Demystifying Black Holes

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1907.07332
1906.03530

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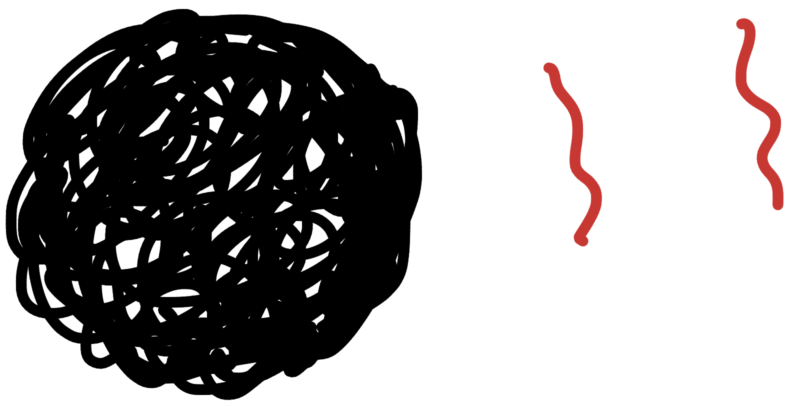
Black holes are considered to be mysterious



⊛ Hawking temperature

$$T = \frac{1}{R}$$

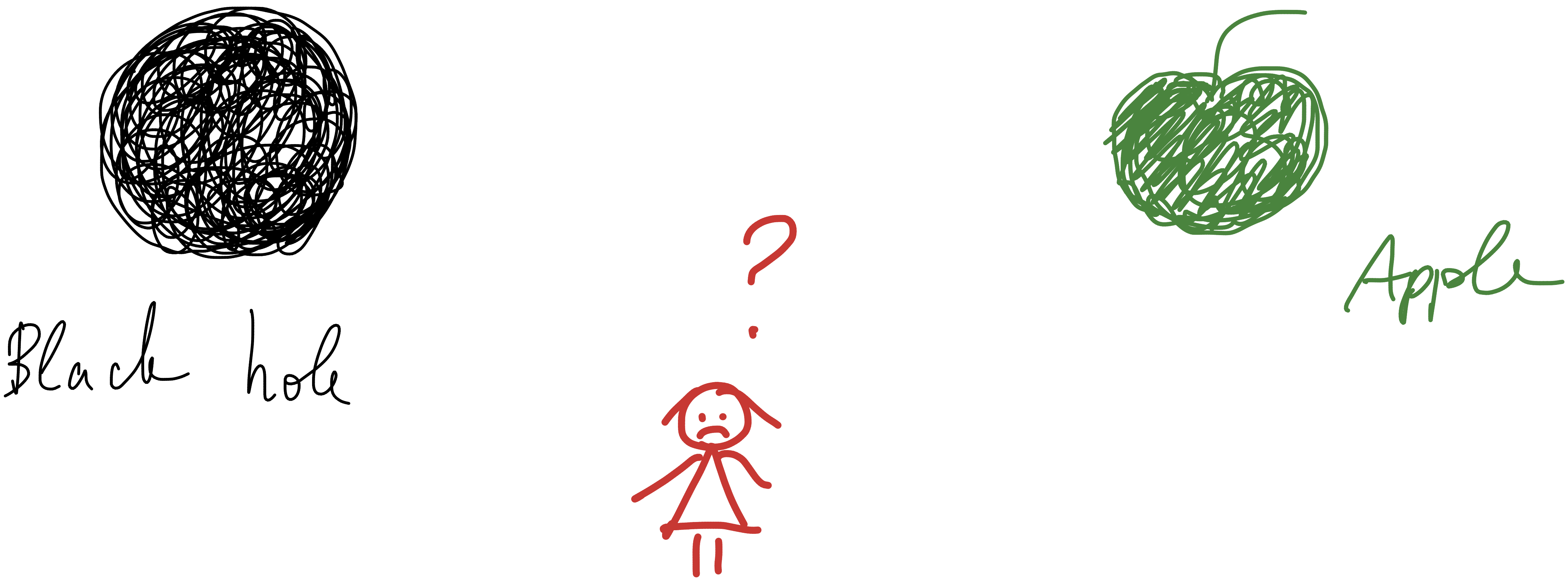
⊛ Bekenstein-Hawking entropy

$$S_{BH} = \frac{\text{Area}}{G_N}$$

⊛ Long time-scale of information retrieval. (Page):

$$t \sim S R \sim \frac{R^3}{G_N}$$

How special are black holes?



In order to compare objects we must bring them into the same universality class.

We wish to show that all these "mysterious" properties are fully shared by objects that have maximal entropy compatible with unitarity.

We call them "Saturons".

In particular, we shall demonstrate their existence in renormalizable calculable theories.

This indicates that:

Black hole = Saturon

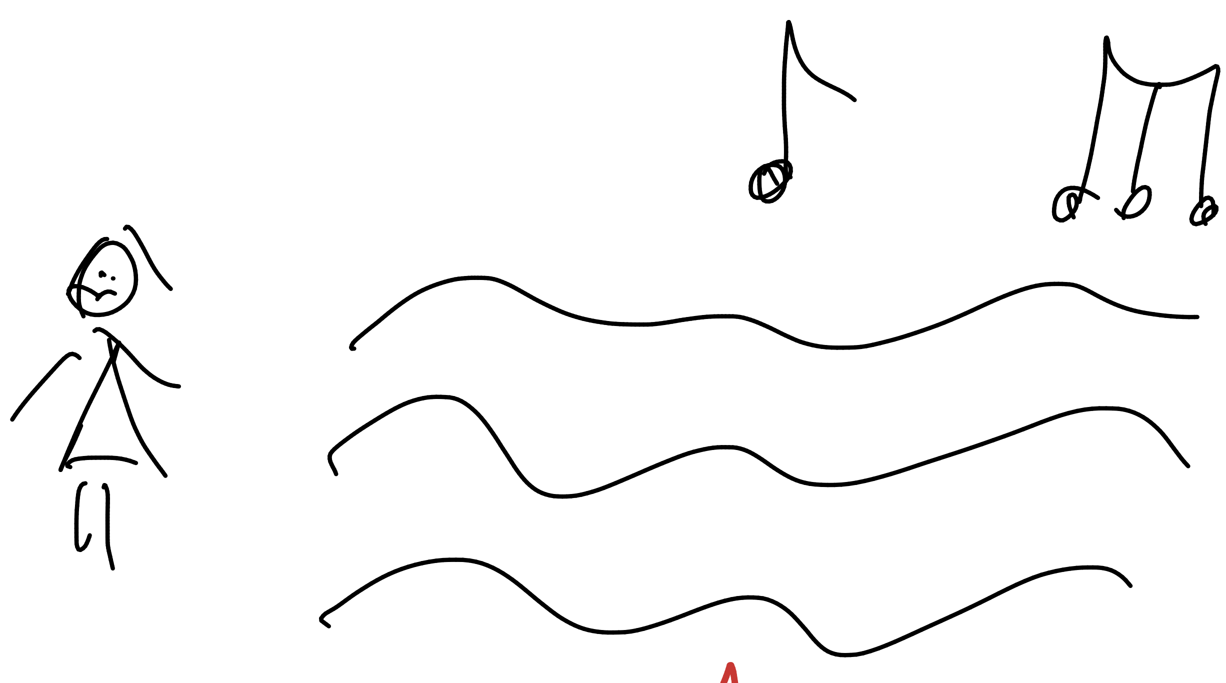
Goldstone theorem:

Spontaneous breaking of global symmetry

$\downarrow$

Gapless Nambu-Goldstone "bosons".

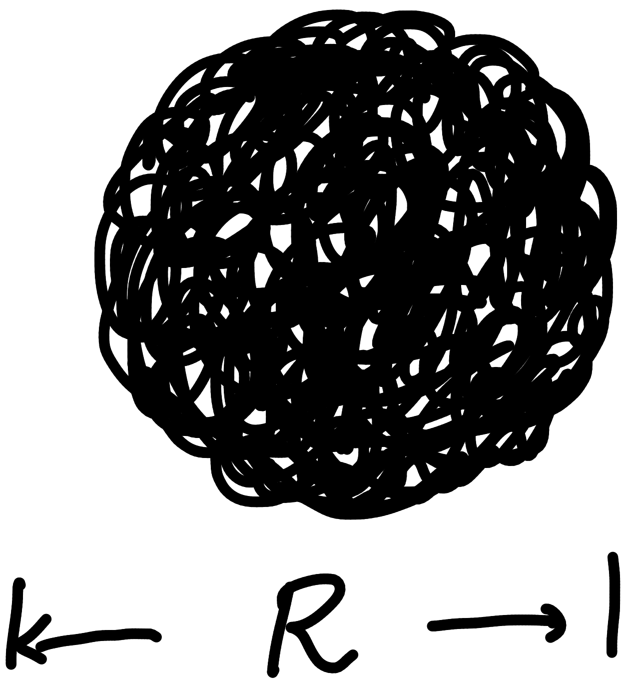
Example: Spontaneous breaking of Poincare symmetry



Soundwaves.

Universal bound on entpory:

(G.D., '19, '20)



For any self-sustained object of size R, the entropy is bounded by

$$S \leq \frac{\text{Area}}{G_{Gold}}$$

$$\text{Area} \equiv R^{d-2}$$

$d \equiv$ number of space-time dimensions

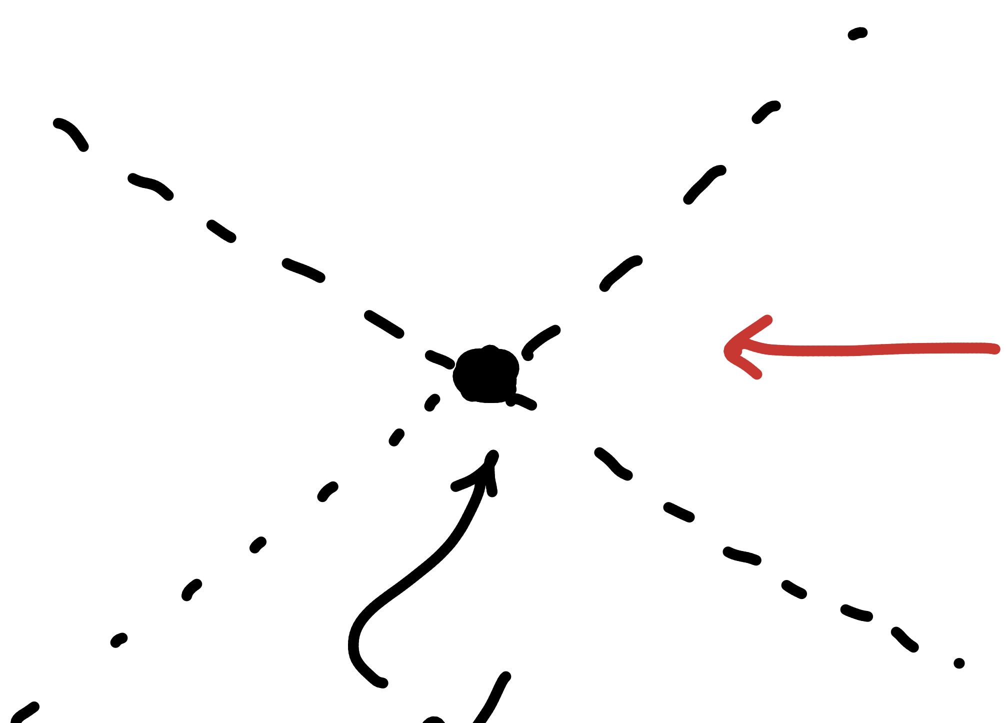
$G_{Gold} \equiv$ Goldstone coupling

$$G_{Gold} \equiv \frac{1}{f^2}$$

$f \equiv$ Goldstone decay constant

Dimensionless quantum coupling of a Goldstone evaluated at the scale (momentum-transfer) $1/R$:

$$\alpha = G_{Gold} R^{2-d} = \frac{G_{Gold}}{\text{Area}}$$

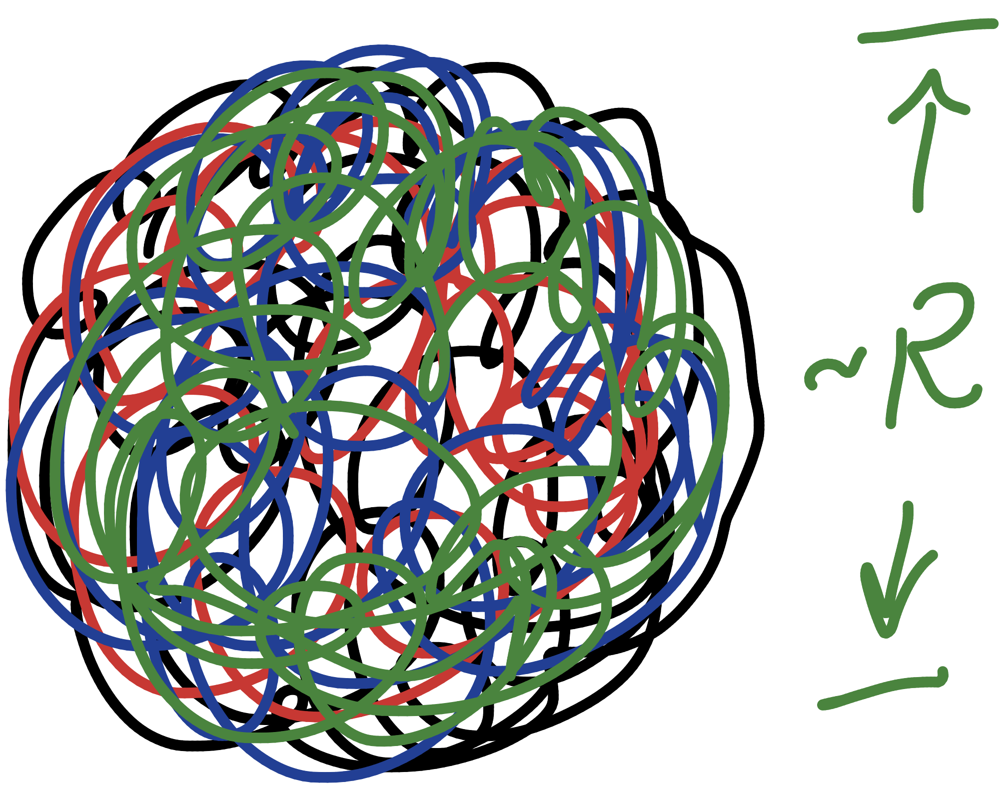


α

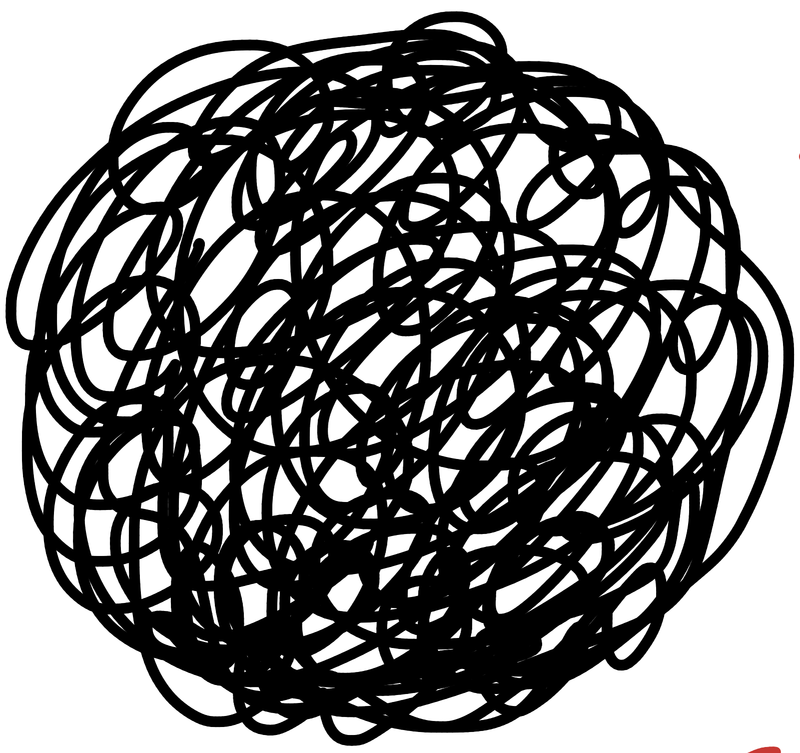
Goldstone–Goldstone amplitude

Thus, the entropy bound can be written as

$$S \leq \frac{1}{\alpha} = \frac{\text{Area}}{G_{\text{Gold}}}$$



Where are the Goldstones coming from?



Any self-sustained object breaks Poincare symmetry spontaneously.

G_{Gold} is unambiguously defined

For a boundstate of N quanta of wavelengths $\sim R$

$$G_{Gold} \equiv \frac{1}{f^2} \equiv \frac{1}{N} \cdot R^{d-2}$$

Note: States of high entropy contain other Goldstone bosons (see later), but Poincare Goldstone is <u>universal</u>.

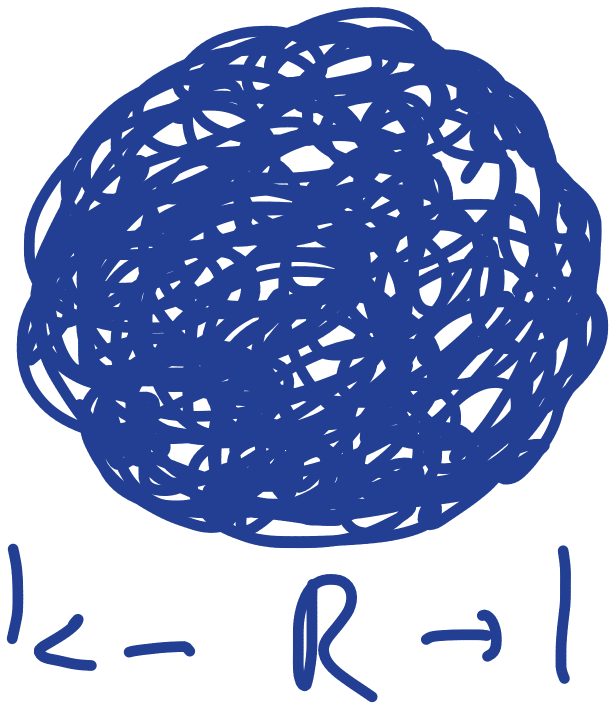
Objects of maximal entropy:

$$S_{MAX} = \frac{1}{\alpha} = \frac{\text{Area}}{G_{Gold}}$$

are called "Saturons".

Universal bound on time-scale of start of information retrieval:

$$t_{min} = \frac{R}{\alpha}$$



Due to saturation of entropy bound can be written as

$$t_{min} = S R = R^3 f^2$$

$$t_{min} \sim \text{Volume} \cdot f^2$$

All saturons have properties very similar to black holes:

* Area-law entropy;
* Thermal evaporation with $T = \frac{1}{R}$;
* Information horizon;
* Time of information retrieval
$$t_{min} \sim \frac{R}{\alpha} \sim SR$$
* Saturate scattering amplitudes.

A model for saturon

A scalar field $\hat{\Phi}^j_i$ in adjoint representation of global $SU(N)$-symmetry

$SU(N)$-"flavor" index $i, j = 1, 2, \ldots N$

$$\hat{\Phi} = \left[N \times N \right] \leftarrow \text{Hermitian matrix} \qquad \mathrm{tr}\, \hat{\Phi} = 0$$

Prototype for many systems

Lagrangian (most general, renormalizable):

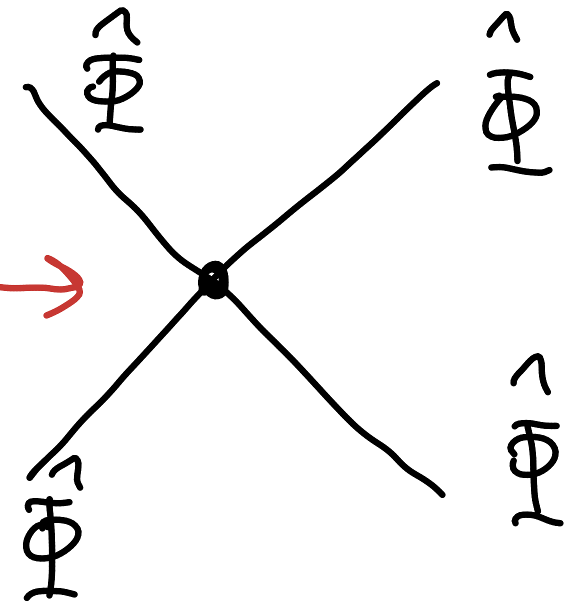
$$\mathcal{L} = \mathrm{tr}\, \partial_\mu \hat{\Phi} \partial^\mu \hat{\Phi} - V(\hat{\Phi})$$

$$V(\hat{\Phi}) \equiv \underset{\text{coupling}}{\alpha}\, \mathrm{tr}\left[\underset{\text{scale}}{f}\, \hat{\Phi} - \hat{\Phi}^2 + \frac{1}{N} \mathrm{tr}\, \hat{\Phi}^2 \right]^2$$

coupling

scale

Fundamental coupling α



can be arbitrarily-weak

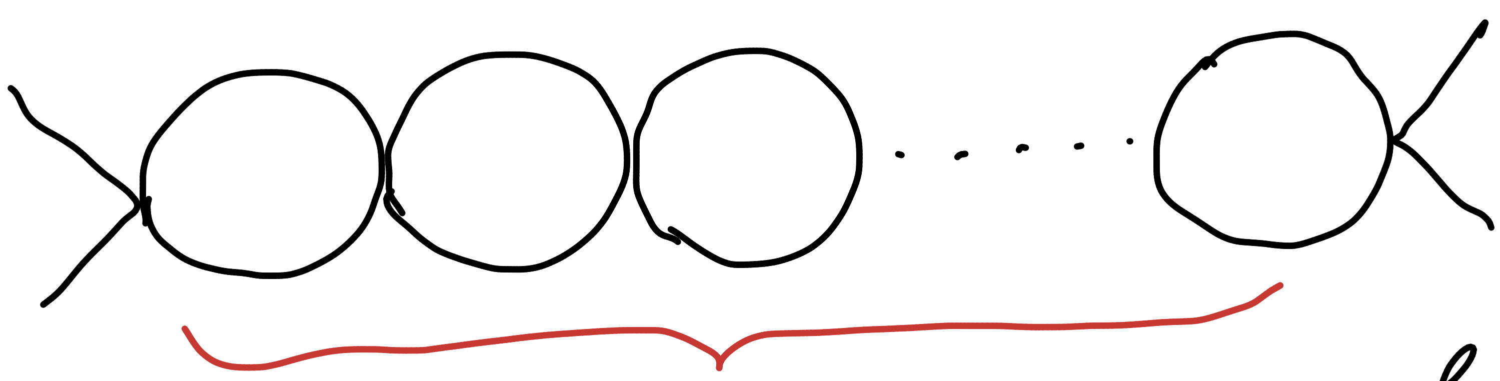
$$\alpha \to 0$$

Unitarity is controlled by the collective coupling $\equiv \alpha N$

Unitarity bound:

$$\alpha N \lesssim 1$$

can be understood in several ways, e.g., breakdown of loop expansion



ℓ-loops $\sim (\alpha N)^{\ell}$

The analysis simplifies in a double-scaling limit (a la 't Hooft)

$$N \to \infty, \qquad \alpha \to 0$$

$$\alpha N = \text{finite}$$

We wish to show that the theory contains saturons which have properties of black holes.

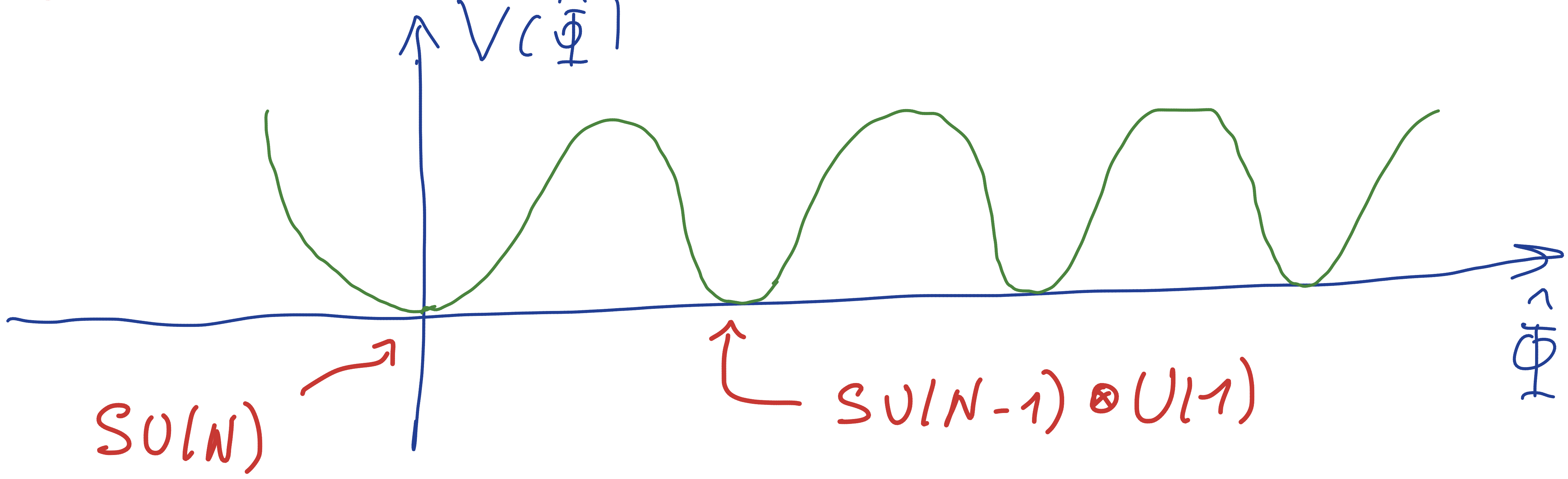
For this, let us choose a vacuum. Vacuum equations:

$$V(\hat{\Phi}) = 0 \longrightarrow f\hat{\Phi} - \hat{\Phi}^2 + \frac{1}{N}\mathrm{tr}\,\hat{\Phi}^2 = 0$$

Vacuum equations:

$$V(\hat{\Phi}) = 0 \longrightarrow f\hat{\Phi} - \hat{\Phi}^2 + \frac{1}{N}\operatorname{tr}\hat{\Phi}^2 = 0$$

Many degenerate vacua



We focus on two:

1. $SU(N)$-symmetric $\langle \hat{\Phi} \rangle = 0$

   Has mass gap $m = \sqrt{\alpha}\, f$

2. $SU(N-1)\otimes U(1)$-symmetric vacuum

$$\langle \hat{\Phi} \rangle = \frac{f}{N}\begin{pmatrix} N-1, & & & & \\ & -1 & & & \\ & & -1 & & \\ & & & \ddots & \\ & & & & -1 \end{pmatrix}$$

$N-1$

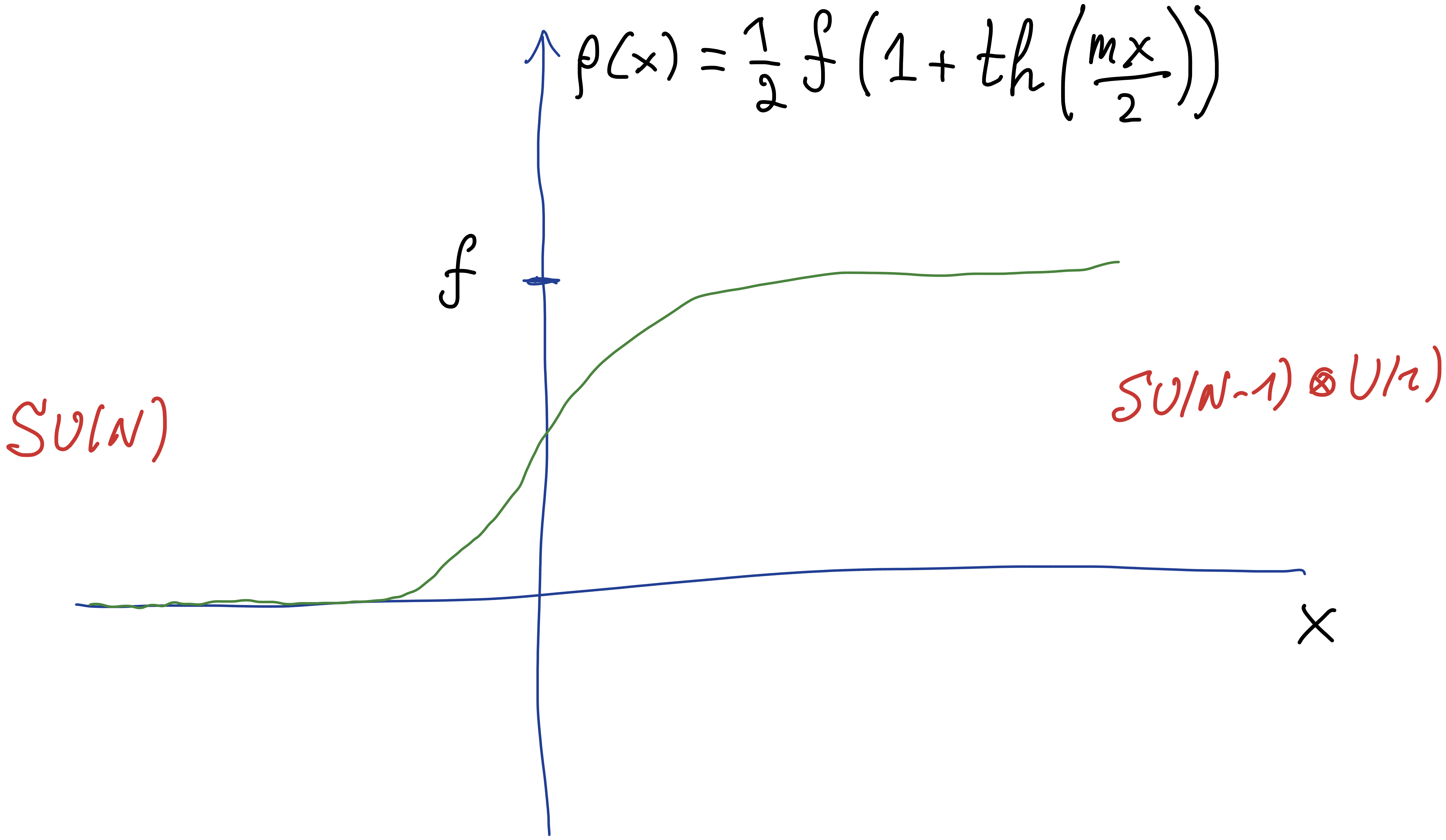
Has $\approx 2N$ gapless Goldstone modes

The vacua can coexist and be separated by a domain wall.

Flat domain wall:

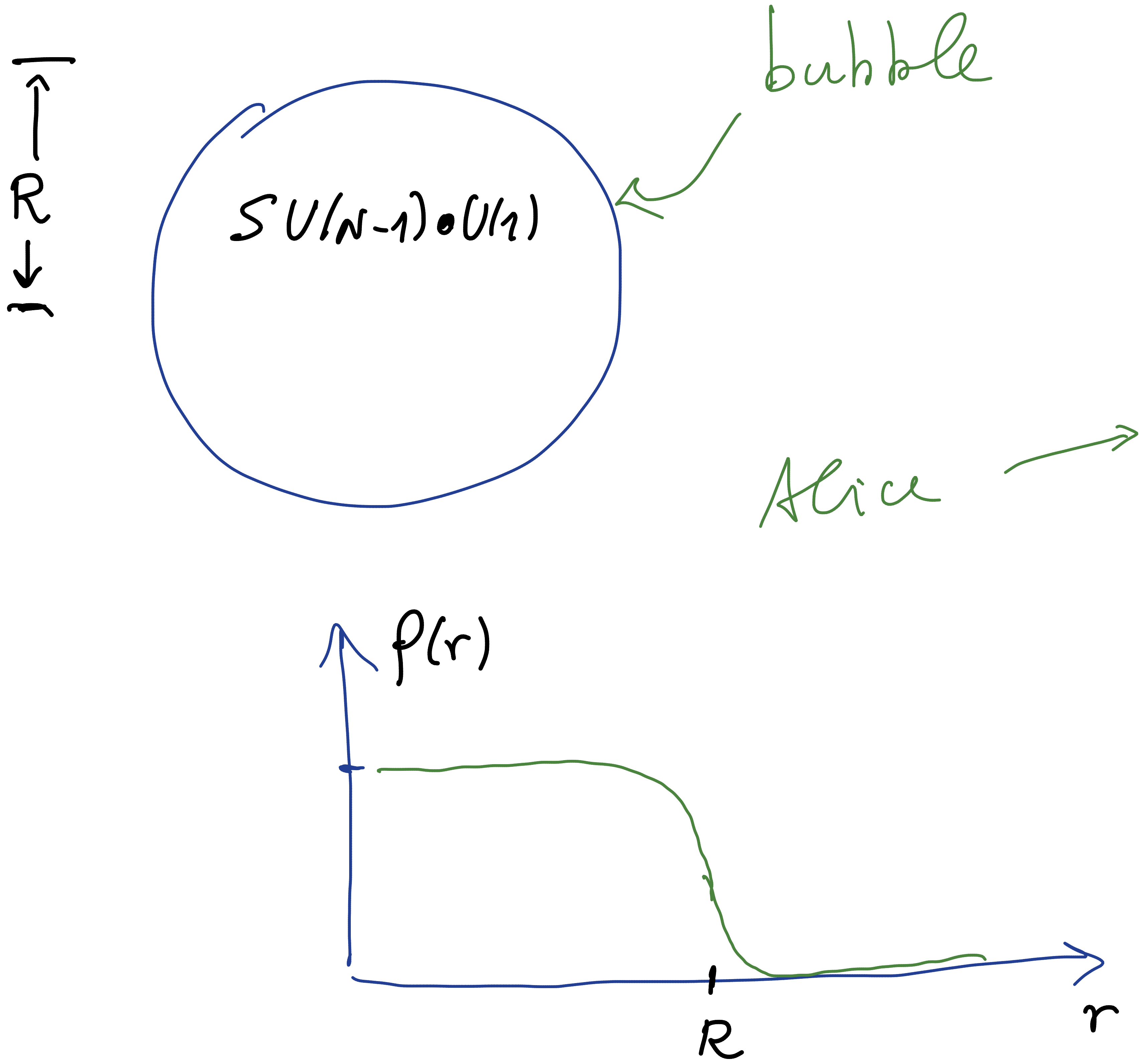
$$\hat{\Phi}(x) = \rho(x)\,\frac{\langle\hat{\Phi}\rangle}{f}$$

$$\rho(x) = \frac{1}{2} f \left(1 + th\left(\frac{mx}{2}\right)\right)$$



$$\text{Wall thickness} \sim \frac{1}{m} = \frac{1}{\sqrt{\alpha}\, f}$$

We choose $SU(N)$-vacuum as asymptotic vacuum and consider a bubble of $SU(N-1)\otimes U(1)$-vacuum



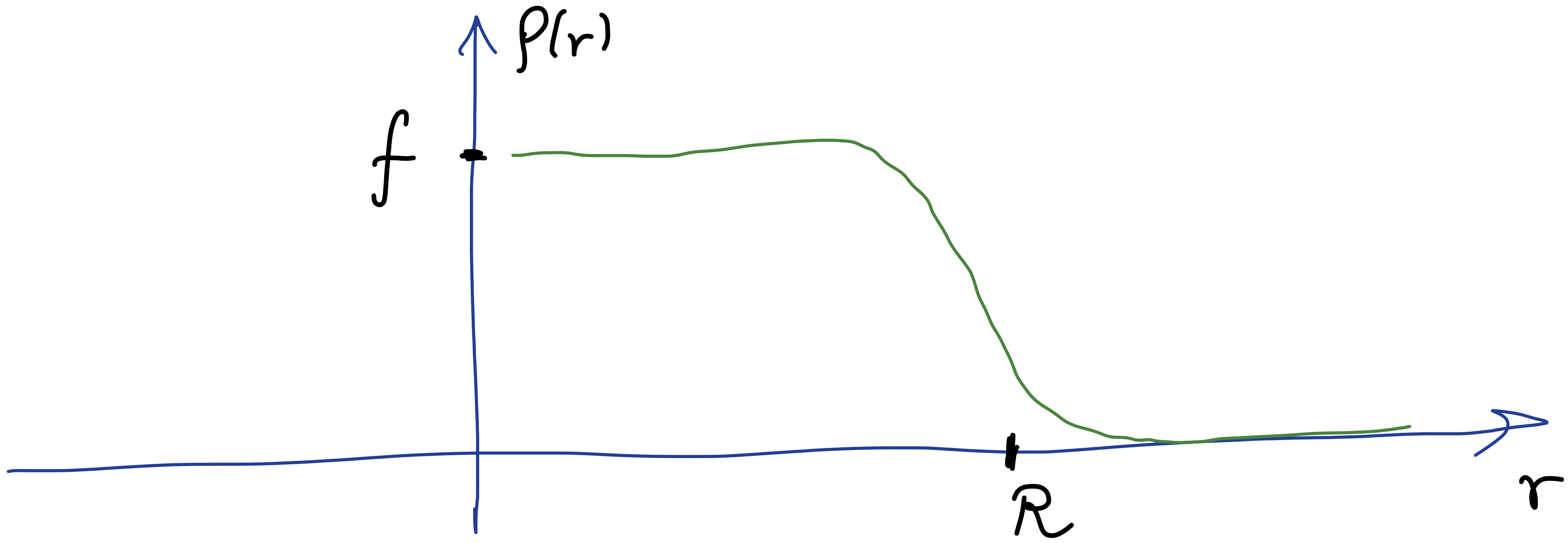
The bubble is highly degenerate and stores quantum information in Goldstone exitations.

For high occupation numbers it can be approximated by a classical solution.

Stationary bubble (a sort of a Q-ball)

$$\hat{\Phi}(r,t) = \frac{\rho(r)}{f}\, e^{i\omega t \hat{T}} \langle \hat{\Phi} \rangle e^{-i\omega t \hat{T}}$$

where
$$\hat{T} \equiv \begin{pmatrix} 0 & -i & \\ i & 0 & \\ & & \end{pmatrix}$$
$\leftarrow$ one of the broken generators



bubble radius:

$$R \sim \frac{m}{\omega^2}$$

Occupation number of Goldstone quanta:

$$n \sim \frac{1}{\alpha}\left(\frac{m}{\omega}\right)^5$$

Energy of a bubble

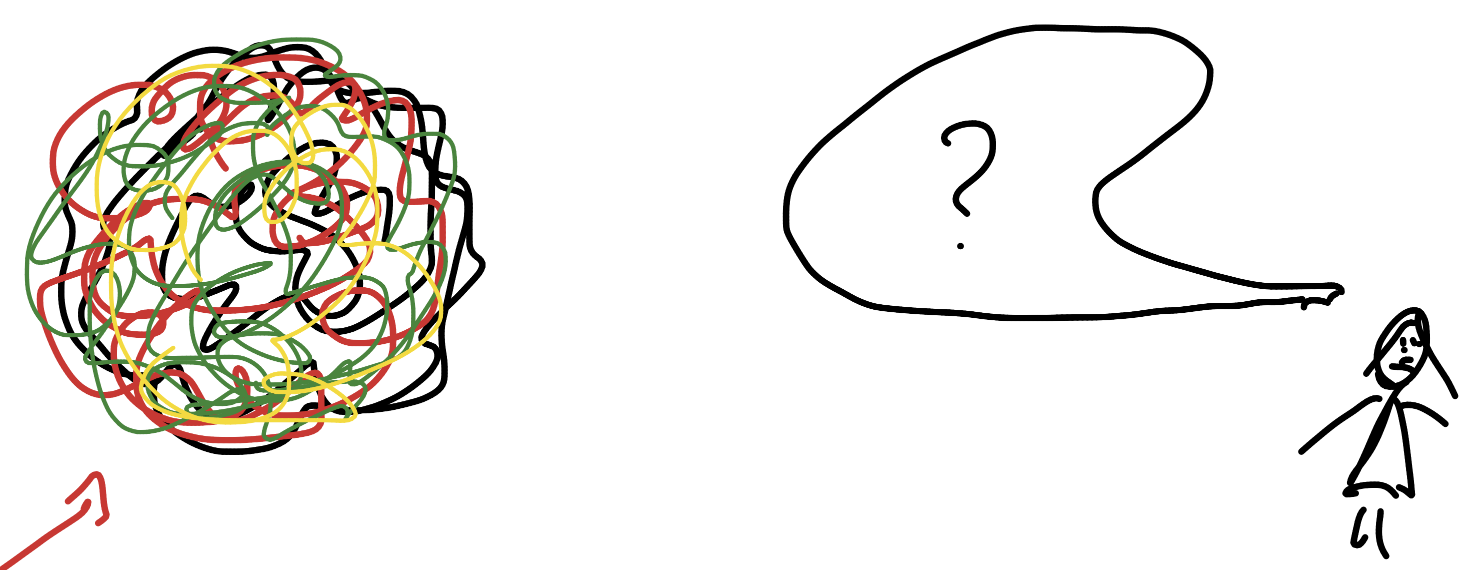
$$E_n \sim n\omega \sim n\sqrt{\frac{m}{R}}$$

Level n has microstate degeneracy

$$n_{st} \simeq \left(1+\frac{2N}{n}\right)^{n}\left(1+\frac{n}{2N}\right)^{2N}$$

Corresponding microstate entropy

$$S = \ln(n_{st}) = 2N \ln\left\{\left(1+\frac{2N}{n}\right)^{\frac{n}{2N}}\left(1+\frac{n}{2N}\right)\right\}$$



SU(N)-flavor state

The parameters of saturon bubble:

⊛ Entropy

$$S = \frac{\text{Area}}{G_{Gold}} = \frac{1}{\alpha}$$

⊛ Mass

$$M = \frac{S}{R}$$

Very similar to black holes.

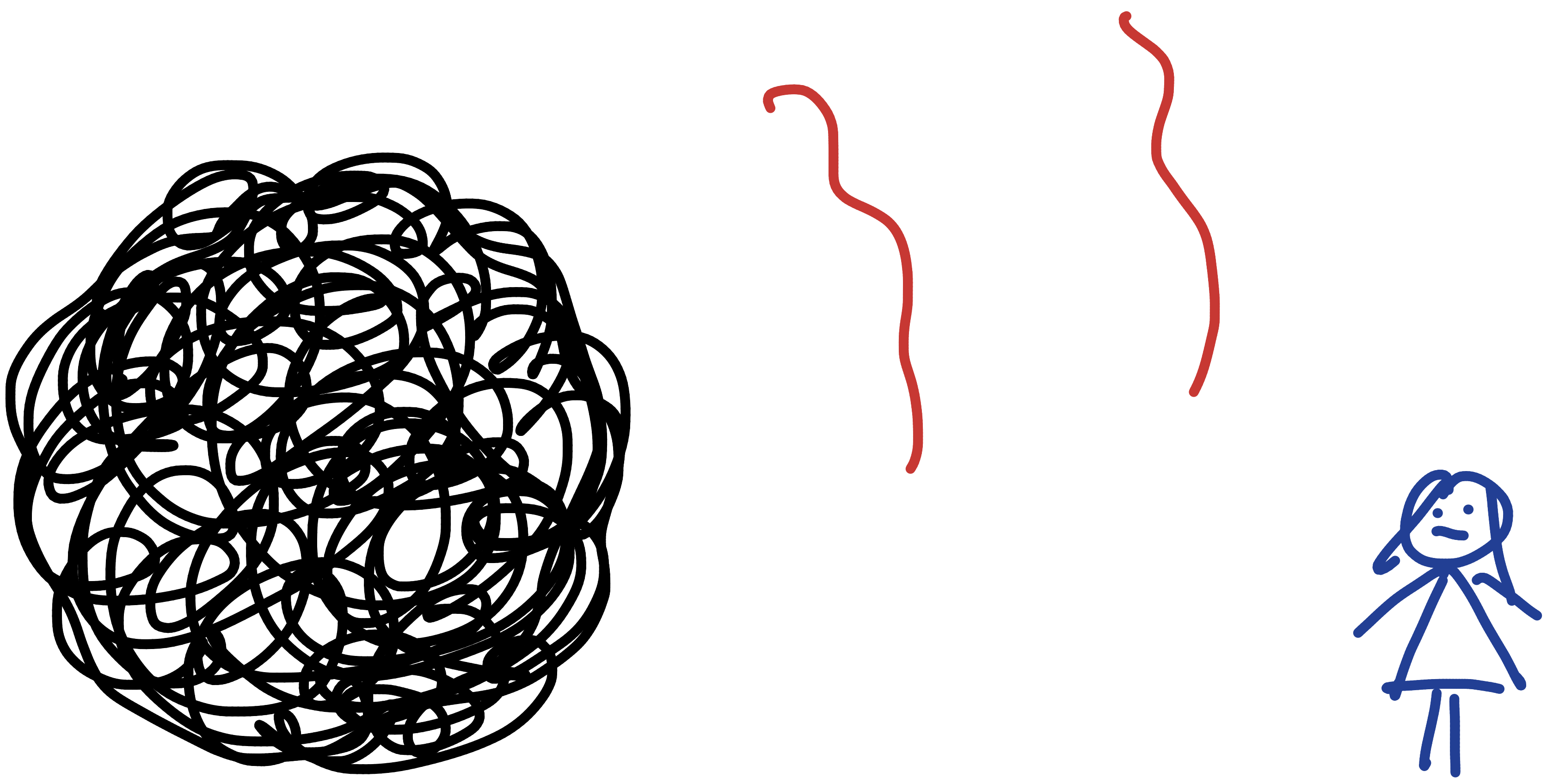
Notice for a black hole:

$$G_{Gold} = G_{Newton}$$

In quantum theory bound state decays.

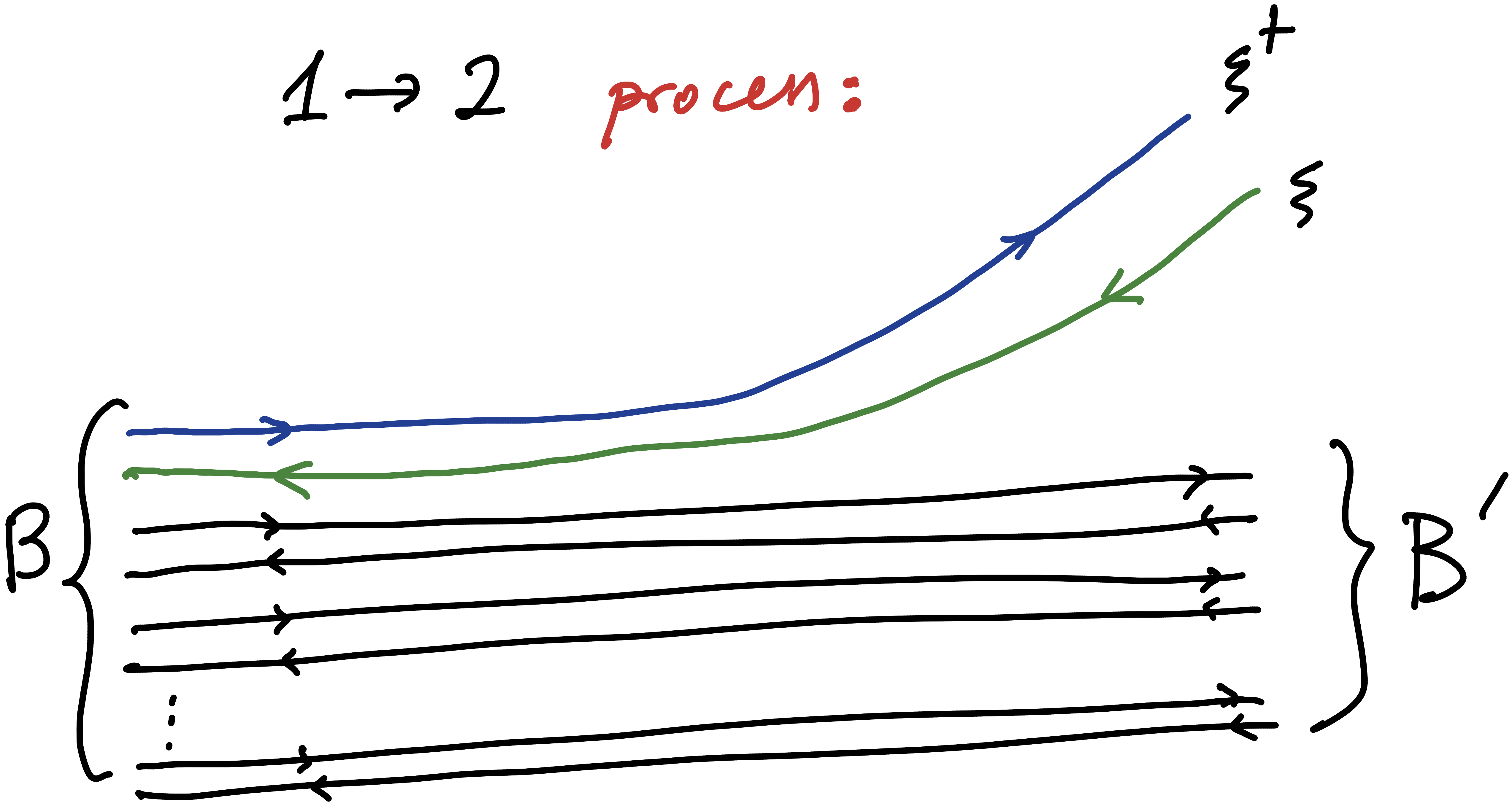
The decay rate of a saturated bubble:

$$\Gamma \sim \frac{1}{R}$$ ← Hawking rate with temperature $T = \frac{1}{R}$!



Emission of massless ξ-quanta

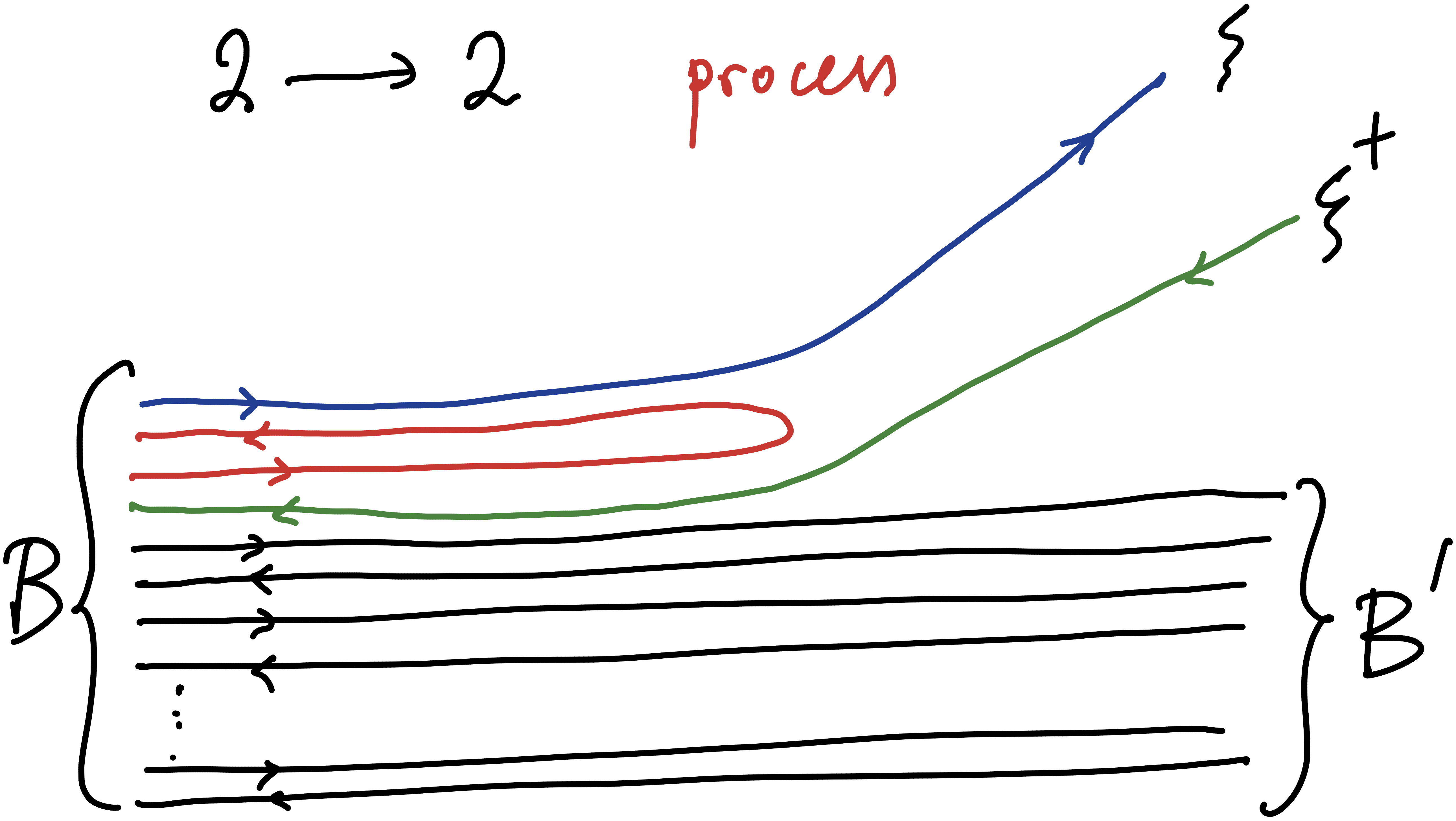
$1 \to 2$ process:



$$\Gamma \sim \frac{1}{R}\,\underbrace{\alpha \cdot N} \sim \frac{1}{R}$$

Recall, $\alpha N = 1$

$2 \longrightarrow 2$ process



$$\Gamma \sim \frac{1}{R}\alpha^2 N^2 \sim \frac{1}{R}$$

$\alpha N = 1 \leftarrow$ saturation condition.

Thus, a saturon evaporates as a black hole with thermal-like rate

In reality the state is pure: Information is carried by $\frac{1}{N} \sim \frac{1}{S}$ corrections.

Quantum information is stored in flavor content of the bound state.

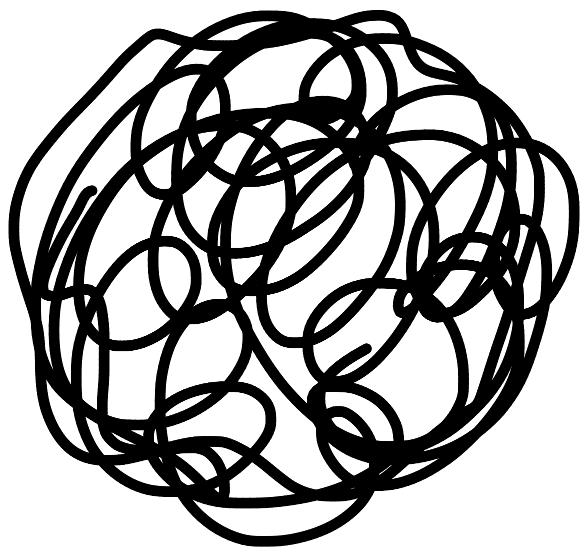
In the semi-classical limit: $N \to \infty$, $\alpha \to 0$,

$(N\alpha) = 1$ $\quad R = \text{finite}$.

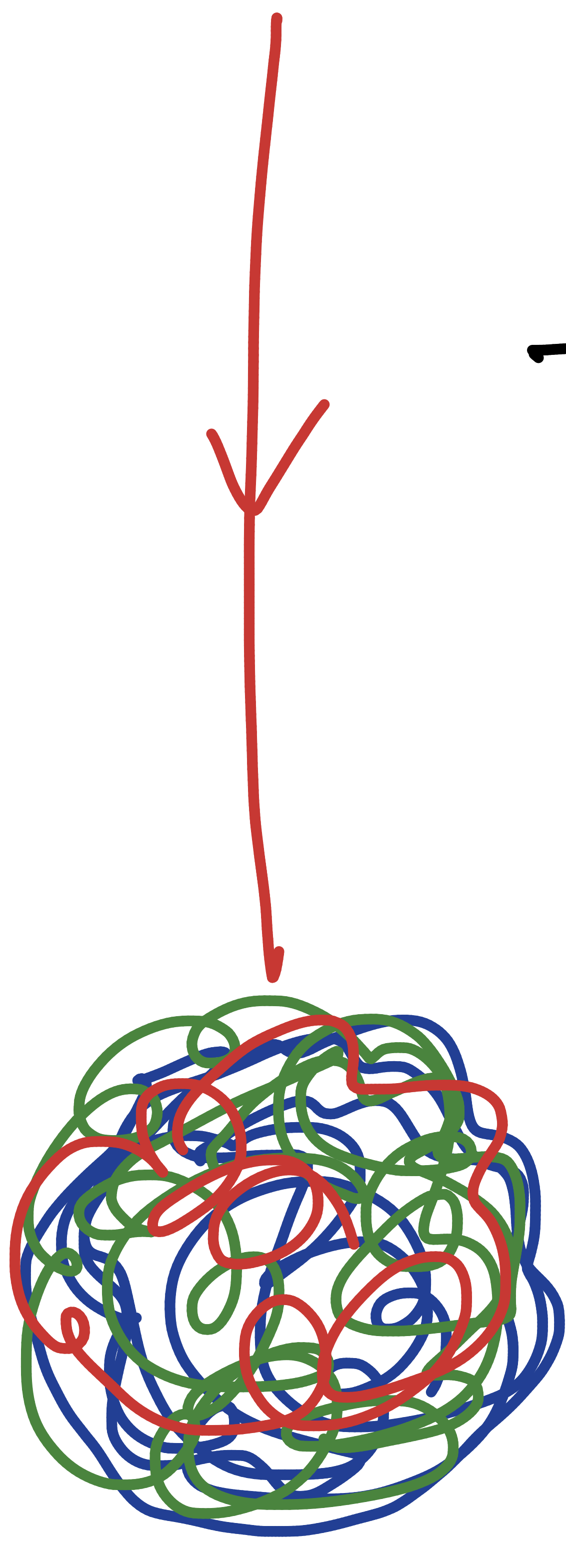
It is unreadable: Saturon has information horizon.

For N = finite, the informations is readable after some time.

Time scale of the <u>start</u> of information retrieval:



$$t_{min} \sim \frac{R}{\alpha} \sim S R \sim \frac{R^3}{G_{Gold}}$$



identical to Page's time for a black hole

Black hole/saturon correspondence:

$$G_N \longrightarrow G_{Gold}$$

All characteristics are identical:

$$\alpha_{gr} \longleftrightarrow \alpha$$

$$S_{BH} \longleftrightarrow S$$

$$T_H \longleftrightarrow T$$

$$t_{Page} \longleftrightarrow t_{min}$$

	Saturon bubble	Black hole
Maximal Spin	$M^2 G_{Gold}$	$M^2 G_{Gold}$
Entropy S	$M^2 G_{Gold}$	$M^2 G_{Gold}$

This offers an interpretation that a black hole reaches maximal spin when graviton condensate develops vorticity.

(Black hole vorticity can have potentially observable consequences.)

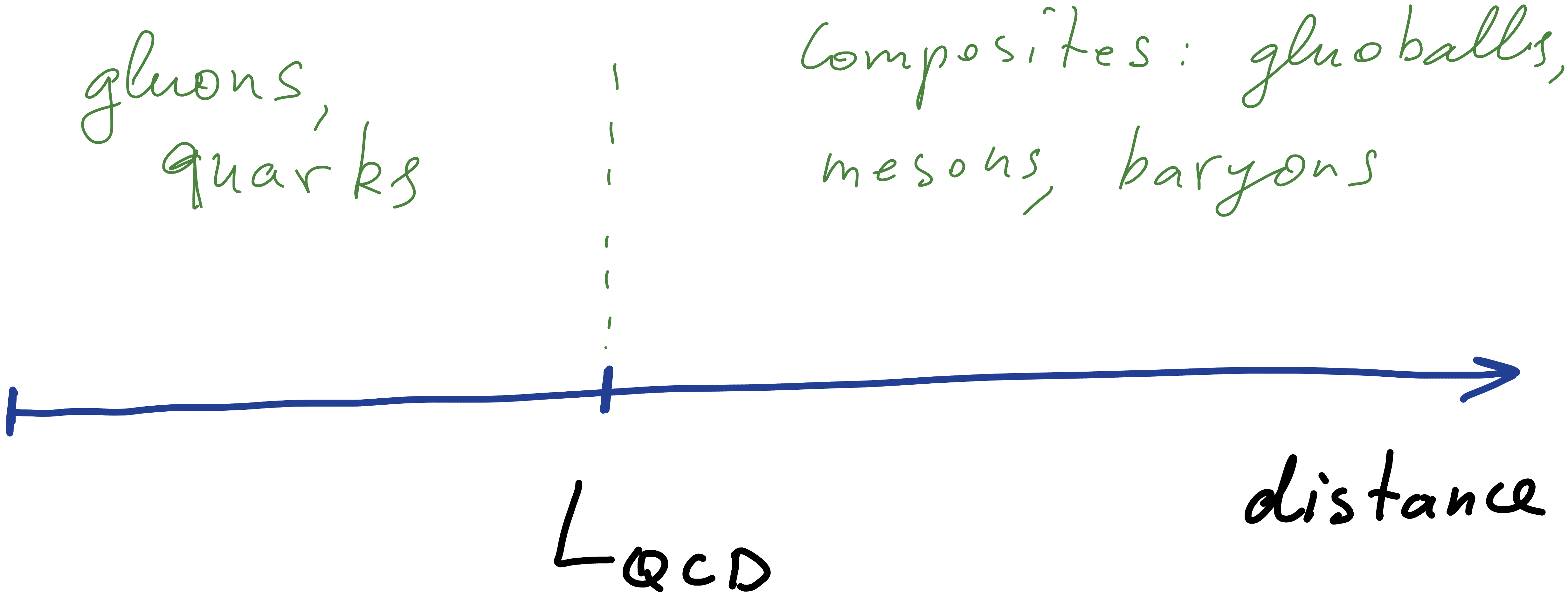
What happens if we push entropy beyond the bound?

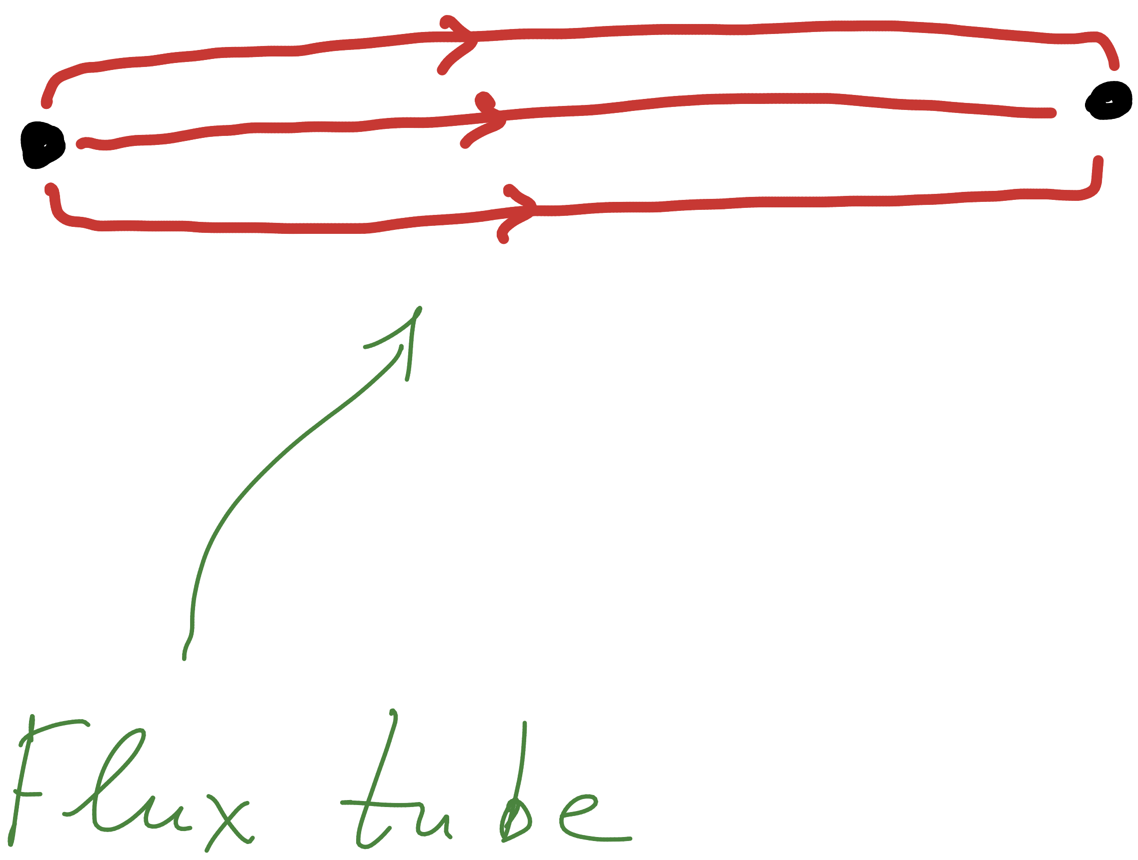
$$S \longrightarrow S \gg \frac{\text{Area}}{G_{\text{Gold}}} \quad ?$$

Change of degrees of freedom.

The theory will change a regime

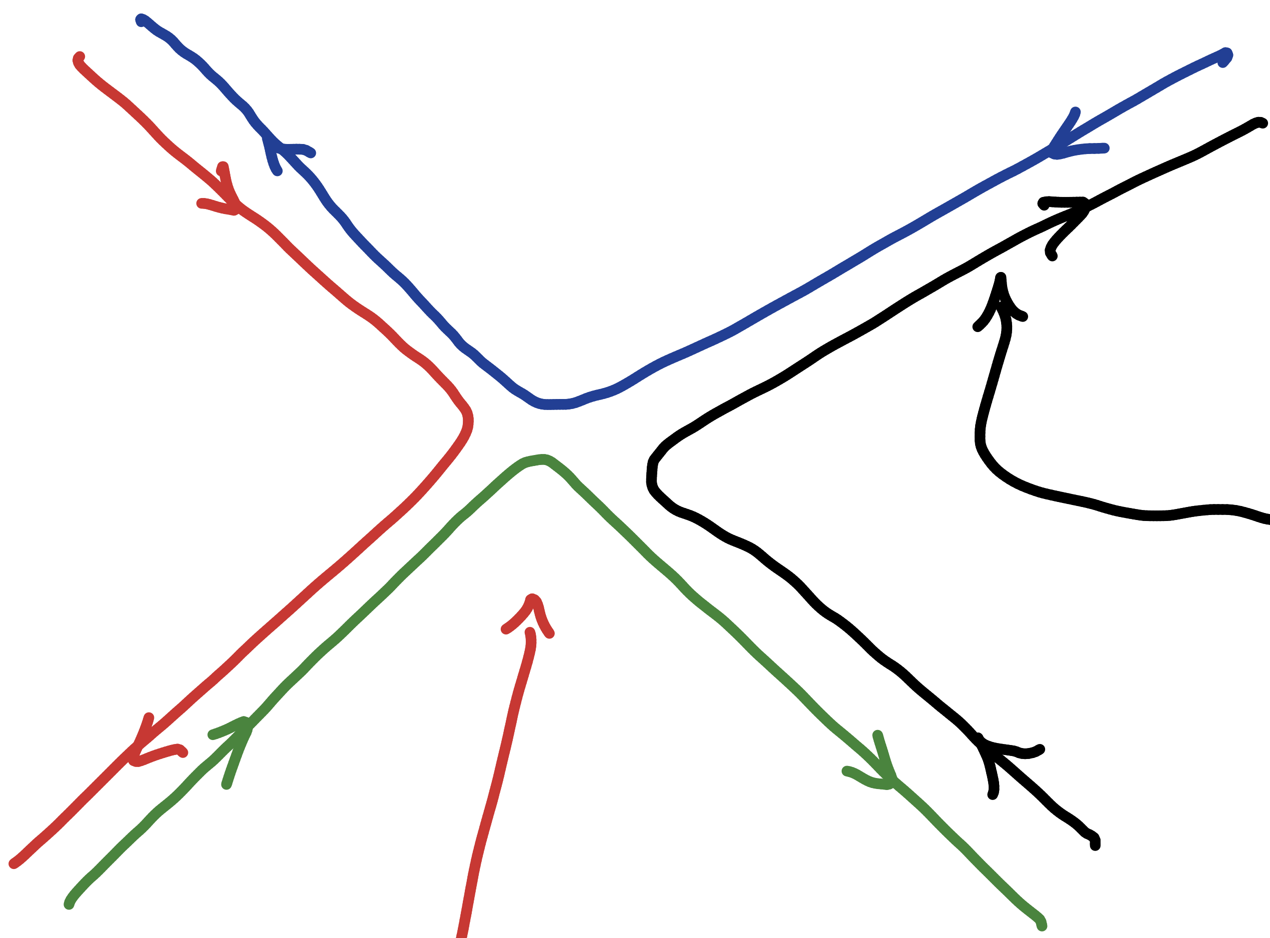
Saturation and Confinement in QCD





$SU(N)$ - Color 't Hooft

Couplings of gluons for $N \gg 1$



$\sum \text{color} = N$

$$\lambda \equiv \alpha_{QCD} \cdot N$$

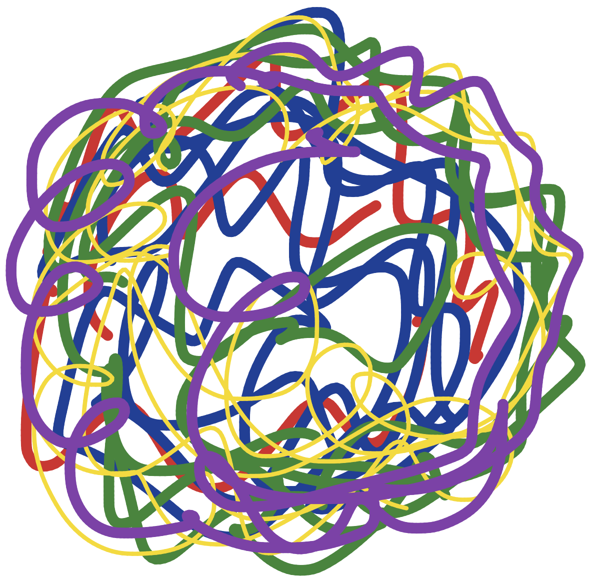
running coupling.

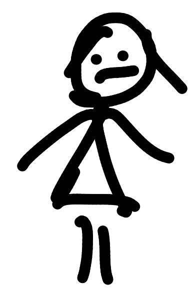
Theory confines at the scale L_{QCD} where

$$\lambda \sim 1$$

Remarkably, at the same scale a high occupation gluon state saturates the entropy bound.

Gluon saturon





Entropy

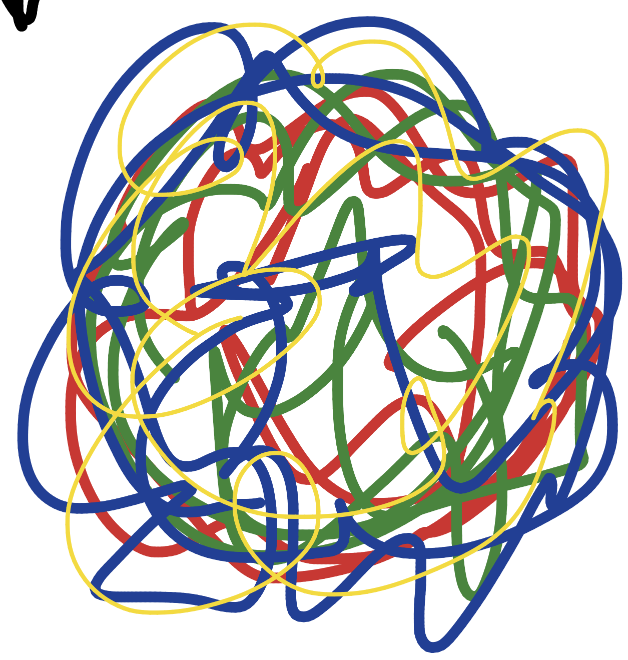
$$S = \frac{\text{Area}}{G_{\text{Gold}}}\left(1 + \ln(\lambda)\right)$$

Saturates the bound for $\lambda \sim 1$.

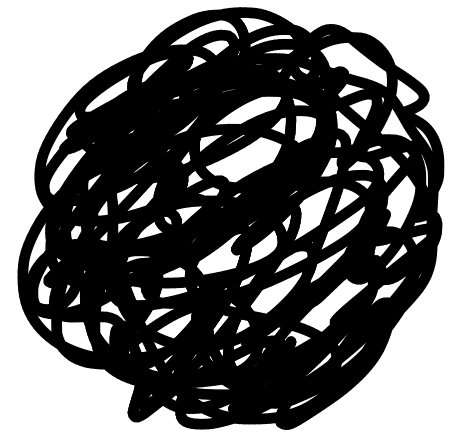
Further growth is prevented by confinement!

Confinement as self defence mechanism against the violation of entropy bound

Colored gluon states



Colorless bound states



L_{QCD}

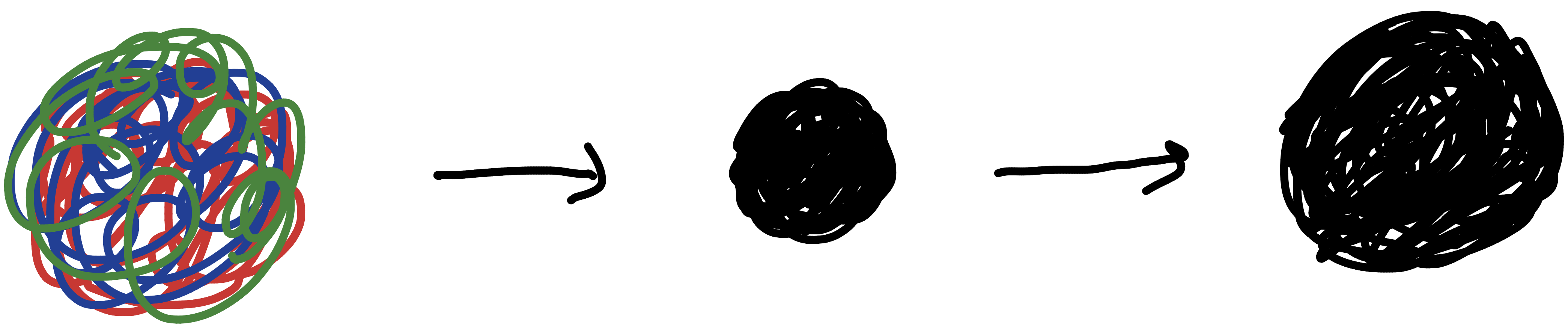
$S < S_{MAX}$

$$S_{MAX} = \frac{Area}{G_{Gold}}$$

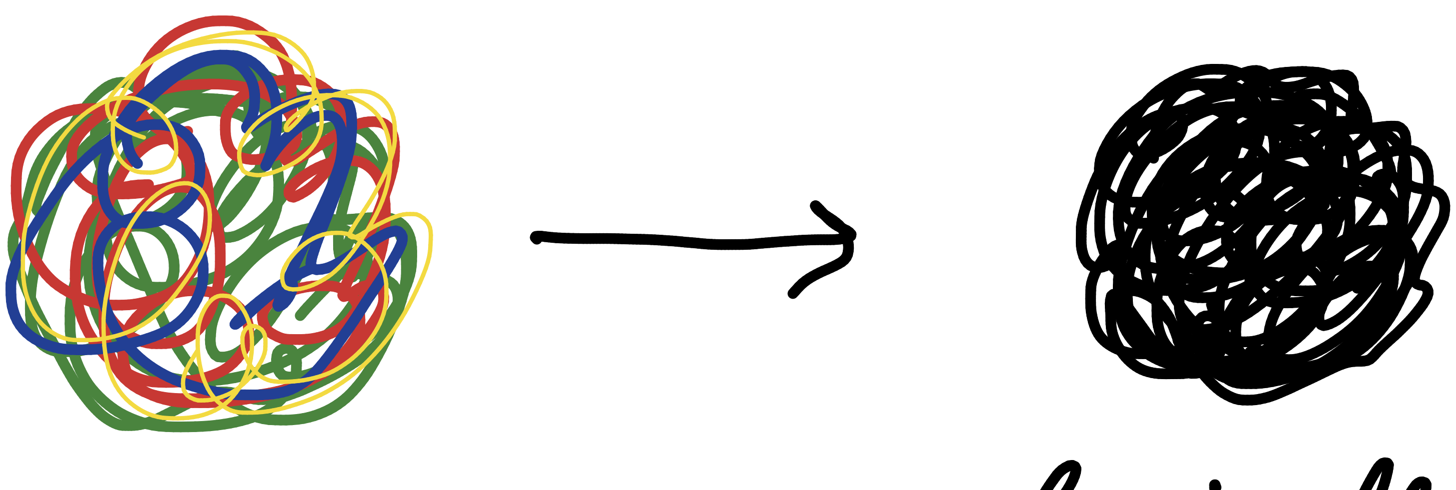
If we push

$$S \to S > S_{max} = \frac{\text{Area}}{G_{Gold}}$$

1. Gravity will form a larger black hole



2. QCD simply confines



glueball, meson, ...

Perhaps a most exciting candidate is CGC in real QCD

G. D., Venugopalan '21

CGC is a saturated state

$$N_{gene} = \frac{1}{\alpha_{QCD}}$$

of gluons in ordinary QCD

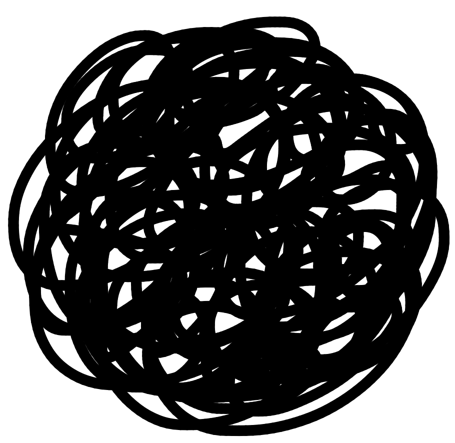
Iancu, McLerran, Venugopalan
Kovner, Korchegov, Balitsky
Lipatov . . . . .

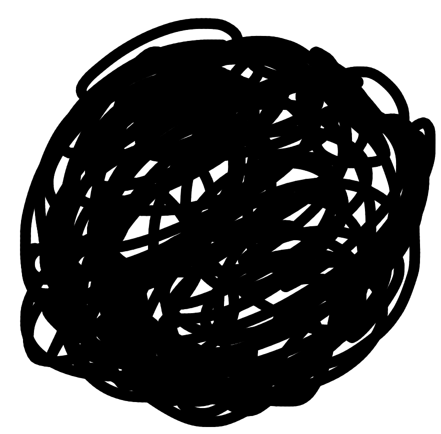
Black hole/saturon correspondence is *independent* of dimensionality and other details of the theory.

It is correspondance between the states in *different* theories

gravity

"ordinary" theory





G_N, α_{gr}

G_{Gold}, α

Trans-theoretic parameters

Saturons exist in $d=2$ Gross-Neveu model:

The bound state of maximal degeneracy is a saturon and exhibits properties of a black hole

G.D., Sakhelashvili '21

Very exciting candidate is Color Glass Condensate in <u>ordinary</u> QCD

G.D., Venugopalan '21

We have seen that mysterious black hole properties are not rooted in gravity.

Rather, they represent generic features of states that saturate unitarity bound on entropy, saturons.

There exist many examples even in ordinary renormalizable theories, which can be reliably studied at weak coupling.

From there, we can predict new features for black holes.

Observing saturons in calculable theories, we see what are the wrong assumptions made in ordinary (semi-classical) treatment of black holes:

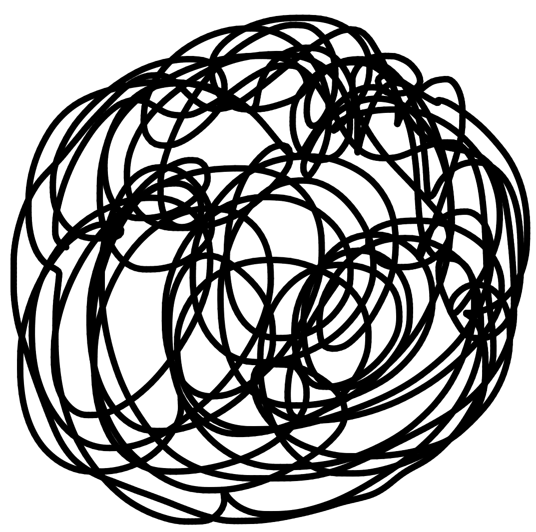
⊛ Evaporation is never thermal for finite S. $1/S$ - corrections break thermality.

⊛ Black hole evaporation is <u>not</u> self-similar.

is broken by "memory burden" effect.

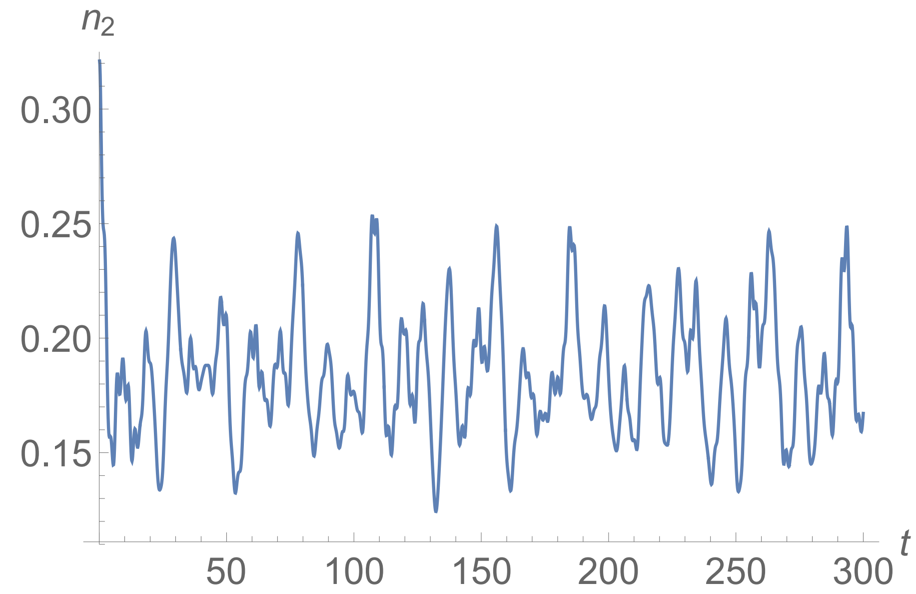
Some interpretations.

Since all known saturated states are states with critical occupation number of quanta, this suggests that black holes are saturated states of gravitons.

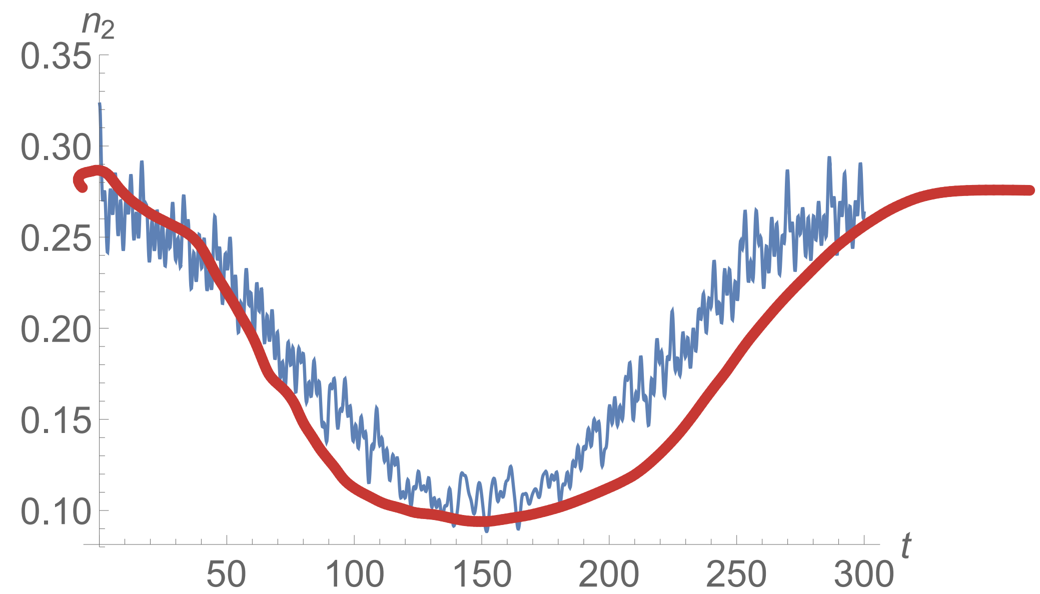
 $\leftarrow \; n \sim \dfrac{1}{\alpha_{gravity}}$

"BH N-portrait" G.D., Gomez '11.

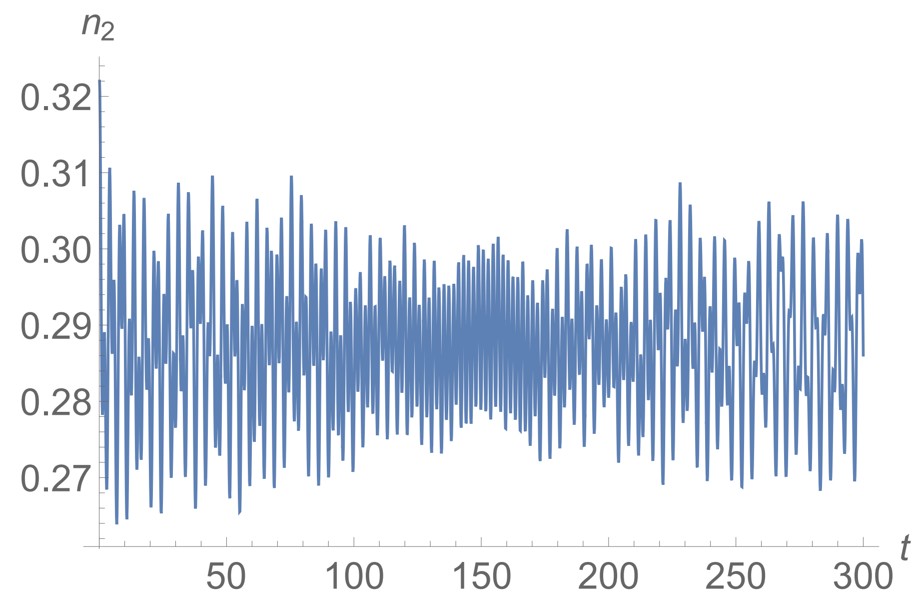
"Saturons" in cold bosons



(a) $\lambda = 1.9$



(b) $\lambda = 2.083$



(c) $\lambda = 2.2$

Figure 6: Time evolution of the quantum state $|\Phi_{\mathrm{inf}}\rangle$, which corresponds to the inflection point of the Bogoliubov Hamiltonian. The value of $n_2(t)$ is plotted for $N = 60$. We observe that lower frequencies dominate around $\lambda \approx 2.083$.

Dvali, Michel, Zell, EPJ Quant. Technology 6 (2019) 1

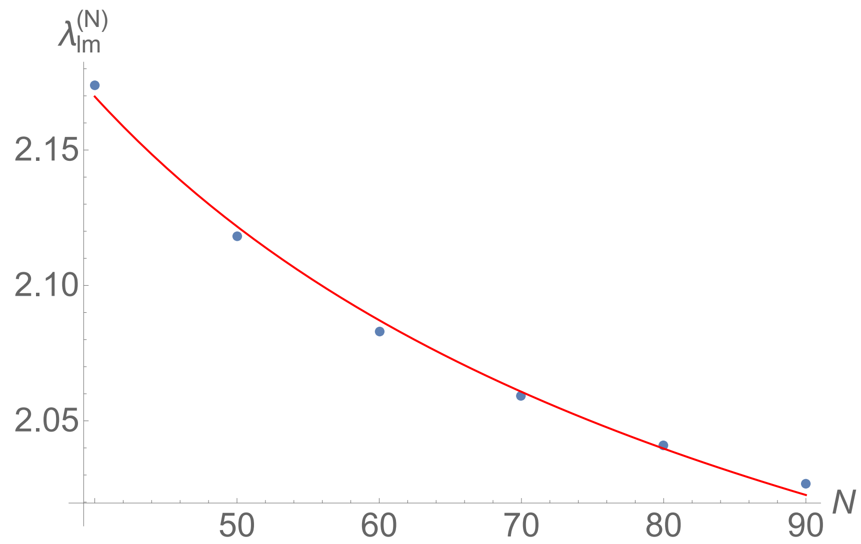


Figure 8: Critical value $\lambda_{lm}^{(N)}$ as a function of particle number N. The positions obtained from numerical simulations are plotted in blue. The fitted function (42) is shown in red.

degenerate microstates

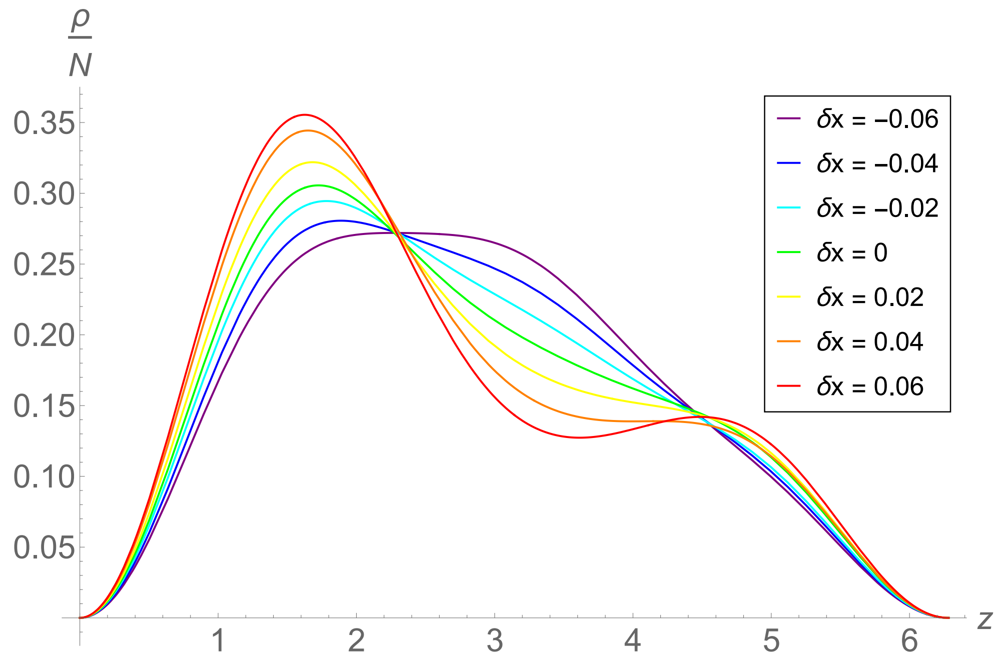


Figure 9: Variations of the critical state at $\lambda = 2.083$ for $N = 60$ in position space. The relative particle density ρ/N is plotted. The green line corresponds to the critical state $|\Phi_{\text{inf}}\rangle$ itself and the adjacent lines are variations of it, which we obtained by slightly changing the value of x used in the minimization procedure that determines the quantum state: $x_i = x_{\text{inf}}(\lambda) + \delta x_i$. The values of δx_i are indicated in the plot.

quantum state: $x_i = x_{\text{inf}}(\lambda) + \delta x_i$. This determines a family of quantum states $|\Phi_{\text{inf, i}}\rangle$, where $|\Phi_{\text{inf, i}}\rangle$ is a state of minimal energy subject to the constraint that its relative occupation of the 2-mode is x_i. Their particles densities are also shown in Fig. 9.

4.3 Comparison with Goldstone Phenomenon

It may be useful to compare our effect with the well-known phenomenon of appearance of gapless excitations in the form of Goldstone bosons. The latter modes emerge as a result of a phase transition with the spontaneous breaking of a global symmetry. The crucial difference is that Goldstone modes consistently exist in a domain past the critical phase. This is not the case in the present model. Our gapless modes only exist at the critical point and they appear due to cancellation between the positive kinetic energy and a

Other implications of Saturons for cosmology, LHC physics, BSM, Quantum information, ...

Thank You!

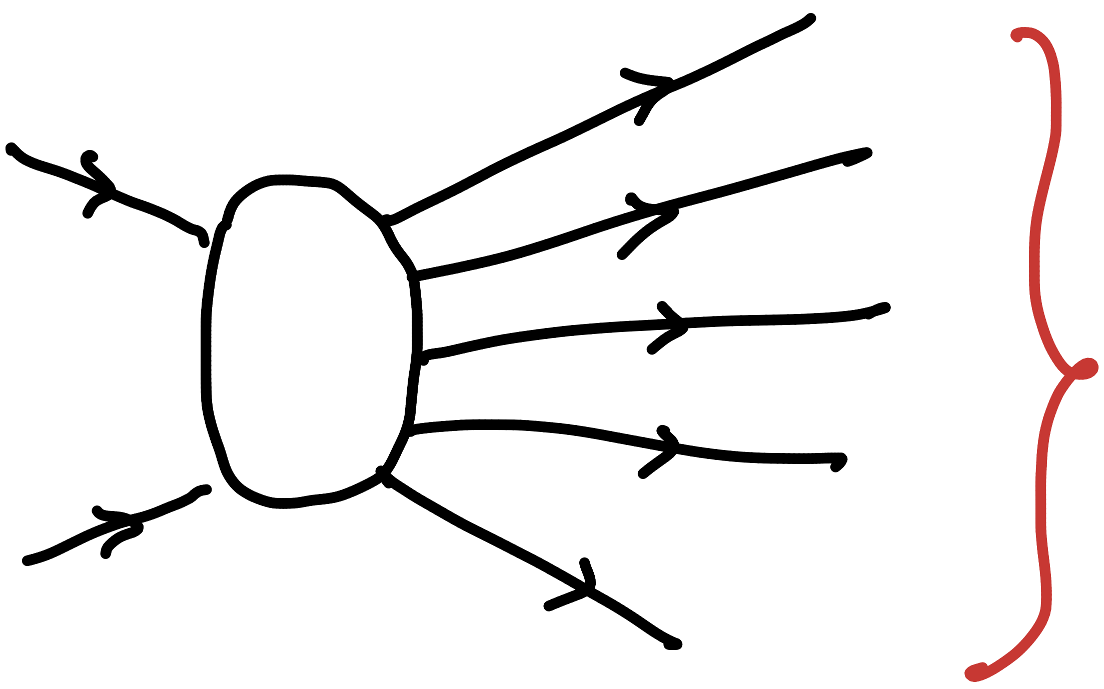
Saturation of these entropy bounds is in one-to-one correspondence with saturation of <u>unitarity</u> by

$2 \to n$ scattering amplitudes

for $n = \frac{1}{\alpha}$

The point of optimal truncation.

$E = nq$

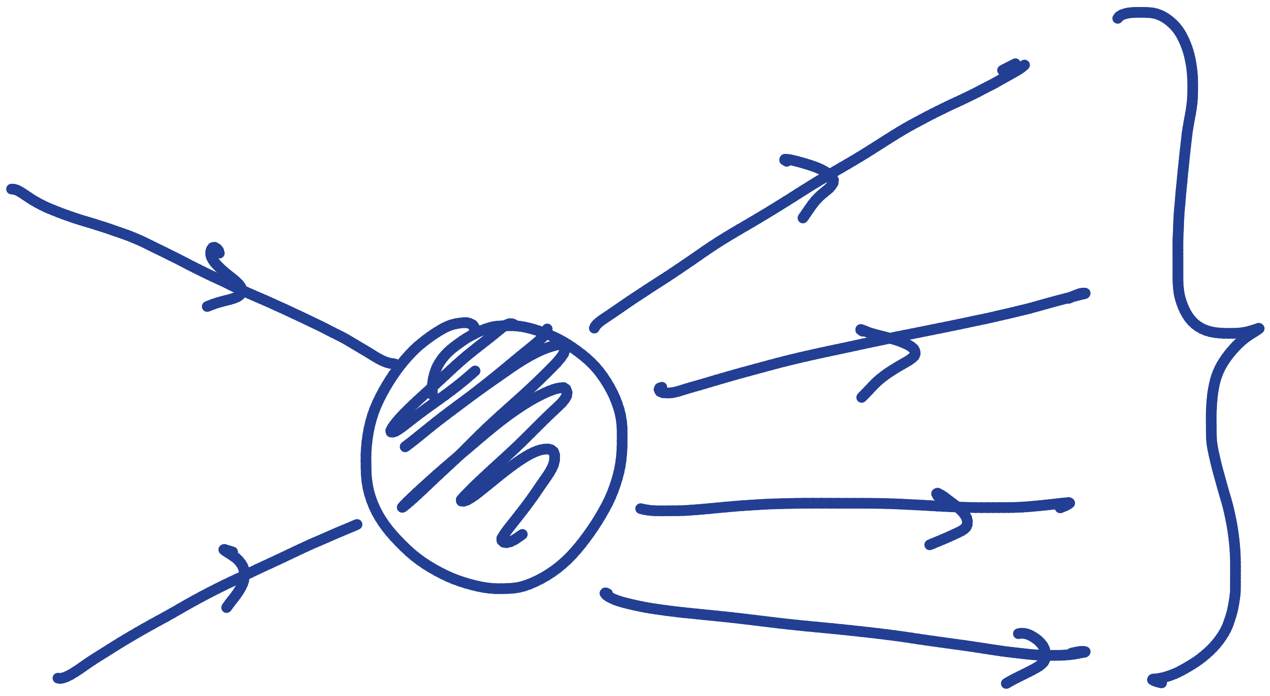


$n = \frac{1}{\alpha}$

momentum-transfer $q = \frac{1}{R}$

Cross section of $2 \to n$ scattering:

Optimal truncation



$$n = \frac{1}{\alpha}$$

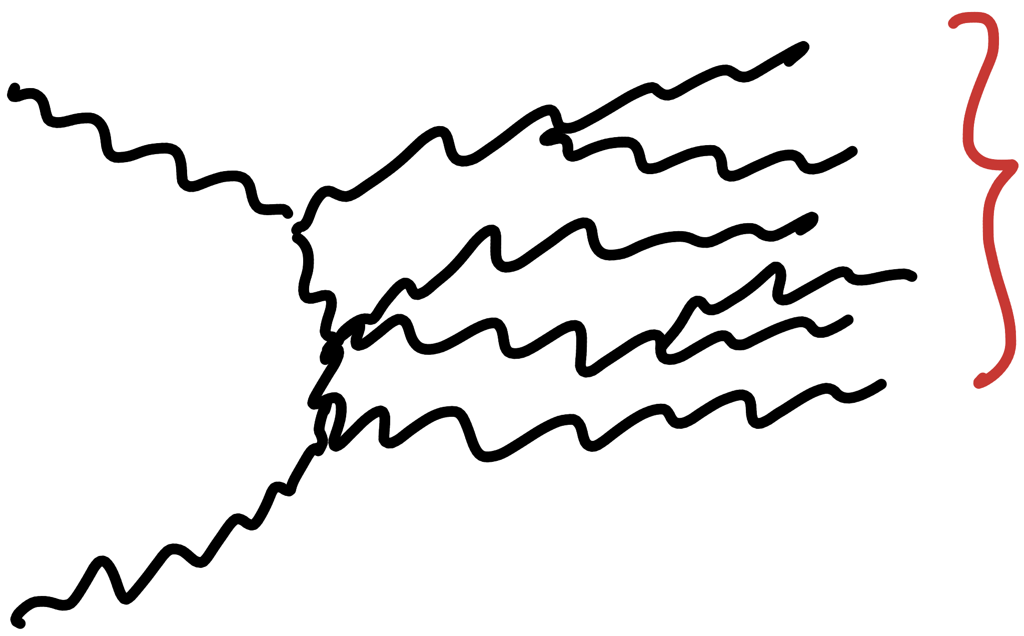
$$\sigma_{2\to n} = e^{-\frac{1}{\alpha} + S}$$

Unitarity bound on entropy:

$$S \leq S_{MAX} = \frac{1}{\alpha}$$

$$S = ER = \frac{1}{\alpha} = (Rf)^2$$

Is correlated to saturation of unitarity by $2 \to n = \frac{1}{\alpha}$ graviton (closed string) amplitudes



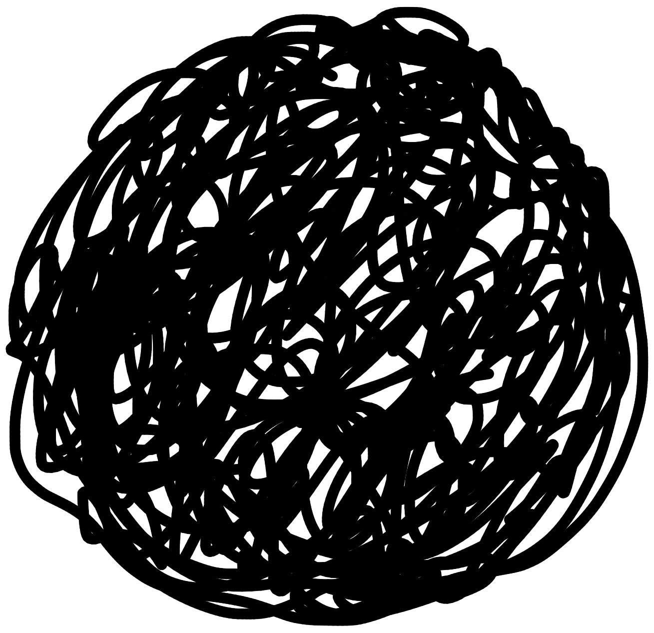
$$n = \frac{1}{\alpha}$$

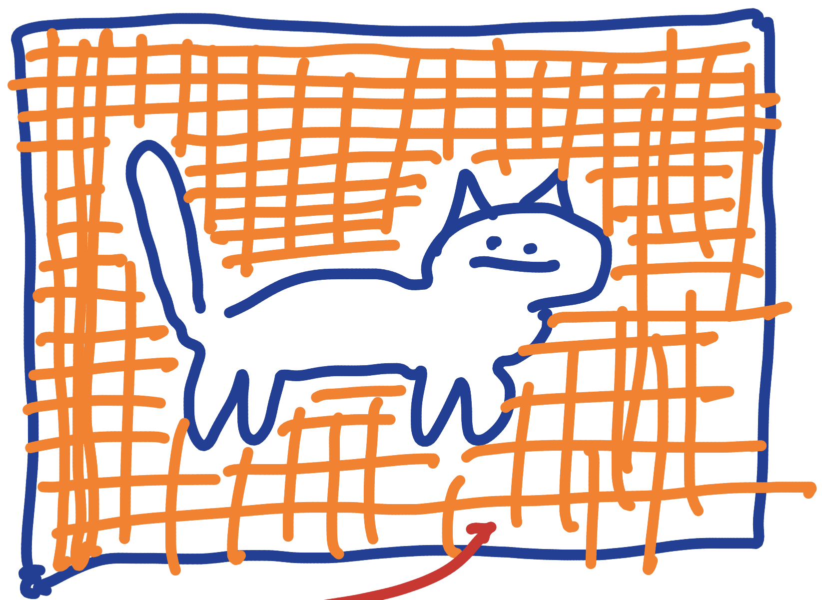
$$\sigma = n!\, \alpha^n e^S = e^{-\frac{1}{\alpha} + S}$$

G.D, Gomez, Isermann, Lüst, Stieberger '14;
Addazi, Bianchi, Veneziano '16.

For example:

$\longleftarrow$ 10cm $\longrightarrow$





$|\!\leftarrow$ 10cm $\rightarrow\!|$

pixel $\sim 10^{-66}\,cm^2$

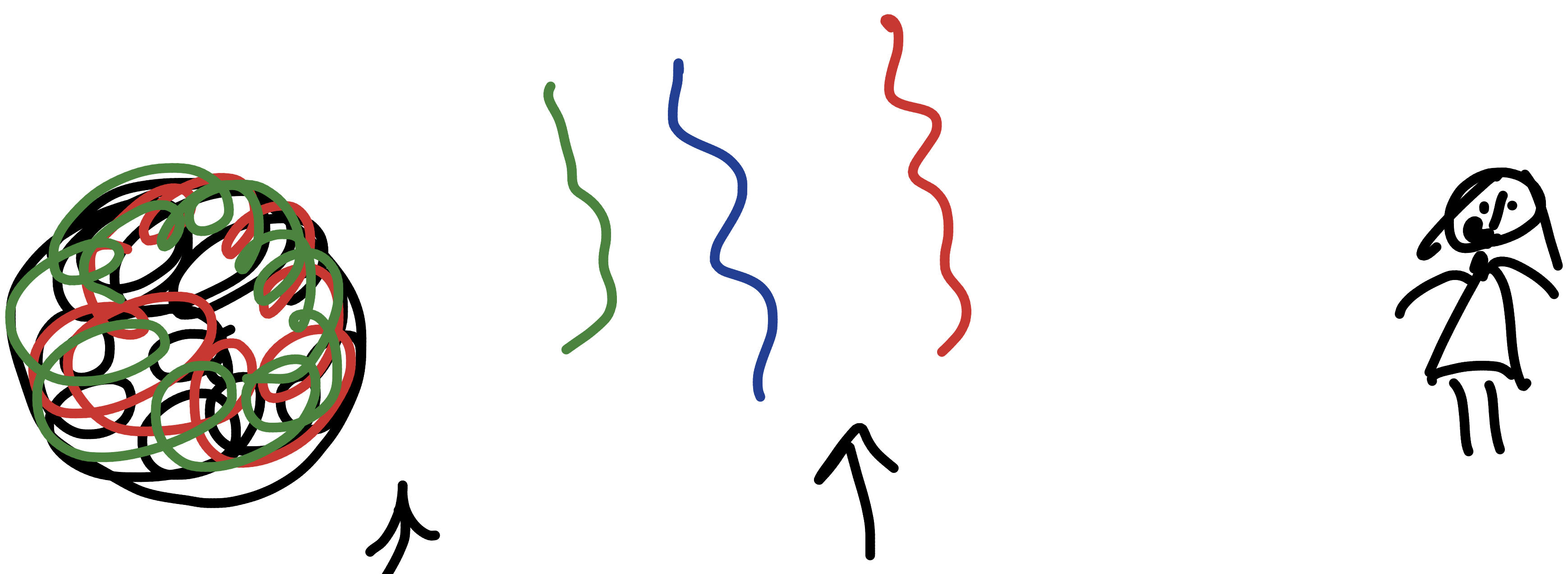
Energy cost of a pattern written in a black hole

Energy cost of the same pattern outside

$$E^{BH}_{cat} \sim 10^{-68} E_{cat}$$

Due to memory burden effect it is impossible to extrapolate Hawking's regime for the later stages of black hole decay.

After $t_{min} \sim S R$ radiation is fully non-thermal.



Features visible