Title: Monodromy in the CMB: Gravity Waves and String Inflation

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Abstract: We present a simple mechanism for obtaining large-field inflation, and hence a gravitational wave signature, from string theory compactified on twisted tori. For Nil manifolds, we obtain a leading inflationary potential proportional to phi^(2/3) in terms of the canonically normalized field phi, yielding predictions for the tilt of the power spectrum and the tensor-to-scalar ratio, $n_sapprox 0.98$ and $rapprox 0.04$ with 60 e-foldings of inflation; we note also the possibility of a variant with a candidate inflaton potential proportional to phi^(2/5). The basic mechanism involved in extending the field range -- monodromy in D-branes as they move in circles on the manifold -- arises in a more general class of compactifications, though our methods for controlling the corrections to the slow-roll parameters require additional symmetries.

Monodromy in the CMB: Gravity Waves and String Inflation ... the (not fully) closed story ...

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(work in progress)

in collaboration with
Liam McAllister & Eva Silverstein

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- position of moving D-branes as inflaton: e.g. realized in the D3-antiD3-brane model [KKLMMT '03], the D3-D7 model [Dasgupta et al. '02], or in DBI-inflation [Alishahiha, Silverstein & Tong '04] ...

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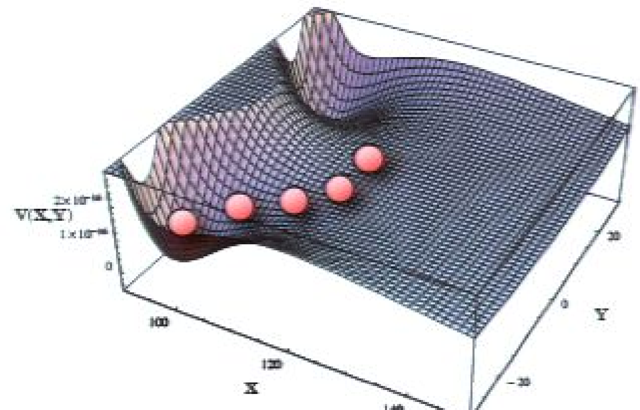
- Modular inflation driven by Kähler moduli [Blanco-Pillado et al. '04/'06, AW '05, Conlon & Quevedo '05, Bond et al. '06, Linde & AW '07] ...



String(y) Inflation ...

- most IIB models are <u>*small-field*</u> models, driving inflation near a saddle or inflection point of the potential:
  [Blanco-Pillado et al. '04/'06, AW '05, Conlon & Quevedo '05, Bond et al. '06, Baumann et al. '07, Krause et al. '07, Linde & AW '07 ...]

- thus no gravity waves due to Lyth bound:

$$r \;\equiv\; \frac{\mathcal{P}_T}{\mathcal{P}_S} \;\leq\; 0.003\;\left(\frac{50}{N_e}\right)^2\left(\frac{\Delta\phi}{M_{\rm P}}\right)^2$$

  however, see multiply wrapped-branes proposals,
  which failed because of excessive back-reaction at $\phi \sim M_P$:
  [Becker et al. '07, Kobayashi et al. '07, Huston et al. '08]

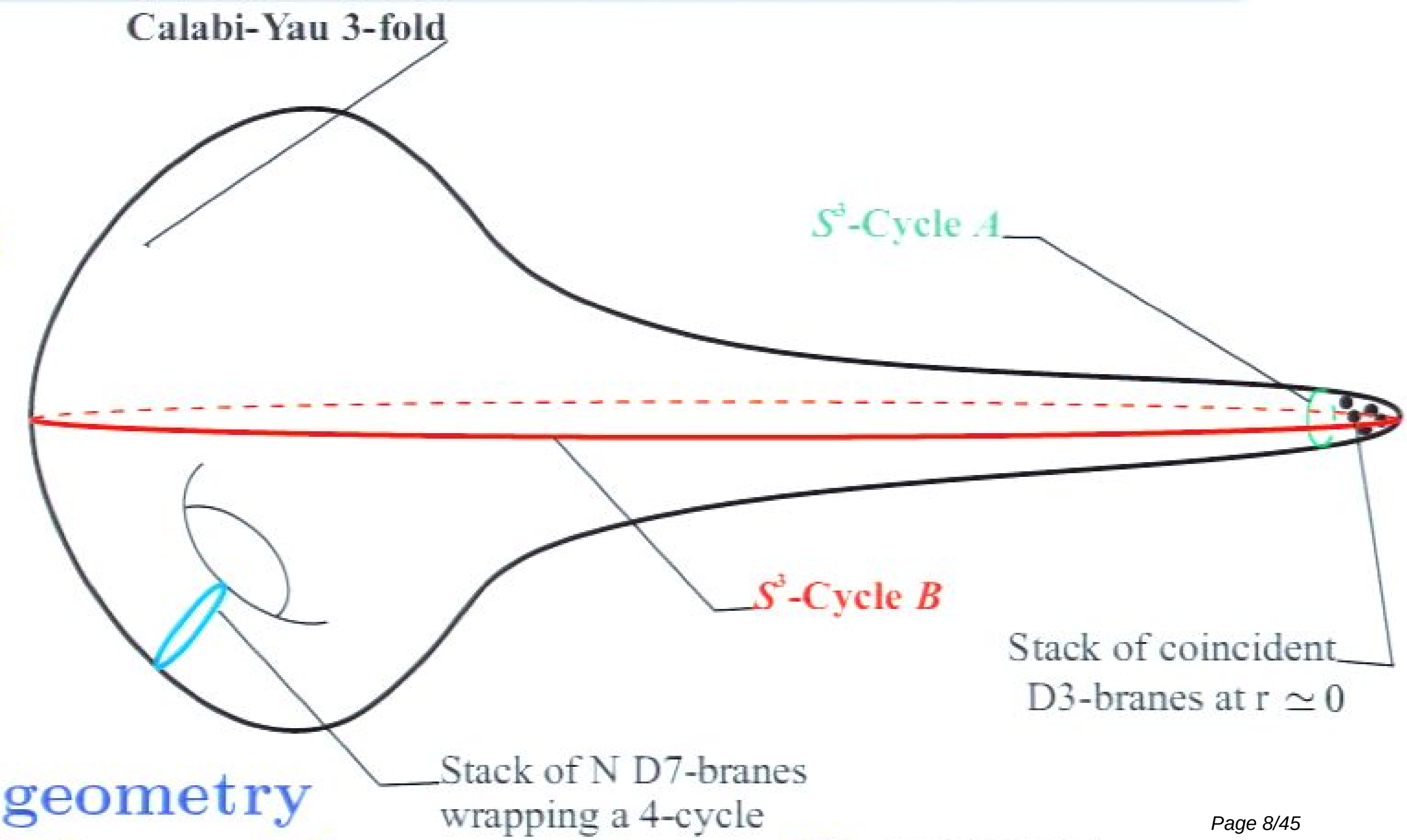
- recent progress:
  monodromies in IIA on Nil manifolds [E. Silverstein's talk]
  extension of Kahler moduli inflation [talks by Quevedo & Cicoli]

- We would like to use monodromies in closed string moduli space on warped CYs in IIB
- motivations: important class of examples with moduli stabilized by fluxes (H_3, F_3) & branes + possibly low-energy SUSY

Turn on fluxes

$$\int_A F_3 = M$$

$$\int_B H_3 = K$$



gives warped geometry

fixes dilaton S & complex structures U_I [GKP '01]

mondromies in IIB Kahler moduli space

- simple IIB-monodromy on a CY: B_2 or C_2

$b \equiv \int_{\Sigma_2} B_2^{\rm NS}$ or $c \equiv \int_{\Sigma_2} C_2^{\rm RR}$ on a 2-cycle Σ_2 wrapped by a 5-brane,

b and c are part of the $\mathcal{N} = 2$ Kähler moduli multiplets

$\Rightarrow$ similar to monodromies of mirror-dual CY-pairs around the large complex structure point [e.g. Candelas et al. '91]

- explicitly visible: wrap a D5-brane on 2-cycle

$$S_{\rm DBI}^{D5} = -\frac{1}{(2\pi)^6 g_S \alpha'^3} \int_{\mathcal{M}_4 \times \Sigma_2} d^6\xi \sqrt{\det(G+B)}$$

$$= -\frac{1}{(2\pi)^4 g_S \alpha'^2} \int d^4x \sqrt{-g} \sqrt{L_{\Sigma_2}^4 + b^2}$$

breaks perturbative shi symmetry in B_2

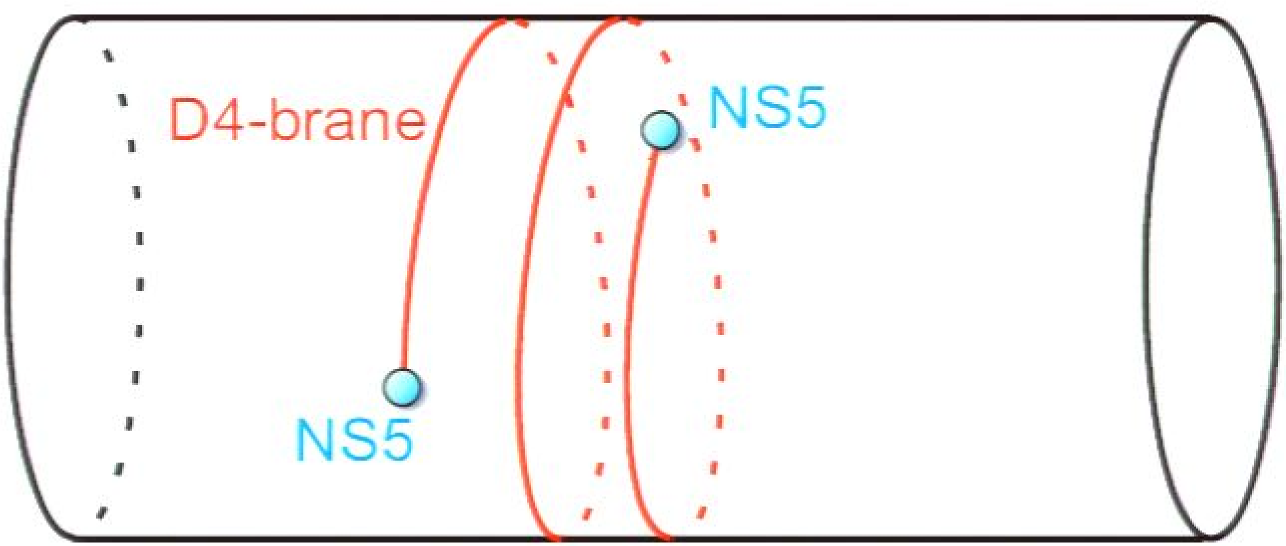
similarly, NS5-brane breaks C_2 shift symmetry

- possible realization:

$\mathbb{C}^2/\mathbb{Z}_2$ orbifold, local model to be glued onto a GKP-style warped CY has $\mathcal{N} = 4$ SUSY broken to $\mathcal{N} = 2$ at fix points

wrap D5 on shrunken blow-up orbifold 2-cycle, turn on B_2 there

described by a gauge group quiver - T-dual to a D4 stretched between 2 NS5's along a circle in IIA:



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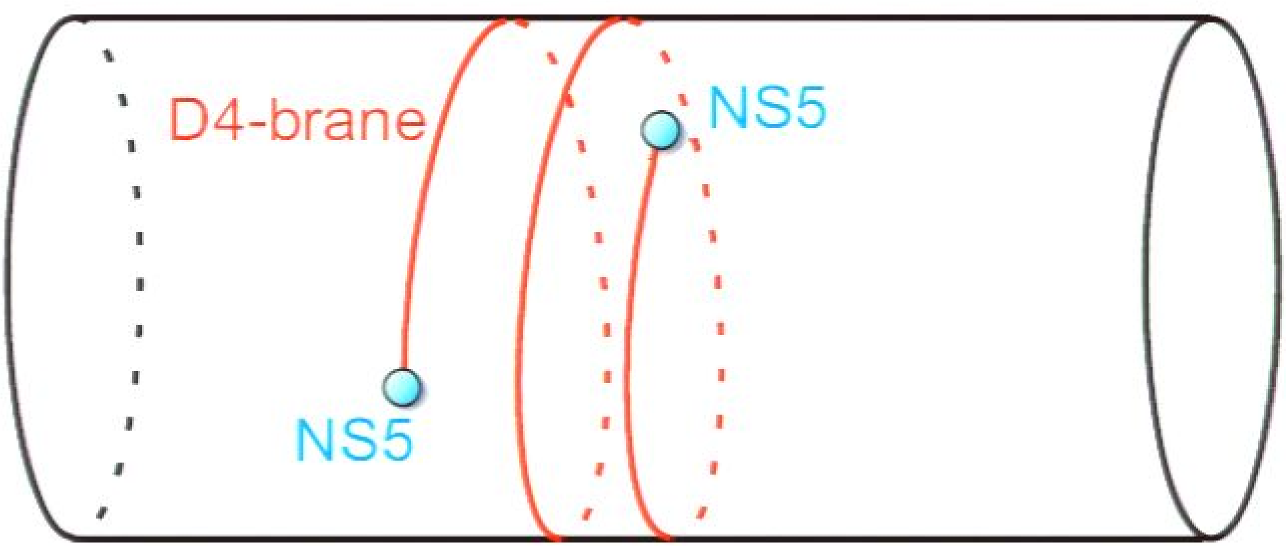

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D5-brane is a BPS-state

S-duality thus links D5- and NS5-tension, implying:

for B_2, C_2 large

$$V_{D5} \sim b \quad \Rightarrow \quad V_{NS5} \sim c$$

- thus *kinematically* unbounded field range - but limited dynamically:

$$V_{D5,NS5} < U_{mod} \text{ , } U_{mod} \text{ scale of moduli potential}$$

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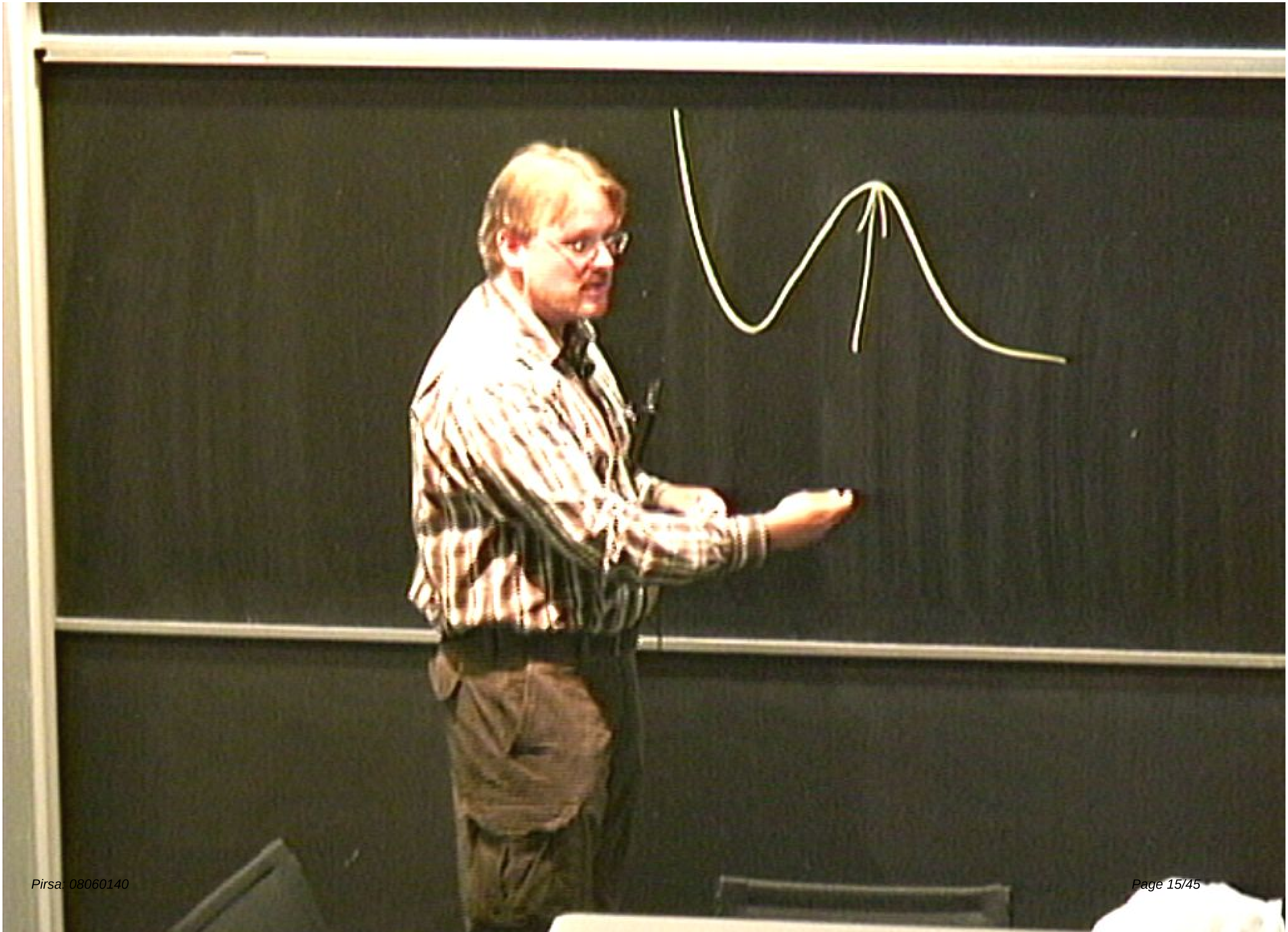

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an η-problem for B_2 as the inflaton ...

structure of 4d N=1 multiplets poses a problem:

O7-orientifold splits 4d $\mathcal{N}=2$ Kahler moduli into chiral multiplets

$$T_\alpha = \frac{vol(\Sigma_4^{(\alpha)})}{g_s} + i\int_{\Sigma_4^{(\alpha)}} C_4 \quad \text{and} \quad G^a = \frac{b^a}{g_s} - ic^a$$

superpotential depends through instantons holomorphically on T_α, G^a [e.g. Grimm '07], thus stabilizes the fields T_α and G^a separately

consider most simple case:

one field T, one field G

then the Einstein frame Calabi-Yau volume $\mathcal{V}_E$ is:

even-odd intersection number: κ_{TGG}

$$\mathcal{V}_E \sim \left[T + \bar{T} - \kappa g_s (G + \bar{G})^2\right]^{3/2}$$

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in Einstein frame, the D5-brane inflaton potential scales as:

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expanding this potential in b gives then a KKLMMT-like η-problem for b ...

$\Rightarrow$ try power-law stabilization mechanisms ...

- Kahler stabilization on a CY: $\Delta K \sim \frac{\alpha'^3}{\mathcal{V}_E} + \frac{\alpha'^4 c_{1-loop}}{\mathcal{V}_E^{4/3}}$
- power-law stabilization on non-CY:

$\Rightarrow$ Riemann surfaces, Nil manifolds

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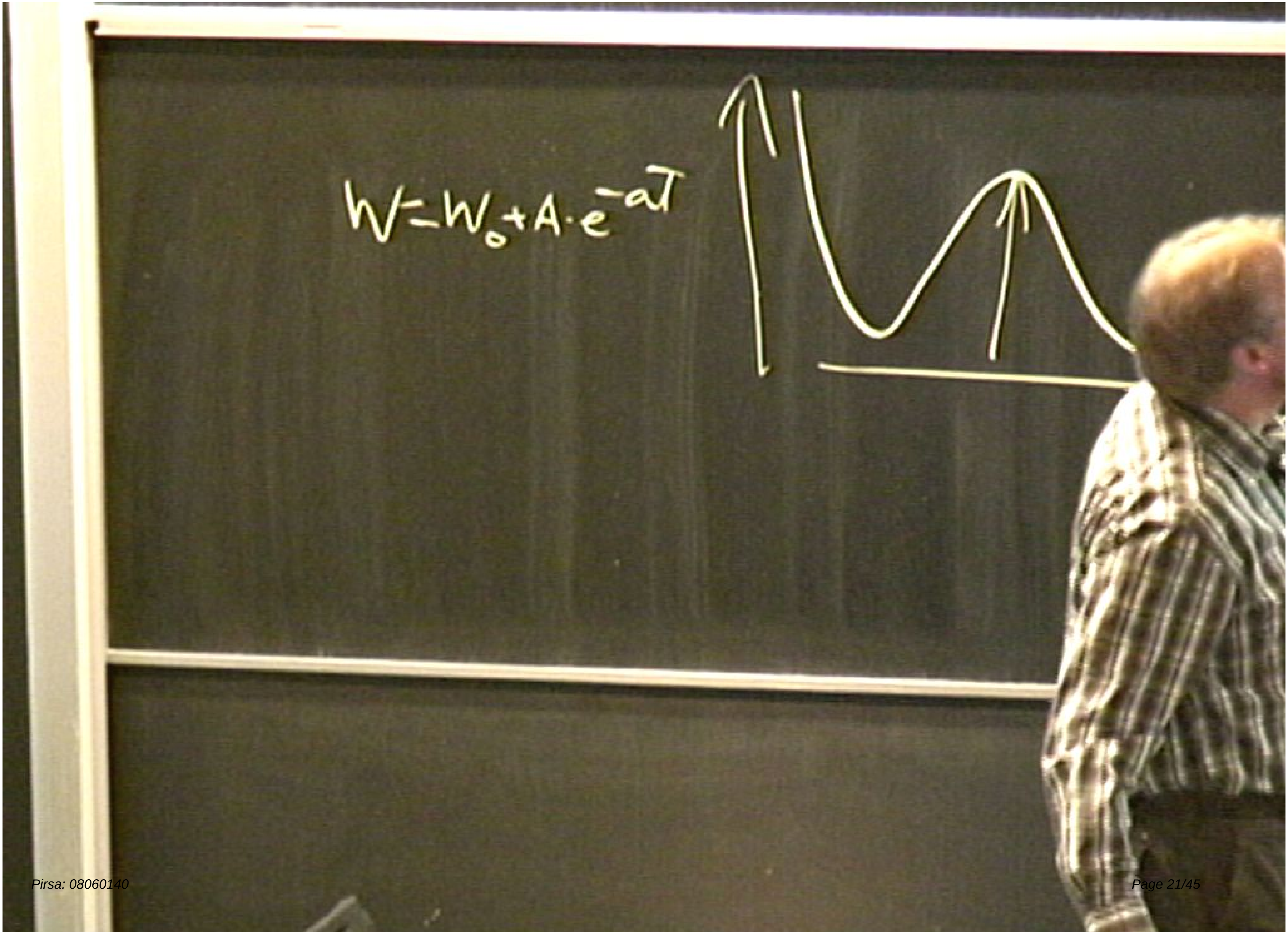
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way out: use C_2 on an NS5-brane ...

- shift symmetry in C_2 preserved in tree-level K

but dangerous:

$ED1$ instantons

$ED3$ instantons with dissolved D1-branes

$$\Rightarrow \quad \Delta W_c = e^{-\frac{b}{g_s}+ic} + e^{-T-\frac{b}{g_s}+ic}$$

gives dangerous $\cos(c)$-dependences in potential

these may be absent, as argued by [Witten '95; Grimm '07]

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ED3 instanton with a dissolved D1 and D-1

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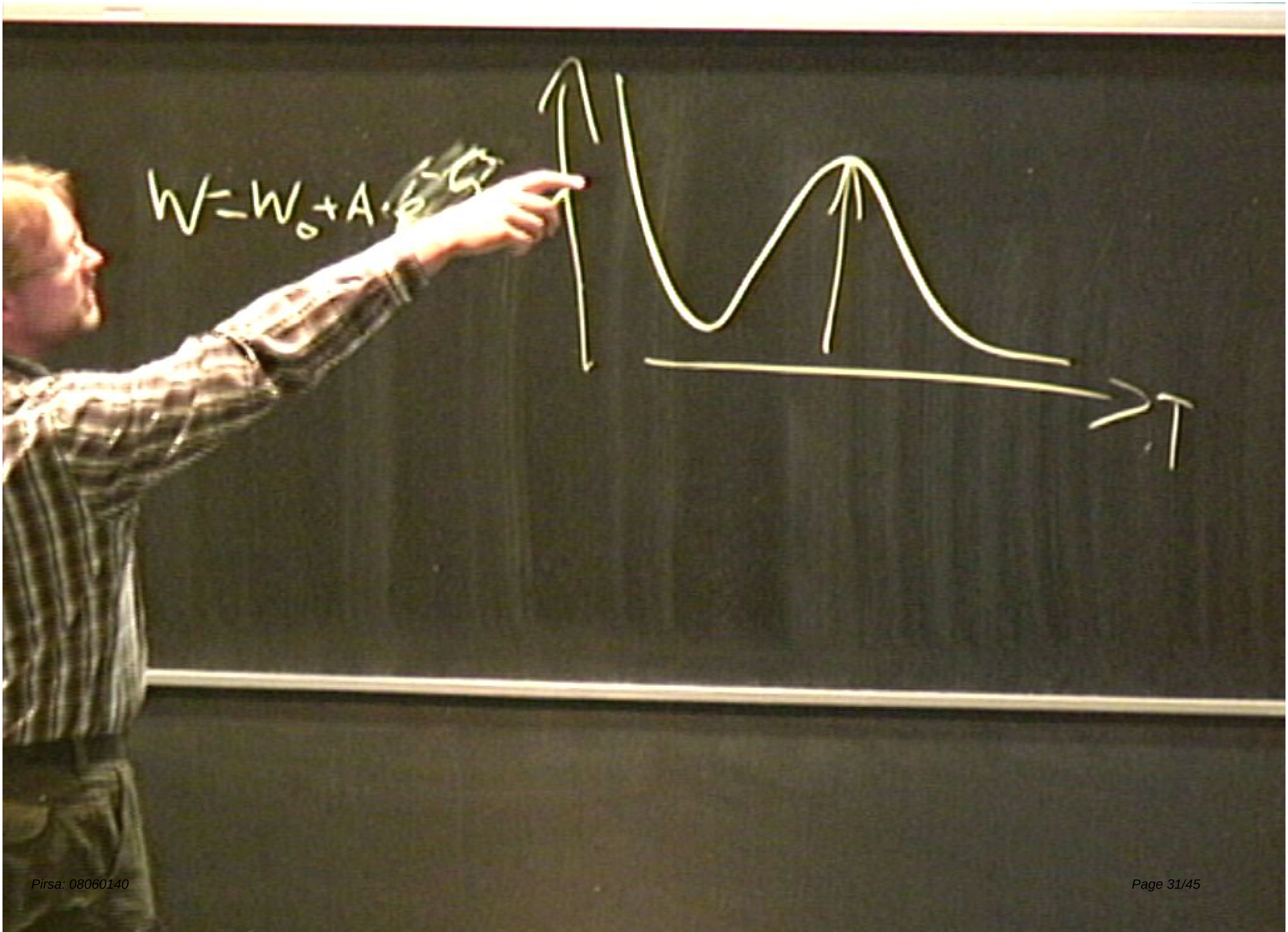
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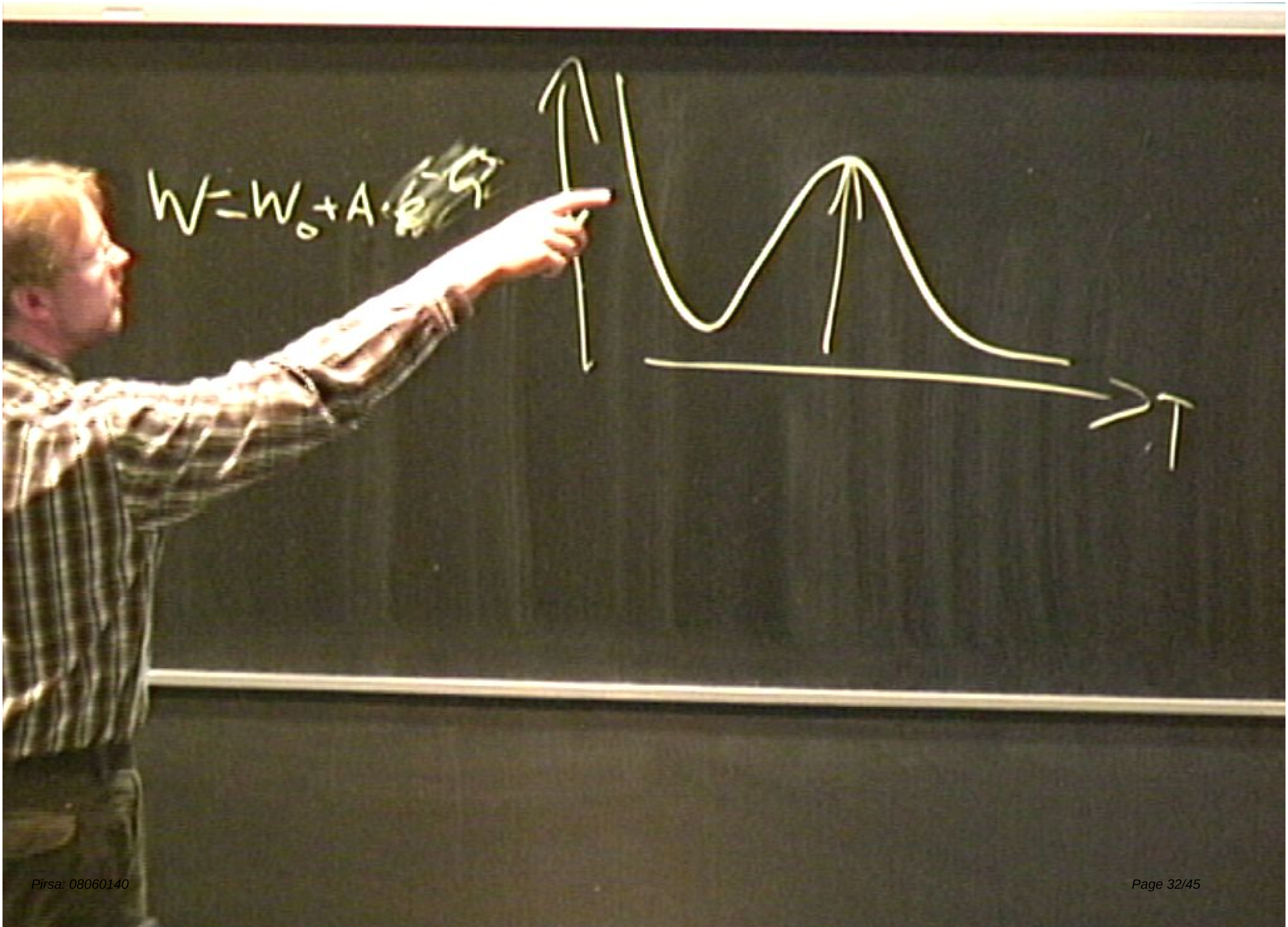
T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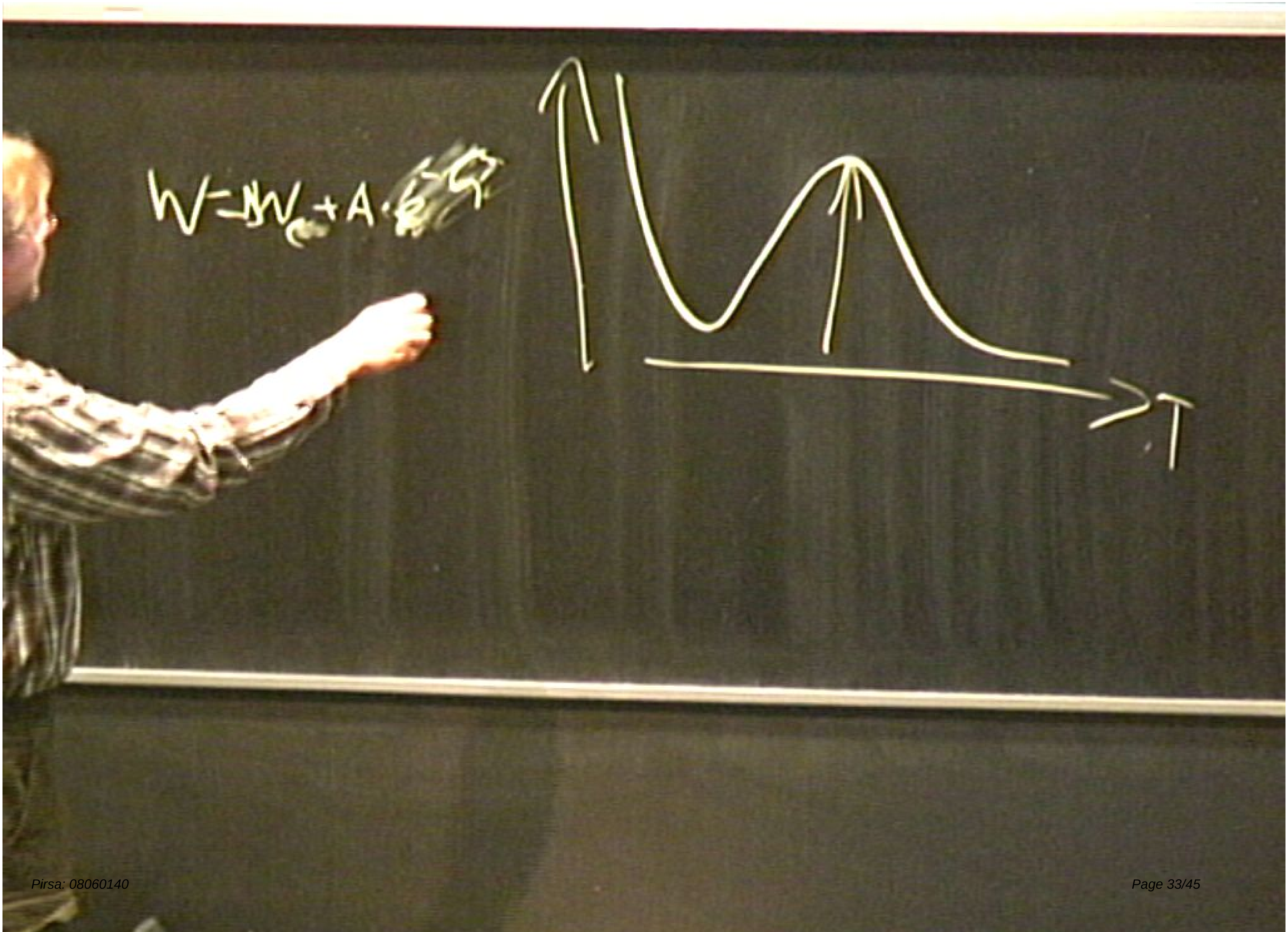
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a version with H >> m3/2 ...

- total superpotential:

$$W = \underbrace{W_0 + A_1 e^{-a_1 T} + A_2 e^{-a_2 T}}_{W_{KL}} + \Delta W_c$$

tuning W_0, stabilize T at $\langle D_T W_{KL} \rangle \simeq 0 \simeq \langle W_{KL} \rangle$

stabilizes T at higher mass scale than G,
mass of G gets small as $\langle W_{KL} \rangle \to 0$

$\cos(c)$ scales with $\langle W_{KL} \rangle$, goes away for $\langle W_{KL} \rangle \to 0$

but $\langle W_{KL} \rangle \to 0$ is also the limit of low-energy SUSY
$\Rightarrow$ this provides further motivation for using C_2 ...

IF all of this works out ...

$$V_{NS5}(\phi) \sim \mu^3 \phi \quad , \quad \phi \sim c \quad \Rightarrow \quad n_s \approx 0.975 \quad \text{and} \quad r \approx 0.07$$

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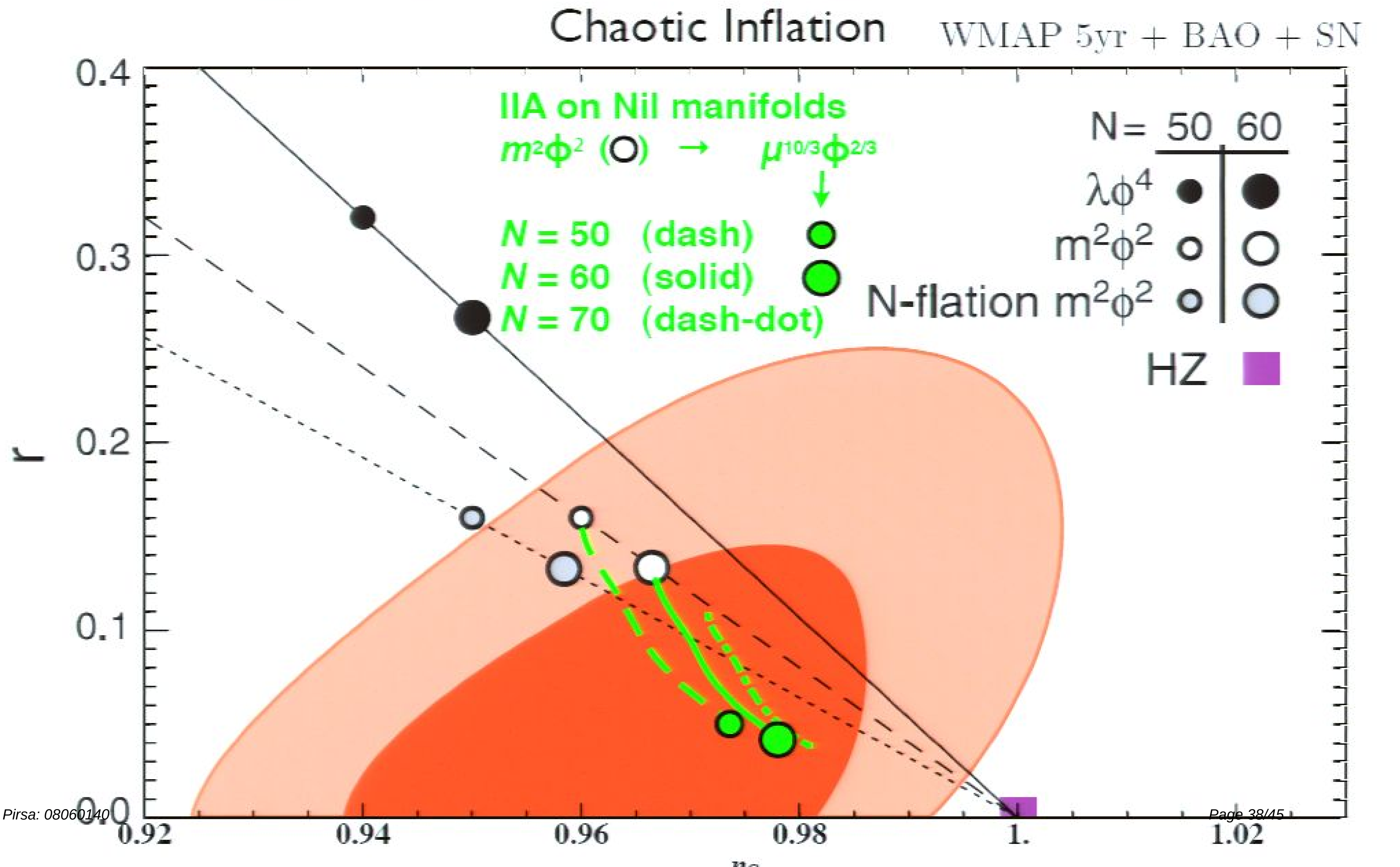

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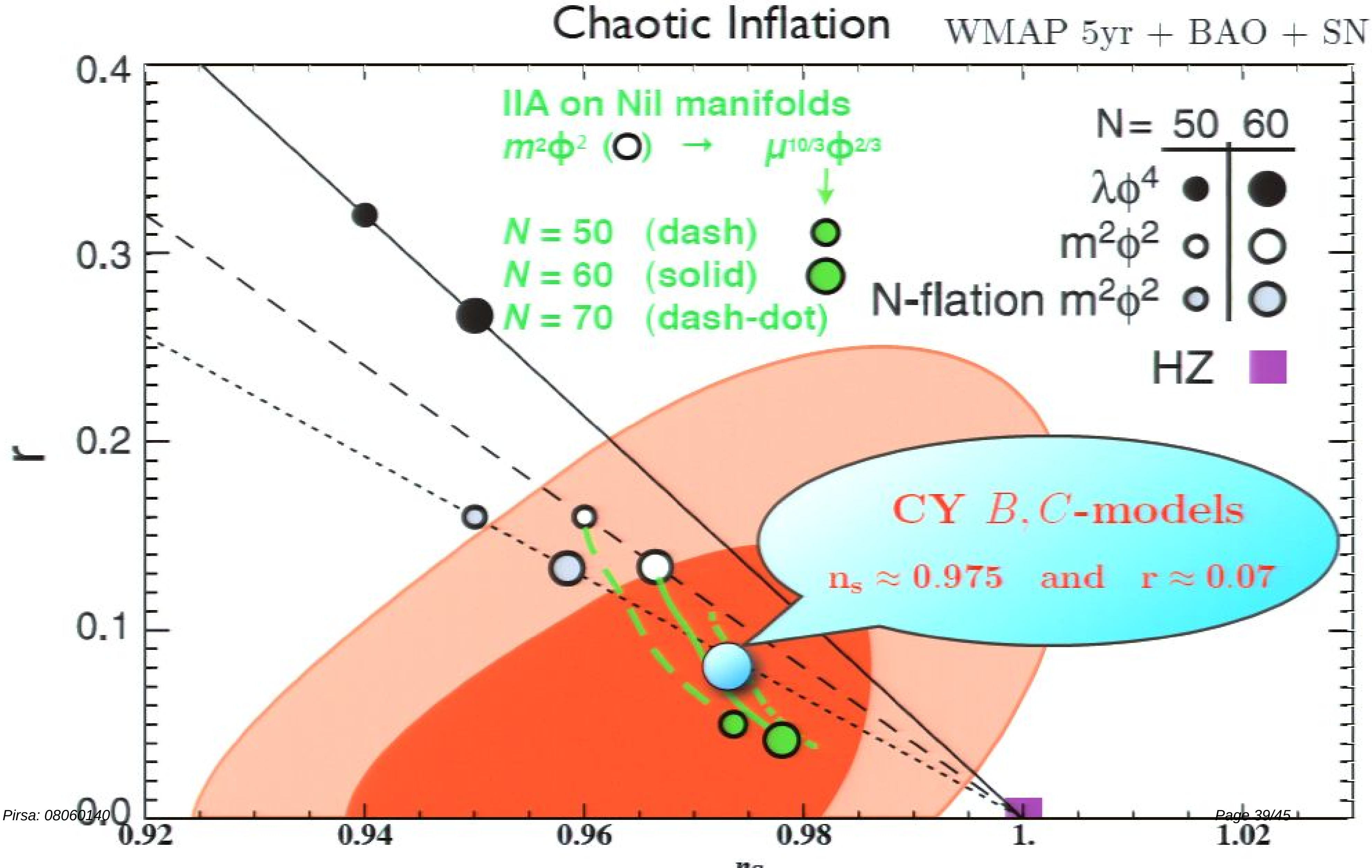

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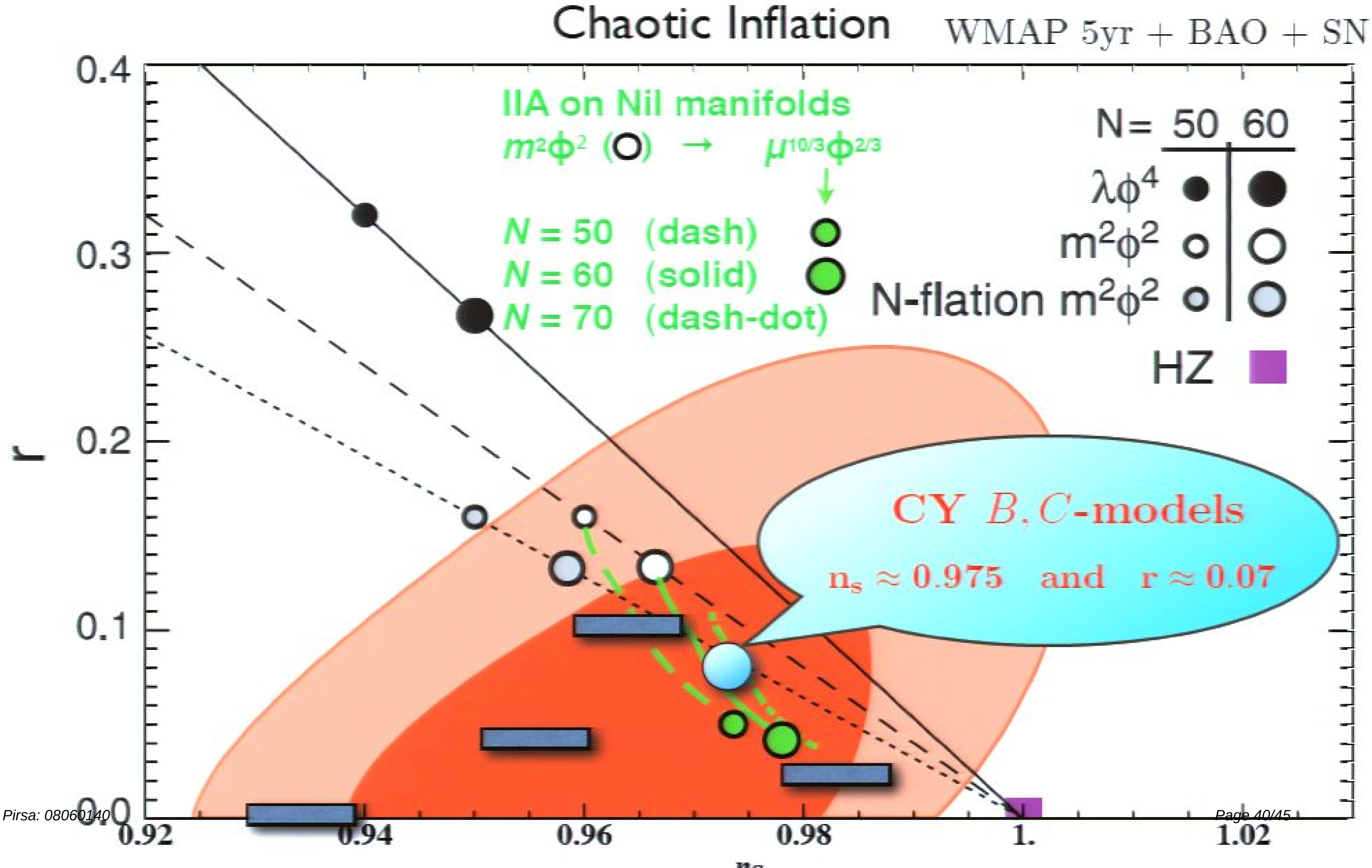


Conclusions

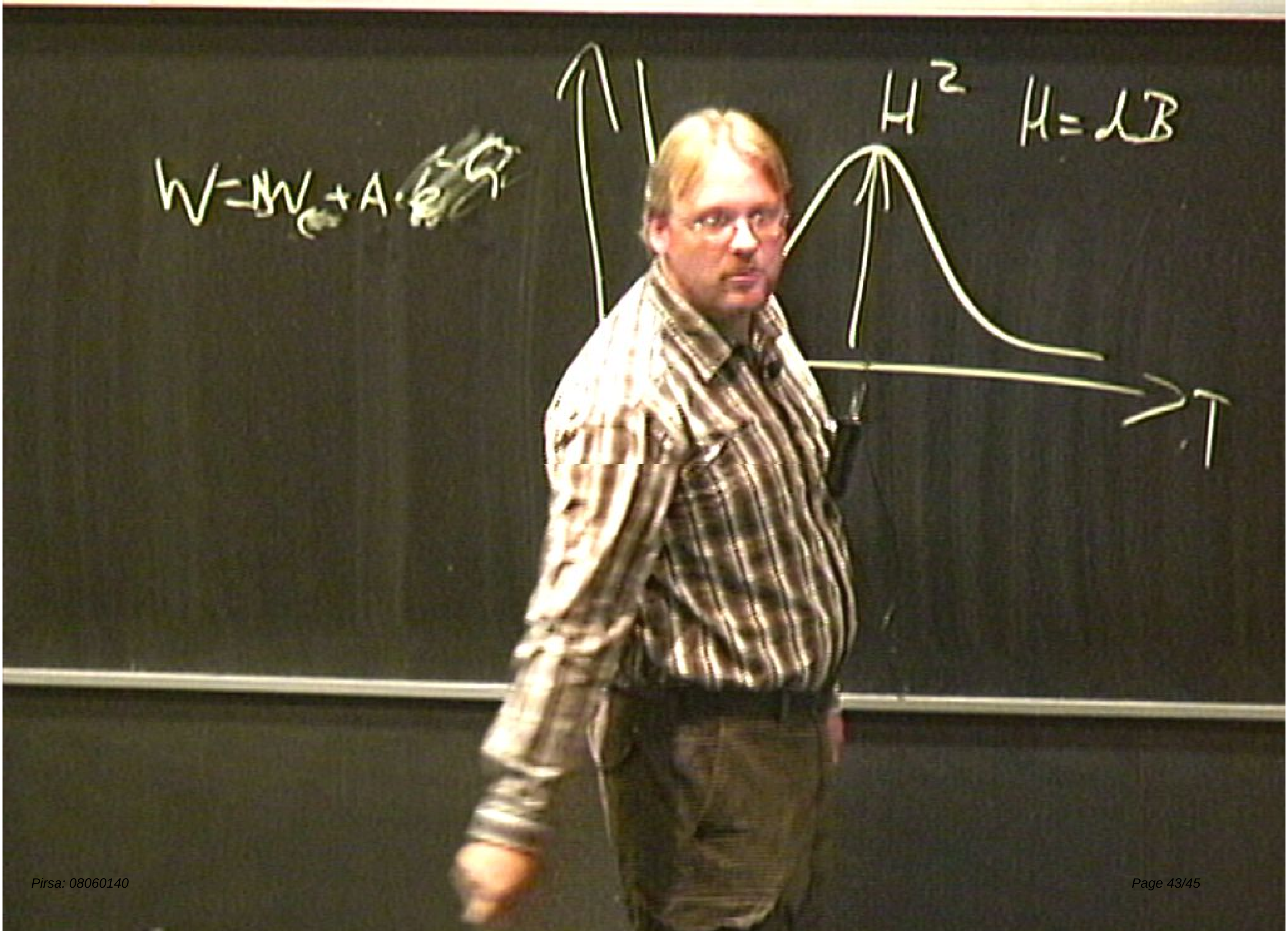
- 5-branes wrapped on 2-cycles generate monodromies of the B_2 or C_2 form fields on the brane; this opens up large field range $\phi \gg M_P$ in IIB on Calabi-Yaus ...

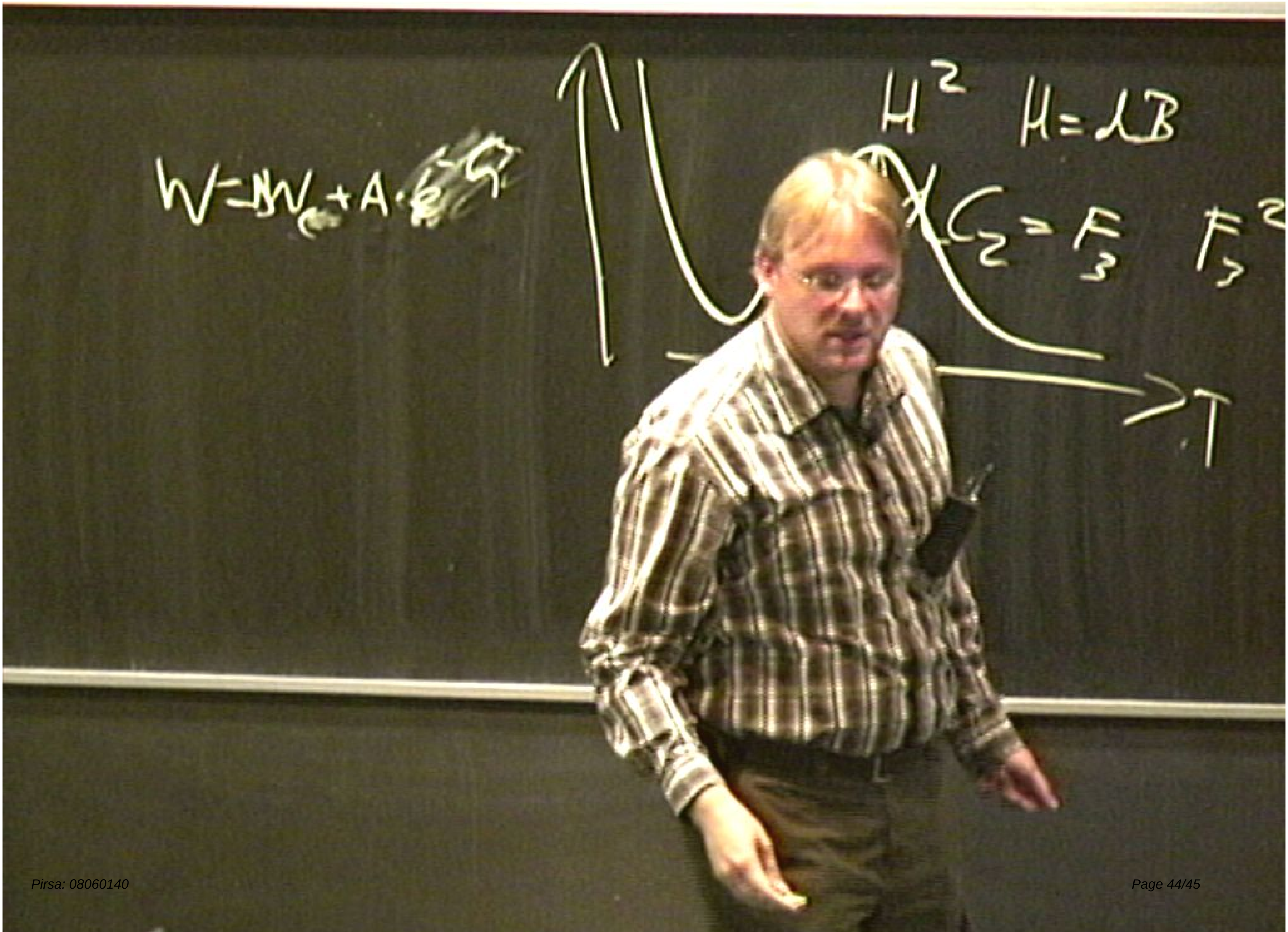
  model with $V(\phi) \sim \phi$: $n_s \approx 0.975$ and $r \approx 0.07$

  $\Rightarrow$ detectable gravity waves

- - especially for C_2 a near-perfect shift-symmetry helps controlling corrections & back-reaction for super-Planckian field range
  - C_2 not a geometric modulus → KL mechanism allows for GUT-scale moduli potential needed for chaotic inflation, while potentially enabling low-energy SUSY

- open questions:
  - incorporating a SM sector / Reheating ?
  - fine-tuning in the KL-sector / symmetries may kill instantons
  - B_2 inflation possible with perturbative high-scale stabilization ?


H
2
H = λB
T



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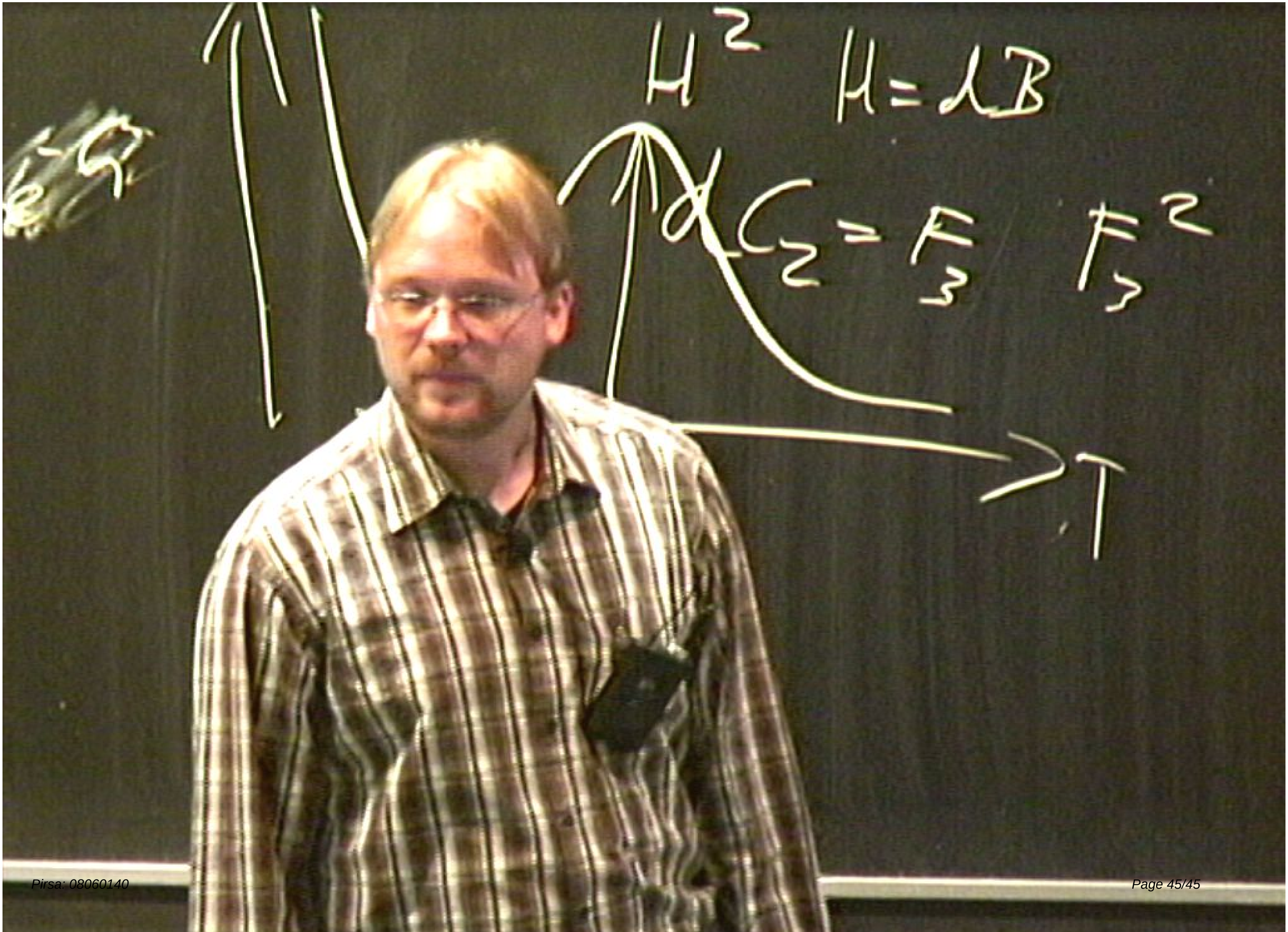
H²
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C₂ = F₃
F₃²
T