COSMIC INFLATION

IN THE NAME OF GOD PARTICLE

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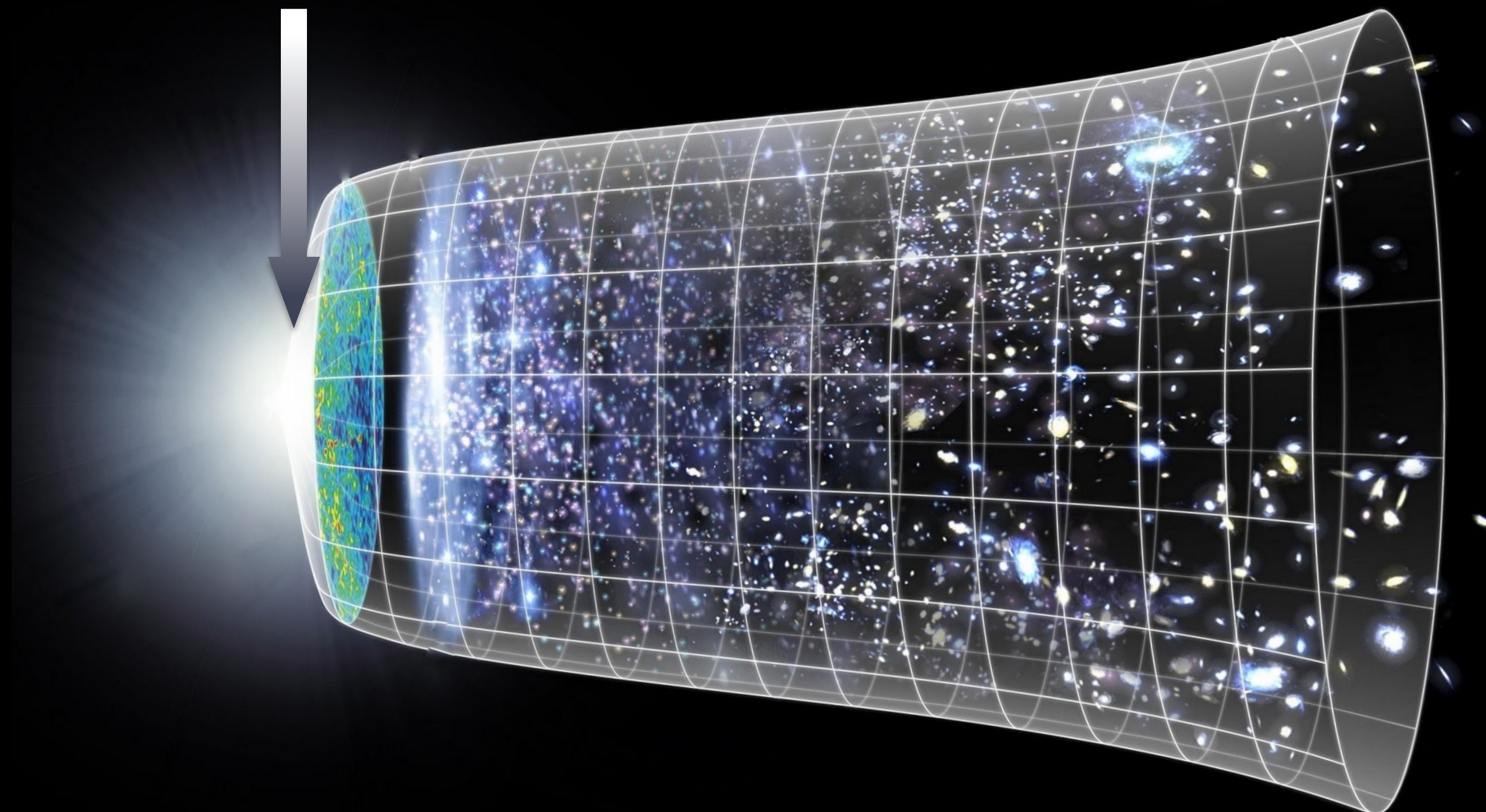
November 9, 2014

Inflation



Quantum fluctuations → Large scale structure

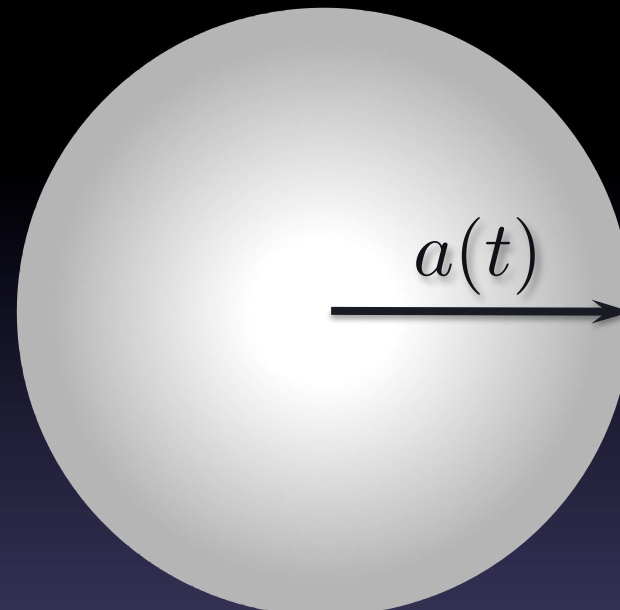
Who drives?

$$\left(\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}t}\right)^2 = \frac{8\pi G}{3}\rho(a)$$

$$a(t) \sim \exp(Ht)$$

$$\Downarrow$$

$\rho_v(a) \sim \mathrm{const.}$ $\longrightarrow$ vacuum energy



$(M_{\mathrm{P}} = 1)$

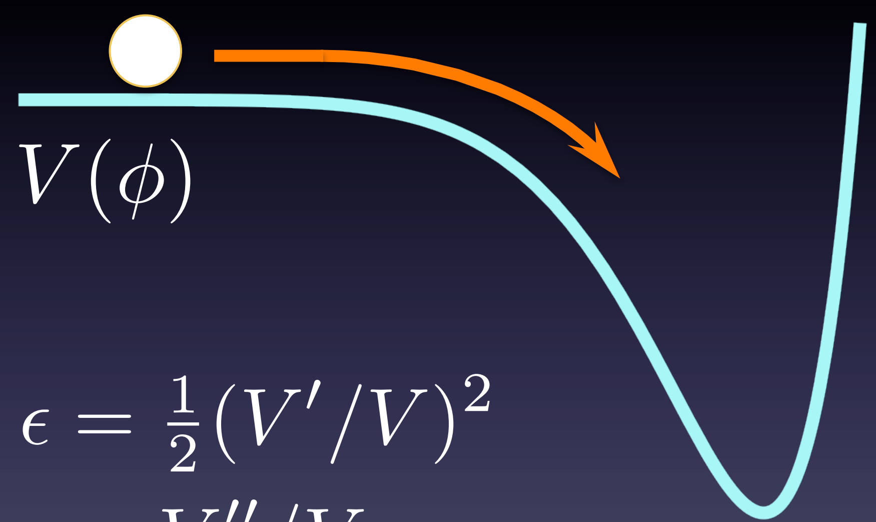
Inflaton

Scalar amplitude
$(V/\epsilon)^{1/4} \simeq 0.027$

Scalar tilt
$n_s = 1 - 6\epsilon + 2\eta$

Tensor-to-scalar ratio $r = 16\epsilon$

… and more



$\epsilon = \frac{1}{2}(V'/V)^2$

$\eta = V''/V$

$(M_{\mathrm{P}} = 1)$

Observables

Scalar amplitude

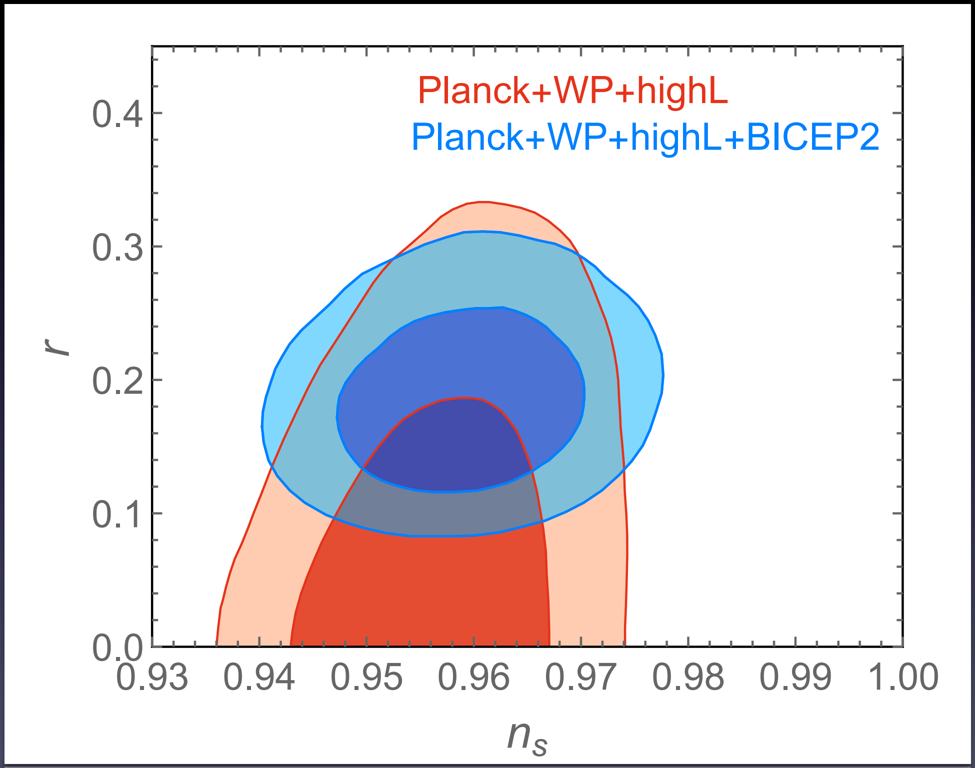
$$(V/\epsilon)^{1/4} \simeq 0.027$$

Scalar tilt

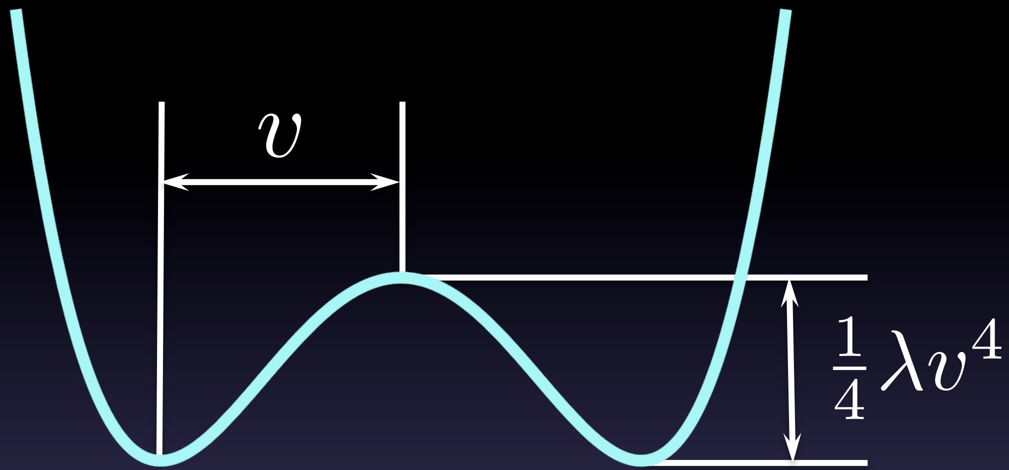
$$n_s = 1 - 6\epsilon + 2\eta$$

Tensor-to-scalar ratio $r = 16\epsilon$

… and more



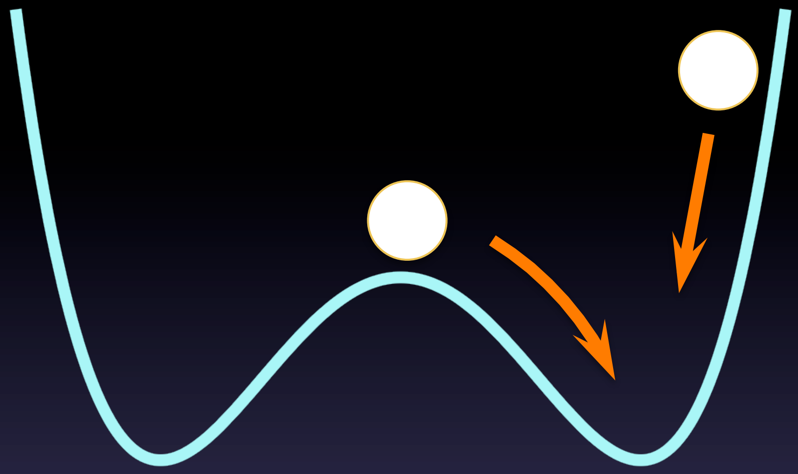
Standard Model Higgs field



$$V(\phi) = \frac{1}{4}\lambda(\phi^2 - v^2)^2$$

$$\lambda \simeq 0.13 \quad v \simeq 246\mathrm{GeV}$$

Standard Model Higgs field



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Unknown Fundamental Theory

High energy

Low energy

$$\mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{GR}}$$

Unknown Fundamental Theory

High energy

Low energy

$$\mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{GR}} + \frac{1}{2}\sqrt{-g}\,\xi R \phi^2$$

$(M_{\mathrm{P}} = 1)$

$$\frac{\mathcal{L}_{\mathrm{J}}}{\sqrt{-g}} = \frac{1}{2}R + \frac{1}{2}\xi R\phi^2 + \frac{1}{2}(\partial_\mu\phi)^2 - V(\phi)$$

$(M_{\mathrm{P}} = 1)$

$$\frac{\mathcal{L}_{\mathrm{J}}}{\sqrt{-g}} = \tfrac{1}{2}R + \tfrac{1}{2}\xi R\phi^2 + \tfrac{1}{2}(\partial_\mu\phi)^2 - V(\phi)$$

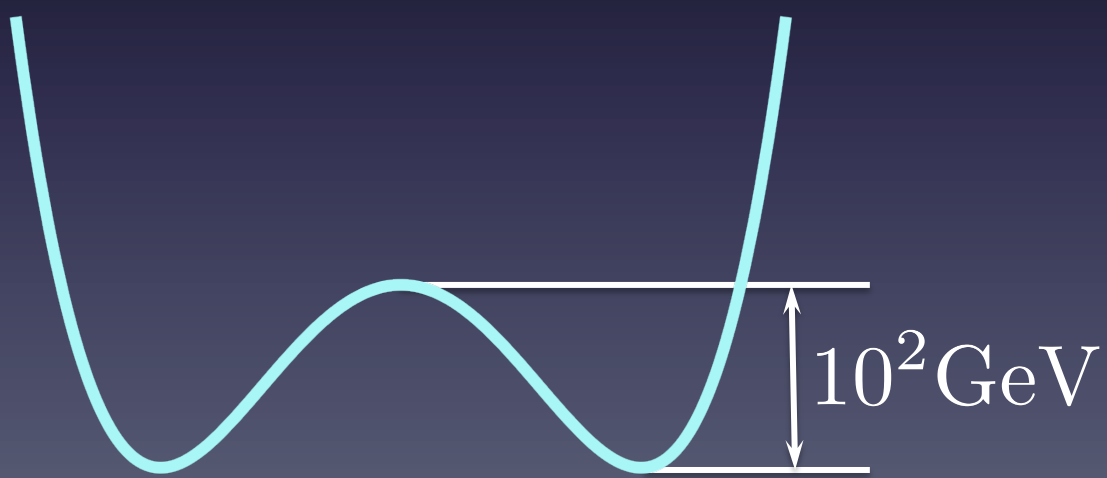
Weyl Transformation

$$g_{\mu\nu} \to \Omega^{-2} g_{\mu\nu}$$

$$\Omega^2 \equiv 1 + \xi\phi^2$$

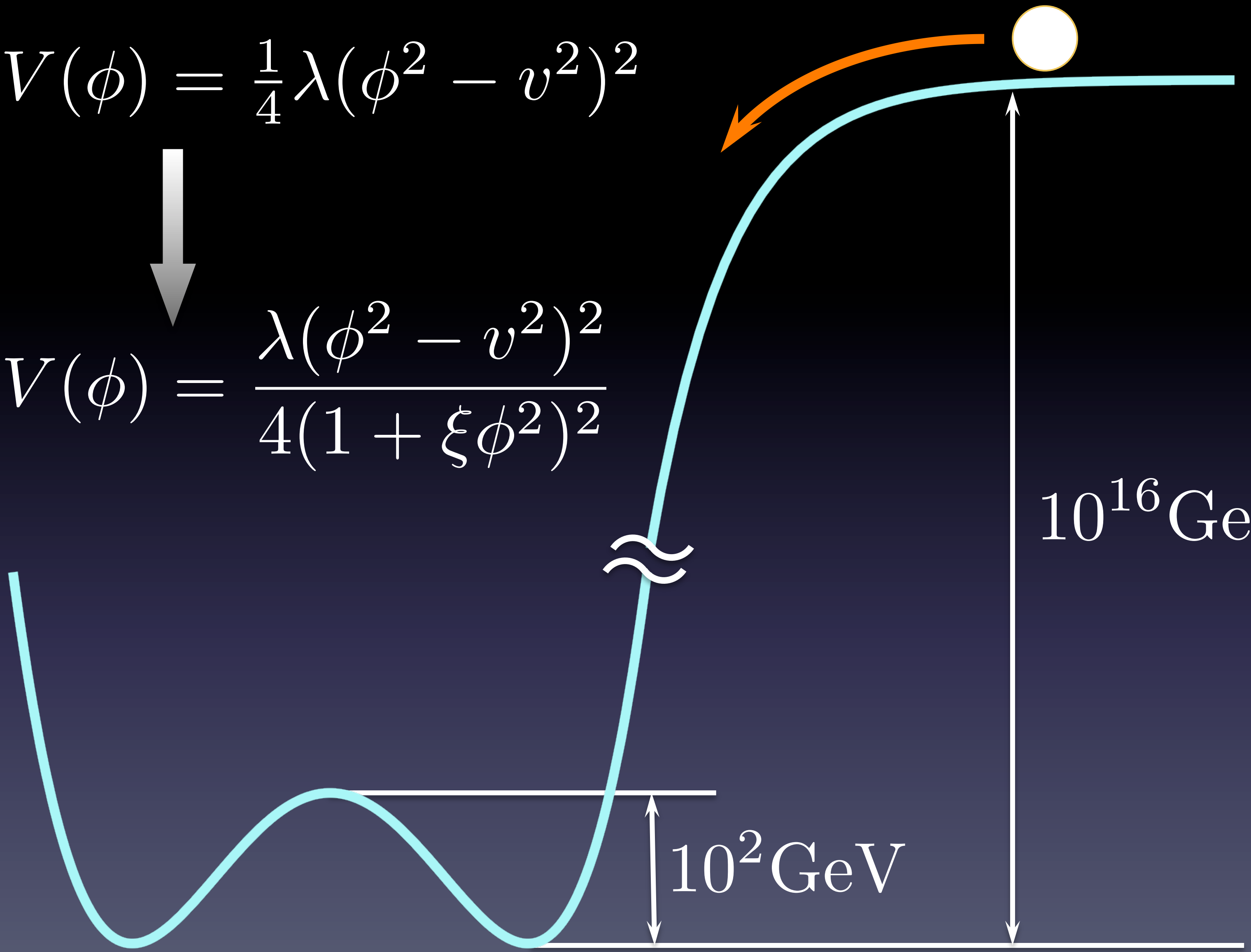
$$\frac{\mathcal{L}_{\mathrm{E}}}{\sqrt{-g}} = \tfrac{1}{2}R + \frac{3(\partial_\mu\Omega)^2}{\Omega^2} + \frac{(\partial_\mu\phi)^2}{2\Omega^2} - \frac{V(\phi)}{\Omega^4}$$

$$V(\phi) = \frac{1}{4}\lambda(\phi^2 - v^2)^2$$



$$V(\phi) = \frac{1}{4}\lambda(\phi^2 - v^2)^2$$

$$V(\phi) = \frac{\lambda(\phi^2 - v^2)^2}{4(1+\xi\phi^2)^2}$$



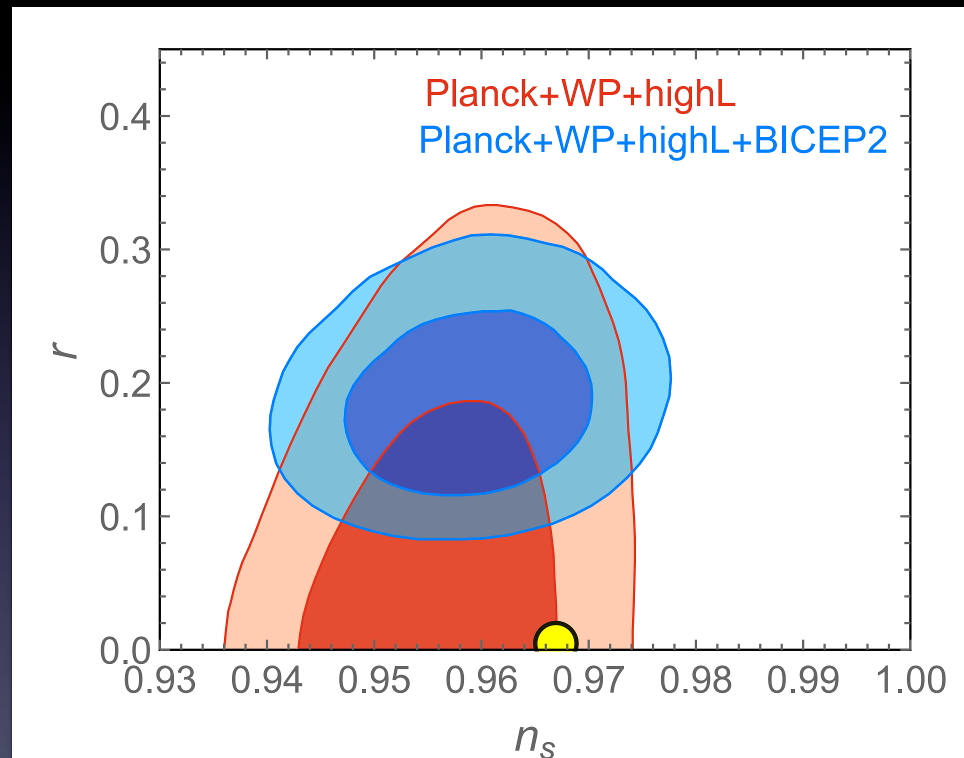
Higgs inflation

$$(V/\epsilon)^{1/4} \simeq 0.027$$

$$\xi \simeq 10^4$$

$$n_s \simeq 0.967$$

$$r \simeq 0.003$$



Is perturbation theory justified?

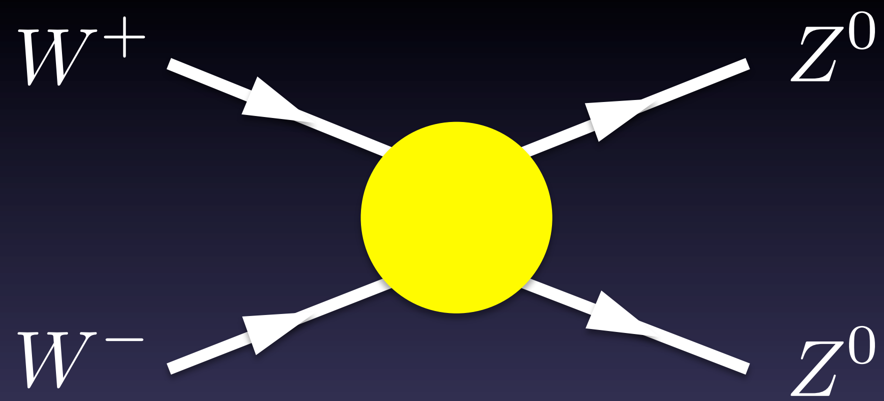
A Large $\xi \sim 10^4$ would ruin perturbation expansion

$(M_{\rm P}=1)$

Unitarity Bound for Nonminimal Coupling

ZZ Xianyu, J Ren, HJ He, Phys. Rev. D **88** (2013) 096013

Unitarity: probability ≤ 1 $\longrightarrow$ amplitude $|a_0| \leq \frac{1}{2}$



Coupled channel analysis:

$$|a_0| = \frac{9\xi^2 E^2}{16\pi} \longrightarrow |\xi| \leq \frac{\sqrt{8\pi}E}{3}$$

$(M_{\mathrm{P}} = 1)$

Unitarity of Higgs Inflation

J Ren, *ZZ Xianyu*, HJ He, JCAP **1406** (2014) 032

Generalization to arbitrary background field ϕ

$WW \to ZZ$ channel:

$$|a_0| = \frac{1+\xi\phi^2}{16\pi\phi^2}\left(1 - \frac{1-\xi\phi^2}{1+6\xi^2\phi^2}\right)E^2$$

$$\phi \ll 1/\xi \quad \Rightarrow \quad |a_0| \simeq \frac{3\xi^2 E^2}{8\pi} \quad \Rightarrow \quad E \lesssim 1/\xi$$

$$\phi \gg 1/\sqrt{\xi} \quad \Rightarrow \quad |a_0| \simeq \frac{\xi E^2}{16\pi} \quad \Rightarrow \quad E \lesssim 1/\sqrt{\xi}$$

Unitarity of Higgs Inflation

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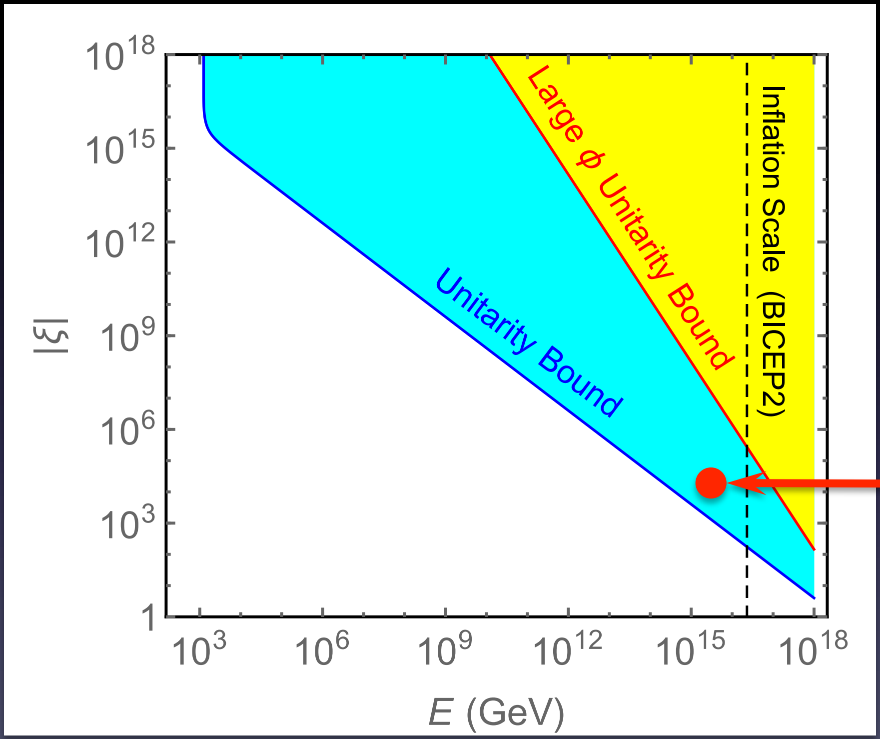

Higgs inflation

Perturbation theory validated

Then we do it order by order

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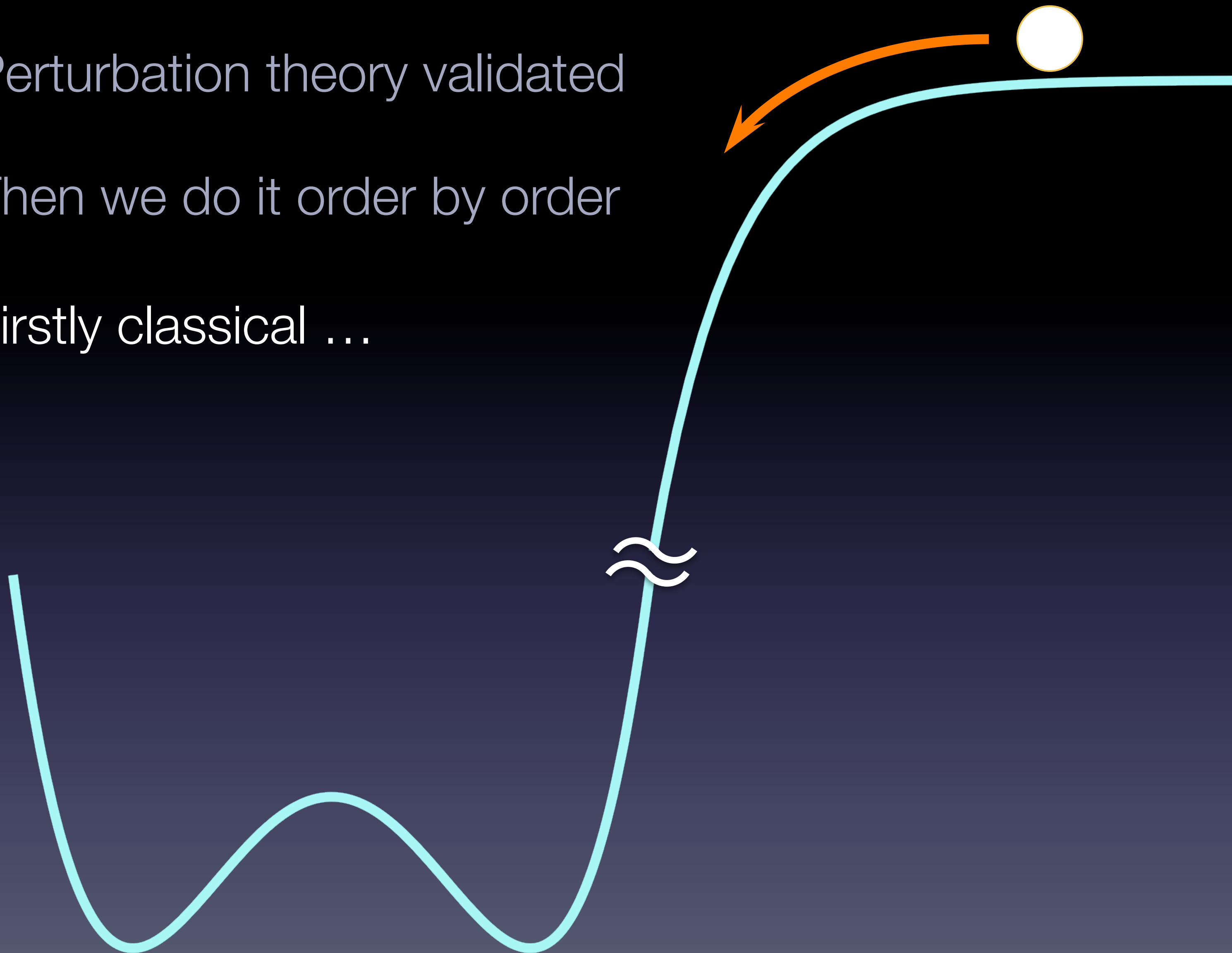
Firstly classical …

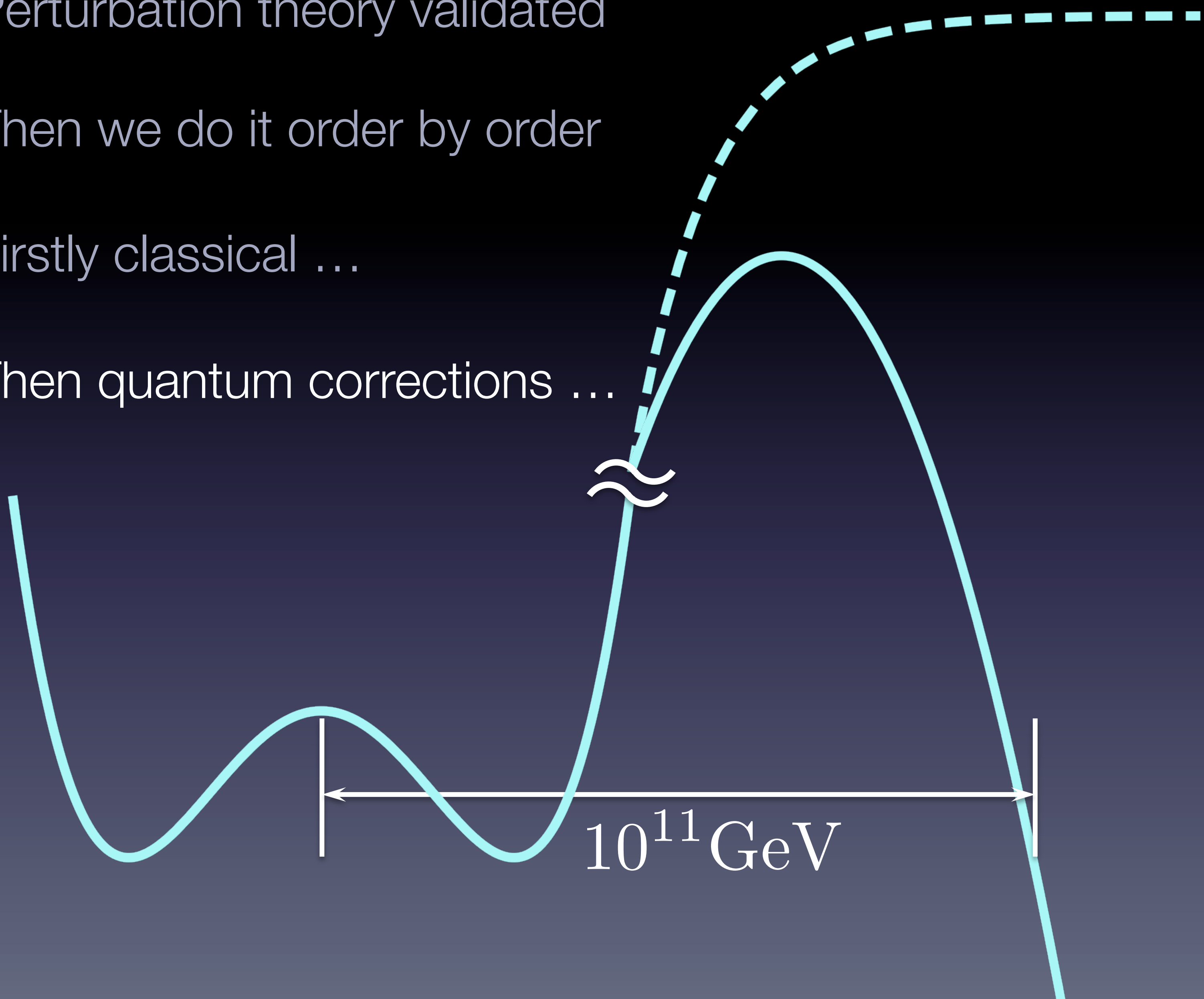


Perturbation theory validated

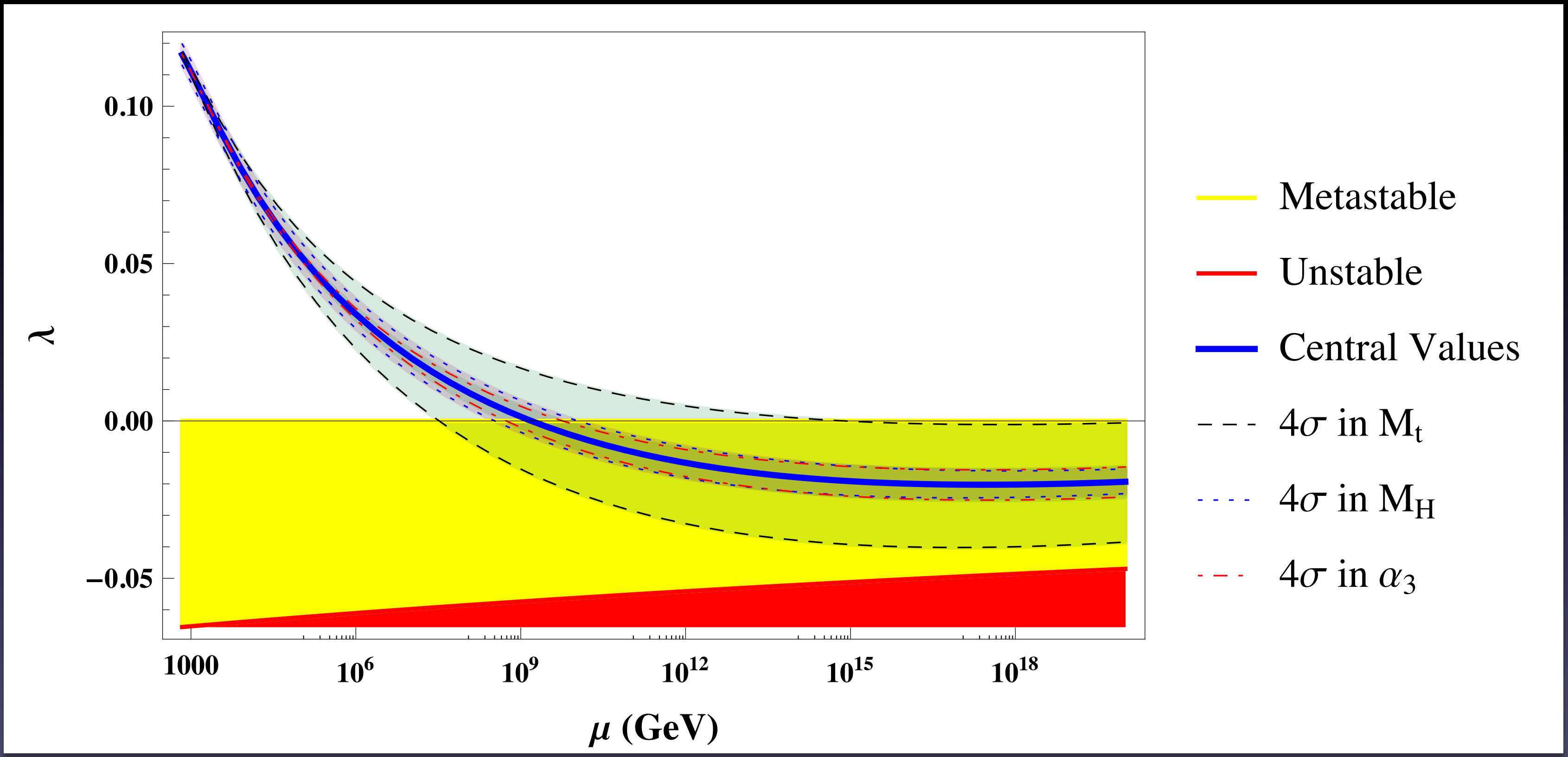
Then we do it order by order

Firstly classical …

Then quantum corrections …



Instability of Higgs potential

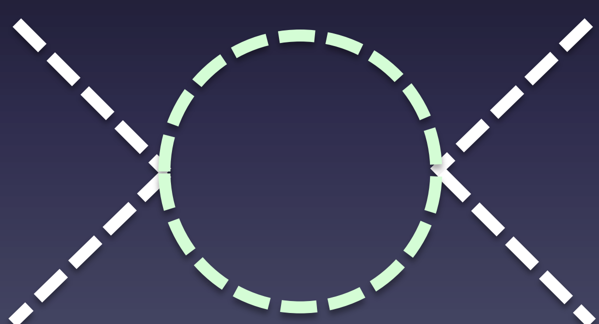


from A. Spencer-Smith, 1405.1975

Instability of Higgs potential

$$\mu \frac{\mathrm{d}\lambda}{\mathrm{d}\mu} = \frac{1}{16\pi^2}\left(24\lambda^2 - 6y_t^4 + \cdots\right)$$

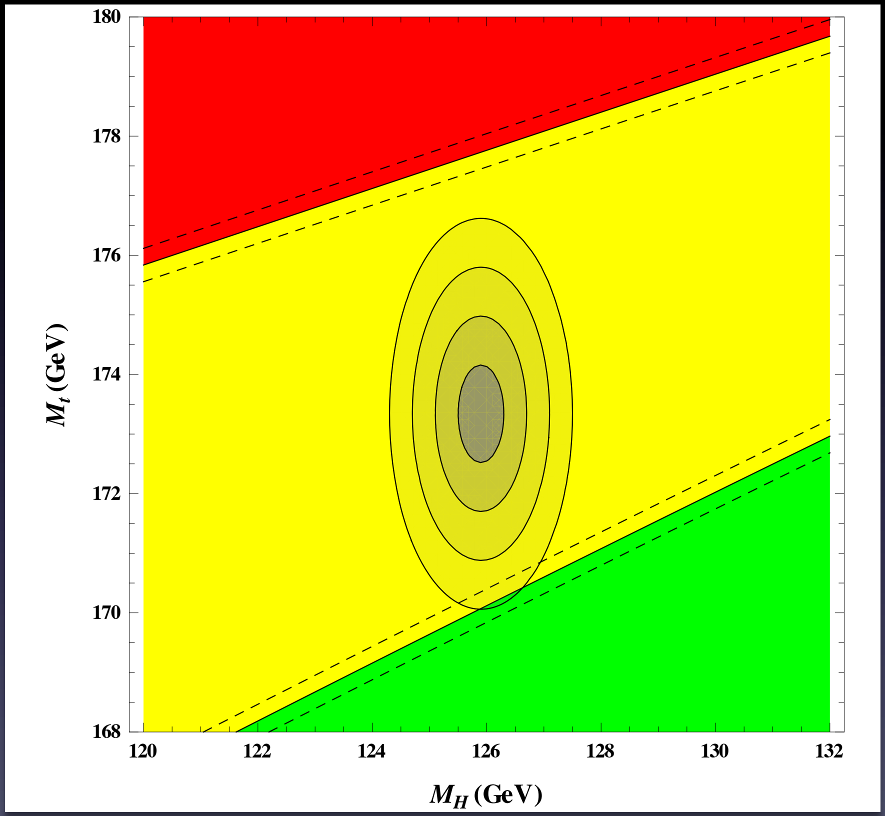
$$\lambda = \frac{M_h^2}{2v^2} \qquad y_t = \frac{M_t}{\sqrt{2}v}$$



Bosonic

Fermionic

Instability of Higgs potential



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Higgs inflation with TeV New Physics

HJ He, *ZZ Xianyu*, JCAP **1410** (2014) 019

Simplest extension: 1 boson + 1 fermion @ TeV scale

$$\begin{aligned} V(H,S) = & -\mu_1^2 H^\dagger H - \tfrac{1}{2}\mu_2^2 S^2 + \lambda_1 (H^\dagger H)^2 \\ & + \tfrac{1}{4}\lambda_2 S^4 + \tfrac{1}{2}\lambda_3 S^2 H^\dagger H + \kappa S \end{aligned}$$

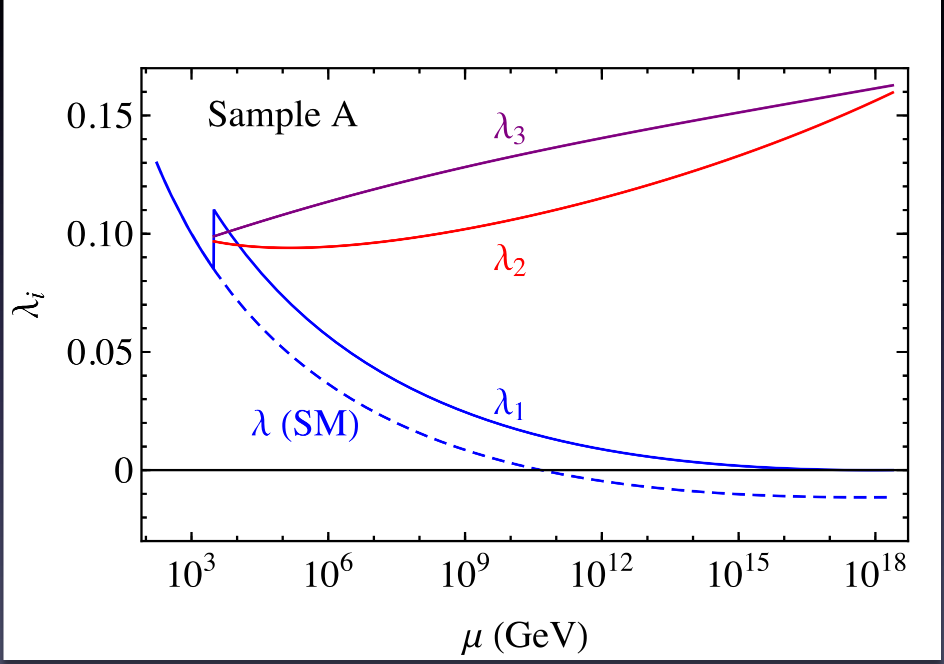
$$\begin{aligned} \mathcal{L}_Y = & - y_1 \bar{Q}_{3L} \tilde{H} t_R - y_2 \bar{Q}_{3L} \tilde{H} T_R \\ & - \frac{1}{\sqrt{2}} y_3 S \bar{T}_L T_R - \frac{1}{\sqrt{2}} y_4 S \bar{T}_L t_R + \text{h.c.} \end{aligned}$$

Higgs inflation with TeV New Physics

HJ He, *ZZ Xianyu*, JCAP **1410** (2014) 019

Simplest extension: 1 boson + 1 fermion @ TeV scale

$$\beta_{\lambda_1} = \frac{1}{16\pi^2}\Big(24\lambda_1^2 - 6y_t^4 + \tfrac{1}{2}\lambda_3 + 12\lambda_1 y_2^2 - 6y_2^4 - 12y_1^2 y_2^2 + \cdots\Big)$$



Higgs inflation with TeV New Physics

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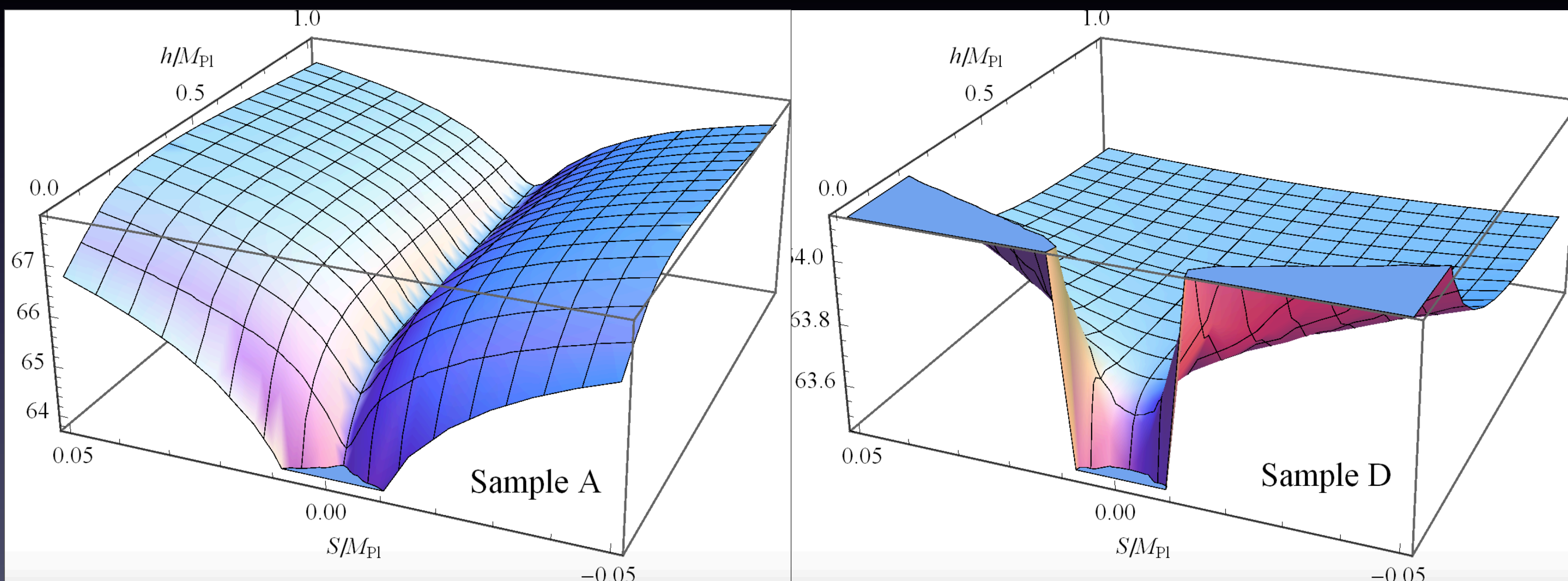
Inflation potential



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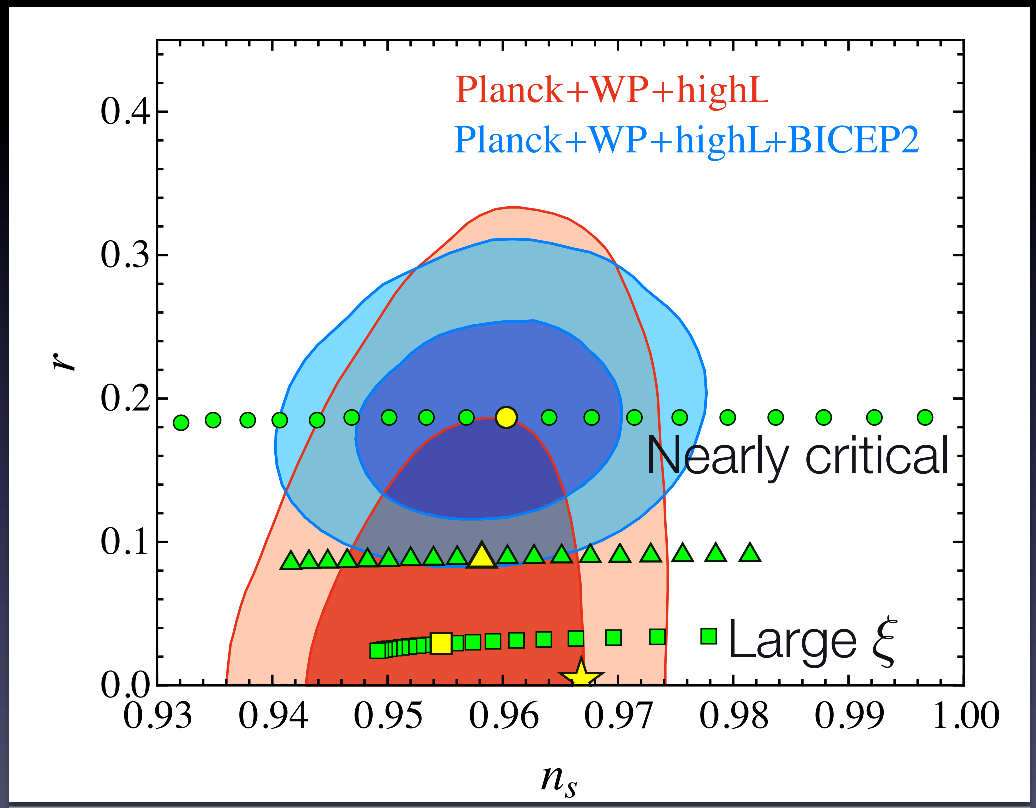
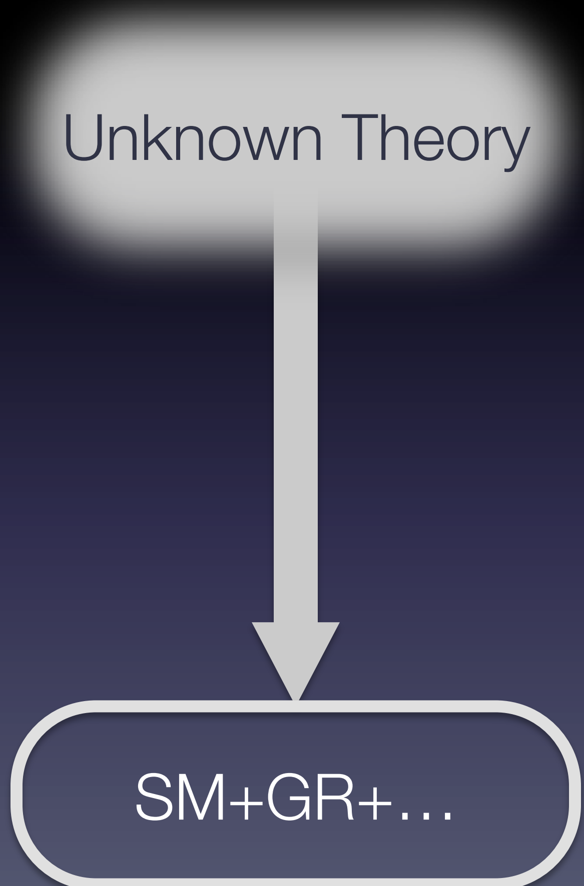


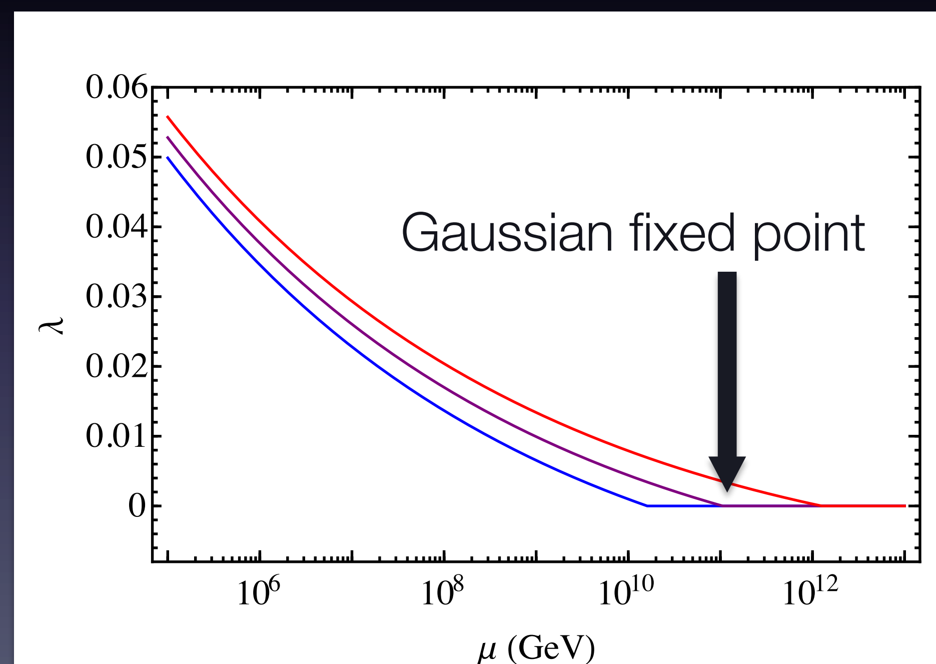
Asymptotically Safe Higgs inflation

ZZ Xianyu, HJ He, JCAP **1410** (2014) 083



Conformal field theory?

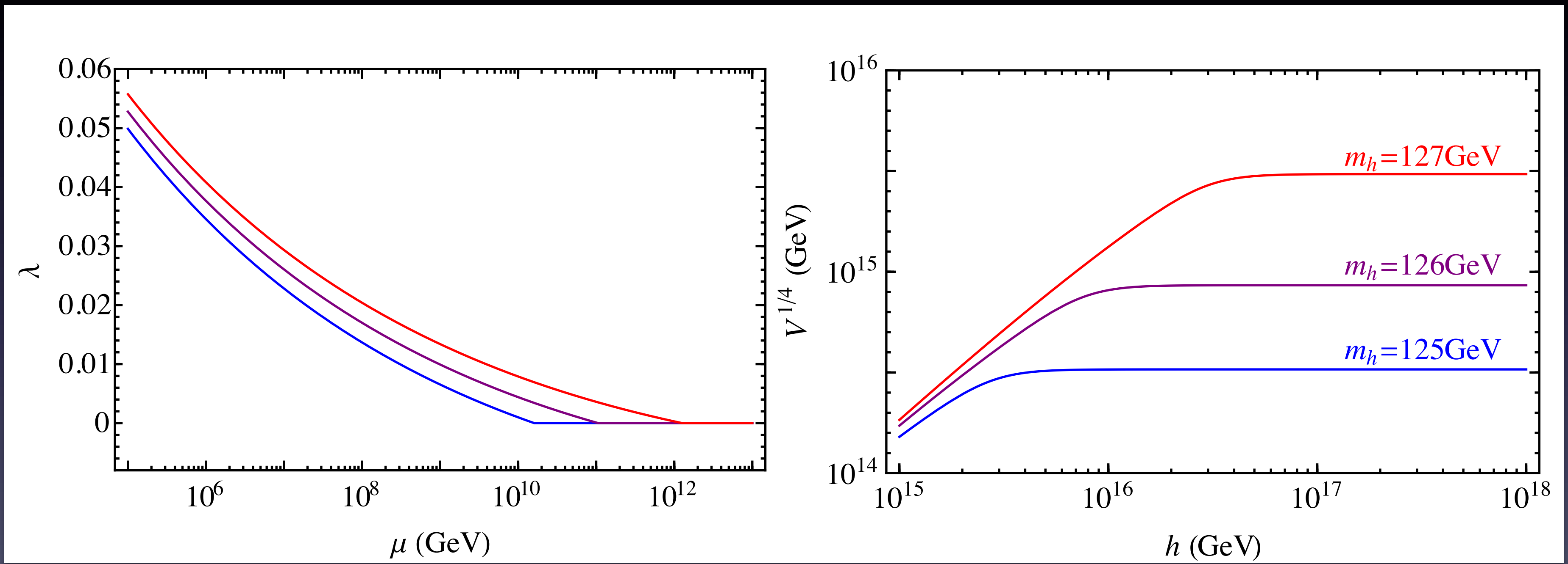
Criticality in Higgs+top sector?



Asymptotically Safe Higgs inflation

ZZ Xianyu, HJ He, JCAP **1410** (2014) 083

$$3M_P^2(H)H^2 = V = \frac{1}{4}\lambda(H)\phi^4$$ – minimally coupled



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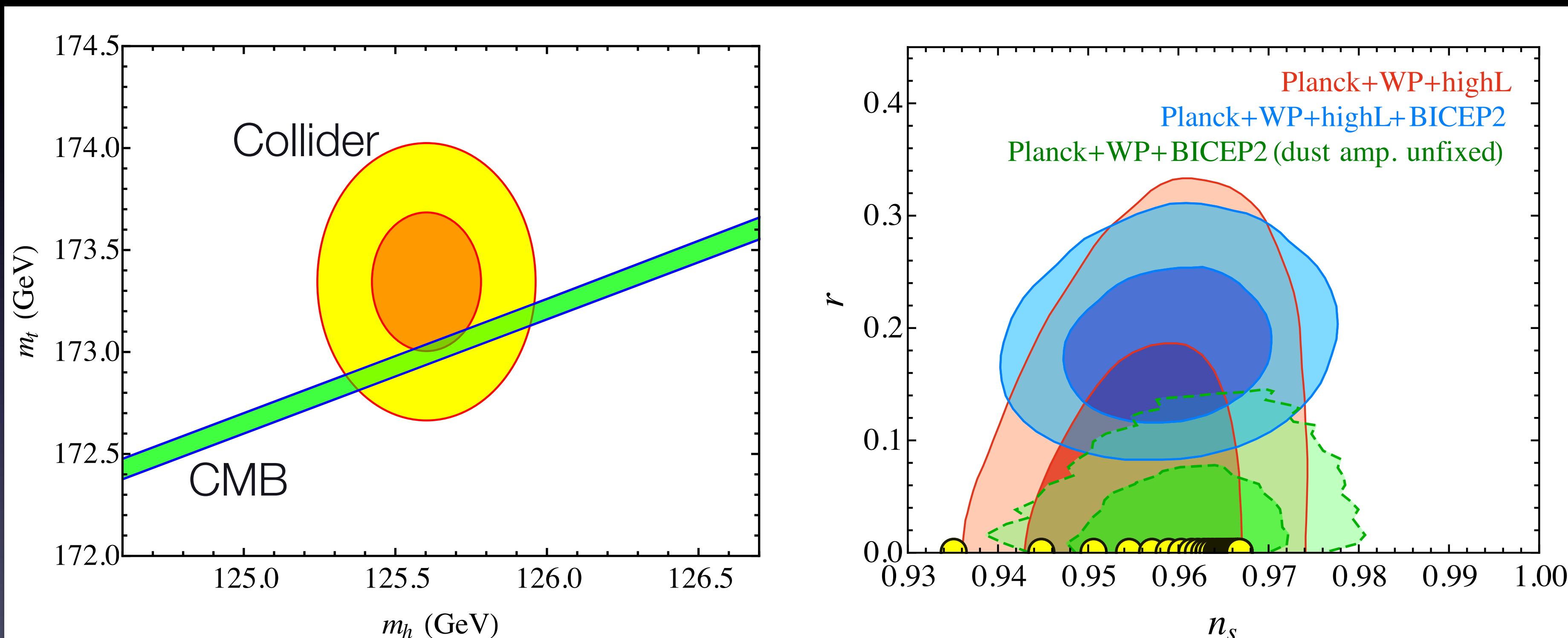

Outlook

- (In)equivalence of Jordan and Einstein frame at quantum level?
- Higgs inflation in more complete new physics models. Supersymmetry? Supergravity?
- Enhanced tensor-to-scalar ratio without critical point (fine-tuning)?

Thank you