# Exclusion of de Sitter Vacua and Naturalness

Gia Dvali

(LMU-MPI, Munich)

# Some Notations

(in units $c = \hbar = 1$):

- ⊛ Newton's constant $\equiv G$
- ⊛ Planck mass $\equiv M_P$
- ⊛ Planck length $\equiv L_P$

$$G = L_P^2 = \frac{1}{M_P^2}$$

- ⊛ Cosmological constant (vacuum energy density) $\equiv \Lambda$
- ⊛ de Sitter curvature radius (Hubble radius) $\equiv R$

# de Sitter:

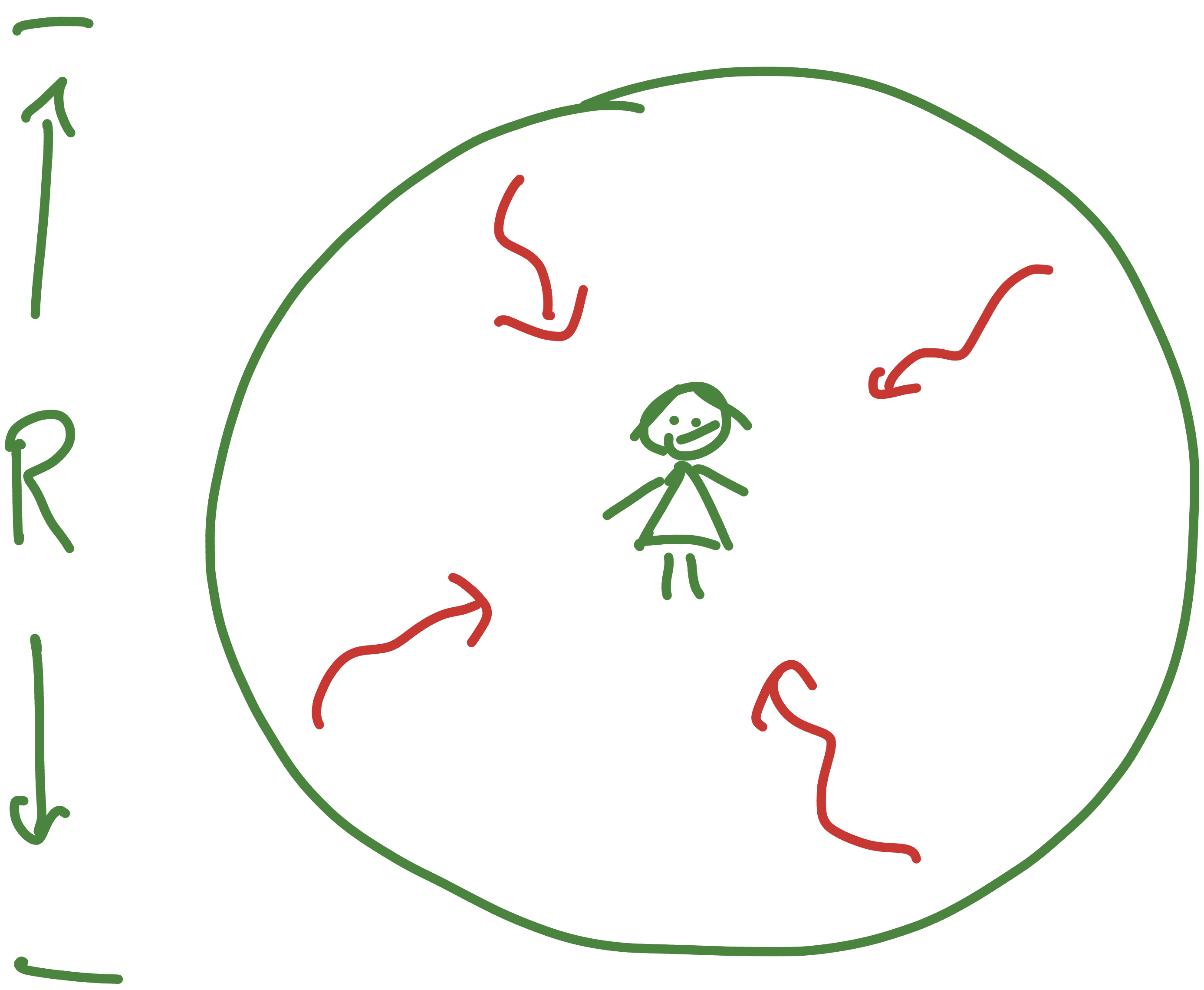
$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2$$

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-like states play important role in cosmology:

⊛ We come from there (inflation)

and

⊛ We are re-entering (are we?)

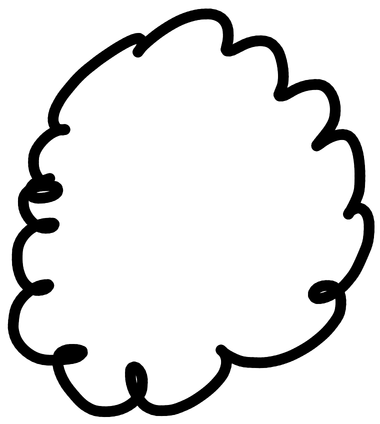
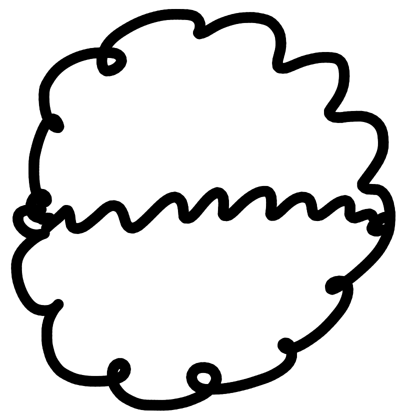
⊛ Why is $\Lambda$ so small?

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

Cosmological constant puzzle.

# Cosmological constant puzzle:

$\Lambda$ is UV-sensitive

$\delta\Lambda =$  $+$  $+ \; \ldots\ldots$

Naive expectation:

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

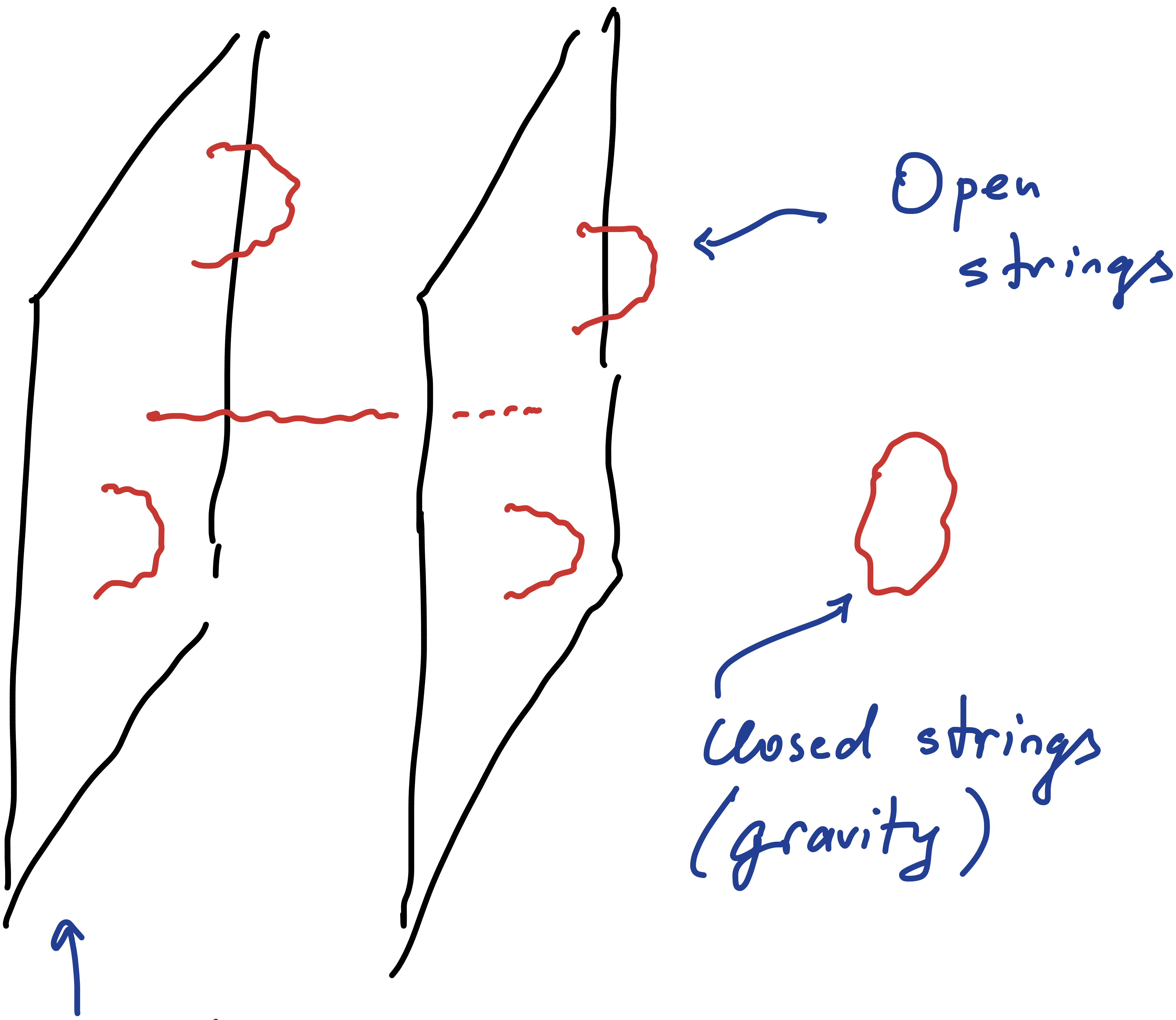
Usualy viewed as <u>naturalness</u> puzzle.

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

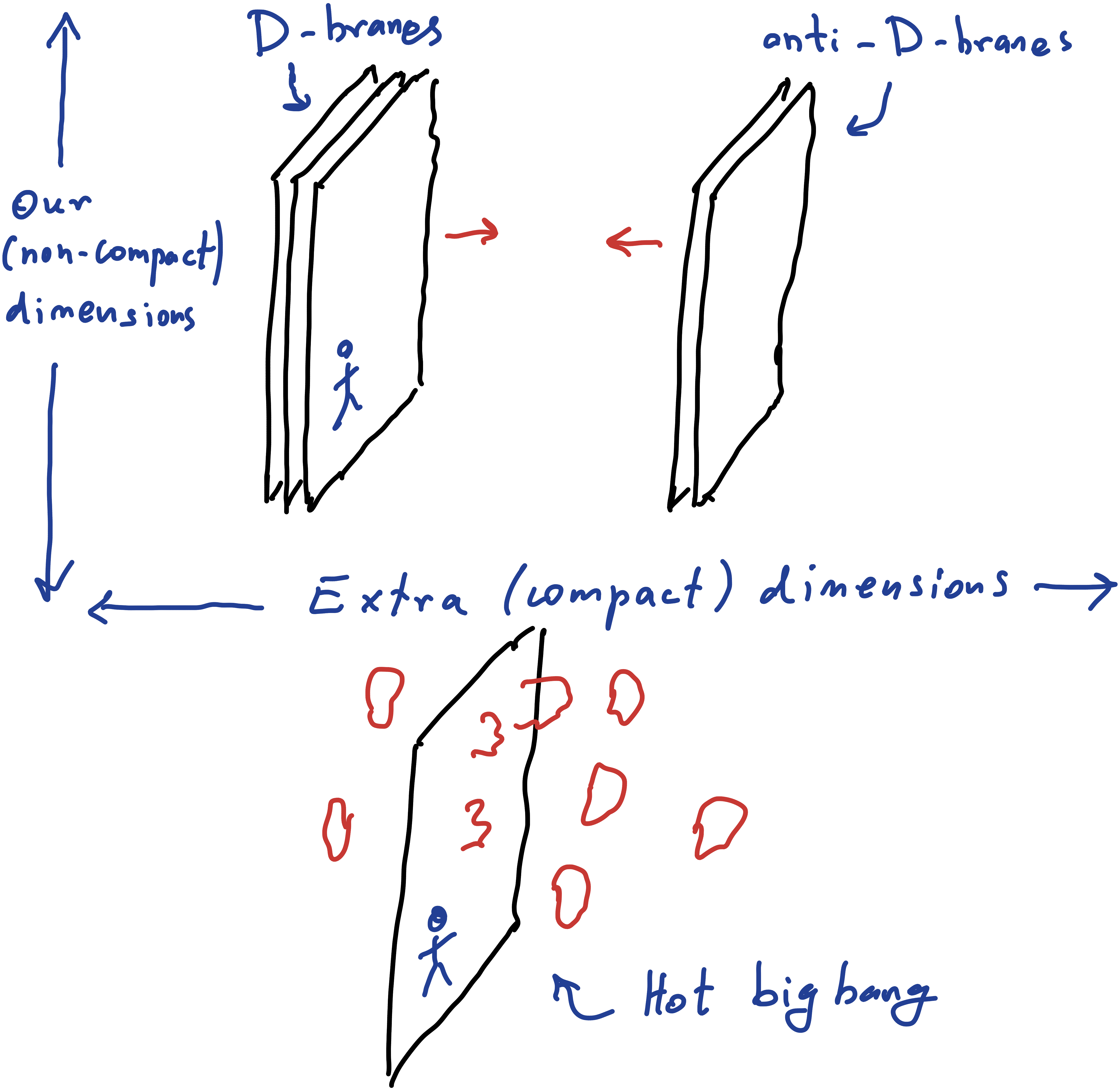
G.D., Tye '98




D-brane (Polchinski '95, ....)

# 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, Notle,

Quevedo, Rajesh, Zhang '01

Kachru et al '03

+ Maldacena, Mc Allister '03

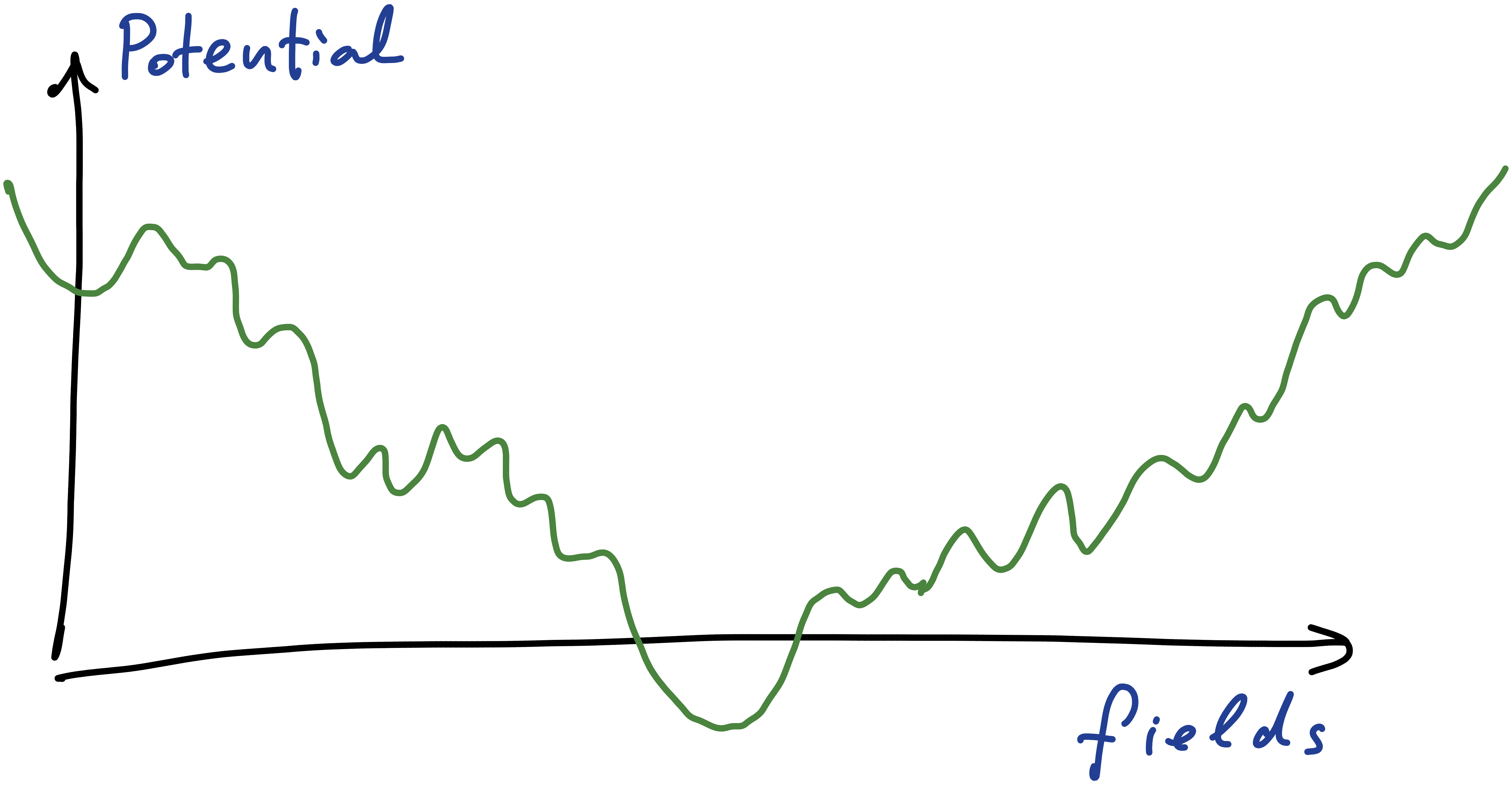
. - - - - - . . .

I am not aware of any

meta-stabilization

(for a good reason)

Often assumed picture:
Plentitude of de Sitter vacua on string landscape

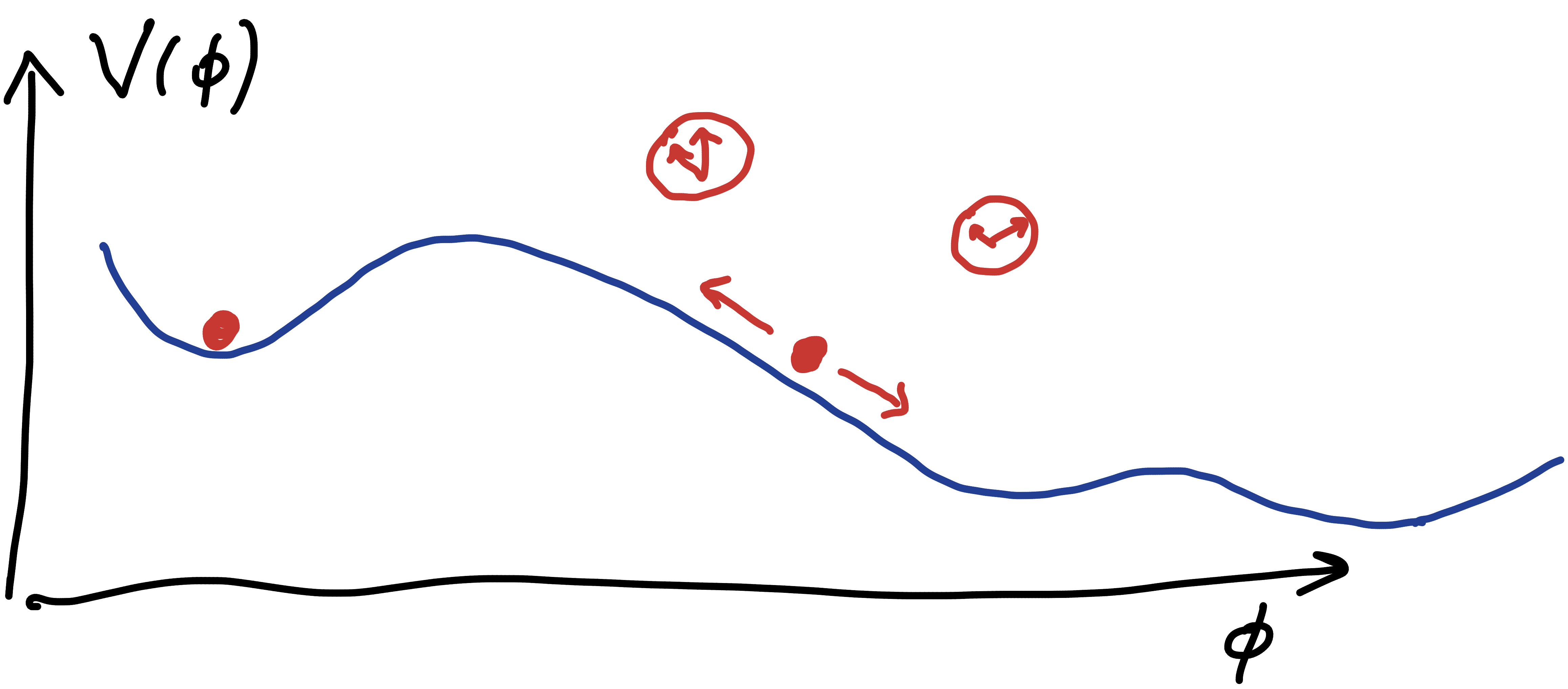



Naturalness can be replaced by Anthropic selection

de Sitter landscape would open a way for anthropic selection.
Carter '74; Carr, Rees '79; Barrow, Tipler '86

Weinberg '87: Small $\Lambda$ is required to form galaxies.

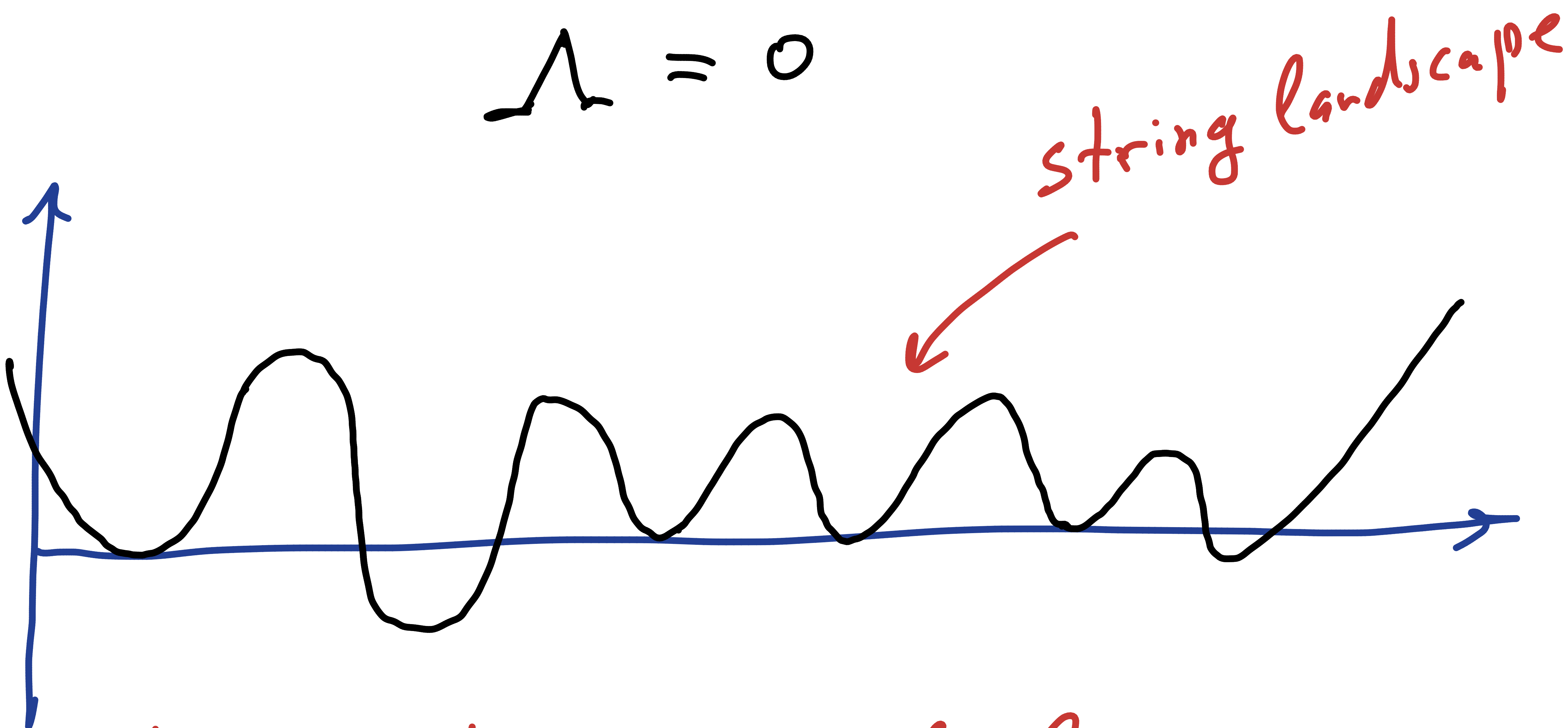
de Sitter landscape can provide an <u>actualization</u> <u>mechanism</u> via <u>eternal</u> <u>inflation</u> Vilenkin '83; Linde '86; ...



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.

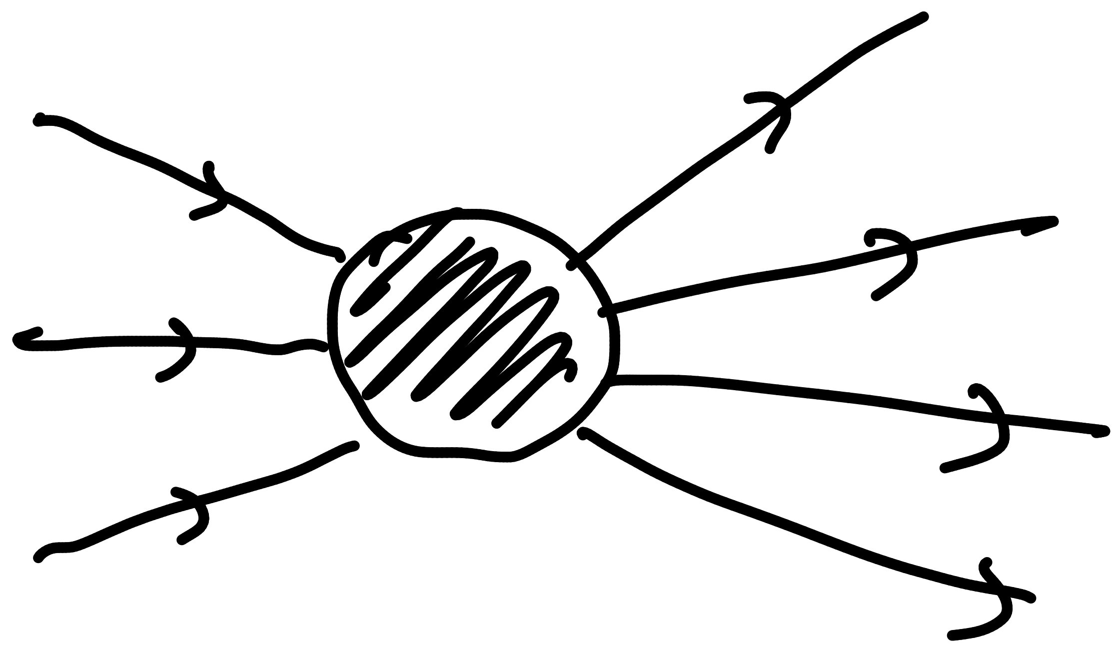
S-matrix is fundamental in this.

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

# S-matrix

in

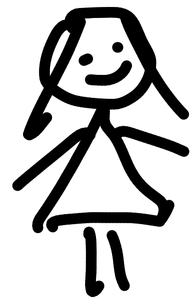
$|i\rangle$

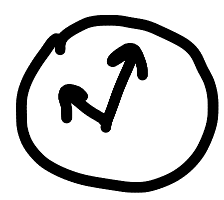


out

$|f\rangle$

$t=-\infty$





$t$

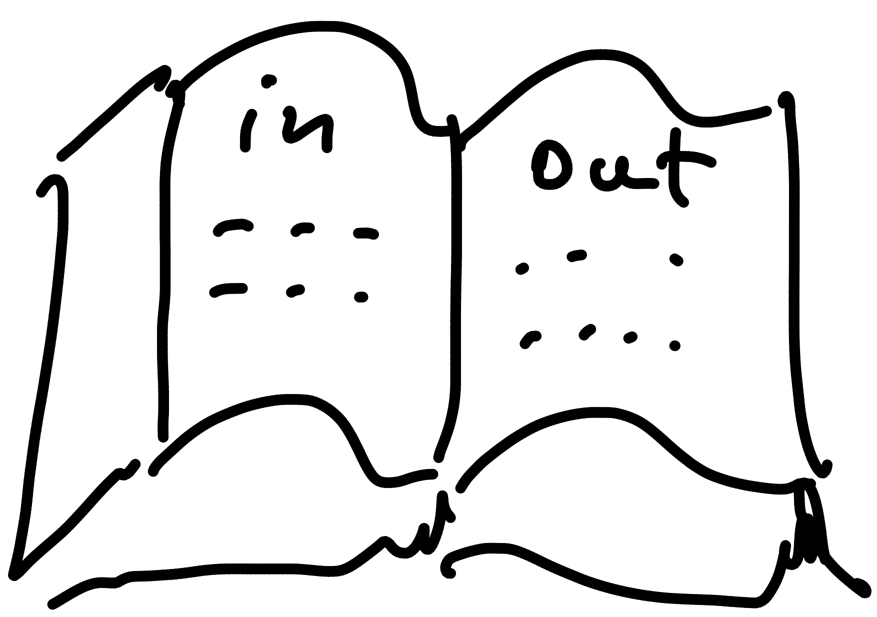
$t=+\infty$

eternal clock

eternal observer, Alice

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

Manual:



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

Necessary conditions:

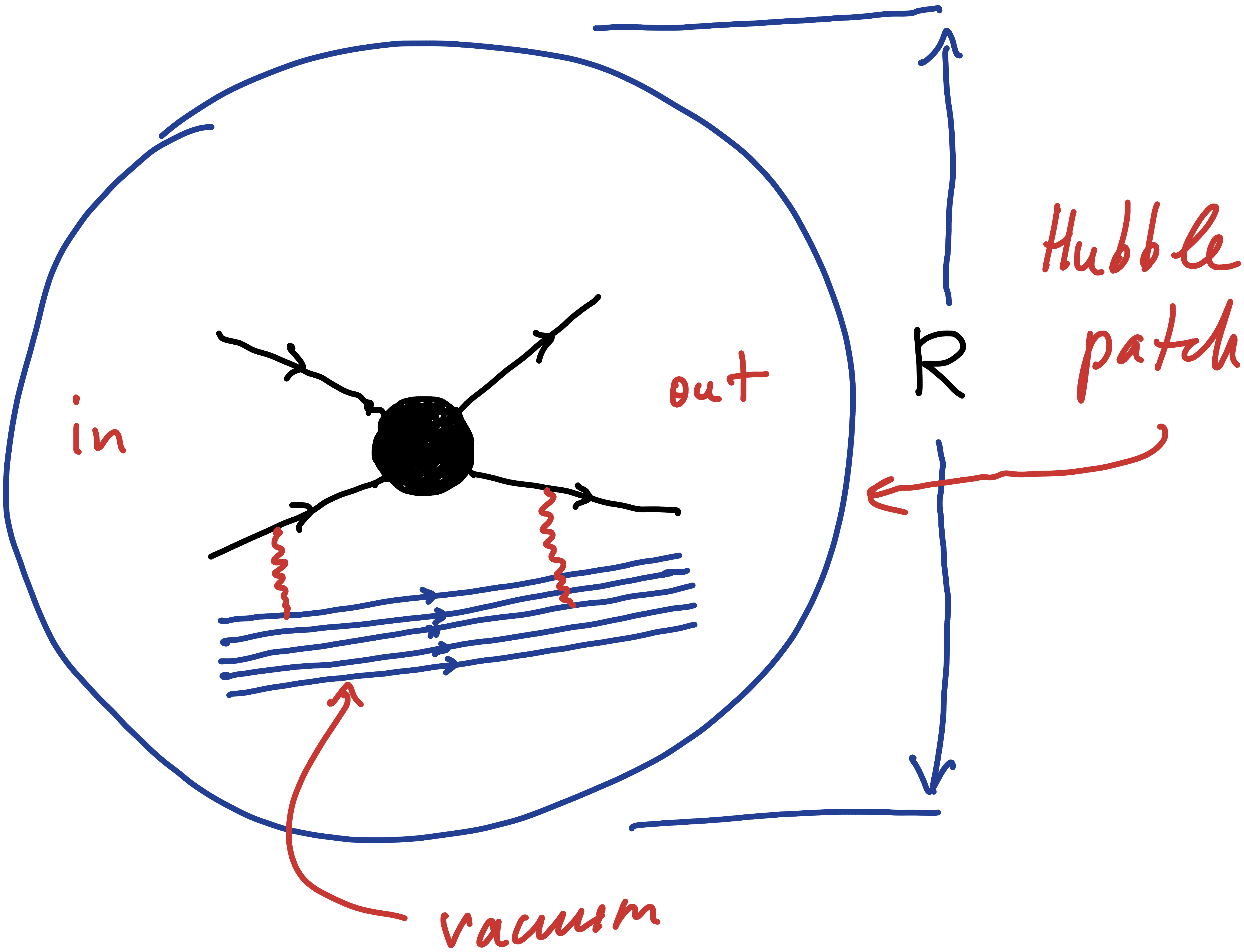
⊛ Globally-definet time;

Absent in classical de Sitter

⊛ $S$-matrix vacuum.

What about quantum theory?

What about effective $S$-matrix?



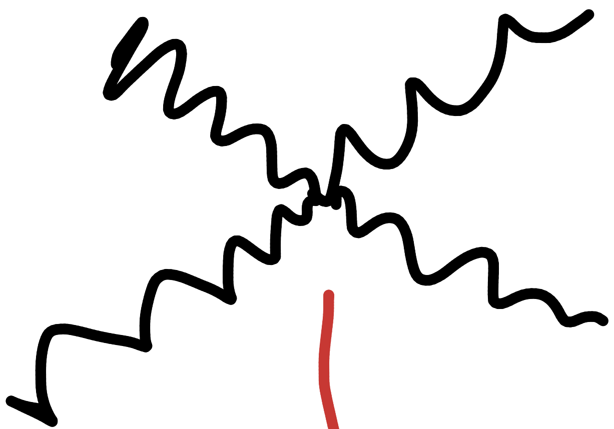

The vacuum should not be able to recoil and absorb some information.

This is only possible in double-scaling limit:

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

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

But in the same limit graviton quantum coupling vanishes



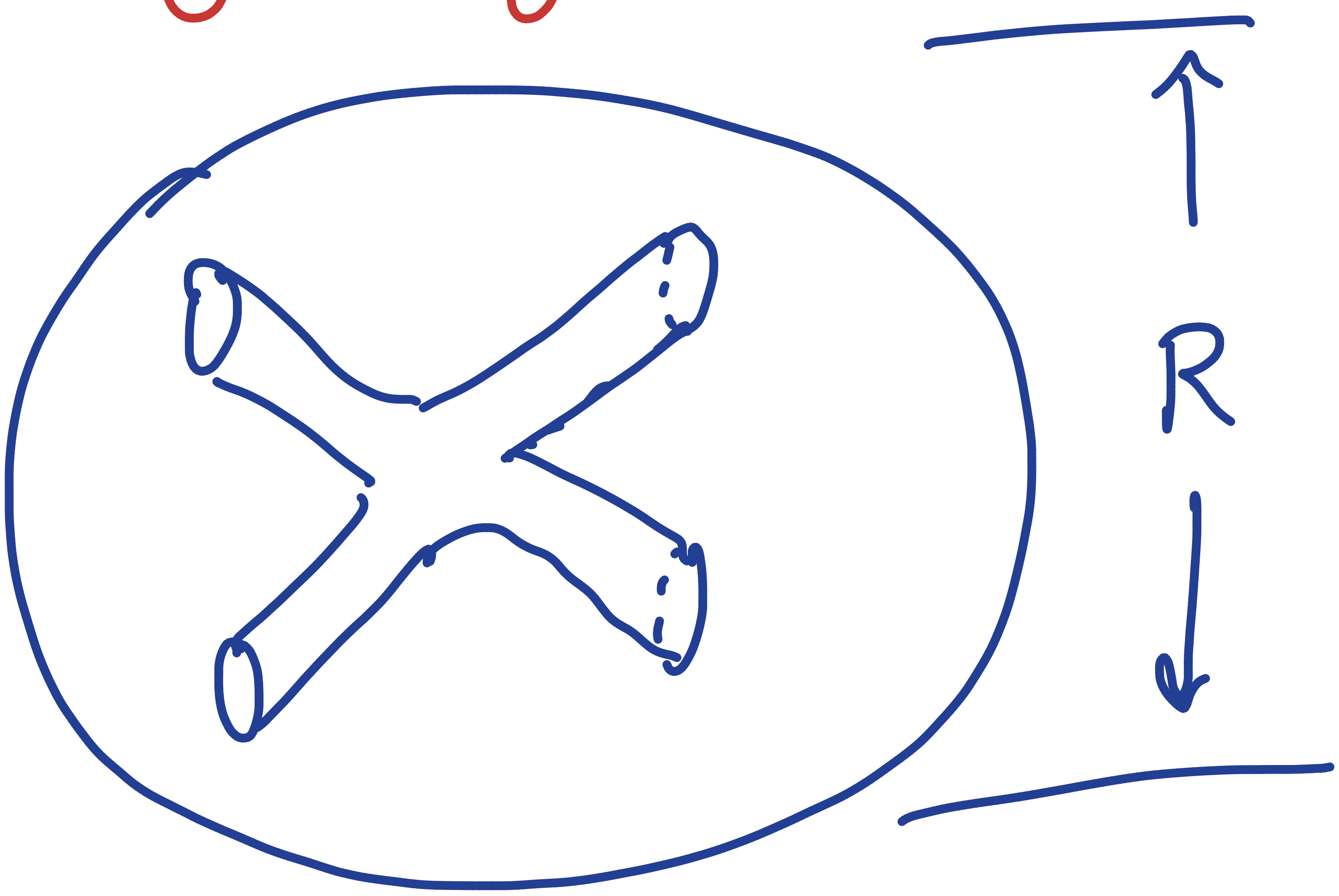
momentum-transfer

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

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:

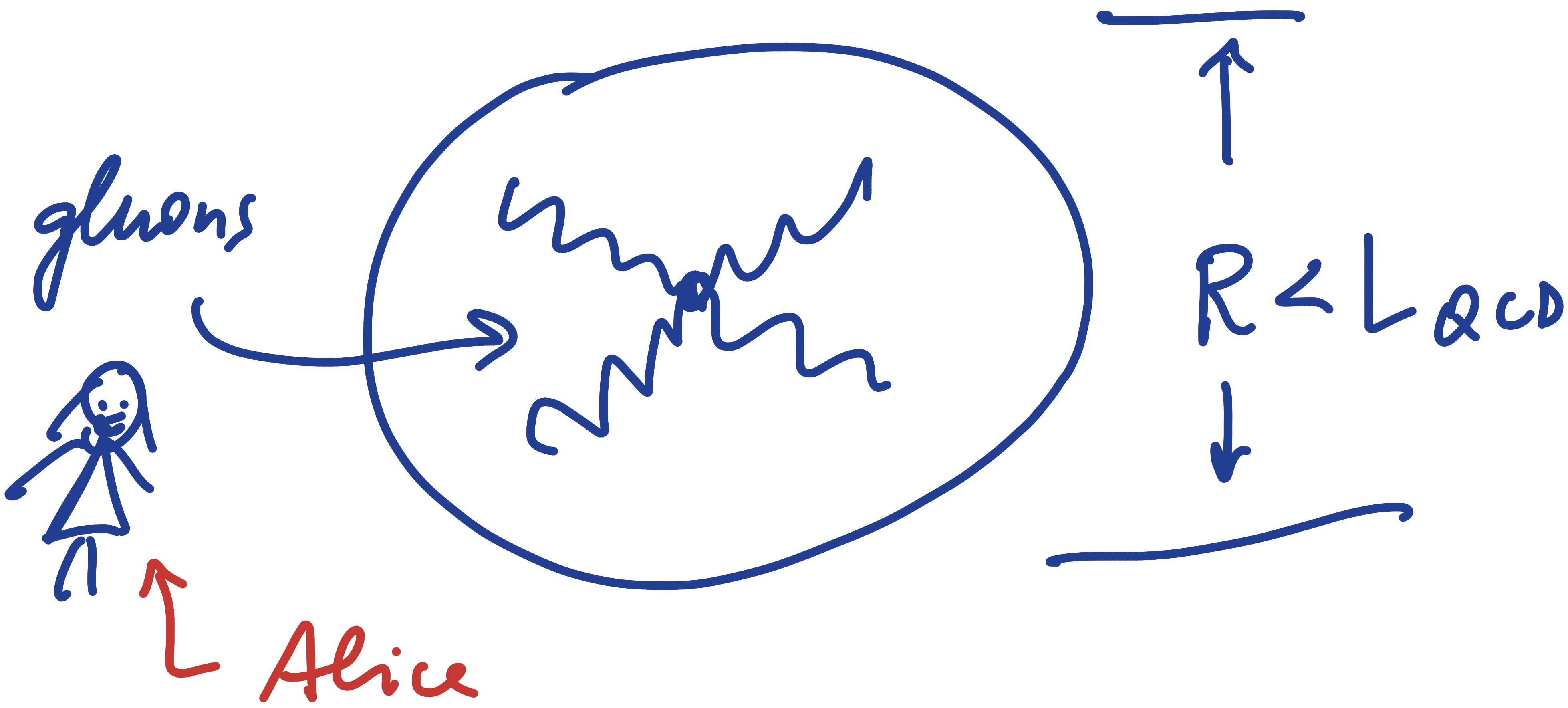
$$\left.\begin{array}{l} \Lambda \to \infty \\ G \to 0 \\ R = \text{finite} \end{array}\right\} \to \quad g_s^2 \to 0$$

Closed string S-matrix is trivial.

(Open strings, more subtle)

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

E.g. QCD



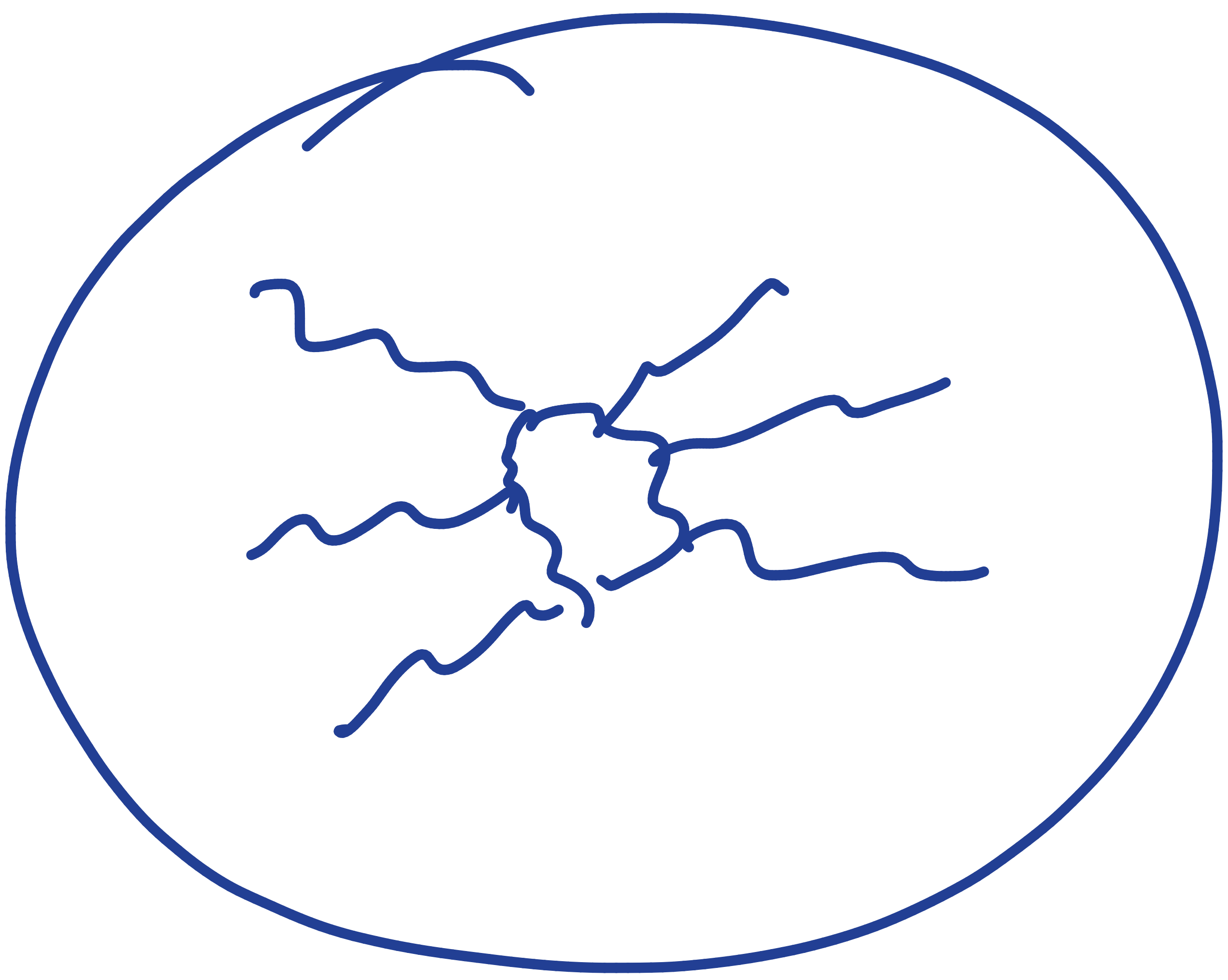

Thus, the issue is quantum gravitational.

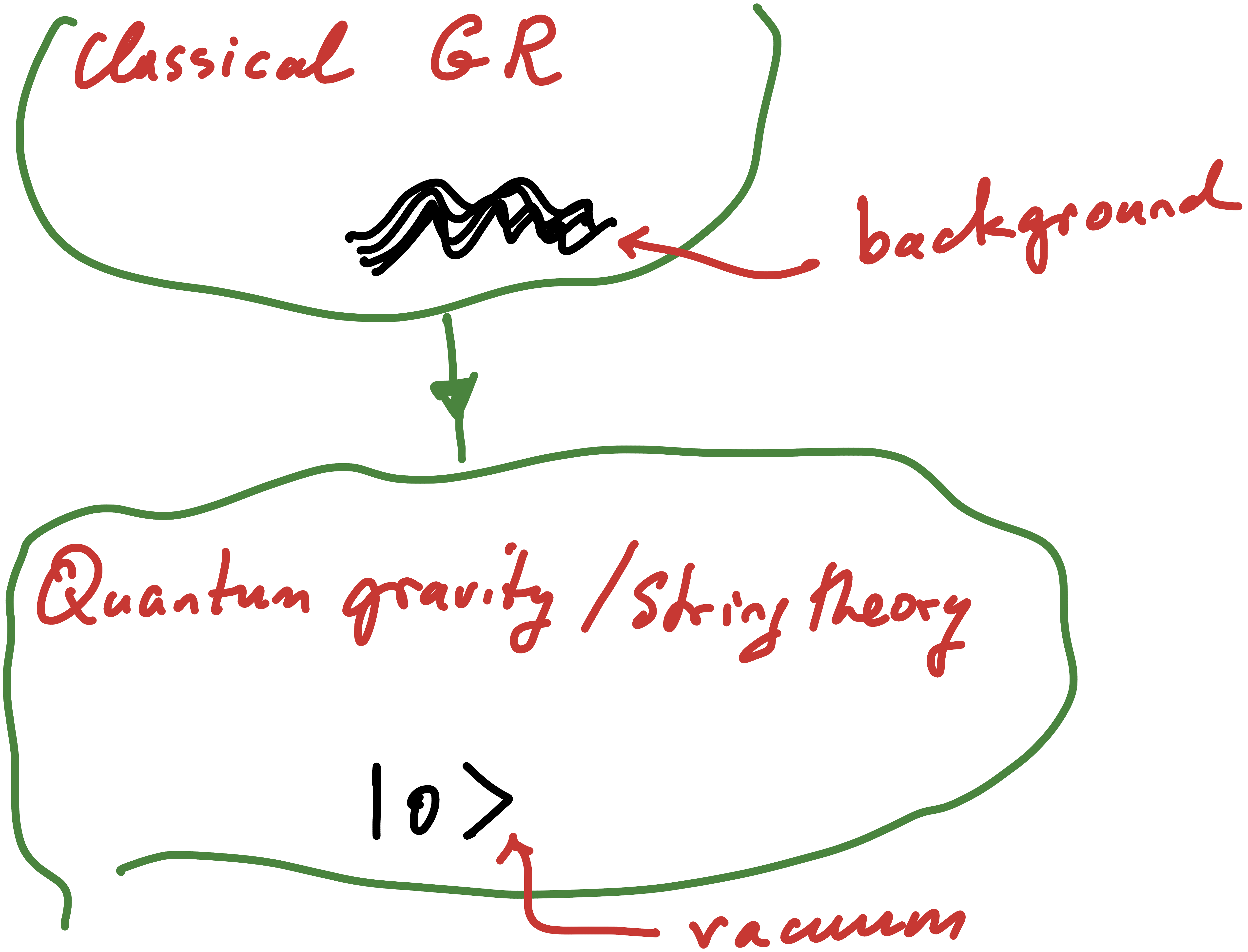
$$(\text{de Sitter} = \text{vacuum}) \rightarrow \begin{array}{l} \alpha_{gr} = 0 \\ g_s = 0 \end{array}$$

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

For example, stattering 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?

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

G.D, Gomez '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 $1/RN$

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

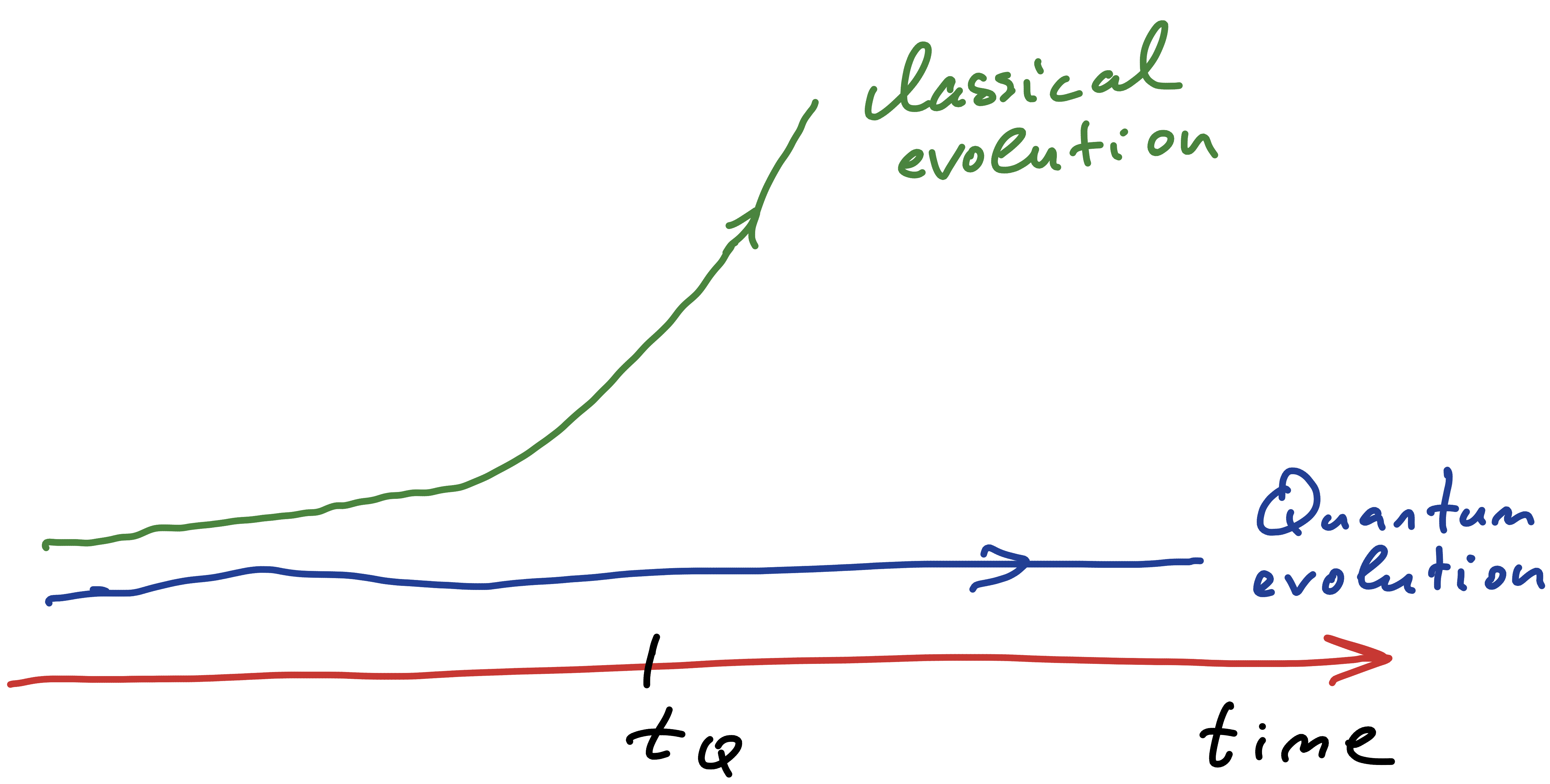
de Sitter is a "Saturon"!

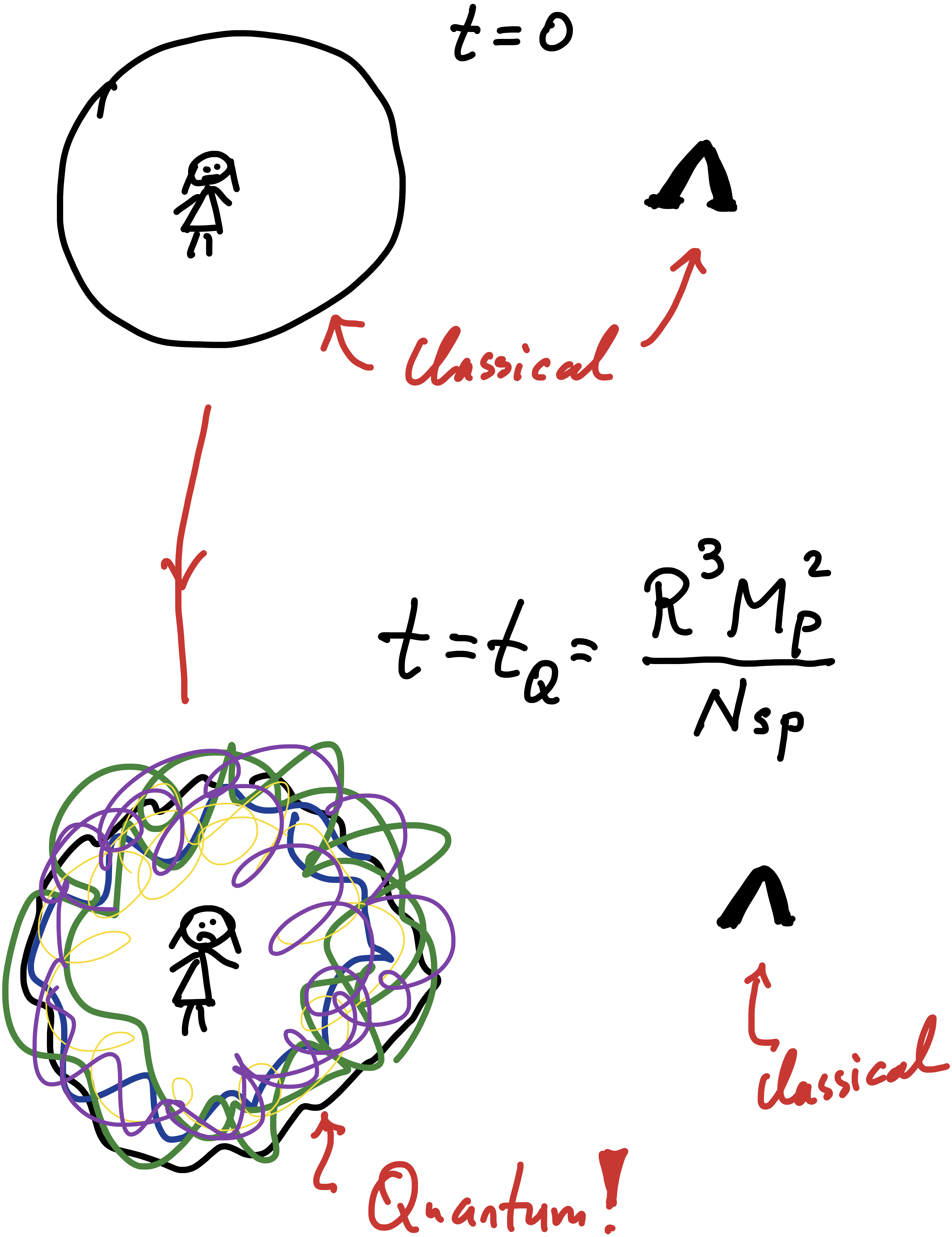
Corpuscular $\frac{1}{N}$-effects lead to anomalous quantum break-time

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
Λ
Classical
$t = t_Q = \frac{R^3 M_P^2}{N_{sp}}$
Λ
Classical
Quantum!

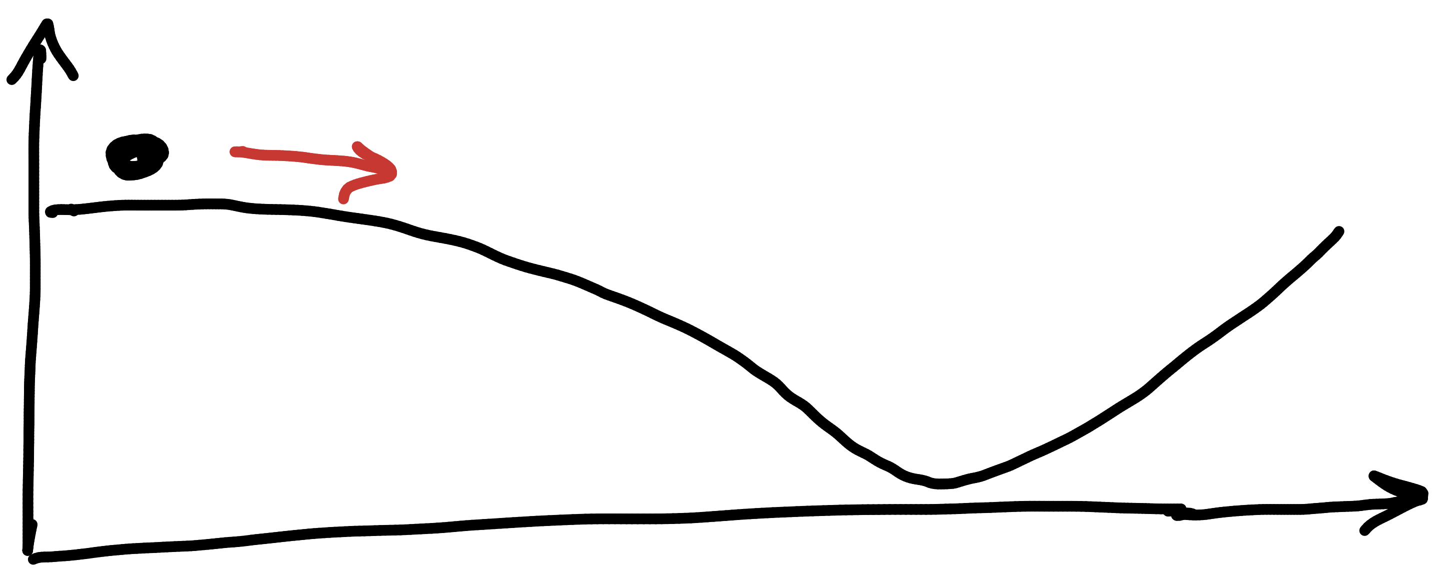
$t_Q$ is much shorter for Lyapunov instability

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

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

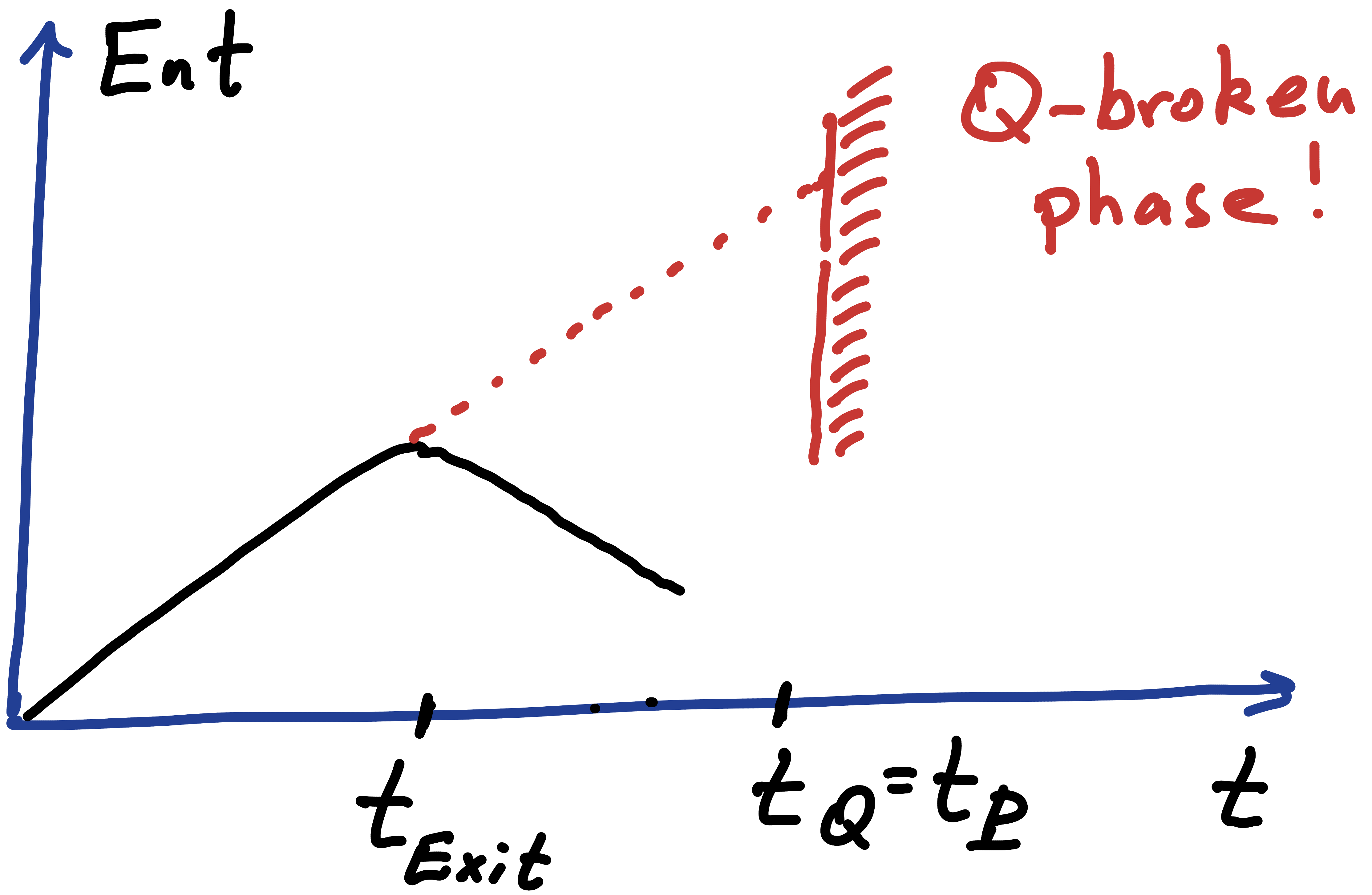
Lyapunov quantum break-time for (inflationary) de Sitter

G.D., Gomez '13



$$t_Q \sim R \ln(S_{GH})$$

de Sitter cannot exist for $t > t_Q$

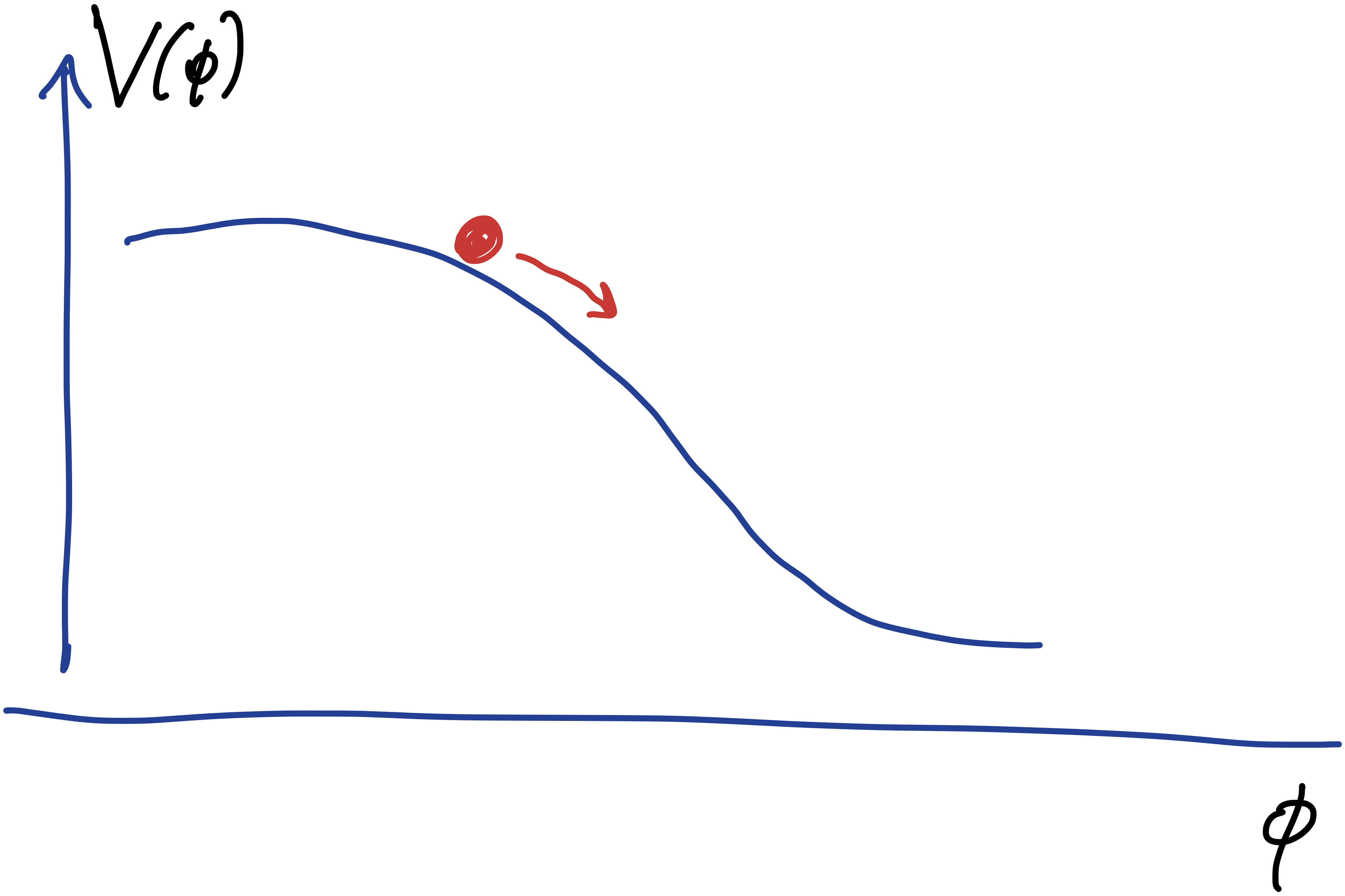



Graceful exit must take place for

$$t_{Exit} \leq t_Q$$

# Universal bound

$$t_{Exit} \le t_Q$$




## Bound on slow-roll

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

Important: Quantum breaking of de Sitter is not instability, it is inconsistency.

If de Sitter is unstable on time-scale $< t_Q$, this would mean that quantum gravity provides a degree of freedom for graceful exit.

This would be only welcome.

Notice:

Quantum break-time,

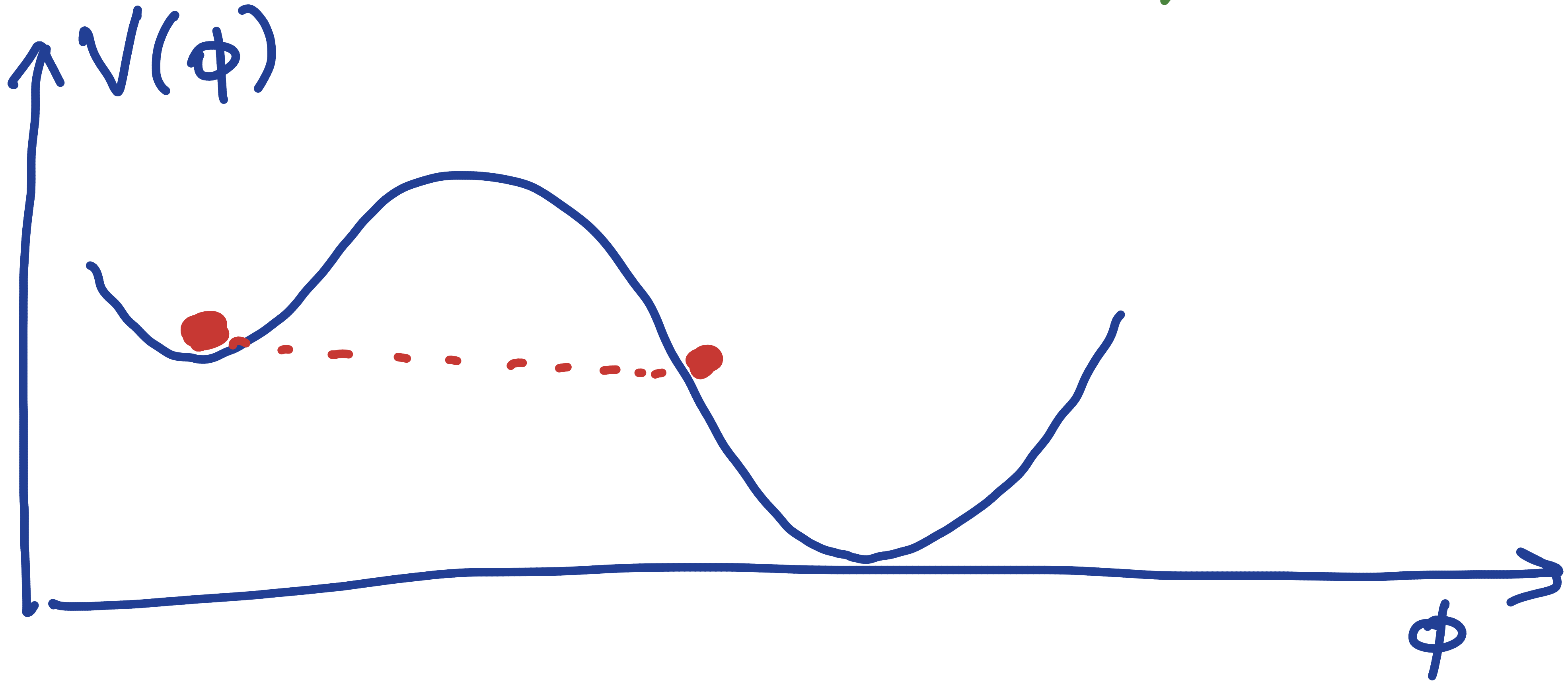
$$t_Q \sim N R$$

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

is much shorter than a typical tunneling time:

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

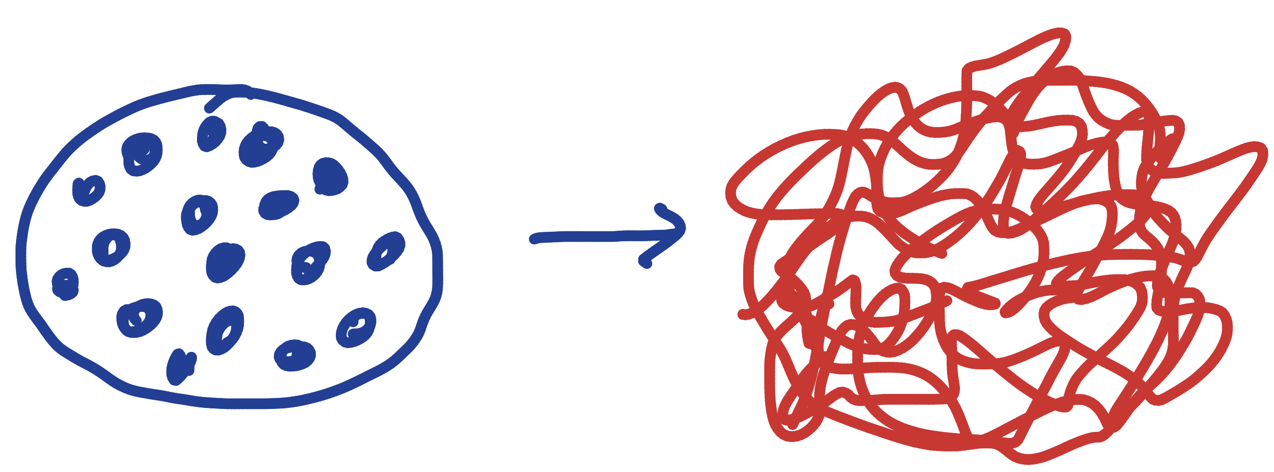
Coleman, De Luccia '80



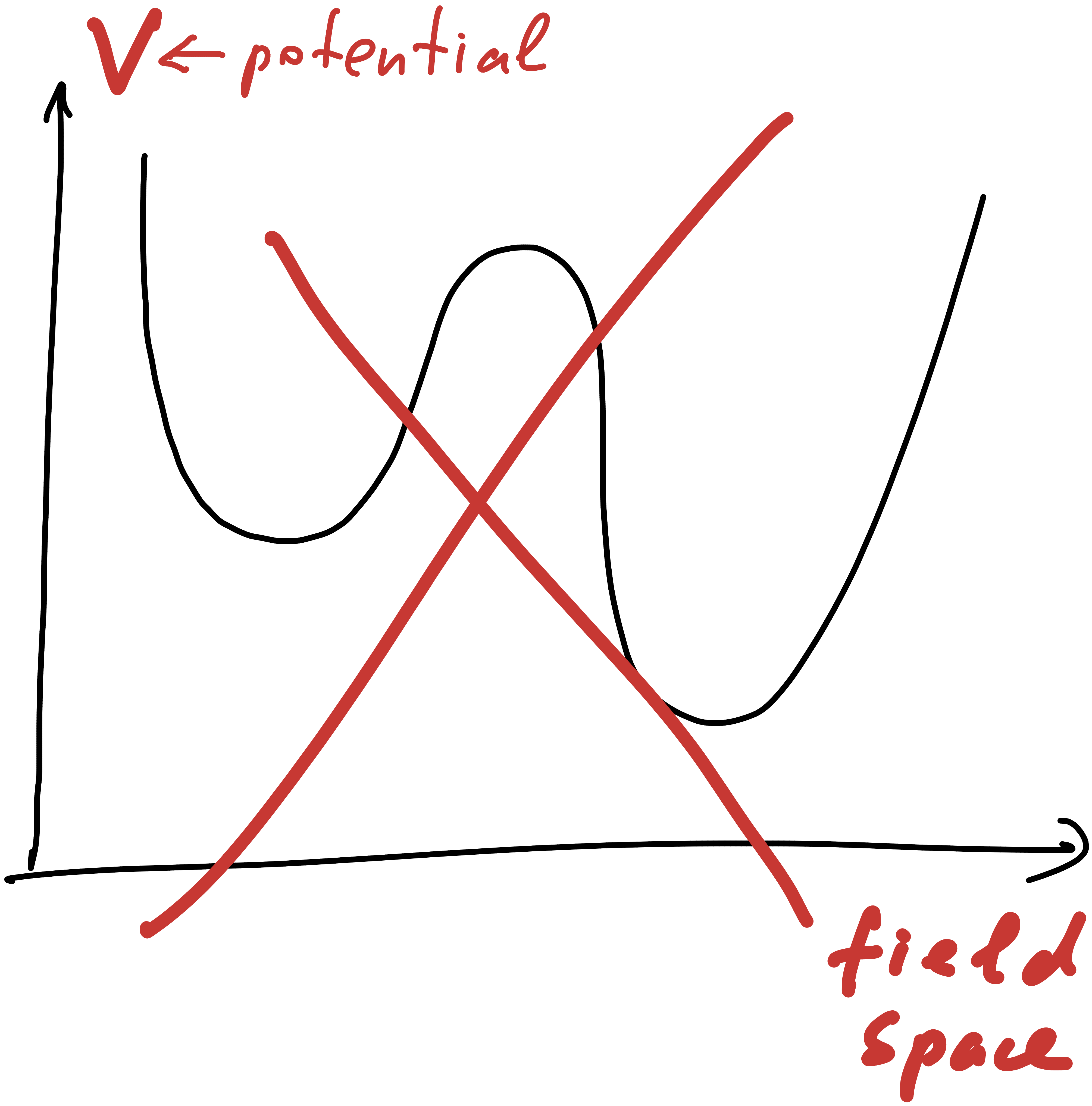
The situation is very similar to Witten-Veneziano $\frac{1}{N}$-effects versus instanton $e^{-N}$-effects by 't Hooft in $SU(N)$ QCD.

Anomaly interpretation:

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



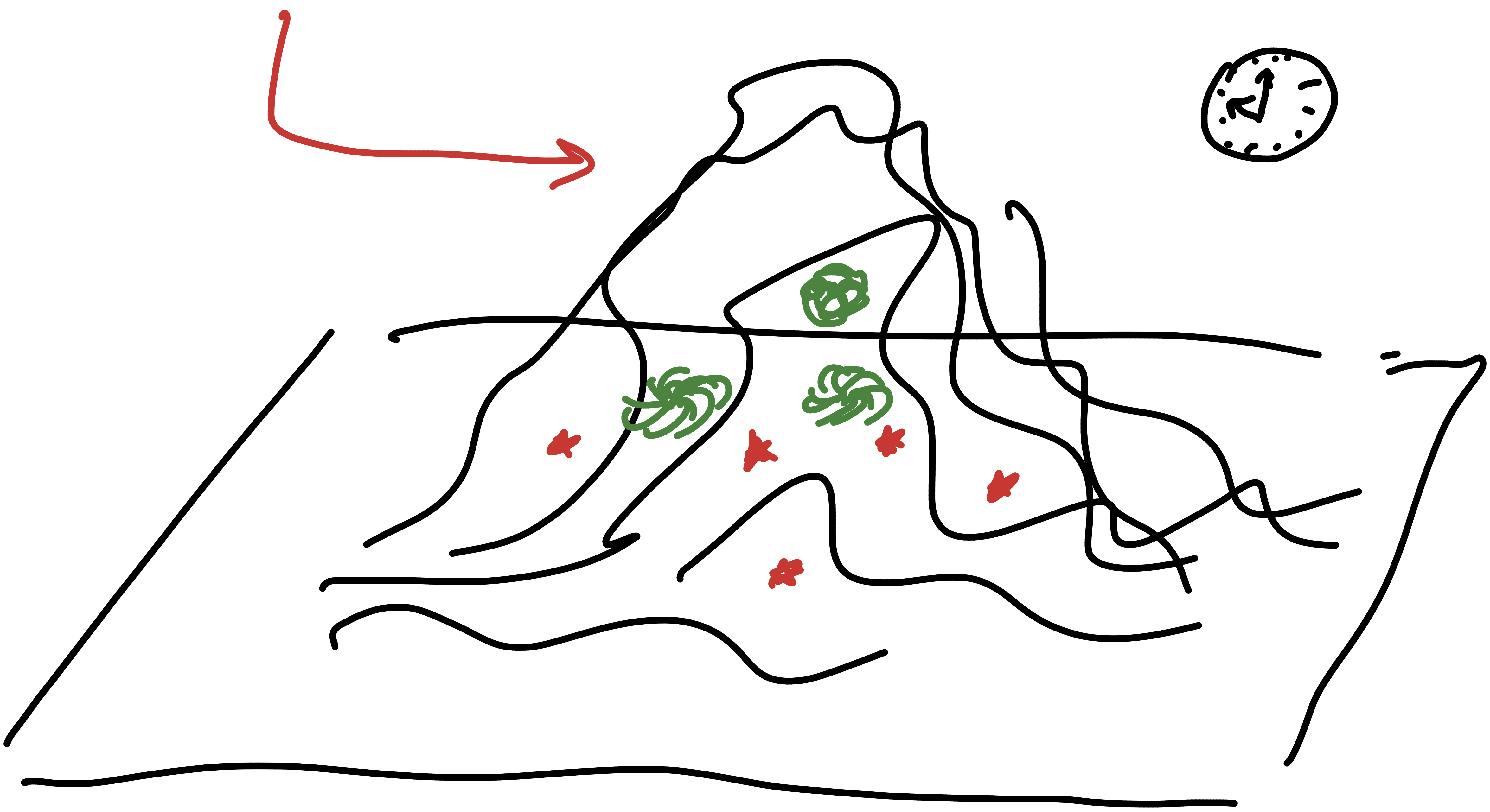
For finite $G_N$ (finite $M_P$),
no de Sitter is possible, neither stable nor meta-stable.



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

Our vacuum is Minkowski.

Everything else (including our cosmic 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 $\Lambda$. It must come from new physics beyond Standar Model + Einstein

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

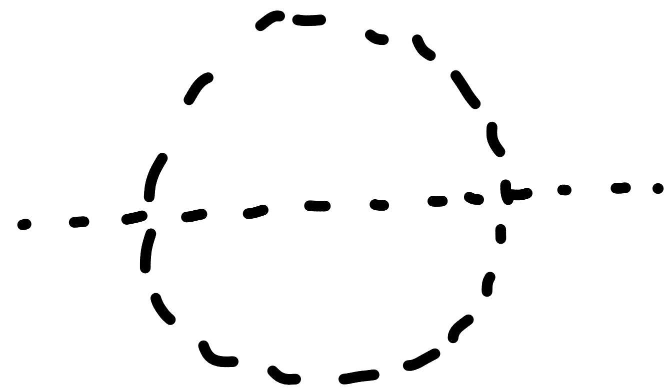
and it must evolve in time pretty fast, over

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

Hubble

## Implication for the "Hierarchy Problem".

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

$\delta m_H^2 \sim$  $+$  $+ \ \ldots$

Expected (by naturalness):

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

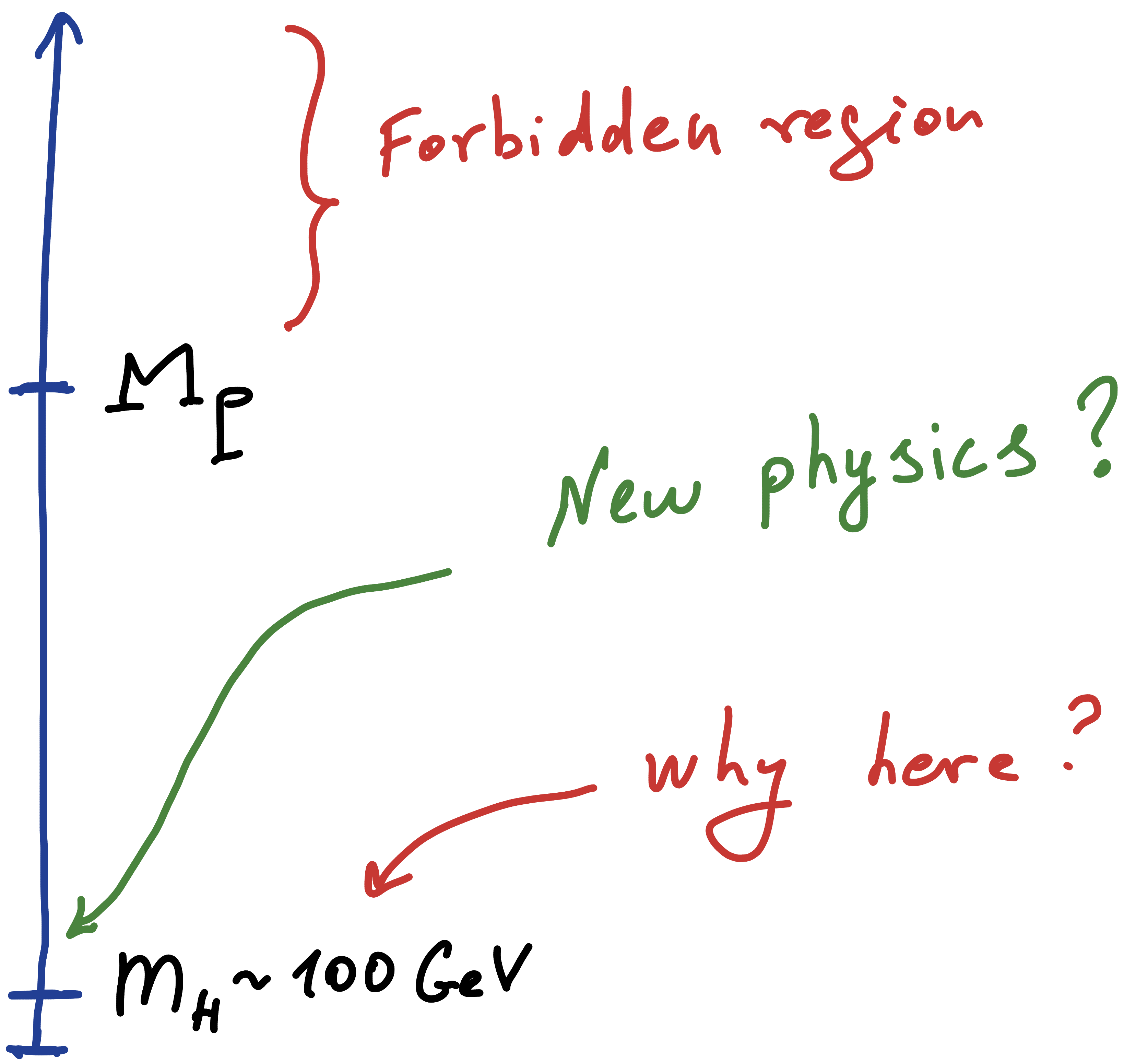
Cutoff is real because of gravity.

No elementary particles of mass

$$m > M_P$$

(would be a black hole!)

Higgs cannot have a solar mass



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

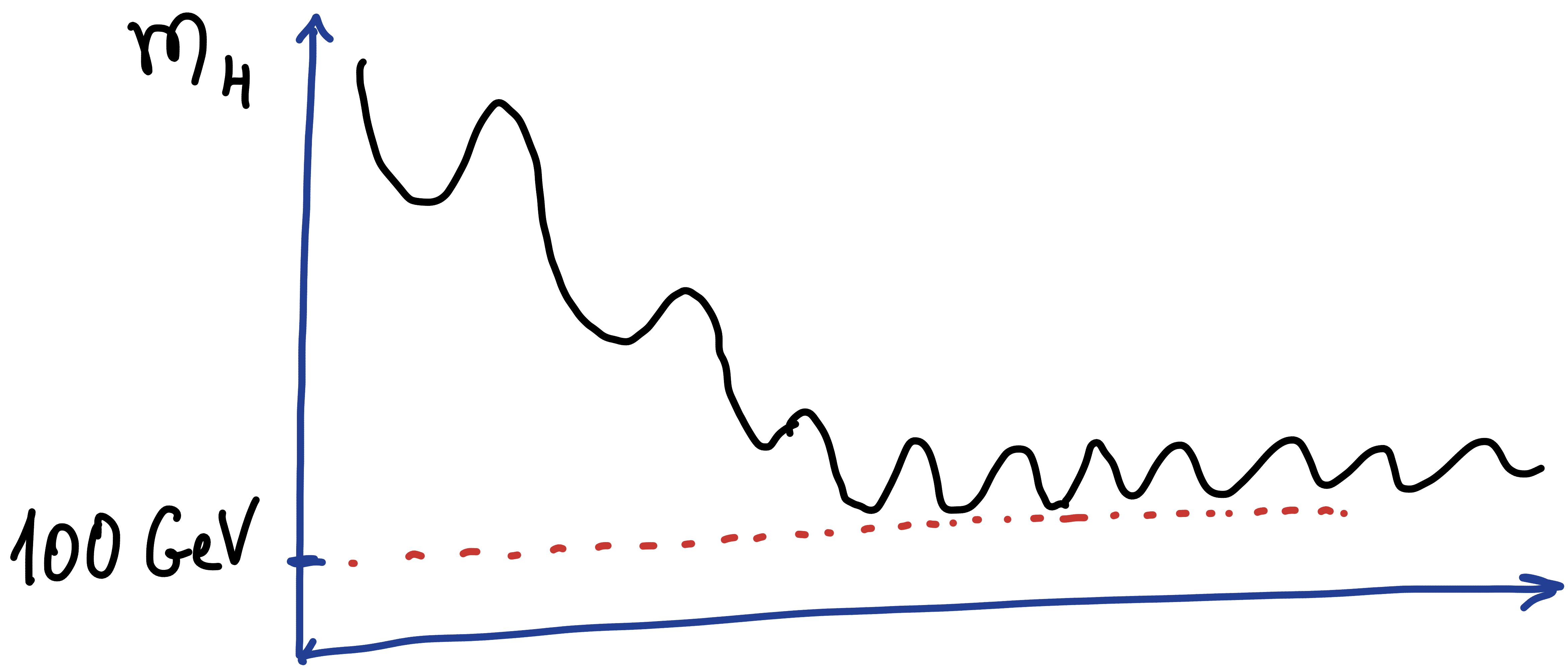
Can $m_H \sim 100\,\mathrm{GeV}$ be anthropic?

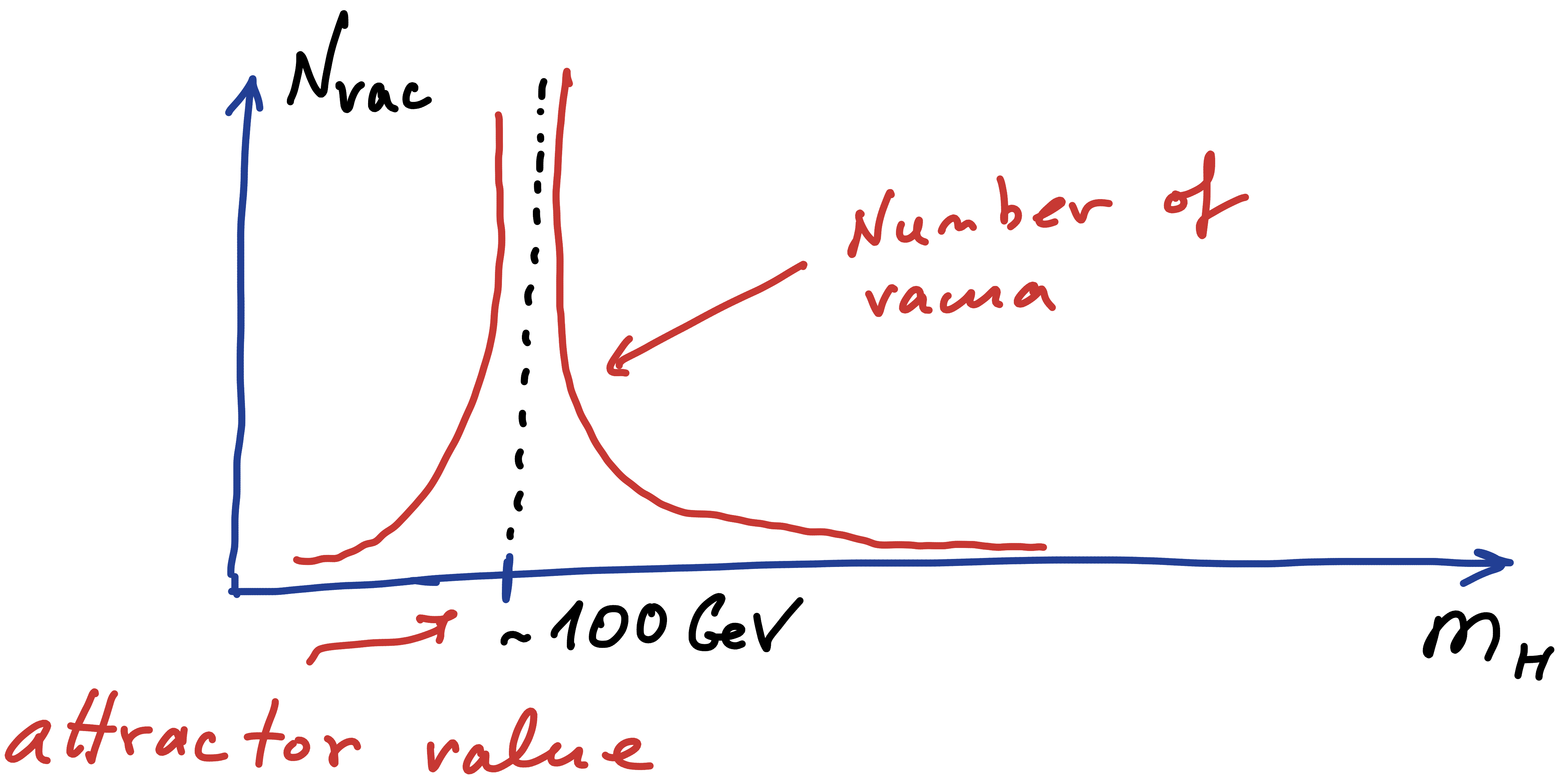
Agrawal, Barr, Donoghue, Seckel '97

Requires cosmological actualization mechanism (Eternal inflation on de Sitter 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

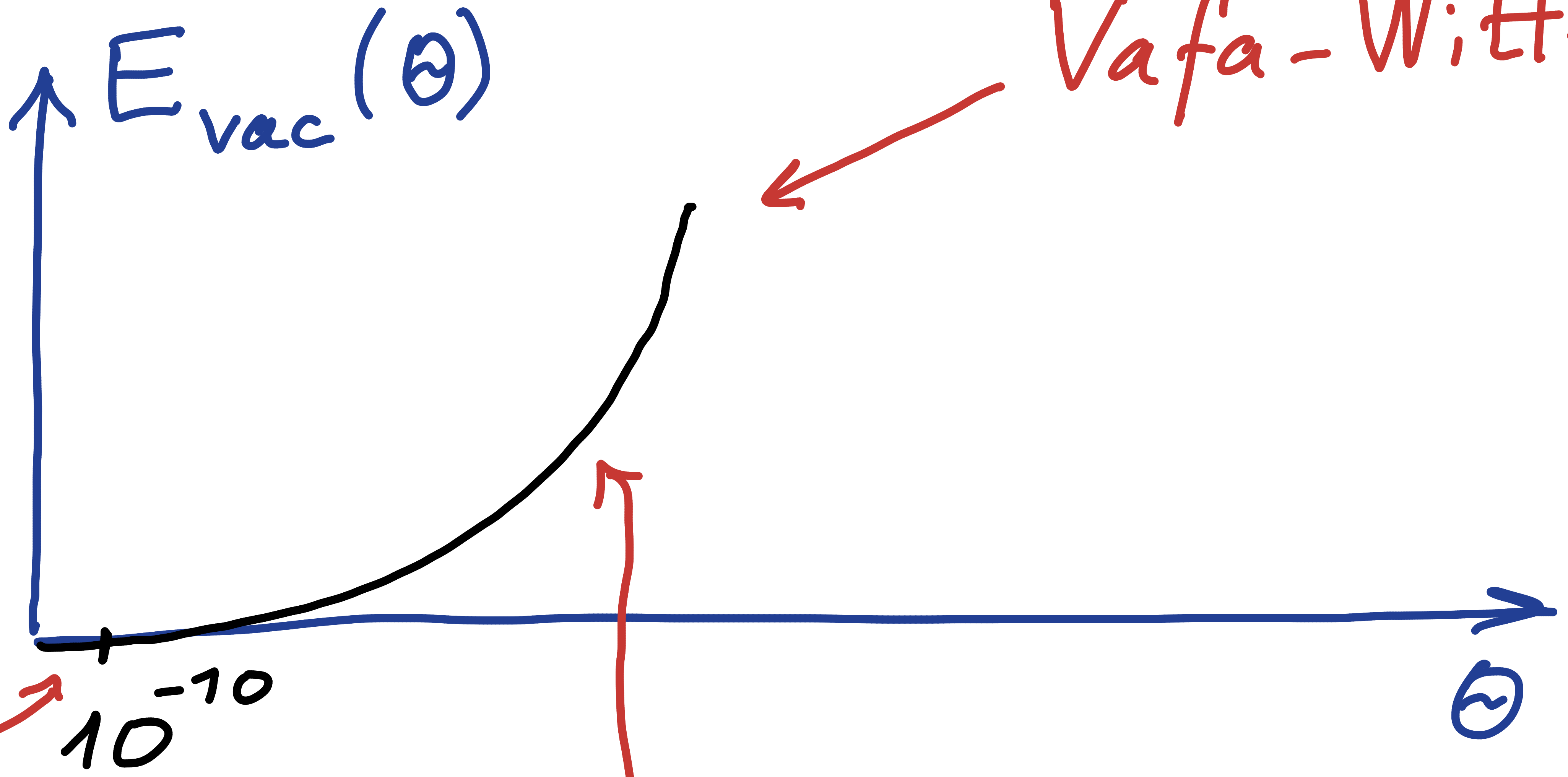
This strengthens the motivation for new physics not far from weak scale.

# Strong-CP puzzle.

$\Theta$-vacua in gauge theories:

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

Vafa-Witten




we are here

Some will be in de Sitter.

This is excluded by S-matrix!

$\Theta$-vacua must be unphysical.

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

# 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!