Quantum phenomena at medium temperatures of 10^{13} K: QCD matter in relativistic heavy ion collisions

Quantum Physics at Low Temperatures
Lammi, 8 Jan 2004

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The point my title wants to make is that:

general principles of quantum physics and thermodynamics work as well at 1 K and at

$$10^{12} \text{ K} = 100 \text{ MeV}$$

and, in fact, up to the Planck scale (well, one thinks they work) 10^{32} K, only the active degrees of freedom change.

Ultimately one wants gravity (massless spin 2 particles).
Then a deep conceptual problem arises: thermodynamic limit ($V \to \infty$) and gravity are incompatible

Jeans instability

I will mainly discuss QCD, its two phases (hadron gas, quark-gluon plasma phase) and their experimental observation.

QCD at $T = 0$ and finite T

Degrees of freedom:

8 coloured massless gluons: $A_\mu^a(t, \mathbf{x})$

N$_f \times$ 3 colours of massless quarks: $\psi_f(t, \mathbf{x})$

$$\mathcal{L}_{\text{QCD}} = \frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a + \sum_{f=u,d,.} \bar{\psi}_f \gamma_\mu (\partial_\mu - igA_\mu)\psi_f$$

1972

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g f^{abc} A_\mu^b A_\nu^c$$

$$\langle \text{operator} \rangle =$$
$$\frac{1}{Z} \int \mathcal{D}A_\mu^a \, \mathcal{D}\psi_f \text{ operator } \exp[i \int d^d x \mathcal{L}_{\text{QCD}}]$$

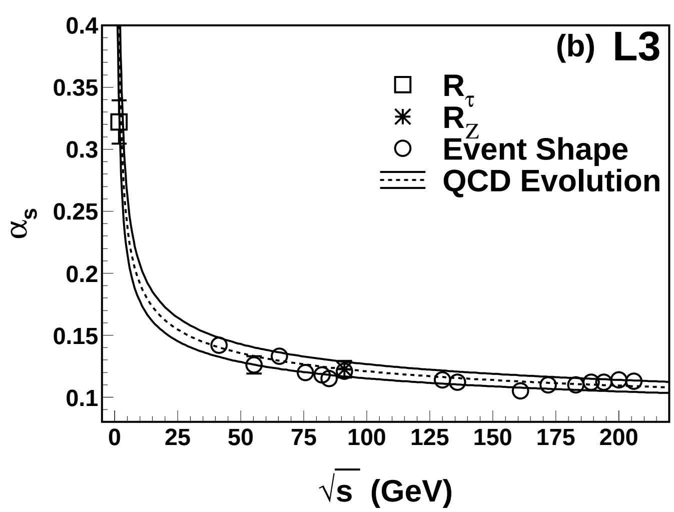
Local $\partial A \cdot A \times A$ and $A \cdot A \cdot A \cdot A$ interactions!

Parameters of QCD:

- Number of colours $N_c = 3$ (symmetry group local SU(N_c))
- Coupling constant g; classically dimensionless (dim=$\hbar$=1)
- Number of quark flavours N_f. To a good approximation u, d are massless, s = strange quark has a small mass. Massless QCD is "chirally symmetric"

Dimensional transmutation, renormalisation necessarily brings in a scale, asymptotic freedom:

$$g^2(Q) \approx \frac{\text{const}}{\log(Q/\Lambda_{\text{QCD}})}$$



Well defined quantum field theory with continuum limit under control! (large energy $\Rightarrow$ small distance $\Rightarrow$ small coupling)

Mystery of quark masses:

QCD with $N_f = 0, 1, 2, 3, ...$ zero mass quarks is a perfectly well defined theory (QCD's...are...theories).

However, quarks have masses! A quark mass is not a physical (renormalisation scheme independent) quantity: it runs like $g^2(\mu)$.

Reason: confinement.

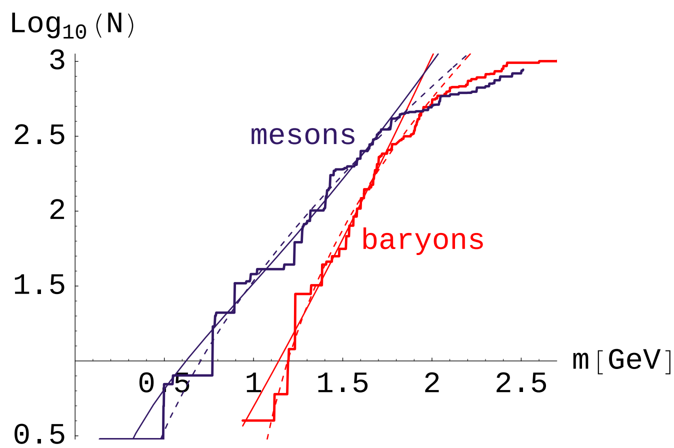
- Light quarks: $m_u(\mu) = 4$ MeV, $m_d(\mu) = 7$ MeV, $m_s \approx 100$ MeV (”light” means relative to $\Lambda_{\rm QCD} \approx 200$ MeV =1/fm)
- Heavy quarks, $m_c \approx 1.5$, $m_b \approx 5$, $m_t \approx 175$ GeV

Spectrum of states can now (in principle, to some extent in practice with lattice Monte Carlo) be computed: π, p, n, K, ...

Then one can also heat up the system $\Rightarrow$ hadron gas.

The highlight: exponential mass spectrum

Today there are 3182 light-flavour (u,d,s) states, plot number of mesonic and baryonic states with mass $< m$:



Exponential spectrum $\rho(E) \sim \exp(bE),\ b \approx 1/m_\pi$ is seen over a range of $m = E$! This would produce a singularity at $T = 1/b \approx m_\pi \approx 150$ MeV in thermodynamics:

$$Z = \exp(-F/T) = \int dE \rho(E) \exp(-E/T).$$

This "Hagedorn temperature" was (1965) a 1st indication of a QCD phase transition from hadron gas to something, later 1975- identified as quark-gluon plasma.

If QCD is so well known, its partition function with all singularities should be calculable! And it is: ”just evaluate”

$$Z = \mathrm{Tr}\exp[-H/T] = \exp[p(T)V/T] =$$

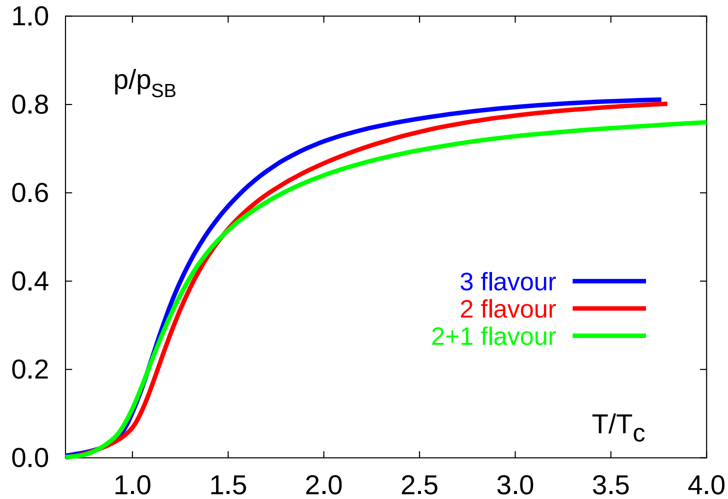
$$\int \mathcal{D}A_\mu^a(\tau,\mathbf{x})\mathcal{D}\bar{\psi}\mathcal{D}\psi\, e^{-\int_0^{1/T} d\tau \int d^3x\, \mathcal{L}[A_\mu^a,\bar{\psi},\psi]}$$

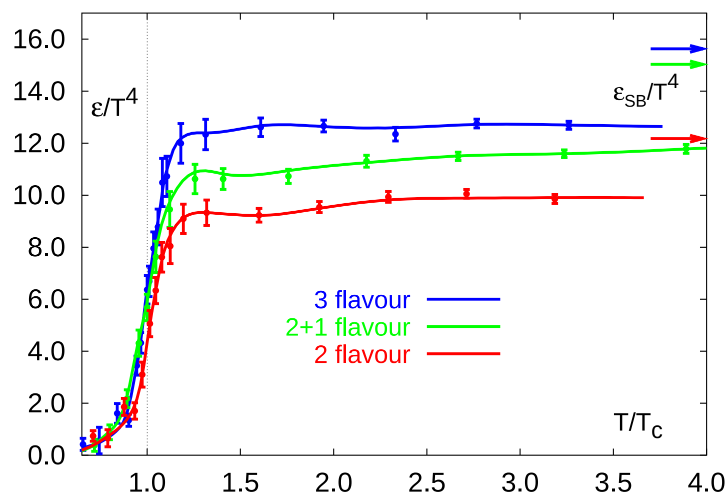
In the most interesting phase transition region at $T = T_c \approx 150$ MeV the computation can only be done with numerical lattice Monte Carlo techniques.

The quark ψ’s are Grassmann variables, must be analytically integrated over $\Rightarrow N^4 \times N^4$ gigantic determinants, highly non-trivial computationally&algorithmically; no final answer

At $T \gg T_c$ coupling is small and perturbation theory can be applied – to an extent.

There is a phase transition (Collins-Perry 1975; lattice data from Bielefeld):





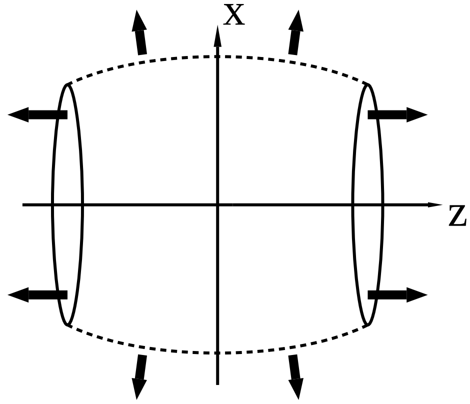
Scaled by ideal gas ($g = 0$):

$$p_{\rm SB}(T) = (16 + \frac{21}{2} N_f) \frac{\pi^2}{90} T^4 .$$

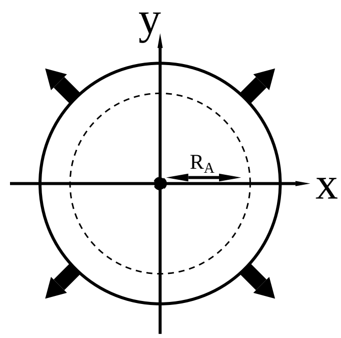
There is a definite *quantitative* prediction
(btw, $p(T_c) \approx 10^{35}$ Pa); can one ever verify it?

Collide two $A \sim 200$ nuclei at $\gamma = 1/\sqrt{1-v^2} = 100$:

Transverse size 10 fm, expands transv. & longit'lly:



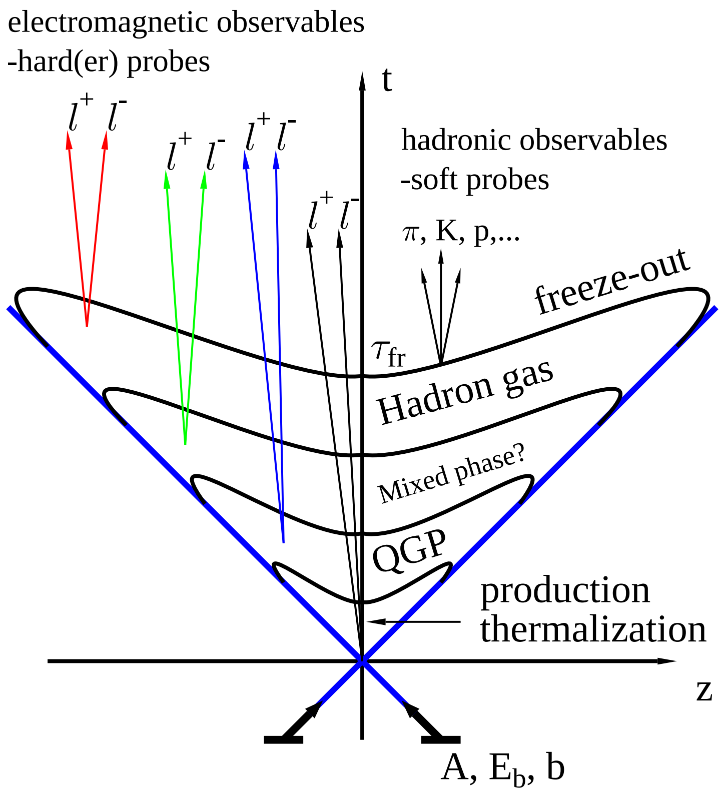
Transverse expansion:



Observe (within $\pm 45^o$ from 90^o) $\sim$ 1000 particles ($\pi, K, p, \gamma, e^{\pm}, \mu^{\pm}$). Prove that

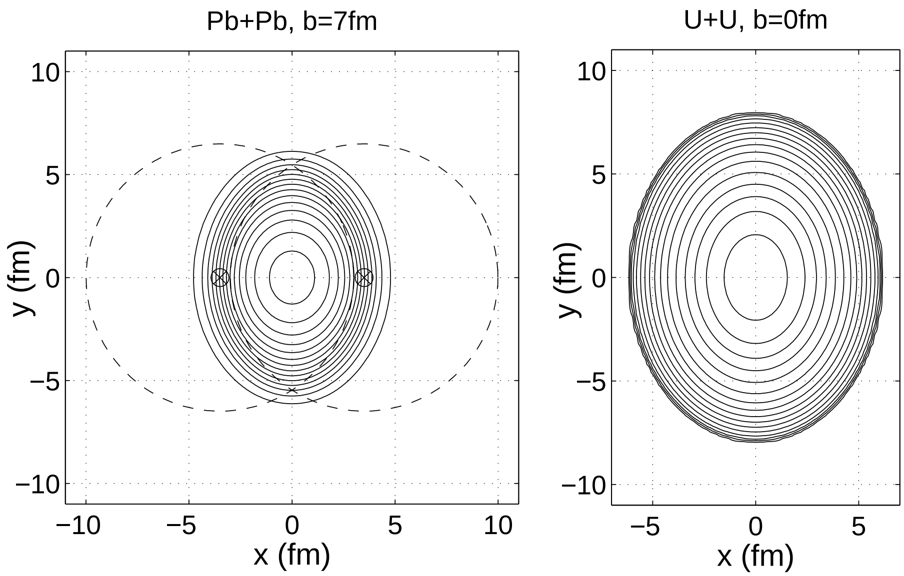
- you see bulk flow of QCD matter
- it absorps fast quarks
- you can tune away the effect by changing energy, A, impact parameter

Time dependence of the evolution of the system; transversally in the center, $x = y = 0$:



1. Prove you see collective flow:

Choose experimentally a noncentral collision:



Idea: measure azimuthal asymmetry, v_2 in

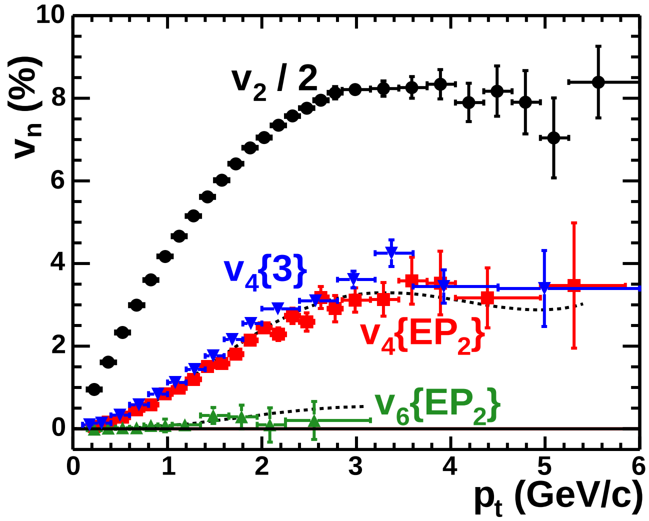
$$\frac{dN}{d\phi} = 1 + 2v_2 \cos(2\phi)$$

- free streaming, nonthermal $\Rightarrow v_2 = 0$.
- thermal, pressure exists, $\nabla_x p > \nabla_y p$, converts spatial asymmetry to ϕ asymmetry.

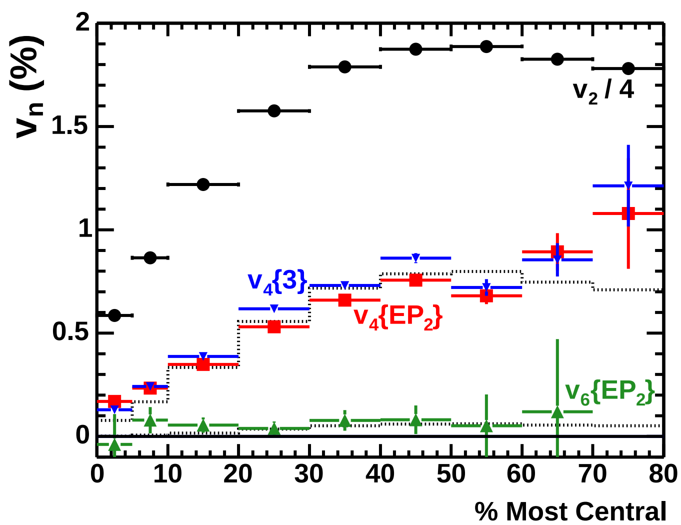
Measure v_2 as a function of impact parameter; find agreement with hydrodynamic locally thermal expansion.

Out of mountains of data just a couple of plots:

Overall magnitude of effect is $1 + 0.3 \cos 2\phi$:

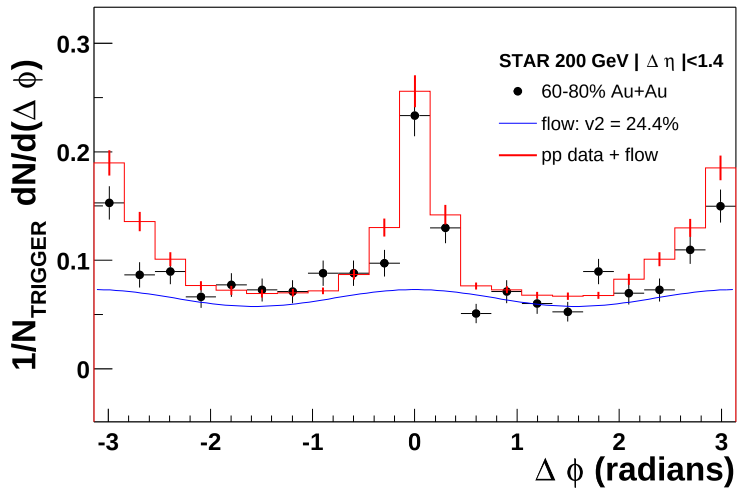


Effect only for non-central collisions:

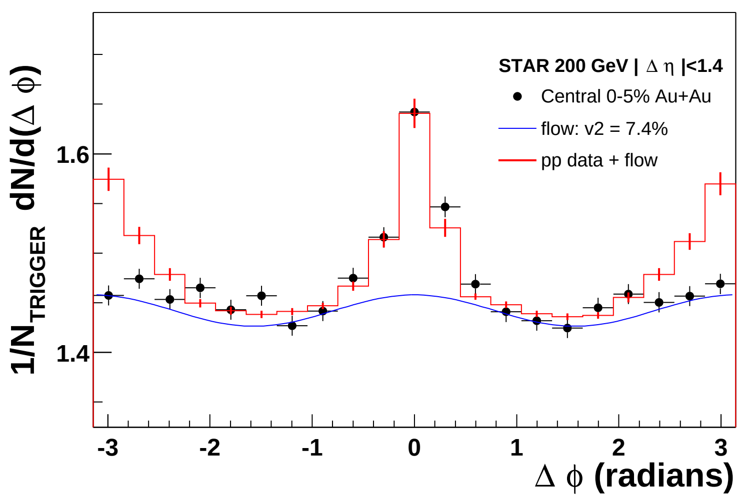


2. Prove you see quark absorption:

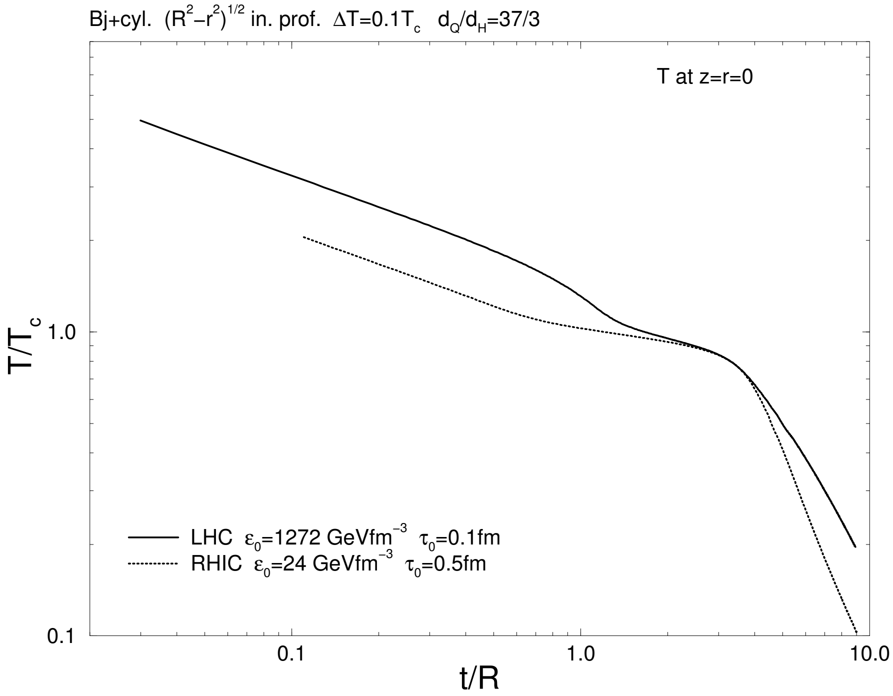
Thin system: see sth (at 0) $\Rightarrow$ see back-to-back jet ($\pm\pi$)

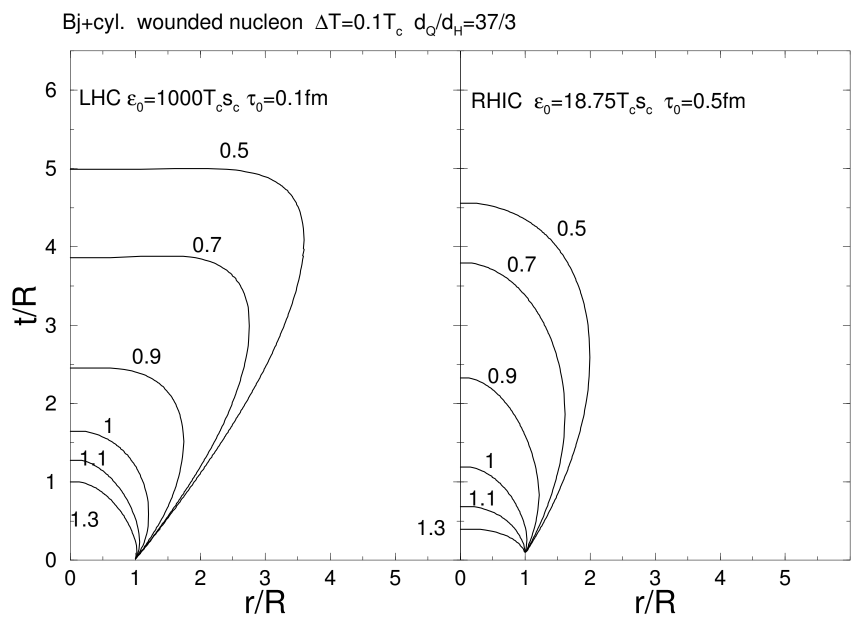


Thick system: see sth (at 0) $\Rightarrow$ see nothing back-to-back ($\pm\pi$)



Temperature as a function of time; radial expansion





Party line:

Transient droplets of QCD matter have been seen at RHIC/BNL,

- created in the quark-gluon plasma phase at $T \approx$ 500 MeV $\approx$ 5$\cdot$ 10^{12}K
- in kinetic thermal equilibrium, chemical equilibration (quarks/gluons) is unknown
- expands, undergoes a phase transition to hadron gas at $T \approx$ 150 MeV
- hadron gas decouples ($\sim$ cosmic ”recombination”) to free hadrons at $\sim$ 120 MeV

Now continue

- to understand theoretically what is happening; why so good a thermalisation, are there some simple effective DOFs?
- to plan for ALICE/LHC experiments at CERN with 30$\times$ RHIC energy

Cosmology

In the big bang scenario, the QCD phase transition for sure took place when time $\sim 10\,\mu$s, horizon ~ 10 km. But

- while we have seen to the T ~3000 K, horizon $\sim$ 100000 km universe (CBR, Cobe, WMAP,etc)
- while the BB scenario has been verified in quantitative detail up to T=MeV=10^{10}K, time ~1 s (light element, He^4, Li, d, nucleosynthesis)
- we have NO qualitative let alone quantitative evidence of the cosmological QCD phase transition - too weak for that
- in principle, we might see to the QCD transition using gravitational radiation of frequency 1/year!

In present BB scenarios the thermal universe started with reheating to some $T \sim 10^{10\ldots15}$ GeV after inflation.

Before that the actors were so far unknown DOFs containing gravity with unknown interactions, obeying laws of QM.

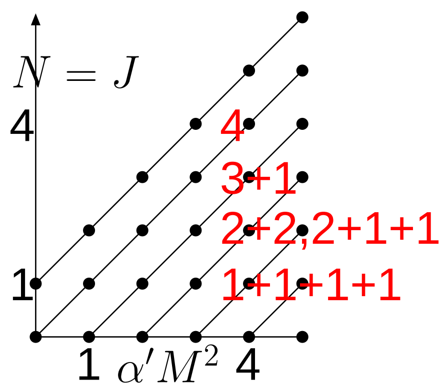
Thermodynamics at the Planck scale,

$$T = \sqrt{\frac{\hbar c^5}{G}} \sim 10^{19}\,\mathrm{GeV} \sim 10^{32}\,\mathrm{K?}$$

String theories, thermodynamics at 10^{32} GeV?

In the 60s, before QCD, strong interaction theory developed via Regge poles and duality to dual models, which then developed into string theories for everything.

Remarkably, in 1969 a count (Fubini-Veneziano) of the states of the dual model gave an exponential density of states:



The exponential density of states follows from the large degeneracy: the same $M^2 = (N-1)/\alpha'$ is obtained by exciting the string in $\sim \exp(2\pi\sqrt{N/6})$ different modes (number of partitions of an integer as a sum of integers, D types)

$$P_{ND} \to \frac{1}{\sqrt{2}}\left(\frac{D}{24}\right)^{(D+1)/4}\frac{1}{N^{(D+3)/4}}\exp\left[2\pi\sqrt{\frac{DN}{6}}\right]$$

Harmonic oscillator: $E \sim N$, density $\sim e^{b\sqrt{E}}$

Dual models: $M^2 \sim N$, $\Rightarrow$ density $\sim e^{bE}$.

String theories have even a massless state at J=2: the graviton!

String theories have an exponential density of states

$\Rightarrow$ they have a singularity in thermodynamics or a phase transition but to what? What is the true nature of the transition?

Open question

Reminder1: String theories contain gravity but gravity and thermodynamic limit (volume, time $\rightarrow \infty$) are not obviously compatible!

Reminder2: In QCD one knew the low T phase (”Hadron gas”) and the dofs of the high T phase were observed only later.

In string theories one does not even *know* the low T phase, let alone the high T one!

Conclude with some equations:

The dofs of a prototype string theory are $X_\mu(\sigma_1, \sigma_2)$ (σ_i are internal one time + one space coordinates, $\mu = 1, \dots d = 10, 26, ..$)

$$S = \frac{T}{2} \int d^2\sigma \sqrt{-h} h^{ab} g^{\mu\nu}(X) \partial_a X_\mu \partial_b X_\nu + ..$$

Only one parameter, the tension $T \equiv 1/(2\pi\alpha')$, getting from 10d to 4d brings more (compactification radii R).

Deceptively "simple", actually one does not even know the "background" X in which strings move. Maybe some remarkably physical one exists?

For $\alpha' \to 0$ mass of string excitations $\to \infty$ and one gets a field theory for zero-mass fields:

$$\int d^d x \sqrt{-G} e^{\phi} [R + (\partial\phi)^2 - \frac{1}{12} H^2 + ..]$$

One hopes to be able to produce the standard model in this way but so far no success. Key issue: is supersymmetry physical reality or mathematics? LHC!

Thermodynamics of string theories is a very actively studied topic today: what is the true ground state at $T = 0$? What is the high T phase? Topological field theory (Atick-Witten 1985)?

To make this empirical science we need particle physics experiments (LHC, CLIC,...)
and cosmological observations