S-matrix and Naturalness

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Fundamental physics is about understanding nature at various length-scales

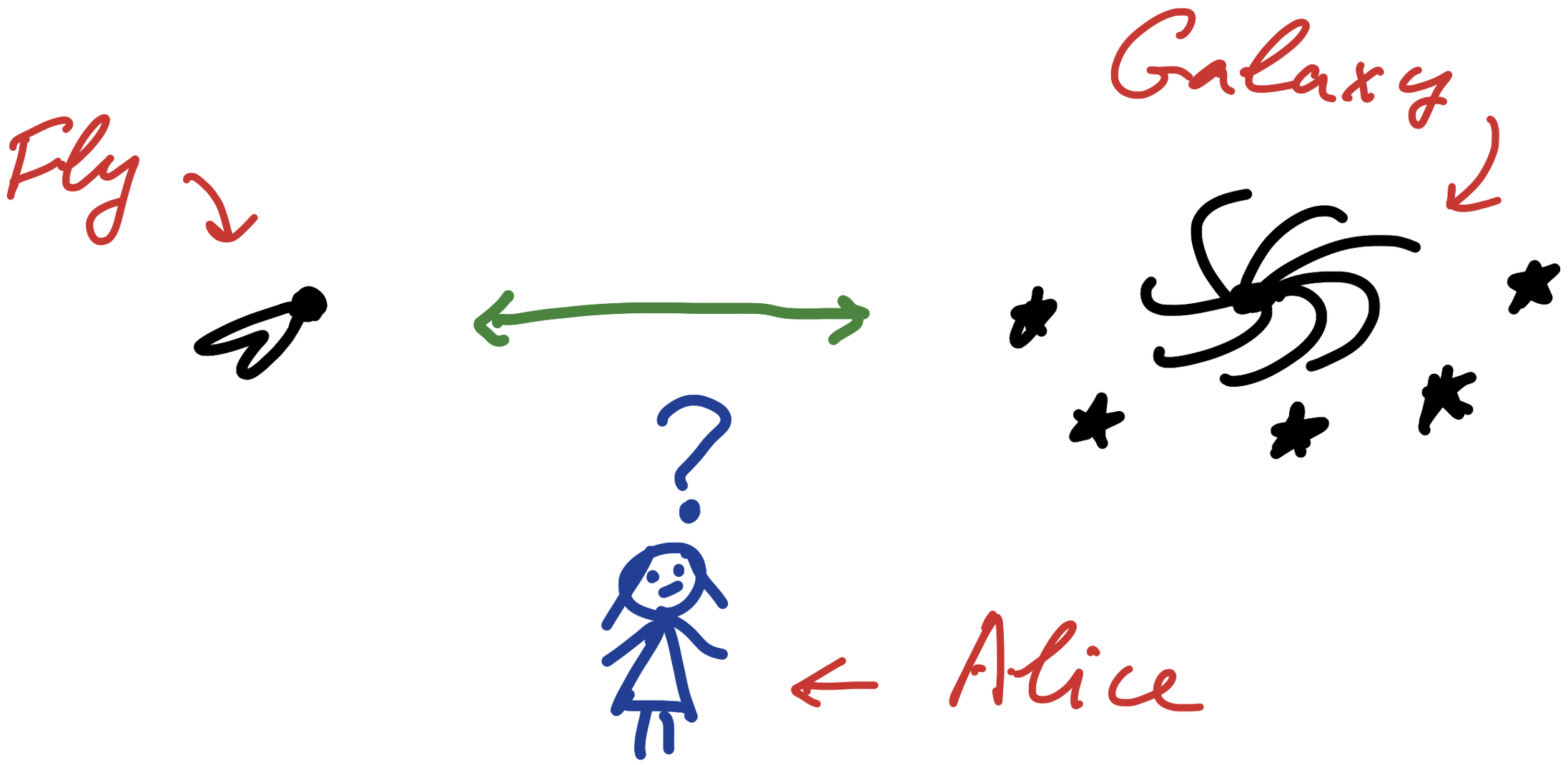
Planck length

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

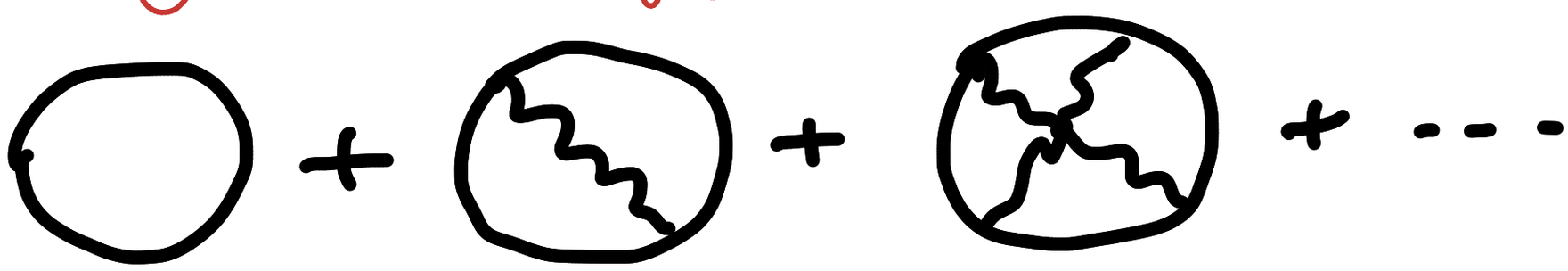
The most celebrated
Hierarchy problem
(and its absence thereof)

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:

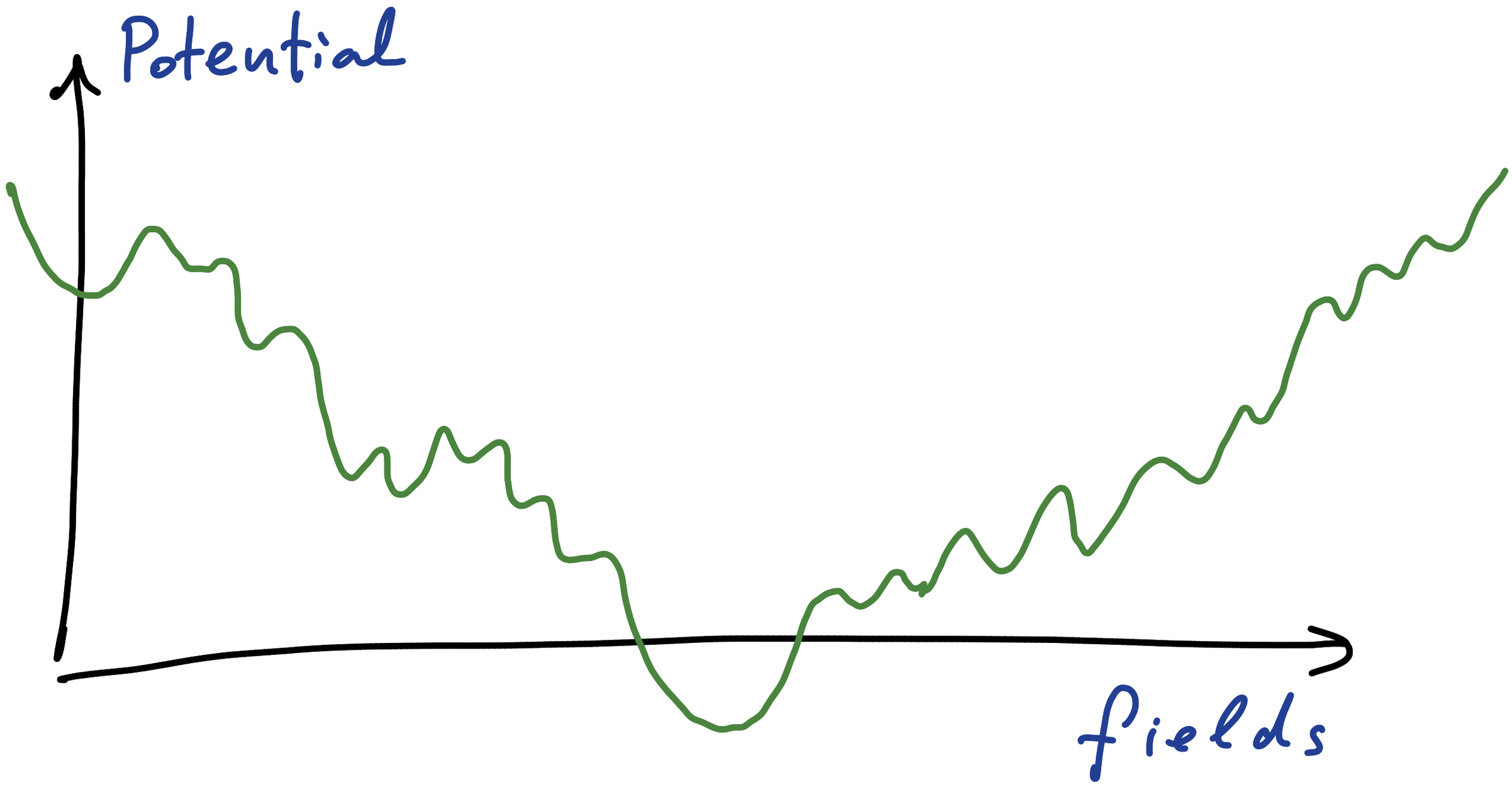
$$\Lambda_{Real} \lesssim (10^{-3}\,eV)^4$$

Naturalness problem:

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

Often assumed picture:

Plentitude of deSitter vacua on string landscape

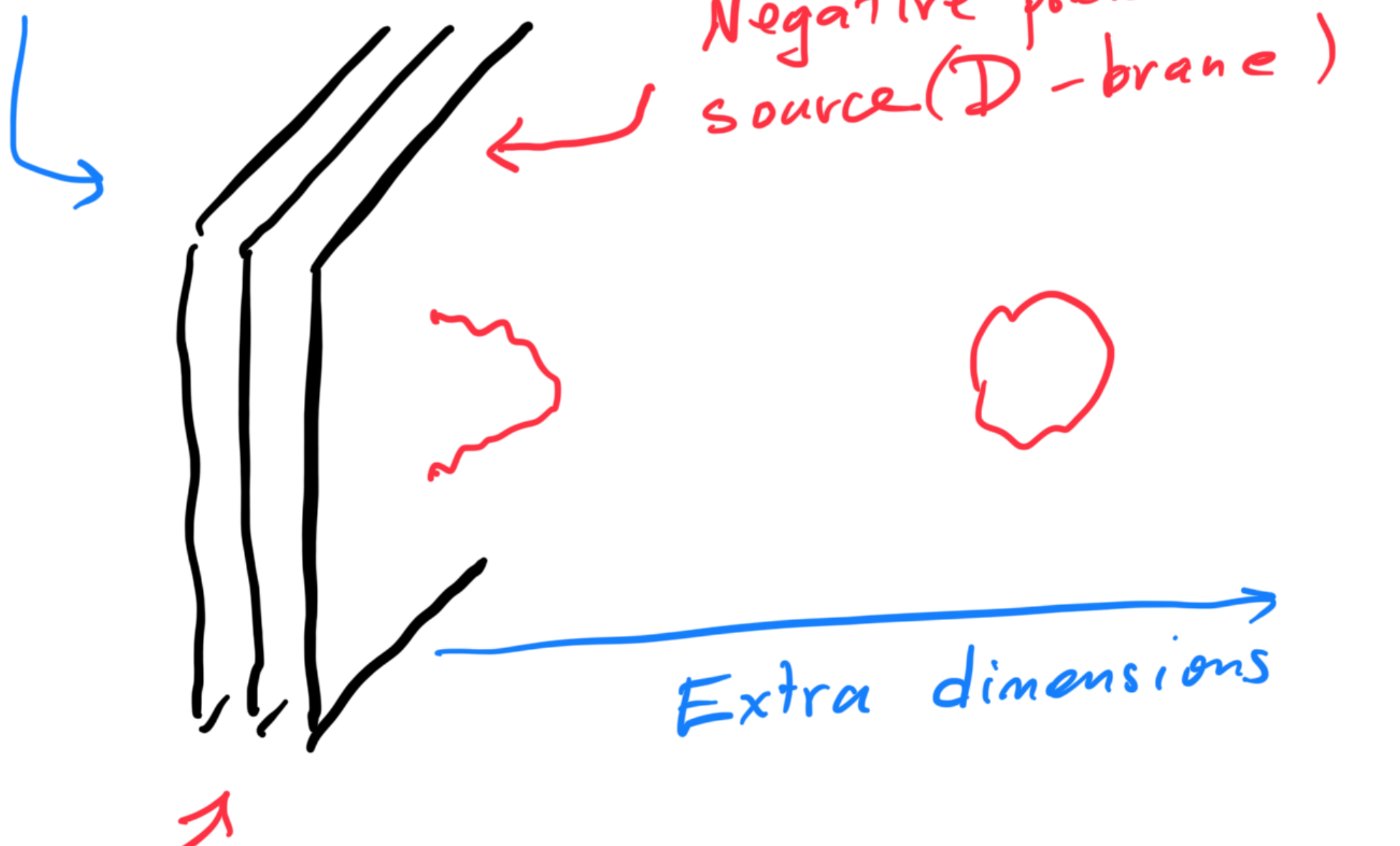


Naturalness can be replaced by Anthropic selection

De Sitter/inflation in String theory

G.D. & Tye '98; G.D. '99;
G.D., Shafi, Solganik '01
Kachru et al '03

D-brane "uplifting"



We see de Sitter/inflation (?)

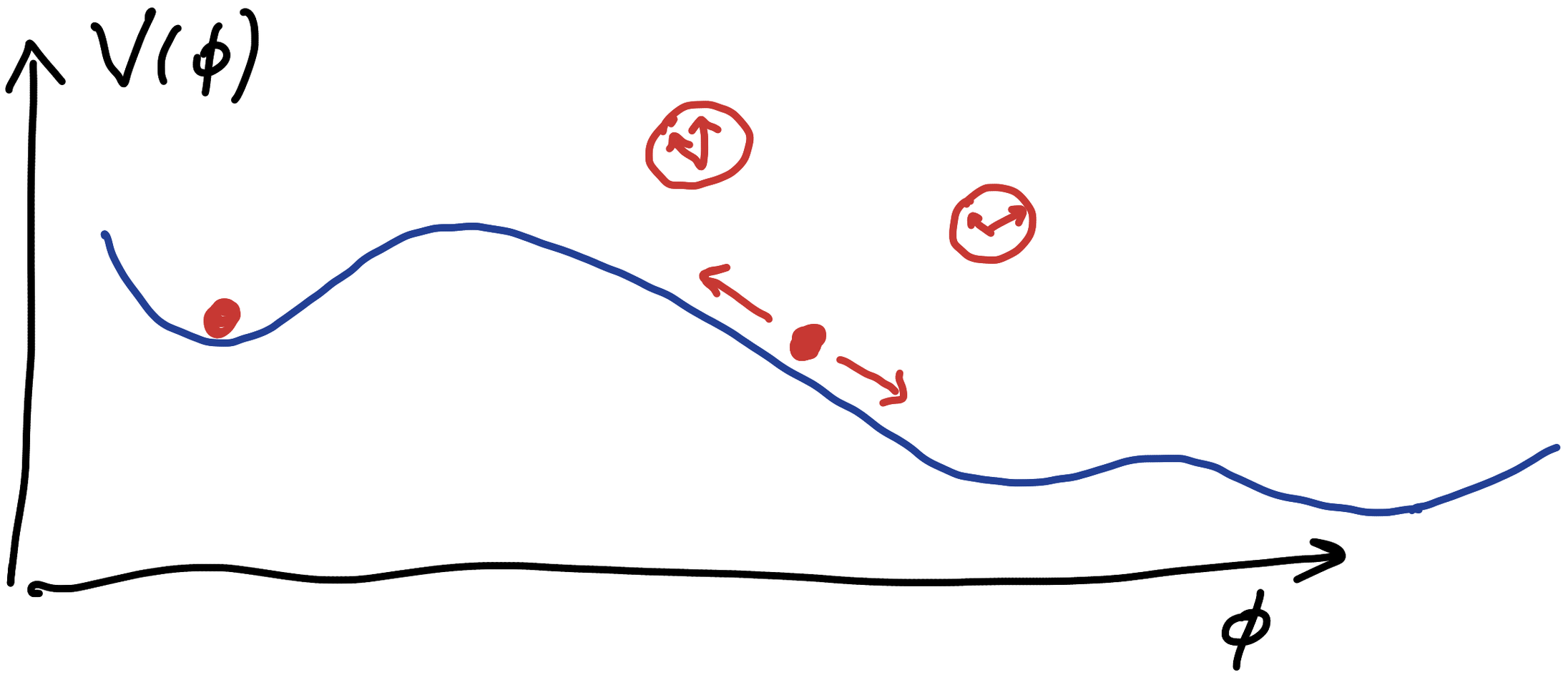
de Sitter landscape would open a way for anthropic selection.

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

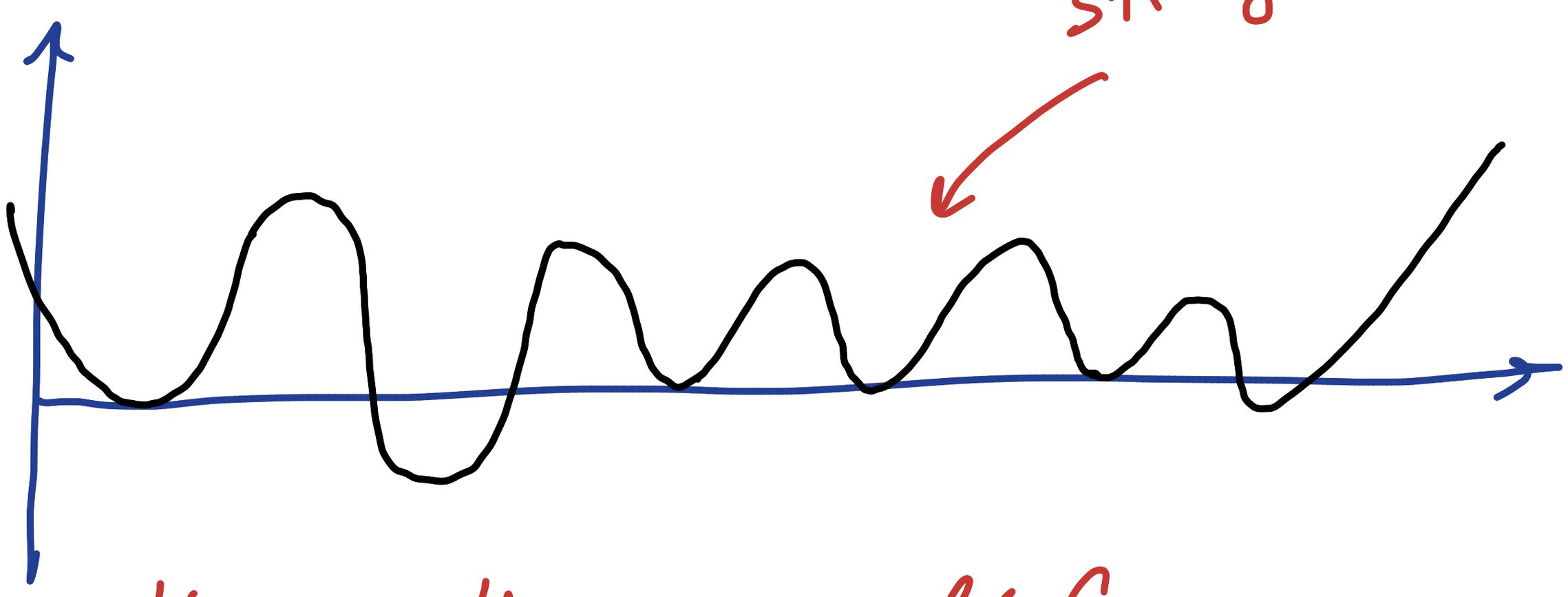
Vilenkin '83; Linde '86; ...



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.

Gravity:

Newton → Einstein → QFT

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

in quantum theory

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

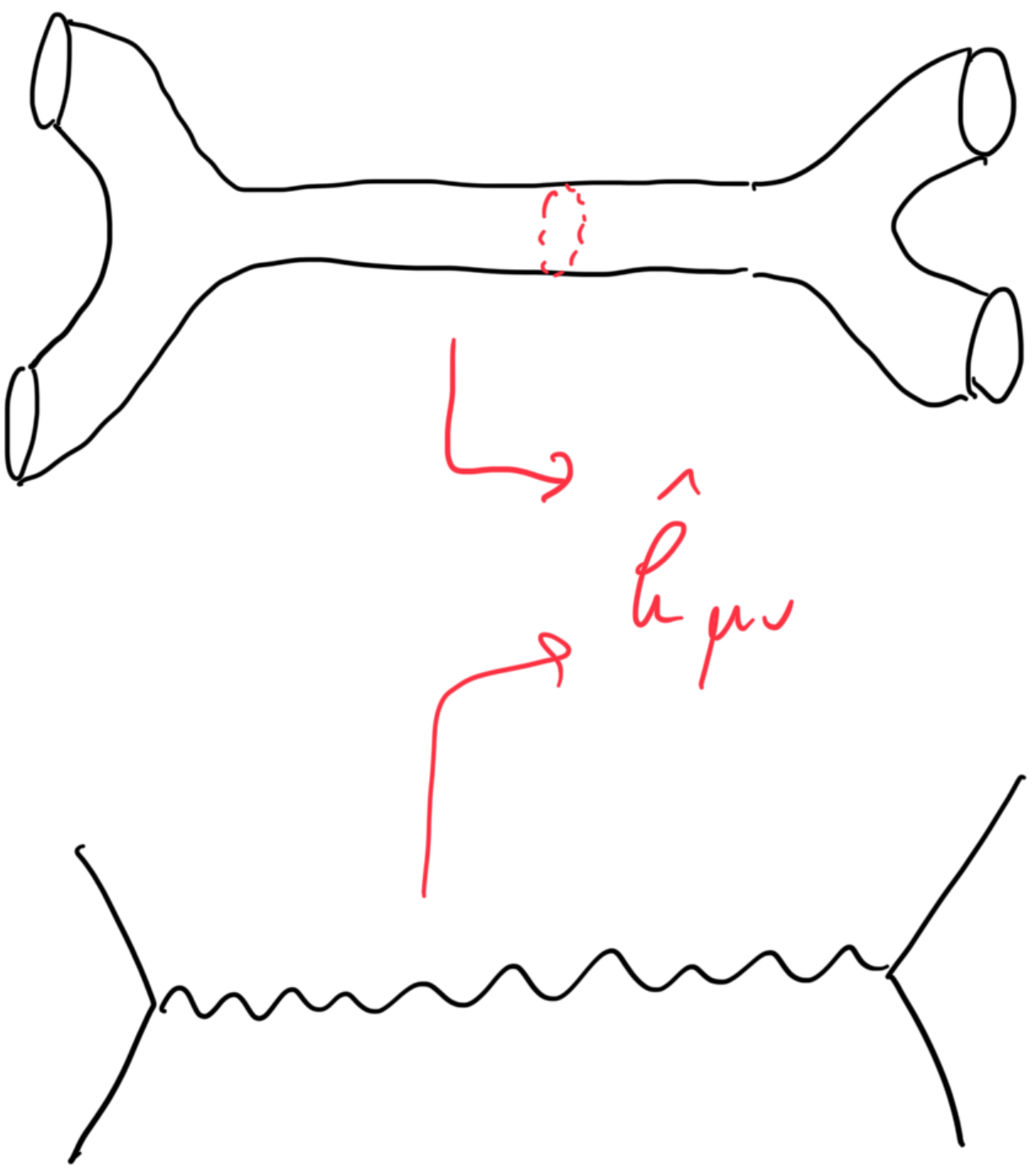
$\hat{h}_{\mu\nu}$ ← graviton

M_P ← Planck mass $\sim 10^{19}$ GeV

$\hat{h}_{\mu\nu}$ → particle with

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

Example: String theory

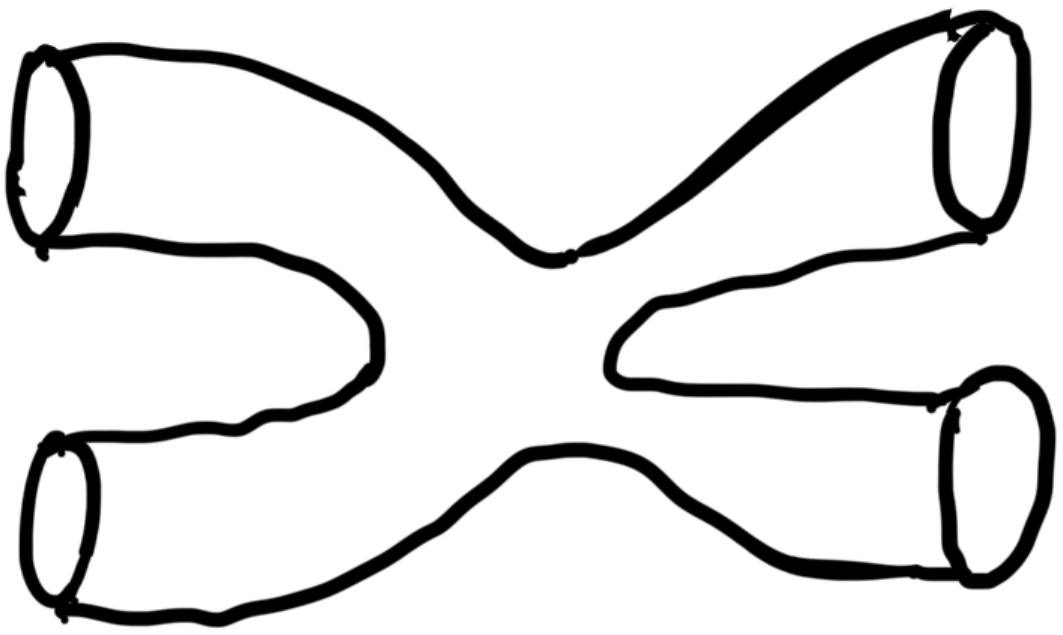


For $r \gg L_s \equiv$ String length

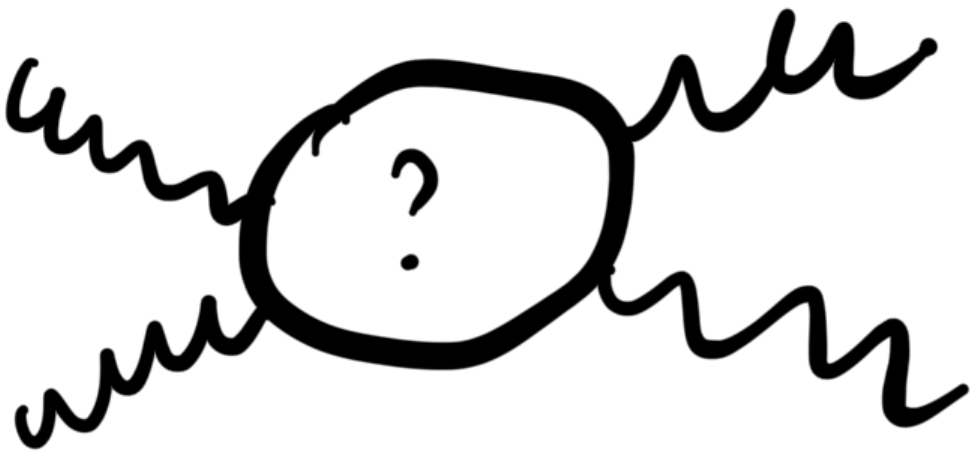
Closed string = graviton

Quantum gravity / String theory

is formulated via S-matrix

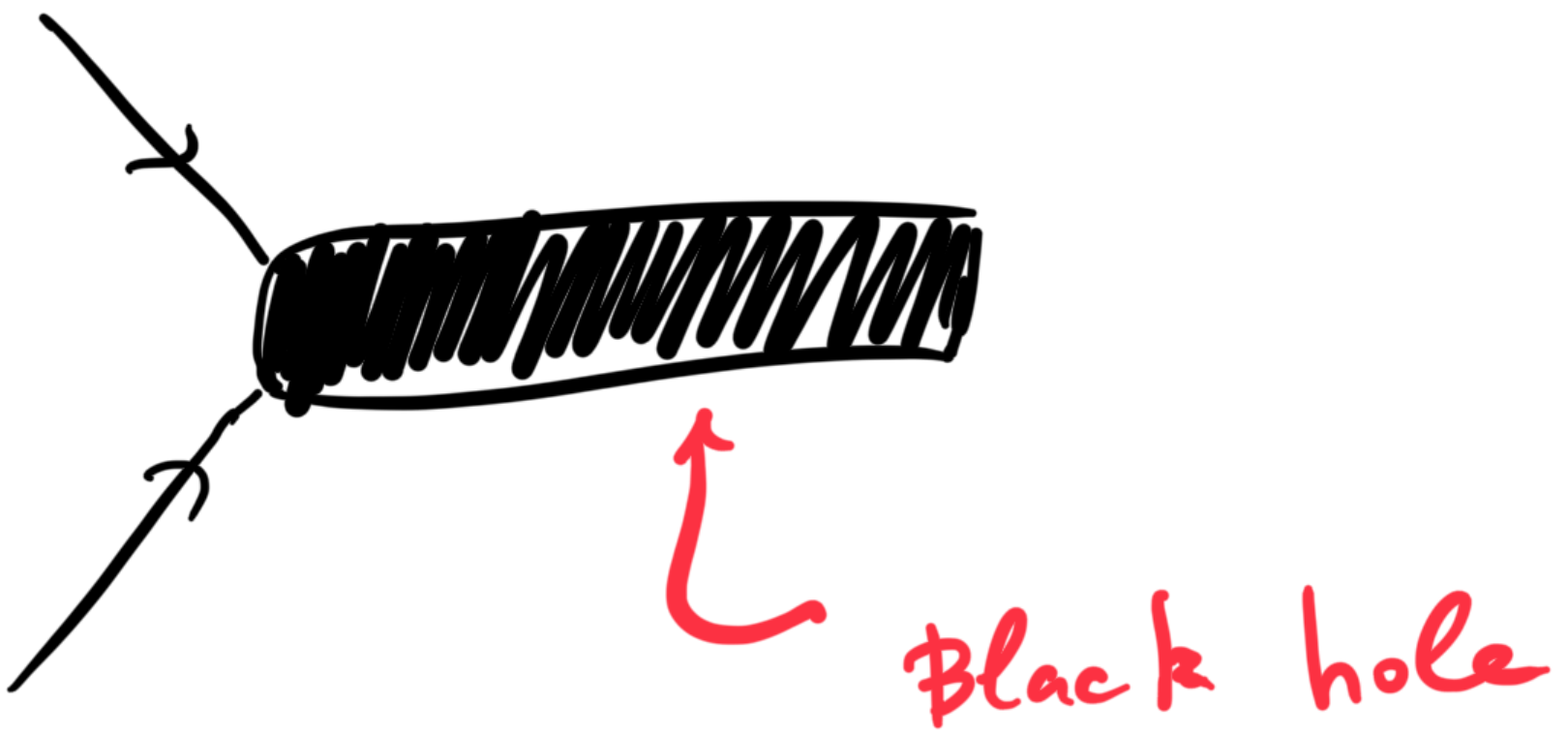


How generic is this?

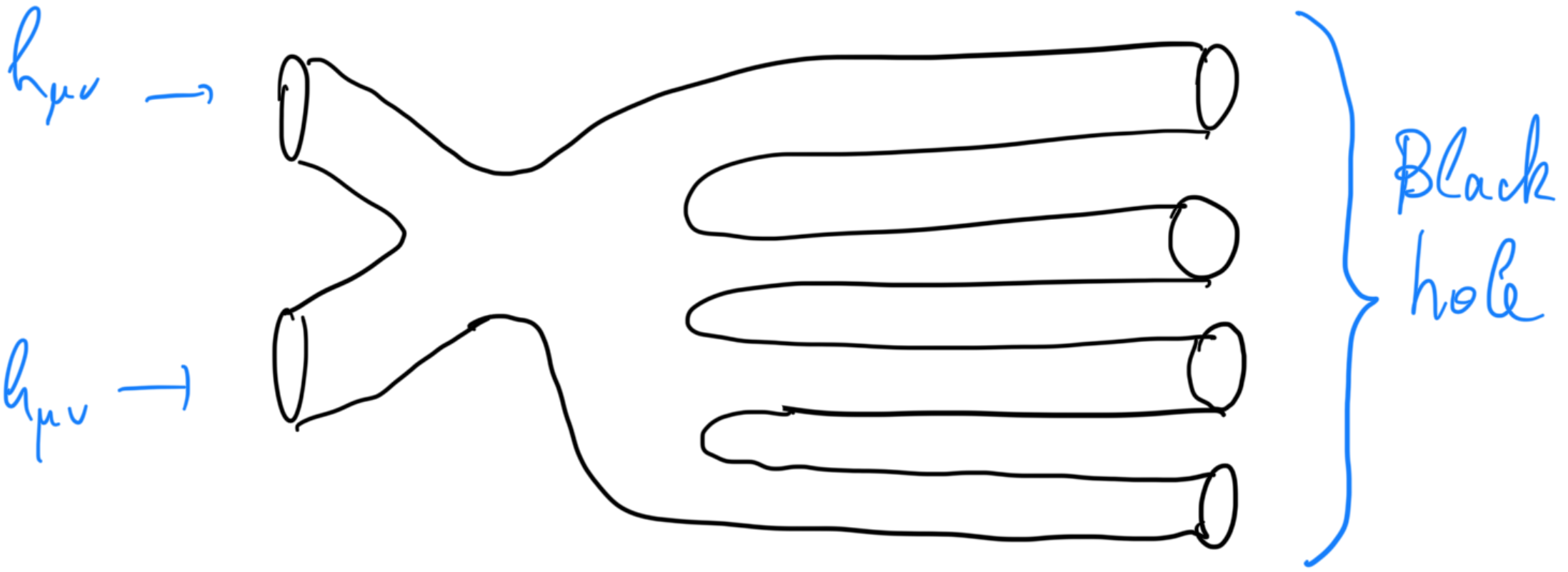


On the other hand, it is known that high energy scattering is dominated by black holes

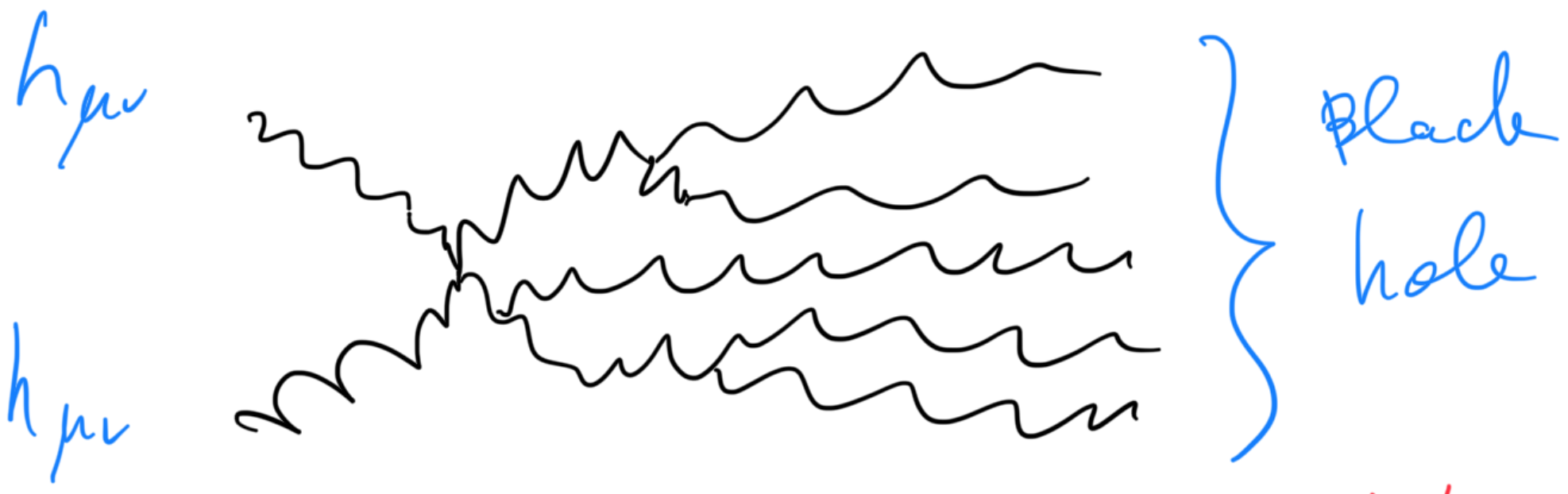
't Hooft '87; Amati, Ciafaloni, Veneziano '87; Gross, Mende '87



S-matrix formulation,



because of black holes, likely extends to arbitrary formulation:



· G.D., Gomez, Isermann, Lüst, Stieberger '14;
Addazi, Bianchi, Veneziano '16

S-matrix is the only existing formulation of quantum gravity.

Organic (but not limited to) string theory.

This puts severe restrictions on vacuum landscape and, in particular, excludes: (see, G.D., 2012 02133 [hep-th] 2209 14219 [hep-ph])

- ⊛ de Sitter, (meta)stable
- ⊛ Landscapes that support eternal inflation (Vilenkin '83, Linde '86)

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

- ⊛ Big crunch cosmologies;
- ⊛ All cosmologies with non-S-matrix-vacua.

Implications for cosmology: Exclusion of de Sitter

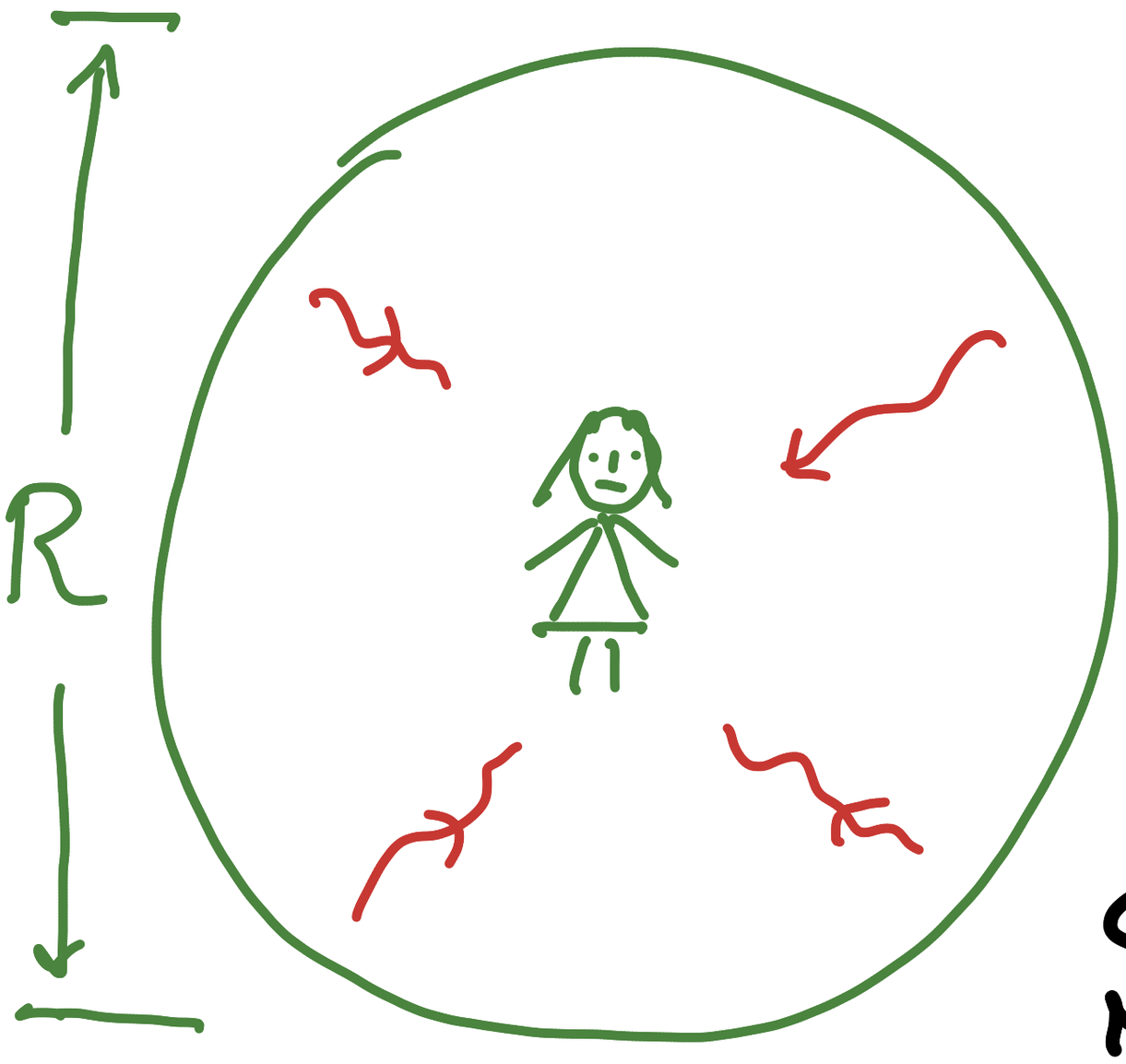
$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2$$

scale factor

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

cosmological constant

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



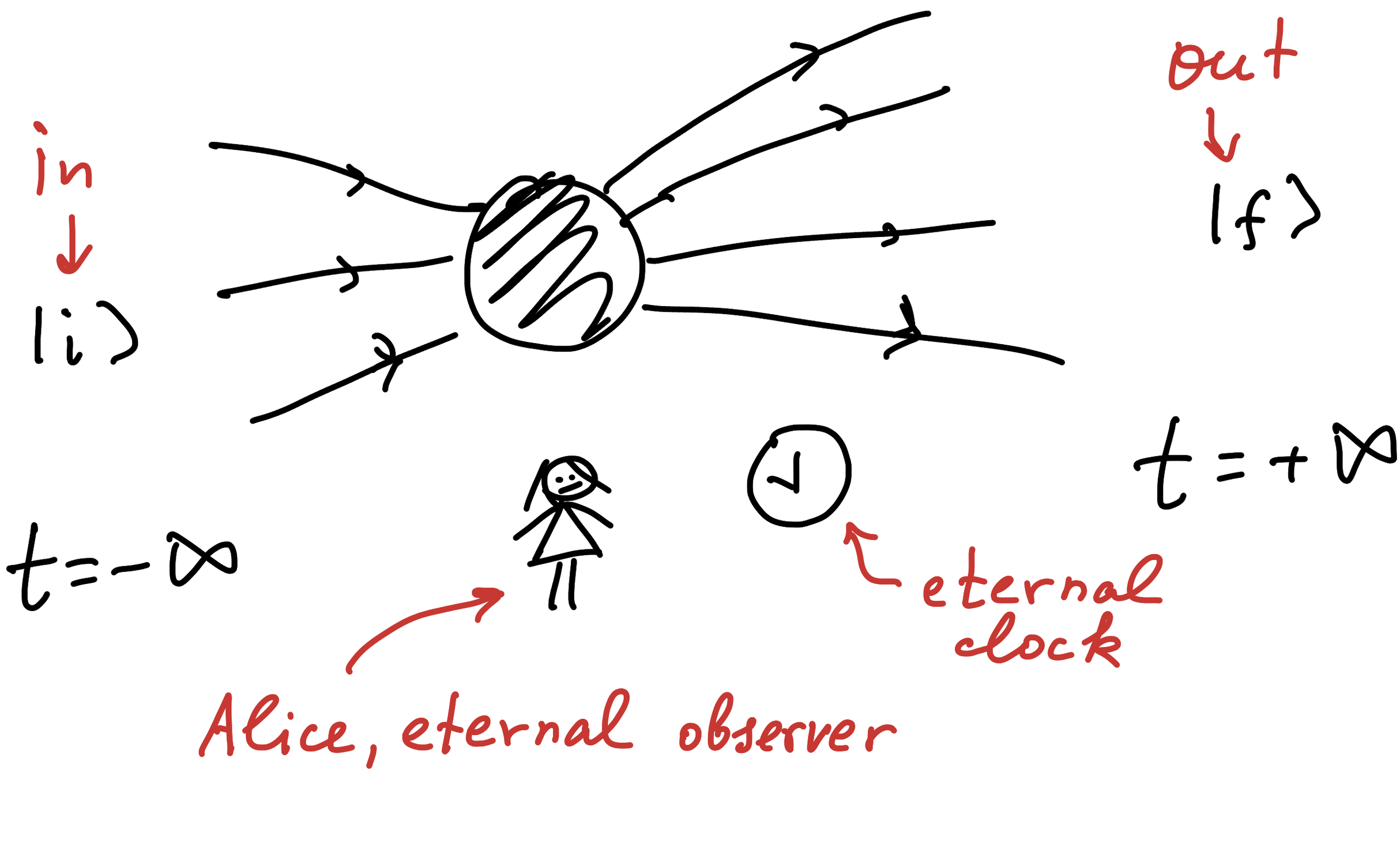
Gibbons-Hawking temperature:

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

and entropy

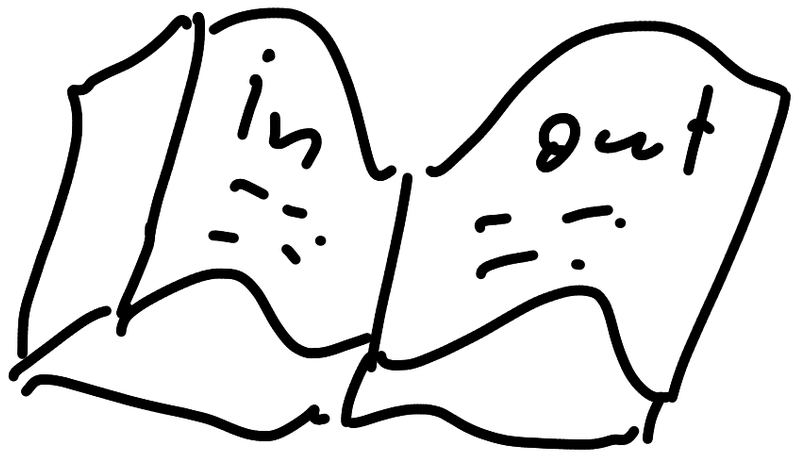
$$S_{GH} = (R M_P)^2$$

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.

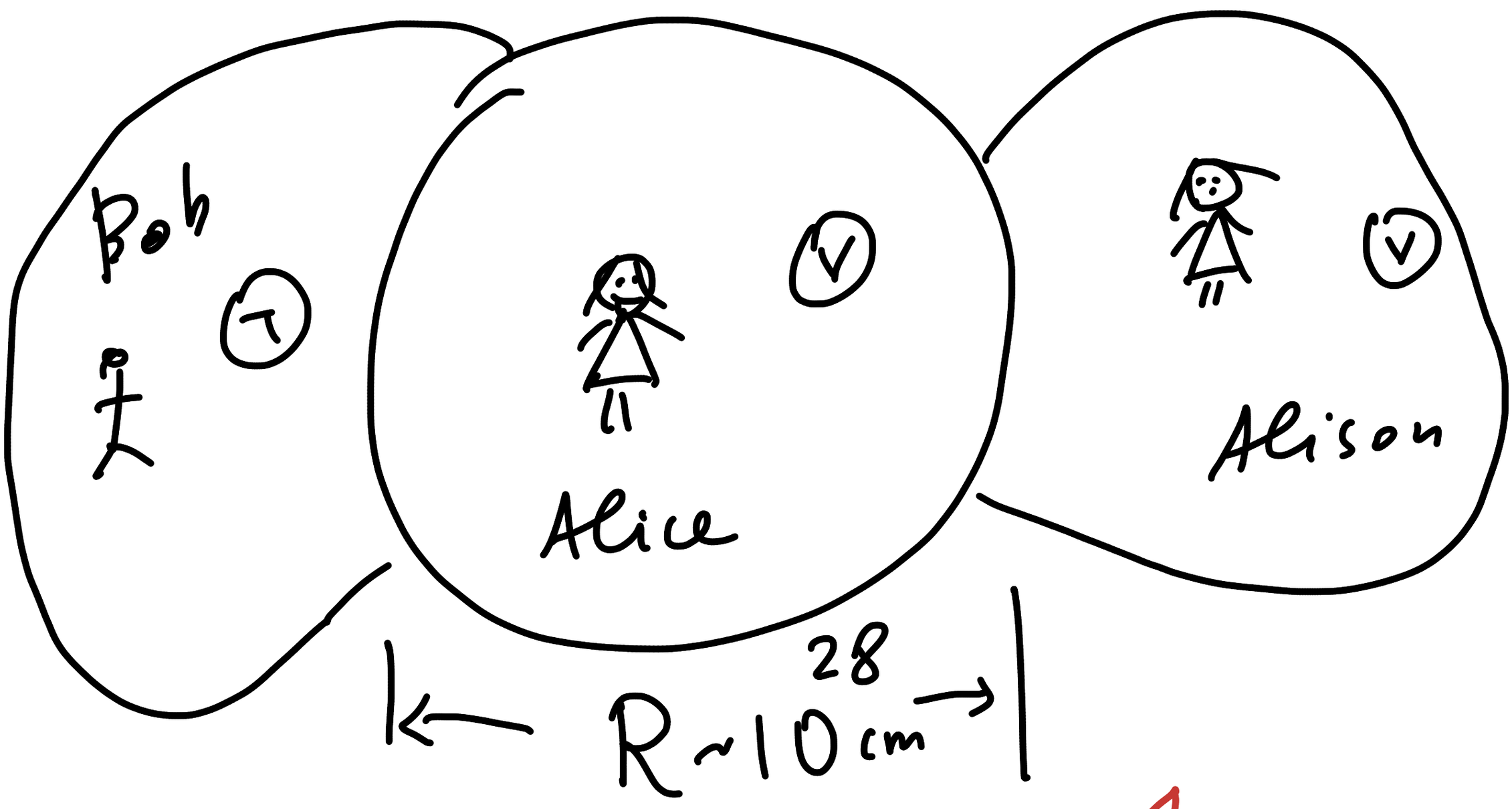
Necesary conditions:

* 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 $|ds\rangle$.

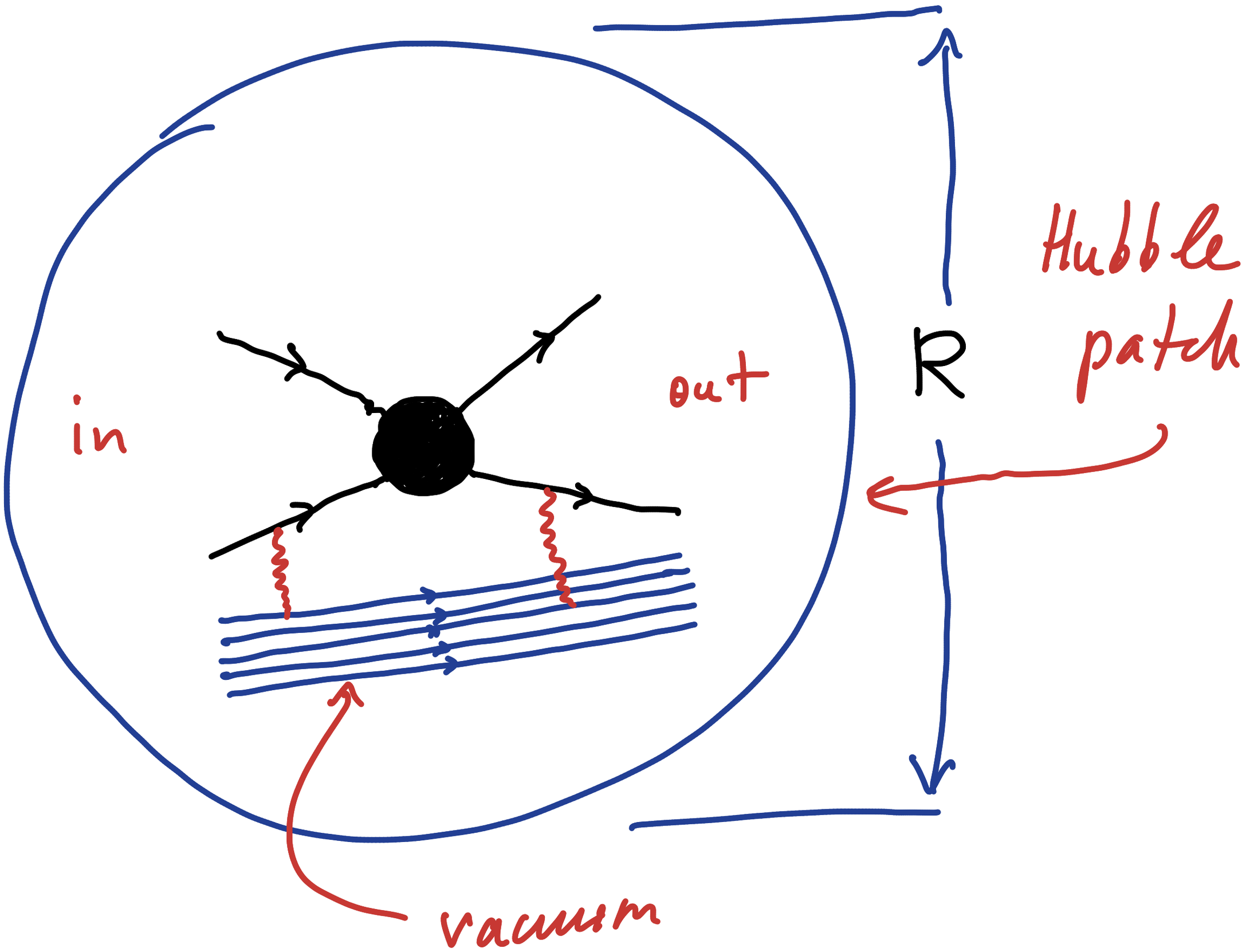


Hubble horizon $\hookrightarrow R = \frac{1}{\sqrt{G_N \Lambda}}$

No global time.

What about quantum theory?

What about effective S-matrix?



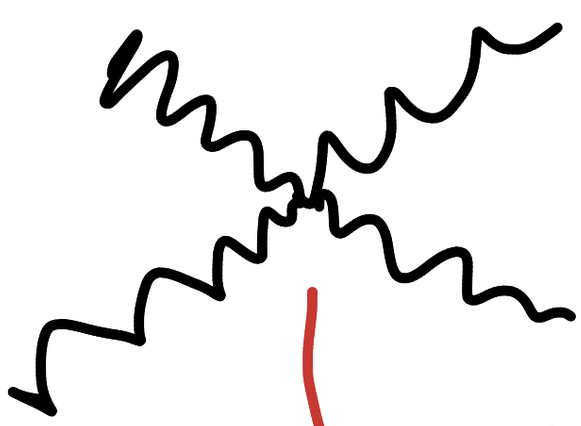
The vacuum should not be able to recoil and absorb some information.

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



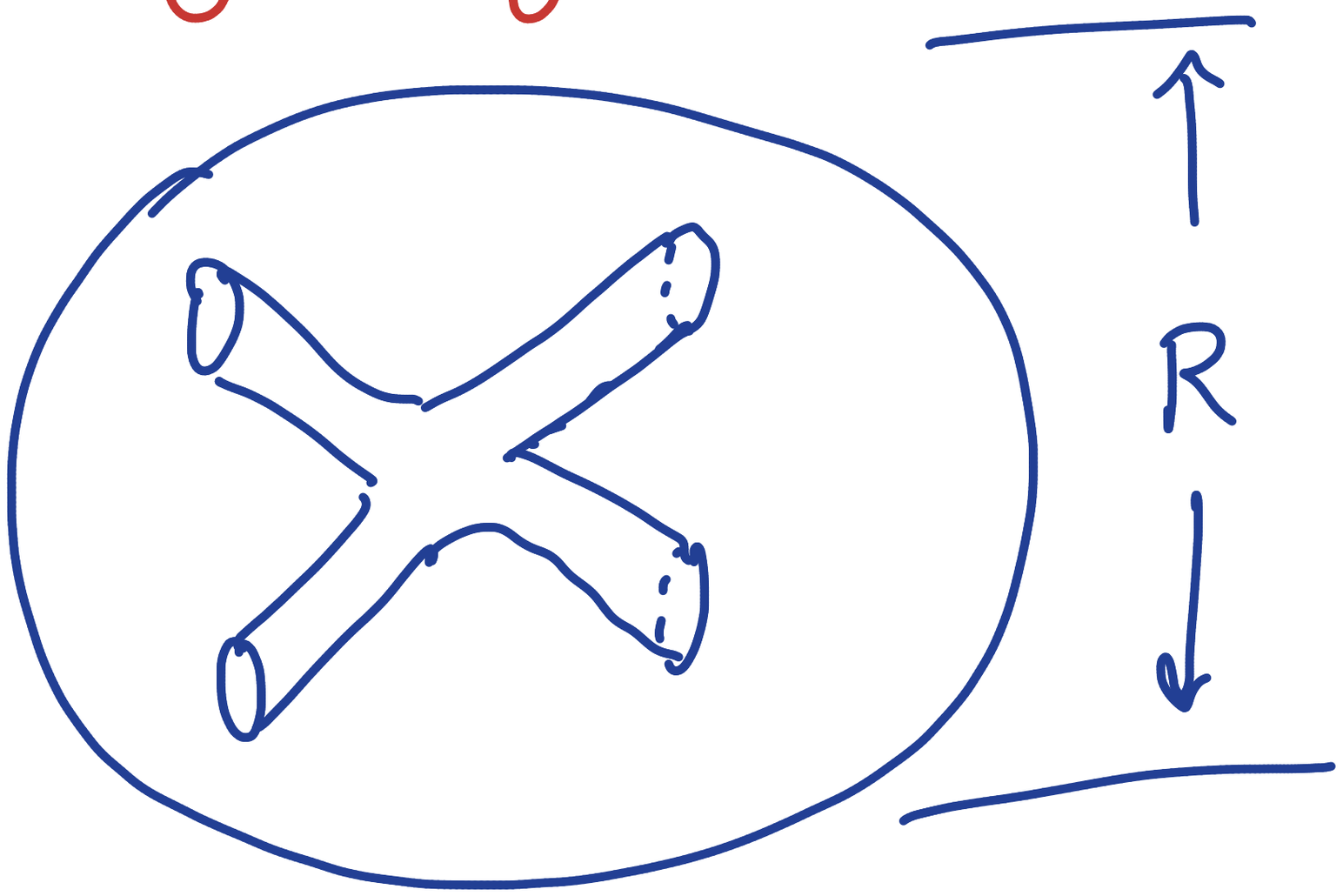
momentum-transfer

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

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:

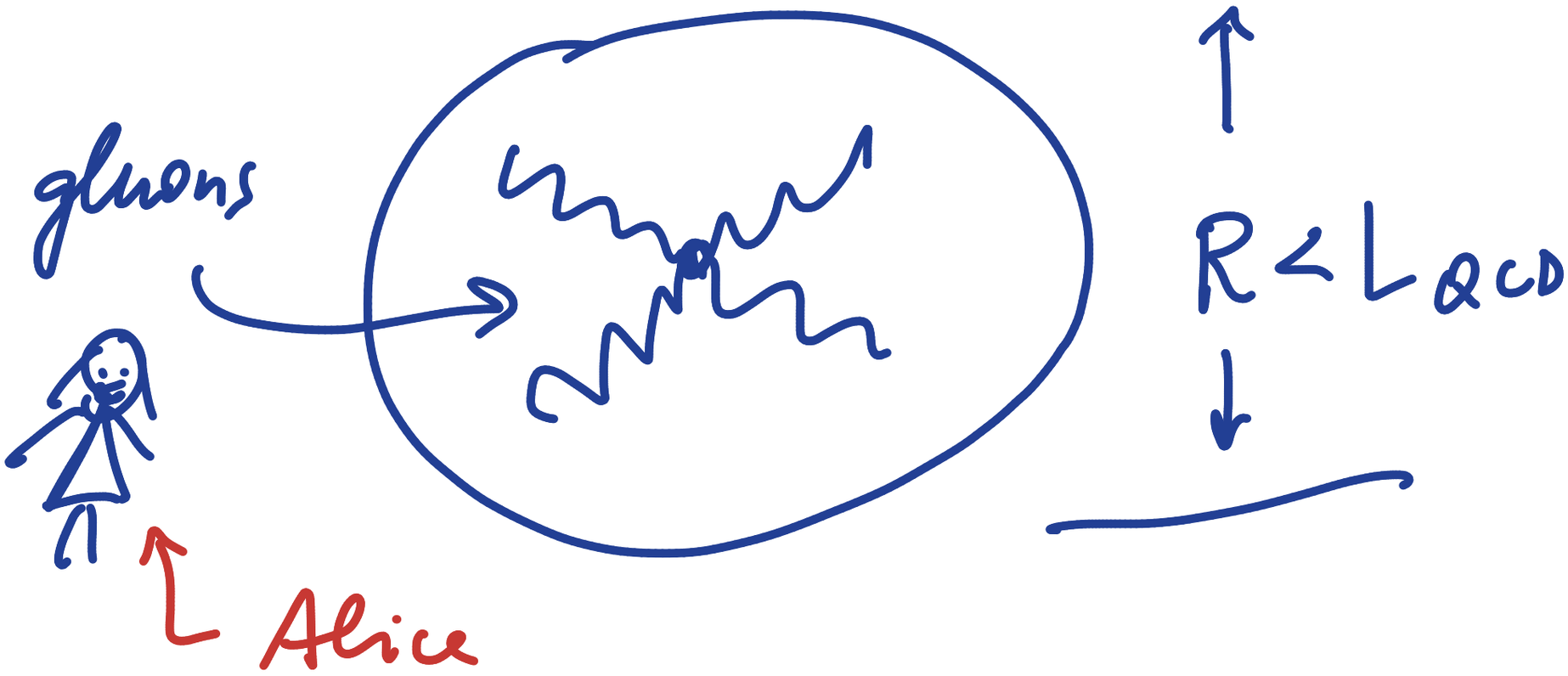
$\Lambda \to \infty$
$G \to 0$
$R = \text{finite}$
$\Big\}$ $\longrightarrow$ $g_s^2 \to 0$

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.

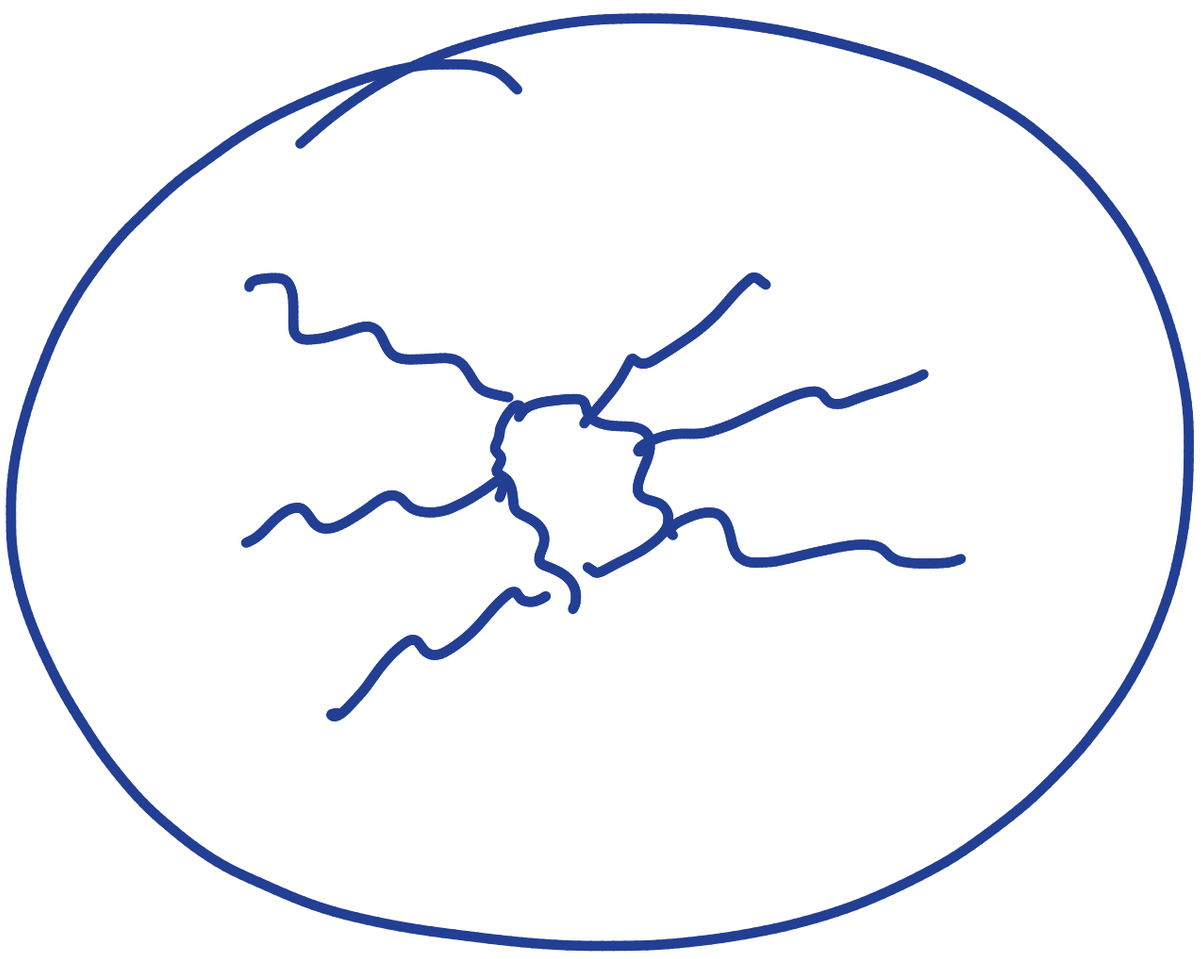
(de Sitter = vacuum) → $\alpha_{gr} = 0$

$g_s = 0$

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

For example, scattering of quanta of center of mass energy

$$E \sim M_p^2 R$$



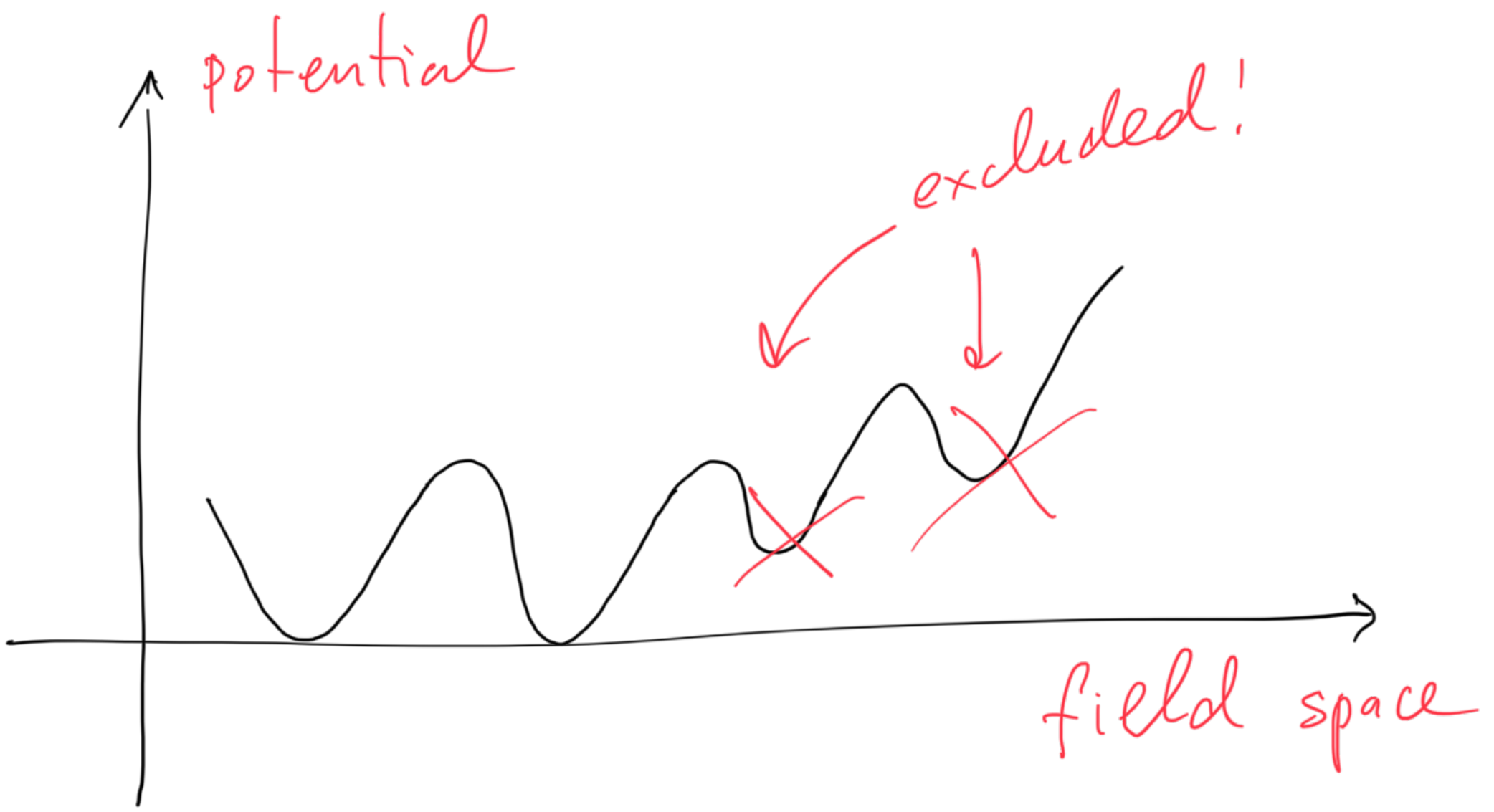
This fixes our framework:

EFT of S-matrix theory

defined on asymptotic

S-matrix vacuum of

Minkowski



First immediate implication:

S-matrix gravity nullifies an outstanding cosmological puzzle:

Cosmological term is Einstein's equation

$$G_{\mu\nu} = T_{\mu\nu} + g_{\mu\nu}\Lambda$$

$\Lambda \to = 0$

Dark energy = New physics

Prediction: Equation of state

$$w > -1$$

(In fact, arguments indicate

$$w + 1 \simeq \frac{1}{260}$$)

Implication for strong-CP prizle

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

$\tilde{\theta}$ - vacua of QCD

$|\tilde{\theta}\rangle$

$\bar{\theta}$ is physical and contributes to EDMN.

The current bound

$$d_n < 2.9 \times 10^{-26} \text{ cm}$$

(Baker et. al. hep-ex/0602020)

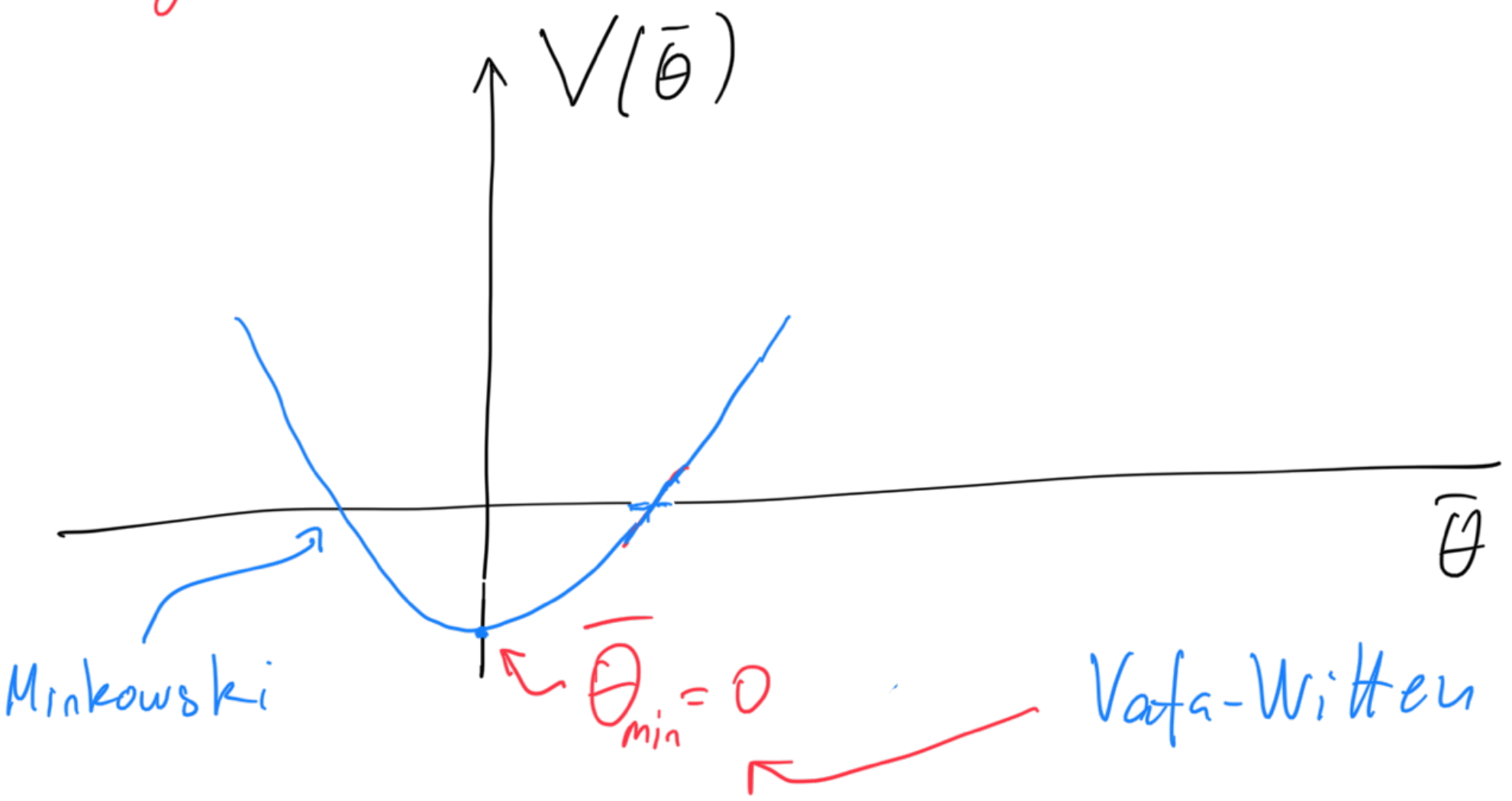
translates as bound

$$|\bar{\theta}| \lesssim 10^{-9}$$

Thus, we live in a vacuum with very small $\bar{\theta}$.

This is the strong-CP puzzle, formulated as naturalness problem.

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

Axion $B_{\mu\nu}$ becomes a longitudinal (Stückelberg) polarization of the 3-form $C_{\mu\nu\alpha}$ and they compose a massive 3-form

$$C^{(massive)}_{\mu\nu\alpha} \equiv C_{\mu\nu\alpha} - f_a \partial_{[\mu} B_{\nu\alpha]}$$

3-form is "Higgsed"

and

the pole at $p^2 = 0$ is removed:

$$\langle c\, c \rangle = \frac{1}{p^2 + M_a^2} + \cdots$$

Correspondigly, $\bar{\theta}$ is unphysical against arbitrary deformations.

The advantage in calculability:

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

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

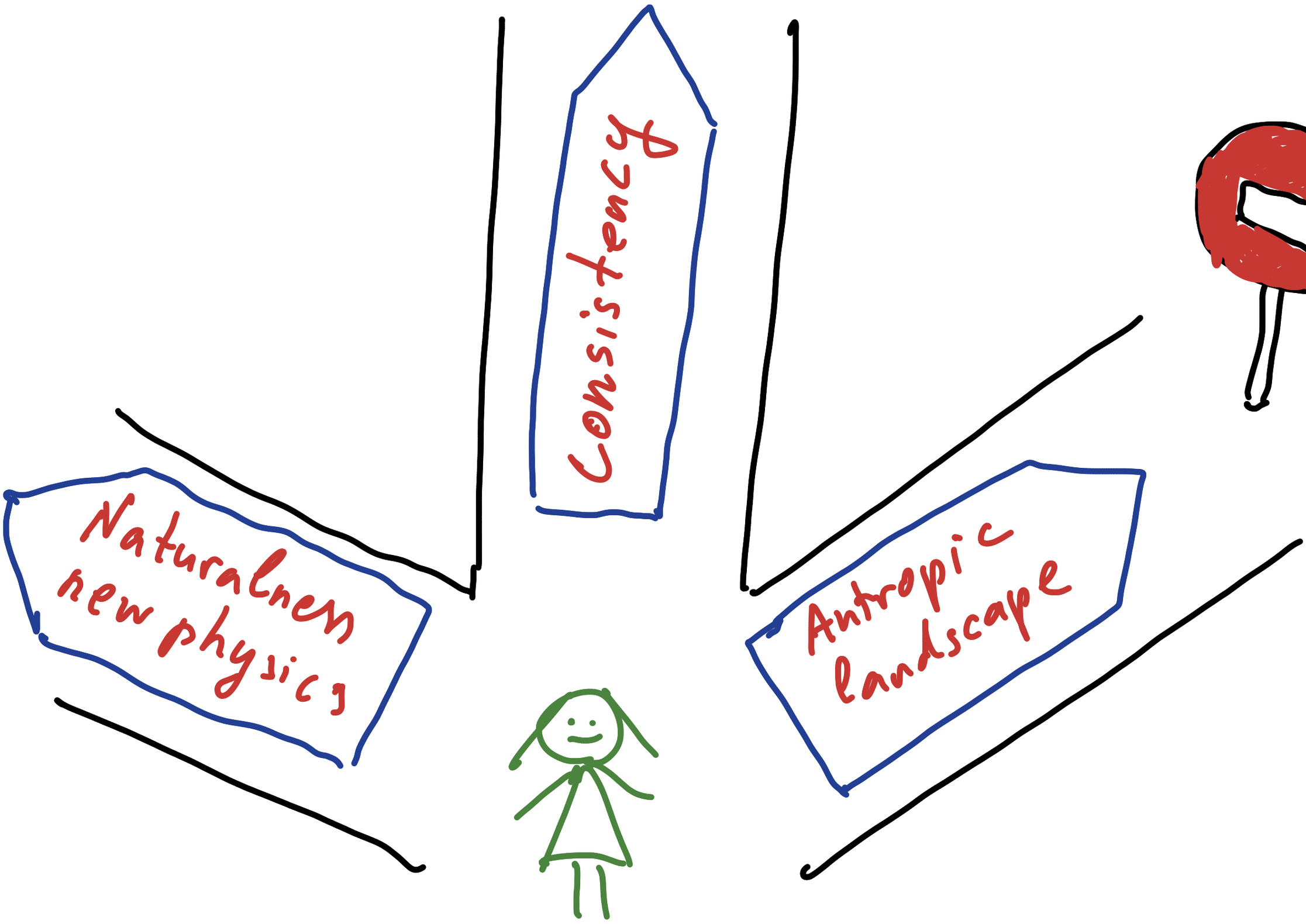
$d_n \sim 10^{-31-32}$ cm Shabalin '79

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