S-matrix constraints on landscape, and naturalness

Gia Dvali

LMU-MPI

de Sitter:

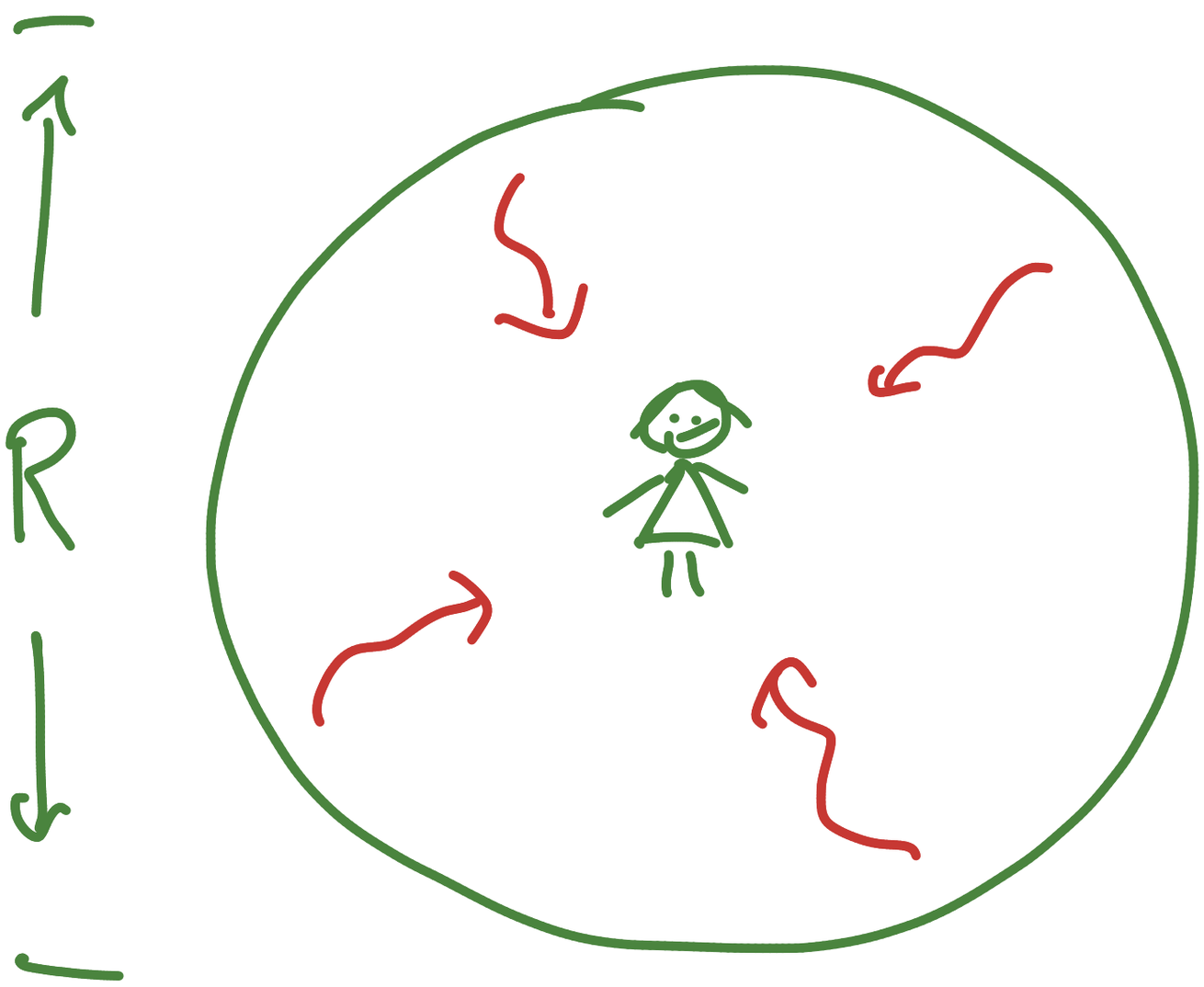
$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2$$

↙ scale factor

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

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

← cosmological constant



Gibbons-Hawking temperature:

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

and entropy:

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

de Sitter-like states play important role in cosmology:

* We come from there (inflation)

and

* We are re-entering (are we?)

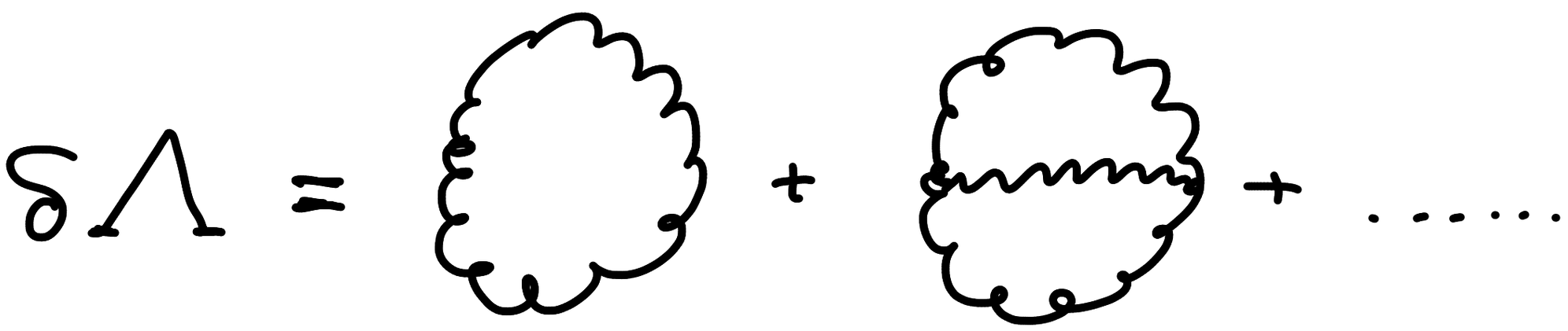
* Why is Λ so small?

$$\Lambda < 10^{-124} M_P^4$$

Cosmological constant puzzle.

Cosmological constant puzzle:

Λ is UV-sensitive



Naive expectation:

$$\Lambda \sim M_{UV}^4$$

Usually viewed as naturalness puzzle.

None of the offered solutions worked, but there is a side of the story that lead to a temporary "settlement" (to be discussed later).

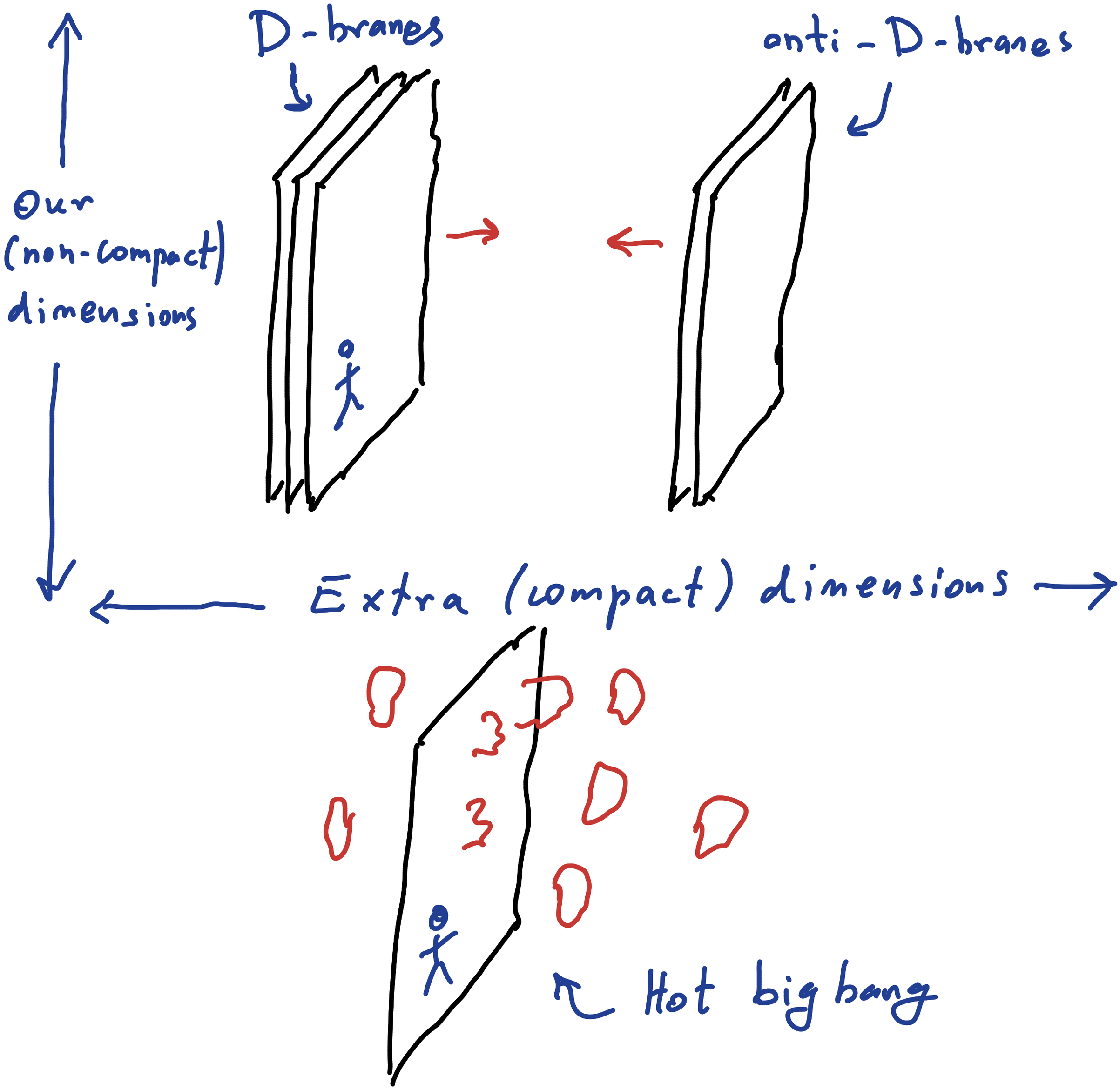
How can we get a de Sitter-like state in string theory?

Idea of D-brane uplifting

G.D., Tye '98

D-brane inflation:

We create non-BPS D-brane configuration and let it go



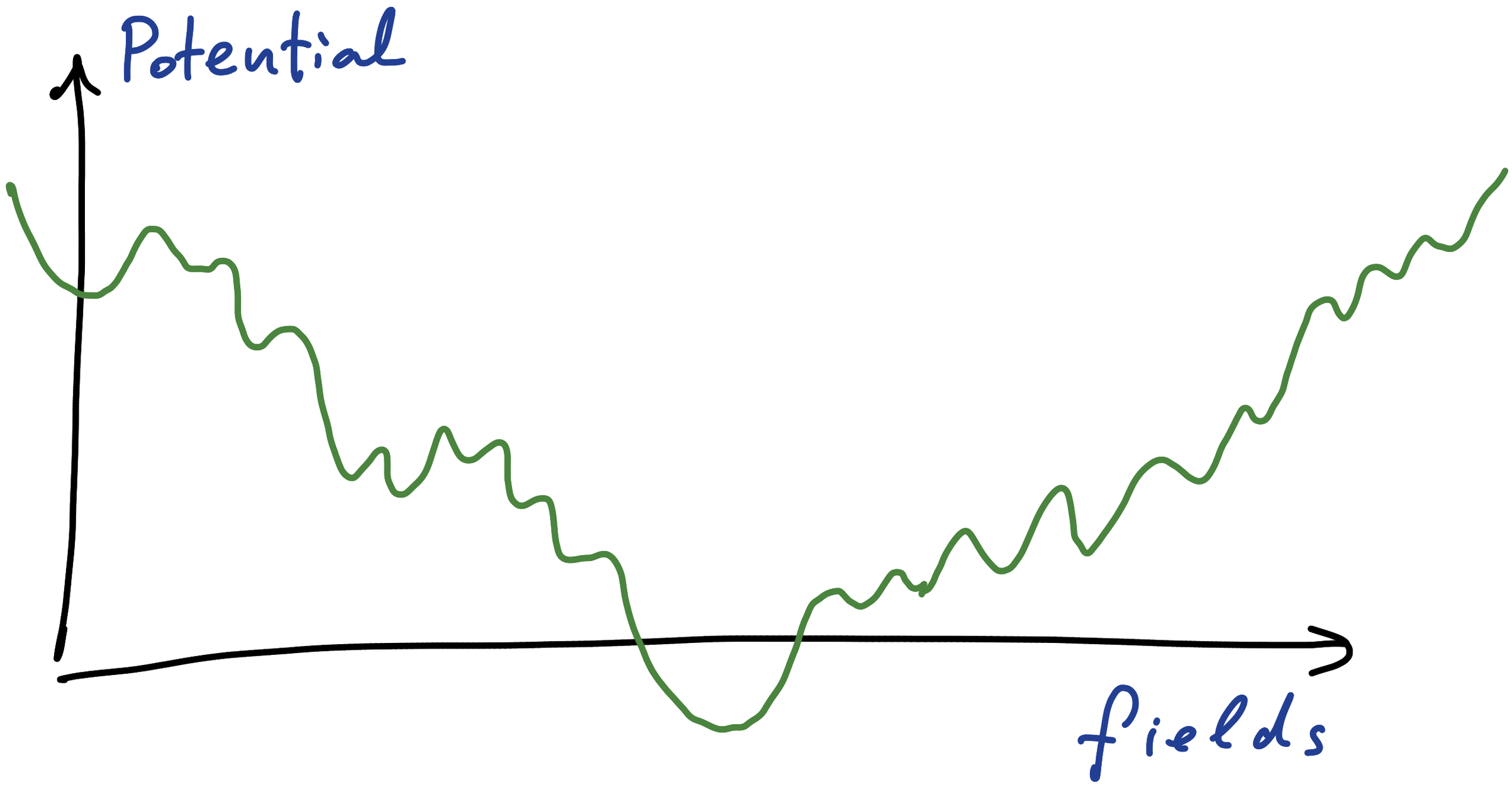
Despite many attempts

G.D., Tye '98;
G.D., '99
G.D., Shafi, Solganic '01
Burgess, Majumdar, Nolte,
Quevedo, Rajesh, Zhang '01
Kachru et al '03
+ Maldacena, Mc Allister '03
- - - - - - ..

I am not aware of any
meta-stabilization
(for a good reason)

Often assumed picture:

Plentitude of deSitter vacua on string landscape



Naturalness can be replaced by Anthropic selection

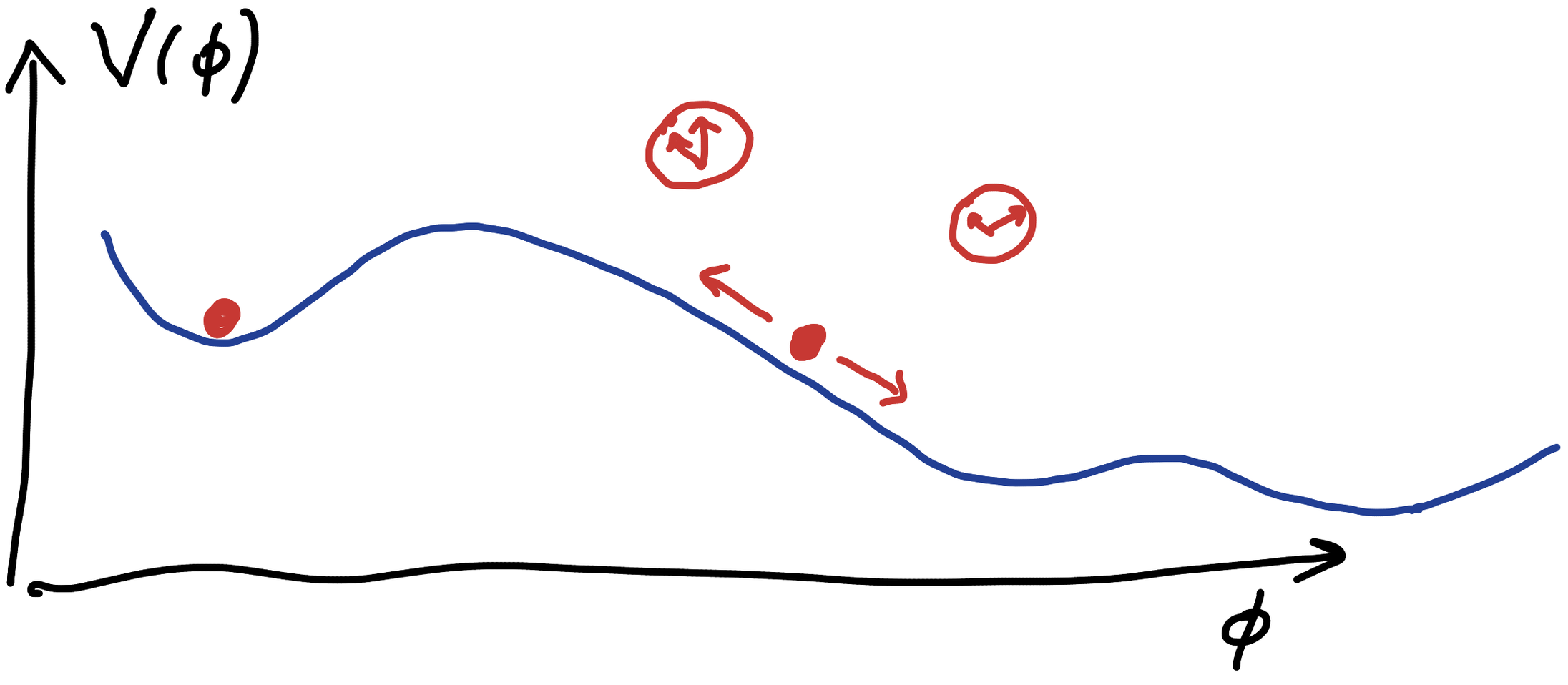
de Sitter landscape would open a way for anthropic selection.

Carter '74; Carr, Rees '79; Barrow Tipler '86

Weinberg '87: Small Λ is required to form galaxies.

de Sitter landscape can provide an actualization mechanism via eternal inflation

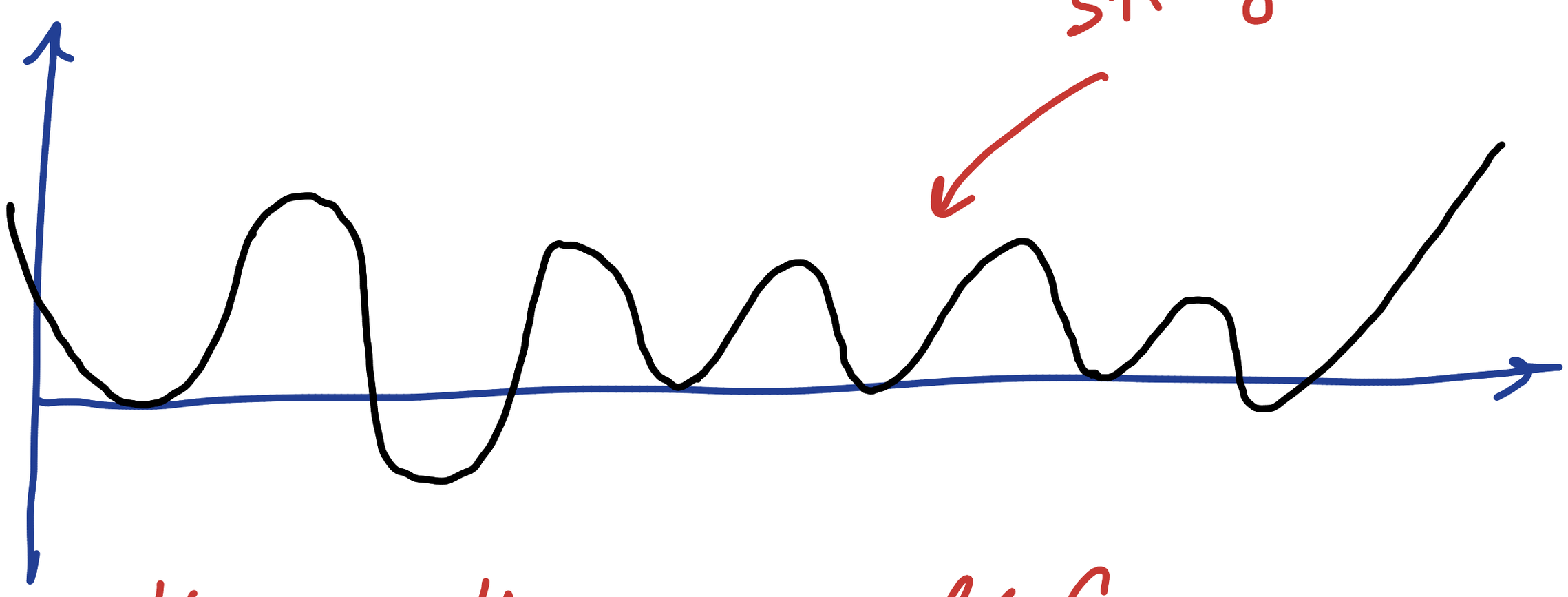
Vilenkin '83; Linde '86; ...



We argue that situation is exact opposite:

If there is any parameter that string theory predicts in our Universe, it is

$\Lambda = 0$



String theory nullifies an outstanding cosmological puzzle.

Back to naturalness.

Main message:

Quantum gravity / String theory
excludes de Sitter "vacua",
both stable and meta-stable

G.D., Gomez '13, '14

No de Sitter future eternity;
No eternal inflation.

S-matrix is fundamental in this.

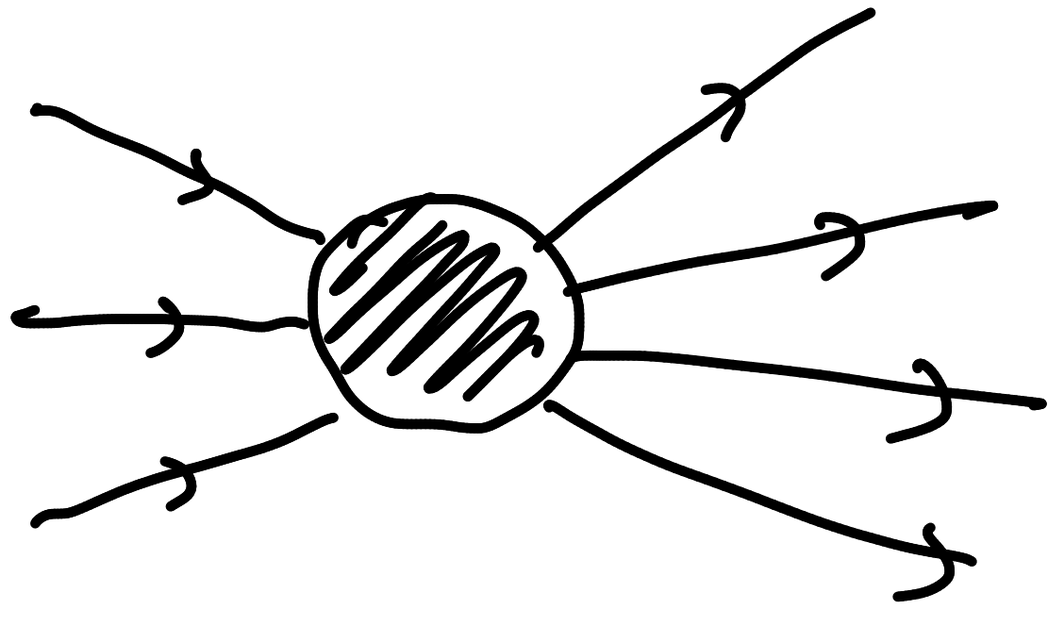
In order to explain,
we follow G.D. 2012.02133 [hep-th]
Symmetry 13(2020)1,3

$\hat{S}$-matrix

in

↓

$|i\rangle$

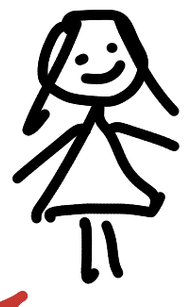


out

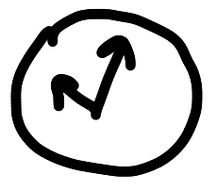
↓

$|f\rangle$

$t = -\infty$



eternal observer, Alice



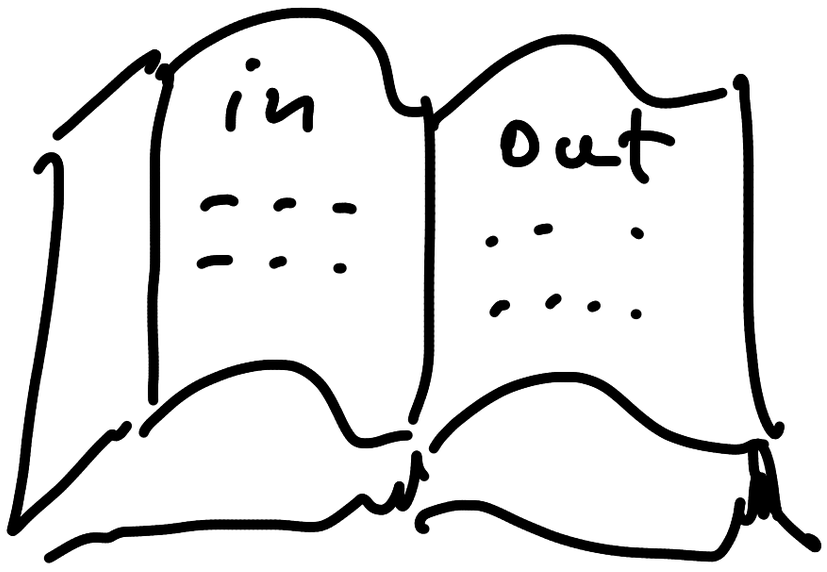
t

eternal clock

$t = +\infty$

$$\hat{S}_{if} = \langle i | \hat{S} | f \rangle$$

Manual:



In string theory S-matrix is the formulation of the theory.

Necesary conditions:

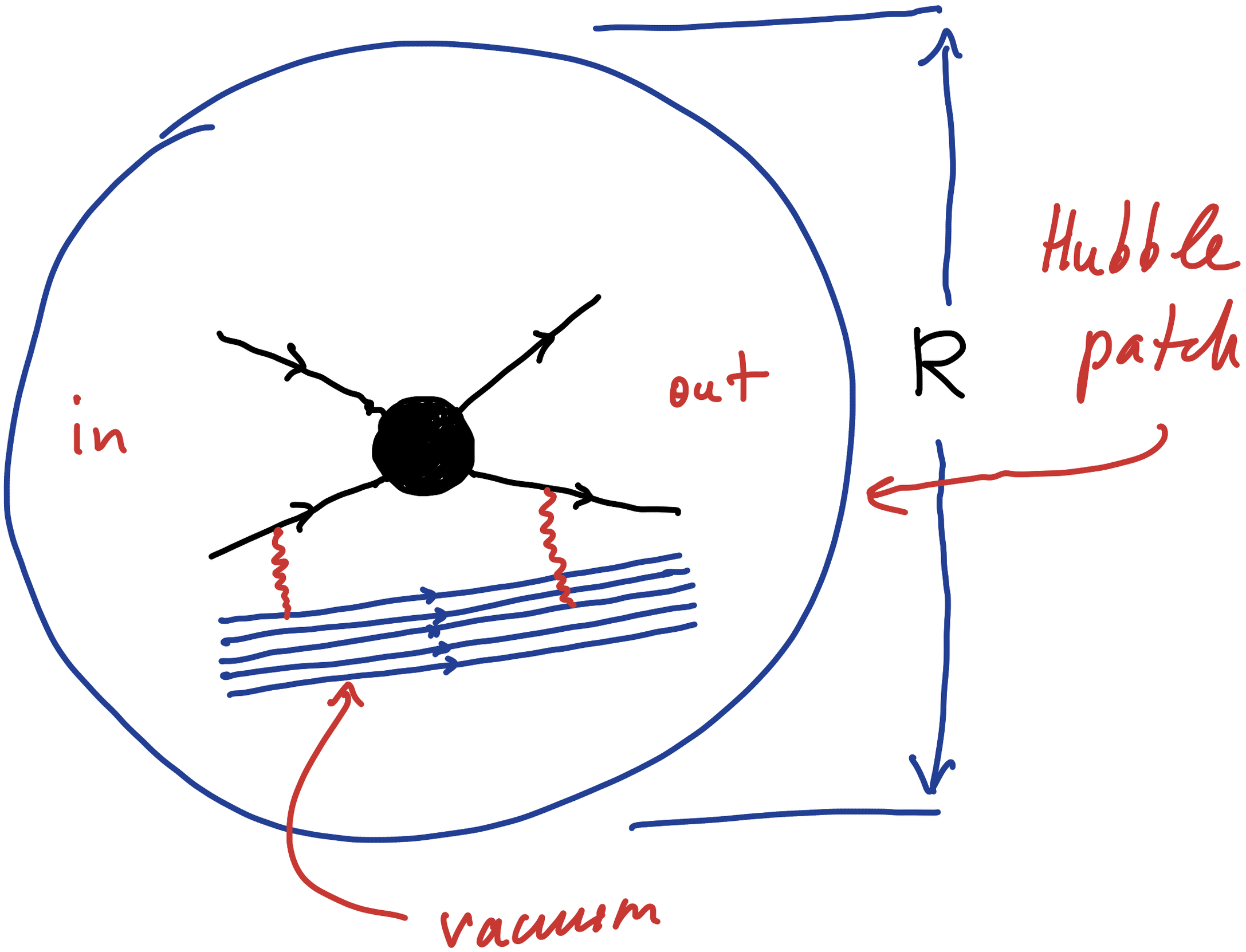
* Globally-definet time;

↳ Absent in classical deSitter

* S-matrix vacuum.

What about quantum theory?

What about effective S-matrix?



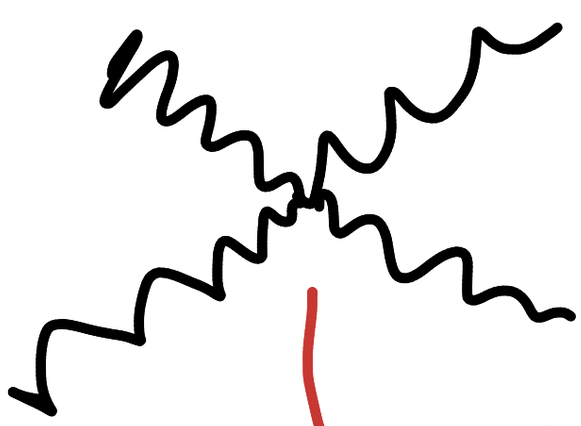
The vacuum should not be able to recoil and absorb some information.

This is only possible in double-scaling limit:

$$\Lambda \to \infty, \qquad \Lambda G = \bar{R}^{-2} = \text{finite}.$$

$$G \to 0 \ (M_p \to \infty),$$

But in the same limit graviton quantum coupling vanishes



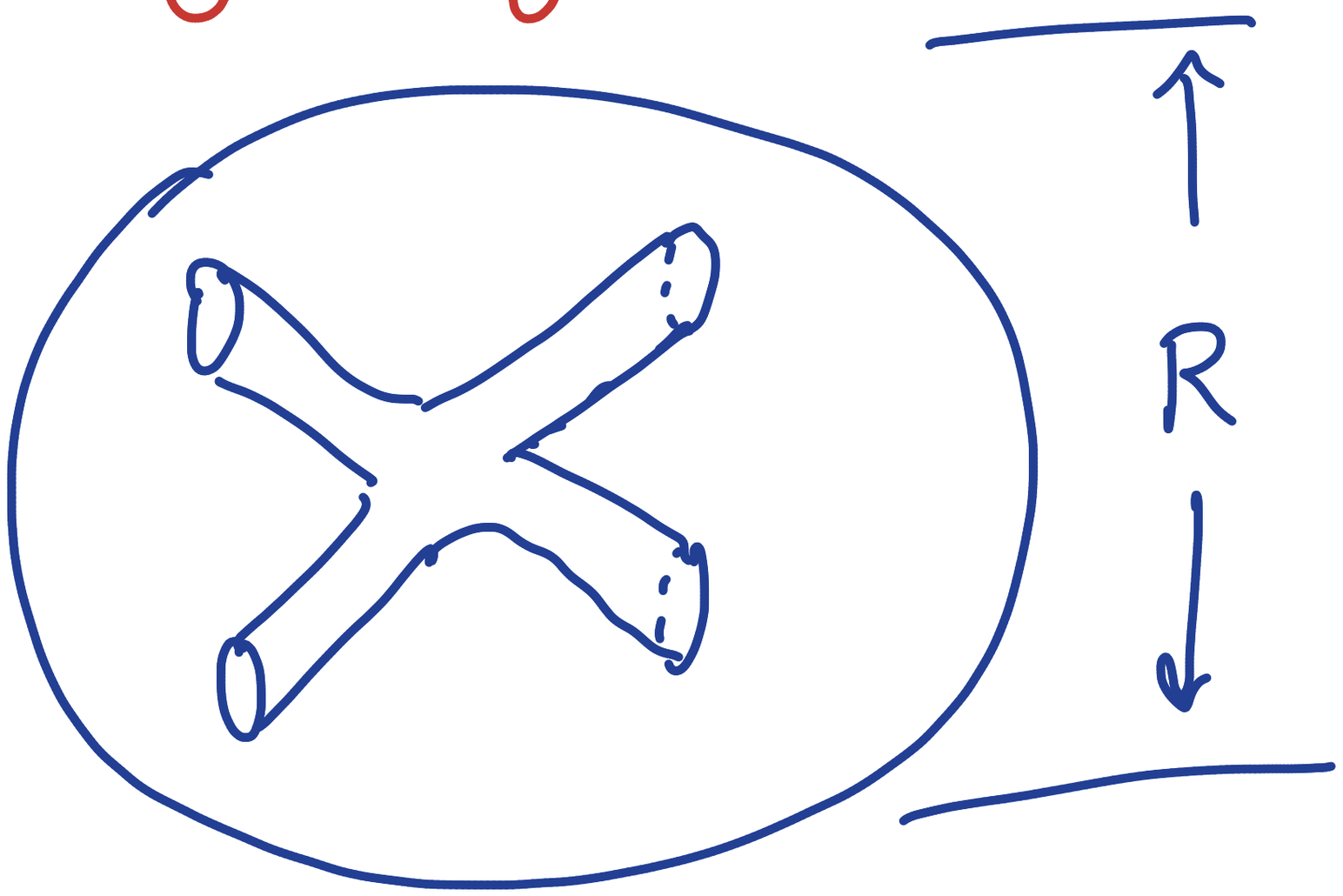
momentum-transfer

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

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:

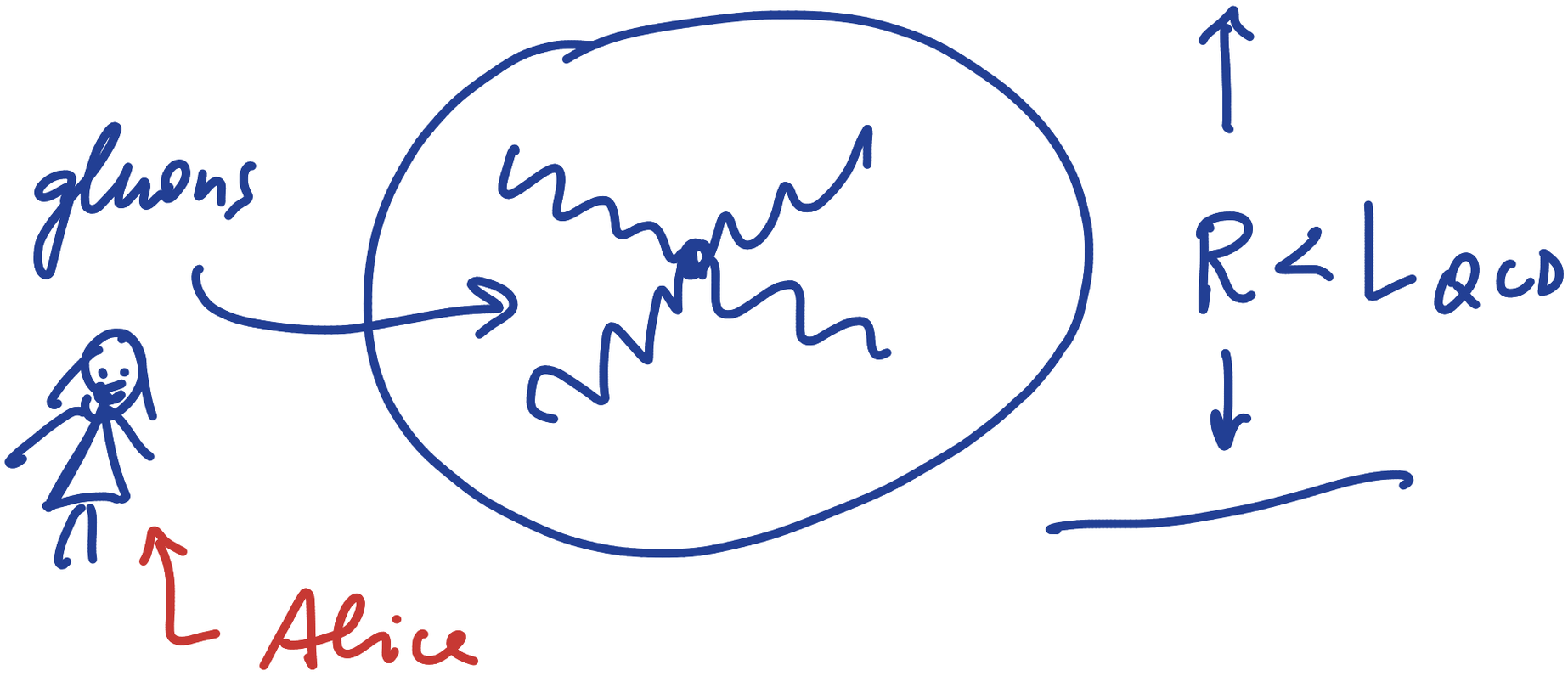
$\Lambda \to \infty$
$G \to 0$
$R = \text{finite}$
$\Big\}$ $\longrightarrow$ $g_s^2 \to 0$

Closed string S-matrix is trivial.

(Open strings, more subtle)

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

E.g. QCD



Thus, the issue is quantum gravitational.

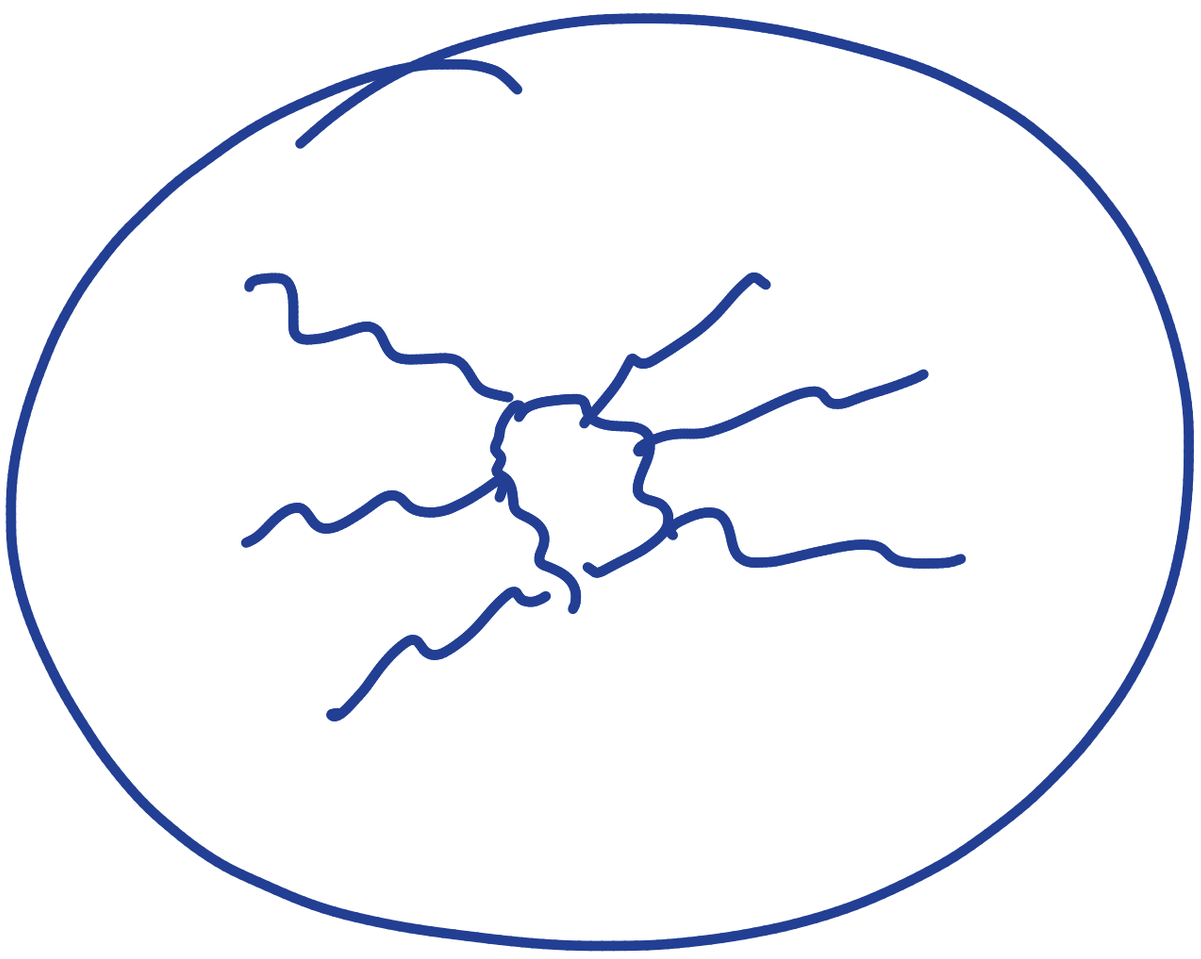
(de Sitter = vacuum) → $\alpha_{gr} = 0$

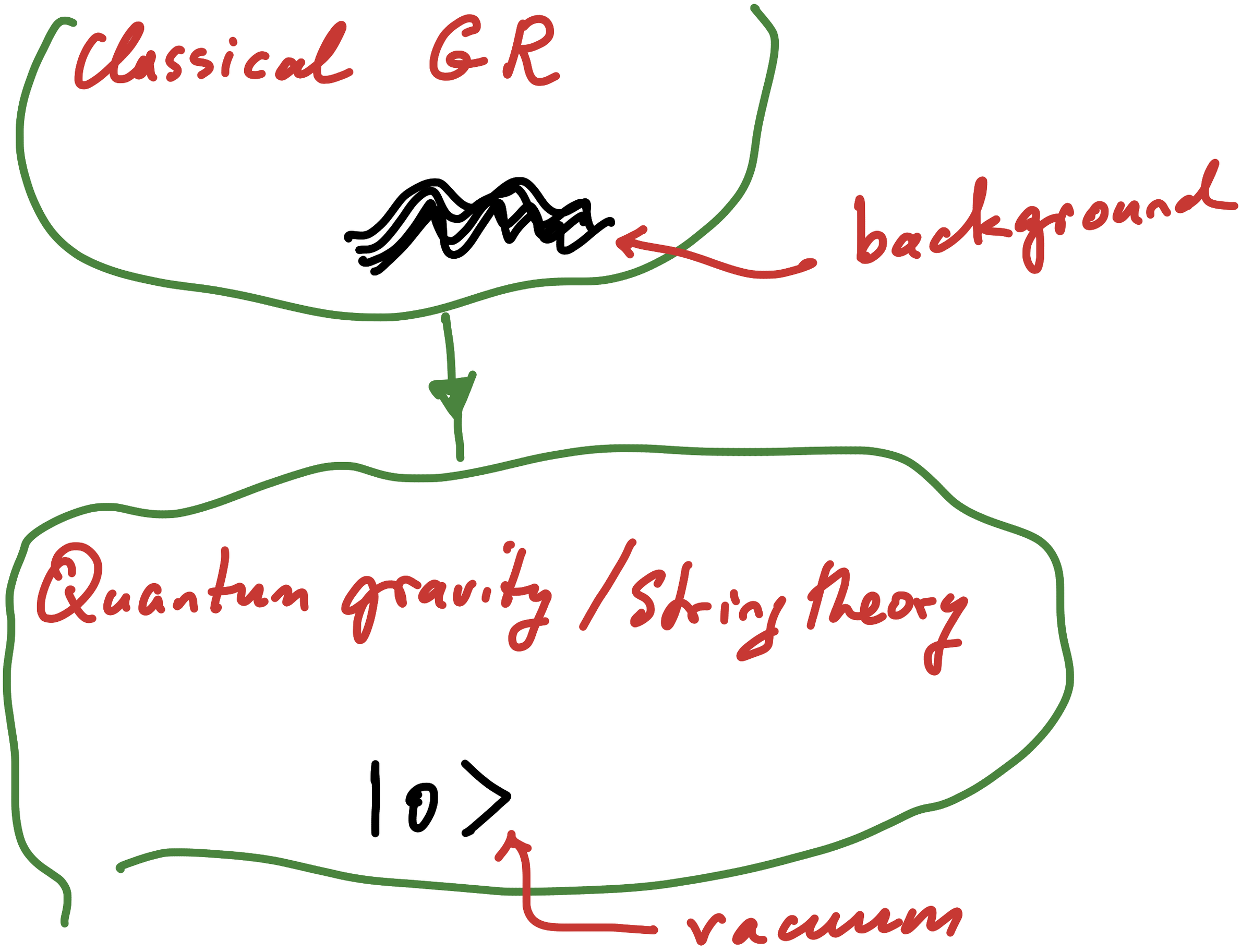
$g_s = 0$

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

For example, scattering of quanta of center of mass energy

$$E \sim M_p^2 R$$





Not every background of classical GR is promoted into a vacuum of QG!

How is the S-matrix constraint enforced?

Corpuscular picture of de Sitter ("N-portrait"):

G.D., Gomer '11, '13, ...

Since $|dS\rangle \neq |vacuum\rangle$,

it must be excited state on S-matrix vacuum (Minkowski)

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

classical de Sitter

New concept:

Corpuscular completion (resolution)

Very different from and insensitive to UV-completion.

$|dS\rangle \longrightarrow |N\rangle$ ← coherent state on Minkowski

Universal relations:

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

Their frequencies $1/R$ and $1/RN$

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

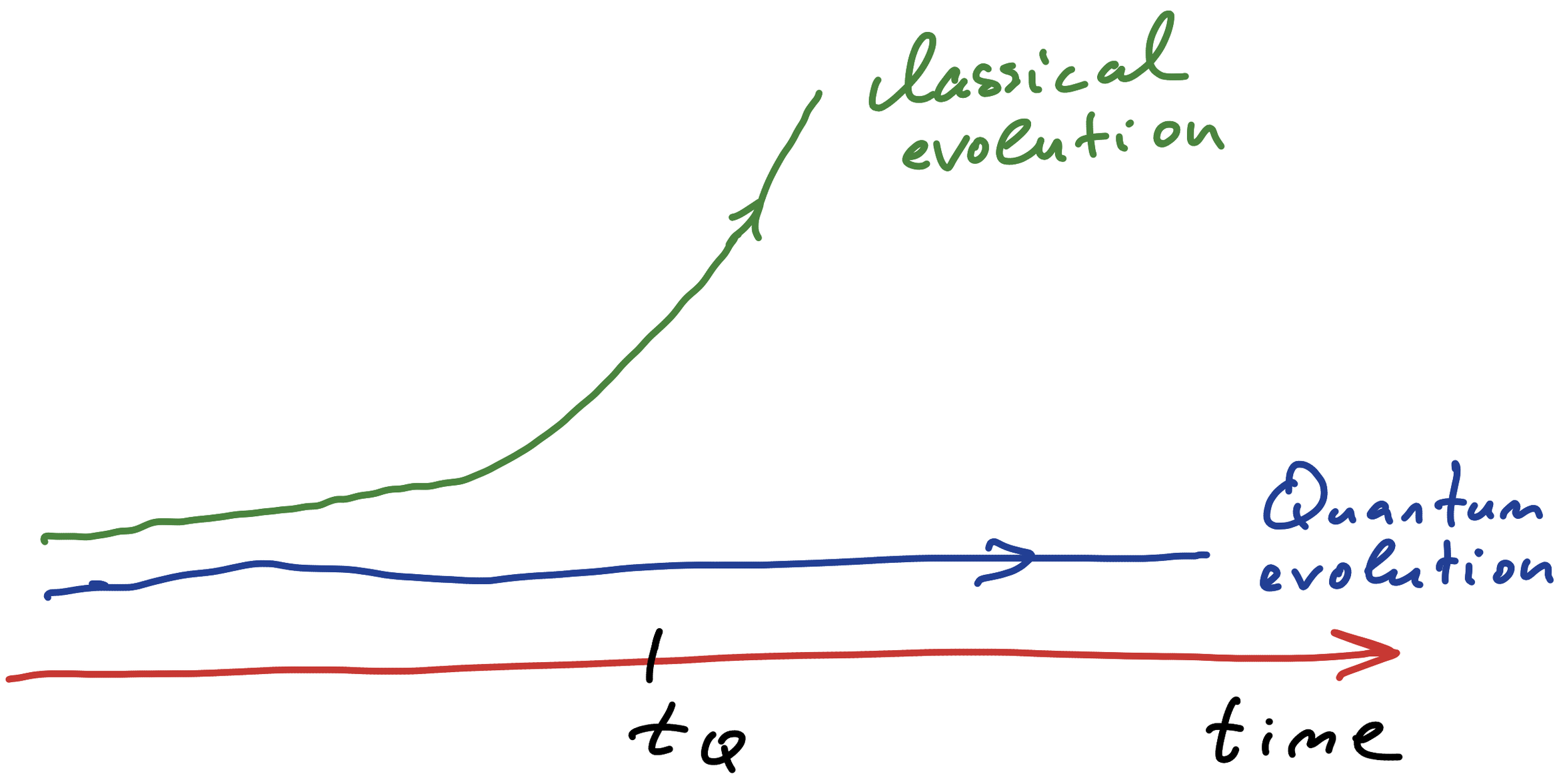
de Sitter is a "Saturon"!

Corpuscular $\frac{1}{N}$ - effects lead to anomalous quantum break-time

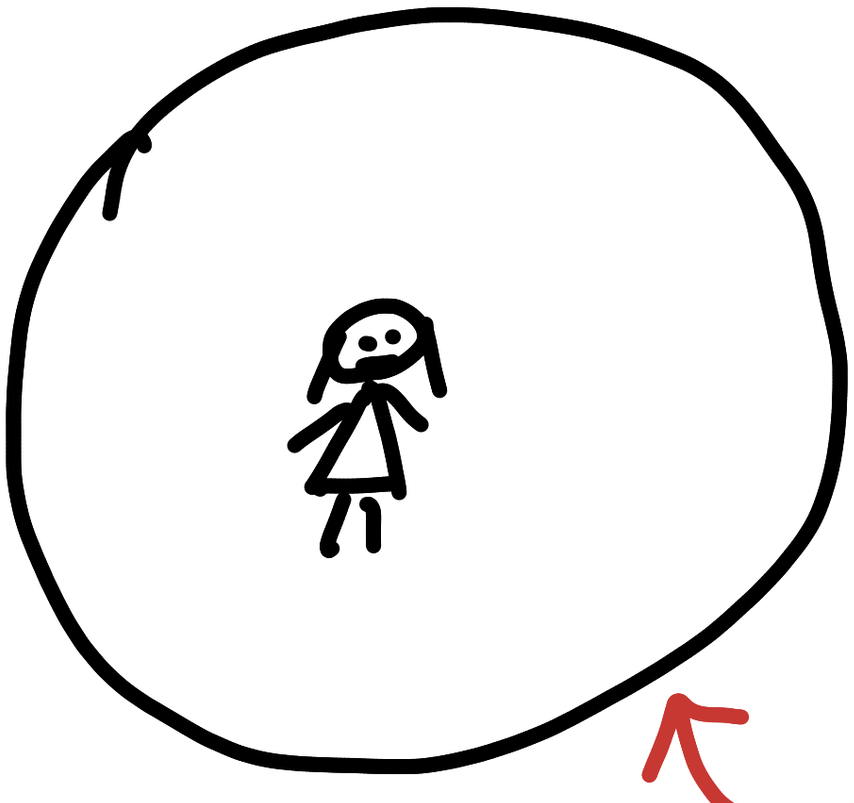
G. D., Gomez '13, '14 + Zell '17;
G.D., '20

$$t_Q = \frac{R^3 M_P^2}{N_{species}}$$

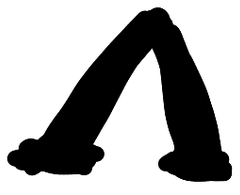
← Number of species



$t = 0$

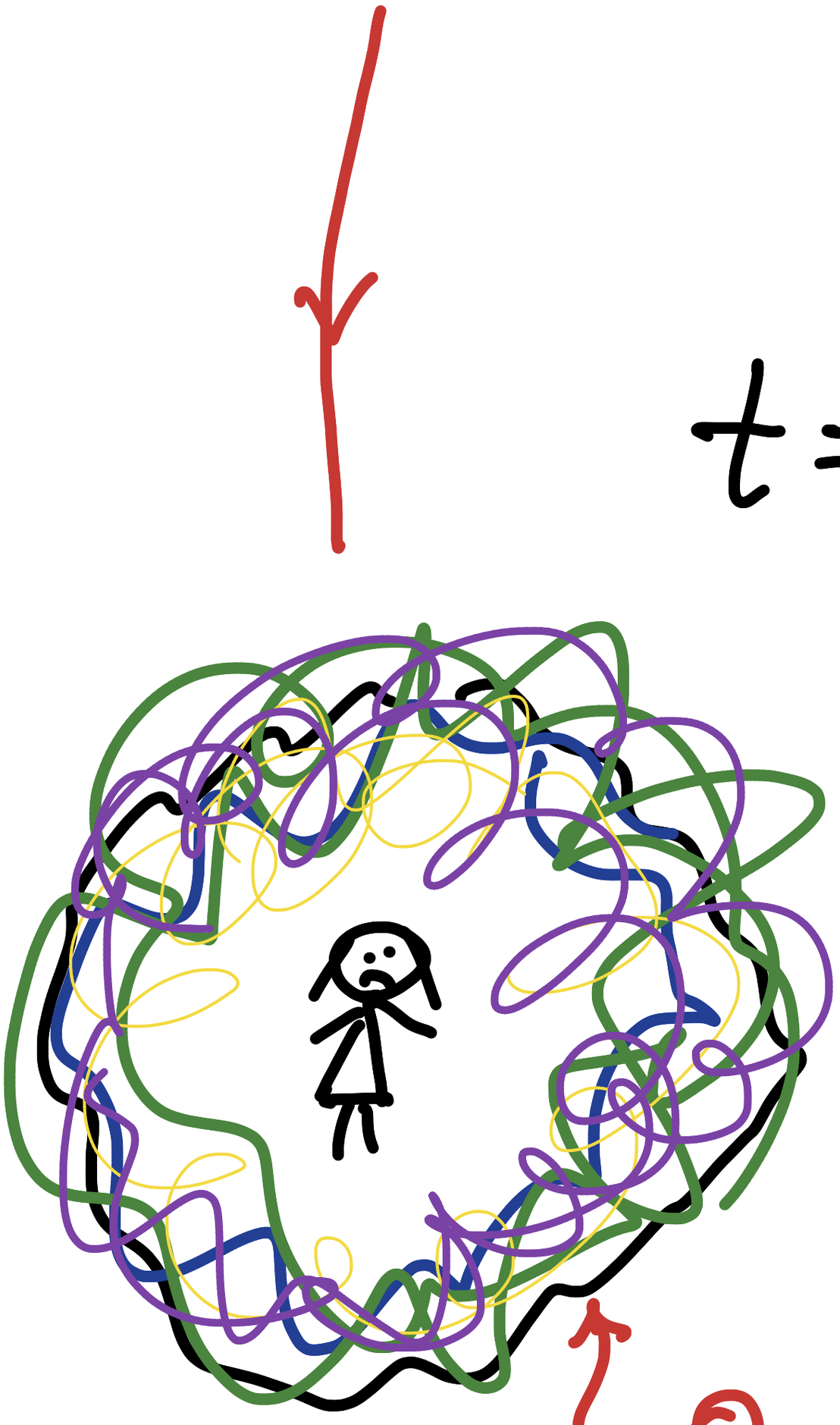


↖ Classical



↑

$$t = t_Q \simeq \frac{R^3 M_P^2}{N_{sp}}$$



↖ Quantum!

↑ classical

t_Q is much shorter for

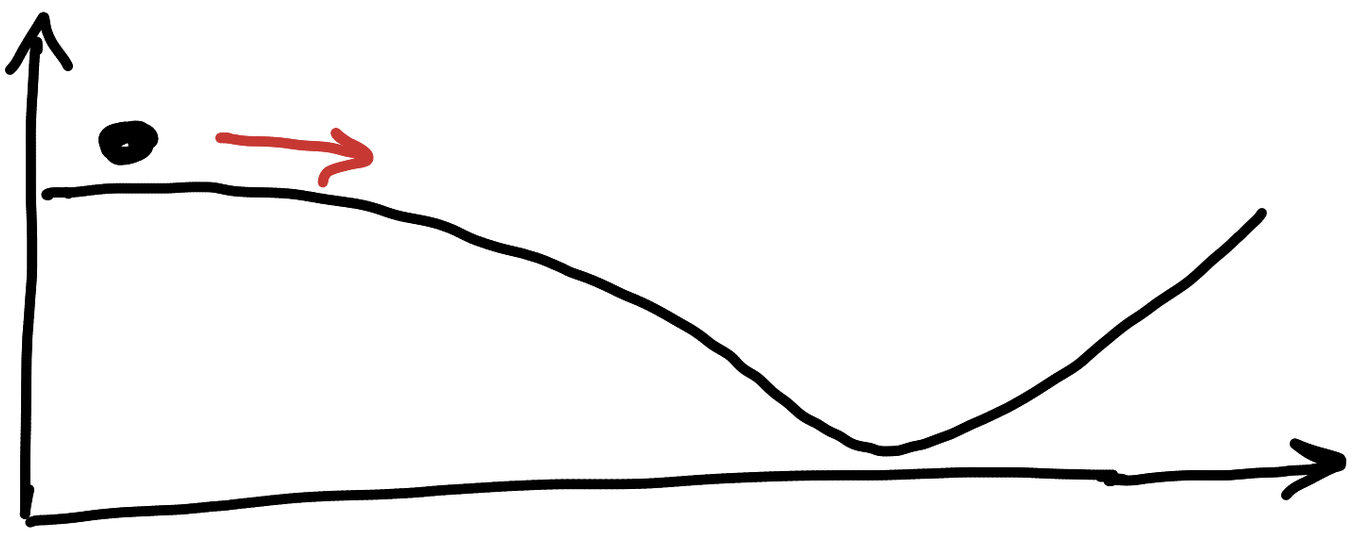
Lyapunov instability

G.P., Flassig, Gomez, Pritzel, Wintergerst '13

$$t_Q = t_{Lyapunov} \ln(N)$$

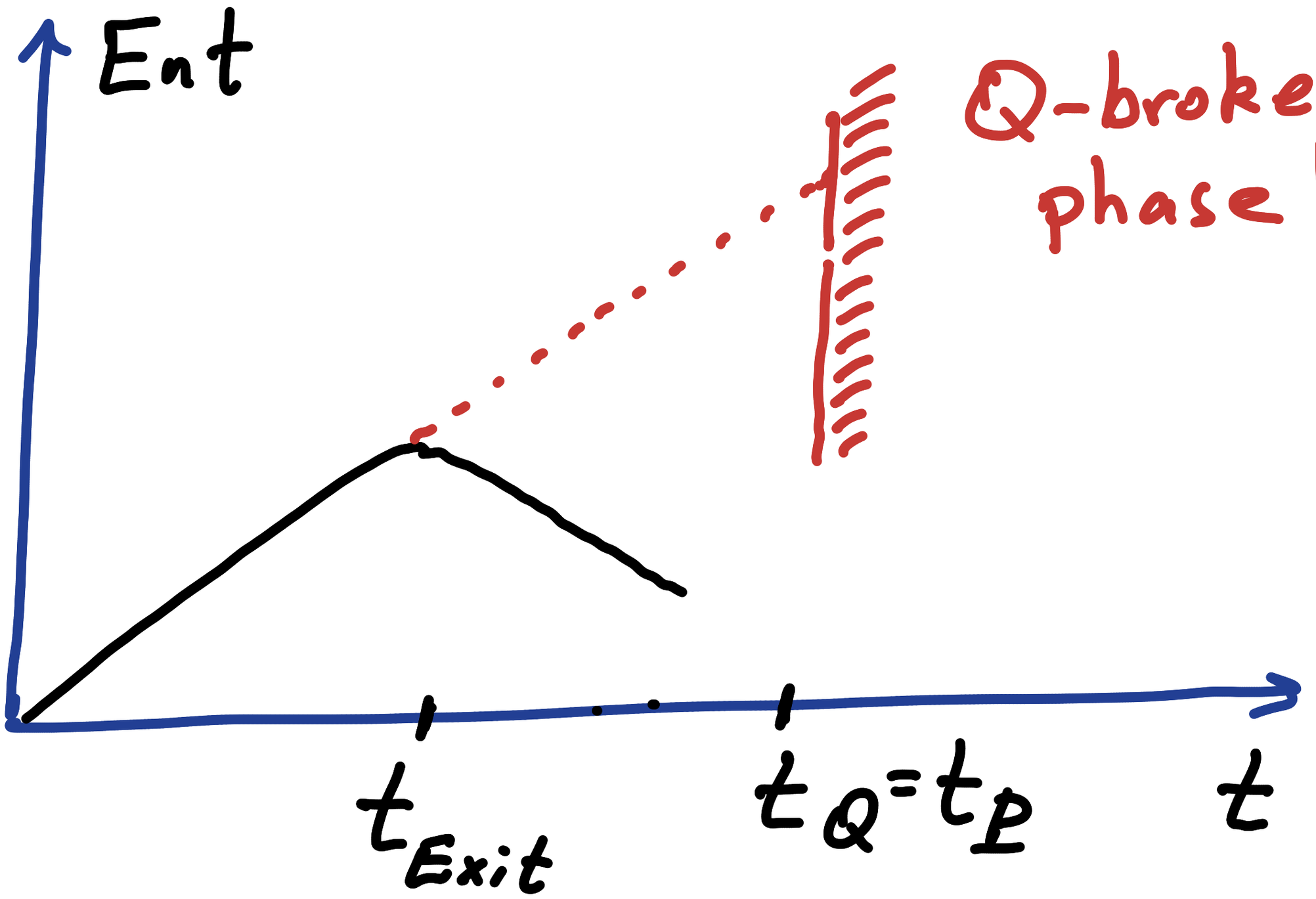
Lyapunov quantum break-time for (inflationary) de Sitter

G.D, Gomez '13



$$t_Q \sim R \ln(S'_{GH})$$

de Sitter cannot exist for $t > t_Q$

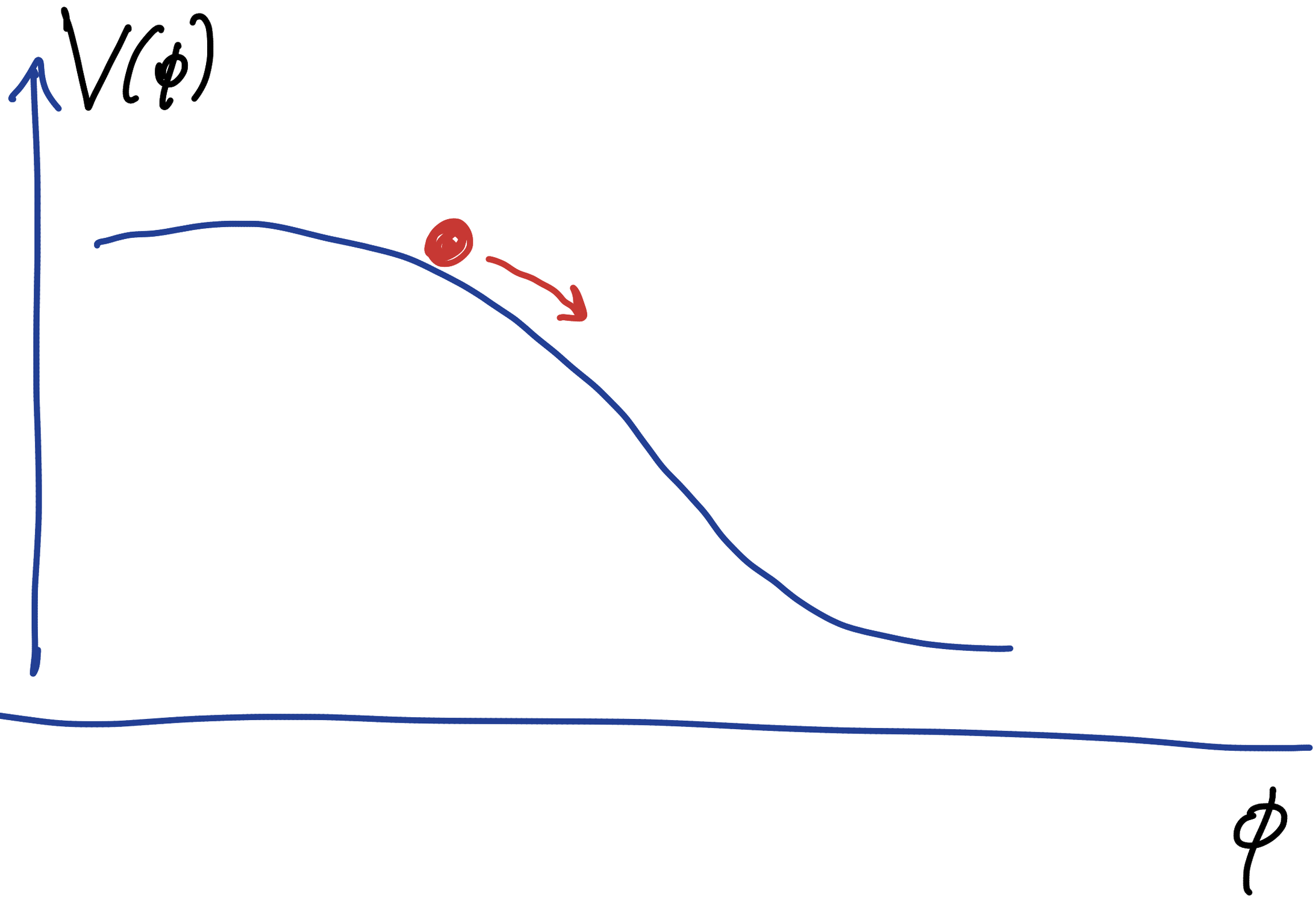


Graceful exit must take place for

$$t_{Exit} \leq t_Q$$

Universal bound

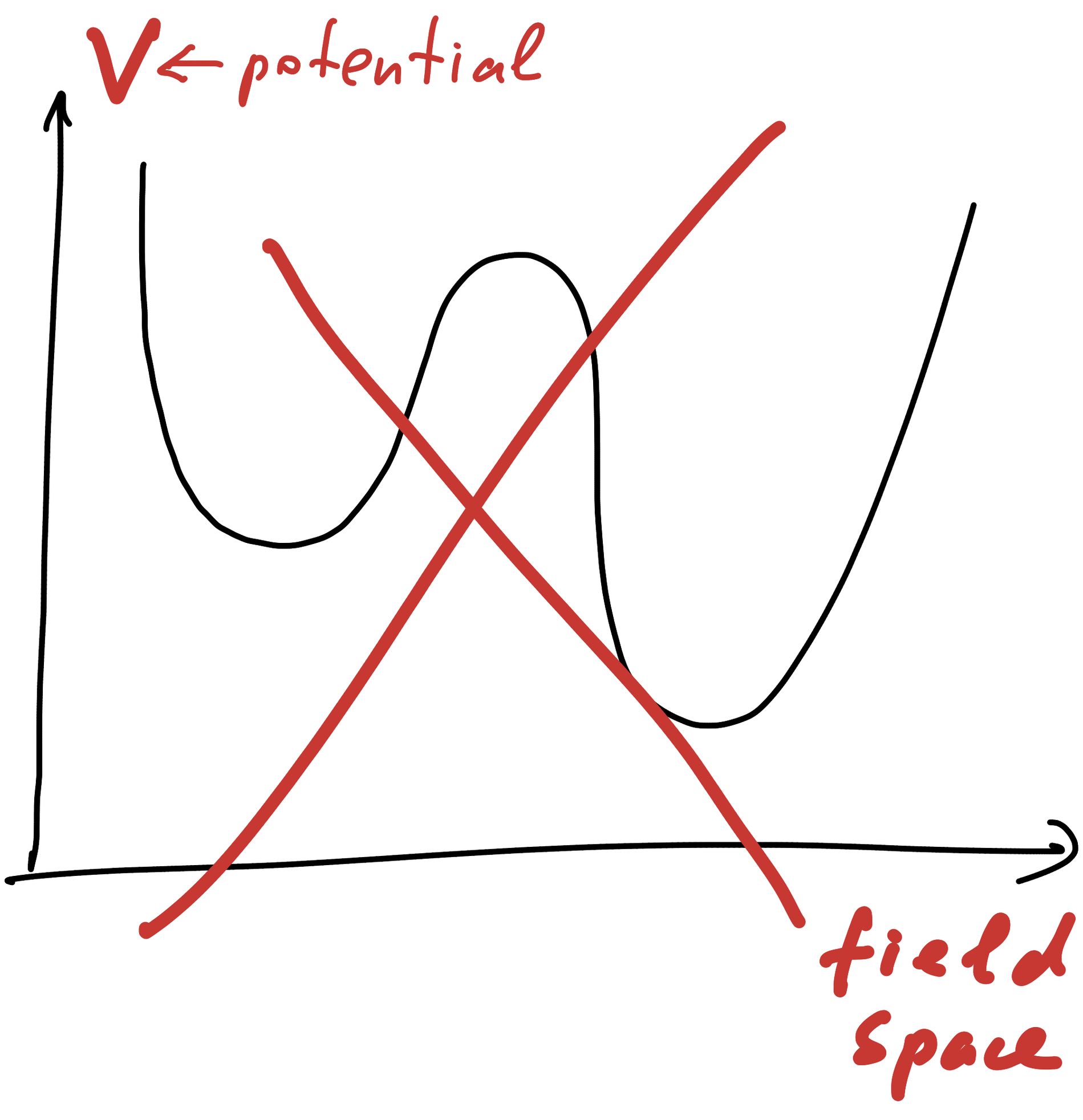
$$t_{Exit} \leq t_Q$$



Bound on slow-roll

$$t_{\text{slow-roll}} < t_Q$$

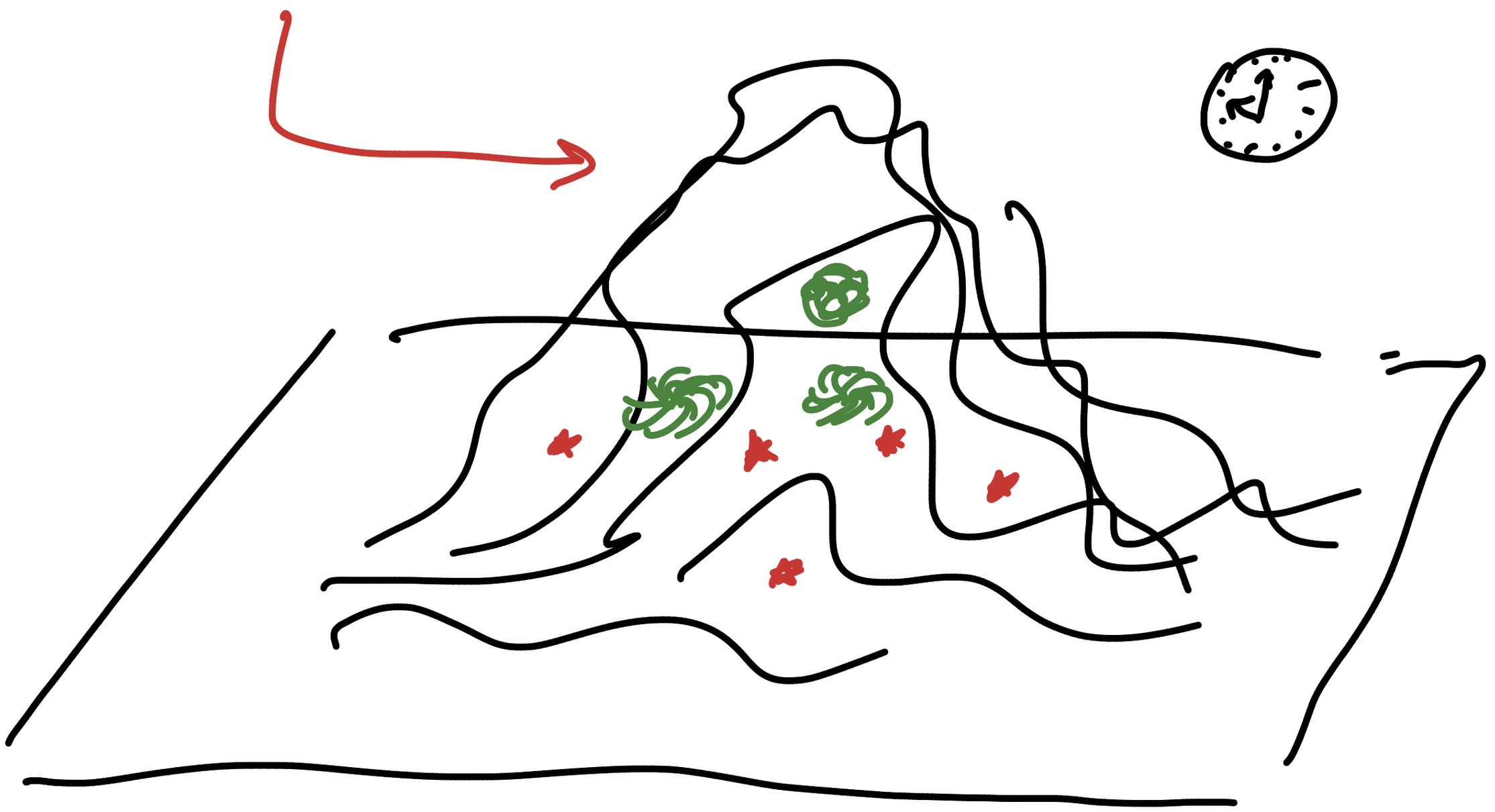
For finite G_N (finite M_p),
no de Sitter is possible, neither stable
nor meta-stable.



Λ is excluded from the energy budget of our Universe by consistency of S-matrix formulation.

Our vacuum is Minkowski.

Everything else (including our comic history) is a temporary excitation on it



Because of S-matrix, formulation of quantum gravity is background-dependent and that's OK.

Through S-matrix, quantum gravity/string theory nullifies an outstanding cosmological puzzle:

$\Lambda = 0$ was never a problem.

What about dark energy?

If it exists in our Universe

↳ (Colin, Mohayaee, Rameez, Sarkar '18)

it cannot be Λ. It must come from new physics beyond Standar Model + Einstein

$$SM + GR + \cancel{\Lambda} + ?$$

and it must evolve in time pretty fast, over

$$t \lesssim R \ln(R^2 M_p^2)$$

$R \sim$ Hubble

Outlook:

- ✱ $\mathcal{S}$-matrix formulation of quantum gravity excludes de Sitter landscape;
- ✱ This nullifies outstanding cosmological puzzle;
- ✱ Predicts imprints of quantum break-time in cosmological observables;
- ✱ Changes the view on background dependence of quantum gravity;
- ✱ Gives new view on naturalness questions: ① Hierarchy ② Strong-CP, ...

Thank You!

Notice:

Quantum break-time,

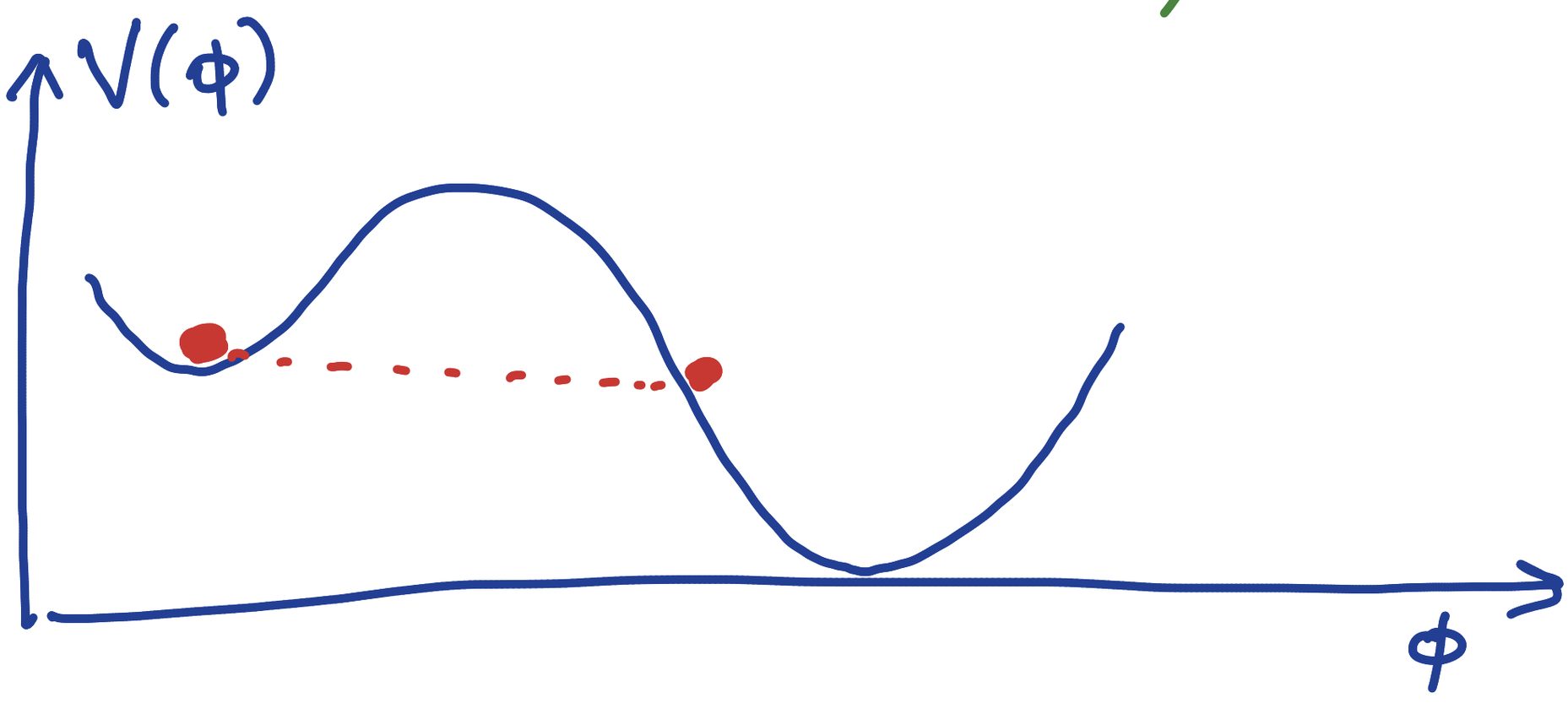
$$t_Q \sim N R$$

or $$t_Q \sim R \ln(N),$$

is much shorter than a typical tunneling time:

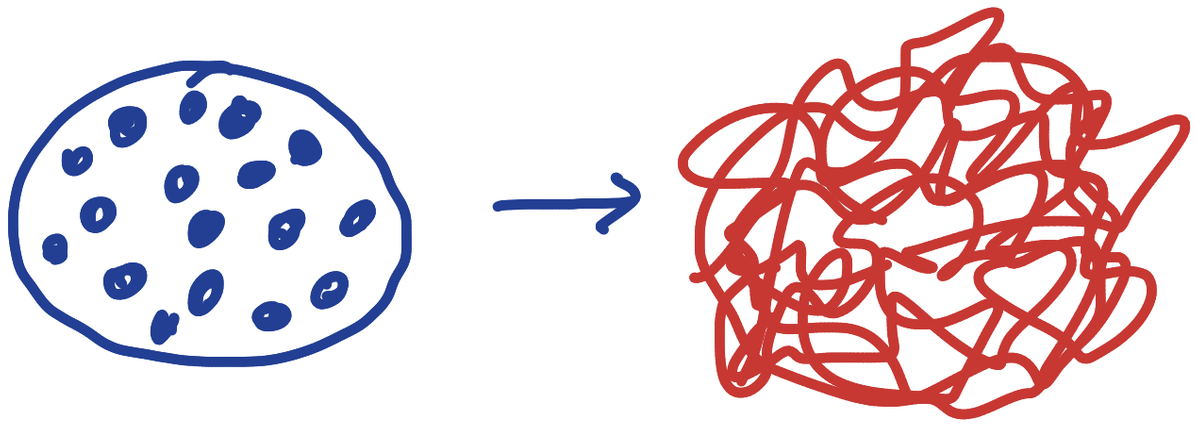
$$t_{tunnel} \sim R\, e^N$$

Coleman, De Luccia '80



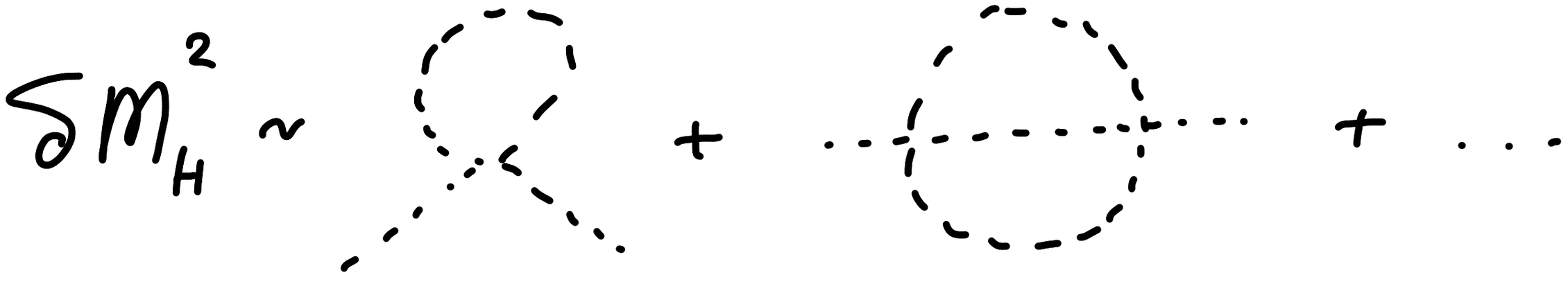
The situation is very similar to Witten-Veneziano $\frac{1}{N}$-effects versus instanton e^{-N}-effects by 't Hooft in $SU(N)$ QCD.

Anomaly interpretation:
Like chiral symmetry in QCD, deSitter is anomalous with respect to corpuscular $\frac{1}{N}$-effects.



Implication for the "Hierarchy Problem".

The essence of the puzzle:
Higgs mass is UV-sensitive



Expected (by naturalness):

$$m_H^2 \sim M_{UV}^2$$

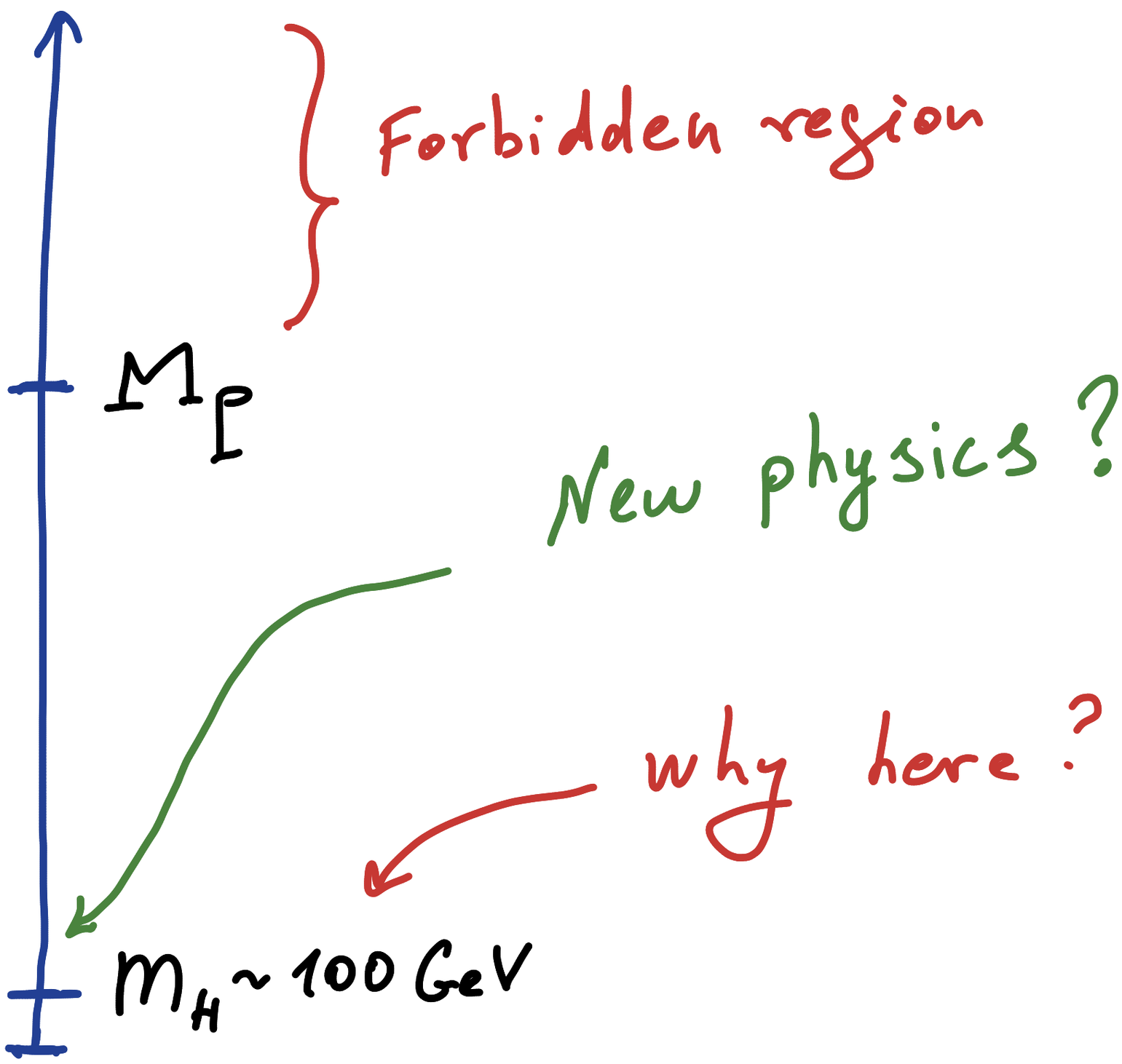
cutoff is real because of gravity.

No elementary particles of mass

$$m > M_P$$

(would be a black hole!)

Higgs cannot have a solar mass



Natural explanations for $m_H \sim 100\,GeV$ without new physics not far from the weak scale.

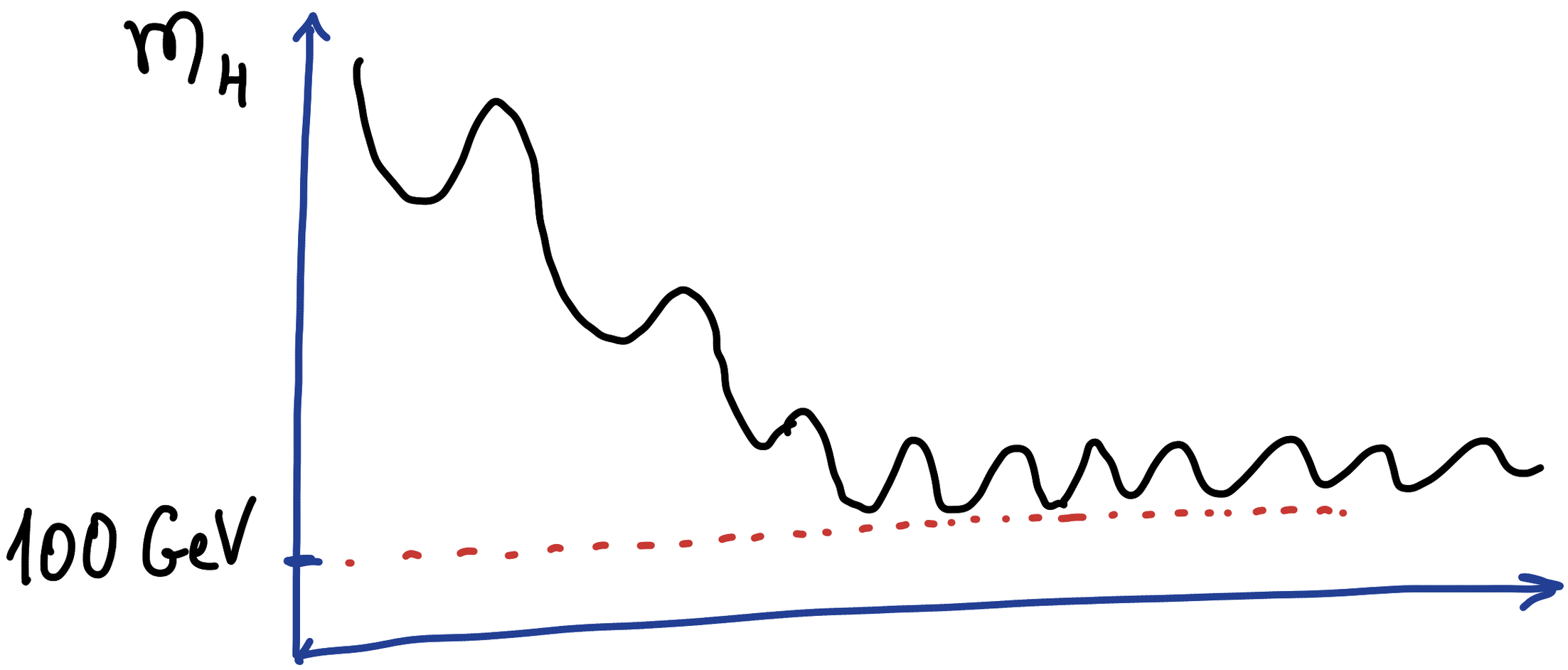
Can $m_H \sim 100\,GeV$ be anthropic ?

Agrawal, Barr, Donoghue, Seckel '97

Requires cosmological actualization mechanism (Eternal inflation on deSitter landsape?).

Cosmological relaxation of the Higgs mass

G.D., Vilenkin '03; G.D., '04;
Graham, Kaplan, Rajendran '15



Both 1) Anthropic selection

and

2) Cosmological relaxation to attractor

require a cosmological actualization mechanism.

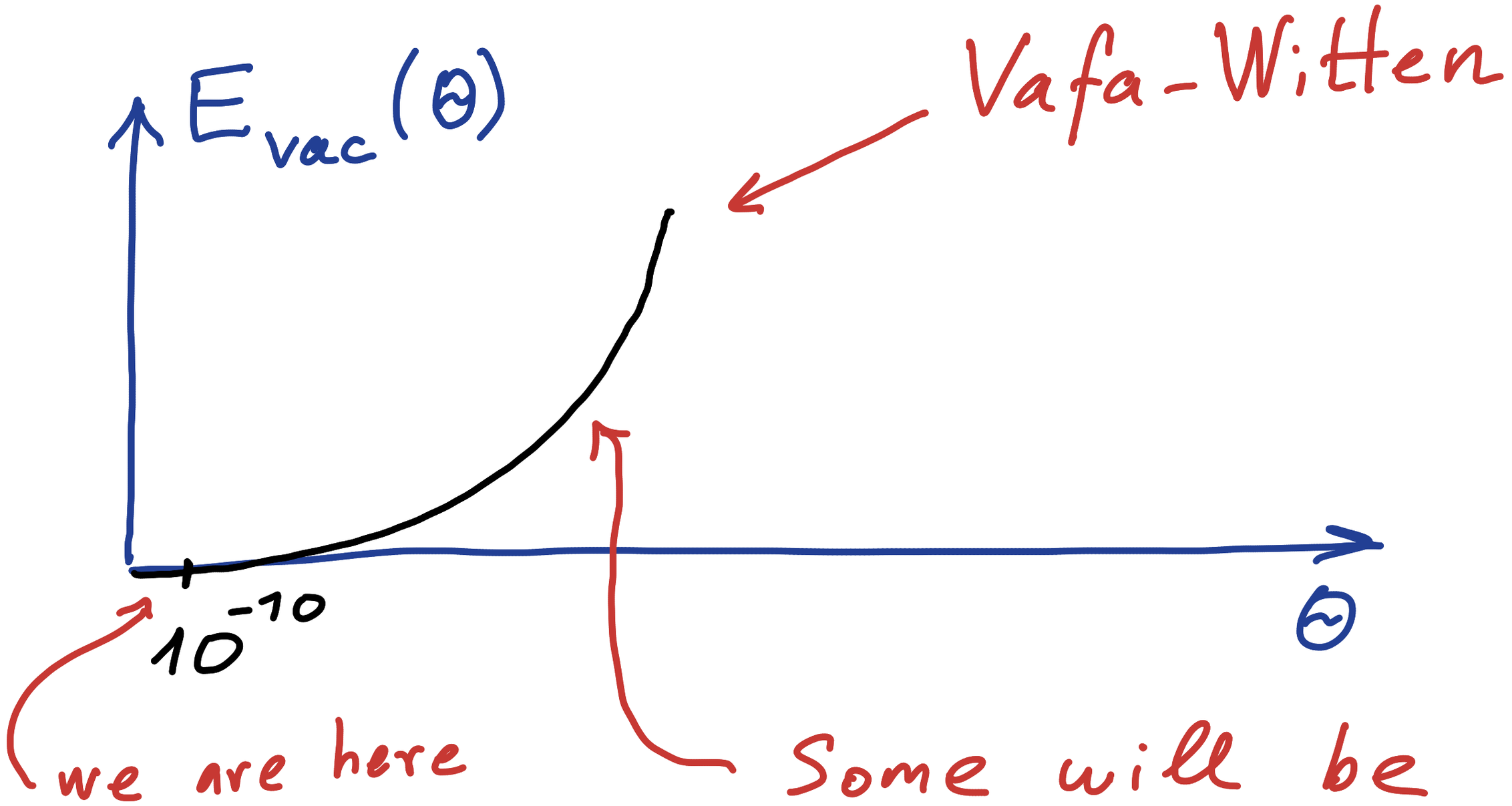
We have argued that eternal inflation on deSitter landscape is incompatible with quantum gravity/string theory

This strengthens the motivation for new physics not far from weak scale.

Strong-CP puzzle.

$\tilde{\Theta}$-vacua in gauge theories:

$$\mathcal{L}_{QCD} = \tilde{\Theta} F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots$$



This is excluded by S-matrix!

$\tilde{\Theta}$-vacua must be unphysical.

(Axion? Massless quark?) G.D, Gomez, Zell '18

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