S-Matrix Exclusion of de Sitter and Consequences

Gia Dvali

LMU - MPI (Munich)

2012.02133 [hep-th]
Symmetry 13 (2020) 1,3

JCAP, 1 (2014) 23,
Ann. Phys. 2016, 528, 68 } + Gomez

JCAP, 06 (2017) 028 } + Gomez, Zell

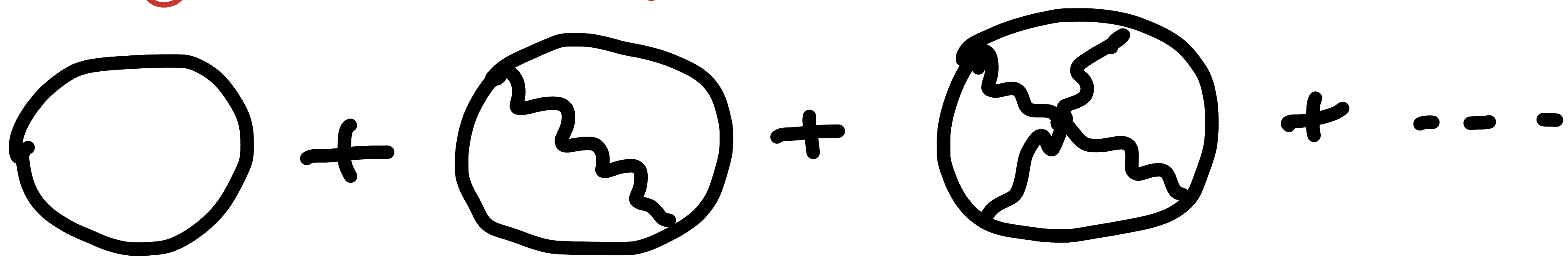
The most celebrated Hierarchy problem (and its absence thereof)

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:

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

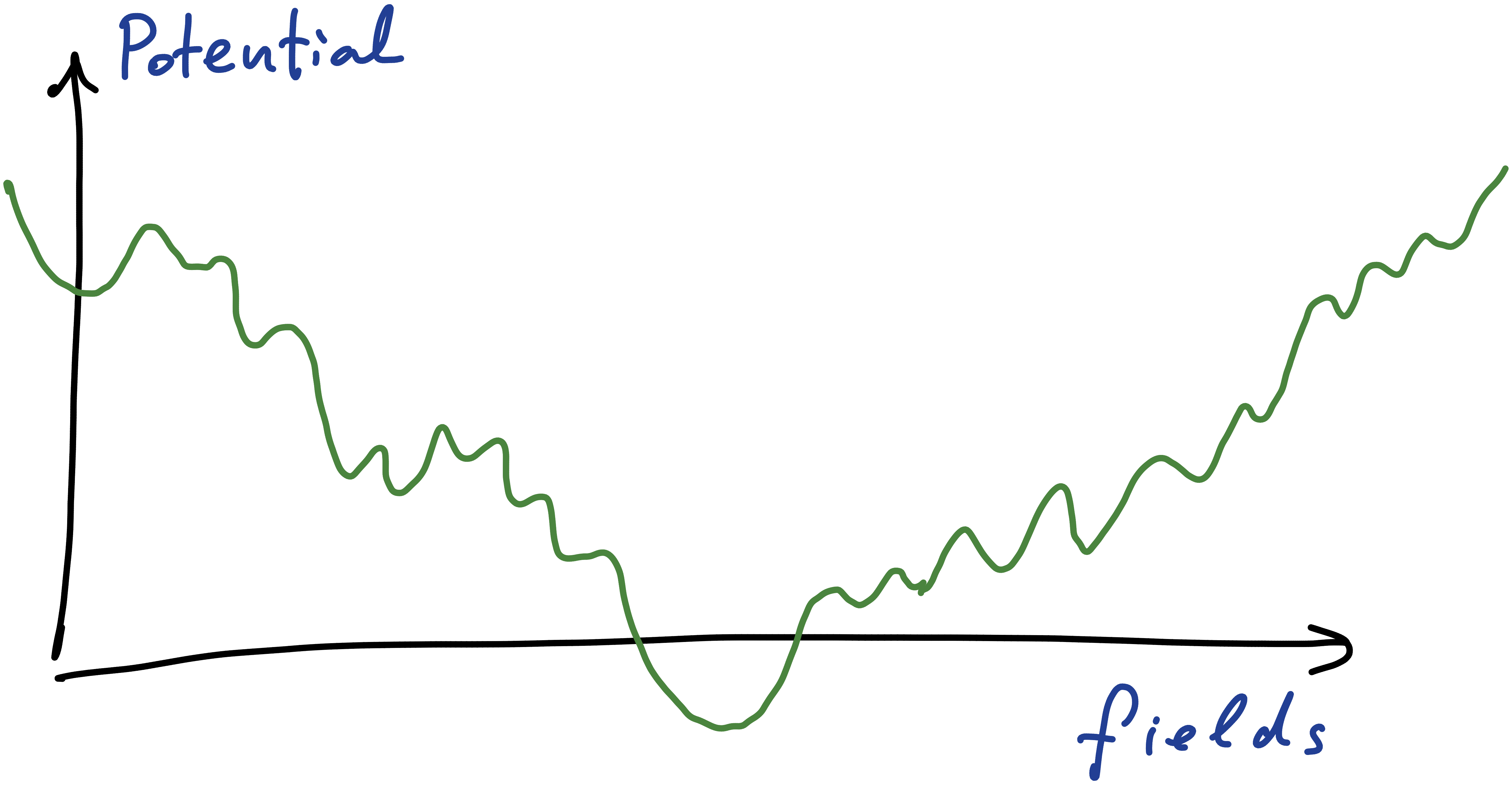
Observational bound:

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

Naturalness problem:

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

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



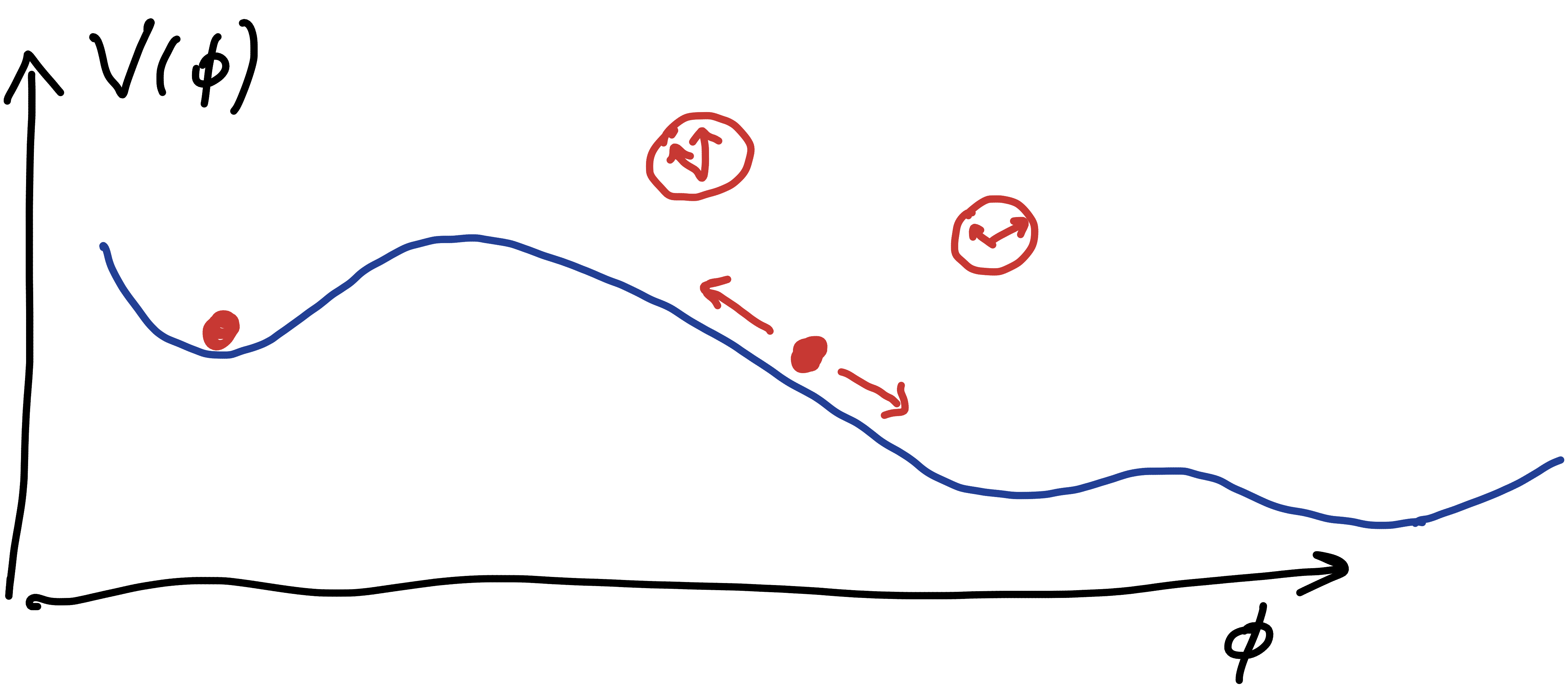
Naturalness can be replaced
by Anthropic selection

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.

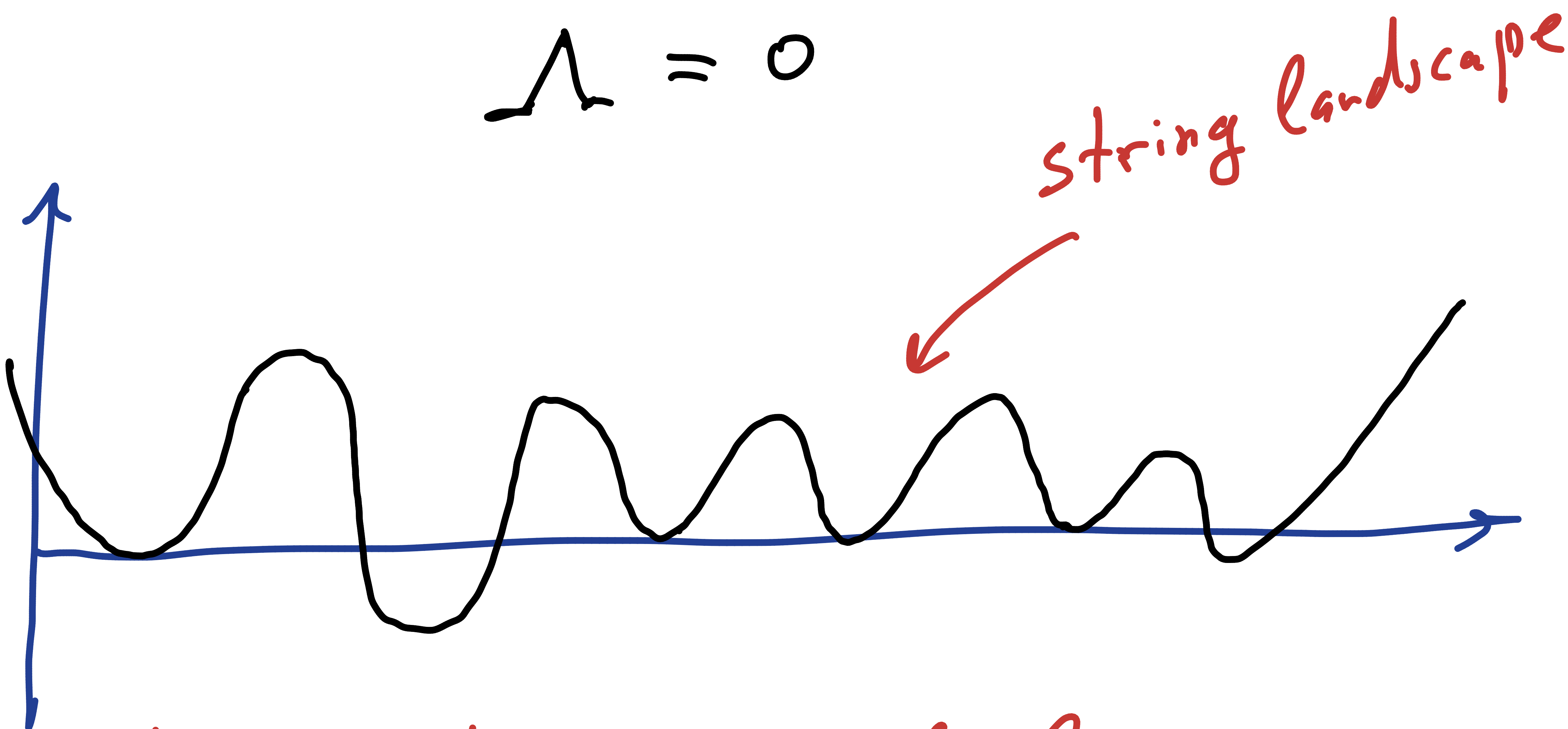
de Sitter landscape can provide an <u>actualization mechanism</u> via <u>eternal inflation</u> Vilenkin '83; Linde '86; ...



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

Gravity:

Newton → Einstein → QFT

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}$$

in quantum theory

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

graviton

Planck mass $\sim 10^{19}$ GeV

$\hat{h}_{\mu\nu} \rightarrow$ particle with

Spin $= 2$, $m = 0$

$\mathcal{S}$-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-$\mathcal{S}$-matrix-vacua.

Implications for cosmology: Exclusion of de Sitter

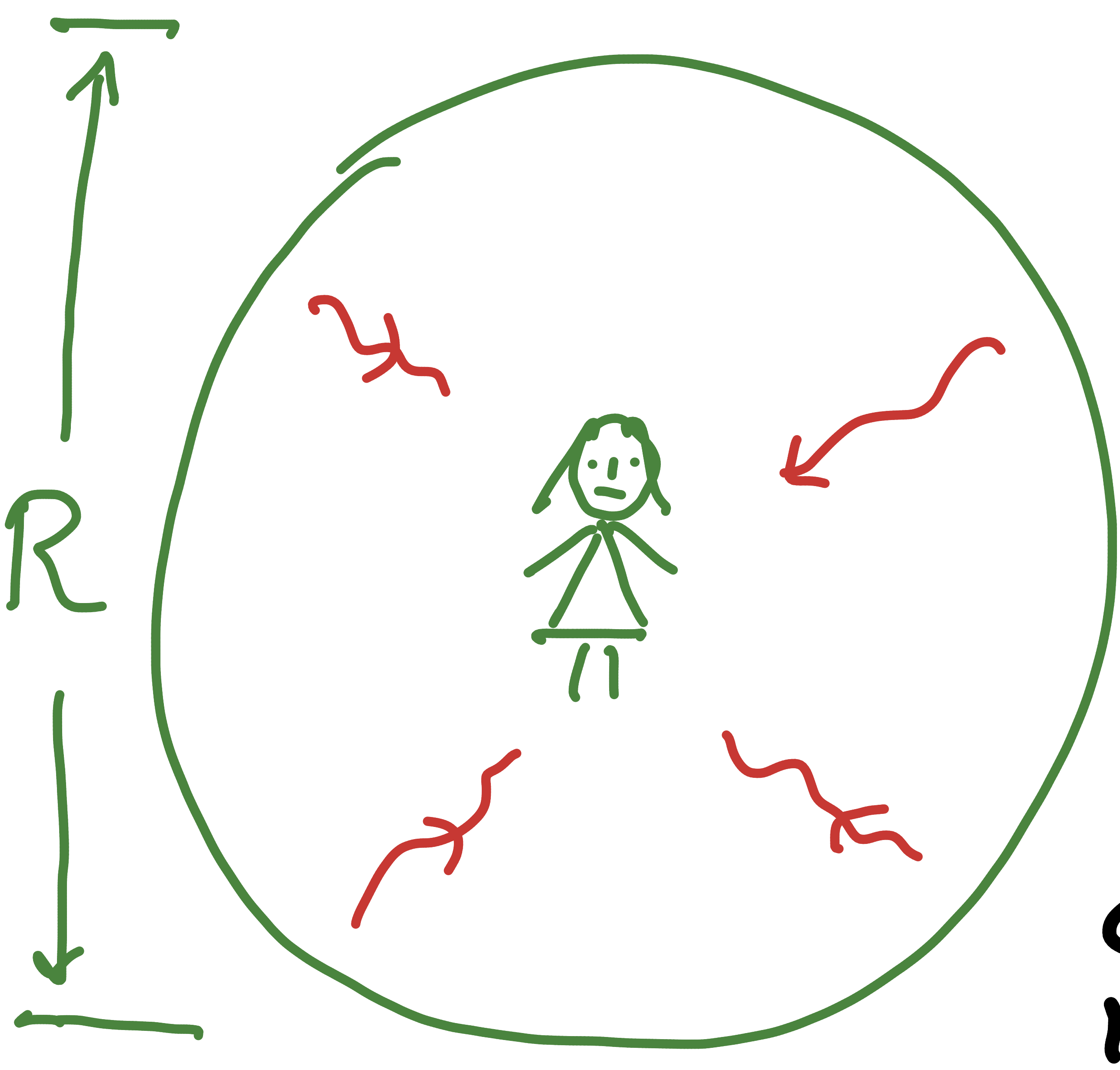
$$ds^2 = dt^2 - a^2(t)\, dx^2$$

scale factor

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

cosmological constant

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



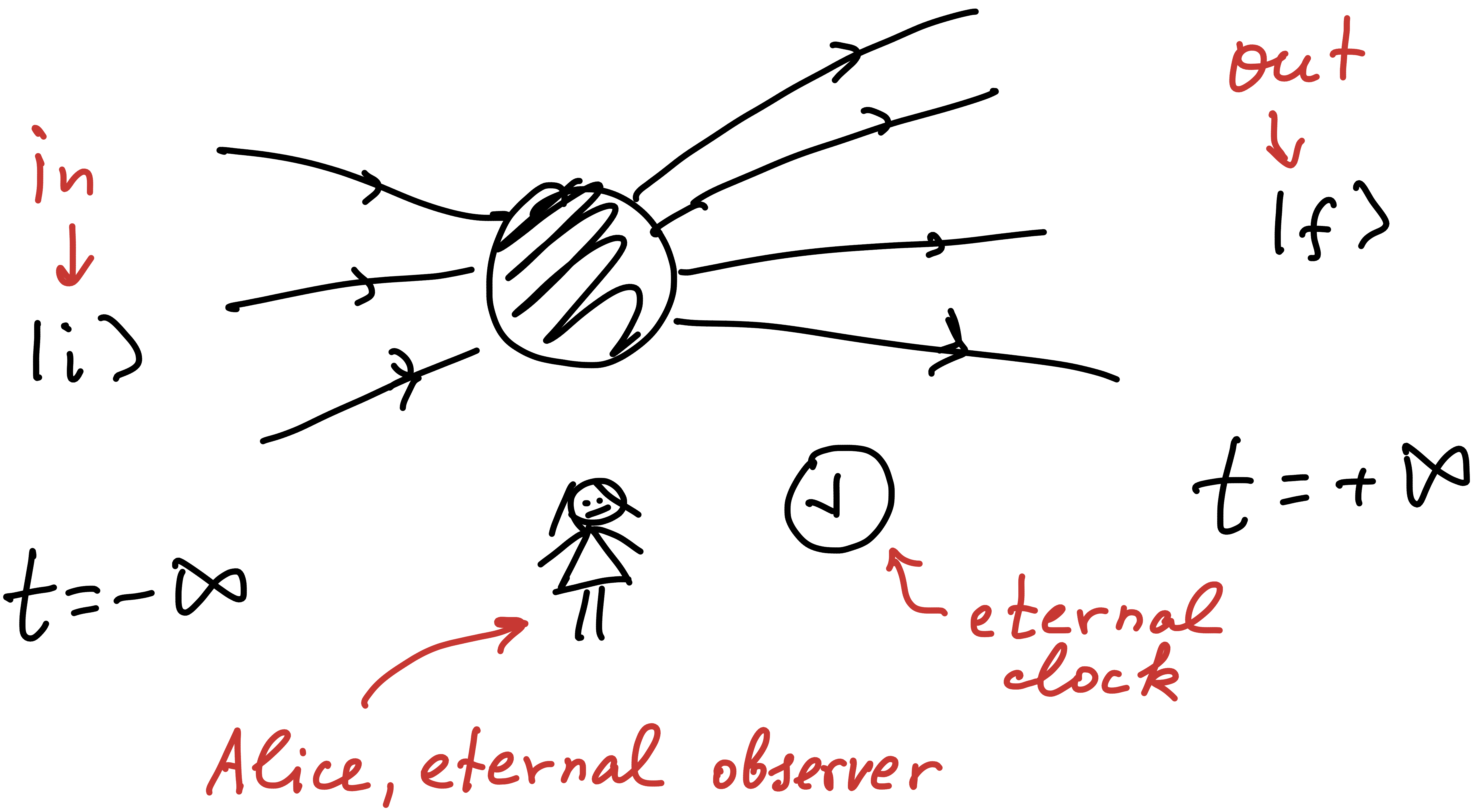
Gibbons-Hawking temperature:

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

and entropy

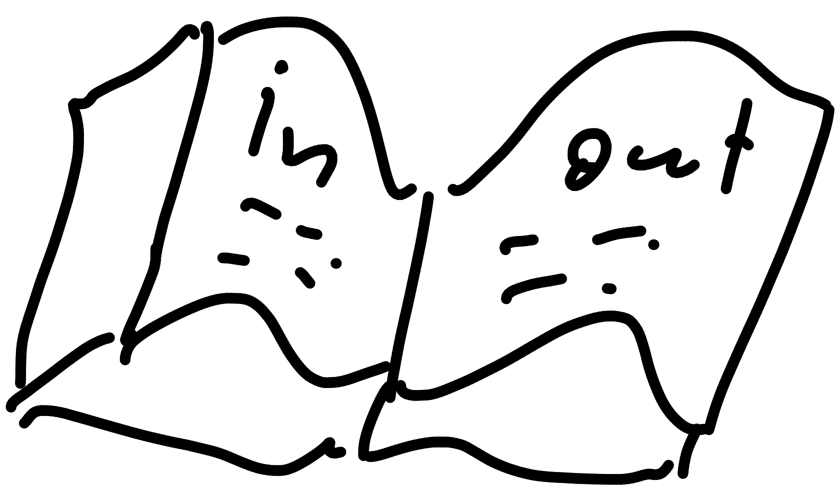
$$S_{GH} = (R M_P)^2$$

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.

Necessary conditions:

⊛ Globally-definet time;

Absent in classical de Sitter

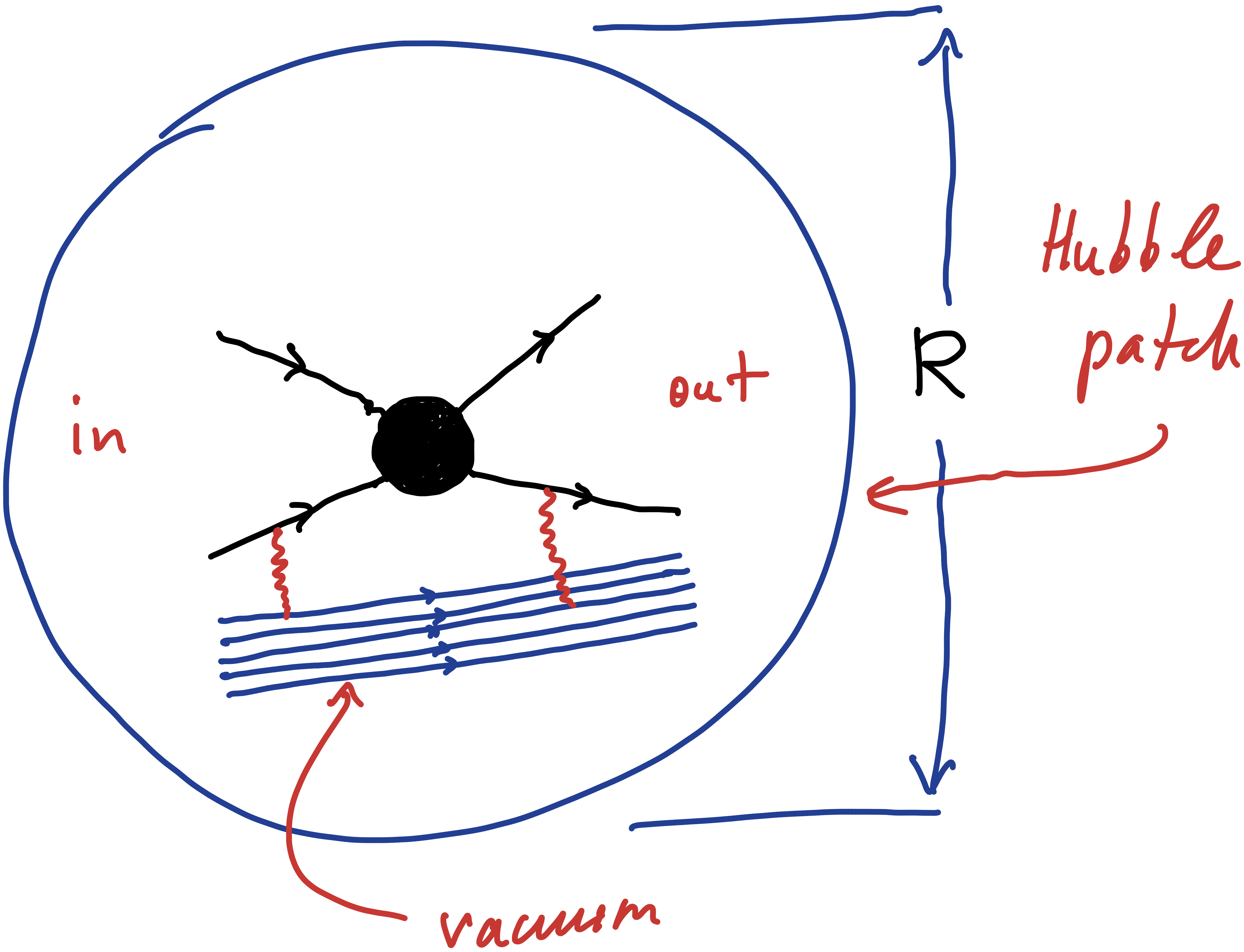
⊛ S-matrix vacuum.

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

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

No global time.

What about quantum theory?
What about effective $\mathcal{S}$-matrix?



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

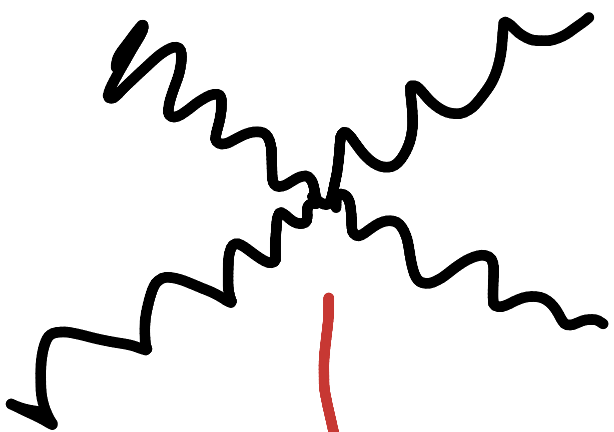
This is only possible in double-scaling limit:

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

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

But in the same limit graviton quantum coupling vanishes

momentum-transfer

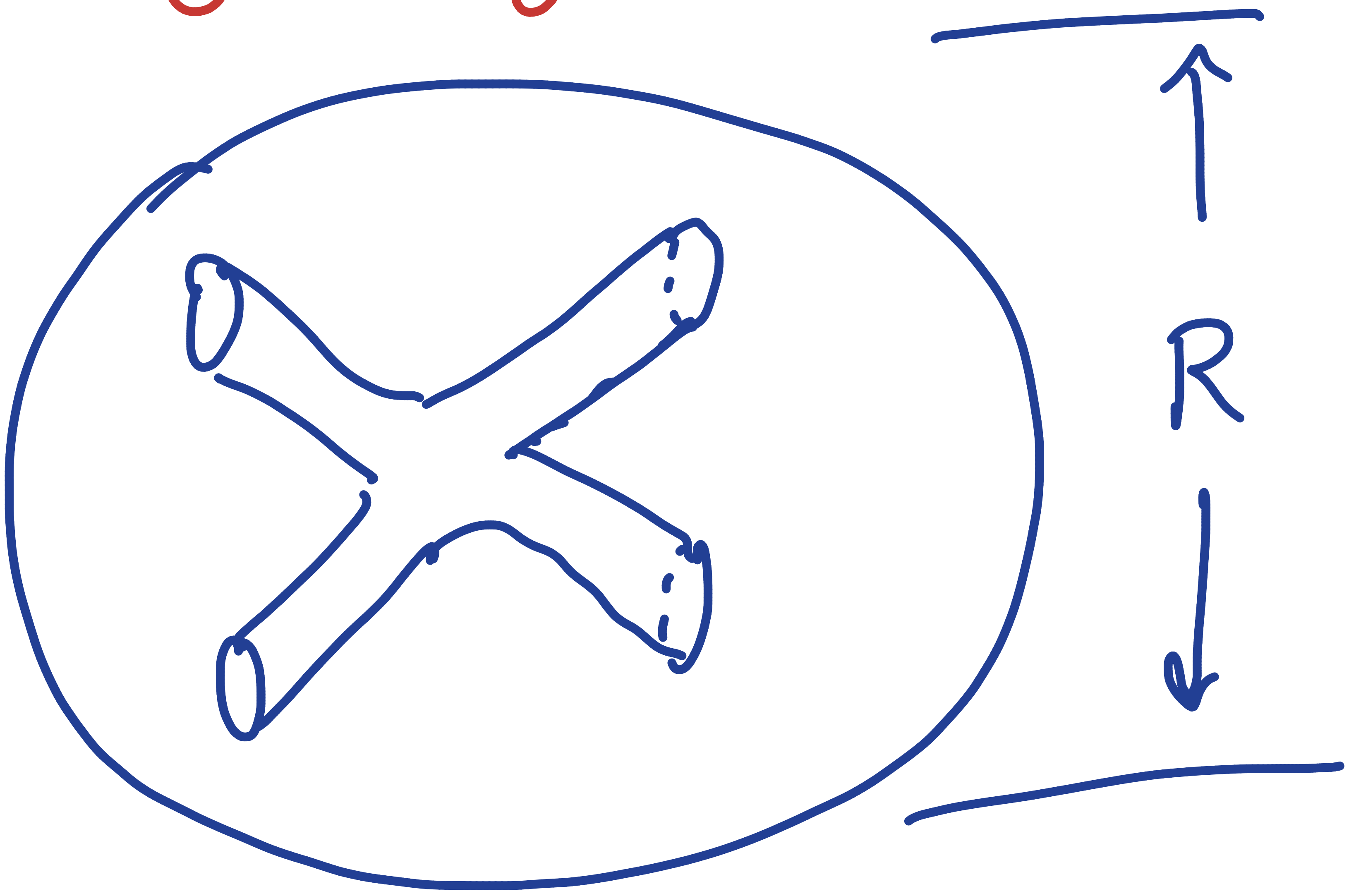


$$\alpha_{gr} = \frac{G}{\lambda^2} = \frac{q^2}{M_p^2} \to 0$$

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:

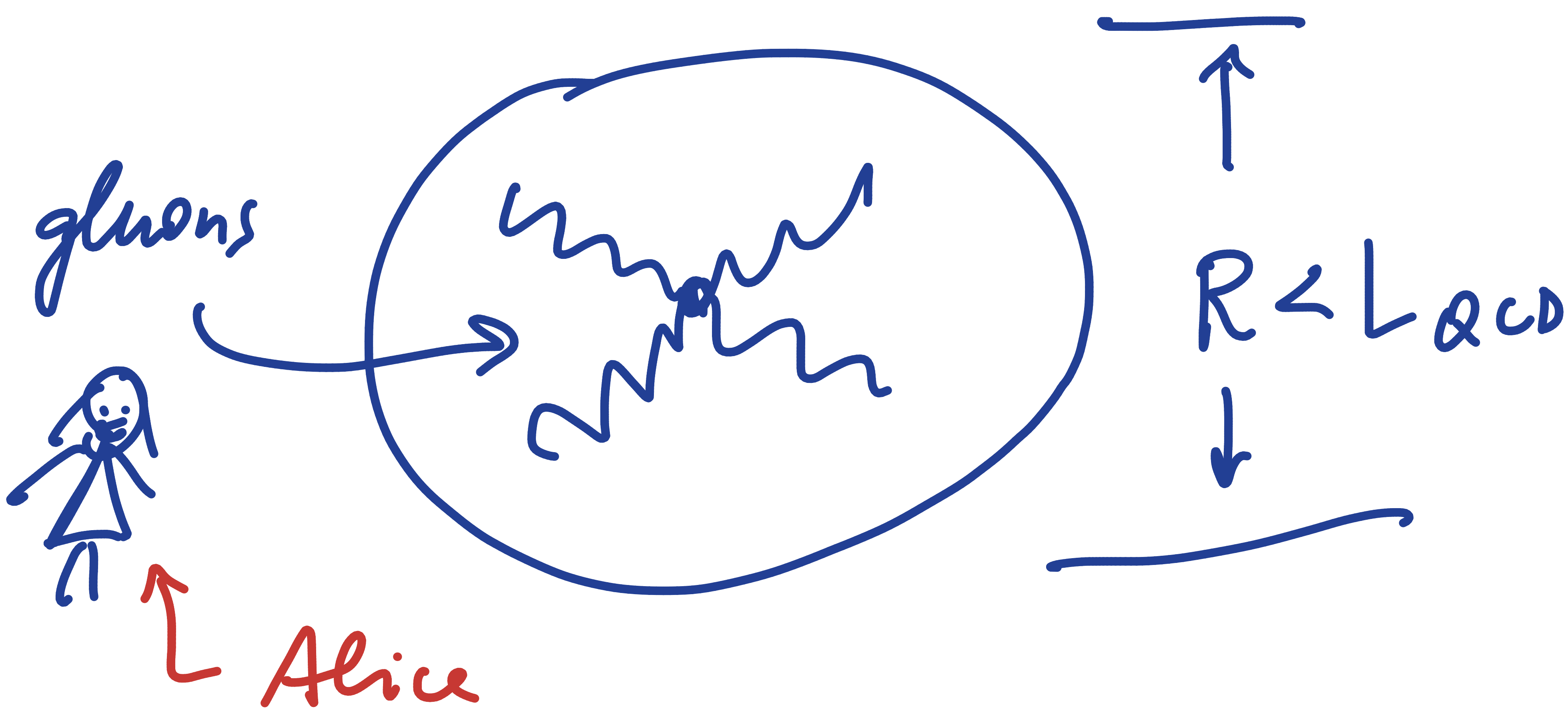
$$\left.\begin{array}{l} \Lambda \to \infty \\ G \to 0 \\ R = \text{finite} \end{array}\right\} \to \quad g_s^2 \to 0$$

Closed string S-matrix is trivial.

(Open strings, more subtle)

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

E.g. QCD



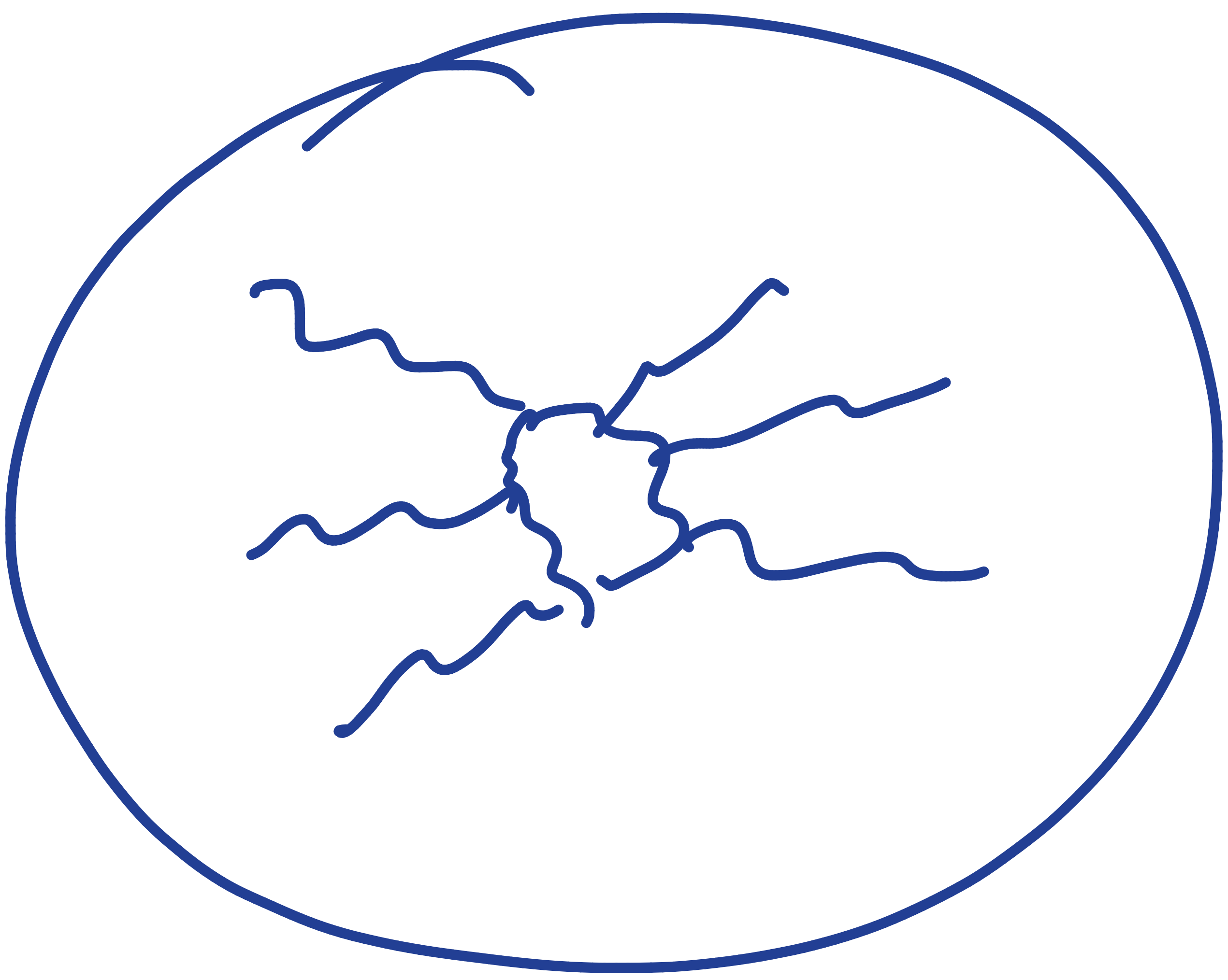
Thus, the issue is quantum gravitational.

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

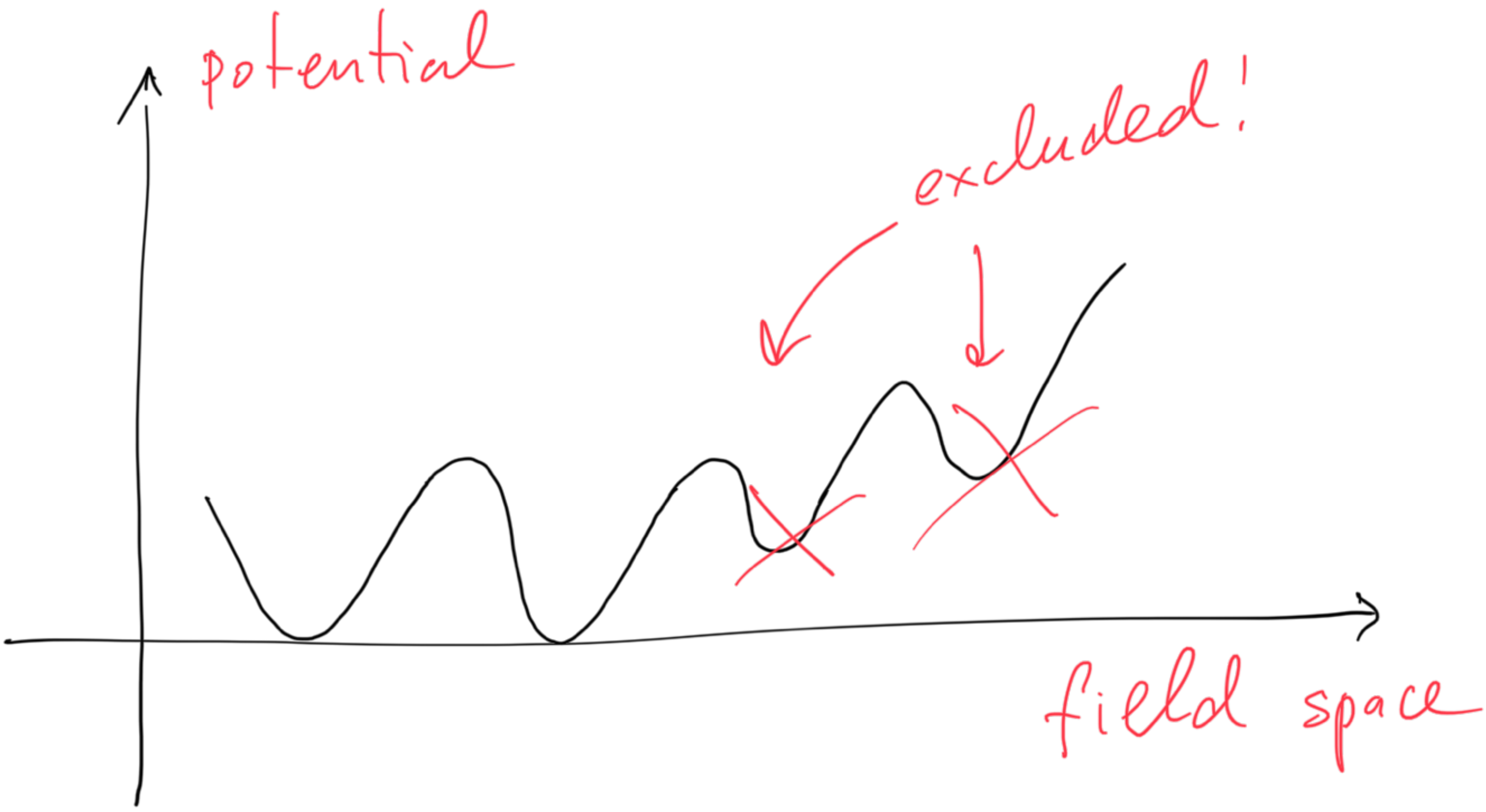
There are clear signals of S-matrix inconsistency already for finite M_p (G).

For example, scattering of quanta of center of mass energy

$$E \sim M_p^2 R$$



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

$$G_{\mu\nu} = T_{\mu\nu} + g_{\mu\nu}\underbrace{\Lambda}_{=0}$$

Dark energy = New physics

Prediction: Equation of state

$$w > -1$$

(In fact, arguments indicate

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

Implication for strong-CP 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

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

$$A_\mu \equiv A^a_\mu T^a \quad \leftarrow \text{gluon matrix}$$

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

Gauge redundancy:

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

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

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

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

The current bound

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

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

translates on bound

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

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

This is the <u>strong-CP puzzle</u>; formulated as <u>naturalness problem</u>.

$\bar{\Theta}$ is physical due to topological susceptibility of vacuum (TSV)

$$\langle F\tilde{F}, F\tilde{F}\rangle_{p\to 0} \equiv$$

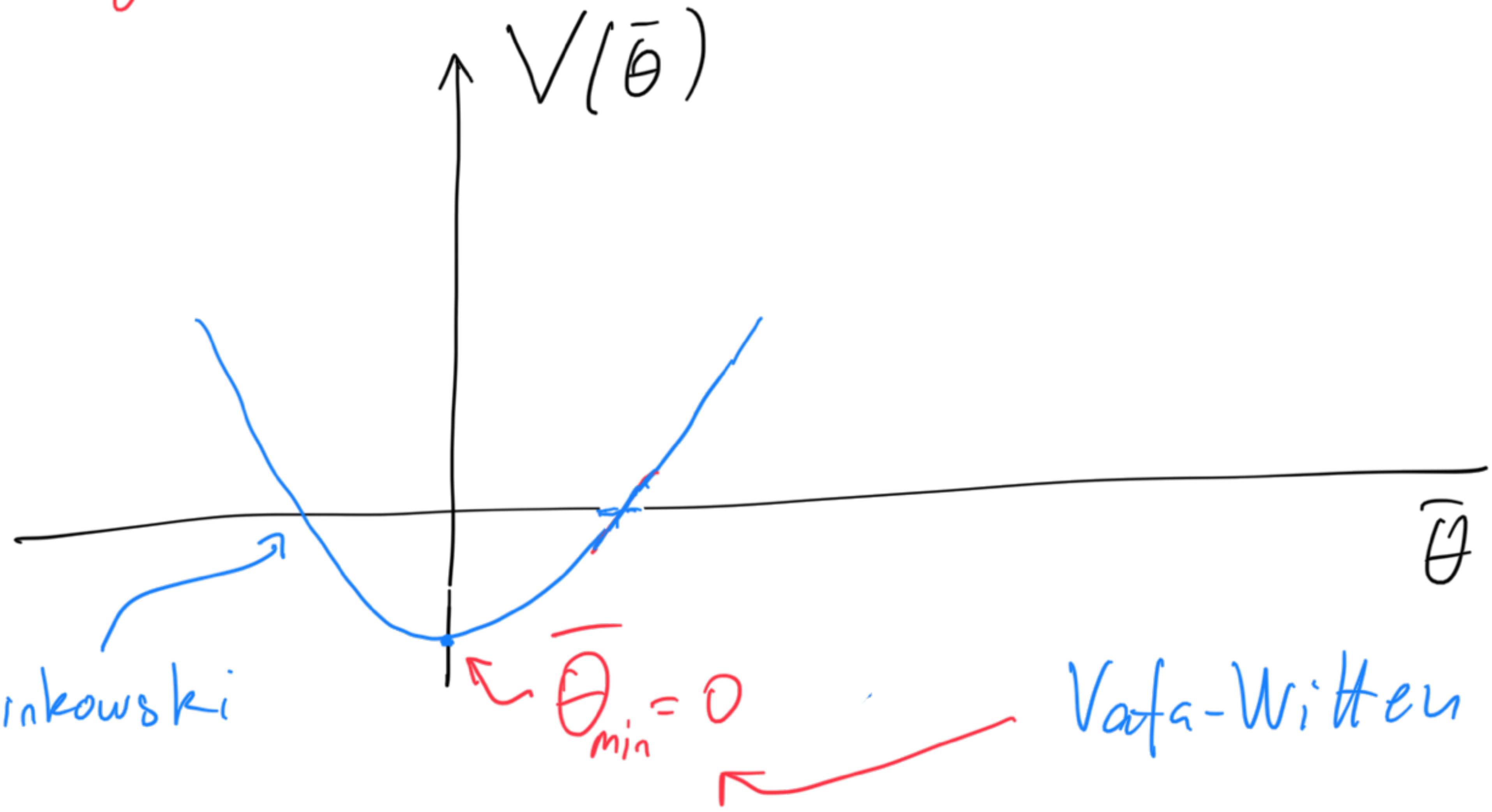
$$\equiv \lim_{p\to 0} \int d^4x\, e^{ipx} \langle T[F\tilde{F}(x), F\tilde{F}(0)]\rangle = \text{const} \neq 0$$

Then, Källén-Lehmann spectral representation:

$$\langle C, C\rangle = \frac{1}{p^2} + \sum_{m\neq 0} \frac{\rho(m^2)}{p^2 - m^2}$$

massless 3-form!

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!

Axion (Weinberg; Wilczek '78)

eliminates $\bar{\theta}$-vacua by making $\bar{\theta}$ dynamical:

$$\mathcal{L}_a = (\partial_\mu a)^2 - \left(\frac{a}{f_a} - \bar{\theta}\right) F\tilde{F}$$

Equivalently, it Higgses the 3-form

G.D., hep-th/0507215

$$\langle cc \rangle = \cancel{\frac{1}{p^2}} + \sum_{m \neq 0} \frac{\rho(m^2)}{p^2 - m^2}$$

But for this, the axion shift symmetry

$$a \to a + \text{const.}$$

must be protected exactly modulo QCD anomaly.

In Peccei-Quinn:

$$\Phi = |\Phi| e^{i\frac{a}{f_a}}$$

Global $U(1)_{PQ}$-symmetry.

$$\Phi \to e^{i\alpha}\Phi \longrightarrow \frac{a}{f_a} \to \frac{a}{f_a} + \alpha$$

Not protected against explicit breaking!

E.g. by operators:

$$\left(\Phi^{+}\right)^{m} \Phi^{n} \qquad m \neq n.$$

S-matrix demands that they must vanish to all-orders.

In Peccei-Quinn formulation of axion as of Goldstone of global $U(1)_{PQ}$

$$\Phi = |\Phi| e^{i\frac{a}{f_a}},$$

$\bar{\Theta}$ is <u>uncalculable</u>:

It is sensitive to arbitrary continuous deformations of the theory by $U(1)_{PQ}$-violating operators

$$(\Phi^{+})^{m} \Phi^{n} \qquad m \neq n$$

This is incompatible with S-matrix (and thus, with gravity).

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 undre 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 unphysical 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:

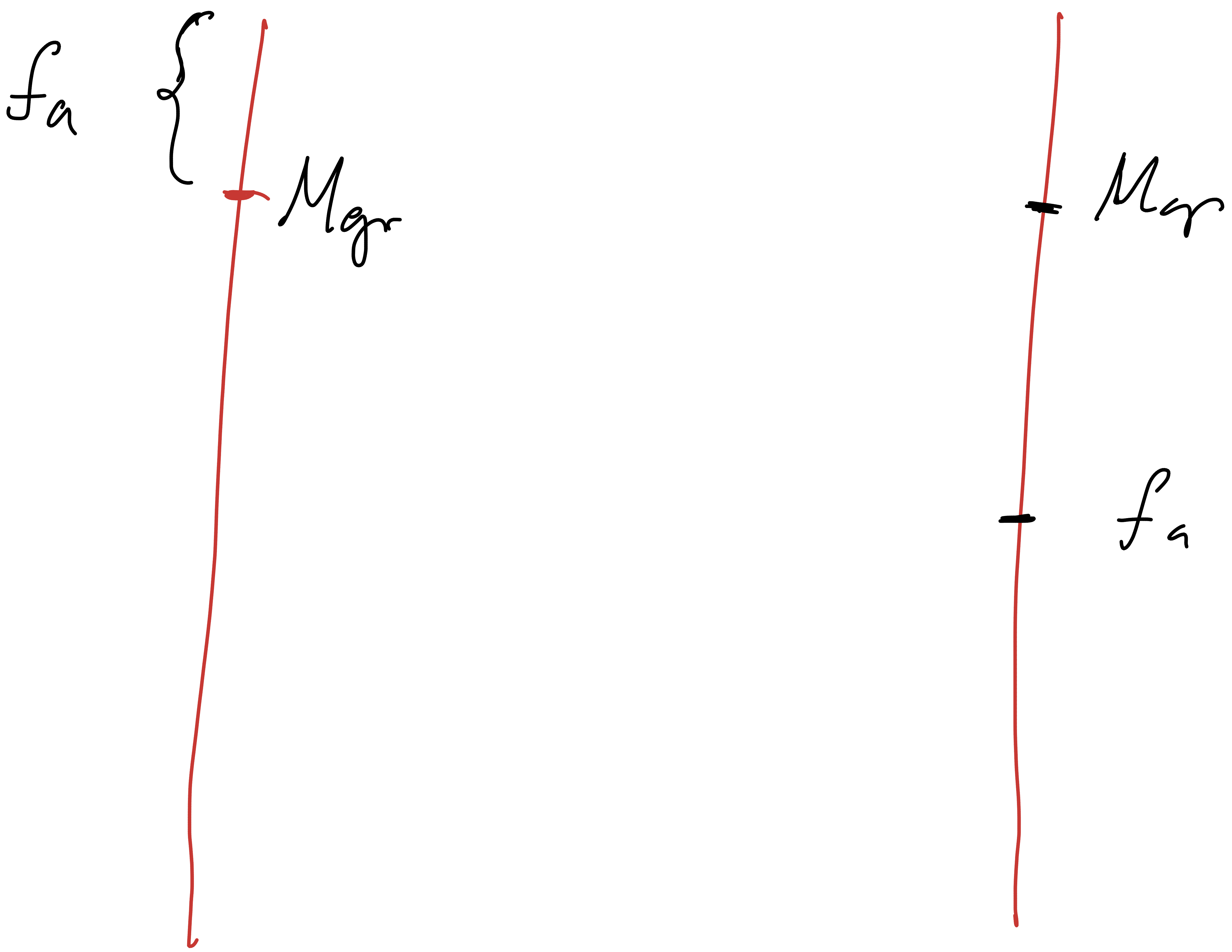
$$\langle C\, C \rangle = \frac{1}{p^2 + m_a^2} + \cdots$$

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

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

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

Gauge axion: Peccei-Quinn



The advantage in calculability:

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

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 Standard Model.

anomalous chiral symmetry of neutrino

$$\nu \to e^{i\alpha\gamma_5}\,\nu$$

can neutralize TVS of gravity, resulting into $m_\nu \neq 0$.

G.D., Folkerts, Franca 1312.7273 [hep-th]
G.D., Funcke, 1602.03191 [hep-ph]

Each 3-form provided by gravity must be accompanied either by axion or a chiral fermion.

QCD axion is safe by consistency of S-matrix gravity.

$$\mathcal{L} = K(E) + m_a^2 (C + \tilde{C} - dB)^2$$
$$+ \tilde{K}(\tilde{E})$$

$\hookrightarrow \tilde{E} \equiv d\tilde{C}$

A candidate in gravity, gravitational Chern-Simons

$$\tilde{C} \equiv \Gamma \wedge d\Gamma + \frac{2}{3} \Gamma \wedge \Gamma \wedge \Gamma$$
$$\tilde{E} \equiv d\tilde{C} = R\tilde{R} = \epsilon^{\alpha\beta\mu\nu} R^i_{j\alpha\beta} R^j_{i\mu\nu}$$

If in pure gravity $\langle R\tilde{R}, R\tilde{R} \rangle_{q\to 0} \neq 0$,

gravity must provide additional axion.

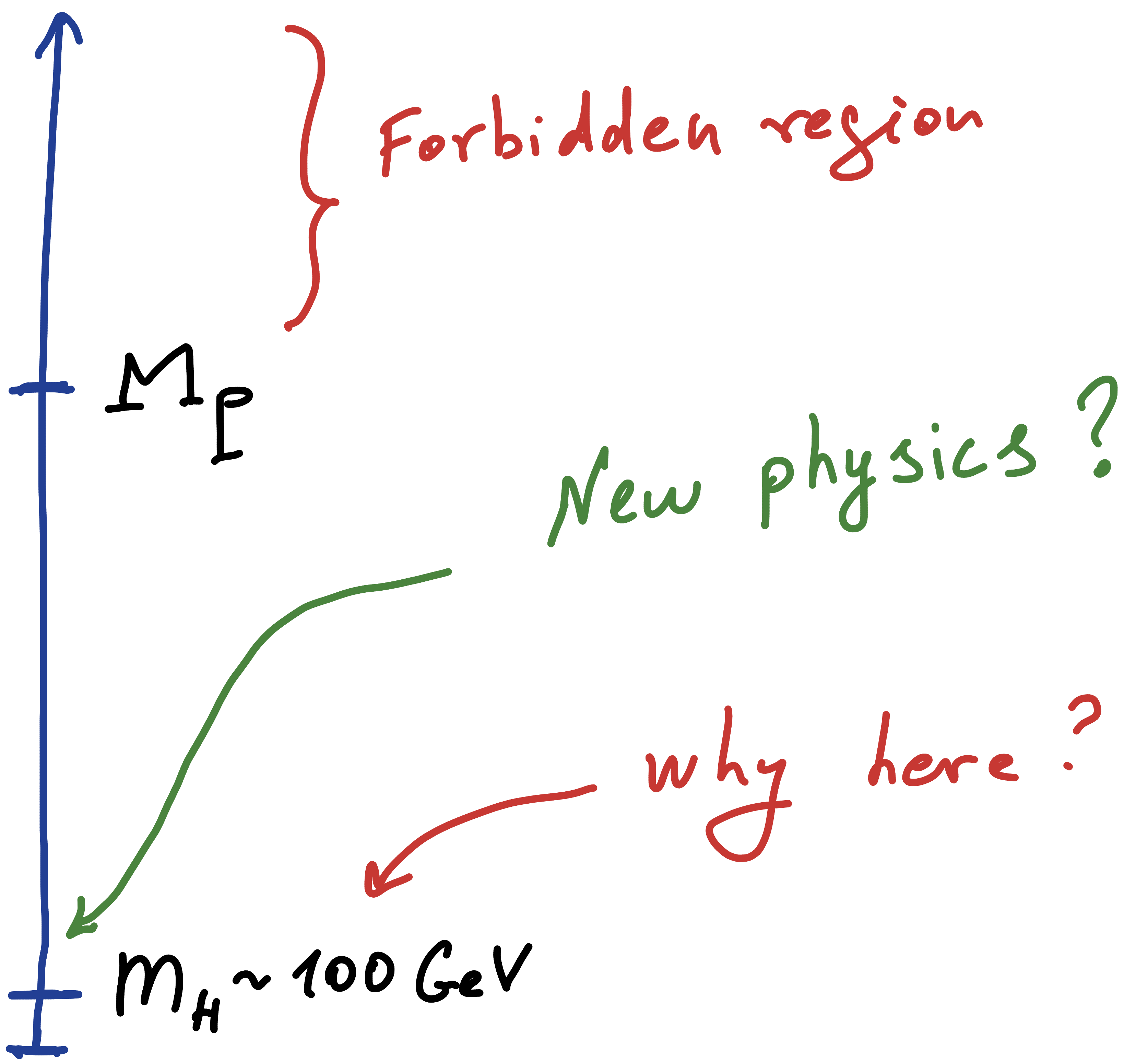
OR

No elementary particles of mass

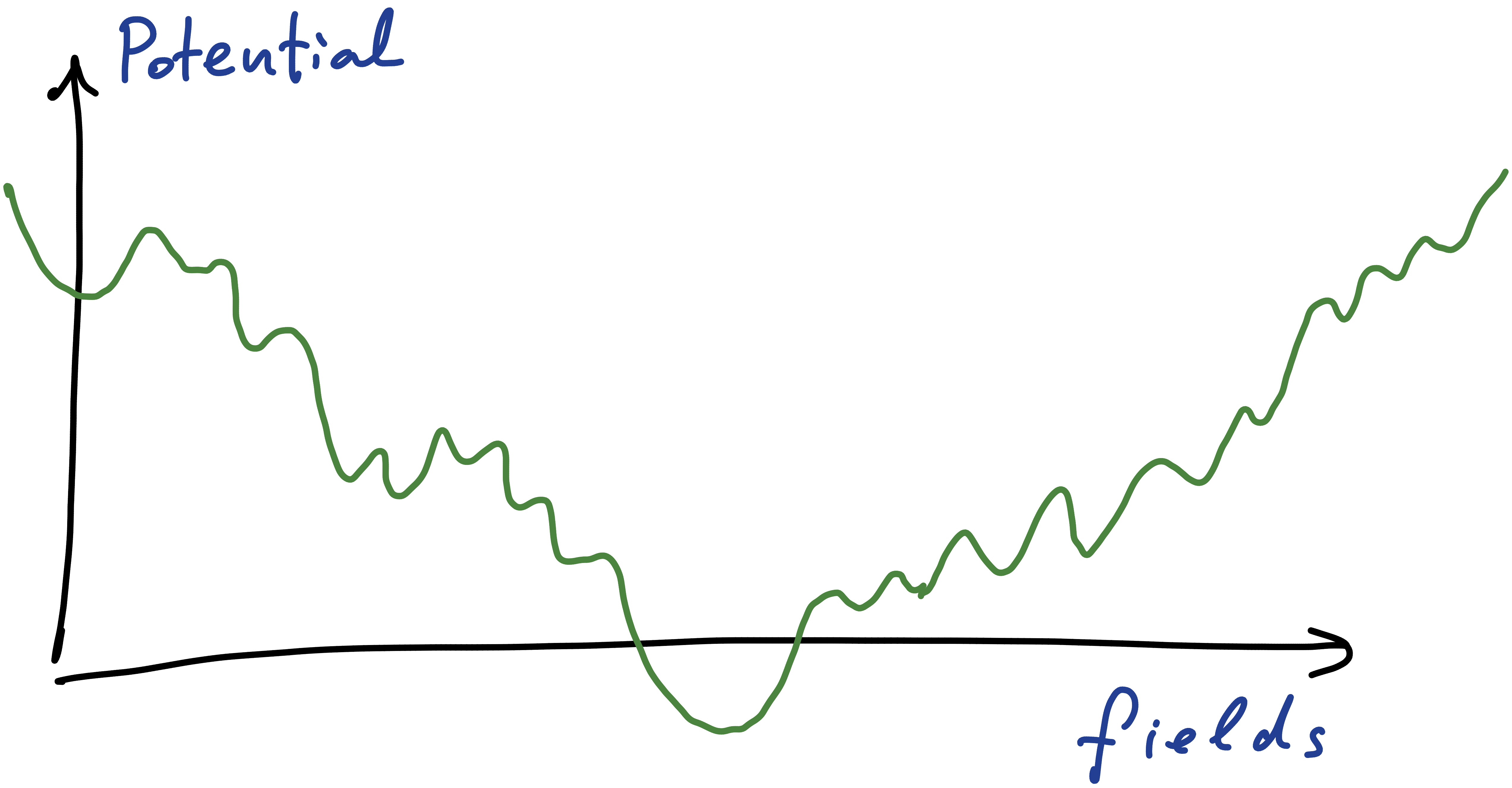
$$m > M_P$$

(would be a black hole!)

Higgs cannot have a solar mass



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

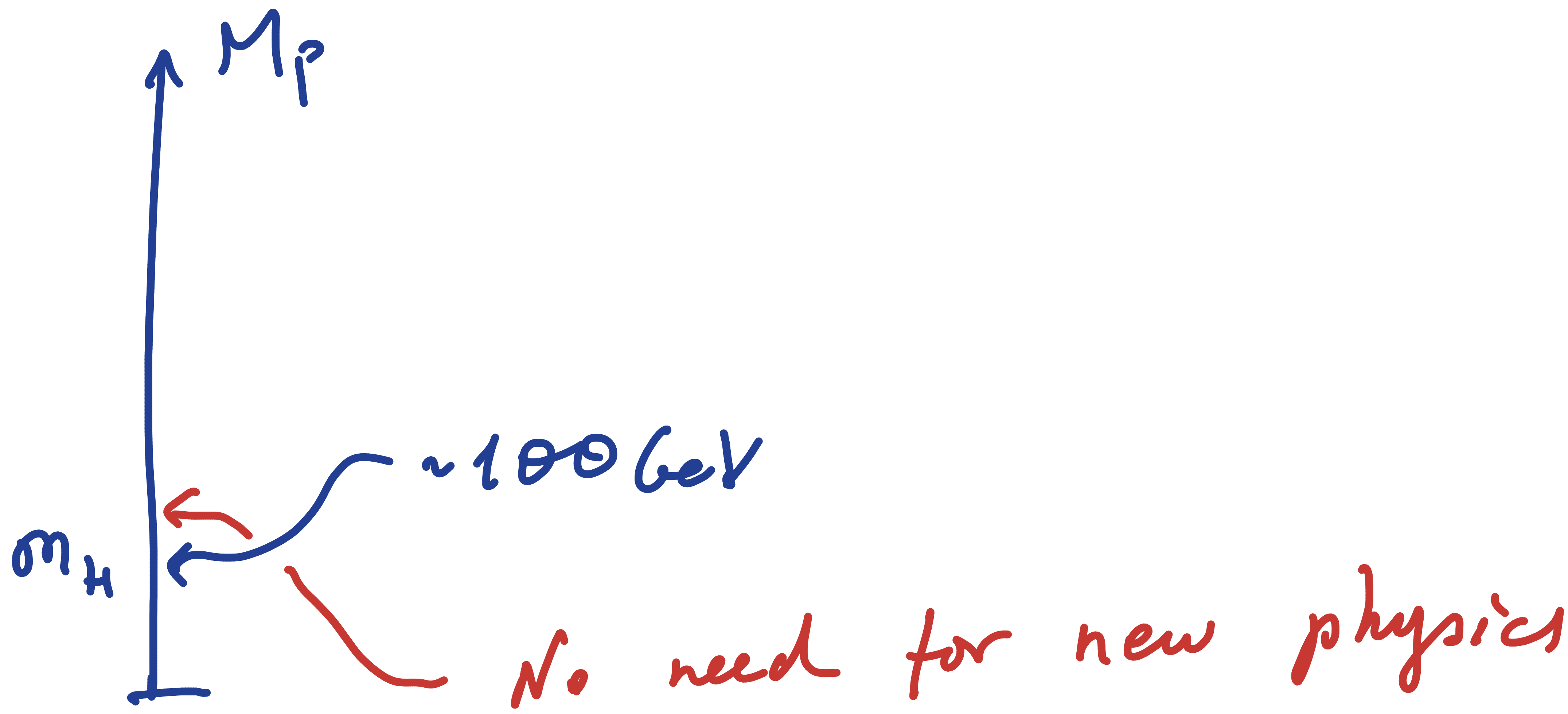


Naturalness can be replaced
by Anthropic selection

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

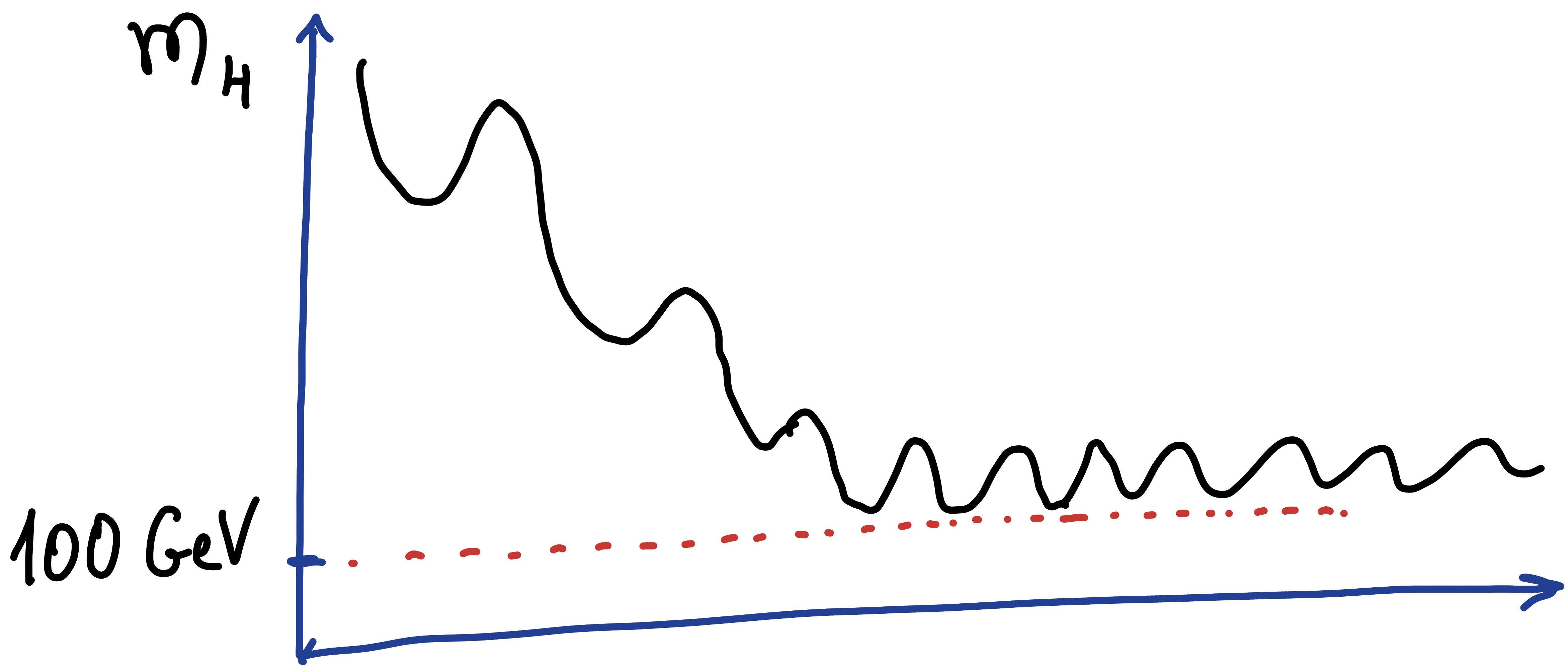
Agrawal, Barr, Donoghue, Seckel '97

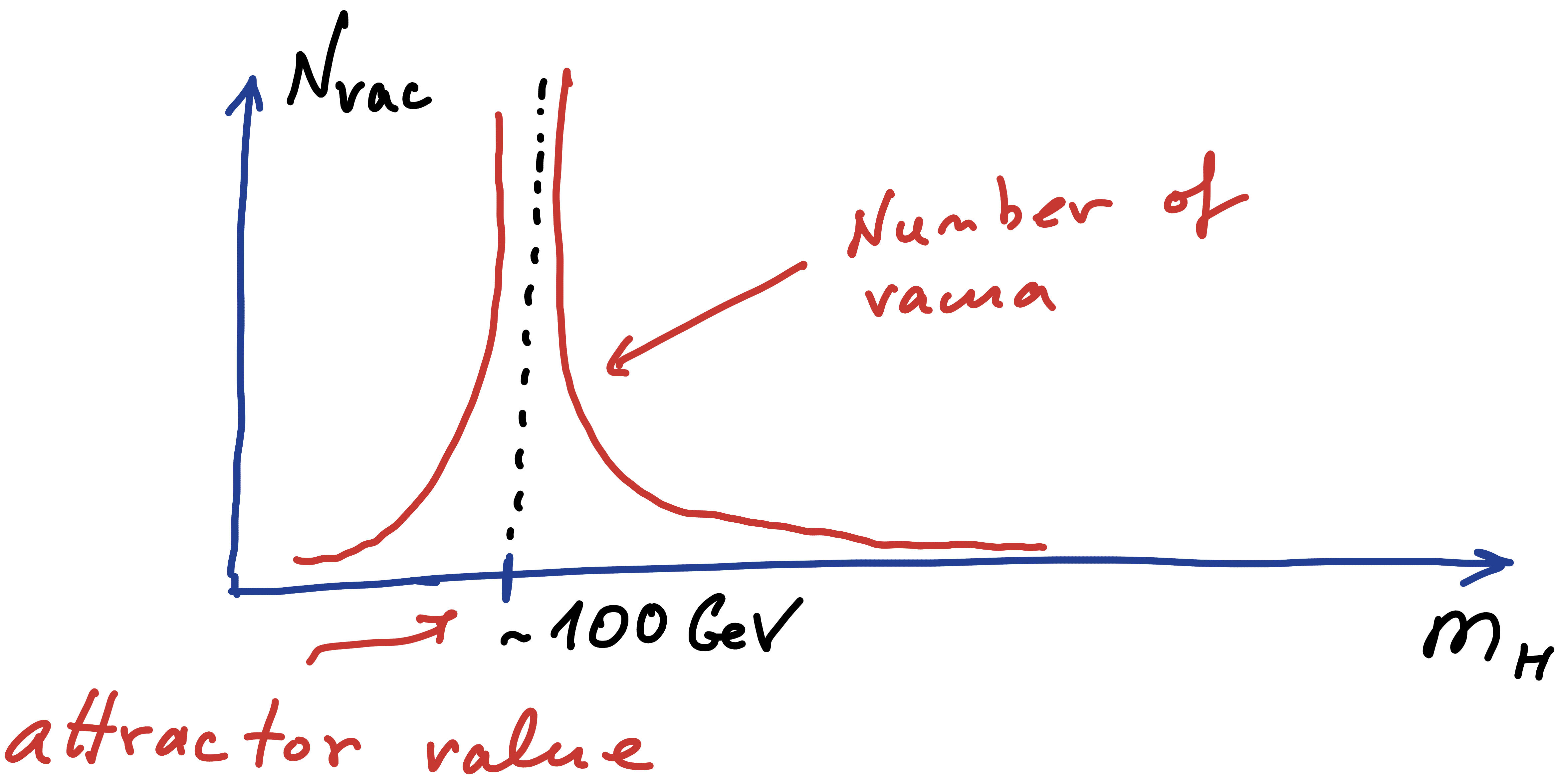
that our existence is sensitive to weak scale (Higgs mass)

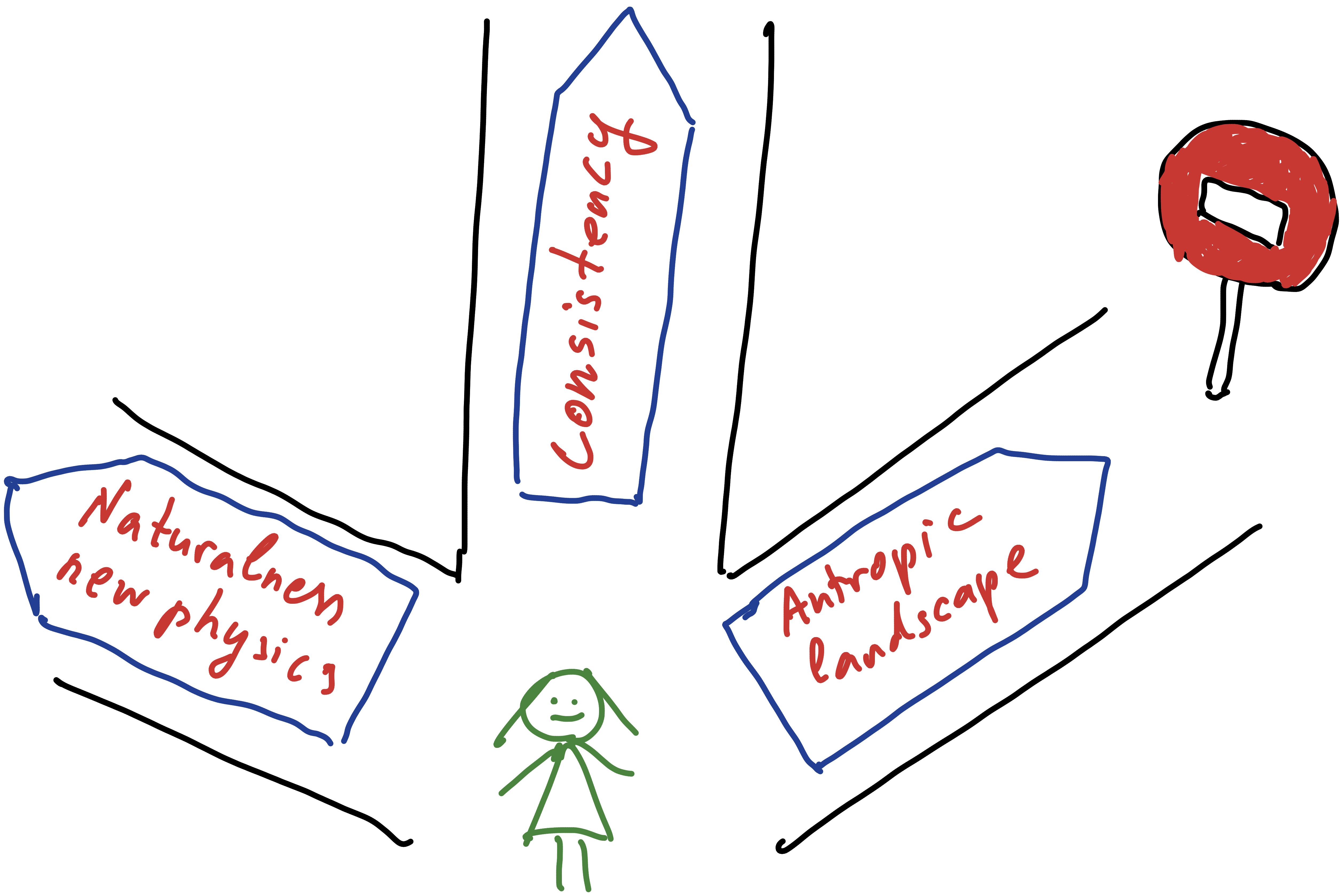


Cosmological relaxation of the Higgs mass

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






Consistency
Naturalness
new physics
Antropic
landscape

EFT:

$$\mathcal{L} = K(E) + \bar{\theta} E + \frac{1}{f_a^2}\left(C - f_a dB\right)^2$$

$$\partial_\mu \frac{\partial K}{\partial E} + \frac{1}{f_a^2} {}^*(C - dB)_\mu = 0$$

$$\partial^\mu {}^*(C - dB)_\mu = 0$$

vacuum: $E = 0 \longleftrightarrow \bar{\theta}$ unphysical

This is insensitive to deformation by arbitrary local operators.

General proof, see, G.D., hep-th/0507215

for some explicit examples, see: Sakhelashvili, 2110.03386 [hep-th].

$$\mathcal{L} = K(E) + m_a^2 (C + \tilde{C} - dB)^2$$

$$+ \tilde{K}(\tilde{E})$$

$\hookrightarrow \tilde{E} \equiv d\tilde{C}$

A candidate in gravity, gravitational Chern-Simons

$$\tilde{C} \equiv \Gamma \wedge d\Gamma + \frac{2}{3} \Gamma \wedge \Gamma \wedge \Gamma$$

$$\tilde{E} \equiv d\tilde{C} = R\tilde{R} = \epsilon^{\alpha\beta\mu\nu} R^i_{j\alpha\beta} R^j_{i\mu\nu}$$

If in pure gravity $\langle R\tilde{R}, R\tilde{R} \rangle_{q \to 0} \neq 0$,

gravity must provide additional axion.

OR

How is the S-matrix constraint enforced?

Corpuscular picture of de Sitter ("N-portrait"): G.D., Gomez '11, '13, ...

Since $|dS\rangle$ is not a vacuum, it can only be an excited state constructed on S-matrix vacuum (Minkowski).

$$|dS\rangle = |N\rangle$$

Number of constituents

We choose coherent state but others are also OK

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

New concept:

Corpuscular completion (resolution)

Very different from and insensitive to UV-completion.

Universal properties:

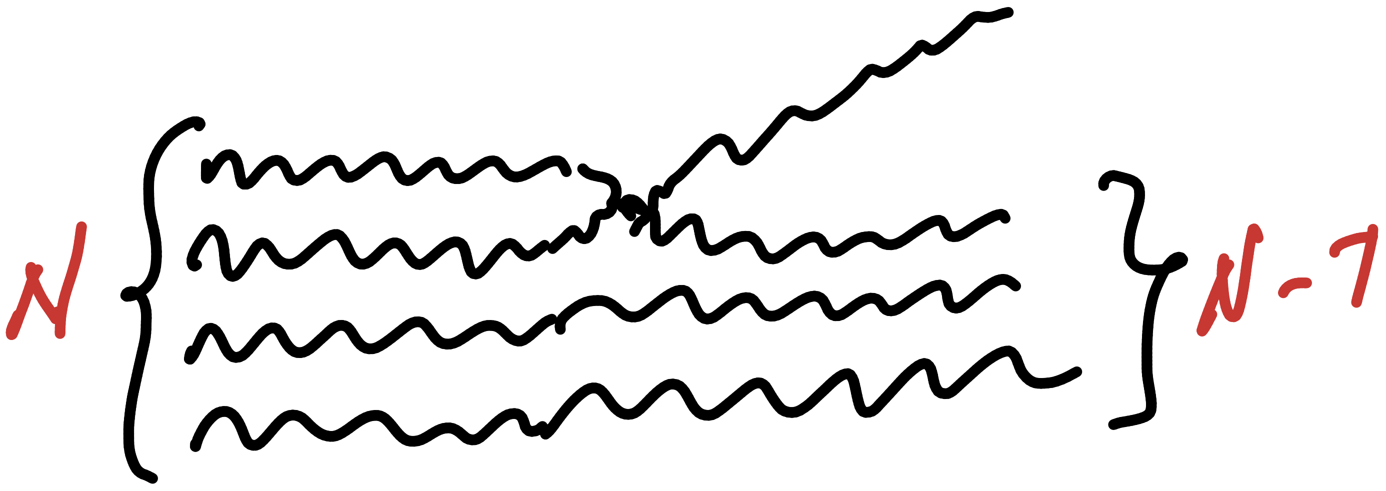
Number of constituent $N = \frac{1}{\alpha_{gr}}$

Their frequencies $\sim \frac{1}{R}$

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

de Sitter is a <u>saturated state</u>.

Gibbons-Hawking radiation is a Hamiltonian process of a decay



Emission rate $\Gamma \sim \alpha^2 N^2 \frac{1}{R} = \frac{1}{R}$

Emission time $\tau = \Gamma^{-1} \sim R$

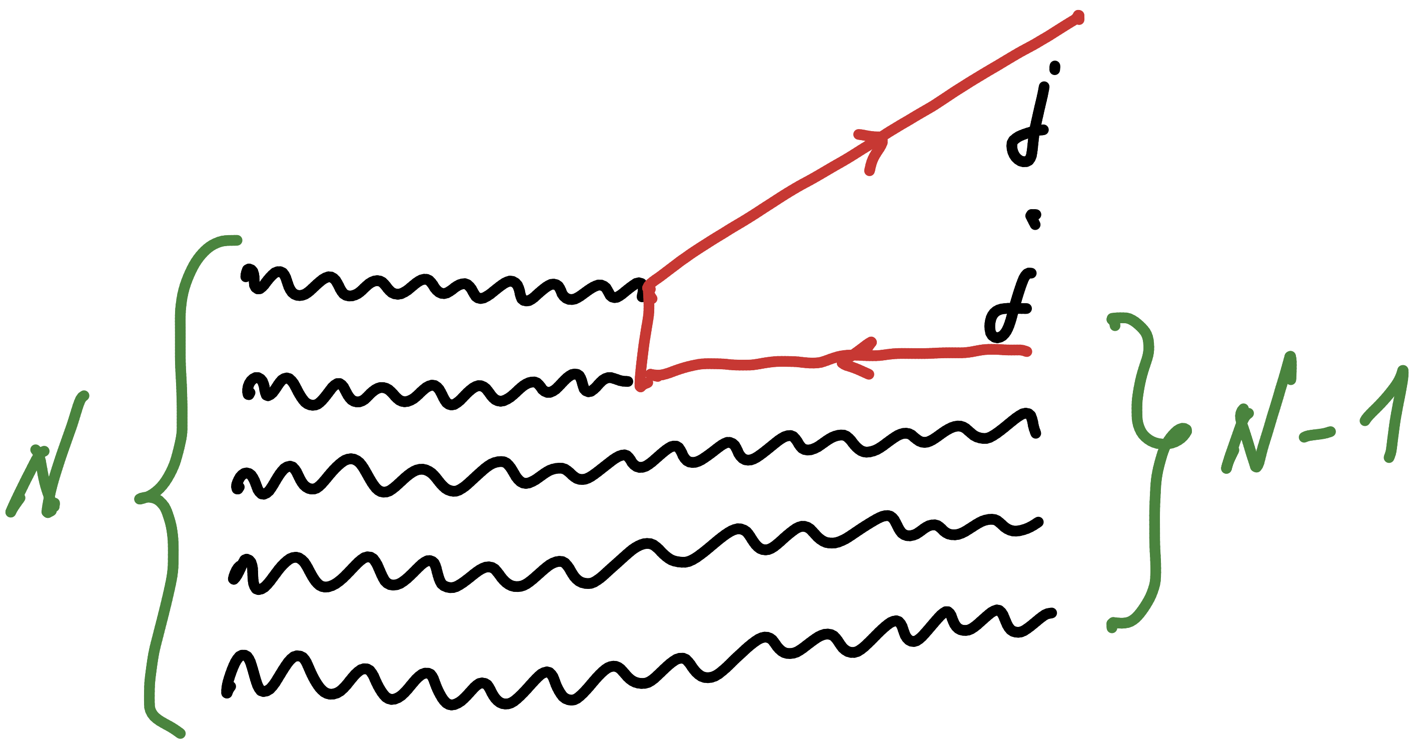
The resulting Gibbons-Hawking temperature $T_{GH} = \frac{1}{R}$

Thus, de Sitter "ages" due to an internal quantum clock.

The decay is democratic in species.

$$j = 1, 2, \ldots\ldots N_{sp}$$

species label



entangled

$$|N\rangle \to \sum_j |N-1\rangle_j \cdot |j\rangle$$

maximal departure from semi-classical evolution after

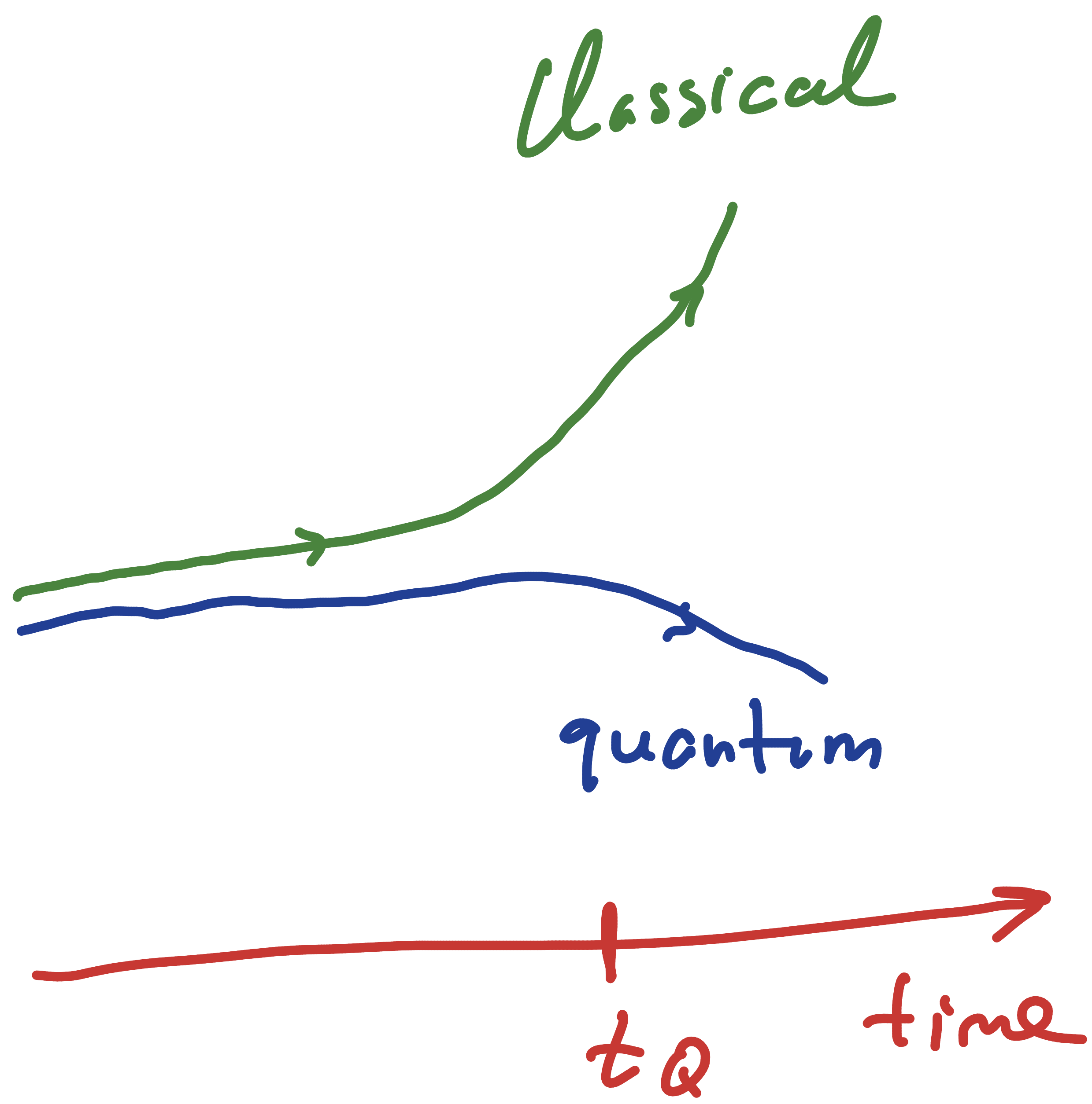
$$t_Q = R\,\frac{N}{N_{sp}} = R\,\frac{(RM_P)^2}{N_{sp}}$$

Quantum break-time for a generic saturated system:

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

$$t_Q = \frac{t_{cl}}{\alpha N_{sp}}$$

quantum coupling



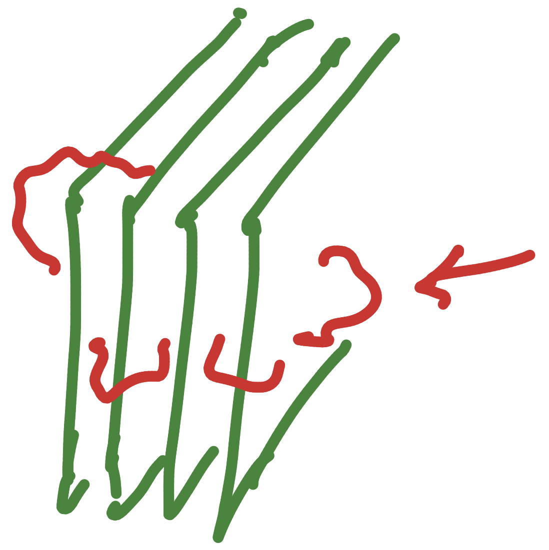
For de Sitter

$$t_{cl} = R \qquad \alpha = \alpha_{gr} = \frac{1}{N} = \frac{1}{(M_p R)^2}$$

So we recover:

$$t_Q = R\,\frac{N}{N_{sp}} = \frac{R\,(RM_p)^2}{N_{sp}}$$

e.g. in $n \times D_g - \bar{D}_g$ example



Chan-Paton species

$$t_Q = \frac{R}{(ng)^6} \qquad N_{sp} = n^2$$

In generic string construction:

$$t_Q = R \frac{(R M_s)^8}{g_s^2} \frac{1}{N_{sp}}$$

Notice, after t_Q also entropy effects contribute into quantum breaking via so-called "memory burden" effect.

Gibbons-Hawking entropy $= N$

G.D, Eisemann, Michel, Zell, '18

If system has Lyapunov time t_L, quantum break-time can be much shorter G.D, Flassig, Gomez, Pritzel, Wintergerst '13

$$t_Q = t_L \ln\left(\frac{1}{\alpha}\right) = t_L \ln(N)$$

See also, Kortun, Zantedeschi '20;
Berezhiani, Zantedeschi '20;

Thus, a Hubble patch must gracefully exit de Sitter phase after time $t_{exit} < t_Q$.

This excludes any sort of meta-stability.

For inflation $t_{exit} = N_e R$

The strength of observable imprints from quantum gravity

$$\delta = \frac{t_{exit}}{t_Q} = N_e \frac{N_{sp}}{N}$$

enhanced by species!

The power of species in enhancing quantum gravity effects

Non-perturbative bound on gravity cuttoff: G.D. '07, G.D, Redi '08

$$M_* \le \frac{M_P}{\sqrt{N_{sp}}}$$

Black hole evaporation

$$\frac{\dot{T}}{T^2} = N_{sp} \frac{T^2}{M_P^2}$$

Thermality breaks at:

$$T_{MAX} = \frac{M_P}{\sqrt{N_{sp}}}$$

The same in de Sitter:
Energy density of Gibbons-Hawking radiation

$$N_{sp} T_{GH}^4 = N_{sp} R^{-4} = N_{sp} \Lambda$$

becomes equal to Λ for

$$R^{-1} = \frac{M_p}{\sqrt{N_{sp}}}$$

Smallest possible radius of de Sitter:

$$\frac{\sqrt{N_{sp}}}{M_p} \equiv M_*^{-1}$$

Quantum break-time gives a new meaning to species bound.

For $N_{sp} = (M_p R)^2$

the quantum break-time is one Hubble!

$$t_Q = \frac{R\,(M_p R)^2}{N_{sp}} = R$$

In other words, the number of species cannot exceed the number of de Sitter constituents:

$$N_{sp} \leq (M_p R)^2 = N$$

Since species shorten t_Q, they provide an exceptional opportunity of observing imprints of quantum gravity.

The corrections from the quantum gravity clock can be potentially very large

$$\delta = N_e \frac{N_{sp}}{N}$$

even when standard fluctuations (from inflaton) are negligible.

Notice, the phenomenological bound on N_{sp} (from LHC, ...) is

$$N_{sp} \lesssim 10^{32}$$

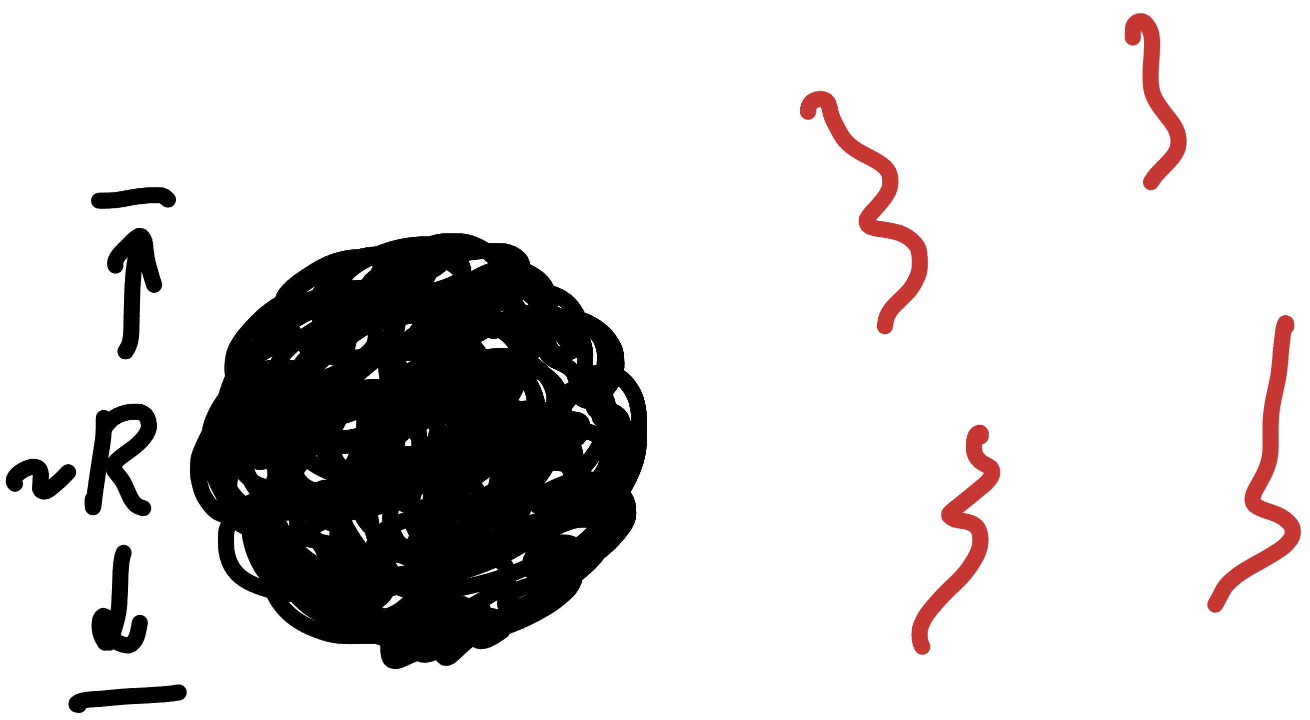
Motivated by Hierarchy Problem.

This gives a large room for dominance of quantum gravitational effects in inflationary scenarios.

Entanglement in de Sitter and in Black Hole

"Page's curves" for de Sitter and Black Hole

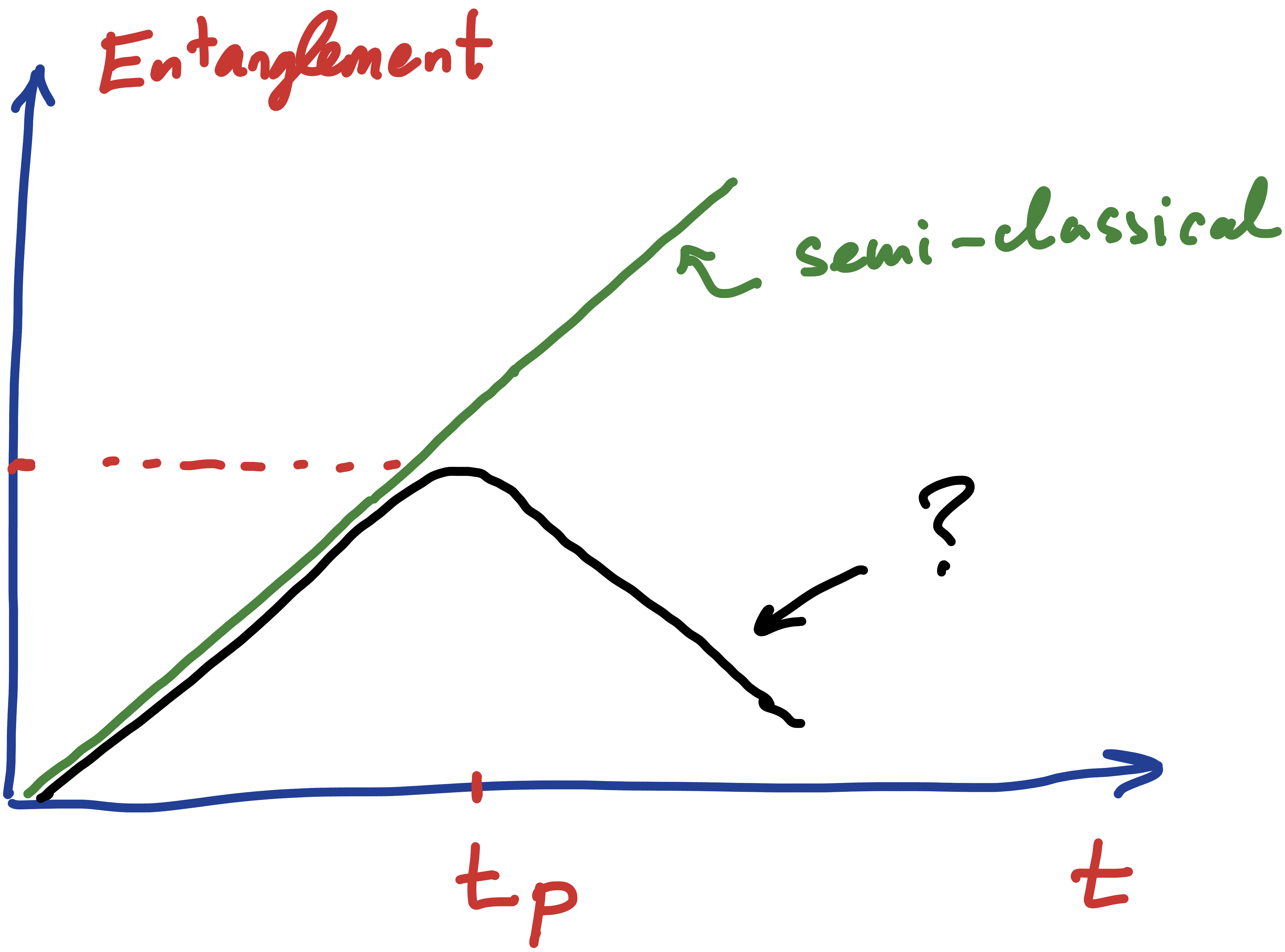
Hawking radiation



$$T_H = \frac{1}{R}$$

Page's time:

$$t_P = R^3 M_P^2 = t_Q$$

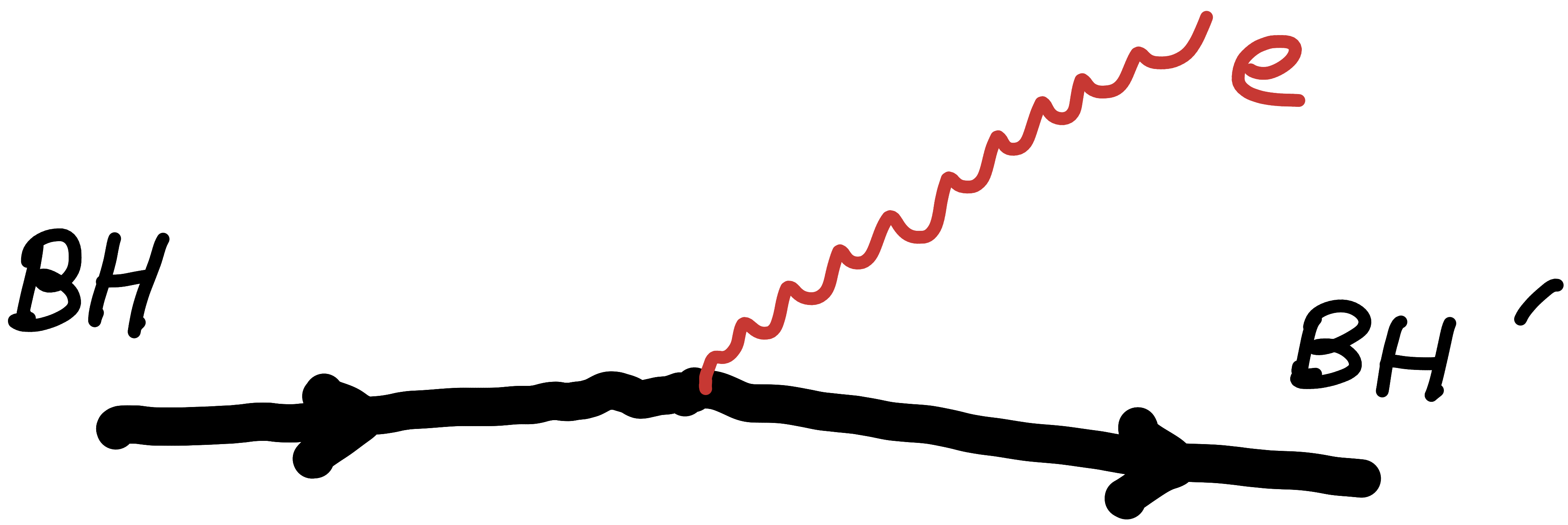


Entanglement must reach maximum.

(Which entanglement?)

In semi-classical picture there is only one type of entanglement:

Between black hole and outgoing quanta



$$|BH\rangle \longrightarrow |\uparrow\rangle_{BH} \cdot |\downarrow\rangle_e + |\downarrow\rangle_{BH} \cdot |\uparrow\rangle_e$$

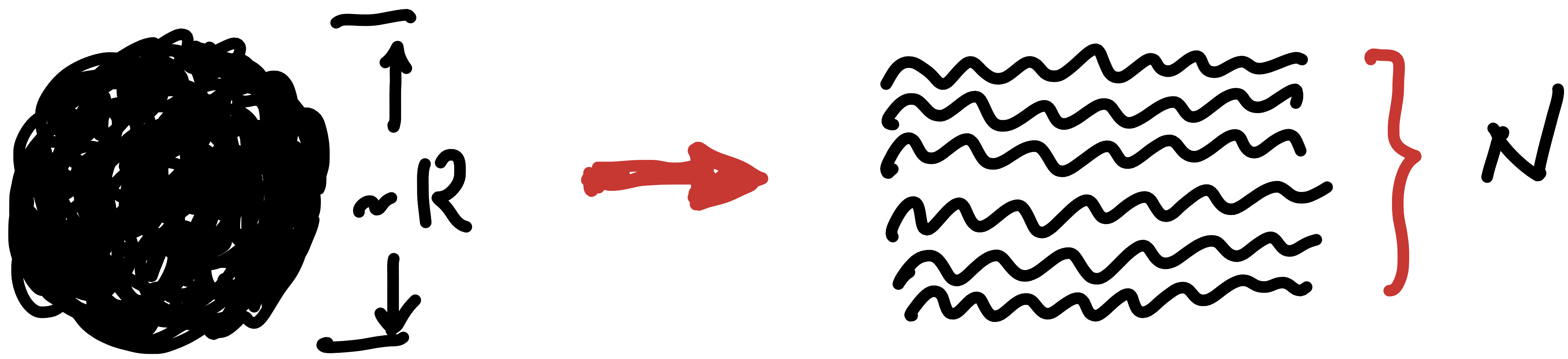
Corpuscular theory reveals a different story.

Microscopic corpuscular theory:

Quantum N-Portrait

G. D., Gomez '11

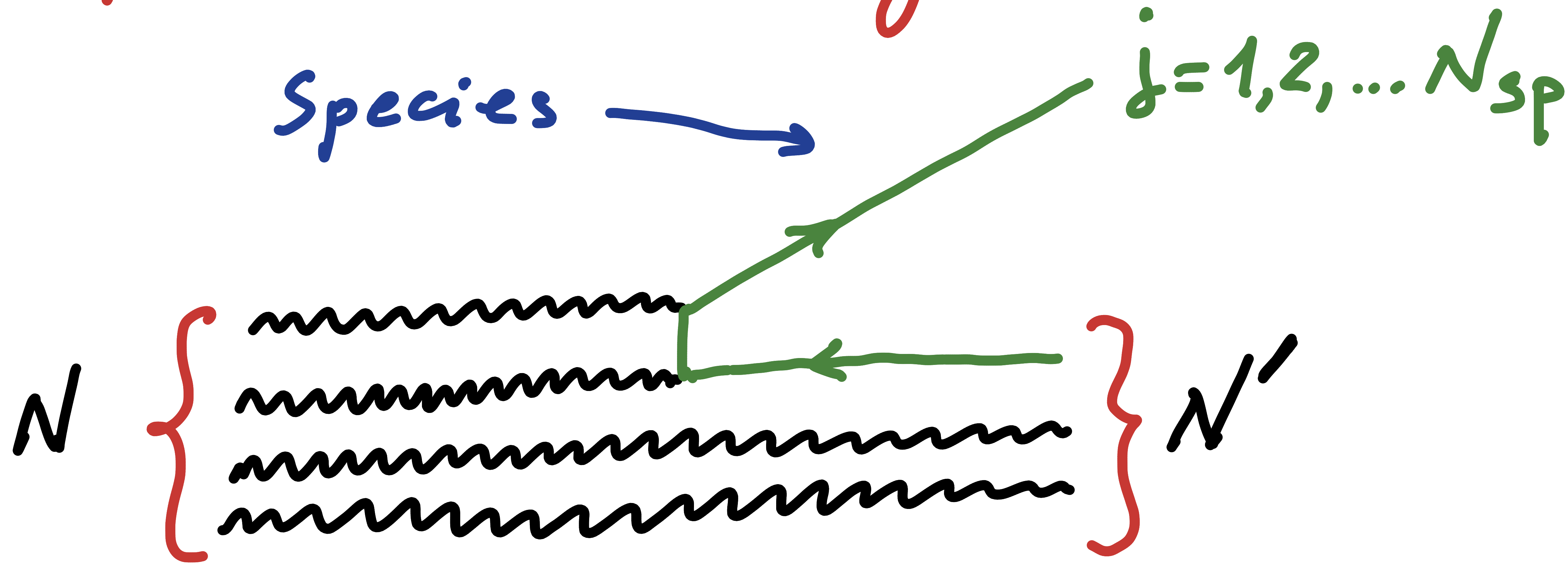
Black hole is a saturated (critical) state of soft gravitons



$$N = \frac{1}{\alpha} = (RM_P)^2 = S$$

number coupling entropy

At initial times, gravitons deplete at Hawking's rate



$$|N\rangle \rightarrow \sum_{j=1}^{N_{sp}} |N', j\rangle \cdot |j\rangle$$

Self-entangled state

The new concept of inner (self) entanglement.

Inner entanglement is present both in black hole and de Sitter.

Not visible in sem-classics.

The engine:

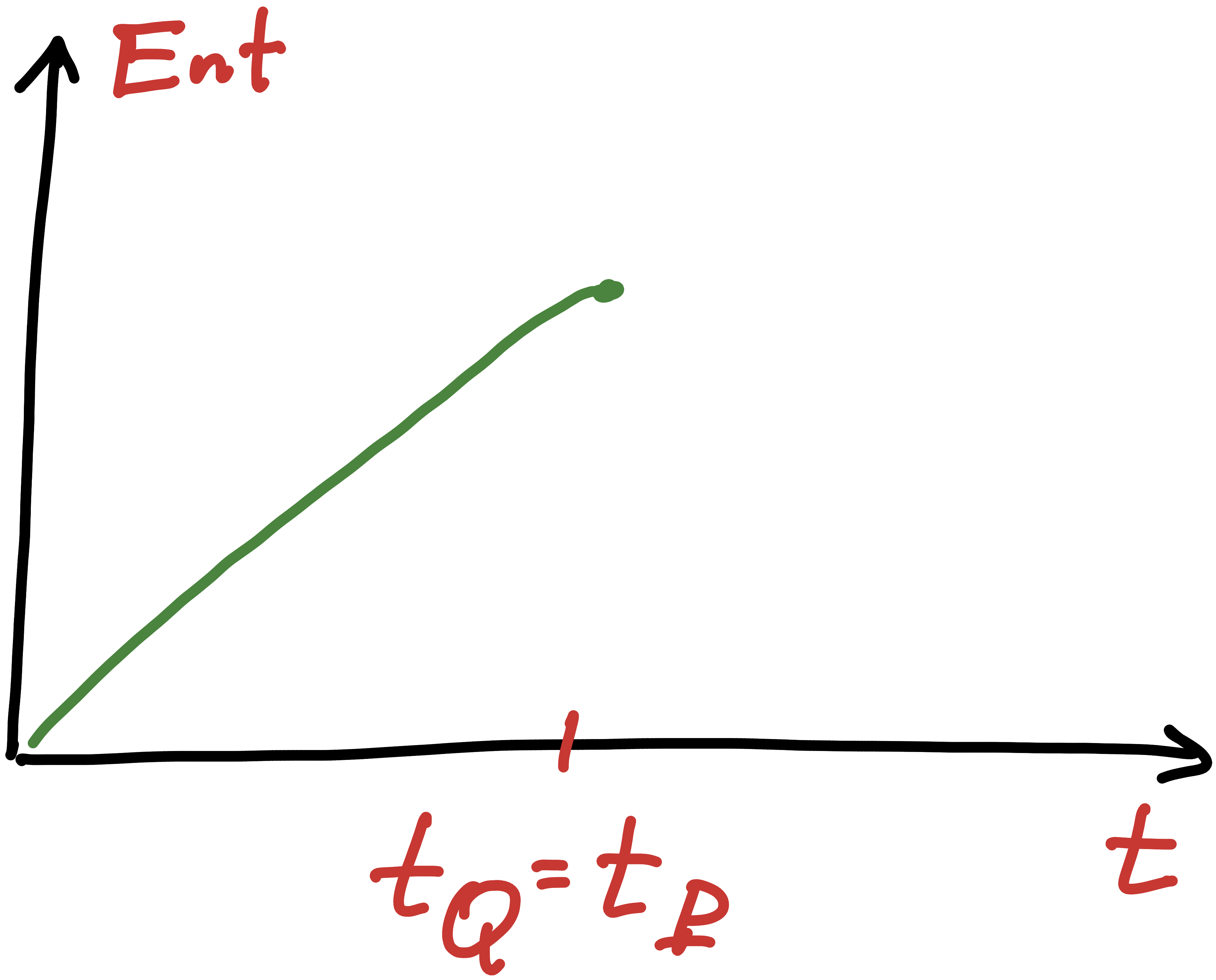
* Entanglement among constituents (soft-modes);

* Entanglement among memory modes (super-soft) information carriers: "Memory burden".

G.D., '17; G.D., Eisemann, Michel, Zell '18

Prihadi; Dwiputra, Zen '20

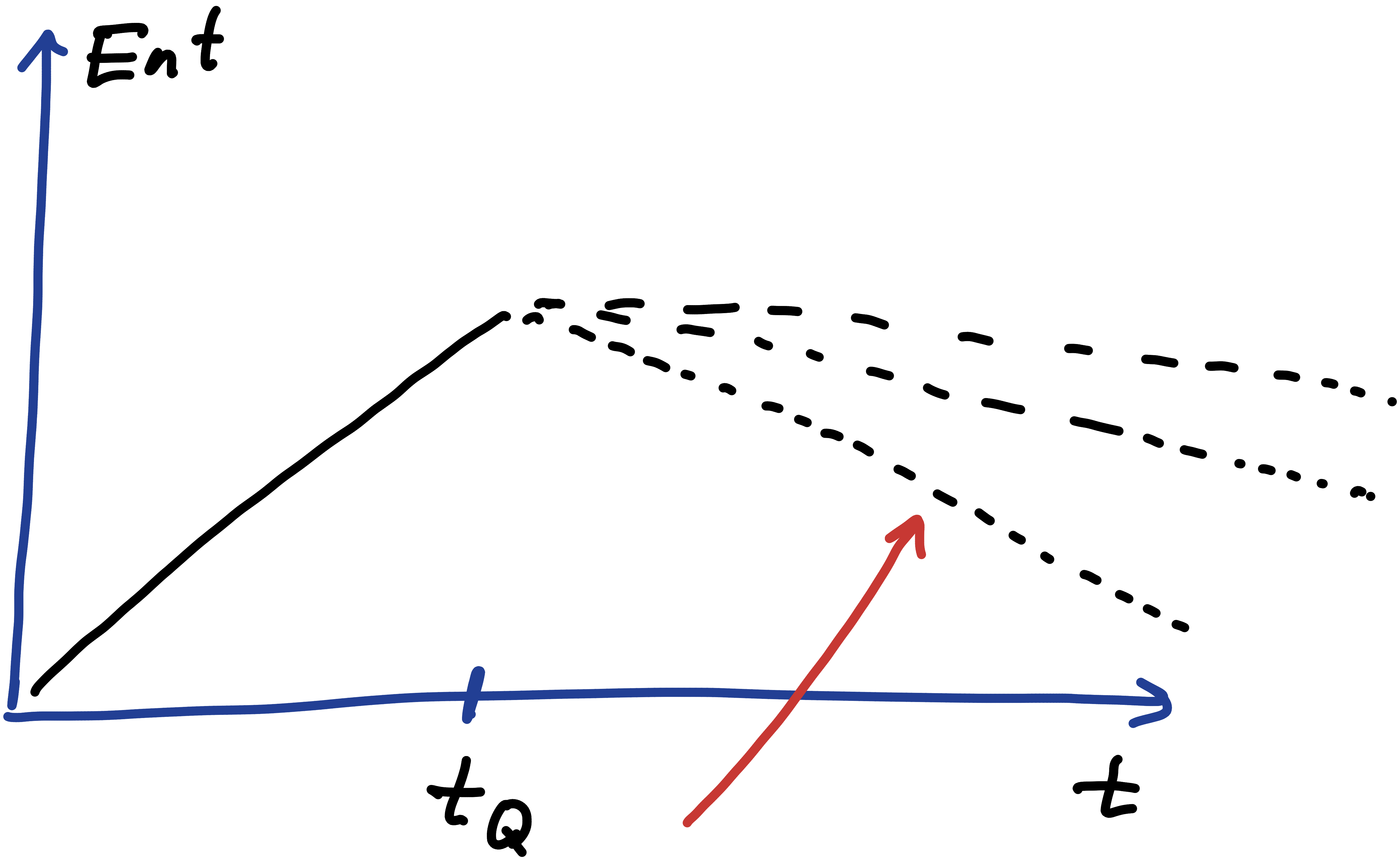
Maximal entanglement at $t_Q = t_P$



Both for de Sitter and Black hole.

For $t > t_Q$ are fundamental differences.

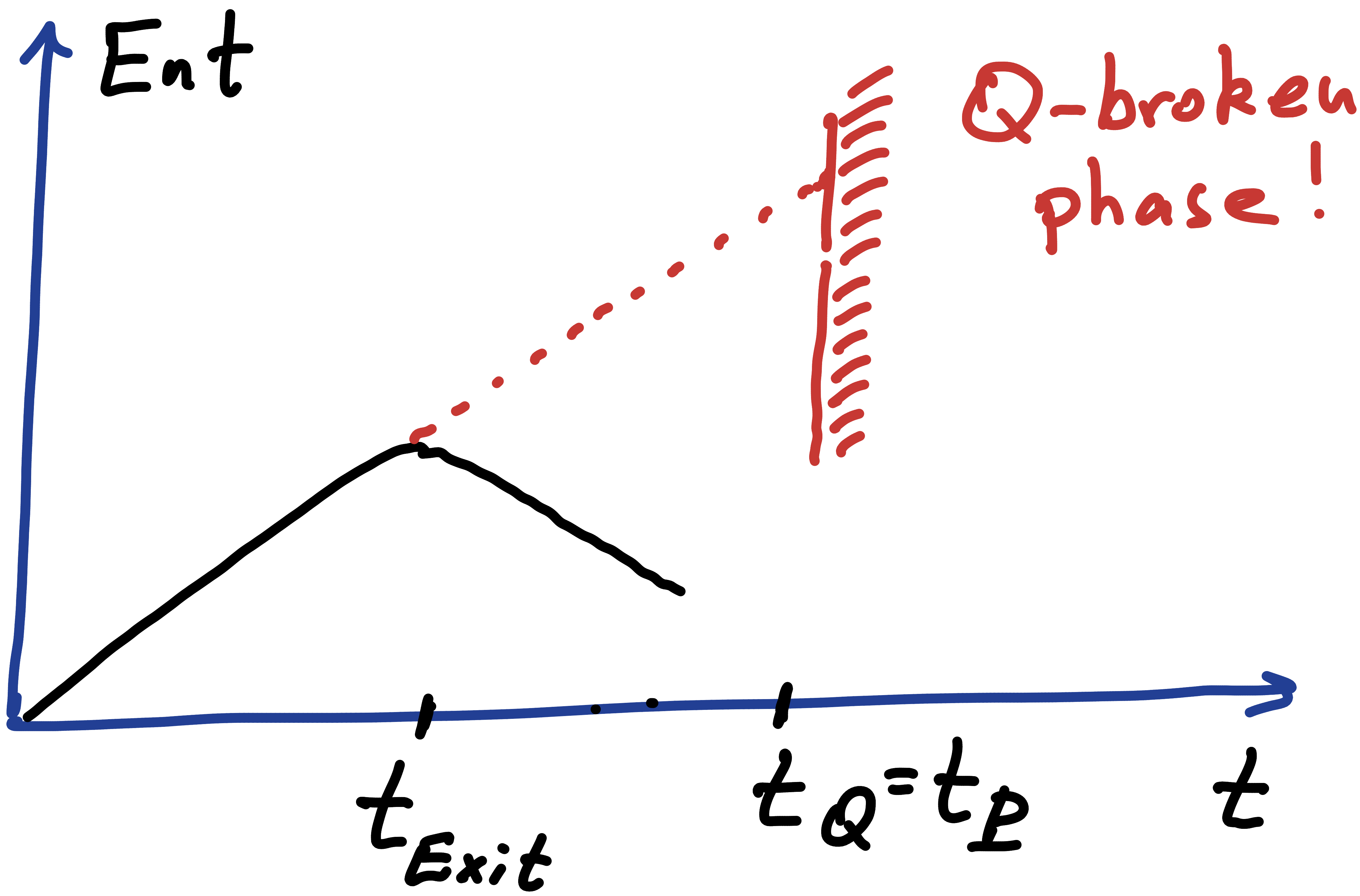
Black holes:



Decay can slow down due to "memory burden".

G.D., Eisemann, Michel, Zell '19.

de Sitter cannot exist for $t > t_Q$



Graceful exit must take place for

$$t_{Exit} \leq t_Q$$

Conclusions:

* S-matrix formulation of gravity (string theory) excludes de Sitter vacua, both stable an meta-stable.

* This imposes a corpuscular view in which de Sitter is a saturated (coherent) state on top of valid S-matrix vacuum of Minkowski (or AdS?)

* The S-matrix constraint is enforsed by an anomalous quantum break-time

$$t_Q = R\frac{(RM_p)^2}{N_{sp}} = R\frac{N}{N_{sp}}$$

(*) Universe must find a gracefull exit from de Sitter within time $t_{exit} < t_Q$

(*) Potentialy observable quantum gravity imprints are

$$\delta = \frac{t_{exit}}{t_Q} = N_e \frac{N_{sp}}{N}$$

and are enhanced by number of particle species N_{sp}.

(*) Bound $N_{sp} \lesssim 10^{32}$ gives room for interesting new effects:

(*) We predicted that Λ cannot be part of Universe's energy budget.

G. D., Gomez '13, ...

Then, what is dark energy?

(More precision analysis is welcome.

Colin, Mohayaee, Rameez, Sarkar '18)