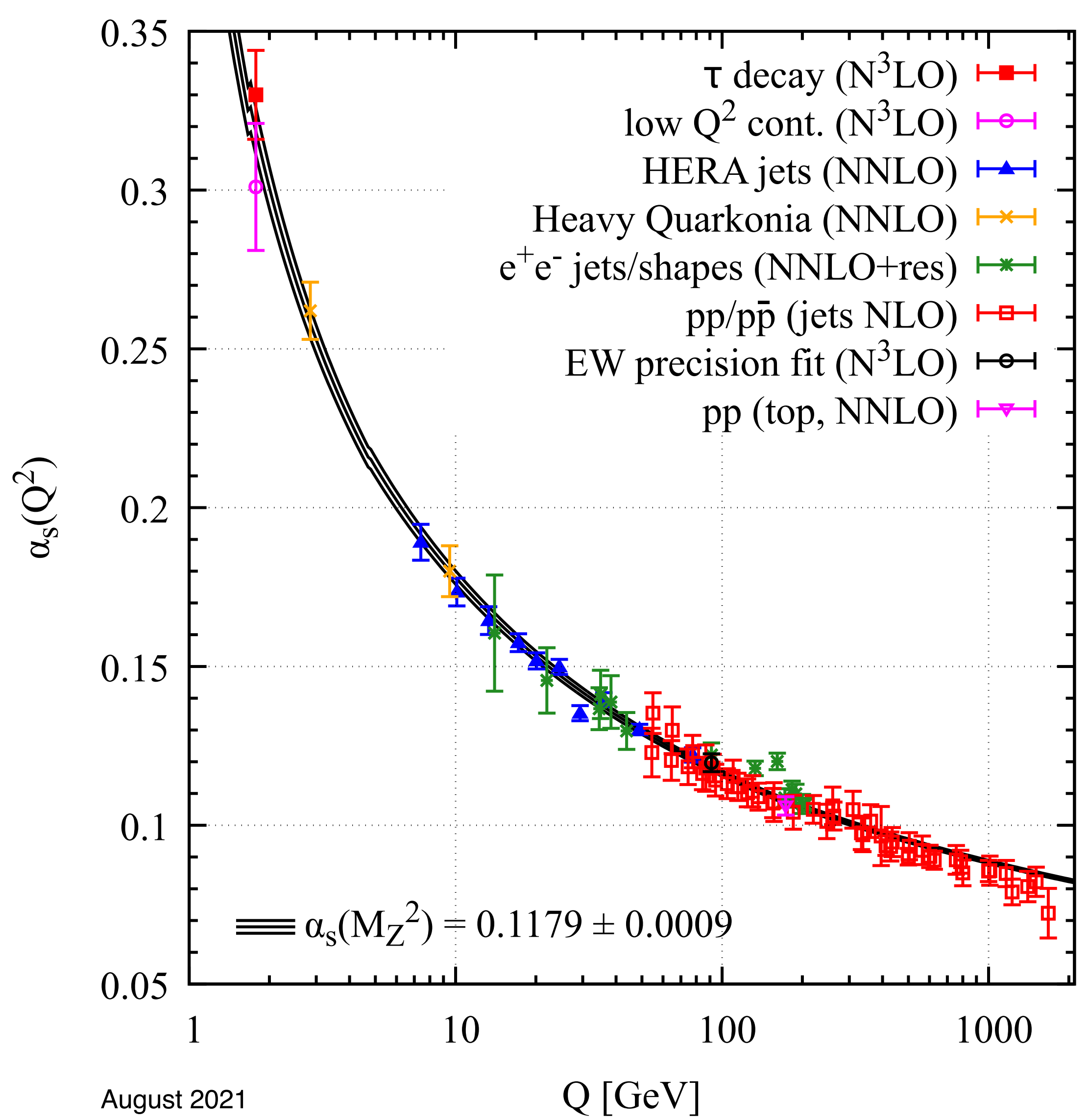
Quark-Gluon Plasma

QCD Matter at high T and p

What happens to quark-gluon matter at high temperature and/or pressure?

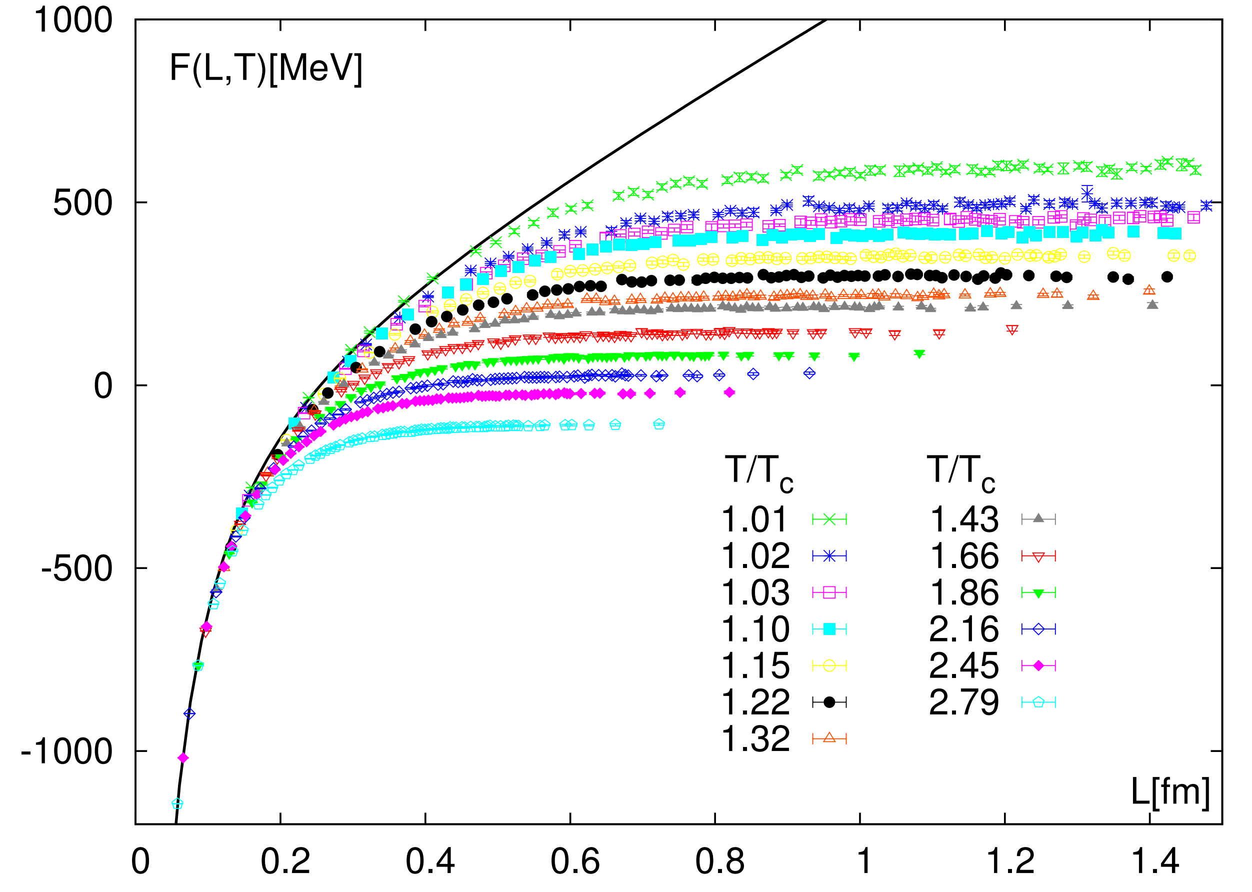
High T implies large average momenta, thus small QCD coupling.



QCD Matter at high T and p

At high enough T quarks and gluons are no longer confined.

Static potential is Debye-screened.



Thus expect at high T a gas of weakly interacting(?) quarks and gluons: quark-gluon plasma (QGP)

QCD Thermodynamics

Hadrons, as well as quarks and gluons can be treated in relativistic thermodynamics as Fermi / Bose gas. Key quantities are:

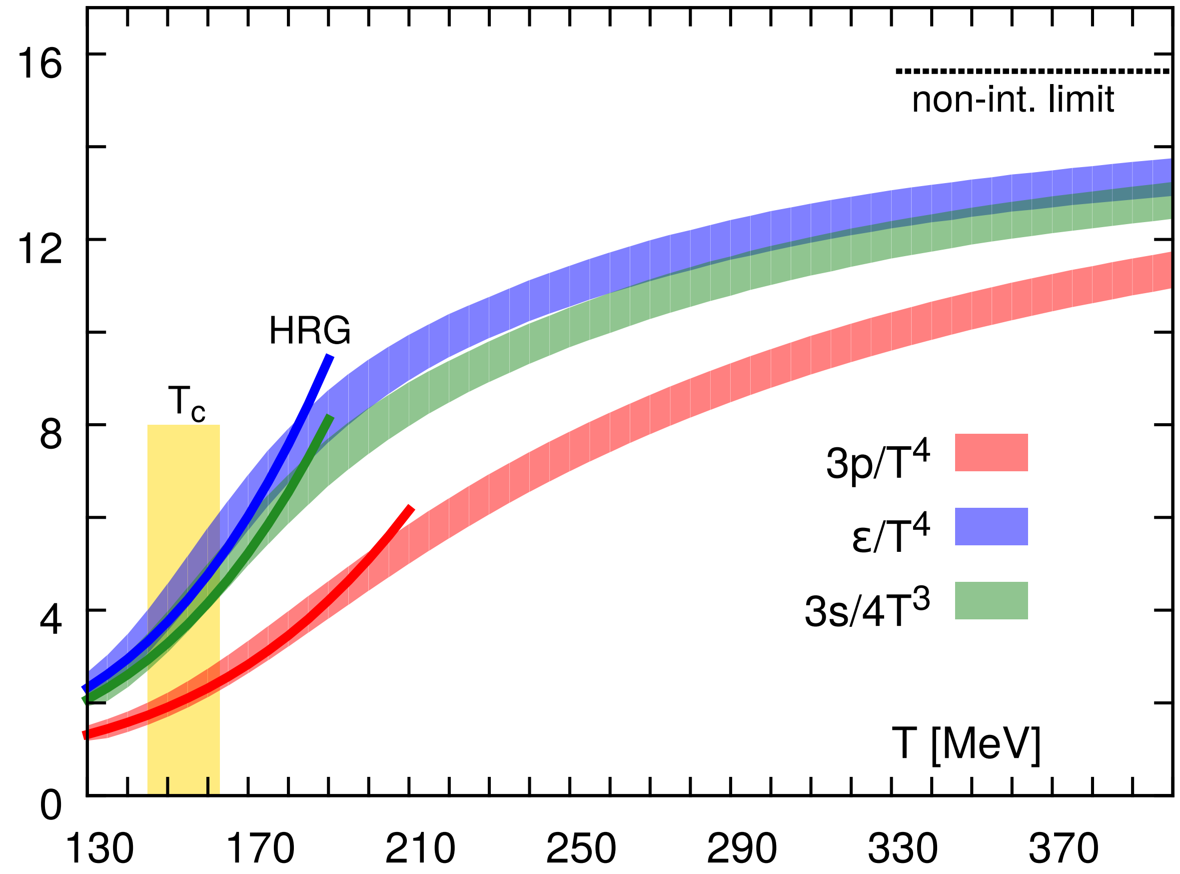
- energy density $\varepsilon \propto T^4$
- pressure $p = \frac{1}{3}\varepsilon \propto T^4$
- entropy density $s \propto T^3$

All of them are proportional to the number of degrees of freedom (for non-interacting gas).

Usually all temperatures measured in MeV. (k_B=1)

QCD Thermodynamics

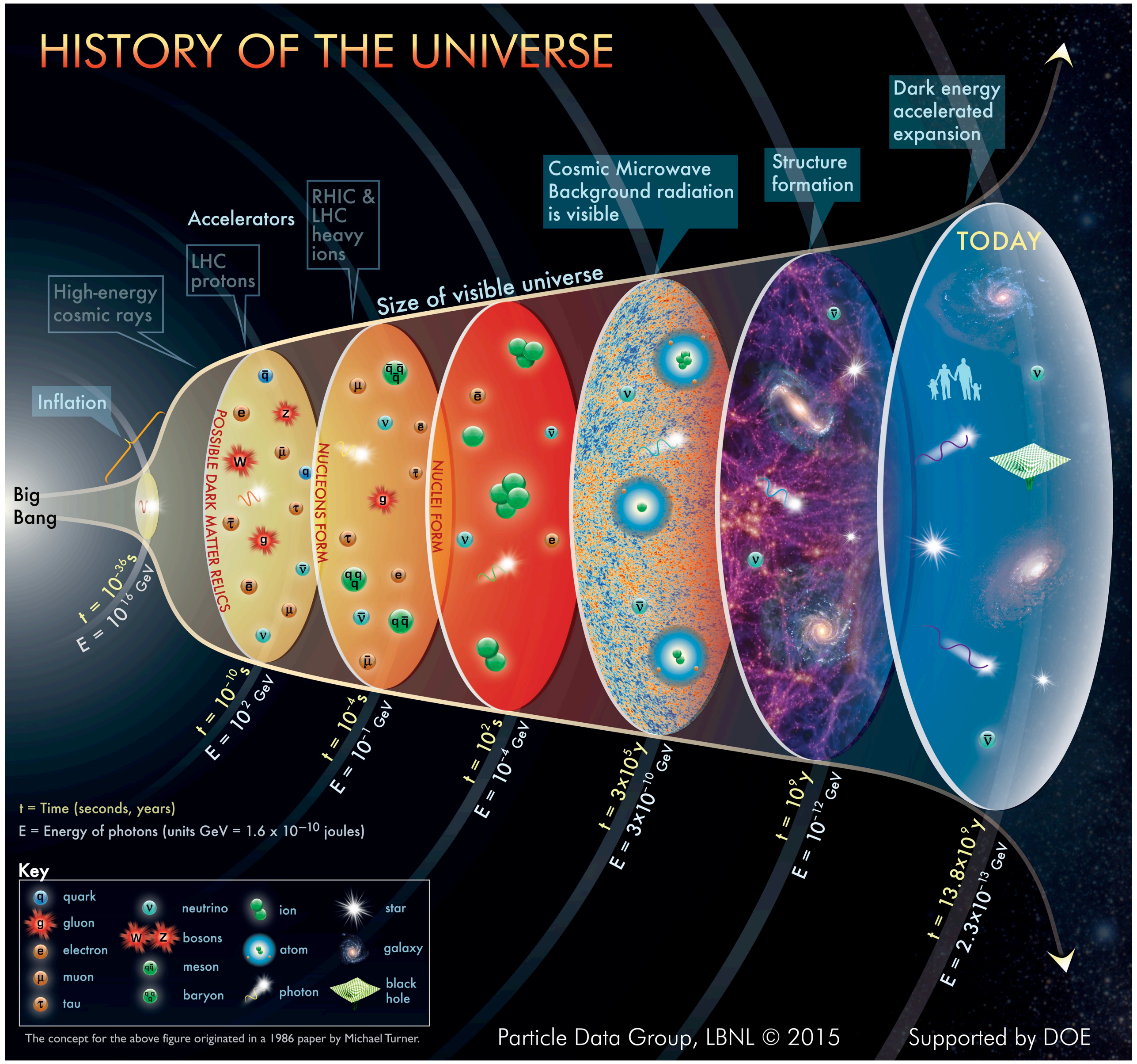
These quantities can be calculated in lattice QCD.



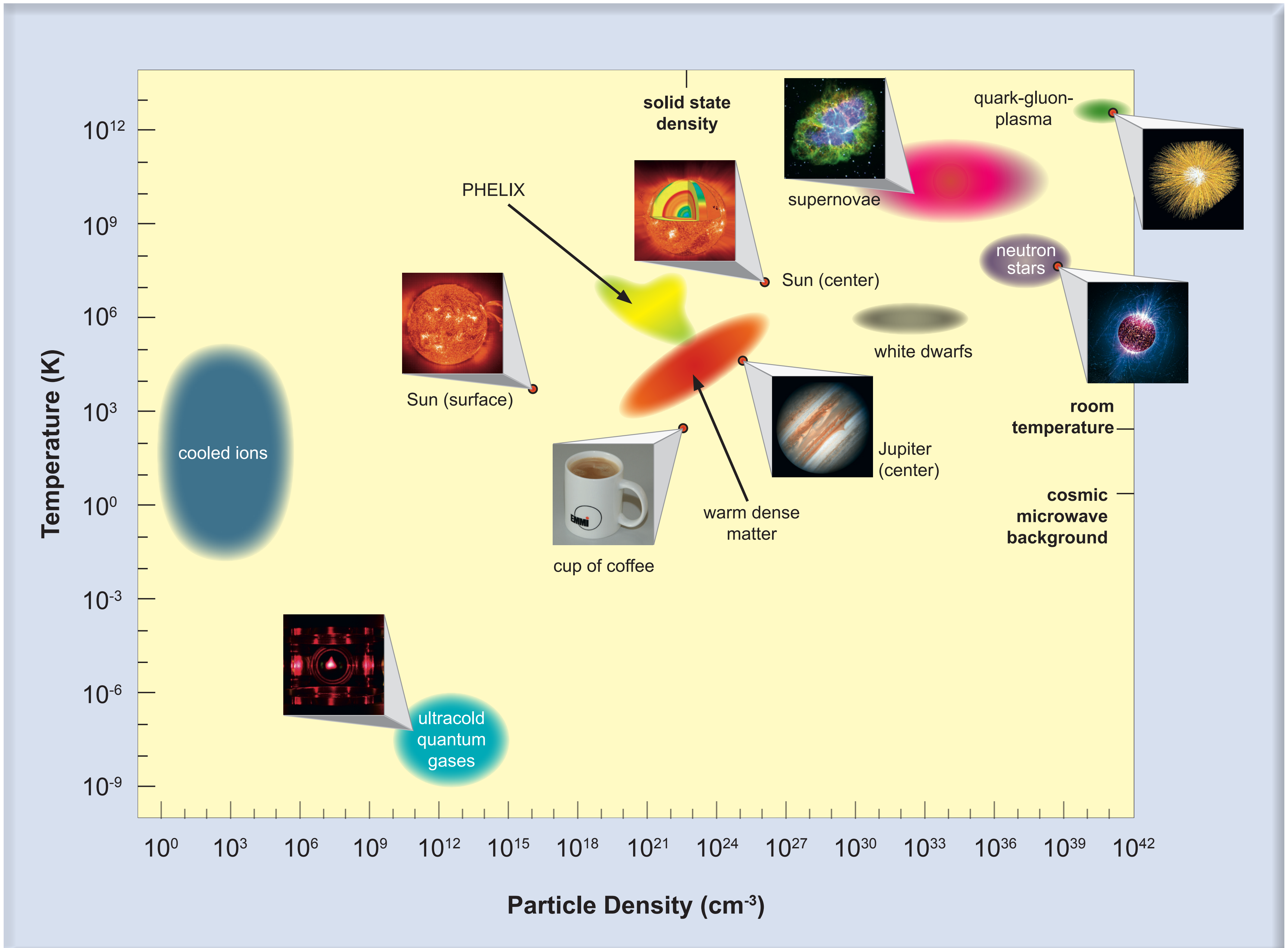
Strong rise at ~155 MeV indicates transition from hadrons to quarks and gluons as d.o.f.

QGP in History of the Universe

QGP should have existed until a few microseconds after the big bang.

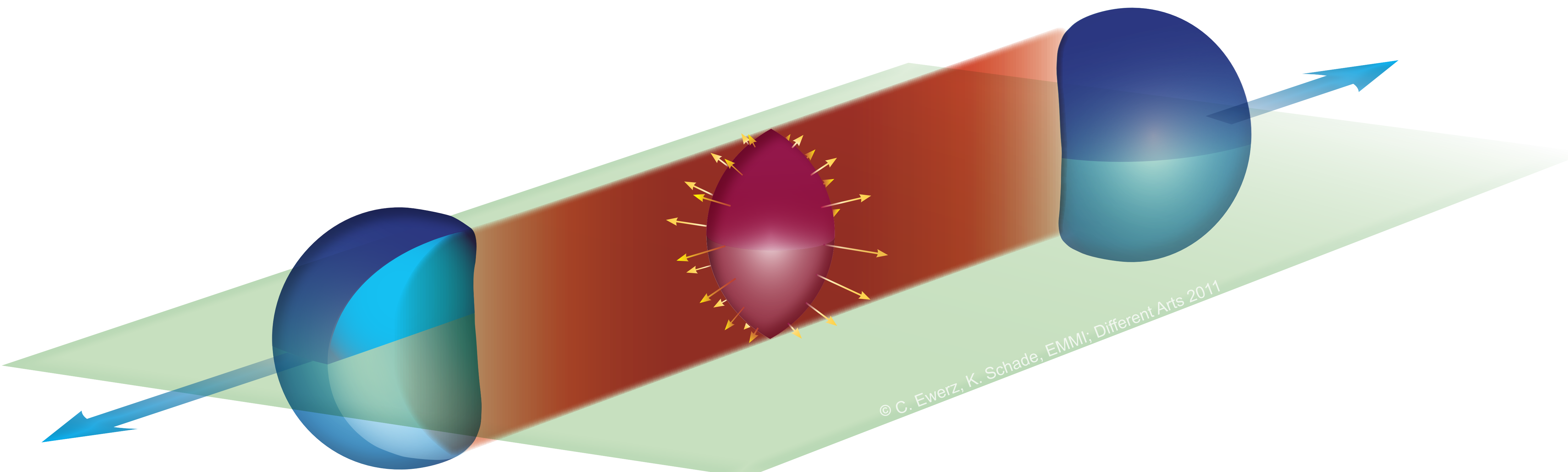


Temperature Scales



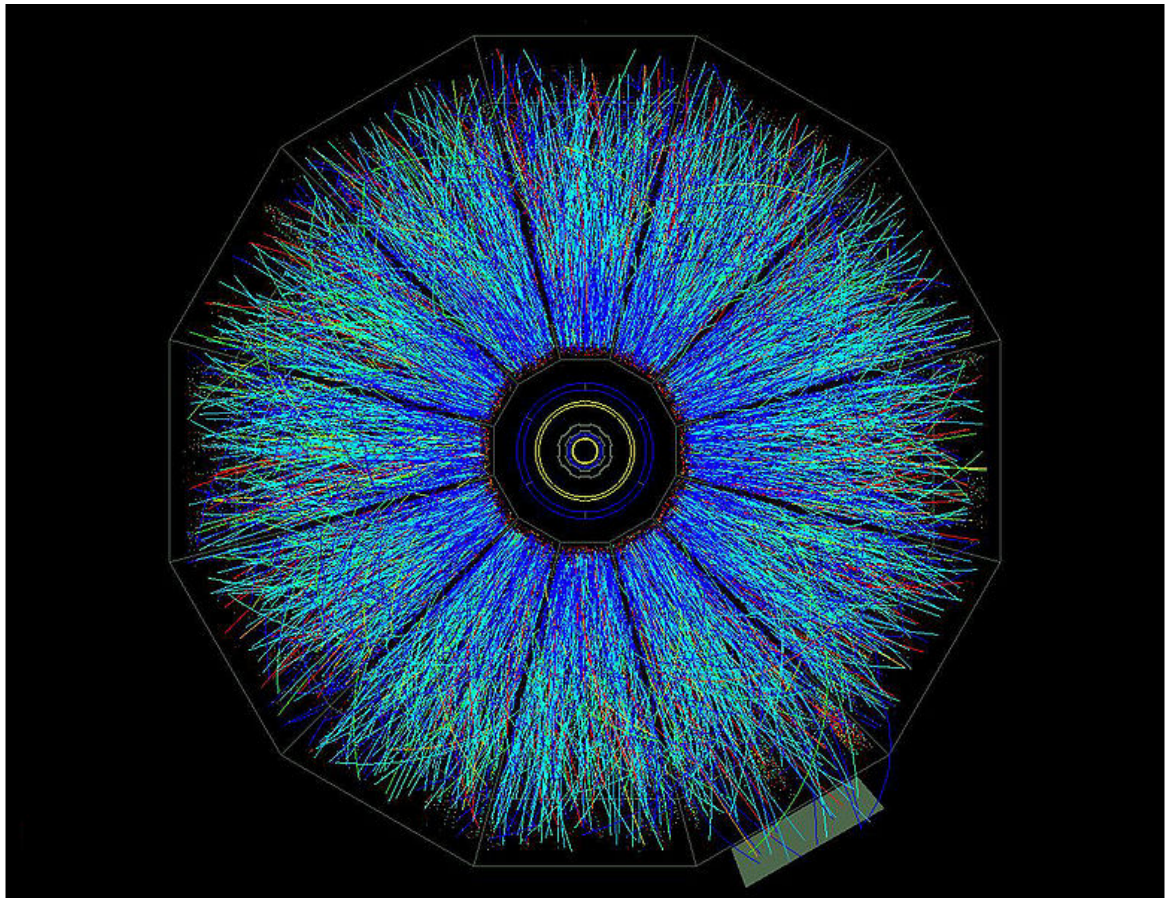
QGP in Heavy-Ion Collisions

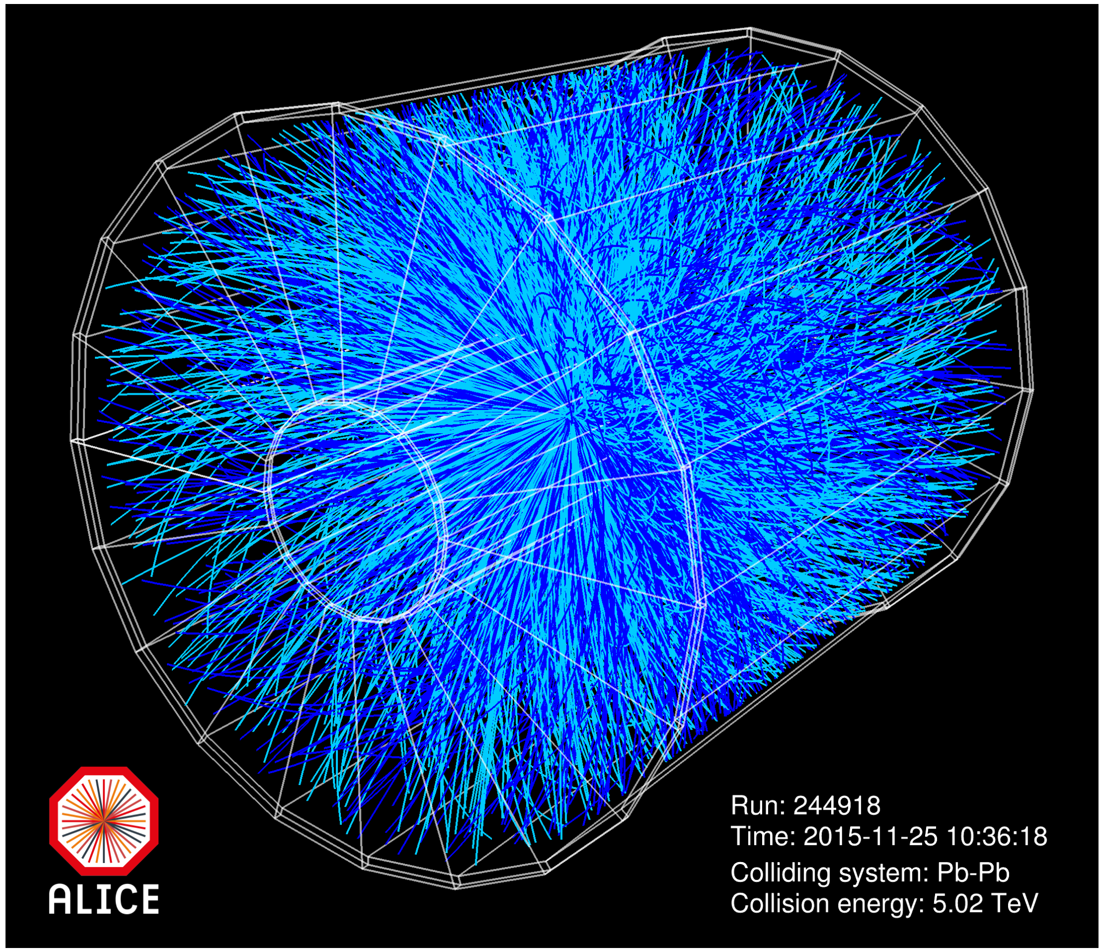
QGP can be created in heavy-ion collisions (HIC), typically of Au or Pb nuclei, for about 10^{-22} sec.



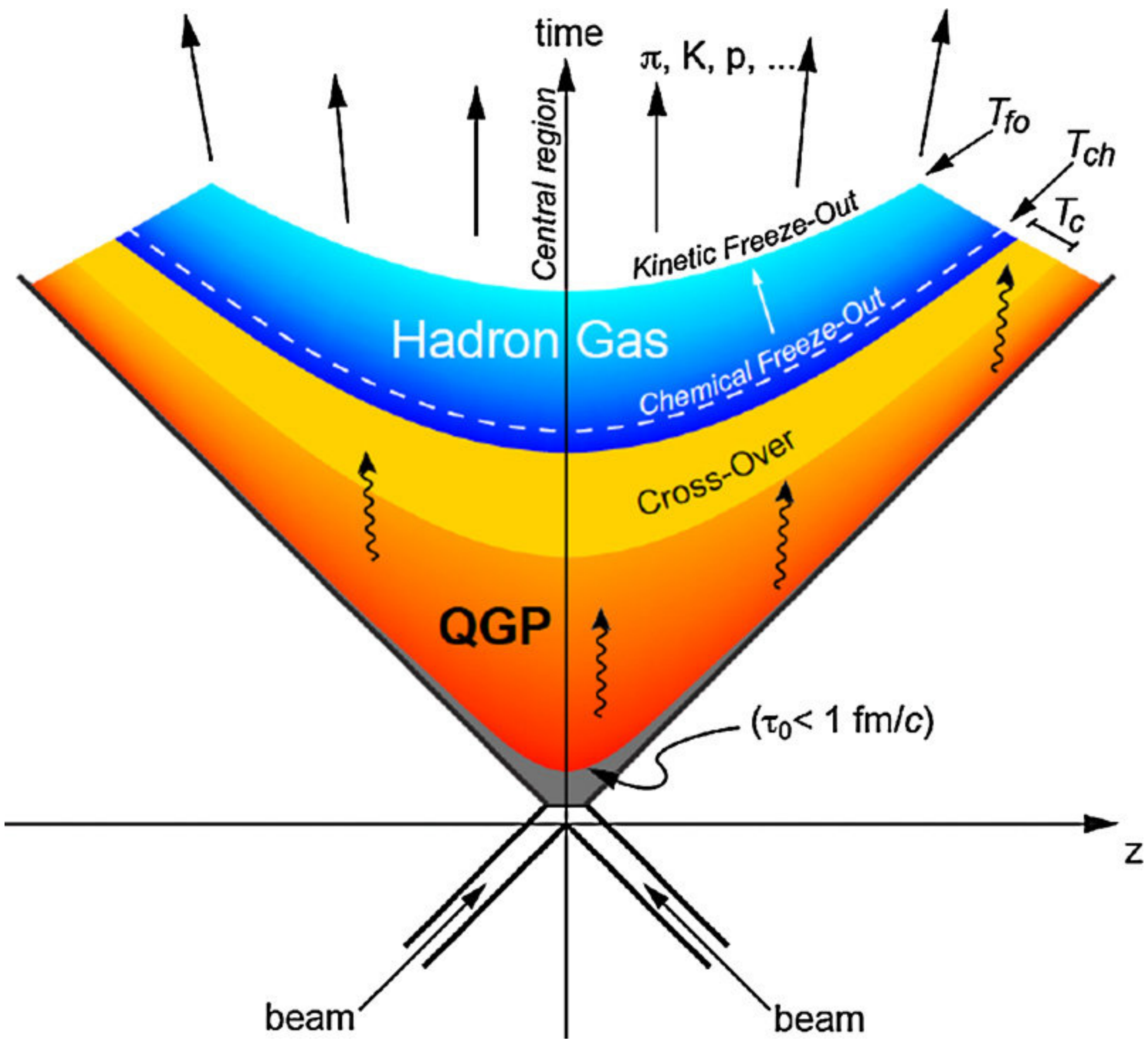
QGP in Heavy-Ion Collisions

Such collisions create several thousands of particles (hadrons).





Space-time Picture of HIC



Theoretical description of fireball evolution requires models / simulations.

QCD Phase Transition Temperature

Phase transition temperature is found to be

T_c = 156.5 MeV

QGP is Perfect Liquid

The QGP created in heavy-ion collisions is actually not a gas but a liquid - even a perfect liquid.

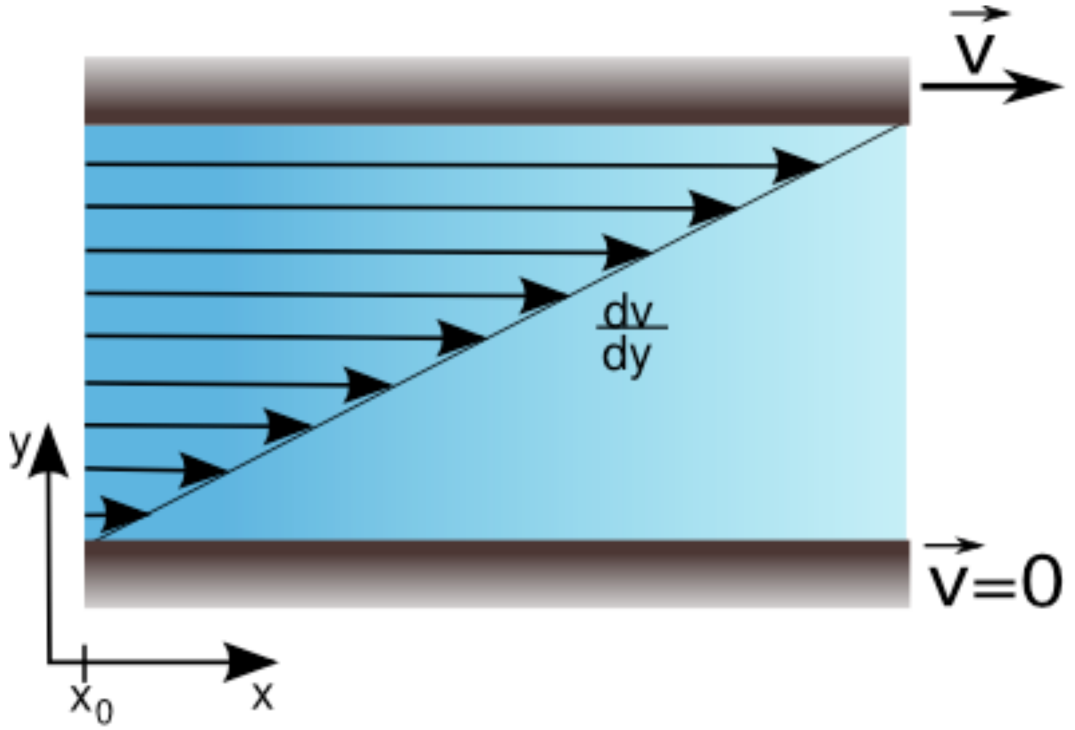
It has the lowest specific viscosity of all known substances (with one exception), ~ 0.2.

N.B.: viscosity of QGP is larger than that of stone, but also number of d.o.f. is huge.

Specific Viscosity

shear viscosity:

$$F = \eta A \frac{dv}{dy}$$

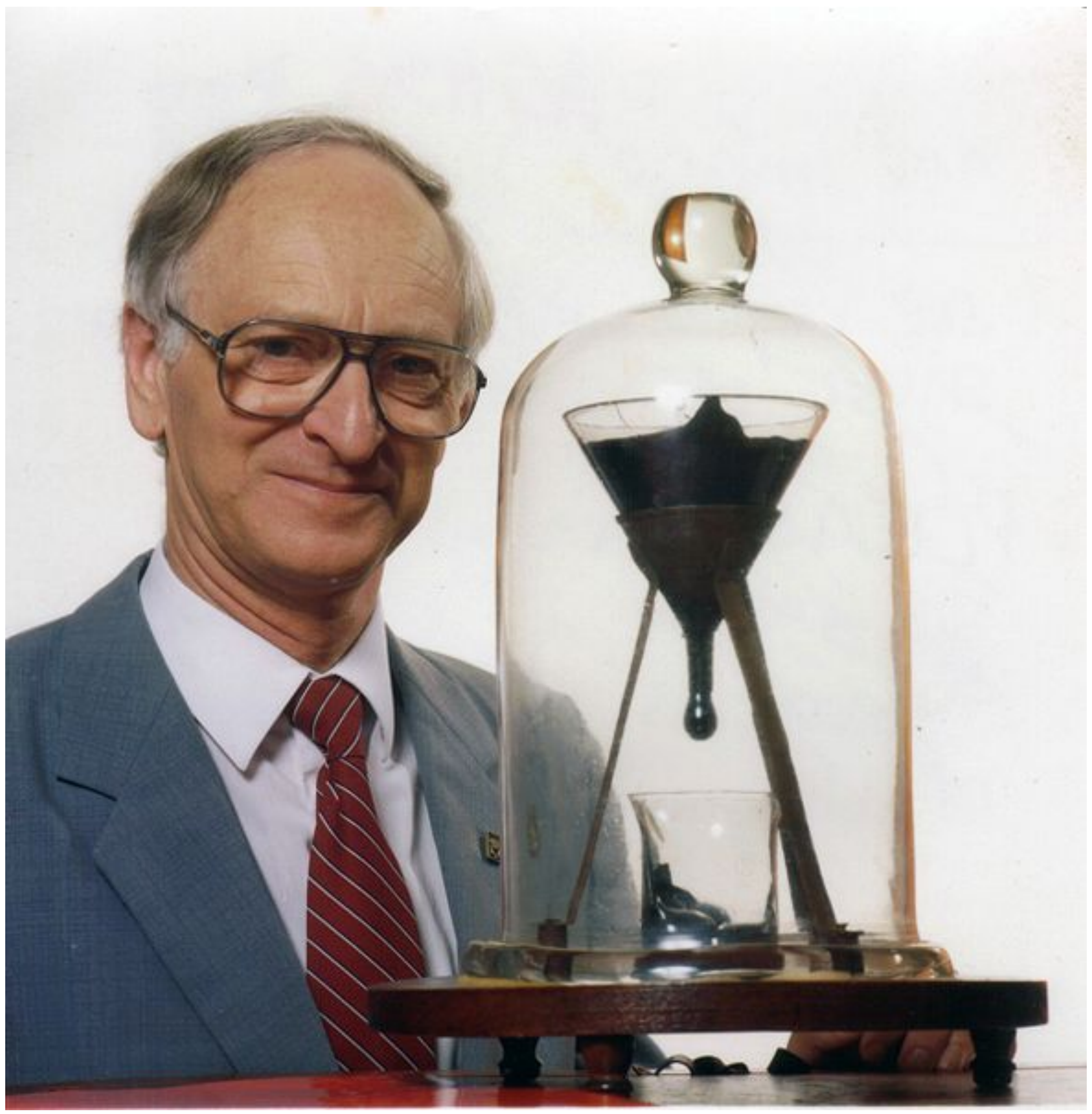


specific viscosity:

divide by entropy density (~ number of d.o.f.)

$$\frac{\eta}{s}$$

Large Viscosity: Pitch



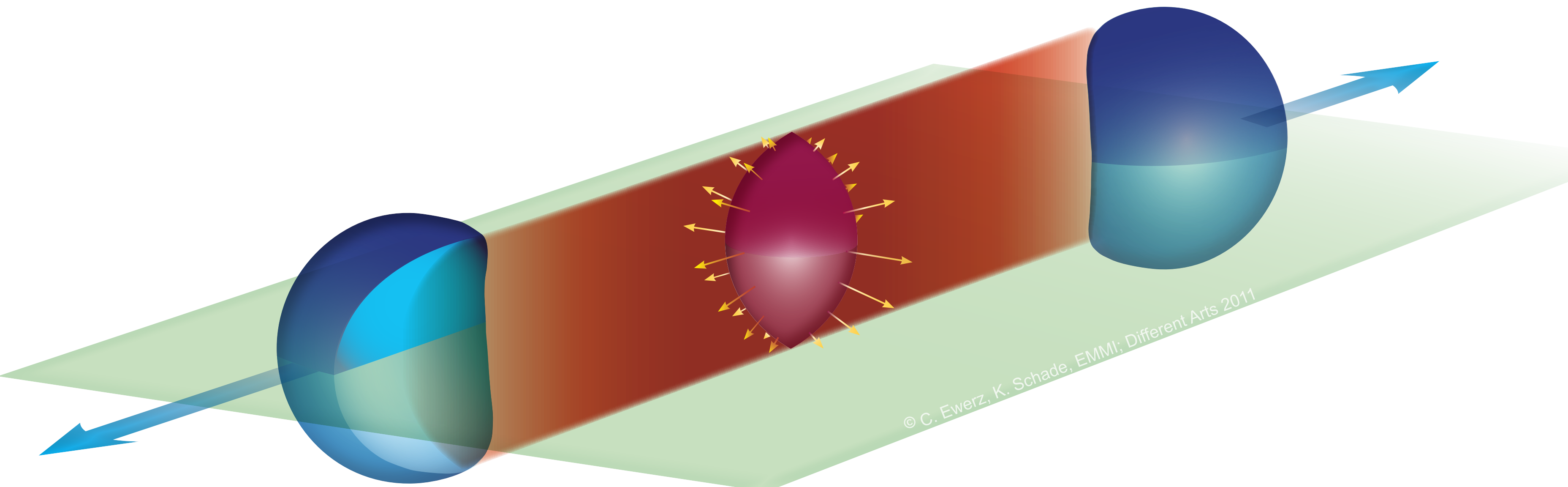
U Queensland

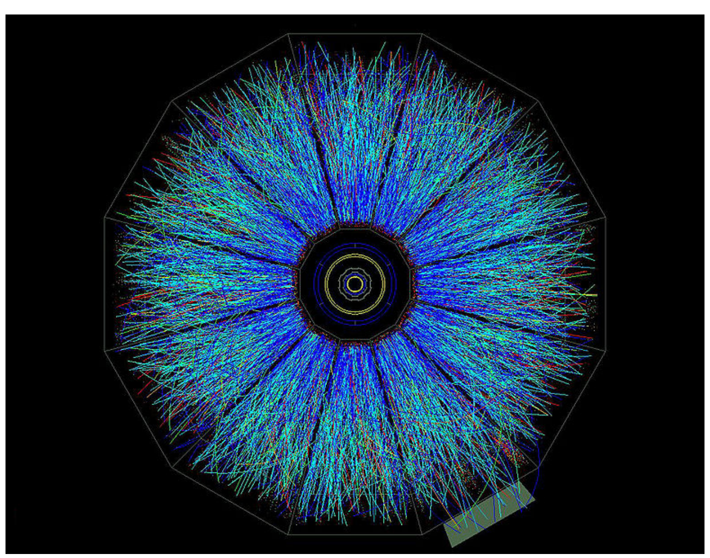
longest-running experiment in physics (1927 -)

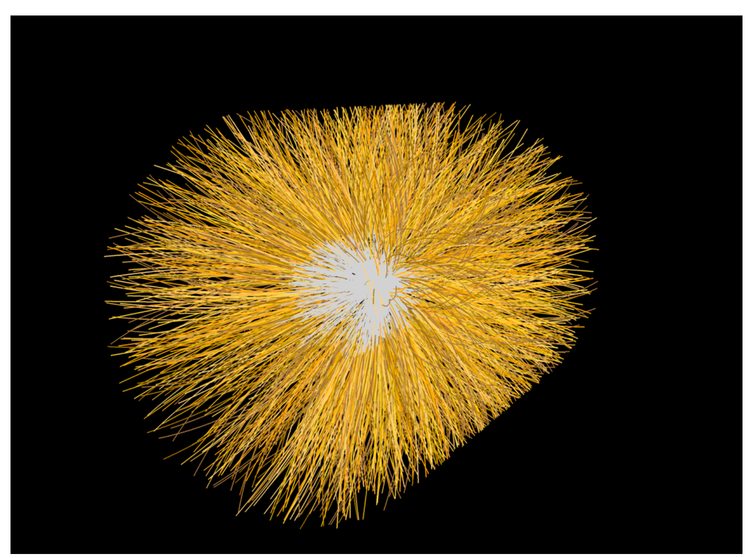
9 drops so far

Specific Viscosity and Expansion

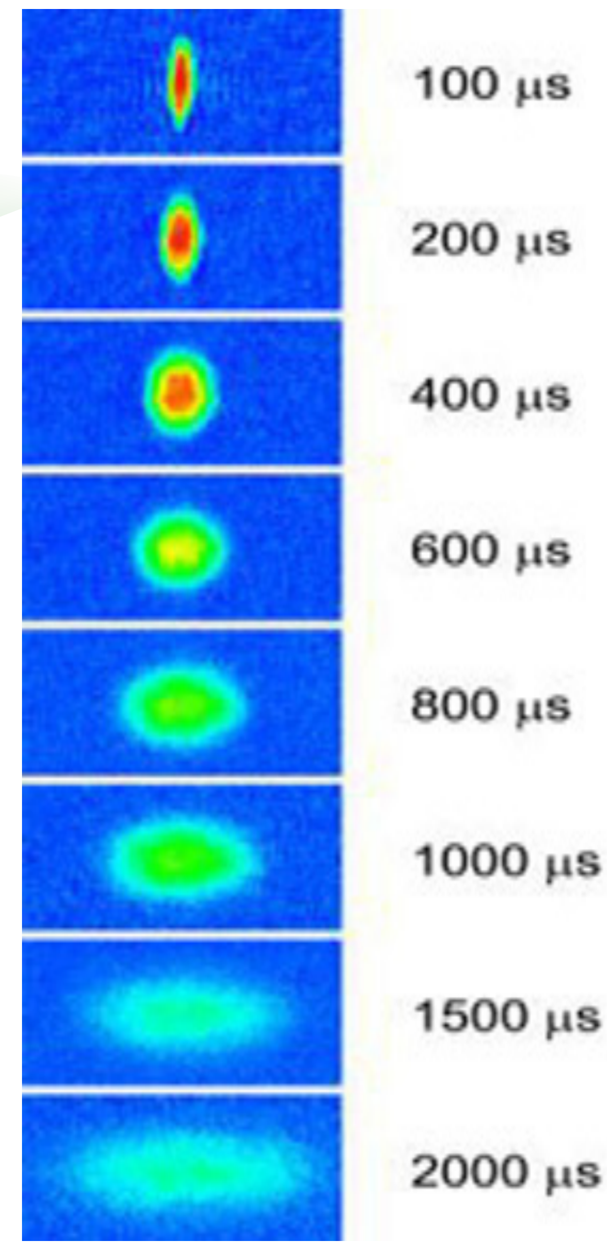
quark-gluon plasma



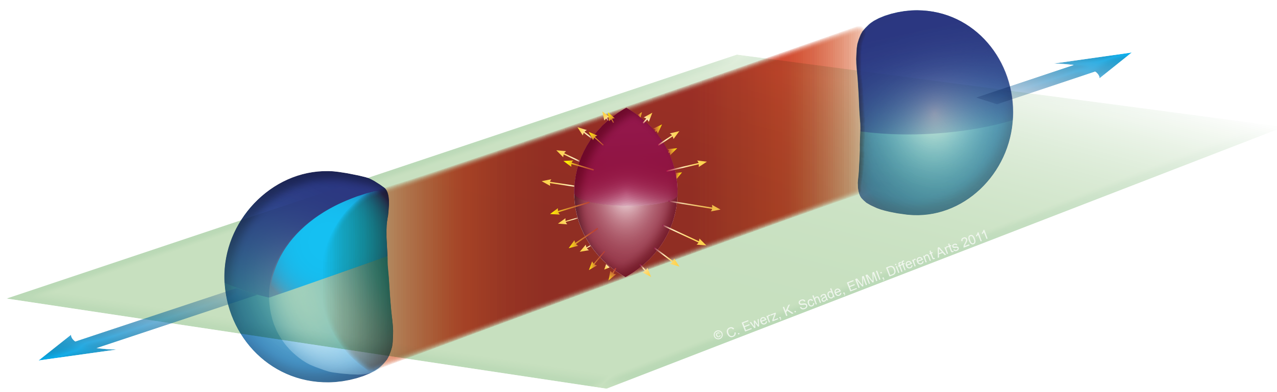


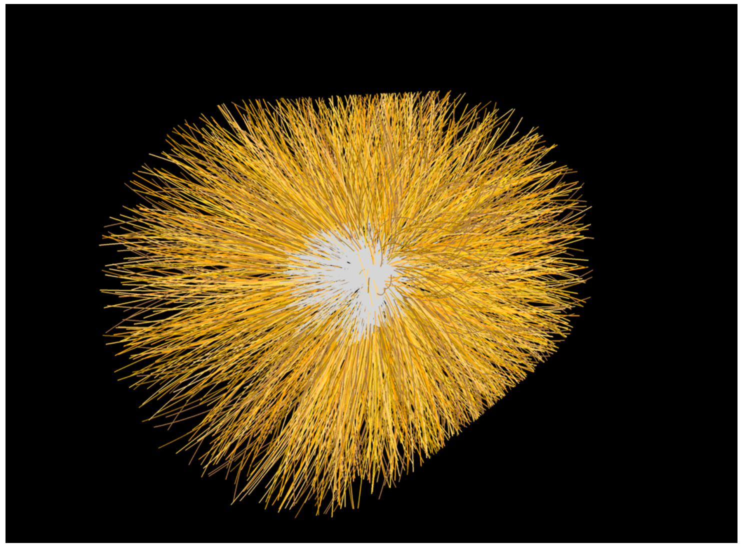


cold quantum gas

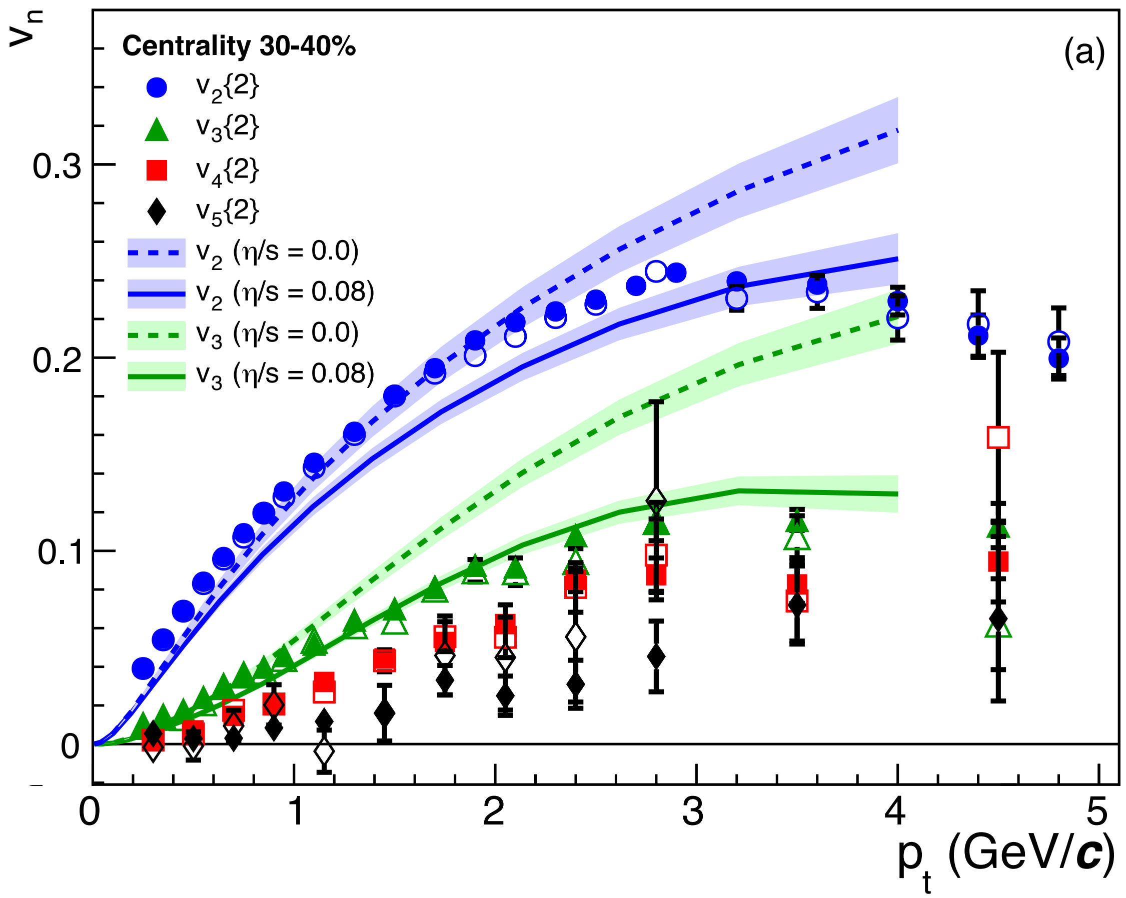


Elliptic Flow





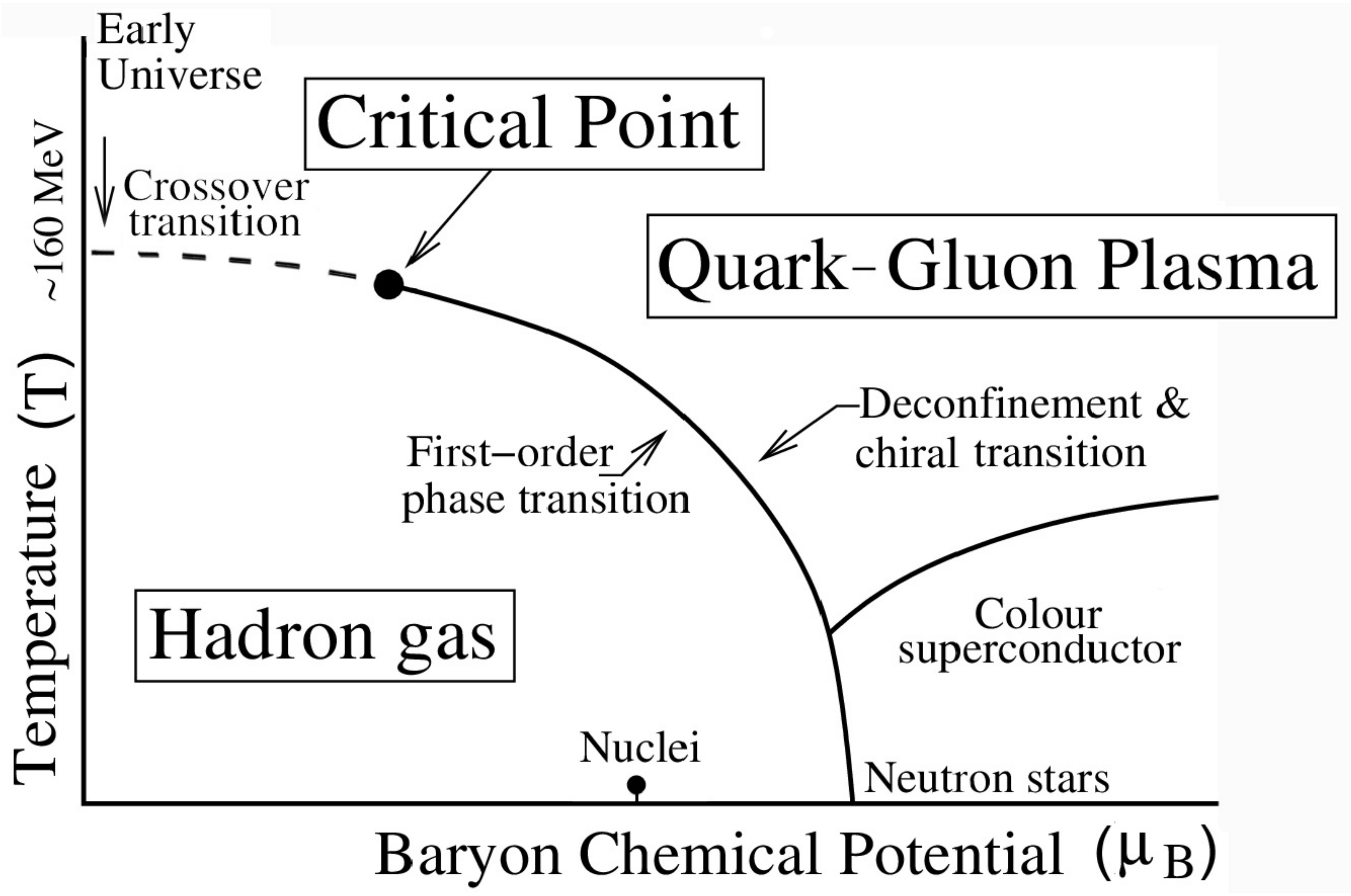
$$p_0 \frac{dN}{d^3p}\bigg|_{p_z=0} = v_0(p_T)\Big(1 + 2v_1(p_T)\cos(\phi - \Psi_1) + 2v_2(p_T)\cos(2\phi - \Psi_2) + \ldots\Big)$$



ALICE

Phase Diagram of QCD

Expected and partly confirmed phase diagram:



corresp. to net baryon density

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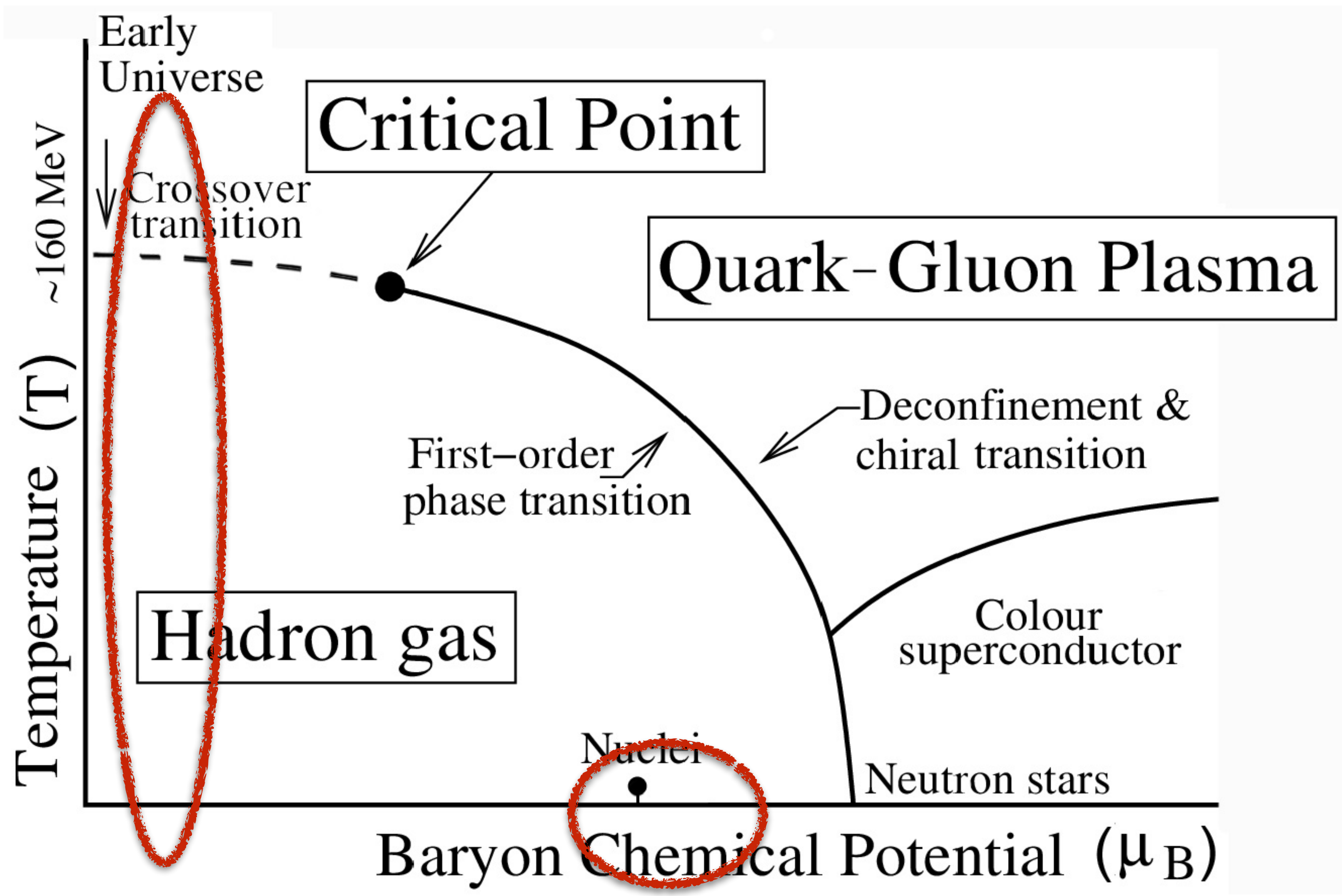

corresp. to net baryon density

Theoretical Difficulty of Finite Density

Finite chemical potential is not accessible for lattice QCD calculations due to sign problem: fermion determinant becomes complex, thus action is strongly oscillating and cannot be calculated by Monte Carlo methods.