

# CP-violating inflation

Venus Keus

University of Helsinki & Helsinki Institute of Physics



In collaboration with Kimmo Tuominen

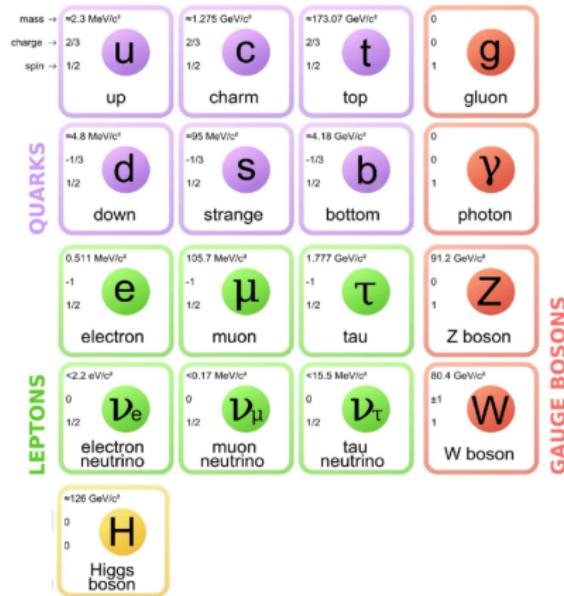
Based on arXiv:2102.07777 and work in progress

Cosmology from Home 2021

# The Standard Model

Its current formulation was finalised in the 70's and predicted:

- the W & Z bosons  
discovered in 1983
- the top quark  
discovered in 1995
- the tau neutrino  
discovered in 2000
- the Brout-Englert-Higgs mechanism  
a scalar boson discovered in 2012



VK

experiment

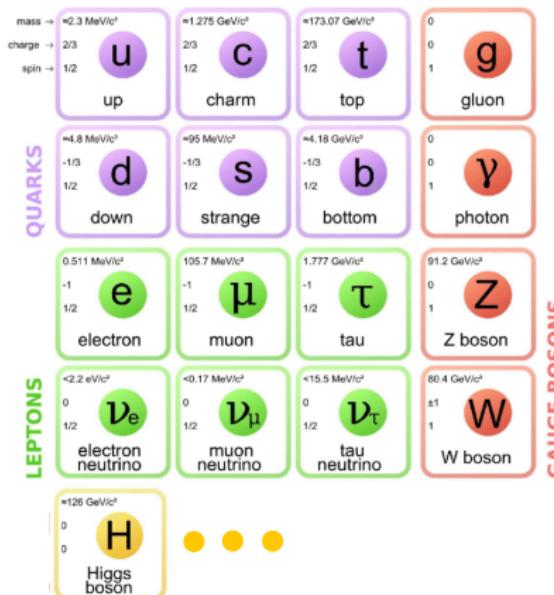
experiment

JFK: Ask not what your country can do for you - ask what you can do for your country.

... and the need to go beyond

What is missing:

- a suitable Dark Matter candidate
  - a successful baryogenesis mechanism
    - strong first order phase transition
    - sufficient amount of CP-violation
  - a natural inflation framework
  - an explanation for the fermion mass hierarchy
  - a stable electroweak vacuum
- ⇒ beyond the Standard Model
- ⇒ scalar extensions of the SM



# 3HDMs: the crown jewel of scalar extensions

## SM + scalar singlets

- Dark Matter severely constrained
- CP-violation not possible
- Inflation DM incompatible

## 2HDM: SM + a doublet

- Dark Matter constrained & CPV incompatible
- CP-violation severely constrained & DM incompatible
- Inflation CPV incompatible

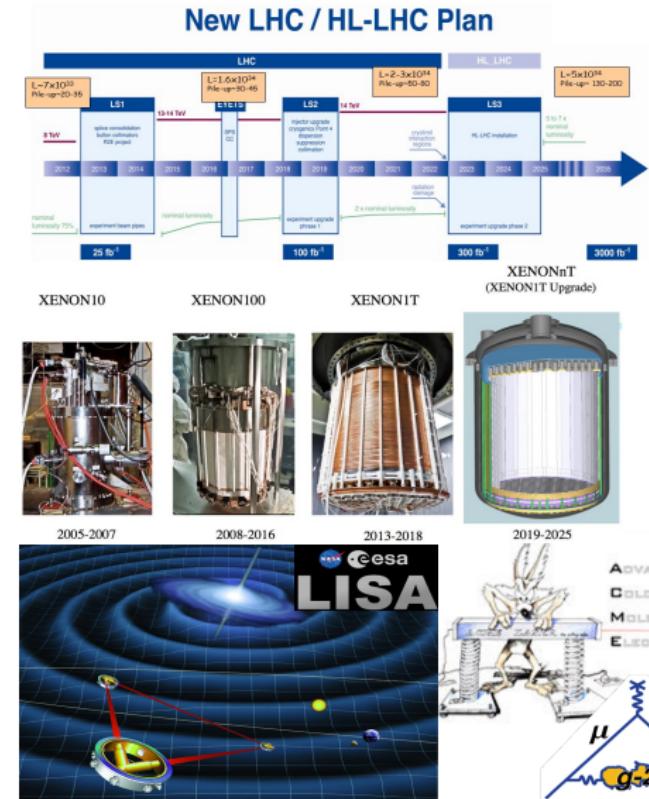
## 3HDM: SM + 2 doublets

- Dark Matter many exotic possibilities
- CP-violation unbounded dark CPV
- Inflation easily achieved + exotic possibilities
- Bonus: fermion mass hierarchy explanation

<b>QUARKS</b>	<b>LEPTONS</b>	<b>GAUGE BOSONS</b>
u: mass $\approx 2.4 \text{ MeV}/c^2$ , charge $2/3$ , spin $1/2$	e: mass $\approx 0.511 \text{ MeV}/c^2$ , charge $-1$ , spin $1/2$	Z boson: mass $\approx 91.19 \text{ GeV}/c^2$ , charge $0$ , spin $1$
c: mass $\approx 1.275 \text{ GeV}/c^2$ , charge $2/3$ , spin $1/2$	$\mu$ : mass $\approx 105.67 \text{ MeV}/c^2$ , charge $-1$ , spin $1/2$	W boson: mass $\approx 80.39 \text{ GeV}/c^2$ , charge $\pm 1$ , spin $1$
t: mass $\approx 172.44 \text{ GeV}/c^2$ , charge $2/3$ , spin $1/2$	s: mass $\approx 95 \text{ MeV}/c^2$ , charge $-1/3$ , spin $1/2$	Higgs I: mass $\approx 125.09 \text{ GeV}/c^2$ , charge $0$ , spin $0$
g: gluon: mass $0$ , charge $0$ , spin $1$	b: mass $\approx 4.18 \text{ GeV}/c^2$ , charge $-1/3$ , spin $1/2$	Higgs II: mass $\approx 177.68 \text{ GeV}/c^2$ , charge $0$ , spin $0$
$\gamma$ : photon: mass $0$ , charge $0$ , spin $1$	d: mass $\approx 4.8 \text{ MeV}/c^2$ , charge $-1/3$ , spin $1/2$	Higgs III: mass $\approx 15.5 \text{ GeV}/c^2$ , charge $0$ , spin $0$
<b>SCALAR BOSONS</b>		

# Upcoming experimental probes

- Collider experiments
  - 2021: LHC-RUN-III
  - 2026: HL-LHC
  - 2028: CEPC
- DM experiments
  - 2020: XENONnT
  - 2022: CTA
- GW experiments
  - 2027: DECIGO
  - 2034: LISA mission
- Precision experiments
  - 2020:  $(g - 2)_\mu$
  - 2020: Advanced ACME



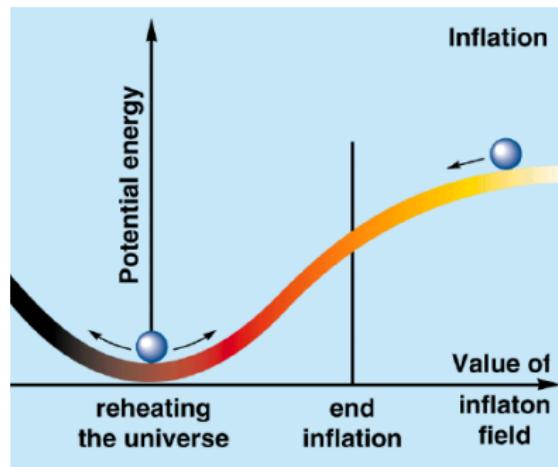
# Slow roll and Higgs inflation

## Slow roll inflation:

driven by a scalar field (inflaton) slowly rolling down its smooth potential.

$$\mathcal{L}_J = \frac{\sqrt{-g_J}}{2} \left[ (\xi \phi^2 + M_{pl}^2) R + (\partial_\mu \phi)^2 - V(\phi) \right]$$

The SM Higgs potential:  $V(\phi) = -\mu_h^2 \phi^\dagger \phi + \lambda_h (\phi^\dagger \phi)^2$



# 3HDMs: 3-Higgs doublet models

two scalar doublets + the SM Higgs doublet

$$\phi_1, \phi_2$$

$$\phi_3$$

$$\phi_1 = \begin{pmatrix} h_1^+ \\ \frac{h_1 + i\eta_1}{\sqrt{2}} \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} h_2^+ \\ \frac{h_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{h_3 + iG^0}{\sqrt{2}} \end{pmatrix}$$

# $Z_2$ -symmetric 3HDM with dark CPV

Lagrangian invariant under a  $Z_2$  symmetry ( $-,-,+ \rangle$ ):

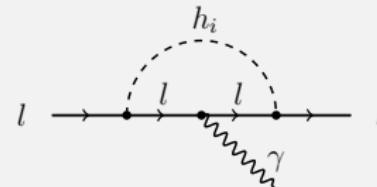
$$\phi_1 \rightarrow -\phi_1, \quad \phi_2 \rightarrow -\phi_2, \quad \text{SM fields} \rightarrow \text{SM fields}, \quad \phi_3 \rightarrow \phi_3$$

and respected by the vacuum  $(0, 0, v)$ :

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h_1 + i\eta_1 \end{pmatrix}, \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ h_2 + i\eta_2 \end{pmatrix}, \quad \phi_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h + h_3 \end{pmatrix}$$

Only  $\phi_3$  can couple to fermions:  $\phi_u = \phi_d = \phi_e = \phi_3$

$$\begin{aligned} -\mathcal{L}_{Yukawa} &= Y_u \bar{Q}'_L i\sigma_2 \phi_u^* u'_R \\ &\quad + Y_d \bar{Q}'_L \phi_d d'_R \\ &\quad + Y_e \bar{L}'_L \phi_e e'_R + \text{h.c.} \end{aligned}$$



No contributions to electric dipole moments (EDMs)

# $Z_2$ -symmetric 3HDM with dark CPV

The scalar potential:  $V = V_0 + V_{Z_2}$  with

$$V_0 = -\mu_i^2(\phi_i^\dagger \phi_i) + \lambda_{ii}(\phi_i^\dagger \phi_i)^2 + \lambda_{ij}(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \lambda'_{ij}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) \quad (i=1,2,3)$$

which is CP-conserving (real parameters),

$$V_{Z_2} = -\mu_{12}^2(\phi_1^\dagger \phi_2) + \lambda_1(\phi_1^\dagger \phi_2)^2 + \lambda_2(\phi_2^\dagger \phi_3)^2 + \lambda_3(\phi_3^\dagger \phi_1)^2 + h.c.$$

which is CP-violating (complex parameters).

The action of the model:

$$S_J = \int d^4x \sqrt{-g} \left[ -\frac{1}{2} M_{pl}^2 R - D_\mu \phi_i^\dagger D^\mu \phi_i - V - \left( \xi_i |\phi_i|^2 + \underbrace{\xi_4 (\phi_1^\dagger \phi_2)}_{Z_2-\text{symmetric}} + h.c. \right) R \right]$$

The sources of CP-violation are  $\lambda_1 = |\lambda_1| e^{i\theta_1}$  and  $\xi_4 = |\xi_4| e^{i\theta_4}$ .

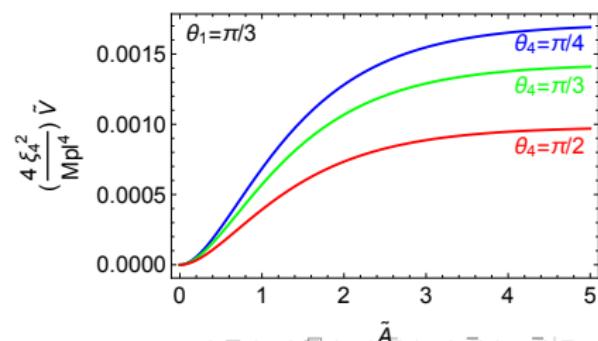
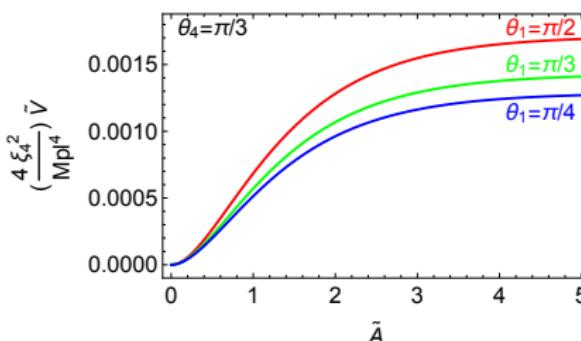
# The inflationary potential $\tilde{V}$

To simplify the analysis:  $\eta_1 = \beta_1 h_1$  and  $h_2 = \beta_2 h_1$

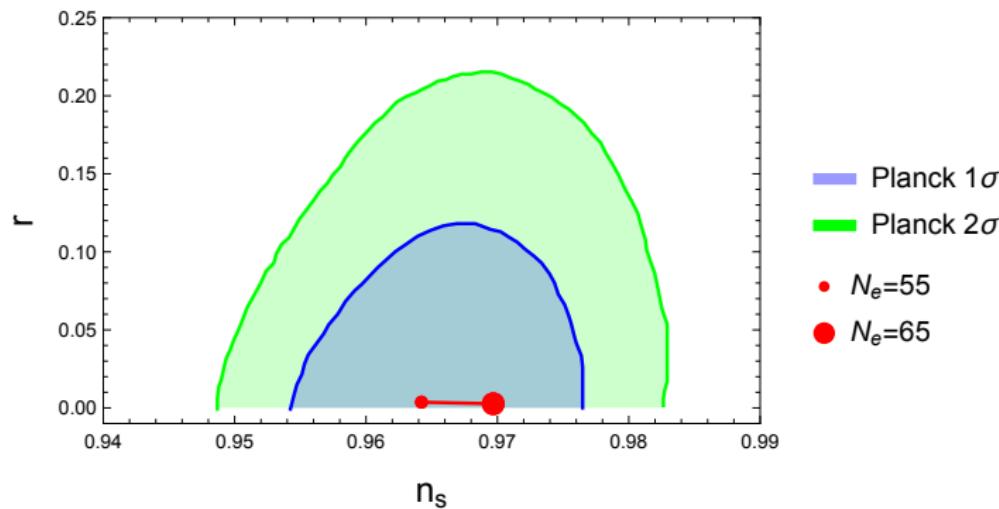
Finding the inflationary direction yields:  $\beta_1(\theta_1, \theta_4)$ ,  $\beta_2(\theta_1, \theta_4)$

Another standard reparametrisation:  $h_1^2 = \frac{M_{pl}^2}{2|\xi_4| \beta_2(c_{\theta_4} + \beta_1 s_{\theta_4})} \left( e^{\tilde{A}} - 1 \right)$

The potential is simplified to:  $\tilde{V} = \left( \frac{M_{pl}^2}{2|\xi_4|} \right)^2 \left( 1 - e^{-\tilde{A}} \right)^2 \underbrace{X(\theta_1, \theta_4)}_{\text{new}}$



# Inflationary predictions for the CMB spectrum parameters



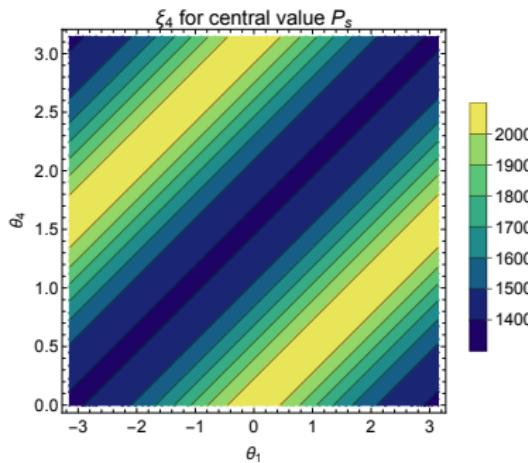
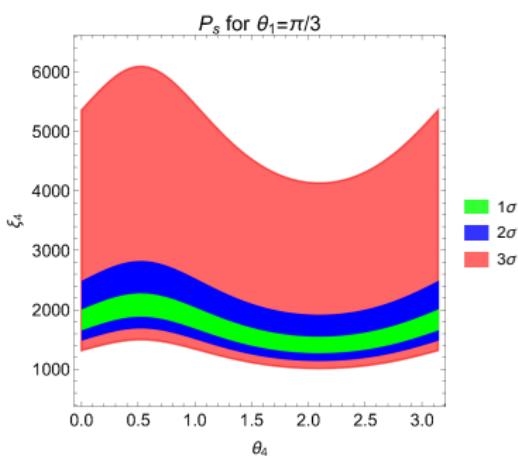
the  $1\sigma$  and  $2\sigma$  regions for  $n_s$  and  $r$  from Planck observation

( $N_e$ : number of  $e$ -folds,  $n_s$ : the spectral index,  $r$ : tensor to scalar ratio)

# The scalar power spectrum $P_s$

Observations from WMAP7 constrain the scalar power spectrum

$$P_s = (2.430 \pm 0.091) \times 10^{-9} = 5.565 \times \frac{X(\theta_1, \theta_4)}{|\xi_4|^2}$$



Fixing  $P_s$  to have the central value:  $|\xi_4| \simeq 47000 \sqrt{\lambda_i} \sqrt{X(\theta_1, \theta_4)}$

In Higgs inflation:  $\xi \simeq 47000 \sqrt{\lambda_h}$

# Reheating and scalar asymmetries

At the exit from inflation: doublets acquire an initial expectation value

$$\begin{cases} \phi_1 \rightarrow \phi_1 - a_1 e^{i\alpha} \\ \phi_1^\dagger \rightarrow \phi_1^* - a_1 e^{-i\alpha} \end{cases} \quad \begin{cases} \phi_2 \rightarrow \phi_2 - a_2 \\ \phi_2^\dagger \rightarrow \phi_2^* - a_2 \end{cases} \quad \begin{cases} \phi_3 \rightarrow \phi_3 - a_3 \\ \phi_3^\dagger \rightarrow \phi_3^* - a_3 \end{cases}$$

where the phase  $\alpha$  is related to  $\theta_1$  and  $\theta_4$ :

$$h_1(\theta_1, \theta_4) \rightsquigarrow a_1 \cos \alpha, \quad \eta_1(\theta_1, \theta_4) = \beta_1 h_1 \rightsquigarrow a_1 \sin \alpha$$

Instant reheating: the inflaton quickly decay to  $\phi_3$

$$\begin{cases} \phi_1 \rightarrow \phi_3 \phi_3 \propto 2a_1 \lambda_3 e^{i(\alpha+\theta_3)} \\ \phi_1^* \rightarrow \phi_3^* \phi_3^* \propto 2a_1 \lambda_3 e^{-i(\alpha+\theta_3)} \end{cases} \quad \begin{cases} \phi_2 \rightarrow \phi_3 \phi_3 \propto 2a_2 \lambda_2 e^{i\theta_2} \\ \phi_2^* \rightarrow \phi_3^* \phi_3^* \propto 2a_2 \lambda_2 e^{-i\theta_2} \end{cases}$$

resulting in unequal number of  $\phi_3$  and  $\phi_3^*$  states with asymmetries

$$A_{CP}^1 \sim 8 a_1^2 \lambda_3^2 \sin 2(\alpha + \theta_3), \quad A_{CP}^2 \sim 8 a_2^2 \lambda_2^2 \sin 2\theta_2$$

Such asymmetries are then transferred to the fermion sector through the couplings of the Higgs/W/Z with the fermions.

# Summary

## SM + scalar singlets

- Dark Matter **severely constrained**
- CP-violation **not possible**
- Inflation **DM incompatible**

## 2HDM: SM + a doublet

- Dark Matter **constrained & CPV incompatible**
- CP-violation **severely constrained & DM incompatible**
- Inflation **CPV incompatible**

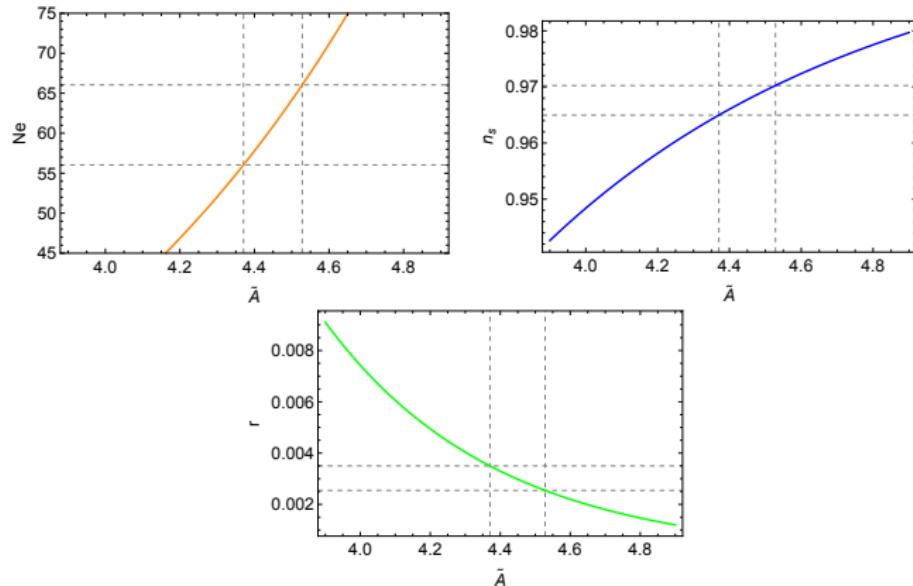
## 3HDM: SM + 2 doublets

- Dark Matter **CP-violating DM**
- CP-violation **unbounded dark CP-violation**
- Inflation **CP-violating inflation**
- Bonus: fermion mass hierarchy explanation

# BACKUP SLIDES

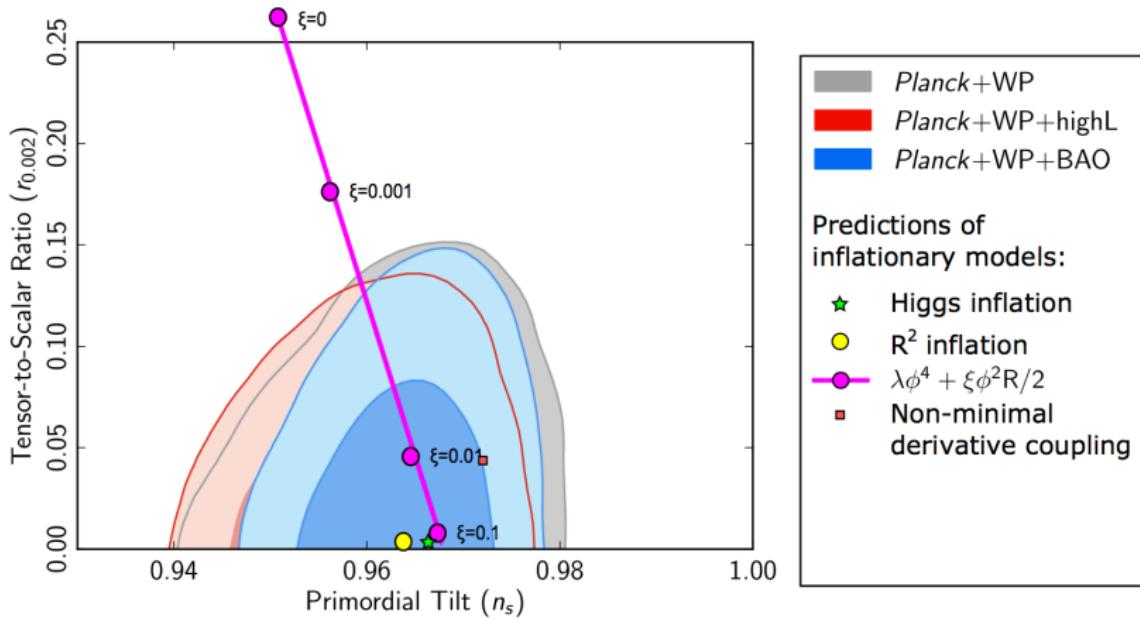
# The slow roll parameters

number of e-folds  $N_e$ , the spectral index  $n_s$ , tensor to scalar ratio  $r$



as a function of  $\tilde{A}$  with the  $55 < N_e < 65$  grid-lines

# Other inflationary models



F. Bezrukov, [Class. Quant. Grav. 30, 214001 (2013)]

# Reheating

