

Title: Cosmology Review - Lecture 10

Date: Feb 04, 2011 11:30 AM

URL: <http://pirsa.org/11020091>

Abstract:

$T_F \approx \frac{1}{2} 2590 \text{ K}$, He, He III



$T_F \approx \frac{1}{2} \cdot 2590 \text{ K} \cdot 10^9$

$T_F \approx \frac{1}{2} \cdot 2590 \text{ K}$

$\approx 10^9 \text{ K}$

$T_F \approx \frac{1}{2} \cdot 25\% \text{ He, H}$

$a \cdot 10^9 \cdot 10^{27}$

BBN

$T_F \sim \frac{1}{2}$ 25% He, H
 $a \sim 10^9 \cdot 10^{27}$

$(T \sim 1 \text{ MeV})$
1 sec - 1 min
 $a \sim 10^{-9}$

CMB

$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

BBN

$T_F \frac{1}{2}$ 25% He, H

$a \cdot 10^9 \cdot 10^{27}$

($T \sim 1 \text{ MeV}$
1 sec - 1 min
 $a \sim 10^{-9}$)

CMB

$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p^+ + e^- \rightarrow H$

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

BBN

$$T_F \sim \frac{1}{2} \quad 25\% \text{ He, H}$$

$$a \cdot 10^9 \quad 10^{27}$$

$$\left(\begin{array}{l} T \sim 1 \text{ MeV} \\ 1 \text{ sec} - 1 \text{ min} \\ a \sim 10^{-9} \end{array} \right)$$

CMB

$$T \sim 1 \text{ eV} \\ \text{few} \times 10^5 \text{ yrs old} \\ a \sim 10^{-3}$$

$$p^+ + e^- \rightarrow H$$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{E - \mu}{T}\right] + 1}$$

BBN

$T_F \sim \frac{1}{2}$ 25% He, H

$a \sim 10^9 \cdot 10^{27}$

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} \sim 1 \text{ min}$
 $a \sim 10^{-9}$

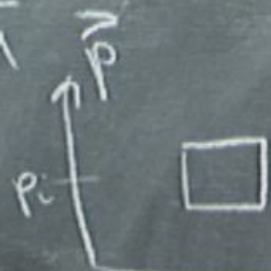
CMB

$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p + \bar{p} \rightarrow H$

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

$$\frac{d^3 \vec{p}}{d^3 \vec{x}} \frac{d^3 \vec{p}}{d^3 \vec{x}} \\ \exp\left[-\frac{p}{T_i}\right] = 1$$



BBN

$$T_F \sim \frac{1}{2} \text{ 25\% He, H}$$

$$a \sim 10^9 \text{ } 10^{27}$$

$$\left(\begin{array}{l} T \sim 1 \text{ MeV} \\ 1 \text{ sec} \sim 1 \text{ min} \\ a \sim 10^{-9} \end{array} \right)$$

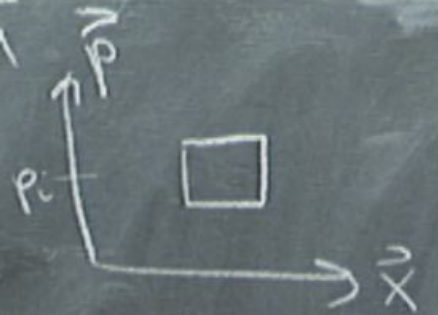
CMB

$$\begin{array}{l} T \sim 1 \text{ eV} \\ \text{few } \times 10^5 \text{ yrs old} \\ a \sim 10^{-3} \end{array}$$



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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p}{T_i}\right]} = 1$$



BBN

$T_F \sim \frac{1}{2}$ 25% He, H

$a \cdot 10^9 \quad 10^{27}$

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$

CMB

$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p^+ + e^- \rightarrow H$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p}{T_i}\right] - 1}$$



BBN

$T_F \frac{1}{2}$ 25% He, H
 $a \cdot 10^9 \cdot 10^{27}$

$(T \sim 1 \text{ MeV})$
1 sec - 1 min
 $a \sim 10^{-9}$

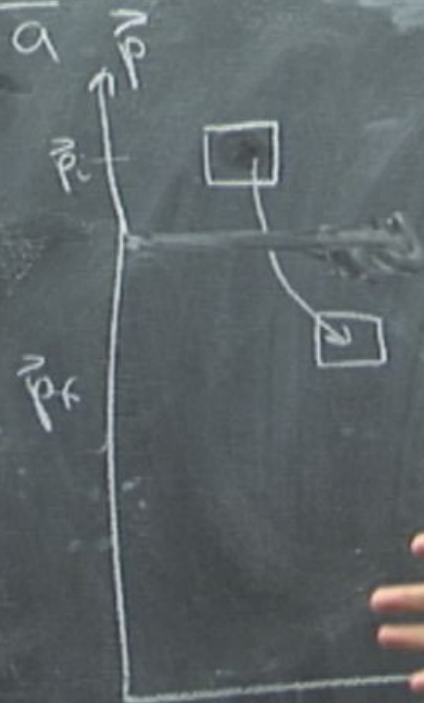
CMB

$T \sim 1 \text{ eV}$
few 10^5 yrs old
 $a \sim 10^{-3}$



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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p}{T}\right] - 1}$$



BBN

$T_F \frac{1}{2}$ 25% He, H
 $a \cdot 10^9 \quad 10^{27}$

$(T \sim 1 \text{ MeV})$
1 sec - 1 min
 $a \sim 10^{-9}$

(1)

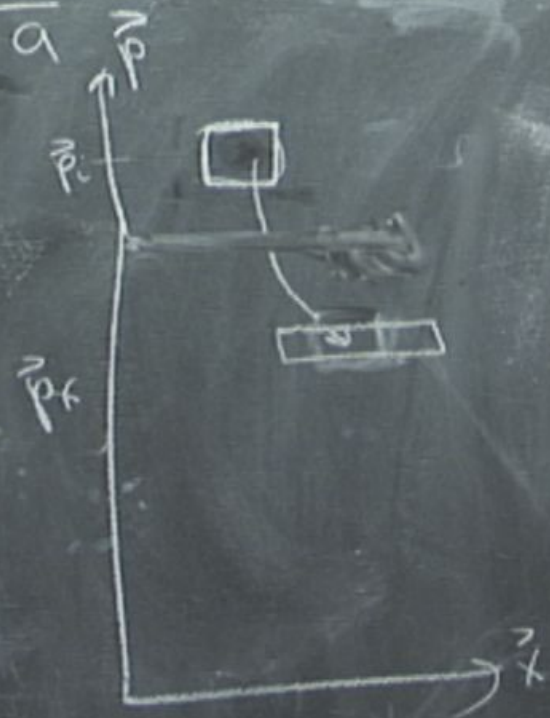
CMB

$T \sim 1 \text{ eV}$
few 10^5 yrs old
 $a \sim 10^{-3}$

$p + \bar{p} \rightarrow H$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p}{T}\right] - 1}$$



BBN

$T_F \frac{1}{2}$ 25% He, H
 $a \cdot 10^9 \cdot 10^{27}$

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} \sim 1 \text{ min}$
 $a \sim 10^{-9}$

CMB

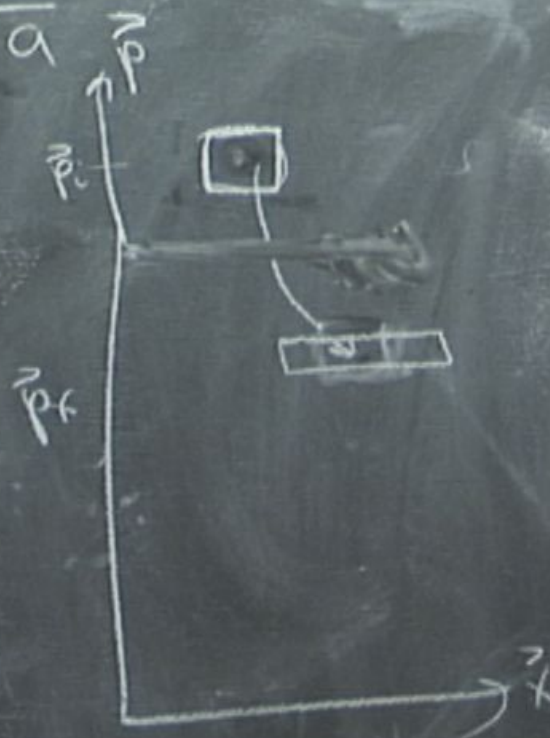
$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p^+ + e^- \rightarrow H$

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

$$\frac{d^3 \vec{p}_i d^3 \vec{x}_i}{\exp\left[\frac{p_i}{T_i}\right]} = 1$$

$$= \frac{d^3 \vec{p}_f d^3 \vec{x}_f}{\exp\left[\frac{p_f}{T_f}\right]} = 1$$



BBN

$T_F \sim \frac{1}{2}$ 25% He, H

$a \sim 10^9 \quad 10^{27}$

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$

CMB

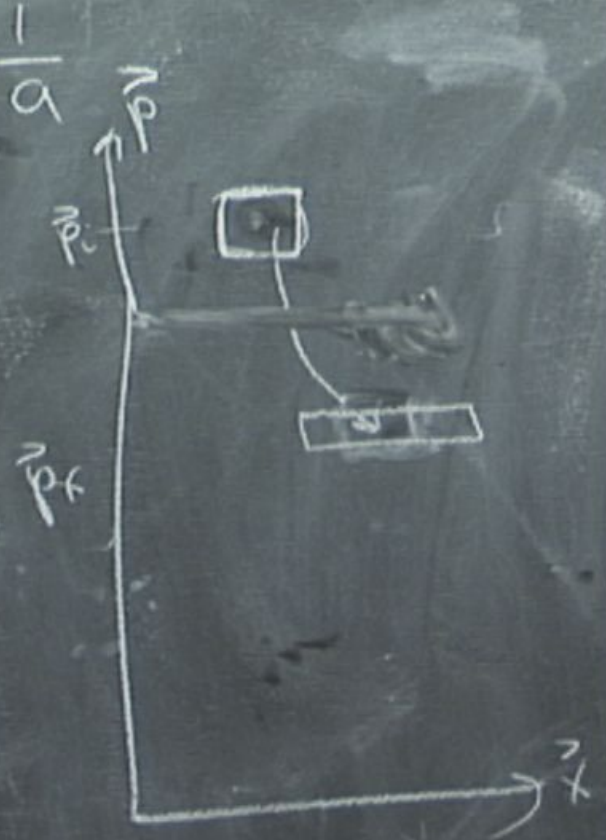
$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p^+ + e^- \rightarrow H$

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

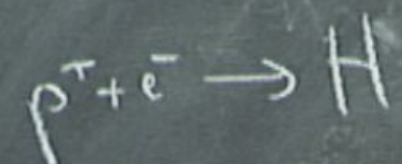
$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i}{T_i}\right] - 1}$$

$$= \frac{d^3 \vec{p}^- d^3 \vec{x}}{\exp\left[\frac{p_i/a}{T/a}\right] - 1}$$



10^{27}

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$



T

$d^3 \vec{p} \cdot d^3 \vec{x}$

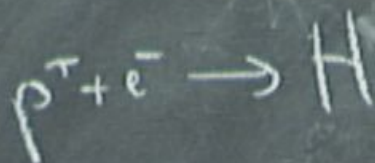
ex $\int d^3x = 1$

$d^3 \vec{p} \cdot \vec{x}$

exp

10^{27}

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$



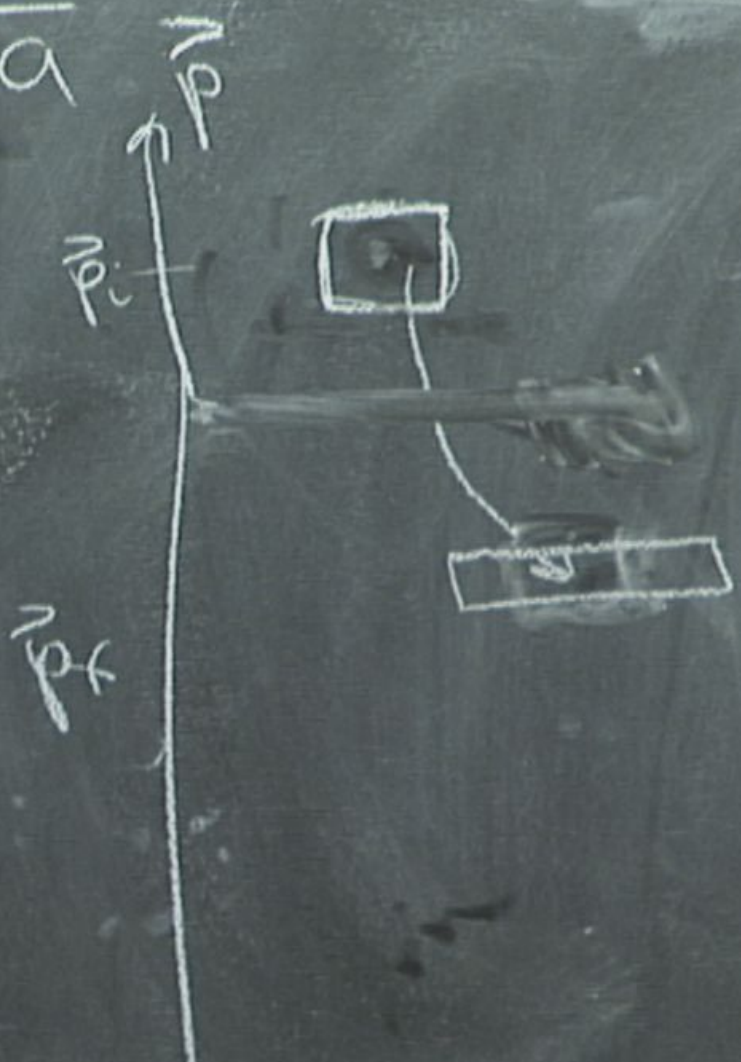
$$T \propto \frac{1}{a}$$

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

$$\exp\left[\frac{p_i}{T_i}\right] - 1$$

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

$$\exp\left[\frac{p_i/a}{T_i/a}\right] - 1$$



10^{27}

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} \sim 1 \text{ min}$
 $a \sim 10^{-9}$

$$p^+ + e^- \rightarrow H$$

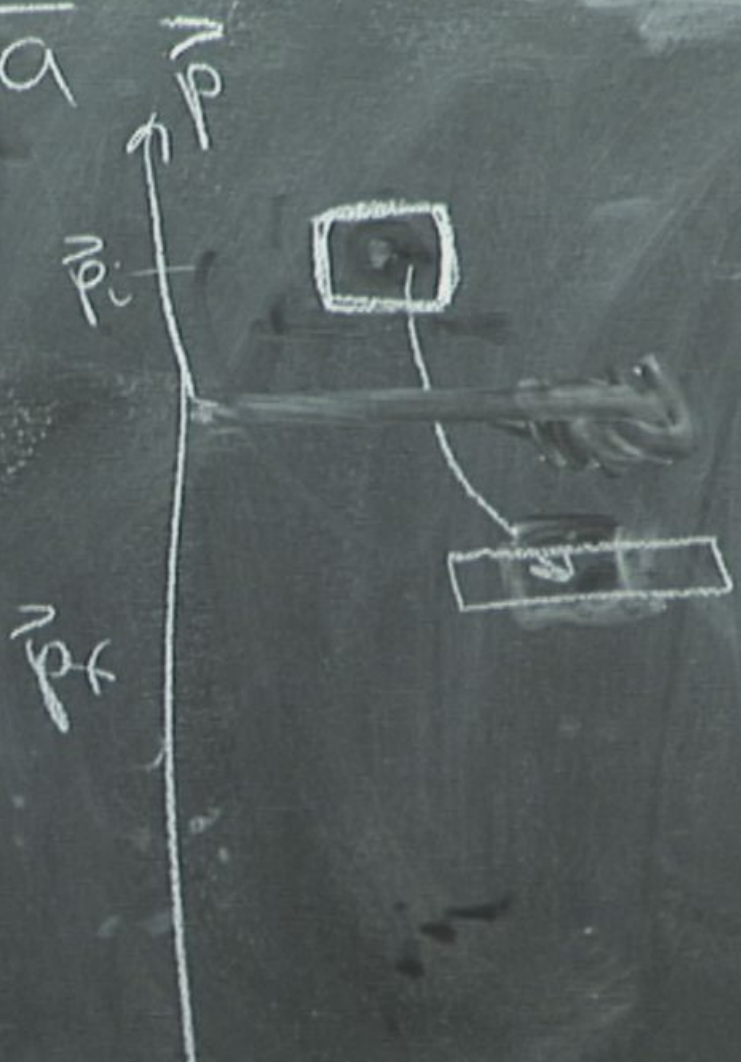
$$T \propto \frac{1}{a}$$

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

$$\exp\left[\frac{p_i}{T_i}\right] = 1$$

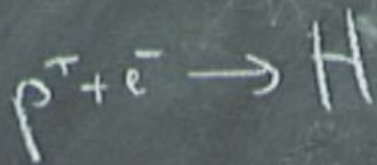
$$\frac{d^3 \vec{p}}{d^3 \vec{x}}$$

$$\exp\left[\frac{p_i/a}{T_i/a}\right] = 1$$



10^{27}

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$



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

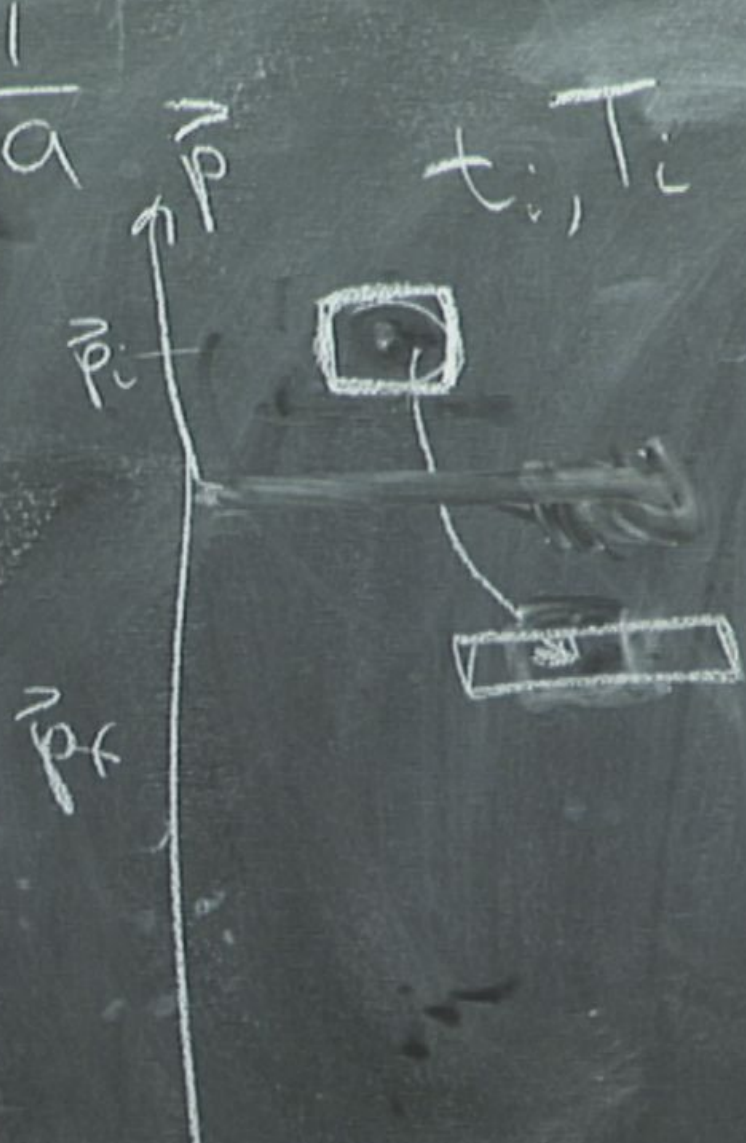
t_i, T_i

$$d^3 \vec{p} \cdot d^3 \vec{x}$$

$$\frac{d^3 \vec{p} \cdot d^3 \vec{x}}{\exp\left[\frac{p_i}{T_i}\right]} = 1$$

$$d^3 \vec{p} \cdot d^3 \vec{x}$$

$$\frac{d^3 \vec{p} \cdot d^3 \vec{x}}{\exp\left[\frac{p_i \cdot a}{T_i \cdot a}\right]} = 1$$



10^{27}

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} \sim 1 \text{ min}$
 $a \sim 10^{-9}$

$$p^{\tau} + e^{-} \rightarrow H$$

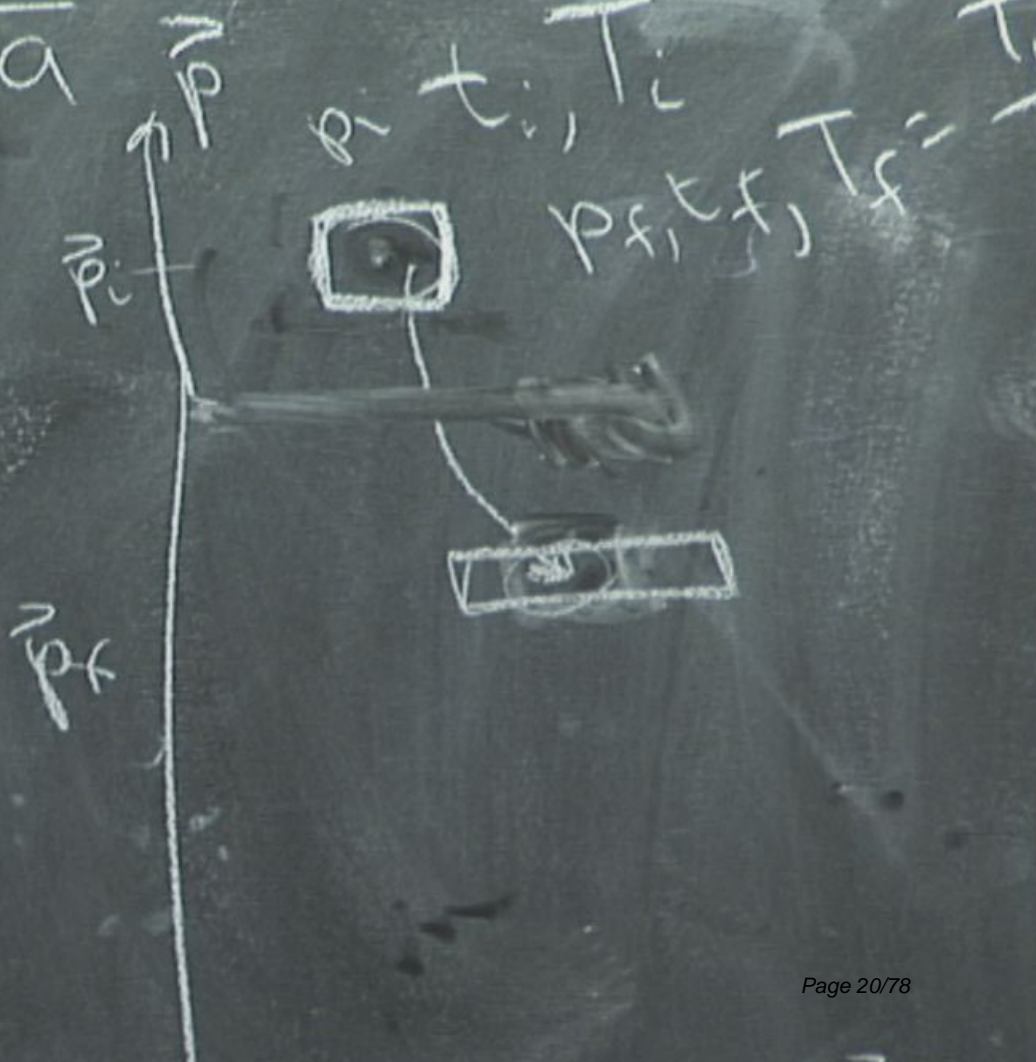
$$T \propto \frac{1}{a}$$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i}{T_i}\right]} - 1$$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i/a}{T_i/a}\right]} - 1$$



H
 $g \sim 10^{22}$

$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} \sim 1 \text{ min}$
 $a \sim 10^{-9}$

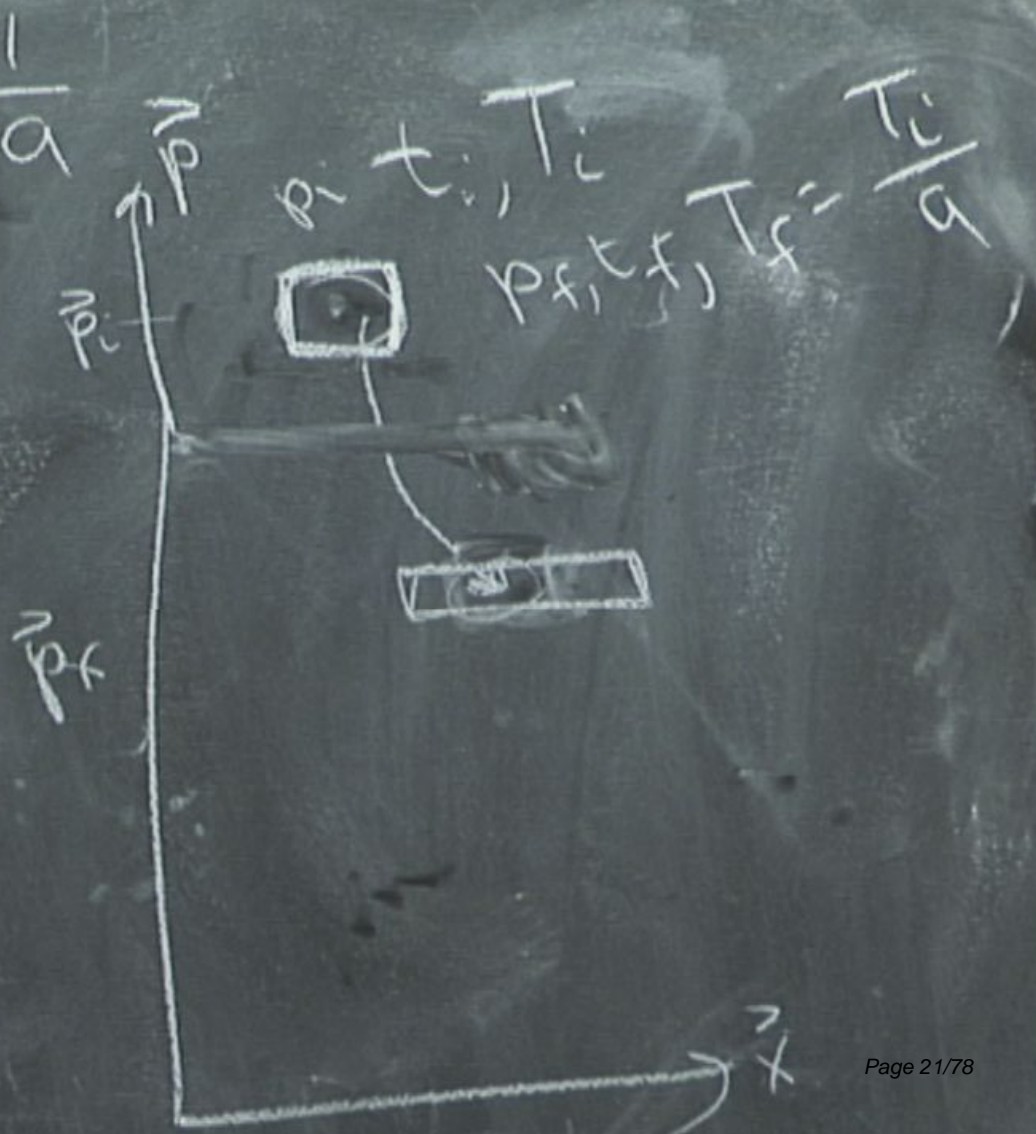
$0 =$

$p^+ + e^- \rightarrow H$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i}{T_i}\right]} = 1$$

$$= \frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i/a}{T_i/a}\right]} = 1$$



H
 $g \sim 10^{27}$

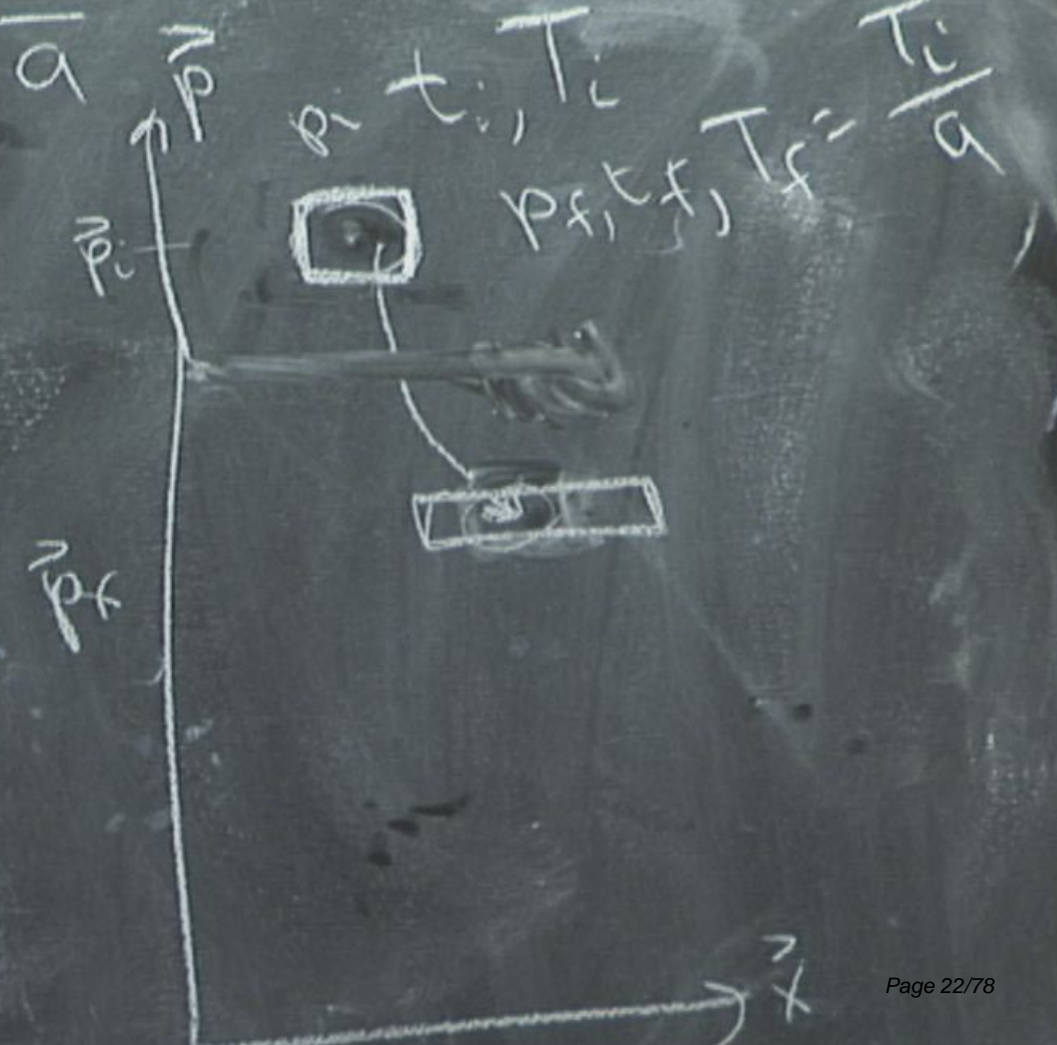
$(T \sim 1 \text{ MeV})$
 $1 \text{ sec} - 1 \text{ min}$
 $a \sim 10^{-9}$

$p^+ + e^- \rightarrow H$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p \cdot u}{T_i}\right] - 1}$$

$$= \frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p \cdot u}{T/a}\right] - 1}$$



BBN

$$T_F \sim \frac{1}{2} \quad 25\% \text{ He, H}$$

$$a \sim 10^9 \quad 10^{27}$$

$$\left(\begin{array}{l} T \sim 1 \text{ MeV} \\ 1 \text{ sec} \sim 1 \text{ min} \\ a \sim 10^{-9} \end{array} \right)$$

CMB

$$T \sim 1 \text{ eV}$$

$$\text{few } 10^5 \text{ yrs old}$$

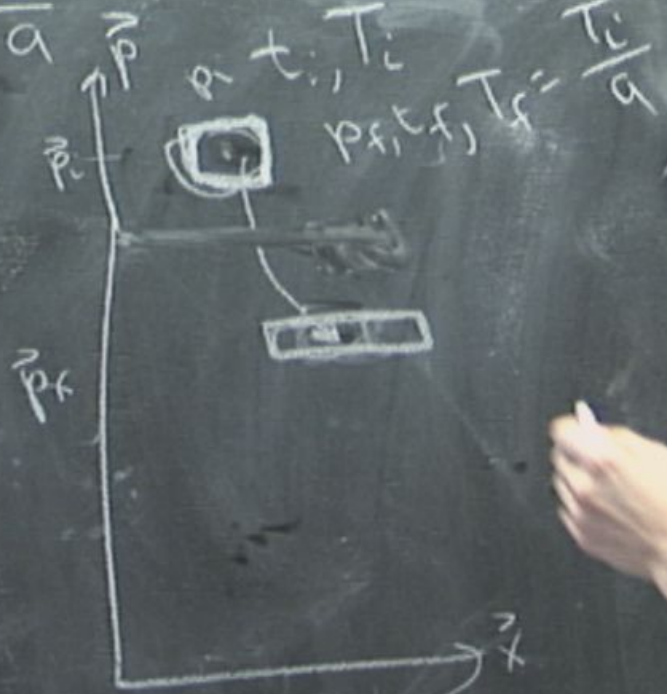
$$a \sim 10^{-3}$$

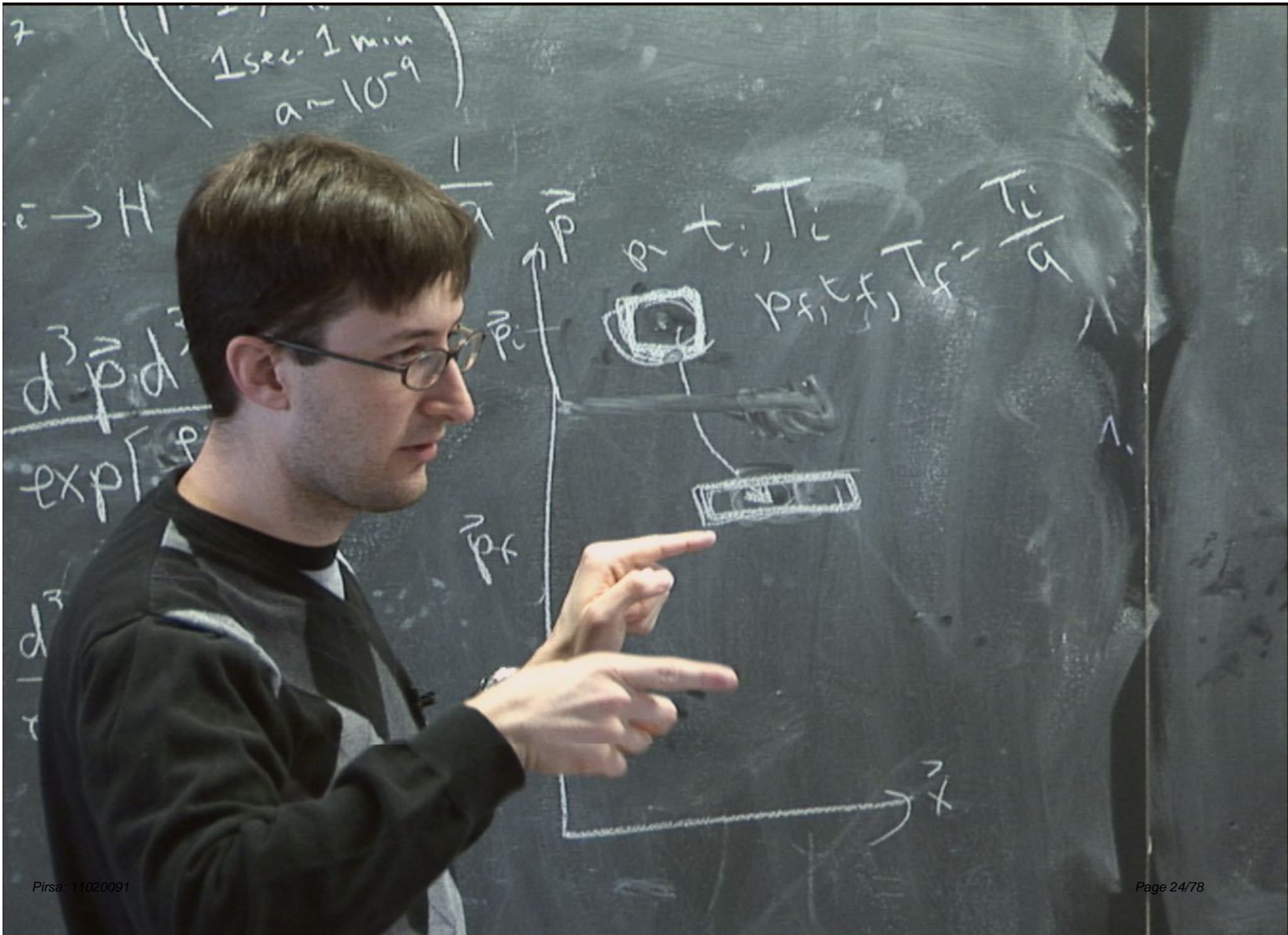


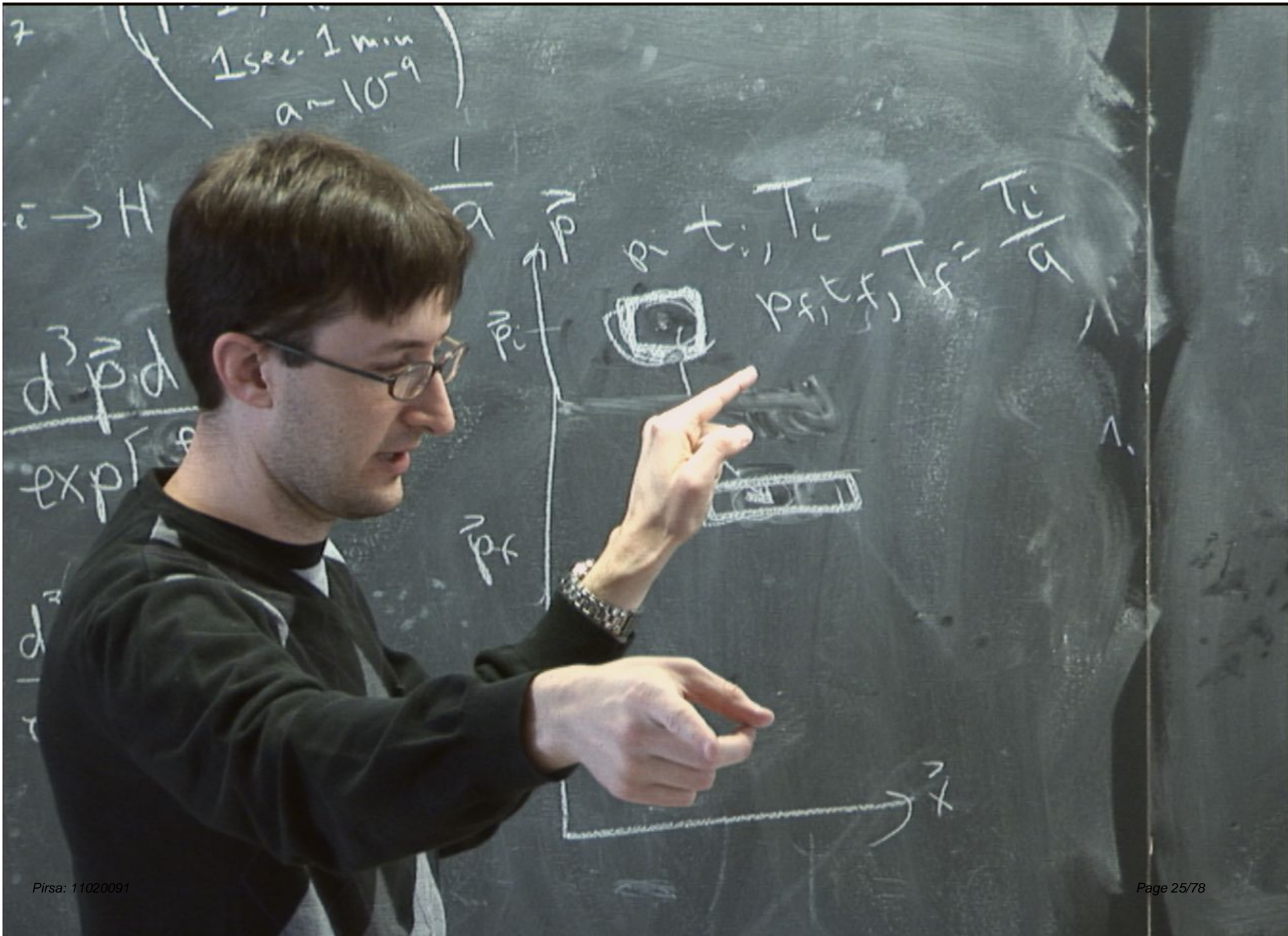
$$T \propto \frac{1}{a}$$

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_0}{T_i}\right] - 1}$$

$$= \frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_0/a}{T_i/a}\right] - 1}$$







BBN

$T_F \sim \frac{1}{2}$ 25% He, H
 $a \sim 10^9 \cdot 10^{27}$

$(T \sim 1 \text{ MeV})$
1 sec - 1 min
 $a \sim 10^{-9}$

$$\eta = \frac{n_b}{n_\gamma}$$

CMB

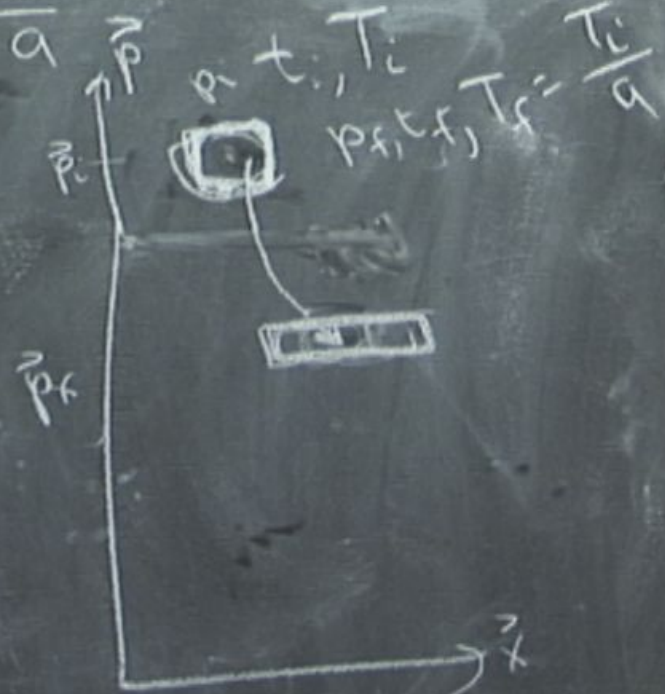
$T \sim 1 \text{ eV}$
few $\times 10^5$ yrs old
 $a \sim 10^{-3}$

$p + \bar{e} \rightarrow H$

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

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i}{T_i}\right]} = 1$$

$$\frac{d^3 \vec{p} d^3 \vec{x}}{\exp\left[\frac{p_i / \hbar}{T_i / a}\right]} = 1$$



$$n \propto \frac{g(3)}{T^3} \left[\frac{3}{T_{\text{CMB}}} \right]$$

$$n \propto \frac{g(3)}{T^3} \left[\frac{3}{T_{\text{CMB}}} \right]$$

BRN

CMB

$$f_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$$

$$f_{de} \approx 70\% \rho_{cr}$$

$$\frac{3H^2}{8\pi G}$$

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$

$\rho_{bar} \approx 4-5\% \rho_{cr}$



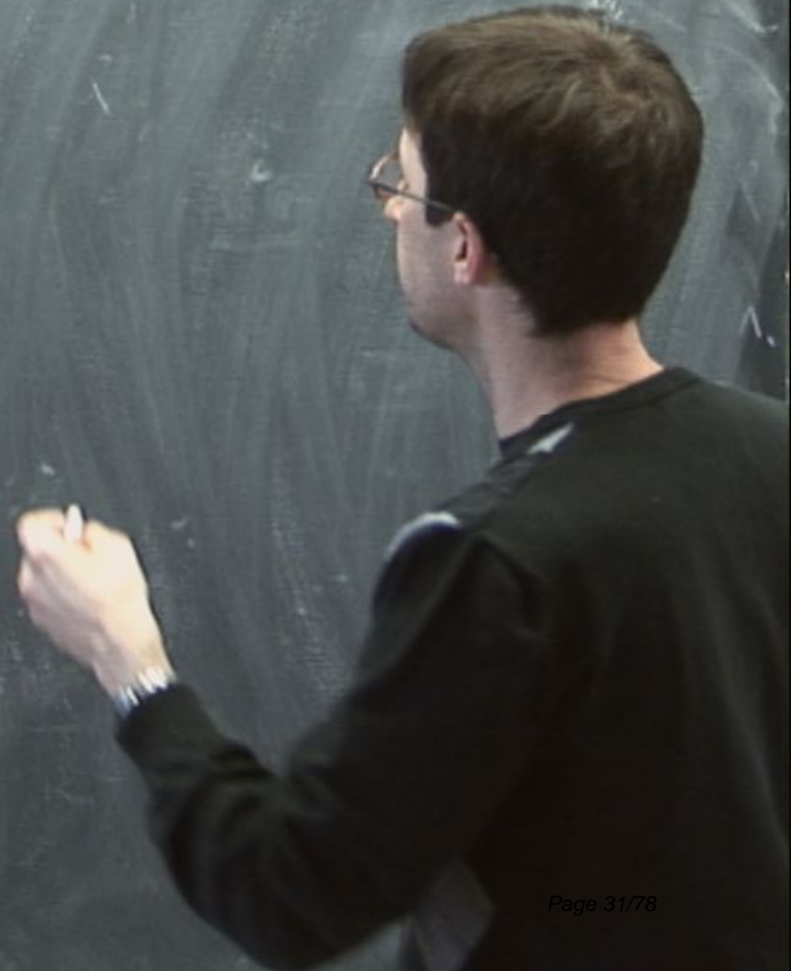
BRN

CMB

Dark Matter

Zwicky

0-



Dark Matter

Zwicky



25/12/77
M

Dark Matter

Zwicky



$$\frac{M}{R^2} \sim \frac{GM}{R^2}$$

Dark Matter

Zwicky

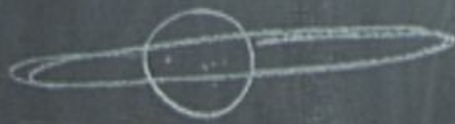


$$\frac{M}{R^2} \sim \frac{GM}{R^2}$$

Dark Matter

Zwicky

Vera Rubin



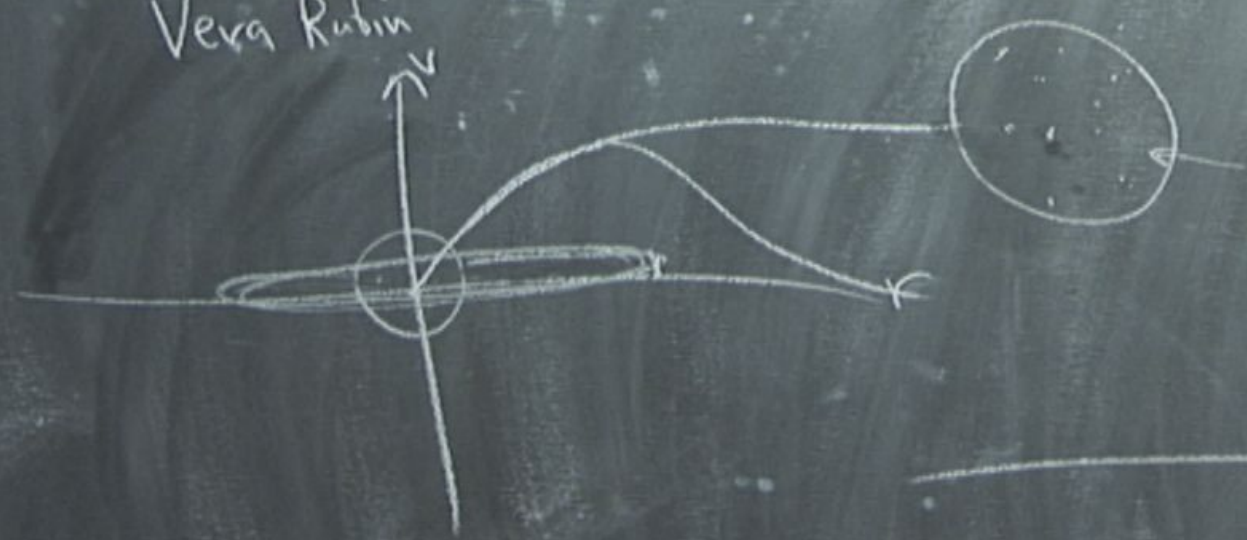
$$M \propto R^2$$
$$\frac{GM}{R^2} \propto \frac{GM}{R^2}$$



Dark Matter

Zwicky

Vera Rubin

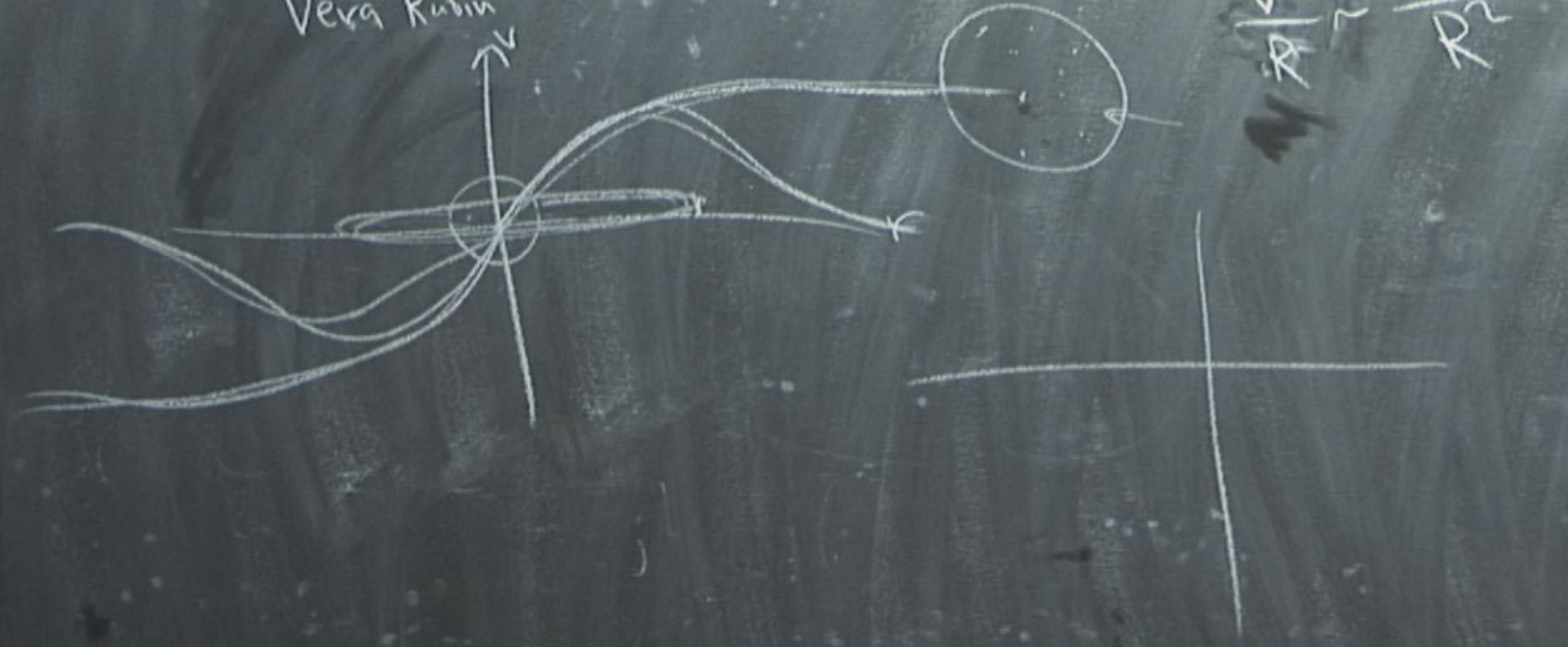


$$M \propto R^2 \quad \sim \frac{GM}{R^2}$$

Dark Matter

Zwicky

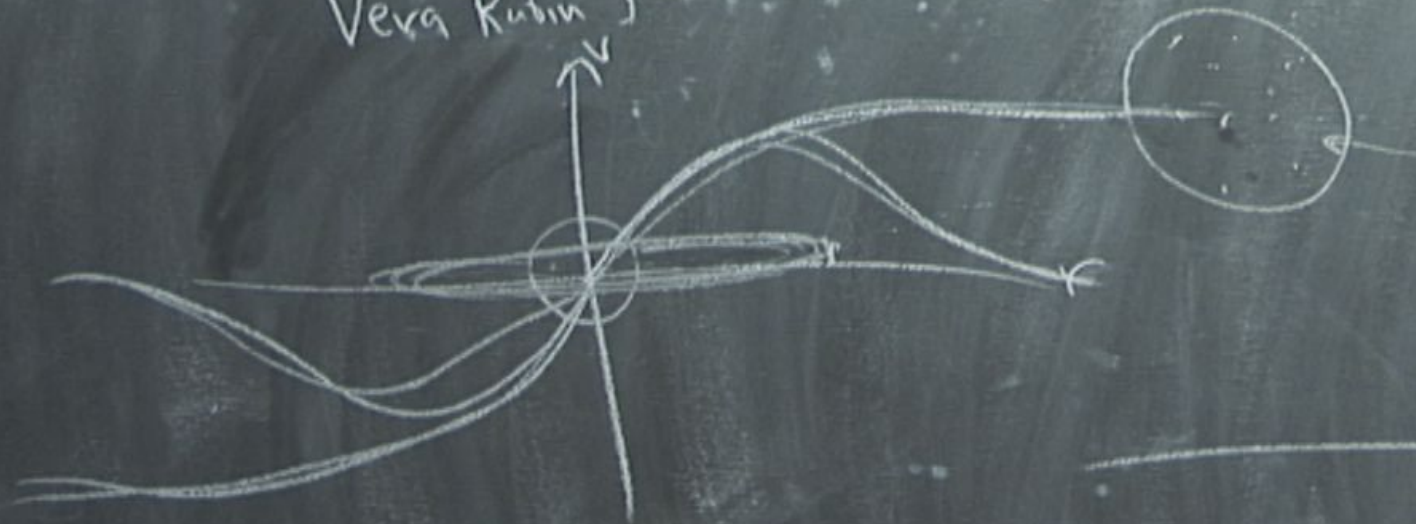
Vera Rubin



Dark Matter

Zwicky

Vera Rubin



$\frac{M}{R^2}$ $\frac{GM}{R^2}$

BRN

CMB

$$\begin{array}{|l} \rho_{dm} \approx 25\% \rho_{cr} \\ \rho_{de} \approx 75\% \rho_{cr} \\ \rho_{bar} \end{array} = \frac{3H^2}{8\pi G}$$

BRN

CMB

$p_{adm} \approx 25\% p_{cr}$
 $p_{de} \approx 70\% p_{cr}$
 $p_{bar} \approx 4-5\% p_{cr}$

$= \frac{3H^2}{8\pi G}$

Dark Matter

Zwicky

Vera Rubin



$$M \propto R^2$$
$$\frac{GM}{R^2}$$

$$\frac{3H^2}{8\pi G}$$

- $p_{dm} \approx 25\% p_{cr}$
- $p_{de} \approx 70\% p_{cr}$
- $p_{curv} \approx 4-5\% p_{cr}$

BRN

CMB

T_{CMB} ~ 3K

ν_{γ}

ν_B ←

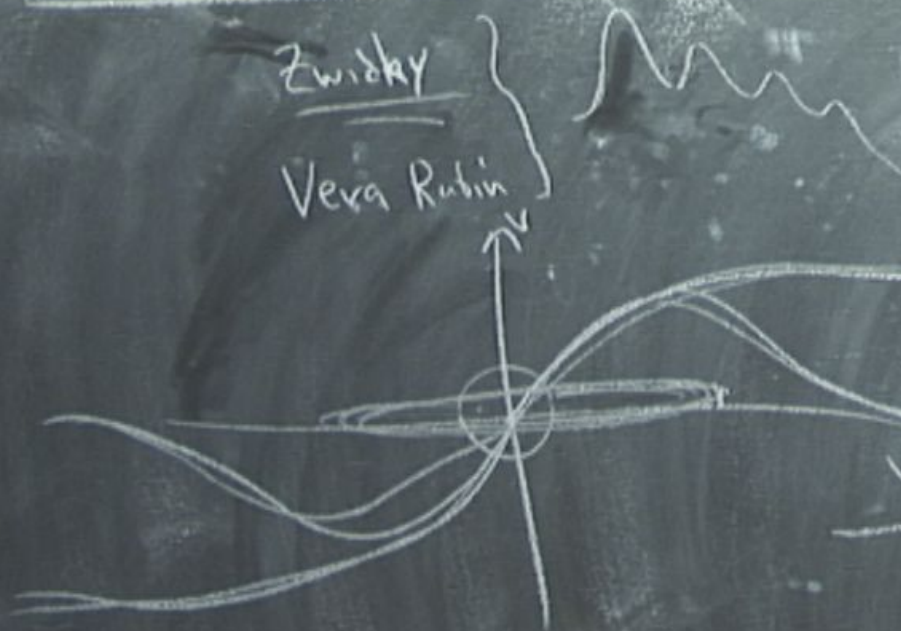
curvature normalized

to be separated from factor-ordering

Dark Matter

Zwicky

Vera Rubin



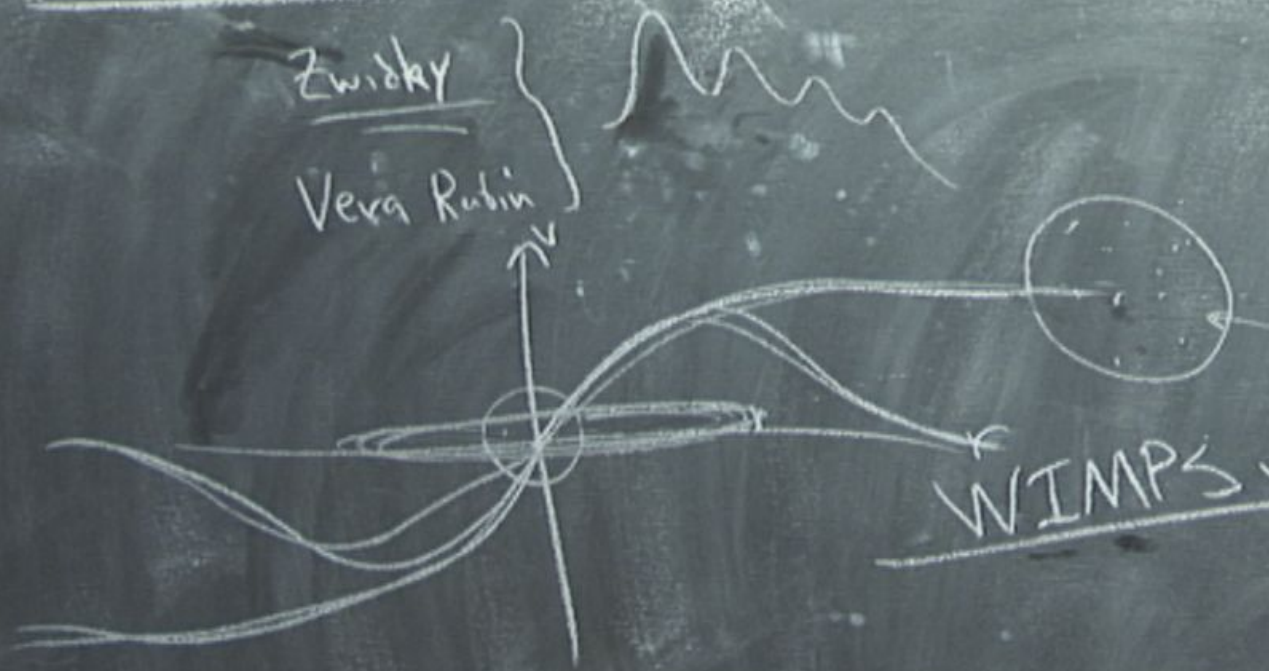
$$\frac{v}{R} \propto \frac{GM}{R^2}$$

WIMPS vs MACHOS

Dark Matter

Zwicky

Vera Rubin



$$v \propto \sqrt{\frac{GM}{R}}$$

WIMPS vs MACHOS

Dark Matter

Zwicky

Vera Rubin

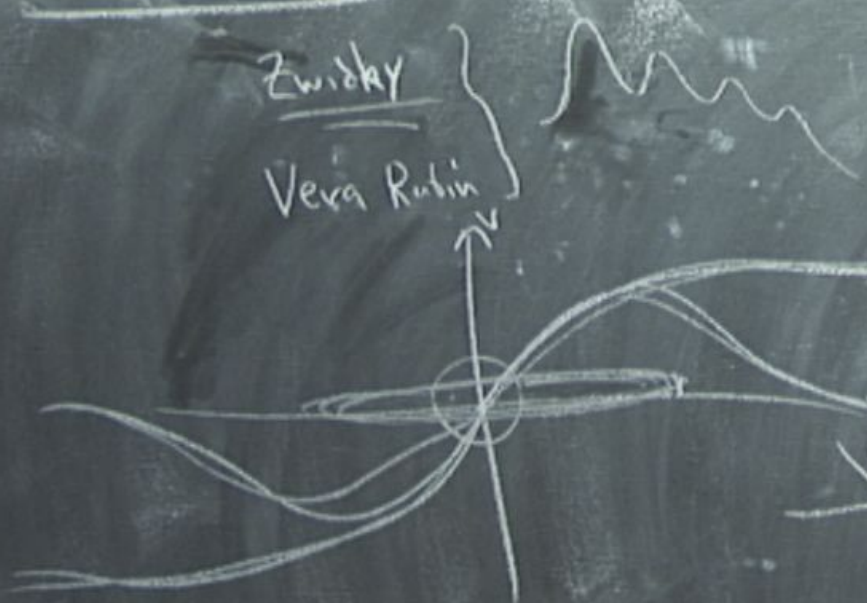


WIMPS vs MACHOS

Dark Matter

Zwicky

Vera Rubin



$$v \propto \frac{GM}{R^2}$$

WIMPS vs. MACHOS

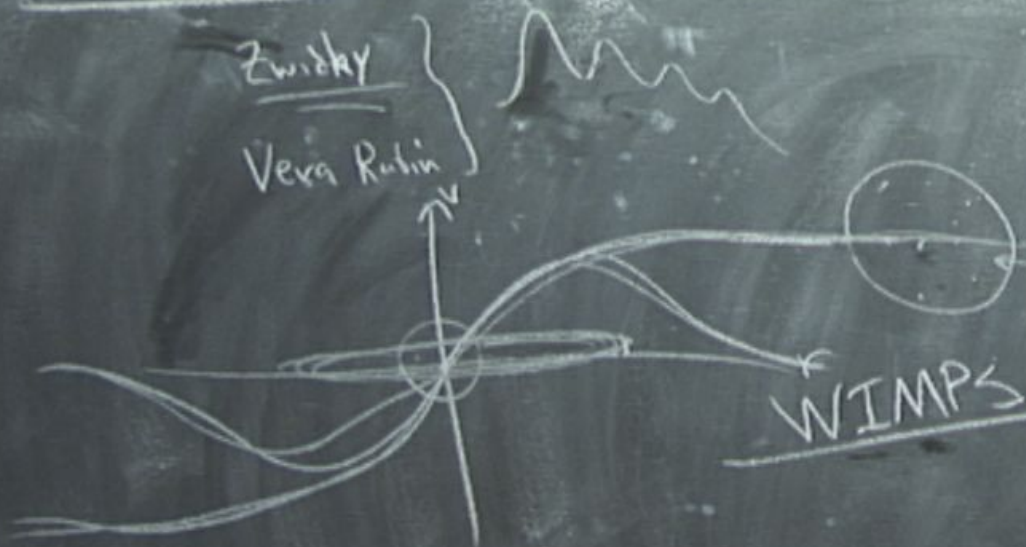
Bohdan Paczynski

Dark Matter

↓ $10^9 M_{\odot} - 10^{12} M_{\odot}$

Zwicky

Vera Rubin



$$\frac{v^2}{R} \sim \frac{GM}{R^2}$$

WIMPS vs MACHOS

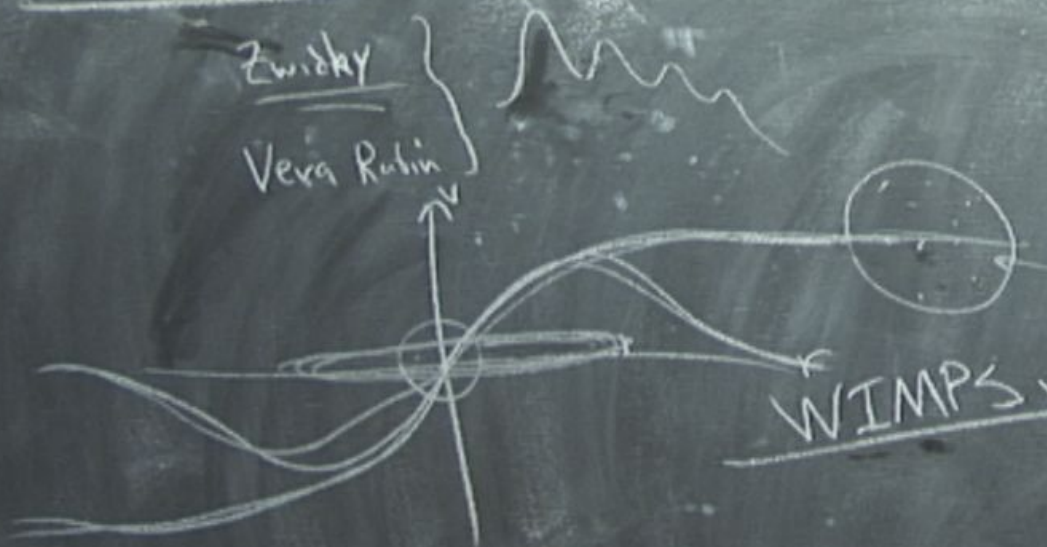
Bohdan Paczynski

Dark Matter

Zwicky

Vera Rubin

$$\downarrow 10^9 M_{\odot} - 10^{12} M_{\odot}$$



$$\frac{v^2}{R} \sim \frac{GM}{R^2}$$

WIMPS vs MACHOS

Bohdan Paczynski

BBN

CMB



$$\begin{aligned} \rho_{dm} &\approx 25\% \rho_{cr} \\ \rho_{de} &\approx 70\% \rho_{cr} \\ \rho_{nr} &\approx 4-5\% \rho_{cr} \end{aligned} = \frac{3H^2}{8\pi G}$$

$T_{CMB} \sim 3K$

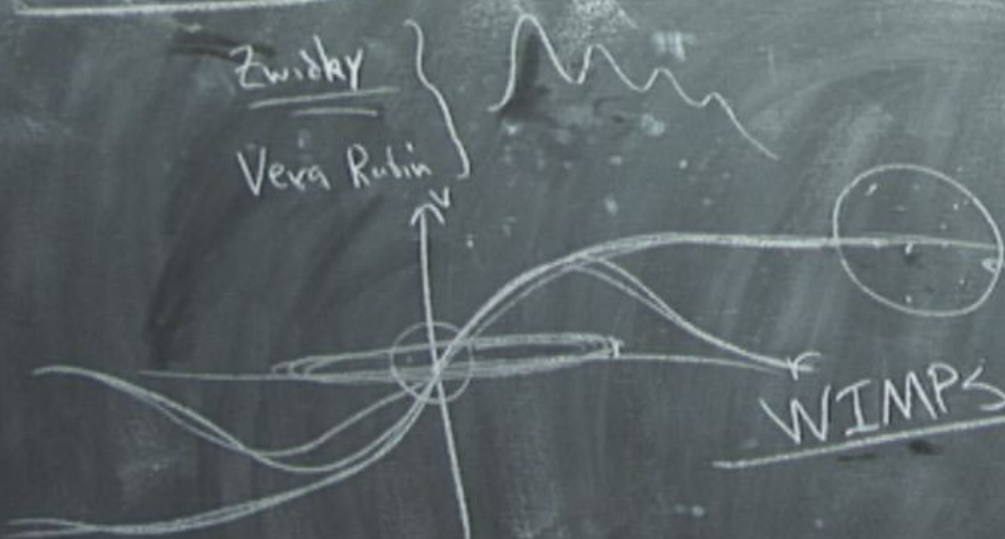
n_s

$n_B \leftarrow$

Dark Matter

Zwicky

Vera Rubin



$10^{11} M_{\odot}$

$10^9 M_{\odot} - 10^{12} M_{\odot}$

$$\frac{v^2}{R} \sim \frac{GM}{R^2}$$

WIMPS vs MACHOS

Bohdan Paczynski

Dark Matter

Zwicky

Vera Rubin

$10^{18} M_{\odot}$ | $10^9 M_{\odot} - 10^{12} M_{\odot}$



$$\frac{v}{R} \sim \frac{GM}{R^2}$$

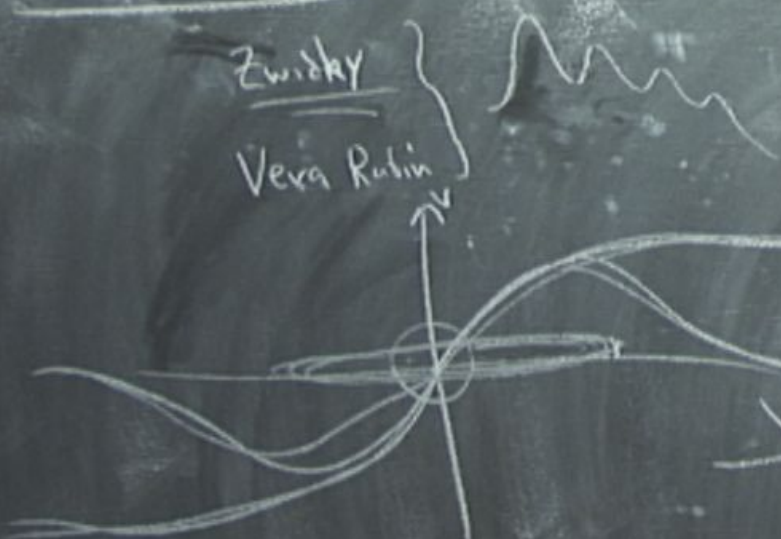
WIMPS vs MACHOS

Bohdan Paczynski

Dark Matter

Zwicky

Vera Rubin



$10^{11} M_{\odot}$ | $10^9 M_{\odot} - 10^{12} M_{\odot}$

$$\frac{v}{R} \sim \frac{GM}{R^2}$$

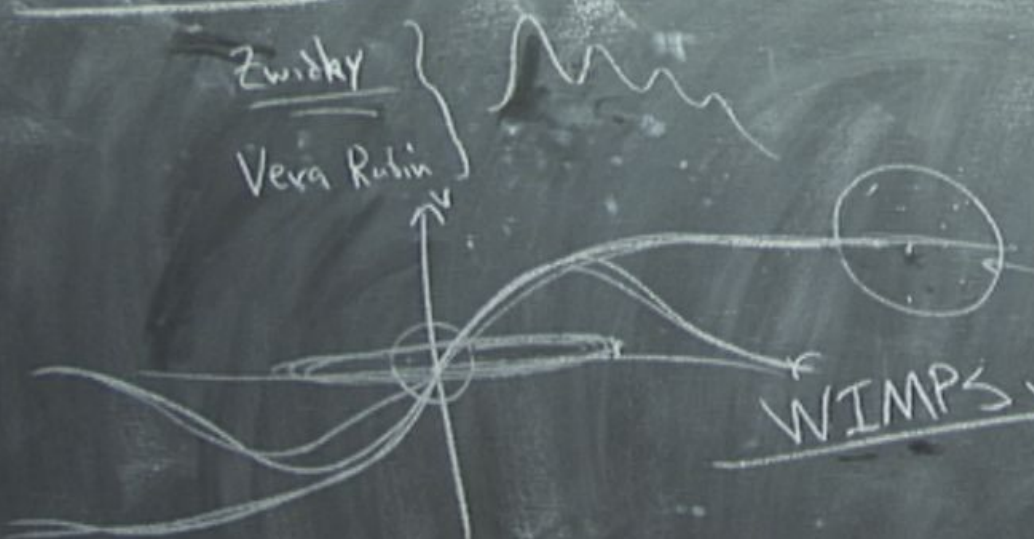
WIMPS vs MACHOS

Bohdan Paczynski

Dark Matter

Zwicky

Vera Rubin



$10^{18} M_{\odot}$ | $10^9 M_{\odot} - 10^{12} M_{\odot}$

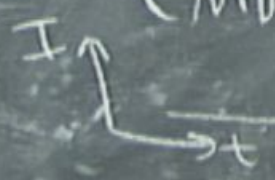
$$\frac{v}{R} \sim \frac{GM}{R^2}$$

WIMPS vs. MACHOS

Bohdan Paczynski

LBN

CMB



$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{hor} \approx 4-5\% \rho_{cr}$

$$= \frac{3H^2}{8\pi G}$$

WIMPS

$T_{CMB} \sim 3K$

ν_γ
 $\nu_B \leftarrow$

LBN

CMB

I

t



WIMPS

thermal

non-thermal

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{dm} \approx 4-5\% \rho_{cr}$

$$= \frac{3H^2}{8\pi G}$$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

m_χ

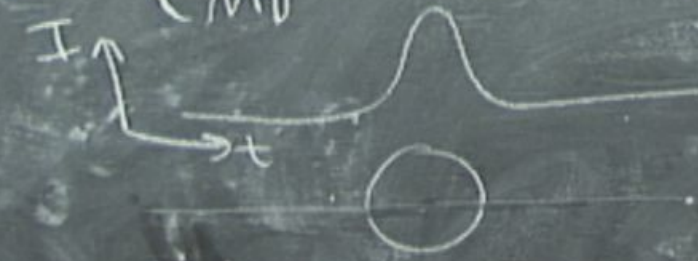
m_B

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{hor} \approx 4-5 \times 10^{-9} \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$\chi \quad T < m_{\chi}$

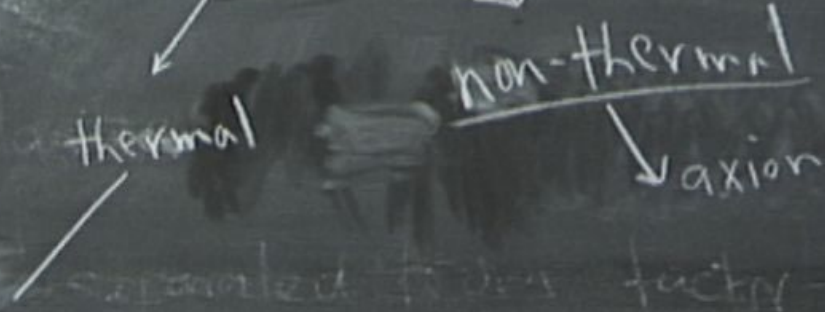
BBN
CMB



$T_{CMB} \sim 3K$

WIMPS

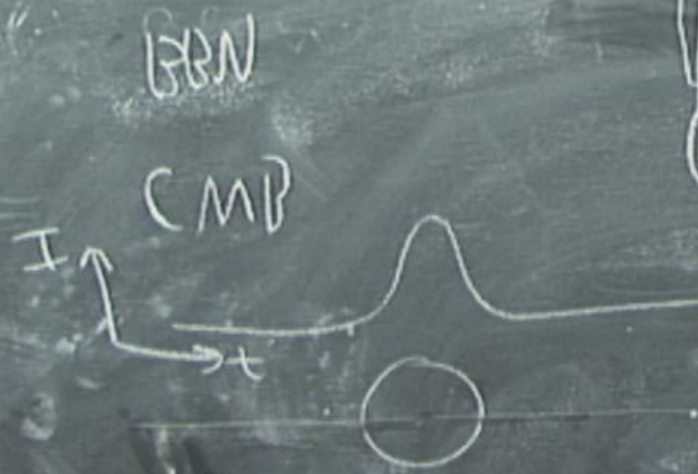
m_{χ}
 $m_B \leftarrow$



$$\frac{3H^2}{8\pi G}$$

- $\rho_{dm} \approx 25\% \rho_{cr}$
- $\rho_{de} \approx 70\% \rho_{cr}$
- $\rho_{bar} \approx 4-5\% \rho_{cr}$

$$T < m_\chi$$

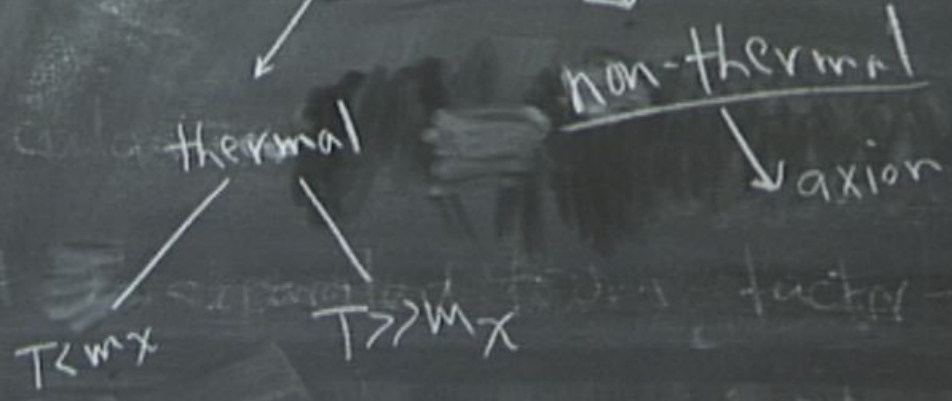


BRN
CMB

$T_{CMB} \sim 3K$

WIMPS

m_χ
 m_B



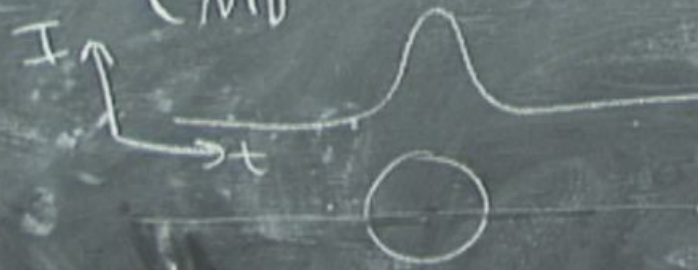
$$\frac{3H^2}{8\pi G}$$

- $\rho_{dm} \approx 25\% \rho_{cr}$
- $\rho_{de} \approx 70\% \rho_{cr}$
- $\rho_{bar} \approx 4-5\% \rho_{cr}$

$$X \quad T < m_X$$

LBN

CMB



$T_{CMB} \sim 3K$

WIMPS

m_X
 m_B

thermal

non-thermal

axion

$T < m_X$

$T \gg m_X$

LSP

$$\frac{3H^2}{8\pi G}$$

- $\rho_{dm} \approx 25\% \rho_{cr}$
- $\rho_{dm} \approx 70\% \rho_{cr}$
- $\rho_{bar} \approx 4-5\% \rho_{cr}$

$$X \quad T < m_X$$

LBN

CMB



$T_{CMB} \sim 3K$

WIMPS

m_X
 m_B

thermal

non-thermal

axion

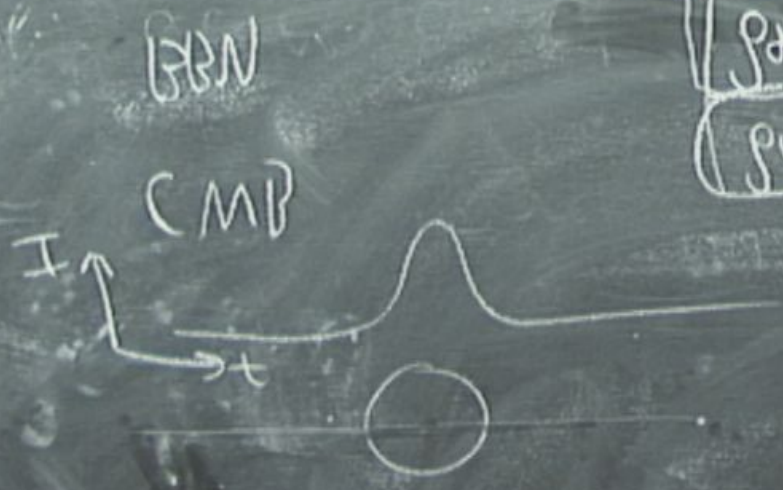
$T < m_X$

$T \gg m_X$

LSP

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\chi \quad T < m_{\chi}$



$T_{CMB} \sim 3K$

WIMPS

m_{χ}
 $m_B \leftarrow$

thermal
 non-thermal
 axion

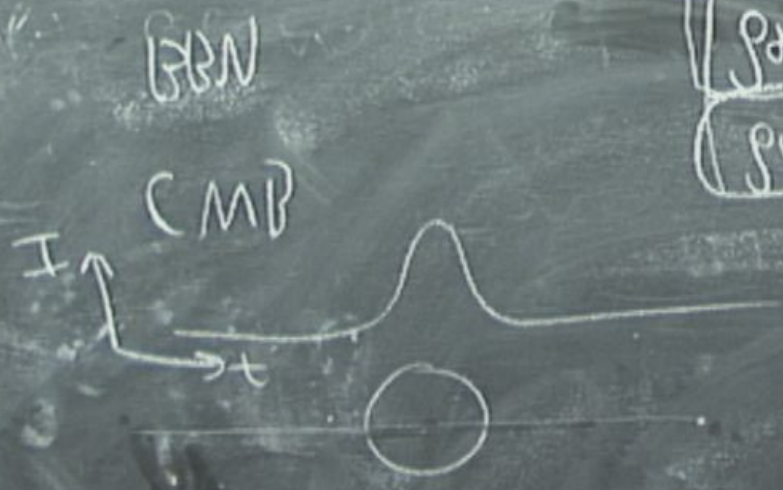
$T < m_{\chi}$

$T \gg m_{\chi}$

LSP

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\chi \quad T < m_{\chi}$



$T_{CMB} \sim 3K$

WIMPS

m_{χ}
 $m_B \leftarrow$

non-thermal

axion

thermal

$T < m_{\chi}$

$T \gg m_{\chi}$

LSP

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\chi \quad T < m_\chi$



$T_{CMB} \sim 3K$

WIMPS

m_χ
 $m_B \leftarrow$

non-thermal

thermal

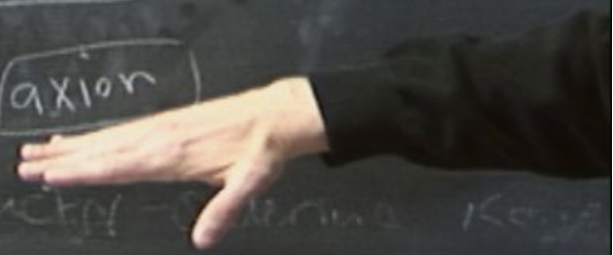
axion

WIMP

$T < m_\chi$

$T \gg m_\chi$

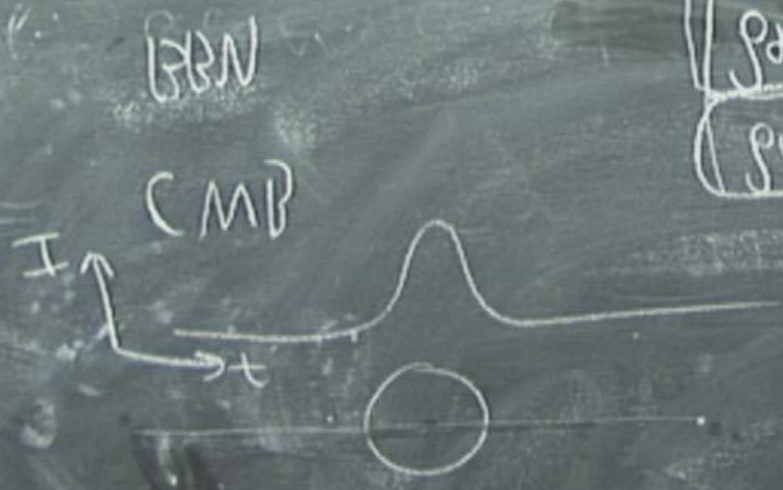
LSP



$$\frac{3H^2}{8\pi G}$$

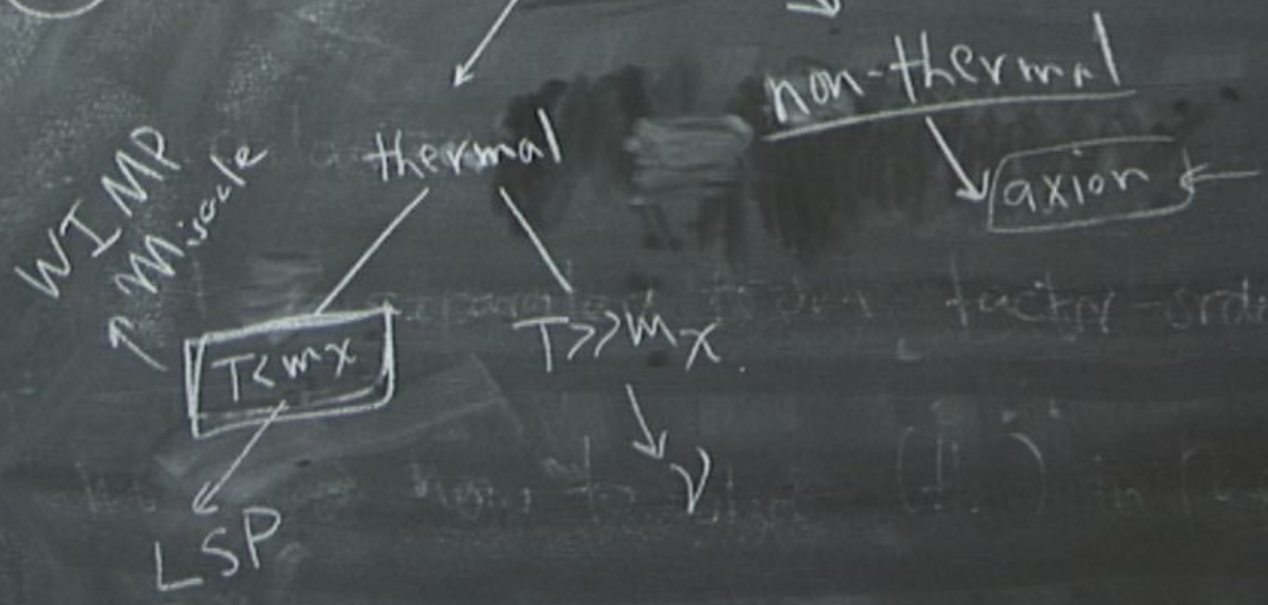
- $\rho_{dm} \approx 25\% \rho_{cr}$
- $\rho_{dm} \approx 70\% \rho_{cr}$
- $\rho_{bar} \approx 4-5\% \rho_{cr}$

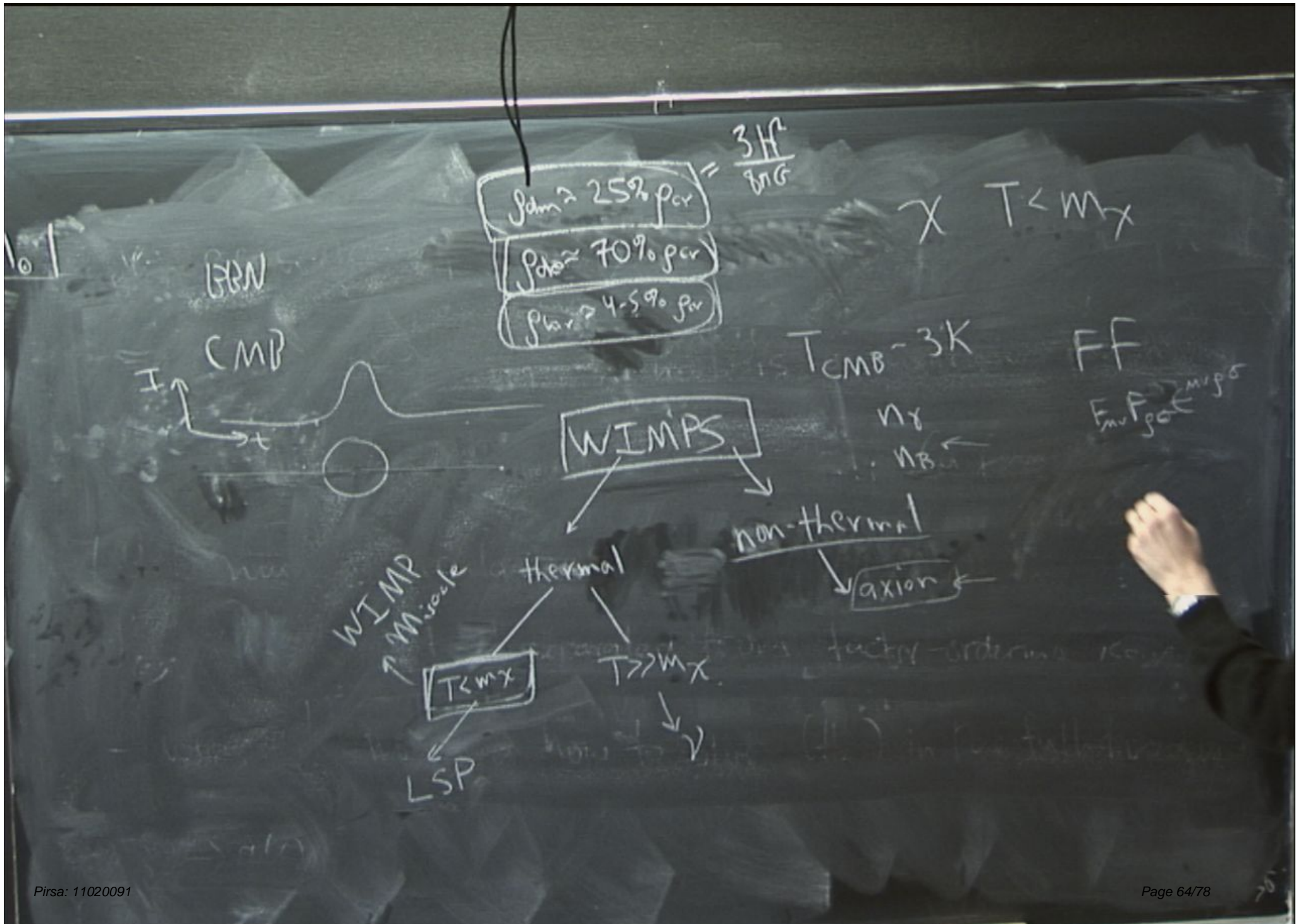
$$T < m_{\chi}$$



$$T_{CMB} \sim 3K$$

WIMPS





$$= \frac{3H^2}{8\pi G}$$

- $\rho_{dm} \approx 25\% \rho_{cr}$
- $\rho_{de} \approx 70\% \rho_{cr}$
- $\rho_{hr} \approx 4-5\% \rho_{cr}$

$$\chi \quad T < m_\chi$$

$$T_{CMB} \sim 3K$$

$$FF$$

$$E_{mv} \left(\frac{m_{\nu} c^2}{2} \right)$$

$$E_{mv}$$

BRN
CMB



WIMPS

non-thermal
axion

WIMP
Micro

thermal

$T < m_\chi$

$T \gg m_\chi$

LSP

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

FF
 $E_{mv} \rho_{cr} e^{m_\chi \rho_{cr}}$
 $\ominus \frac{E_{mv} \rho_{cr}}{E_{mv}}$

WIMPS

non-thermal

axion

thermal

WIMP miracle

$T < m_\chi$

$T \gg m_\chi$

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

FF

$E_{mv} \sim \frac{1}{2} m_\nu v^2$
 $E_{pot} \sim m_\nu \phi$
 $E_{mv} \sim E_{pot}$

WIMPS

non-thermal

axion

WIMP miracle

thermal

$T < m_\chi$

$T \gg m_\chi$

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

FF

$E_{mv} \sim \frac{1}{2} m_\nu^2 v^2$
 $E_{pot} \sim m_\nu \phi$
 $E_{mv} \sim E_{pot}$

WIMPS

non-thermal

axion

thermal

WIMP miracle

$T < m_\chi$

$T \gg m_\chi$

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{de} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

FF

WIMPS

m_χ

NB

$\approx 10^{-9}$
 $F_{mv} F_{pot} \approx m_\nu \rho_{cr}$
 $F_{mv} F_{mv}$
 Pecci-Quinn

non-thermal

axion

thermal

WIMP
 miracle

$T < m_\chi$

$T \gg m_\chi$

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$
 $T < m_{\chi}$

$T_{CMB} \sim 3K$

WIMPS

non-thermal

thermal

axion

WIMP
 \uparrow miracle

$T < m_{\chi}$

LSP

$T \gg m_{\chi}$

FF
 $F_{mv} F_{pot}^{m\nu p\sigma}$
 $F_{mv} F_{mv}$
 Ricci-Quinn

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

$\chi \quad T < m_\chi$

$T_{CMB} \sim 3K$

FF
 $F_{mv} F_{pot}^{mvp}$
 $\times 10^{-11}$
 $F_{mv} F_{mv}$
 Ricci-Quinn

WIMPS

non-thermal

axion

thermal

$T < m_\chi$

$T \gg m_\chi$

LSP


WIMP
 miracle



$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

χ $T < m_\chi$



$T_{CMB} \sim 3K$

FF
 $F_{mv} F_{pot}^{mvp}$
 $F_{mv} F_{mv}$
 Ricci-Quinn

WIMPS

non-thermal

axion

thermal

$T < m_\chi$

$T \gg m_\chi$

LSP

WIMP miracle

$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$
 $\rho_{do} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

$\chi \quad T < m_\chi$



$T_{CMB} \sim 3K$

FF
 $F_{nu} F_{pot}^{m_{\nu} \rho}$
 $F_{nu} F_{nu}$
 Rees-Quinn

WIMPS

non-thermal

axion

thermal

$T < m_\chi$

$T \gg m_\chi$

WIMP miracle

LSP

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

$\chi \quad T < m_\chi$



$T_{CMB} \sim 3K$

FF

WIMPS

m_χ

ν_B

$F_{mv} F_{pot}^{m\nu p\sigma}$
 $\times 10^{-10}$
 $F_{mv} F_{mv}$

non-thermal

Recci-Quinn
 $\phi \cos(\frac{q}{m}) + const$

axion

thermal

WIMP
 \uparrow miracle

$T < m_\chi$

$T \gg m_\chi$


LSP

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$\frac{3H^2}{8\pi G}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

χ $T < m_\chi$



$T_{CMB} \sim 3K$

WIMPS

non-thermal

thermal

axion

$T \gg m_\chi$

$T < m_\chi$

LSP

WIMP
 \uparrow miracle

FF
 $F_{mv} F_{pot}^{m\nu\phi}$
 $\rightarrow F_{mv} F_{mv}$
 Recci-Quinn
 $\phi = \cos(\frac{g}{f}) + \text{const}$

$\rho_{dm} \approx 25\% \rho_{cr}$
 $\rho_{dm} \approx 70\% \rho_{cr}$
 $\rho_{bar} \approx 4-5\% \rho_{cr}$

$= \frac{3H^2}{8\pi G}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

$\chi \quad T < m_\chi$



$T_{CMB} \sim 3K$

FF

WIMPS

m_χ

ν_B

non-thermal

$\times 10^{-11}$
 $F_{\nu} F_{\nu}^{*}$
 $F_{\nu} F_{\nu}^{*}$
 $\text{Re}(e^{iQ_{min}})$
 $\phi \cos(\frac{q}{m}) + \text{const}$

thermal

axion

WIMP
 \uparrow miracle

$T < m_\chi$

$T \gg m_\chi$

LSP

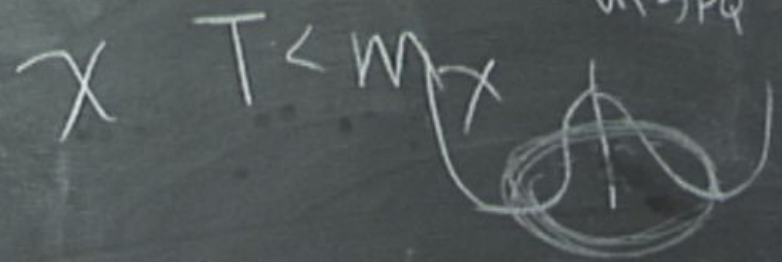
$$\rho_{dm} \approx 25\% \rho_{cr} = \frac{3H^2}{8\pi G}$$

$$\rho_{dm} \approx 70\% \rho_{cr}$$

$$\rho_{bar} \approx 4-5\% \rho_{cr}$$

$$SU(3) \times SU(2) \times U(1)$$

$$\times U(1)_{PQ}$$



$T_{CMB} \sim 3K$

WIMPS

thermal

non-thermal

axion

WIMP miracle

$T < m_\chi$

LSP

$T \gg m_\chi$

FF

$$F_{mv} F_{pot} \sim m_{pl}^2 \rho$$

$$F_{mv} F_{mv}$$

$\sim 10^{-11}$

Recei-Quinn

$$\phi \sim \mu \cos(\frac{q}{f} \phi) + const$$

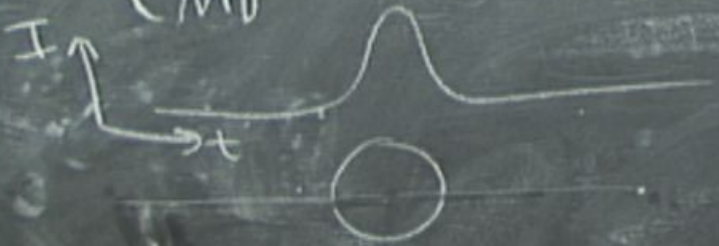
$\rho_{dm} \approx 25\% \rho_{cv}$
 $\rho_{de} \approx 70\% \rho_{cv}$
 $\rho_{bar} \approx 4-5\% \rho_{cv}$

$\frac{3H^2}{8\pi G}$

$SU(3) \times SU(2) \times U(1)$
 $\times U(1)_{PQ}$

χ $T < m_\chi$

LBN
CMB



$T_{CMB} \sim 3K$

FF

WIMPS

m_χ
 m_B

$\approx 10^{-2}$
 $F_{mv} F_{mv}$
 $F_{mv} F_{mv}$
 $\phi \cos(\frac{q}{m}) + const$

non-thermal

axion

thermal

WIMP molecule

$T < m_\chi$

$T \gg m_\chi$

LSP