Superconformal Subcritical Hybrid Inflation

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Kanazawa University

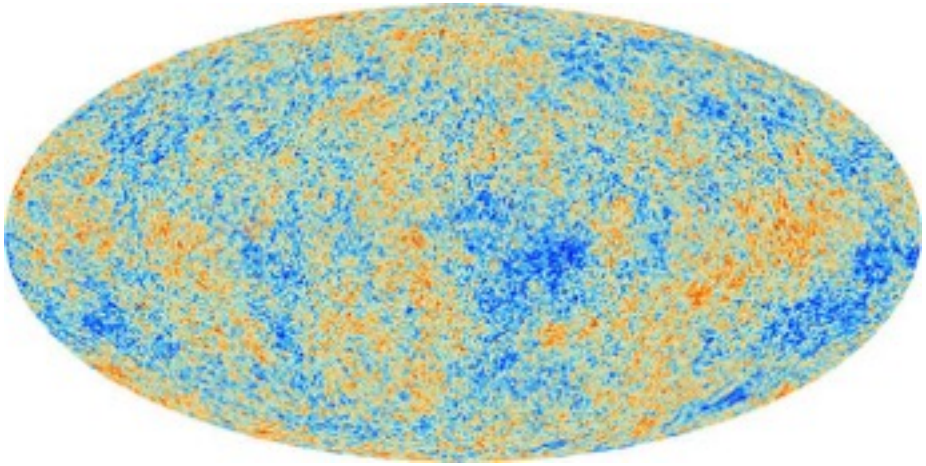
Based on PLB782 (2018) 367-371

SUSY18, July 26, 2018

1. Introduction

Cosmic Microwave Background (CMB)

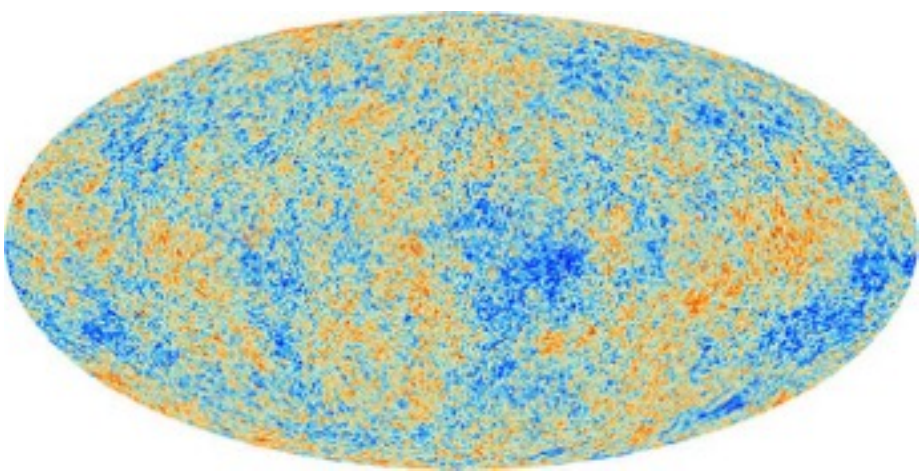
- It tells the
- It strongly supports inflation

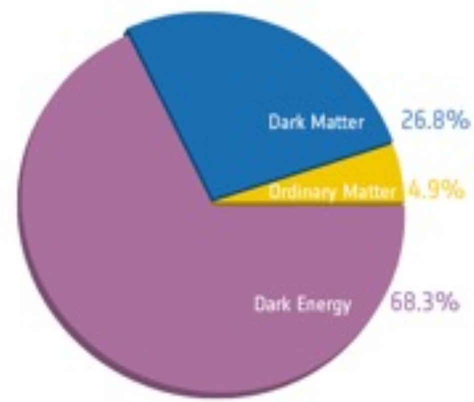


Planck ’13

Cosmic Microwave Background (CMB)

- It tells the fundamental cosmological parameters
- It strongly supports inflation





Planck '13

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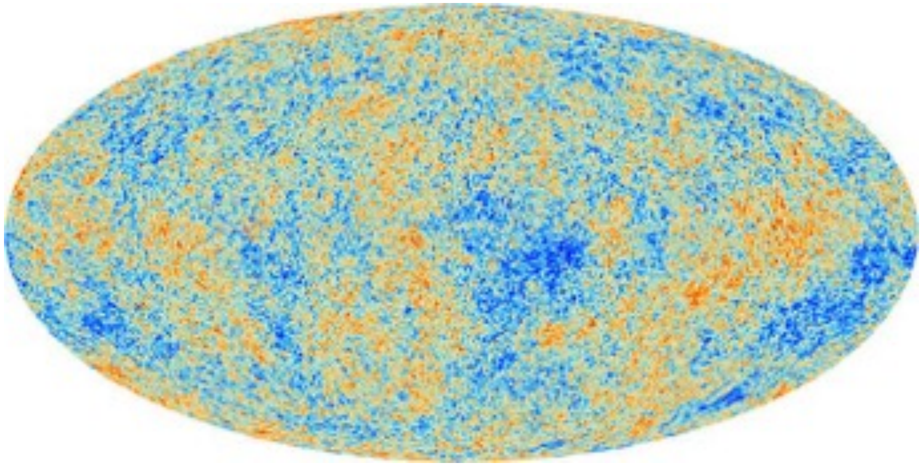
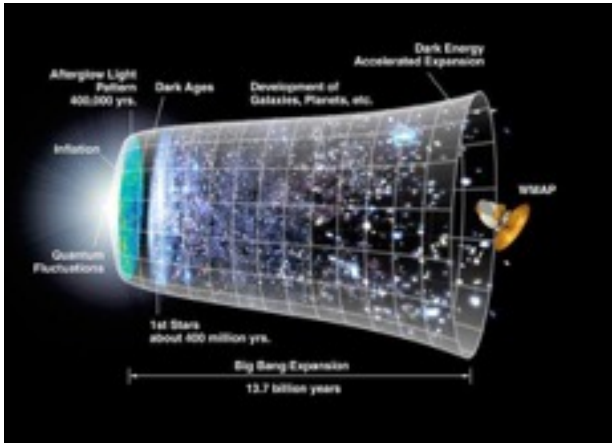
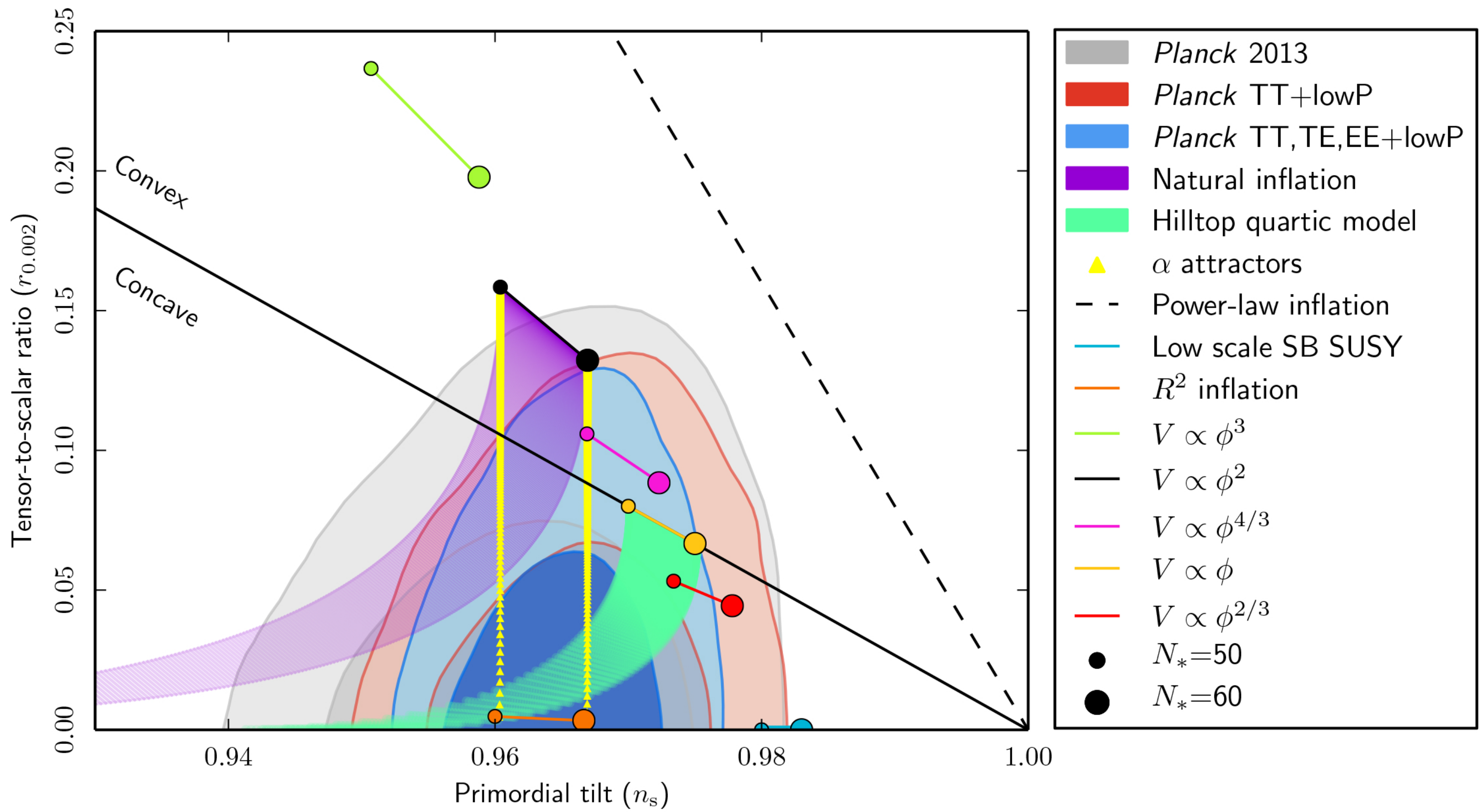




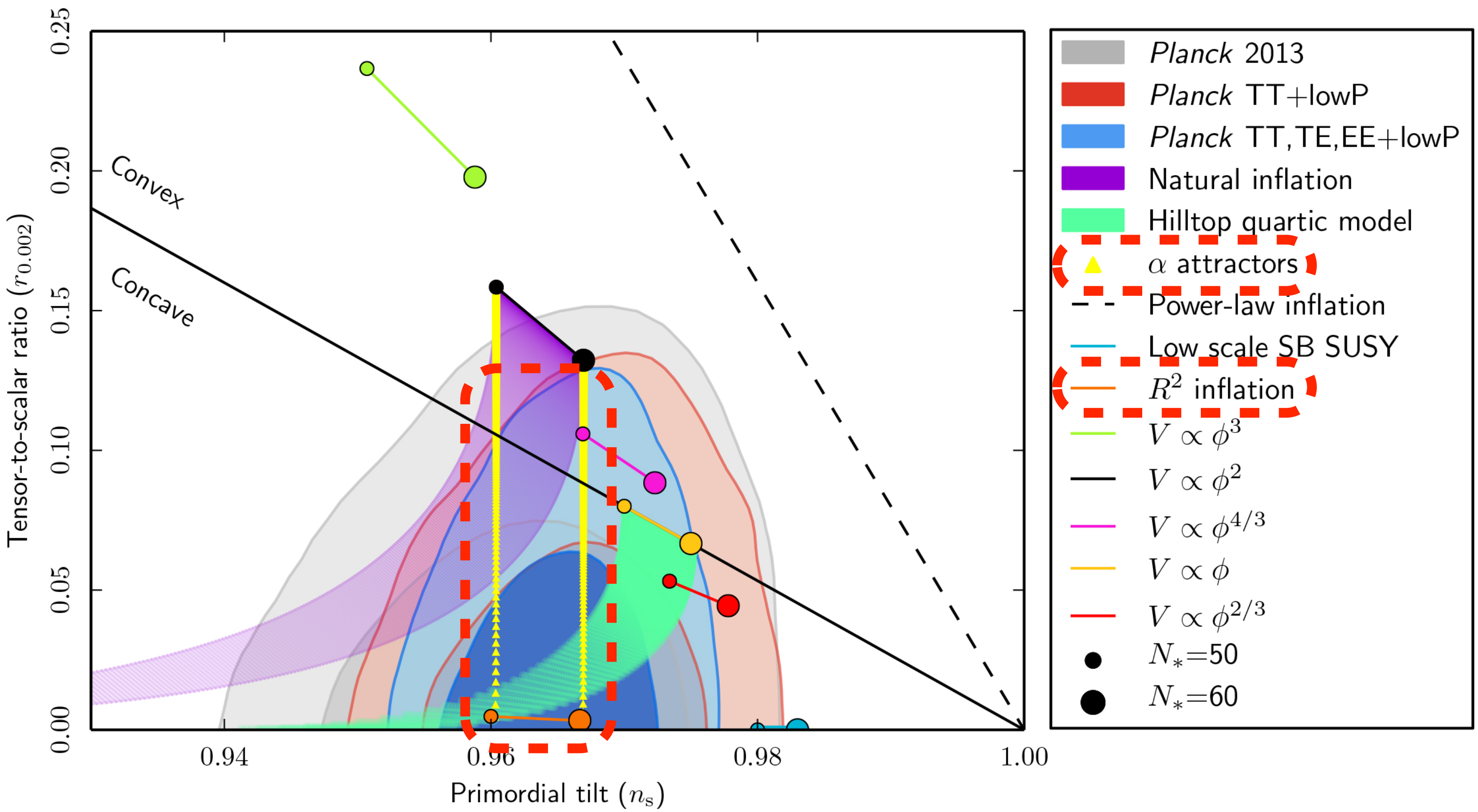
WMAP, Planck ’13



$$n_s = 0.9655 \pm 0.0062\,(68\%\,\text{C.L.})$$

$$r < 0.10\,(95\%\,\text{C.L.})$$

Planck ’15



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Planck '15

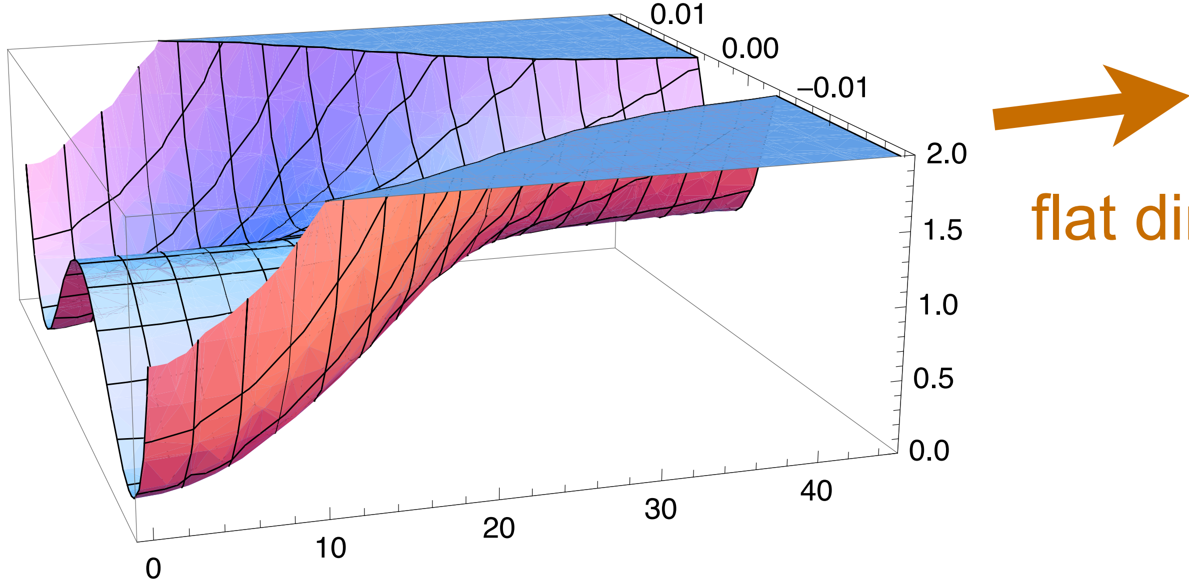
In theoretical side, inflation is interesting because it may be involved with high scale physics

$$\rho_{\rm inf}^{1/4} \simeq 1.8 \times 10^{16}\,{\rm GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

SUSY is one of possible candidates for new physics

- String theory requires SUSY
- Gauge coupling unification at the GUT scale

In fact, SUSY is compatible with inflation because it can have a flat direction in potential



flat direction = inflaton field

Many hybrid inflation models have been considered

$$V_{\mathrm{SUSY}} = V_F + V_D$$

F/D-term hybrid inflation

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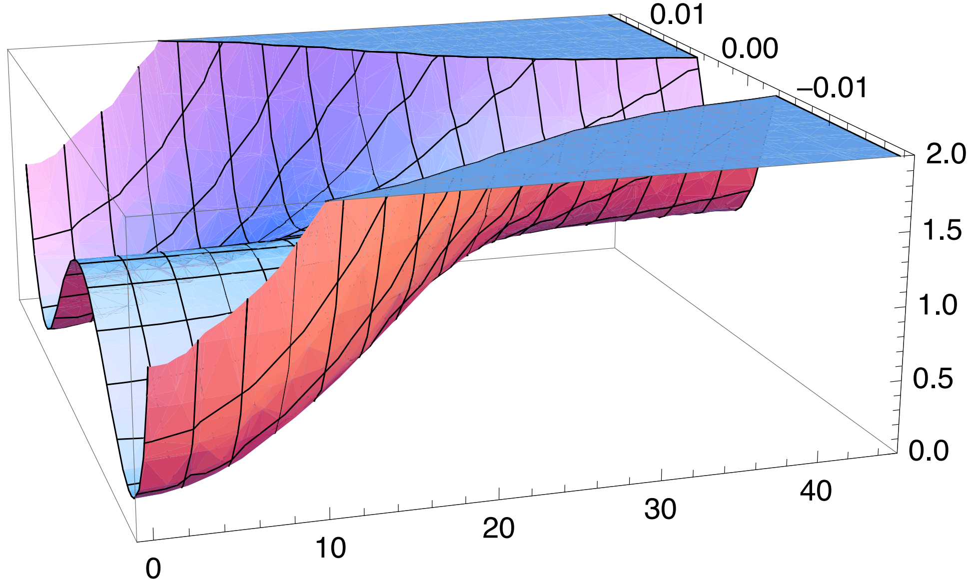


flat direction = inflaton field

Many hybrid inflation models have been considered

$$V_{\rm SUSY} = V_F + V_D$$

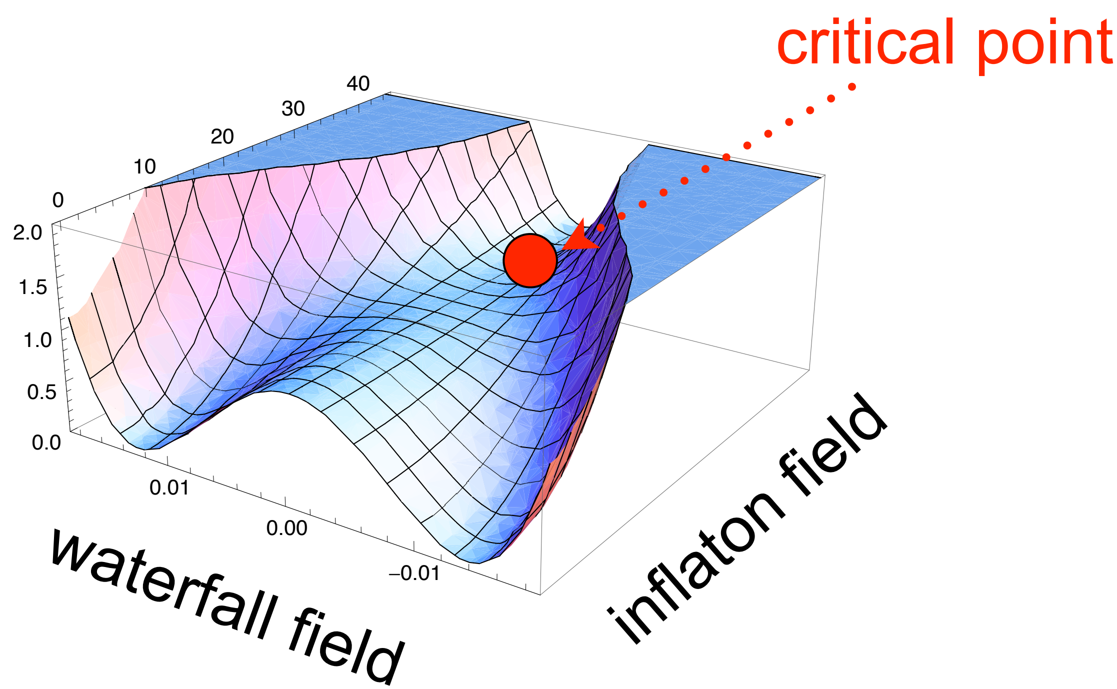
F/D-term hybrid inflation

D-term hybrid inflation (canonical case)

Binetruy, Dvali '96

Halyo '96

- Inflaton field slowly rolls down to the critical point
- At the critical point, “waterfall field” becomes tachyonic, and then inflation ends



However, the time evolution of inflaton/waterfall field depends on Kähler potential

- Canonical Kähler potential gives usual *hybrid inflation*

- Supercomformal or no-scale Kähler potential gives *Starobinsky model*

Buchmüller, Domcke, Schmitz '12
Buchmüller, Domcke, Kamada '13
Buchmüller, Domcke, Wieck '13

- Shift-symmetric Kähler potential gives "*chaotic regime*" below the critical point

Buchmüller, Domcke, Schmitz '14
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- Shift-symmetric Kähler potential gives “*chaotic regime*” below the critical point

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In our work

We study *subcritical regime* of *superconformal* D-term hybrid inflation

- Inflation continues for the subcritical inflaton value
- The potential in the subcritical regime has similar structure to superconformal α attractor models

Outline

1. Introduction
2. Subcritical regime in superconformal D-term inflation
3. Cosmological consequences
4. Conclusion

2. Subcritical regime in superconformal D-term inflation

Canonical superconformal supergravity models

Ferrara, Kallosh, Linde, Marrani, Van Proeyen ’10, ’11

Canonical superconformal supergravity models

Ferrara, Kallosh, Linde, Marrani, Van Proeyen '10, '11

- Lagrangian in Jordan frame becomes very simple form

$$\frac{1}{\sqrt{-g}}\mathcal{L}^{\text{scalar-grav}}_{\text{s.c.}} = -\frac{1}{6}\mathcal{N}(X,\bar{X})R - \eta_{I\bar{J}}D^{\mu}X^{I}D_{\mu}\bar{X}^{\bar{J}} - V_{\text{s.c.}}$$

with

$$V_{\text{s.c.}} = \eta^{I\bar{J}}\mathcal{W}_I\bar{\mathcal{W}}_{\bar{J}} + \frac{1}{2}(\text{Re}f)^{-1AB}\mathcal{P}_A\mathcal{P}_B$$

$$\eta_{0\bar{0}} = -1,\ \eta_{\alpha\bar{\beta}} = \delta_{\alpha\bar{\beta}}$$

X^0 : scalar compensator

X^{α} : matter scalar fields

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canonical kinetic term

with

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- Compensator fields are decoupled from matter sector

$$\frac{1}{\sqrt{-g_J}}\mathcal{L}^0_{\rm sugra} = \frac{M_{pl}^2}{2}(R_J + 6A_\mu A^\mu)$$ ⟵ compensator part

$$\frac{1}{\sqrt{-g_J}}\mathcal{L}^{\rm m}_{\rm s.c.} = -\frac{1}{6}|X^\alpha|^2 - \delta_{\alpha\bar\beta}D_\mu X^\alpha D^\mu \bar X^{\bar\beta} - V_J$$ ⟵ matter part

with $V_J = \delta^{\alpha\bar\beta}\mathcal{W}_\alpha\bar{\mathcal{W}}_{\bar\beta} + \frac{1}{2}({\rm Re}f)^{-1AB}\mathcal{P}_A\mathcal{P}_B$

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superconformal

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Ferrara, Kallosh, Linde, Marrani, Van Proeyen '10, '11

Jordan frame ⟶ Einstein frame

$$g_{J\mu\nu} = \Omega^2 g_{E\mu\nu} \quad \text{with} \quad \Omega^{-2} = 1 - \frac{|X^\alpha|^2}{3M_{pl}^2}$$

$$\frac{1}{\sqrt{-g_E}}\mathcal{L}^E_{\rm sugra} = \frac{M_{pl}^2}{2}R_E - K_{\alpha\bar\beta}D_\mu X^\alpha D^\mu \bar X^{\bar\beta} - V_E$$

$$K_{\alpha\bar\beta} = \frac{\partial^2 K}{\partial X^\alpha \partial \bar X^{\bar\beta}}$$

with

$$K = -3M_{pl}^2 \log \Omega^{-2}$$

$$V_E = \Omega^4 V_J$$

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kinetic term is not canonical

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with

"no-scale" Kähler potential

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scalar potential has a simple form

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Einstein frame

- No-scale Kähler potential $$K = -3M_{pl}^2 \log \Omega^{-2}$$
- Simple scalar potential $$V_E = \Omega^4 V_J$$
- Matter part is superconformal $$\Omega^{-2} = 1 - \frac{|X^\alpha|^2}{3M_{pl}^2}$$

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- Matter part is superconformal $$\Omega^{-2} = 1 - \frac{|X^\alpha|^2}{3M_{pl}^2} + \ldots$$

~~Superconformal~~ term

(since superconformality is broken)

The model

Buchmüller, Domcke, Schmitz '12
Buchmüller, Domcke, Kamada '13

Superconformal D-term hybrid inflation model

	Φ	S_+	S_-
U(1)	0	q	$-q$

$q > 0$

- Superpotential: $W = \lambda \Phi S_+ S_-$
- Kähler potential: $K = -3 \log \Omega^{-2}$

with $$\Omega^{-2} = 1 - \frac{1}{3}\left(|S_+|^2 + |S_-|^2 + |\Phi|^2\right) - \frac{\chi}{6}\left(\Phi^2 + \bar{\Phi}^2\right)$$

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Superconformal D-term hybrid inflation model

(with an explicit ~~superconformal~~ term)

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~~Superconformal~~ term

$$
\begin{aligned}
K &= -3\log\Omega^{-2}\\
&\qquad \Omega^{-2} = 1 - \frac{1}{3}\left[(1+\chi)(\mathrm{Re}\,\Phi)^2 + (1-\chi)(\mathrm{Im}\,\Phi)^2 + |S_+|^2 + |S_-|^2\right]\\
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$$

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Kähler potential has a shift symmetry

$$\mathrm{Re}\,\Phi \to \mathrm{Re}\,\Phi + \mathrm{const} \quad \text{for} \quad \chi = -1$$

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In the following discussion, we focus on

$\chi \simeq -1$ (and $\lambda \ll 1$) and $\mathrm{Re}\,\Phi$ as inflaton

Scalar potential (in Einstein frame)

- F-term

$$V_F = \Omega^4 \lambda^2 \left[|\Phi|^2 \left(|S_+|^2 + |S_-|^2 \right) + |S_+ S_-|^2 - \frac{\chi^2 |S_+ S_- \Phi|^2}{3 + \frac{\chi}{2}\left(\Phi^2 + \bar{\Phi}^2\right) + \chi^2 |\Phi|^2} \right]$$

- D-term

$$V_D = \frac{1}{2} g^2 \left(q\Omega^2 (|S_+|^2 - |S_-|^2) - \xi \right)^2$$

$\xi (> 0)$: constant Fayet-Iliopoulos term

Buchmüller, Domcke, Schmitz '12

see also

Binetruy, Dvali, Kallosh, Proeyen '04
Dienes, Thomas '09
Komargodski, Seiberg '10
Catino, Villadoro, Zwirner '11

$$\longrightarrow \quad V_{\rm tot}(\phi, s) = V_F + V_D$$
$$= \frac{\Omega^4(\phi, s)\lambda^2}{4} s^2\phi^2 + \frac{g^2}{8}\left(q\Omega^2(\phi, s)s^2 - 2\xi\right)^2$$
$$\Omega^{-2}(\phi, s) = 1 - \frac{1}{6}\left(s^2 + (1+\chi)\phi^2\right)$$

$s \equiv \sqrt{2}|S_+|$ → waterfall field

$\phi \equiv \sqrt{2}{\rm Re}\,\Phi$ → inflaton field

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Suppose the initial inflaton value is super-Planckian (due to the approximated shift symmetry)

We have found that the dynamics of the inflaton/ waterfall fields are similar to *subcritical hybrid inflation*

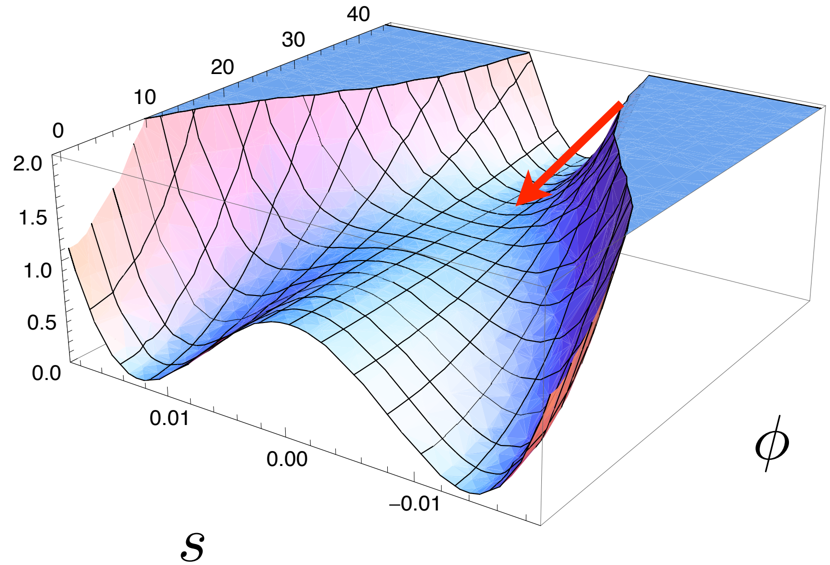
Subcritical hybrid inflation

Buchmüller, Domcke, Schmitz ’14
Buchmüller, KI ’15

1) Inflaton rolls down to the critical point from super-Planckian value

2) At

3) Inflaton is still slow-rolling and inflation continues



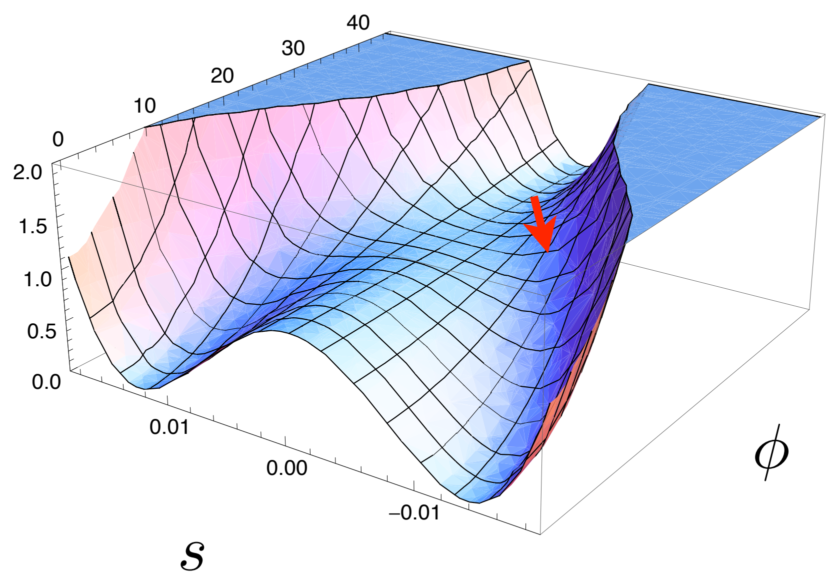
Subcritical hybrid inflation

Buchmüller, Domcke, Schmitz ’14
Buchmüller, KI ’15

1) Inflaton rolls down to the critical point

2) At the critical point, waterfall field begins to grow

3) Inflaton is still slow-rolling and inflation continues



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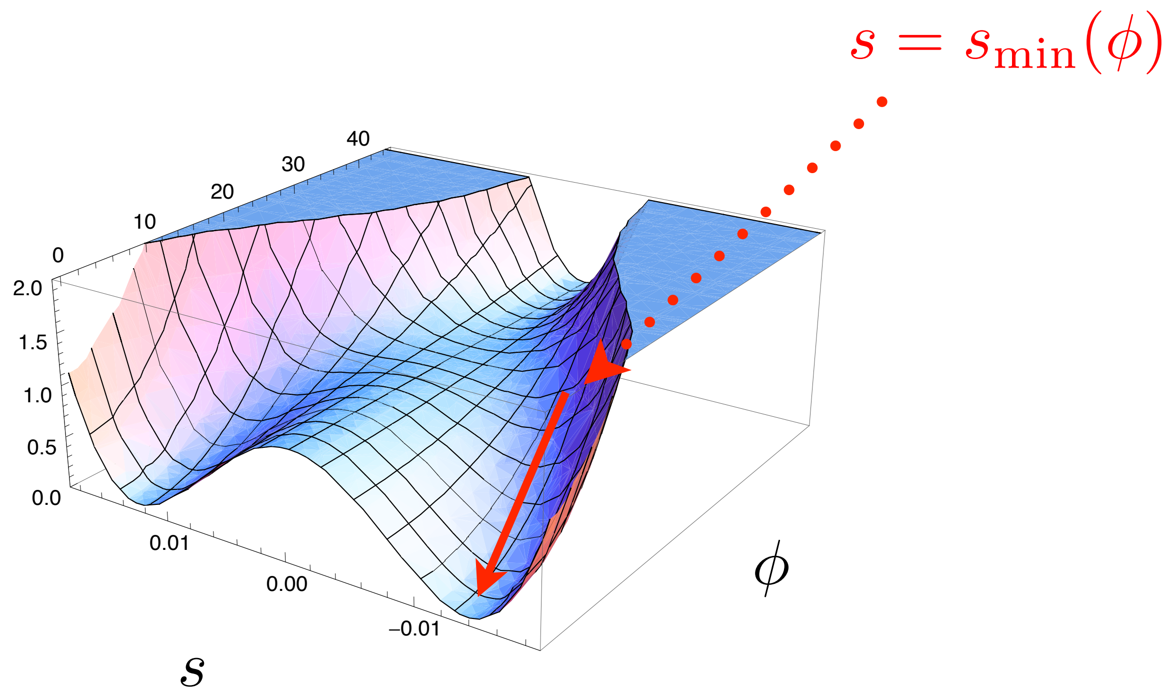

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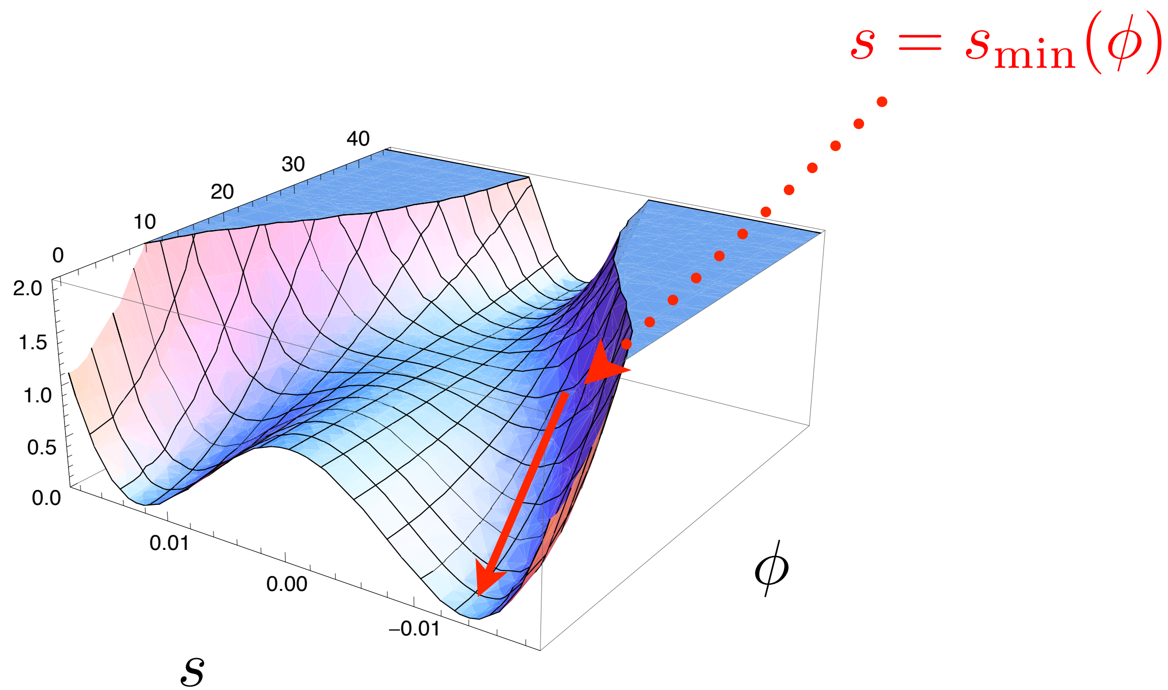
→ Cosmological consequences are determined by the subcritical regime



Potential in subcritical regime

$$V \equiv V_{\rm tot}(\phi, s_{\rm min})$$

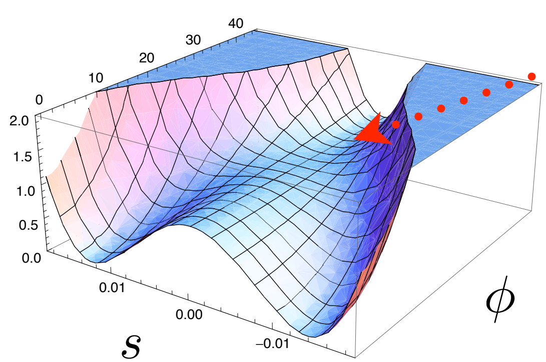
$$= g^2\xi^2(1+\tilde{\xi})\Psi^2 \frac{1 - \frac{\Psi^2}{2(1+\tilde{\xi})}}{1+2\tilde{\xi}\Psi^2}$$

$$\Psi \equiv \frac{\Omega(\phi, 0)\phi}{\Omega(\phi_c, 0)\phi_c}$$

$$\tilde{\xi} \equiv \xi/(3q)$$

$$\phi_c^2 = \frac{6qg^2\xi}{3\lambda^2 + (1+\chi)qg^2\xi}$$

critical point



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$$\tilde{\xi} \equiv \xi/(3q)$$

$$\phi_c^2 = \frac{6qg^2\xi}{3\lambda^2 + (1+\chi)qg^2\xi}$$

→ Remaining task:

Solve the dynamics of the inflaton to give cosmological parameters

3. Cosmological consequences

Observables

- Scalar spectral index: n_s
- Tensor-to-scalar ratio: r
- Scalar amplitude: A_s

$$A_s = 2.198^{+0.076}_{-0.085} \times 10^{-9}$$

Planck '15

← Slow-roll parameters $\epsilon, \, \eta$ for given number of e-folds N_*

→ n_s and r are determined for given N_*

Preparation for numerical study

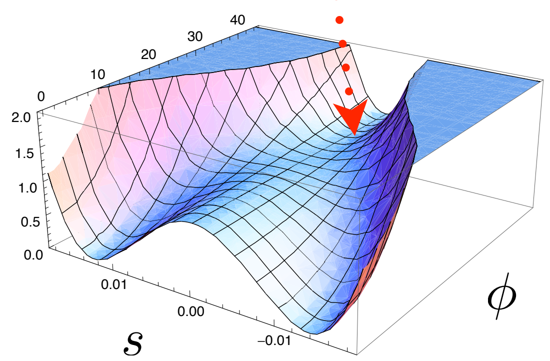
- We rewrite χ as

$$\chi = -1 - \frac{3\lambda^2}{qg^2\xi}\delta\chi \qquad (0 < \delta\chi < 1)$$

$$\phi_c^2 = \frac{2qg^2\xi}{\lambda^2(1-\delta\chi)} > 0$$

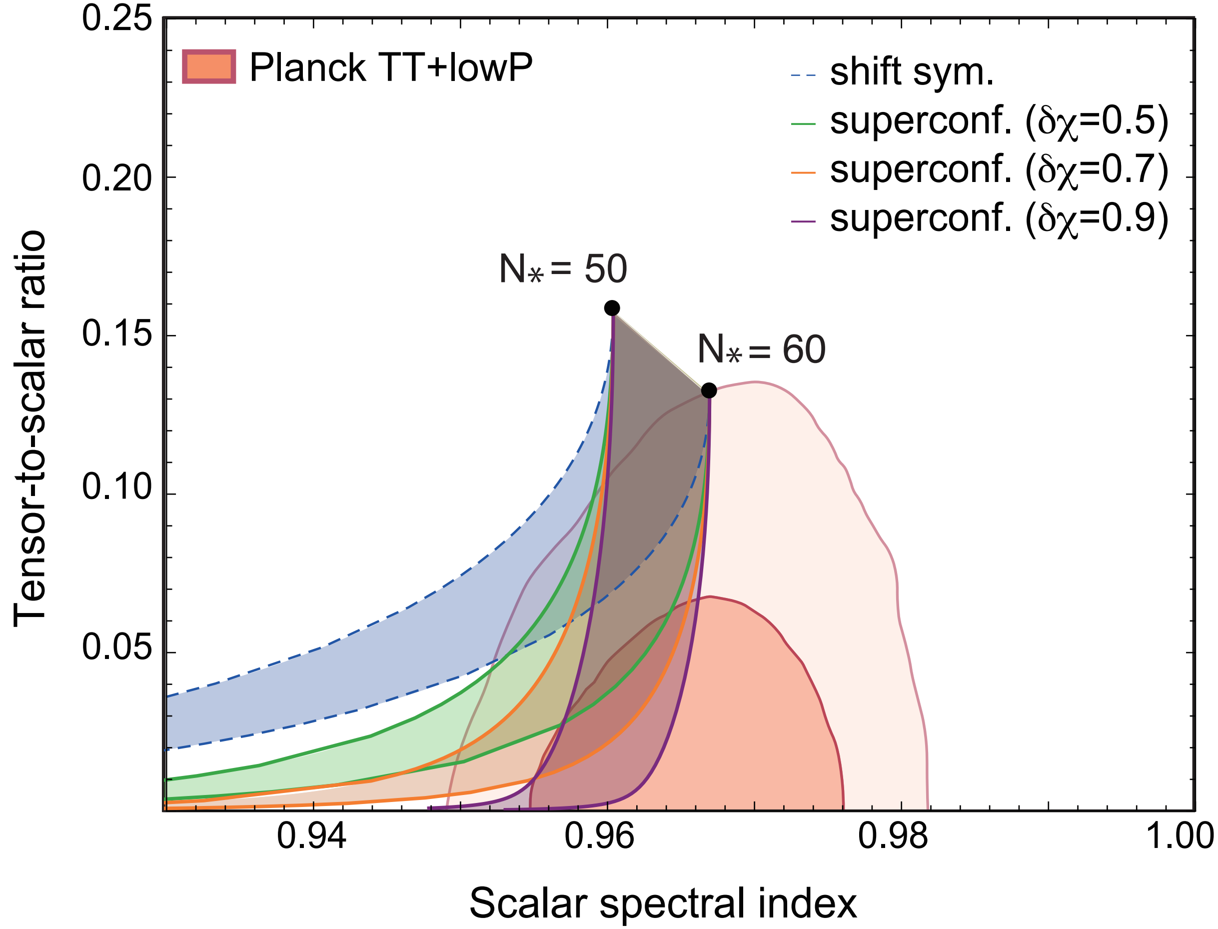
critical point value

critical point

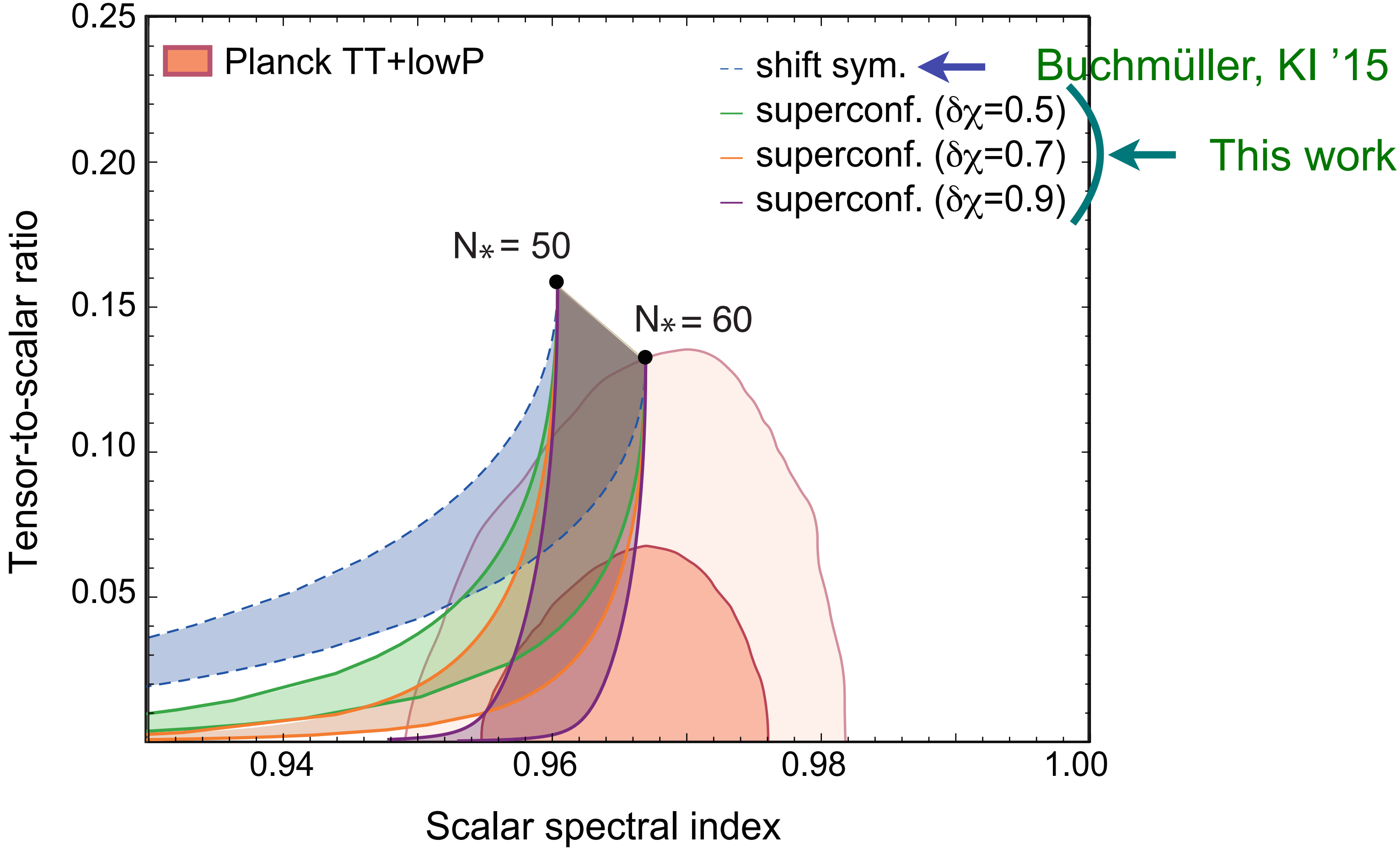


- $q,\ g$ can be absorbed in redefinition of $\lambda,\ \xi$

$$\longrightarrow \quad q = g = 1$$



- $\delta\chi \to 0$
- $\delta\chi \to 1$ α



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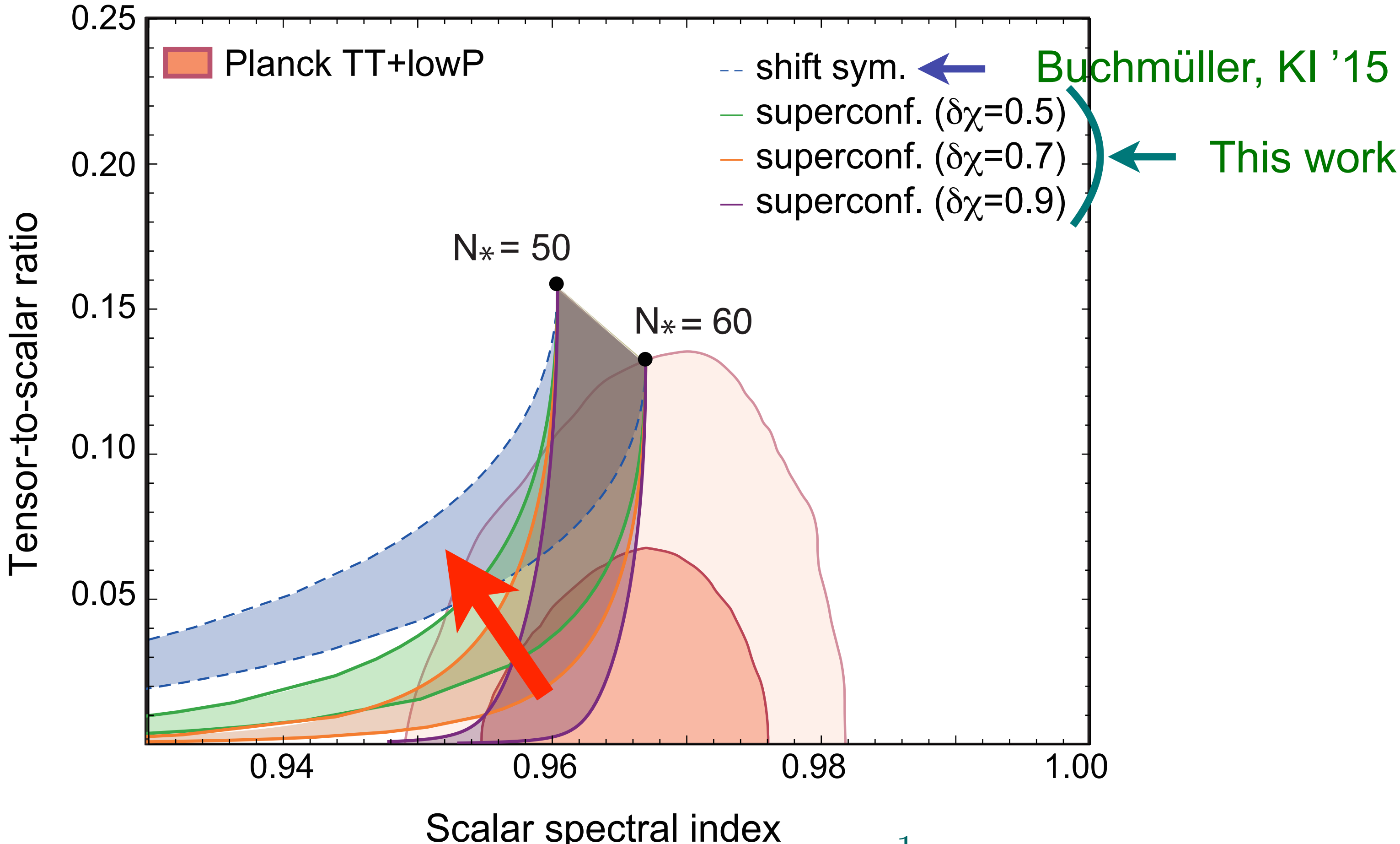
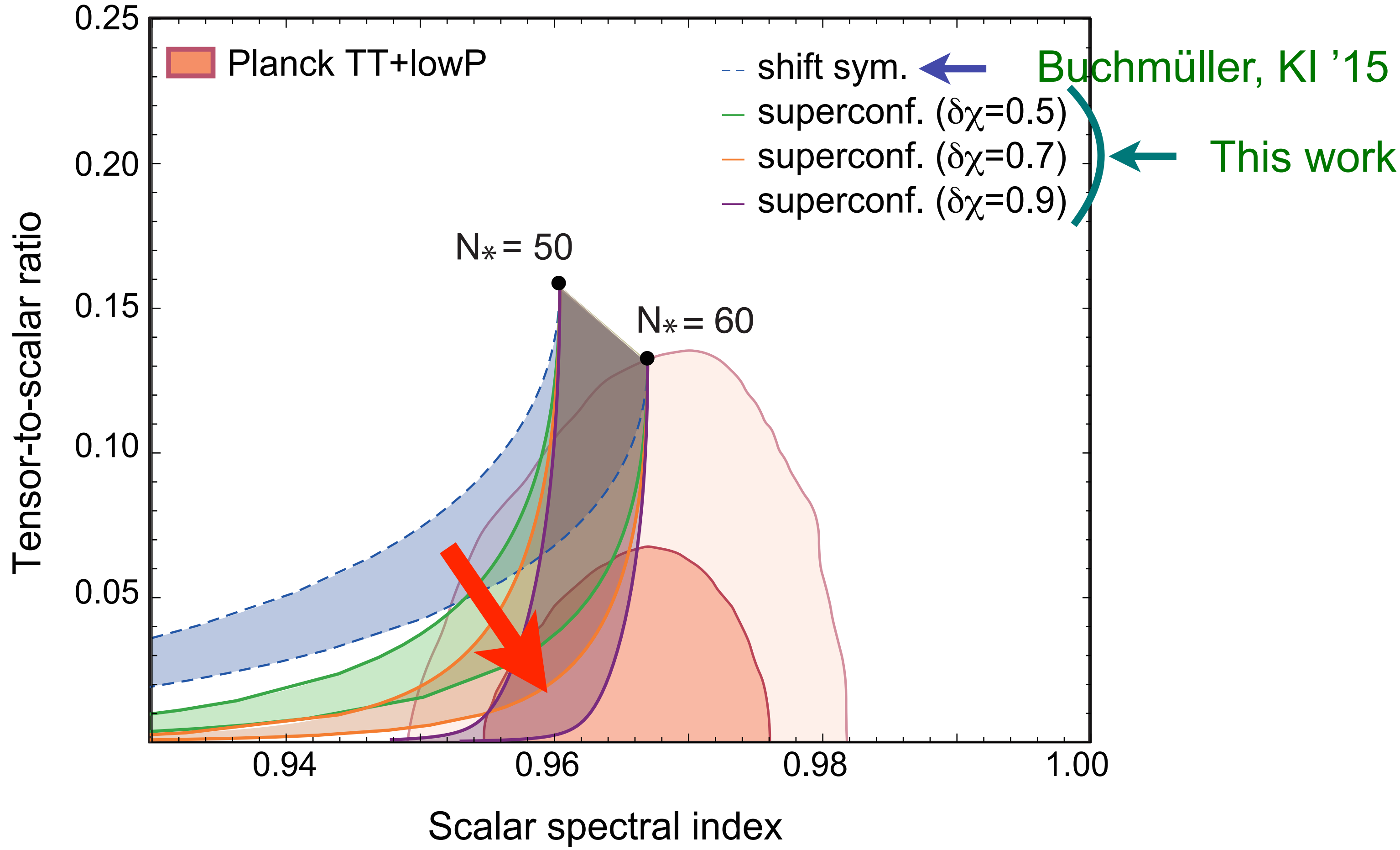


$$K = \frac{1}{2}(\Phi + \bar{\phi})^2 + |S_+|^2 + |S_-|^2$$

- $\delta\chi \to 0$ approaches to the shift symmetric Kähler case
- $\delta\chi \to 1$ α



- $\delta\chi \to 0$
- $\delta\chi \to 1$ looks similar to α attractor models

To understand the behavior,
let's derive the potential in canonically-normalized inflaton field $\hat{\phi}$

$$\frac{d\phi}{d\hat{\phi}} = K_{\Phi\bar{\Phi}}^{-1/2} \simeq \sqrt{1 - \frac{1}{6}(1+\chi)\phi^2}$$

$$\longrightarrow \quad \phi = \frac{1}{\sqrt{\beta}} \sinh \sqrt{\beta}\hat{\phi}$$

$$\beta = \frac{\lambda^2}{2qg^2\xi}\delta\chi$$

$$\longrightarrow \quad V \simeq g^2\xi^2\delta\chi^{-1} \tanh^2 \sqrt{\beta}\hat{\phi} \left[1 - \frac{\delta\chi^{-1}}{2} \tanh^2 \sqrt{\beta}\hat{\phi}\right]$$

- $\delta\chi \to 0$

$$V \simeq g^2 \xi^2 \frac{\hat{\phi}^2}{\phi_c^2} \left(1 - \frac{\hat{\phi}^2}{2\phi_c^2} \right)$$

Buchmüller, Domcke, Schmitz ’14
Buchmüller, KI ’15

⟶ Same potential in shift sym. Kähler: $K = \frac{1}{2}(\Phi + \bar{\Phi})^2 + |S_+|^2 + |S_-|^2$

- $\delta\chi \to 1$

$$V \simeq \frac{1}{2} g^2 \xi^2 \left[1 - 16 e^{-4\sqrt{\beta}\hat{\phi}} \right]$$ (for large $\hat{\phi}$)

⟶ Same asymptotic form with Starobinsky model or R^2 inflation or simplest class of superconformal α attractor model

Whitt ’
Kallosh, Linde ’
Kallosh, Linde, Roest ’

- $\delta\chi \to 0$

$$V \simeq g^2\xi^2 \frac{\hat{\phi}^2}{\phi_c^2}\left(1 - \frac{\hat{\phi}^2}{2\phi_c^2}\right)$$

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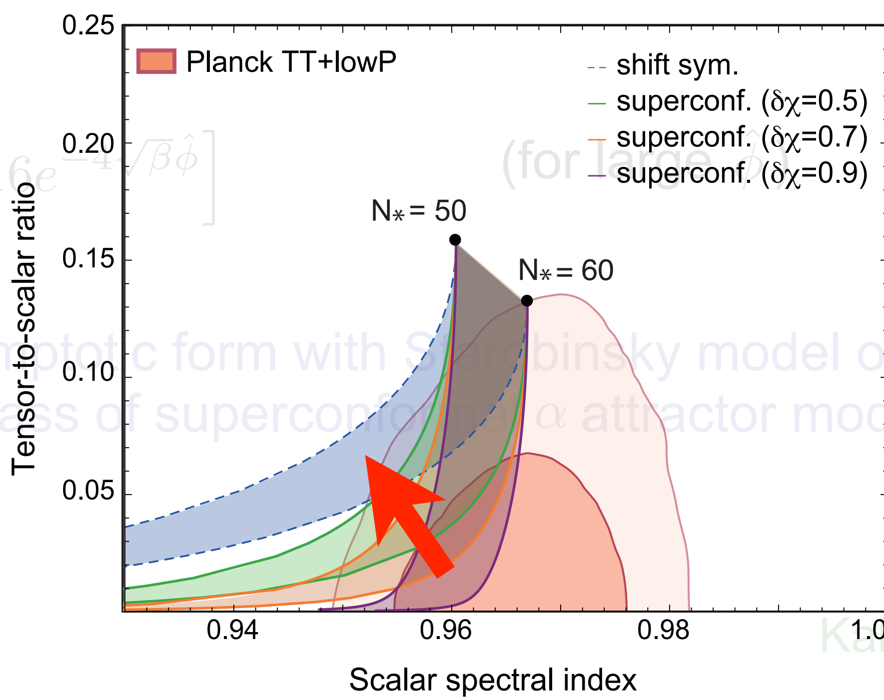

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Buchmüller, Domcke, Schmitz '14
Buchmüller, Kl '1

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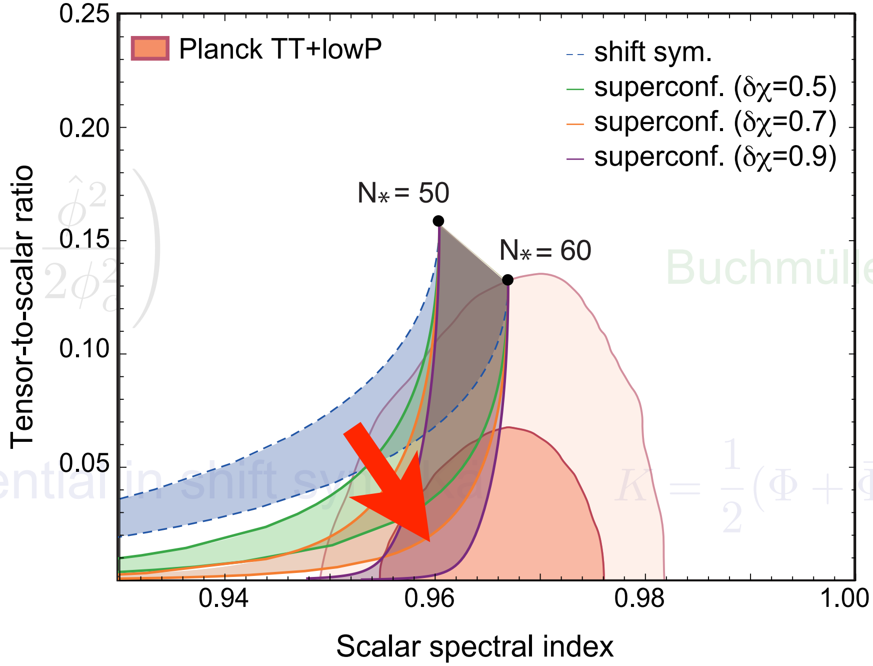
⟶ Same asymptotic form with Starobinsky model or R^2 inflation or α attractor model

Whitt '84
Kallosh, Linde '13
Kallosh, Linde, Roest '13



- $\delta\chi \to 1$

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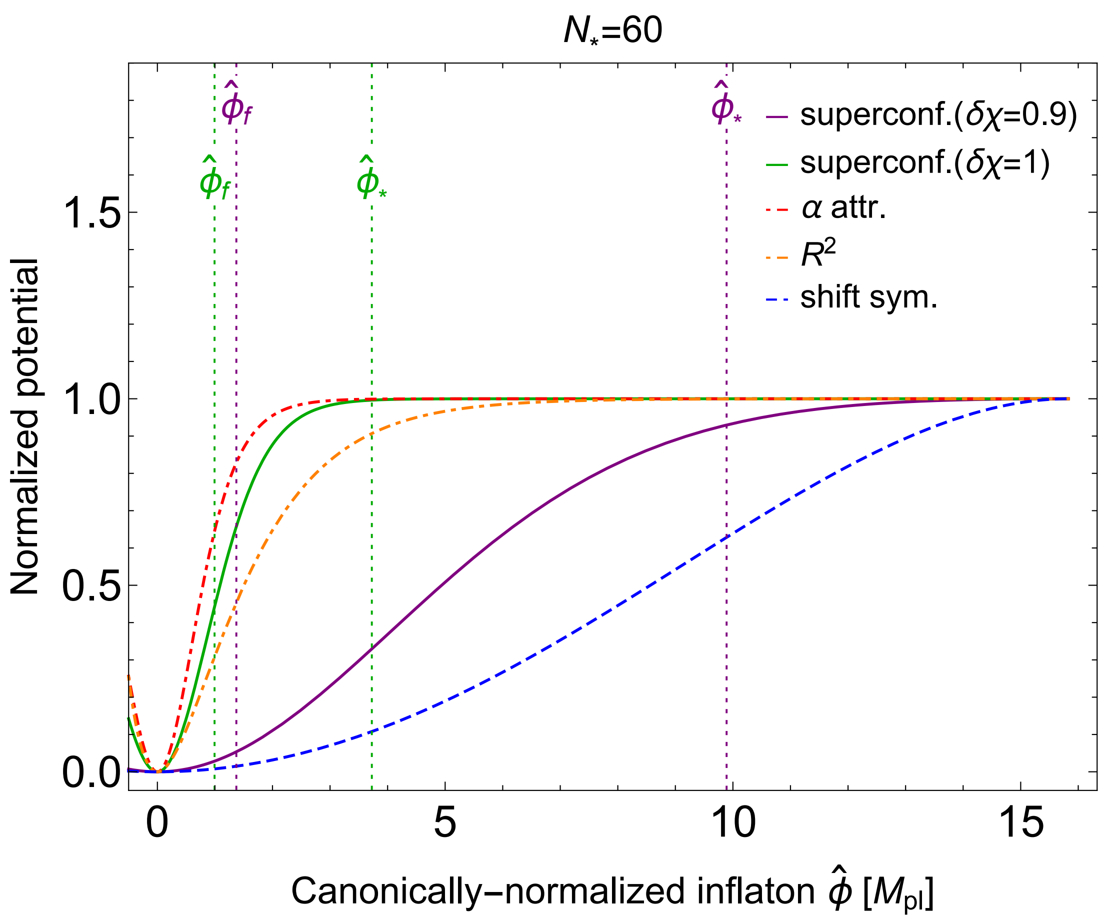
⟶ Same asymptotic form with Starobinsky model or R^2 inflation or α attractor model

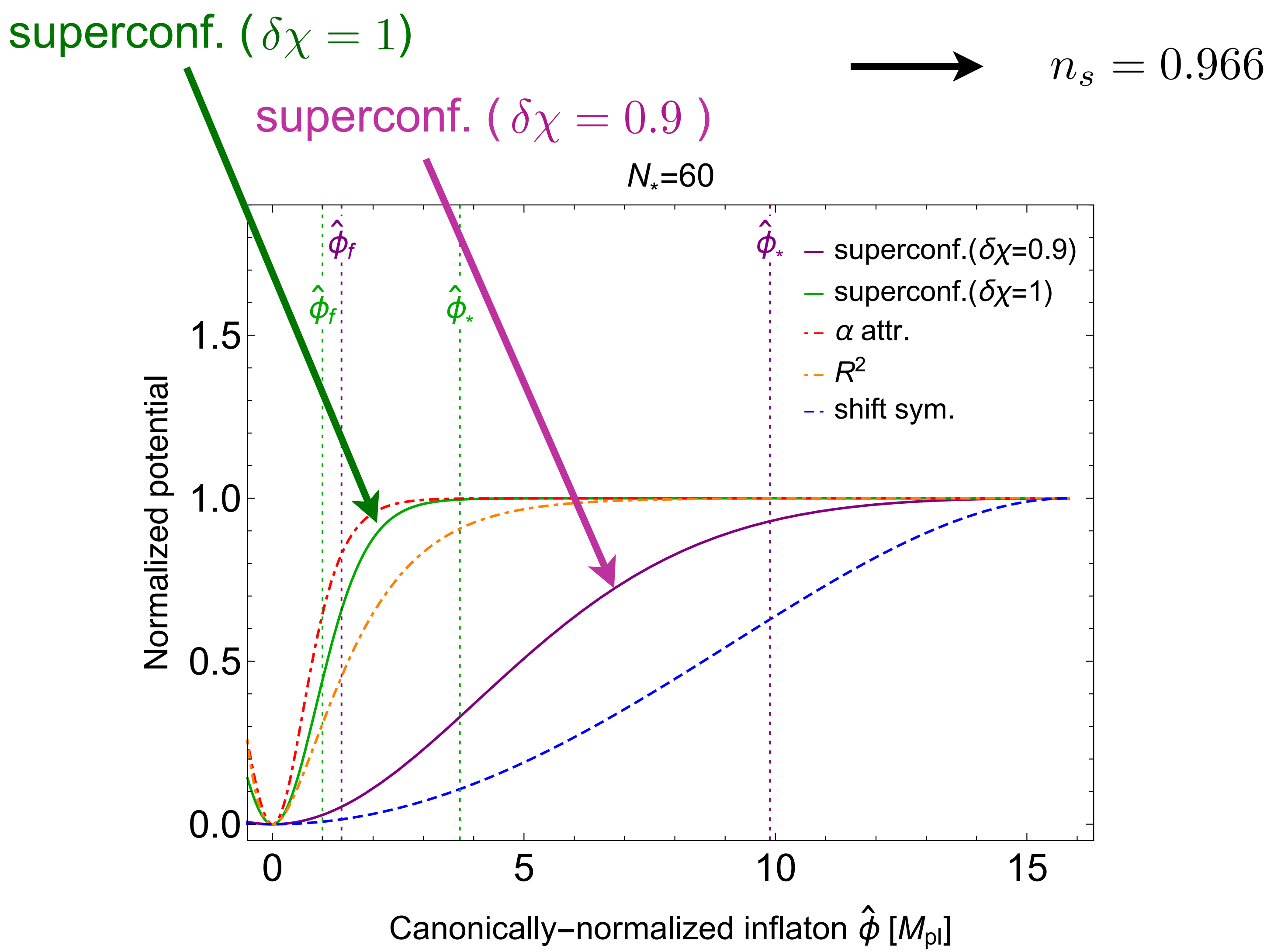
Whitt '84

Kallosh, Linde '13

Kallosh, Linde, Roest '13



N_*=60
$\hat{\phi}_f$
$\hat{\phi}_*$
$\hat{\phi}_f$
$\hat{\phi}_*$
superconf.($\delta\chi$=0.9)
superconf.($\delta\chi$=1)
α attr.
R^2
shift sym.
Normalized potential
1.5
1.0
0.5
0.0
0
5
10
15
Canonically–normalized inflaton $\hat{\phi}$ [$M_{\rm pl}$]



superconf. ($\delta\chi = 1$)
$n_s = 0.966$
superconf. ($\delta\chi = 0.9$)
N_*=60
$\hat{\phi}_f$
$\hat{\phi}_*$
$\hat{\phi}_f$
$\hat{\phi}_*$
superconf.($\delta\chi$=0.9)
superconf.($\delta\chi$=1)
α attr.
R^2
shift sym.
Normalized potential
1.5
1.0
0.5
0.0
0
5
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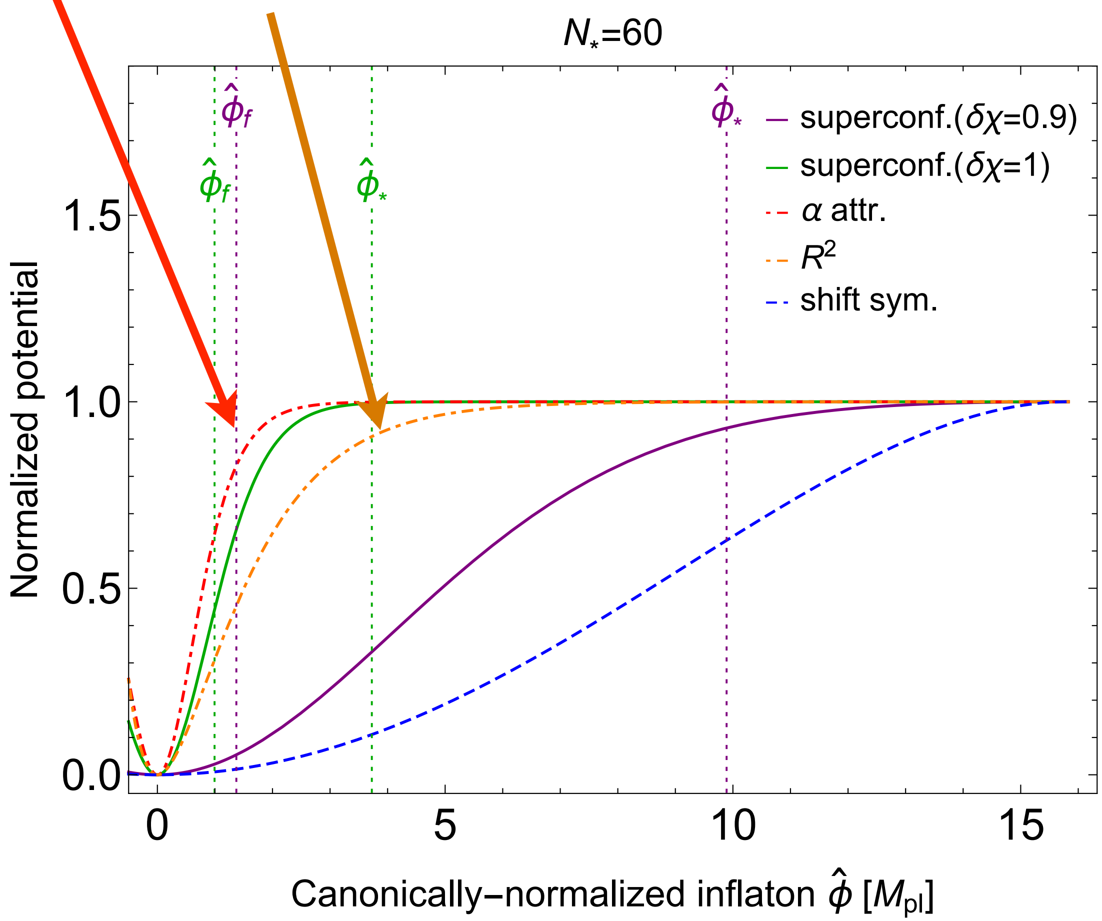
Canonically–normalized inflaton $\hat{\phi}$ [$M_{\rm pl}$]

α attractor

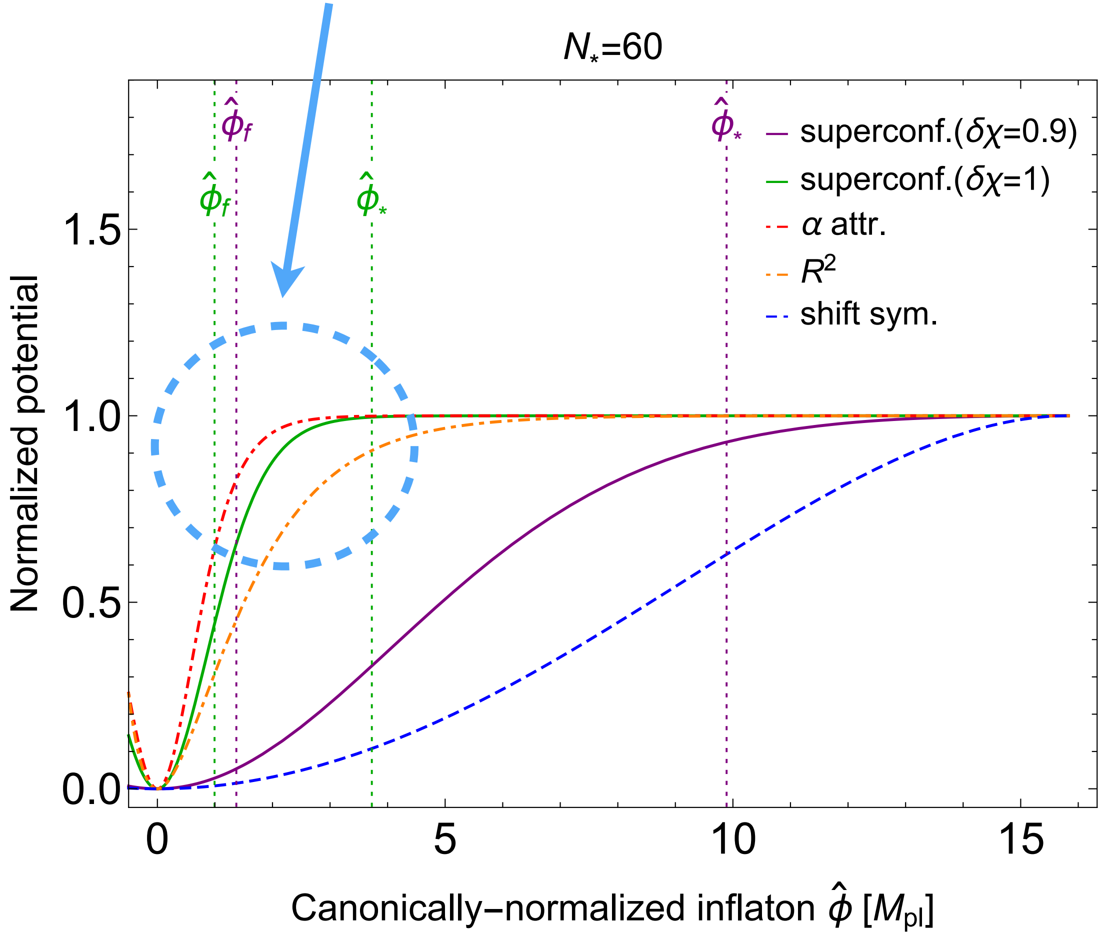
R^2

) the same asymptotic form as $\delta\chi = 1$



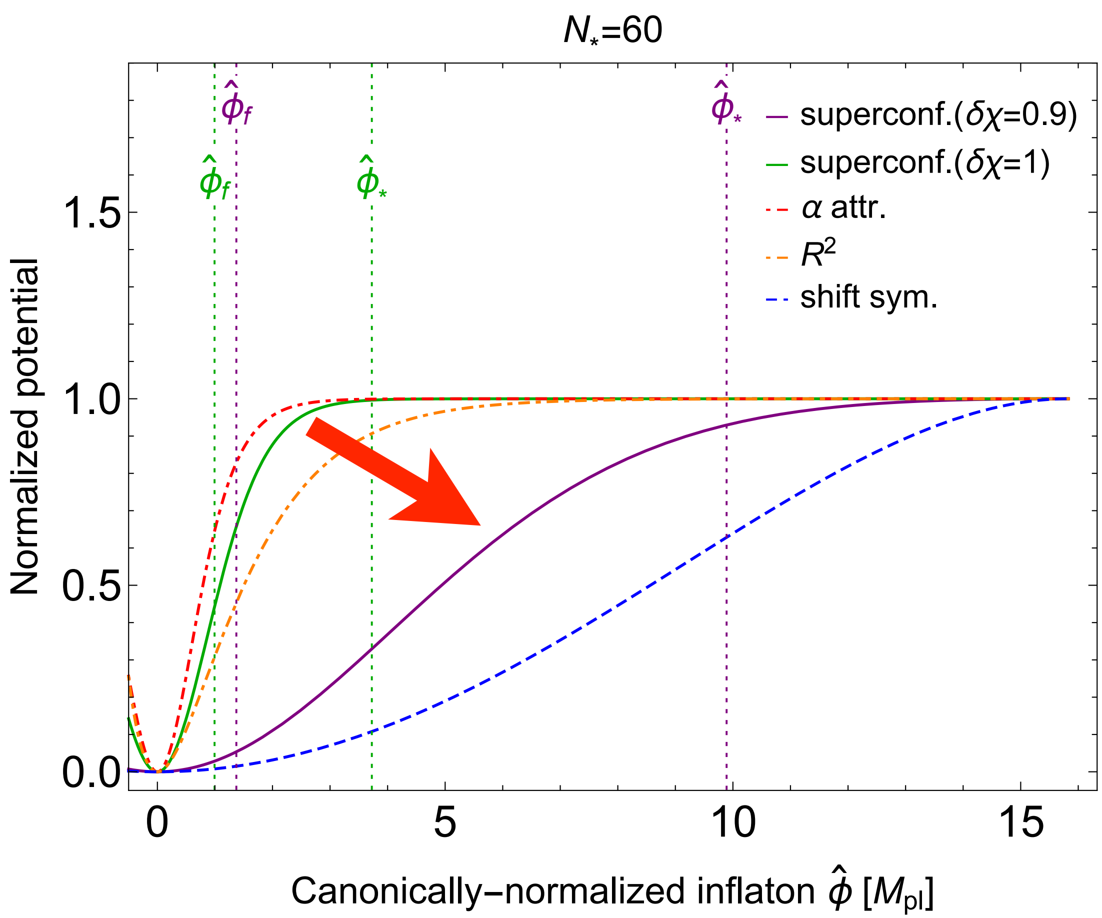
$\delta\chi = 1$ behaves similar to α attractors and R^2 model

But not exactly the same



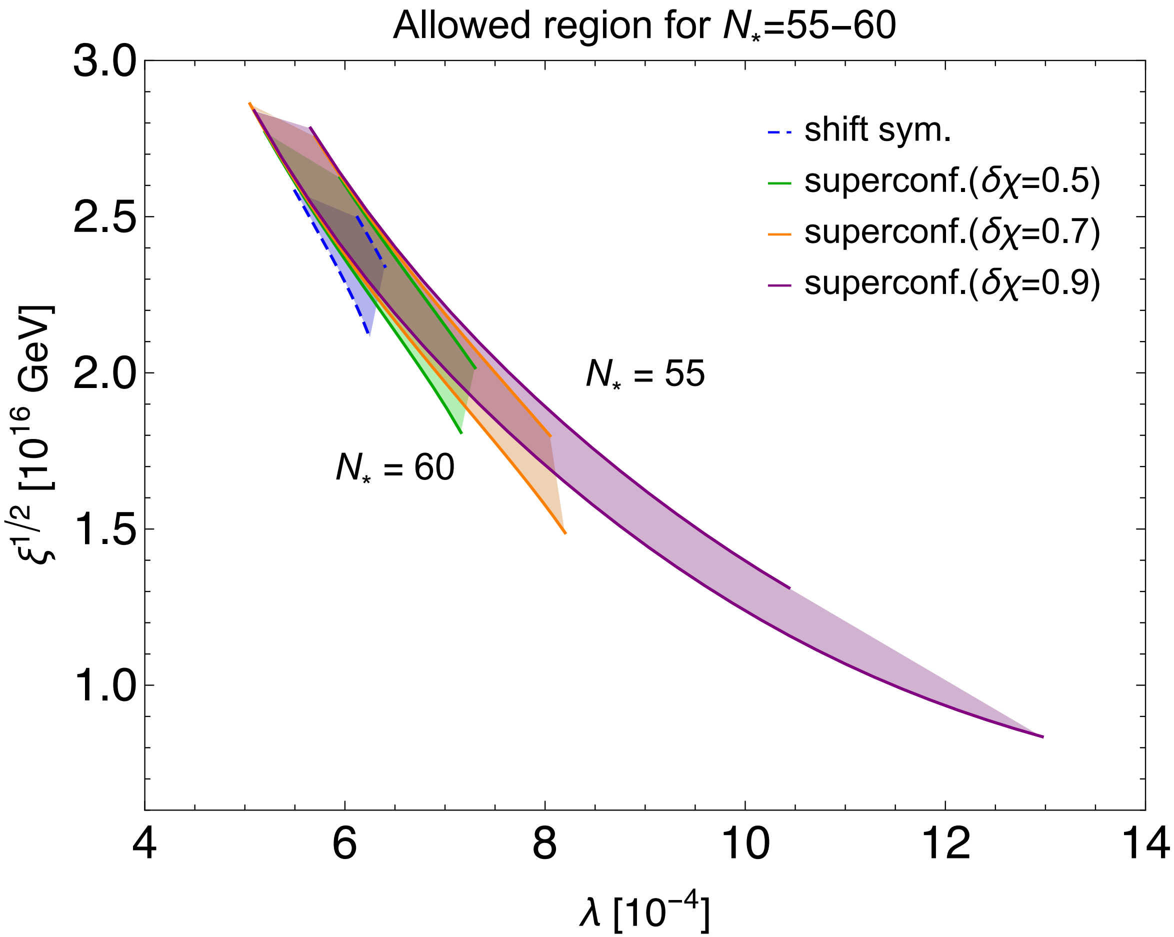
$r = 0.00052$ for superconf. ($\delta\chi = 1$)

$r = 0.00044$ for α attractor , R^2



The deviation from the α attractors and R^2 model gets larger even for $\delta\chi = 0.9$

→ $r = 0.051$



$\lambda \sim 10^{-4}$-10^{-3} and $\sqrt{\xi} \sim 10^{16}\,\mathrm{GeV}$ are consistent with the data

Consistency in the parameters

- A shift symmetry for $\chi = -1$

- $\phi_c^2 > 0$

$$K = -3 \log \Omega^{-2}$$

$$\Omega^{-2} \simeq 1 - \frac{1}{6}(1+\chi)\phi^2$$

$$W = \lambda \Phi S_+ S_-$$

$$\chi = -1 - \frac{3\lambda^2}{\xi}\delta\chi \qquad (0 < \delta\chi < 1)$$

↑

$\phi_c^2 > 0$

$\chi \simeq -1$ ⟶ $\lambda \ll 1$ (expectation)

(ϕ as inflaton)

Consistency in the parameters

- A shift symmetry for $\chi = -1$

$$K = -3 \log \Omega^{-2}$$

$$\Omega^{-2} \simeq 1 - \frac{1}{6}(1+\chi)\phi^2$$

$$W = \lambda \Phi S_+ S_-$$

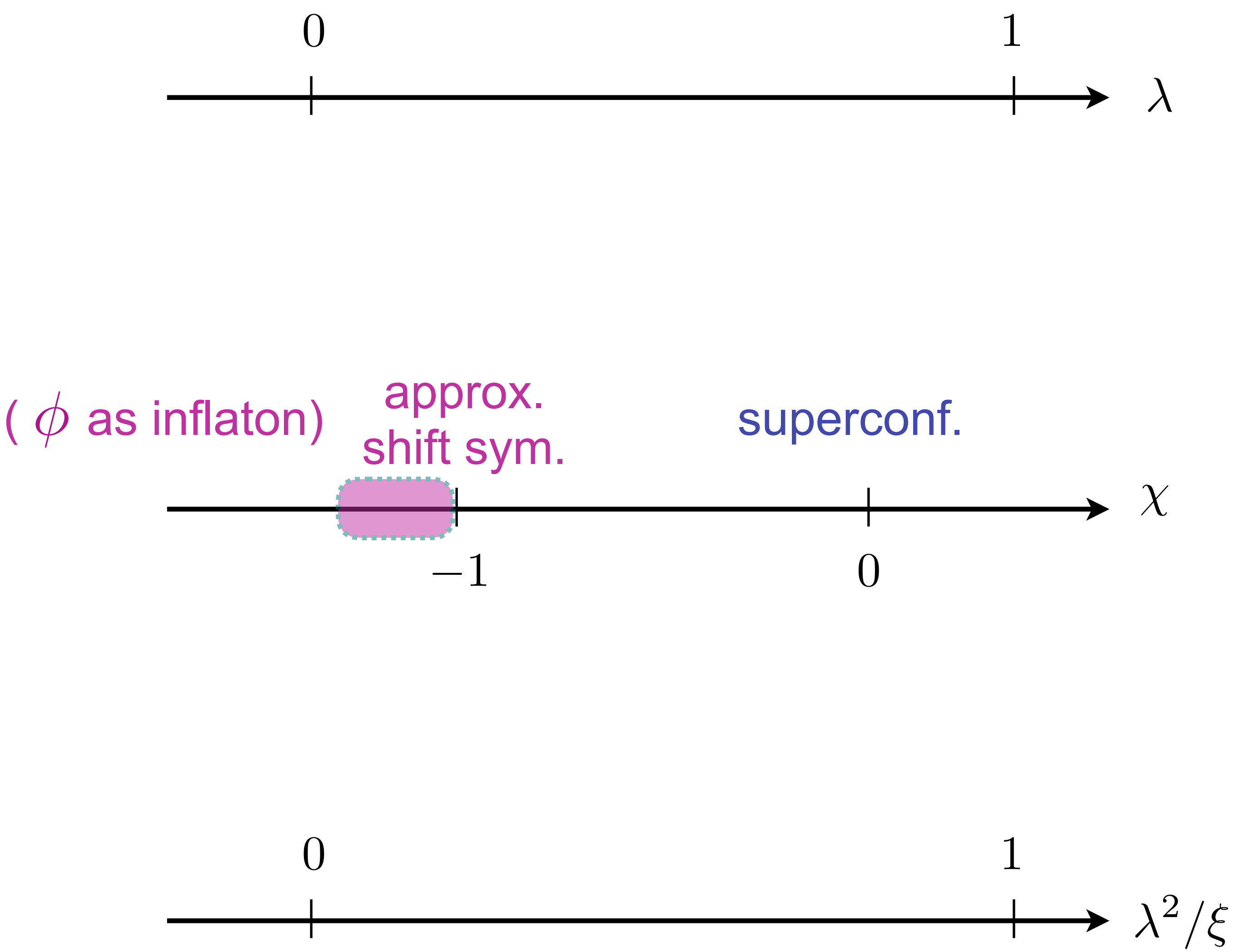
- $\phi_c^2 > 0$

$$\chi = -1 - \frac{3\lambda^2}{\xi}\delta\chi \qquad (0 < \delta\chi < 1)$$

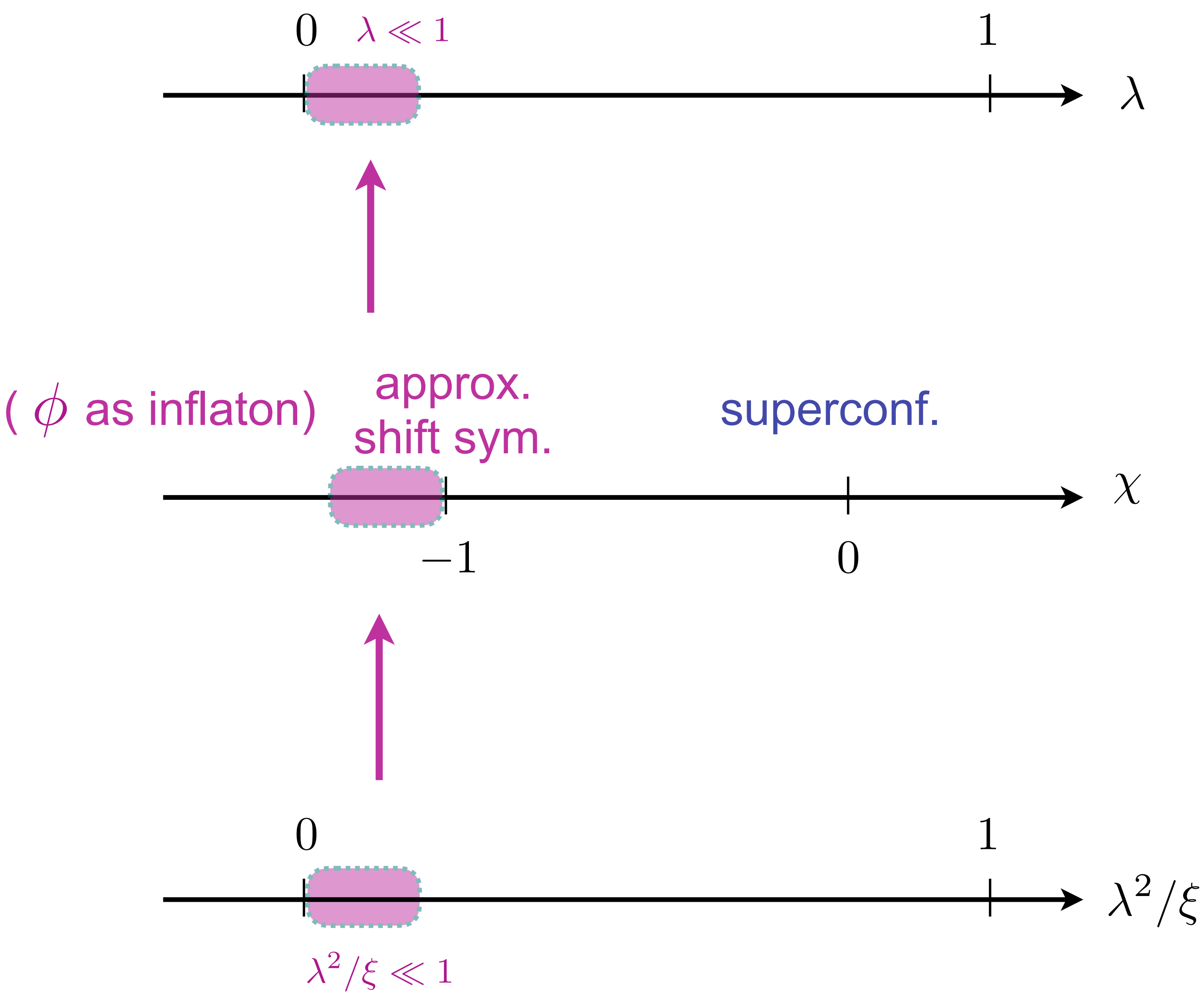
$$\phi_c^2 > 0$$

$$\chi \simeq -1 \longleftarrow \lambda^2/\xi \ll 1$$

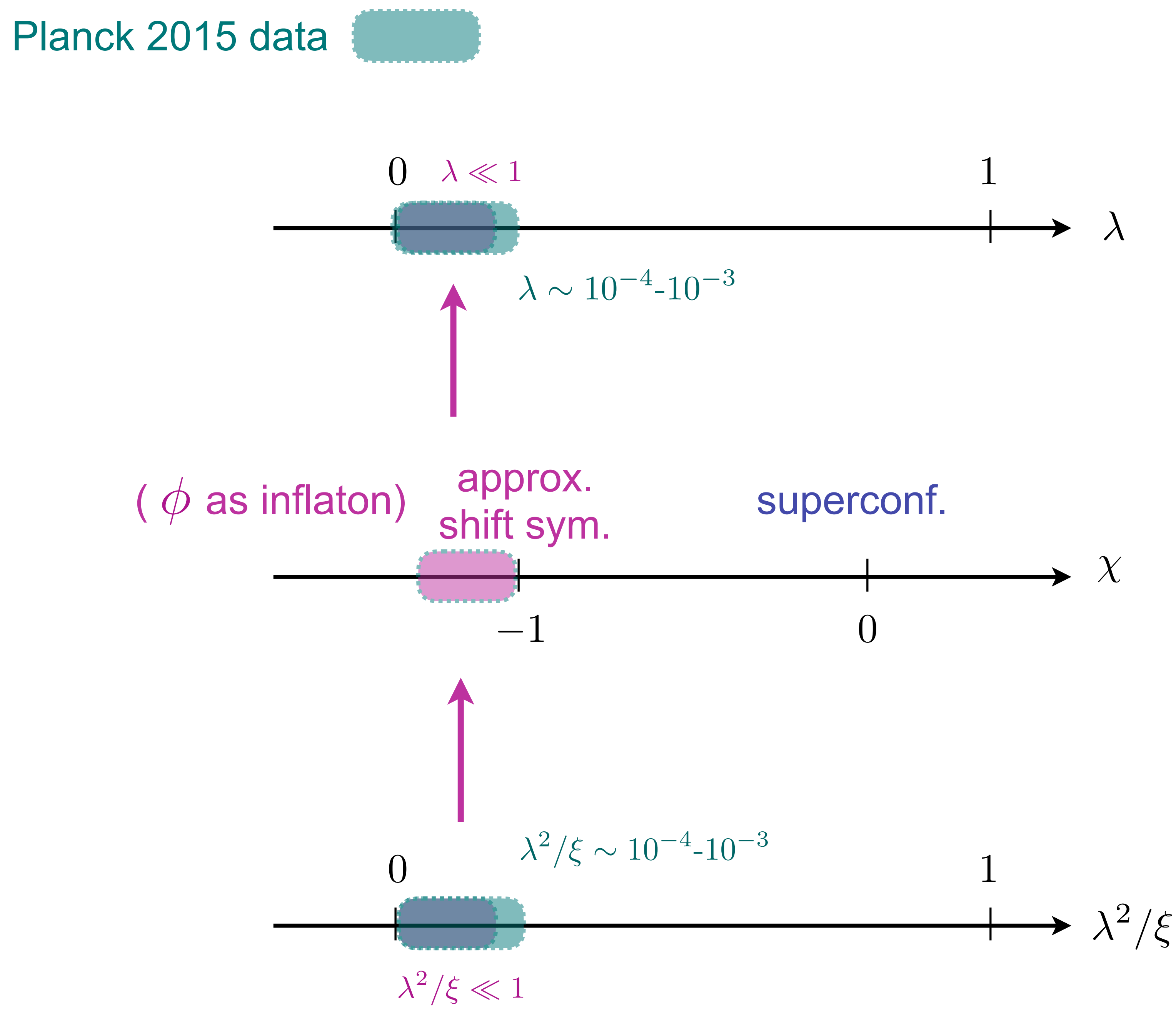
(ϕ as inflaton)



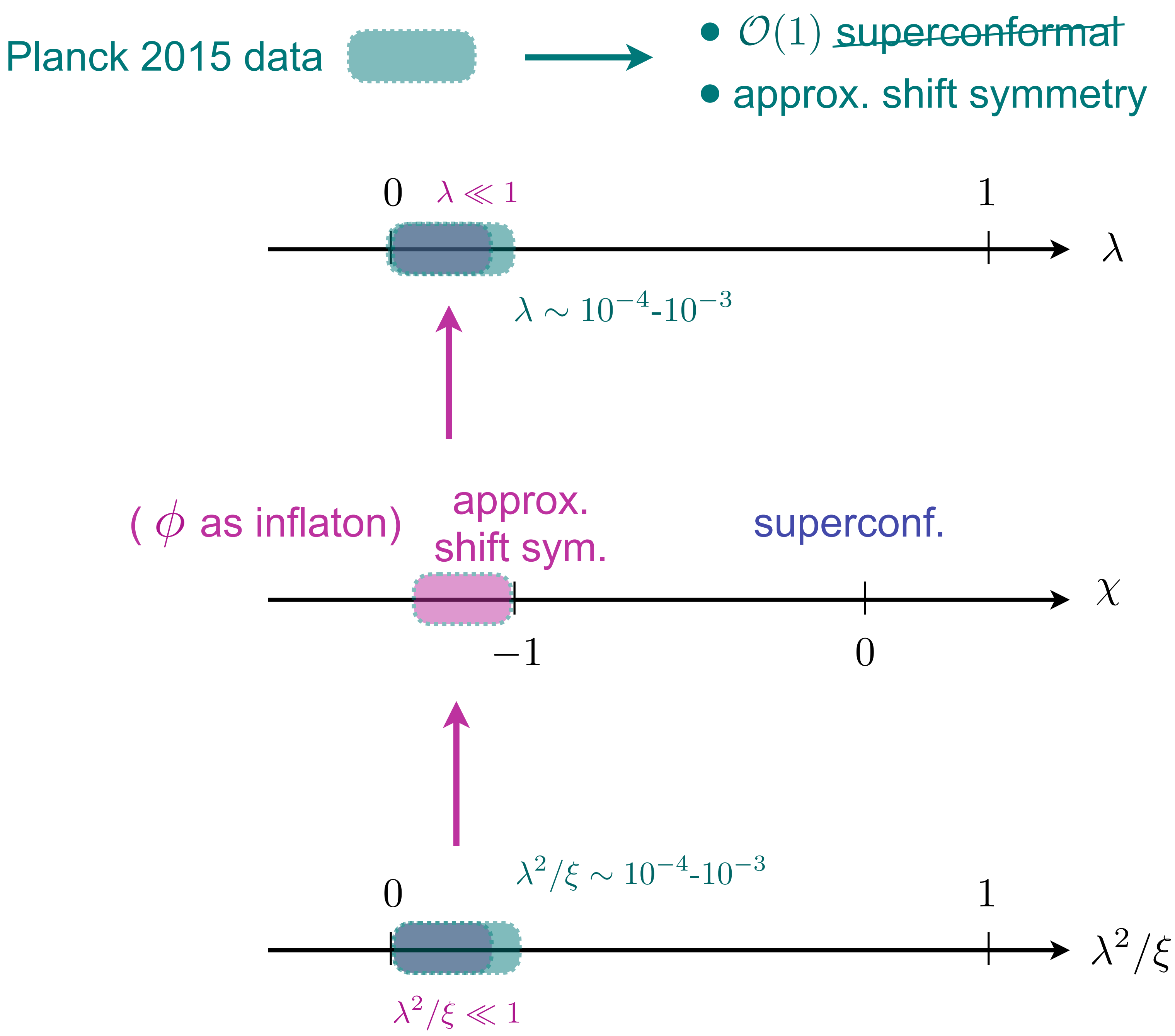
0
1
λ
(ϕ as inflaton)
approx.
shift sym.
superconf.
χ
-1
0
0
1
λ^2/ξ



0
$\lambda \ll 1$
1
λ
(ϕ as inflaton)
approx.
shift sym.
superconf.
χ
-1
0
0
1
λ^2/ξ
$\lambda^2/\xi \ll 1$



Planck 2015 data
0
$\lambda \ll 1$
1
λ
$\lambda \sim 10^{-4}$-10^{-3}
(ϕ as inflaton)
approx.
shift sym.
superconf.
χ
-1
0
$\lambda^2/\xi \sim 10^{-4}$-$10^{-3}$
0
1
λ^2/ξ
$\lambda^2/\xi \ll 1$


Planck 2015 data
• $\mathcal{O}(1)$ ~~superconformal~~
• approx. shift symmetry
0
$\lambda \ll 1$
1
λ
$\lambda \sim 10^{-4}$-10^{-3}
(ϕ as inflaton)
approx. shift sym.
superconf.
χ
-1
0
$\lambda^2/\xi \sim 10^{-4}$-$10^{-3}$
0
1
λ^2/ξ
$\lambda^2/\xi \ll 1$

4. Conclusion

We have revisited hybrid inflation in superconformal supergravity

- Inflation continues in subcritical regime in part of parameter space, and consequently a new type of inflation emerges

- Inflaton potential has turns out to be similar to one in the simplest version of superconformal α attractor model but with an additional term, which leads to a different prediction for cosmological parameters

- The predictions changes due to superconformal breaking parameter χ and the Planck 2015 data prefers to the region where approximate shift symmetry resides