Relating Inflationary Predictions to the Modulus Mass

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September, 2015

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Phys.Rev. D91 (2015) 4, 043503

arXiv:1409.7037[hep-ph]

KUMAR DAS (Saha Institute)

ANSHUMAN MAHARANA (HRI, Allahabad)

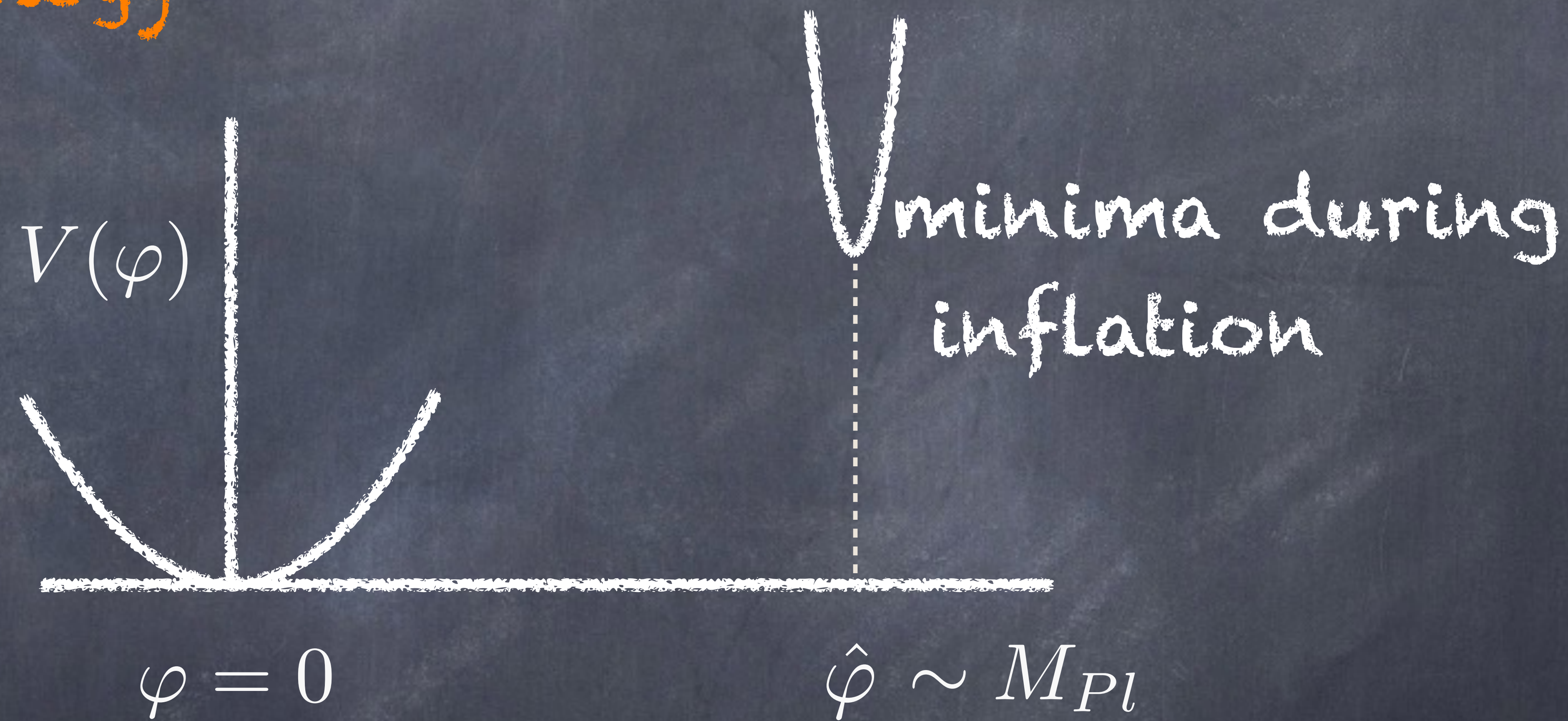
arXiv:1506.05745[hep-ph]

some ongoing work ..

Prologue

'Modular Cosmology'

$m < H_{inf}$



post-inflationary moduli mass

$$Y = \hat{\varphi}/M_{Pl} \sim 1$$

Outline

- Inflation 101

- Cosmology with moduli

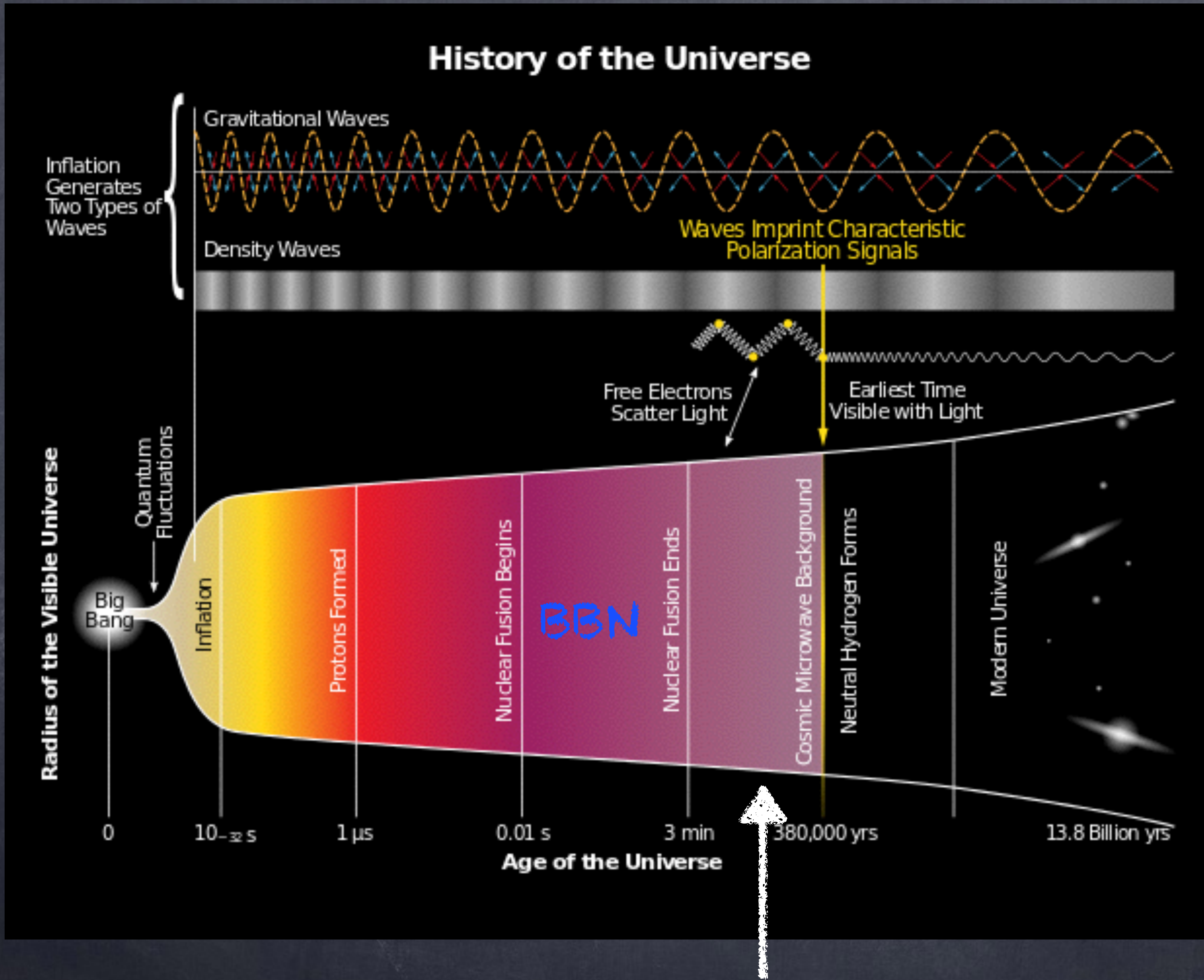
- Constraint on moduli mass/inflation

- Implications ..

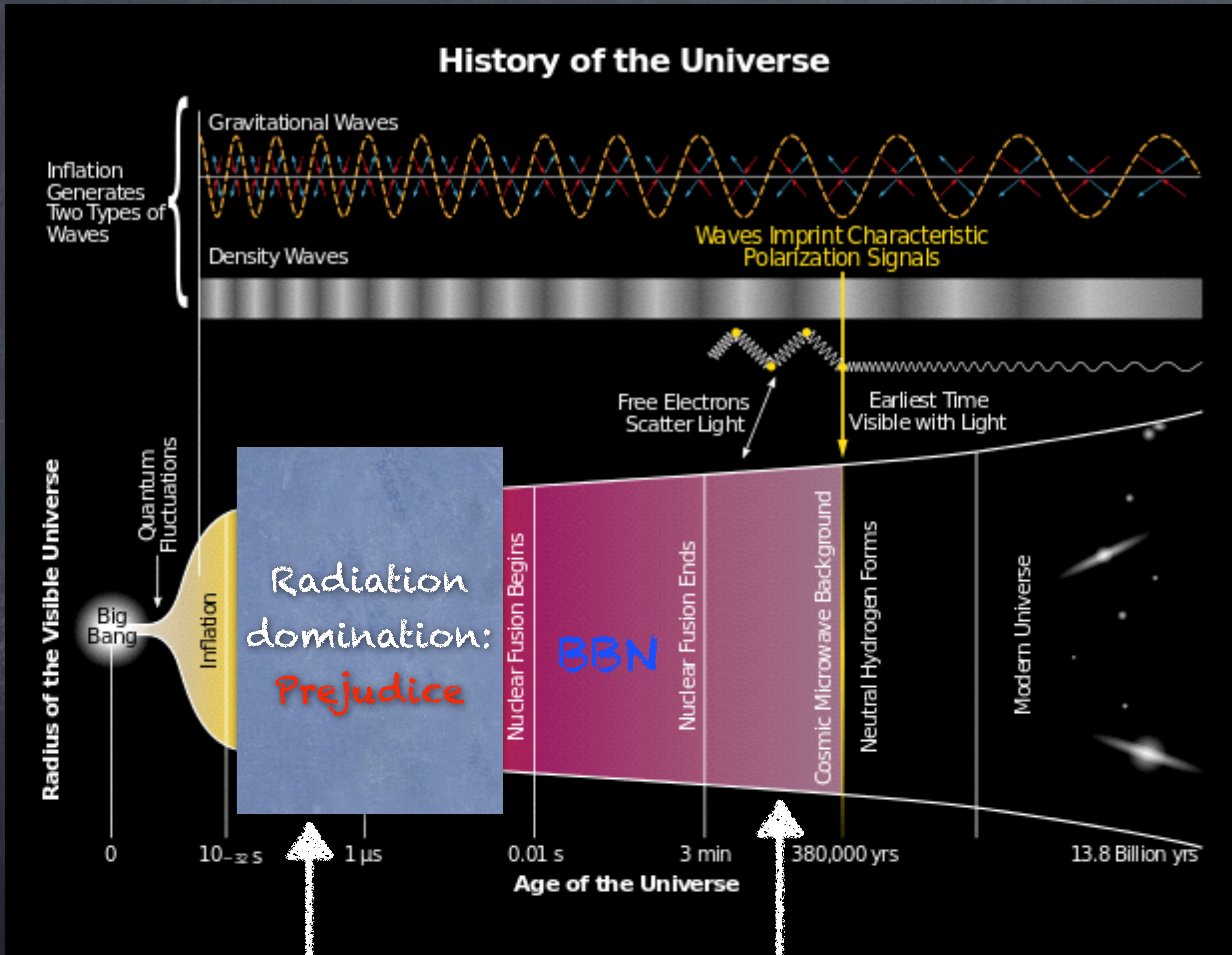
- Inflationary paradigm is the leading candidate for the early universe cosmology: Many reasons ....

- Must be compatible with our knowledge about high energy physics: Probably the only probe ....

- Consequences of precision CMB data



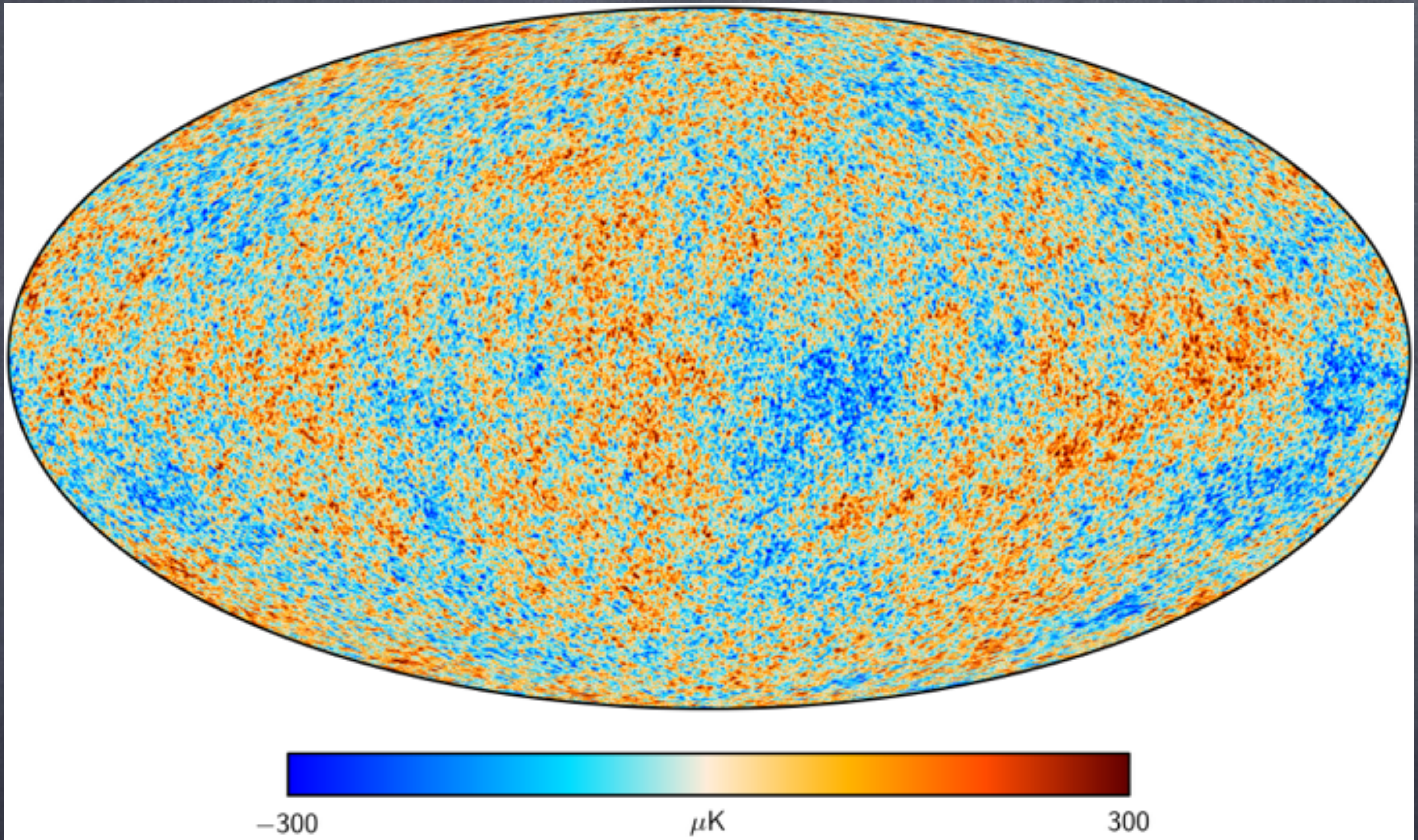
Matter domination



non-thermal epoch

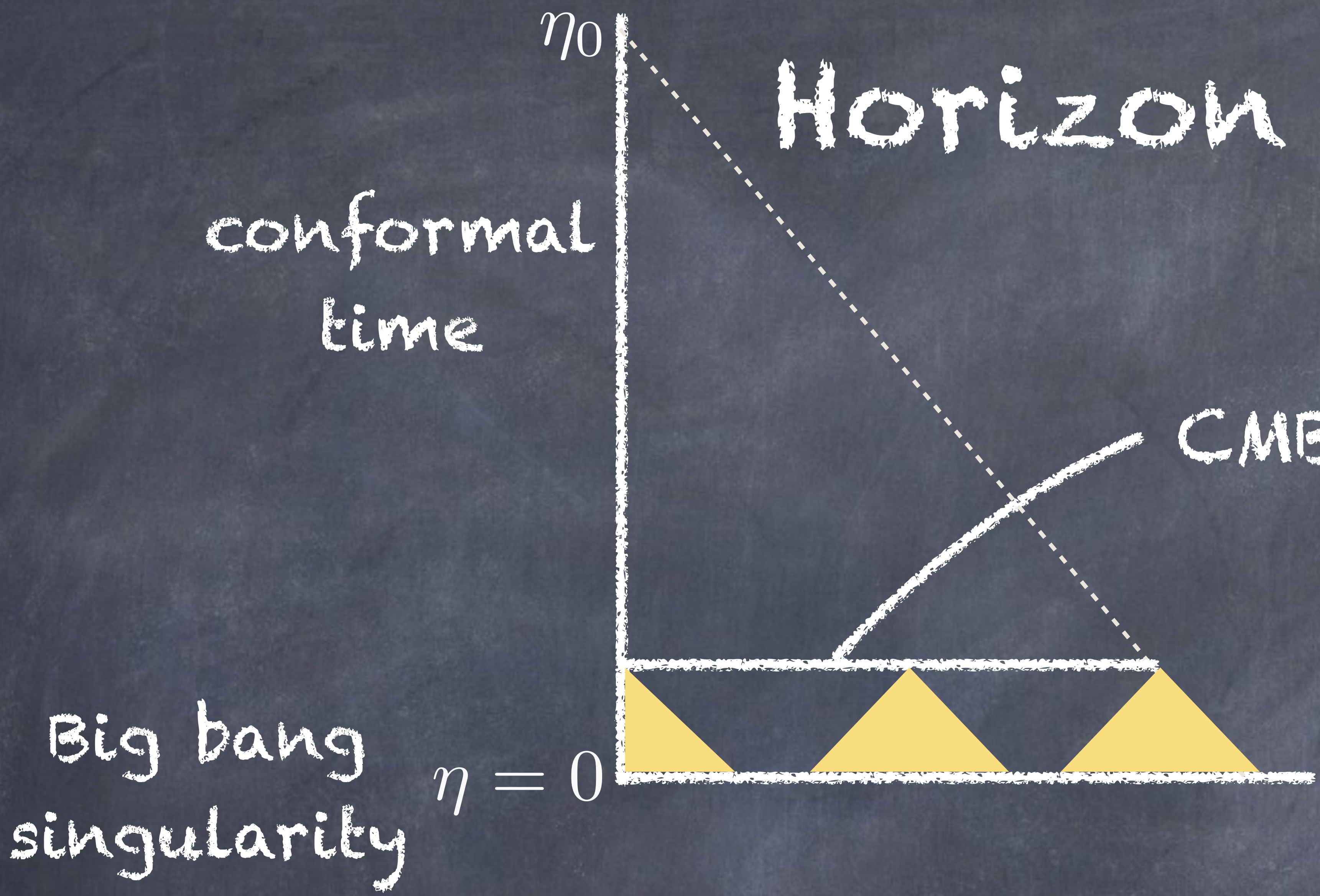
Matter domination

PLANCK 2015

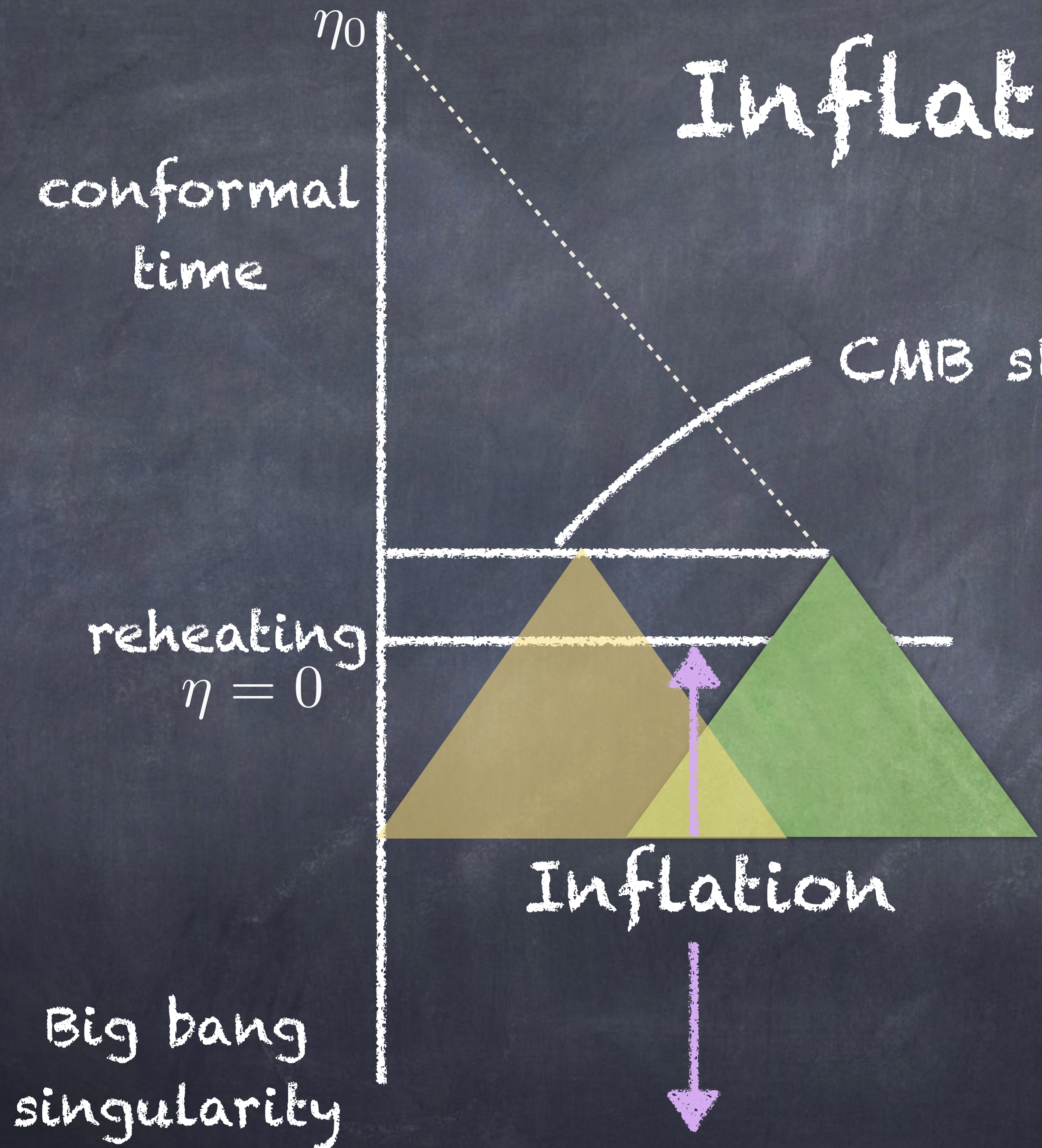


Fluctuations ~ 0,00001

Horizon Problem



Inflation



η_0
conformal time
CMB sky
reheating
$\eta = 0$
Inflation
Big bang singularity

Inflation

$$1 - \Omega_{Tot} = -\frac{k}{(aH)^2}$$

Flatness problem

Inflation

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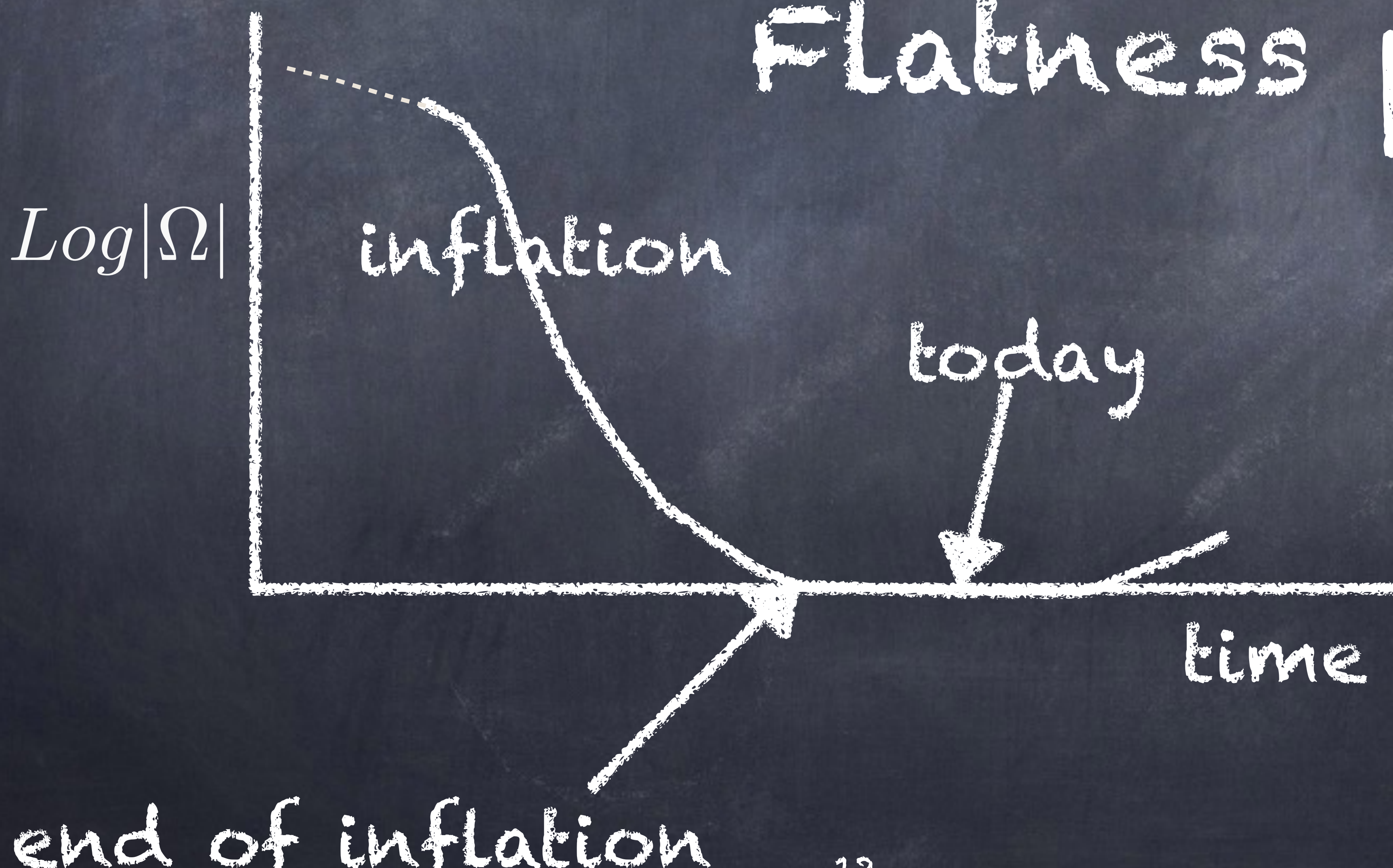
Flatness problem



Inflation

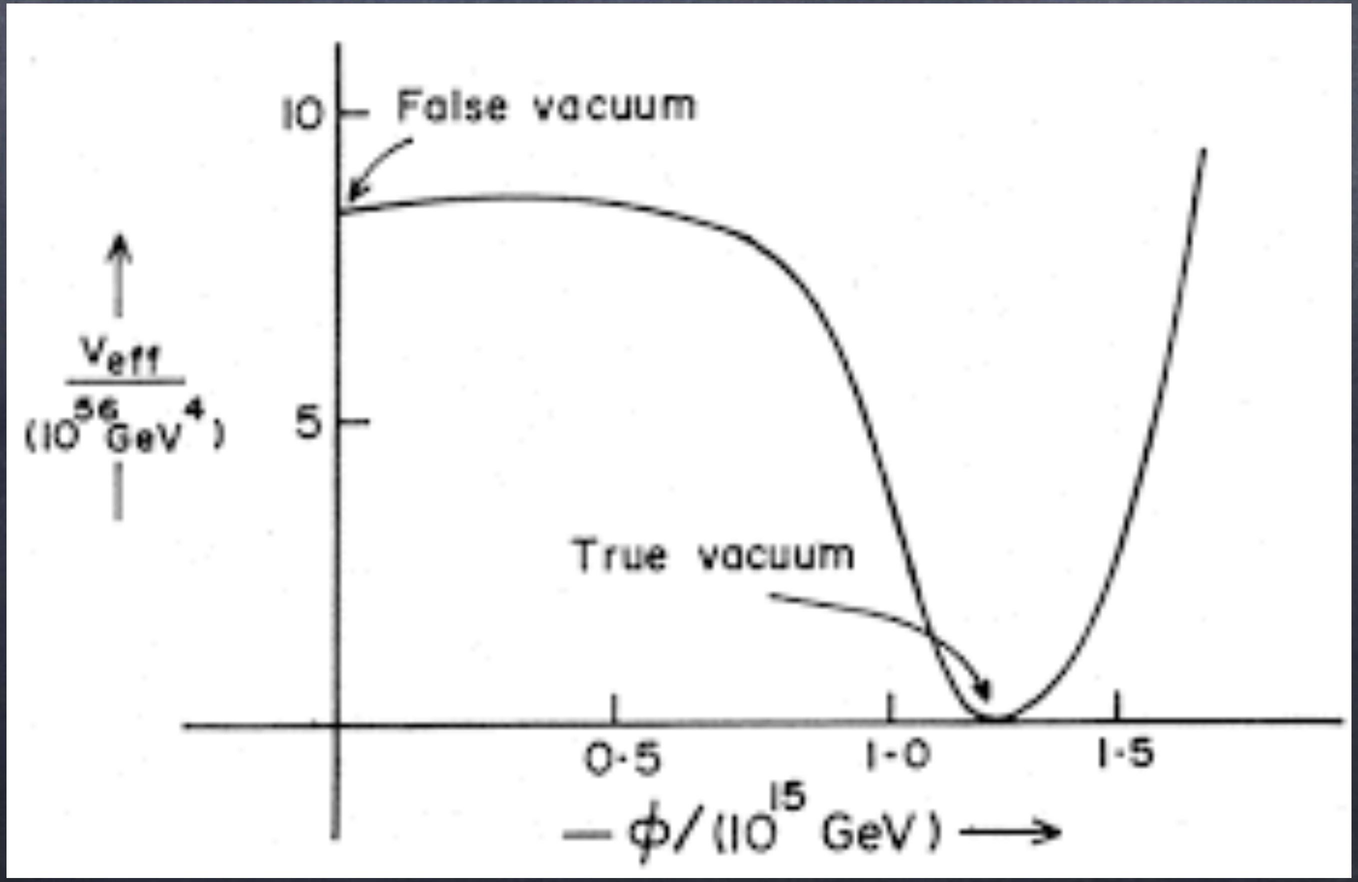
$$\frac{d}{dt}((aH)^{-1}) < 0$$

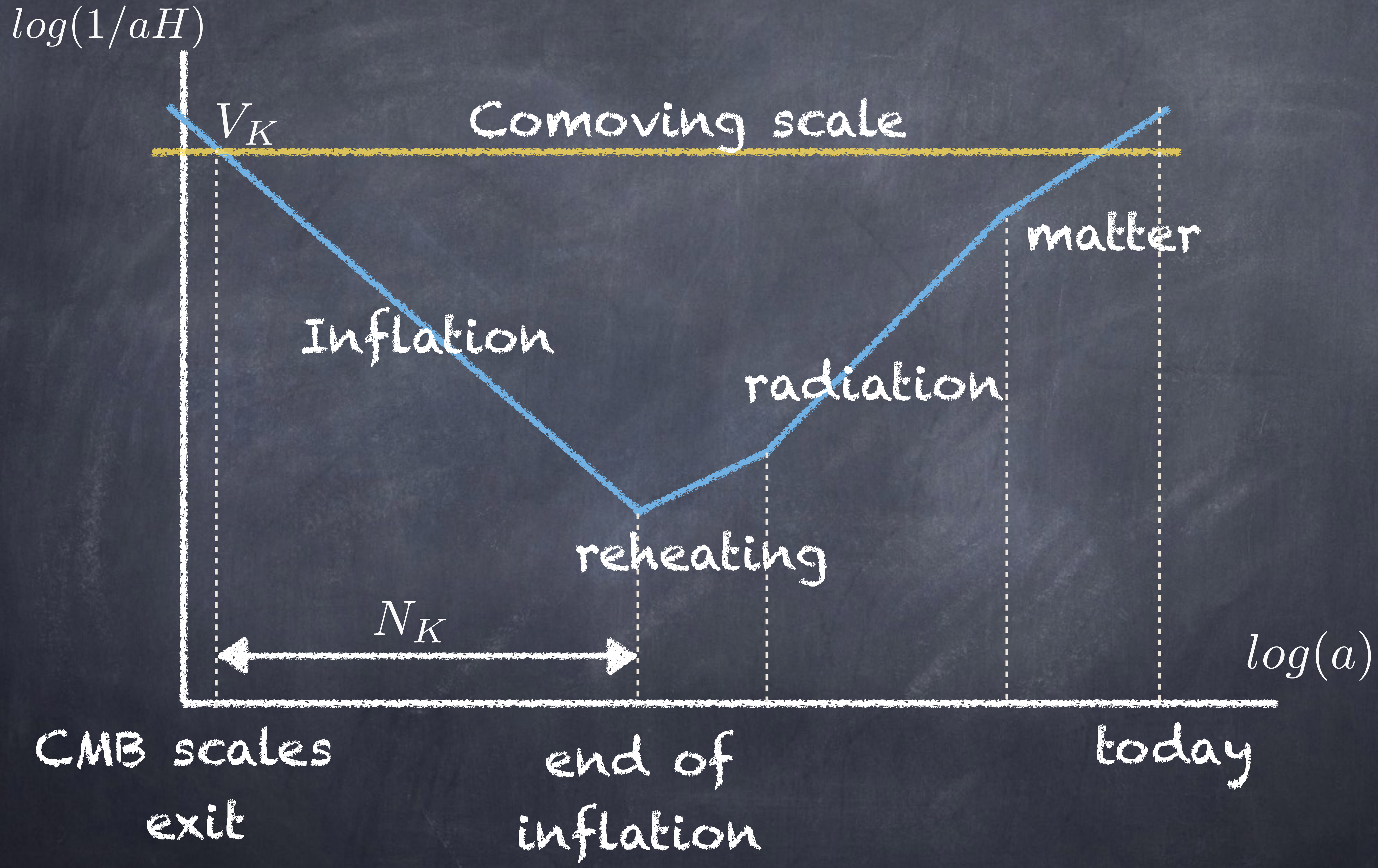
$$\ddot{a} > 0$$

Inflation

$$\frac{d}{dt}((aH)^{-1}) < 0 \quad \Longleftrightarrow \quad \ddot{a} > 0$$

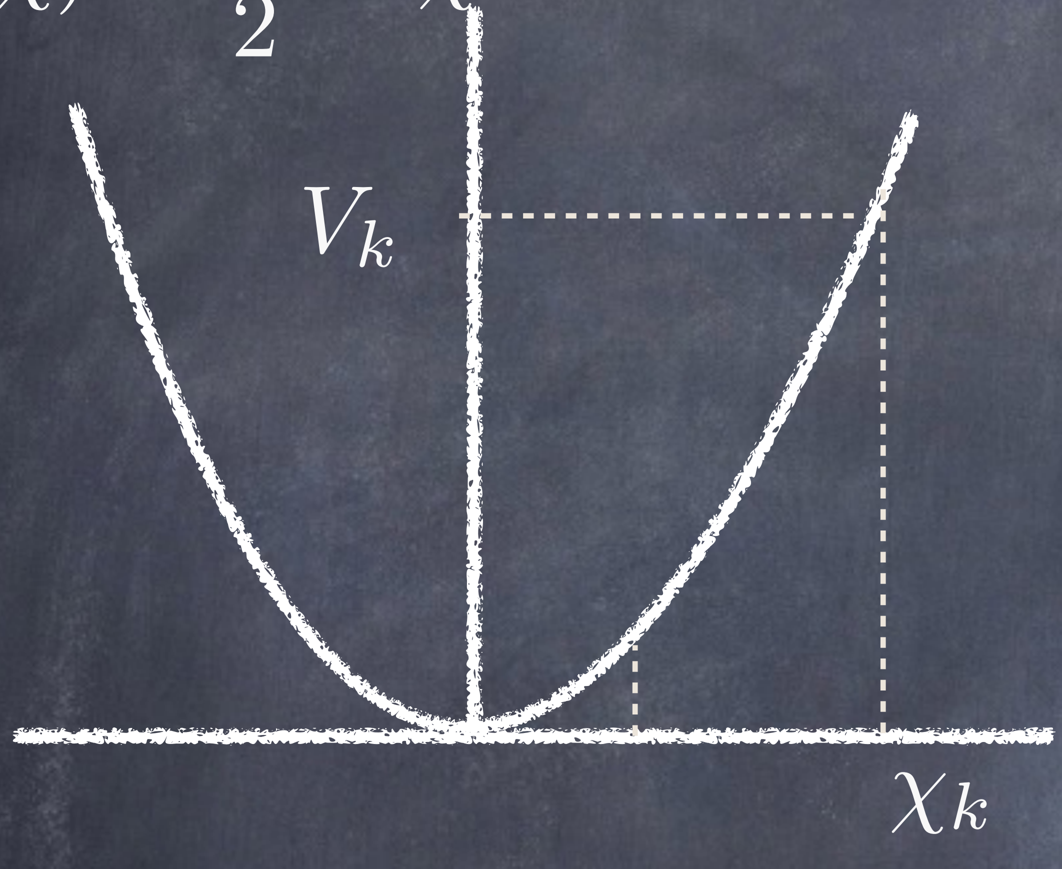
implemented by 'slowly rolling' scalar field whose potential energy dominates!




$log(1/aH)$
V_K
Comoving scale
matter
Inflation
radiation
reheating
N_K
$log(a)$
CMB scales exit
end of inflation
today

Inflation: Case Study

$$V(\chi) = \frac{1}{2}m^2\chi^2$$



$$N_k \simeq \frac{\chi_k^2}{4M_{Pl}^2} \qquad n_s - 1 = -\frac{2}{N_k}$$

Inflation: Case Study

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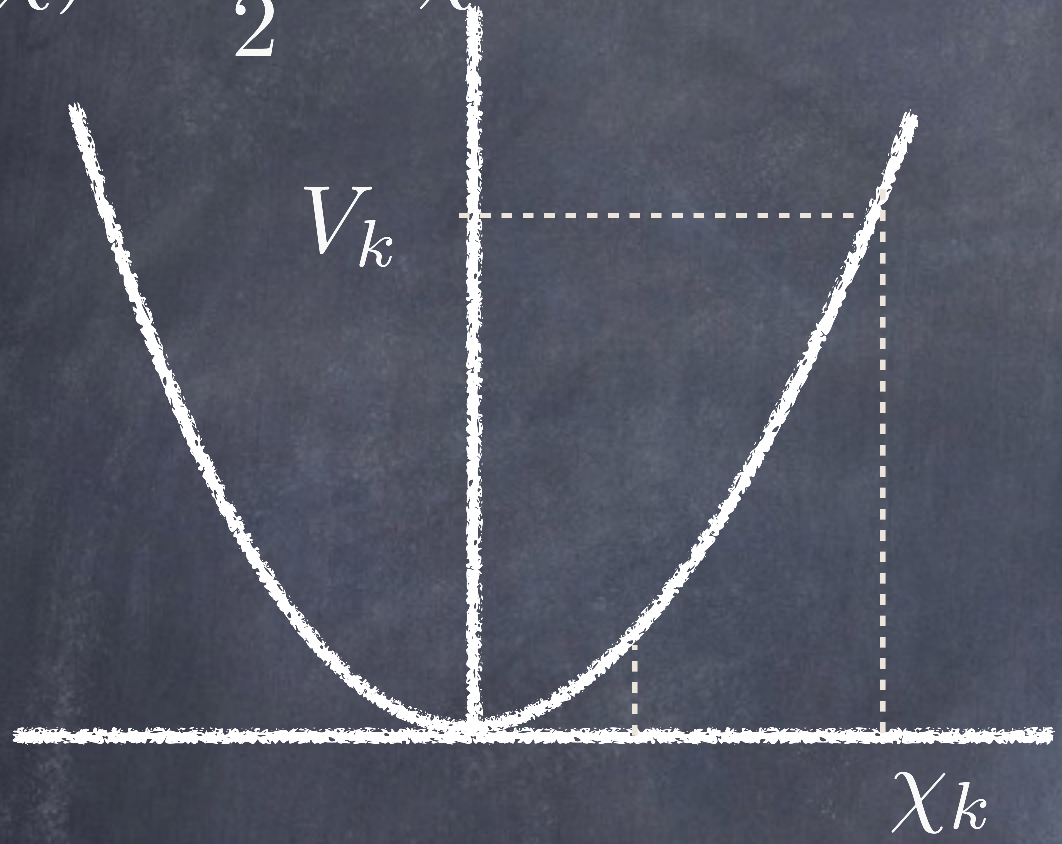

$$N_k \simeq \frac{\chi_k^2}{4M_{Pl}^2} \qquad n_s - 1 = -\frac{2}{N_k}$$

$$n_s = 0.968 \pm 0.006$$

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precision measurement of spectral index can pin down the e-folds during inflation

Inflation & Density Perturbations

$$A_s = \frac{2}{3\pi^2 r}(\frac{\rho_k}{M_{Pl}^4})$$

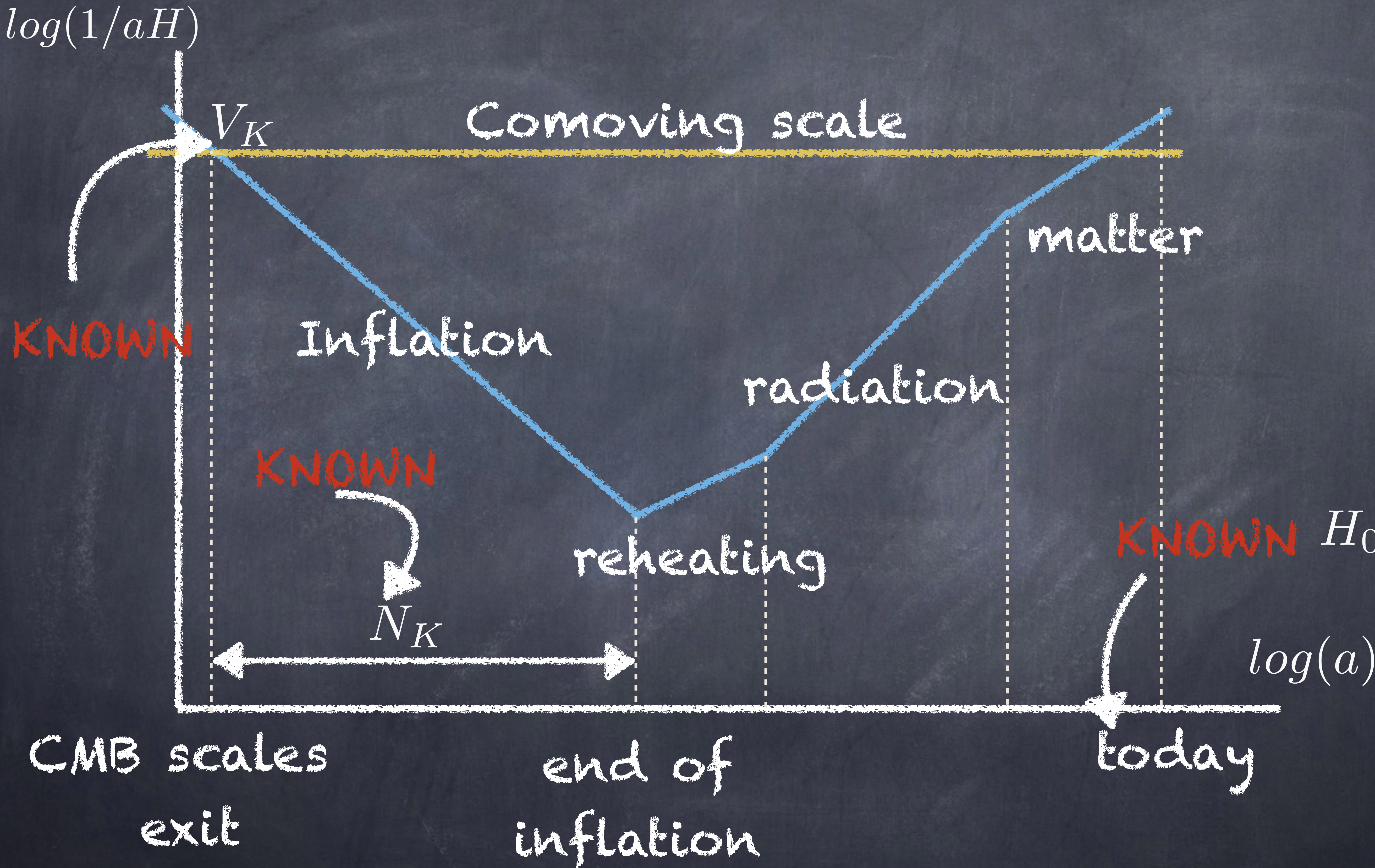
Energy density at the time of horizon exit

strength of gravity wave

$A_s = 2.2 \times 10^{-9}$ @ $k = 0.05 Mpc^{-1}$

knowing scalar amplitude and 'r' we know initial energy density

Single field inflation: A_s conserved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Consistency

V_k must be evolved to H_0

Any post inflationary evolution must be evolved to the present energy density

Consistency Condition

$$N_{inf} + \frac{1}{4}(1 - 3w_{rh})N_{rh} = 55 + \frac{1}{4}lnr + \frac{1}{4}ln(\rho_k/\rho_{end})$$

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Equivalent

$$N_* \approx 71.21 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{M_{\rm pl}^4}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{\rho_{\rm end}}\right) + \frac{1 - 3w_{\rm int}}{12(1 + w_{\rm int})}\ln\left(\frac{\rho_{\rm th}}{\rho_{\rm end}}\right),$$

PLANCK paper

Making predictions ..

$$N_{inf} + \frac{1}{4}(1 - 3w_{rh})N_{rh} = 55 + \frac{1}{4}lnr + \frac{1}{4}ln(\rho_k/\rho_{end})$$

$$N_{inf} = 55 \pm 5$$

Making predictions ..

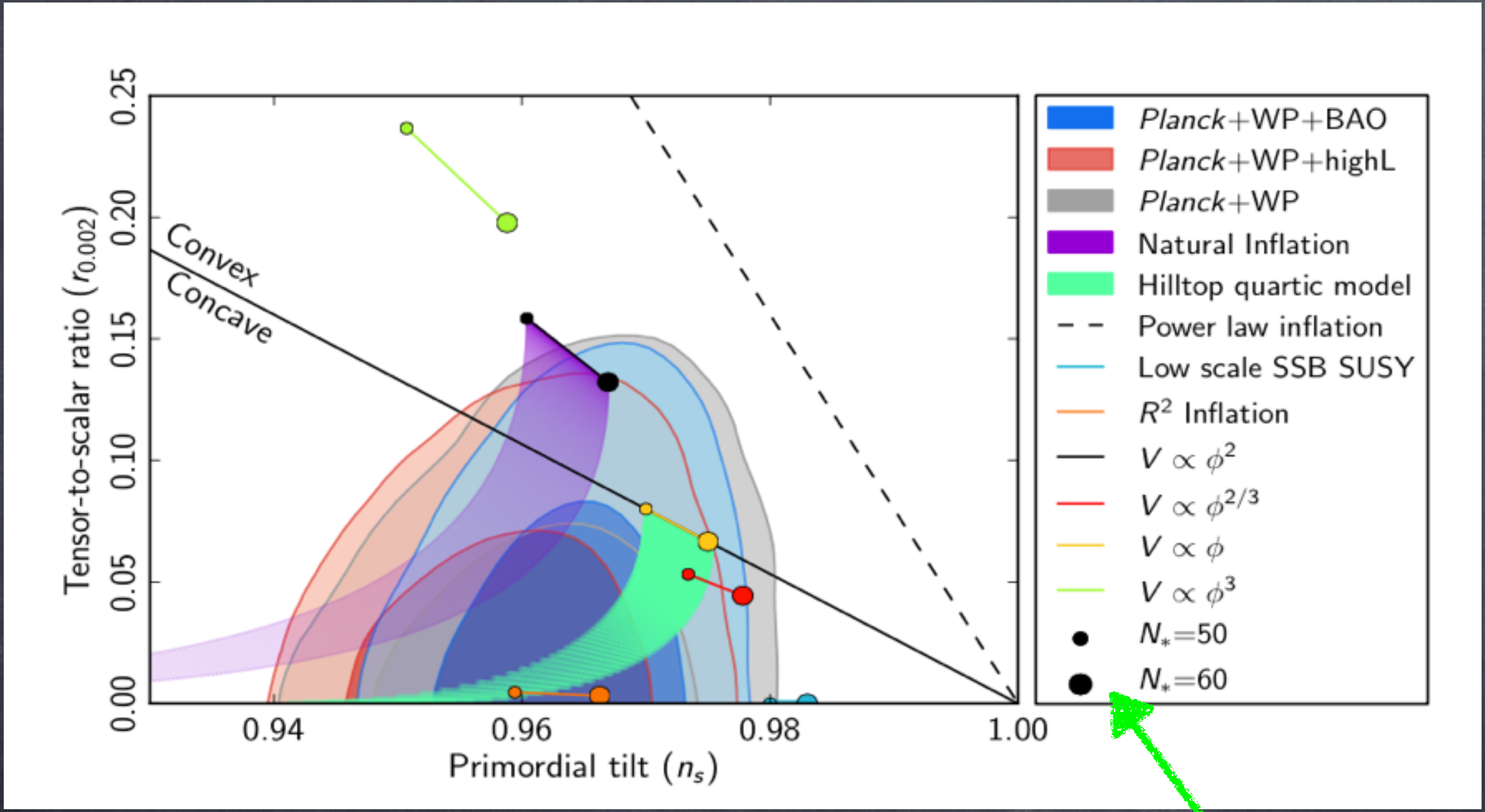
$$N_{inf} + \frac{1}{4}(1 - 3w_{rh})N_{rh} = 55 + \frac{1}{4}ln r + \frac{1}{4}ln(\rho_k/\rho_{end})$$

$$N_{inf} = 55 \pm 5$$

<u>'Theoretical prior'</u>

compute observables in terms of N_{inf} and see whether it fits data for N = 50-60!

$$V(\chi) = \frac{1}{2}m^2\chi^2 \qquad n_s - 1 = -\frac{2}{N_k} \qquad r = 8/N_K$$



'Theoretical prior'

How does making predictions change for modular cosmology?

Moduli ..

- moduli: light scalar fields with Planck suppressed interactions

- at tree level effective Lagrangian of string theory/SUGRA, moduli are massless

- moduli must acquire masses (thus fixed vev) to become phenomenologically viable

- moduli stabilisation: KKLT etc…

Moduli ..

- Conservative approach: Make ALL modulus much heavier than the Hubble scale .. decouple from inflation

- Wishful ....

- In practice, few fields remain parametrically light in the post-inflationary vacua .. (e.g Many LVS constructions ..)

A typical case

$$\mathcal{L} \supset -\frac{1}{2}m^2\varphi^2 - \frac{1}{2}H^2(\varphi - \hat{\varphi})^2 - V_{inf}(\chi)$$

$m < H_{inf}$

post-inflationary moduli mass

minima during inflation

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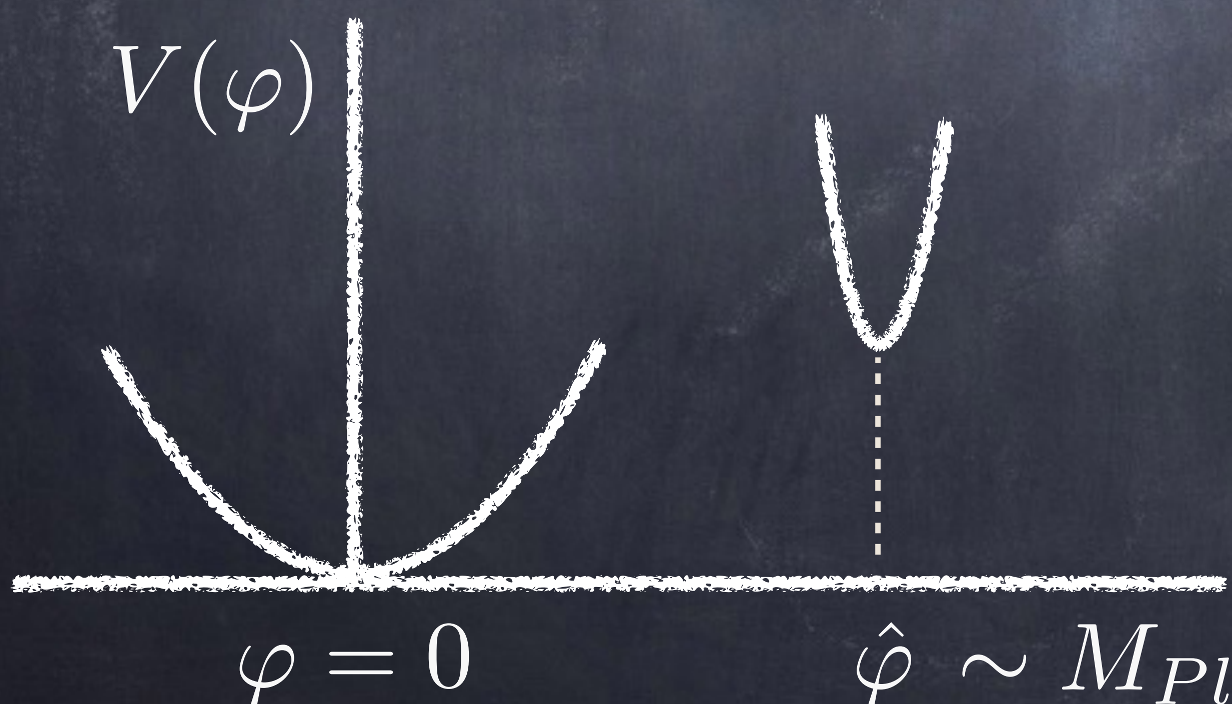

$$Y = \hat{\varphi}/M_{Pl} \sim 1$$

Dine, Randall, Thomas (1995)

SUGRA ...

$$V = e^{K[\varphi,\bar{\varphi}]} V_0[\varphi,\chi] \sim H^2 M_{Pl}^2 f\left(\frac{\varphi}{M_{Pl}}\right)$$

$V'' \sim H^2$ $\eta -$ problem

Scale of variations M_{Pl} $Y = \hat{\varphi}/M_{Pl} \sim 1$

Dine, Randall, Thomas (1995)

Dvali (1995)

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Scale of variations M_{Pl} $\qquad$ $Y = \hat{\varphi}/M_{Pl} \sim 1$

Dine, Randall, Thomas (1995)

Dvali (1995)

Toy example ..

$$V = (m_{3/2}^2 - a^2H^2)|\varphi|^2 + \frac{1}{2M_{Pl}^2}(m_{3/2}^2 + b^2H^2)|\varphi|^4$$

$\hat{\varphi} \sim (a/b)M_{Pl}$ $\qquad$ "Fibre inflation" .. $\qquad$ Cicoli, Burgess, Quevedo

$$\hat{\varphi} \sim 0.1 M_{Pl}$$

Sequence of events ..

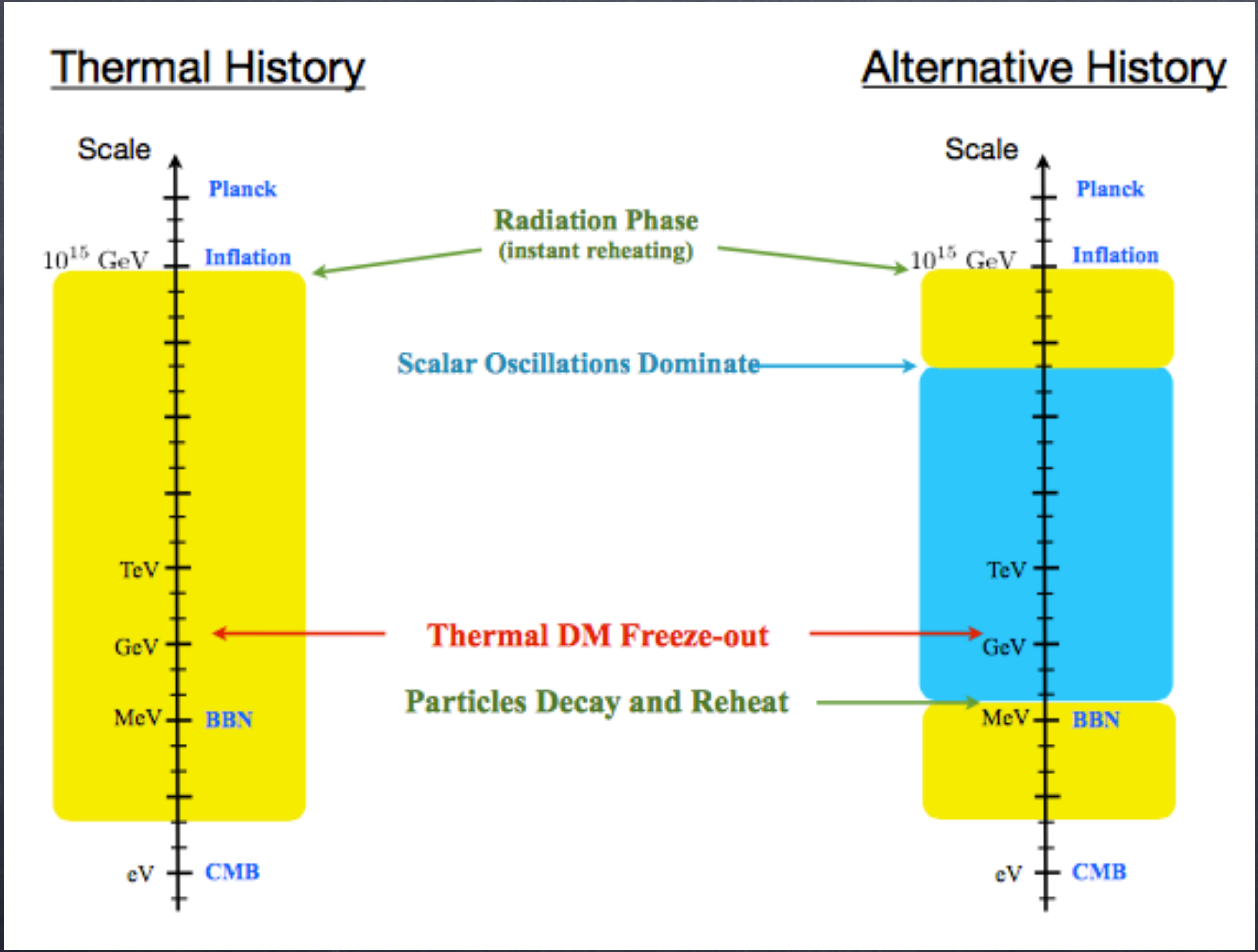
- when m < H_inf, moduli is stuck due to the Hubble friction

- inflation ends with $\varphi = \hat{\varphi}$

- When H < m, the field starts to move toward its post inflationary minima $\varphi = 0$

- Oscillations around the minima behaves as matter $\rho_\varphi \sim a^{-3}(t)$

Review: B. S. Acharya, G. Kane, and P. Kumar (2012)



Kane, Sinha, Watson (2015)

Consistency

V_k must be evolved to H_0

N_k is known

Any post inflationary evolution must be evolved to the present energy density

Decay of Modulus

moduli must decay so that it does not overclose the Universe

$$\Gamma_{mod} \sim \frac{m_\varphi^3}{16\pi M_{Pl}^2}$$

G. D. Coughlan, W. Fischler, E. W. Kolb, S. Raby and G. G. Ross 1984

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$$\rho_{mod}(t_{decay}) = g\frac{\pi^2}{30}T_{reheat}^4 \quad = 3H^2 M_{Pl}^2$$

decay happens

$H \to \Gamma_{mod}$

Decay of Modulus

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$$\rho_{mod}(t_{decay}) = g\frac{\pi^2}{30}T_{reheat}^4 \quad = 3H^2 M_{Pl}^2$$

$\uparrow$ decay happens

Γ_{mod}

$$T_{reheat} \sim \sqrt{\Gamma M_{Pl}}$$

$T_{reheat} > MeV$ successful BBN

$m_\varphi > 30\ TeV$ BBN bound

phenomenological implications .. SUSY breaking ..

Tom Banks, David B. Kaplan, and Ann E. Nelson

B. de Carlos, J. Casas, F.Quevedo, E.Roulet

Inflation → reheating → radiation

N_{inf} N_{rh1} ↓ N_{rad}

reheating ← moduli (matter)

N_{rh2} 'non-standard' N_{mod}

↓ BBN

today

Inflation → reheating → radiation

N_{inf} N_{rh1}

↓ N_{rad}

reheating ← moduli (matter)

N_{rh2} 'non-standard' N_{mod}

↓ BBN

today

K.D, Maharana

arXiv:1409.7037[hep-ph]

$$N_{inf} + \frac{1}{4}(1 - 3w_{rh1})N_{rh1} + \frac{1}{4}N_{mod} + \frac{1}{4}(1 - 3w_{rh2})N_{rh2}$$

$$= 55.43 + \frac{1}{4}ln\ r + \frac{1}{4}ln(\frac{\rho_k}{\rho_{end}})$$

non-thermal history

constraint ..

$$\Gamma_{mod} \sim \frac{m_\varphi^3}{16\pi M_{Pl}^2}$$

$$N_{mod} \sim \frac{2}{3} ln(\frac{16\pi M_{Pl}^2 Y^4}{m_\phi^2})$$

initial displacement $Y = \hat{\varphi}/M_{Pl}$

constraint ..

$$\Gamma_{mod} \sim \frac{m_\varphi^3}{16\pi M_{Pl}^2} \qquad N_{mod} \sim \frac{2}{3} ln(\frac{16\pi M_{Pl}^2 Y^4}{m_\phi^2})$$

initial displacement $Y = \hat{\varphi}/M_{Pl}$

$$\frac{1}{6} ln(\frac{16\pi M_{Pl}^2 Y^4}{m_\varphi^2}) + \frac{1}{4}(1-3w_{rh1})N_{re1} + \frac{1}{4}(1-3w_{rh2})N_{re2}$$

$$= 55.43 - N_{inf} + \frac{1}{4} ln\ r + \frac{1}{4} ln(\frac{\rho_k}{\rho_{end}})$$

analytical/numerical understanding of reheating: $w_{re} < 1/3$

inflationary potentials

$$N_{inf} + \frac{1}{4}(1 - 3w_{rh1})N_{rh1} + \frac{1}{4}(1 - 3w_{rh2})N_{rh2}$$

$$= 55 - \frac{1}{3}\left(\frac{\sqrt{16\pi}M_{Pl}Y^2}{m_\varphi}\right) + \frac{1}{4}lnr\frac{1}{4}ln\left(\frac{\rho_k}{\rho_{end}}\right)$$

- central value shifts
- significant impact for inflation models

Implications: I

Central value of e-folding shifts

$$N_{inf} = 55 \pm 5$$

$$N_{inf} = \left(55 - \frac{N_{mod}}{4}\right) \pm 5$$

$$\Gamma_{mod} \sim \frac{m_\varphi^3}{16\pi M_{Pl}^2}$$

$$N_{inf} = \left(55 - \frac{1}{3} ln\left(\frac{\sqrt{16\pi} M_{pl} Y^2}{m_\varphi}\right)\right) \pm 5$$

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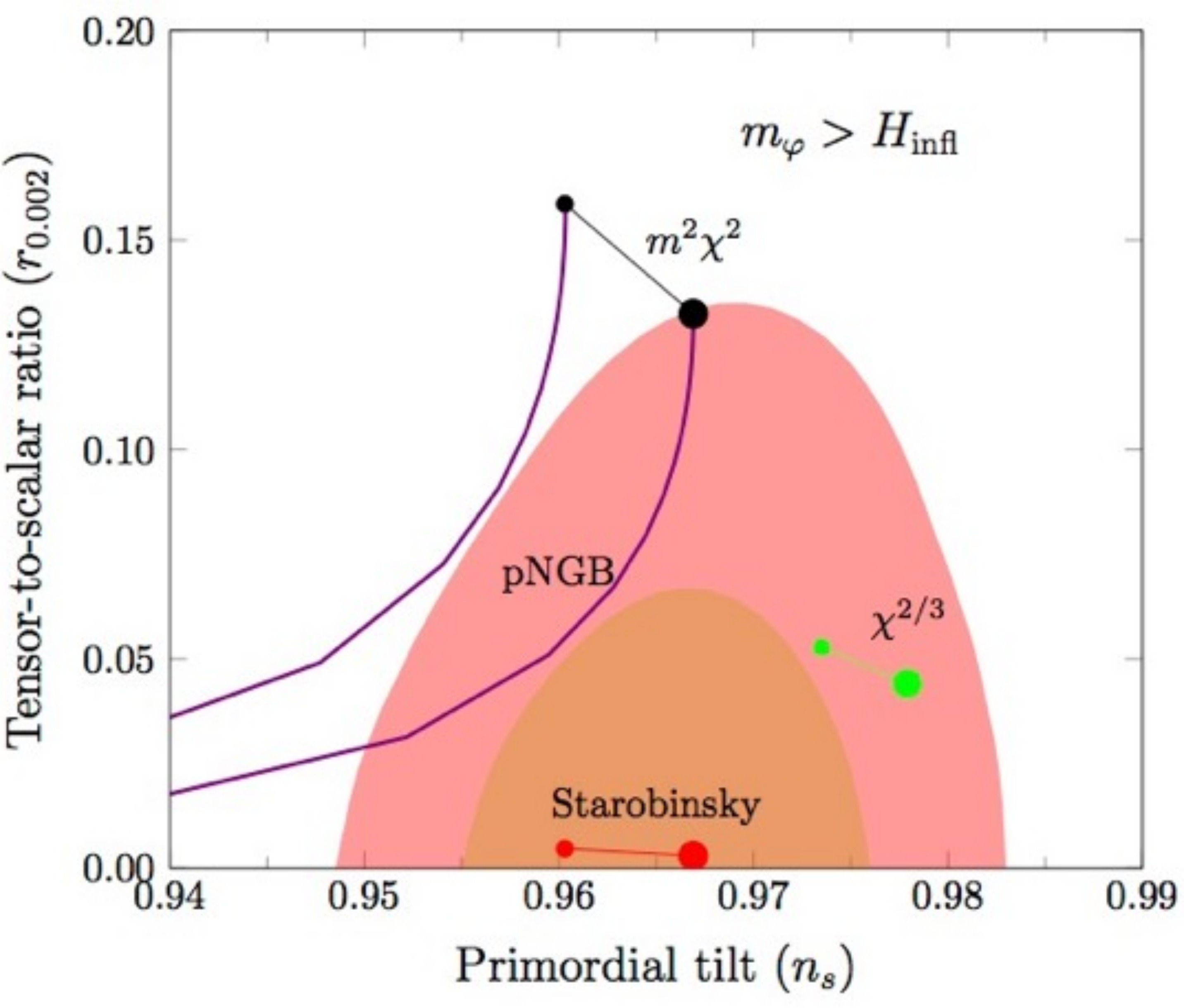
Central value of e folding shifts

For $m_\varphi \sim 10^3$ TeV : $N_{inf} = 41 \quad - \quad 51$

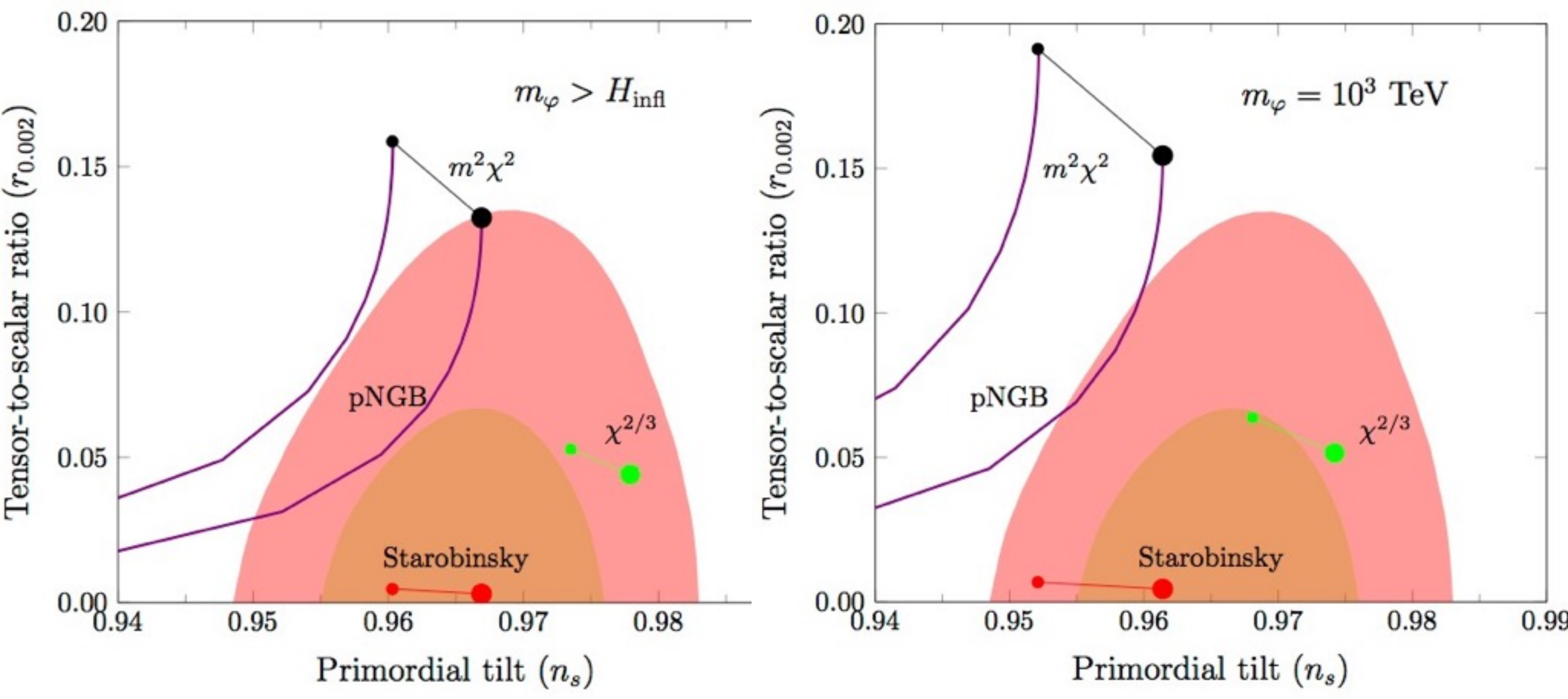
For $m_\varphi \sim 10^6$ TeV : $N_{inf} = 43 \quad - \quad 53$

(used to be 50 - 60)

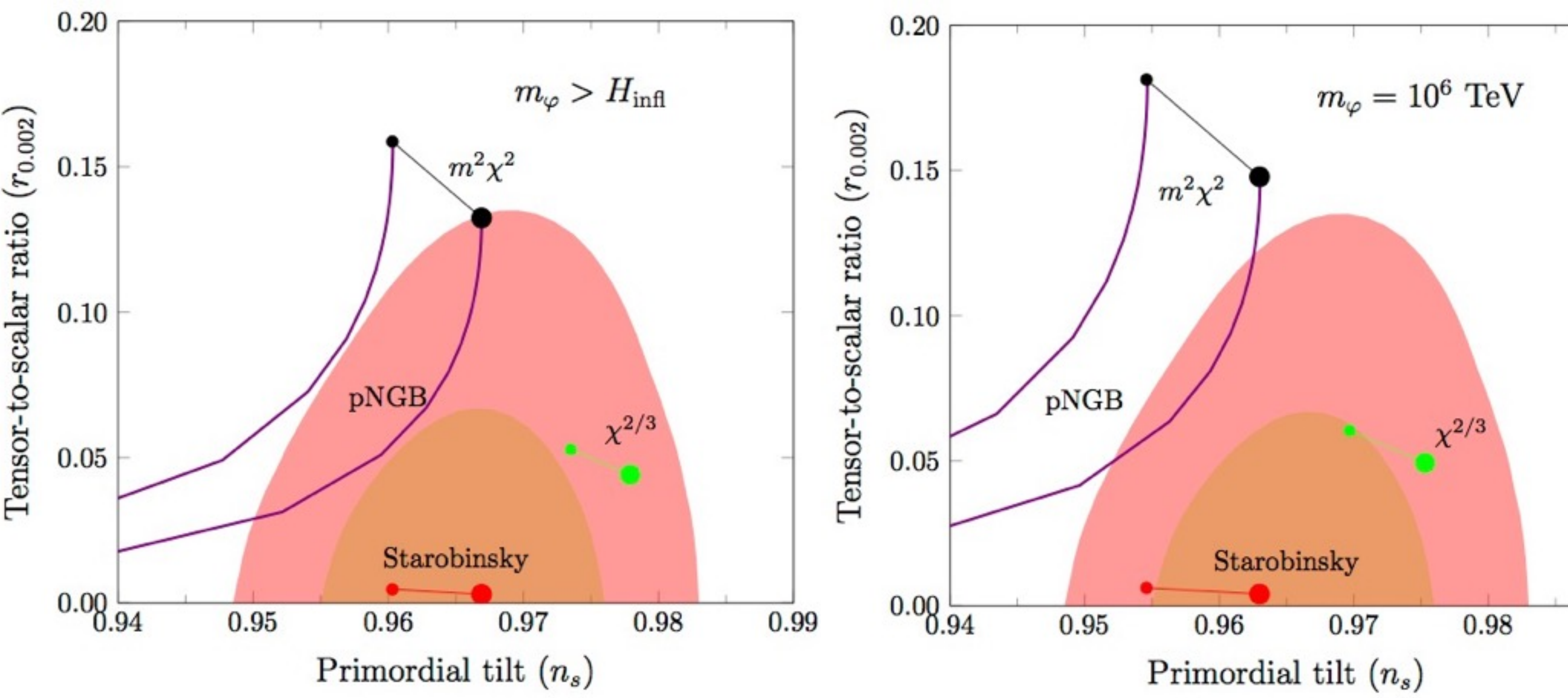
(Y ~ 0.1 assumed)



$m_\varphi > H_{\rm infl}$
$m^2\chi^2$
pNGB
$\chi^{2/3}$
Starobinsky
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.20
0.15
0.10
0.05
0.00
0.94
0.95
0.96
0.97
0.98
0.99



Das, Maharana, K.D



Das, Maharana, K.D

sensitivity $n_s \sim 10^{-3}$ DECIGO/PRISM/21 Cm

The central value reaches N = 50 for

$$m_\varphi \sim 10^{10} GeV$$

The effects of modulus mass must be taken for inflation models for $m_\varphi \lesssim 10^{10} GeV$

constraint on modulus mass

$$\frac{1}{6}ln(\frac{16\pi M_{Pl}^2 Y^4}{m_\varphi^2}) + \frac{1}{4}(1-3w_{rh1})N_{re1} + \frac{1}{4}(1-3w_{rh2})N_{re2}$$

usually positive definite

$$= 55.43 - N_{inf} + \frac{1}{4}ln\ r + \frac{1}{4}ln(\frac{\rho_k}{\rho_{end}})$$

analytical/numerical understanding of reheating: $w_{re} < 1/3$

Ellis, Garcia, Nanopoulos, Olive

1505.06986

constraint ..

$$m_\varphi \gtrsim \sqrt{16\pi} M_{\rm pl} Y^2 \; e^{-3\left(55.43 - N_k + \frac{1}{4}\ln(\frac{\rho_{\rm k}}{\rho_{\rm end}}) + \frac{1}{4}\ln r\right)}$$

- Dependence correlated

- larger the value of N_{inf}, stronger the bound

- smaller the value of 'r' stronger the bound

- bound depends on the nature of inflationary potentials via the ratio of energy densities

small field models

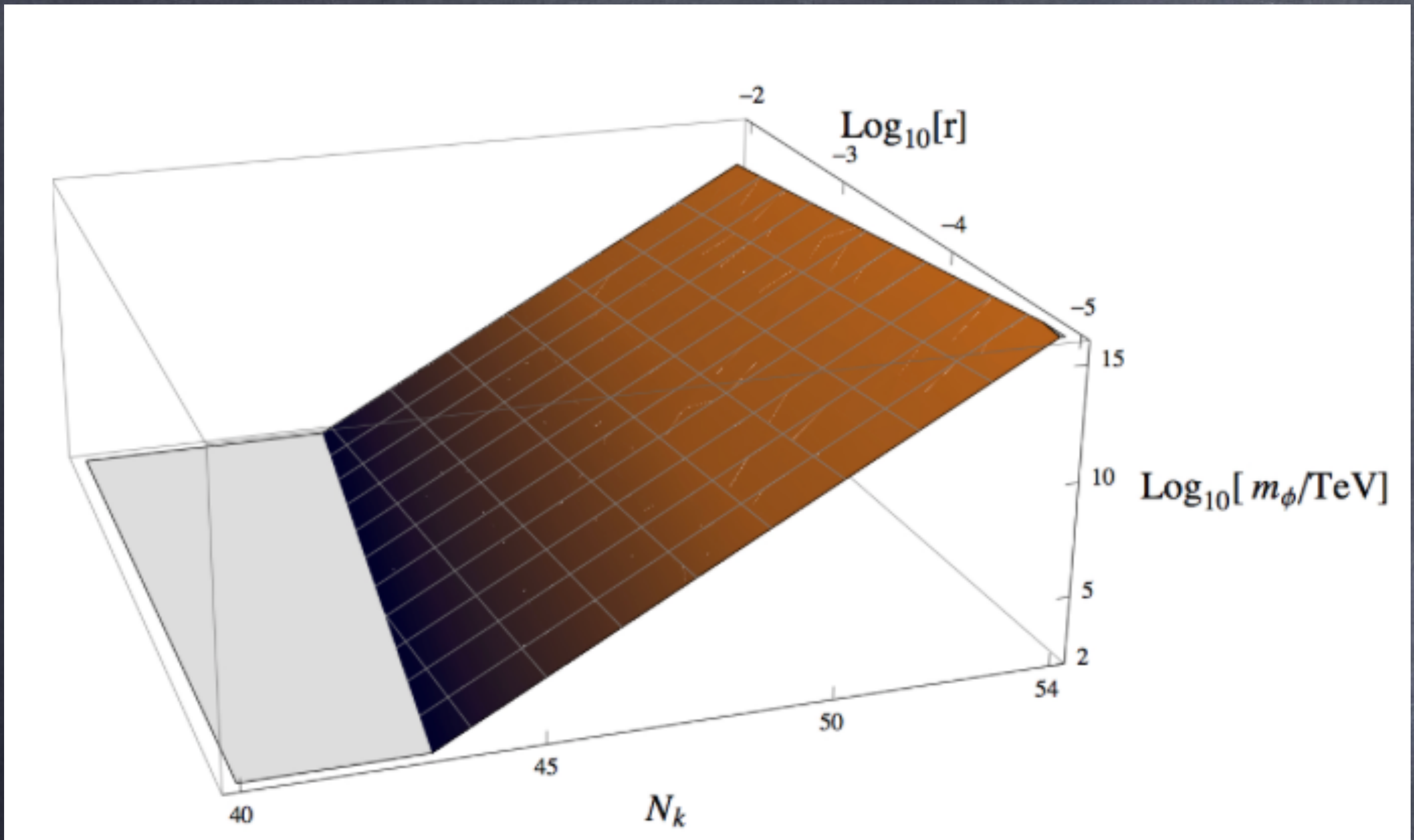
$$m_\varphi \gtrsim \sqrt{16\pi} M_{\rm pl} Y^2 \; e^{-3\left(55.43 - N_k + \frac{1}{4}\ln(\frac{\rho_{\rm k}}{\rho_{\rm end}}) + \frac{1}{4}\ln r\right)}$$

- conservative estimate r ~ 0.01 stronger the bound
- potential plateau like .. ratio of energy densities negligible
- take Y = 0.01, then for N = 50

$$m_\varphi \gtrsim 4.5 \times 10^6 TeV$$

much stronger than BBN bound

small field models



for N > 44.5, the bound much stronger than BBN bound

Fibre Inflation: $r < 0.01$ and $N > 50$ for CMB observations

large field models

$$m_\varphi \gtrsim \sqrt{16\pi} M_{\rm pl} Y^2 \; e^{-3\left(55.43 - N_k + \frac{1}{4}\ln(\frac{\rho_{\rm k}}{\rho_{\rm end}}) + \frac{1}{4}\ln r\right)}$$

$$V_\chi = m^{4-\alpha}\chi^\alpha$$

chaotic inflation
axion monodormy

$$m_\phi \gtrsim$$

$$\sqrt{16\pi} M_{\rm pl} Y^2 e^{-3\left(55.85 - \frac{(2+\alpha)}{2(1-n_s)} + \frac{\alpha}{8}\ln 2 + \frac{1}{8}(\alpha-2)\ln\left(\frac{2+\alpha}{\alpha(1-n_s)}\right)\right)}$$

$\alpha = 2, \quad m_\varphi >> H_{inf}$ Modular cosmology incompatible

$m_\varphi >> 10^{10}\ \mathrm{TeV}$ PLANCK: 1-sigma lower limit

$\alpha = 2/3$ Bound insignificant

Implications

- guiding principle for modular cosmology (Independent from CMP bound)
- modulus mass related to soft masses in SUSY (gravity mediated SUSY breaking)
- Large SUSY breaking scale ...
- for many models N_k > 50, and the bound is much stronger than BBN bound for PLANCK central value ..

Conclusions

- modulus dominated cosmology is a generic feature of string/sugra motivated scenario

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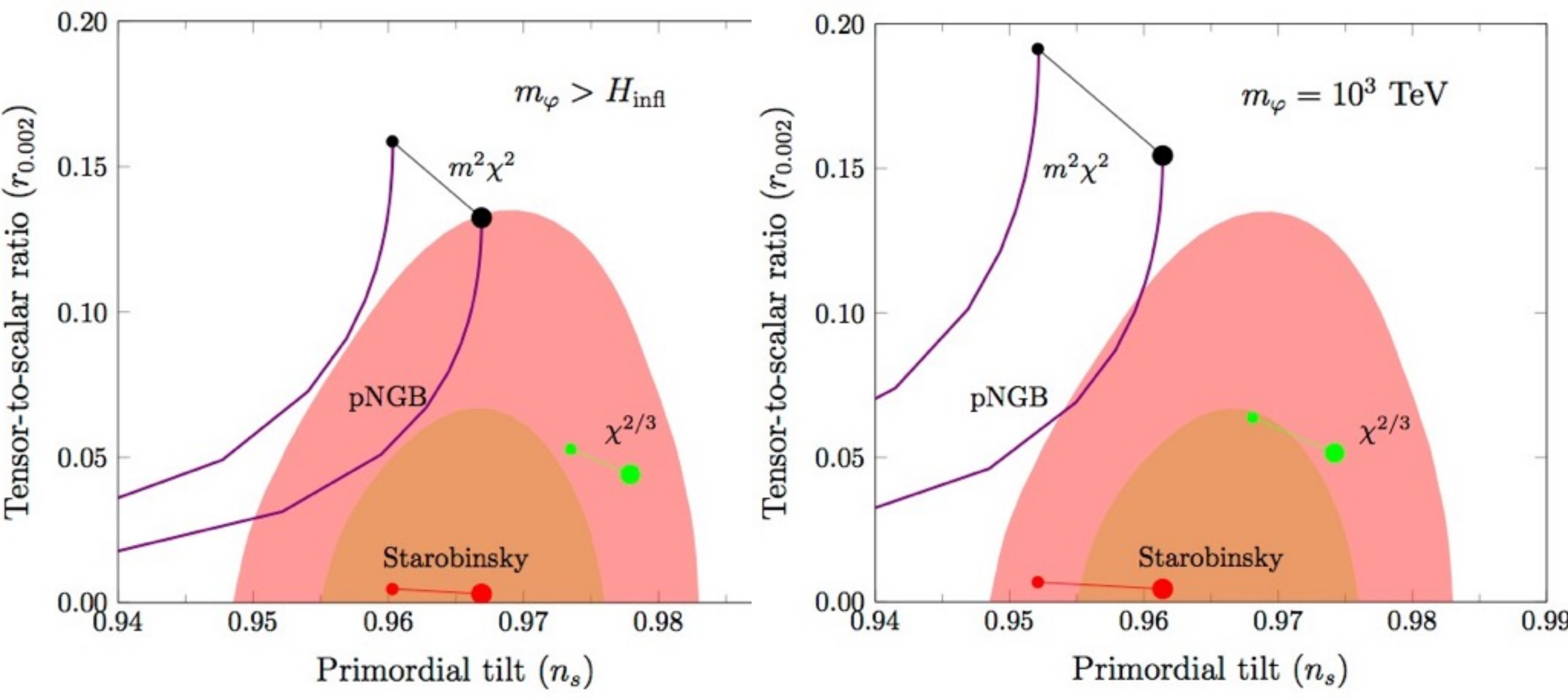
$$\frac{1}{6}ln(\frac{16\pi M_{Pl}^2 Y^4}{m_\varphi^2}) + \frac{1}{4}(1-3w_{rh1})N_{re1} + \frac{1}{4}(1-3w_{rh2})N_{re2}$$

$$= 55.43 - N_{inf} + \frac{1}{4}ln\ r + \frac{1}{4}ln(\frac{\rho_k}{\rho_{end}})$$

Conclusions

- modulus dominated cosmology is a generic feature of string/sugra motivated scenario

$$\hat{N}_{inf} = 55 - \frac{1}{3}\left(\frac{\sqrt{16\pi}M_{Pl}Y^2}{m_\varphi}\right)$$



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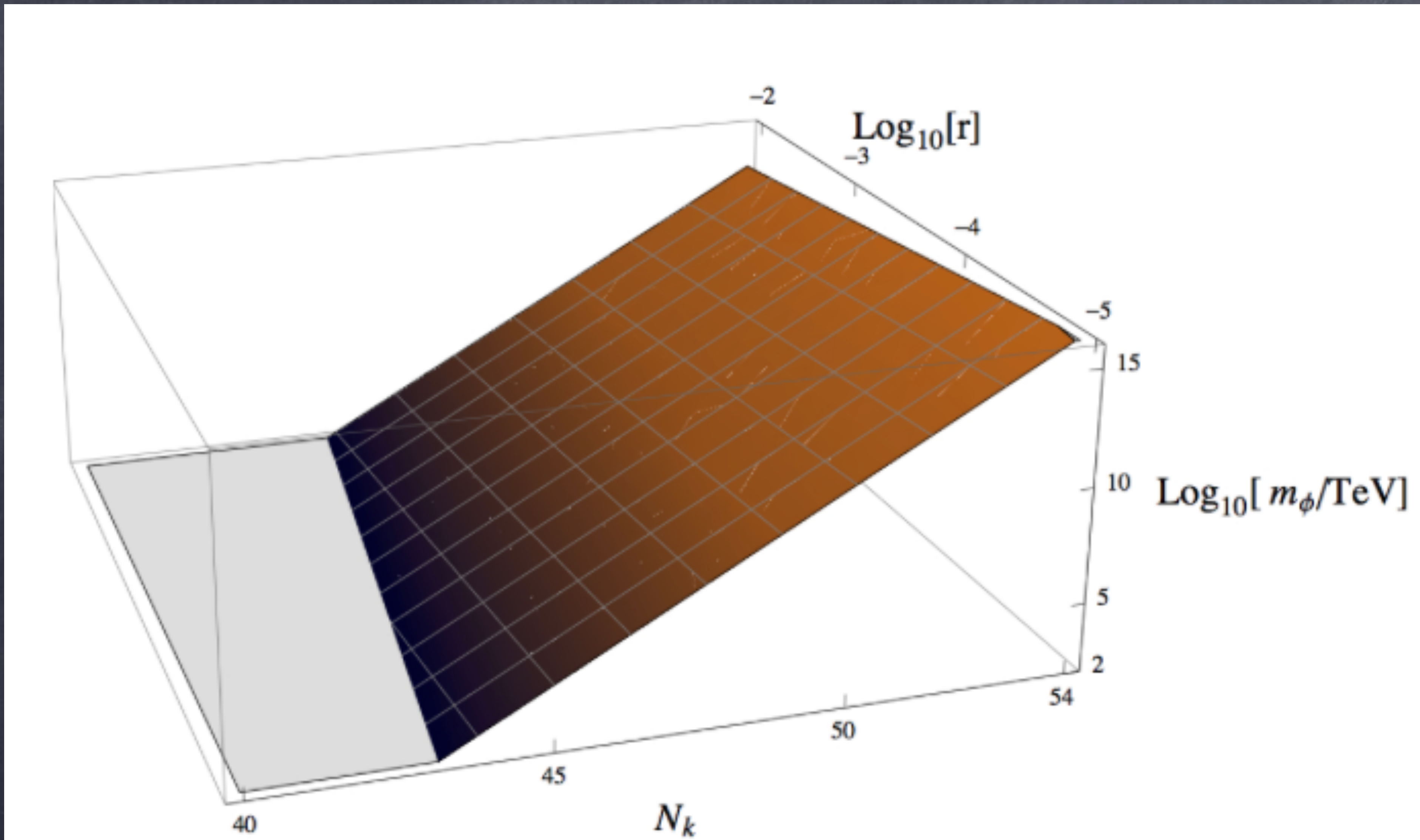
Bound..



for N > 44.5, the bound much stronger than BBN bound

Fibre Inflation: r < 0.01 and N > 50 for CMB observations

Strong bound for chaotic inflation

Insignificant for monodormy models ..

Conclusions

- modulus dominated cosmology is a generic feature of string/sugra motivated scenario

$$\hat{N}_{inf} = 55 - \frac{1}{3}\left(\frac{\sqrt{16\pi} M_{Pl} Y^2}{m_\varphi}\right)$$

- Independent constraint on modulus mass derived using precision CMB data

Thank You