Eternal Higgs inflation

Kin-ya Oda (Osaka)

with

Yuta Hamada & **Hikaru Kawai** (Kyoto)

PRD (2013), PTEP (2014), PRD (2015);

+ **Seong Chan Park** (Sungkyunkwan)

PRL (2014), PRD (2015);

(Hamada, KO) + **Fuminobu Takahashi** (Tohoku)

PRD (2014);

Masatoshi Yamada (Kanazawa)

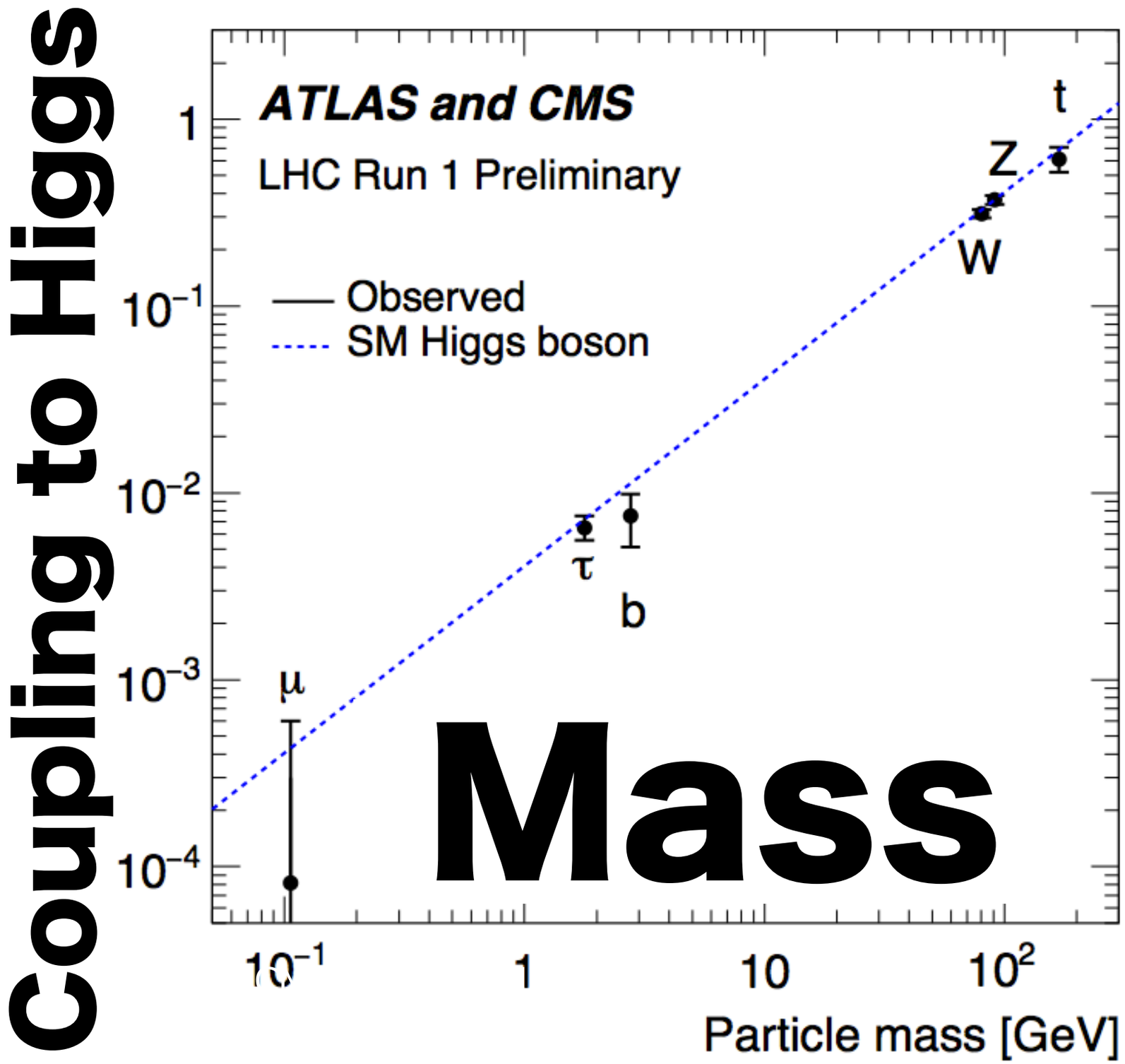
to appear.

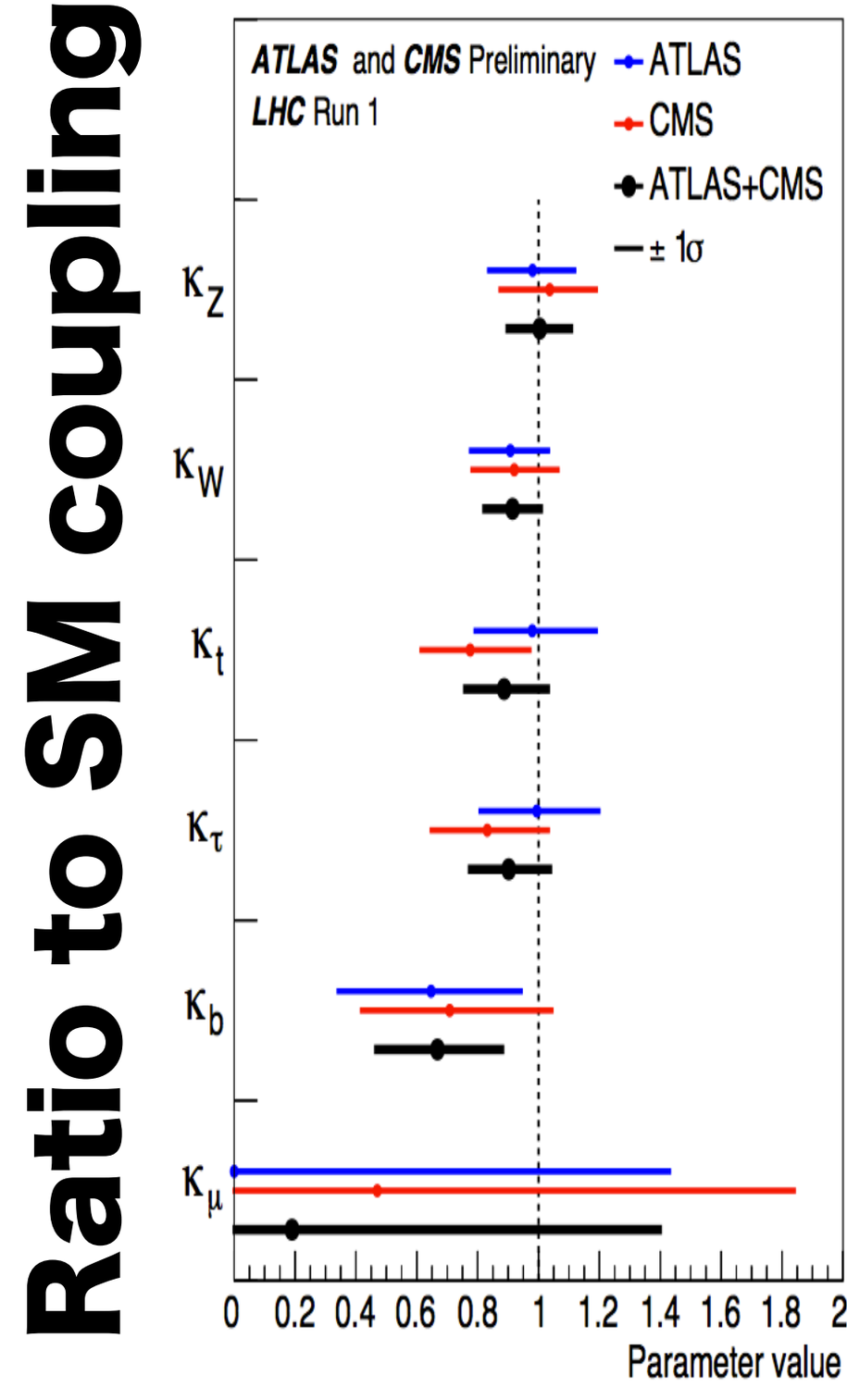
At LHC,

picture from web

And nothing else.

Higgs ever more SM-ish





https://indico.cern.ch/event/389531/session/31/contribution/51/attachments/1147368/1650410/LHCHCP_MarcoPieri_fin_1.pdf

Where to go?

A possible way

- ✦ Extrapolate SM ($+\alpha$) toward very high scales.
- ✦ See what we can say.
- ✦ Will see rather rich ground to explore.

Outline

1. SM criticality: Triple coincidence

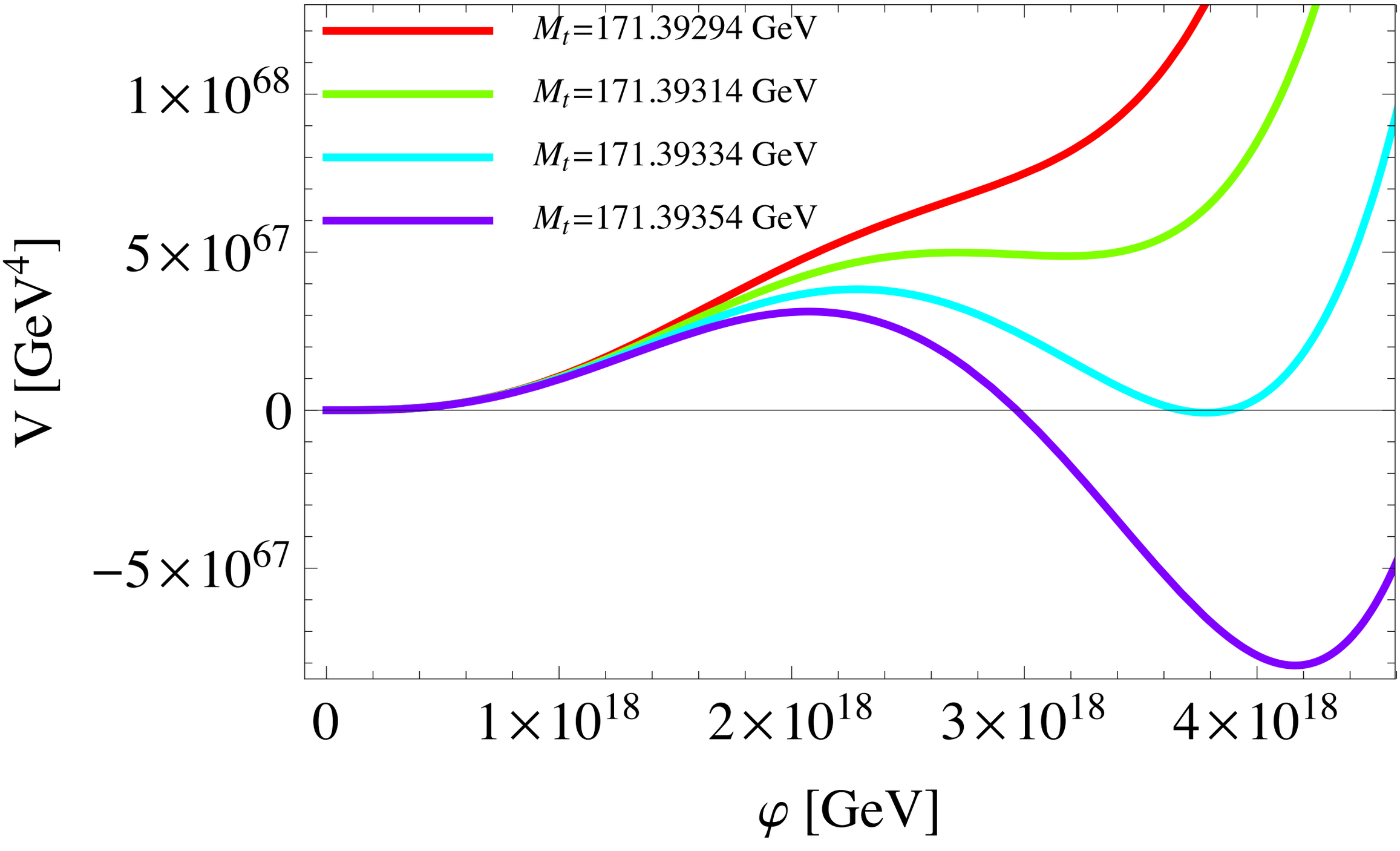
2. Higgs inflation with SM criticality
   - Milder non-minimal coupling ξ
   - Allows larger tensor-to-scalar ratio *r*

3. Eternal Higgs inflation
   - Saves from horizon problem

SM criticality

picture from web

Vacuum (in)stability

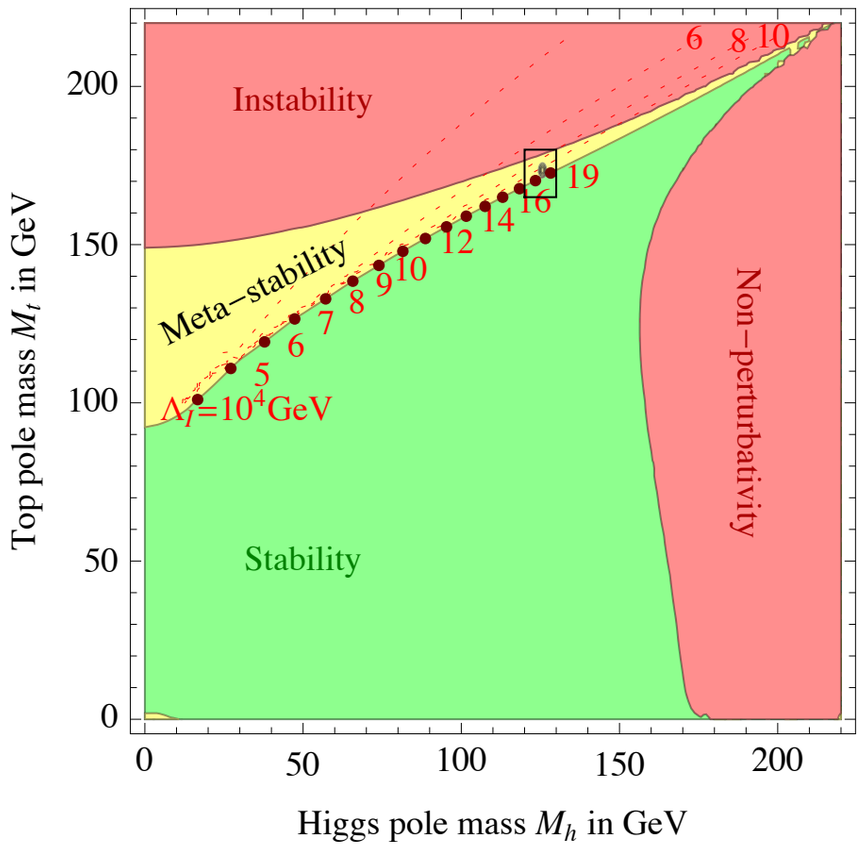


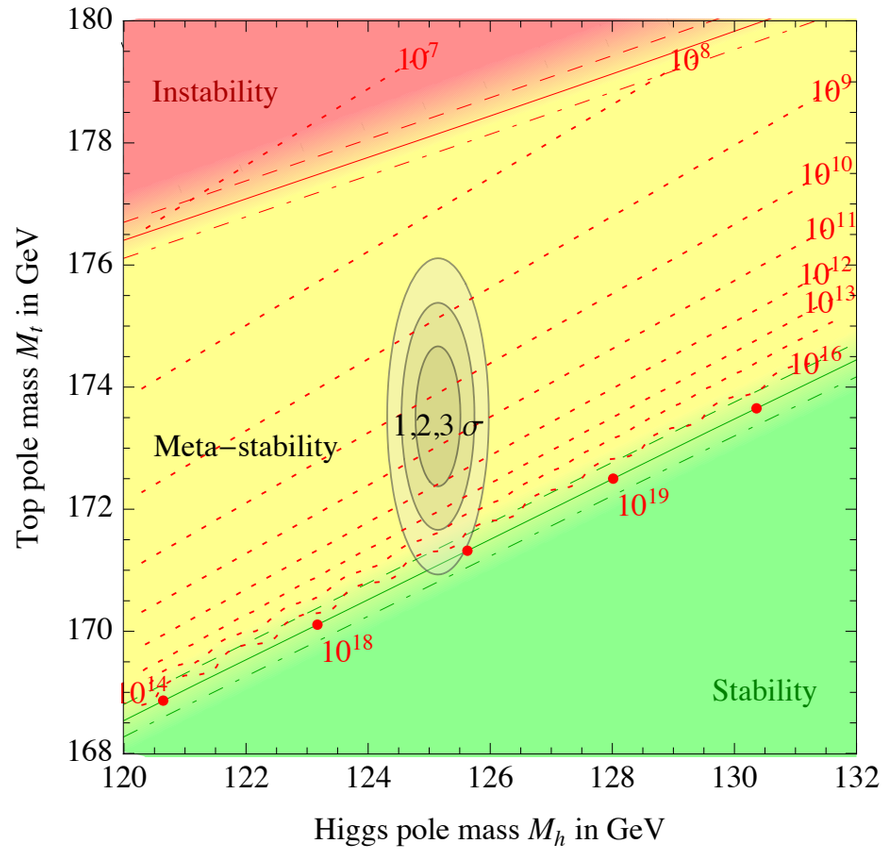
(m_t numbers given just to show amount of tuning)

[Hamada, Kawai, **KO**, Park, *PRD* 2015]

Mt vs Mh

[Buttazzo et al. 1307.3536]





- Note what is meant by “top mass”.

[E.g. Hamada, Kawai, **KO**, Park, *PRD* 2015]

$$M_t^{\rm pole} = \begin{cases} 171.2 \pm 2.4 \text{ GeV}, & \text{MITP [99]}, \\ 176.7^{+4.0}_{-3.4} \text{ GeV}, & \text{PDG [136]}, \end{cases}$$

$$M_t^{\rm Pythia} = \begin{cases} 173.21 \pm 0.51 \pm 0.71 \text{ GeV}, & \text{direct measurment, PDG [136]} \\ 174.98 \pm 0.76 \text{ GeV}, & \text{D0[137]}, \\ 174.34 \pm 0.64 \text{ GeV}, & \text{D0 + CDF [138]}, \\ 173.34 \pm 0.76 \text{ GeV}, & \text{ATLAS [139]}, \\ 172.38 \pm 0.10 \pm 0.65 \text{ GeV}, & \text{CMS [140]}. \end{cases}$$

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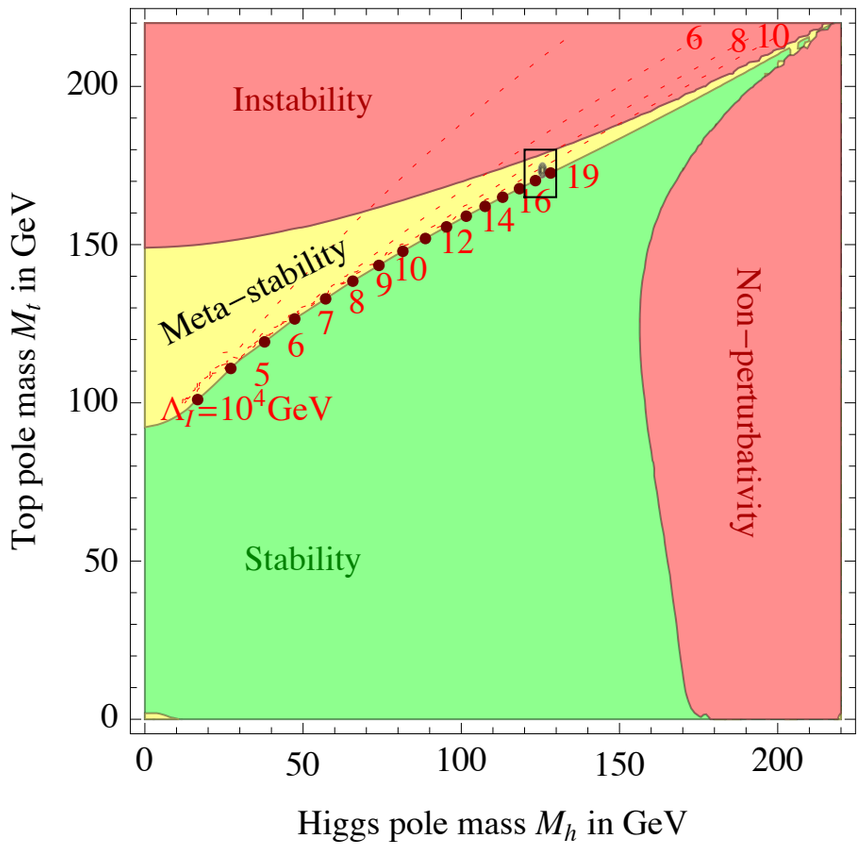
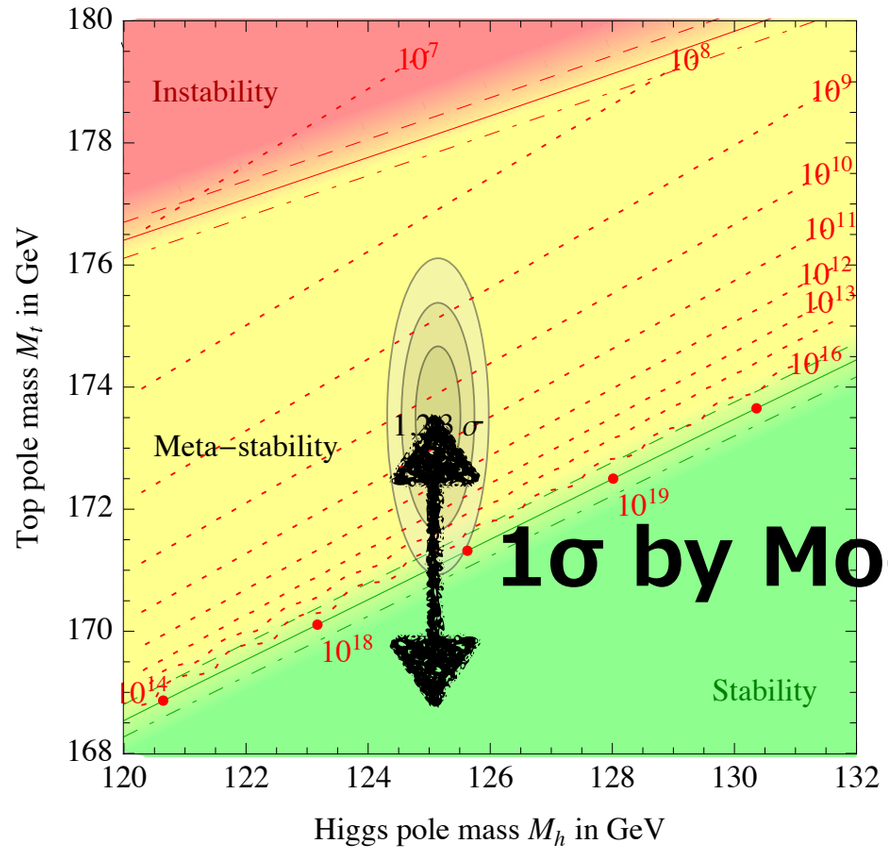
[Buttazzo et al. 1307.3536]





1σ by Moch et al.

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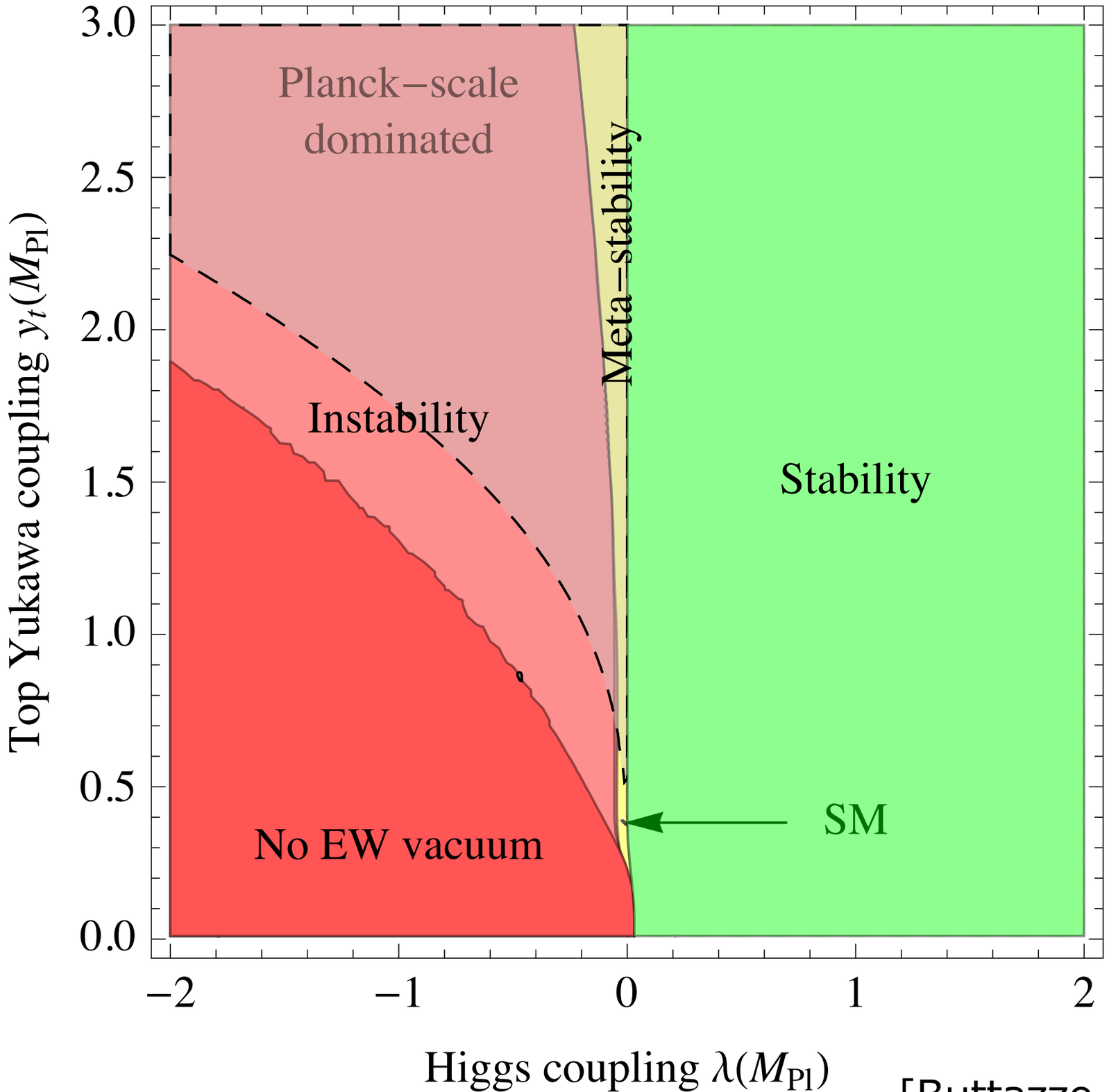
Anyway,

We are put on the edge



[Buttazzo et al. 1307.3536]

On the edge

Our Universe

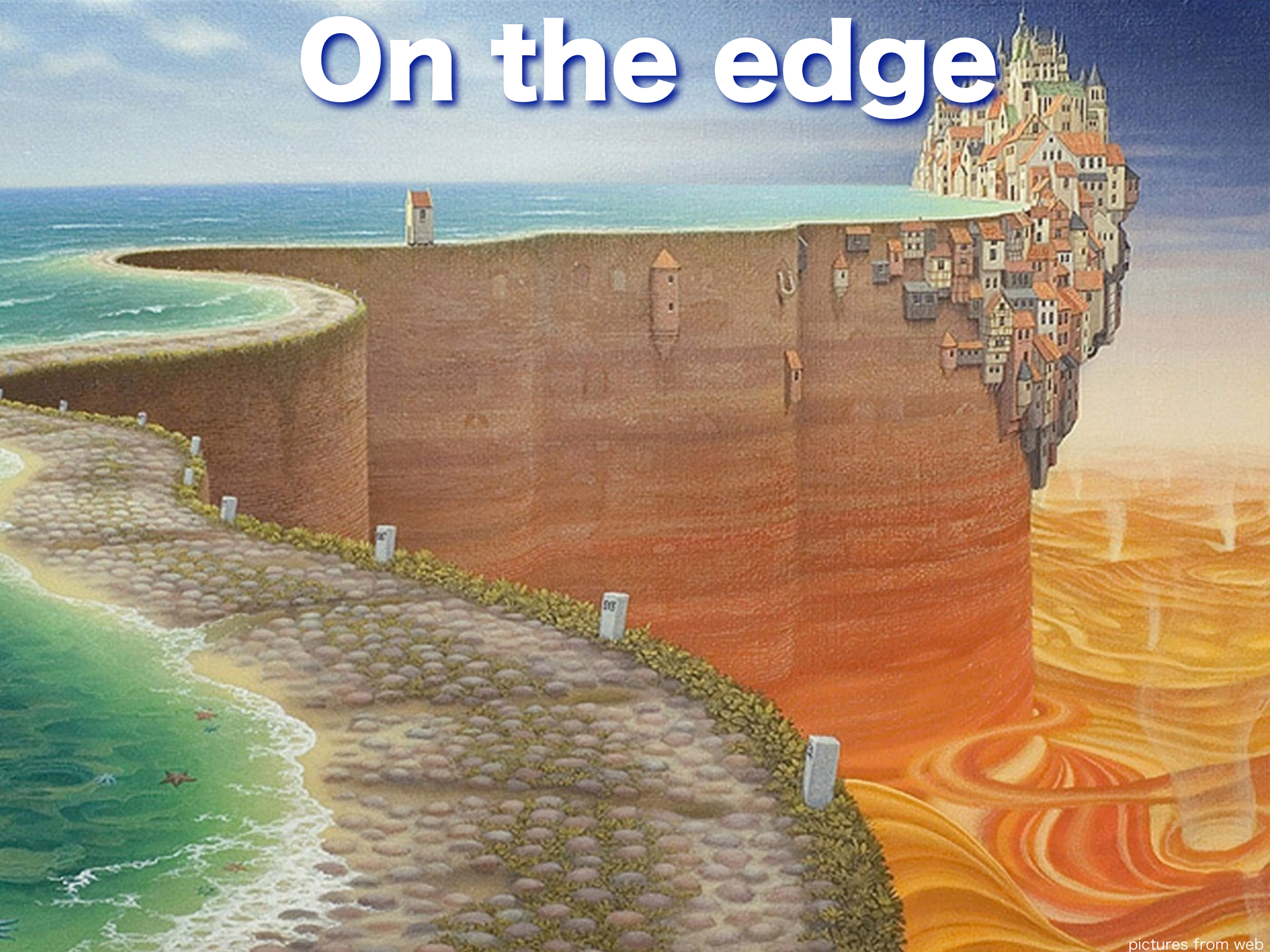
pictures from web

On the edge

Our Universe

pictures from web

On the edge



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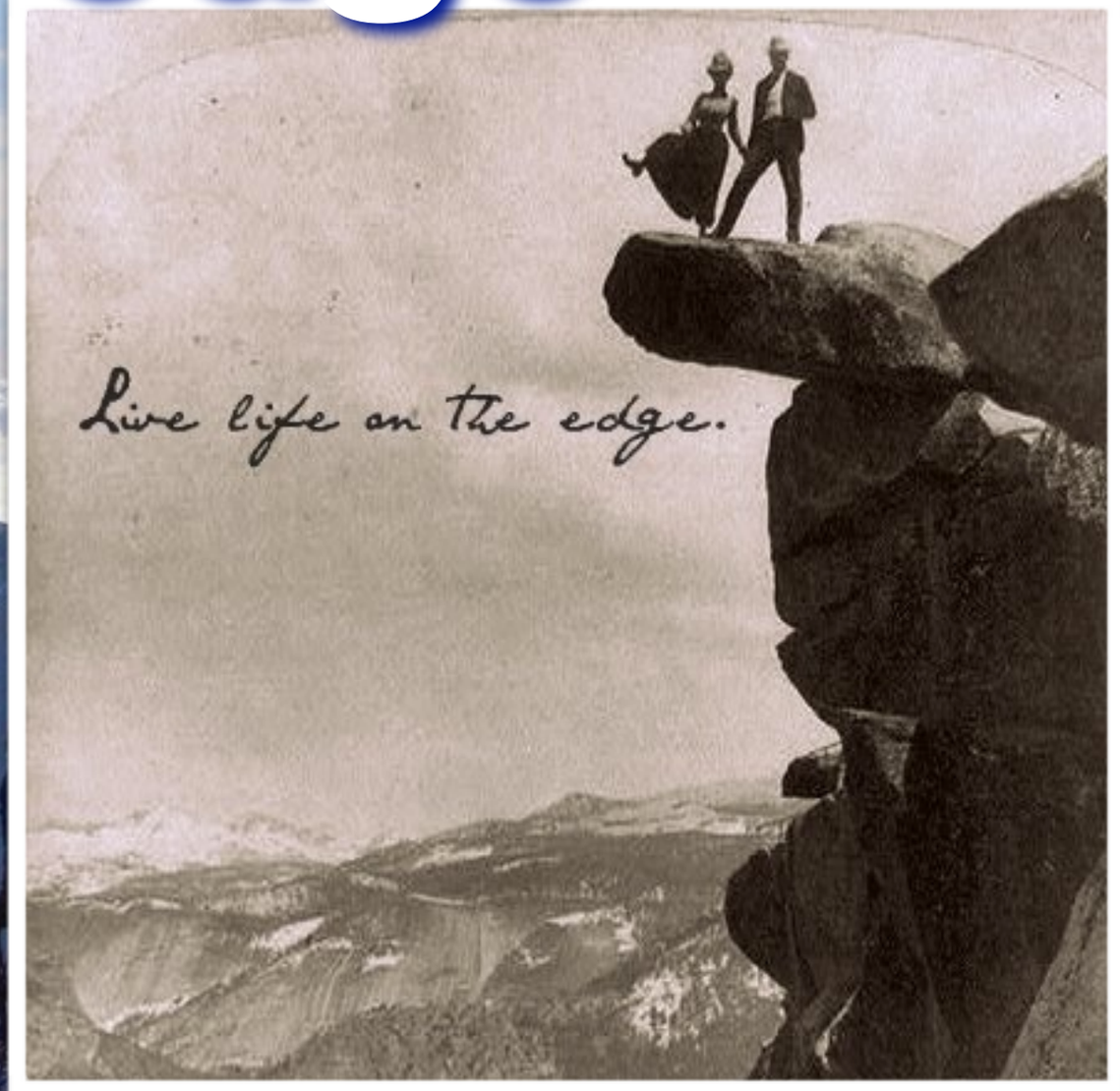

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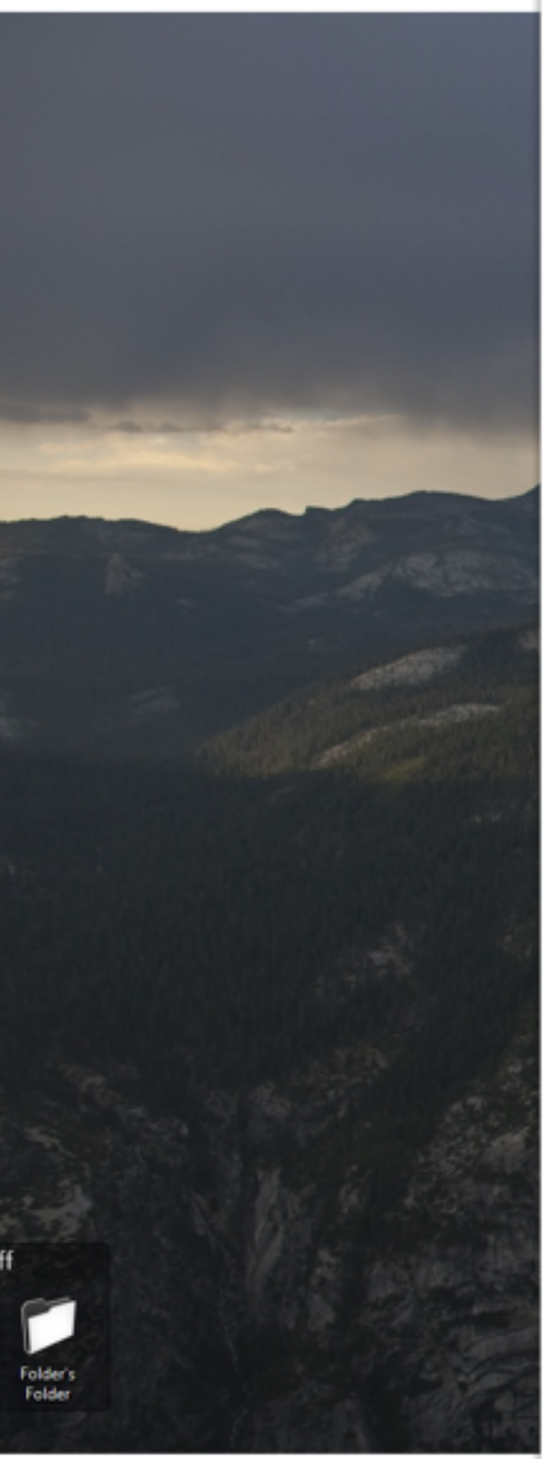

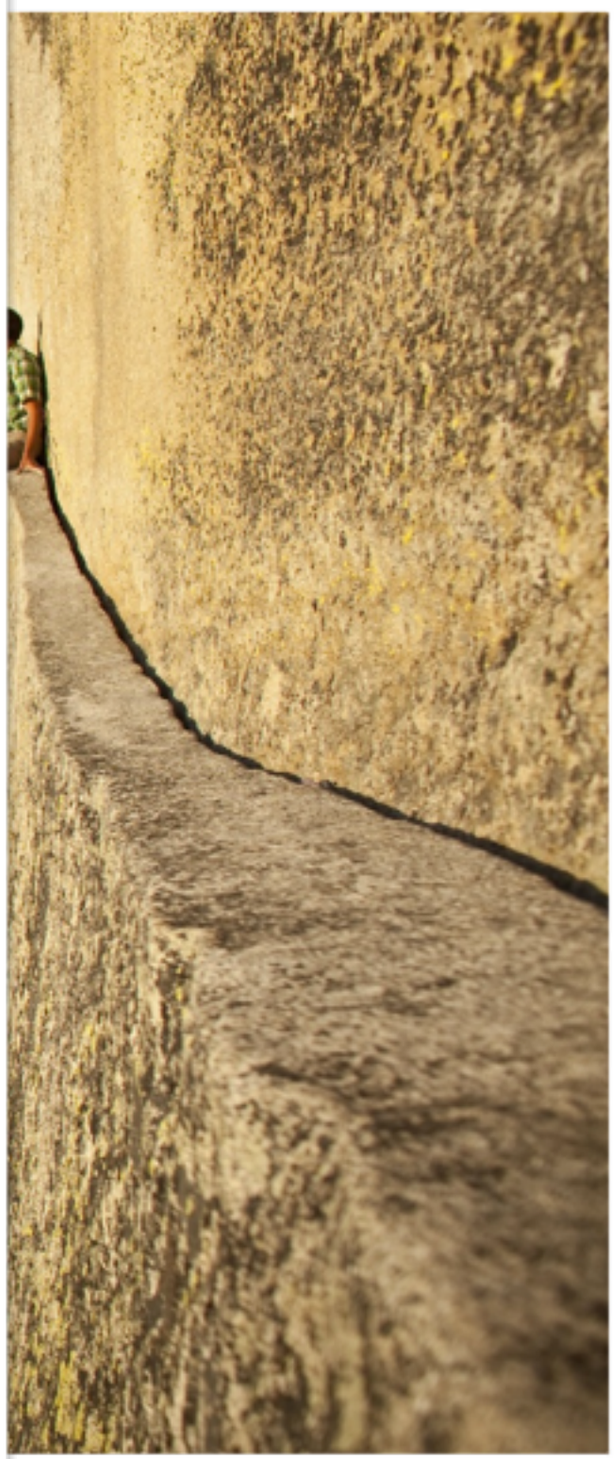

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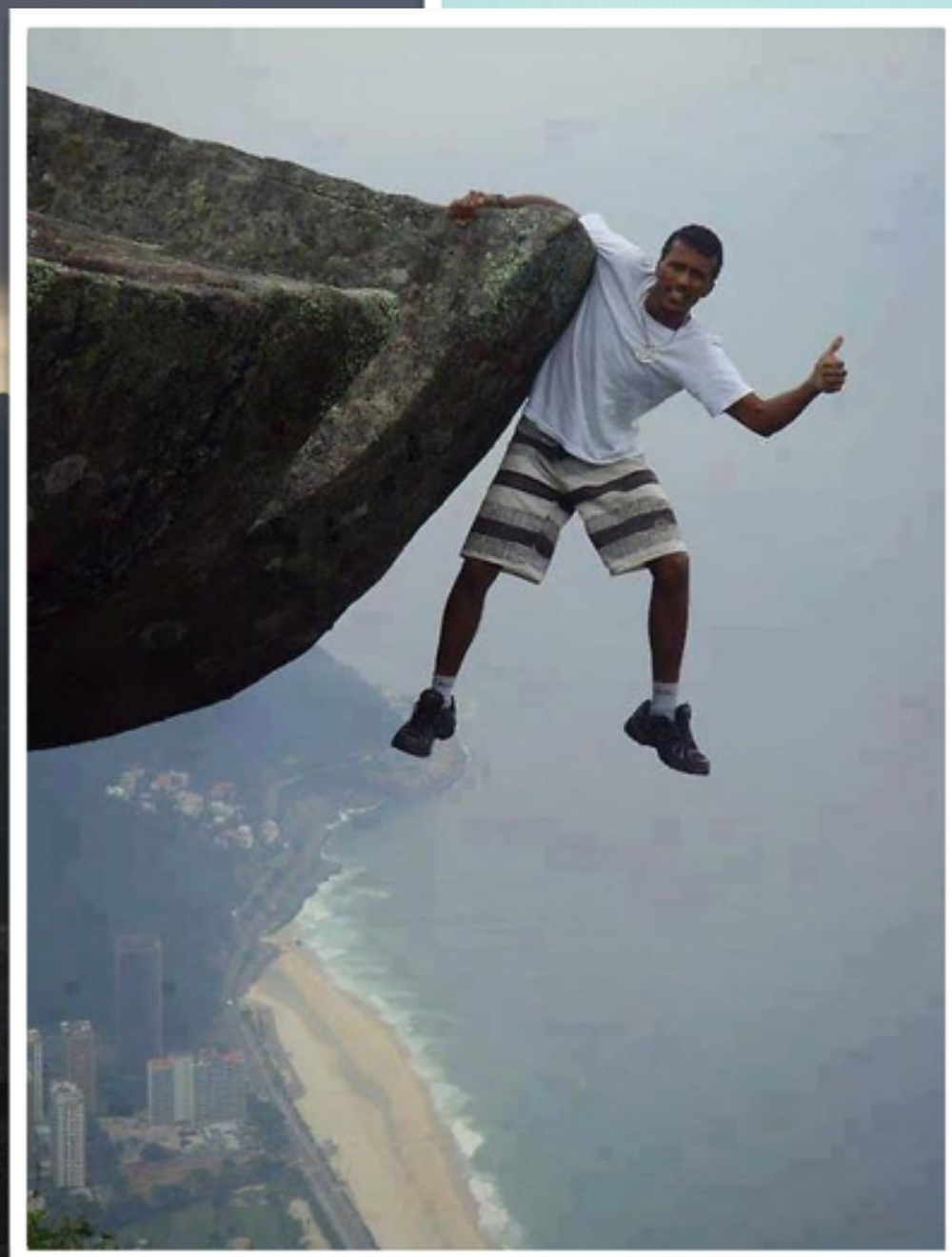

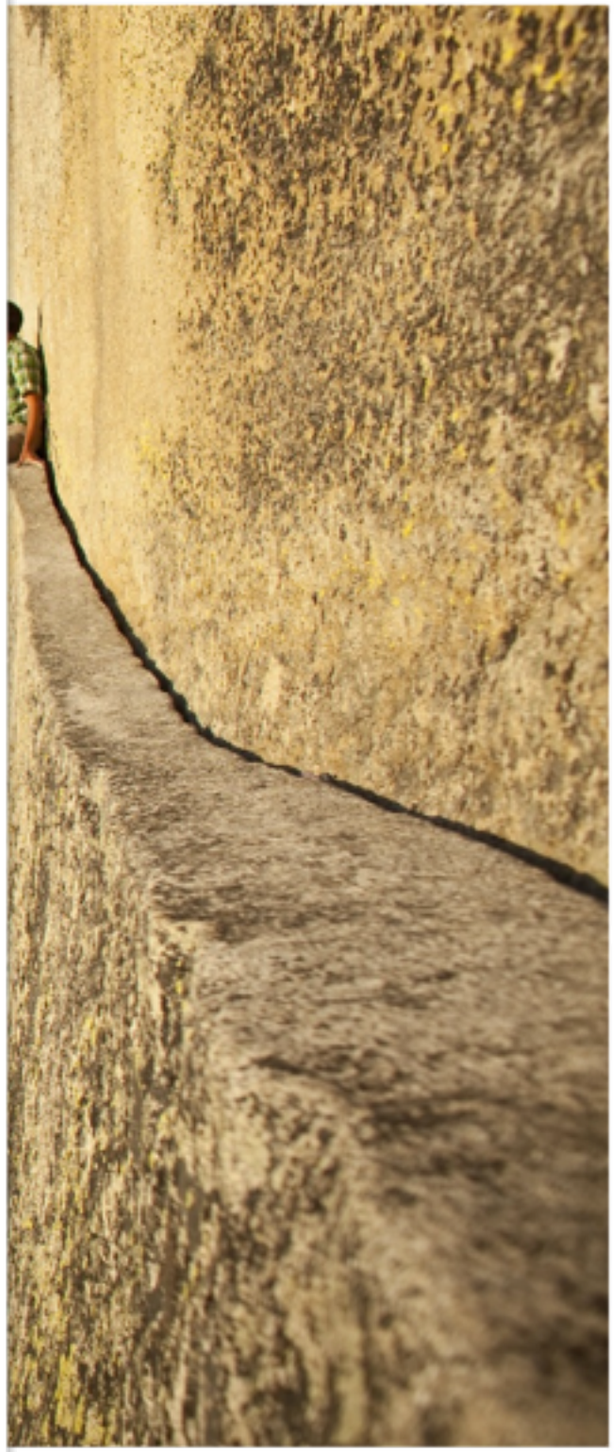

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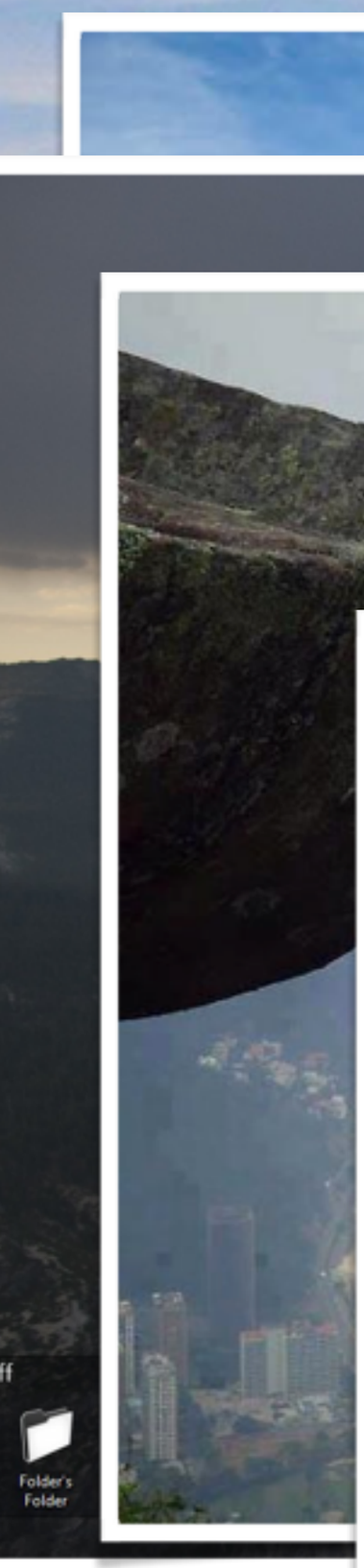
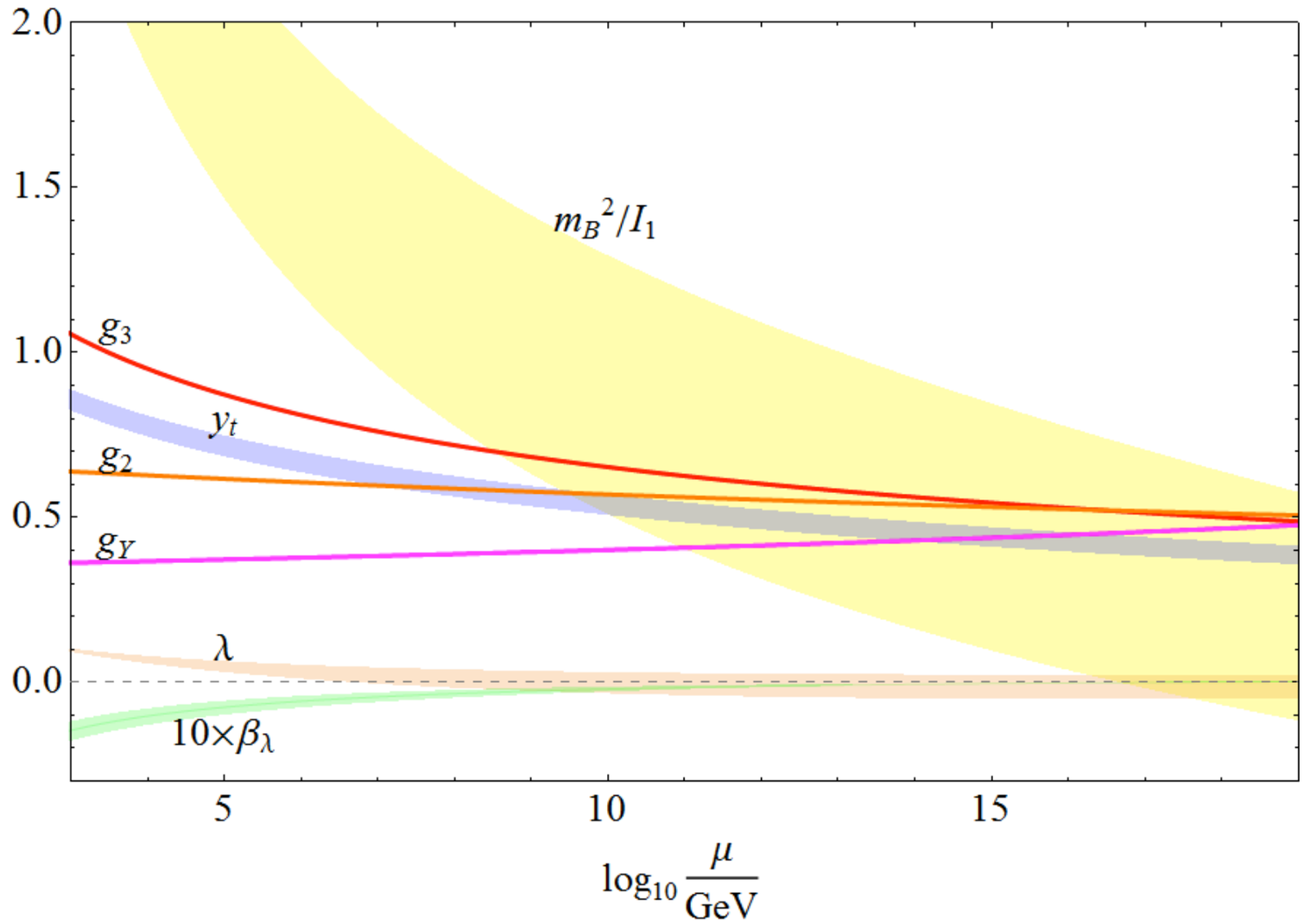


pictures from web

Also,

Bare Higgs mass

- Can be small for Planck scale cutoff.



- Triple coincidence: λ, β_λ, $m_B^2 \sim 0$.

- Must indicate something!

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

To explain more,

Hierarchy "problem"

★ $m_R^2 = m_B^2 + (\lambda + \cdots)\,\Lambda^2/16\pi^2 + \cdots$

ren. mass　bare mass　radiative corrections

★ $\underline{(100\mathrm{GeV})^2 = (10^{18}\mathrm{GeV})^2 - (10^{18}\mathrm{GeV})^2}$?

★ With SUSY,

★ Top loop is cancelled by stop loop etc.

★ Λ^2 is replaced by **SUSY breaking scale**.

★ As we haven't seen SUSY up to TeV,

subtraction problem emerges again.

★ Matter of religious belief: 1% sect, 1‰ sect, etc.

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, *APP* 1981]

  - Two loop corrections to bare mass are small. [Hamada, **KO**, Kawai, 2013]

- SUSY may well be broken at string/Planck scale. [Hamada, **KO**, Kawai, 2015]

  - 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.

Recent model building: Blaszczyk, Groot Nibbelink, Loukas, Ramos-Sanchez, *JHEP* 2014.

SM criticality

- May be realized by a principle beyond ordinary QFT:

★Multiple point criticality [Froggatt, Nielsen (1996); ⋯]

★Classical conformality [Meissner, Nicolai (2008); Foot, Kobakhidze, McDonald, Volkas (2008), Iso, Okada, Orikasa (2009); ⋯]

★Asymptotic safety [Weinberg (1979); Shaposhnikov, Wetterich (2010); ⋯; **KO**, Yamada (to appear); ⋯]

★Hidden duality [Kawamura (2013); ⋯]

★Maximum entropy principle [Kawai (2013); Hamada, Kawai, Kawana (2015); ⋯]

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a review in Hamada, Kawai,

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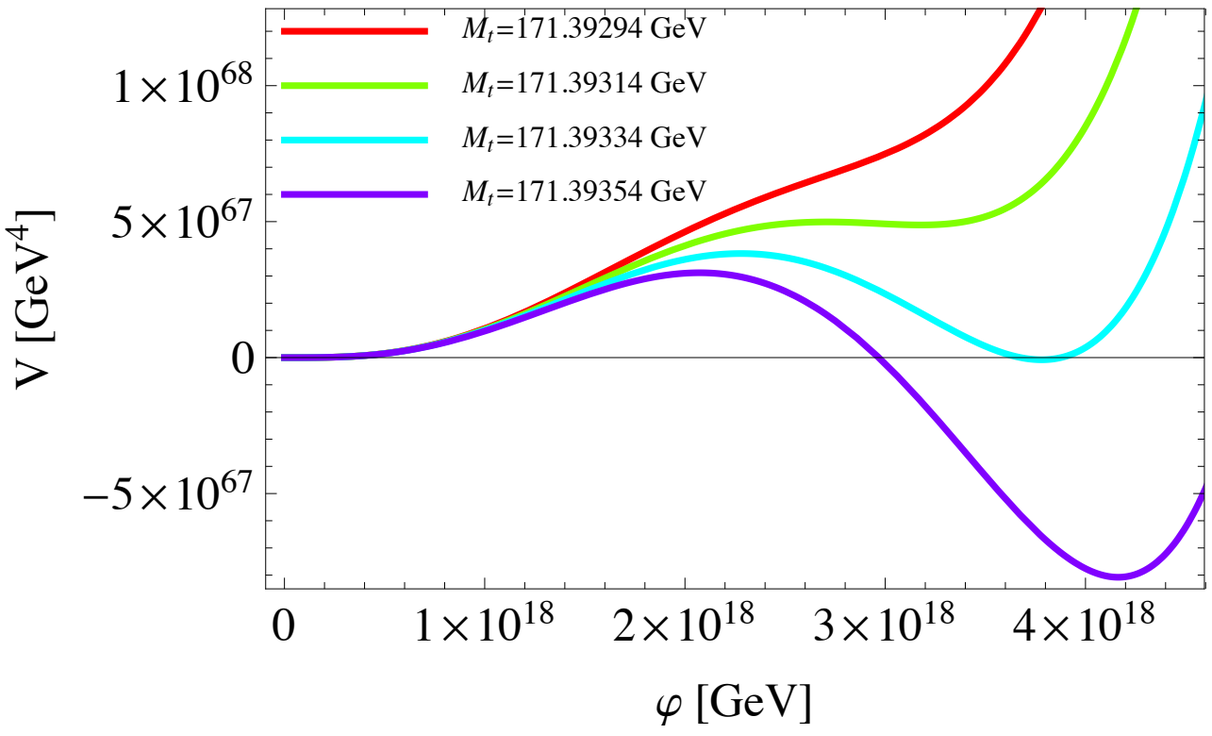
Note: Flat or degenerate?

- Phenomenologically, we do not distinguish principles requiring

  - "flat" potential

  - degenerate vacua



- as they are parametrically identical.

Outline

1. SM criticality: Triple coincidence

2. Higgs inflation with SM criticality

- Milder non-minimal coupling ξ
- Allows larger tensor-to-scalar ratio *r*

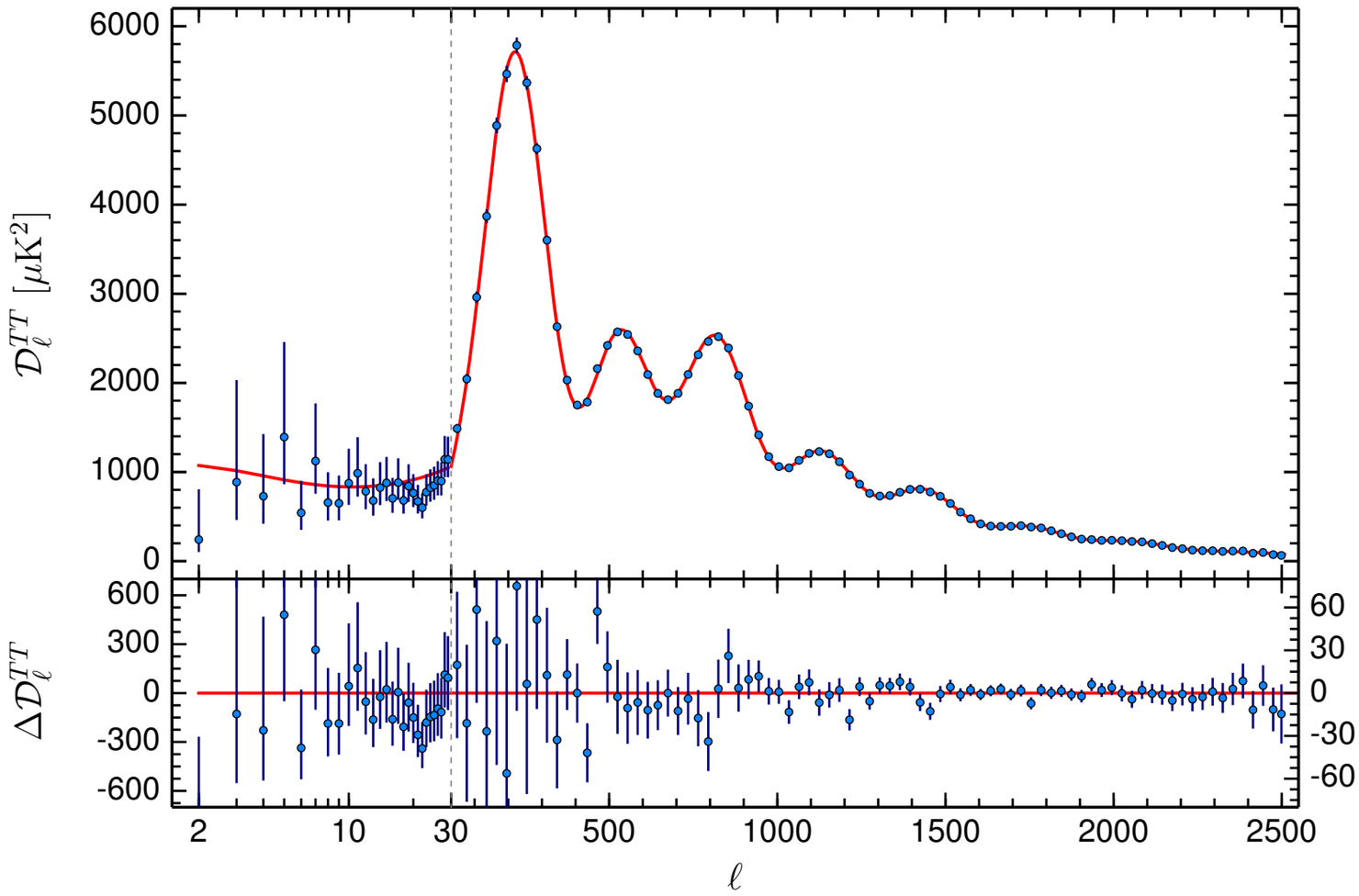
3. Eternal Higgs inflation

- Saves from horizon problem

Observable inflation

picture from web

Inflation paradigm established



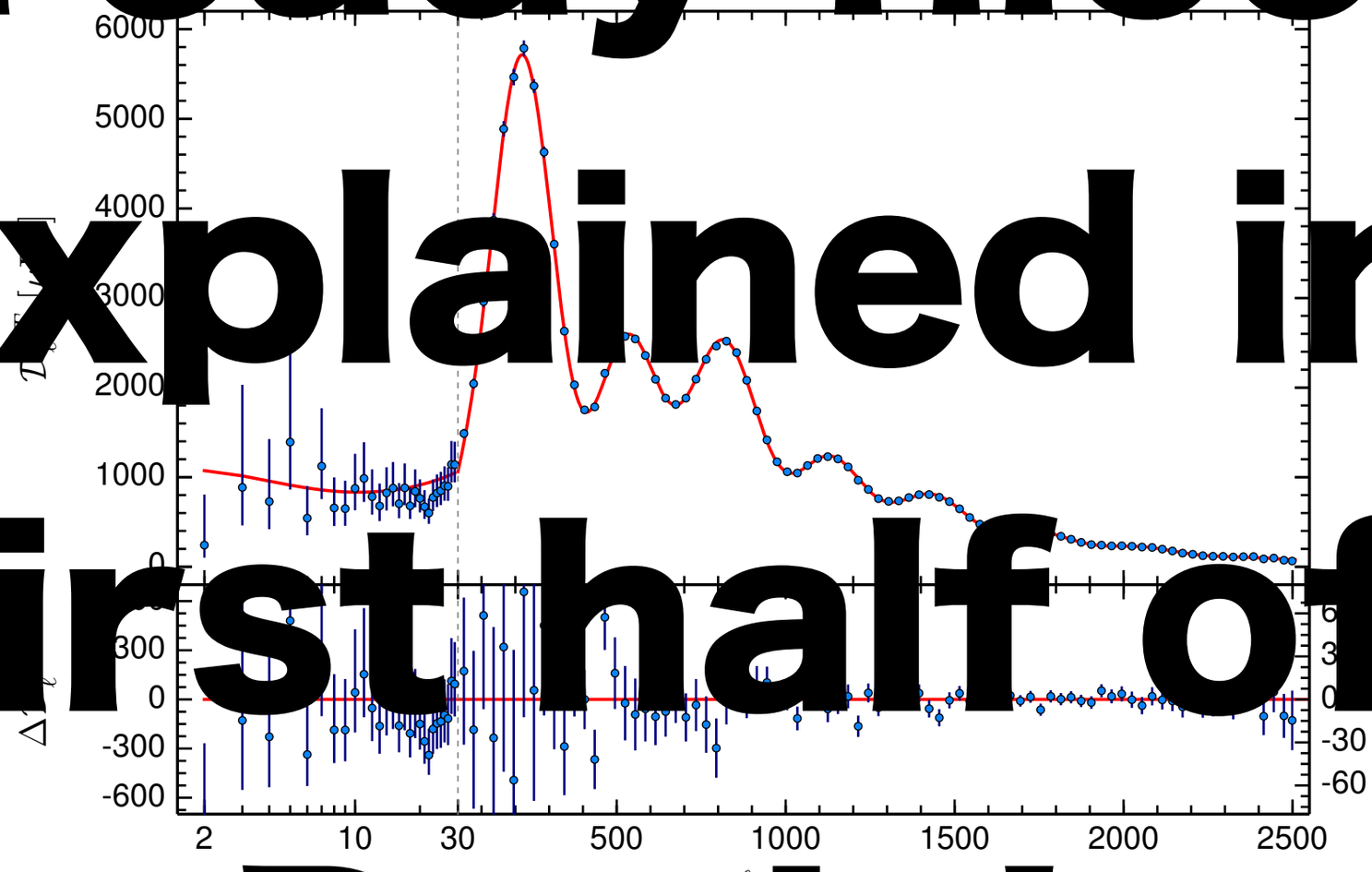
Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	−0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	−0.1
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	−0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	−0.1

- ✦ 70 points nicely fit by few parameters (2 from inflation)

[Planck 2015]

Inflation paradigm established

Already nicely explained in (first half of) Daniel Baumann's talk



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$\Omega_b h^2$	0.02 ± 0.0	0 ± 0.00025	0.0240 ± 0.00	0.02225 ± 0.00016	−0.1
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- Data precisely fit by few parameters (of simple inflation)

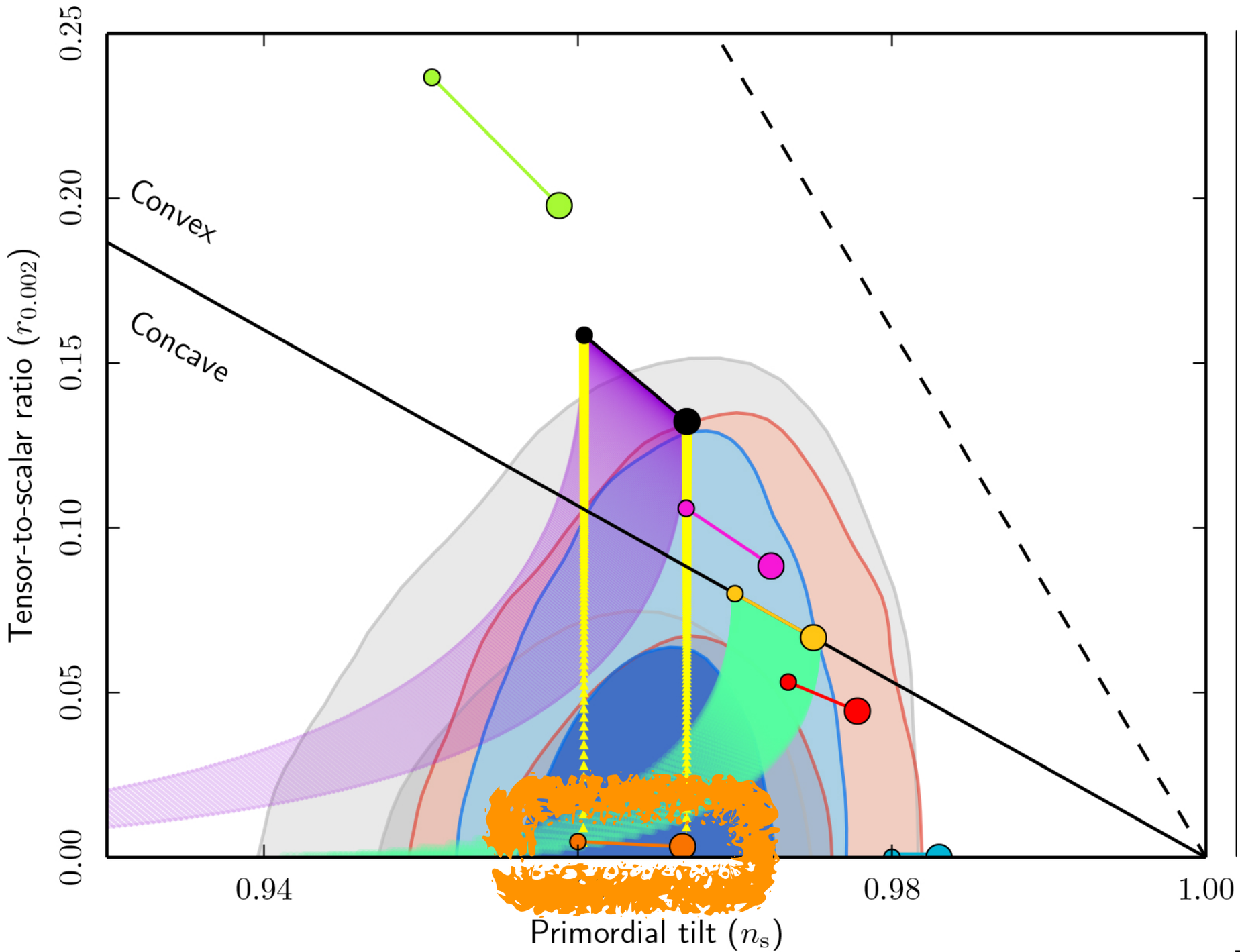
[Planck 2015]

Inflationary data important, as both gravity & quantum fluctuations matter.

Higgs inflation

picture from web

Higgs inflation at center



[Planck 2015]

Recap: Higgs inflation

Marvelous idea by Bezrukov & Shaposhnikov (2008)

- Start from general action:

$$S = \int d^4x\sqrt{-g}\left[\left(1+\xi\frac{\varphi^2}{M_P^2}+\cdots\right)\frac{M_P^2}{2}R - (\partial\varphi)^2 - \left(\frac{\lambda}{4}\varphi^4+\cdots\right)\right]$$

- Can switch to Einstein frame by $(R \sim g^{\cdot\cdot}g^{\cdot\cdot}g^{\cdot\cdot}\partial_{\cdot}g_{\cdot\cdot}\partial_{\cdot}g_{\cdot\cdot} \propto (g_{\cdot\cdot})^{-1})$

$$\left(1+\xi\frac{\varphi^2}{M_P^2}+\cdots\right) g_{\mu\nu} \to g^E_{\mu\nu}$$

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- Potential rescaled:

$$\left(\frac{\lambda}{4}\varphi^4+\cdots\right) \to \frac{\frac{\lambda}{4}\varphi^4+\cdots}{\left(1+\xi\frac{\varphi^2}{M_P^2}+\cdots\right)^2}$$

Flat potential for large Higgs

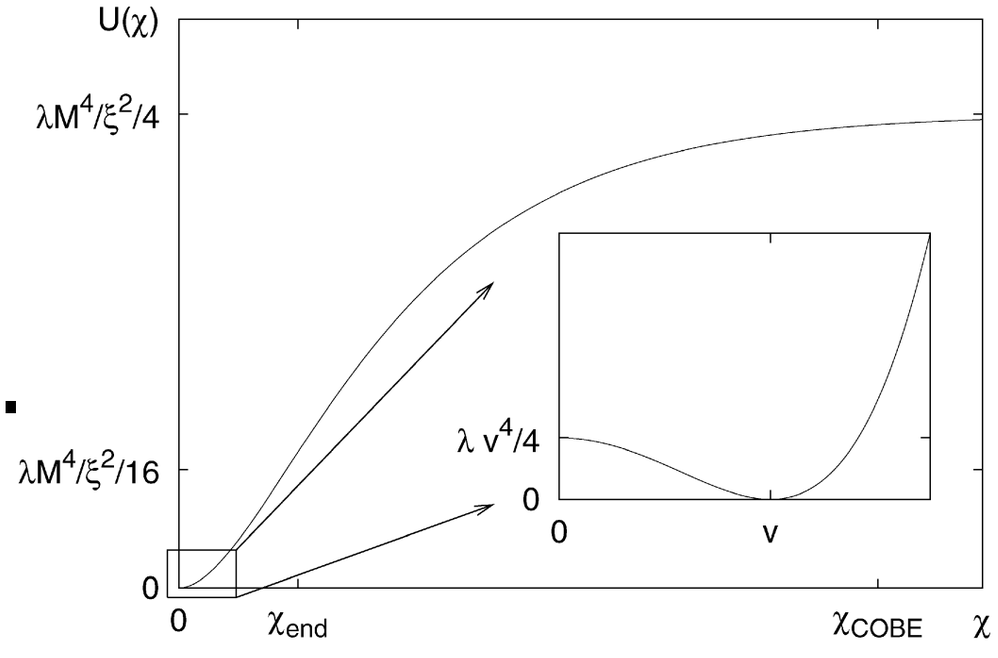
✦ Potential rescaled:

$$\left(\frac{\lambda}{4}\varphi^4 + \cdots\right) \rightarrow \frac{\frac{\lambda}{4}\varphi^4 + \cdots}{\left(1 + \xi\frac{\varphi^2}{M_P^2} + \cdots\right)^2}$$

✦ Flat potential at $\varphi \gg M_P/\sqrt{\xi}$

★ If "…" do not contribute much.

✦ Needs $\xi \sim 10^{5\text{-}6}$ for $\lambda \sim 0.1$



Bezrukov & Shaposhnikov (2008)

✦ Needs $\xi \sim 10^{5\text{-}6}$ for $\lambda \sim 0.1$

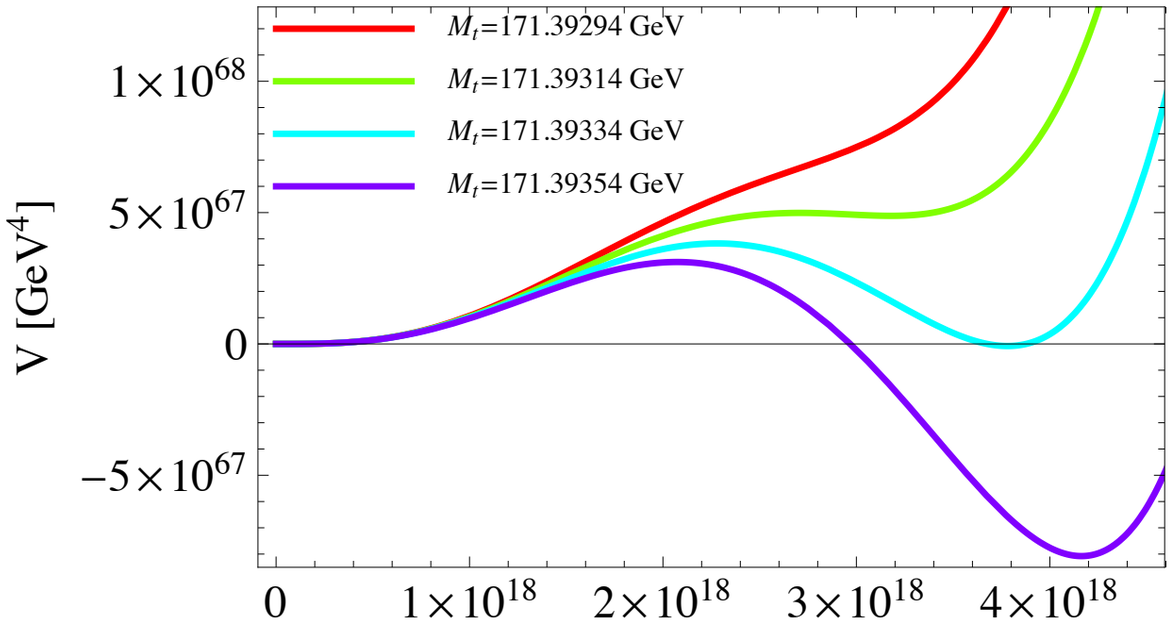
Can we evade such a large $\xi \sim 10^{5\text{-}6}$?

Yes we can

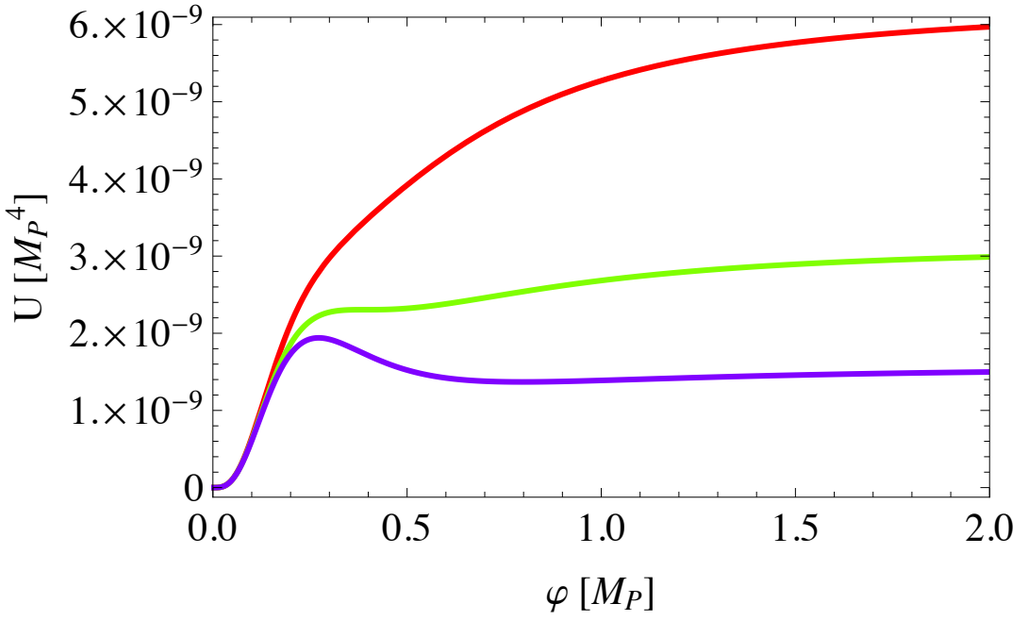
(We really can, in this case.)

Higgs inflation from SM criticality

Hamada, Kawai, **KO**, Park, *PRL* 2014, *PRD* 2015;
Bezrukov, Shaposhnikov, *PLB* 2014;
also Cook, Krauss, Long, Sabharwal, *PRD* 2014.



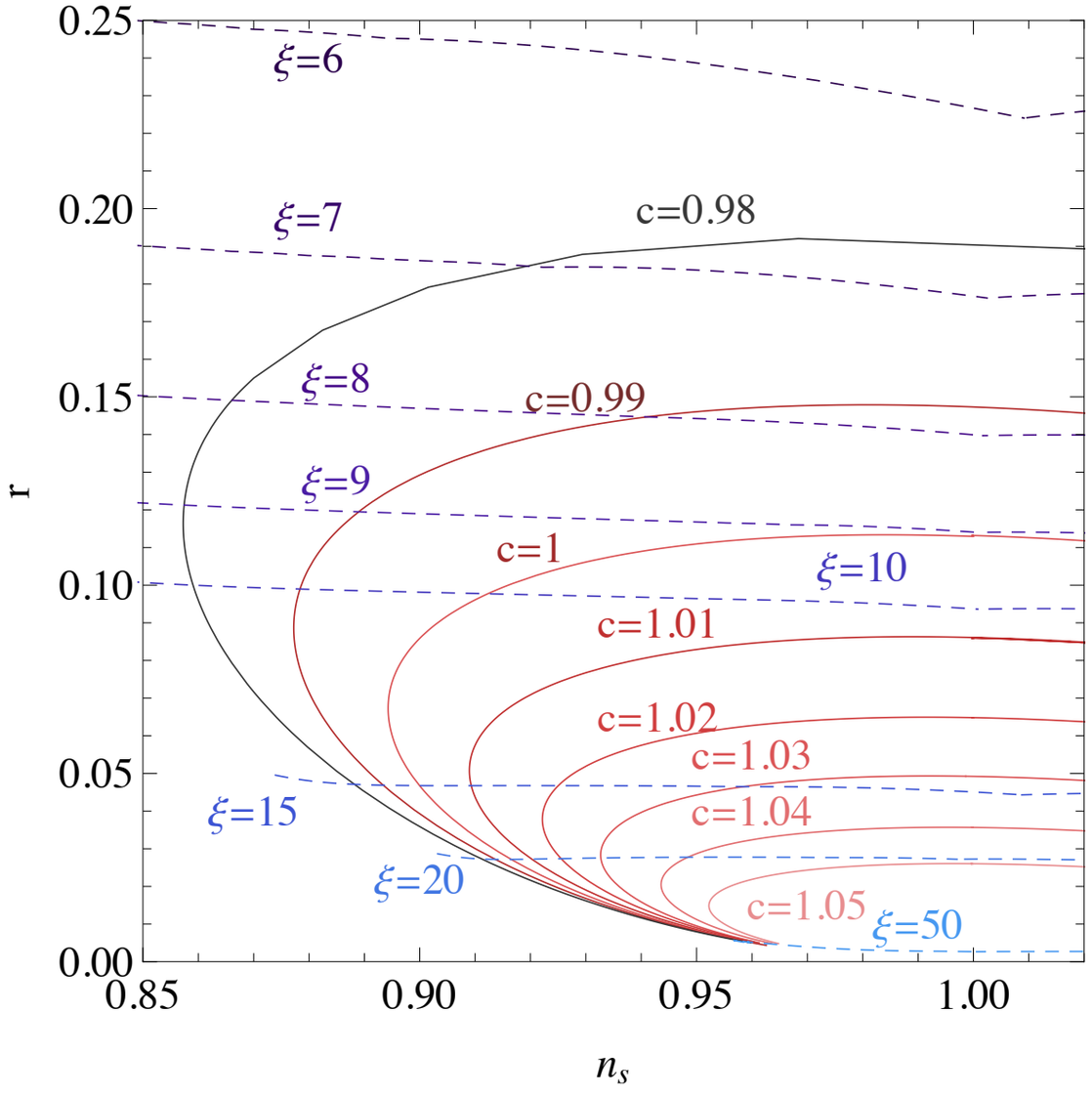
- SM criticality:
  - ✳ **Flat potential**
- Combine with original idea by Bezrukov & Shaposhnikov.
  - ✳ Need only $\xi\sim10$.
  - ✳ Biproduct:
    - ✤ Tensor-to-scalar ratio can be as large as $r\sim0.1$.
    - ✤ May be seen in near future.

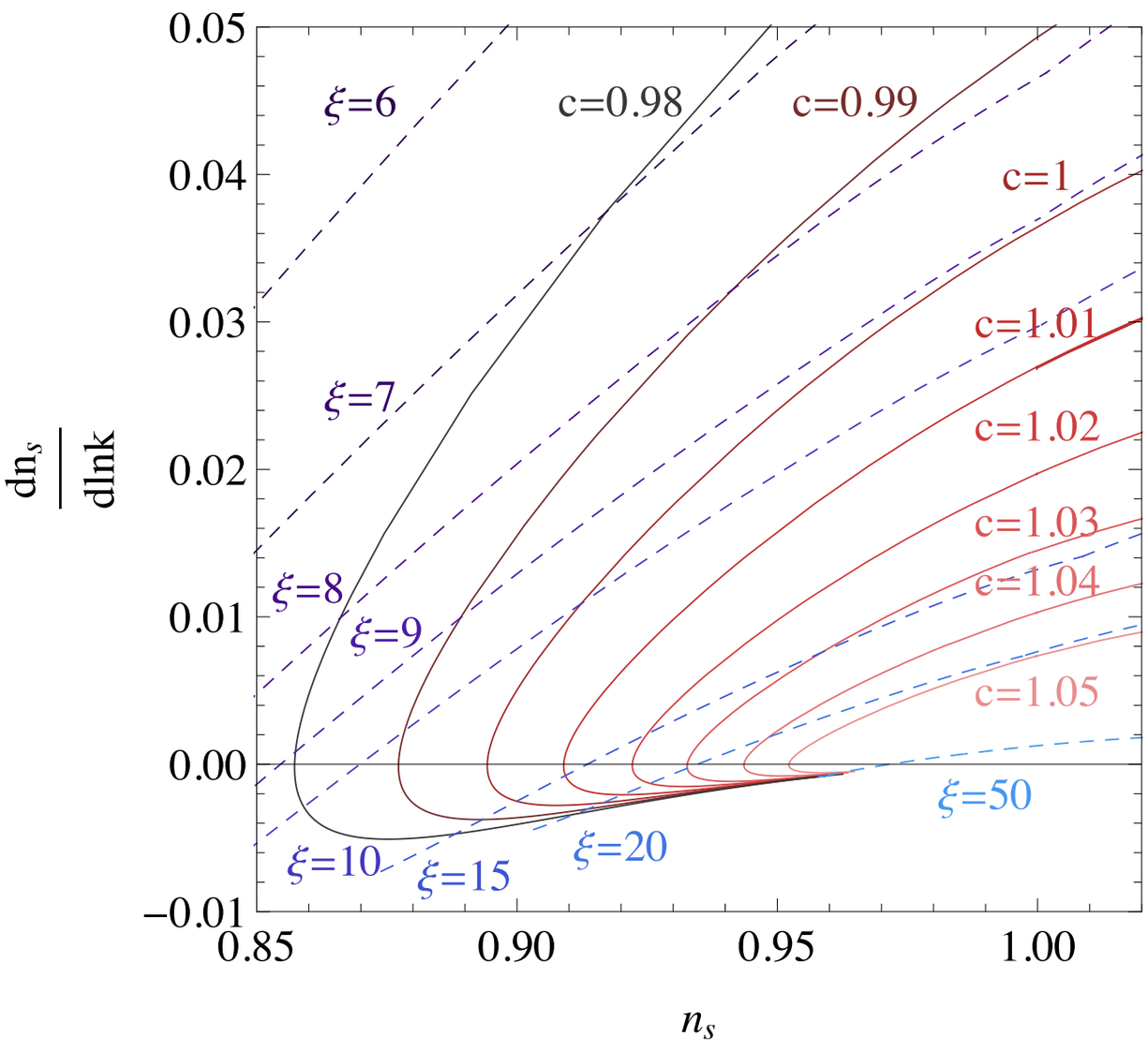


Predictions of (very) minimal model (skippable)

★$c := \mu_{\rm min} / (M_P/\sqrt{\xi})$

[Hamada, Kawai, **KO**, Park, *PRD* 2015]





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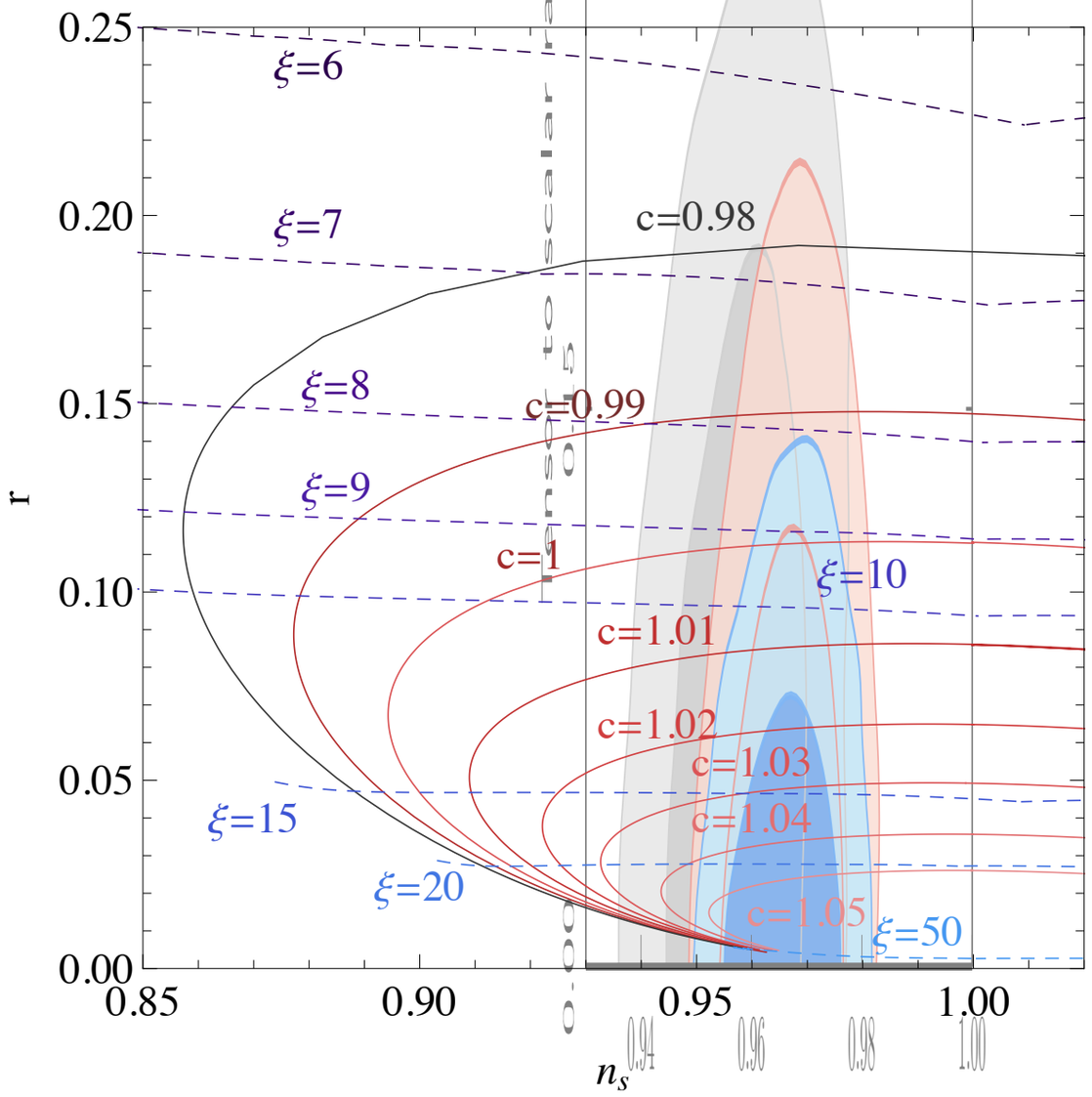
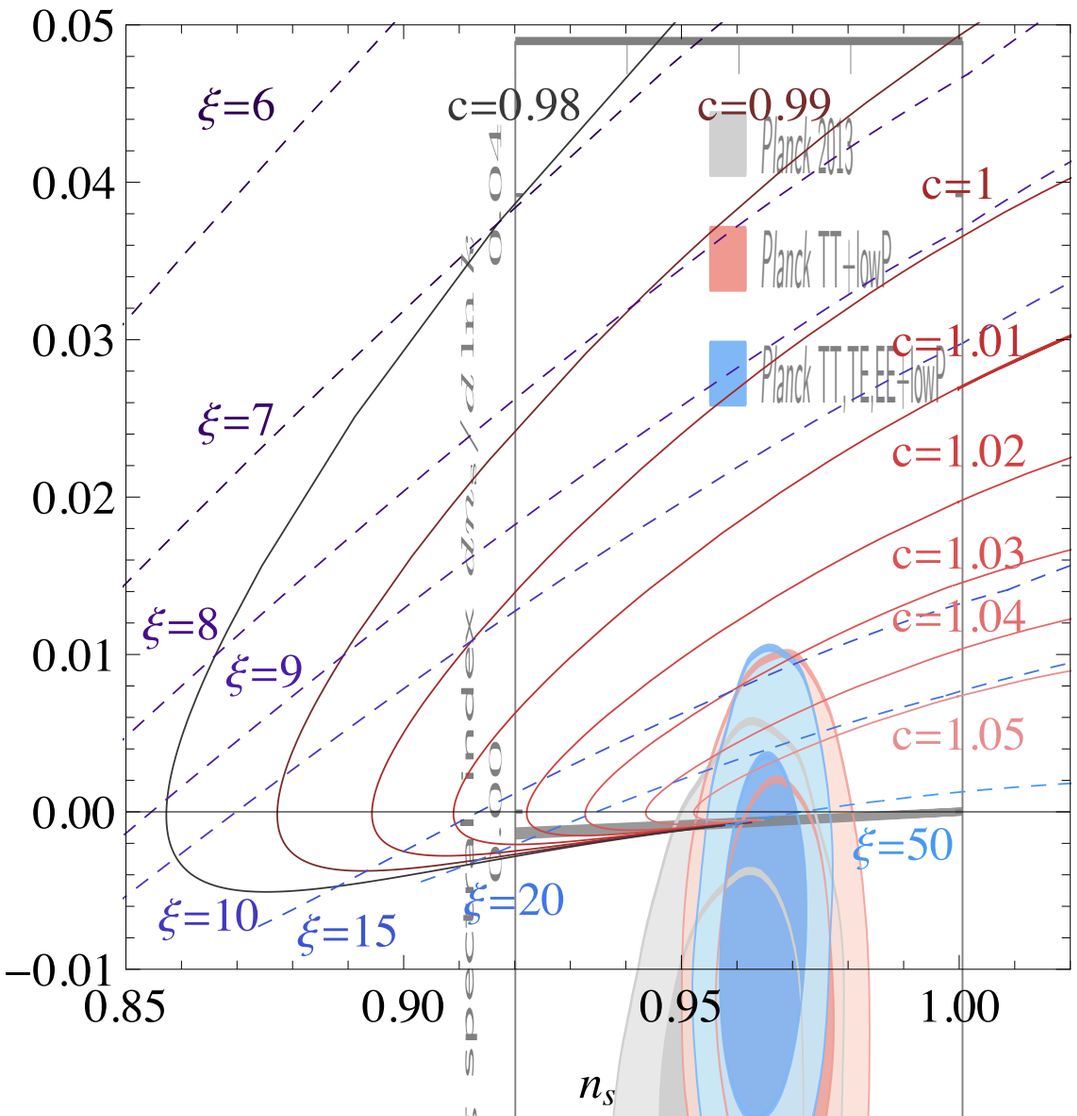




Higgs portal Z_2 DM (skippable)

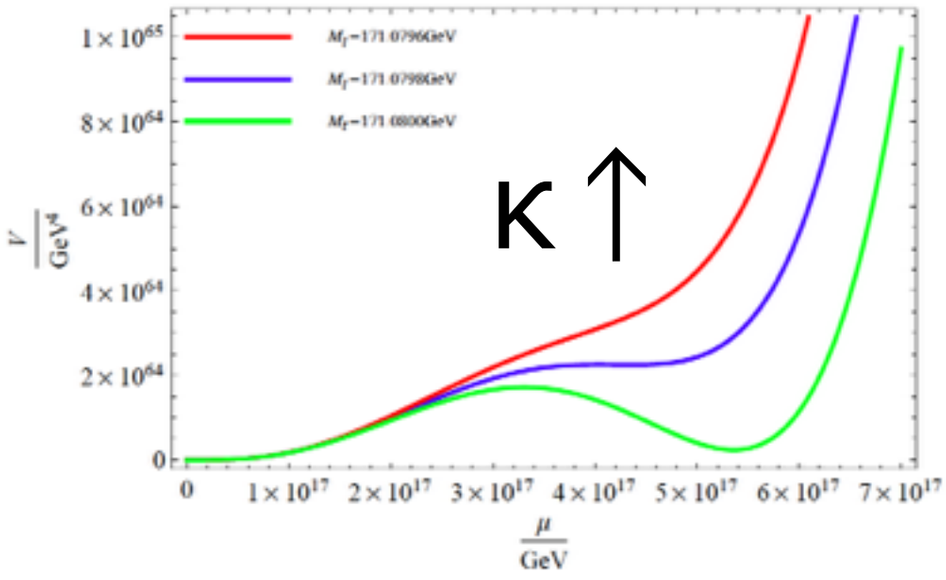
[Hamada, Kawai, **KO**, *JHEP* 2014]

[Also done by (several combinations of) Haba, Ishida, Kaneta & Takahashi.]

★Higgs portal DM:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - \frac{\rho}{4!}S^4 - \frac{\kappa}{2}S^2 H^\dagger H.$$

✳ κ works like g_Y on running λ(μ)



✳ Testable relation btn m_{DM} & m_t

- ✦ Upper bound: m_{DM}<1TeV. (next)

✳ Criticality → $\underline{m_{DM} \sim 400\text{GeV}}$.

Outline

1. SM criticality: Triple coincidence

2. Higgs inflation with SM criticality

   - Milder non-minimal coupling ξ
   - Larger tensor-to-scalar ratio *r*

3. Eternal Higgs inflation

   - Saves from horizon problem

Eternal (pre)inflation

picture from web

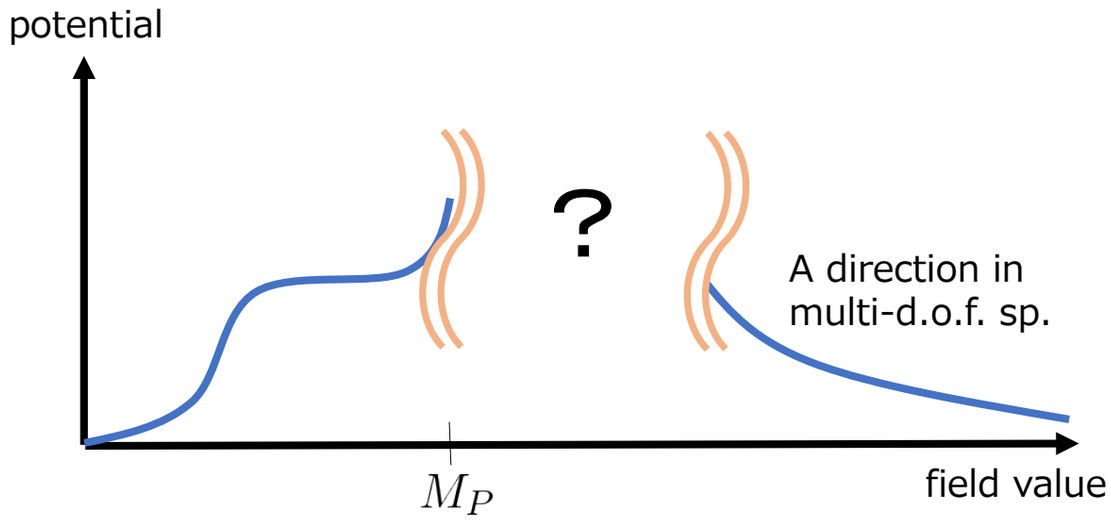
Slow-roll inflation does NOT solve horizon problem

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

Eternal (pre)inflation at domain wall

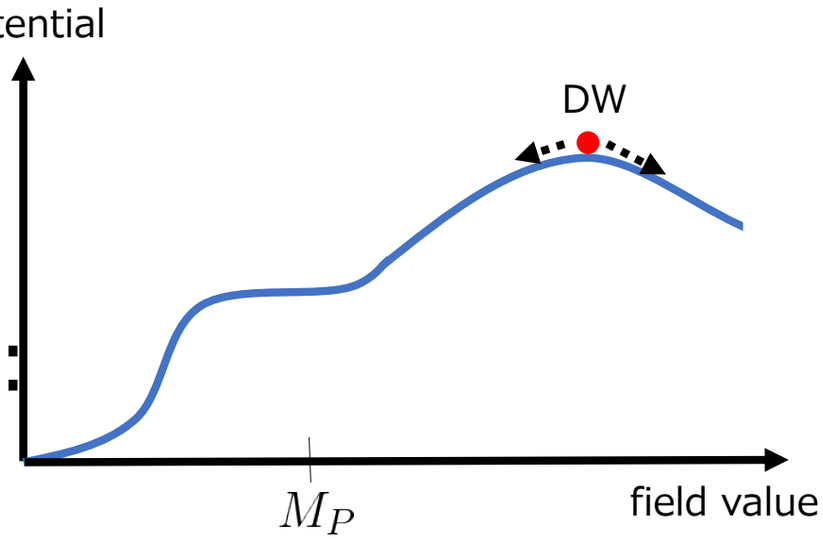
[Hamada, **KO**, Takahashi, *PRD* 2014]

- In string theory: we see there are two degenerate vacua.



[Hamada, Kawai, **KO**, *PRD* 2015;
also Hamada, Kawai, Kawana, *PTEP* 2015]

- Domain wall, formed between two vacua:



  - For a given random, say chaotic, initial condition.

- If relative curvature at maximum is not large: $\eta < 1.4$

[Sakai, Shinkai, Tachizawa & Maeda, 1996]

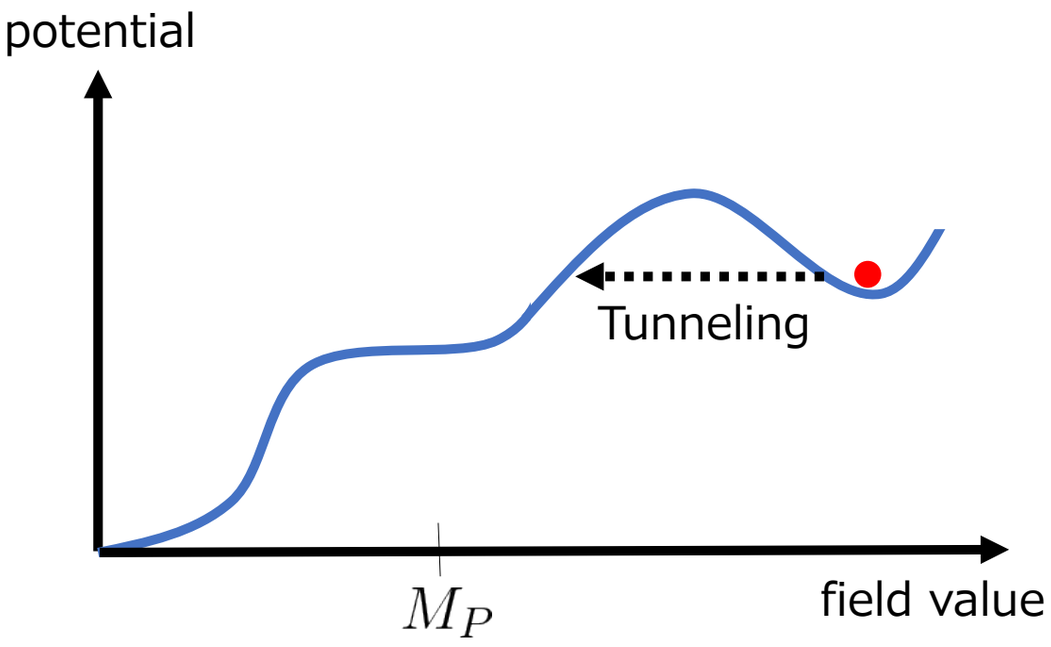
  - DW supports inflation forever.

  - A solution to horizon problem!

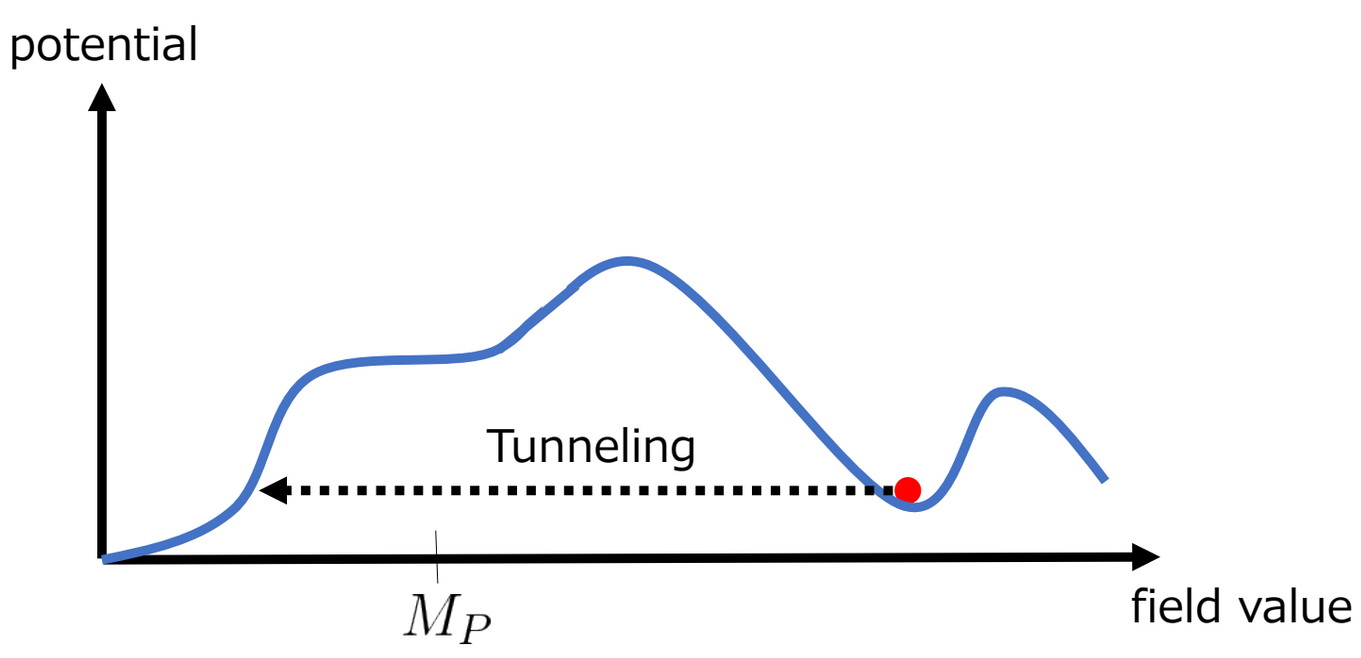
Eternal inflation at false vacuum

[Hamada, Kawai, **KO**, *PRD* 2015]

✦ False vacuum eternal (pre)inflation also possible.



Higgs inflation works.



Need another inflaton.

Many things to do

- ★**Anything** intermediate between weak and Planck scales (affecting running of quartic coupling) changes inflation prediction.

- ✴ Higgs portal DM, right-handed neutrino, etc.

Summary

1. SM criticality: Triple coincidence

2. Higgs inflation with SM criticality

   - Milder non-minimal coupling ξ
   - Larger tensor-to-scalar ratio *r*

3. Eternal Higgs inflation

   - Saves from horizon problem

Thank you!

picture from web