Hunting Inflaton at FASER

Digesh Raut

draut@udel.edu

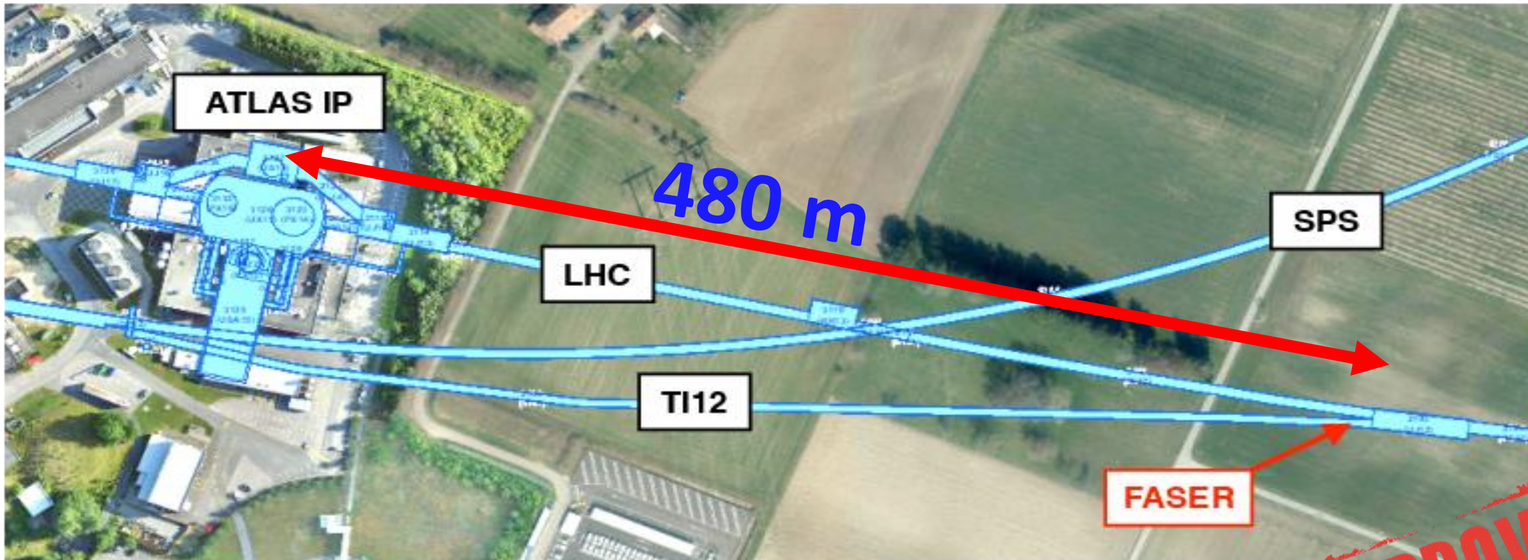
University of Delaware

arXiv:2002.07110

A work in collaboration with
Nobuchika Okada (University of Alabama)

Forward Physics Facility - Kickoff Meeting
Nov 9-10, 2020

FASER- Forward Search Experiment at LHC



FASER specializes in search for

- **A Light,**
- **Weakly Interacting,**
- **Electrically Neutral,**
- **Long-lived Particle.**

Possible New Light Physics from Beyond the Standard Model accessible to FASER:

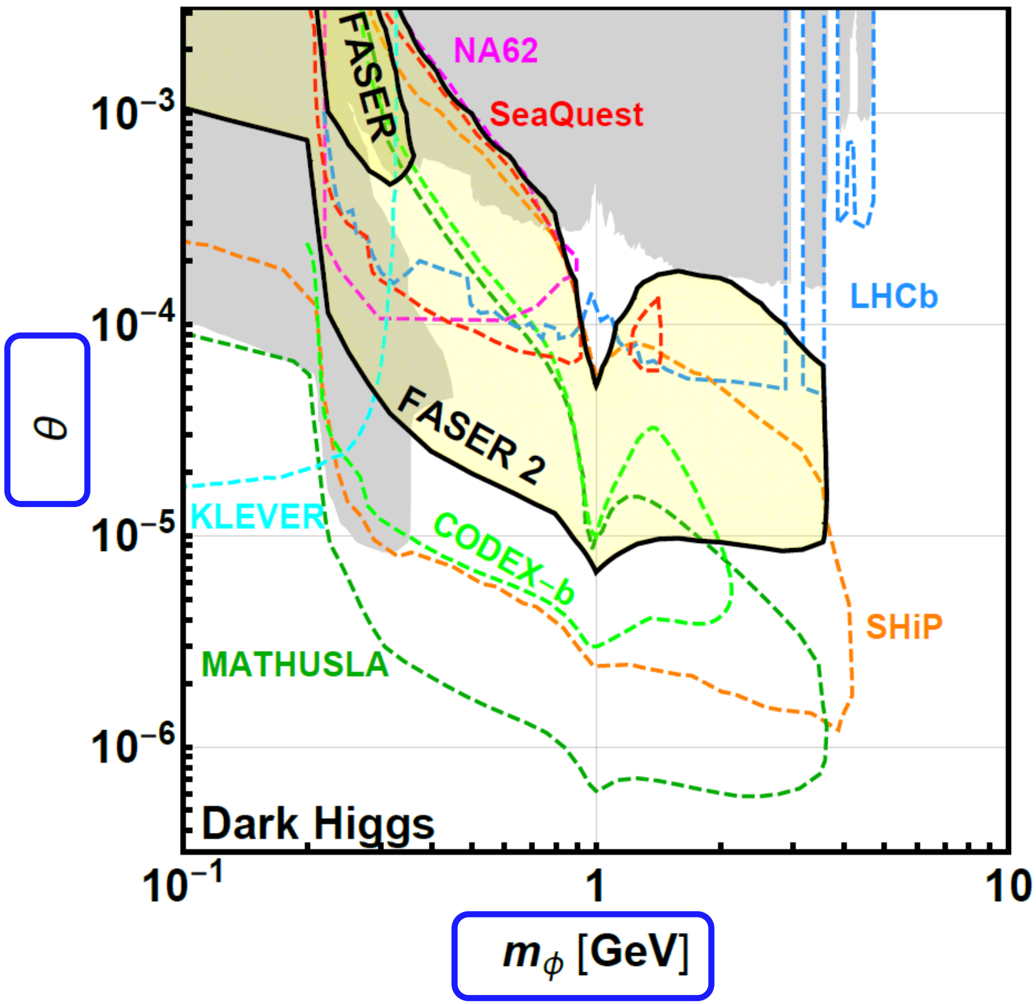
- Dark New Vector Bosons
- Dark Scalars
- Pseudo-Scalars (Axion-Like Particles)
- Dark Pseudo-Scalars
- Neutral Leptons

arXiv: 1811.12522

(I) FASER Search for Dark Higgs

FASER : LHC RUN-3
FASER2 : HL-LHC

arXiv: 1811.12522



Scalar/Higgs Mixing

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

Flavor Basis — **Mass Basis**

Gray Shaded Region Excluded by CHARM, Belle and LHCb Experiments

OUR WORK:

Dark Higgs ⟷ Inflaton

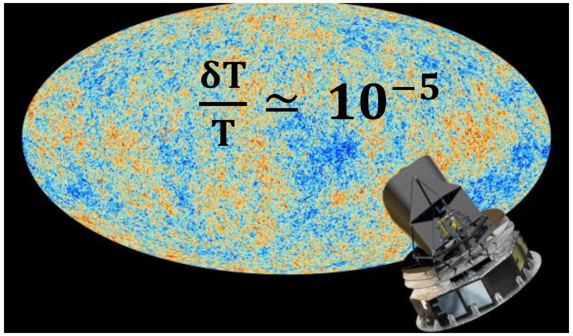
(II) Cosmological Inflation

Rapid Accelerated Expansion of Early Universe

Solves Three Major Cosmic Puzzles:

Alan H. Guth
Phys. Rev. D 23, 347

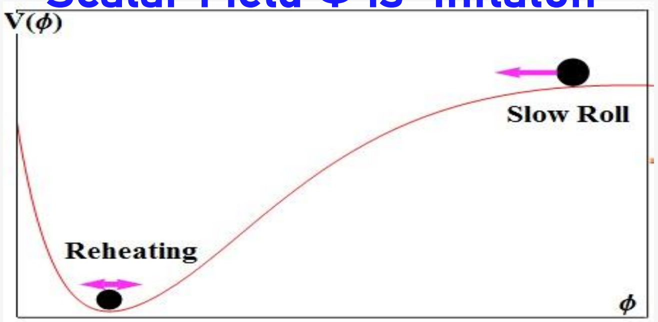
- Flatness of the Universe
- Uniformity of Cosmic Microwave Background
- Explains the origin of these "tiny" fluctuation which are essential to produce the large scale structures we see today!



Slow-roll Inflation

- Universe expand when "inflaton" slowly rolls down its "flat" potential.
- Inflation decays and reheats the universe (Big Bang Nucleosynthesis)

Scalar Field Φ is "Inflaton"



Q. What is the connection between inflation and particle physics?

Non-Minimal Inflation Scenario

D. S. Salopek, J. R. Bond, and J. M. Bardeen, Phys. Rev. D 40, 1753

Action:

$$\mathcal{S}_J = \int \mathrm{d}^4x \sqrt{-g} \left[-\frac{1}{2} f(\phi)\mathcal{R} - \frac{1}{2}(\nabla\phi)^2 - V_J(\phi) \right]$$

Non-Minimal Gravitational Coupling: $f(\phi) = 1 + \xi\,\phi^2$ $\quad \xi > 0$

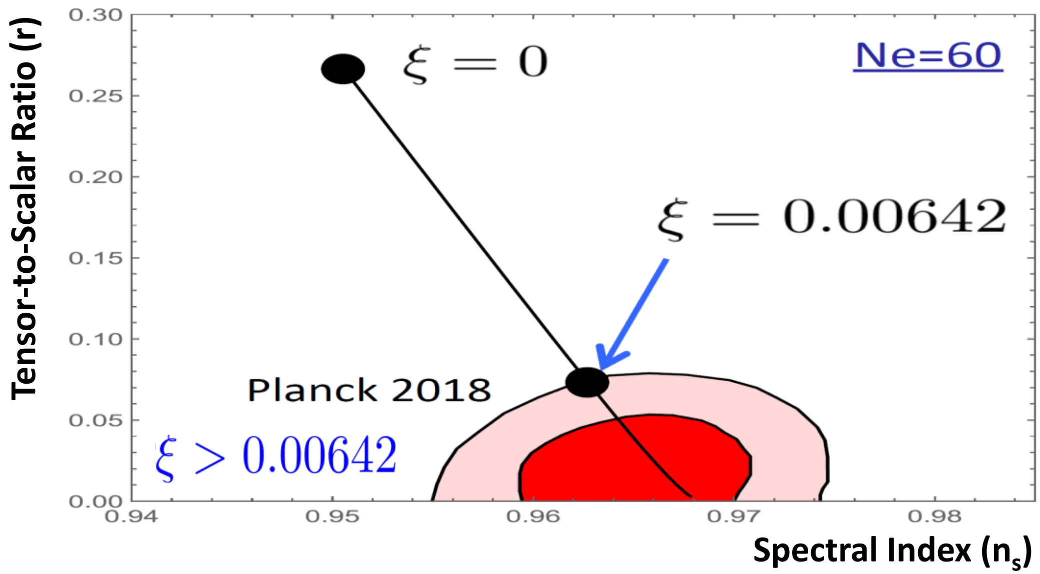
Inflationary Predictions: Uniquely Determined by ξ

Inflaton Potential

$$V_J = \frac{\lambda}{4}\phi^4$$

$$\lambda \leftrightarrow \xi$$

One-to-One



(III) Classical Conformal $U(1)_X$ Extended SM

S. Oda, N. Okada, and D. s. Takahashi, [arXiv:1504.06291 [hep-ph]]

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
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

Scalar Field Φ is "Inflaton"

Z' is the $U(1)_X$ gauge boson

$$Q_X = Q_Y x_H + Q_{B-L}$$

- ❑ x_H is a free parameter
- ❑ B-L Limit: $(x_H \to 0)$

S. Oda, N. Okada and D. s. Takahashi, [arXiv:1504.06291 [hep-ph]]

Scalar Potential

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

- **Classical Conformal Invariance Forbids Mass Terms**
- **Electroweak Symmetry Breaking induced by Φ VEV**

CW Inflaton Potential

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

$$\beta_\Phi \simeq \frac{1}{16\pi^2}\left(96 g_X^4 - 3 Y_M^4\right)$$

$$\langle\Phi\rangle = v_X/\sqrt{2}$$

Mass Spectrum

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

$$m_\phi^2 = \frac{3}{2}\frac{\overline{g_X}^2}{\pi^2} m_{Z'}^2 \left(1 - 2\left(\frac{m_N}{m_{Z'}}\right)^4\right)$$

$$m_{Z'} > 2^{1/4} m_N$$

$$\theta \simeq \frac{v_h}{v_X} = \frac{2\overline{g_X}\, v_h}{m_{Z'}} \ll 1$$

All the couplings are evaluated at v_X

Benchmark

$\left(m_N = \frac{m_{Z'}}{3}\right)$

$$(m_\phi\,,\ \theta) = \mathrm{FUN}\left[m_{Z'}, \overline{g_X}\right]$$

$m_\phi \leftrightarrow \theta$

One-to-One

(IV) Inflaton and Collider Physics

Low Energy Collider Physics

High Energy Inflationary Physics

$$\lambda_\Phi(v_X)$$

Renormalization Group Running ⟷

S. Oda, N. Okada, D. Raut and D. s. Takahashi, arXiv:1711.09850 [hep-ph]

$$\lambda_\Phi(\phi_I)$$

↕ **LHC Z' Search**

$$\mathrm{FUN}\,[\,\overline{g_X}\,,\ m'_Z\,]$$

↕ **FASER Inflaton Search**

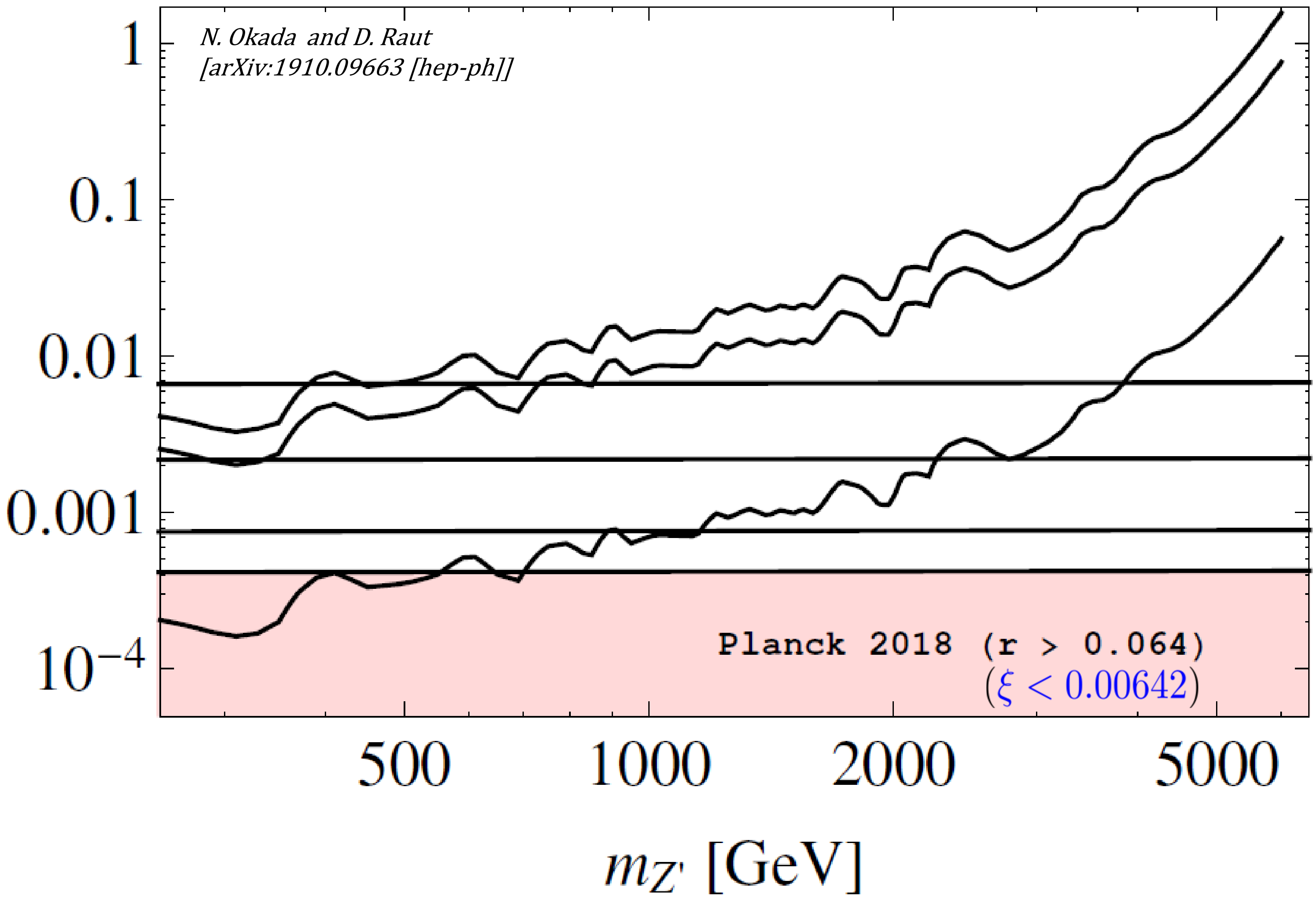
$$\mathrm{FUN}\,[m_\phi\,,\ \theta]$$

↕ **PLANCK Search**

$$\mathrm{FUN}\,[\,\xi\,]$$

ϕ_I : Inflaton field value at the onset of inflation

Z' Boson Resonance Search at LHC



$x_H = -0.8$

$x_H = 0$

$x_H = +10$

$\xi = 10$

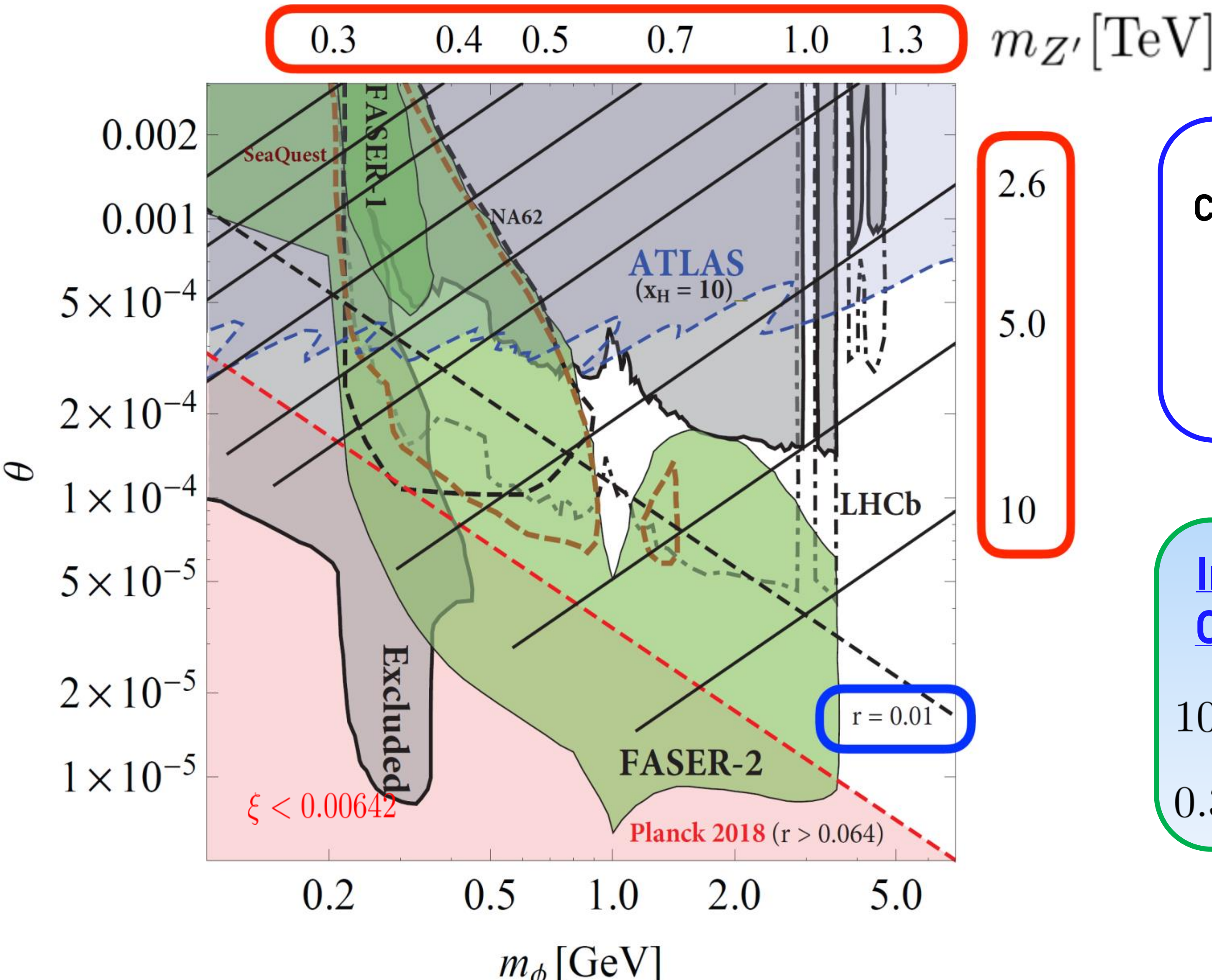
$\xi = 1$

$\xi = 0.069$

$\xi = 0.0064$

Hunting Inflaton at FASER

N. Okada and D. Raut
[arXiv:1910.09663 [hep-ph]]



CW Potential with Classical Conformal Invariance

$$m_\phi \leftrightarrow \theta$$

(One-to-One)

Inflaton Mass & Coupling Range

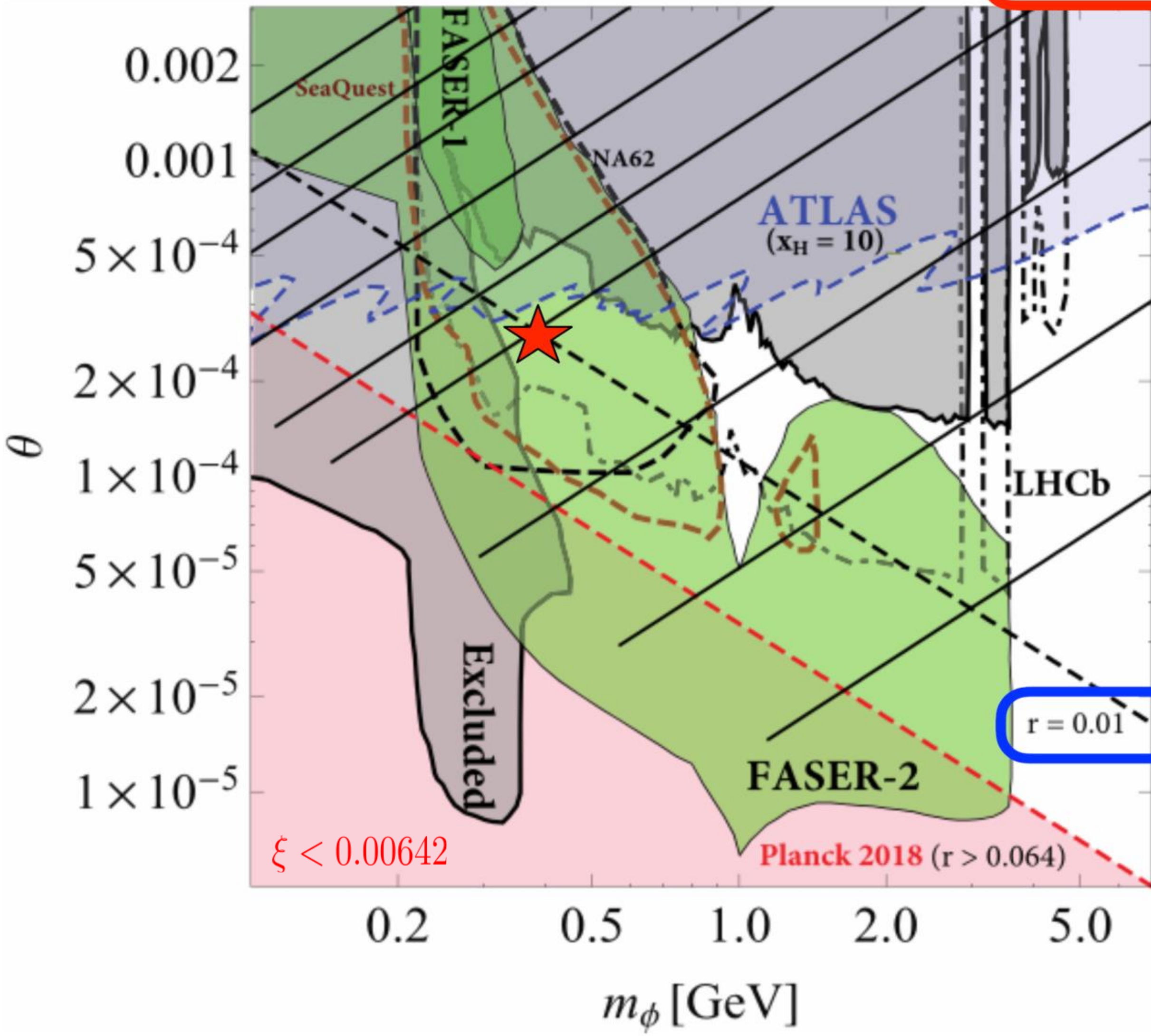
$$10^{-5} \lesssim \theta \lesssim 10^{-3}$$

$$0.3 \lesssim m_\phi[\text{GeV}] \lesssim 3$$

Complementarity with Other Searches

N. Okada and D. Raut [arXiv:1910.09663 [hep-ph]]

$m_{Z'}\,[\text{TeV}] = 1.3$



Cross checked by

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

Summary

We considered a non-minimal quartic inflation scenario in the minimal $U(1)_X$ model with classical conformal invariance, where the $U(1)_X$ Higgs field is identified to be the inflaton.

- **We have shown that the FASER can search for the inflaton:**

Inflaton Mass & Coupling

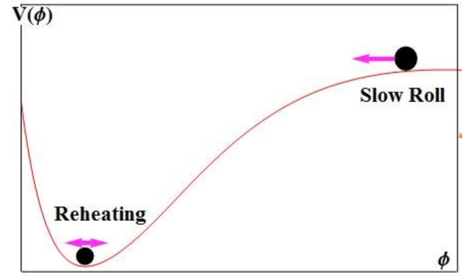
$$10^{-5} \lesssim \theta \lesssim 10^{-3}$$

$$0.3 \lesssim m_\phi[\mathrm{GeV}] \lesssim 3$$

- **Because of classical conformal invariance and the radiative $U(1)_X$ symmetry breaking, the FASER search is complementary and accessible to:**
  - **Z boson Resonance Search at the LHC**
  - **Future CMB Measurementss**

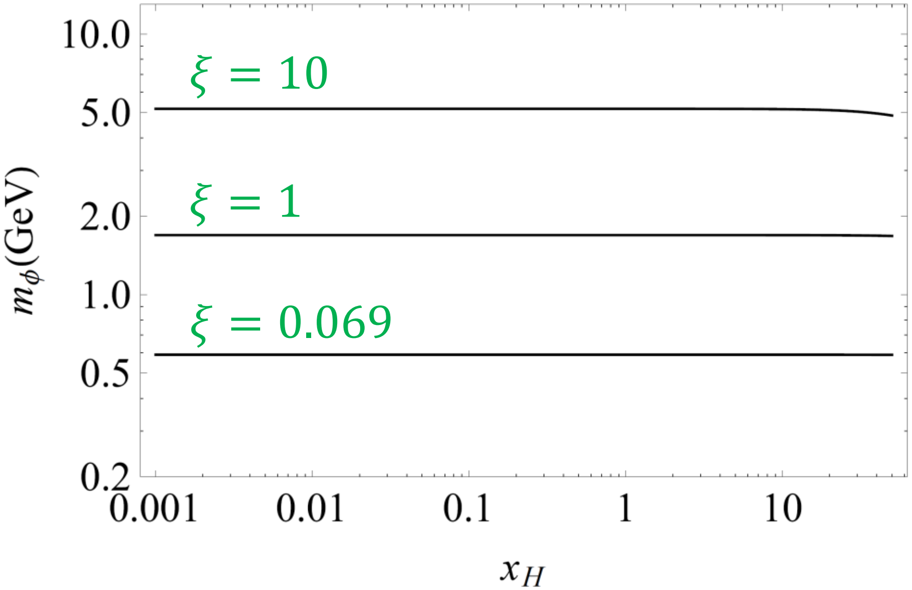
$m_{Z'}$[TeV]	The range covered by FASER
0.7	$5.7 \times 10^{-3} \leq r \leq 6.0 \times 10^{-3}$
1.0	$5.3 \times 10^{-3} \leq r \leq 1.0 \times 10^{-2}$
1.3	$6.1 \times 10^{-3} \leq r \leq 1.4 \times 10^{-2}$
2.6	$7.7 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2}$
5.0	$4.7 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2}$
10	$7.0 \times 10^{-3} \leq r \leq 6.4 \times 10^{-2}$

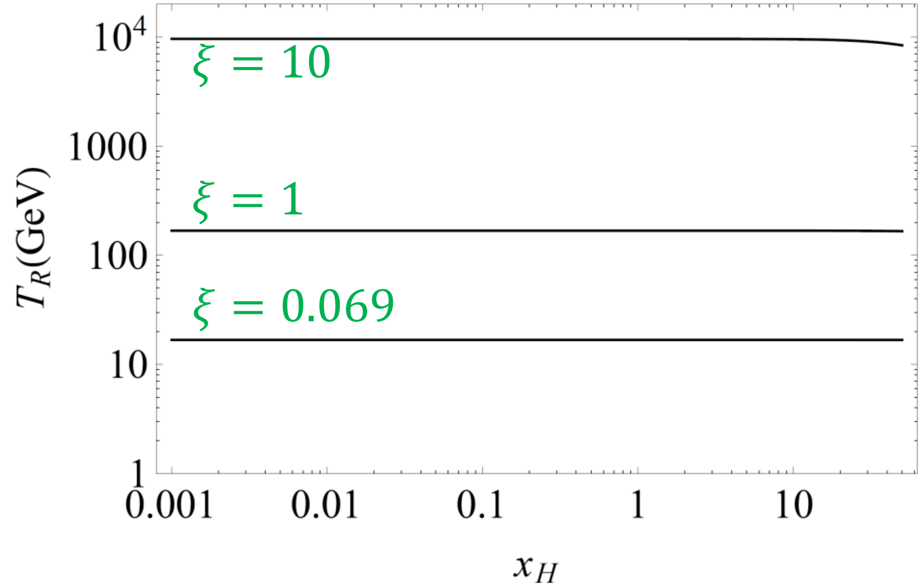
Backup Slides: Reheating



$$T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma_\phi M_P}$$

N. Okada and D. Raut [arXiv:1910.09663 [hep-ph]]





$$T_R \simeq 486\text{GeV}\ \sqrt{\text{N}_\text{c}} \left(\frac{m_f[\text{GeV}]}{1}\right) \left(\frac{\theta}{10^{-3}}\right) \left(\frac{g_X}{10^{-3}}\right)^{1/2} \left(\frac{1000}{m_{Z'}[\text{GeV}]}\right)^{1/2}$$