Multiple point principle in (non-super) superstring, and

Higgs inflation

Kin-ya Oda (Osaka)

with

Yuta Hamada, Hikaru Kawai, Yukari Nakanishi, and Seong Chan Park

Multiple point principle

- God wants **another (nearly) degenerate vacuum** at $\varphi \sim M_P$
- *"PREdicted the Higgs mass"* 135±9 GeV, Froggatt, Nielsen (1995)
  - Via $\underline{\lambda(\mu)|_{\mu=M_P}=0}$ so that $\underline{V_{\text{1-loop}} \sim \lambda(\varphi)\,\varphi^4=0}$ at $\underline{\varphi \sim M_P}$.
  - Title taken from Nielsen (2012)
- Derived by assuming QFT as **micro canonical ensemble**
  - A human-understandable review in Appendix D in *"Eternal Higgs inflation and cosmological constant problem"* Hamada, Kawai, **KO** (2015)


We may be seeing greater desert than we thought.
Picture from web.

With some oasis of DM+

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Plan

- MPP review
- More non-SUSY vacua than SUSY ones
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Canonical vs micro-canonical

- Path integral resembles **canonical** ensemble

$$Z(\{\lambda\}) = \int [\mathrm{d}\varphi]\, e^{-S(\{\lambda\})[\varphi]}$$

$$Z(\beta) = \sum_n e^{-\beta H_n}$$

- **Micro-canonical** more fundamental

$$\Omega(E) = \sum_n \delta(H_n - E)$$

Micro-canonical QFT

- **Field value** (integrated over spacetime vol) fixed, **couplings** integrated over:

$$\overline{\Omega}(I_0, I_2, I_4, \ldots) = \left(\int \mathrm{d}\Lambda \int \mathrm{d}m^2 \int \mathrm{d}\lambda \cdots \right) e^{\Lambda I_0 + m^2 I_2 + \lambda I_4 + \cdots} Z(\Lambda, m^2, \lambda, \ldots)$$

- Cf. **energy** fixed, **temperature** integrated over:

$$\overline{\Omega}(E) := \int \mathrm{d}\beta \, e^{\beta E} Z(\beta)$$

- Thermodynamic (large vol) limit:

$$\to e^{S(E)} = \Omega(E)$$

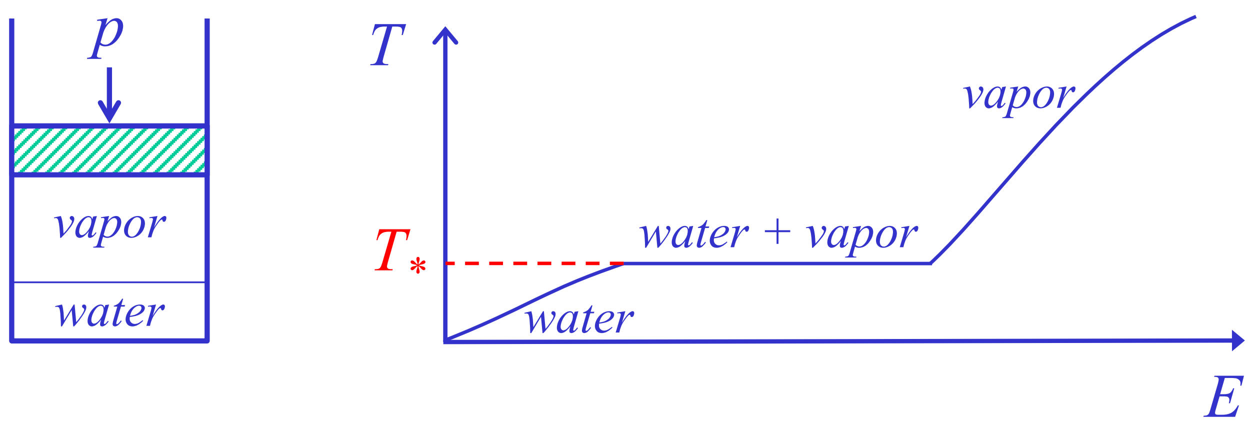
Backup

$$
\begin{aligned}
\overline{\Omega}(I_0, I_2, I_4, \dots) &= \left(\int \mathrm{d}\Lambda \int \mathrm{d}m^2 \int \mathrm{d}\lambda \cdots\right) e^{\Lambda I_0 + m^2 I_2 + \lambda I_4 + \cdots} Z\big(\Lambda, m^2, \lambda, \dots\big) \\
&= \left(\int \mathrm{d}\Lambda \int \mathrm{d}m^2 \int \mathrm{d}\lambda \cdots\right) e^{\Lambda I_0 + m^2 I_2 + \lambda I_4 + \cdots} \int [\mathrm{d}\varphi]\, e^{-S\left(\Lambda, m^2, \lambda, \dots\right)[\varphi]} \\
&= \left(\int \mathrm{d}\Lambda \int \mathrm{d}m^2 \int \mathrm{d}\lambda \cdots\right) \left(\int \mathrm{d}\mathcal{I}_0 \int \mathrm{d}\mathcal{I}_2 \int \mathrm{d}\mathcal{I}_4 \cdots\right) \\
&\qquad \times e^{-\Lambda(\mathcal{I}_0 - I_0) - m^2(\mathcal{I}_2 - I_2) - \lambda(\mathcal{I}_4 - I_4) + \cdots} \\
&\qquad \times \left[\int [\mathrm{d}\varphi]\, e^{-\int \mathrm{d}^D x\, (\partial\varphi)^2} \right. \\
&\qquad\quad \left. \delta\left(\int \mathrm{d}^D x - \mathcal{I}_0\right) \delta\left(\int \mathrm{d}^D x\ |\varphi|^2 - \mathcal{I}_2\right) \delta\left(\int \mathrm{d}^D x\ |\varphi|^4 - \mathcal{I}_4\right) \cdots \right],
\end{aligned}
$$

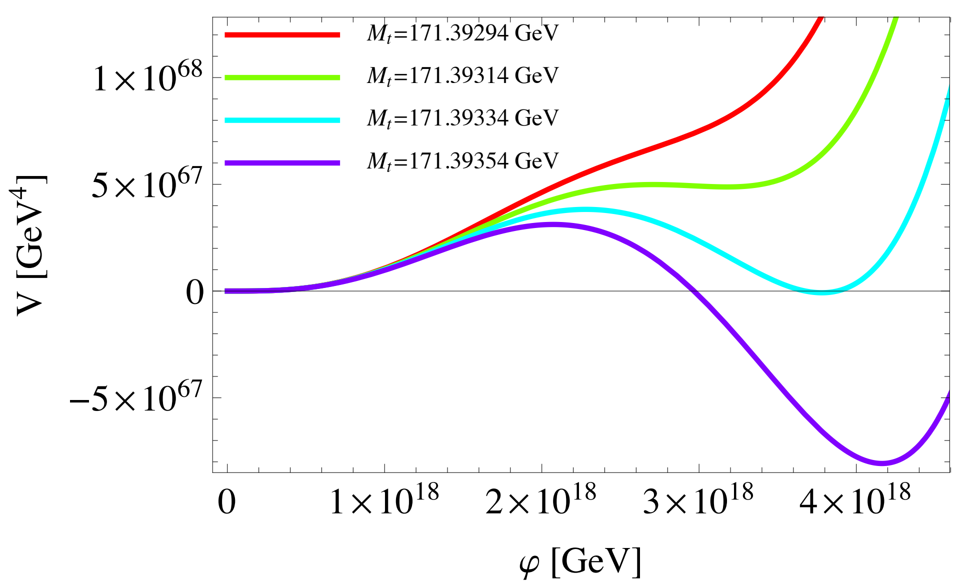
$$
\begin{aligned}
\overline{\Omega}(E) := \int \mathrm{d}\beta\, e^{\beta E} Z(\beta) &= \int \mathrm{d}\beta \int \mathrm{d}\mathcal{E} \left(\sum_n \delta(H_n - \mathcal{E})\right) e^{-\beta(\mathcal{E} - E)} \\
&= \int \mathrm{d}\beta \int \mathrm{d}\mathcal{E}\, \Omega(\mathcal{E})\, e^{-\beta(\mathcal{E} - E)} \\
&= \int \mathrm{d}\beta \int \mathrm{d}\mathcal{E}\, e^{\mathcal{S}(\mathcal{E}) - \beta(\mathcal{E} - E)},
\end{aligned}
$$

Thermodynamic limit

- **Temperature** (coupling constants) automatically chosen to allow **multiple phases (vacua)** for wide range of **energy** (field value)



- To repeat, **coupling constants** wants to allow **multiple vacua**
  - **Another vacuum at φ∼M_P** allows **any input value** of φ in between.



(m_t numbers given just to show amount of tuning) [Hamada, Kawai, **KO**, 2014]

Statement may be relaxed to allow slight non degeneracy, Nielsen (2012)

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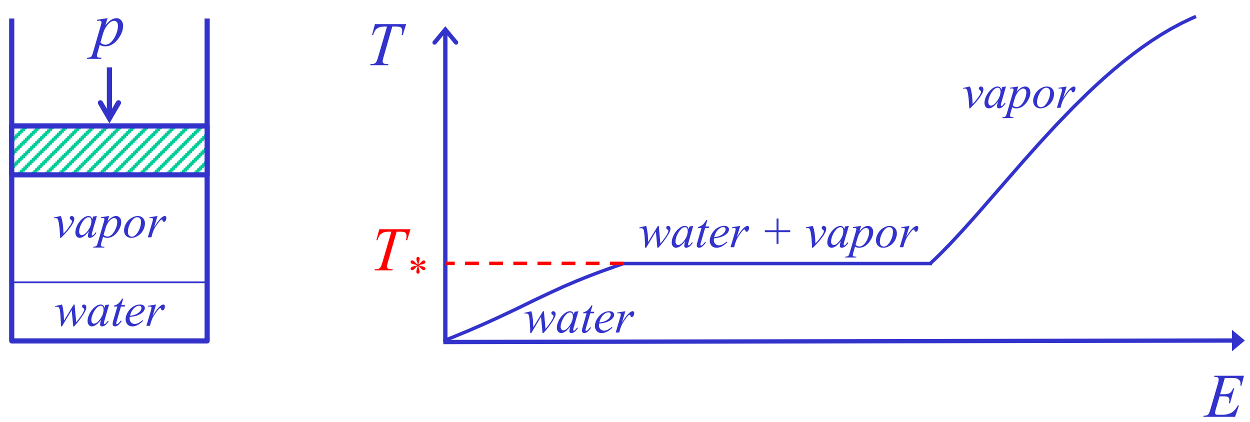

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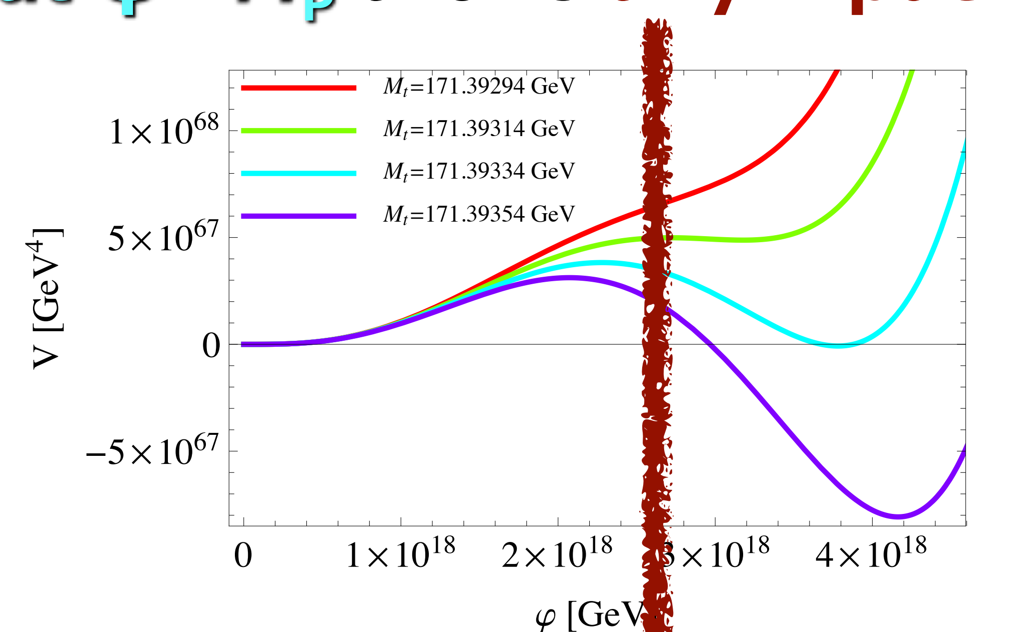

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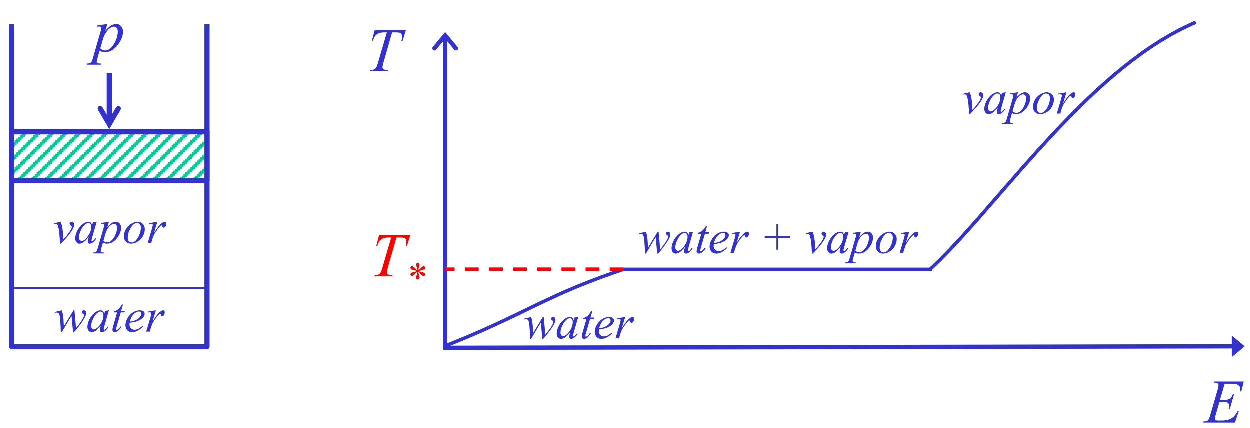

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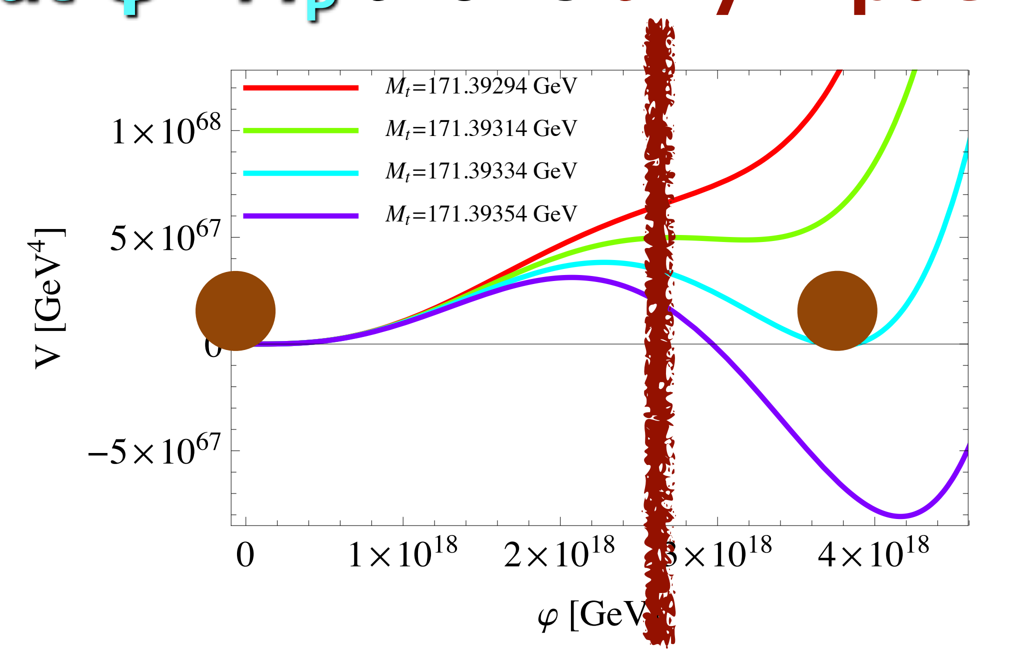

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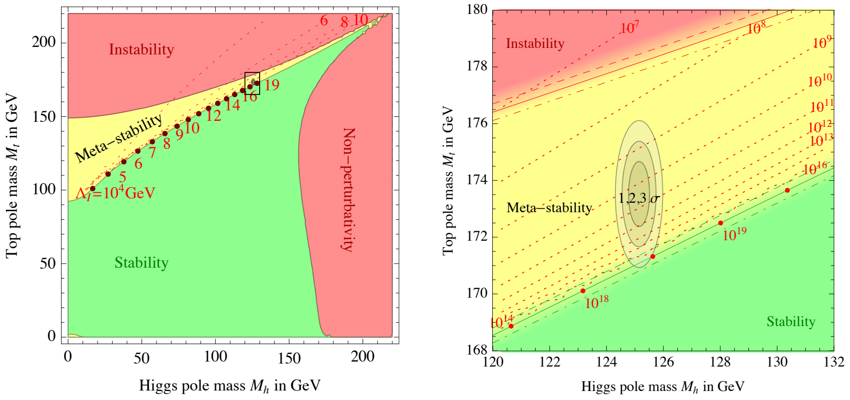
SM criticality

We are put on the edge of vacuum instability

As we have seen in many talks in HPNP2017.



[Buttazzo et al. 1307.3536]

On the edge

※ Pictures from web.

On the edge

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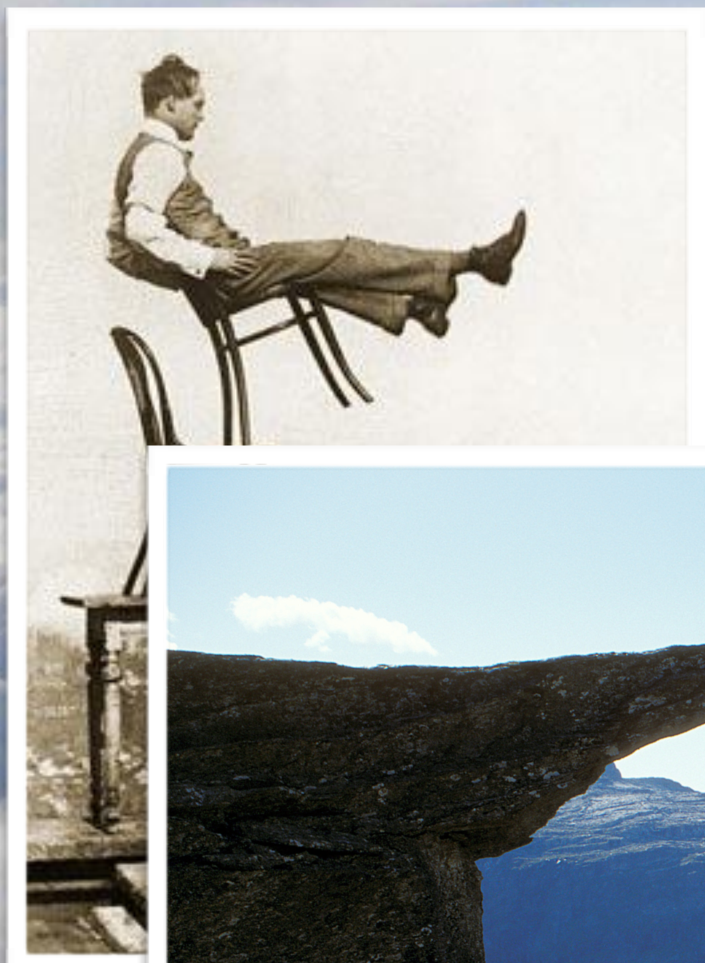

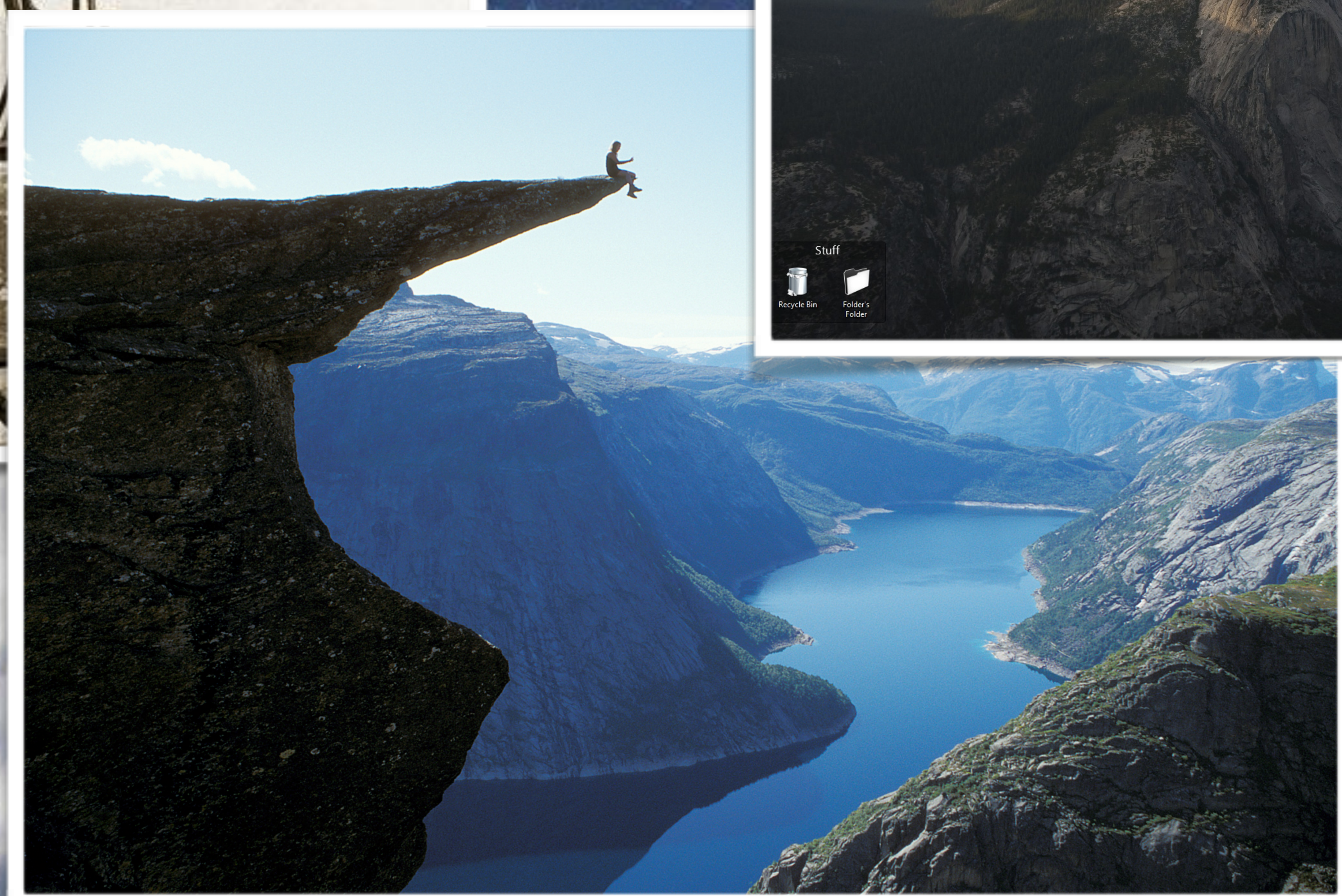

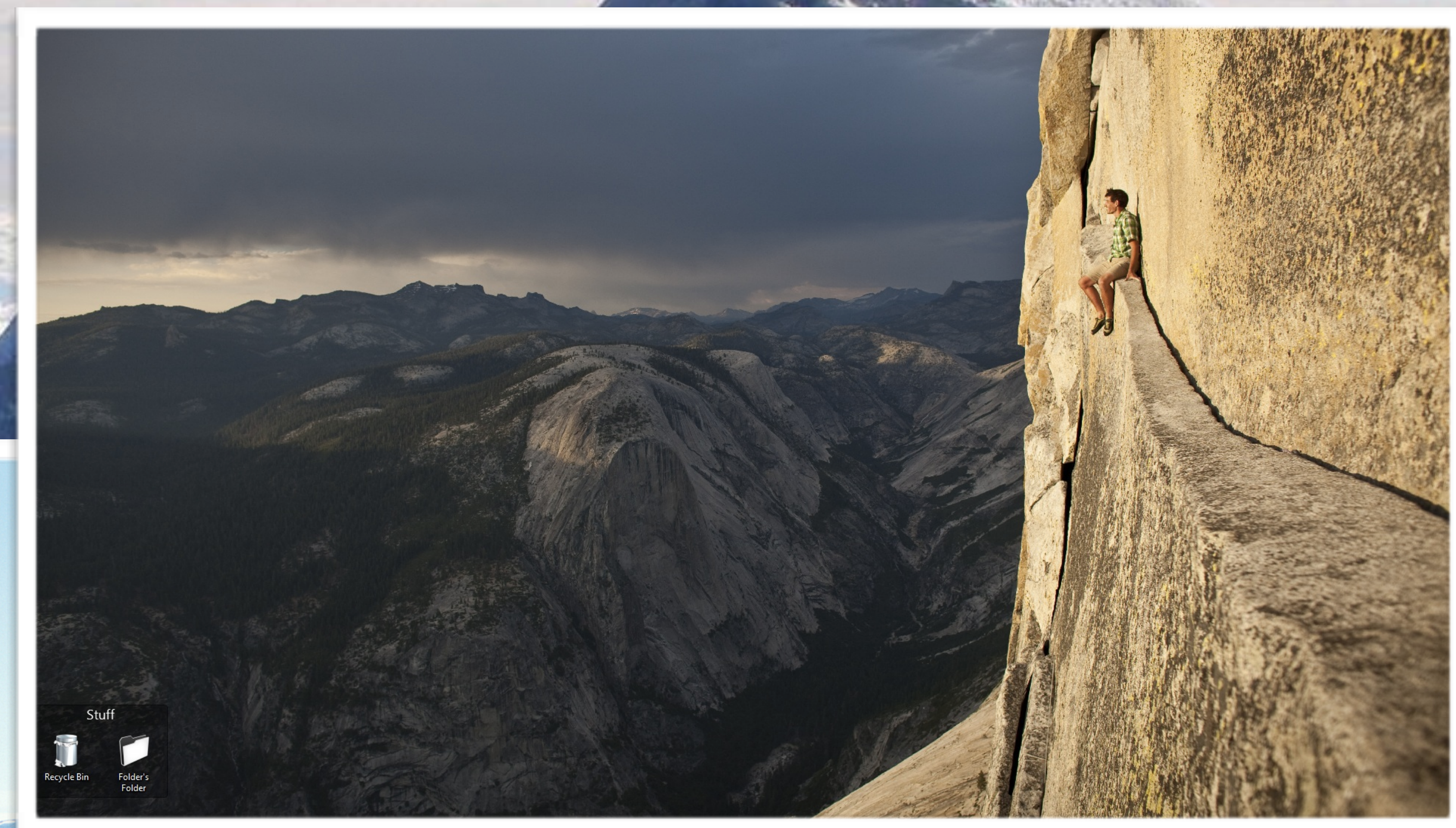

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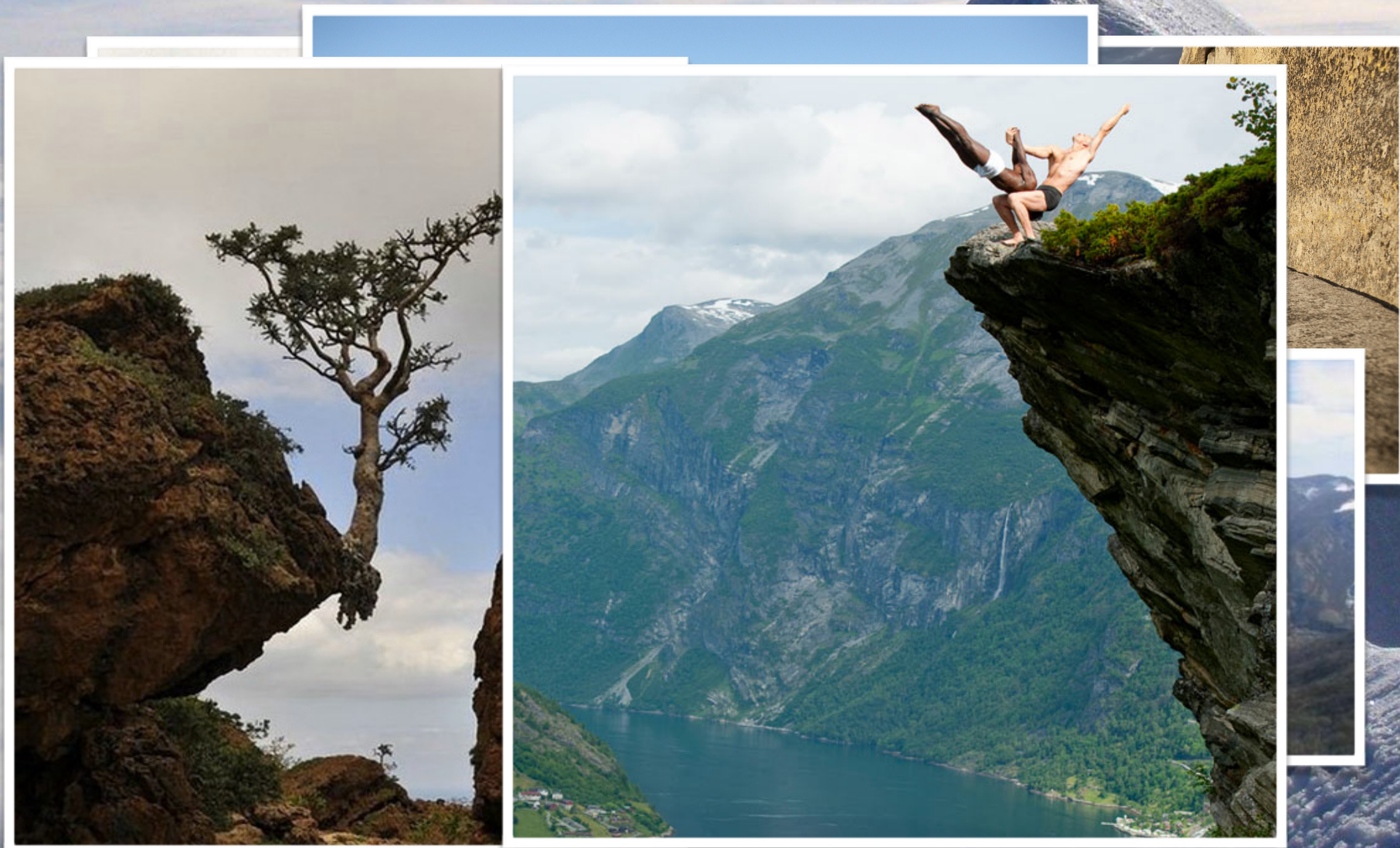

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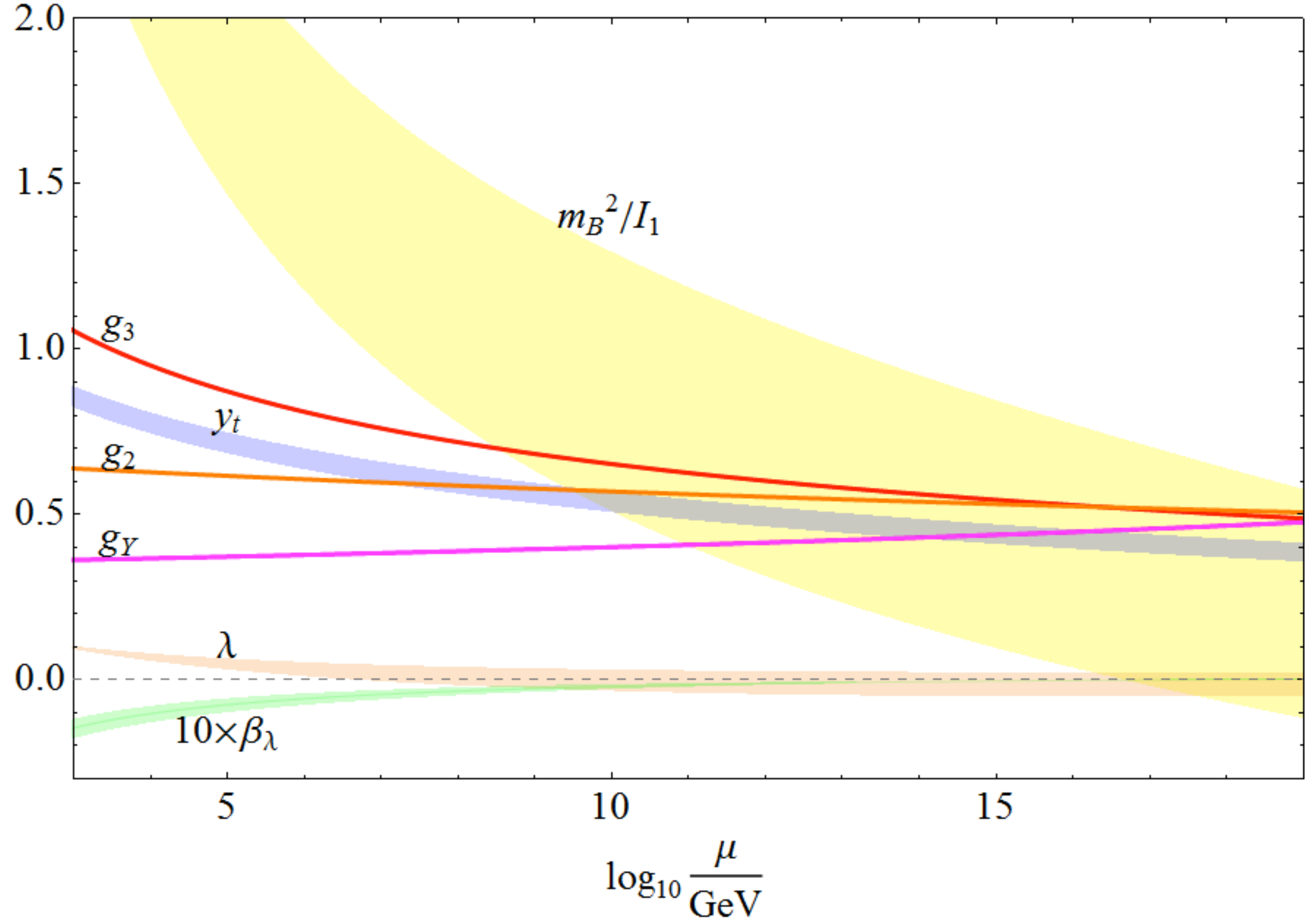
Bare Higgs mass also

- ✦ Can be small for Planck scale cutoff.



- ✦ Triple coincidence: λ, β_λ, $m_B{}^2 \sim 0$

- ✦ Must indicate something!

[Hamada, Kawai, **KO**, 2013]

Veltman condition

- *"This mass-relation, implying a certain cancellation between bosonic and fermionic effects, would in this view be due to an underlying supersymmetry."* [Veltman, 1981]

- SUSY may well be broken at string/Planck scale.
  - Indeed there are more **non-super string theories** than superstring theories
    - in 4D fermionic construction. *[Kawai, Lewellen & Tye, 1986, 1987]*
    - They are **tachyon free** unlike 26D bosonic string theory.

- We assume:
  - Higgs is a **massless** mode (Recall $m_B^2 \sim 0$)
  - in a superstring theory <u>without spacetime supersymmetry</u>.

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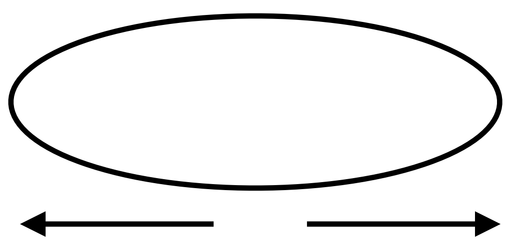
Higgs in non-super string

- Assumption: Higgs emission vertex separates into left and right movers for *k*=0:

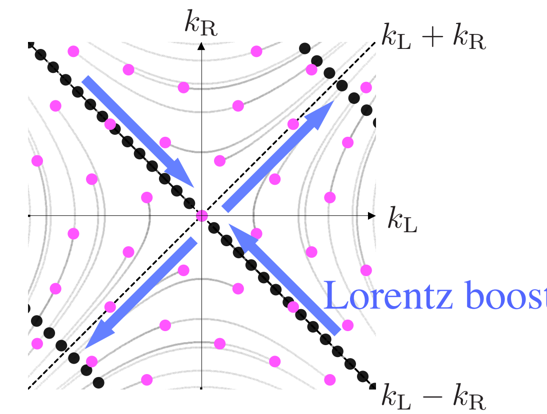
$$\mathcal{O}(z,\bar{z}) = \mathcal{O}_L(z)\ \mathcal{O}_R(\bar{z})$$



- This is in general the case when Higgs is from e.g.
  - **Extra-dim. component of gauge field**, as in GHU.
  - **Untwisted sector** in orbifold construction.
    - Blaszczyk, Groot Nibbelink, Loukas & Ramos-Sanchez, *"Non-supersymmetric heterotic model building"* [arXiv:1407.6362] JHEP (2014).
  - Only one field in **fermionic construction**.

Decompactification in large field limit

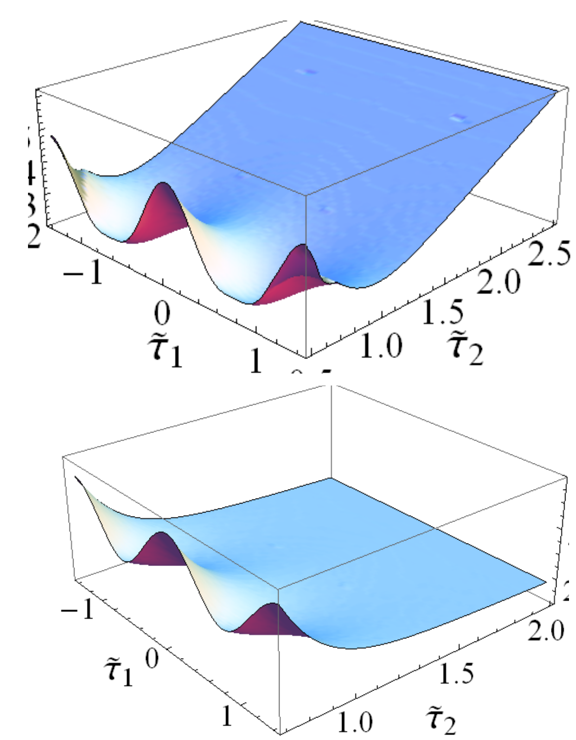
[Hamada, Kawai, **KO**, 2012]



- Limit of **large Higgs field** generally leads to opening up **extra dimension**.

Toy model:
Heterotic SO(16)×SO(16) on S^1

- Energy of this runaway vacuum is **exactly zero**.

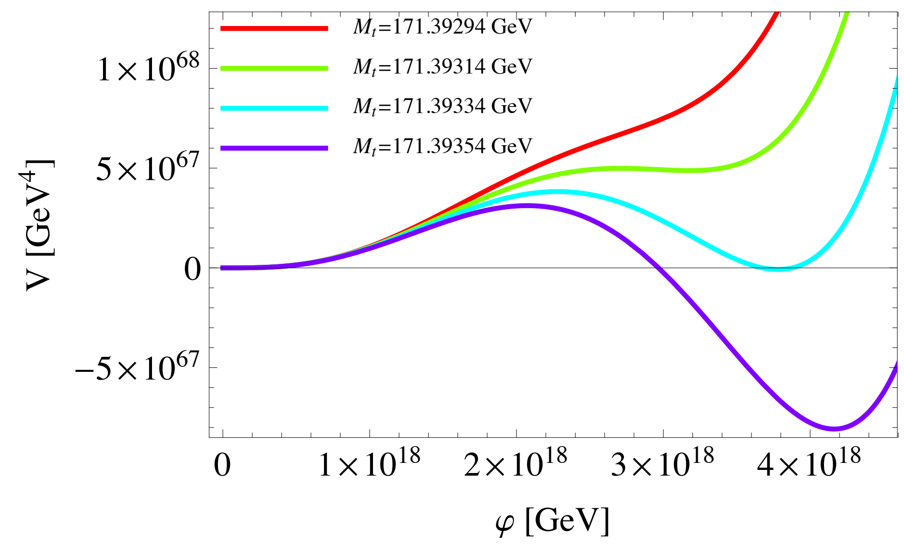


  - Nicely fits in **MPP**! (later)

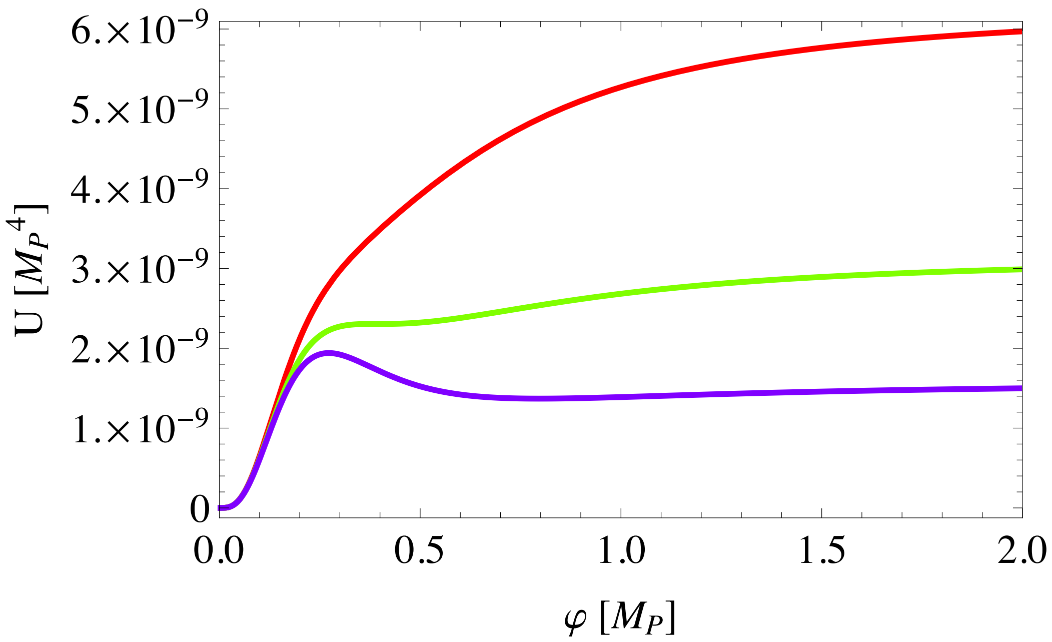
Higgs inflation at criticality

[Hamada, Kawai, **KO**, Park 2014]

- Extrapolation of SM potential.
  - Can be **flat** as in (extended) MPP.
  - Use for inflation?



- Combine with original Higgs inflation by Bezrukov & Shaposhnikov.
  - Not-so-large $\xi\sim10$.
  - Large tensor-to-scalar ratio: $r\sim0.1$.
    - Can be seen in near future.



However,

There remains initial condition problem.

Slow-roll inflation does NOT solve horizon problem

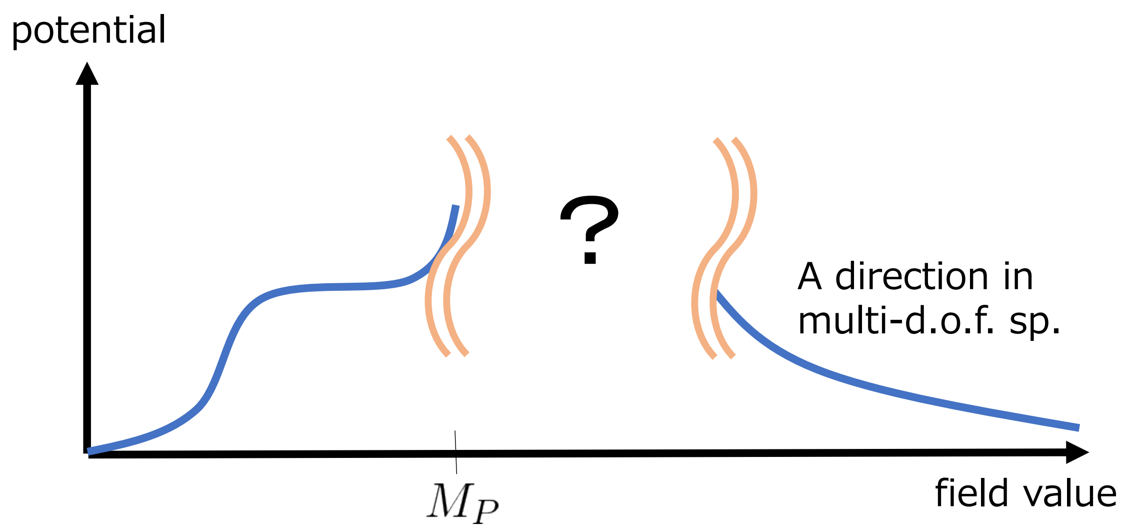
- E.g. in chaotic inflation,
  - A **lager** region than Hubble length scale
  - must have the **same** field value
  - **simultaneously** & **coherently**.
- How about having **eternal inflation** before the one we observe by CMB?

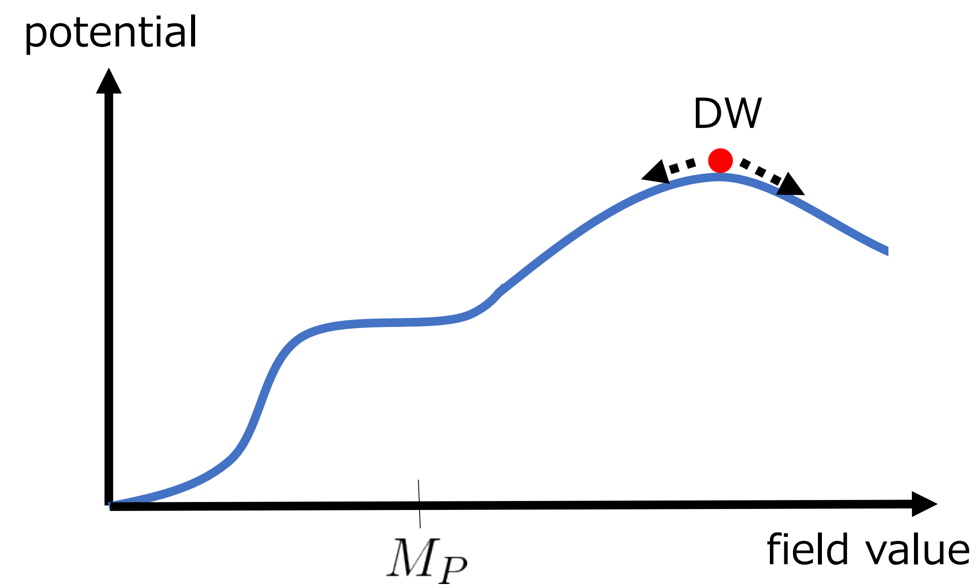
Eternal inflation at domain wall

[Hamada, **KO**, Takahashi, 2014]

[Hamada, Kawai, **KO**, 1501.04455]

- We see there are **two vacua**:





- **Domain wall** between two vacua:
  - For a given random initial condition.
- If relative curvature at maximum is one, $\eta := M_P^{\ 2}\ U_{XX}/U < 1.4$,

[Sakai, Shinkai, Tachizawa & Maeda, 1996]

  - DW supports inflation **forever**.
  - A solution to **horizon problem**.

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Solution to CC problem

- ✦ $r\to\infty$ runaway vacuum with CC exactly zero.
- ✦ MPP requires our vacuum be degenerate with this.
  - ✴ **New solution to CC problem.**
- ✦ How to explain observation?

$$\rho_\Lambda^{\mathrm{obs}} = (0.686 \pm 0.020)\, 3H_0^2 M_P^2 \simeq (2.2\,\mathrm{meV})^4$$

$$H_0 = (67.4 \pm 1.4)\, \frac{\mathrm{km/s}}{\mathrm{Mpc}}$$

CC as fluctuation

- Partition function *Z*, while *i* spacetime points.

$$Z = \int \left[\prod_i \mathrm{d}\varphi_i\right] e^{-S}$$
$$= \prod_i \left(\int \mathrm{d}S_i \frac{\mathrm{d}\varphi_i}{\mathrm{d}S_i} e^{-S_i}\right)$$
$$= \prod_i \left(\int \mathrm{d}S_i \, e^{-f_i(S_i)}\right),$$

$$S_* = \sum_{i=1}^{r_U^4/l_P^4} S_{i*} \sim \frac{r_U^4}{l_P^4}$$

$$r_U = 1/H \simeq 10^{27}\,\mathrm{m}$$

$\because \quad S_i \sim O(1)$

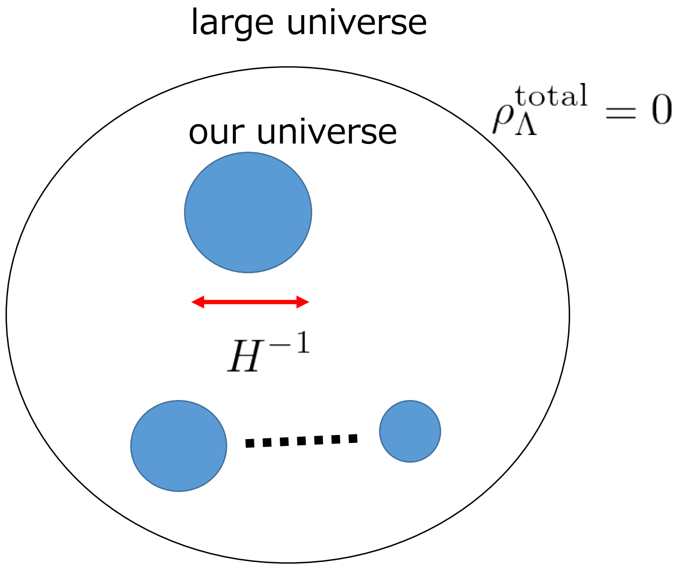
- Then

$$\rho_\Lambda \overset{?}{\sim} \frac{1}{l_P^4} = M_P^4$$

This is the CC problem.

Our proposal

- MPP + runaway vacuum gives $\rho_\Lambda^{\text{total}}=0$。
- Average fluctuation from it: $\langle S^2\rangle \sim N := \dfrac{r_U^4}{l_P^4}$



- Energy density:

$$\rho_\Lambda \sim \frac{\sqrt{\langle S^2\rangle}}{r_U^4} \sim \frac{1}{l_P^2 r_U^2} \sim (\,\mathrm{meV})^4$$

(This is not really a "solution" but "explanation".)

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  explained within MPP


Thank you!!