Classicalization and Self-Completion

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Cesar Gomez;

+ Alex Kehagias, Gian Giudice,

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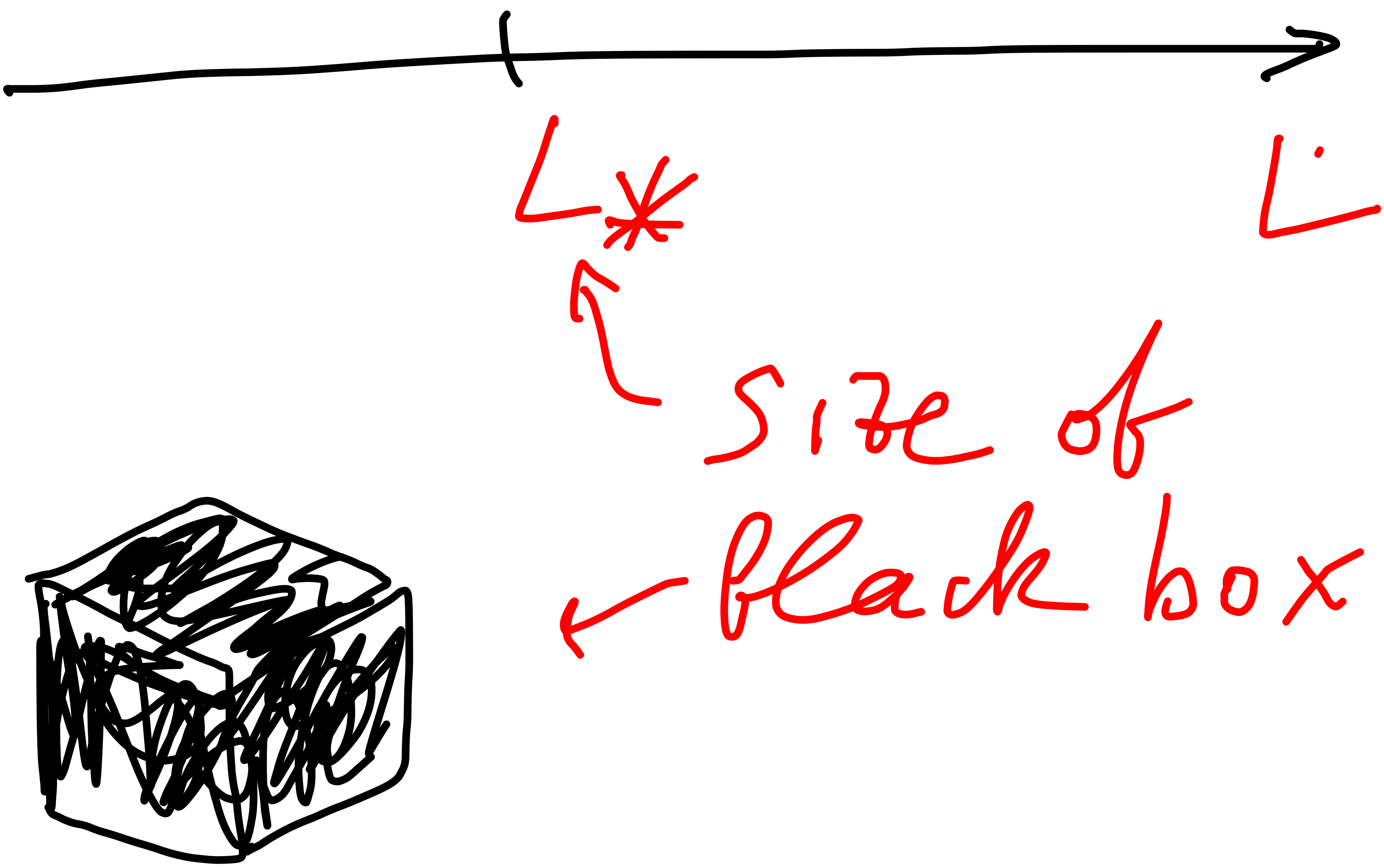
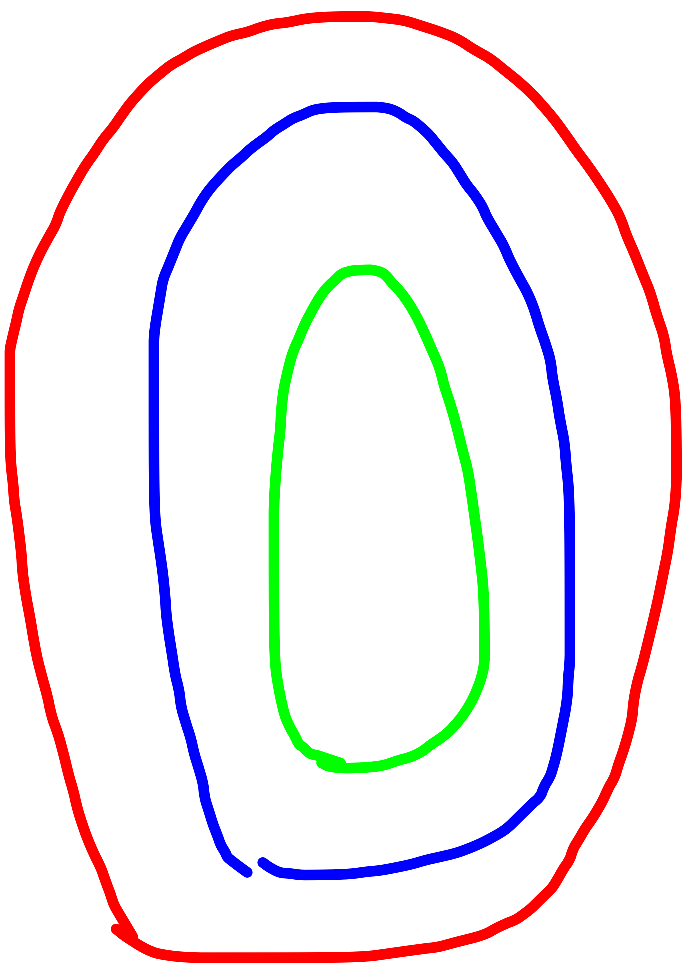
(ERICE, 2015)

Fundamental physics is about understanding nature at various length scales



Theories describing nature at different length-scales are embedded in one another like Russian dolls



UV-theory IR-theory

L_*

IR-theory is telling us about new UV-physics by becoming strongly coupled and violating perturbative unitarity.

Air molecules | Sound-waves

L_*

Think about the air in this room. Aair spontaneously breaks translation invariance and there are Nambu-Goldstone bosons, sound-waves!

IR-theory of sound-waves is analogous to IR-theory of longitudinal W-bosons.

For,

$$\lambda \ll \begin{pmatrix} \text{Inter-molecular} \\ \text{distance} \end{pmatrix}$$

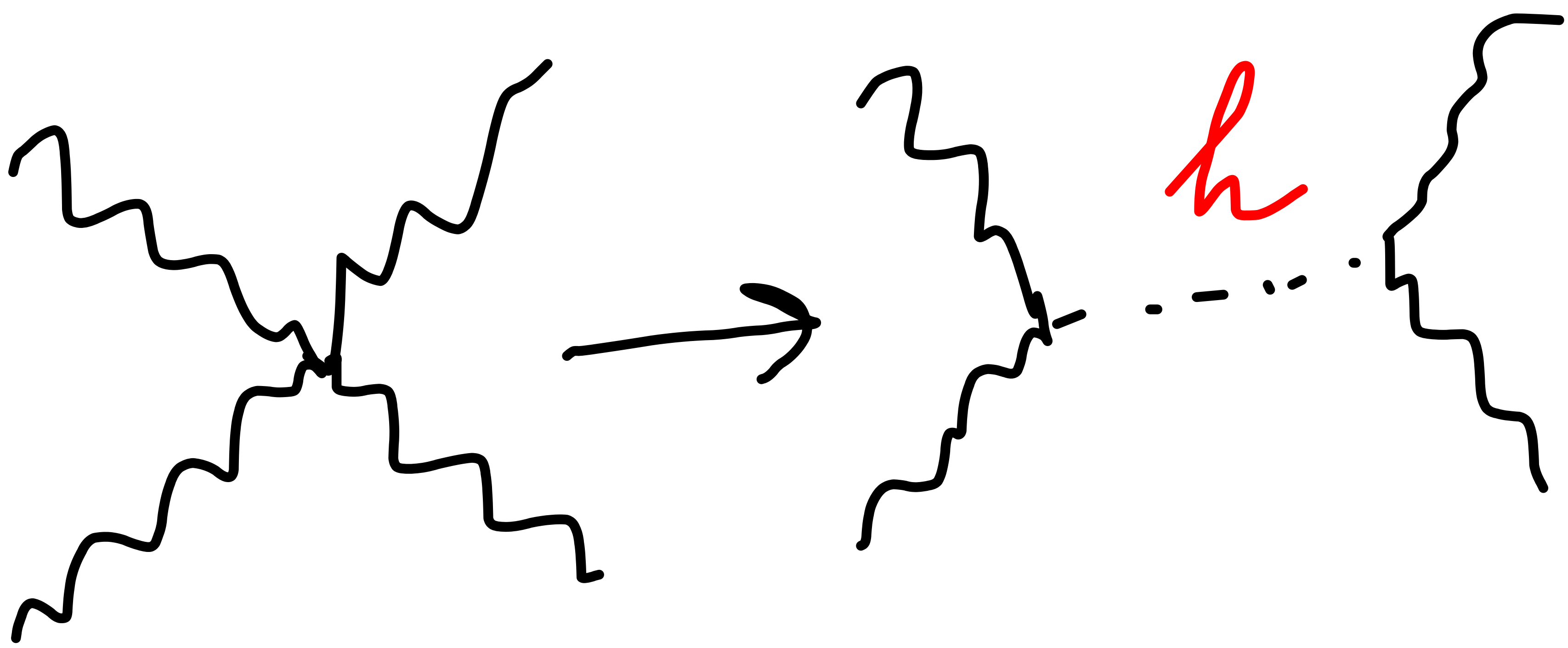
sound-wave description breaks down and unitarity is restored by molecular description.

In usual (Wilsonian) UV-completion one integrates in some new weakly coupled physics at distances $L < L_*$

Examples:

weakly-coupled Higgs, SUSY, ...

Due to this, Higgs restores perturbative unitarity violated by longitudinal W-s



Characteristic property of such Wilsonian UV-completion is that high energy scattering cross section diminishes

$$\sigma \sim \frac{\alpha^2}{s} \equiv r_*^2(s)$$

$r_*(s) \equiv$ scattering radius

It has been realized recently that UV-completion of the SM may not be Wilsonian.

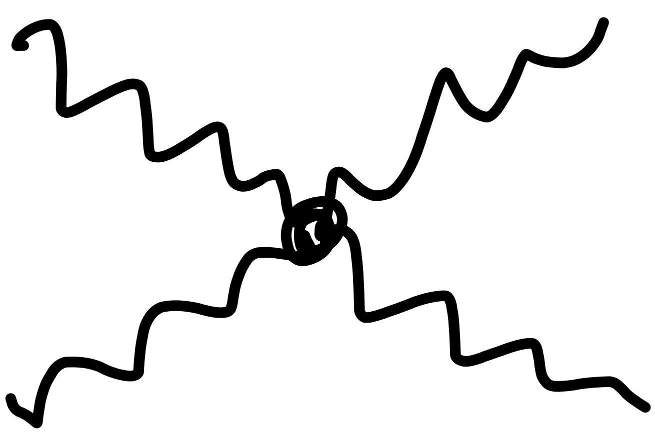
G.D. & Gomez; + Giudice Kehagias

In some theories no one or two-particle states exist at

$$L \ll L_*$$

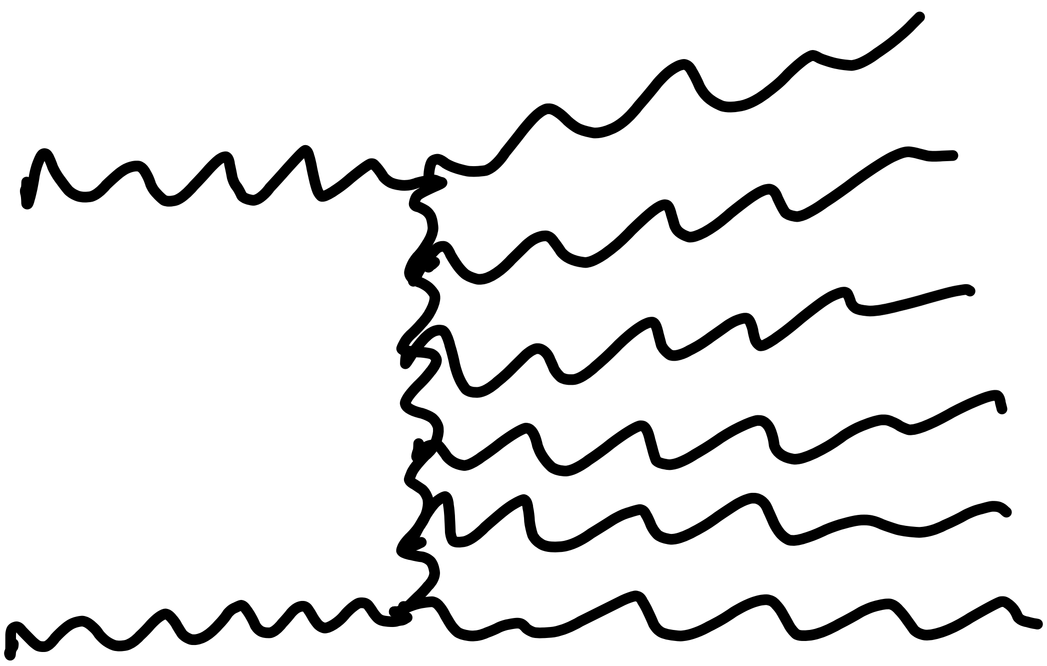
.

Above the cutoff the naive coupling becomes strong



$$\alpha_{\text{naive}} \sim \frac{s}{M_p^2}$$

But, in reality the theory becomes a theory of many soft quanta



$N = \alpha_{haire}$

$$\alpha = \frac{1}{N} = \frac{M_p^2}{s} \; !$$

One example of classicality interaction is gravity.

Imagine LHC could collide protons at

$$\sqrt{s} \sim M_{\odot} \sim 10^{57}\,\mathrm{GeV}$$

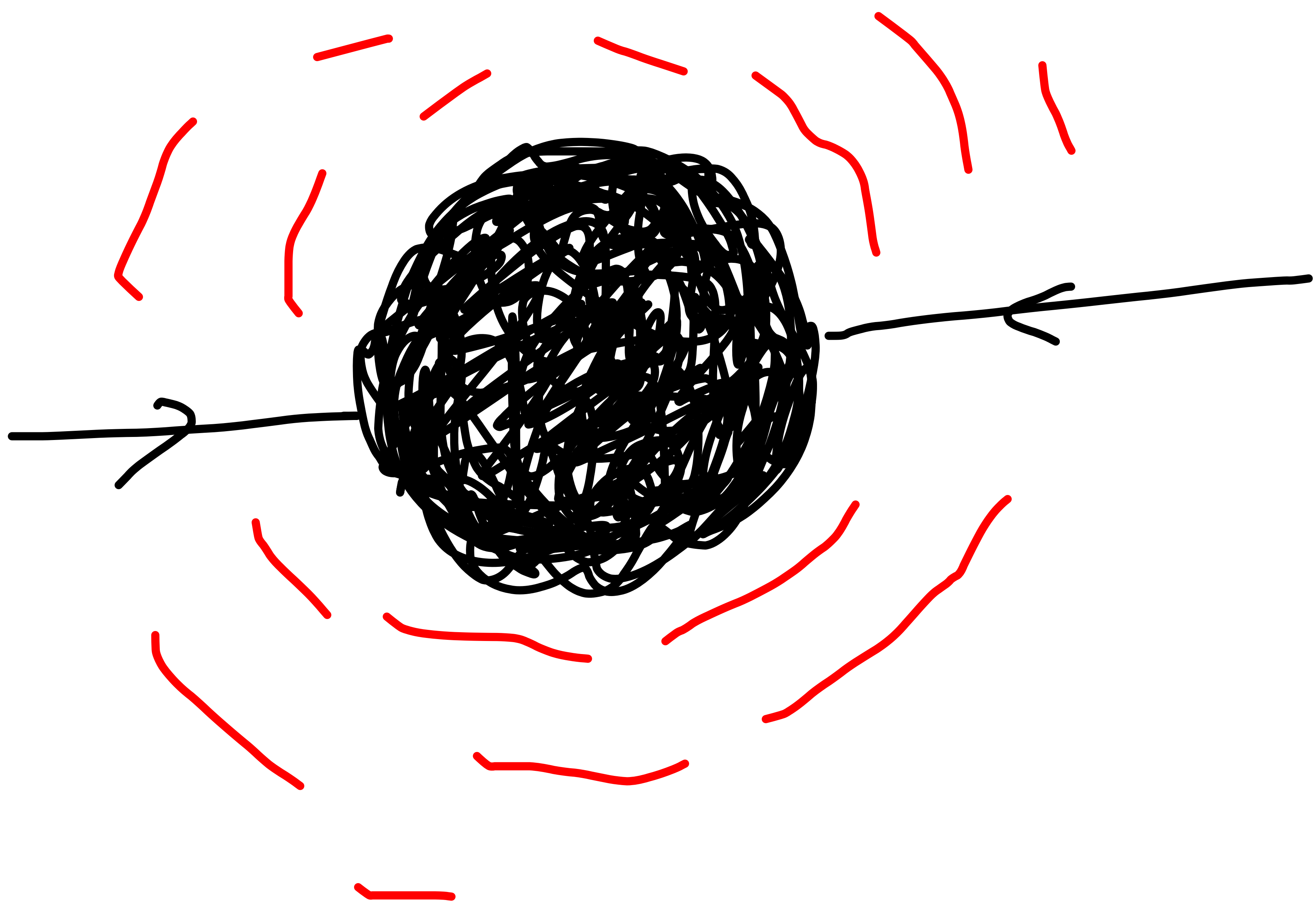
Naively, probed distances are

$$L = \frac{\hbar}{\sqrt{s}} \sim 10^{-71}\,\mathrm{cm}$$

This is wrong.

In reality a solar mass black hole is formed and the probed distance is

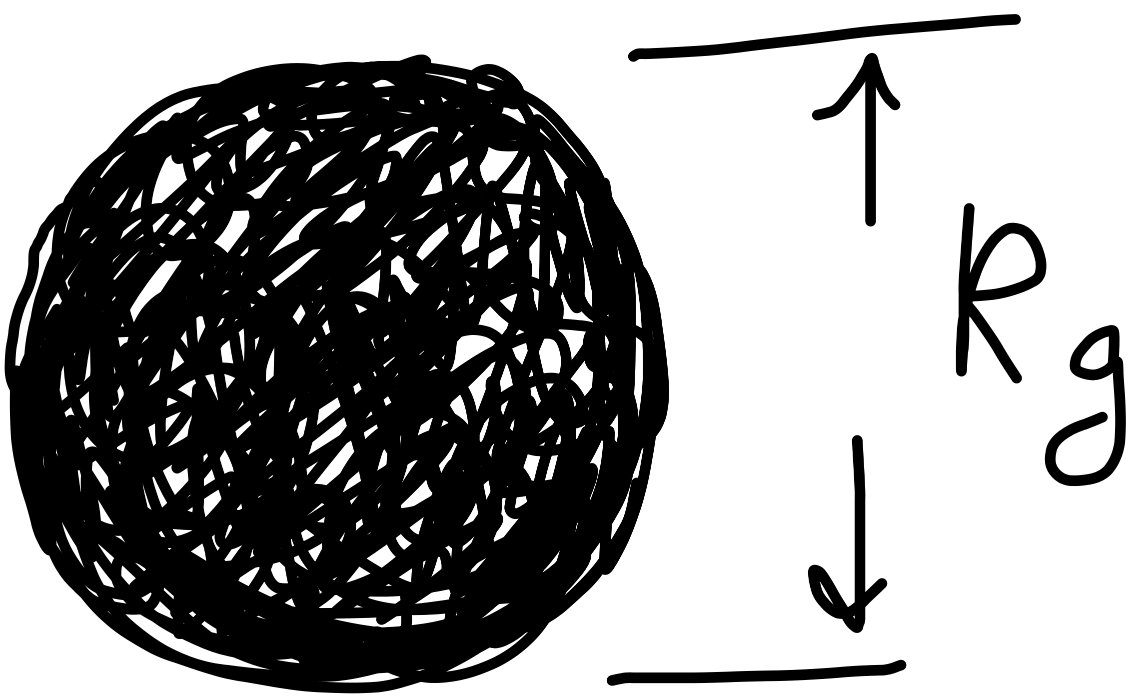
$$L \sim 10^{5}\ \mathrm{cm}$$



In gravity any source of mass M has a corresponding gravitational Schwarzshild radius

$$R_g \equiv 2 G_N M$$

Any source of size $R < R_g$ is a black hole



Such a black hole then will deplete slowly in extremely soft quanta of number

$$N \sim 10^{76}$$

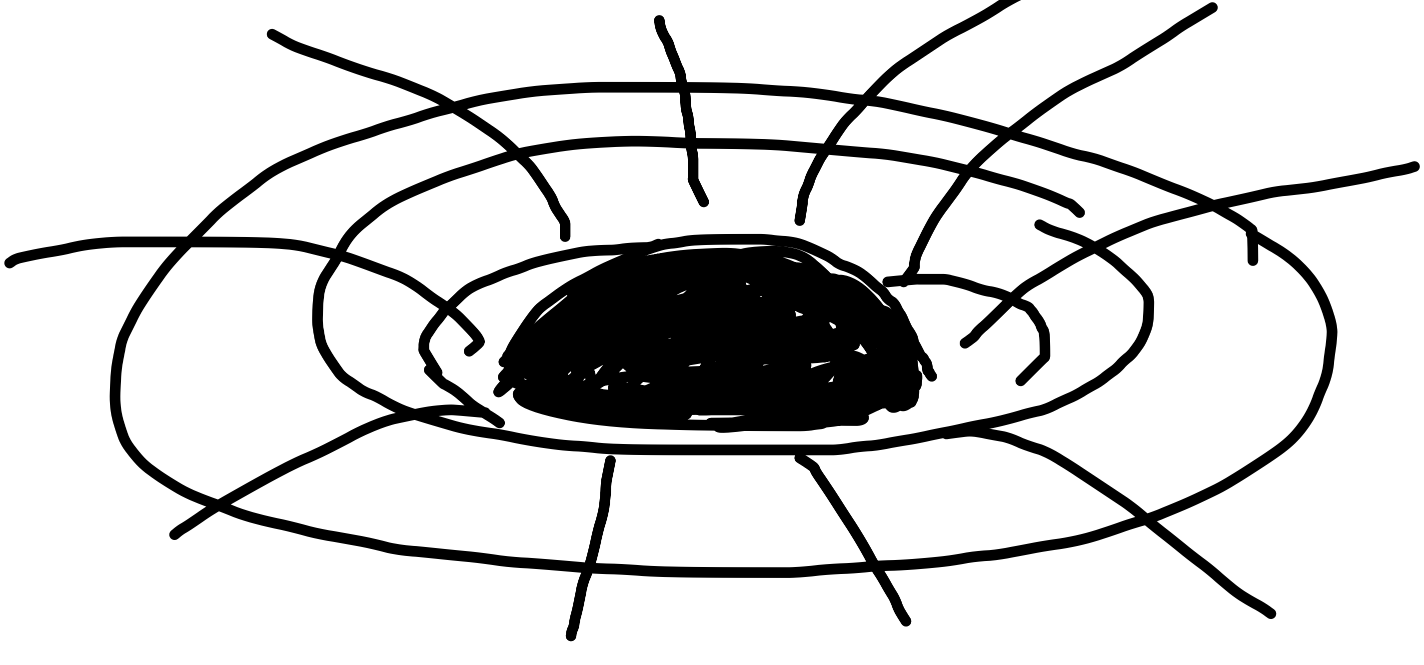
most of them of wave-length

$$\lambda \sim 10^{5} cm$$

of Hawking-type spectrum

Recall:

Schwarzschild black hole is a solution in GR



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

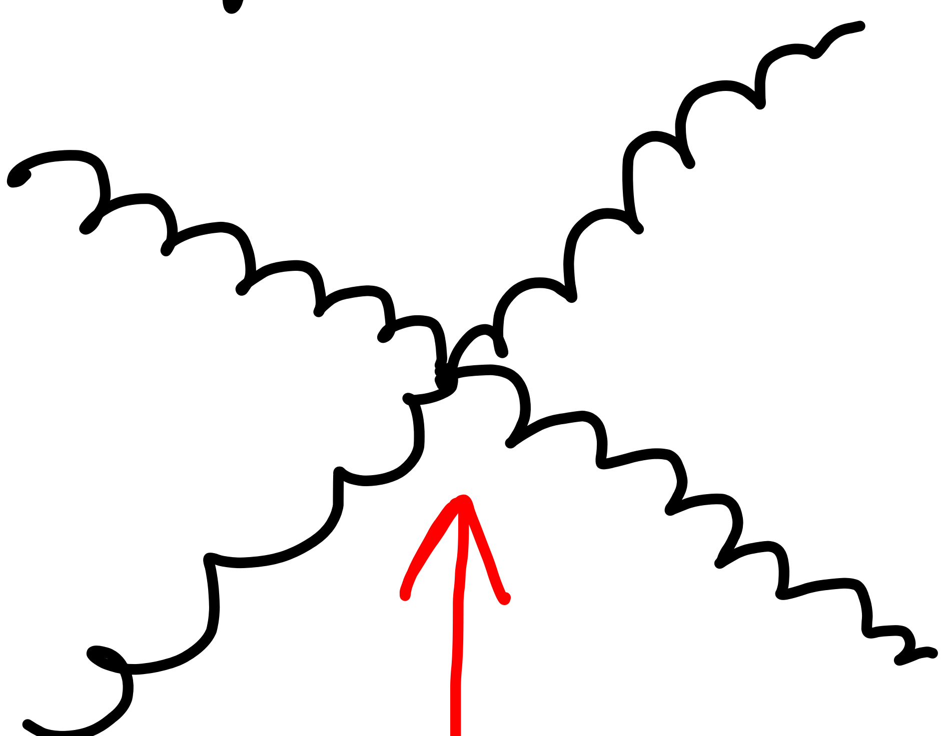
Intrinsically-classical concept!

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

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

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

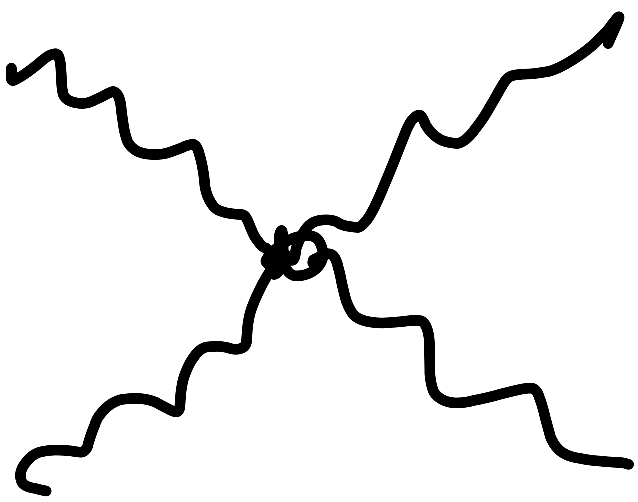
In classical limit ($\hbar \to 0$)

$$L_p \to 0$$

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

For example: For $\lambda \sim \mathrm{cm}$,

$$\alpha \equiv \left(\frac{L_P}{\lambda}\right)^2 \sim 10^{-66}$$



$$\Gamma \sim \left(10^{132}\,\mathrm{cm}\right)^{-1}$$

Scattering time

$$\tau \equiv \Gamma^{-1} \sim 10^{132}\,\mathrm{cm} \sim 10^{114}\,\mathrm{Y} \;!$$

The key point of our theory:

Black hole is a self-sustained quantum criticality.

That is:

① Black hole is a bound-state of N soft gravitons of wavelength $\lambda = \frac{M}{M_p^2}$ and the occupation number $N = \frac{M^2}{M_p^2}$.

and

② The system is at the quantum critical point $N = \frac{1}{\alpha}$

Classical theory: Geometry of radius R

$\Downarrow$

Quantum theory: N-particle state $|N\rangle$ (coherent state or Bose-Einstein condensate)

with:

$$\lambda = R$$

$$N = \left(\frac{R}{L_p}\right)^2 \equiv \frac{1}{\alpha}$$

How many gravitons of wave-length $\lambda \gg L_p$ form a black hole?

$$M = N\frac{\hbar}{\lambda}$$

$$R \equiv G_N M = N\frac{\hbar G_N}{\lambda} = \lambda$$

$$N = \left(\frac{\lambda}{L_p}\right)^2 = \frac{1}{\alpha}\ !$$

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

$$E_k + V = 0$$

$$\downarrow$$

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

A self-sustained boundstate is formed for

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

Further evidence for our composite picture:

* Black hole production in $2 \to N$ graviton scattering;

* Scrambling of quantum information.

It is commonly accepted that black holes should be produced in trans-Planckian scattering

e.g.

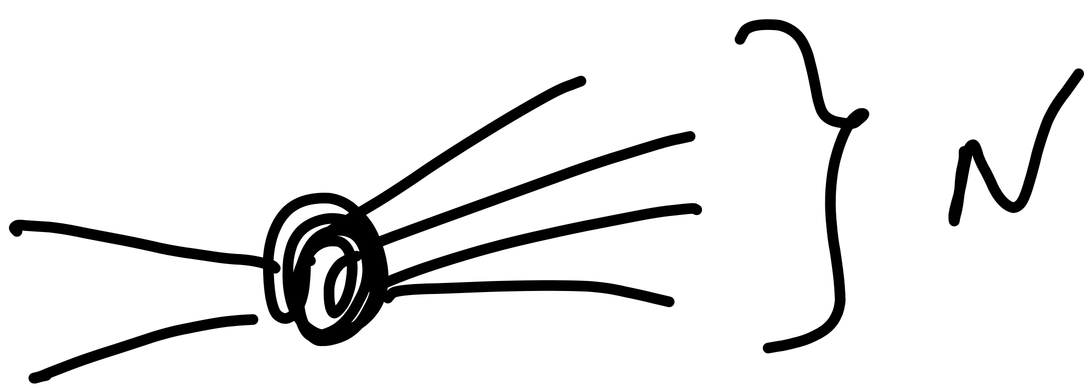
$$e^+ + e^- \longrightarrow BH$$

('t Hooft; Amati, Ciafaloni, Veneziano; Gross, Mende, ...)

Was even predicted at LHC (Antoniadis, Arkani-Hamed, Dimopoulos, GD)

We have such a microscopic theory which predicts that the relevant process is

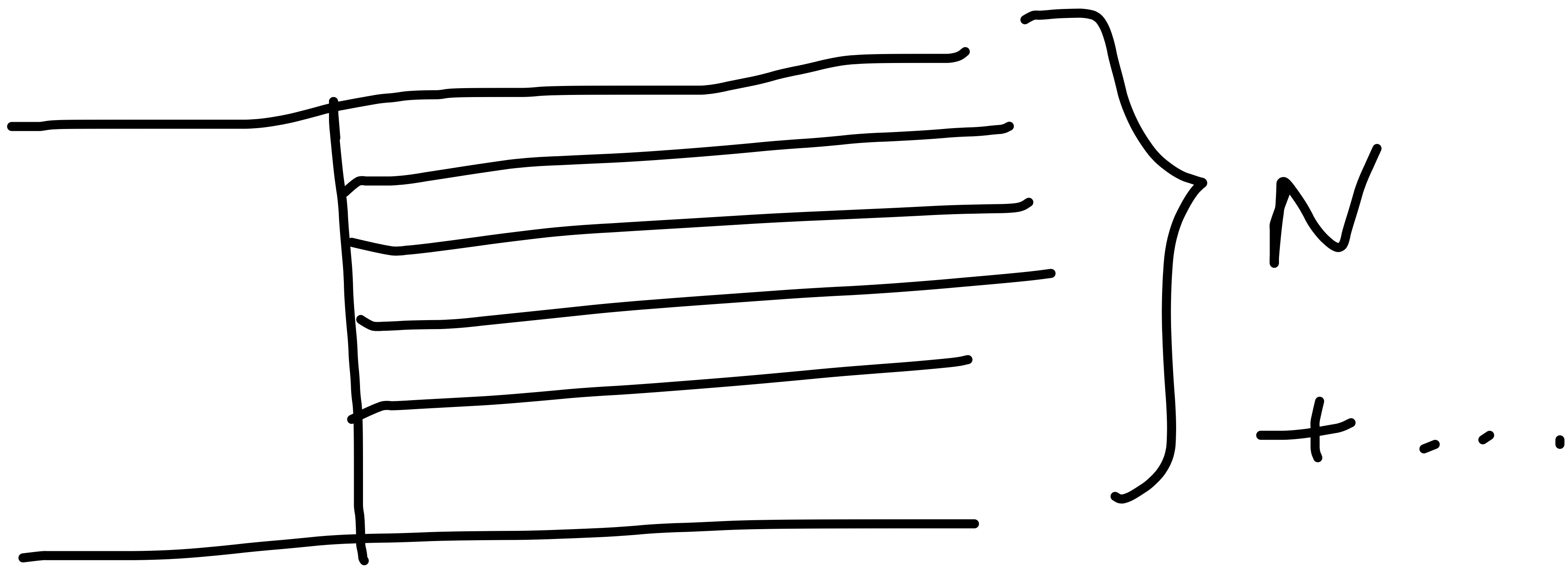
$$2 \to N \text{ gravitons}$$



with $N = \dfrac{s}{M_P^2} \gg 1$

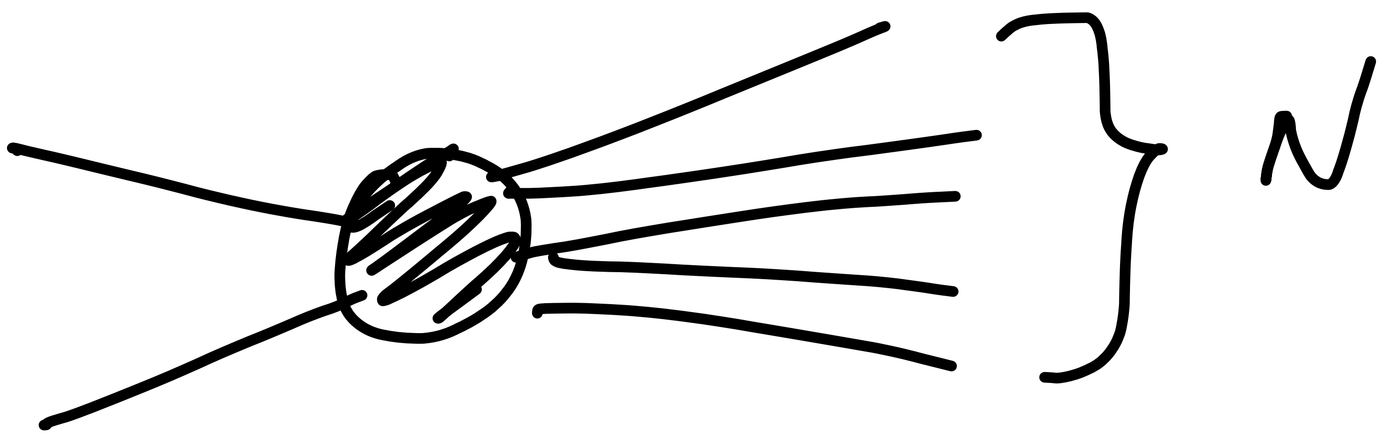
$2 \to N$ graviton scattering

GD, Gomez, Isermann, Lüst, Stieberger, hep-th/1409.7405



In our kinematic regime loops are suppressed by $\sim \frac{1}{N}$

for $2 \to N$ amplitude we get

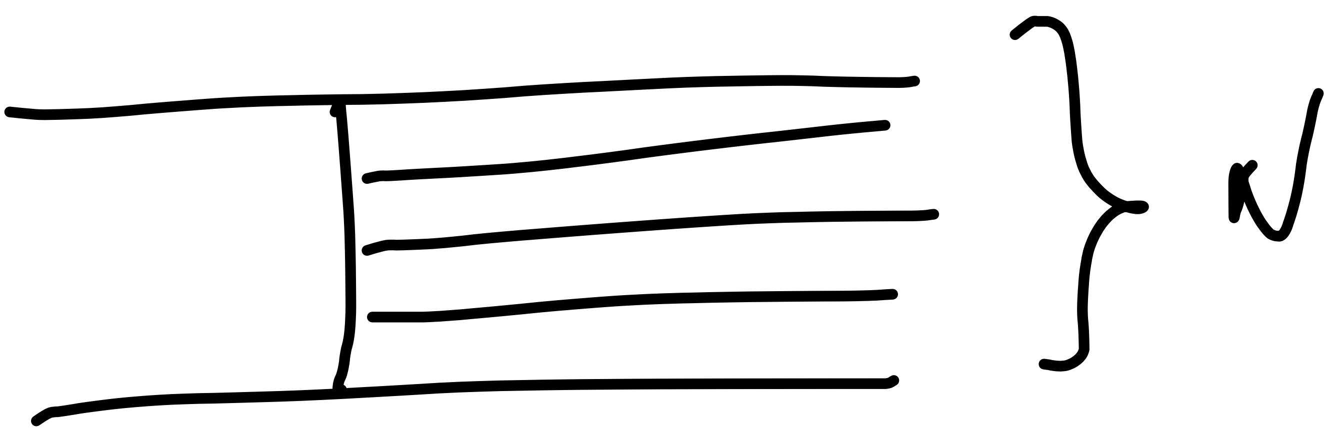


$$\sigma_{2\to N} = \frac{s}{M_p^4}\left(\frac{1}{N}\right)^N N! = \frac{s}{M_p^4} e^{-N}$$

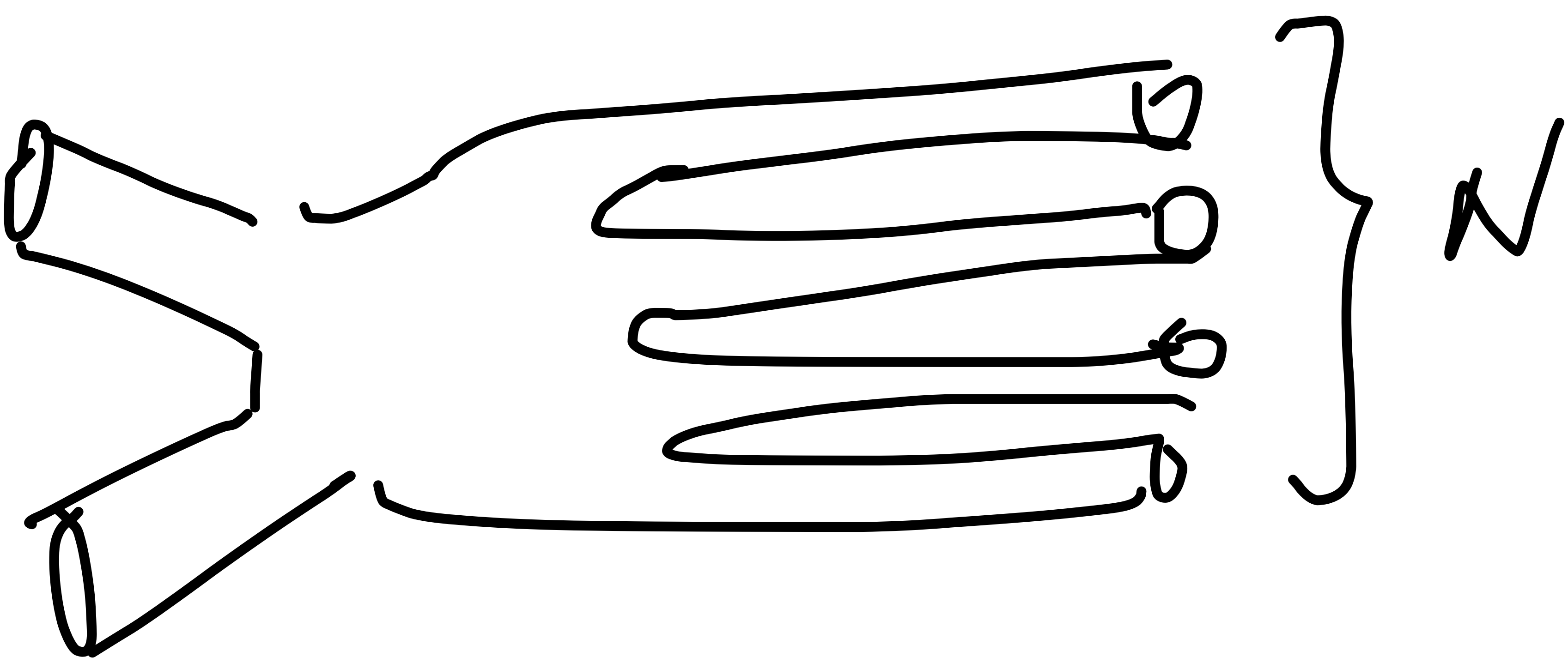
This exactly matches the black hole entropy factor!

Our result are UV-insensitive:

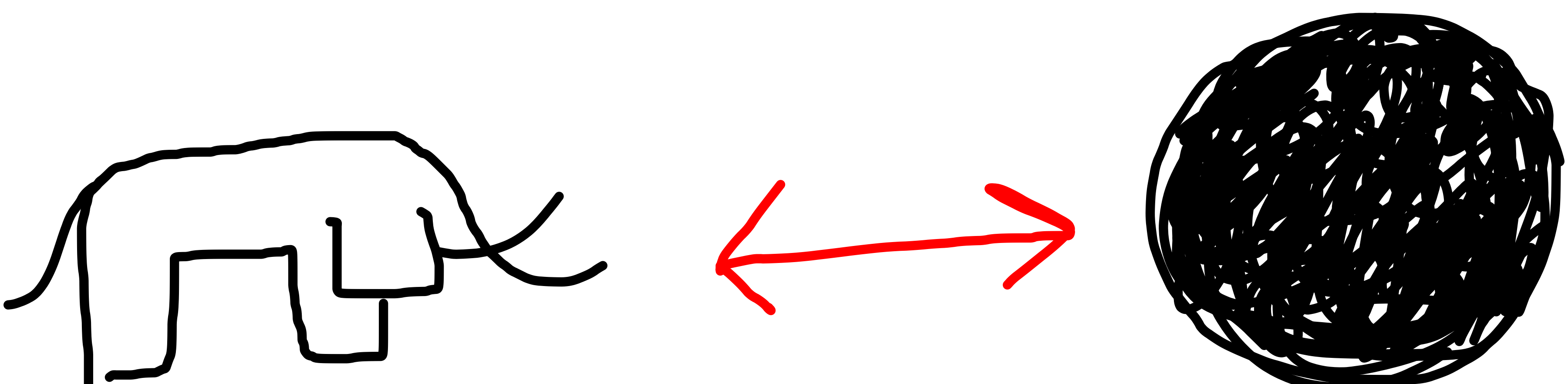
We get the same result in field theory



and string theory

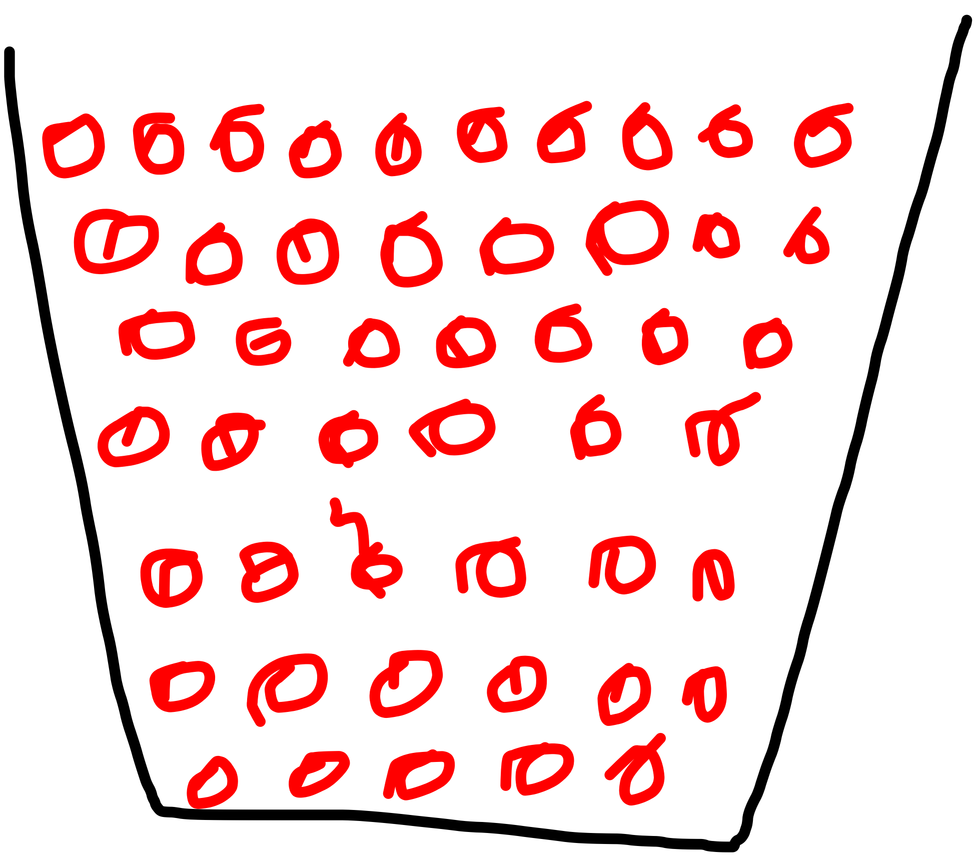


The answer is that Black Holes are macroscopic, but quantum!

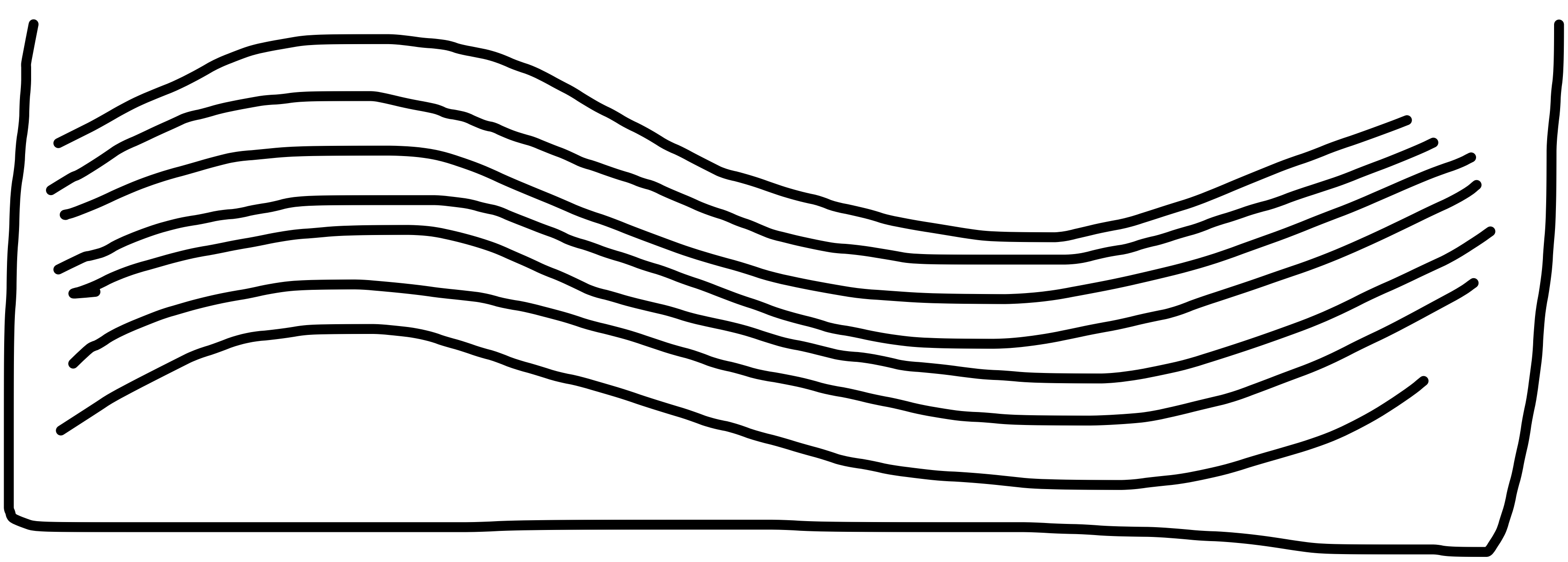


$$\sim e^{-N} \longleftrightarrow \sim 1$$

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.



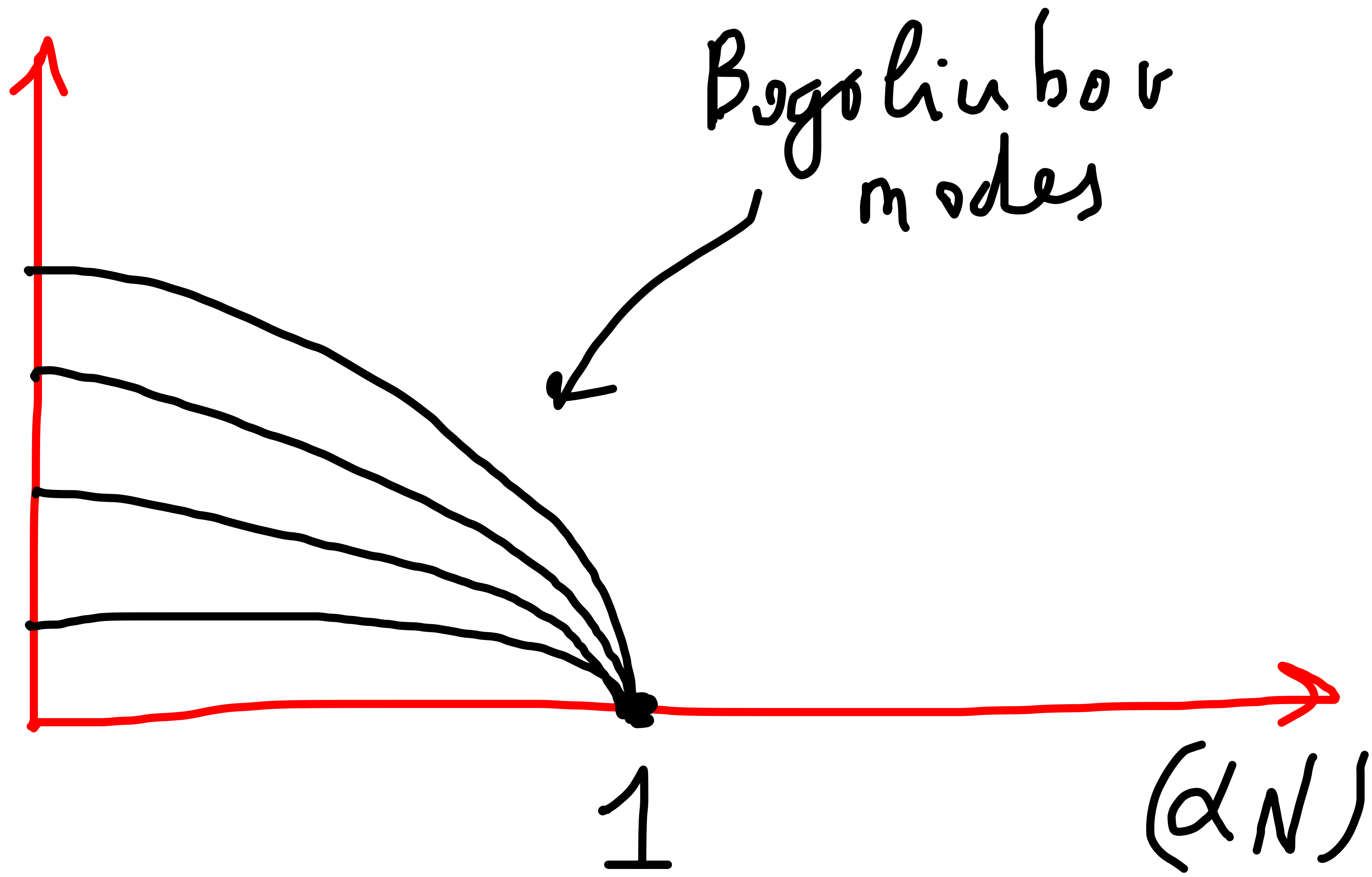
For such systems we can define a quantity

$$(N\alpha)$$

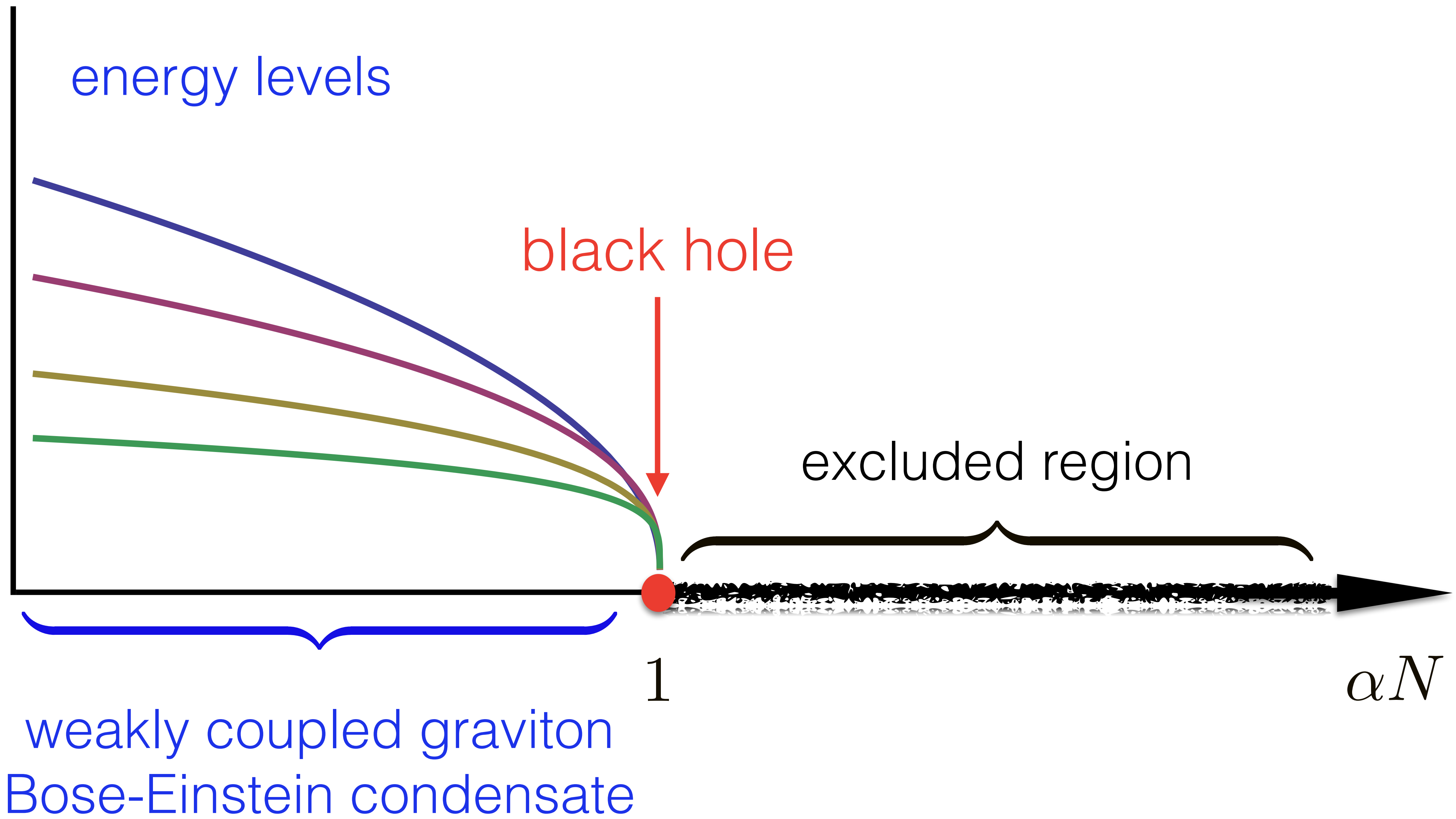
Something very special takes place at

$$N\alpha = 1$$

Critical point of quatum phase transition.



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


energy levels
black hole
excluded region
1
αN
weakly coupled graviton
Bose-Einstein condensate

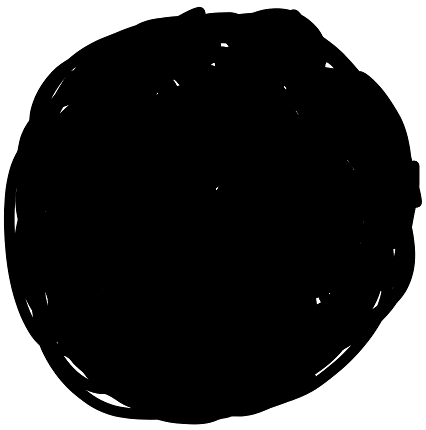
Energy gap

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

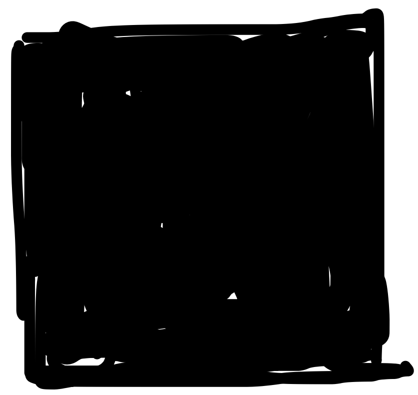
These Bogoliubov modes are quantum ("holographic") degrees of freedom responsible for

Bekenstein entropy.

Black Hole



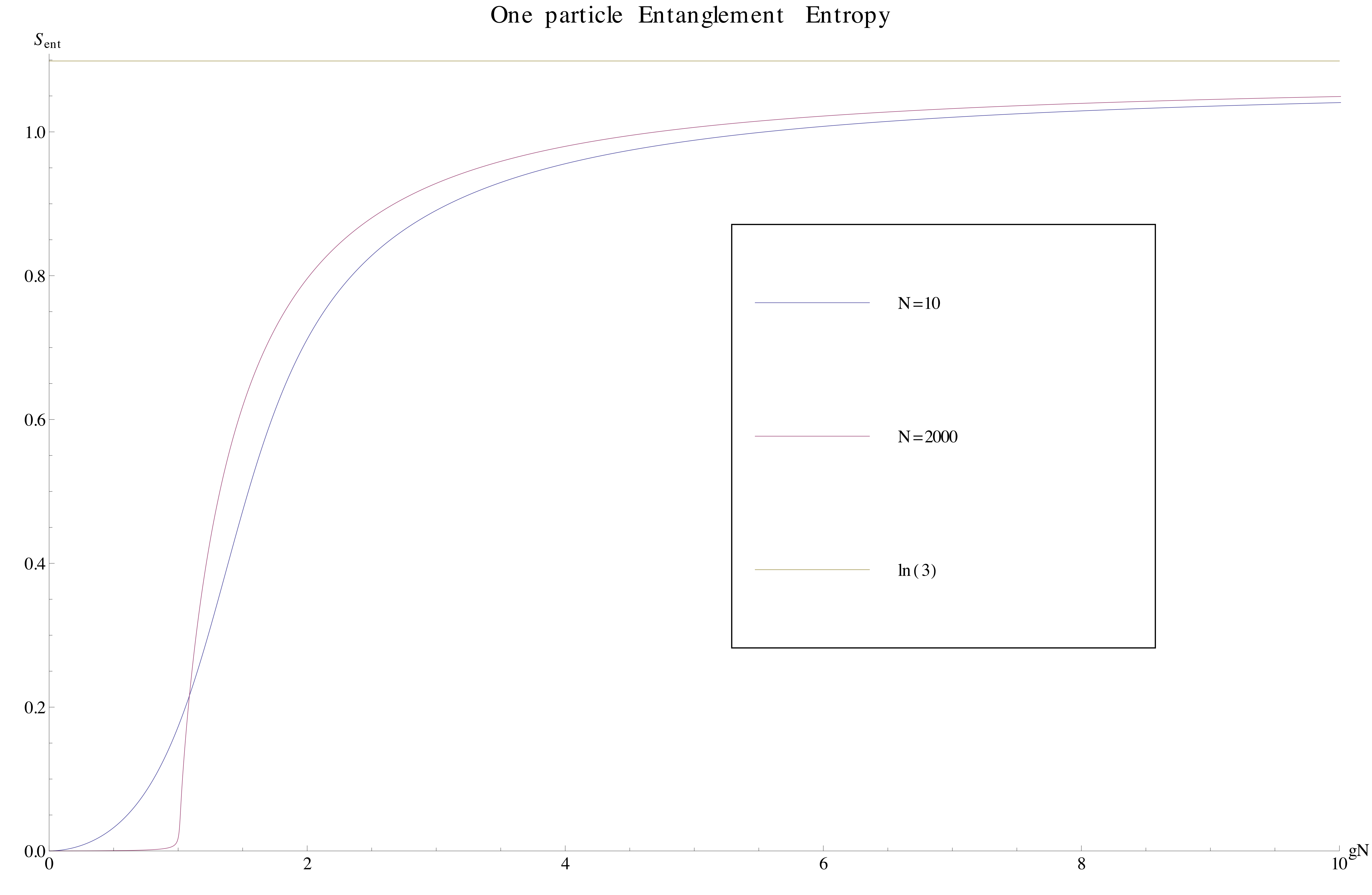
Malevich's Black Square



Quantum Black Hole carries maximal information!

Some numerical studies by:

Daniel Flassig,
Alex Pritzel,
Nico Wintergerst



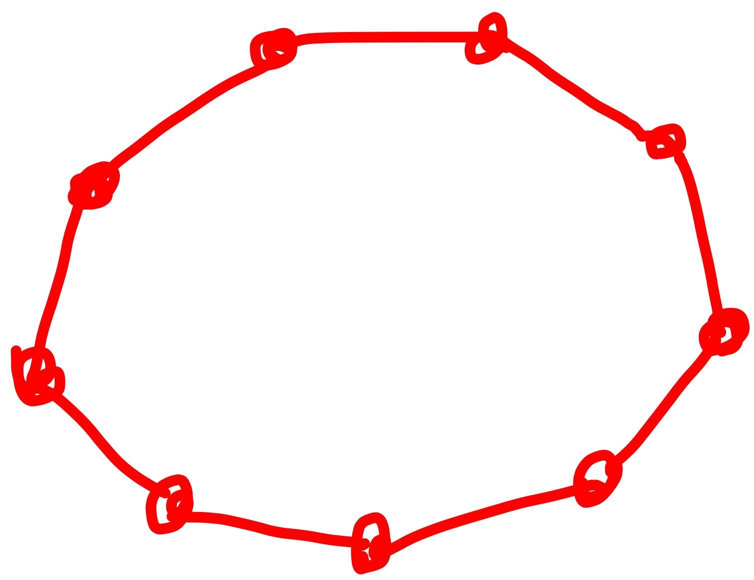
One particle Entanglement Entropy
S_{ent}
gN
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
N=10
N=2000
ln(3)

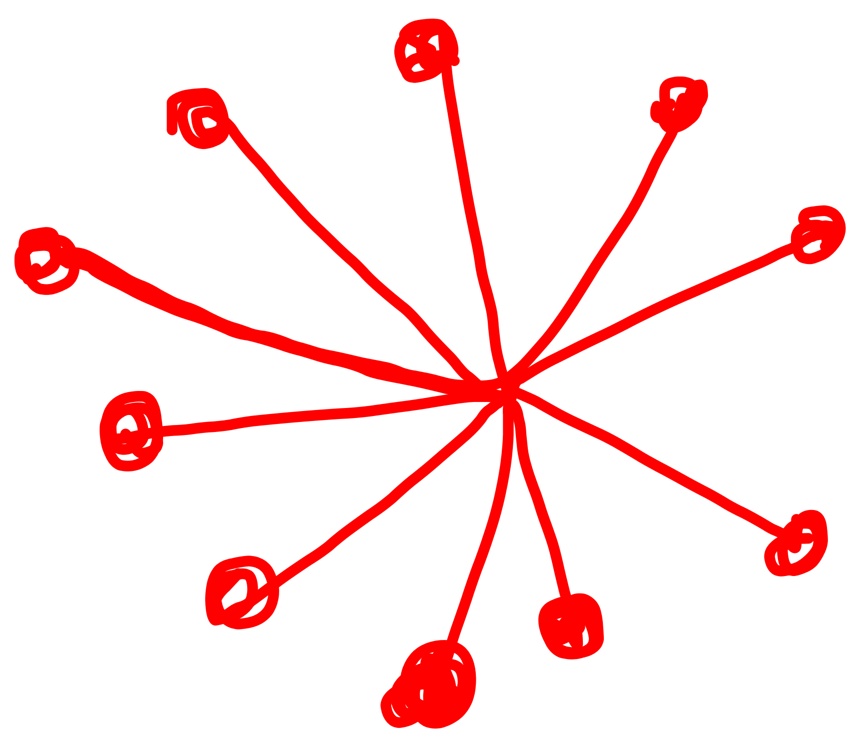
Scrambling of Information

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

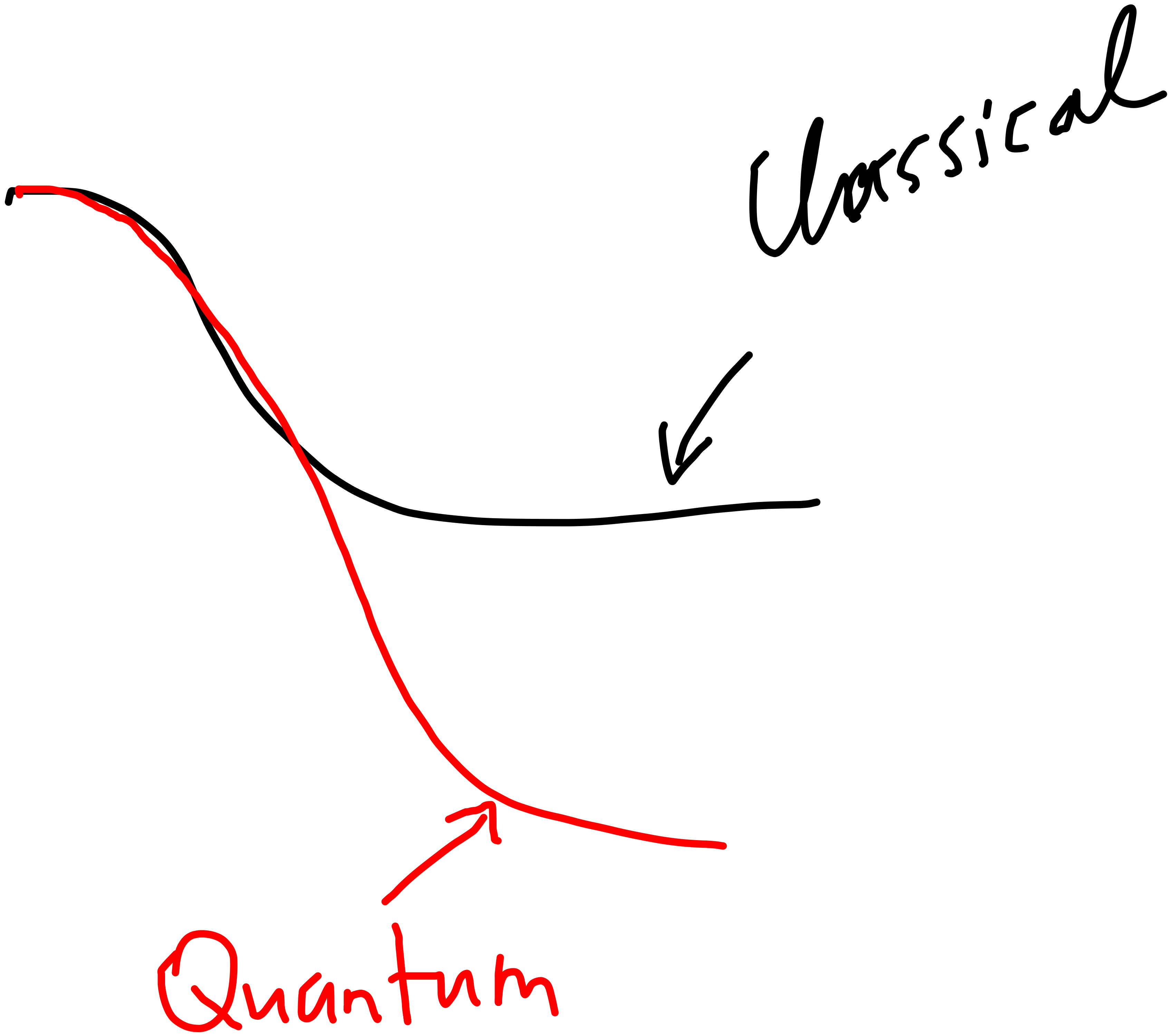
$$t_{sramb} \sim \ln R$$

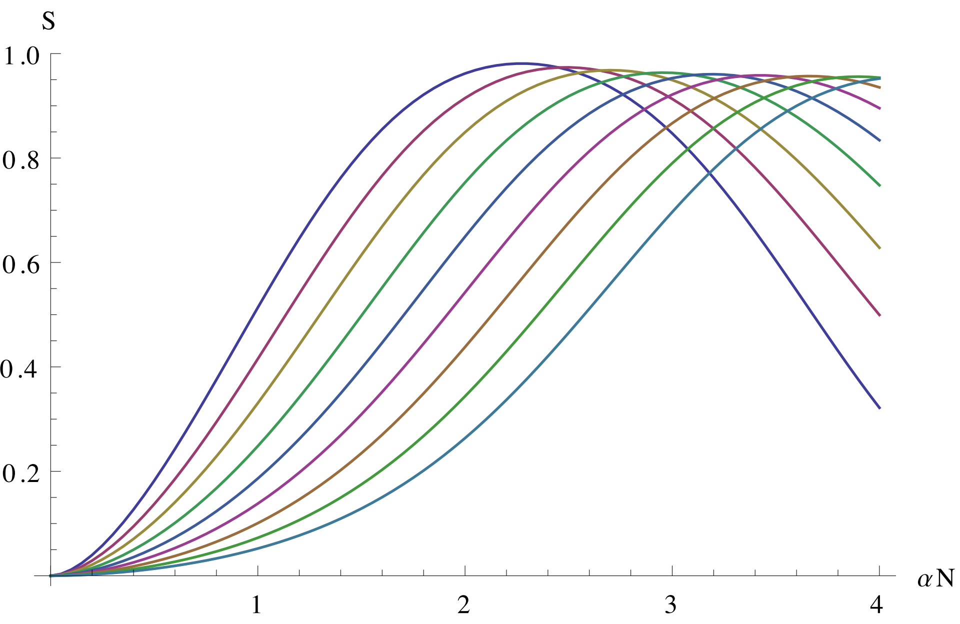
Roughly speaking scrambling is an ability of a system to spread information among the constituents

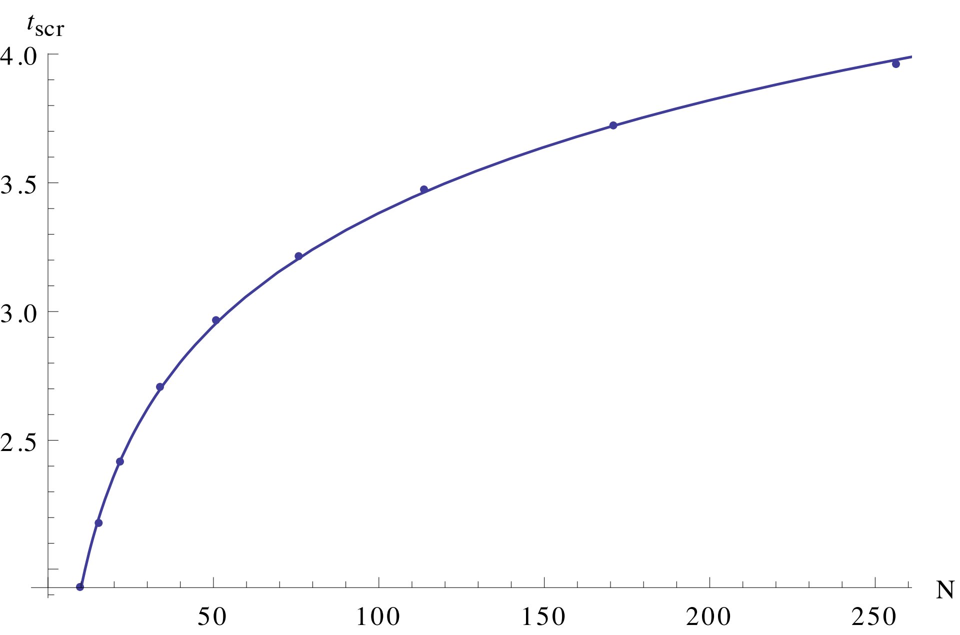




Quantum break time:




S
1.0
0.8
0.6
0.4
0.2
1
2
3
4
αN

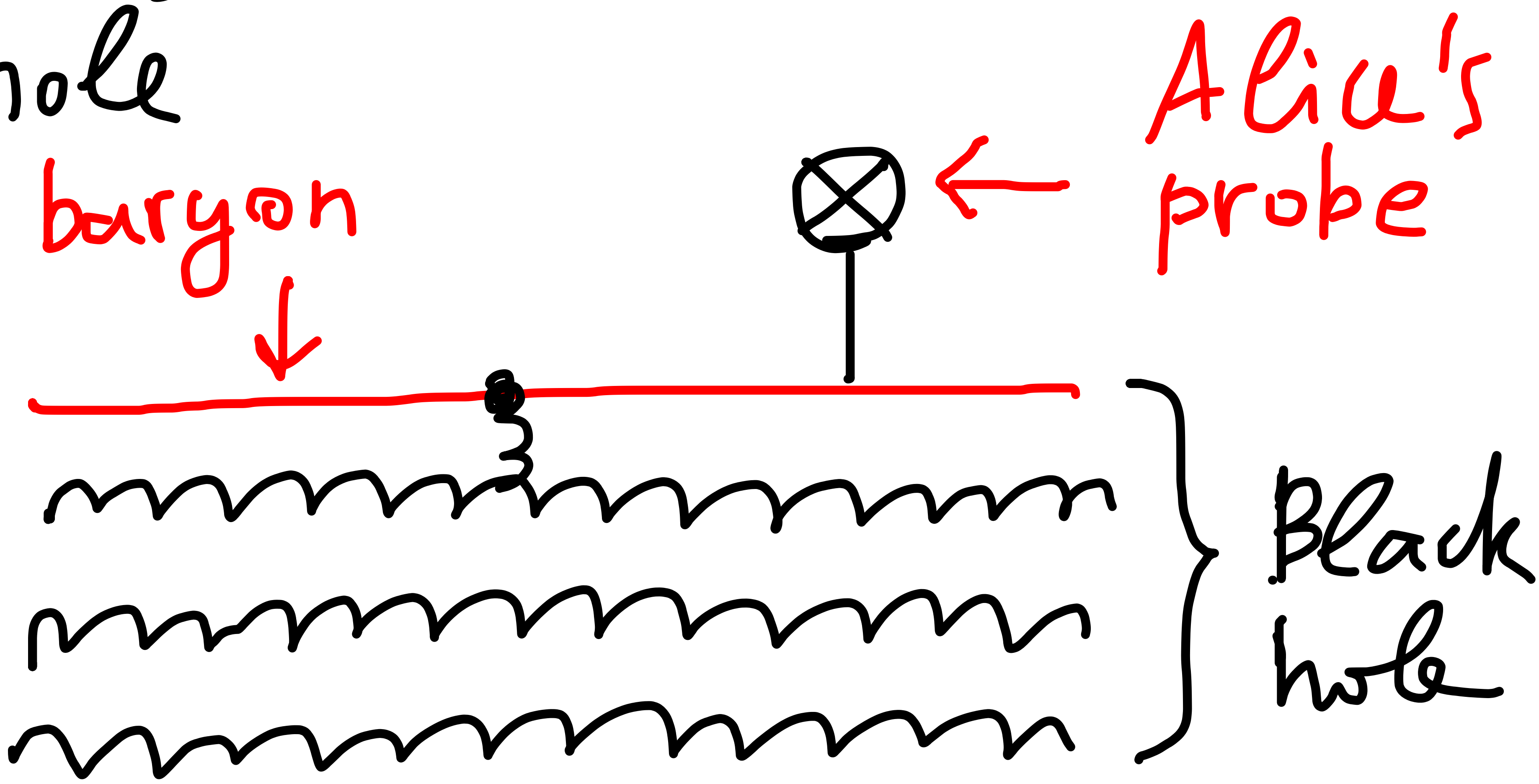

t_{scr}
4.0
3.5
3.0
2.5
N
50
100
150
200
250

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



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

Depletion law for a global charge for $N \gg N_B \gg 1$:

$$\dot{N}_B = -\frac{1}{\sqrt{N}\,L_p}\,\frac{N_B}{N} + \ldots$$

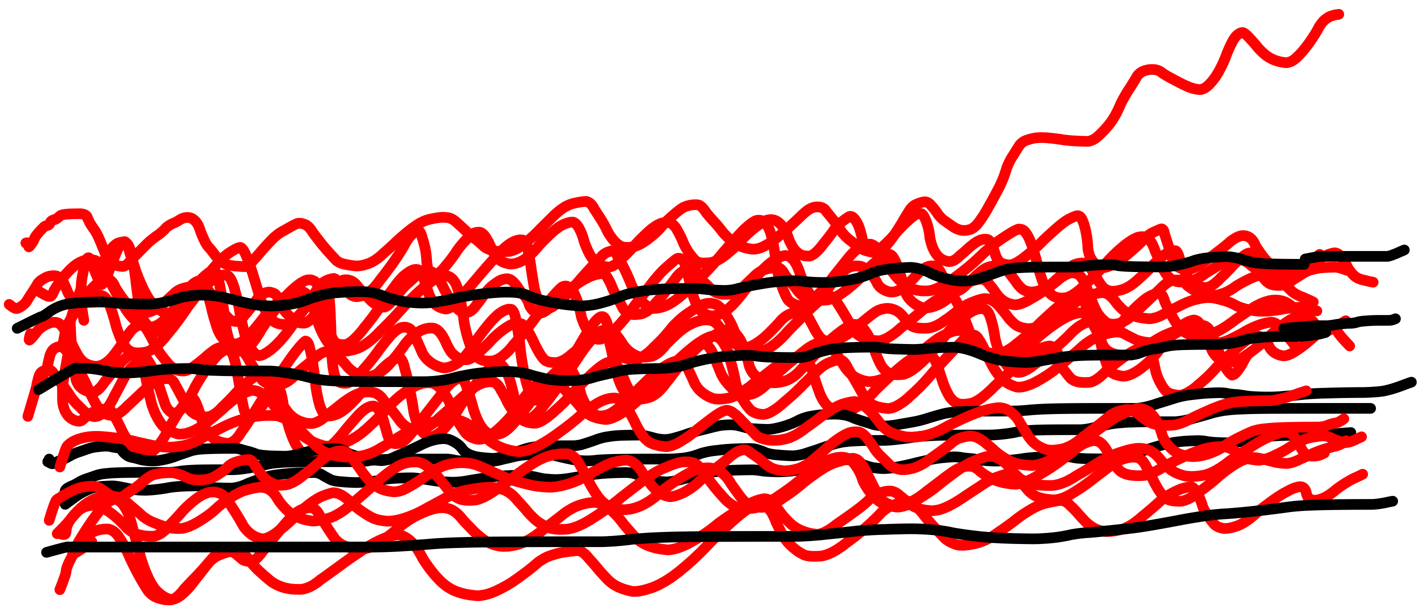
$$\boxed{\tau = \frac{2}{3}\frac{t}{L_p}}$$

$$\downarrow$$

$$N(\tau) = (\tau_* - \tau)^{\frac{2}{3}}$$

$$N_B(\tau) = \left(1 - \frac{\tau}{\tau_*}\right)^{\frac{2}{3}} N_B(0)$$

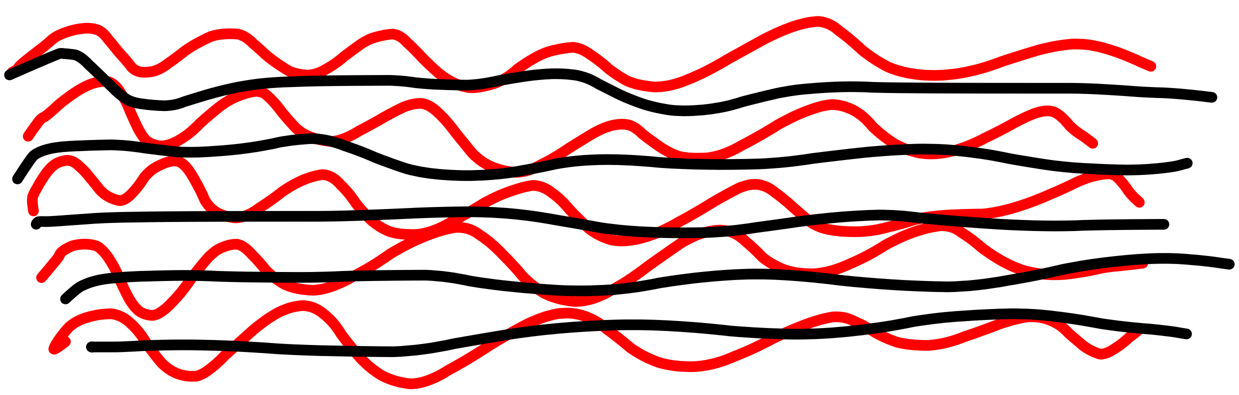
(microscopic reason for Page's information retrieval)



For $N_B \ll N$ the depletion and leakage continues untill non-gravitational interaction between "baryons" becomes important!

For example for "baryons" interacting with gravitational strength, this will happen when

$$N_B \sim N$$



what happense after?

Depends on a delicate balance between gravity and non-gravitational forces.

One thing is certain. Beyond this point evolution of a macroscopic black hole is nothing like we thought before.

The interesting case for Dark Matter is when short-range "baryonic" forces balance gravity.

There is an indication that for

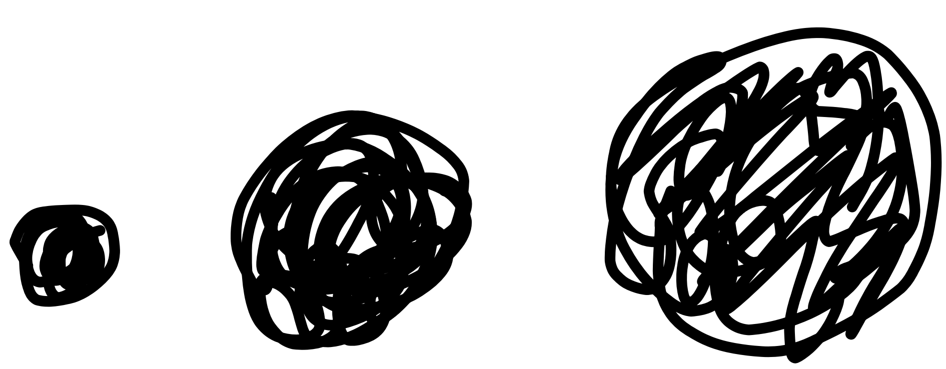
$$R_{BH} < L_{QCD}$$

this is the case for

$$N_B \sim N$$

If true, such black holes can be intersting Dark Matter candidates with masses in new range

$$M_p < M_{DM} < 10^{17}\,g$$



DM Species

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

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

in the semi-classical limit

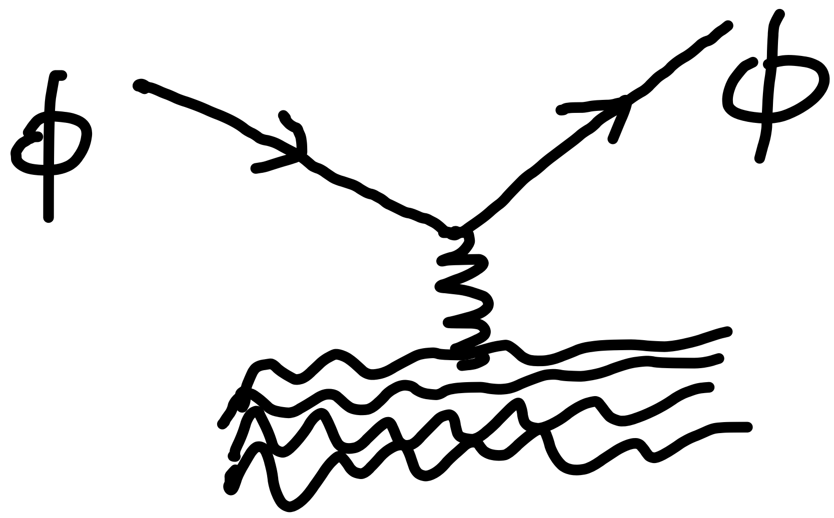
$N \to \infty$, $L_p \to 0$, $\sqrt{N}L_p = \text{fixed}$

We get Stefan-Boltzmann law for Hawking evaporation

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

In corpuscular picture GR emerges as mean-field description in $N \to \infty$

$T^{\mu\nu}(\phi)\, h_{\mu\nu}$

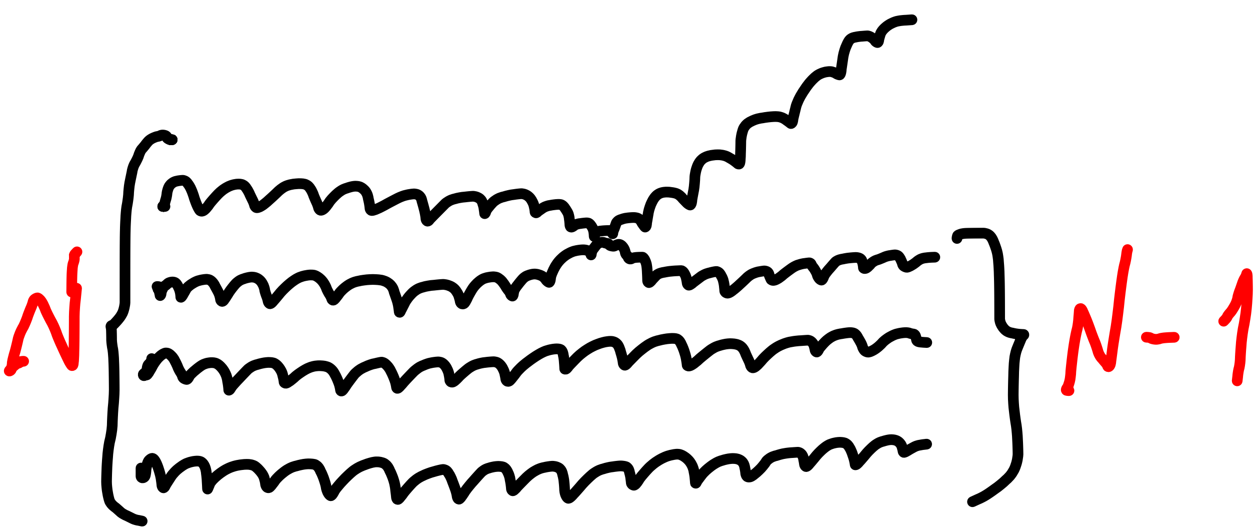


$$\langle N', \phi_f | \hat{S} | N, \phi_{in} \rangle =$$

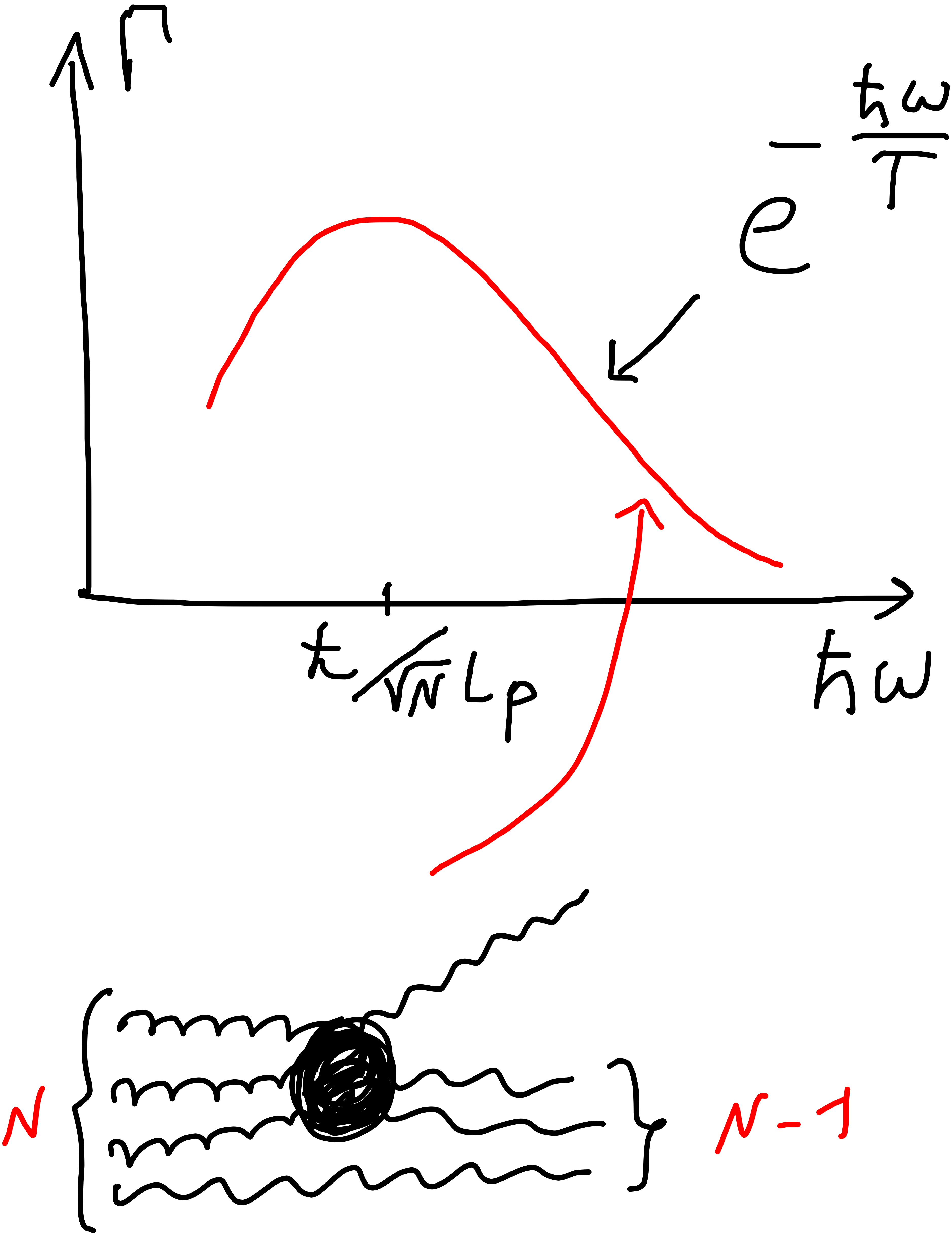
$$= \int g_{\mu\nu} T^{\mu\nu}(\phi) + \frac{1}{N} \text{ – corrections}$$

Quantum!

Particle production is not a vacuum process.
Instead it is a quantum depletion of existing particles!



$$\dot{N} = -\frac{1}{\sqrt{N}\,L_p} + O\left(\frac{1}{N}\right)$$


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

Semi-classical limit:

$$M \to \infty$$

$$G_N \to 0$$

$$R \equiv M G_N = \text{finite}$$

$$\hbar = \text{finite}$$

In this limit

$$L_p^2 \equiv \hbar G_N \to 0$$

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

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

in the semi-classical limit

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

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

Daniel Flassig, Alex Fritzel, Nico Wintergerst, Andre Franca, Valentino Foit, Sarah Folkerts, Mischa Panchenko, Tehseen Rug, Lukas Gründing, Alexander Gussmann, Artem Averin, Sophia Müller, ...

Recent article with: Gomez, Isermann, Lüst, Stieberger.

See work by: Florian Kühnel & Bo Sundborg

See also:

Casadio, Giugno, Orlandi;

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