

# *Inflation*

## *with a large tensor mode*

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Ref: 1403.5055 and 1404.3102

# § Inflation

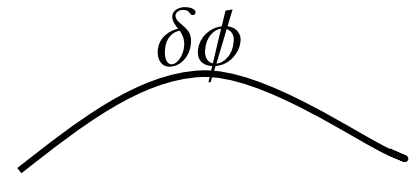
Inflation solves [Guth, Sato ... (1981)]

- the flatness problem
- the horizon problem
- ...

provides

- seeds of the density perturbation

[Hawking, Starobinsky, Guth and Pi (1982)]



# § Inflation

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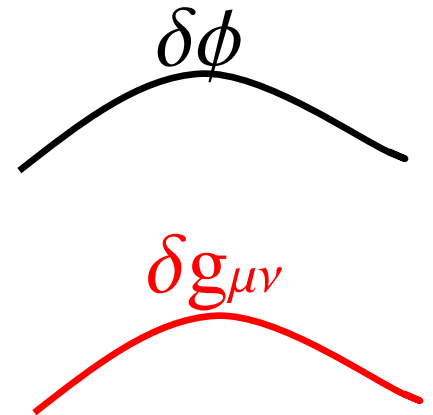
provides

- seeds of the density perturbation

[Hawking, Starobinsky, Guth and Pi (1982)]

- **gravitational wave background**

[Starobinsky (1979), Rubakov et al (1982)]



# Situation completely changed

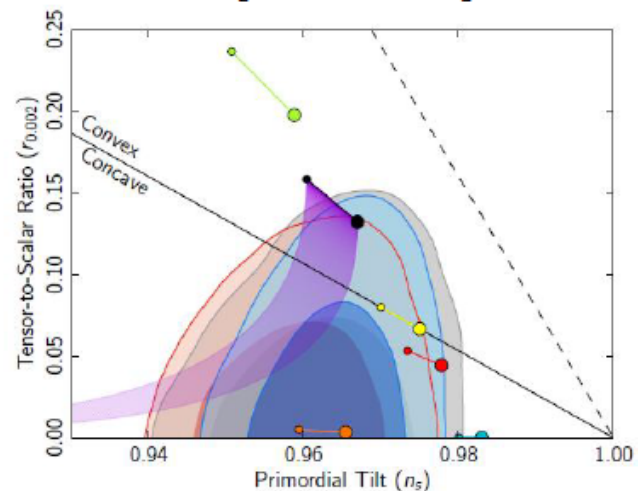
- c.f. one slide of my talks at the last year.

## § Introduction : Planck data



Anomalies gone, no surprise (fNL rT).

- Many of single field inflation models have been disfavoured by Planck data. [Planck 2013]
- R+R<sup>2</sup> inflation
- ...
- $\phi^2$ : dying
- hybrid: almost excluded
- ...



# § Slow roll inflation

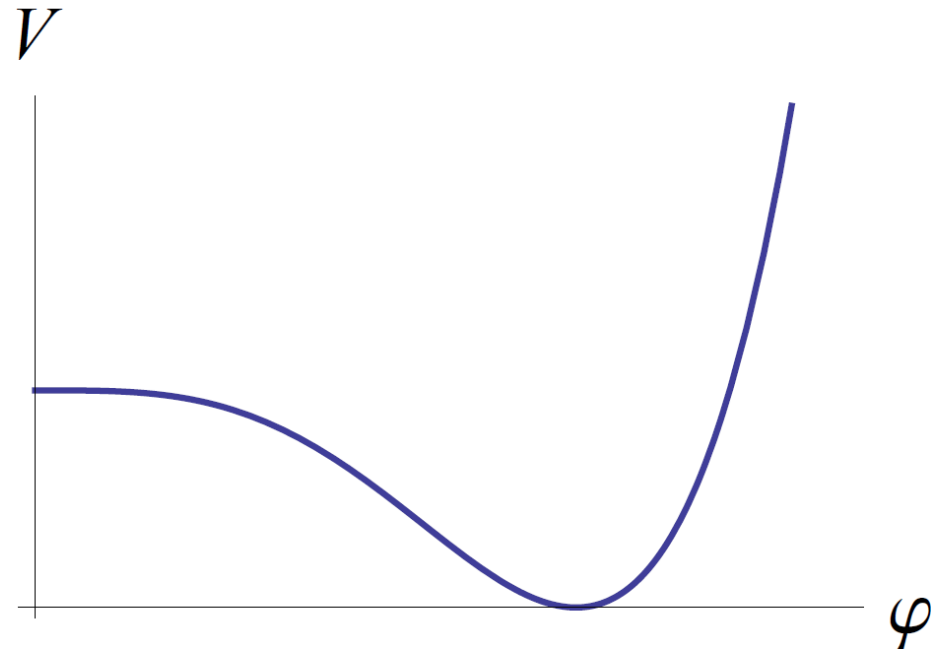
- Potential for inflaton needs to be flat

- Slow roll parameters

$$\epsilon = \frac{1}{2} \left( \frac{V_\varphi}{V} \right)^2$$

$$\eta = \frac{V_{\varphi\varphi}}{V}$$

$$\xi = \frac{V_\varphi V_{\varphi\varphi\varphi}}{V^2}$$



# § § Perturbation from inflation

- Power spectrum of density (scalar) perturbation

$$\mathcal{P}_\zeta = \left( \frac{H^2}{2\pi|\dot{\varphi}|} \right)^2 = \frac{V}{24\pi^2\epsilon}$$

- Spectral index

$$n_s = 1 + 2\eta - 6\epsilon$$

- Running of the spectral index

$$\alpha_s = 16\epsilon\eta - 24\epsilon^2 - 2\xi$$

- Tensor-to-scalar ratio

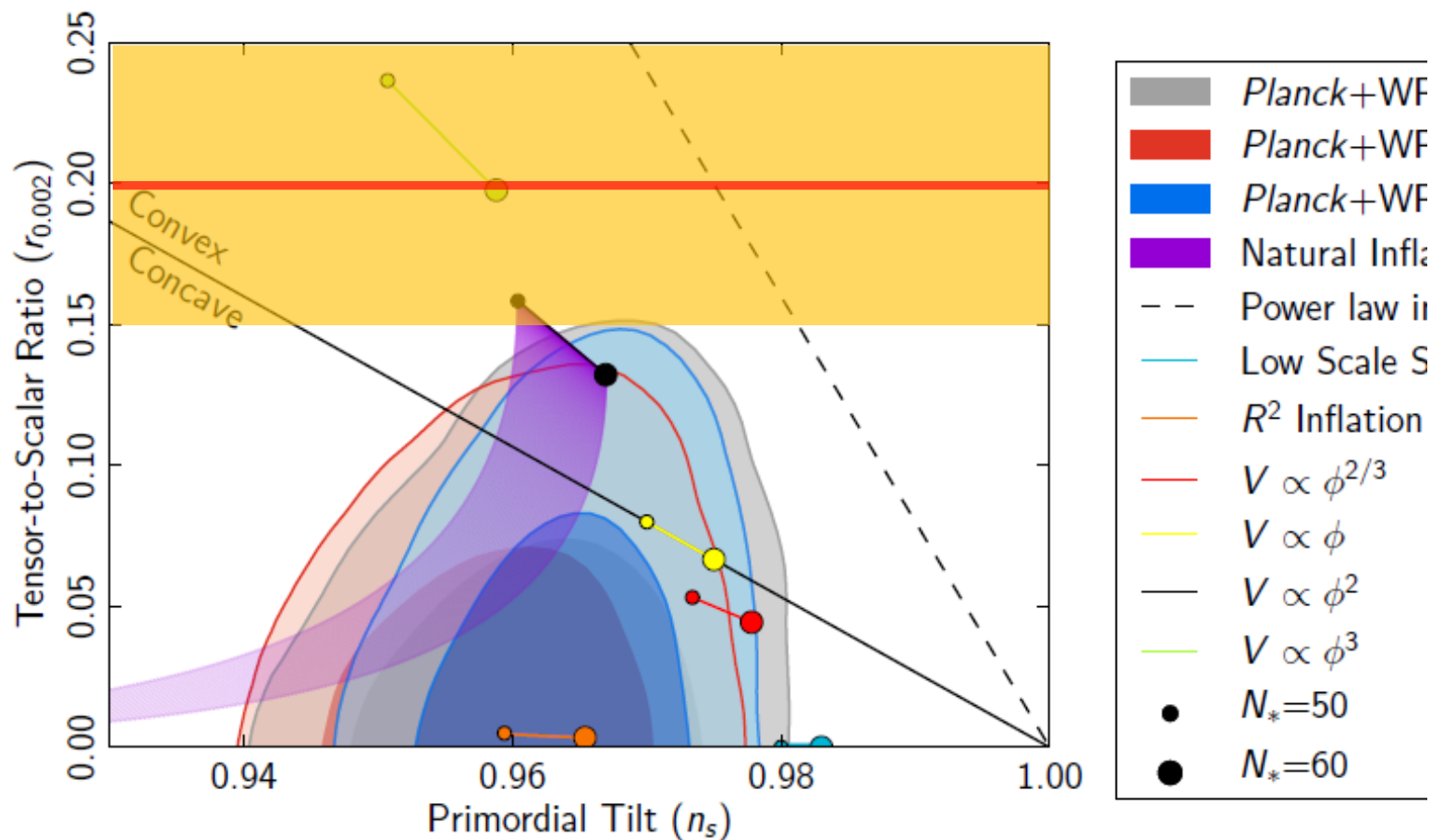
$$r_T = 16\epsilon$$

# contents

- Polynomial inflation
- SUSY hybrid inflation
- Double inflation

# § With BICEP2 data

- Although  $\phi^3$  fits well, well behaved potential?



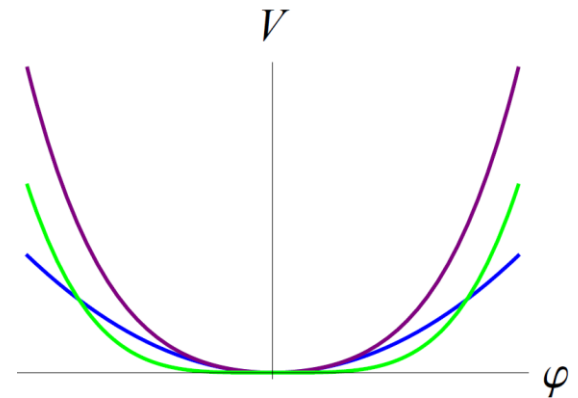


# § Inflation by polynomial potential

- General potential  $V = c_1 + c_2\phi^2 + c_4\phi^4$

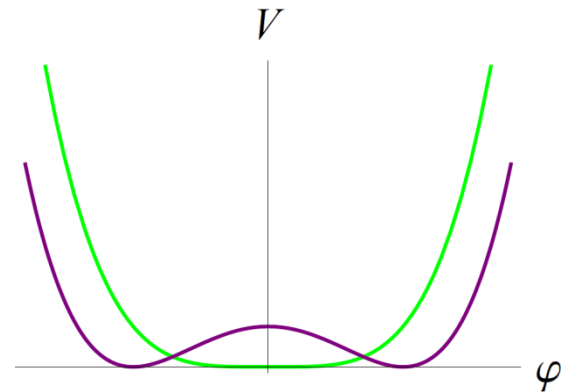
(1) Potential = Quadratic + quatic

$$V = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$$



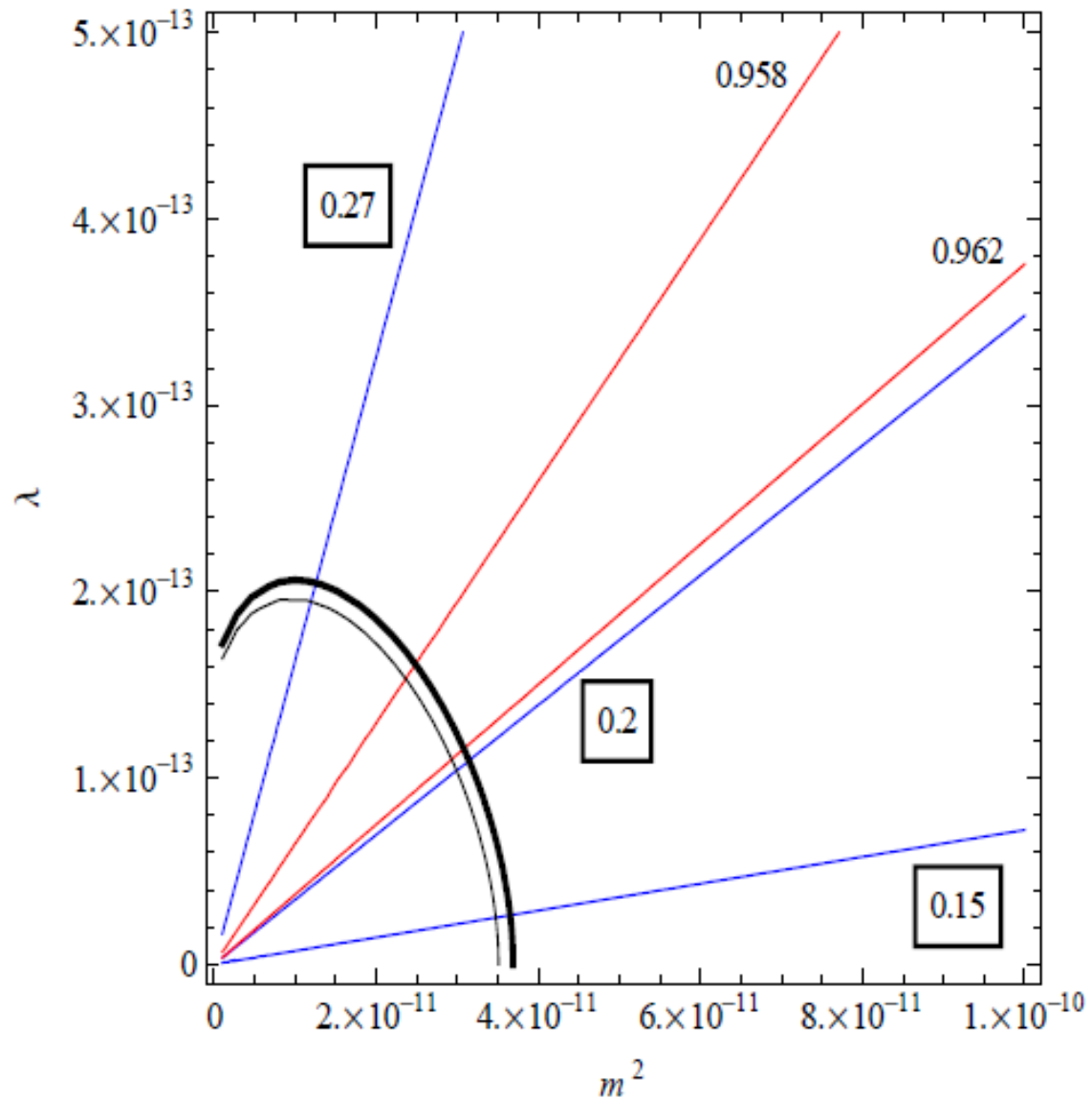
(2) Negative quadratic + quatic = double well

$$V = V_0 - \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4$$

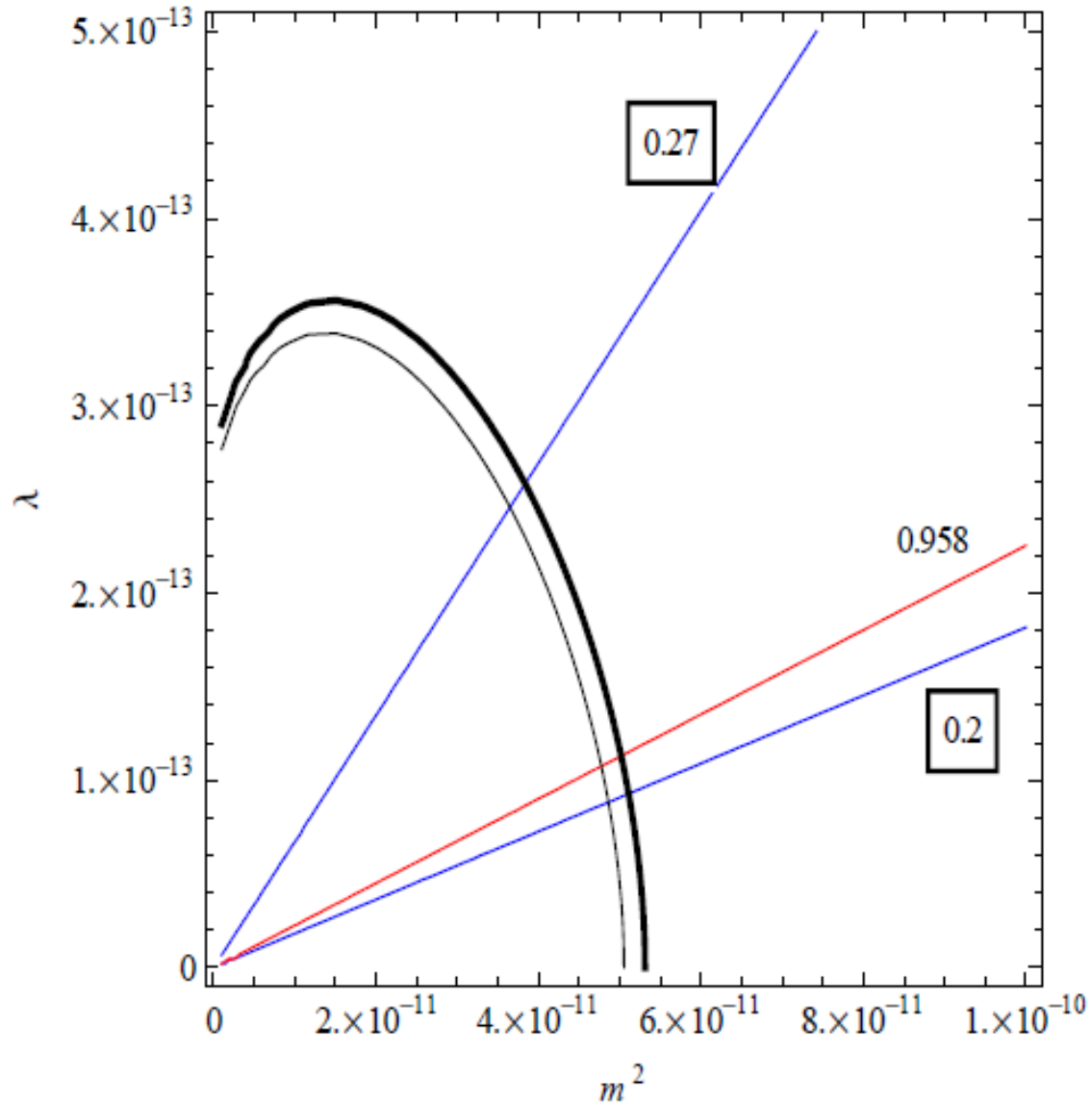


- Only two parameters in potentials

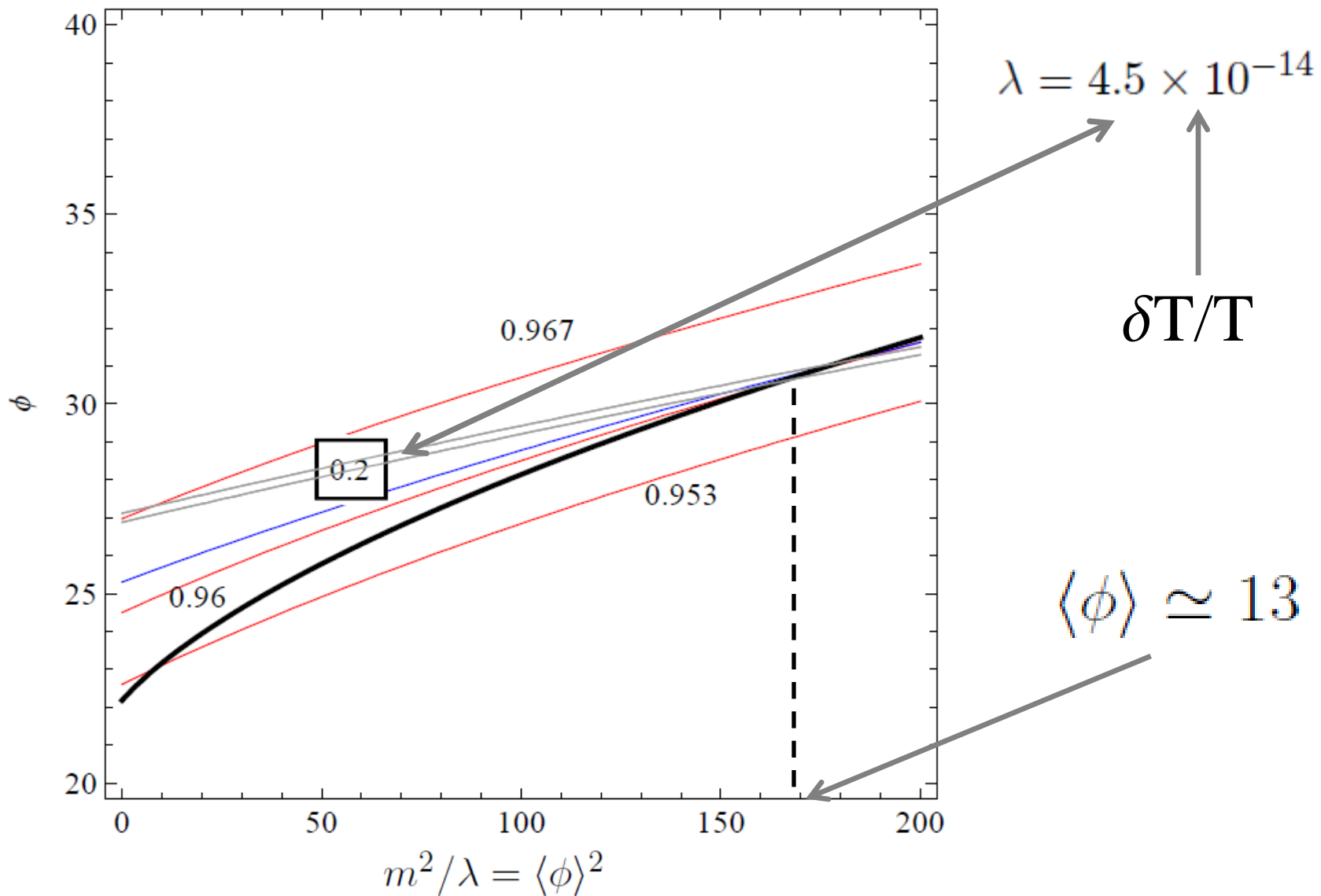
# (1) N=60



# (1) N=50



## (2) Double well potential: $N=60$

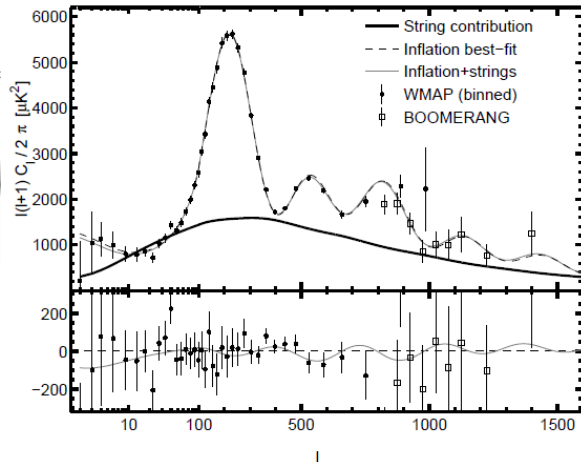
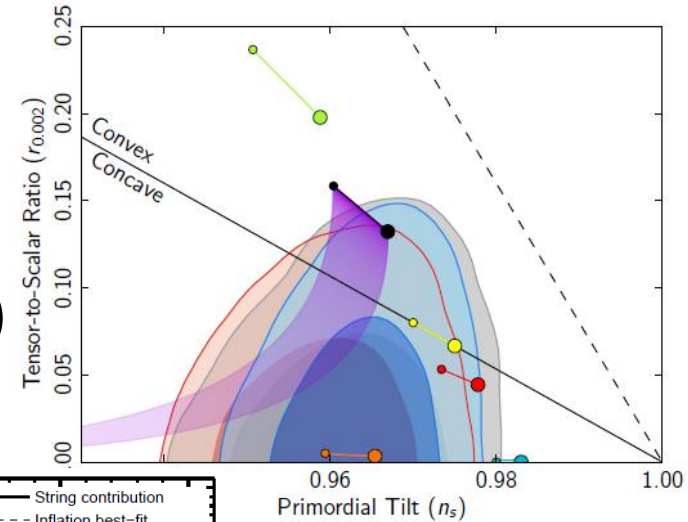
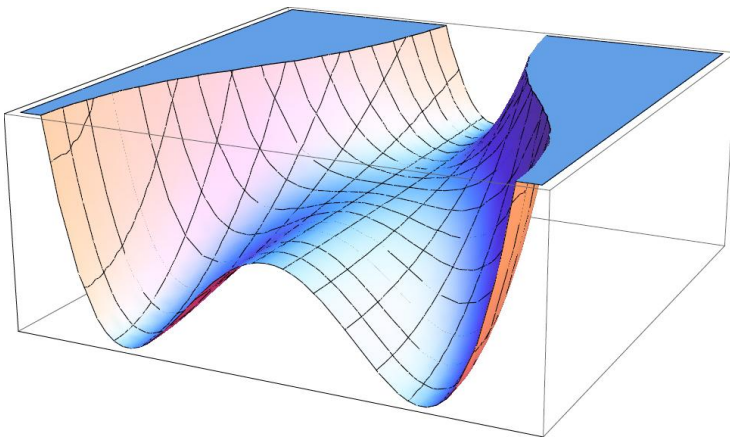


# § Hybrid inflation

- Hybrid inflation [Linde, Copeland et al (1994)]
- Pros
  - easy construction (in SUSY [Dvali et al(1994)])
  - field value  $\lesssim$  Planck scale
- Pros? or Cons?
  - associate with phase transition
- Cons
  - apparently disfavored by current data.

# SUSY Hybrid inflation is disfavored, isn't it?

- Spectral index  $n_s = 1 - 1/N$ ,  
 $n_s \cong 0.98$  for  $N = 50$
- Topological defect



[Bevis et al(2008)]

- Tiny tensor  $< 0.02$  [Civiletti et al (2014)] (for BICEP2)

# SUSY Hybrid inflation is disfavored

## How did we find this?

- $n_s = 1 - 1/N \cong 0.98$ ,  $r_T \ll 1$  from  $V$

$$n_s = 1 + 2\eta - 6\epsilon$$

$$r_T = 16\epsilon \quad \text{with}$$

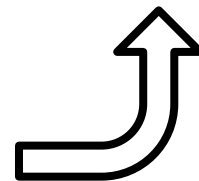
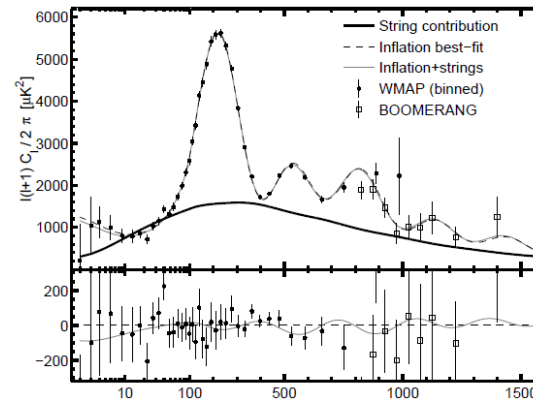
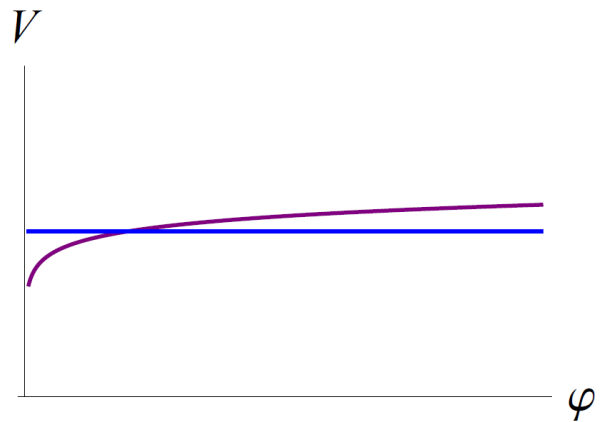
$$\eta \sim -(y^2/4 \pi^2)/\sigma^2,$$

$$\epsilon \sim (y^2/4 \pi^2)^2 / 2\sigma^2 \ll \eta \quad \text{true for } (y^2/4 \pi^2) \ll O(1)$$

$$\sigma^2/2 \sim (y^2/4 \pi^2) N$$

and

$$\underline{N=50}$$



# SUSY Hybrid inflation is disfavored Toward $r_T \sim 0.1 \dots$

- $n_s = 1 - 1/N \cong 0.98$ ,  $r_T \ll 1$  from

$$n_s = 1 + 2\eta - 6\epsilon$$

$$r_T = 16\epsilon \quad \text{with}$$

$$\eta \sim -(y^2/4 \pi^2)/\sigma^2,$$

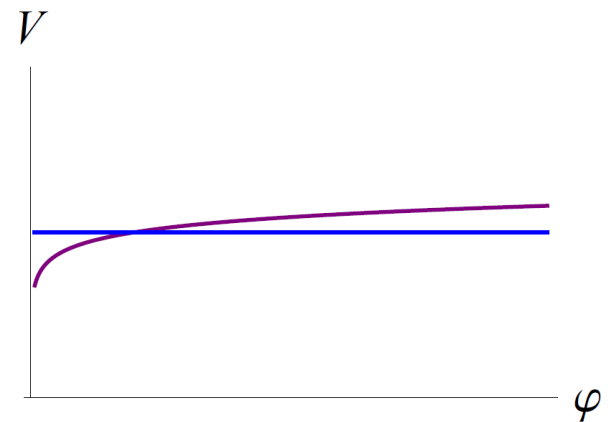
$$\epsilon \sim (y^2/4 \pi^2)^2 / 2\sigma^2 \sim \underline{\eta} \quad \text{true for } (y^2/4 \pi^2) = O(1)$$

$$\sigma^2/2 \sim (y^2/4 \pi^2) N \quad \rightarrow \quad r_T \uparrow$$

and

$$\underline{N < 50}$$

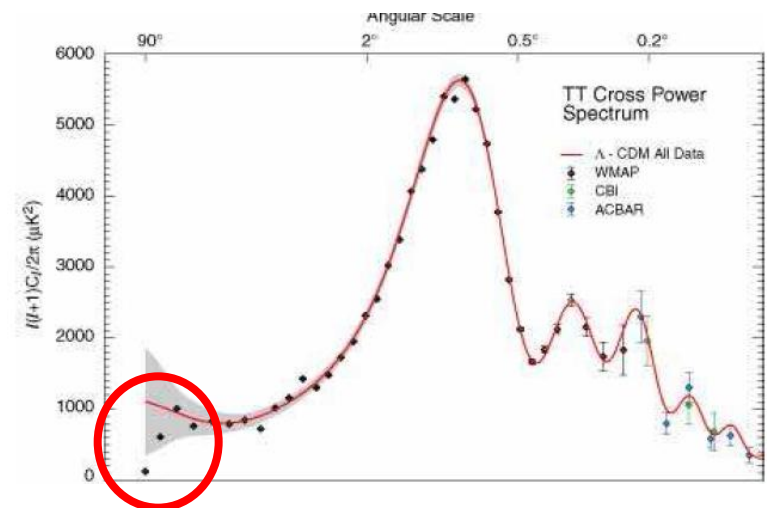
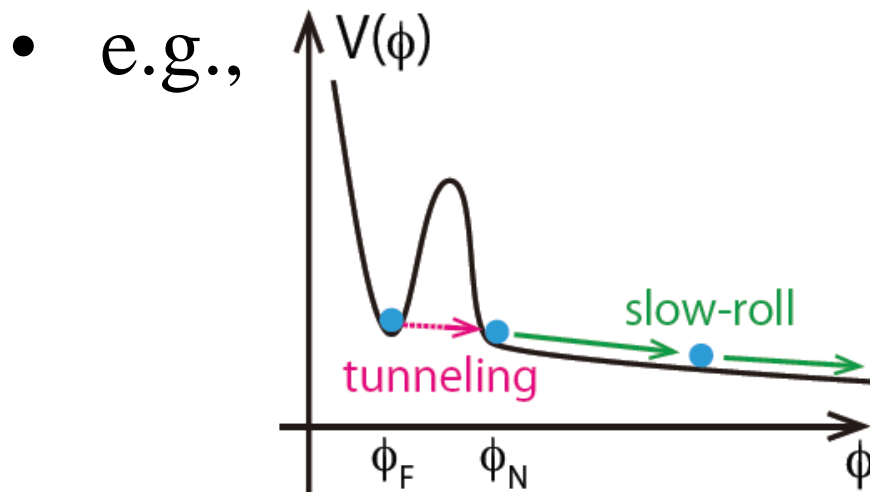
$$\rightarrow n_s \downarrow \downarrow \quad \leftarrow \uparrow \text{ supergravity}$$





# Is $N < 50$ O.K.?

- What to do with the horizon and flatness problem?
- $N < 50$  is by **ONLY** first hybrid inflation. the Universe might undergo inflation twice. ``Double inflation'' [mid 80's ~]



# ``Double inflation''

- Total inflation = hybrid inflation( $N \sim 10$ )  
+ any other inflation( $N \sim 50$ )

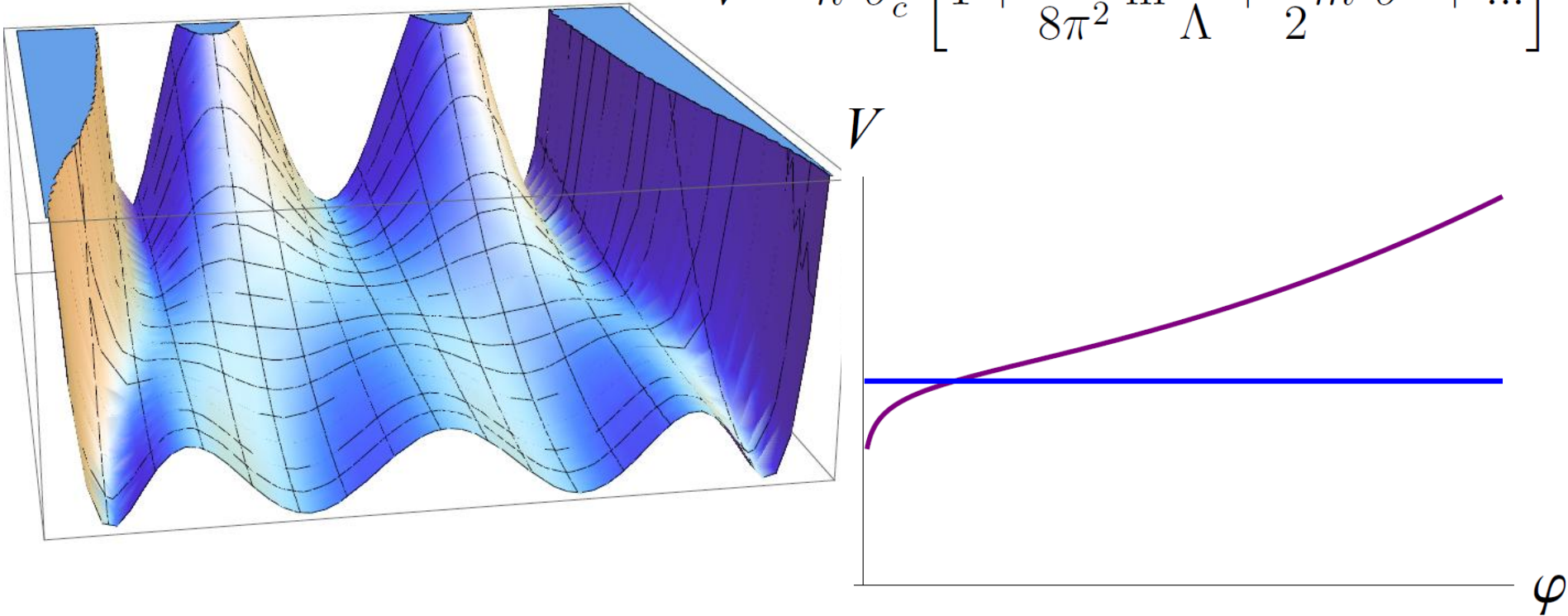
hybrid( $N \sim 7$ )+hybrid( $N \sim 50$ ) [Choi and Kyaе(2014)]

- Let me concentrate ``first hybrid inflation part''

# § SUSY hybrid inflation

- Potential

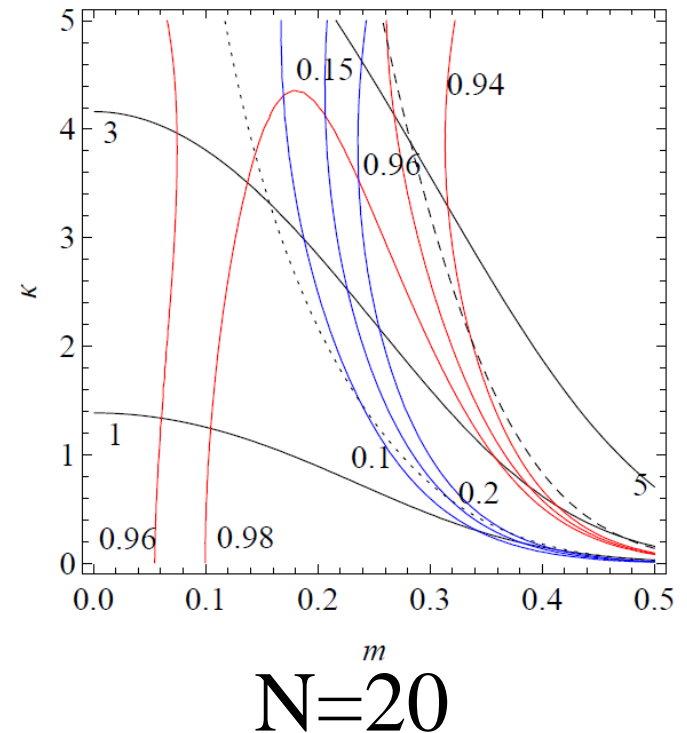
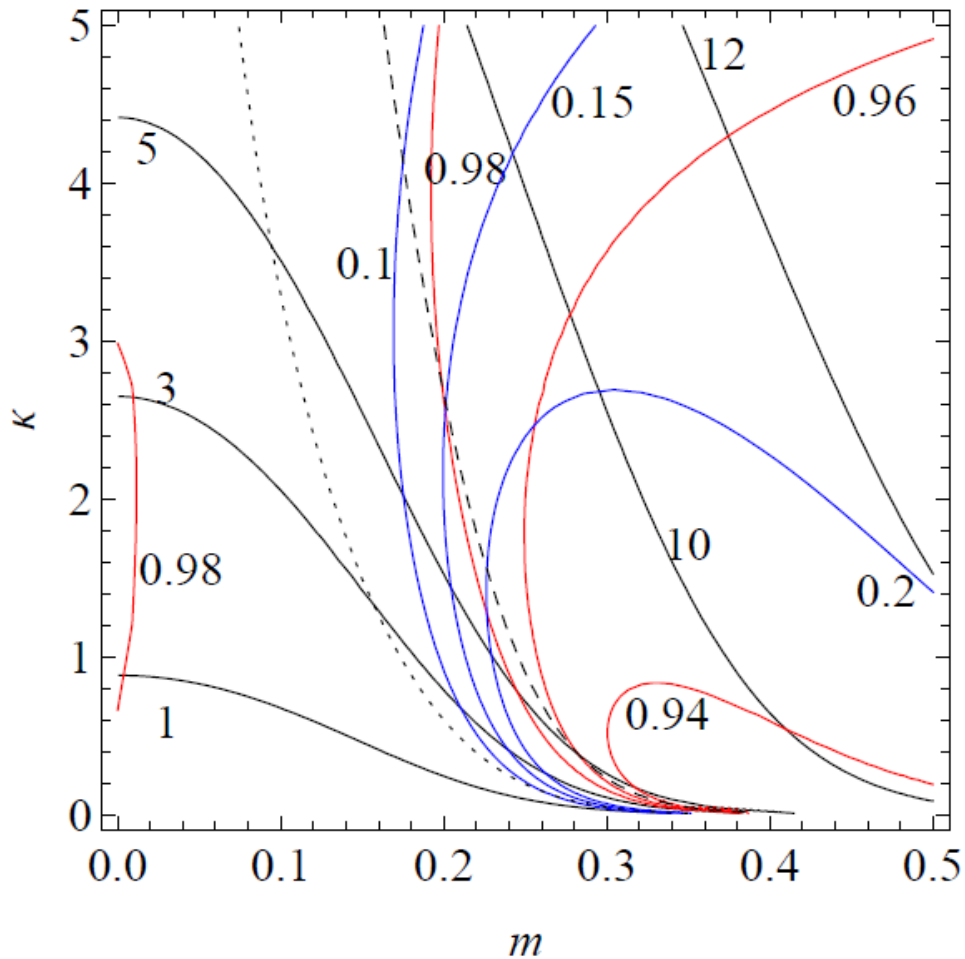
$$V = \kappa^2 \sigma^4 \left[ 1 + \frac{\kappa^2}{8\pi^2} \ln \frac{\sigma}{\Lambda} + \frac{1}{2} m^2 \sigma^2 + \dots \right]$$



Shifted hybrid inflation [Jeannerot et al(2000)]

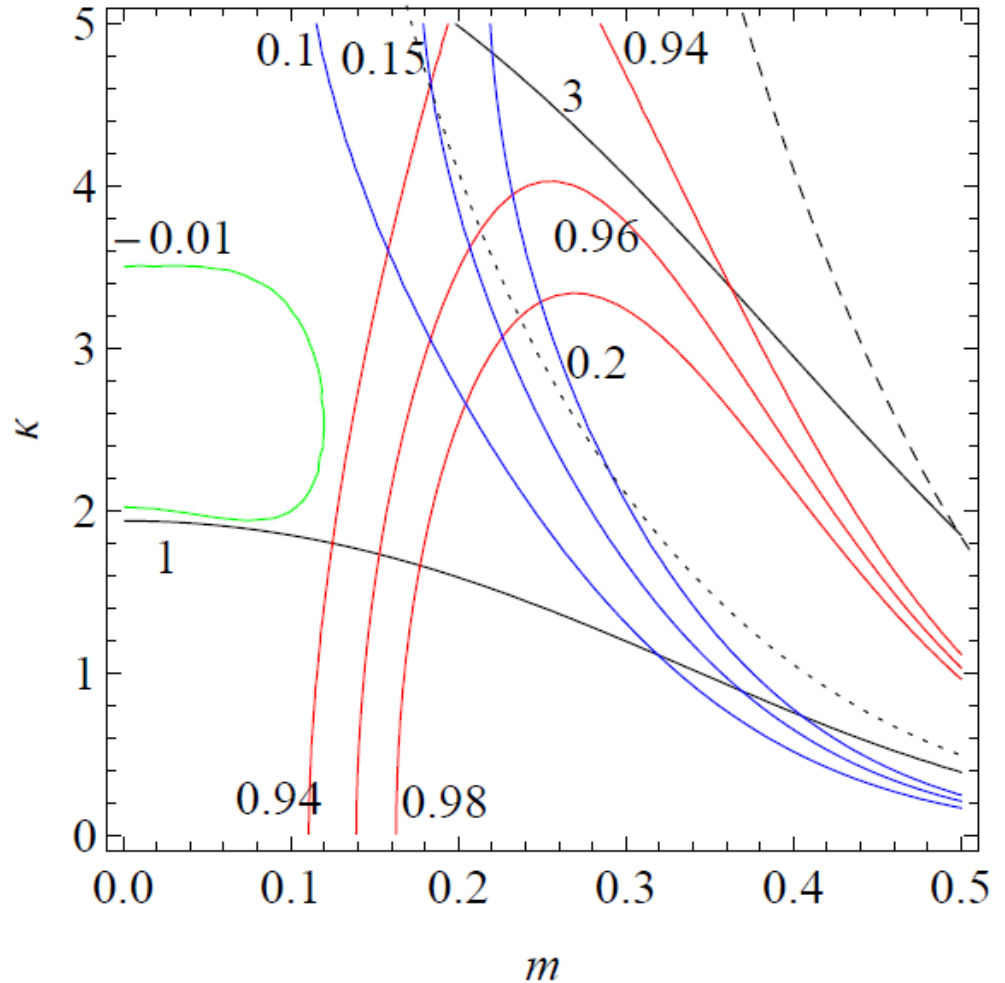
# § SUSY hybrid inflation

- Results  $N=50$



# § SUSY hybrid inflation

- Results  $N=10$

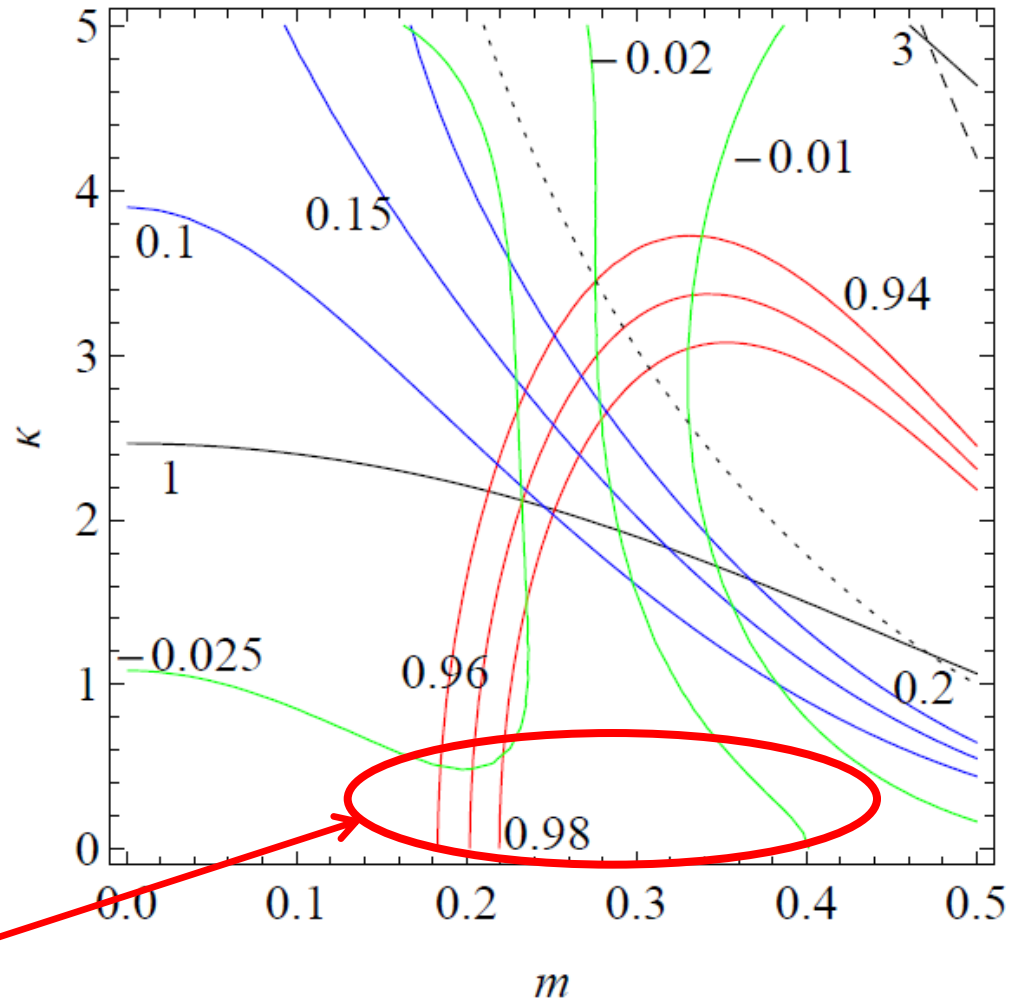


# § SUSY hybrid inflation

- Results  $N=6$

One obvious modification is to allow the initial scalar perturbation spectrum to depart from the simple power law form which is assumed in the base  $\Lambda$ CDM model. A standard way in which this is done is by introducing a “running” parameter  $dn_s/d\ln k$ . In Planck Collaboration XVI (2013) the constraint relaxes to  $r < 0.26$  (95% confidence) when running is allowed with  $dn_s/d\ln k = -0.022 \pm 0.010$  (68% for the *Planck*+WP+highL data combination). In Figure 13 we show the constraint contours when allowing running as taken from Figure 23 of Planck Collaboration XVI (2013), and how these change when the BICEP2 data are added. The red contours on the plot are simply the Monte Carlo Markov Chains

BICEP2 ♥♥ Planck ?



[Kawasaki et al (2003)]

# § Summary

- We consider several inflation models generating large B mode.
- Quadratic (and quatic) model works well, as you know.
- SUSY hybrid inflation (non super-Planckian model) is still in part available and reproduce  $r_T$  (and  $\alpha_s$ ). **What's new?  $N \sim 10$ ,  $\kappa = O(1)$ !**