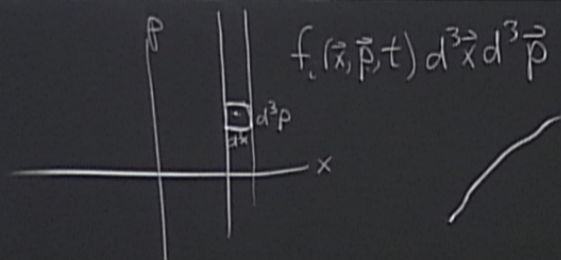


Title: 12/13 PSI - Cosmology Review Lecture 8

Date: Feb 28, 2013 11:30 AM

URL: <http://pirsa.org/13020108>

Abstract:

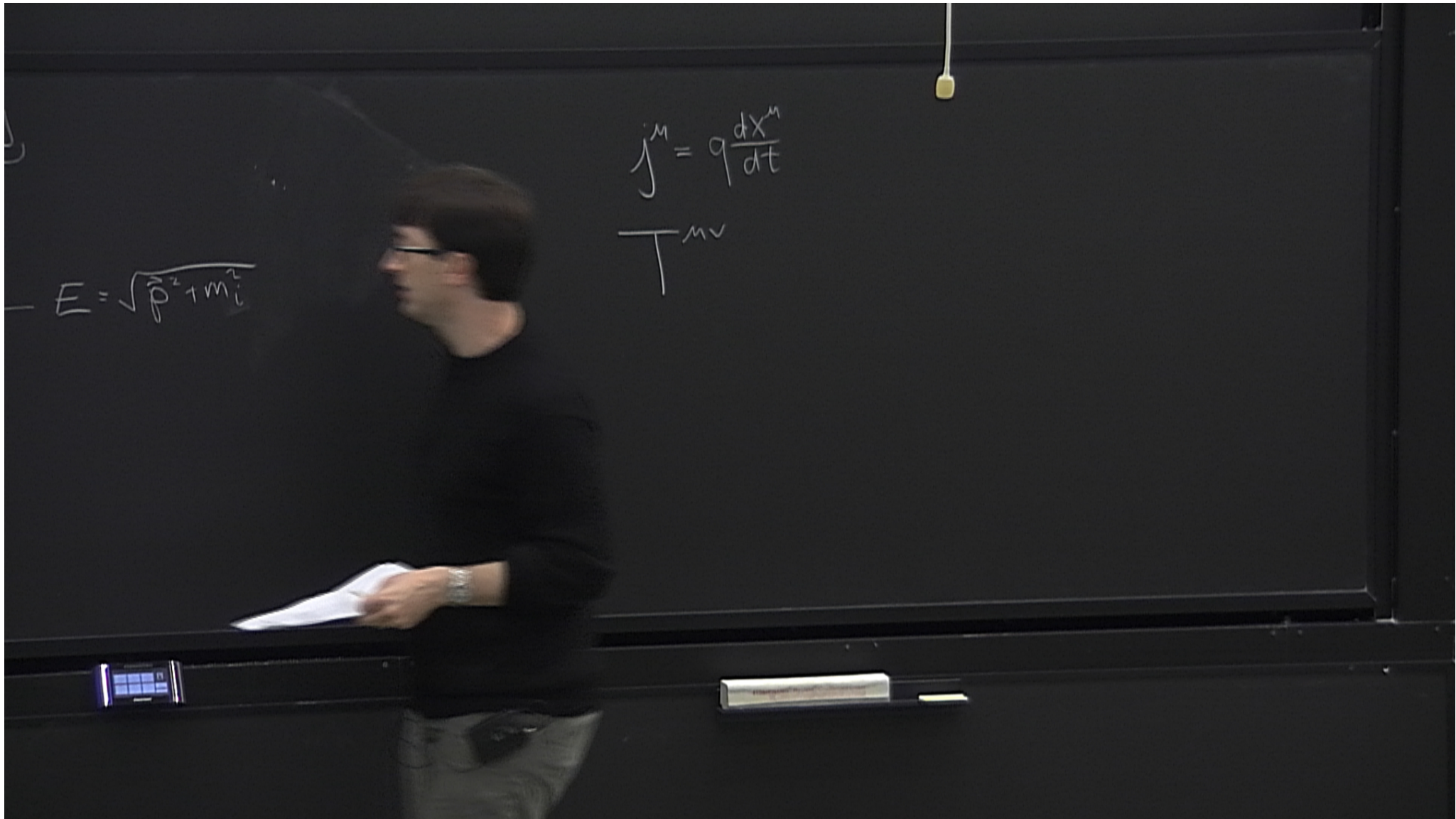


Boltzmann $(\quad)f_i = C[f]$

$$n_i = \int d^3\vec{p} f_i(\vec{x}, \vec{p}, t)$$

$$p_i = \int d^3\vec{p} f_i(\vec{x}, \vec{p}, t) E \leftarrow E = \sqrt{\vec{p}^2 + m_i^2}$$

$$p_i = \int d^3\vec{p} f_i(\vec{x}, \vec{p}, t) \frac{\vec{p}^2}{3E}$$



$$E = \sqrt{\vec{p}^2 + m_i^2}$$

$$j^m = q \frac{dx^m}{dt}$$

$$p^m = \frac{dx^m}{dt}$$

$$T^{mv} = p^v \frac{dx^m}{dt} = p^v \frac{p^m}{p^0}$$

$$T^m_v = \begin{pmatrix} -\mathcal{L} & 0 \\ 0 & p_p \end{pmatrix}$$

$$E = \sqrt{\vec{p}^2 + m_i^2}$$

$$j^m = q \frac{dx^m}{dt}$$

$$p^m = \frac{dx^m}{dt}$$

$$T^{m\nu} = p^\nu \frac{dx^m}{dt} = p^\nu \frac{p^m}{p^0}$$

$\frac{\vec{p}^2}{3E}$

$$T^m_\nu = \begin{pmatrix} -\rho & 0 \\ 0 & p_p \end{pmatrix}$$

$$\frac{d^3p}{d^3x}$$

$$h^3 = (2\pi\hbar)^3$$

$$\frac{1}{\exp[(E - m_i)/T_i] + 1}$$

Relativistic

$T_i \gg m_i, m_e$

$$n_i = \frac{g_i}{\pi^2} T_i^3$$

$$p_i = \frac{\pi^2}{30} T_i^4$$

$$P_i = \frac{1}{10} n_i$$

$$\frac{d^3p}{d^3x}$$

$$\frac{h^3 = (2\pi\hbar)^3}{\exp[(E - m_i)/T_i] + 1}$$

Relativistic

$$T_i \gg m_i, m_i$$

$$n_i = \frac{g_i}{\pi^2} T_i^3$$

$$\hbar = c = 1$$

$$p_i = \frac{\pi^2}{30} T_i^4$$

$$\rho_i = \frac{\pi^2}{90} T_i^4$$

$$\frac{d^3p}{d^3\lambda}$$

$$h^3 = (2\pi\hbar)^3$$

$$\exp\left[\frac{(E - m_i)}{T_i}\right] \mp 1$$

Relativistic

$$T_i \gg m_i, m_i$$

$$n_i = \frac{g_i}{\pi^2} T_i^3$$

$$p_i = \frac{\pi^2}{30} T_i^4$$

$$\rho_i = \frac{\pi^2}{90} T_i^4$$

$$k_B = \hbar = c = 1$$

$$E$$

$$\int d^3p$$

$$h^3 = (2\pi\hbar)^3$$

$$\frac{1}{\exp[(E - m_i)/k_B T_i] + 1}$$

$$E = \vec{p}^2 + m_i^2$$

Relativistic

$$T_i \gg m_i, m_i$$

$$n_i = \frac{g_i}{\pi^2} T_i^3$$

$$p_i = \frac{\pi^2}{30} T_i^4$$

$$\rho_i = \frac{\pi^2}{90} T_i^4$$

$$k_B = \hbar = c = 1$$

$$G_N = \frac{1}{m_{Pl}^2}$$

$$\int \frac{d^3p}{(2\pi)^3}$$

$$h^3 = (2\pi\hbar)^3$$

$$\frac{1}{\exp[(E - m_i)/k_B T_i] + 1}$$

$$E = \vec{p}^2 + m_i^2$$

Relativistic

$$T_i \gg m_i, m_e$$

$$n_i = \frac{g(3)}{\pi^2} T_i^3$$

$$p_i = \frac{\pi^2}{30} T_i^4$$

$$\rho_i = \frac{\pi^2}{90} T_i^4$$

$$k_B = \hbar = c = 1$$

$$G_N = \frac{1}{m_{Pl}^2}$$

$$\frac{p_i}{\rho_i} = \frac{1}{3} = w_i$$

$$E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$m_{Pl} \sim 10^{19} \text{ GeV}$$

m_i, m_i

$$k_B = \hbar = c = 1 \quad E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$G_N = \frac{1}{m_{pl}^2}$$

$$m_{pl} \sim 10^{19} \text{ GeV}$$

$$\frac{p_i}{p_i} = \frac{1}{3} = w_i$$

Non-Rel $T_i \ll m_i$ (

$$m_i, m_i$$

$$k_B = \hbar = c = 1 \quad E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$G_N = \frac{1}{m_{pl}^2}$$

$$m_{pl} \sim 10^{19} \text{ GeV}$$

$$\frac{p_i}{p_i} = \frac{1}{3} = w_i$$

Non-Rel $T_i \ll m_i$ ($m_i > m_i$)

$$m_i, m_i$$

$$k_B = \hbar = c = 1 \quad E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$G_N = \frac{1}{m_{pl}^2} \leftarrow m_{pl} \sim 10^{19} \text{ GeV}$$

$$\frac{p_i}{g_i} = \frac{1}{3} = w_i$$

$$\text{Non-Rel } T_i \ll m_i \quad (m_i > M_i)$$

$$n_i =$$

$$\left[\begin{array}{l} g_i = m_i n_i \\ p_i = T_i n_i \end{array} \right]$$

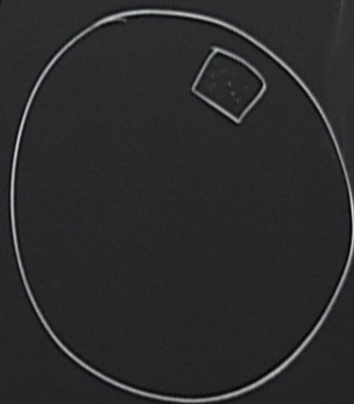
$$\frac{p_i}{g_i}$$

$$m_i, m_i$$

$$k_B = \hbar = c = 1 \quad E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$G_N = \frac{1}{m_{pl}^2} \leftarrow m_{pl} \sim 10^{19} \text{ GeV}$$

$$\frac{p_i}{g_i} = \frac{1}{3} = w_i$$



Non-Rel $T_i \ll m_i$ ($m_i > M_i$)

$$n_i =$$

$$g_i = n_i \quad p_i =$$

$$p_i =$$

$$m_i, m_i$$

$$k_B = \hbar = c = 1 \quad E \sim M \sim T \sim \frac{1}{L} \sim \frac{1}{T}$$

$$G_N = \frac{1}{m_{pl}^2} \leftarrow m_{pl} \sim 10^{19} \text{ GeV}$$

$$\frac{p_i}{g_i} = \frac{1}{3} = w_i$$



Non-Rel $T_i \ll m_i$ ($m_i > m_i$)

$$n_i = \left(\frac{m_i T_i}{2\pi} \right)^{3/2} \exp \left[-\frac{m_i - m_i}{T_i} \right]$$

$$\left[\begin{array}{l} g_i = m_i n_i \\ p_i = T_i n_i \end{array} \right] \quad \frac{p_i}{g_i} \approx 0 = w_i$$

$$\int d^3p$$

$$\frac{1}{h^3} = (2\pi\hbar)^3$$

$$\exp\left[\frac{(E - m_i)}{k_B T_i}\right] + 1$$

$$E = \vec{p}^2 + m_i^2$$

$$T \gg m_i$$

Relativistic

$$T_i \gg m_i, m_e$$

$$\frac{\pi^2}{2} T_i^3$$

$$\frac{\pi^2}{30} T_i^4$$

$$\frac{\pi^2}{90} T_i^4$$

$$k_B = \hbar = c = 1$$

$$G_N = \frac{1}{m_{Pl}^2}$$

$$\frac{p_i}{\rho_i} = \frac{1}{3} = w_i$$

$$\int \frac{d^3p}{(2\pi)^3}$$

$$h^3 = (2\pi\hbar)^3$$

$$\frac{1}{\exp[(E - m_i)/k_B T_i] + 1}$$

$$E = \vec{p}^2 + m_i^2$$

$$T \gg m_i$$

$$T \ll m_i$$

Relativistic

$$T_i \gg m_i, m_i$$

$$n_i = \frac{g_i}{\pi^2} T_i^3$$

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$$k_B = \hbar = c = 1$$

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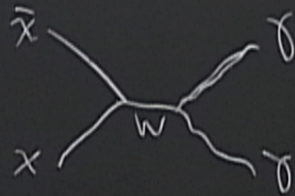
$$\frac{p_i}{\rho_i} = \frac{1}{3} = w_i$$

$\chi + \bar{\chi}$

m_χ

WIMP

$m_\chi \sim 1 \text{ GeV}$

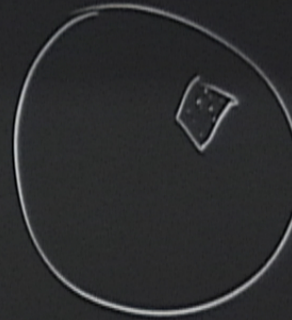


$$\chi + \bar{\chi}$$

$$m_\chi$$

WIMP

$$m_\chi \sim 1 \text{ GeV}$$



$$n_i \propto \frac{1}{a^3}$$

e^+

e^-

γ

$$\frac{1}{\exp[(E-m_+)/T] + 1}$$

$e^+ \quad e^- \quad \gamma$

$$\frac{1}{\exp[(E-m_+)/T] + 1}$$

$\uparrow$

$$\frac{1}{\exp[(E-m)/T] + 1}$$

$\nearrow \vec{p}^2 + m^2$

e^+ e^- γ

$$\frac{1}{\exp[(E-m_+)/T] + 1}$$

$\uparrow$

$$\frac{1}{\exp[(E-m)/T] + 1}$$

$\nearrow \vec{p}^2 + m^2$

$$\underline{\bar{\chi} + \chi \rightarrow \gamma + \gamma}$$

$$e^+$$

$$e^-$$

$$\gamma$$

$$e^+$$

$$\underline{S = \frac{p+p}{T}}$$



$$\underline{S = \frac{p+p}{T} = \frac{2\pi^3}{45} T^3}$$

$\Gamma \gg H$



$$\underline{S = \frac{\rho + p}{T} = \frac{2\pi^3}{45} T^3}$$

$$S \propto a^{-3}$$

$$T \propto \frac{1}{a}$$

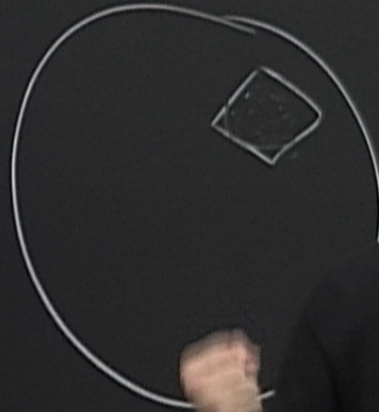
$$\begin{array}{ccc} \Gamma & \gg & H \\ \downarrow & & \downarrow \\ \frac{1}{\Gamma} & \ll & \frac{1}{H} \end{array}$$



$$S = \frac{\rho + p}{T} = \frac{2\pi^3}{45} T^3$$

$$S \propto a^{-3}$$

$$T \propto \frac{1}{a}]$$



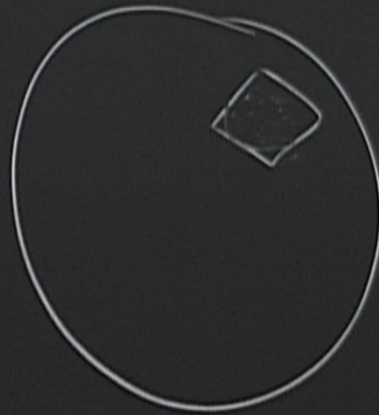
$$\Gamma \rightarrow H$$



$$\underline{S = \frac{\rho + p}{T} = \frac{2\pi^3}{45} T^3}$$

$$S \propto a^{-3}$$

$$T \propto \frac{1}{a}]$$

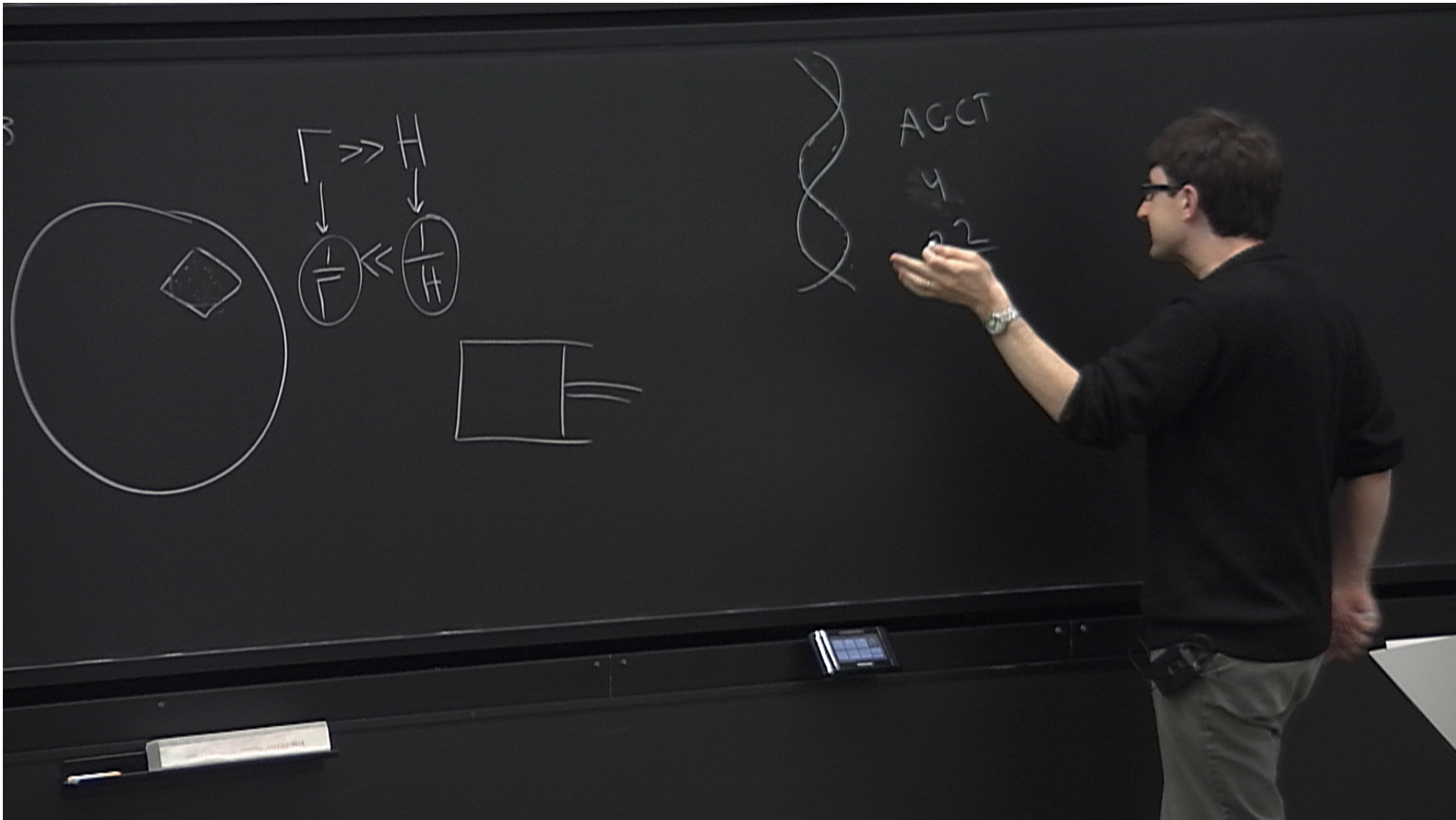


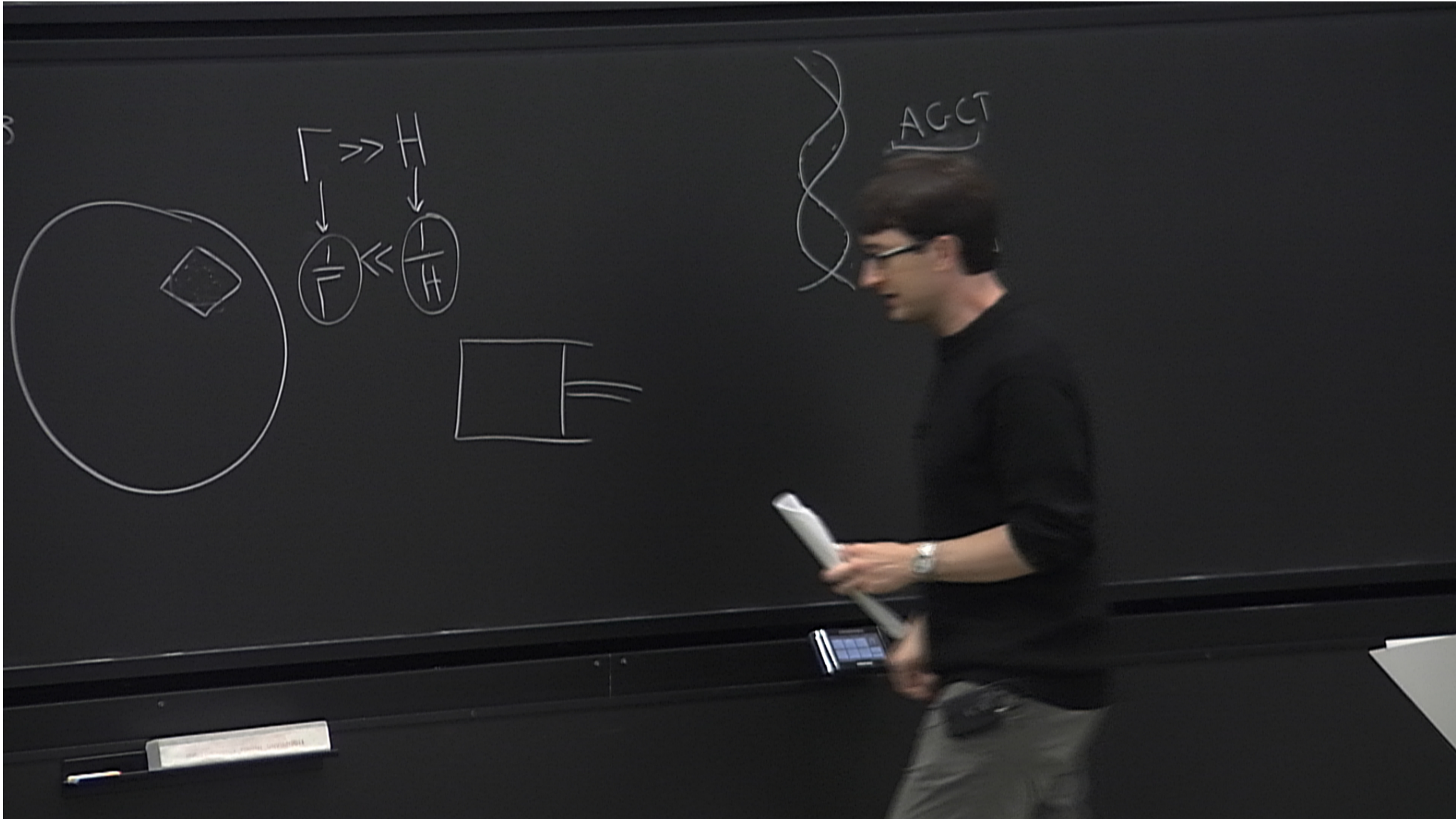
$$\Gamma \gg H$$

$$\downarrow \quad \downarrow$$

$$\left(\frac{1}{\Gamma}\right) \ll \left(\frac{1}{H}\right)$$







$$\overline{X} + X \rightarrow \gamma + \gamma$$

 e^+
 e^-
 γ
