Signals of collective behavior in high-energy nuclear collisions

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Strong-interaction matter under extreme conditions

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Signals of collective behavior in high-energy nuclear collisions

- What is the purpose of colliding heavy nuclei at high energy?
  - Motivation(s) from particle physics
  - Relevance in nature?
- Salient findings
  - Experimental results
  - Standard paradigm for the system dynamics
- Beyond the standard paradigm?

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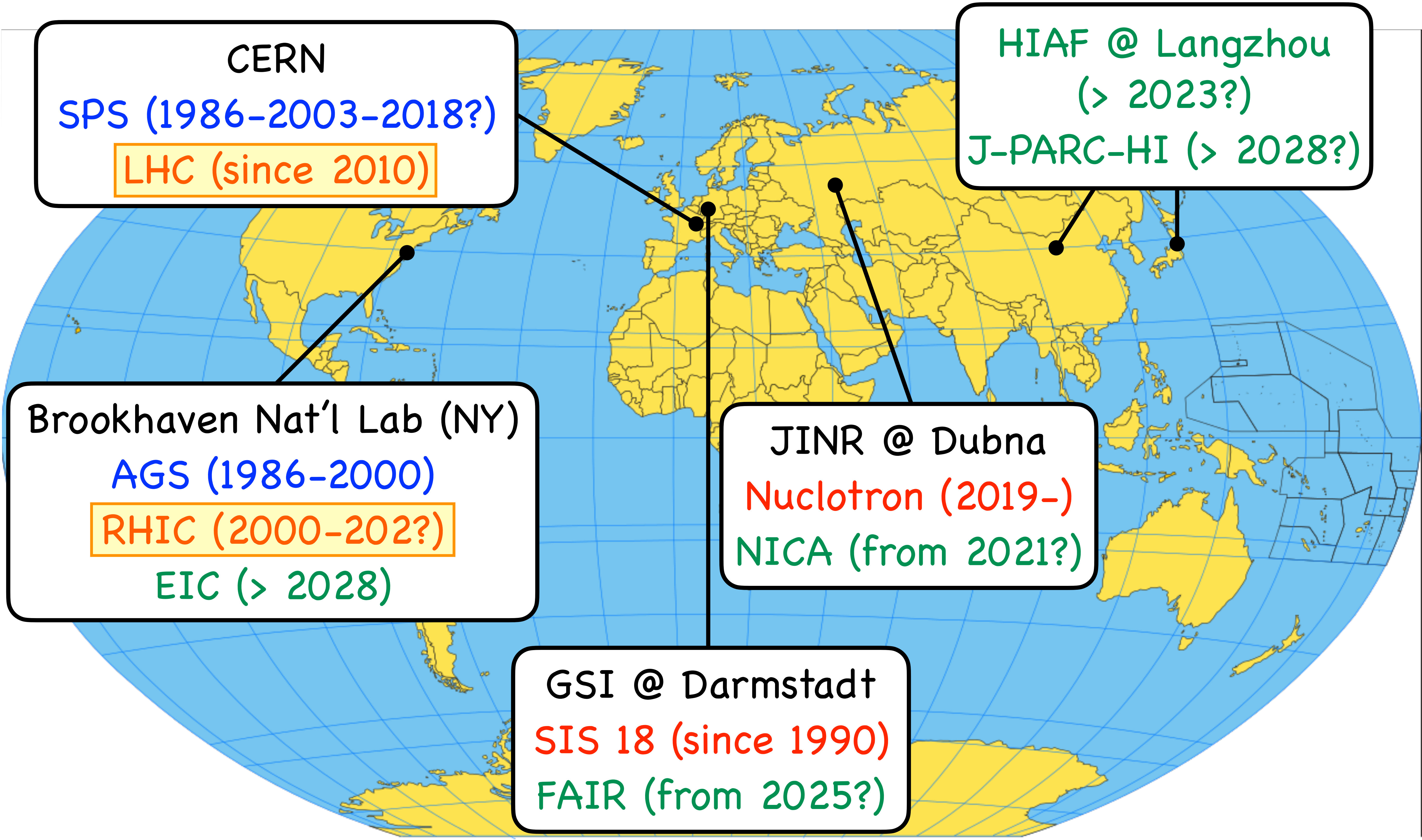
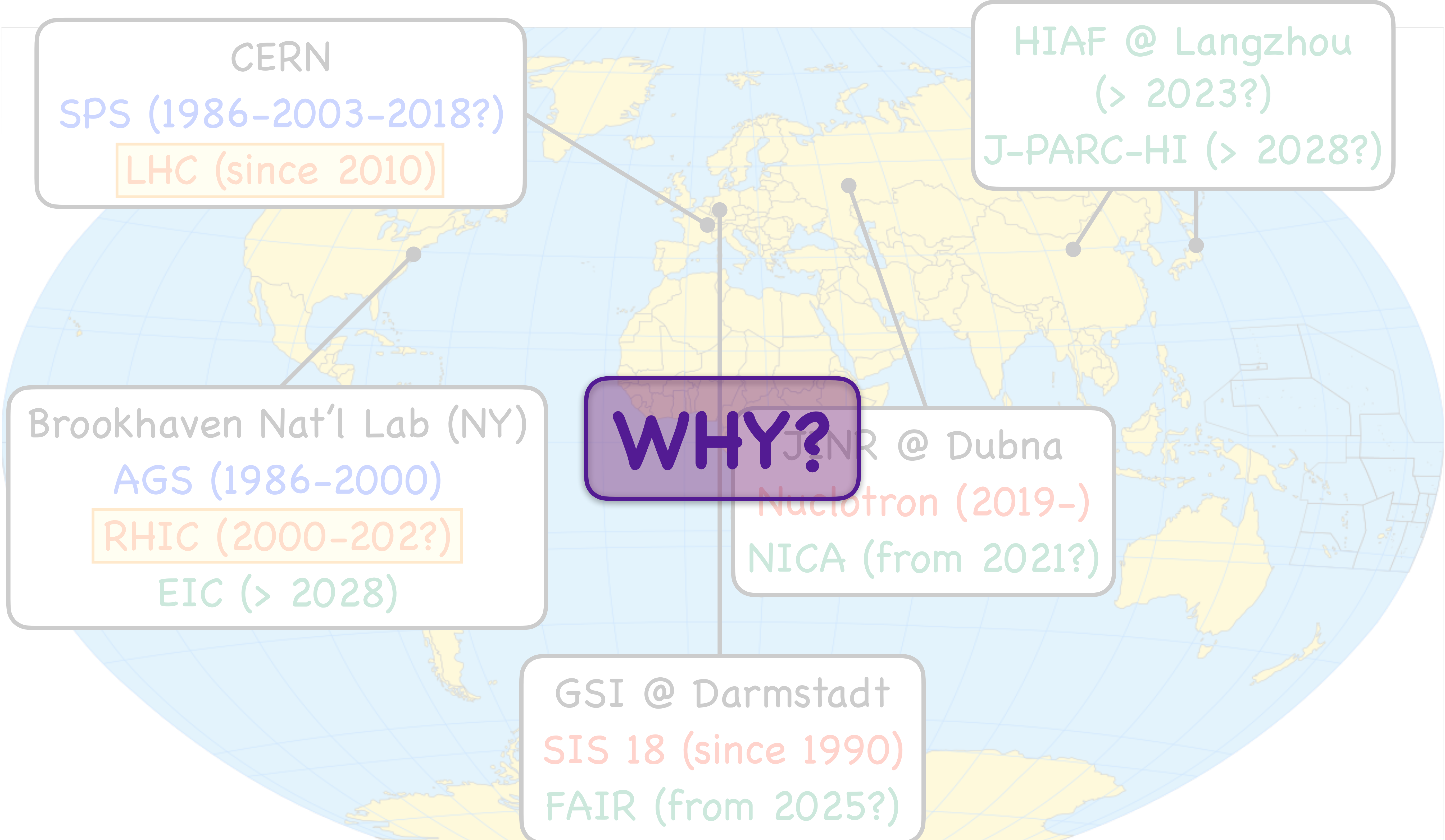
High-energy heavy ion experiments



with ultrarelativistic nuclei

High-energy heavy ion experiments



with ultrarelativistic nuclei

A few scales & units to keep in mind...

- Radius of nucleus with atomic mass number A: $R_A \approx 1.1\,A^{1/3}$ fm

  1 fm (femtometer / Fermi) = 10^{-15} m

  ☞ for ^{208}Pb, $R_{\rm Pb} \approx 6.6$ fm

- The corresponding "natural" time scale is $\dfrac{R_{\rm Pb}}{c} = 6.6$ fm/c (!) ≈ 22 ys

  1 fm/$c \approx 3.3$ ys (yoctosecond) = $3.3 \cdot 10^{-24}$ s

- Mass of the ^{208}Pb nucleus $m_{\rm Pb} \approx 208 m_{\rm N}$

  with $m_{\rm N}$ = 0.939 GeV/c^2 = $1.67 \cdot 10^{-27}$ kg

☛ typical length, time, mass, energy scales: fm, fm/c, GeV/c^2, GeV.

For example, the energy density of a nucleon (proton/neutron) at rest is ≈ 1 GeV/fm^3.

Units...

I shall be somewhat inconsistent!

- Questions from high-energy physics
  - The natural(!) choice is as usual to set

$$\hbar = c = k_{\mathrm{B}} = 1$$

  - ... and accordingly to express
    - energies, masses, momenta, temperatures in MeV or GeV
    - lengths, time durations... in MeV^{-1} or GeV^{-1}
    - resulting in energy densities in MeV^4 or GeV^4
    - (velocities are dimensionless)
  - Yet I will use fm for lengths, fm/c for times & durations, $\mathrm{GeV/fm}^3$ for energy densities...

Why high-energy heavy-ion collisions?

- What does "high-energy collisions" mean?
  - ☞ in 2015-2018 the kinetic energy of a ^{208}Pb nucleus at LHC was

$$E_{\rm kin} = 522\ \text{TeV} = 208\times 2.51\ \text{TeV} \approx 2700\, m_{\rm Pb}\, c^2$$

ultrarelativistic regime! $v_{\rm Pb} \approx (1 - 7\cdot 10^{-8})\,c$

  - ☞ in a single Pb-Pb collision at LHC, the available energy is $2E_{\rm kin}$.

- If 10% of this energy is deposited in a volume of about 1000 fm^3, then the energy density in this volume is $e \approx 100$ GeV/fm^3.

- Such an energy density amounts* to a temperature $k_{\rm B}T \approx 500$ MeV, i.e. $T \approx 6\cdot 10^{12}$ K ($\gg 15\cdot 10^6$ K at the center of the Sun!)

  ☛ hot (& dense) medium: "new state of matter"

* modulo an appropriate equation of state (see later)

Why high-energy heavy-ion collisions?

☞ To create a system with extreme conditions

What are the theoretical expectations for nuclear matter under such conditions?

Note: electrons (and more generally leptons) and photons are absent from the following considerations.

A short, incomplete history…

- 1910-32: Atomic nuclei exist and are made up of protons & neutrons, bound together by a strong (nuclear) force.

- 1960's: Protons & neutrons (and their relatives that undergo the strong force: hadrons) are made up of more elementary constituents: quarks. These come in various flavors — u, d, s, c… — and in turn each flavor can come up in 3 "colors".

Hadrons are color-neutral: the quarks are bound together by gluons — which are themselves color-charged. Colored particles & antiparticles cannot be isolated: "confinement".

A short, incomplete history...

- Early 1970's: The theory of the strong interaction between quarks and gluons is formulated — as a gauge field theory with group $SU(3)_c$:

  Quantum Chromodynamics (QCD)

- 1973: Gross, Politzer & Wilczek show that QCD possesses asymptotic freedom: at small distances — or equivalently in processes with large four-momentum exchanges —, the coupling constant becomes small.

  ≠ Quantum Electrodynamics

☞ Closely packed quarks (and gluons) interact "weakly"* with their closest neighbors: they behave as if they were free = non-interacting.

* Throughout, the electromagnetic & weak interactions of quarks are assumed to be negligible...

A short, incomplete history...

- 1973: Gross, Politzer & Wilczek show that QCD possesses asymptotic freedom: closely packed quarks & gluons behave as if they were free

☞ where could one observe that?

- 1975: Collins & Perry: if you pack nucleons (= protons & neutrons) close together — in particular: high density inside a neutron star —, they overlap, and the quarks are "freed".

If this is the case, there might be "pure" neutron stars, hybrid stars — with a quark core —, quark stars (without neutrons)...

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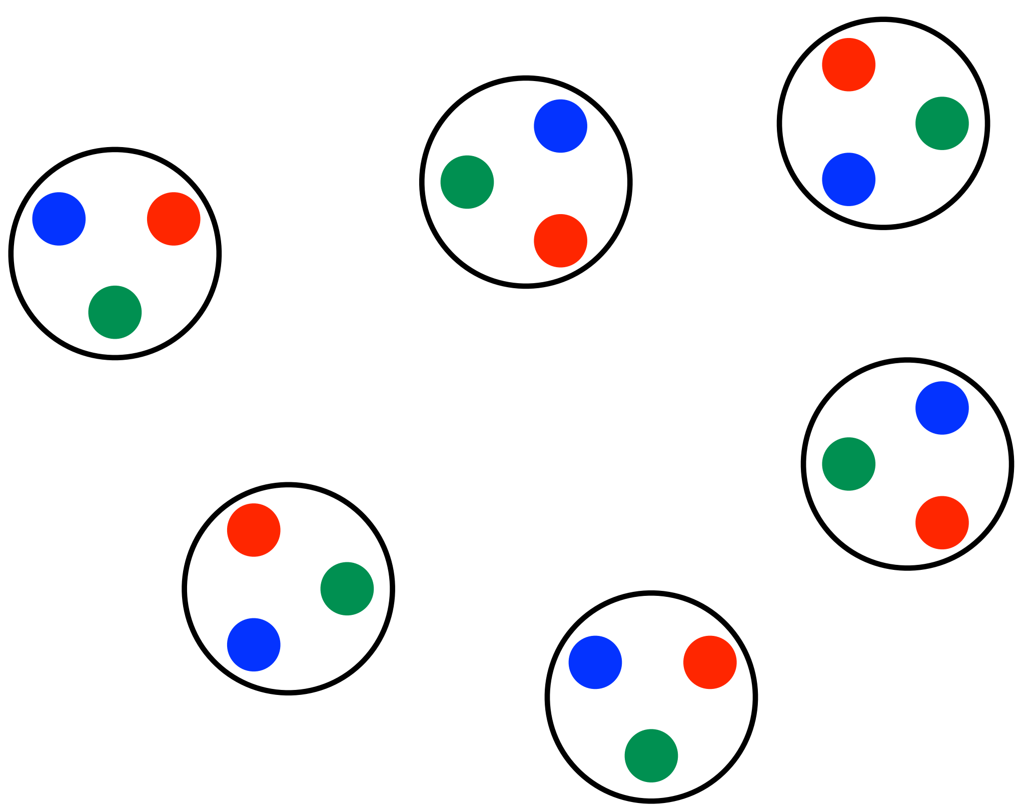
Naïve picture:

Low density:



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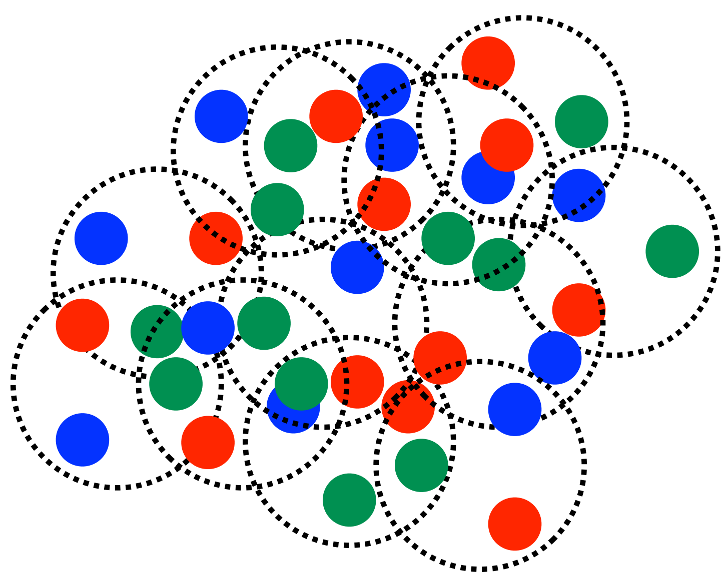
High density:



how do the quarks know "where they belong" (and should stay confined)?

A short, incomplete history...

- 1973: Gross, Politzer & Wilczek show that QCD possesses asymptotic freedom: closely packed quarks & gluons behave as if they were free

☞ where could one observe that?

- 1975: Collins & Perry: if you pack nucleons (= protons & neutrons) close together — in particular: high density inside a neutron star —, they overlap, and the quarks are "freed".

To be more specific, the high density mentioned here is a (net) baryon number density n_B.

(Baryons: hadrons with half-integer spin, in particular protons & neutrons. Net baryon number: difference of the numbers of baryons and antibaryons.)

A short, incomplete history...

- 1973: Gross, Politzer & Wilczek show that QCD possesses asymptotic freedom: closely packed quarks & gluons behave as if they were free

☞ where could one observe that?

- 1975: Collins & Perry: quarks may be "freed" at high net baryon number density n_B.

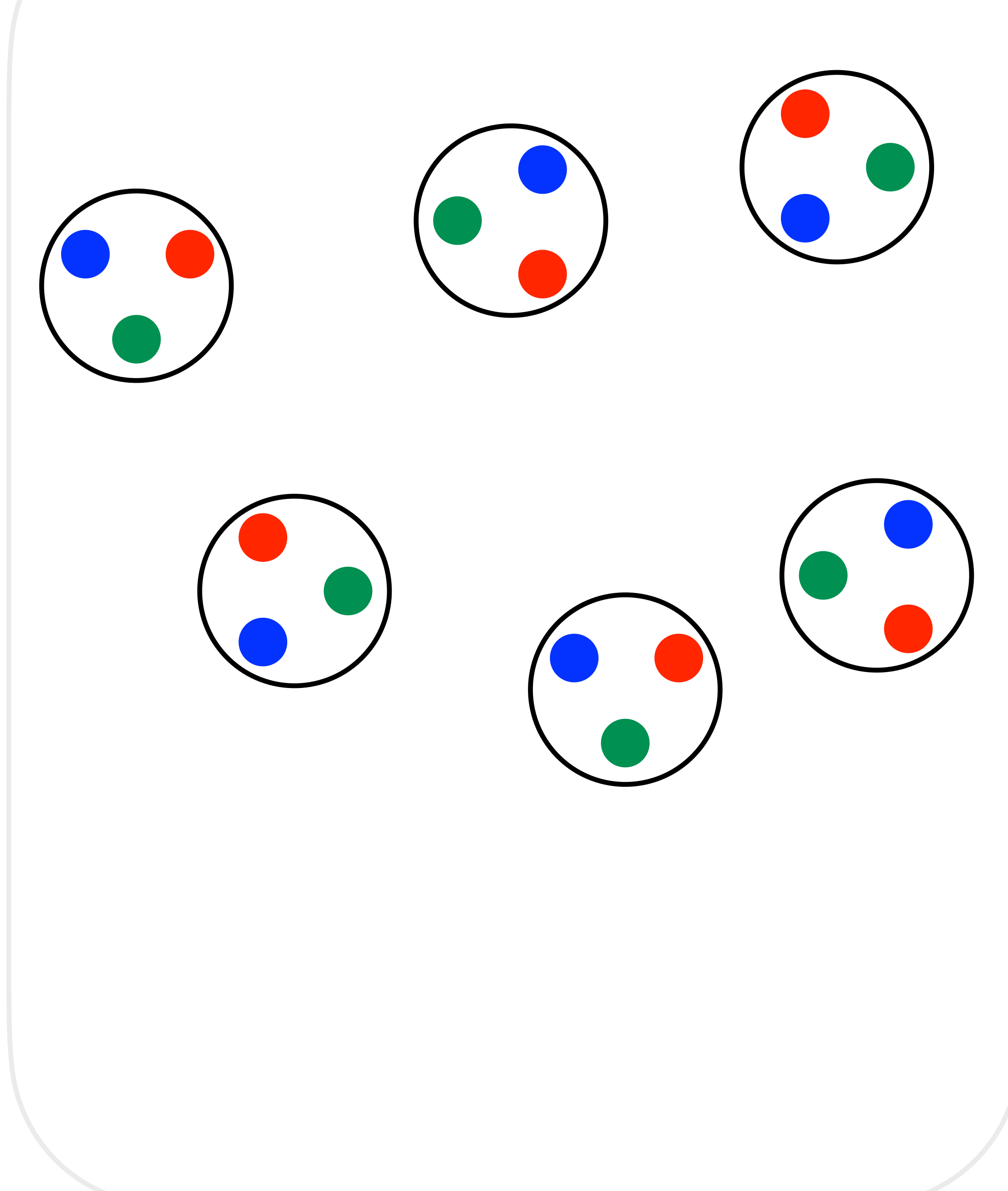
- 1975: Cabibbo & Parisi: if you increase the temperature of matter sufficiently, you also "liberate" quarks...

Not an ionization-like mechanism! By increasing temperature enough, the creation of quark-antiquark-pairs becomes possible, so that the density of color carriers increases — and the distance between them decreases — even though n_B remains fixed.

A short, incomplete history...

At high enough temperature, you “liberate” quarks:

Naïve picture:



A short, incomplete history…

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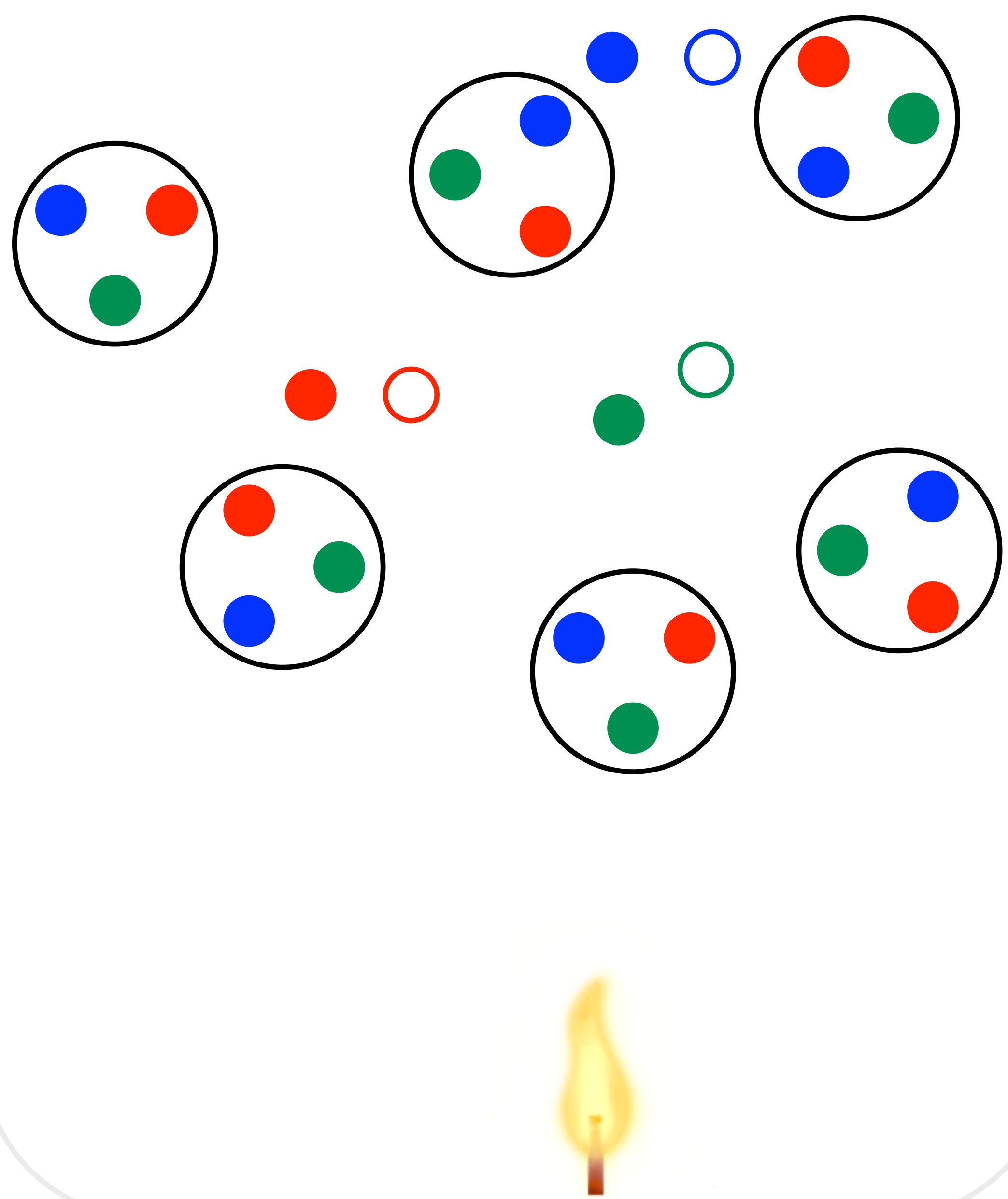

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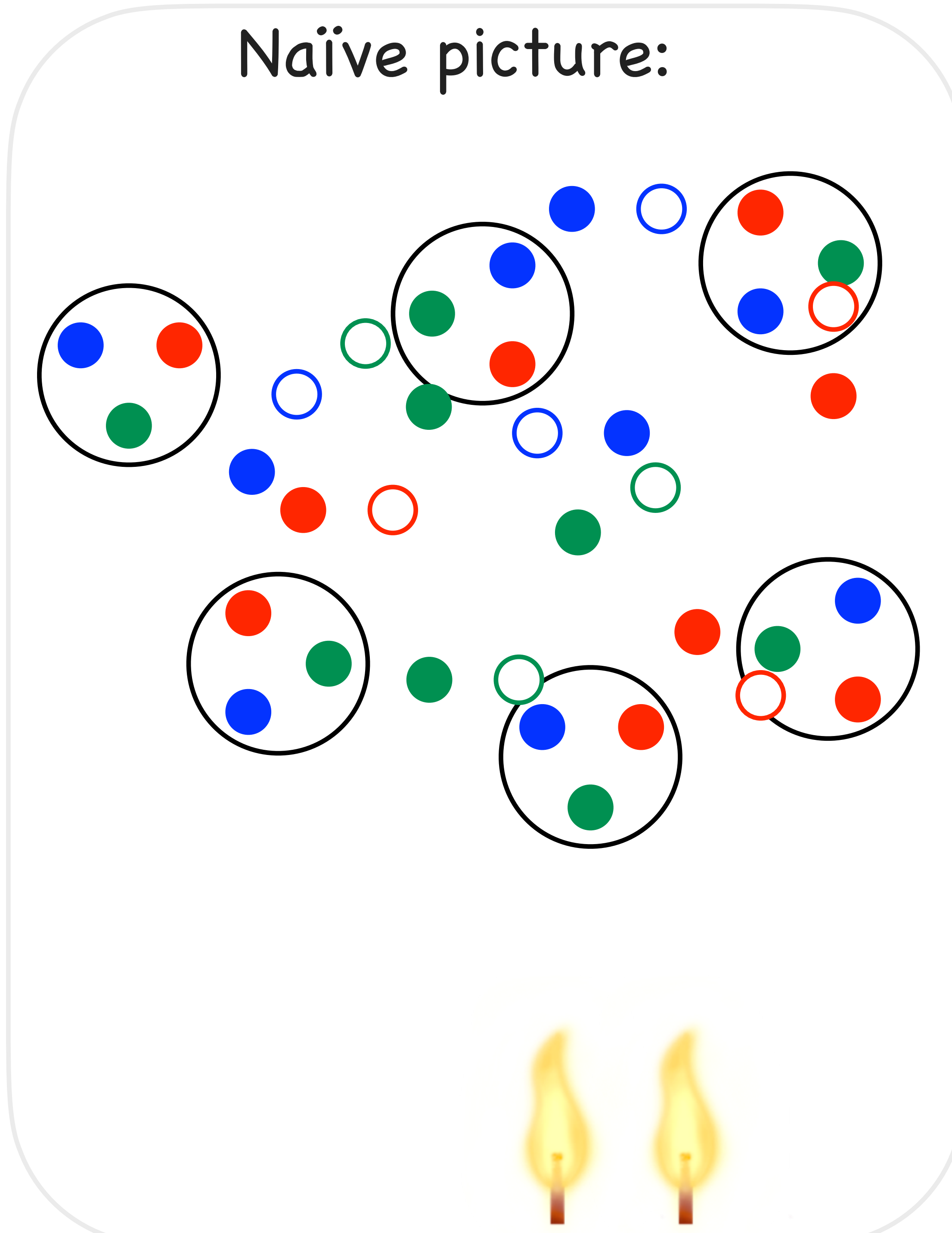

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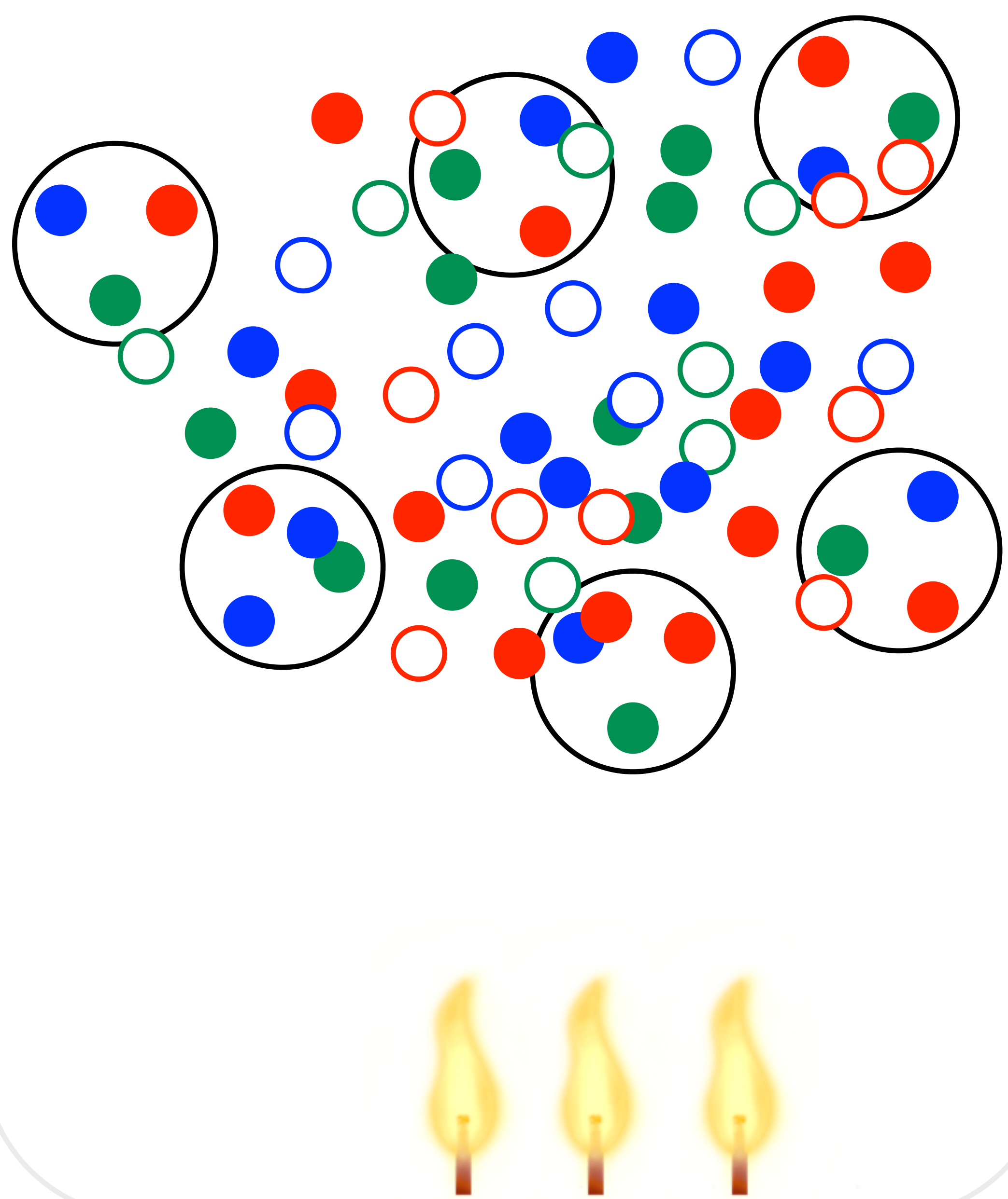

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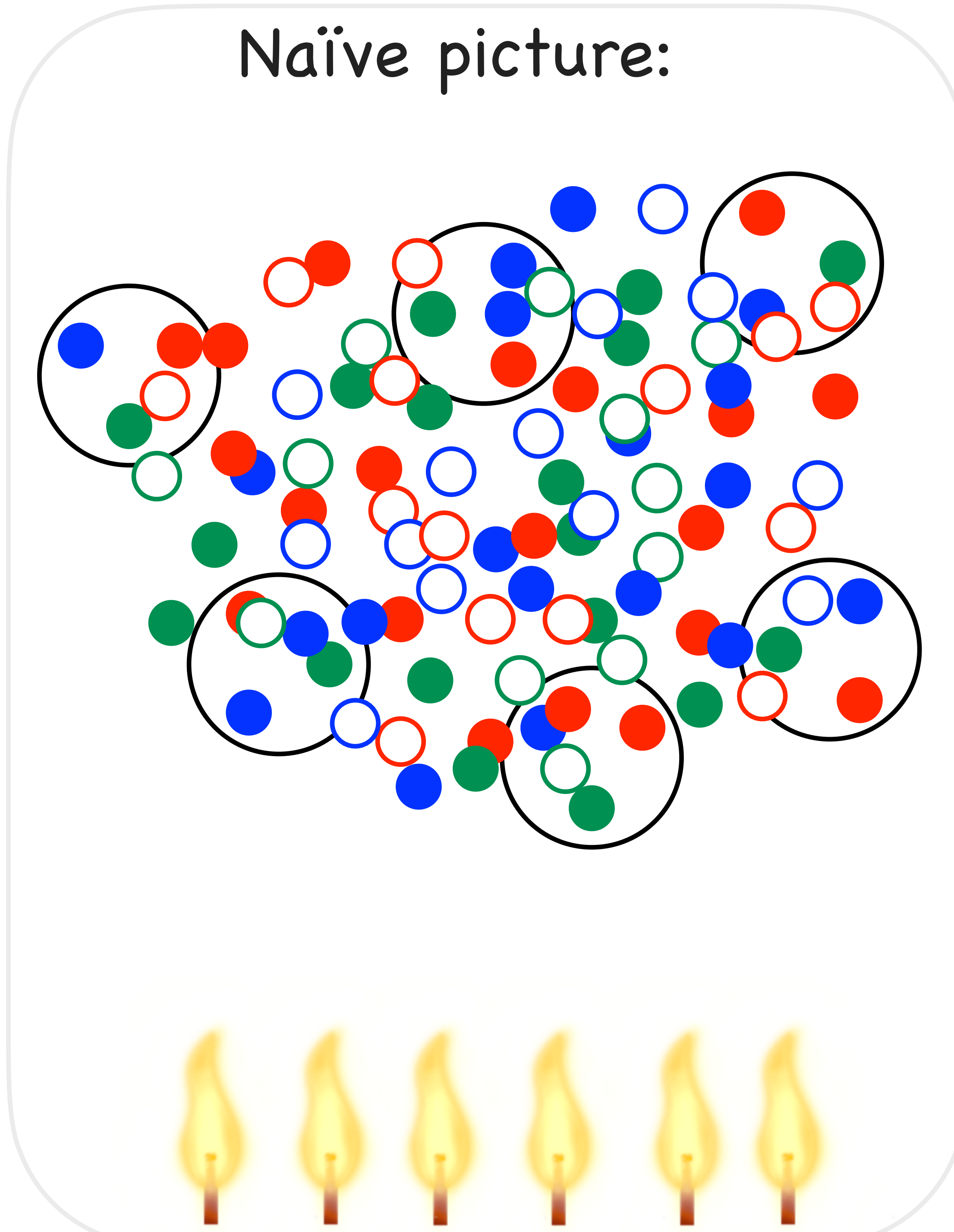

A short, incomplete history…

- 1973: Gross, Politzer & Wilczek show that QCD possesses asymptotic freedom: closely packed quarks & gluons behave as if they were free

☞ where could one observe that?

- 1975: Quarks may be "freed" at high net baryon number density n_B

- … or at high temperature T

- … thereby creating a new state of matter, dubbed (Shuryak, 1980) quark-gluon plasma (QGP).

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

When the *energy* density ε exceeds some typical hadronic value ($\sim$1 GeV/fm^3), 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.

Thermodynamics!

A hint from lattice QCD

Numerical computations of QCD thermodynamics in a discretized space-time

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]

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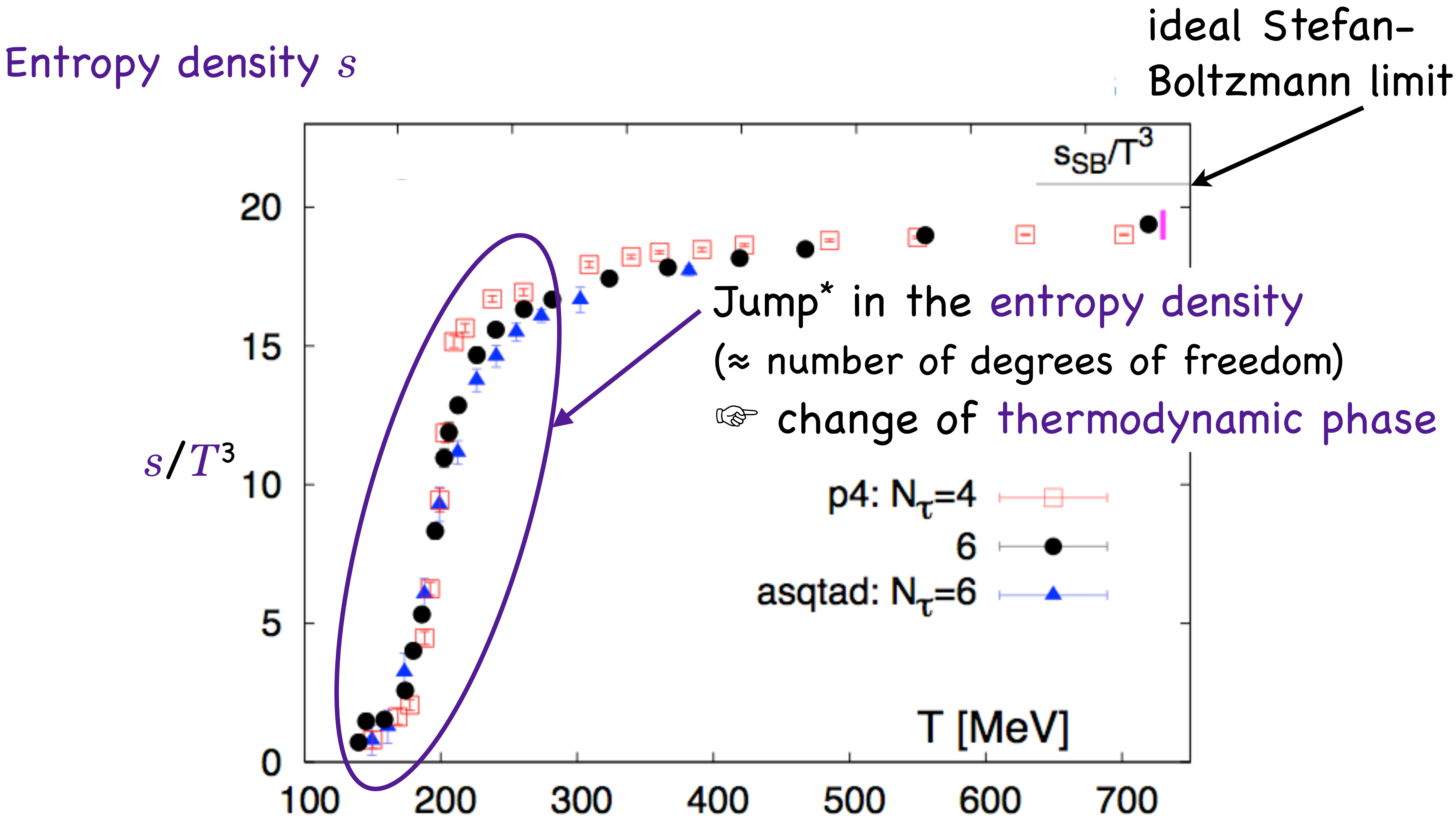
(Received 2 October 2007; published 22 January 2008)

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

A hint from lattice QCD

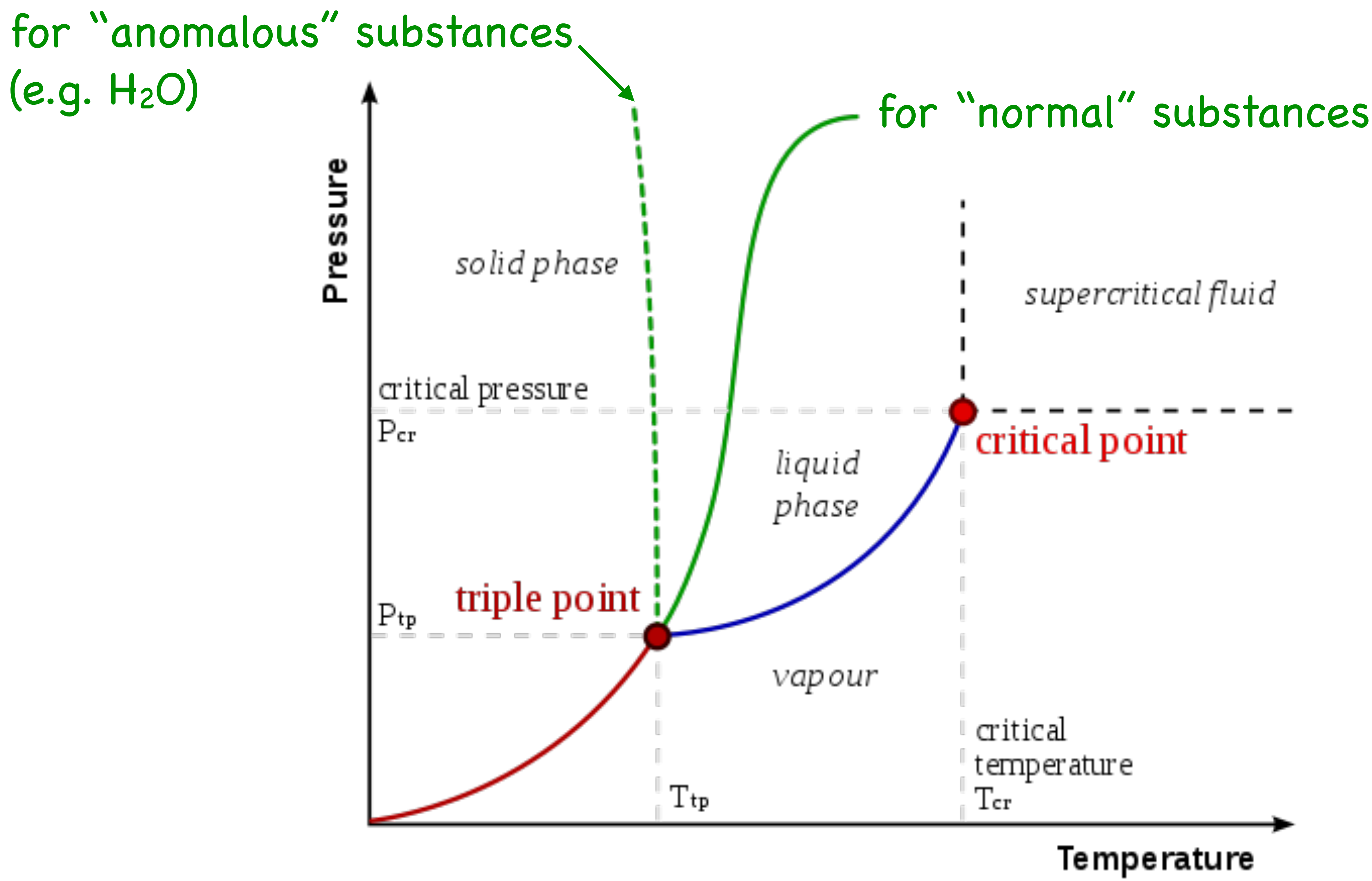


HotQCD Coll., Phys. Rev. D **77** (2008) 045511

* yet not a step: not a 1st order transition

Phases of a thermodynamic system

... are usually displayed in a phase diagram (PT-diagram):



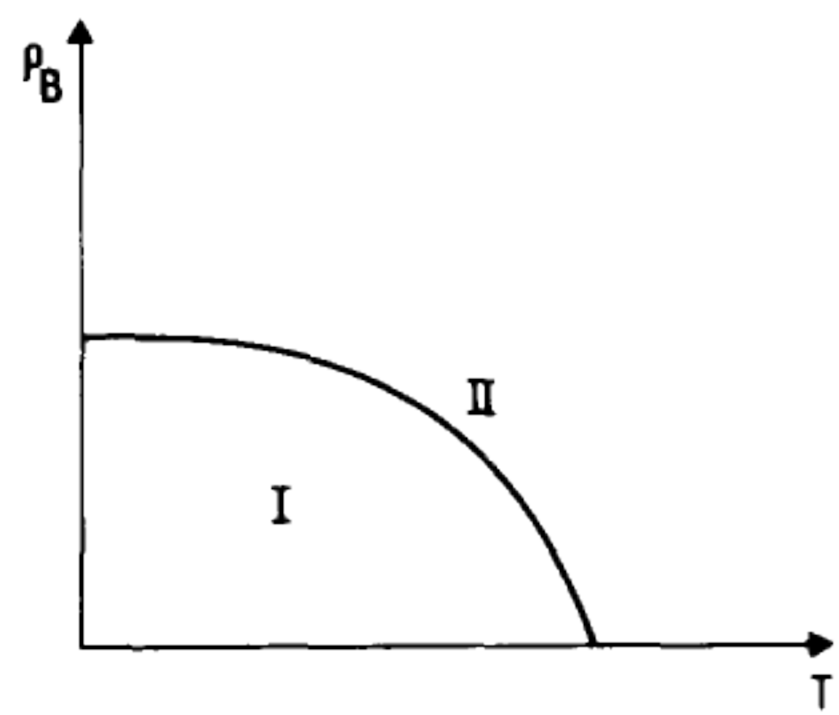
Phase diagram of nuclear matter

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

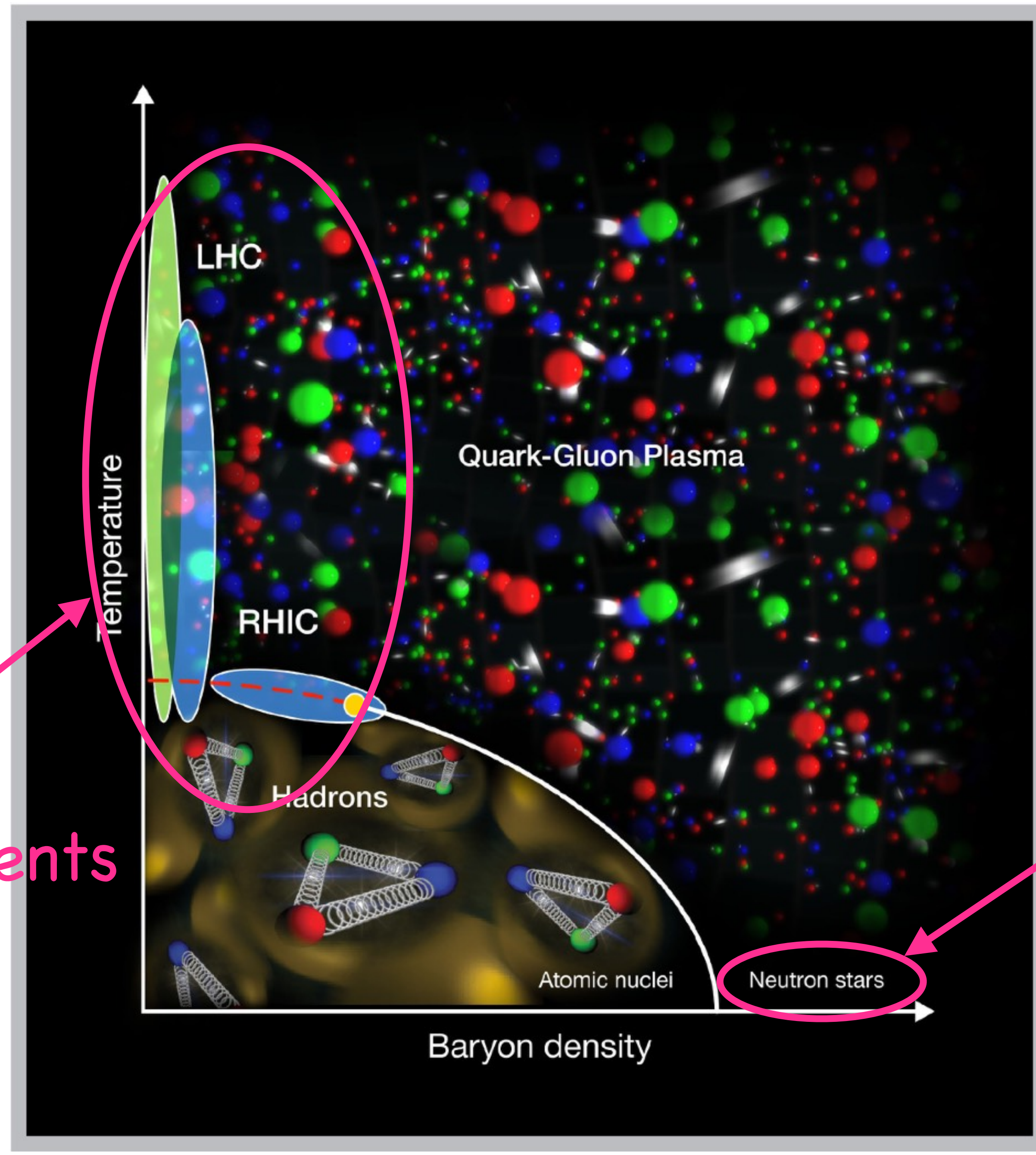


schematic!

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.

Phase diagram of nuclear matter

A 2013 version (from Brookhaven Nat'l Lab):



Still schematic!

the old suggestion

Heavy-ion experiments are mentioned!

[BNL News, Sep. 2013]

Why heavy ion collisions?

Traditional answers:

- To create a quark-gluon plasma in the laboratory.
- To explore the phase diagram of nuclear matter.
- To test our understanding of QCD.
- ...

Actually, already a question by T.D.Lee at a workshop (Bear Mountain) in 1974:

Can one create abnormal states of nuclear matter in collisions?

"It would be interesting to explore new phenomena by distributing high energy or high nucleon density over a relatively large volume."

What about the QGP in Nature?

- In the early Universe

  In the standard cosmological model, the Universe was filled with a QGP — in equilibrium with electrons, muons and neutrinos — in the first microsecond after the Big Bang.

- In compact astrophysical objects (neutron stars / quark stars)?

- Elsewhere?

QGP in compact astrophysical objects?

Highly disputed (to say the least) possibility.

Due to the difference in the equations of state of neutron matter and quark matter / QGP (possibly with enhanced strangeness content), astrophysical objects with a given mass would have different radii.

The issue may be settled by observations of gravitational waves from the collisions of such objects!

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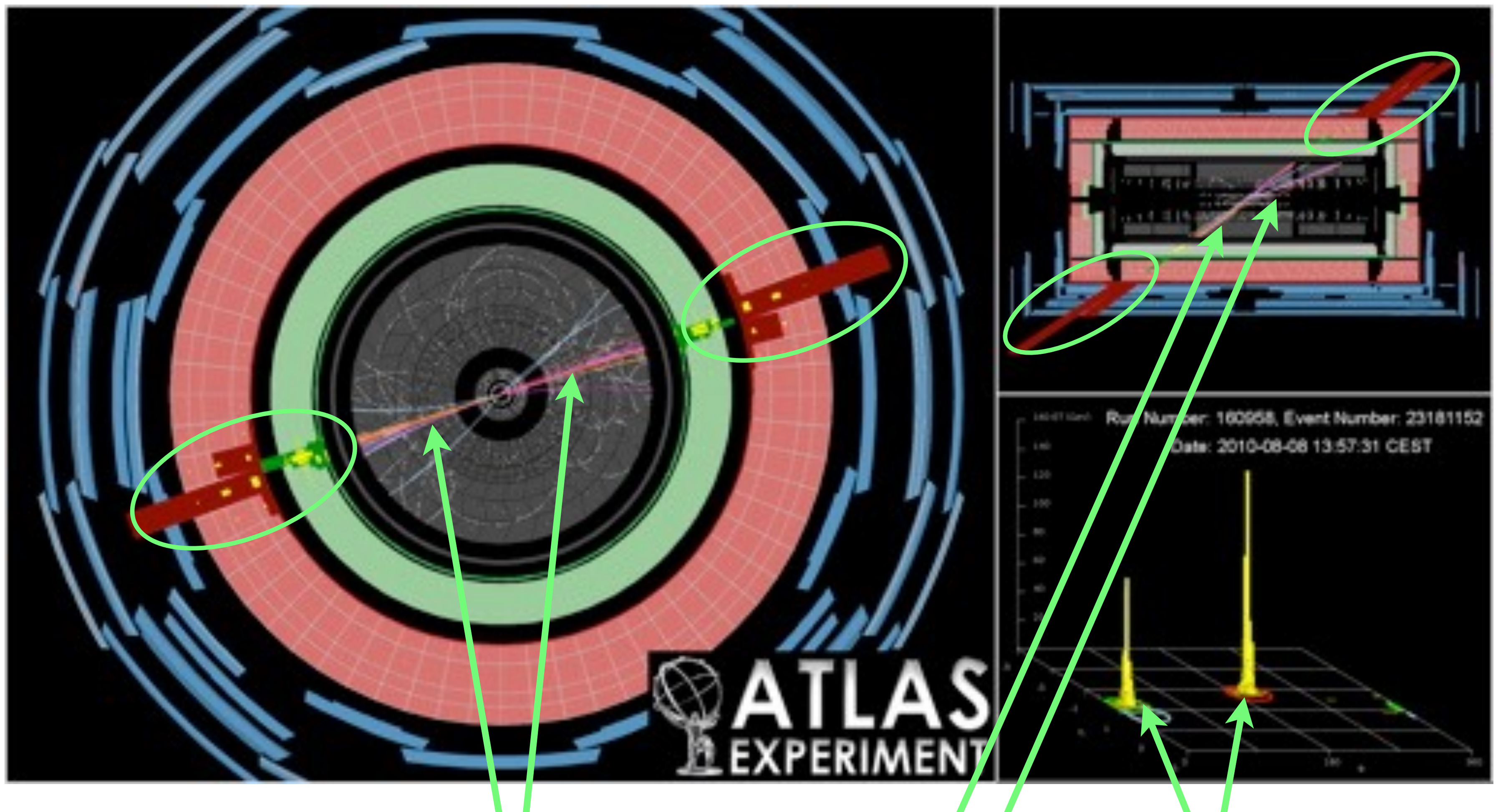
- Beyond the standard paradigm?

30+ years of heavy ion collisions later

Has an "abnormal state of matter" been created in such collisions?

Views from a proton-proton collision at the LHC:

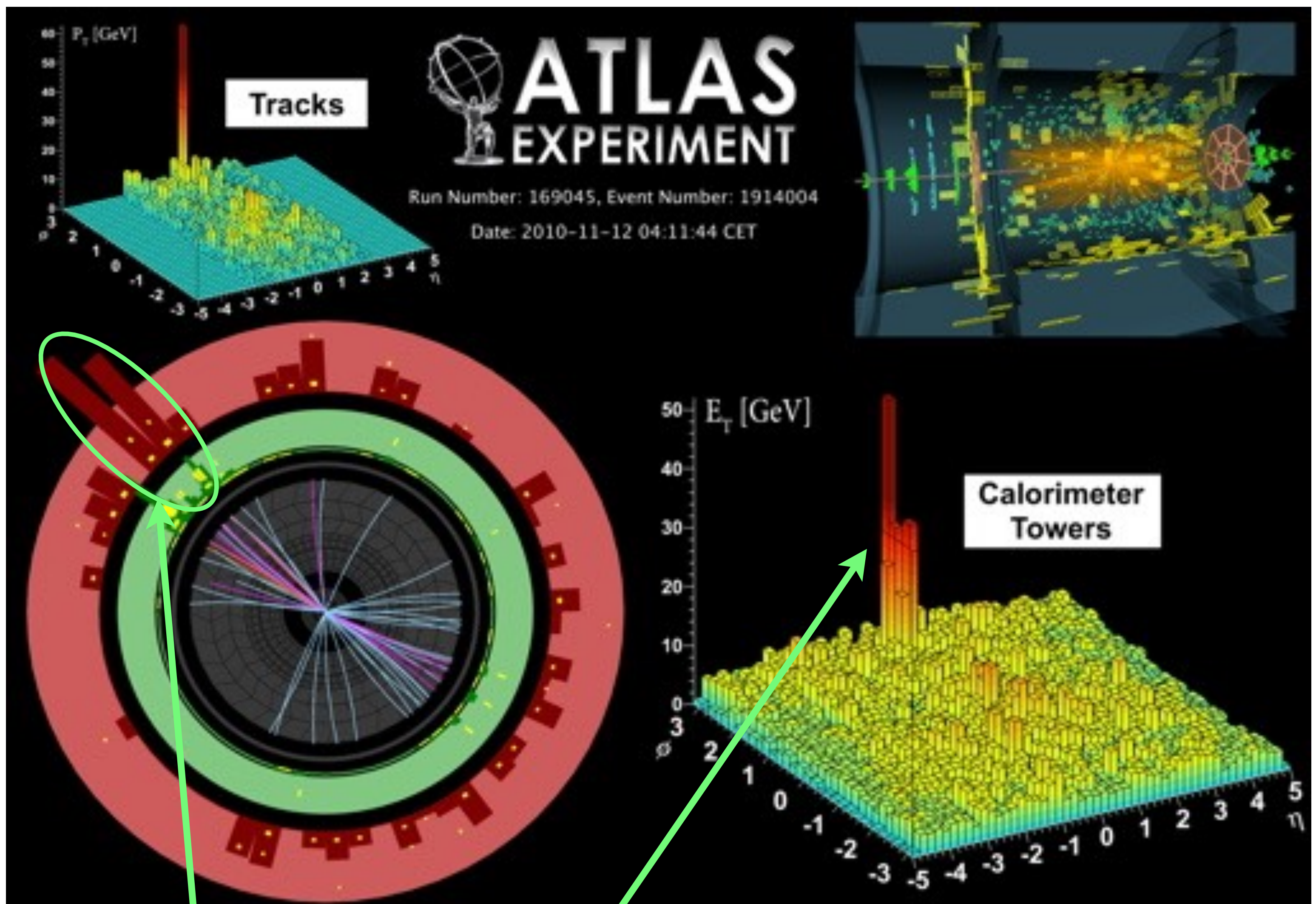


2 back-to-back "jets" of highly energetic hadrons, that traverse meter-long detectors, depositing energy in calorimeters

30+ years of heavy ion collisions later

Has an "abnormal state of matter" been created in such collisions?

Views from a Pb-Pb collision at the LHC:

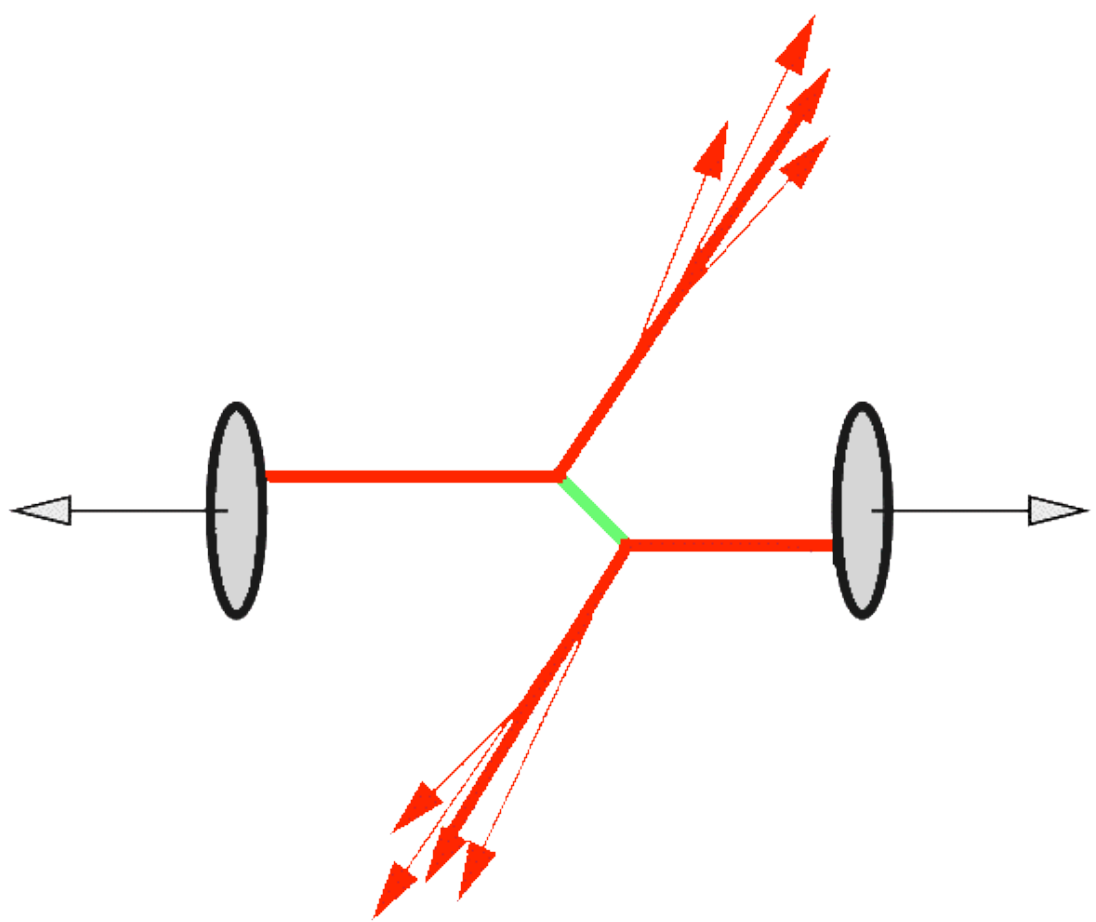


a single "jet", which has lost its back-to-back counterpart...

ATLAS Collaboration, Phys. Rev. Lett. 105 (2010) 252303

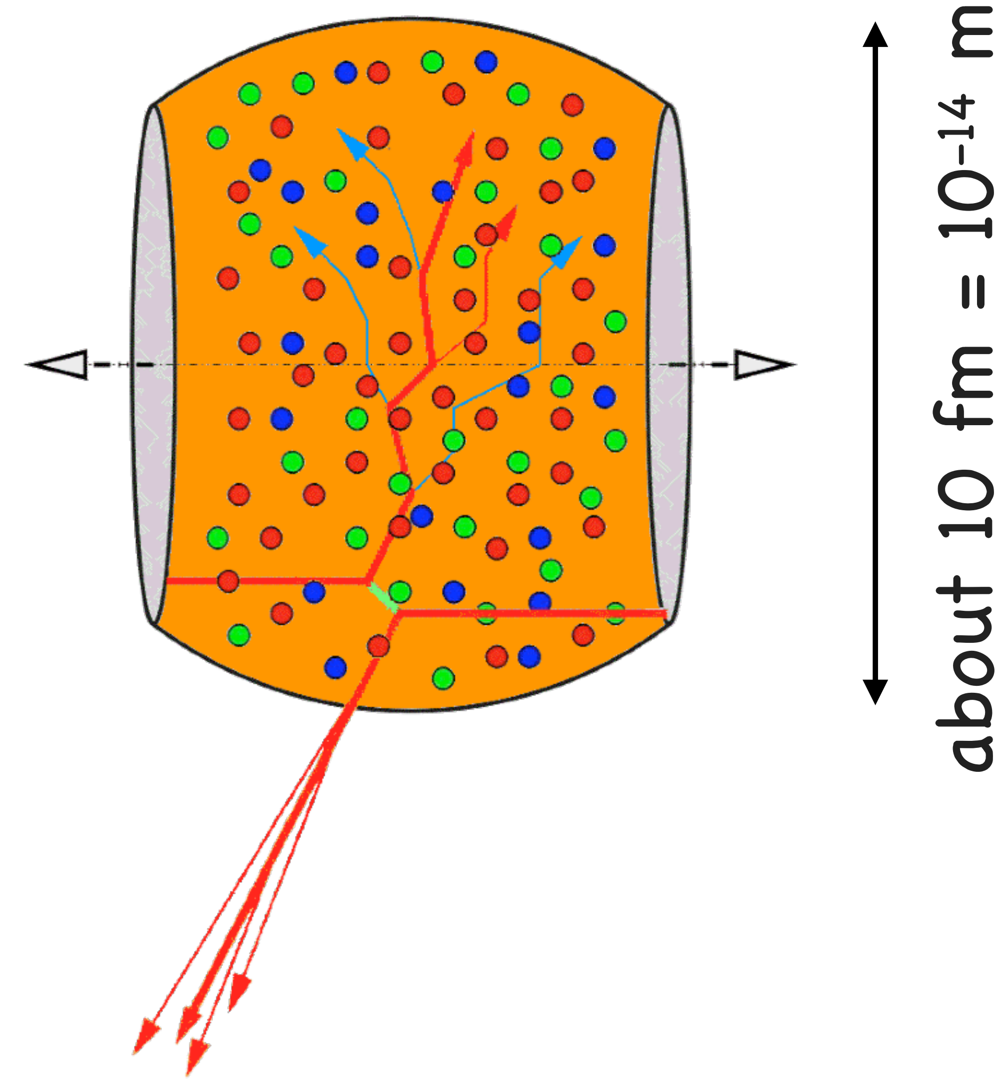
30+ years of heavy ion collisions later

proton-proton collision
at the LHC



2 back-to-back "jets" that can travel meters inside detectors (= ordinary QED-interacting matter)

Pb-Pb collision at the LHC



One of the "jets" is already stopped by 10 fm of QCD-matter!

30+ years of heavy ion collisions later

YES

There is a very opaque medium,
which can stop jets over short distances

30+ years of heavy ion collisions later

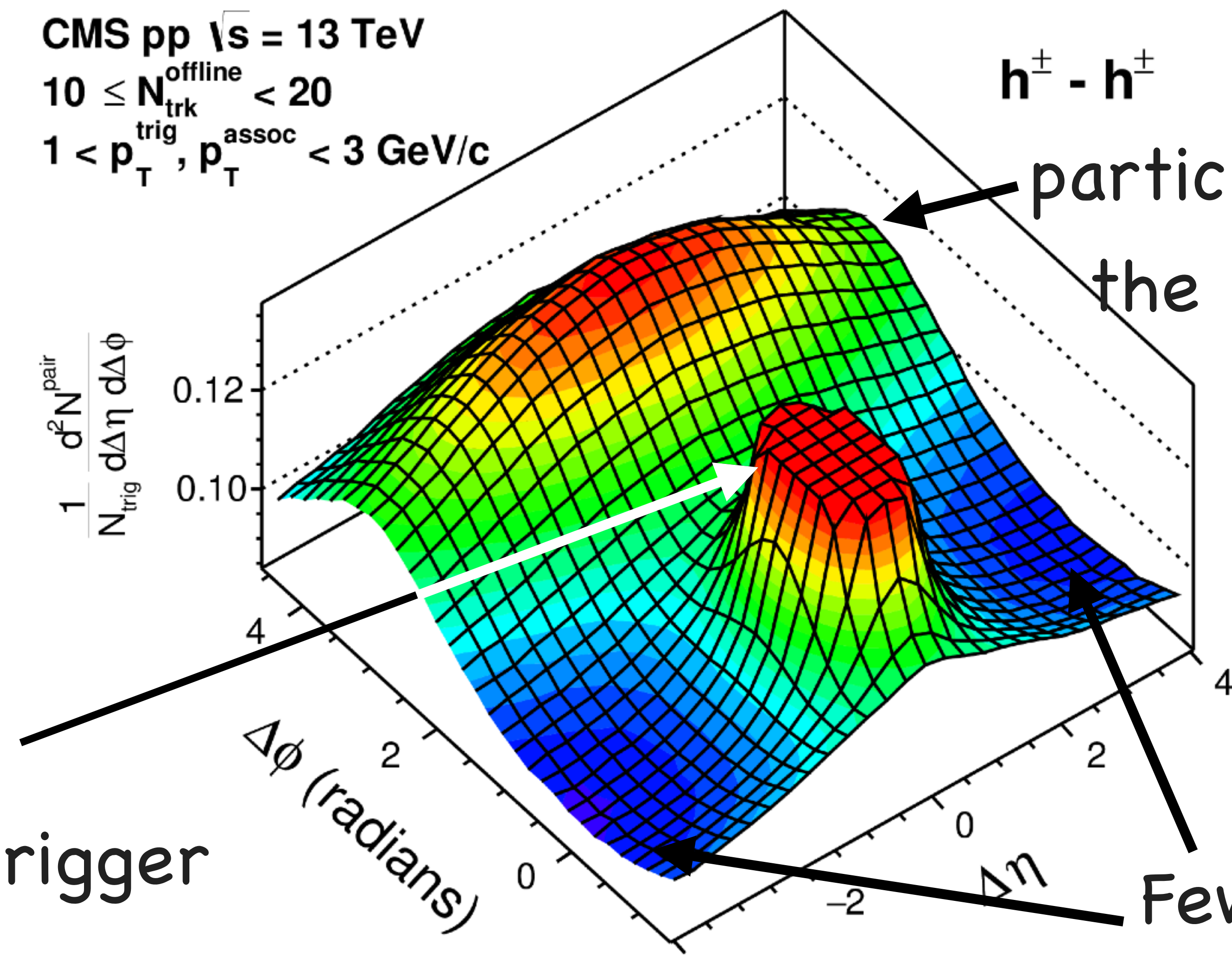
"Two-particle angular correlations"

- In the outcome of a given collision, select a first "trigger" particle
  - Study the distribution in momentum space of the other particles ("associated") with respect to the trigger particle:
    ☞ angular separations $\Delta\phi$ (azimuthal angle about the collision axis) and $\Delta\eta$ ($\approx$ polar angle w.r.t. collision axis)
  - Loop over associated particles: count the number of pairs with given $\Delta\phi$, $\Delta\eta$
- Loop over trigger particles
- Repeat the same procedure over many collisions (with the same particle multiplicity)

30+ years of heavy ion collisions later

"Two-particle angular correlations"

… for "normal" proton-proton collisions at the LHC:



particles back-to-back to the trigger ($\Delta\phi \simeq 180°$): momentum balance!

particles in the vicinity of the trigger (understood)

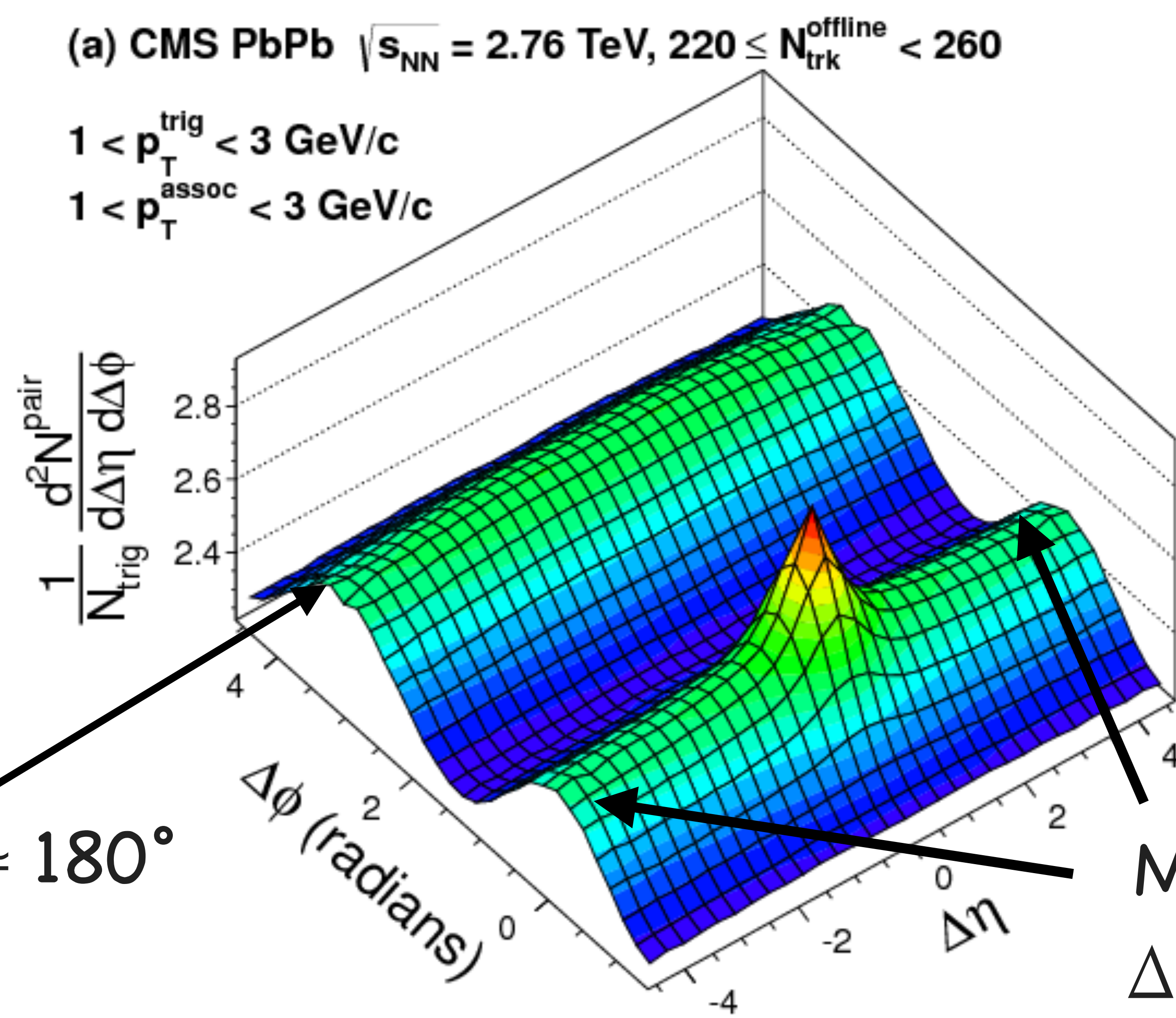
Few pairs with $\Delta\phi \simeq 0$ and $|\Delta\eta| \gtrsim 1$

CMS Collaboration, Phys. Lett. B 765 (2017) 193

30+ years of heavy ion collisions later

"Two-particle angular correlations"

… in Pb–Pb collisions at the LHC:



The signal at $\Delta\phi \simeq 180°$ is flat in $\Delta\eta$

Many pairs with $\Delta\phi \simeq 0$, $|\Delta\eta| \gtrsim 1$:

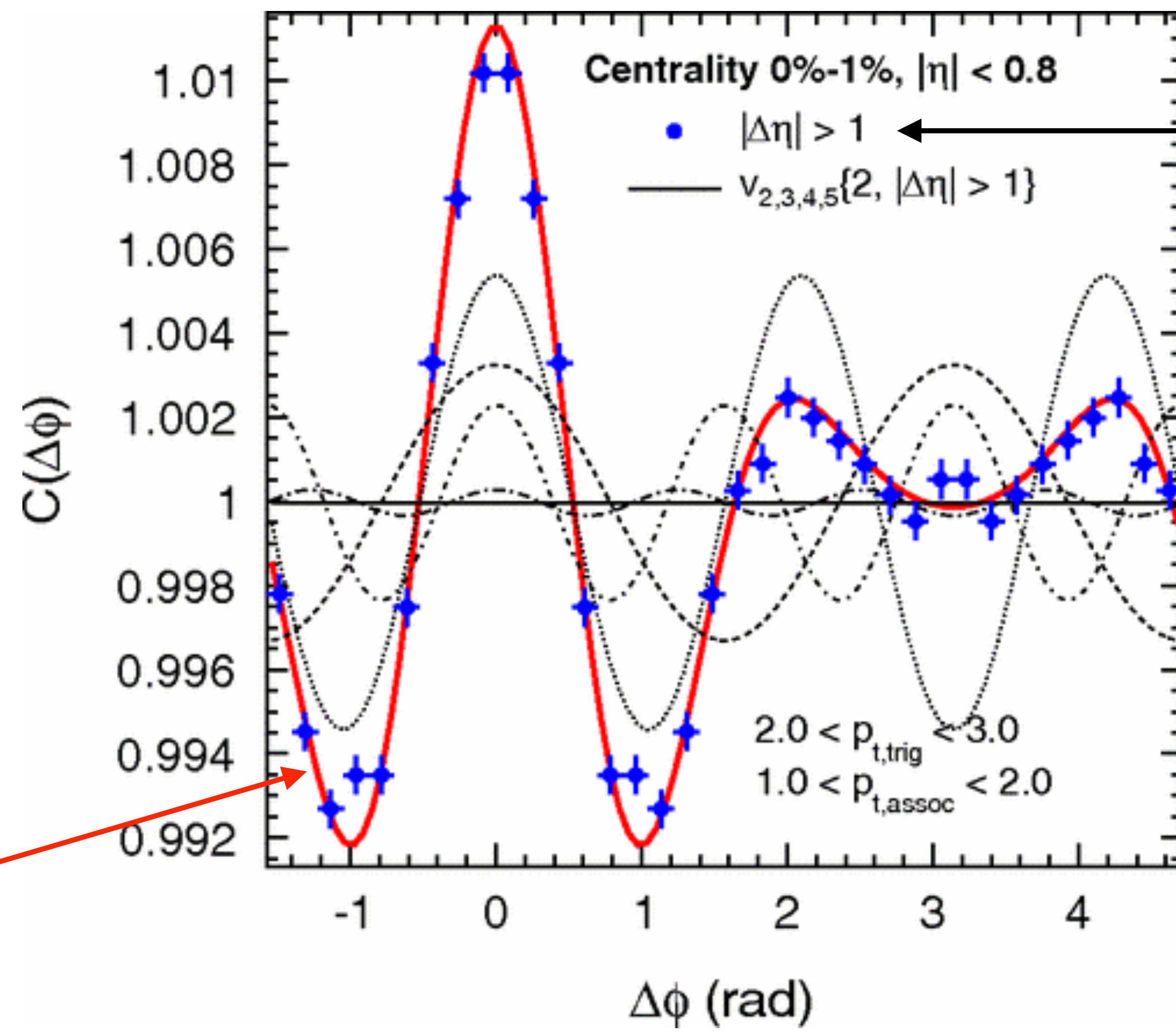
☞ **long-range correlations**

CMS Collaboration, Phys. Lett. B 724 (2013) 213

30+ years of heavy ion collisions later

"Two-particle angular correlations"

... in Pb–Pb collisions at the LHC, looking at the $\Delta\phi$ distribution only:



to remove the short-range peak

Fit with

$$C(\Delta\phi) = 1 + 2v_2^2\cos(2\Delta\phi) + 2v_3^2\cos(3\Delta\phi) + 2v_4^2\cos(4\Delta\phi) + 2v_5^2\cos(5\Delta\phi)$$

ALICE Collaboration, Phys. Rev. Lett. 107 (2011) 032301

High-energy nuclear collisions: standard scenario

The long-range azimuthal correlations are naturally explained within the standard paradigm used to describe the dynamics of the system created in heavy ion collisions:

- At $\tau = 0$, the (Lorentz-contracted!) nuclei collide.

  ≈ Independent "nucleon–nucleon" scatterings

- Instead of flying directly to the detectors (= free streaming), the outcome — fields / particles — of these initial scatterings interact with each other: "rescatterings".

  Collective dynamical behavior arises!

- Eventually, the rescatterings cease.

High-energy nuclear collisions: modeling the standard scenario

- At $\tau = 0$: the nuclei collide

  ☞ Release of energy / color fields / quarks & gluons

- $0^+ < \tau \lesssim 1$ fm/c: out-of-equilibrium dynamics (sometimes omitted).

  Ensures "hydrodynamization"

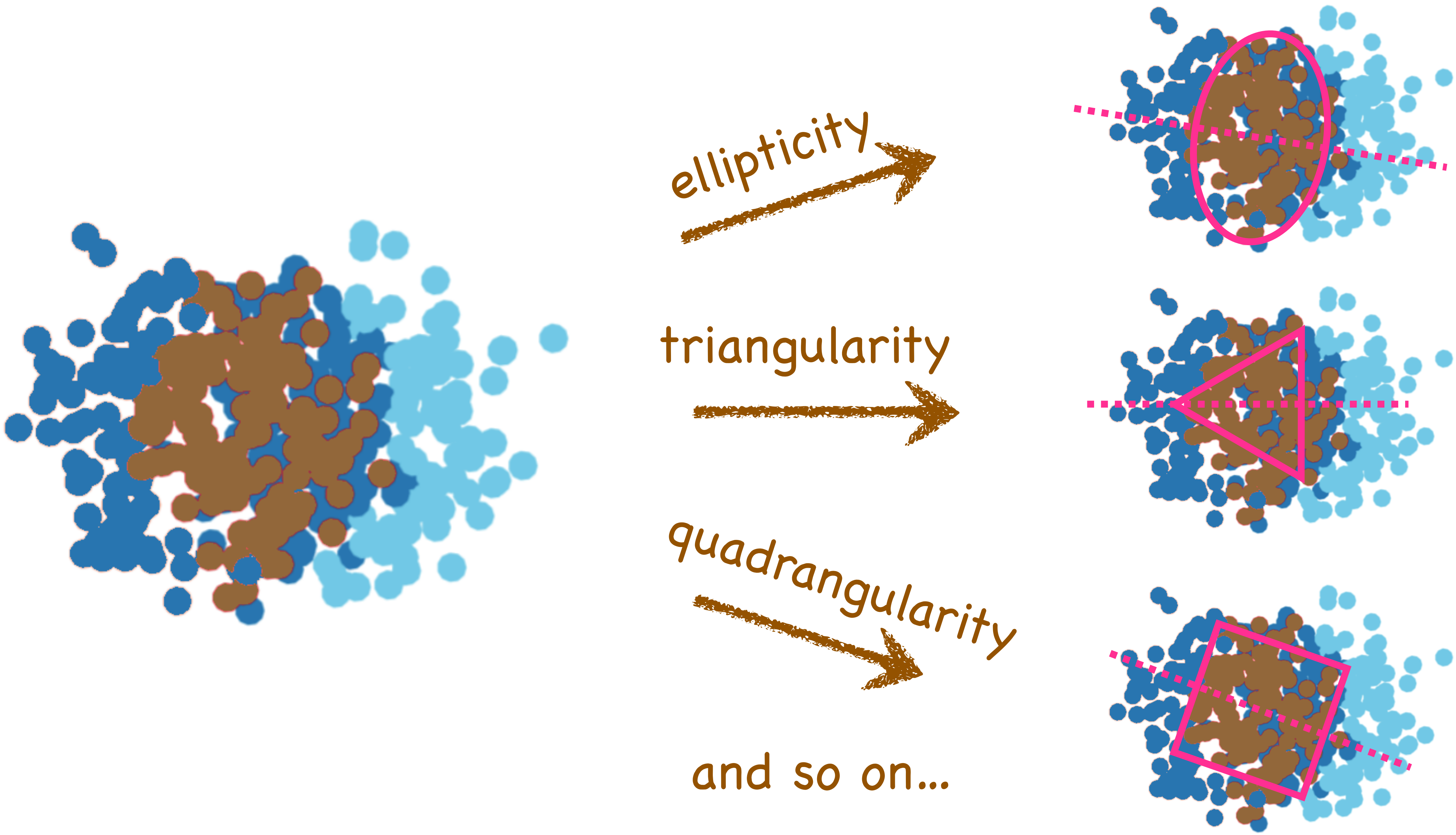
- $1 \lesssim \tau \lesssim 10$ fm/c: system described as a fluid, governed by relativistic fluid dynamics.

  ☞ Link to computations of thermodynamical QCD properties

- $10 \lesssim \tau \lesssim 20$ fm/c: system described as a cascading hadron gas. At the end, the hadrons are free streaming.

High-energy nuclear collisions: standard scenario

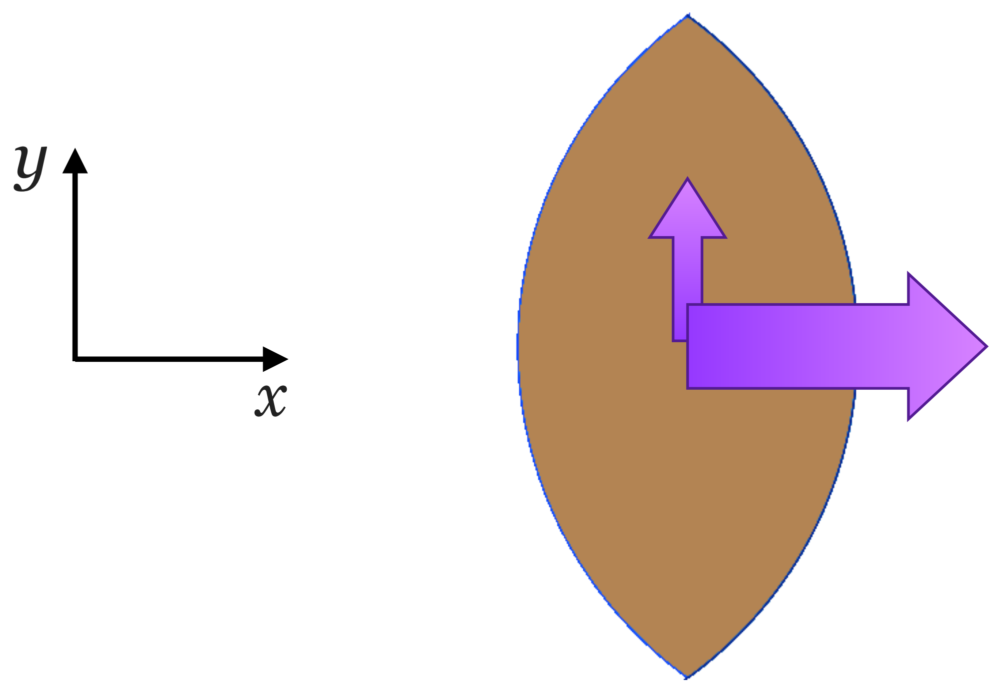
- At τ = 0: the nuclei collide ☞ complex overlap zone:



High-energy nuclear collisions: standard scenario

- The collective expansion stage — either out-of-equilibrium or fluid dynamical — converts the initial asymmetry of the geometry into a final state anisotropy in momentum space.

  For example (fluid-dynamical description):



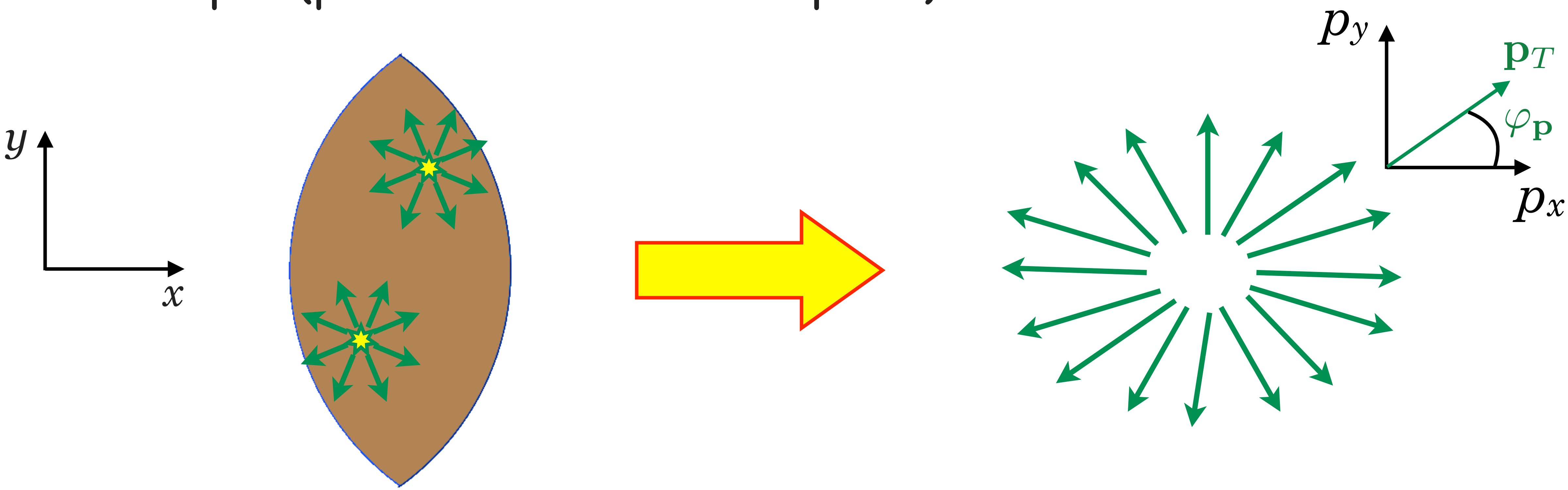
The larger pressure gradient along x leads to a stronger fluid acceleration.

☞ anisotropic particle emission
"anisotropic flow"

High-energy nuclear collisions: standard scenario

- The collective expansion stage — either out-of-equilibrium or fluid dynamical — converts the initial asymmetry of the geometry into a final state anisotropy in momentum space.

  For example (particle-based description):



The particles emitted along x have a higher escape probability.

High-energy nuclear collisions: standard scenario

- Rescatterings lead to a final state anisotropy in momentum space:
  - ☞ quantified by a Fourier series

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi_{\mathbf{p}}} \propto 1 + 2\sum_{n\geq 1} v_n \cos[n(\varphi_{\mathbf{p}} - \Phi_n)]$$

... which leads at once to the two-particle probability

$$C(\Delta\phi) = 1 + 2v_2^2\cos(2\Delta\phi) + 2v_3^2\cos(3\Delta\phi) + 2v_4^2\cos(4\Delta\phi) + \cdots$$

measured experimentally.

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Collective dynamics in high-energy nuclear collisions

In the most popular implementation of the standard paradigm, (part of) the system is modeled as a fluid for a fraction of its evolution.

☞ obeys — possibly non-standard — relativistic fluid dynamics.

Does this make sense for a system of ≈ 10,000 particles expanding into the vacuum? (For a system confined in a box, most probably yes)

And what if the system consists of only 1,000 particles? Of only 100 particles?

☞ Motivation for investigating alternative descriptions.

Signals of collective behavior in high-energy nuclear collisions

A possible alternative description of the system dynamics is in terms of interacting particles.

Is this reasonable? Not necessarily...

But the approach — particle cascade / Boltzmann equation — is known to reproduce fluid dynamics in the limiting regime of a large number of rescatterings per particles ($\langle N_{\rm resc}\rangle$ in the following slides) and can easily be continuously extended to the other limiting case of a non-interacting system.

☞ One can study the onset of the collective observables typical of high-energy nuclear collisions — hereafter anisotropic flow.

Signals of collective behavior in high-energy nuclear collisions

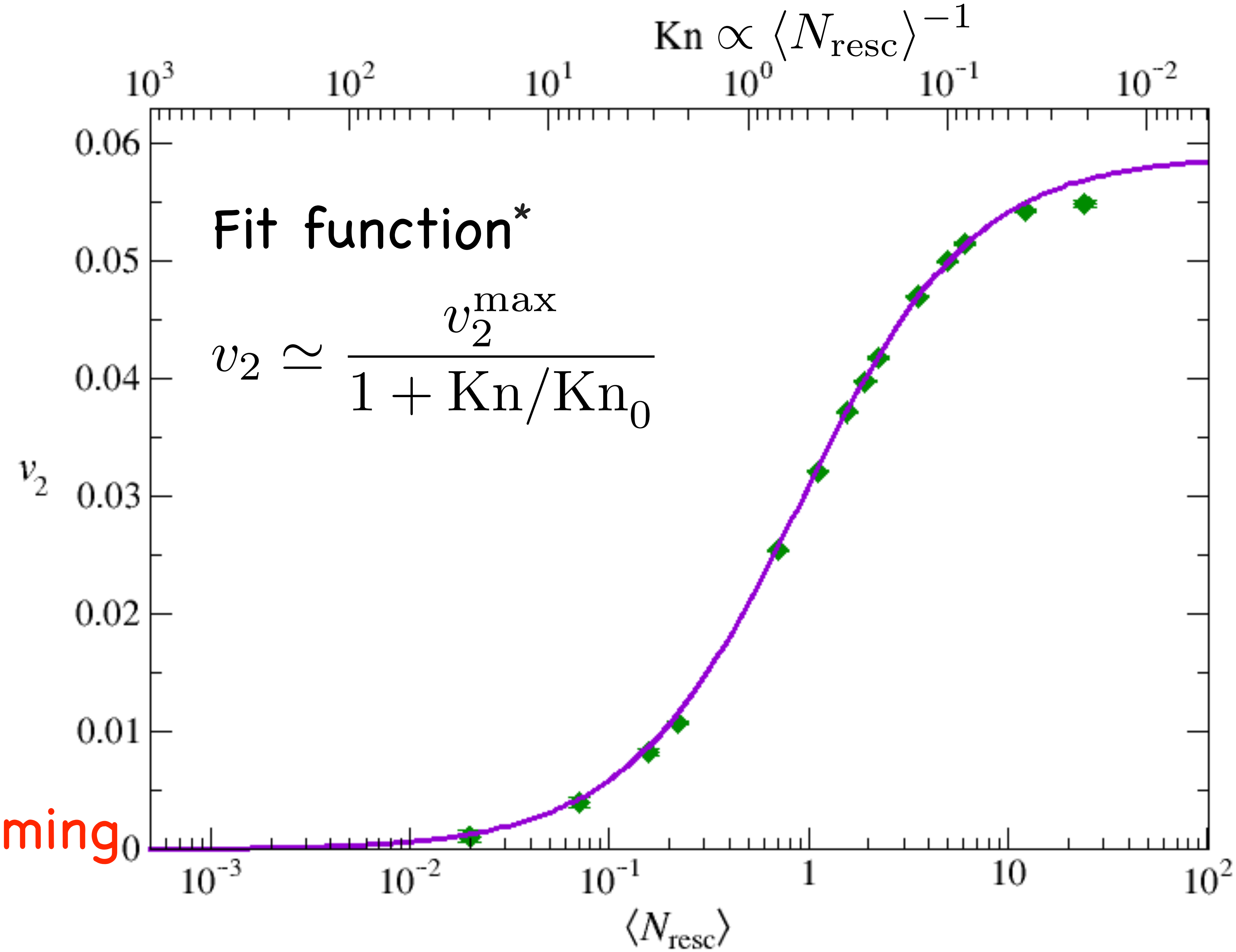
In the following slides, I'll show a few results

- from a 2D (faster simulations!) relativistic transport code with massless particles undergoing elastic 2-to-2 scatterings, in which we can tune the cross section to vary $\langle N_{\rm resc}\rangle$;
- and from (semi-)analytical calculations with the Boltzmann equation for the same setup (with an approximation!) in the limit of very small $\langle N_{\rm resc}\rangle$, i.e. close to free streaming.
- From my students Marc Borrell, Nina Kersting & Hendrik Roch.

(hopefully the papers — with much more — will still come out in 2020)

Transport model of collective flow

v_2 as a function of the number of rescatterings per particle



(almost)
free streaming
system

fluid

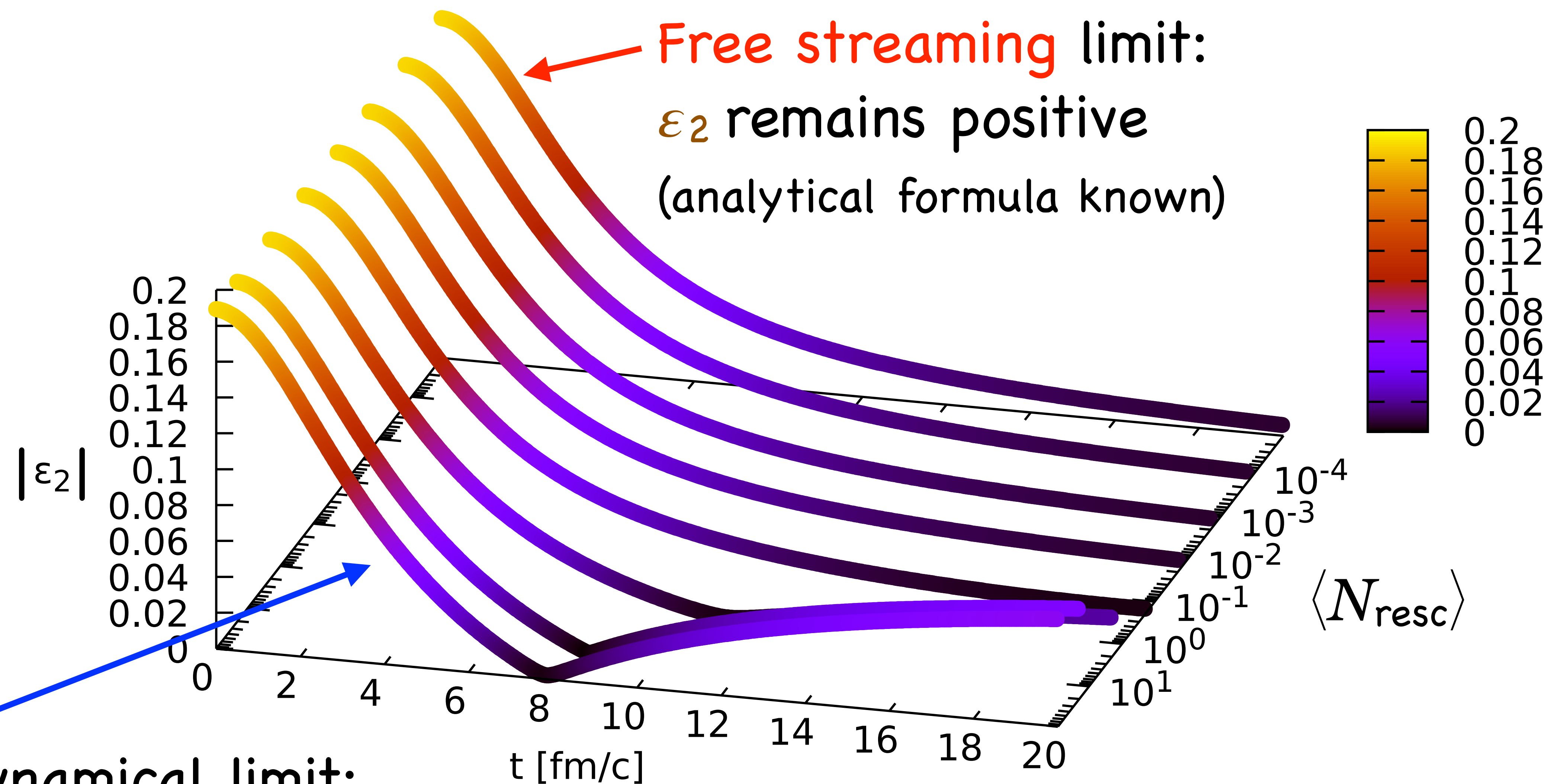
calculations by Hendrik Roch

* anticipated in Bhalerao, Blaizot, N.B., Ollitrault, Phys. Lett. 627 (2005) 49

Transport model of collective flow

Geometrical eccentricity ε_2 as a function of time vs. number of rescatterings per particle during the evolution.

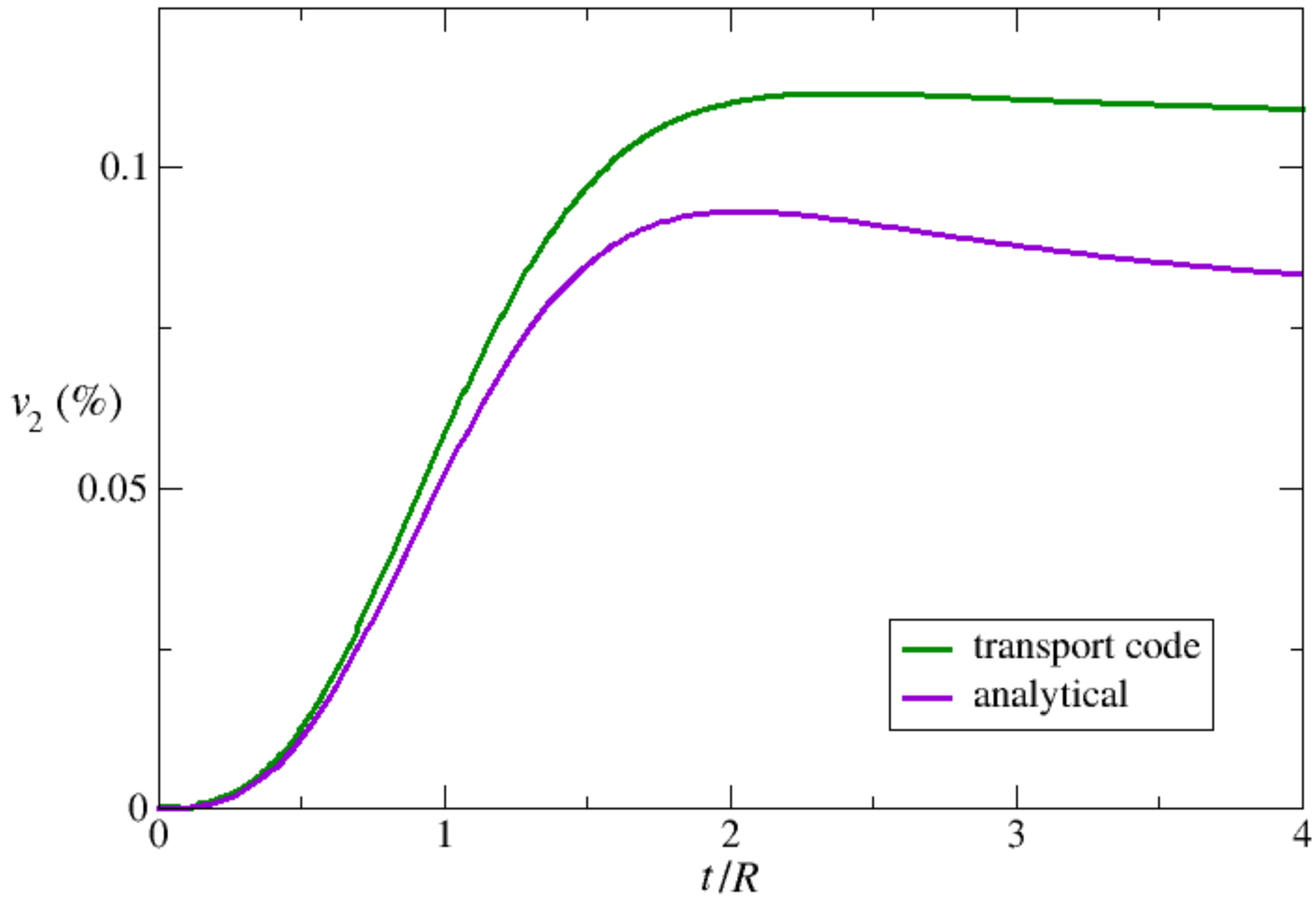
(typical system size at $t = 0$: $R \approx 5$ fm)



calculations by Hendrik Roch

Transport model of collective flow

In the limit of very few rescatterings (here $\langle N_{\rm resc}\rangle = 0.02$ per particle), an analytical approximation of the Boltzmann equation is feasible...
(We also recover results (with explicit expressions) known in hydro.)



calculations by Nina Kersting, Hendrik Roch & N.B.

Transport model of collective flow

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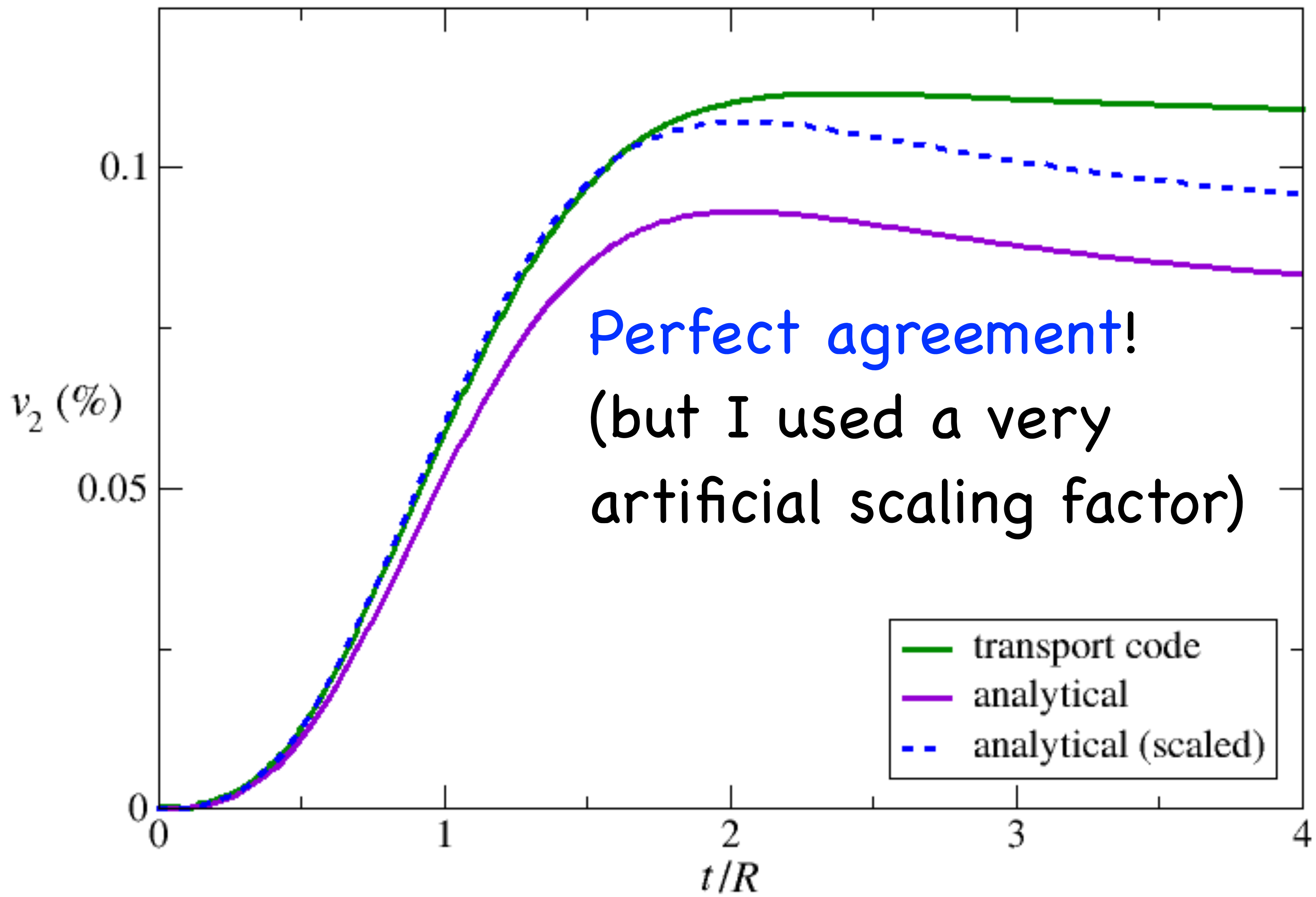

calculations by Nina Kersting, Hendrik Roch & N.B.

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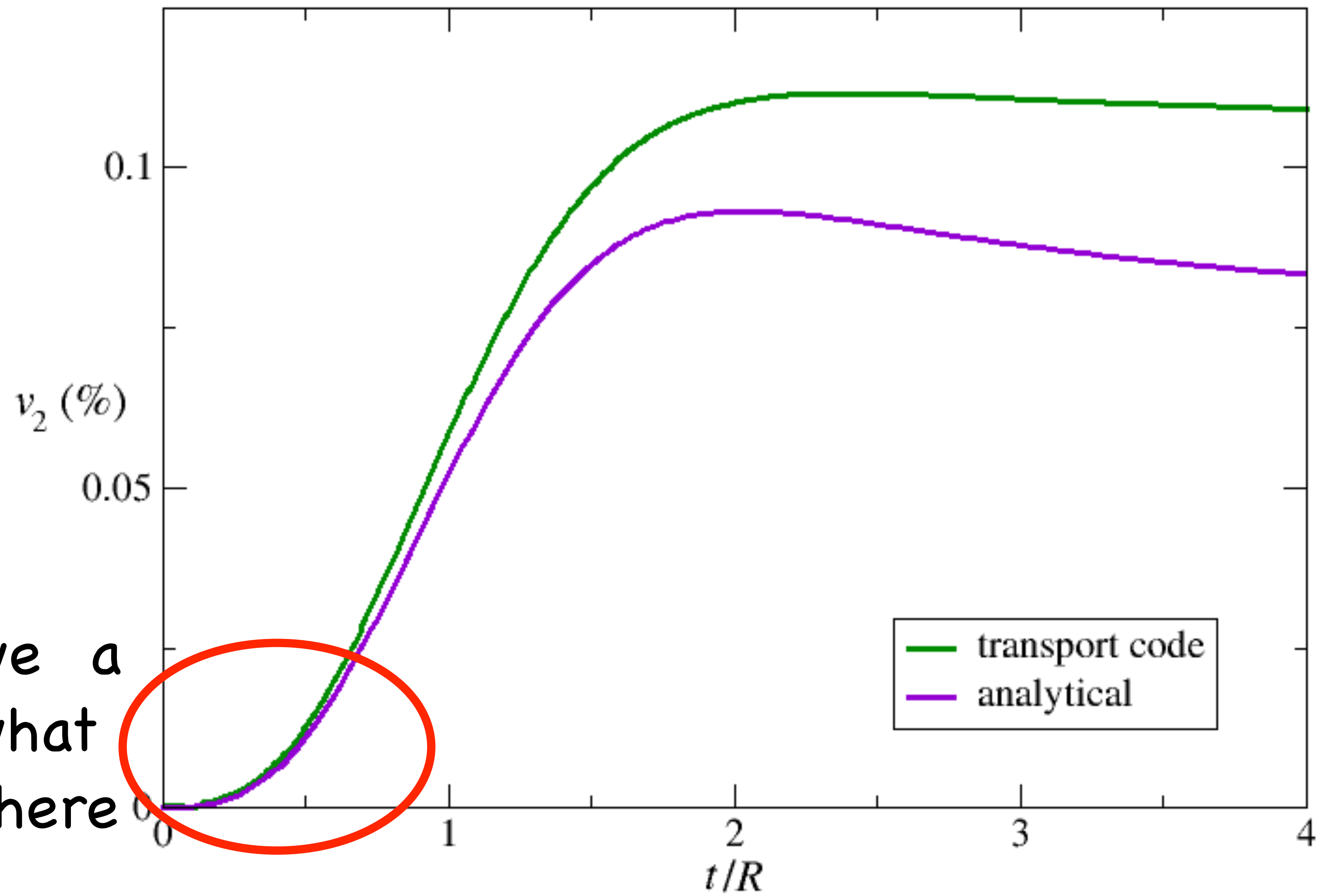
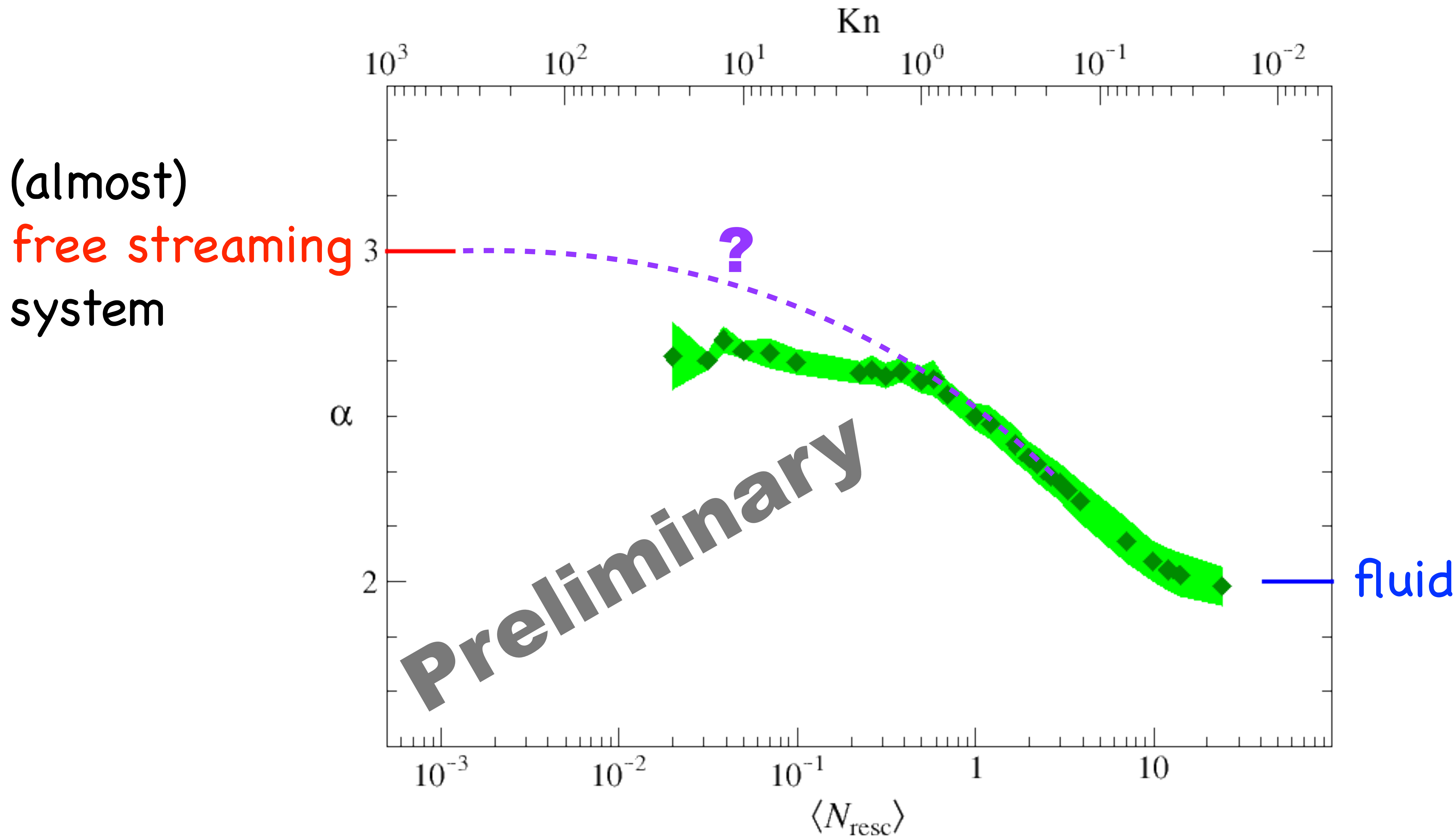
Let's have a look at what happens here



calculations by Nina Kersting, Hendrik Roch & N.B.

Transport model of collective flow

Early time behavior: $v_2(t) \propto t^\alpha$



☞ difference between the two limits?

calculations by Marc Borrell, Nina Kersting, Hendrik Roch & N.B.

Signals of collective behavior in high-energy nuclear collisions

- In high-energy collisions of heavy ions, a high density system is created, which exhibits clears signals of collective dynamical behavior.
- Modeling with relativistic fluid dynamics, with the equation of state computed for high-temperature QCD, describes data very well.
- Does the use of a fluid model remain warranted in smaller systems (e.g.: high multiplicity pp collisions)?

☞ Look at alternative dynamical descriptions to investigate the dependence of the collective observables on the system size.