Title: Inflation model building and cosmic microwave background

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Abstract:

"CMB and inflation model building"
--particle theorist's view--

Kenji Kadota
Particle Astrophysics Center, Fermilab

- Can the CMB say anything about inflation?
- An example for inflation model building : Modular Cosmology

K.K. & Ewan Stewart

"Successful Modular Cosmology" (hep-ph/0304127)

"Inflation on Moduli Space and Cosmic Perturbations" (hep-ph/0311240)

Donghui Jeong, K.K.,Wan-Il Park & Ewan Stewart

"Modular Cosmology, Thermal Inflation, Baryogenesis and Preditions for Particle Accelerators" (hep-ph/0406136)

- Another example (more phenomenology oriented)

K.K.& Jun'ichi Yokoyama

"Right-handed Snuetrino Inflation and Leptogenesis" (hep-ph/0512???)

- Inflationary parameter estimation from the cosmological data

"Parameterizing the power spectrum: Beyond the Truncated Taylor expansion"

Kevork Abazajian, K.K. & Ewan Stewart (astro-ph/0507224)

- Summary and Conclusion

CMB

China Motor Bus (Hong Kong)
Center for Mathematical Biology
Chase Manhatten Bank
Central Massachusetts Bandits
Please don't get confused ...

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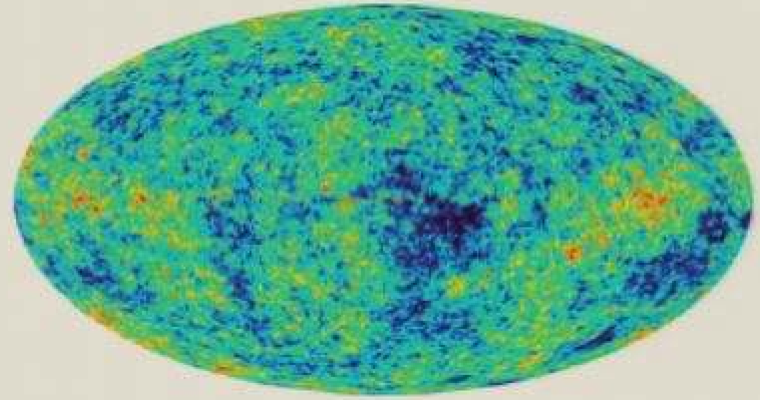
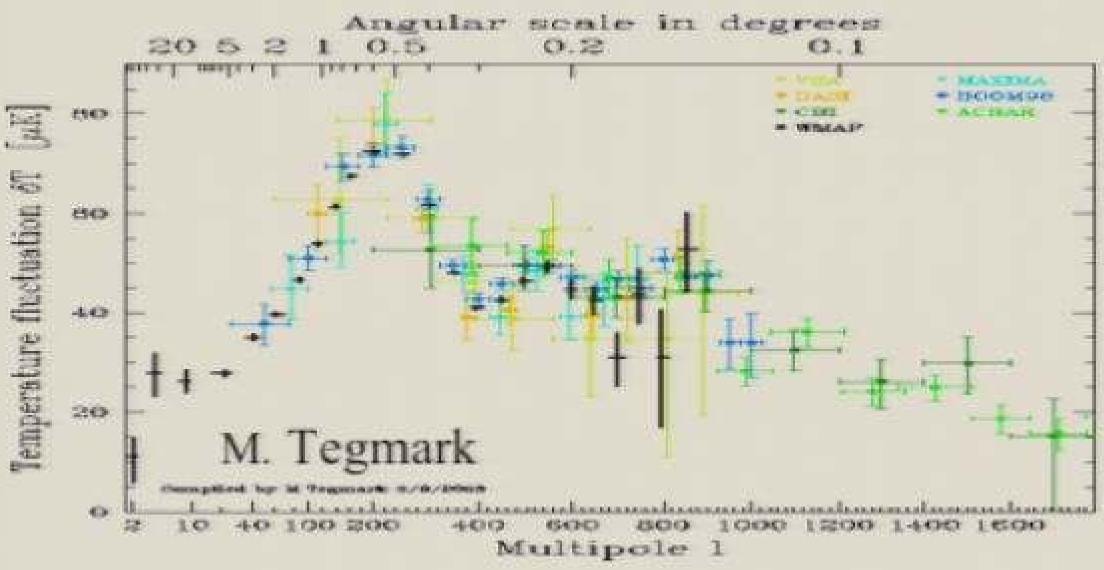
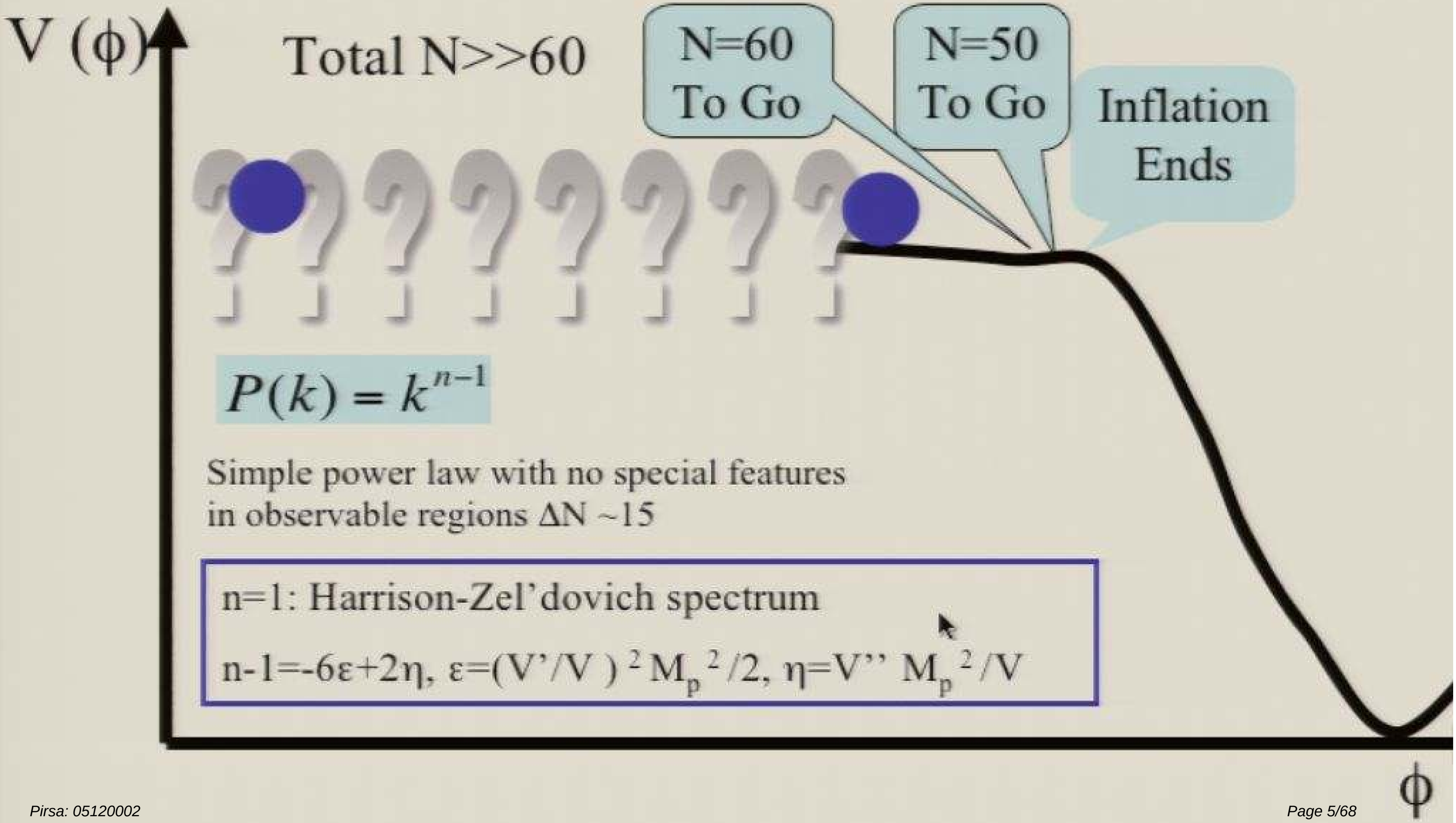




- Dominant component of current radiation energy
- 380,000 yrs after Big Bang

(z ~1100, T ~3000k, E ~0.1 eV)

Can we guess the nature of inflation from the CMB ?



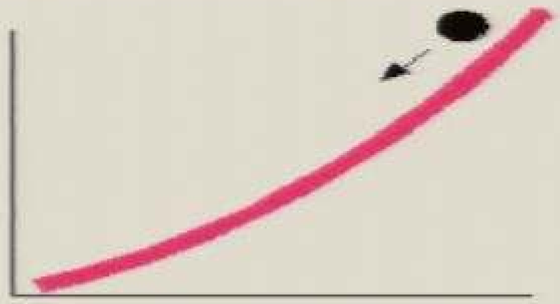
$$P(k) = k^{n-1}$$

Simple power law with no special features
in observable regions ΔN ~15

n=1: Harrison-Zel'dovich spectrum

$n-1=-6\varepsilon+2\eta$, $\varepsilon=(V'/V)^2 M_p^2/2$, $\eta=V'' M_p^2/V$

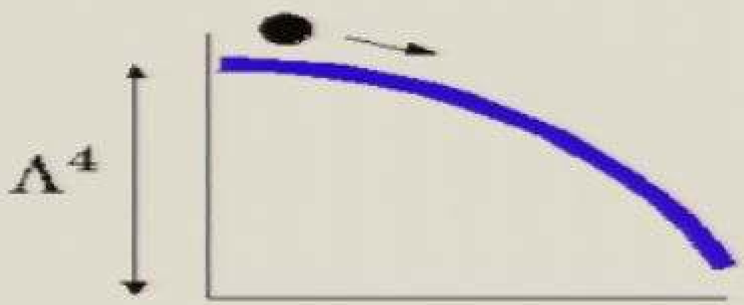
Can CMB tell anything about type of inflation?



Large field $-\epsilon < \eta \le \epsilon$

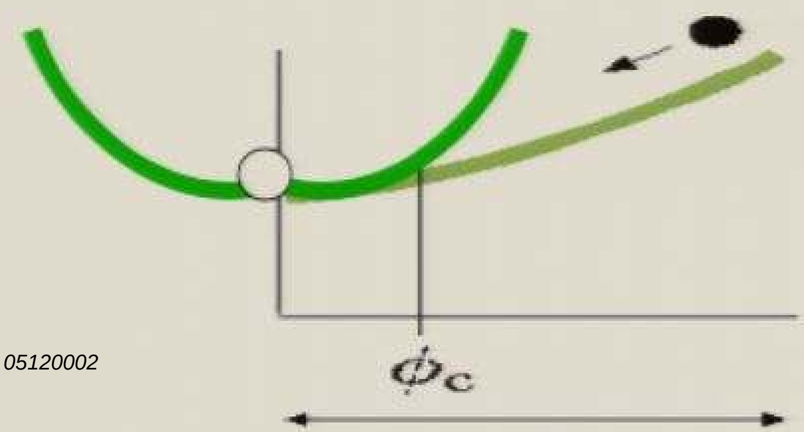
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 \exp(\phi/\mu)$$



Small field $\eta < -\epsilon$

$$V(\phi) = \Lambda^4 [1 - (\phi/\mu)^p]$$



Hybrid $0 < \epsilon < \eta$

$$V(\phi) = \Lambda^4 [1 + (\phi/\mu)^p]$$

Can CMB tell anything about inflation?

Regions in the (*r*,*n*) plane

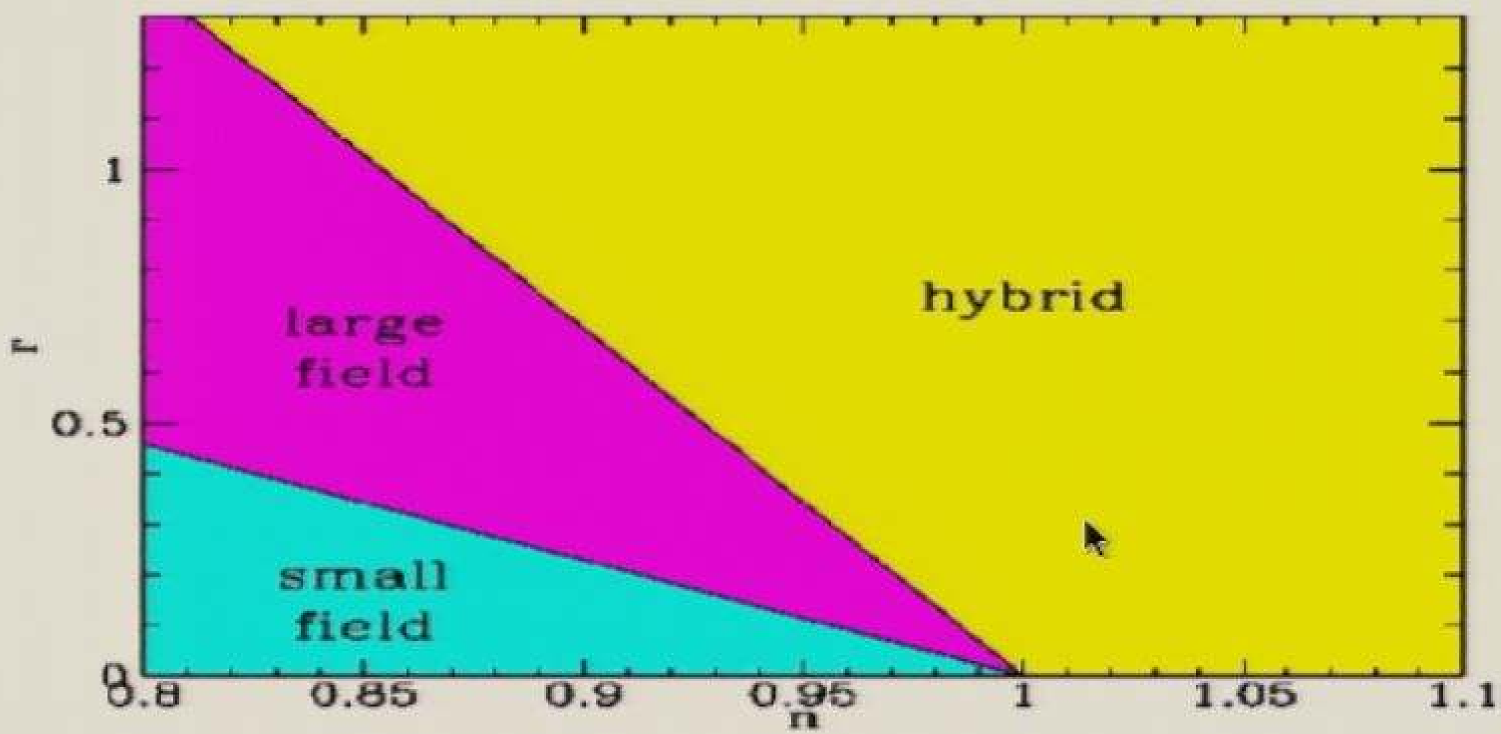


Figure from Scott, Will & Rocky

The bottom line

Thousands of inflation models can lead to an identical CMB spectrum.

Constraining inflation models from CMB data alone is

<u>HARD</u>

Inflation Model Building through an example

“Which is the best inflation model?” D. Lyth [hep-th/0311040]

Table 1: Suggested ranking of inflation models

Model	Potential	Problems	$n(k)$
NEW INFLATION			
2-field mod.	various	—	1.00?
bulk mod.	$V_0 - m^2\phi^2$	(v)	~ 0.9
p.n.g.b.	$V_0 - M\phi^3$	(iv)	0.92
~m.s.s.m.	$V_0 - m^2\phi^2 - \lambda\phi^4$	(iii)	1.00
original	$V_0 + \lambda\phi^4 \log(\phi/Q)$	(ii)	0.94
XmodularX	$V_0 - m^2\phi^2$	(i)	~ 0.9
HYBRID INFLATION			
running	$V_0 - m^2\phi^2 \log\phi$	—	$n' > 0$
D to F	various	—	?
p.n.g.b.	various	—	?
F-term	$V_0(1 + g^2 \log\phi)$	—	0.99
coll. brane	various	(vi)	~ 0.97
‘supernatural’	$V_0 + m^2\phi^2$	(v)	~ 1.1
quartic	$V_0 + \lambda\phi^4$	(iv)	1.00
dyn. s. b.	$V_0 + c\phi^{-p}$	(iv)	1.00
D-term	$V_0(1 + g^2 \log\phi)$	(iii)	0.99
~m.s.s.m.	$V_0 \pm m^2\phi^2$	(ii)	1.00
CHAOTIC INFLATION			
quadratic	$m^2\phi^2$	see note	0.96
X?quarticX?	$\lambda\phi^4$	(i)?(ii)	0.94
XEXTENDED INFLATIONX		killed by COBE (1991)	

Need particle theory to judge them!

References for Table 1

Taken from D. Lyth

NEW	
2-field mod.	Kodata & Stewart 2003
Bulk mod.	Banks 1999
p.n.g.b.	Adams, Ross & Sarkar 1997
~m.s.s.m.	Dine & Riotto 1997
original	Linde 1982, Albrecht & Steinhardt 1982
modular	Binetruy & Gaillard 1986
HYBRID	
running	Stewart 1997
D to F	Copeland, Liddle, Lyth, Stewart & Wands 1
	Gaillard, Lyth & Murayama 1998
F term	CLLSW 1994; Dvali, Schaeffer & Shafi 19
collid. brane	Dvali & Tye 1998
supernatural	Randall, Soljacic & Guth 1996
p.n.g.b.	Cohn & Stewart 2000
quartic	Linde 1991
dynam. S. B.	Kinney & Riotto 1998
D-term	Stewart 1995; Binetruy & Dvali 1996;
	Halyo 1996
~m.s.s.m.	Bastero-Gil & King 1997
CHAOTIC	
quadratic	Linde 1983;
	Arkani-Hamed, Cheng, Creminelli
	& Randall 2003
quartic	Linde 1983
EXTENDED	La & Steinhardt 1989

FAQ for inflation model building

(Particle theory is important)

- What is the inflaton field?

- What is the form of the inflaton potential?

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  -What kind of fields were there in early Universe?

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-How was supersymmetry broken in early Universe ?

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Hidden Sector Supersymmetry Breaking

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Hidden Sector Supersymmetry Breaking

(CMB is important)

Particle Theory Setup: Moduli (Working Definition)

Flat at tree level

The form of potential :

$$V(\phi) = M_s^{\ 4} f\left(\frac{\phi}{M_P}\right)$$

(f is function with O(1) coefficients)

gravitational-strength decay

Properties:

$$V_0 \sim M_s^{\ 4},\ m_\phi \sim M_s^{\ 2} / M_p, V'' / V \sim O(1$$

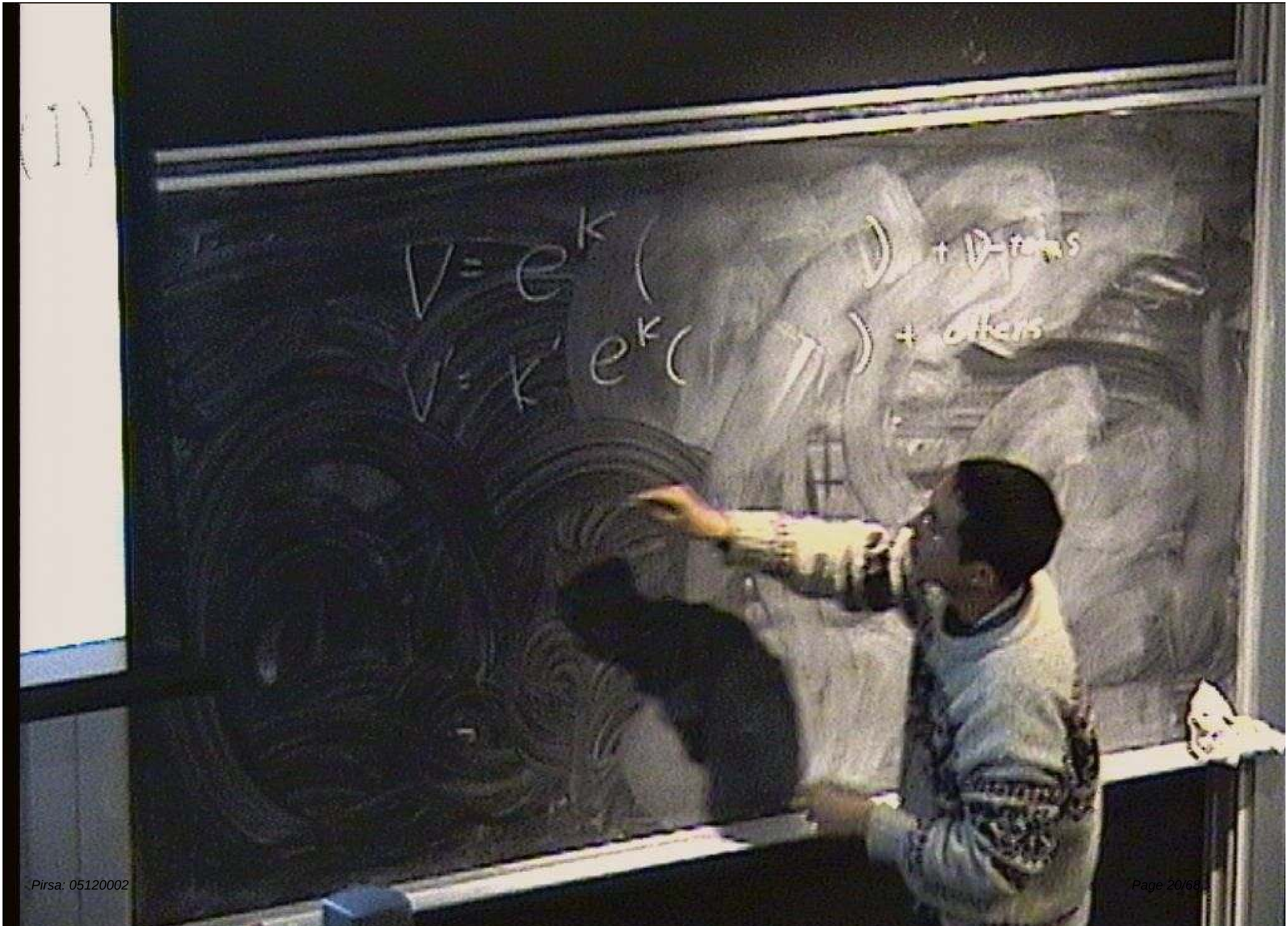
THE energy scale of potential

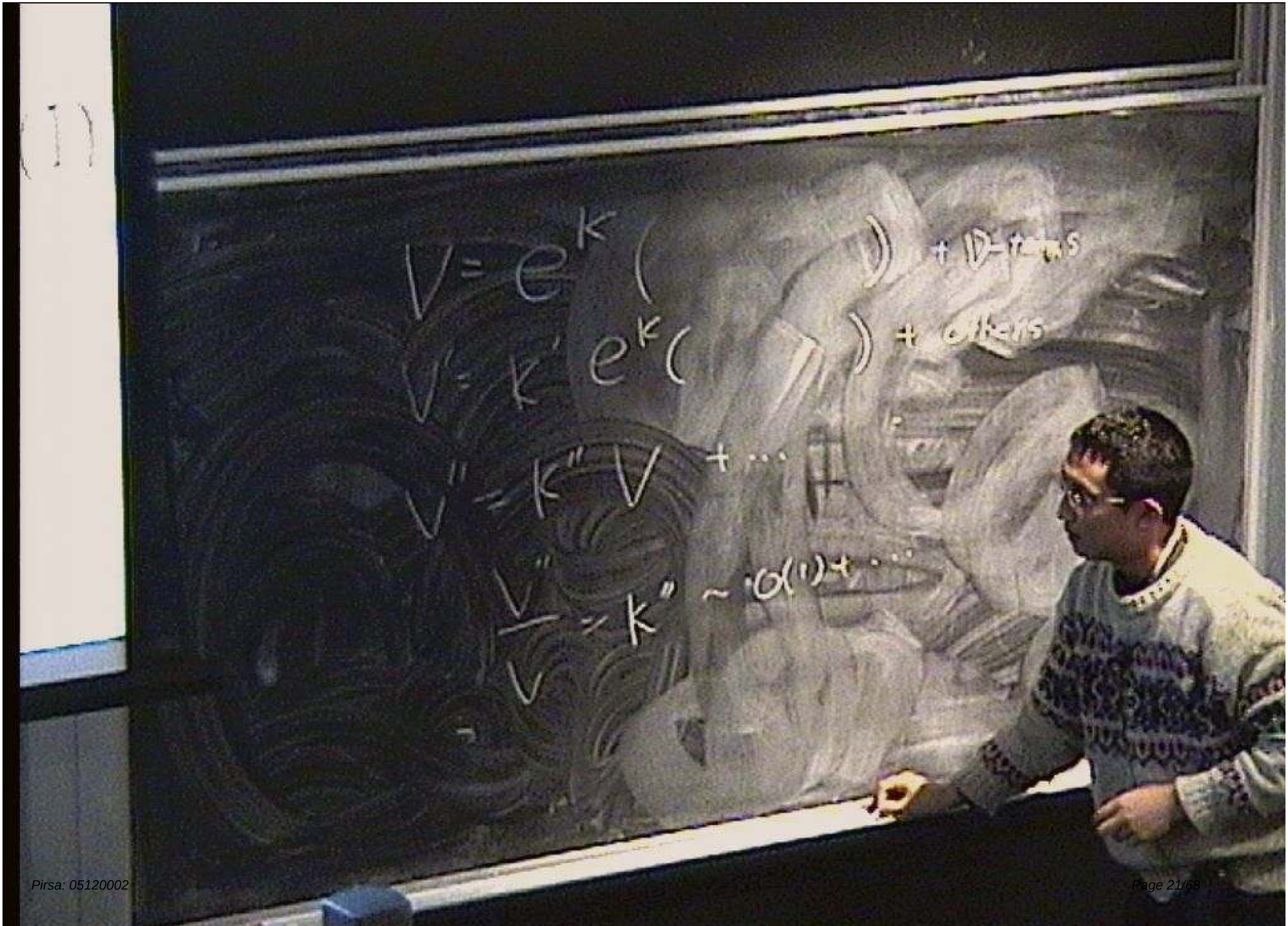
$$V_0^{1/4} \sim M_s \sim 10^{10\text{-}11}\,\mathrm{GeV}$$

THE mass of field

$$m_\phi \sim M_s^{\ 2} / M_p \sim 10^{2-3}\, GeV$$

Other choices of parameter values would be unnatural fine-tuning


V = e^K ( ) + D-terms
V = K' e^K ( ) + others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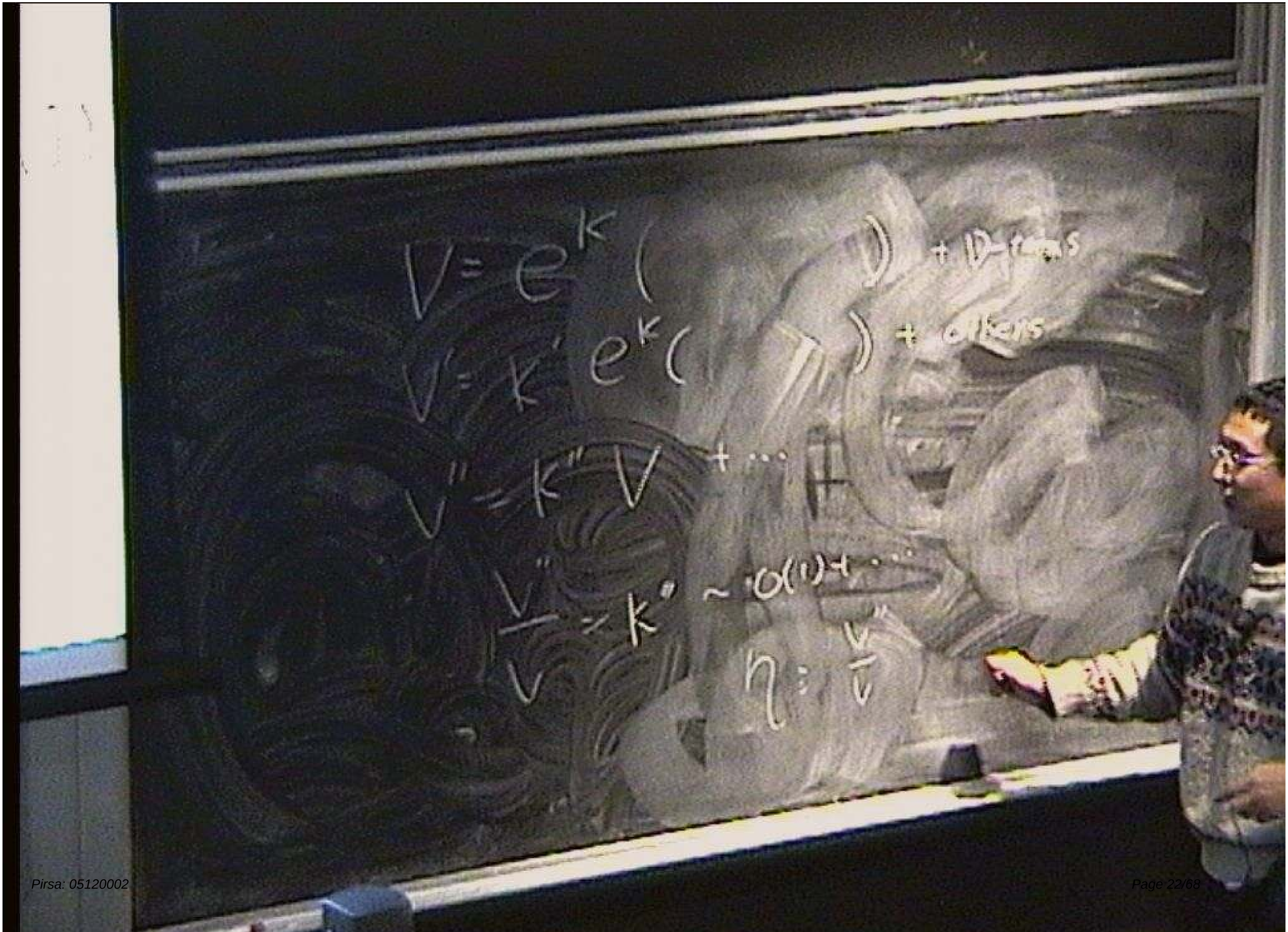
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η = V''/V

Now Ask:

- Can self-consistent cosmology scenario be realized from this natural setup ?

(without any modifications or unnatural fine-tuning)

- What is the prediction for this particular scenario?

"Successful Modular Cosmology" (K.K.&E. Stewart, 04)

"Inflation on Moduli Space and Cosmic Perturbations" (K.K.&E. Stewart, 04)

Also related work by, for instance,

S. Thomas "Moduli Inflation from Dynamical Supersymmetry Breaking"

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" …. Several speculative explanations of the discrepancy between SUSY breaking scale (10^{10} GeV) and apparent inflation scale (10^{16} GeV). …"

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Difficulties in Modular Cosmology & Its Possible Resolutions

- Cosmic perturbations: Fine-tuning necessary??

- Cosmological moduli problem ⇒Late entropy productio
  Thermal inflation

- Baryon Asymmetry
  ⇒Leptogenesis at low energy scale (H ~ 10^{-25}

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Cosmic Perturbations

MODEL

Energy Scale of Potential

$$V_0^{1/4} \sim M_s \sim 10^{10}\,\mathrm{GeV}$$

Mass of Field

$$m_\phi \sim M_s^2 / M_p \sim TeV$$

Cosmic Perturbations: Match Observation ?

Let's try calculating Cosmic Perturbations now.

Not slow-roll $m^2 \sim V_0 \sim (TeV)^2$

(Radial Fluctuation has highly suppressed spectrum)

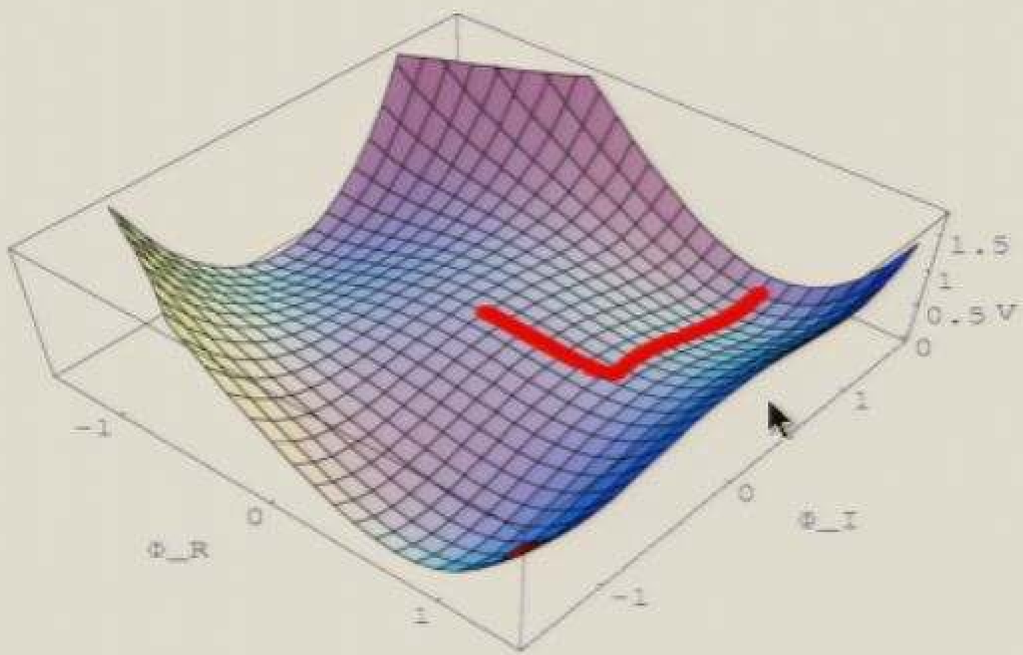
$$\delta\phi, \delta\theta$$

Radial fluctuations (too red spectrum, which is good!)

Match Observations?

Angular Fluctuations $\delta\theta \sim \frac{H}{\phi}$ Still non-flat!

$$V = V_0 - m_\phi{}^2 |\Phi|^2 + \frac{1}{3} m_\phi{}^2 (\Phi^3 + h.c.) + m_\phi{}^2 |\Phi|^4$$



Points of Enhanced Symmetry

The points in moduli space where symmetry is enhanced

(generic and robust properties of moduli space in string theory)

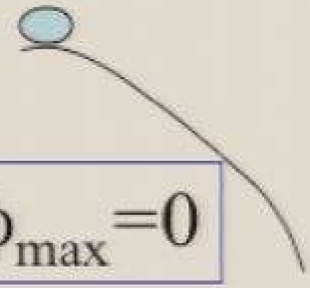
-Properties-

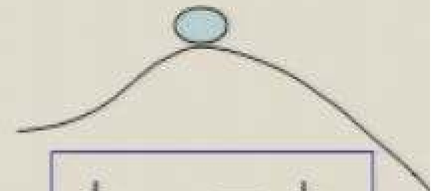
- Fixed points of symmetry group
  (local maximum/minimum or saddle points)

- New interactions: $\chi^2|\phi - \phi_0|^2$
  (corresponds to Higgs in low-energy effective theory)
  New interactions show up and consequent renormalization of potential

Flattening Pot'l by Loop Corrections
At Enhanced Symmetric Point

$$V = V_0[1 - \frac{1}{2} f(\beta \ln \phi)\phi^2 + \ldots)$$





$\phi_{max} = 0 \quad \Rightarrow \quad \phi_{max} = \phi_*$

$\Delta\phi \quad \Rightarrow \phi_* + \Delta\phi \sim \phi_*$

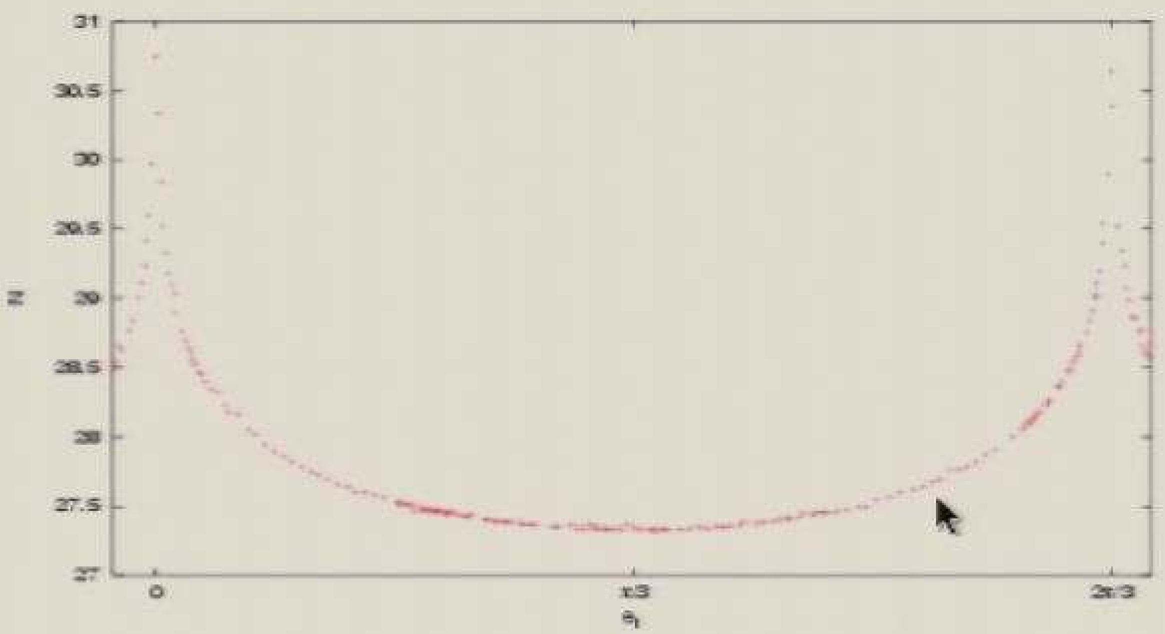
$H/\phi \Rightarrow H/\phi_*$

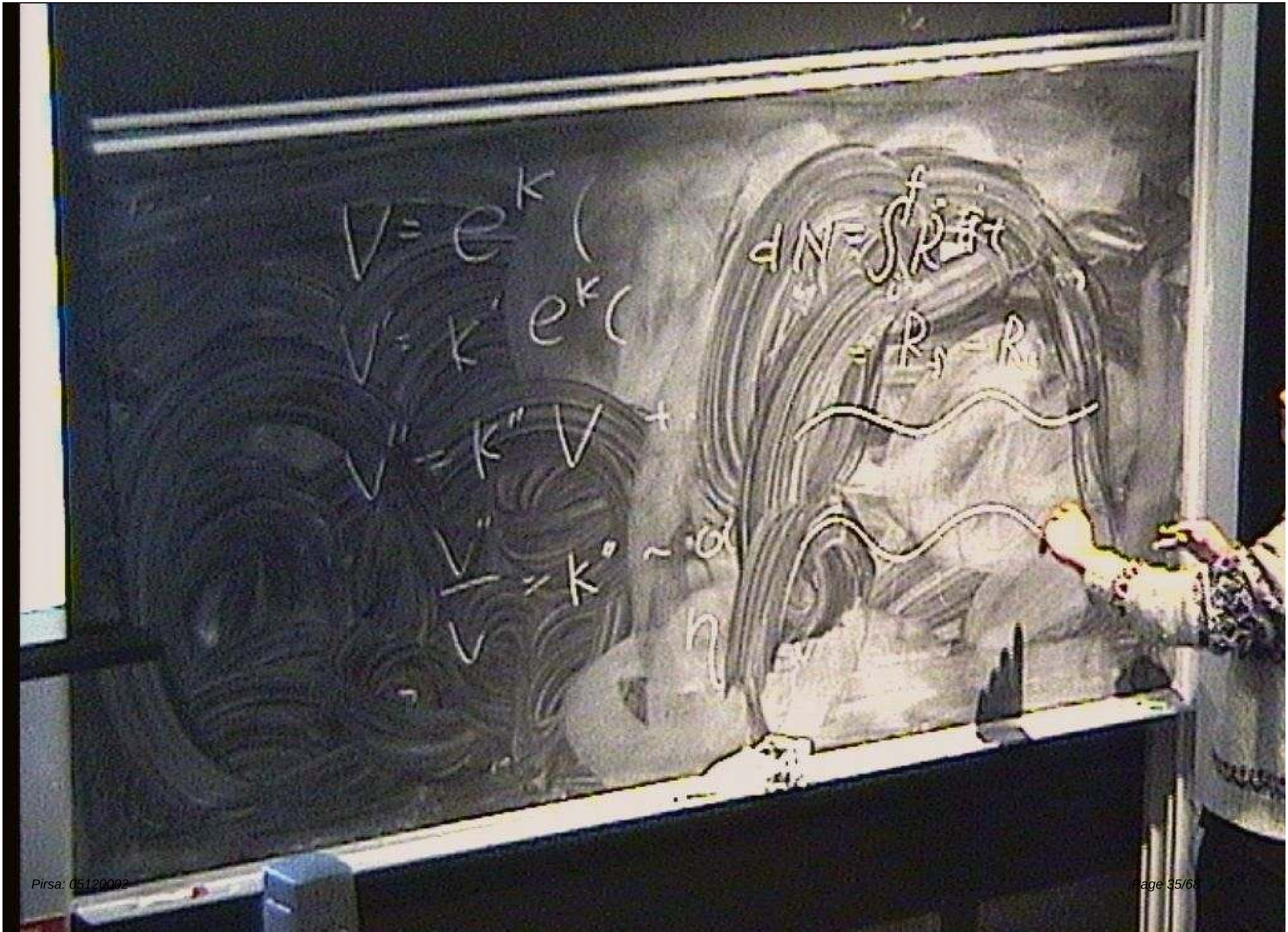
H/ϕ_* is now flat

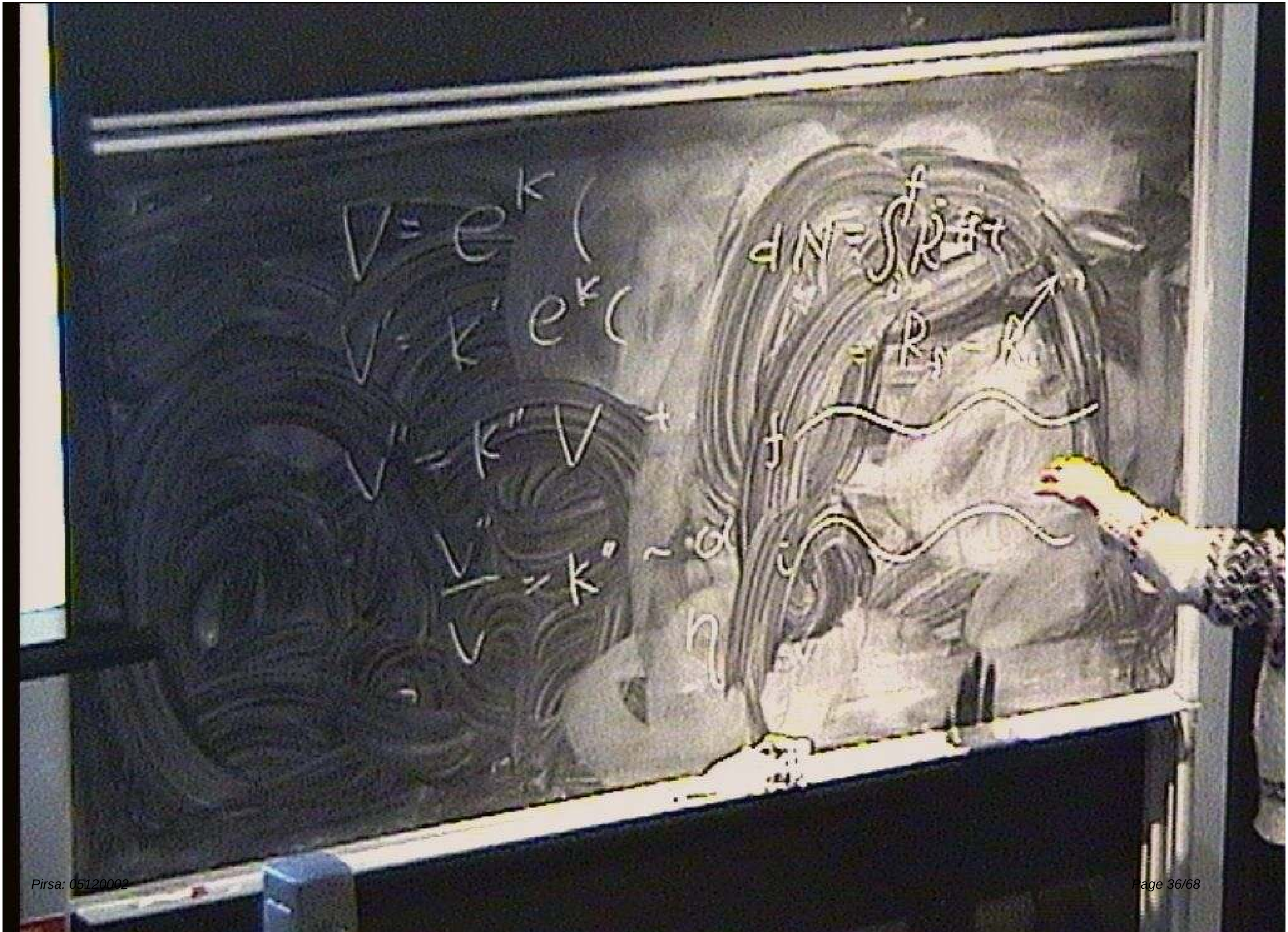
$$R = \frac{\partial N}{\partial \phi}\delta\phi + \frac{\partial N}{\partial \theta}\delta\theta$$ (Sasaki&Stewart '96)

Angular Component Fluctuations

$$\frac{\partial N}{\partial \theta}\delta\theta \sim \frac{\partial N}{\partial \theta}\frac{H}{\phi}$$




V = e^K (
V' = K' e^K (
V'' = K'' V +
V''/V ~ K'' ~ α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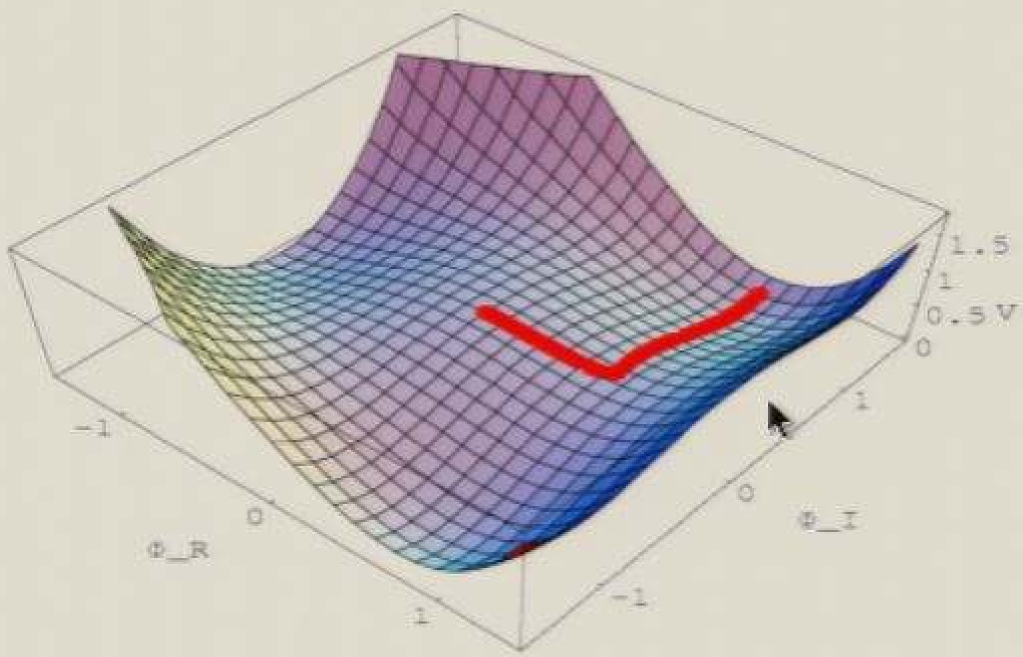

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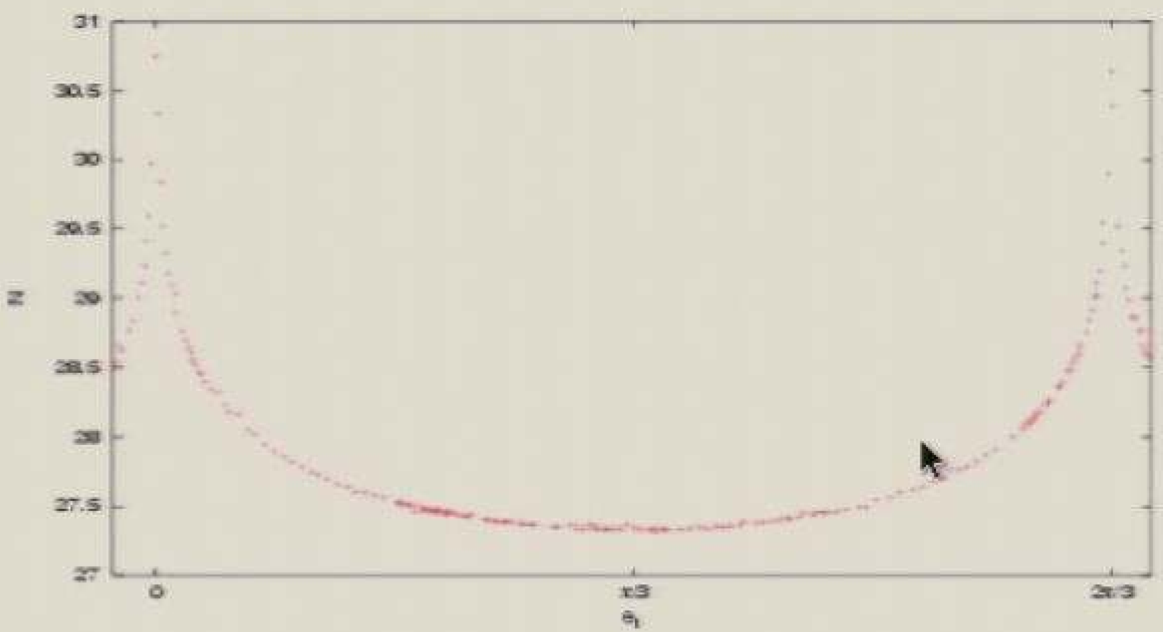


Predicted Cosmic Perturbations

$$n - 1 \equiv \frac{d\ln P}{d\ln k}$$

$$n - 1 = -Ak^{2\alpha}$$

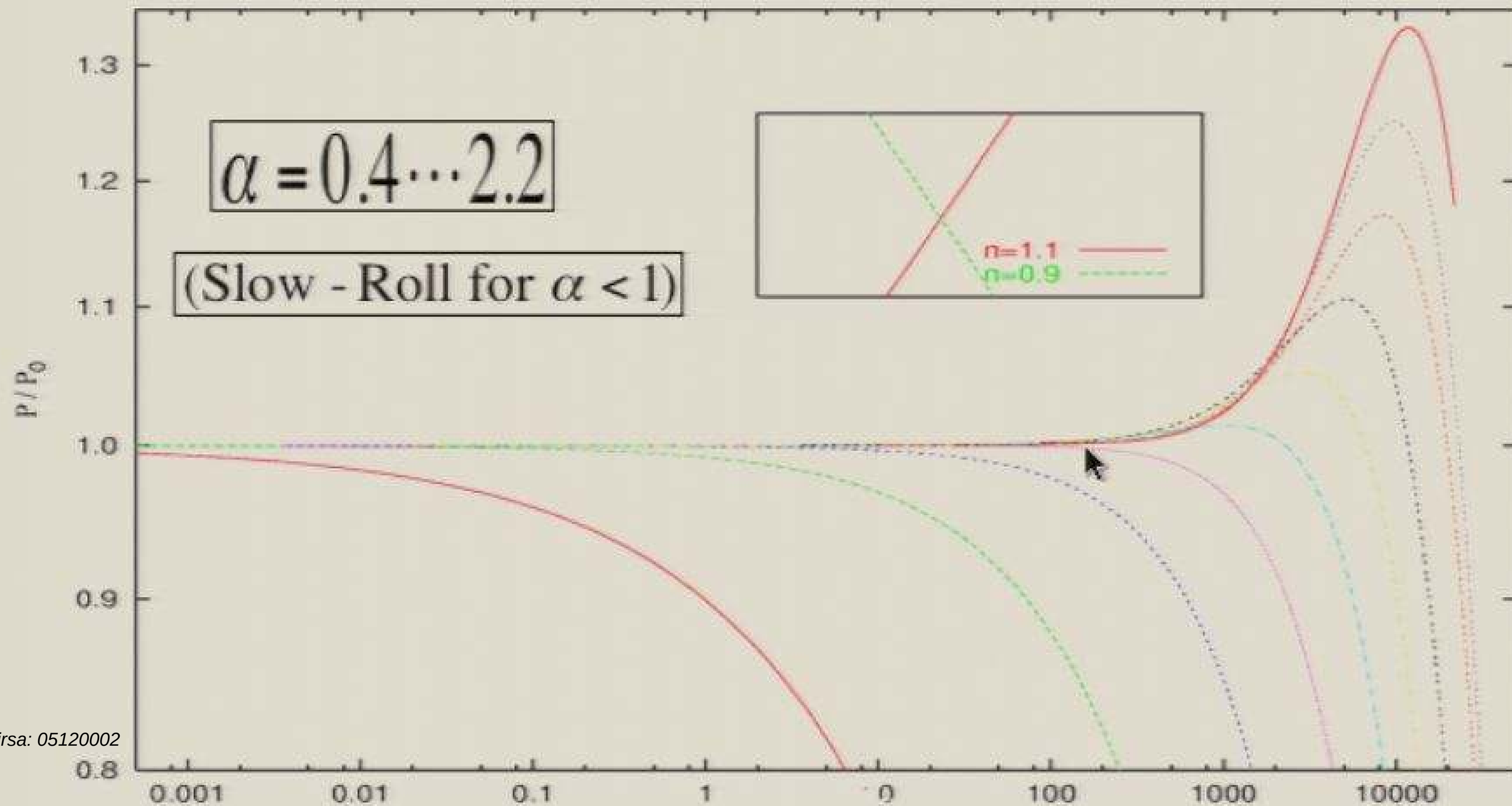
$$n' \equiv \frac{dn}{d\ln k} = -2\alpha A k^{2\alpha}$$

$$|n-1| \sim |n'| \sim |n''| \text{ for } \alpha \sim 1$$

Watch Out ! Running of running

(Can't use slow-roll approximations .

Low-energy scale inflation preferable



Difficulties in Modular Cosmology & Its Possible Resolutions

- Cosmic perturbations
- Cosmological moduli problem ⇒Late entropy productio
  Thermal inflation
- Baryon Asymmetry
  ⇒Leptogenesis at low energy scale (H ~ 10^{-25}

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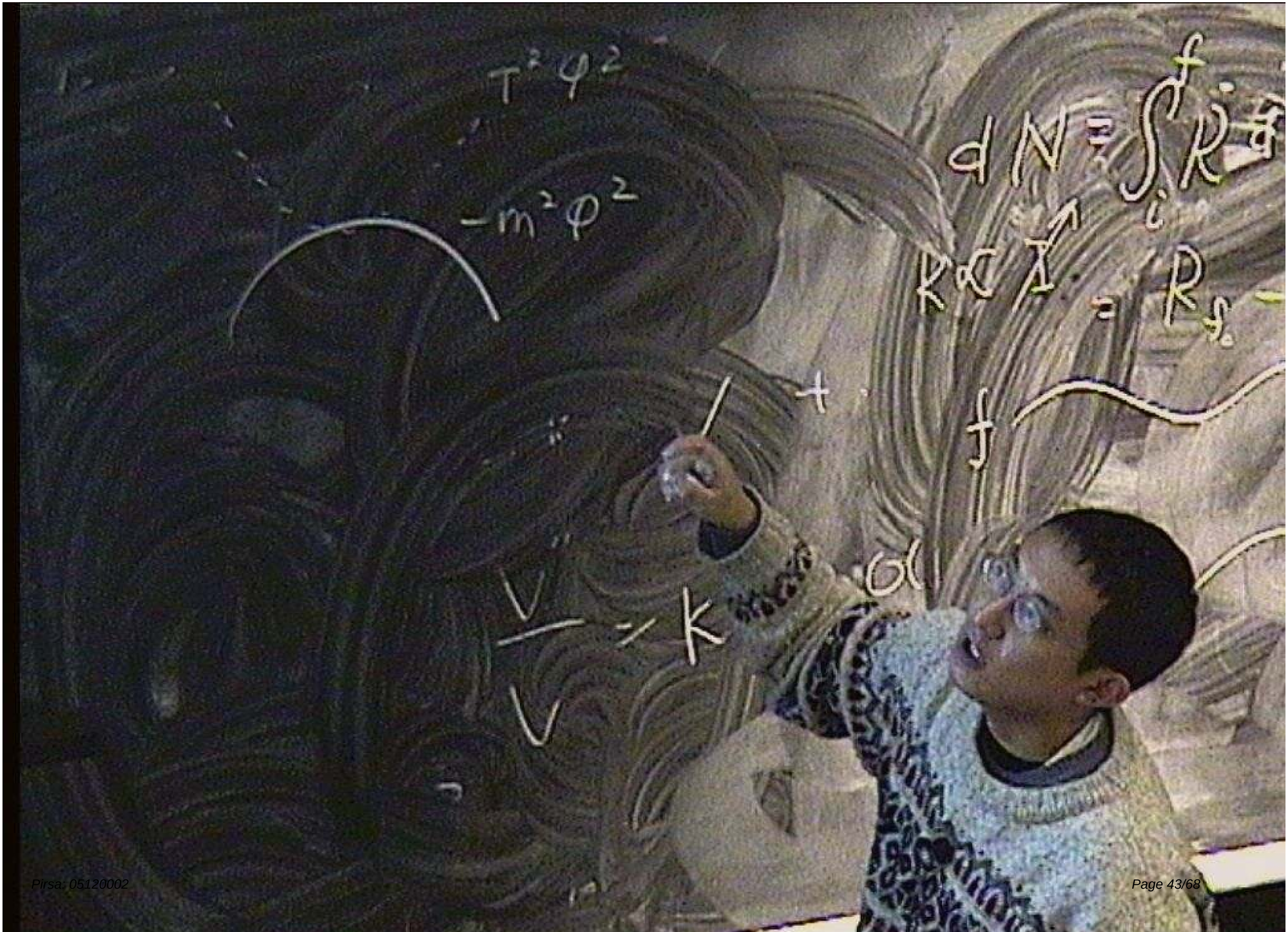
Thermal Inflation

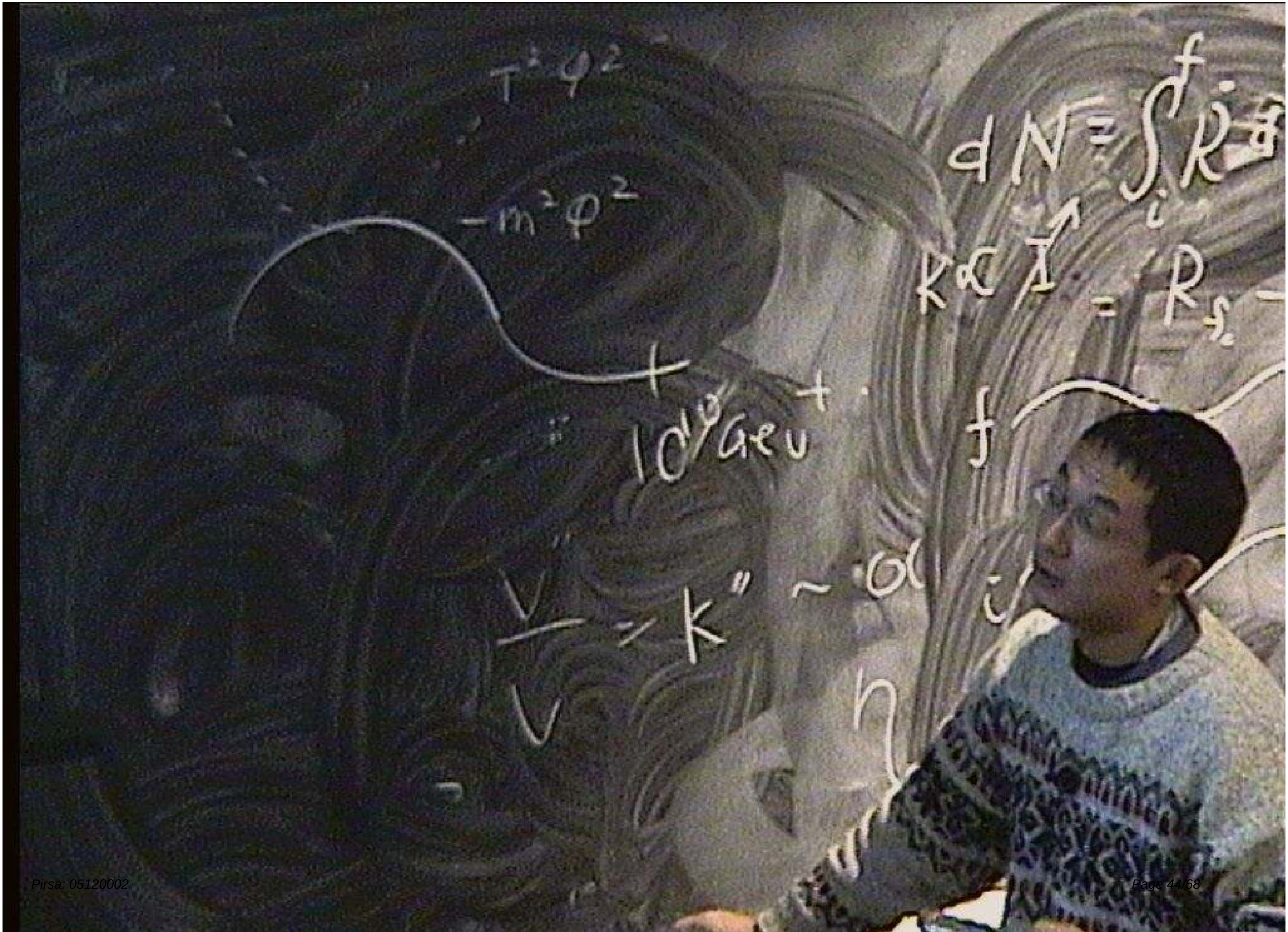
$$V = V_0 + (g^2 T^2 - m^2)|\sigma|^2 + (A\lambda\sigma^n + h.c.) + |\lambda|^2 |\sigma|^{2n-2}$$

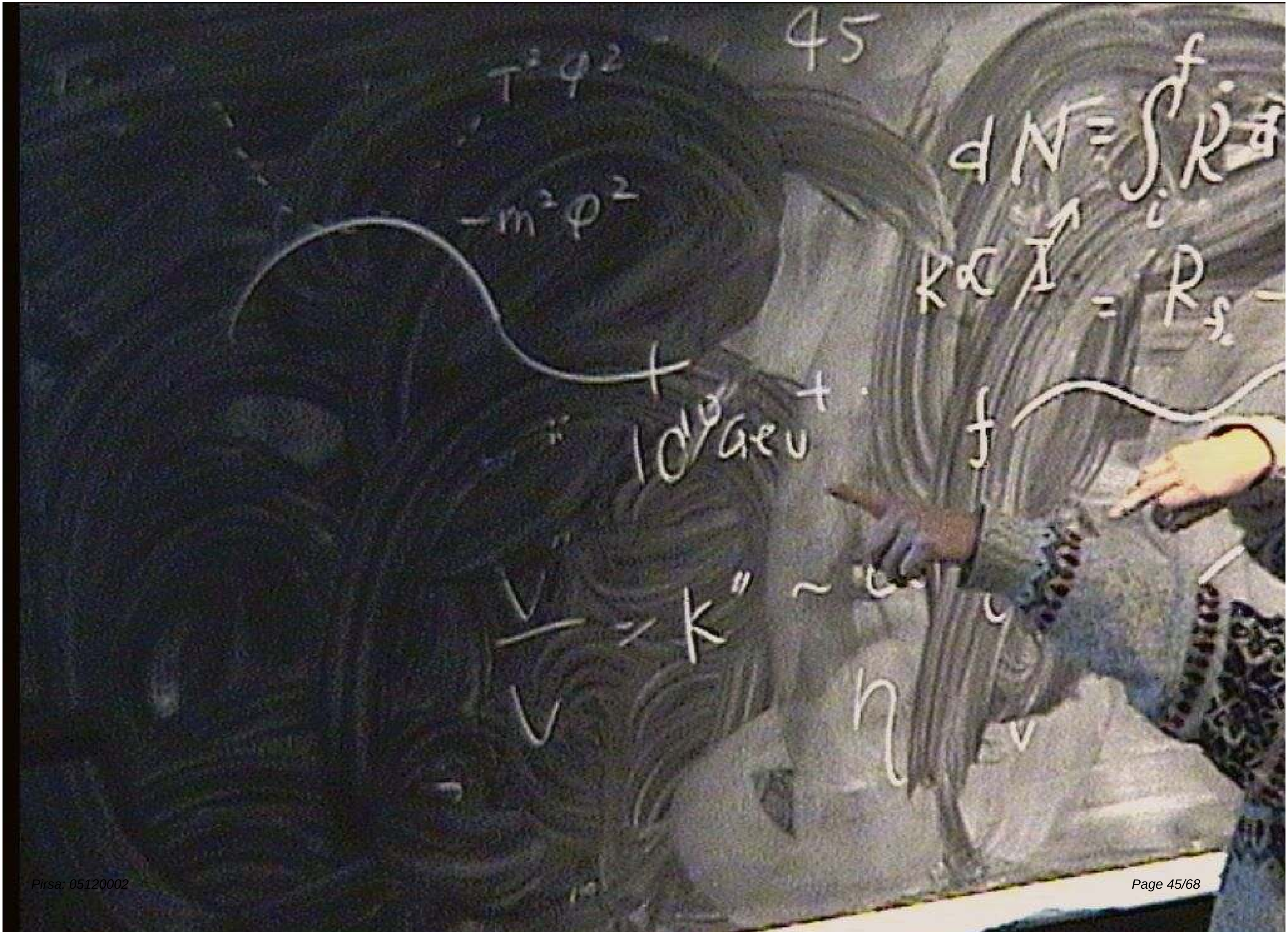
- Flat direction lifted by $W_{non-ren} = \frac{\lambda}{nM^{n-3}}\Sigma^n$
- Inflation for $m \le T \le V_0^{1/4}$

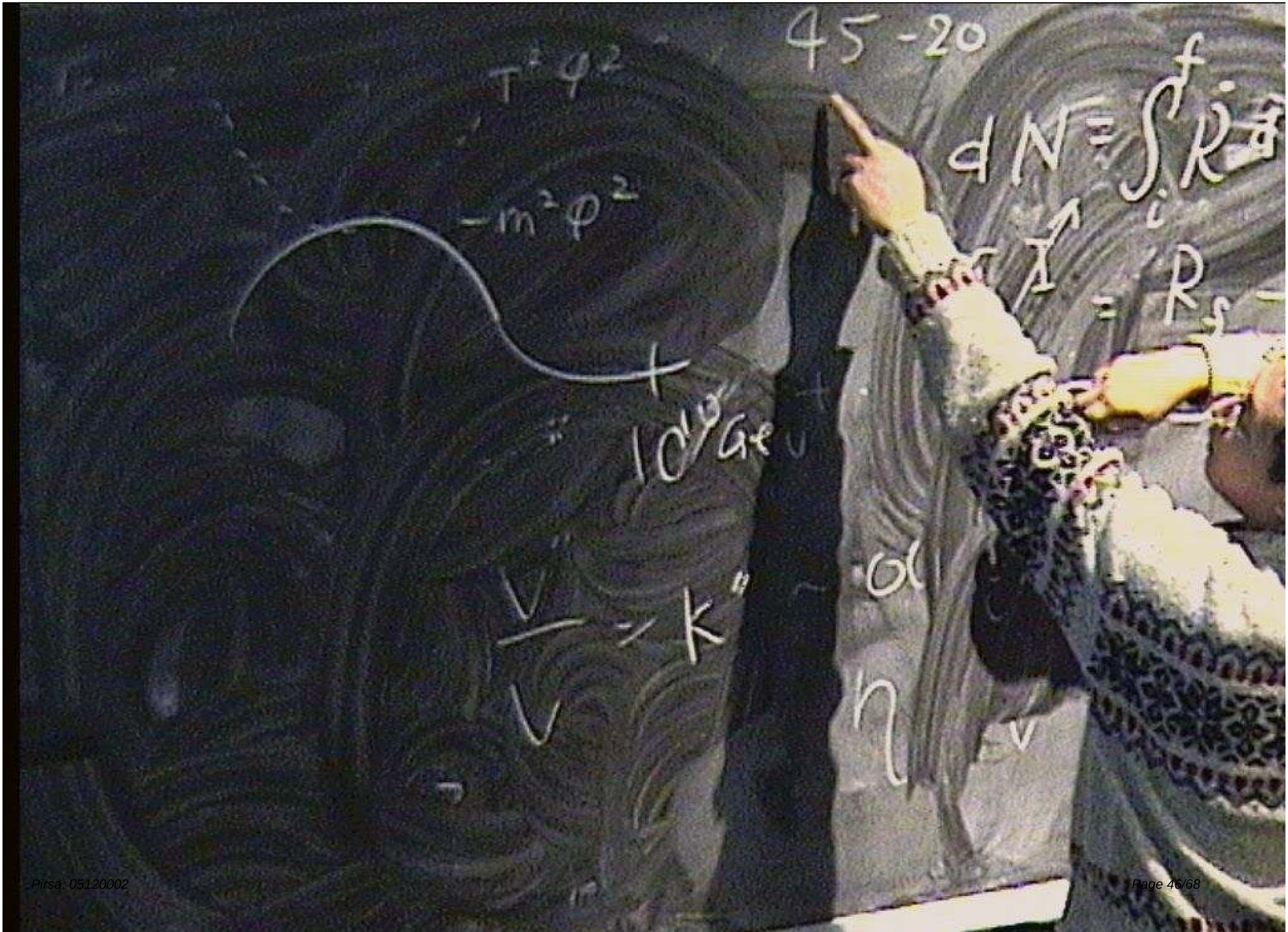
$N \sim 5-10,\ T_R \sim GeV$ (high enough for BBN)

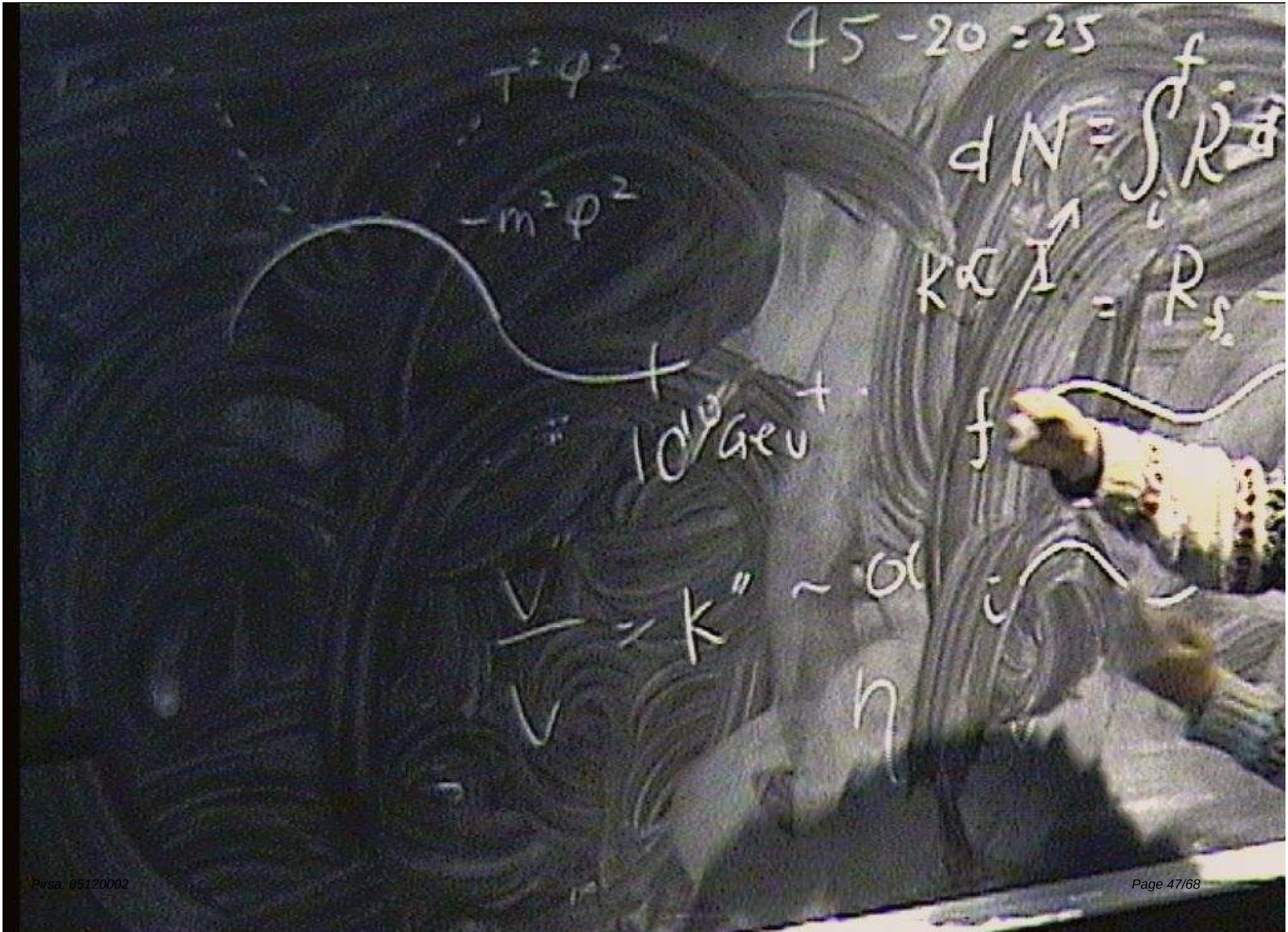
- Finite temperature effects in presence of SUSY flat direction solves Polonyi/Moduli problem.




$T^2\varphi^2$
$-m^2\varphi^2$
10^{19} GeV


45


45 -20
T² φ²
−m² φ²
10⁹ GeV


45-20=25
10^19 GeV

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"Affleck-Dine" Leptogenesis in thermal inflation scenario

Cosmological moduli problem

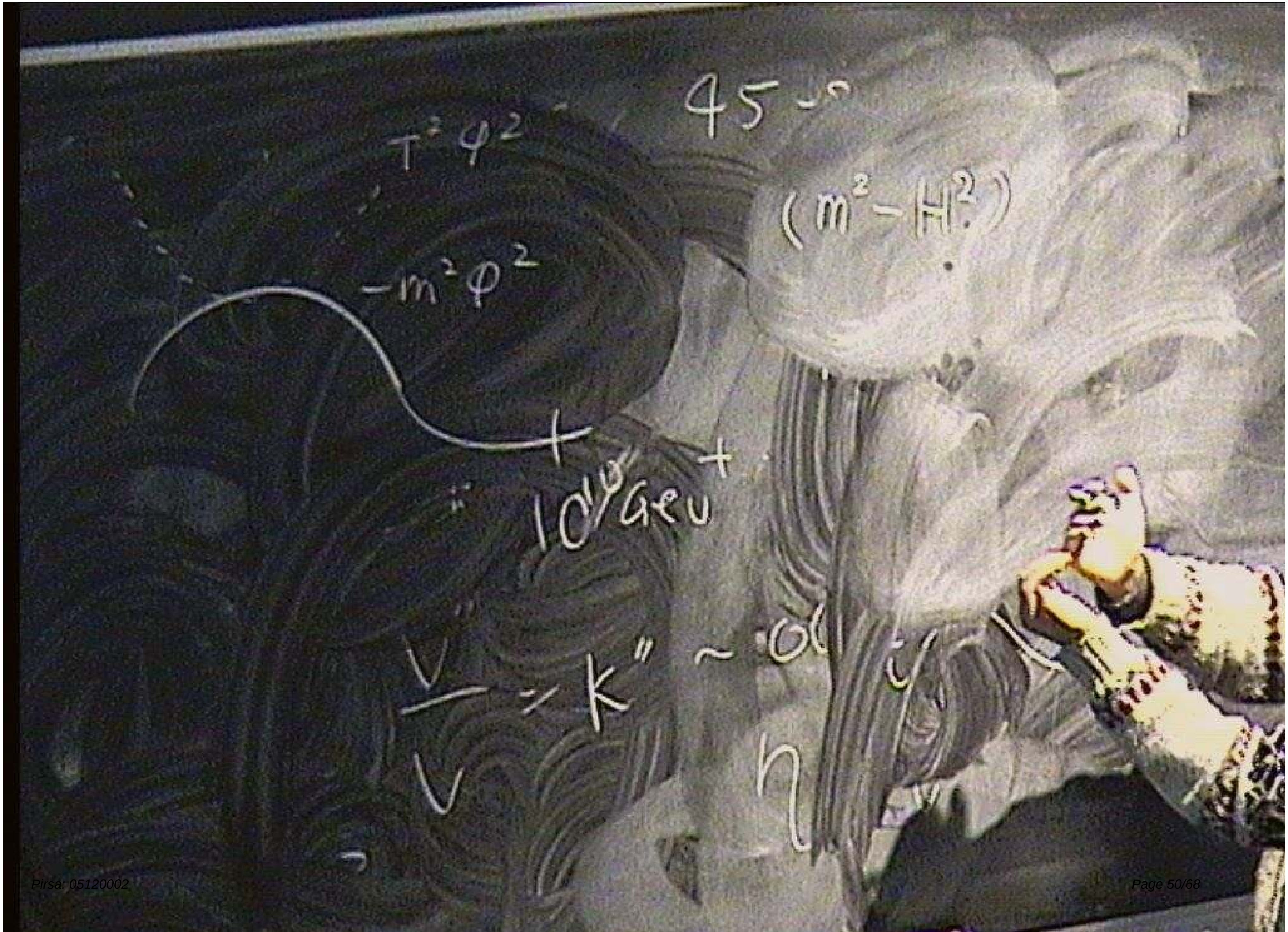
Thermal inflation , $H \sim 10^{-25}$

$\Rightarrow$ Baryon asymmetry production at low energy scale

"Standard" baryogenesis mechanism doesn't work

E. Stewart, M. Kawasaki and T. Yanagida (hep-ph/9603324)

D. Jeong, K.K.,W. Park and E. Stewart (hep-ph/0406136)


$T^2\varphi^2$
45
$(m^2 - H^2)$
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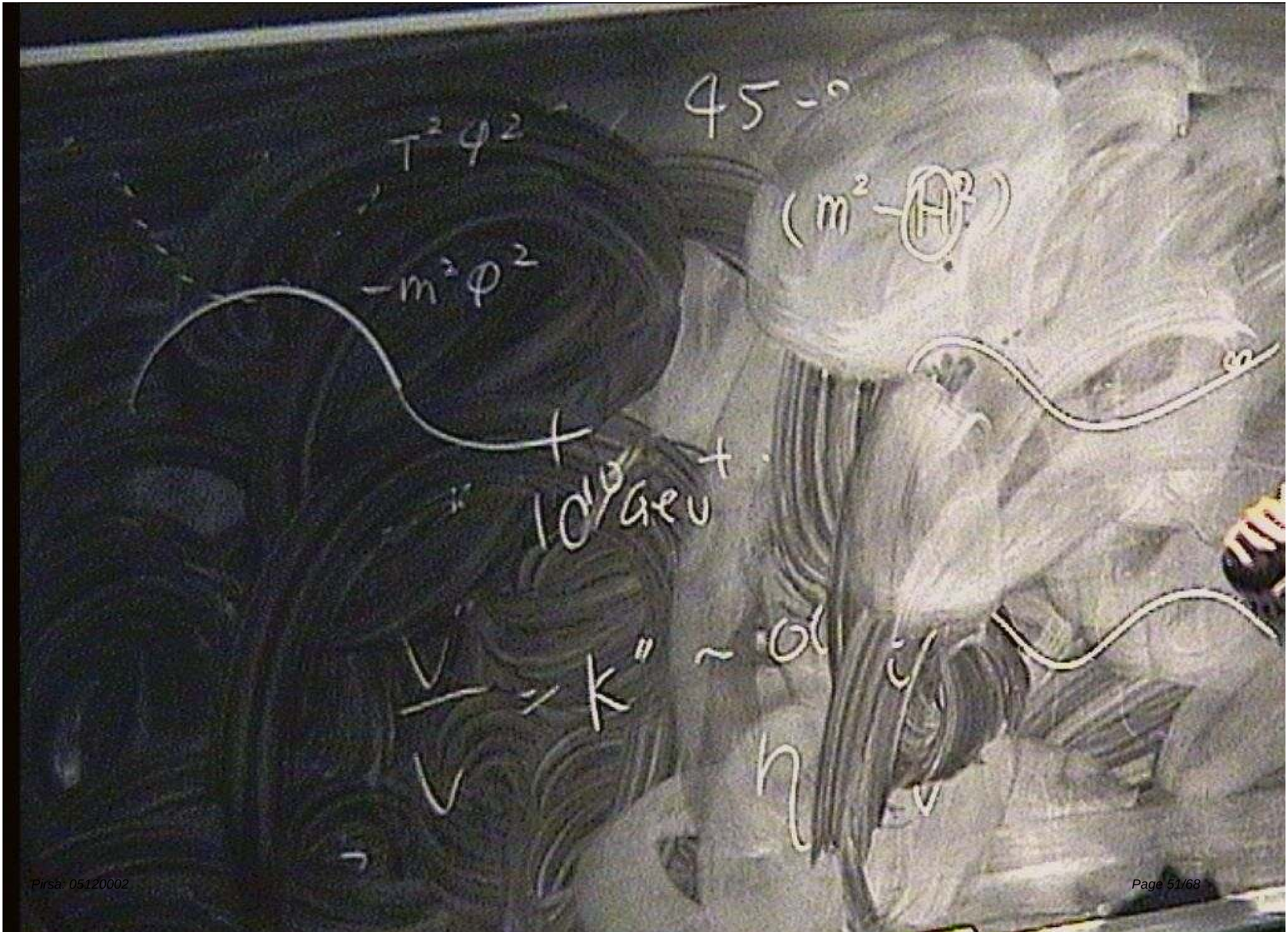
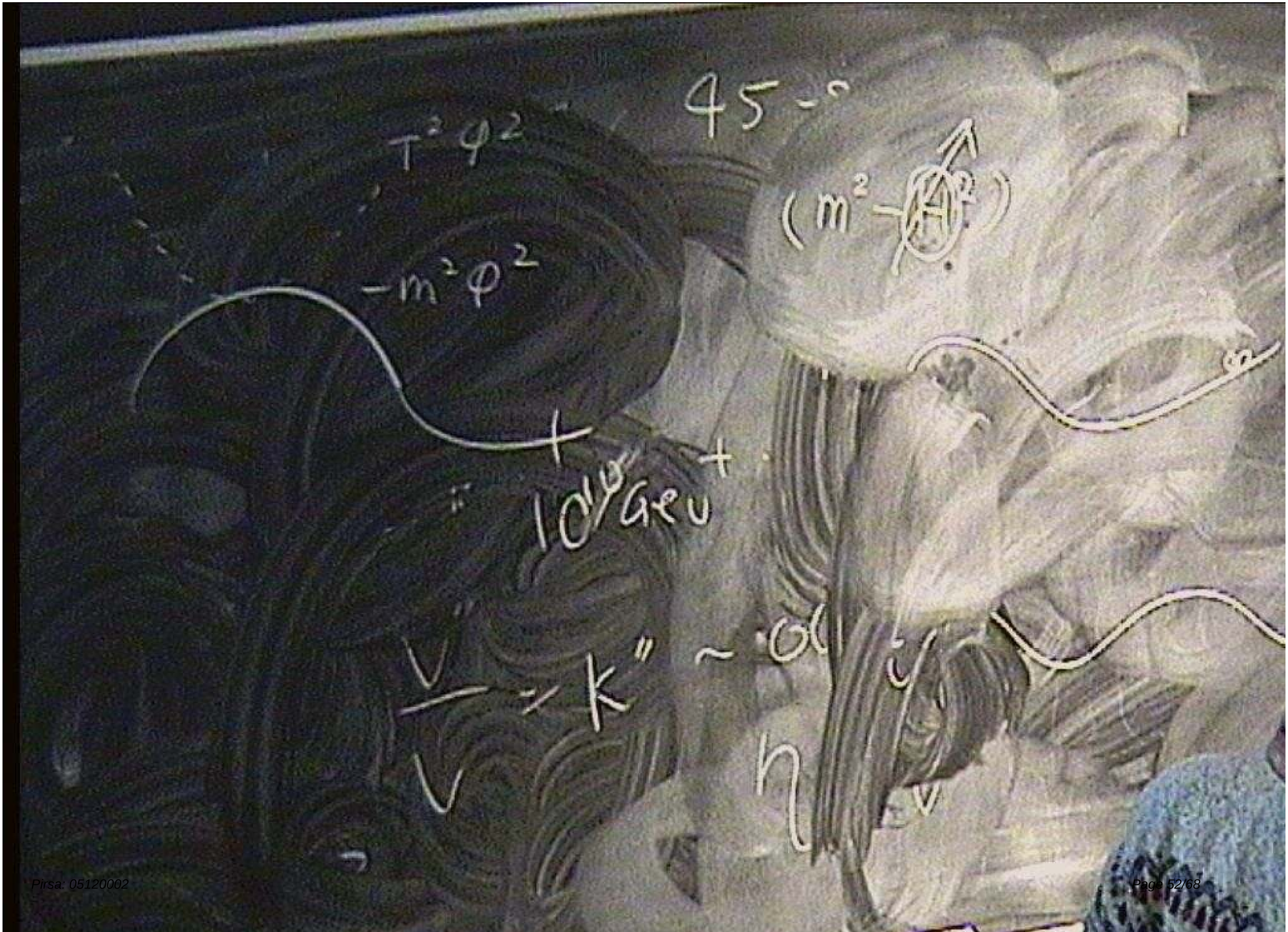

$T^2\varphi^2$
$(m^2 - H^2)$
$-m^2\varphi^2$
10^9 GeV


45
$T^2\varphi^2$
$-m^2\varphi^2$
10^{19} GeV

"Affleck-Dine" Leptogenesis in thermal inflation scenario

$W = \text{Yukawa} + \phi^2 H_u H_d + \phi^4 + LH_u\, LH_u$

1. Relevant fields trapped at the origin (thermally)
2. LH_u starts rolling first away from the origin [assume: $m_L{}^2 + m_{Hu}{}^2 <$ (

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- F-term $|\phi^2 H_u|^2$ gives LH_u positive mass squared
- Phase of LH_u : Initially by A-term $LH_u LH_u$

  Now by cross term $\phi^{*2} H_d^* L^2 H_u$

"Affleck-Dine" Leptogenesis in thermal inflation scenario

$W = \text{Yukawa} + \phi^2 H_u H_d + \phi^4 + LH_u\, LH_u$

1. Relevant fields trapped at the origin (thermally)
2. LH_u starts rolling first away from the origin [assume: $m_L{}^2 + m_{Hu}{}^2 < 0$
3. Flaton ϕ starts rolling away

- F-term $|\phi^2 H_u|^2$ gives LH_u positive mass squared
- Phase of LH_u : Initially by A-term $LH_u\, LH_u$

  Now by cross term $\phi^{*2} H_d^* L^2 H_u$

(For thermal inflation, $H \sim 10^{-25} \Rightarrow$ Standard AD mechanism doesn't work)

- Non-zero H_d (due to A-term $\phi^2 H_u H_d$ and cross terms)

  Q and L are stabilized via $|QH_d|^2$ and $|LH_d|^2$ at MSSM minimum

$m_L{}^2 + m_{Hu}{}^2 < 0 \Rightarrow$ Deep non-MSSM minimum.

Charge and Colour Breaking bounds violated.

c.f. A. Kusenko, P.Langacker and G. Serge (hep-ph/9602414)

" Phase transition and Vacuum Tunneling into Charge and color breaking minima in the MSSM"

Summary So Far

- ❑ Thousands of inflation models can lead to identical observations
- ❑ An example for inflation model building :

particle theory should be able to tell us

- ➢ what THE inflaton is
- ➢ what THE values of the parameters such as inflation energy scale are
- ➢ what THE inflaton potential should look like, etc

Based on those setups, particle theory can make “testable” predictions.

- ❑ Cosmological observations can falsify/justify particle theory’s prediction

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Parameterizing the Power Spectrum: Beyond the Truncated Taylor Expansion

Kevork Abazajian, K.K. and Ewan D. Stewart

JCAP08(2005)008, [astro-ph/0507224])

Traditional Approach: Truncated Taylor Expansion of the Power Spectrum

$$\ln P(k) = \ln P_* + (n_* - 1)\ln\left(\frac{k}{k_*}\right) + n'_* \ln^2\left(\frac{k}{k_*}\right)$$

$$n - 1 \equiv \frac{d\ln P}{d\ln k}, n' \equiv \frac{dn}{d\ln$$

$$\left|(n_* - 1)\ln\left(\frac{k}{k_*}\right)\right| >> \left|n'_* \ln^2\left(\frac{k}{k_*}\right)\right|$$

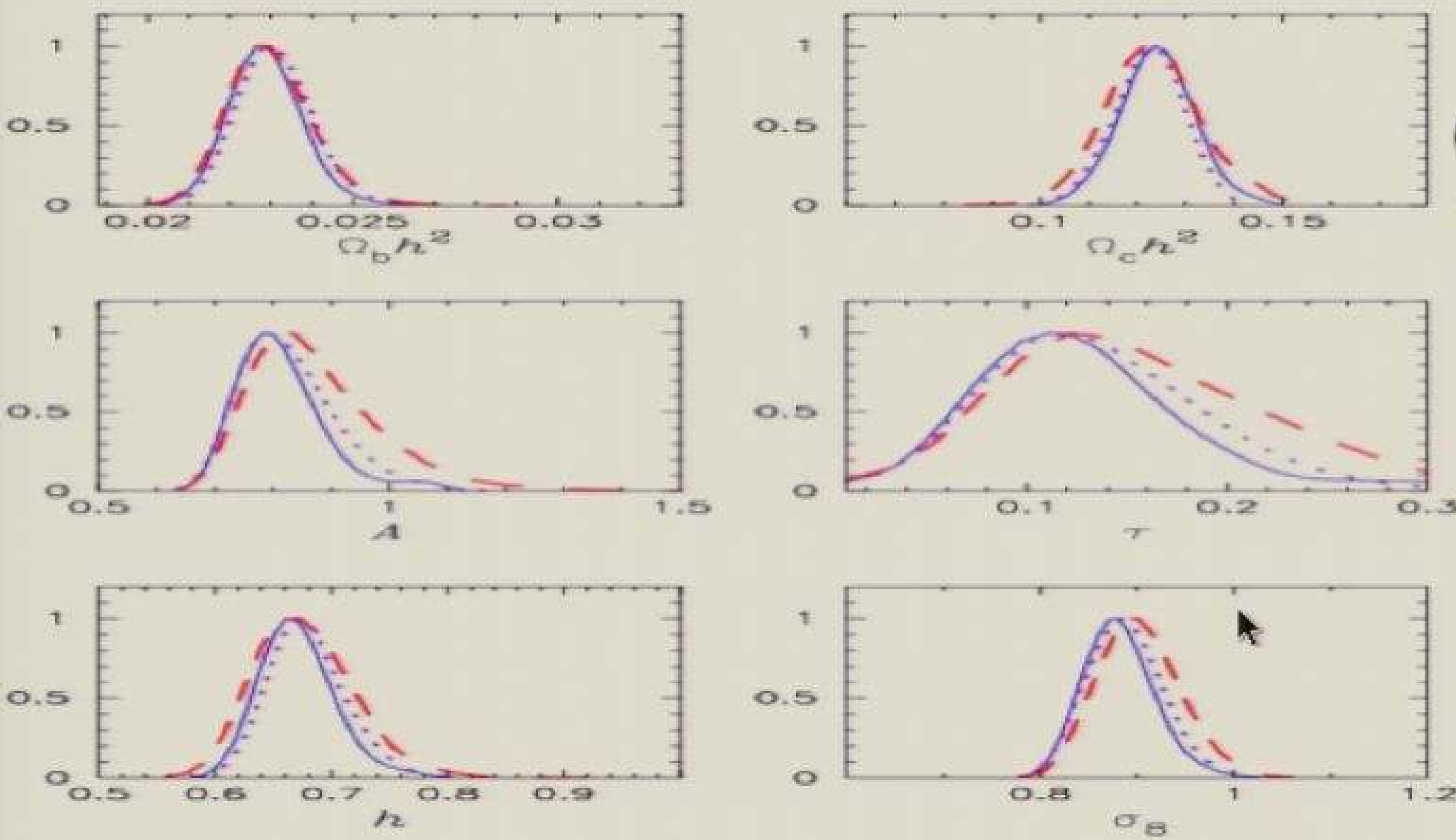
⇐Not a trivial assumption, in particular for $|\ln k/k_*| \gtrsim 1$.

In fact, the current observations are consistent with

$$\left|(n_* - 1)\ln\left(\frac{k}{k_*}\right)\right| \sim \left|n'_* \ln^2\left(\frac{k}{k_*}\right)\right|$$

Likelihood analysis for the cosmological parameters

- Markov-Chain Monte-Carlo(MCMC) using the data from WMAP, ACBAR, CBI, VSA, SDSS and Lyman-α (covering up to k~5h/Mpc)



(Marginalized 1-D PDI
Solid:Ours,
Dashed:Taylor,
Dotted: Constant n)

Not a big difference within the currently available data, but would change once we get more data at higher k with better precision

Improved parameterization and its inflationary motivation

$$\ln P(k) = \ln P_* - Ak^{\nu}, n-1 = -\nu Ak^{\nu}$$

General slow-roll formula: |n-1|≳|n'|≳|n''|…
(Stewart '02, Lee et al '05)

$$\ln P = C - B\xi^{-\nu}$$

$$\left(\xi \equiv -\int \frac{dt}{a}\right)$$

(concrete particle theory motivated example, e.g. Kadota&Stewart '03)

General slow-roll formula gives

$$\ln P(k) = C - Ak^{\nu} \text{ for } \nu < 2$$

$$\ln P(k) = C - Ak^{2} \text{ for } \nu \geq 2$$

$$\frac{n'_*}{n_* - 1} = \begin{cases} \nu & \text{for } \nu < 2 \\ 2 & \text{for } \nu \geq 2 \end{cases}$$

($n_*'/(n_*-1) \leq 2$ would be a consistency check for our analytical justification of the form of our parameterization)

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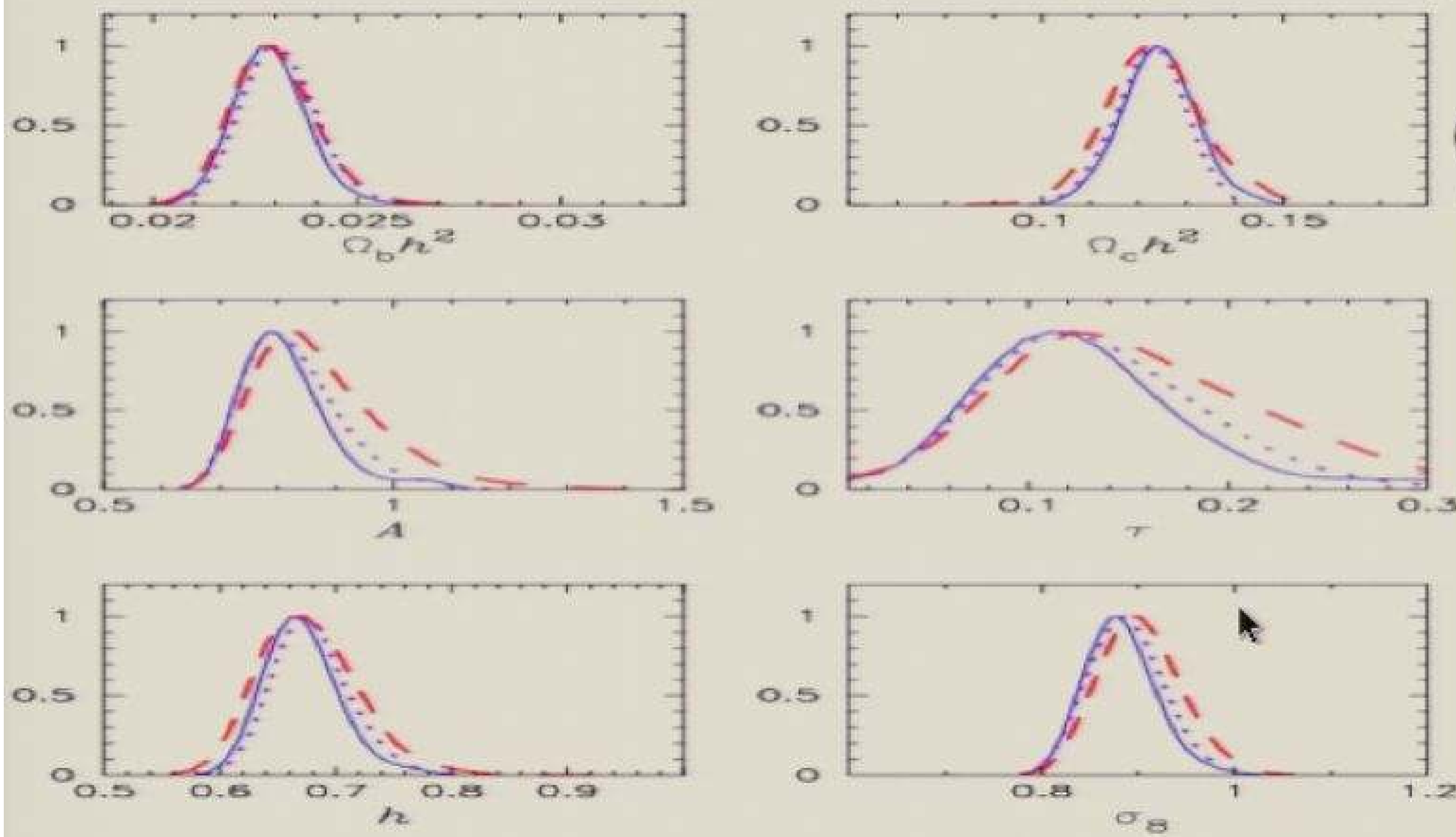

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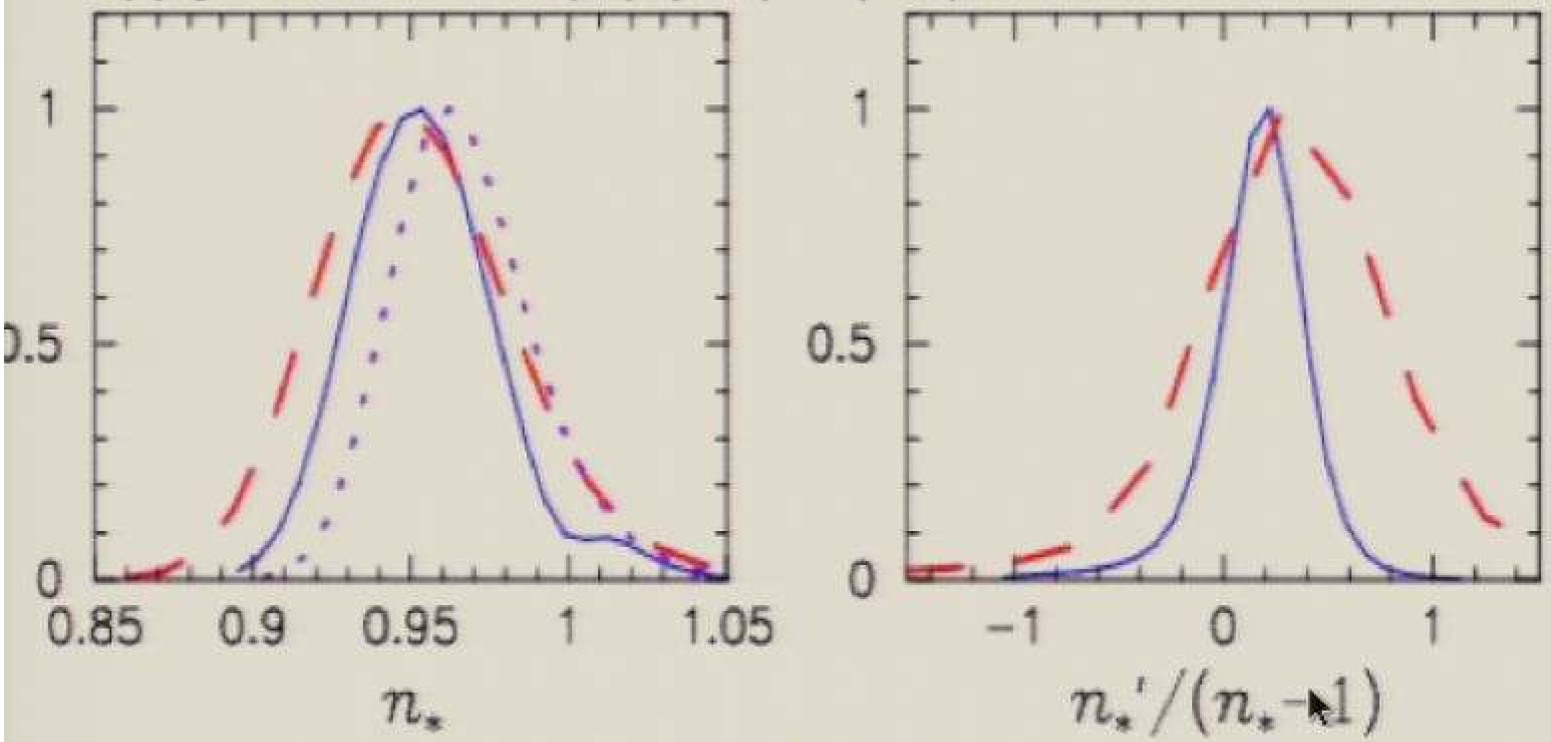
Likelihood analysis for the inflationary parameters

Simple single component inflation models where the standard slow-roll approximatio apply often leads to |n'|~|n-1|²<<|n-1|



(Marginalized 1-D PD
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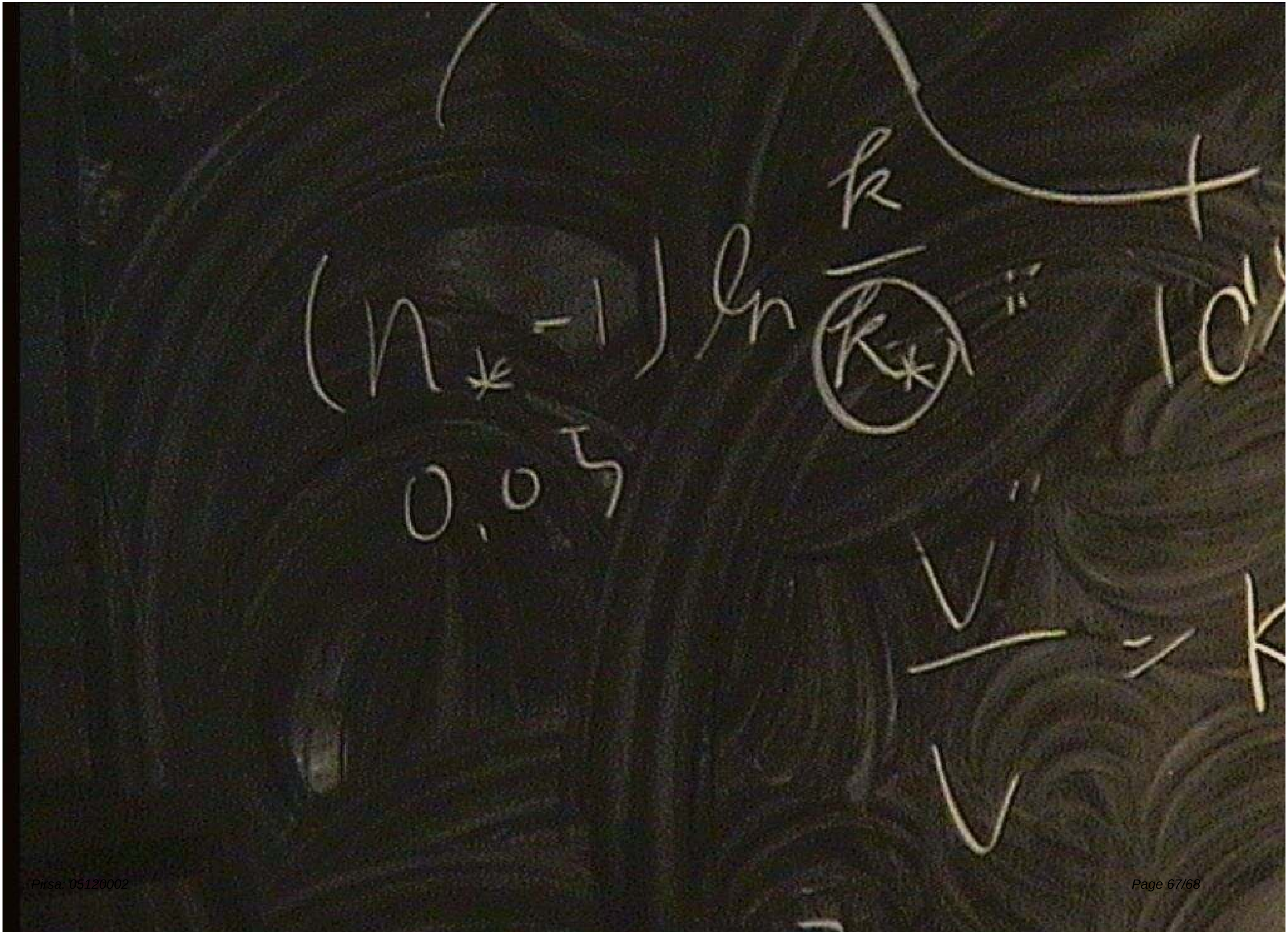
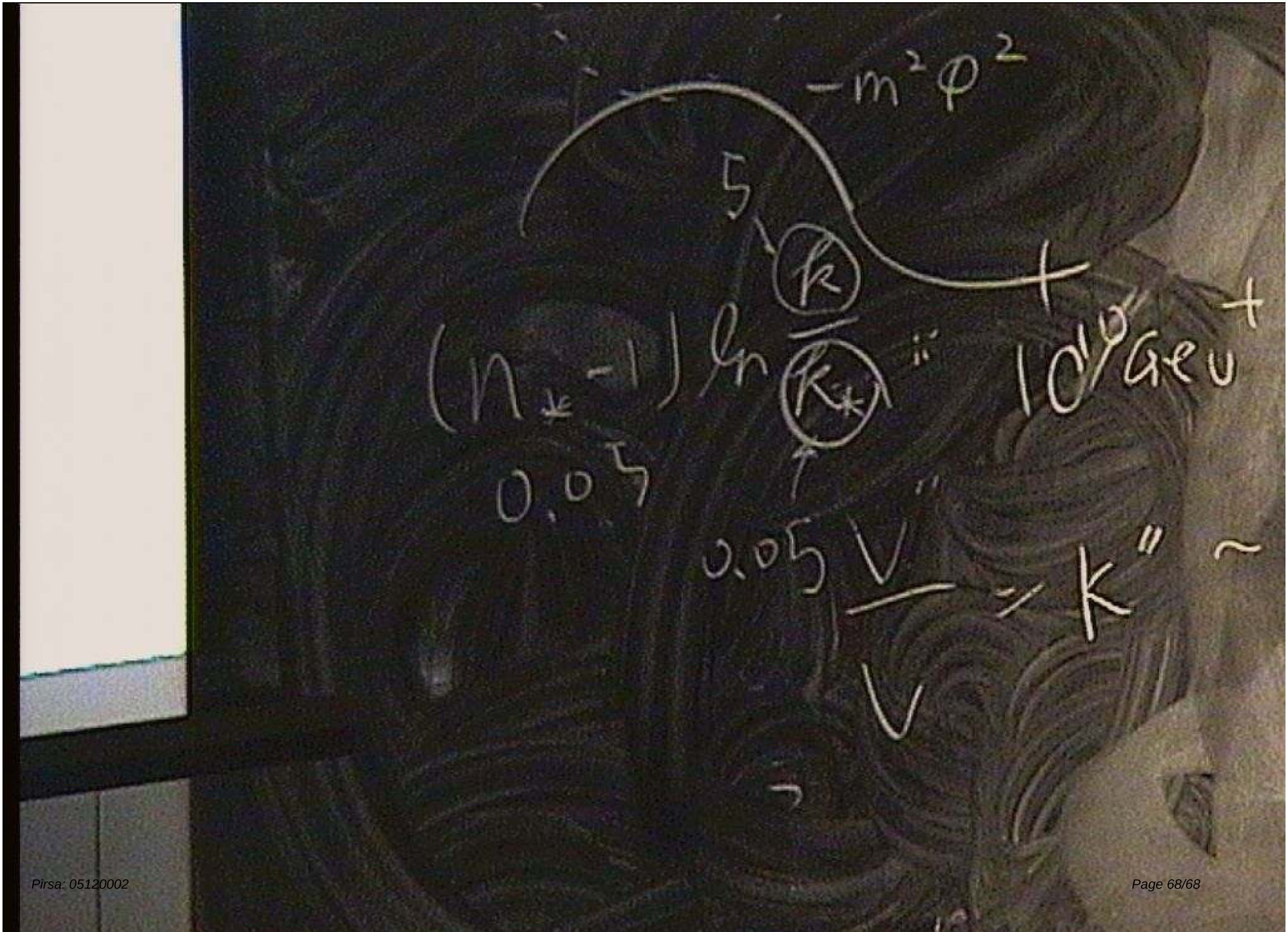
(Central values: ours n'.=-0.0087±0.0084, trunceted Taylor n'. =-0.019±0.014)

Our improved parameterization and even the truncated Taylor series expansion show that |n'|~|n-1| is still consistent with the data.

$\left|(n_*-1)\ln\left(\frac{k}{k_*}\right)\right| >> \left|n_*'\ln^2\left(\frac{k}{k_*}\right)\right|$ is not valid (our data covers Δlnk~10).


(n* -1) ln k/k*
0.05



$-m^2\varphi^2$
5
$(n_* - 1)\ln \frac{k}{k_*}$
0.05
10^{16} GeV