Demystifying Black Holes.

(Saturons: Black-hole-like bound states in ordinary theories)

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2003.05546 [hep-th]

1907.07332

1906.03530

+ with O. Kaikov, J. Valbuena '21

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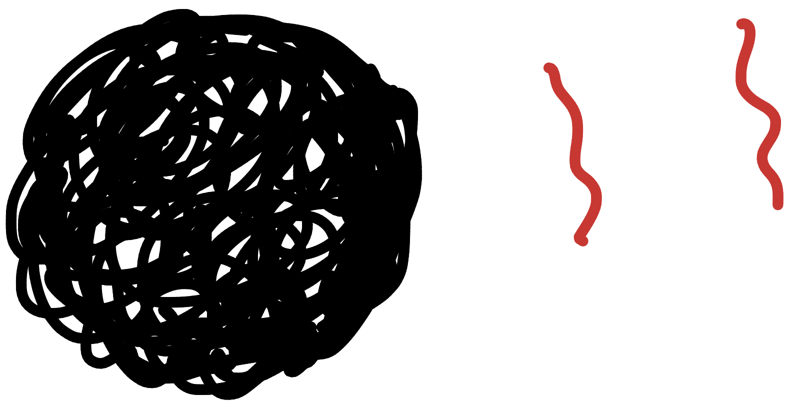
2111.03620 [hep-th]

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):

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

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

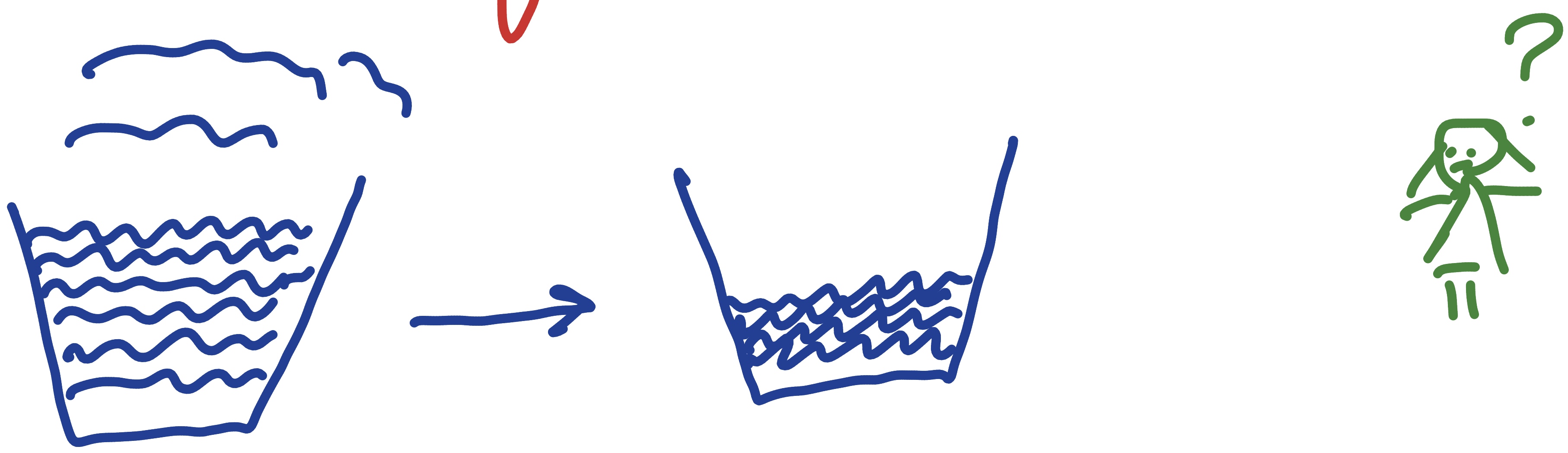
We call them "Saturons".

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

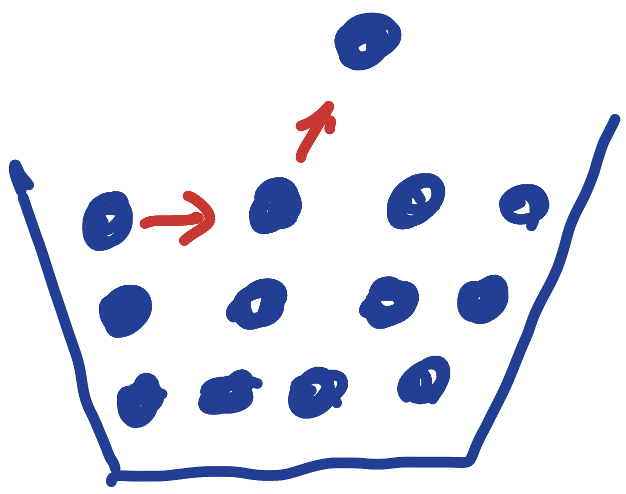
This indicates that:

Black hole = Saturon

When encountering a mysterious phenomenon of nature:



⊛ Create a microscopic theory (corpuscular resolution)



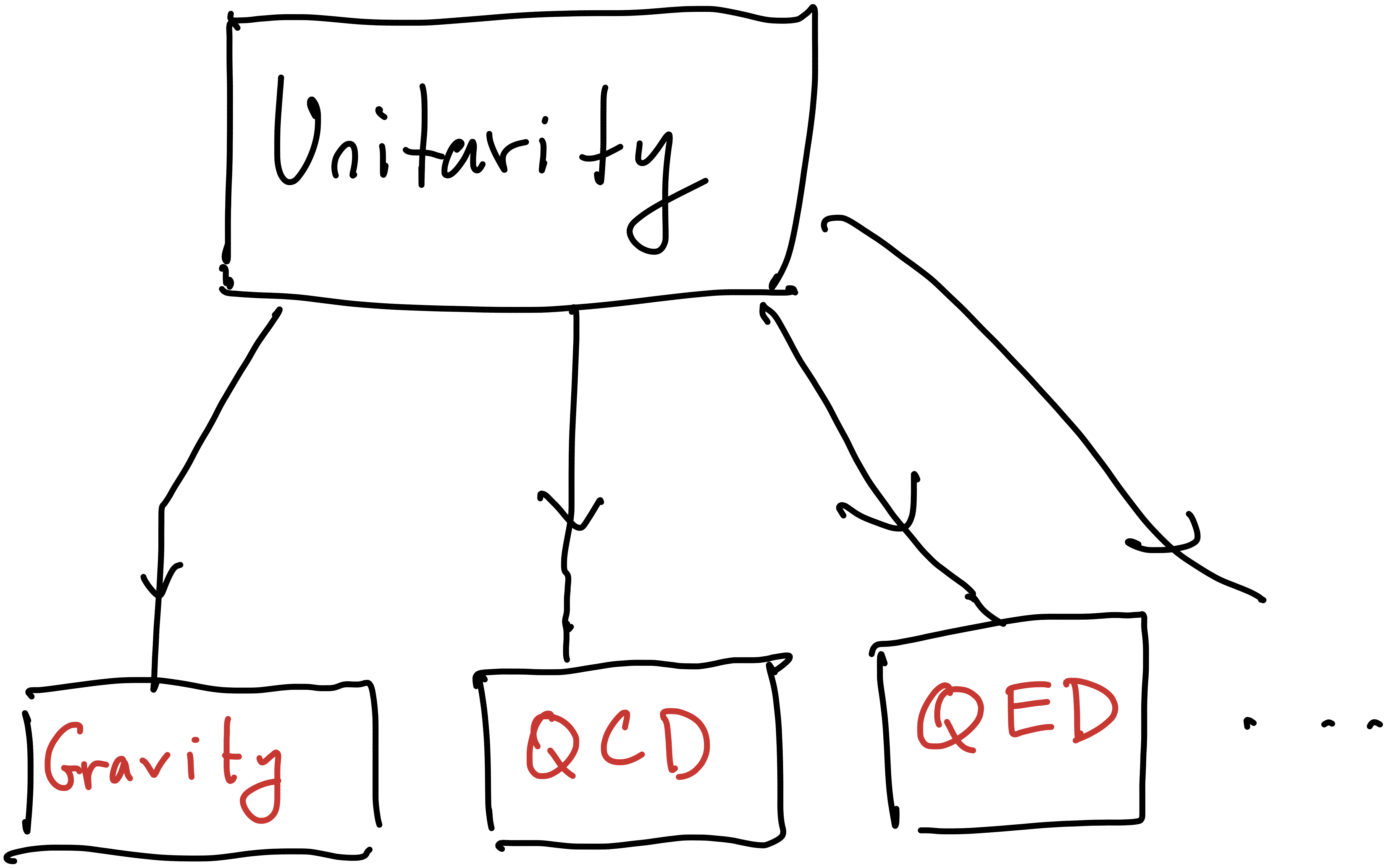
"N-Portrait" of Black hole

G.D., Gomez '11

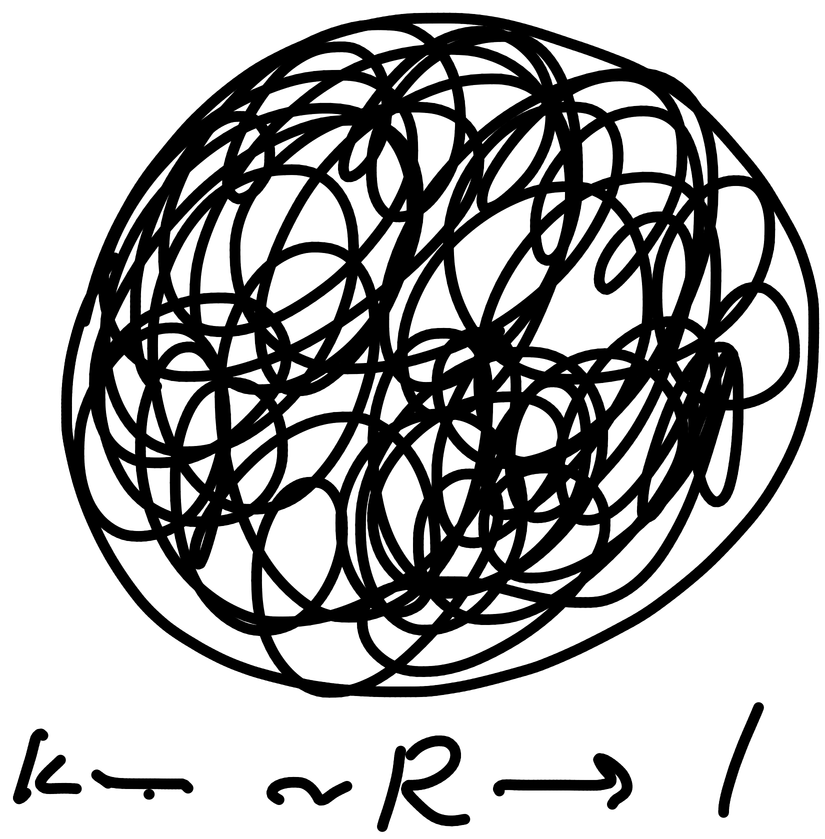
⊛ Try to capture universal properties

Water Mercury Ethanol

Most prominent constraint:



Unitarity bound on entropy:



For any self-sustained object of size R

$$S \leq \frac{1}{\alpha}$$

$\alpha \equiv$ running quantum coupling evaluated at scale $\frac{1}{R}$

Goldstone form of entropy bound

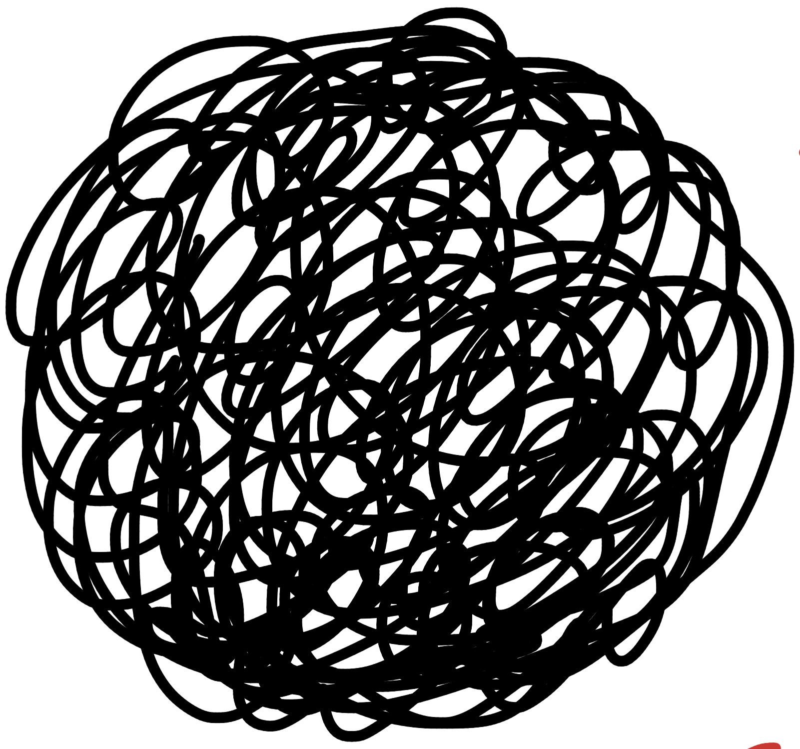
$$S \leq \frac{\text{Area}}{G_{\text{Gold}}}$$

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

$G_{\text{Gold}} \equiv$ Coupling of Goldstone

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

$f \equiv$ Goldstone decay constant



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".

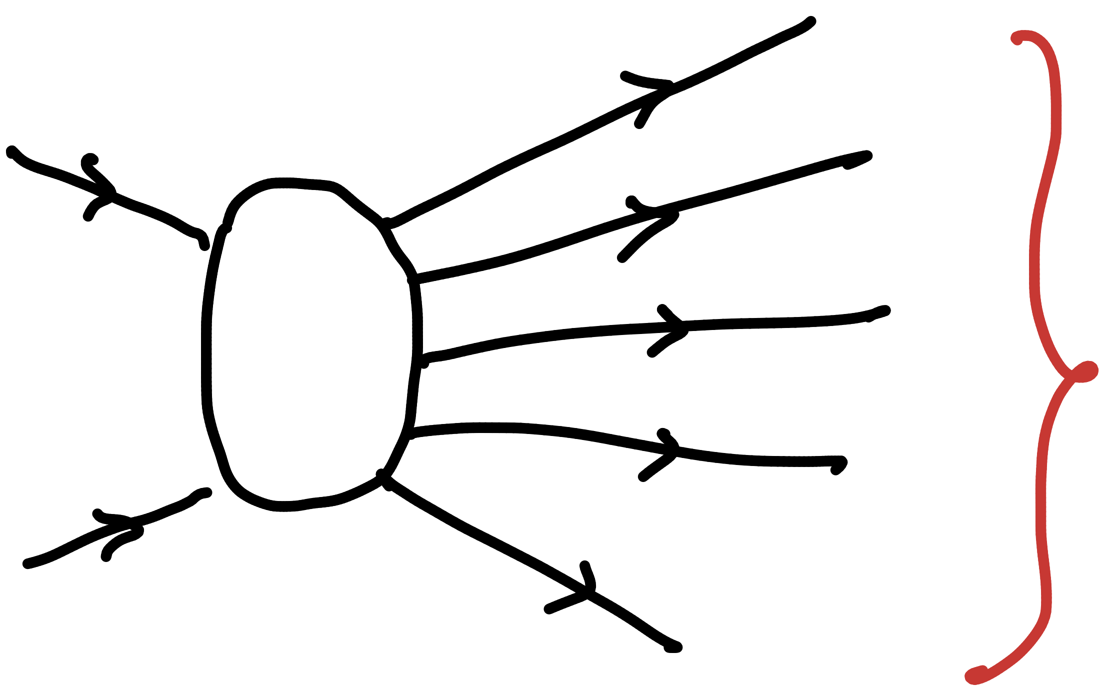
Saturation of these entropy bounds is in one-to-one correspondence with saturation of <u>unitarity</u> by

$2 \to n$ scattering amplitudes

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

The point of optimal truncation.

$E = nq$

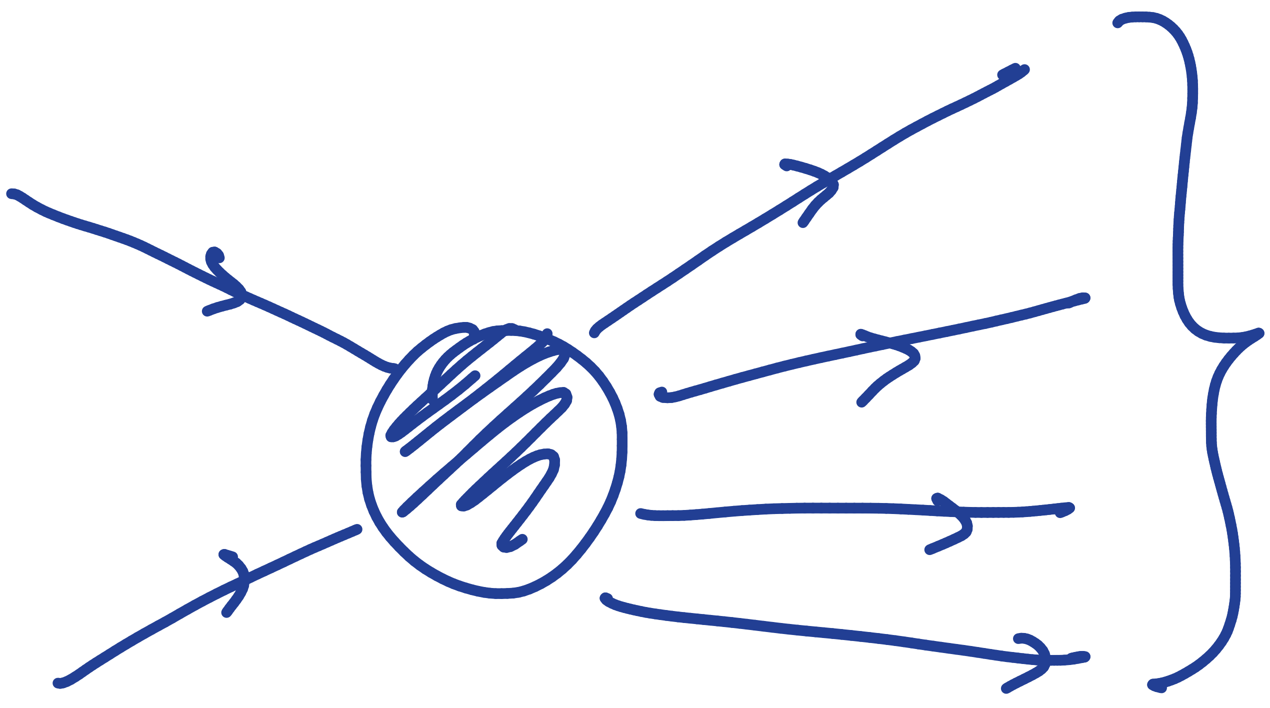


$n = \dfrac{1}{\alpha}$

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

Cross section of $2 \to n$ scattering:

Optimal truncation



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

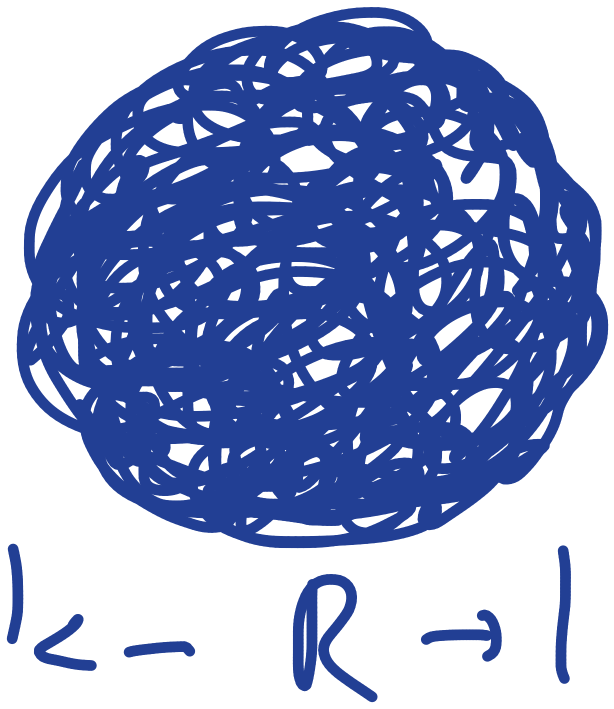
$$\sigma_{2\to n} = e^{-\frac{1}{\alpha} + S}$$

Unitarity bound on entropy:

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

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 $t_{min} \sim \frac{R}{\alpha} \sim S R$
* Saturate scattering amplitudes.

Black-hole-like bound states in $d=4$

A model

G.D., '20; G.D., Kaikov & Valbuena '21

$SU(N)$ with adjoint Φ^α_β + fundamental ξ_α

$\alpha, \beta = 1 \ldots N$

Lagrangian (most general renormalizable)

$$\mathcal{L} = \frac{1}{2} \mathrm{Tr}\, \partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2} \partial_\mu \xi^+ \partial^\mu \xi - V(\Phi, \xi)$$

$$V = \frac{\alpha}{2} \mathrm{Tr} \left[f \Phi - \Phi^2 + \frac{\hat{I}}{N} \mathrm{Tr} \Phi^2 \right]^2 +$$

$$+ \alpha_\xi\, \xi^+ \Phi^2 \xi + \tilde{\alpha}_\xi (\xi^+ \xi)^2 \mathrm{Tr} \Phi^2 +$$

$$+ \bar{\alpha}_\xi (\xi^+ \xi)^2$$

Many degenerate vacua with spontaneously broken symmetry

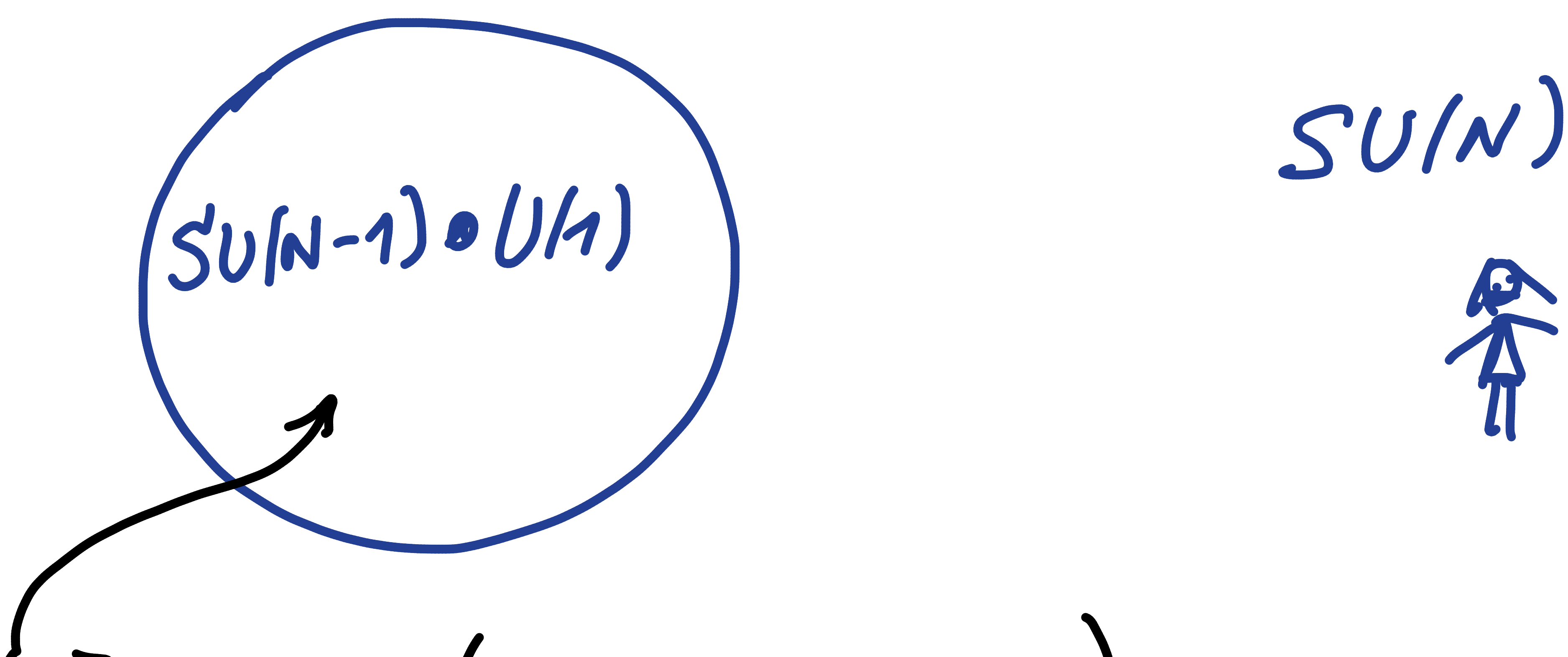
$$SU(N) \to SU(N-K) \otimes SU(K) \otimes U(1)$$

$$0 < K < N$$

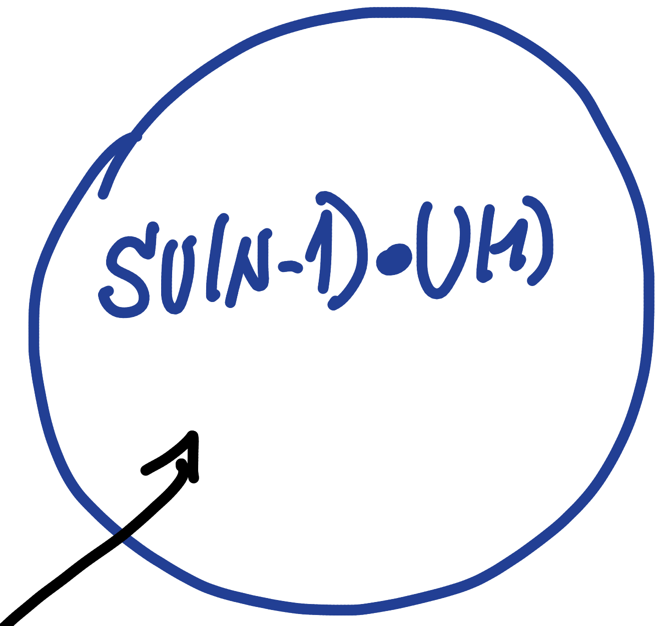
We choose $SU(N)$ invariant vacuum as asymtotic S-matrix vacuum.

In this vacuum, there exist an infinite tower of bound states:

Bubbles of $SU(N-1) \otimes U(1)$-vacuum:



$$\Phi = \mathrm{diag}(N-1, -1, -1, \ldots -1)$$



In outer vacuum there is a mass gap

$$m^2 = \alpha f^2$$

$N_G \sim N$ Goldstone species θ^a, $a = 1, 2, \dots 2N$

$f \equiv$ Goldstone decay constant

$$G_{Gold} = \frac{1}{f^2} \leftarrow \text{Goldstone coupling}$$

There exists an infinite tower of classically-stable bubbles.

They represent bound states of Goldstones with total occupation number n.

The spectrum of bound-states

$$E_n = n\sqrt{\frac{m}{R}}$$

One can think of them as sort of non-topological solitons, or Q-balls.

However, they are not ordinary solitons, due to degeneracy:

Level E_n has microstate degeneracy:

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

Correspondingly, they carry a microstate entropy

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

Now, theory saturates unitarity for

$$N\alpha \sim 1$$

Thus, entropy is saturating unitarity bound $S \sim \frac{1}{\alpha}$ for

$$\boxed{n \sim N \sim \frac{1}{\alpha}}$$

saturation point

Thus, entropy of saturon is

$$S \sim \frac{1}{\alpha} \sim N \sim n$$

Notice, Goldstone decay constant both for Poincare and for $SU(N)$ is

$$f^2 = \frac{N}{R^2}$$

Goldstone coupling:

$$G_{Gold} = \frac{1}{f^2} = \frac{R^2}{N}$$

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

Parameters of the saturated bound state:

* Mass $$M = \frac{N}{R} = \frac{1}{\alpha R} = \frac{S}{R}$$

* Entropy

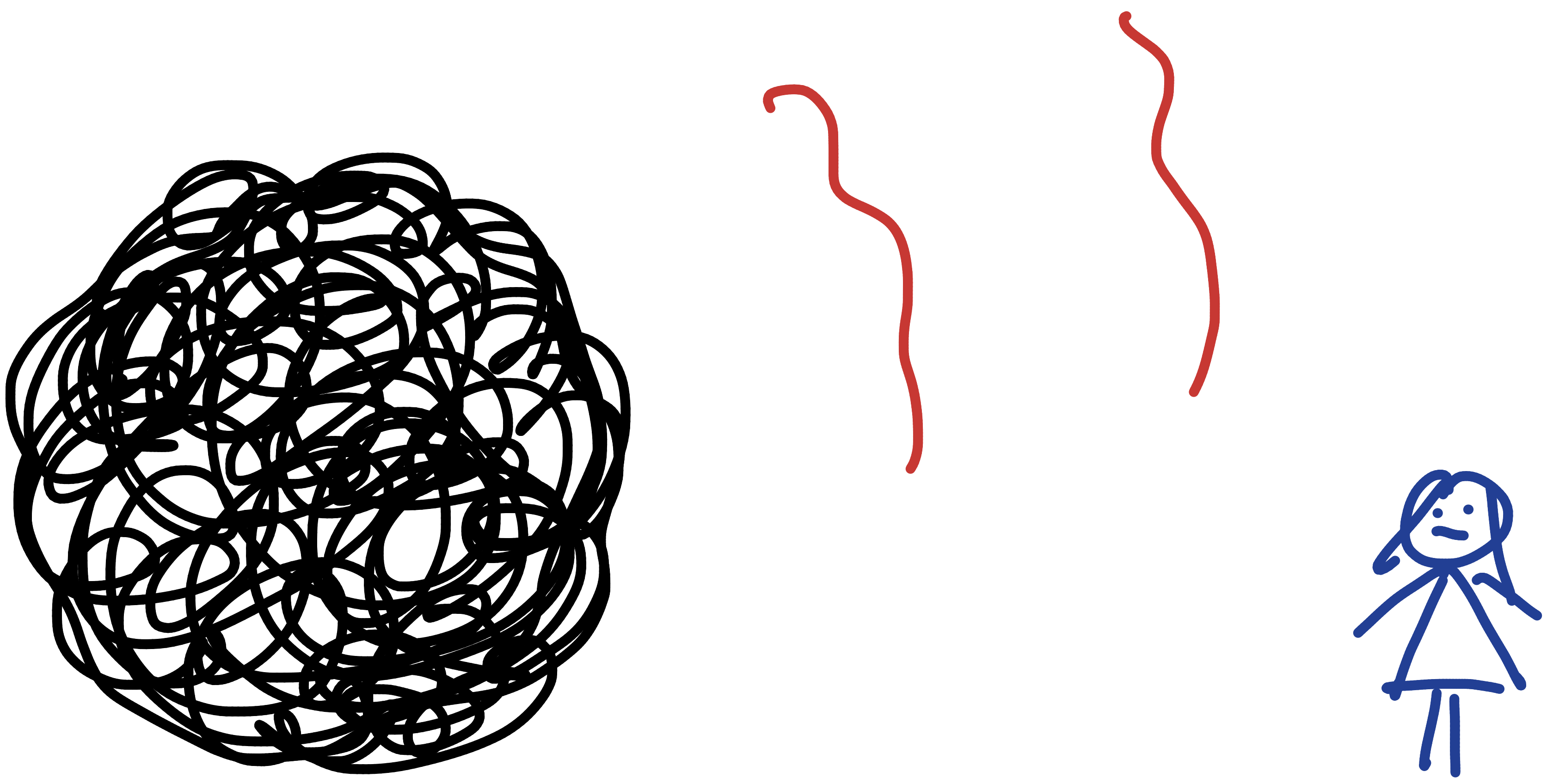
$$S = \frac{1}{\alpha} = \frac{\text{Area}}{G_{Gold}} = N$$

* Size $$R = m^{-1}$$

In quantum theory bound state decays.

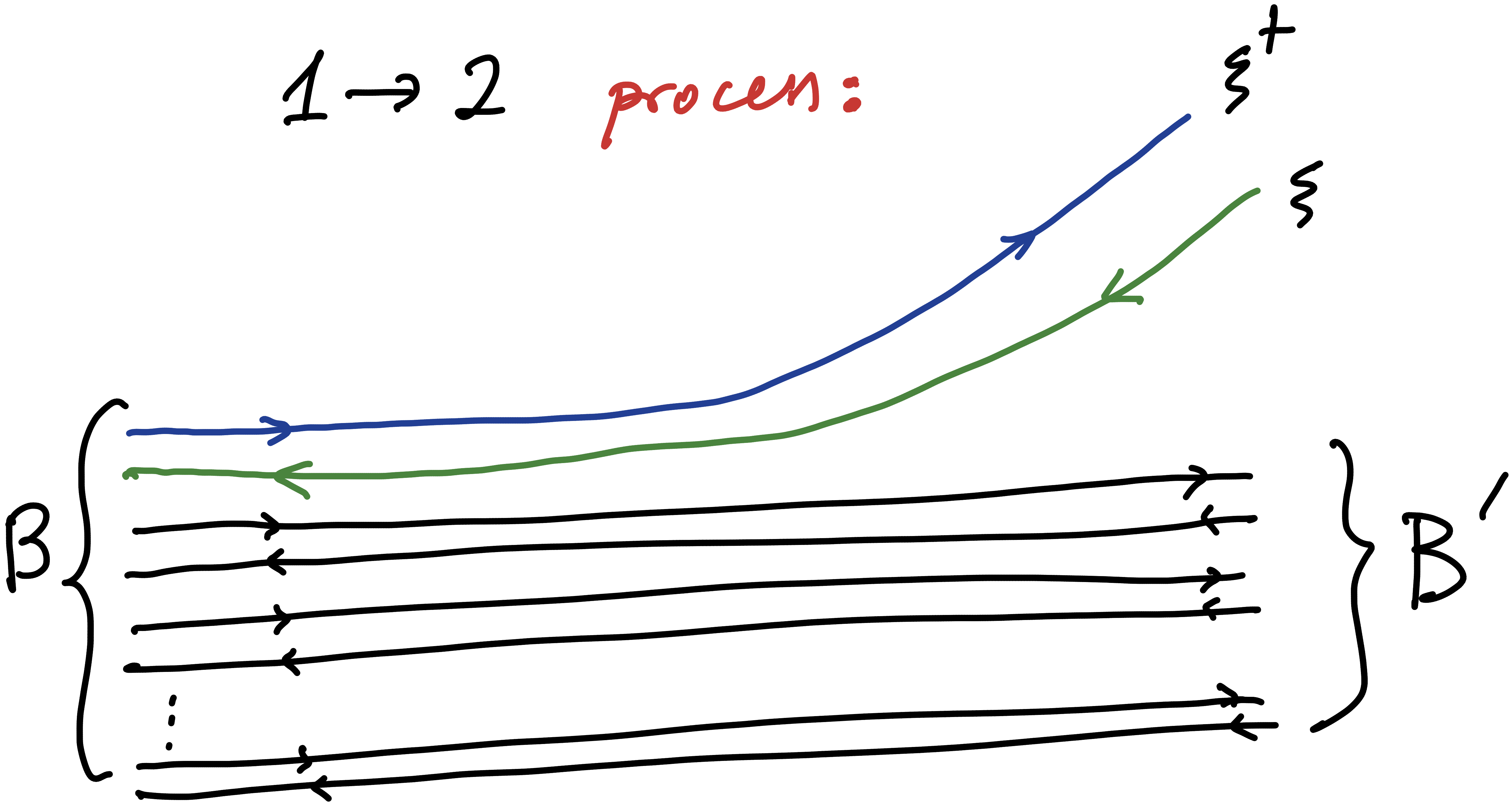
The decay rate of a saturated bubble:

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



Emission of massless ξ-quanta

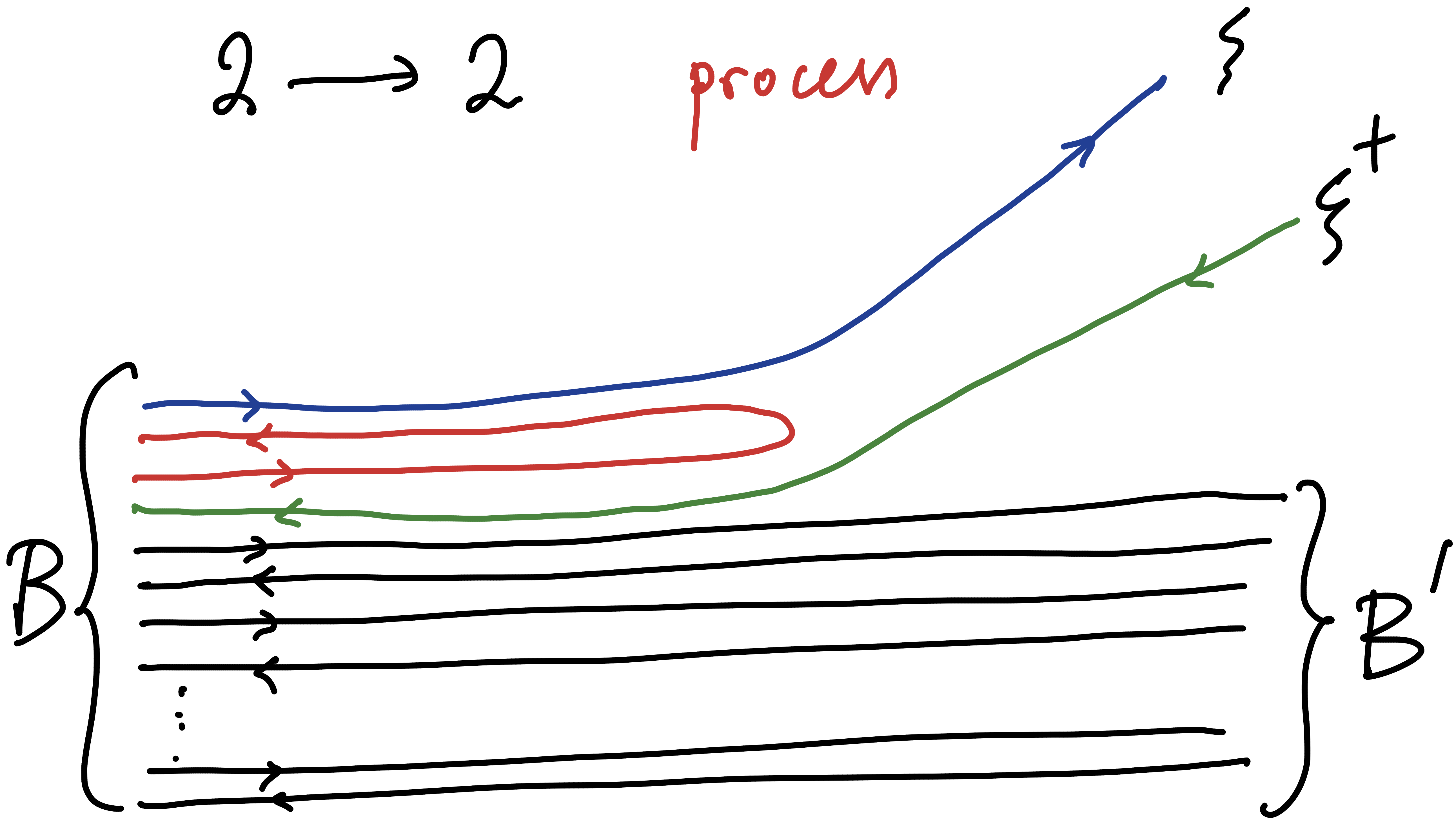
$1 \to 2$ process:



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

Recall, $\alpha N = 1$

$2 \longrightarrow 2$ process



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

$\alpha N = 1$ ← saturation condition.

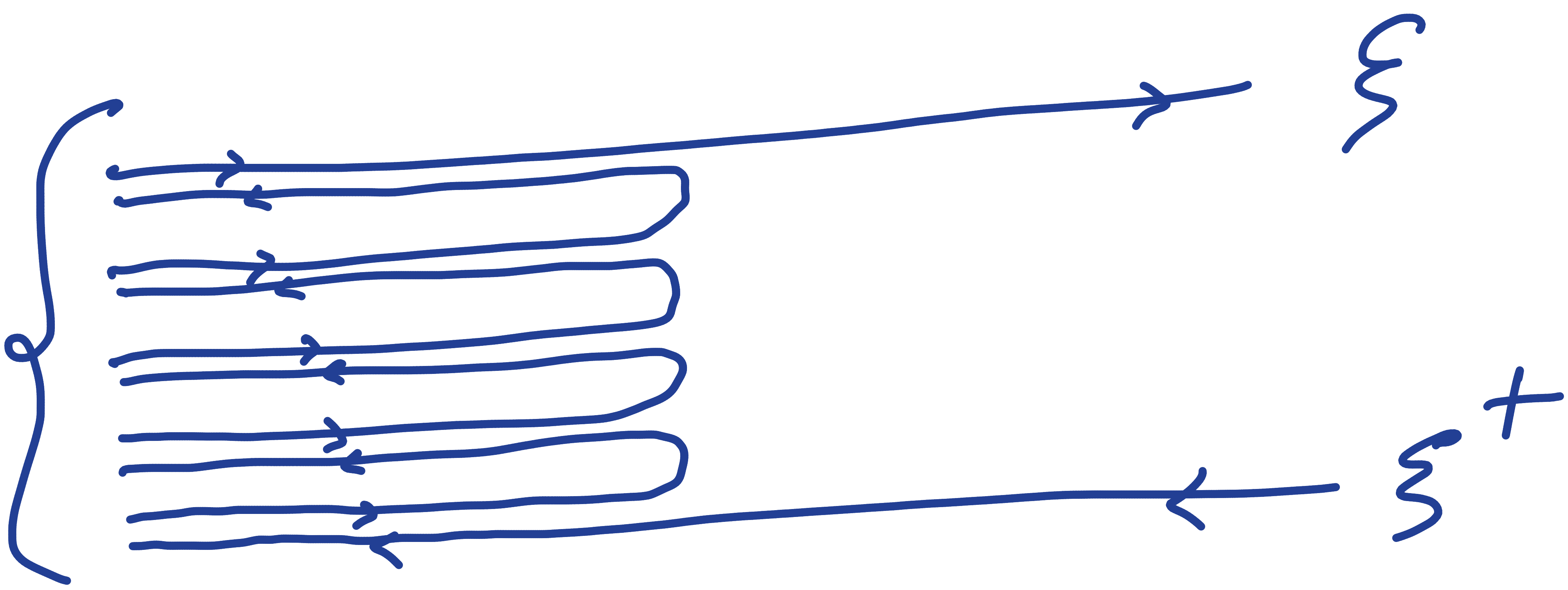
Notice, emission of more energetic quanta is "Boltzmann" suppressed:

$$E_{\xi+\xi^+} \gg \frac{1}{R}$$

rate is exponentially suppressed

$$\Gamma \sim e^{-\frac{E_{\xi+\xi^+}}{T}}$$

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



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.

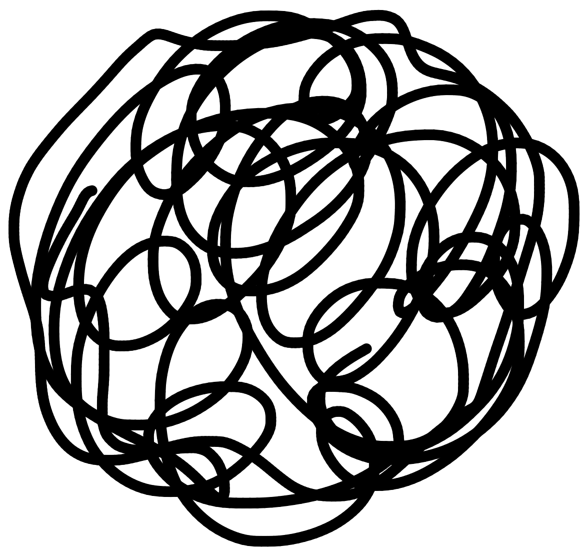
In the semi-classical limit: $N \to \infty$, $\alpha \to 0$,

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

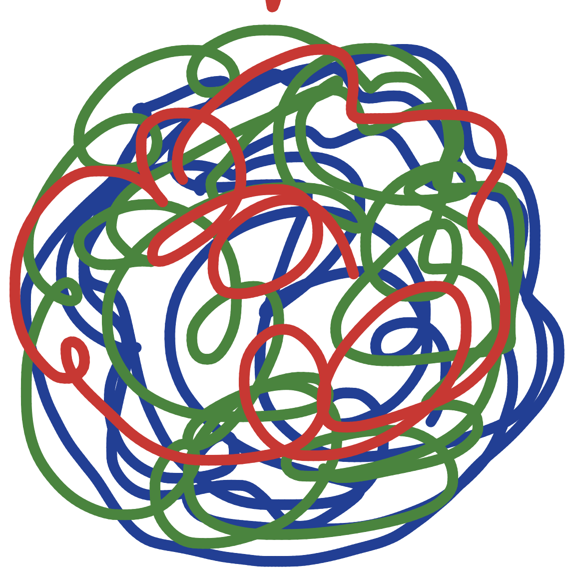
It is <u>unreadable</u>: Saturon has information horizon.

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

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



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



identical to Page's time for a black hole

Black hole/saturon correspondence:

$$G_N \longrightarrow G_{Gold}$$

All characteristics are identical:

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

$$S_{BH} \longleftrightarrow S$$

$$T_H \longleftrightarrow T$$

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

Saturons in $d=2$

G.D., Sakhelashvili '21

Gross-Neveu Model

$$\mathcal{L} = i\bar{\psi}\not{\partial}\psi + \frac{\alpha}{2}\left(\bar{\psi}\psi\right)^2$$

$2N$ Majorana fermions with flavor group $SO(2N)$

The model is asymptotically free and the spectrum of bound states is known.

The spectrum of bound states (exact in $N \to \infty$):

Boundstate of n fermions ($n < N$)

$$M_n = m_f \frac{2N}{\pi} \sin\left(\frac{n\pi}{2N}\right)$$

is anti-symmetric tensor of $SO(2N)$

the degeneracy:

$$n_{st} = \frac{2N!}{n!\,(2N-n)!}$$

The boundstate of maximal degeneracy $n = N-1$:

$$M_n = \frac{2N}{\pi} m_f \quad \text{has size} \quad R = m_f^{-1}$$

Entropy

$$S = \ln(n_{st}) = 2N \ln(2)$$

Saturates unitarity bound for

$$N \sim \frac{1}{\alpha}$$

The cross section of

$$\text{Vacuum} \longrightarrow 2N$$

process scales as

$$\sigma = e^{-\frac{2}{\alpha} + S}$$

Can be interpreted as the process of saturon pair creation

Very similar to saturation of $2 \to N$ graviton process by black holes

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

At the saturation point the entropy of a bound state exhibits complete correspondence with Bekenstein-Hawking entropy of a black hole

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

the quantity

"Area" $= R^{d-2}$ is well defined for $d=2$

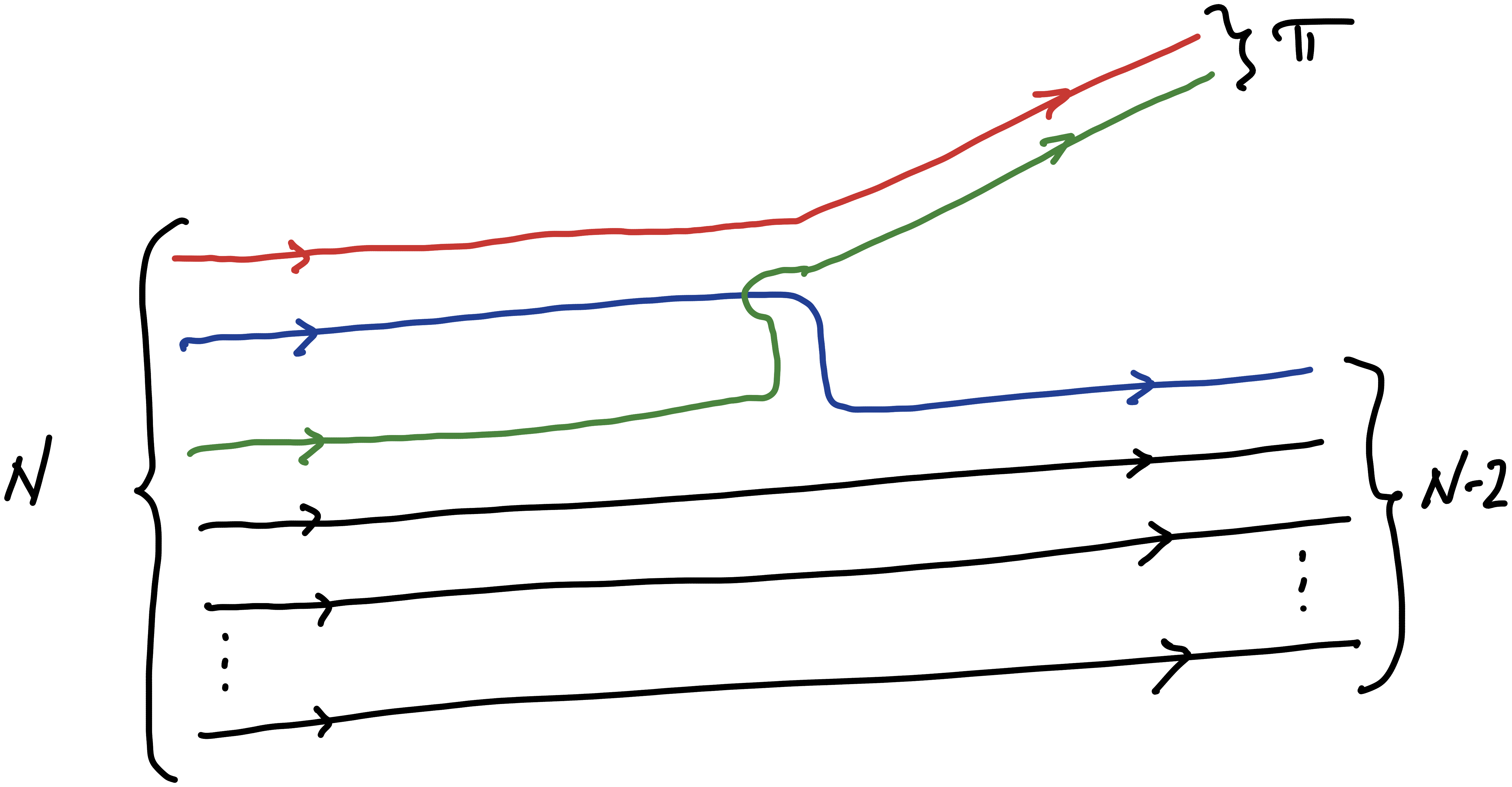
Hawking evaporation of GN saturon.

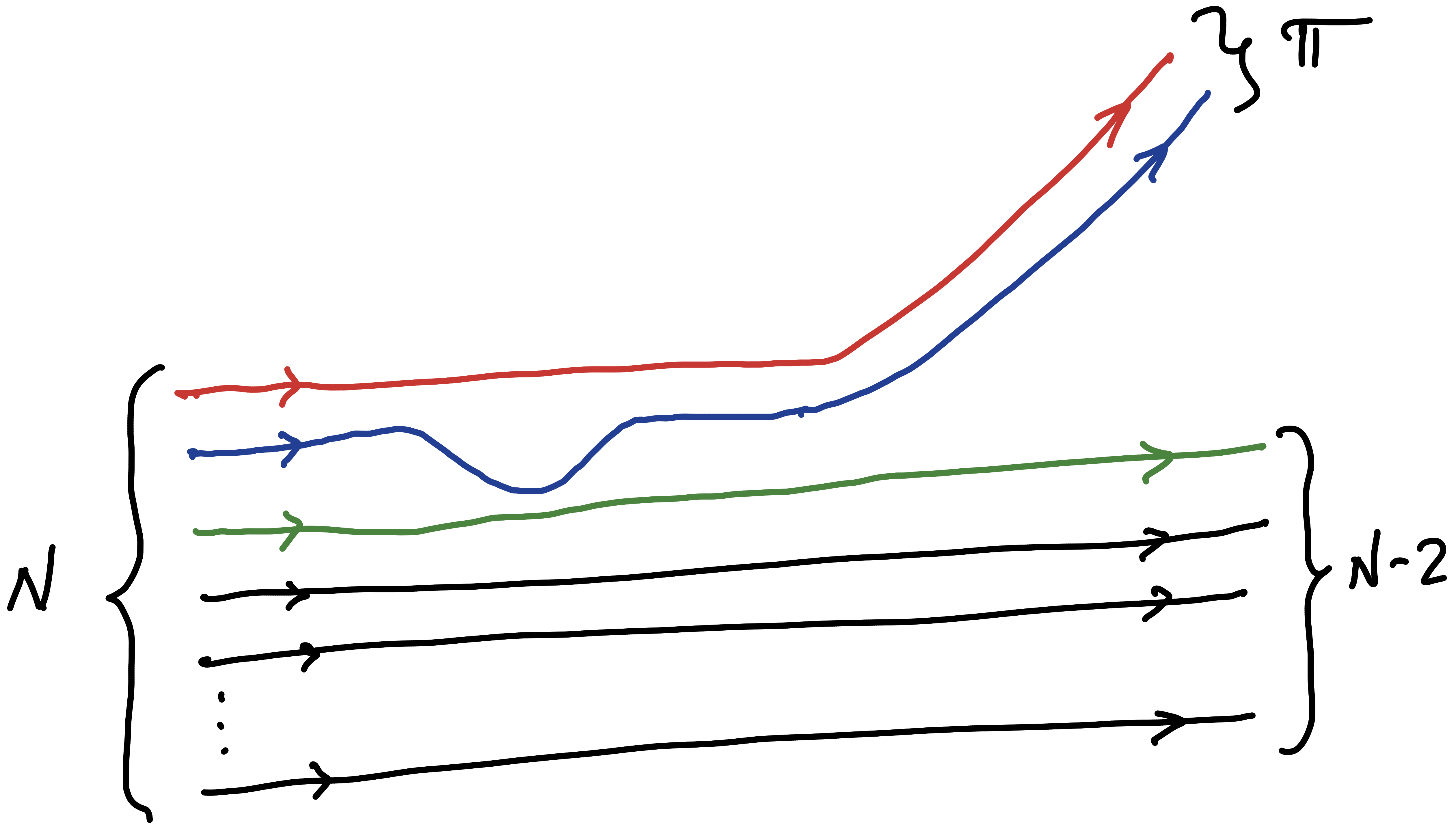
Coupling to pion:

$$\mathcal{L}_{\pi} = \partial_\mu \pi_{ij} \partial^\mu \pi_{ij} + \frac{m_f}{f_\pi} \pi_{ij} \bar{\psi}_i \gamma_5 \psi_j$$

The saturon emits pion and evaporates with the rate.

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





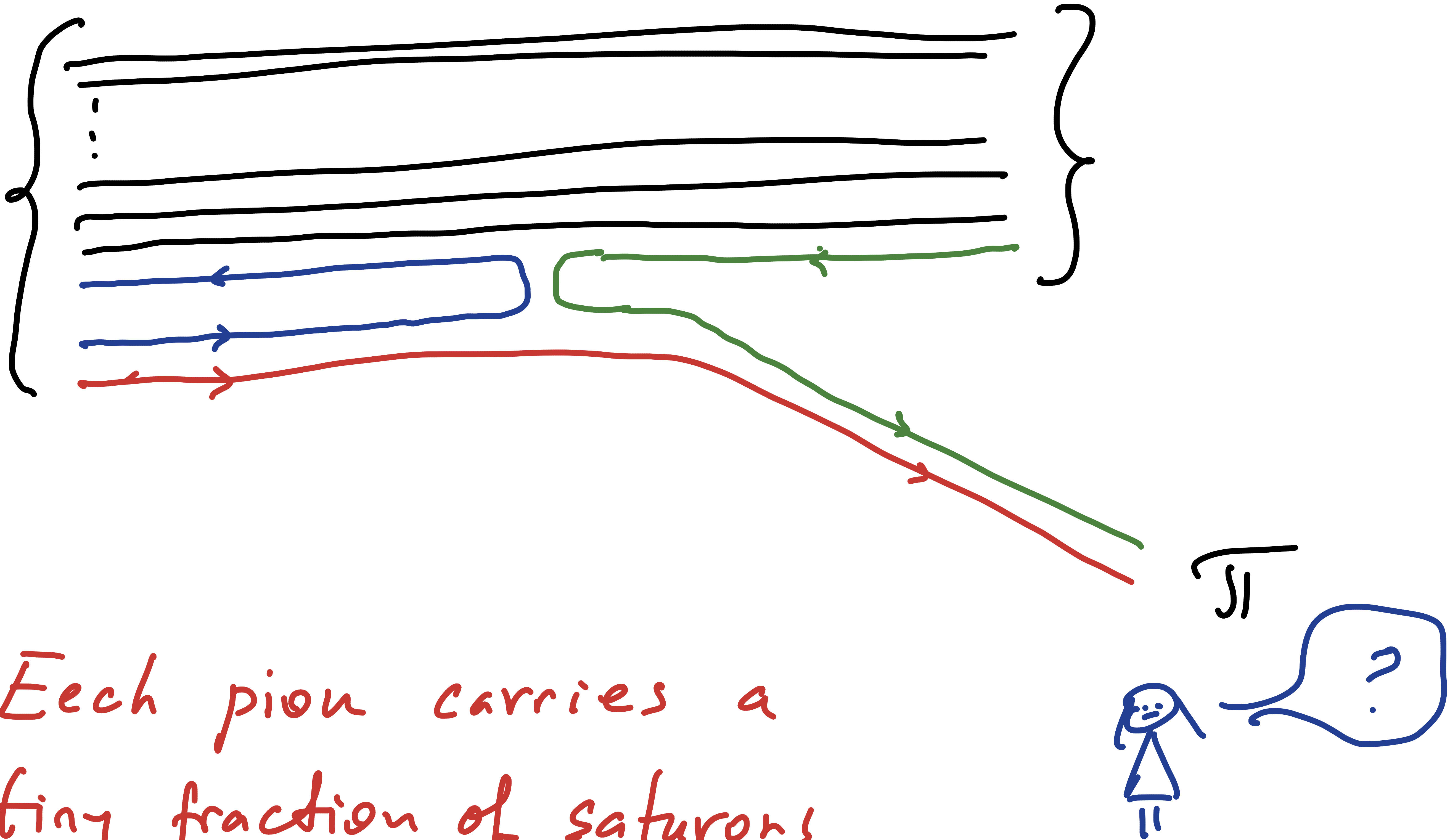
rate $\Gamma \sim \frac{1}{R}\,\alpha^2 \frac{1}{f_\pi^2} N^3 \sim \frac{1}{R}$

We are dealing with thermal evaporation rate of temperature

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

The information is hidden in $\frac{1}{N} \sim \frac{1}{S}$ corrections.

It is carried by flavor quantum numbers of pions.



Eech pion carries a tiny fraction of saturons information.

Alice has to collect $\sim N$ pions and decode their flavor.

This is only a <u>start</u> of information retrieval:

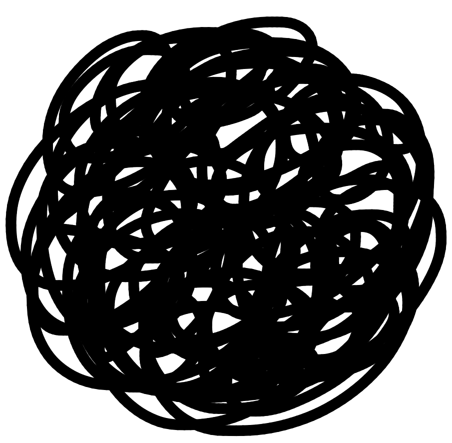
$$t_{min} \sim N \cdot R \sim S R \sim \frac{R}{\alpha} \sim \frac{R^{d-1}}{G_{Gold}}$$

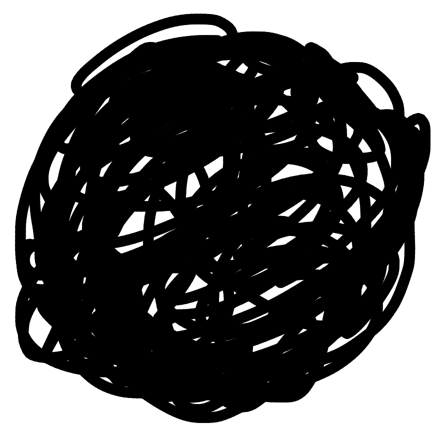
Black hole/saturon correspondence is independent of dimensionality and other details of the theory.

It is correspondance between the states in different theories

gravity

"ordinary" theory





G_N, α_{gr}

G_{Gold}, α

Trans-theoretic parameters

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.