Hunting Inflaton at Colliders

Digesh Raut

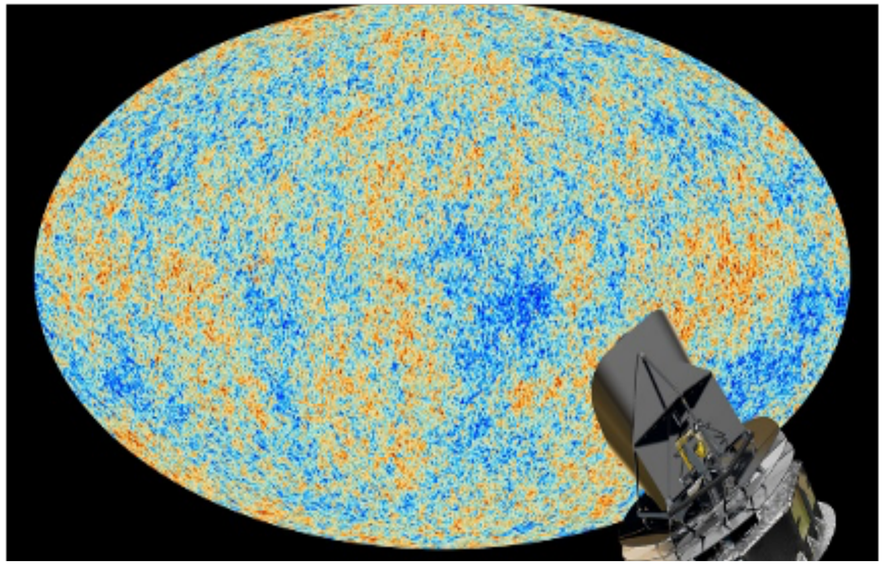
draut@smcm.edu

arXiv: 24xx.xxxx (In Preparation)

with A. Goshal (Warsaw U.) and N. Okada (Alabama U.)

Cosmological Inflation

COSMIC INFLATION: A near exponential expansion of early Universe

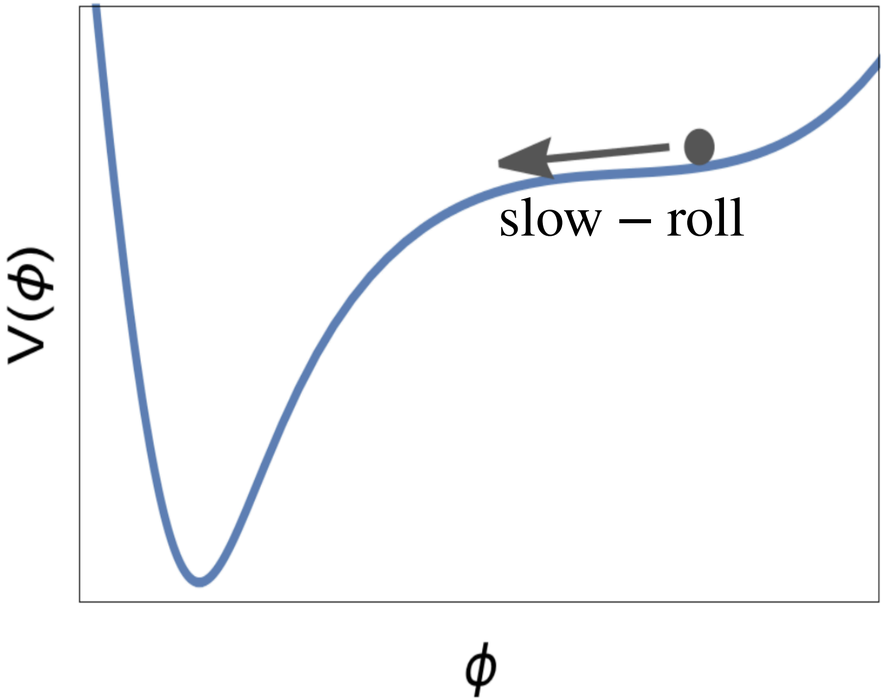


$$\left.\frac{\Delta T}{T}\right|_{average} = 10^{-5}$$

Triumphs of Inflation

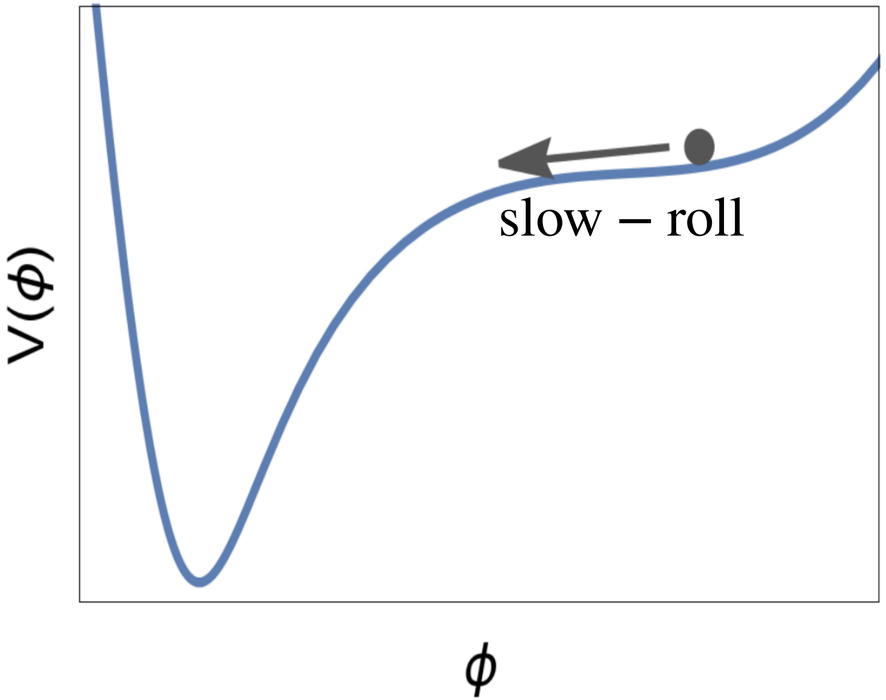
- Flatness of Universe
- Uniformity of CMB Temperature
- Origin “tiny Temperature fluctuations” in CMB

Cosmology



Inflationary Predictions depend on the shape of the Inflaton (scalar field) potential.

Cosmology



Inflationary Predictions depend on the shape of the Inflaton (scalar field) potential.

Particle Physics

Scalar Field

⇕

Symmetry Breaking

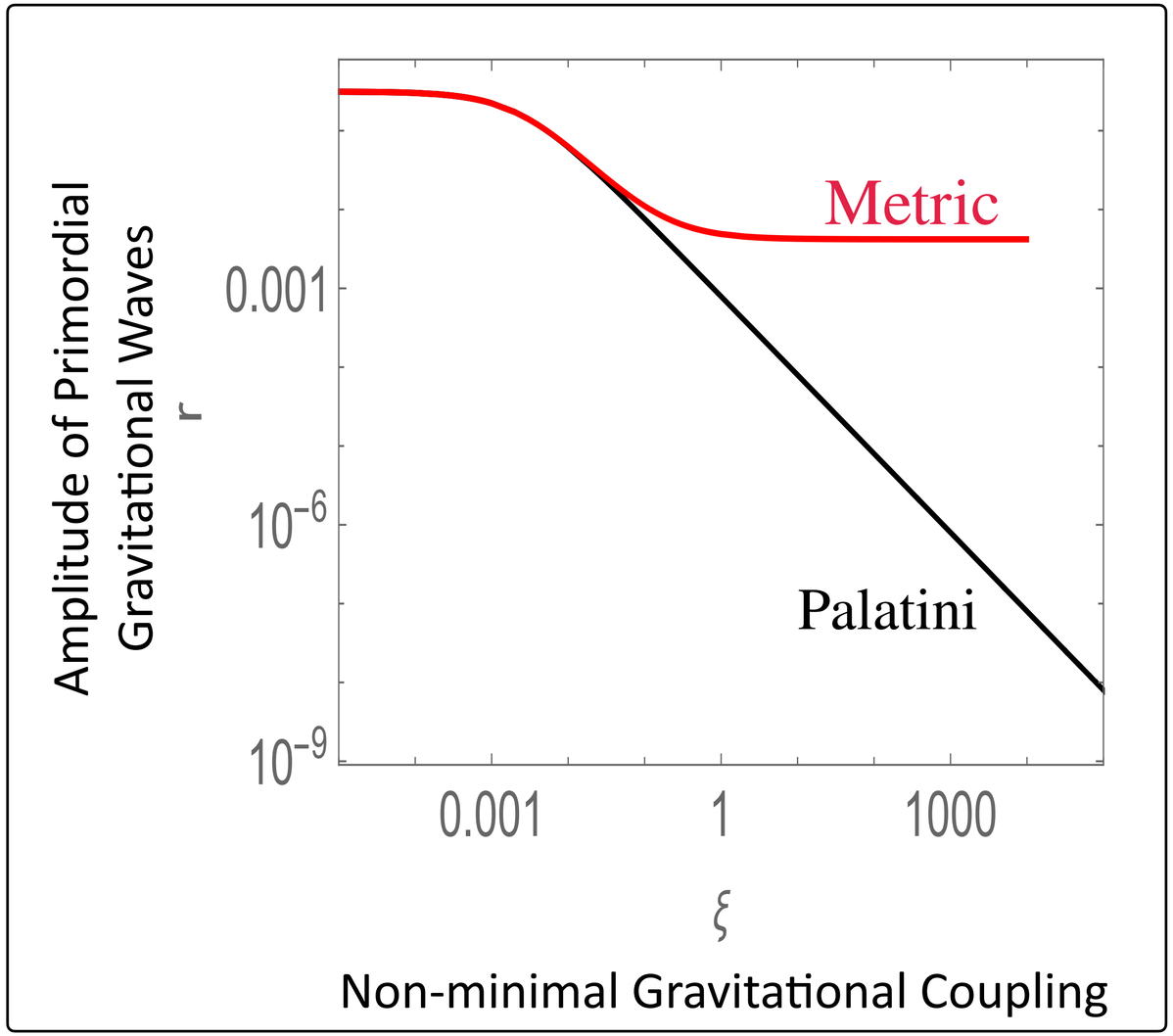
The shape of the potential depends on the interactions of Inflaton (ϕ) with other particles.

Inflaton (ϕ) with Non-Minimal Gravitational Coupling (ξ)

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

$$f(\phi) = 1 + \xi\,\phi^2$$

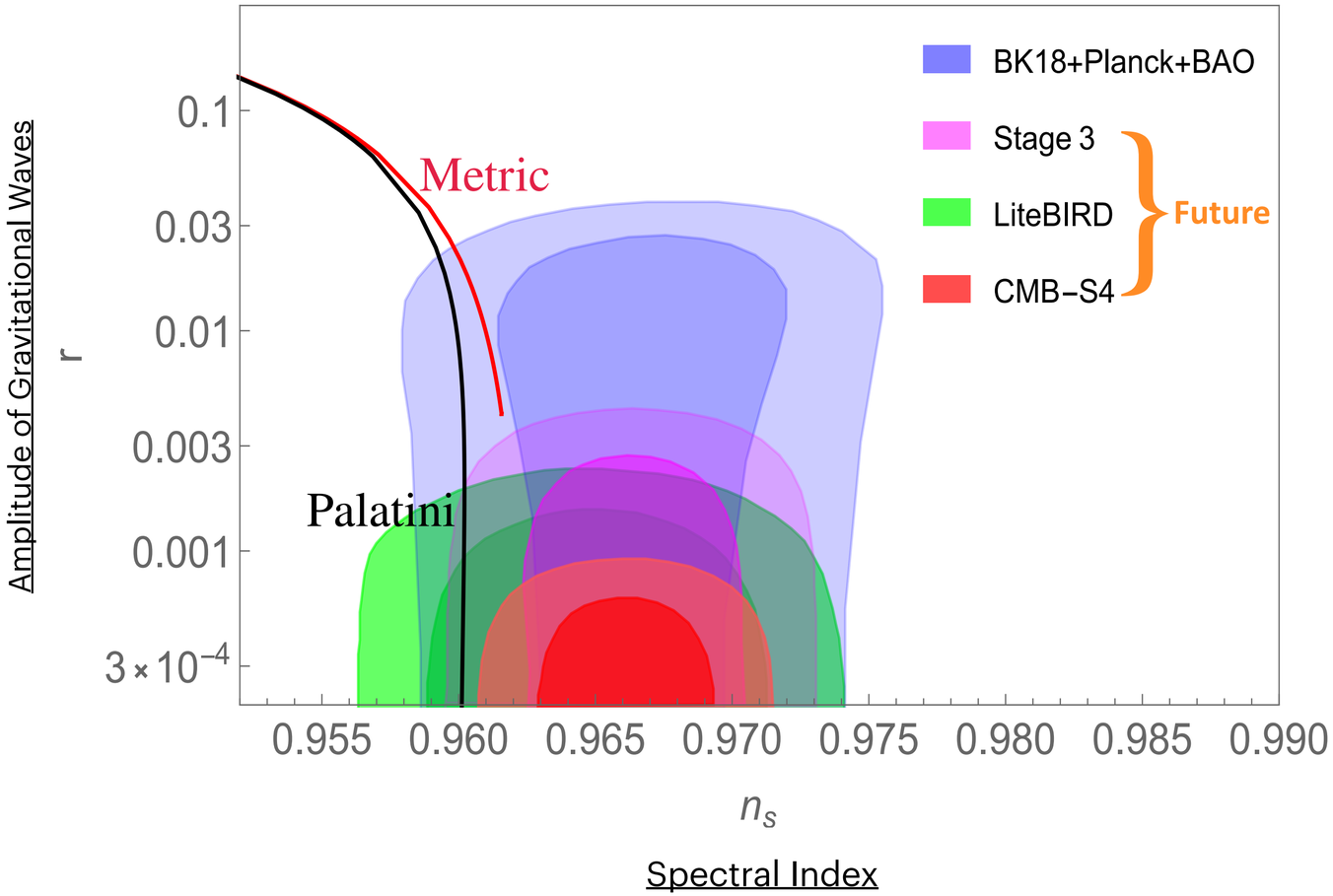
$$V_J = \frac{1}{4}\lambda\,\phi^4$$



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

$$f(\phi) = 1 + \xi\,\phi^2$$

$$V_J = \frac{1}{4}\lambda\,\phi^4$$



Model: Non-Minimal $U(1)_X$ Higgs Inflation + Conformal Symmetry

$U(1)_X$ Extended SM

Standard Model (SM)

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	
q_L^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$	⇔ New Boson (Z' – Boson)
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	⇔ New Fermions
Φ	1	1	0	2	⇔ New Higgs Inflaton

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

- (B – L) Limit : $x_H \to 0$

$U(1)_X$ **Extended SM**

Standard Model (SM)

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	
q_L^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$	⇔ New Boson ($Z' -$ Boson)
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	⇔ New Fermions
Φ	1	1	0	2	⇔ New Higgs Inflaton

Classical Conformal Invariance:

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

- The $U(1)_X$ symmetry is broken by Coleman Weinberg Mechanism.
- $U(1)_X$ breaking triggers electroweak symmetry breaking through H and Φ mixing

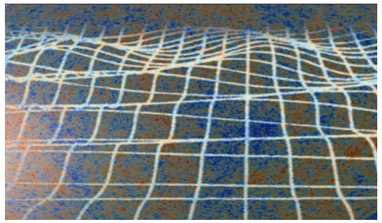
$$m_{\text{higgs}}^2 = \lambda_{\text{mix}} v_X^2$$

Cosmology

Search for Inflationary Gravitational Wave

PLANCK

(r, n_s)

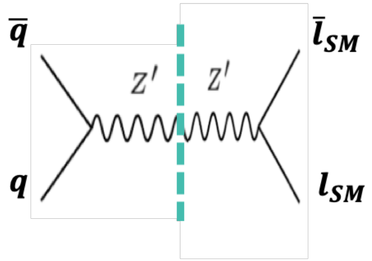


$(\lambda \leftrightarrow \xi)$

Elementary Particle Physics

Production and Detection of Z'

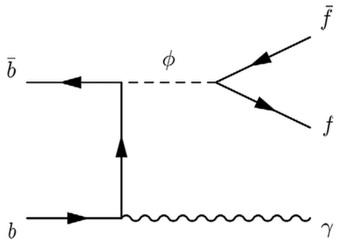
LHC Z' Search



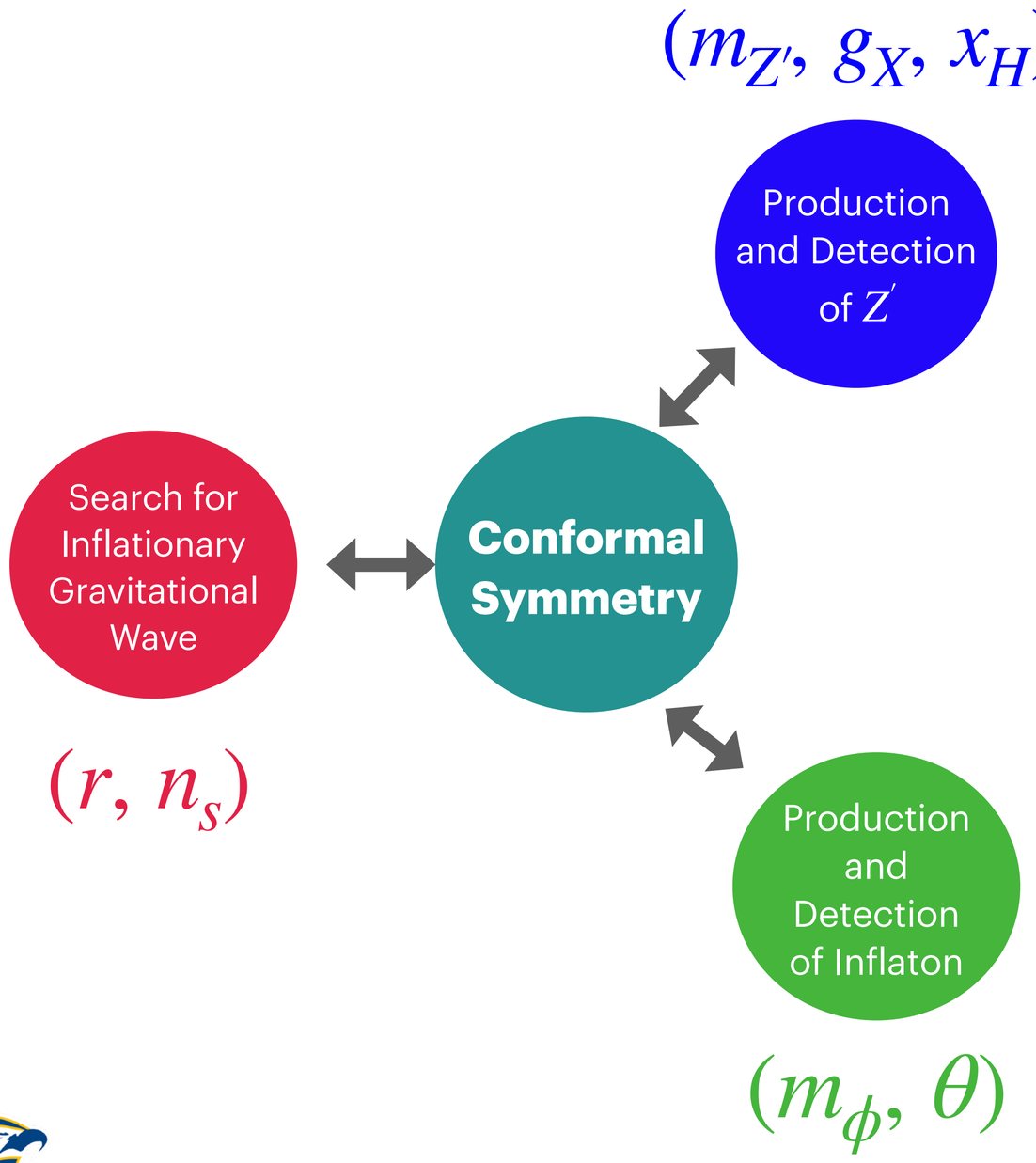
$(m_{Z'}, g_X, x_H)$

Production and Detection of Inflaton

Collider Inflaton Search



(m_ϕ, θ)



Conformal Symmetry

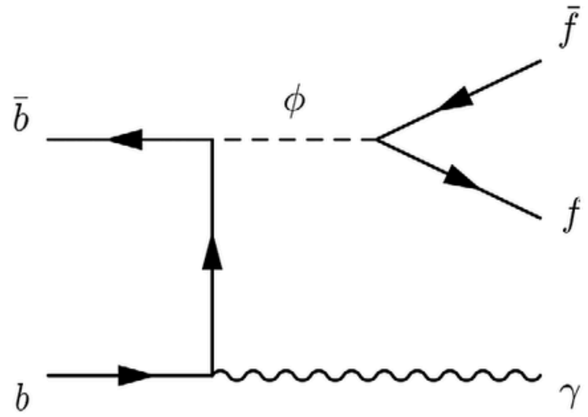
$$\Downarrow$$

Only 3 Independent Parameters

$$\left(x_H,\ m_\phi,\ \theta\right)$$

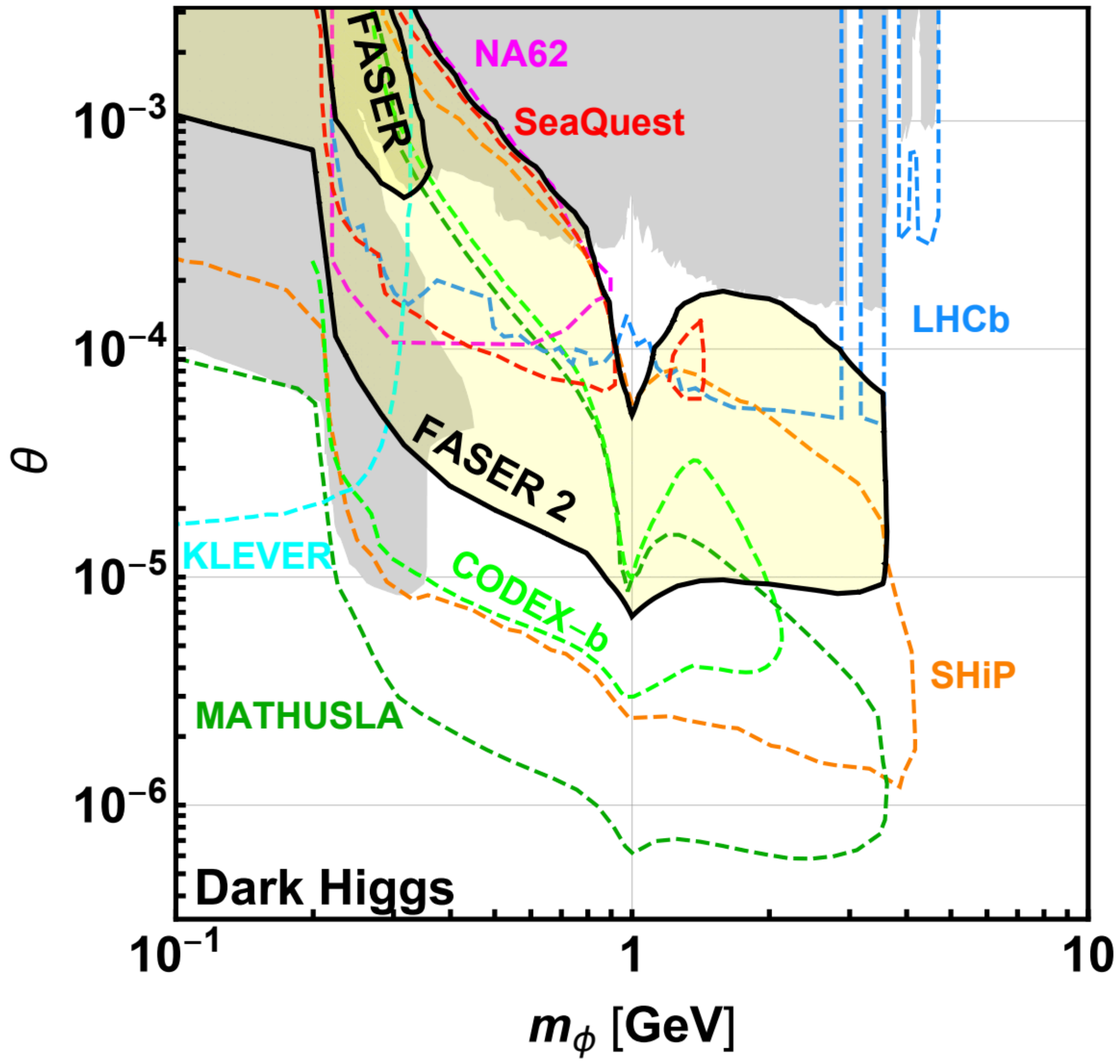
Inflaton Production at Collider through Higgs Mixing

$$V \supset \lambda_{\text{mix}} \left(H^\dagger H\right)\left(\Phi^\dagger \Phi\right)$$

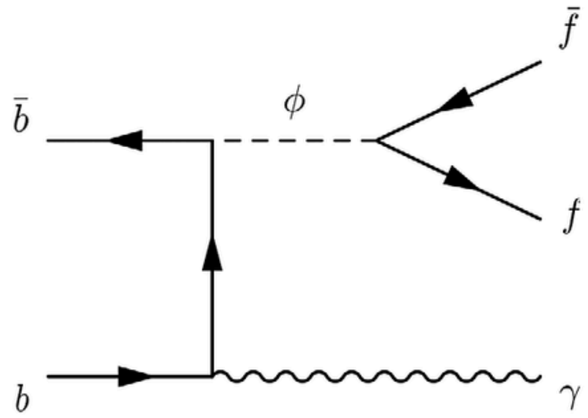


FASER's Physics Reach for Long-Lived Particles

Phys. Rev. D 99, 095011 (2019)



$$V \supset \lambda_{mix}\left(H^\dagger H\right)\left(\Phi^\dagger \Phi\right)$$



Non-Minimal $U(1)_X$ Higgs Inflation + Conformal Symmetry

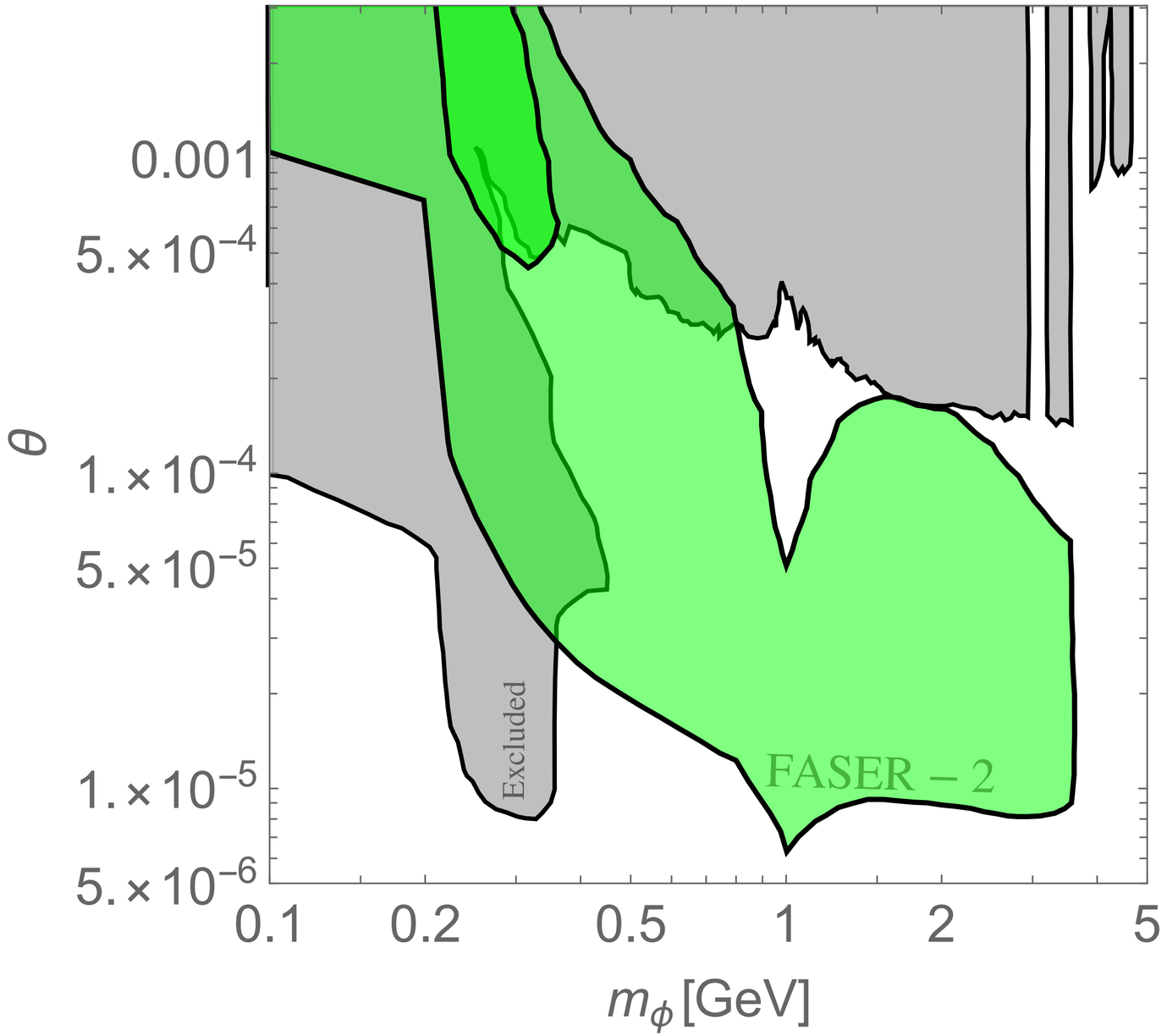
Inflaton Mass : $$m_\phi^2 = \frac{3}{2\pi^2} g_x^2 \, m_{Z'}^2 \left(1 - 2\frac{m_N^4}{m_{Z'}^4}\right)$$

Mixing Angle : $$\theta \sim \frac{v_h}{v_X}$$

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

Results for fixed $x_H = 10$

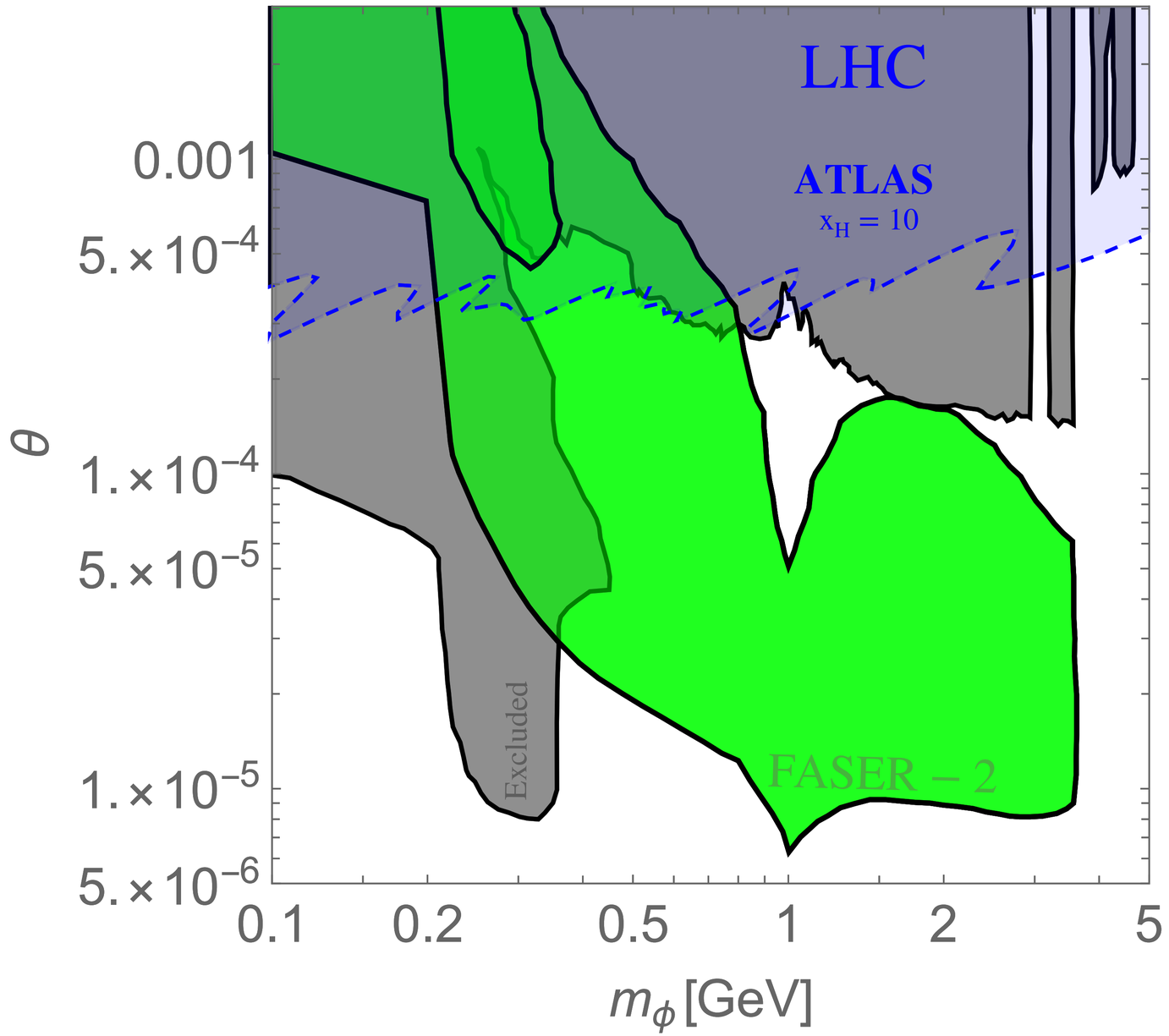
- **Search Reach:**
  FASER



*Nobuchika Okada, **DR**, arXiv: 1910.09663*

Results for fixed $x_H = 10$

- **Search Reach:**
  FASER
- **Exclusion:**
  Z' Search LHC (ATLAS)

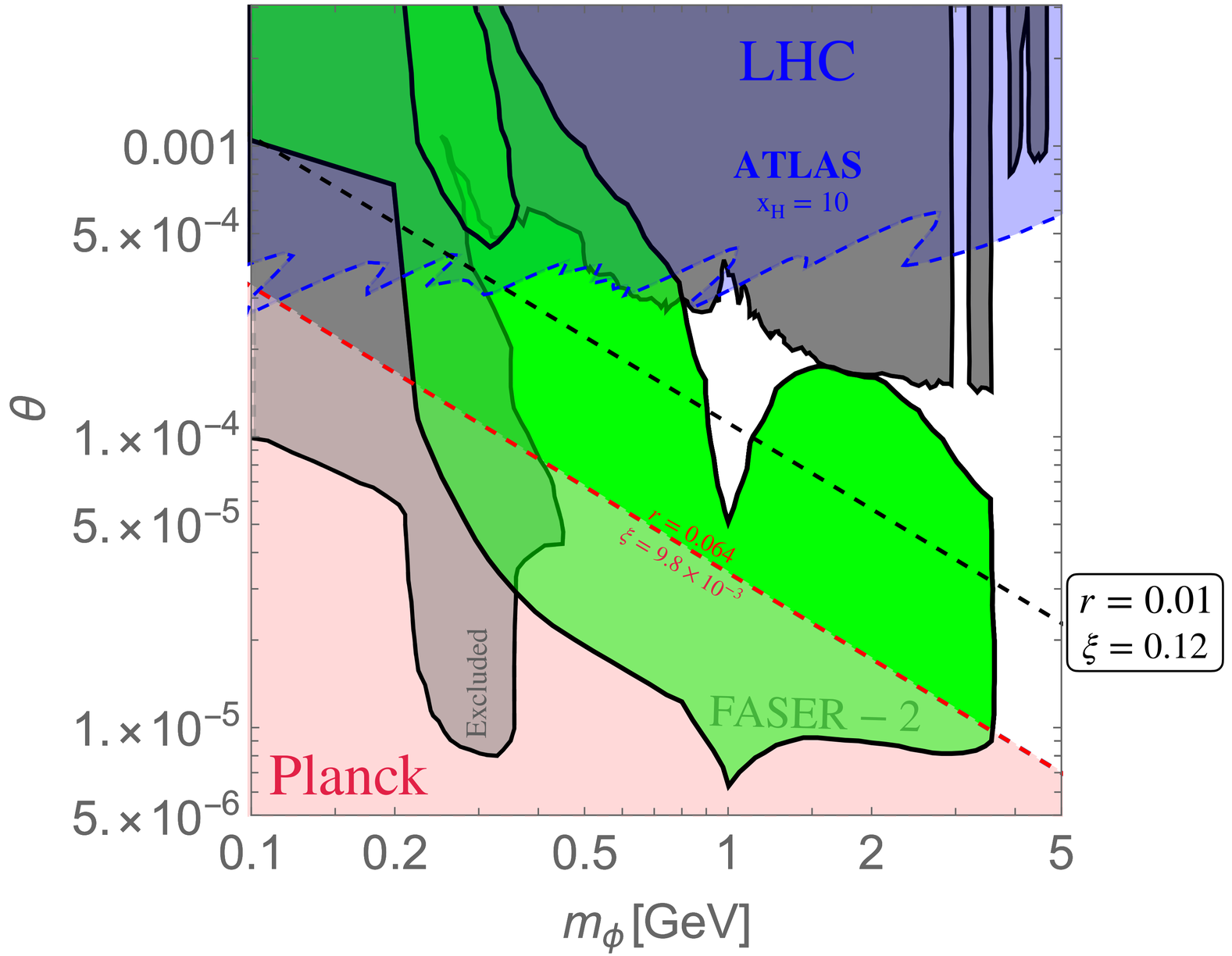


*Nobuchika Okada, **DR**, arXiv: 1910.09663*

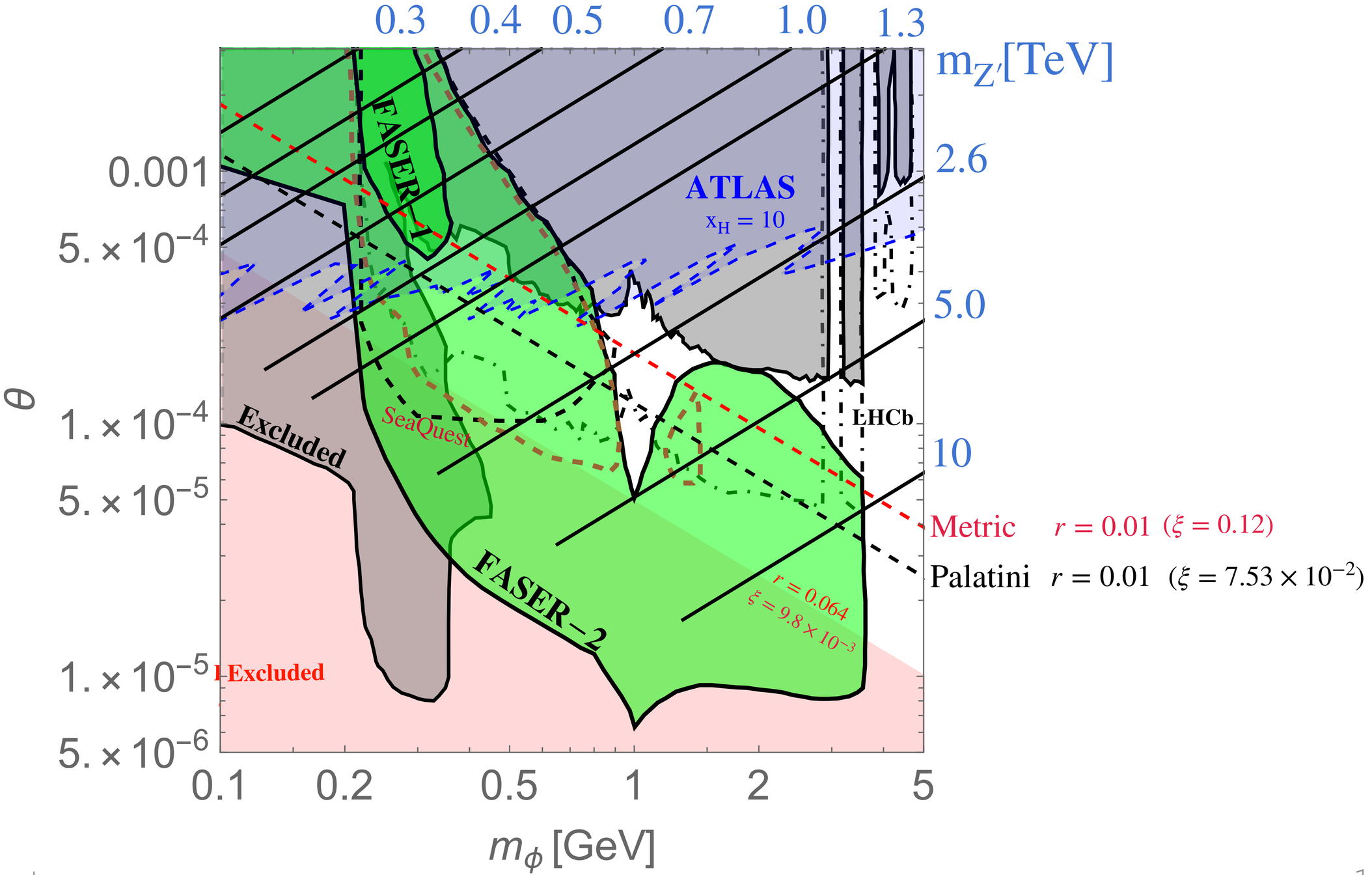
The Forward Physics Facility at the High-Luminosity LHC, arXiv 2203.05090

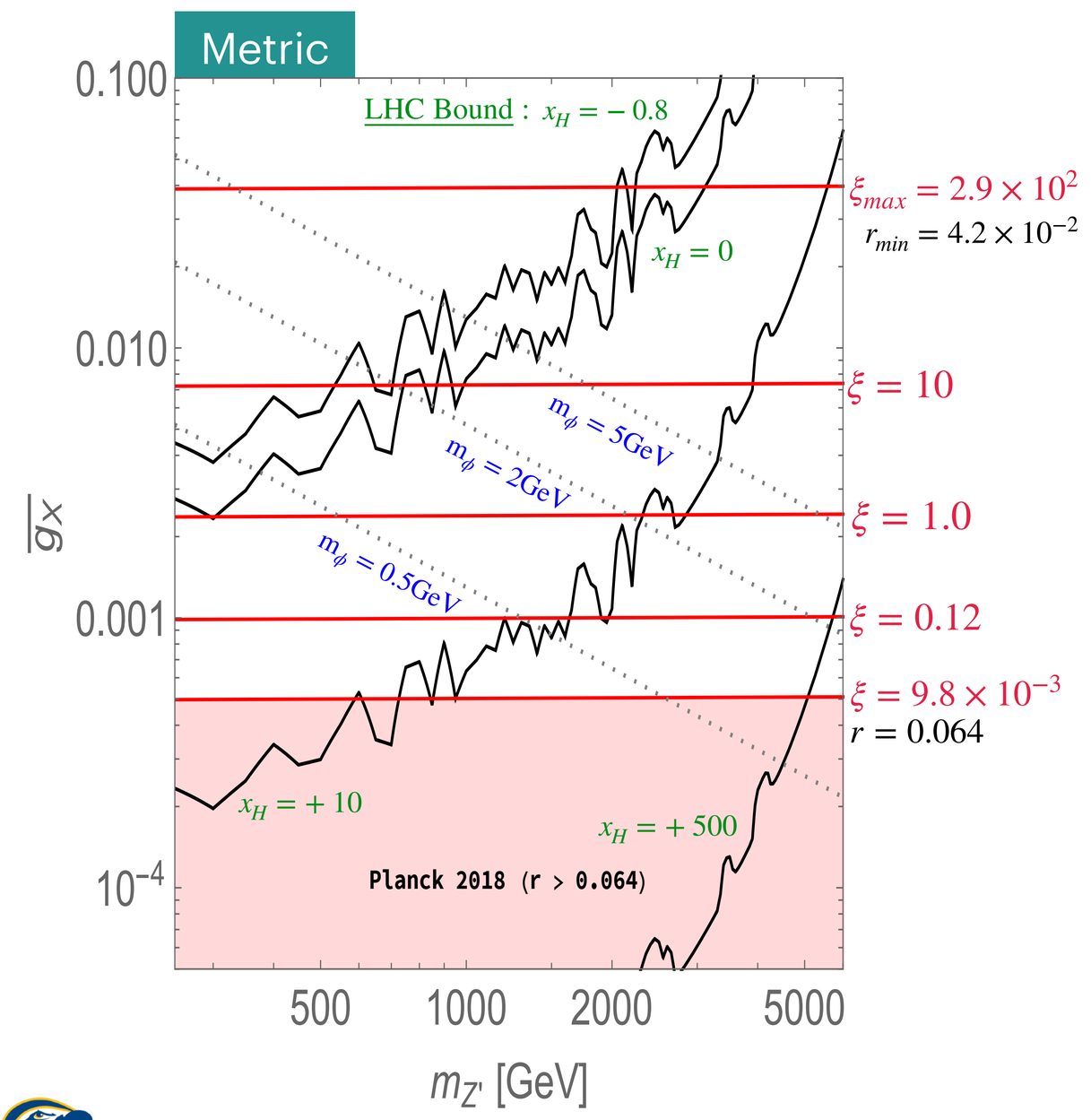
Results for fixed $x_H = 10$

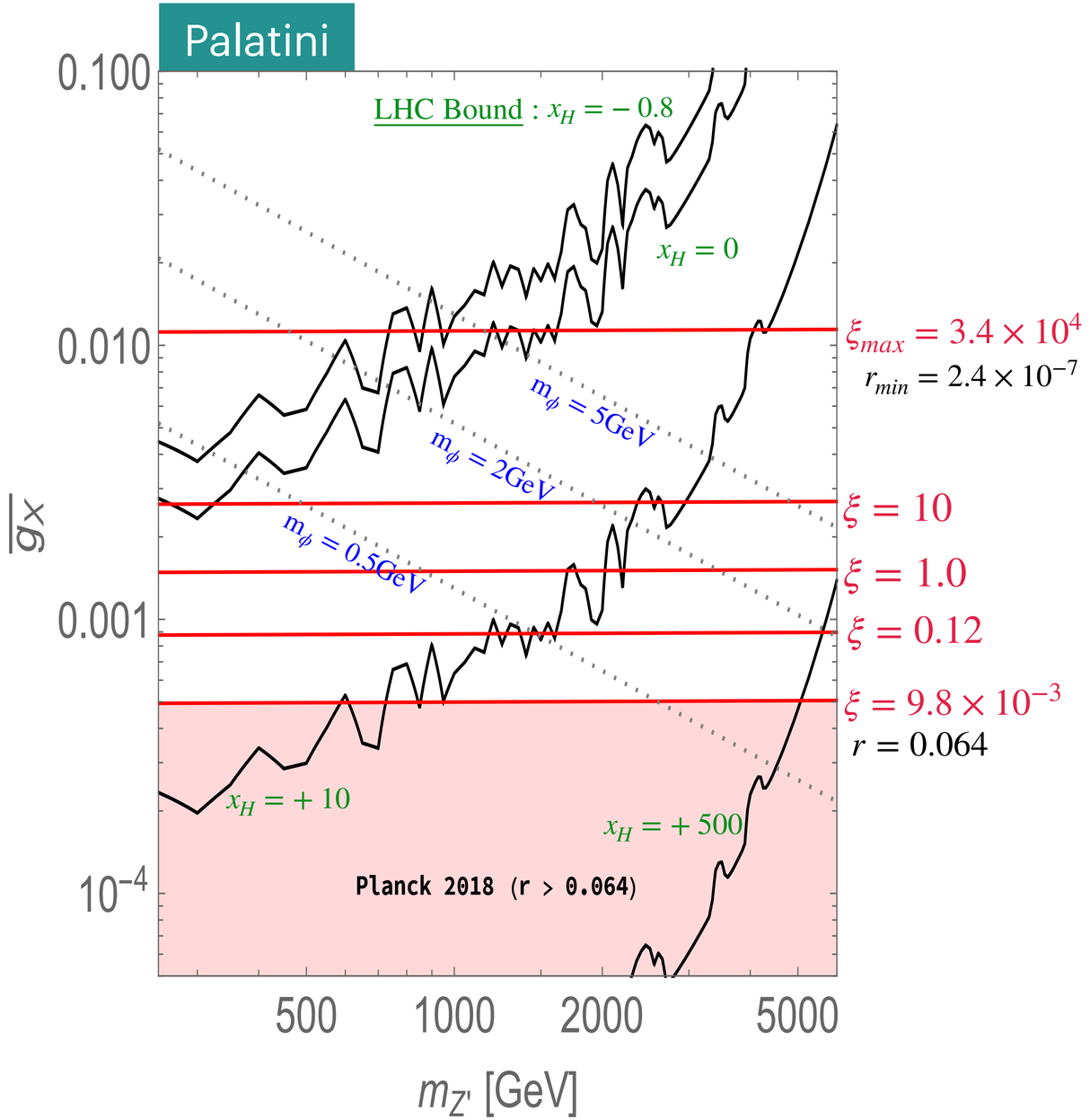
- **Search Reach:**
  FASER
- **Exclusion:**
  Z' Search LHC (ATLAS)
- **Exclusion:**
  Planck (2018) bound on r



This work


0.3
0.4
0.5
0.7
1.0
1.3
$m_{Z'}$[TeV]
2.6
5.0
10
ATLAS
$x_H = 10$
FASER−1
SeaQuest
Excluded
FASER−2
LHCb
Excluded
$r = 0.064$
$\xi = 9.8 \times 10^{-3}$
Metric $r = 0.01$ $(\xi = 0.12)$
Palatini $r = 0.01$ $(\xi = 7.53 \times 10^{-2})$
θ
0.001
$5. \times 10^{-4}$
$1. \times 10^{-4}$
$5. \times 10^{-5}$
$1. \times 10^{-5}$
$5. \times 10^{-6}$
0.1
0.2
0.5
1
2
5
m_ϕ [GeV]


Metric
LHC Bound : $x_H = -0.8$
$x_H = 0$
$x_H = +10$
$x_H = +500$
$m_\phi = 5\,\mathrm{GeV}$
$m_\phi = 2\,\mathrm{GeV}$
$m_\phi = 0.5\,\mathrm{GeV}$
$\xi_{max} = 2.9 \times 10^2$
$r_{min} = 4.2 \times 10^{-2}$
$\xi = 10$
$\xi = 1.0$
$\xi = 0.12$
$\xi = 9.8 \times 10^{-3}$
$r = 0.064$
Planck 2018 (r > 0.064)
$|g_X|$
$m_{Z'}$ [GeV]
0.100
0.010
0.001
10^{-4}
500
1000
2000
5000

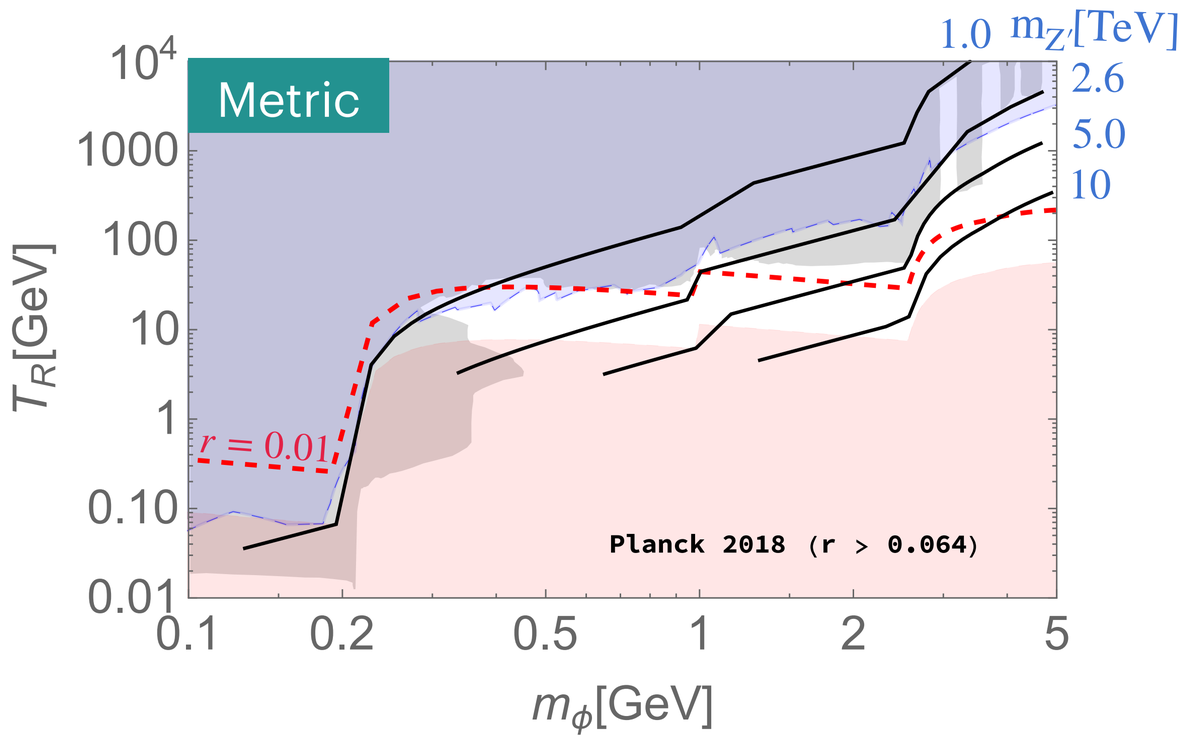

Palatini
LHC Bound : $x_H = -0.8$
$x_H = 0$
$x_H = +10$
$x_H = +500$
$m_\phi = 5\,\mathrm{GeV}$
$m_\phi = 2\,\mathrm{GeV}$
$m_\phi = 0.5\,\mathrm{GeV}$
$\xi_{max} = 3.4 \times 10^4$
$r_{min} = 2.4 \times 10^{-7}$
$\xi = 10$
$\xi = 1.0$
$\xi = 0.12$
$\xi = 9.8 \times 10^{-3}$
$r = 0.064$
Planck 2018 (r > 0.064)
$|g_X|$
$m_{Z'}$ [GeV]
0.100
0.010
0.001
10^{-4}
500
1000
2000
5000

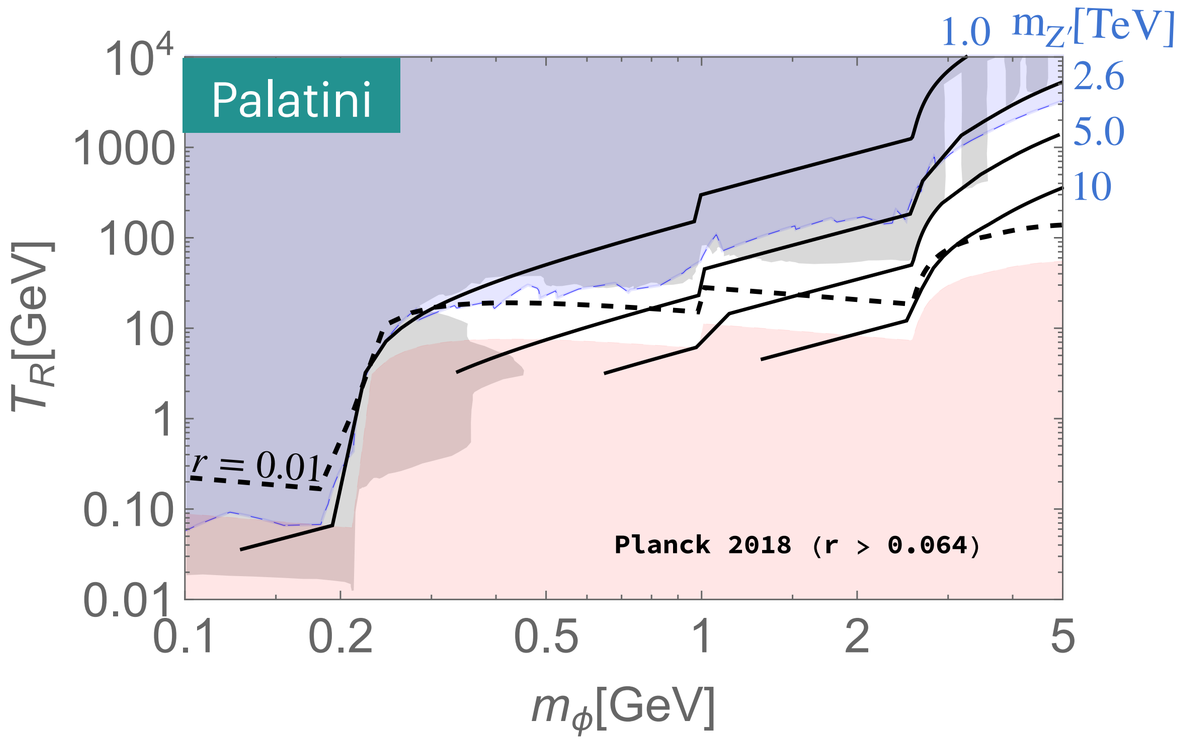
Inflaton Decay and Reheating

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

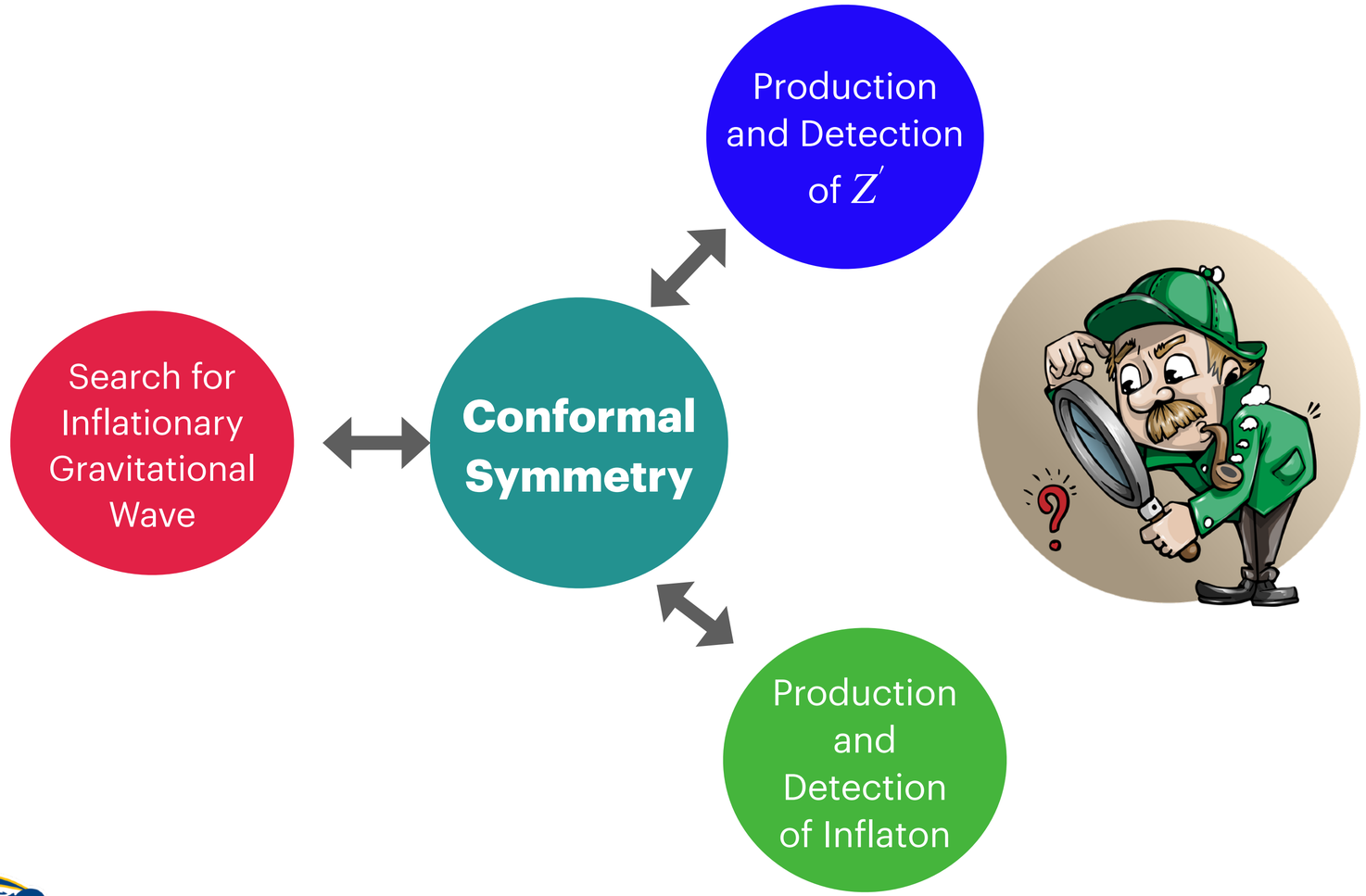
BBN Bound

$T_R > \mathcal{O}(1)$ MeV





Non-Minimal $U(1)_X$ Higgs Inflation
+
Conformal Symmetry



Hunting Inflaton at Colliders

ANY Questions?

draut@smcm.edu

Backup Slides

$$V = \frac{1}{4}\lambda_\Phi(\phi)\,\phi^4$$

$$\frac{d\lambda_\Phi}{d\ln\phi} = \beta_\lambda \simeq 96\alpha_X^2 - 3\alpha_Y^2,$$
$$\frac{d\alpha_X}{d\ln\phi} = \beta_g = \frac{72 + 64x_H + 41x_H^2}{12\pi}\alpha_X^2,$$
$$\frac{d\alpha_Y}{d\ln\phi} = \beta_Y = \frac{1}{2\pi}\alpha_Y\left(\frac{5}{2}\alpha_Y - 6\alpha_X\right).$$

Inflation : $\lambda_\Phi(\phi_{\rm pivot}) \leftrightarrow \xi$

(n_s, r)

RG Running

$$m_h^2 = \lambda_{\rm mix} v_X^2 = 2\lambda_H v_h^2$$
$$m_\phi^2 = \frac{3}{2}\frac{\overline{g_X}^2}{\pi^2} m_{Z'}^2\left(1 - 2\left(\frac{m_N}{m_{Z'}}\right)^4\right) \qquad m_{Z'} > 2^{1/4} m_N$$
$$\theta \simeq \frac{v_h}{v_X} = \frac{2\overline{g_X}\, v_h}{m_{Z'}} \ll 1$$

Collider : $\lambda_\Phi(\mathrm{v}_\phi)$ ⟷ Conformal Symmetry ⟷ $(m_\phi, m_{Z'}, x_H, g_X, v_X)$

Free Parameters :

Benchmark

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

$$\left(x_H,\ m_\phi,\ \theta\right)$$