Hunting Inflaton at FASER

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Ref: NO & Raut, arXiv: 1910.09663

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1. Inflationary Universe

- Standard paradigm in modern cosmology
  - Solving Horizon & Flatness problems
  - Generating primordial density fluctuations

- Slow-roll inflation
  - A simple viable model
  - A scalar field (``inflaton’’) with a flat potential
  - Constraints from CMB data (Planck 2018)

Non-minimal Quartic Inflation: simple & successful scenario

Action in Jordan Frame

See, for example,
NO, Rehman & Shafi, PRD 82 (2010) 04352

$$\boxed{\mathcal{S}_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}f(\phi)\mathcal{R} + \frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V_J(\phi)\right]},$$

- Non-minimal gravitational coupling

$\boxed{f(\phi) = (1+\xi\phi^2)}$ with a real parameter $\xi > 0$,

- Quartic coupling dominates during inflation

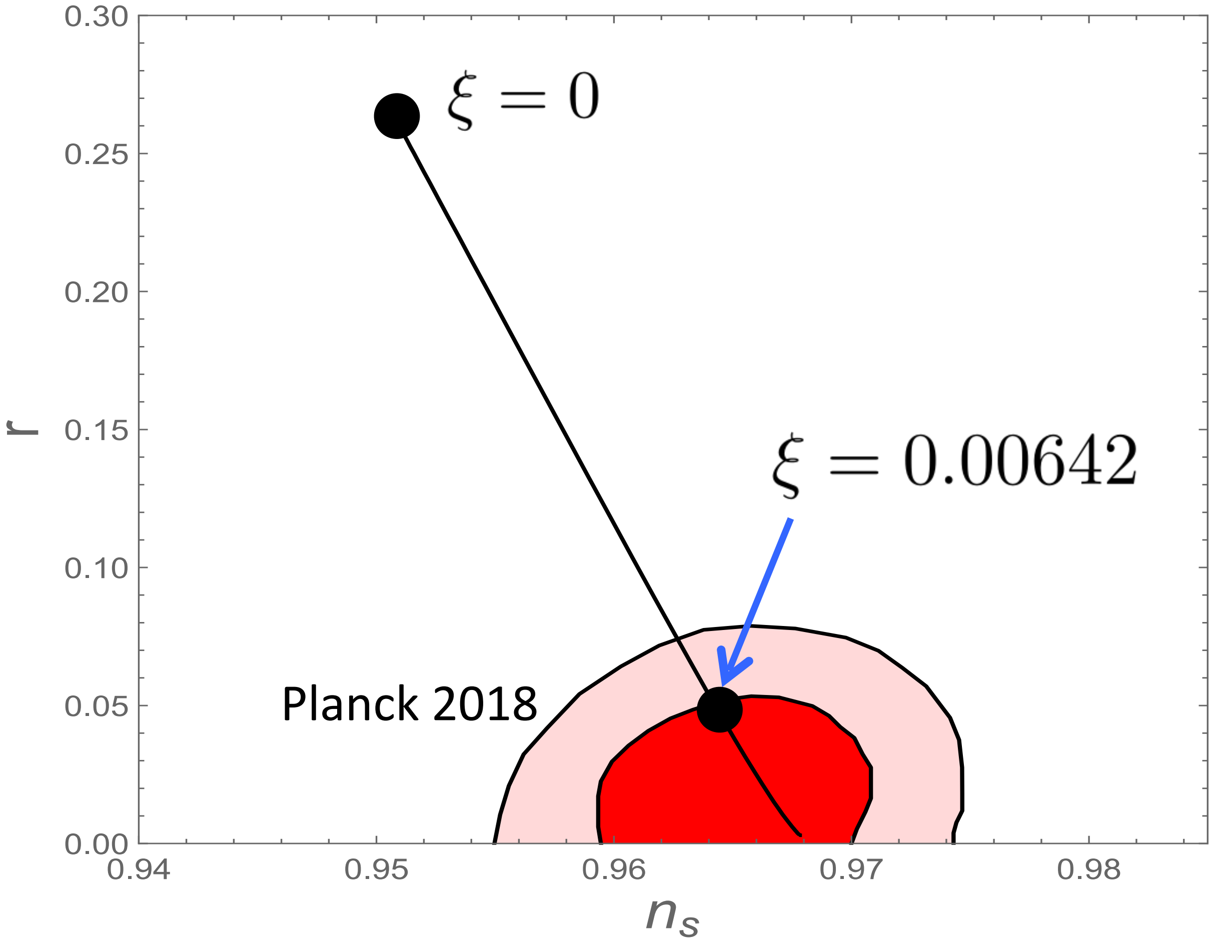
$$\boxed{V_J(\phi) = \frac{1}{4}\lambda\phi^4}$$

Inflationary Predictions VS Planck 2018 results

Spectral index: $n_s = 1 - 6\epsilon + 2\eta,$

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

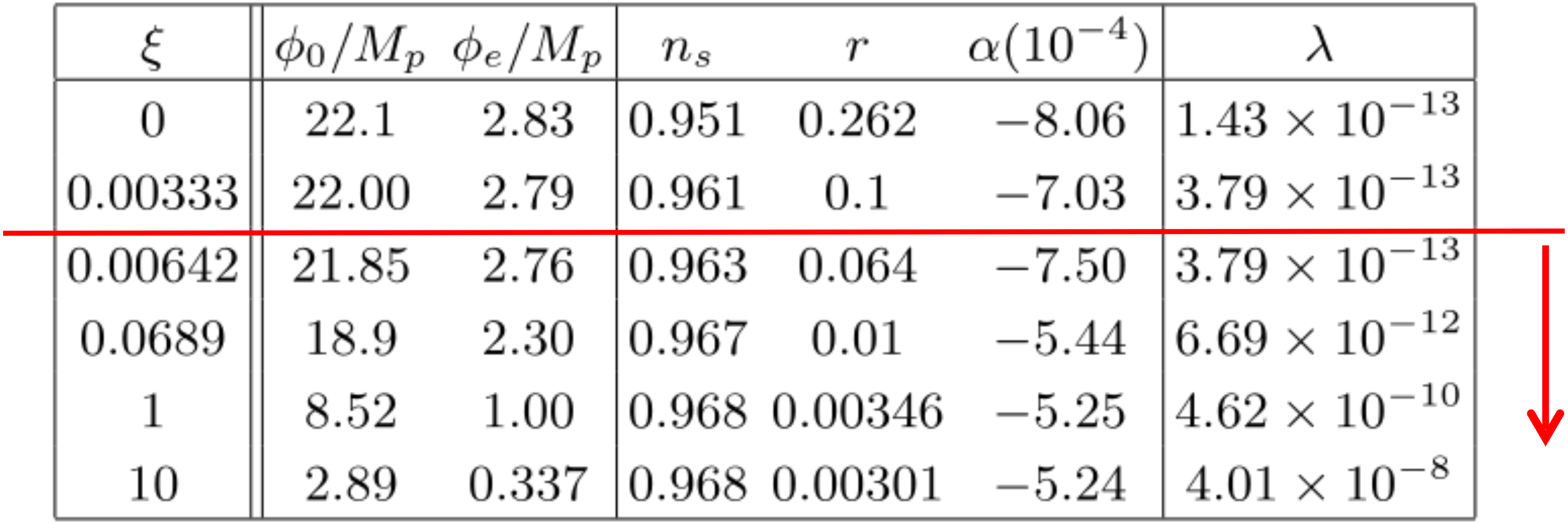
Running spectral index: $\alpha = 16\epsilon\eta - 24\epsilon^2 - 2\zeta$



$$\Delta^2_{\mathcal{R}} = 2.099 \times 10^{-9}$$

$$k_0 = 0.05 \text{ Mpc}^{-1}$$

Inflationary Predictions VS Planck 2018 results



ξ	ϕ_0/M_p	ϕ_e/M_p	n_s	r	$\alpha(10^{-4})$	λ
0	22.1	2.83	0.951	0.262	-8.06	1.43×10^{-13}
0.00333	22.00	2.79	0.961	0.1	-7.03	3.79×10^{-13}
0.00642	21.85	2.76	0.963	0.064	-7.50	3.79×10^{-13}
0.0689	18.9	2.30	0.967	0.01	-5.44	6.69×10^{-12}
1	8.52	1.00	0.968	0.00346	-5.25	4.62×10^{-10}
10	2.89	0.337	0.968	0.00301	-5.24	4.01×10^{-8}

Non-minimal quartic inflation

- Controlled by only one free parameter ξ
- Consistent with Planck 2018 dta for $\xi \geq 0.00642$
- Any scalars with a quartic potential term can be inflaton

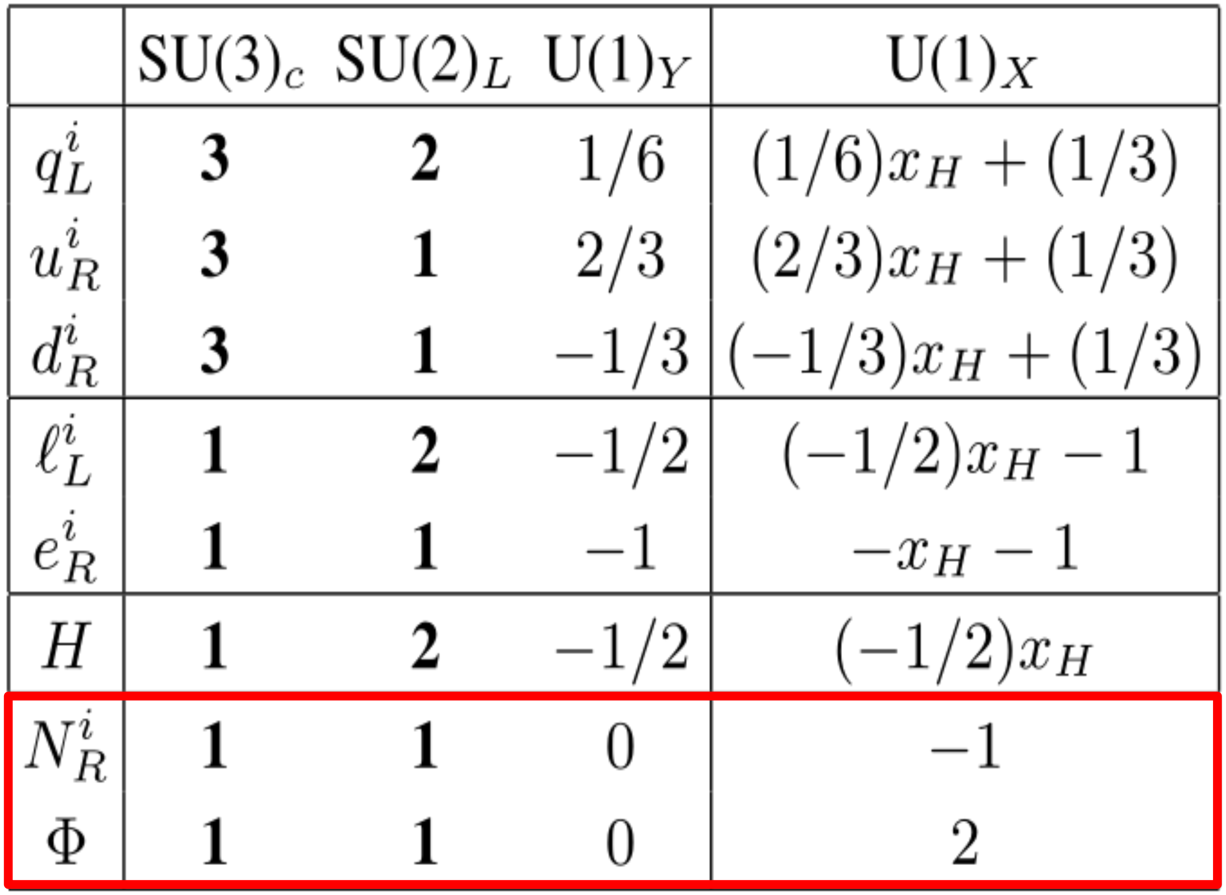
Open Question

- Can inflaton play another important role in physics?

We consider a scenario in which inflaton is identified with a Higgs field in New Physics Models

2. Classically Conformal U(1)x extended SM

Generalization of the minimal B-L model



	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
q_L^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$
u_R^i	**3**	**1**	$2/3$	$(2/3)x_H + (1/3)$
d_R^i	**3**	**1**	$-1/3$	$(-1/3)x_H + (1/3)$
ℓ_L^i	**1**	**2**	$-1/2$	$(-1/2)x_H - 1$
e_R^i	**1**	**1**	-1	$-x_H - 1$
H	**1**	**2**	$-1/2$	$(-1/2)x_H$
N_R^i	**1**	**1**	0	-1
Φ	**1**	**1**	0	2

3 RHNs

U(1)x Higgs

- U(1)x charge: $Q_X = Q_Y x_H + Q_{B-L}$ (xH=0 is the B-L model)
- Anomaly free
- Seesaw Mechanism is automatically implemented

Higgs sector with classical conformal invariance

$$\boxed{V = \lambda_H \left(H^\dagger H\right)^2 + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 - \lambda_{\rm mix} \left(H^\dagger H\right)\left(\Phi^\dagger \Phi\right)}$$

- No mass term
- We set $\lambda_{H,\Phi,{\rm mix}} > 0$
- No symmetry breaking at the tree-level

Assuming a small mixing quartic coupling, the symmetry breaking occurs in the following way………

1st: Radiative U(1) symmetry breaking by Colemen-Weinberg mechanism

1-loop effective Coleman-Weinberg potential

$$\boxed{V(\phi) = \frac{\lambda_\Phi}{4}\phi^4 + \frac{\beta_\Phi}{8}\phi^4\left(\ln\left[\frac{\phi^2}{v_X^2}\right] - \frac{25}{6}\right),}$$

where $\phi = \sqrt{2}\Re[\Phi]$,

$$\boxed{16\pi^2\beta_\Phi \simeq 96\, g_X^4}$$

* Here, we set Majorana Yukawa being smaller than the gauge coupling, for simplicity.

Stationary condition relates quartic coupling to gauge coupling

$$dV/d\phi\big|_{\phi=v_X} = 0 \;\rightarrow\; \boxed{\overline{\lambda_\Phi} = \frac{11}{6}\overline{\beta_\Phi} \simeq 176\,\overline{\alpha_X}^4}$$

U(1)x Higgs mass relates to gauge coupling & Z’ mass

$$m_\phi^2 = \left.\frac{d^2V}{d\phi^2}\right|_{\phi=v_X} = \overline{\beta_\Phi}\,v_X^2 \simeq \boxed{\frac{6}{\pi}\overline{\alpha_X}\,m_{Z'}^2}$$

Here, barred quantities are evaluated at VEV

$$\overline{\alpha_X} = \frac{\overline{g_X}^2}{4\pi}$$

$$m_{Z'} = 2\overline{g_X}\,v_X$$

2nd: Radiative U(1) breaking triggers the EW symmetry breaking

Iso, NO & Orikasa,
PLB 676 (2009) 81

$$V \supset -\lambda_{\rm mix}\left(\Phi^\dagger\Phi\right)\left(H^\dagger H\right)+\lambda_H\left(H^\dagger H\right)^2$$

$$\rightarrow -\boxed{\lambda_{\rm mix}\langle\Phi^\dagger\Phi\rangle}\left(H^\dagger H\right)+\lambda_H\left(H^\dagger H\right)^2$$

Negative mass squared generated!

Higgs mass relations

$$\boxed{m_h^2=\lambda_{\rm mix}v_X^2=2\lambda_H v_h^2}$$

$$\boxed{\mathcal{L}\supset-\frac{1}{2}\begin{bmatrix}h & \phi\end{bmatrix}\begin{bmatrix}m_h^2 & \lambda_{\rm mix}v_X v_h\\ \lambda_{\rm mix}v_X v_h & m_\phi^2\end{bmatrix}\begin{bmatrix}h\\ \phi\end{bmatrix}}$$

* mh=125 GeV, vh=246 GeV

Diagonalizing the scalar mass matrix

$$\boxed{\begin{bmatrix} h \\ \phi \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \tilde{h} \\ \tilde{\phi} \end{bmatrix}}$$

Here, we consider a very light U(1)x Higgs boson

$$m_\phi^2 \ll m_h^2 \text{ and } \lambda_{\text{mix}} \ll 1$$

$$\rightarrow \quad \boxed{\theta \simeq \frac{v_h}{v_X} = \frac{\sqrt{16\pi\overline{\alpha_X}}\, v_h}{m_{Z'}} \ll 1}$$

In Classically Conformal U(1)x extended SM,

$\boxed{m_\phi, \ \theta}$ are determined by $\boxed{\overline{\alpha_X}, \ m_{Z'}}$

3. Search for Inflaton at FASER

- Now we identify the U(1)x Higgs as inflaton in Non-minimal U(1)x Inflation

  - From the structure of non-minimal quartic inflation,

    All parameters are fixed

    Once $\boxed{\xi}$ is fixed → $\boxed{\begin{array}{l}\phi_0,\ \lambda_\Phi(\mu=\phi_0),\\ n_s,\ r,\ \alpha\end{array}}$

  - From the structure of the CW mechanism,

    $\boxed{m_\phi,\ \theta}$ are determined by $\boxed{\overline{\alpha_X},\ m_{Z'}}$

RG evolutions connect $\lambda_\Phi(\mu = \phi_0)$ and $\overline{\alpha_X}$

$$\frac{d\lambda_\Phi}{d\ln\phi} = \beta_\lambda \simeq 96\alpha_X^2$$

$$\frac{d\alpha_X}{d\ln\phi} = \beta_g = \frac{72 + 64x_H + 41x_H^2}{12\pi}\alpha_X^2$$

* For small gauge coupling values, we find the result is almost independent of xH.

Therefore, once $\boxed{\xi}$ is fixed

$\boxed{m_\phi, \ \theta}$ are determined by only $\boxed{m_{Z'}}$

FASER Search for Dark Scalar

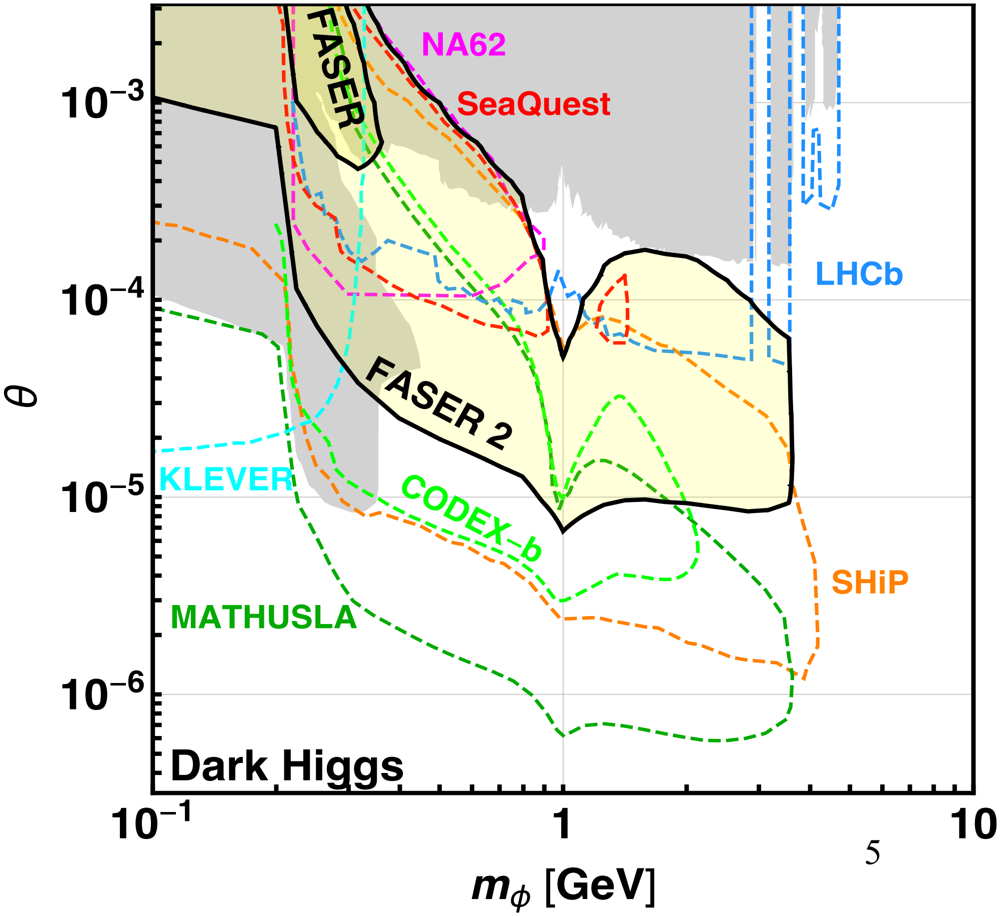
Upcoming FASER experiment will search for a light ``Dark Scalar'' mainly produced from rare B-meson decays through the mixing with the SM Higgs boson

- FASER at LHC Run-3
- FASER-2 at HL-LHC

$$\begin{bmatrix} h \\ \phi \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \tilde{h} \\ \tilde{\phi} \end{bmatrix}$$

* Gray shaded region is already excluded by CHRAM, Belle & LHCb

arXiv: 1811. 12522



★ The U(1)x Higgs/Inflaton in the classically conformal U(1)x extended SM can be search for by the FASER & other Lifetime Frontier experiments!

★ Crucial point is that we have a connection among FASER search region, Inflationary predictions & Z’-boson search

m_ϕ, θ : Lifetime Frontier Exps. Search region

↕

$\alpha_X, m_{Z'}$: Z’ boson resonance search

↕

ξ : Inflationary predictions

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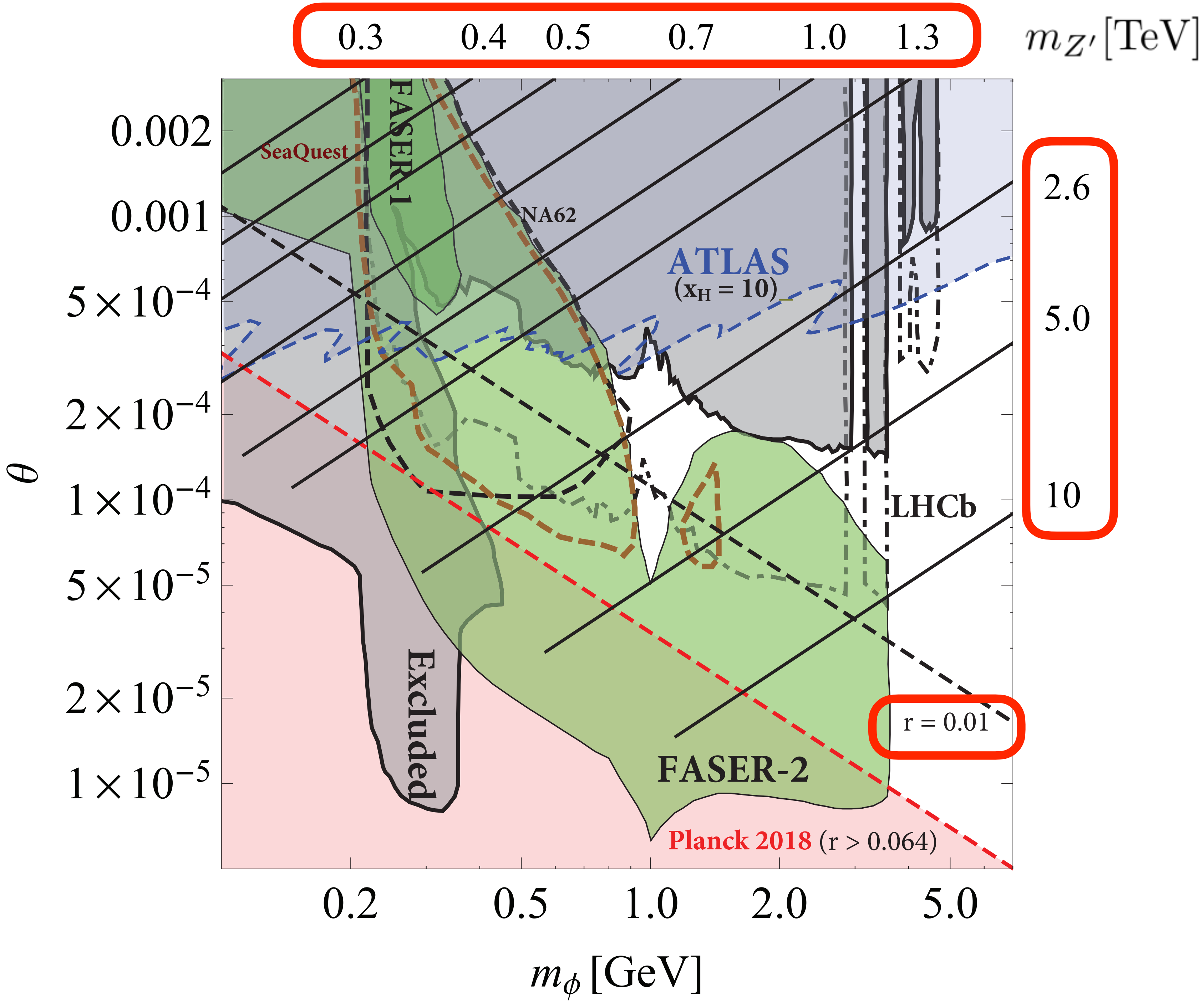
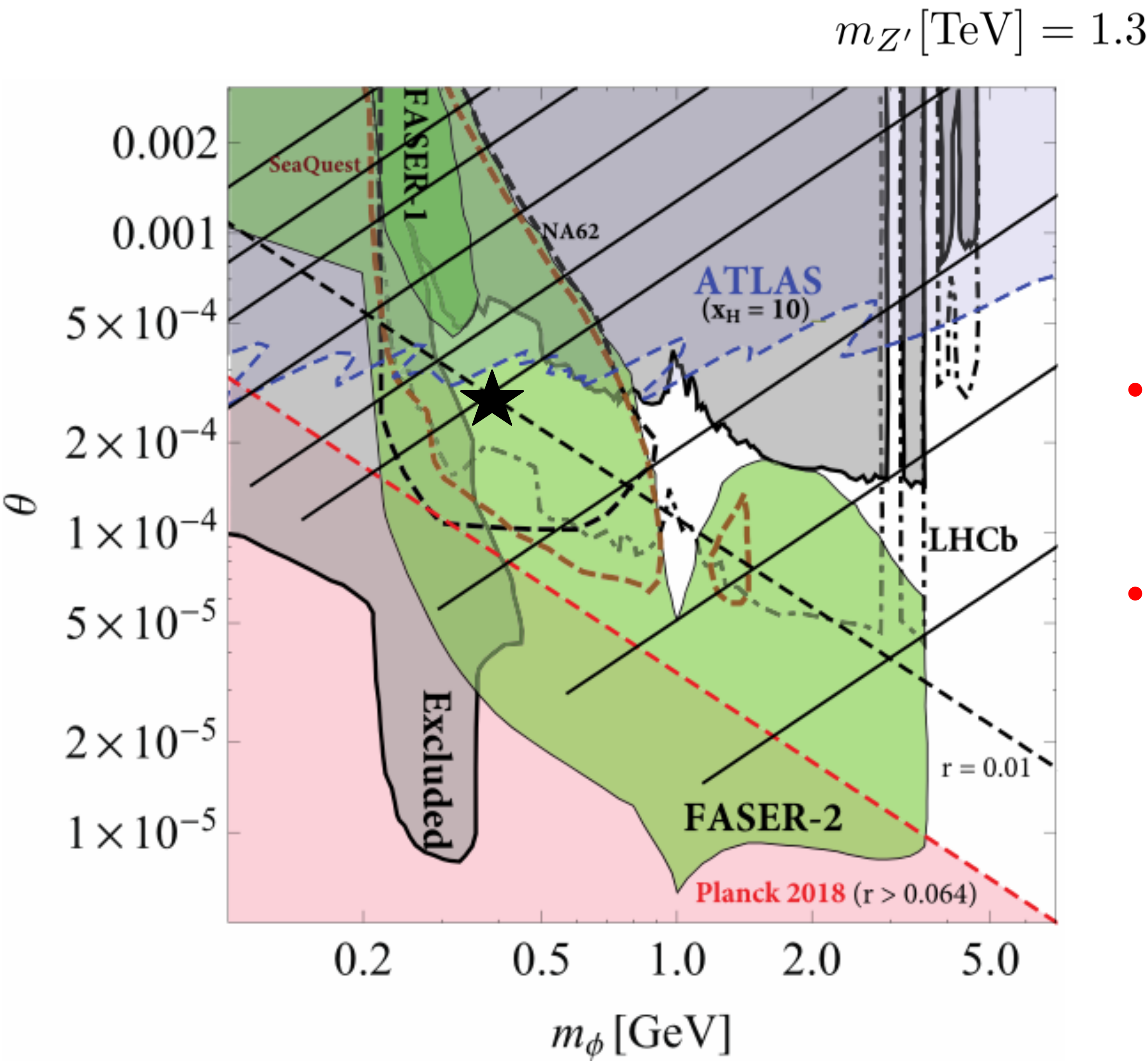


Best case scenario (discovery)



Cross checked by

- Future CMB measurements
- Z' resonance search at HL-LHC

4. Summary

- We have considered the non-minimal quartic inflation scenario in the minimal U(1)x extended SM with classical conformal invariance

- Inflaton is identified with the U(1)x Higgs

- The recently approved FASER can search for the inflaton

- By virtue of the classical conformal invariance & the radiative U(1)x symmetry breaking by the Coleman-Weinberg mechanism, the inflaton search by FASER, Z' boson resonance search at the LHC, and the future measurement of CMB anisotropy are complementary to test this scenario