High-energy heavy-ion collisions.
Selected phenomenological aspects

Nicolas BORGHINI

Universität Bielefeld

Joint B-D-NL graduate school, Texel, September 2008

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Selected phenomenological aspects

- Lecture I. Introduction - First steps
  - Motivation(s)
  - Multiplicity distributions: characterizing the collision geometry
- Lecture II. "Collective flow"
- Lecture III. "Hard probes": high-p_T particles

Short incomplete history...

- 60's: protons & neutrons are made up of coloured quarks (bound together by gluons). Quarks cannot escape a nucleon.

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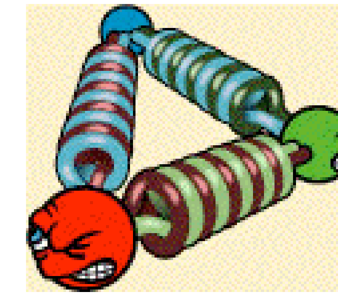

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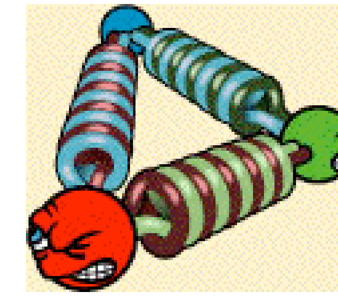

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> When the *energy* density ε exceeds some typical hadronic value (~1 GeV/fm³), matter no longer consists of separate hadrons (protons, neutrons, etc.), but of their fundamental constituents, quarks and gluons. Because of the apparent analogy with similar phenomena in atomic physics we may call this phase of matter the QCD (or quark-gluon) plasma.

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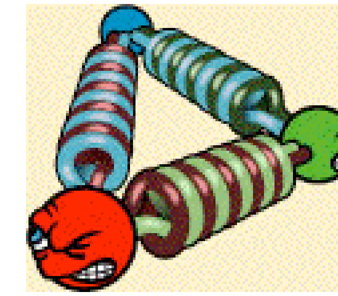

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$\simeq 3\times 10^{18}$ kg/m^3

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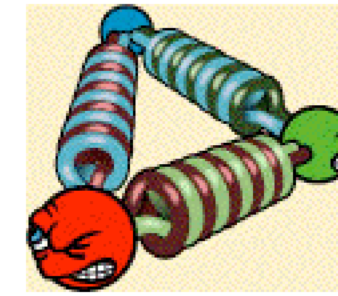

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- cf. Hagedorn (1965): there is a highest possible temperature for a hadron gas ("for strong interactions"), $T \approx 158$ MeV.

Phase diagram of hadronic matter

Volume 59B, number 1 PHYSICS LETTERS 13 October 1975

EXPONENTIAL HADRONIC SPECTRUM AND QUARK LIBERATION

N. CABIBBO
Istituto di Fisica, Universitá di Roma,
Istituto Nazionale di Fisica Nucleare, Sezione di Rome, Italy

G. PARISI
Istituto Nazionale di Fisica Nucleare, Frascati, Italy

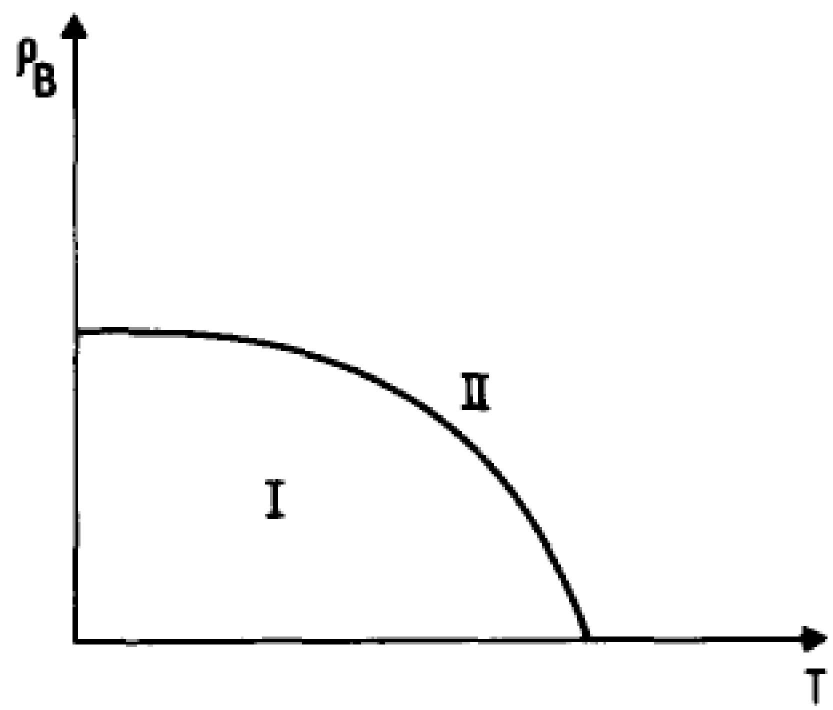

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

QCD transition in the early Universe

- Just after the Big Bang, the Universe, at a temperature ≈ 1 TeV, was filled with a plasma of quarks and gluons.

- About 10 ms after the Big Bang, the temperature is down to about 170 MeV and the quarks and gluons are confined into hadrons.

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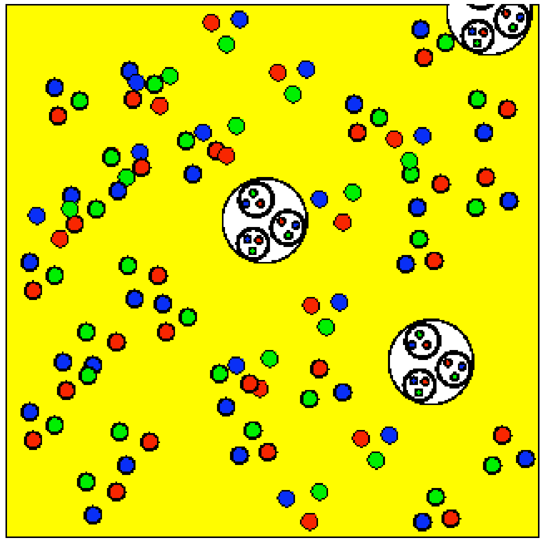

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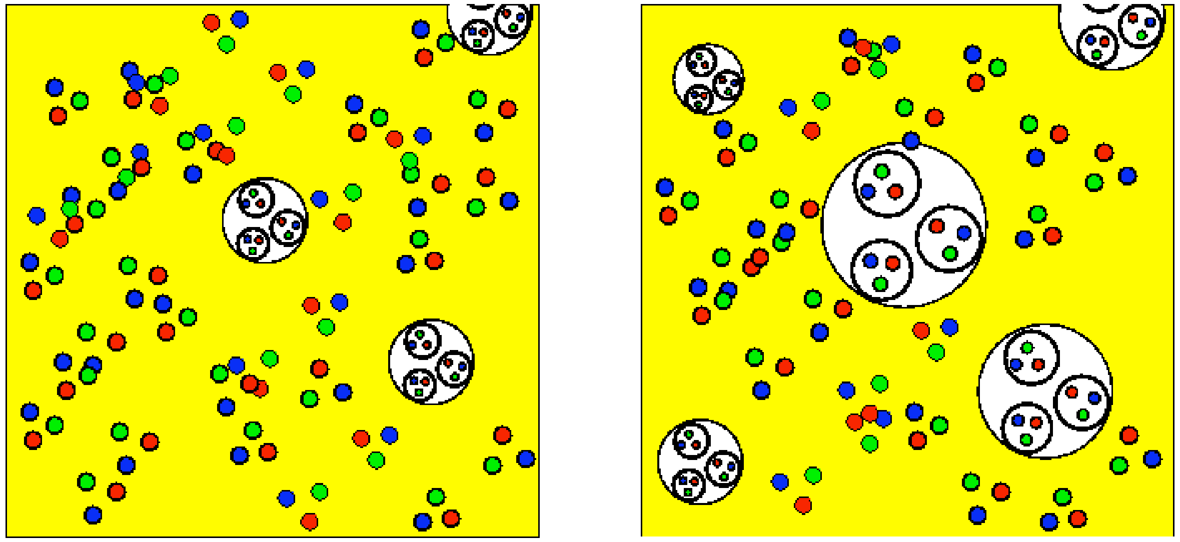

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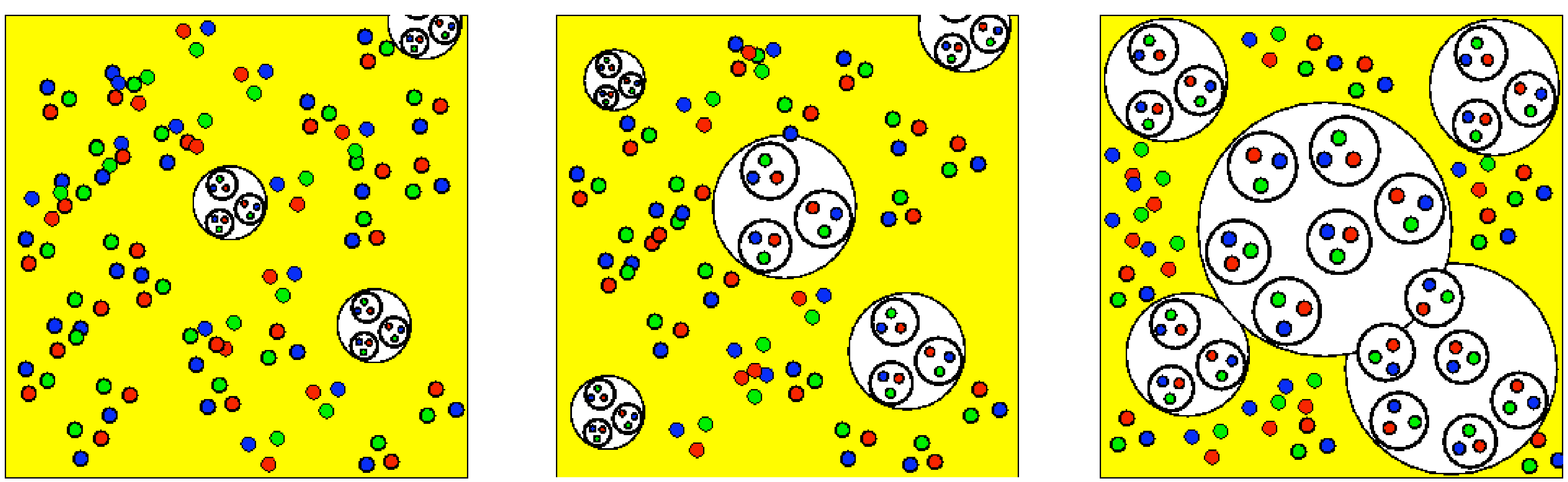

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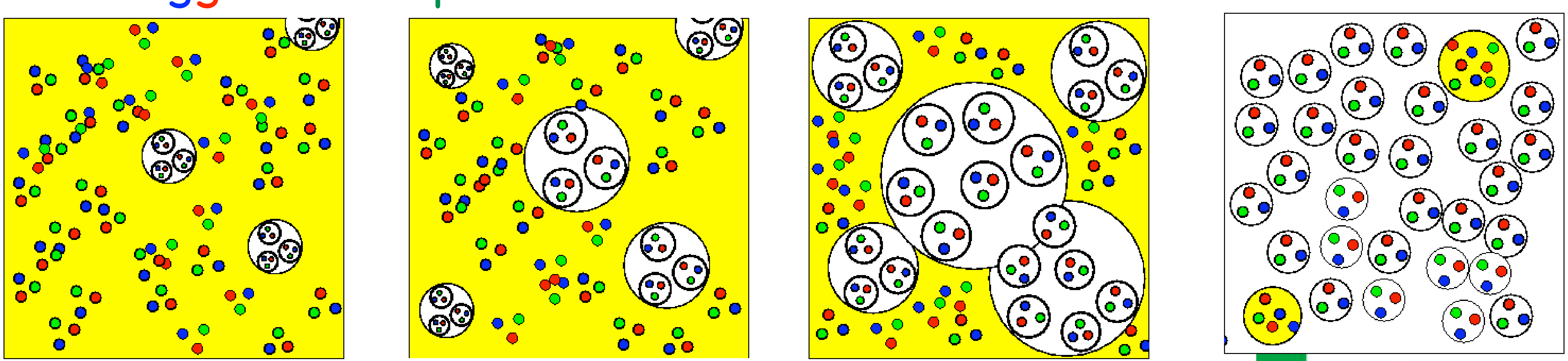
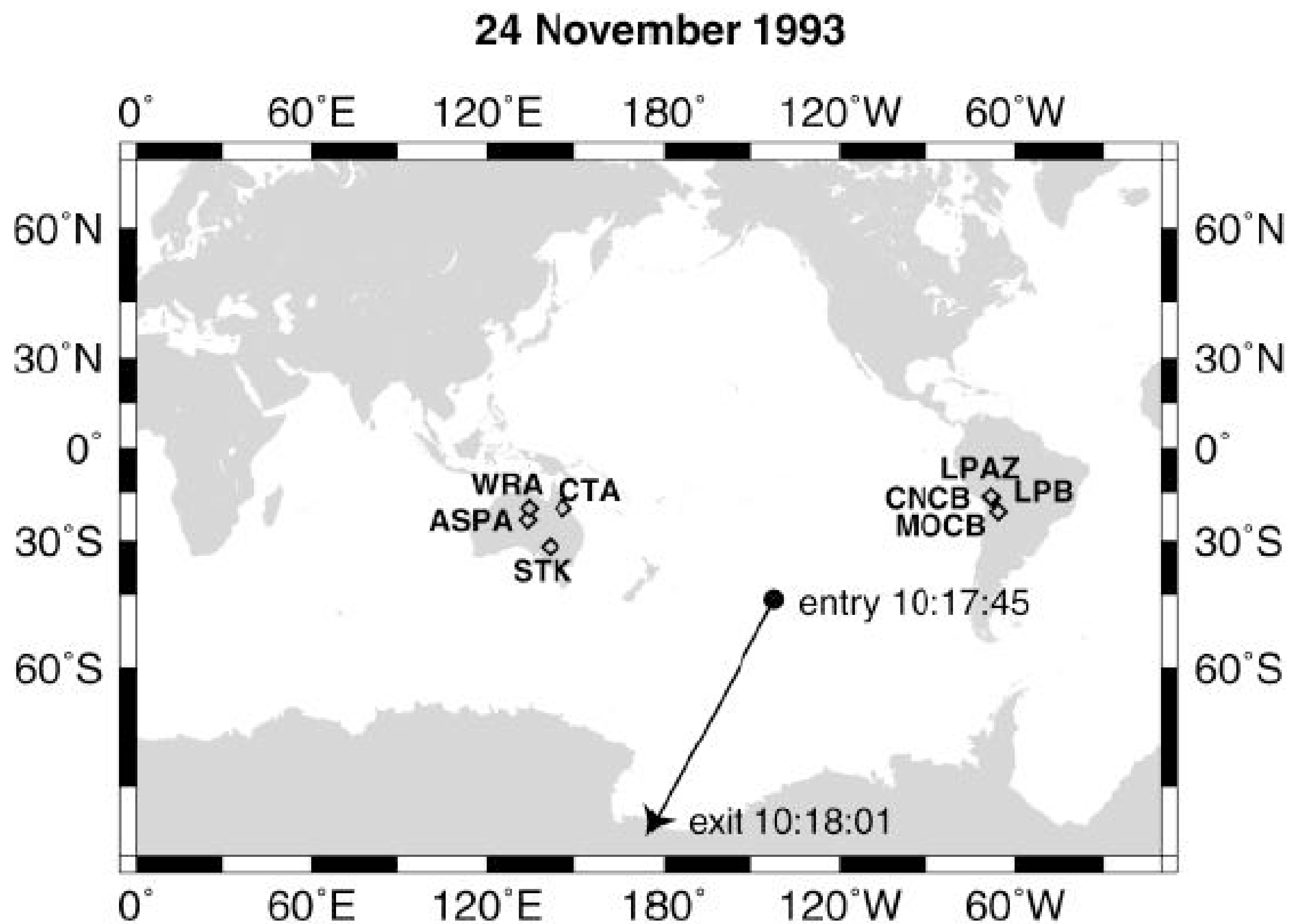
Eventually, the whole Universe is made of hadrons, except for isolated quark nuggets... or quark stars?



Quark-Gluon Plasma in the Universe?

Two unexplained seismic quakes with unusual properties (events with a very high propagation speed ≈ 400 km.s^{-1}):

Did strangelets traverse the Earth?



http://www.geology.smu.edu/~dpa-www/sqm/index.html

Quark stars?

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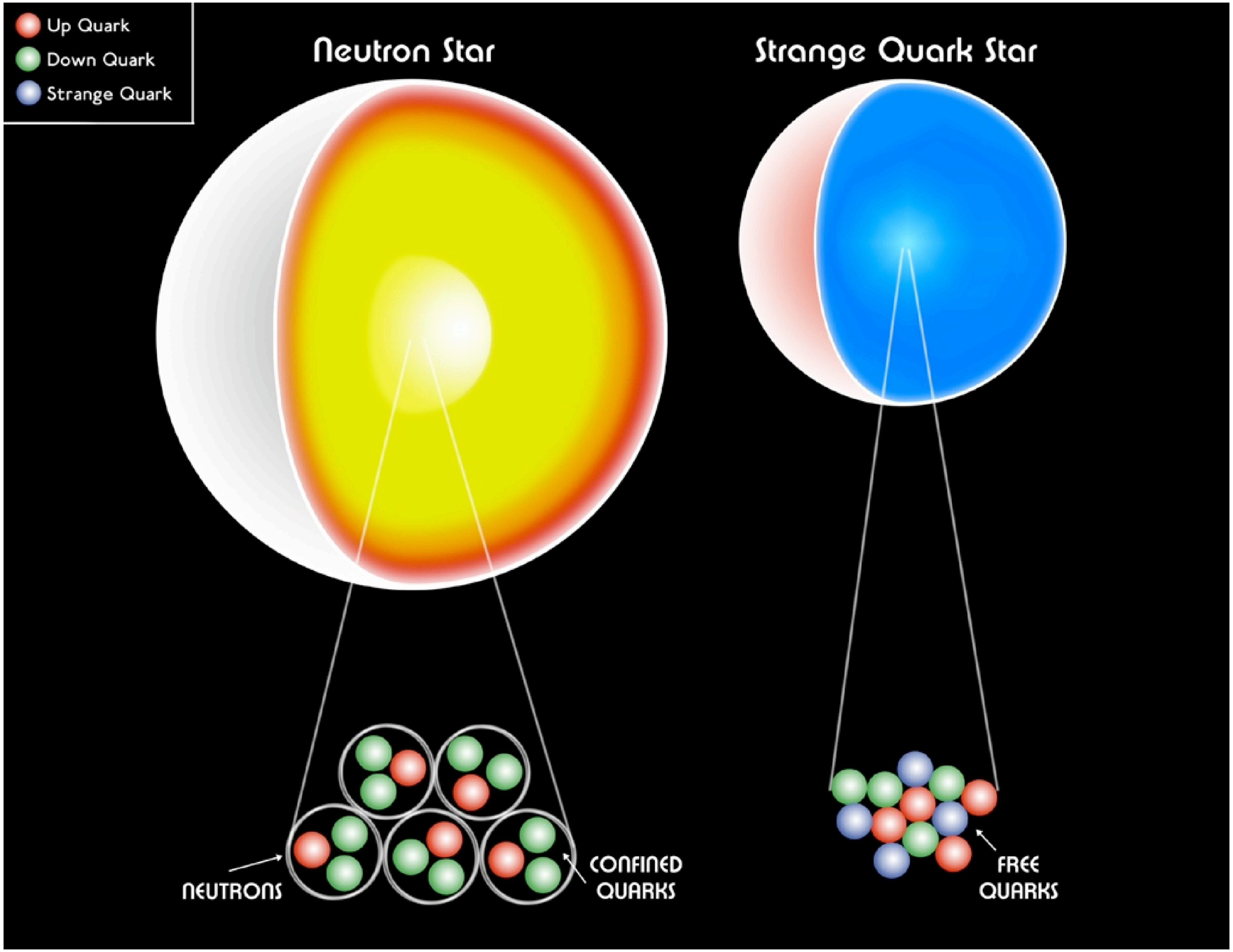


Quark stars?

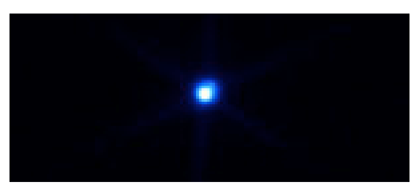
Have quark stars been observed?

NASA National Aeronautics and Space Administration

News Release Marshall Space Flight Center - Huntsville, Ala. 35812
http://www.msfc.nasa.gov/news

For release: 04/10/02
Release #: 02-082

Cosmic X-rays reveal evidence for new form of matter



NASA's Chandra X-ray Observatory has found two stars – one too small, one too cold — that reveal cracks in our understanding of the structure of matter. These discoveries open a new window on nuclear physics, offering a link between the vast cosmos and its tiniest constituents.

Photo: Newly discovered star RXJ 1856 is too small for standard models. (NASA et al.)

Read entire story

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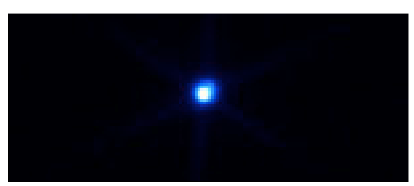

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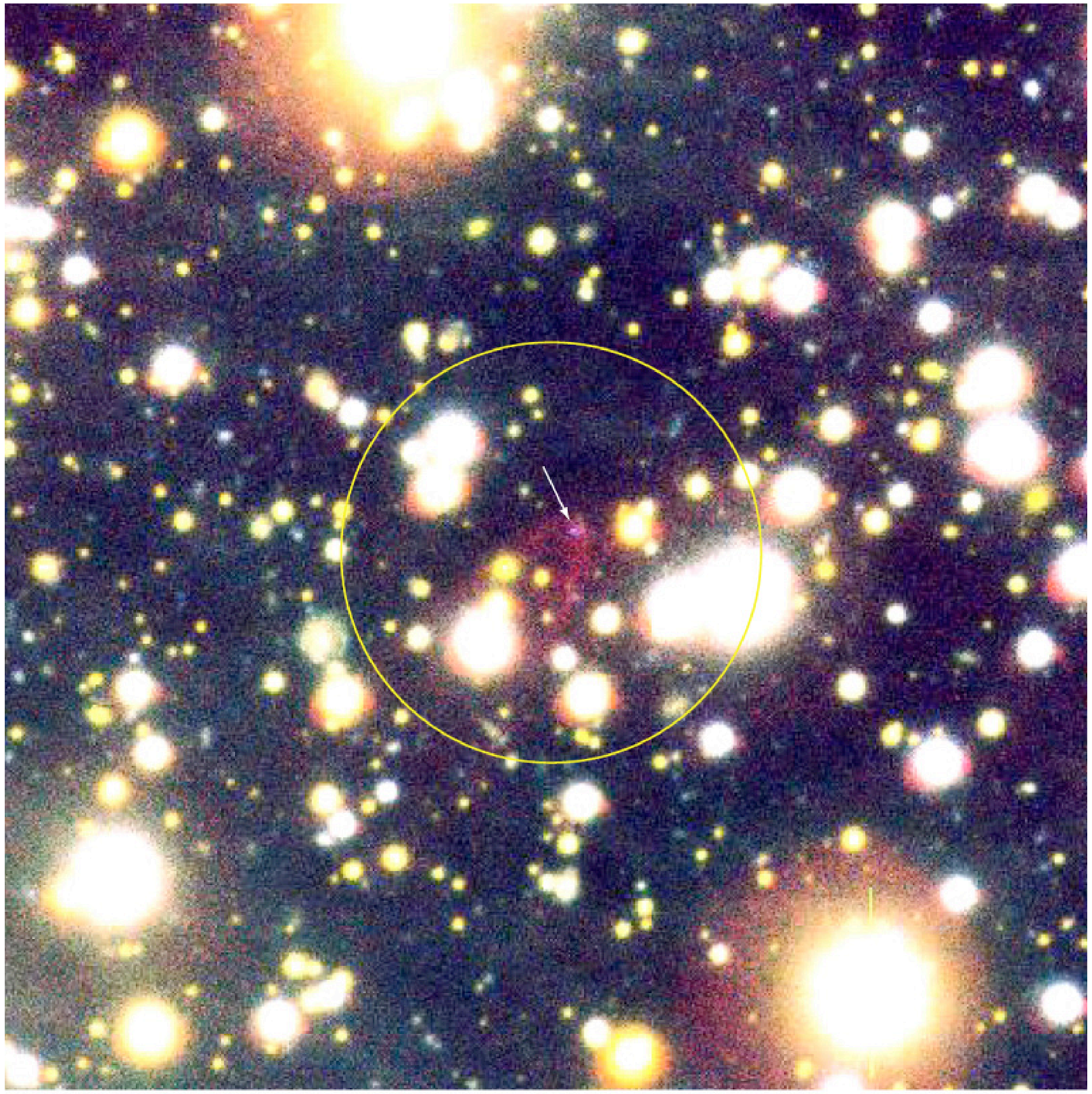
Read entire story

Chandra's observations of RXJ1856.5-3754 and 3C58 suggest that the matter in these stars is even denser than nuclear matter found on Earth. This raises the possibility these stars are composed of pure quarks or contain crystals of sub-nuclear particles that normally have only a fleeting existence following high-energy collisions.

Quark stars?



A Bowshock Nebula Near the Neutron Star RX J1856.5-3754 (Detail)
(VLT KUEYEN + FORS2)

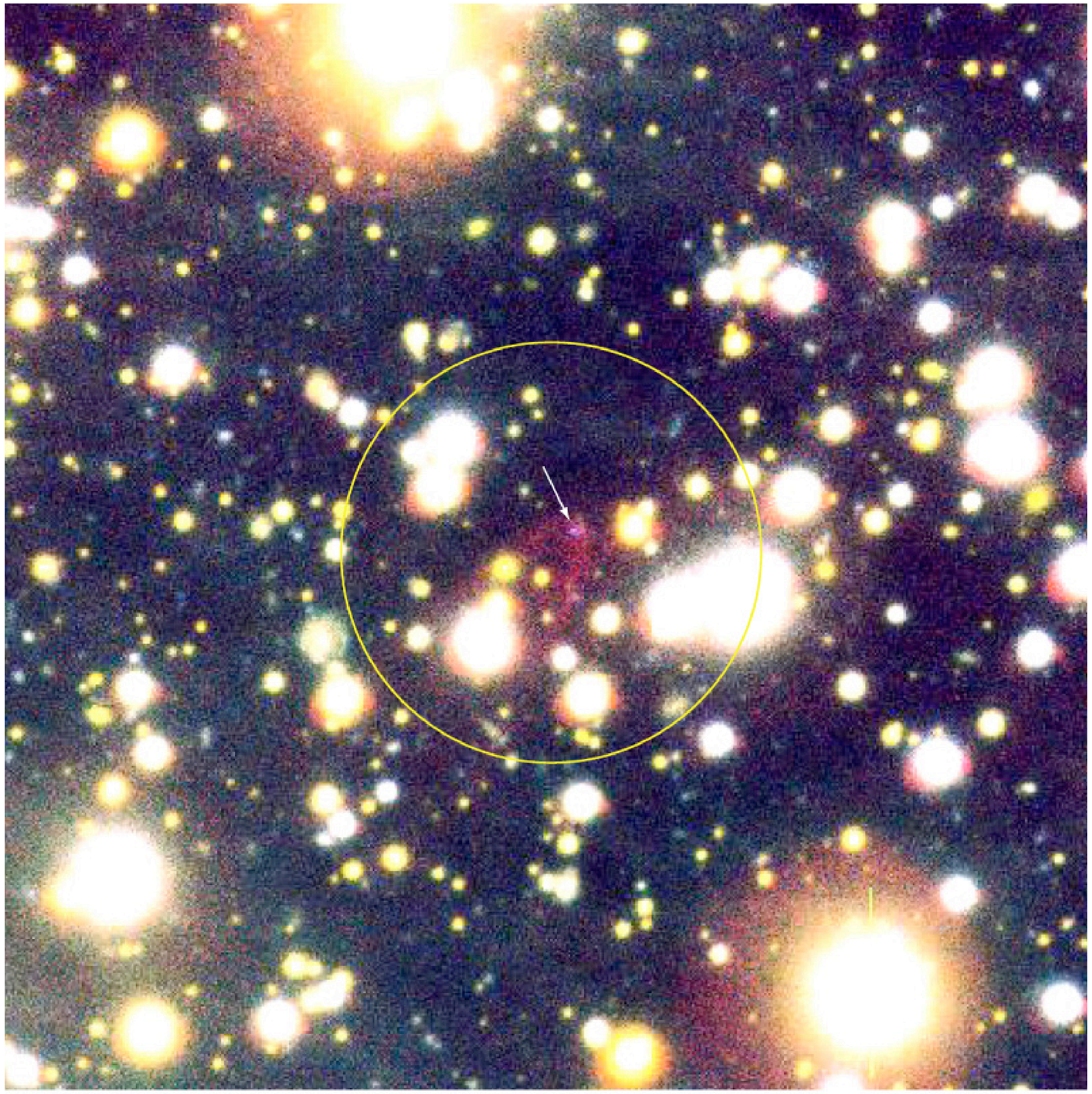
ESO PR Photo 23b/00 (11 September 2000) ©European Southern Observatory

By combining Chandra and Hubble Space Telescope data, astronomers found that RXJ 1856 radiates like a solid body with a temperature of 1.2 million degrees Fahrenheit (700,000 degrees Celsius) and has a diameter of about 7 miles (11.3 kilometers). This size is too small to reconcile with standard models for neutron stars — until now the most extreme form of matter known.

http://www.msfc.nasa.gov/news/news/releases/2002/02-082.html

one is too small (for its assumed mass)

Quark stars?



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Observations by Chandra of 3C58 also yielded startling results. A team composed of Patrick Slane and Steven Murray, also of CfA, and David Helfand of Columbia University, New York, failed to detect the expected X-radiation from the hot surface of 3C58, a neutron star believed to have been created in an explosion witnessed by Chinese and Japanese astronomers in 1181 AD. The team concluded that the star has a temperature of less than one million degrees Celsius, which is far below the predicted value.

"Our observations of 3C58 offer the first compelling test of models for how neutron stars cool and, the standard theory fails," said Helfand. "It appears that neutron stars aren't pure neutrons after all — new forms of matter are required."

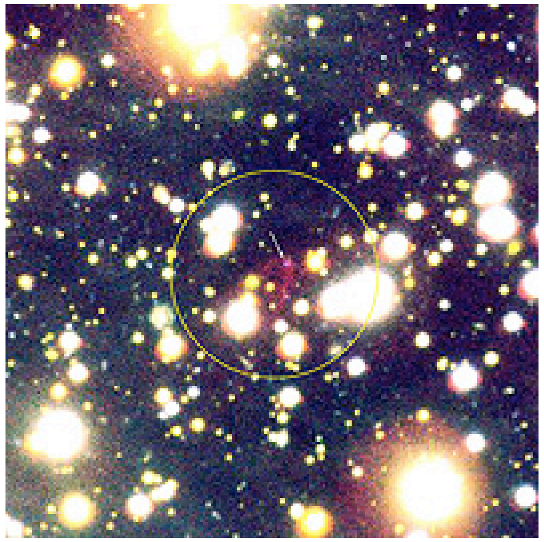
the other is too cold (for its conjectured age)

one is too small (for its assumed mass)

Quark stars?

European Space Agency

XMM-Newton finds the leader of the Magnificent Seven in a spin



VLT image of RXJ1856 sky region

9 March 2007

A decade-long mystery has been solved using data from ESA's X-ray observatory XMM-Newton. The brightest member of the so-called 'magnificent seven' has been found to pulsate with a period of seven seconds.

The discovery casts some doubt on the recent interpretation that this object is a highly exotic celestial object known as a quark star.

The magnificent seven is a collection of young neutron stars. Neutron stars are the dead hearts of once massive stars. They contain about 1.4 times the mass of the Sun but are compressed by gravity into ultra-dense spheres just 10–15 kilometres in diameter. A one Euro coin made of neutron star material would weigh more than the entire population of Earth. What sets the magnificent seven apart from the 1700 other neutron stars seen as radio pulsars is that they are not detected at radio frequencies but their surfaces are hot enough to emit X-rays.

http://www.esa.int/esaCP/SEM1WRN0LYE_index_0.html

Quark stars?

- Quark stars would be a good candidate for dark matter, especially for the MAssive Compact Halo Objects detected by microlensing.

- On April 10, 2002, NASA announced the observation of two quark stars: "Cosmic X-rays reveal evidence for new form of matter".
(But these were probably mis-identified neutron stars.)

- According to QCD computations on a lattice (see next slides!), the (de)confinement phase transition is not first order for the values of the baryon density relevant for cosmology — it is rather a crossover which invalidates Witten's idea.

- Yet these computations have to be confirmed by experiment

$\Rightarrow$ ultrarelativistic heavy-ion collisions

Hints from lattice QCD

(cf. Owe Philipsen's lectures)

Volume 113B, number 5 PHYSICS LETTERS 1 July 1982

THE HIGH-TEMPERATURE BEHAVIOUR OF LATTICE QCD WITH FERMIONS

J. ENGELS, F. KARSCH and H. SATZ
Fakultät für Physik, Universität Bielefeld, Bielefeld, Germany

Received 29 March 1982

By Monte Carlo simulation on the lattice, we calculate the high-temperature behaviour of the energy density ϵ in SU(2) and SU(3) QCD with Wilson fermions. From the leading term of the hopping parameter expansion, we find that ϵ converges very rapidly to the Stefan–Boltzmann limit of an asymptotically free quark–gluon gas. ...

Hints from lattice QCD

PHYSICAL REVIEW D **77**, 014511 (2008)

QCD equation of state with almost physical quark masses

M. Cheng,[1] N. H. Christ,[1] S. Datta,[2] J. van der Heide,[3] C. Jung,[4] F. Karsch,[3,4] O. Kaczmarek,[3] E. Laermann,[3] R. D. Mawhinney,[1] C. Miao,[3] P. Petreczky,[4,5] K. Petrov,[6] C. Schmidt,[4] W. Soeldner,[4] and T. Umeda[7]

[1]*Physics Department, Columbia University, New York, New York 10027, USA*
[2]*Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*
[3]*Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*
[4]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[5]*RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[6]*Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[7]*Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Ibaraki 305-8571, Japan*

(Received 2 October 2007; published 22 January 2008)

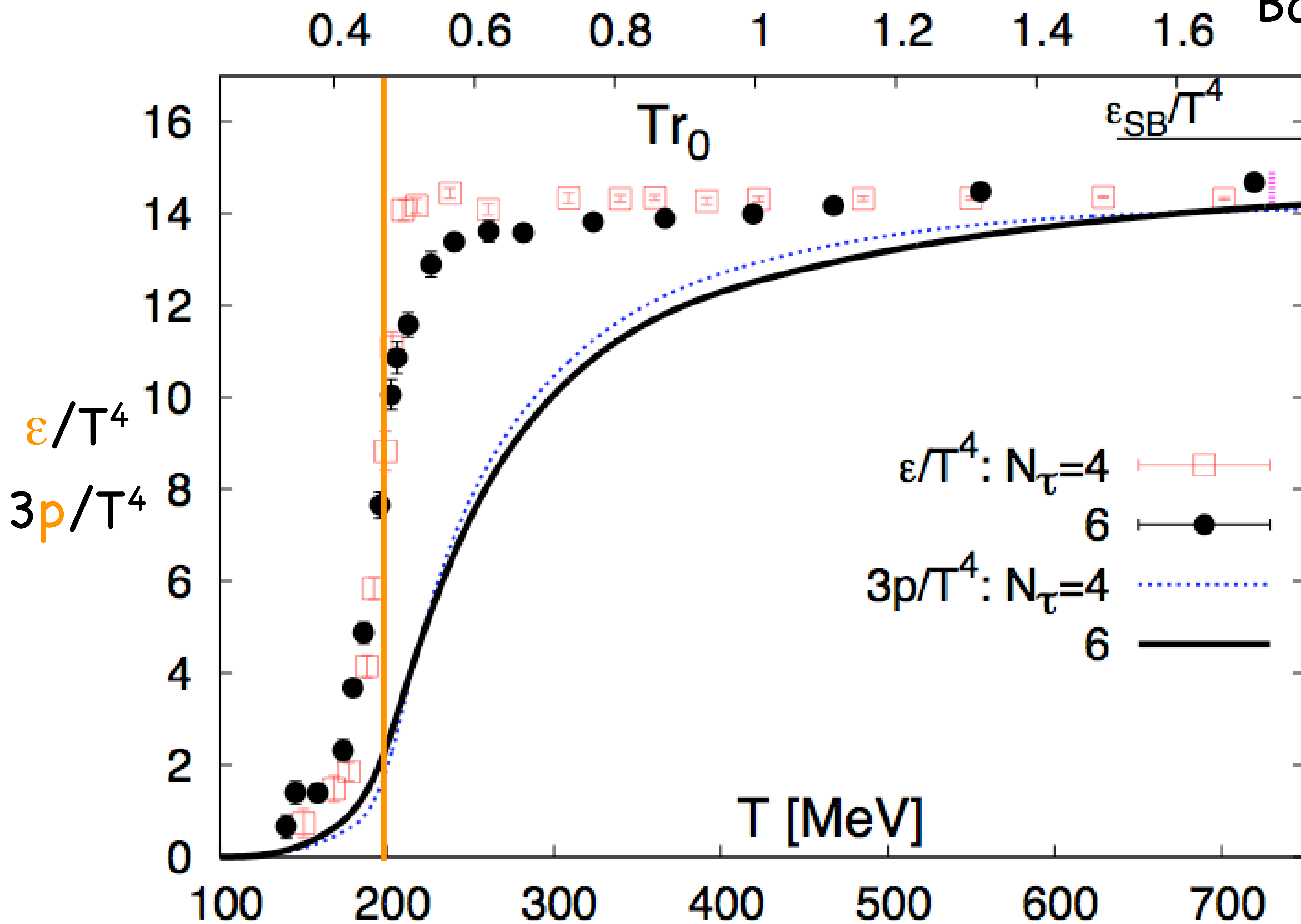
We present results on the equation of state in QCD with two light quark flavors and a heavier strange quark. Calculations with improved staggered fermions have been performed on lattices ...

"2+1" flavors, $m_\pi \approx 220$ MeV, $m_K \approx 500$ MeV

Hints from lattice QCD

Energy density ε & pressure p:

ideal Stefan-Boltzmann limit



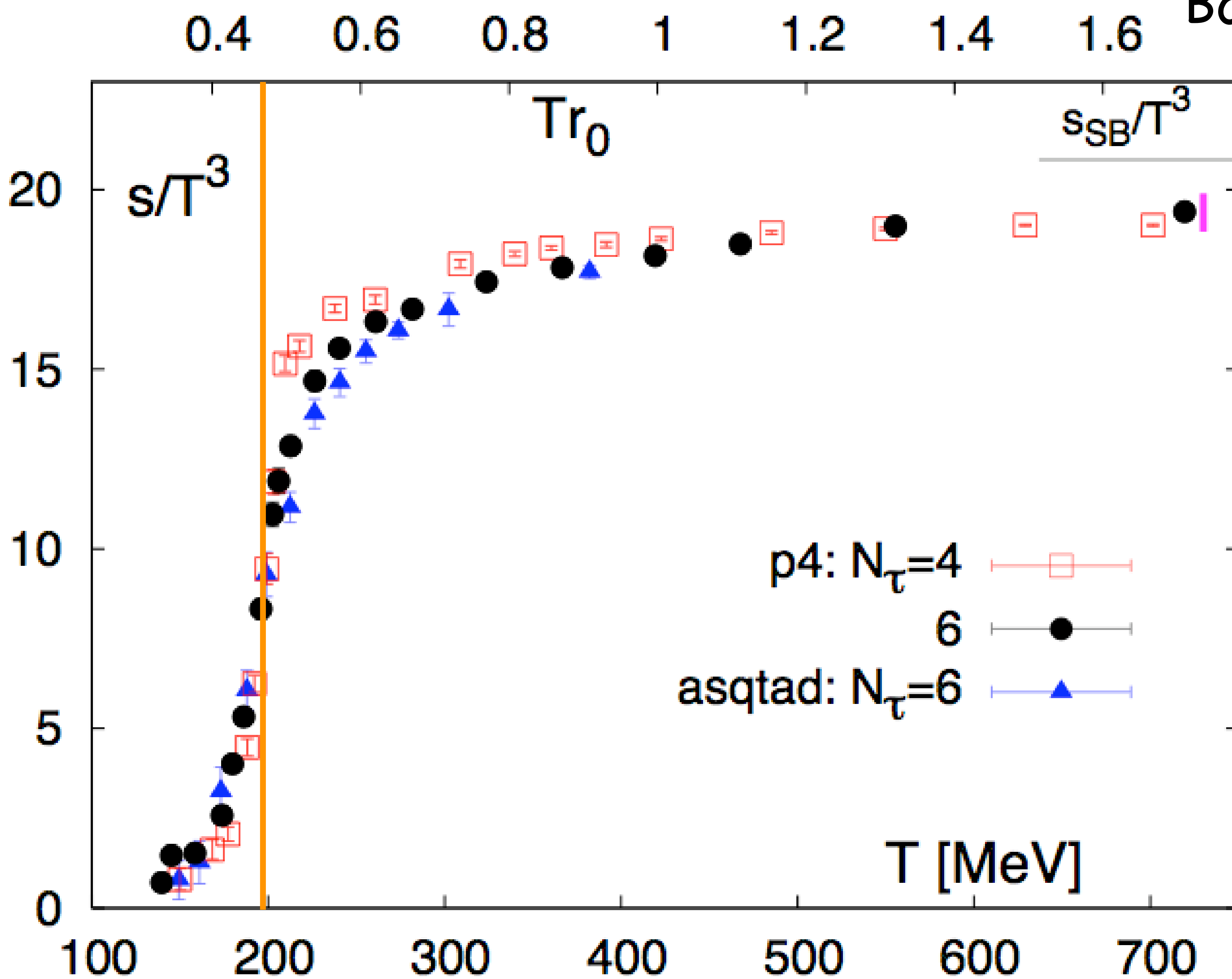
PRD 77 (2008) 045511

Hints from lattice QCD

Entropy density s

ideal Stefan-Boltzmann limit

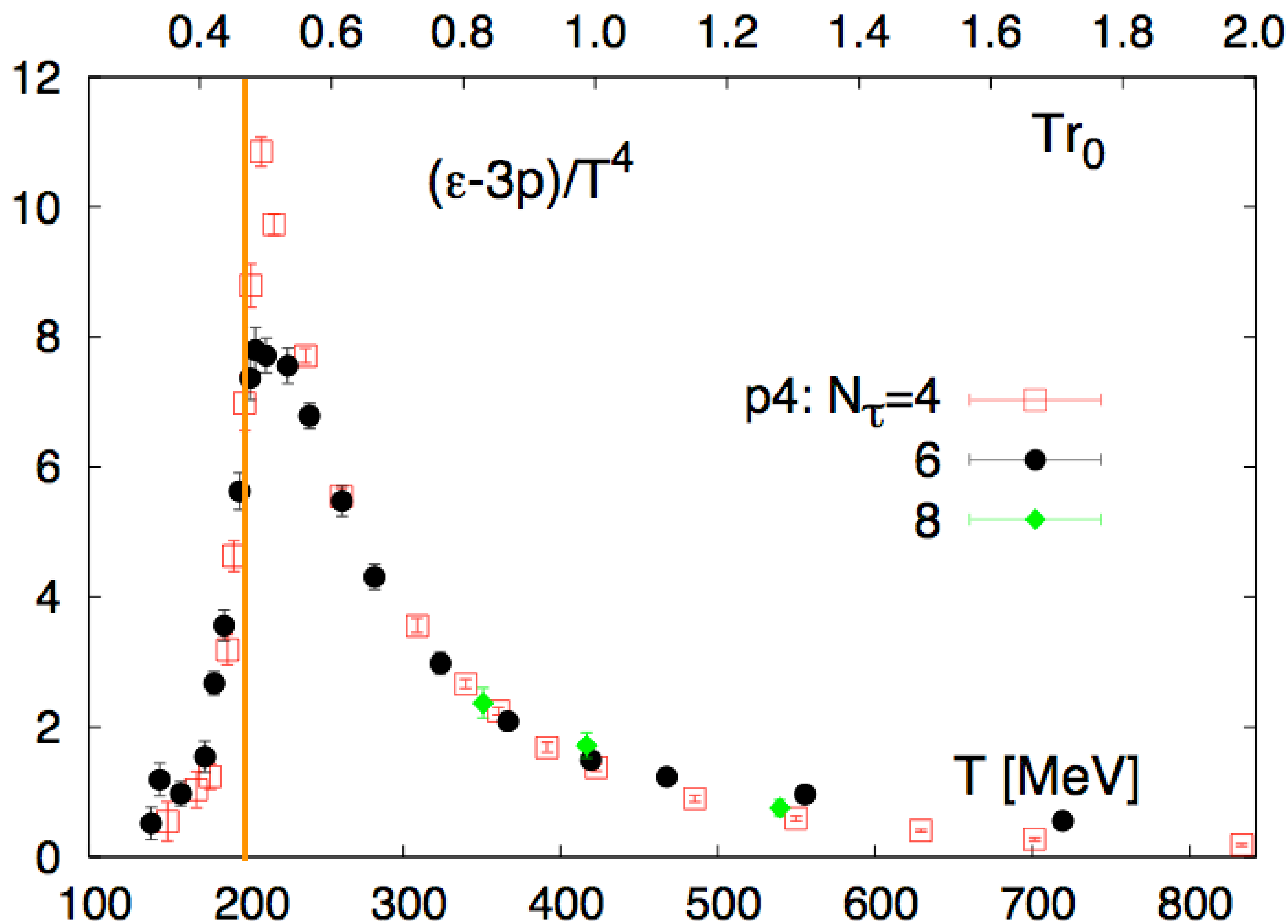
s/T^3



PRD 77 (2008) 045511

Hints from lattice QCD

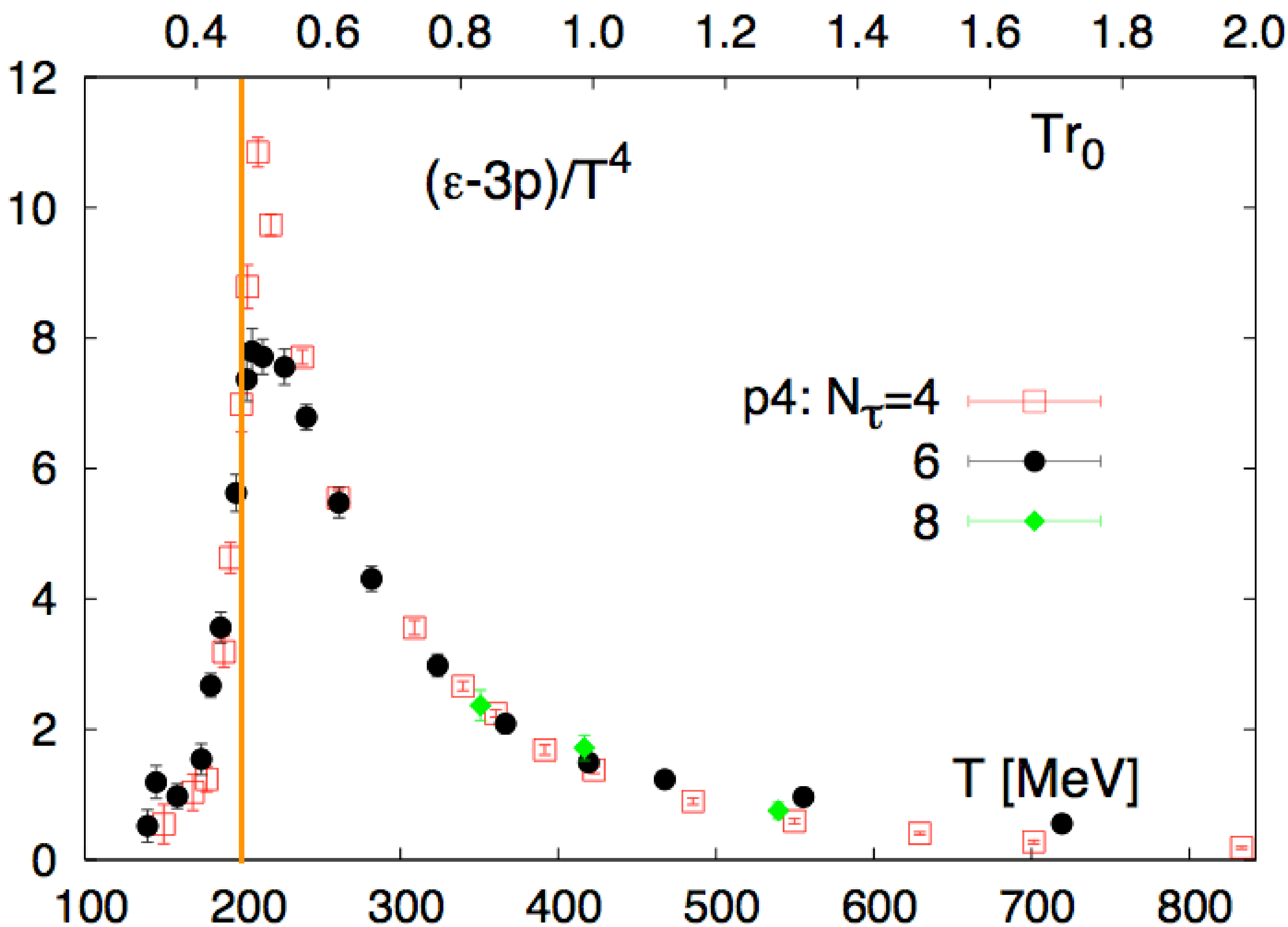
Critical temperature T_c = 196±4 MeV



PRD 77 (2008) 045511

Hints from lattice QCD

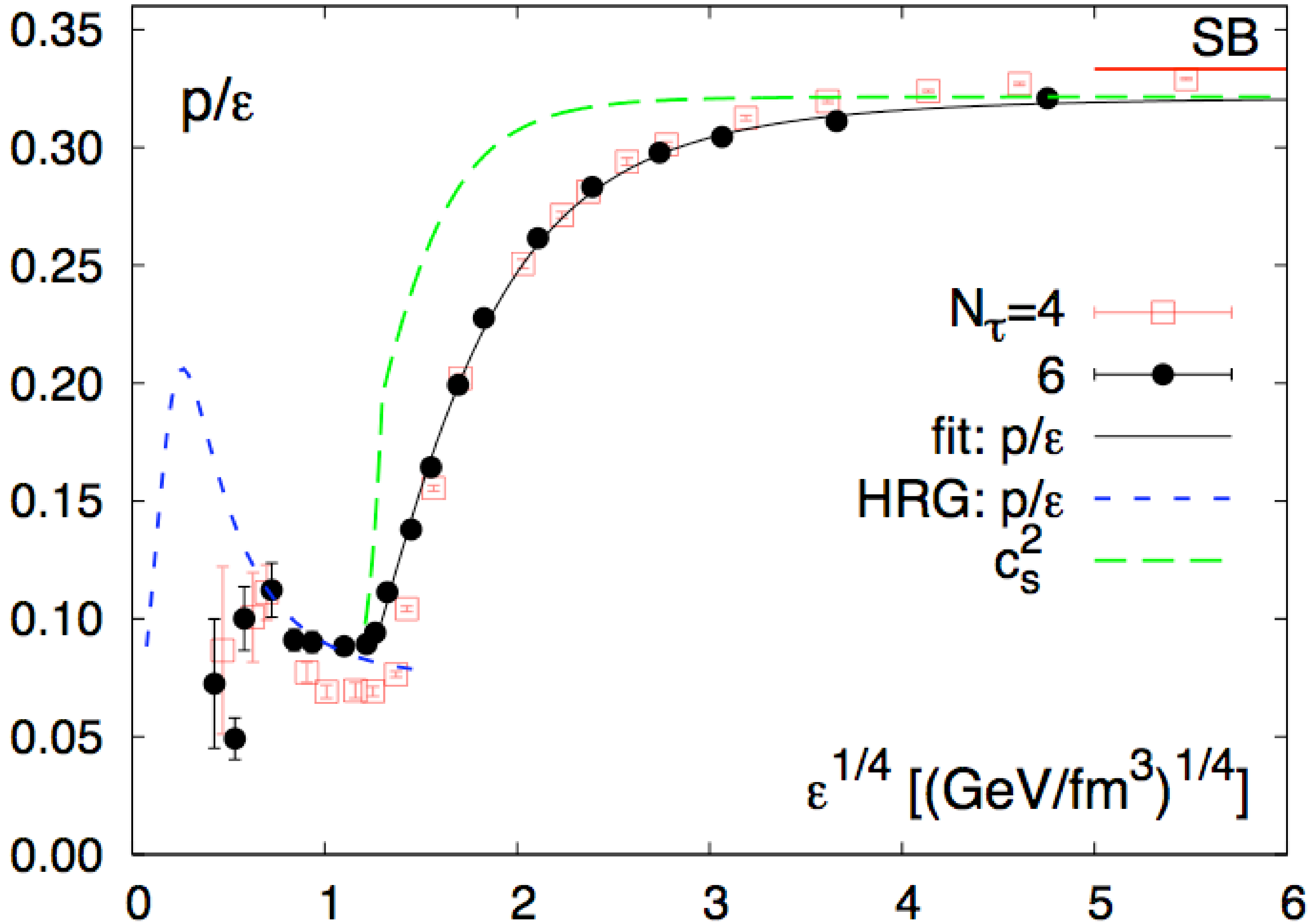
Critical temperature $T_c \approx$ 150–200 MeV



PRD 77 (2008) 045511

Hints from lattice QCD

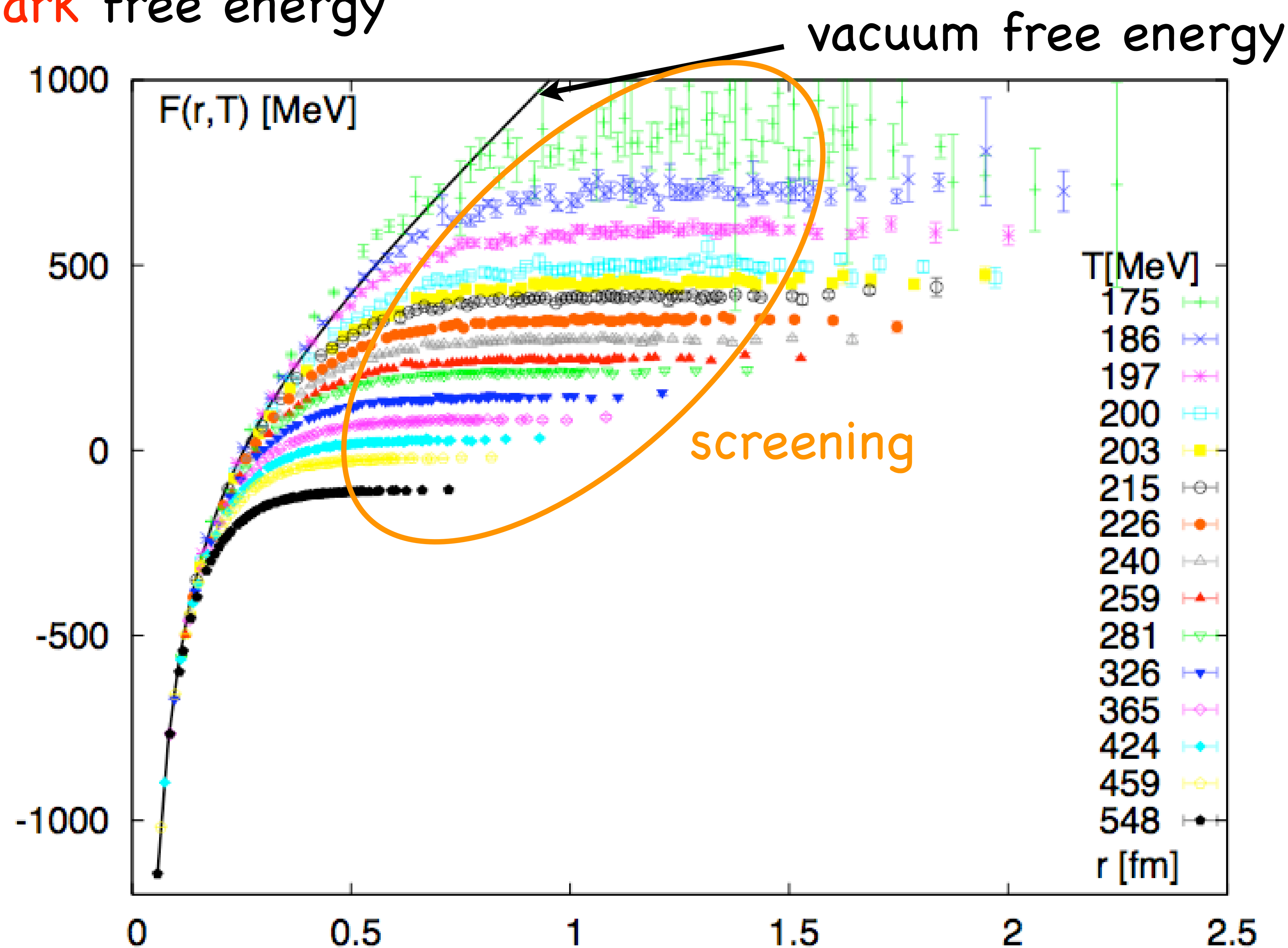
$\frac{p}{\varepsilon}$ ☞ sound velocity c_s: $\quad c_s^{\,2} = \frac{\mathrm{d}p}{\mathrm{d}\varepsilon} = \varepsilon\frac{\mathrm{d}(p/\varepsilon)}{\mathrm{d}\varepsilon} + \frac{p}{\varepsilon}$



PRD 77 (2008) 045511

Hints from lattice QCD

Heavy quark free energy



O.Kaczmarek, PoS CPOD07 (2007) 043

Hints from lattice QCD

- Rapid change of thermodynamic quantities (energy density, pressure, entropy density...) ☞ transition / crossover between two states:

  hadron gas vs. Quark-Gluon Plasma

- Screening of the heavy-quark potential in the high-temperature phase.

- Equation of state, sound velocity... (+ much more, not shown)

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- However lattice simulations of QCD at finite temperature are not (yet) performed with "physical" light-quark masses.

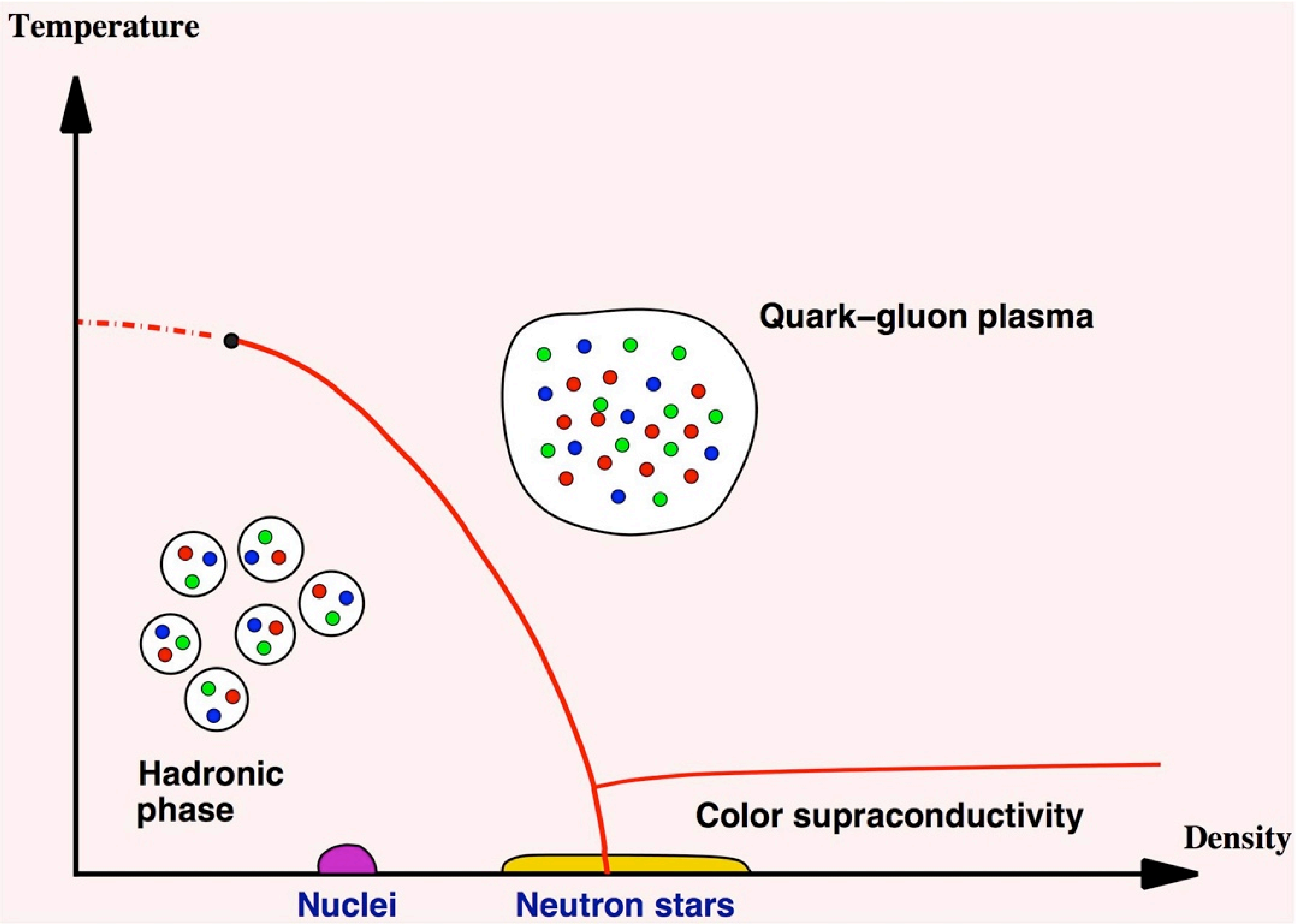
- They do not provide any phase diagram,

- nor transport coefficients.

(yet?)

Phase diagram of nuclear matter

(a sketch)



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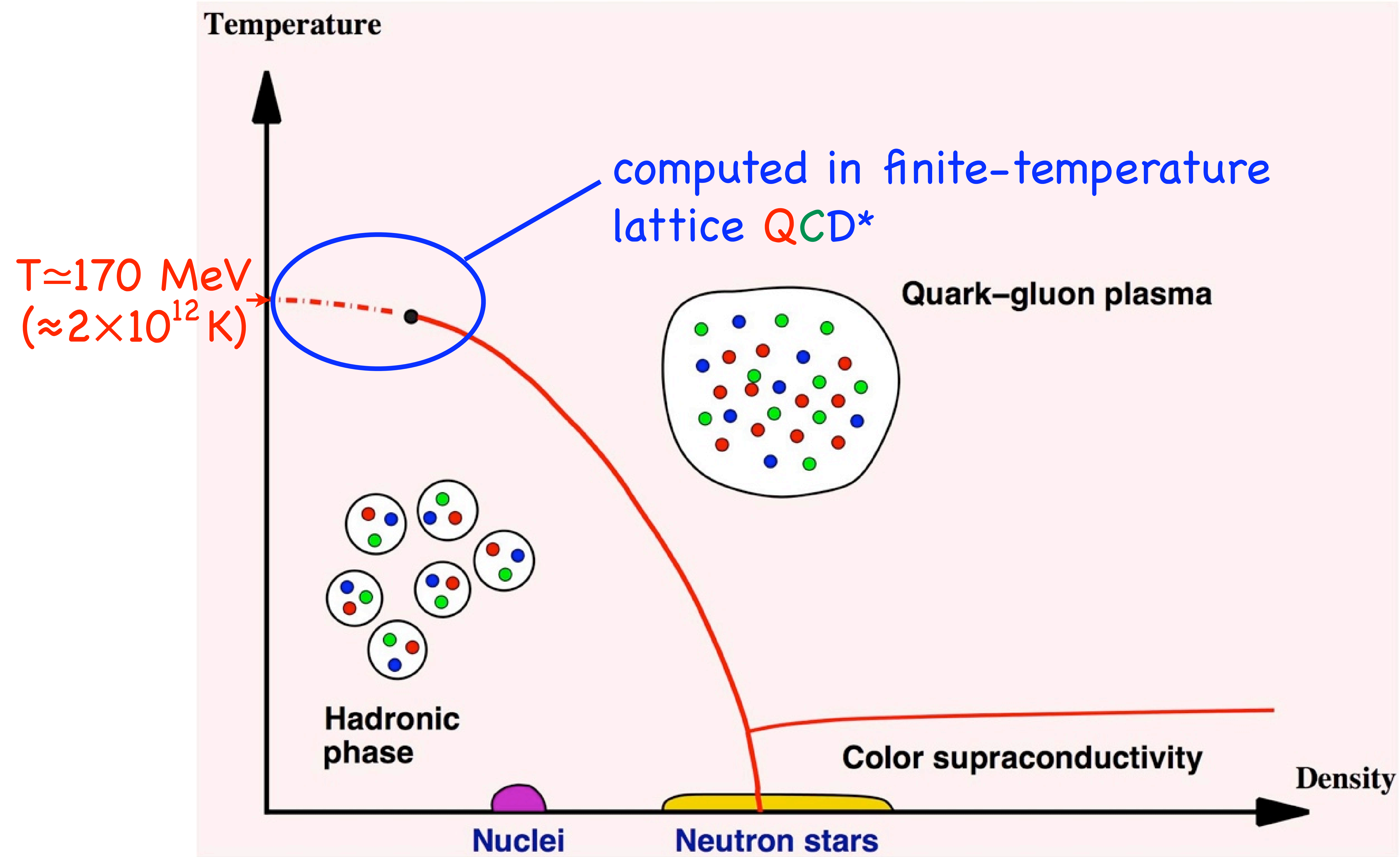

* the existence of a first-order transition line is disputed, cf. O.Philipsen

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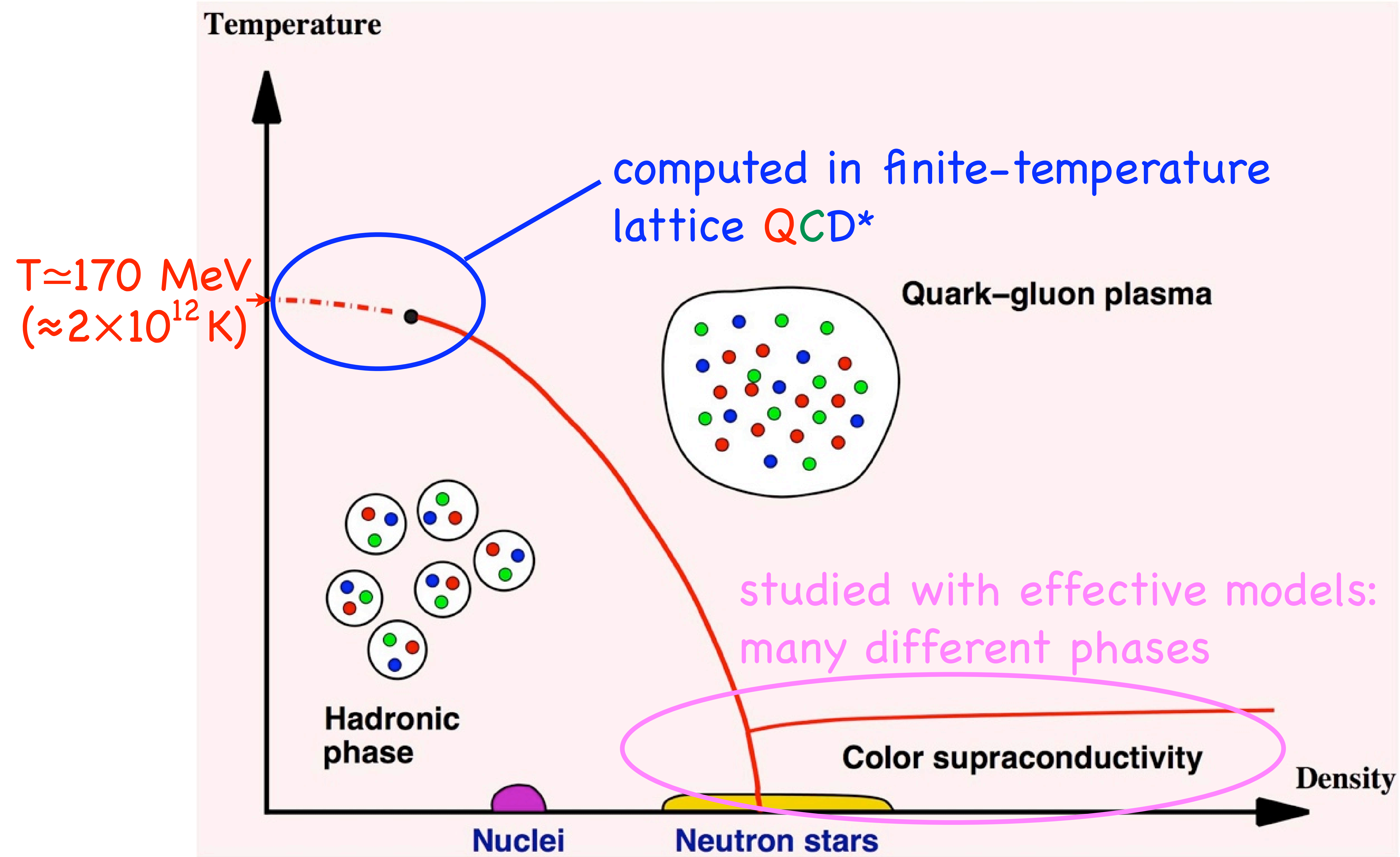

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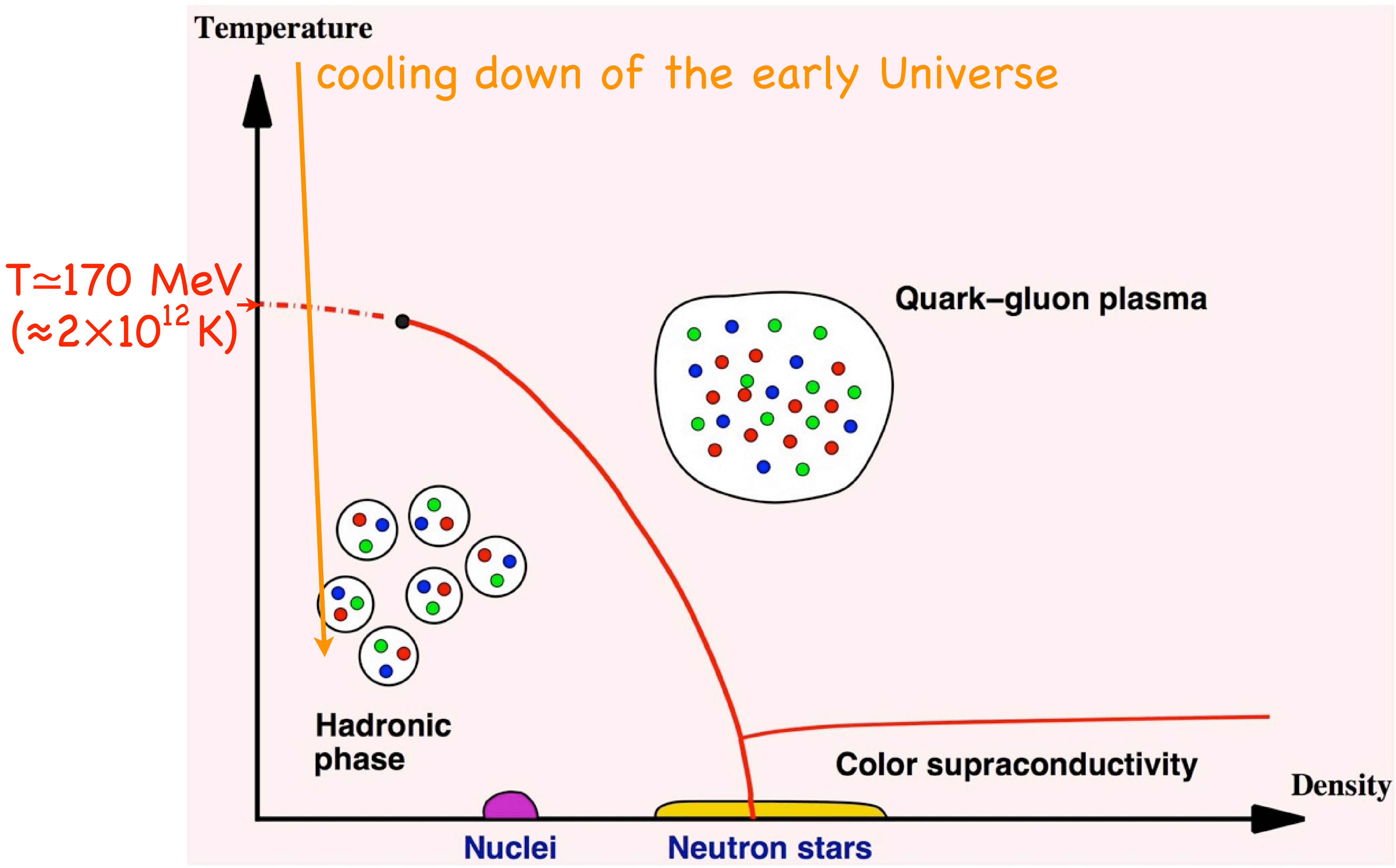

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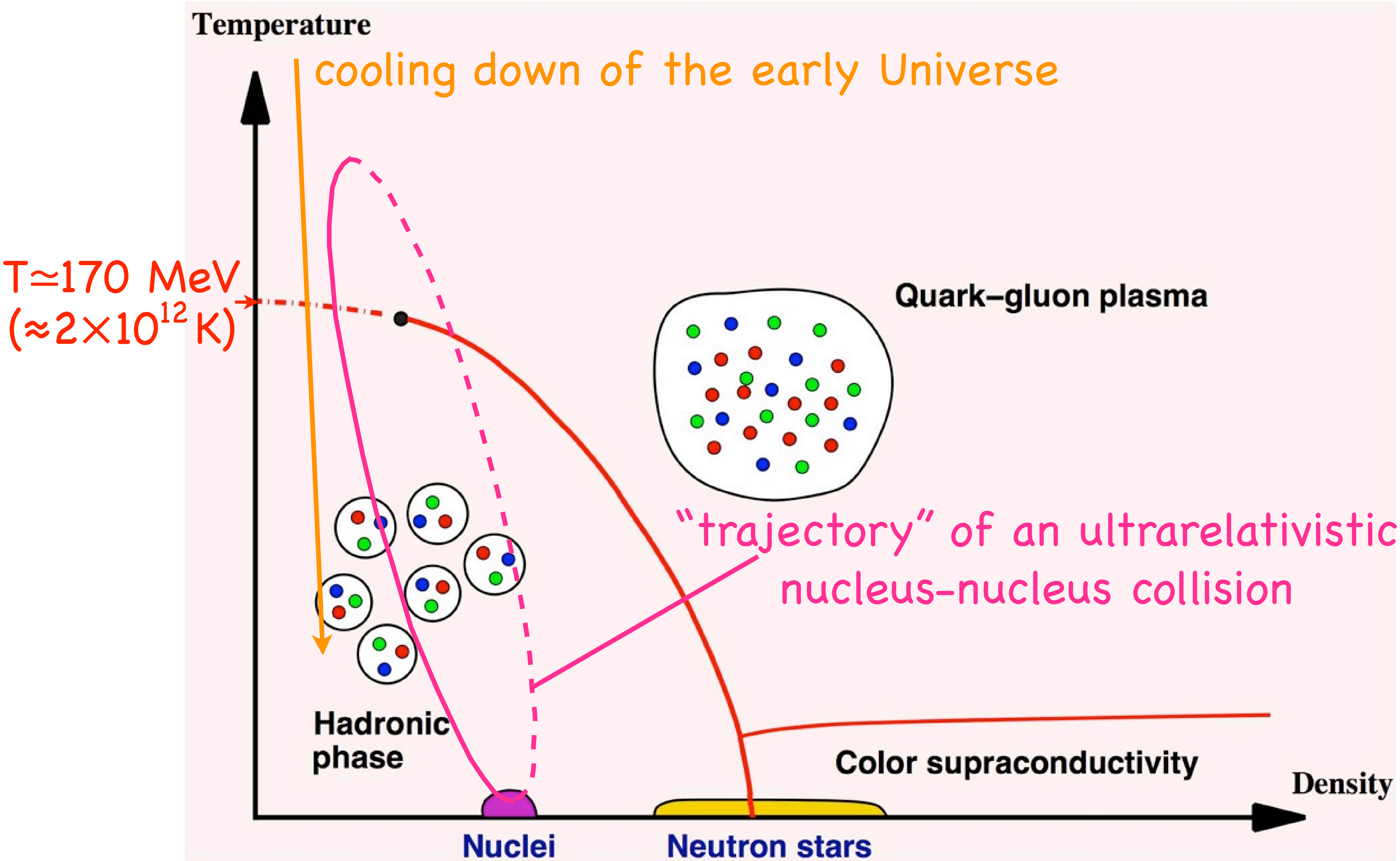

Why heavy-ion collisions?

- Repeatedly heard answers:

  "to create a quark-gluon plasma and study its properties"

  "to study the phase diagram of nuclear matter"

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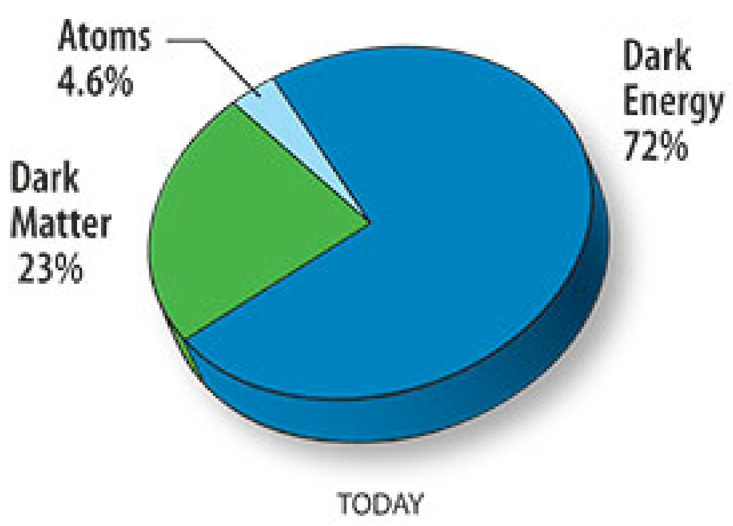
is studying dark matter / dark energy more sexy?



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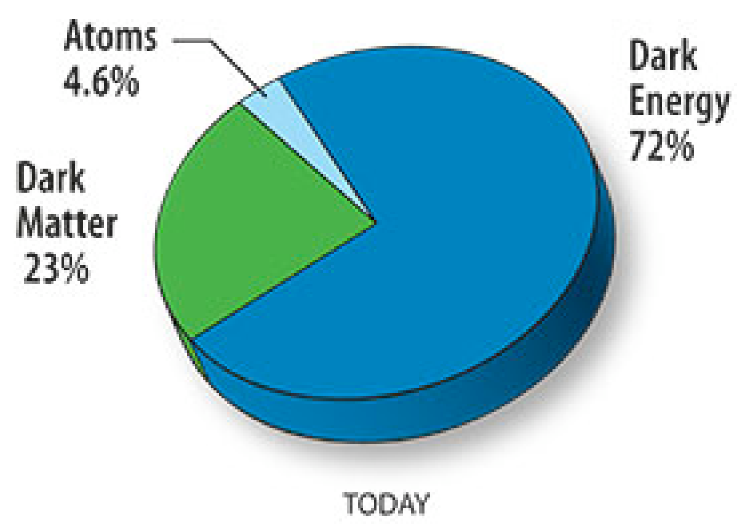

or, better, the "particle of God", which is "responsible for the mass"?

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"to create a quark-gluon plasma and study its properties"

"to study the phase diagram of nuclear matter"

- A remark: well, actually, do we really understand mass?

u $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1.5 to 3.3 MeV [a] Charge = $\frac{2}{3}$ e $I_z = +\frac{1}{2}$

m_u/m_d = 0.35 to 0.60

d $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 3.5 to 6.0 MeV [a] Charge = $-\frac{1}{3}$ e $I_z = -\frac{1}{2}$

m_s/m_d = 17 to 22

$\overline{m} = (m_u + m_d)/2$ = 2.5 to 5.0 MeV

p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000013$ u

Mass $m = 938.27203 \pm 0.00008$ MeV [a]

n $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.0086649156 \pm 0.0000000006$ u

Mass $m = 939.56536 \pm 0.00008$ MeV [a]

(Review of Particle Properties 2008)

or do I miss 99% of my own mass?

☞ study deconfinement to understand confinement, as well as, perhaps, the mass (and spin?) of the nucleon!

A remark for purists...

Actually, there are two transitions:

- (de)confinement transition:

  the Z(3) center symmetry is manifest in the QCD vacuum (☞ creation of free quarks requires an infinite energy), spontaneously broken in the high-temperature phase,

  Order parameter: Polyakov loop

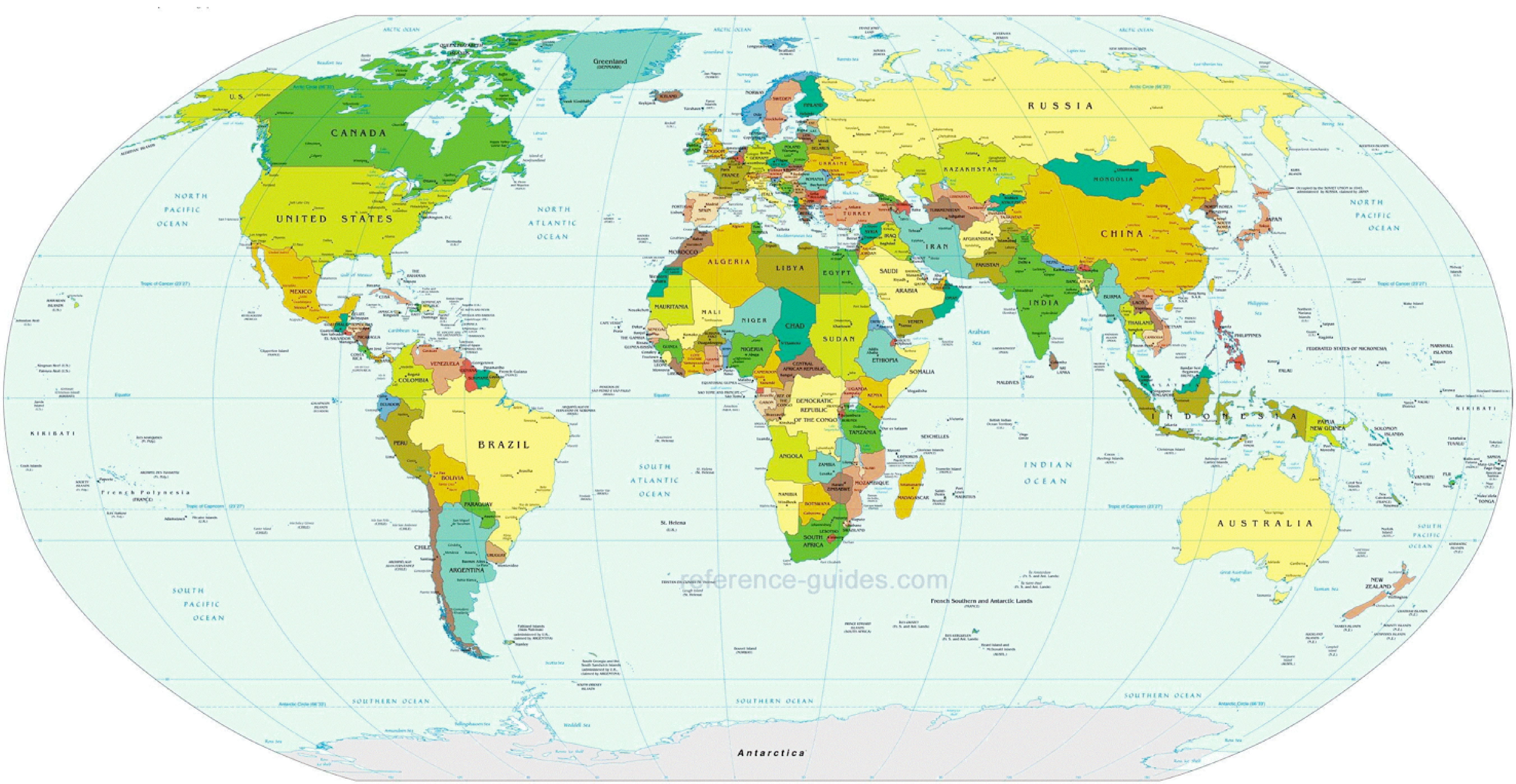
- chiral transition:

  chiral symmetry is broken in the low-temperature phase, (partially) restored in the high-temperature one.

  Order parameter: chiral condensate

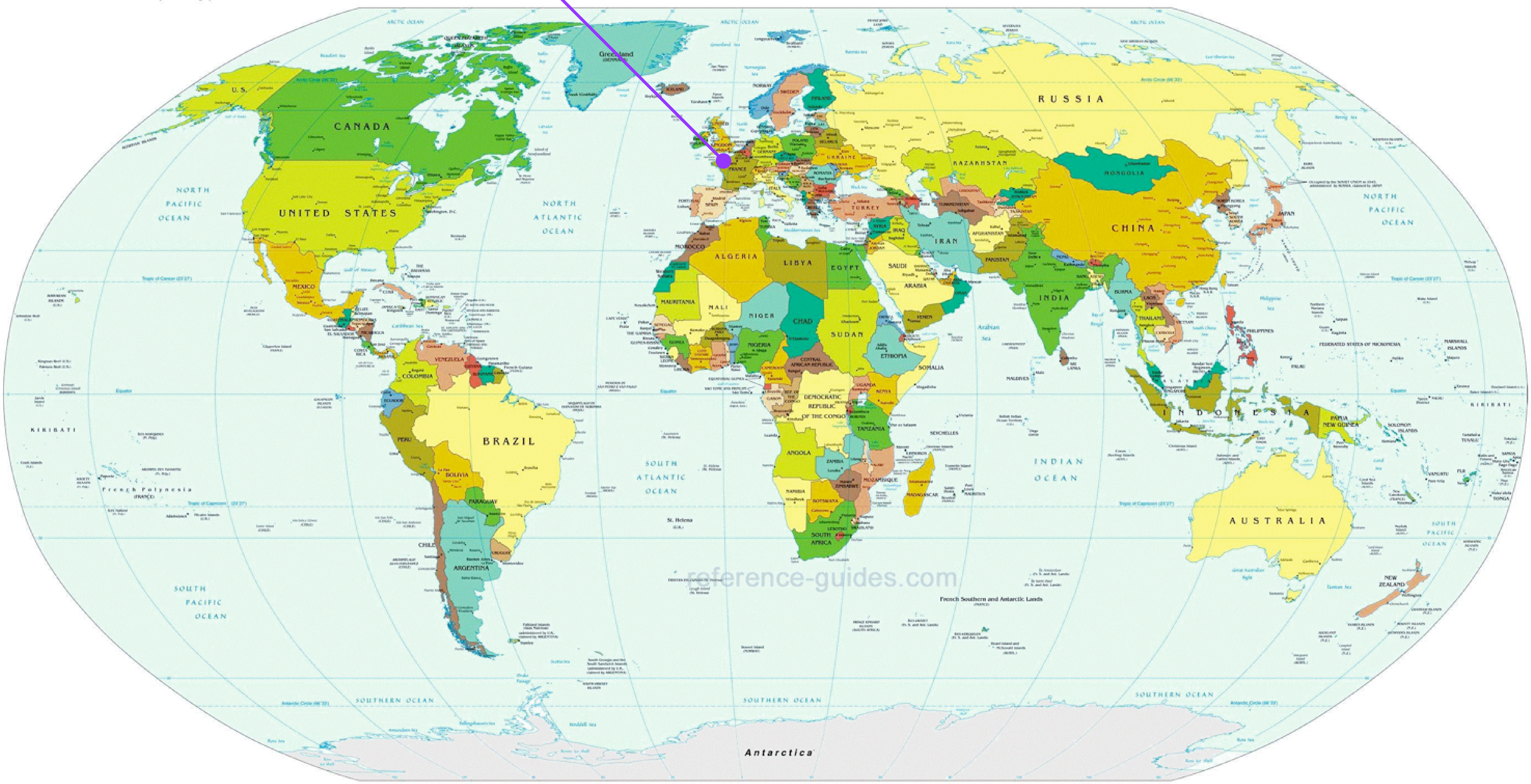
In present-day lattice QCD computations, these "transitions" seem to occur at the same critical temperature (according to most groups; according to one group, they occur at two relatively close yet different temperatures).

Heavy ion experiments



Heavy ion experiments

GANIL $\lesssim$ 100 MeV/u



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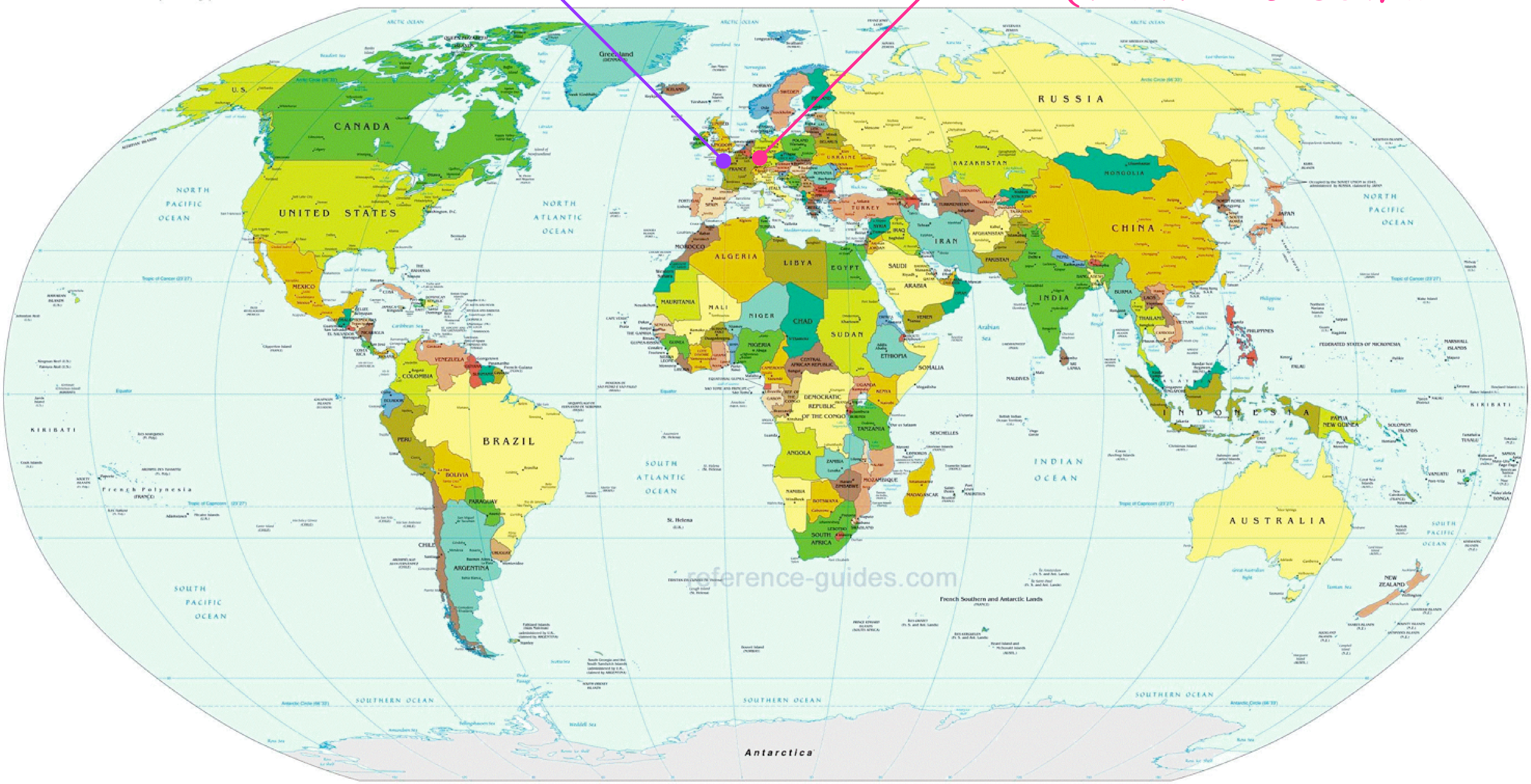

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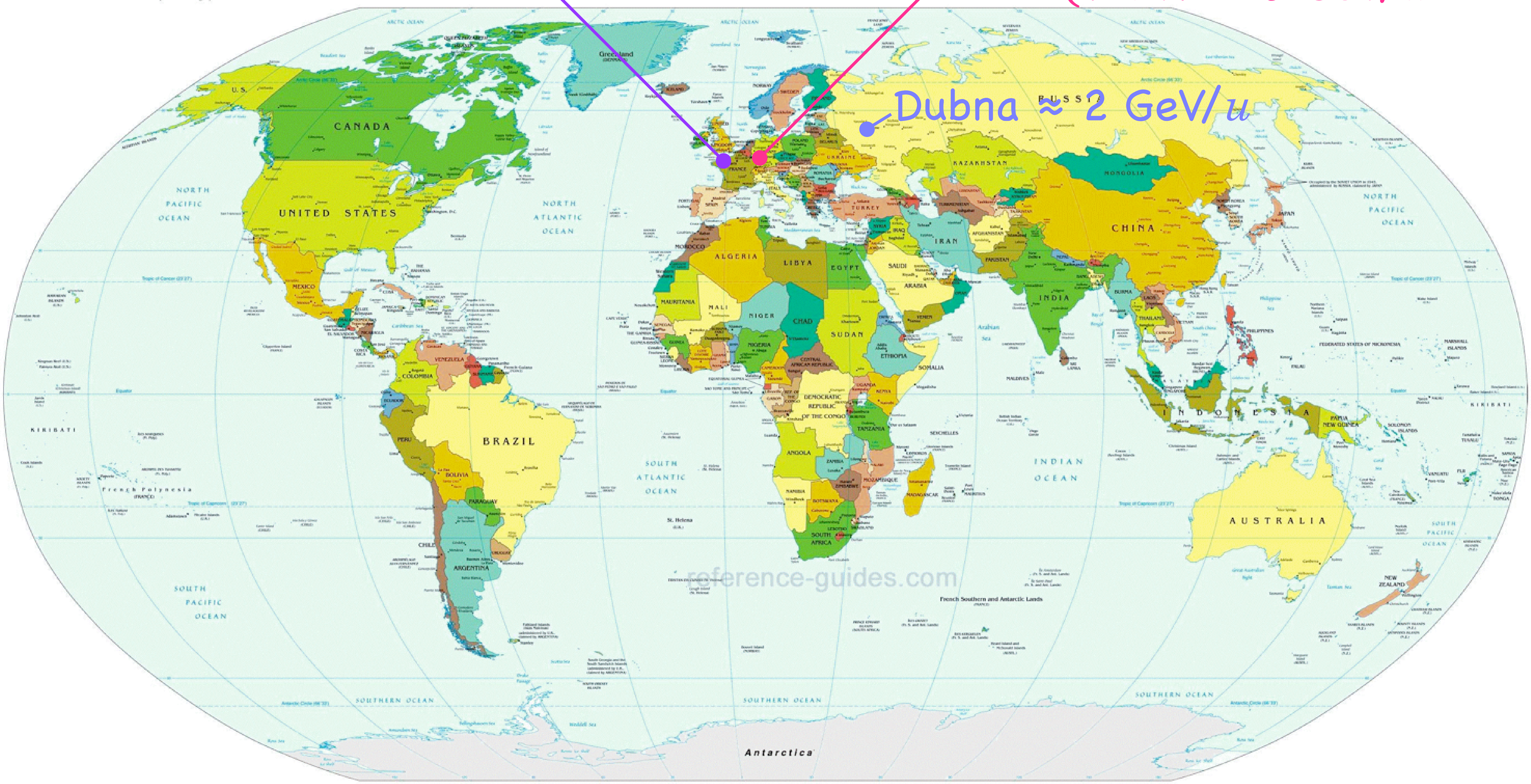

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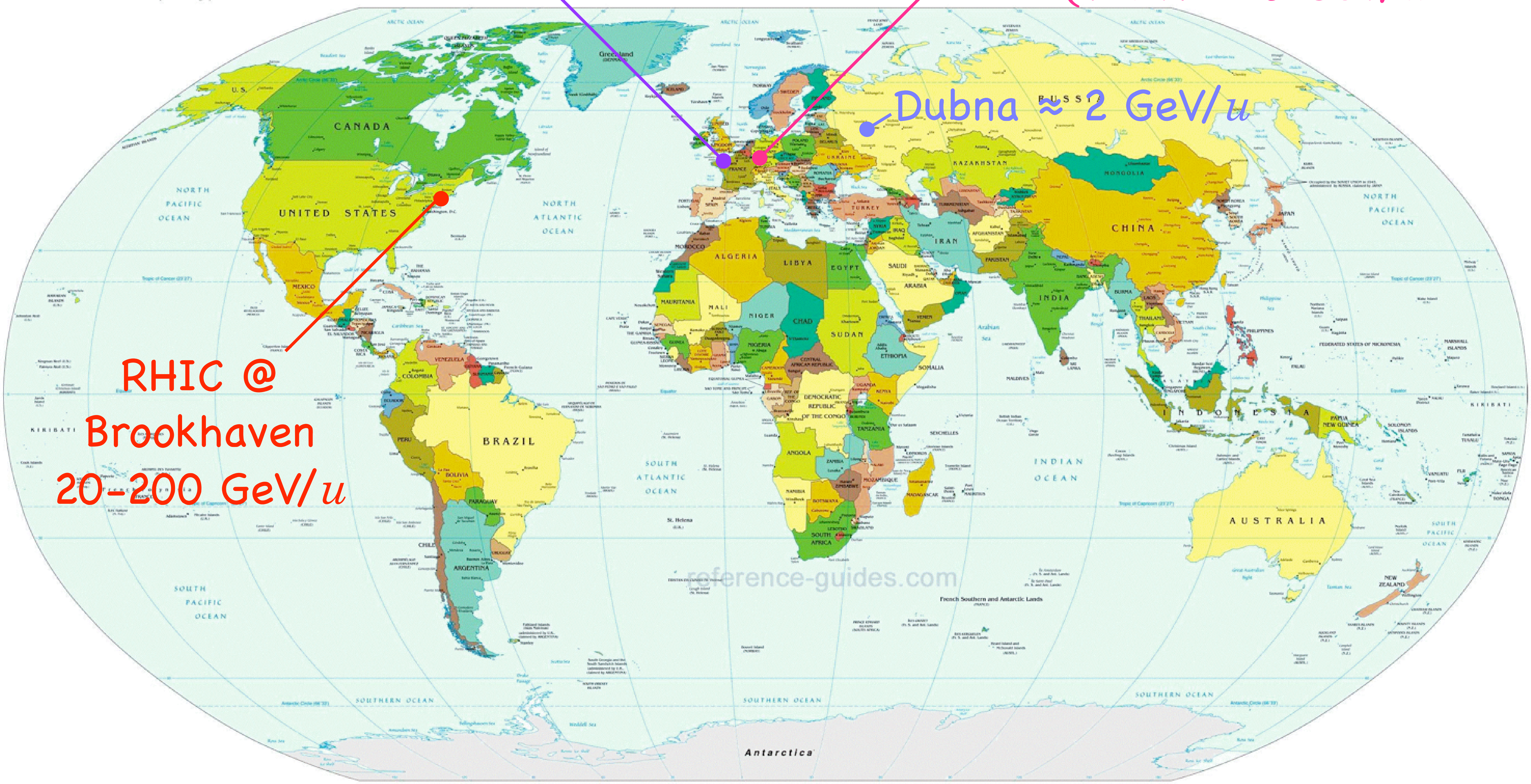
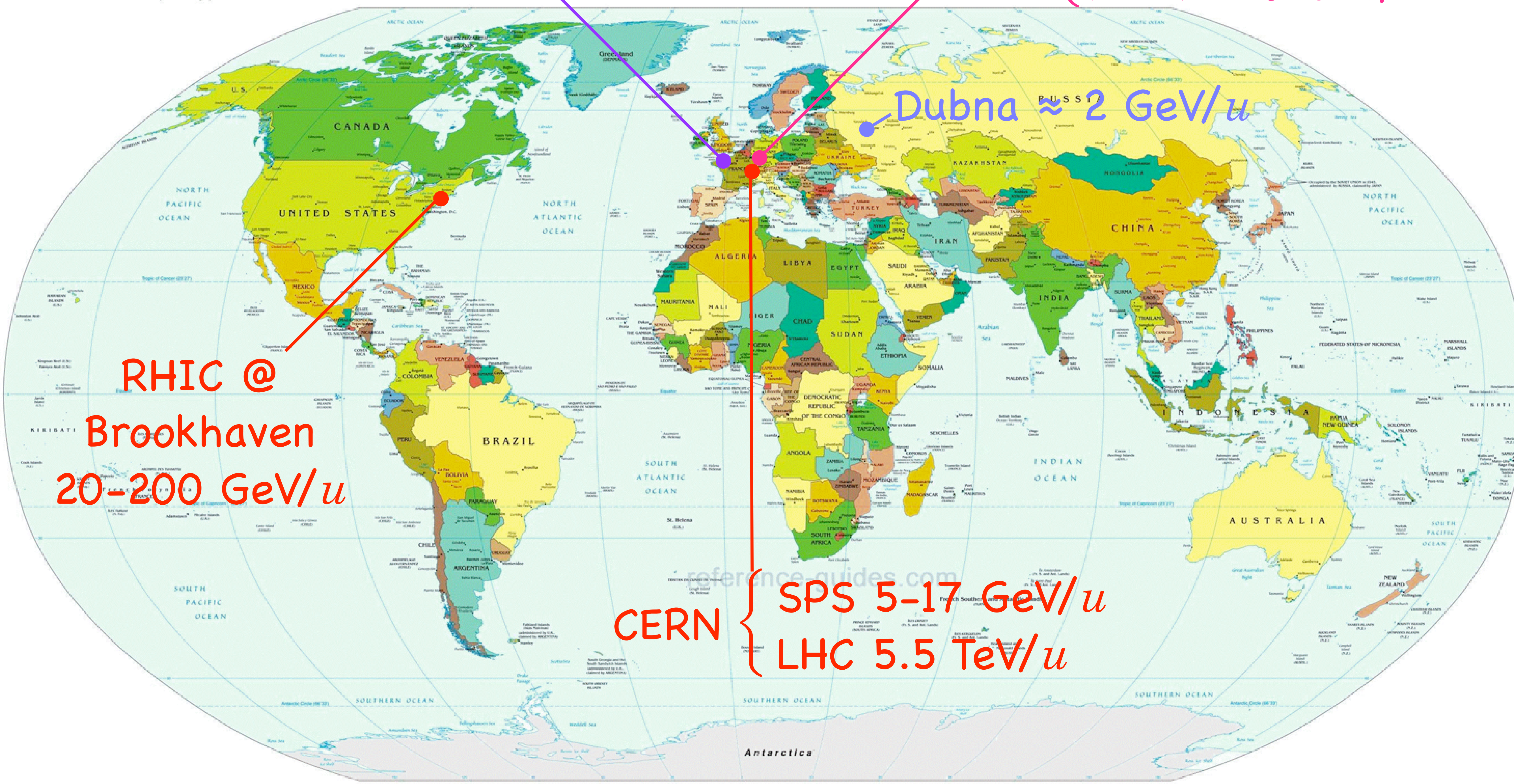
Dubna ≈ 2 GeV/u

RHIC @ Brookhaven 20–200 GeV/u



Heavy ion experiments



Relativistic Heavy Ion Collider

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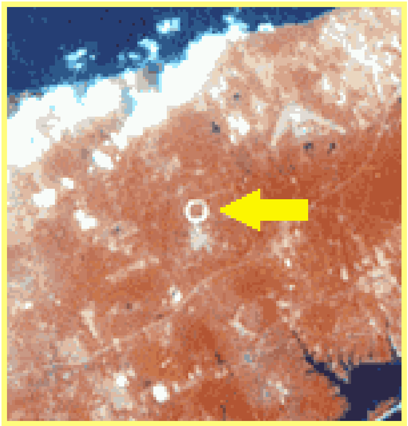
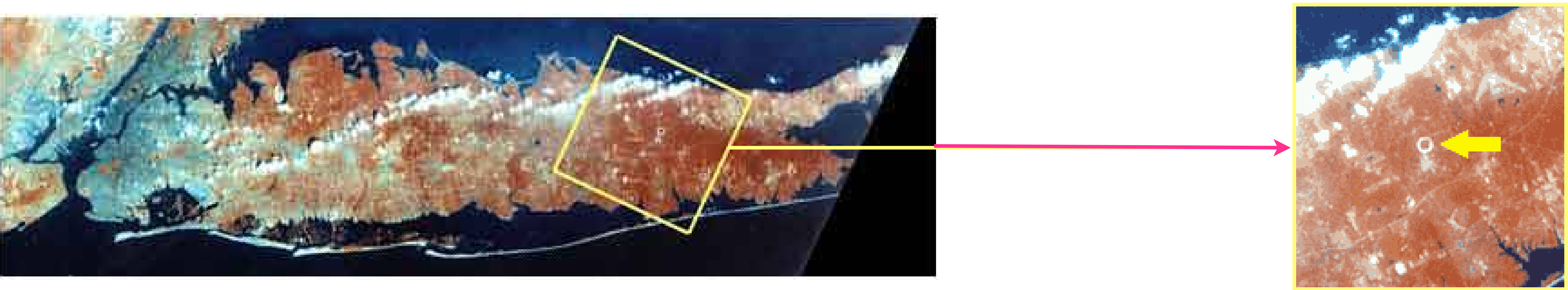


Relativistic Heavy Ion Collider



A 4 km-long dedicated machine, operating since 2000:
Au-Au & Cu-Cu collisions at
$\sqrt{s_{NN}}$ = 19.6 (one week), 22.4, 62.4, 130 & 200 GeV
(+ proton-proton & d-Au collisions)

4 experiments (BRAHMS, PHENIX, PHOBOS, STAR)

Heavy ion experiments

THE result

(first seen at SPS, at RHIC? in the end, it doesn't matter)

In heavy-ion collisions at ultra-relativistic energies, something "new" is created, namely a "mesoscopic" region (size ≈ several fm, much larger than that of a hadron) in which the acting degrees of freedom carry a color charge.

Heavy ion experiments

THE result

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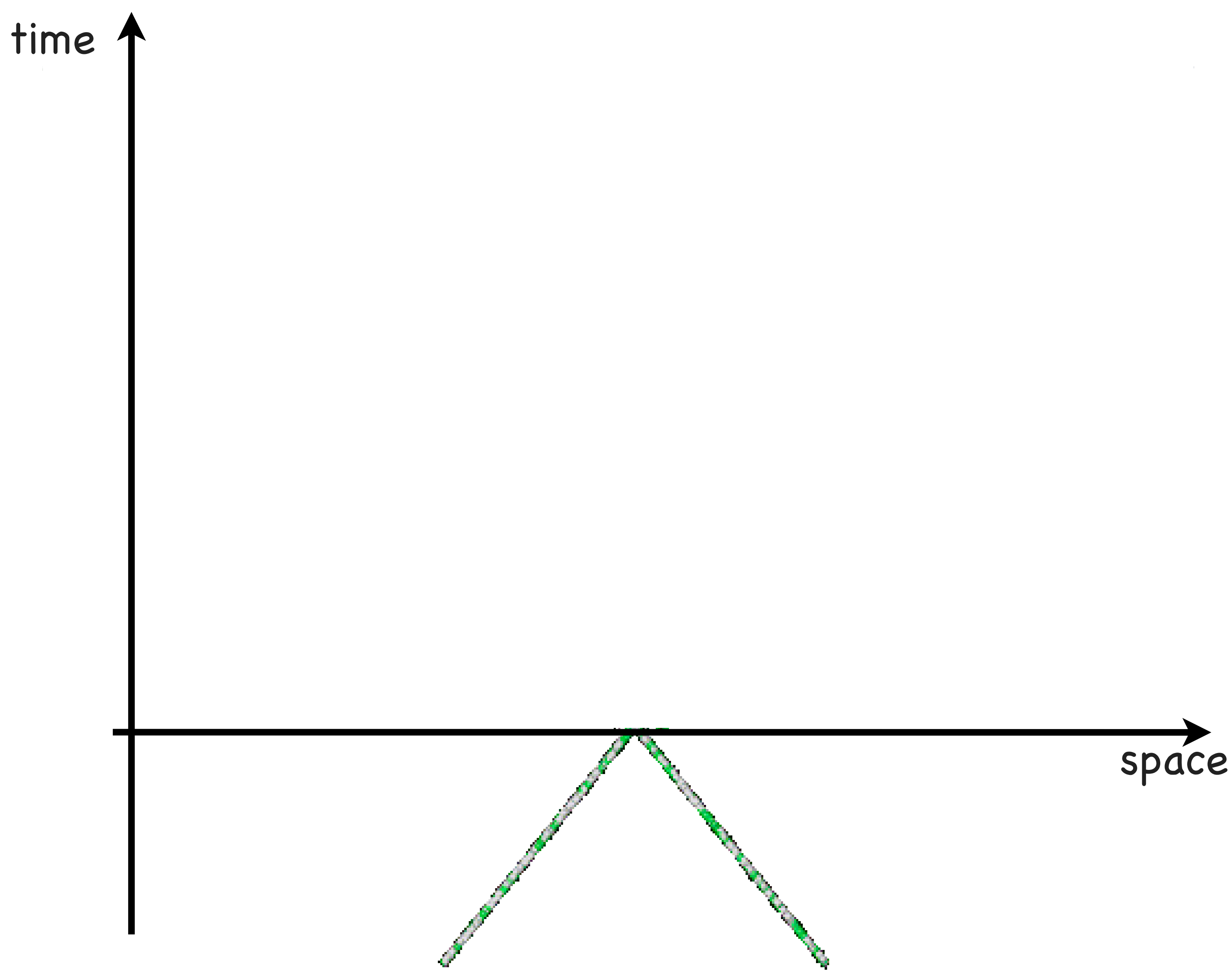
In heavy-ion collisions at ultra-relativistic energies, something "new" is created, namely a "mesoscopic" region (size ≈ several fm, much larger than that of a hadron) in which the acting degrees of freedom carry a color charge.

Should it be called a quark-gluon plasma?

(issues about thermal equilibrium...)

In any case, what is formed has to be characterized quantitatively.

Time evolution of a heavy-ion collision



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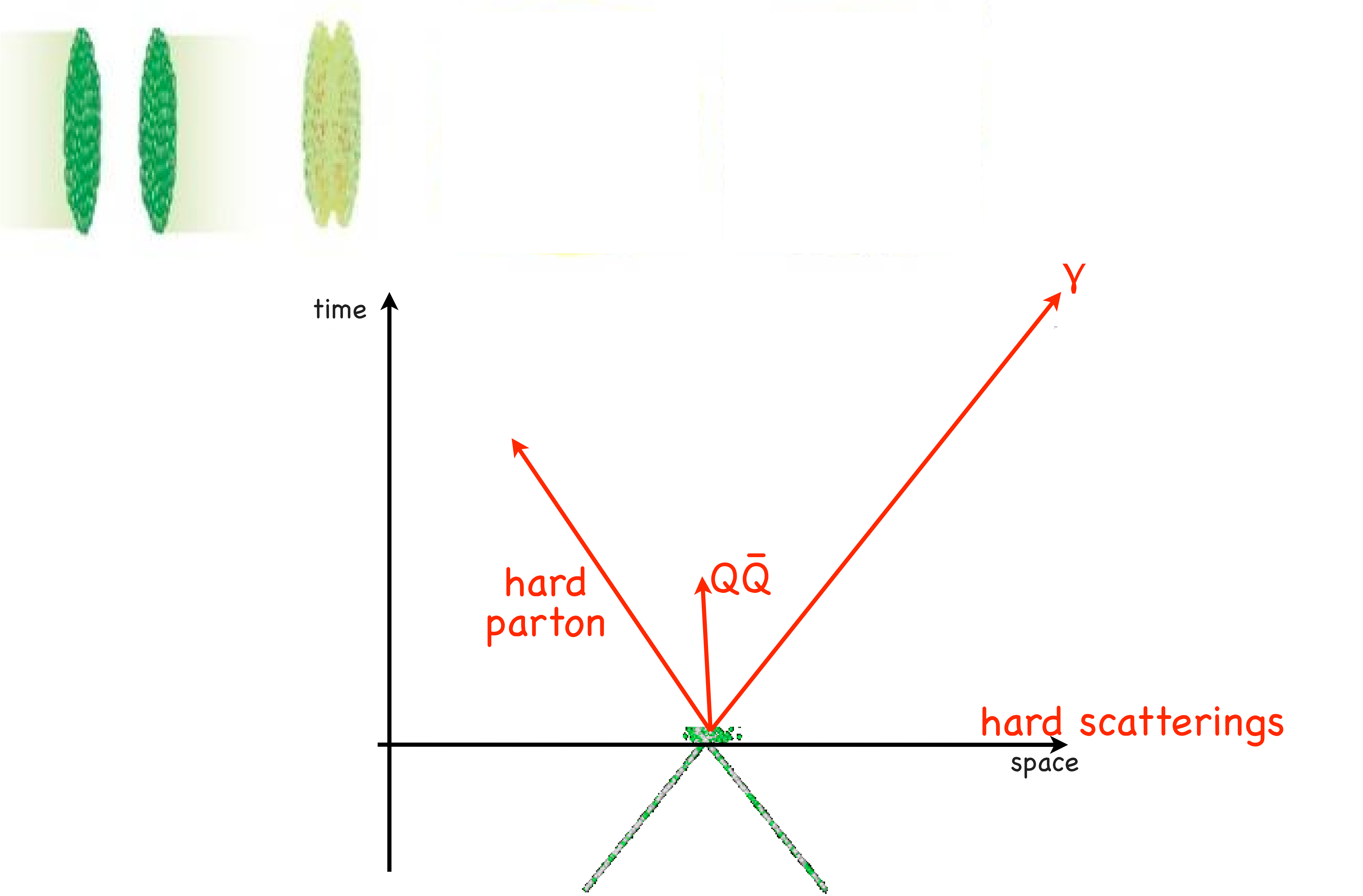

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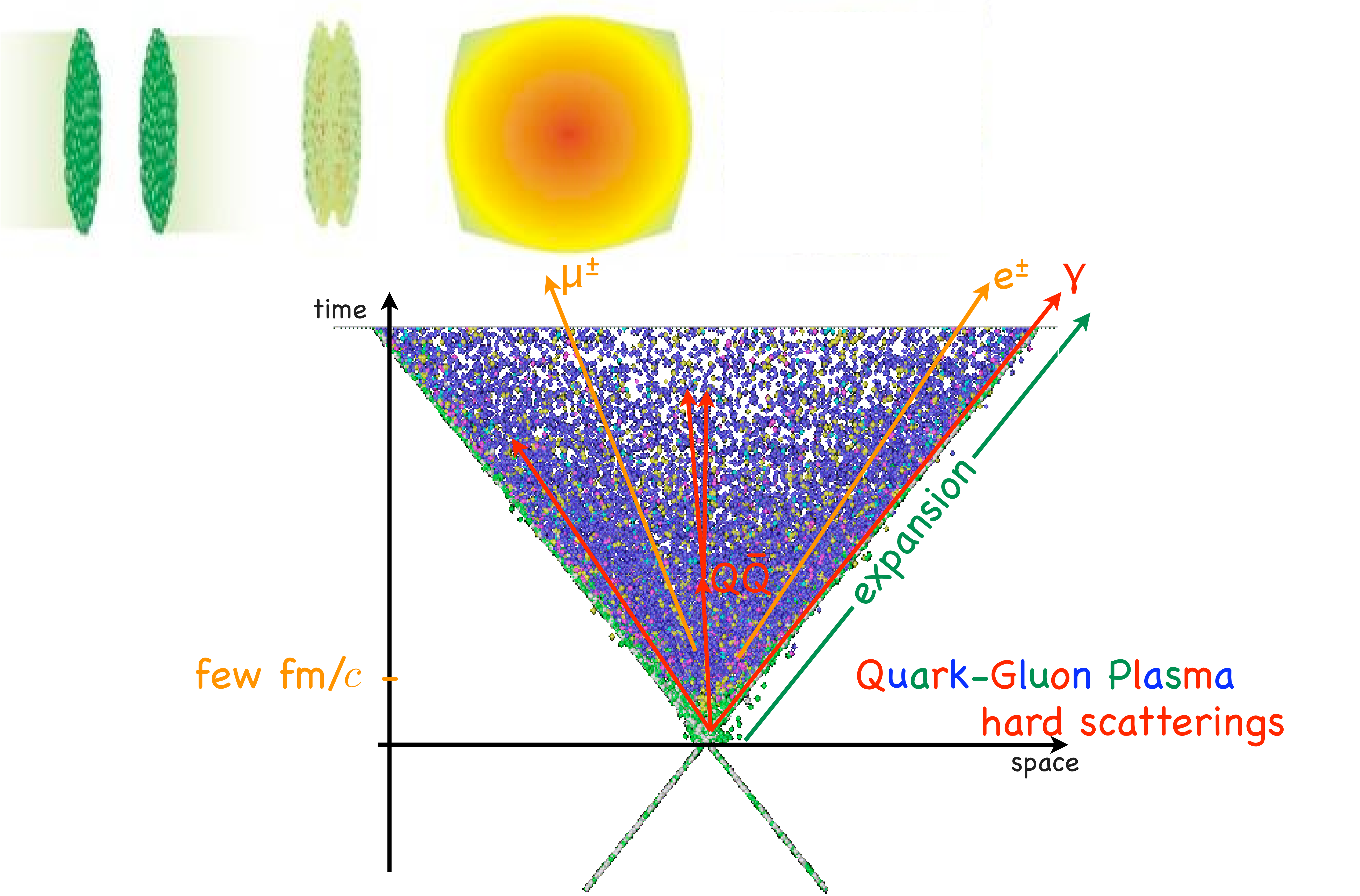

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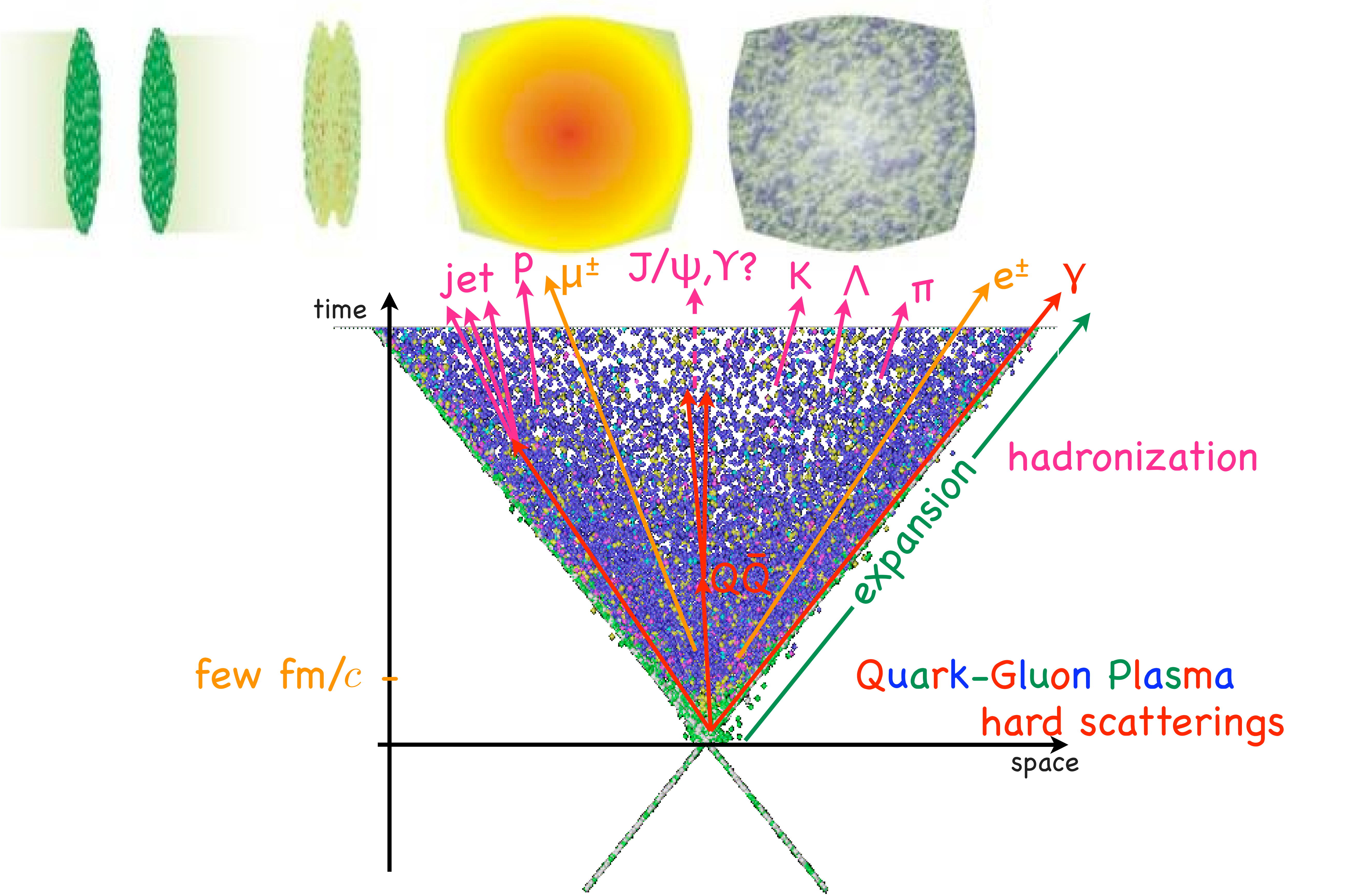

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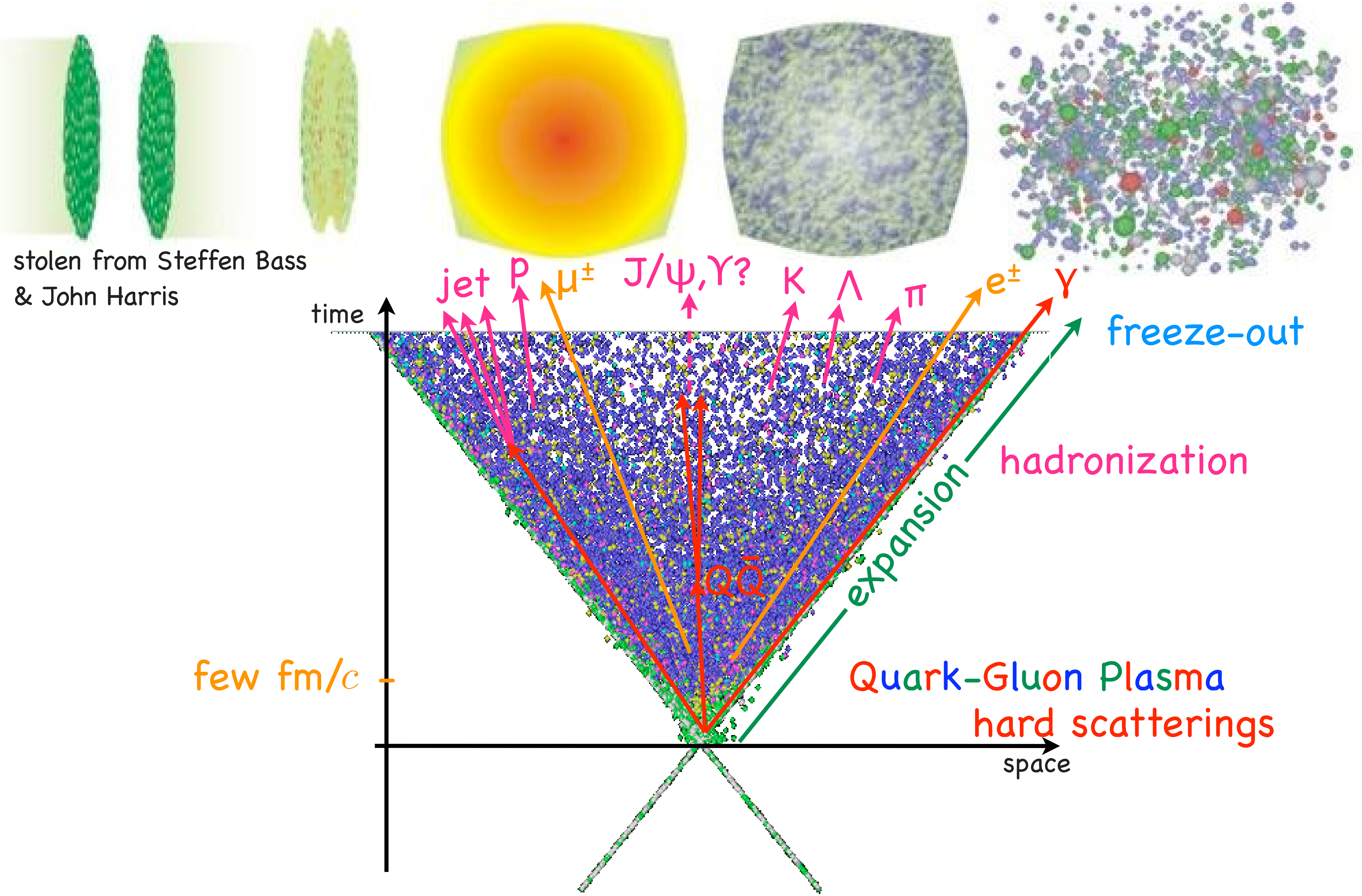


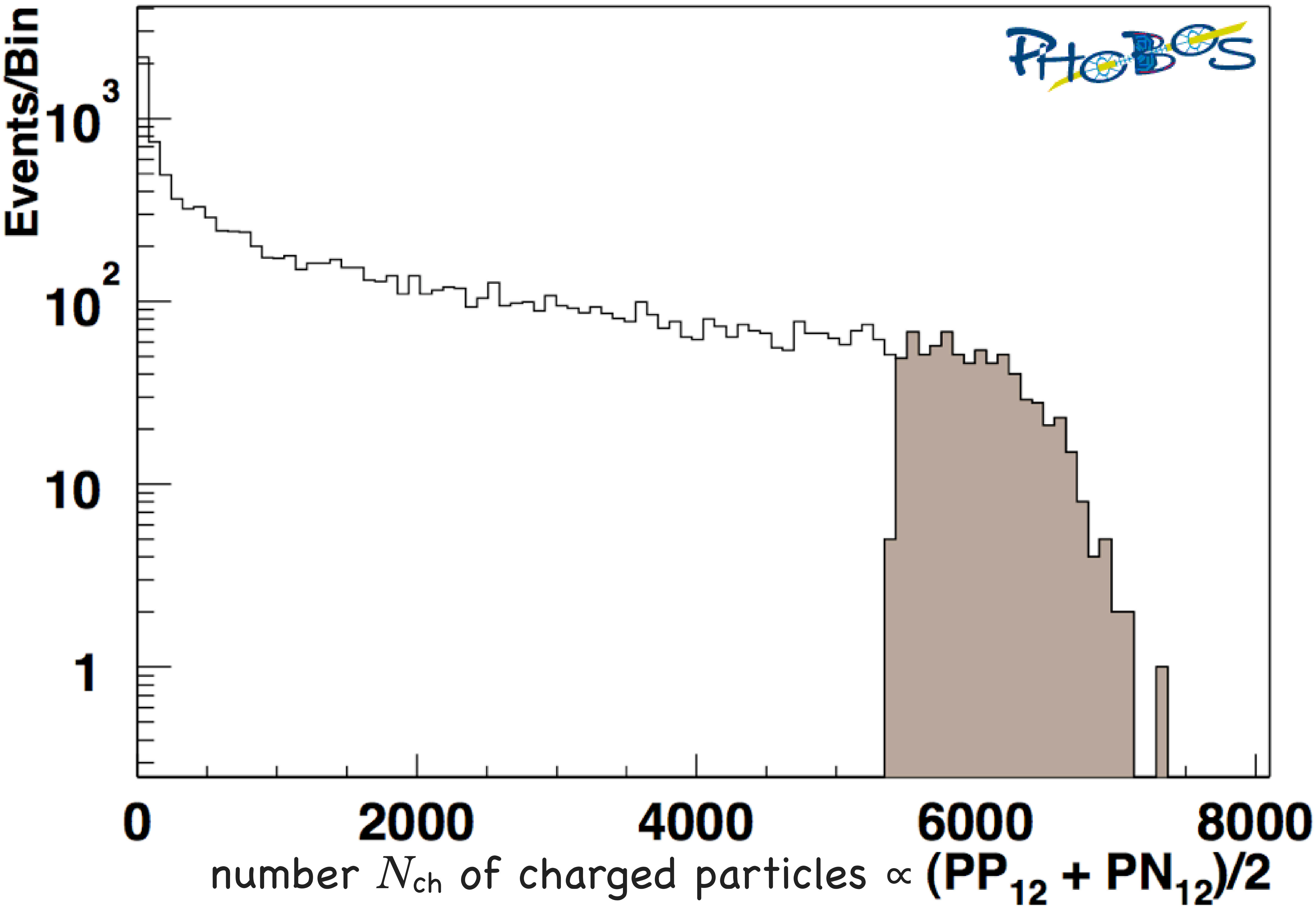
Phenomenology of heavy-ion collisions

How can one characterize what is created in a heavy-ion collision?

Focus on "collective phenomena" present in nucleus-nucleus collisions, but absent in pp collisions ("condensed matter physics of QCD")

- Establish a reference, in which collective effects are absent.
- Quantify the deviation from these benchmarks in nucleus-nucleus collisions.
- Analyze the origin of these deviations.

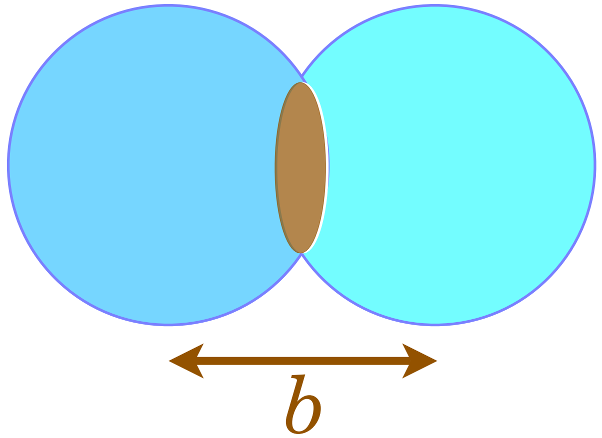
First measurement: multiplicity



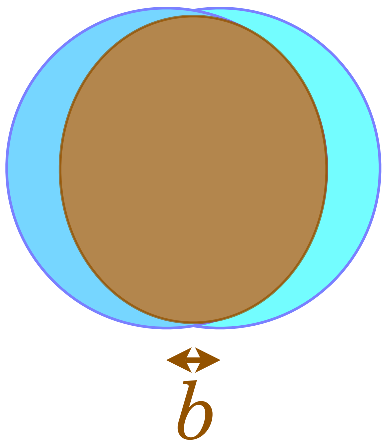
Heavy-ion collisions: geometry

Heavy nuclei have a finite radius!

☞ In a collision the impact parameter plays a role:



- the nuclei might barely graze each other (large impact parameter, "peripheral" collision)



- or the collision might be almost head-on (small impact parameter, "central" collision)

The (almond-shaped) overlap regions of the nuclei are different in either case (size, eccentricity...).

Multiplicity vs. geometry

The multiplicity distribution $\dfrac{\mathrm{d}N_{\mathrm{evts}}}{\mathrm{d}n_{\mathrm{ch}}}$ in heavy-ion collisions is largely determined by geometry, i.e., by the value of the impact parameter $|\mathbf{b}|$ of the nucleus-nucleus (A-B) collision

To relate geometry and multiplicity, one needs a counting rule:

- $\mathbf{b}$ determines some "equivalent number" of nucleon-nucleon (N-N) collisions, whose superposition would constitute the nucleus-nucleus collision: $N_{\mathsf{coll}}^{A\text{-}B}$;

- with the help of the inelastic N-N cross-section $\sigma_{N\text{-}N}^{\mathsf{inel}}$ one can relate $N_{\mathsf{coll}}^{A\text{-}B}$ to the multiplicity.

For instance, Glauber theory.

Glauber theory: N-A collisions

Nuclear profile function $T_A(\mathbf{b}) = \int_{-\infty}^{\infty} \mathrm{d}z \, \underbrace{\rho_A(\mathbf{b}, z)}_{\text{nuclear probability density}}$

Average number of N-N collisions in a nucleon-nucleus collision N-A at impact parameter $\mathbf{b}$:

$$\bar{N}_{\text{coll}}^{N\text{-}A}(\mathbf{b}) = A\,T_A(\mathbf{b})\sigma_{N\text{-}N}^{\text{inel}}$$

Average number of participant nucleons in a nucleon-nucleus collision N-A at impact parameter $\mathbf{b}$:

$$\bar{N}_{\text{part}}^{N\text{-}A}(\mathbf{b}) = 1 + \bar{N}_{\text{coll}}^{N\text{-}A}(\mathbf{b}) = A\,T_A(\mathbf{b})\sigma_{N\text{-}N}^{\text{inel}}$$

Inelastic nucleon-nucleus N-A cross-section: $\sigma_{N\text{-}A}^{\text{inel}} = \int \mathrm{d}\mathbf{b}\,\sigma_A(\mathbf{b})$

$$\sigma_A(\mathbf{b}) \equiv 1 - \left[T_A(\mathbf{b})\sigma_{N\text{-}N}^{\text{inel}}\right]^A \simeq 1 - \exp\left[A T_A(\mathbf{b})\sigma_{N\text{-}N}^{\text{inel}}\right]$$

Glauber theory: A-B collisions

Nuclear overlap function $T_{A\text{-}B}(\mathbf{b}) \equiv \int \mathrm{d}\mathbf{r}\, T_B(\mathbf{r})\, T_A(\mathbf{b}-\mathbf{r})$

Inelastic nucleus-nucleus A-B cross-section: $\sigma^{\text{inel}}_{A\text{-}B} = \int \mathrm{d}\mathbf{b}\, \sigma_{A\text{-}B}(\mathbf{b})$

$$\sigma_{A\text{-}B}(\mathbf{b}) \equiv 1 - \left[T_{A\text{-}B}(\mathbf{b})\, \sigma^{\text{inel}}_{N\text{-}N}\right]^{AB} \simeq 1 - \exp\left[AB\, T_{A\text{-}B}(\mathbf{b})\, \sigma^{\text{inel}}_{N\text{-}N}\right]$$

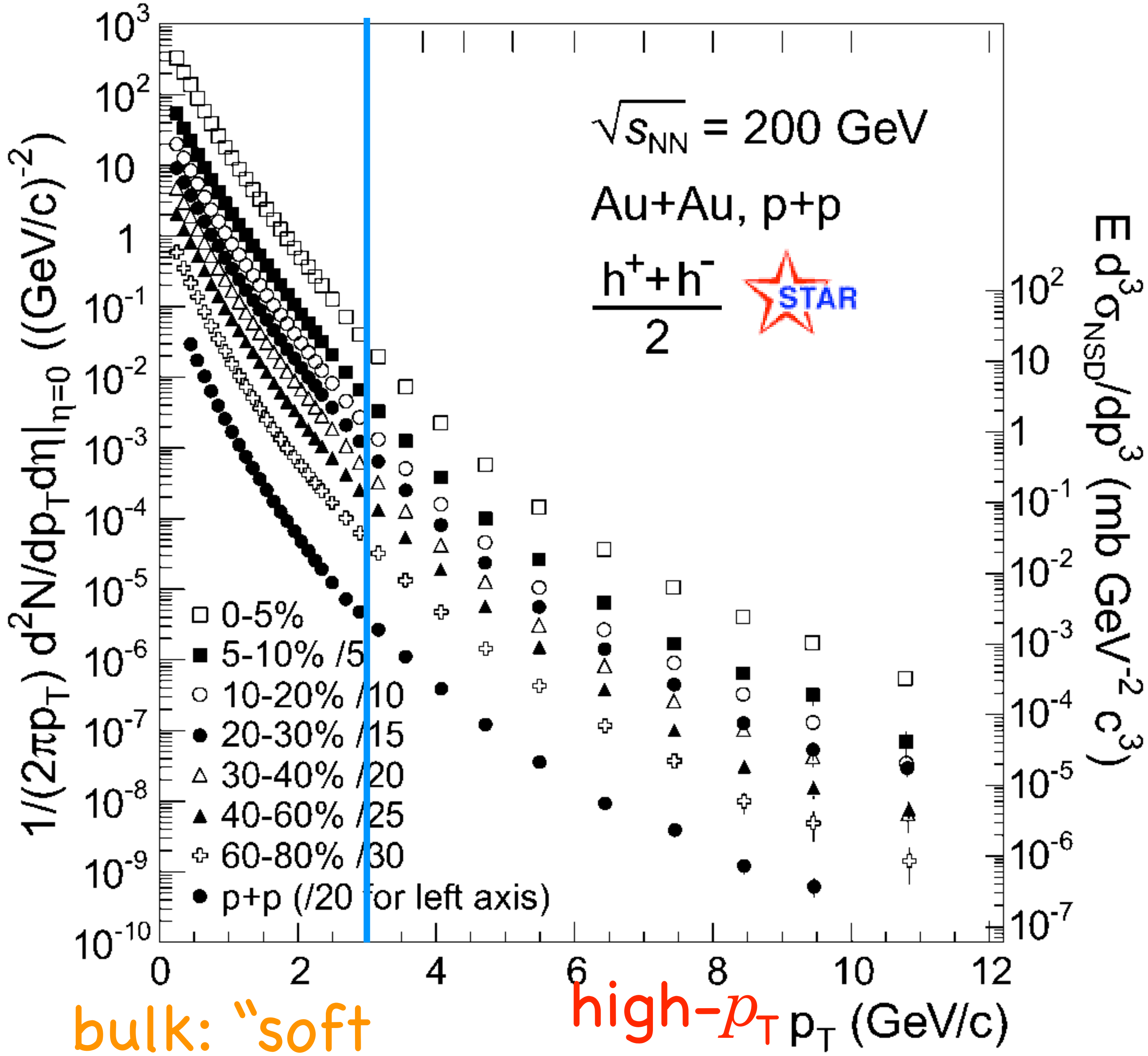
Average number of participant nucleons in a nucleus-nucleus collision A-B at impact parameter $\mathbf{b}$:

$$\bar{N}^{A\text{-}B}_{\text{part}}(\mathbf{b}) = \frac{B\,\sigma_A(\mathbf{b})}{\sigma_{A\text{-}B}(\mathbf{b})} + \frac{A\,\sigma_B(\mathbf{b})}{\sigma_{A\text{-}B}(\mathbf{b})}$$

in particular $\bar{N}^{A\text{-}A}_{\text{part}}(\mathbf{b}) \propto A$

Average number of N-N collisions in a nucleus-nucleus collision A-A at impact parameter $\mathbf{b}$: $\bar{N}^{A\text{-}A}_{\text{coll}}(\mathbf{b}) \propto A^{4/3}$

Multiplicity



bulk: "soft particles"

$\propto N^{A\text{-}B}_{\text{part}}$

high-p_T probes

$\propto N^{A\text{-}B}_{\text{coll}}$

Multiplicity distribution

Vary the equivalent number of nucleon–nucleon collisions between $\bar{N}^{A\text{-}B}_{\rm part}(\mathbf{b})$ and $\bar{N}^{A\text{-}B}_{\rm coll}(\mathbf{b})$:

$$\bar{n}_{A\text{-}B}(\mathbf{b}) = \left(\frac{1-x}{2}\bar{N}^{A\text{-}B}_{\rm part}(\mathbf{b}) + x\bar{N}^{A\text{-}B}_{\rm coll}(\mathbf{b})\right)\bar{n}_{N\text{-}N}$$

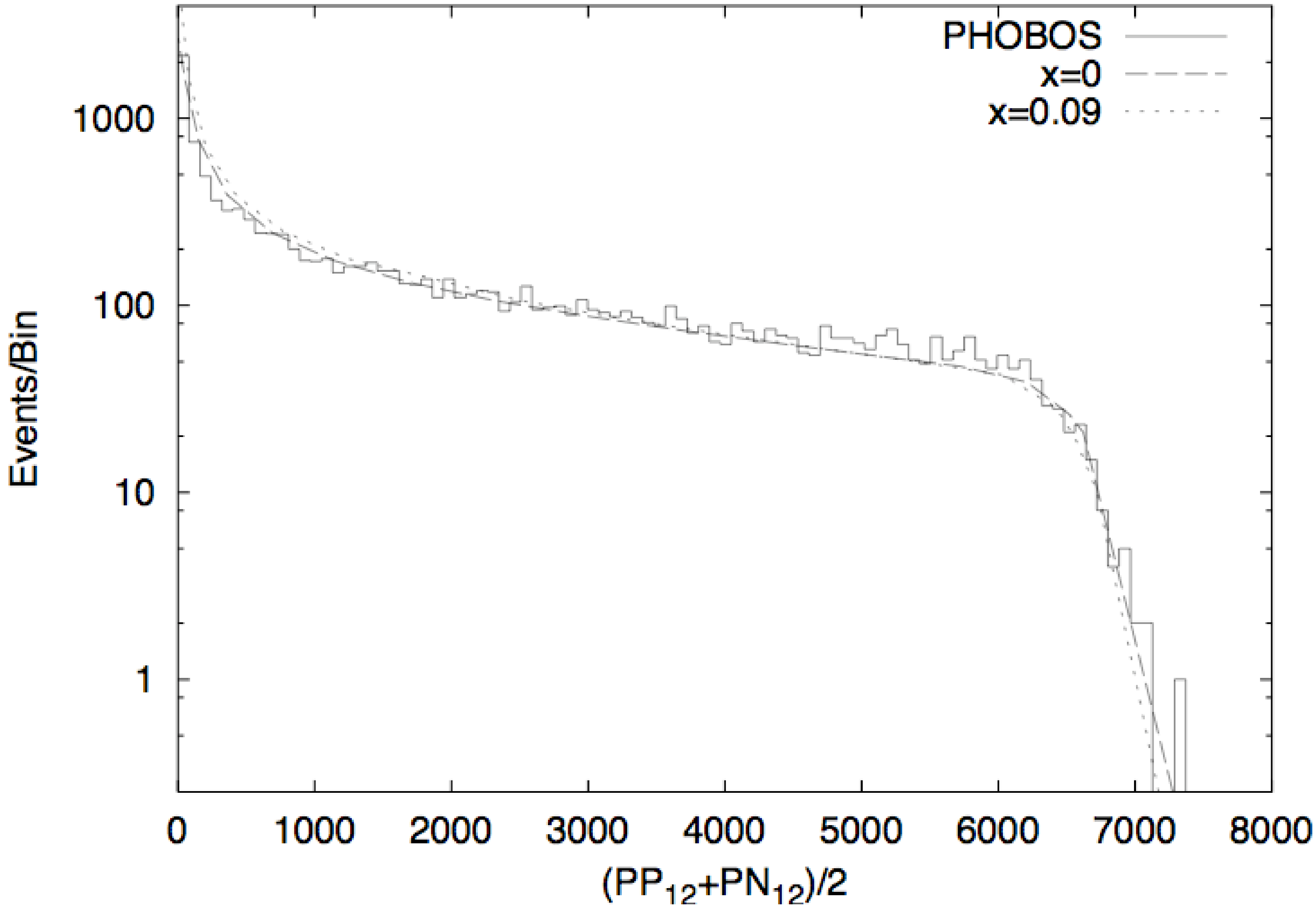
Probability $P(n,\mathbf{b})$ to find a multiplicity n in a particular A-B collision at impact parameter $\mathbf{b}$ is Gaussian around $\bar{n}_{A\text{-}B}(\mathbf{b})$, with some (model-dependent) dispersion.

☞ event-multiplicity distribution:

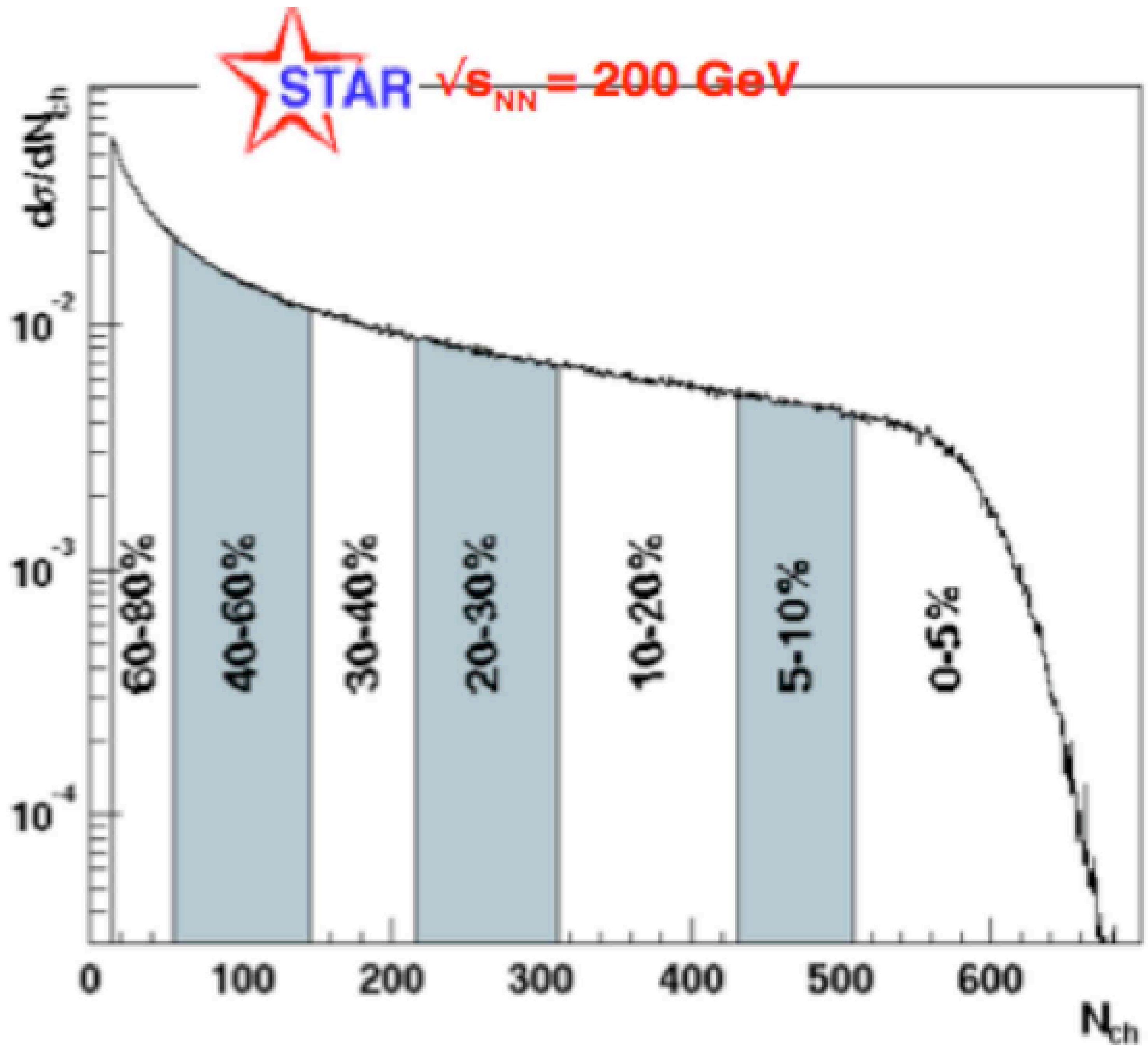
$$\frac{\mathrm{d}N_{\rm evts}}{\mathrm{d}n} = \int \mathrm{d}\mathbf{b}\, P(n,\mathbf{b}) \underbrace{\left[1-\left(1-\sigma^{\rm inel}_{N\text{-}N}T_{A\text{-}B}(\mathbf{b})\right)^{AB}\right]}_{\text{probability that an inelastic process occur}}$$

Multiplicity distribution

$$\frac{\mathrm{d}N_{\mathrm{evts}}}{\mathrm{d}n} = \int \mathrm{d}\mathbf{b}\, P(n,\mathbf{b}) \Big[1 - \big(1 - \sigma^{\mathrm{inel}}_{N\text{-}N} T_{A\text{-}B}(\mathbf{b})\big)^{AB}\Big]$$



Multiplicity vs. geometry



Multiplicity vs. geometry