Title: Thermalization after Inflation and Supersymmetery

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Abstract: tba

Thermalization after inflation and supersymmet

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Theory Group, TRIUMF

Tuesday, September 20, 2005

- R. Allahverdi and A.

- Introduction.
- Thermalization after inflation.
- Late thermalization in supersymmetry.
- Quasi-thermal phase.
- Modifications to particle production

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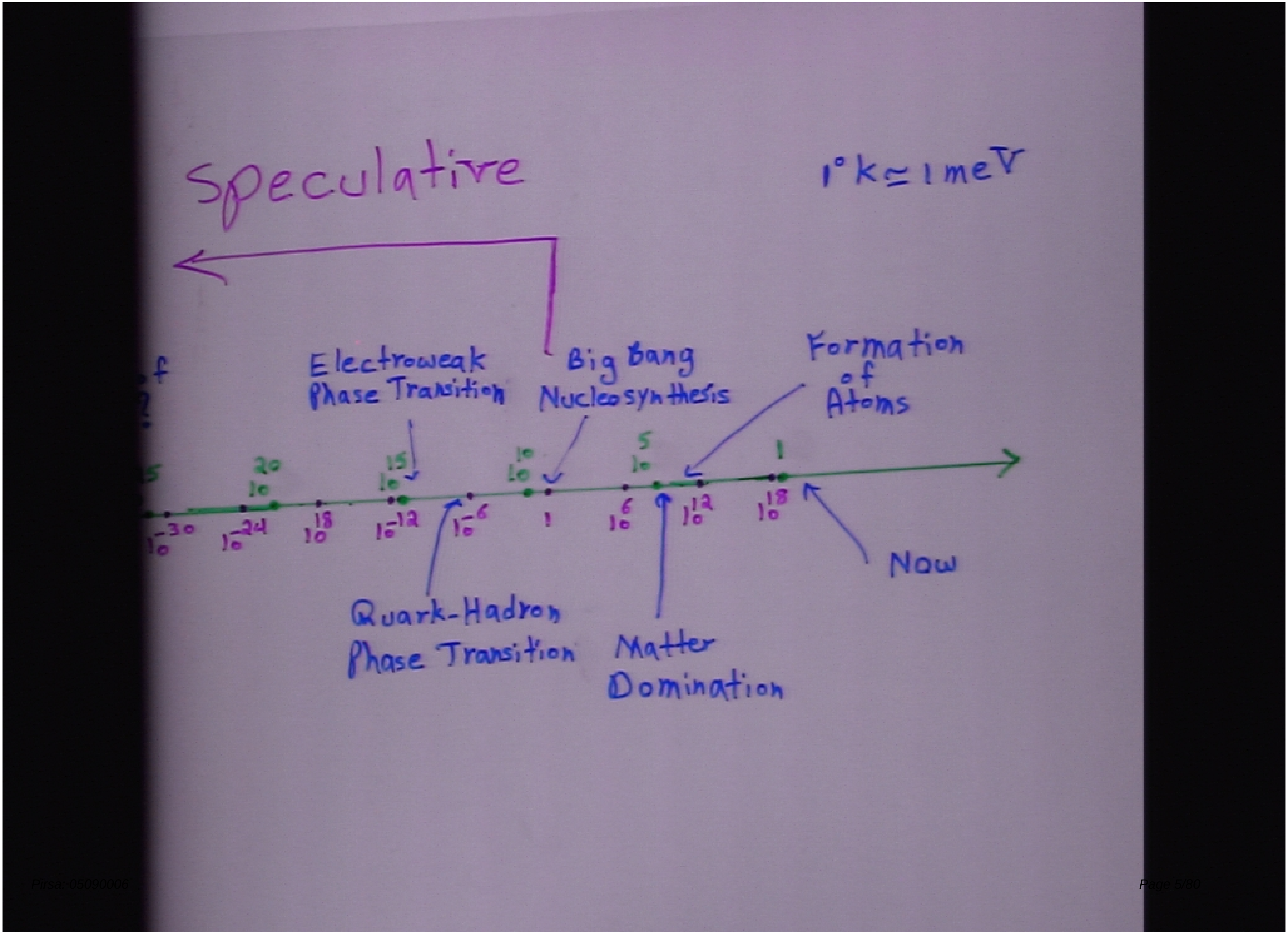
- Conclusion.


Speculative
1°k ≃ 1 meV
Electroweak Phase Transition
Big Bang Nucleosynthesis
Formation of Atoms
20
10
15
10
10
10
5
10
1
10^-30
10^-24
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1
10^6
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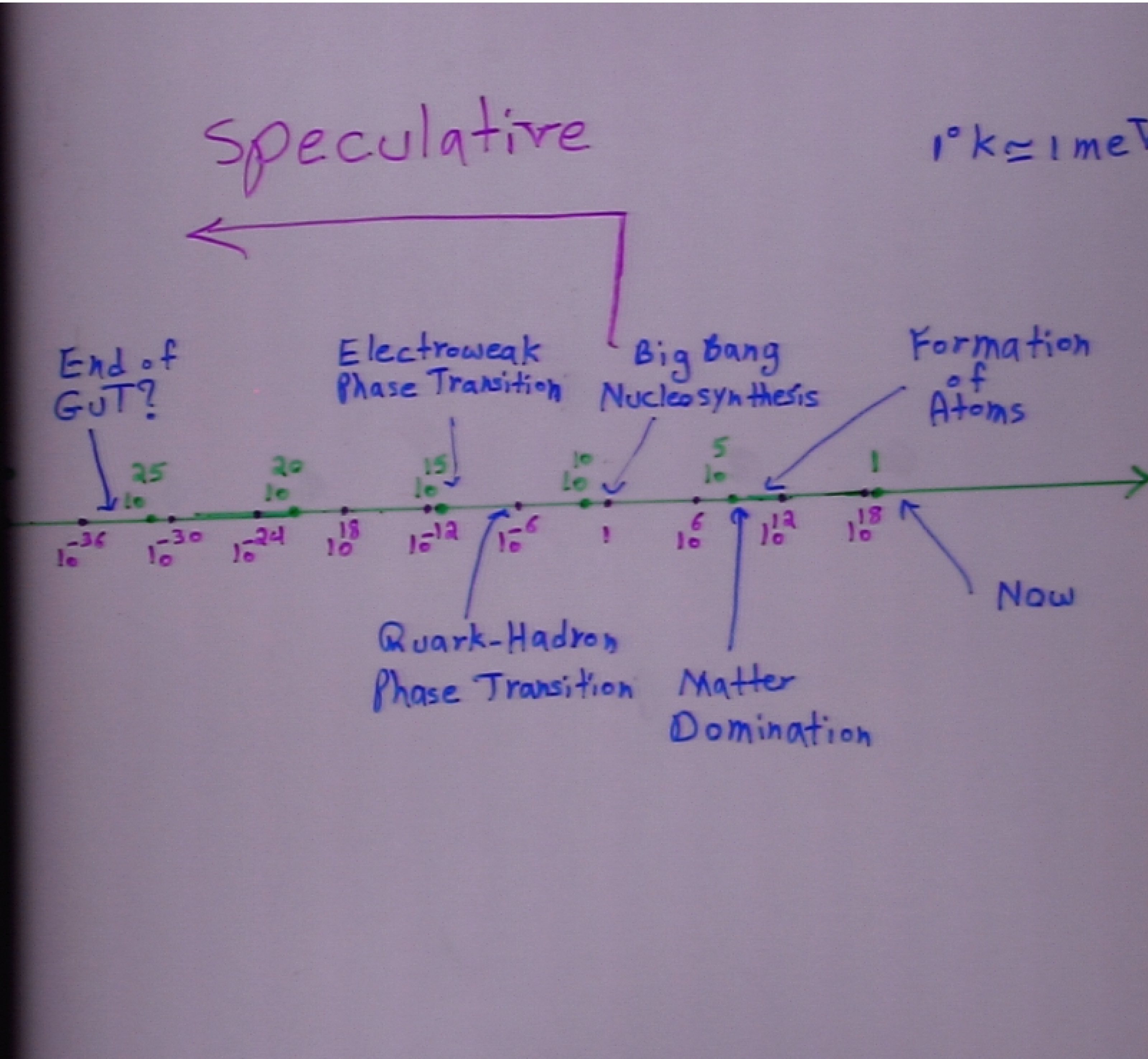
Quark-Hadron Phase Transition
Matter Domination
Now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• Introduction:

Different stages in the early universe:

1- Inflation (solves flatness and isotropy problems
creates seeds for structure formation).

2- Inflaton domination (universe cold and empty).

3- Hot big bang (thermal bath of elementary part
cles).

Reheating: Transition from 2 to 3, creation
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- Inflaton decay.

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- Generation of adiabatic perturbations.

Implications for particle physics:

Thermal and non-thermal prodcution of stable of long-lived particles.

Constraints on the reheat temperture $T_{\rm R}$:

BBN gives a *model-independent* lower bound: $T_{\rm R} \gtrsim \mathcal{O}(\text{MeV})$.

Other but model-depnedent bounds:

- Electroweak baryogenesis $\Rightarrow T_{\rm R} \gtrsim 100$ GeV.
- Leptogenesis $\Rightarrow T_{\rm R} > 10^9$ GeV.
- Gravitino production for $m_{3/2} \sim \mathcal{O}(\text{TeV}) \Rightarrow T_{\rm R} \leq 10^{10}$ GeV.

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Last stage of inflaton decay perturbative if:

$$\Gamma_d \ll \frac{m_\phi^2}{M_P}. \quad (1)$$

Full equilibrium:

$$\rho = \frac{\pi^2}{30} g_* T^4 \,, \; n = \frac{\zeta(3)}{\pi^2} g_* T^3$$

$$E \simeq 3T \quad \rightarrow \quad n \sim E^3. \quad (2)$$

Upon inflaton decay:

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Dilute plasma formed. Composition of the plasma model-dependent.

Deviation from equilibrium quantified by

$$A \equiv \frac{n}{E^3} \sim \frac{\Gamma_d^2 M_P^2}{m_\phi^4}. \quad (4)$$

Note:

$$\frac{n}{n_{eq}} \sim A^{1/4} \quad , \quad \frac{E}{E_{eq}} \sim A^{-1/4}. \quad (5)$$

- Example: gravitationally coupled inflaton.

$$\Gamma_d \sim \frac{m_\phi^3}{M_P^2} \quad , \quad m_\phi = 10^{13}\ \text{GeV}$$

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n must INCREASE by a factor of 10^3.

Evolution towards full equilibrium:

- Number-conserving processes ⇒ kinetic equilibrium, rate $\Gamma_{\rm kin}$.

- Number-violating processes ⇒ chemical equilibrium, rate $\Gamma_{\rm thr}$.

Three time scales involved:

$$\Gamma_{\rm d}^{-1} \;,\; \Gamma_{\rm kin}^{-1} \;,\; \Gamma_{\rm thr}^{-1}.$$

For particles with gauge interactions:

$$\Gamma_{\rm thr} \sim \alpha^3 \left(\frac{M_{\rm P}}{m_\phi}\right) \Gamma_{\rm d}. \tag{7}$$

$\alpha \sim 10^{-2}$: gauge fine structure constant, $m_\phi \leq 10^{13}$ GeV ⇒ $\Gamma_{\rm thr} \gtrsim \Gamma_{\rm d}$.

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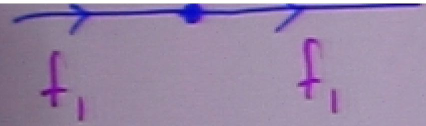
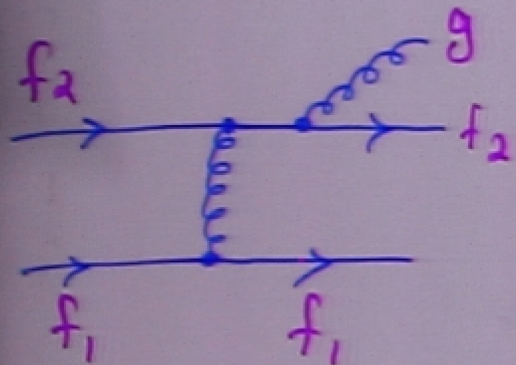




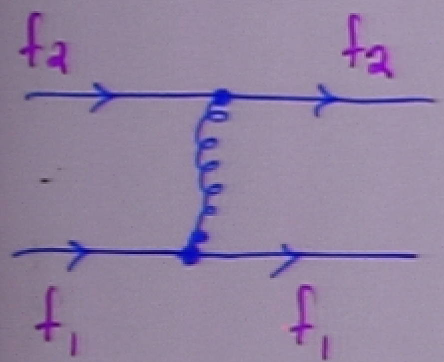
$\Rightarrow$ Chemical equilibrium

Naive estimates based on dimensional grounds

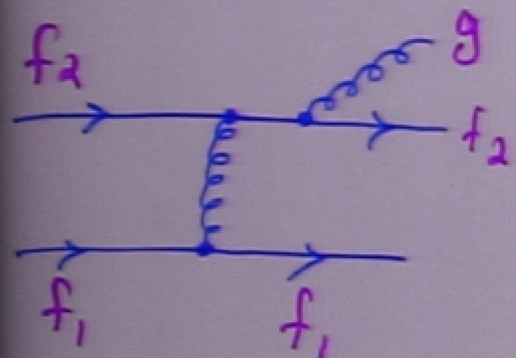
$$\sigma \sim \frac{1}{E^2}$$

Actual situation:

$$\sigma \gg \frac{1}{E^2}$$



$\Longrightarrow$ kinetic equilibrium



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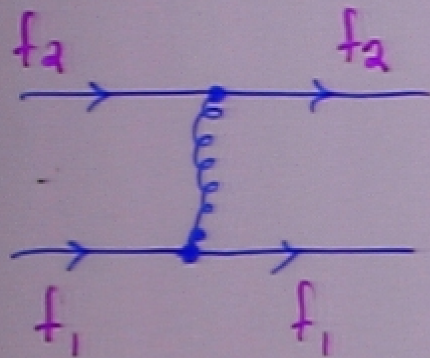

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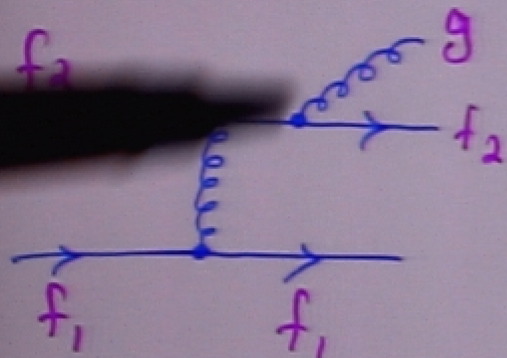

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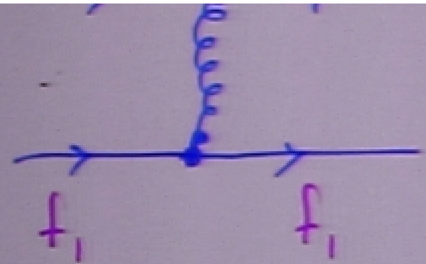
Actual calculation



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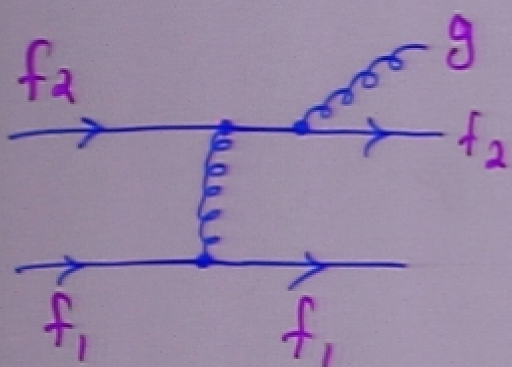

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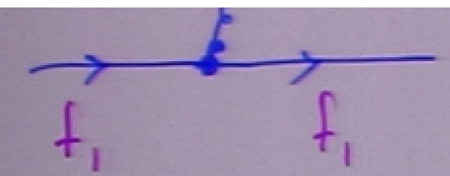

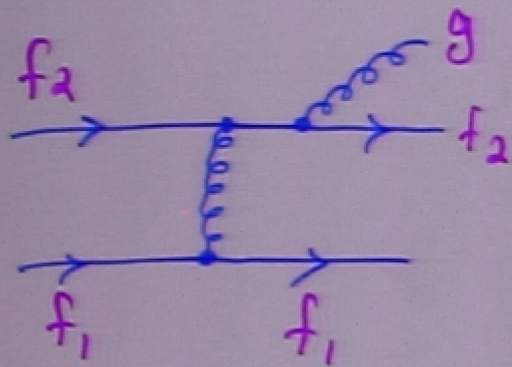

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Universe thermalizes IMMEDIATELY after inflaton decay:

$$T_{\mathrm{R}} \sim (\Gamma_{\mathrm{d}} M_{\mathrm{P}})^{1/2}. \qquad (8)$$

Gravitational decay: $T_{\mathrm{R}} \sim 10^{10}$ GeV.

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- Late thermalization in supersymmetry:

  SUSY theories have a large number of flat directions. Massless in unbroken SUSY, lifted by soft term $m_0 \sim \mathcal{O}(\mathrm{TeV})$ after SUSY breaking.

  ~ 300 directions made up of squark, slepton and Higgs fields.

  Flat directions are light, acquire a large VEV φ_0 during inflation.

  φ_0:

  - Spontaneously breaks gauge symmetries.

  - Induces a large mass $\sim \varphi_0$ for gauge fields in the early universe.

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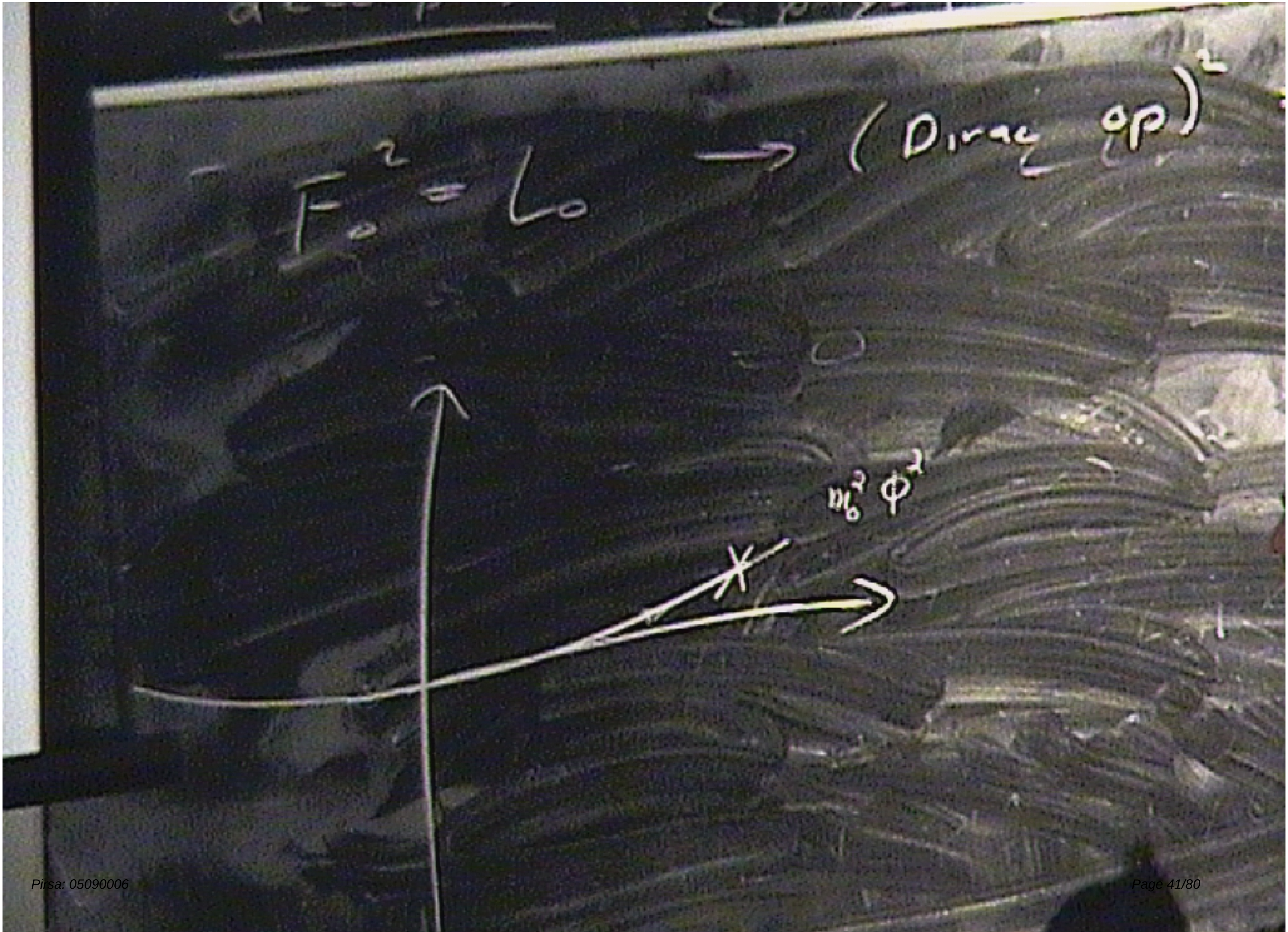
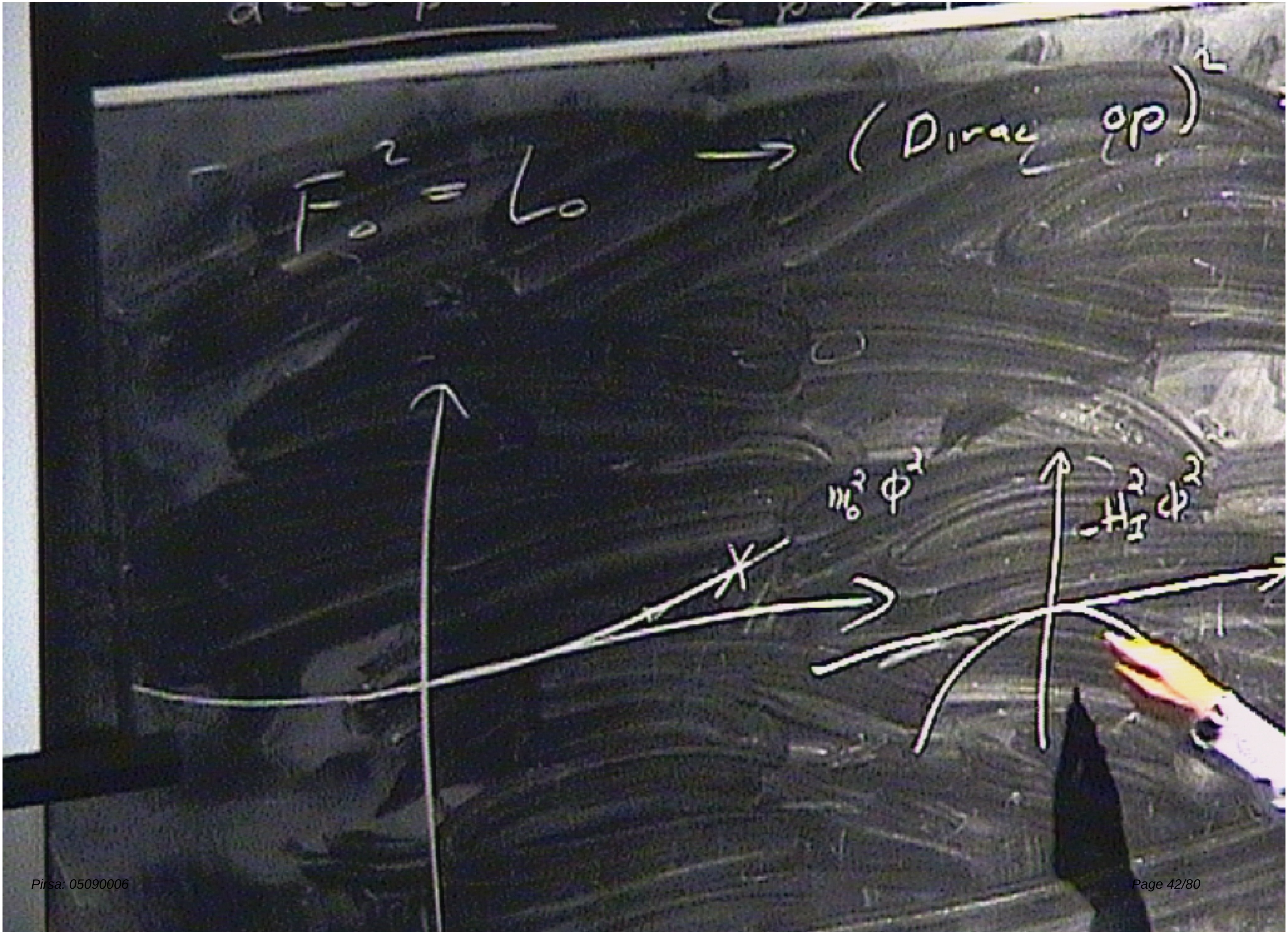
$\Rightarrow$ Thermalization rate suppressed.


F₀² = L₀ → (Dirac op)²
m₀² φ²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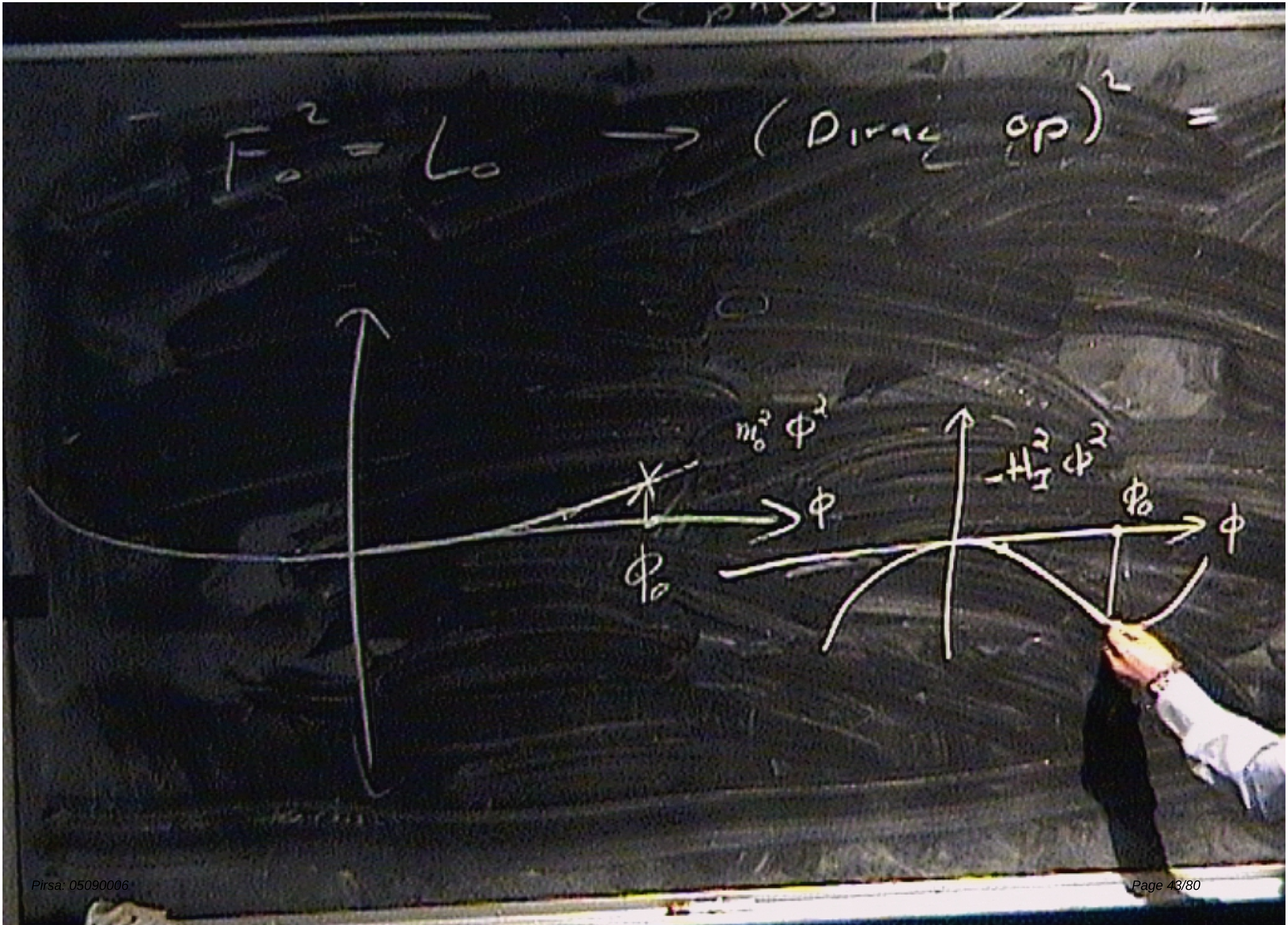

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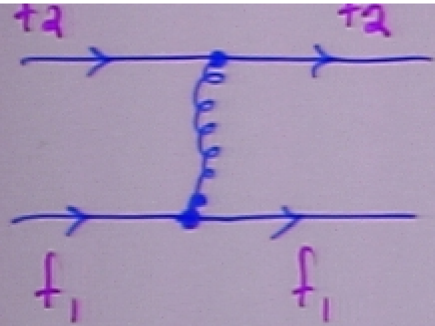
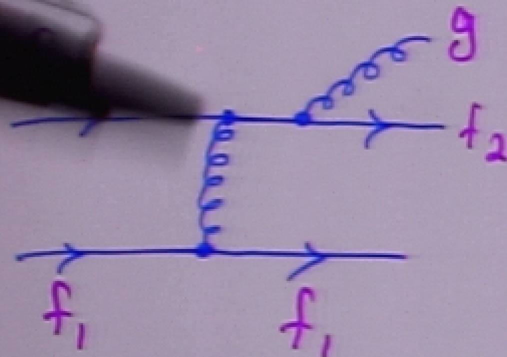


$\Longrightarrow$ Kinetic equilibrium



$\Longrightarrow$ Chemical equilibri

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$$\Gamma_{\mathrm{thr}} \sim \alpha^2 \left(\frac{M_{\mathrm{P}}}{\varphi_0}\right)^2 \frac{m_0^2}{m_\phi}. \tag{9}$$

Now:

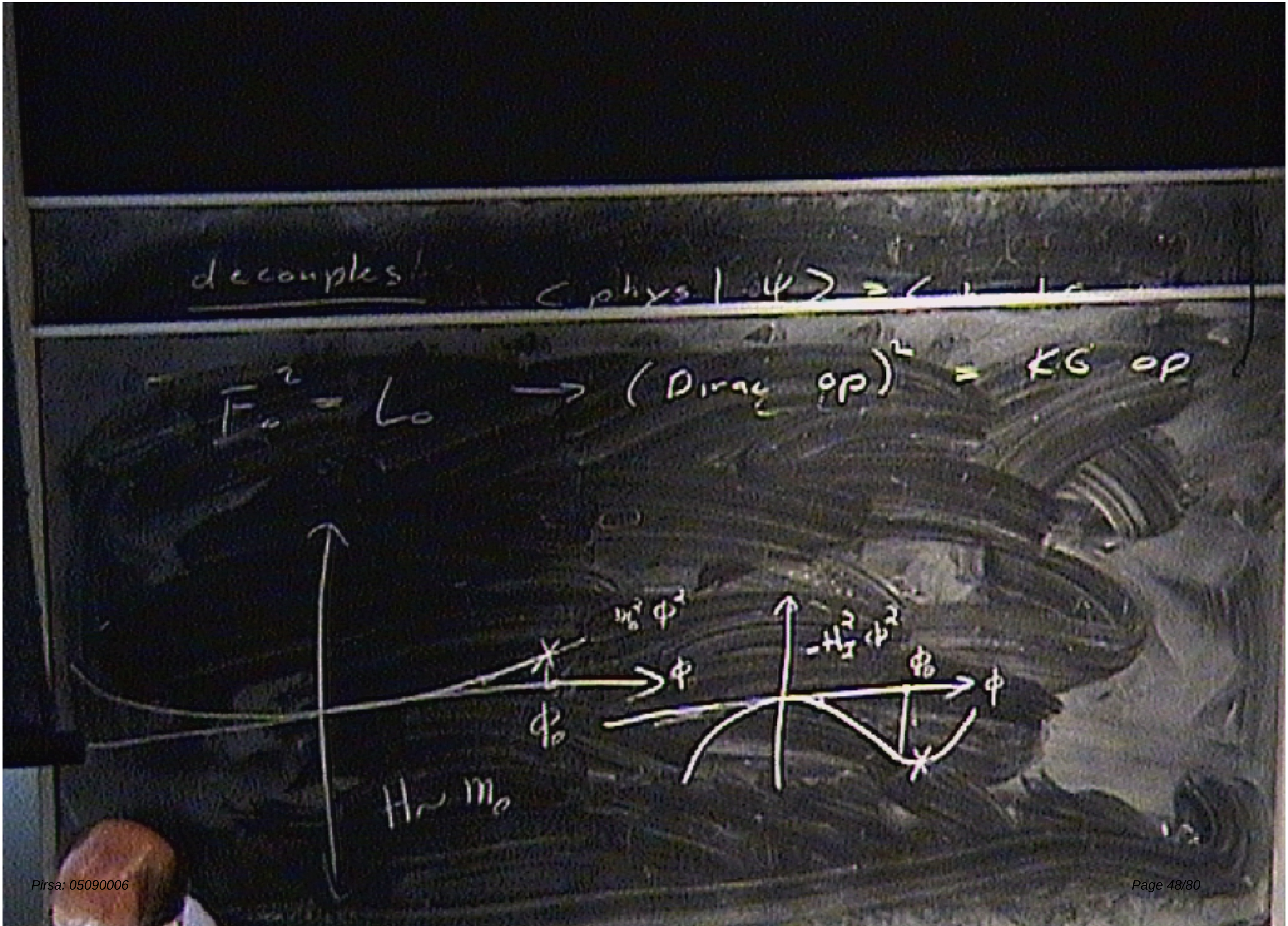
$$T_{\mathrm{R}} \sim (\Gamma_{\mathrm{thr}} M_{\mathrm{P}})^{1/2}. \tag{10}$$

T_{R} independent from Γ_{d}, generically very low.

Note:

$$m_\phi \lesssim \varphi_0 \lesssim M_{\mathrm{P}}. \tag{11}$$

$\varphi_0 \sim M_{\mathrm{P}}$ natural if an R-symmetry protects su-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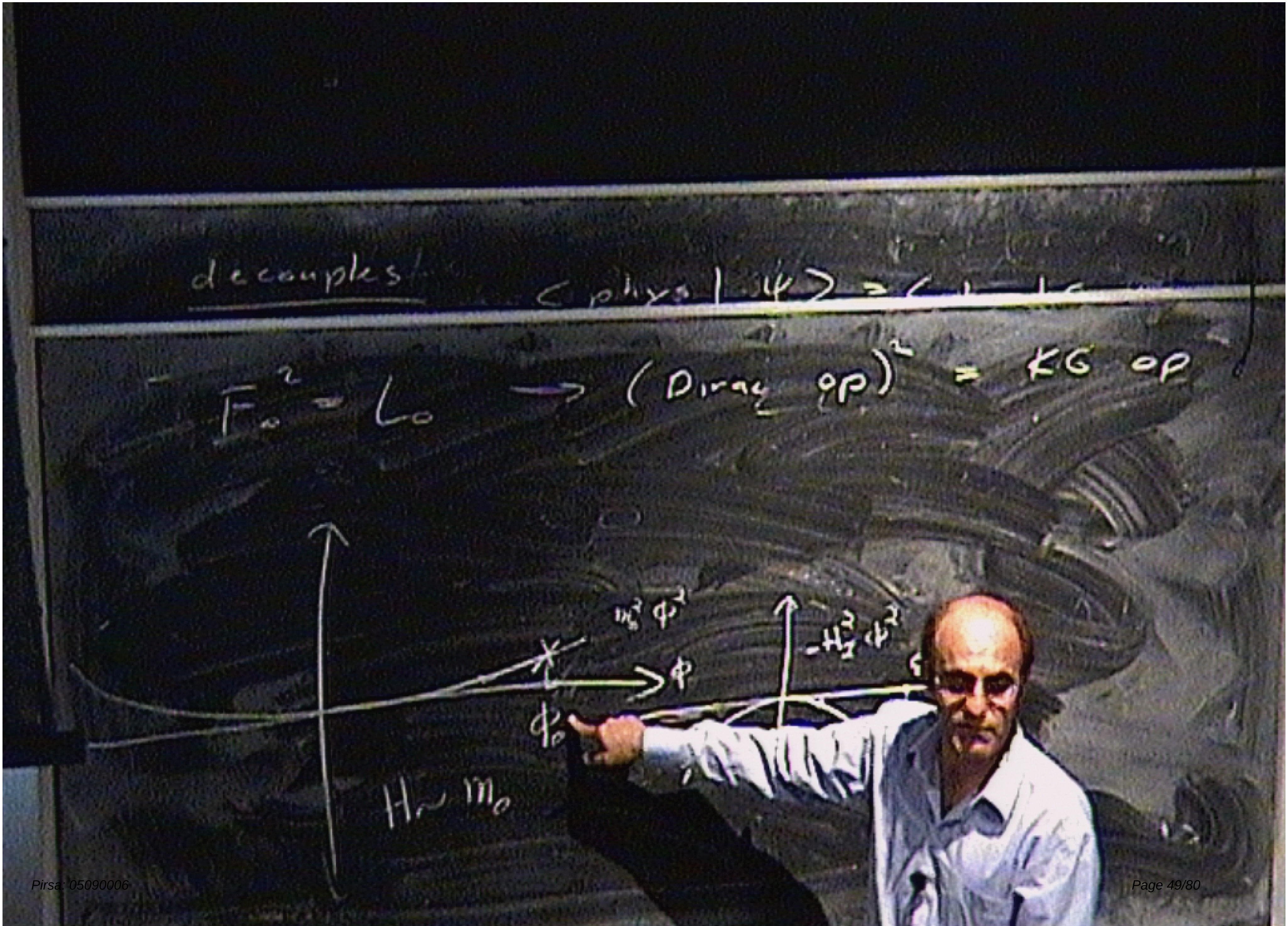
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$$T_{\rm R} \sim (\Gamma_{\rm thr} M_{\rm P})^{1/2}. \tag{10}$$

$T_{\rm R}$ independent from $\Gamma_{\rm d}$, generically very low.

Note:

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$\Rightarrow$ $T_R \sim 1$ TeV, regardless of how fast inflaton decays!

- Quasi-thermal phase:

Typical situation:

$$\Gamma_{\mathrm{thr}} \ll \Gamma_{\mathrm{kin}} \ll \Gamma_{\mathrm{d}}.$$

Universe enters a long period of quasi-therm
phase after inflaton decay.

$\Gamma_{\mathrm{thr}} < H < \Gamma_{\mathrm{d}}$: Comoving number density ar
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For the i–th degree of freedom:

$$n_i \sim A_i T^3 \ , \ \rho_i \sim A_i T^4 \quad A = \sum_i A_i. \qquad (13)$$

The Hubble expansion rate is given by:

$$H \sim A^{1/2} \frac{T^2}{M_\mathrm{P}}. \quad (14)$$

Highest temperature $T_\mathrm{max} \sim m_\phi$, just after inflaton decay.

Lowest temperature $T_\mathrm{min} \sim \left(\frac{\Gamma_\mathrm{thr}}{\Gamma_\mathrm{d}}\right)^{1/2} m_\phi$.

- $H \simeq \Gamma_\mathrm{thr}$: Number of particles increases rapidly, full equilibrium established. Temperature sharply drops from T_min to T_R.

Final entropy density:

$$s = \frac{2\pi^2}{45} g_* T_\mathrm{R}^3. \quad (15)$$

⇒ Thermal production of particles in the plasma considerably modified.

Consider a weakly coupled particle χ, with mass m_χ:

$$\dot{n}_\chi + 3Hn_\chi = \langle \sigma_\chi v_{\text{rel}} \rangle \; n^2. \qquad (16)$$

- $T_{\text{min}} \leq T \leq T_{\text{max}}$: $n \sim AT^3$, $H \sim A^{1/2} \frac{T^2}{M_{\text{P}}}$.

- $m_\chi \lesssim T \leq T_{\text{R}} \Rightarrow n \sim T^3$, $H \sim \frac{T^2}{M_{\text{P}}}$.

Cosmologically interesting particles: gravitino, right-handed (s)neutrino, supersymmetric dark matter, etc.

Production dominant around the highest tem-perature:

$$\left(\frac{n_{3/2}}{s}\right)_{eq} \sim \left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right) \times 10^{-12}. \qquad (17)$$

$$\left(\frac{n_{3/2}}{s}\right)_{quasi} \sim A^{+3/4} \left(\frac{T_{\max}}{10^{10}\ \mathrm{GeV}}\right) \times 10^{-12}. \qquad (18)$$

$m_{3/2} \sim \mathcal{O}(\mathrm{TeV})$: gravitinos decay during or after BBN, decay prodcuts dissociate light elements. Constraint from BBN:

$$\frac{n_{3/2}}{s} < (10^{-16} - 10^{-12})$$

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Similar bounds obtained from the dark matter limit if gravitino is stable.

Situation after preheating:

$n \gg n_{eq}$, $E \ll E_{eq}$

$\Rightarrow$ Number of particles must DECREASE.

- Large occupation numbers.
- Large effective masses.
- No asymptotic states.

Initially, approximation with classical fields

kinetic equilibrium reached very quickly,

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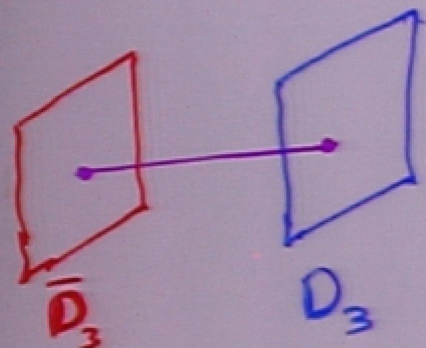
Proper field theoretical treatment required →
non-equilibrium quantum field theory.

compactifications with multiple throats:

- Inflationary throat: effective string scale M



Inflation → $\bar{D}_3 D_3$ annihilation → massive clos

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Tunneling to

- SM throat: effective string scale $M_{SM} \sim$

KK modes decay to matter.

Further considerations:

- KK modes in the inflationary throat and

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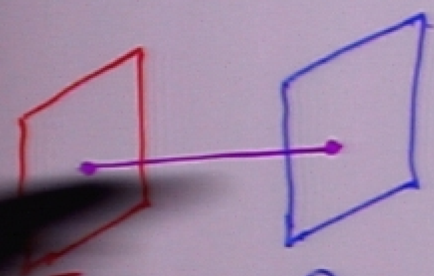

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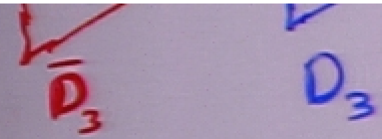

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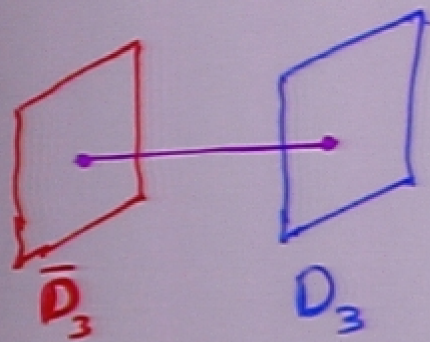

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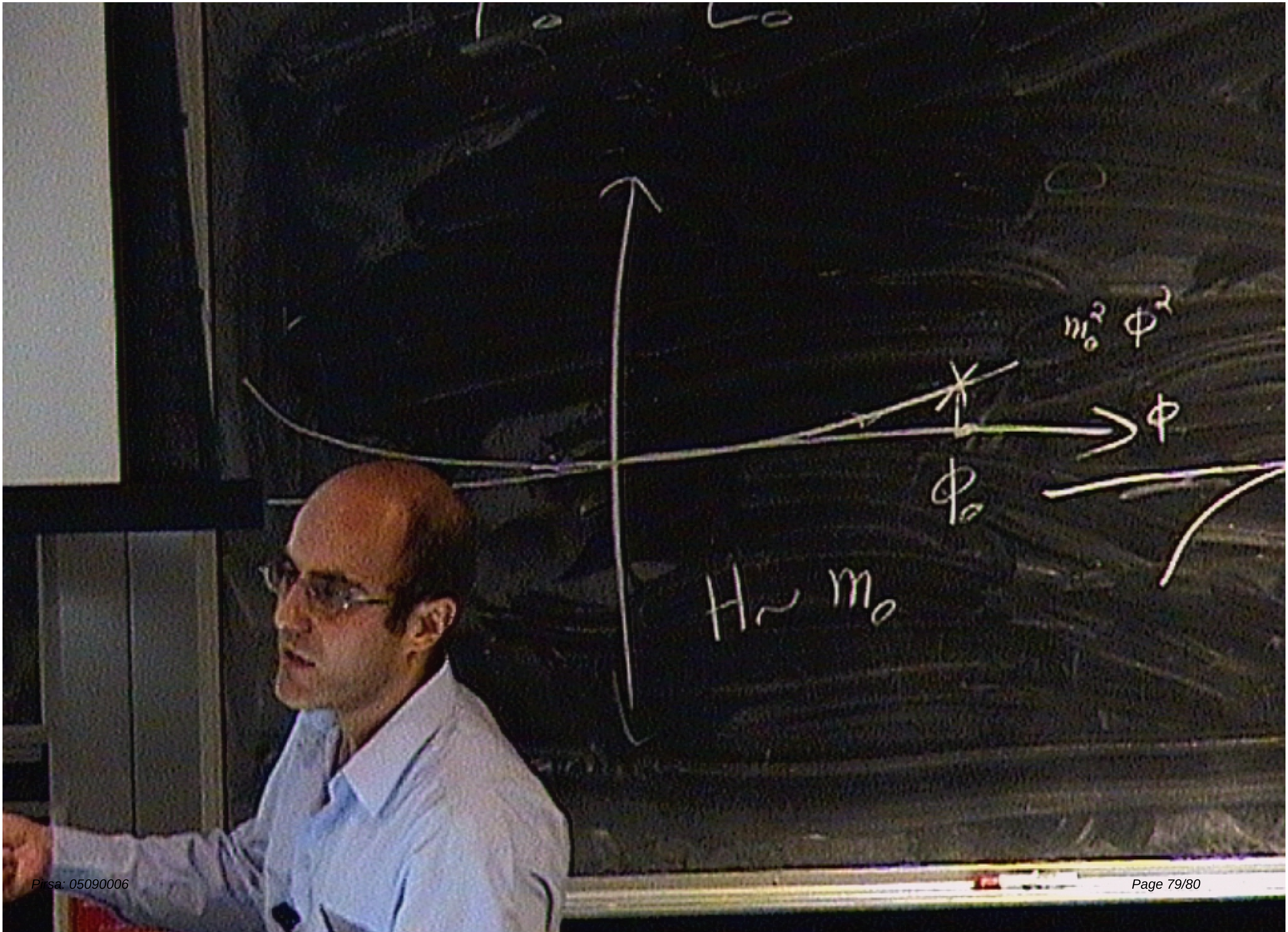

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