Hagedorn, the dual resonance model, and strings: an old love affair

Gabriele Veneziano

COLLÈGE DE FRANCE 1530

CERN European Organization for Nuclear Research

La Sapienza, Rome

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Preamble

Shortly after the 1994 Conference in Divonne I met Hagedorn in a CERN corridor. He thanked me for my contribution and added something like:

"The Dual resonance model/string theory gives a microscopic explanation for the spectrum I obtained from my bootstrap argument.
It reminds me of what stat. mech. did to thermodynamics by providing a microscopic interpretation of entropy"

A surprising degeneracy

- My 1968 amplitude for 2->2 scattering has discrete poles at α's = N = J_{max}, identified with the maximal spin of the corresponding states.

- It was already known that each pole contained also lower spins all the way down to J = 0. The expected degeneracy was therefore $O(N^2)$.
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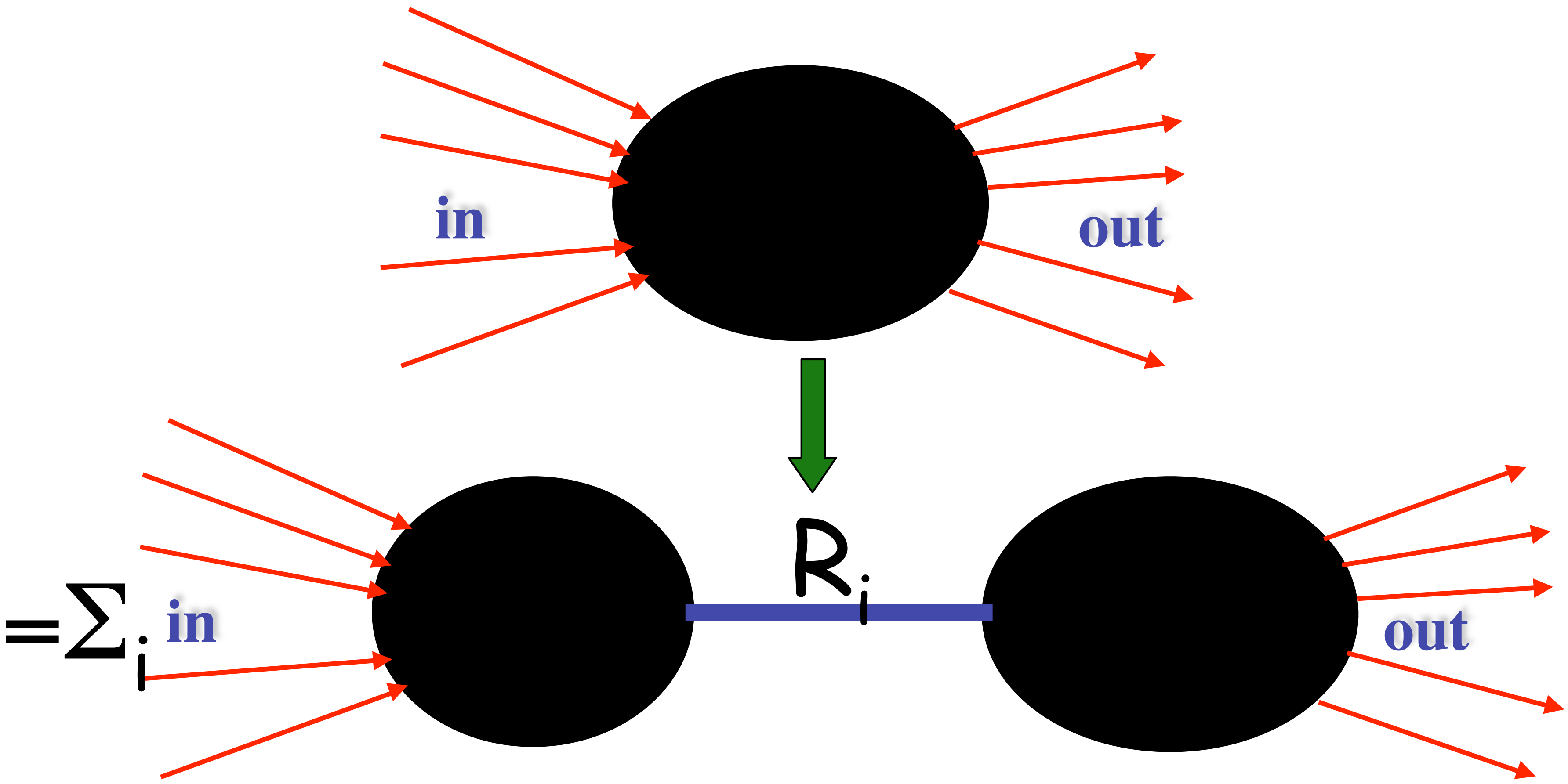
- However, in order to find out the real degeneracy one had to start with arbitrary initial and final states and ask the question:

How many terms are needed (in the sum over i) in order to have, for **all in and out** states,



- The result (FV, BM, 1969) turned out to be very surprising.

- The number of states grew much faster than expected, like $\exp(b\,M)$, with b a precise constant of order $(\alpha'/h)^{1/2}$.

- Although unexpected, this was just the behaviour postulated by Hagedorn a few years earlier (1965) from his hadronic bootstrap and also motivated on more phenomenological grounds (e.g. a Boltzmann factor exp(-E/T) in final particle spectra).
- Taken at face value, such a density of states leads to a limiting (maximal, Hagedorn) temperature T_H given by $T_H \sim (\alpha'/h)^{-1/2} \sim 150$ MeV.

But should we have been surprised?

- Perhaps no! Regge behaviour implies that, to exp.[al] accuracy, the imaginary part of the forward (or fixed partial wave) elastic amplitude is asymptotically constant.
- But by DHS duality, it is also given in terms of individual resonance contributions:

$$\mathrm{Im} A_{el} \simeq \frac{1}{E} \sum_{Res} \Gamma^R_{2b} = \sum_{Res} \frac{\Gamma^R_T}{E} B^R_{2b} \leq N(E) \cdot \bar{B}_{2b}$$

- Matching the two gives: $N(E) \geq \bar{B}_{2b}^{-1}$
- If B_{2b} exp.lly small, N(E) exp.[lly] large!

- What is surprising in DRM is not the density of states but the amount of degeneracy, hint of a large, yet to be understood symmetry.
- The FV-BM factorization procedure was cumbersome. It was soon replaced by a much more handy operator formalism (Fubini, Gordon, GV & Nambu)
- The operator formalism immediately suggested (Nambu, Susskind, Nielsen) the existence of an underlying string (although it took till the work by GGRT to find the precise connection)

- Within string theory the number of states can be interpreted as (D-2) units of entropy per string bit of length $l_s \sim (\alpha' h)^{1/2}$.
- The length of a string of mass M is $\alpha' M$ and thus the number of bits is:

$$S \sim (D-2)\frac{\alpha' M}{\sqrt{\alpha' \hbar}} = (D-2)\frac{\sqrt{\alpha'} M}{\sqrt{\hbar}} \equiv (D-2)\frac{M}{M_s}$$

With M_s the characteristic mass scale of quantum string theory $(\alpha'/h)^{-1/2}$

The QCD crisis

- Around 1972-73 both string theory and the Hagedorn limiting temperature underwent a “QCD crisis”
- String theory had phenomenological problems (massless particles, lack of hard constituents)
- The Hagedorn temperature was reinterpreted as a deconfining temperature.
- Yet QCD, in the large-N limit, should give some sort of tree-level string theory and I bet its spectrum should be Hagedorn/DRM/string like although probably without its huge degeneracy.

So far for the hadronic string

Revival

- After 10 years of deep sleep string theory made a smashing comeback in 1984 when Green and Schwarz vindicated an earlier idea (1974) of Sherk and Schwarz reinterpreting the old string theory as a theory of (among others) quantum gravity.
- Suddenly, the softness of string theory (and of Hagedorn's model) became a big plus making gravity (and all other interactions) not just renormalizable, but finite!

A second life for the Hagedorn temperature?

- Within the reinterpretation of string theory, the concept of limiting temperature should be applicable again to the real world albeit at a much higher (nearly Planckian) energy scale
- I can see two important domains where it should be extremely relevant

A maximal T in quantum BH physics?

- The Hagedorn temperature present in each string theory appears to have a new interpretation as maximal Hawking temperature of a string black hole.
- This conclusion can be reached in (at least) two ways:

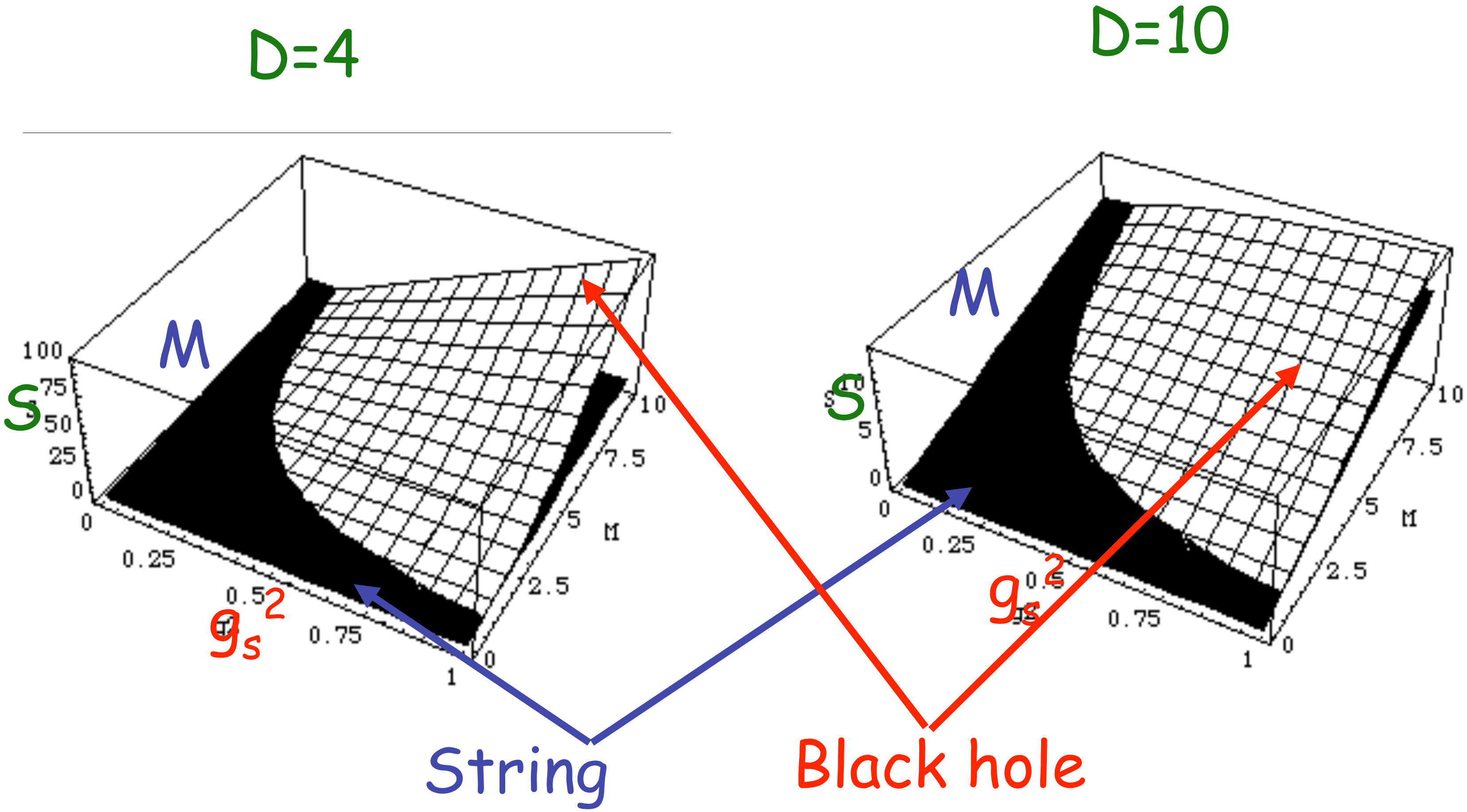
- The 1st is that strings have minimal size of order $l_s \sim (\alpha' h)^{1/2}$ and therefore can only give collapsed objects if the gravitational radius is larger than l_s.
- Since the Hawking temperature is inversely proportional to the horizon radius this implies a maximal BH temperature of order Hagedorn T.

- The same conclusion is reached by looking at BH entropy. This grows like the area of the horizon, therefore as M^2.

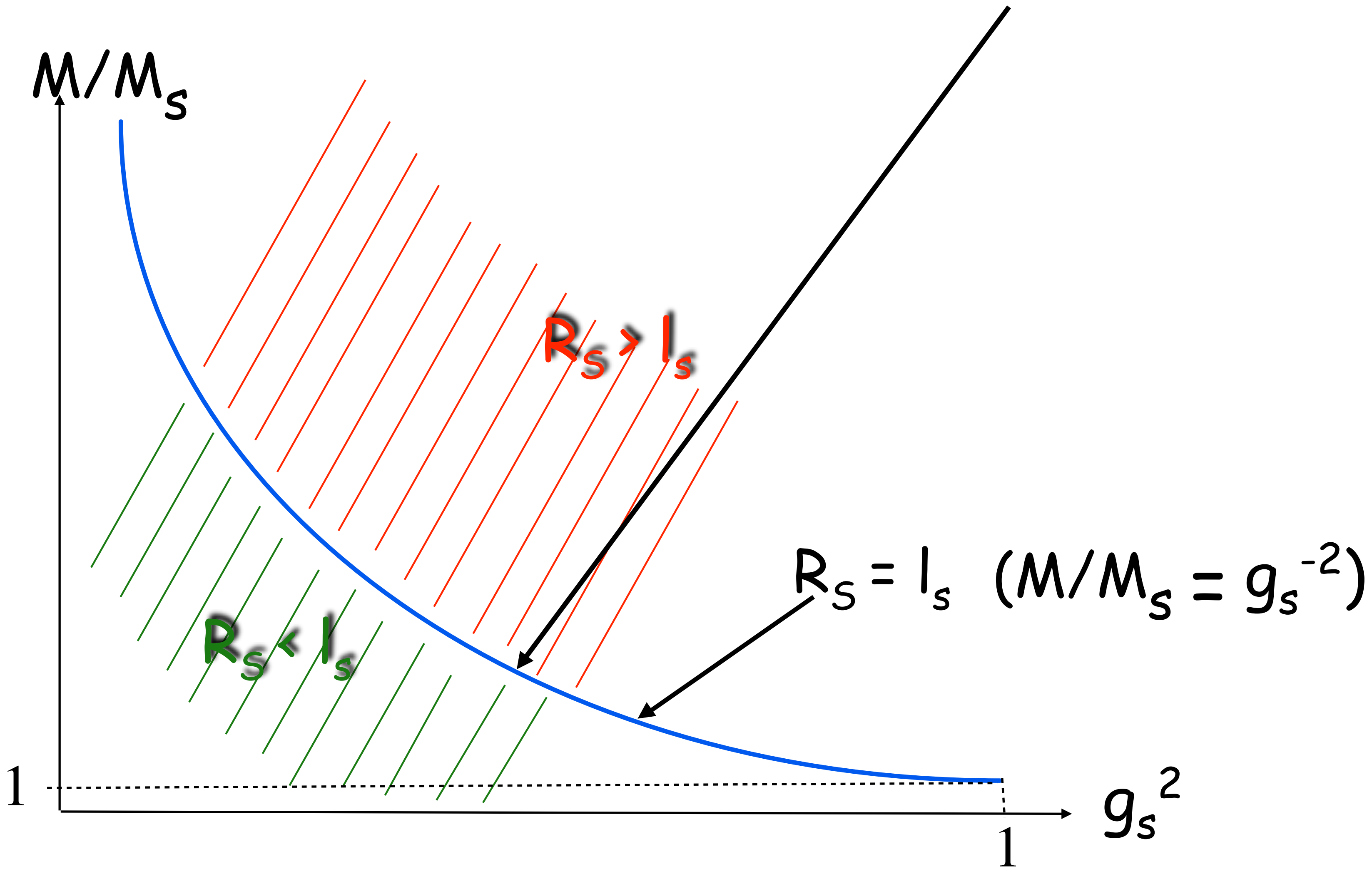
- Thus, at large M, BH entropy is larger than (tree-level) string entropy.

- At small M the opposite is true. If BH are the most entropic states in Nature (Cf. holographic ideas), one gets a contradiction unless BH mass has an lower bound.

Comparing entropies in D=4, 10



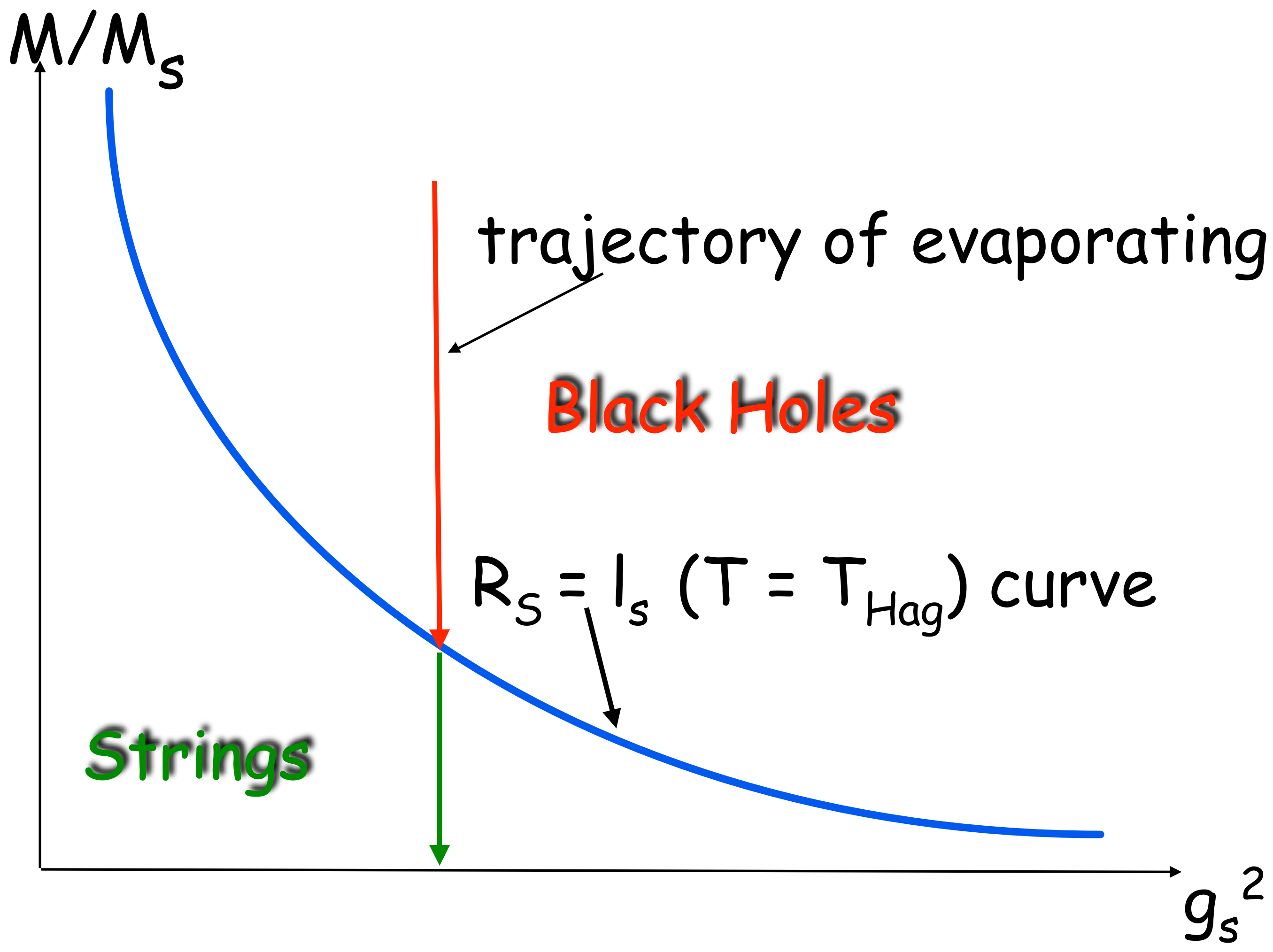
On the BH/string correspondence curve $T_H = T_{H'}$ and $S_{BH} = S_{st} = g_s^{-2}$



Deconfinement -> Decollapse?

- As a BH evaporates its temperature grows until it reaches the Hagedorn temperature, at which points it becomes a “decollapsed“ objet and decays as a “normal’ heavy string into lighter ones (Bowick et al. 1987).

Singularity at the end of evaporation avoided?



A maximal T in cosmology?

- Another situation in which an unbounded temperature is often advocated is the big bang singularity. What we were taught till the eighties is that, as we go forward in time, the Universe expands and cools down till, today, it has its very small temperature of 3K. Conversely, as we go back in time the Universe contracts and becomes hotter and hotter.

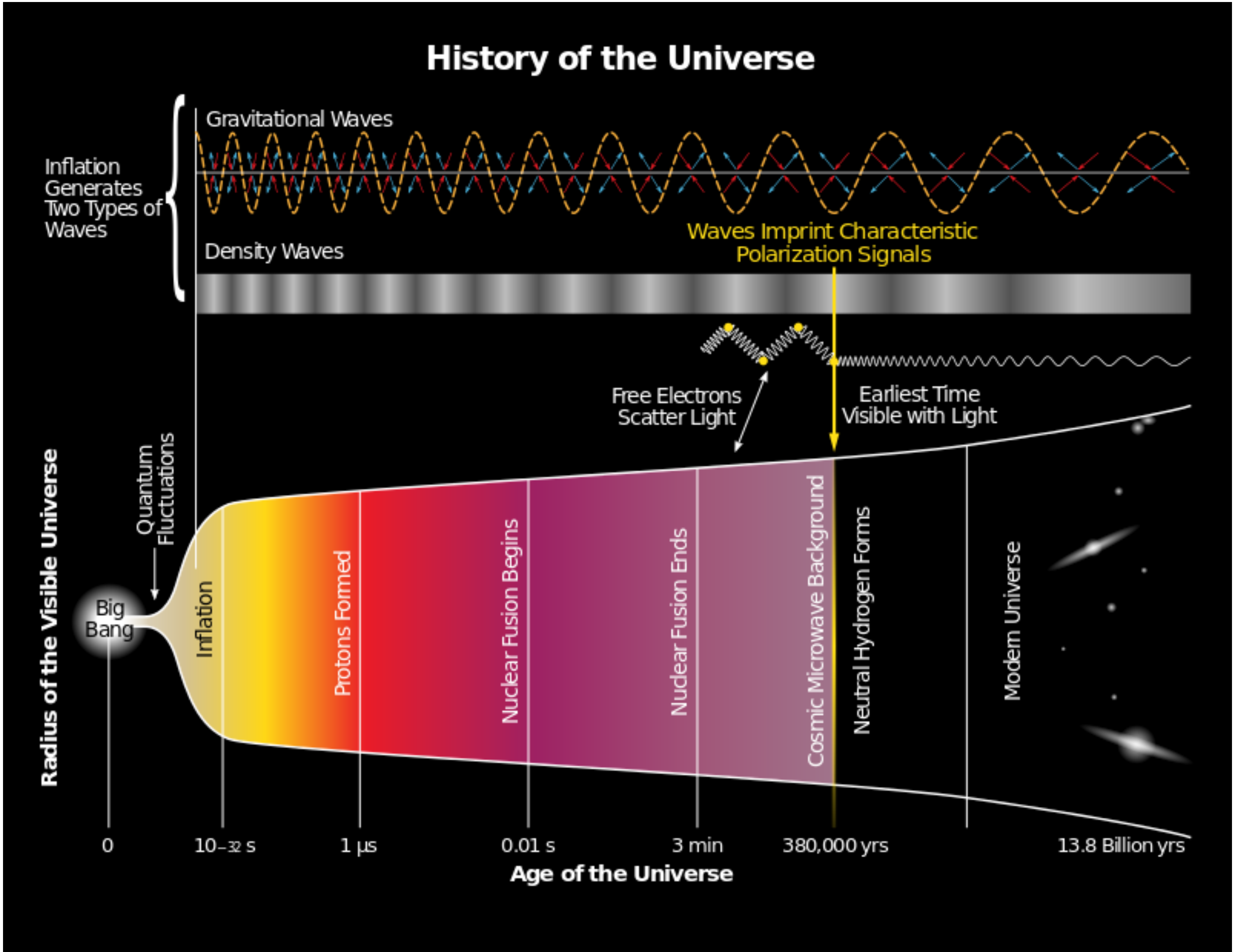
Already a revolution?

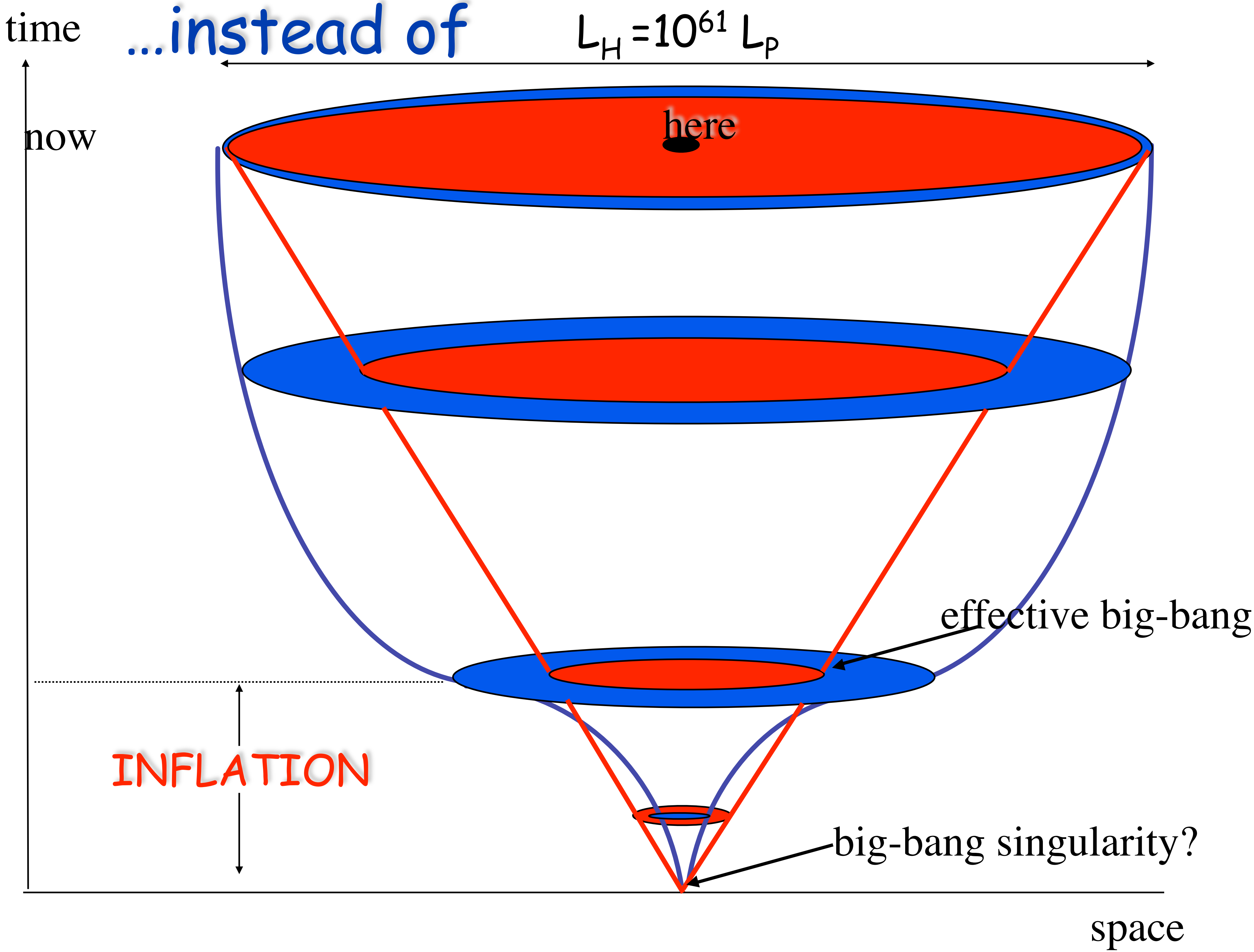
Inflation tells us that this must be false. At the end of inflation the Universe still expands but its temperature suddenly shoots up (this is the so-called reheating after inflation)!
Quantum phenomena can do that: non adiabatic processes of particle creation produce heat, entropy, and growth of temperature.
Of course the reheating temperature is finite, hopefully large enough for BBN...
Yes, Big Bang Nucleosynthesis!
But which Big Bang? Obviously the one that occurred AFTER inflation!

About being honest…

- Even the well educated public is confused. For decades we taught them: BB = beginning of time! It was indeed so in the old hot-big-bang scenario based on classical GR.
- In the inflationary paradigm we ought to distinguish the "physical" (non-singular) BB at the end of inflation from a hypothetical "mathematical" BB **possibly** preceding inflation, but about which we can only make guesses.
- In any case, the BB we know something about had nothing to do with a singularity or with the beginning of time!

The (often shown) wrong picture…




time
...instead of
$L_H = 10^{61} L_P$
now
here
effective big-bang
INFLATION
big-bang singularity?
space

How about the beginning of time?

- We do not know the answer to this question but we know that it must depend on which is the "right" theory of quantum gravity.
- What happened before inflation is sensitive to which quantum theory of gravity replaces Classical GR at very short distances!
- Il the correct theory of quantum gravity is of the string/Hagedorn kind the classical singularity should be removed and the mathematical BB should be replaced by a Hagedorn phase.

- In the past 25 years or so I have been playing with the idea of a long (actually infinite) pre BB phase where the second "B" should rather stand for Bounce, a bounce in curvature and temperature.
- Understanding precisely the physics of the bounce itself is a hard and still unsolved problem. In 0312182 I proposed "A model for the Big Bounce": a closely packed gas of "string-holes" i.e. of strings lying on the correspondence curve (and thus at $T = T_H$).
- Such a gas would saturate all sorts of bounds:

$$T = T_H \ ; \ R = l_s^{-2} \ ; \ S/V \sim H l_P^{-2}$$

Conclusion

The old love story is still very much alive heading confidently towards its own 50^{th} aniversary!

Thank You!