Outlook

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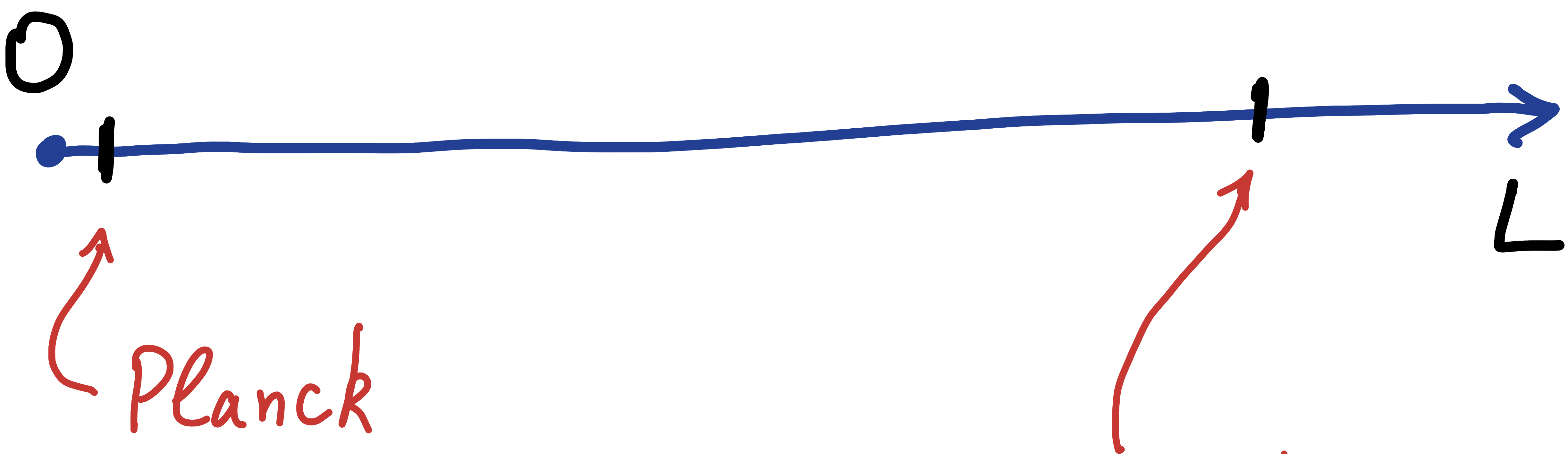
LMU-MPI

Blois 2021: 32nd Recontres de Blois on "Particle Physics and Cosmology"

Fundamental physics is about understanding nature at various length-scales



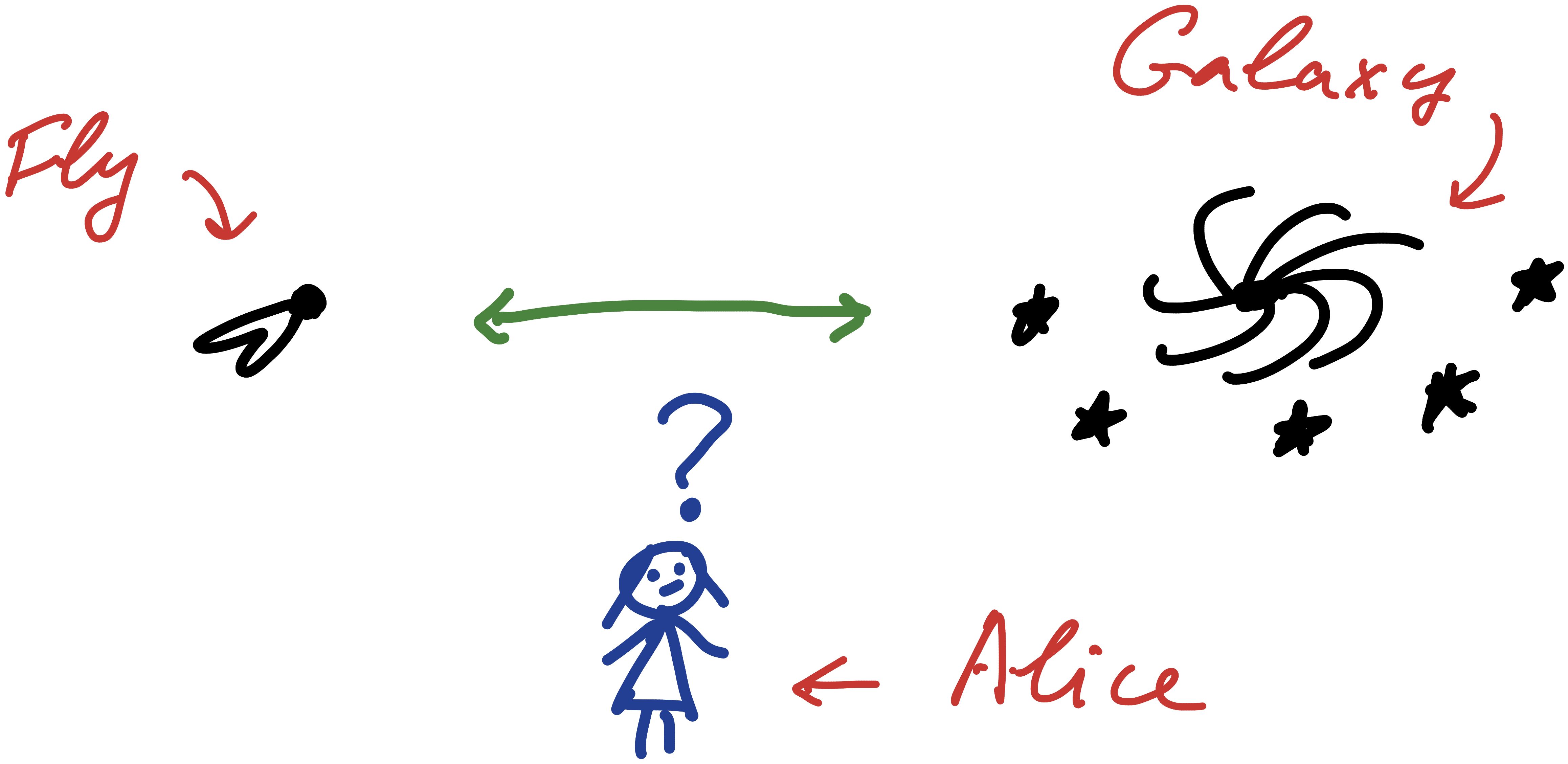
Planck length

$L_P \sim 10^{-33}\,\text{cm}$

Present Hubble radius

$L_H \sim 10^{28}\,\text{cm}$

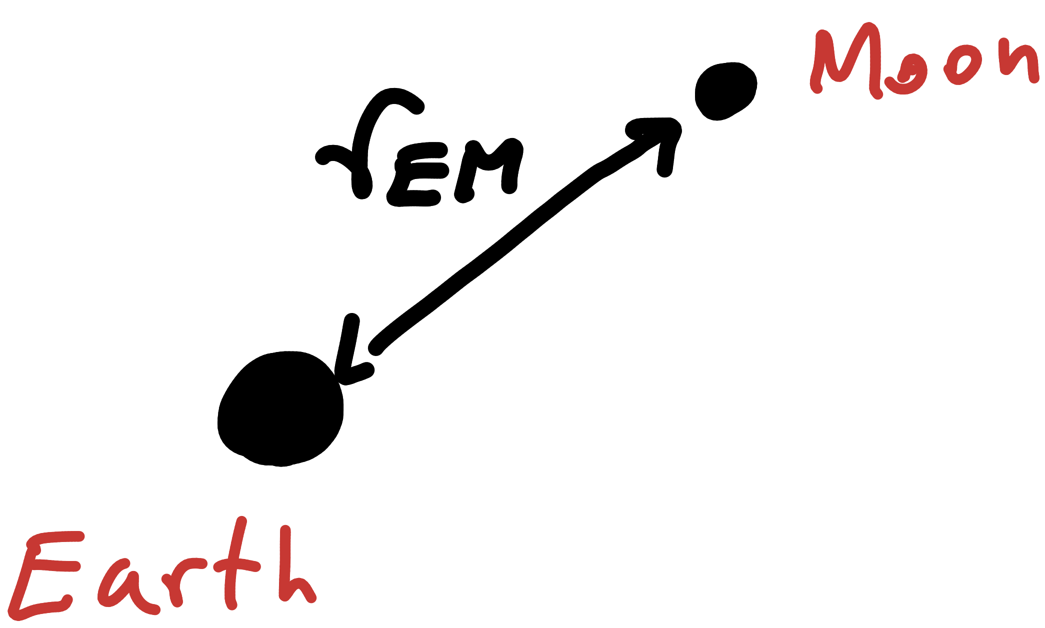
On this road we encounter many hierarchies between physical quantities

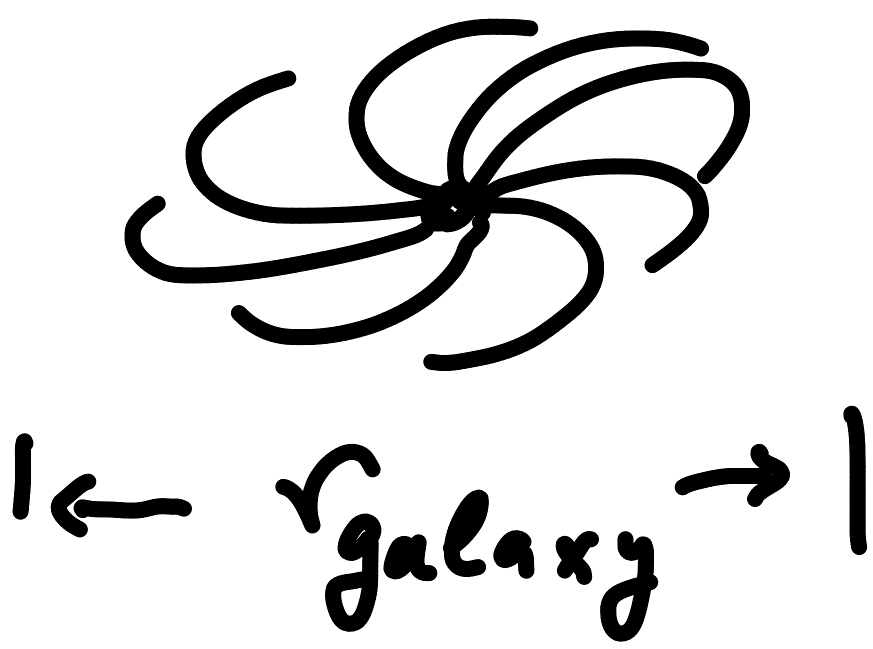


What do they tell us about fundamental physics?

Hierarchies can emerge from one and the same interaction or be a signal of different ones.

Example of hierarchies:
Gravitational orbits

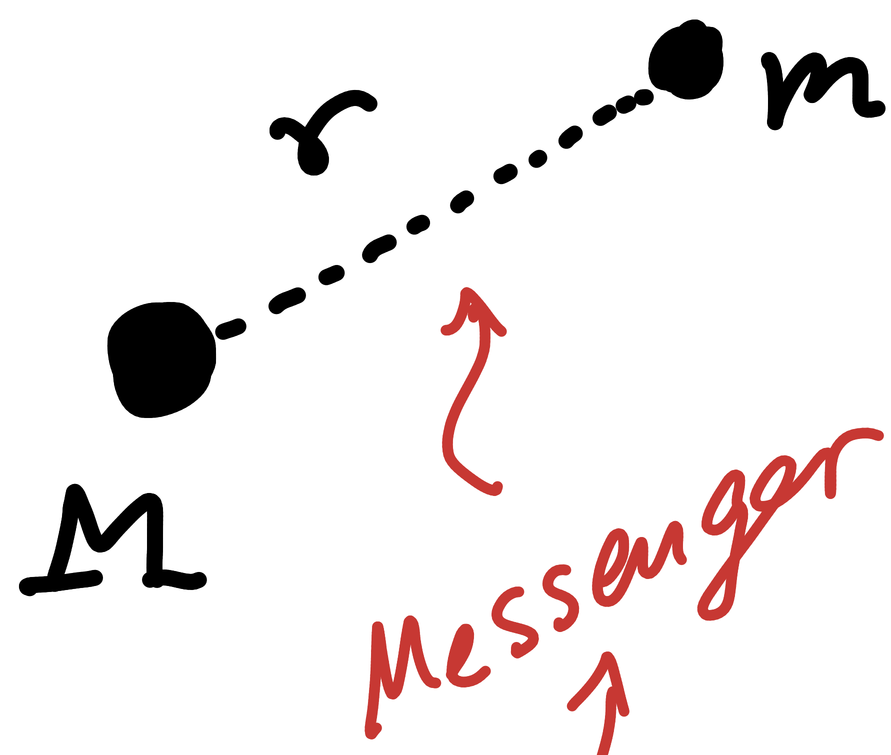




This acquires a deep meaning within a specific framework

Newton → Einstein → Field theory

$$V(r) = -\frac{Mm}{r} G_N$$



$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$ ← graviton

The hierarchy means that gravity is a long-range force: Graviton is light

(In Einstein it is <u>massless</u>!)

But, if we take this ($i.e.$, $m_{\text{graviton}} = 0$) as a starting point, hierarchies become trivial:

Nothing fundamental about them.

<u>Lesson</u>: What we learn from the hierarchies of orbits, depends on the starting point of our framework.

Encounter with "naturalness":

Graviton an photon do not experience quantum corrections to their masses due to

Gauge redundancy

Discontinuity in number of degrees of freedom

$$m_g = 0 \qquad\qquad m_g \neq 0$$

$$2 \qquad\qquad 5 = 2 + 3$$

Einstein

Pauli-Fierz

van Dam, Veltman, Zakharov

So, one can say that

$$m_{graviton} = 0, \quad m_{photon} = 0$$

is natural.

What about other spins?

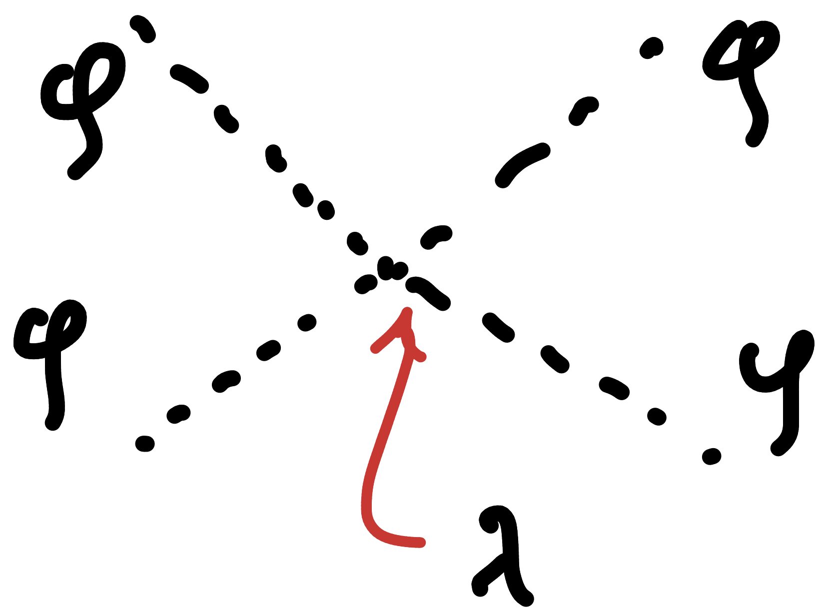
Fermions are "protected" by chiral symmetry

$$\psi_L \to e^{i\alpha} \psi_L \qquad \psi_R \to e^{-i\alpha} \psi_R$$

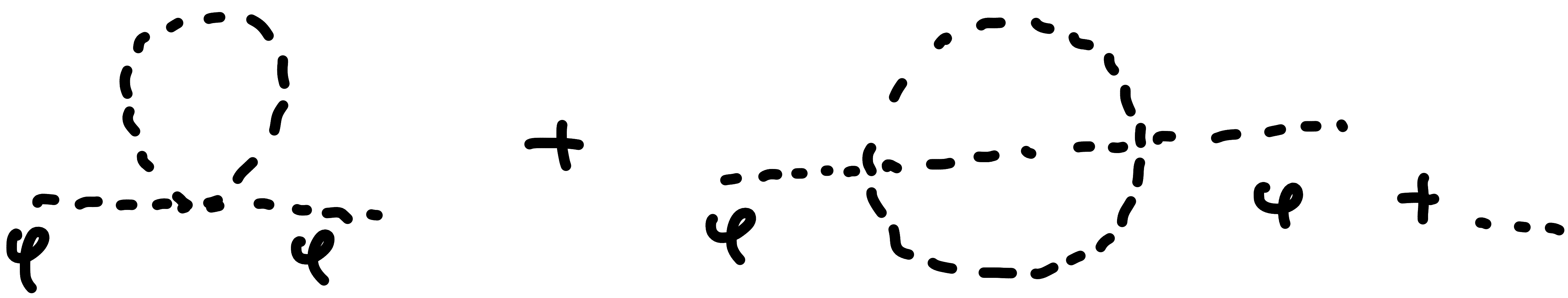
$$\cancel{M_\psi \bar{\psi}_L \psi_R} + h.c.$$

Scalars (in general) are not

$\lambda\varphi^4$



Quantum corrections:



$\sim\lambda$ $\sim\lambda^2$

$$\delta m_\varphi^2 \approx M_*^2\left\{\lambda+\lambda^2+\dots\right\}$$

cutoff.

Is <u>real</u> because of gravity.

Elementary particle of mass $= m$

Compton wavelength (Quantum):

$$L_c = \frac{\hbar}{m}$$

Gravity brings two other length-scales:

* Gravitational radius (classical):

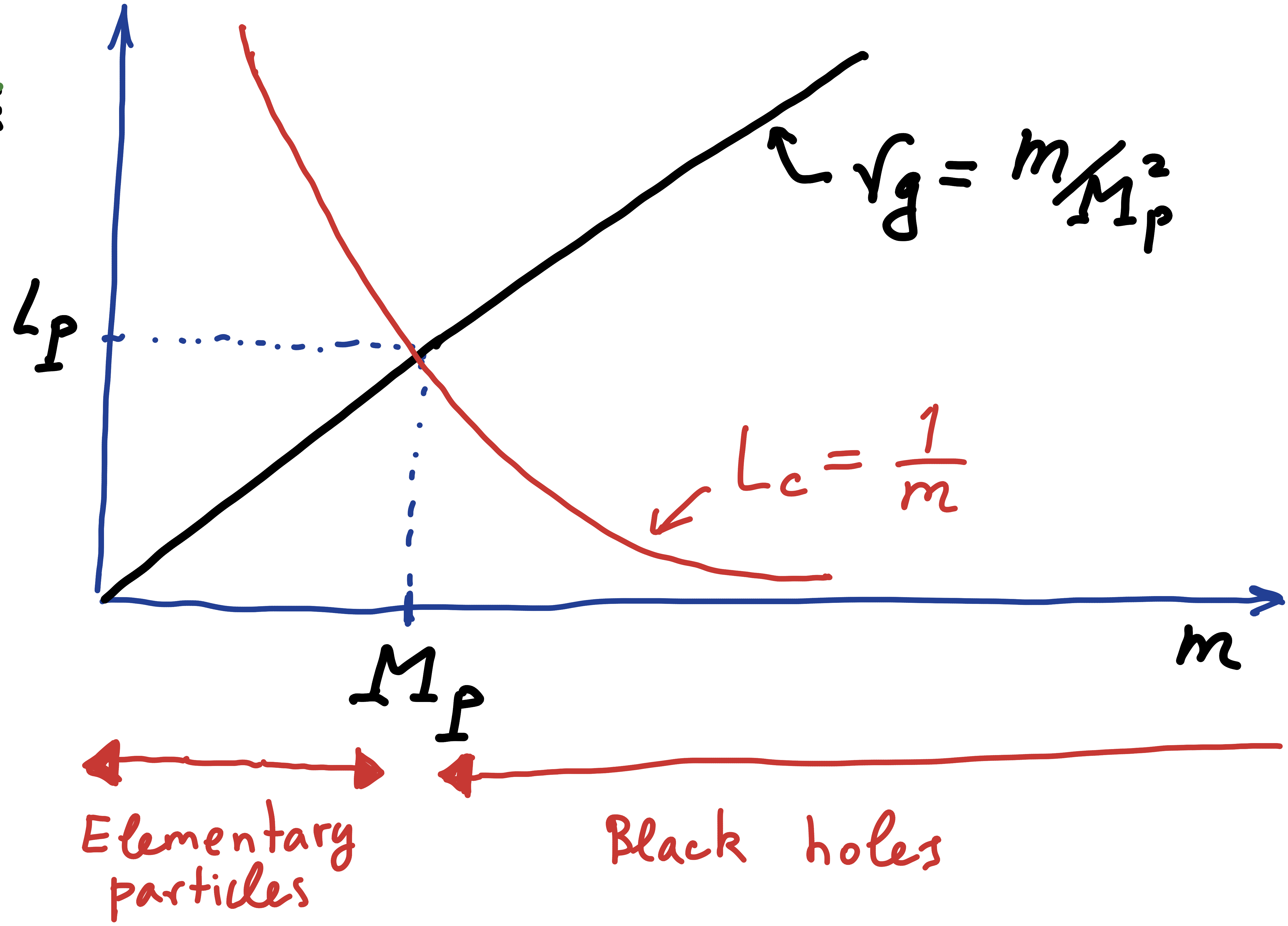
$$R_g = G_N m$$

* Planck length (Quantum):

$$L_p = \sqrt{\hbar G_N} \sim 10^{-33}\,cm$$

Planck mass

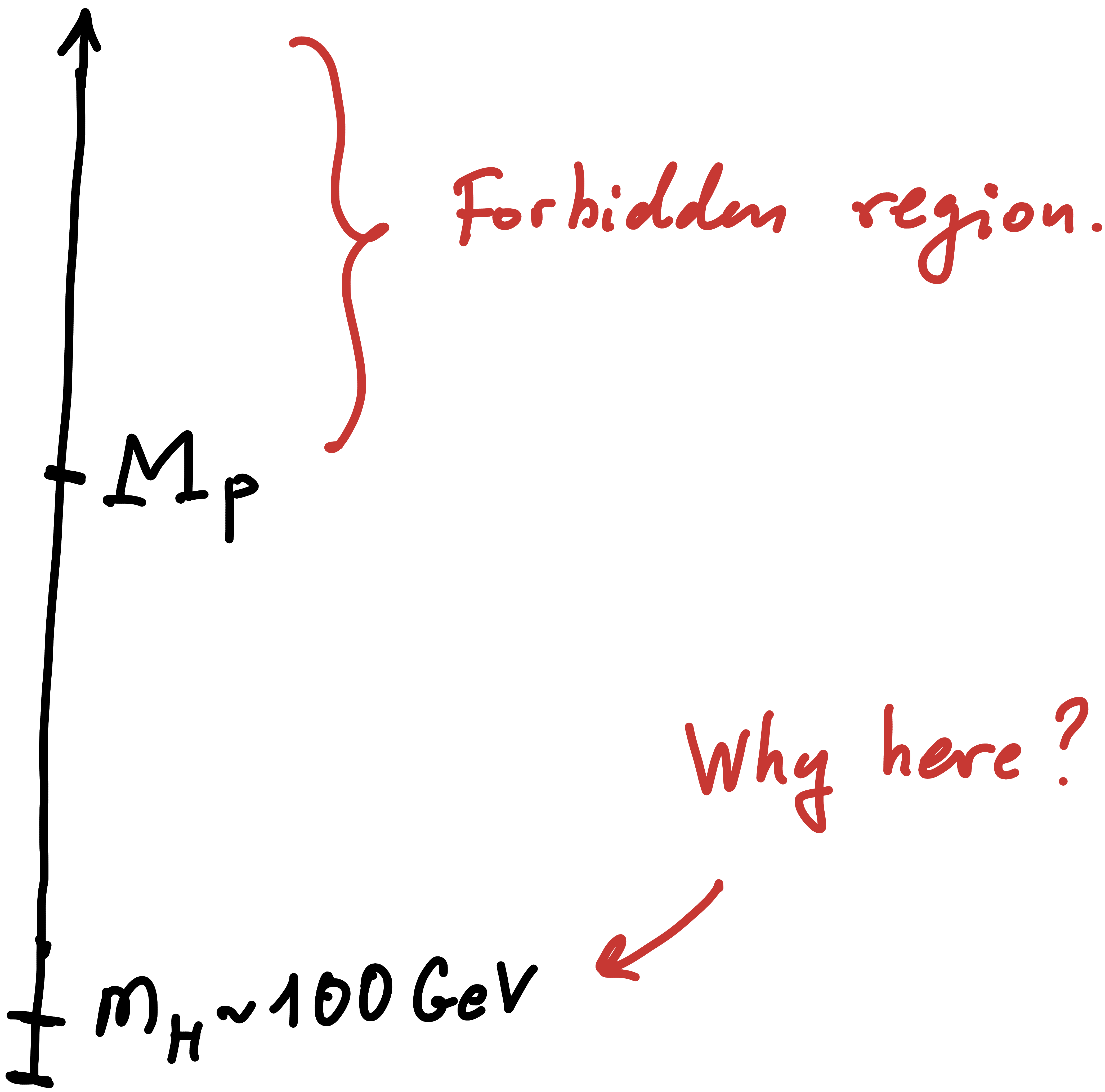
$$M_p = \frac{\hbar}{L_p} \sim 10^{19}\,GeV \sim 10^{-5}\,g$$



No elementary particles of mass

$$m > M_p$$

Thus, a scalar (e.g. Higgs) cannot have a solar mass



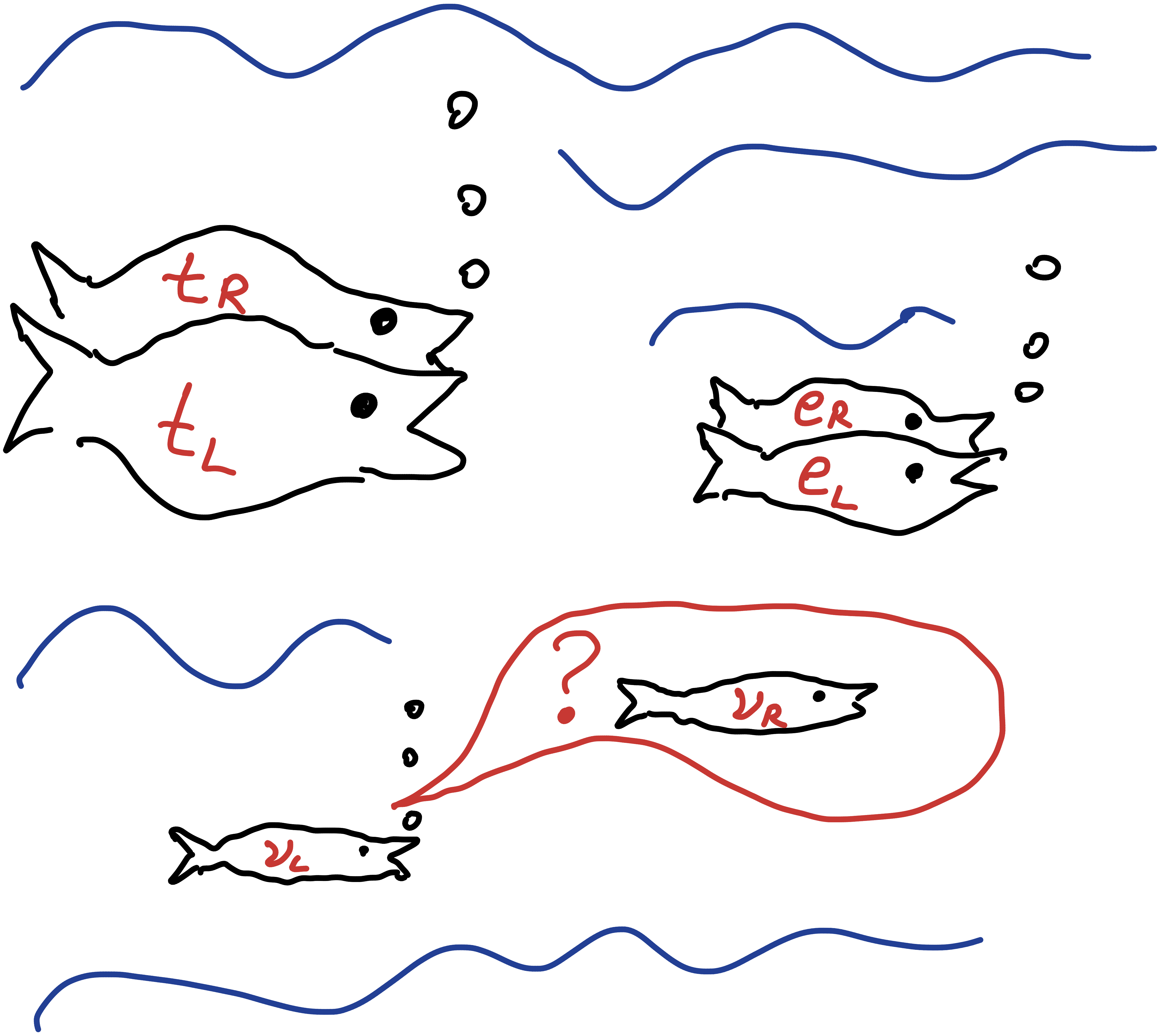
The Hierarchy Probem for Higgs:

We live in a sea of the Higgs condensate

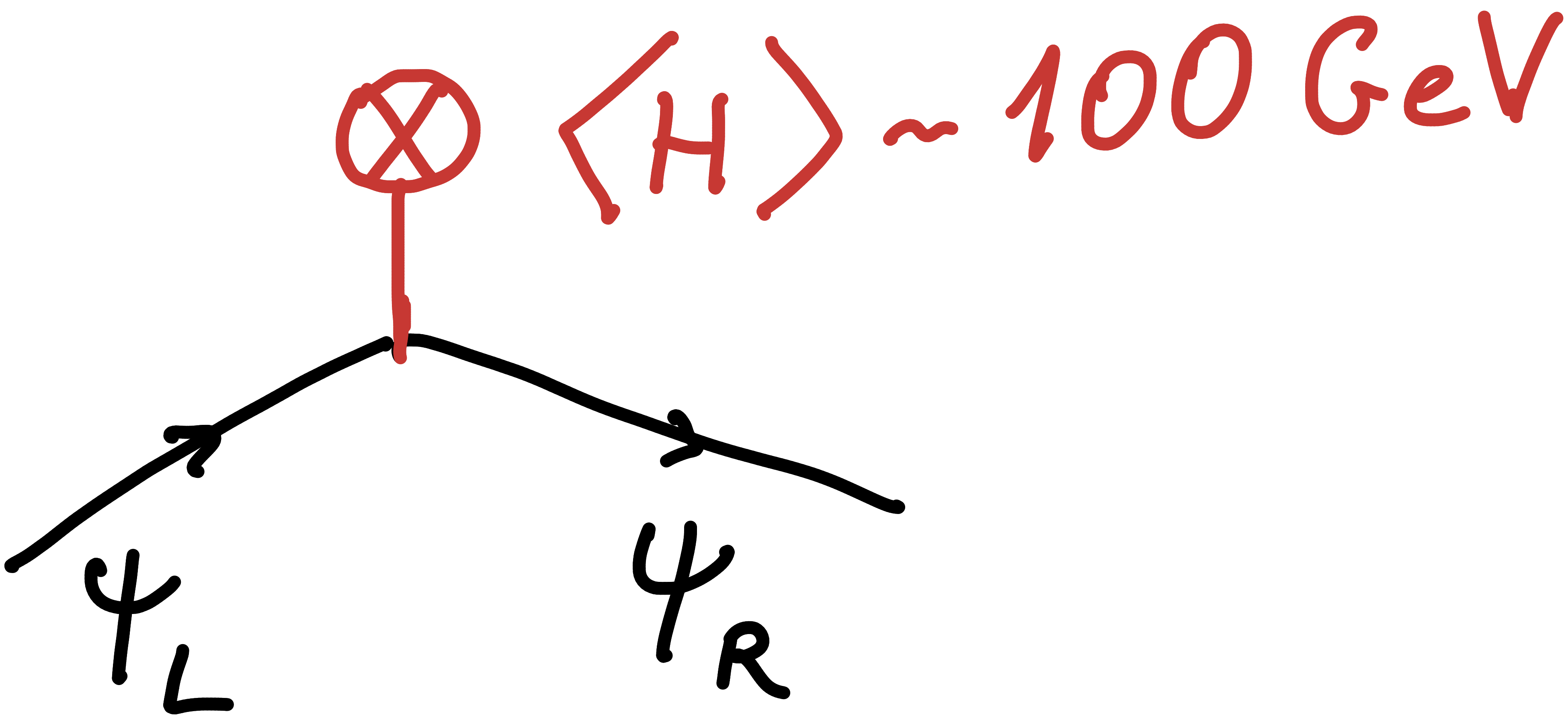
$$\langle H \rangle \neq 0$$

$$SU(2)_W \otimes U(1)_Y \longrightarrow U(1)_{EM}$$

Gives masses to W, Z-bosons and charged fermions (quarks, e, μ, τ)



t_R
t_L
e_R
e_L
?
ν_R
ν_L



$\langle H \rangle \sim 100$ GeV
ψ_L
ψ_R

Higgs condensate propagates waves, Higgs particles, with mass

$$m_H \sim 100\,\mathrm{GeV}$$

Why $\dfrac{m_H^2}{M_p^2} \sim 10^{-34}$?

or

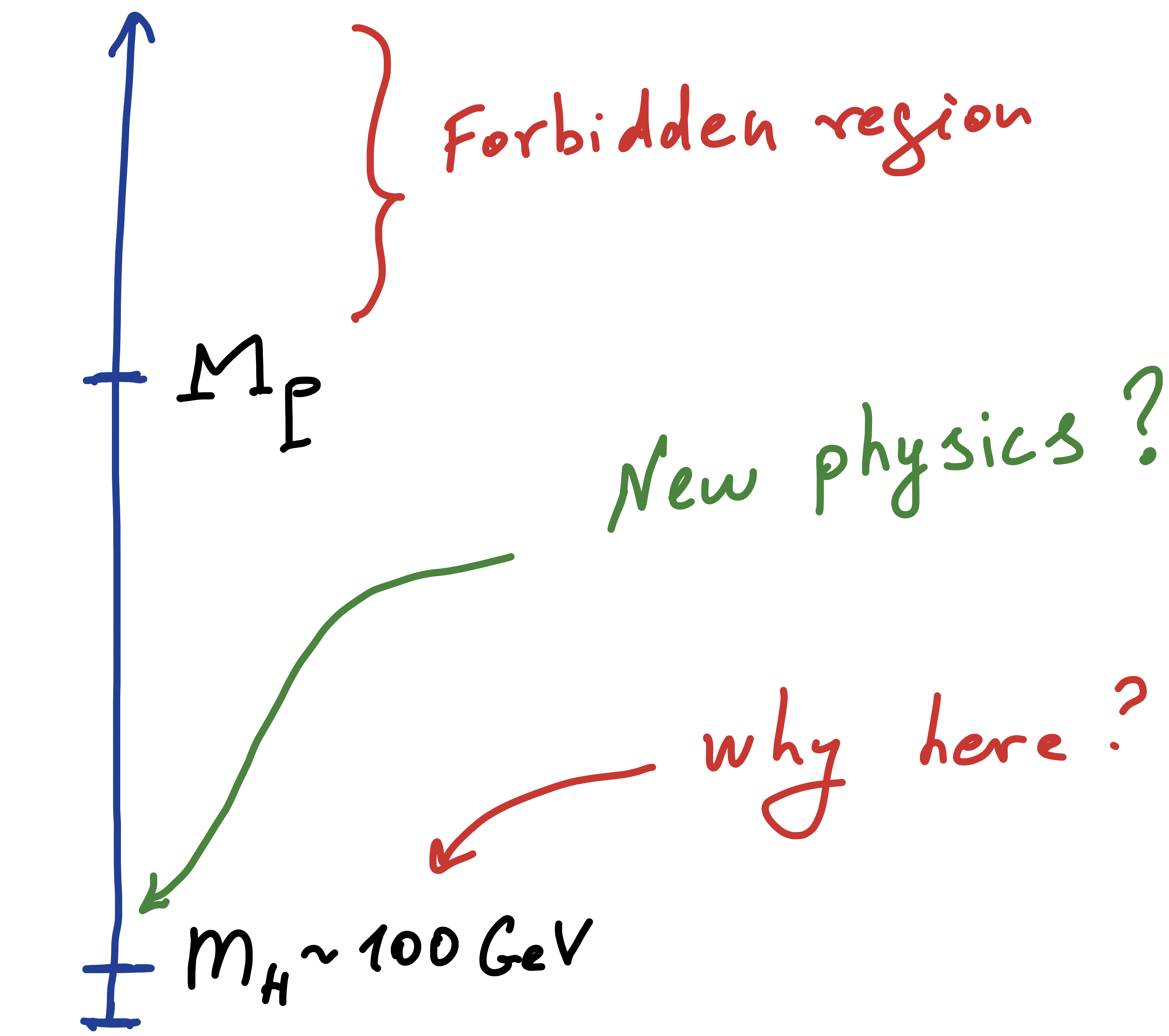
Why $\dfrac{G_N}{G_F} \sim 10^{-34}$?

No elementary particles of mass

$$m > M_P$$

(would be a black hole!)

Higgs cannot have a solar mass



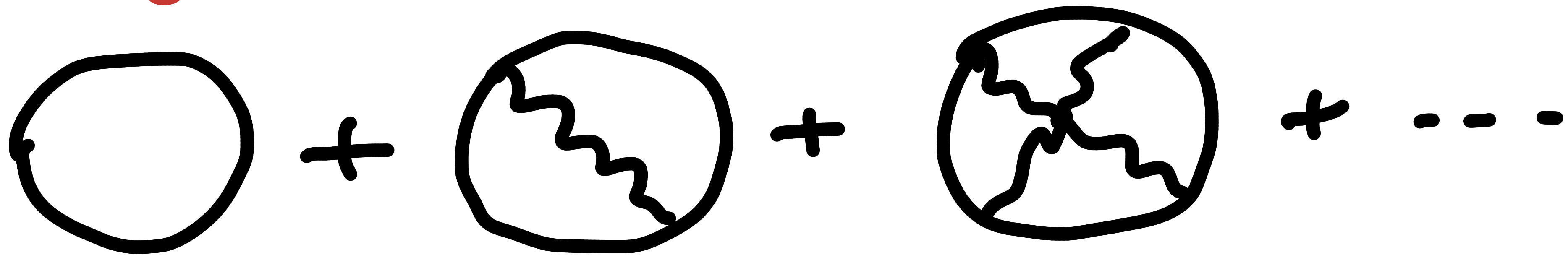
The most celebrated Hierarchy problem (and its absence thereof)

The cosmological constant puzzle.

$$S_E = \int \sqrt{-g}\,\{M_P^2 R + \Lambda\}$$

vacuum energy

highly cutoff-sensitive



$$\hookrightarrow \sim M_*^4 \sim M_p^4$$

Naturally-expected value:

$$\Lambda_{\text{Expected}} \sim M_P^4 \sim \left(10^{19}\,\text{GeV}\right)^4$$

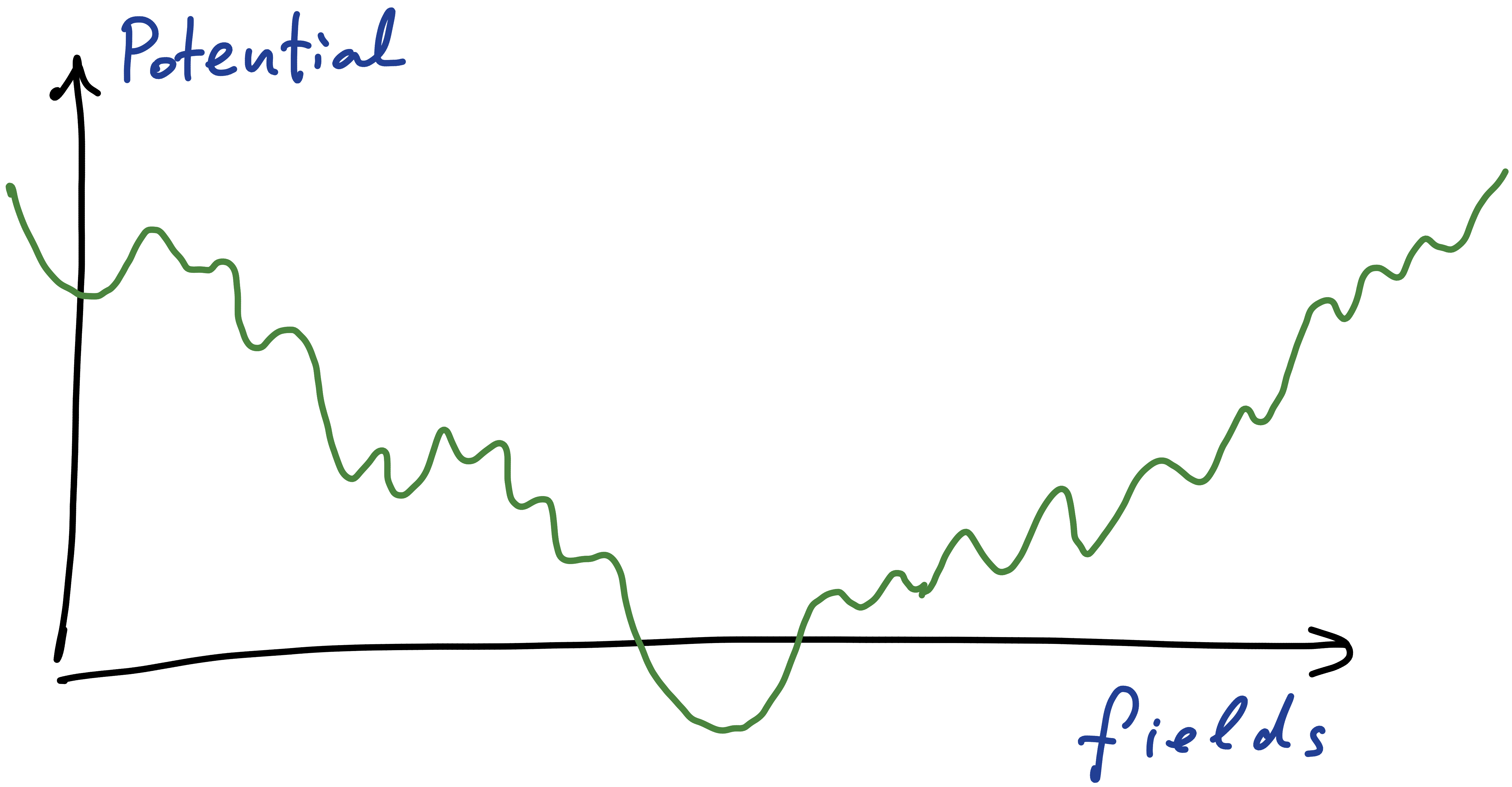
Observational bound:

$$\Lambda_{\text{Real}} \lesssim \left(10^{-3}\,\text{eV}\right)^4$$

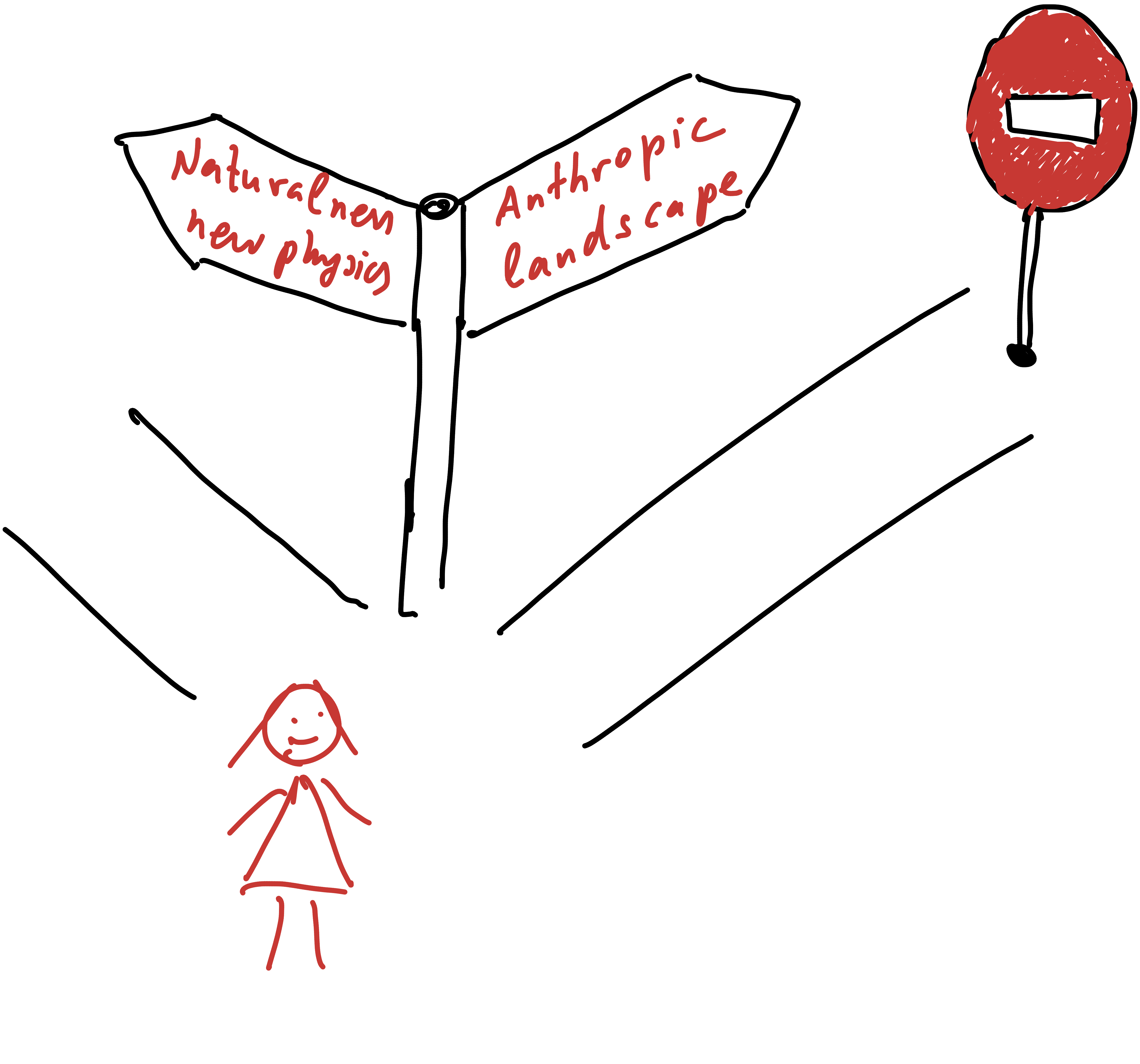
Naturalness problem:

$$\frac{\Lambda_{\text{Expected}}}{\Lambda_{\text{Real}}} \gtrsim 10^{120}\,!$$

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



Naturalness can be replaced
by Anthropic selection

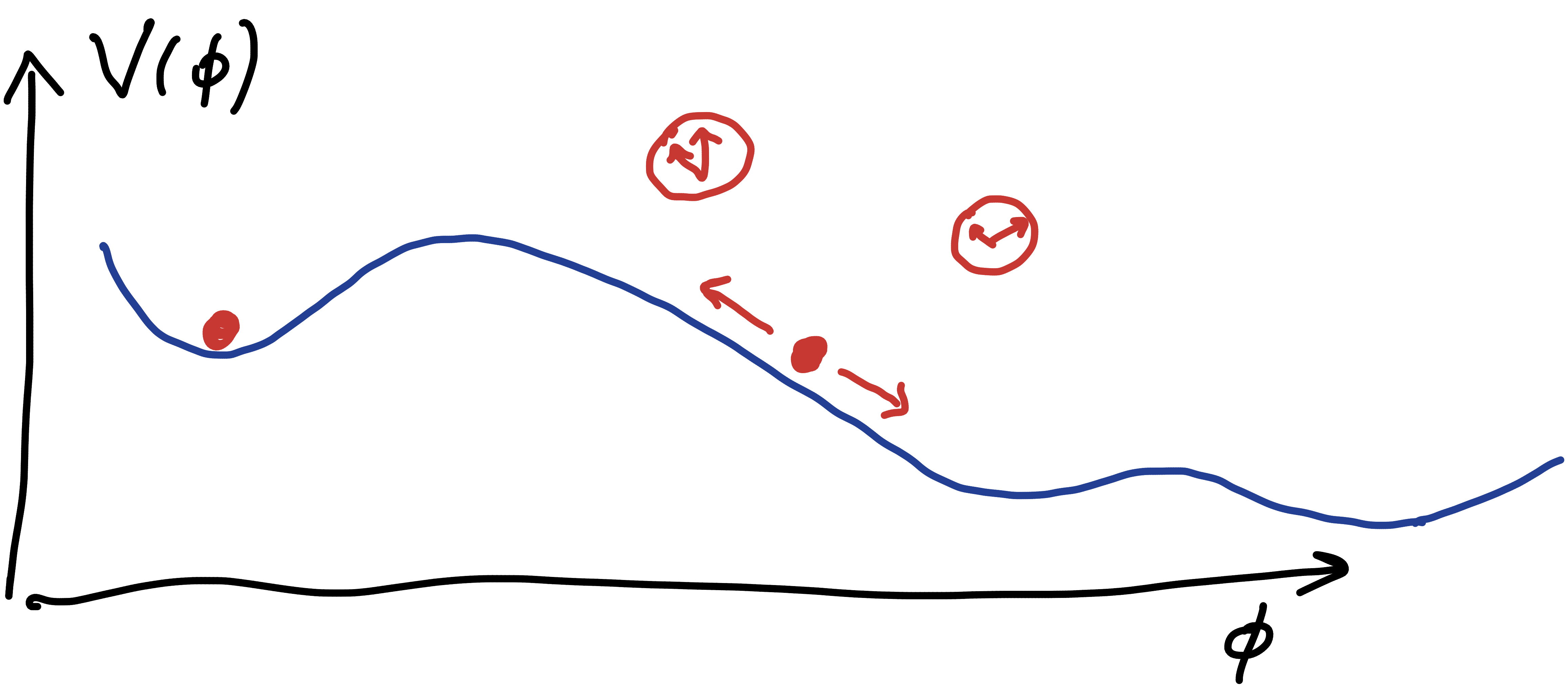

Naturalness
new physics
Anthropic
landscape

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.

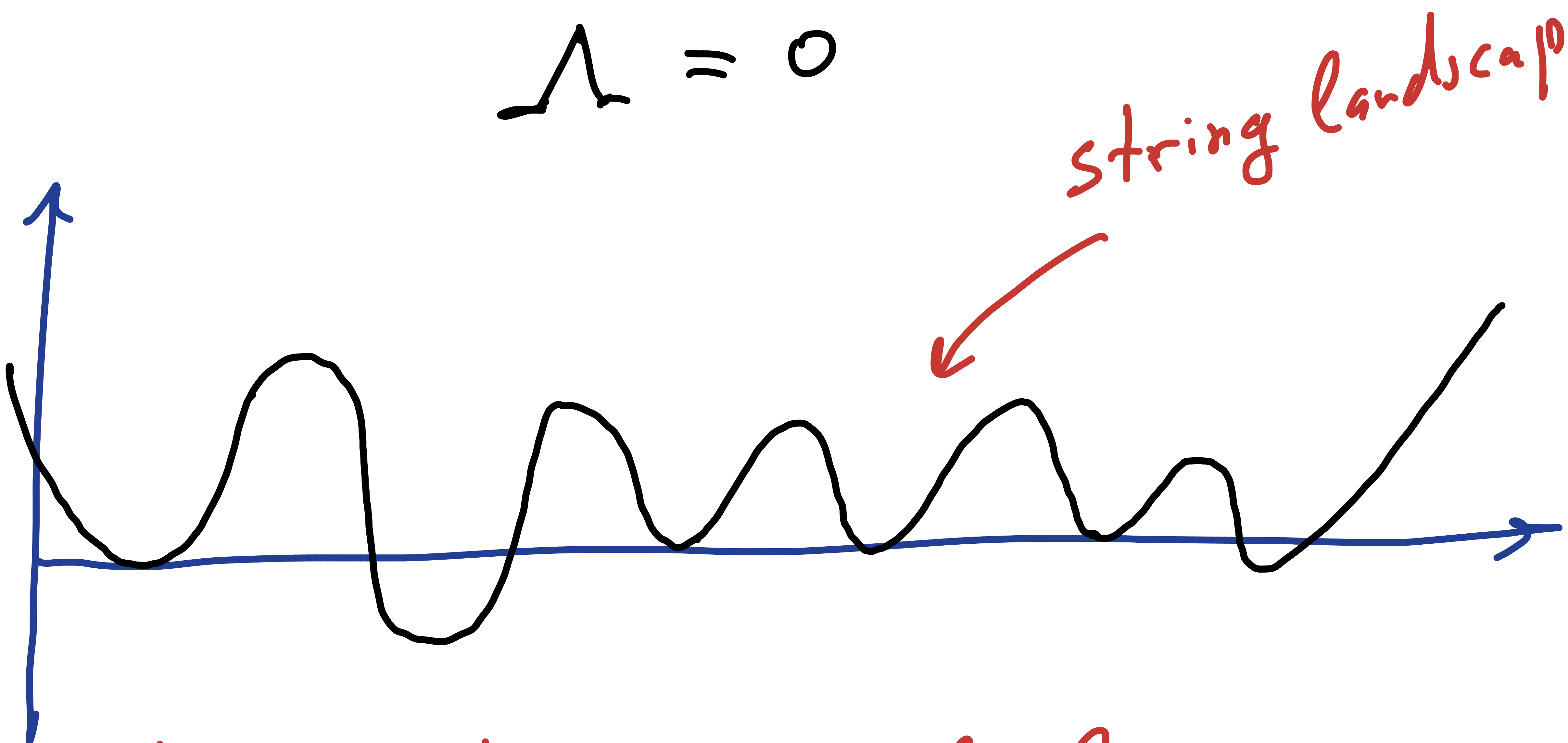
de Sitter landscape can provide an <u>actualization</u> <u>mechanism</u> via <u>eternal</u> <u>inflation</u> Vilenkin '83; Linde '86; ...



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

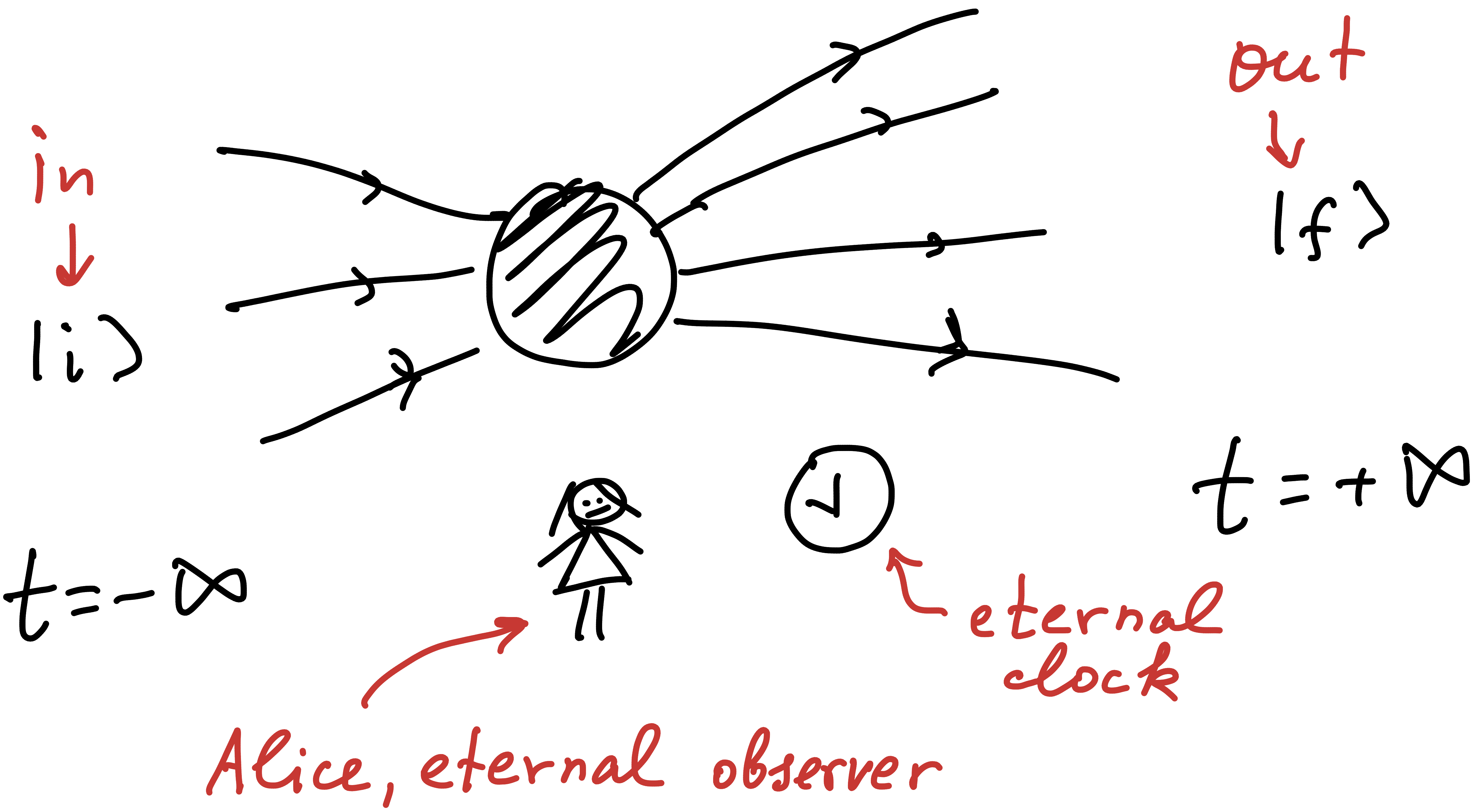
G.D., Gomez '13, '14

No de Sitter future eternity;
No eternal inflation.

S-matrix is fundamental in this.

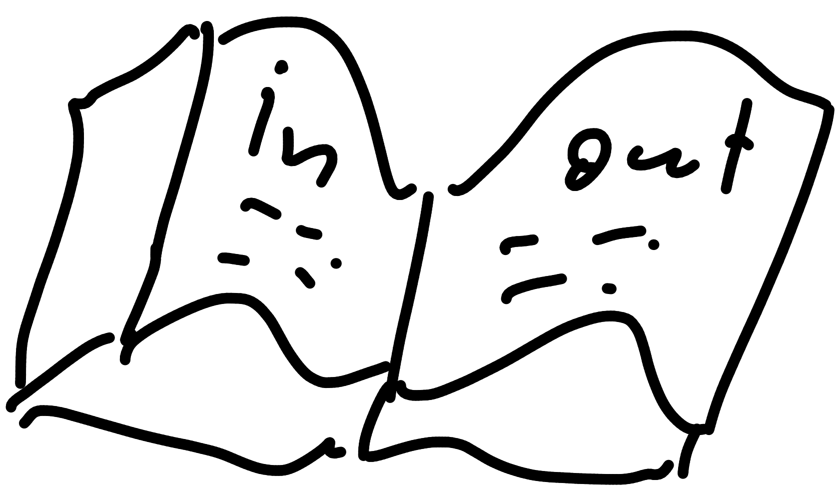
In order to explain,
we follow G.D. 2012.02133[hep-th]
Symmetry 13 (2020) 1, 3

We kept forgetting about S-matrix formulation of quantum gravity



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

Directory



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

Necessary conditions:

(*) Globally-defined time;

Absent in classical de Sitter

(*) S-matrix vacuum.

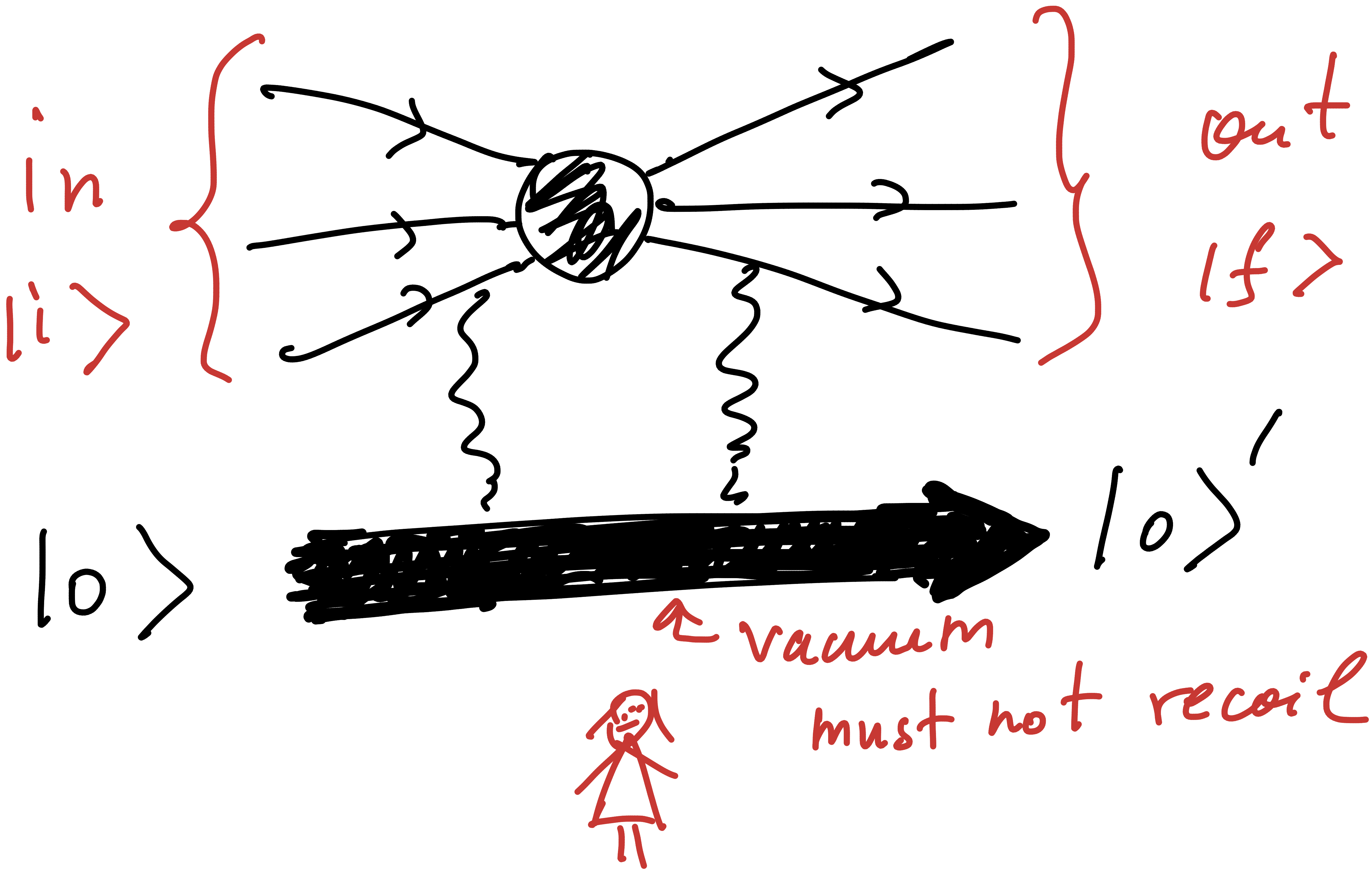
If the observed acceleration of the Universe's expansion were due to Λ, we would be entering into de Sitter state $|dS\rangle$.

Hubble horizon $\rightarrow$ $R = \frac{1}{\sqrt{G_N \Lambda}}$

No global time.

S-matrix requires:

- ⊛ Globaly-defined time;
- ⊛ Vacuum $|0\rangle$ with no recoil.



What about the vacuum?

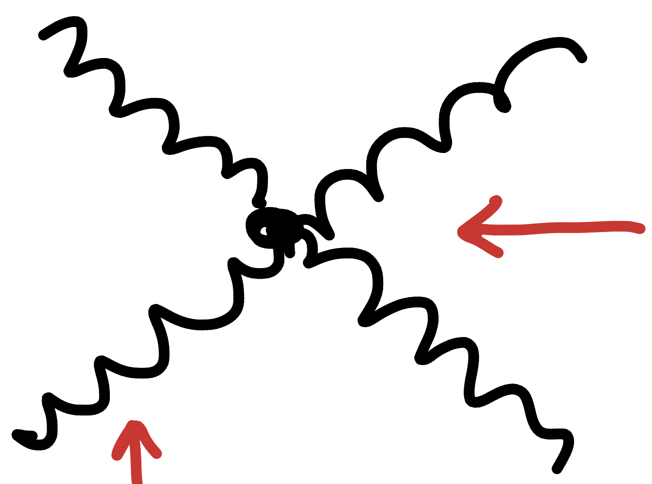
A double-scaling argument (G.D., '20):

$|dS\rangle \longrightarrow |\text{vacuum}\rangle$ only if:

$$G_N \to 0, \quad \Lambda \to \infty,$$

$$R = \frac{1}{\sqrt{G_N \Lambda}} = \text{finite}$$

But then, gravitons cannot scatter:

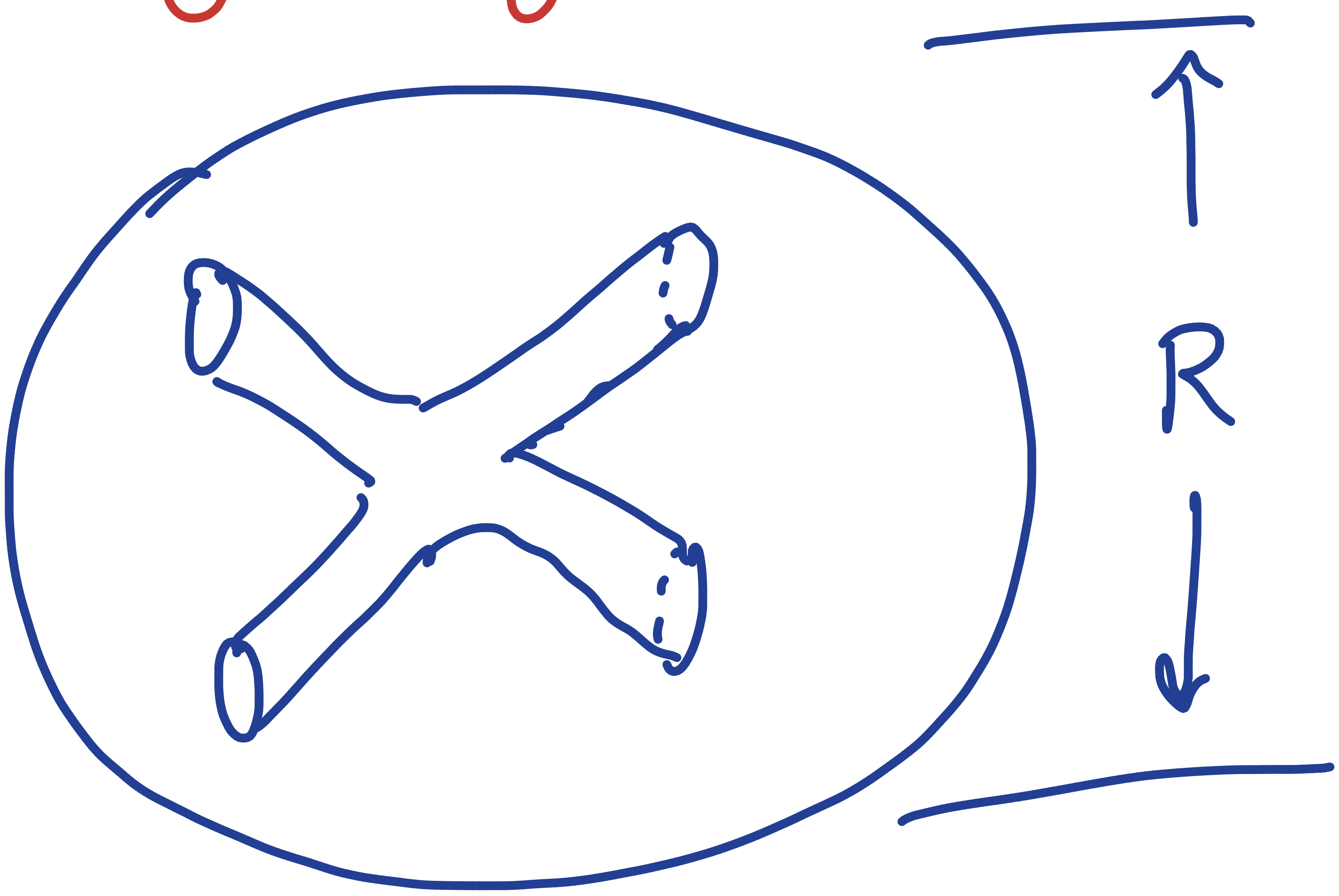


gravitons

$$\alpha_{\text{gravity}} = \underbrace{P^2}_{\text{momentum transfer}} G_N = 0$$

For $|\text{de Sitter}\rangle = |\text{vacuum}\rangle$,
quantum gravity trivializes!

In string theory



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

in rigid Limit:

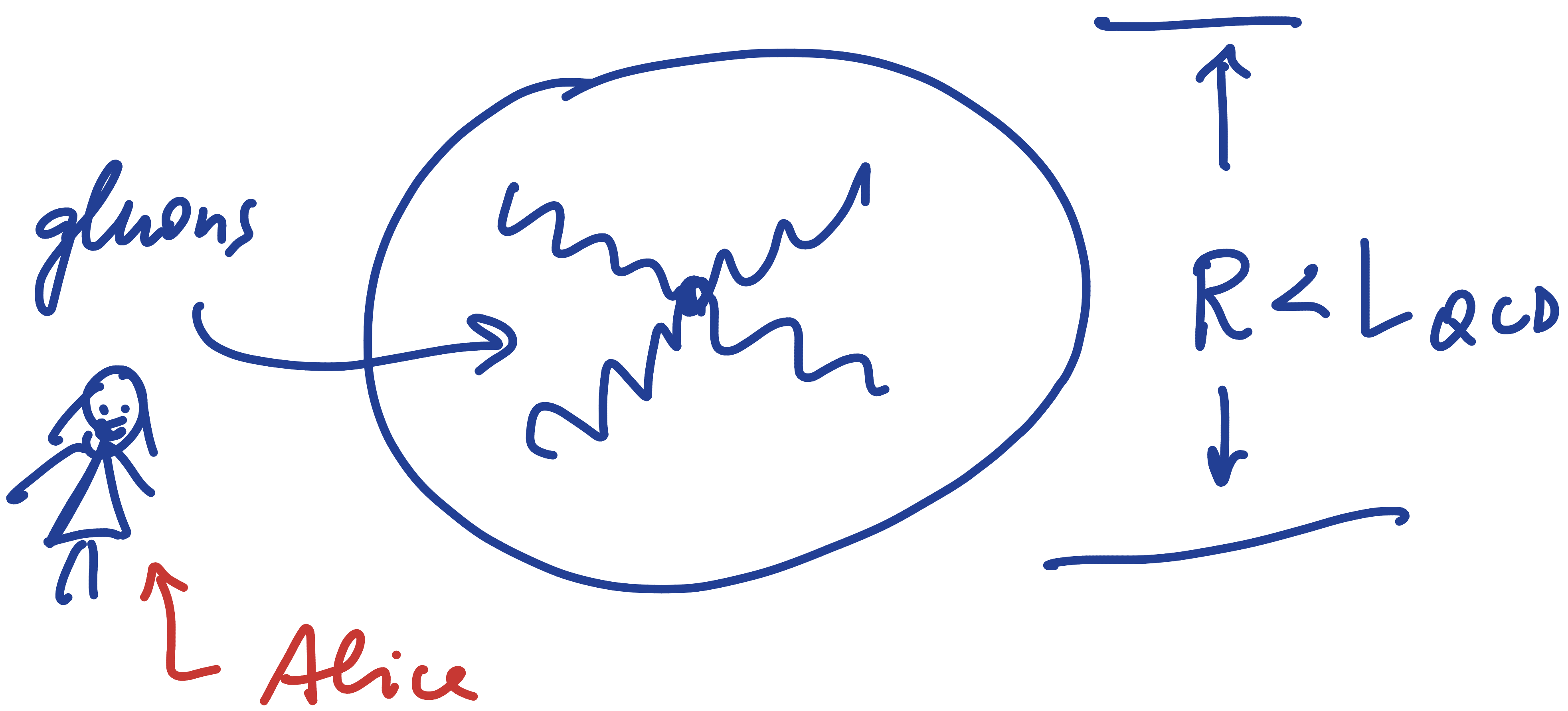
$$\left.\begin{array}{l} \Lambda \to \infty \\ G \to 0 \\ R = \text{finite} \end{array}\right\} \rightarrow \quad g_s^2 \to 0$$

Closed string S-matrix is trivial.

(Open strings, more subtle)

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

E.g. QCD



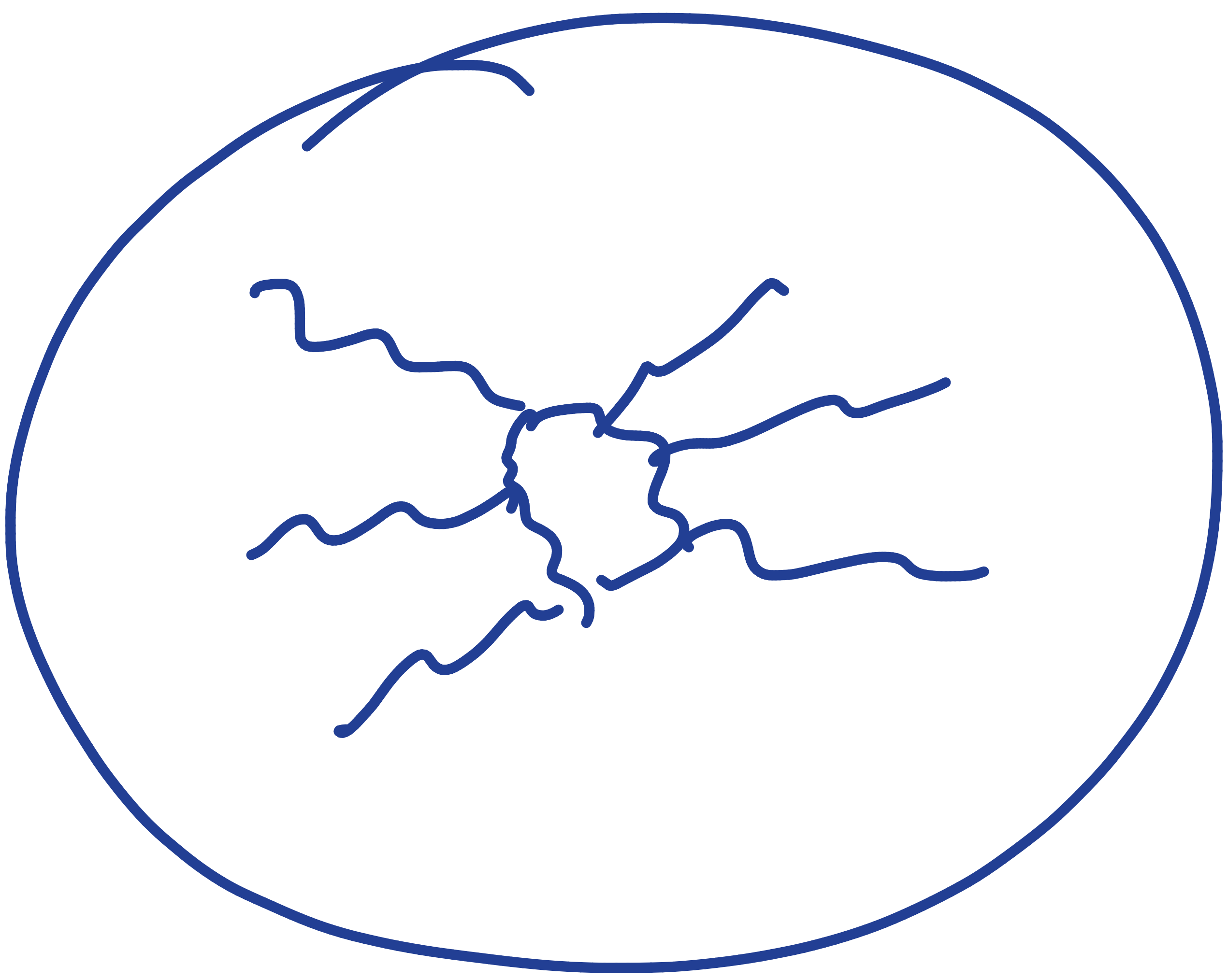
Thus, the issue is quantum gravitational.

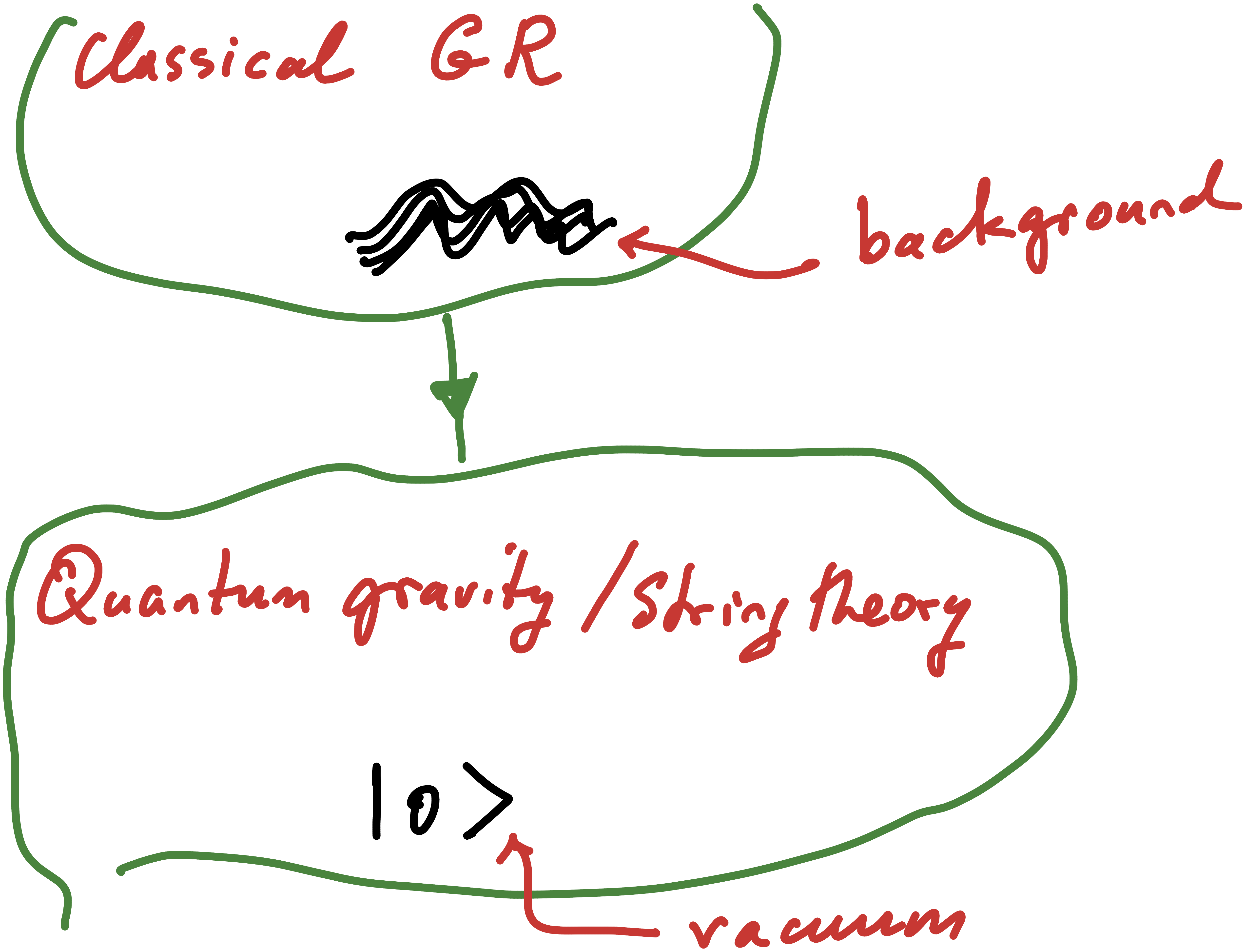
$$(\text{de Sitter} = \text{vacuum}) \rightarrow \begin{array}{l} \alpha_{gr} = 0 \\ g_s = 0 \end{array}$$

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

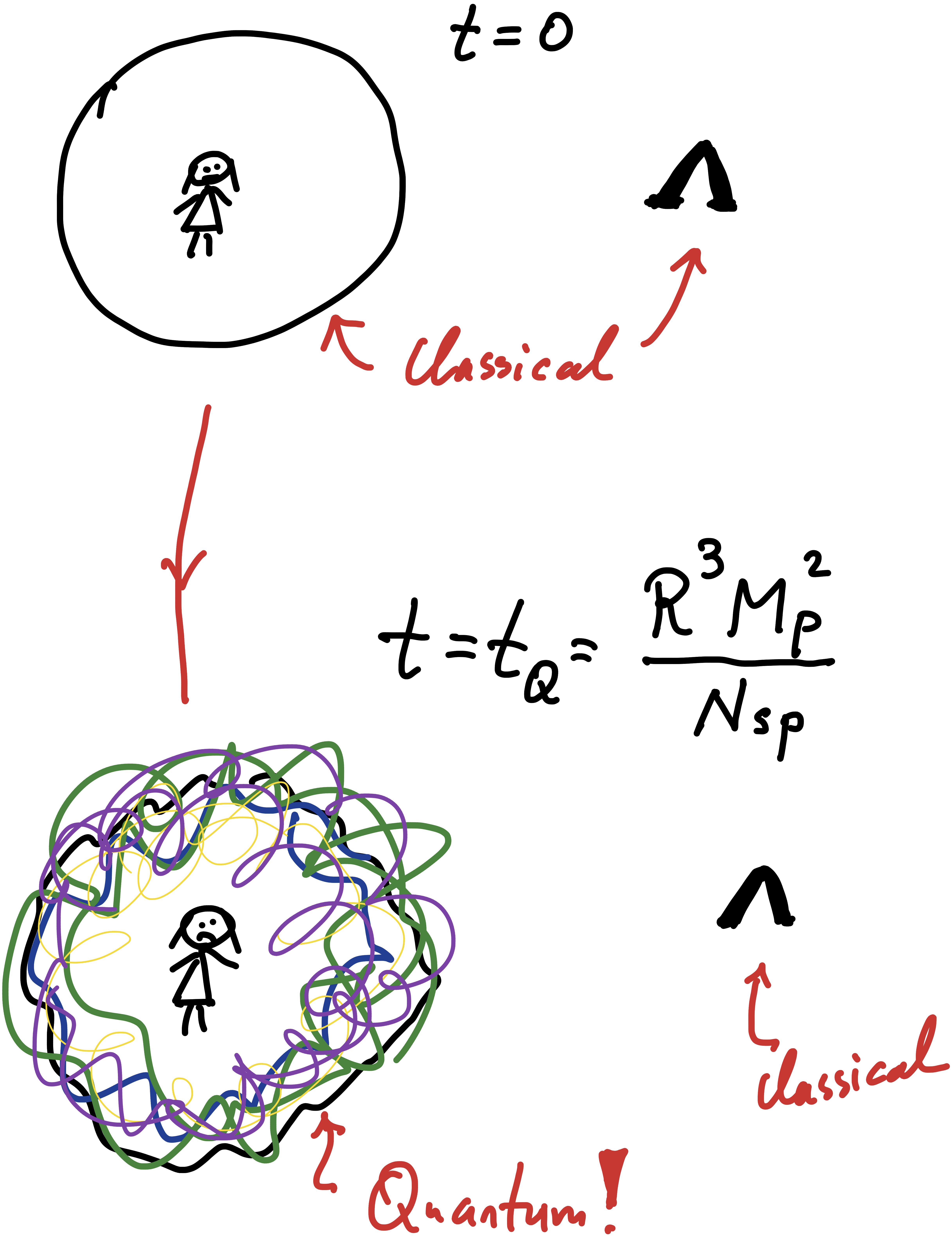
For example, scattering of quanta of center of mass energy

$$E \sim M_p^2 R$$



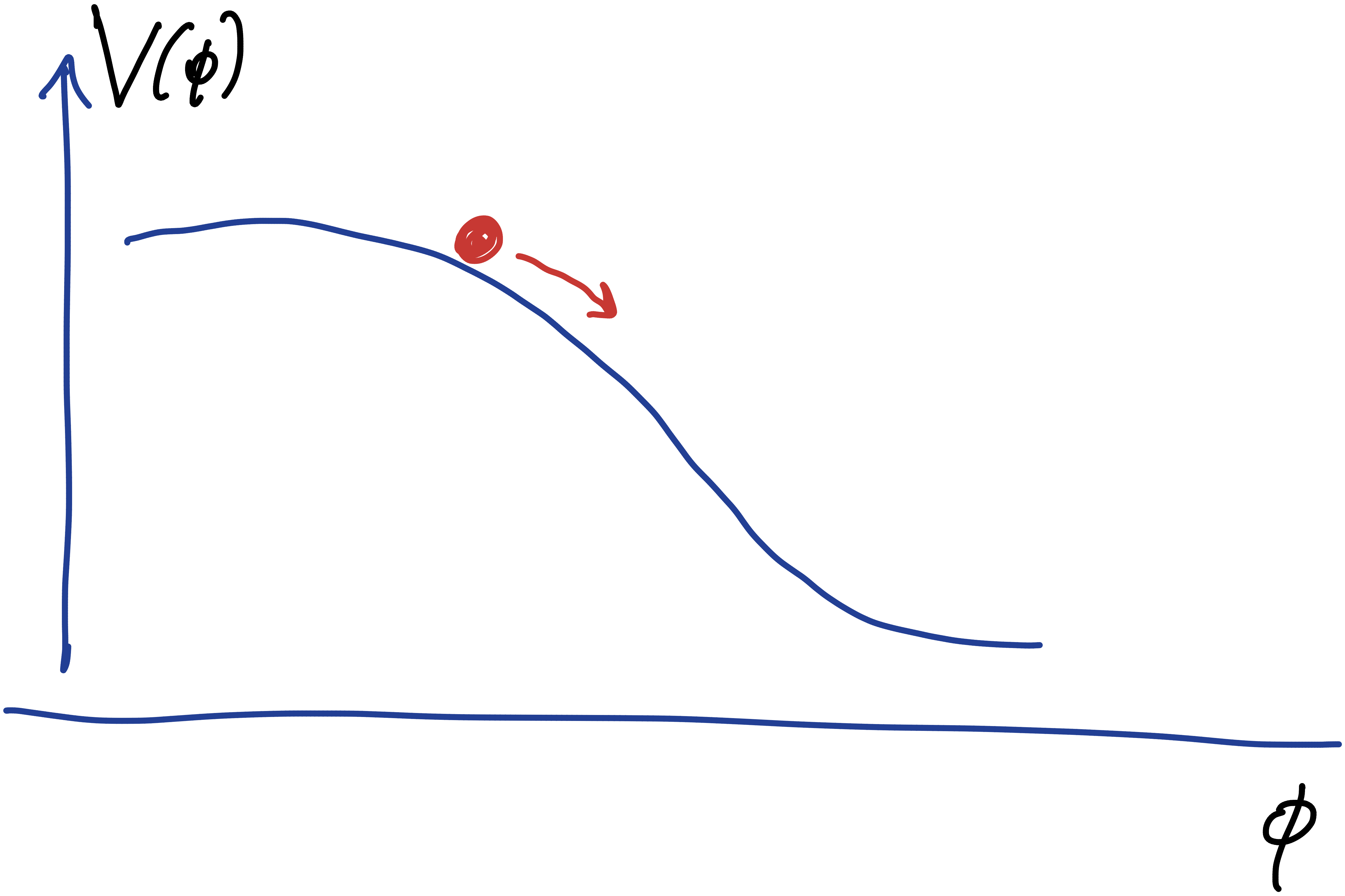


Not every background of classical GR is promoted into a vacuum of QG!


$t=0$
Λ
Classical
$t = t_Q = \frac{R^3 M_p^2}{N_{sp}}$
Λ
classical
Quantum!

Universal bound

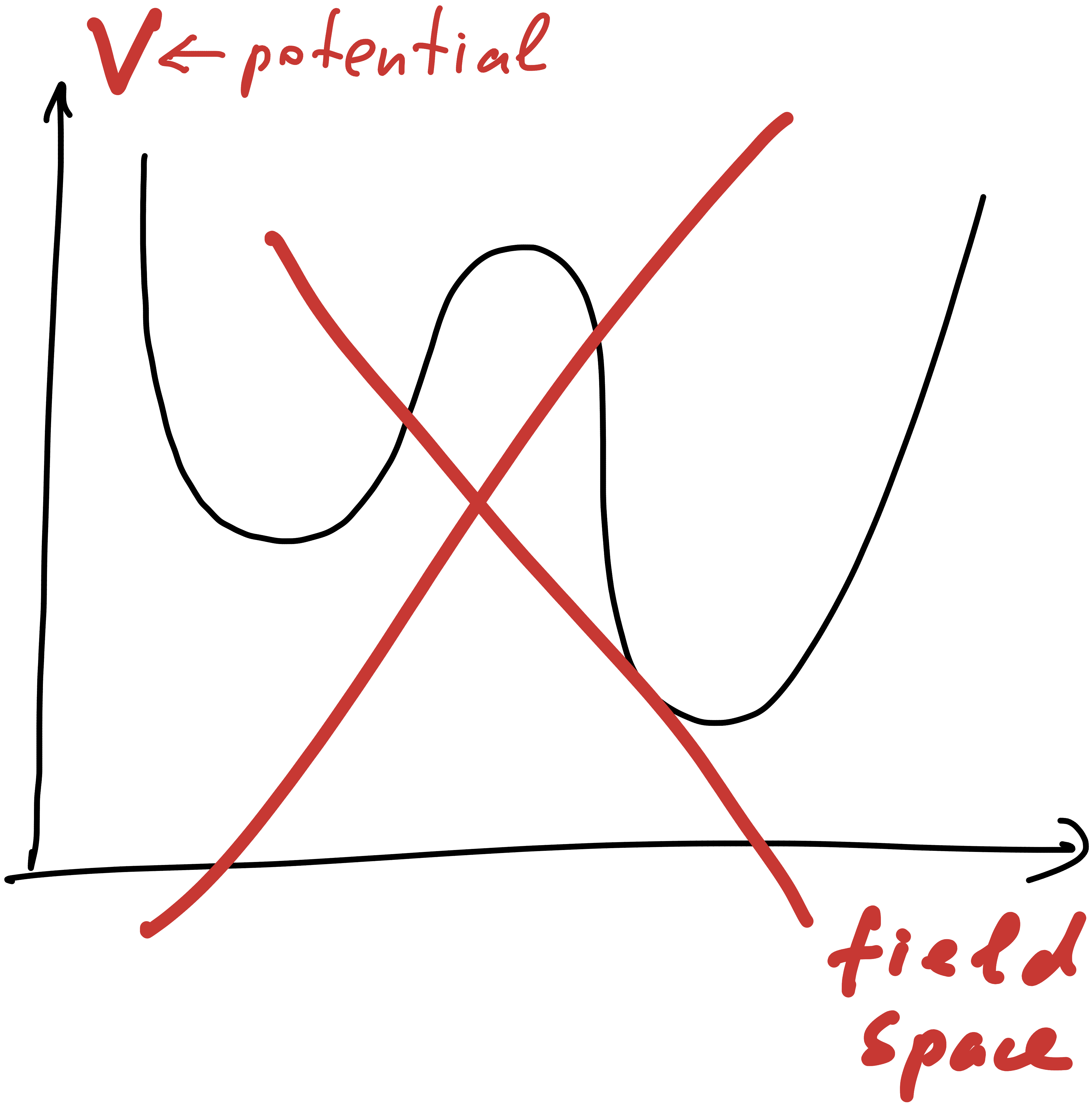
$$t_{Exit} \leq t_Q$$



Bound on slow-roll

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

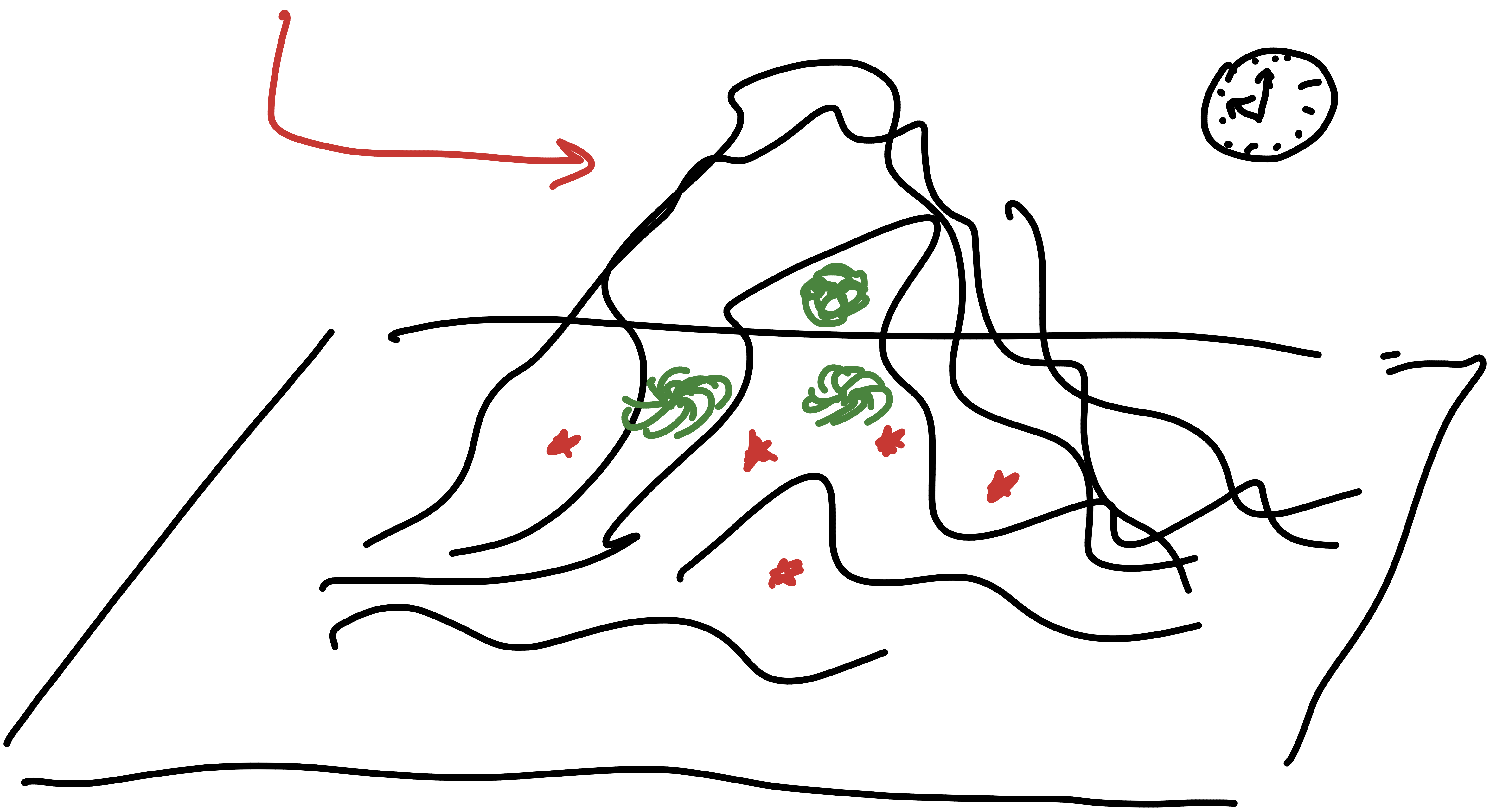
For finite G_N (finite M_P),
no de Sitter is possible, neither stable nor meta-stable.



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

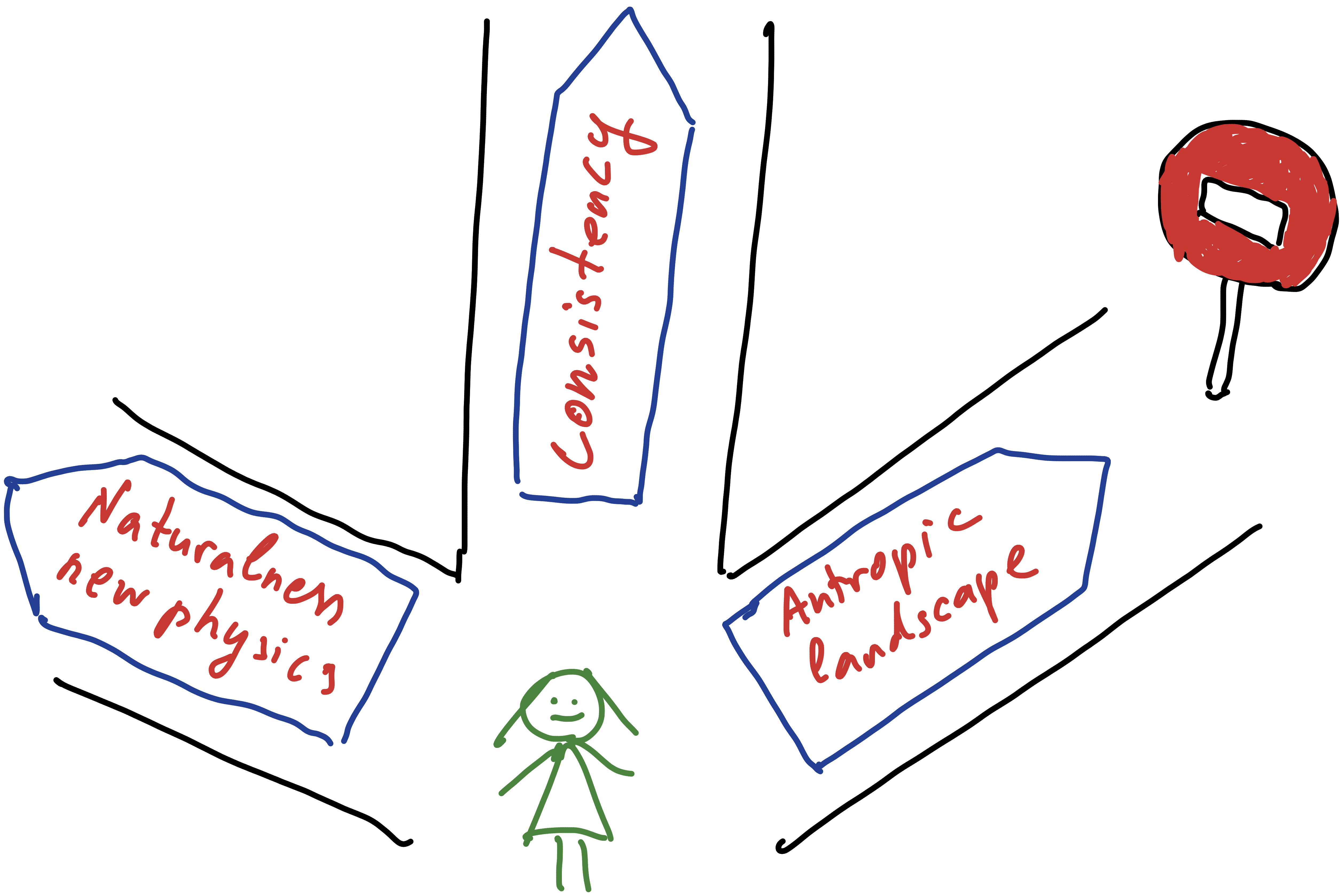
Our vacuum is Minkowski.

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



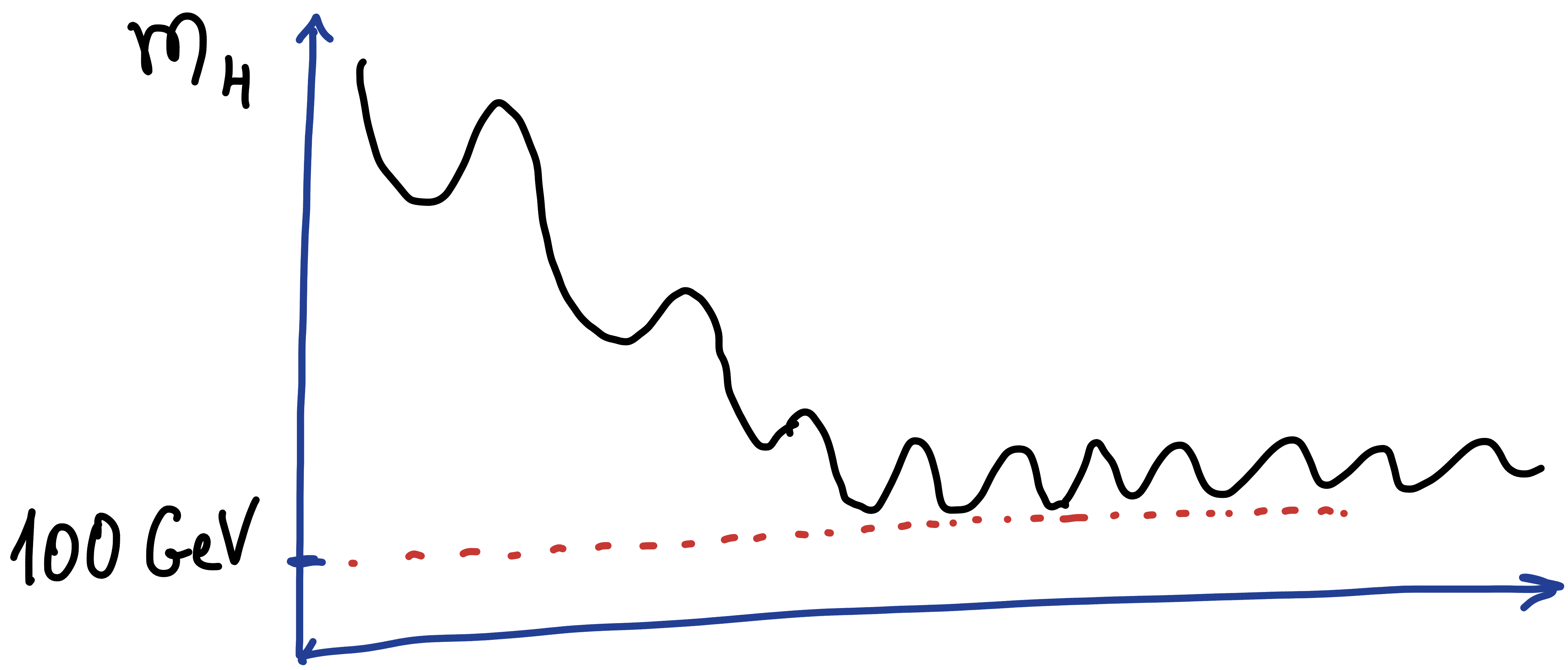
If there exists a dark energy in our Universe, it must come from some new physics, from beyond Standard Model and beyond Einstein

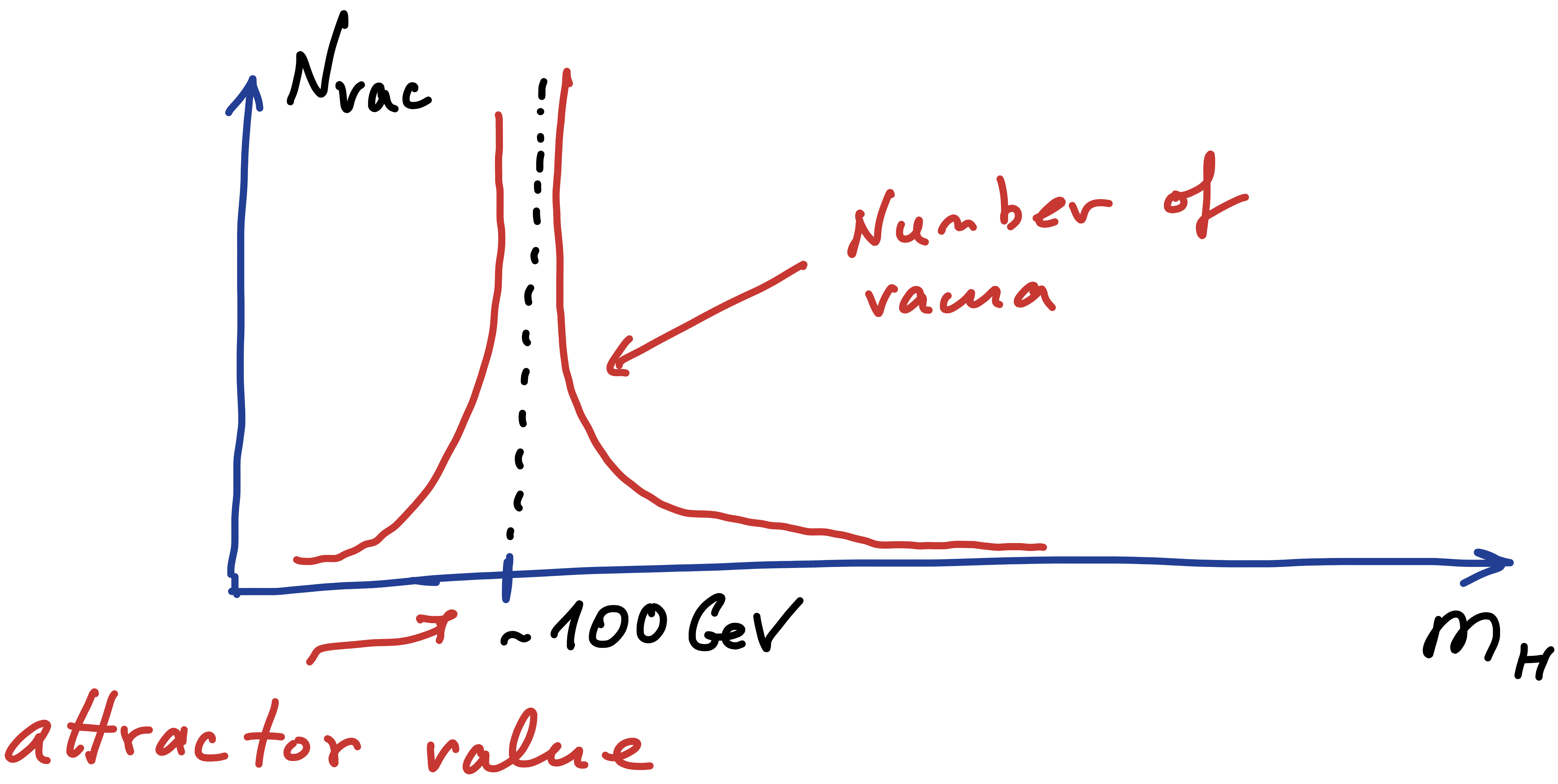
$$SM + GR + \cancel{\Lambda} + ?$$


Consistency
Naturalness
new physics
Antropic
landscape

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

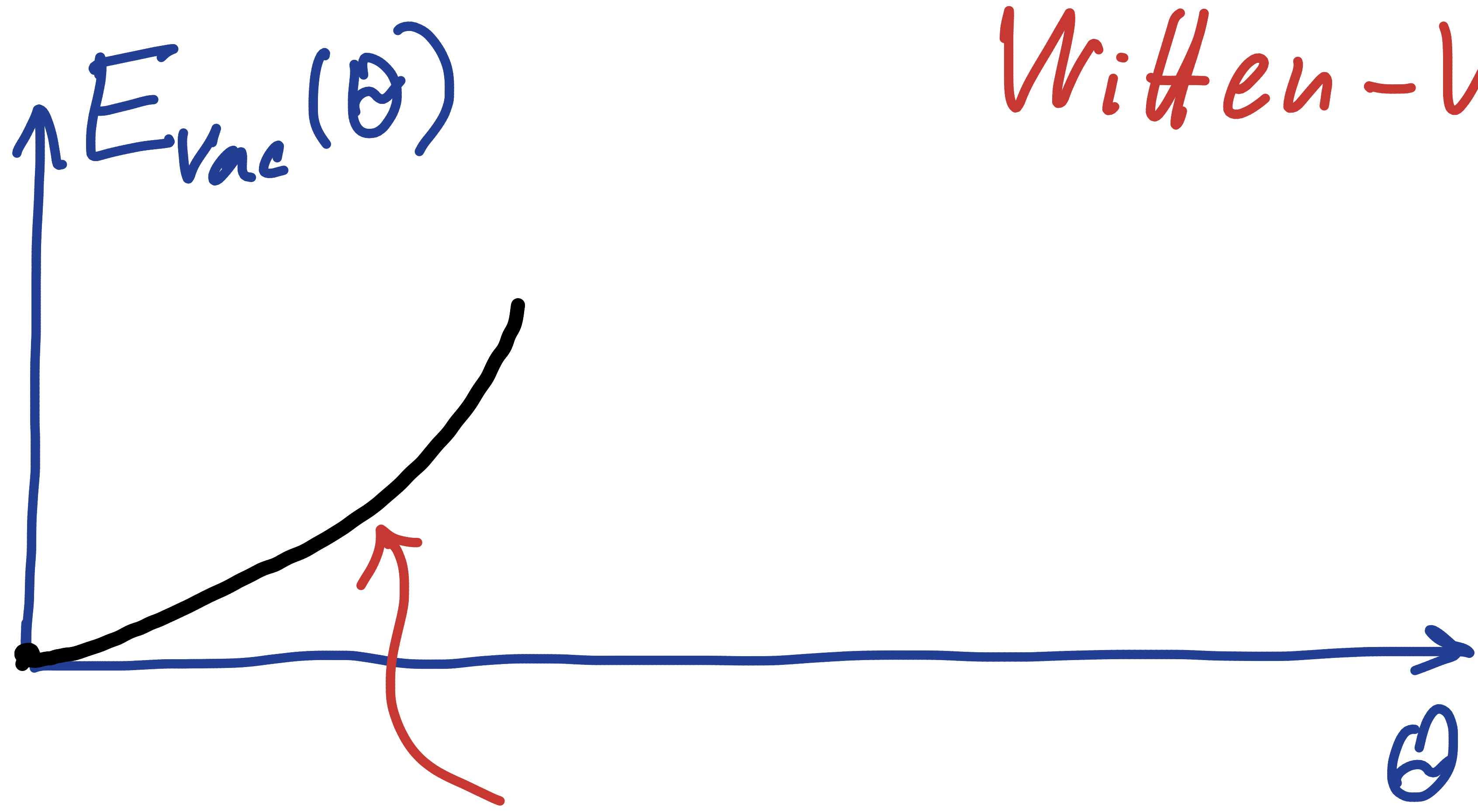
This strengthens the motivation for new physics not far from weak scale.

Many phenomenological implications.

Eliminating Θ-vacua in gauge theories?

G.D., Gomez, Zell '18

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



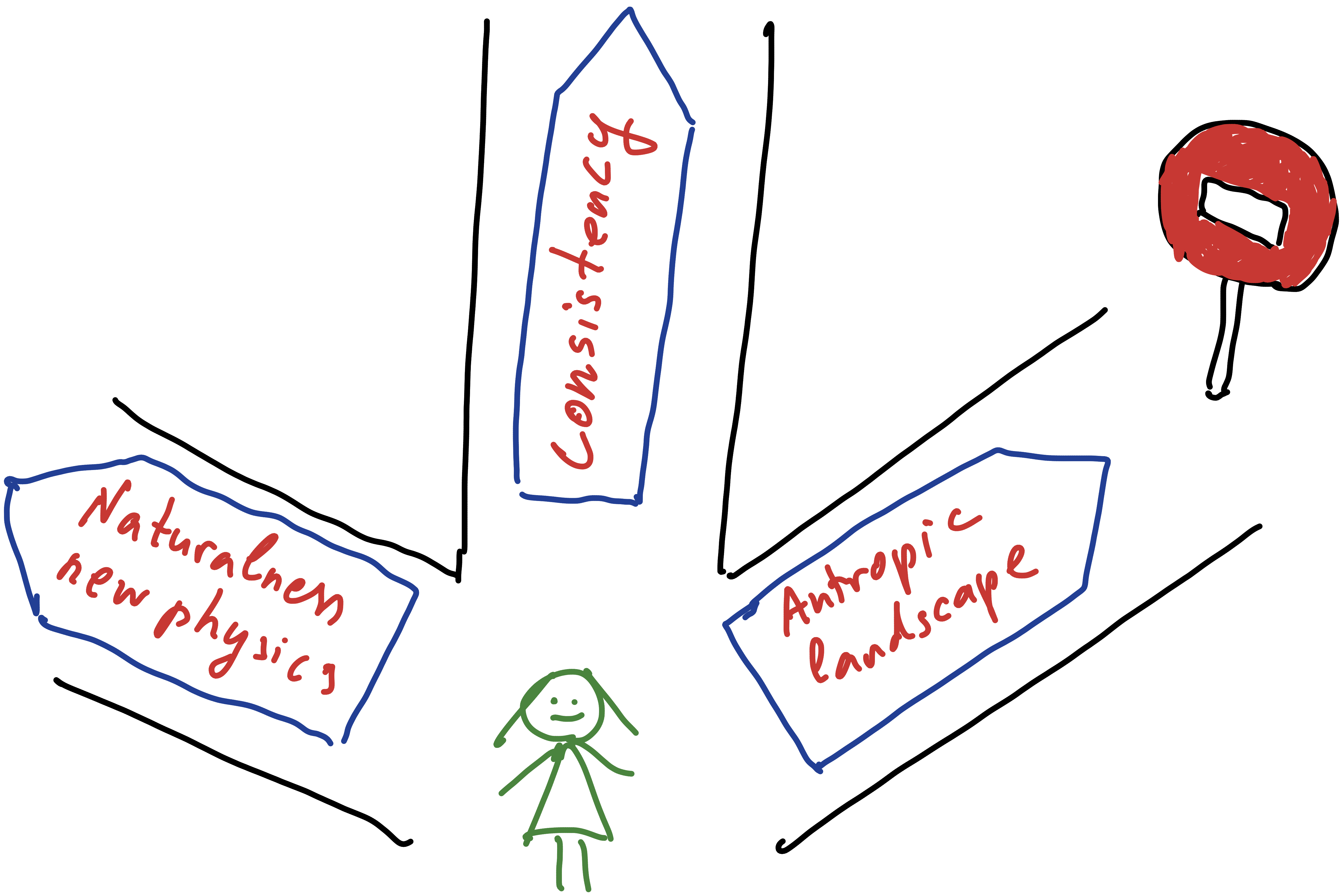
Witten-Vafa

Some will be in de Sitter and this is excluded by our arguments. No Θ-vacua!

(Proof of axion?)

Outlook:

- ⊛ $\mathcal{S}$-matrix excludes de Sitter landscape;
- ⊛ This nullifies outstanding cosmological puzzle;
- ⊛ It also abolishes possibility of anthropic selection and of cosmological relaxation;
- ⊛ Brings new guidelines for new physics;
- ⊛ . . . .


Consistency
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Thank You!