Title: A Graceful Exit for Old Inflation and a Solution to the Hierarchy Problem

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Abstract:

A Graceful Exit for Old Inflation and a Solution to the Hierarchy Problem

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Feb. 7th 2006 / Seminar @ Perimeter Institute

[1] In collaboration with

Outline

1. Motivation
   - Inflation from a False Vacuum
2. Our proposal
   - Basic idea
   - After Inflation
   - The Lagrangian
   - Dynamics
3. Hierarchy Problem
   - A new proposal
4. Cosmology Constraints
   - Sufficient Inflation
   - Cosmological Perturbations
5. Experimental signatures
   - GW at LISA
   - Particle Physics

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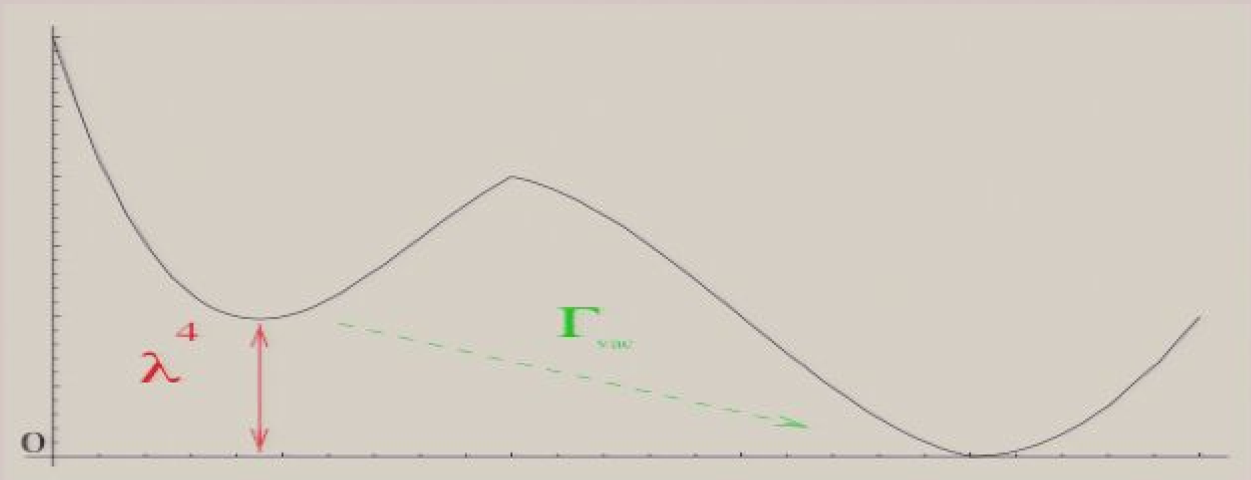

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- Old Inflation does not have Graceful Exit: non-successful Bubble Nucleation $\Rightarrow$ need for Slow-Roll inflation.
- Go back to Old Inflation, no flat potentials.

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Way-out:

- Start with $\Gamma_{vac} \ll H^4$
- And then $\Gamma_{vac} \simeq H^4$

Previous models...

- One possibility: make H variable

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- But EI had a prediction ($n_S \lesssim 0.8$) ...and in 1992, COBE ruled it out. [4]
- Many other models, quite complicated, were proposed to cure the problem.
- Our model is still as simple as original EI and viable.

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Our proposal

In the presence of a Non-Minimally coupled scalar field (ϕ) the transition becomes viable.

An initial Lagrangian

- As a starting point we take the action[5]:

$$S_1 = \int d^4x\sqrt{-g}\left[\frac{1}{2}M^2R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \beta\phi^2R - \lambda^4\right]$$

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- But it is generically present.
- Assume $U(\phi)$ to be negligible before tunneling ($U \lesssim \lambda^4$).

5

Early Time Evolution

$$\boxed{S_1 = \int d^4x\sqrt{-g}\left[\frac{1}{2}M^2R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\beta\phi^2R - \lambda^4\right]},$$

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$$H_I^2 = \frac{\lambda^4}{3M^2}$$

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3. When $\sqrt{\beta}\phi \simeq M$ transition to power-law expansion.
4. $H \propto \frac{1}{t}$ and when $H = \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit.

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Phase I

- Friedmann equation:

$$H^2 = \frac{1}{3(M^2 + \beta\phi^2)} \left[\frac{1}{2}\dot{\phi}^2 - 6H\beta\phi\dot{\phi} + \lambda^4 \right] ,$$

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$$\Rightarrow R = 12H_I^2$$

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- and its growing solution is:

$$\phi(t) = \phi_0 e^{(\epsilon H_I t)/2}$$

where

$$\epsilon \equiv 3\left(-1 + \sqrt{1 + \frac{16}{3}\beta}\right) \qquad (\epsilon \simeq 8\beta \text{ for small } \beta)\,.$$

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    $\Rightarrow$ they overwhelm the Universe.

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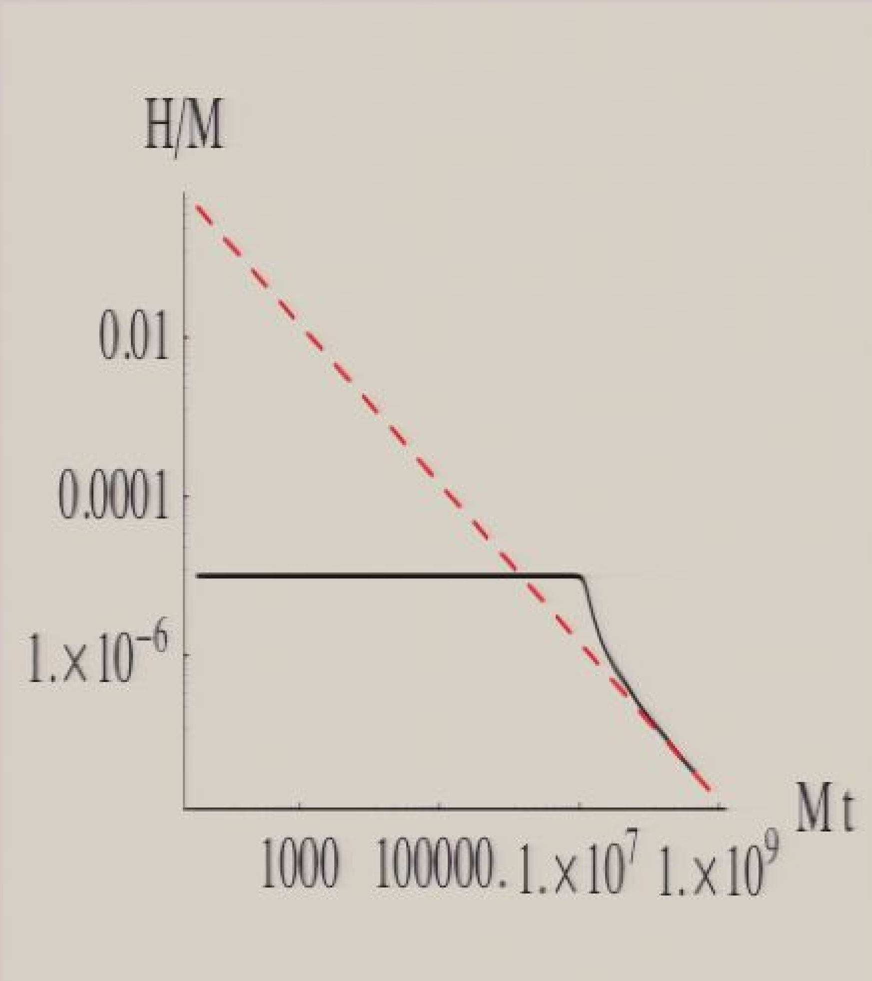
- Solution:

$$a(t) \sim t^{\alpha}\,, \qquad \phi(t) \sim Bt\,,$$

where:

$$\alpha \equiv \frac{1+2\beta}{4\beta}\,, \qquad B \equiv \frac{4\sqrt{\beta}\lambda^2}{\sqrt{60\beta^2 + 28\beta + 3}}\,.$$

Evolution of H



$(\beta = 1/56)$

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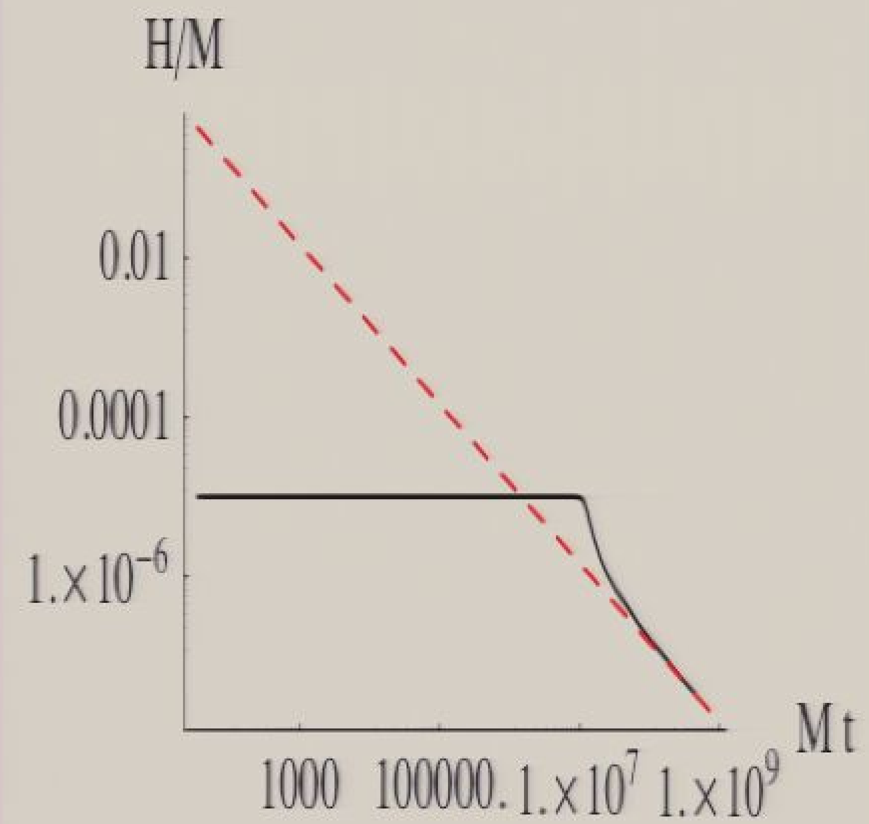

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Crucially

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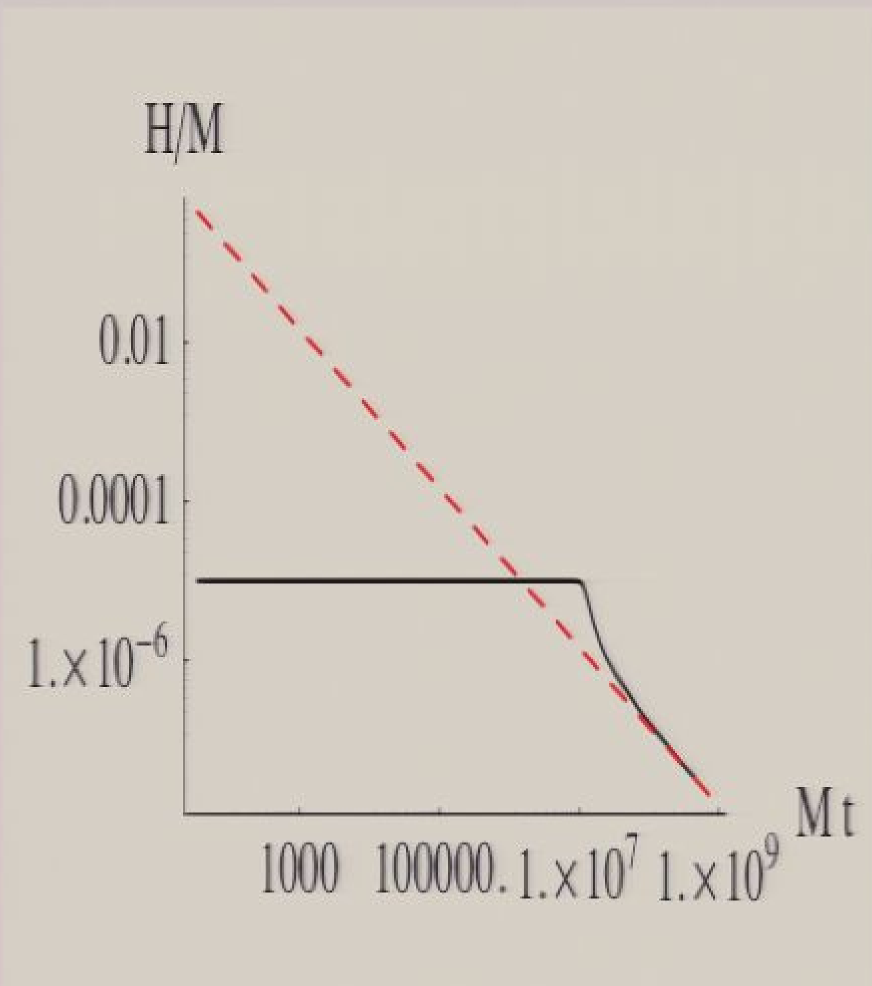

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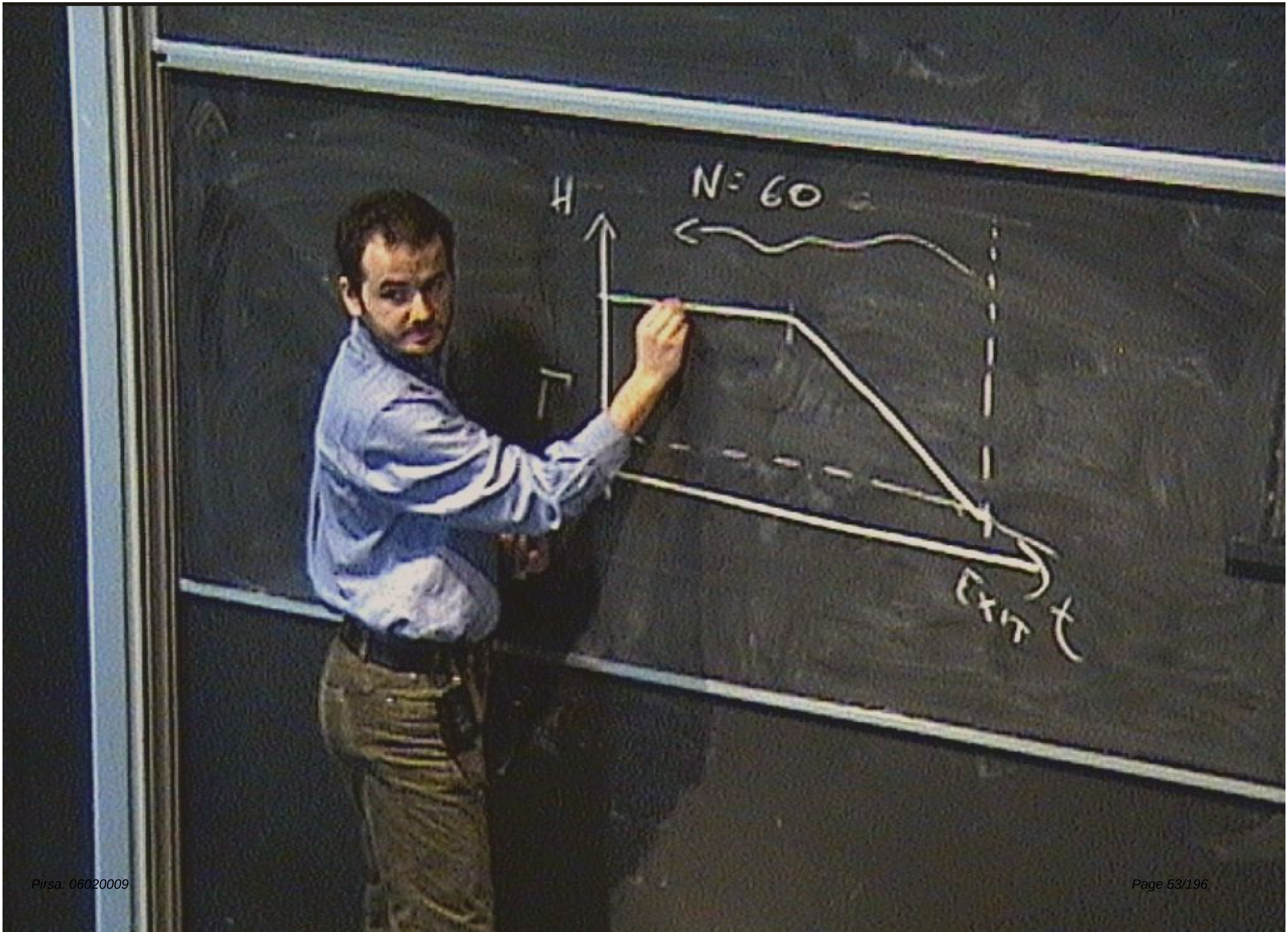
Crucially

- If Phase II short enough


H
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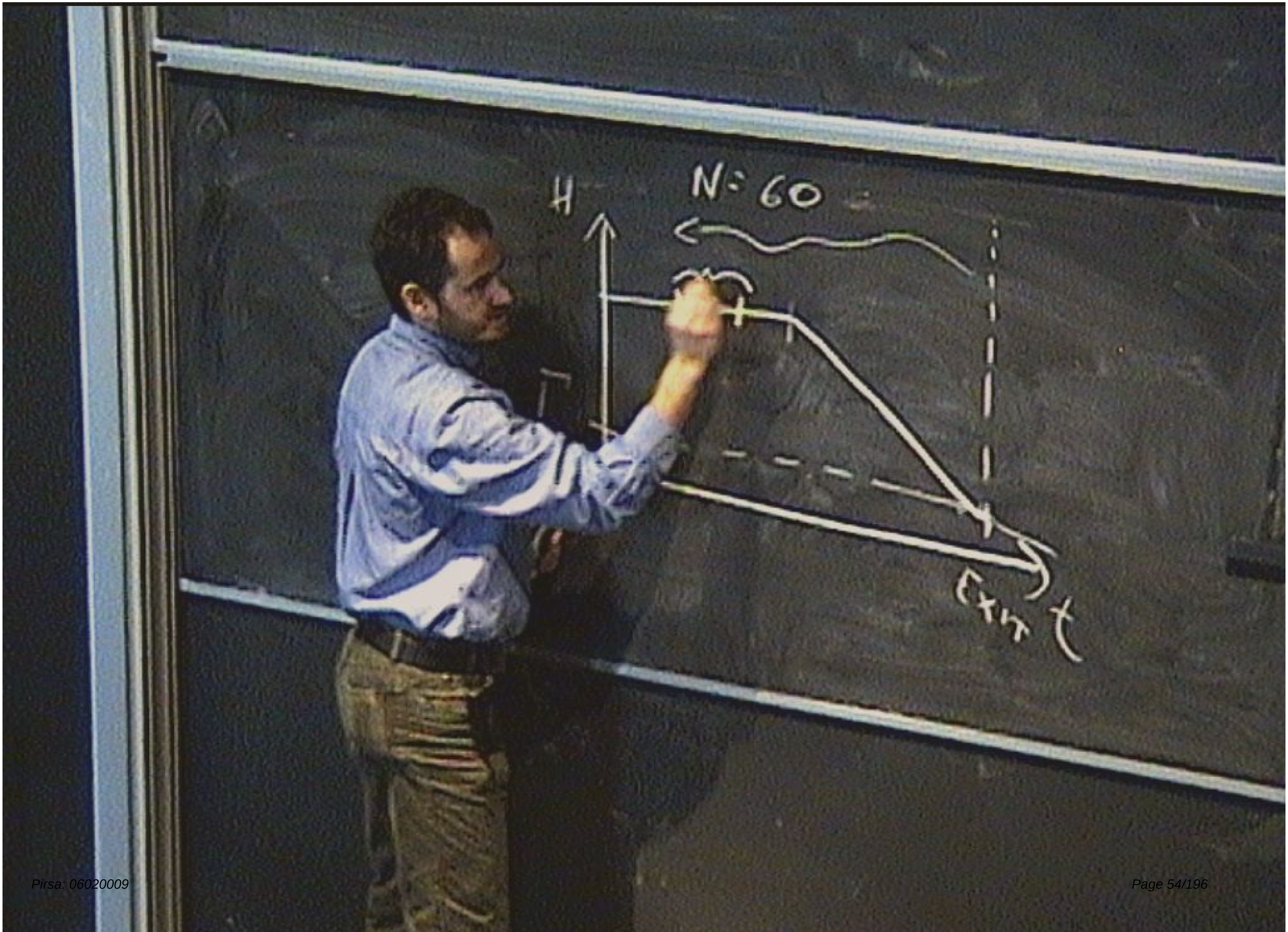
Exit
t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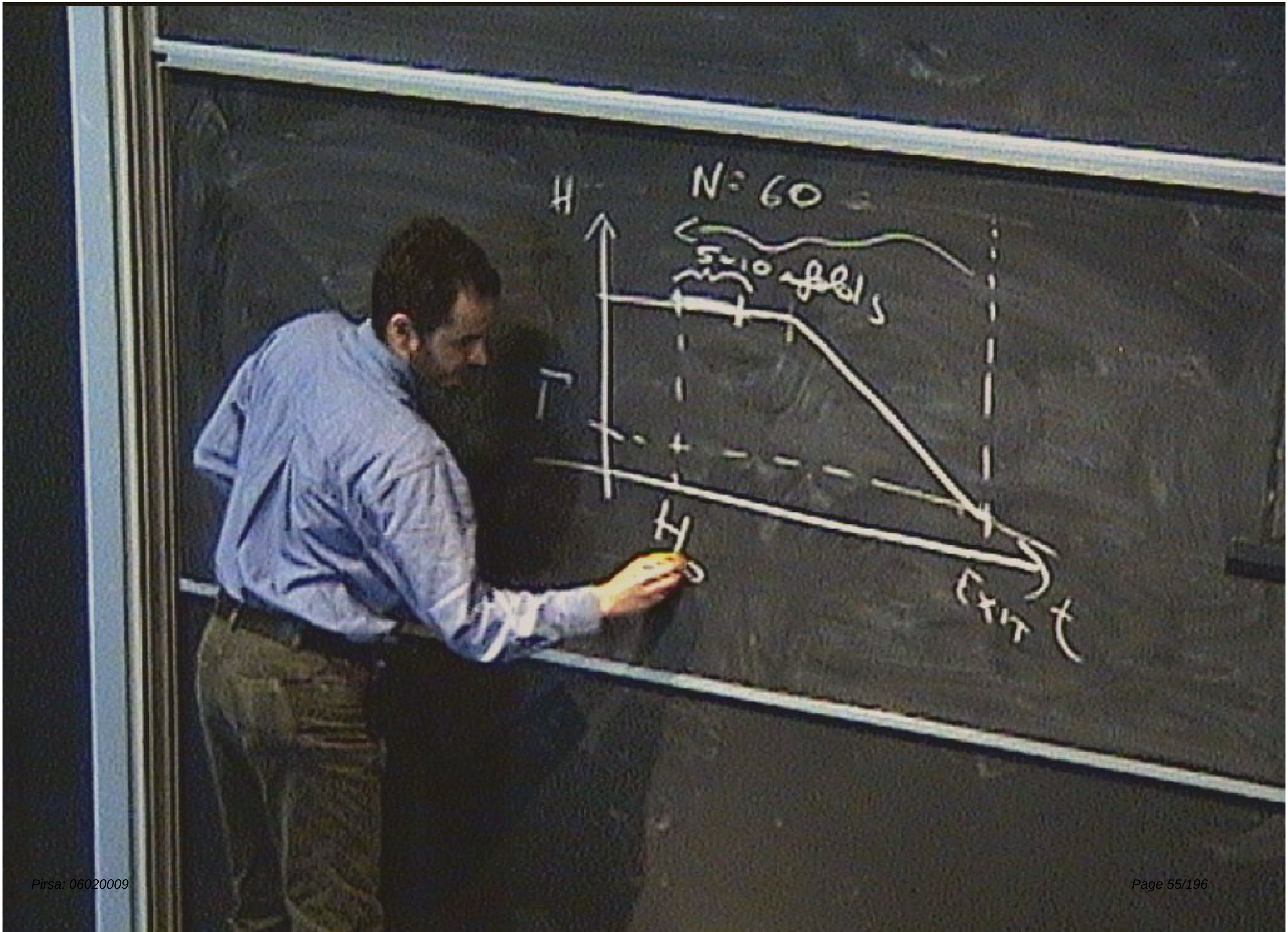

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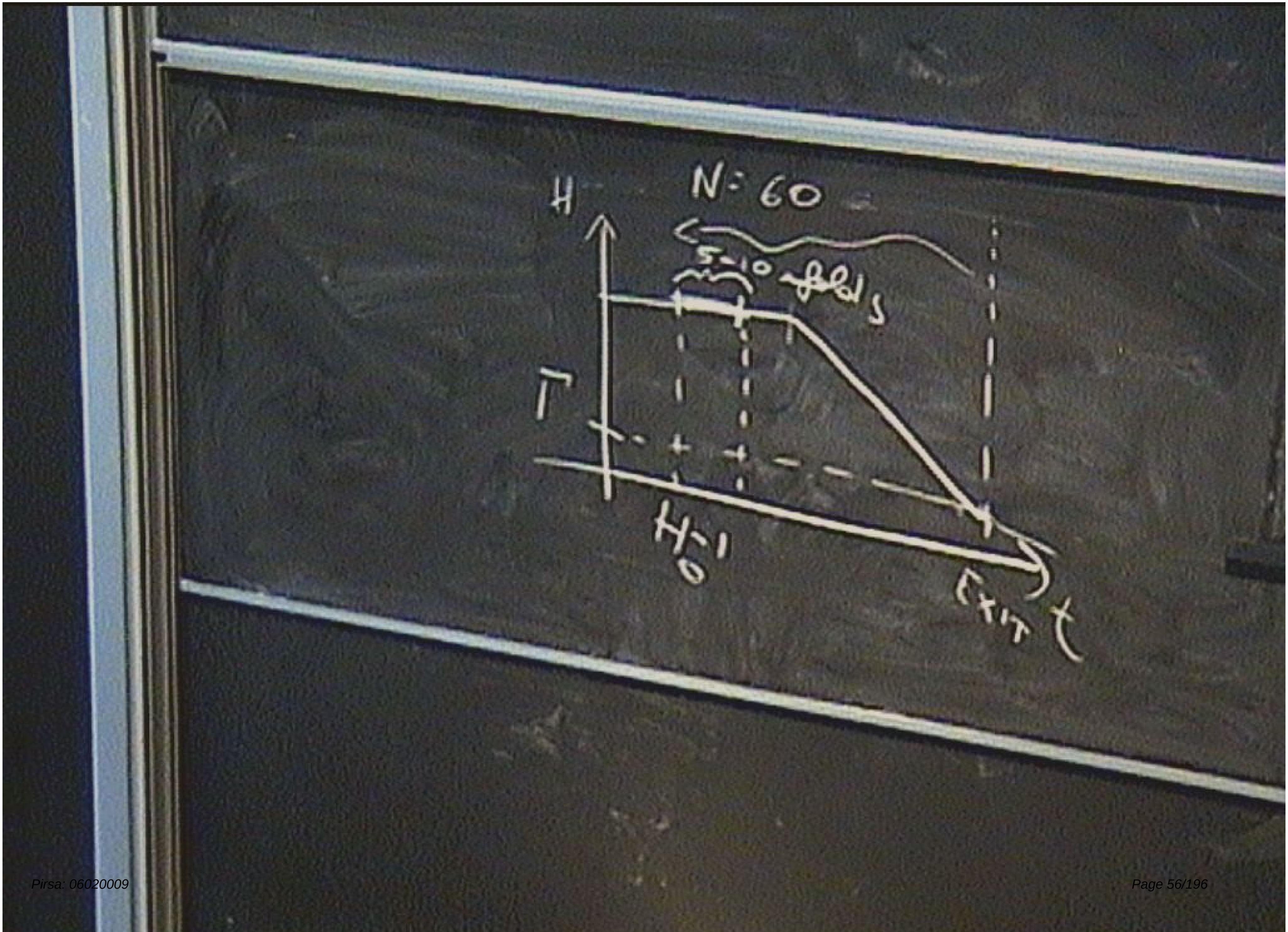
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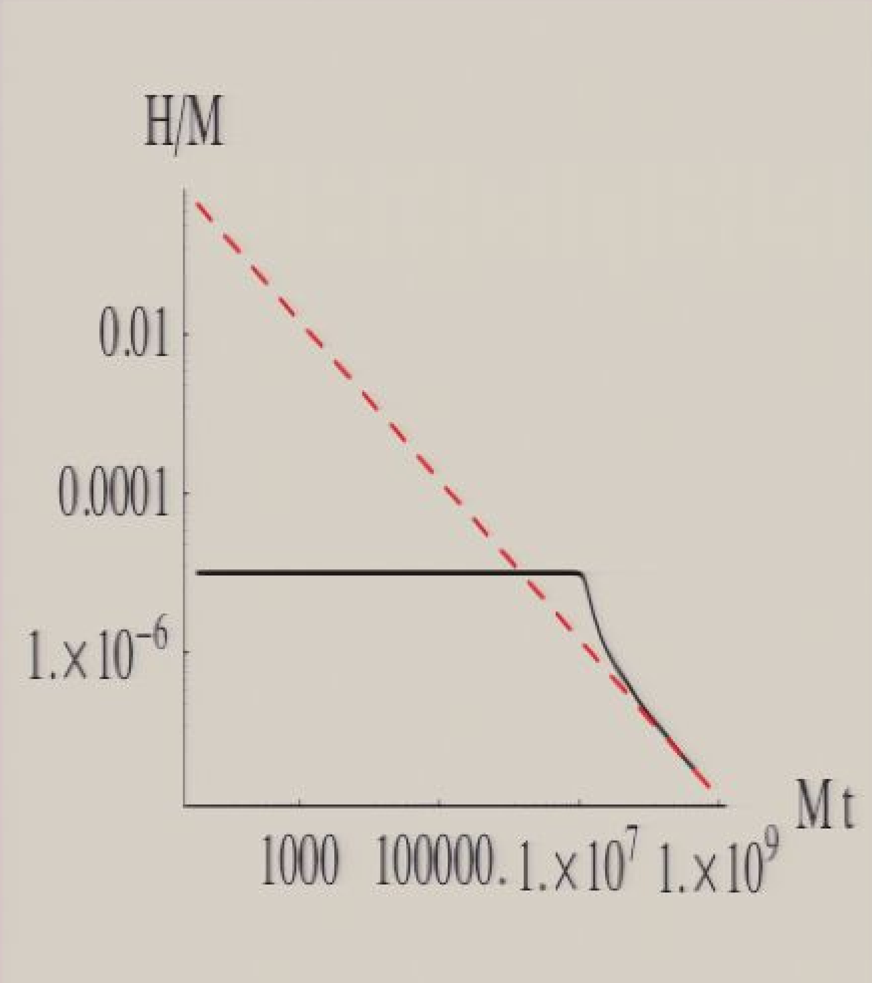

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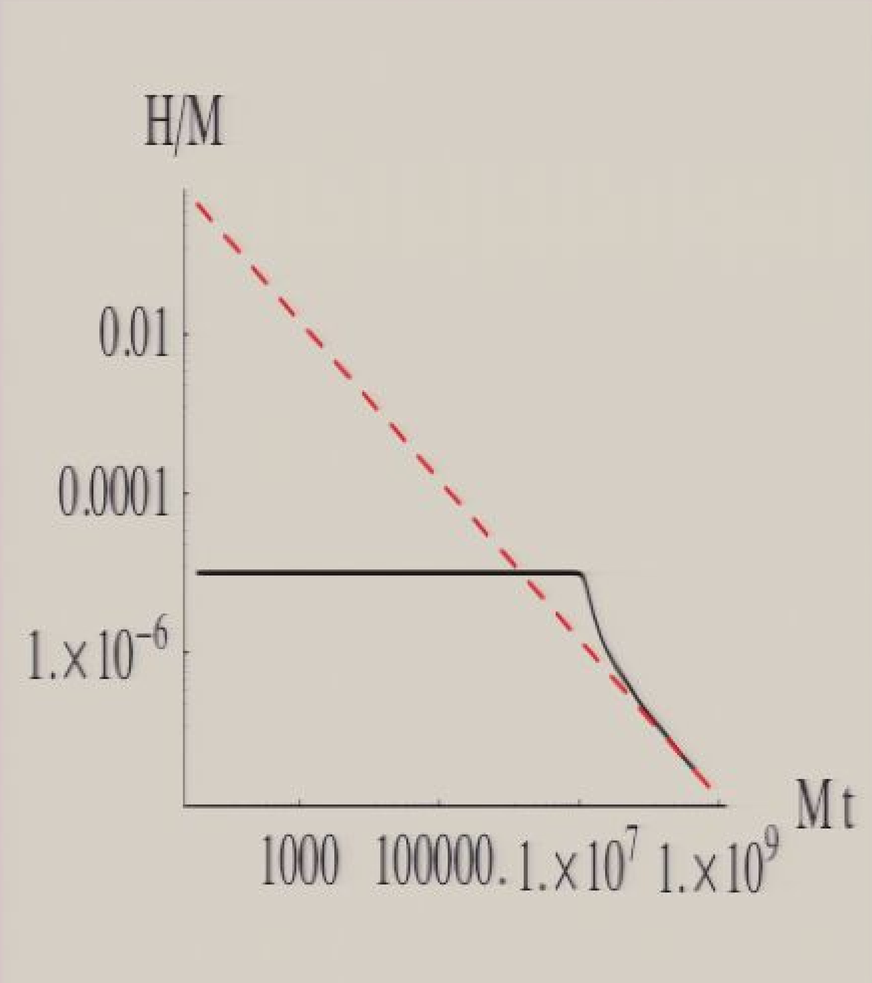
Crucially

- If Phase II short enough
- *Phase I*: Perturbations that we see
- H decreases rapidly
- When $H \simeq \Gamma_{vac}^{1/4} \Rightarrow$ Graceful Exit

Evolution of H



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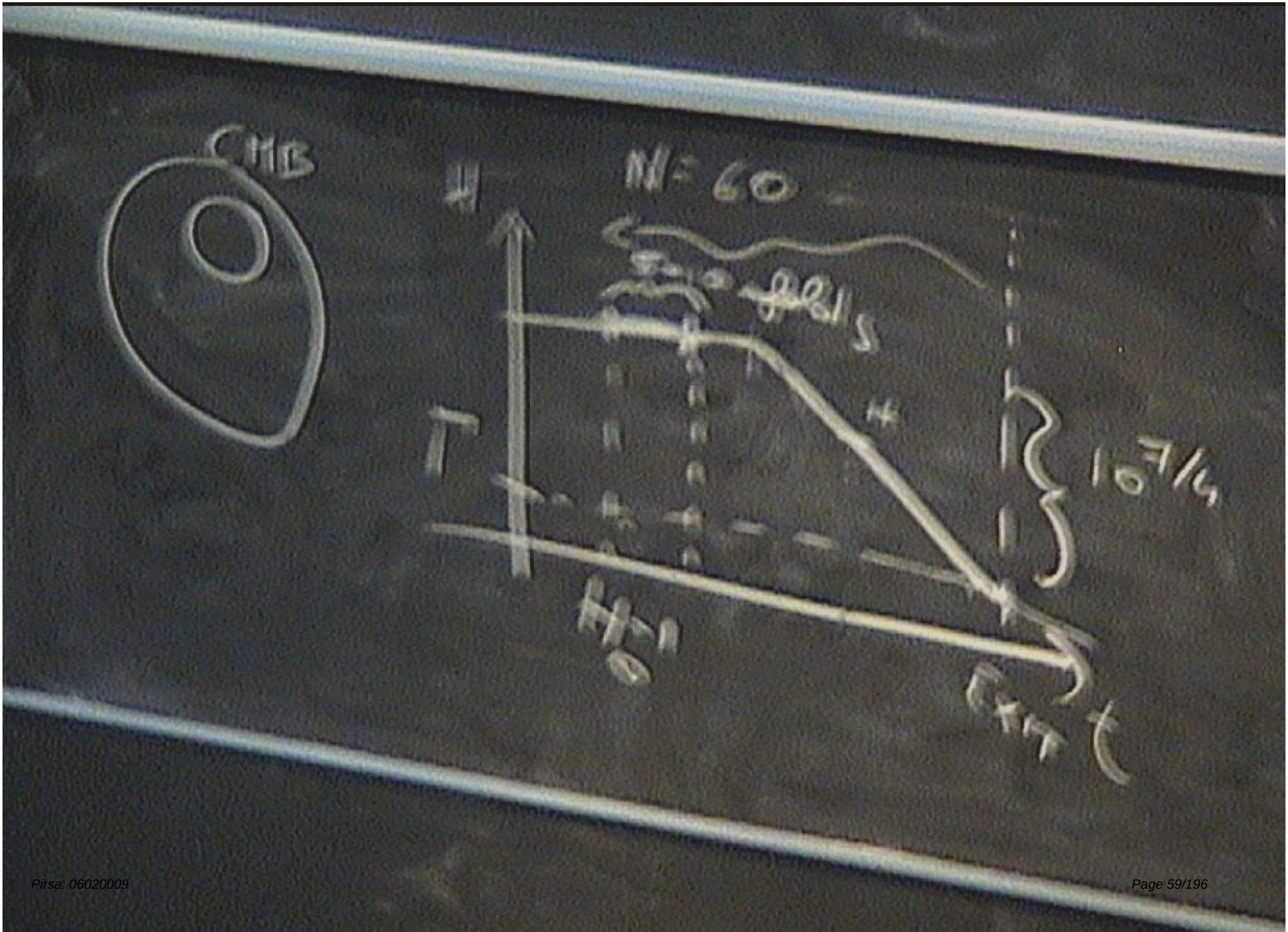

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Difference with Extended Inflation

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- Therefore only the power-law phase present
- H has to decrease fast to avoid early production of Large Bubbles
- COBE discovered almost flat spectrum

Transition to radiation and Stabilization

- When $H^4 \simeq \Gamma_{vac}$ many bubbles of true vacuum are nucleated
- They collide producing radiation, with T_{RH} given by

$$\frac{T_{RH}^4}{M_{pl}^2} \simeq \Gamma_{vac}^{1/2}$$

- During radiation ϕ does not evolve:

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Stabilization of ϕ

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  - 5^{th} force constraints
  - variation of G_N after equivalence.
- We reintroduce the potential $U(\phi)$ in the original Lagrangian
- Assumed to be irrelevant before ($U \lesssim \lambda^4$).
- Any potential with a minimum is good...

Potential

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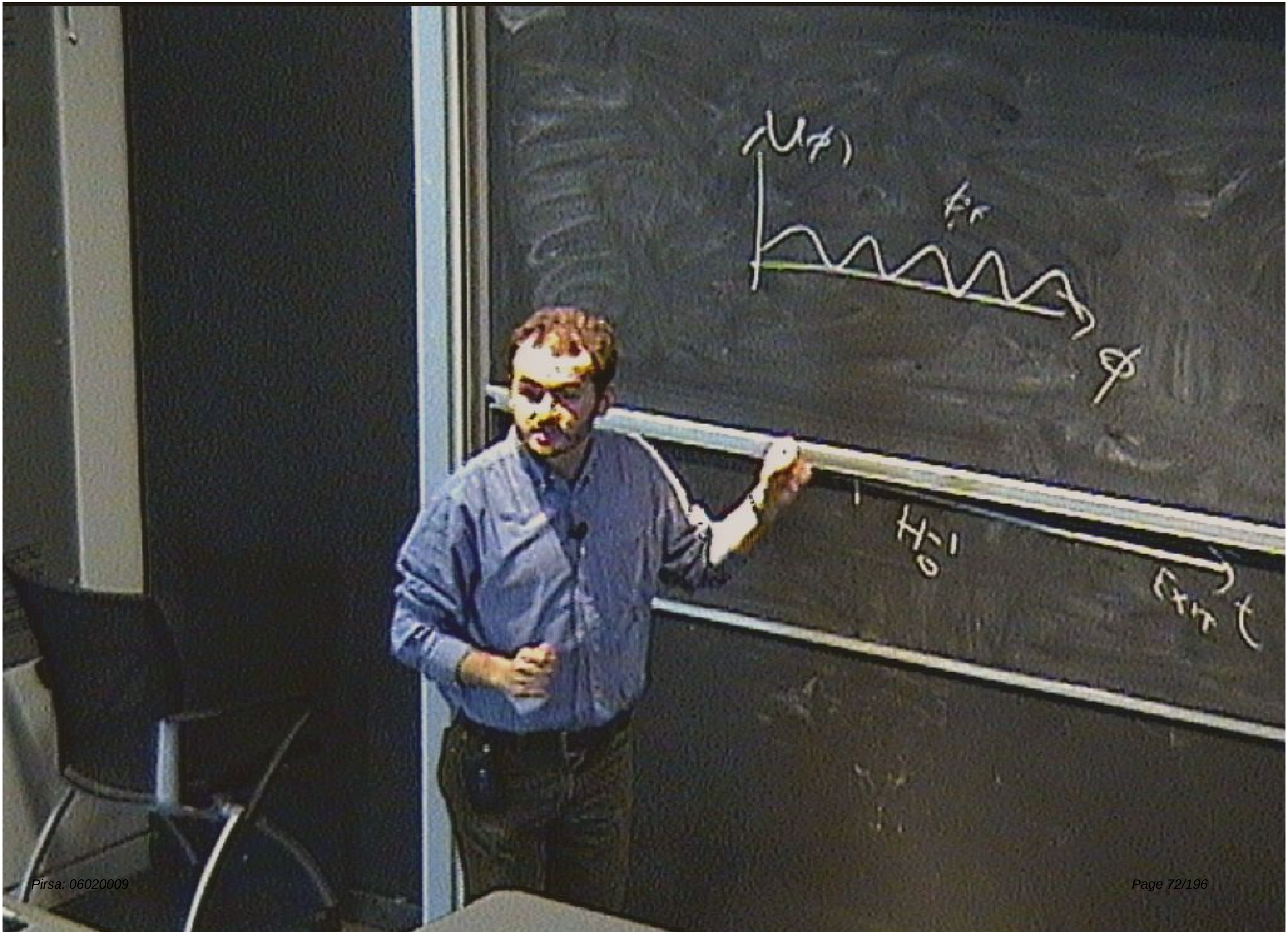
- For example: periodic potential (axion?)



Generalizing the Lagrangian

- We generalize as

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M^2 f(\phi) R - \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \lambda^4 + U(\phi) + \mathcal{L}_m \right]$$

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- The transition is strong enough (decelerated expansion), independently on the exact form of $f(\phi)$!

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- For $\phi \gg M$ assume $f(\phi) > \phi^2$
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(with a cutoff scale of order M).

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and the false vacuum energy, in this frame

$$-S_{vac} = \int d^4x \, \sqrt{-\bar{g}} \frac{\lambda^4}{f^2(\phi)} \equiv \int d^4x \sqrt{\bar{g}} \, \bar{V}(\phi) \,.$$

becomes a potential (but it disappears at decay!)

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- When ϕ of order M: end of slow-roll

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- In this phase:

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- So we introduce a canonical variable via

$$\Phi \equiv \sqrt{\frac{3}{2}} M \ln f ,$$

- The kinetic term is canonical and the potential becomes:

$$\bar{V}(\Phi) = \lambda^4 \exp\left(-2\sqrt{\frac{2}{3}}\frac{\Phi}{M}\right) .$$

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- Therefore the final field value ϕ_F is given by:

$$f(\phi_F) \simeq \frac{\lambda^2}{M\bar{\Gamma}_{vac}^{1/4}}\,.$$

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The Hierarchy Problem

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- At which scale new physics will appear? (important for LHC)
- Why the Higgs is so light? (if the mass is quadratically sensitive to the cutoff $\gg M_{EW}$)

Other explanations

- Popular solutions are:

[8] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998)

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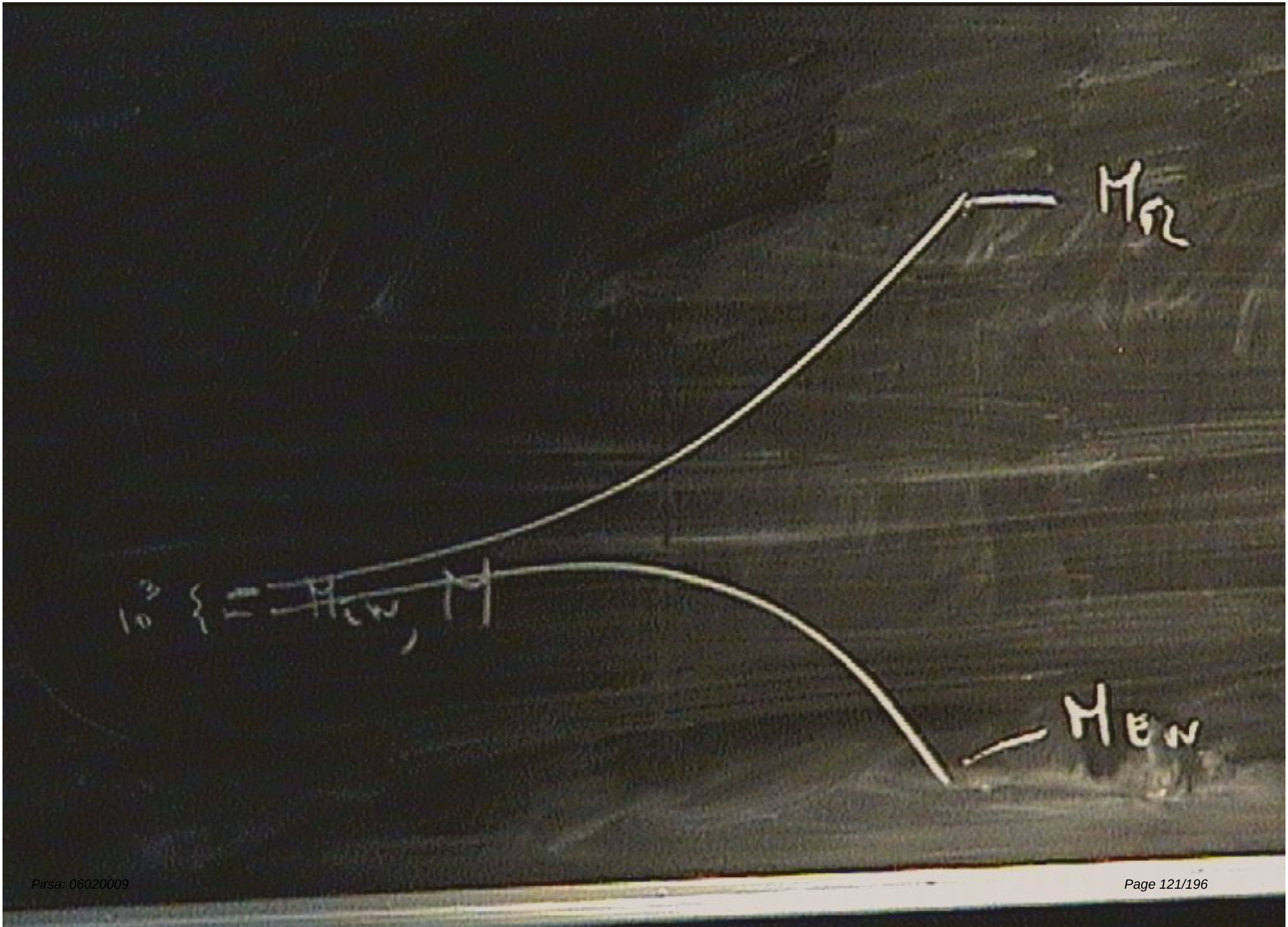

M_{GL}
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Scales in the problem

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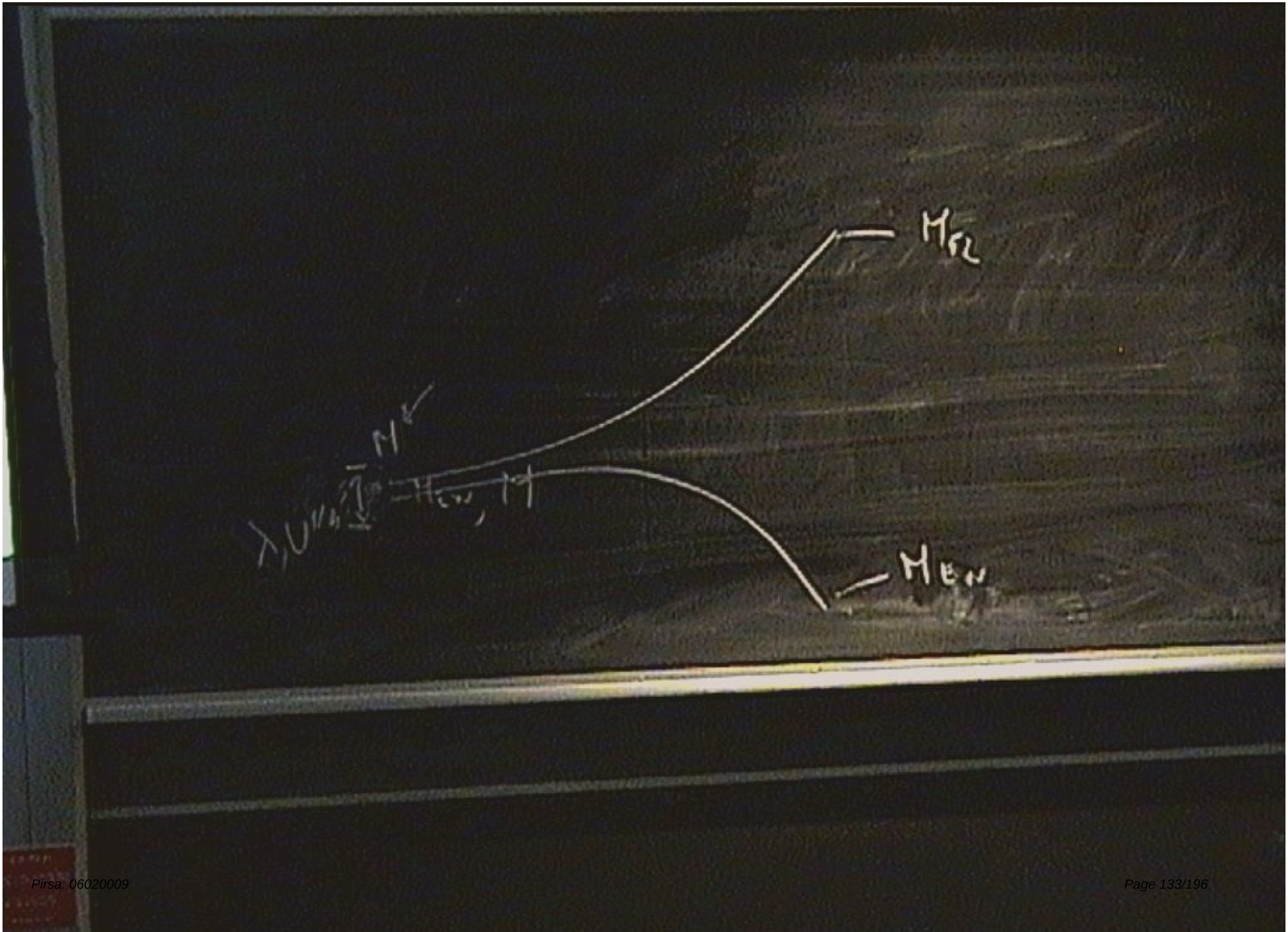
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- In any case we explain how M_{Pl} becomes so big.

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Our proposal
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The Lagrangian
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- Use:

$$\begin{cases} n_S - 1 = 2\eta - 6\epsilon \\ A^2 = \left(\frac{\bar{H}_I}{M}\right)^2 \frac{1}{8\pi^2\epsilon}\Bigg|_{\phi=\phi(\bar{N}\approx\bar{N}_{3000h^{-1}Mpc})} \end{cases}$$

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- We expect to see some red tilt

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- If $\lambda \gg TeV$ (only Inflation, no solution to Hierarchy)$\Rightarrow$ higher frequency (LIGO, Virgo, TAMA?)

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- Combination of three very different observations:

$$\left\{ \begin{array}{l} \text{Gravity waves (LISA)} \\ \text{Particle physics (LHC)} \\ \text{Spectral index (WMAP? Planck?)} \end{array} \right.$$

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ϕNN

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