THE RUNNING SPECTRAL INDEX AS A PROBE OF <u>PHYSICS</u> AT HIGH SCALES

DSU'06

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- ★ INFLATION : Simple (SUSY) Model
- ★ WMAP Indications for a Running Scalar Spectral Index
- ★ Attempts to produce $dn/d\ln k$
- ★ General Remarks

Based on

G. Ballesteros, J.A. Casas, J.R.E. [hep-ph/0601134] JCAP 0603(2006)001
+ R. Ruiz de Austri [work in progress]

INFLATION

Can explain flatness, homogeneity and isotropy plus huge entropy of our Universe, through a period of superluminal expansion driven by a new scalar field ϕ with nearly constant potential energy $\quad a \to e^{Ht} a_0 \qquad H \equiv \dot{a}/a$

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{\partial V}{\partial \phi} \qquad H^2 = \frac{1}{3M_{Pl}^2}\left(V + \frac{1}{2}\dot{\phi}^2\right)$$

SLOW-ROLL $\qquad 3H\dot{\phi} \simeq -\frac{\partial V}{\partial \phi} \qquad H^2 = \frac{1}{3M_{Pl}^2} V$

Determined by $\qquad \epsilon = \frac{1}{2} M_{Pl}^2 \left(\frac{V'}{V}\right)^2 \qquad \eta = M_{Pl}^2 \frac{V''}{V} \qquad \ll 1$

\# e-folds of expansion $\qquad N_e = \int_{t_i}^{t_e} H\,dt \quad \sim 50-60$

SIMPLE EXAMPLE

Binètruy-Dvali '96

Use flat directions, ubiquitous in SUSY models

U(1) gauged $\qquad \phi\ (0) \qquad H_+\ (+1) \qquad H_-\ (-1)$

with $\qquad W = \lambda \hat{\phi} \hat{H}_+ \hat{H}_- - \mu^2 \hat{\phi}$

$$\Rightarrow \quad V_F = |\lambda H_+ H_- - \mu^2|^2 + \lambda^2 |\phi|^2 (|H_+|^2 + |H_-|^2)$$

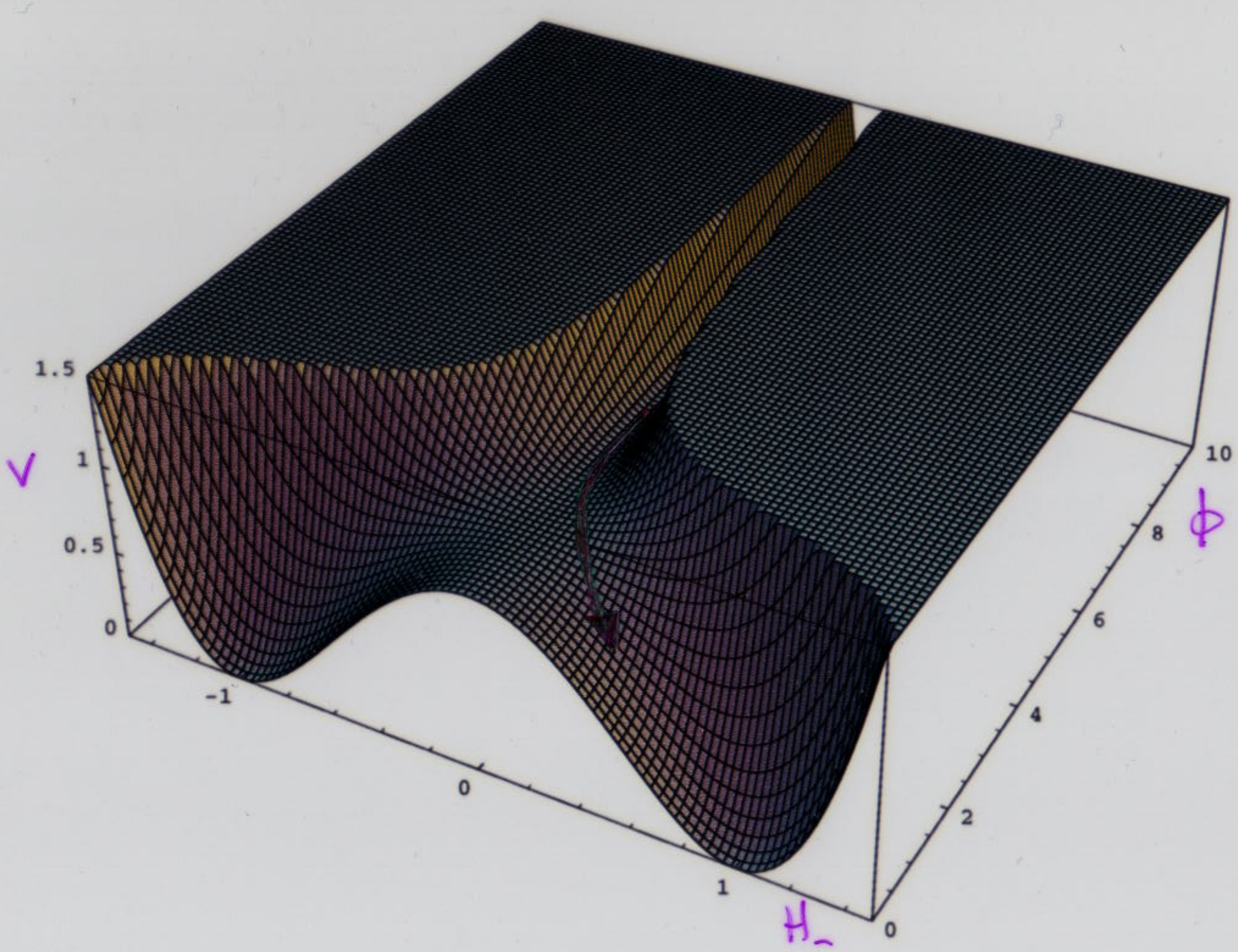
$$V_D = \frac{1}{2} g^2 \left[|H_+|^2 - |H_-|^2 + \xi_D \right]^2$$

Fayet-Iliopoulos term $(\sim M^2)$

∴ Simple and well motivated from particle physics POV.

$\Rightarrow$ $\boxed{\text{D-term hybrid inflation model}}$

INFLATON VALLEY



Along valley $(H_+ = H_- = 0\ ,\ \phi \neq 0)$

$$V \simeq \rho \equiv \mu^4 + \frac{1}{2} g^2 \xi_D^2$$

Tree-level flatness lifted by rad. corr.

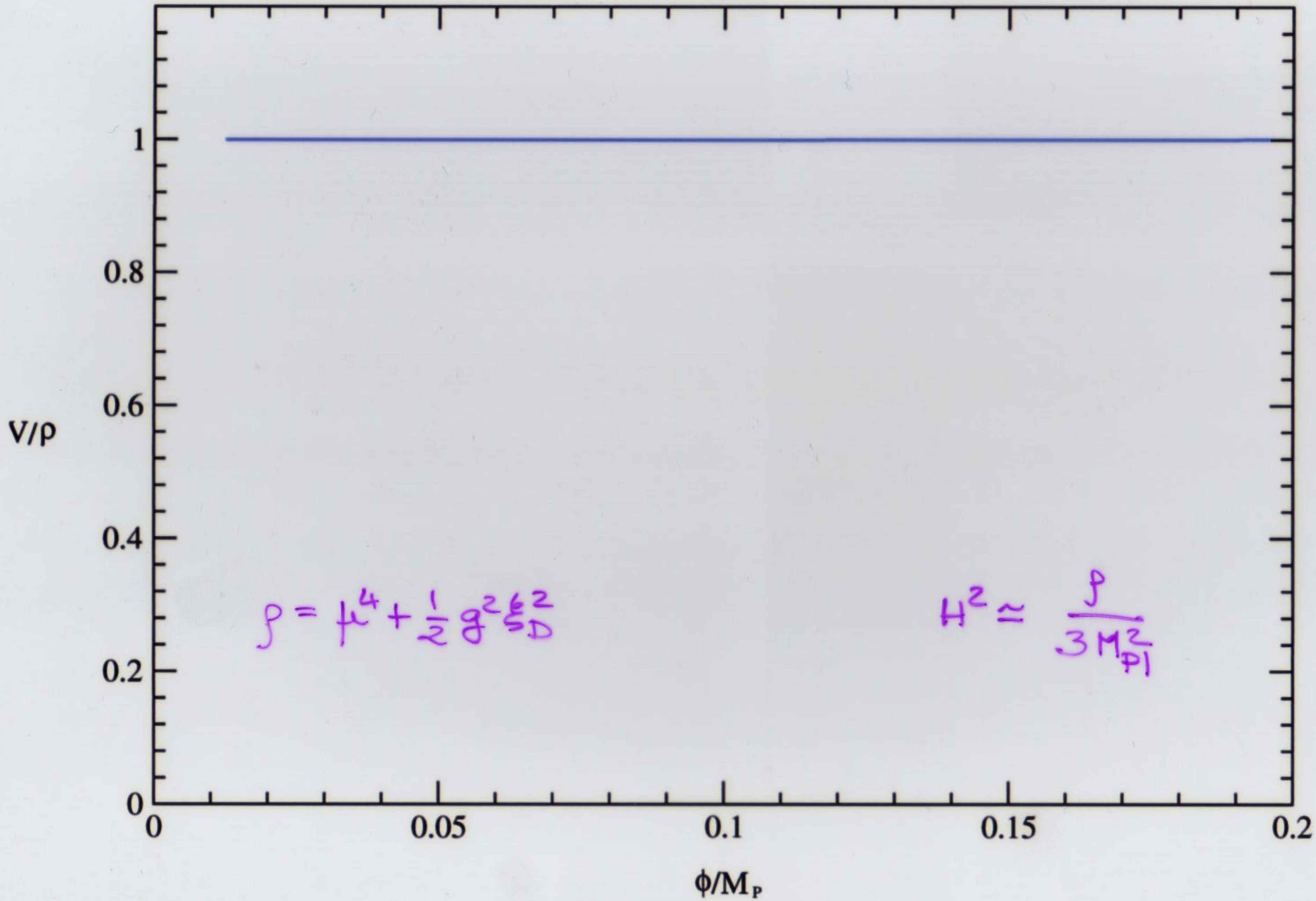
⇩

$$V = \rho + \beta \log(\phi/Q)$$

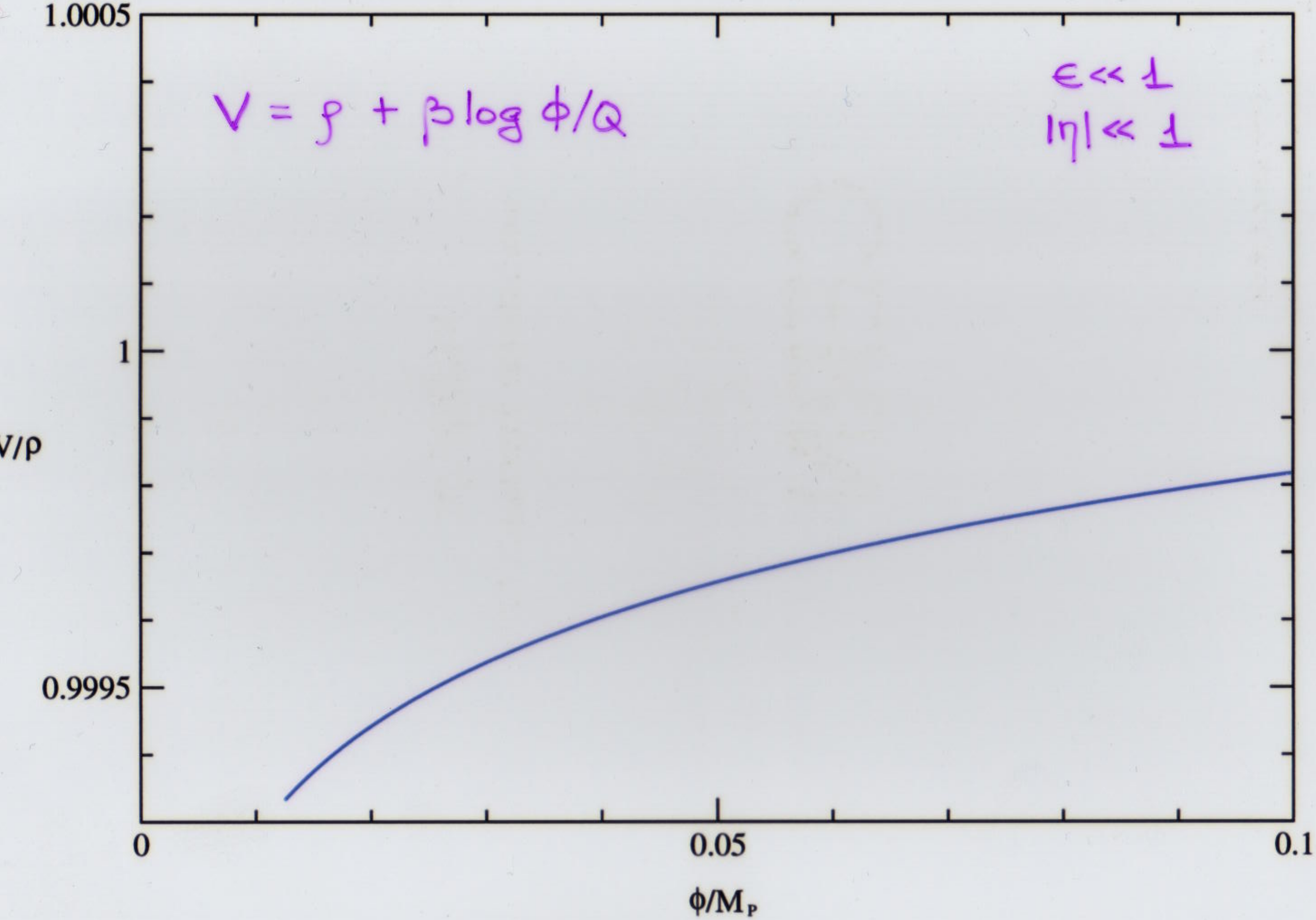
⇩

SMALL SLOPE

POTENTIAL ALONG ϕ



POTENTIAL ALONG ϕ



STRUCTURE FORMATION

Through the stretching of quantum fluctuations of ϕ

$$\hat{\phi}(x,t) = \phi(t) + \varphi(x,t)$$

Frozen at superhorizon scales with amplitudes det by H and a flat spectrum

$$\langle \varphi^2 \rangle = \frac{H^2}{(2\pi)^2} \int \frac{dk}{k}$$

$k \to$ comoving momentum (scale $\sim 1/k$)

Diff. $\varphi \Rightarrow$ Diff $t_{end} \Rightarrow \delta t = \varphi / \dot{\phi}$

$\Rightarrow$ Inhomogeneities $\quad \delta\rho/\rho \sim H\delta t \sim H^2/\dot{\phi}$

$$\Rightarrow \quad \frac{\delta\rho}{\rho} = c \cdot \left. \frac{V^{3/2}}{M_{Pl}^3 \, V'} \right|_{end} \quad \sim \text{nearly } k\text{-indep}$$

Parametrize departure from scale independence with SCALAR SPECTRAL INDEX n

$$\left(\frac{\delta\rho}{\rho}\right)^2 \propto k^{n-1}$$

$n = 1 \Leftrightarrow$ SCALE INDEP SPECTRUM.

In terms of slow-roll parameters

$$n \simeq 1 + 2\eta - 6\epsilon$$

Inflation typically predicts $n \simeq 1$

WMAP INDICATIONS FOR RUNNING n

Updated 14 June

ΛCDM, constant n:

$$n(0.002) = 0.951 \pm 0.016$$

ΛCDM, running n:

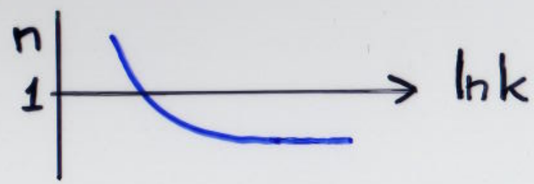
$$n(0.002) = 1.050^{+0.059}_{-0.058}$$

$$\frac{dn}{d\ln k} = -0.055^{+0.030}_{-0.031}$$

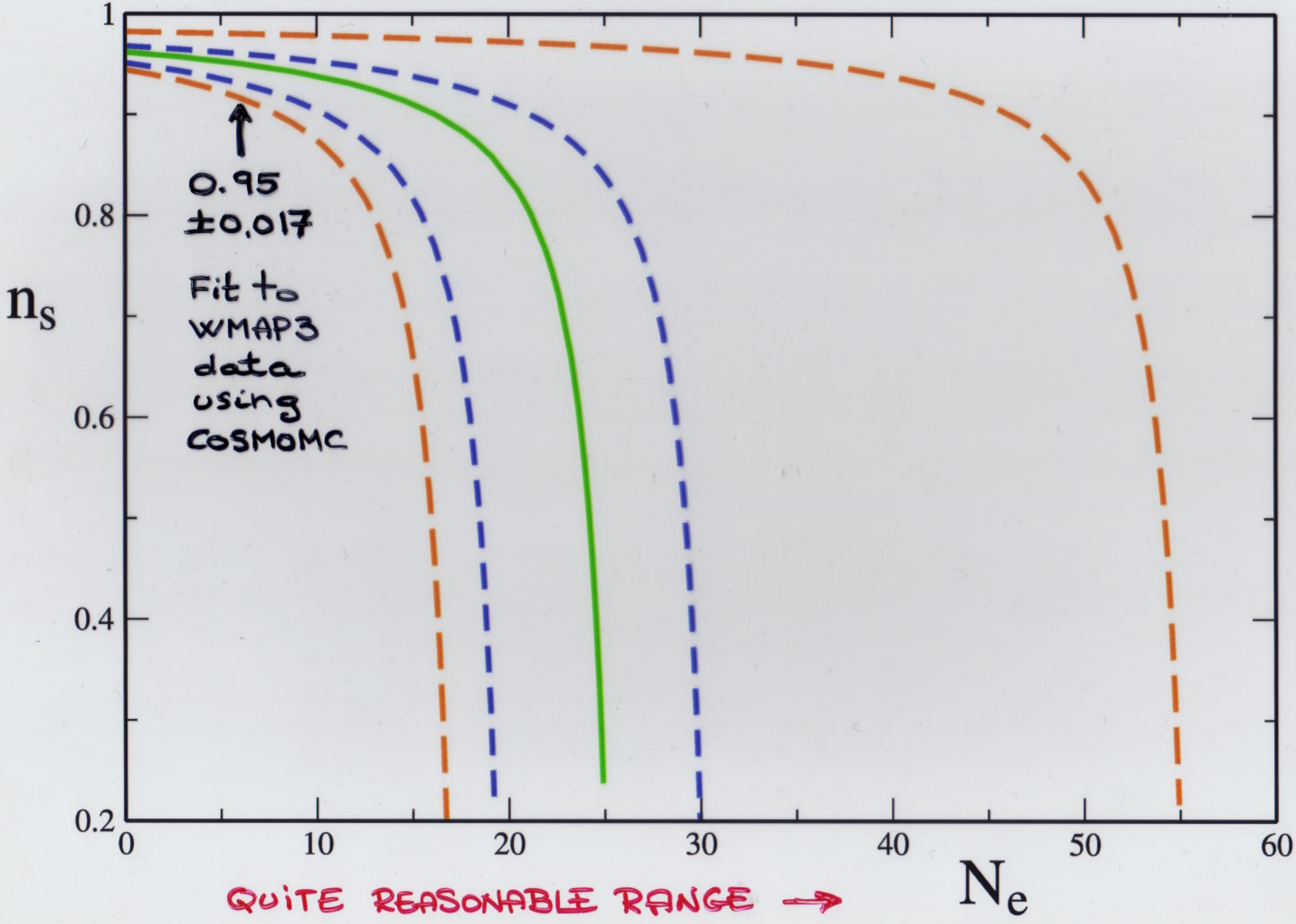
Still with us after 3 year's worth of data

Large $\frac{dn}{d\ln k}$ ⇨ gives $n < 1$ for larger k.

Expect

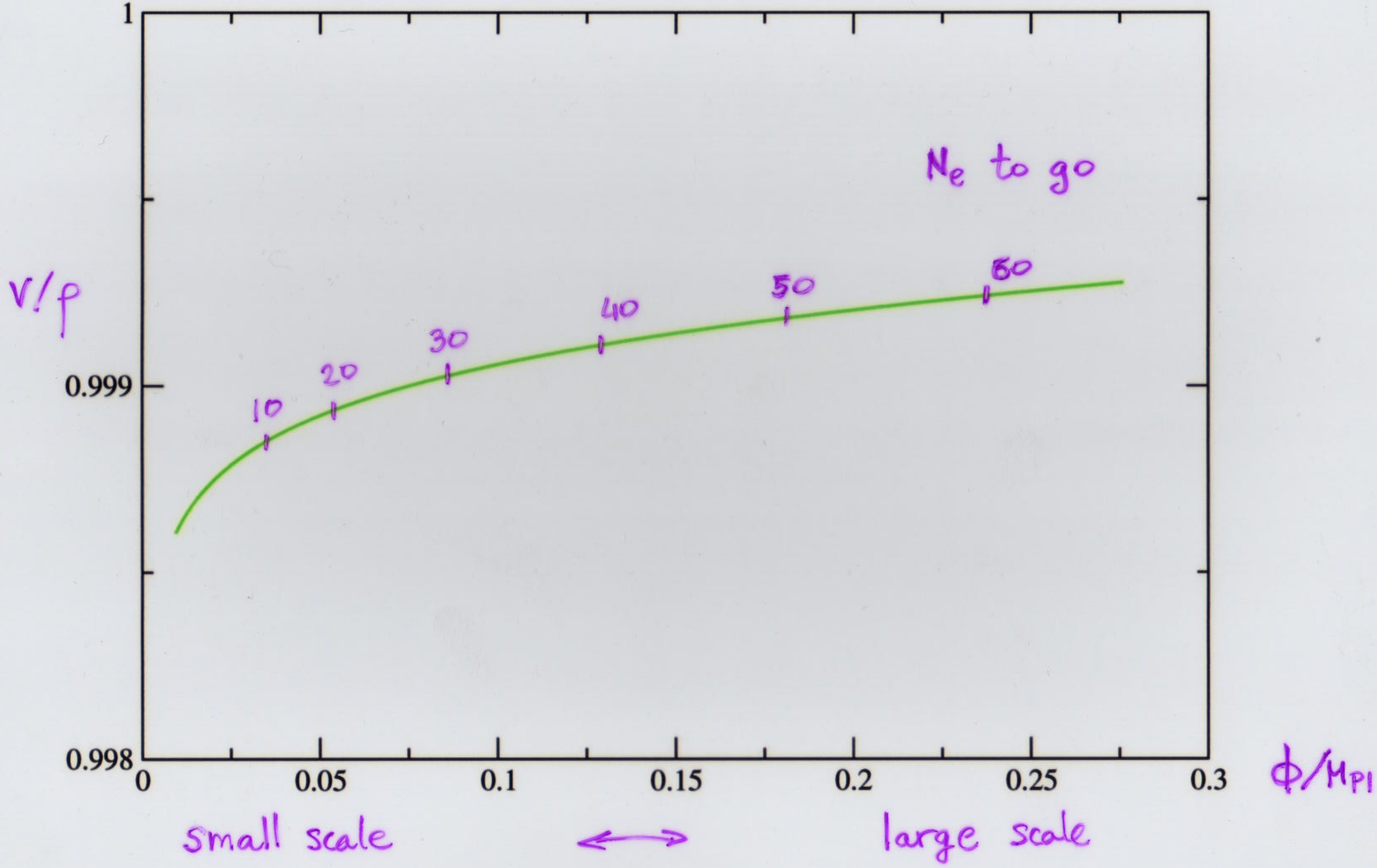


$$n = 1 - \frac{1}{N_e - \ln(k/k_*)} \Rightarrow n < 1 \ , \ \frac{dn}{d\ln k} = -(n-1)^2$$



QUITE REASONABLE RANGE →

ROLLING ϕ SCANS IN ENERGY AND 1/k



CAN INFLATION ACCOMODATE $\frac{dn}{d\ln k}$ NATURALLY?

→ start with simple D-term hybrid model

→ Try to modify* the potential at high energy to reproduce $dn/d\ln k$ at large scales

* in a well motivated way!

- In terms of slow-roll parameters

$$\frac{dn}{d\ln k} = 16\,\epsilon\eta - 24\epsilon^2 - 2\xi$$

with $\xi \equiv M_{Pl}^4 \frac{V' V'''}{V^2}$

SIZEABLE $\frac{dn}{d\ln k}$ requires sizeable ξ → effect in V'''

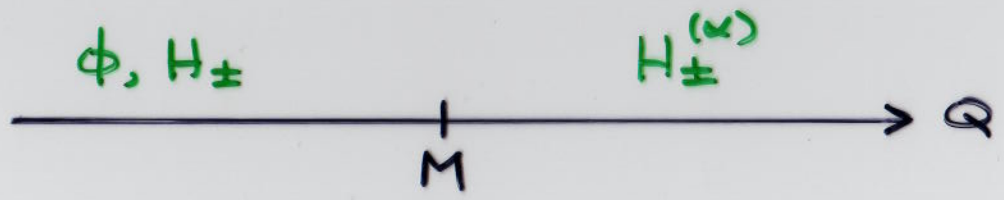
FIRST ATTEMPT

Couplings in $V(\phi)$ getting strong in the UV

$\rightarrow$ Changes shape of inflaton potential

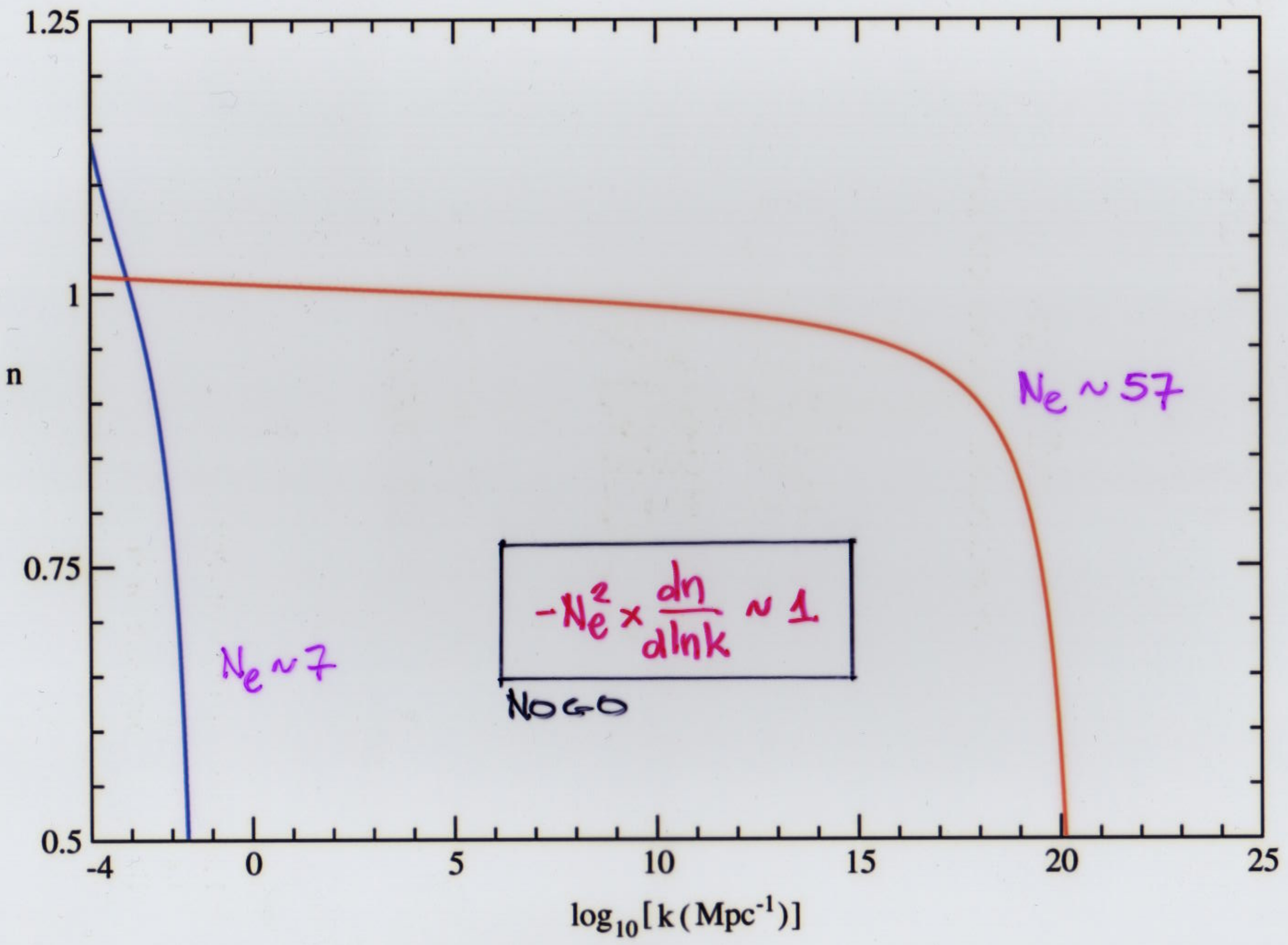
SECOND ATTEMPT

New Physics threshold crossed by ϕ



$$V = \rho + \beta \log \frac{\phi}{Q} + \frac{1}{2} \tilde{\beta} \log \frac{M^2 + \lambda^2 \phi^2}{Q^2}$$

CAN GET LARGE dn/dlnk BUT $N_e \downarrow$



THIRD (SUCCESFUL!) ATTEMPT

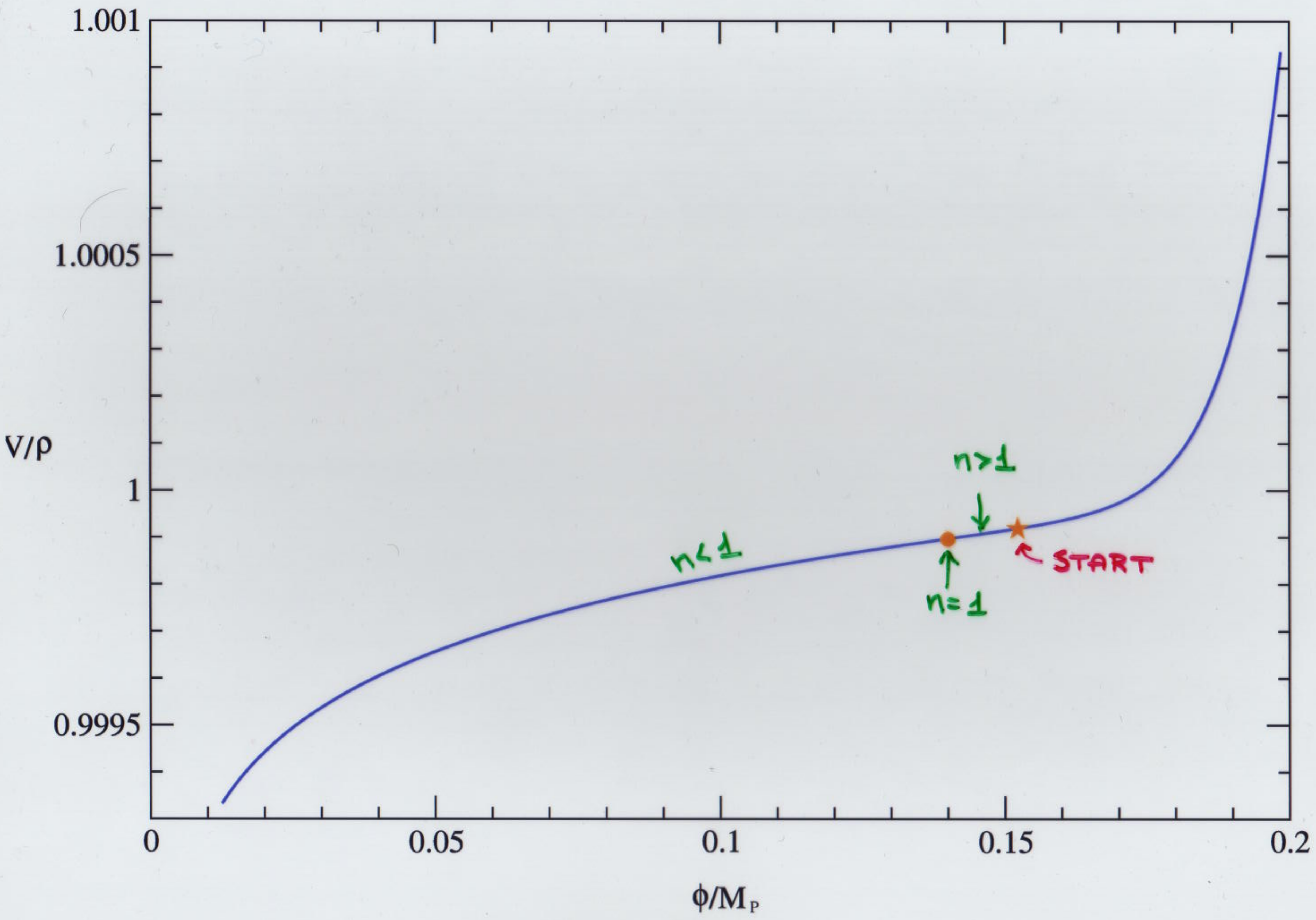
BCE'06

Effect of heavy physics through NROs

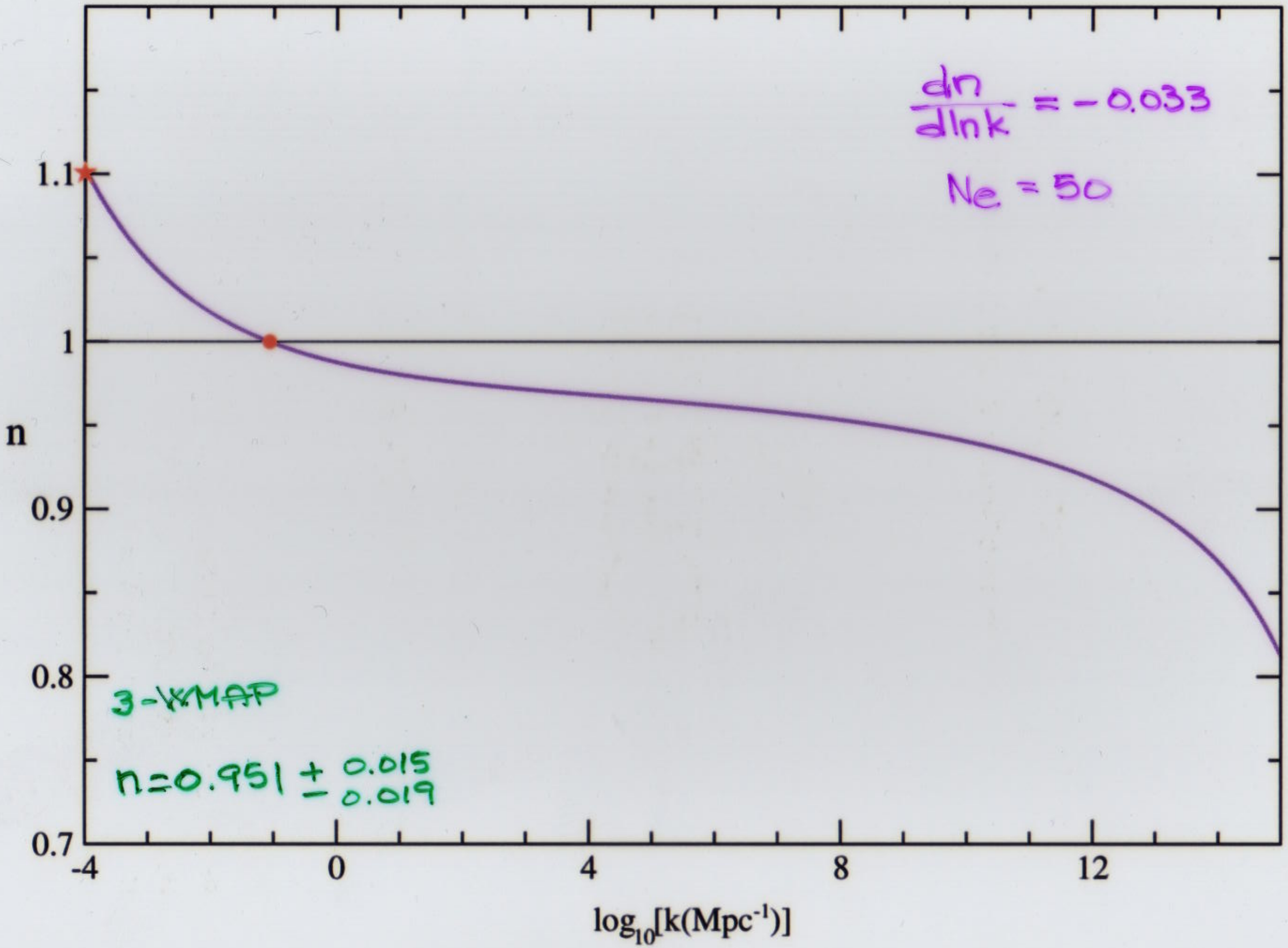
$$V = \rho + \beta \log \phi/Q + \phi^4 \frac{\phi^{2N}}{M^{2N}}$$

NOTE : choose $\phi_{in} \ll M$ for effective theory to be valid

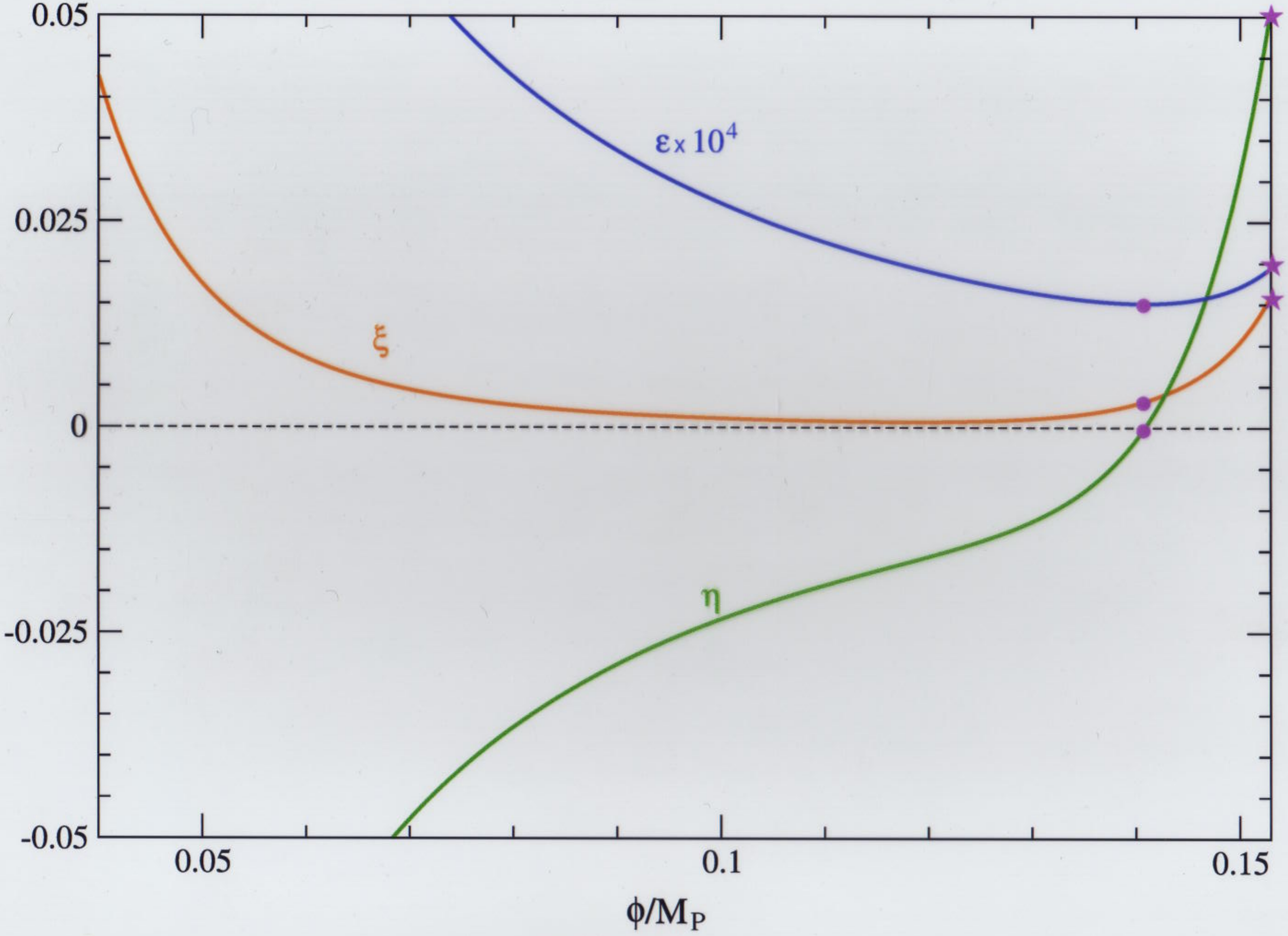
INFLATON POTENTIAL WITH NRO



RUNNING SPECTRAL INDEX (N=9)



SLOW-ROLL PARAMETERS



SOME COMMENTS

- Effect of NRO can be important because the potential is so flat

- Effect on 3rd derivative enhanced wrt to 1st and 2nd : allows to keep ϵ, η small but ξ larger

  $\Rightarrow$ helps in $\frac{dn}{d\ln k} \uparrow$ keeping N_e large

SOME COMMENTS (CONT'D)

- Lifting of SUSY flat directions by high-order NROS is naturally expected (MSSM, Strings)

- V can arise from reasonable superpotentials like

$$W = \lambda \phi H_+ H_- + \frac{1}{2} m \phi'^2 + \frac{1}{(P+2)} \phi' \phi^2 \frac{\phi^P}{M^P}$$

$$\Downarrow$$

$$V = V_D + \phi^4 \frac{\phi^2}{m^2} \frac{\phi^{4P}}{M^{4P}}$$

$\Rightarrow$ Gives $N=9$ for $P=4$

REMARKS / CONCLUSIONS

- ★ WMAP INDICATION OF RUNNING n IS VERY INTERESTING FOR PHYSICS AT HIGH ENERGY SCALES
- ★ NOT TOO DIFFICULT TO ACCOMODATE IN SIMPLE AND WELL MOTIVATED MODELS
- ★ STILL,... IT IS PUZZLING :

WHY SHOULD THE RUNNING OCCUR NEAR $N_e \sim 60$?

→ NEW COINCIDENCE PROBLEM ?

(Mersini-Houghton)