QCD

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IGFAE - Santiago de Compostela

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Yocto/LHC
Yoctosecond imaging of QCD collectivity using jet observables
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IGFAE Instituto Galego de Física de Altas Enerxías
USC
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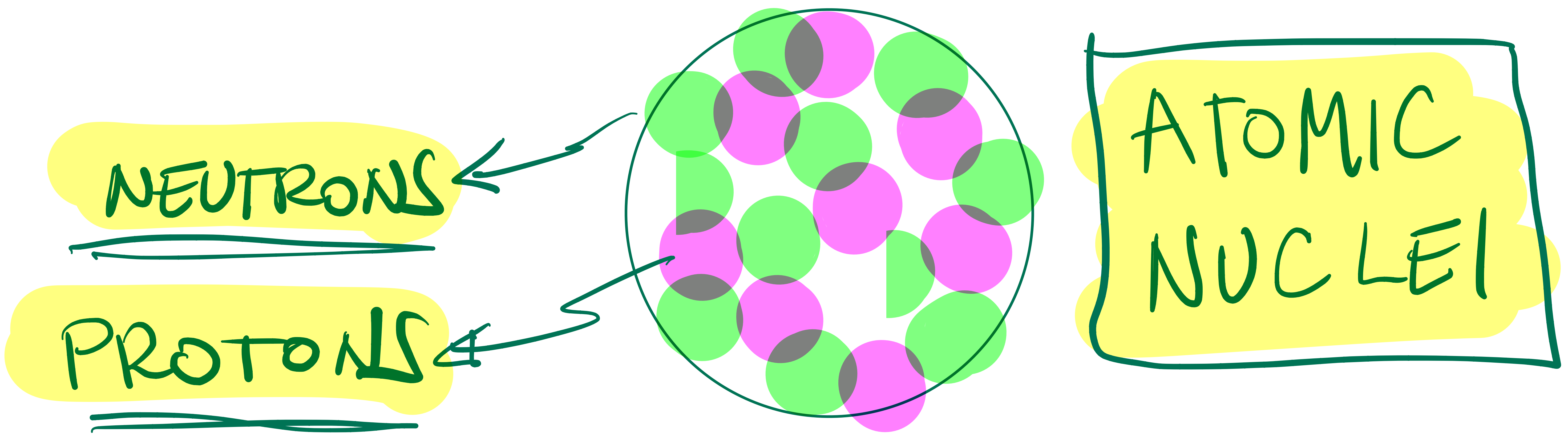
Quantum Chromo-Dynamics

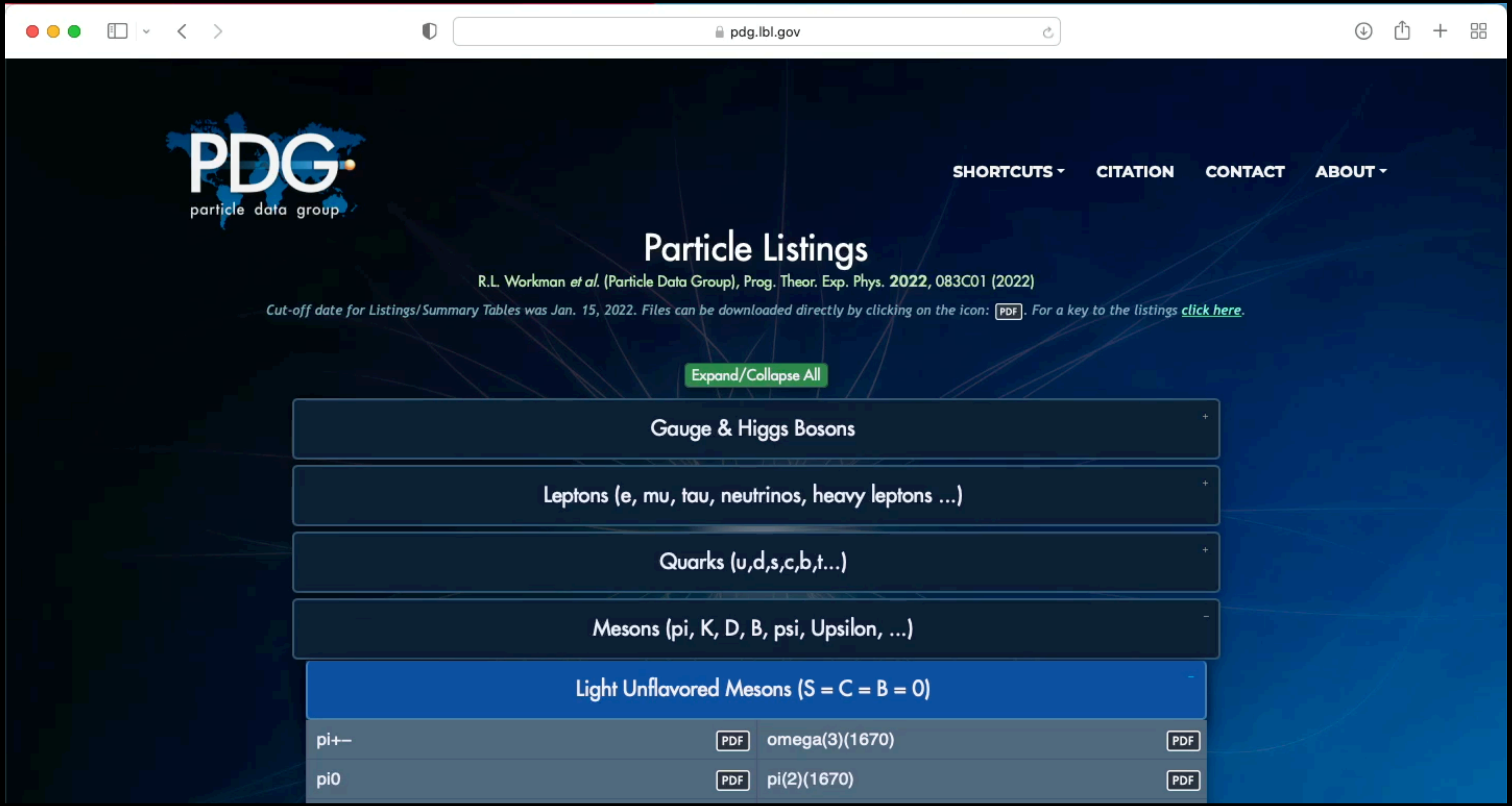
QCD is the theory that describes the **Strong interaction** that binds together **protons and neutrons in the atomic nuclei**



HADRONS = those particles that feel the strong interaction

$\parallel$

$\boxed{\text{PROTONS + NEUTRONS + COUSINS}}$



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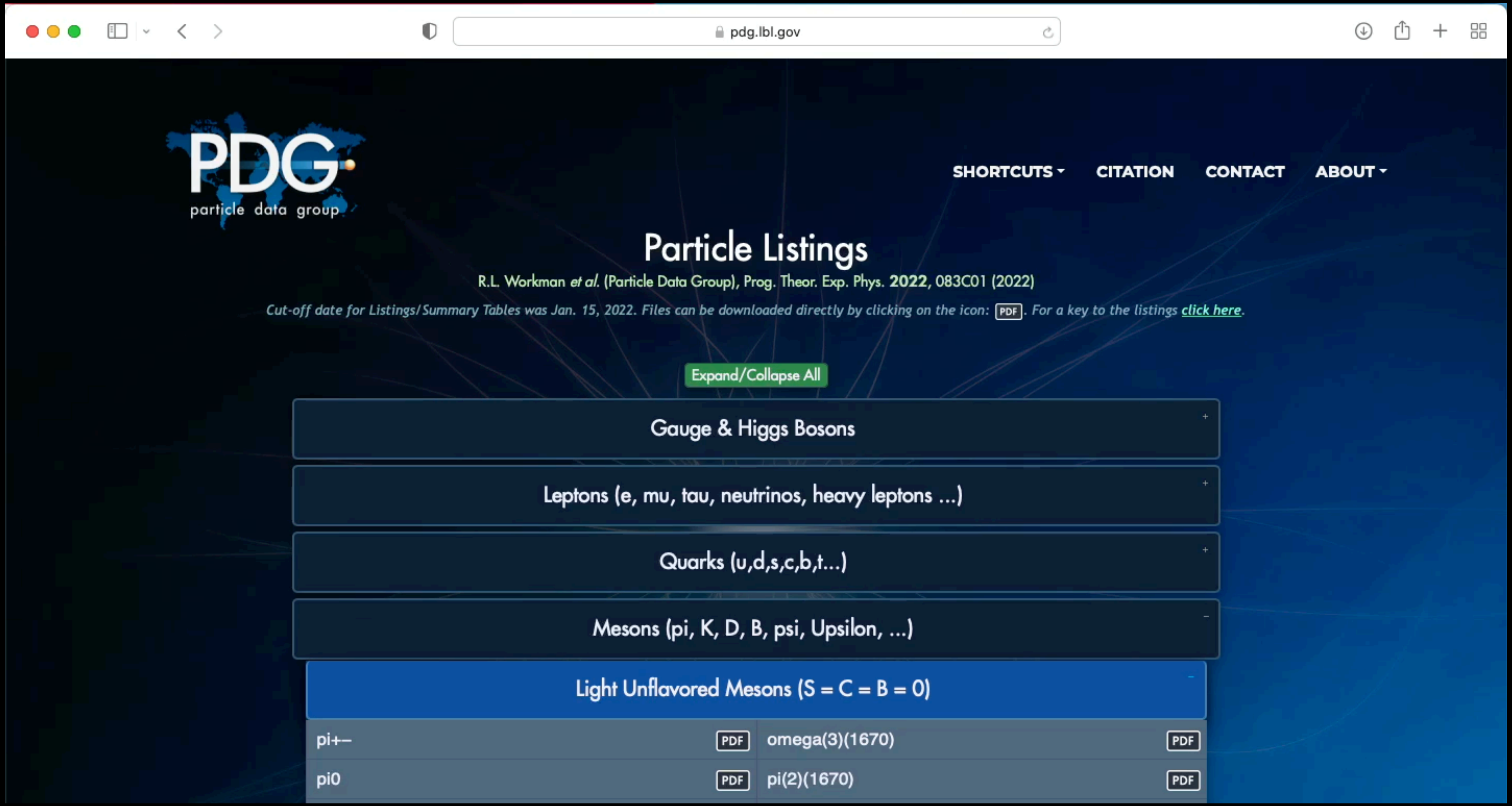

HADRONS = those particles that feel the strong interaction

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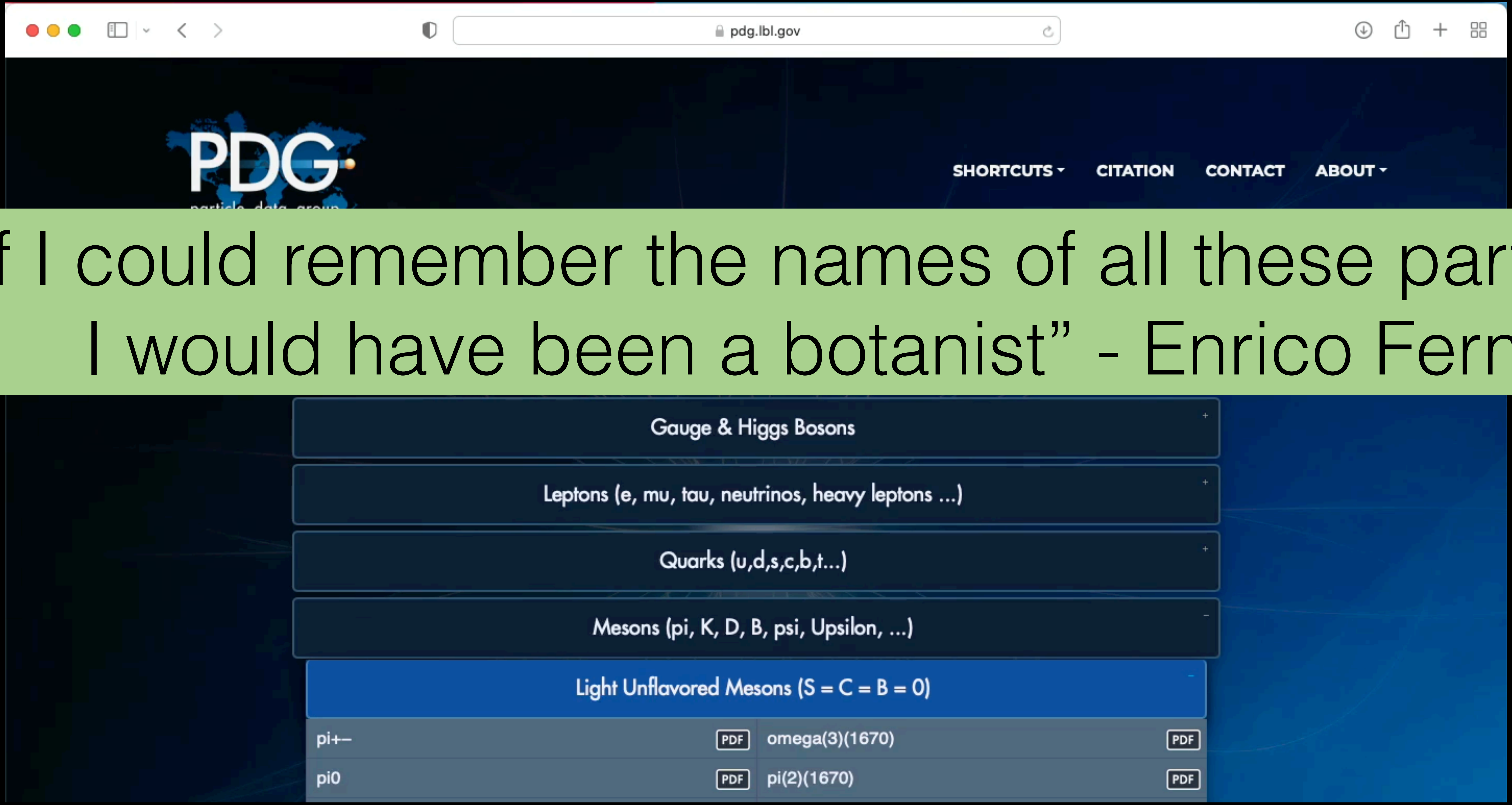
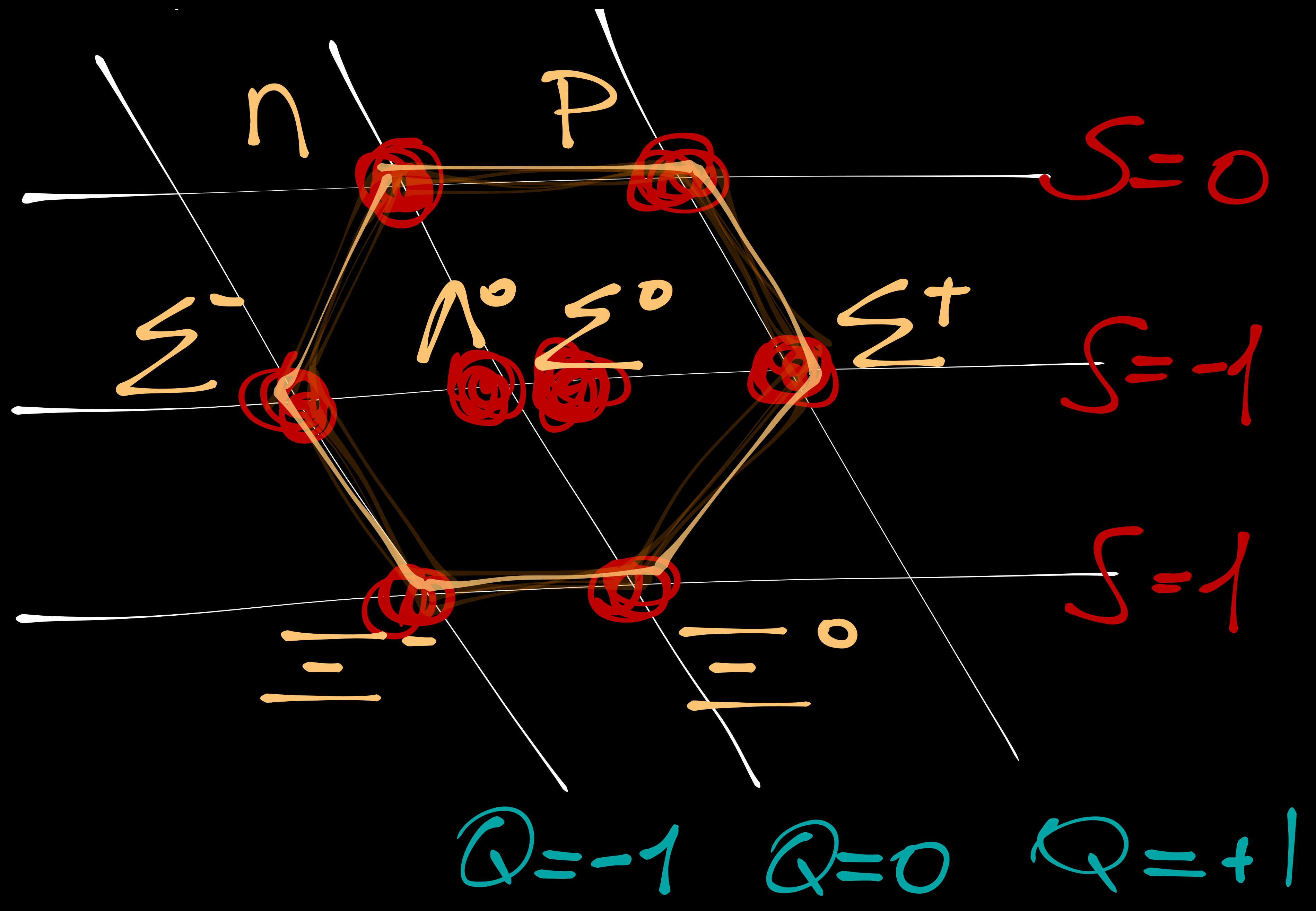
PROTONS + NEUTRONS + COUSINS → TOO MANY!



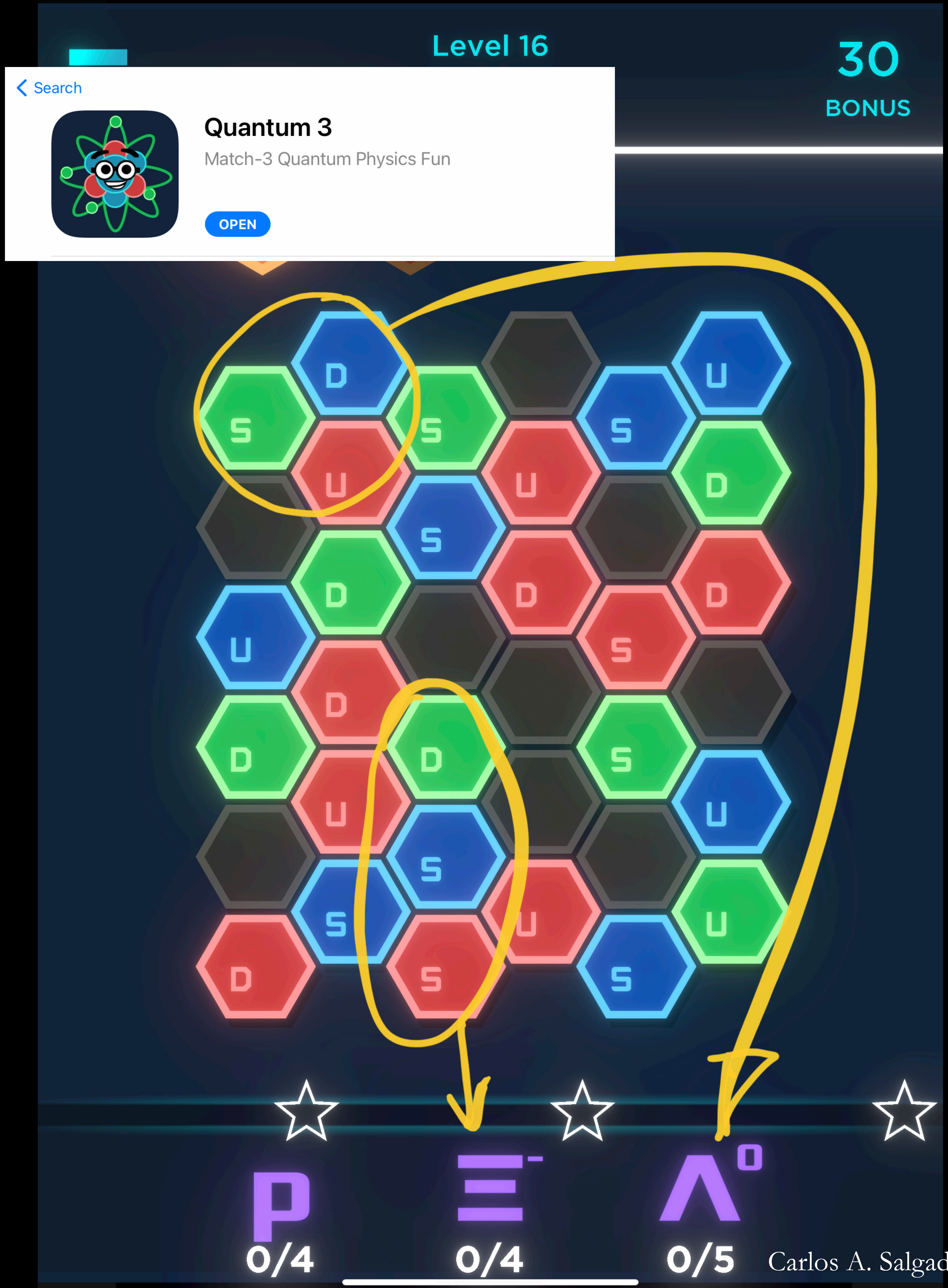
"If I could remember the names of all these particles, I would have been a botanist" - Enrico Fermi

“Periodic table” of hadrons

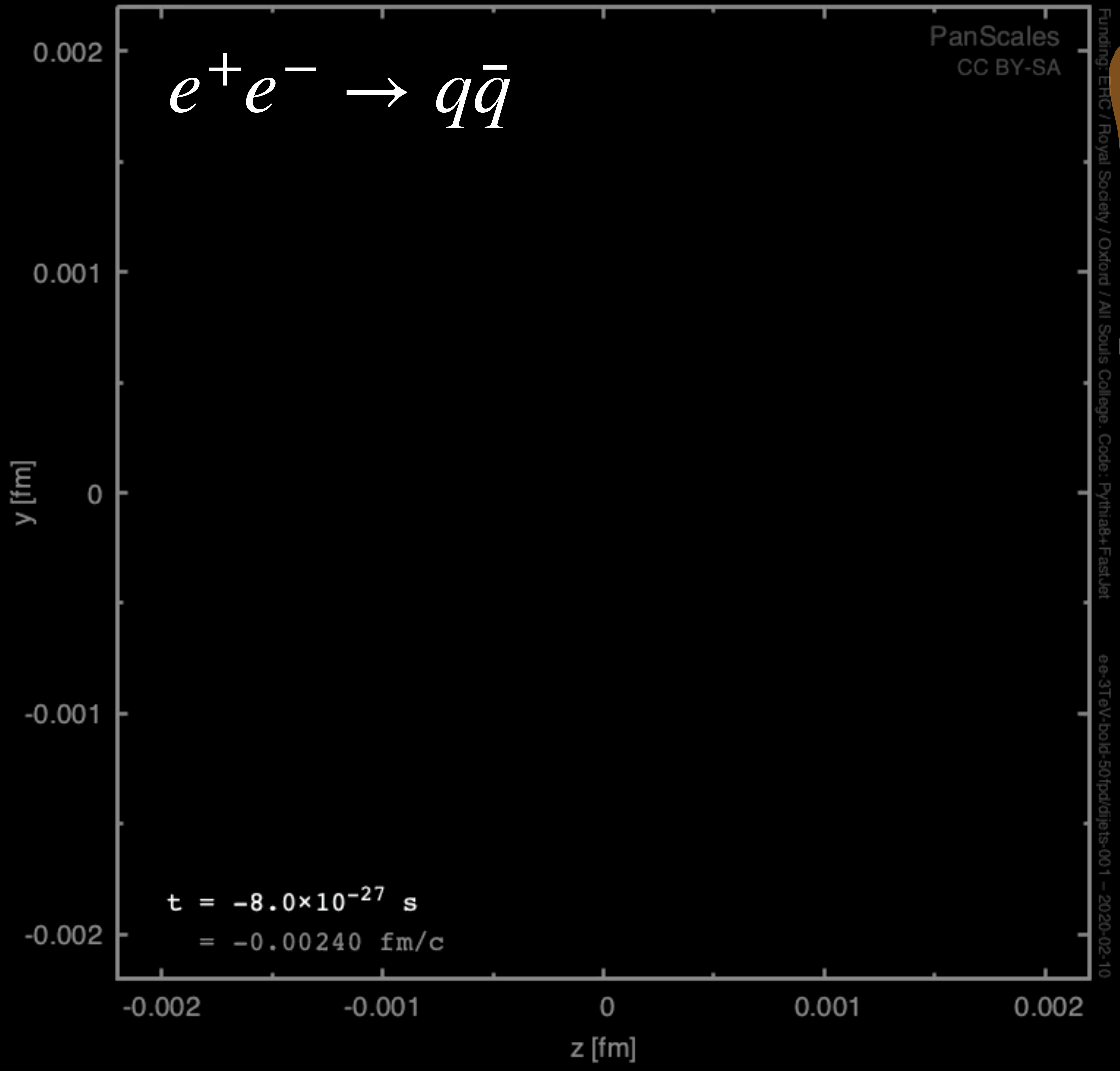


Hidden symmetry : internal structure

QUARKS



https://gsalam.web.cern.ch/gsalam/panscales/videos.html



Can we "see" the quarks ?

3TeV e^+e^- events

Initial particles in yellow
Intermediate particles in blue
Final particles in red
[details in the web page]

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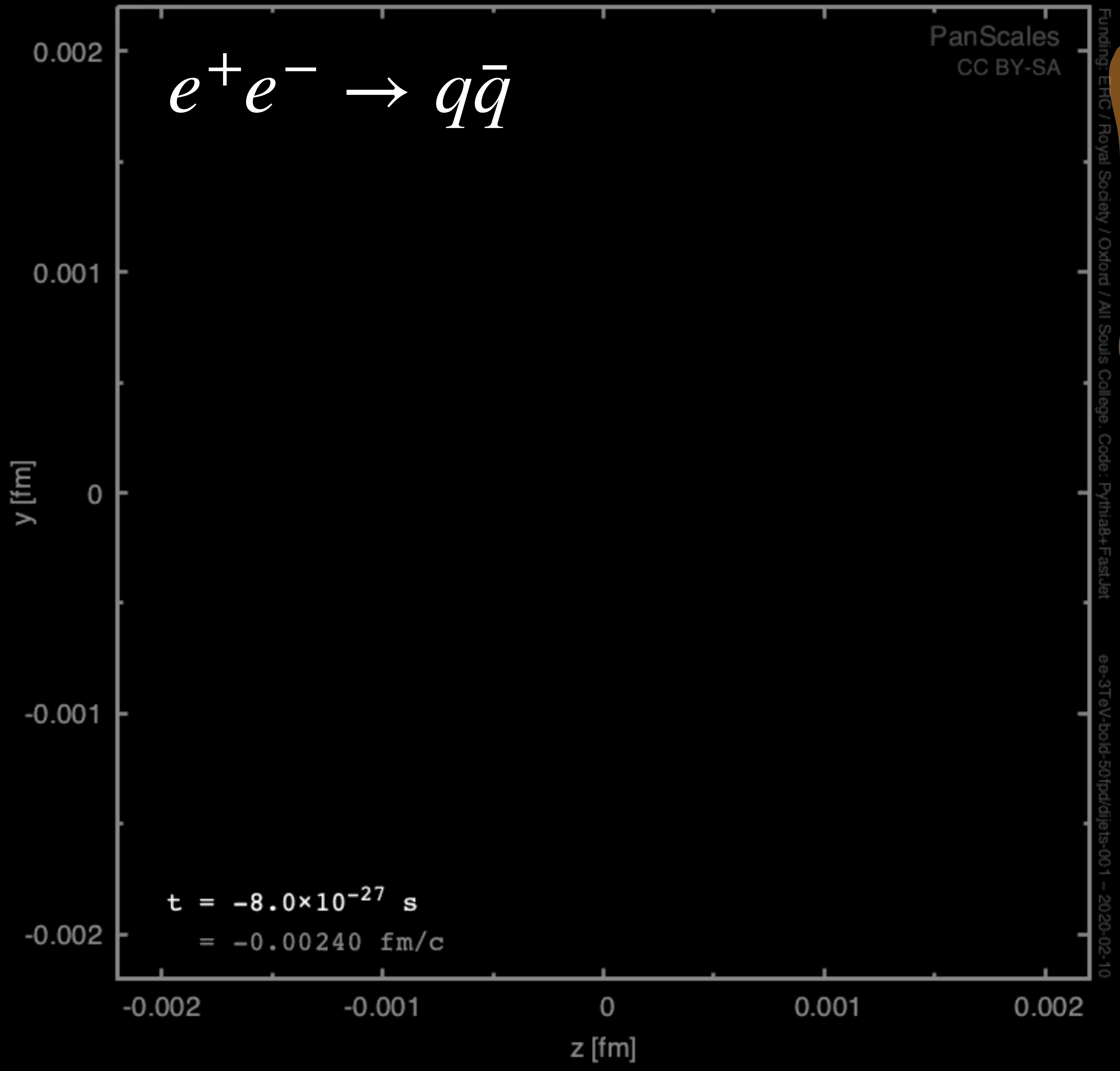

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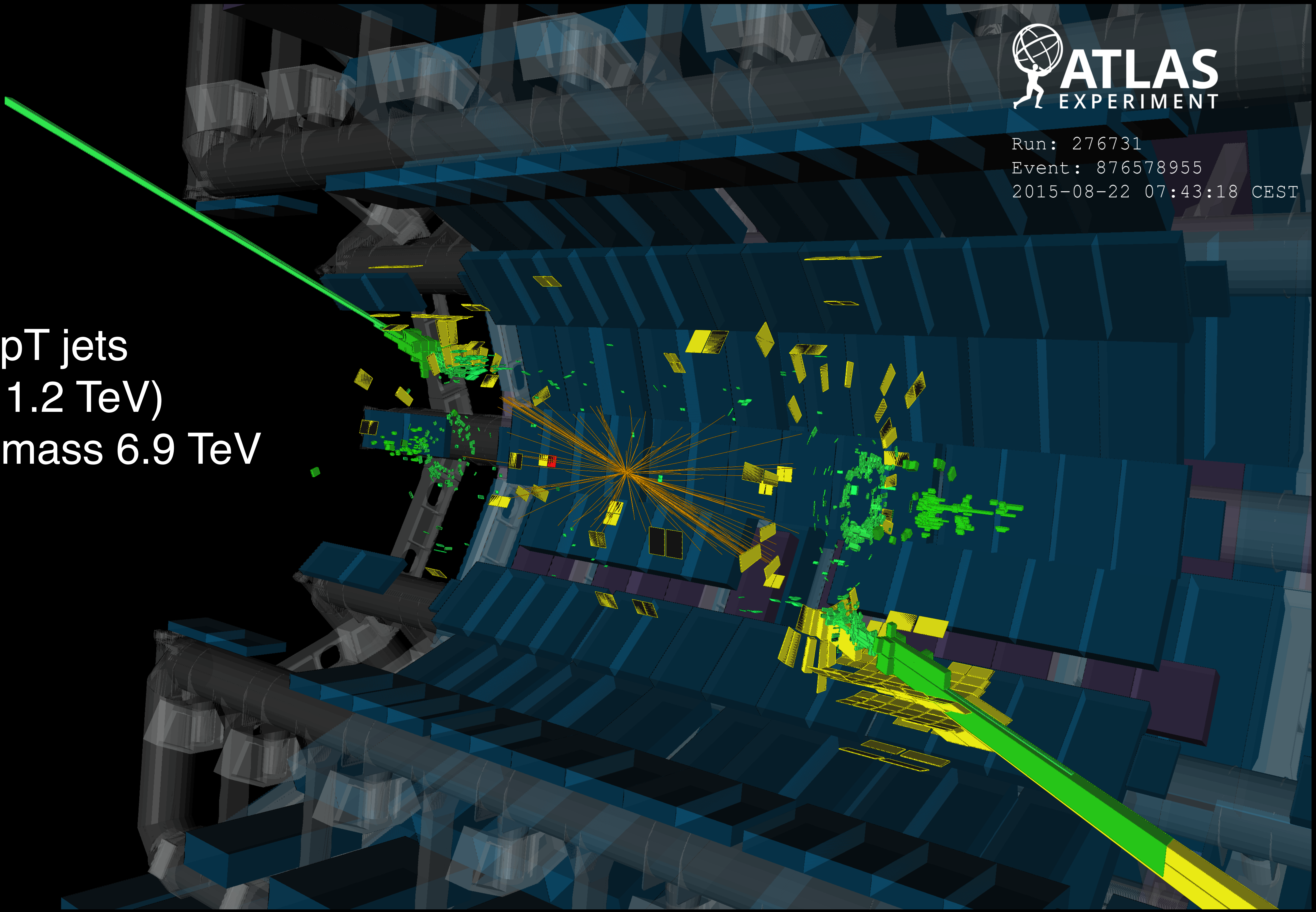
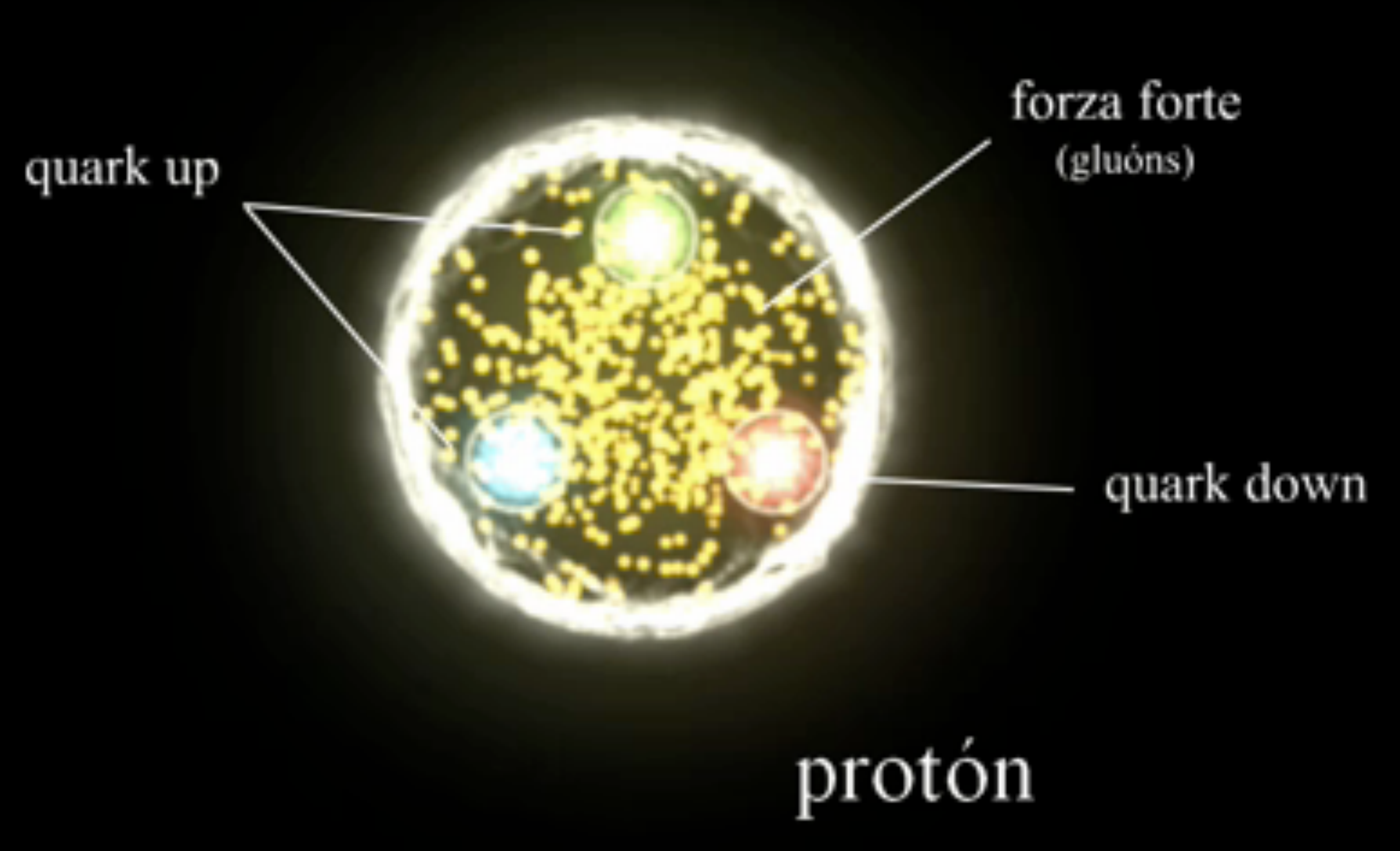
Jets in hadronic colliders

2 high pT jets
(1.3 and 1.2 TeV)
with invariant mass 6.9 TeV



The PROTON



Two (valence) up quarks + one (valence) down quark
+ a cloud of quarks, antiquarks and gluons - quantum fluctuations

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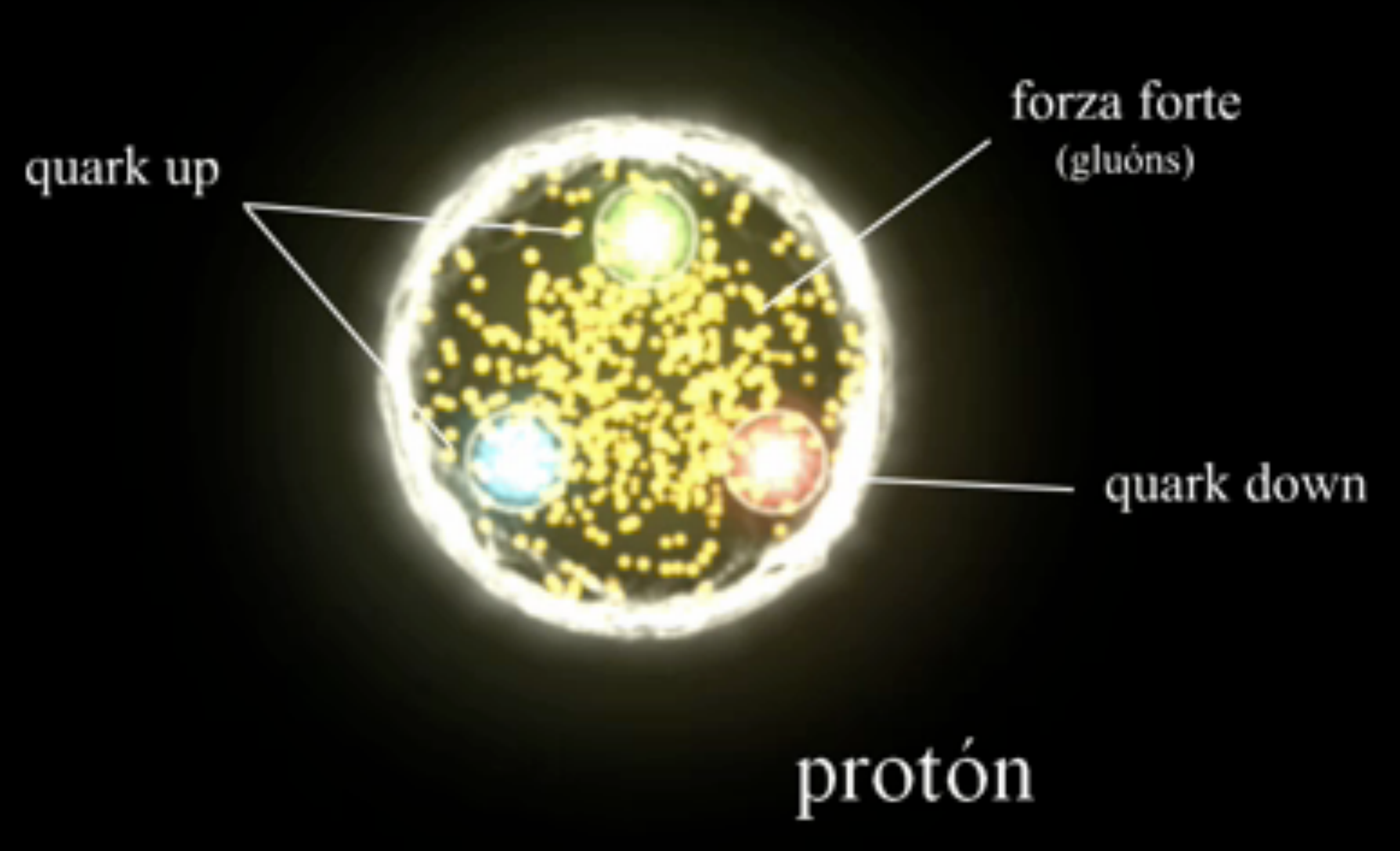

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+ a cloud of quarks, antiquarks and gluons - quantum fluctuations

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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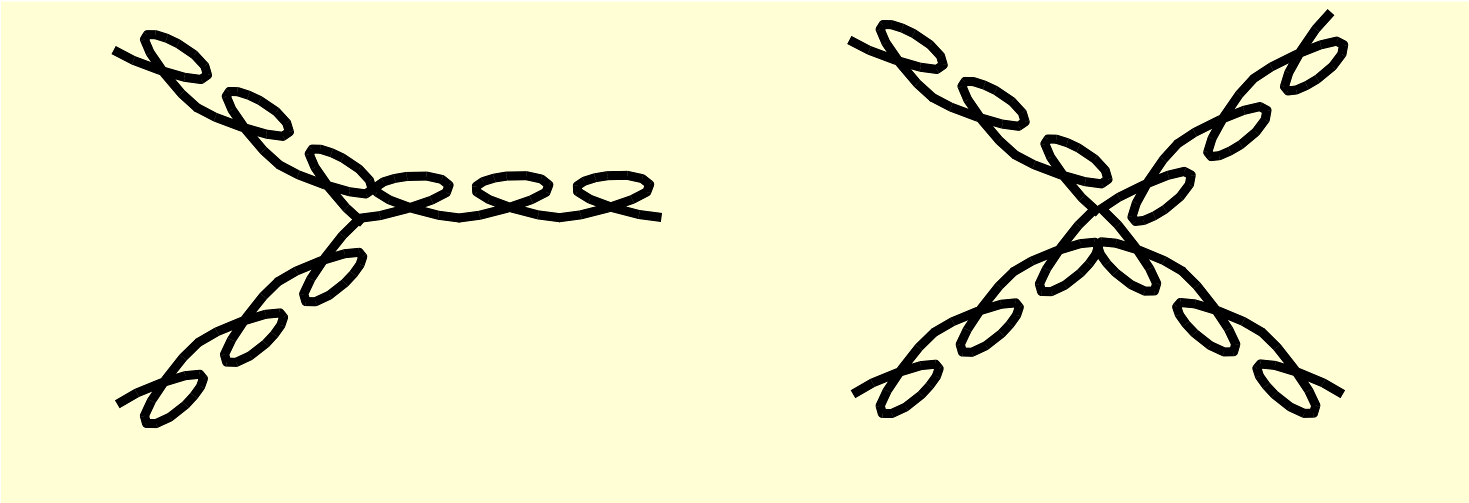
⇒ Quarks and gluons in the Lagrangian

- 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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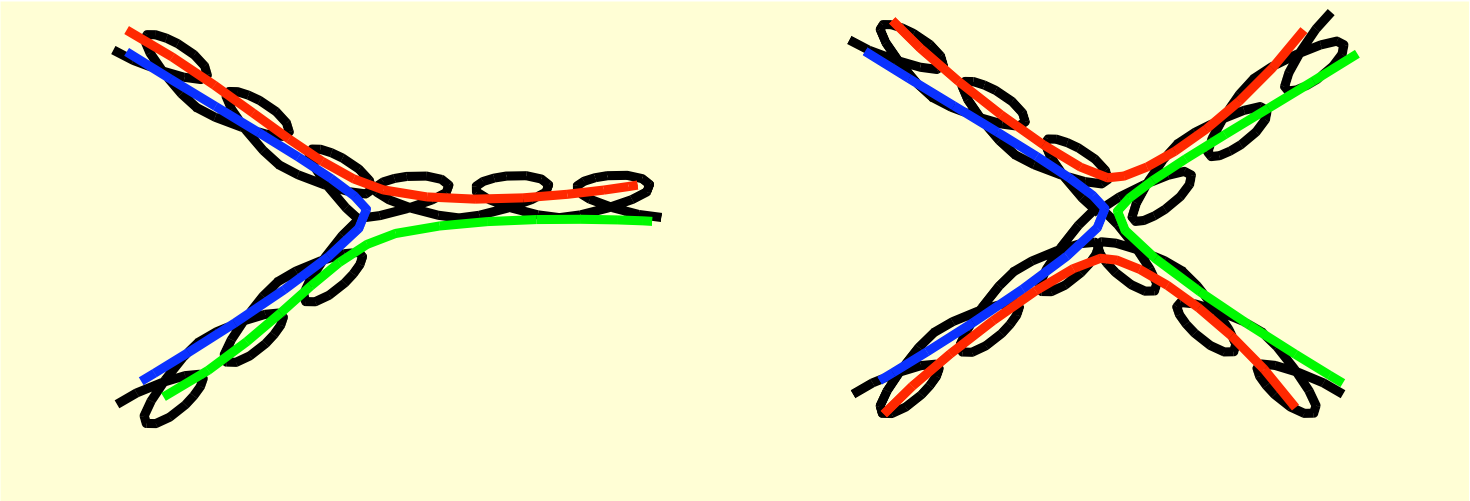

- Gluons carry color charge $\longrightarrow$ This changes everything...

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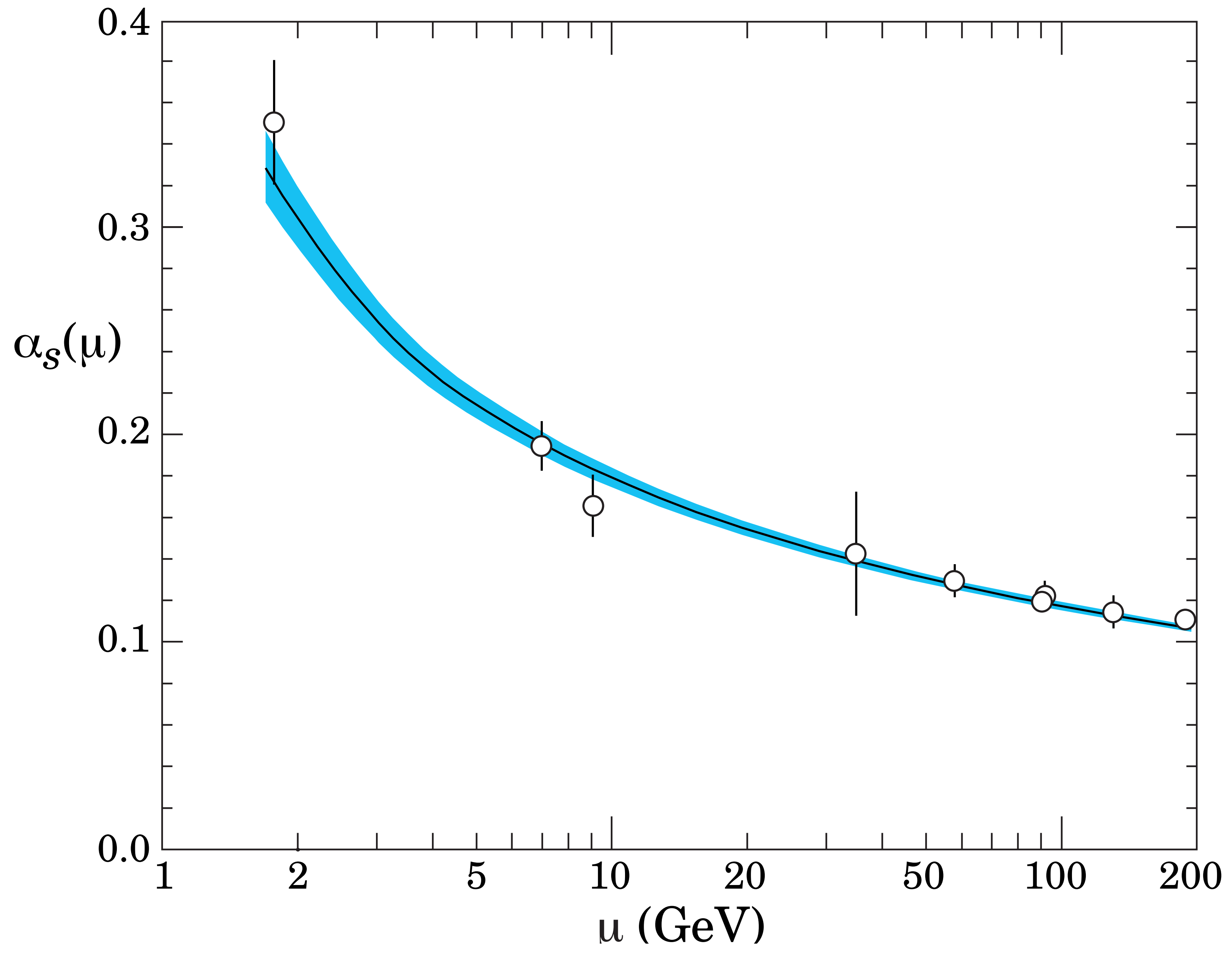
⇛ No free quarks and gluons: Confinement.

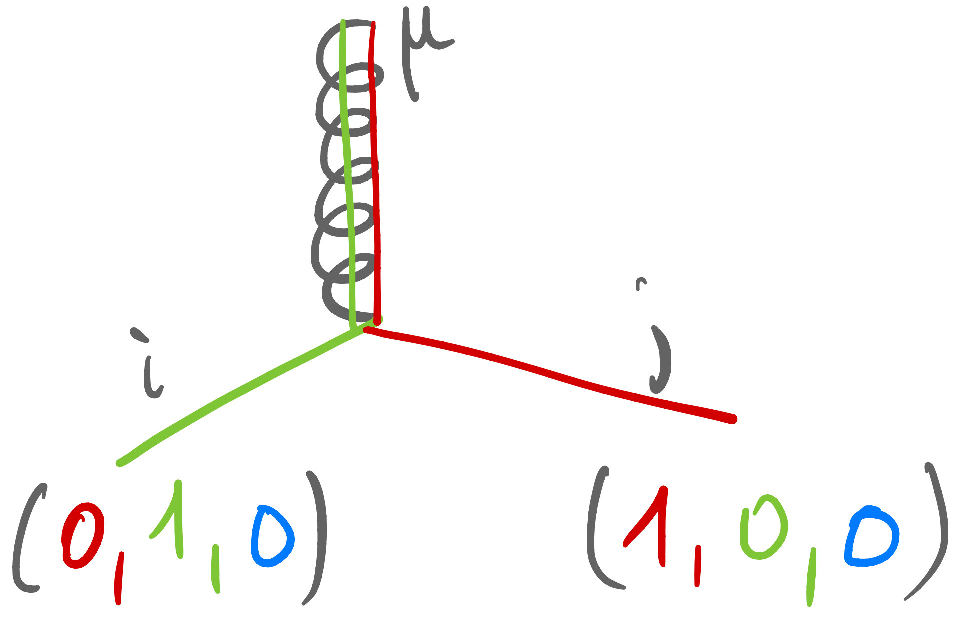
⇛ Strength smaller at smaller distances: Asymptotic freedom.



Gluons have color charge

Gluons change the color of the quark

[the corresponding vertex in QED does not change the charge of the electron]



$$\bar{\Psi}_i\left(-ig\,t^a_{ij}\gamma^\mu\right)\psi_j$$

[THIS IS JUST AN EXAMPLE]

$$\underbrace{(0,1,0)}_{\bar{\Psi}_i}\underbrace{\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}}_{t^1_{ij}}\underbrace{\begin{pmatrix}1\\0\\0\end{pmatrix}}_{\psi_j}$$

Color transformations with the Gell-Mann matrices $t_a = \dfrac{1}{2}\lambda_a$

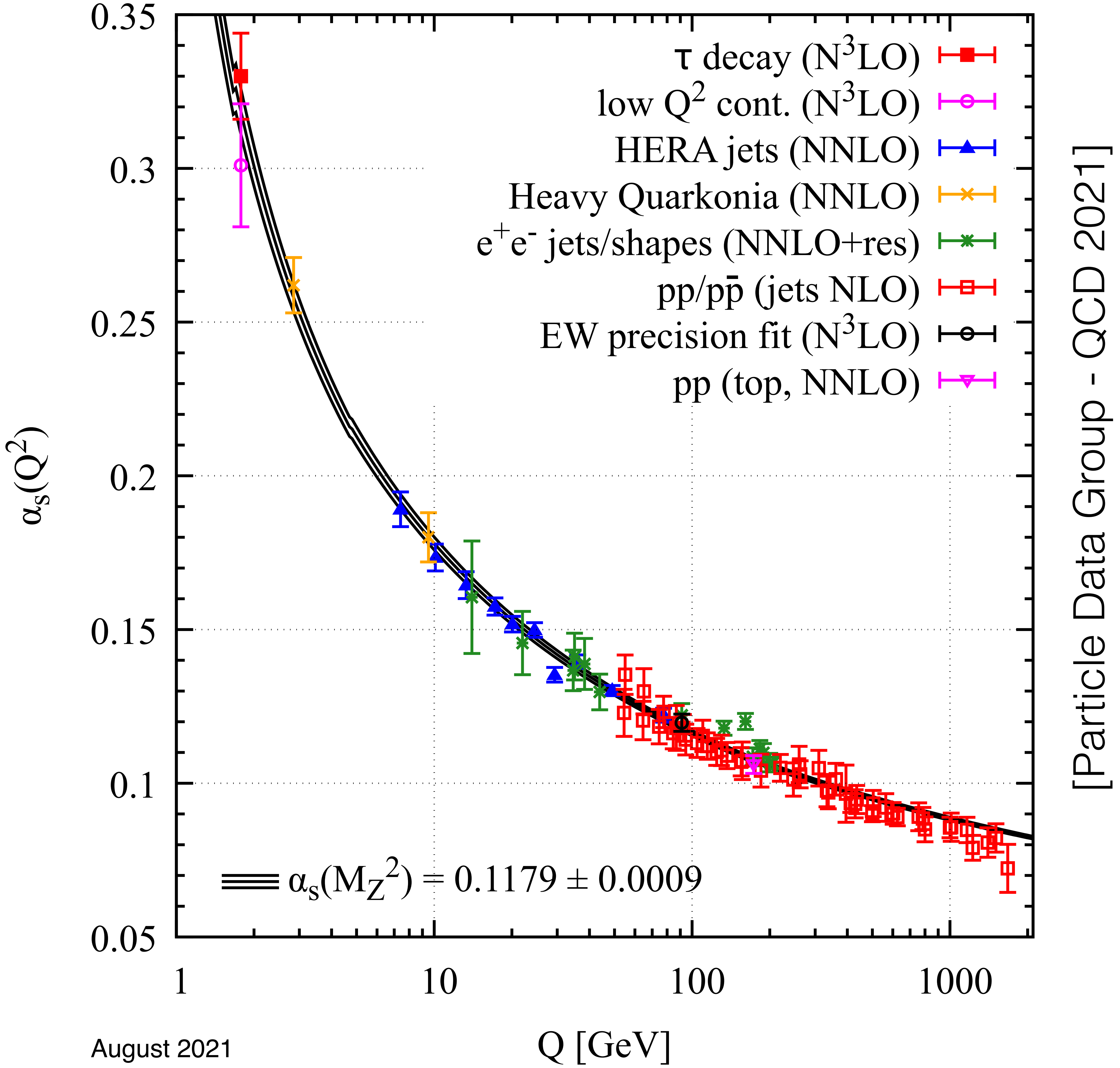
$$\lambda^1=\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix},\ \lambda^2=\begin{pmatrix}0&-i&0\\i&0&0\\0&0&0\end{pmatrix},\ \lambda^3=\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix},\ \lambda^4=\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix},$$

$$\lambda^5=\begin{pmatrix}0&0&-i\\0&0&0\\i&0&0\end{pmatrix},\ \lambda^6=\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix},\ \lambda^7=\begin{pmatrix}0&0&0\\0&0&-i\\0&i&0\end{pmatrix},\ \lambda^8=\begin{pmatrix}\frac{1}{\sqrt{3}}&0&0\\0&\frac{1}{\sqrt{3}}&0\\0&0&\frac{-2}{\sqrt{3}}\end{pmatrix},$$

Quark's color - fundamental representation of SU(3)

$$[t^a, t^b] = i f_{abc} t^c$$

Asymptotic freedom



$$\mu_R^2 \frac{d\alpha_s}{d\mu_R^2} = \beta(\alpha_s) = -(b_0\alpha_s^2 + b_1\alpha_s^3 + b_2\alpha_s^4 + \cdots)$$

Take $b_1 = b_2 = \dots = 0$

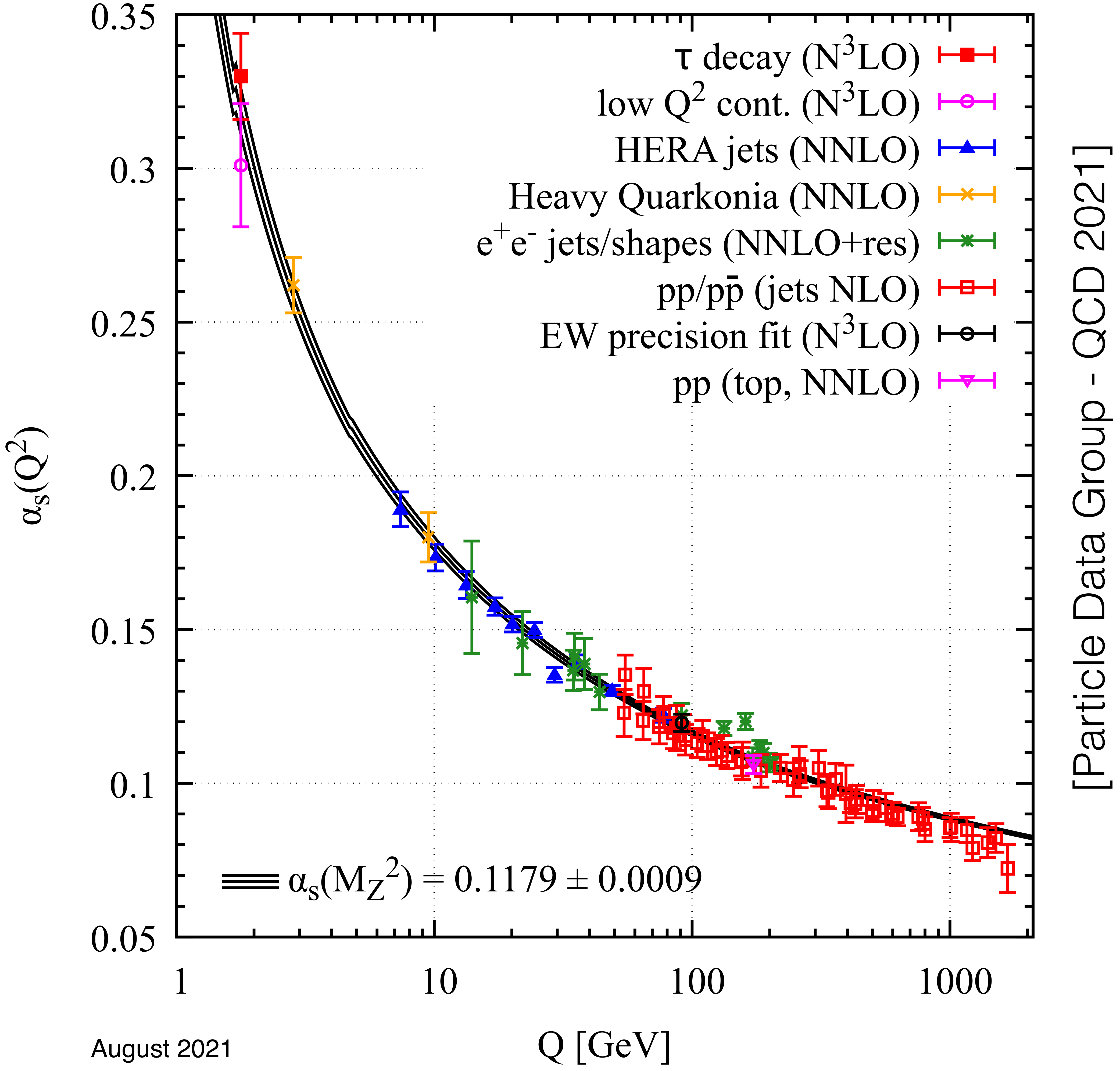
$$\boxed{\frac{d\alpha_s}{d\log\mu_R} = -b_0\alpha_s}$$

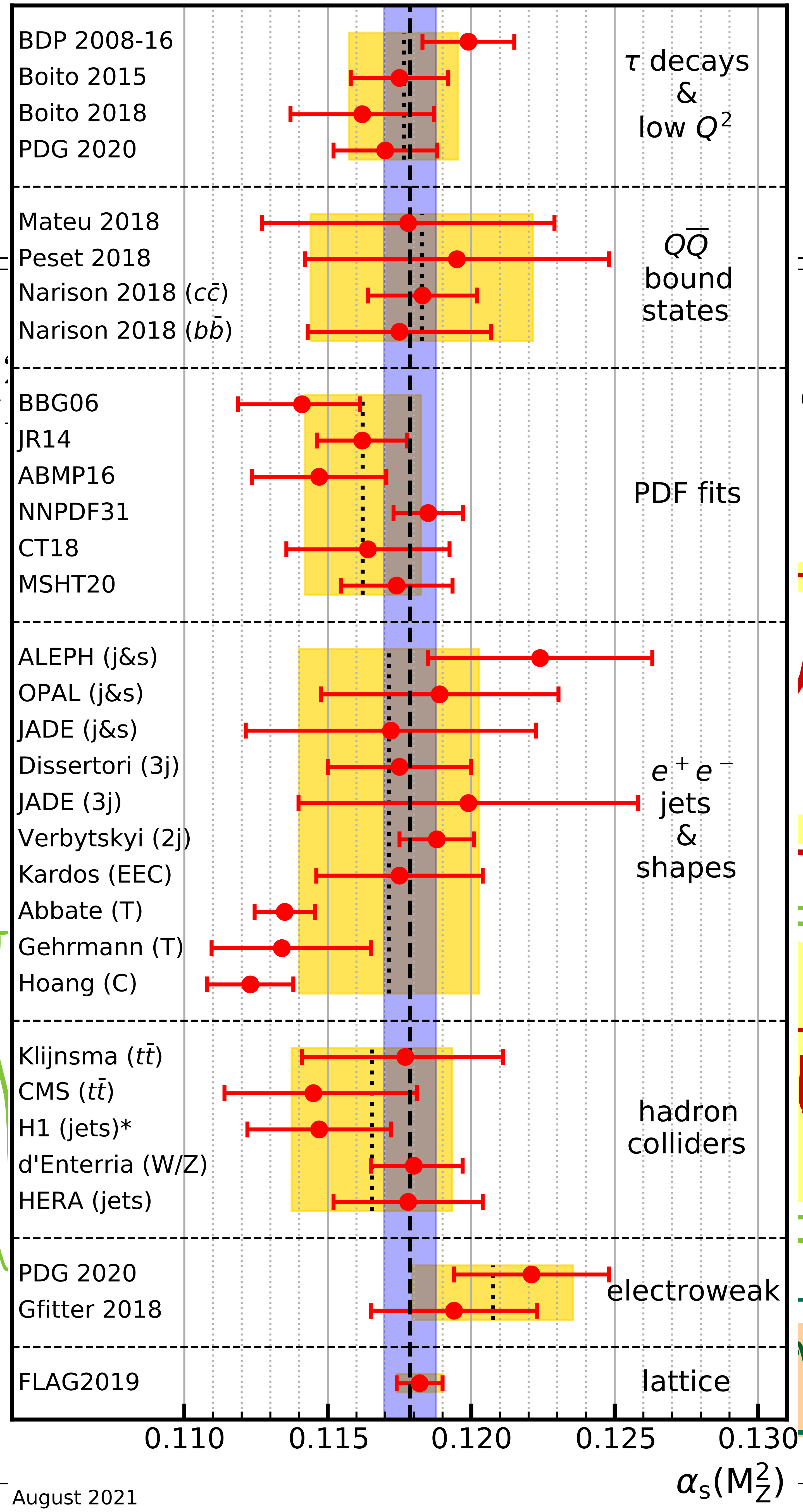
$$\alpha_s(\mu^2) = \frac{\alpha_s(\mu_0^2)}{1 + b_0\,\alpha_s(\mu_0^2)\log\frac{Q^2}{\mu_0^2}} \equiv \frac{1}{b_0 \log^2\frac{Q^2}{\Lambda^2_{QCD}}}$$

$\alpha_s \ll 1$ FOR $Q^2 \gg \Lambda^2_{QCD}$

Asymptotic

μ ... $\alpha_s^3 + b_2\alpha_s^4 + \cdots)$

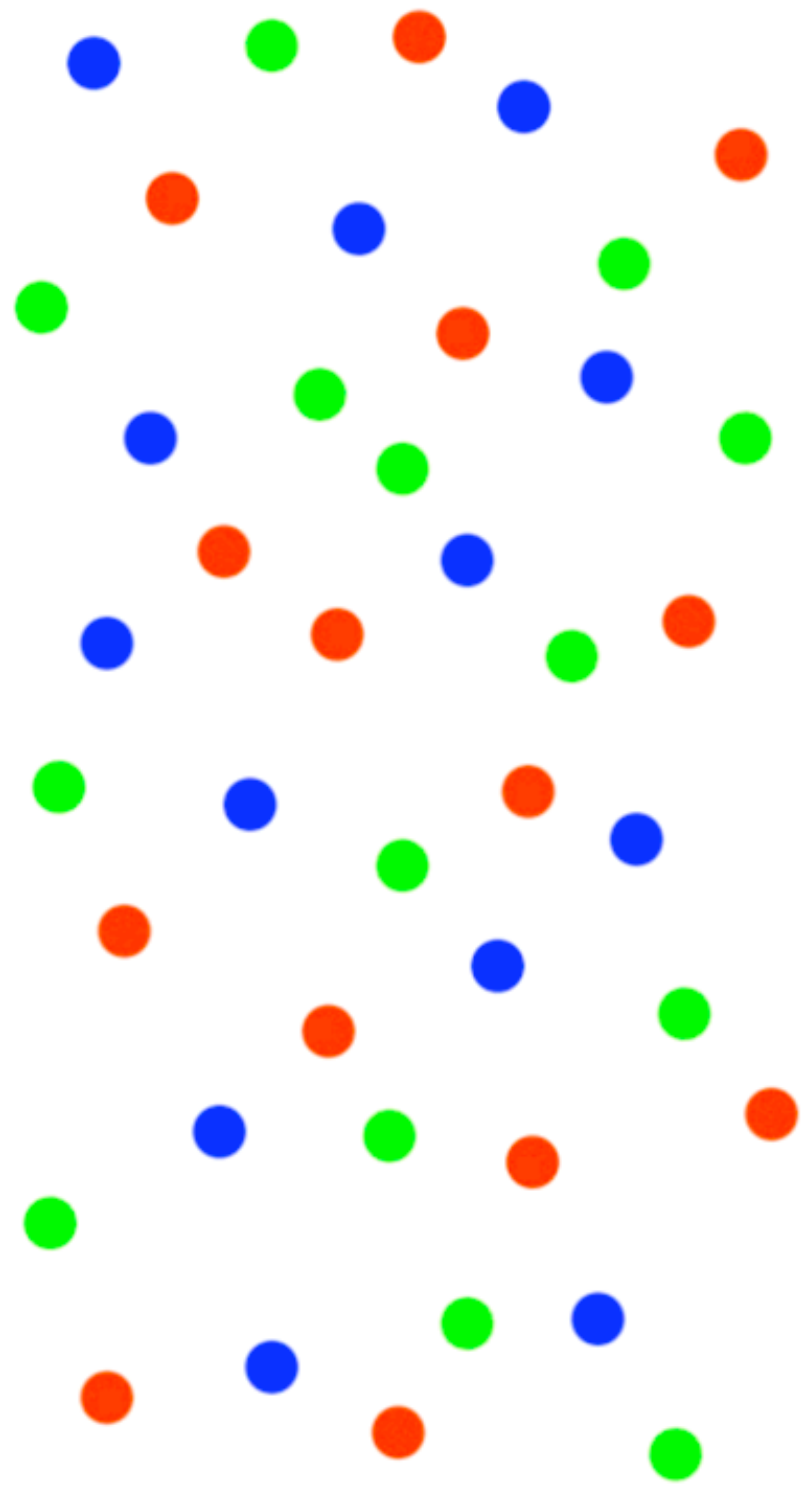




$\frac{1}{b_0 \log^2 \frac{Q^2}{\Lambda^2_{QCD}}}$

A picture of confinement

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



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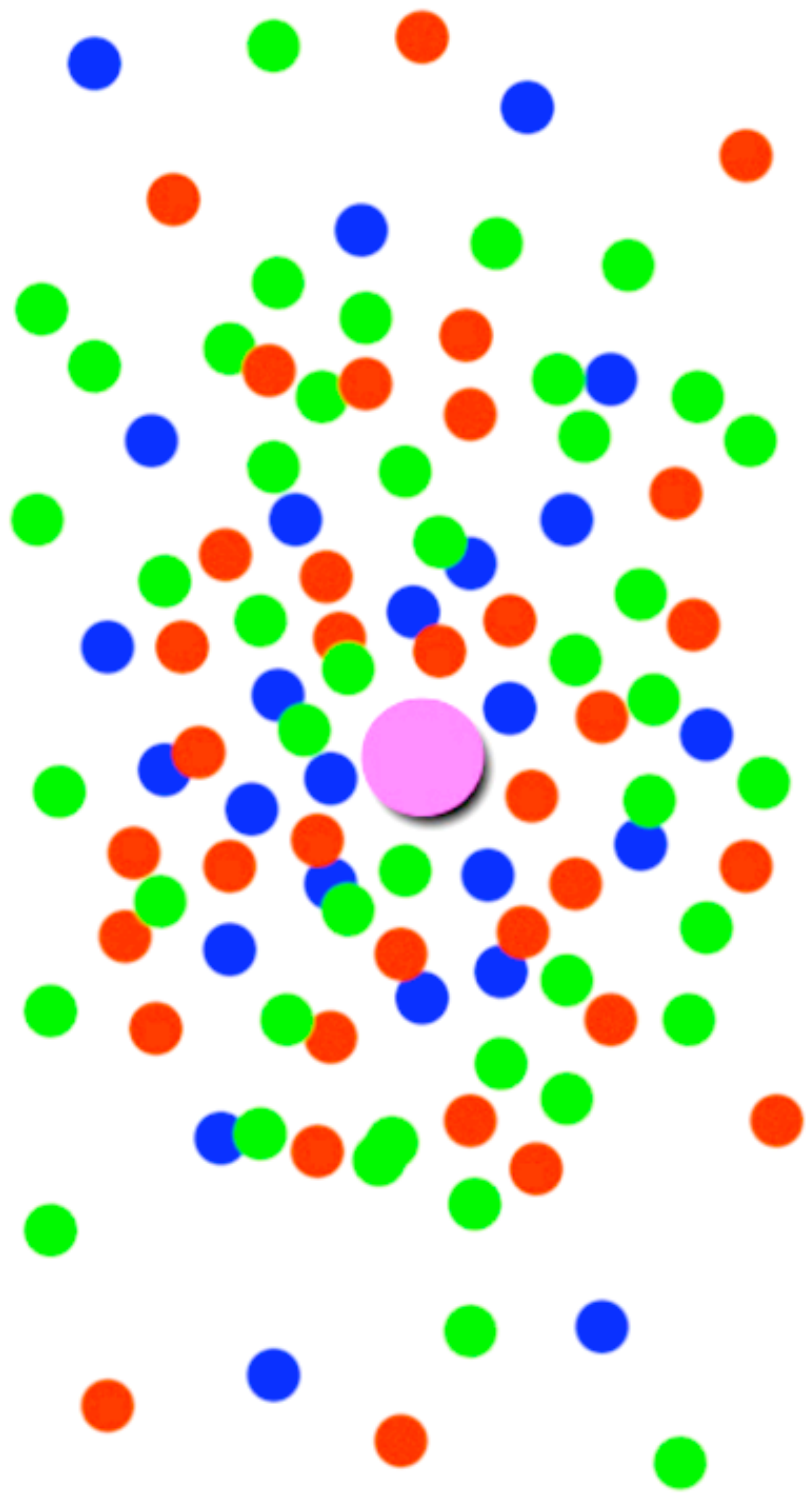
- confinement $\Longrightarrow$ isolated quarks (gluons) = infinite energy



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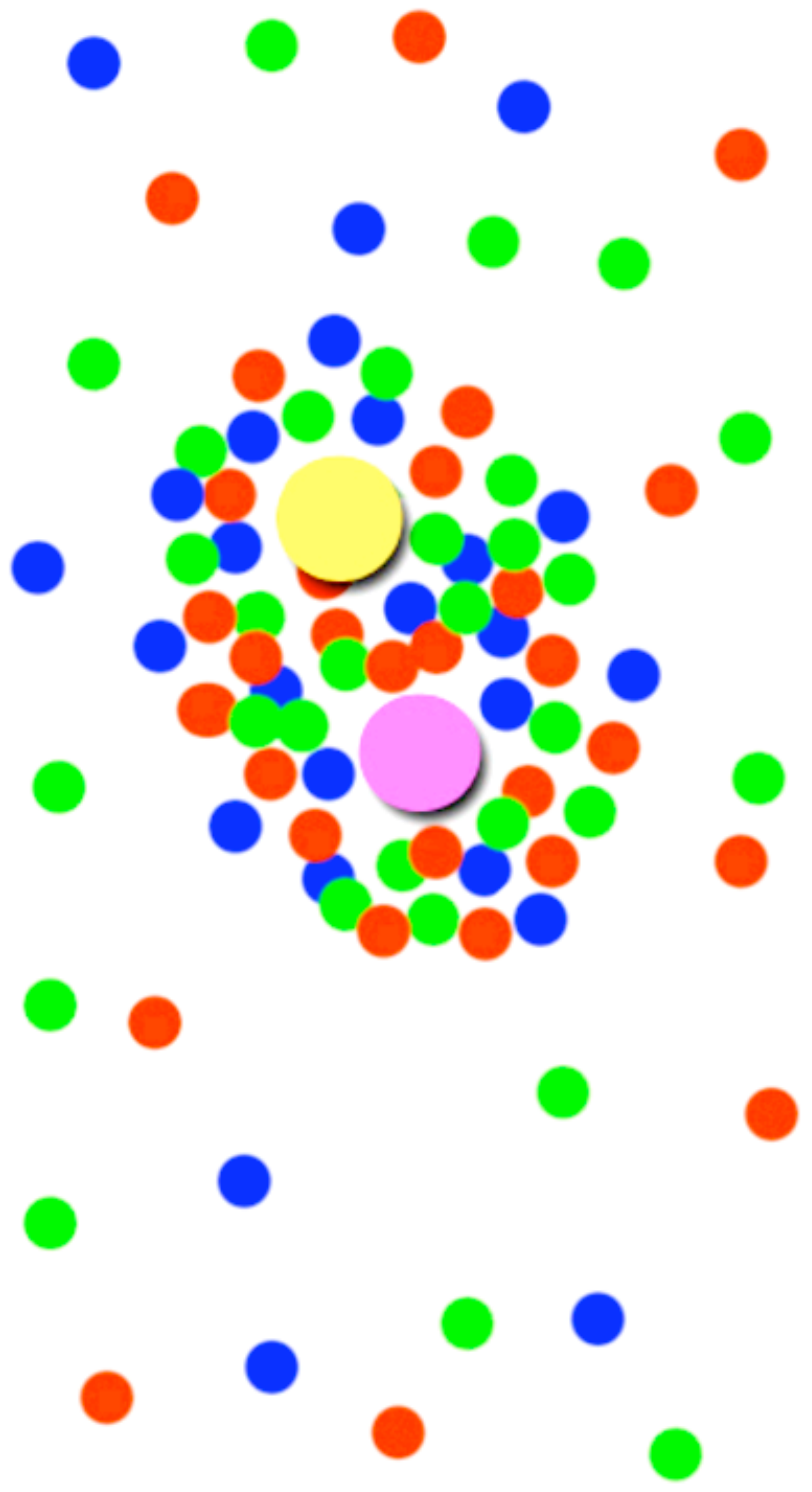
- $\Rightarrow$ colorless packages (hadrons) $\Longrightarrow$ vacuum excitations.



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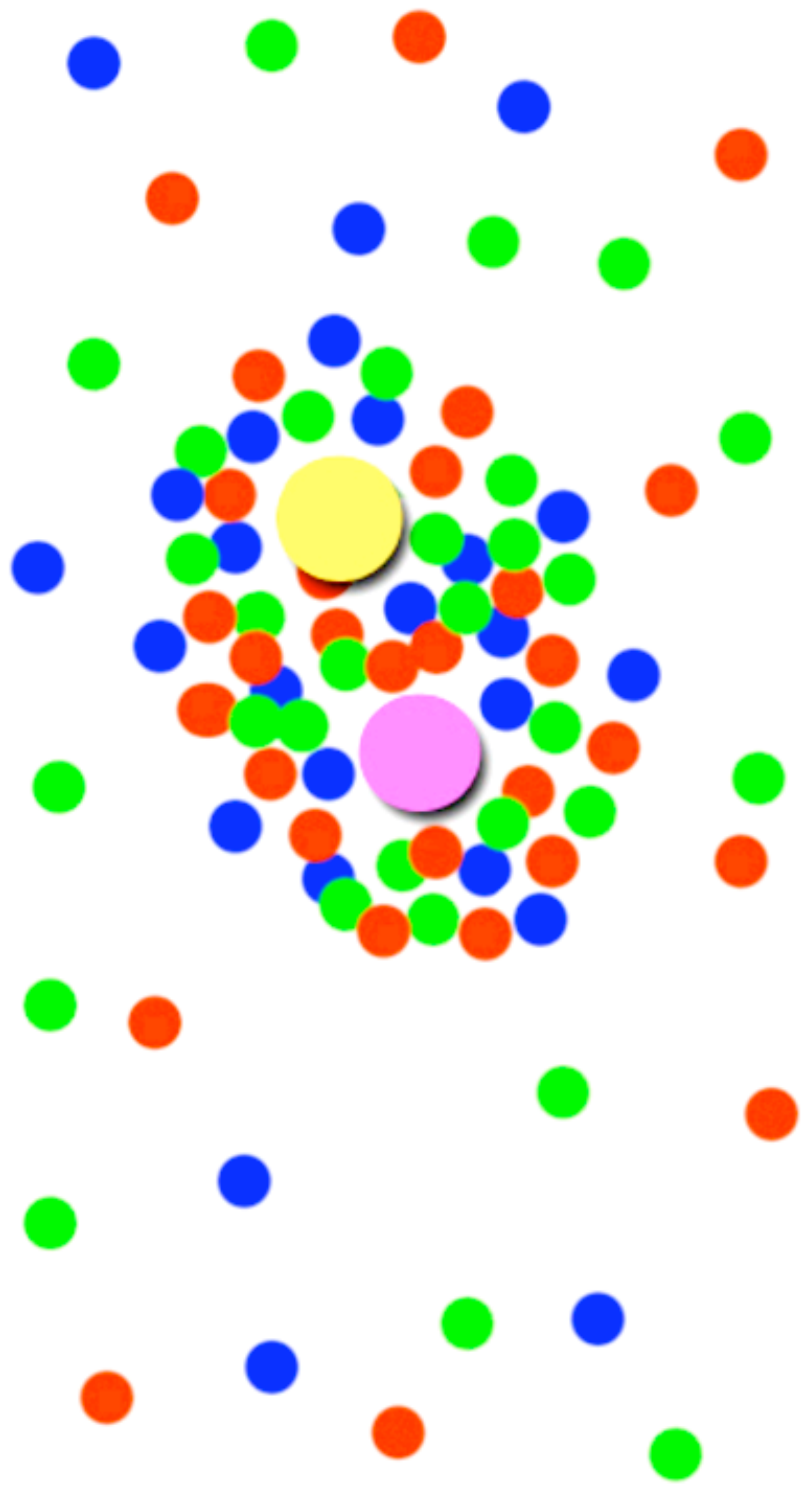
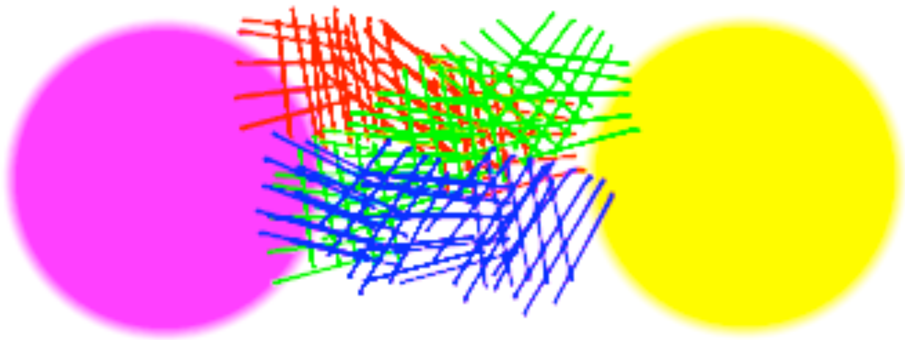
- ⇛ colorless packages (hadrons) $\Longrightarrow$ vacuum excitations.
- ⇛ masses:

	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



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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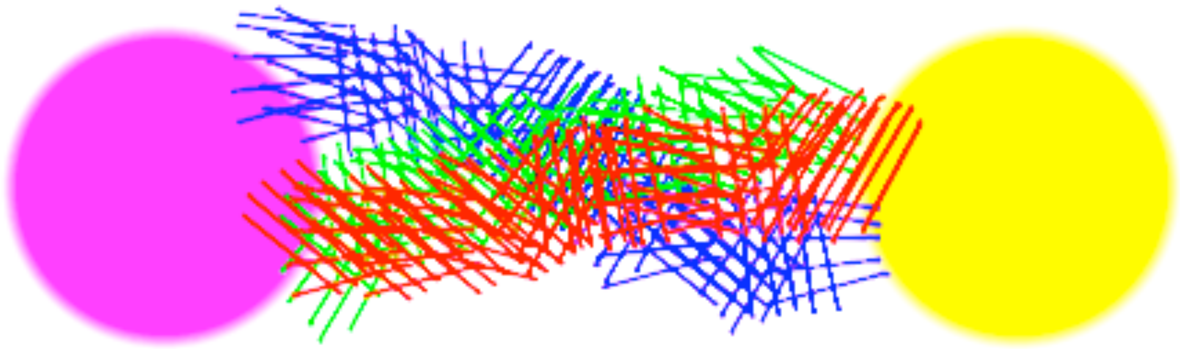

⇛ Colorless object

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

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

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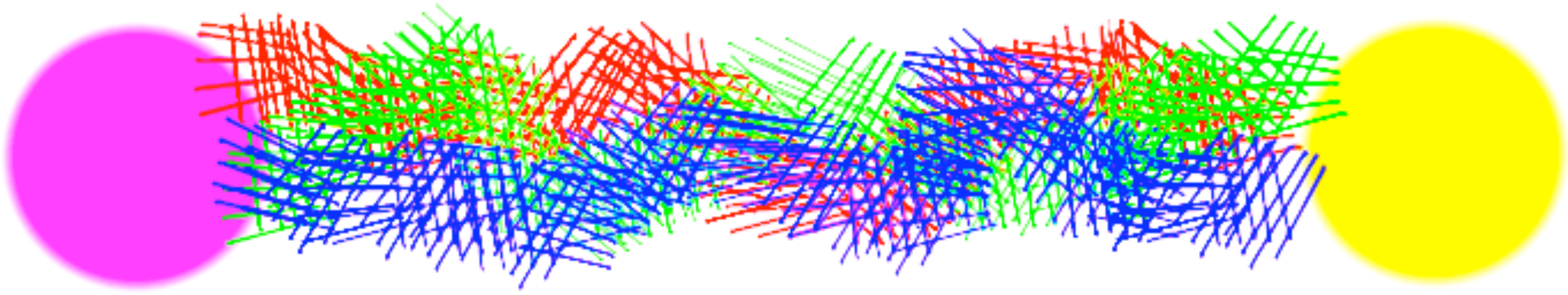

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⇛ In the limit $m_q \to \infty$ the string cannot break (infinite energy)

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

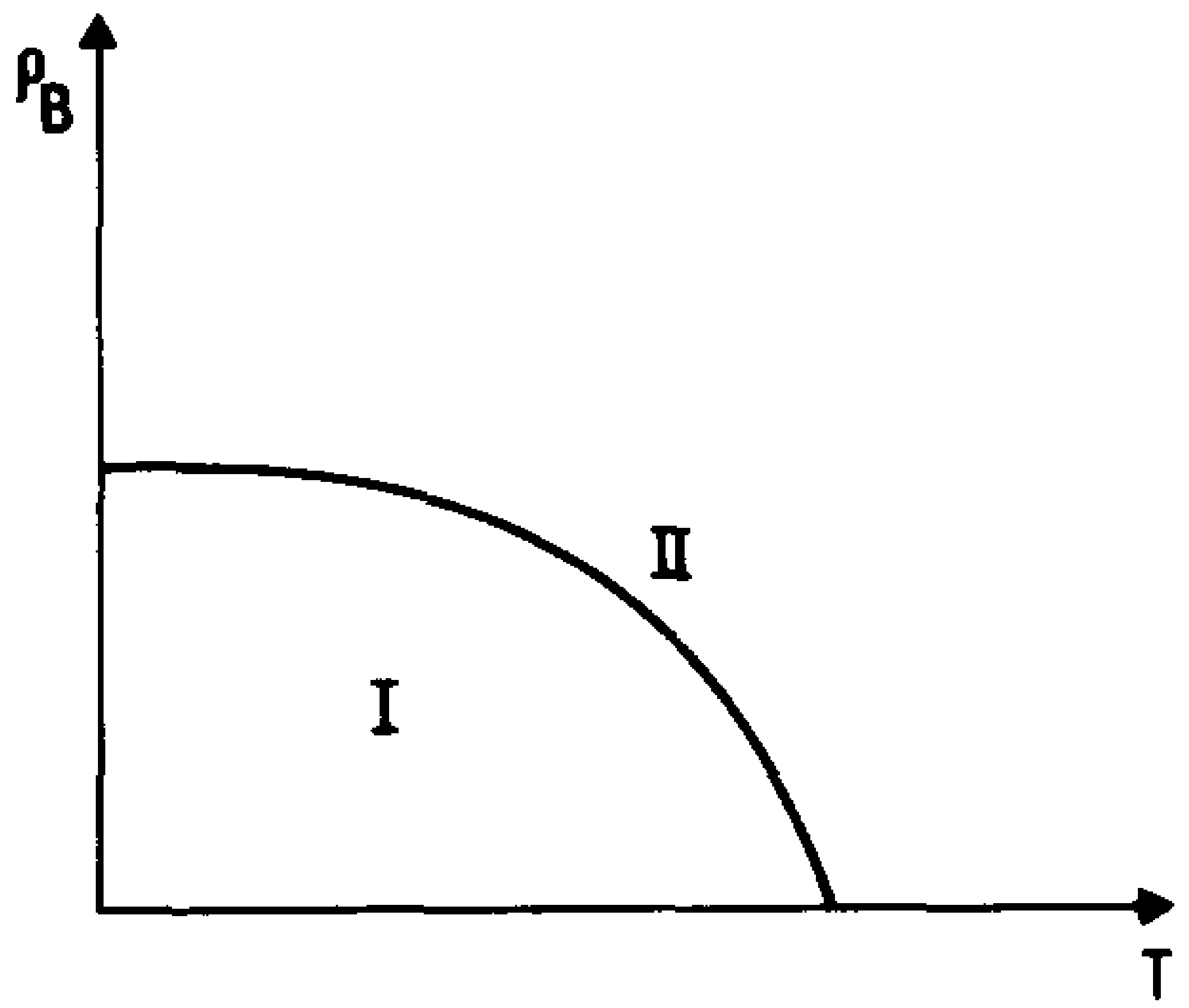
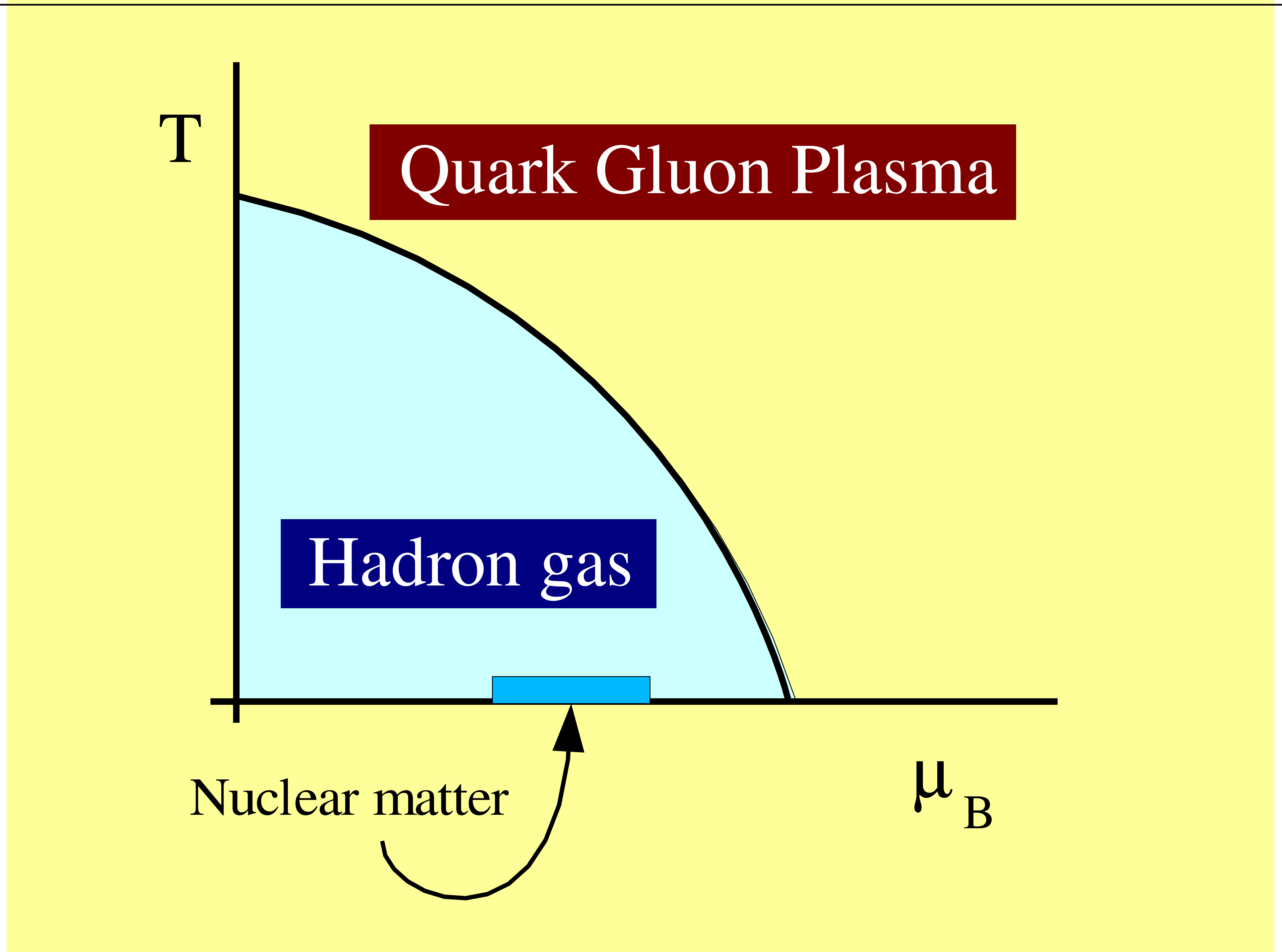


Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

[Cabibbo and Parisi 1975]

QCD phase diagram



$\Rightarrow$ First lattice calculation found a first order phase transition

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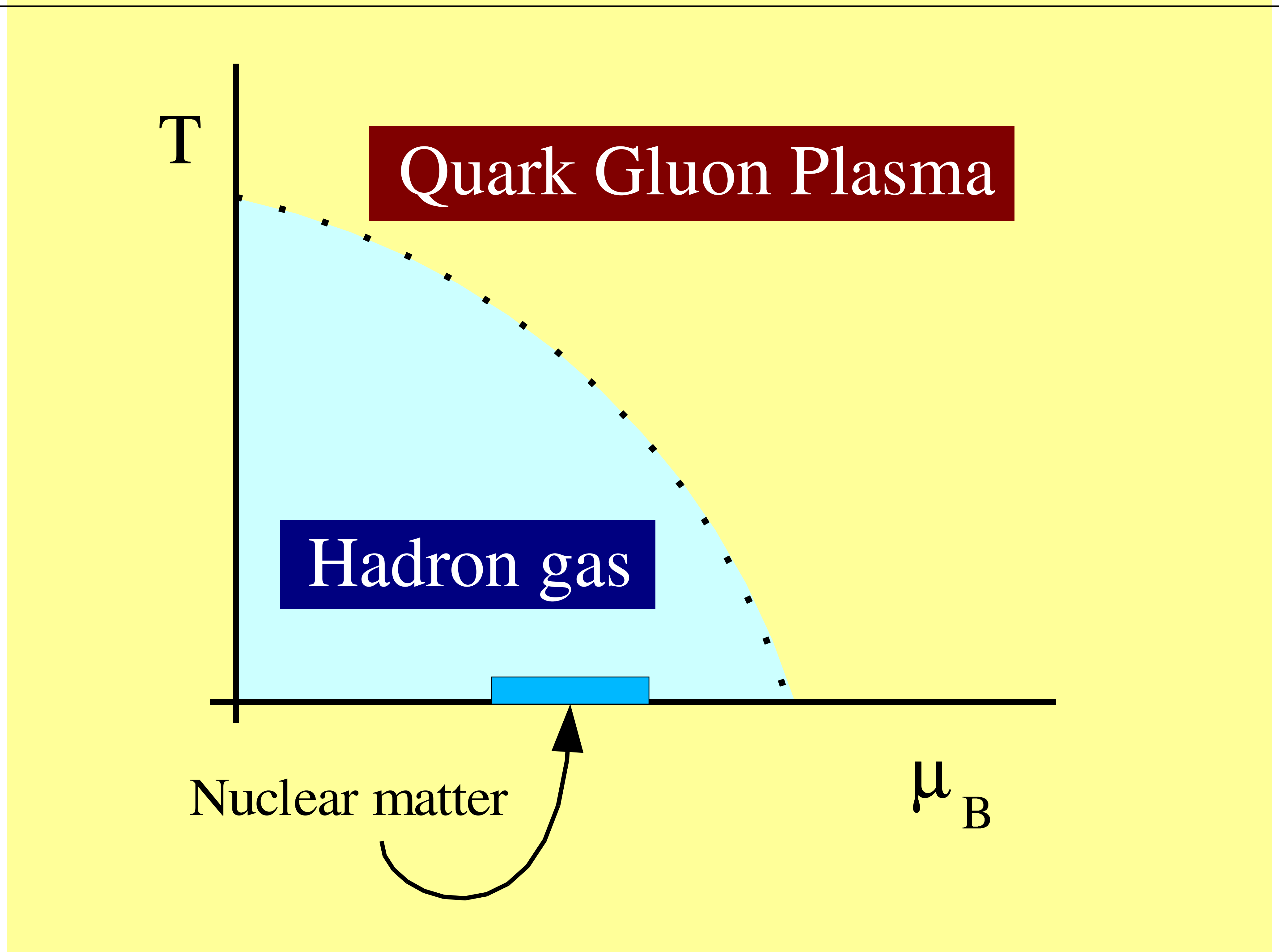

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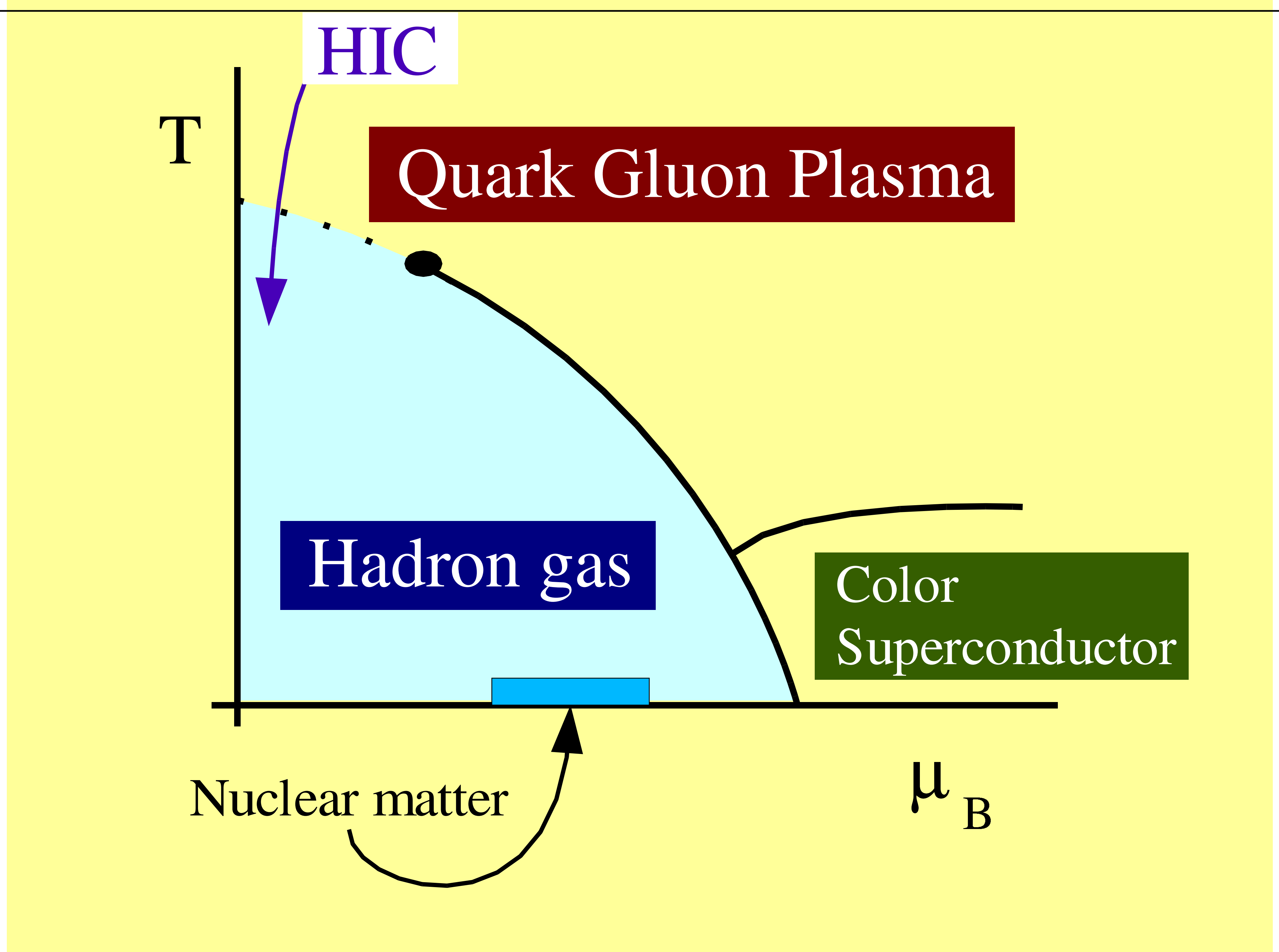

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⇛ Present status: several different phases found.

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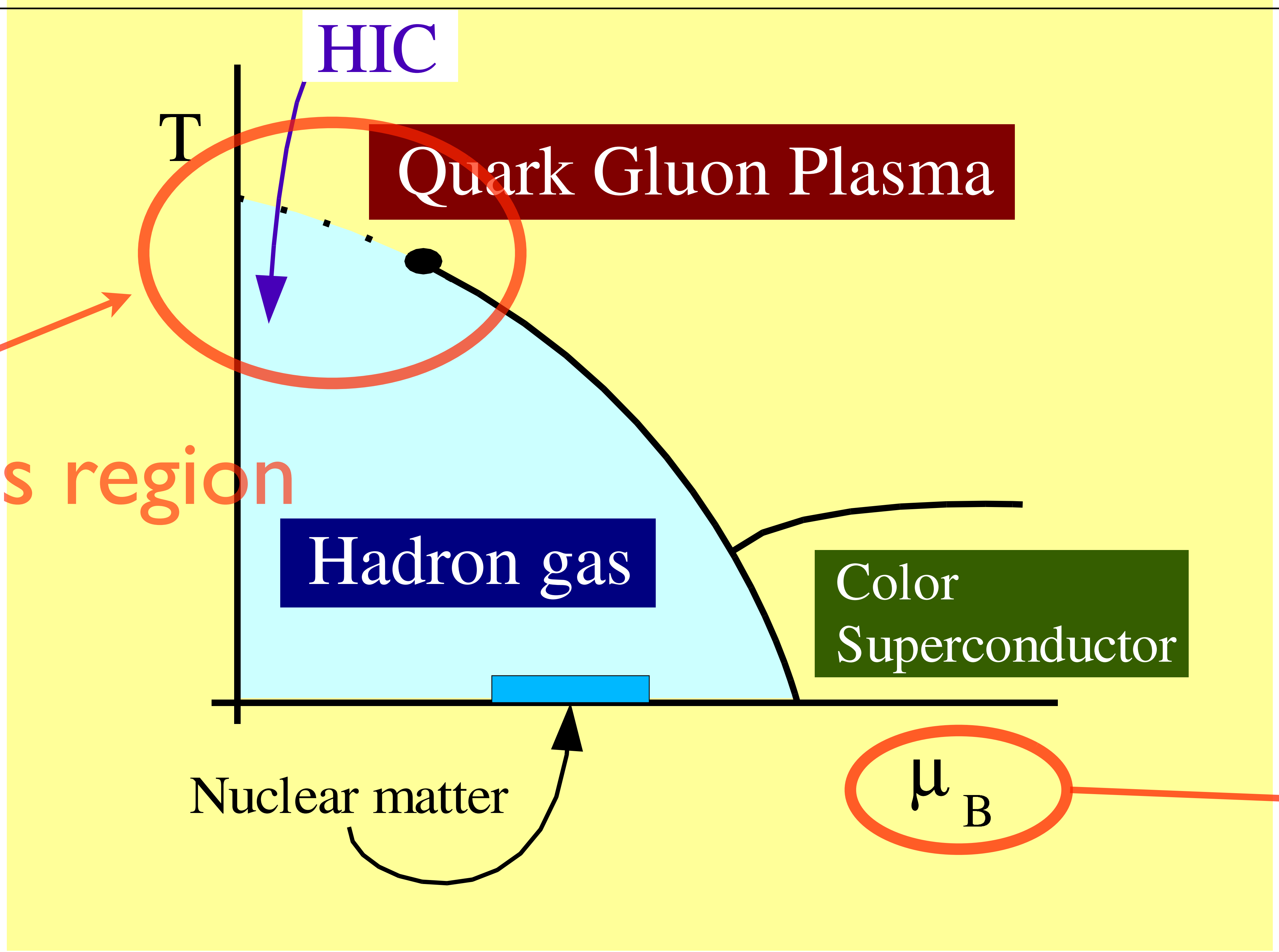

We study this region

$\sim \boxed{\#q - \#\bar{q}}$

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- ⇛ Present status: several different phases found.

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

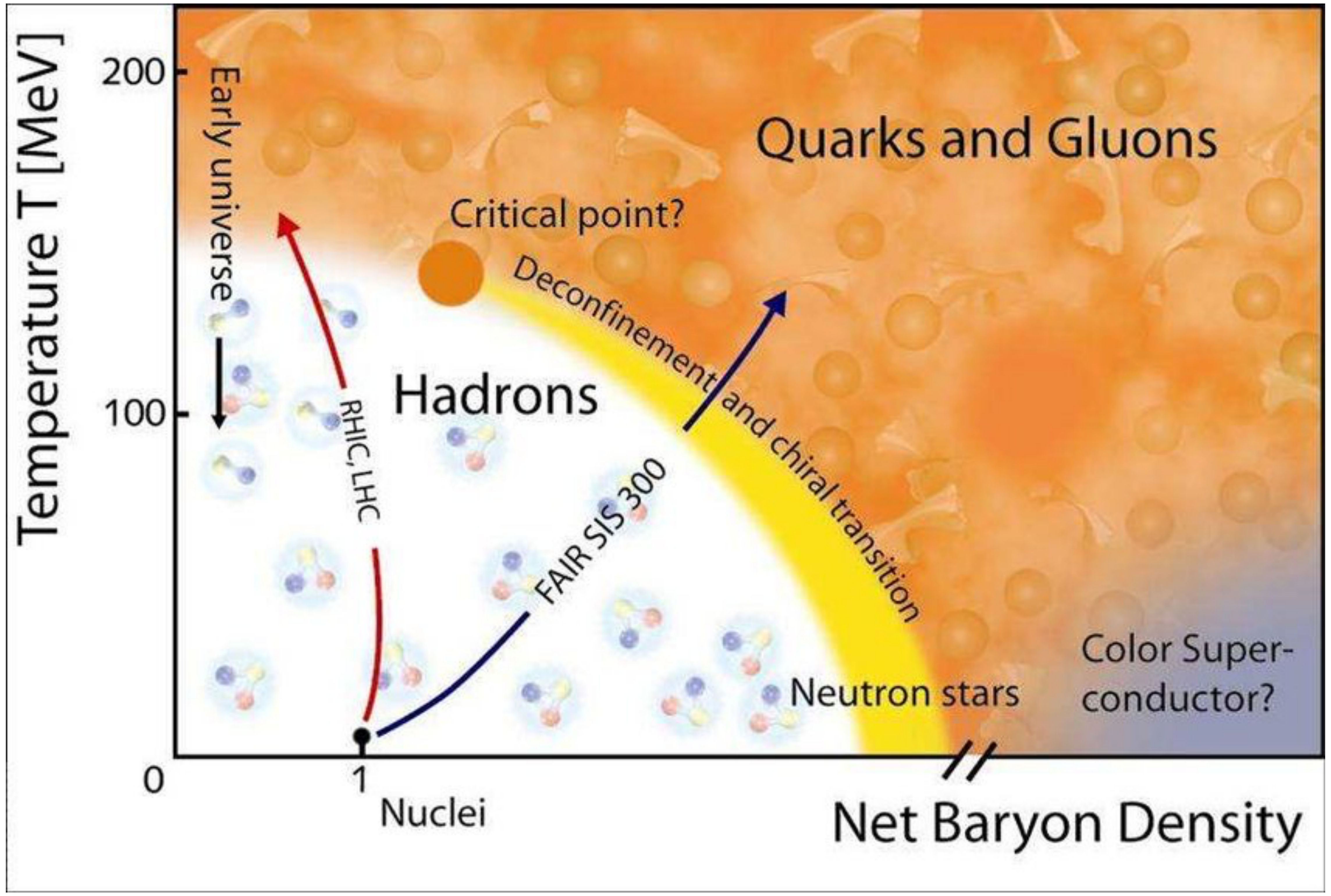
FAIR at GSI

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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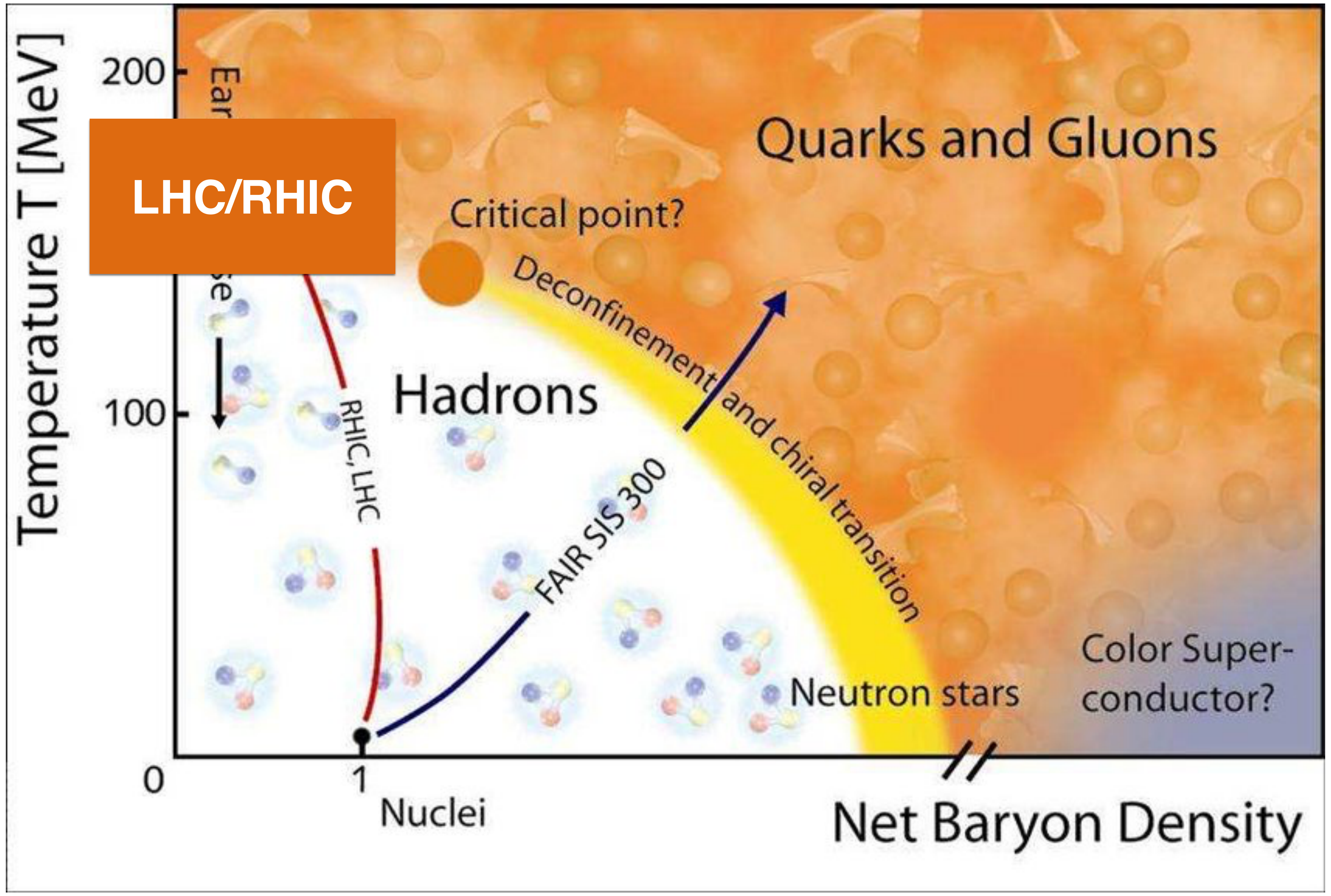

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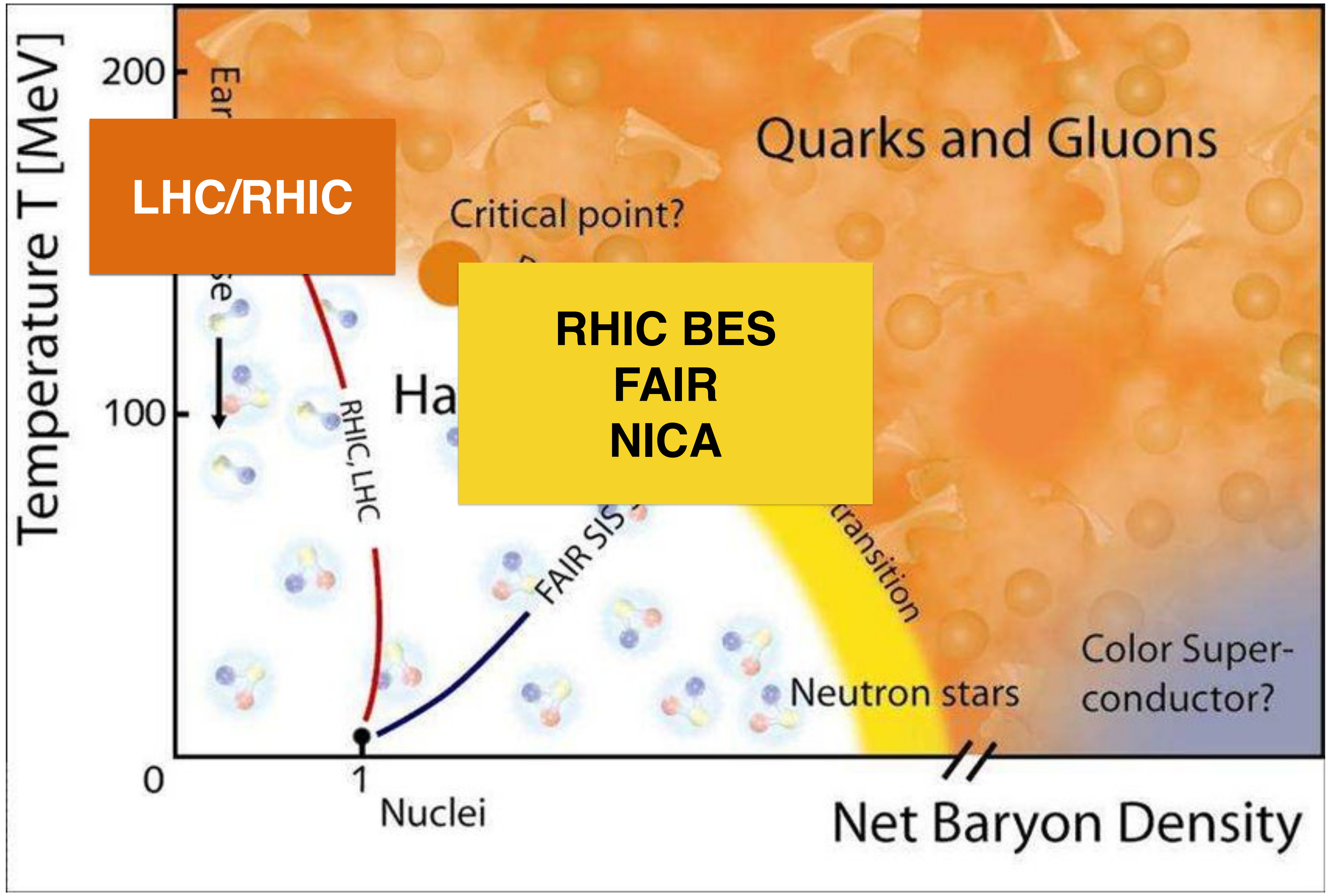

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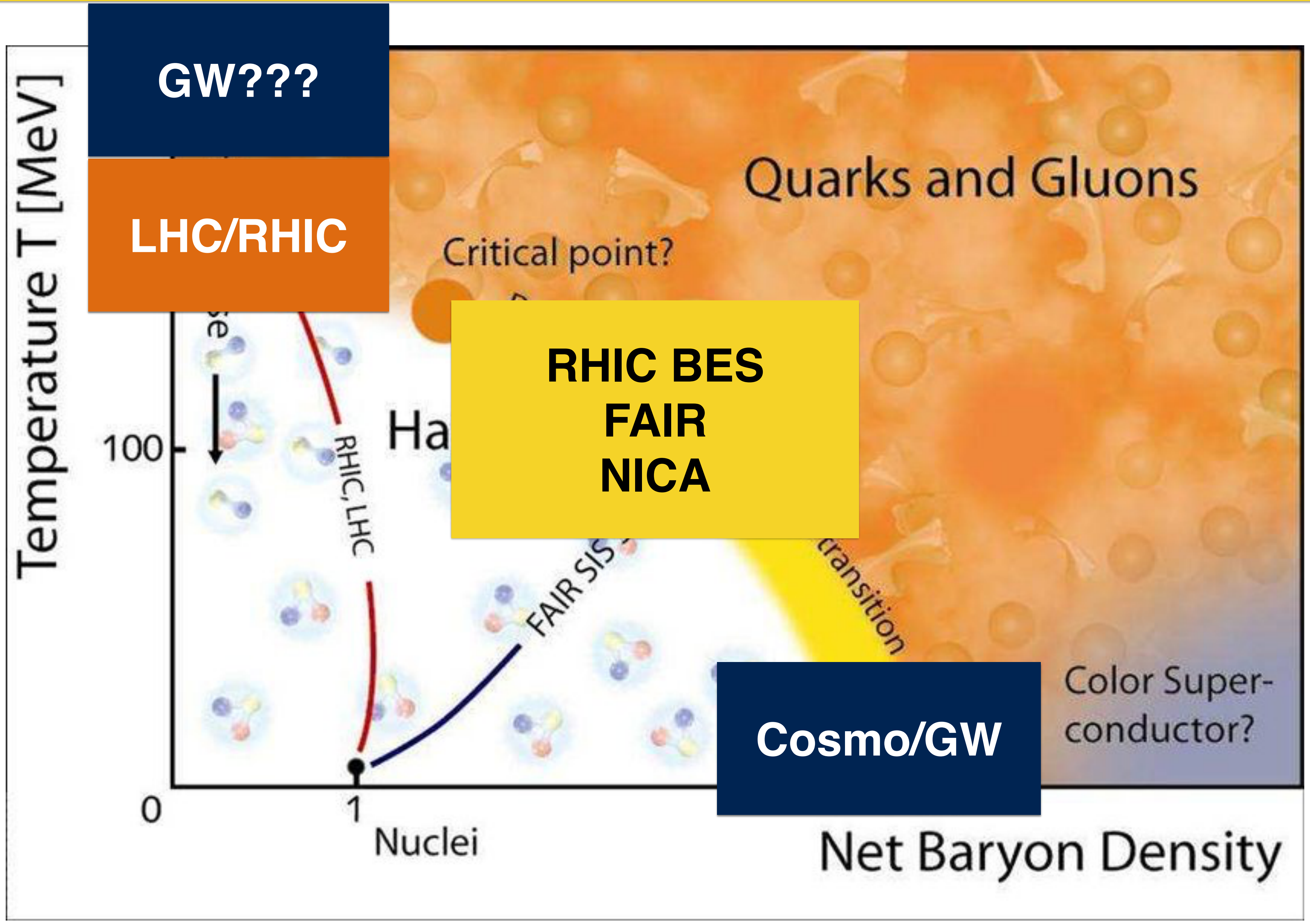
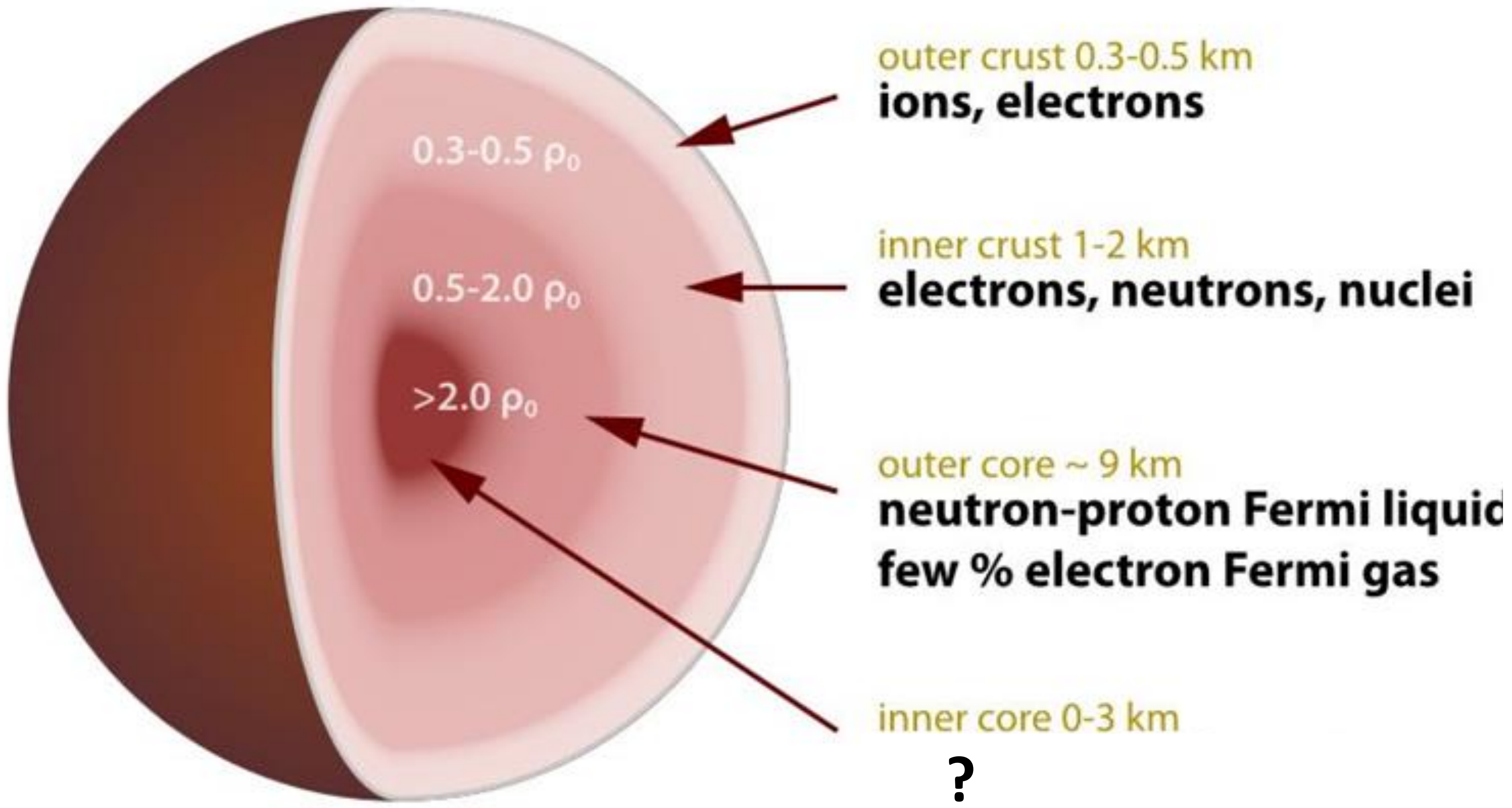
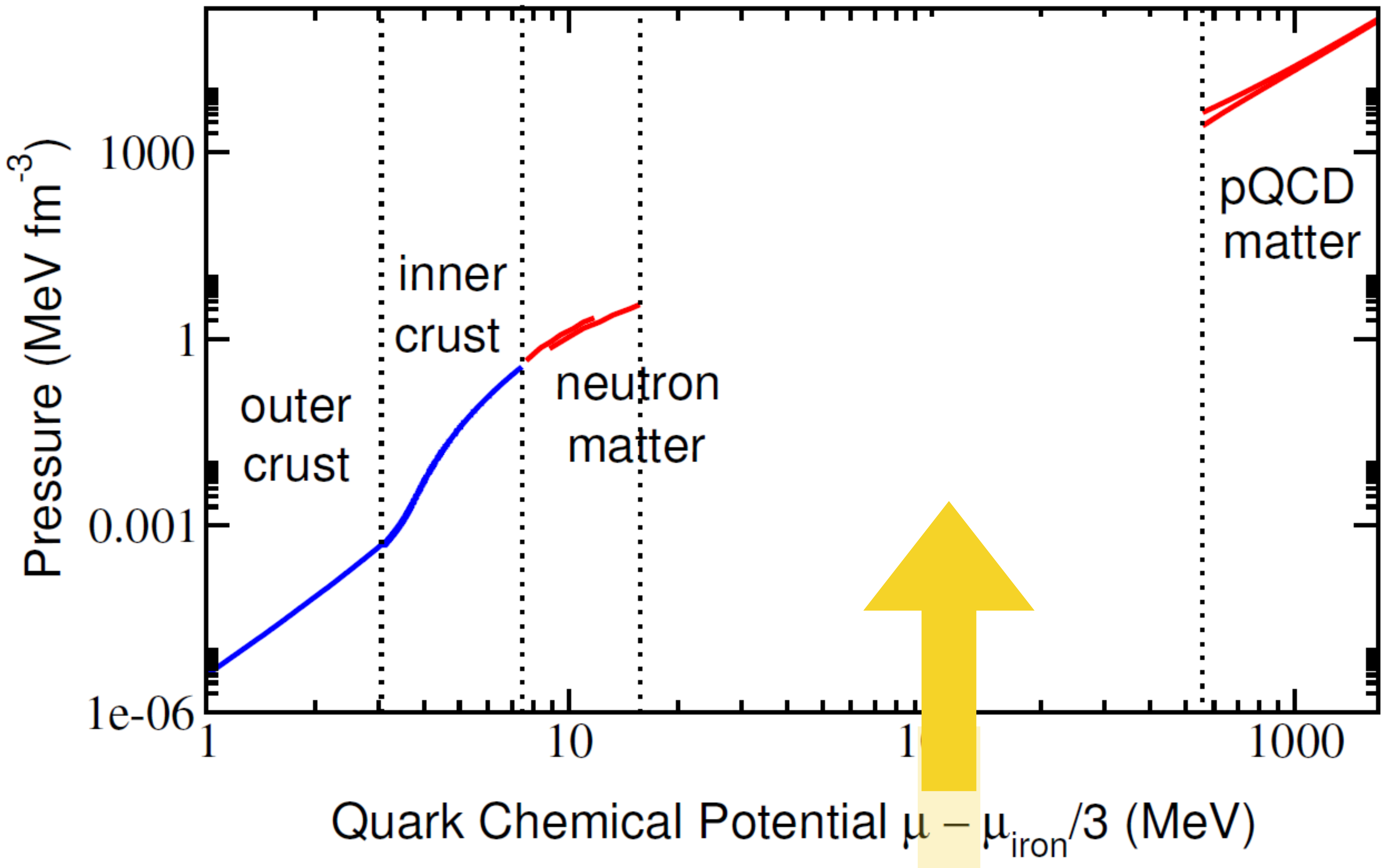


Neutron stars

EoS determines neutron star structure



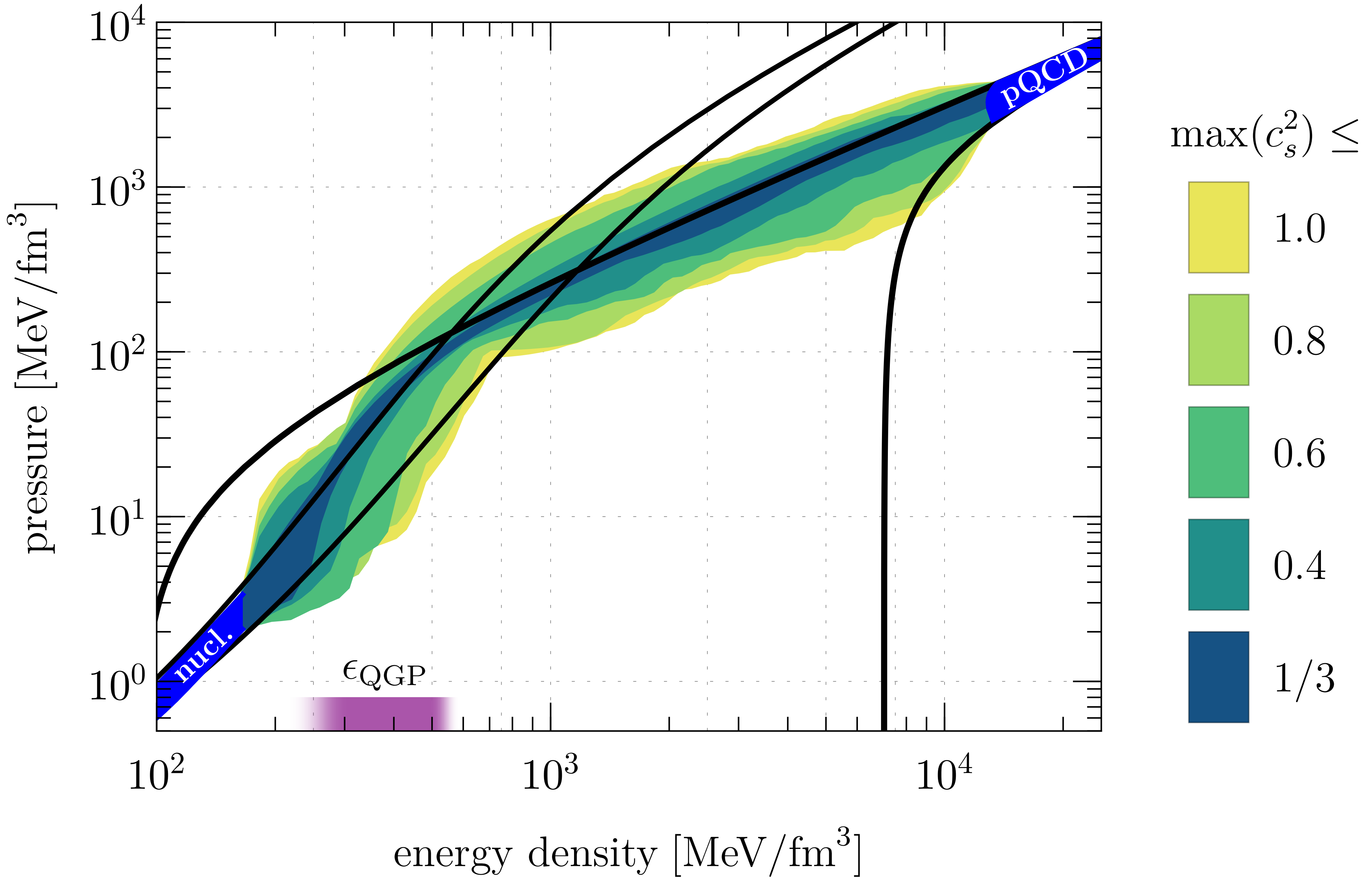


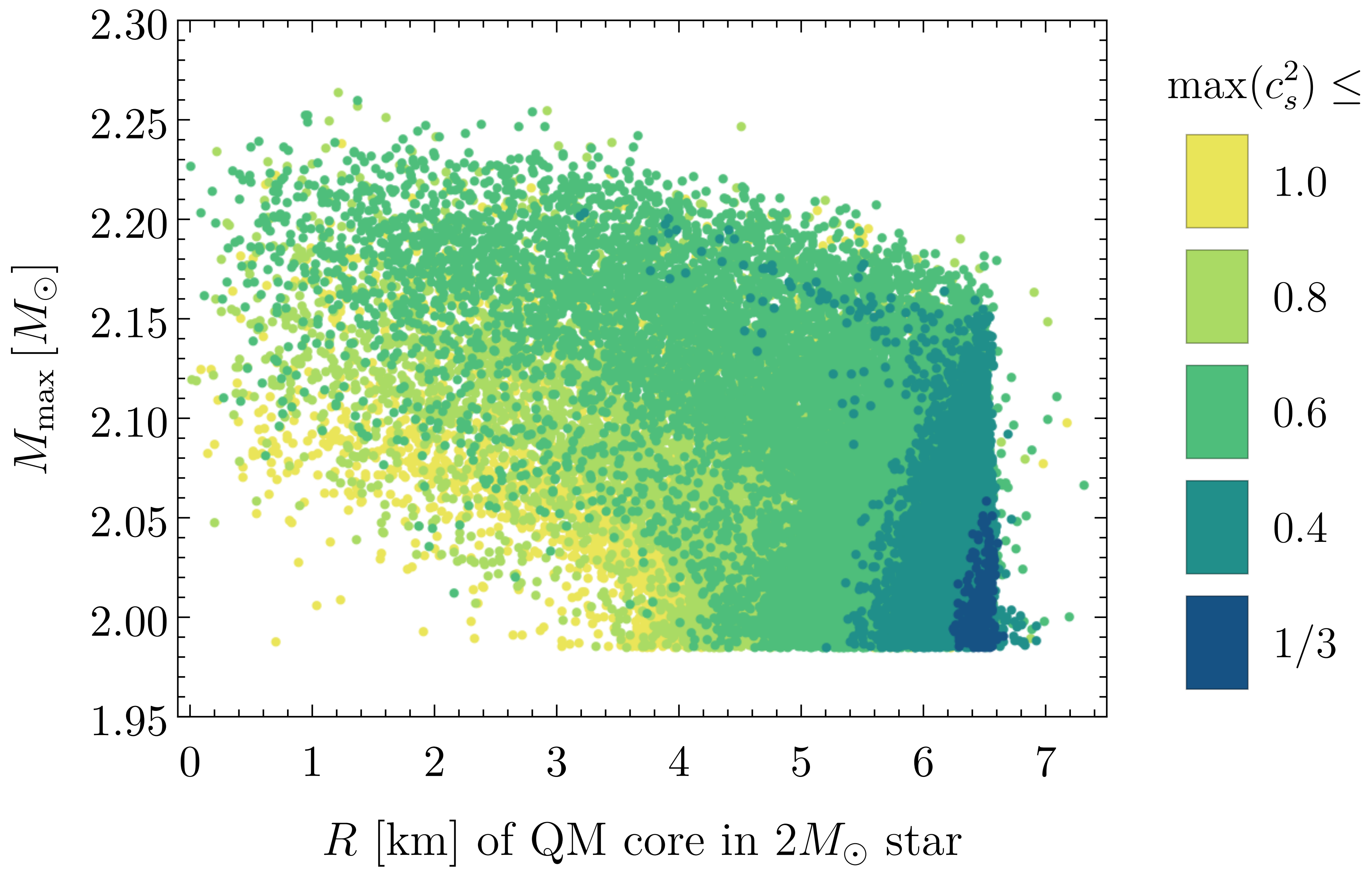
[A Vuorinen QM2018]

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

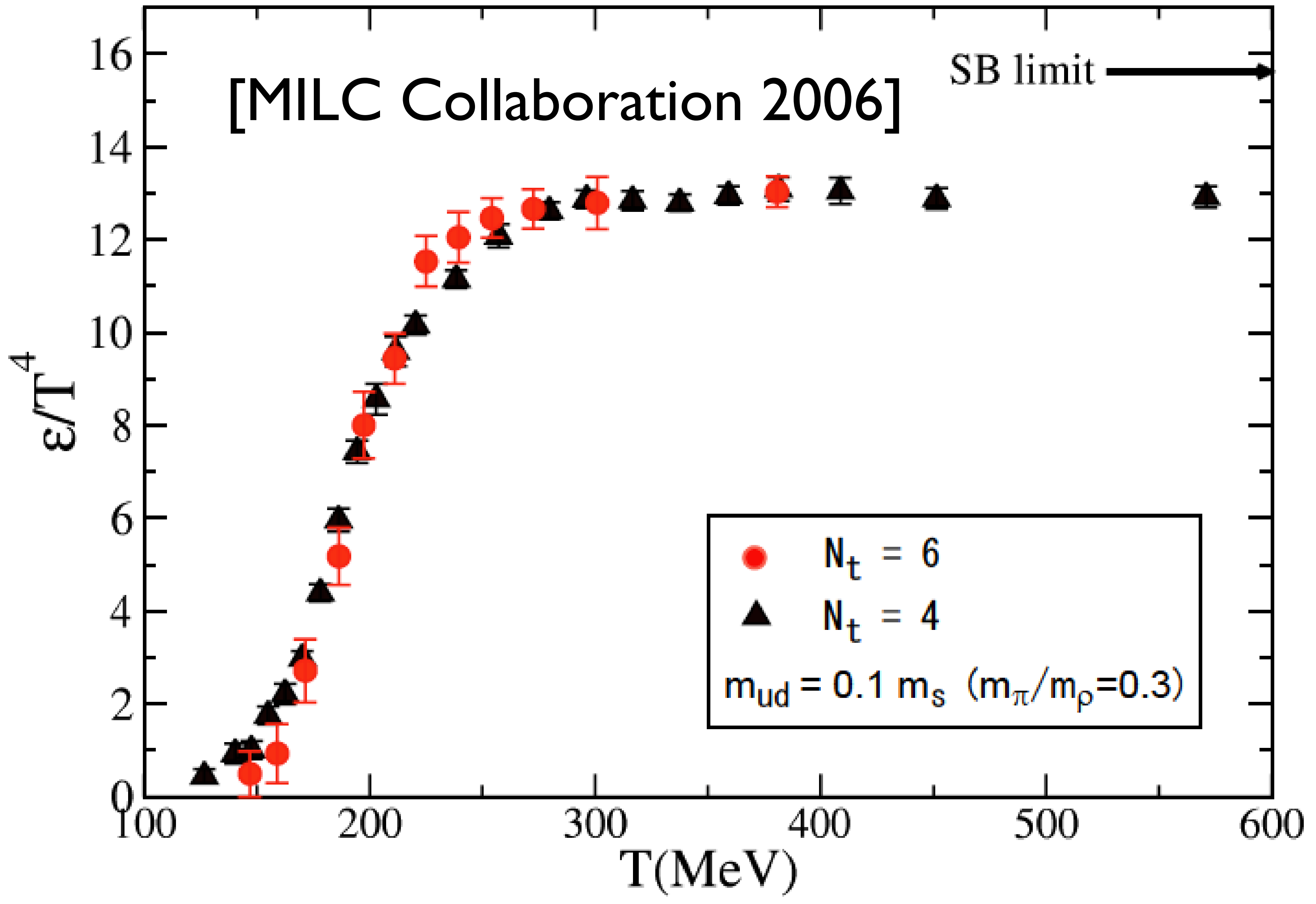
- Perturbative expansion
  - $\alpha_S(T)$ small for large $T \longrightarrow$ bad convergence, but some results obtained.
- Lattice QCD
  - Discretization in $(1/T, V)$ space
  - Contributions to Z are computed by random configurations of fields in the lattice
  - Most of the results for $\mu = 0$

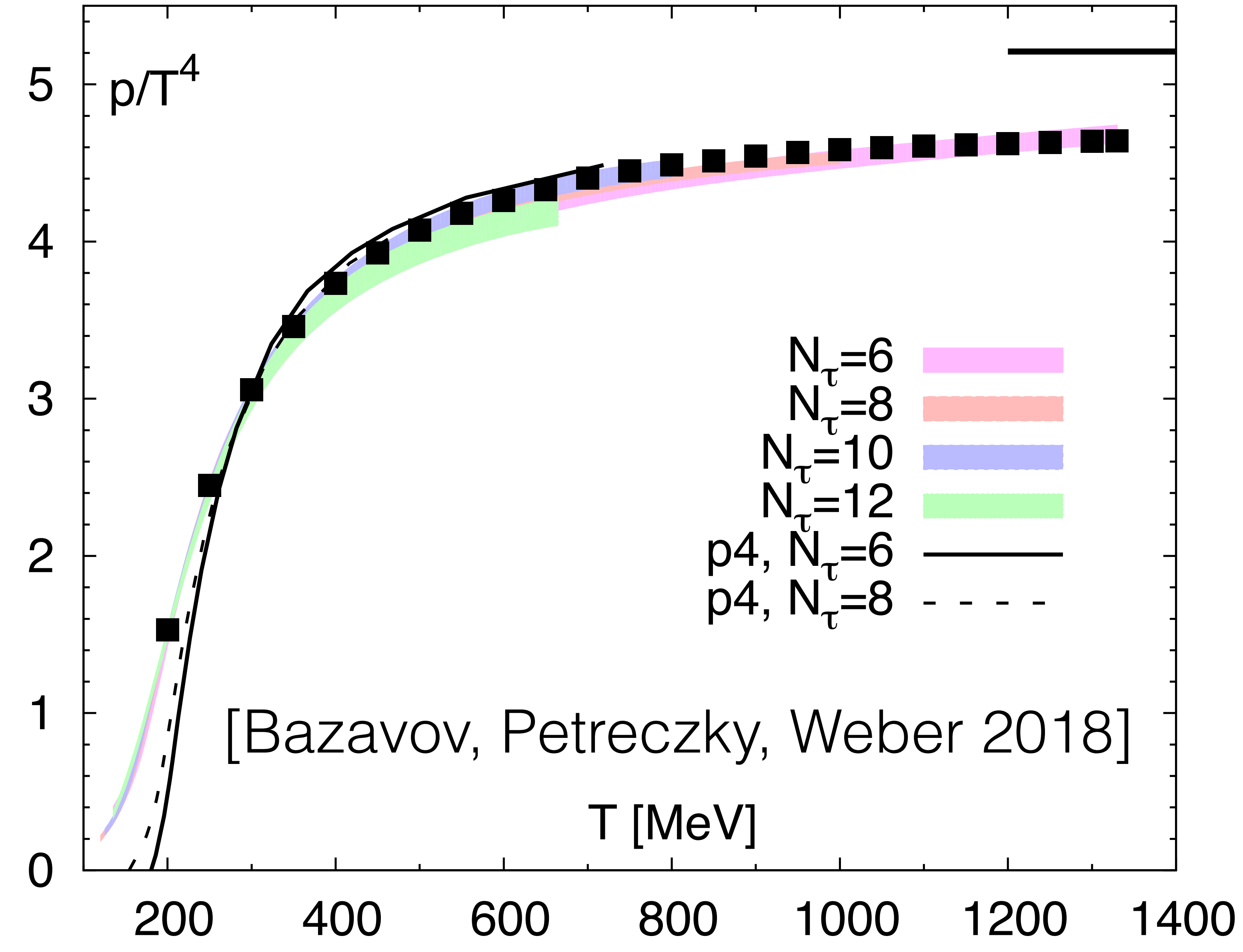
First example: EoS

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]



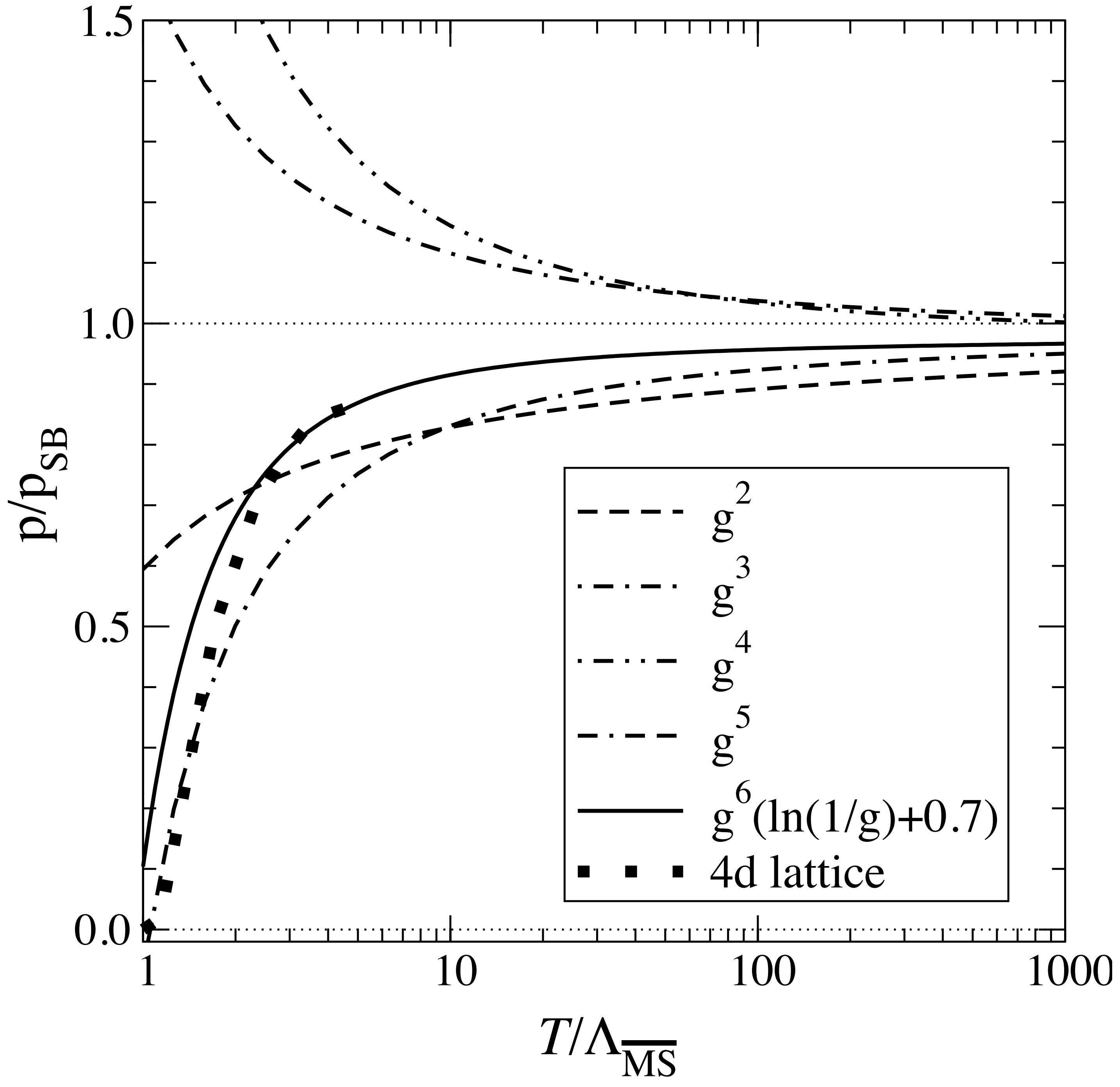


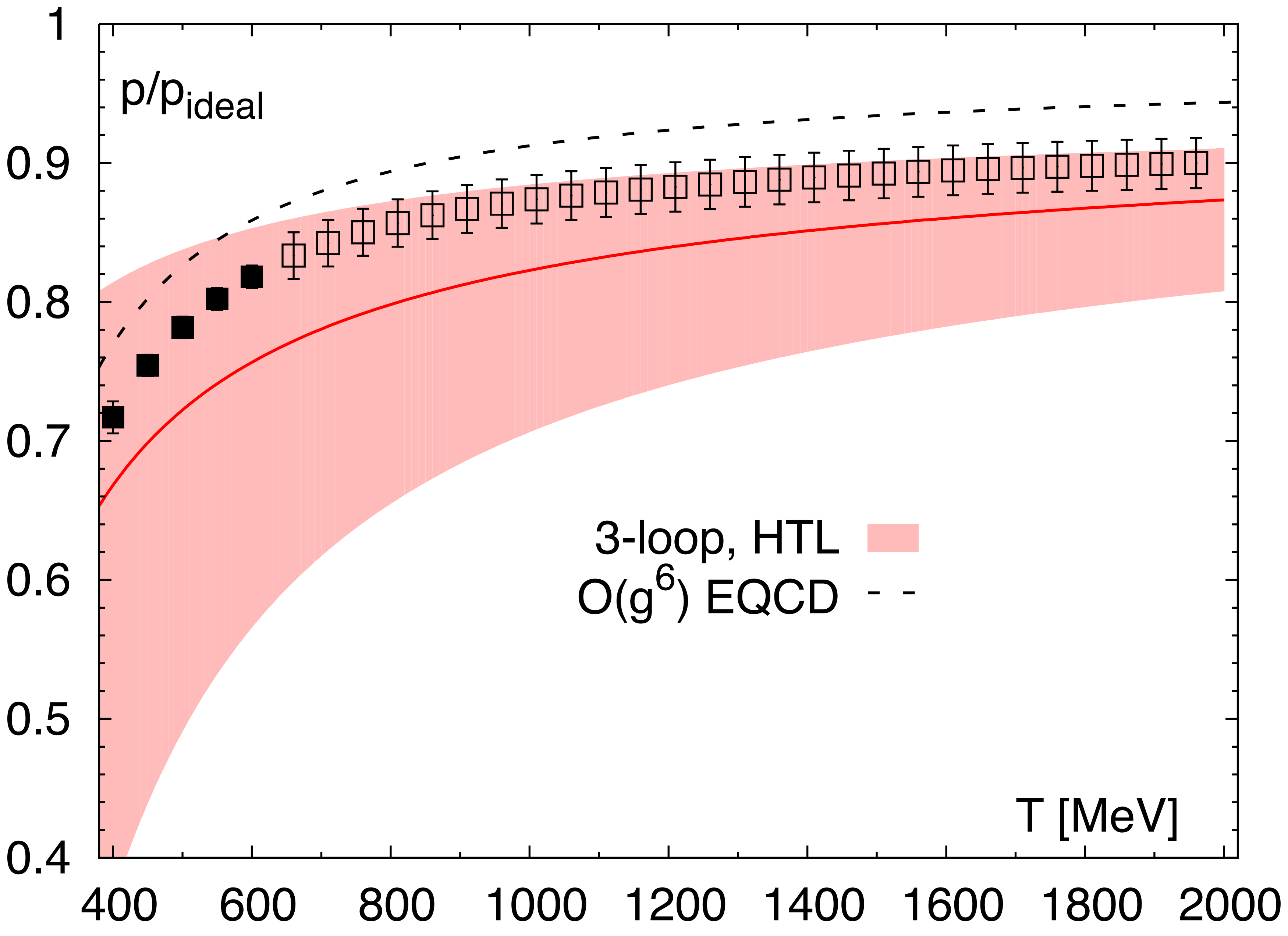
Perturbative calculations

Different orders in PT compared to lattice results

[Kajantie, Laine, Rummukainen, Schroder 2003]

[Plot from Bazavov, Petreczky, Weber 2018]

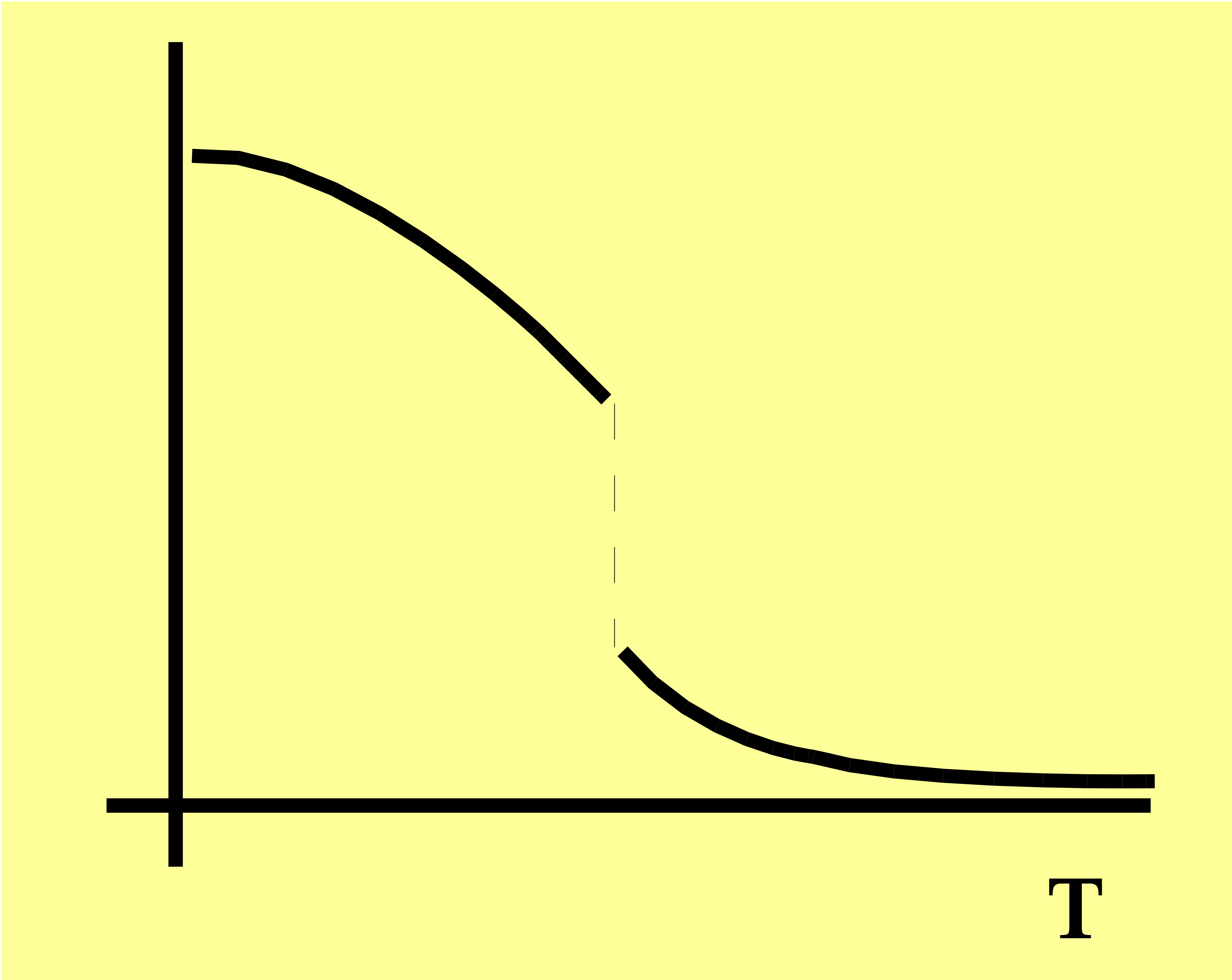




Convergence for very large temperature

Order parameters

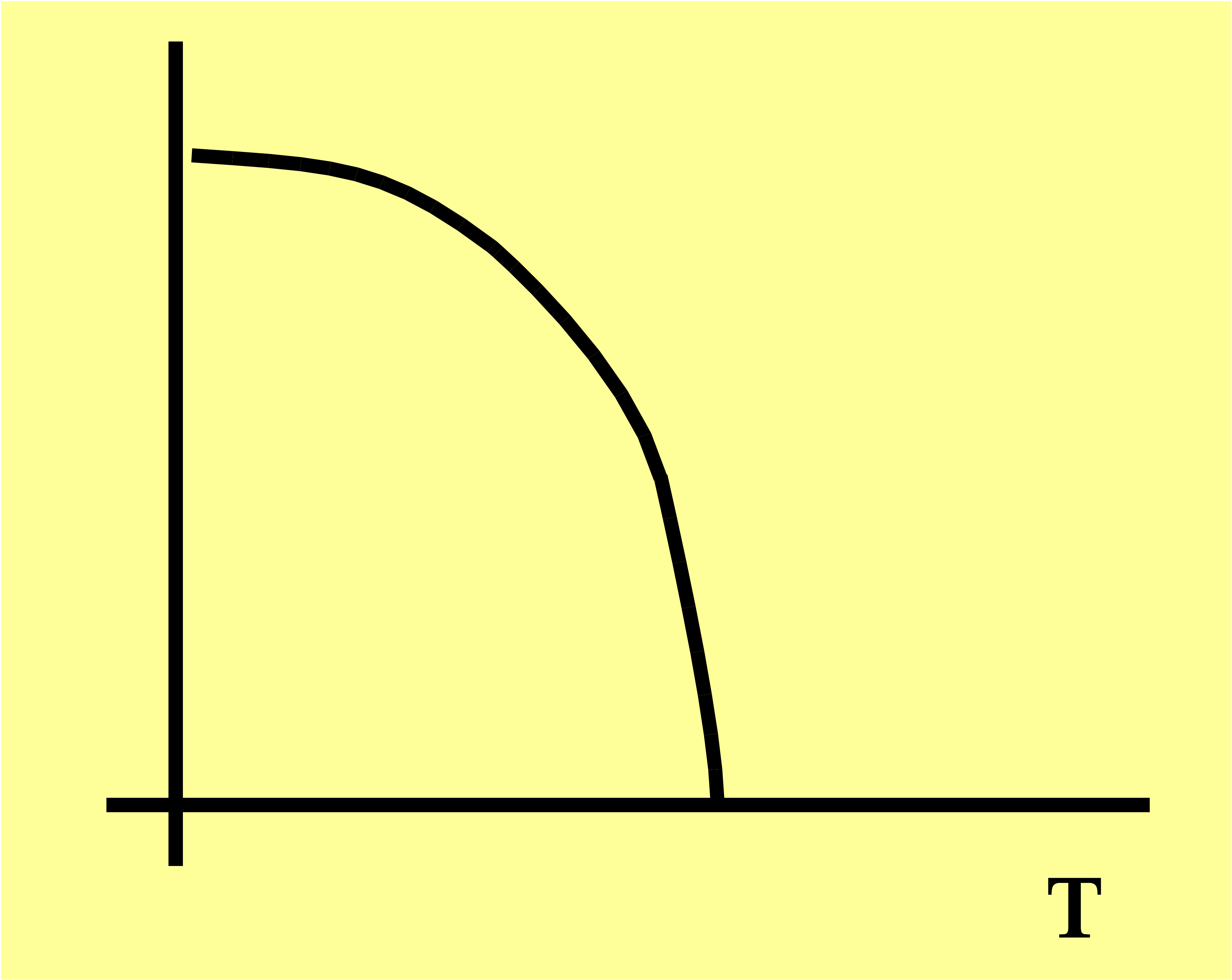
In order to know whether the change from a hadron gas to a QGP is a phase transition or a rapid cross-over order parameters are needed



First order: discontinuity in the order parameter

Order parameters

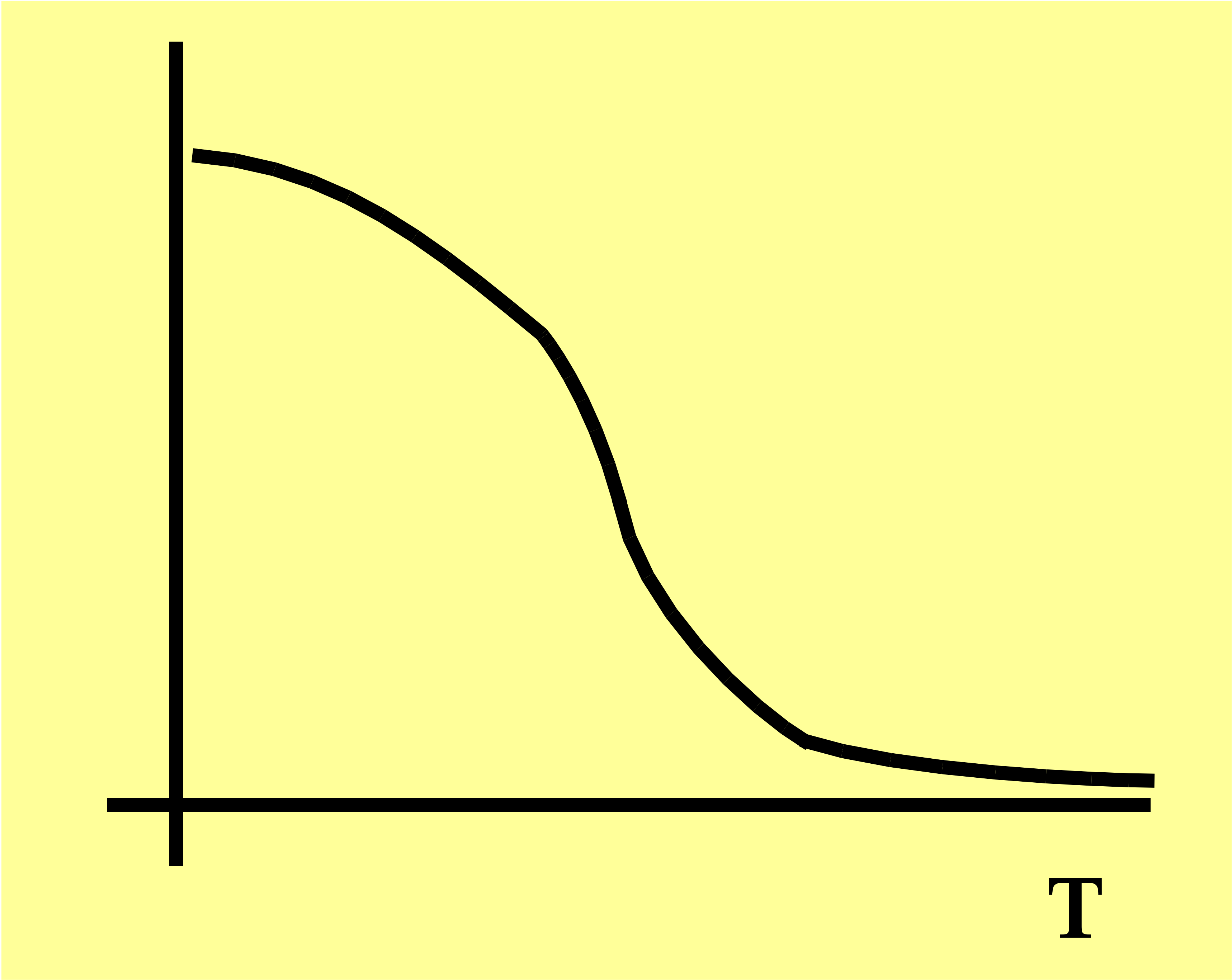
In order to know whether the change from a hadron gas to a QGP is a phase transition or a rapid cross-over order parameters are needed



Second order: discontinuity in the derivative

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



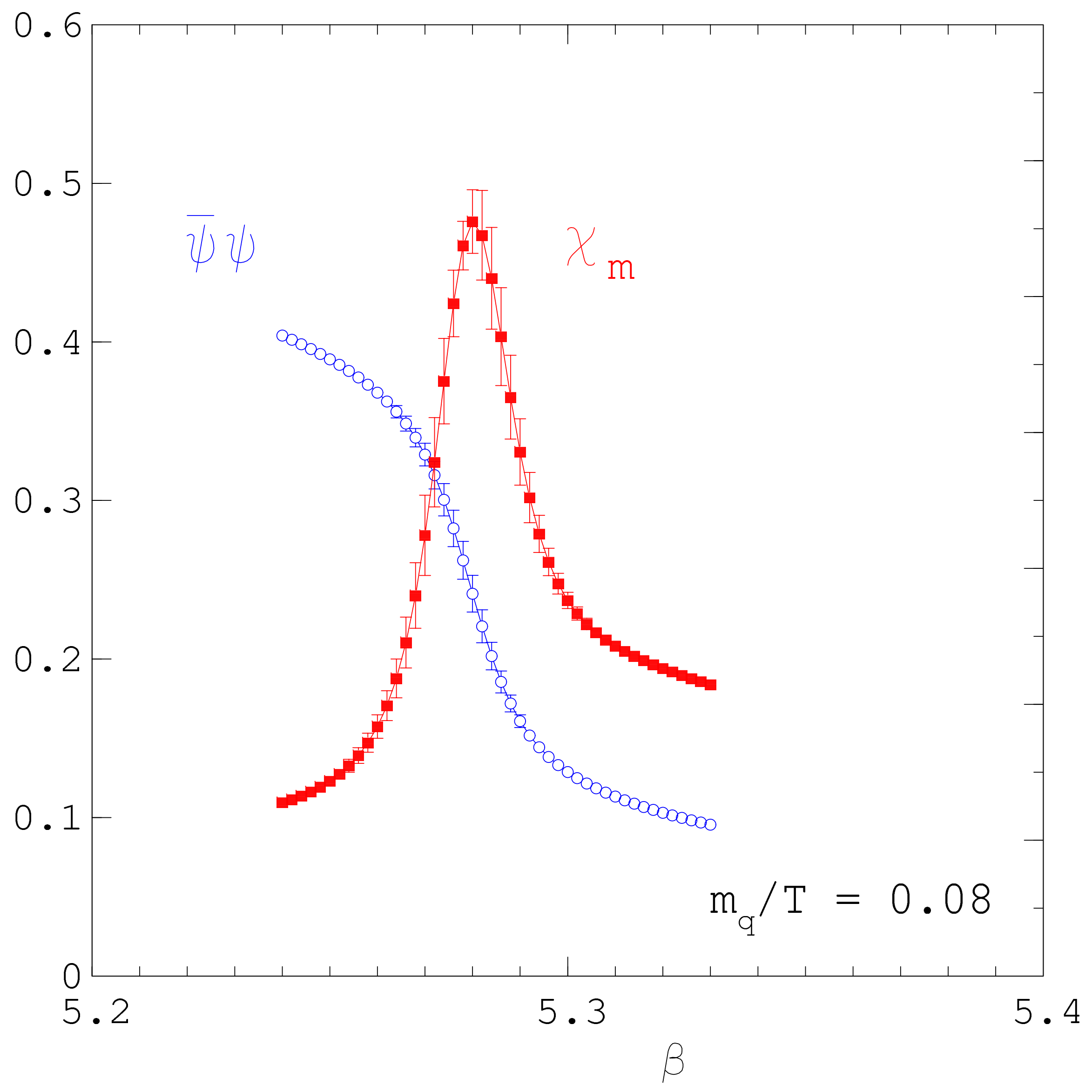
Cross-over: continuous function

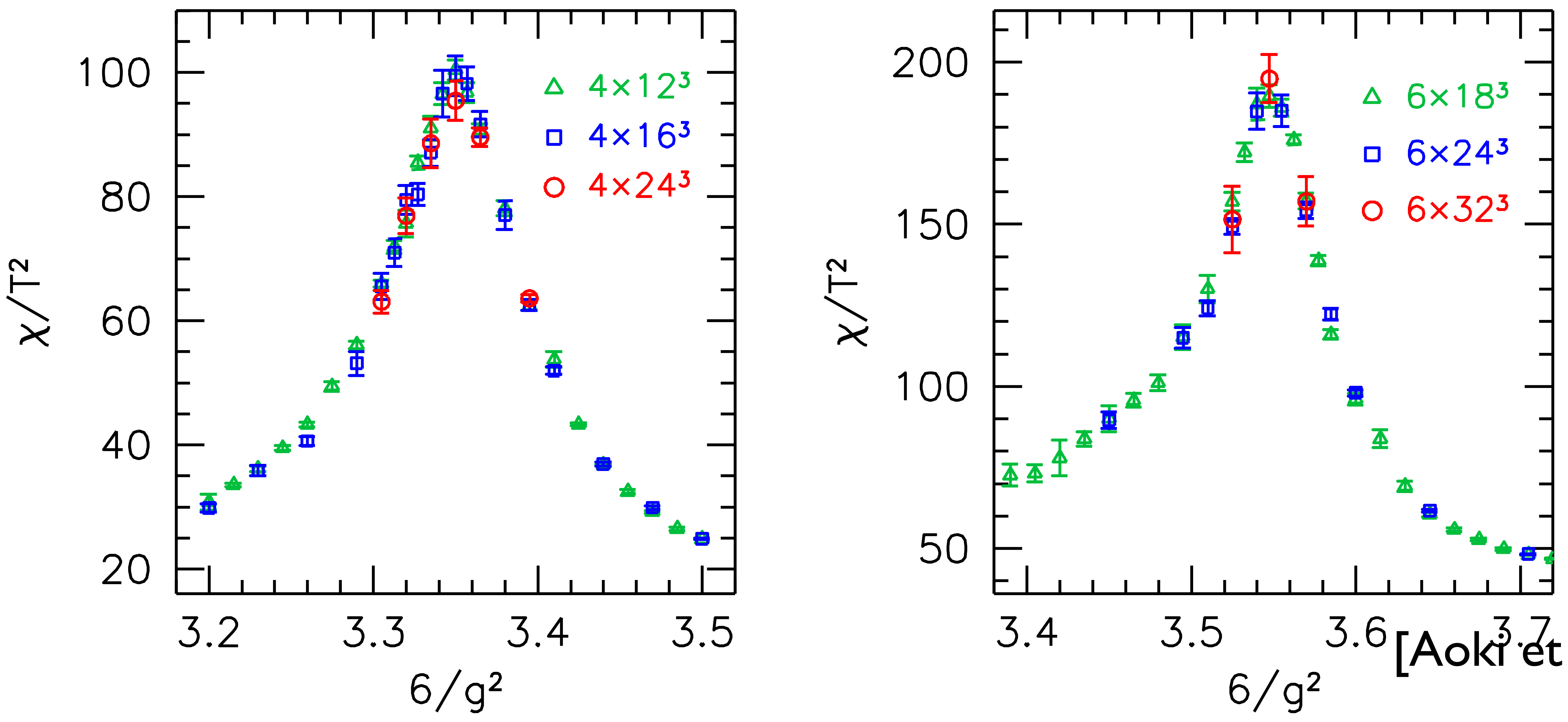
QCD order parameters I

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

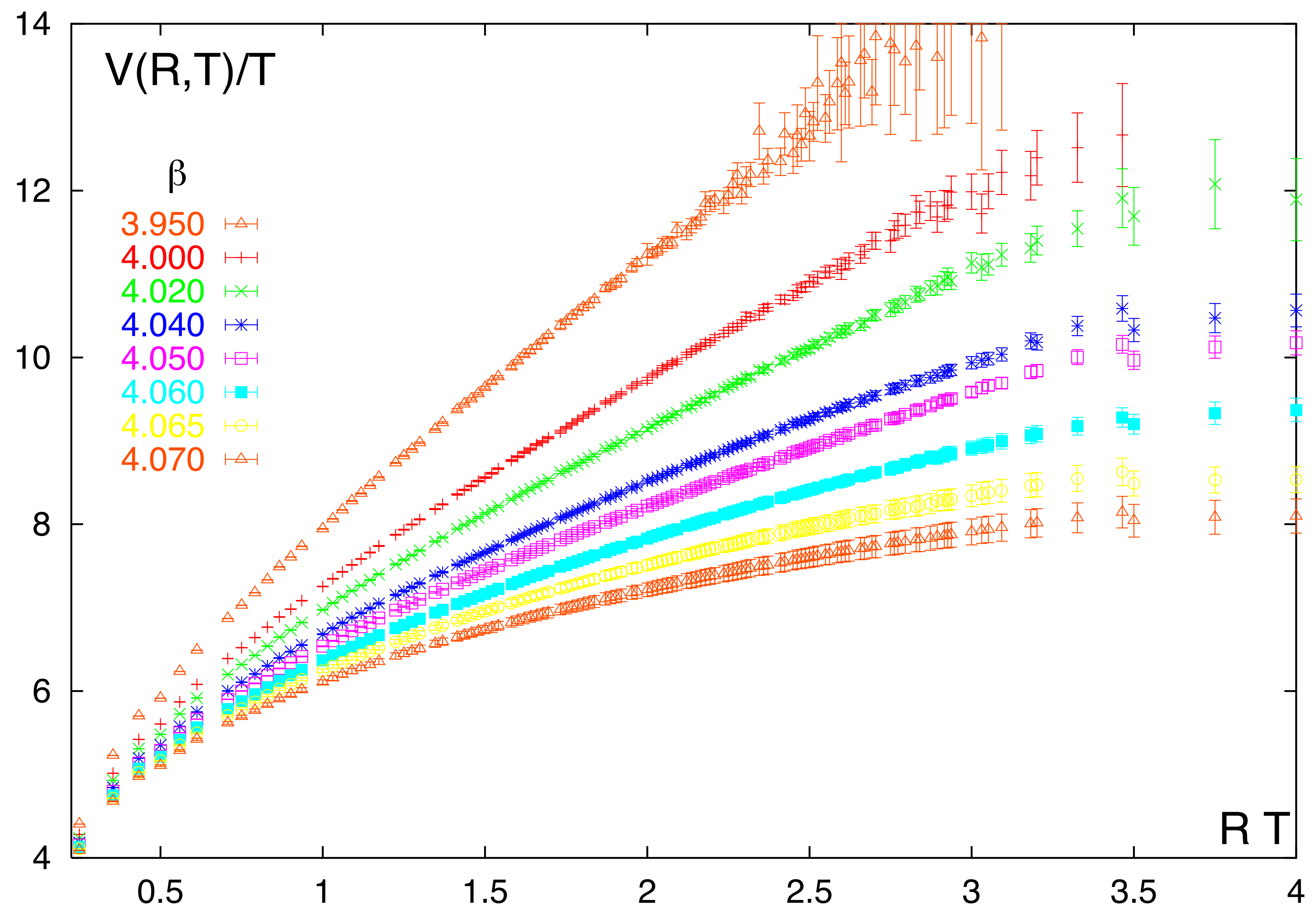


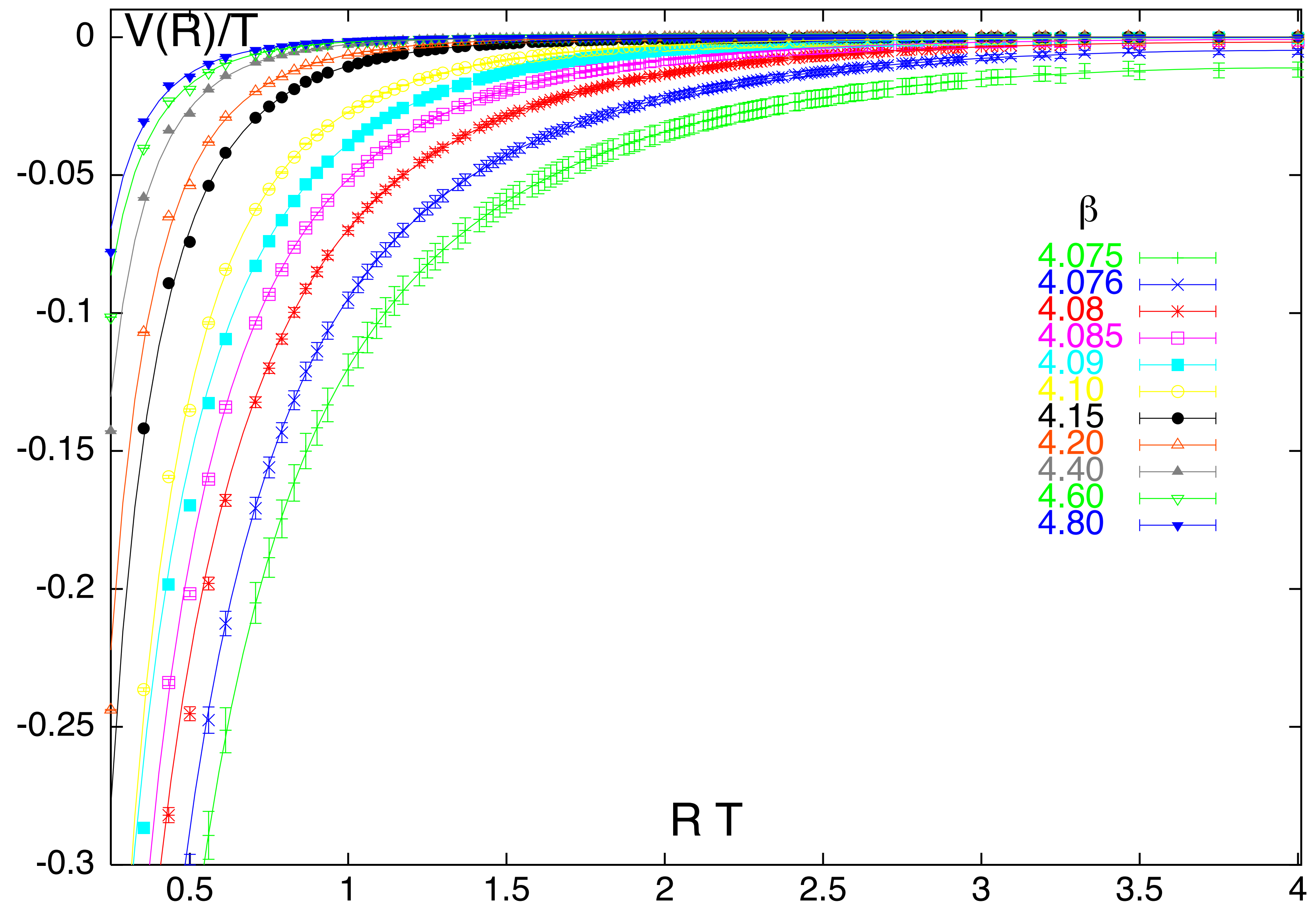


[Aoki et al 2006]

QCD order parameters II

Confinement: for. $m_q \to \infty$ the order parameter is the potential



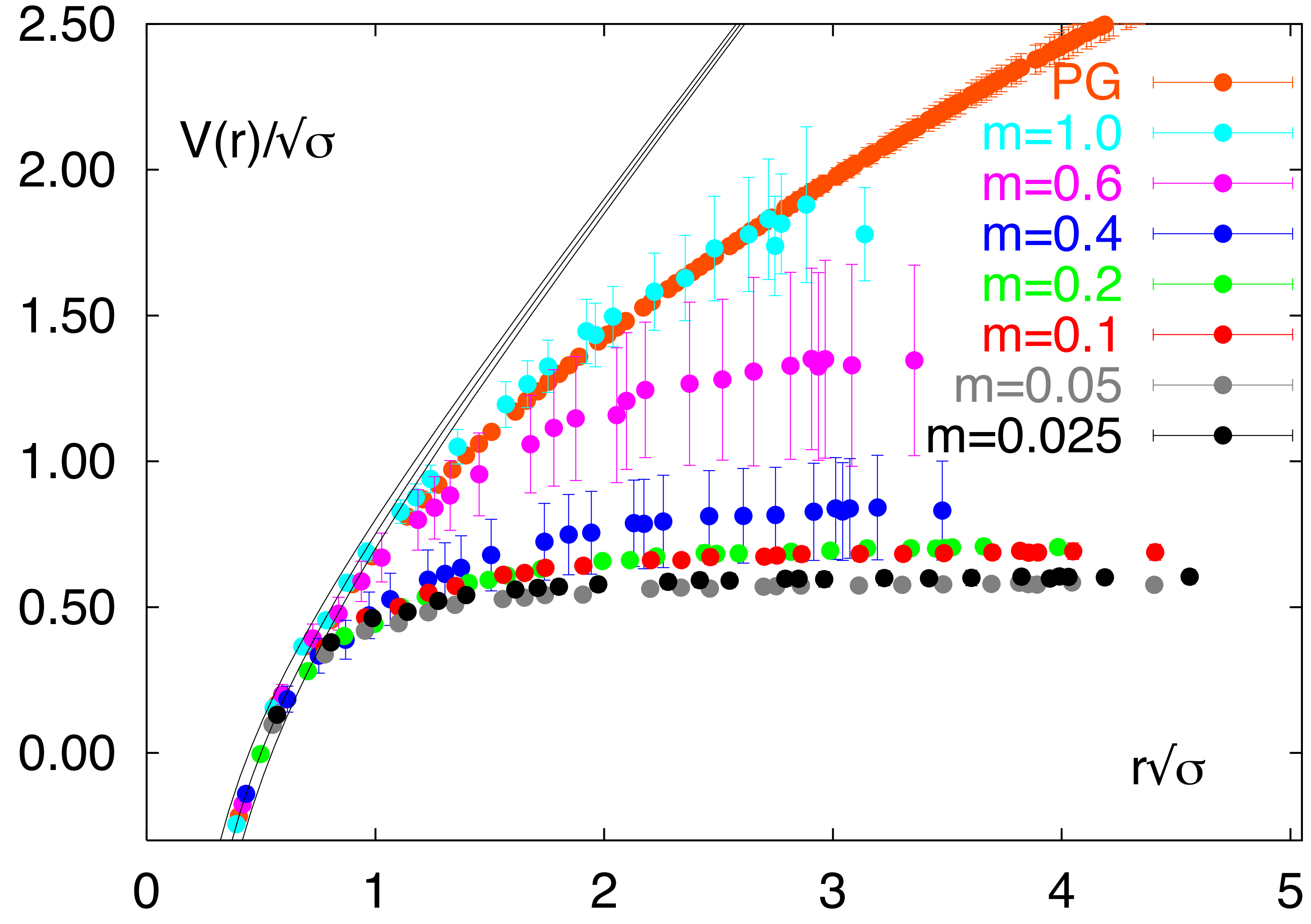


$T < T_c$ $\qquad$ $T > T_c$

[Kaczmarek et al 2000]

However…

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



[Karsch, Laermann, Peikert 2001]

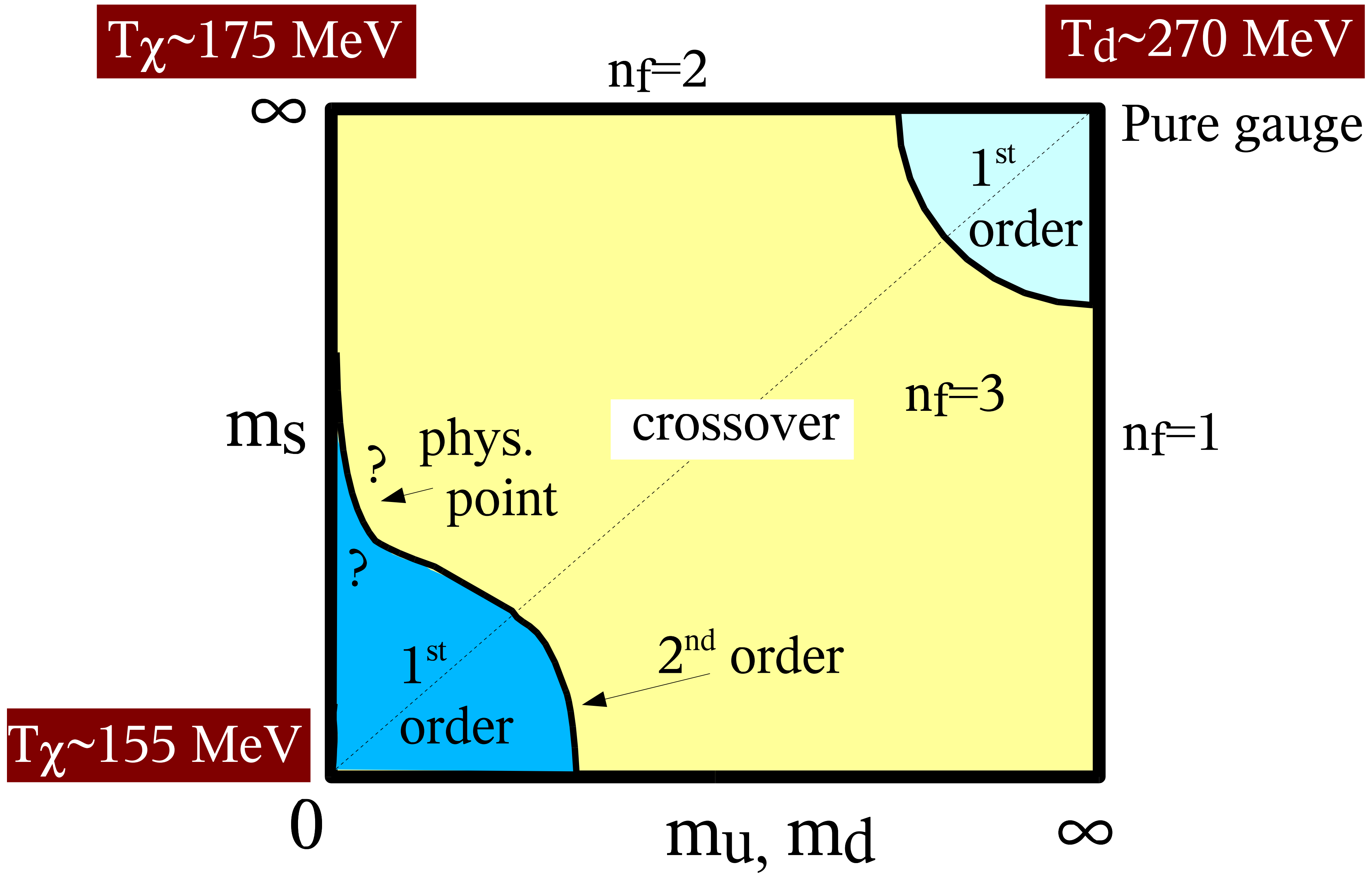
Light $\bar{q}q$ pair creation breaks the string

Physical quark masses

Two order parameters

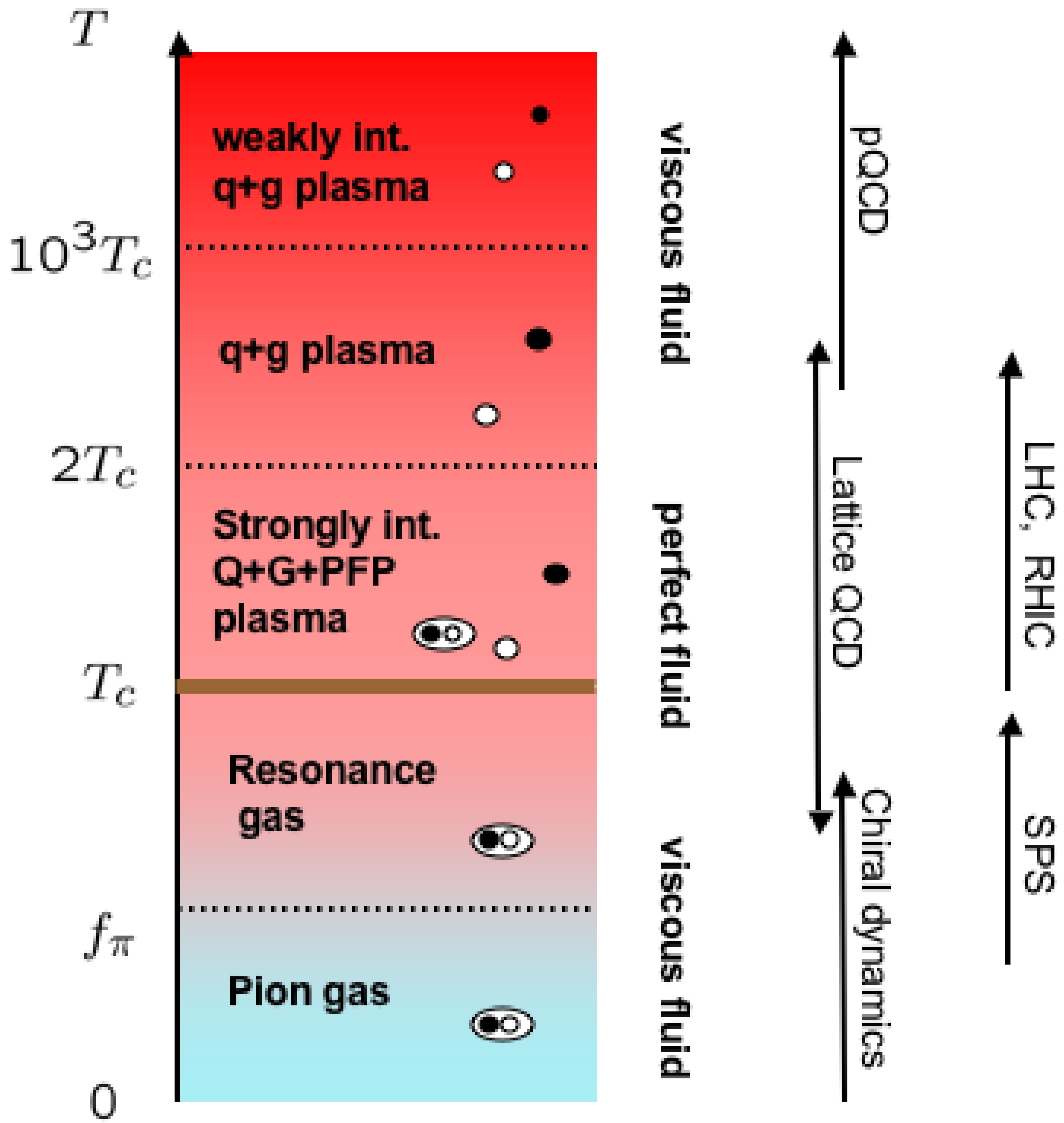
$\Rightarrow$ $m_q = 0 \longrightarrow$ Chiral condensate

$\Rightarrow$ $m_q = \infty \longrightarrow$ Potential



For physical masses, all results indicate a cross over

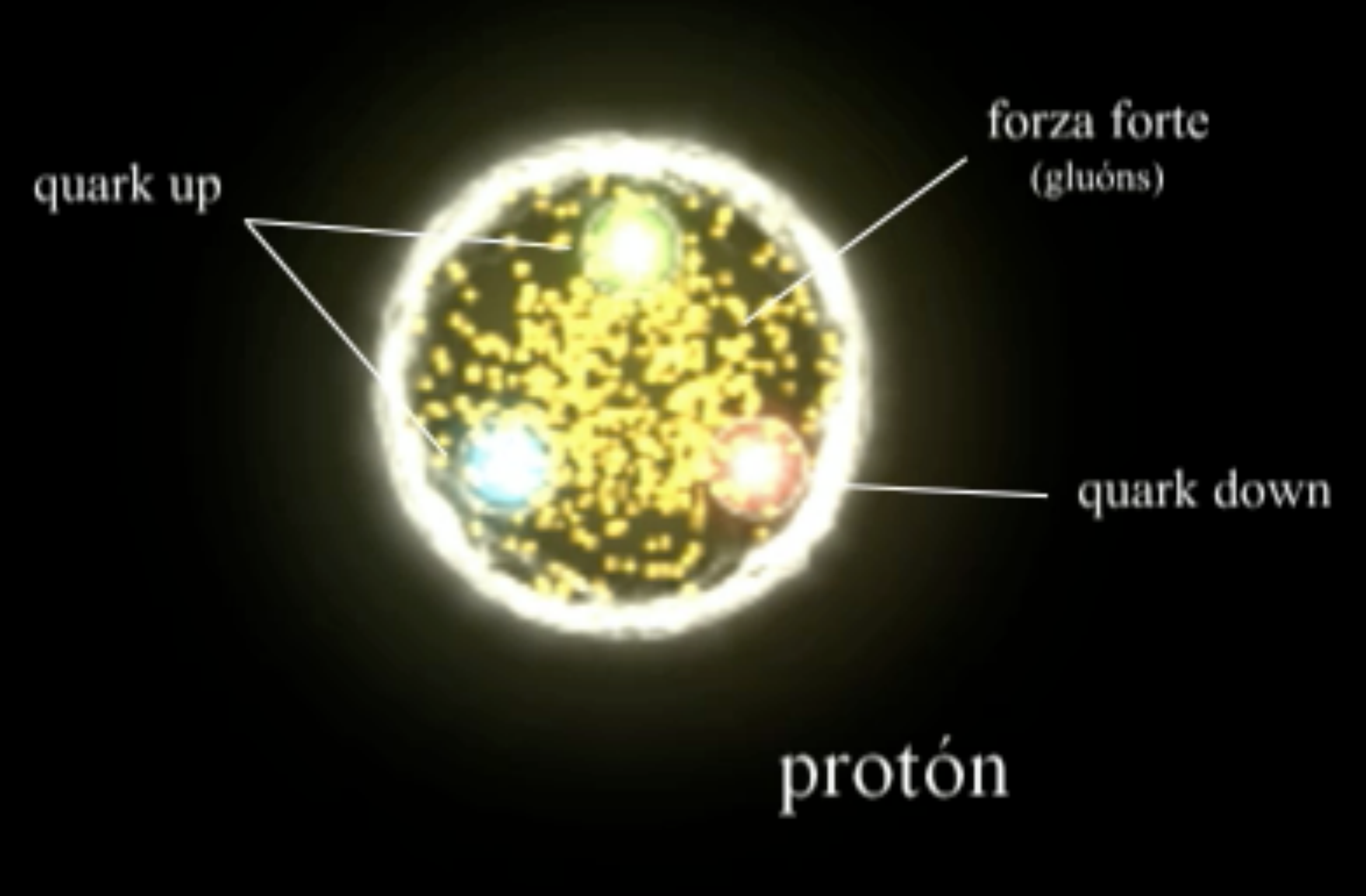
A possible picture of hot QCD



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

High energy heavy ion collisions: Collectivity and new phases of QCD

QCD: first levels of complexity at the most fundamental level
at scales easy to reach in collider experiments



[Confinement; chiral symmetry breaking and mass generation; new phases of matter; hadronic spectra; non-trivial vacuum structure; asymptotic freedom…]

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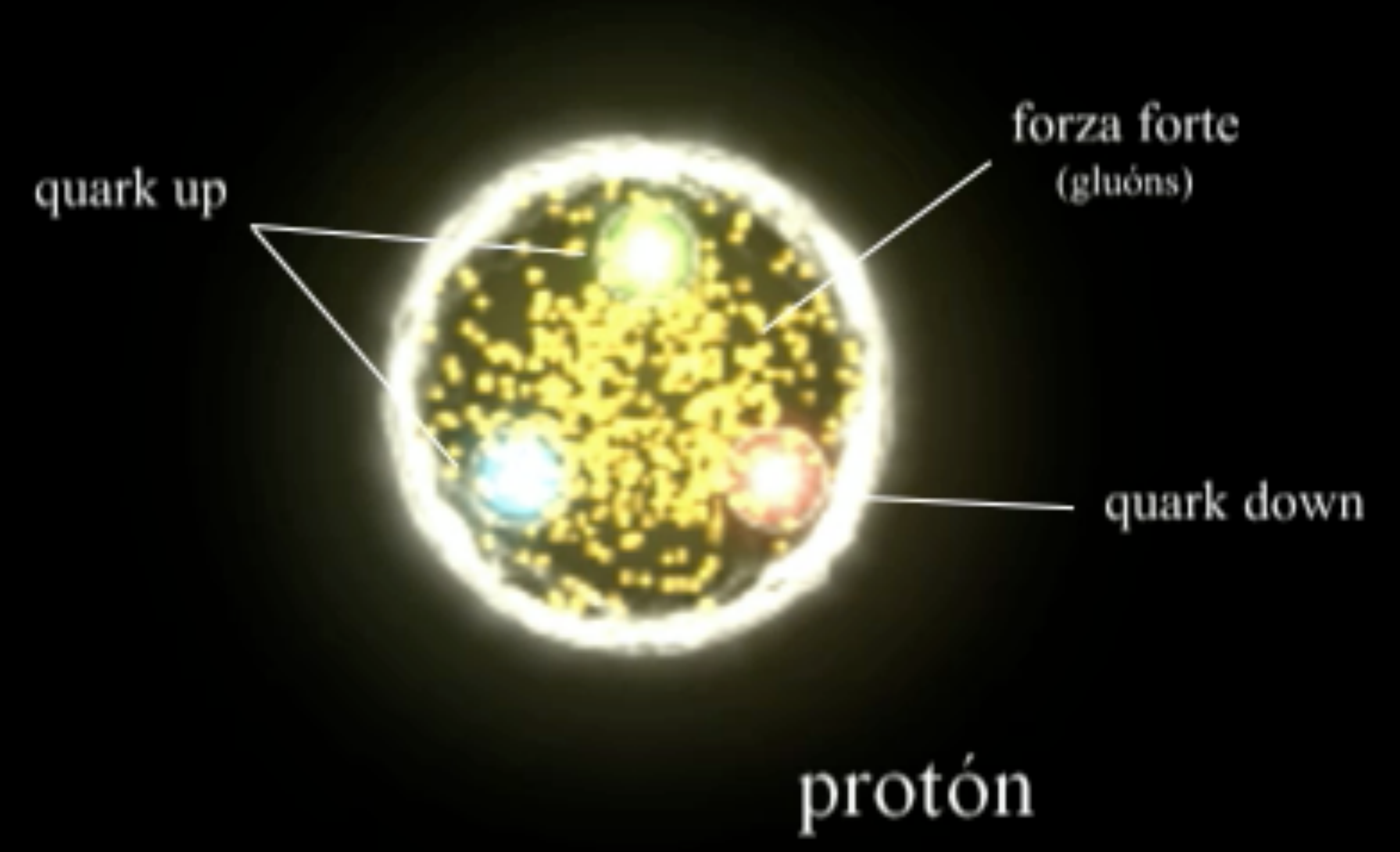
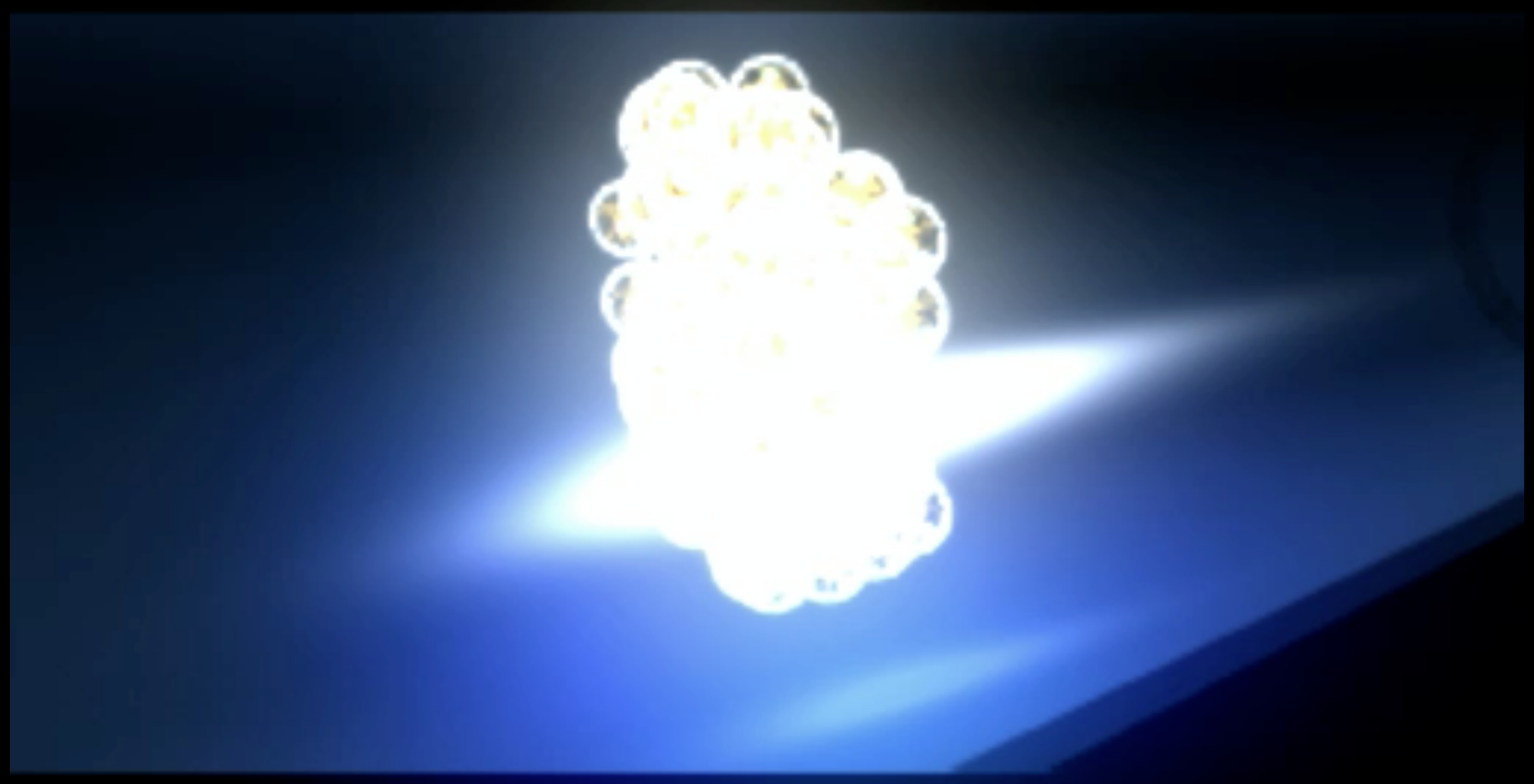
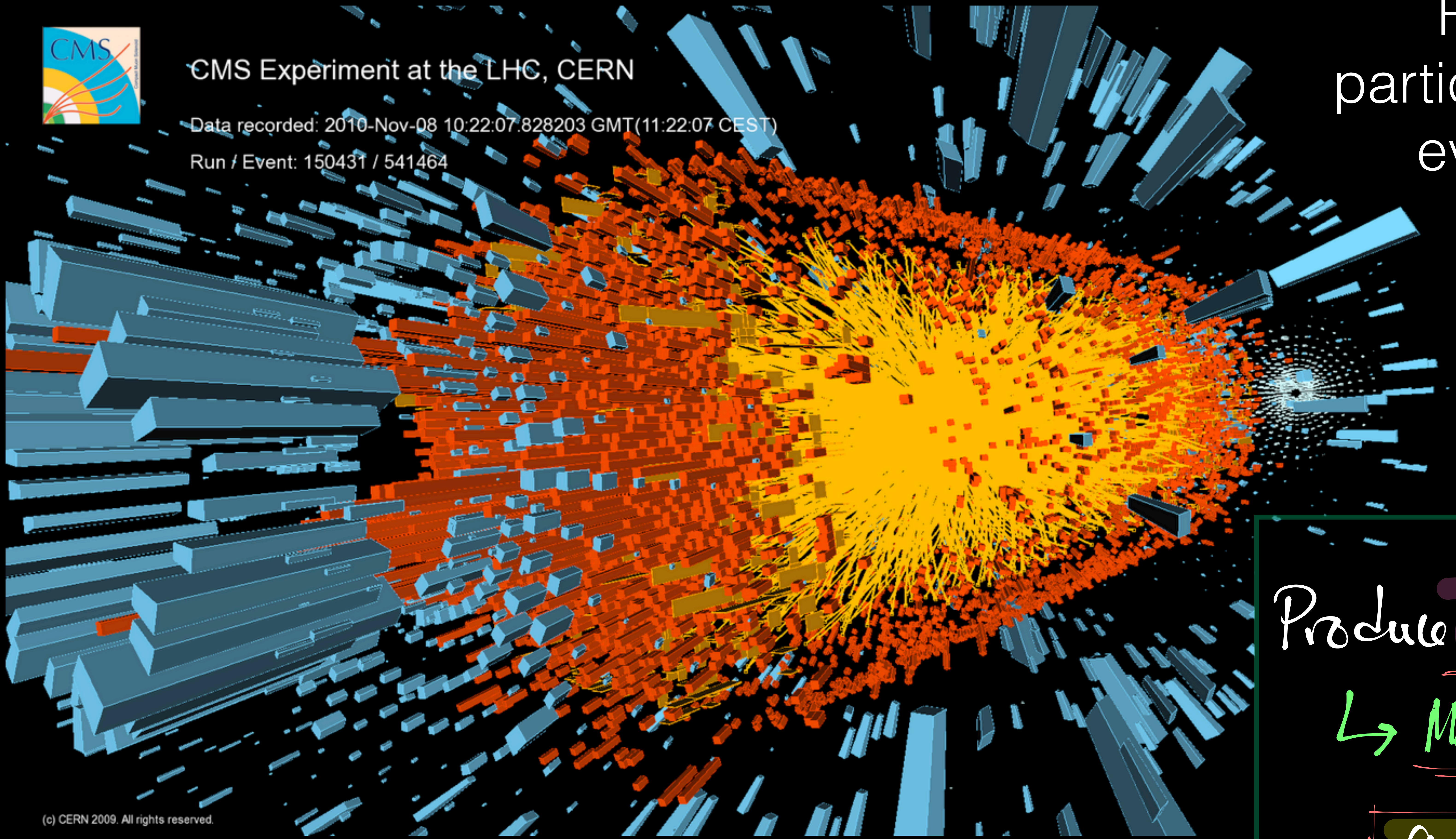




[Confinement; chiral symmetry breaking and mass generation; new phases of matter; hadronic spectra; non-trivial vacuum structure; asymptotic freedom…]



Huge number of particles in central PbPb events at the LHC

Produce "large" objects

↳ Macroscopic in QCD scale

Collide heavy nuclei

Summary

QCD is the theory of strong interactions

- **QCD has a rich dynamical content well within experimental reach**
  - 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
- Needed for all phenomenology at hadron colliders (and most of other colliders as well)

— not that much mentioned here but very important…

Asymptotic freedom allows to perform perturbative computations at large scales

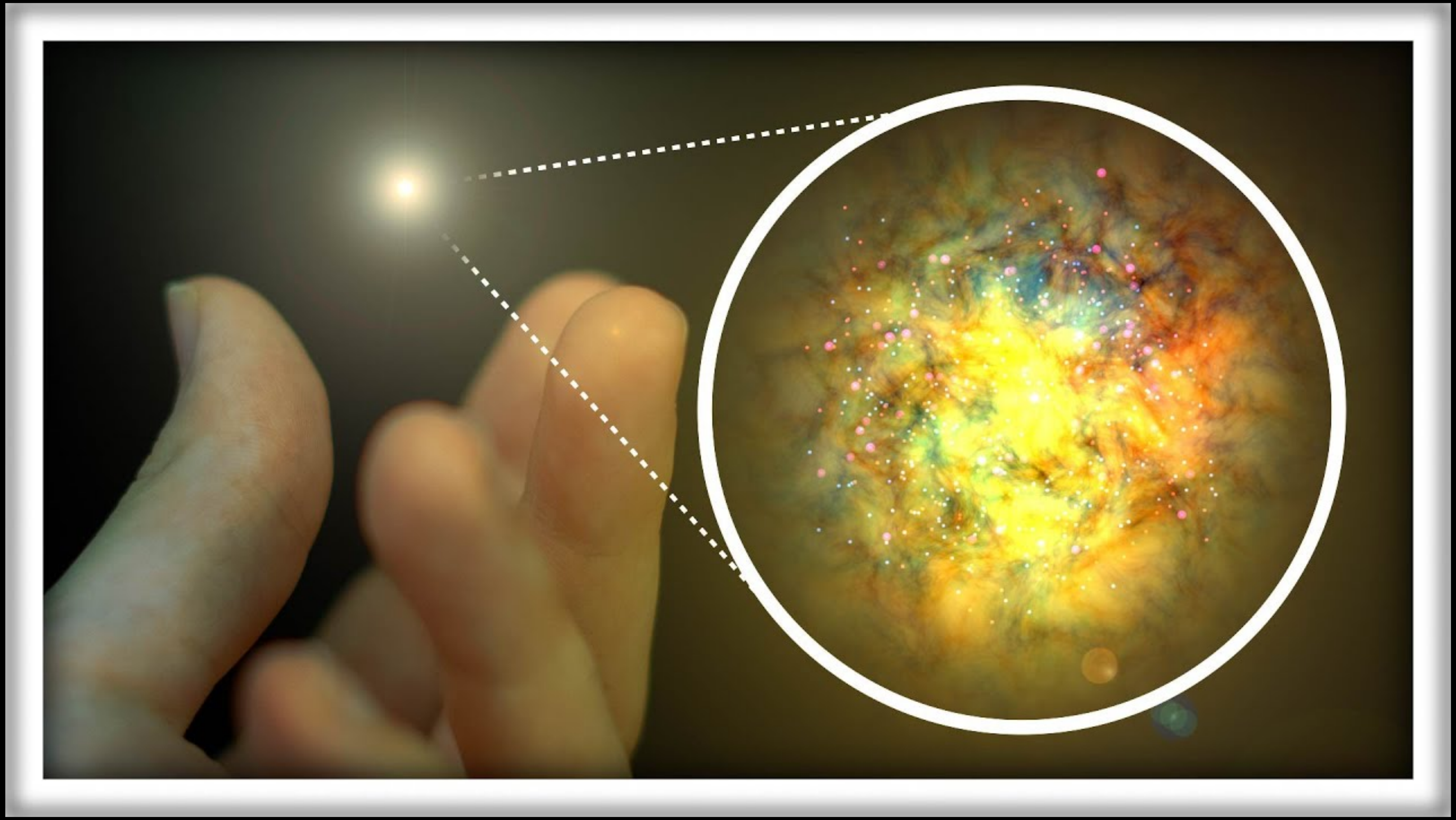
- However, non-perturbative contributions always present (due to confinement)

Jets and Parton Distribution Functions (PDFs) two main tools at the LHC

Huge effort in precision computations at NNLO and more

For Fun

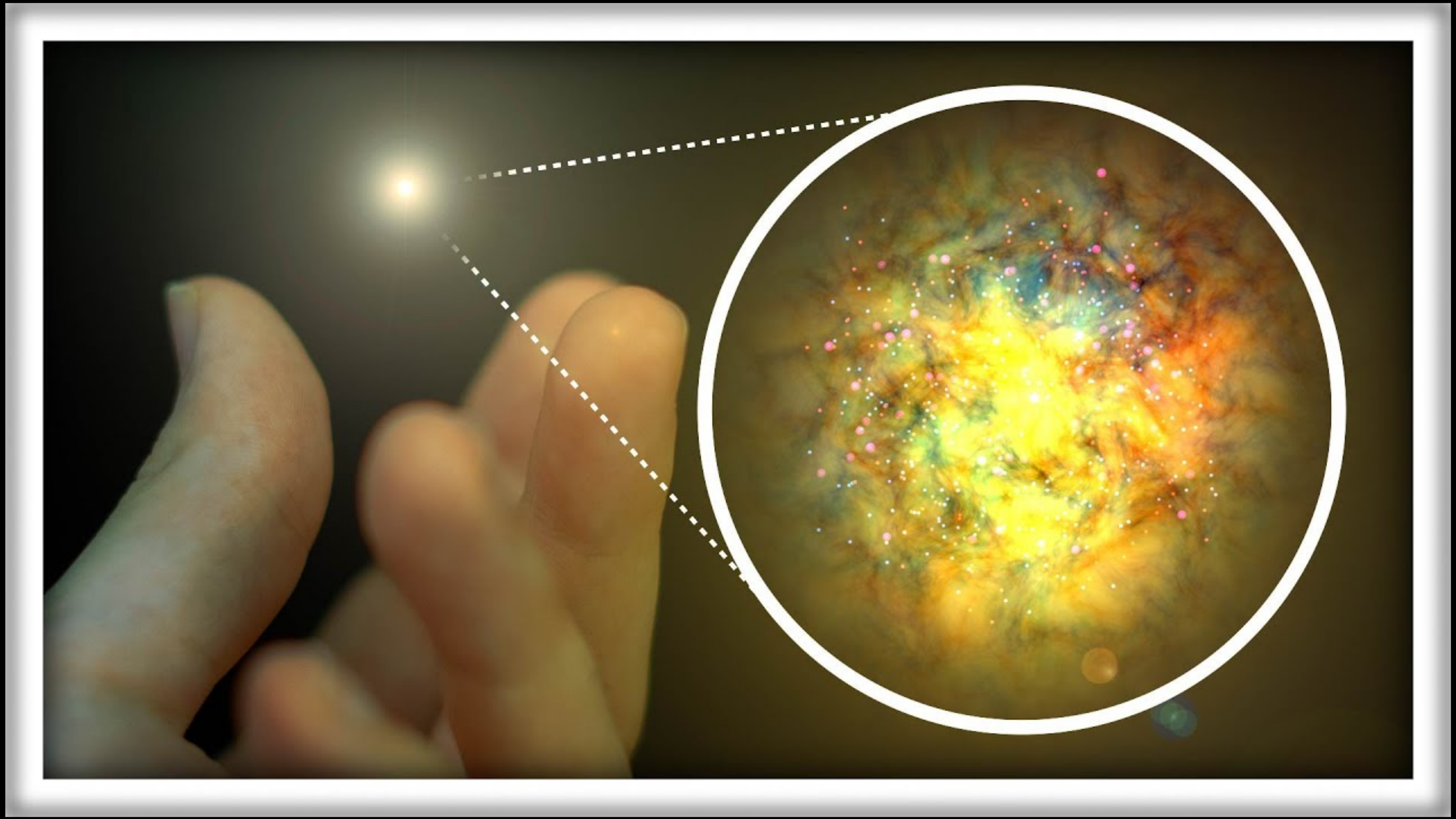
Youtube video - QGP (in Spanish)



https://youtube.com/watch?v=JdahywF2_D4

For Fun

Youtube video - QGP (in Spanish)



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