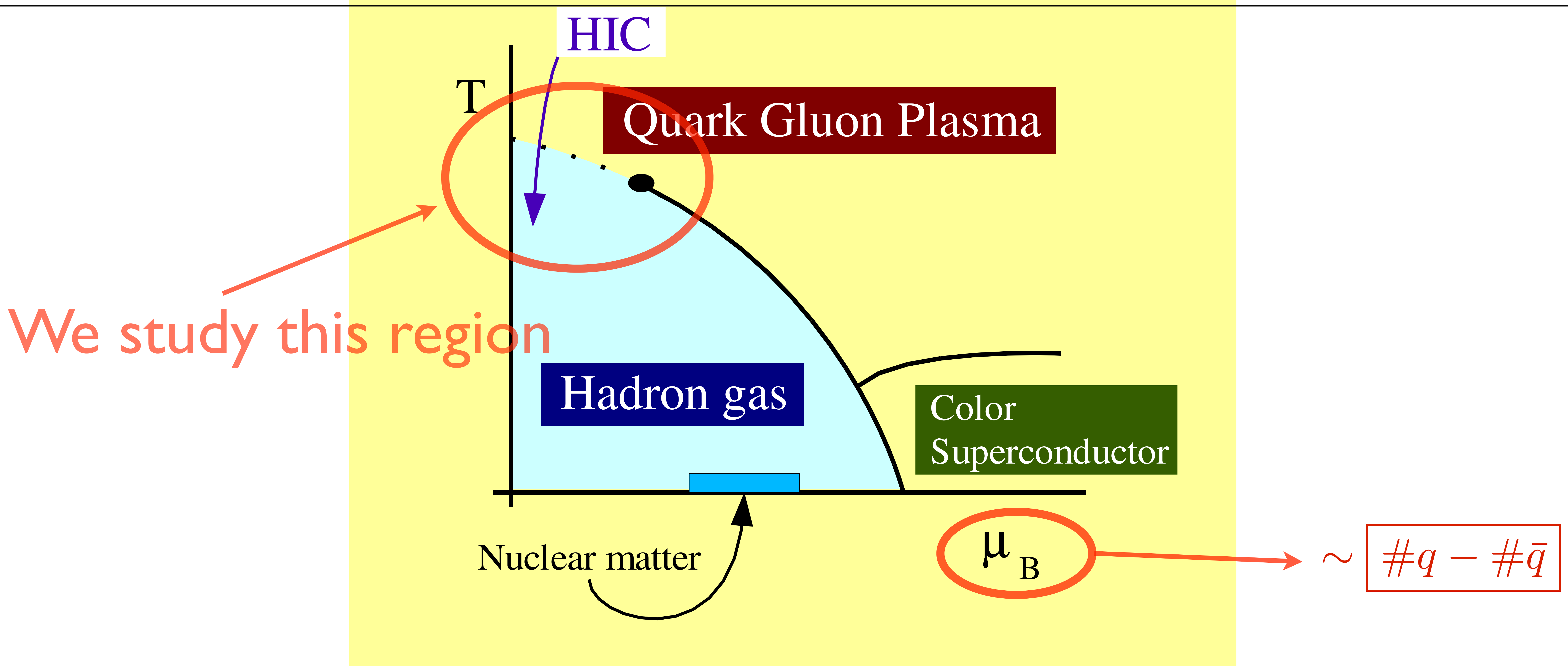

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QCD phase diagram

QCD — rich dynamical content, with emerging dynamics
that happens at scales easy to reach in collider experiments — e.g. EoS

Experimental tools

High-energy heavy-ion coll. [high T, low n_B]

LHC — pp, pPb, PbPb, XeXe, (other lighter ions under study)

RHIC — pp, dAu, AuAu, CuCu, UU,…

Medium energies HIC [moderate T, high n_B]

RHIC Beam Energy Scan

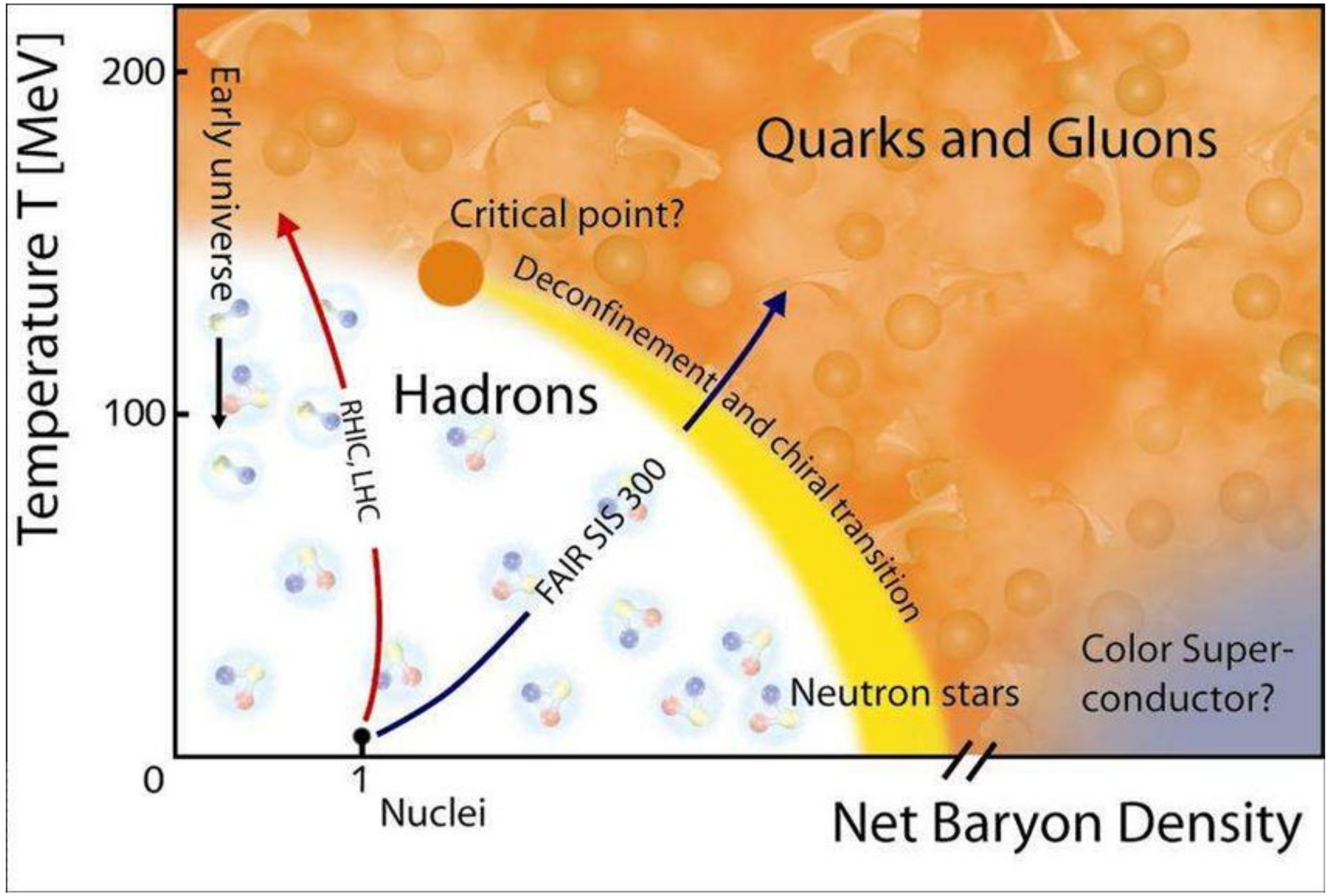
FAIR at GSI

NICA at Dubna

Cosmological observations — notably GWs

Neutron star coalescence - **low T, high n_B**

Future — access to QCD transition in early Universe?



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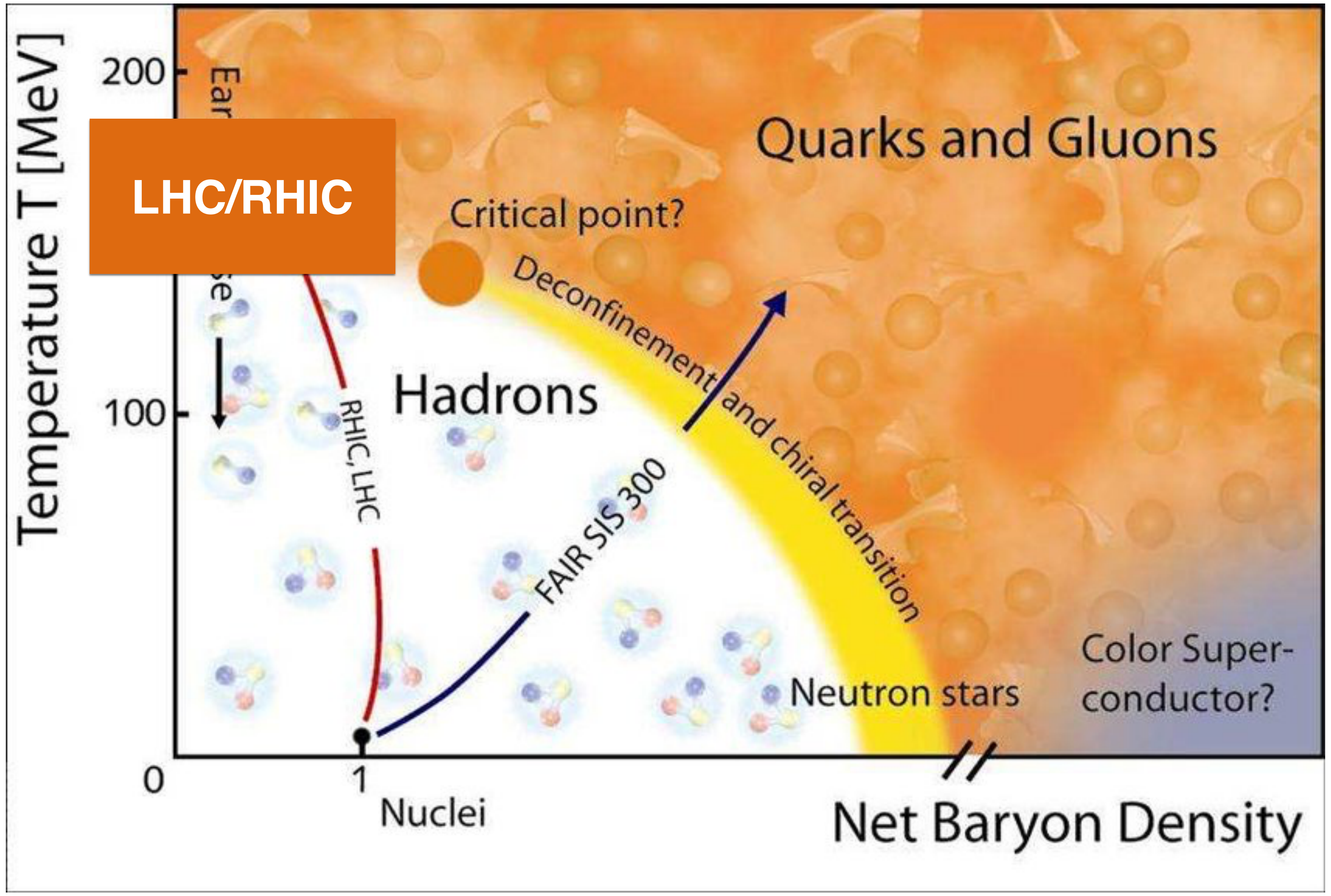

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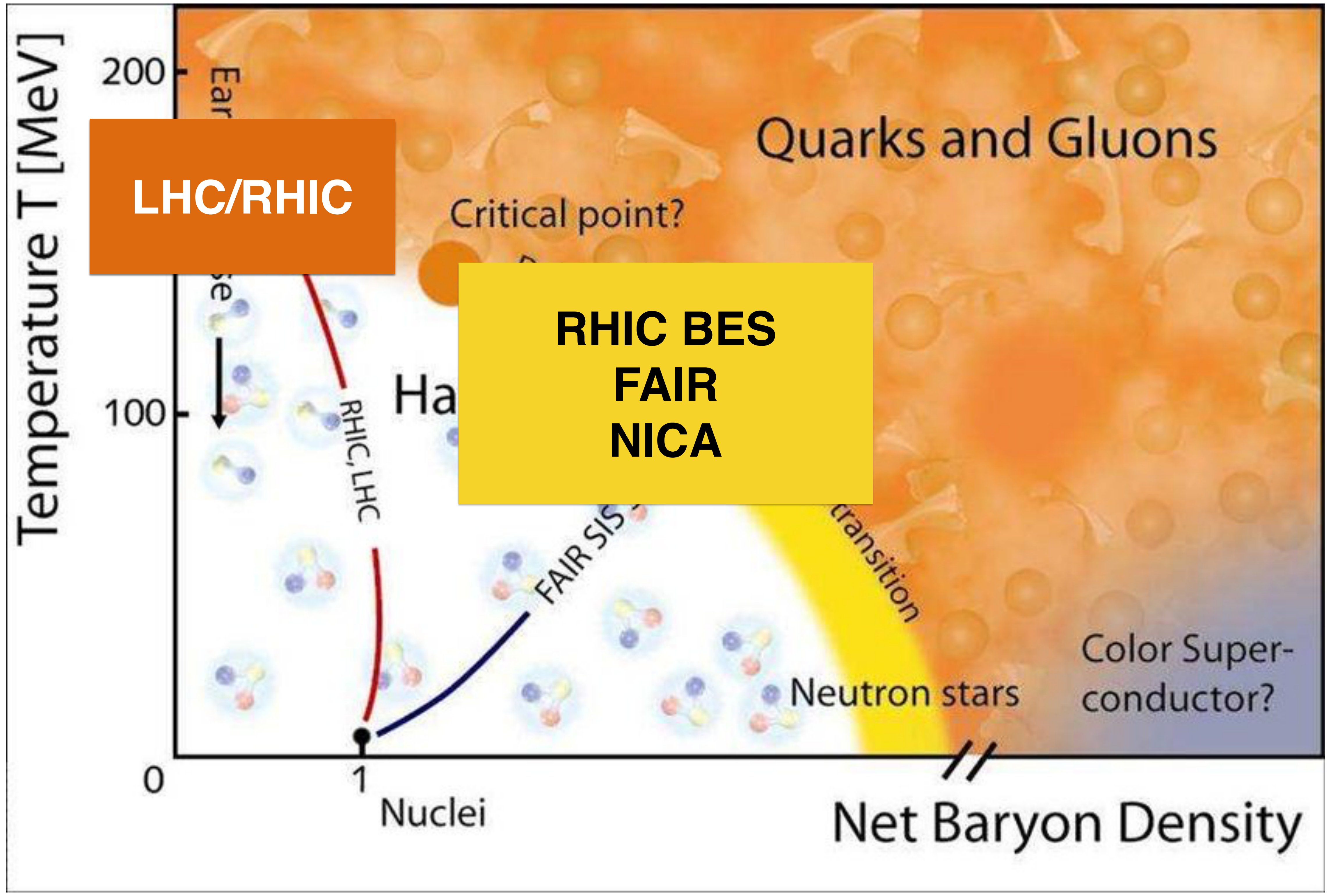

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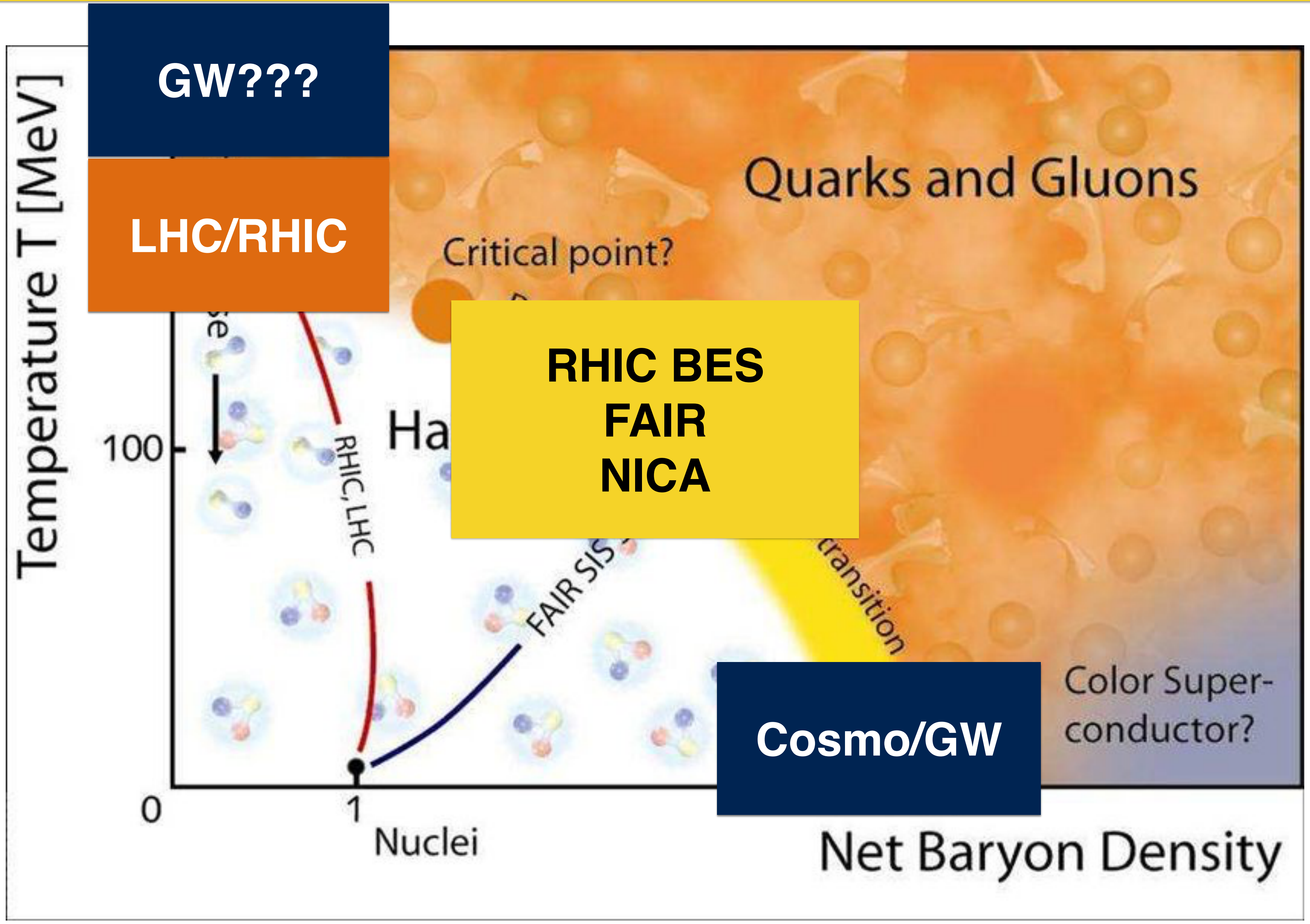
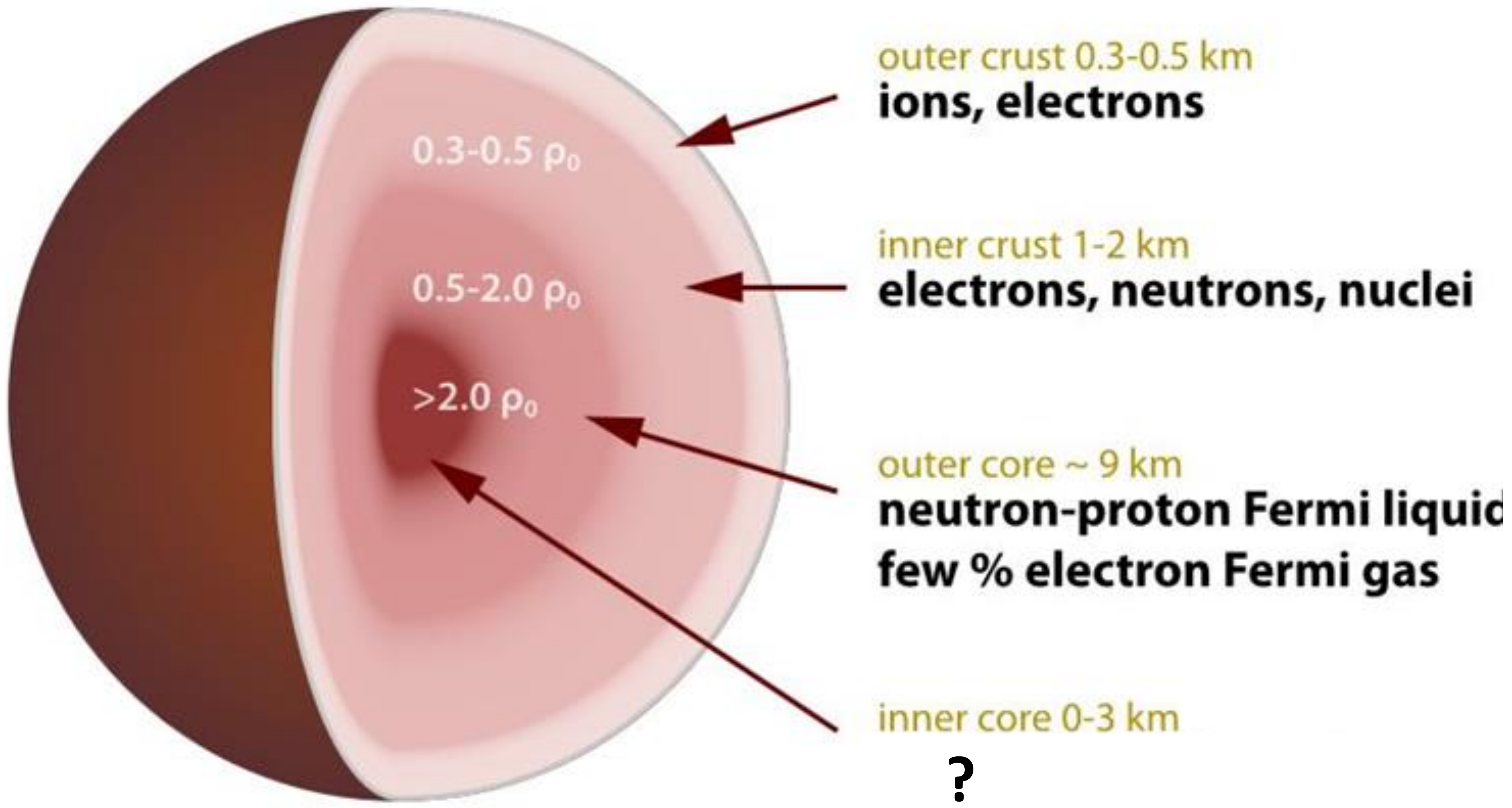
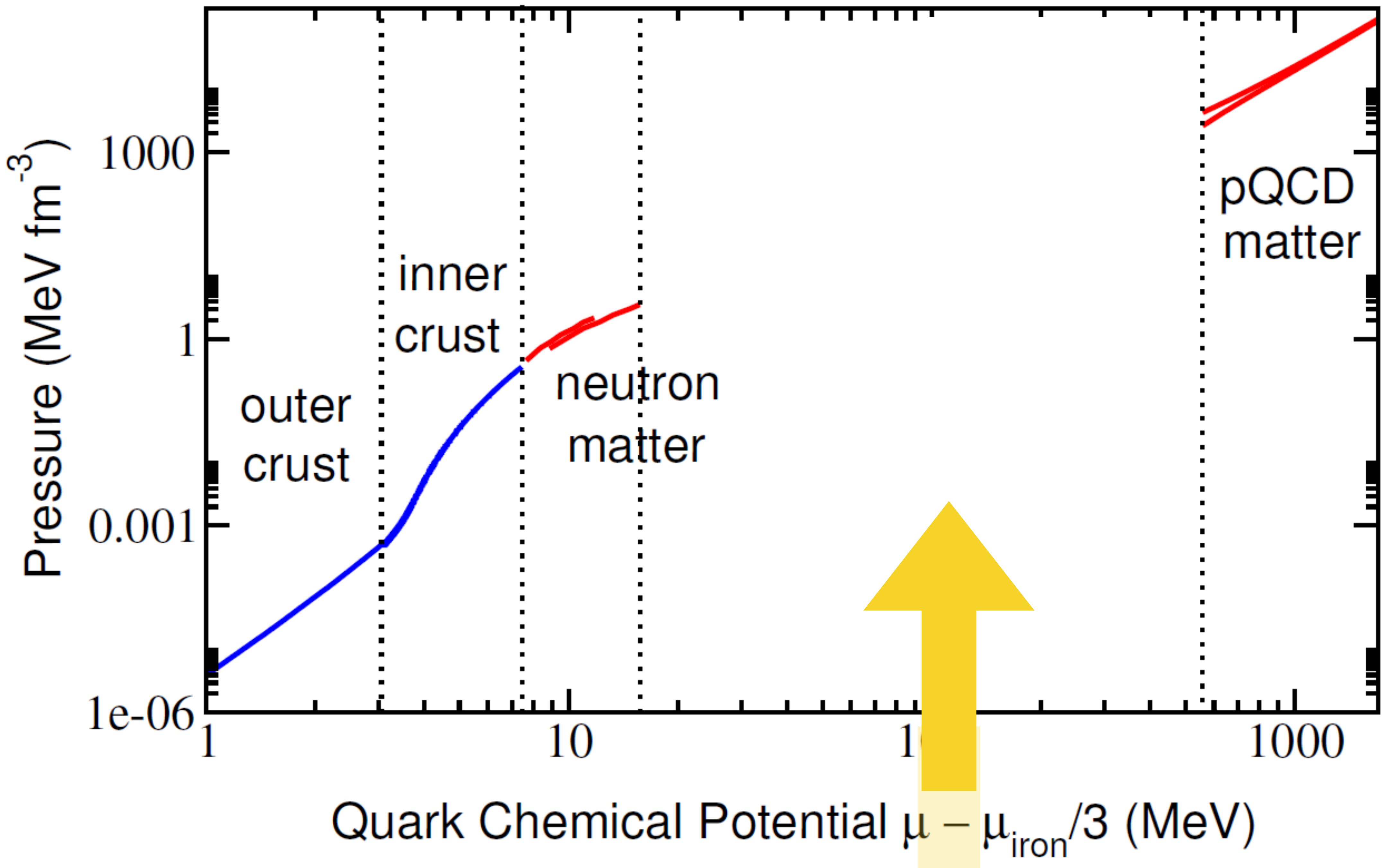


Neutron stars

EoS determines neutron star structure



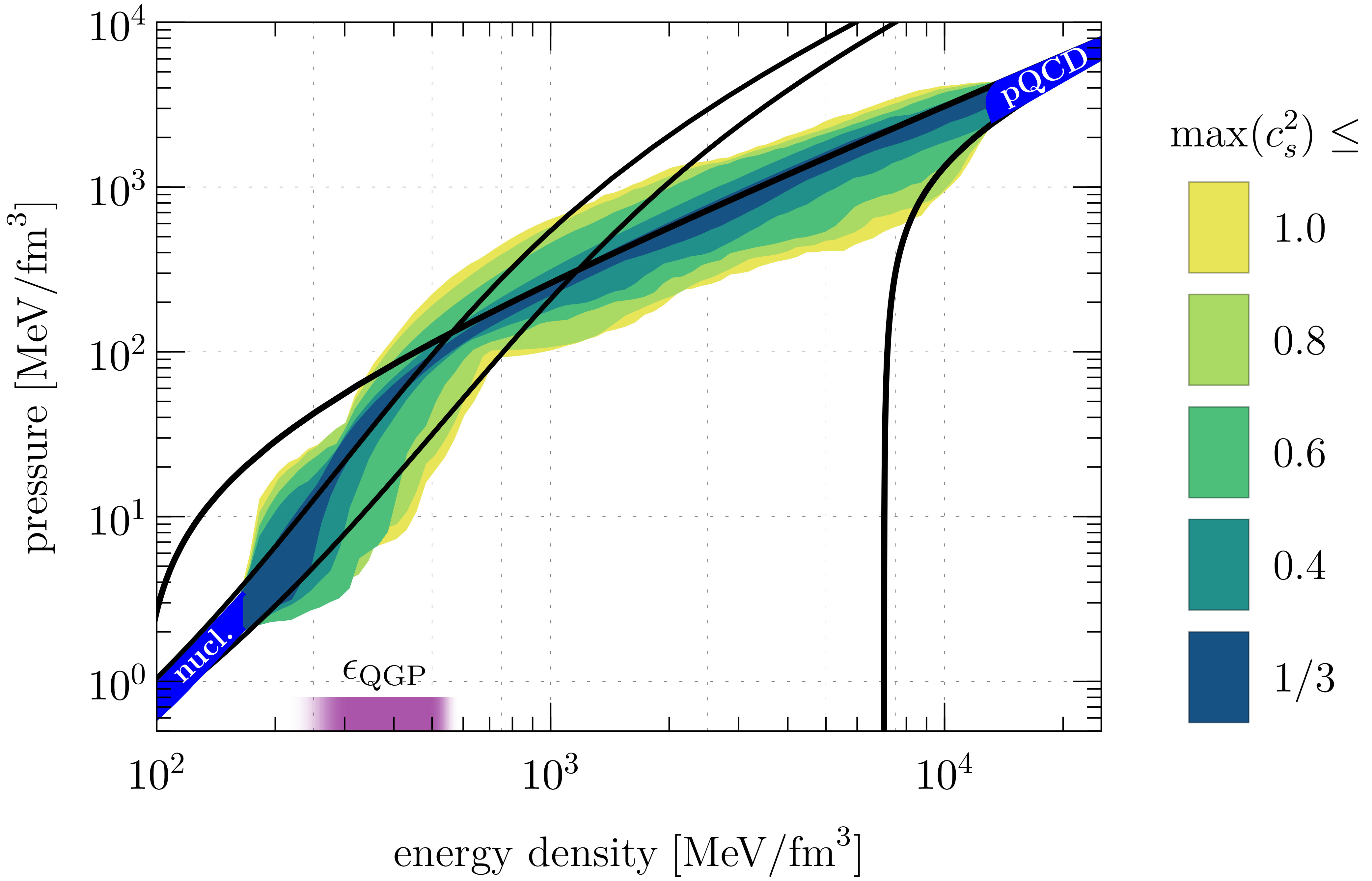


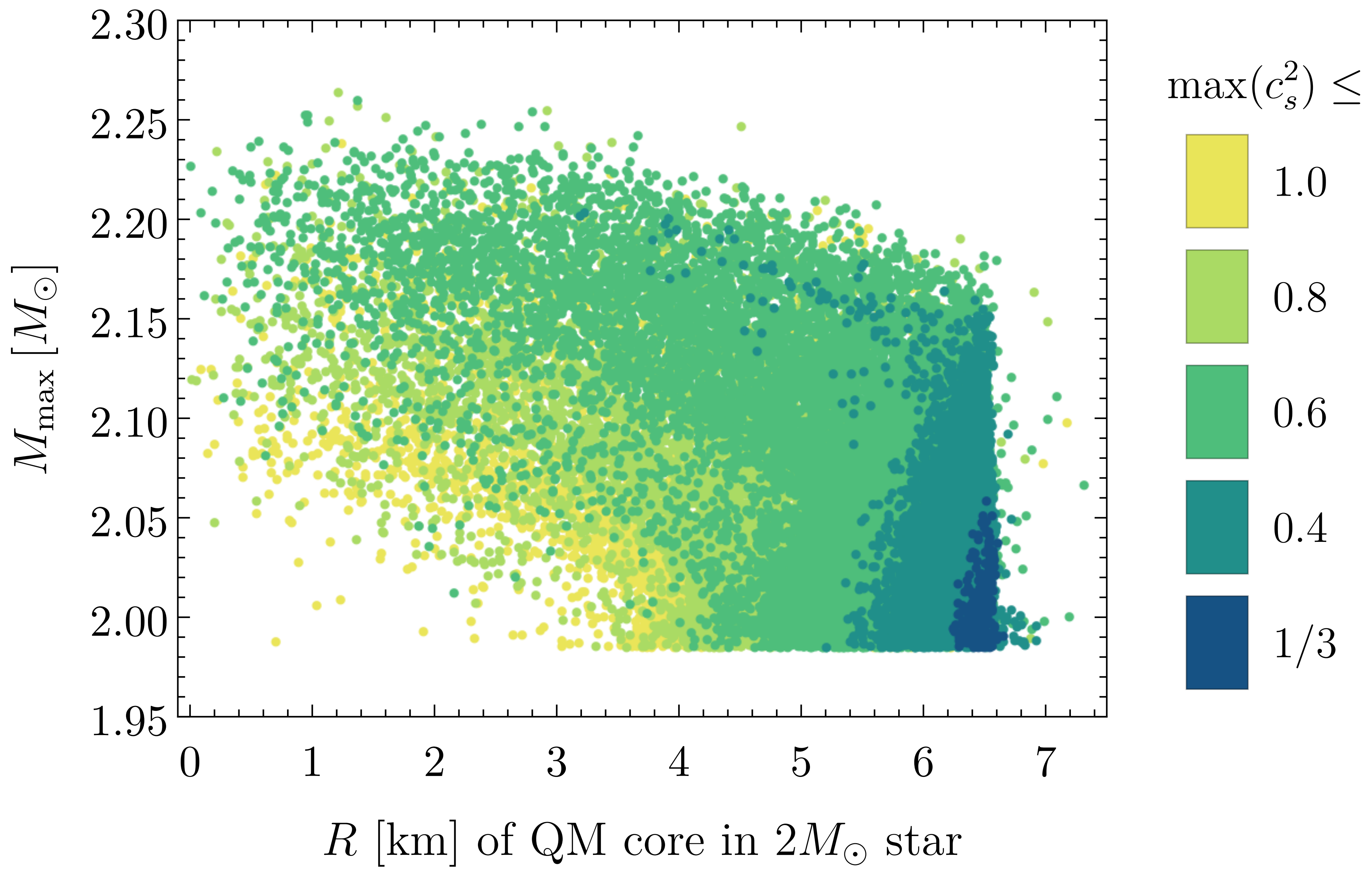
[A Vuorinen QM2018]

Lattice QCD
very challenging at finite μ_B

Region relevant for neutron star structure largely unknown

EoS constraints from GW





[Annala, Gorda, Kurkela, Vuorinen 2018; Annala, Gorda, Kurkela, Nattila, Vuorinen 2019; also Most et al. 2018; Dexheimer et al. 2019 - More recent studies available, not shown]

The existence of quark-matter core found to be a common feature of the allowed EoS

Further constraints for the EoS at higher and higher baryon density in future experiments FAIR, NICA

QCD thermodynamics I

⇒ In the grand canonical ensemble, the thermodynamical properties are determined by the (grand) partition function

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

where $k_B = 1$, H is the Hamiltonian and N_i and μ_i are conserved number operators and their corresponding chemical potentials.

⇒ The different thermodynamical quantities can be obtained from Z

$$P = T\frac{\partial \ln Z}{\partial V}\,, \quad S = \frac{\partial (T\ln Z)}{\partial T}\,, \quad N_i = T\frac{\partial \ln Z}{\partial \mu_i}$$

⇒ Expectation values can be computed as

$$\langle \mathcal{O}\rangle = \frac{\mathrm{Tr}\mathcal{O}\exp\{-\frac{1}{T}(H-\sum_i \mu_i N_i)\}}{\mathrm{Tr}\exp\{-\frac{1}{T}(H-\sum_i \mu_i N_i)\}}$$

QCD thermodynamics II

In order to obtain Z for a field theory with Lagrangian $\mathcal{L}$ one normally makes the change $-it = 1/T$, with this, the action

$$iS \equiv i\int dt\mathcal{L} \longrightarrow S = -\int_0^{1/T} d\tau\mathcal{L}_E$$

and the grand canonical partition function can be written (for QCD) as

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

where $\mathcal{N} \equiv \bar{\psi}\gamma_0\psi$ is the number density operator associated to the conserved net quark (baryon) number.

Additionally, (anti)periodic boundary conditions in $[0, 1/T]$ are imposed for bosons (fermions)

$$A^\mu(0,\mathbf{x}) = A^\mu(1/T,\mathbf{x})\,,\quad \psi(0,\mathbf{x}) = -\psi(1/T,\mathbf{x})$$

QCD thermodynamics III

In order to solve these equations

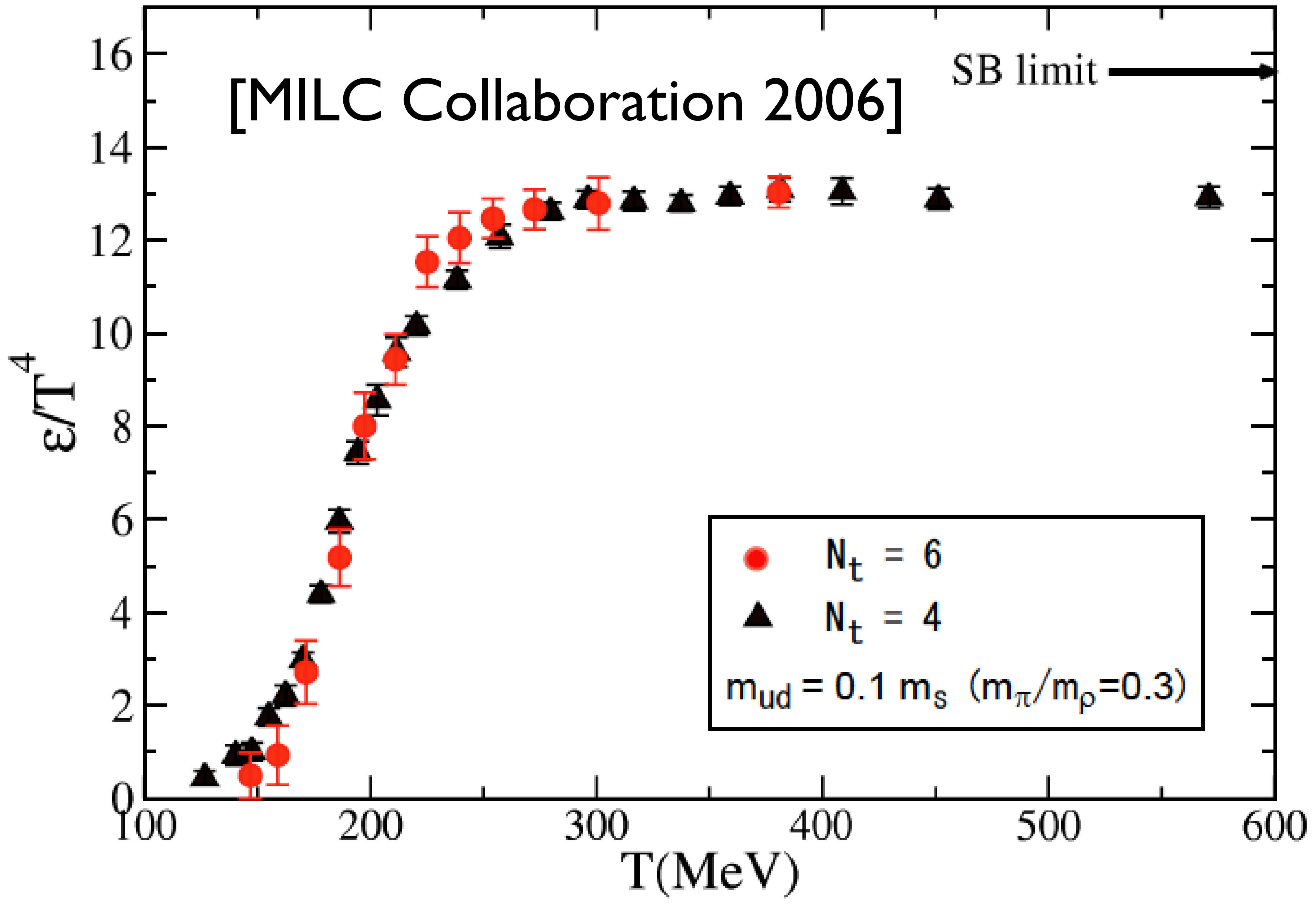
- Perturbative expansion
  - $\alpha_S(T)$ small for large $T \longrightarrow$ bad convergence, but some results obtained.
- Lattice QCD
  - Discretization in $(1/T, V)$ space
  - Contributions to Z are computed by random configurations of fields in the lattice
  - Most of the results for $\mu = 0$

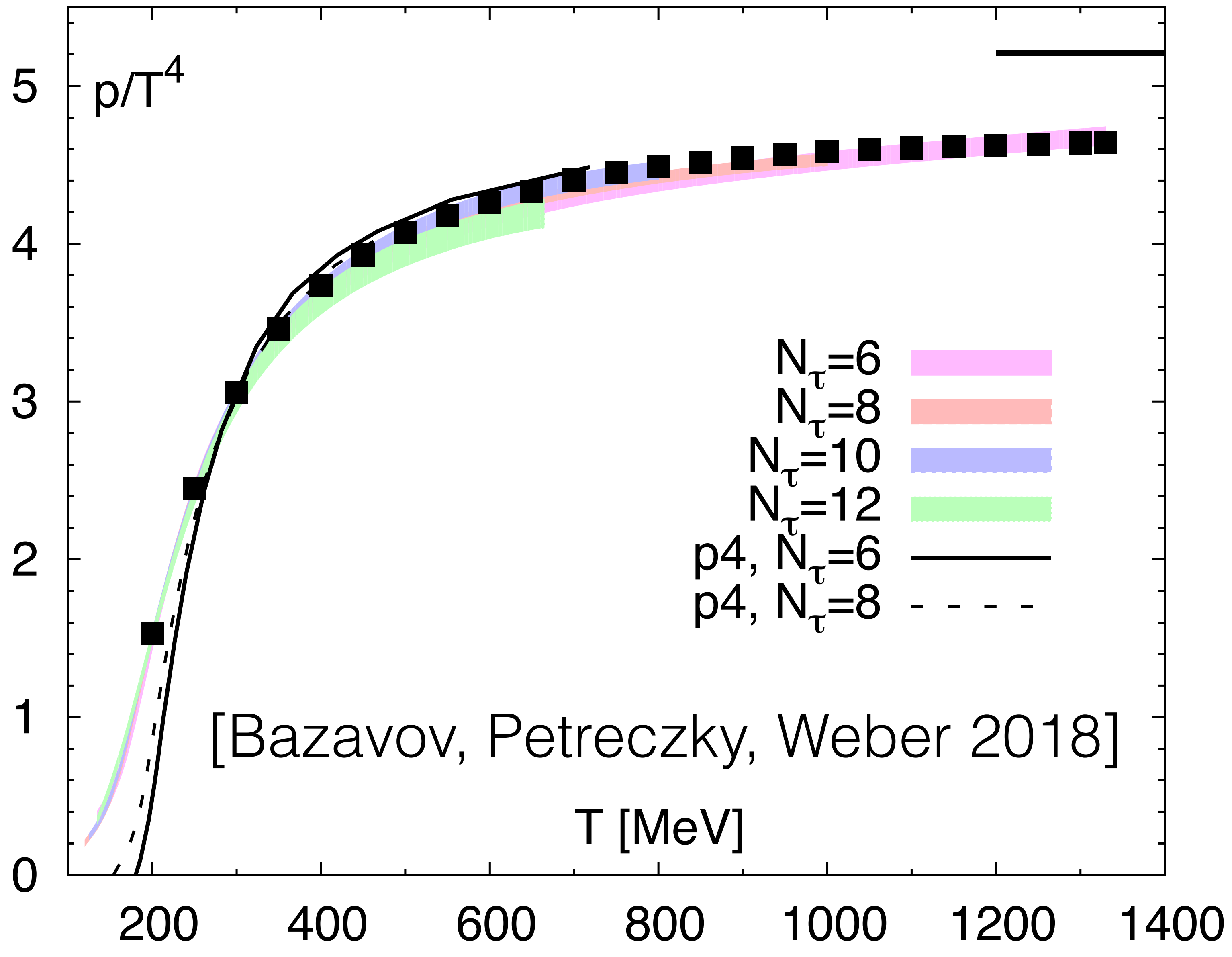
First example: EoS

Naïve estimation: Let's fix $\mu = 0$, the pressure of an ideal gas (of massless particles) is proportional to the number of d.o.f: $P \propto NT^4$

$$P_\pi \propto 3 \times T^4 \,; \qquad P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

[notice that proportionality factors are different, Fermi/Bose-Einstein statistics]

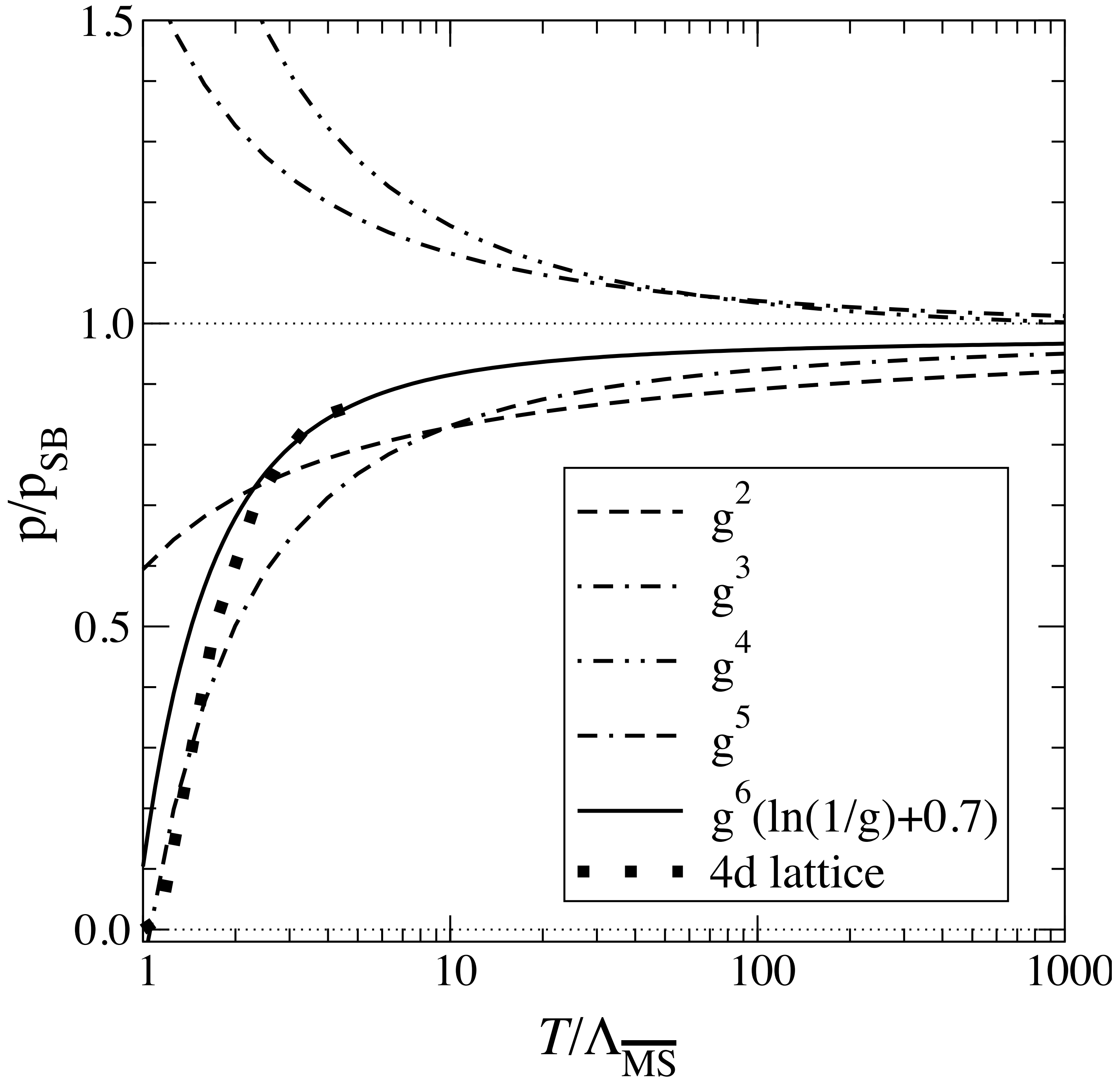




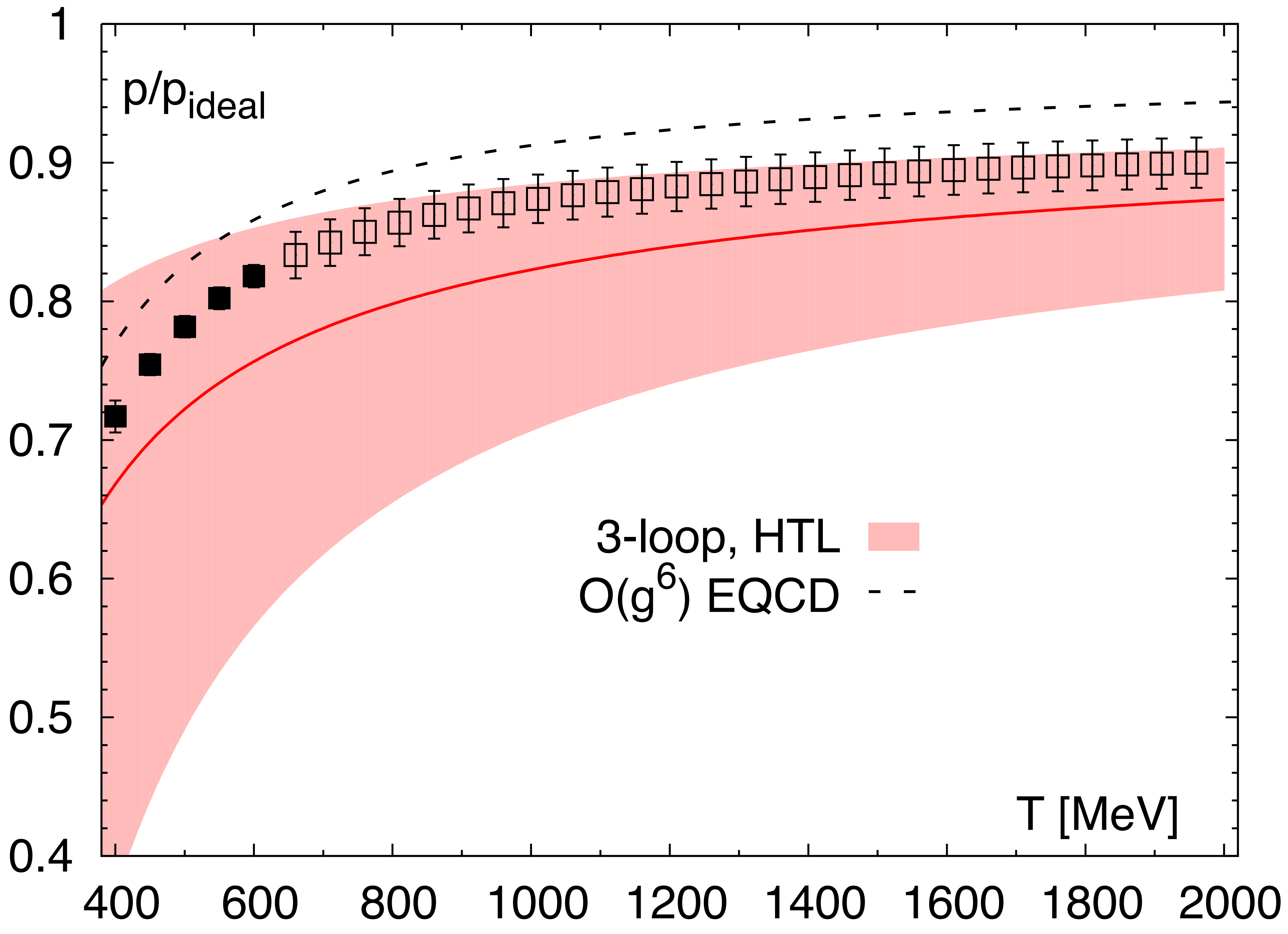
Perturbative calculations

Different orders in PT compared to lattice results

[Kajantie, Laine, Rummukainen, Schroder 2003]



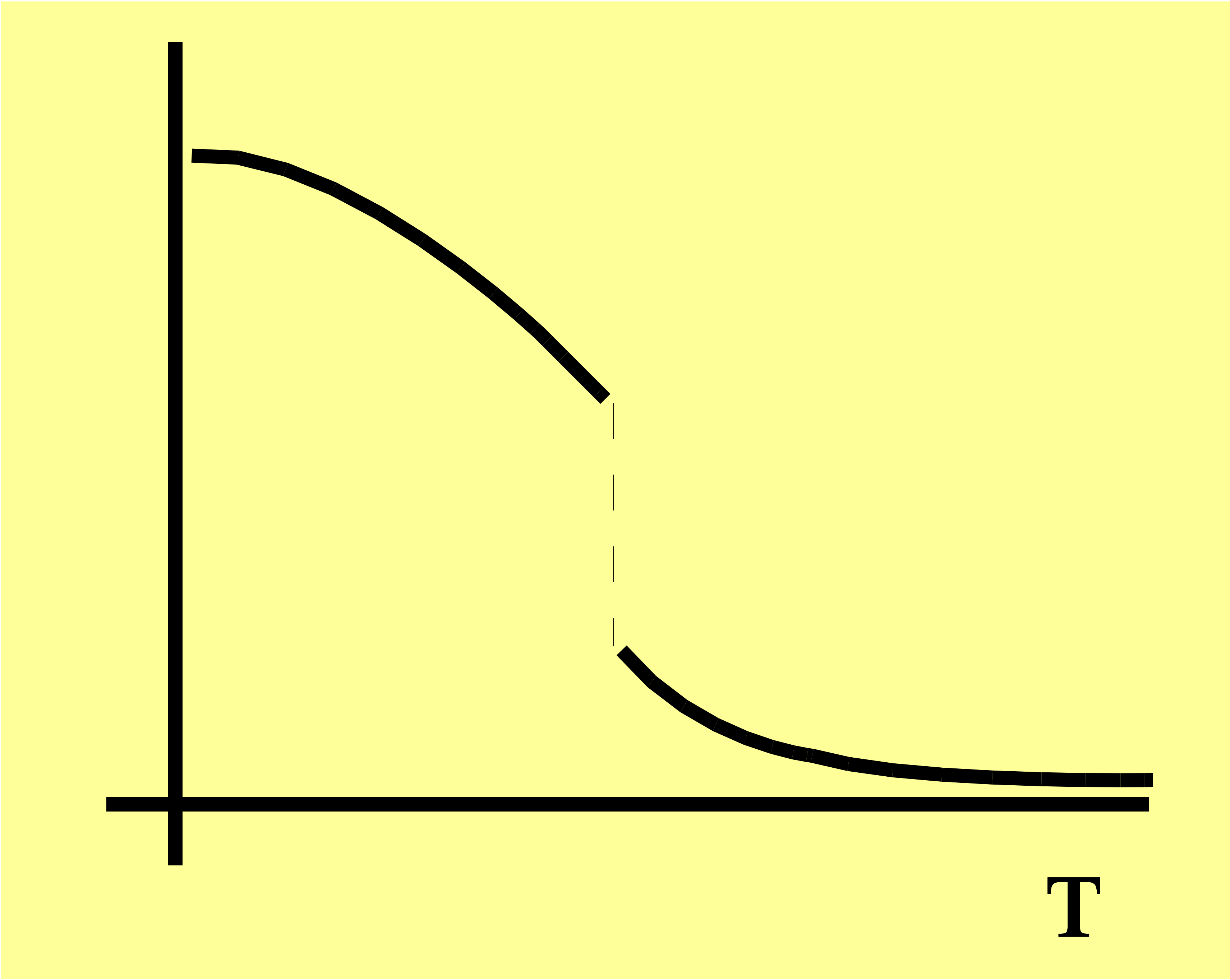
[Plot from Bazavov, Petreczky, Weber 2018]



Convergence for very large temperature

Order parameters

In order to know whether the change from a hadron gas to a QGP is a phase transition or a rapid cross-over order parameters are needed



First order: discontinuity in the order parameter

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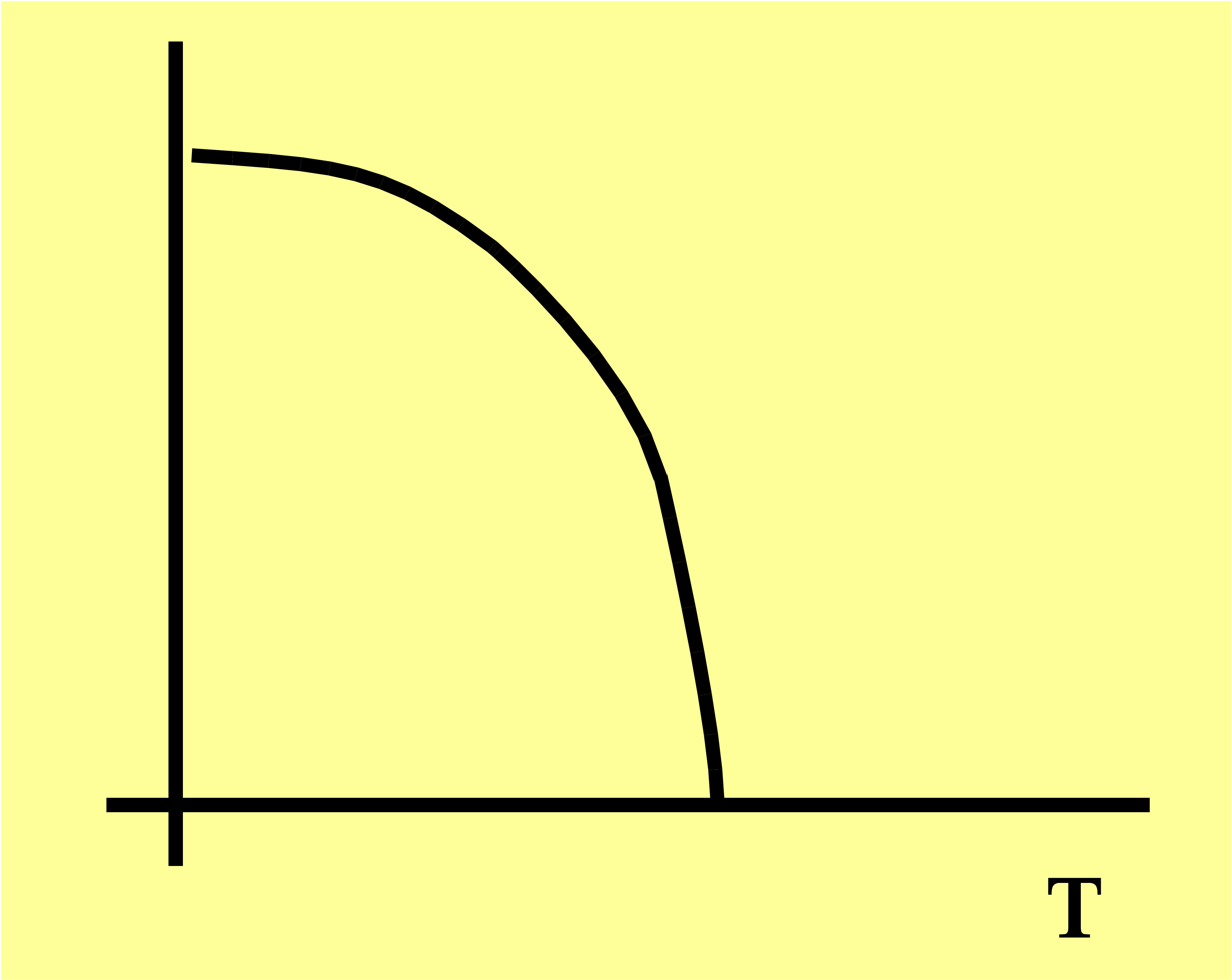

Second order: discontinuity in the derivative

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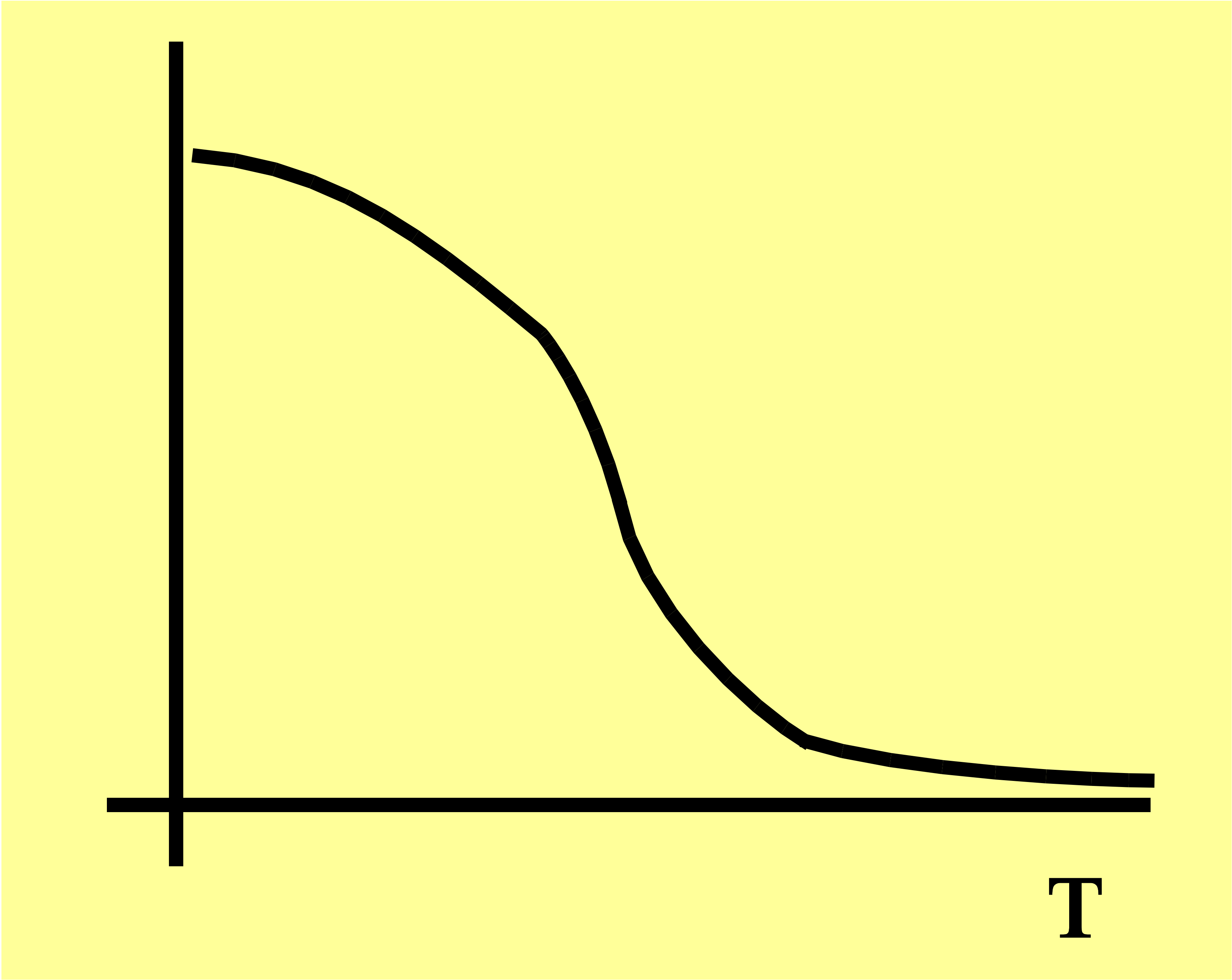


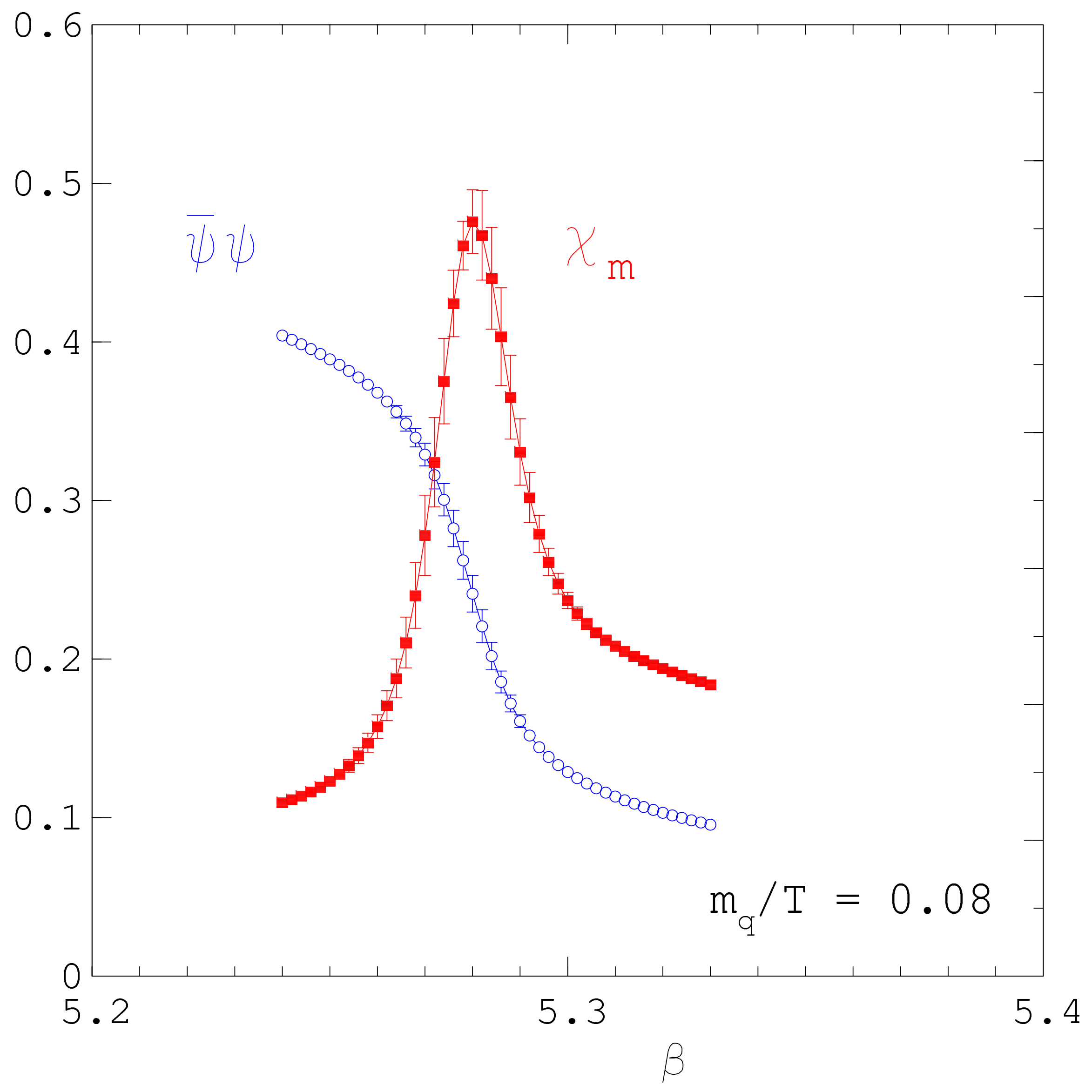
Cross-over: continuous function

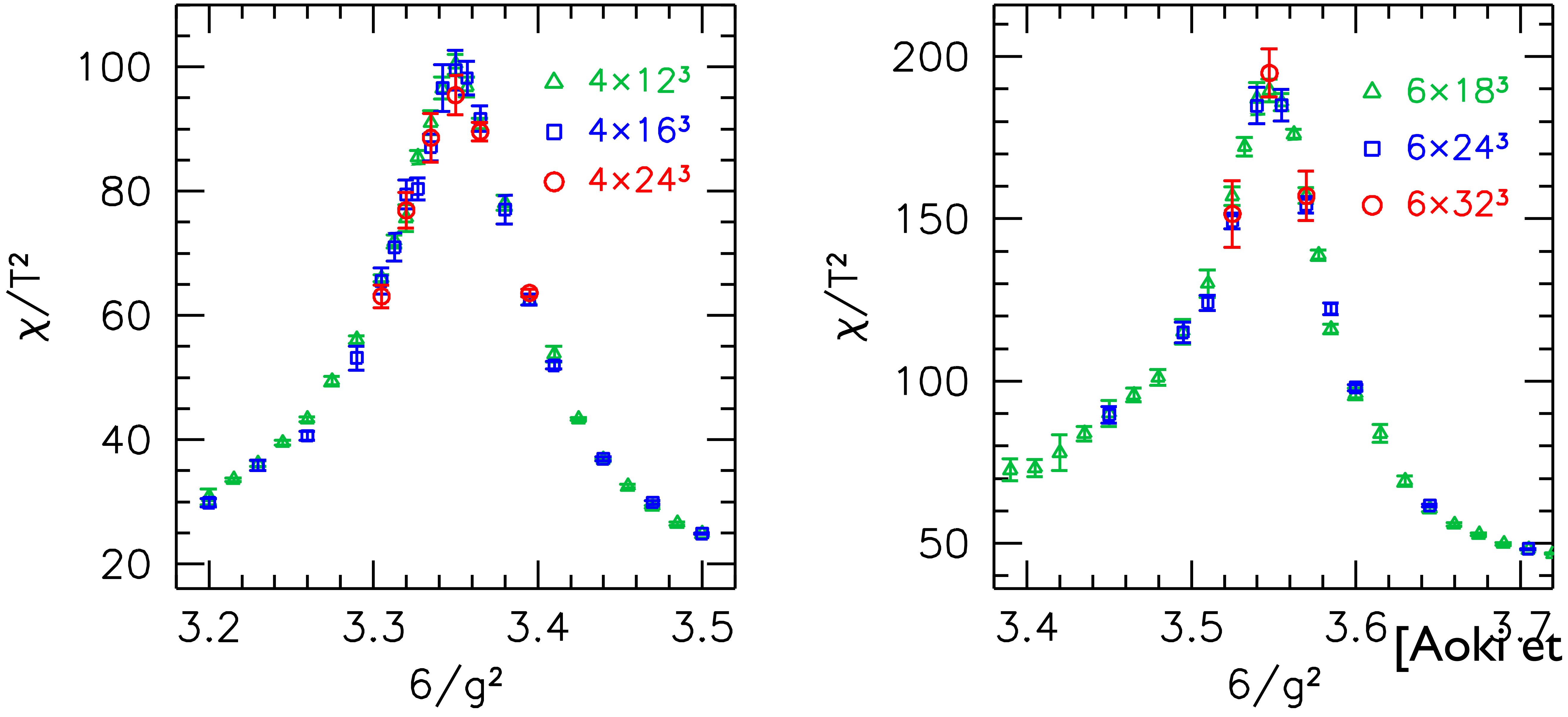
QCD order parameters I

<u>Chiral symmetry restoration</u>: for $m_q = 0$
chiral condensate is the order parameter

$$\langle 0|\bar{q}_L q_R|0\rangle \neq 0 \quad \xrightarrow[T\to\infty]{} \quad \langle 0|\bar{q}_L q_R|0\rangle = 0$$

Susceptibility: $\chi_m = \frac{\partial}{\partial m_q}\langle \bar{q}q\rangle$

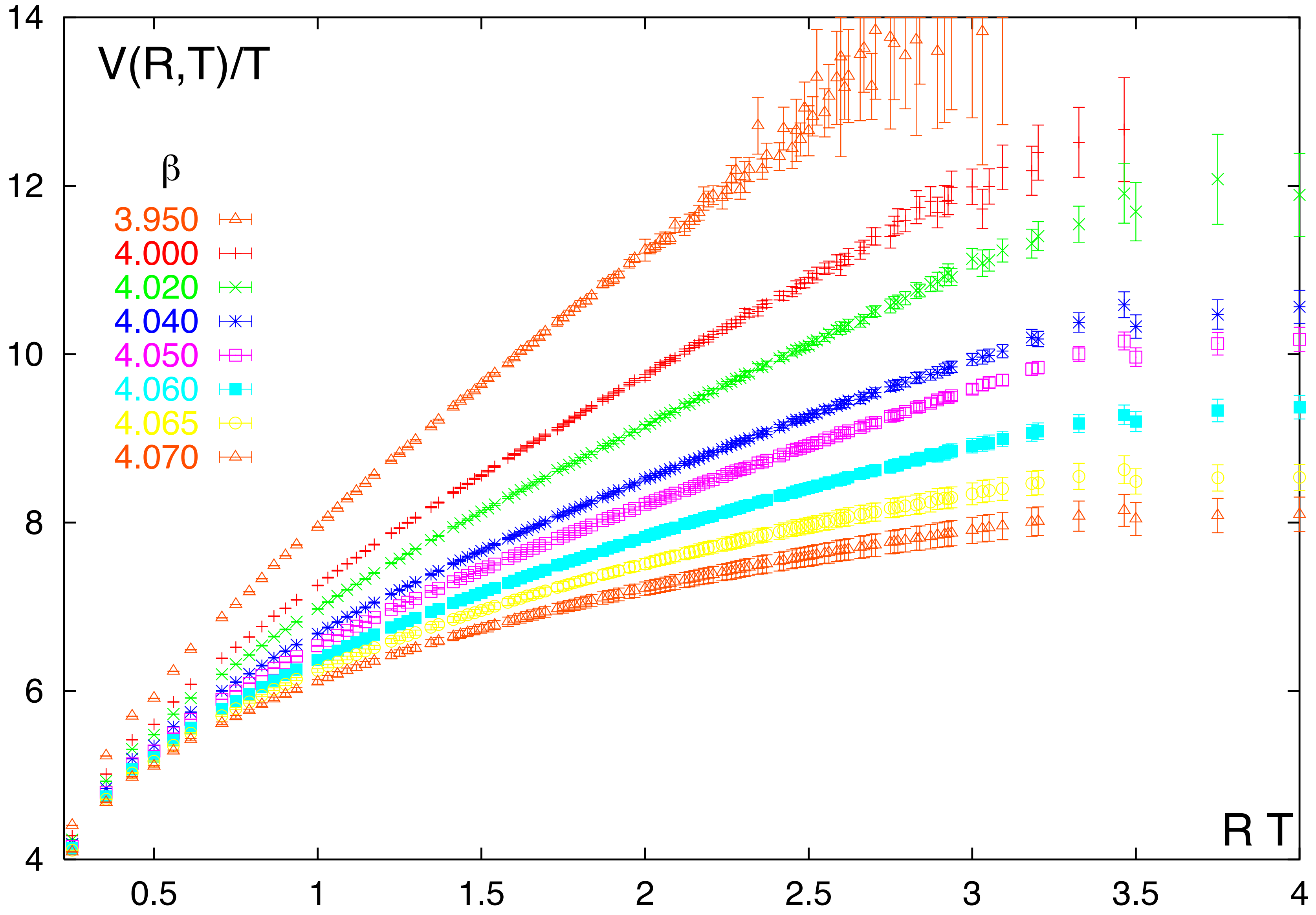




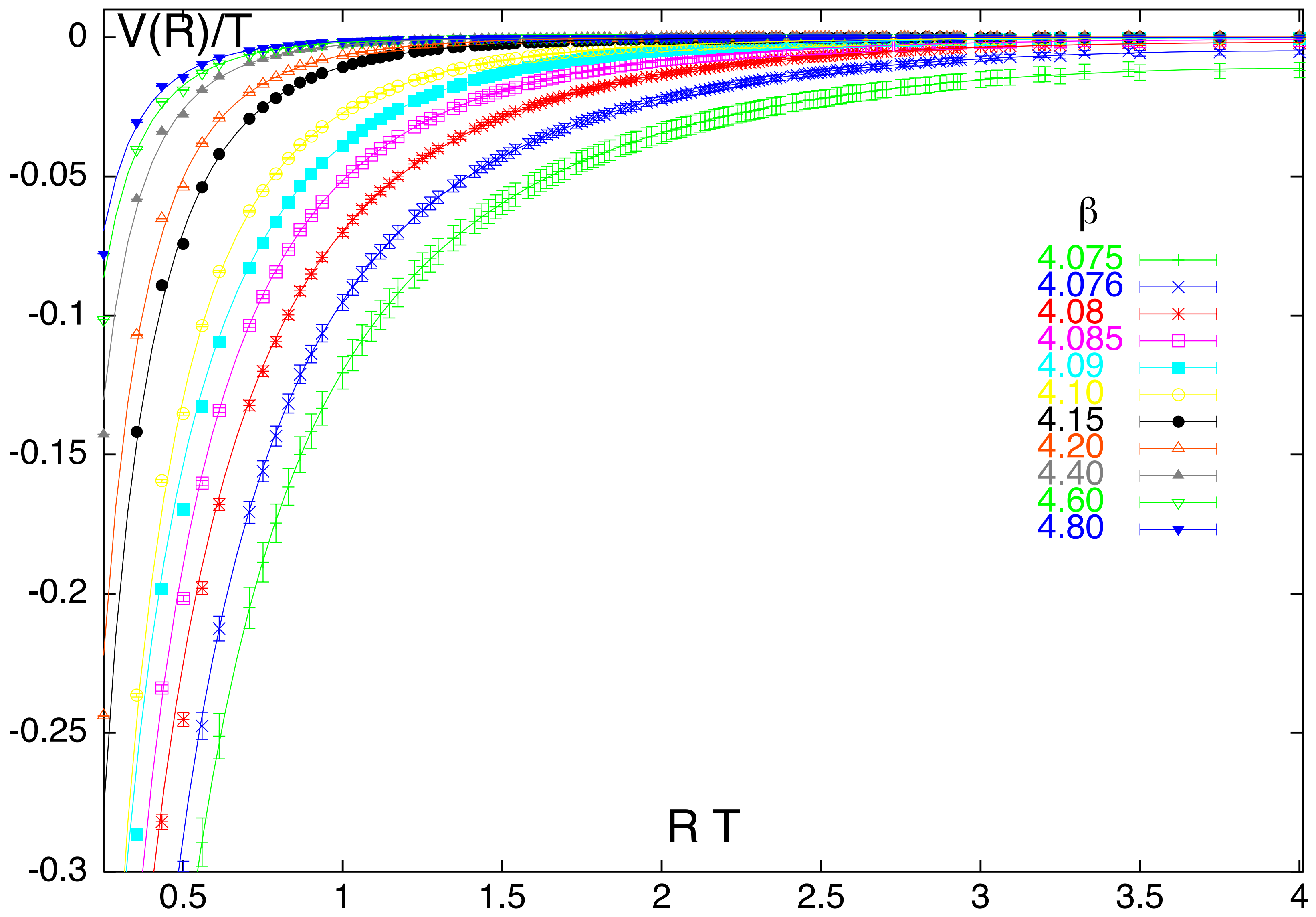
[Aoki et al 2006]

QCD order parameters II

<u>Confinement</u>: for. $m_q \to \infty$ the order parameter is the potential



$T < T_c$

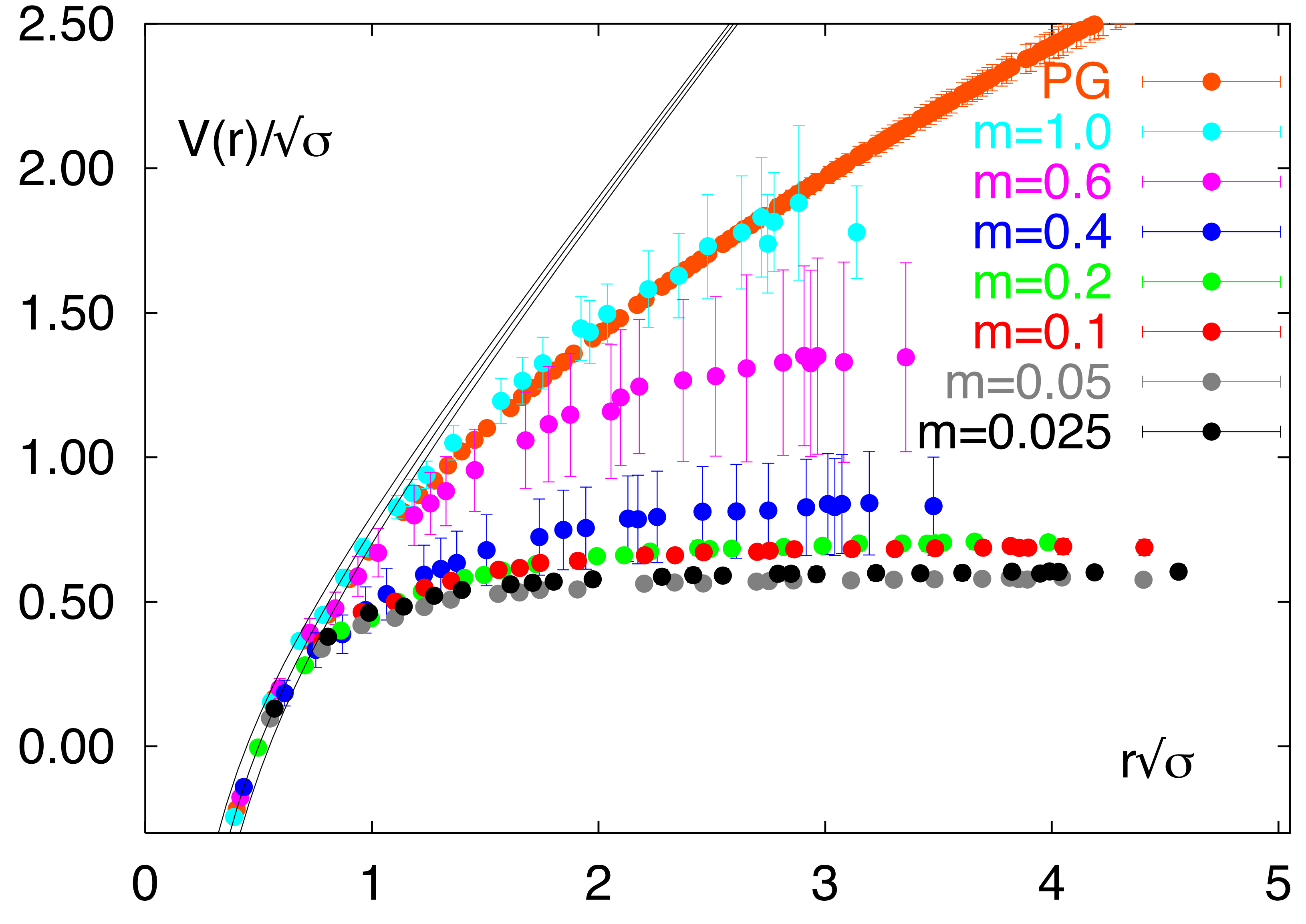


$T > T_c$

[Kaczmarek et al 2000]

However...

When masses are taken into account the potential is screened even below T_c



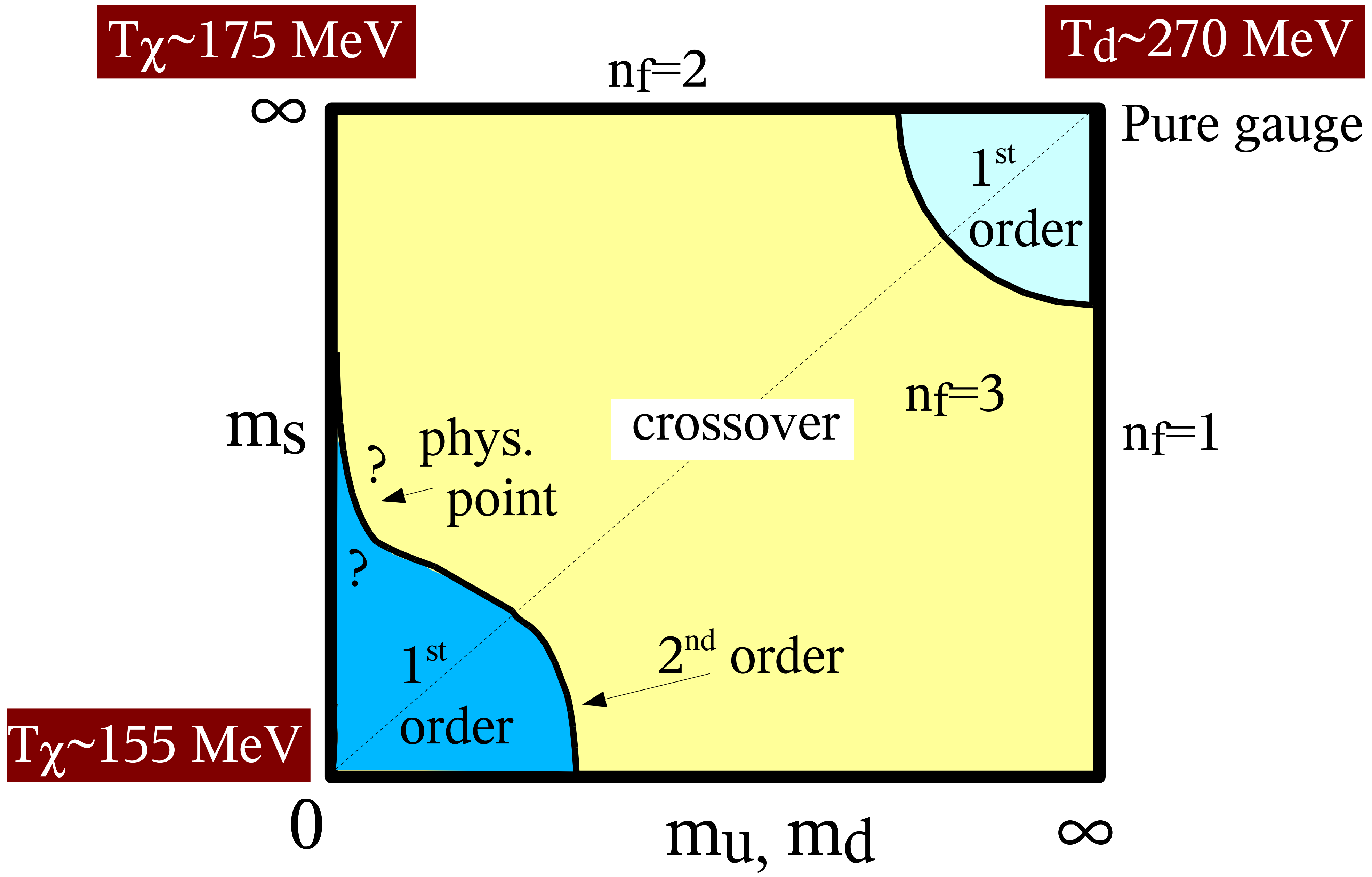
[Karsch, Laermann, Peikert 2001]

Light $\bar{q}q$ pair creation breaks the string

Physical quark masses

Two order parameters

- $\Rightarrow$ $m_q = 0 \longrightarrow$ Chiral condensate
- $\Rightarrow$ $m_q = \infty \longrightarrow$ Potential

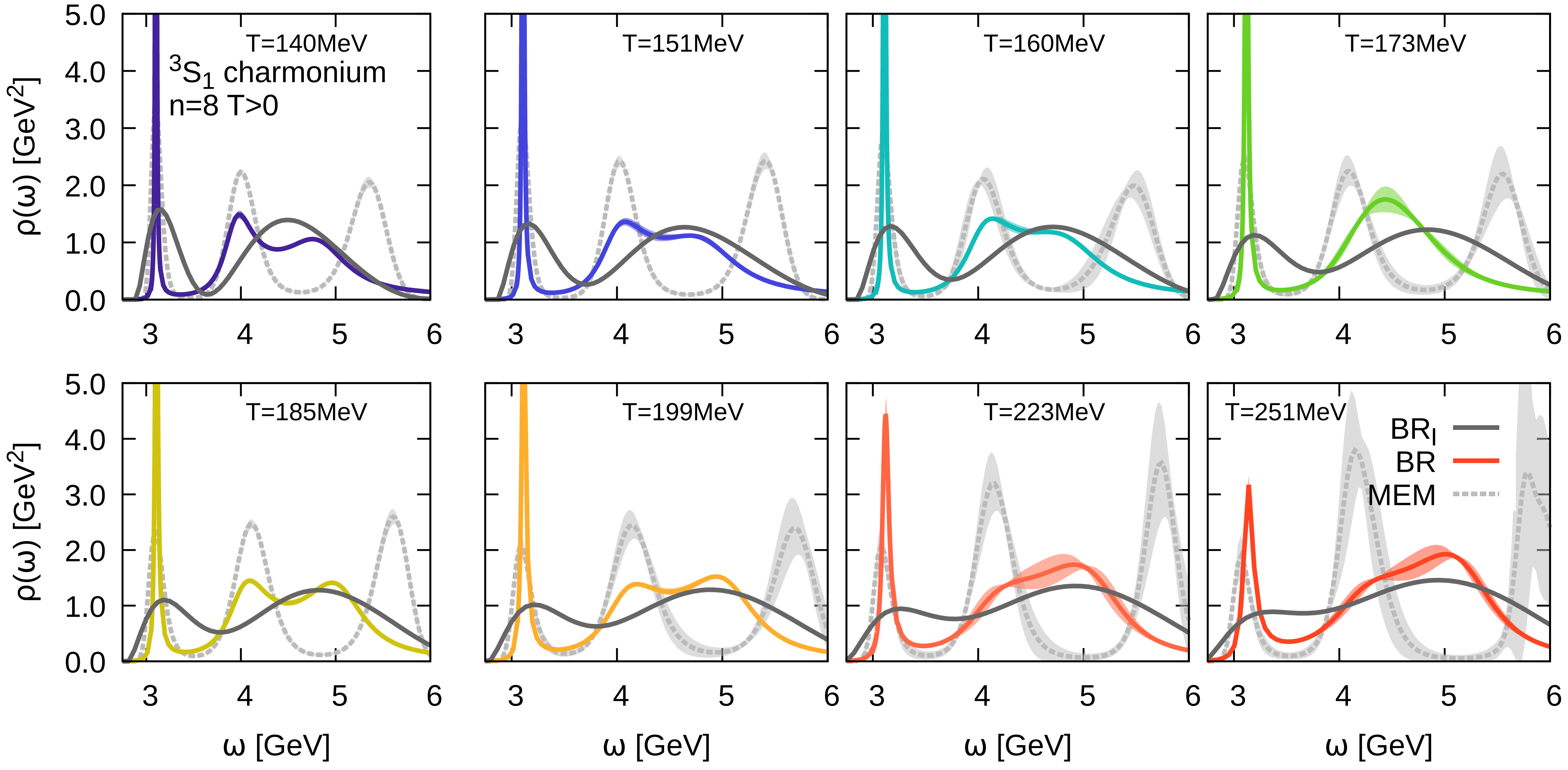


For physical masses, all results indicate a cross over

Quarkonia spectral functions

Naively, all bound states are destroyed in deconfinement. Quarkonia should then disappear in HIC [Matsui, Satz 1986]. The situation is, however, more complicated

[Kim, Petreczky, Rothkopf 2018]

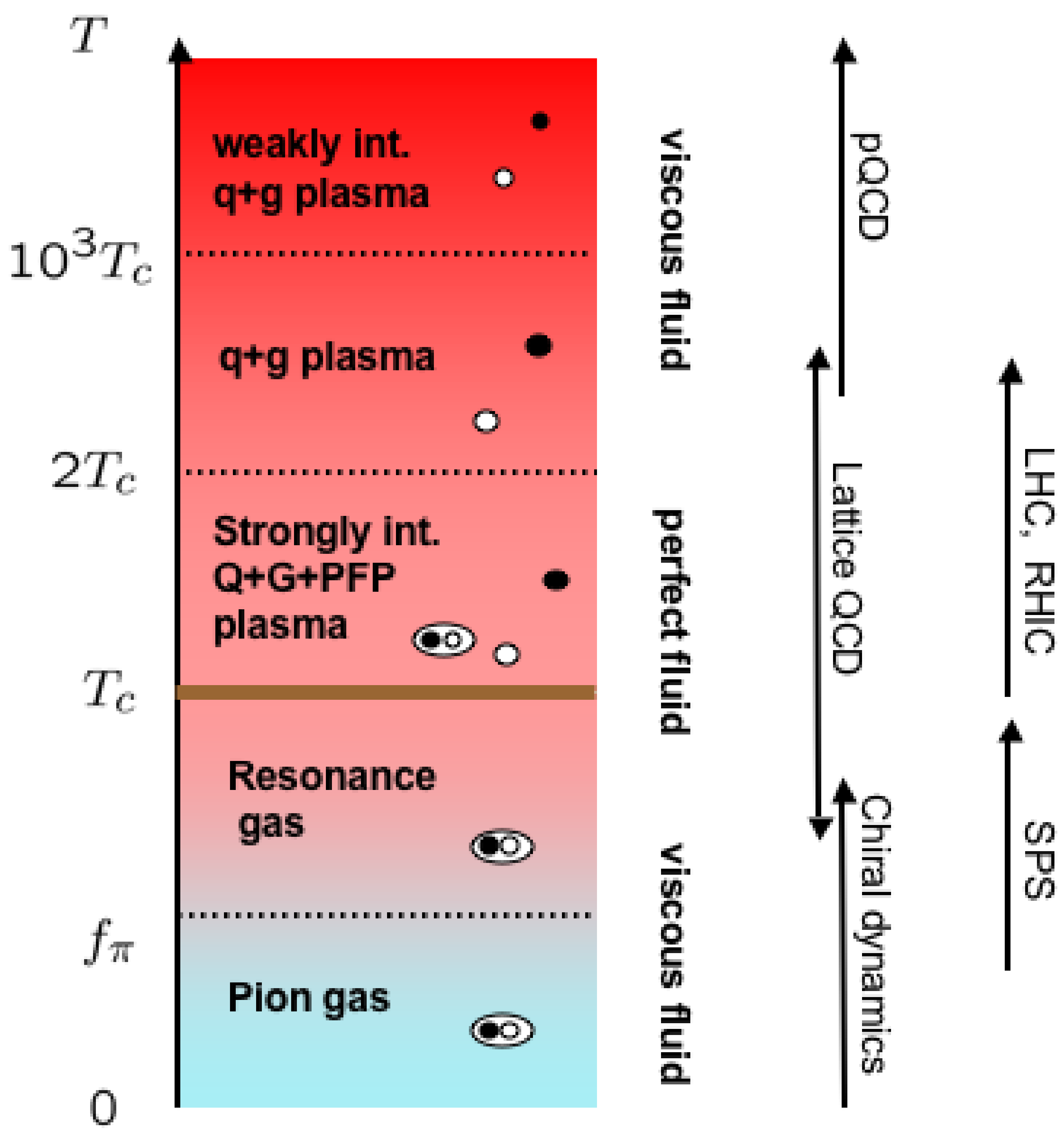


Different quarkonia states melt at different temperatures
[some bound states survive transition]

Sequential suppression

Υ	>2.63Tc
χ_{b1}	1.19 — 1.44 Tc
J/Ψ	1.29 — 1.35 Tc
χ_{c1}	1.19 Tc

A possible picture of hot QCD



[Taken from Hatsuda, J/Ψ workshop BNL, May 2006]

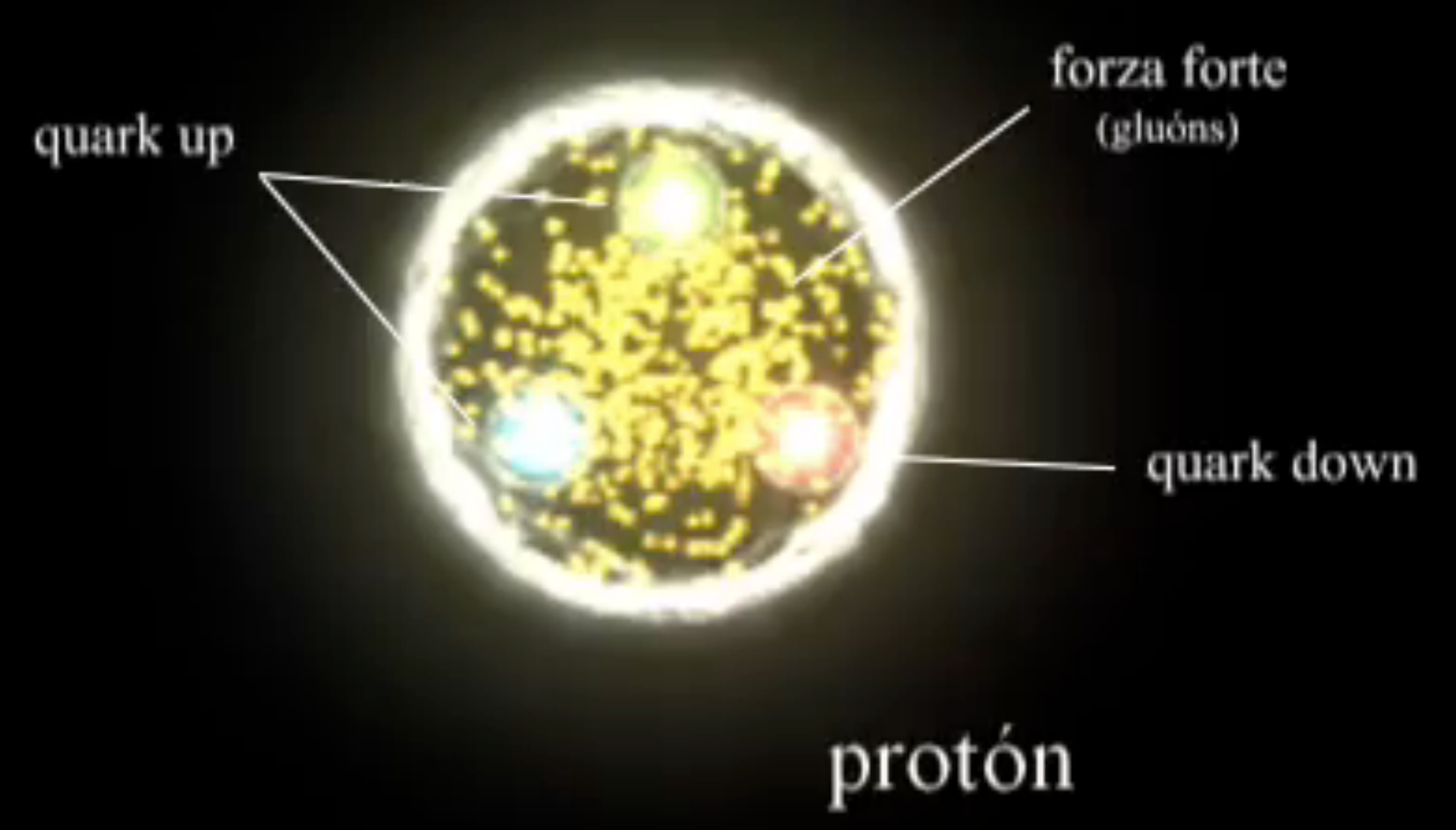
Experimenta tool

Heavy-ion collisions main goal

Study QCD under extreme conditions

↳ High density

↳ High temperature



High-densities/temperatures

- In the early Universe
- Core of neutron stars
- Heavy-ion collisions

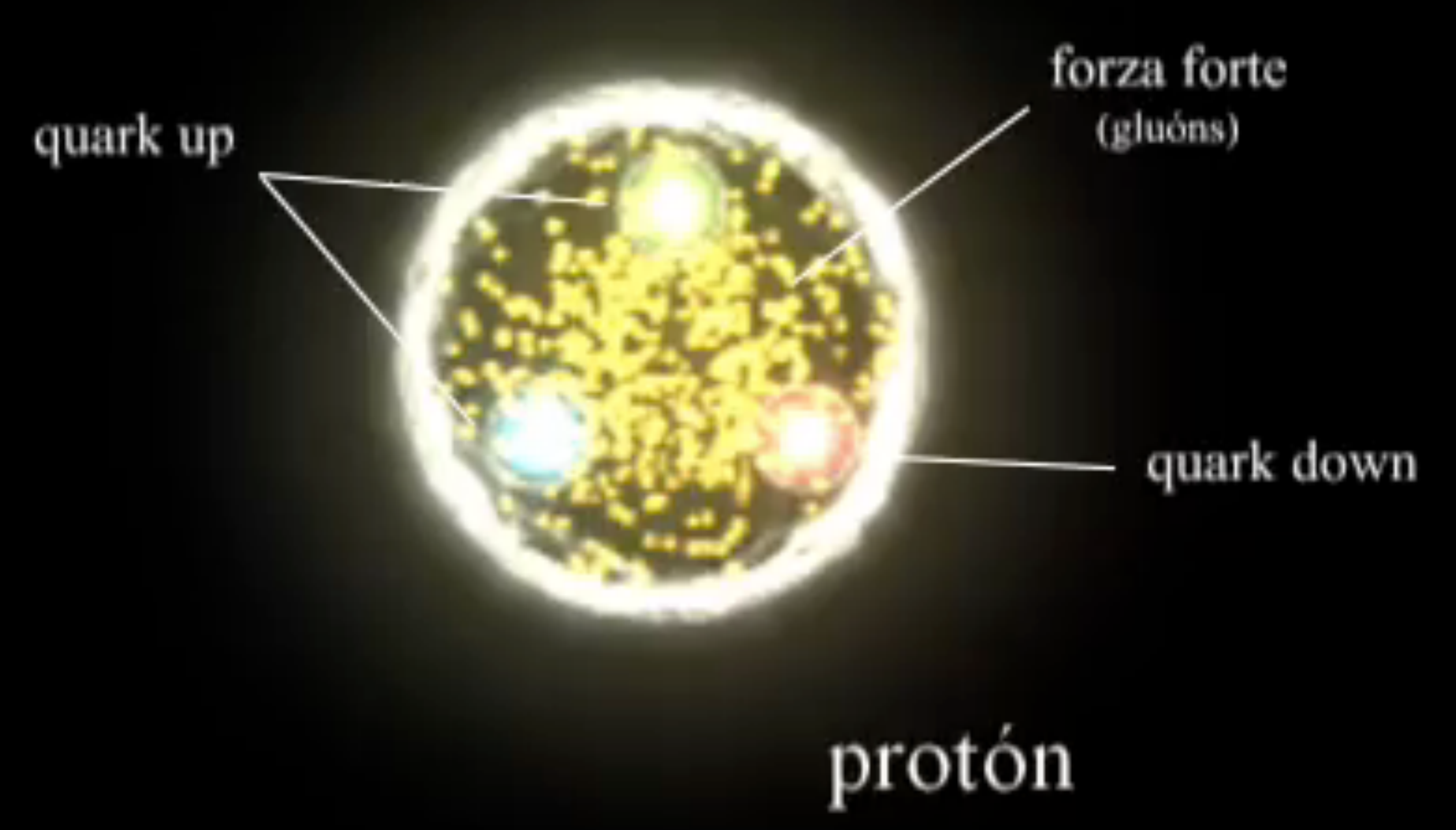
Experimenta tool

Heavy-ion collisions main goal

Study QCD under extreme conditions

↳ High density

↳ High temperature



High-densities/temperatures

- ☐ In the early Universe
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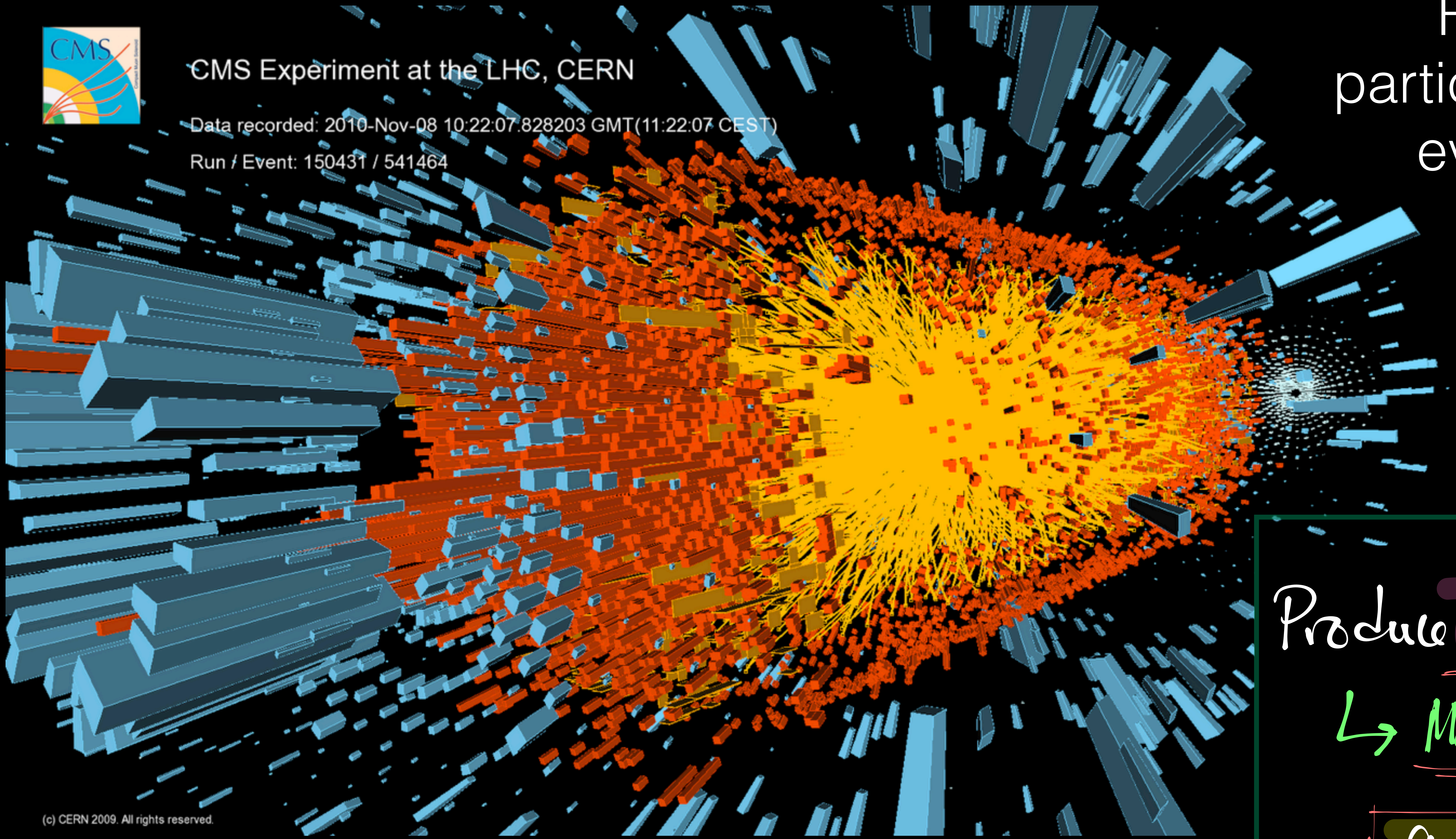
- ☐ Heavy-ion collisions



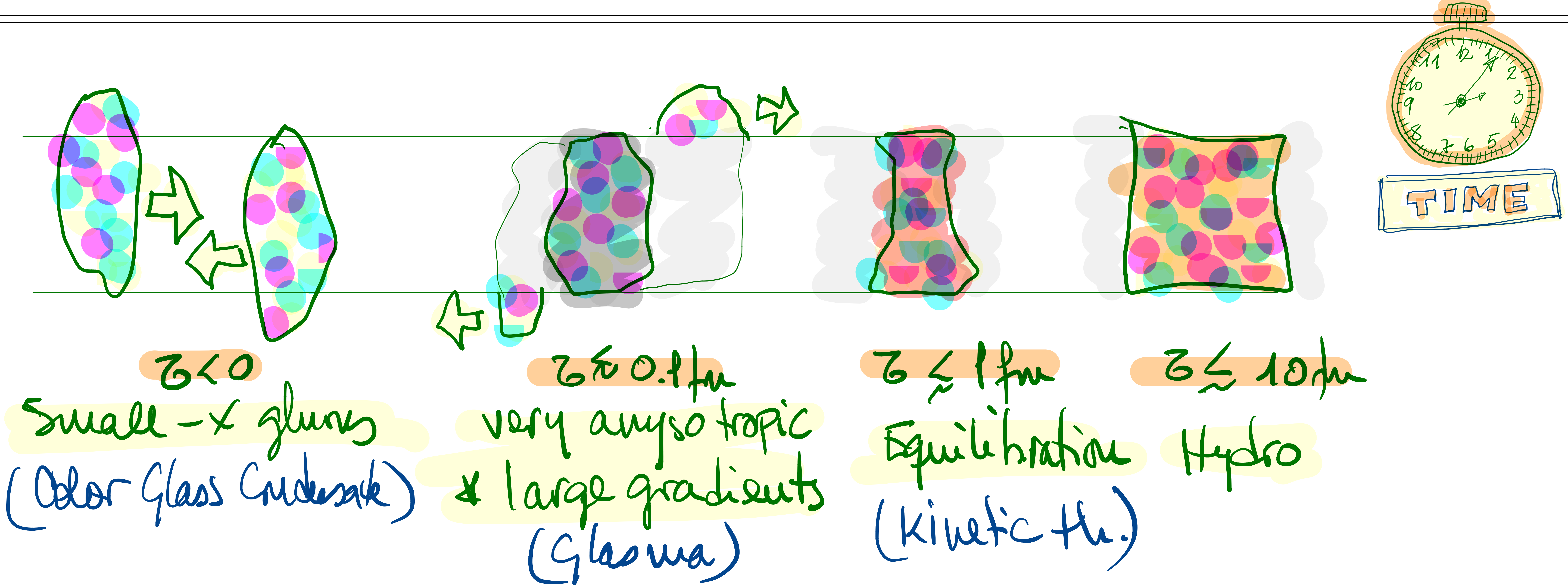
Huge number of particles in central PbPb events at the LHC

Produce "large" objects

↳ Macroscopic in QCD scale

Collide heavy nuclei

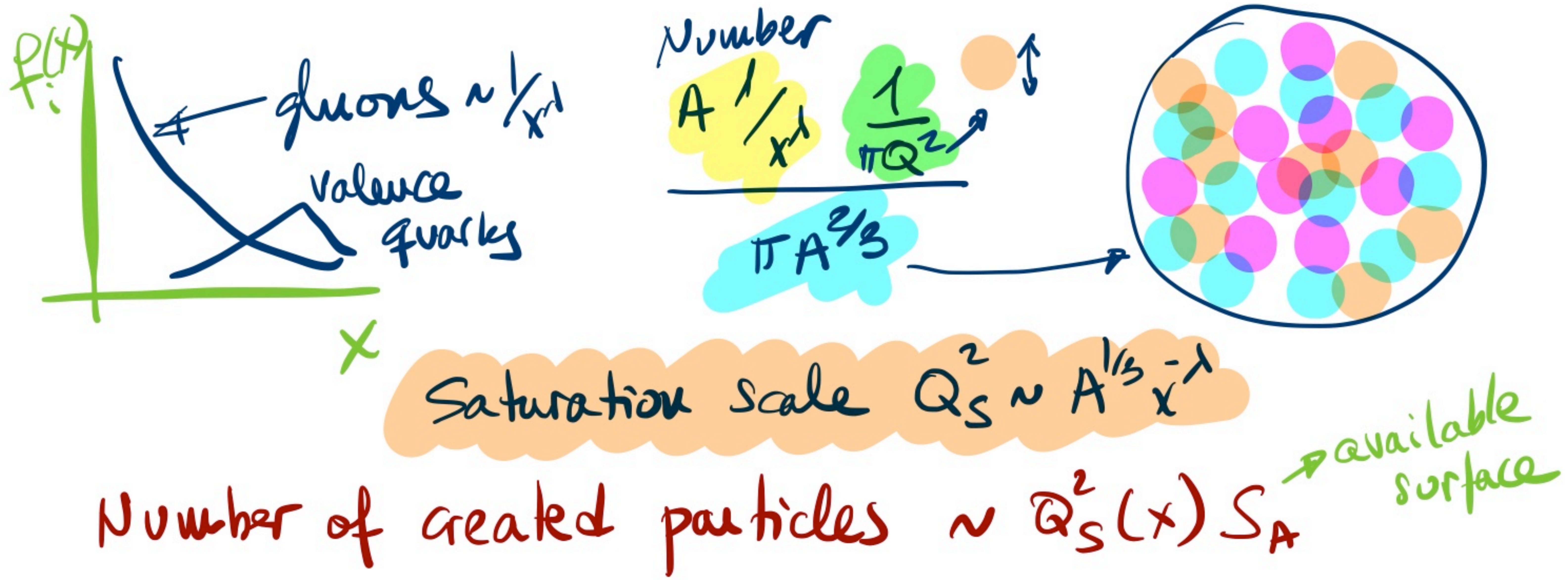
(A possible) Time evolution of a HIC

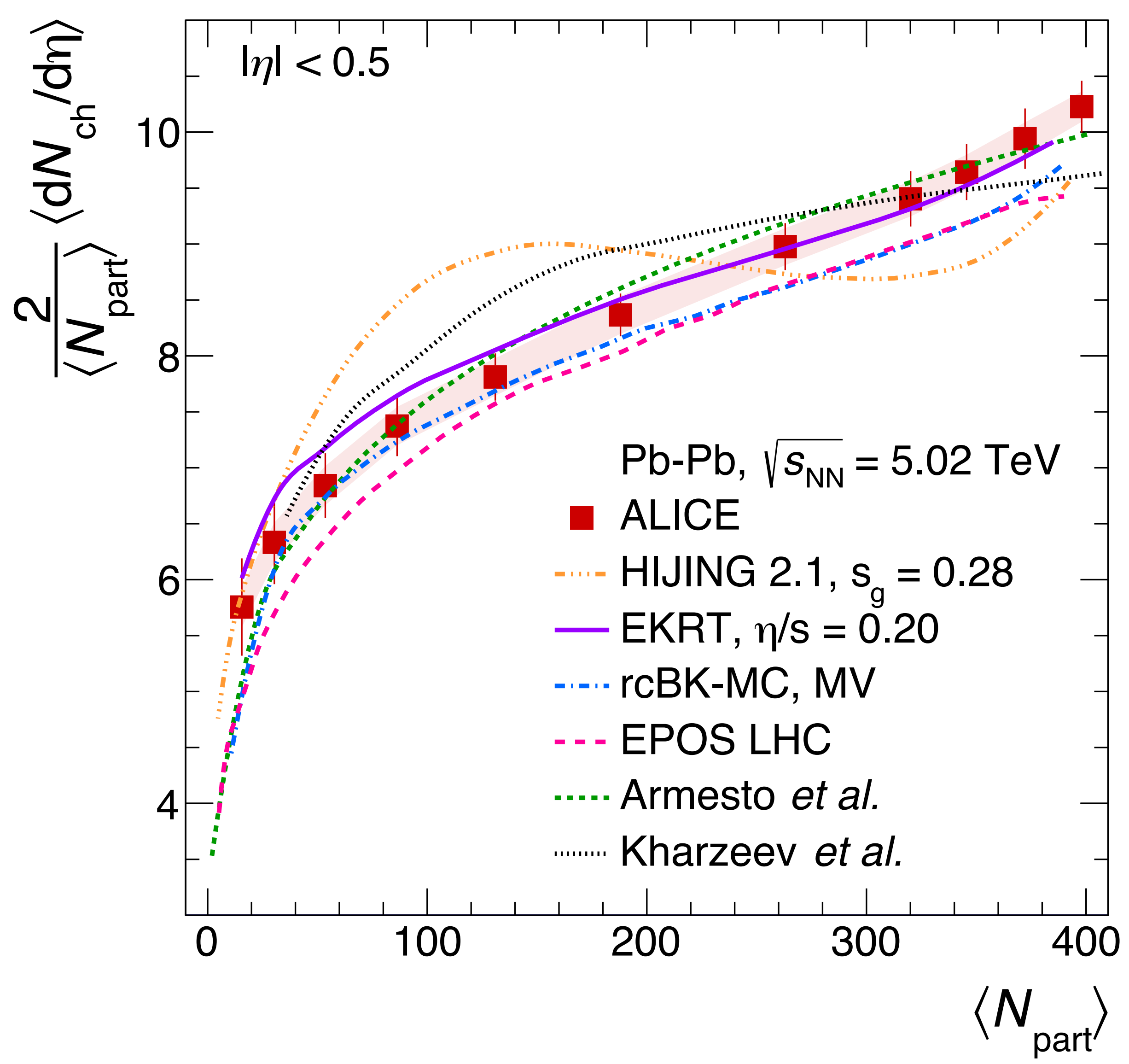


In contrast to usual HEP, **time and distance are relevant variables** in heavy-ion collisions

Building collectivity in extended (macroscopic) systems

Saturation - Color Glass Condensate



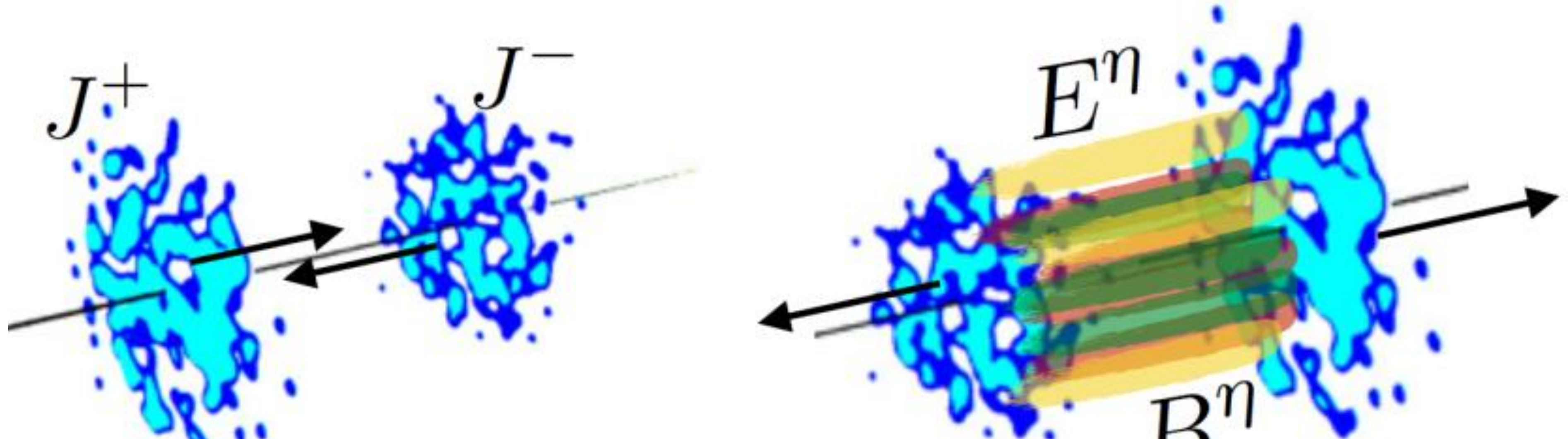


Color Glass Condensate

Large occupation numbers - classical fields

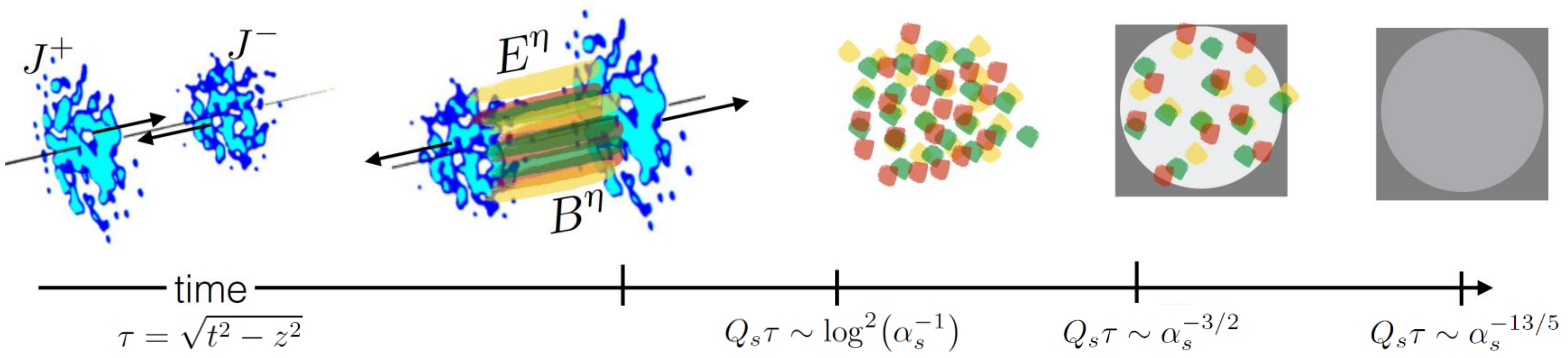
Quantum Corrections - evolution eqs.

Color Glass Condensate provides a general framework to compute initial stages



$$D_\mu F^{\mu\nu} = J^\nu$$

A picture for equilibration



Sören Schlichting

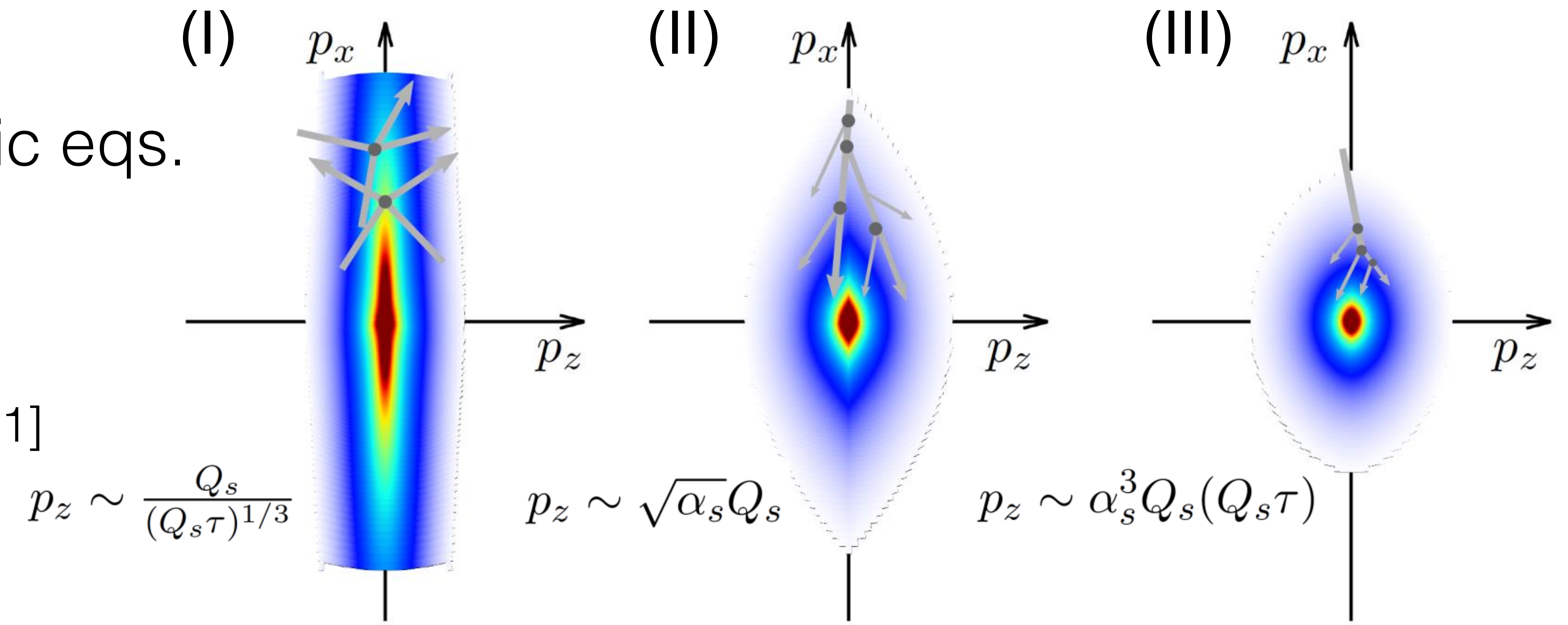
[Classical statistical/lattice gauge theory…]

Evolution of boost-invariant system with kinetic eqs.

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{2\leftrightarrow 2}[f] + C_{1\leftrightarrow 2}[f]$$

[Bottom-up thermalization — Baier, Mueller, Schiff, Son 2001]

[Arnold, Moore, Yaffe 2001; Kurkela, Zhu 2015; Keegan, Kurkela, Mazeliauskas, Teaney 2016; Kurkela Mazeliauskas, Paquet, Schlichting, Teaney 2019…]



Hydrodynamics $\partial_\mu T^{\mu\nu} = 0$

$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}$ + viscosity corrections

(+ Equation of State)

+ initial time
+ freeze-out temperature

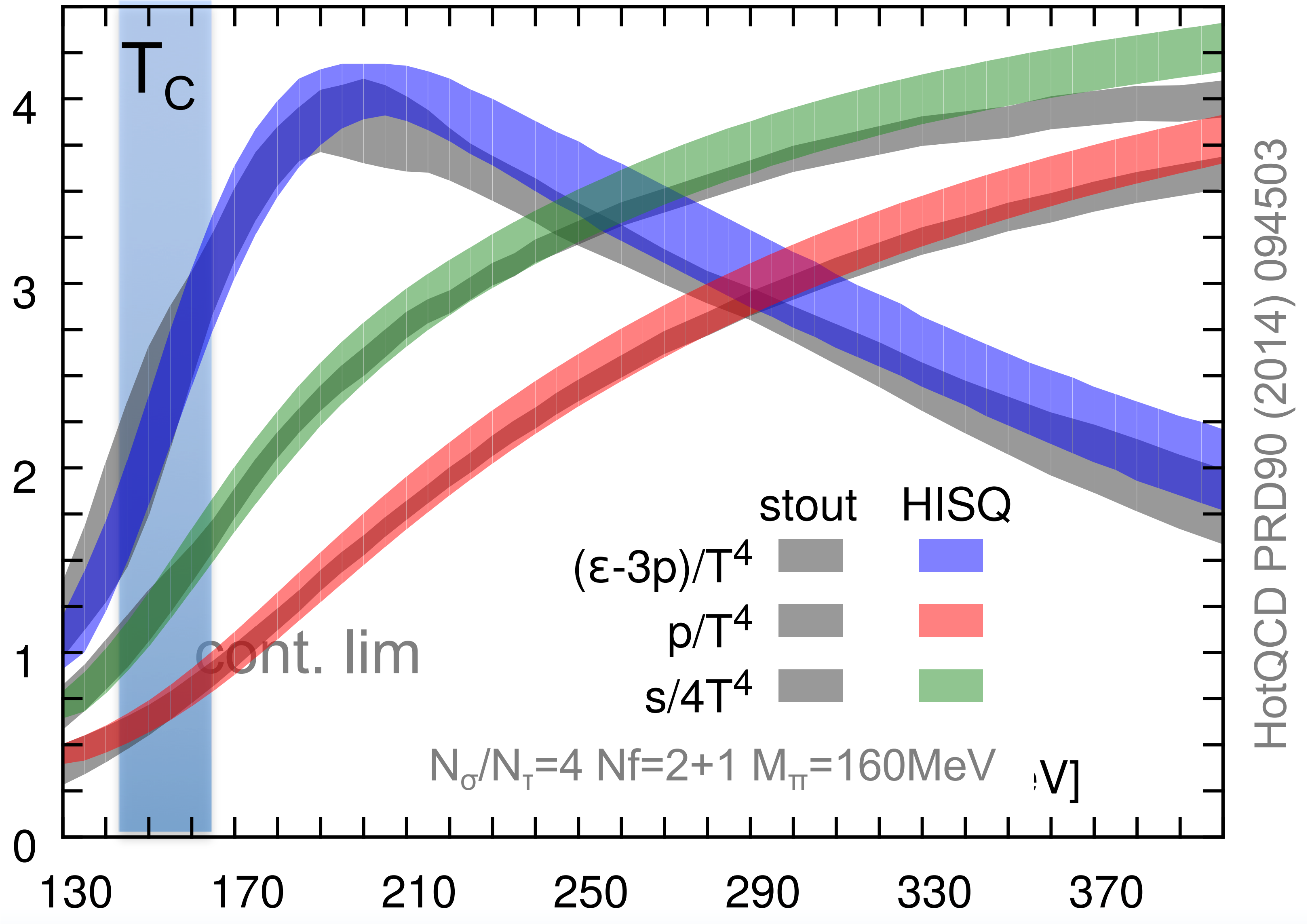
Far from equilibrium initial state needs to equilibrate fast (~1 fm or less)

Most of the theoretical progress in the last years:

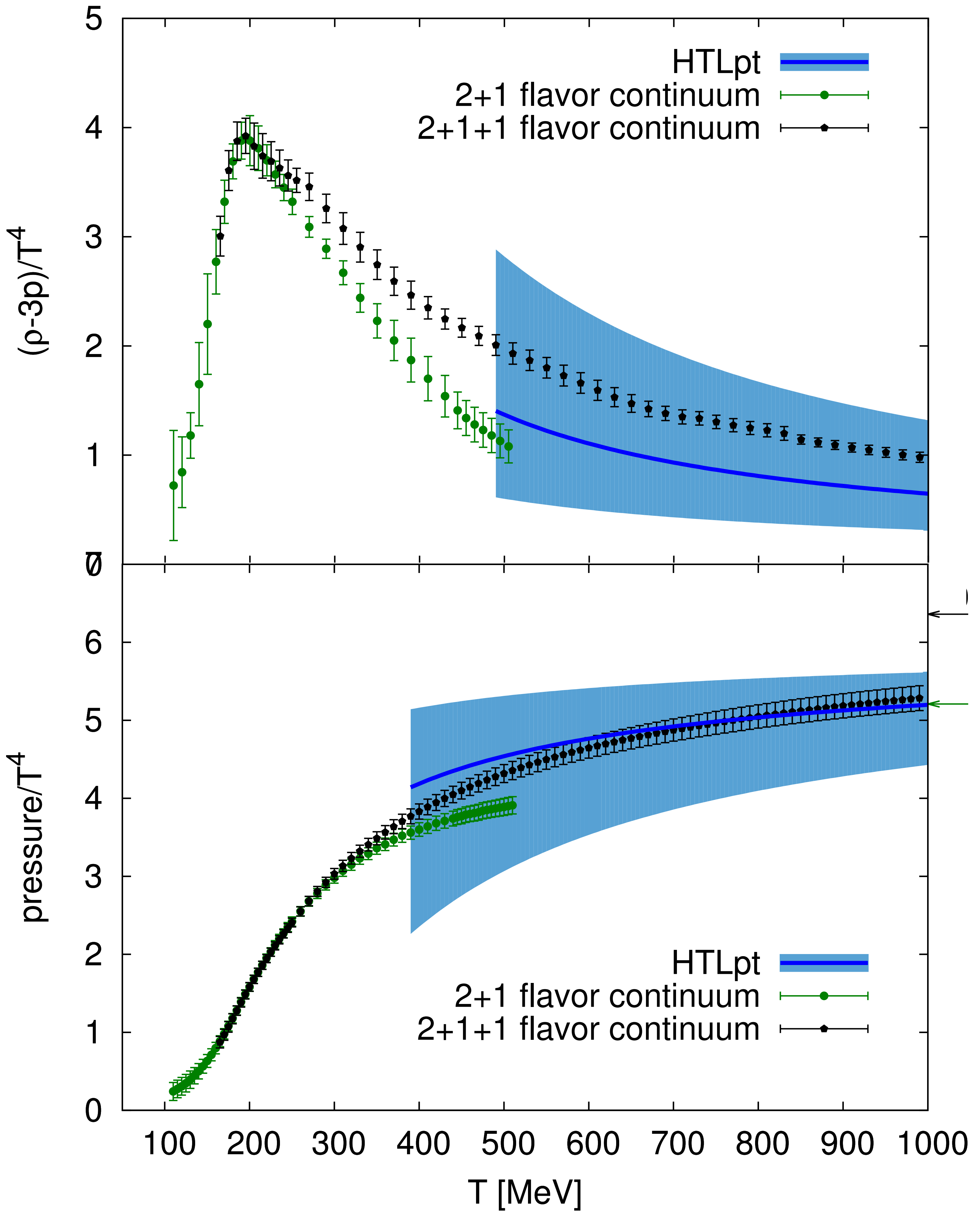
- Viscosity corrections and consistency
- Fluctuations in initial conditions
- Emergence of hydro from kinetic eqs, holography, etc…

EoS — high temperature

Equation of state at μ_B=0 is rather well known by lattice at moderate temperature — reasonably good matching with perturbative at $T \lesssim 1 GeV$



[Included in hydro simulations]



[Borsanyi et al Nature 539 (2016) no.7627, 69-71]

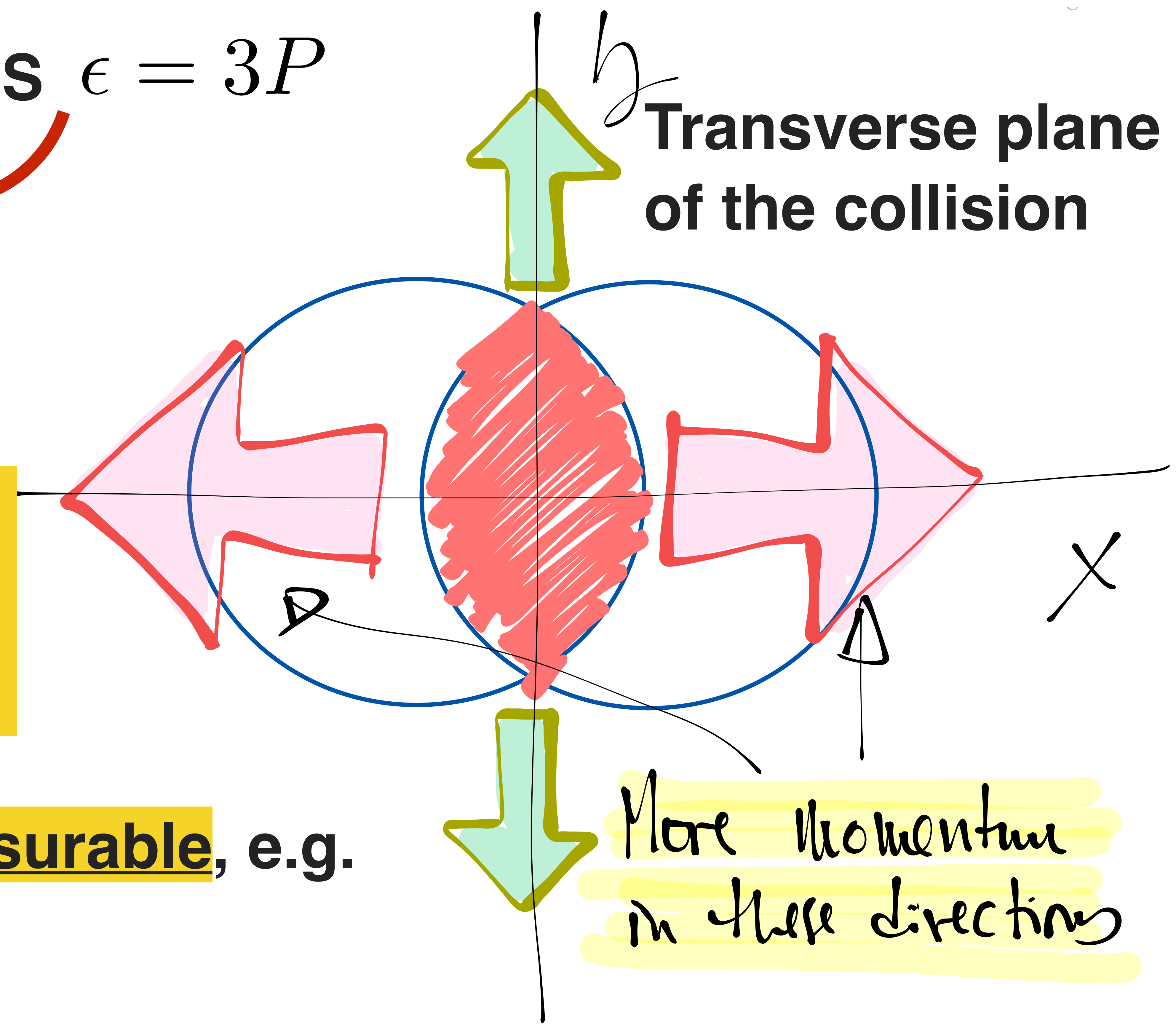
Harmonics: the golden measurement

[simplified discussion]

Remember the Euler eqs. — and use conformal EoS $\epsilon = 3P$

$$\frac{\partial \beta}{dt} = -\frac{c^2}{\epsilon + P}\nabla P \propto -\nabla \epsilon$$

Initial state <u>spatial</u> anisotropies → **Final state <u>momentum</u> anisotropies**



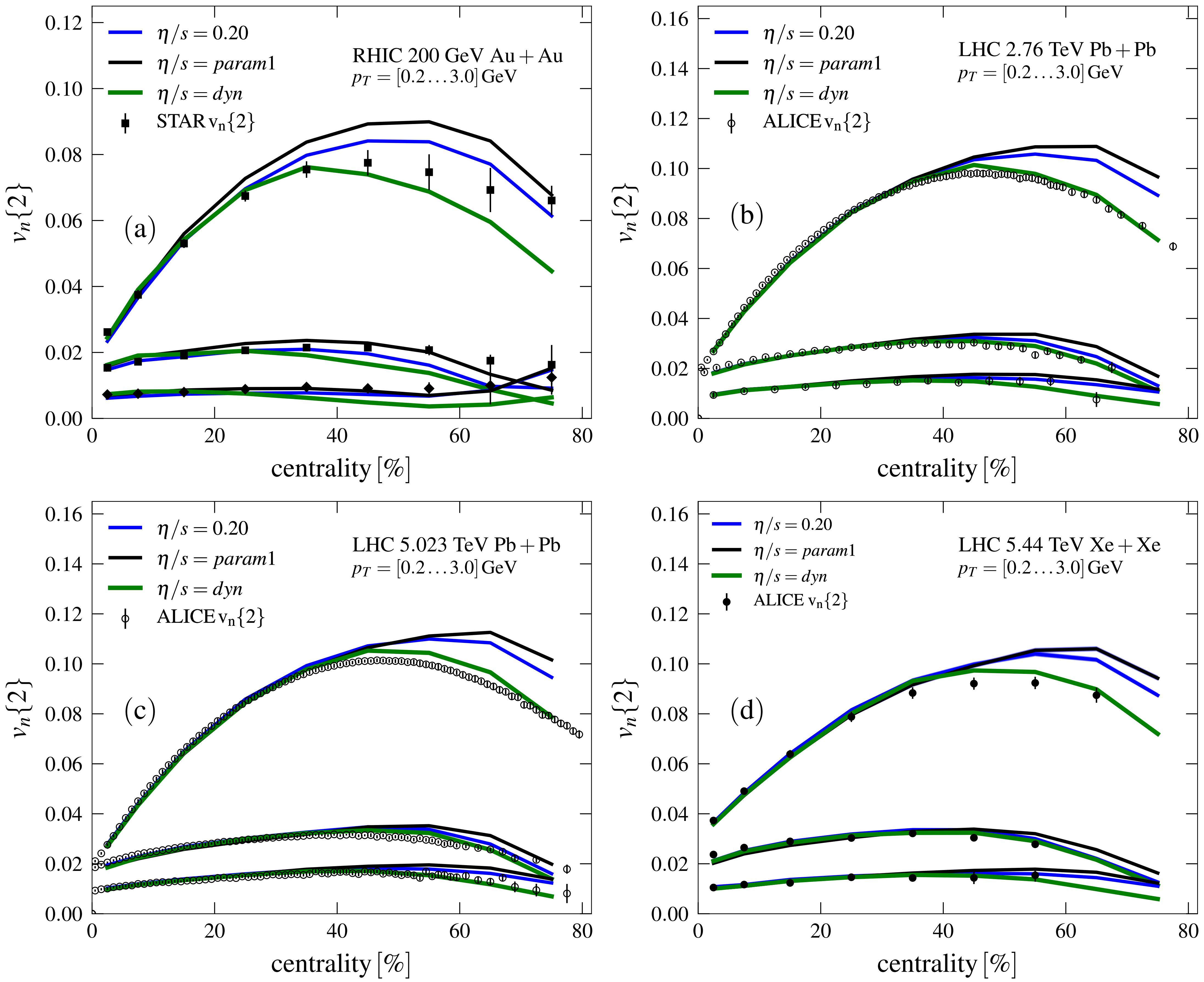
These final state momentum anisotropies are <u>measurable</u>, e.g.

$$\frac{dN}{d\phi} \propto 1 + 2 v_2 \cos 2\phi$$

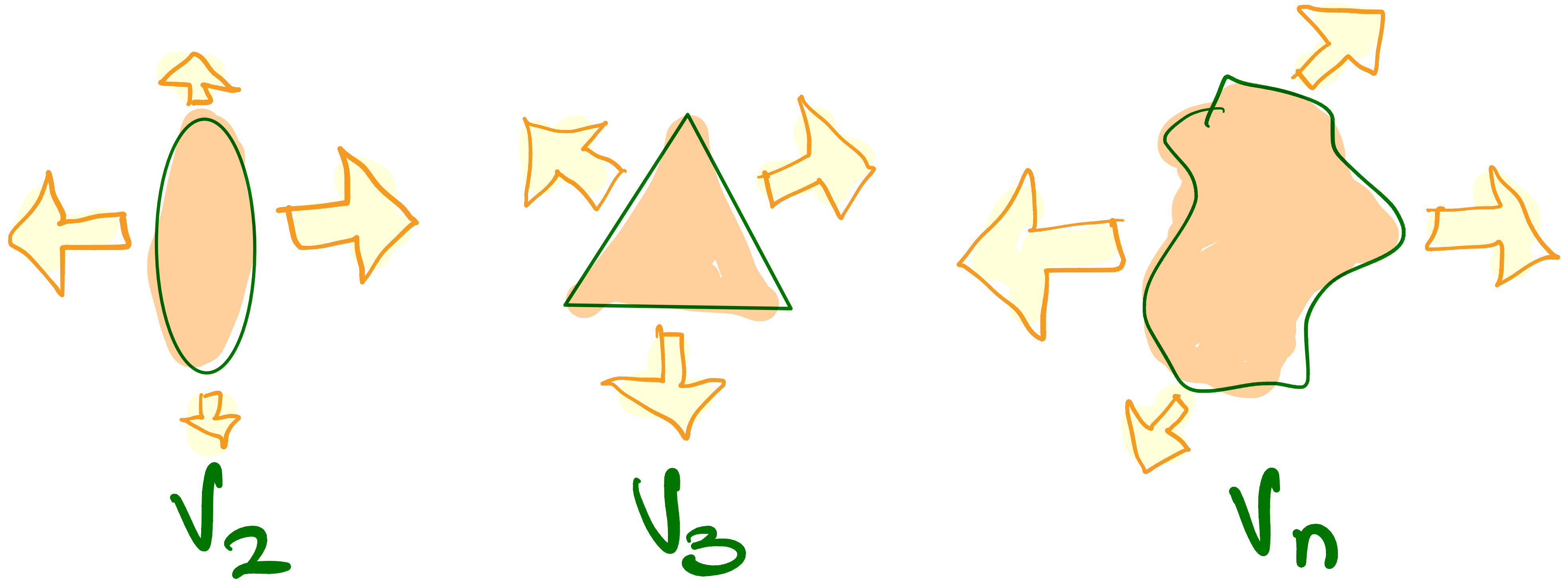
↳ Elliptic Flow

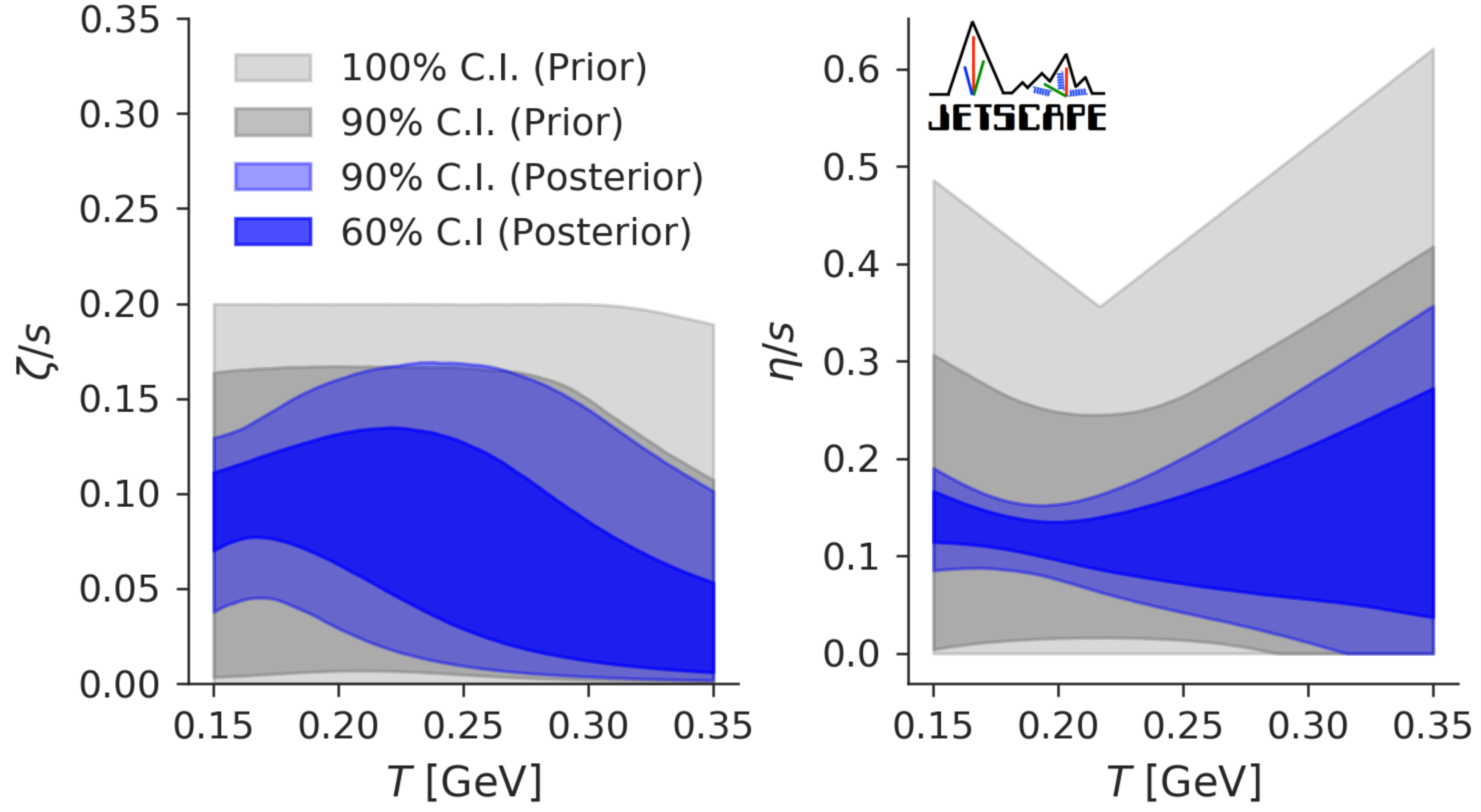
Description of data and viscosity

[Hirvonen, Eskola, Niemi 2022]



Fluctuation in I.C. generate higher harmonics



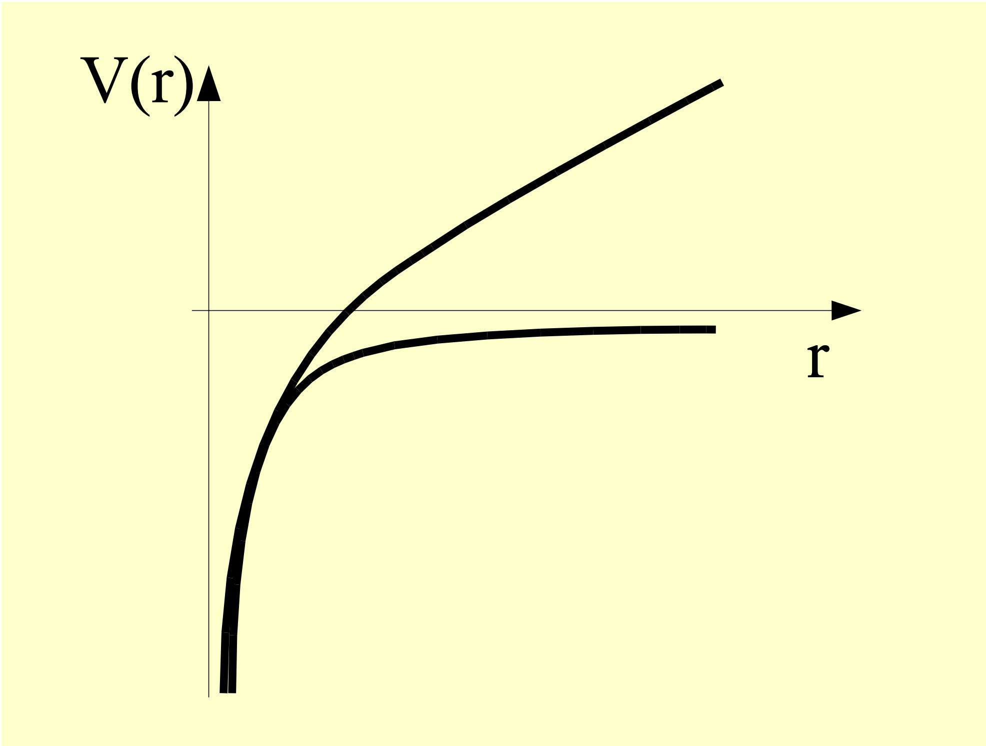


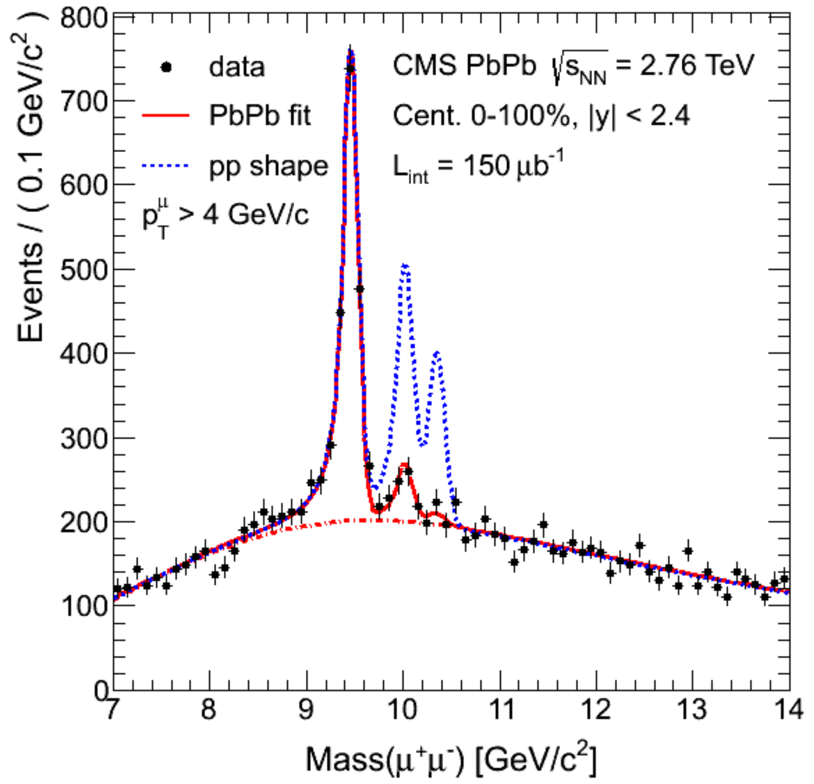
[Everett et al. 2021]

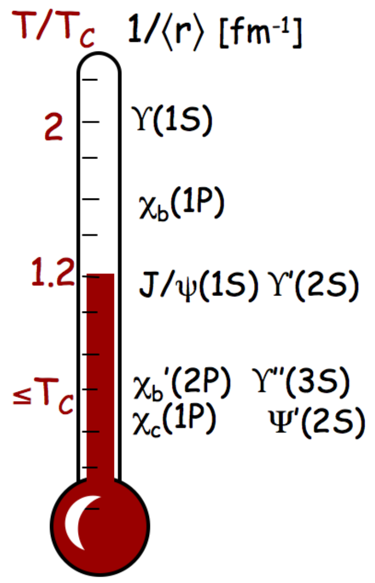
Quarkonia suppression

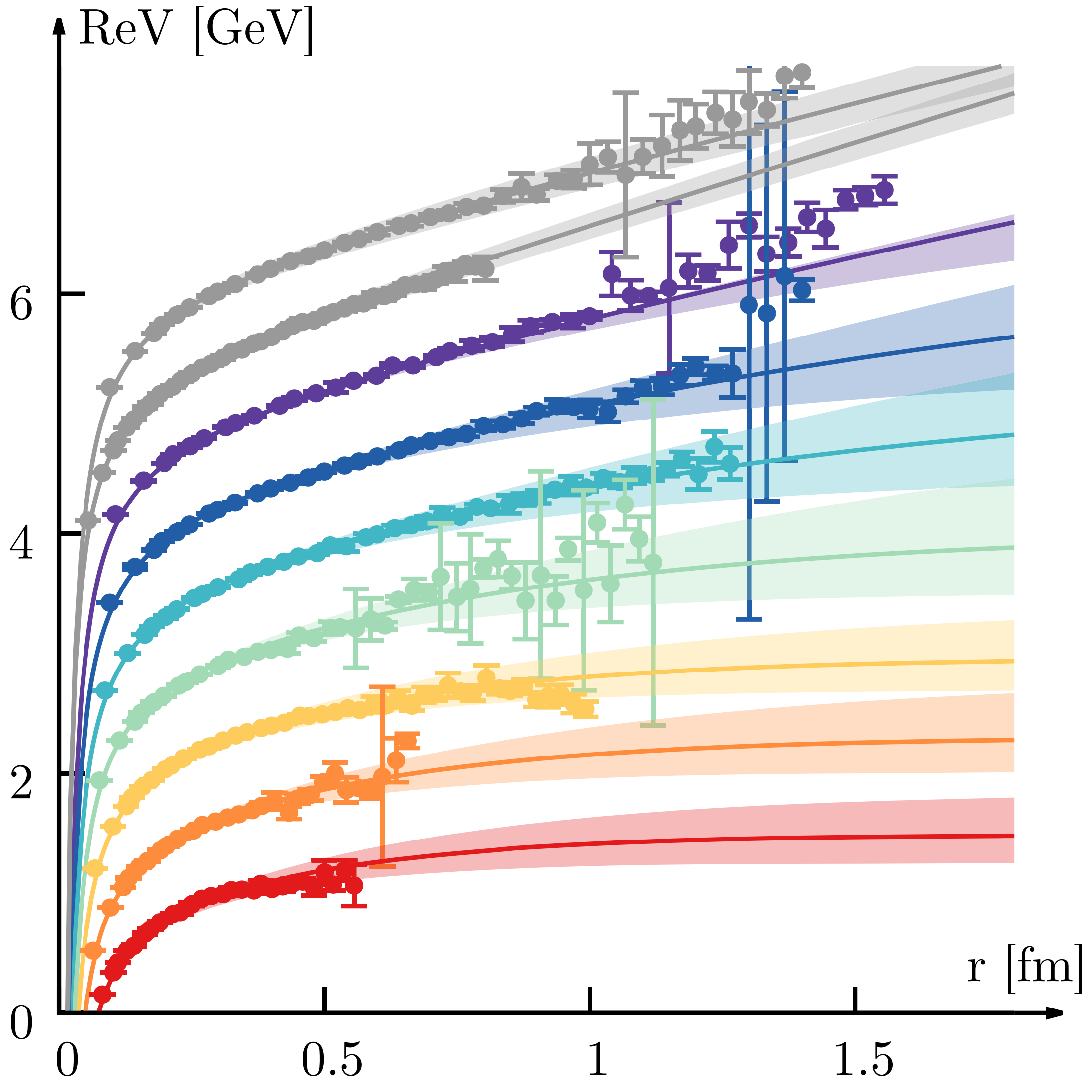
Simple intuitive picture [Matsui & Satz 1986]

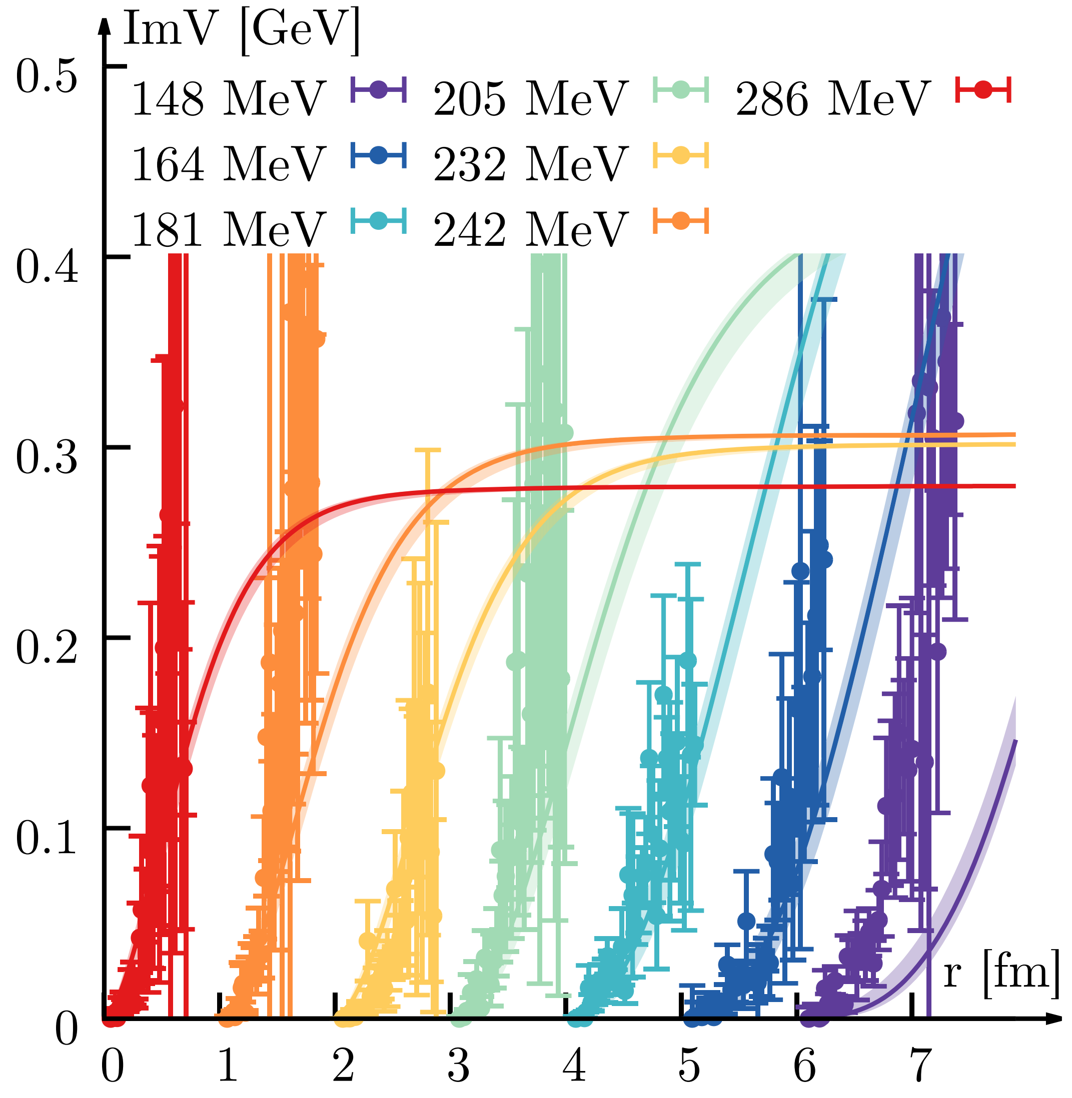
- Potential screened at high-T
- Quarkonia suppressed
- Sequential suppression of excited states
- **Quarkonia as a thermometer**











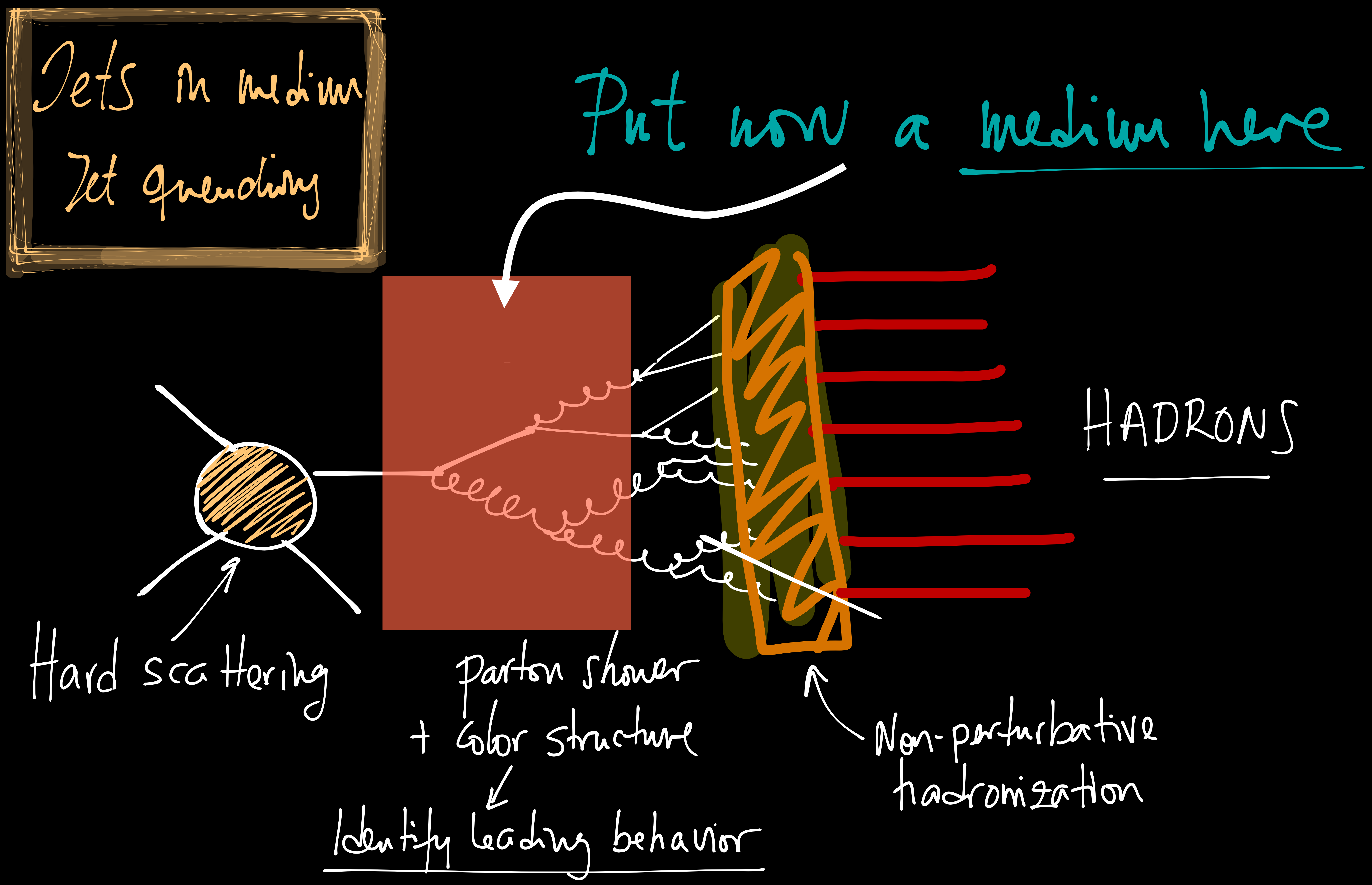
[Lafferty, Rothkopf 2020]

Dynamical picture:

- different effects:
  - screening / rescattering / recombination
- Induced transition between quarkonia states

Quarkonia as an open quantum system

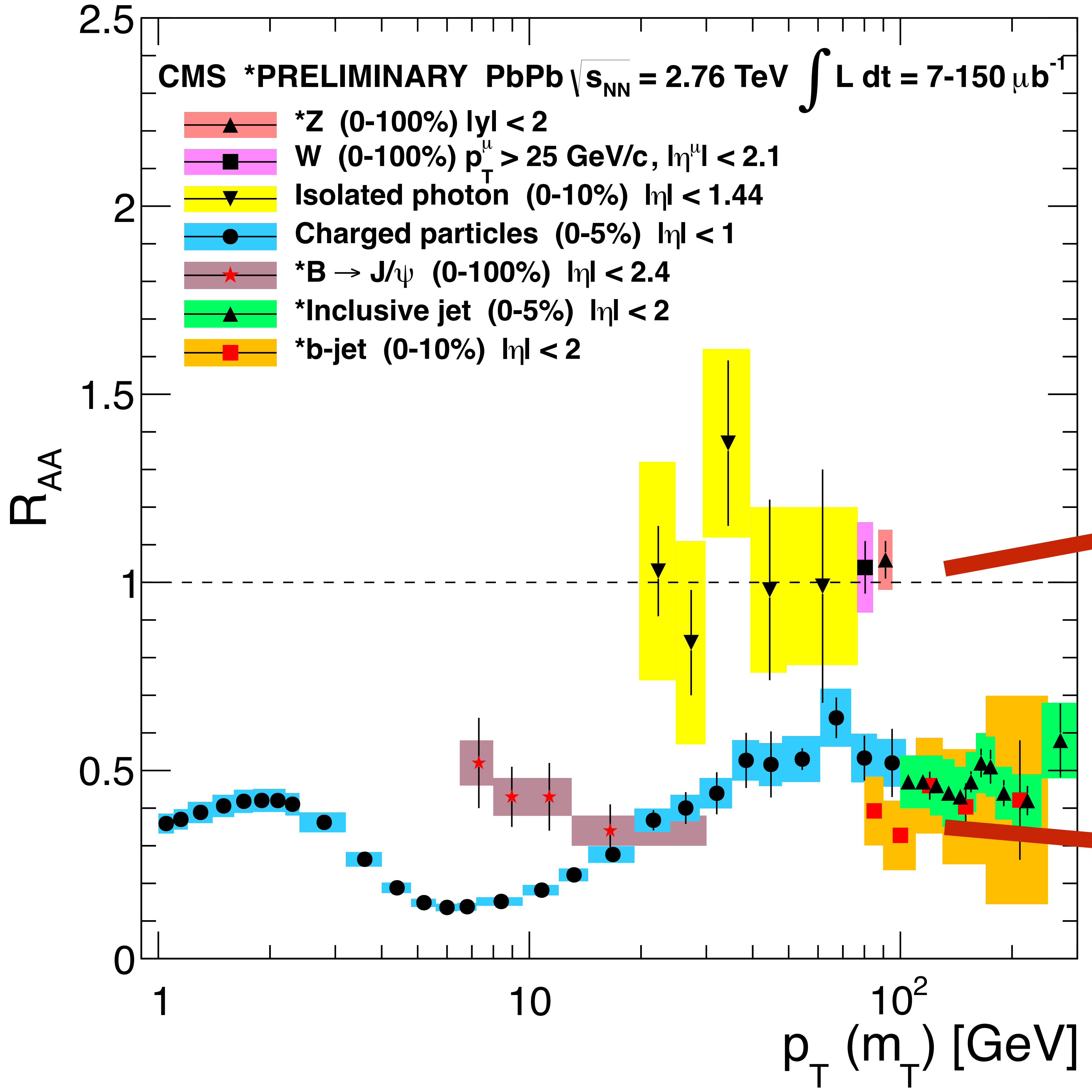
[Bambrilla, Soto, Escobedo, Vairo, Ghiglieri, Petreczky, Strickland, Blaizot, Rothkopf, Kaczmarek, Asakawa, Katz, Gossiaux, Kajimoto, Akamatsu, Borghini …]



Jets are extended objects - ideal to study space-time evolution

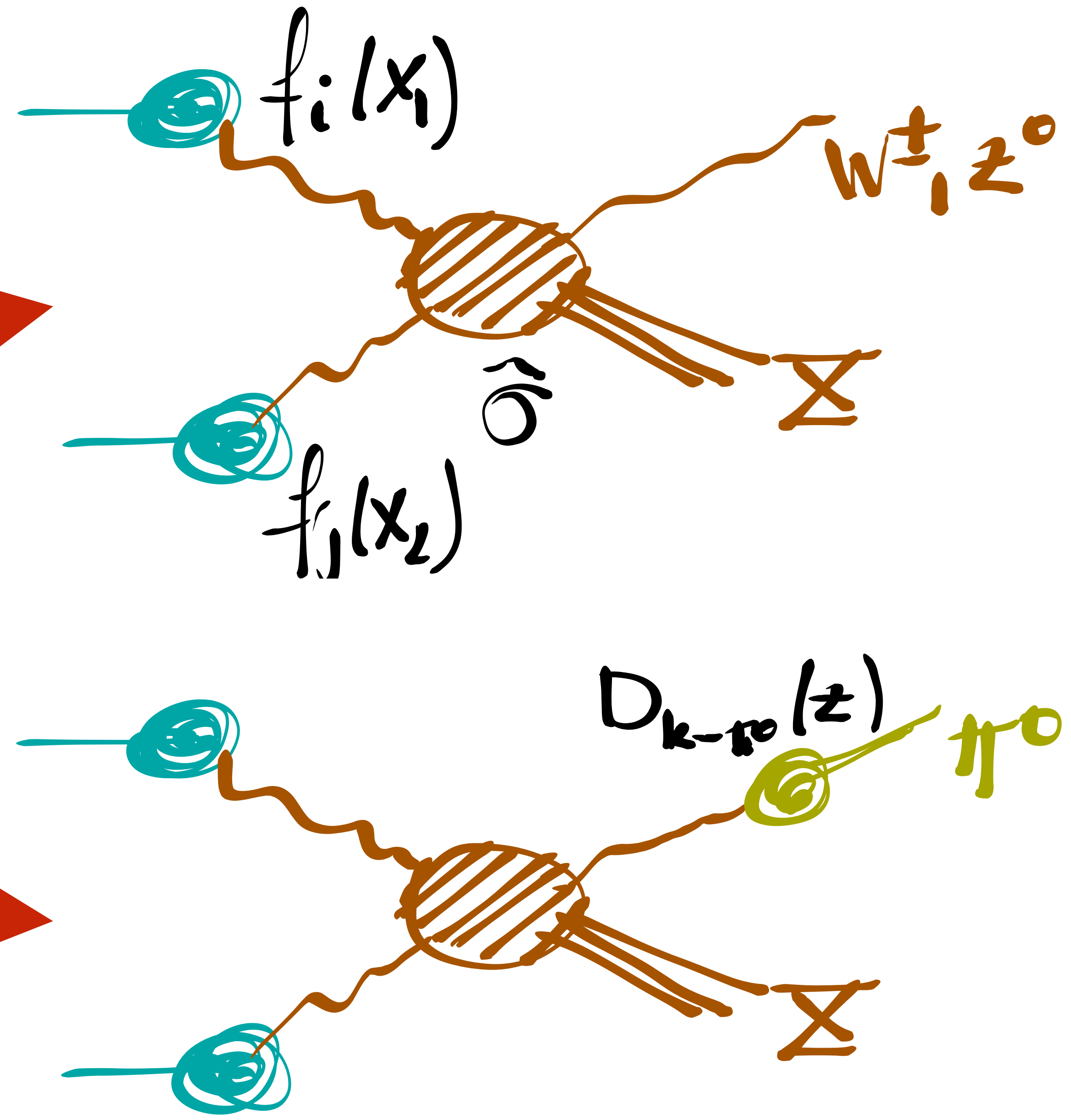
Jet quenching

Particles with color are suppressed by interaction with the medium



[A. Florent - Hard Probes 2013]

$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$



Conclusions - lecture 2

QCD has a **rich dynamical content**

- Confinement and chiral symmetry breaking in vacuum
- New phases of matter at high energies/densities
- Quark gluon plasma universal form of matter at high enough energies

Heavy ion collisions are the experimental tools

However, QGP is only one of the manifestations of a **wider and richer accessible physics**

QCD is the only sector in the Standard Model where studies of collectivity at the fundamental level are experimentally possible