String Swampland Conjectures and Implications for Particle Phenomenology and dS Cosmology

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Two days with particle physics, SBU, Aban 1400

Introduction: The Standard Model

- The Standard Model of particle physics gives an excellent understanding of the Universe at the microscopic scales.

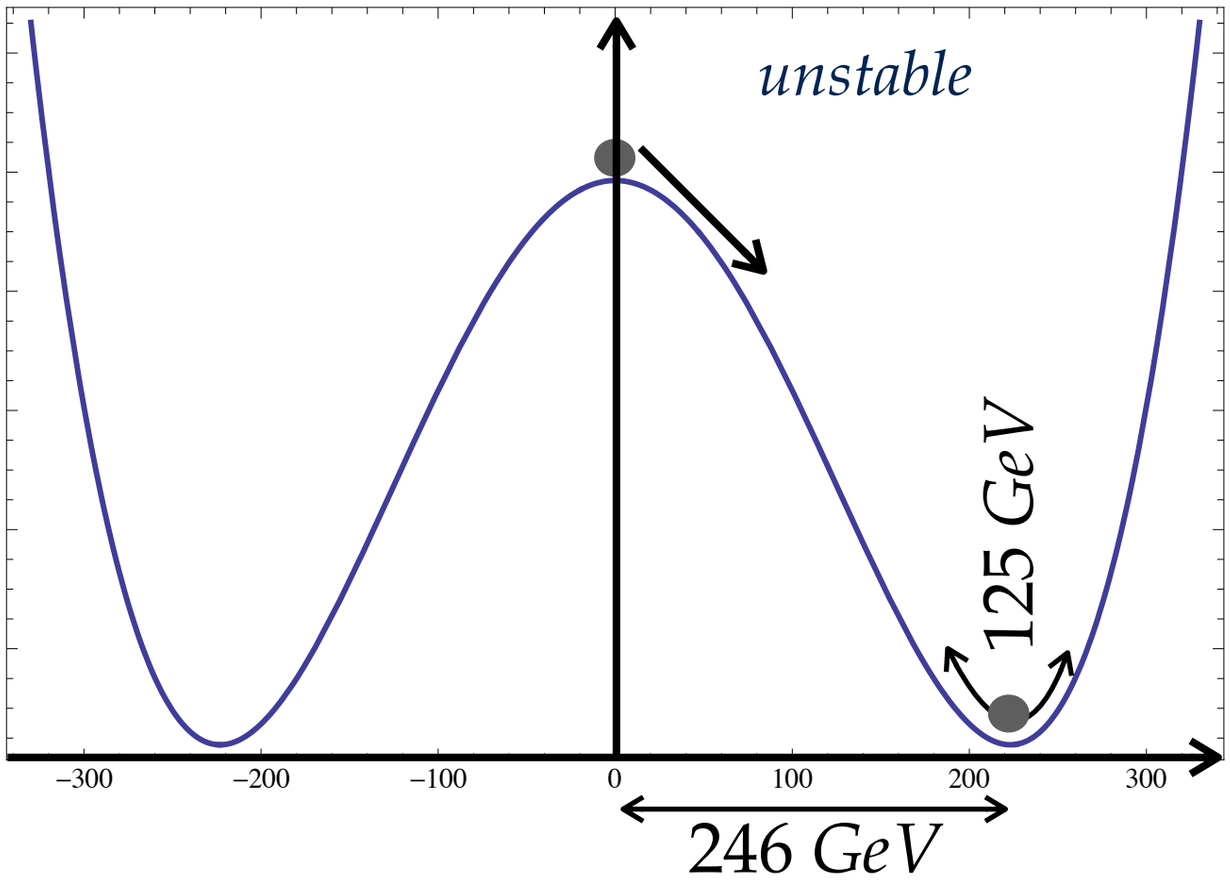
- The SM is a quantum field theory describing interacting *118* degrees of freedom (different particles), as excitations of quantum fields.

Field	$SU(3)_c \times SU(2)_L \times U(1)_Y$	$ISO(1,3)$
$L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}$	$(1, 2, -1)$	$(1/2, 0)$
e_R^c	$(1, 1, 2)$	$(1/2, 0)$
$Q = \begin{bmatrix} u_L \\ d_L \end{bmatrix}$	$(3, 2, 1/3)$	$(1/2, 0)$
u_R^c	$(\bar{3}, 1, -4/3)$	$(1/2, 0)$
d_R^c	$(\bar{3}, 1, 2/3)$	$(1/2, 0)$
$H = \begin{bmatrix} \sigma^1 + i\sigma^2 \\ h + i\sigma^3 \end{bmatrix}$	$(1, 2, 1)$	$(0, 0)$
g	$(8, 1, 0)$	$(1/2, 1/2)$
W	$(1, 3, 0)$	$(1/2, 1/2)$
B	$(1, 1, 0)$	$(1/2, 1/2)$

- *19* free parameters. Only *1* mass parameter: The Higgs mass parameter
- As an input parameter, it sets the scale of the SM, and parametrically gives all particle masses.

The Higgs Sector

- The Higgs potential $V_{\rm SM} = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$



$$m \approx 89 \text{ GeV}$$
$$\lambda \approx 0.13$$

- The Higgs mechanism for the electroweak symmetry breaking

$$\langle H \rangle \neq 0 \qquad SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$$

- So far it was classical dynamics.
- At the quantum level? $\hbar \neq 0$

The Higgs Sector

- Quantum fluctuations modify *parameters* of the theory
- The scalar mass parameter, changes drastically (singlet scalar bilinear)

$$m^2_{Higgs} = m^2 + y\, M^2\, Log(M/m)$$

observable pole mass — parameter — Any physics from UV regime

$$(125\ GeV)^2 = \left(-1+0.000000000000000000000000000000000125\right)*(10^{18}GeV)^2 + (10^{18}GeV)^2$$

- The situation gets worse, if there are more species

$$m^2_{Higgs} = m^2 + y_1\, M_1^2\, Log(M/m) + y_2\, M_2^2\, Log(M/m) + \ldots$$

- SM scale too sensitive to UV physics.

Huge amount of fine-tuning is need to get the pole mass: not Natural.

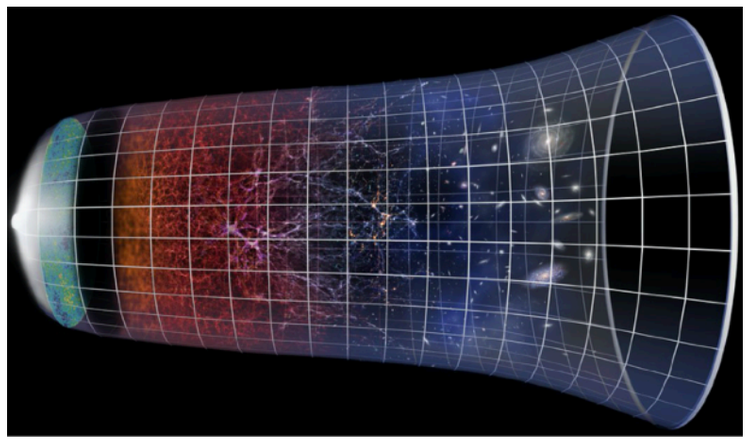
- The Higgs mass parameter is UV sensitive, its small value is not protected by a symmetry: a technical problem.

The Cosmological Constant

- The Universe is accelerating expanding on cosmological scales (de Sitter spacetime).

- A positive cosmological constant (*a.k.a.* dark energy) explains that

$$\Lambda_{\rm obs} \sim (10^{-12}{\rm GeV})^4$$



- Another mass scale. What is the physics?

- To account for quantum fluctuations, a mass parameter is added to the SM potential.

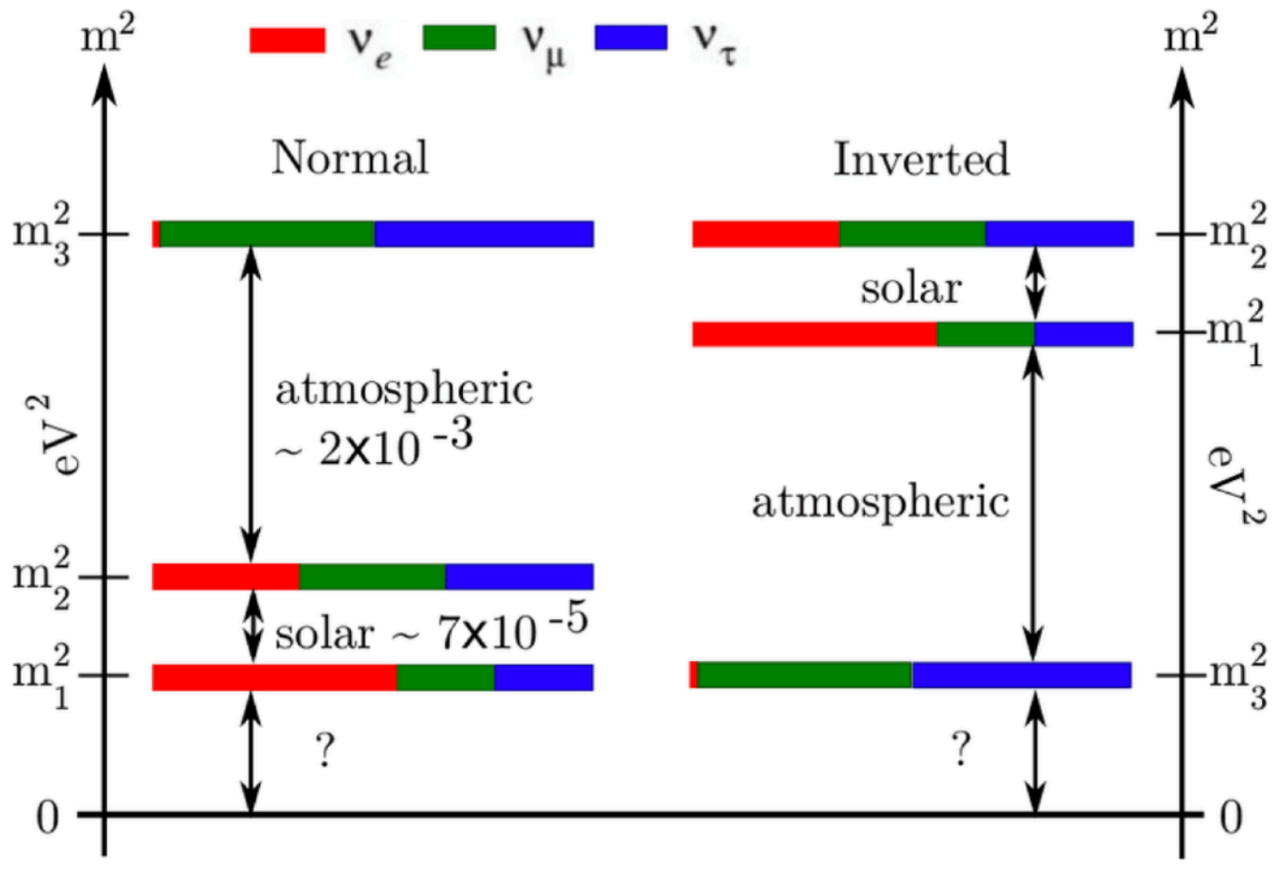
$$V_{\rm SM} = -m^2 H^\dagger H + \lambda (H^\dagger H)^2 + \Lambda$$

- The Lagrangian parameter is UV sensitive, it's not protected by any symmetry and suffers from fine-tuning problem.

$$\Lambda_{\rm obs} = \Lambda + \Delta V$$

The Neutrino Mass

- Solar/atmospheric/accelerator neutrino experiments indicate that neutrino flavors oscillate: neutrinos are massive!



$$m_\nu \sim 10^{-12}\mathrm{GeV}$$

- Technically natural small value.
- Neutrino physics: Dirac or Majorana? Beyond SM.
- Close to the C.C. value: is it a coincidence?

Beyond the Standard Model

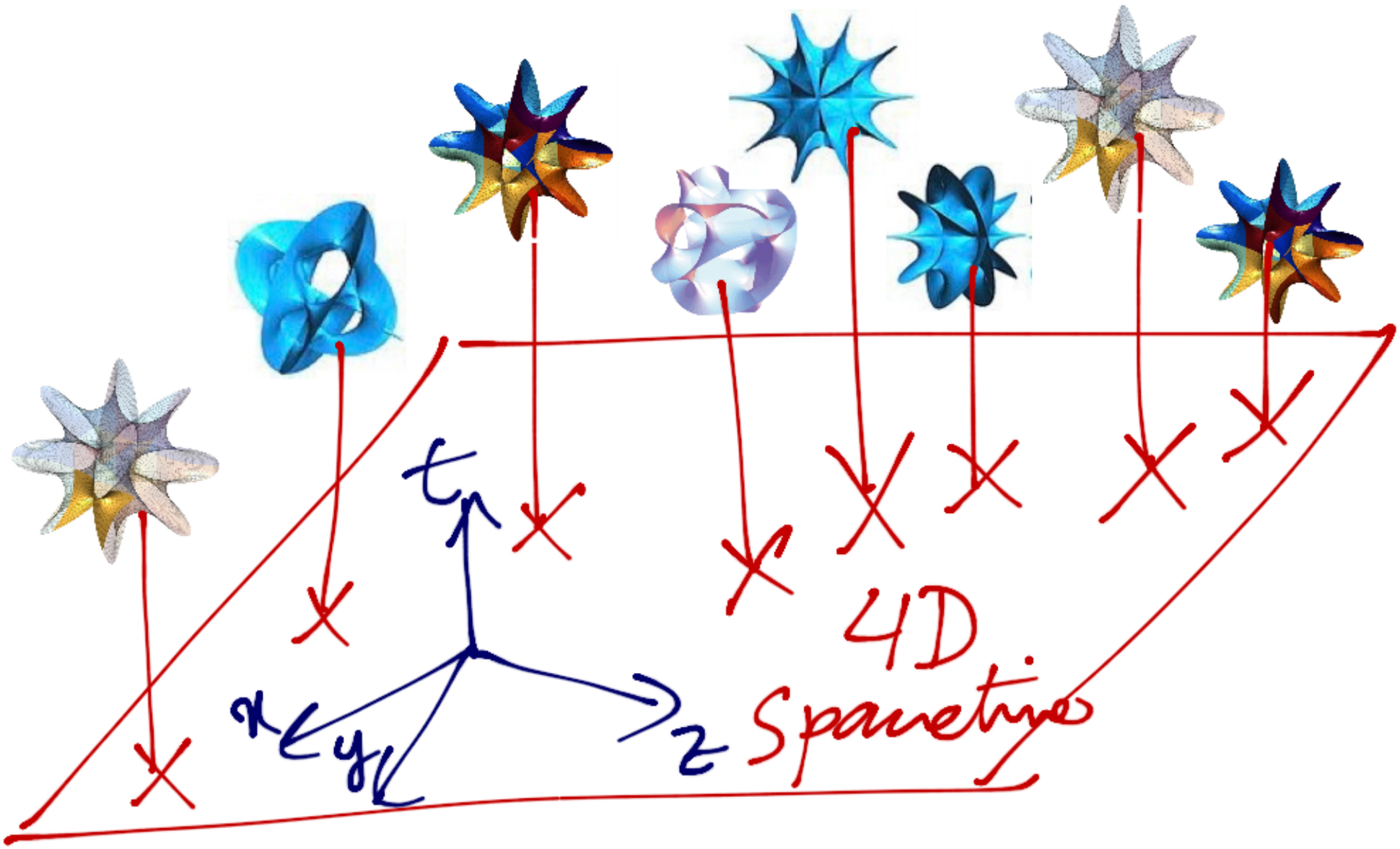
- The SM is not complete: we need to go beyond it. In what direction?
- In what direction? The parameter space of BSM's are vast.
- We also ignored quantum gravity (Planck scale effect).
- We normally *assume* that any QFT can reconcile with QG.
- *String Theory* as a theory of QG tells us that this picture is wrong:

  Not every consistently-looking QFT is consistent with QG.
- Could this tell us about the BSM?

In the remaining, we will see how this helps us explain particle physics.

String Landscape

- String theory predicts 6 extra dimensions.
- ED must curl up in compact manifold with particular holonomy.
- At each 4D spacetime point there is one such manifold.
- The shape/topology determine the parameters/fields of a 4D EFT in the IR.
- A priori, it seems there are *many many* possibilities…

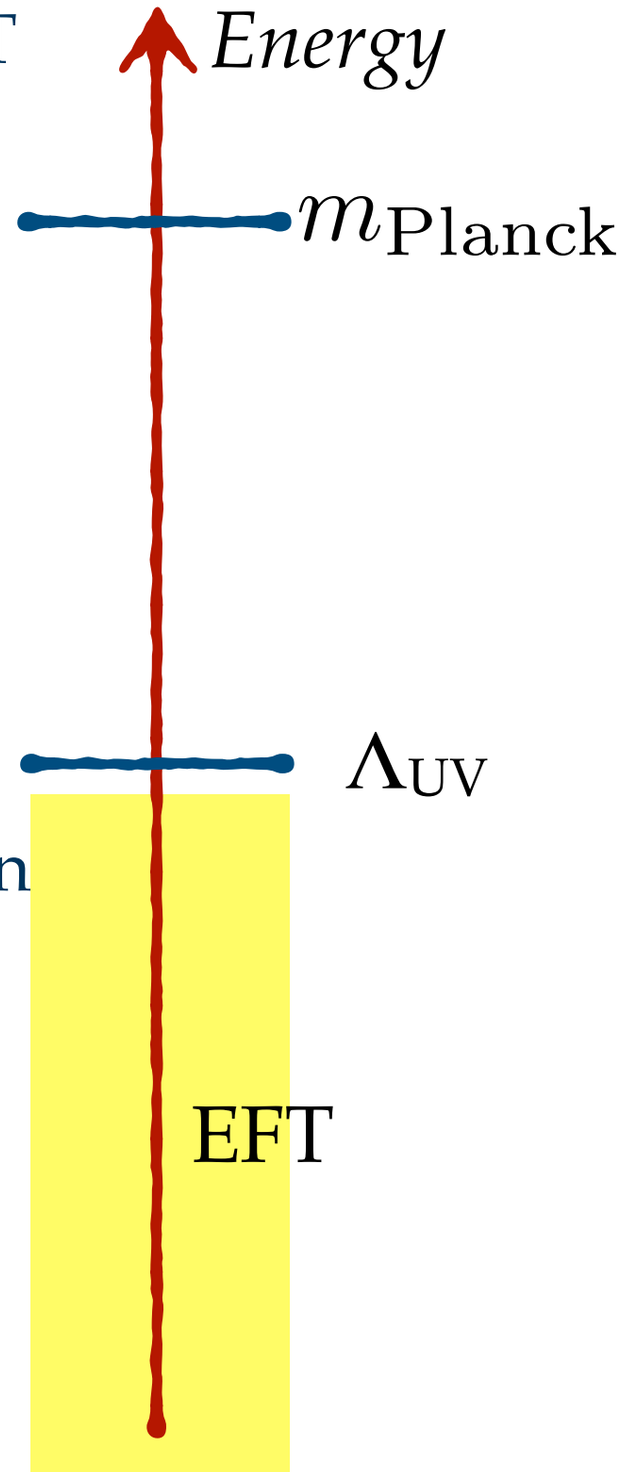


String Landscape

◆ Given vast landscape, we naively assume consistent 4D EFT can be descended from some string compactification.

◆ Moreover, al a Wilson, we assume that scales are separated; UV/IR physics are decouple. UV physics only sets the boundary conditions for IR parameter.

◆ Ignore quantum gravity. It is relevant only in deep UV. Any consistent-looking EFT, by itself, is good in the IR and can be coupled to gravity in the UV if needed.



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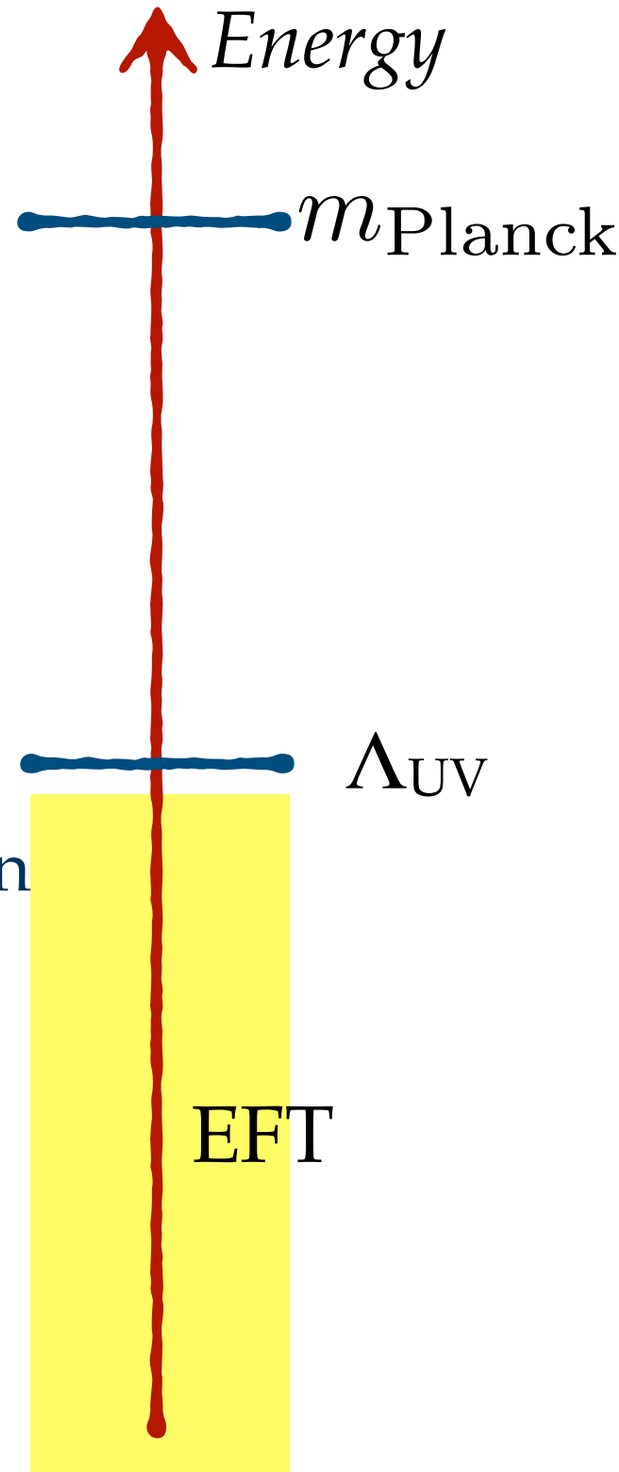
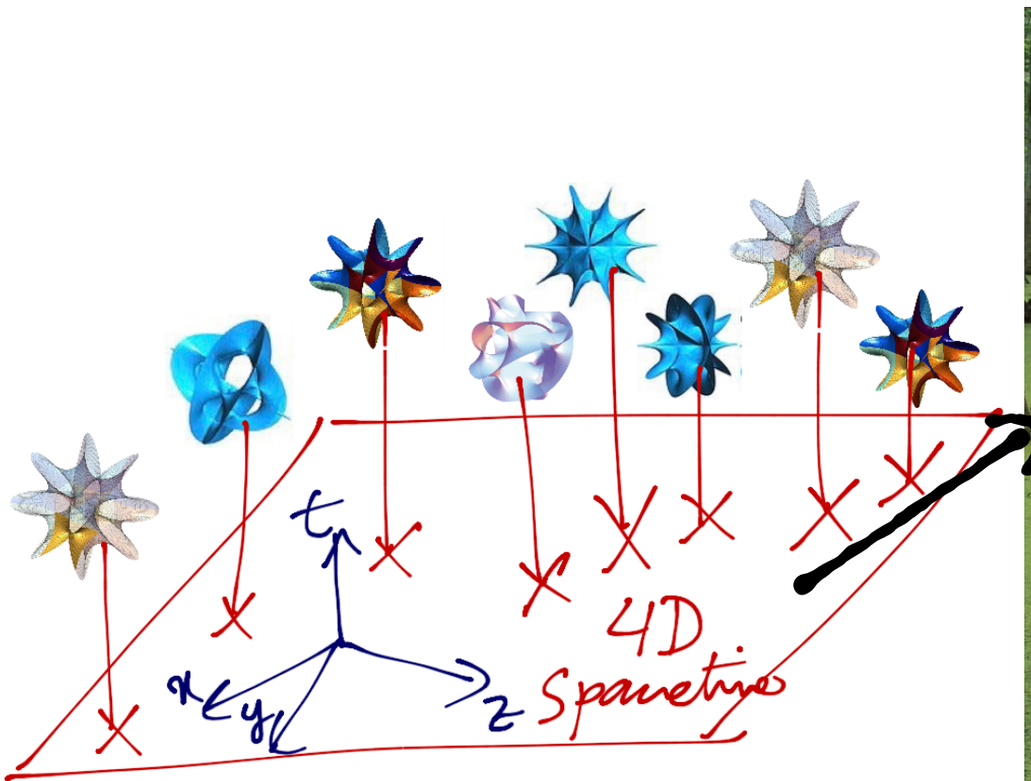


String Theory teaches us this picture is wrong!

[Vafa 2005]

Swampland Conjectures

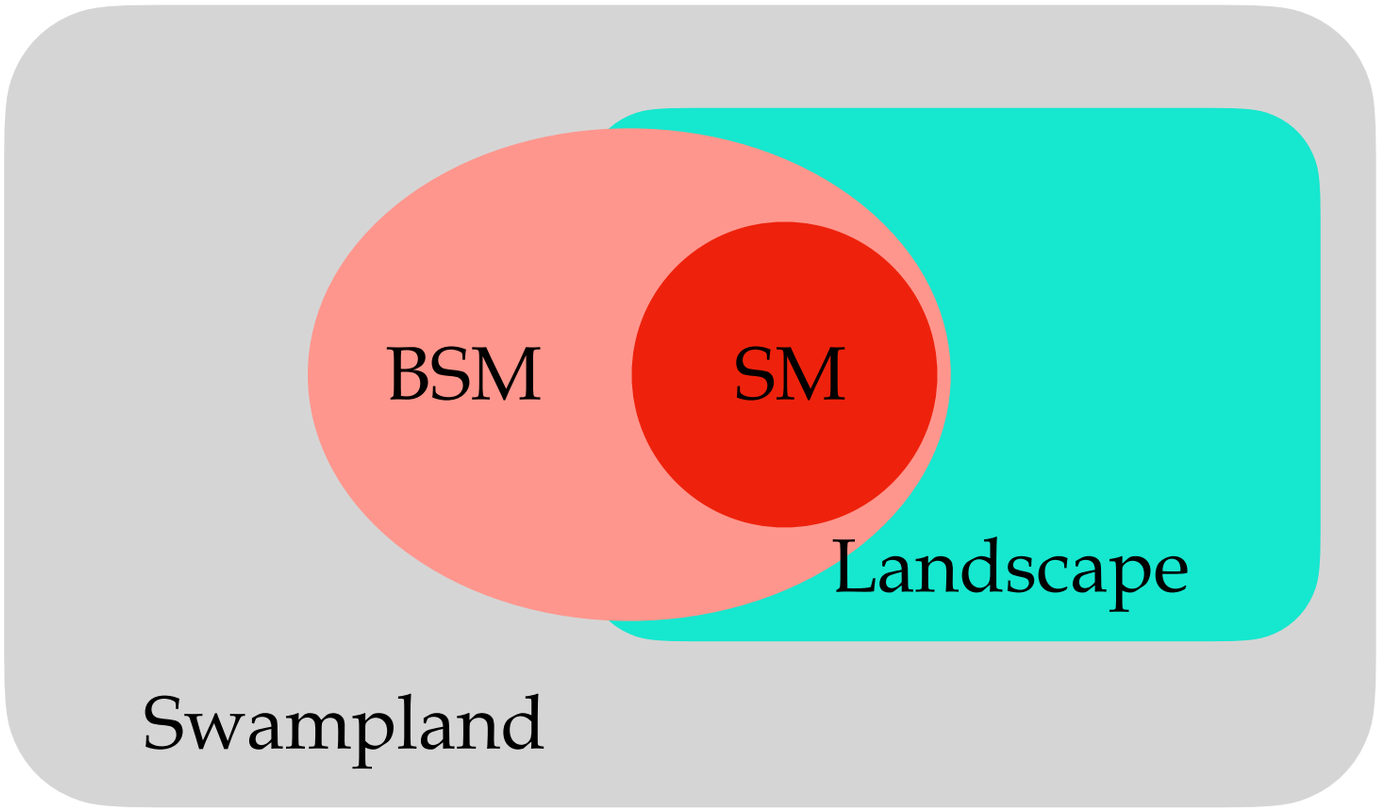
- Model buildings: not *everything* is possible in string theory constructions.
- Most EFT's cannot be consistently coupled to quantum gravity.
- The Swampland Conjectures: A list of criteria for consistent EFT's
- If an EFT respects them, it comes from some compactification, otherwise it is in the swamp.



The *landscape* is surrounded by an even a bigger *swampland*.

Swampland Conjectures and BSM

- The SM is not complete: we need to go beyond it. In what direction?



- Swampland conjectures can be used in a bottom-up approach as model-selection principles, or as constraints on the parameter space.

- Swampland conjectures also shed lights into naturalness problems.

Swampland Conjectures

- Thorough studying explicit models we construct from string compactifications, we find some generic features all have.

  - No Global Symmetry Conjecture
  - Weak Gravity Conjecture
  - Festina Lente Bound
  - No Stable non-SUSY AdS
  - Distance Conjecture
  - de Sitter Conjectures
  - Trans-Planckian Censorship Conjectures
  - …

- No proof yet. No counter-example though

For review see
[Brennan,Carta,Vafa 1711.00864]
[Palti 1903.06239]

No Global Symmetry Conjecture

- There is no EXACT global symmetry in a consistent EFT.

[Vafa 2005]

- Global symmetry in a theory which contain BH's in the spectrum, violates the Bekenstein-Hawking entropy bound and no-hair theorem.

- Accidental low energy global symmetries: must be either gauged or broken

- e.g. The most general renormalizable gauge invariant operators in the SM show accidental B, L, B-L global symmetries.

- Generically, BSM's break or gauge global symmetries.

Weak Gravity Conjecture

- Gravity is the weakest force! [Arkan-Hamed,Vafa etal 2005]

- For a massive charged particle: the electric version of WGC implies

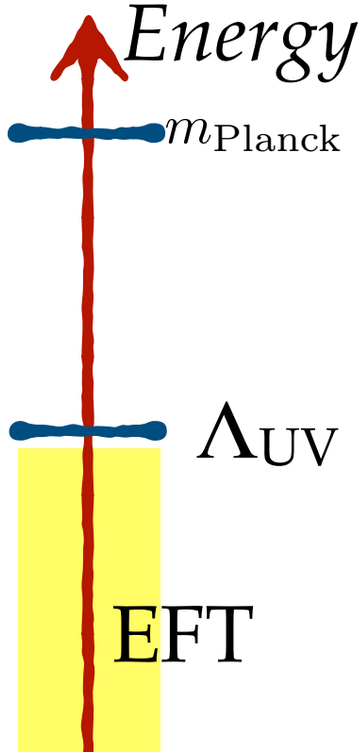
$$m < (qg) m_{\rm Pl}$$

- Certainly satisfied in our Universe, now we have an explanation.

- Closely related to no global symmetry conjecture (vanishing coupling).

- The magnetic version of WGC: the UV cut-off is bounded

$$\Lambda < g m_{\rm Pl}$$



No stable AdS Conjecture

- Supersymmetry: boson-fermion degeneracy in the spectrum
- Anti-de Sitter spacetime: solution to GR with negative CC
- Non-supersymmetric anti-de Sitter vacua are not stable.

[Ooguri-Vafa 2006]

- If an EFT is constant with QG, it is consistent on any background.
- SM compactified on a circle: a landscape of non-SUSY 3D theories.

Non of them can be in the swampland.

- Compactification introduces another scalar field (the radius).
- We compute the one-loop effective potential.

[Arkani-Hamed etal 2007]

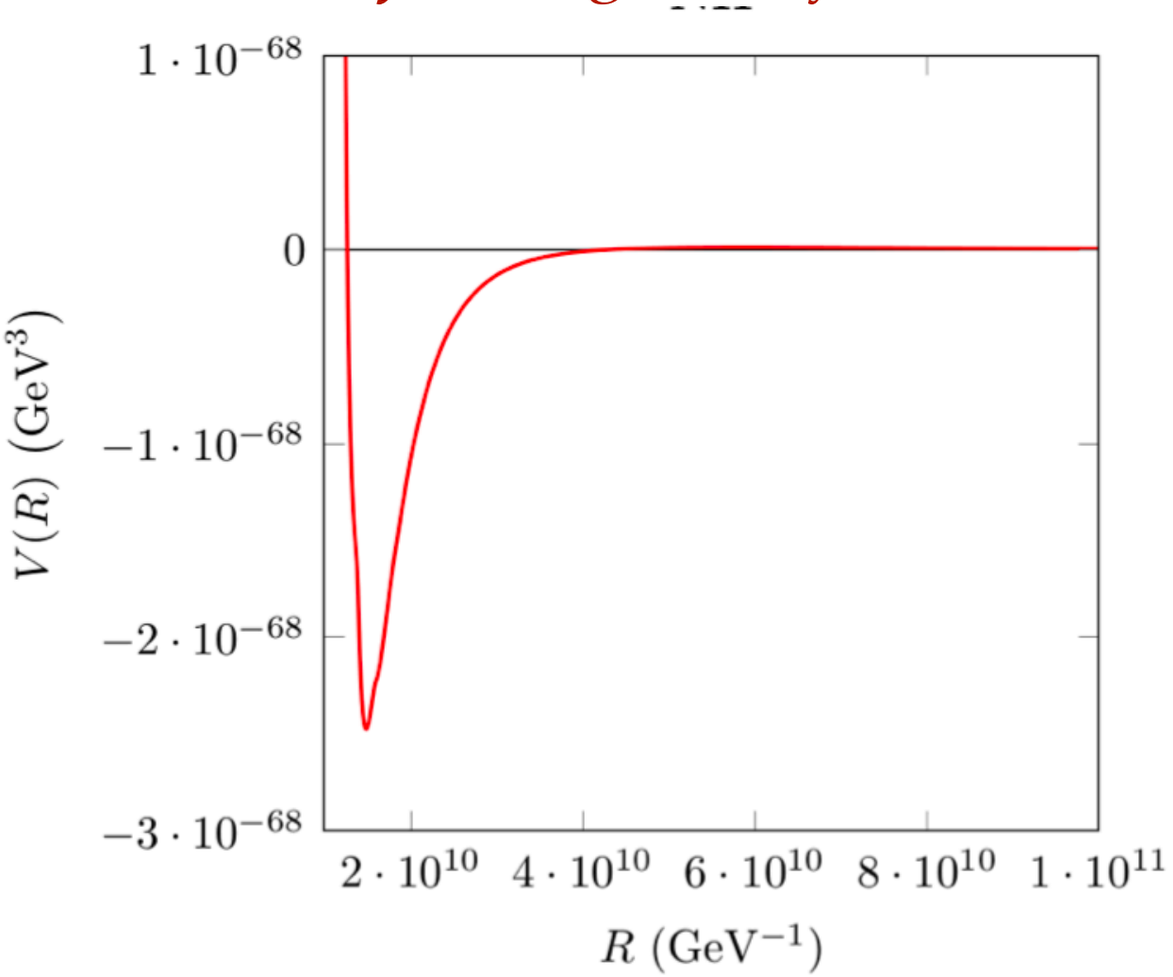
[Arnold etal 2010]

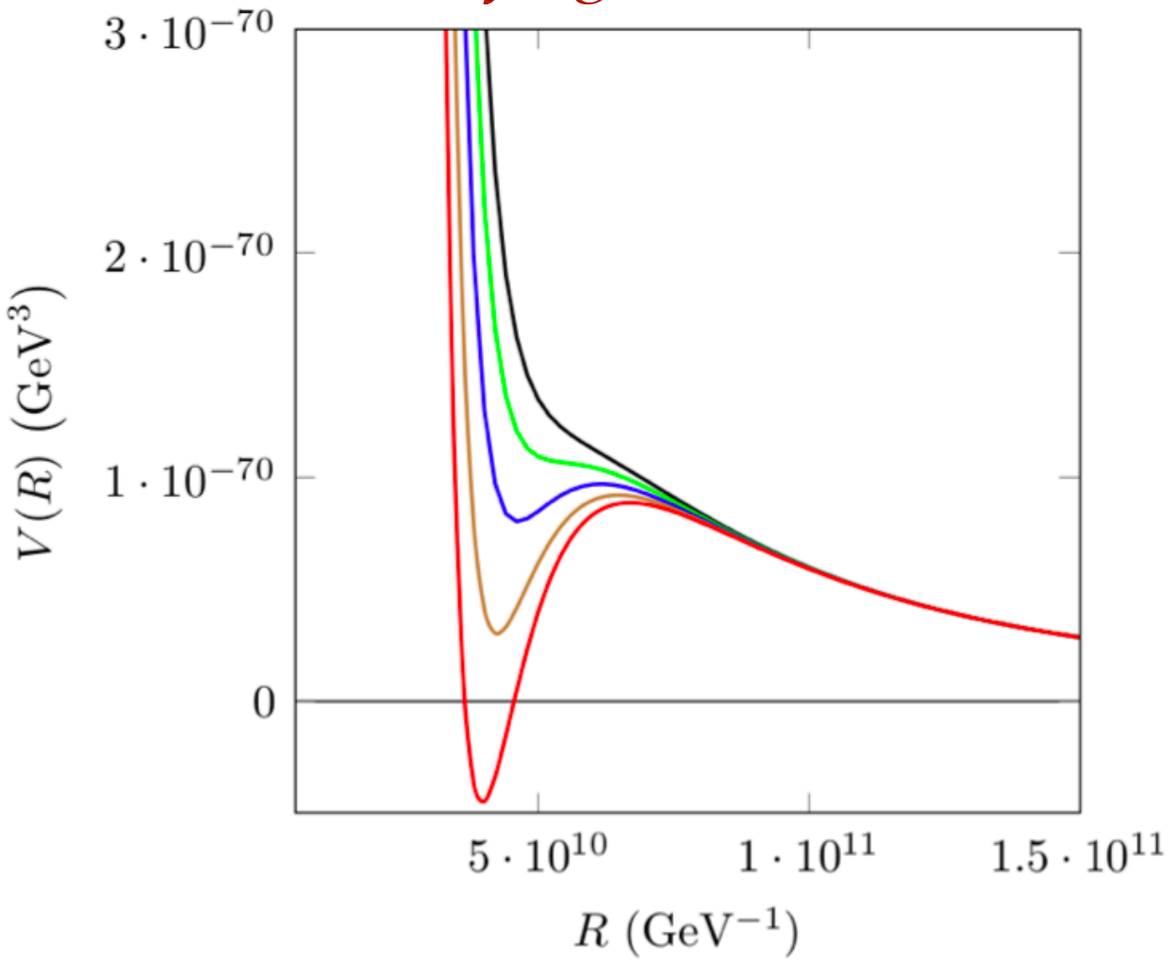
No stable AdS Conjecture

- For small radius, massless/light fields gives dominant contribution.

2 photons, 2 gravitons bosonic dof: negative contribution.

2 from light Majorana neutrino, 4 and more if light Dirac neutrino





- Non-supersymmetric anti-de Sitter vacua are not stable.
- Lightest neutrino cannot be Majorana [Ibanez-Valenzuela 2017]
- Neutrino Dirac mass in bounded $m_\nu \lesssim V_0^{1/4} \sim \text{meV}$

No stable AdS Conjecture

- Neutrino Dirac mass in bounded [Ibanez-Valenzuela 2017]

$$m_\nu \lesssim V_0^{1/4} \sim \text{meV}$$

- Particle physics (massive neutrino) implies non-vanishing cosmological constant to avoid AdS vacuum.

- Interesting coincidence, also related to the EW scale

- Dirac neutrino $m_\nu = y_\nu v$ $y_\nu \sim 10^{-14}$

$$v \lesssim \frac{V_0^{1/4}}{y_\nu} \sim 10^3 \text{GeV}$$

- An upper bound on the electroweak scale

- Shed light on naturalness problem?

- BSM's generically predict many light particles… constraint on parameter space

Festina Lente Bound

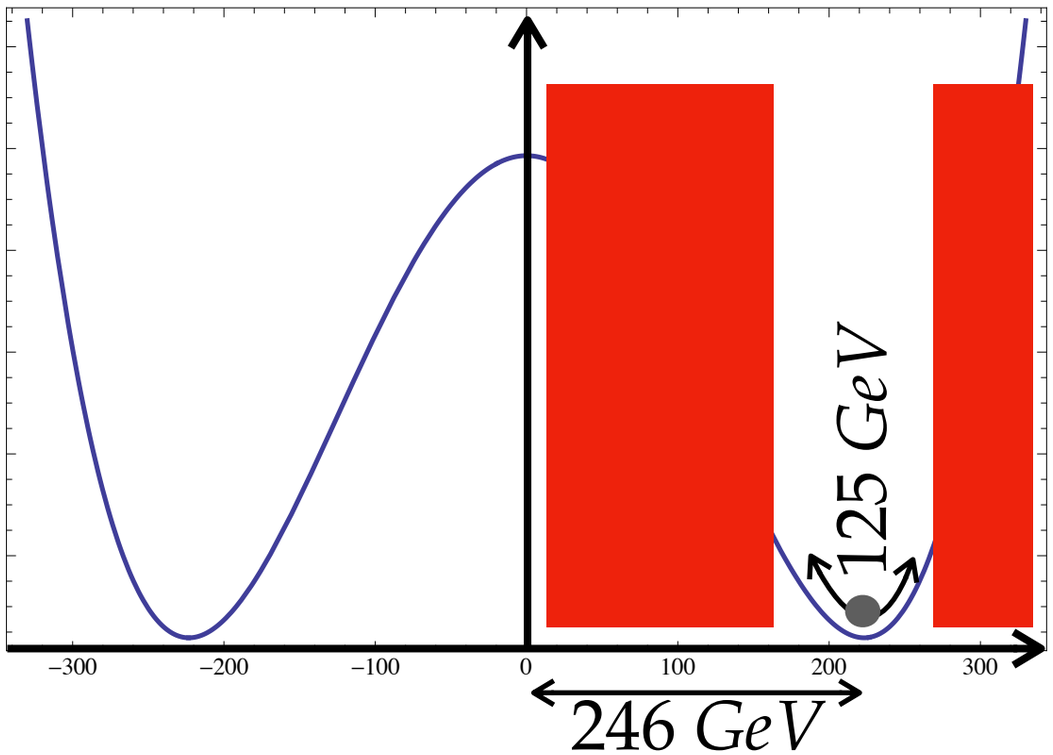
- For charged massive particle in dS space [Montero-Vafa et al 2021]

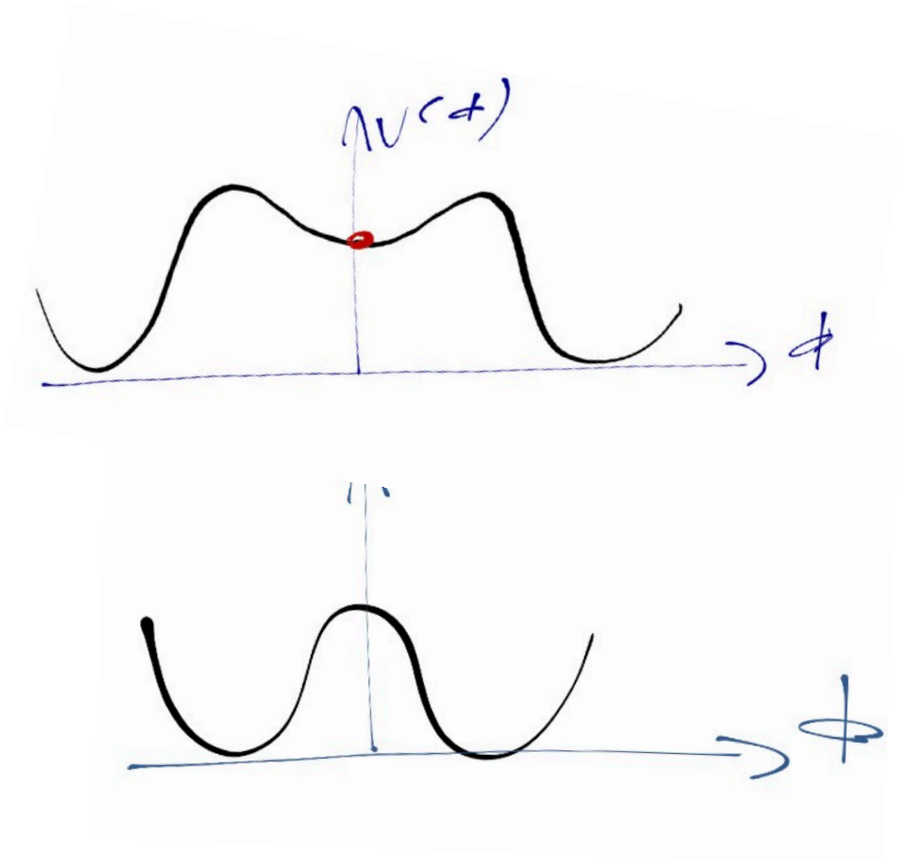
$$\frac{m^4}{g^2} \geq V \sim H^2 m_{\rm Pl}^2$$

- In the present vacuum: easily satisfied $\frac{m}{\sqrt{g}} \geq \mathrm{meV}$

- Found also from studying charged large BHs in dS space

- Shape of the Higgs potential?

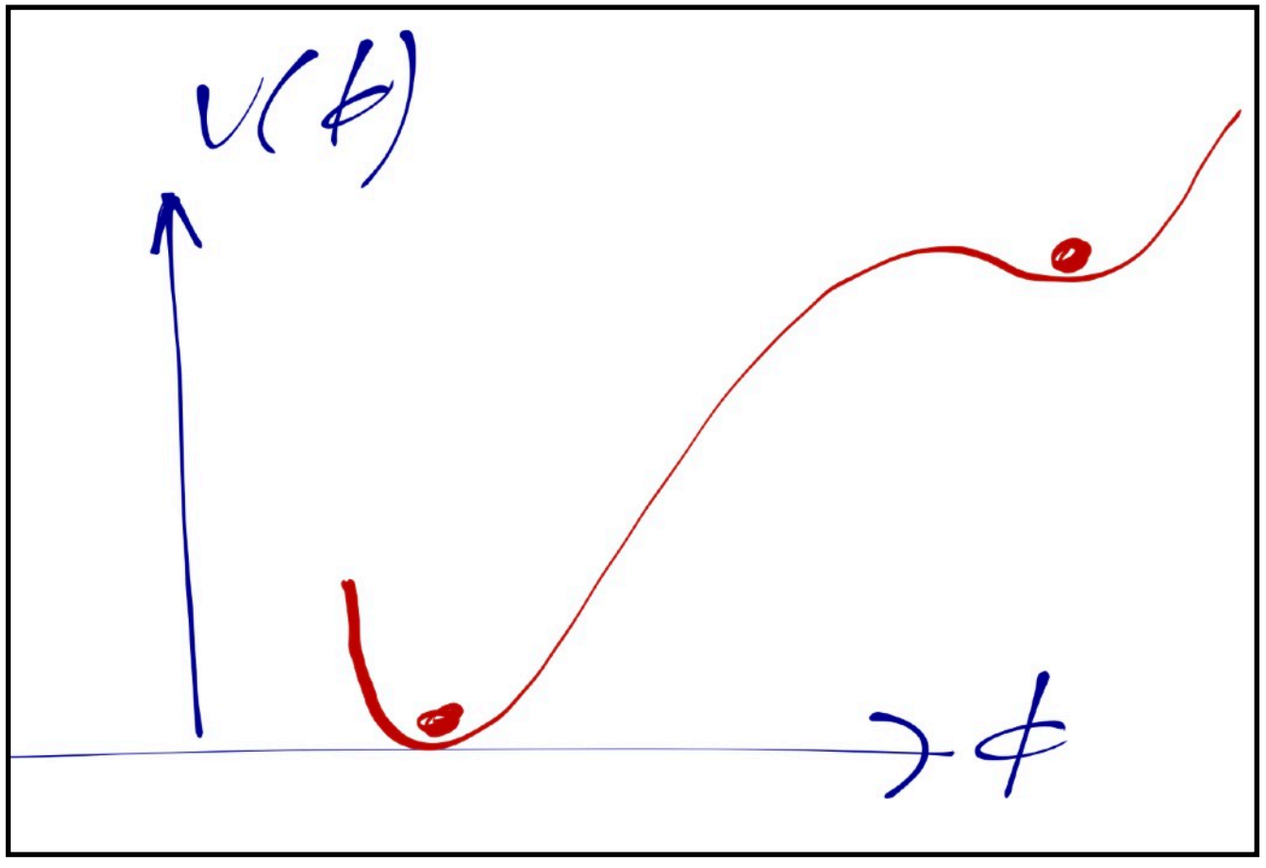




Festina Lente Bound

- Shape of the Higgs potential in the early inflationary era?

$$\frac{m^4}{g^2} \geq V \sim H^2 m_{\rm Pl}^2$$



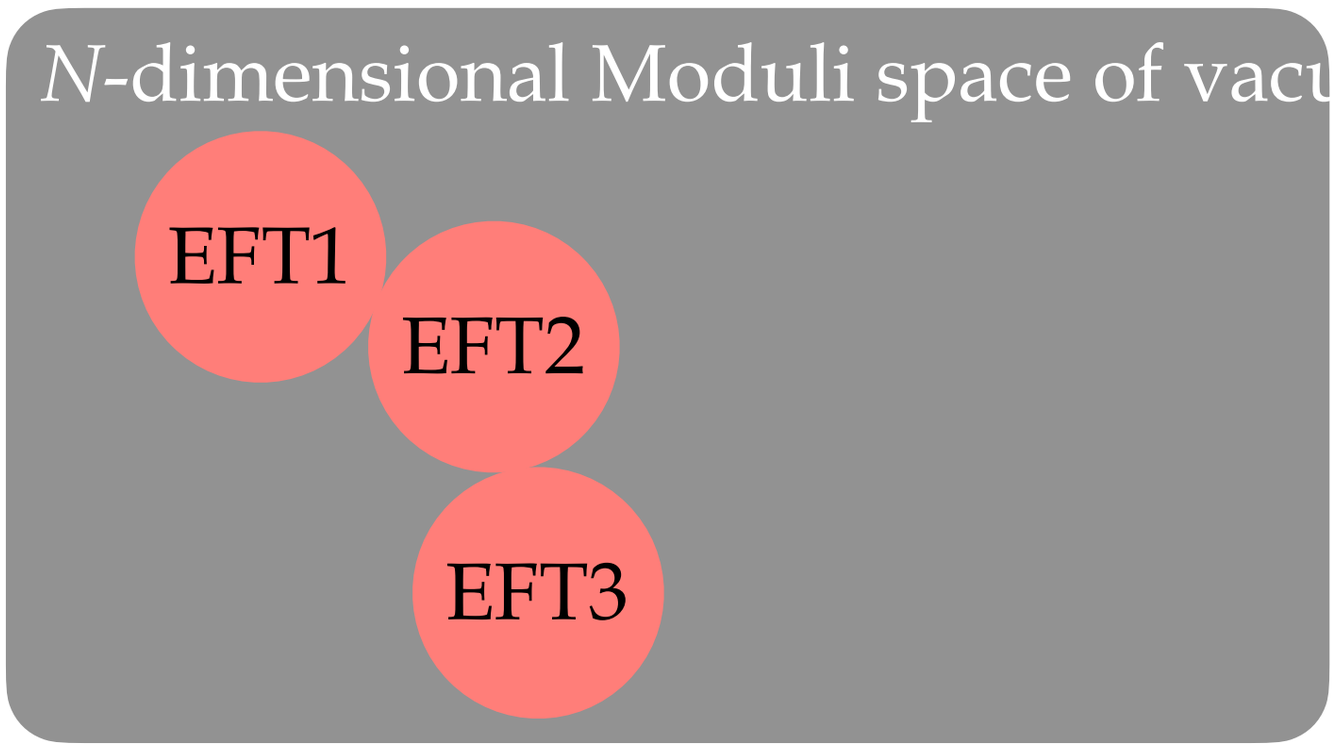
Swampland Distance Conjecture

Scalar field value (excursion) is bounded

$$\Delta\phi \lesssim m_{\rm Pl}$$

[Vafa 2005]

- No single patch/EFT to cover all moduli space, no single description.
- In every patch, there is new dof's, new symmetries and new Lagrangian.



- *Corollary*: EFT's with superPlanckian excursions are in the swampland.
- Implication for cosmological model building.

Duality Symmetries

- Dualities are one of the most important *lessons* from String Theory.

- When vary a parameter to an extreme limit, the degrees of freedom and the symmetries all change.

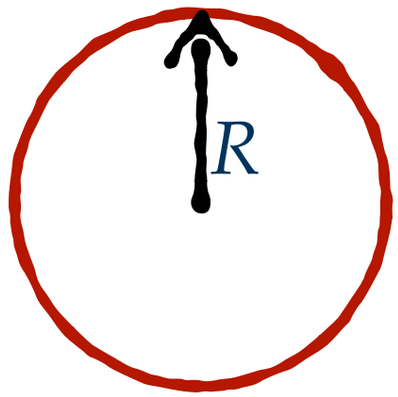
- Although the former theory become very cumbersome, we find a new theory which better describe physics.

- There is no single description for whole parameter space.

T-Duality

T-duality: Extended objects + Extra dimensions

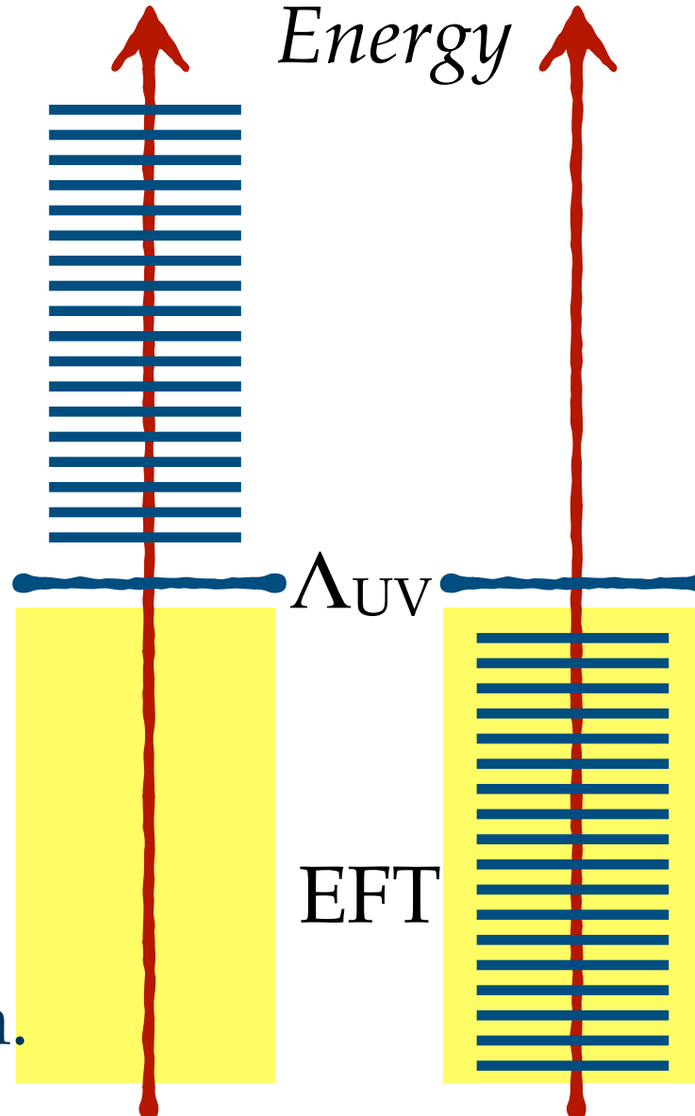
- Circle compactification: $ds^2 = g_{\mu\nu}\, dx^\mu dx^\nu + R^2(x)\, dy^2$



$$\mathcal{L} \supset m_{pl}^2\, \frac{\partial_\mu R\, \partial^\mu R}{(m_{pl} R)^2}$$

$$\varphi = m_{pl} \ln R \qquad \mathcal{L} \supset (\partial_\mu \varphi)^2$$

- Kaluza-Klein modes: $m_{KK} = \frac{n}{R} = n\, e^{-\varphi/m_{pl}}$
- Towers of states become exponentially light in extreme points of the moduli space $\varphi \longrightarrow \infty$
- Winding modes: $m_{winding} = n R = n\, e^{\varphi/m_{pl}}$
- Better description in terms of new degrees of freedom.



de Sitter Conjecture

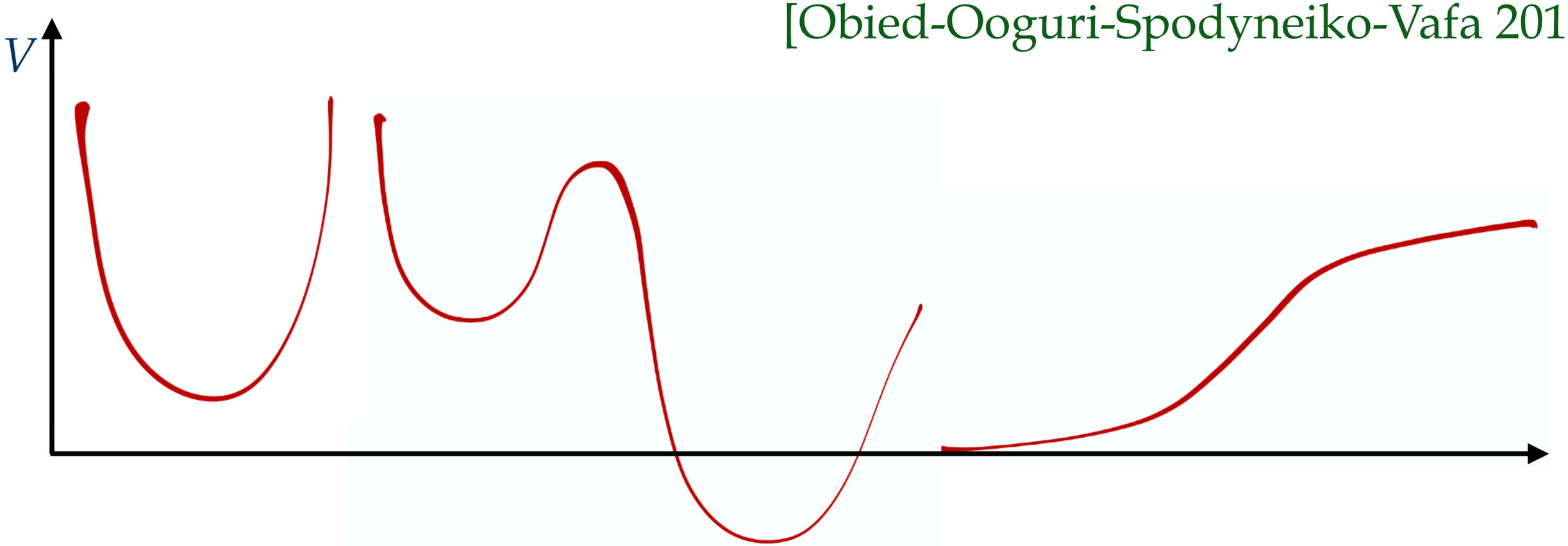
The shape of the scalar potential is constrained

$$m_{\rm Pl}\frac{|\nabla V|}{V} \geq c, \qquad \text{or}$$

$$m_{\rm Pl}^2\frac{\min(\nabla_i\nabla_j V)}{V} \leq -c'$$

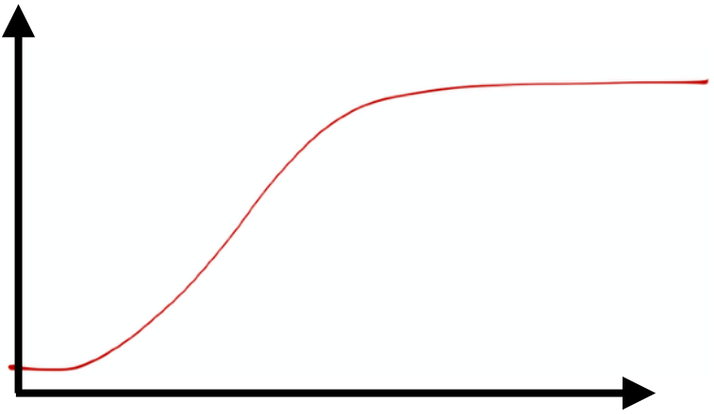
- *Corollary*: There exist no stable dS. Not even meta-stable dS.

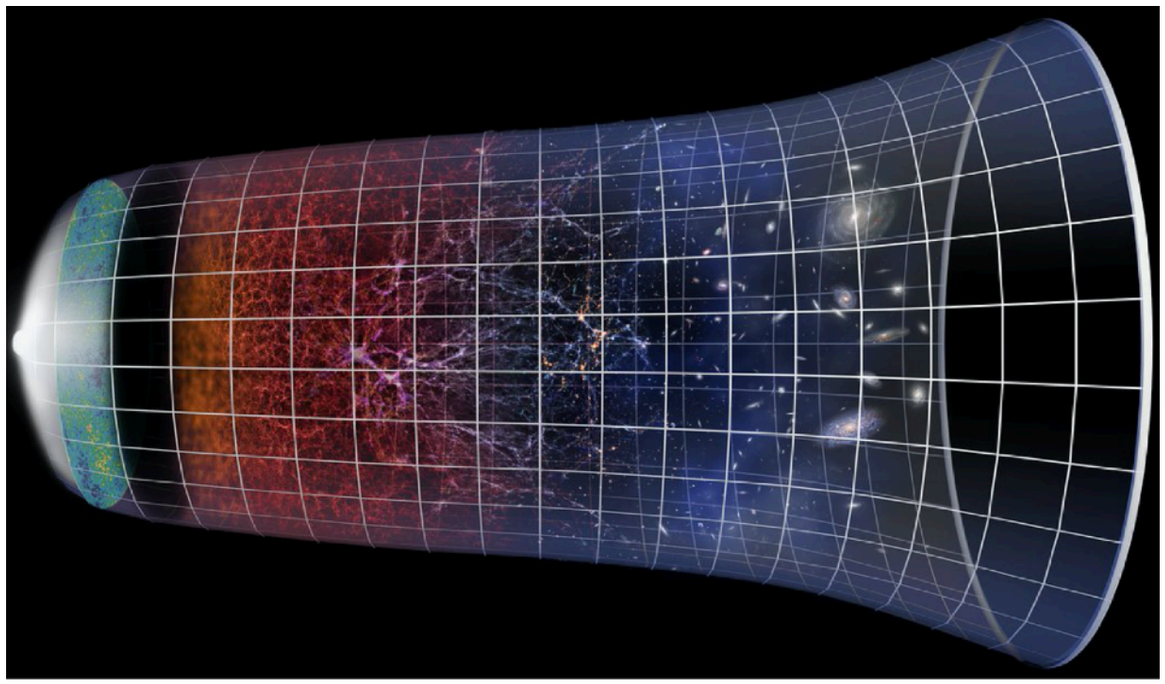
[Ooguri-Vafa 2017]
[Obied-Ooguri-Spodyneiko-Vafa 2018]

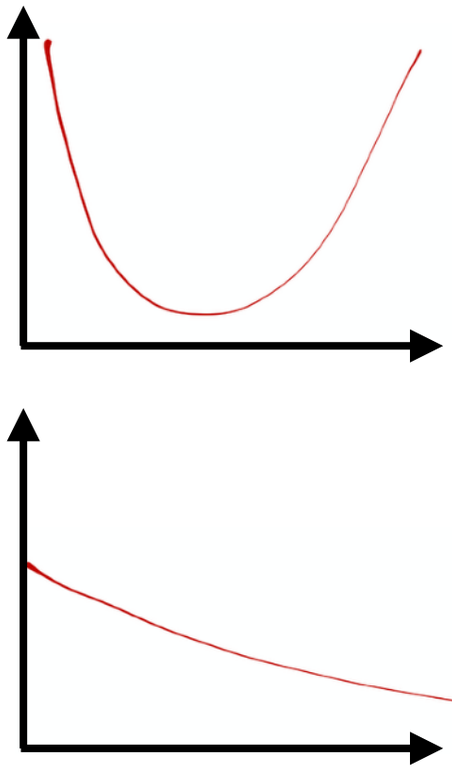


De Sitter Cosmology

◆ Observations strongly indicate that the *observable universe* is experiencing an accelerating expansion. Moreover, a similar phase, *a.k.a.* cosmic inflation, can explain many features of the observable universe.







◆ Whether these potentials naturally arise in string compactifications or they are in swampland?

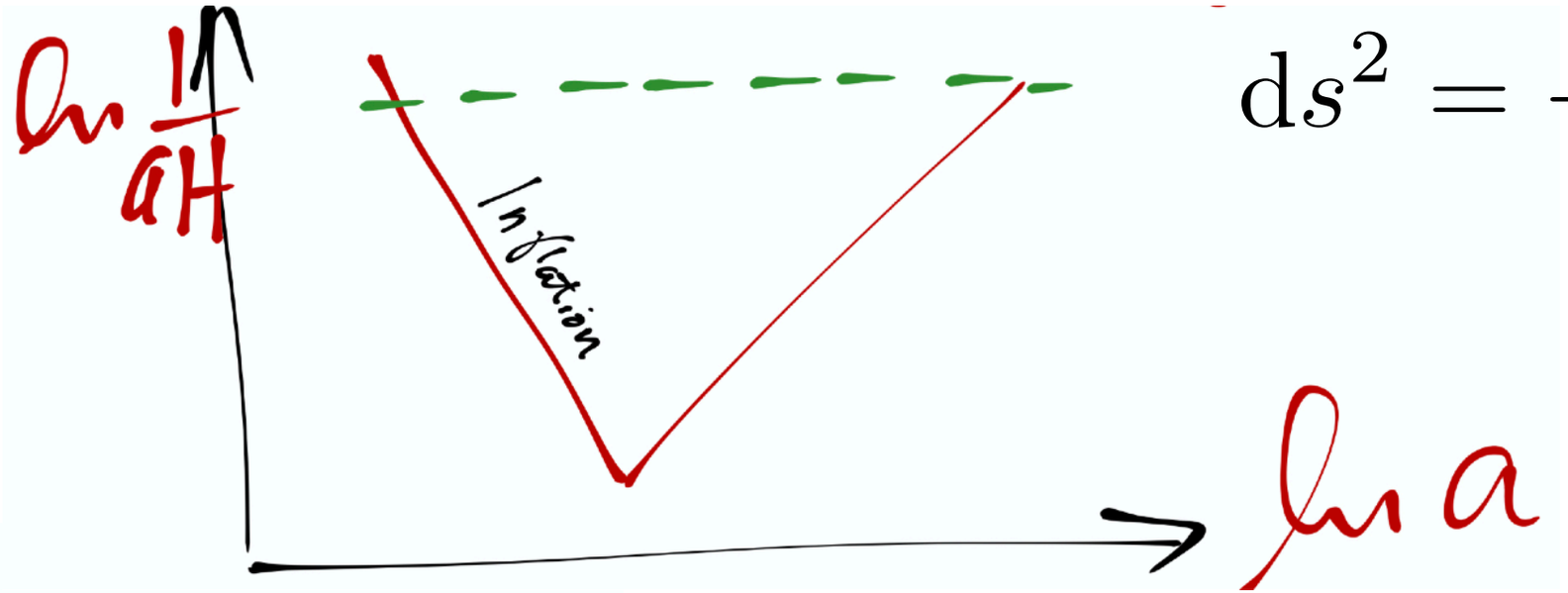
Primordial Inflation

- Standard Paradigm of Hot Big-Bang Cosmology: Expansion, CMB, BBN
- Initial condition/Horizon problem:

The present horizon is smooth better than *1* part in 10^5. So, it is composed of around 10^9 causally disconnected patches at the time of recombination, around 10^{27} causally disconnected patches at the time of nucleosynthesis, around 10^{96} causally disconnected patches at the Planck time,

$$1 \leq \frac{L_0 H_0}{L_* H_*} = \frac{a_0 H_0}{a_* H_*} \sim \frac{T_*}{T_0}$$

- solution: shrinking comoving Hubble horizon



$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2 \mathrm{d}x^2$$

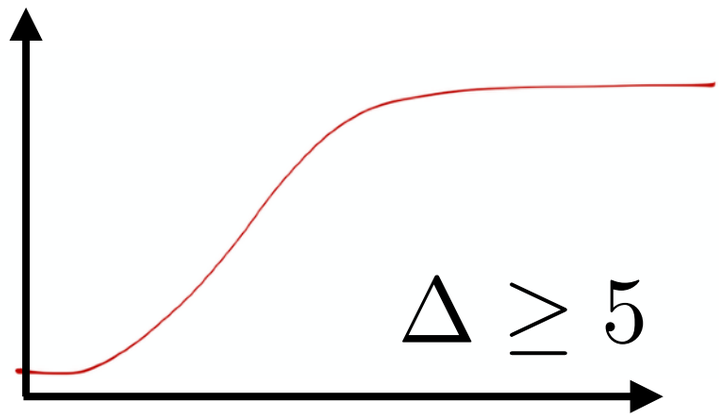
$$\boxed{H \equiv \frac{a}{\dot{a}}}$$

dS Conjecture and Inflation

- Tension with distance conjecture: $\Delta\phi \leq \Delta \sim \mathcal{O}(1)$

Enough e-folding needs super-Planckian excursion.

$$\Delta\phi \sim N_e\sqrt{2\epsilon}$$



- Tension with dS conjecture: $\nabla_\phi V/V \geq c \sim \mathcal{O}(1)$

Observational limit of B-mode polarization (2016)

$$r \approx 16\epsilon < 0.07 \text{ or } \epsilon < 0.0044$$

$$\epsilon \approx \frac{1}{2}\left(\frac{|\nabla_\phi V|}{V}\right)^2$$

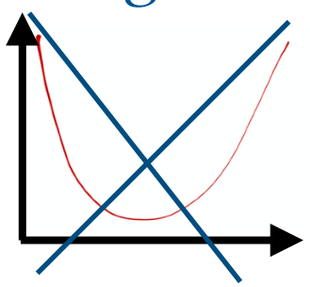
$$|\nabla_\phi V|/V < 0.09$$

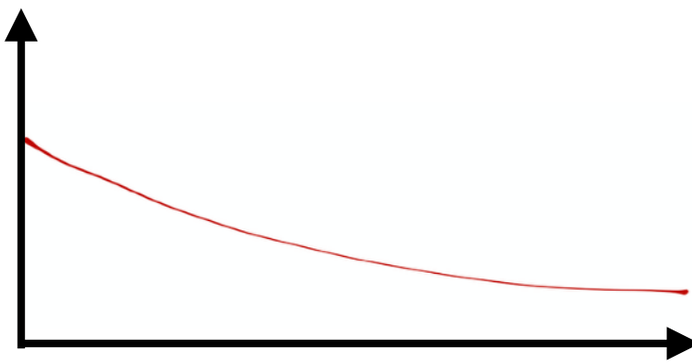
[Agrawal-Obied-Steinhardt-Vafa 2018]

dS Conjecture and Dark Energy

- Data: present universe is dominated by dark energy.

The dS conjecture: not from minimum of a potential, rolling maybe.
Favors a *quintessence model* over the *cosmological constant*





Astrophysical observations (SNeIa,CMB,BAO) constrain:

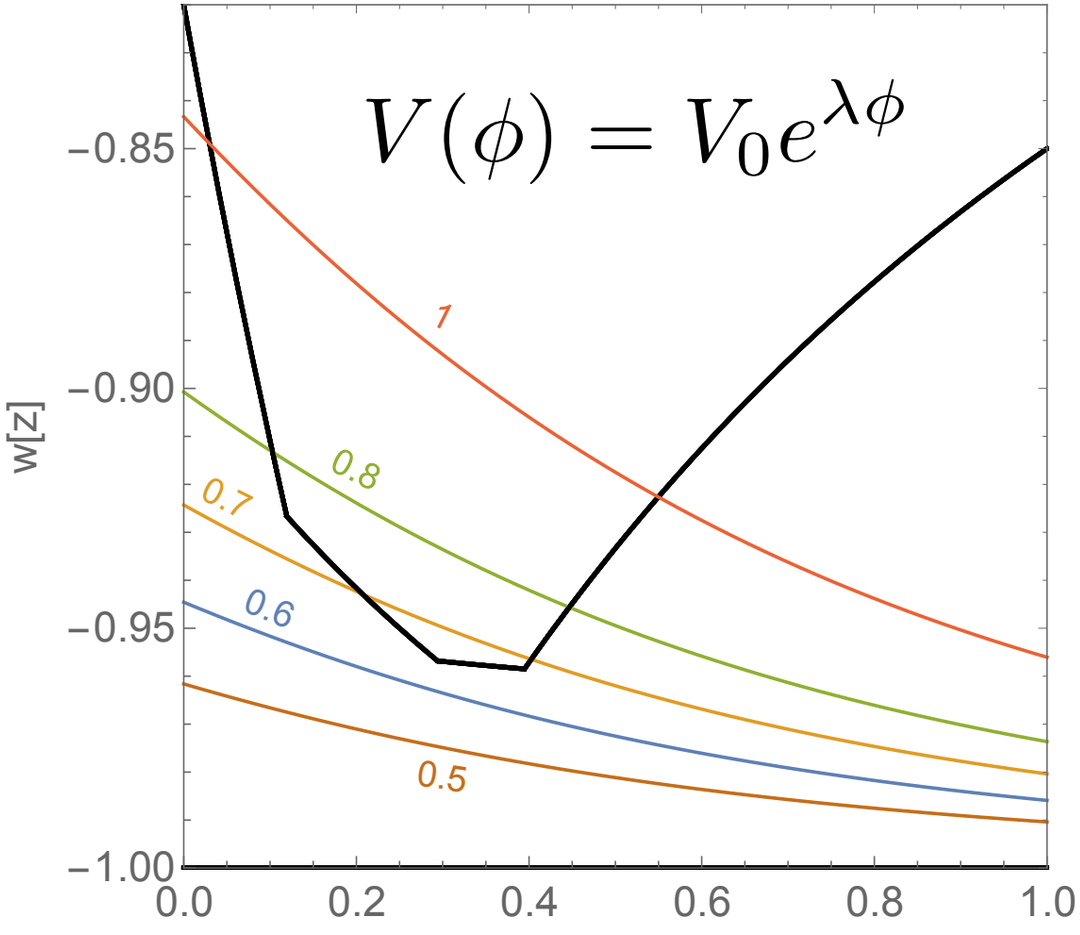
$$\Omega_\phi(z) \text{ and } w(z)$$

$$1 + w(z) \ll 2/3 \text{ for } z < 1$$

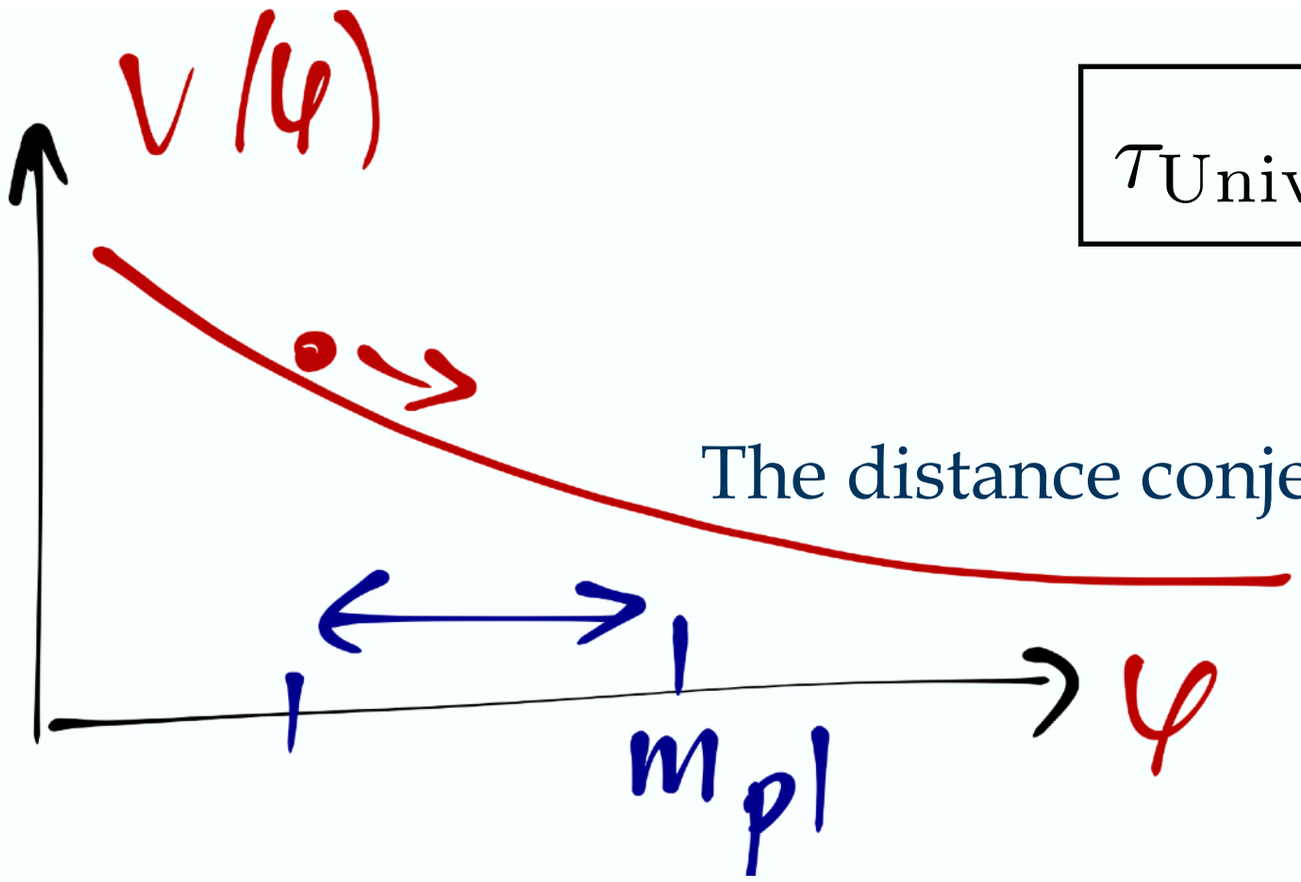
$$\Omega_\phi(z = 0) \equiv \Omega_\phi^0 \approx 0.7$$

$$\Omega_\phi(z > 1) \ll 1$$

[Agrawal-Obied-Steinhardt-Vafa 2018]

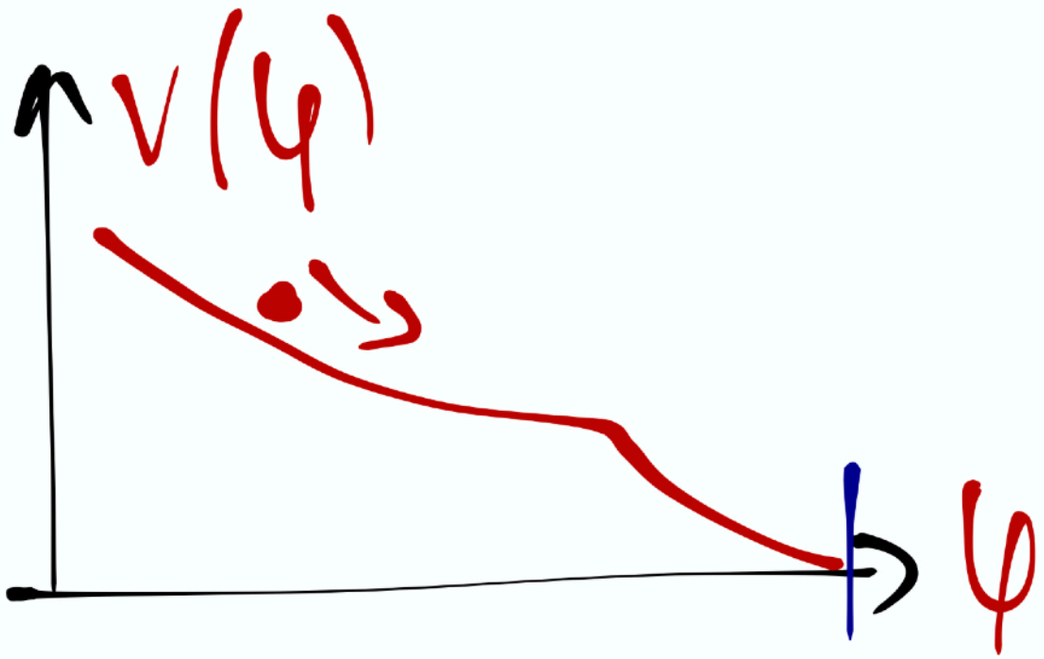


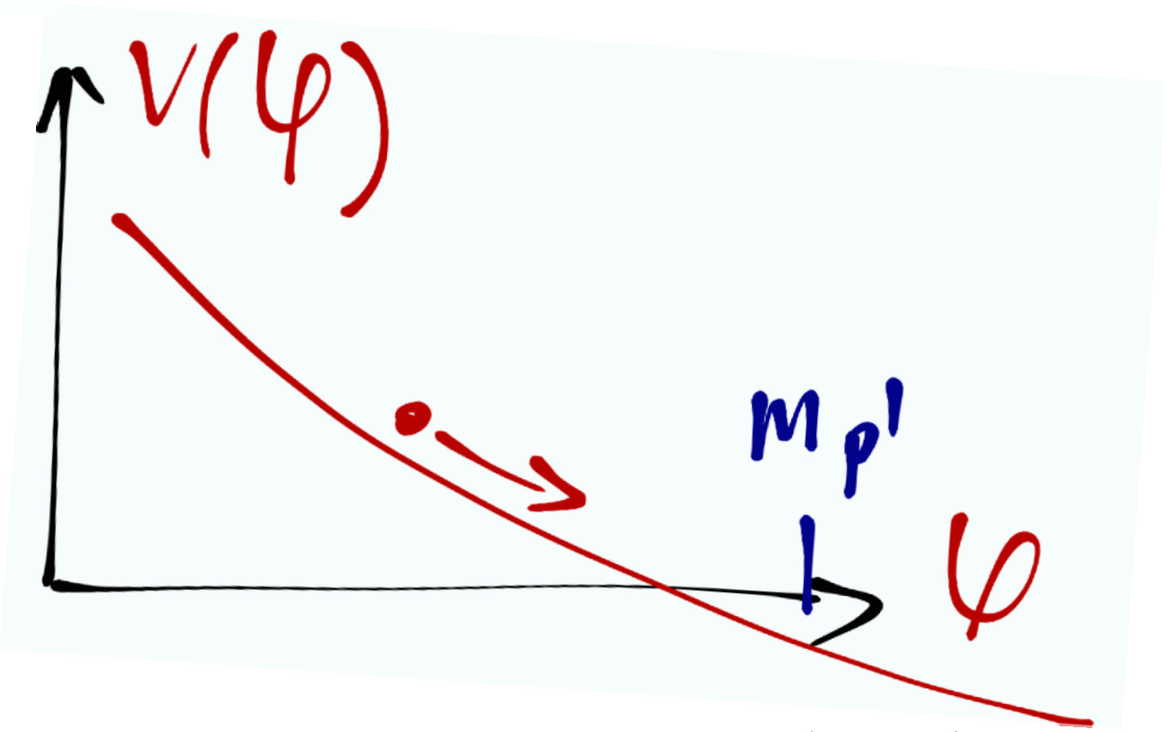
Swampland Conjectures and Fate of the Universe



$$\tau_{\rm Universe} \lesssim 50 H_0^{-1}$$

The distance conjecture is violated.

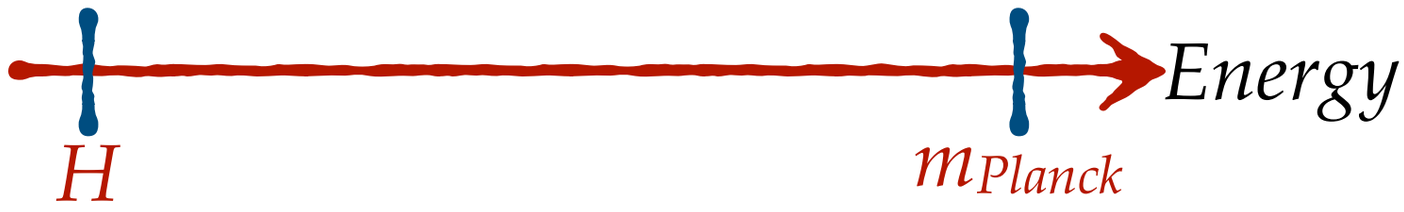




The distance conjecture is not violated.

Trans-Planckian Censorship Conjecture

- In de Sitter: a UV cut-off m_{Planck} and an IR cutoff H



- In a theory of quantum gravity, UV/IR scales are not decoupled.
- The TCC establishes a connection between cut-off:

[Bedroya-Vafa 2019] $\boxed{e^N H < m_{\rm Pl}}$ $\qquad N = \int_{t_i}^{t_f} H \mathrm{d}t$

- In an accelerating expanding spacetime quantum modes are stretched beyond the horizon, freeze and get classicalized: seeds of LS structures.

The *TCC*: In an EFT consistent with quantum gravity sub-Planckian quantum modes never become classical and super-horizon/superhorizon.

TCC and late Universe

$$\boxed{e^N H < m_{\rm Pl}} \qquad N = \int_{t_i}^{t_f} H \mathrm{d}t$$

[Bedroya-Vafa 2019]

- Meta-stable dS is possible with finite life-time:

$$\boxed{T \leq H_f^{-1} \ln\left(\frac{m_{\rm Pl}}{H_f}\right)}$$

The life-time of our Universe:

$$T_{\rm universe} \leq 140\ t_{\rm universe} \sim 2 \text{ trillion years}$$

- Solve cosmic coincidence problem: why the age of universe is *1/H*?

TCC and Inflation

$$\boxed{e^N H < m_{\rm Pl}}$$

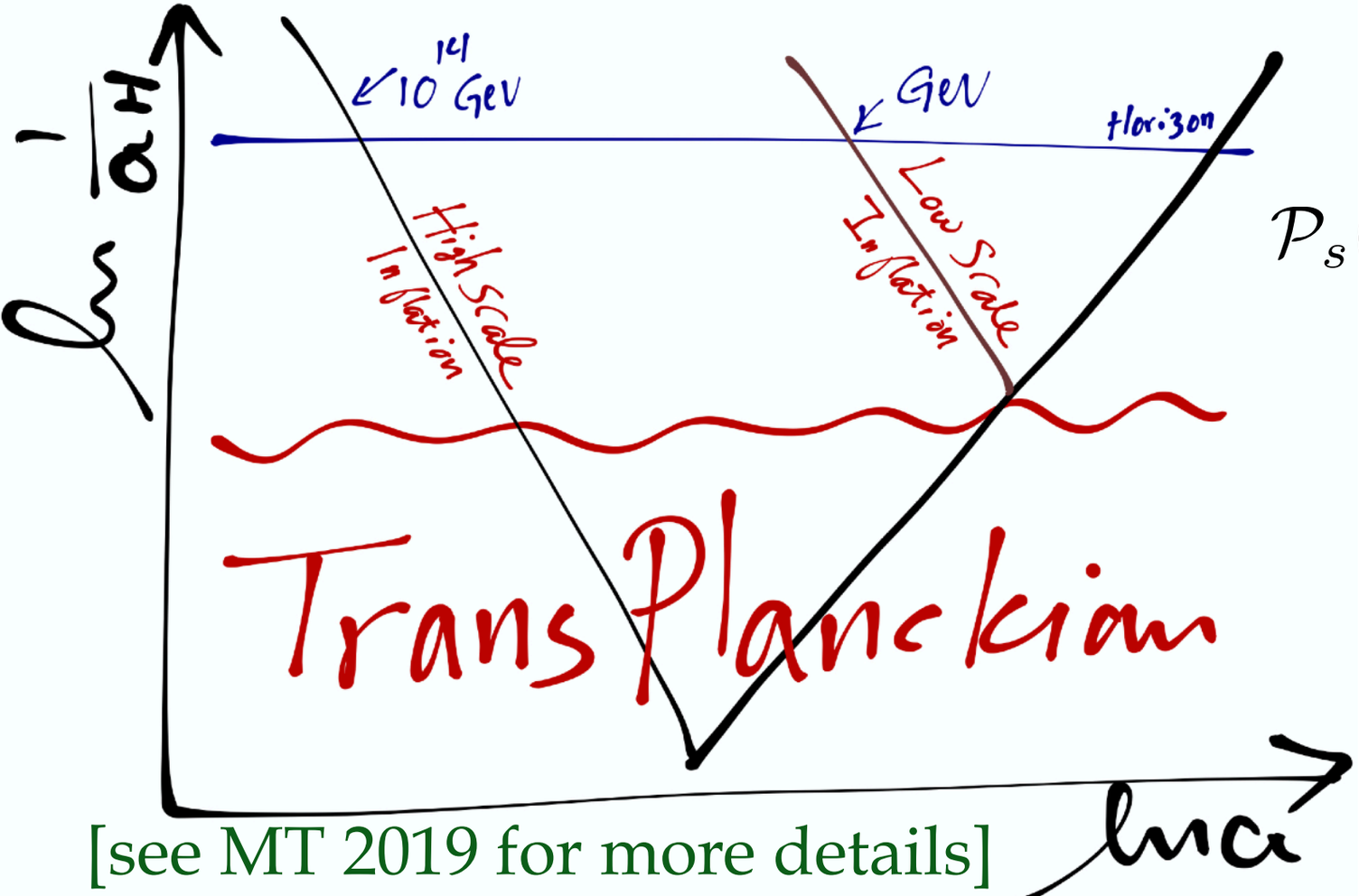
An upper bound on $H_{\rm inf}$

A upper bound on number of *e-folds* or the life-time

To explain the present horizon:

$$1 \geq \frac{a_{\rm ini} H_{\rm inf}}{a_0 H_0} = e^{-N} \frac{a_{\rm end}}{a_{\rm rad}} \frac{T_0}{T_{\rm rad}} \frac{H_{\rm inf}}{H_0} = e^{-N} \frac{T_0}{T_{\rm rad}} \frac{H_{\rm inf}}{H_0} \left(\frac{H_{\rm rad}}{H_{\rm inf}} \right)^{\frac{2}{3(1+w)}}$$

[Bedroya-Brandenberger-Loverde-Vafa 2019]



[see MT 2019 for more details]

$$V_{\rm inf}^{w=1/3} \sim (3 \times 10^{-10} m_{\rm Pl})^4$$

$$\mathcal{P}_s(k) = \frac{1}{8\pi^2 \epsilon} \left[\frac{H_{\rm inf}(k)}{m_{\rm Pl}} \right]^2 \sim 10^{-9}$$

$$\boxed{\epsilon < 10^{-31}}$$

$$\boxed{r = 16\epsilon < 10^{-30}}$$

TCC and Inflation

◆ Prediction: Given a vanilla model for inflation, no primordial gravitational waves will be detected.

◆ Fine-tuning of initial condition at the onset of inflation:
Around 10^{30} similar patches at the Planck time bust be prepared.
[Recall: inflation was supposed to solve the I.C. problem of cosmology!
Even 10^{16} GeV inflation needs 10^{6} smooth patches prepared]

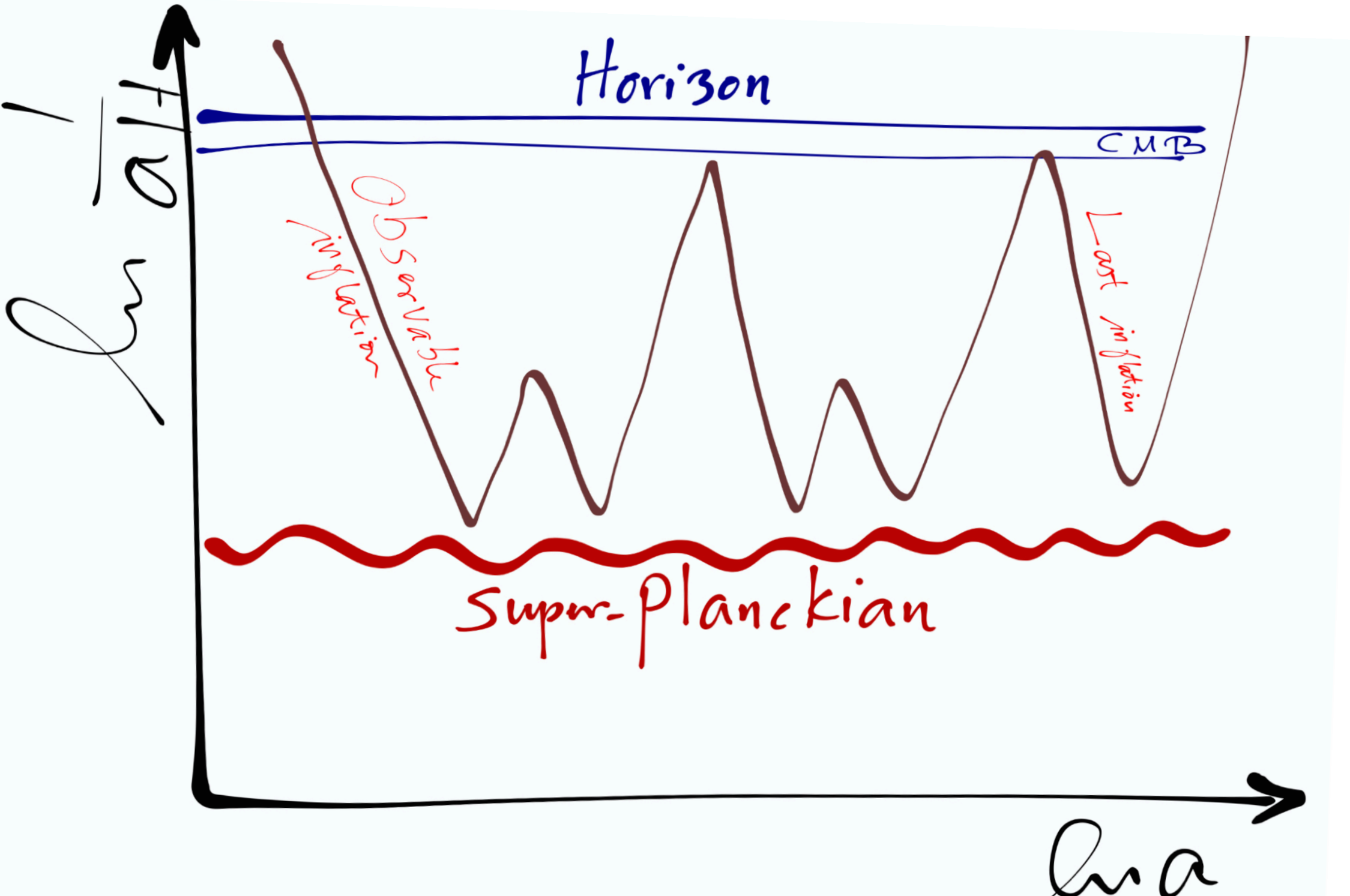
◆ In the following we propose a scenario to realize a high-scale inflation and alleviate the fine-tuning problem.

[MT 1910.06867,1911.12304]

Breathing Comoving Hubble

- Multiple stages of inflation collectively explain the present horizon.

There is an *observable* one, follows by non-observable inflations.

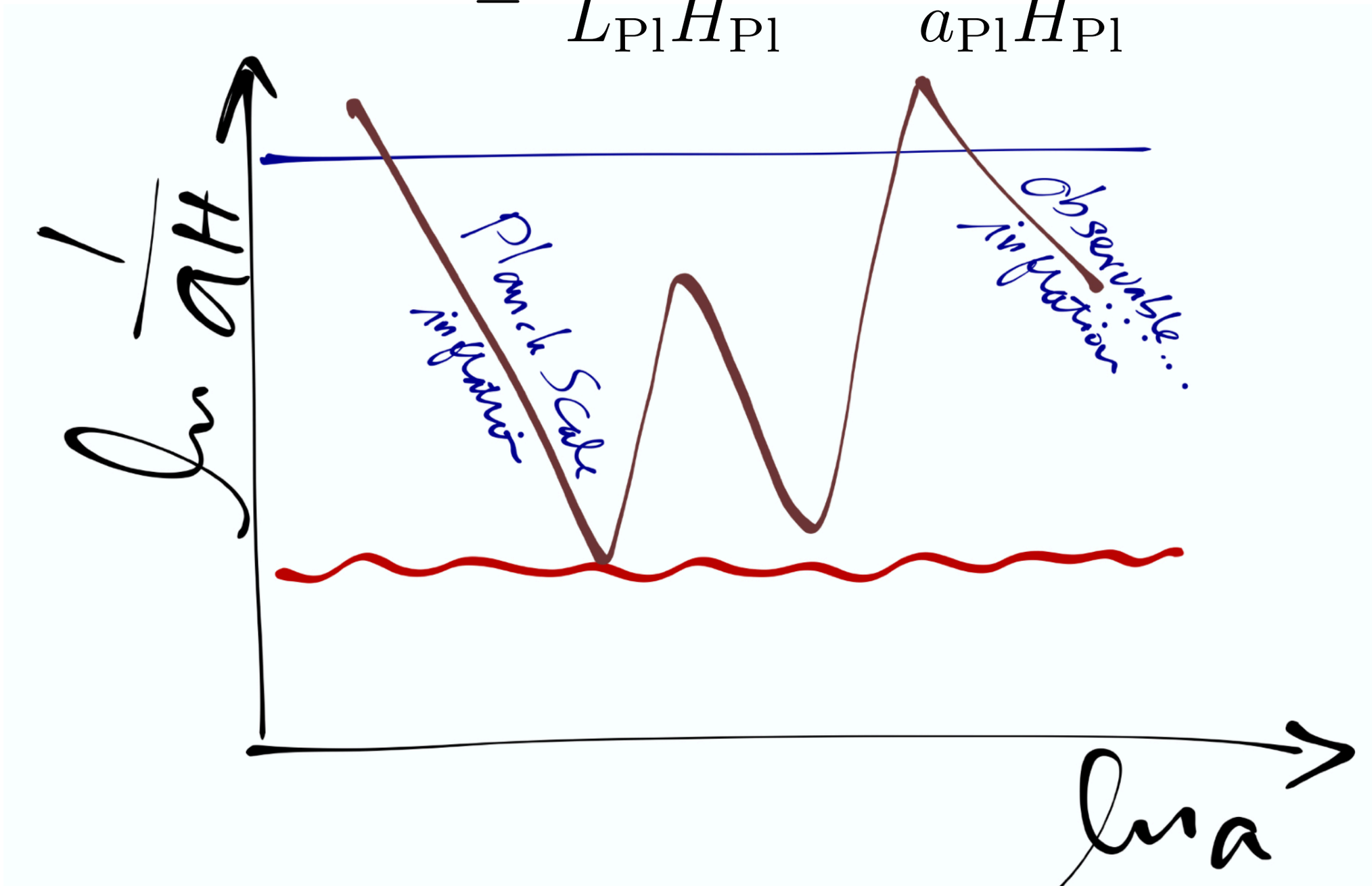


Breathing Comoving Hubble

- Initial condition for the observable inflation

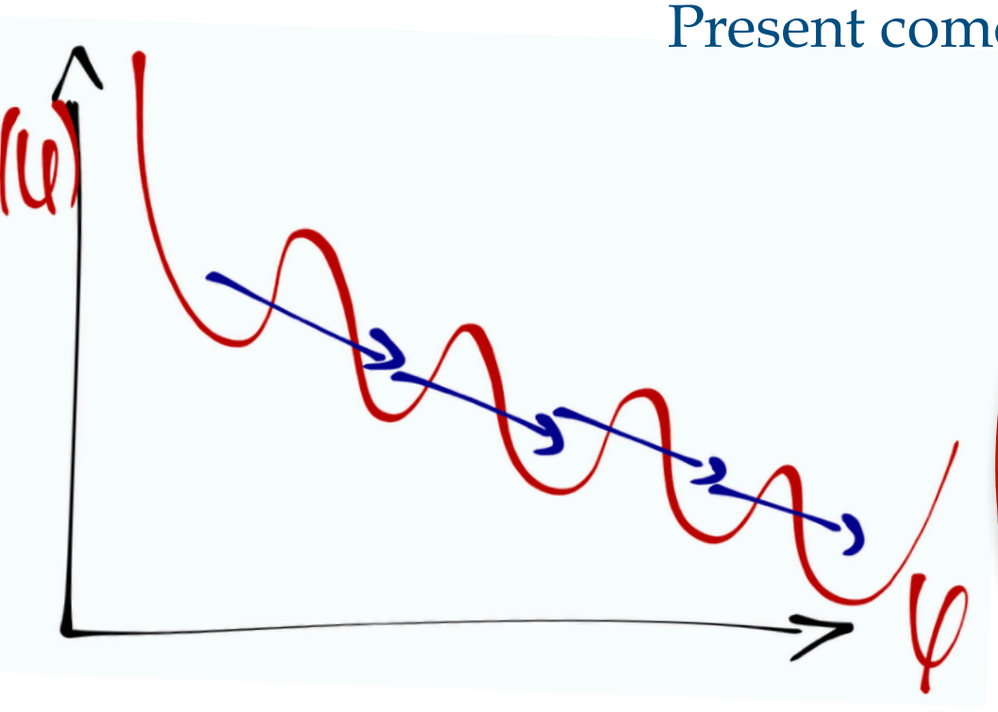
10^{16} GeV scale inflation needs *10^{6}* smooth patches prepared at Planck time.

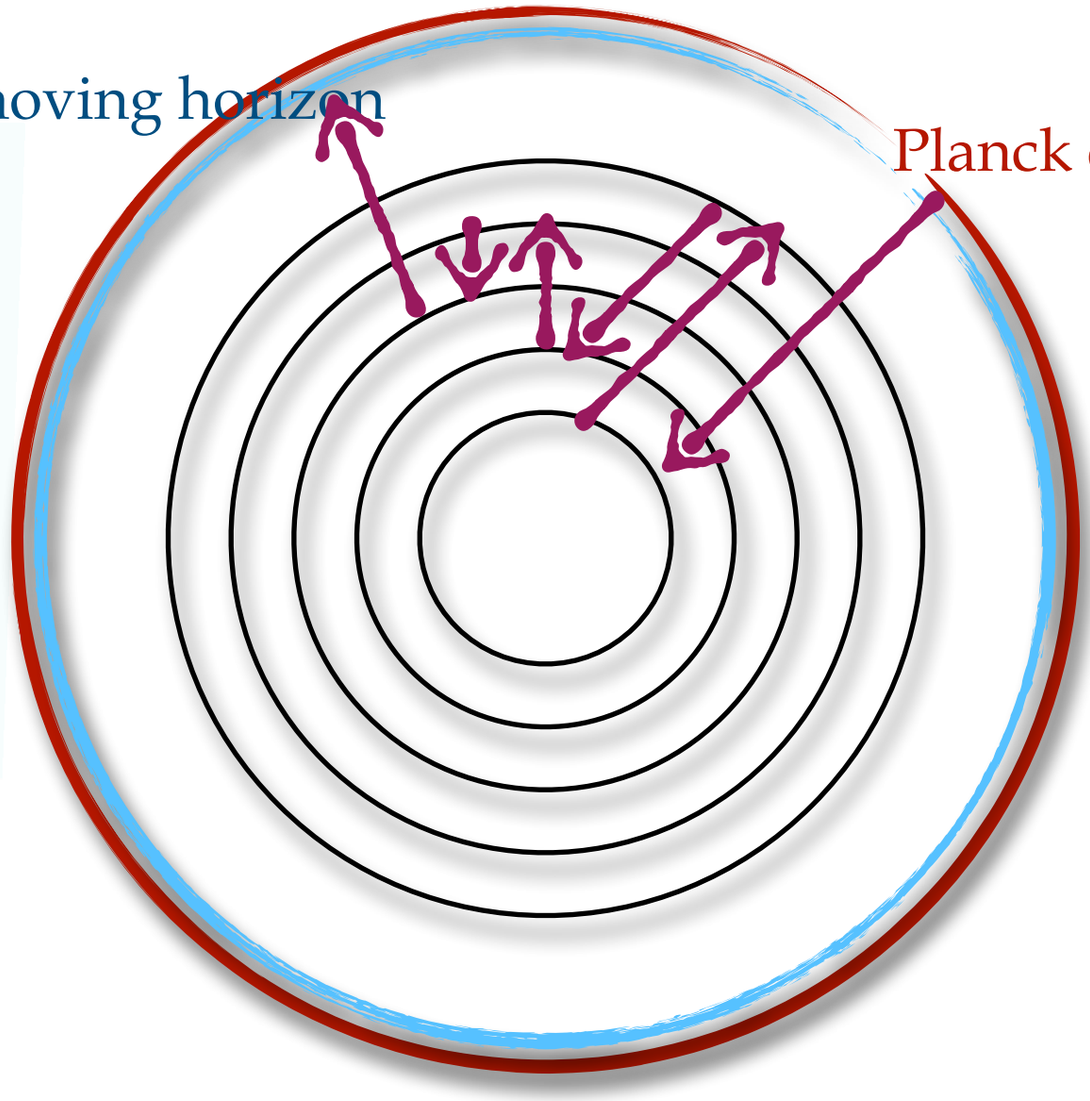
$$1 \leq \frac{L_{\rm ini} H_{\rm inf}}{L_{\rm Pl} H_{\rm Pl}} = \frac{a_{\rm ini} H_{\rm inf}}{a_{\rm Pl} H_{\rm Pl}}.$$



Breathing Comoving Hubble

- A scalar potential that yields multiple inflation:





- Shrinking and expanding comoving Hubble horizon
- The moral: Model building is not easy!

Summary

- String theory proposes a list of conditions every EFT consistent with quantum gravity must respect (generic from compactifications).

- This is what *gravity* adds that we would not have otherwise.

- These are UV conditions.

- They can be used as model-selection principle in the IR.

- Given a model, more likely to be in the swampland.

- Seems like they are related to each other. Find as much as we can.

- Can we understand them based on some fundamental principles?

Thanks for Attention