Title: The nu physics in the dark sector

Date: Nov 28, 2006 02:00 PM

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Abstract: Existence of dark energy and nonzero nu mass are two most exciting discoveries of recent years. More excitingly, the similarity between the energy scales of these two raise the question: "Are they related?" I will explore how such connection could be there in nature and its cosmological consequences mainly in structure formation.

The ν Physics in The Dark Sector

Subinoy Das
CCPP , NYU

- Existence of dark sector as 96% of the energy budget !

What I am going to talk about

- A brief review of quintessence and DE eos and observation constraints.

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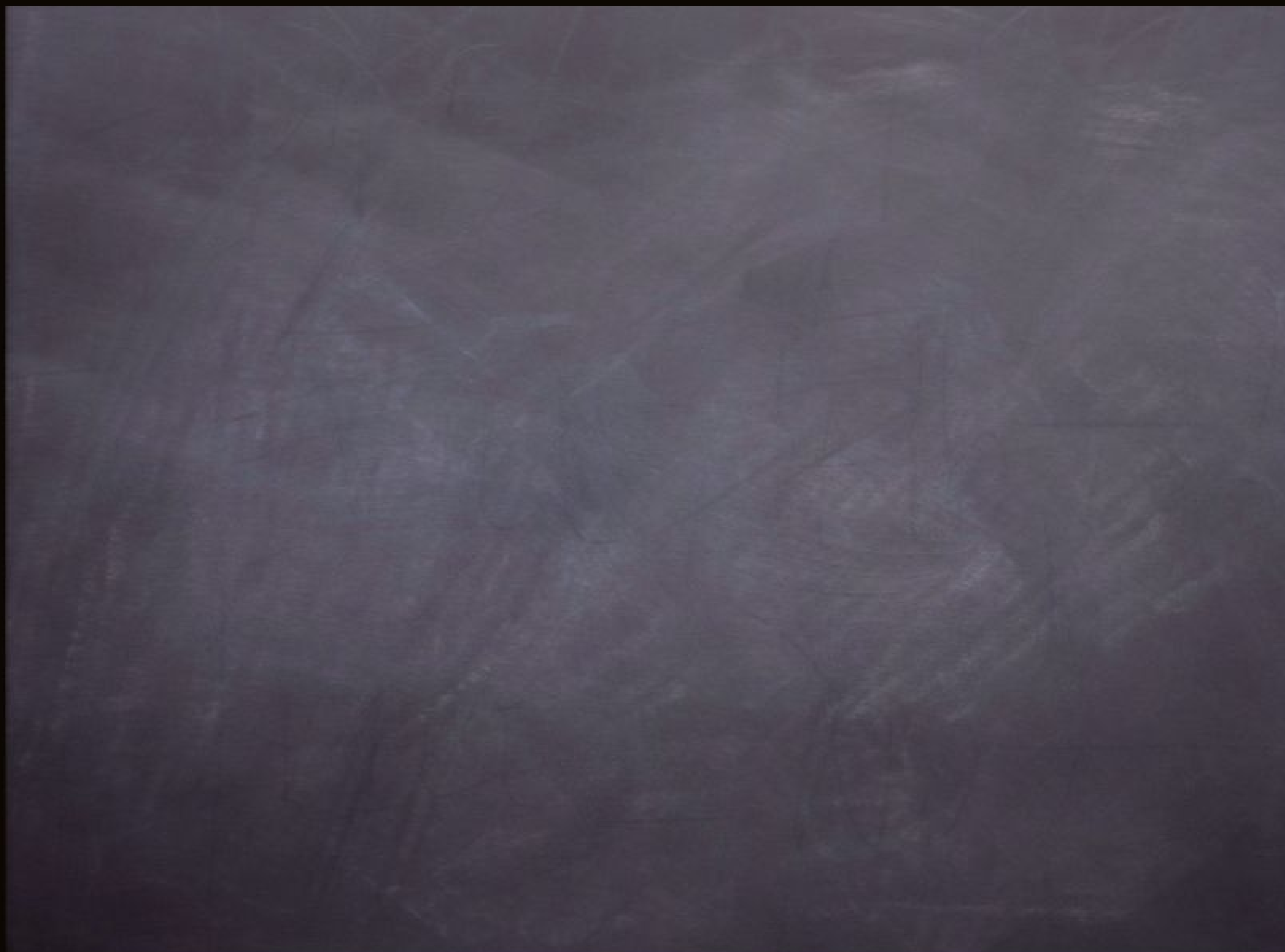
- Dark Energy from Relic Neutrino ? .... MaVaN
- Late Forming Dark Matter and possible mechanism for coincidence puzzle.



Quintessence : motivation

- nature would be cruel if DE equation of state w = -1 , observations would offer no further guidance to explain its minuteness whether due to physical mechanism or anthropic reasoning.

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- more fertile outcome $w \neq -1$, vacuum energy changing in a Hubble time , hence new physics.
  A well studied candidate is quintessence where a scalar field ϕ rolls down a self-interacting potential.

A brief review of Quintessence

$$\rho_M \sim \frac{1}{a^3}$$

$$\rho_{RD} \sim \frac{1}{a^4}$$

$$\rho_\phi = \frac{1}{2}(\frac{d(\phi)}{dt})^2 + \frac{M^{4+\alpha}}{(\phi)^\alpha}$$

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Coincidence problem

- Why the DM and DE energy density are of the same order NOW ?

- For a large class of potentials (for eg.) $\frac{M^{4+\alpha}}{(\phi)^\alpha}$

ρ_ϕ tracks ρ_M

Success : insensitive to initial condition

- For a large range of initial value of ϕ and $\frac{d\phi}{dt}$, DE is pre-destined to take matter
  to make DE domination happen at present epoch
  need to fine tune M

- Bad news : requiring $w \sim -1$ constrains the large basin of initial condition.

- Is it possible to have DE model without fine tuning ?

Neutrino As A Portal Into The Dark Sector

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- Neutral in low energy theory, can mix with Dark Sector.
- relic neutrino from smooth background ~ like DE.

MODEL (Fardon, Nelson,Weiner)

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active neutrinos ν

Higgs field H

tiny Yukawa $O(10^{-11} - 10^{-15})$

$yH\nu n$

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Dark sector

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- "Sterile fermion" n
- Yukawa λAnn
- potential $V(A)$

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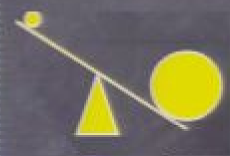

mini-seesaw

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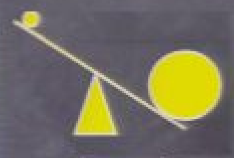

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Neutrino mass matrix

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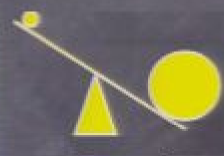

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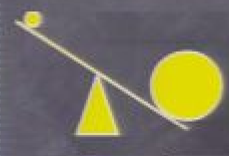

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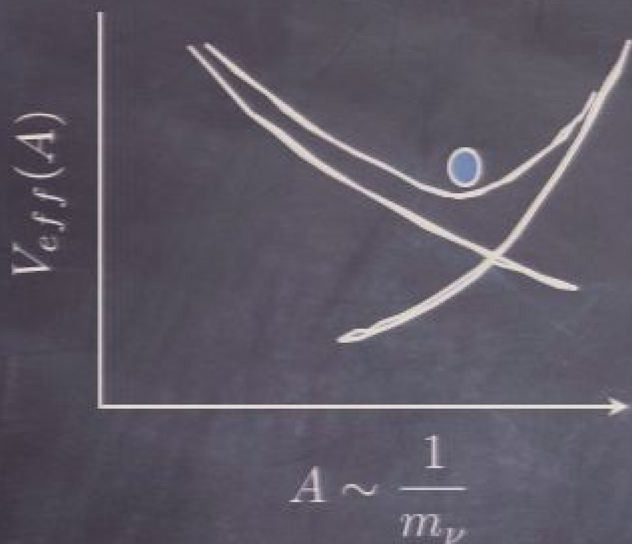

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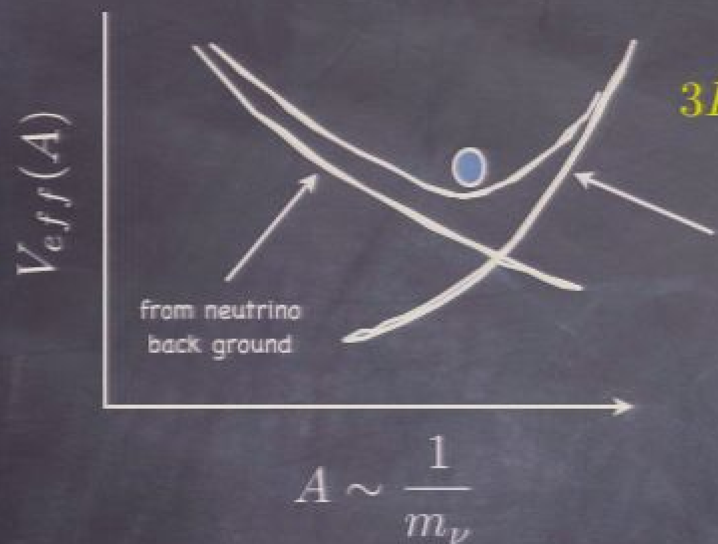

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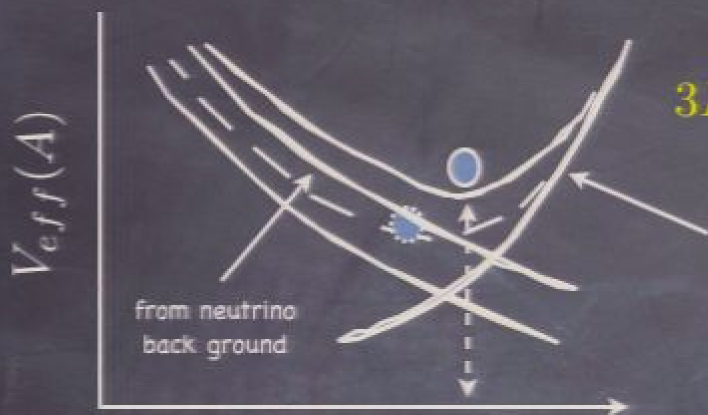

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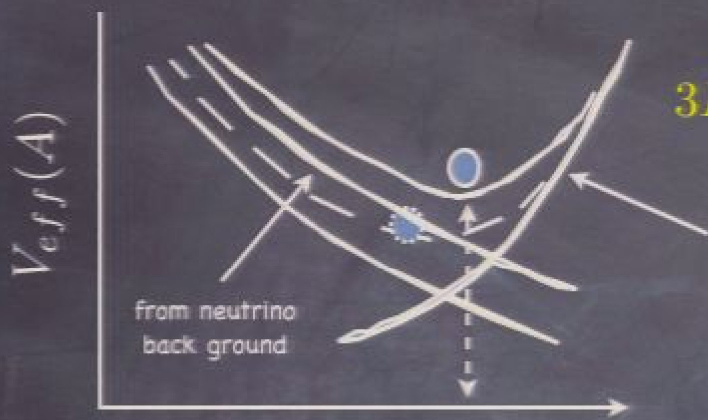

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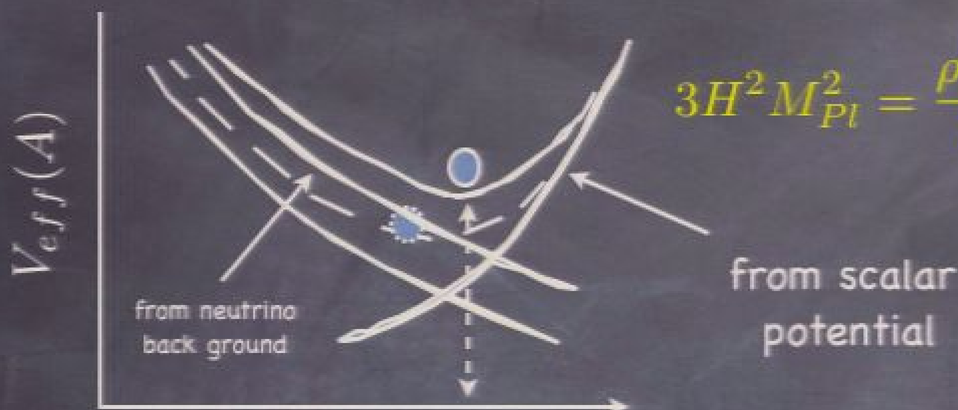

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Success of the model :

Neutrino mass and DE density is not a mere coincidence today, it holds from long time back , so m_ν varies with z.

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All of the above issues taken care under Supersymmetrization.

A brief review of supersymmetric MaVaN

Nelson, Weiner ,2005

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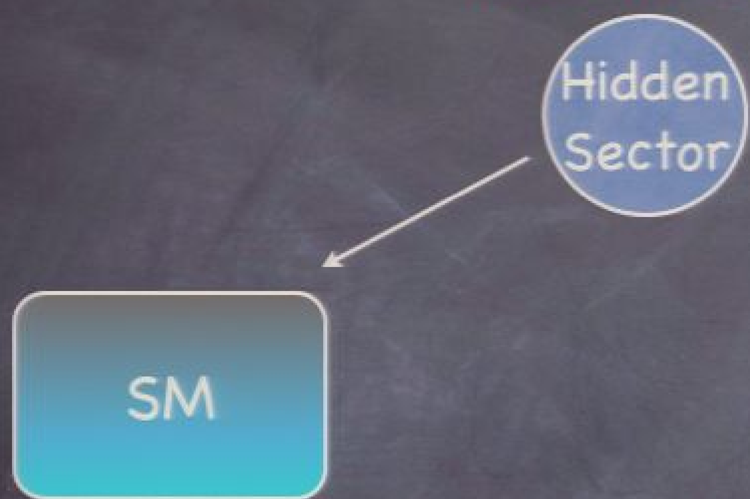

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Susy Breaking at
<F>/M ~ TeV
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$m_{3/2} \sim 10^{-3} eV$

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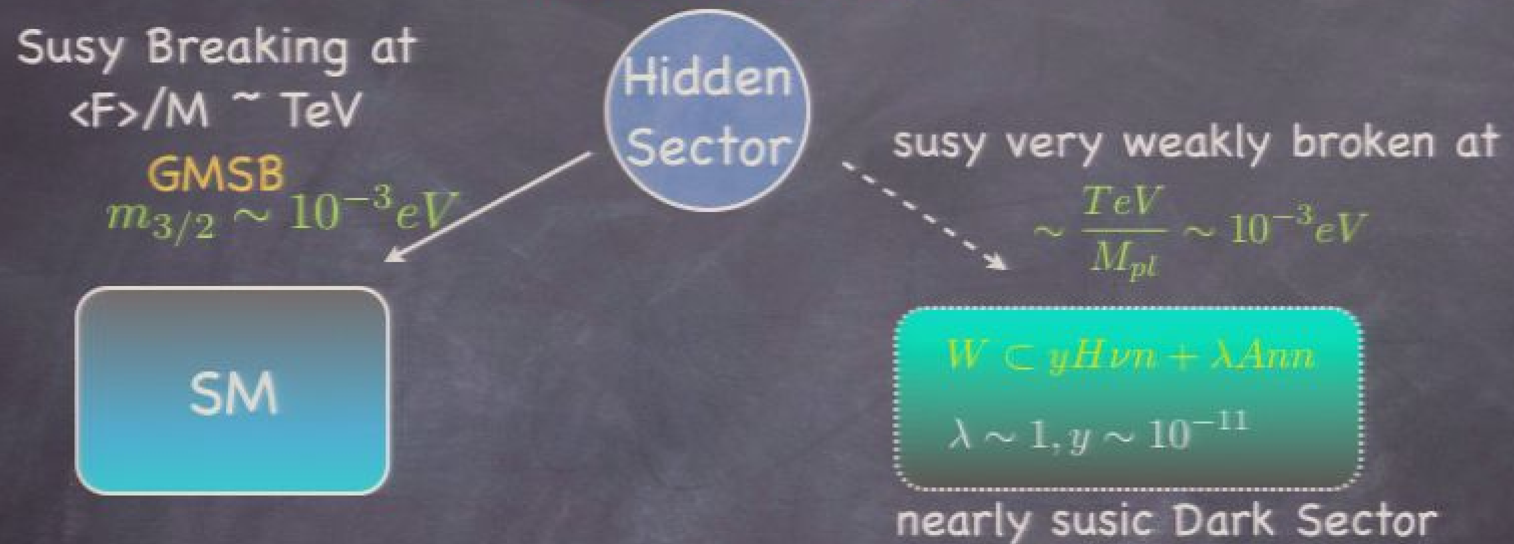

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susy very weakly broken at
$\sim \frac{TeV}{M_{pl}} \sim 10^{-3} eV$

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nearly susic Dark Sector

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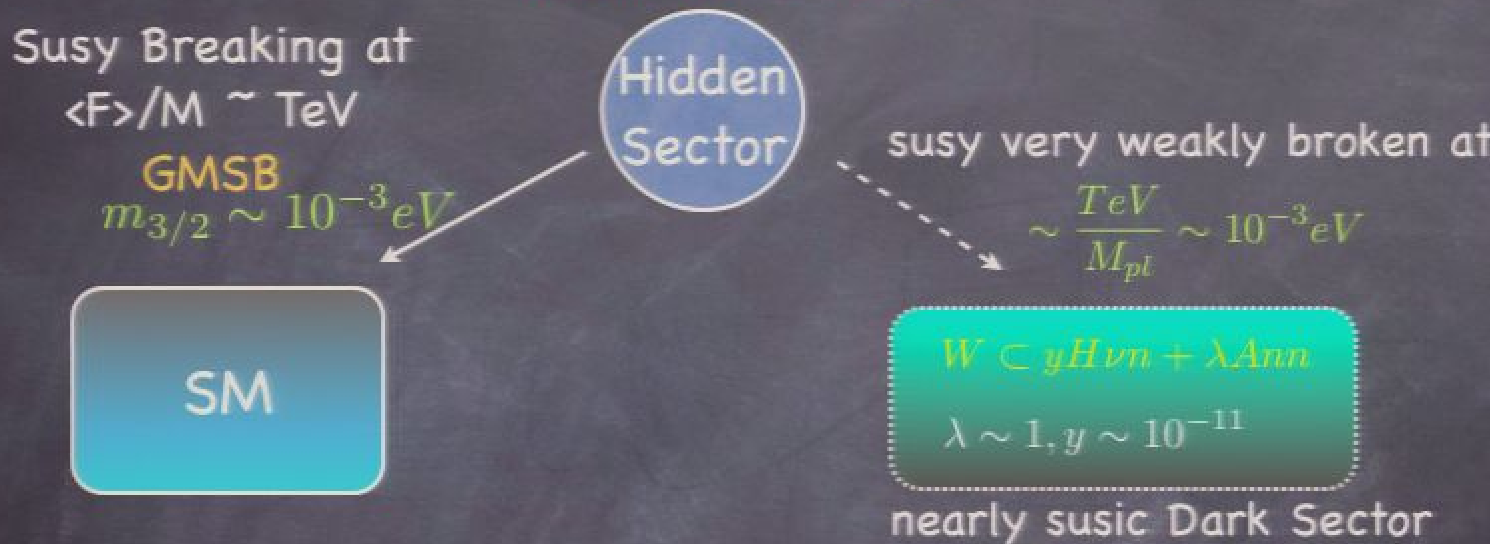

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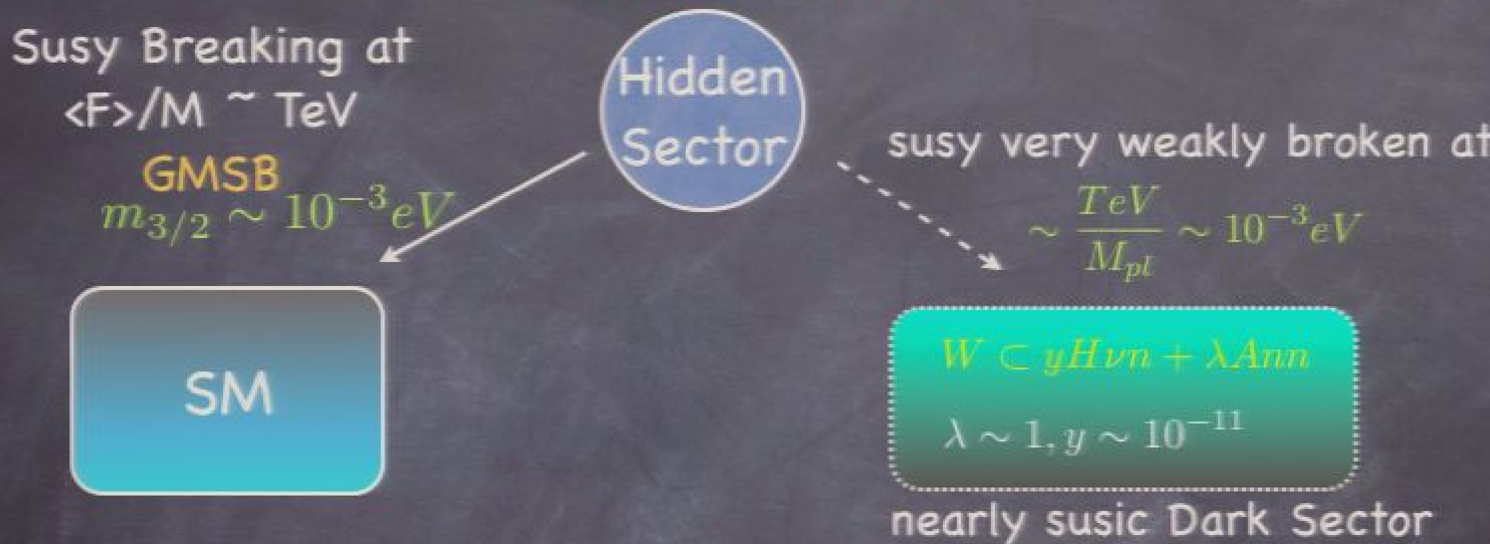

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- Fine tune vacuum energy to zero
- Add contribution of finite neutrino density $\rho_\nu \frac{m_D^2}{\lambda A}$

History repeats !!

Hybrid potential of A and $\tilde{n}$

$$V \subset |\lambda\tilde{n}^2 - \lambda\mu^2|^2 + 4\lambda^2 |A\tilde{n}|^2 + \rho_\nu(\frac{m_D^2}{\lambda A}) + \mathcal{M}^2 |A|^2$$

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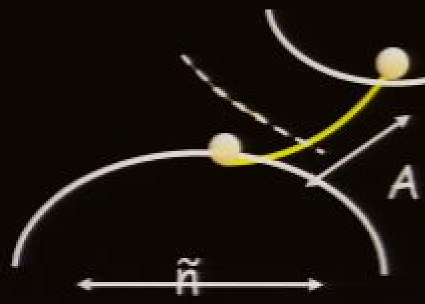

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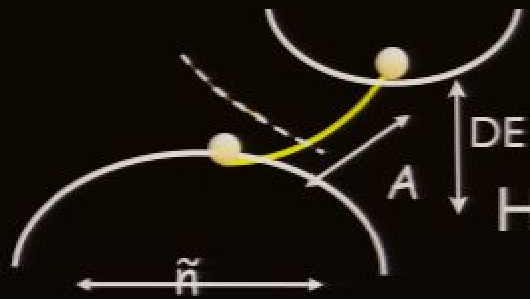

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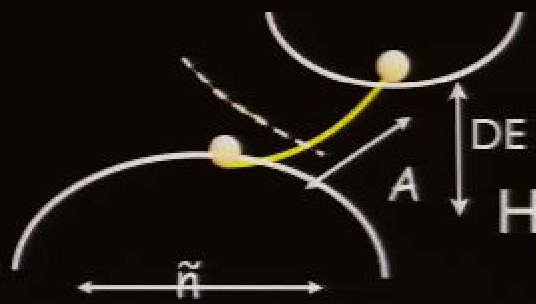
- A -> Slow-rolling field due to evolving neutrino density



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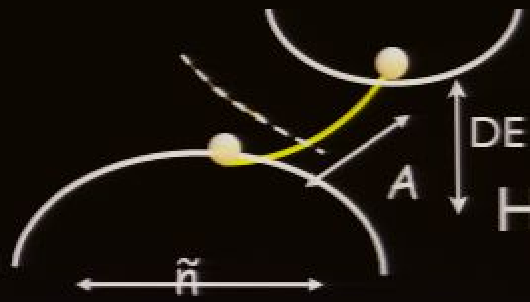

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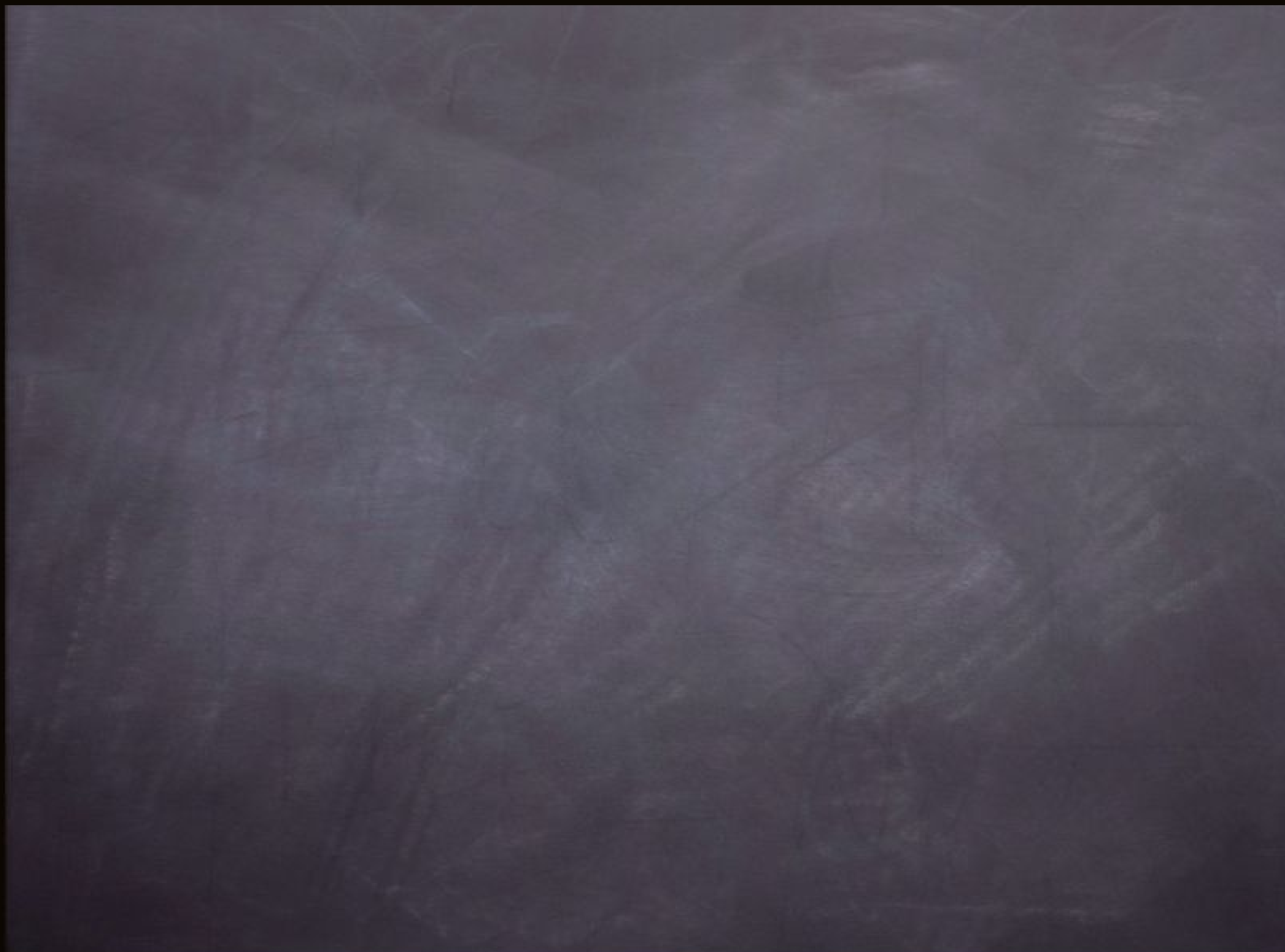
- Non vanishing energy behaves as DE $\sim \lambda^2\mu^4 \sim \frac{m_D^4}{\lambda^2}$

with w ~ -1



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- Now minimizing effective V and requiring $\lambda A \geq m_D$

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This is good ..

- Neutrino nuggets form unless $\frac{m_D}{T} \leq 7$

  So , in MaVaN susy lightest neutrino will not clump.

New physics @ TeV ?

- ☆ Relevant parameter m_H^2 sensitive to high scale unless new TeV physics cuts of quantum correction.
- ☆ Else fine tuning
- ☆ Or anthropic selection

New physics @ meV ?

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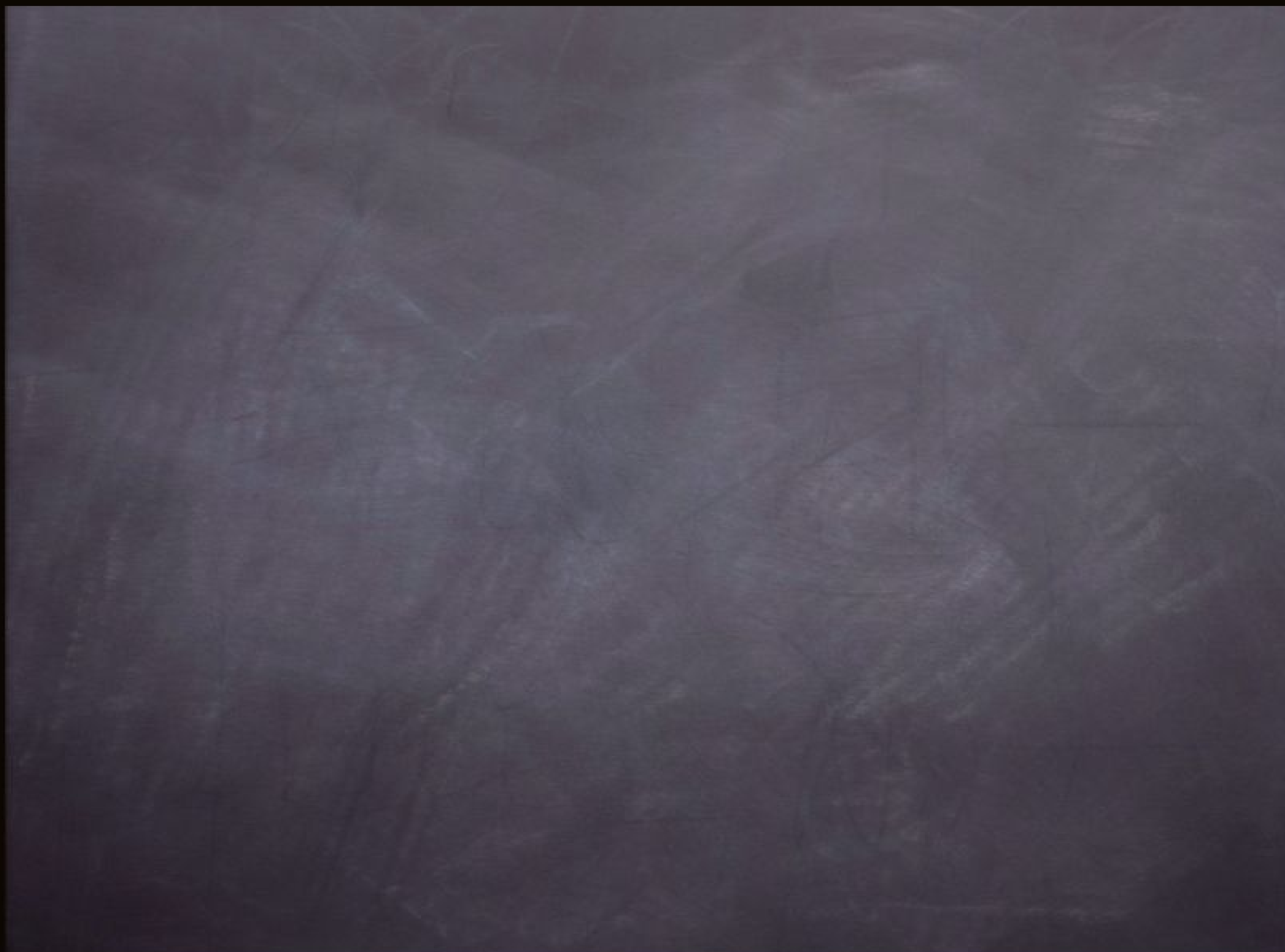
Neutrino itself not DM .
free streaming



Unified Dark Matter , Dark Energy

...... A general consideration

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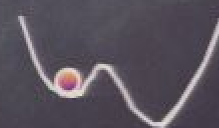
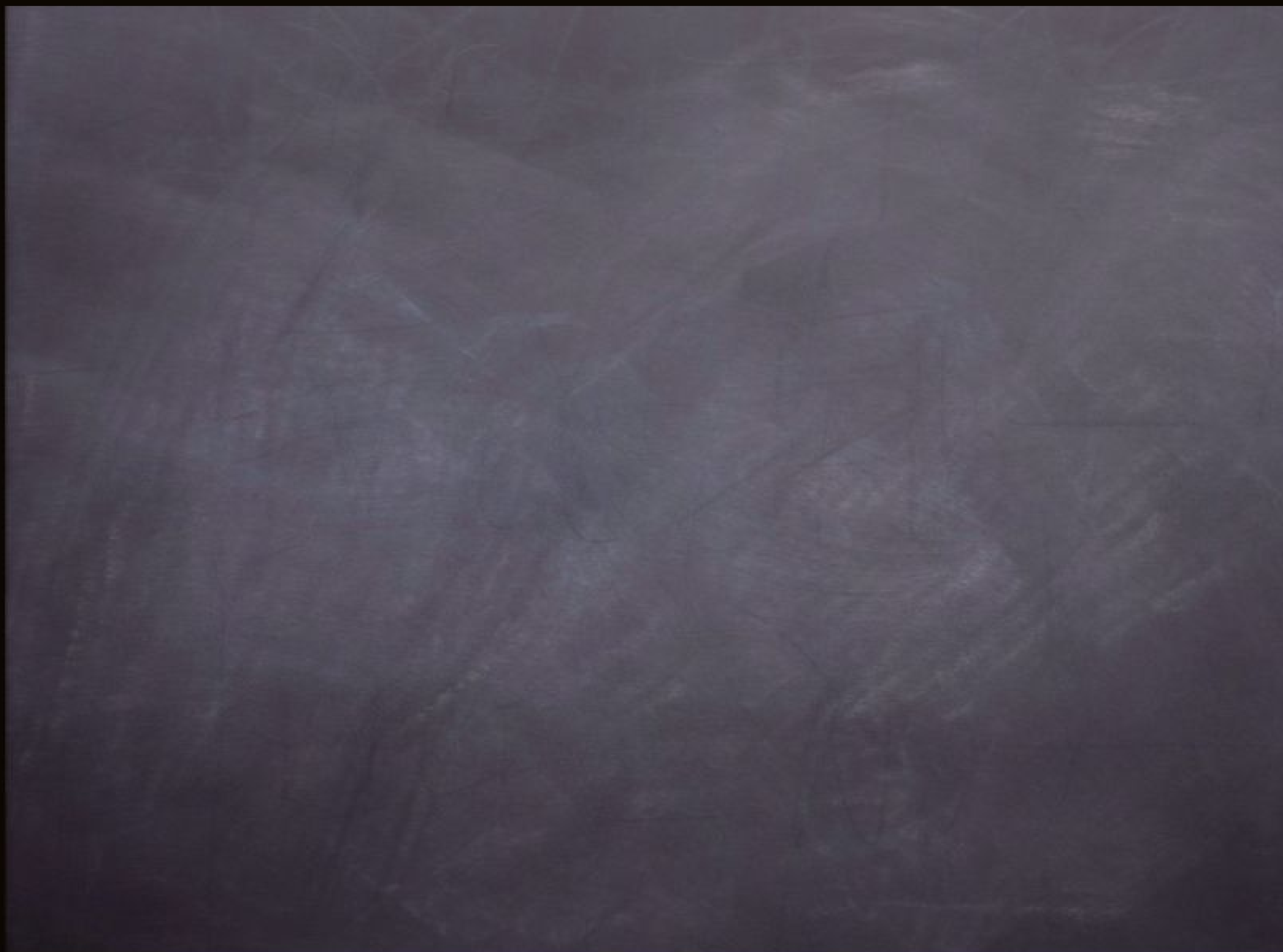
- after $T = \sqrt{\frac{\lambda m^2 + 2\epsilon^2}{2D\lambda}}$, new minima appears 

- @ $T_{tach} = \frac{m}{\sqrt{2D}}$, begins to oscillate around true minima

(which behaves as DM $E \sim O(\epsilon^4/\lambda^3)$ **)**



Good News:

DM candidate arises naturally in Hybrid Model !

Late Forming Dark Matter in the theories of neutrino dark energy (SD, N. Weiner , astro-ph/0611353)

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Exciting possibility : for multiple neutrinos -> multiple hybrid models.

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Exciting possibility : for multiple neutrinos -> multiple hybrid models.

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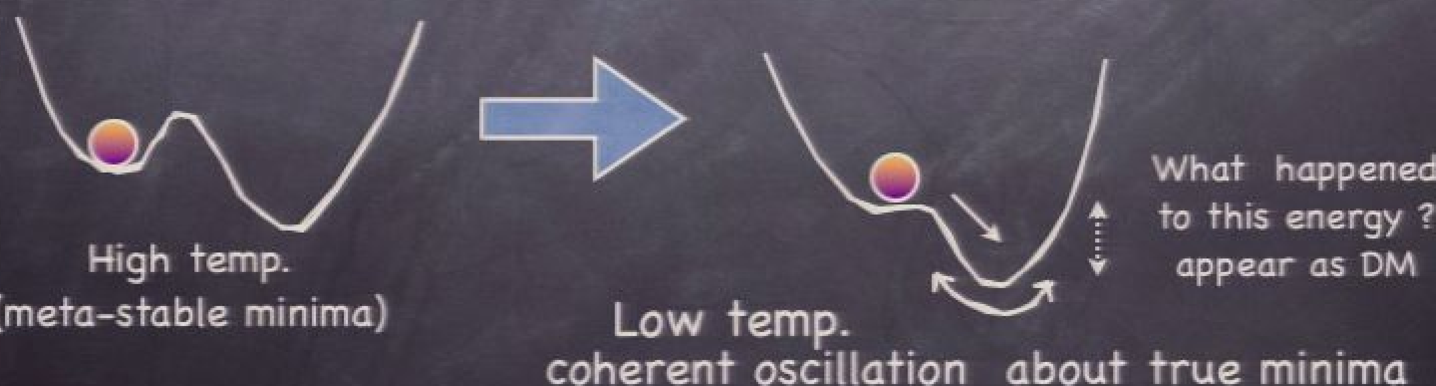

logical signature on matter power spectra

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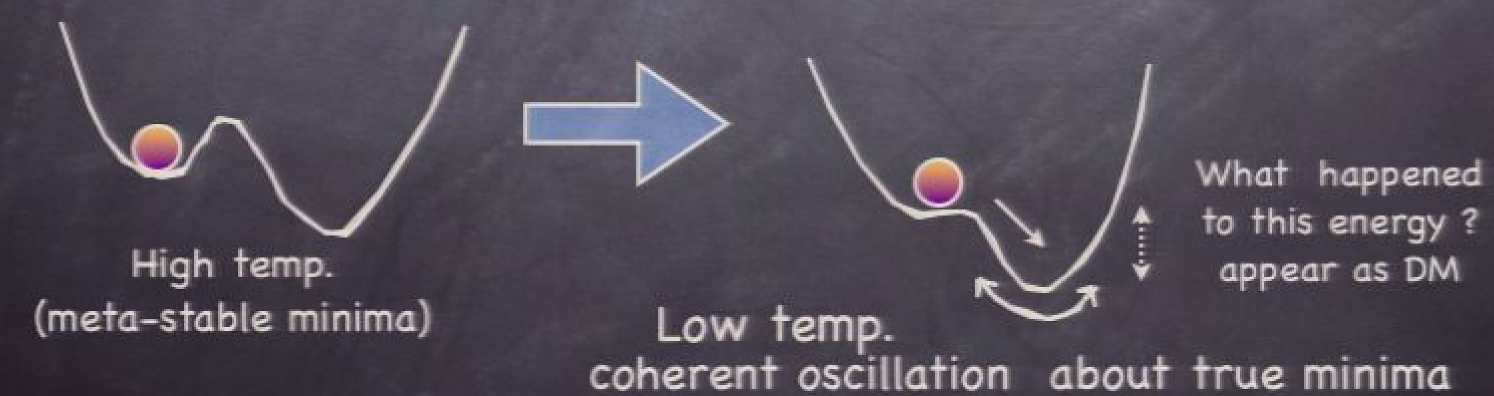
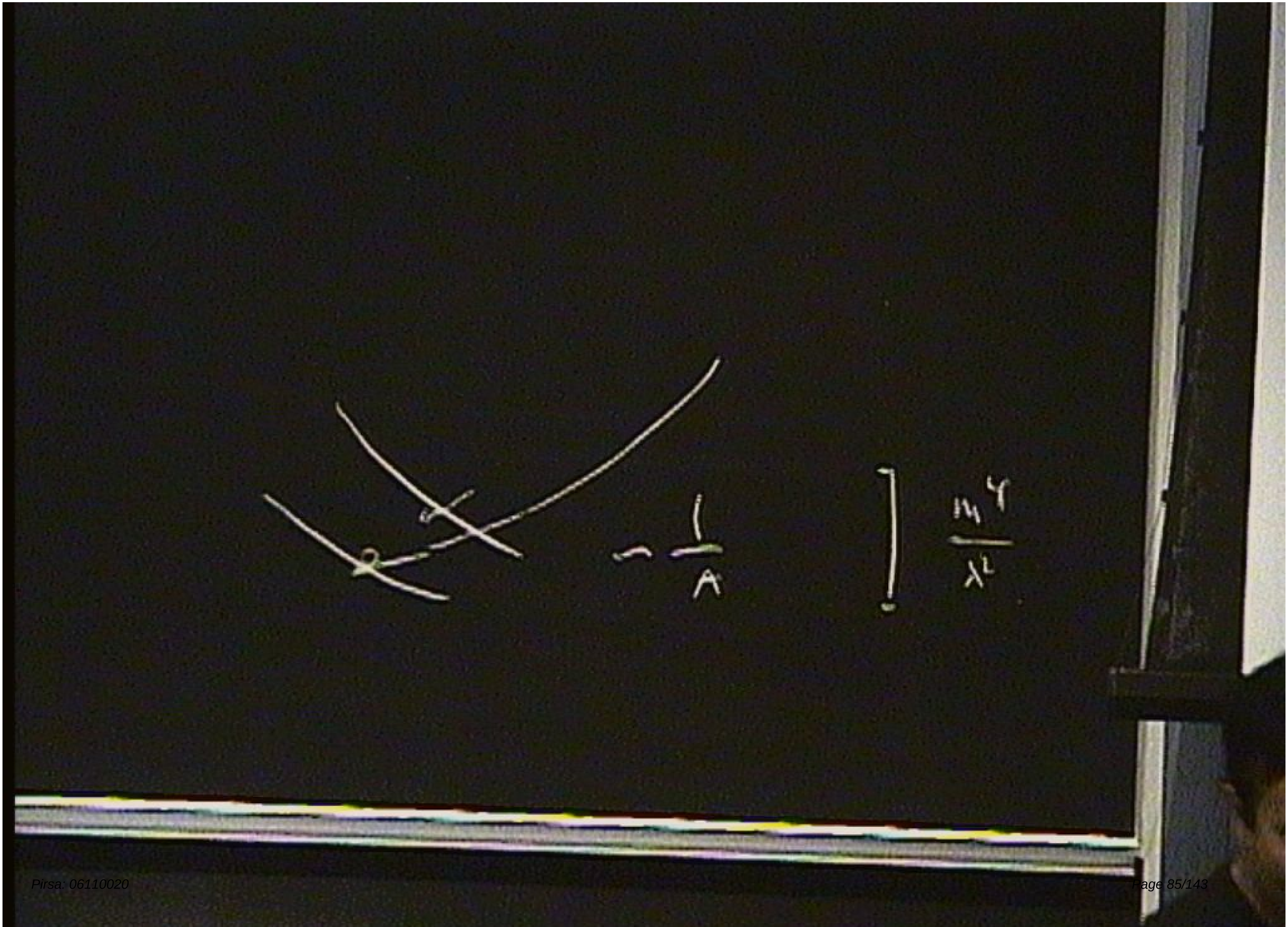
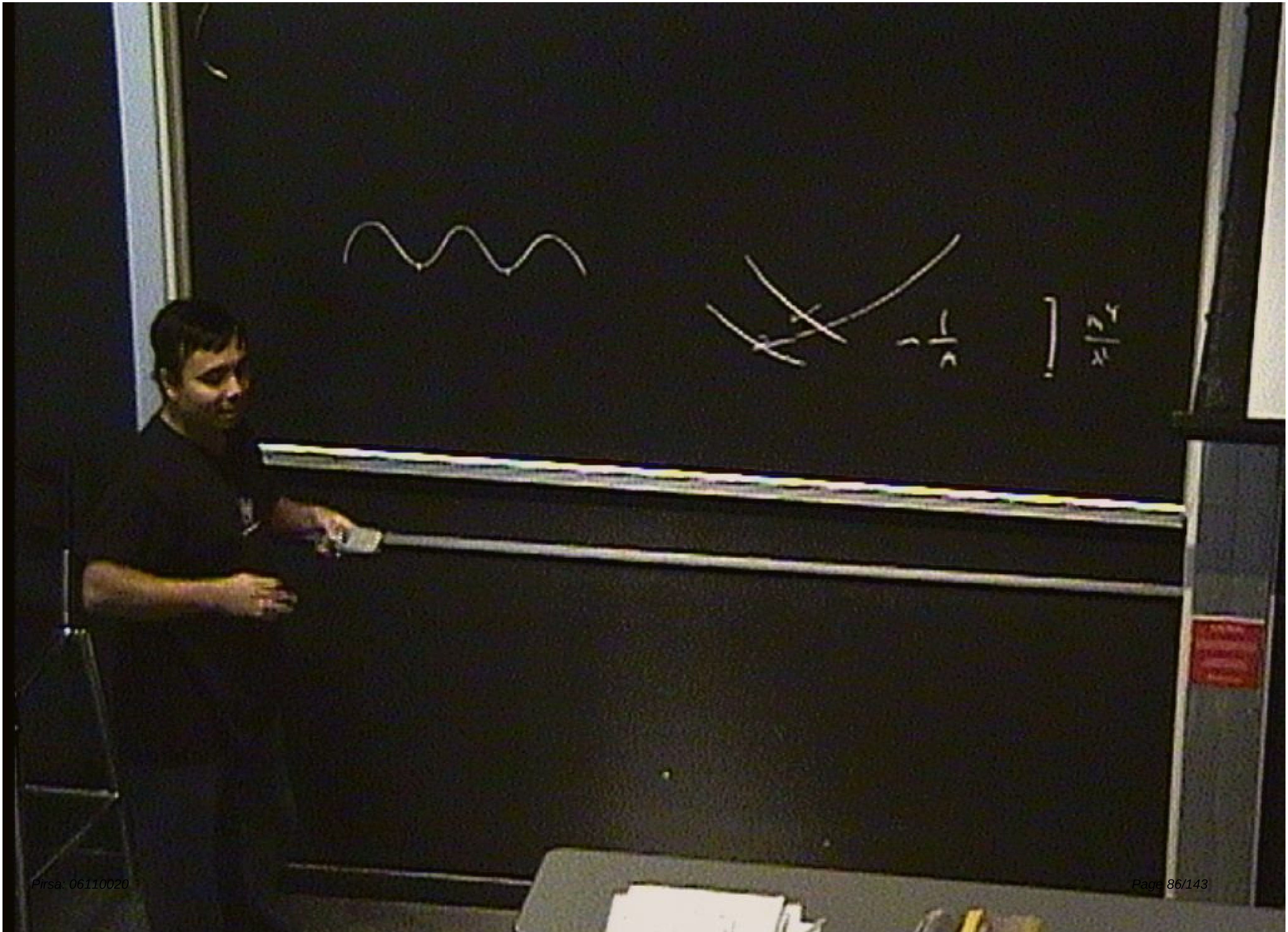
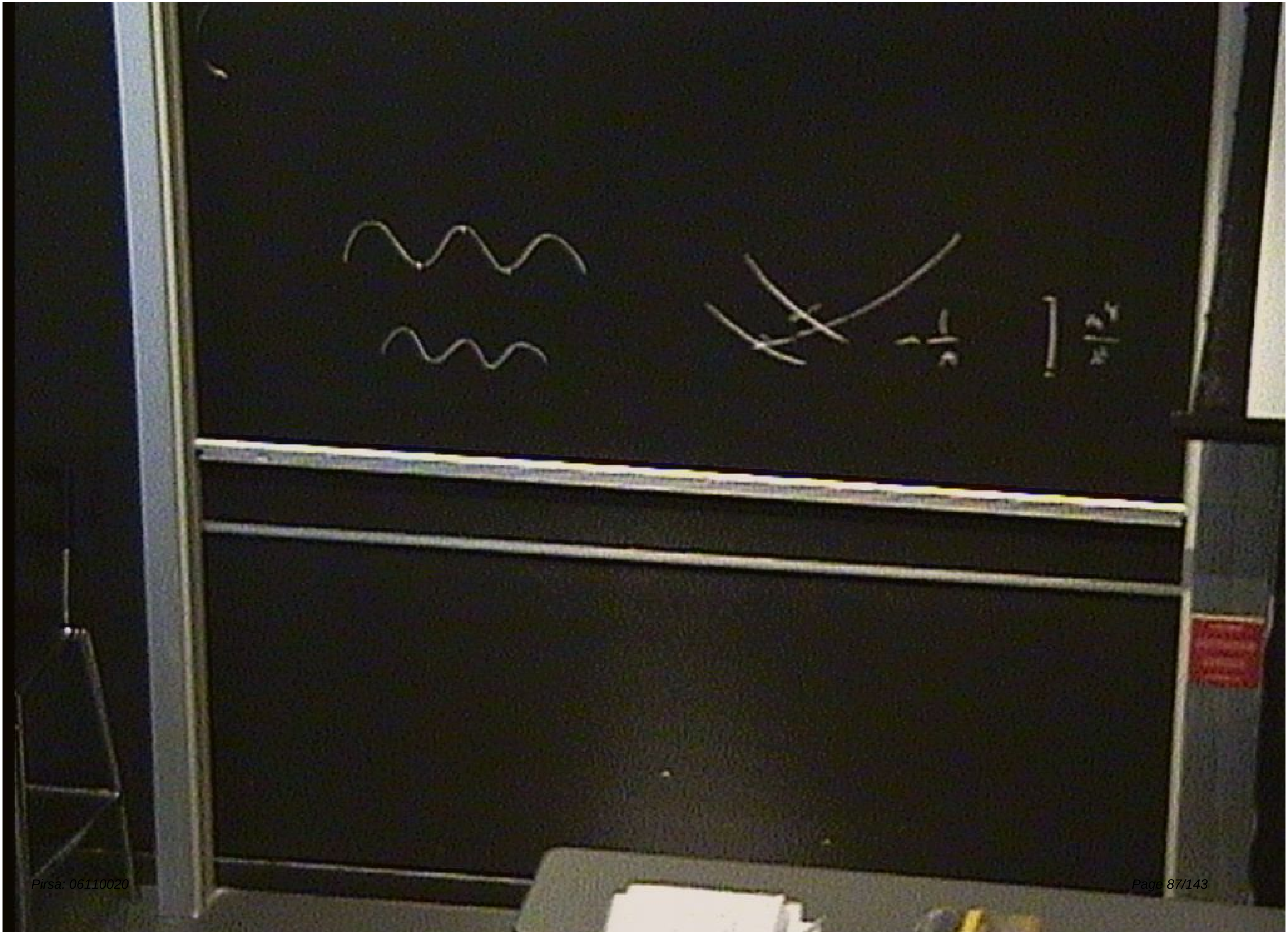


★ *Strong cosmological signature on matter power spectra*

Late Forming Dark Matter (Cont...)


~ 1/A
m^4/λ^2





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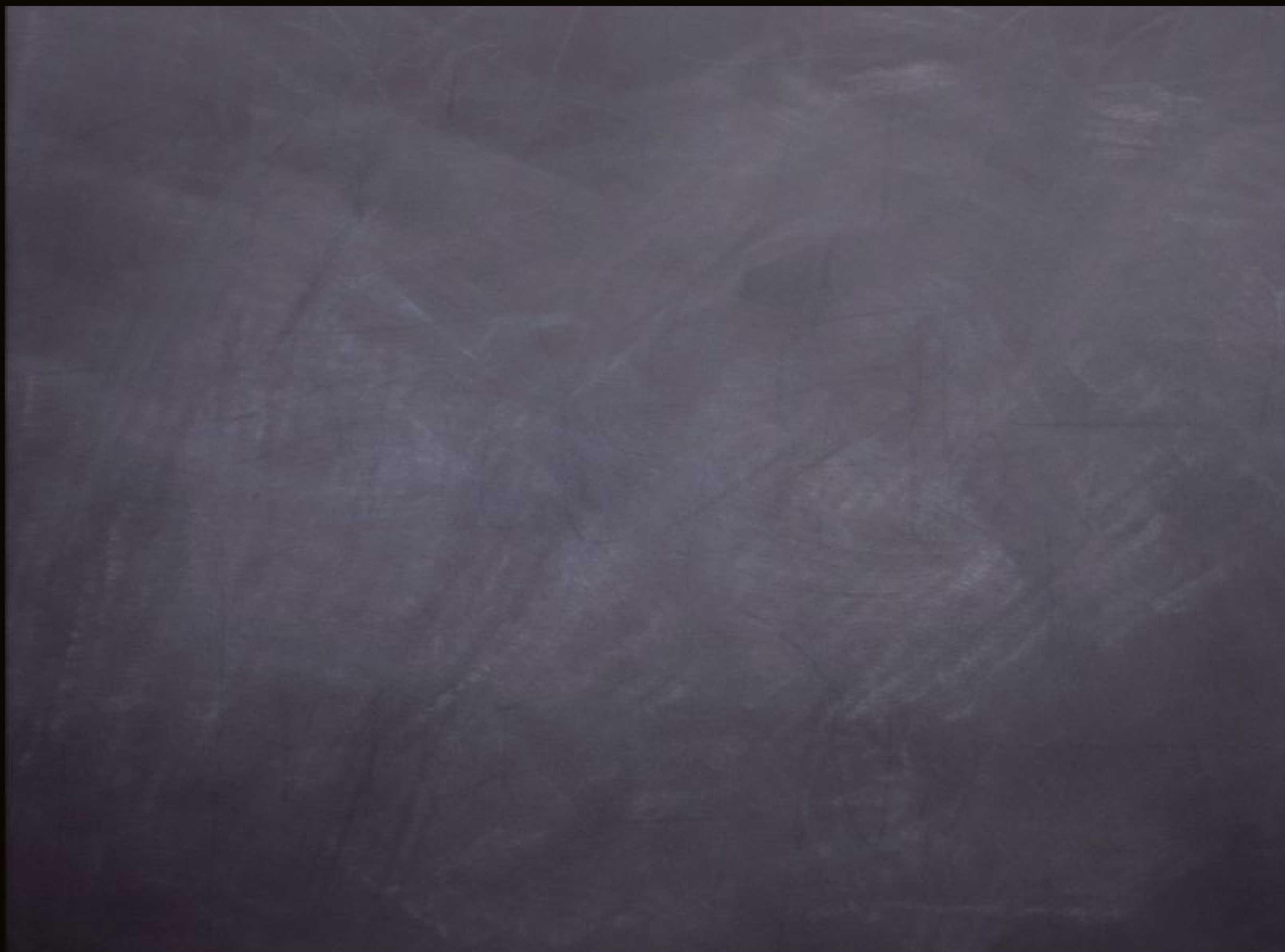
- From this point LFDM power will grow just like CDM



Calculation of Power Spectra

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may have been free-streaming
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$$L[f] = \frac{Df}{D\tau} = C[f]$$

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$$\dot{F}_{\nu l} = \frac{k}{2l+1}[(l+1)F_{\nu(l+1)} - lF_{\nu(l-1)}],\ l \geq 2$$

$$\Rightarrow \quad \ddot{\delta}_\nu = -\frac{1}{3}k^2\delta_\nu - \frac{4}{3}k^2\phi + 4\ddot{\psi} - \frac{4}{3}k^2\sigma_\nu$$

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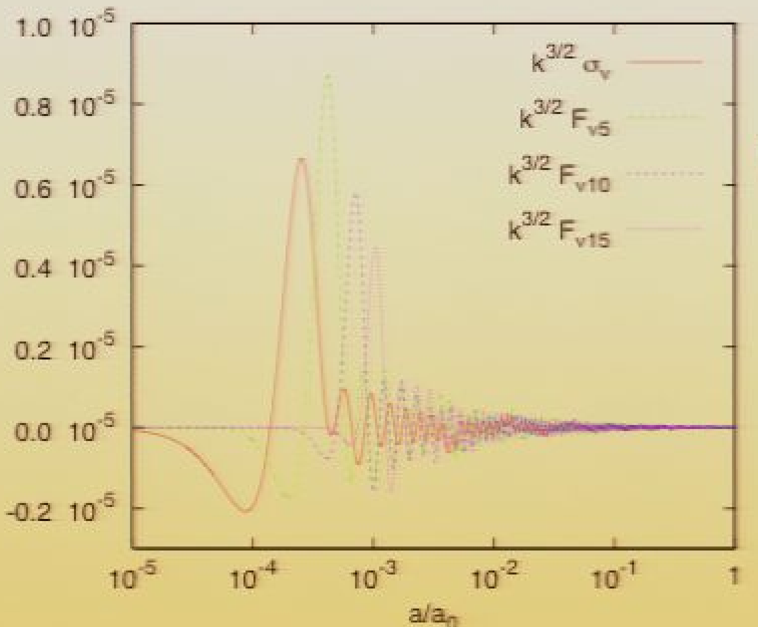
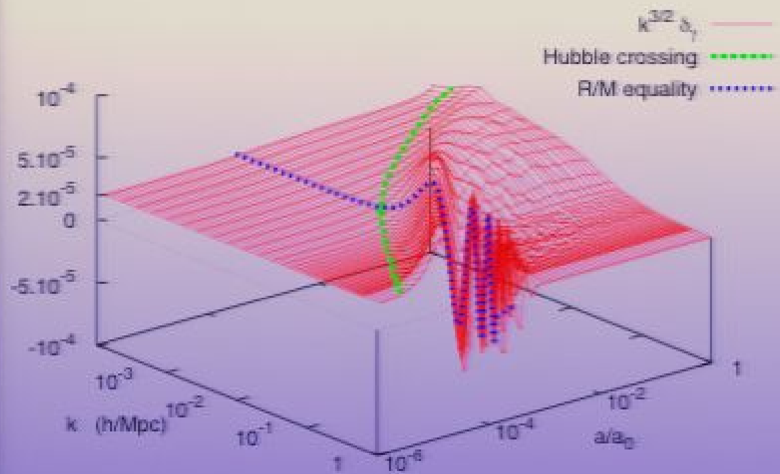
(very close to photon equation in absence of shear)

In general for neutrino shear becomes important inside Hubble length and couples the equation to whole multipole hierarchy , is damped and power is transferred to higher multipoles.



When averaged , highly damped

For interacting neutrino tightly coupled approximation holds , Only keep the first two moments, system behaves very similar to photon.


$k^{3/2}\,\delta_\gamma$
Hubble crossing
R/M equality
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1
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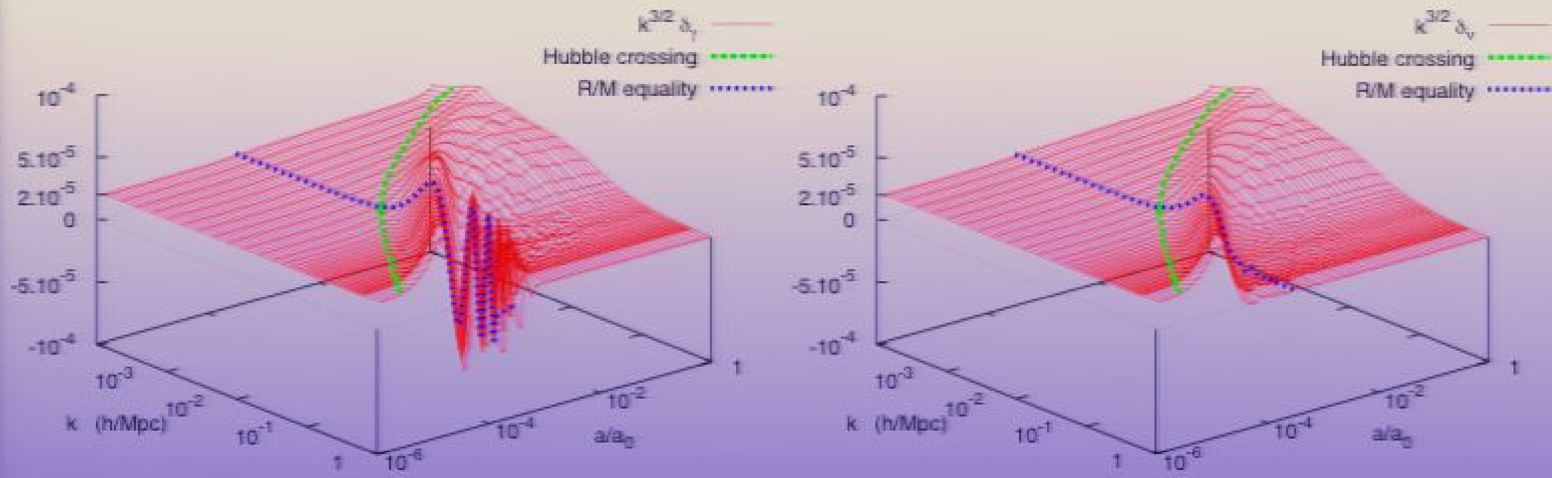
10^{-6}
10^{-4}
10^{-2}
1
a/a_0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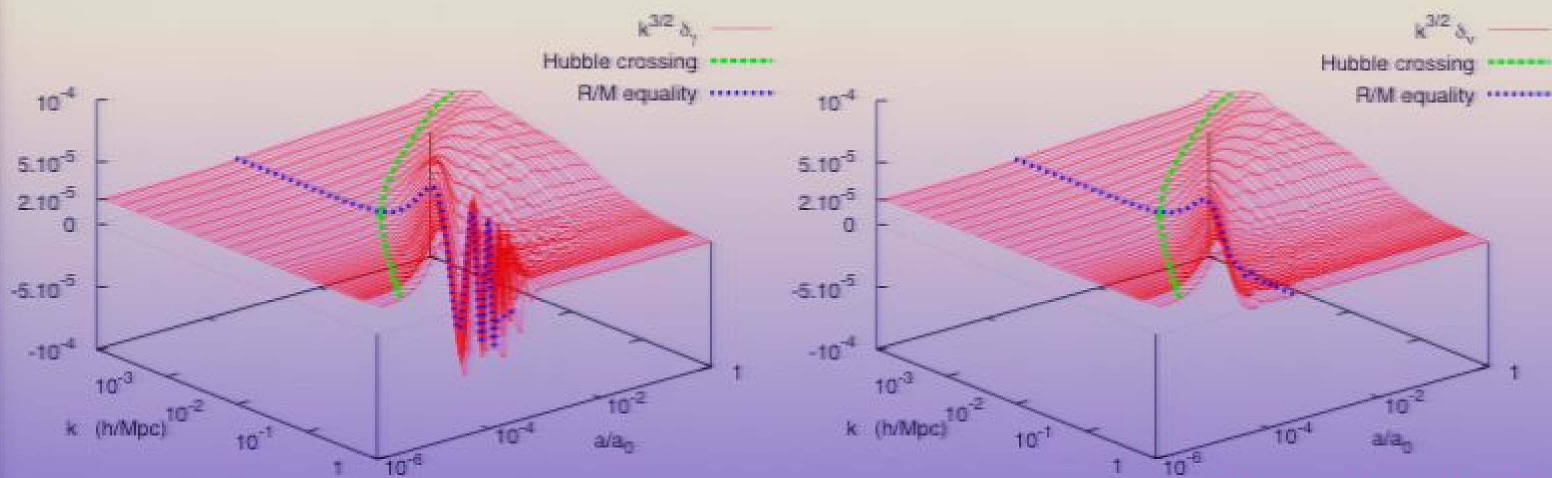

$$\dot{\delta} = -(1+w)\left(\theta + \frac{\dot{h}}{2}\right) - 3\frac{\dot{a}}{a}\left(\frac{\delta P}{\delta \rho} - w\right)\delta$$

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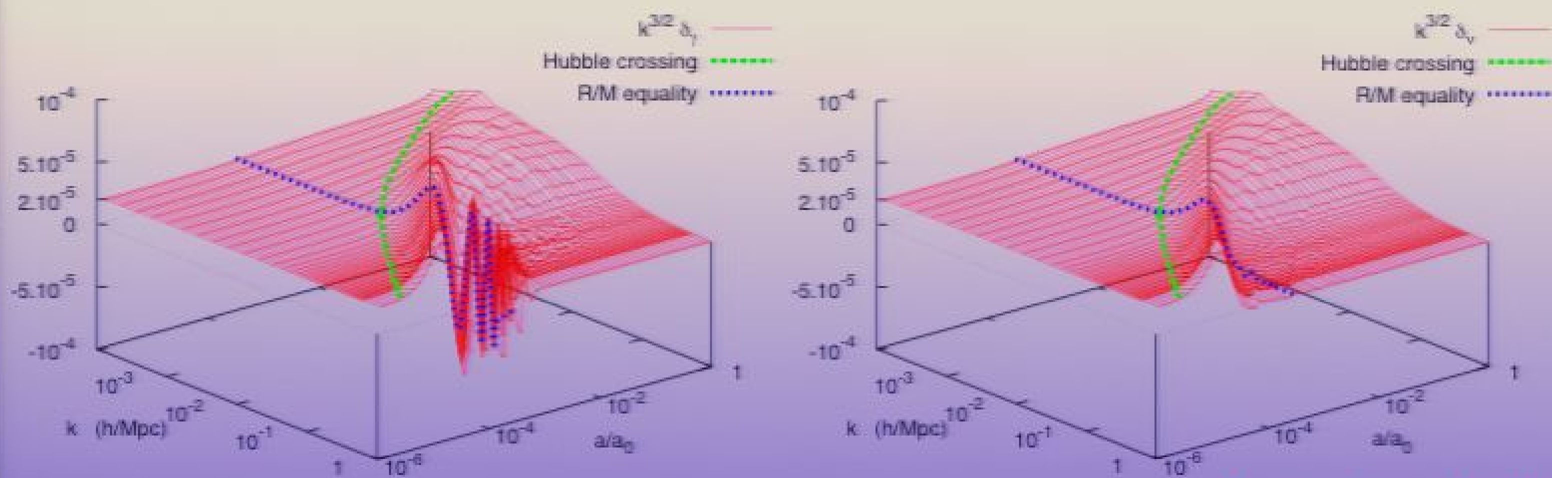
As strongly coupled fluid
: interactions like ..



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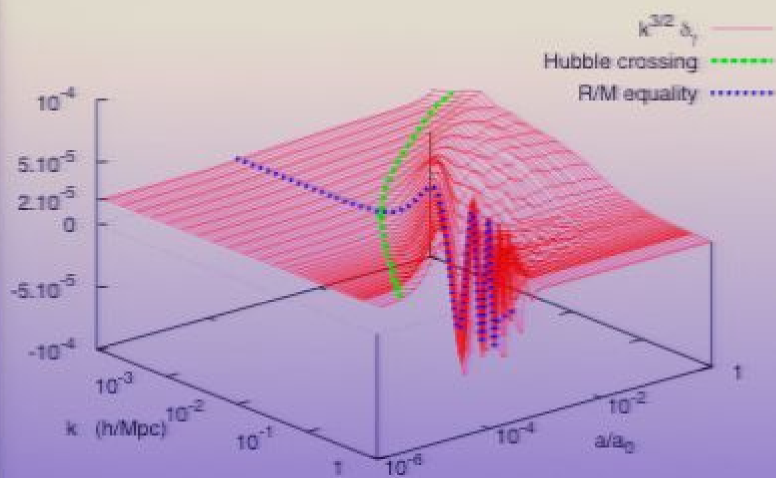

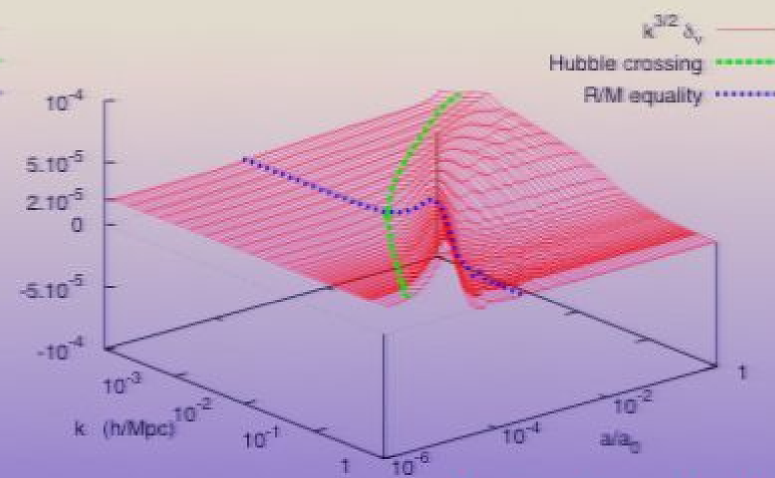

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CDM P(k) gives snapshot of universe @ z_{tach}

Power Spectra of LFDM

Modify CAMB /CMBFAST to get power at z_{tach}

Then prepared a separate code to evolve until today.

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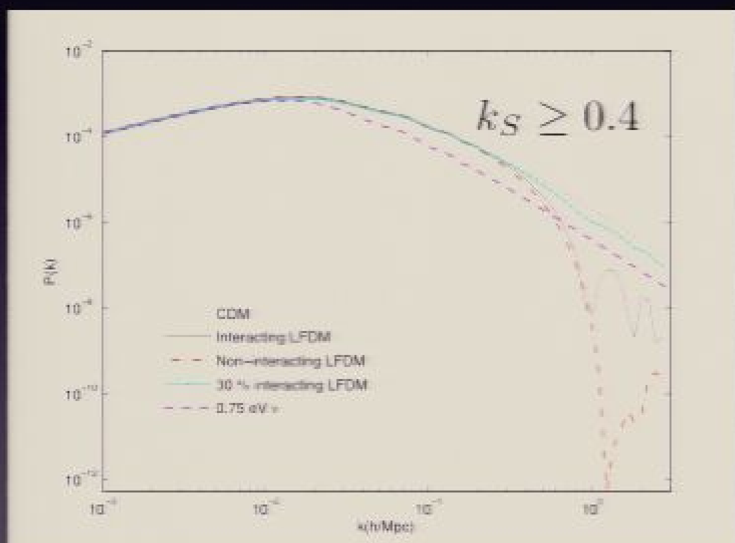

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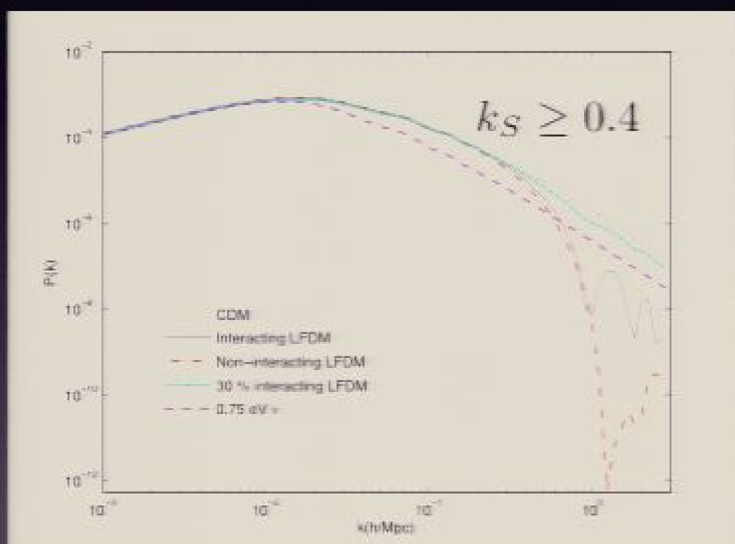

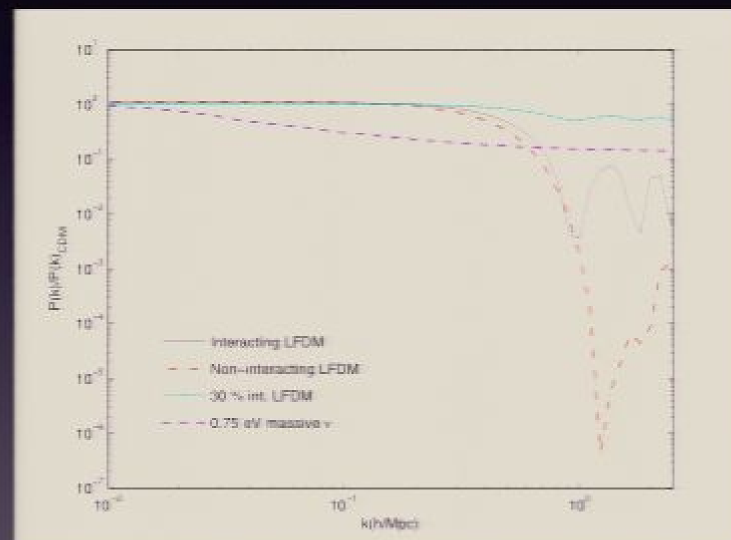

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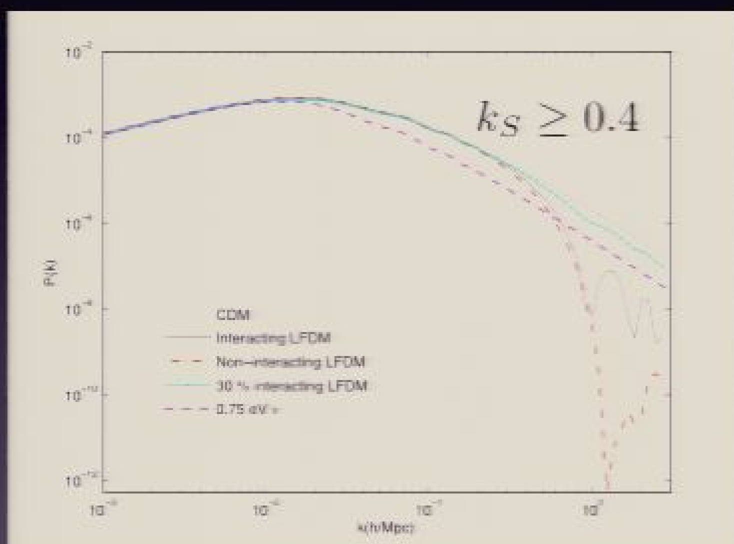

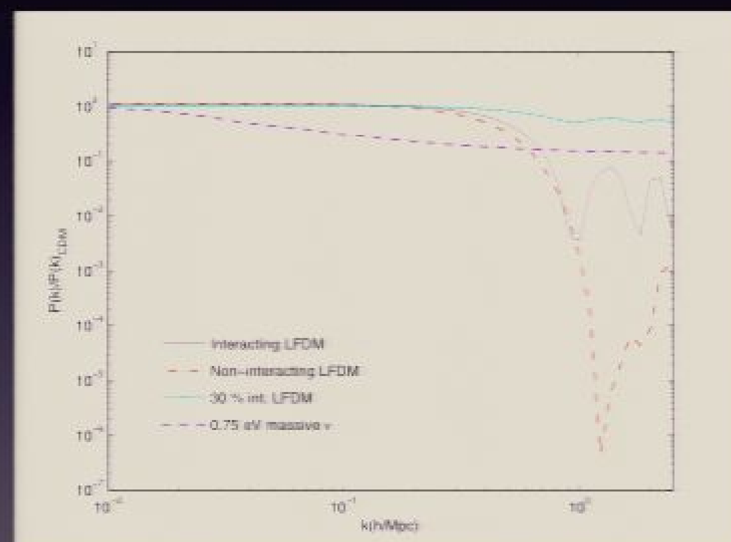

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In MaVaN Susy , estimate $10^{-3} \leq k_{tach} \leq 10^{2}$

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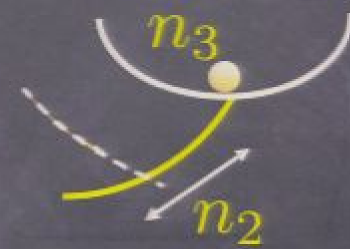

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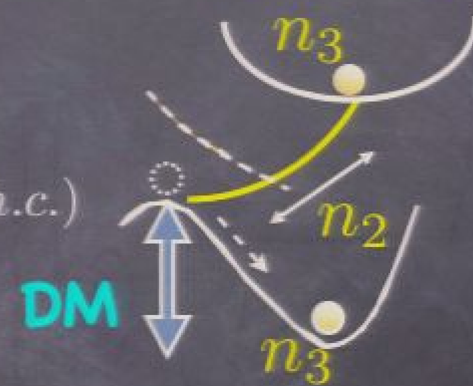

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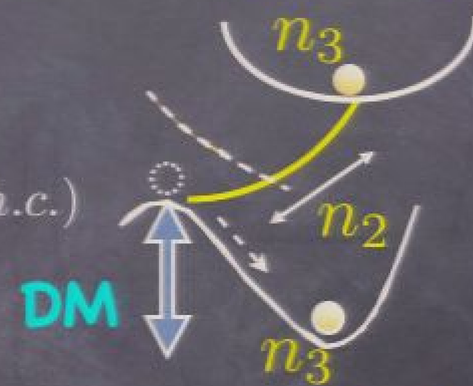

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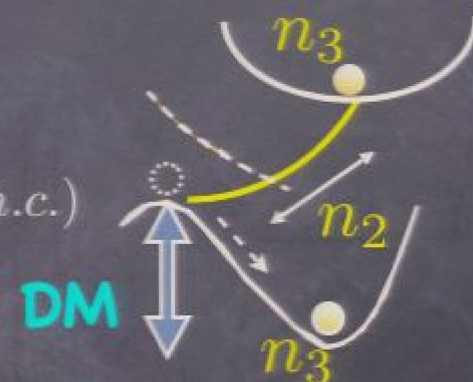

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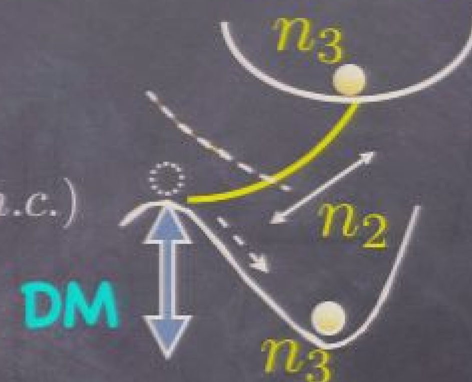

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Note: Non zero $< n_2 >$ also contributes positive mass of n_3

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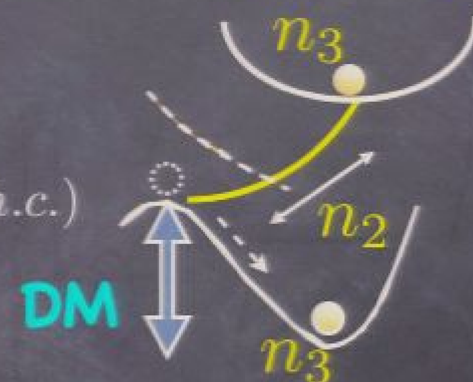

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- Varying neutrino mass parameter we get

$10^{-3} eV \leq T_{MRE} \leq 10^{7} eV$ and $10^{-1} \leq T_{MRE}/T_{DMDE} \leq 10^{13}$

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$$\rho_{LFDM} \sim 10^{-3} \tilde{a}_3^4 / \lambda^6$$

$$\rightarrow \quad T_{MRE} = 3\sqrt{3/2}\, \tilde{a}_3^4 m_3^6 / 64 \lambda^3 m_2^3 \tilde{m}_3^6$$

- Varying neutrino mass parameter we get

$10^{-3} eV \leq T_{MRE} \leq 10^7 eV$ and $10^{-1} \leq T_{MRE}/T_{DMDE} \leq 10^{13}$

✓ Now if this is the solution for coincidence

we can set λ by fixing T_{MRE}

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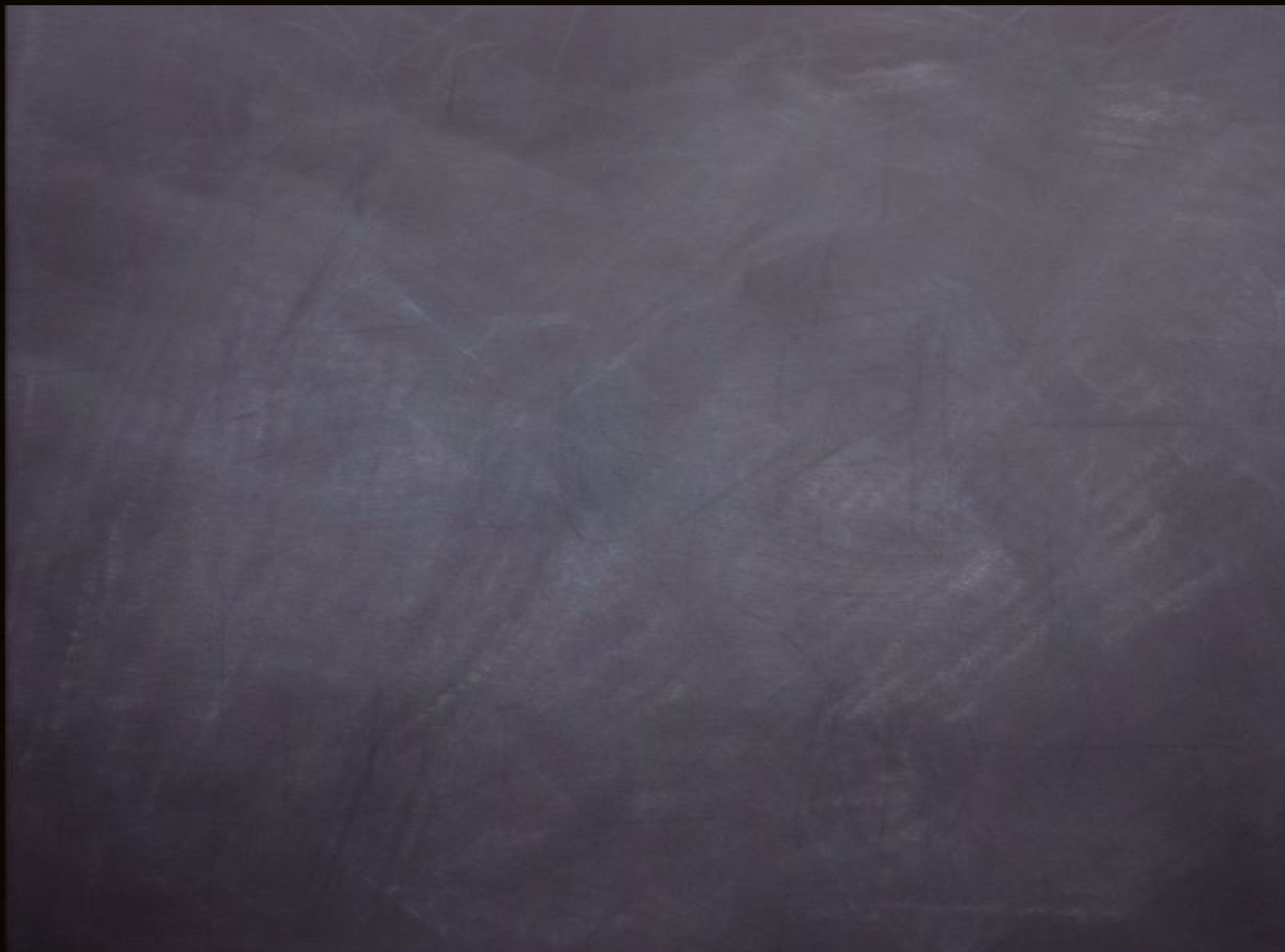
$1eV \leq T_{tach} \leq 10^3 eV$: *should see a sharp cut off in power spectra*

between $2\times 10^{-2}hMpc^{-1} \leq k_{tach} \leq 20hMpc^{-1}$



Summary

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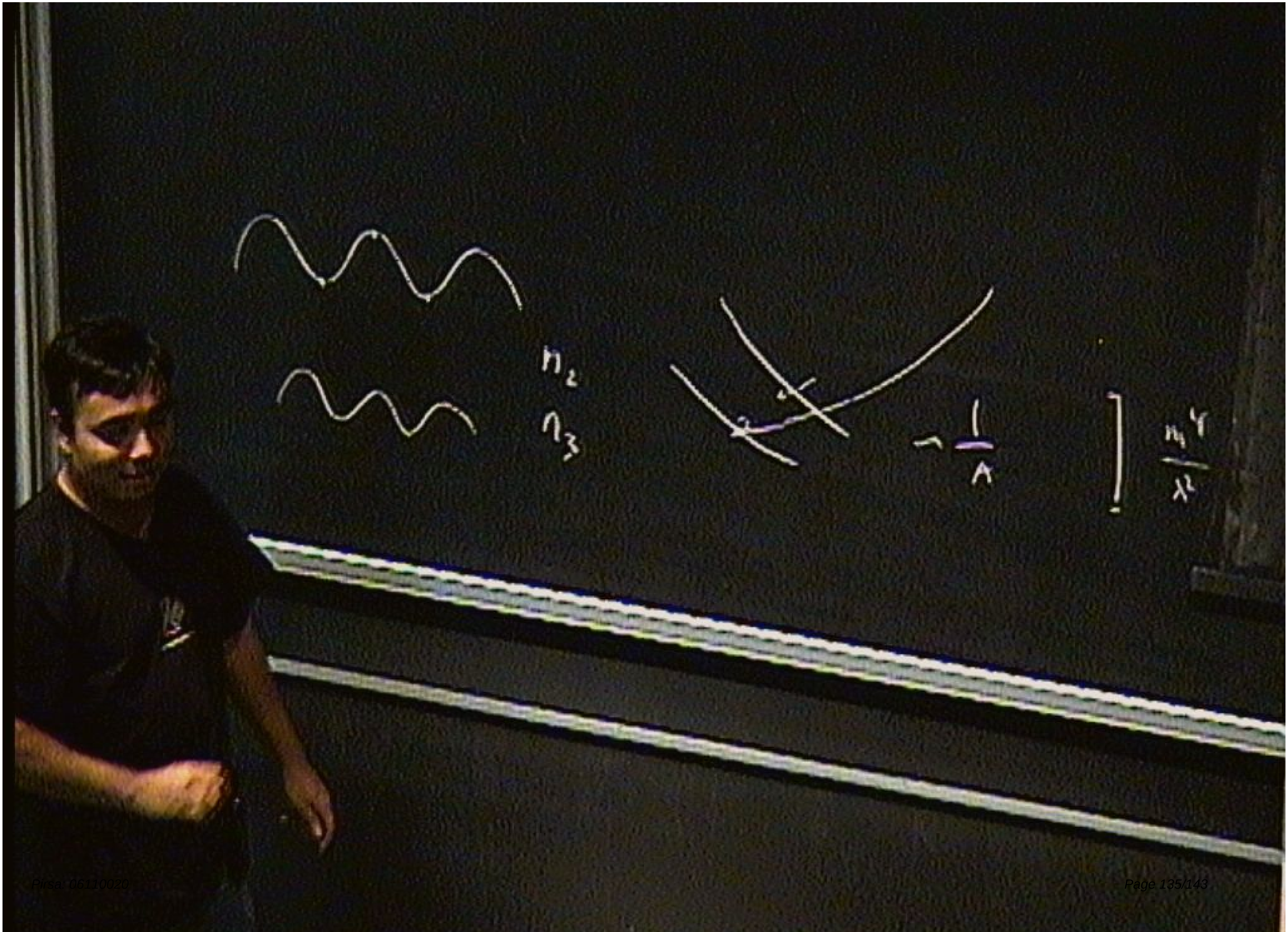
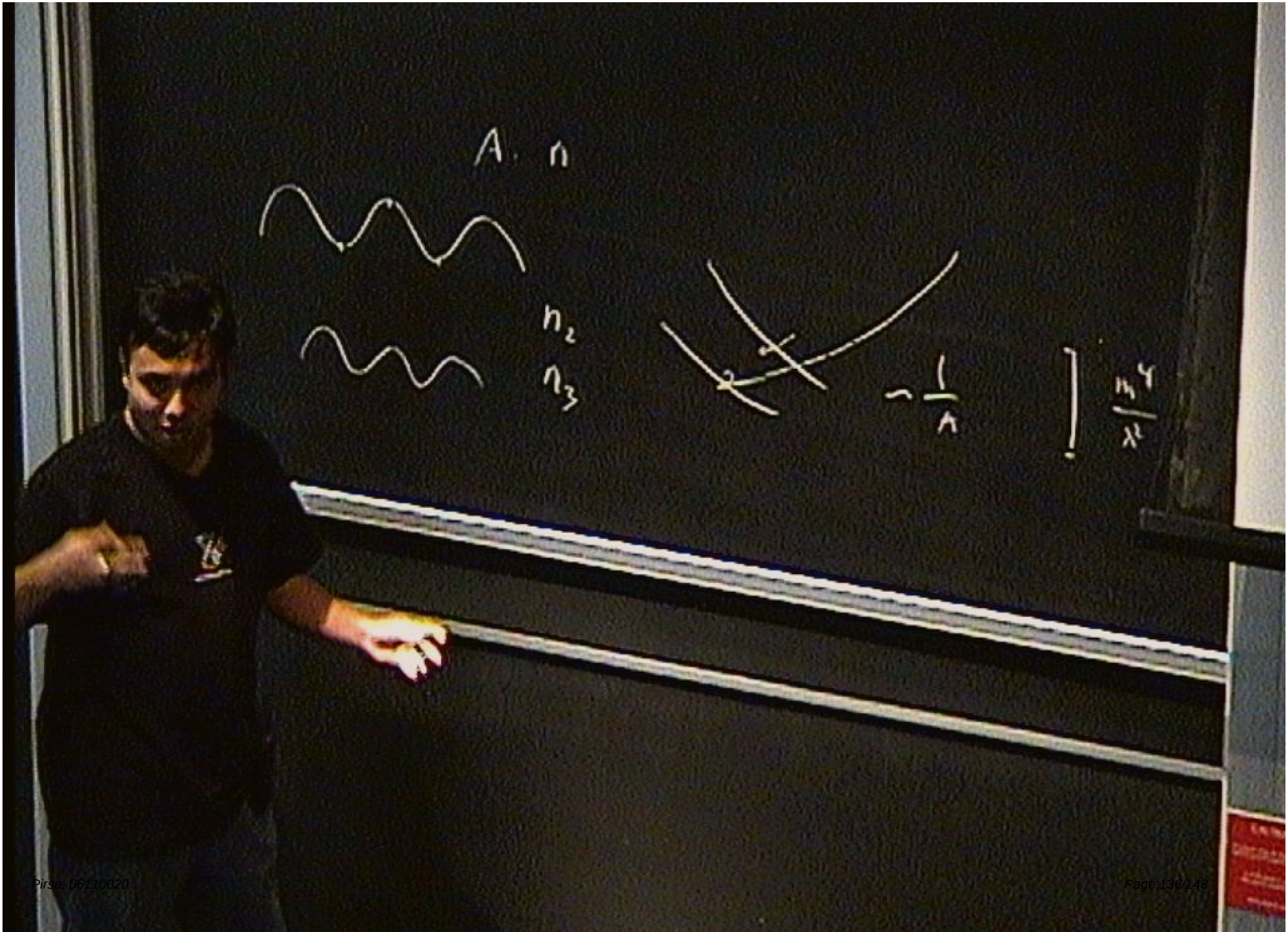
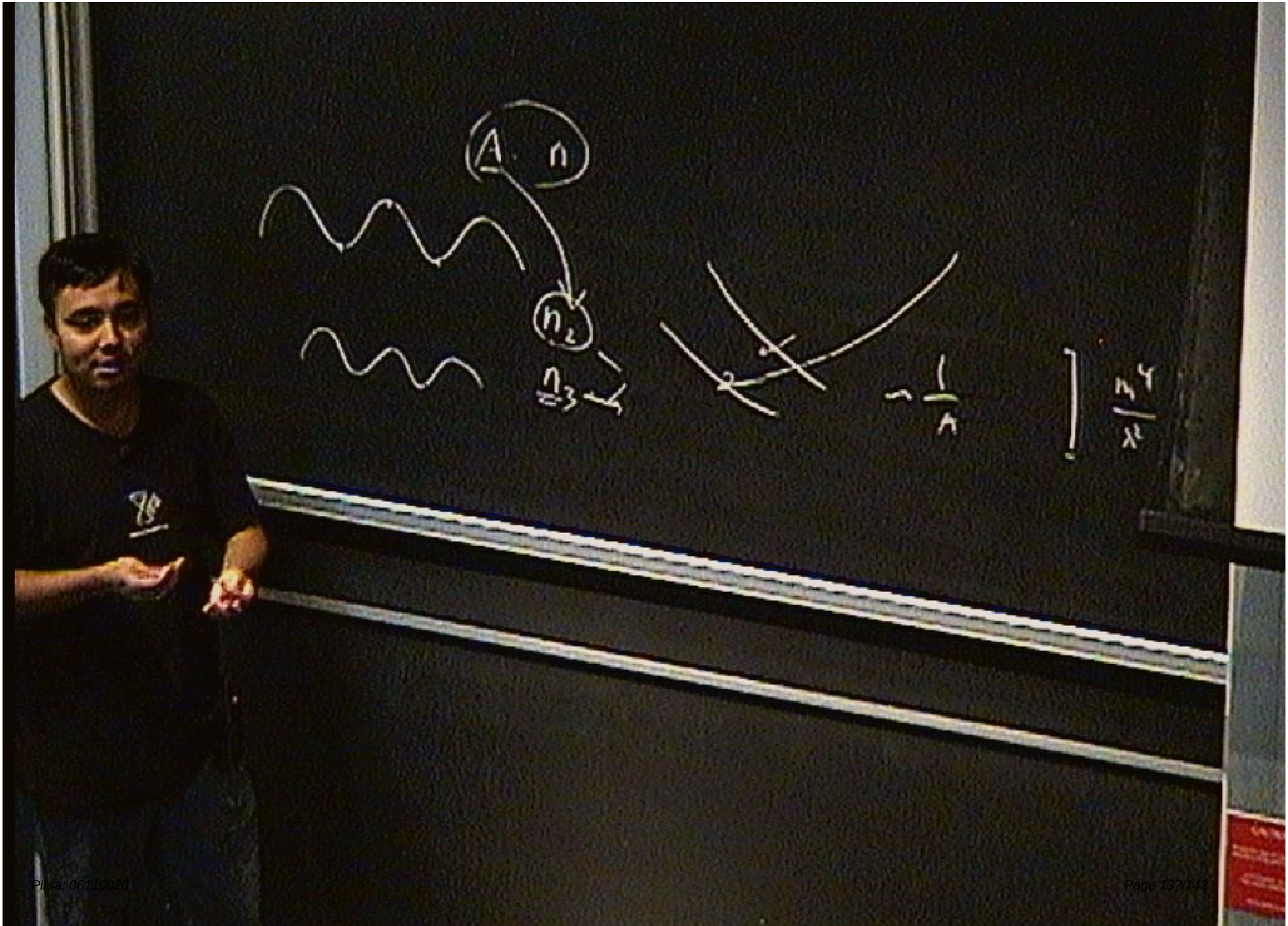
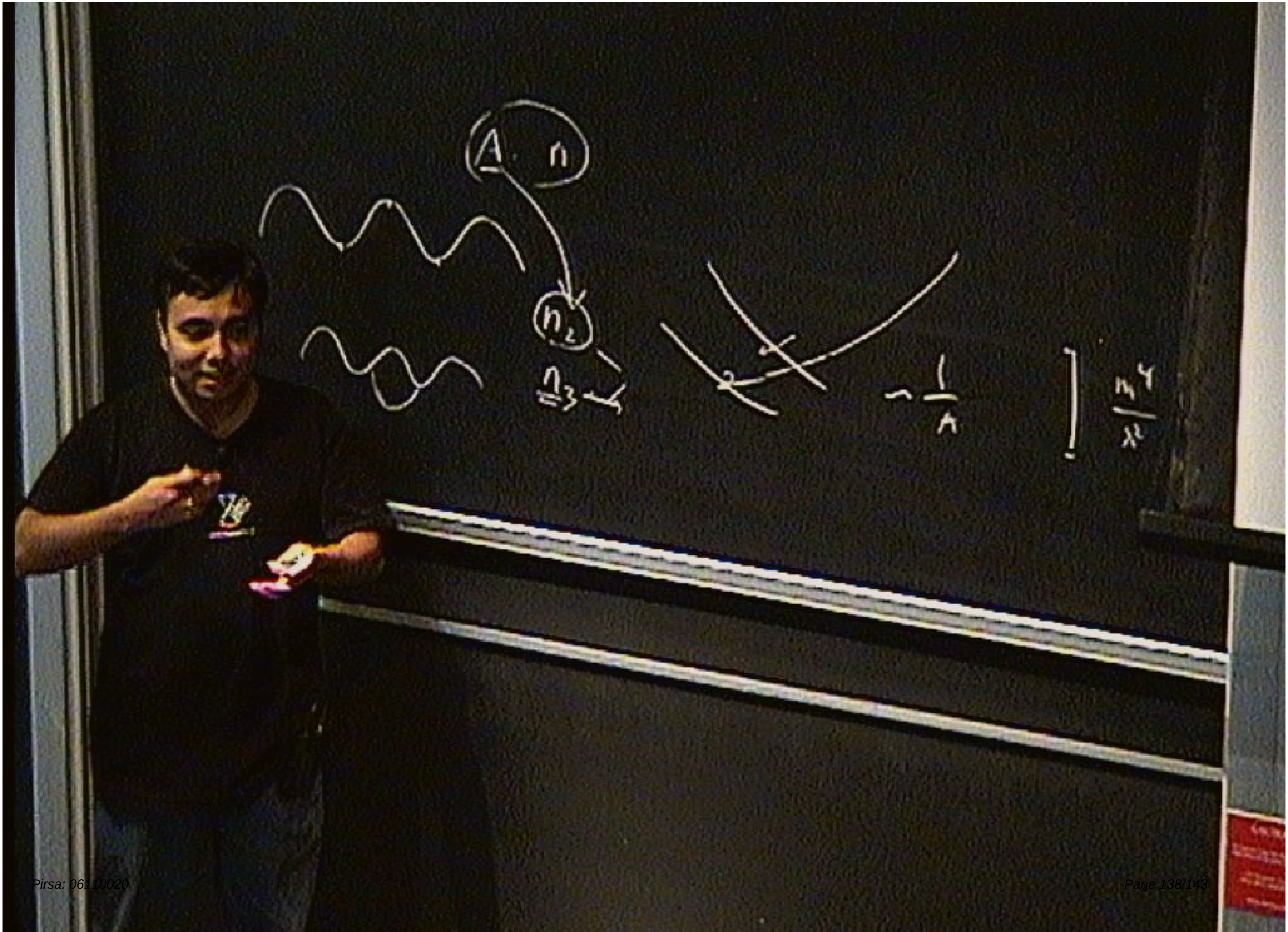
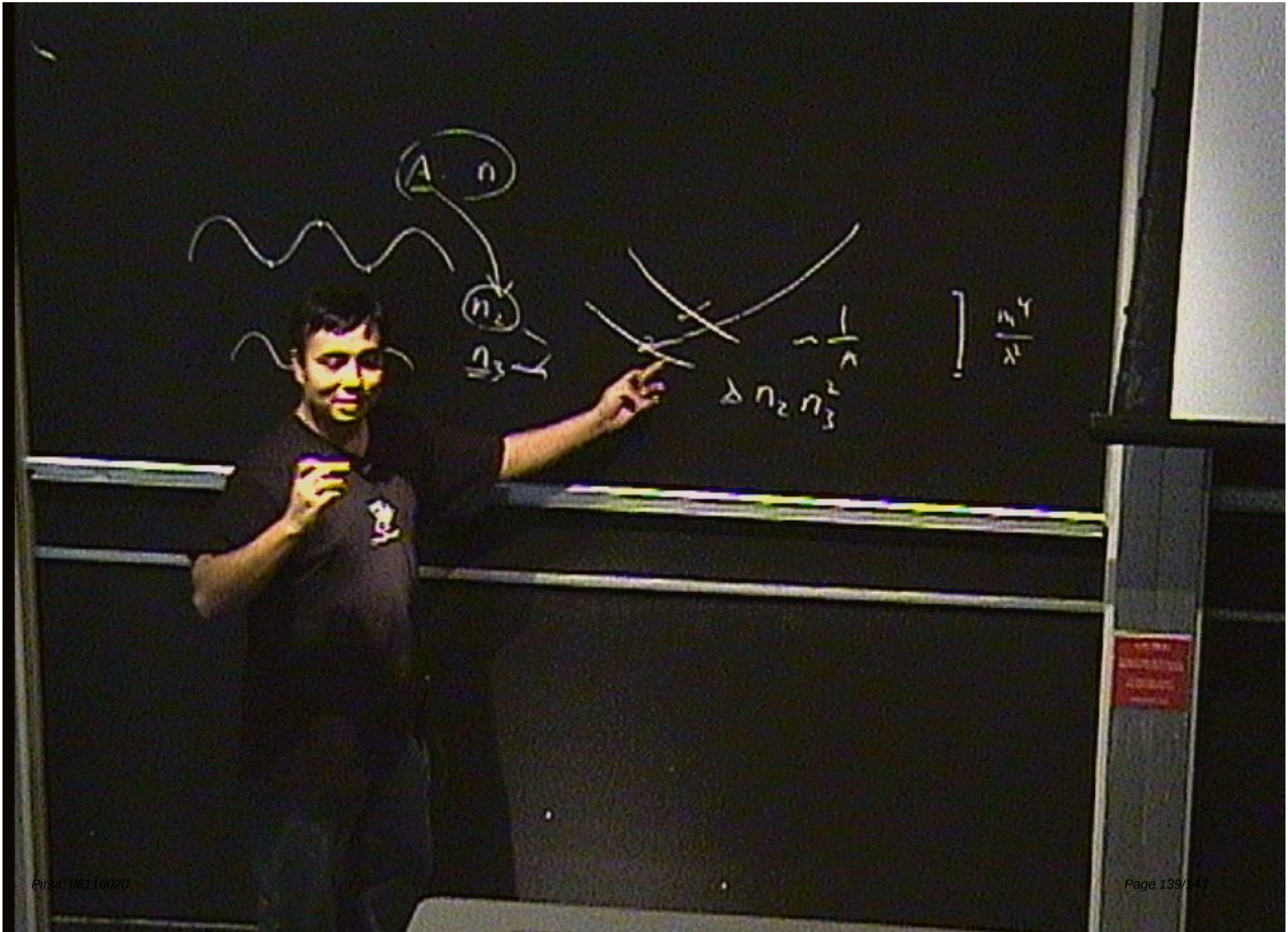
- Through SUSY MaVaN , both DE and late forming DM arise naturally.
- As neutrino mass connects both DE and DM, a great clue for coincidence.

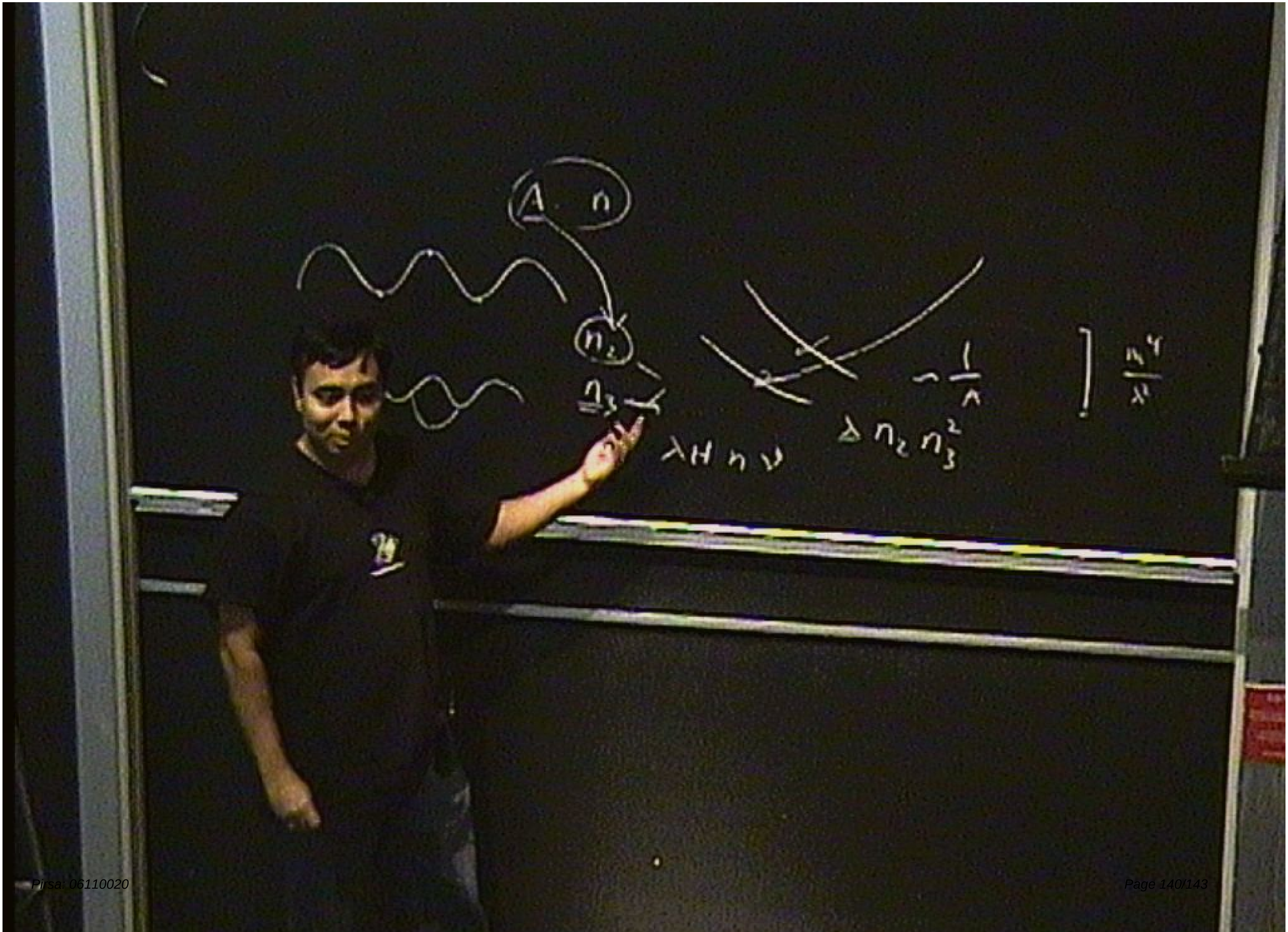

n2
n3


A. n
n2
n3

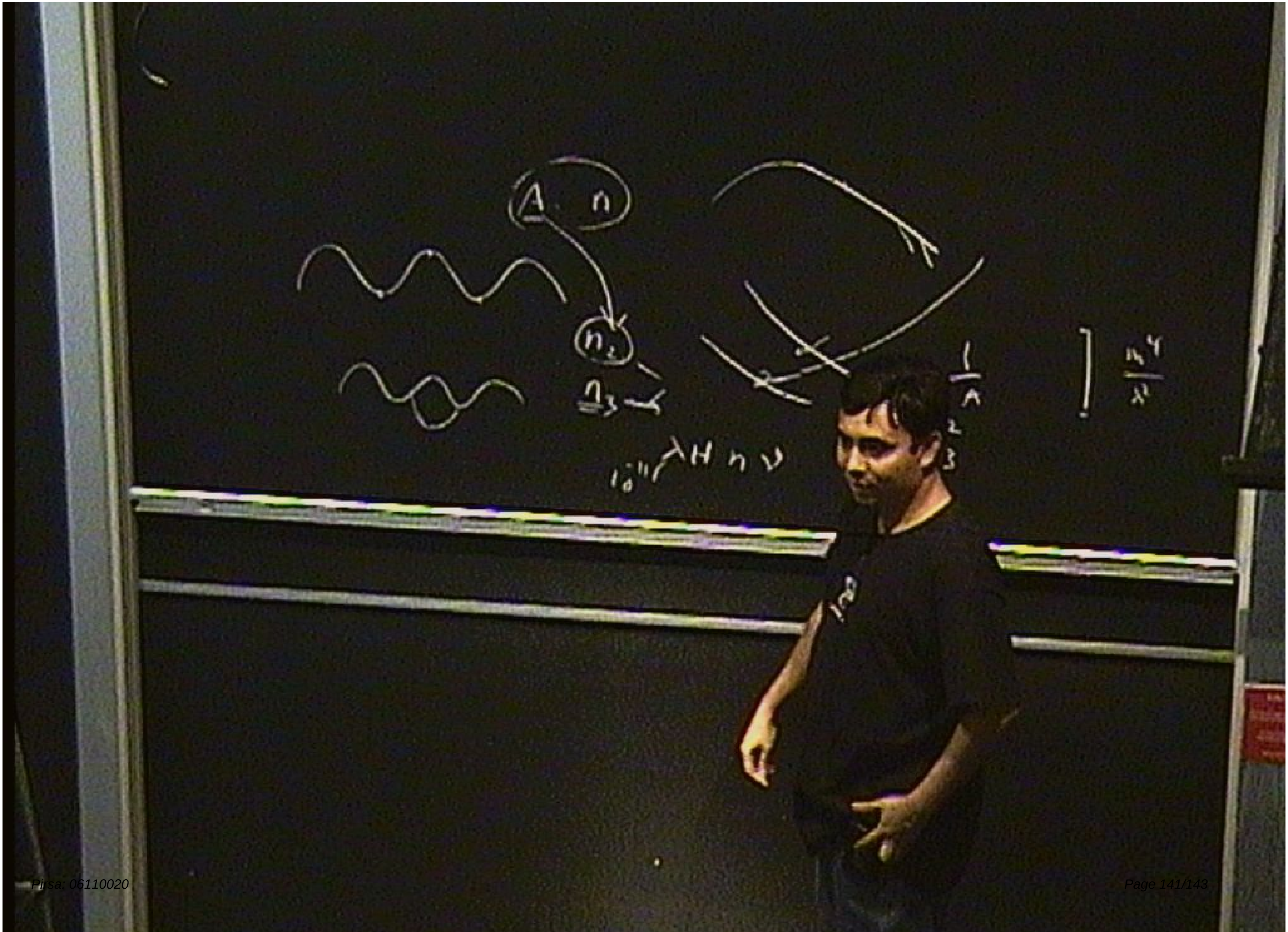


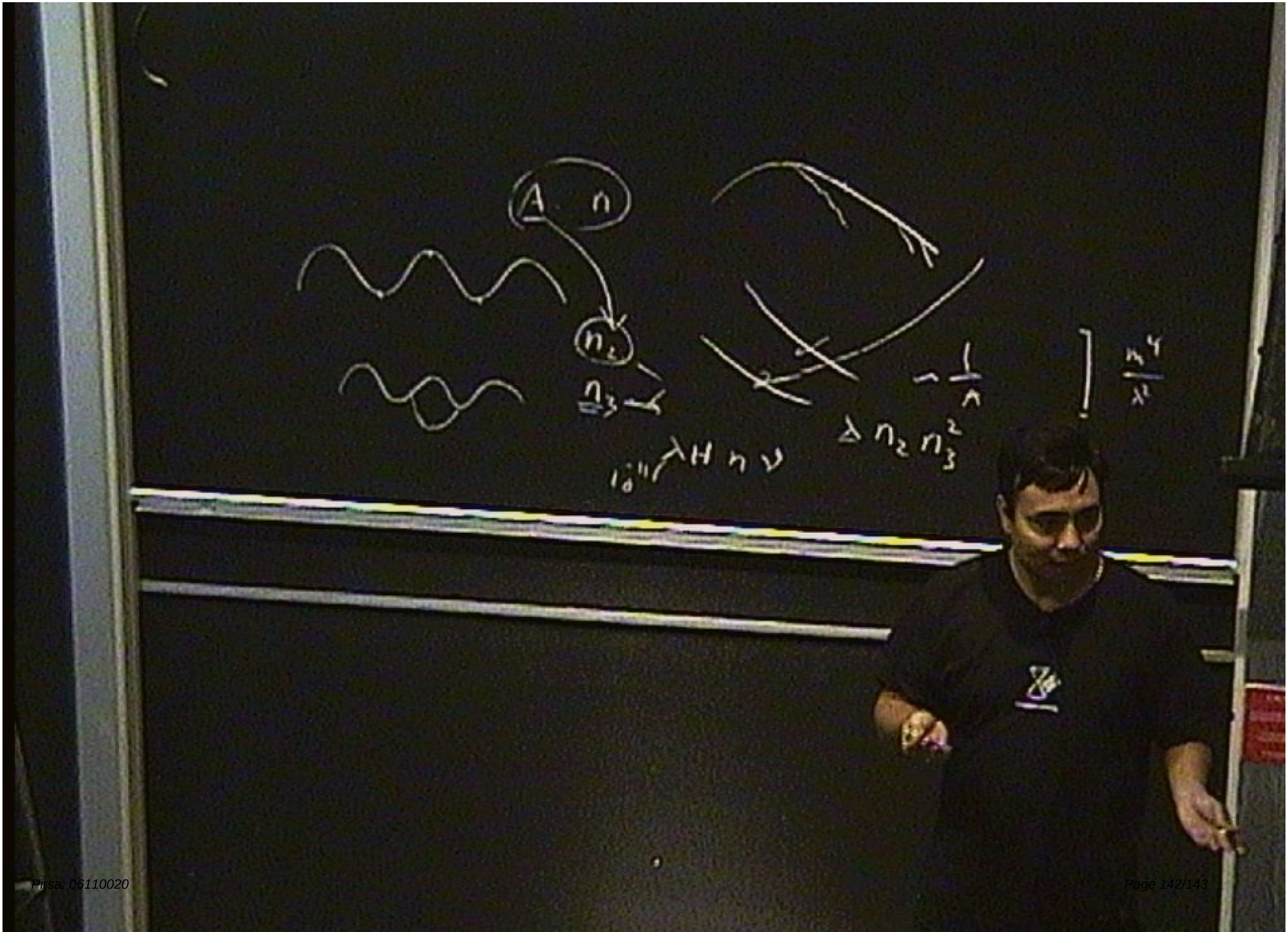


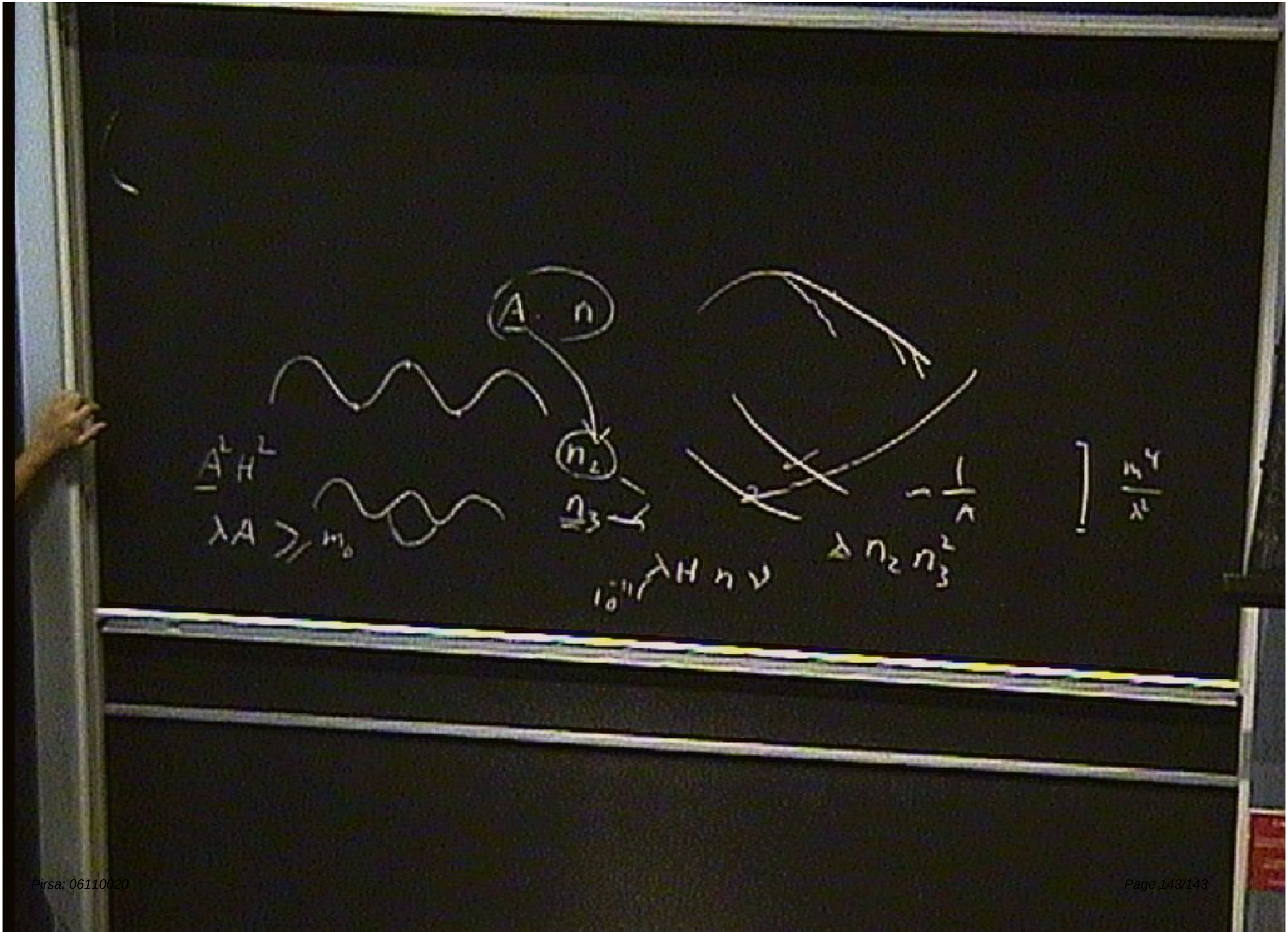




Δ n
n₂
n₃
λH n ν
Δ n₂ n₃²
~ 1/λ






A n
n2
n3
A2 H2
λA ≥ m0
λH n v
λ n2 n3 2