Naturalness and New Physics

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Fundamental physics is about understanding nature at various length-scales

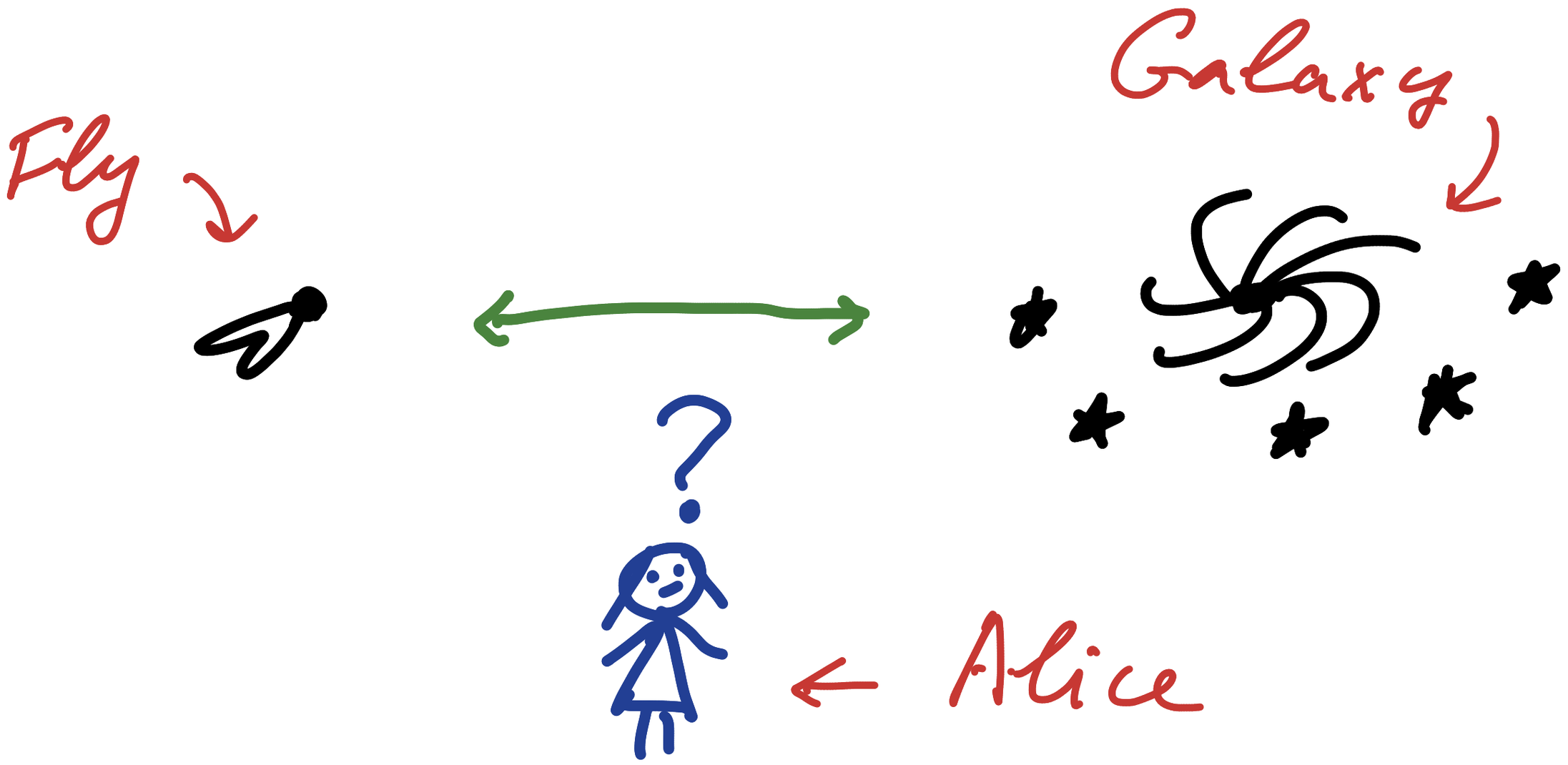
Planck length

$L_p \sim 10^{-33}$ cm

Present Hubble radius

$L_H \sim 10^{28}$ cm

On this road we encounter many hierarchies between physical quantities



What do they tell us about fundamental physics?

THE SEARCHES OF THE NEW (BEYOND THE STANDARD MODEL) PHYSICS AT THE LARGE HADRON COLLIDER ARE (Mainly) MOTIVATED BY THE HIERARCHY PROBLEM, AN INEXPLICABLE STABILITY OF THE WEAK INTERACTION SCALE ($M_W = 10^2$ GeV) VERSUS THE PLANCK MASS ($M_P = 10^{19}$ GeV),

WHY IS $M^2_W/M^2_P = 10^{-34}$?

THE HIERARCHY PROBLEM IS NOT ABOUT BIG/SMALL NUMBERS!

THERE ARE PLENTY OF BIG/SMALL NUMBERS IN NATURE THAT ARE OF NO MYSTERY.

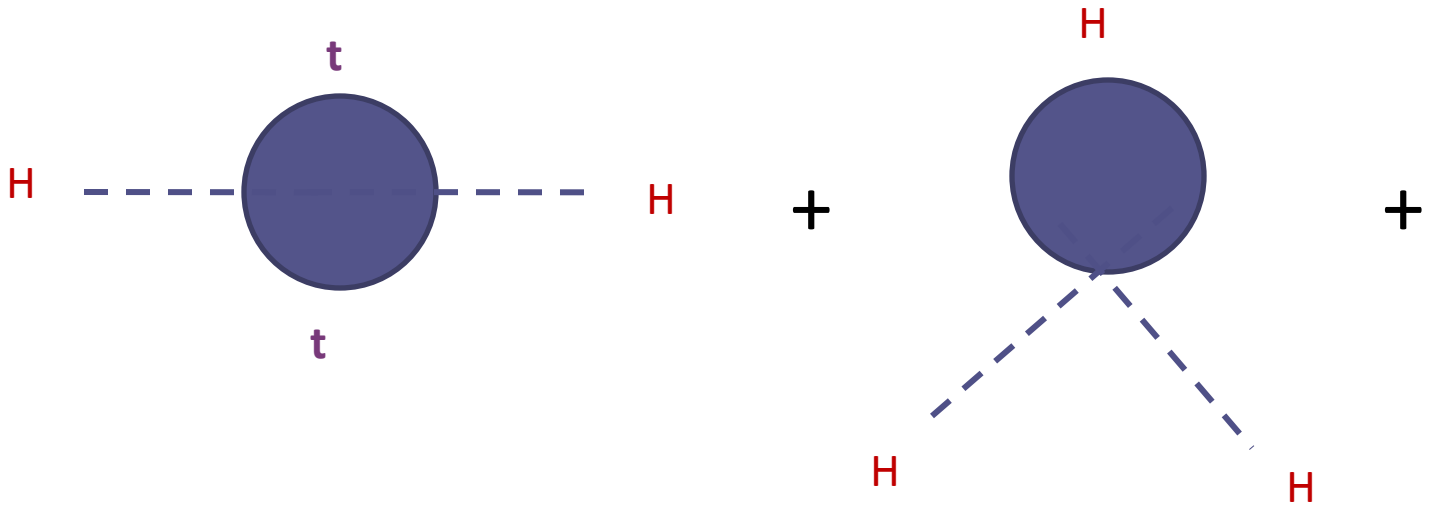
$$L = 10^{12} L$$

ELEPHANTS (OR HUMANS) ARE BIG, BECAUSE THEY CARRY A HUGE BARYON NUMBER.

THE HIERARCHY PROBLEM IS ABOUT THE UV STABILITY OF THE VERY SMALL NUMBER

$$M^2_W/M^2_P = 10^{-34}$$

UV-instability of the Higgs mass

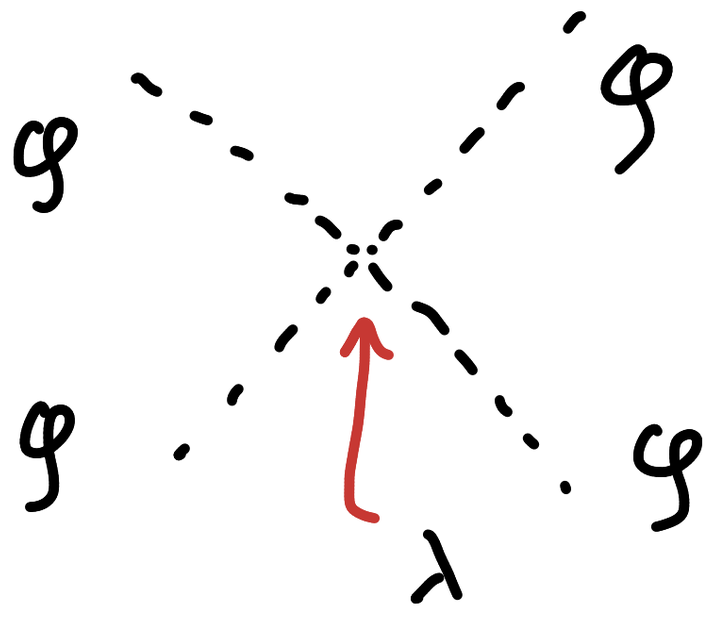


$$\delta m^2_H \approx \Lambda^2 \quad !$$

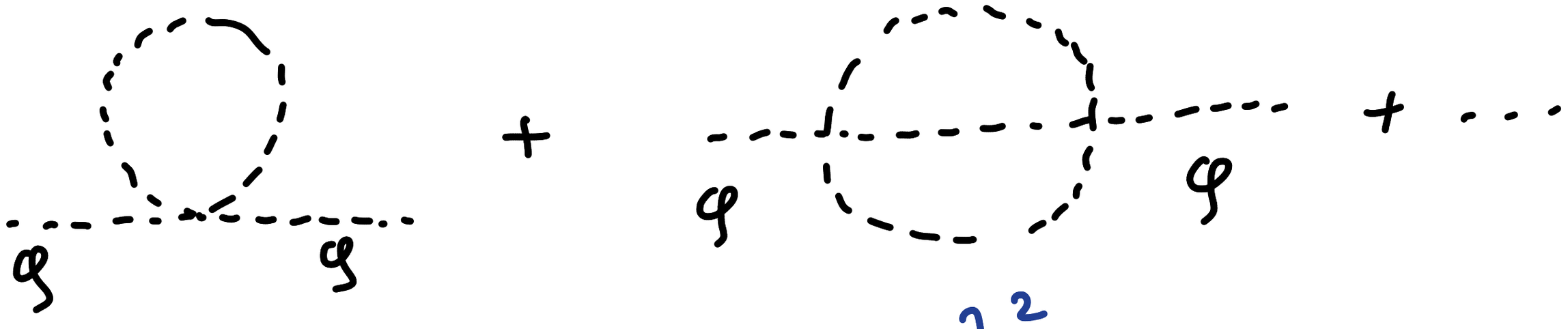
The natural cutoff is the gravity scale $\Lambda = M_P$

Masses of scalar are UV-sensitive

$\lambda\varphi^4$



Quantum corrections:



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

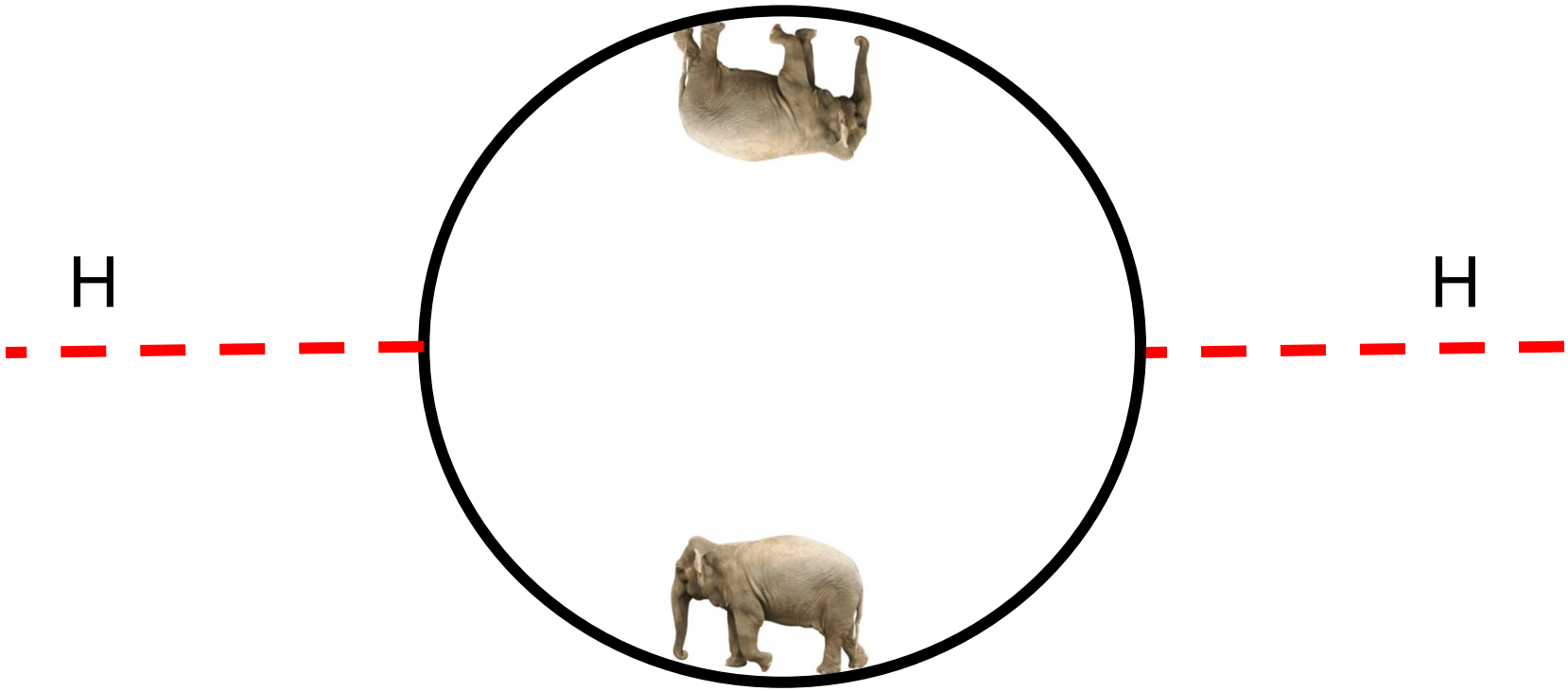
$$\delta m_\varphi^2 = M_*^2 \{\lambda + \lambda^2 + \dots\}$$

↑ UV-cutoff

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

Without gravity the problem could have been less severe, but with gravity there is no way out:

The particles running in the loop cannot have arbitrarily high energies without becoming big black holes!



Elementary particle of mass = m

Compton wavelength (Quantum):

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

Gravity brings two other length-scales:

* Gravitational radius (classical):

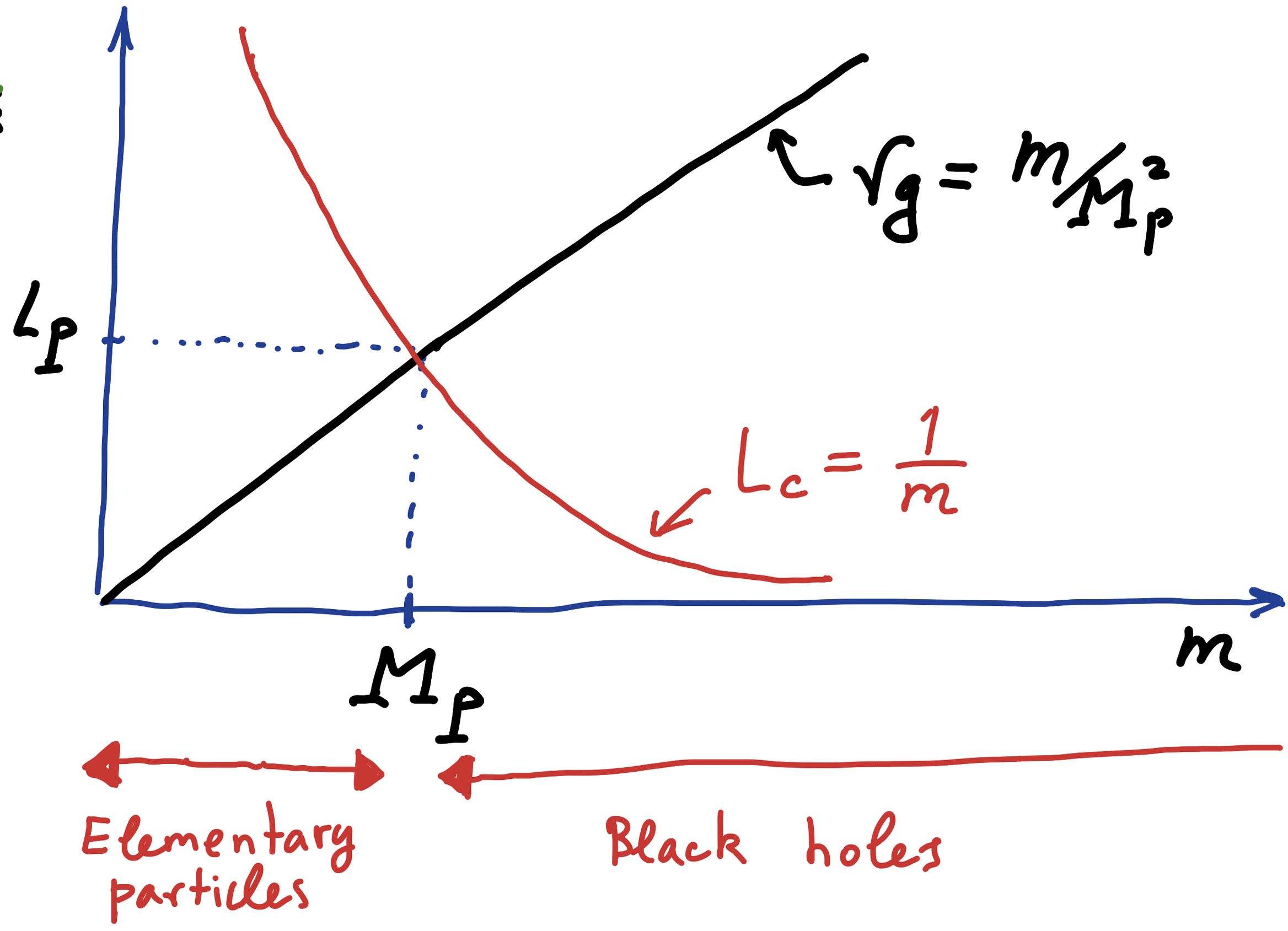
$$R_g = G_N m$$

* 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

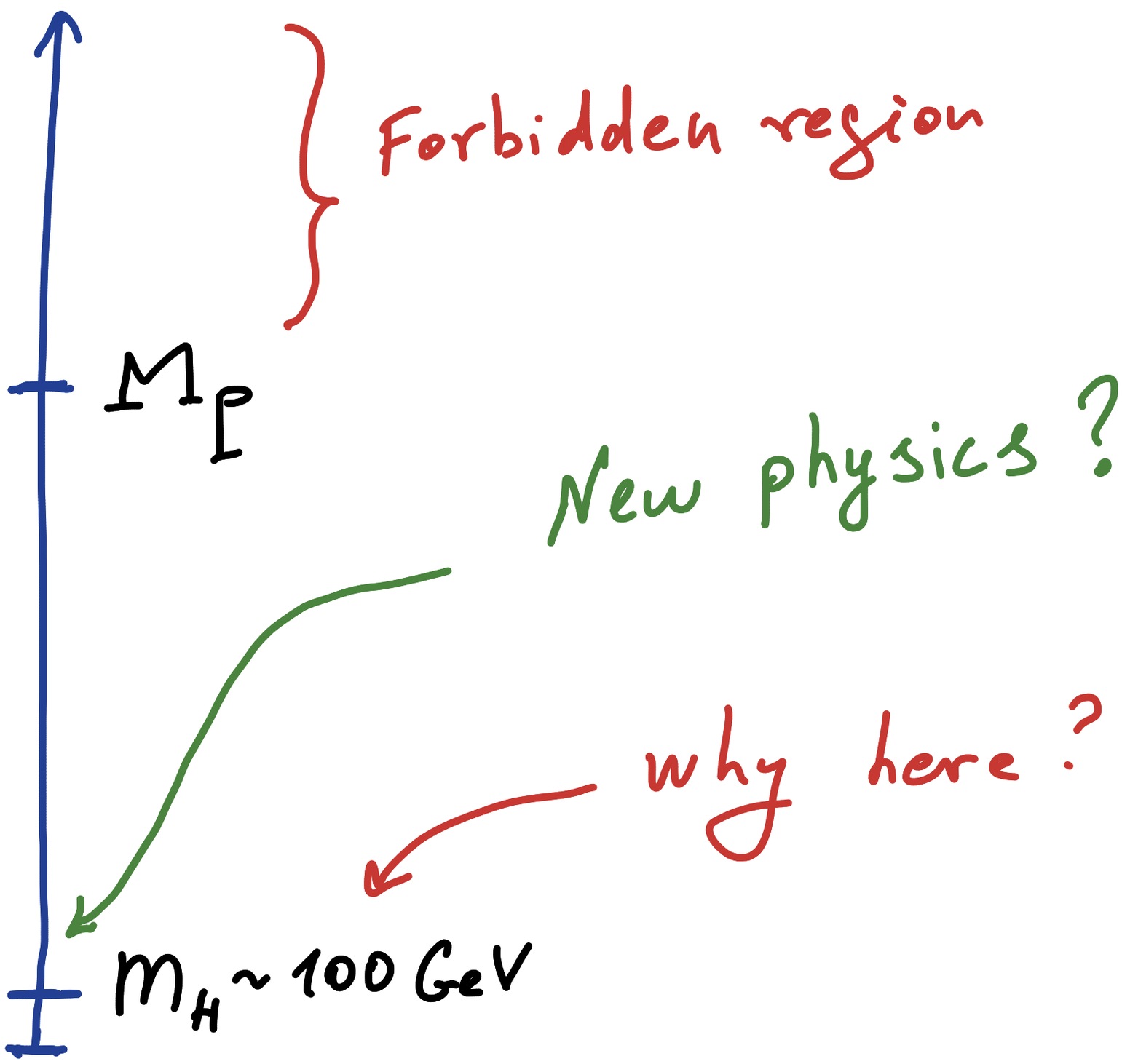
$$m > M_P$$

No elementary particles of mass

$$m > M_P$$

(would be a black hole!)

Higgs cannot have a solar mass



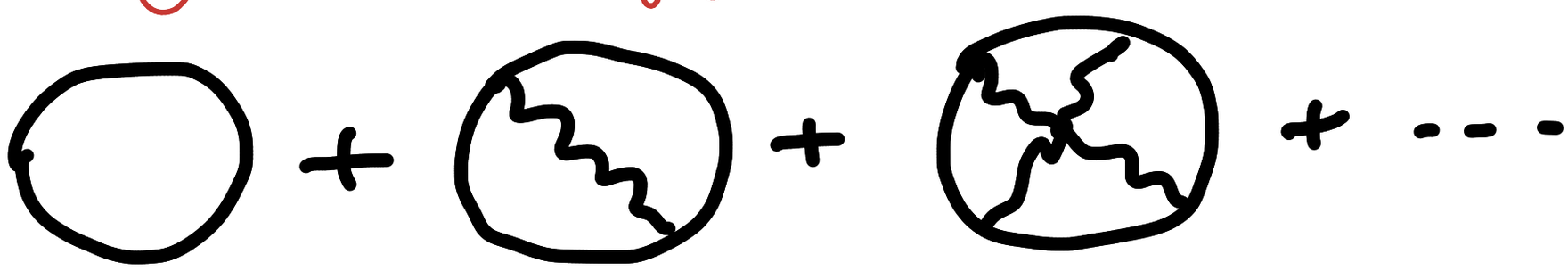
The most celebrated
Hierarchy problem
(and its absence thereof)

The cosmological constant
puzzle.

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

Vacuum energy

highly cutoff-sensitive



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

Naturally-expected value:

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

Observational bound:

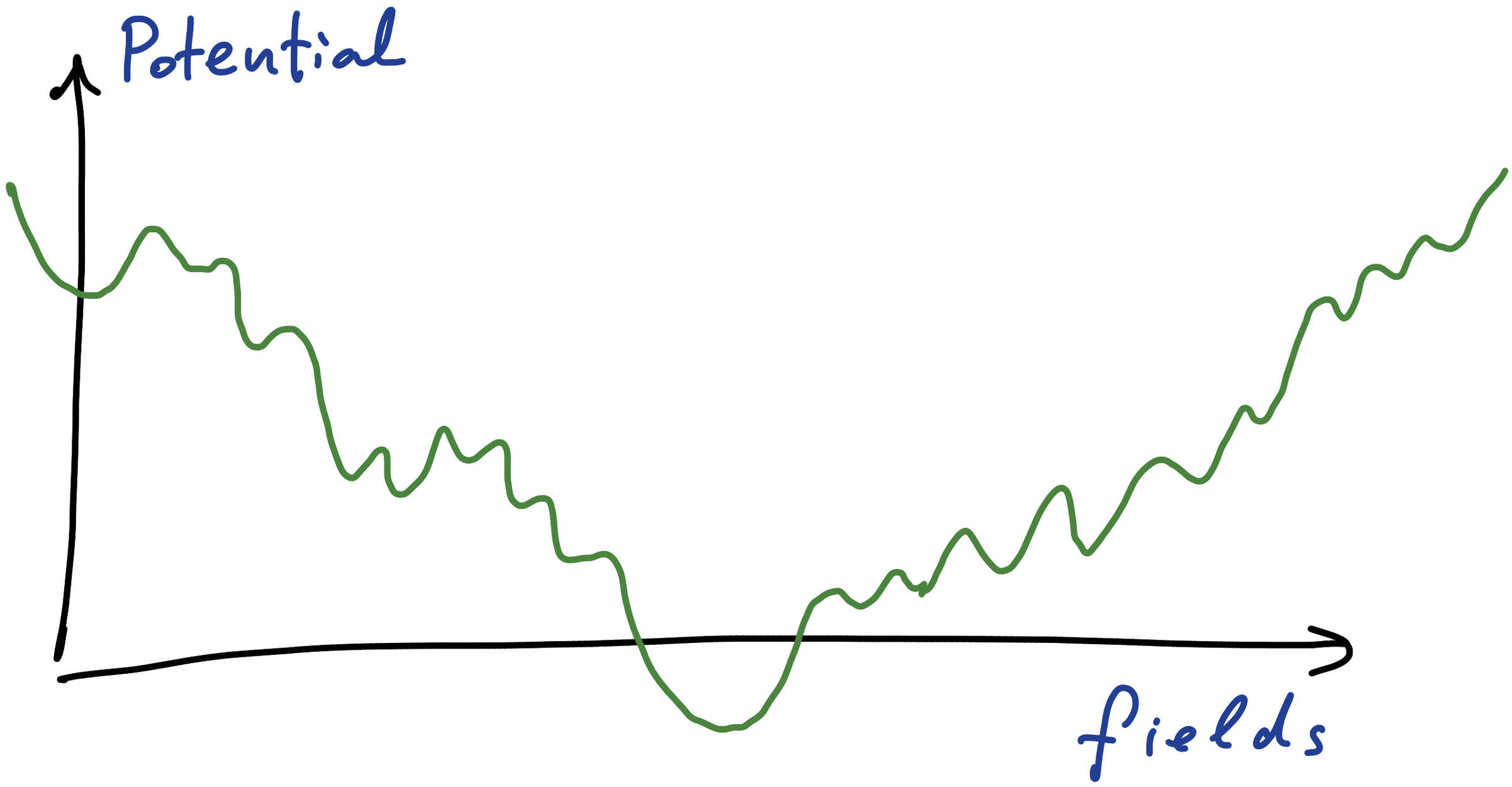
$$\Lambda_{Real} \lesssim (10^{-3}\,eV)^4$$

Naturalness problem:

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

Often assumed picture:

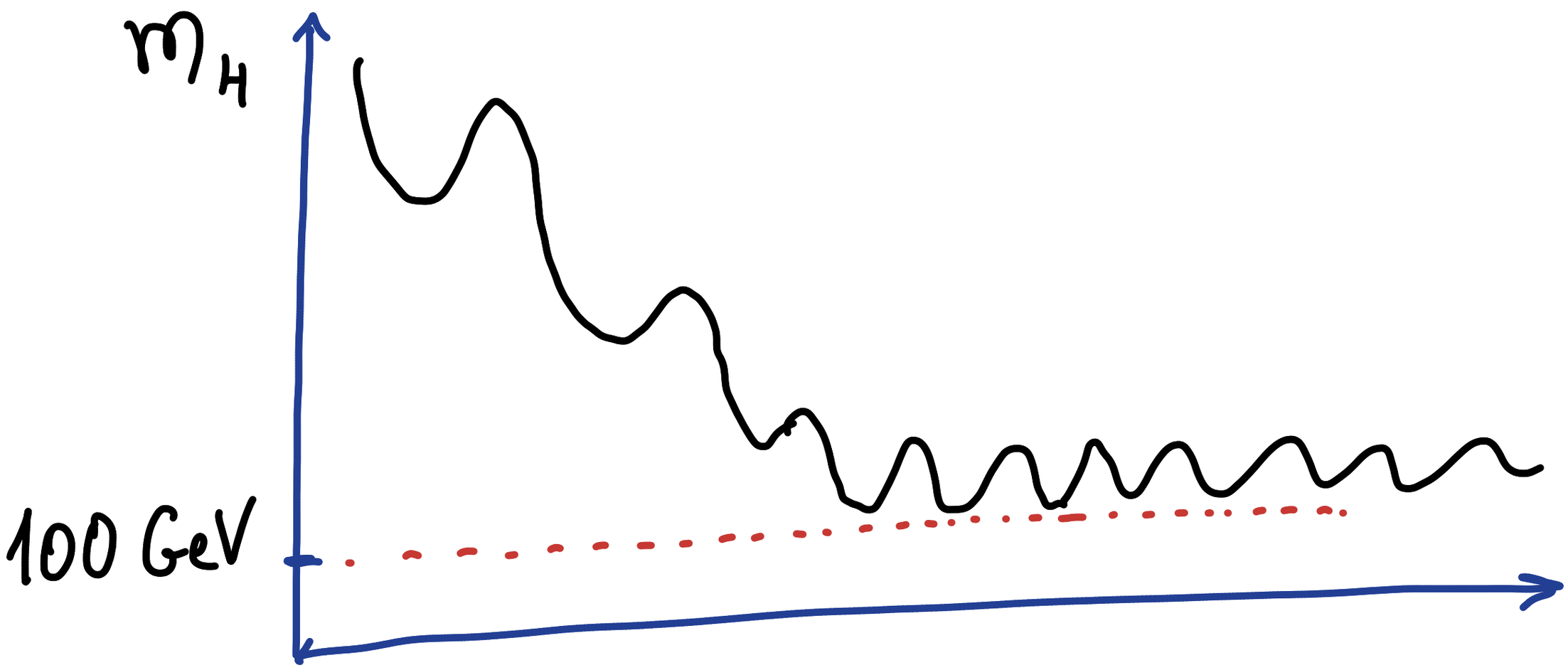
Plentitude of deSitter vacua on string landscape



Naturalness can be replaced by Anthropic selection

Cosmological relaxation of the Higgs mass

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



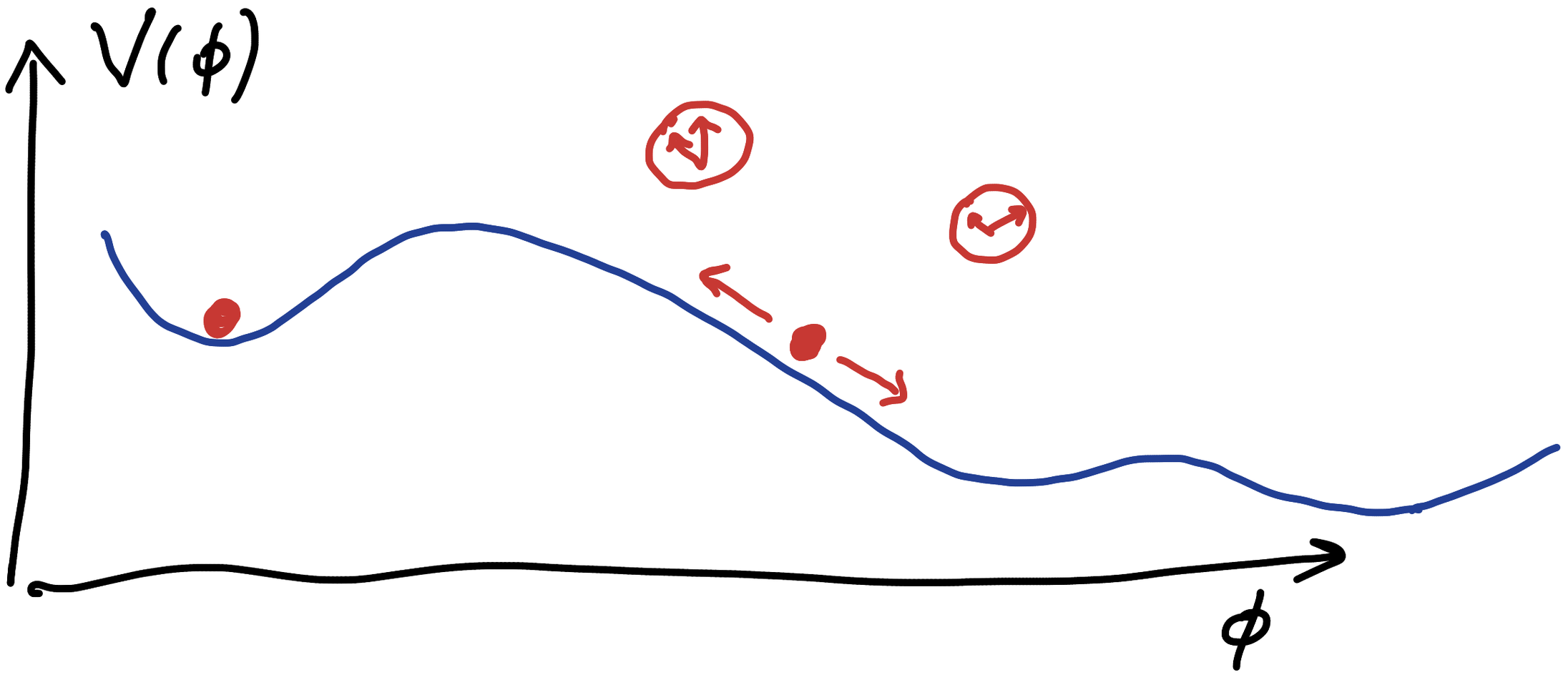
de Sitter landscape would open a way for anthropic selection.

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

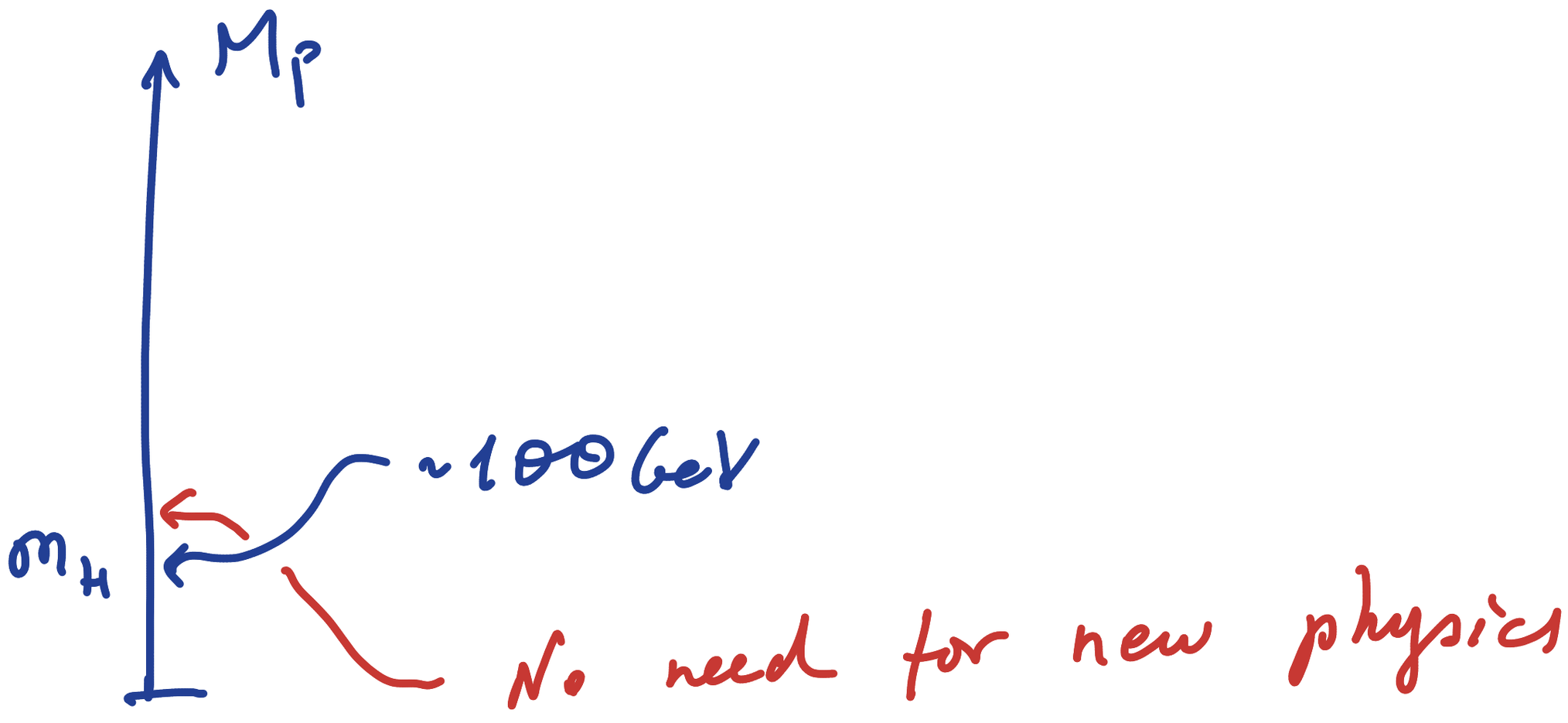
Vilenkin '83; Linde '86; ...



This would also open up a way for anthropic solution to the Hierarchy Problem, since it has been argued

Agrawal, Barr, Donoghue, Seckel '97

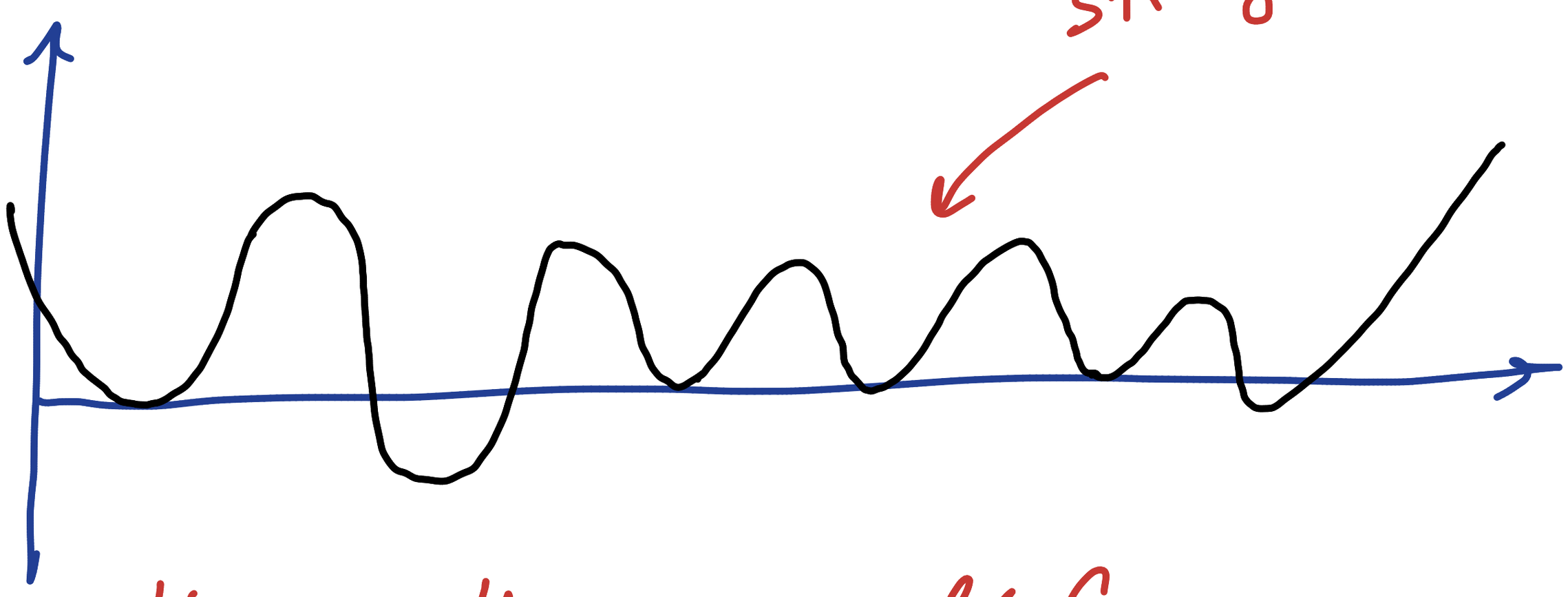
that our existence is sensitive to weak scale (Higgs mass)



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

Gravity:

Newton → Einstein → QFT

$$g^{(x)}_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

in quantum theory

$$h_{\mu\nu} = \frac{\langle \hat{h}_{\mu\nu} \rangle}{M_P}$$

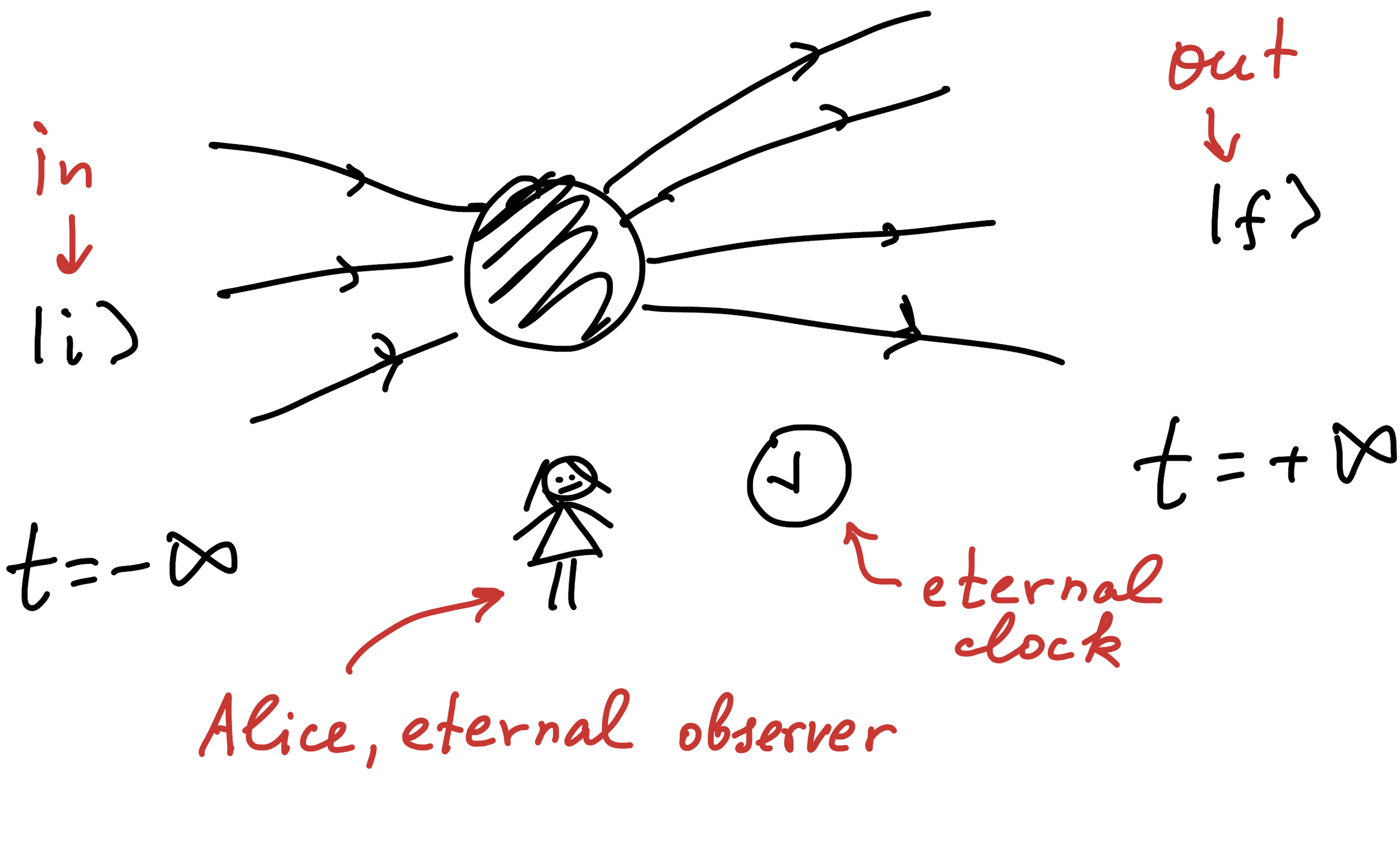
$\hat{h}_{\mu\nu}$ ← graviton

M_P ← Planck mass $\sim 10^{19}$ GeV

$\hat{h}_{\mu\nu}$ → particle with

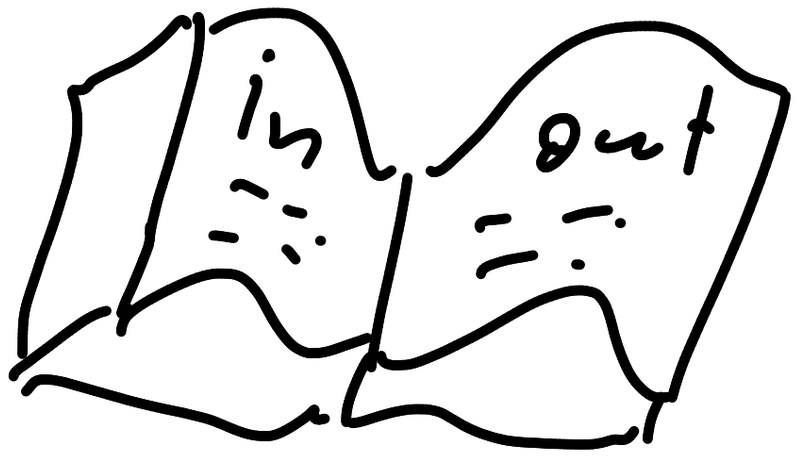
$$Spin = 2, \quad m = 0$$

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.

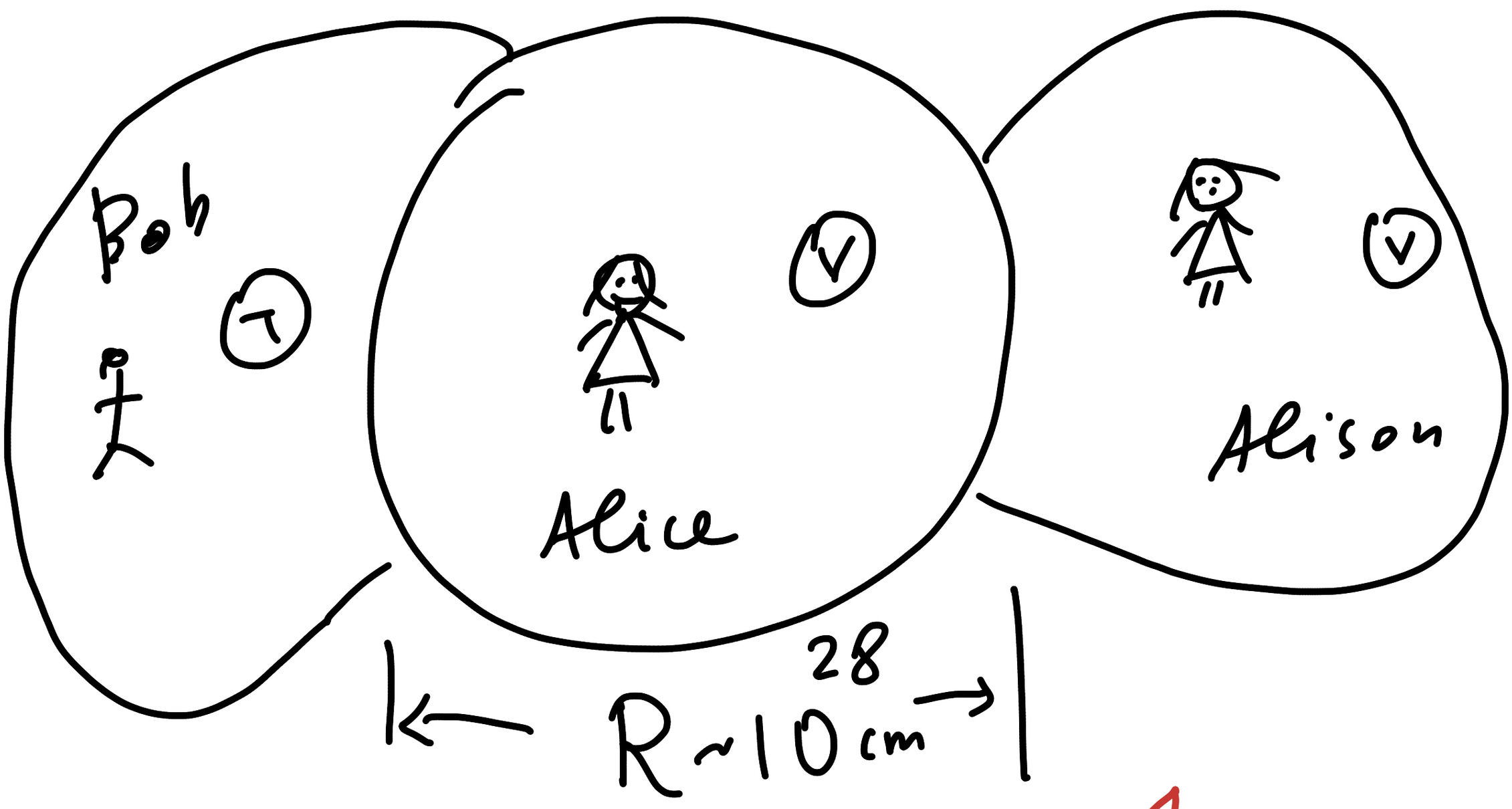
Necesary conditions:

* Globally-definet time;

↳ Absent in classical deSitter

* S-matrix vacuum.

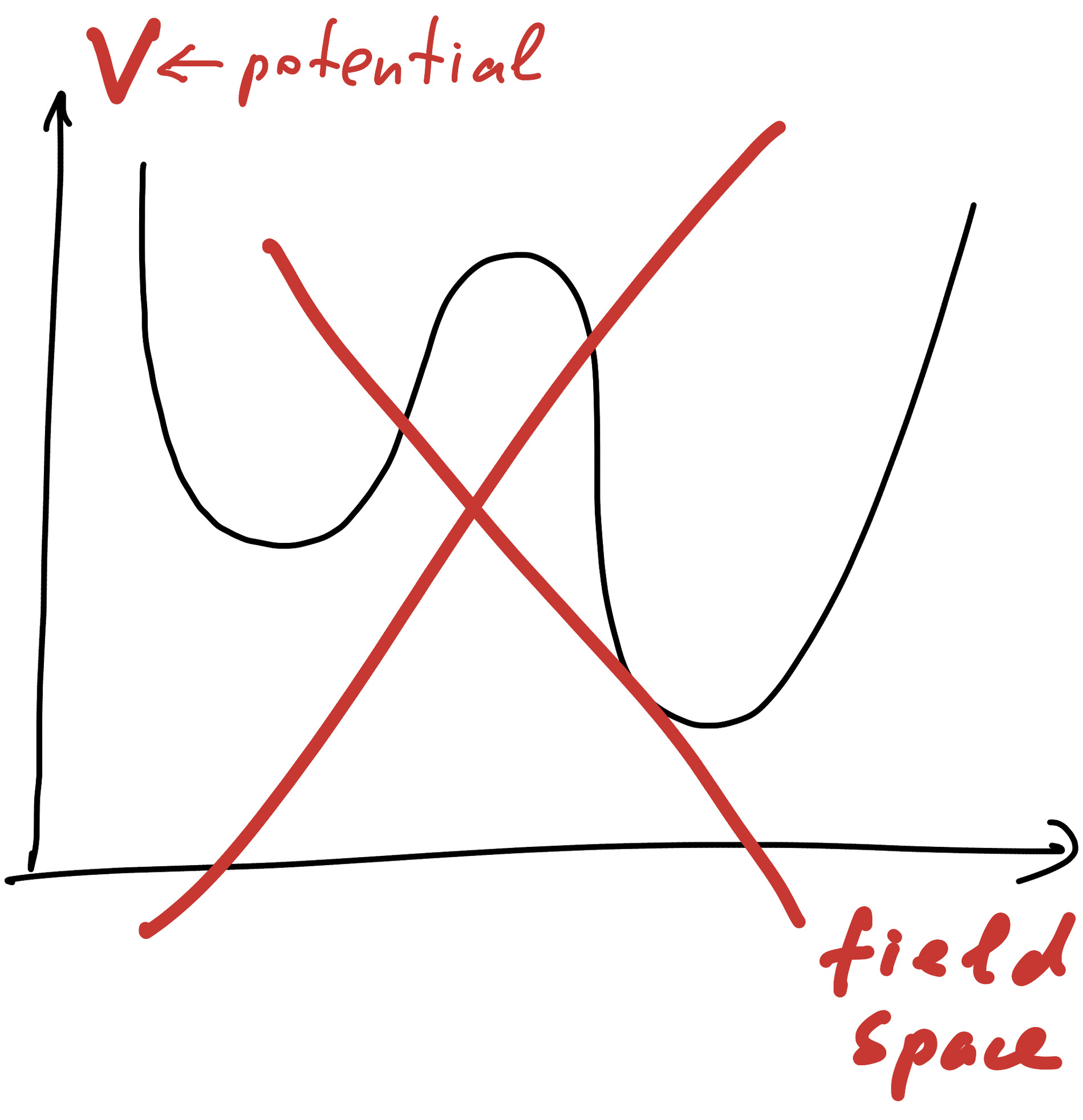
If the observed acceleration of the Universe's expansion were due to Λ, we would be entering into <u>de Sitter</u> state $|ds\rangle$.



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

No global time.

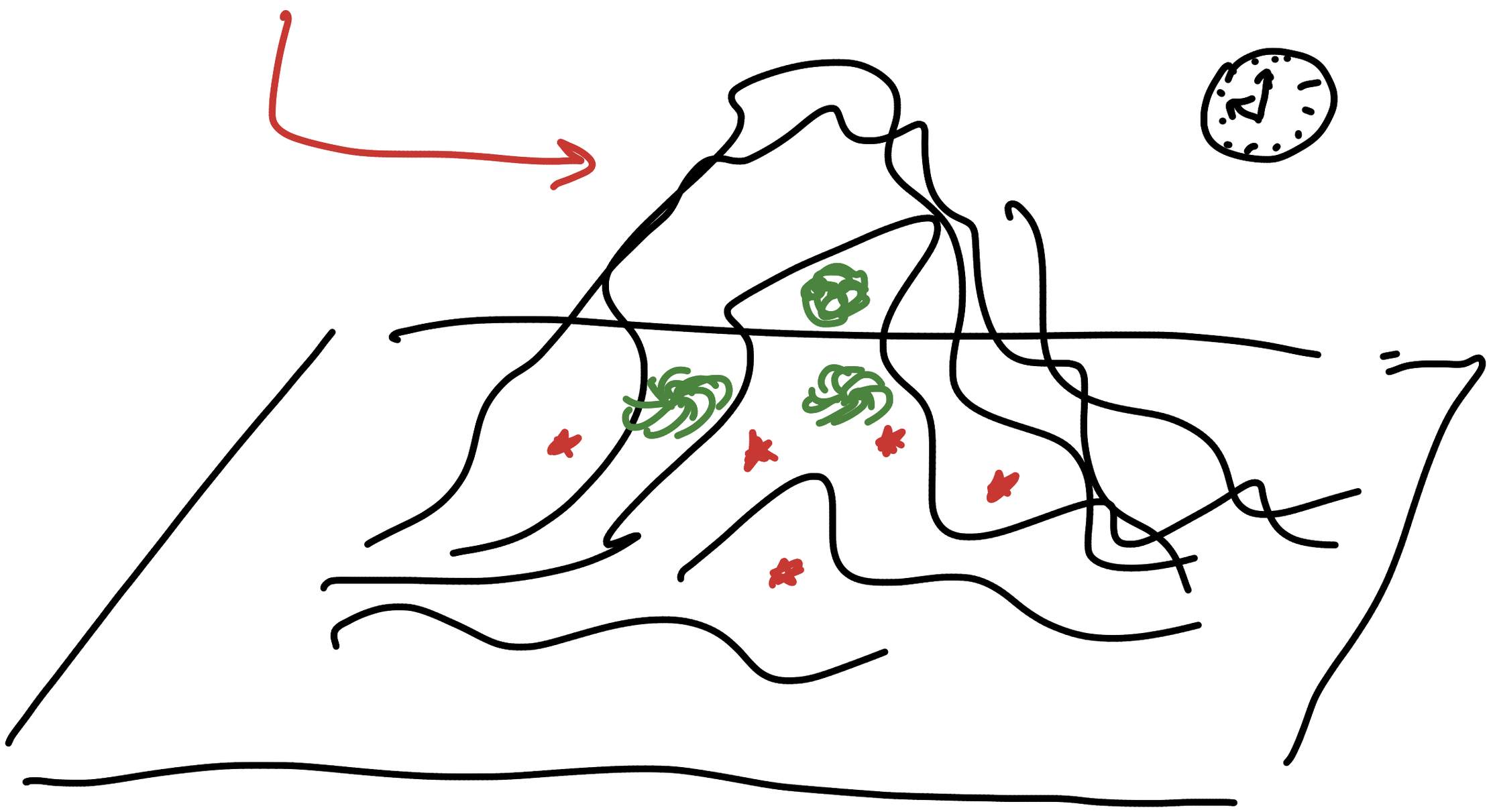
For finite G_N (finite M_p),
no de Sitter is possible, neither stable
nor meta-stable.



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



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

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

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.

Implication for strong-CP puzzle

$$\mathcal{L} = \mathcal{L}_{QCD} + \bar{\theta} F\tilde{F}$$

$$\bar{\theta} = \theta + \arg.\det.M_q$$

$$F\tilde{F} \equiv \varepsilon^{\mu\nu\alpha\beta}\,\partial_\mu C_{\nu\alpha\beta}$$

chern-Simons 3-form

$$C_{\nu\alpha\beta} \equiv tr\left(A_{[\nu}\partial_\alpha A_{\beta]} + \frac{2}{3}A_{[\nu}A_\alpha A_{\beta]}\right)$$

$$A_\mu \equiv A_\mu^a T^a$$ ← gluon matrix

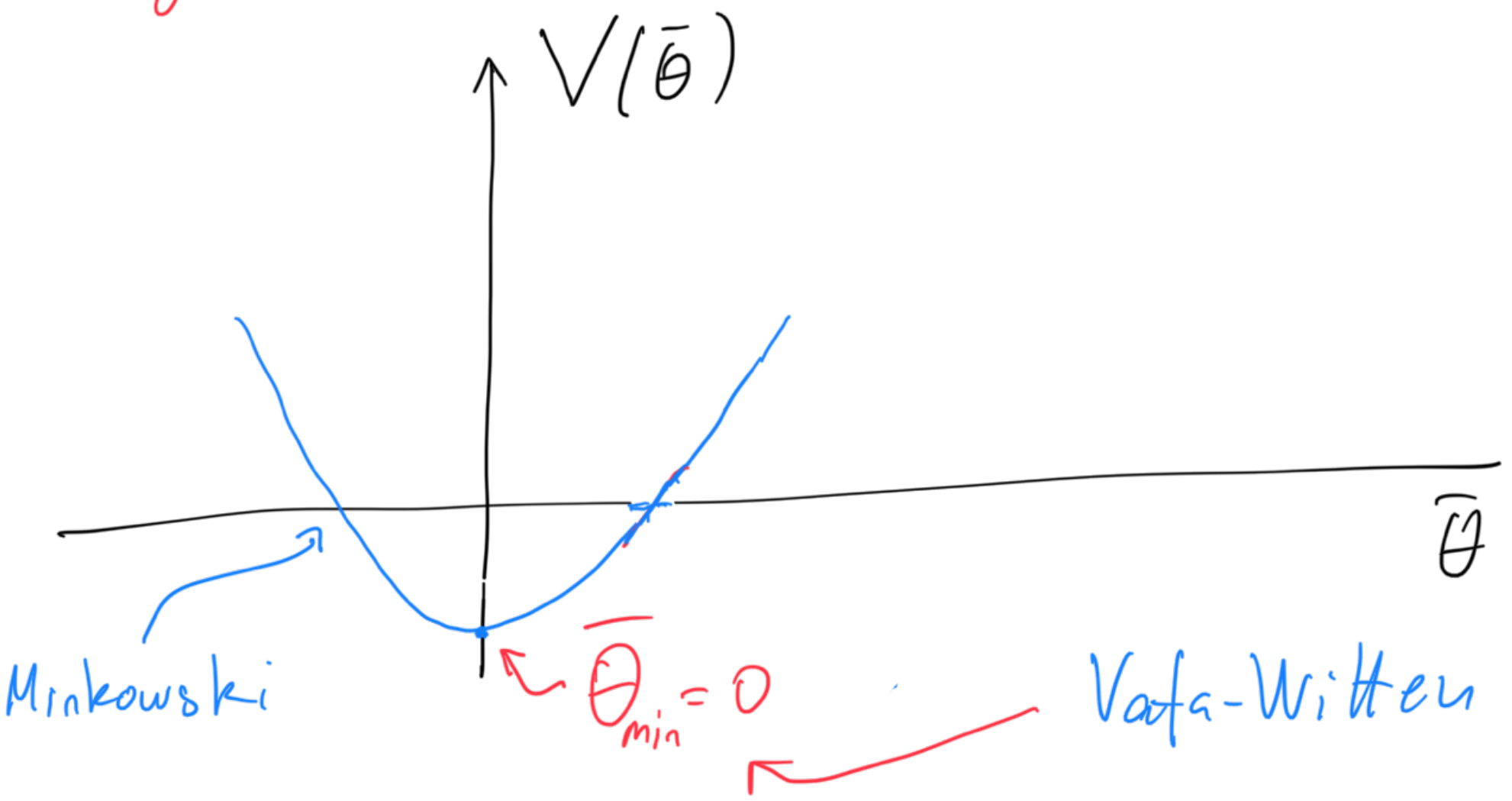
Gauge redundancy: $U = e^{-i\omega^a T^a}$

$$A_\mu \to U A_\mu U^\dagger + U^\dagger \partial_\mu U$$

$$C_{\mu\nu\alpha} \to C_{\mu\nu\alpha} + \partial_{[\mu}\Omega_{\nu\alpha]}$$

$$\Omega_{\nu\alpha} = tr\, A_{[\mu}\partial_{\nu]}\omega$$

The θ-vacua are not degenerate



If one $\bar{\theta}$ is Minkowski, the others are not.

This is excluded by S-matrix gravity:

θ-vacua must be eliminated by consistency.

G.D, Gomez, Zell '18
G.D, '22

Gravity = Axion.

Must be exact!

This favors the alternative pure-gauge formulation of QCD axion: G.D., hep-th/0507215

All we need is to introduce a single degree of freedom $B_{\mu\nu}$, with a proper gauge charge under QCD:

$$B_{\mu\nu} \to B_{\mu\nu} + \frac{1}{f_a}\Omega_{\mu\nu}$$

$$C_{\alpha\mu\nu} \to C_{\alpha\mu\nu} + \partial_{[\alpha}\Omega_{\mu\nu]}$$

$$\Omega^{(x)}_{\mu\nu} = \mathrm{tr}\, A_{[\mu}\partial_{\nu]}\omega^{(x)}$$

QCD gauge redundancy

In this theory the axion is an intrinsic part of QCD.

It is protected by gauge symmetry under arbitrary local deformations of the theory.

Theory:

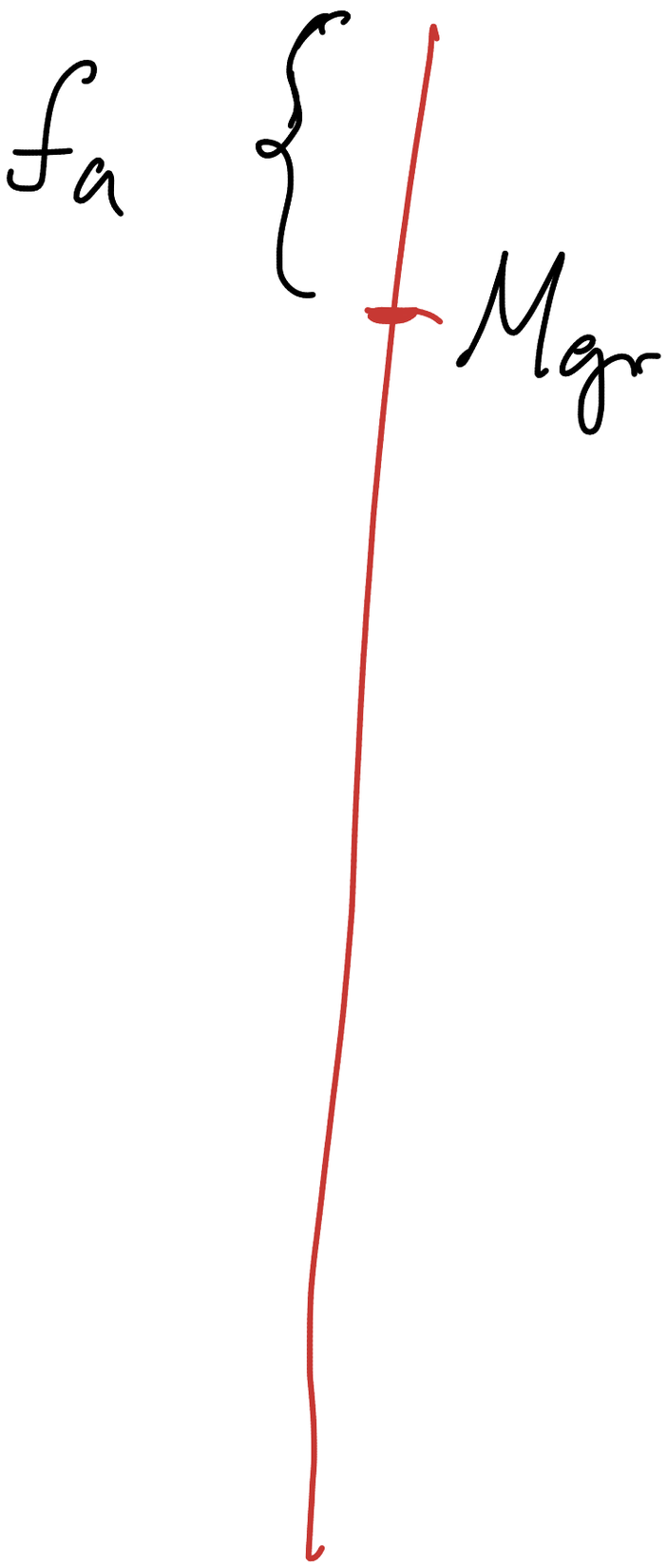
$$\mathcal{L} = \mathcal{L}_{QCD} + \bar{\theta} F\tilde{F} + \frac{1}{f_a^2}\left(C - f_a\, dB\right)^2$$

$\bar{\theta}$ is a physical to all orders in operator expansion

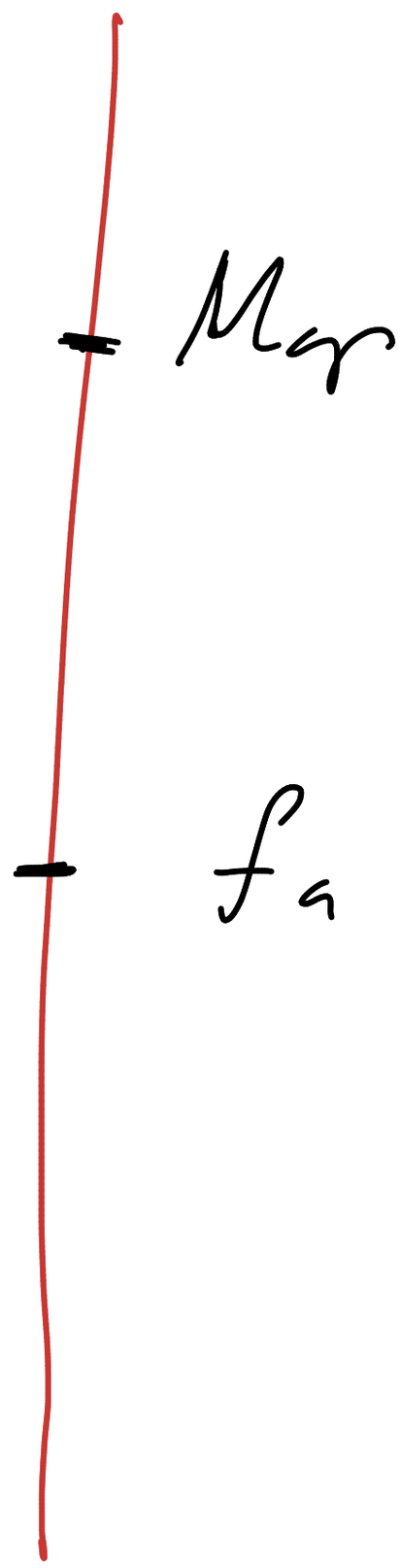
Thus, S-matrix motivates gauge formulation of QCD axion. This suggests that

$f_a \gtrsim M_{gr} \equiv$ scale of gravity

Gauge axion:



Peccei-Quinn



The advantage in calculability:

Gaye axion predicts: $\bar{\theta} = 0$.

The weak contribution to EDMN is too small for near-future detection

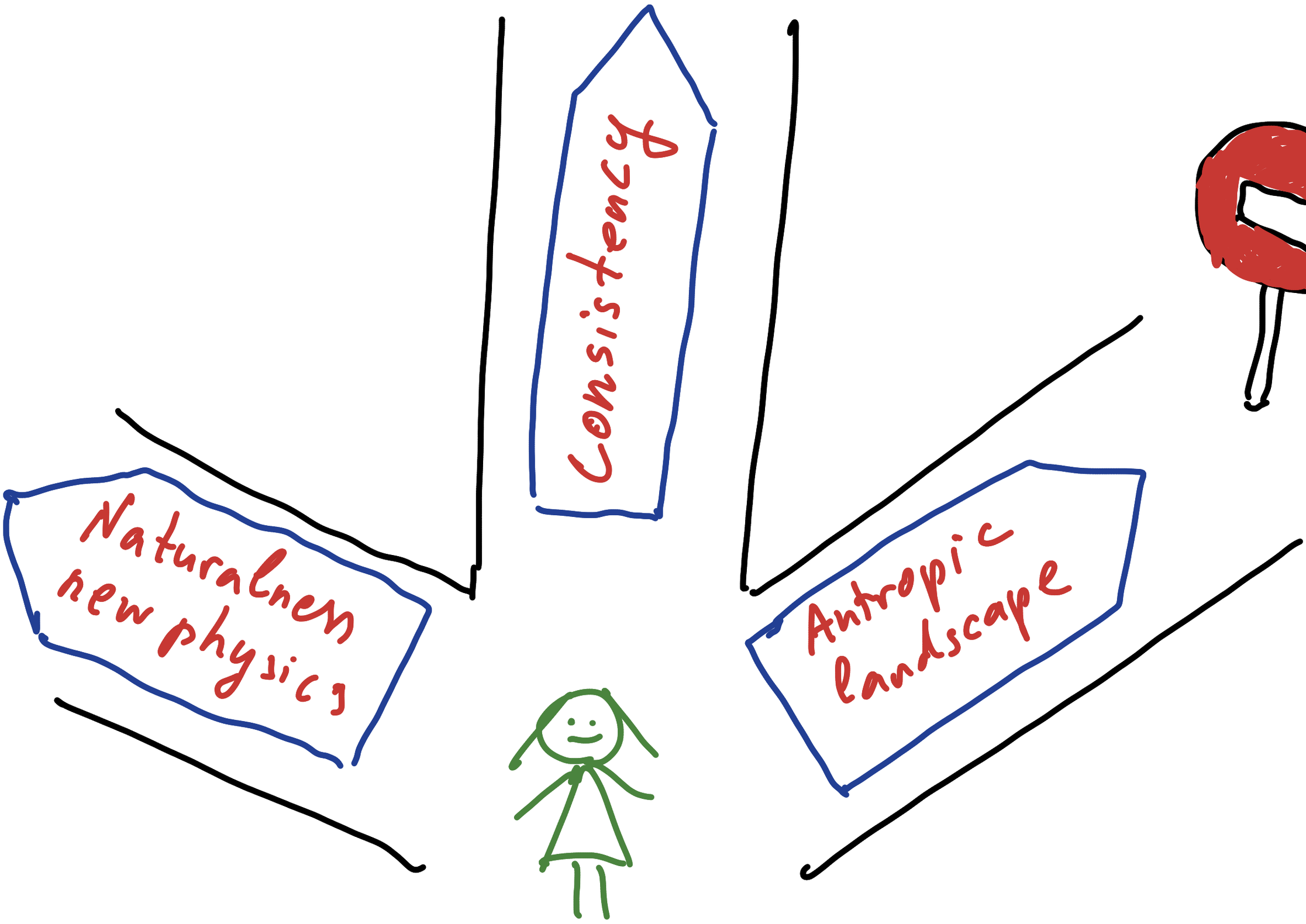
$d_n \sim 10^{-31-32}$ cm Shabalin '79

Ellis, Gaillard '79

Thus, a near-future detection of EDMN will be a signal for new CP-violating physics beyond Standar Model:

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
Naturalness
new physics
Antropic
landscape