S-Matrix Exclusion of de Sitter and Consequences

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2012.02133 [hep-th]
Symmetry 13 (2020) 1,3

JCAP, 1 (2014) 23,
Ann. Phys. 2016, 528, 68 } + Gomez

JCAP, 06 (2017) 028 } + Gomez, Zell

Some notations:

Vacuum energy density $\equiv \Lambda$

Newton's gravitational coupling $\equiv G$

4D Planck mass $\equiv M_P = \frac{1}{\sqrt{G}}$

de Sitter (Hubble) radius $\equiv R$

$$R^{-2} = \Lambda G$$

Number of particle species $\equiv N_{sp}$

string coupling $\equiv g_s$

String scale $\equiv M_s$

Implications for cosmology: Exclusion of de Sitter

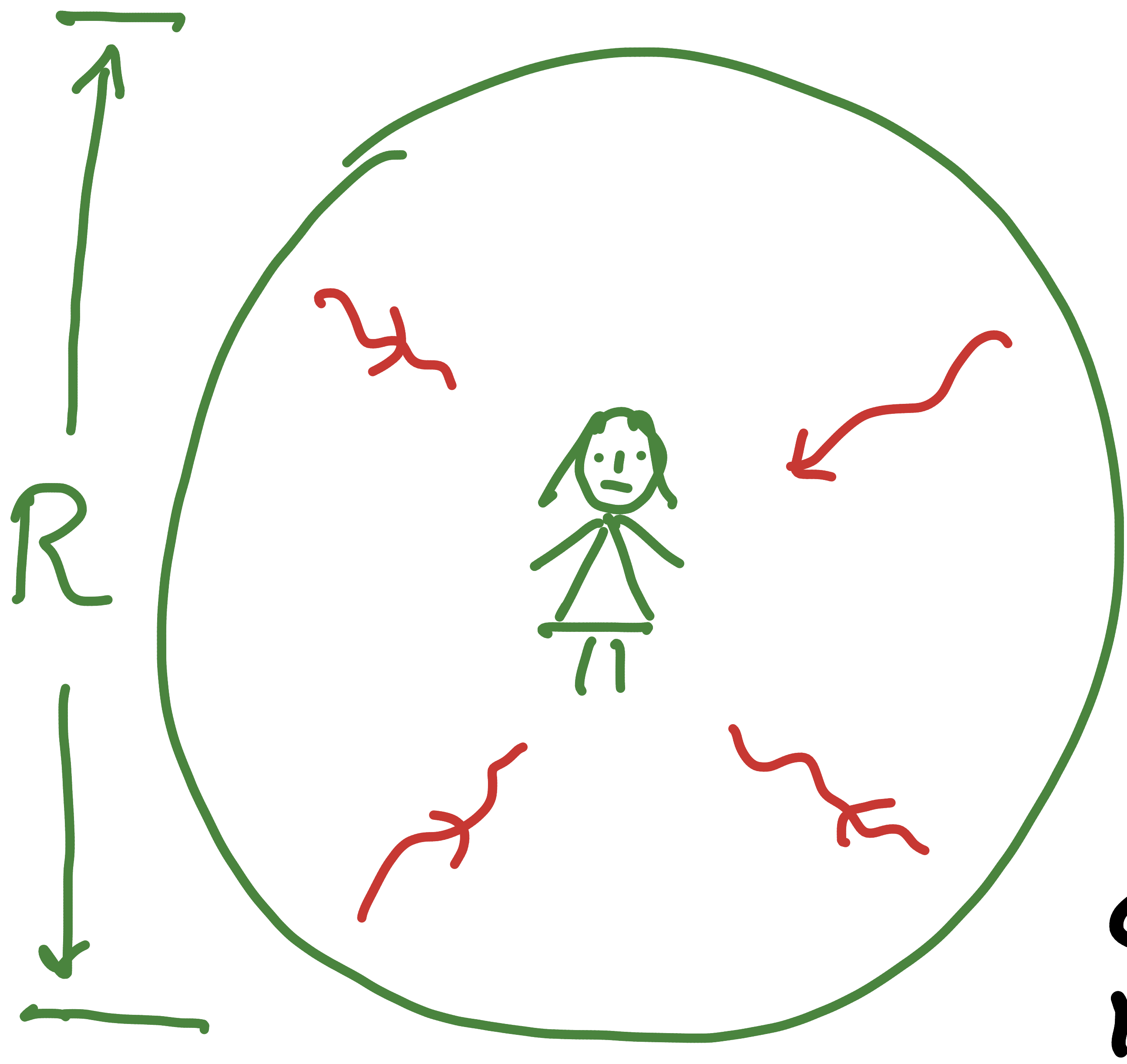
$$ds^2 = dt^2 - a^2(t)\, dx^2$$

scale factor

$$a(t) \propto e^{\frac{t}{R}}$$

cosmological constant

$$\frac{1}{R^2} = \frac{\Lambda}{M_P^2}$$



Gibbons-Hawking temperature:

$$T_{GH} = \frac{1}{R}$$

and entropy

$$S_{GH} = (R M_P)^2$$

De Sitter (dS)-like states are of fundamental importance in cosmology and particle physics.

They also create a puzzle (why is Λ small?)

What does quantum gravity has to say about de Sitter?

We shall argue that quantum gravity/string theory excludes de Sitter vacua, both <u>stable</u> and <u>meta-stable</u>.

No de Sitter future eternity.

The story is profound and S-matrix plays a fundamental role in it.

In string theory/quantum gravity the S-matrix is:

- A computational tool;
- The formulation of the theory.

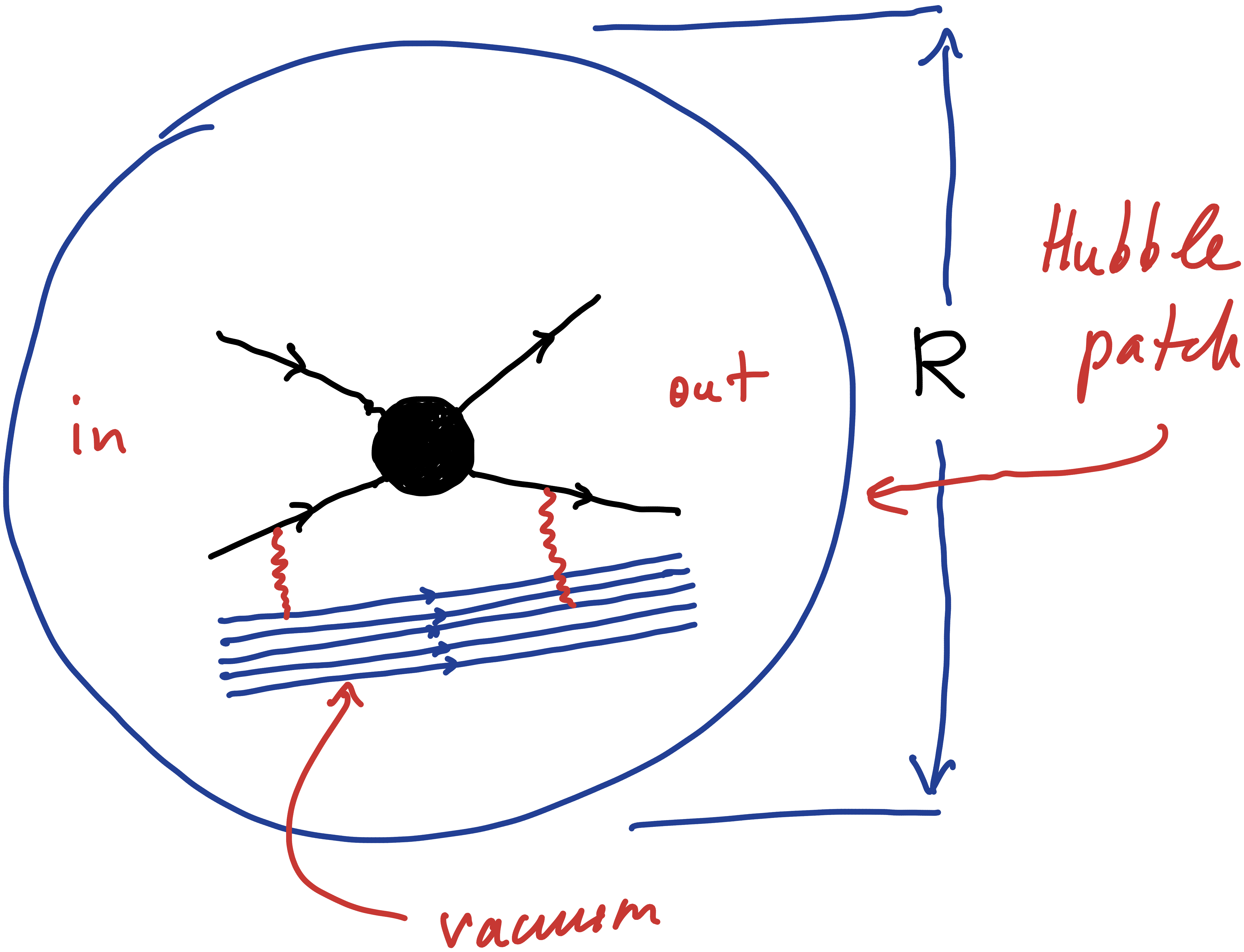
Necessary conditions:

1. Globally-defined time;

   Absent in classical de Sitter.

2. S-matrix vacuum.

What about quantum theory?
What about effective $\mathcal{S}$-matrix?

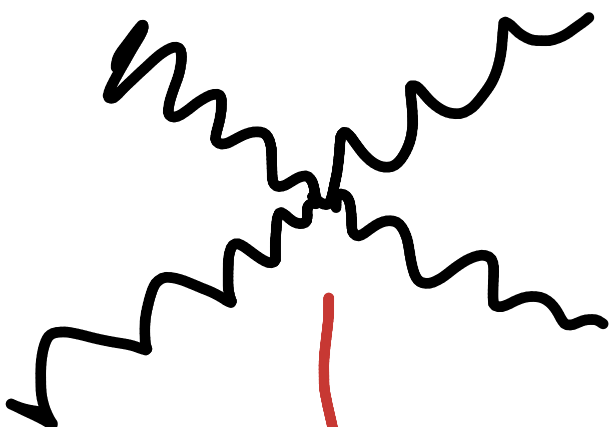


The vacuum should not be able to recoil and absorb some information.

This is only possible in double-scaling limit:

$$\Lambda \to \infty, \qquad \Lambda G = R^{-2} = \text{finite}.$$
$$G \to 0 \ (M_p \to \infty),$$

But in the same limit graviton quantum coupling vanishes



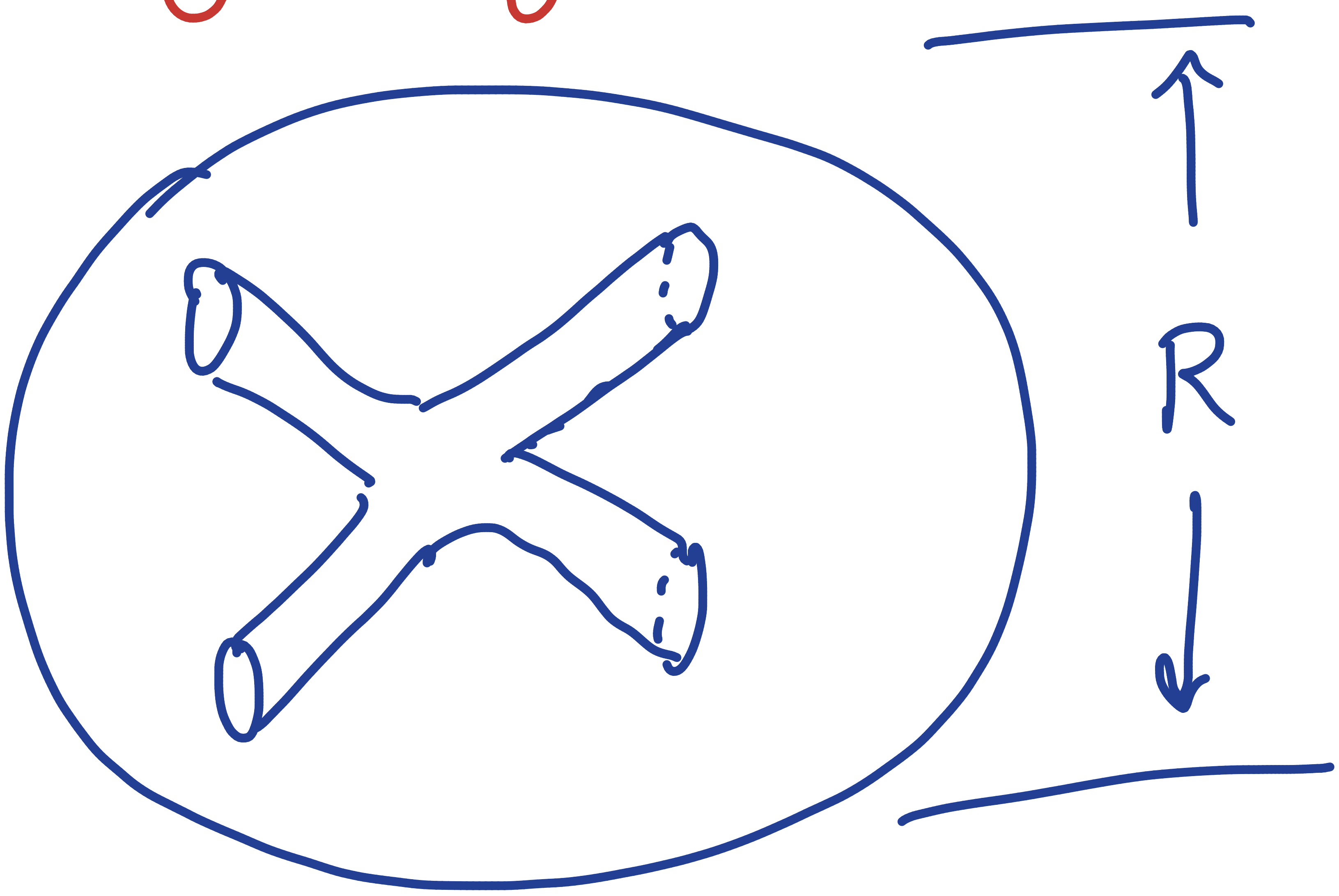
momentum-transfer

$$\alpha_{gr} = \frac{G}{\lambda^2} = \frac{q^2}{M_p^2} \to 0$$

wavelength

graviton S-matrix is trivial!

In string theory



$$R^{-2} = \Lambda G = \Lambda \frac{g_s^2}{M_s^8} = \text{finite}$$

in rigid Limit:

$$\left.\begin{array}{l}\Lambda \to \infty \\ G \to 0 \\ R = \text{finite}\end{array}\right\} \to \quad g_s^2 \to 0$$

Closed string S-matrix is trivial.

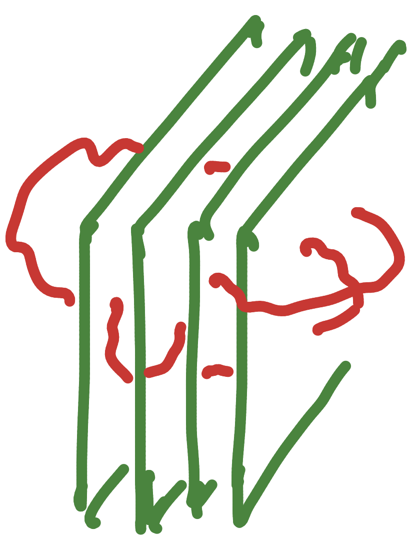
(Open strings, more subtle)

A bit more explicit: deSitter from D-brane uplifting

G.D., Tye '98; G.D. '99; G.D., Shafi, Solganic '01; Burgess, Majumdar, Nolte, Quevedo, Rajesh, Zhang, '01; Kachru, Kallosh, Linde, Trivedi '03; + Maldacena, McAllister '03

Take e.g. $n \times D_9 - \bar{D}_9$ in IIB

(Of course system has tachyon, Srednicki '98, Sen '99, ...)



$$\Lambda \cdot G = R^{-2}$$

$$\downarrow \qquad \downarrow \qquad \downarrow$$

$$n\,\frac{M_s^{10}}{g_s} \cdot \frac{g_s^2}{M_s^8} = (n g_s)\, M_s^2$$

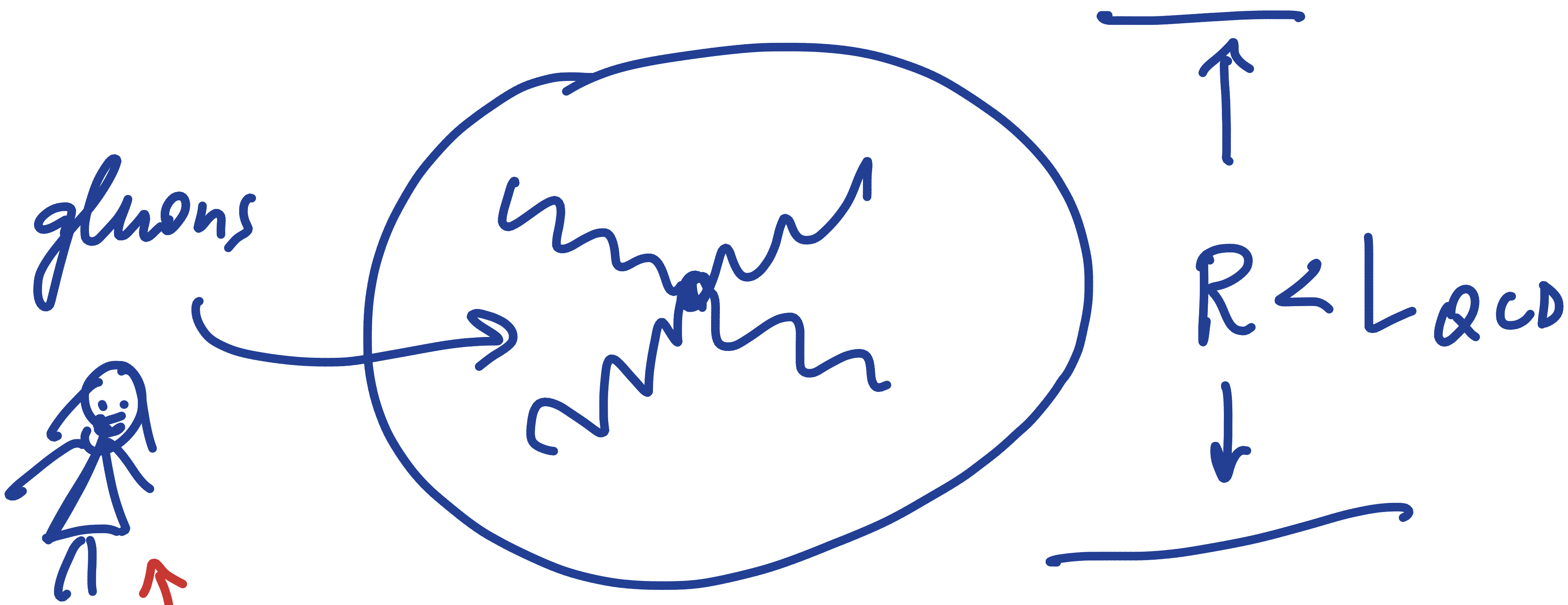
rigid limit: $\to 0$ $\quad \to \infty$ $\quad \to$ finite

Only possible if: $g_s \to 0$ $\quad n g_s = \text{finite}$

for $M_s = \text{finite}$

Notice, there is no problem of keeping other (Wilsonian) interactions intact.

E.g. QCD



Alice

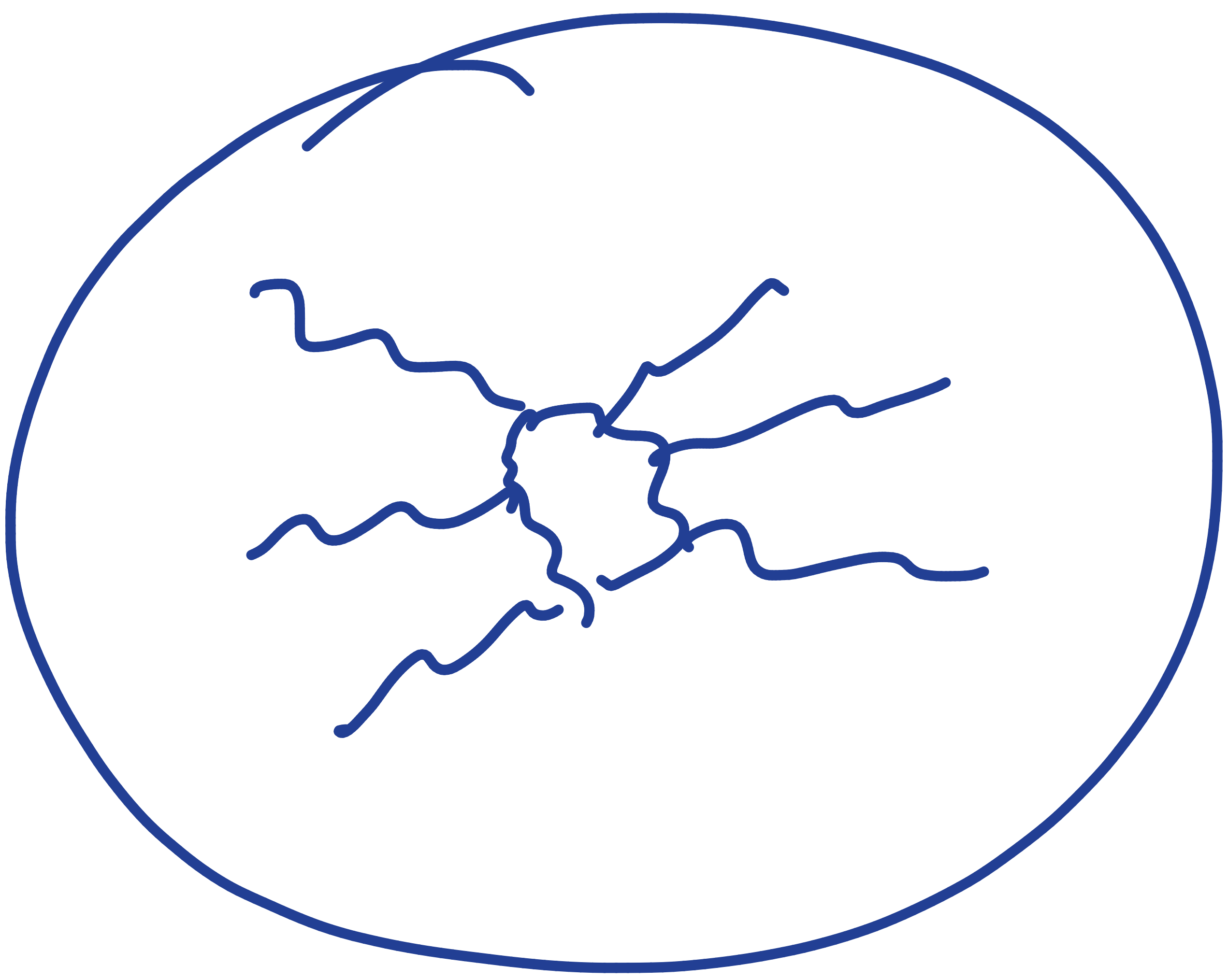
Thus, the issue is quantum gravitational.

$$(\text{de Sitter} = \text{vacuum}) \rightarrow \begin{matrix} \alpha_{gr} = 0 \\ g_s = 0 \end{matrix}$$

There are clear signals of S-matrix inconsistency already for finite M_p (G).

For example, scattering of quanta of center of mass energy

$$E \sim M_p^2 R$$



How is the S-matrix constraint enforced?

Corpuscular picture of de Sitter ("N-portrait"): G.D., Gomez '11, '13, ...

Since $|dS\rangle$ is not a vacuum, it can only be an excited state constructed on S-matrix vacuum (Minkowski).

$$|dS\rangle = |\underset{\uparrow}{N}\rangle$$

Number of constituents

We choose coherent state but others are also OK

$$\langle N|\hat{g}_{\mu\nu}|N\rangle = g_{\mu\nu} \leftarrow$$ classical dS

New concept:

Corpuscular completion (resolution)

Very different from and insensitive to UV-completion.

Universal properties:

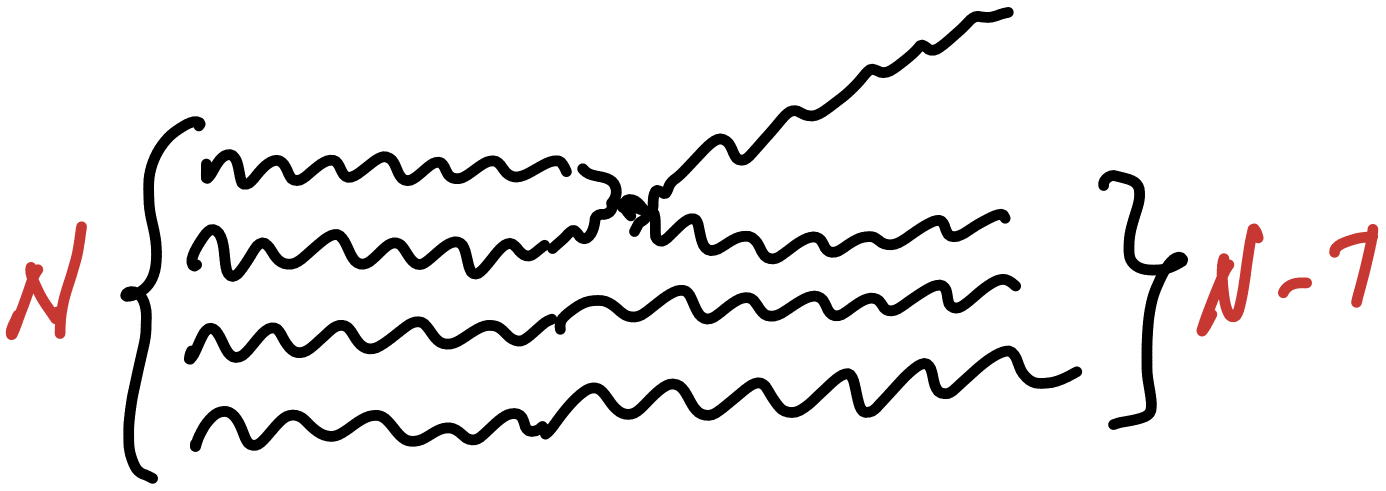
Number of constituent $N = \frac{1}{\alpha_{gr}}$

Their frequencies $\sim \frac{1}{R}$

$$\alpha_{gr} = \frac{1}{(M_p R)^2} = \frac{1}{N}$$

de Sitter is a <u>saturated</u> <u>state</u>.

Gibbons–Hawking radiation is a Hamiltonian process of a decay



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

Emission time $\tau = \Gamma^{-1} \sim R$

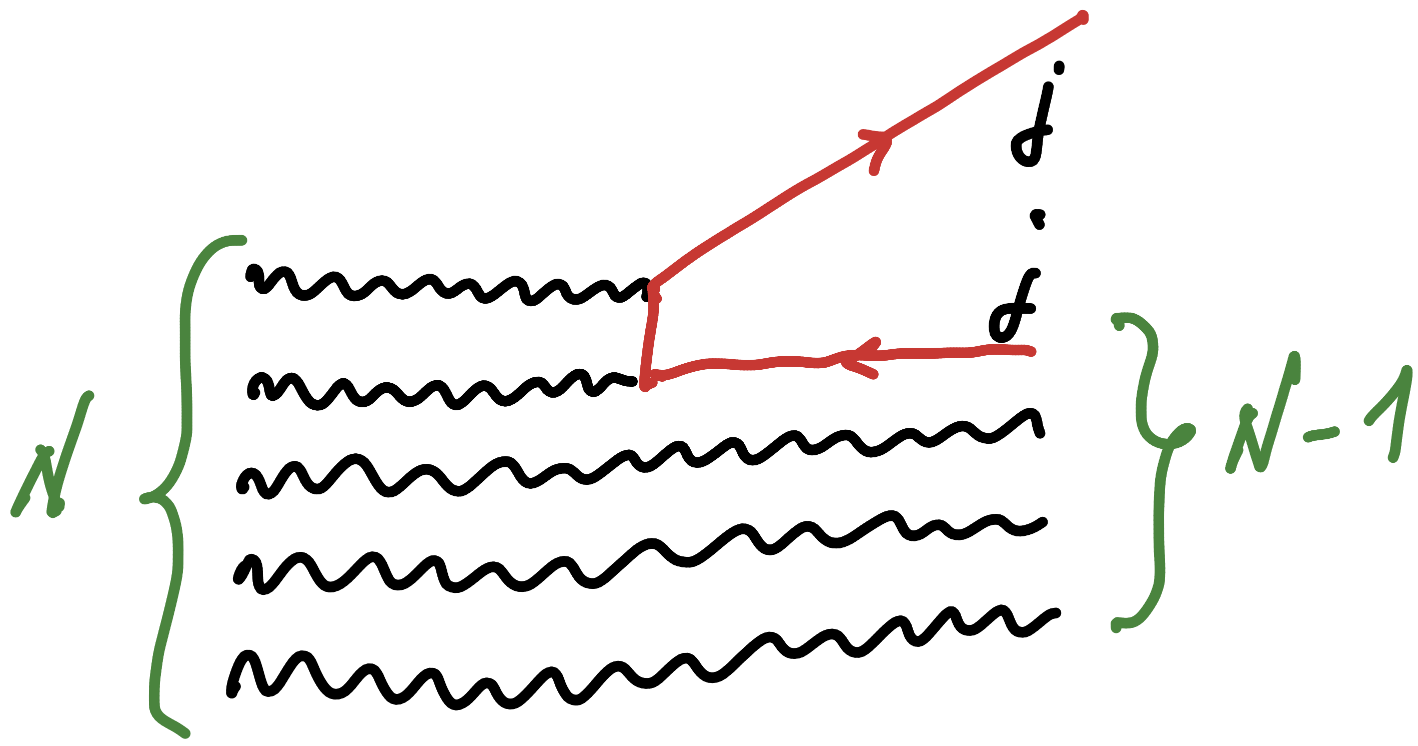
The resulting Gibbons–Hawking temperature $T_{GH} = \frac{1}{R}$

Thus, de Sitter "ages" due to an internal quantum clock.

The decay is democratic in species.

$$j = 1, 2, \ldots\ldots N_{sp}$$

species label



entangled

$$|N\rangle \to \sum_j |N-1\rangle_j \cdot |j\rangle$$

maximal departure from semi-classical evolution after

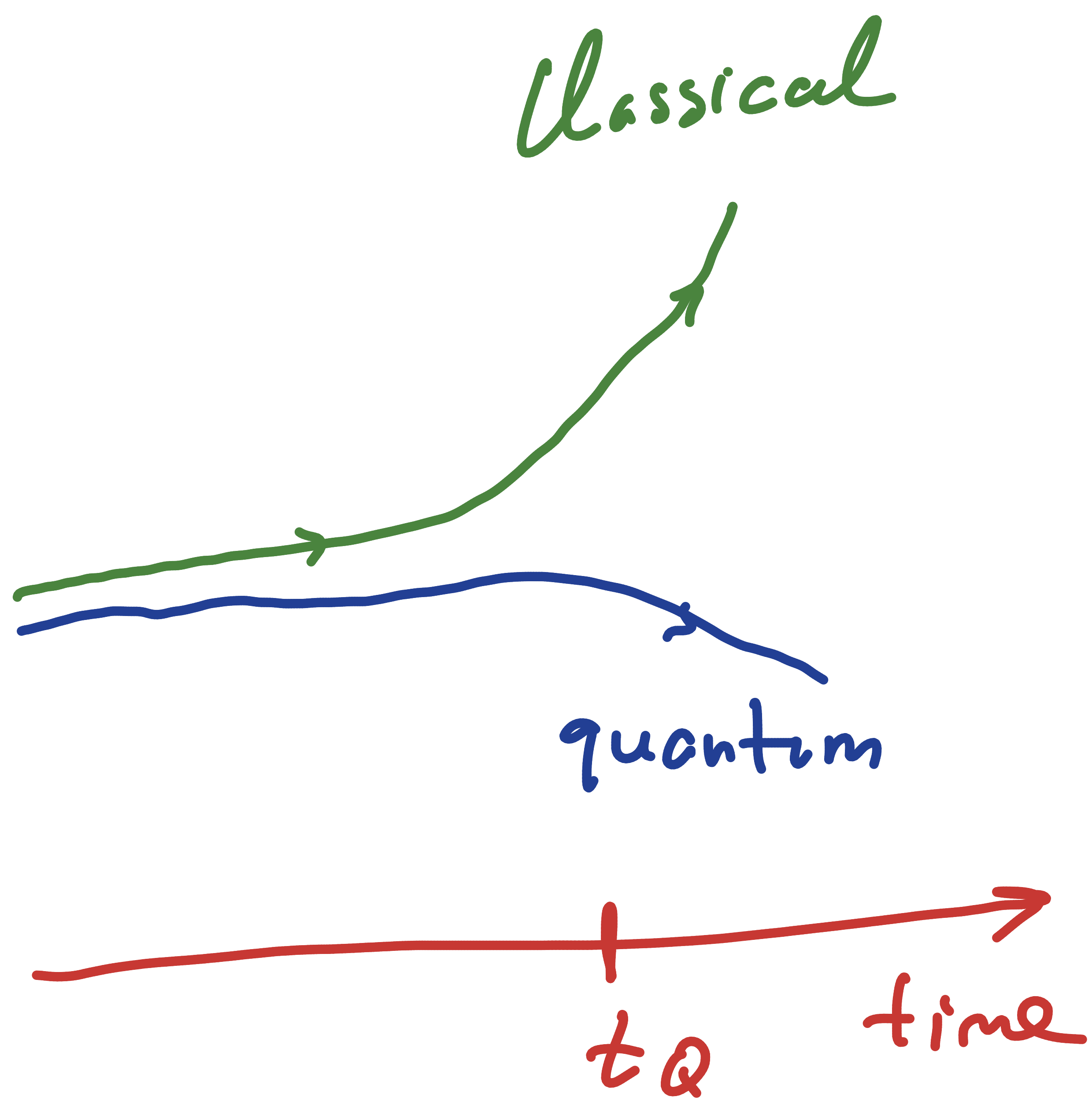
$$t_Q = R\,\frac{N}{N_{sp}} = R\,\frac{(RM_p)^2}{N_{sp}}$$

Quantum break-time for a generic <u>saturated</u> system:

G.D., Gomez '13, + Zell '17

$$t_Q = \frac{t_{cl}}{\alpha N_{sp}}$$

quantum coupling



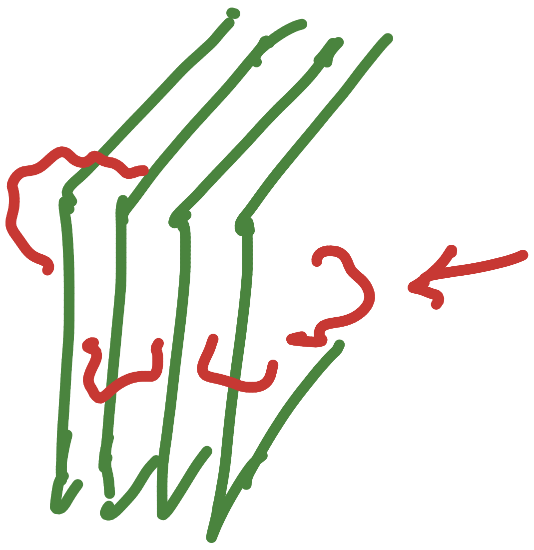
For de Sitter

$$t_{cl} = R \qquad \alpha = \alpha_{gr} = \frac{1}{N} = \frac{1}{(M_p R)^2}$$

So we recover:

$$t_Q = R\frac{N}{N_{sp}} = \frac{R(RM_p)^2}{N_{sp}}$$

e.g. in $n \times D_g - \bar{D}_g$ example



Chan-Paton species

$$t_Q = \frac{R}{(ng)^6} \qquad N_{sp} = n^2$$

In generic string construction:

$$t_Q = R \, \frac{(RM_s)^8}{g_s^2} \, \frac{1}{N_{sp}}$$

Notice, after t_Q also entropy effects contribute into quantum breaking via so-called "memory burden" effect.

Gibbons-Hawking entropy $= N$

G.D, Eisemann, Michel, Zell, '18

If system has Lyapunov time t_L, quantum break-time can be much shorter G.D, Flassig, Gomez, Pritzel, Wintergerst '13

$$t_Q = t_L \ln\left(\frac{1}{\alpha}\right) = t_L \ln(N)$$

See also, Kortun, Zantedeschi '20;
Berezhiani, Zantedeschi '20;

Thus, a Hubble patch must gracefully exit de Sitter phase after time $t_{exit} < t_Q$.

This excludes any sort of meta-stability.

For inflation $t_{exit} = \mathcal{N}_e R$

The strength of observable imprints from quantum gravity

$$\delta = \frac{t_{exit}}{t_Q} = \mathcal{N}_e \frac{N_{sp}}{N}$$

enhanced by species!

The power of species in enhancing quantum gravity effects

Non-perturbative bound on gravity cutoff: G.D. '07, G.D, Redi '08

$$M_* \leq \frac{M_P}{\sqrt{N_{sp}}}$$

Black hole evaporation

$$\frac{\dot{T}}{T^2} = N_{sp} \frac{T^2}{M_P^2}$$

Thermality breaks at:

$$T_{MAX} = \frac{M_P}{\sqrt{N_{sp}}}$$

The same in de Sitter:
Energy density of Gibbons-Hawking radiation

$$N_{sp} T_{GH}^4 = N_{sp} R^{-4} = N_{sp} \Lambda$$

becomes equal to Λ for

$$R^{-1} = \frac{M_p}{\sqrt{N_{sp}}}$$

Smallest possible radius of de Sitter:

$$\frac{\sqrt{N_{sp}}}{M_p} \equiv M_*^{-1}$$

Quantum break-time gives a new meaning to species bound.

For $N_{sp} = (M_p R)^2$

the quantum break-time is one Hubble!

$$t_Q = \frac{R(M_p R)^2}{N_{sp}} = R$$

In other words, the number of species cannot exceed the number of de Sitter constituents:

$$N_{sp} \leq (M_p R)^2 = N$$

Since species shorten t_Q, they provide an exceptional opportunity of observing imprints of quantum gravity.

The corrections from the quantum gravity clock can be potentially very large

$$\delta = N_e \frac{N_{sp}}{N}$$

even when standard fluctuations (from inflaton) are negligible.

Notice, the phenomenological bound on N_{sp} (from LHC, ...) is

$$N_{sp} \lesssim 10^{32}$$

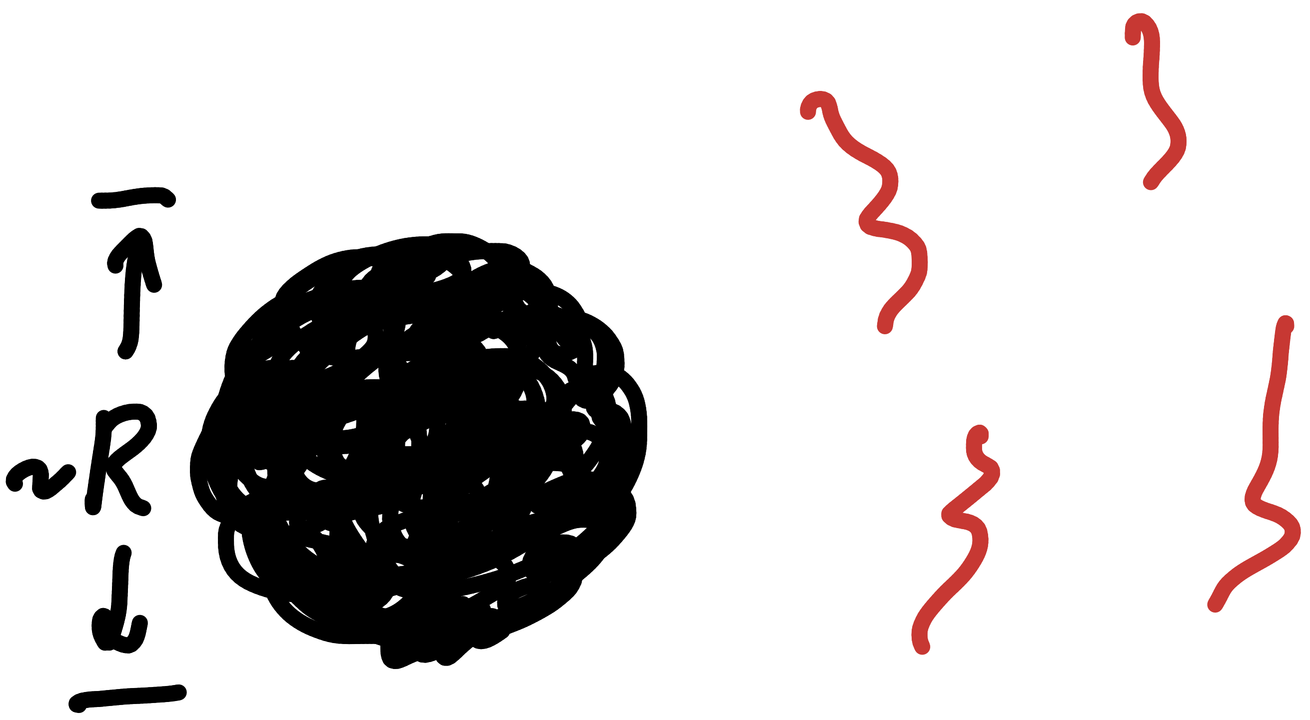
Motivated by Hierarchy Problem.

This gives a large room for dominance of quantum gravitational effects in inflationary scenarios.

Entanglement in de Sitter and in Black Hole

"Page's curves" for de Sitter and Black Hole

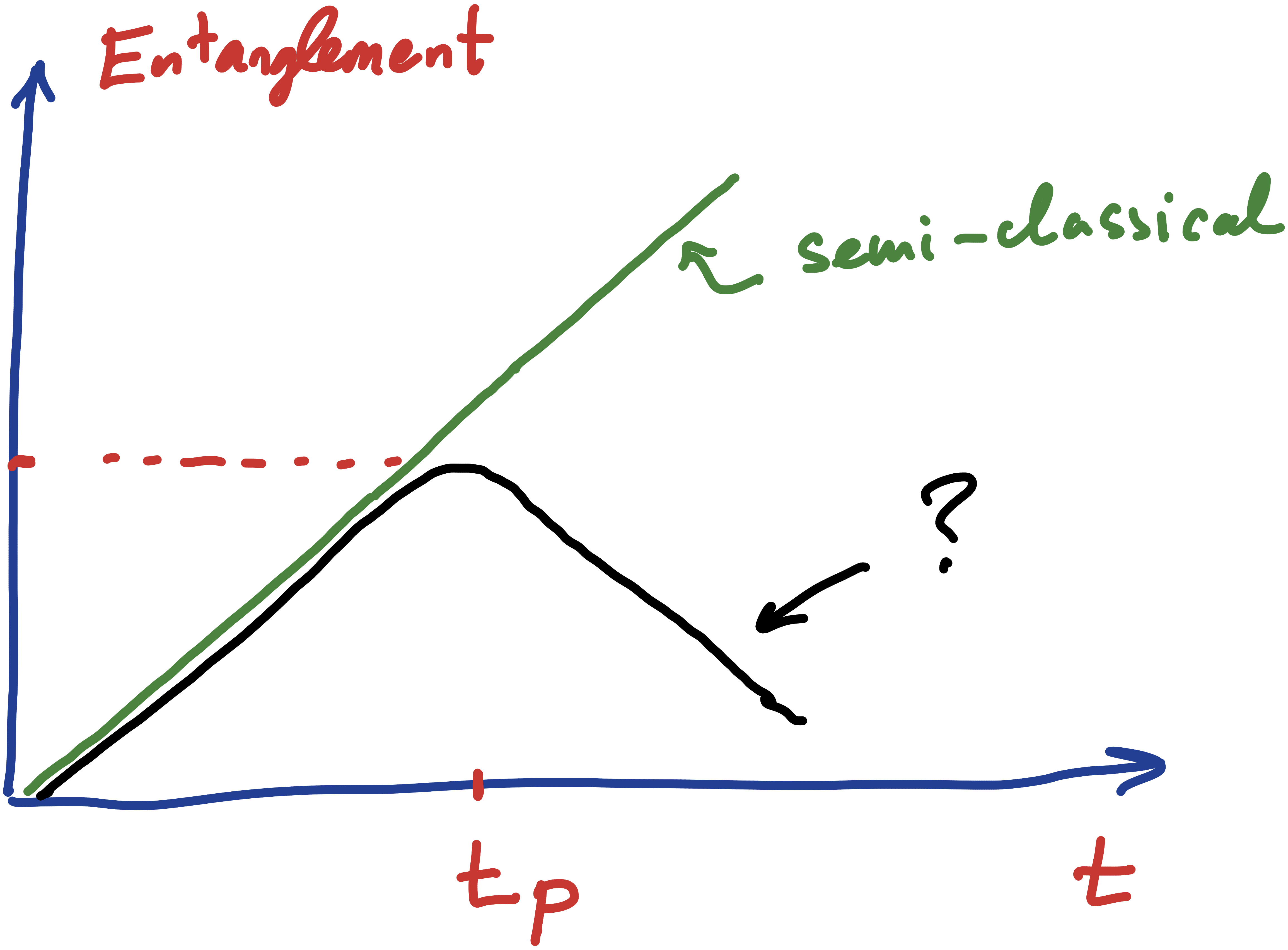
Hawking radiation



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

Page's time:

$$t_P = R^3 M_P^2 = t_Q$$

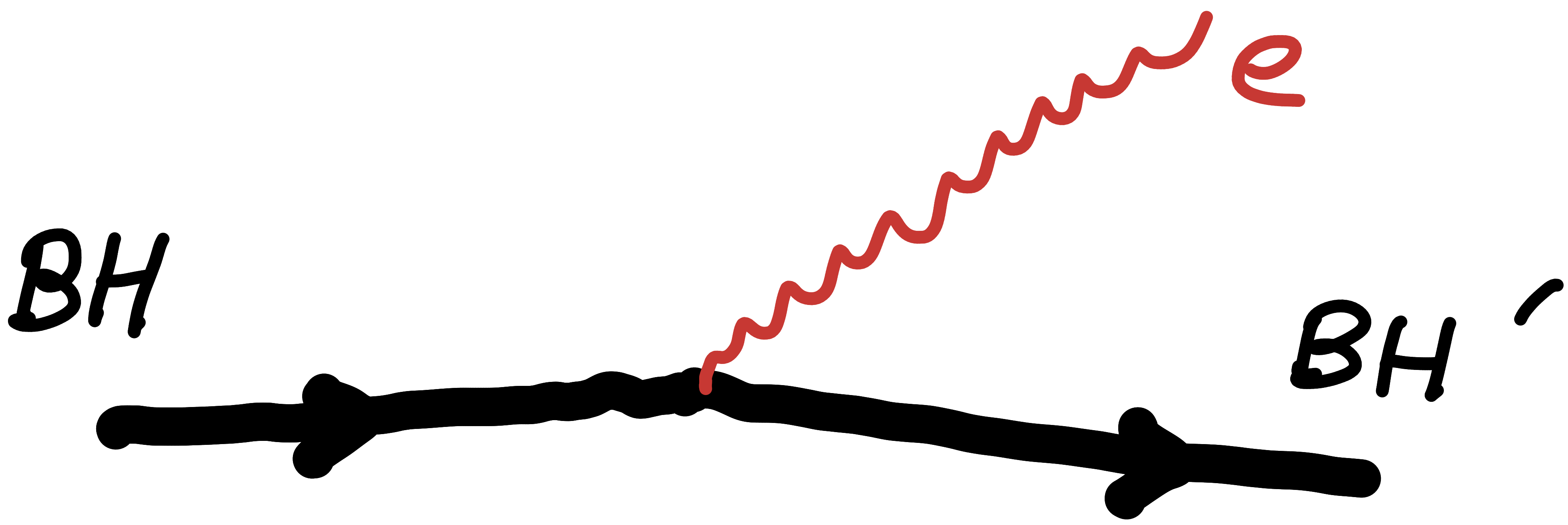


Entanglement must reach maximum.

(Which entanglement?)

In semi-classical picture there is only one type of entanglement:

Between black hole and outgoing quanta



$$|BH\rangle \longrightarrow |\uparrow\rangle_{BH} \cdot |\downarrow\rangle_{e} + |\downarrow\rangle_{BH} \cdot |\uparrow\rangle_{e}$$

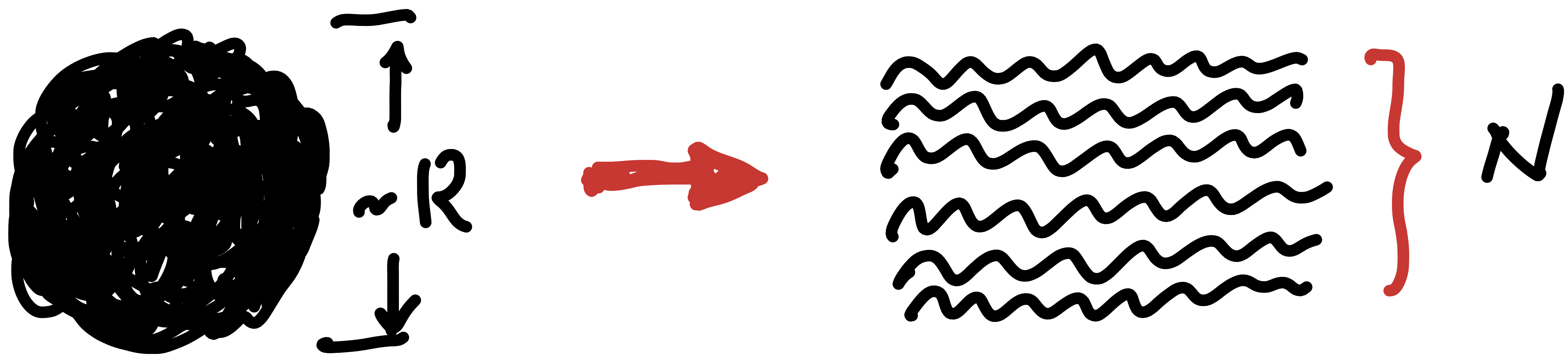
Corpuscular theory reveals a different story.

Microscopic corpuscular theory:

Quantum N-Portrait

G. D., Gomez '11

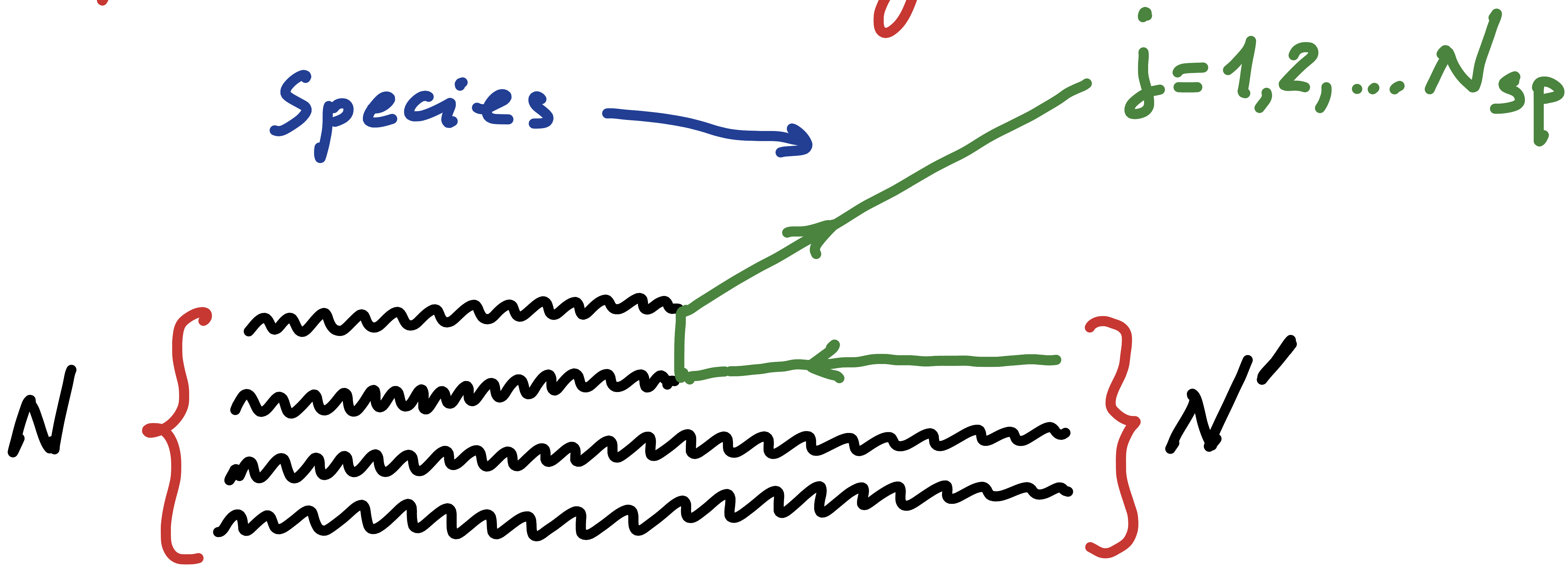
Black hole is a saturated (critical) state of soft gravitons



$$N = \frac{1}{\alpha} = (RM_P)^2 = S$$

number coupling entropy

At initial times, gravitons deplete at Hawking's rate



$$|N\rangle \rightarrow \sum_{j=1}^{N_{sp}} |N', j\rangle \cdot |j\rangle$$

Self-entangled state

The new concept of inner (self) entanglement.

Inner entanglement is present both in black hole and de Sitter.

Not visible in sem-classics.

The engine:

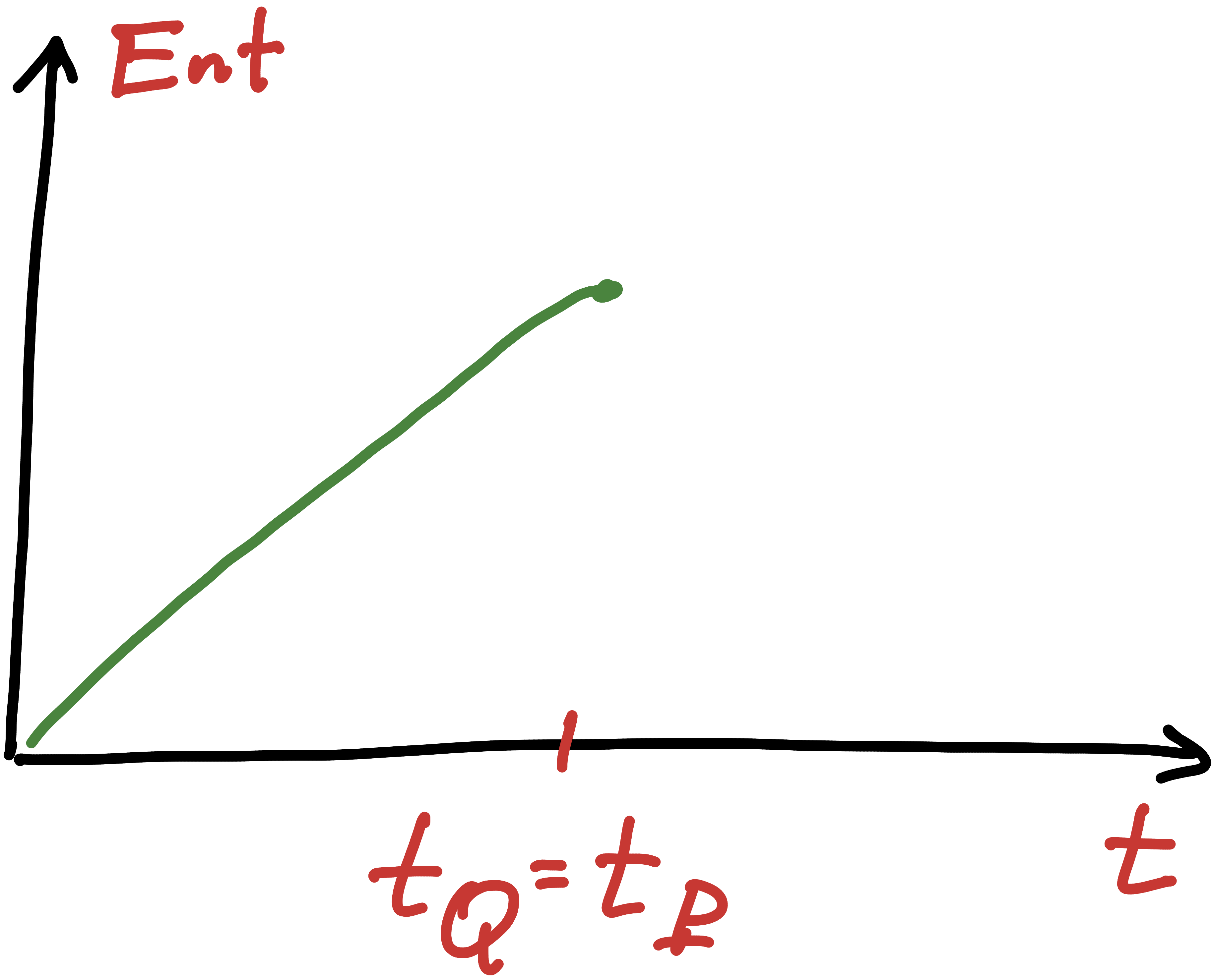
(*) Entanglement among constituents (soft-modes);

(*) Entanglement among memory modes (super-soft) information carriers: "Memory burden".

G.D., '17; G.D., Eisemann, Michel, Zell '18

Prihadi, Dwiputra, Zen '20

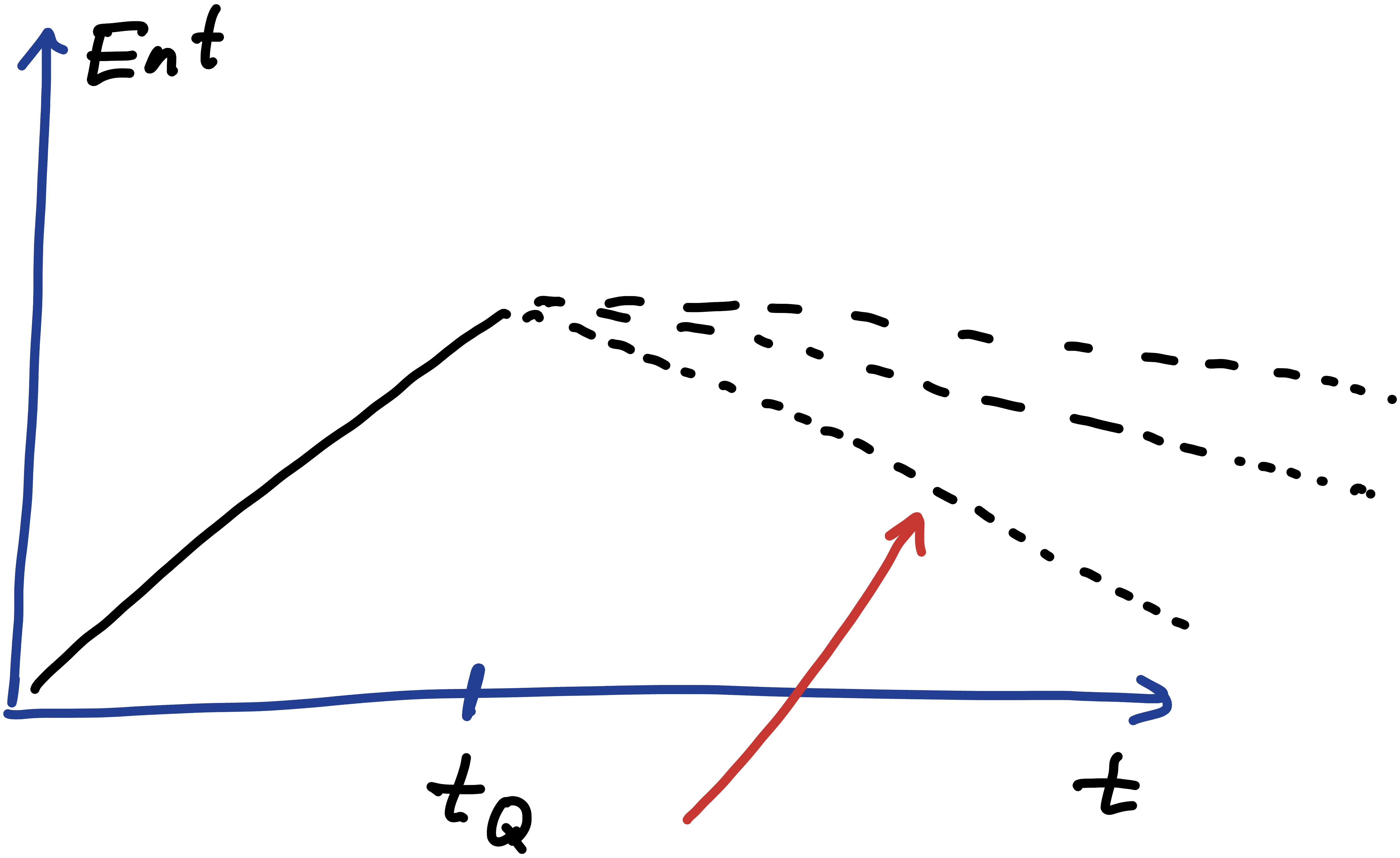
Maximal entanglement
at $t_Q = t_P$



Both for de Sitter and
Black hole.

For $t > t_Q$ are fundamental
differences.

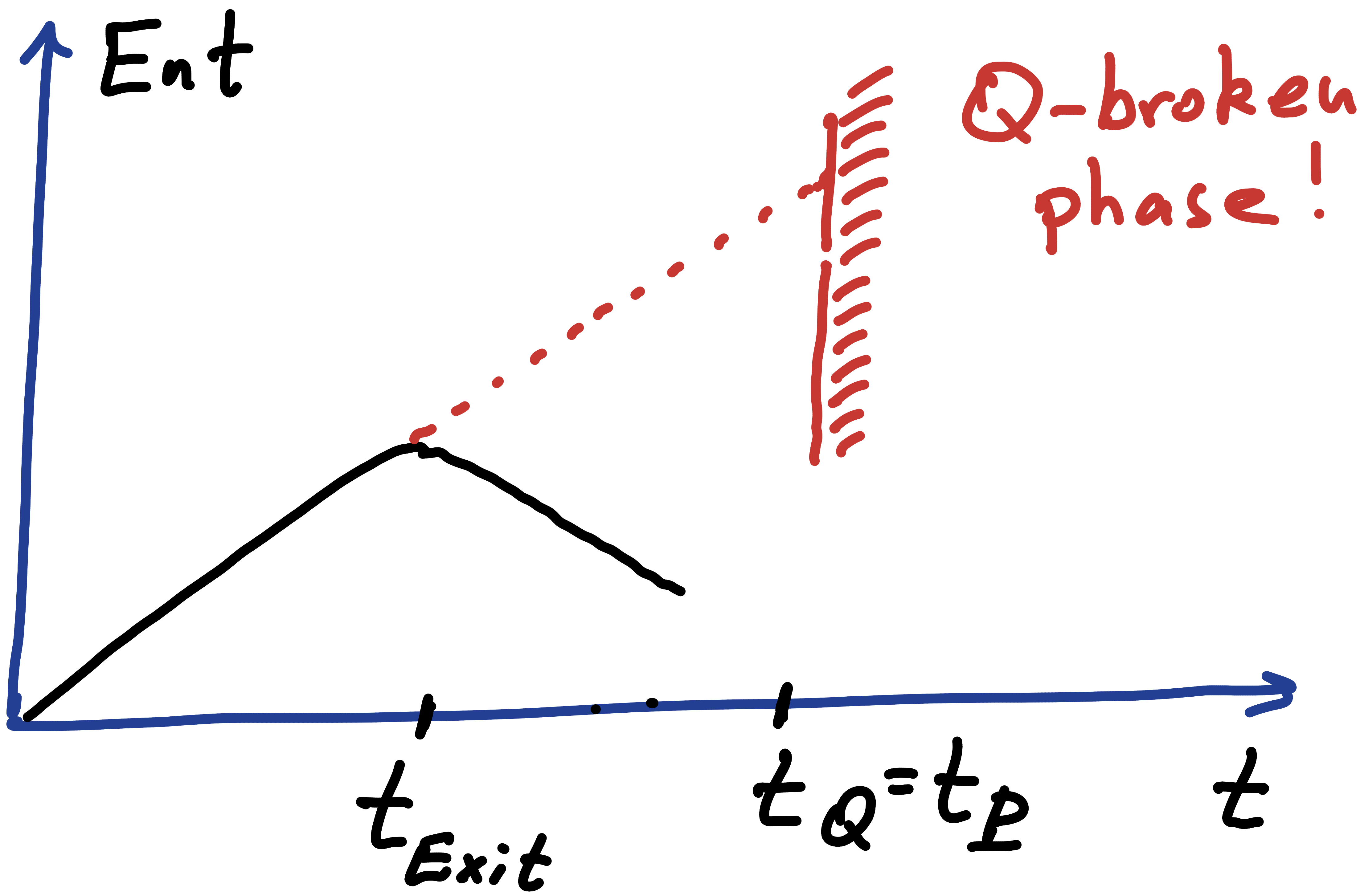
Black holes:



Decay can slow down due to "memory burden".

G.D., Eisemann, Michel, Zell '19.

de Sitter cannot exist for $t > t_Q$



Graceful exit must take place for

$$t_{Exit} \leq t_Q$$

Conclusions:

(*) S-matrix formulation of gravity (string theory) excludes de Sitter vacua, both stable an meta-stable.

(*) This imposes a corpuscular view in which de Sitter is a saturated (coherent) state on top of valid S-matrix vacuum of Minkowski (or AdS?)

(*) The S-matrix constraint is enforsed by an anomalous quantum break-time

$$t_Q = R\frac{(RM_p)^2}{N_{sp}} = R\frac{N}{N_{sp}}$$

(*) Universe must find a gracefull exit from de Sitter within time $t_{exit} < t_Q$

(*) Potentialy observable quantum gravity imprints are

$$\delta = \frac{t_{exit}}{t_Q} = N_e \frac{N_{sp}}{N}$$

and are enhanced by number of particle species N_{sp}.

(*) Bound $N_{sp} \lesssim 10^{32}$ gives room for interesting new effects:

⊛ We predicted that Λ <u>cannot</u> <u>be</u> part of Universe's energy budget.

G.D., Gomez '13, ...

Then, what is dark energy?

(More precision analysis is welcome.

Colin, Mohayaee, Rameez, Sarkar '18)