Higgs potential and inflation

Yuta Hamada（Kyoto University）

Collaborators

Hikaru Kawai（Kyoto）

Kin-ya Oda（Osaka）

Seong Chan Park（Sungkyunkwan）

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This talk

- We assume SM is valid up to high scale such as string scale~$10^{17\text{-}18}$GeV.

- SM potential is flat around $10^{17\text{-}18}$GeV.
- propose Higgs inflation scenario where $\lambda \sim \beta_\lambda \sim 0$ plays crucial role.
- discuss implications of our scenario on Higgs portal DM.

Plan

1. Higgs inflation from SM criticality
2. Z_2 scalar DM mass prediction

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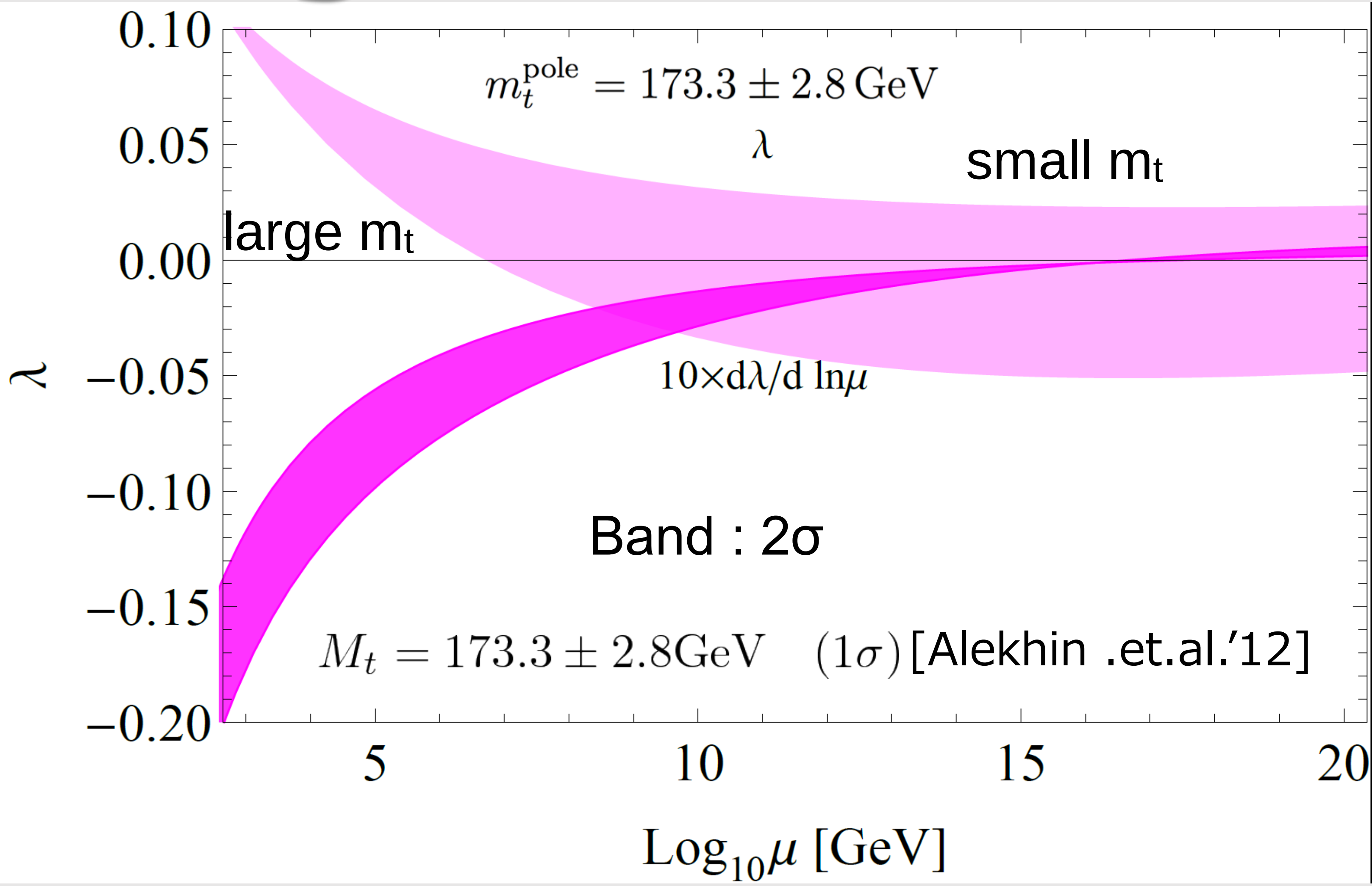
$\lambda \sim \beta_\lambda \sim 0$ at high scale

[Bezrukov .et.al.'12,
Degrassi.et.al. '12,
………]

$$V_{\rm SM} \simeq \frac{\lambda(\varphi)}{4}\varphi^4$$

- If M_t=171GeV, λ=0 at $10^{17\sim18}$GeV.
- β_λ also becomes zero at $10^{17\sim18}$GeV.

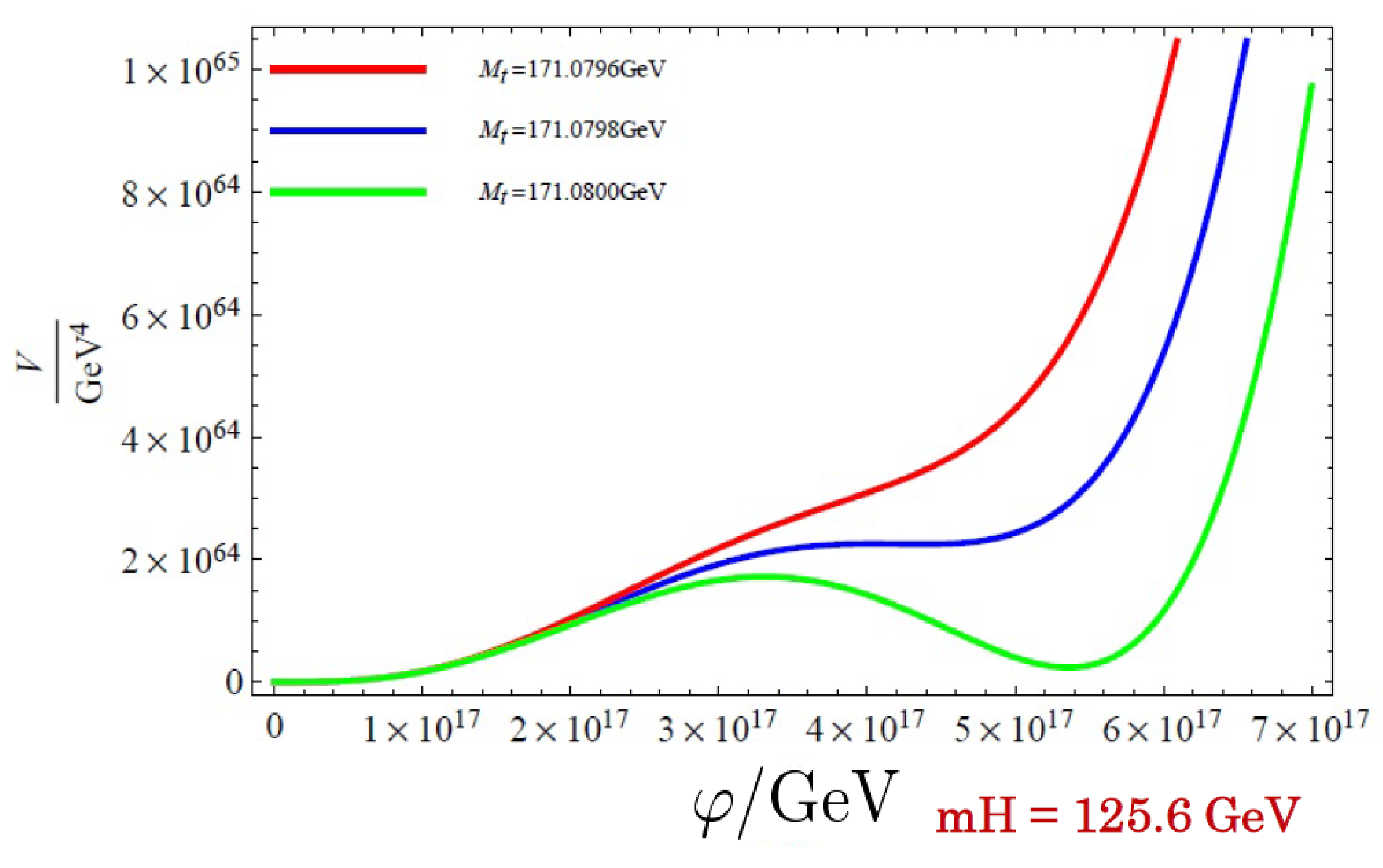


[YH,Kawai,Oda '12,13]

Higgs potential at high scale

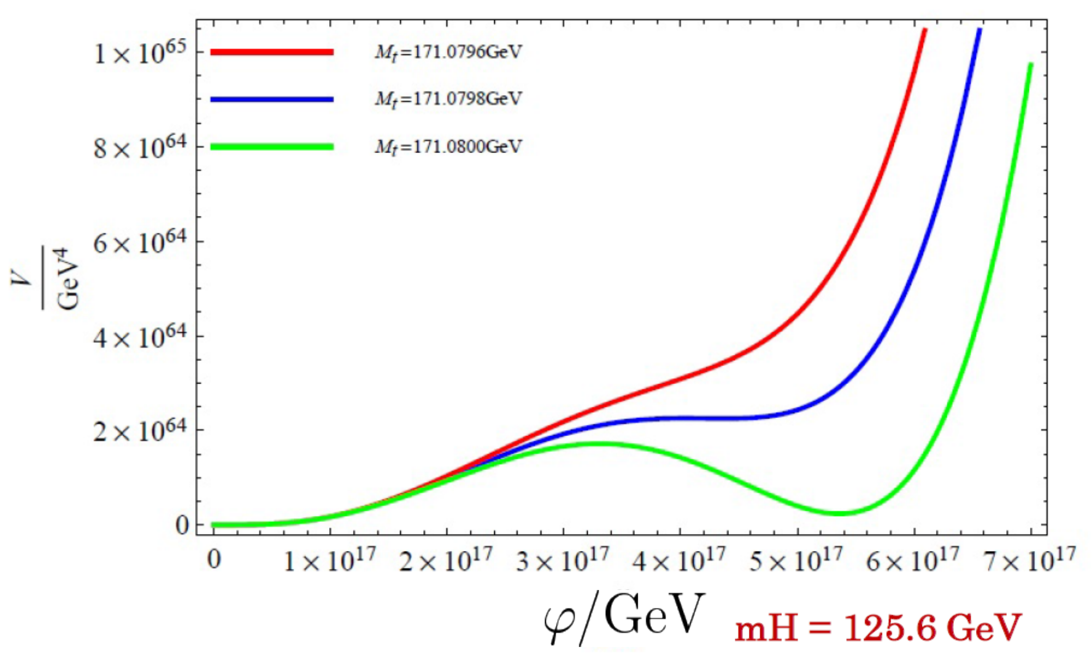
$$V_{\rm SM} \simeq \frac{\lambda(\varphi)}{4}\varphi^4$$

- By tuning M_t, SM potential is flat because $\lambda \sim \beta_\lambda \sim 0$.
- Inflation possible ?



No ! Too large A_s

- We can realize saddle point by tuning M_t.
- For sufficiently expansion $N_* \sim 60$, φ_* needs to be close to saddle point($\varepsilon <<< 1$)
- As a result, too large density perturbation. ($A_s >> 1$ in this case)



$$A_s \simeq \frac{V}{24\pi^2 M_{\rm pl}^4 \epsilon} \qquad A_s(\text{exp}) \simeq 2 \times 10^{-9}$$

Higgs inflation

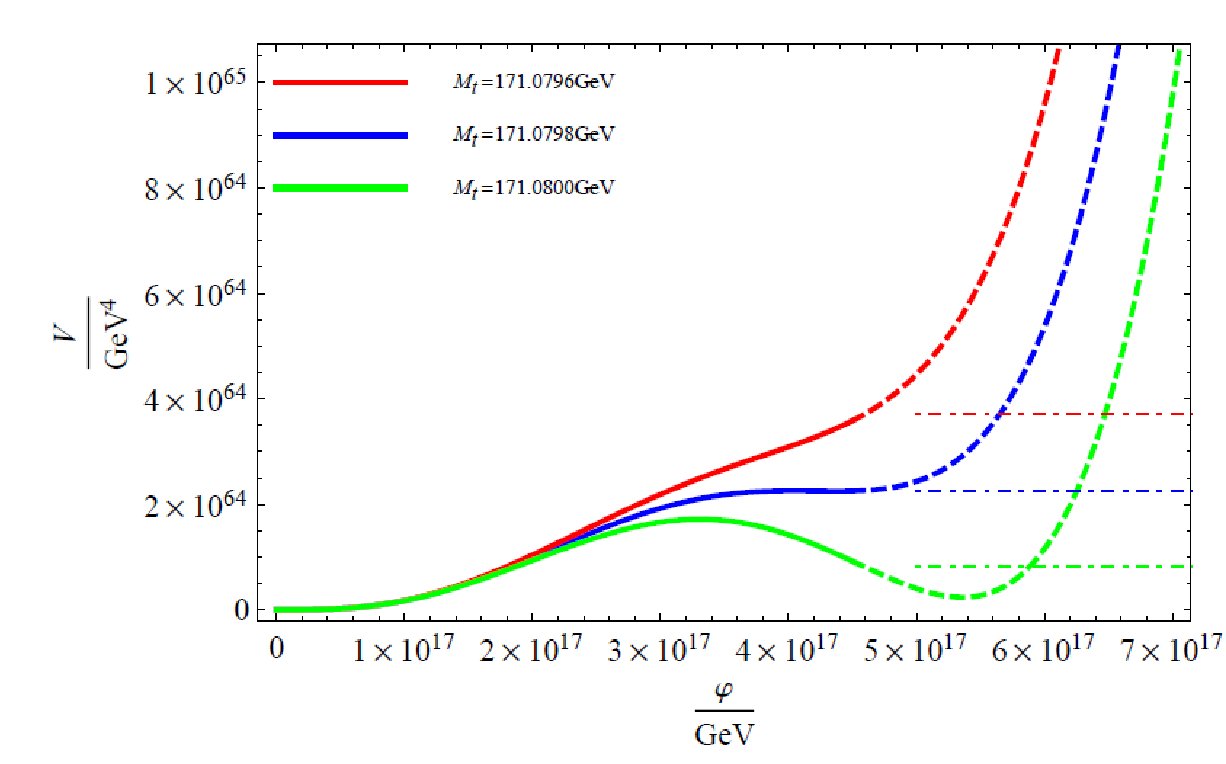
1. conservative approach
   We trust effective potential only below SM cutoff scale Λ, and try to make bound on parameters, Λ and M_t.
   [YH,Kawai,Oda '13]

2. Radical approach
   We introduce non-minimal coupling between scalar curvature and Higgs.
   We trust flat potential at high field value.
   [Bezrukov, Shaposhnikov '08]
   [YH,Kawai,Oda,Park '14, Bezrukov, Shaposhnikov '14]

Conservative approach

- We assume for field value φ>Λ, potential is flat and inflation occurs above Λ.
  - New physics would make potential flat.

- Though it is ad-hoc assumption, we obtain useful constraint on M_t and Λ (necessary conditions).



Necessary conditions

- Scalar perturbation and observation of tensor mode give upper bound on potential.

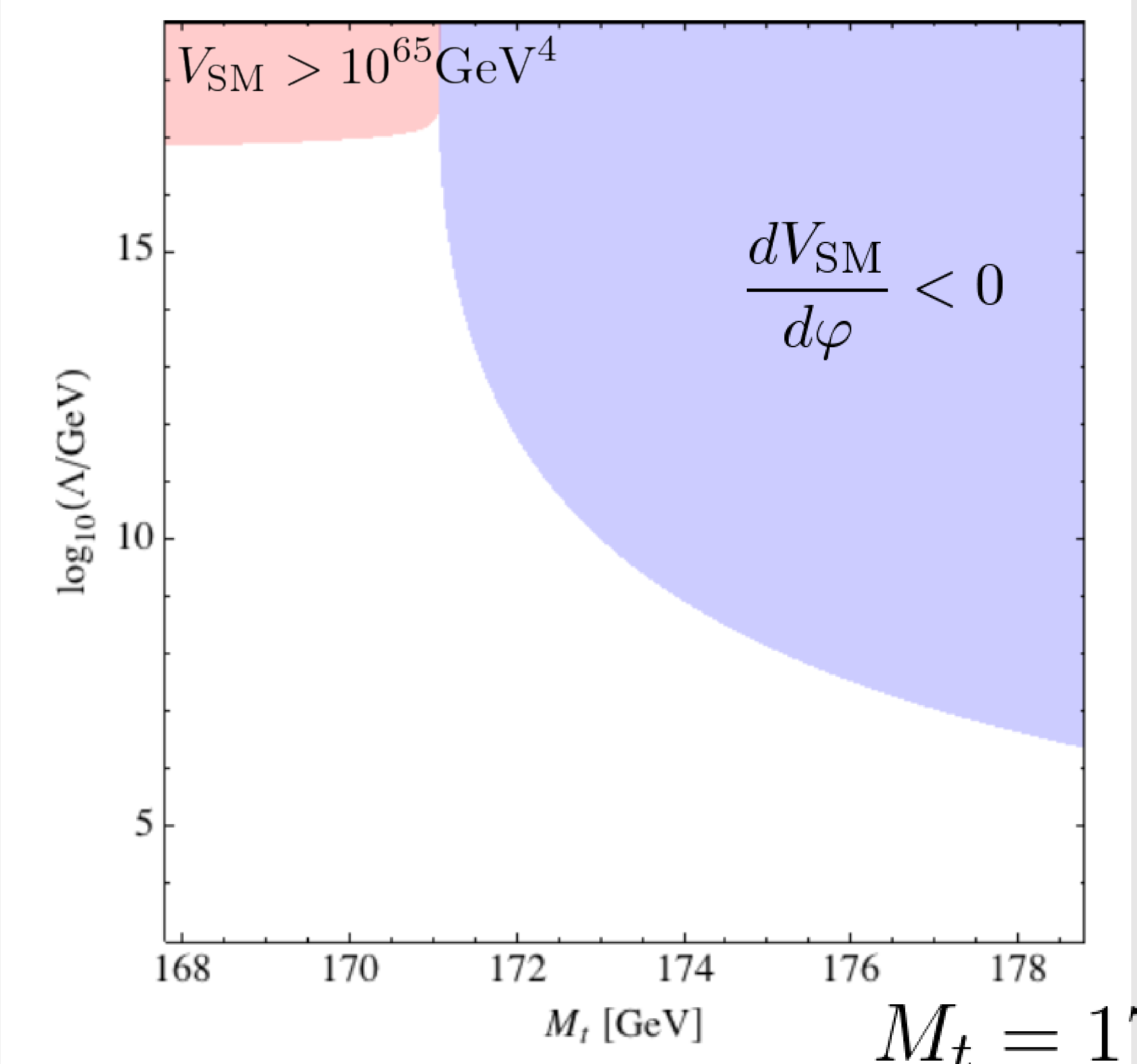
$$V_{\mathrm{SM}}(\Lambda) < 1.3 \times 10^{65}\mathrm{GeV}^4$$

$$A_s \simeq \frac{V}{24\pi^2 M_{\mathrm{pl}}\epsilon} \sim 10^{-9} \qquad r \simeq 16\epsilon \sim 0.1$$

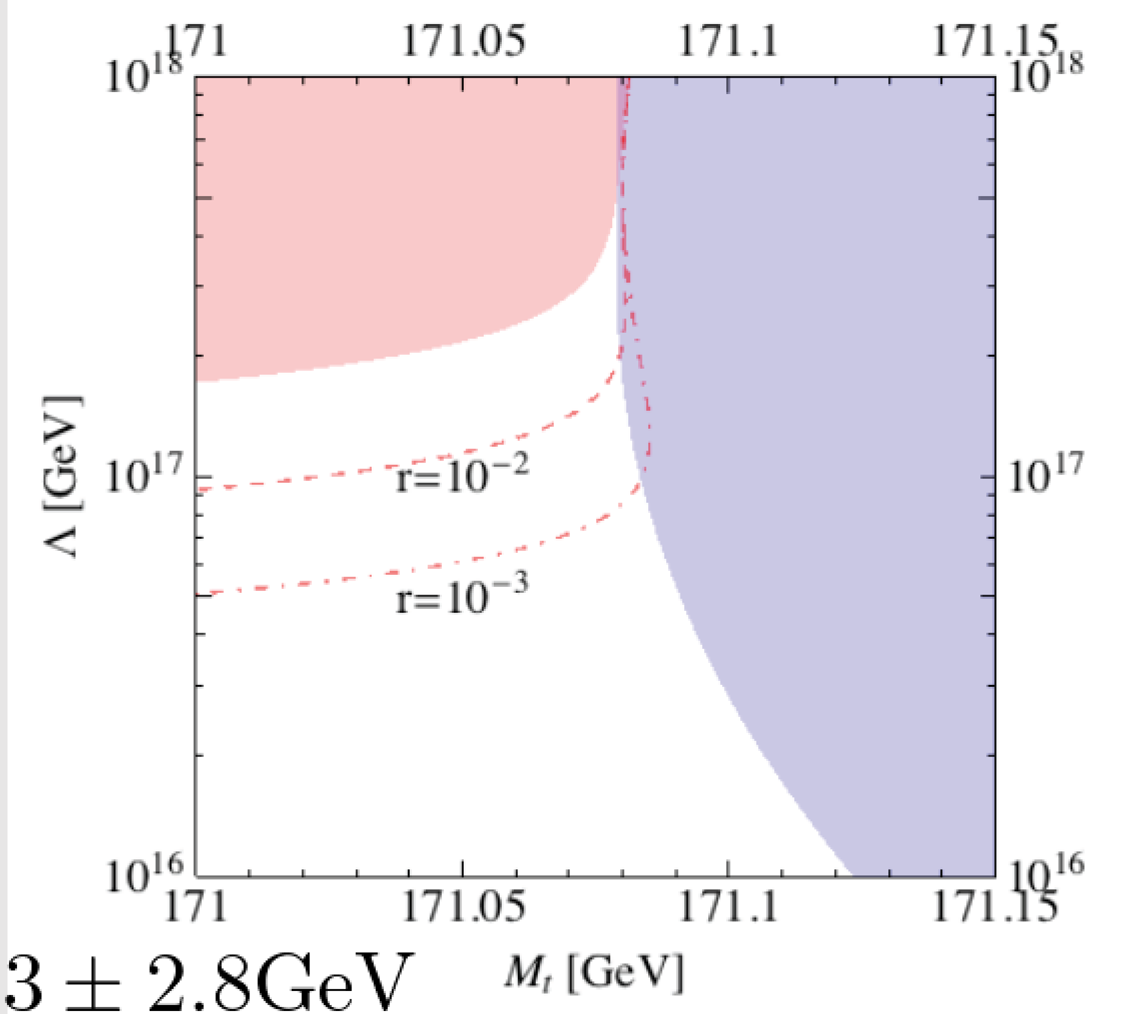
- Potential should be monotonically increasing function to avoid graceful exit problem.

[YH,Kawai,Oda '13]

Constraint on M_t and Λ



Enlarged view



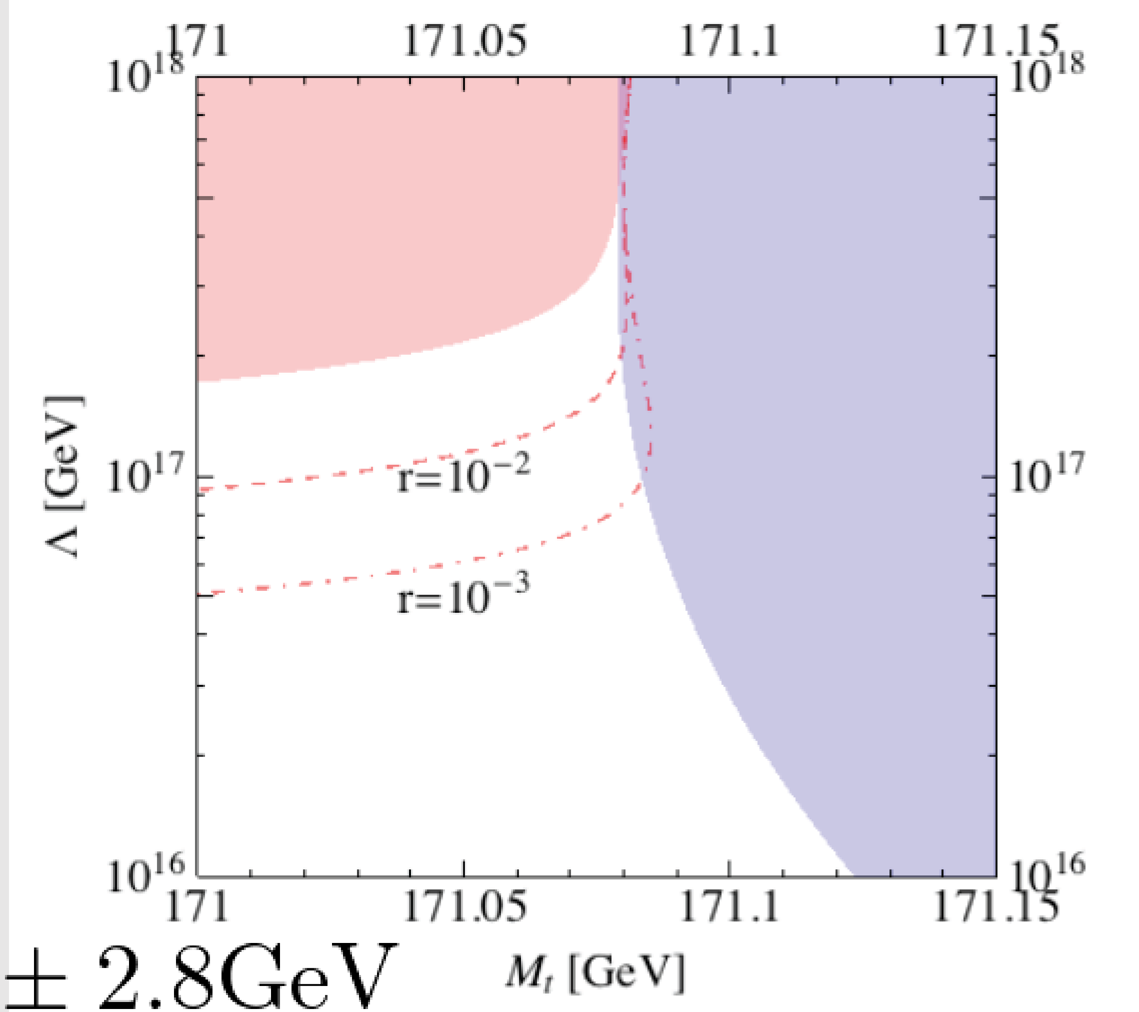
$$M_t = 173.3 \pm 2.8 {\rm GeV}$$

[YH,Kawai,Oda '13]

Constraint on M_t and Λ

- $\Lambda < 5\times10^{17}$GeV
- String scale appears.
- Situation in which $\Lambda \sim 10^{17}$GeV and inflation above Λ is OK.

Enlarged view



$$M_t = 173.3 \pm 2.8\text{GeV}$$

Radical approach: ξ|H|²R

- Jordan frame

$$S = \int d^4x \sqrt{-g} \left\{ -\frac{M_{pl}^2 + \xi\varphi^2}{2} R + \frac{(\partial_\mu \varphi)^2}{2} - \frac{\lambda}{4}\varphi^4 \right\}$$

- Conformal transformation $\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 = 1 + \frac{\xi\varphi^2}{M_{pl}^2}$

$$S = \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_{pl}^2}{2}\hat{R} + \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda}{4}\frac{\varphi^4}{(1+\xi\varphi^2/M_{pl}^2)^2} \right\}$$

$$\frac{d\chi}{d\varphi} = \sqrt{\frac{\Omega^2 + 6\xi^2\varphi^2/M_{pl}}{2\Omega^4}} \qquad \varphi \simeq \frac{M_{pl}}{\sqrt{\xi}} \exp\left(\frac{\chi}{\sqrt{6}M_{pl}}\right), \quad \text{for} \quad \varphi \gg \frac{M_{pl}}{\sqrt{\xi}}$$

- Potential becomes flat at high φ $V = \frac{\lambda(\mu)}{4}\frac{\varphi^4}{(1+\xi\varphi^2/M_{pl}^2)^2}$

RG improvement

- Where is renormalization scale μ ?
- Usually, μ~(effective mass of top/gauge boson).
  - Prescription1(effective mass in Einstein frame)

$$\mu = \frac{\varphi}{\sqrt{1+\xi\varphi^2/M_{pl}^2}}$$

    - μ becomes constant at high field value.
  - Prescription2(effective mass in Jordan frame)

$$\mu = \varphi$$

- We don't know which prescription is correct.
- Let's see Higgs inflation in both descriptions.

Higgs inflation

- If λ is not small at high scale (~O(0.1)), small r is predicted.

$$\epsilon = \frac{4M_{pl}^4}{3\xi^2\varphi^4} \qquad \eta = -\frac{4M_{pl}^2}{3\xi\varphi^2}$$

$$r \simeq 3 \times 10^{-3} \qquad n_s \simeq 0.97$$

[Bezrukov, Shaposhnikov '08]

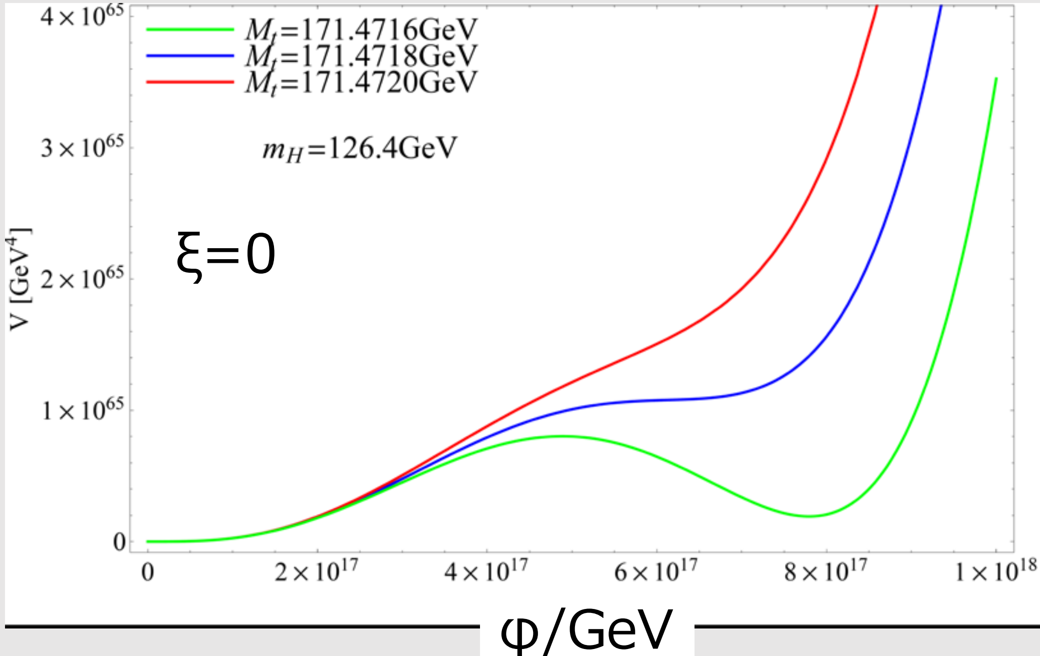
- But, taking into account λ~0 at high scale (SM criticality), prediction drastically changes.

[YH,Kawai,Oda,Park '14, Bezrukov, Shaposhnikov '14]

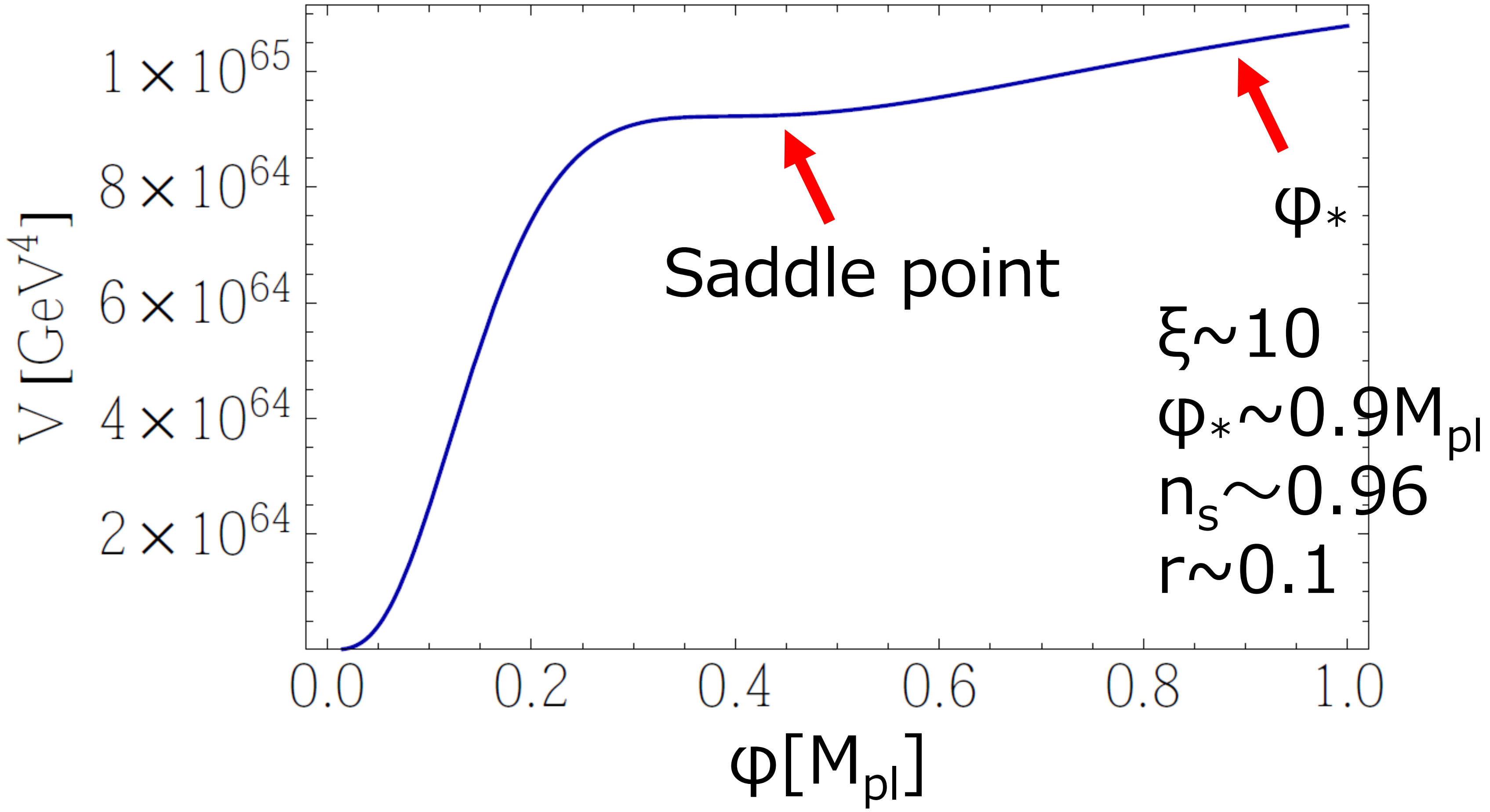
Prescription1:saddle point

- By tuning top mass, we can make saddle point without ξ.
- By adding ξ, potential becomes flat above saddle point.
  - e-folding is earned in passing the saddle point.
  - Observational density perturbation corresponds to φ_* above saddle point.

$$\mu = \frac{\varphi}{\sqrt{1+\xi\varphi^2/M_{pl}^2}}$$



Prescription1:saddle point



Prescriotion2:chaotic

- Around minimum

$$\mu = \varphi$$

$$\lambda(\mu) = \lambda_{\min} + \frac{\beta_{2\lambda}}{2}\left(\ln\frac{\mu}{\mu_{\min}}\right)^2$$

$$\beta_{2\lambda} = \frac{d\beta_\lambda}{d\ln\mu}$$

- Using canonical field in Einstein frame

$$\hat{\chi} \simeq \sqrt{6}M_{pl}\ln\frac{\varphi M_{pl}}{\sqrt{\xi}\mu_{\min}^2}$$

$$\beta_{2\lambda,\mathrm{SM}} \simeq \frac{1.2}{(16\pi^2)^2}$$

- Potential becomes

$$V = \frac{\lambda(\mu)}{4}\frac{\varphi^4}{(1+\xi\varphi^2/M_{pl}^2)^2} \simeq \frac{\lambda_{\min}M_{pl}^4}{4\xi^2} + \frac{\beta_{2\lambda}}{192\xi^2}\hat{\chi}^2$$

- Putting into SM value, if ξ~100, quadratic chaotic inflation and n_s~0.96,r~0.15

Plan

1. Higgs inflation from SM criticality
2. Z_2 scalar DM mass prediction

Z_2 scalar dark matter

- Add gauge singlet real scalar DM S.
  - Z_2 charge: SM particle is even. S is odd.

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

- S modifies β_λ. At one-loop level,

$$\beta_\lambda = \beta_{\lambda,\rm SM} + \frac{1}{16\pi^2}\frac{1}{2}\kappa^2$$

Positive contribution

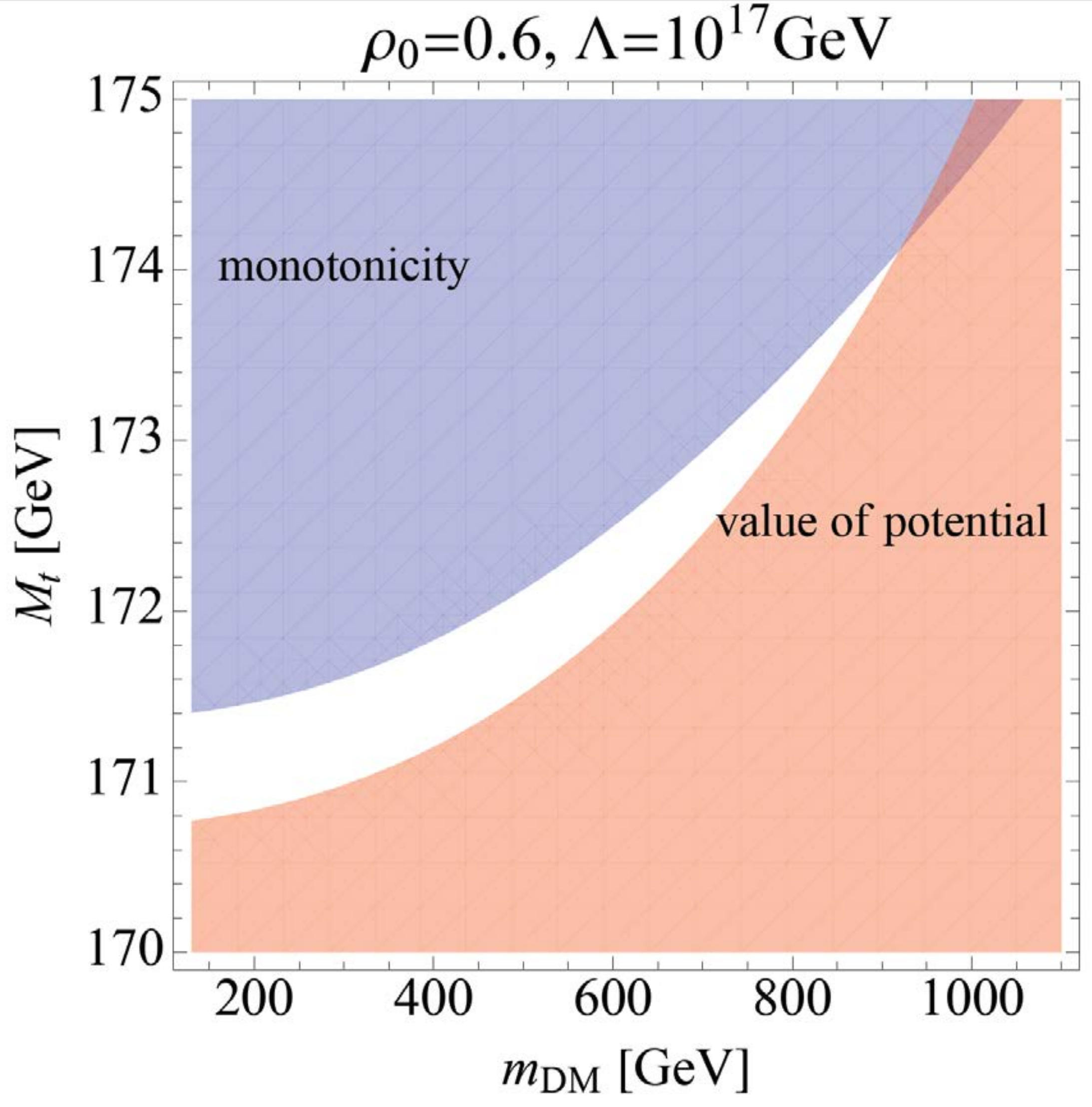
- λ is larger than λ_{SM} at high scale.

[YH,Kawai,Oda ‘14]

Constraint on m_{DM}

- m_{DM} and M_t are correlated.
- m_{DM}<1000GeV
- If we further impose saddle point at 10^{17}GeV,
  DM mass is 400~470GeV.

$\rho_0=\rho(m_{weak})$



Summary

- We consider scenario where SM is valid up to string scale$\sim 10^{17\text{-}18}$GeV.
- find SM potential is flat around $10^{17\text{-}18}$GeV.
- propose Higgs inflation scenario where $\lambda \sim \beta_\lambda \sim 0$ plays crucial role.
- In this scenario, Z_2 scalar DM mass is constrained depending on M_t.

Backup

Inflation

- Inflation solves several problems.
  - Flatness problem
  - Horizon problem
- Inflation can generate density perturbation.
  - Generate by quantum fluctuation of inflaton
  - Predictive and good agreement with observation

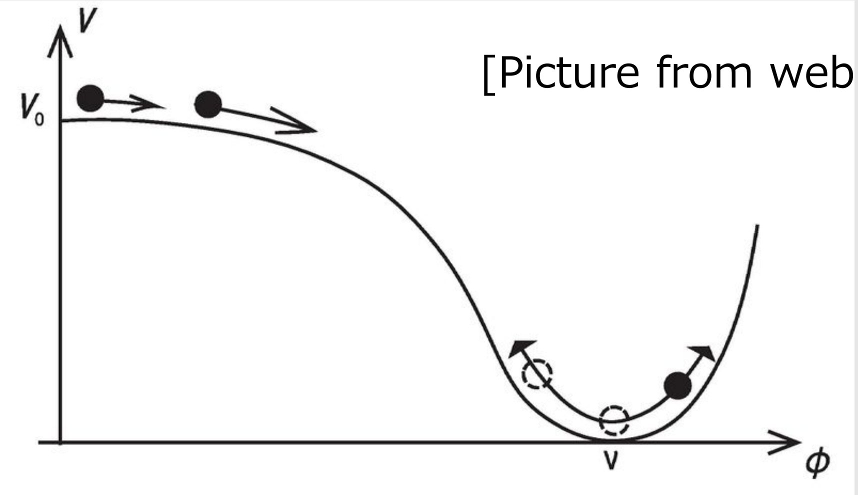
Slow roll inflation

- Flat potential realize exponential expansion.

$$ds^2 = -dt^2 + a^2(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2) \qquad H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{3M_{pl}^2}\left(\frac{1}{2}\dot{\varphi}^2 + V\right)$$

- Flatness of potential is characterized by slow roll parameters.

$$\epsilon = \frac{M_{\rm pl}^2 V_\varphi^2}{2V^2} \ll 1 \qquad \eta = \frac{M_{\rm pl}^2 V_{\varphi\varphi}}{V^2} \ll 1$$



- Expansion is given by e-foldings.

$$N_* = \int_{a_*}^{a_{\rm end}} d\ln a \simeq \frac{1}{M_{\rm pl}} \int_{\varphi_*}^{\varphi_{\rm end}} d\varphi \frac{1}{\sqrt{2\epsilon}} = 50 \sim 60$$

for successful inflation

Scalar and tensor perturbation

scalar perturbation

$$\mathcal{P}_{\mathcal{R}} = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$$

$$A_s \simeq \frac{V}{24\pi^2 M_{pl}^4 \epsilon}$$

tensor perturbation

$$\mathcal{P}_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

$$A_t \simeq \frac{2V}{3\pi^2 M_{pl}^4}$$

spectral index

$$n_s - 1 \simeq 2\eta - 6\epsilon$$

$$n_t \simeq -2\epsilon$$

tensor to scalar ratio

$$r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_{\mathcal{R}}} \simeq 16\epsilon$$

Knowing A_s(Planck) and r(BICEP2) → Inflation scale!!

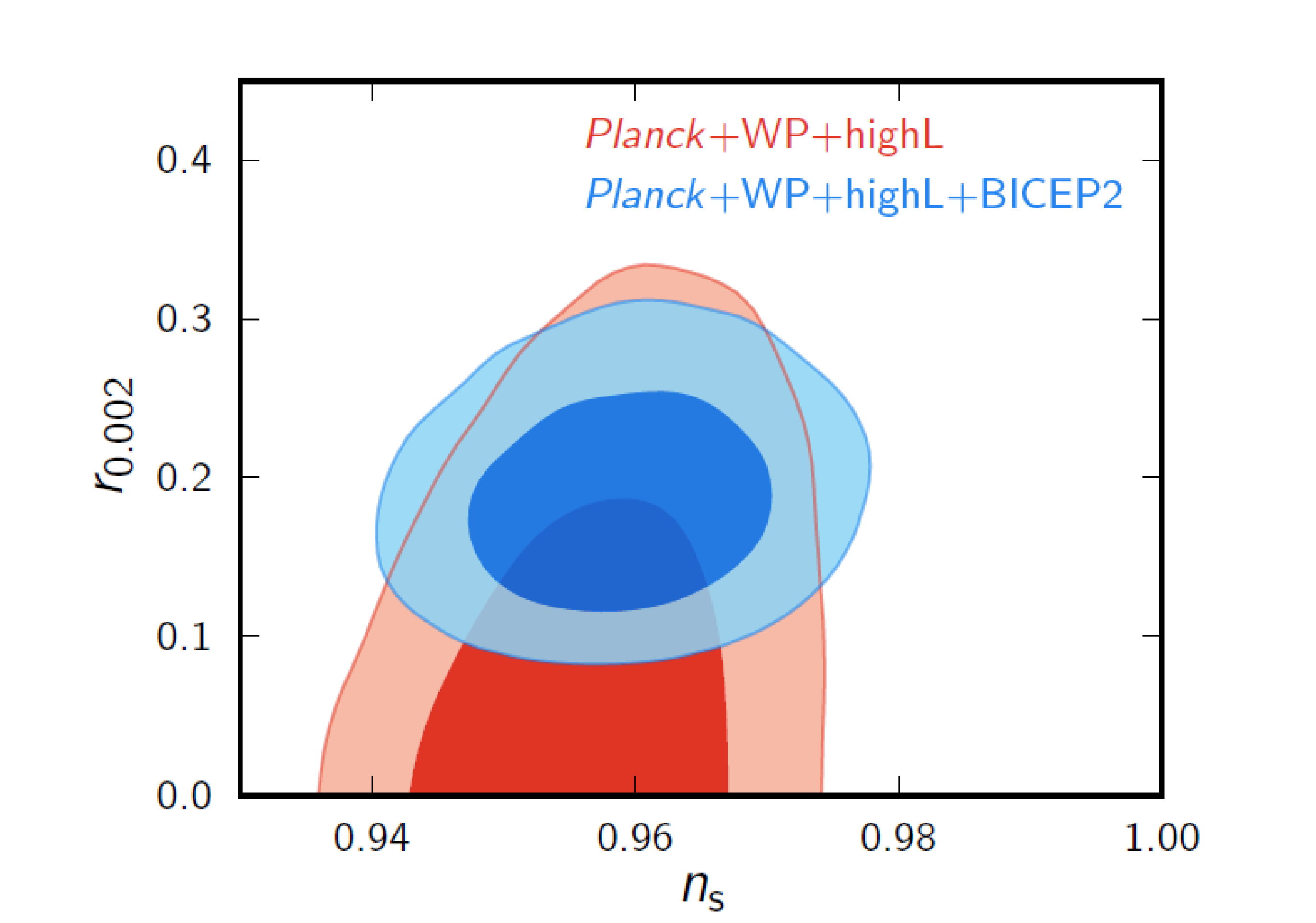
Observations

$$A_s(\exp) \simeq 2 \times 10^{-9}$$

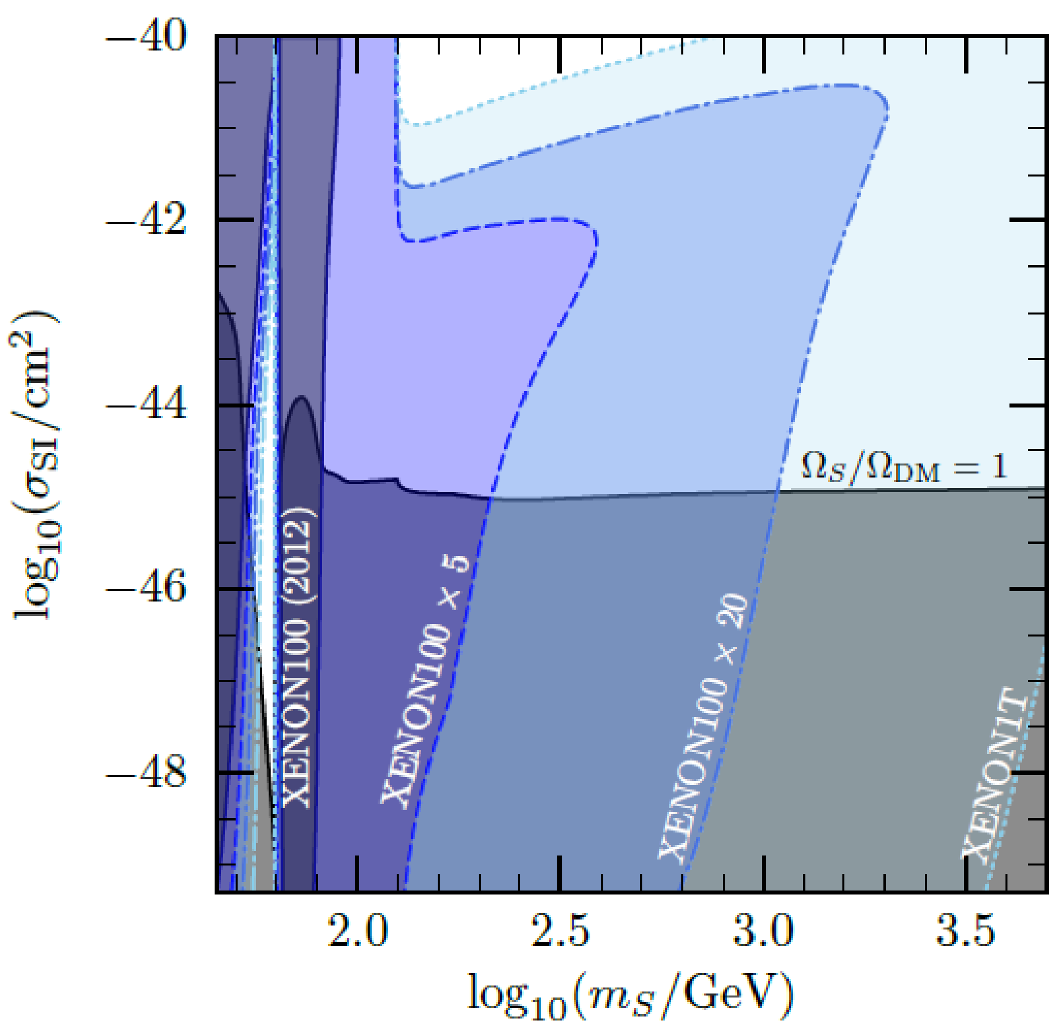
$$n_s(\exp) \simeq 0.96$$ [Planck '13]

$$r(\exp) = 0.2^{+0.07}_{-0.05}$$ [BICEP '14]

$$V_{\inf} \simeq (2 \times 10^{16}\mathrm{GeV})^4 \left(\frac{r}{0.1}\right)$$



Test



[Cline et. al. '13]

Prediction can be tested by XENON.

Einstein frame