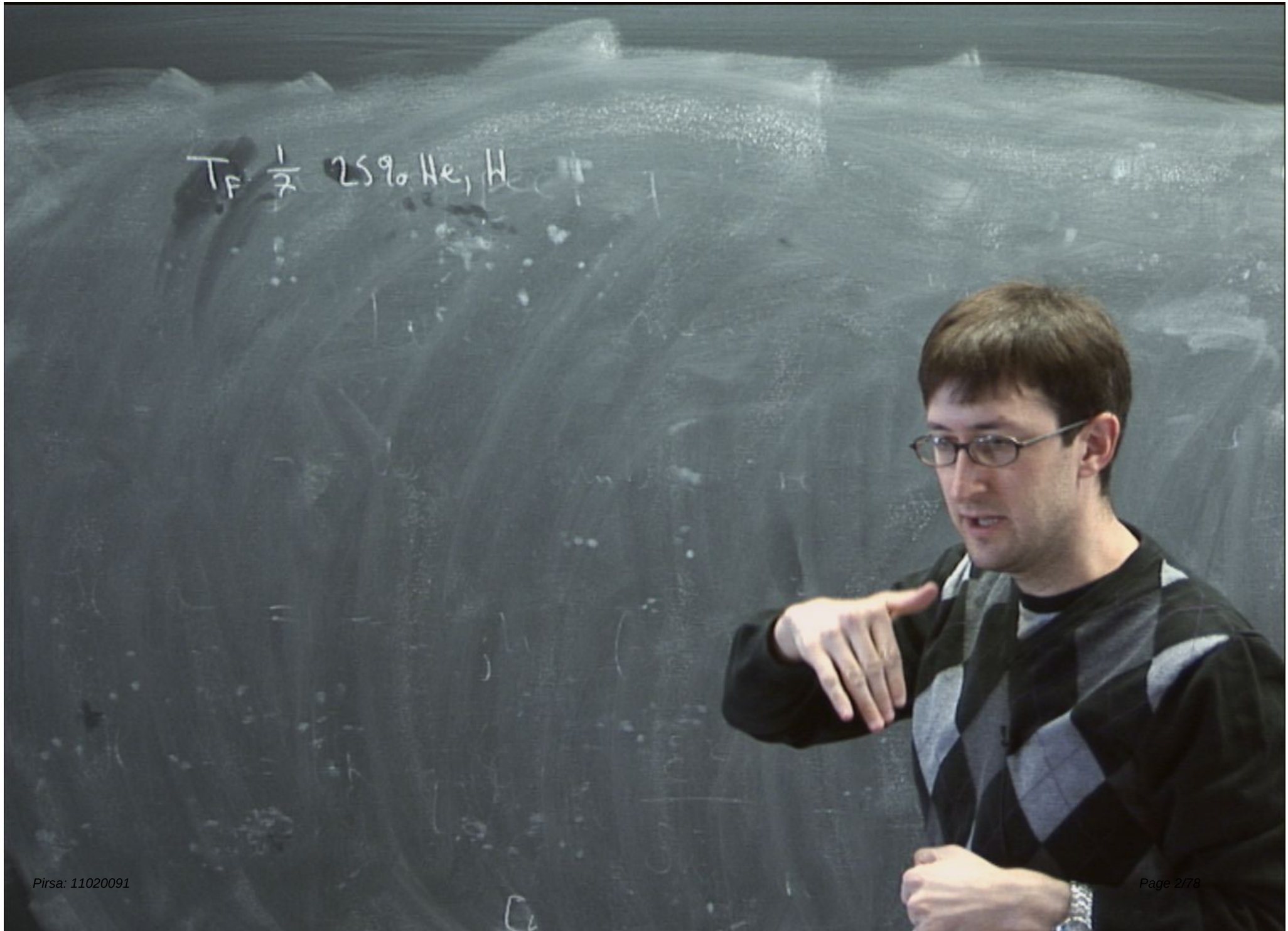
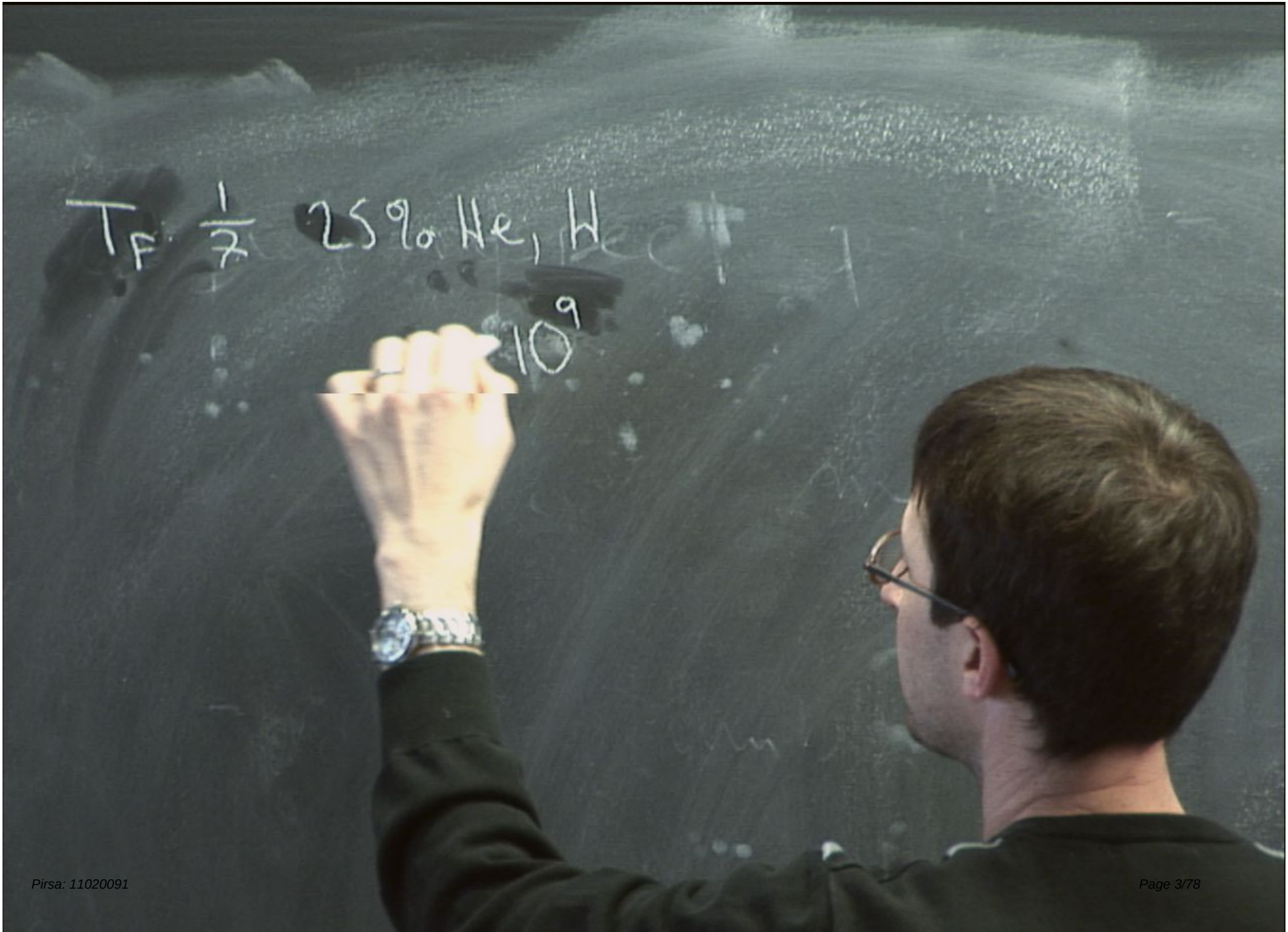
Title: Cosmology Review - Lecture 10

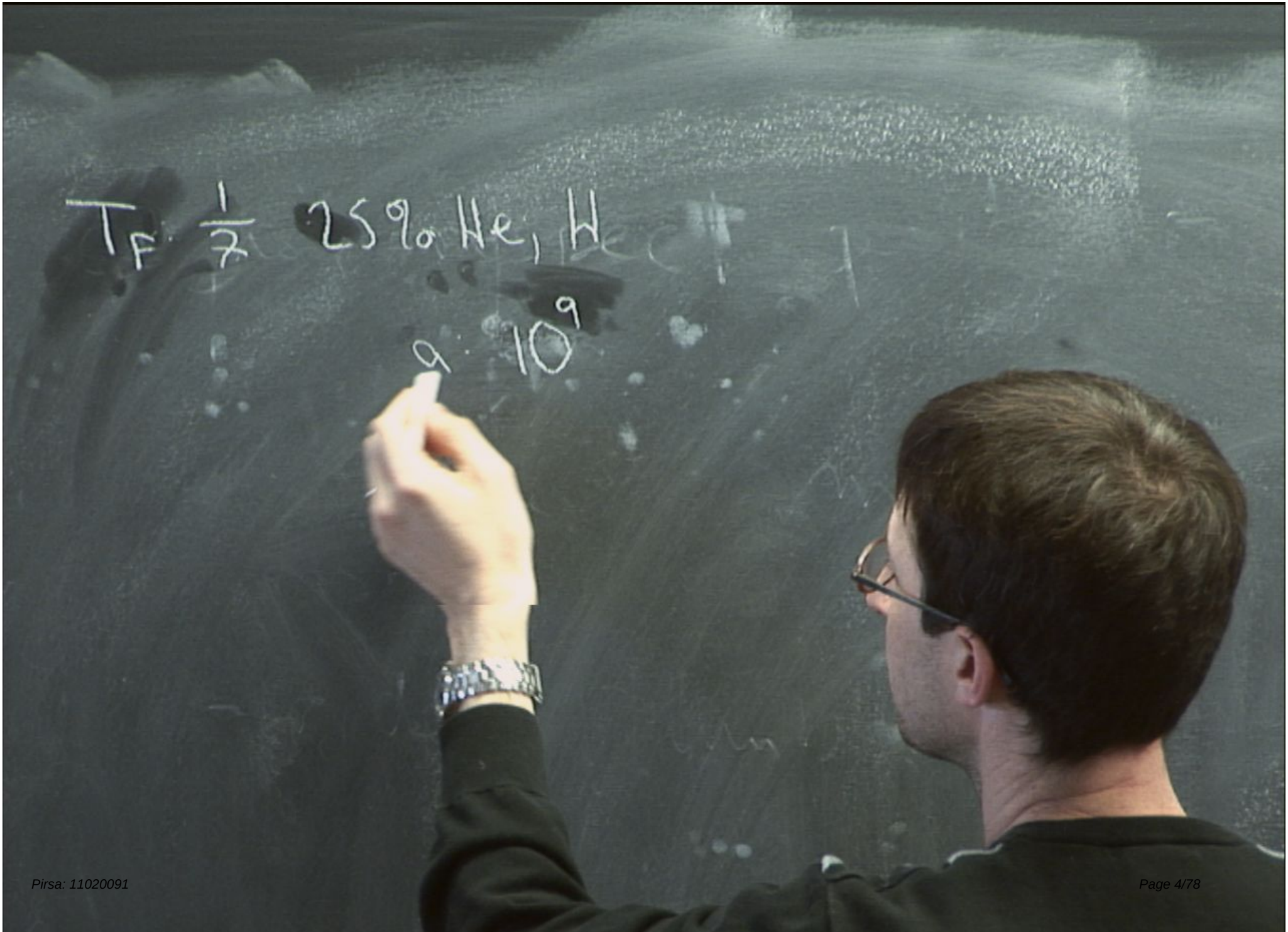
Date: Feb 04, 2011 11:30 AM

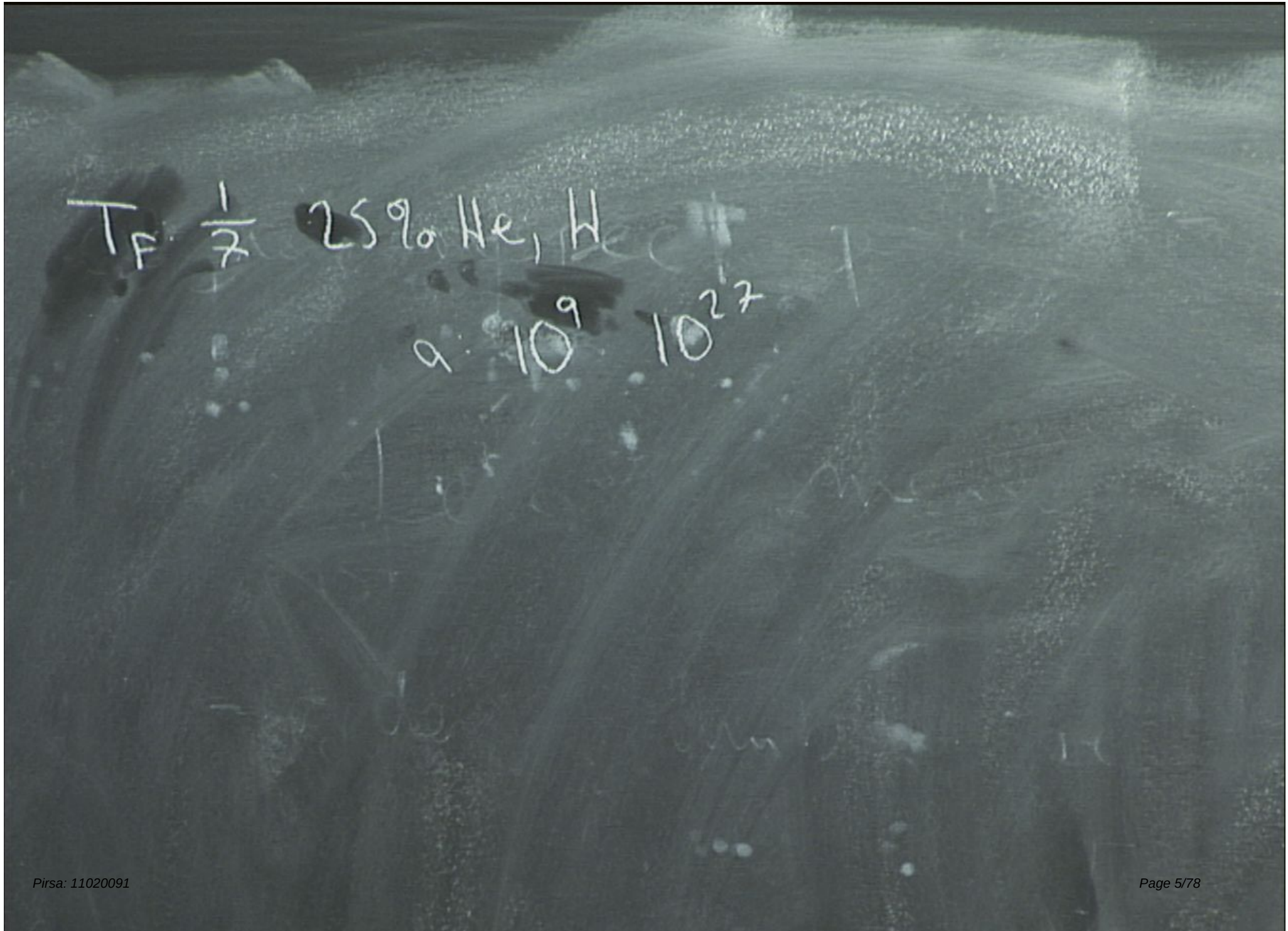
URL: http://pirsa.org/11020091

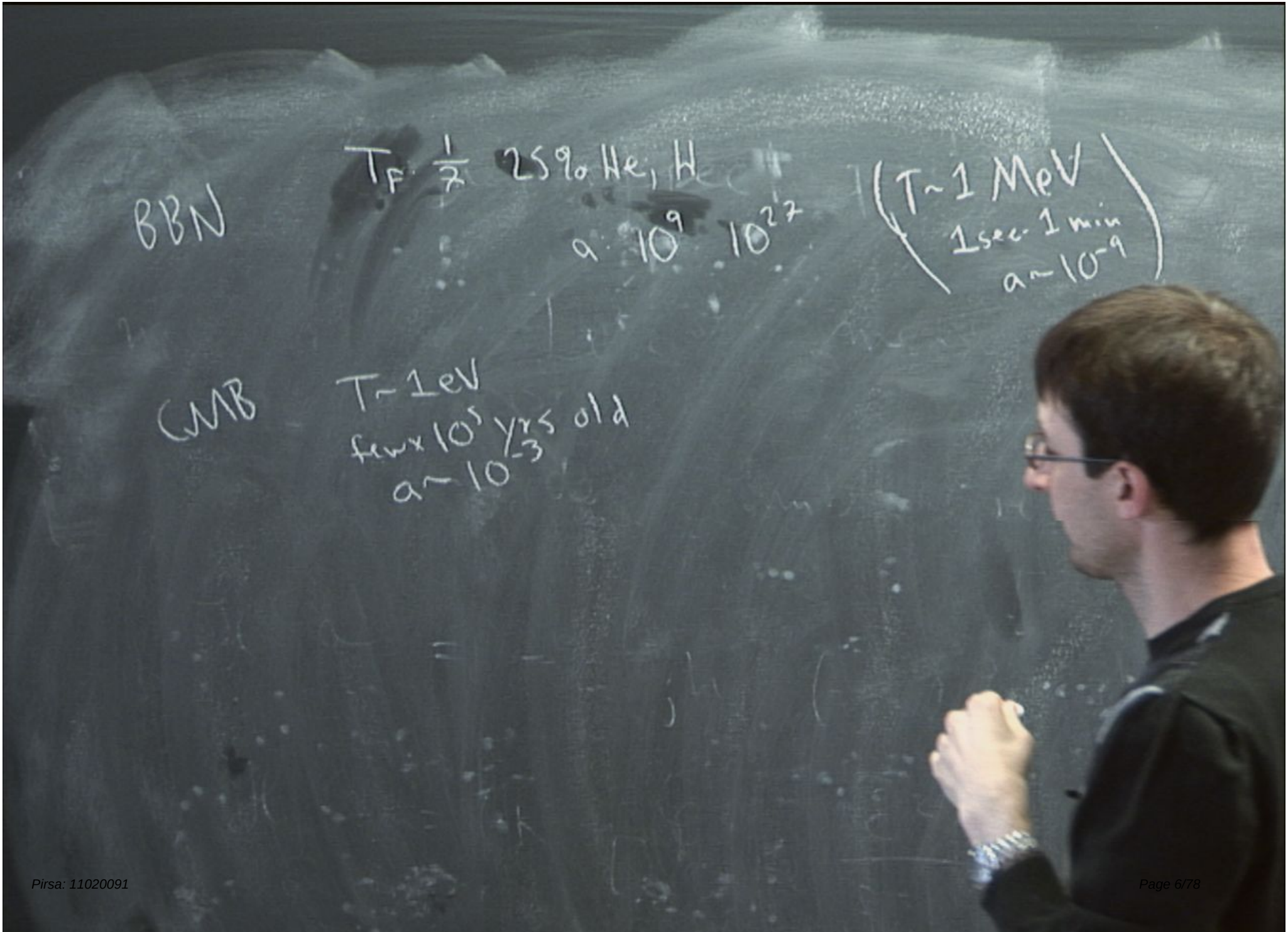
Abstract:


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


$T_F \cdot \frac{1}{7}$ 25% He, H
10^9


$T_F \cdot \frac{1}{7}$ 25% He, H
$9 \cdot 10^9$


$T_F \cdot \frac{1}{7}$ 25% He, H
$a \cdot 10^{9} \cdot 10^{27}$


BBN
$T_F \cdot \frac{1}{2}$ 25% He, H
$a \cdot 10^{9}$ 10^{21}
(T~1 MeV
1 sec. 1 min
$a \sim 10^{-9}$)
CMB
T~1eV
few x 10^{5} yrs old
$a \sim 10^{-3}$

BBN $T_F \cdot \frac{1}{7}$ 25% He, H

$a: 10^{9} \; 10^{27}$

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

CMB $T \sim 1$ eV

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

$a \sim 10^{-3}$

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

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

BBN $T_F \cdot \frac{1}{7}$ 25% He, H $a: 10^9 \; 10^{27}$ $\left(T \sim 1\,\text{MeV}, \; 1\,\text{sec}\; 1\,\text{min}, \; a \sim 10^{-9}\right)$

CMB $T \sim 1\,\text{eV}$ few $\times 10^5$ yrs old $a \sim 10^{-3}$ $p^+ + e^- \rightarrow H$ $T \propto \frac{1}{a}$

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

BBN

$T_F \sim \frac{1}{7}$ 25% He, H

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

$T \sim 1$ MeV
1 sec. 1 min
$a \sim 10^{-9}$

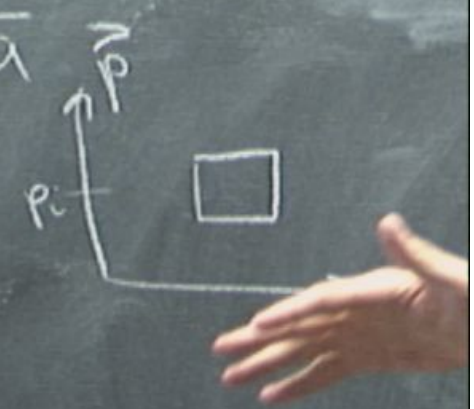
CMB

$T \sim 1$ 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 $\frac{1}{7}$ 25% He, H

$a: 10^{9}$ 10^{27}

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

CMB

$T \sim 1$ eV

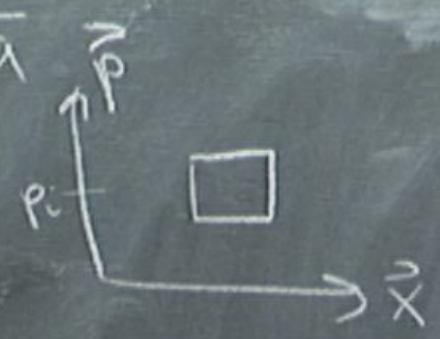
few $\times 10^{5}$ yrs old

$a \sim 10^{-3}$

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

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

$$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left(\frac{p}{T_i}\right) - 1}$$



BBN $T_F \cdot \frac{1}{7}$ 25% He, H $a \cdot 10^9$ 10^{27} ($T \sim 1$ MeV, 1 sec. 1 min, $a \sim 10^{-9}$)

CMB $T \sim 1$ 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 $\frac{1}{7}$ 25% He, H $(T \sim 1\,\text{MeV}$ 1 sec. 1 min $a \sim 10^{-9})$

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

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

$p^{+} + e^{-} \rightarrow H$ $T \propto \frac{1}{a}$

$$\frac{d^3\vec{p}\,d^3\vec{x}}{\exp\left(\frac{p}{T_i}\right) - 1}$$

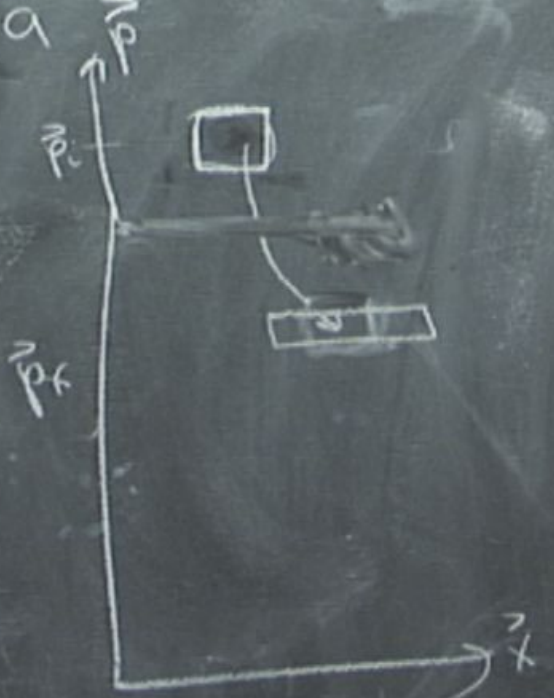
BBN T_F $\frac{1}{7}$ 25% He, H $(T \sim 1\,MeV$ 1 sec. 1 min $a \sim 10^{-9})$

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

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

$p^{+} + e^{-} \rightarrow H$ $T \propto \frac{1}{a}$

$$\frac{d^3\vec{p}\,d^3\vec{x}}{\exp\left(\frac{p}{T_i}\right) - 1}$$

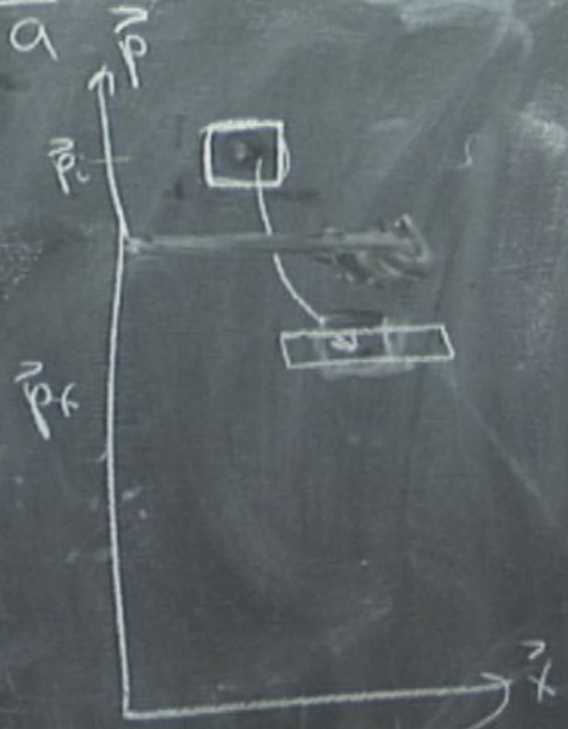


BBN T_F $\frac{1}{2}$ 25% He, H $a \sim 10^{9}$ 10^{21} ($T \sim 1$ MeV, 1 sec. 1 min, $a \sim 10^{-9}$)

CMB $T \sim 1$ 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 $T_F \cdot \frac{1}{7}$ 25% He, H

$a \cdot 10^{9}$ 10^{21} $\left(T \sim 1\ \text{MeV}, \ 1\ \text{sec}, 1\ \text{min}, \ a \sim 10^{-9}\right)$

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

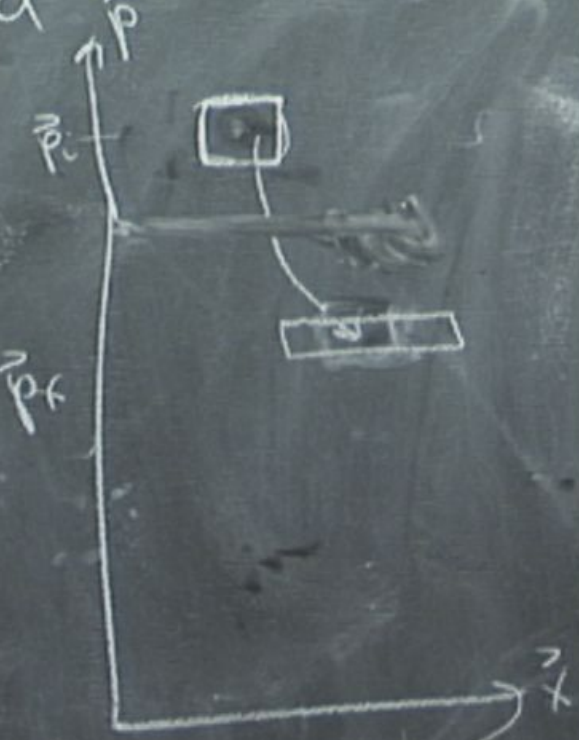
few $\times 10^{5}$ yrs old

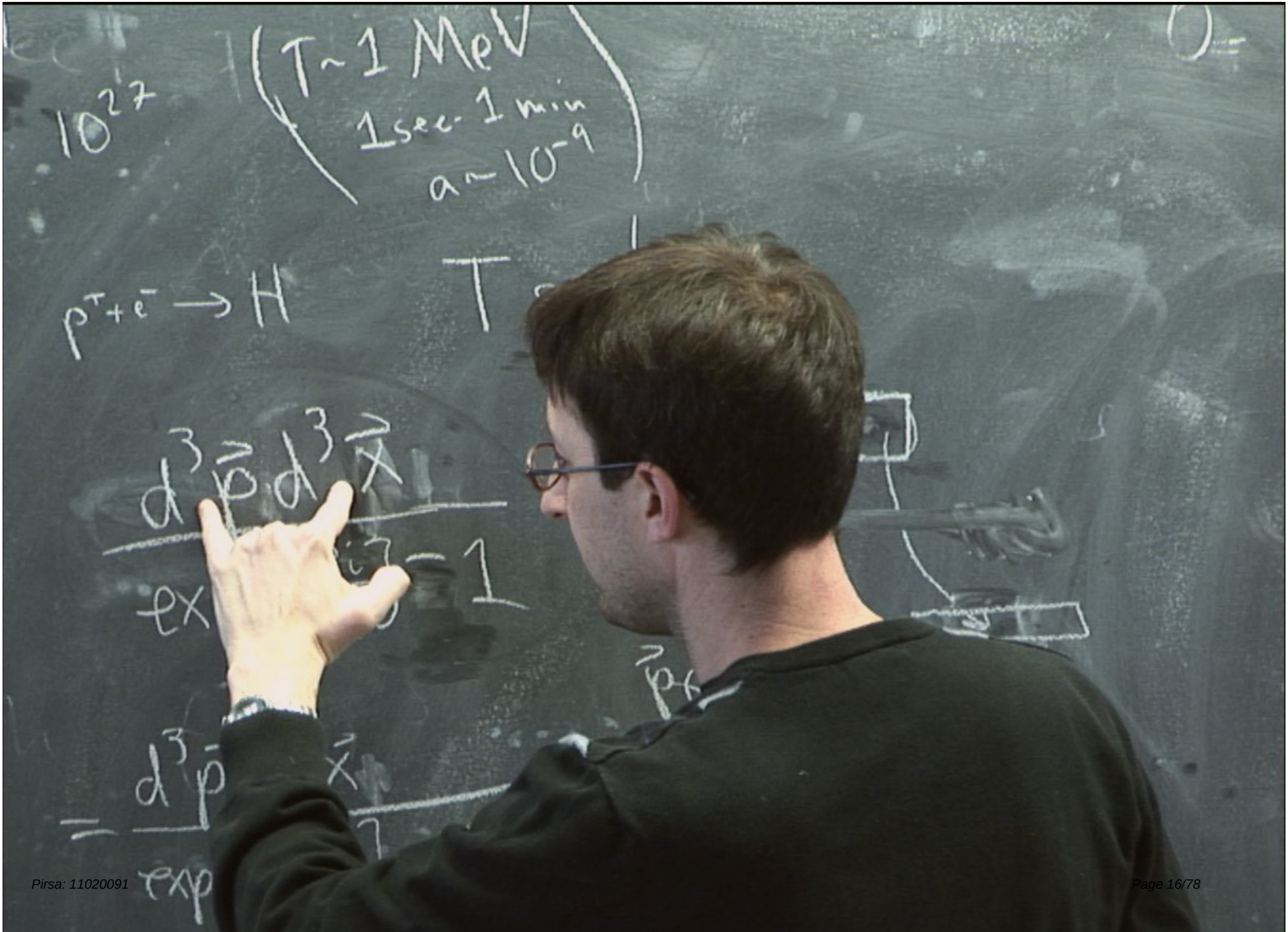
$a \sim 10^{-3}$

$p^{+} + e^{-} \rightarrow H$ $\quad T \propto \frac{1}{a}$

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

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




10^{27}
T~1 MeV
1 sec. 1 min
$a \sim 10^{-9}$
$p^+ + e^- \rightarrow H$
$d^3\vec{p}\, d^3\vec{x}$
$\vec{p}_1$
$d^3\vec{p}$
$\vec{x}$
exp

10^{27}

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

1 sec. 1 min

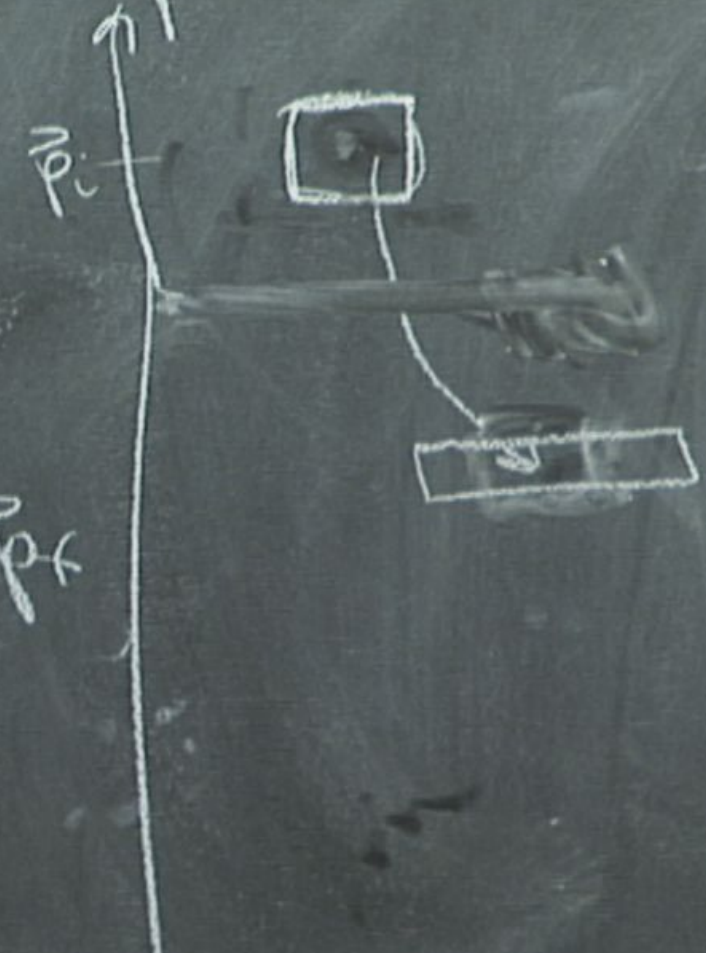
$a \sim 10^{-9}$

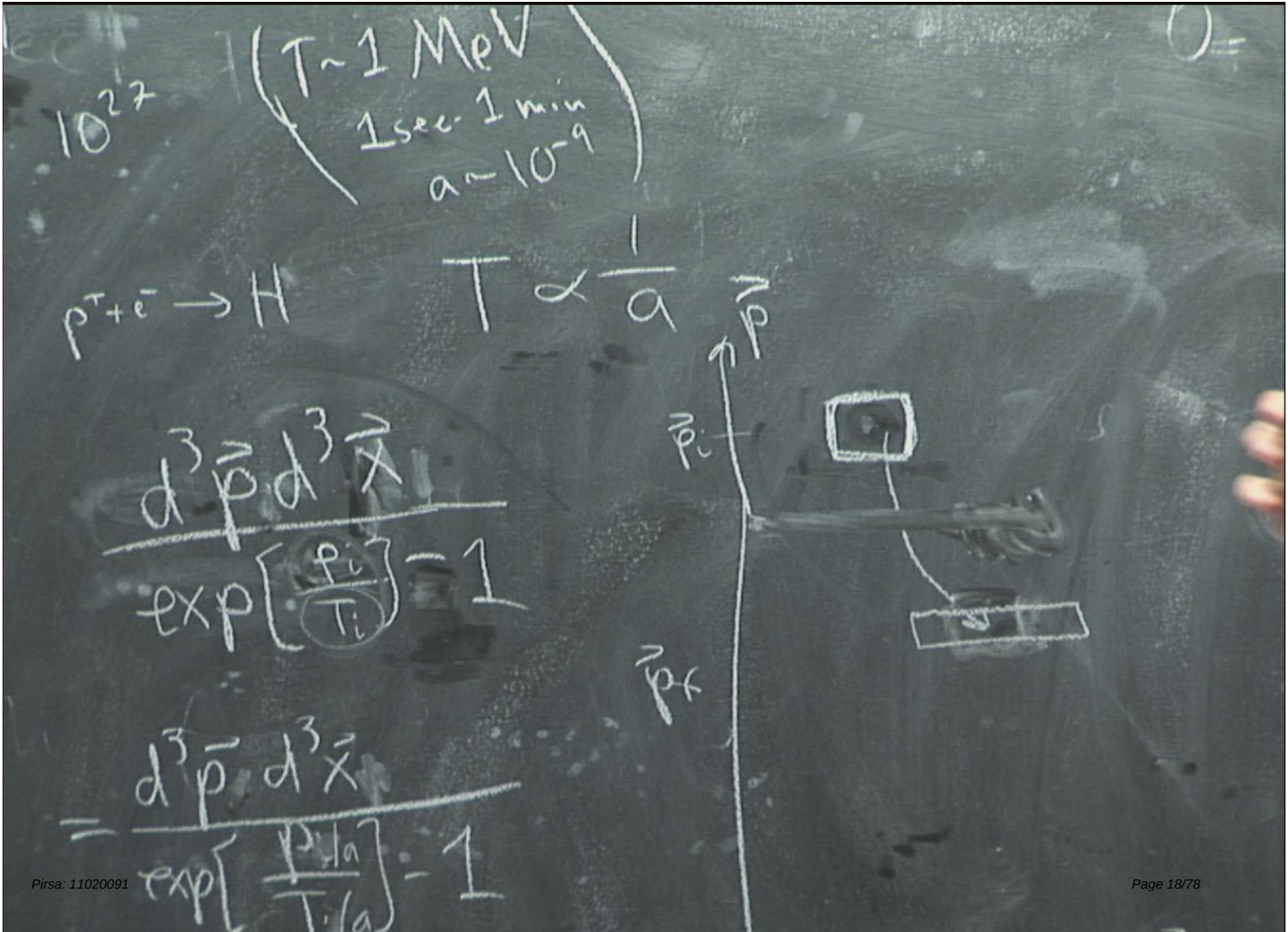
$p^+ + e^- \rightarrow H$

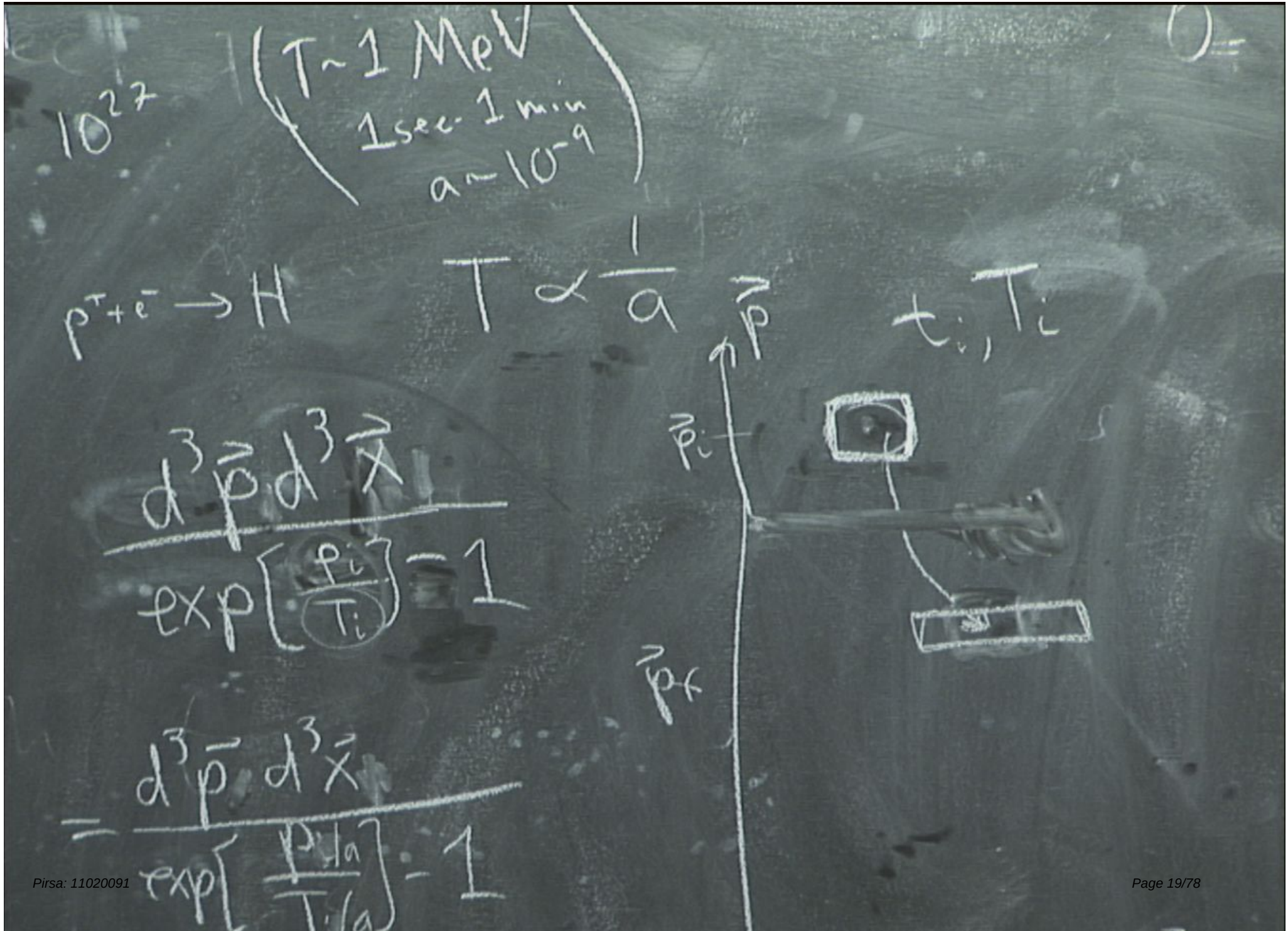
$T \propto \frac{1}{a}$

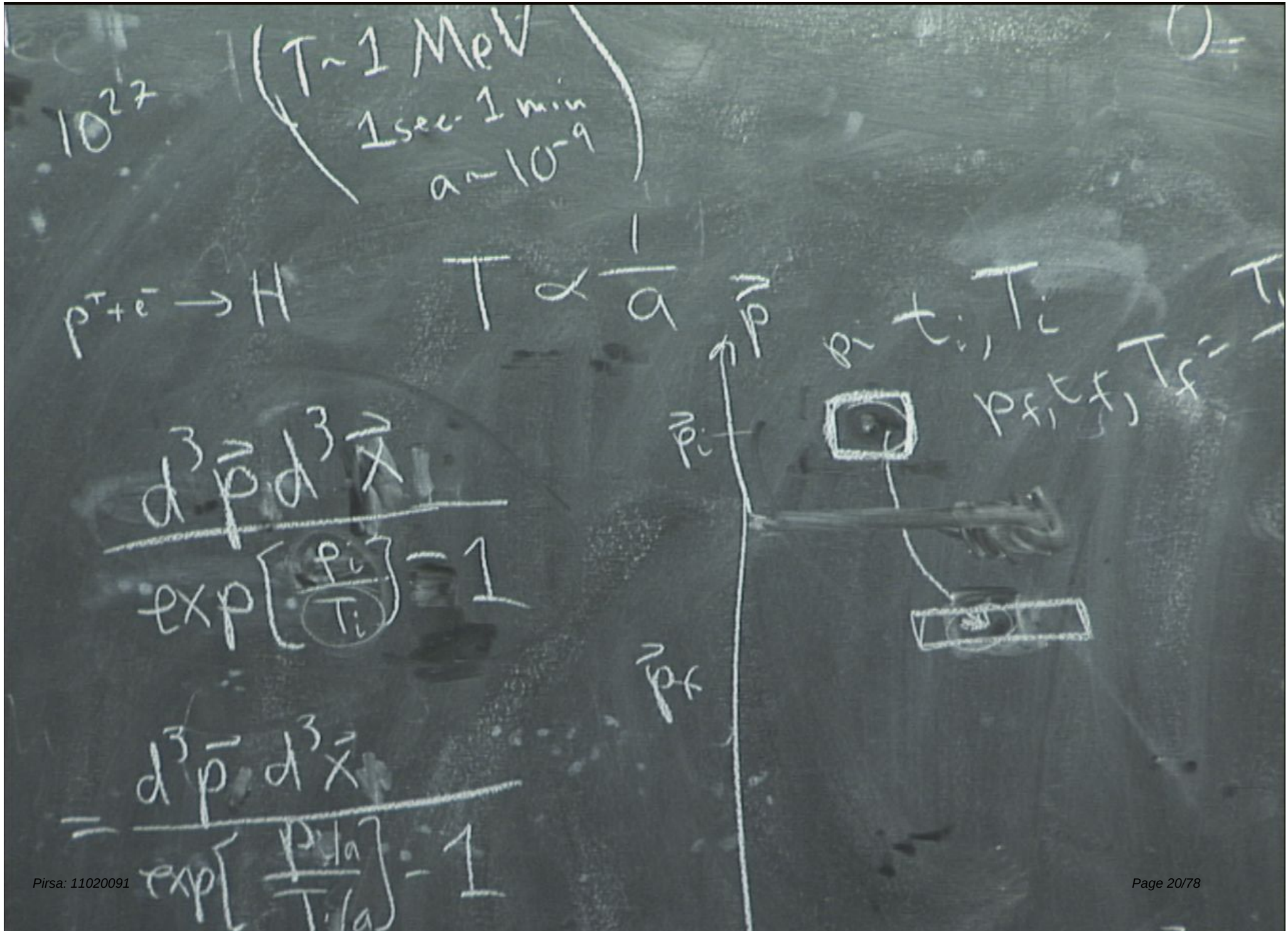
$$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left(\frac{p_i}{T_i}\right) - 1}$$

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




10^{27}
$T \sim 1\ MeV$
1 sec. 1 min
$a \sim 10^{-9}$
$p^+ + e^- \rightarrow H$
$T \propto \frac{1}{a}$
$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i}{T_i}\right] - 1}$
$= \frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i a}{T_i a}\right] - 1}$
$\vec{p}$
$\vec{p}_i$
$\vec{p}_f$


10^{27}
$T \sim 1\ MeV$
1 sec. 1 min
$a \sim 10^{-9}$
$p^+ + e^- \rightarrow H$
$T \propto \frac{1}{a}$
$\vec{p}$
t_i, T_i
$\vec{p}_i$
$\vec{p}_f$
$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i}{T_i}\right] - 1}$
$= \frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i a}{T_i a}\right] - 1}$


10^{27}
$T \sim 1$ MeV
1 sec. 1 min
$a \sim 10^{-9}$
$p^+ + e^- \rightarrow H$
$T \propto \frac{1}{a}$
$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i}{T_i}\right] - 1}$
$= \frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left[\frac{p_i/a}{T_i/a}\right] - 1}$
$\vec{p}$
$\vec{p}_i$
$\vec{p}_f$

H

10^{27}

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

1 sec. 1 min

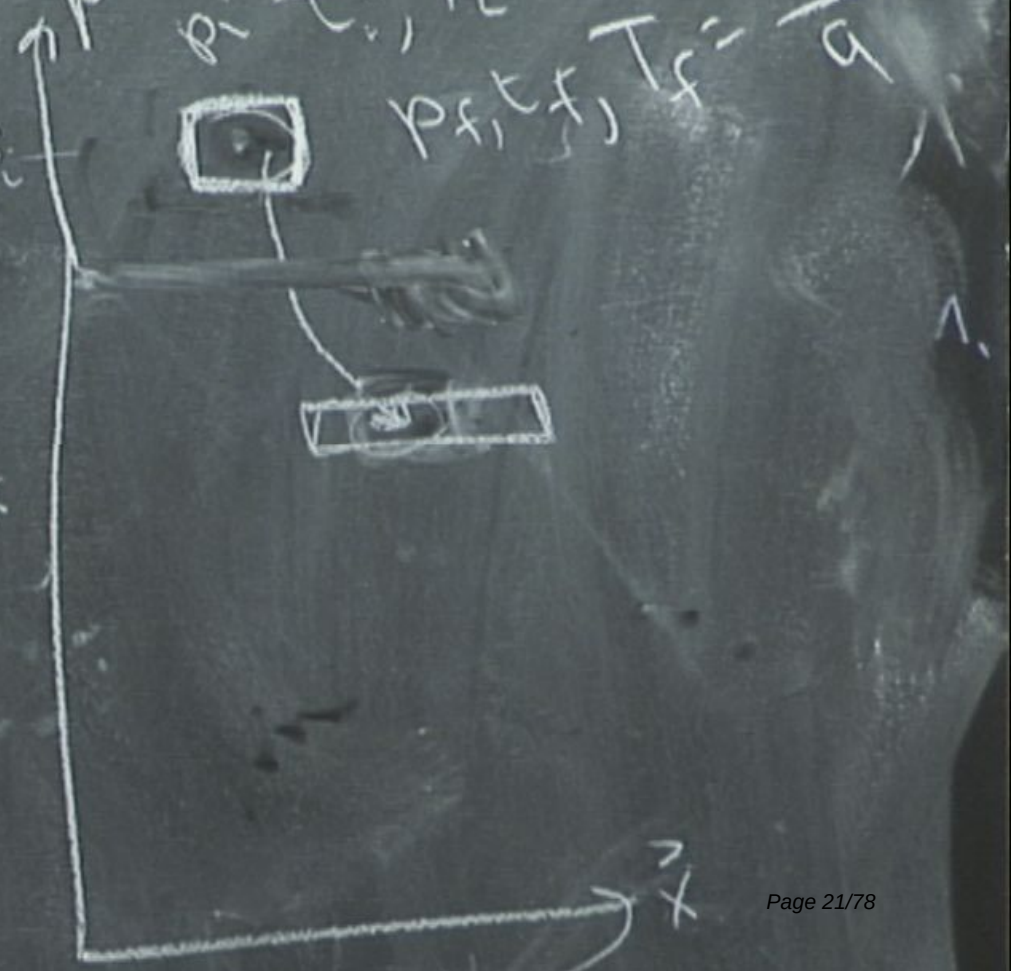
$a \sim 10^{-9}$

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

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

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

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



H

10^{27}

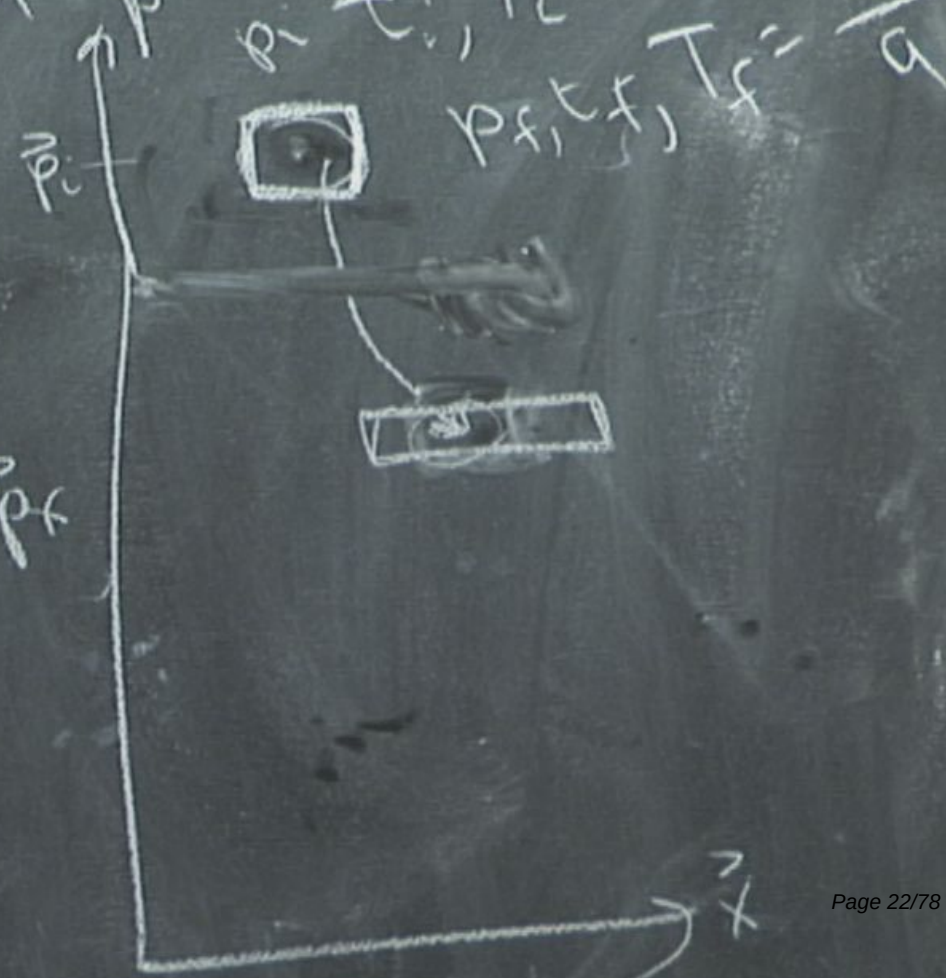
$\left(T \sim 1\ \text{MeV}\right.$
1 sec. 1 min
$a \sim 10^{-9}$

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

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

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

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

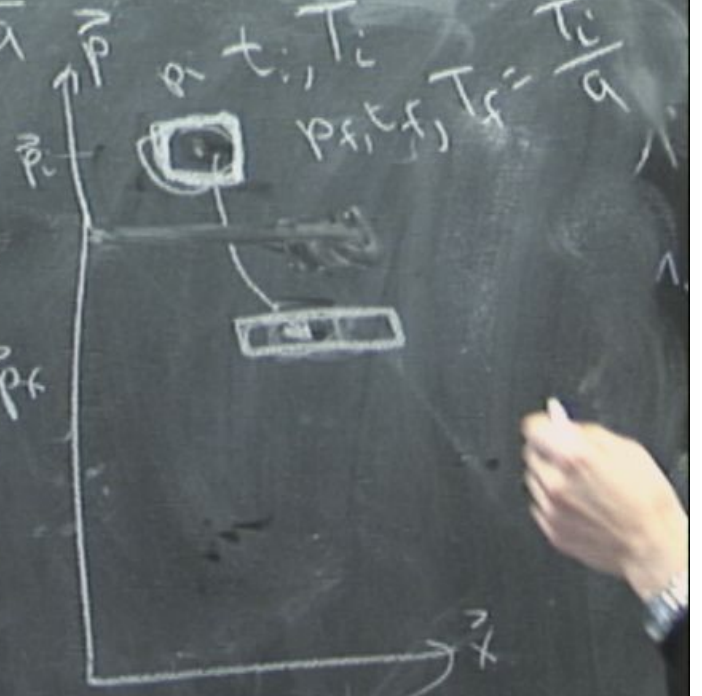


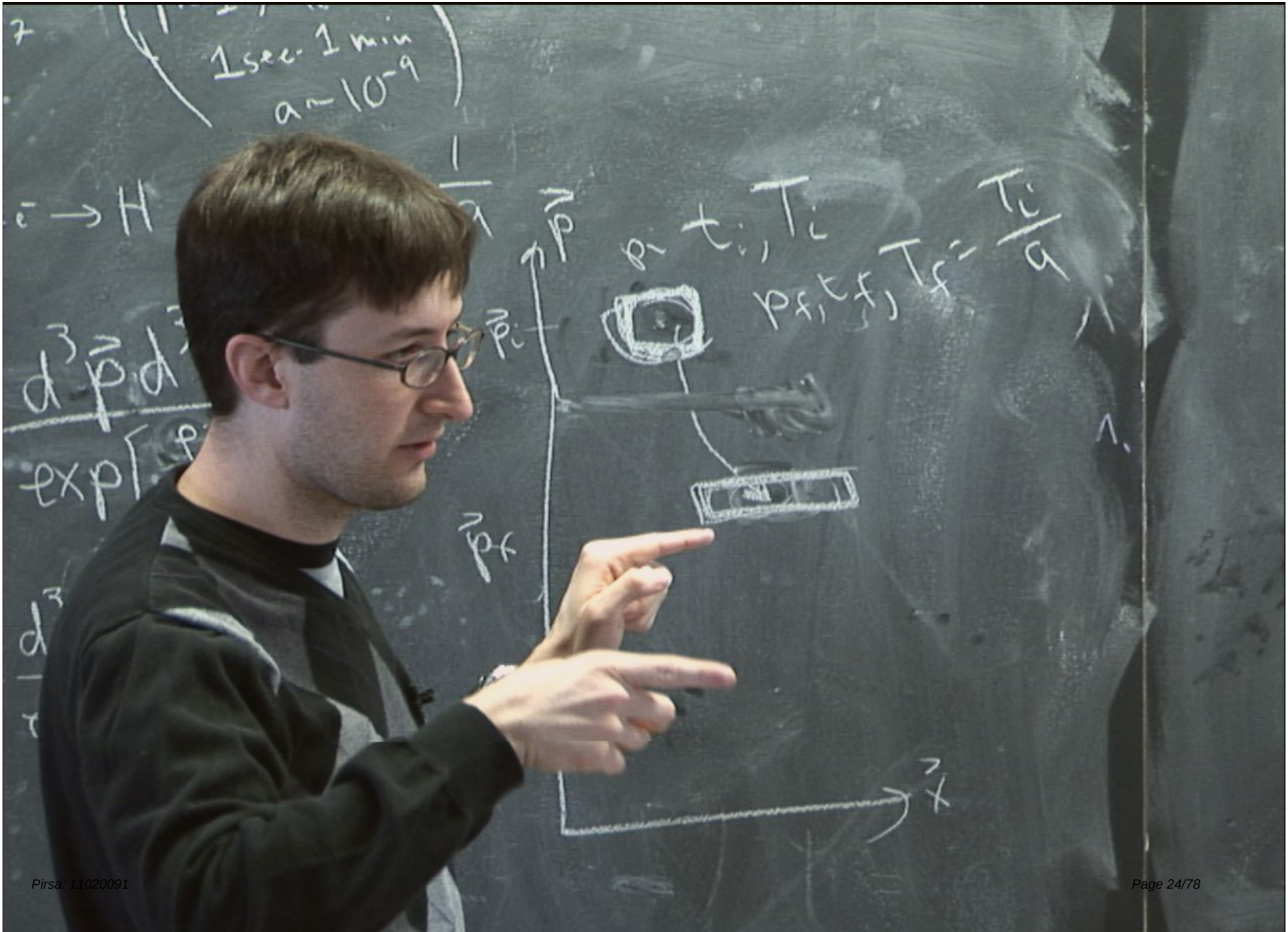
BBN $T_F \sim \frac{1}{7}$ 25% He, H $a \sim 10^9$ 10^{27} ($T \sim 1$ MeV, 1 sec. 1 min, $a \sim 10^{-9}$)

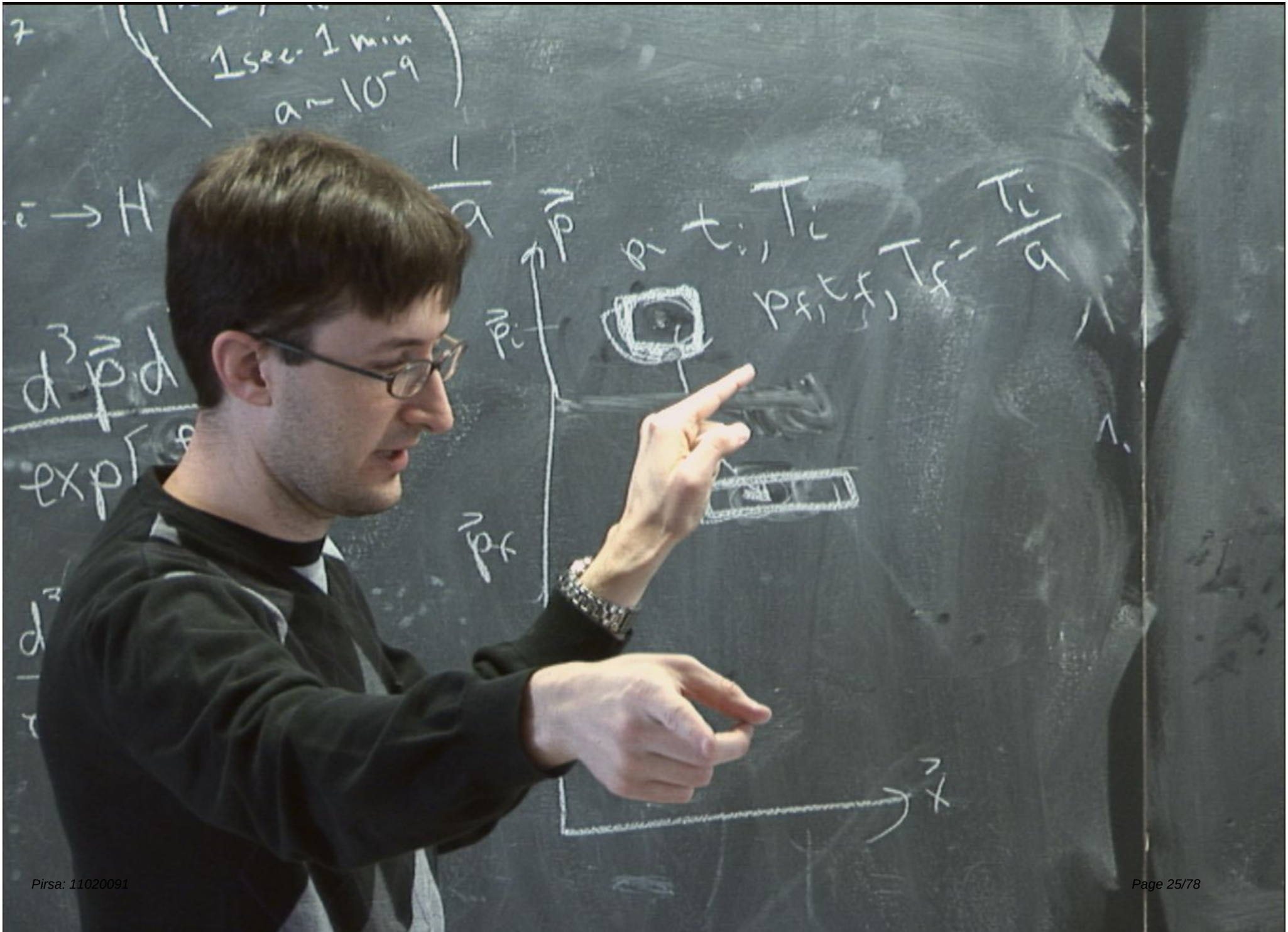
CMB $T \sim 1$ eV, few $\times 10^5$ yrs old, $a \sim 10^{-3}$ $p^+ + e^- \to H$ $T \propto \frac{1}{a}$

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

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




1 sec. 1 min
$a \sim 10^{-9}$
$\vec{p}$
$\vec{p}_i$
$\vec{p}_f$
$\vec{x}$

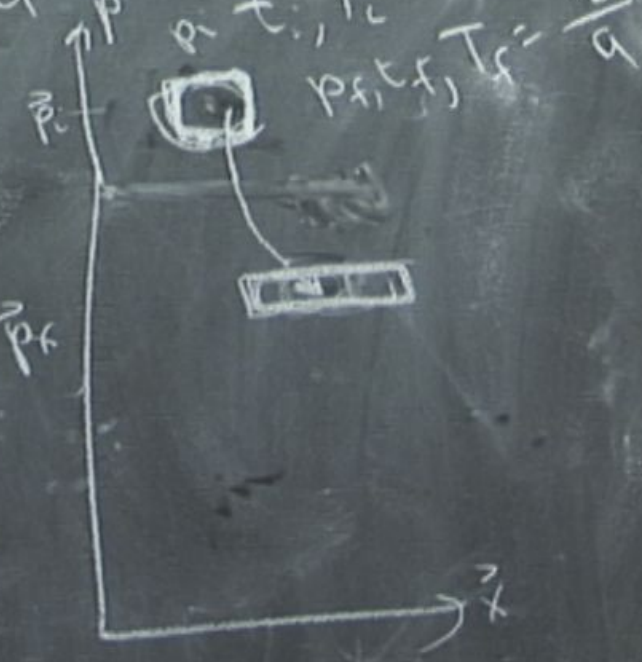

1 sec. 1 min
$a \sim 10^{-9}$
$\frac{1}{a}$
$\vec{p}$
$\vec{p}_i$
$\vec{p}_f$
$\vec{x}$
$\frac{T_i}{a}$

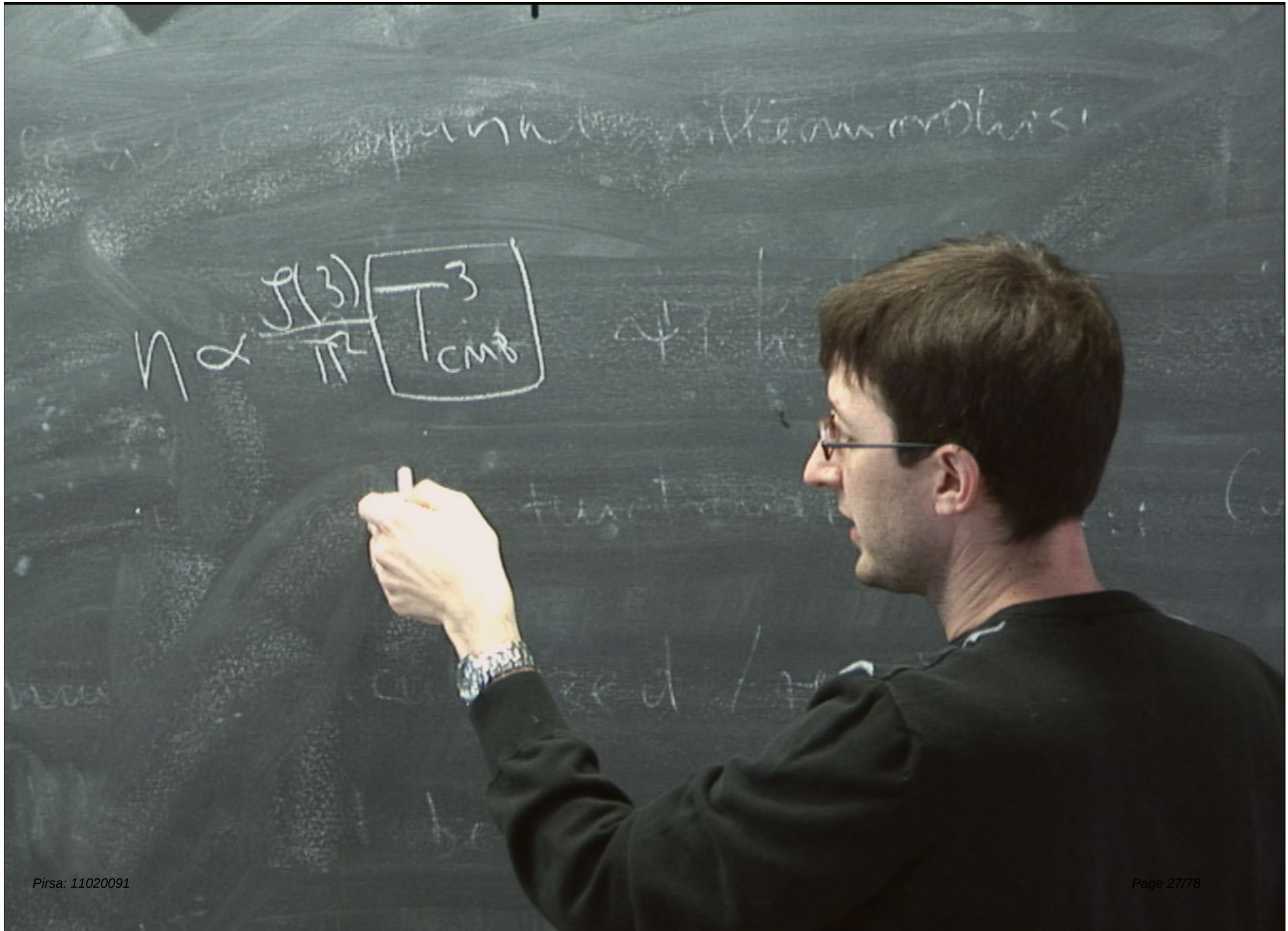
BBN $T_F \frac{1}{7}$ 25% He, H $a \cdot 10^{9}$ 10^{27} $\left(T \sim 1\ \text{MeV}, \text{1 sec}, \text{1 min}, a \sim 10^{-9}\right)$ $\eta = \frac{n_b}{n_\gamma}$

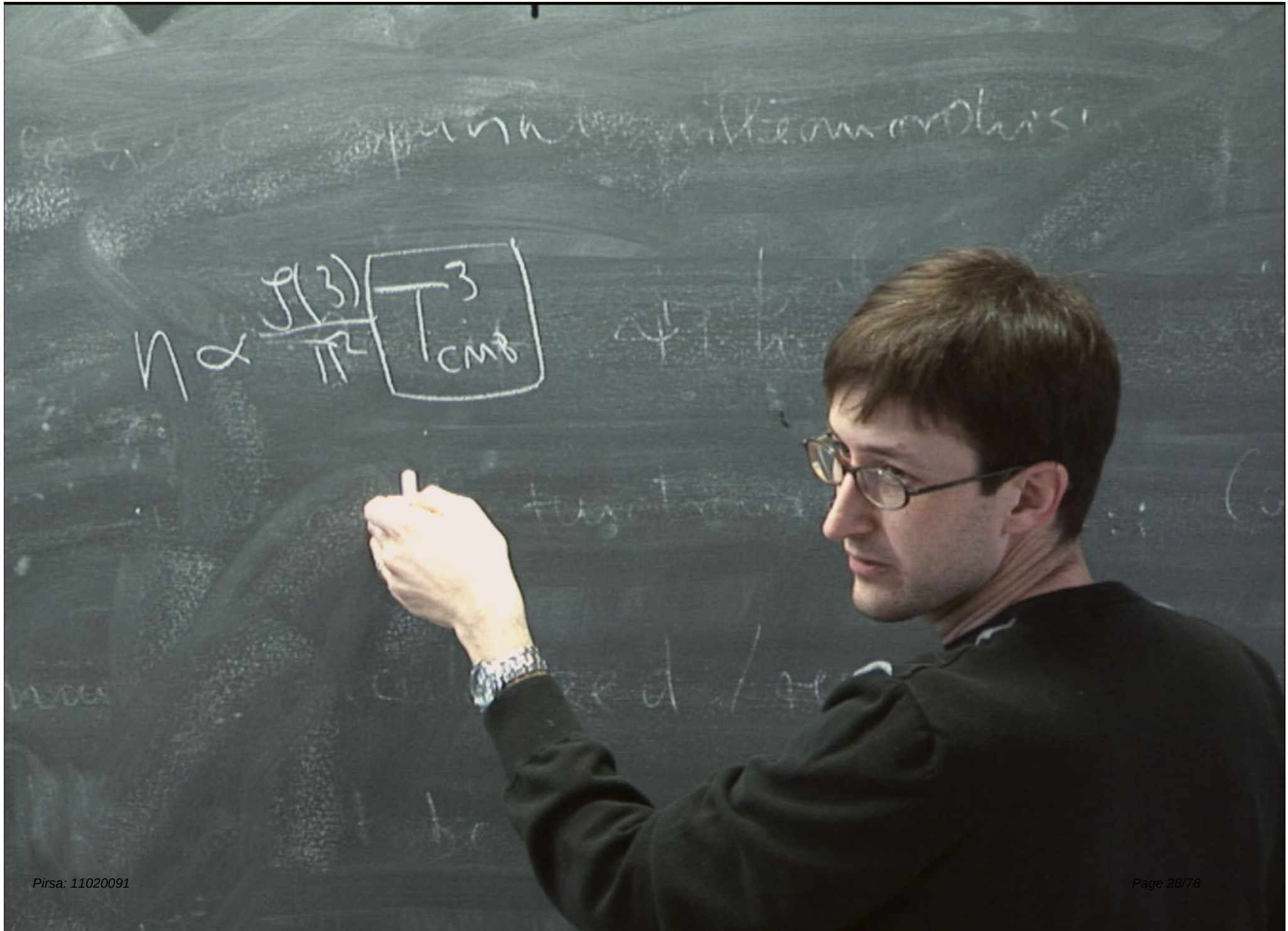
CMB $T \sim 1\ \text{eV}$ few $\times 10^5$ yrs old $a \sim 10^{-3}$ $p^+ + e^- \to H$ $T \propto \frac{1}{a}$

$$\frac{d^3\vec{p}\, d^3\vec{x}}{\exp\left(\frac{p_i}{T_i}\right) - 1}$$

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




$n \propto \frac{\zeta(3)}{\pi^2} T_{CMB}^3$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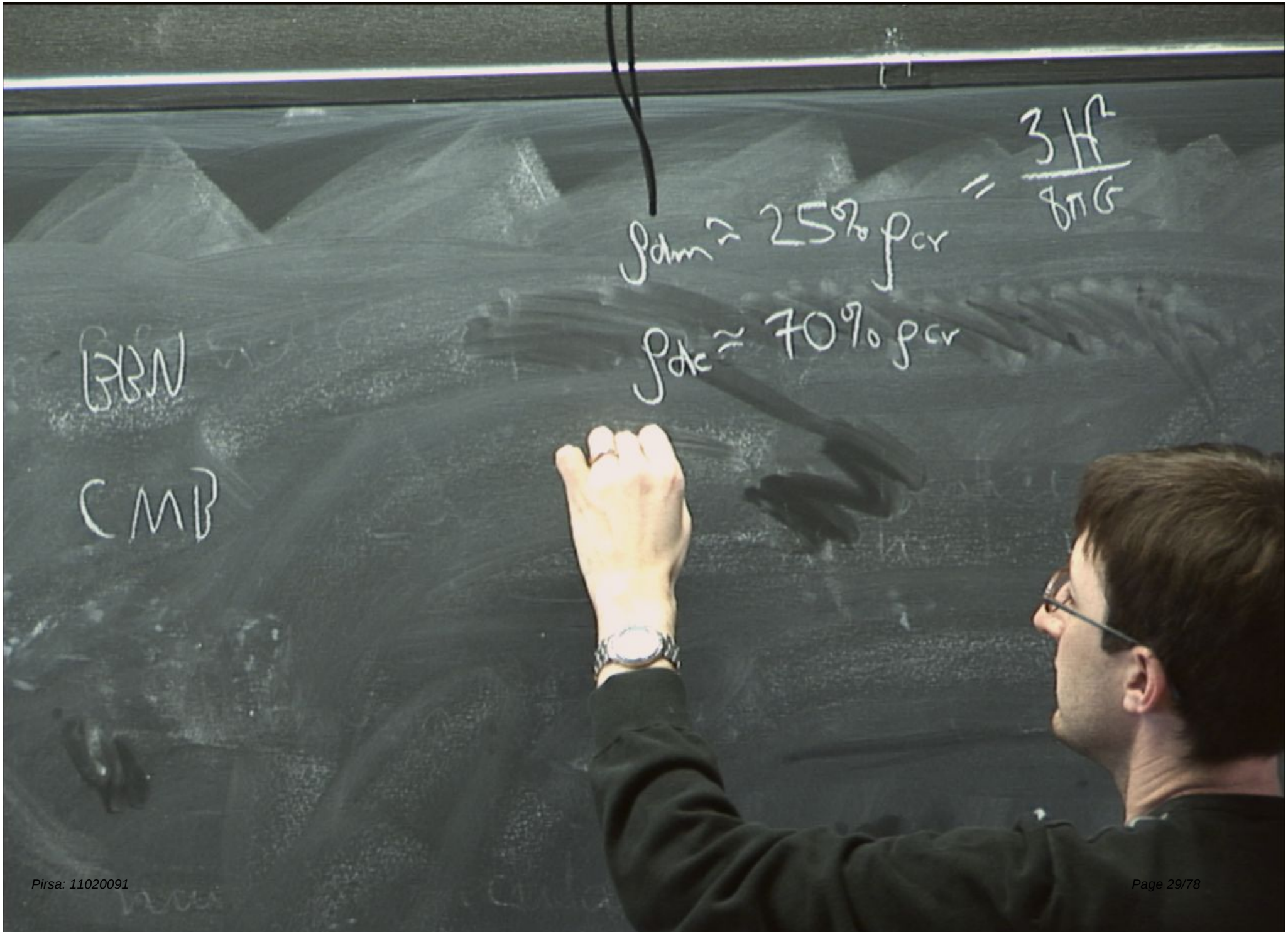
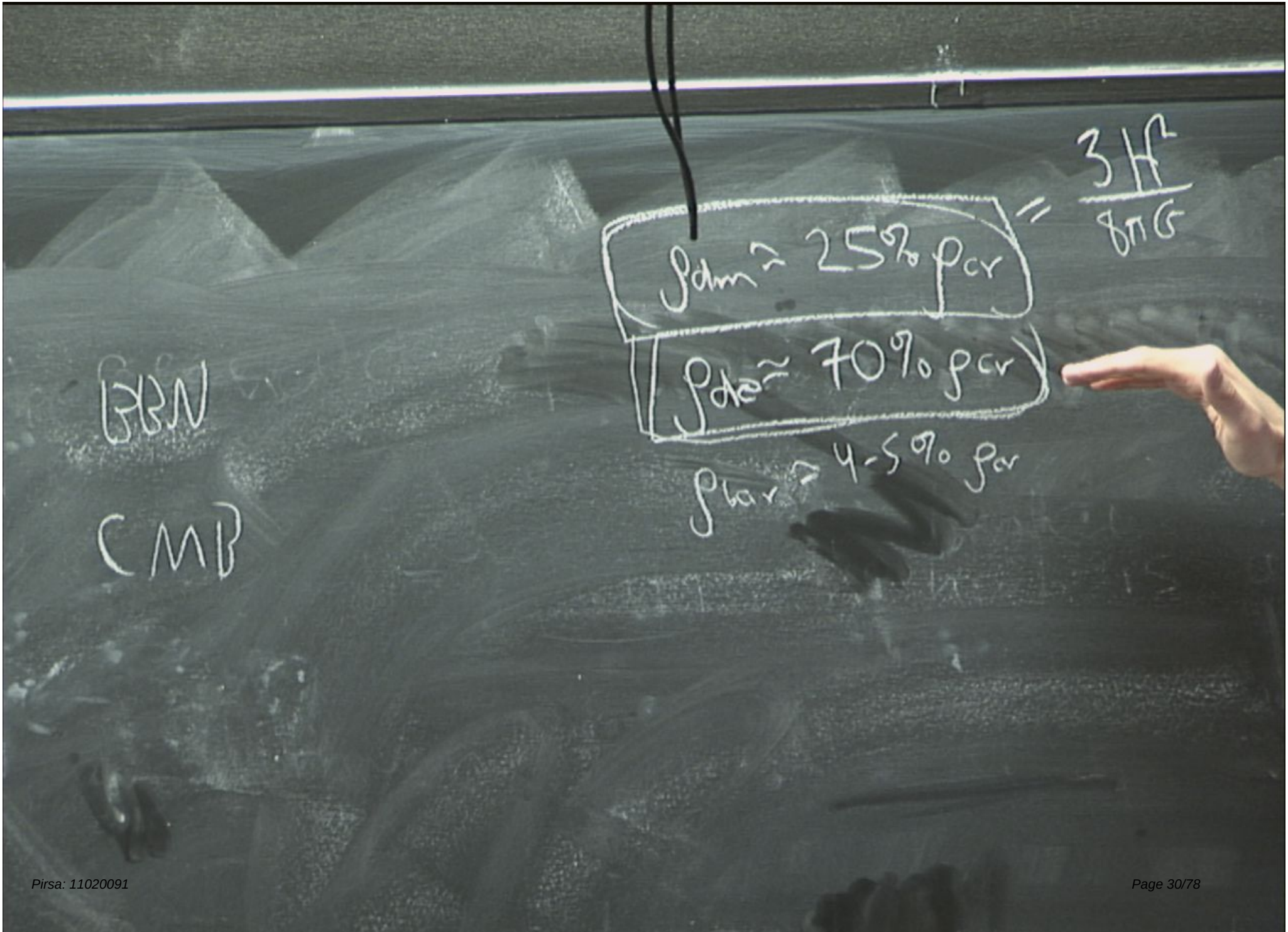
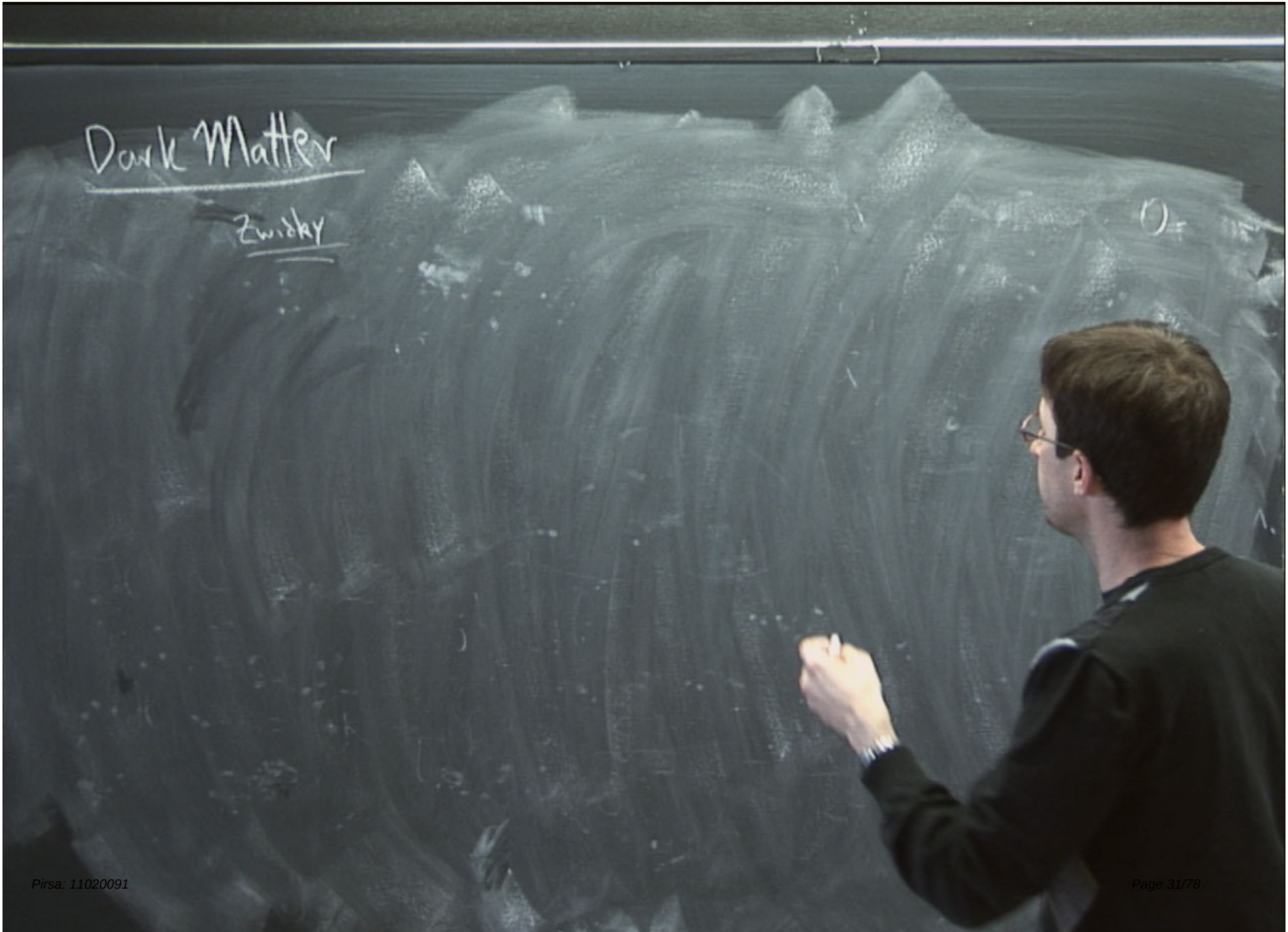

$\rho_{dm} \approx 25\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
$\rho_{de} \approx 70\% \rho_{cr}$
BBN
CMB


$\rho_{dm} \simeq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
BBN
CMB

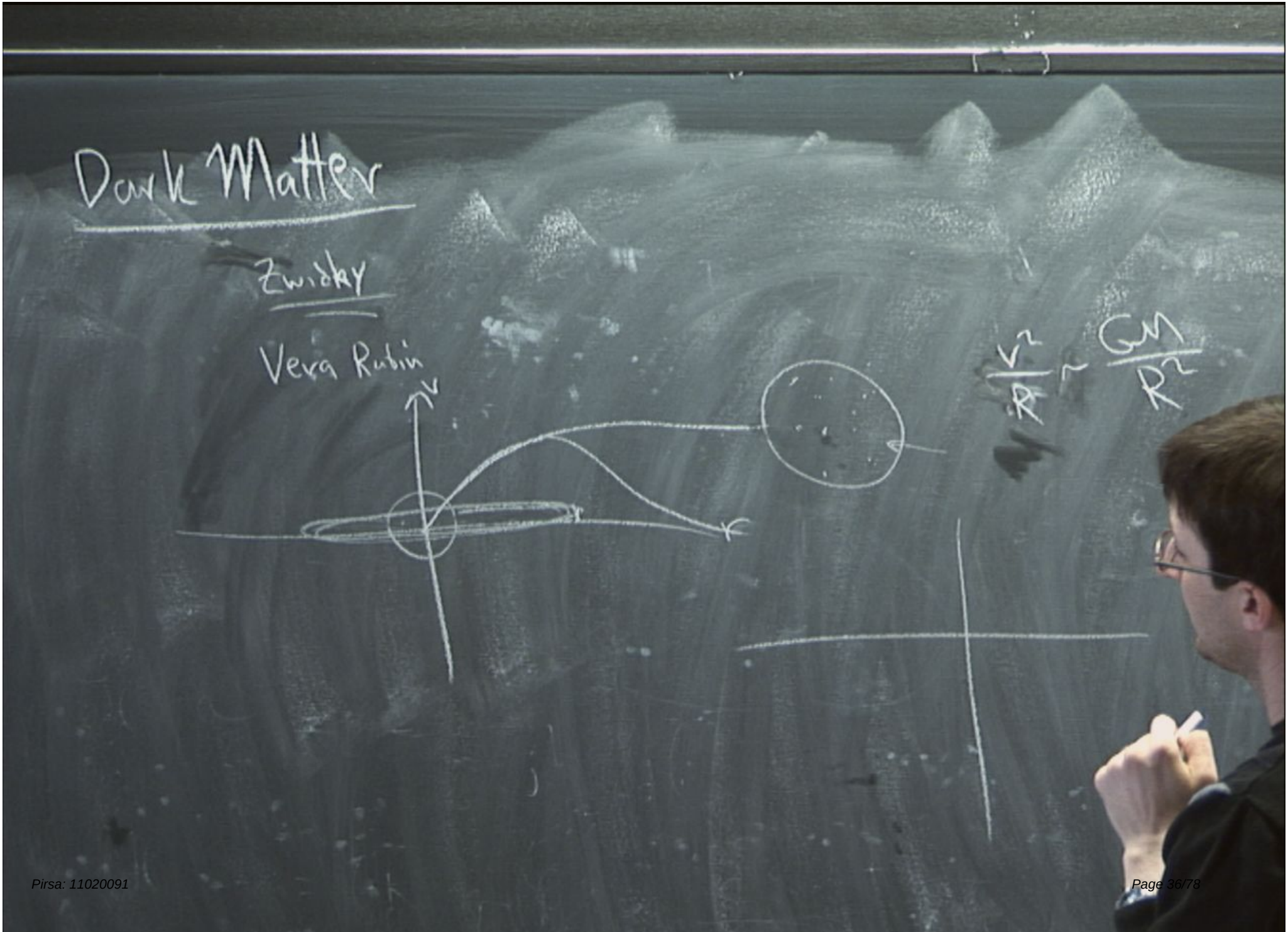

Dark Matter
Zwicky


Dark Matter
Zwicky
$\frac{v^2}{R} \sim$


Dark Matter
Zwicky
$\frac{v^2}{R} \sim \frac{GM}{R^2}$


Dark Matter
Zwicky
$\frac{v^2}{R} \sim \frac{GM}{R^2}$

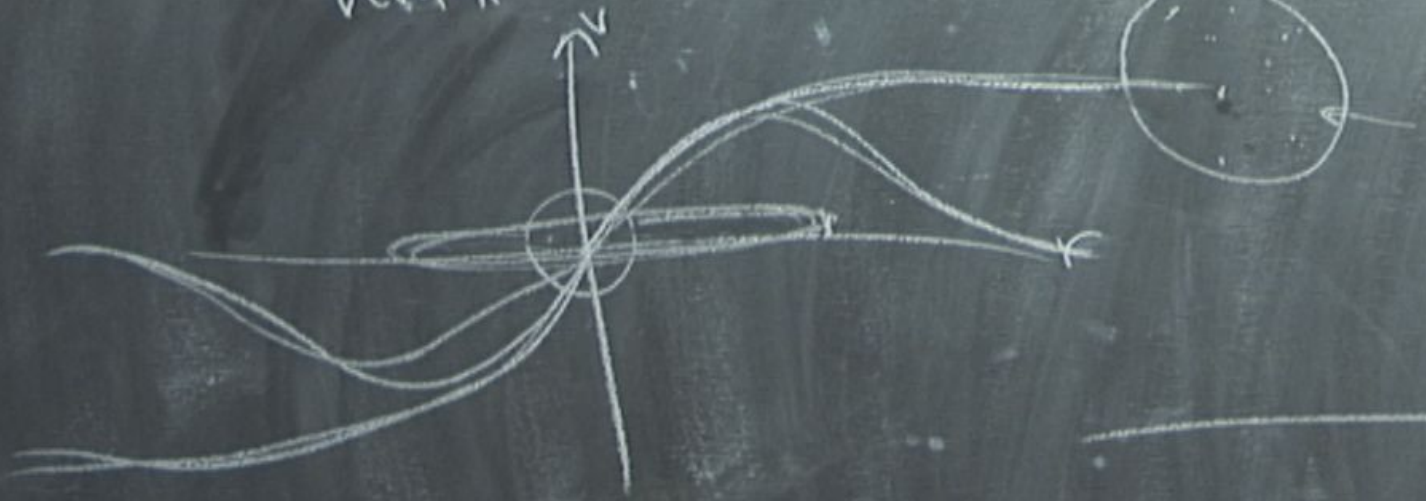

Dark Matter
Zwicky
Vera Rubin
$\frac{v^2}{R} \sim \frac{GM}{R^2}$


Dark Matter
Zwicky
Vera Rubin
v
r
$\frac{v^2}{R} \sim \frac{GM}{R^2}$

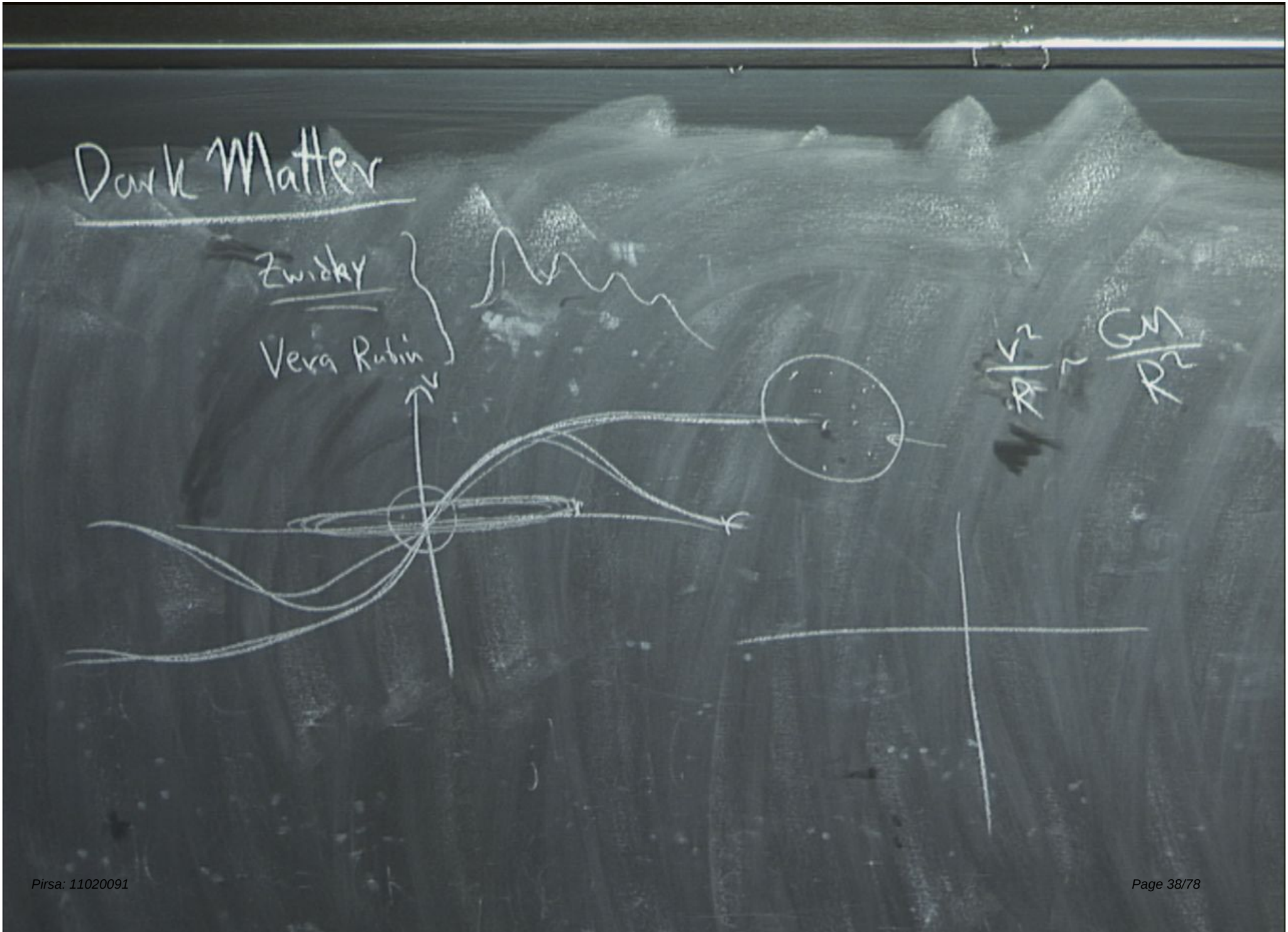
Dark Matter

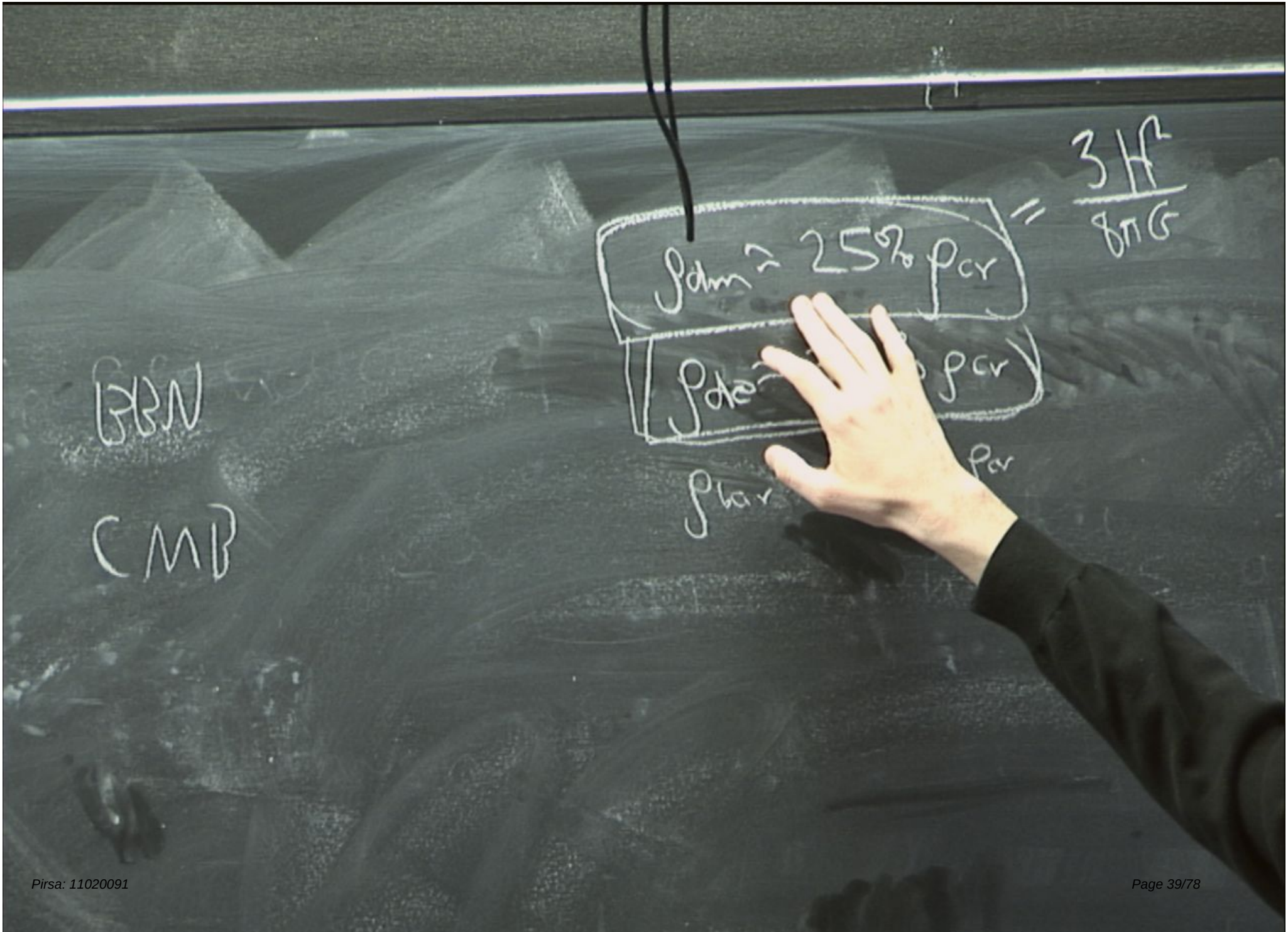
Zwicky

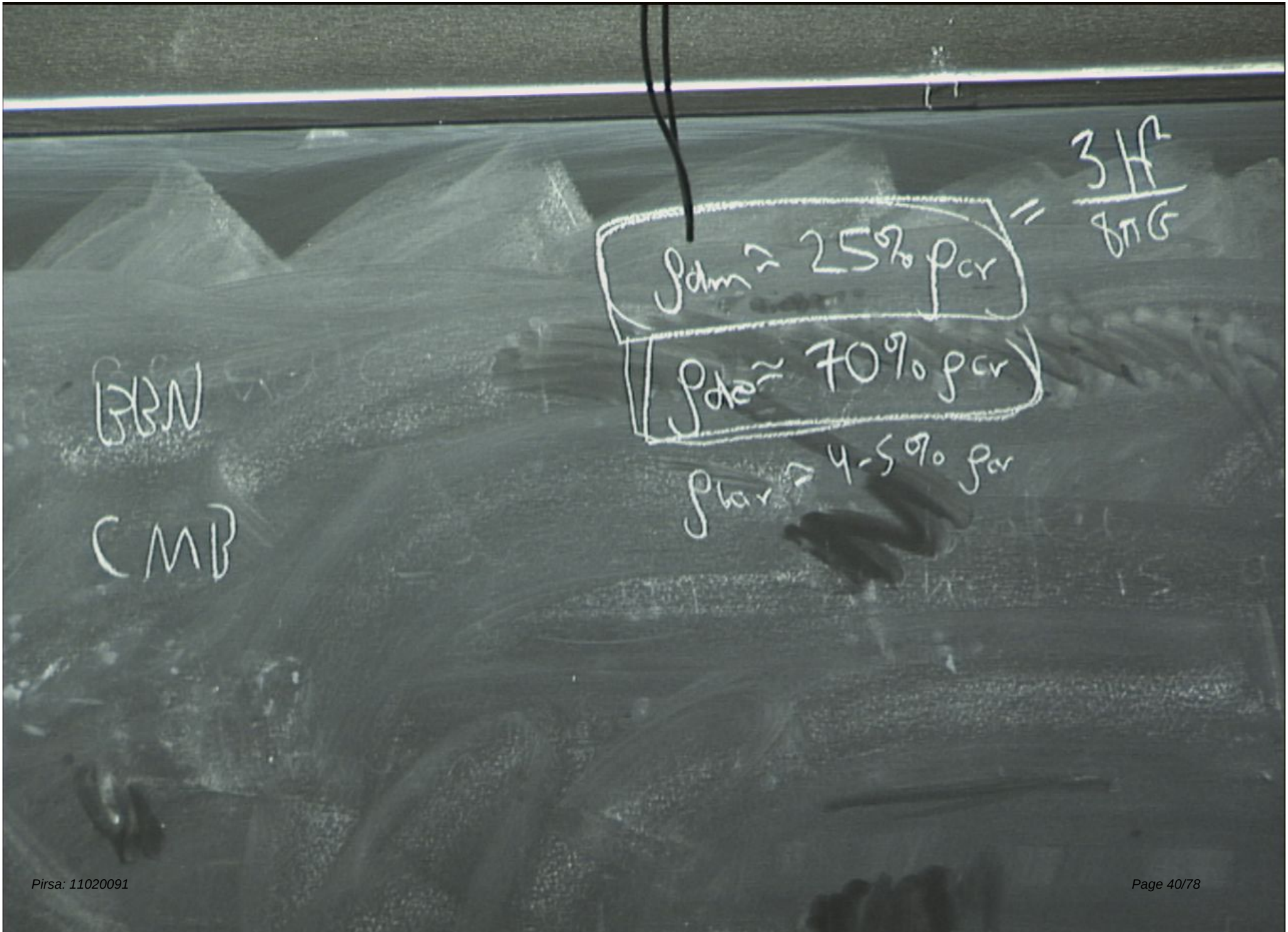
Vera Rubin

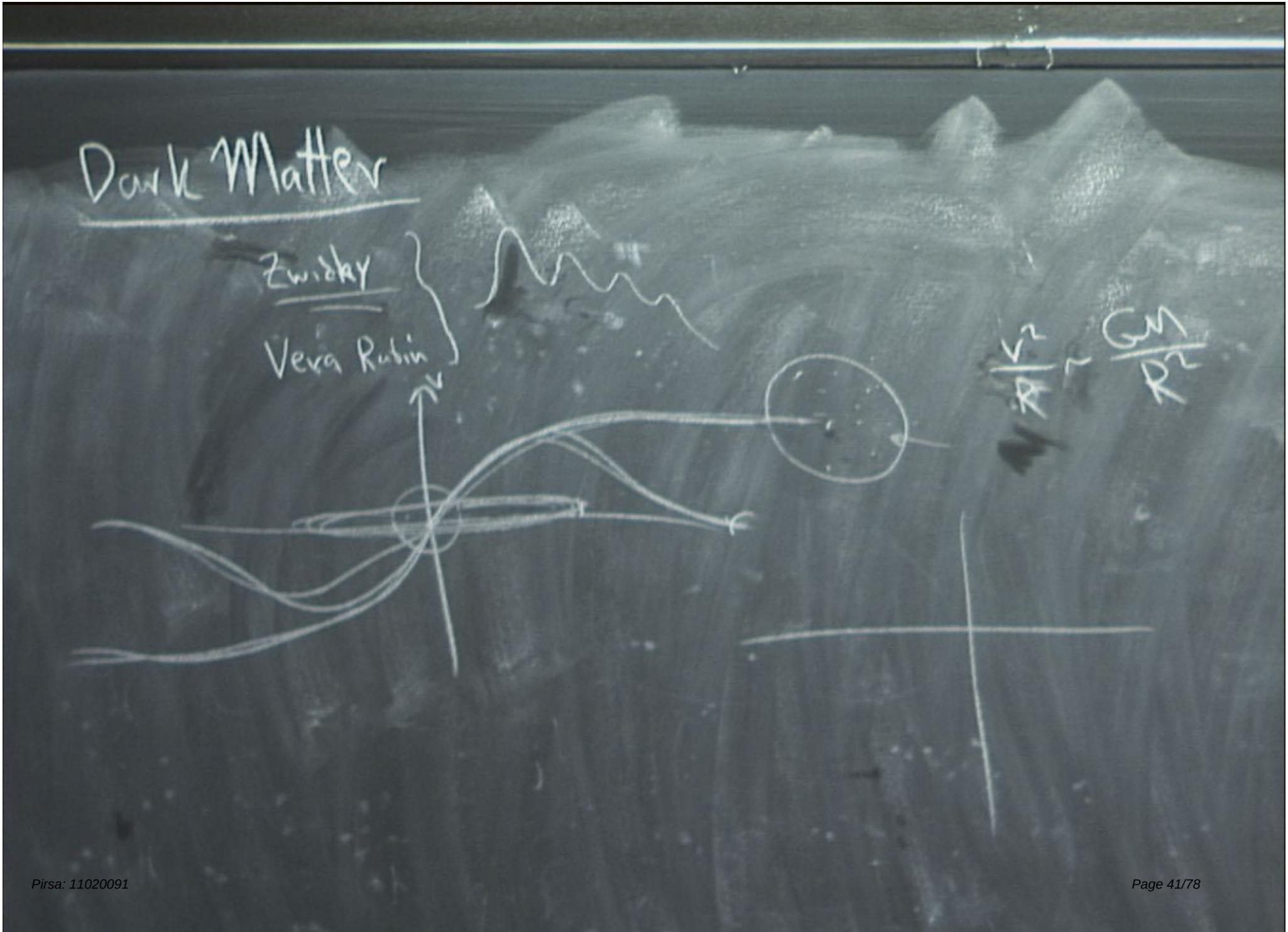


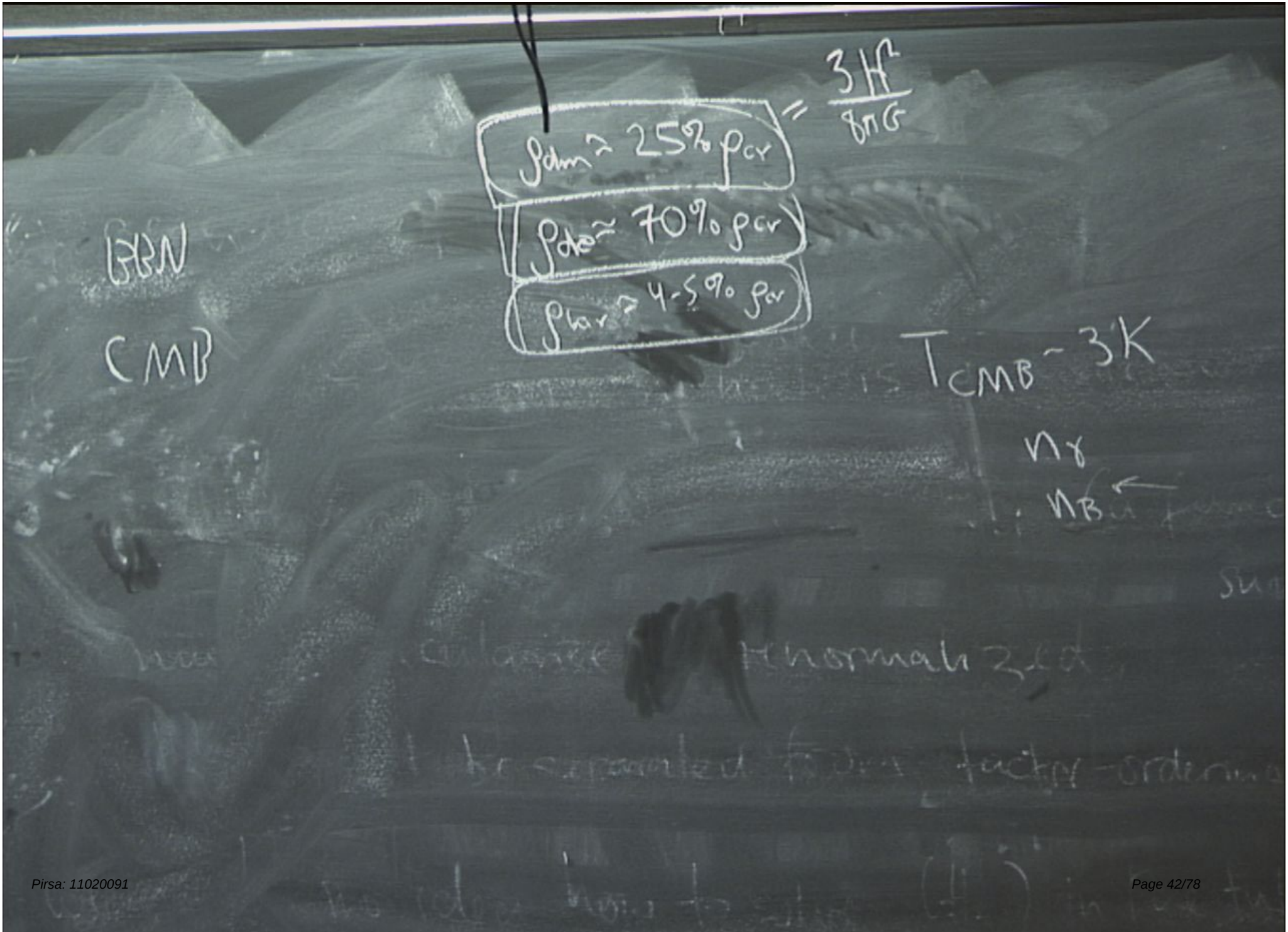
$\frac{v^2}{R} \sim \frac{GM}{R^2}$


Dark Matter
Zwicky
Vera Rubin
v
r
$\frac{v^2}{R} \sim \frac{GM}{R^2}$


BBN
CMB
$\rho_{dm} \simeq 25\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
ρ_{cr}


BBN
CMB
$\rho_{dm} \simeq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$


Dark Matter
Zwicky
Vera Rubin
v
$\frac{v^2}{R} \sim \frac{GM}{R^2}$


$\rho_{dm} \simeq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
BBN
CMB
$T_{CMB} \sim 3K$
n_γ
n_B

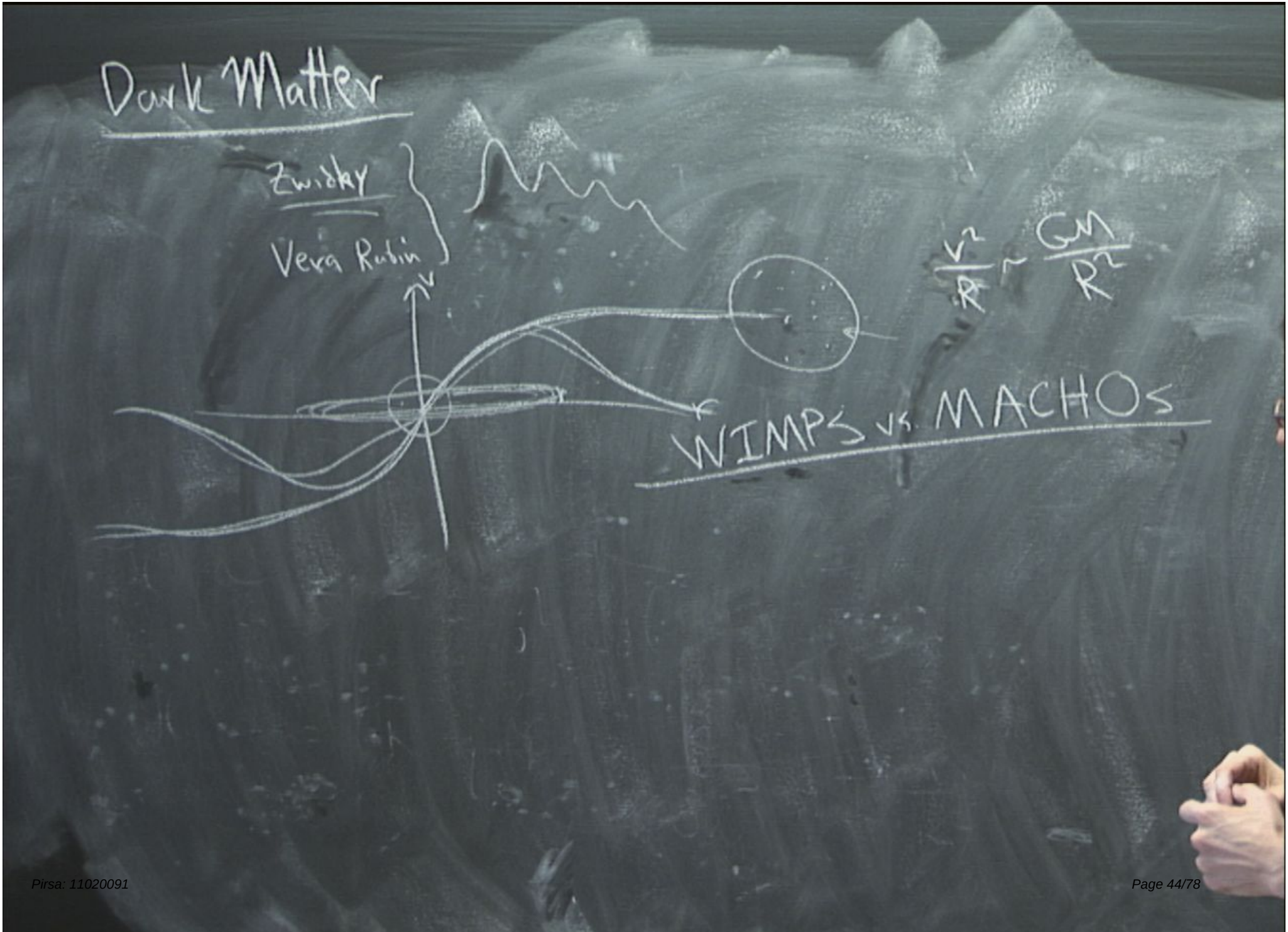
Dark Matter

Zwicky

Vera Rubin

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

WIMPs vs. MACHOs


Dark Matter
Zwicky
Vera Rubin
v
$\frac{v^2}{R} \sim \frac{GM}{R^2}$
WIMPS vs. MACHOS

Dark Matter

Zwicky

Vera Rubin

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

WIMPS vs MACHOs

Dark Matter

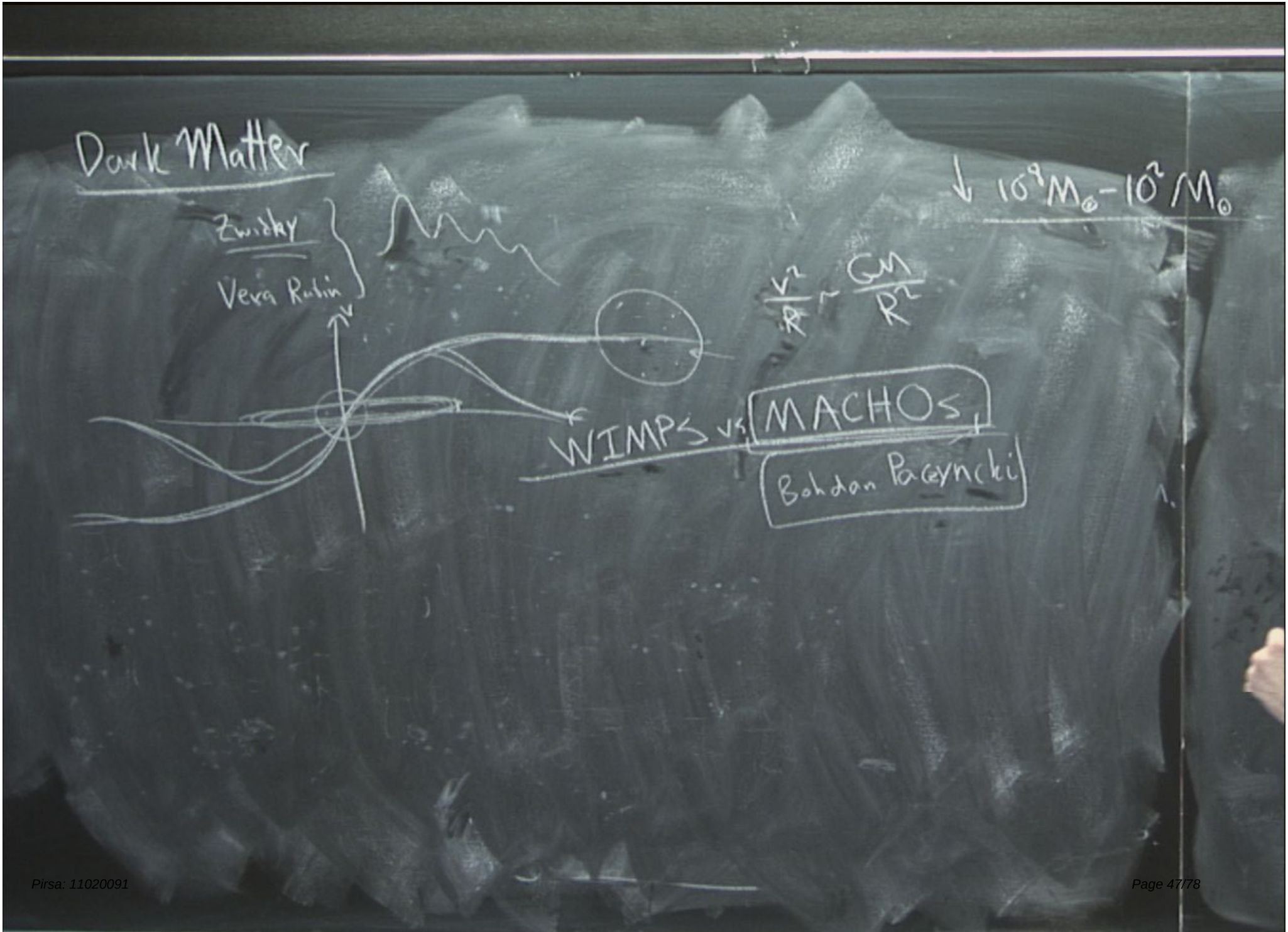
Zwicky

Vera Rubin

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

WIMPs vs MACHOs

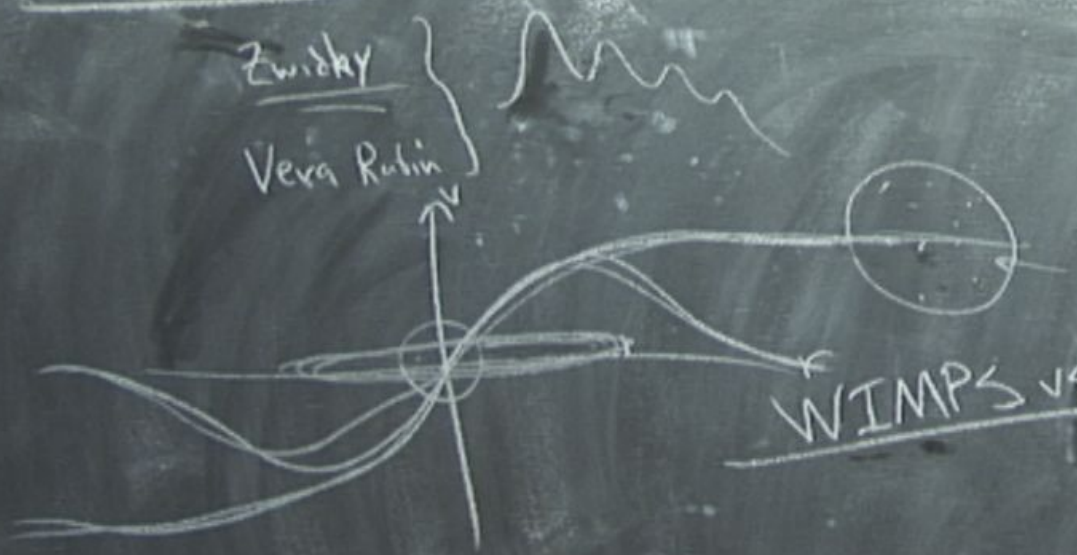
Bohdan Paczynski


Dark Matter
Zwicky
Vera Rubin
$\frac{v^2}{R} \sim \frac{GM}{R^2}$
$\downarrow 10^9 M_\odot - 10^2 M_\odot$
WIMPS vs MACHOs
Bohdan Paczynski

Dark Matter

Zwicky

Vera Rubin

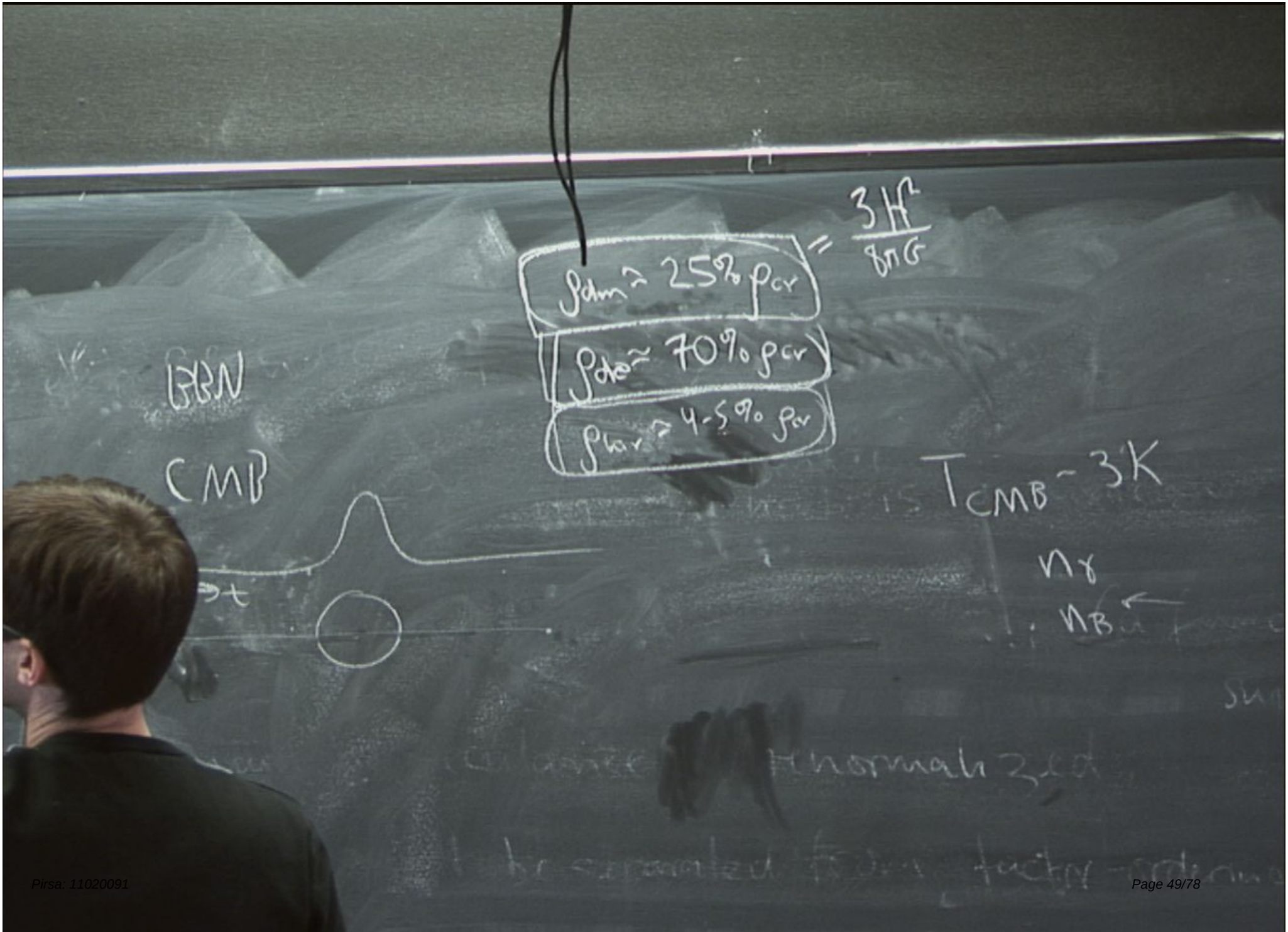


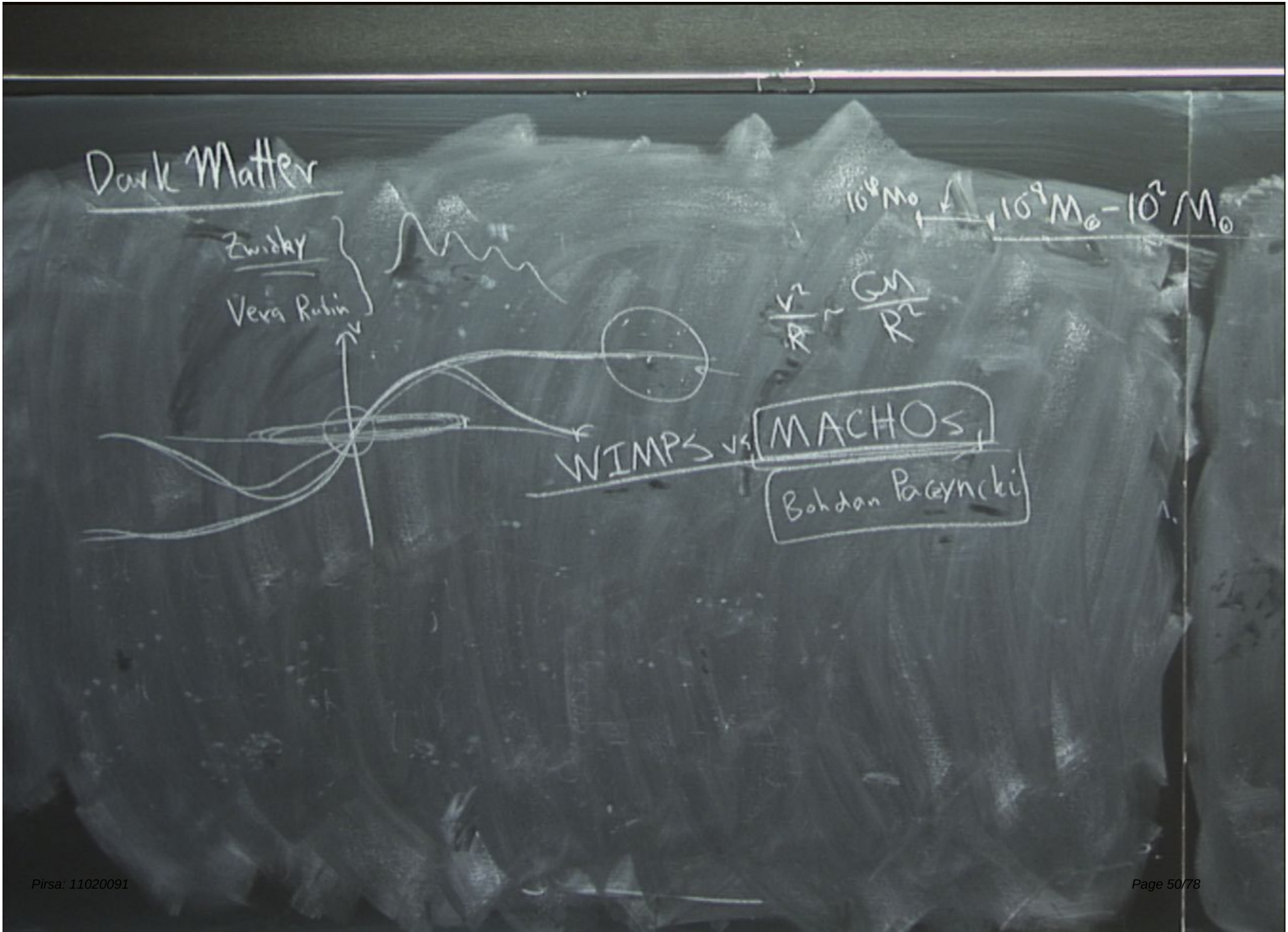
$\frac{v^2}{R} \sim \frac{GM}{R^2}$

$\downarrow 10^9 M_\odot - 10^2 M_\odot$

WIMPS vs MACHOs

Bohdan Paczynski


$\rho_{dm} \simeq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
BBN
CMB
$T_{CMB} \sim 3K$
n_γ
n_B


Dark Matter
Zwicky
Vera Rubin
v
$10^8 M_\odot$
$10^9 M_\odot - 10^2 M_\odot$
$\frac{v^2}{R} \sim \frac{GM}{R^2}$
WIMPS vs MACHOs
Bohdan Paczynski

Dark Matter

Zwicky

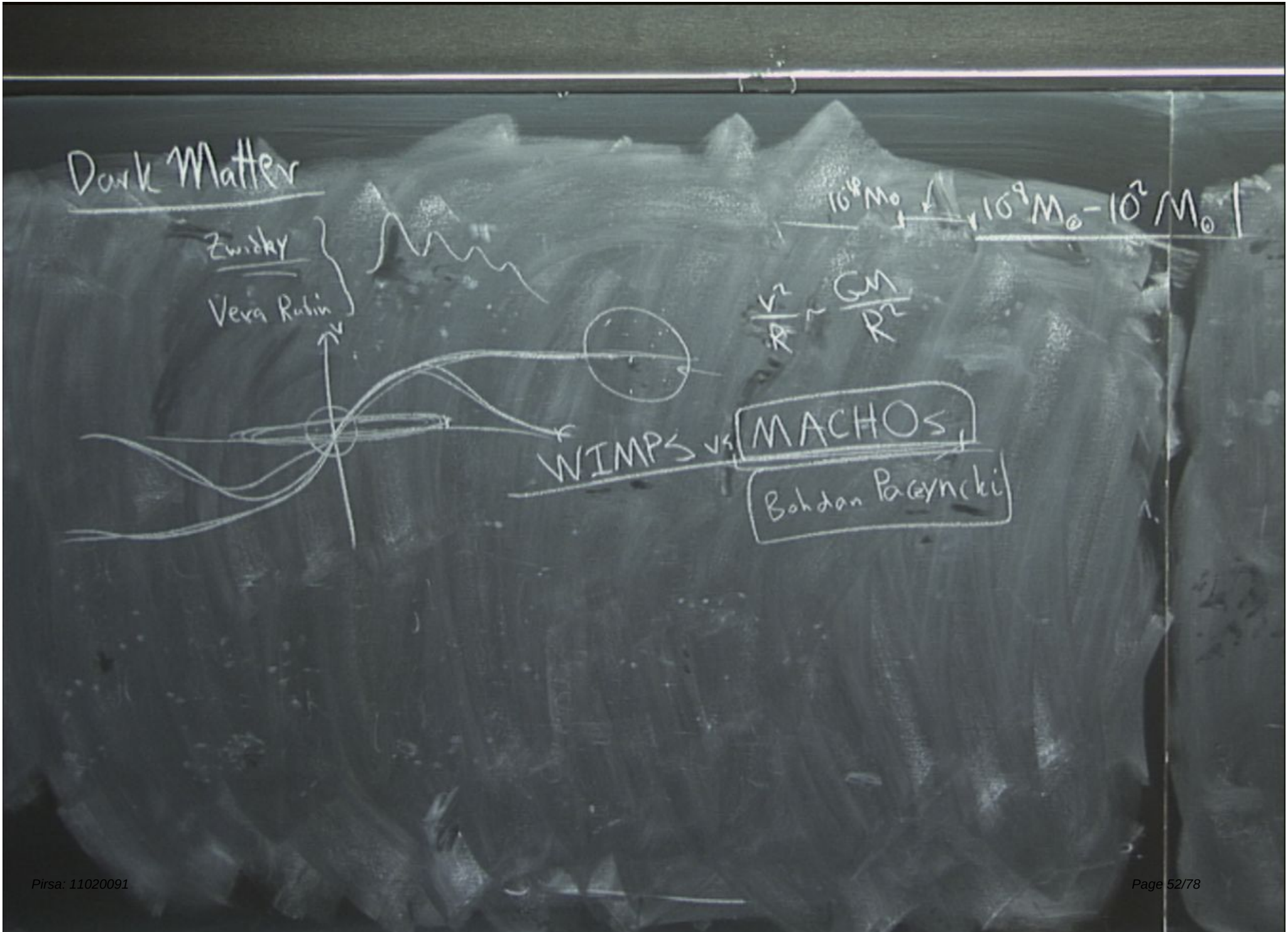
Vera Rubin

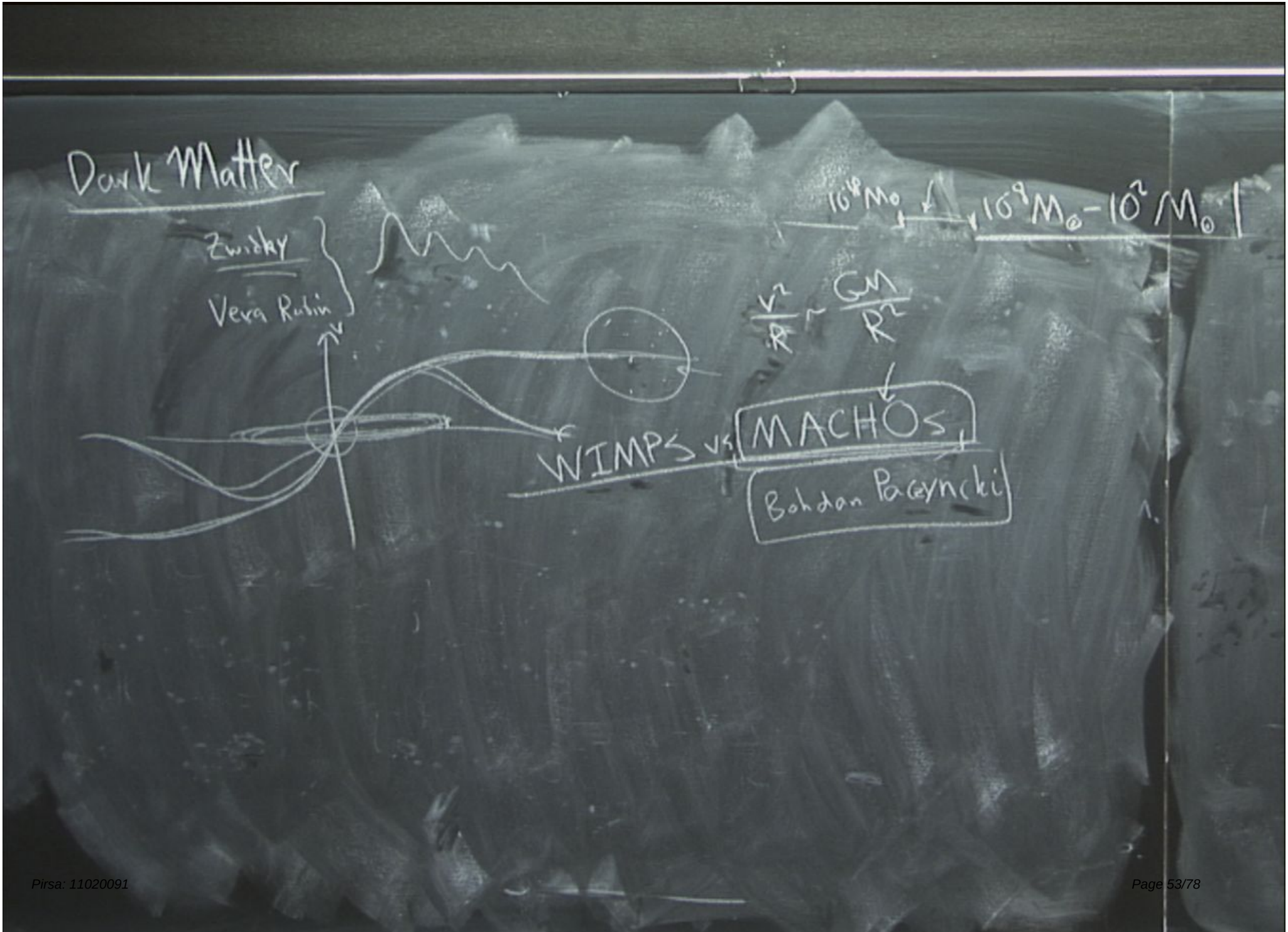
$10^8 M_\odot$ — $10^9 M_\odot - 10^2 M_\odot$

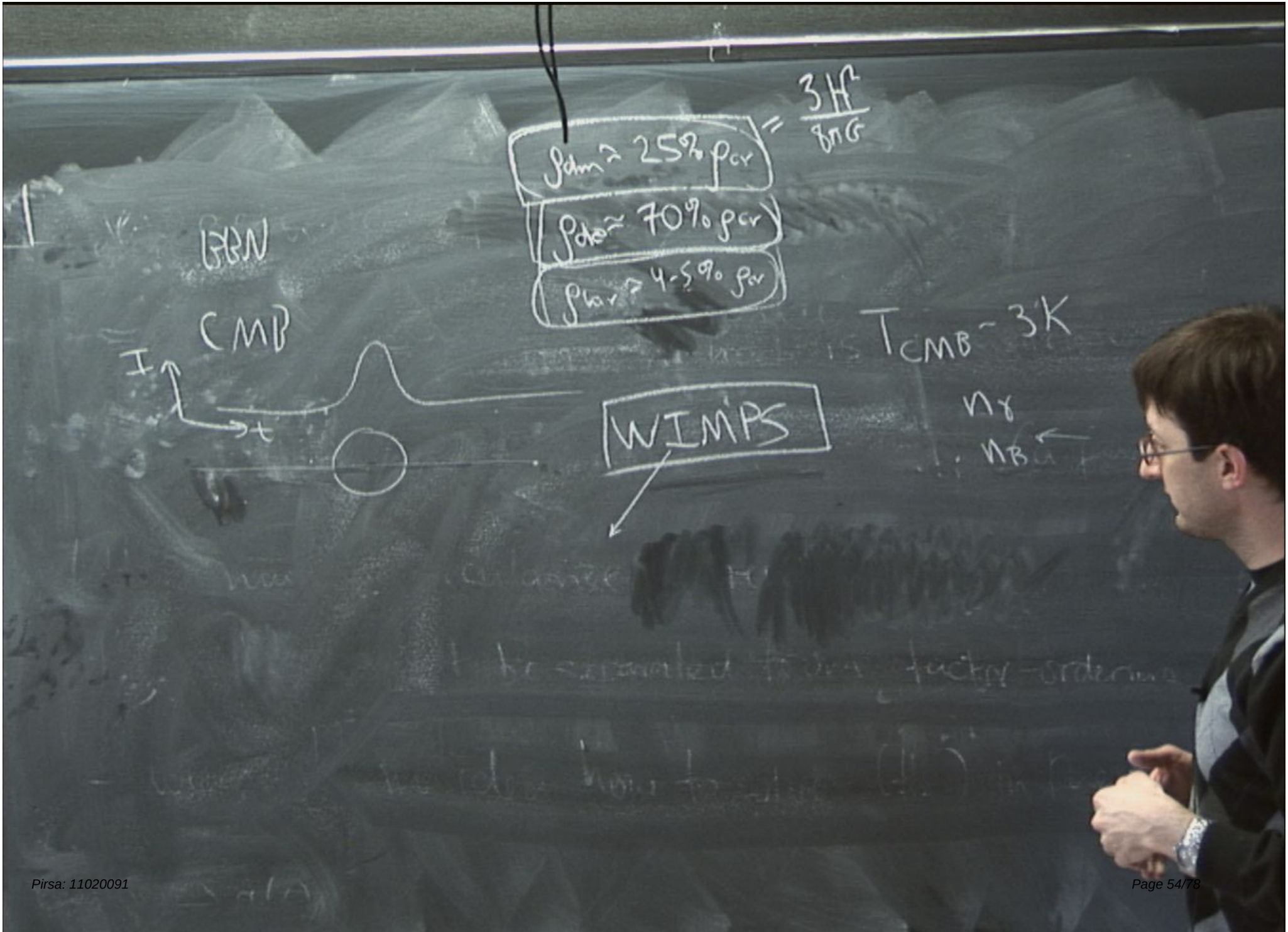
$\frac{v^2}{R} \sim \frac{GM}{R^2}$

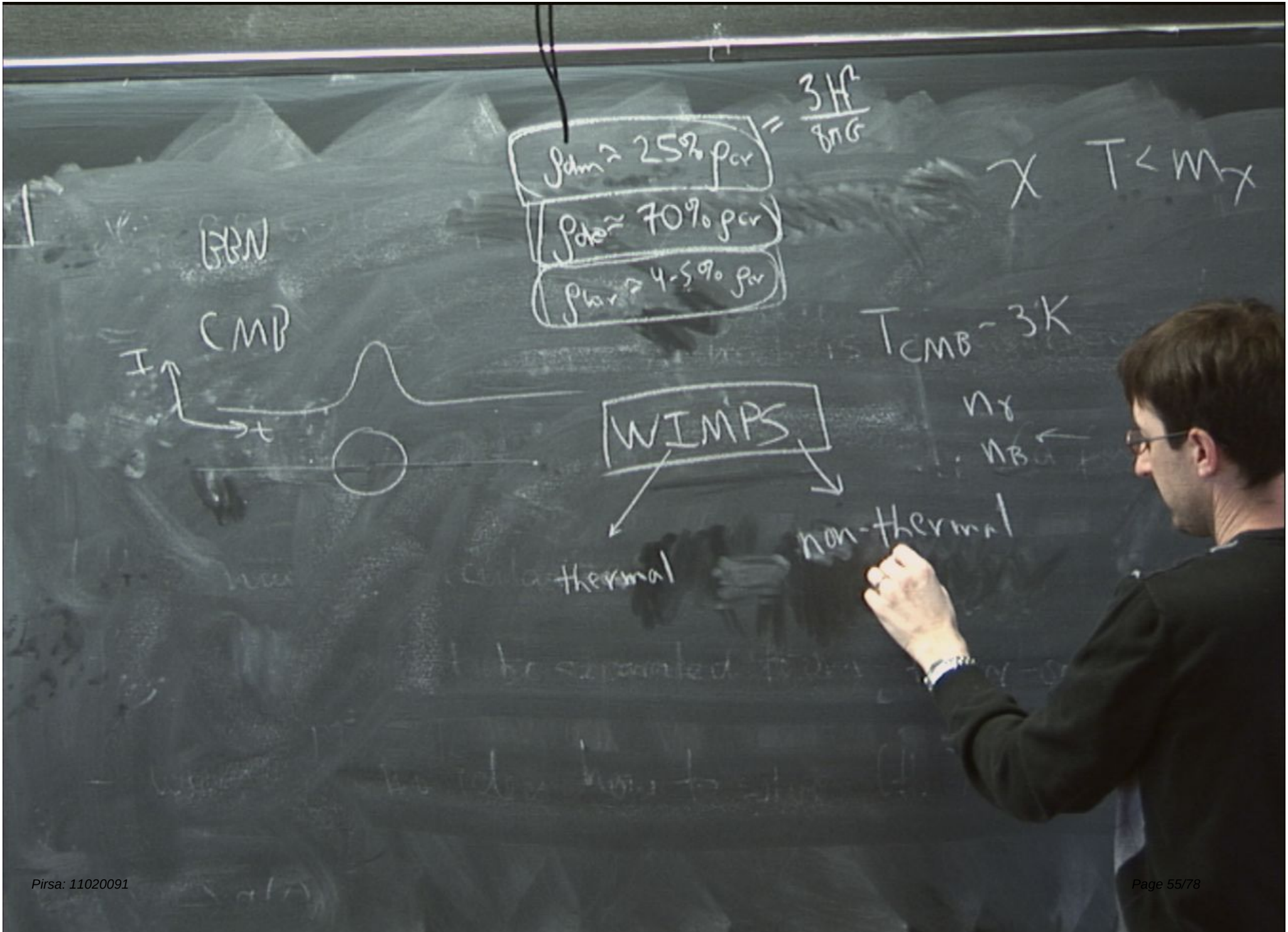
WIMPS vs MACHOs

Bohdan Paczynski


Dark Matter
Zwicky
Vera Rubin
v
r
$10^{18} M_\odot$
$10^9 M_\odot - 10^2 M_\odot$
$\frac{v^2}{R} \sim \frac{GM}{R^2}$
WIMPS vs
MACHOs
Bohdan Paczynski


Dark Matter
Zwicky
Vera Rubin
$10^{18} M_\odot$
$10^9 M_\odot - 10^2 M_\odot$
$\frac{v^2}{R} \sim \frac{GM}{R^2}$
WIMPS vs MACHOs
Bohdan Paczynski


$\rho_{dm} \geq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \geq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
BBN
CMB
$T_{CMB} \sim 3K$
WIMPS
n_γ
n_B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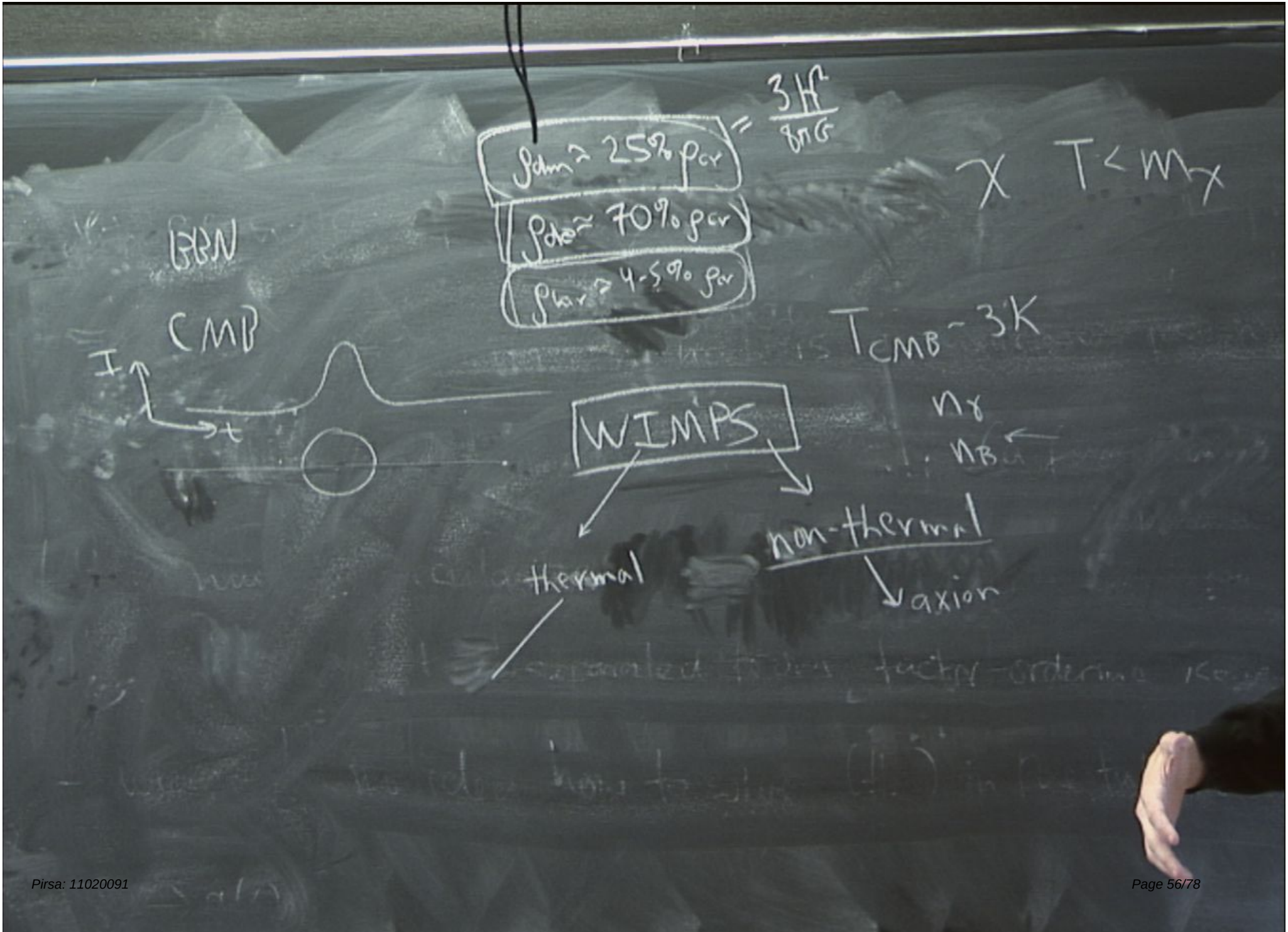
$= \frac{3H^2}{8\pi G}$
χ $T < m_\chi$
BBN
CMB
$T_{CMB} \sim 3K$
n_γ
n_B
WIMPS
thermal
non-thermal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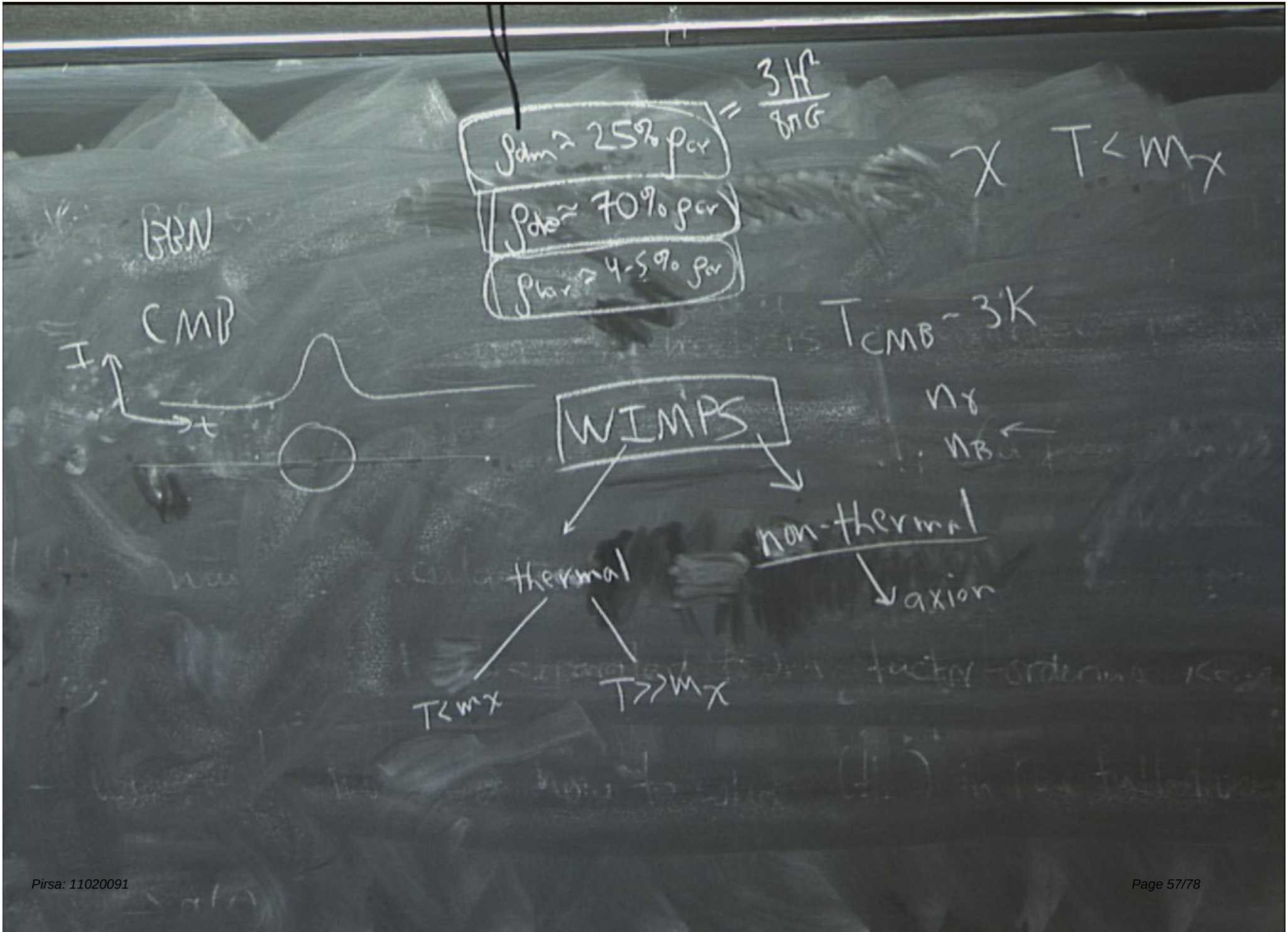
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \gtrsim 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
BBN
CMB
I
t
$T_{CMB} \sim 3K$
WIMPS
n_γ
n_B
thermal
non-thermal
axion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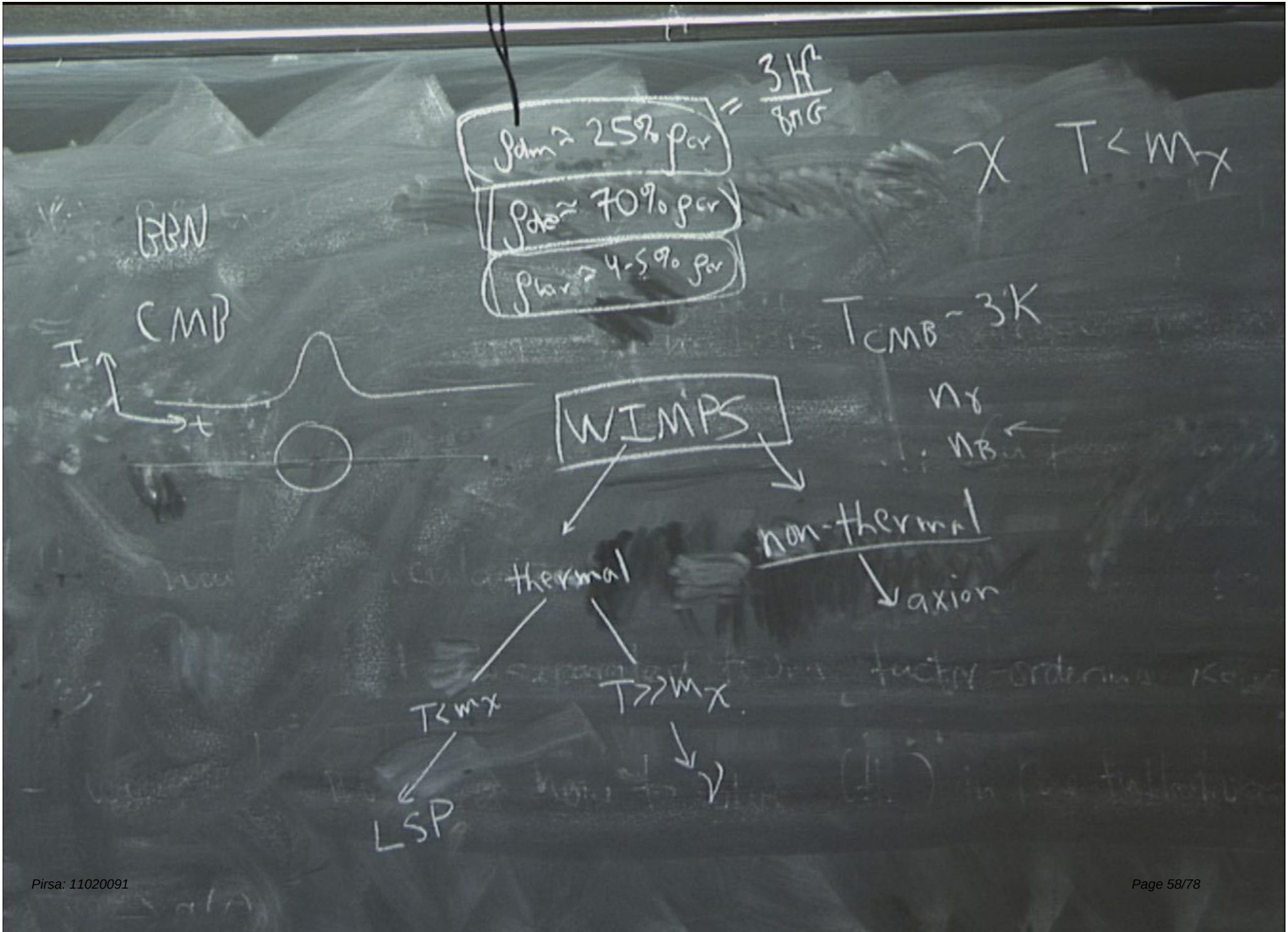
χ $T < m_\chi$
BBN
CMB
$T_{CMB} \sim 3K$
WIMPS
n_χ
n_B
thermal
non-thermal
axion
$T < m_\chi$
$T >> m_\chi$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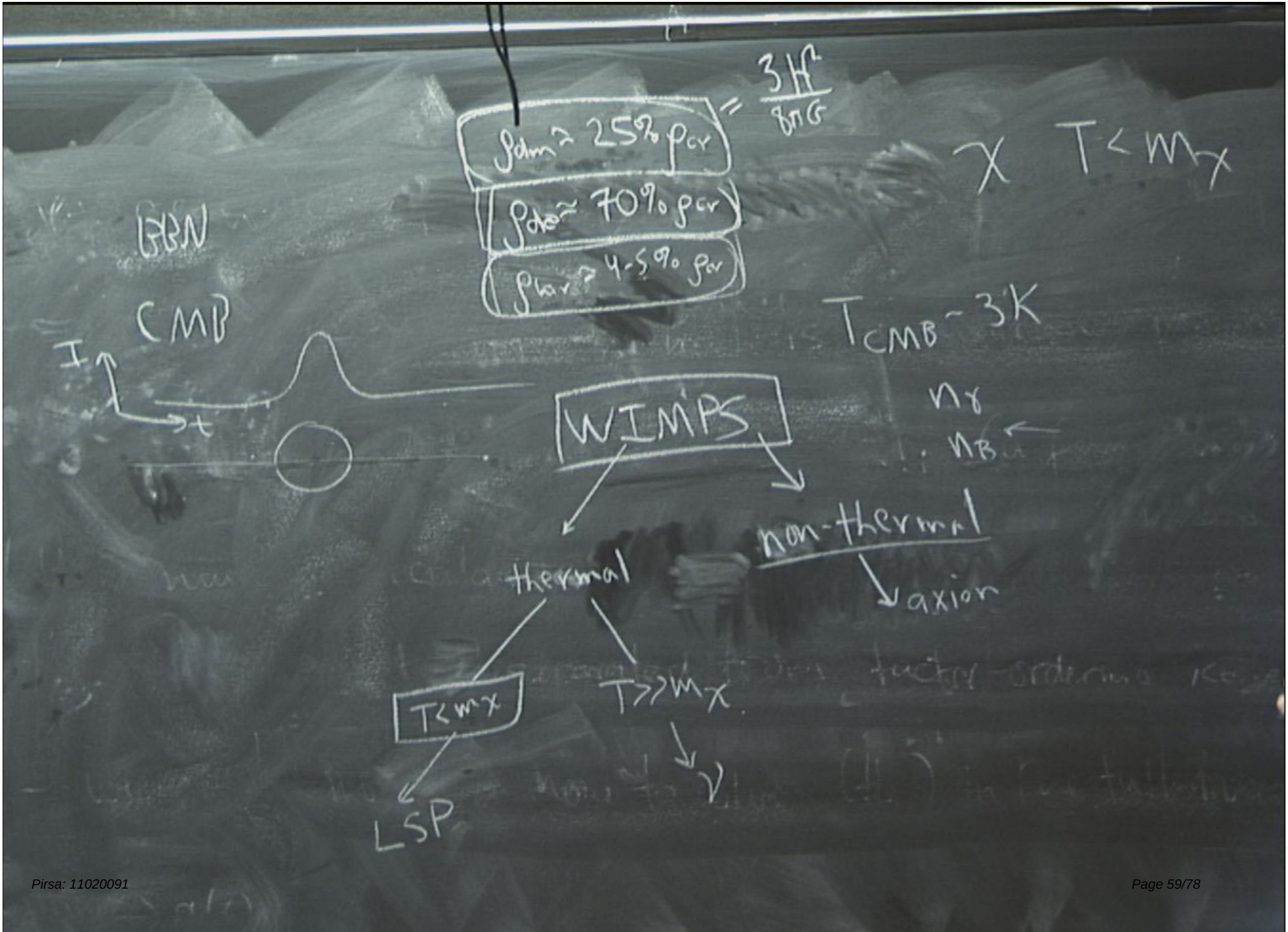
χ $T < m_\chi$
BBN
CMB
$T_{CMB} \sim 3K$
WIMPS
n_χ
n_B
thermal
non-thermal
axion
$T < m_\chi$
$T \gg m_\chi$
LSP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WIMPS
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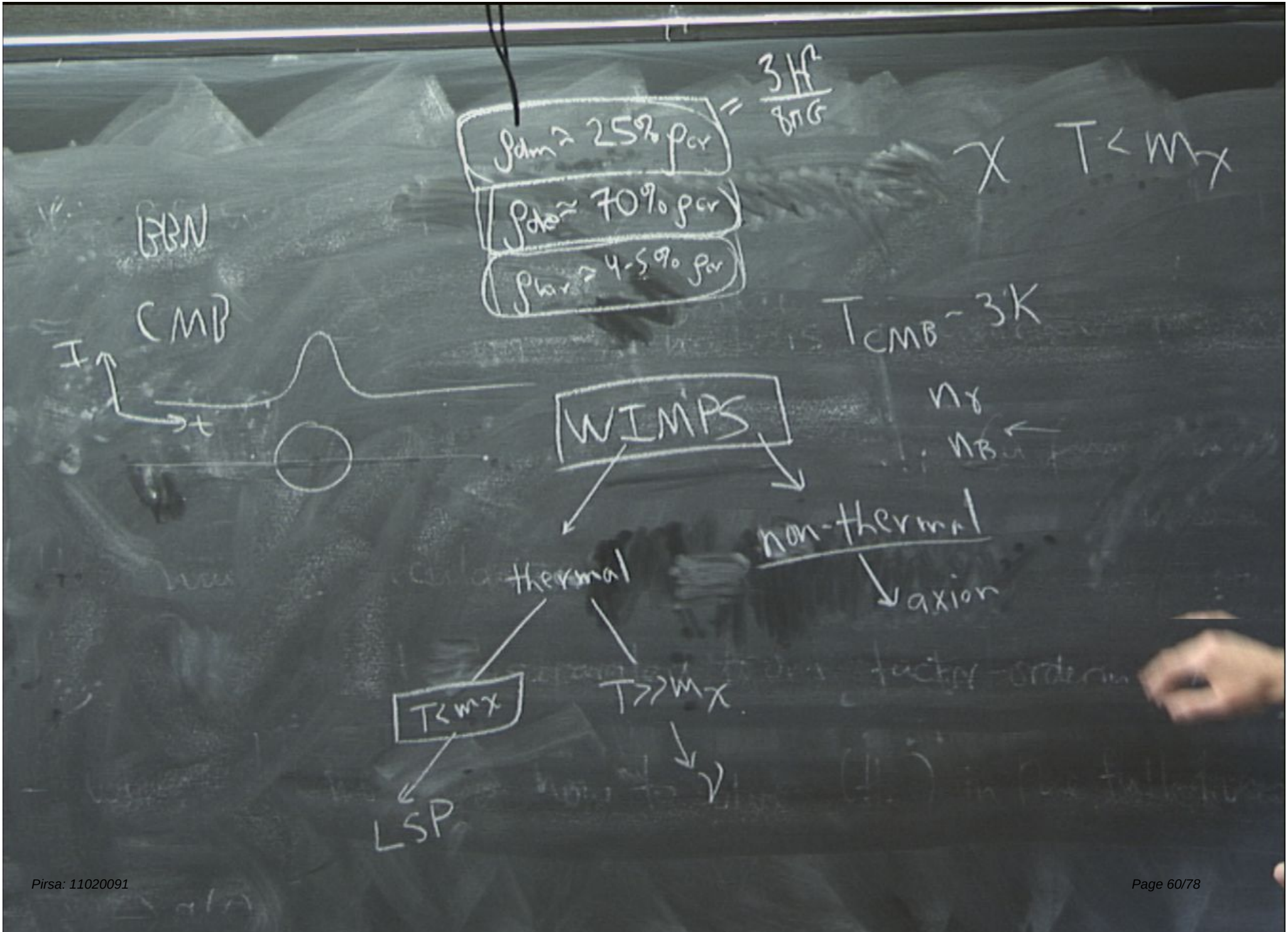
thermal
non-thermal
axion
$T < m_\chi$
$T >> m_\chi$
LSP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BBN
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I
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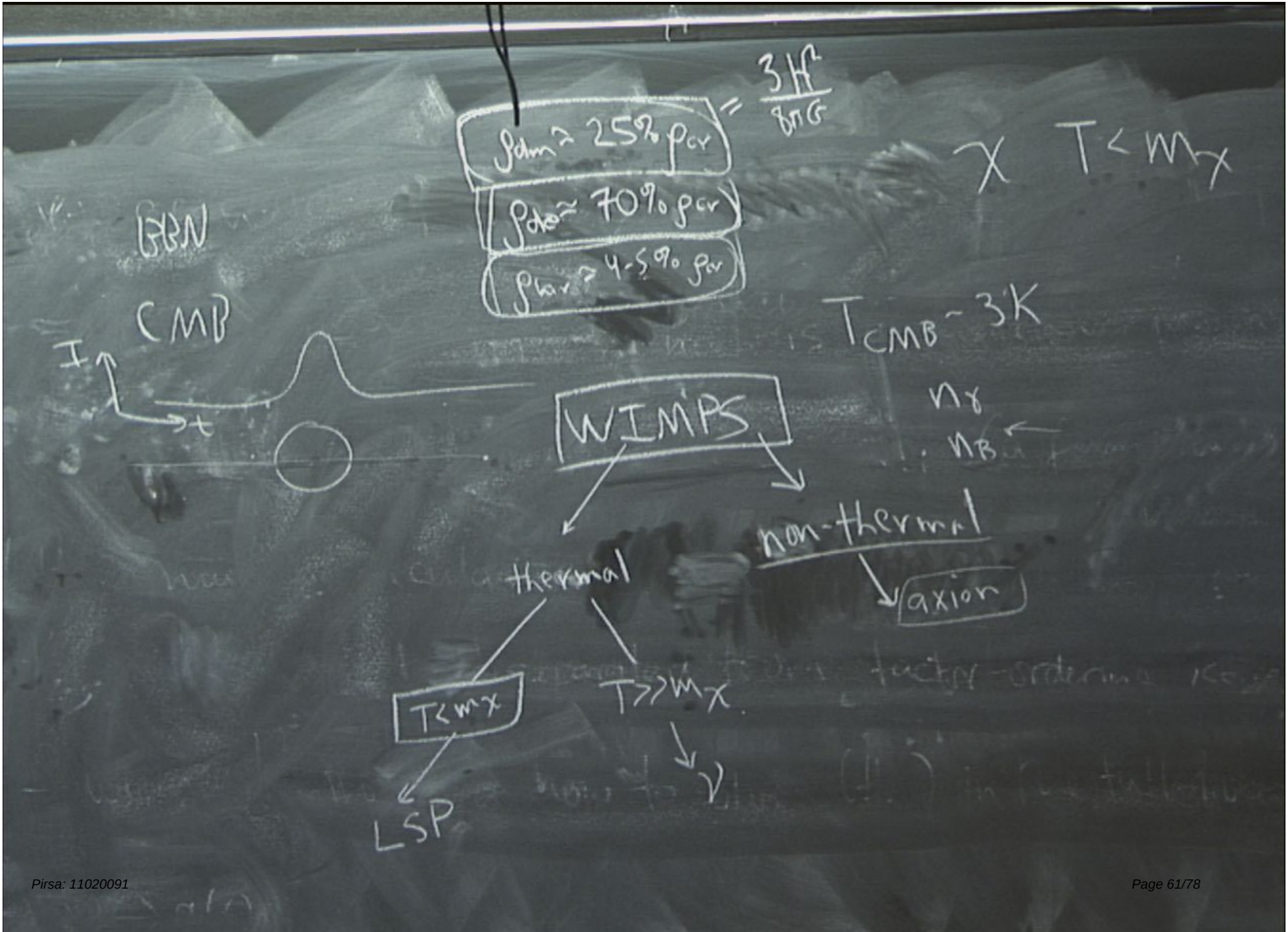
WIMPS
n_χ
n_B
thermal
non-thermal
axion
$T < m_\chi$
$T >> m_\chi$
LSP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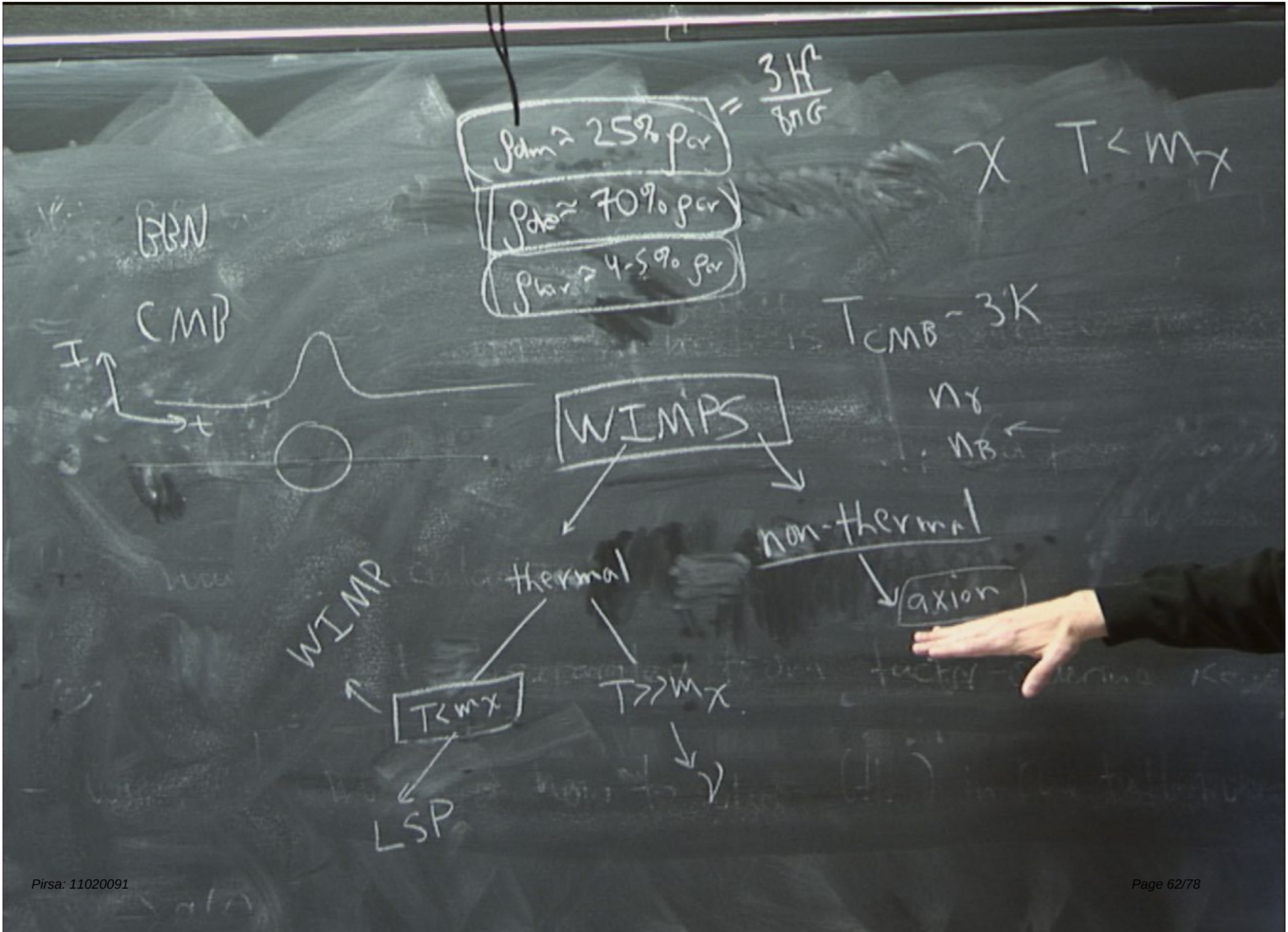
$T < m_\chi$
$T >> m_\chi$
LSP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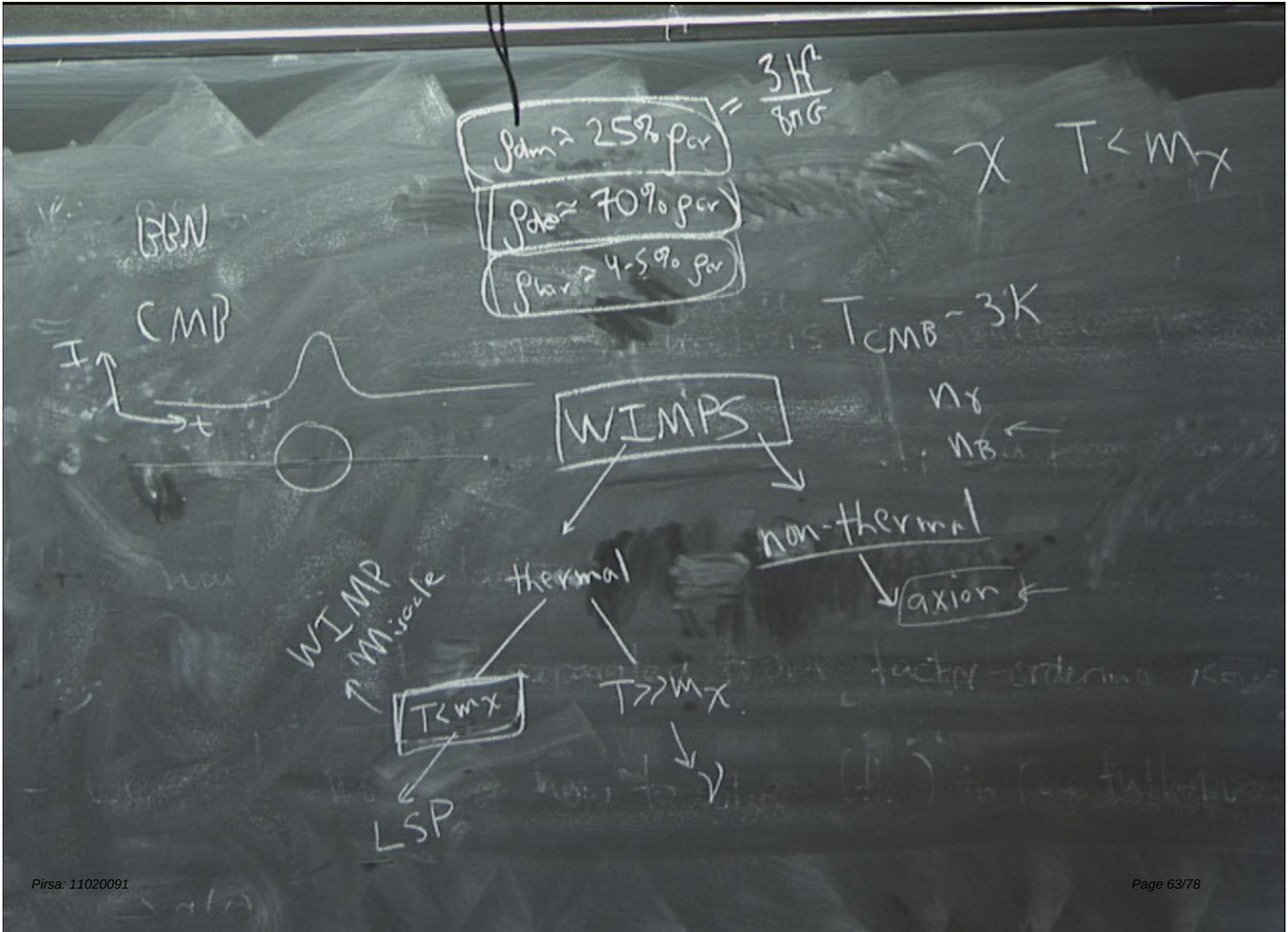
BBN
CMB
$T_{CMB} \sim 3K$
WIMPS
n_γ
n_B
non-thermal
axion
thermal
WIMP
$T < m_\chi$
$T >> m_\chi$
LSP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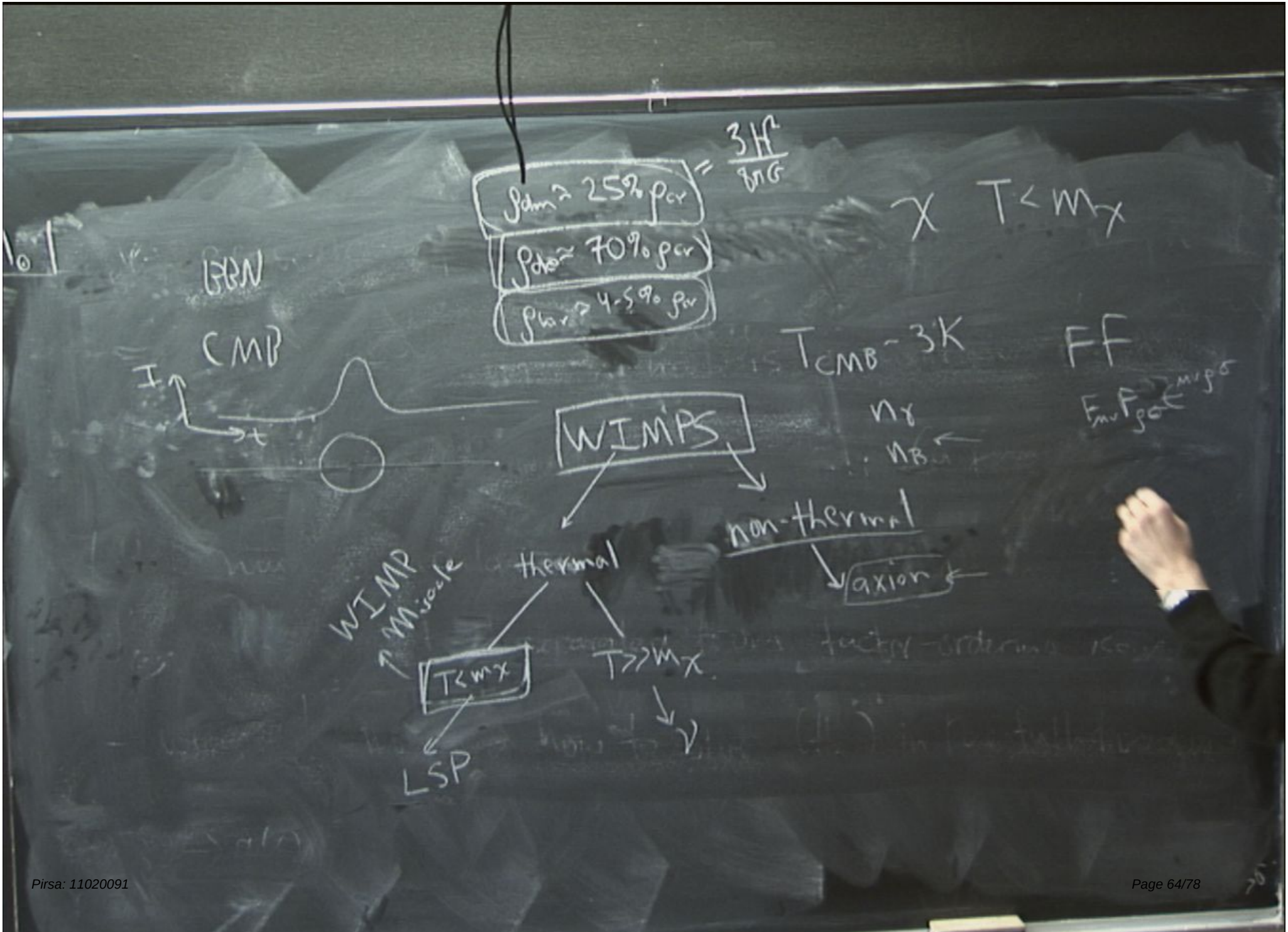
BBN
CMB
$T_{CMB} \sim 3K$
I
t
WIMPS
n_γ
n_B
non-thermal
axion
thermal
WIMP
Miracle
$T < m_\chi$
$T >> m_\chi$
LSP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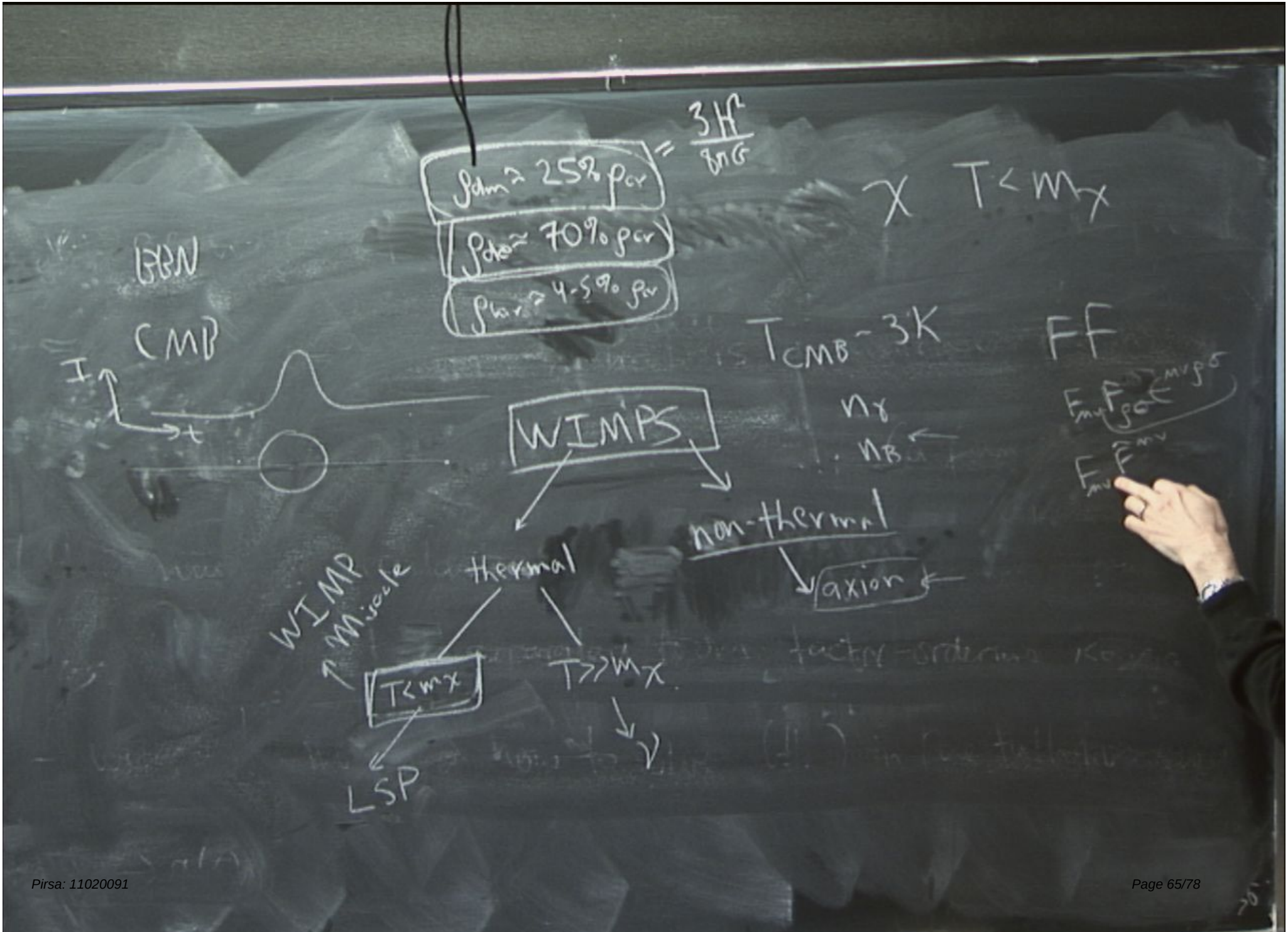
CMB
$T_{CMB} \sim 3K$
WIMPS
n_γ
n_B
non-thermal
thermal
axion
WIMP
$T < m_\chi$
$T >> m_\chi$
LSP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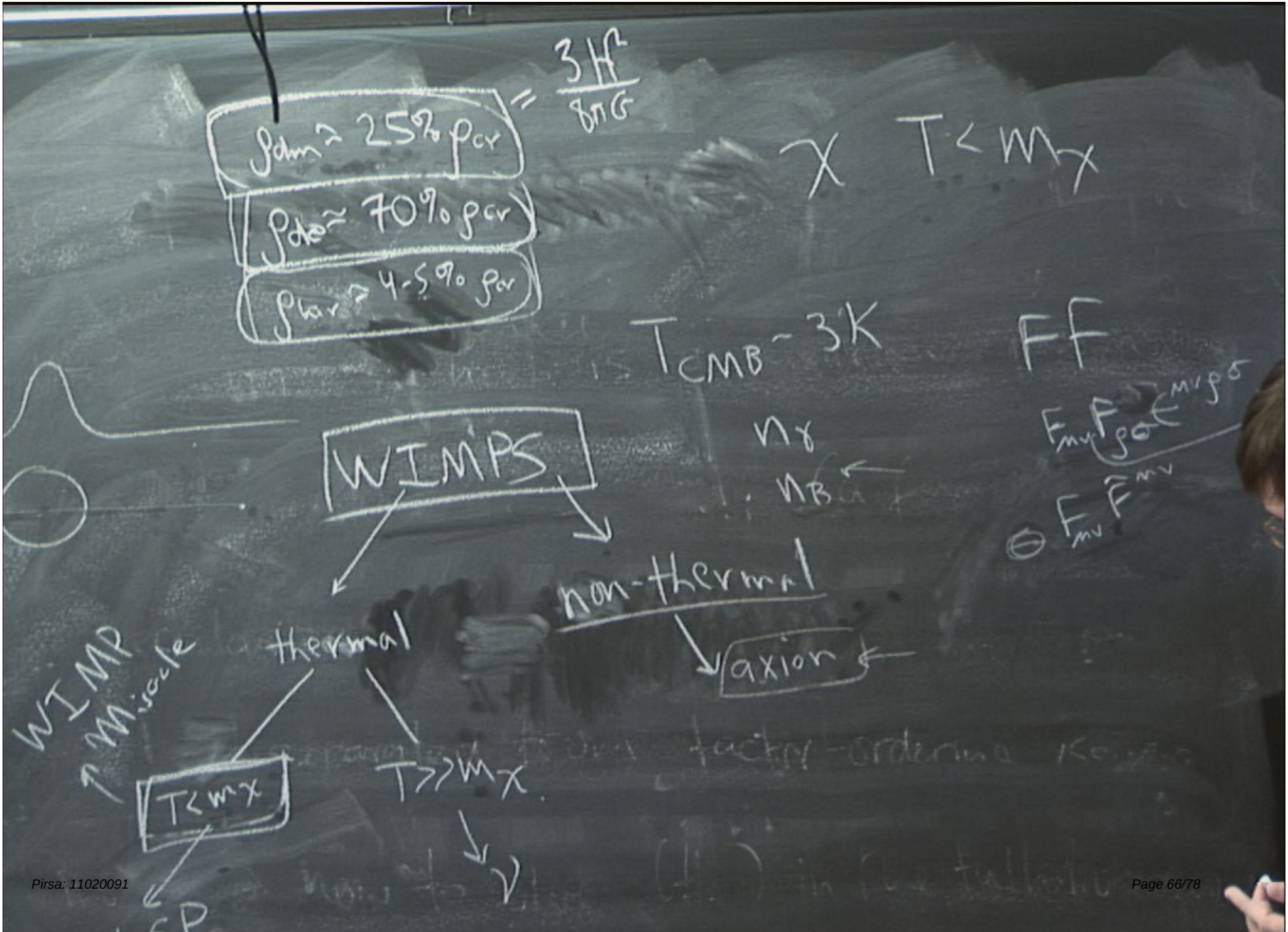
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
χ $T < m_\chi$
BBN
CMB
$T_{CMB} \sim 3K$
FF
WIMPS
n_γ
n_B
non-thermal
axion
thermal
WIMP
$m_{particle}$
$T < m_\chi$
$T >> m_\chi$
LSP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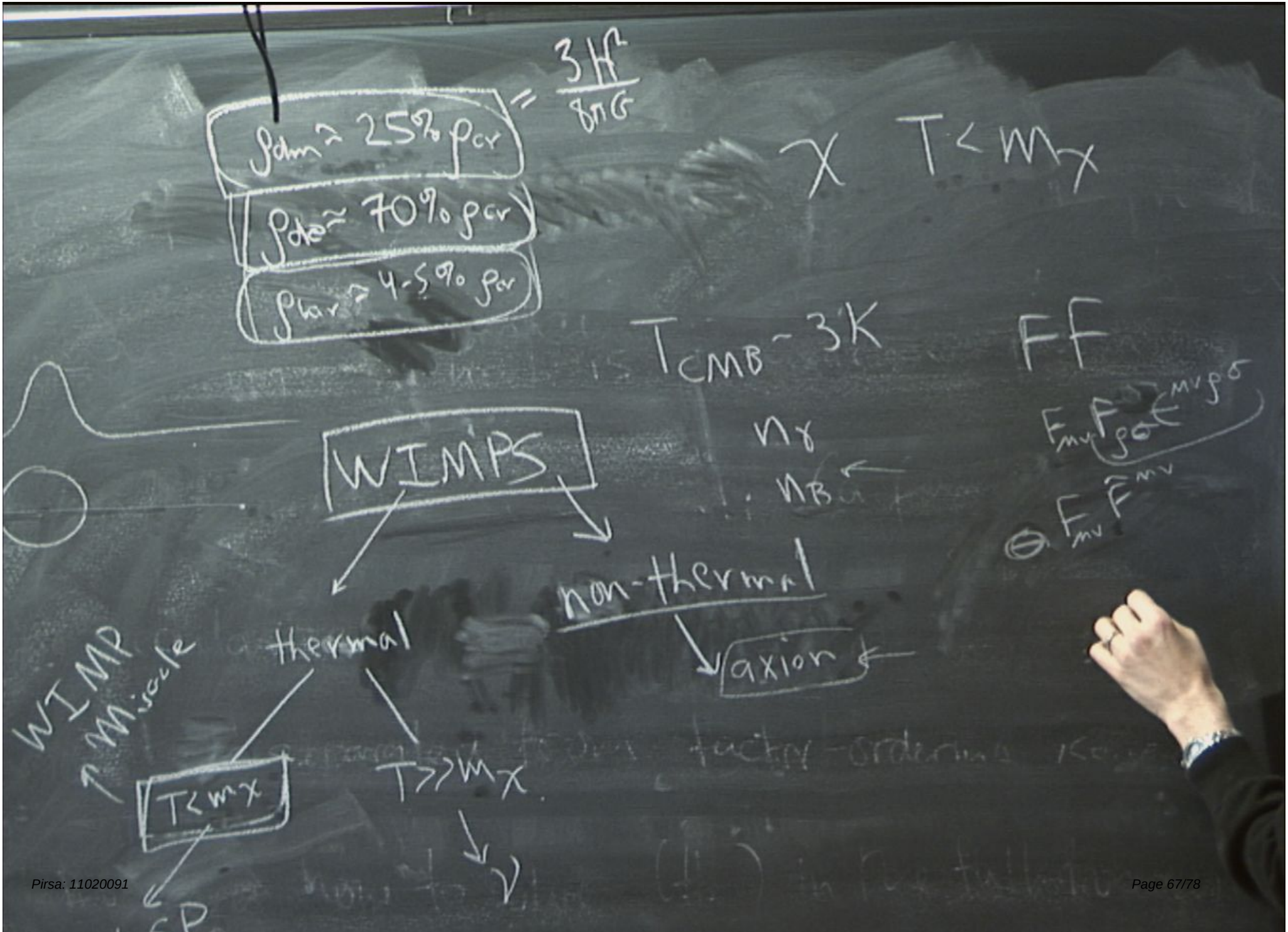
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
$\ominus F_{\mu\nu} \tilde{F}^{\mu\nu}$
n_χ
n_B
WIMPS
non-thermal
axion
thermal
WIMP
Miracle
$T < m_\chi$
$T >> m_\chi$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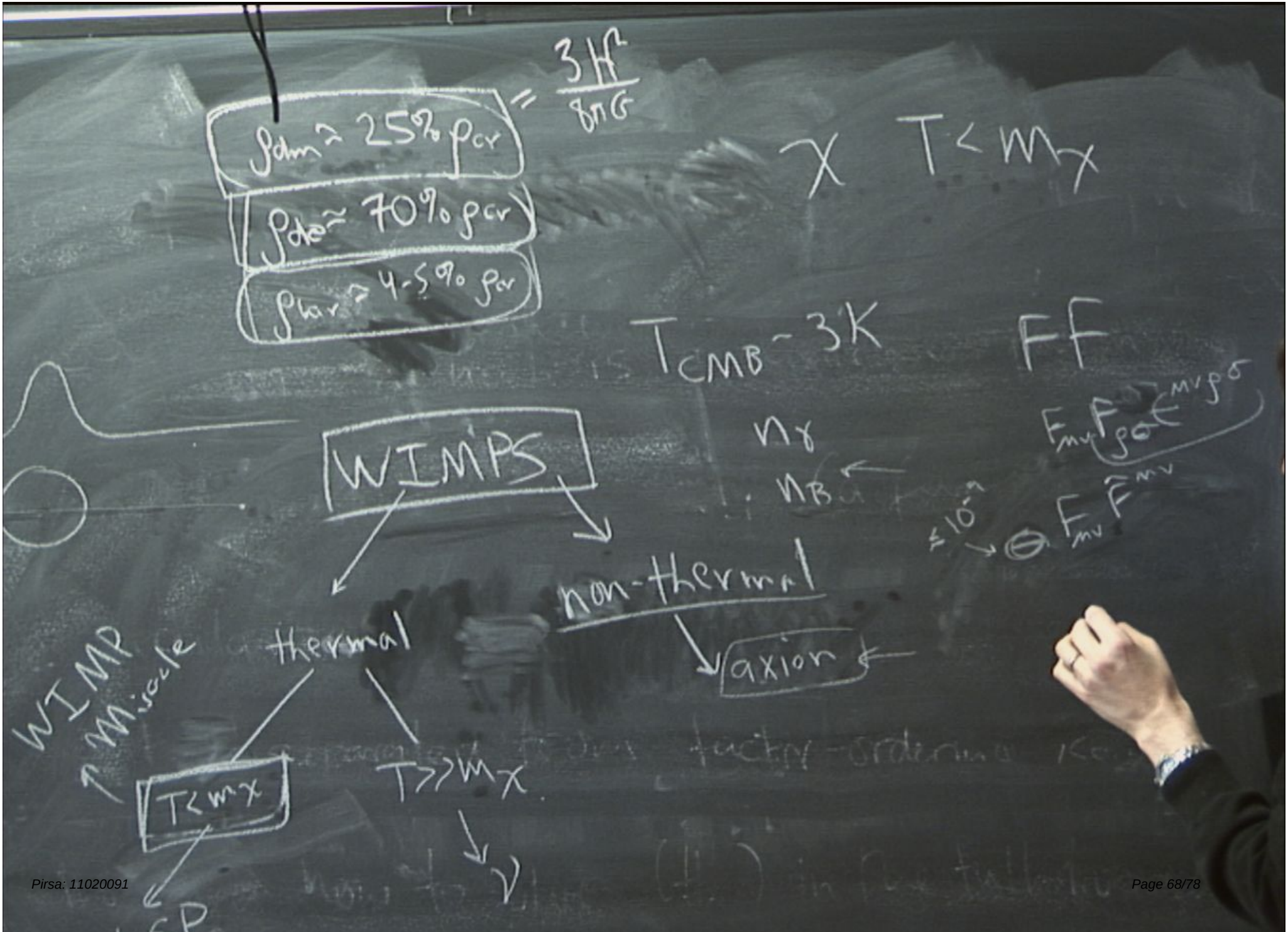
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_χ
n_B
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
WIMPS
non-thermal
axion
thermal
WIMP
Miracle
$T < m_\chi$
$T >> m_\chi$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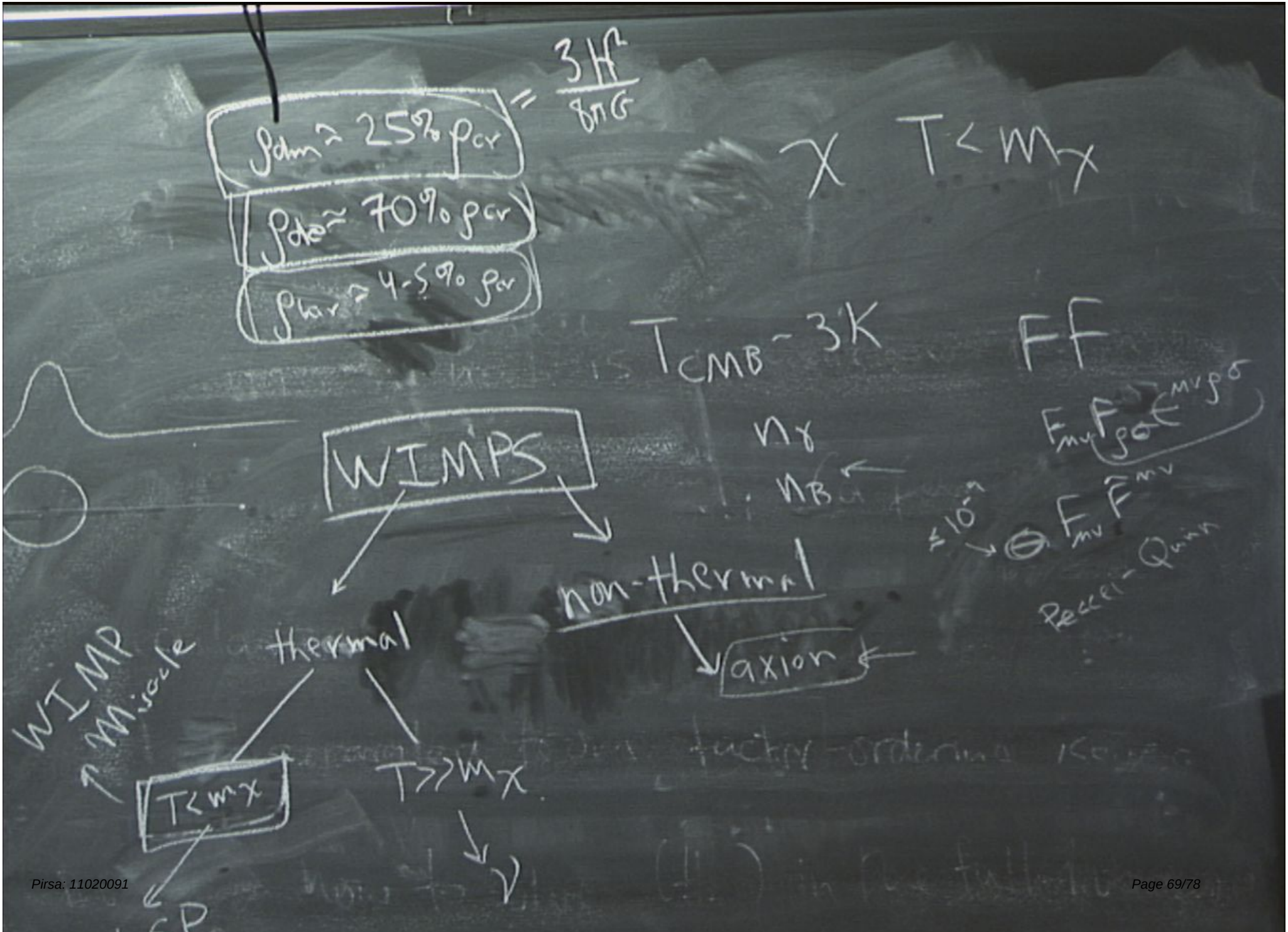
$= \frac{3H^2}{8\pi G}$
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
n_γ
n_B
$\leq 10^{-9}$
WIMPS
non-thermal
axion
thermal
WIMP
Miracle
$T < m_\chi$
$T >> m_\chi$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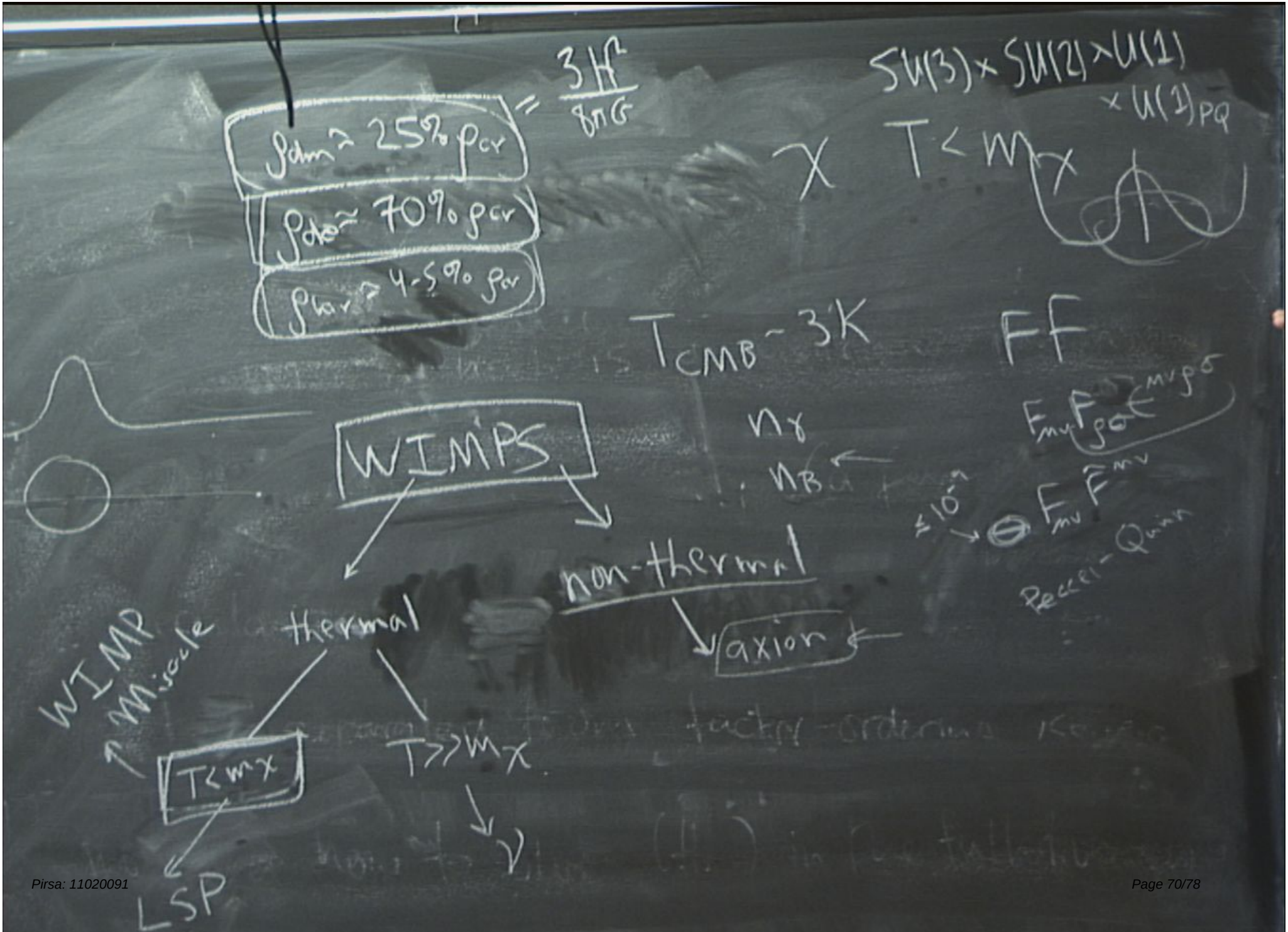
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_χ
n_B
WIMPS
$\lesssim 10^{-9}$
Θ $F_{\mu\nu} \tilde{F}^{\mu\nu}$
Peccei-Quinn
non-thermal
thermal
axion
WIMP
Miracle
$T < m_\chi$
$T \gg m_\chi$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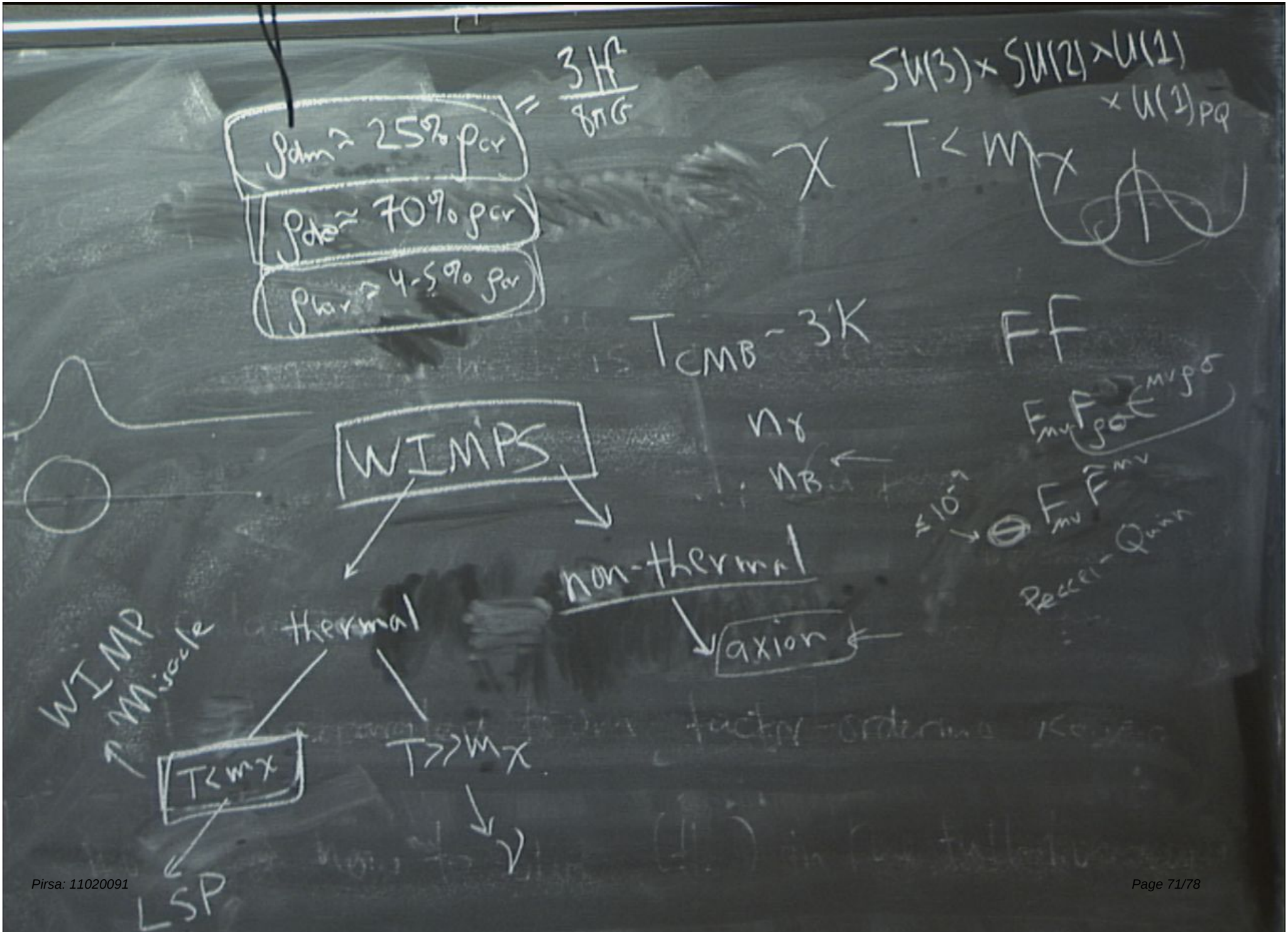
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
$SU(3) \times SU(2) \times U(1)$
$\times U(1)_{PQ}$
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_γ
n_B
$\sim 10^{-9}$
$F_{\mu\nu} F^{\mu\nu}$
Peccei-Quinn
WIMPS
non-thermal
axion
thermal
WIMP
$m_{particle}$
$T < m_\chi$
$T >> m_\chi$
LSP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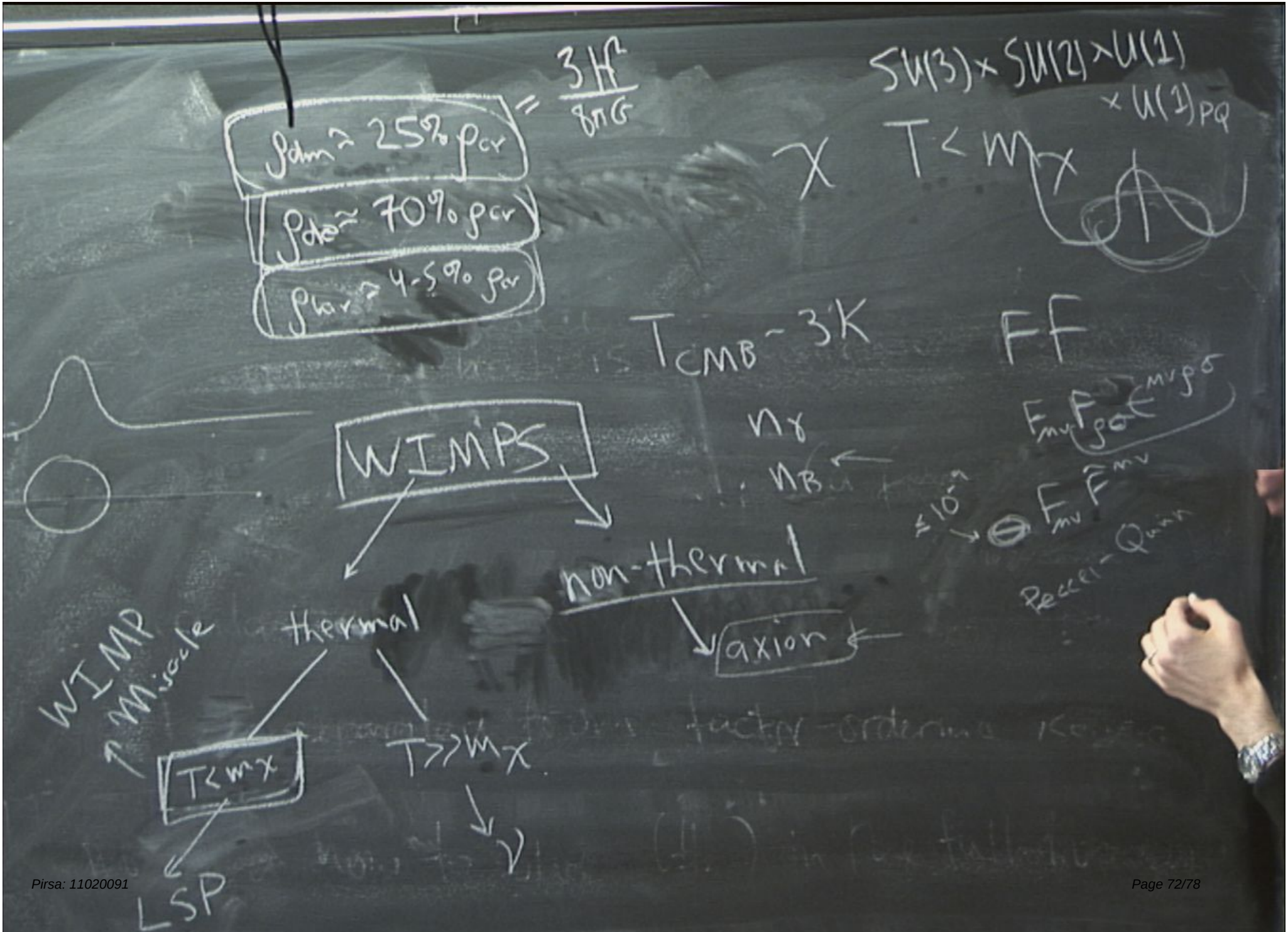
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_γ
n_B
WIMPS
$\leq 10^{-9}$
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
Peccei-Quinn
non-thermal
thermal
axion
WIMP
Miracle
$T < m_\chi$
$T >> m_\chi$
LSP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$SU(3) \times SU(2) \times U(1)$
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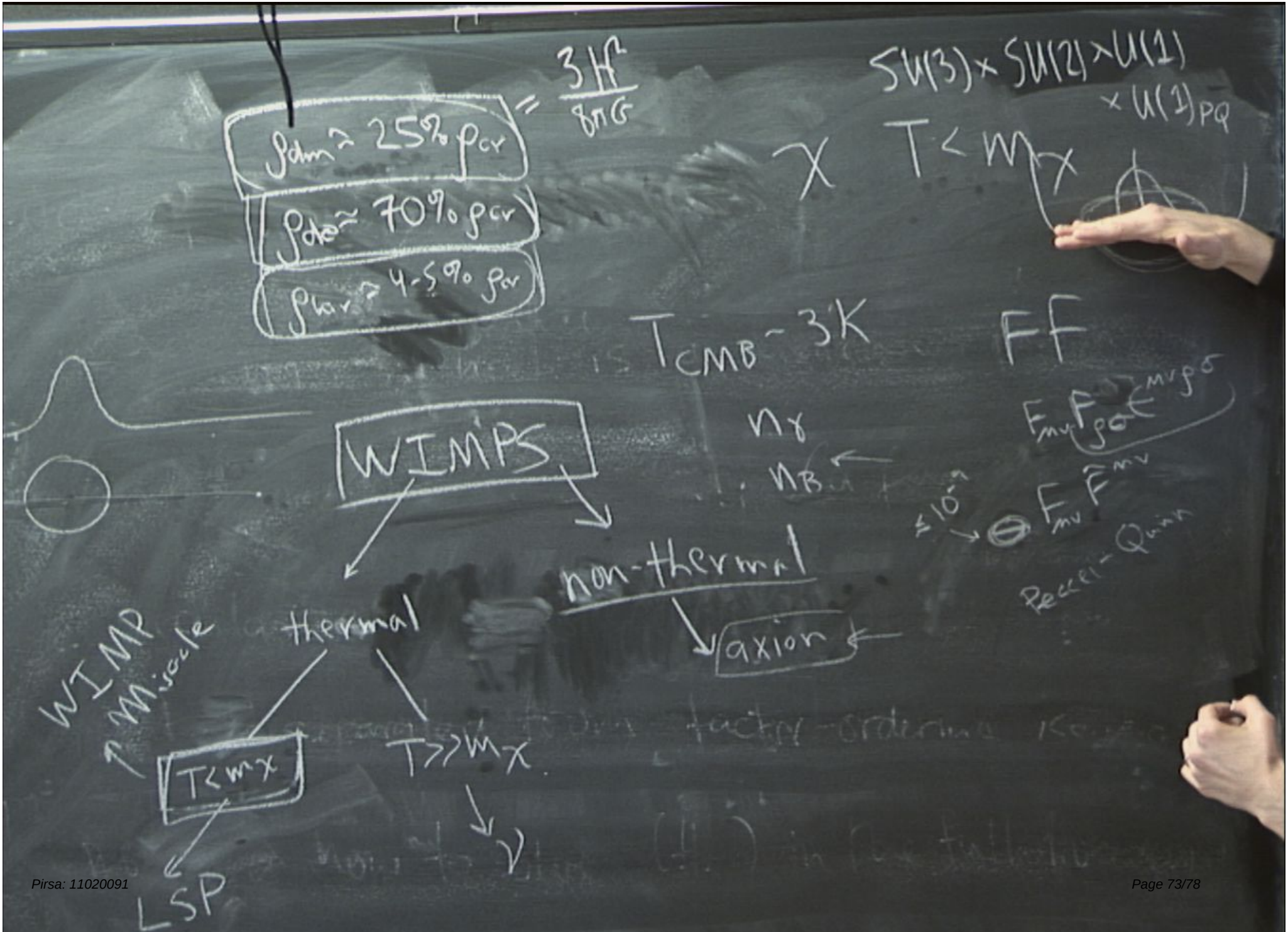
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_γ
n_B
$\sim 10^{-9}$
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
Peccei-Quinn
WIMPS
non-thermal
axion
thermal
WIMP
$m_{molecule}$
$T < m_\chi$
$T >> m_\chi$
LSP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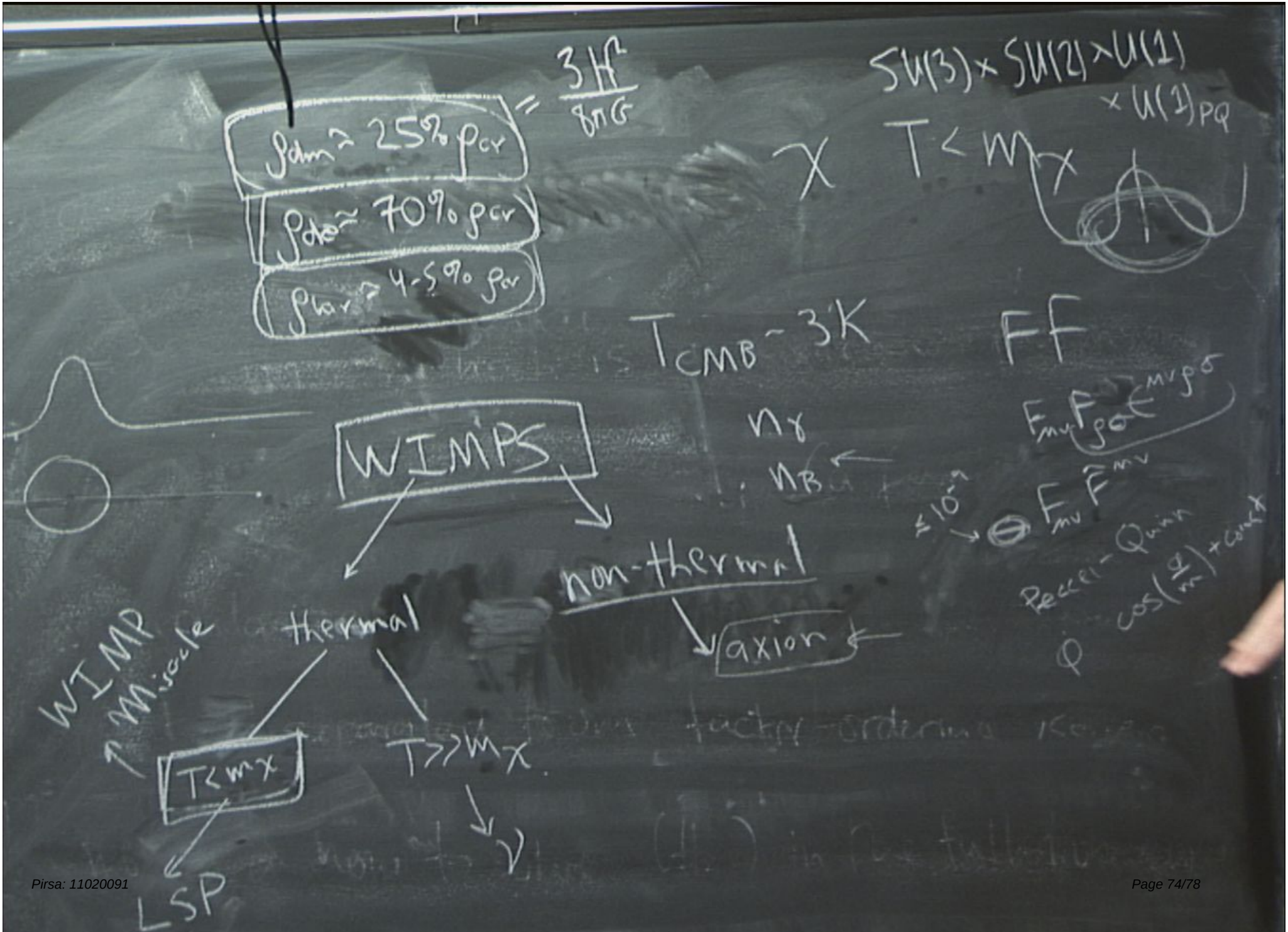
χ $T < m_\chi$
$T_{CMB} \sim 3K$
n_χ
n_B
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
$\leq 10^{-}$
Peccei-Quinn
WIMPS
non-thermal
thermal
axion
WIMP
m_{WIMP}
$T < m_\chi$
$T >> m_\chi$
LSP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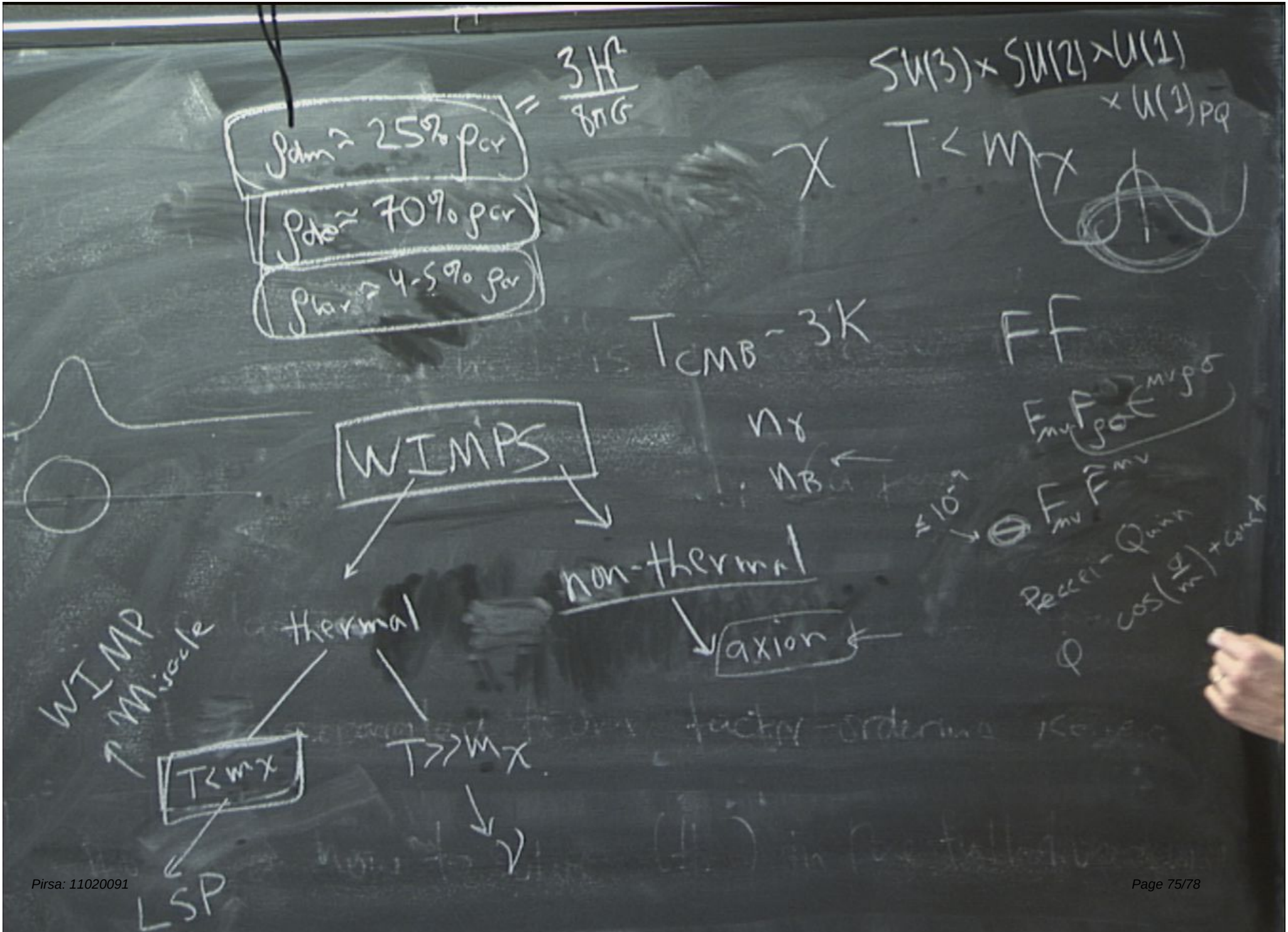
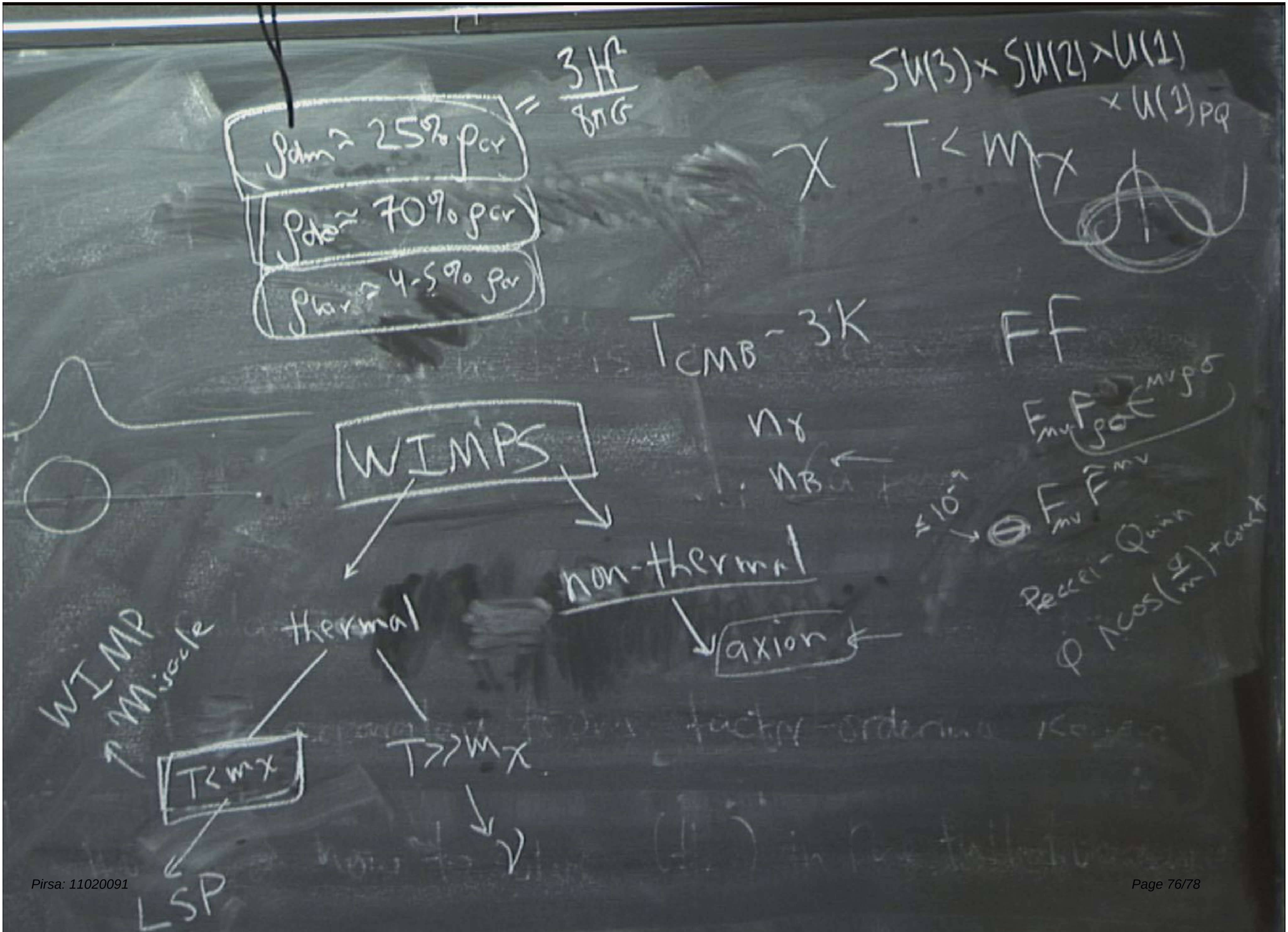
n_γ
n_B
$\sim 10^{-9}$
$F_{\mu\nu} F^{\mu\nu}$
Peccei-Quinn
$\cos(\frac{a}{f_a}) + const$
WIMPS
non-thermal
axion
thermal
WIMP
$m_{nucleon}$
$T < m_\chi$
$T >> m_\chi$
LSP


$\rho_{dm} \simeq 25\% \rho_{cr}$
$\rho_{de} \simeq 70\% \rho_{cr}$
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$= \frac{3H^2}{8\pi G}$
$SU(3) \times SU(2) \times U(1)$
$\times U(1)_{PQ}$
χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_χ
n_B
$\sim 10^{-9}$
$F_{\mu\nu} \tilde{F}^{\mu\nu}$
WIMPS
non-thermal
thermal
axion
WIMP
m_{nucleon}
$T < m_\chi$
$T >> m_\chi$
LSP



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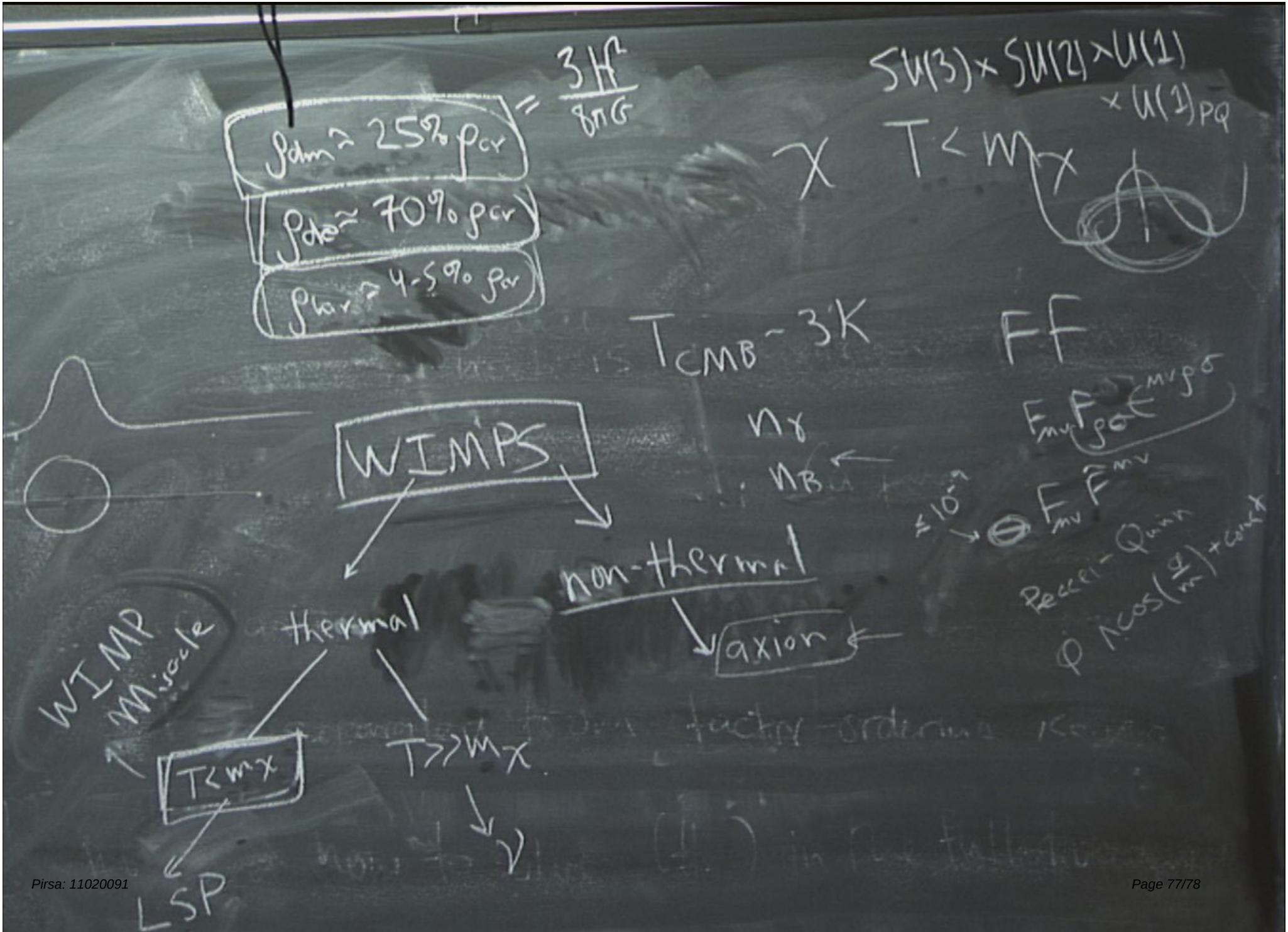
$\rho_{bar} \simeq 4\text{-}5\% \rho_{cr}$
$SU(3) \times SU(2) \times U(1)$
$\times U(1)_{PQ}$
$\chi \quad T < m_\chi$
$T_{CMB} \sim 3K$
$F\tilde{F}$
n_γ
n_B
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
$\lesssim 10^{-9}$
$\theta F_{\mu\nu} \tilde{F}^{\mu\nu}$
Peccei-Quinn
$\varphi \, \Lambda \cos(\frac{\varphi}{m}) + \text{const}$
WIMPS
non-thermal
axion
thermal
WIMP Miracle
$T < m_\chi$
$T \gg m_\chi$
ν
LSP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χ $T < m_\chi$
$T_{CMB} \sim 3K$
FF
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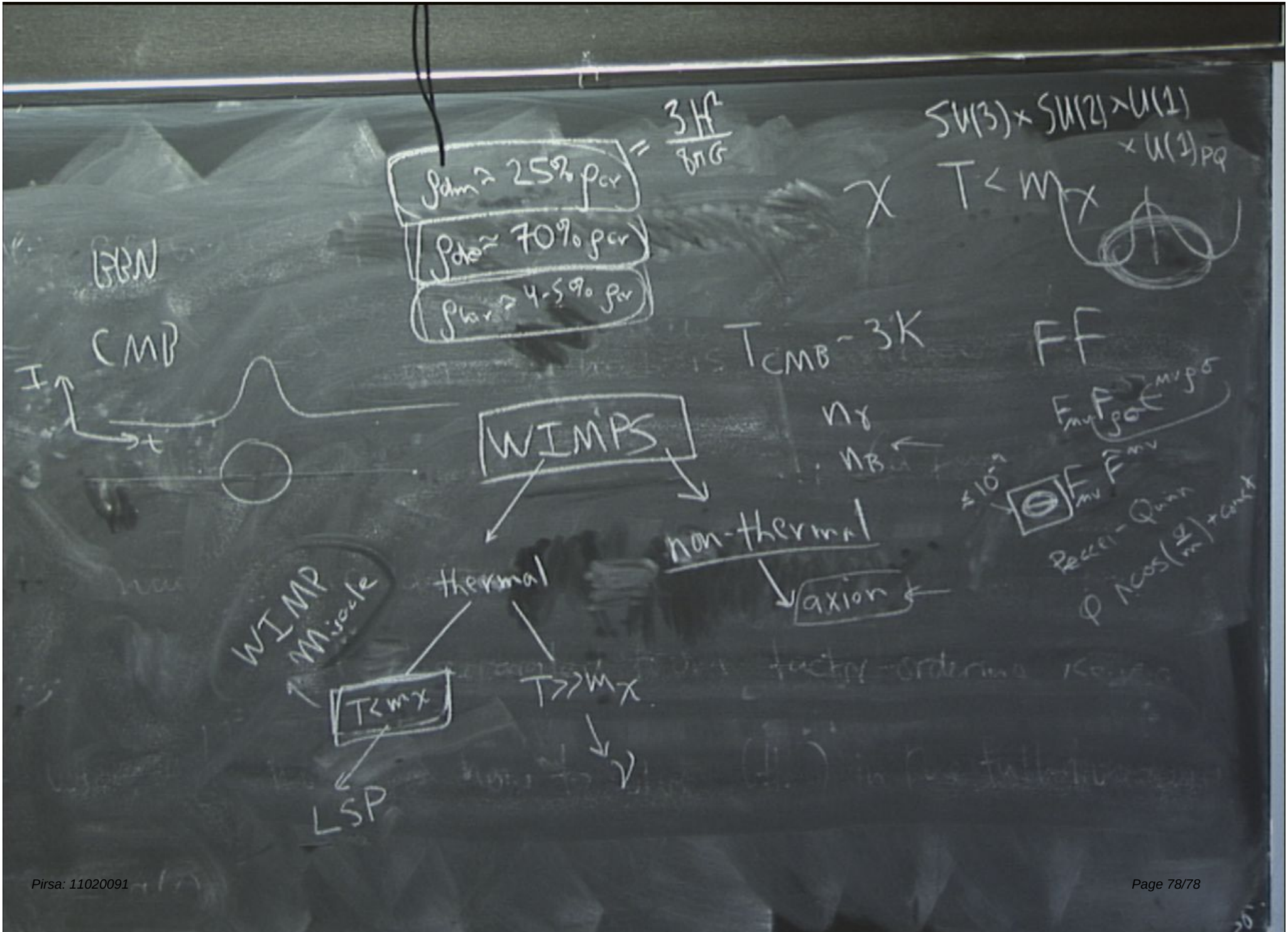
Peccei-Quinn
$\rho \cos(\frac{a}{f_a}) + const$
non-thermal
thermal
axion
WIMP
$m_{particle}$
$T < m_\chi$
$T >> m_\chi$
LSP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$\times U(1)_{PQ}$
χ $T < m_\chi$ χ
BBN
CMB
$T_{CMB} \sim 3K$
FF
$F_{\mu\nu} F_{\rho\sigma} \epsilon^{\mu\nu\rho\sigma}$
n_γ
n_B
WIMPS
$\leq 10^{-9}$
$F_{\mu\nu} F^{\mu\nu}$
Peccei-Quinn
$Q \cos(\frac{a}{f_a}) + \text{const}$
non-thermal
axion
thermal
WIMP
$m_{particle}$
$T < m_\chi$
$T >> m_\chi$
LSP