Probes of high-energy heavy-ion collisions

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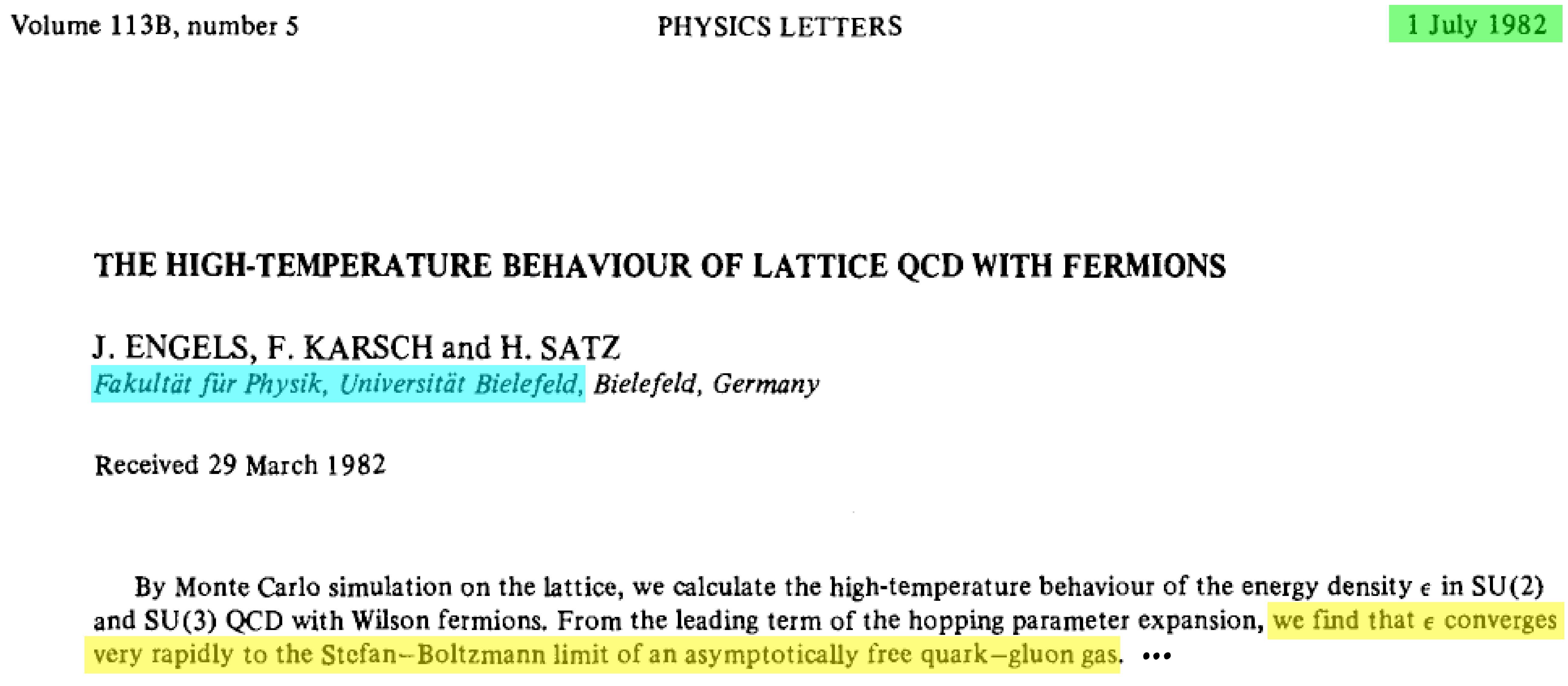
Probes of high-energy heavy-ion collisions

Physical aspects

- Mandatory motivation slides
- Time evolution of an ultra-relativistic heavy-ion collision
- Hard probes
- Collective probes

Hints from lattice QCD



Volume 113B, number 5 PHYSICS LETTERS 1 July 1982

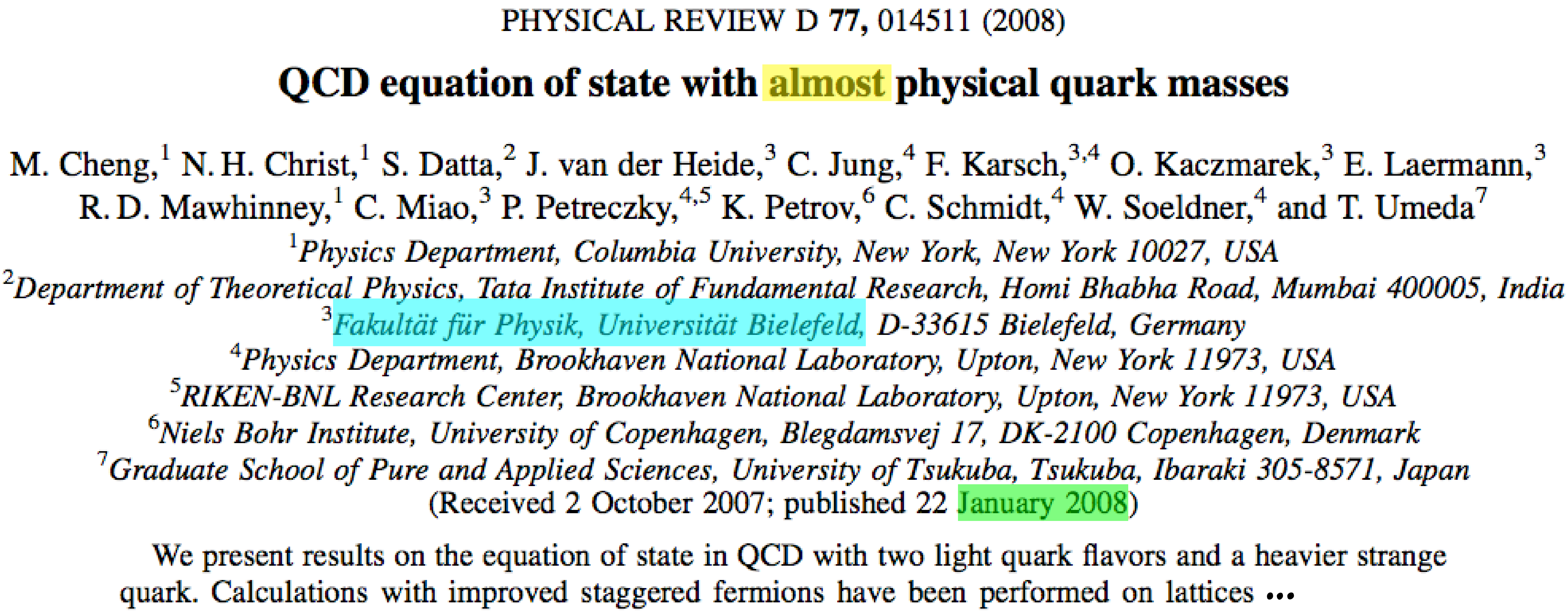
THE HIGH-TEMPERATURE BEHAVIOUR OF LATTICE QCD WITH FERMIONS

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

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(Received 2 October 2007; published 22 January 2008)

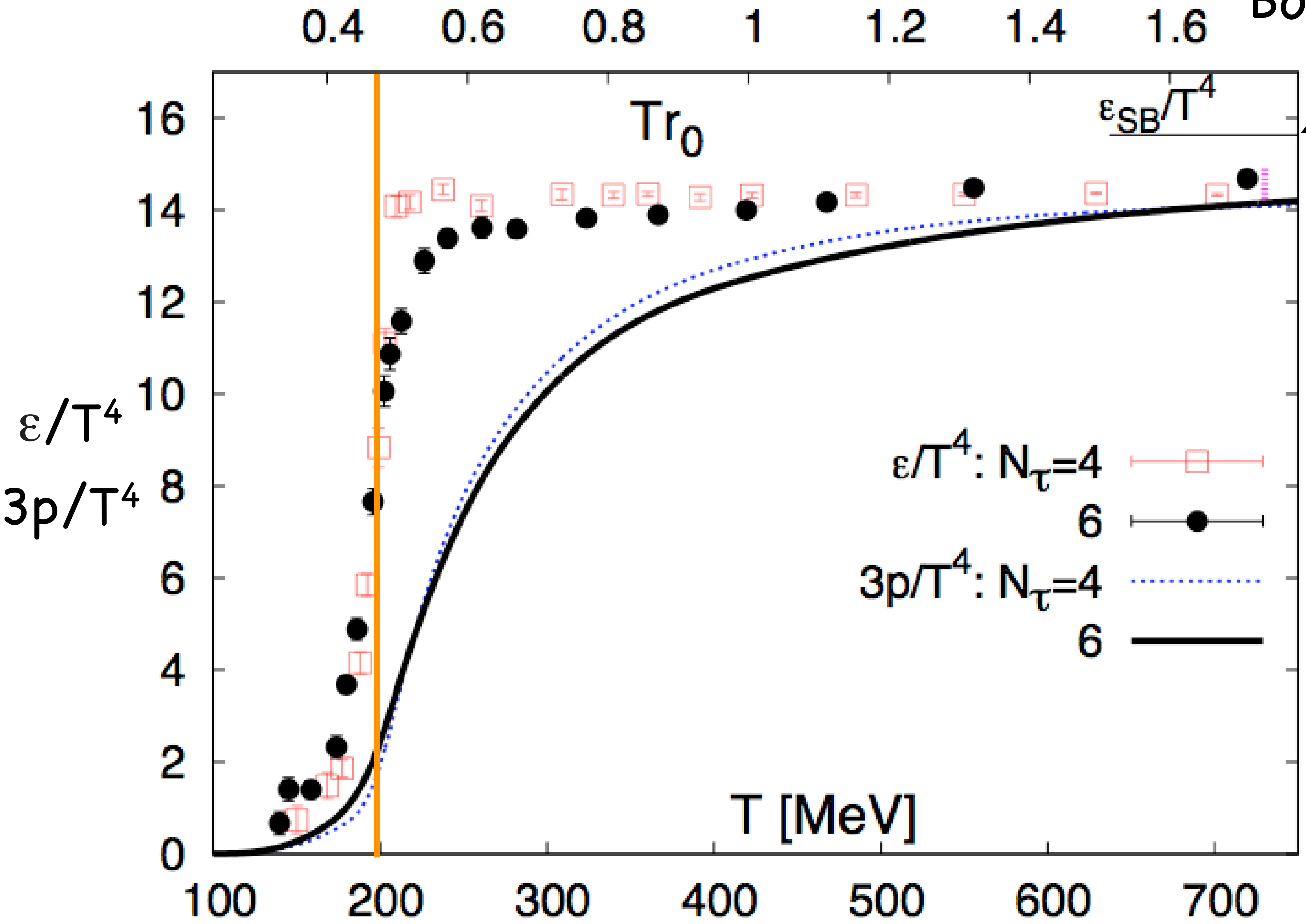
We present results on the equation of state in QCD with two light quark flavors and a heavier strange quark. Calculations with improved staggered fermions have been performed on lattices ...

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

Hints from lattice QCD

Energy density ε & pressure p:

ideal Stefan-Boltzmann limit

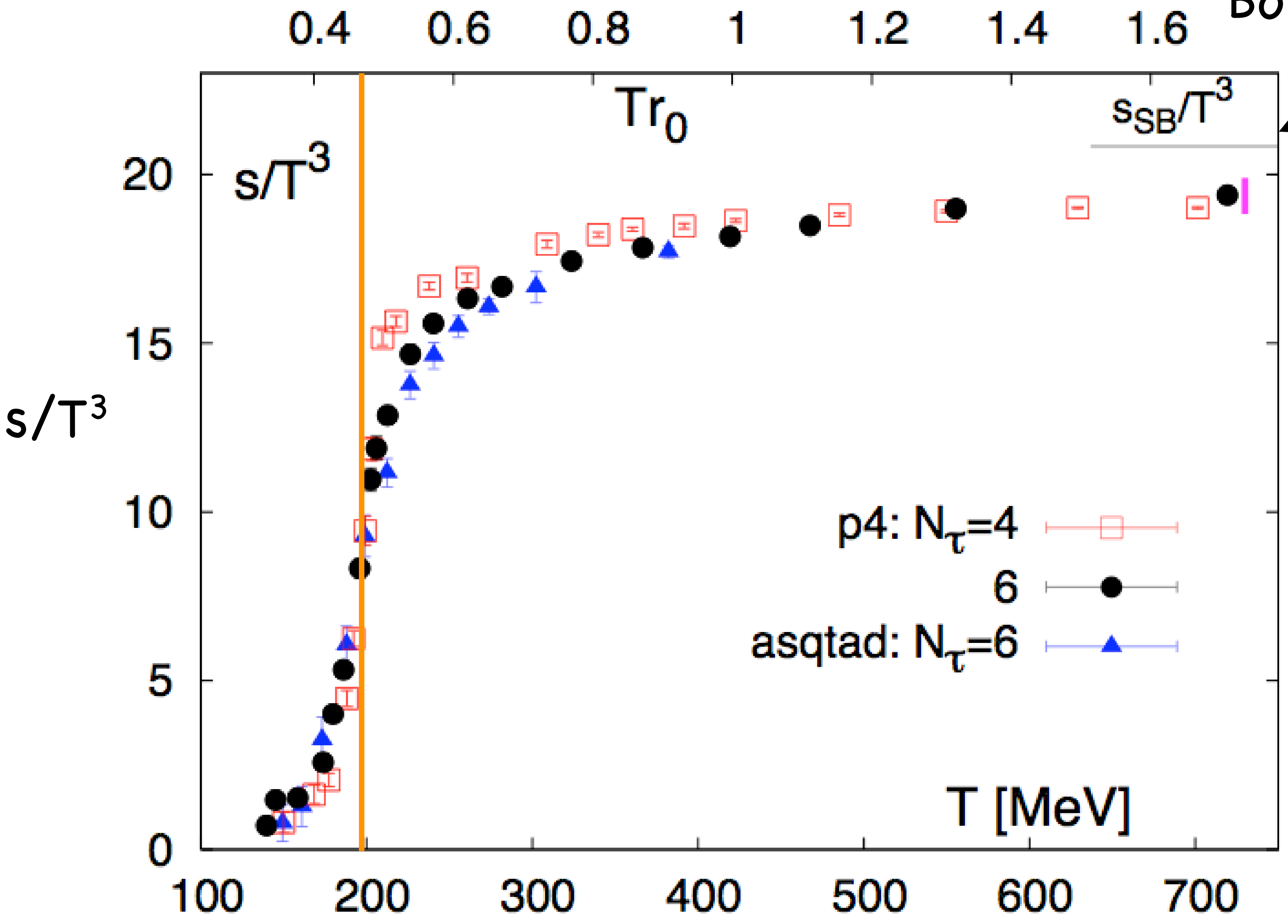


PRD 77 (2008) 045511

Hints from lattice QCD

Entropy density s

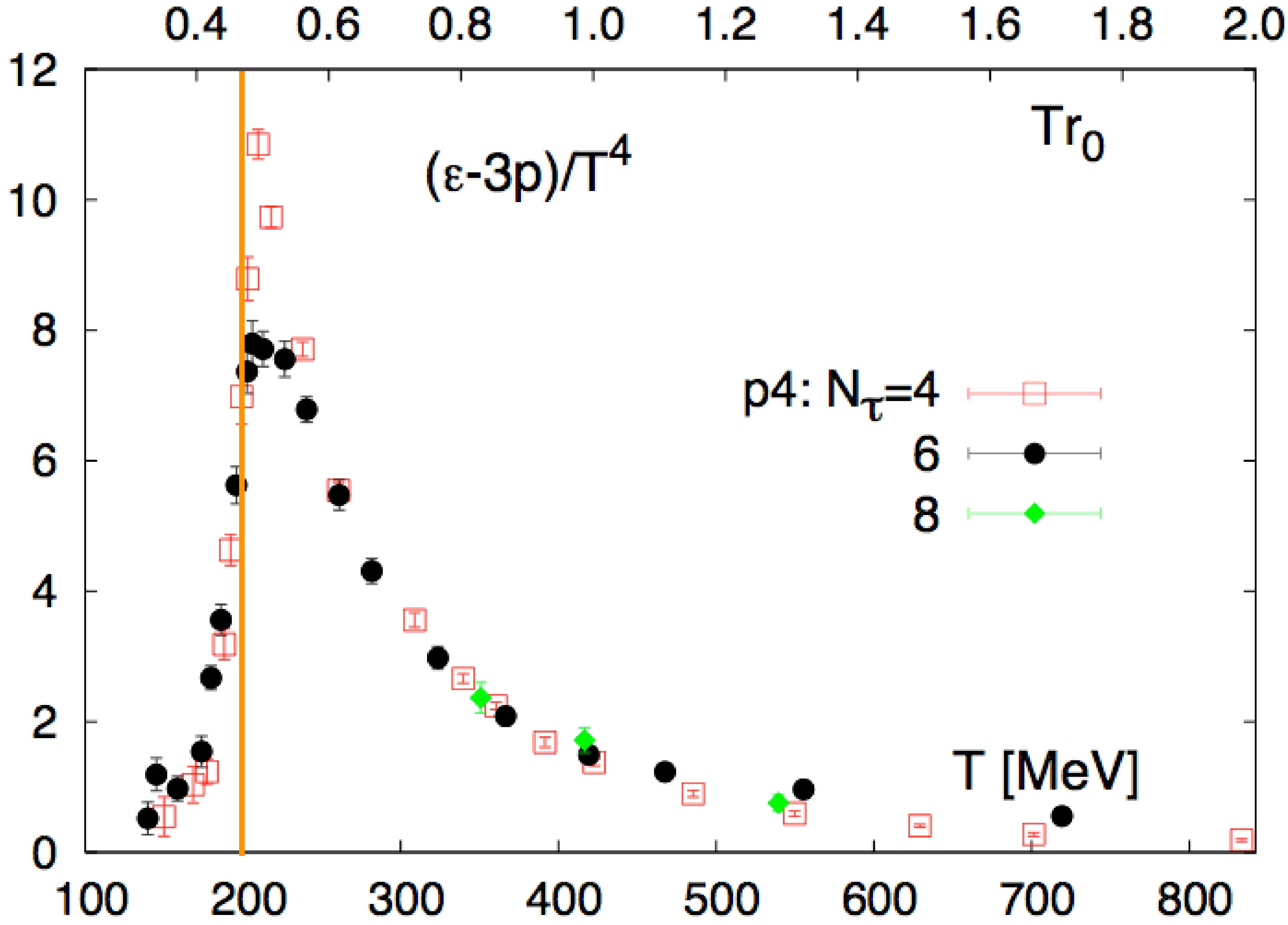
ideal Stefan-Boltzmann limit



PRD 77 (2008) 045511

Hints from lattice QCD

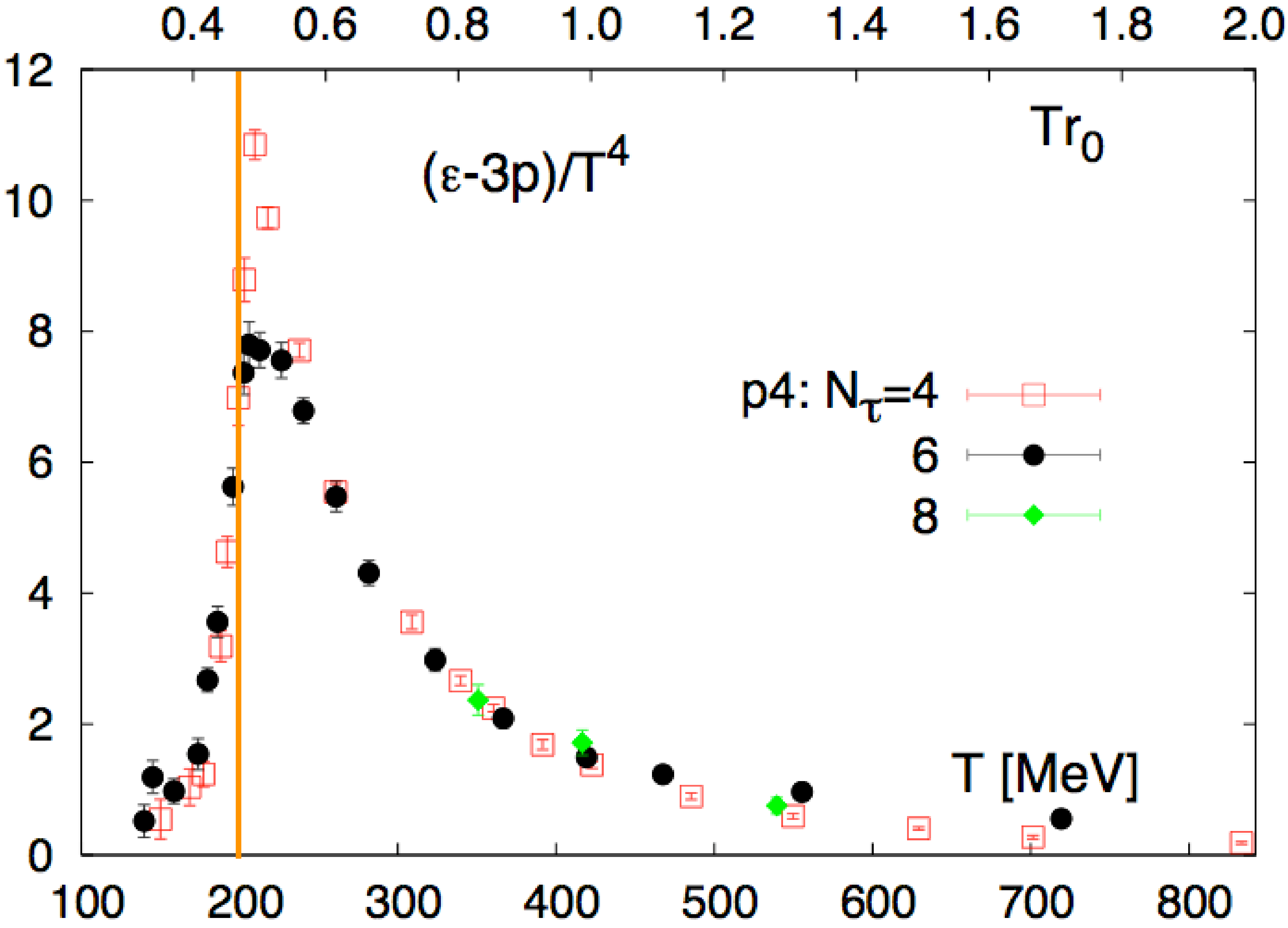
Critical temperature T_c=196±4 MeV



PRD 77 (2008) 045511

Hints from lattice QCD

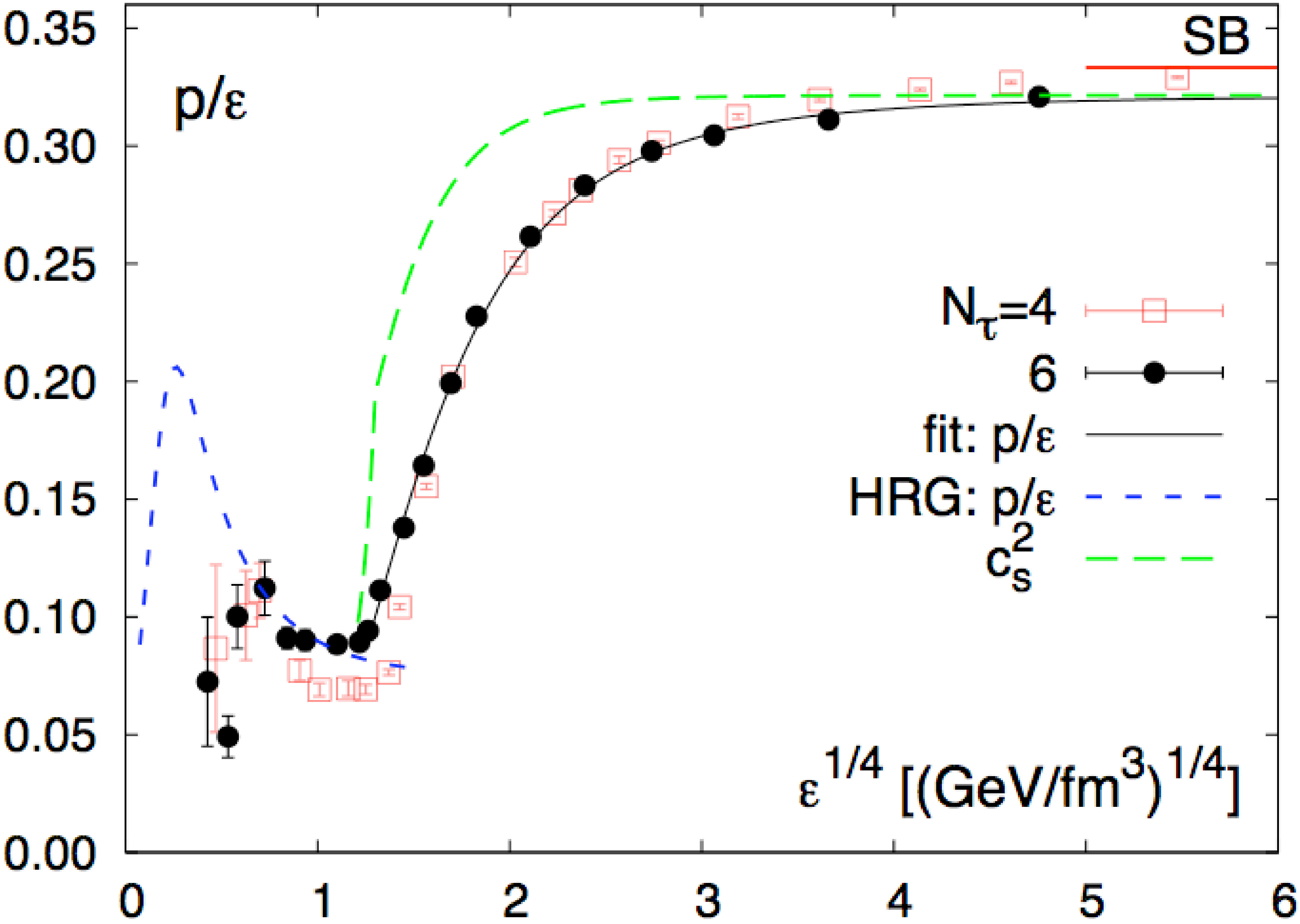
Critical temperature $T_c \approx 150\text{-}200$ MeV



PRD 77 (2008) 045511

Hints from lattice QCD

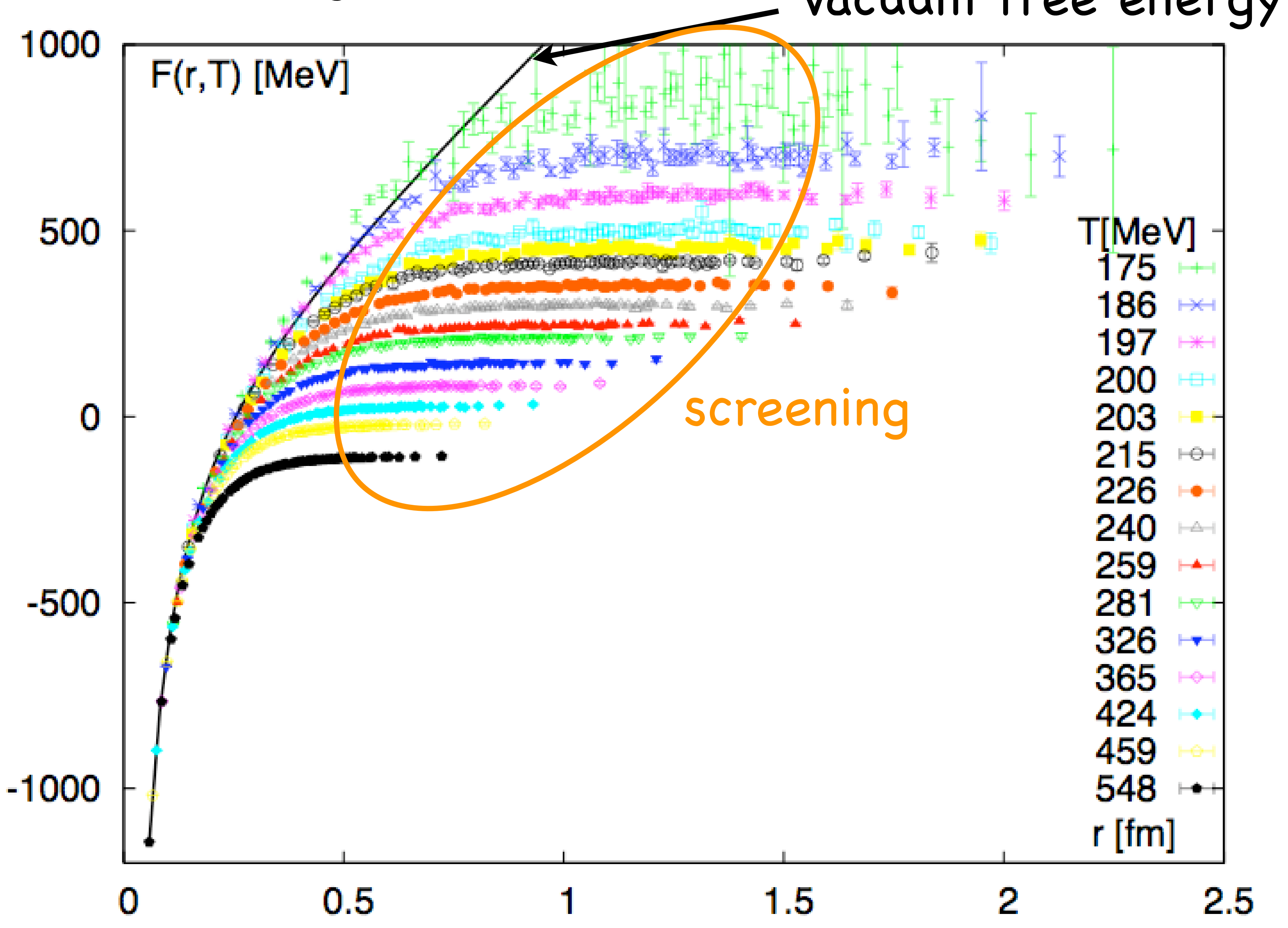
$\frac{\mathrm{d}p}{\mathrm{d}\varepsilon}$ ☞ sound velocity c_s: $$c_s^2 = \frac{\mathrm{d}p}{\mathrm{d}\varepsilon} = \varepsilon\frac{\mathrm{d}(p/\varepsilon)}{\mathrm{d}\varepsilon} + \frac{\mathrm{d}p}{\mathrm{d}\varepsilon}$$



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...

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...

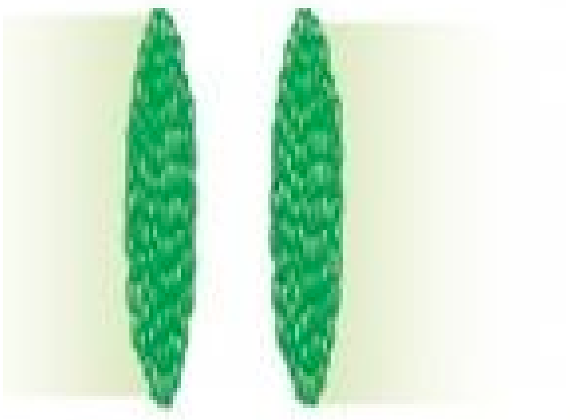
- However lattice simulations of QCD at finite temperature are not (yet) performed with "physical" light-quark masses.

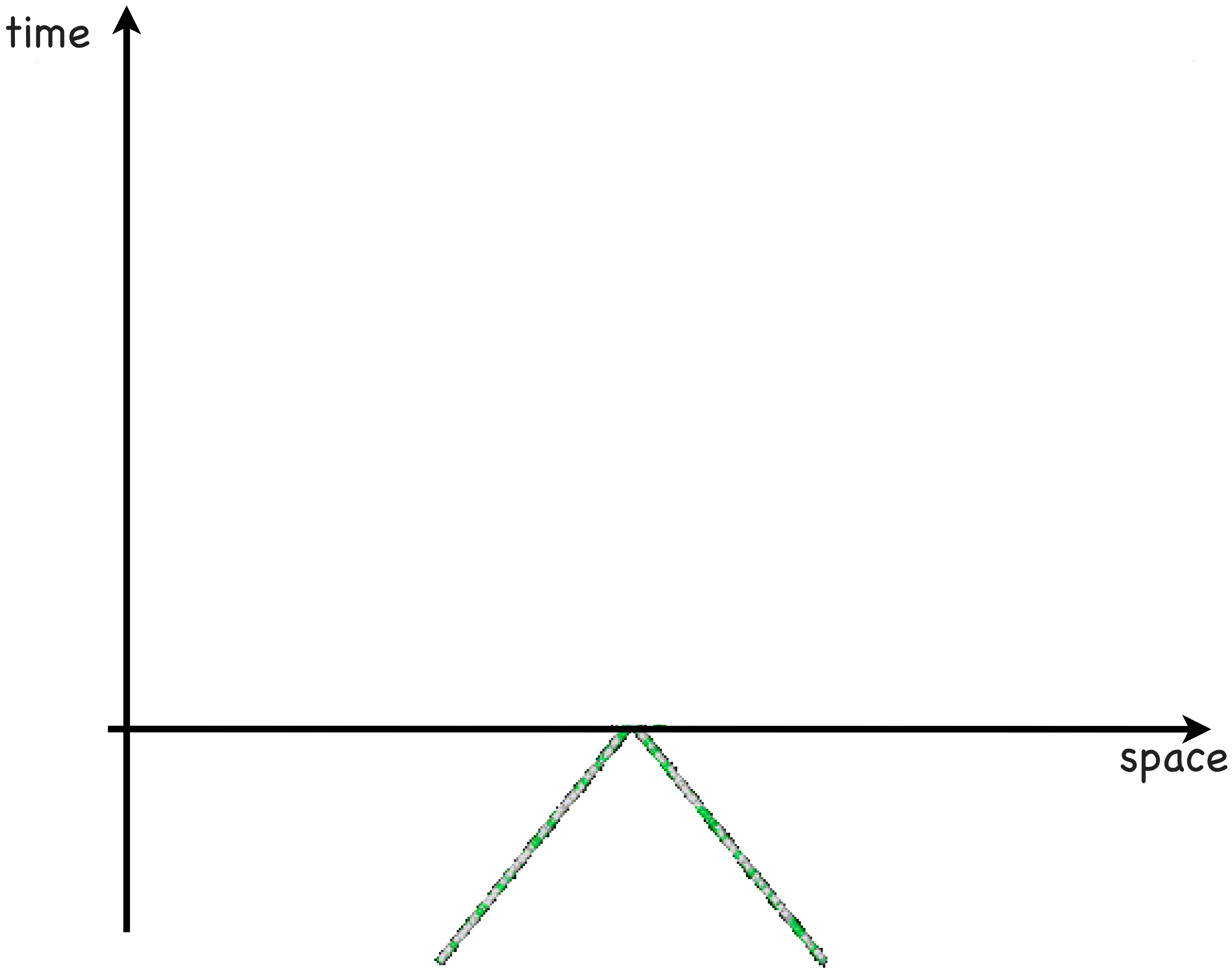
- They do not provide any phase diagram,

- nor transport coefficients.

(yet?)

Time evolution of a heavy-ion collision





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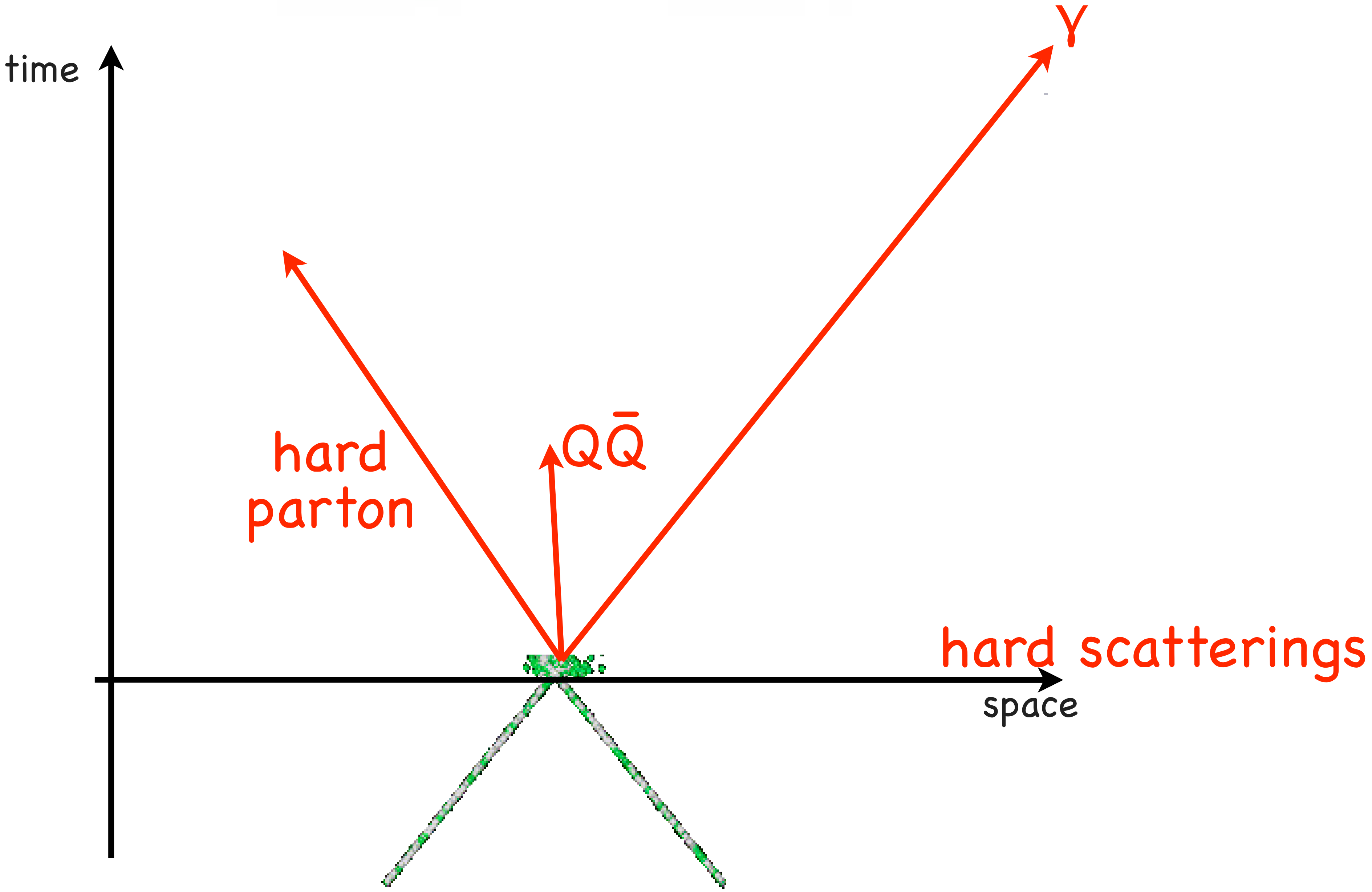
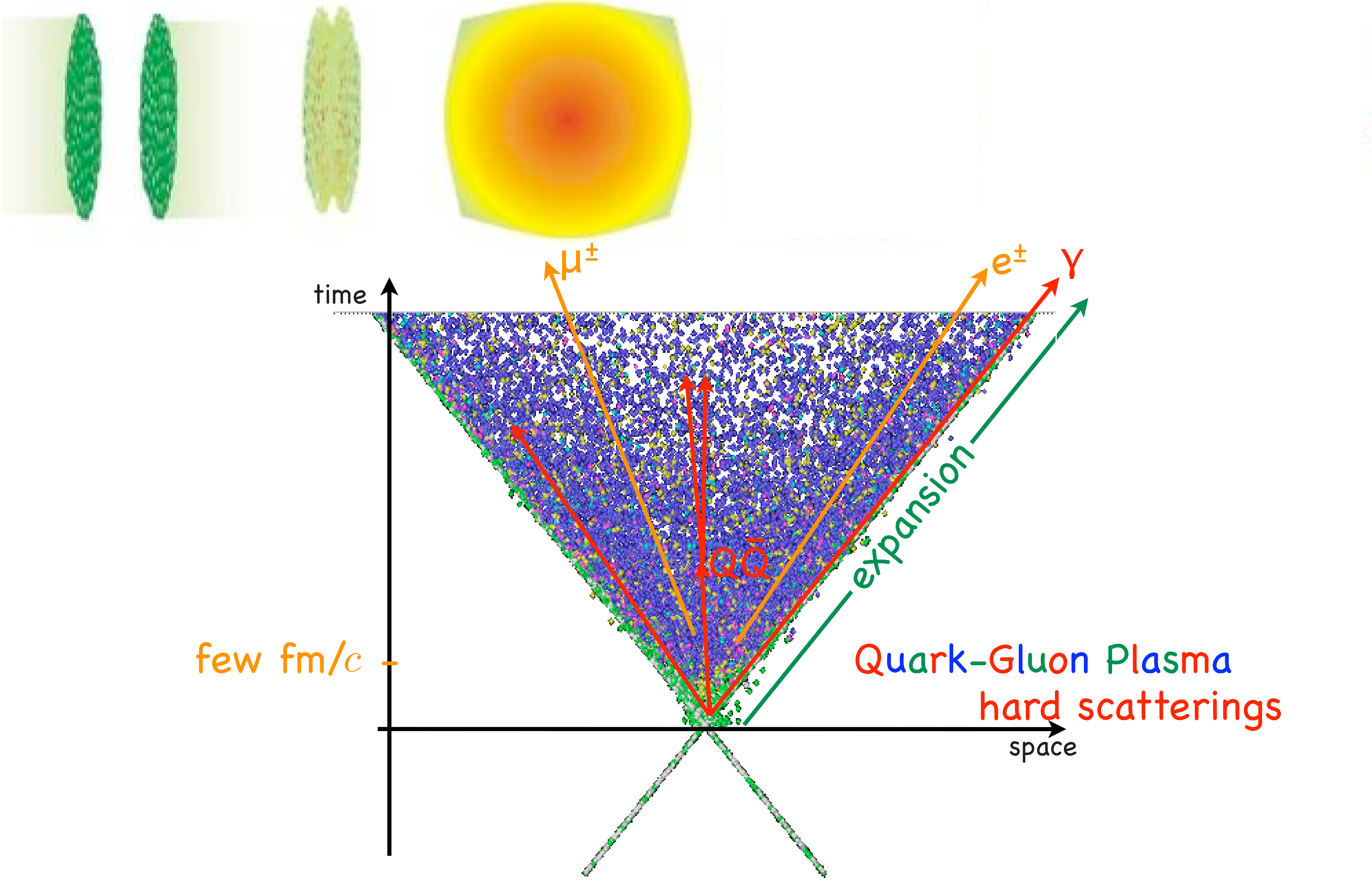


Time evolution of a heavy-ion collision



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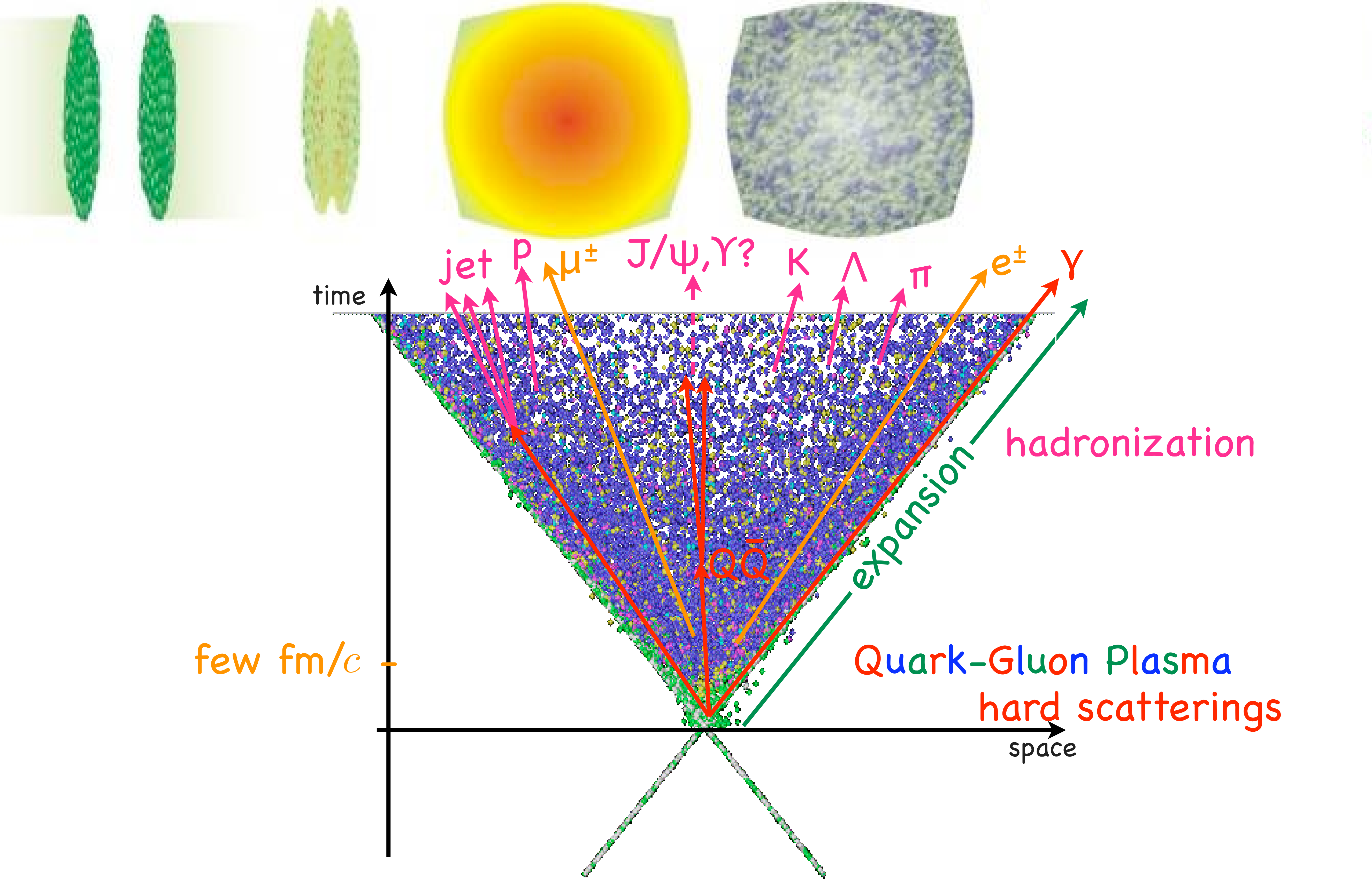

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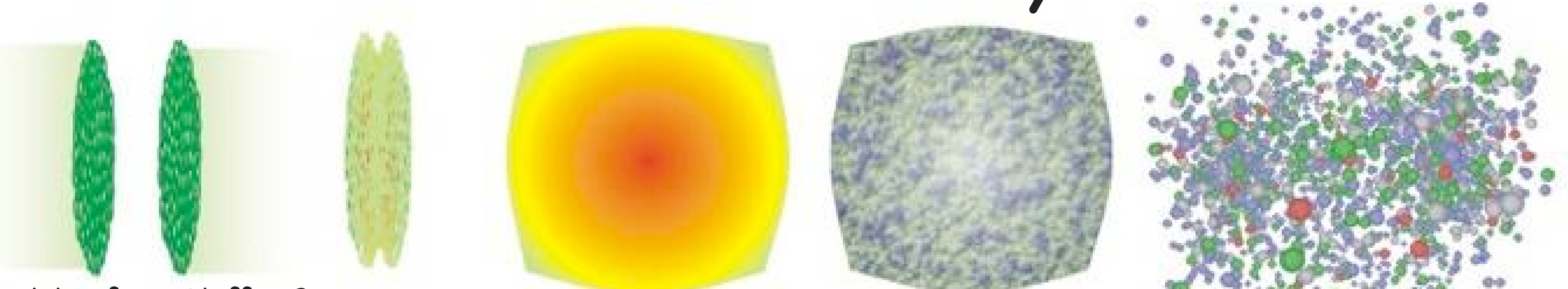
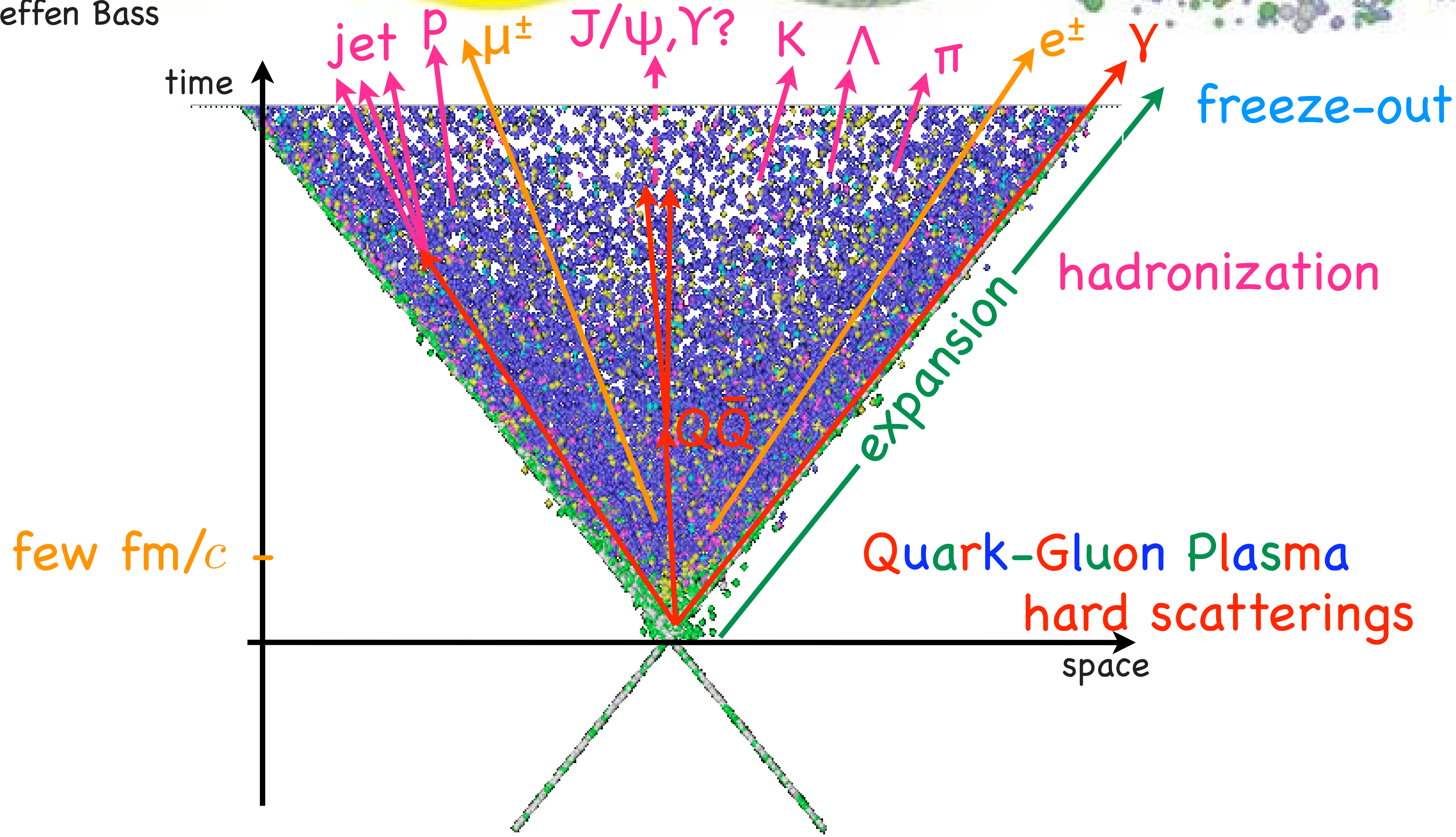
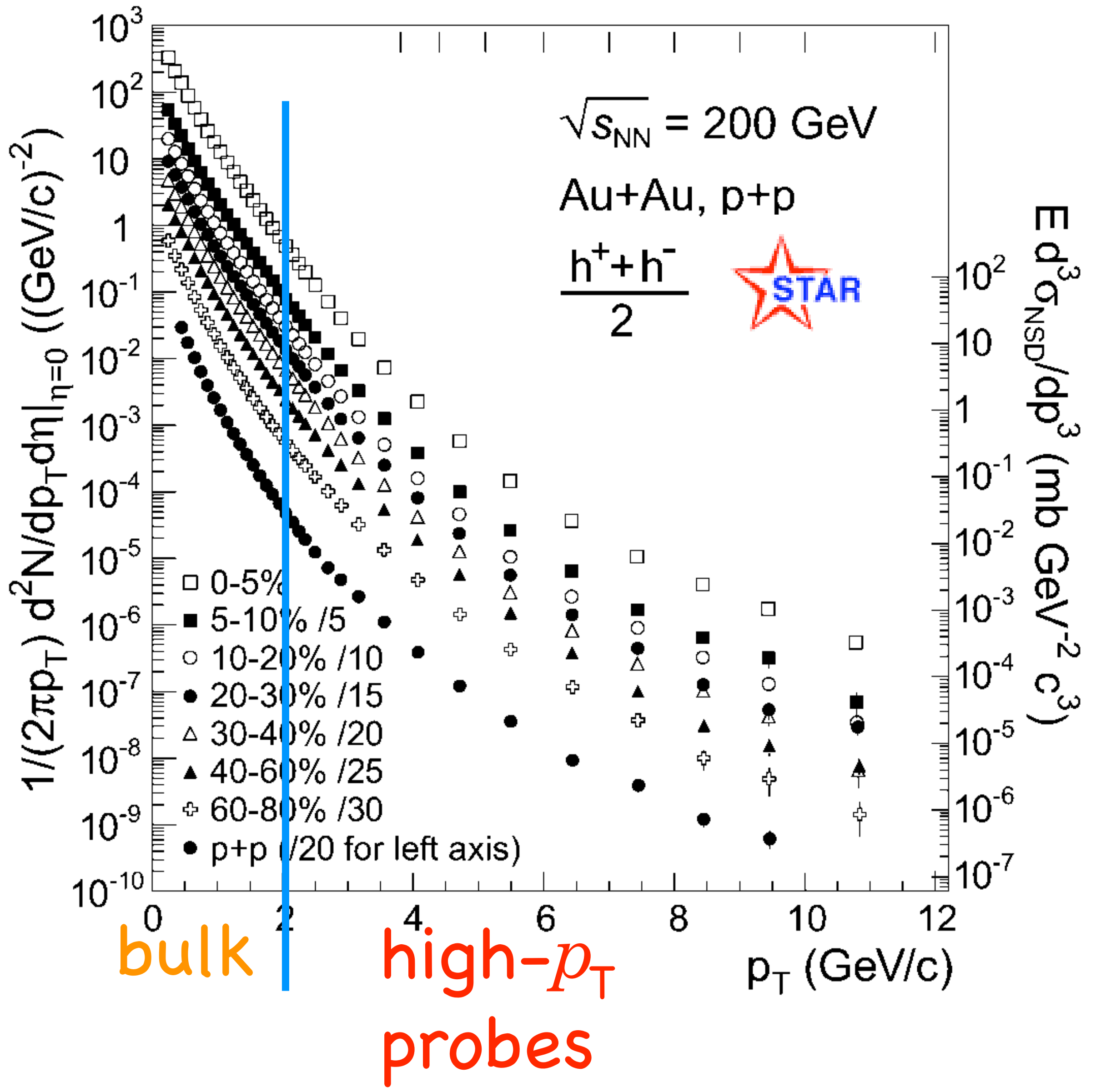


stolen from Steffen Bass
& John Harris

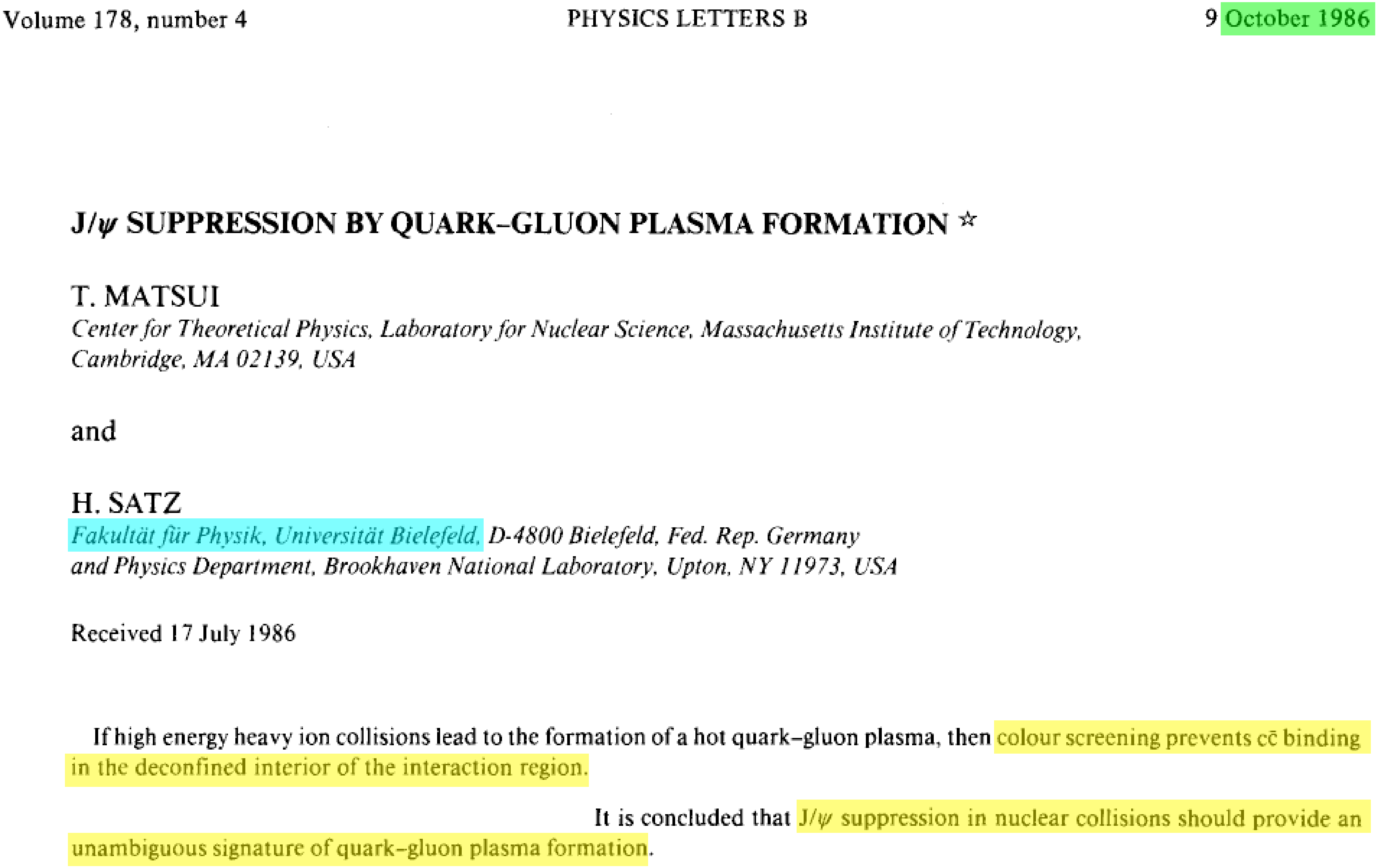


Bulk observables vs. hard probes



Only few particles with high transverse momenta (or containing heavy quarks), but their production mechanism is a priori better understood (perturbative QCD): can probe the bulk.

Hard probes (1): quarkonia suppression



Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region.

It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

Hard probes (1): quarkonia suppression

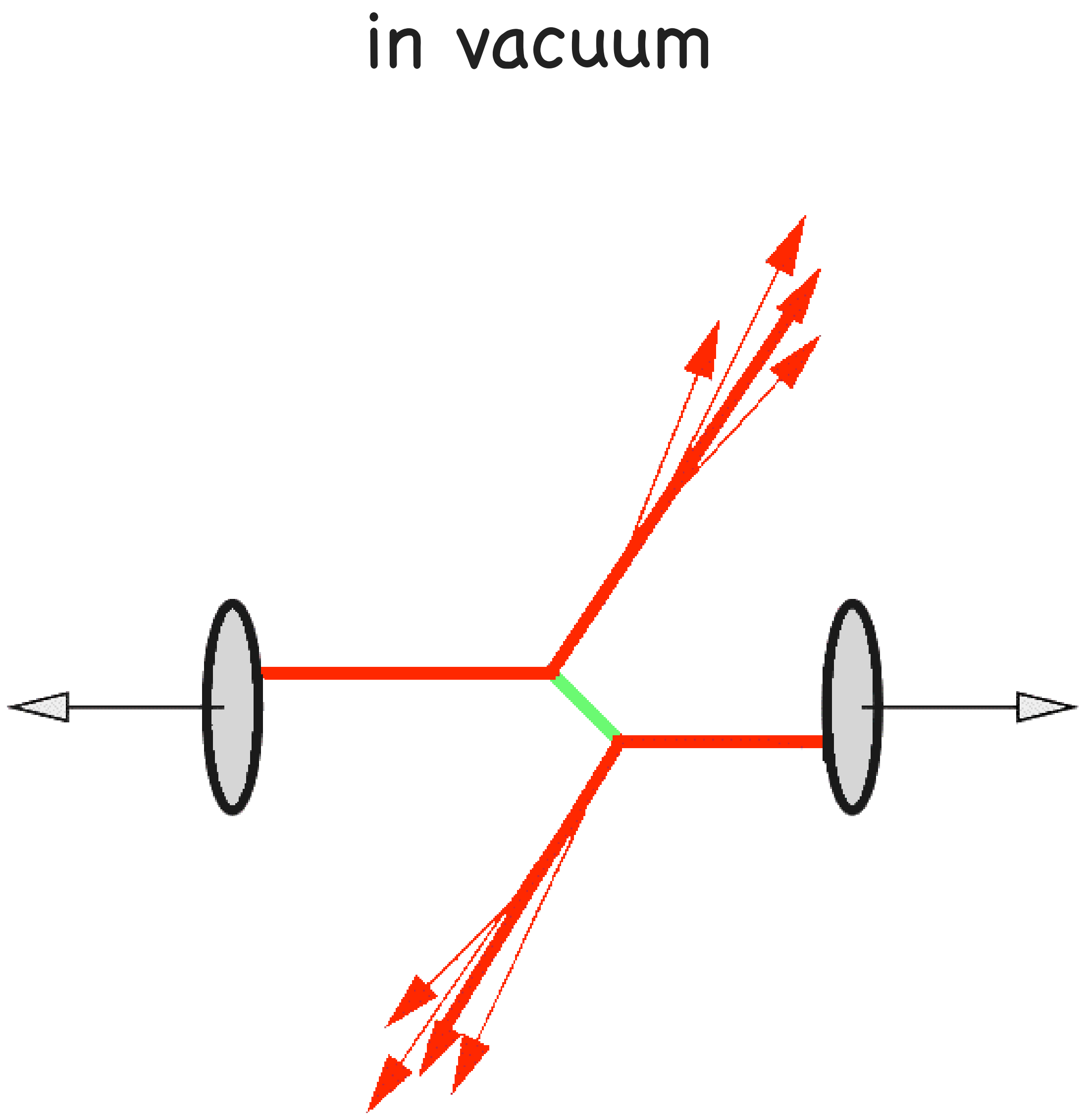
Screening of the heavy-quark-antiquark potential (cf. lattice results)

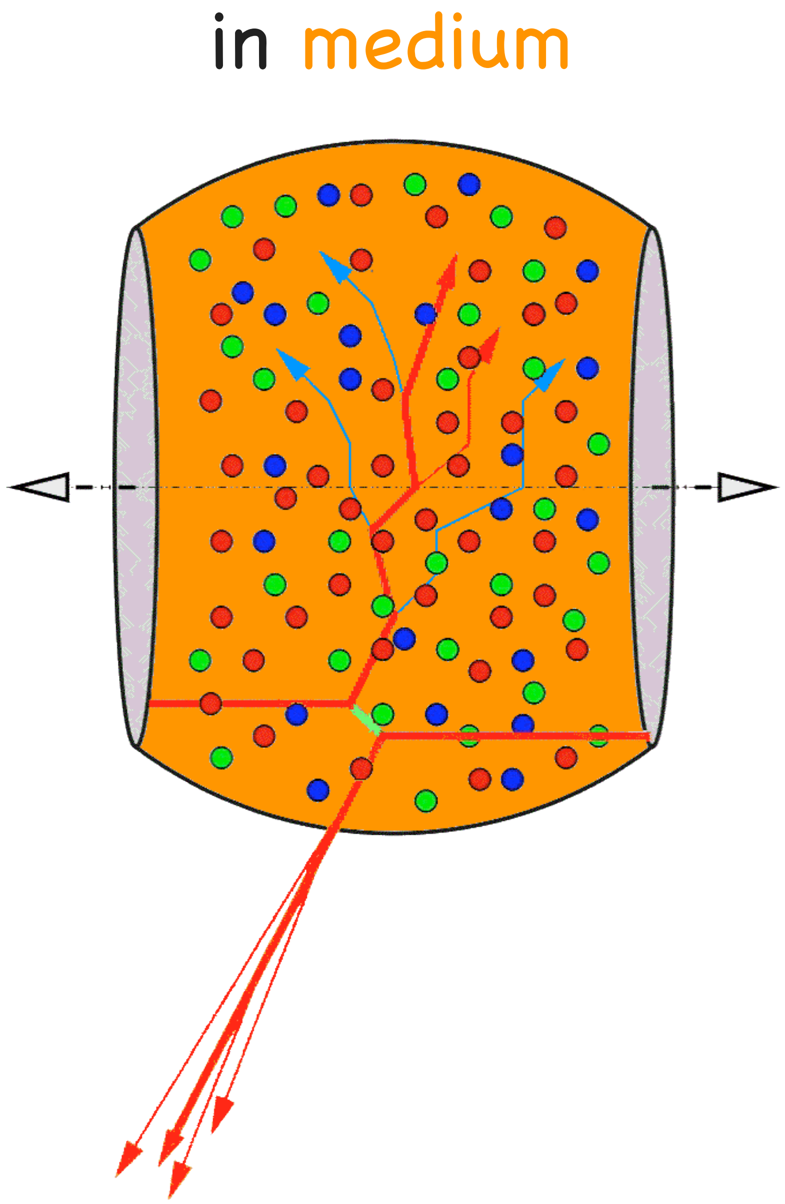
☞ suppression of heavy quarkonia.

Life is unfortunately not so easy...

Hard probes (2): "jet quenching"

A fast parton propagating through a dense medium will "lose" part of its energy-momentum.
(cf. energy loss of electrically charged particles in matter: Bethe-Bloch...)
The resulting jet of hadrons (if any!) is distorted: "quenching".

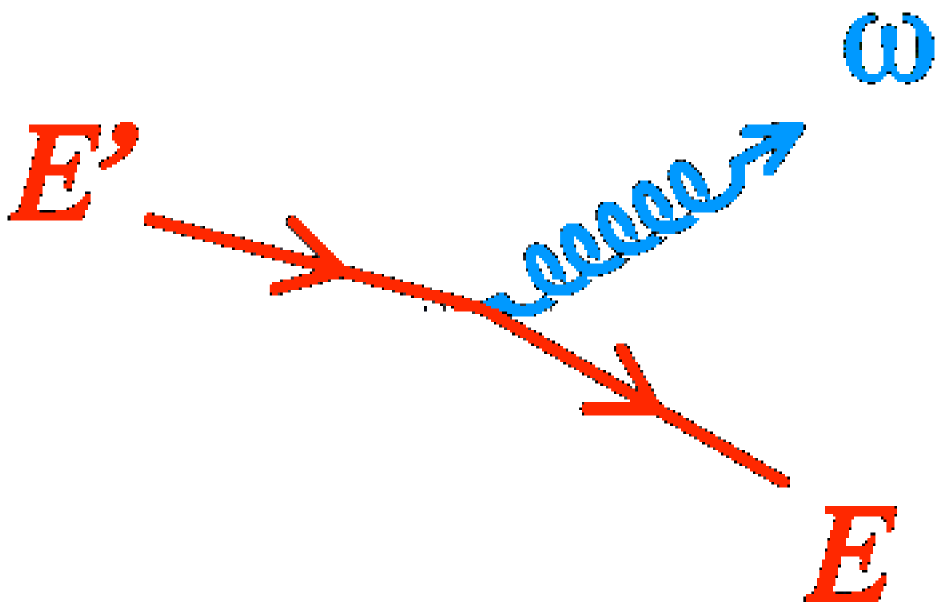




Hard probes (2): “jet quenching”

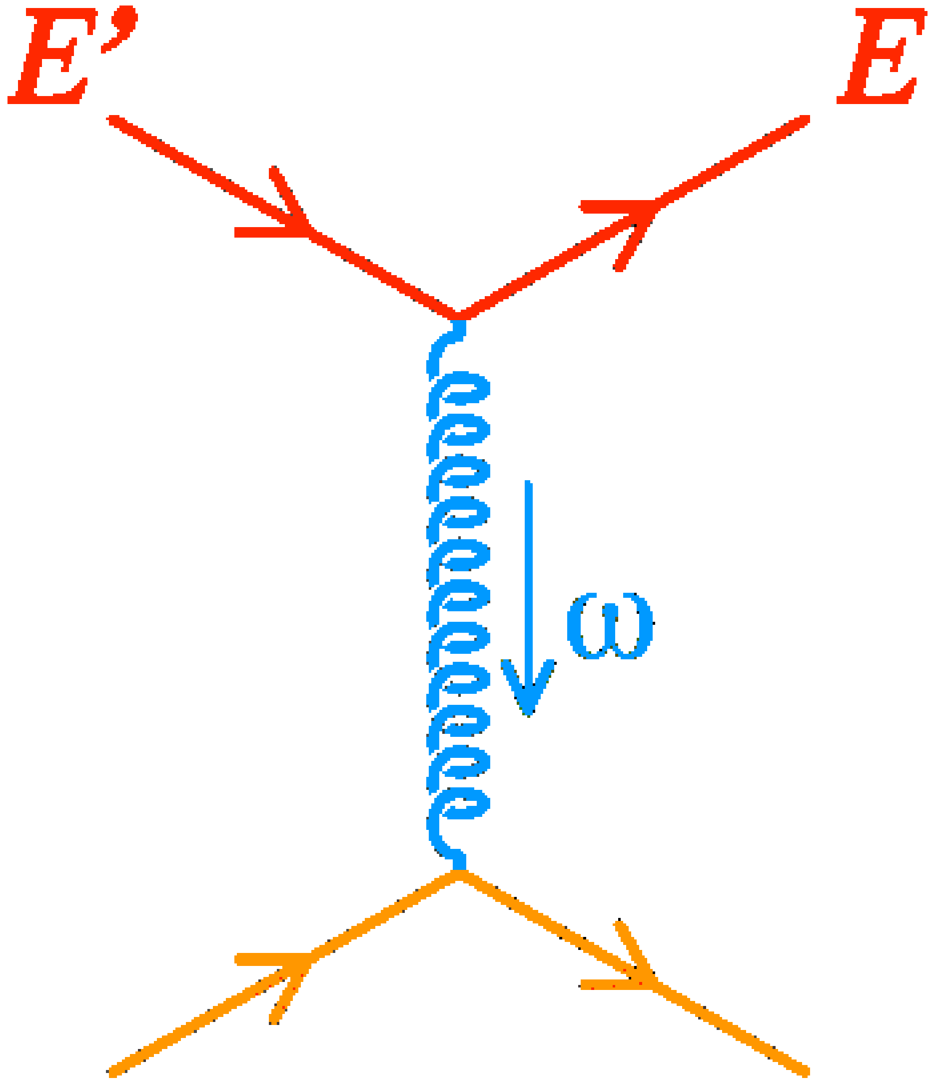
Two different processes leading to the loss of energy by a fast parton:

“radiative” process (Bremsstrahlung)



also “in vacuum” (DGLAP evolution), yet modified by the presence of a (colored) medium

“collisional” process

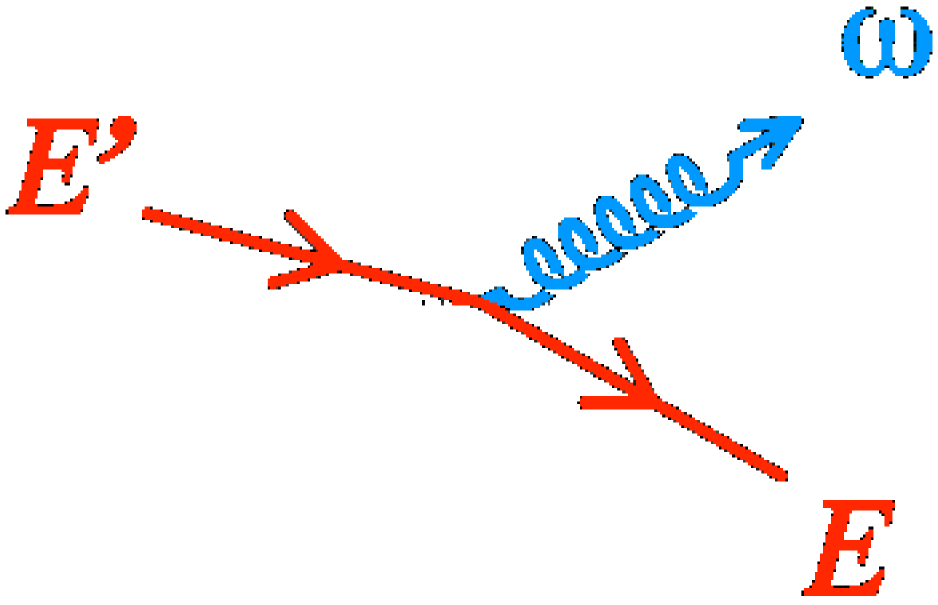


Hard probes (2): "jet quenching"

Two different processes leading to the loss of energy by a fast parton:

inelastic

"~~radiative~~" process (Bremsstrahlung)

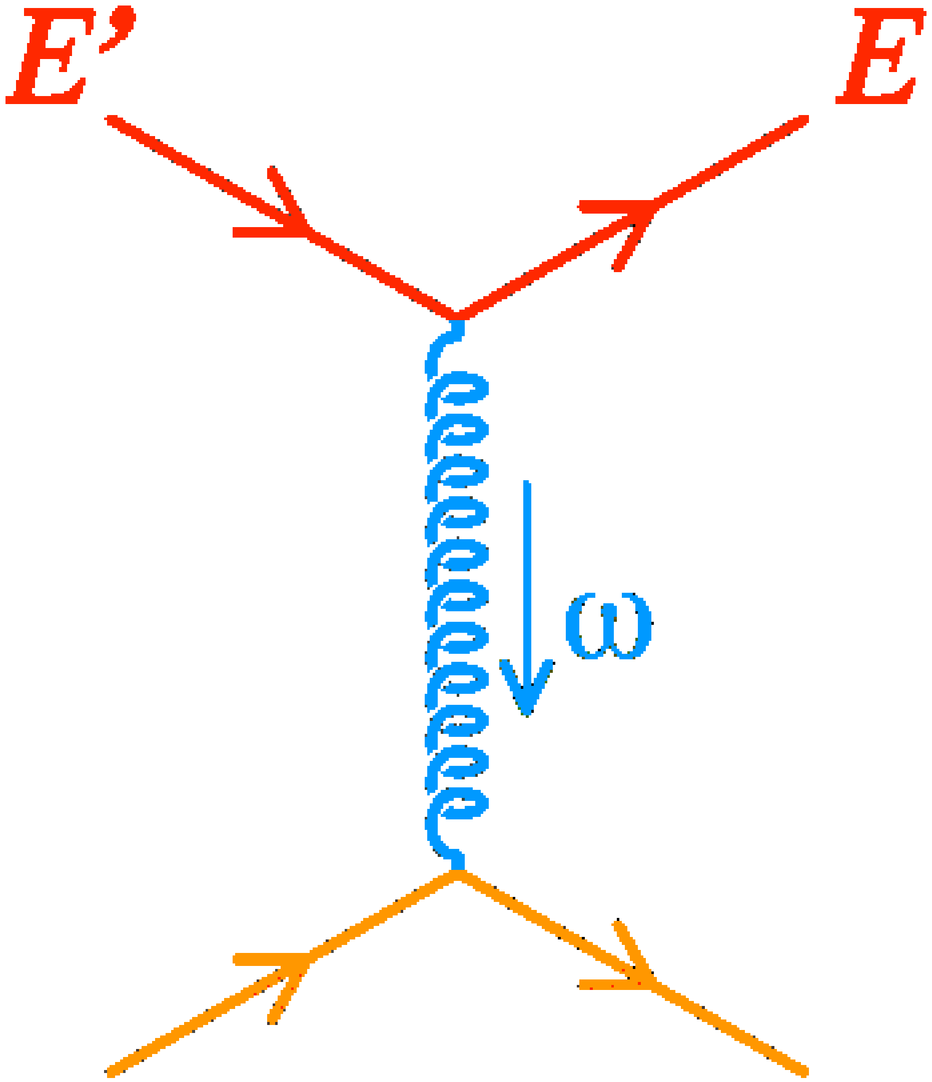


also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

collisions!

elastic

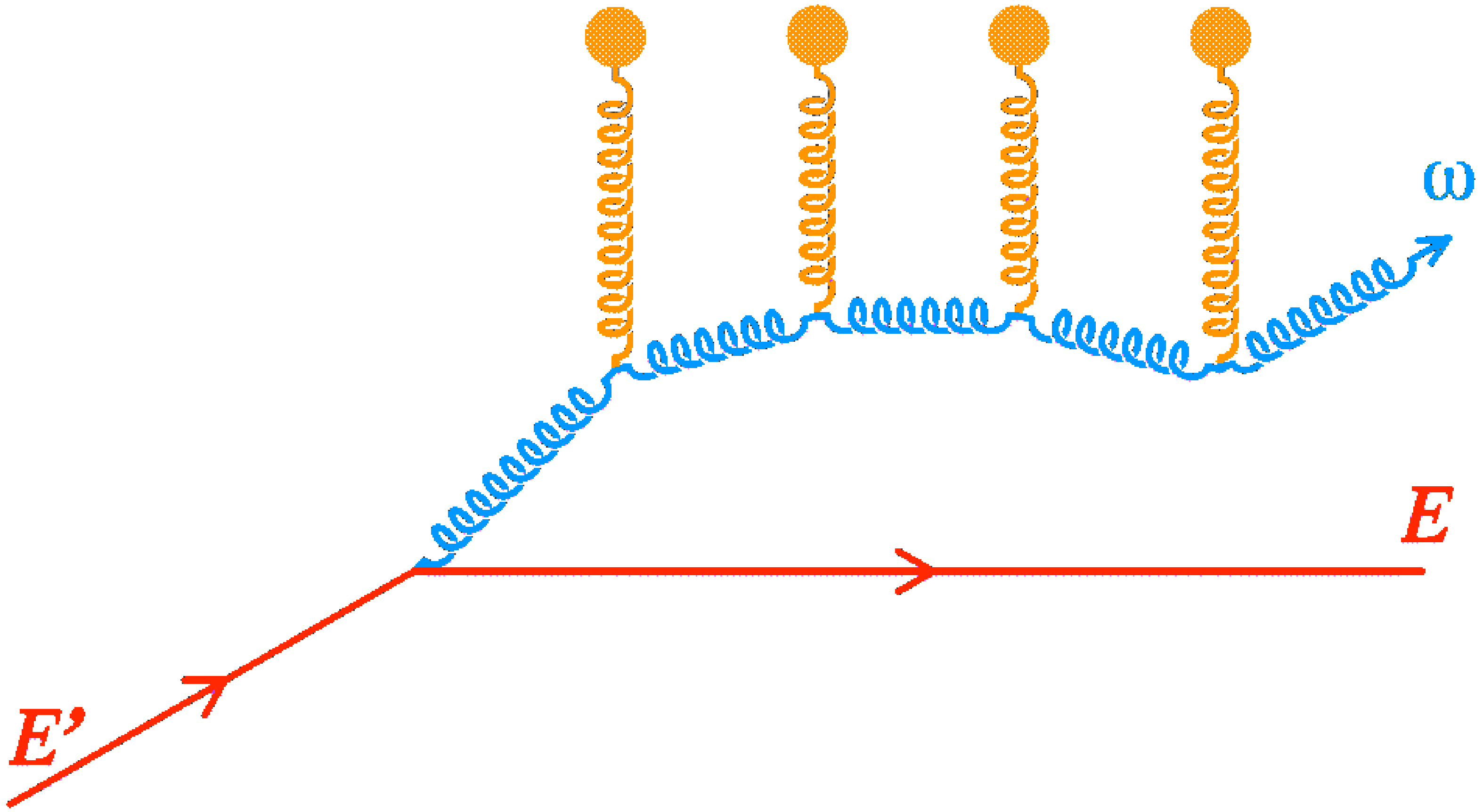
"~~collisional~~" process



Hard probes (2): "jet quenching"

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

The propagating high-p_T parton traverses a **thick target**.

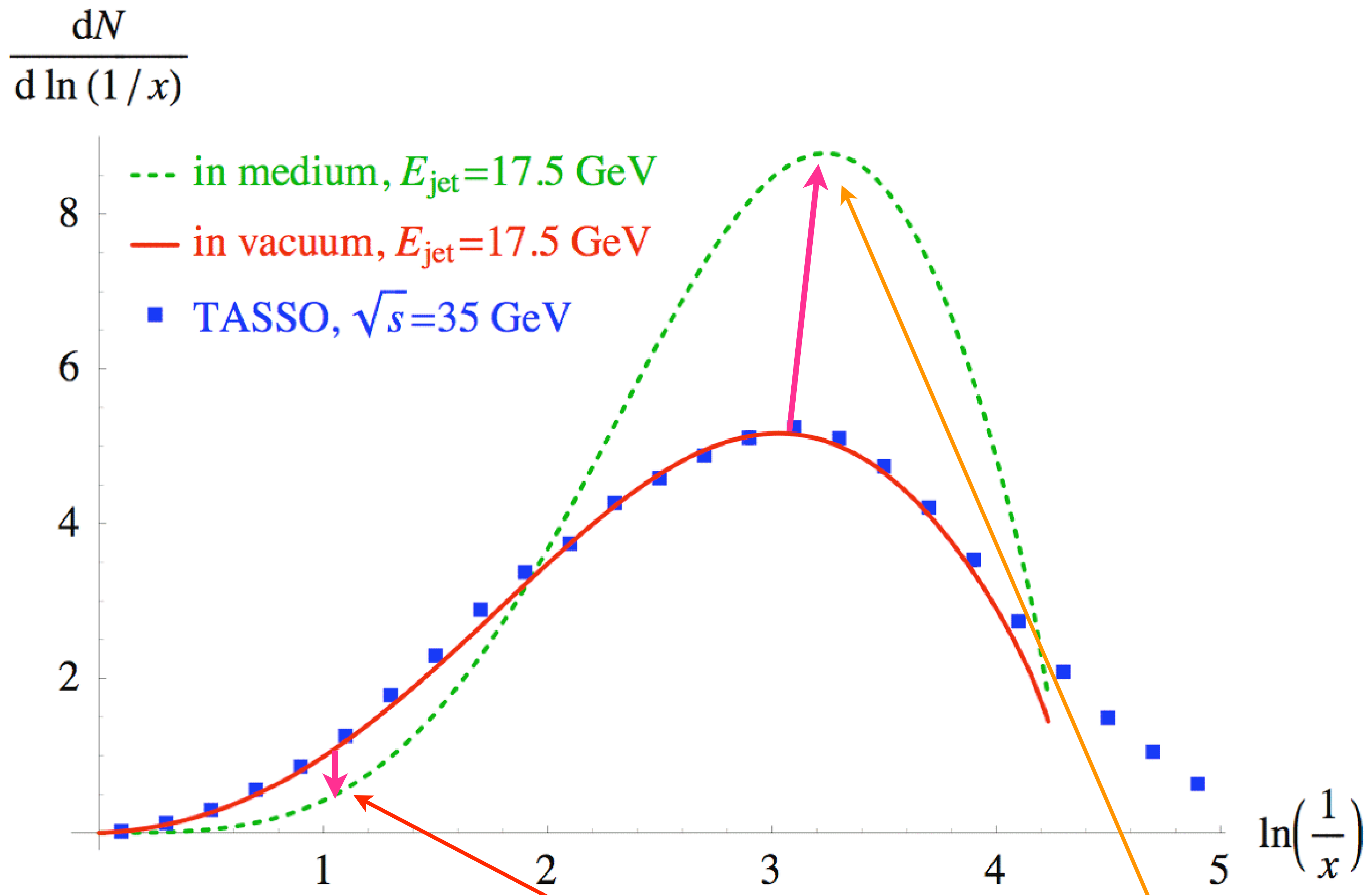


It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon spectrum.

☞ transport coefficient $\hat{q}$

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov

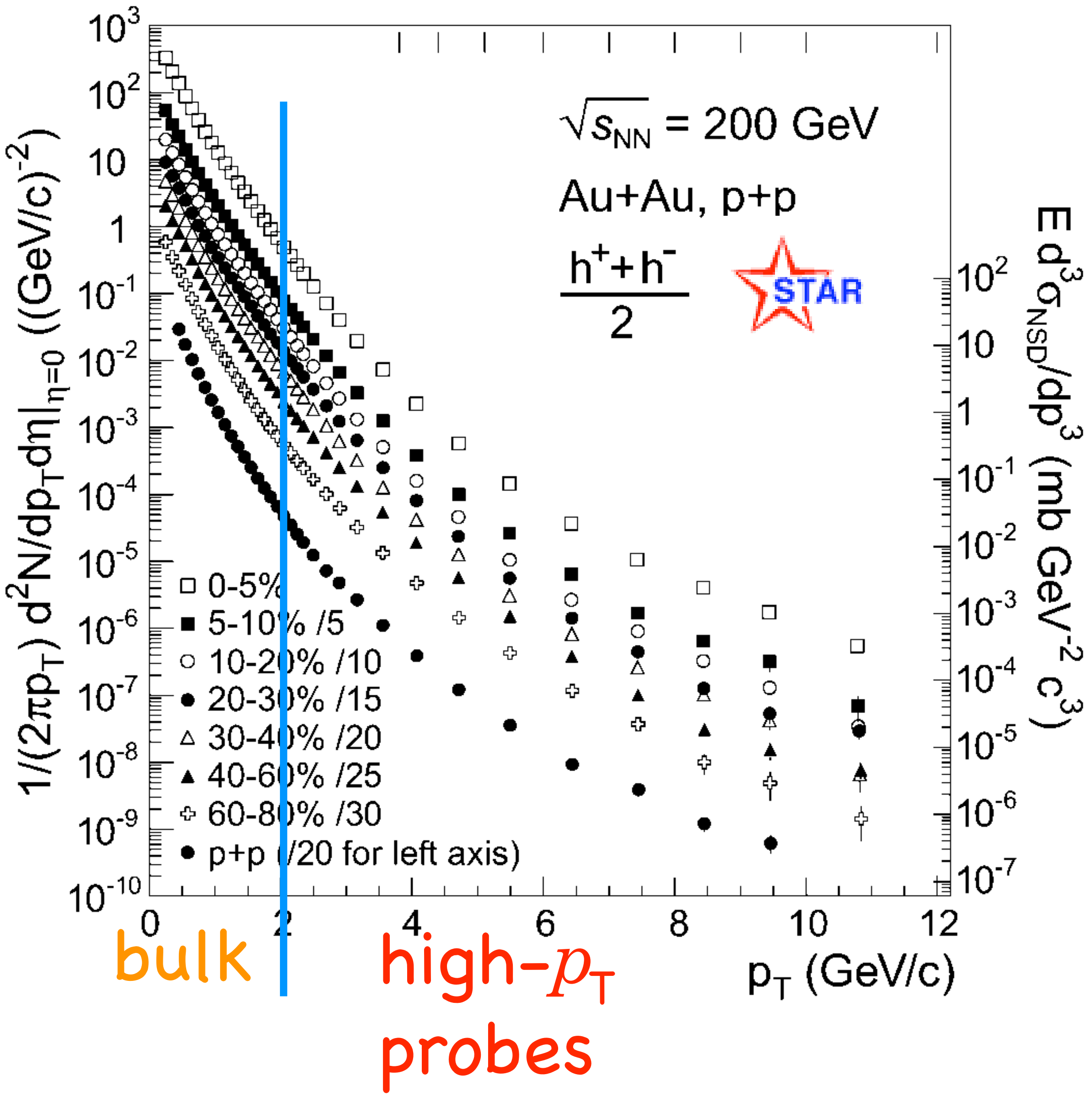
Parton distribution inside a jet in the presence of a medium



Partons are redistributed from high p_T (large x) to low p_T (small x)

NB, U.A.Wiedemann, hep-ph/0506218

Bulk observables vs. hard probes



The bulk represents at least 99% of the hadrons!

It should be possible to extract some information with high statistical significance.

Heavy-ion collisions: fluid-dynamics description

⓪ Creation of a dense "collection" of particles.

Heavy-ion collisions: fluid-dynamics description

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☞ fireball can be described by fluid dynamics

Heavy-ion collisions: fluid-dynamics description

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② The fluid expands: density decreases, λ increases (system size also).

Heavy-ion collisions: fluid-dynamics description

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① If the mean free path λ is much smaller than the dimensions of the system, after some time it thermalizes (temperature $T_{\rm in.}$).

☞ fireball can be described by fluid dynamics

② The fluid expands: density decreases, λ increases (system size also).

③ At some time, the mean free path is of the same order as the system size: fluid dynamics is no longer a valid description:

(kinetic) “freeze-out”

usually parameterized in terms of a temperature $T_{\rm f.o.}$.

Fluid dynamics: various types of flows

- Thermodynamic equilibrium?
  - Kn $\gg 1$: free-streaming limit
  - Kn $\ll 1$: liquid (hydro) limit

☞ Knudsen number Kn $\equiv \dfrac{\lambda}{L}$

mean free path → λ

system size → L

- Viscous or inviscid ("ideal")?
  - Re $\gg 1$: ideal (non-viscous) flow
  - Re $\lesssim 1$: viscous flow

☞ Reynolds number Re $\equiv \dfrac{\varepsilon L v_{\text{fluid}}}{\eta}$

$\eta \sim \varepsilon \lambda c_s$ → η

shear viscosity

- Compressible or incompressible?
  - Ma $\ll 1$: incompressible flow
  - Ma $\gtrsim 1$: compressible flow

☞ Mach number Ma $\equiv \dfrac{v_{\text{fluid}}}{c_s}$

Fluid dynamics: various types of flows

Three dimensionless numbers:

$$\mathrm{Kn} \equiv \frac{\lambda}{L}, \qquad \mathrm{Re} \equiv \frac{\varepsilon L v_{\rm fluid}}{\eta}, \qquad \mathrm{Ma} \equiv \frac{v_{\rm fluid}}{c_s}$$

An important relation:

$$\mathrm{Kn} \times \mathrm{Re} = \frac{\varepsilon \lambda v_{\rm fluid}}{\eta} \sim \frac{v_{\rm fluid}}{c_s} = \mathrm{Ma}$$

In a heavy-ion collision, the created matter expands into the vacuum

$\Rightarrow$ compressible flow

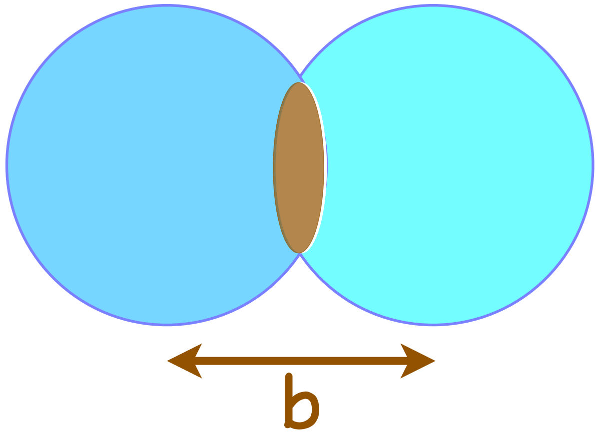
compressible liquids are ideal $\Leftrightarrow$ viscidity $\equiv$ departure from equilibrium

☞ To access the shear viscosity, try to estimate Kn ($\Leftrightarrow$ mean number of collisions per particle): find an observable that depends on the latter.

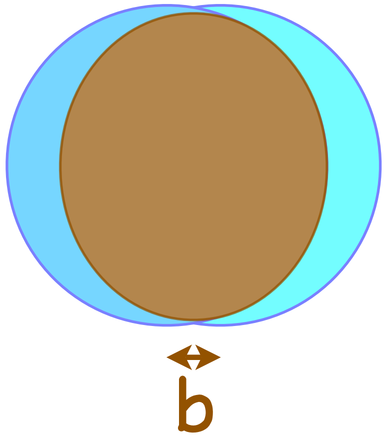
Heavy-ion collisions: geometry

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" collisions)

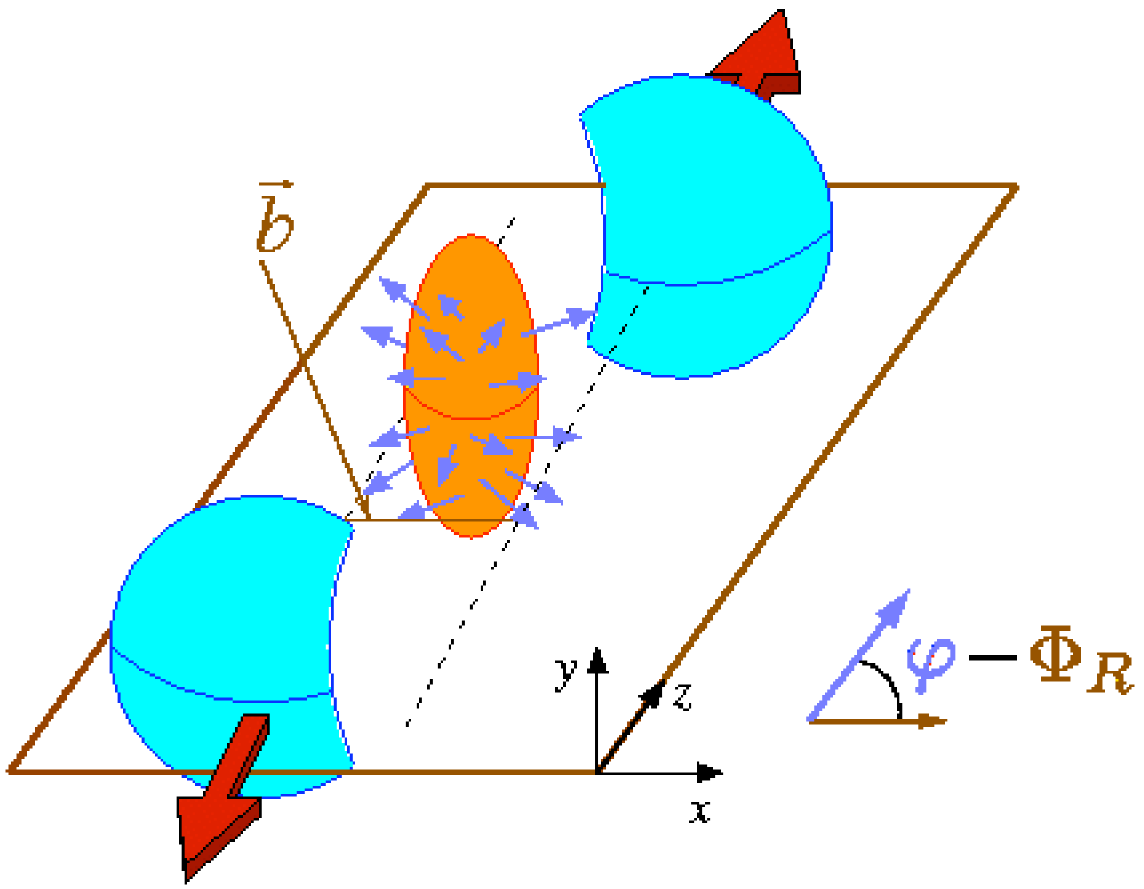


- or the collision might be almost head-on (small impact parameter, "central" collision)

The (almond-shaped) overlap regions of the nuclei are different in either case (size, eccentricity...): possible control parameter(s) for the mean number of collisions Kn^{-1}.

Anisotropic (collective) flow

Consider a non-central collision:



anisotropy of the source (in the plane transverse to the beam)

⇒ anisotropic pressure gradients (larger along the impact parameter)

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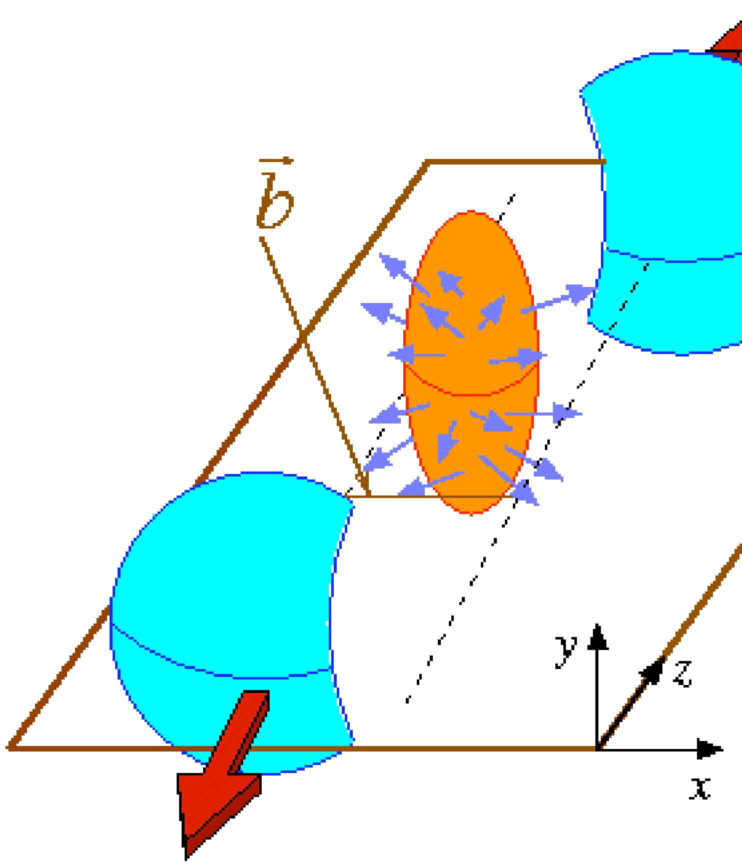

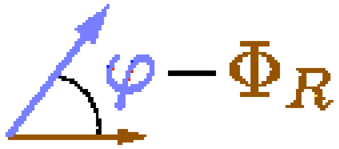

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⇒ anisotropic fluid velocities

anisotropic emission of particles:

"anisotropic collective flow"

$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left[1+2\,v_1\cos\left(\varphi-\Phi_R\right)+2\,v_2\cos 2(\varphi-\Phi_R)+\cdots\right]$$

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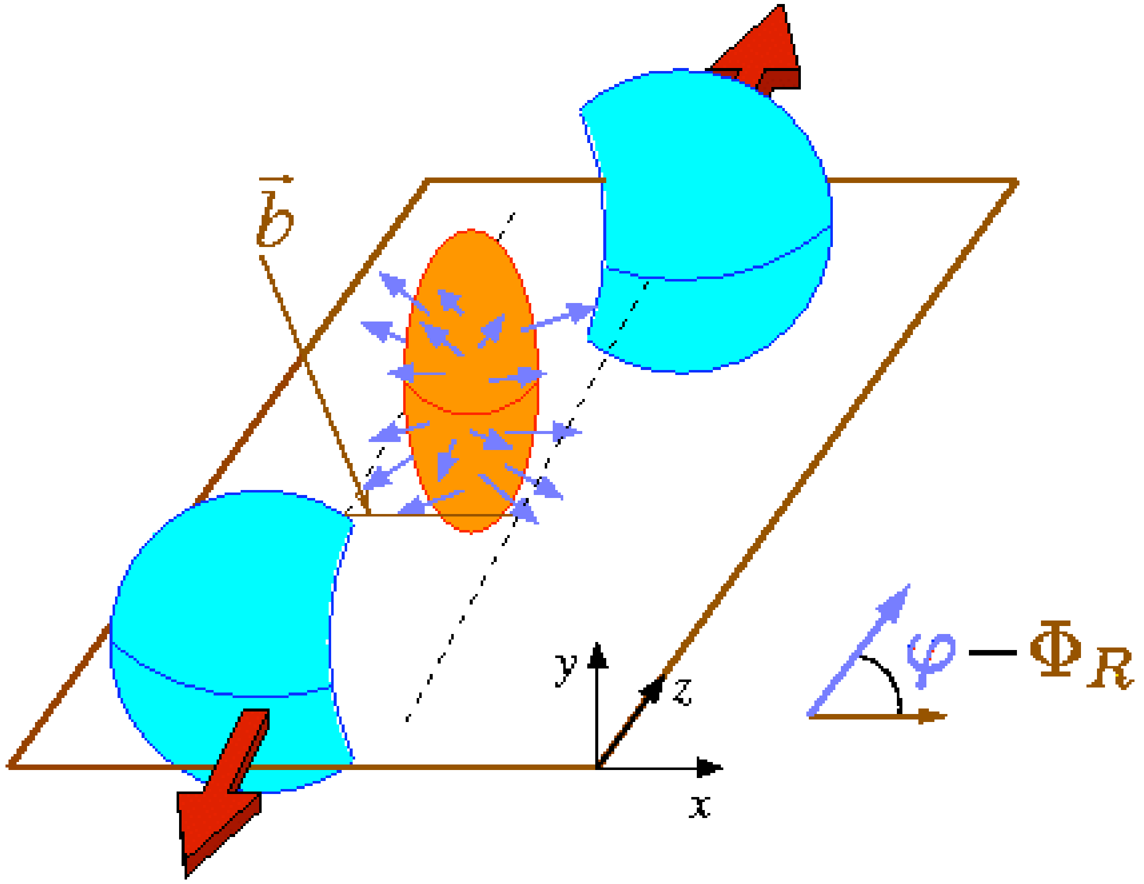

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$$E\frac{\mathrm{d}N}{\mathrm{d}^3\mathbf{p}} \propto \frac{\mathrm{d}N}{p_T\,\mathrm{d}p_T\,\mathrm{d}y}\left[1 + 2\,v_1\cos\left(\varphi - \Phi_R\right) + 2\,v_2\cos 2(\varphi - \Phi_R) + \cdots\right]$$

More particles along the impact parameter ($\varphi - \Phi_R = 0$ or 180°) than perpendicular to it ☞ "elliptic flow" $v_2 \equiv \langle\cos 2(\varphi - \Phi_R)\rangle > 0$.

average over particles →

Anisotropic (collective) flow

⚠ Despite the terminology, "flow" does not imply fluid dynamics.

An exact computation of the dependence of v_2, v_4 on the number Kn^{-1} of collisions undergone by particles requires a microscopic transport model, yet one can guess the general tendency.

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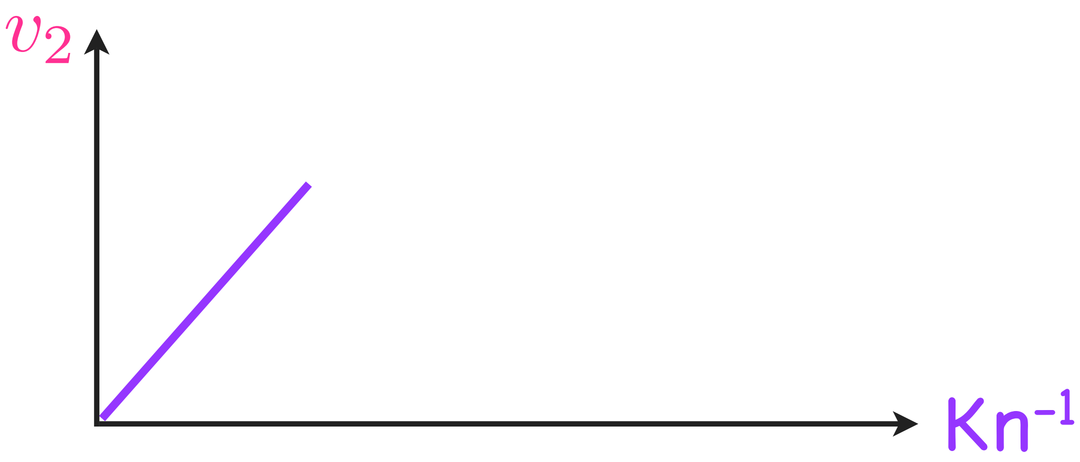

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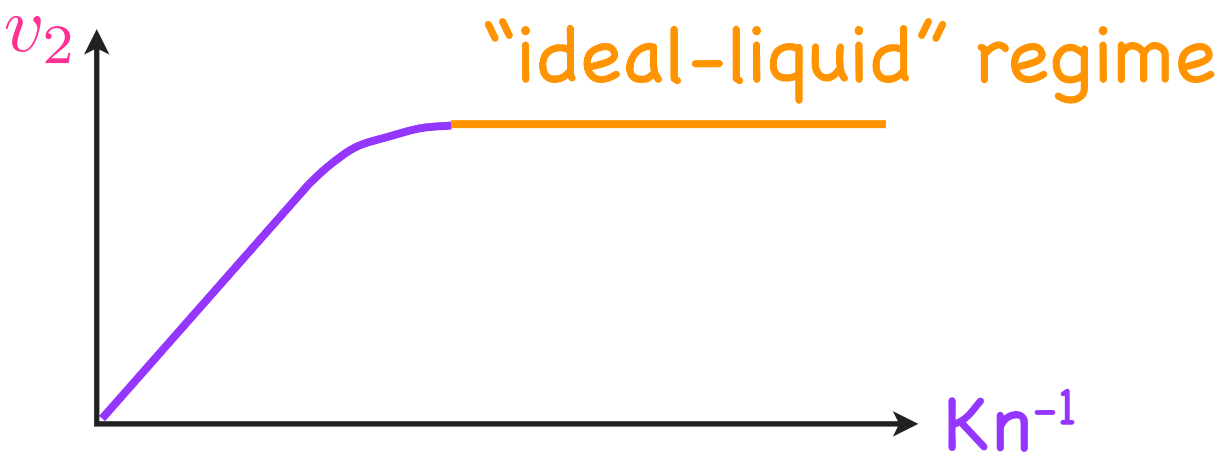
- In the absence of rescatterings ("gas"), no flow develops.
- The more collisions, the larger the flow.
- For a given number of collisions, the system thermalizes: further collisions no longer increase v_2.



R.S.Bhalerao, J.-P.Blaizot, NB, J.-Y.Ollitrault, PLB 627 (2005) 49

Anisotropic (collective) flow

Possible experimental control knobs for the mean number of collisions per particle Kn^{-1}:

- centrality of the collisions
- size of the colliding nuclei
- center-of-mass energy of the collisions
- transverse momentum / rapidity of the emitted particles

Anisotropic (collective) flow

Possible experimental control knobs for the mean number of collisions per particle Kn^{-1}:

- centrality of the collisions
- size of the colliding nuclei
- center-of-mass energy of the collisions
- transverse momentum / rapidity of the emitted particles

However, the "absolute size" of the signal (the hydro-regime value) can also depend on these handles:

- centrality of the collisions ☞ $v_2{}^{\rm hydro} = \mathrm{const} \times \epsilon$ (eccentricity), where the constant depends on c_s
- the center-of-mass energy of the collisions influences the initial conditions in the overlap region ☞ entropy density, eccentricity...

Probes of high-energy heavy-ion collisions

Physical aspects

- Theoretical hints (in particular from lattice QCD) that the relevant degrees of freedom for the description of bulk nuclear matter may change when the temperature increases.

- Time evolution of an ultra-relativistic heavy-ion collision: several stages, all of them contributing to the signal in the detectors.

- Hard probes: quarkonium suppression, jet quenching...

- Collective probes: anisotropic flow...

- Many omitted interesting topics!