Black Holes and Self-Completion

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The main motivation for BSM-physics at LHC is the

Hierarchy Problem:

Why the Higgs is not almost a black hole?

Gravity is crucial for HP!

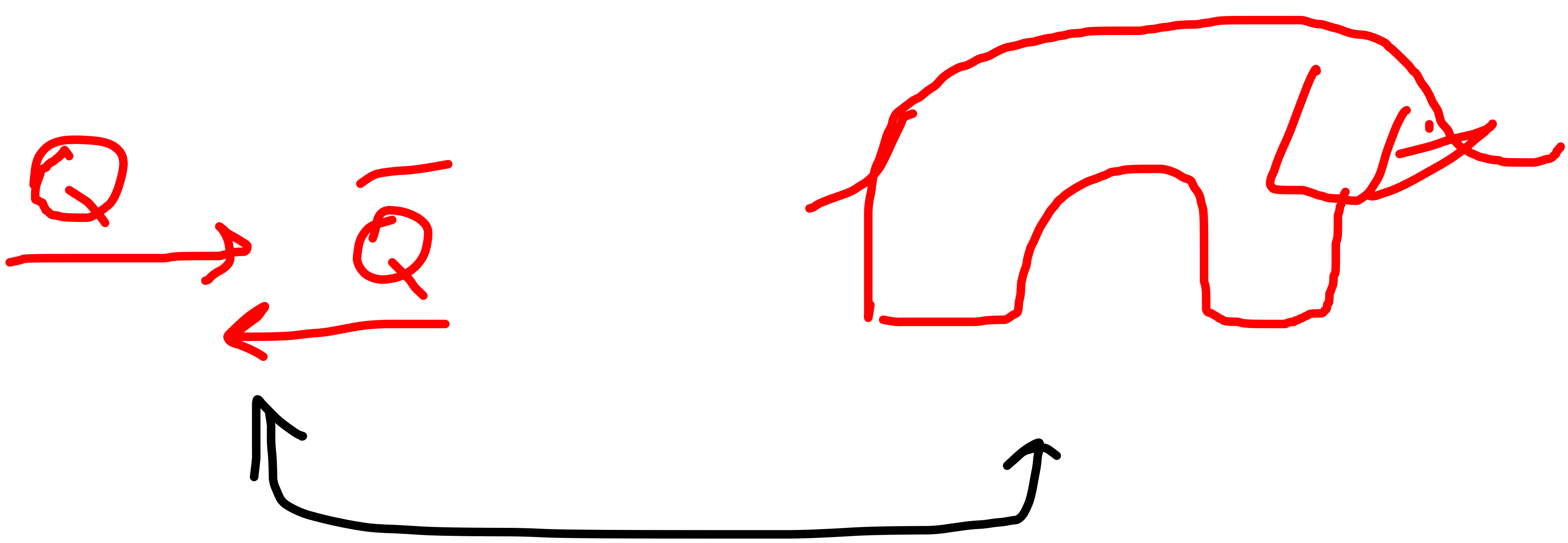
Why?

Because gravity has black holes.

Imagine I ask you whether an object of mass M is quantum (microscopic) or classical (macroscopic)?

In a world without gravity this question cannot be answered.

For example a quark-anti-quark pair with center of mass energy of a mass of an elephant



So in the world without gravity I have to tell you more (e.g. that the elephant contains many particles).

The story is very different in gravity because of new length scales.

The length-scales of M:

$$L_c \equiv \frac{\hbar}{M}$$

$$\left.\begin{array}{l} R_g \equiv G_N M \\ L_p^2 \equiv \hbar G_N \end{array}\right\} \text{gravity}$$

Planck mass $\quad M_p \equiv \dfrac{\hbar}{L_p}$

Any particle heavier than M_p becomes a Black hole and is no longer a particle!

Thus:

$$M_{Higgs} < M_p$$

Self-completion idea:
because of black holes
gravity is

Self-UV-Complete

Cesar Gomez & G.D.
(2010)

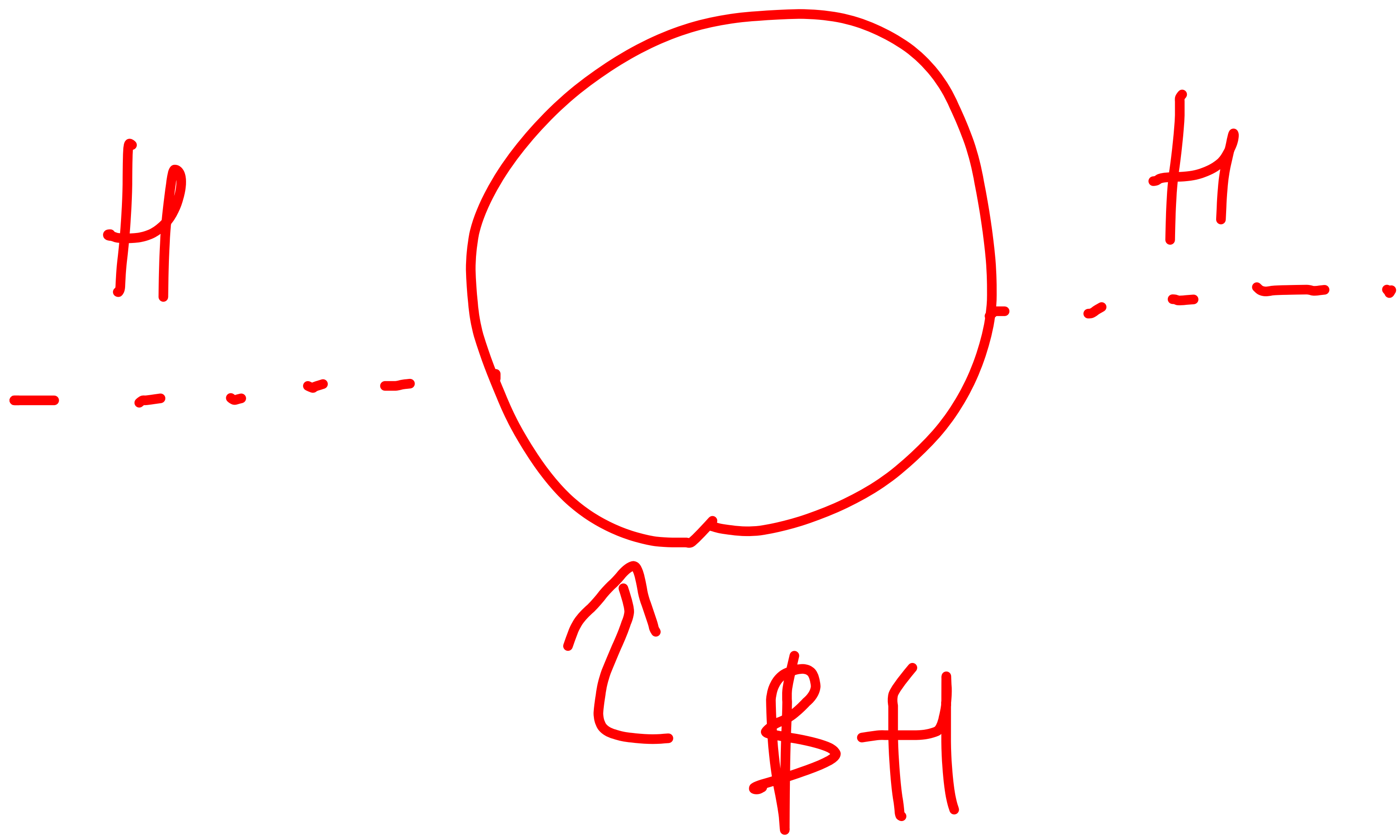
G.D., Folkerts, Germani

Then there are some deep questions.

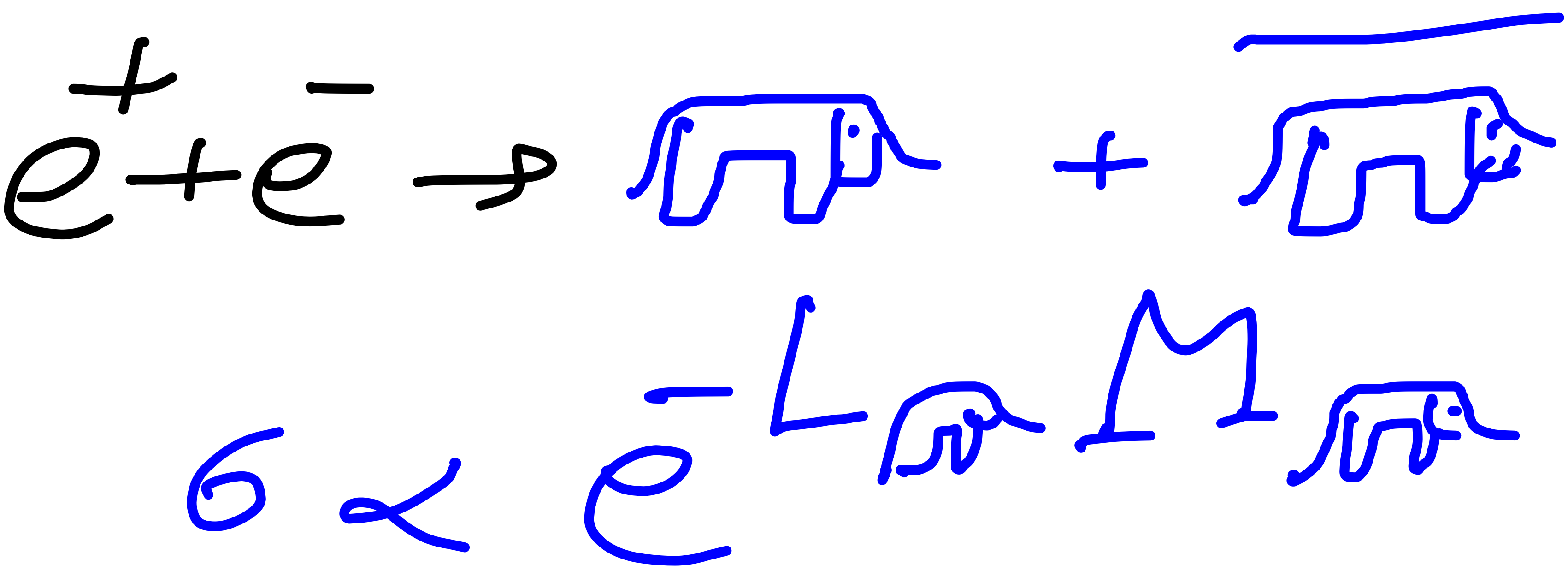
Self-completeness implies that there are micro black-holes that are like quantum particles of mass

$$M \sim M_p$$

Do they destabilize the hierarchy?



How can a theory be UV-completed by classical objects?



So what is special about the black holes?

In order to answer these (and many other) questions we need to have a <u>quantum microscopic</u> picture of black holes.

Must resolve the black hole constituents!

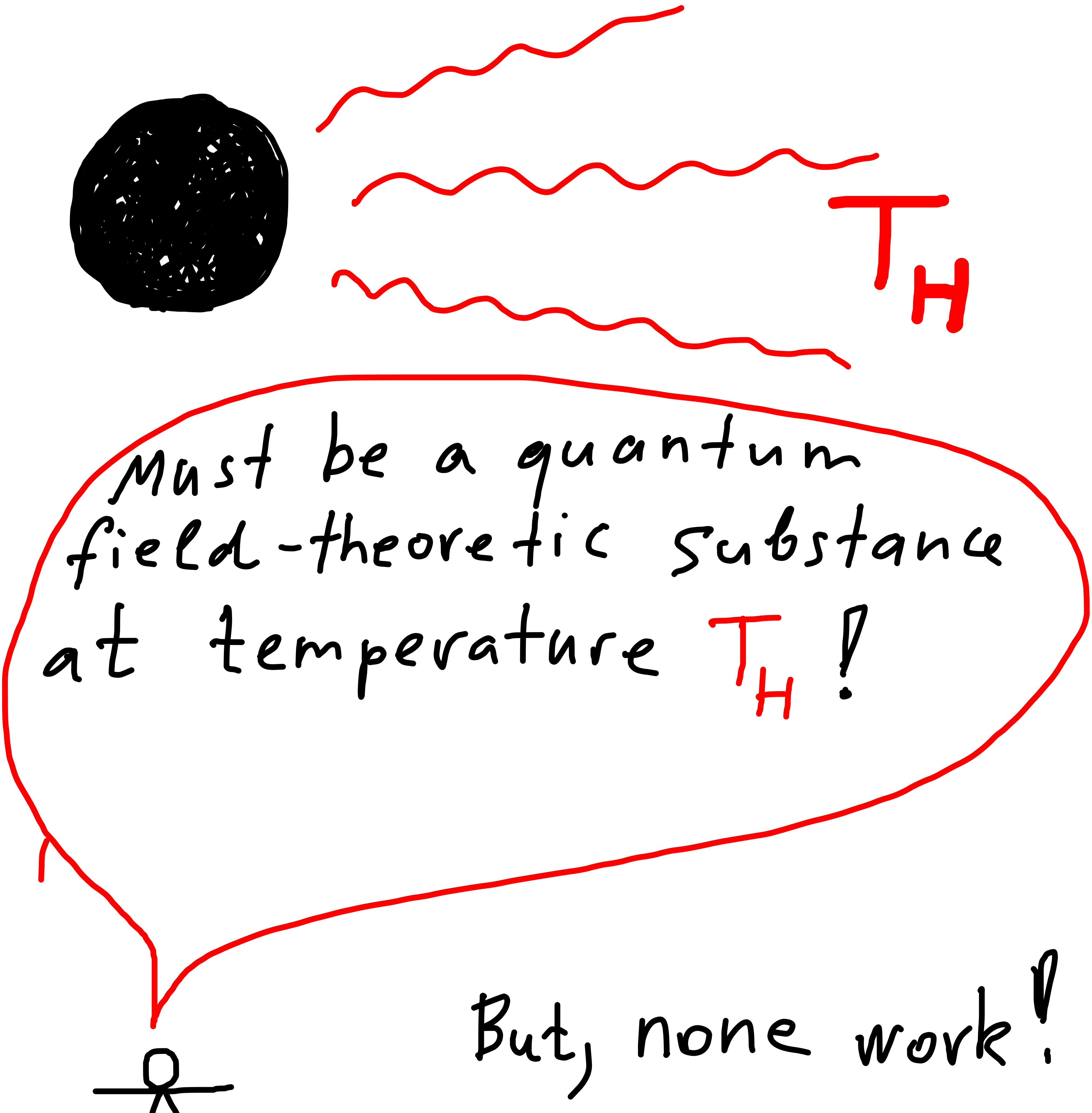
Black Hole Mysteries (semi-classically):

*) Absence of hair;

*) Exact thermality of Hawking radiation and negative heat;

*) Bekenstein entropy;

*) ......


T_H
Must be a quantum field-theoretic substance at temperature T_H!
But, none work!

Absence of hair and exact thermality

+

A small logical gap filled with a seemgly-logical assumption

=

*) "Folk theorems" about no global charges (e.g. baryon and lepton numbers).

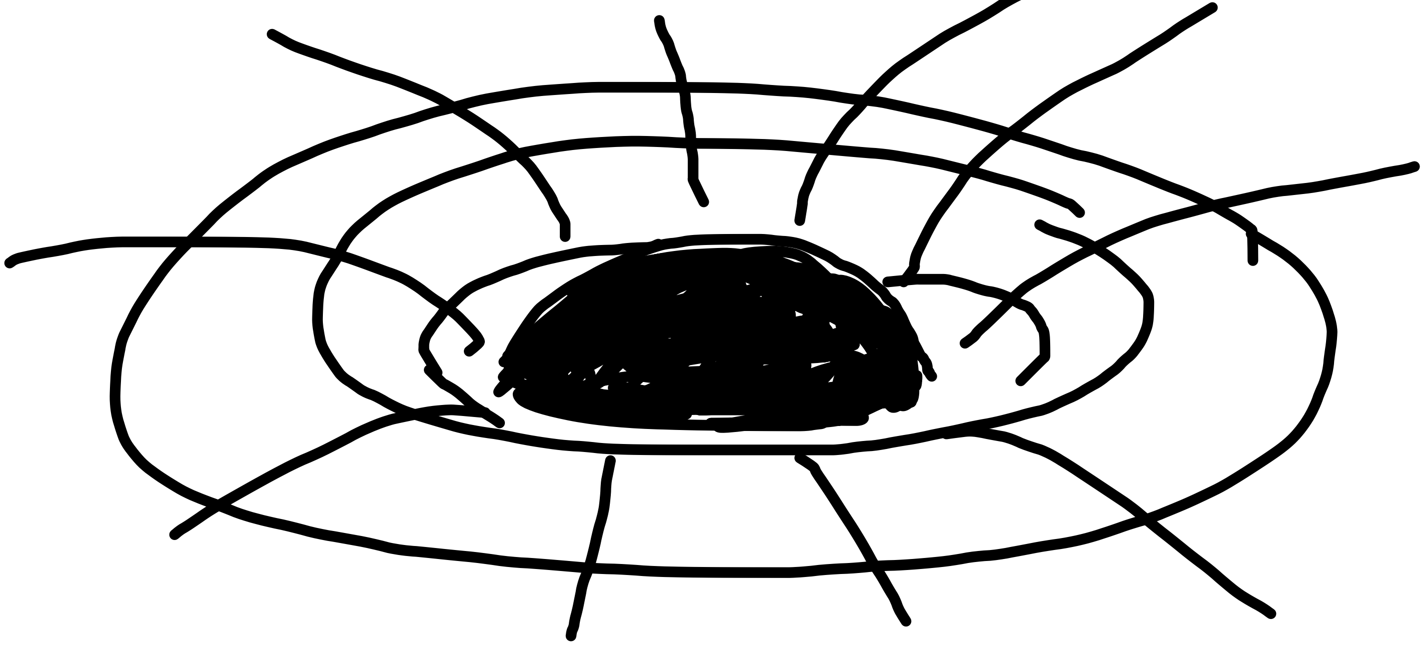
*) "Information Paradox".

To resolve these "paradoxes", and to close the logical gap, we need a microscopic quantum theory.

In this talk we shall provide such a theory and show how it demystifies semi-classical black hole properties.

Recall:

Schwarzschild black hole is a solution in GR



$g_{\mu\nu}(x)$

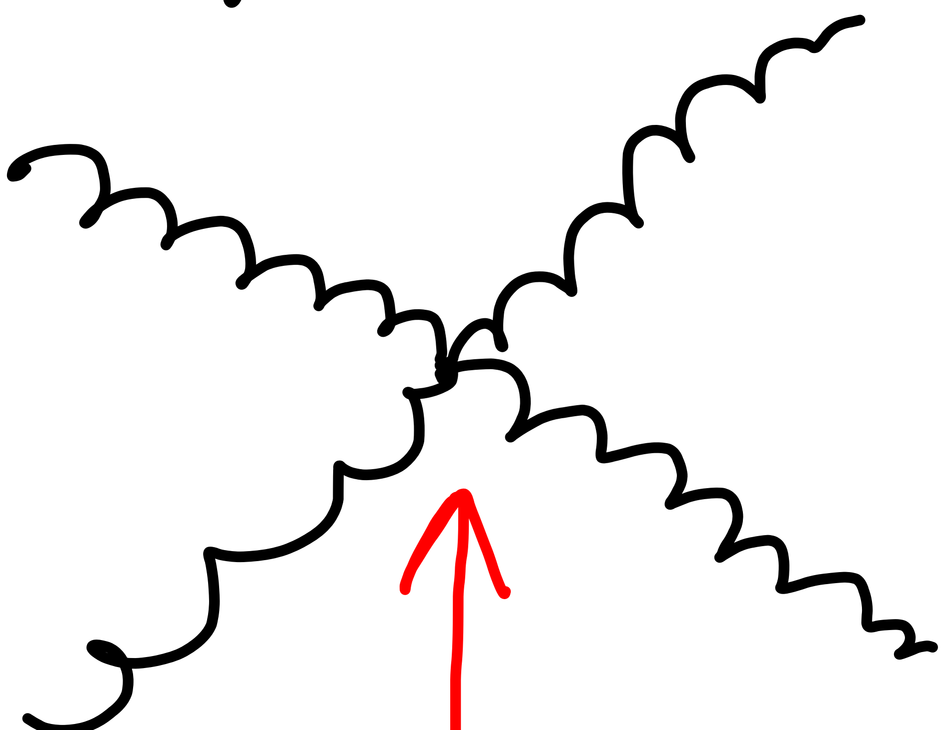
Intrinsically-classical concept!

In quantum field-theory the building blocks are particles:

$$a^{\dagger}|0\rangle = |1\rangle$$

There is nothing else.

Gravity is a quantum theory of a particle (graviton) of $m = 0$ and spin $= 2$



$$\alpha_{gr} \equiv \hbar G_N \bar{\lambda}^{-2}$$

Quantum entities:
Planck length and Mass

$$L_p^2 \equiv \hbar G_N, \quad M_p \equiv \frac{\hbar}{L_p}$$

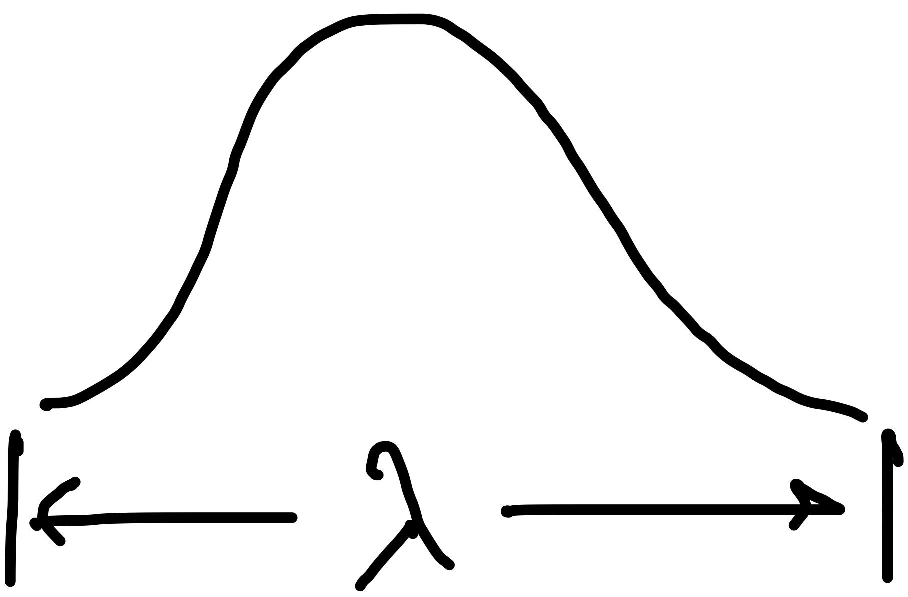
$$\alpha_{gr} = \frac{L_p^2}{\lambda^2}$$

In classical limit ($\hbar \to 0$)

$$L_p \to 0$$

$$\alpha_{gr} \longrightarrow 0$$

Now, try to form a graviton wave packet.



For $\lambda \gg L_p$

$$\alpha_{gr} \ll 1$$

A typical Hartree situation:

Eech graviton sees a collective potential.

Collective binding potential for $r \sim \lambda$

$$V = -N\alpha_{gr}\frac{\hbar}{\lambda}$$

and kinetic energy

$$E_k = \frac{\hbar}{\lambda}$$

The boundstate condition

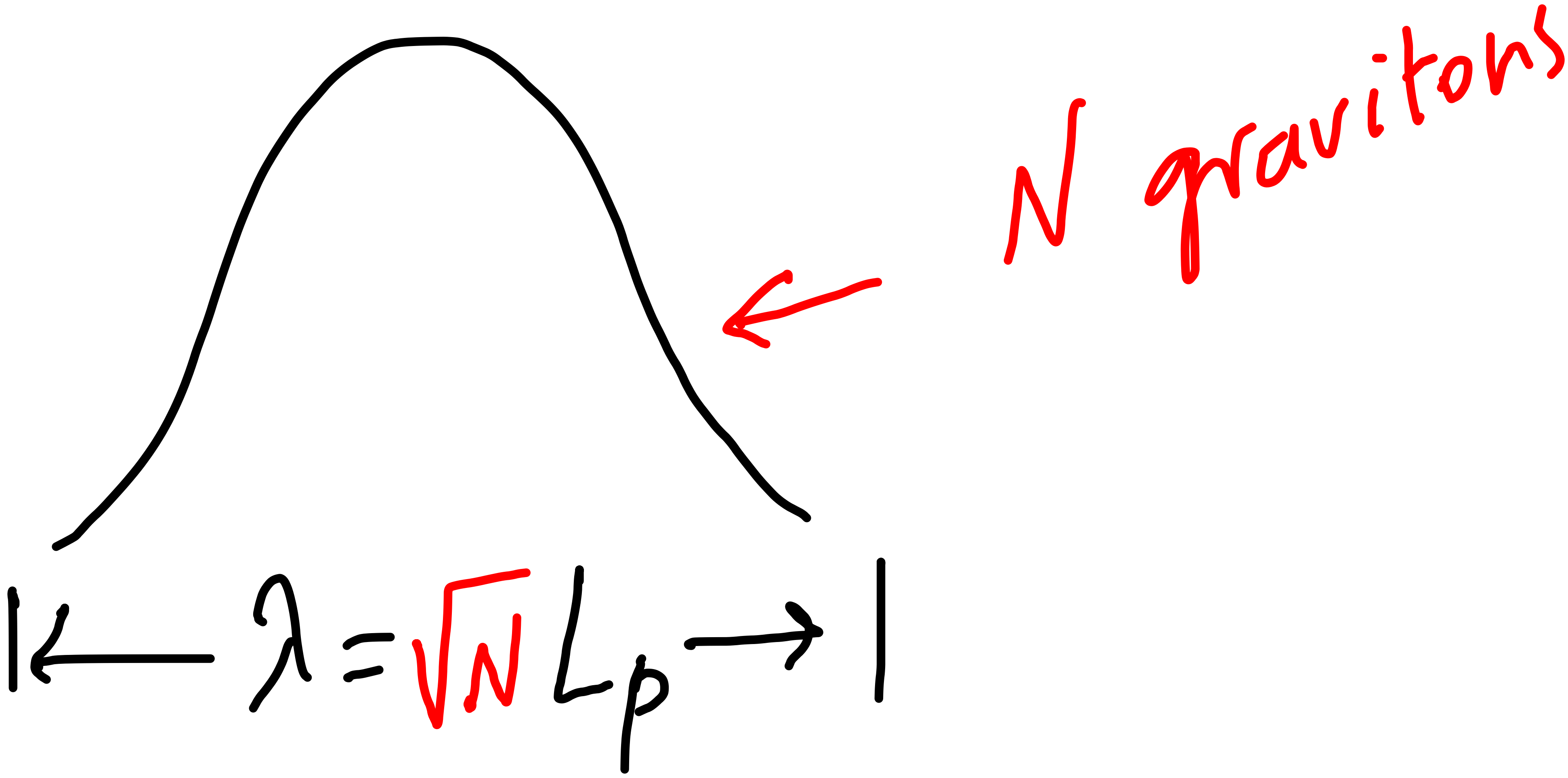
$$E_k + V = 0$$

$$\downarrow$$

$$\left(1 - N\alpha_{gr}\right)\frac{\hbar}{\lambda} = 0$$

A self-sustained boundstate is formed for

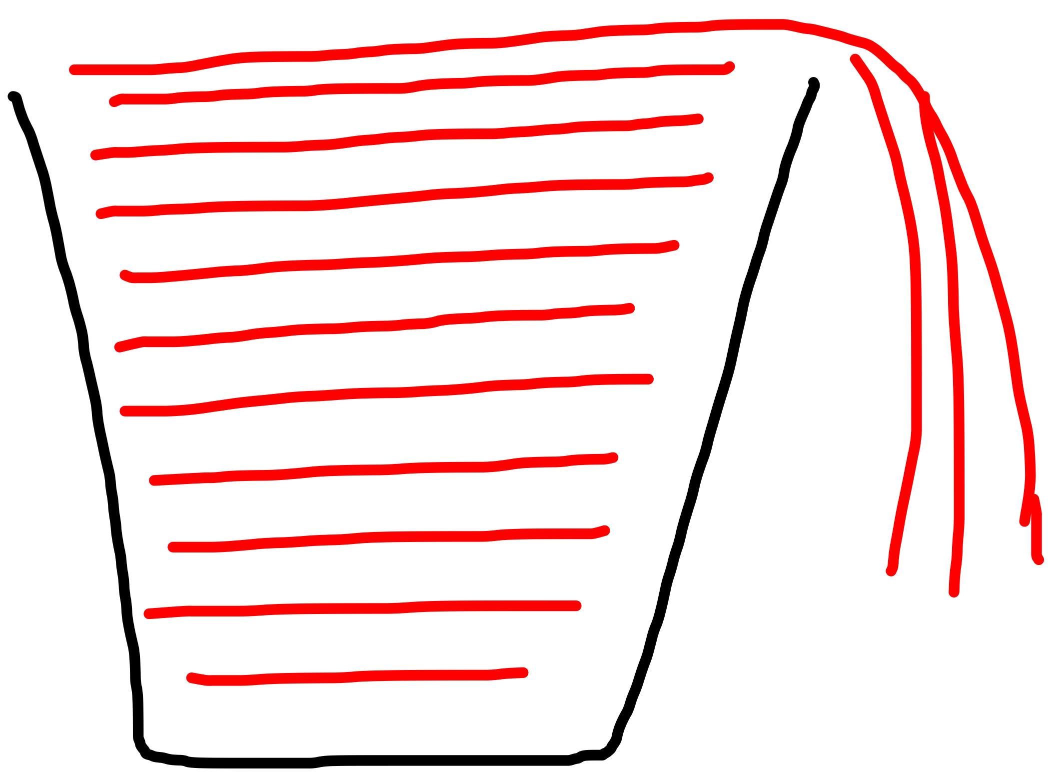
$$\alpha_{gr} = 1/N \;!$$



This self-sustained boundstate is a black hole

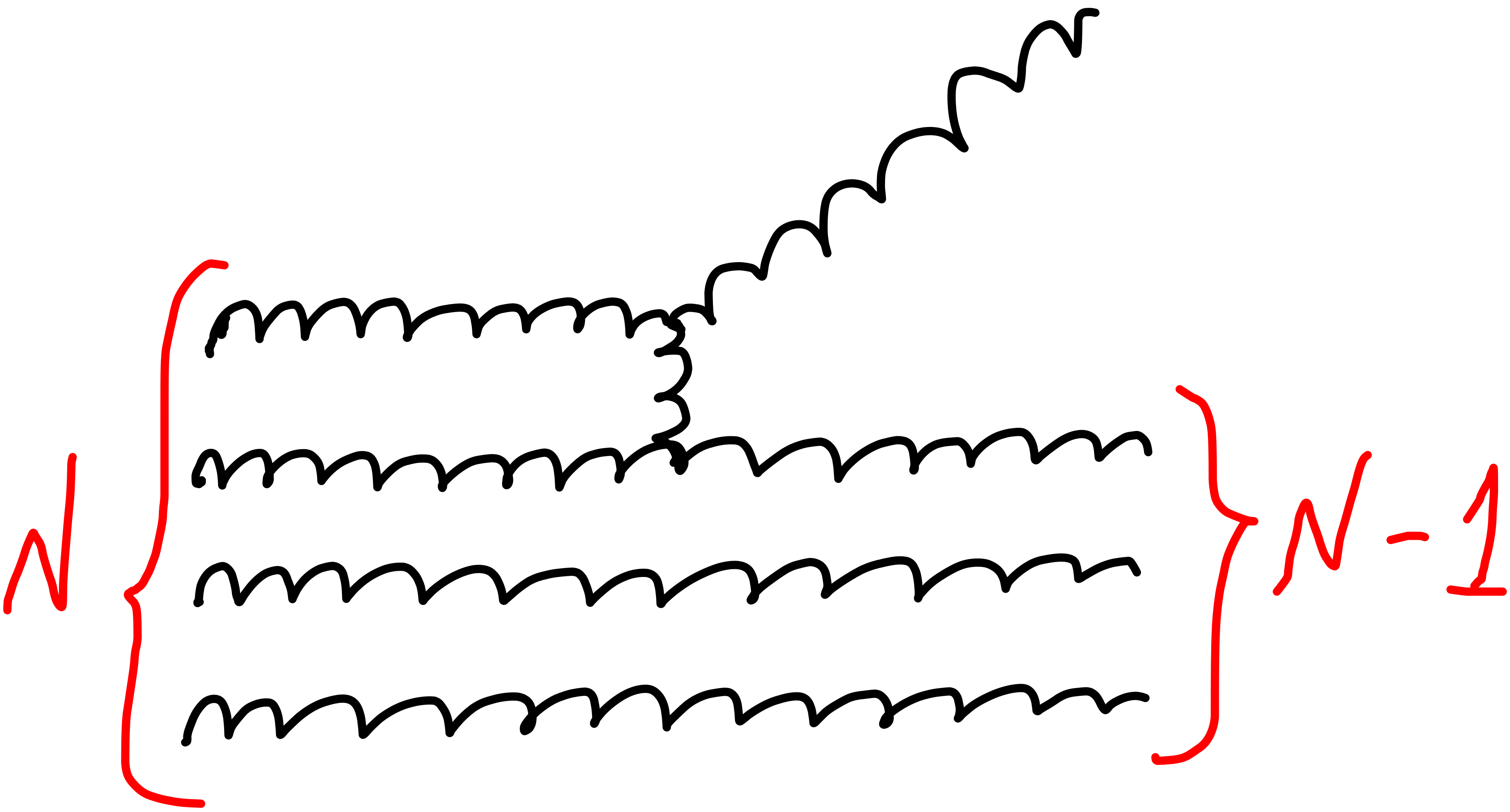
$$\lambda = \sqrt{N} L_p, \quad \alpha_{gr} = \frac{1}{N}$$

This self-sustained Bose-condensate exists for any N and for any N it is leaky



The condensate depletes self-similarly

$$N \to N-1$$



depletion law

$$\dot{N} = -\frac{1}{\sqrt{N}\,L_P} + O\left(\frac{1}{N^{3/2}}\right)$$

$$\dot{N} = -\frac{1}{\sqrt{N}\,L_p}$$

Defining $T \equiv \frac{\hbar}{\sqrt{N}\,L_p}$,

in the semi-classical limit

$N \to \infty$, $L_p \to 0$, $\sqrt{N}\,L_p = \text{fixed}$

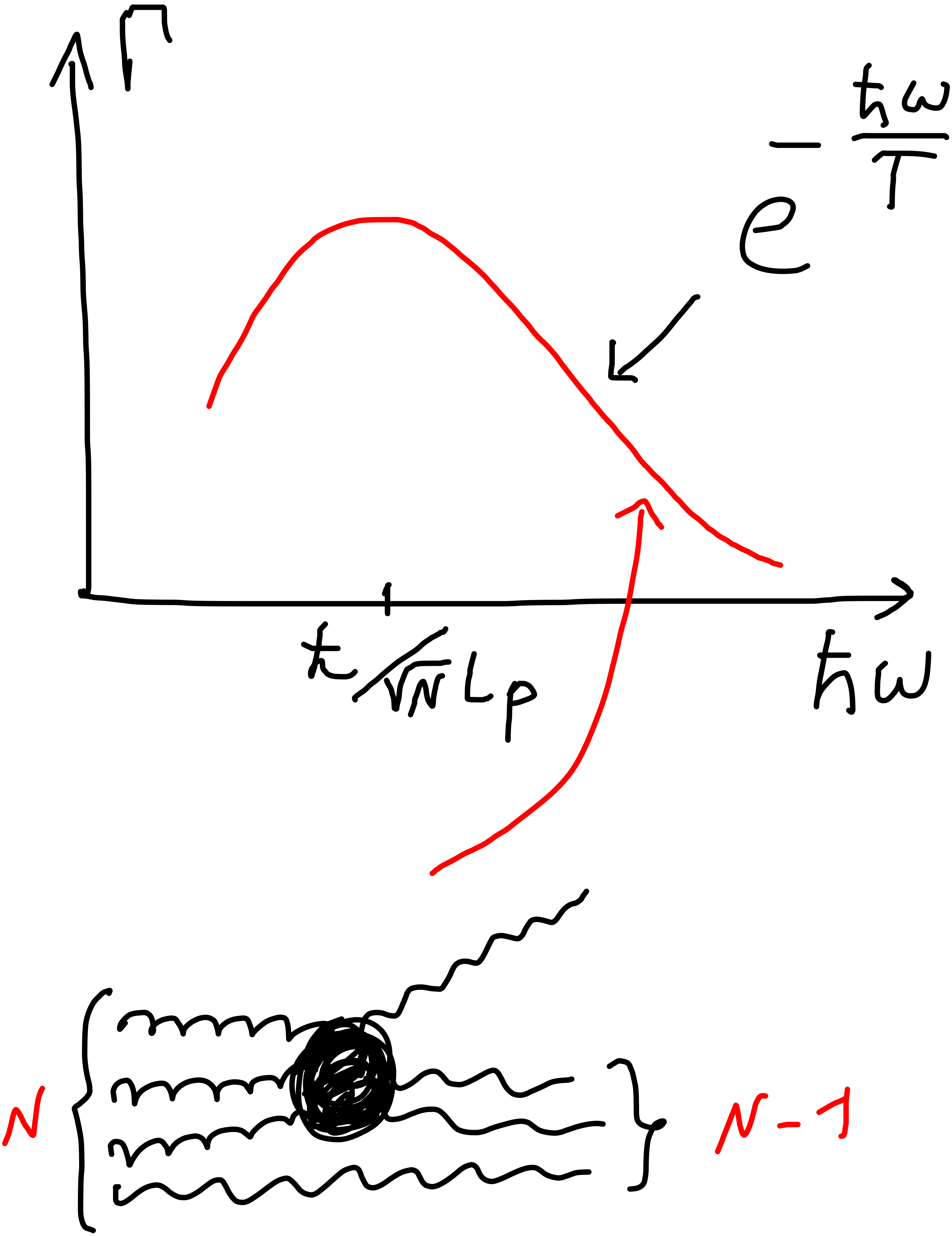
We get Stefan-Boltzmann law for Hawking evaporation

$$\dot{M} = -T^2/\hbar$$

We discover that thermality is an "optical illusion".

Spectrum is thermal because of the self-similarity of depletion, not because the source is hot.

The graviton condensate is cold!



Γ
$e^{-\frac{\hbar\omega}{T}}$
$\hbar/\sqrt{N}L_p$
$\hbar\omega$
N
$N-1$

We see:

*) Thermality of the source is an "optical illusion".

*) Deviations are $\sim \frac{1}{N}$, not e^{-N}.

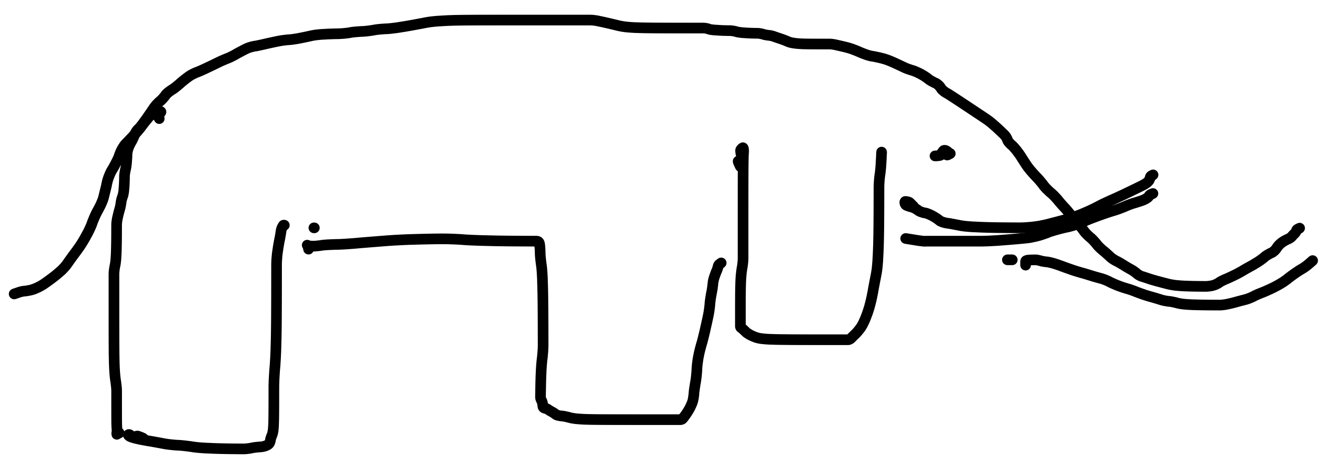
Thus, quantum effects are 100% important on scales $\sim N$!

All the black hole "paradoxes" are result of semi-classical treatment.

But, how can quantum effects be important for macroscopic objects?

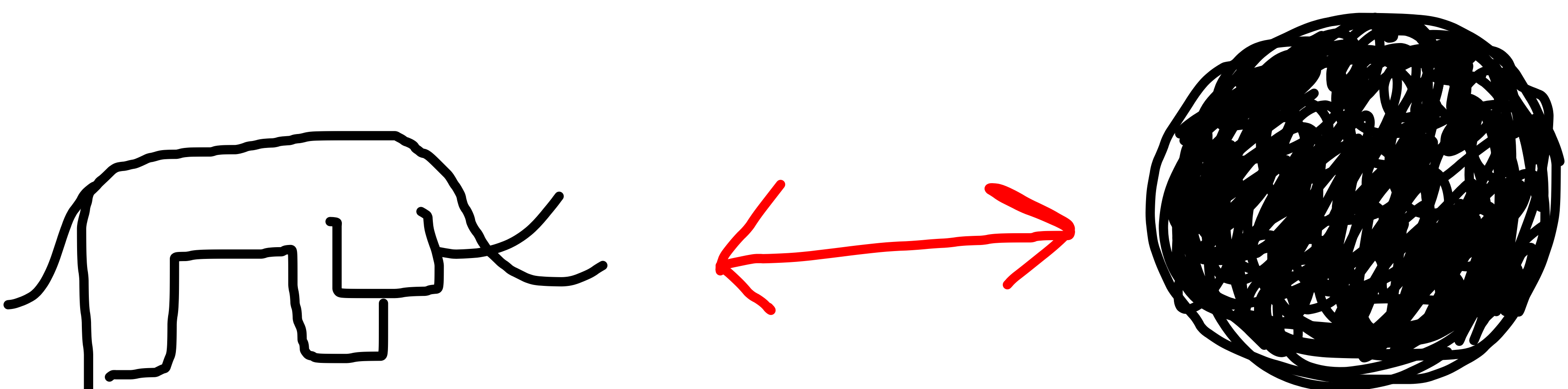
After all, treating semi-classically stars, planets, elephants, ... is fine.

Naively, this contradicts to usual intuition that macroscopic objects are (almost) classical.



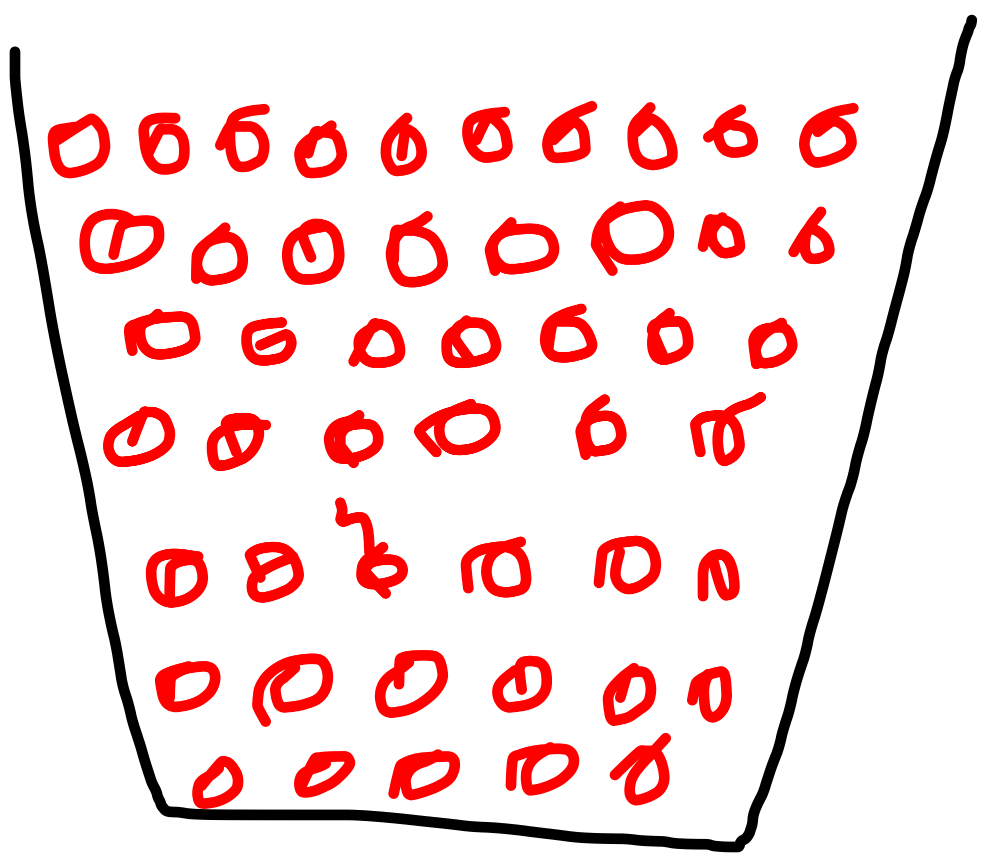
quantum gravity $\sim e^{-M_E L_E}$

The answer is that Black Holes are macroscopic, but quantum!

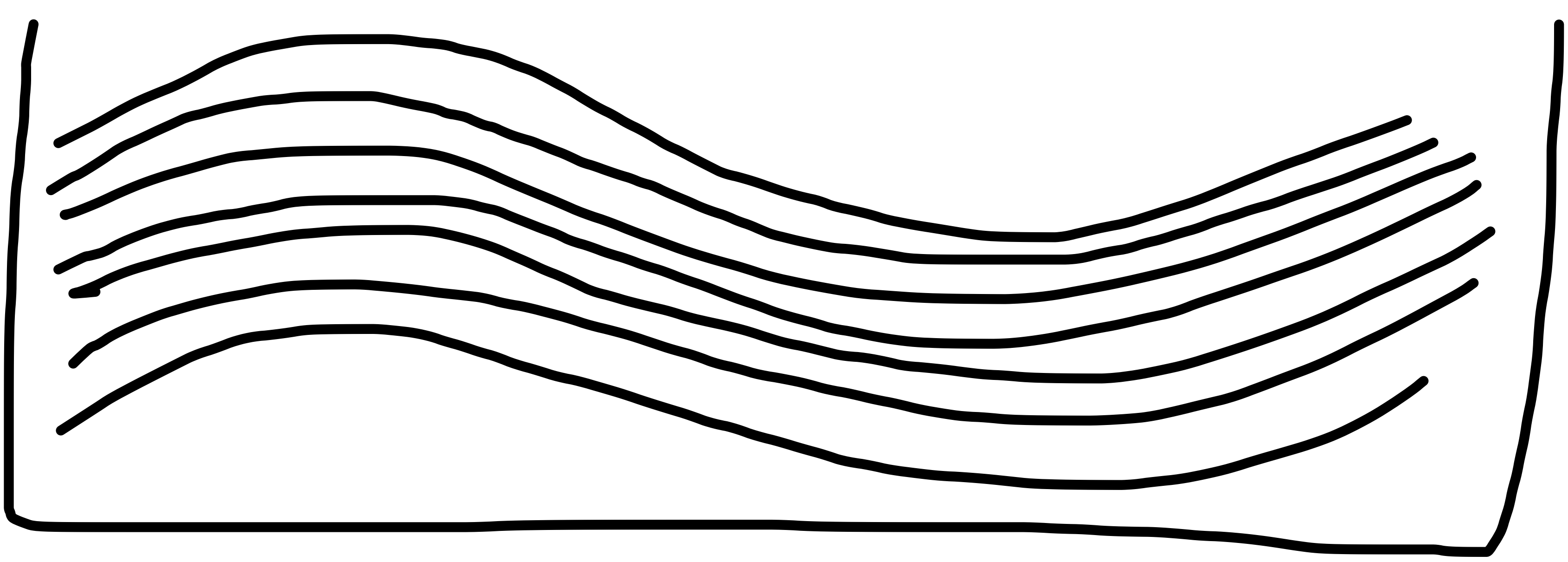


$$\sim e^{-N} \longleftrightarrow \sim 1$$

Marcoscopic objects are characterized by number of constituents N, their coupling strength α, ...



However α has an universal meaning in the systems in which everybody talks to each other at a same strength, such as Bose-Einstein condensates.



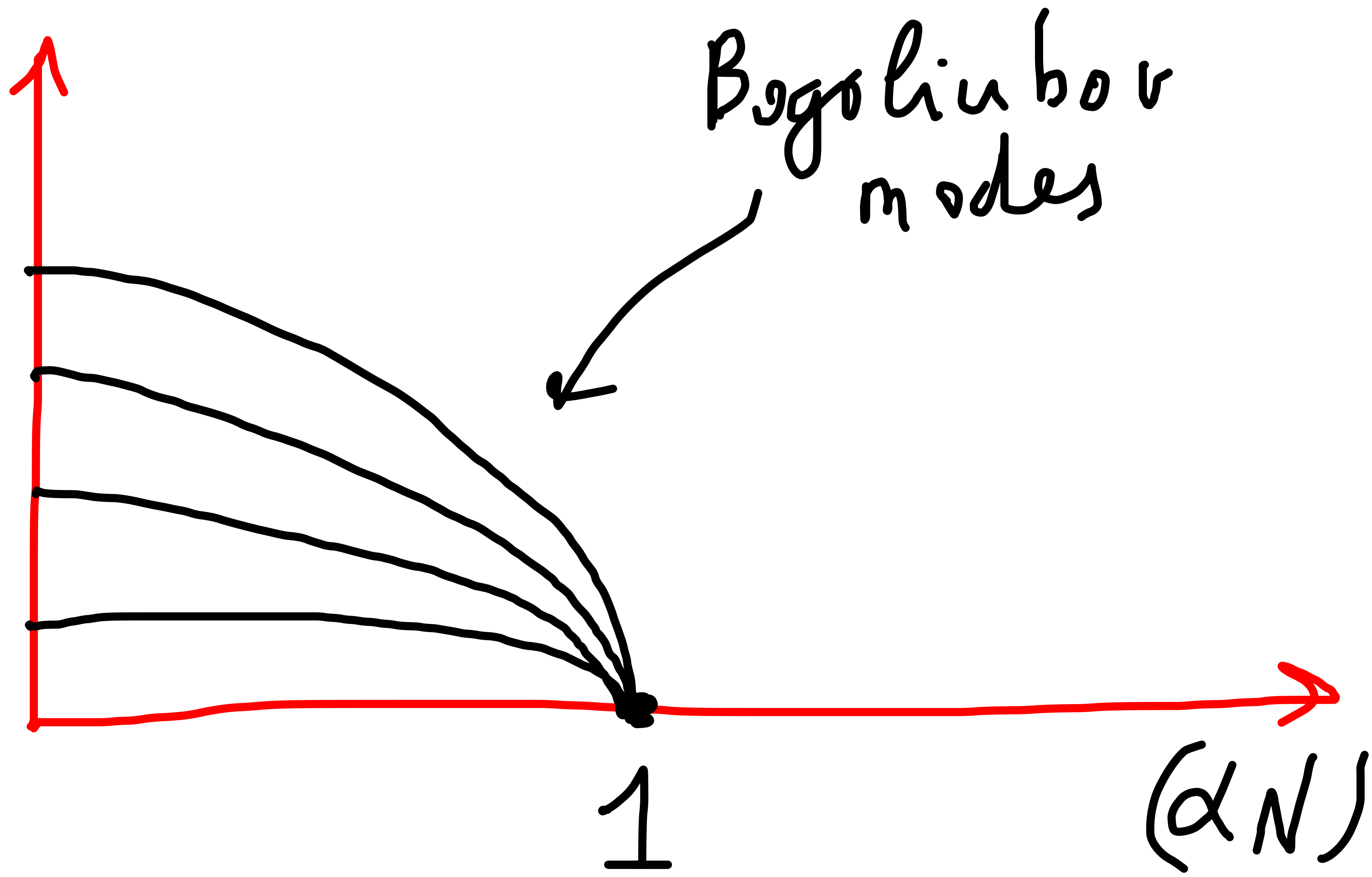
For such systems we can define a quantity

$$(N\alpha)$$

Something very special takes place at

$$N\alpha = 1$$

Critical point of quatum phase transition.



Such a system although multi-particle in reality is fully quantum.

Black hole reduced to bare essentials.

Bose-gas order parameter $\equiv \Psi$

$$n(x) = \langle \psi(x)\, \psi(x) \rangle$$

Hamiltonian

$$H = \int_V -\hbar L_0 \psi^\dagger \Delta \psi - \hbar L_p^2 \psi^\dagger \psi^\dagger \psi \psi$$

Normalization

$$\int_V \psi^\dagger \psi = N$$

$$\Psi = \sum_k \frac{a_k}{\sqrt{V}} e^{\frac{ikx}{\hbar}}$$

$$[a_k, a^+_{k'}] = \delta_{kk'}$$

$$\mathcal{H} = \sum_k k^2 a^+_k a_k - \frac{\alpha}{4} a^+_{k+p} a^+_{k'-p} a_k a_{k'}$$

Bogoliubov replacement:

$$a^+_0 = a_0 = \sqrt{N_0} \simeq \sqrt{N}$$

$$a^+_0 a_0 + \sum_{k\neq 0} a^+_k a_k = N$$

$$\mathcal{H} = \sum_{k\neq 0} \left(k^2 + \frac{\alpha N}{2}\right) a_k^+ a_k -$$

$$- \frac{1}{4}(\alpha N)\left(a_k^+ a_{-k}^+ + a_k a_{-k}\right)$$

Bogoliubov transform

$$a_k = u_k b_k + v_k^* b_k^+$$

$$u, v = \pm\frac{1}{2}\left(\frac{k^2 - \alpha N/2}{\varepsilon(k)} \pm 1\right)$$

$$\varepsilon(k) = \sqrt{k^2\left(k^2 - \alpha N\right)}$$

$$\mathcal{H} = \sum_k \varepsilon(k)\, b_k^+ b_k$$

collapses to $\frac{1}{N}$ at the critical point. Depletion sets in

$$n_k = |\beta_k|^2$$

$$\Delta N \sim n_1 = \left(\frac{1 - \frac{\alpha N}{2}}{\sqrt{1-\alpha N}} - 1 \right) \simeq \sqrt{N}$$

Energy gap

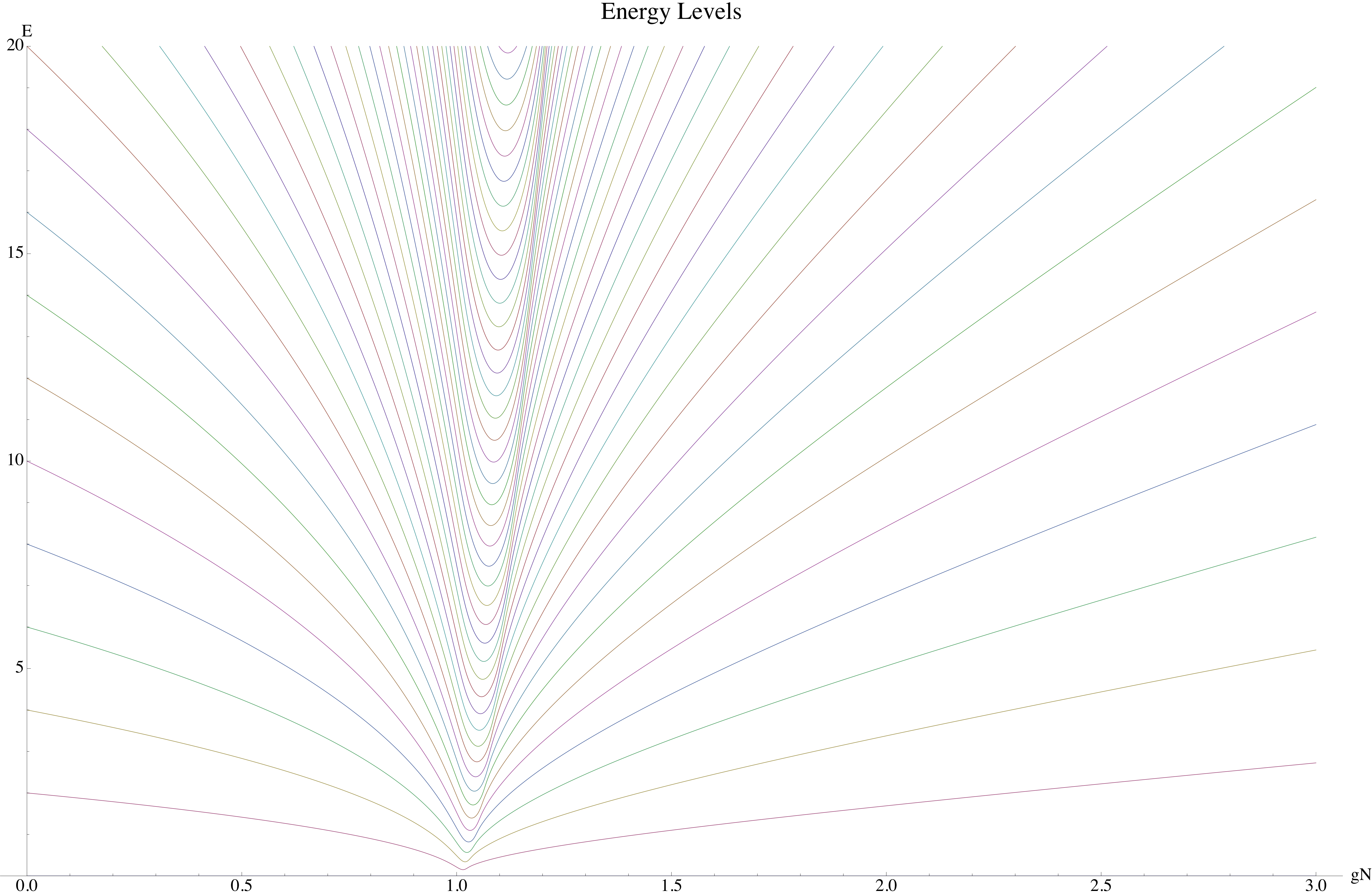
$$\varepsilon_1 = \frac{\hbar}{\lambda\sqrt{N}} = \frac{1}{N}\frac{\hbar}{L_P} \; !$$

These Bogoliubov modes are quantum ("holographic") degrees of freedom responsible for

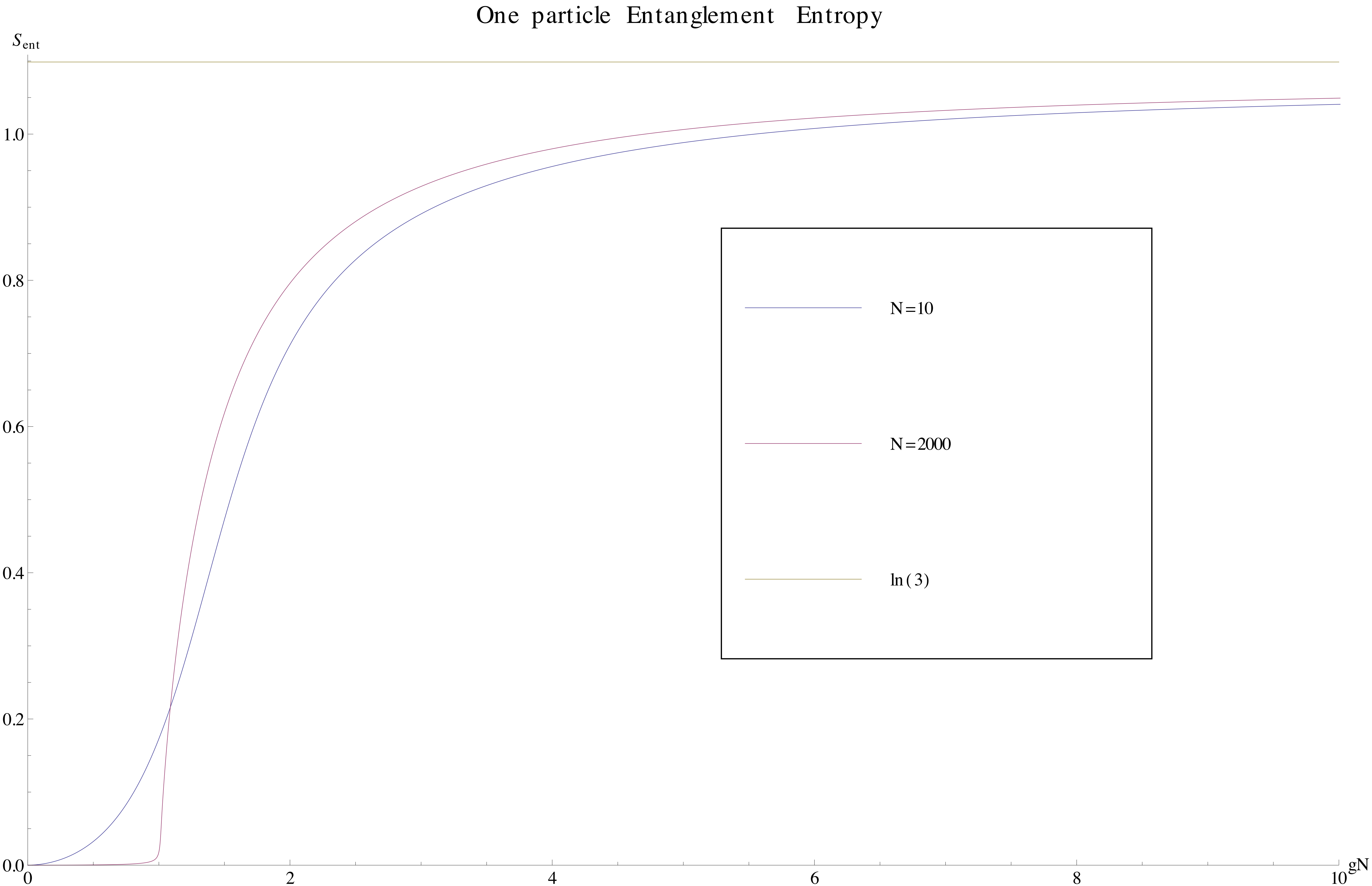
Bekenstein entropy.

Some numerical studies by:

Daniel Flassig,
Alex Pritzel,
Nico Wintergerst



Energy Levels
E
20
15
10
5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
gN



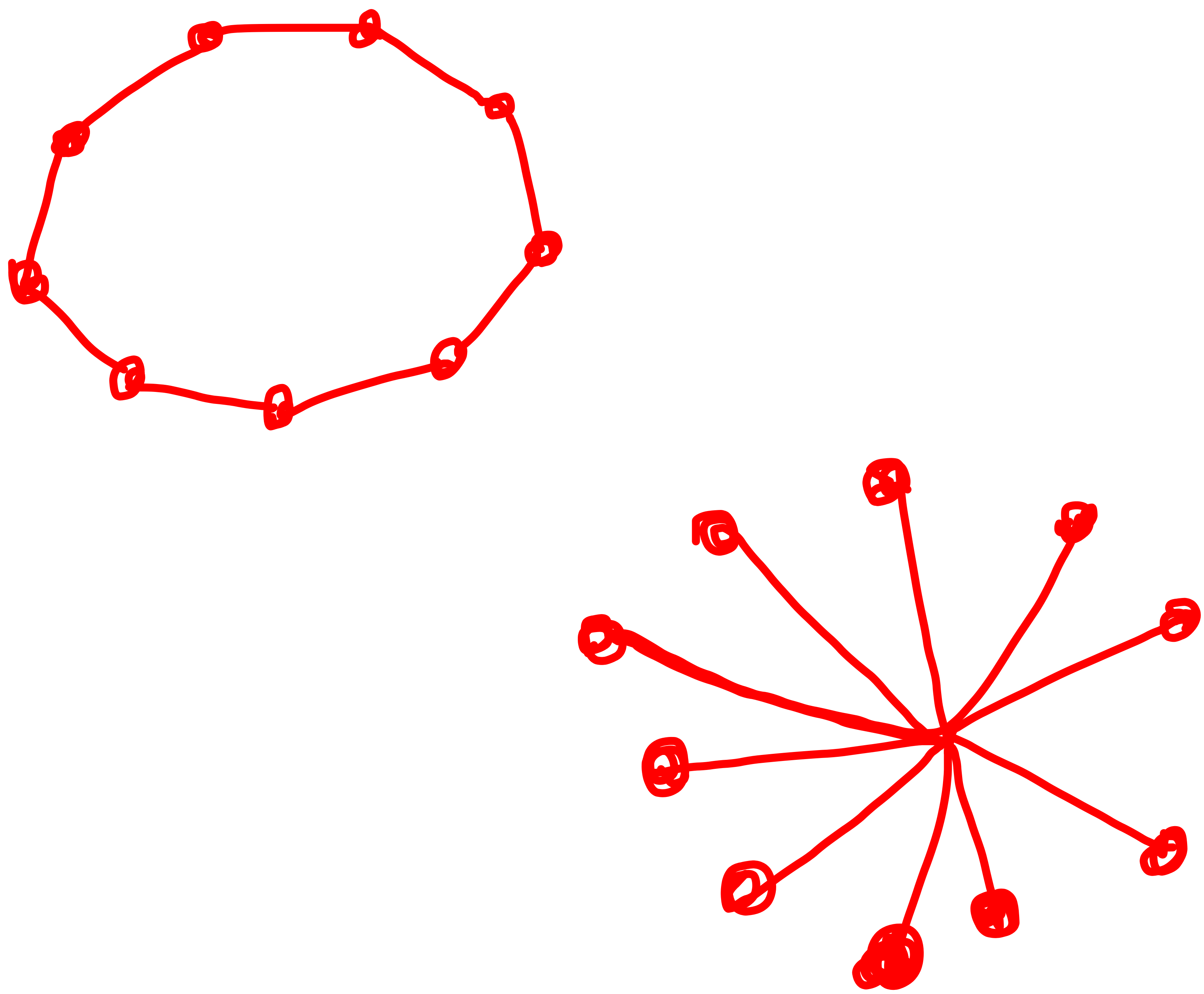
One particle Entanglement Entropy
S_{ent}
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
gN
N=10
N=2000
ln(3)

Scrambling of Information

Hayden & Preskill and Sekino & Susskind argued that black holes must be fast scramblers

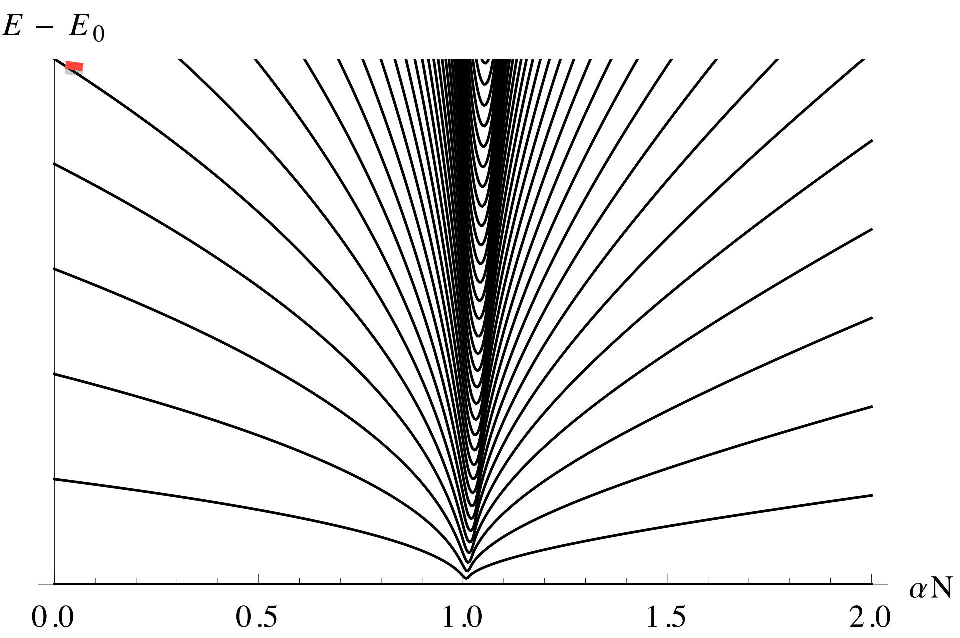
$$t_{sramb} \sim \ln R$$

Roughly speaking scrambling is an ability of a system to spread information among the constituents

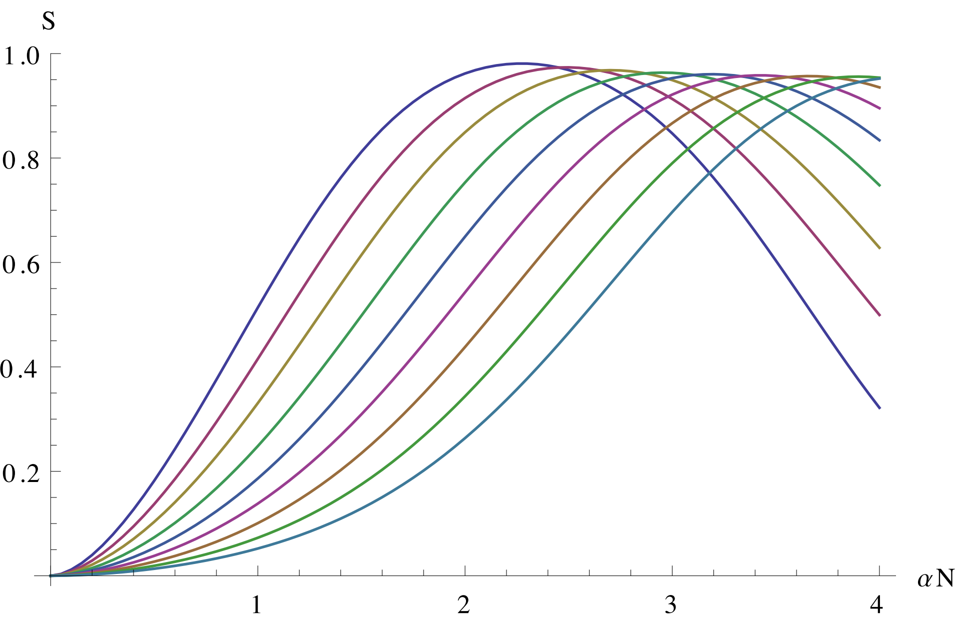


It is impossible to either verify this claim or understand its underlying dynamics without having a microscopic quantum picture.

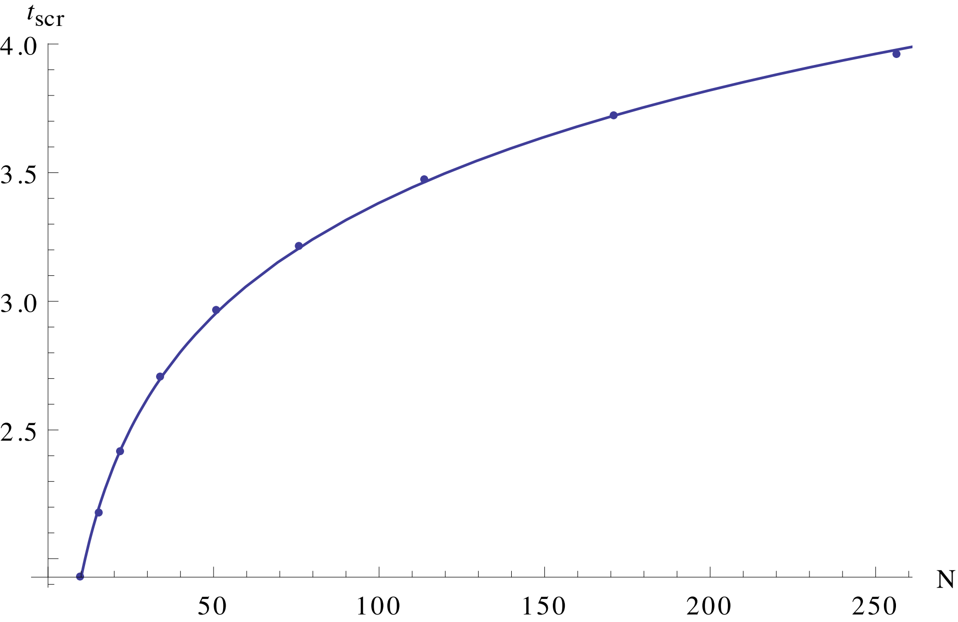
In our picture we have such understanding in xac terms of quantum break time of graviton condensate.



$E - E_0$
αN
0.0
0.5
1.0
1.5
2.0



S
1.0
0.8
0.6
0.4
0.2
1
2
3
4
αN

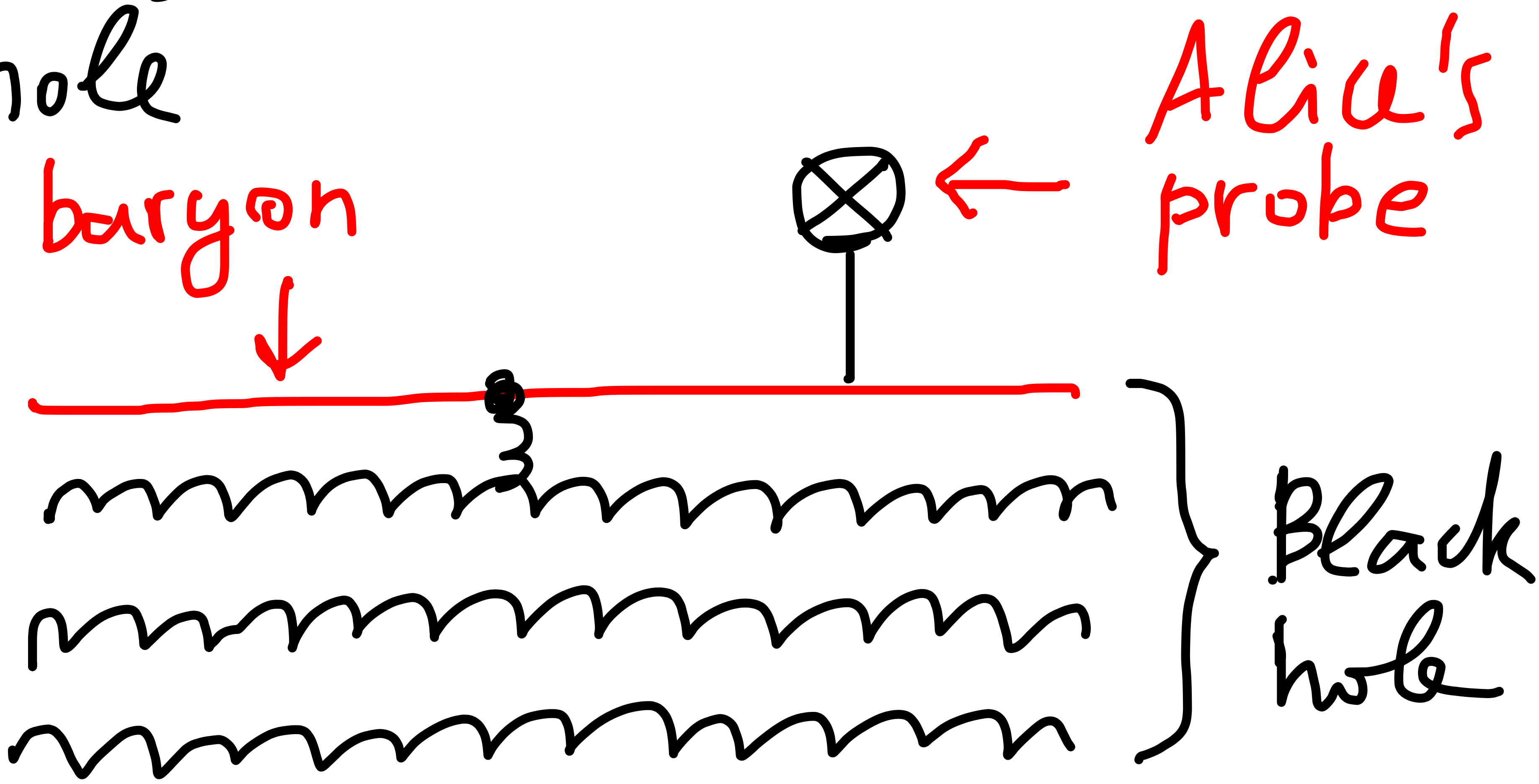

t_{scr}
4.0
3.5
3.0
2.5
N
50
100
150
200
250

Another (false) artifact of semi-classical limit is the absence of hair.

In reality black holes carry a detectable hair as

$$\frac{N_B}{N} \text{ - effect}$$

How Alice detect a baryonic hair of a black hole



$$\Gamma_{hair} = \frac{1}{\sqrt{N} L_p} \left(\frac{N_B}{N} \right)$$

For Astrophysical black holes (that carry large baryonic or leptonic charges) the hair can be an observable effect.

Extrapolating this picture to $N \sim 1$ it is evident that micro black holes (e.g. that could be seen at LHC) will be fully-quantum states and will decay into very few and very energetic quanta.

Among many potential applications is Cosmology:

The Universe is the largest black hole we know.

It's a graviton Condensate with

$$N \sim 10^{120}$$

Outlook

Black hole's quantum portrait is a microscopic framework which allows to address questions that in the conventional treatment cannot even be formulated.

It demystifies the known semi-classical puzzles in black hole physics.

Our picture suggests the following quantum foundation of holography:

Gravitational systems that exhibit holography are Bose-Einstein condensates at the critical point of quantum phase transition.

The "holographic" degrees of freedom then are nearly gapless (and conformal) Bogoliubov modes.

First, what is <u>classicality</u>?

Nature is quantum $\hbar \neq 0$.

Classicality implies many particles.

For example, earth's gravitational field is classical because it contains $N \sim 10^{66}$ gravitons!

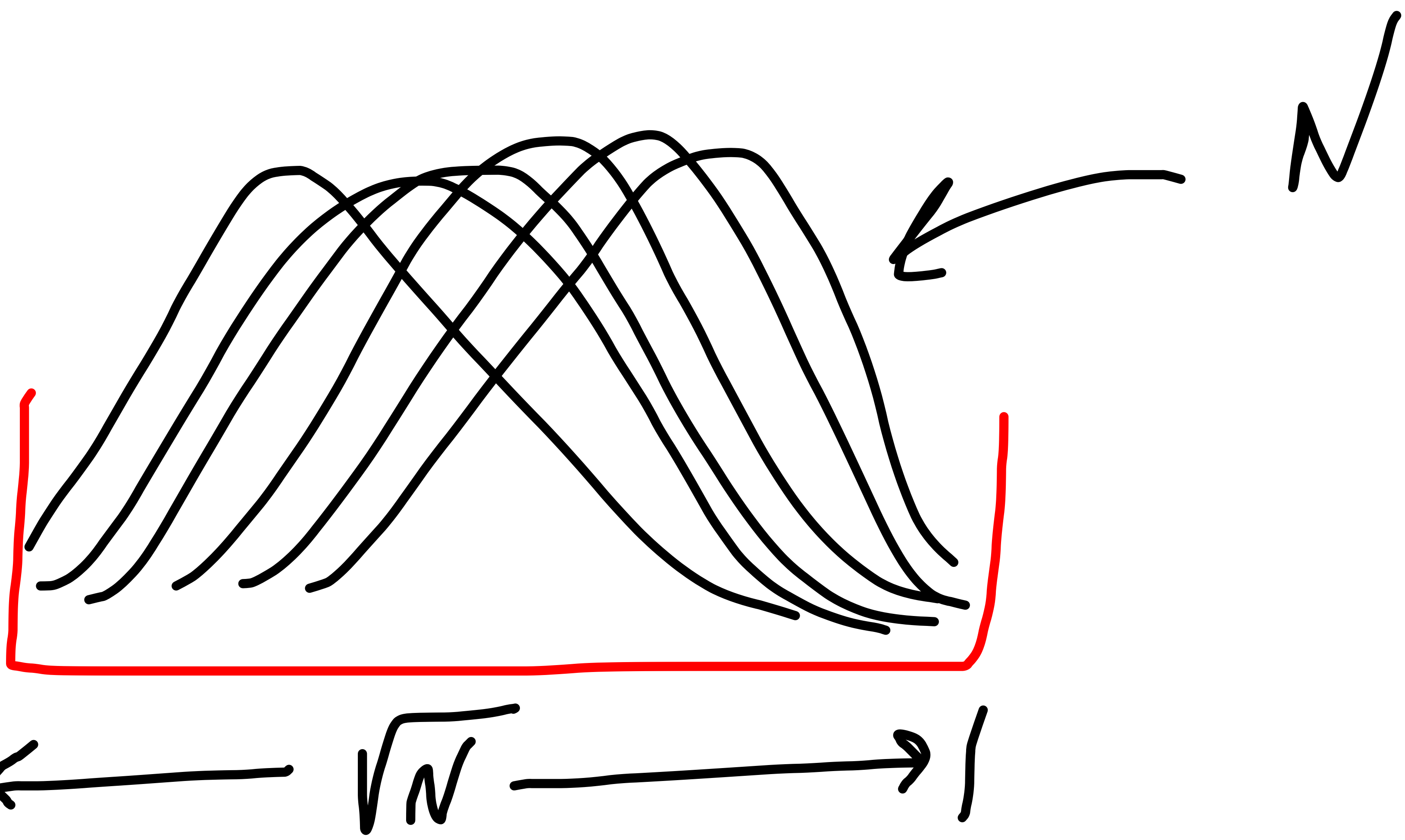
In contrast, gravitational field created by a single electron contains only

$$N \sim 10^{-44}$$

gravitons!

(This is why the electron is not a black hole.)

Black hole is a
most overpacket quantum
system of nature
and
because of this it is
maximally simple



Black hole quantum physics is remarkably simple, with a singe parameter N:

$$M = \sqrt{N}, \quad \lambda = \sqrt{N},$$

$$\alpha_{gr} = \frac{1}{N}$$

It is a *large-N* physics (in 't Hooft's sence) and is a result of maximal overpacking.

we shall see:

Black holes do carry hair under global charges (baryonic and leptonic numbers), which can be of 100% astrophysical importance.