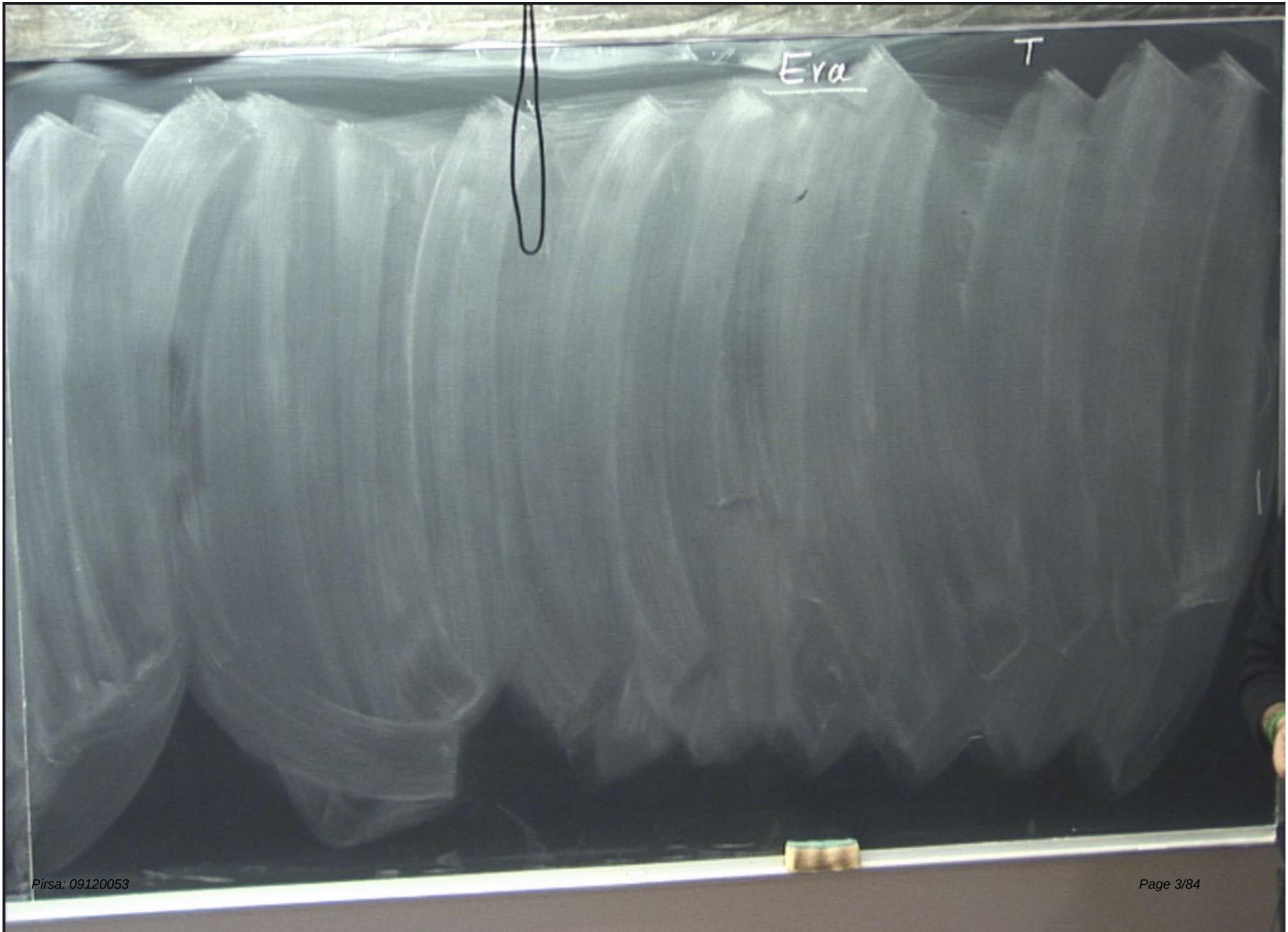
Title: Cosmology - Review (PHYS 621) - Lecture 5

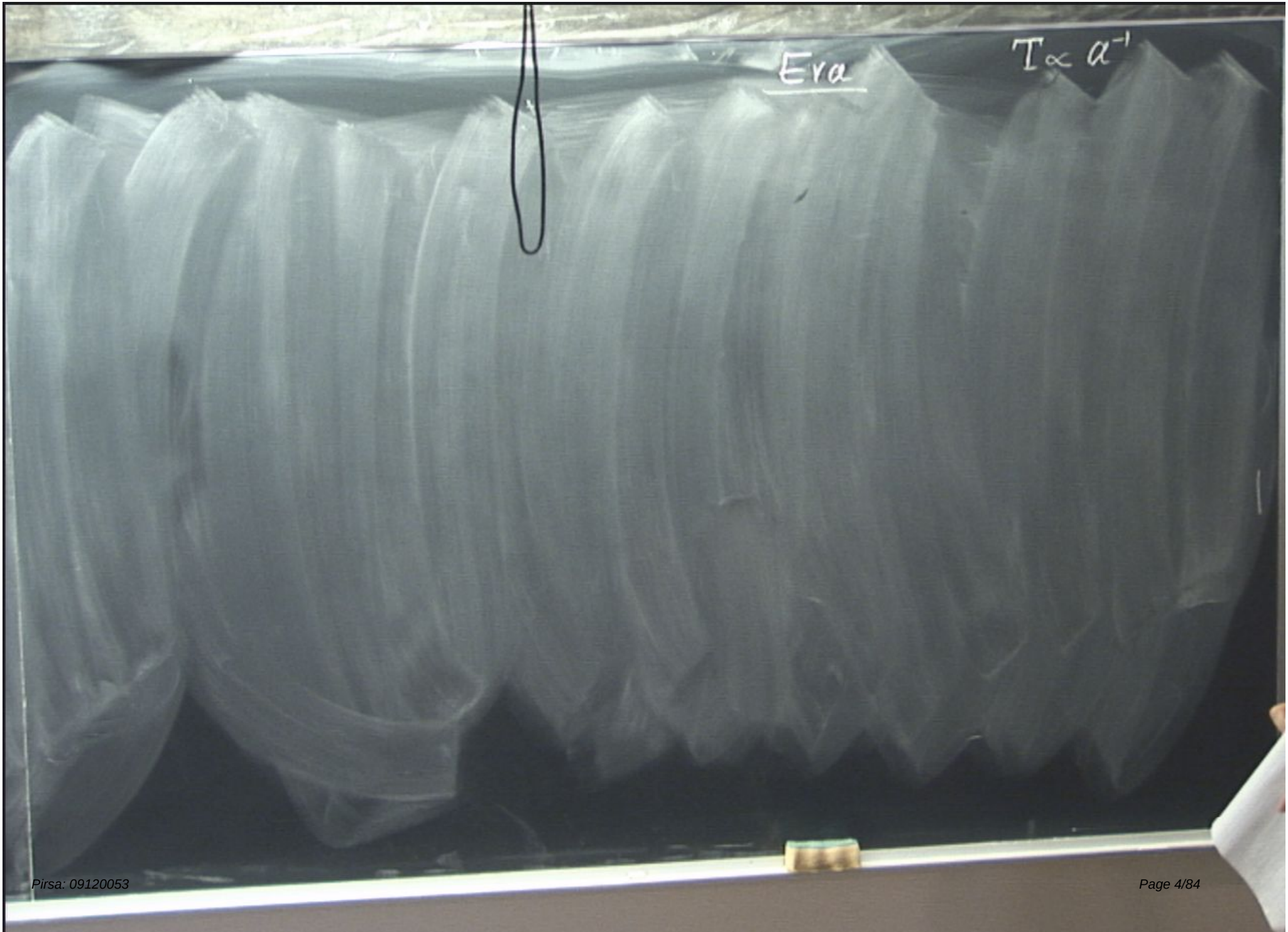
Date: Dec 04, 2009 10:00 AM

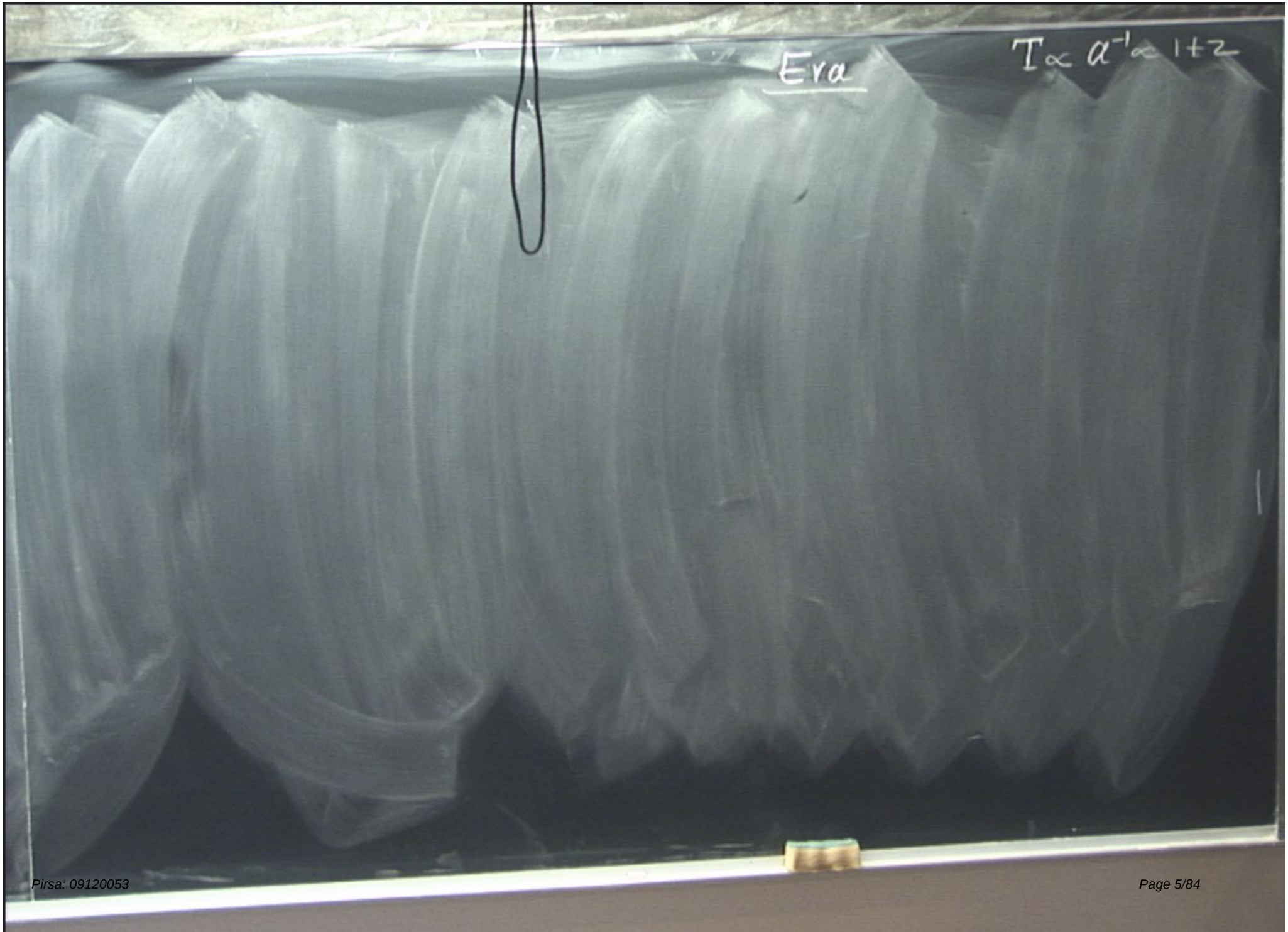
URL: http://pirsa.org/09120053

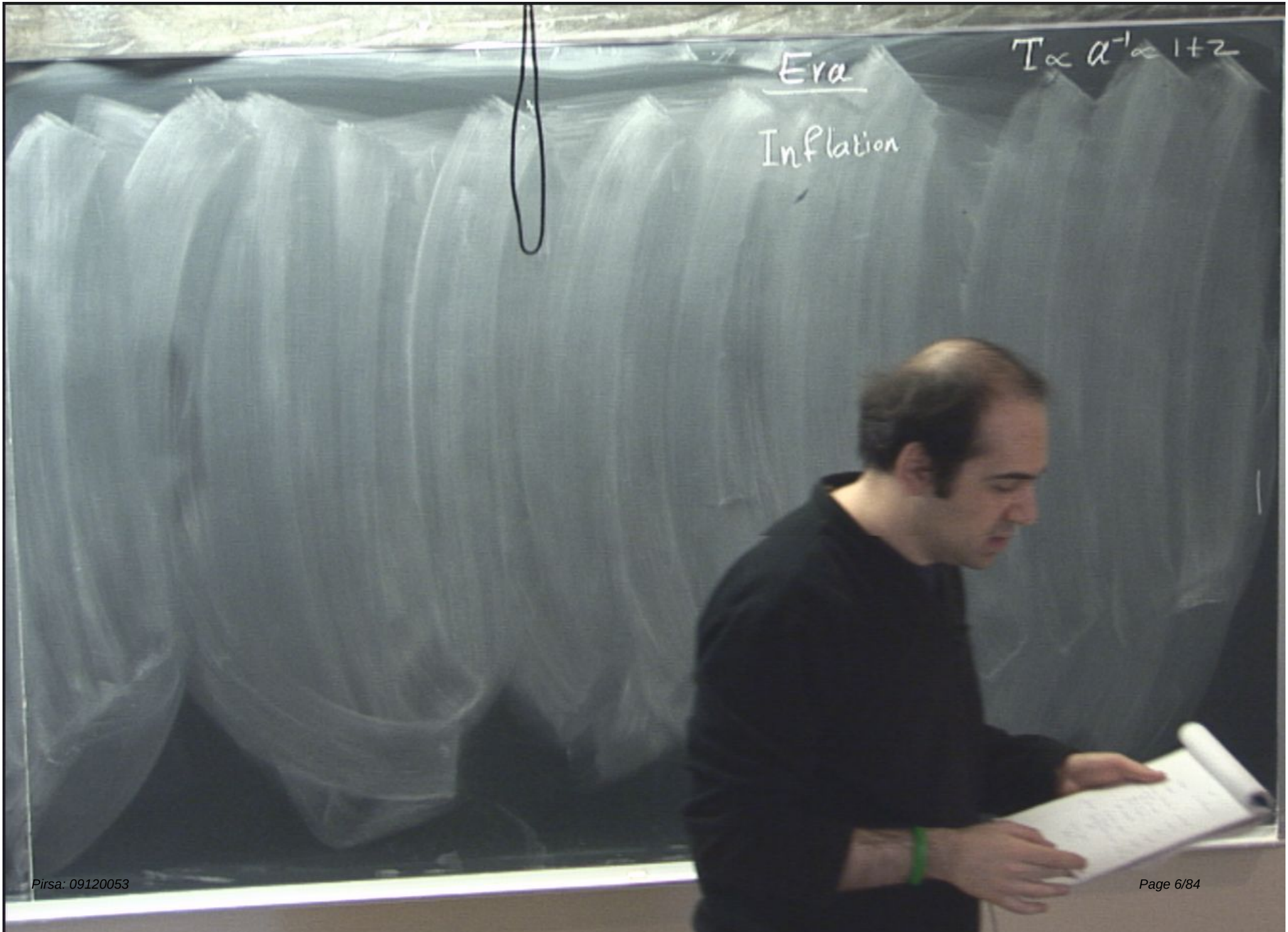
Abstract:

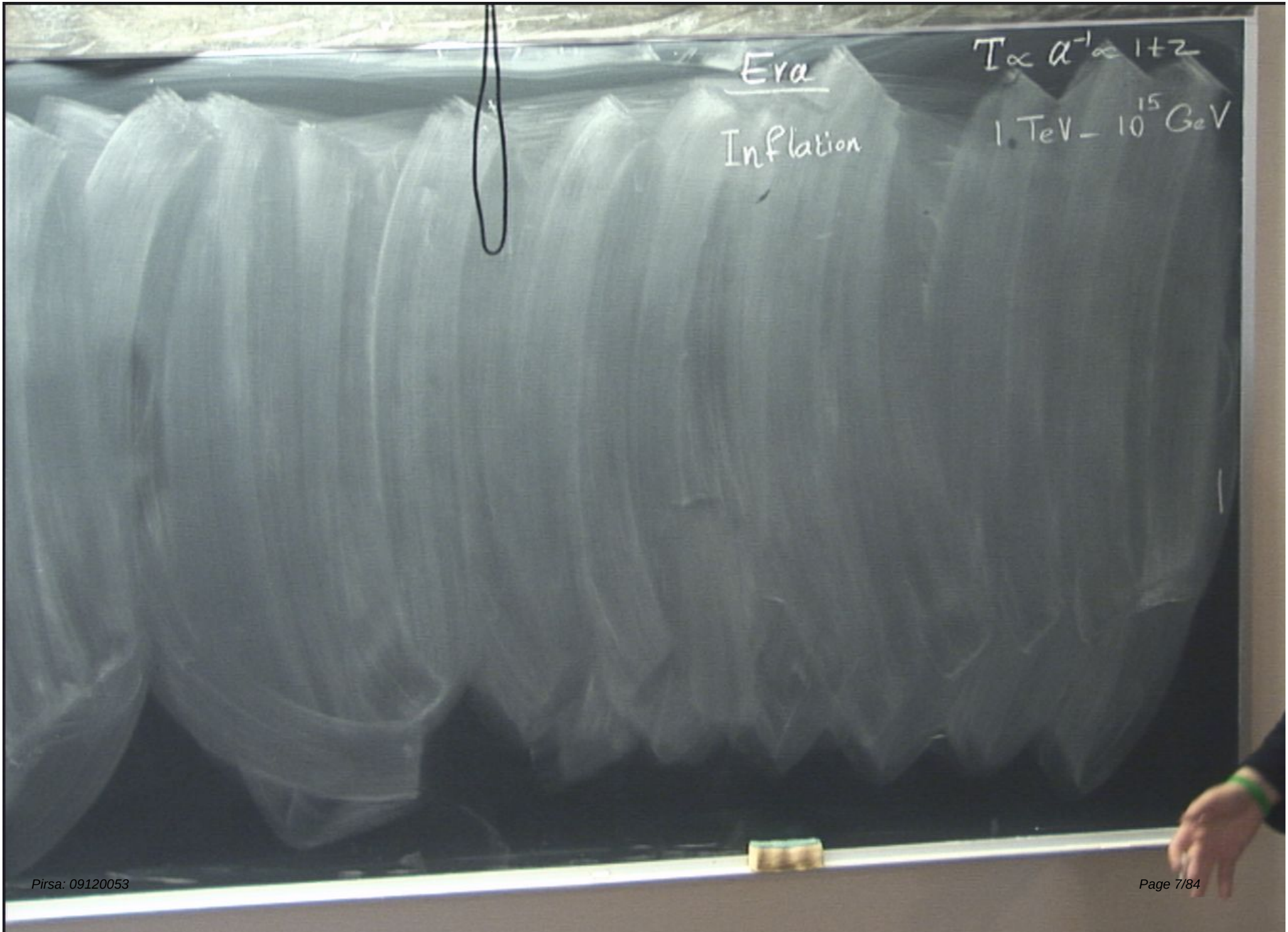
PERIMETER
INSTITUTE FOR THEORETICAL PHYSICS

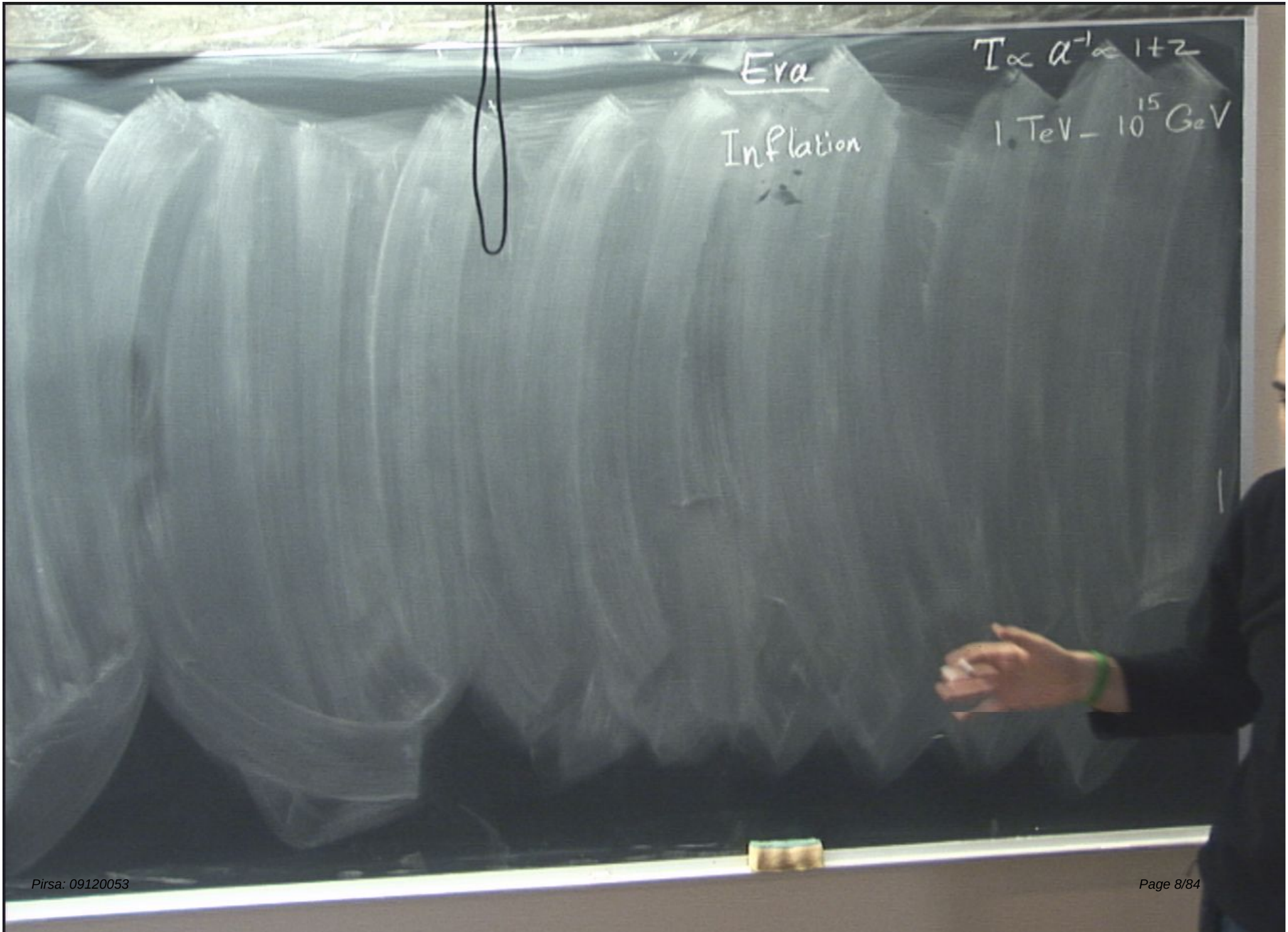

Era
T


Era
$T \propto a^{-1}$


Era
$T \propto a^{-1} \propto 1+z$


Era
Inflation
$T \propto a^{-1} \propto 1+z$


Era
Inflation
$T \propto a^{-1} \propto 1+z$
1 TeV – 10^{15} GeV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Inflation
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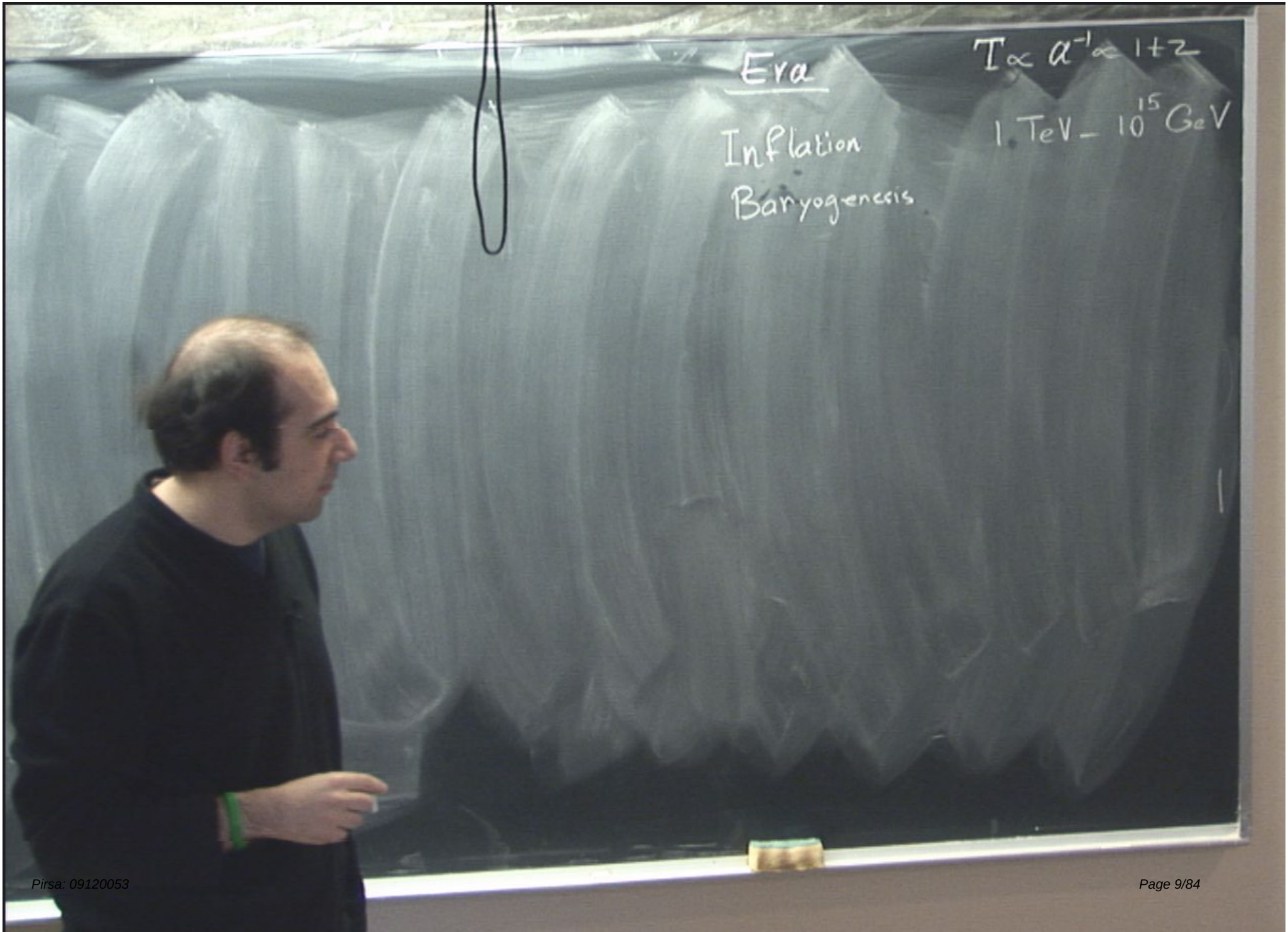
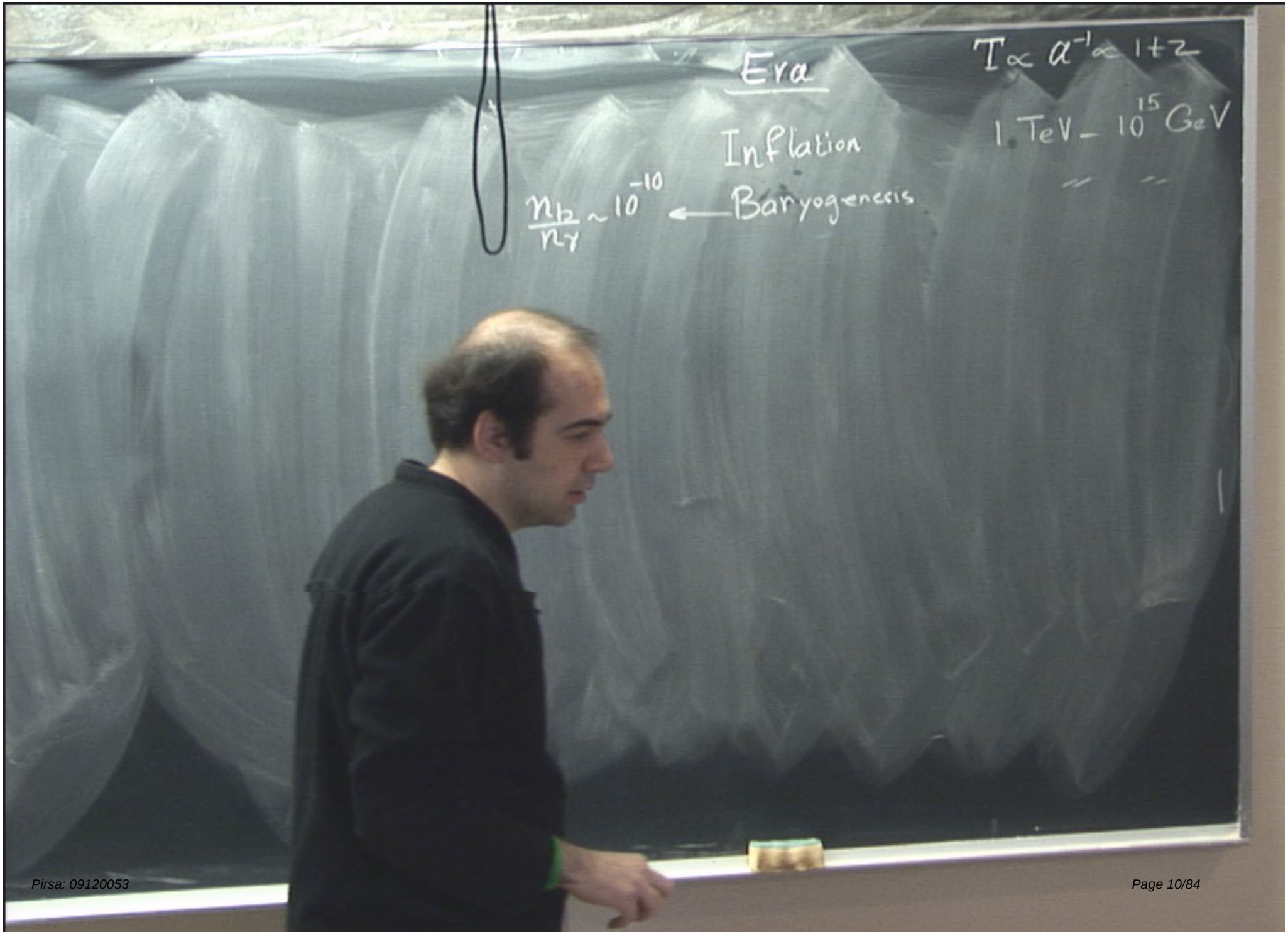
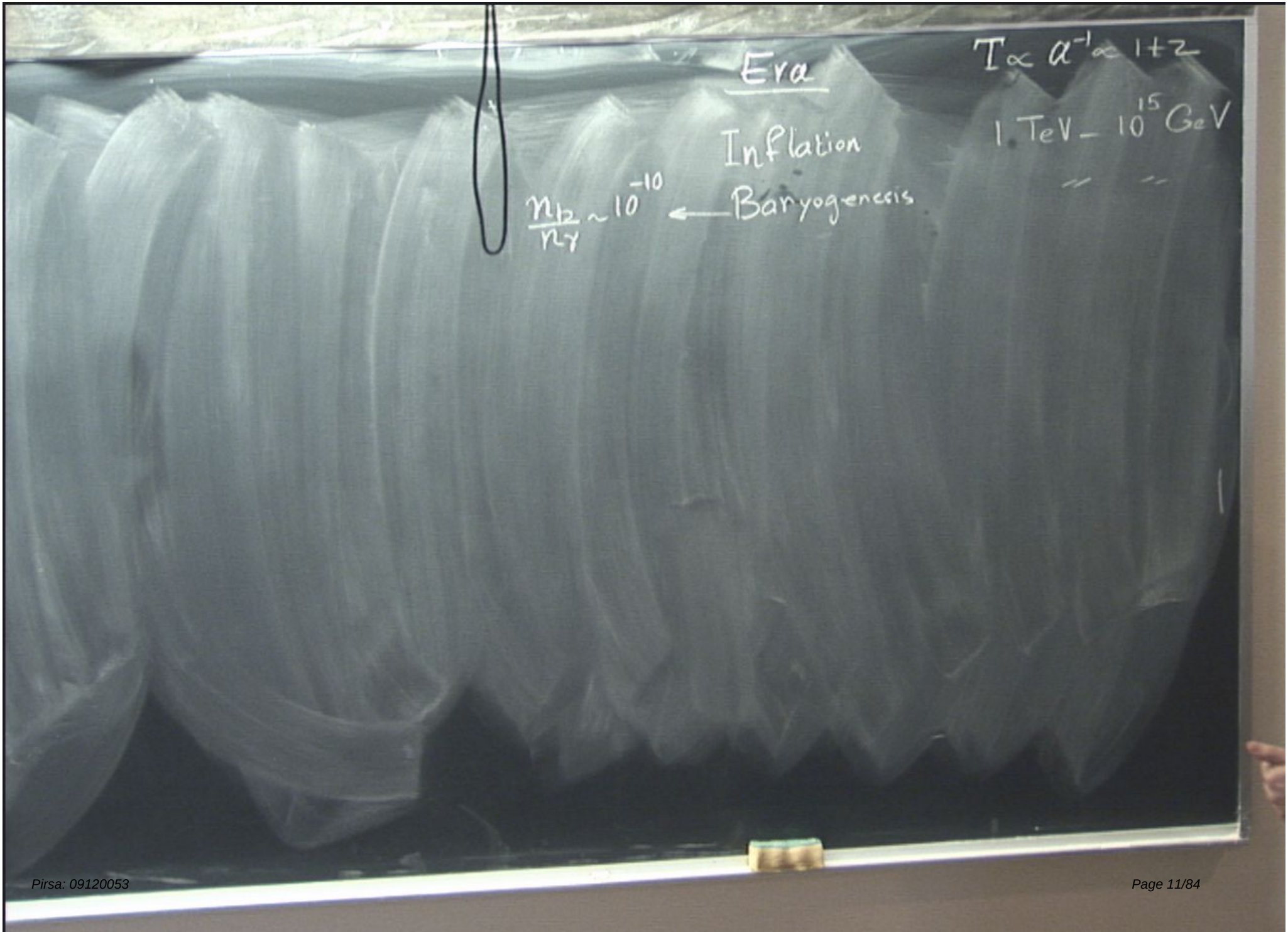
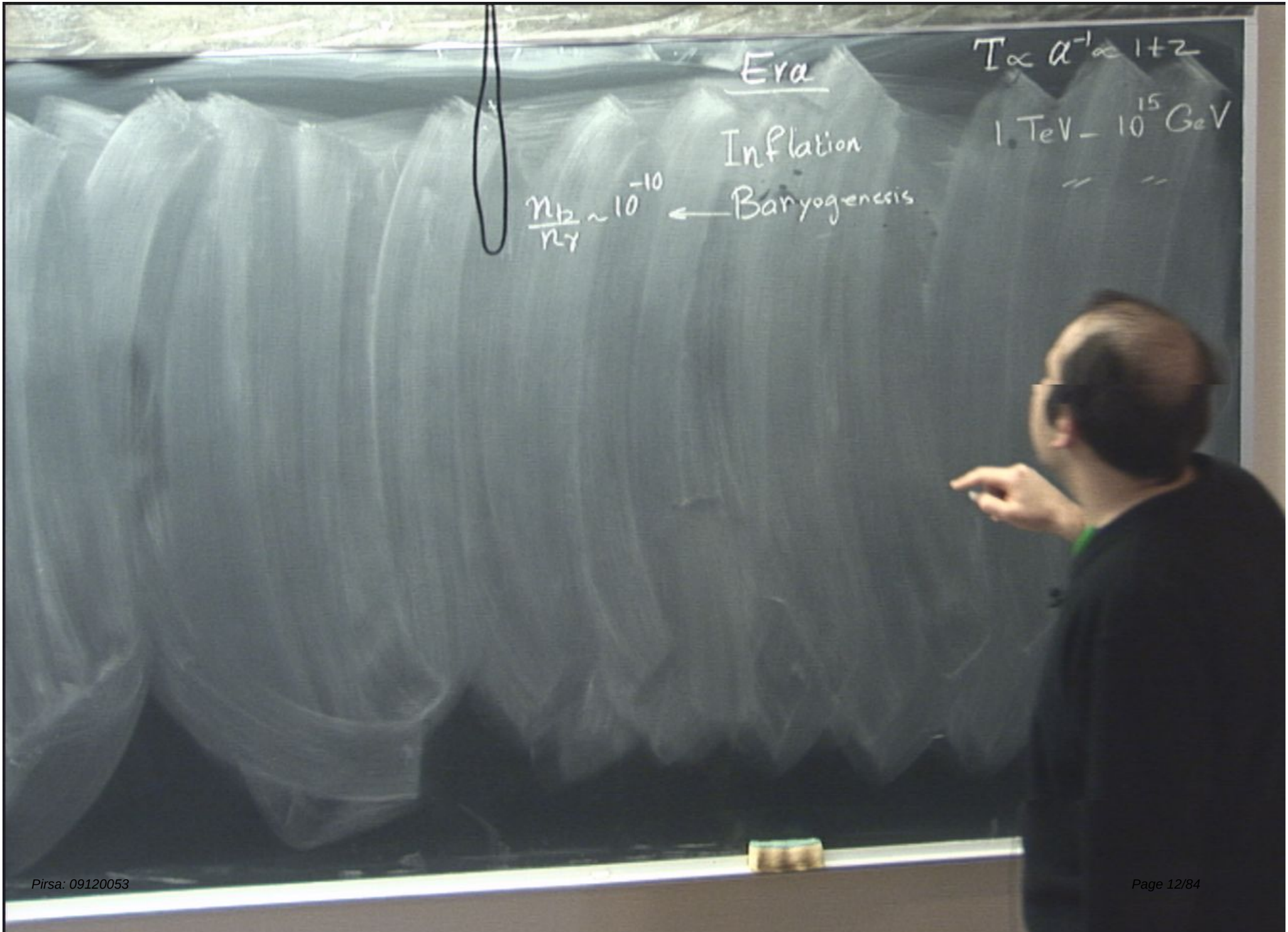
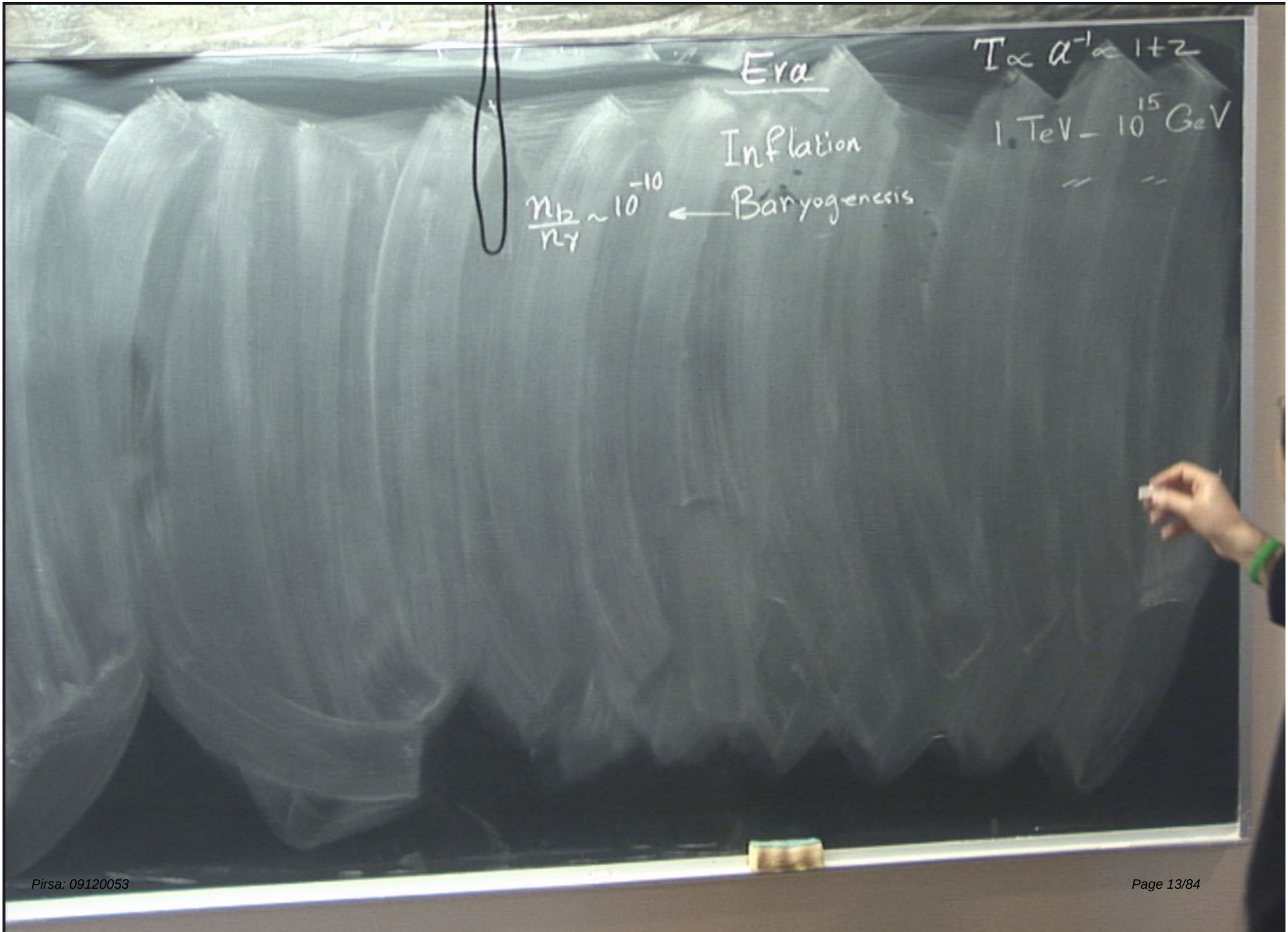
1 TeV – 10^{15} GeV

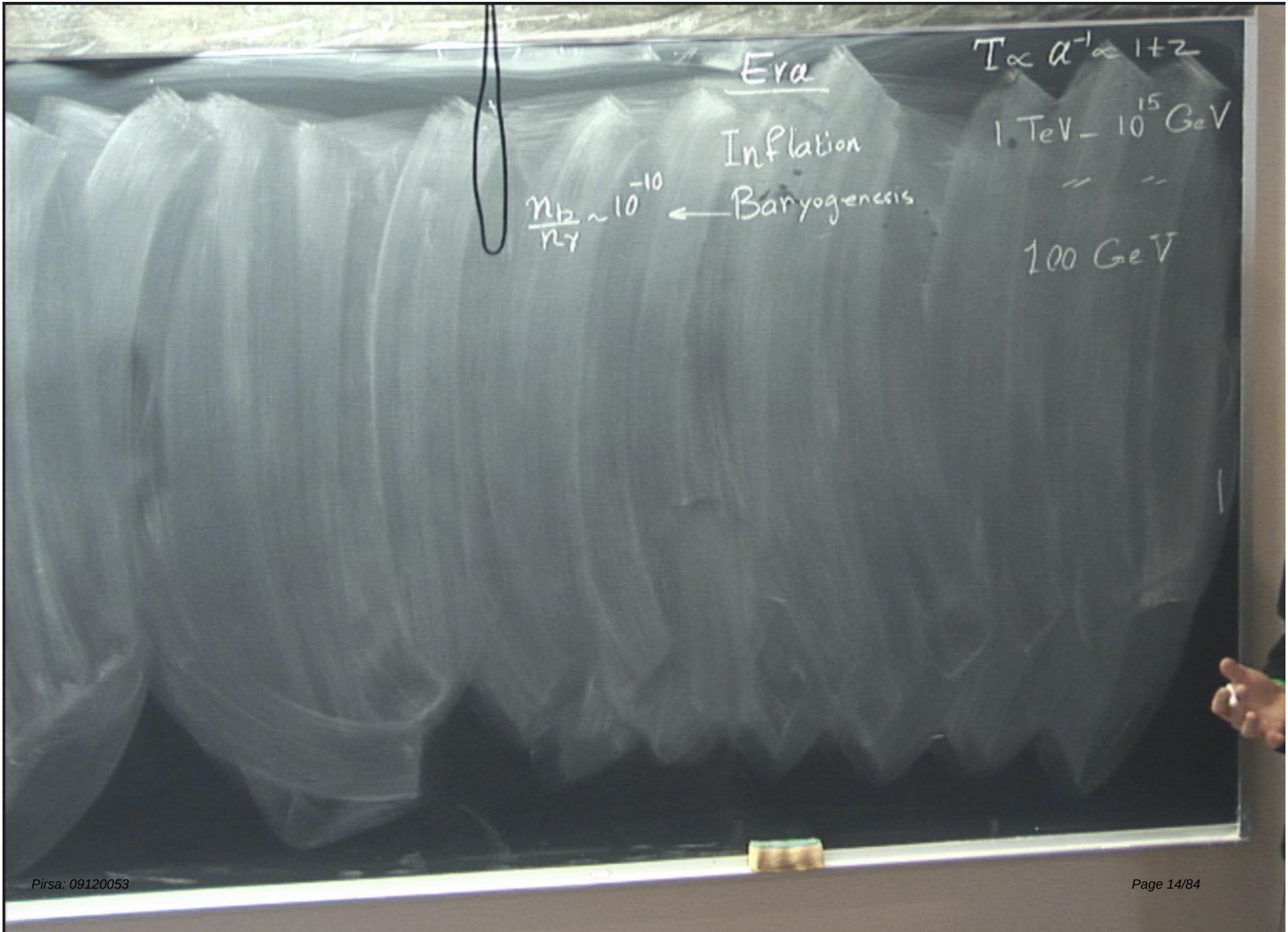

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
Baryogenesis

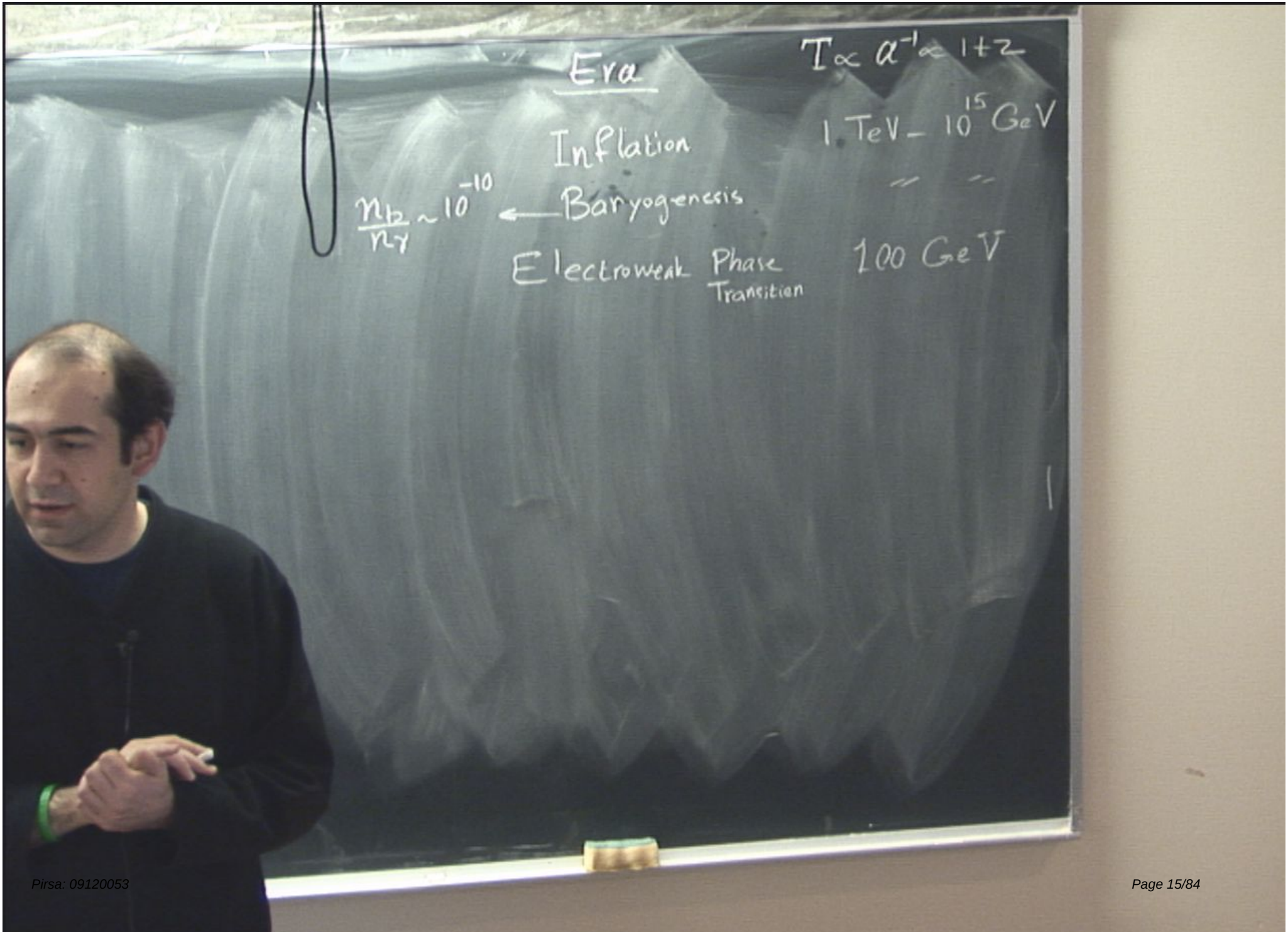

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis

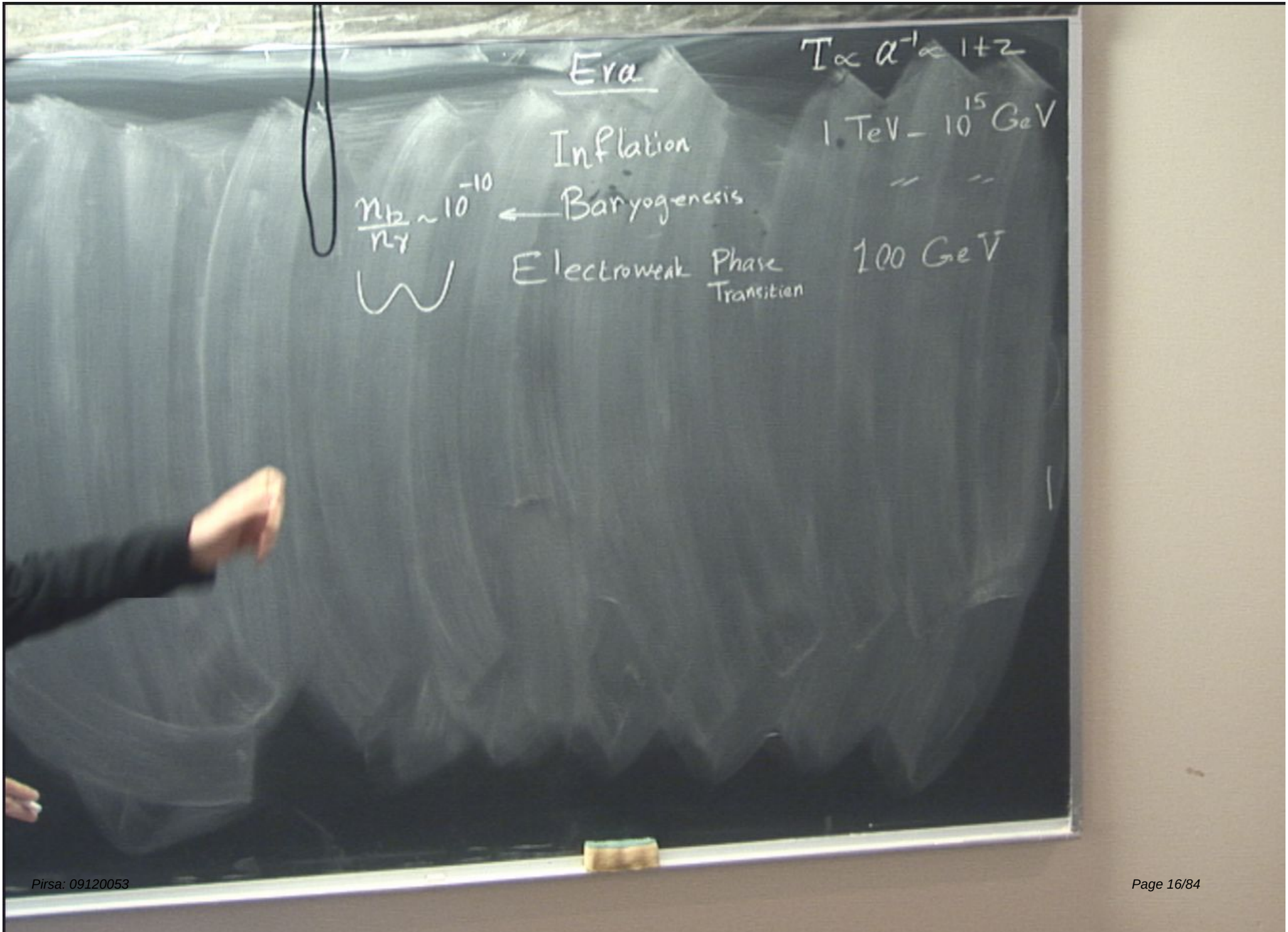

Era
$T \propto a^{-1} \propto 1+z$
Inflation
$1\ TeV - 10^{15}\ GeV$
$\frac{n_B}{n_\gamma} \sim 10^{-10}$ ← Baryogenesis

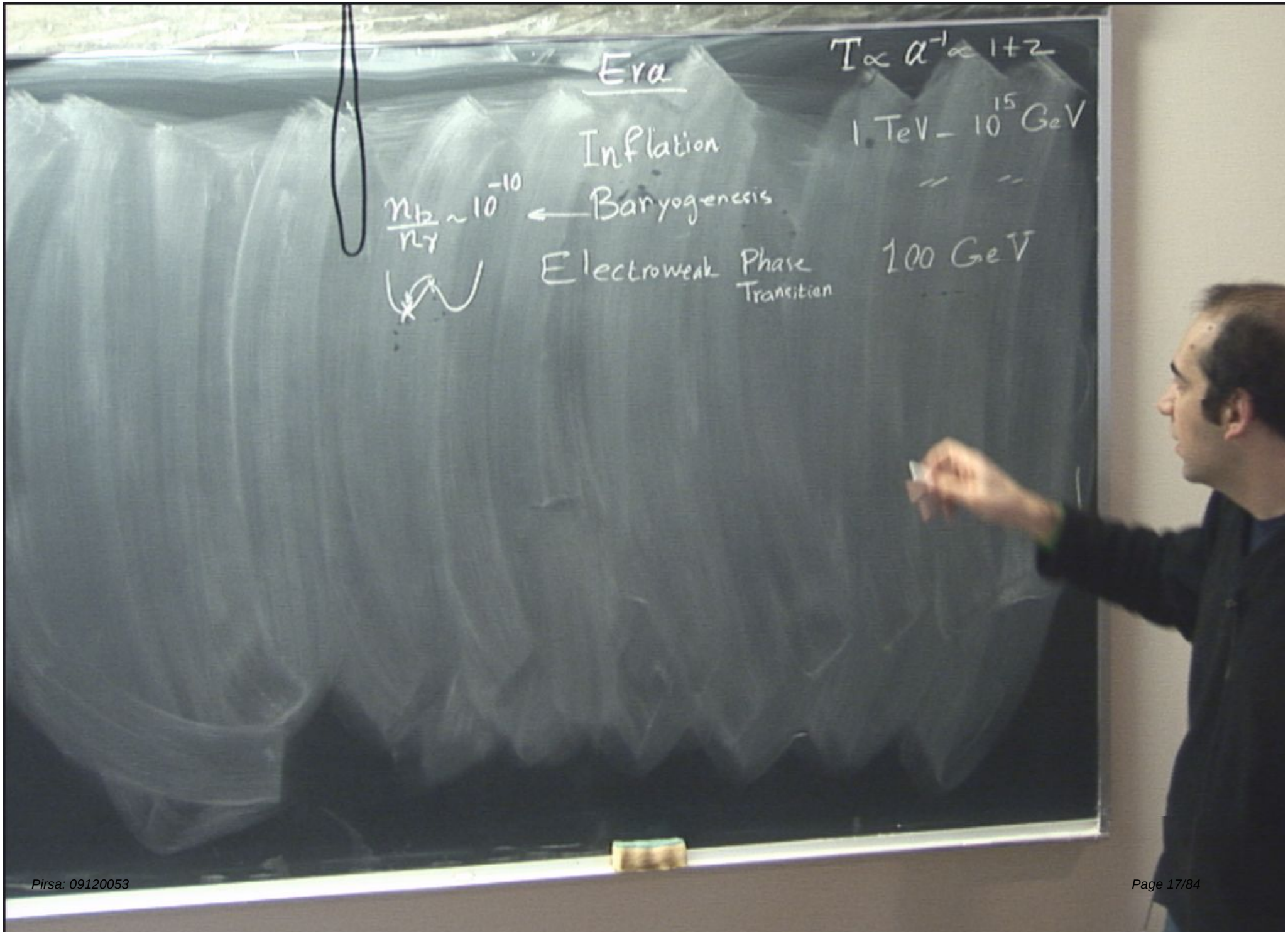

Era
Inflation
Baryogenesis
$\frac{n_{b\bar{b}}}{n_\gamma} \sim 10^{-10}$
$T \propto a^{-1} \propto 1+z$
1 TeV – 10^{15} GeV

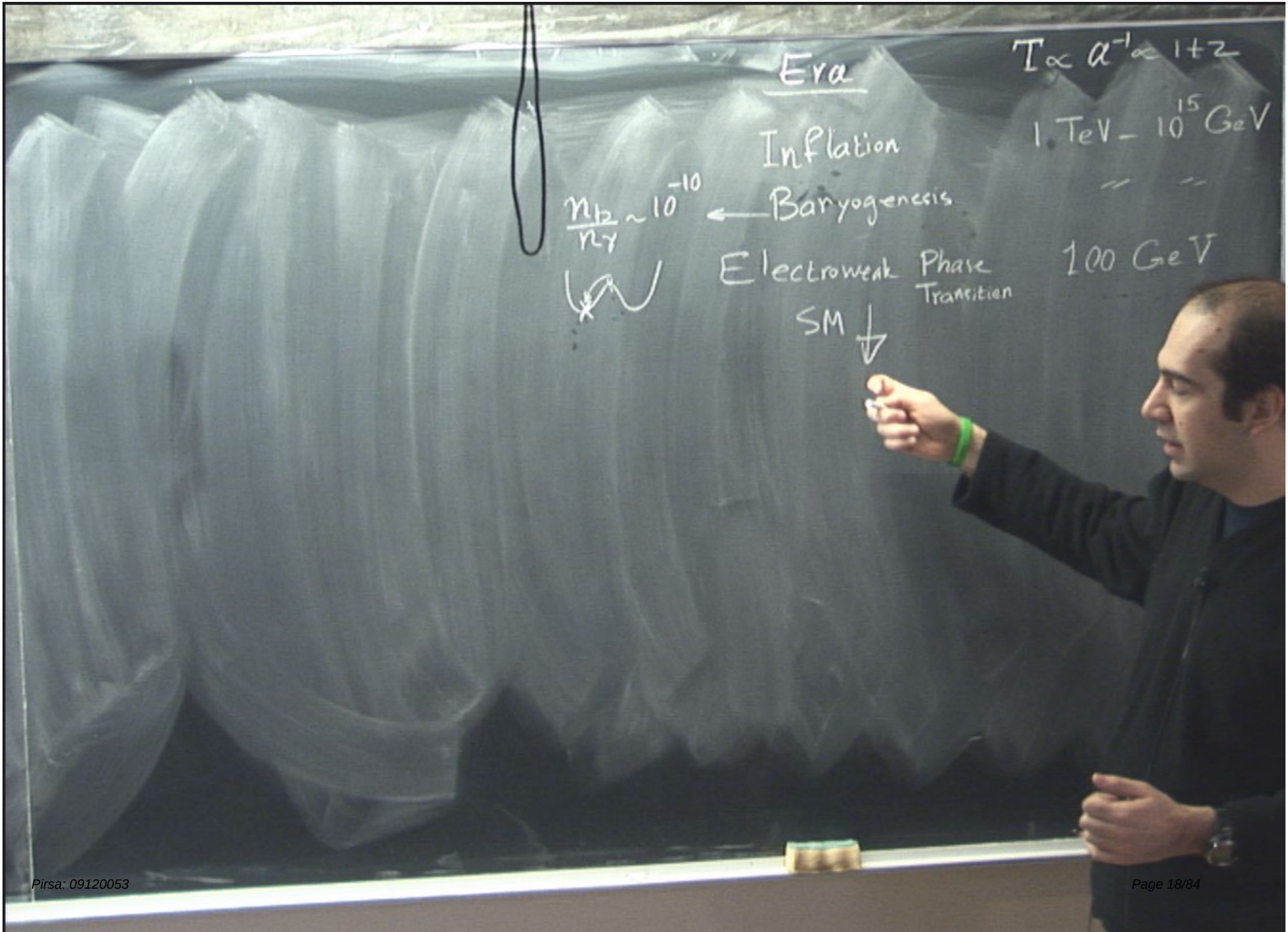

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$ ← Baryogenesis

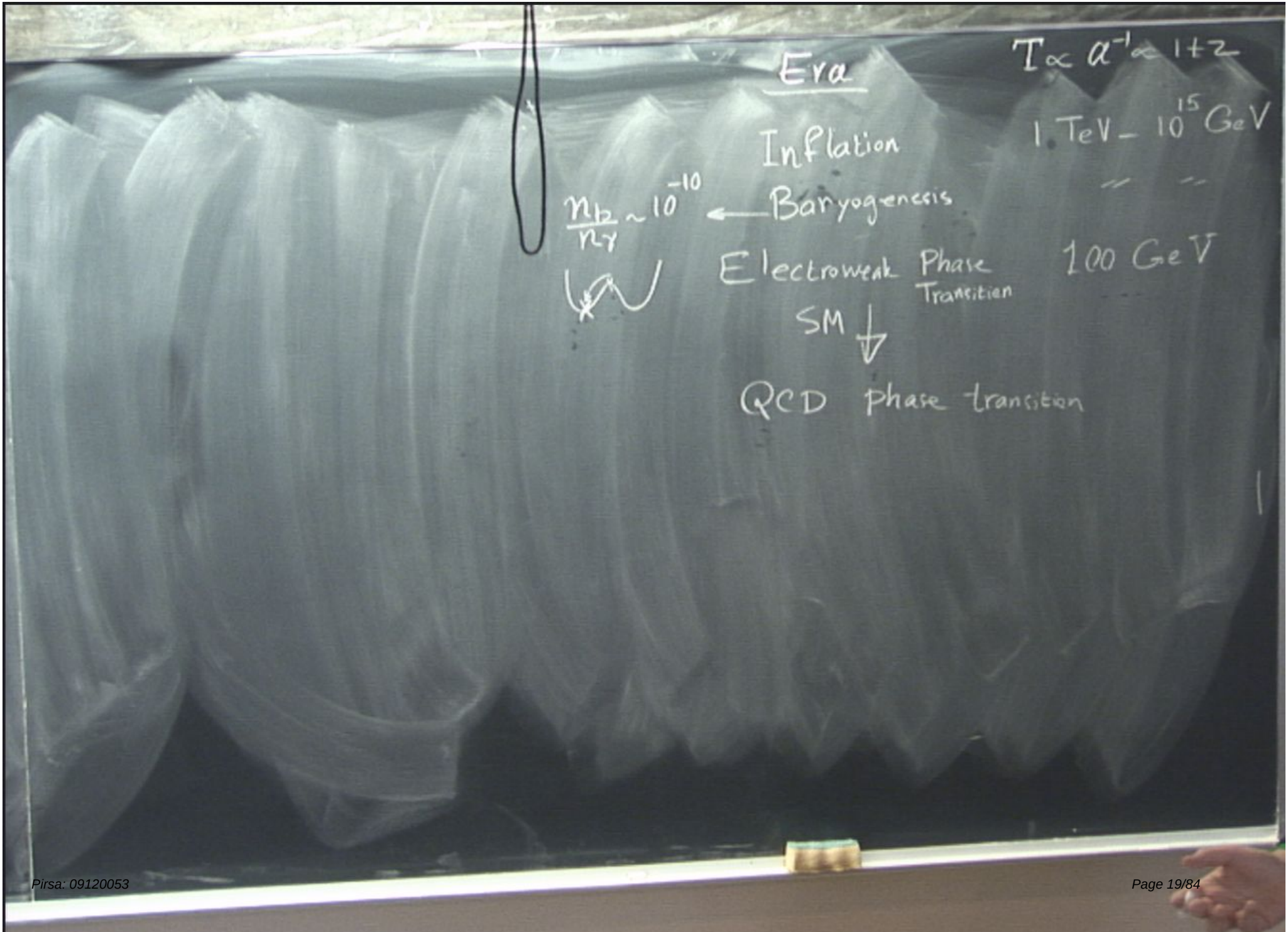

Era
Inflation
$\frac{n_b}{n_\gamma} \sim 10^{-10}$ ← Baryogenesis
$T \propto a^{-1} \propto 1+z$
1 TeV – 10^{15} GeV
100 GeV

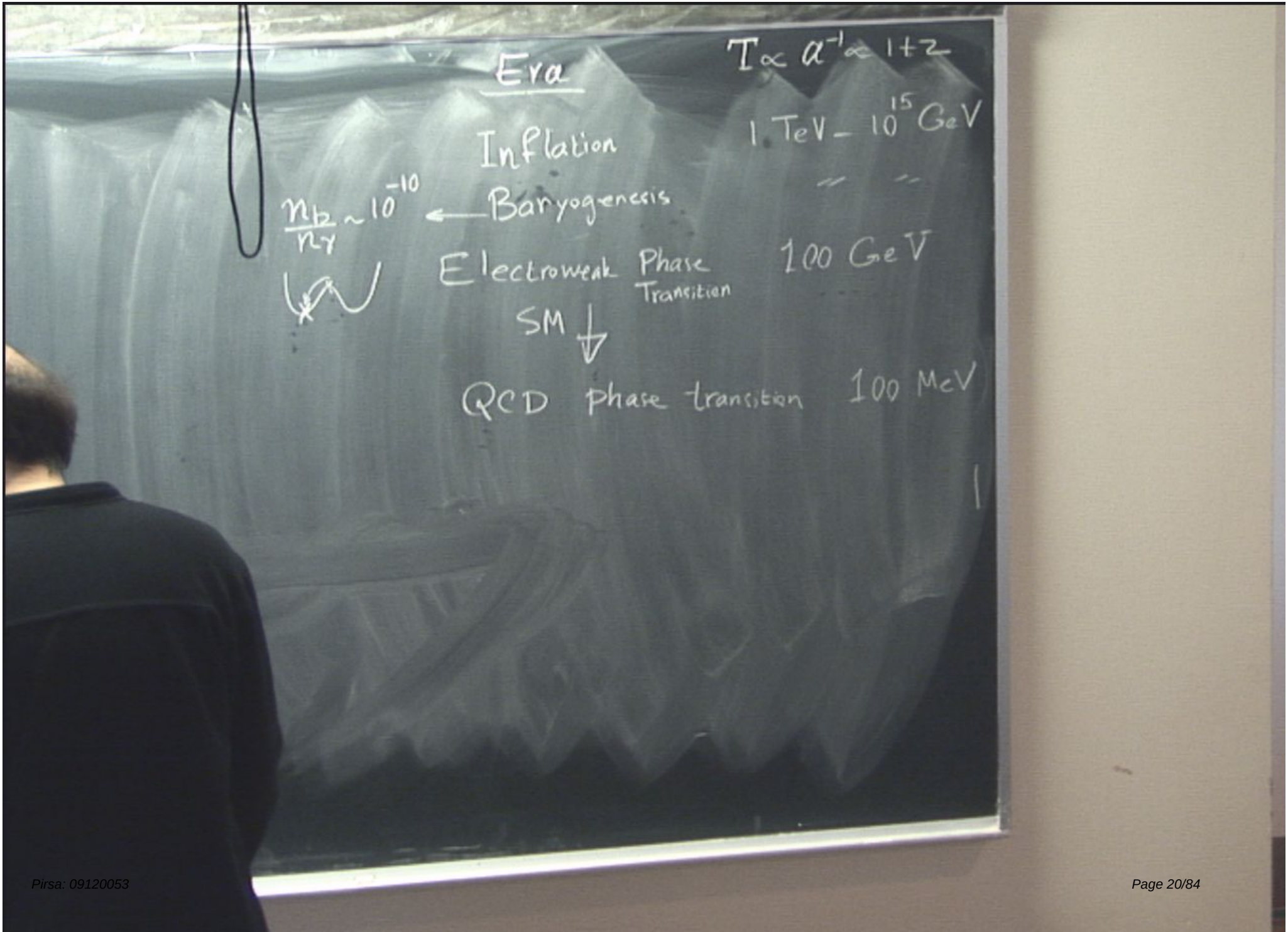

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV

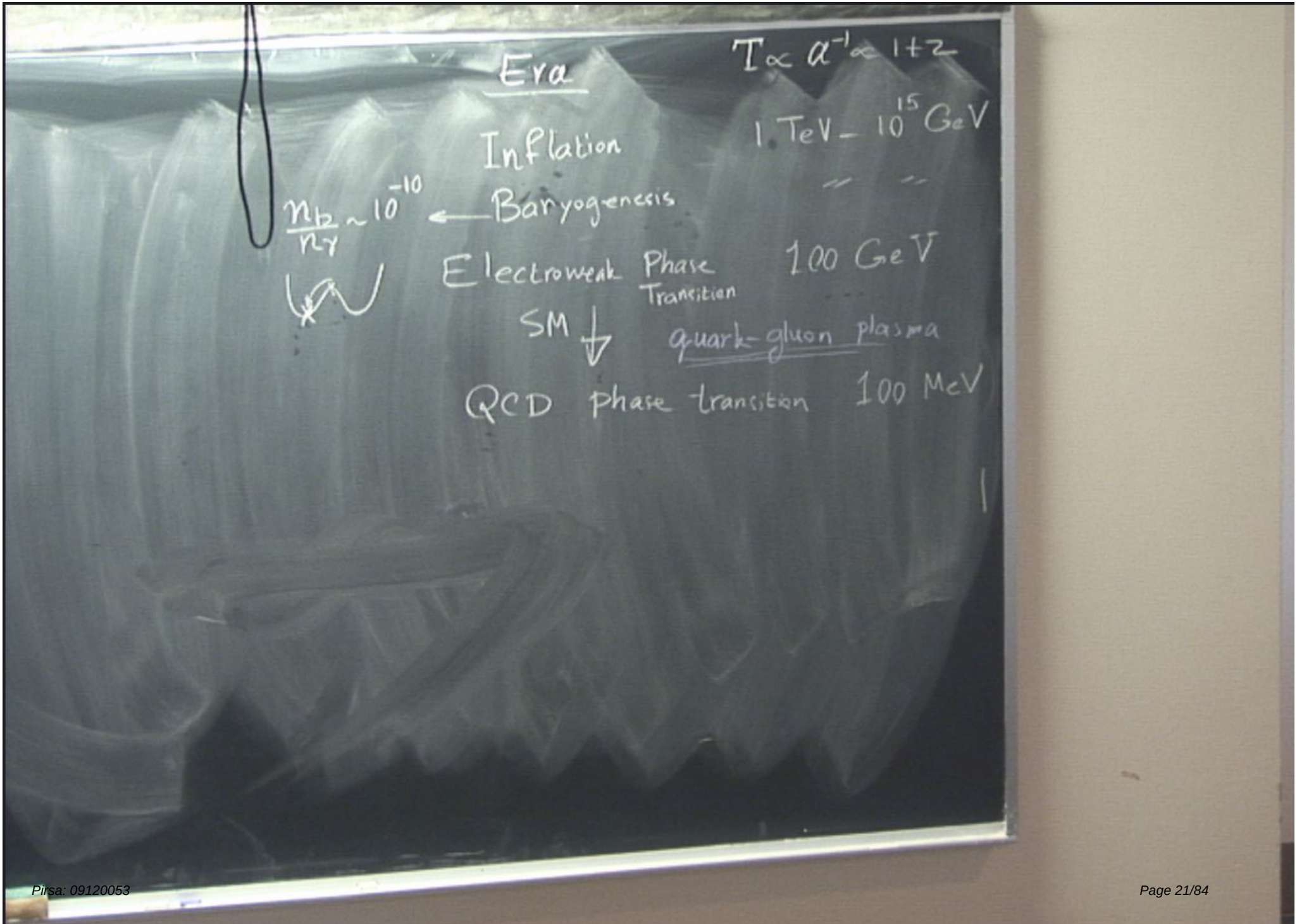

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV

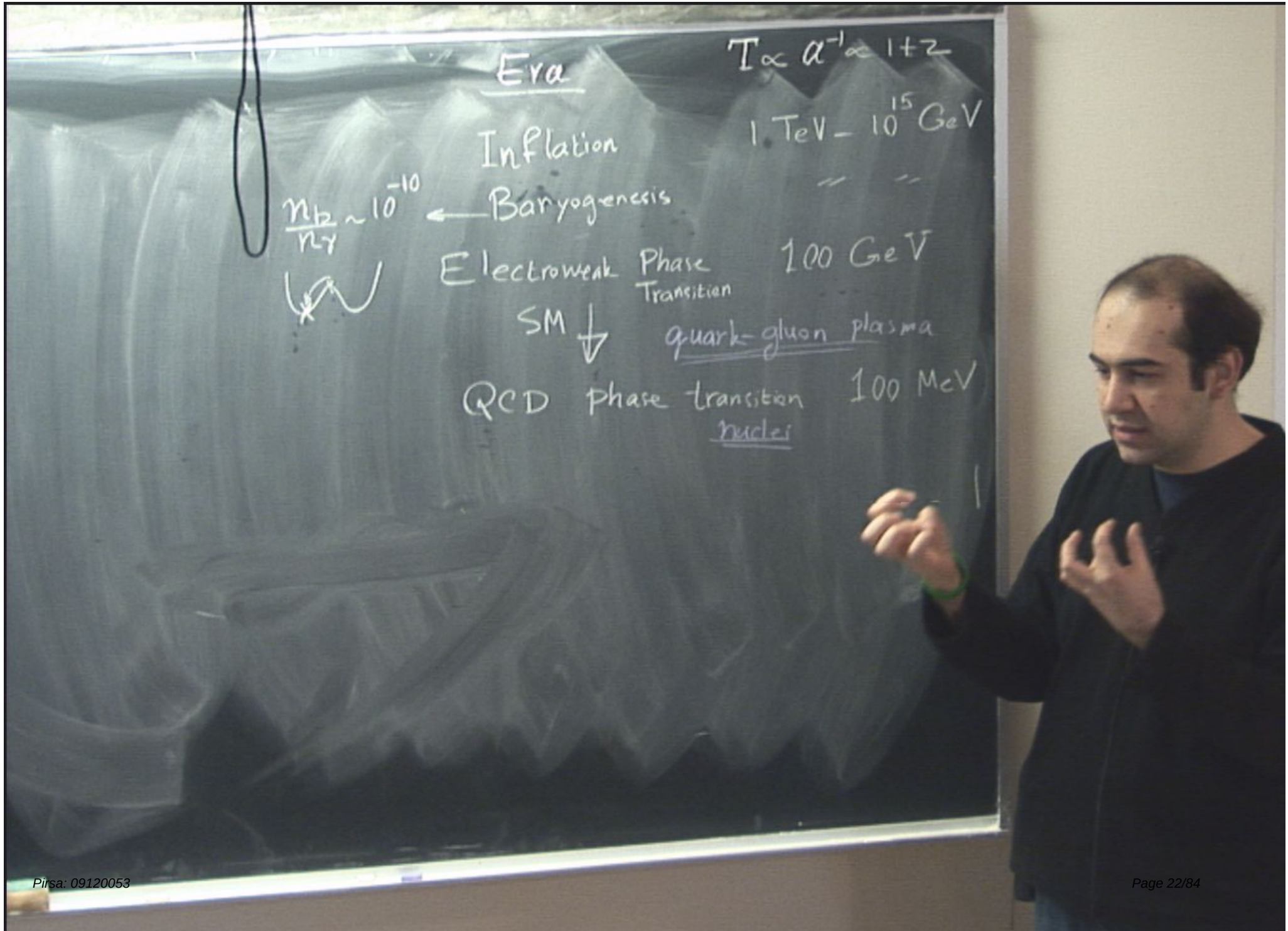

Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV


Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_{B2}}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV
SM


Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
QCD phase transition


Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
QCD phase transition
100 MeV


Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
$\frac{n_b}{n_\gamma} \sim 10^{-10}$ ← Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
QCD phase transition
100 MeV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Inflation
1 TeV – 10^{15} GeV
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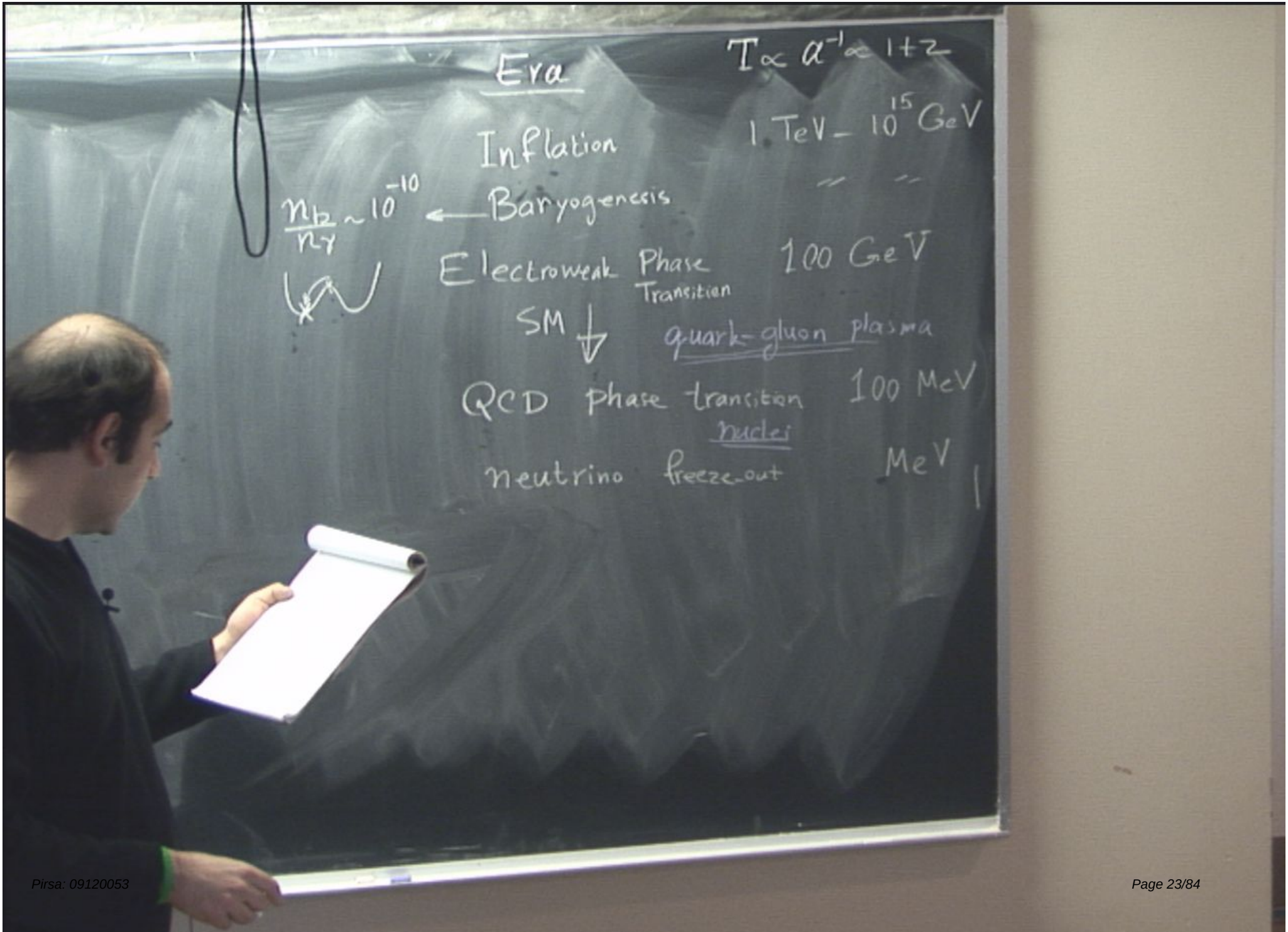
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
QCD phase transition
100 MeV
nuclei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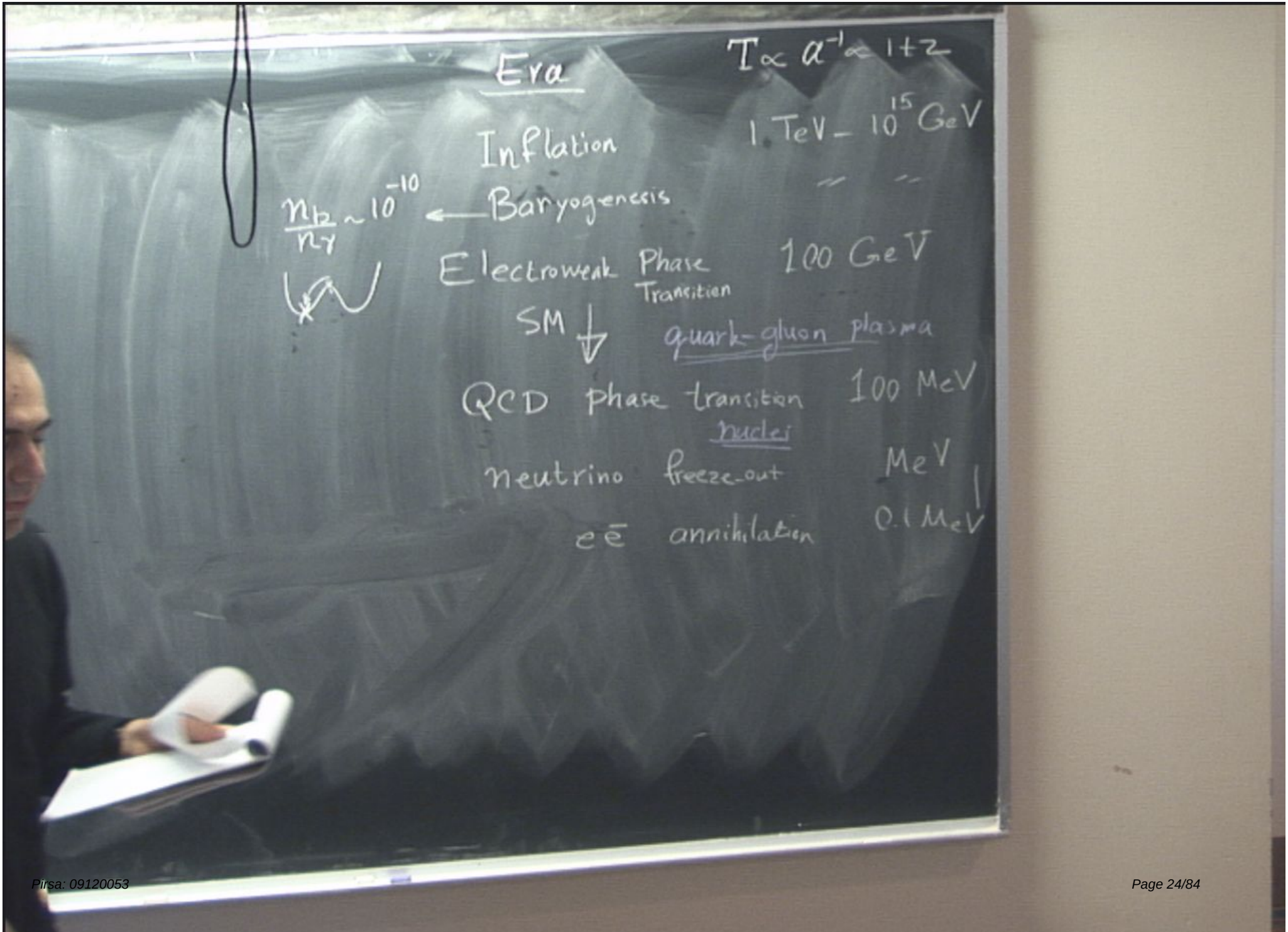
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
QCD phase transition
100 MeV
nuclei
neutrino freeze-out
MeV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QCD phase transition
100 MeV
nuclei
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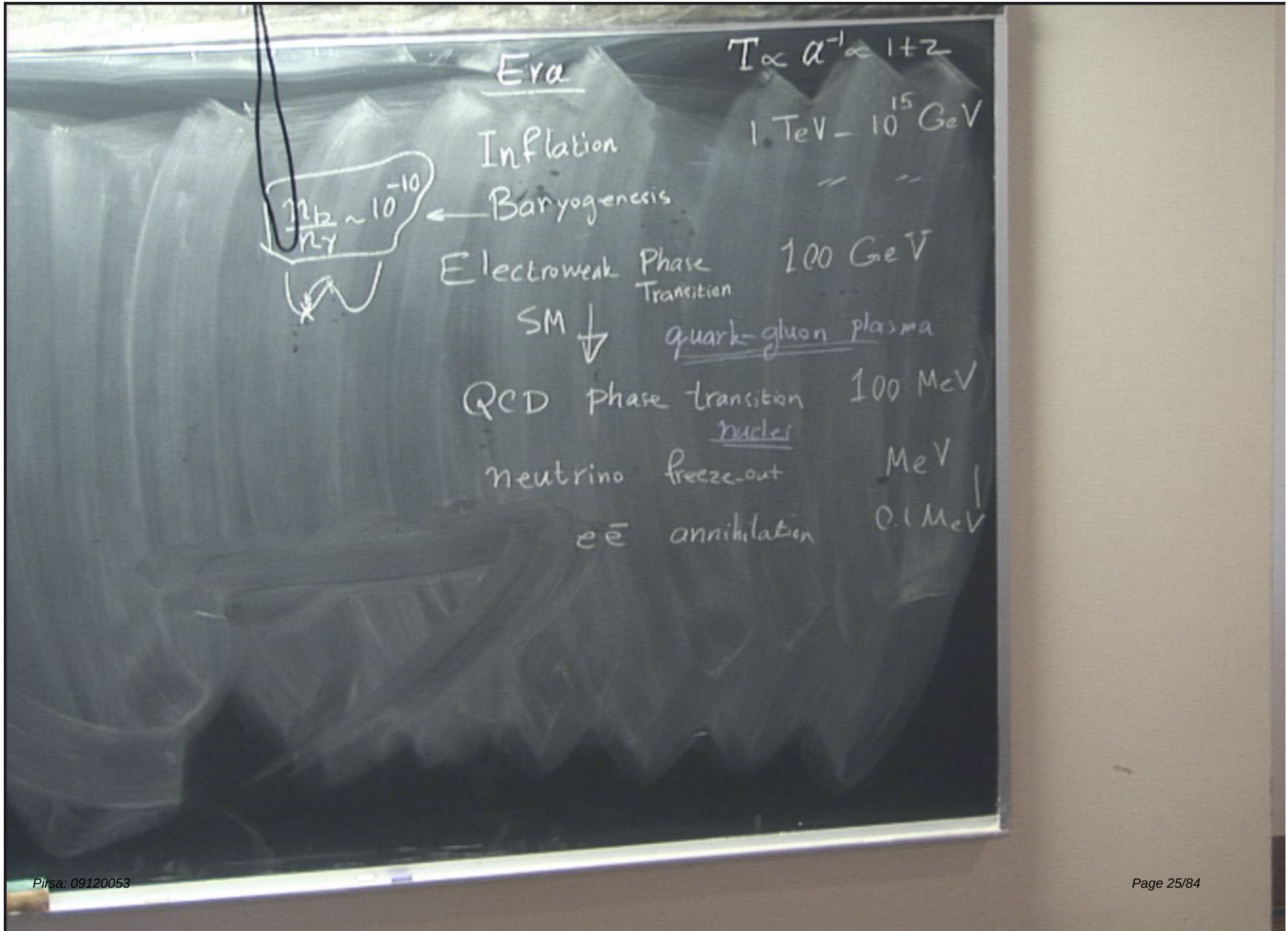
MeV
$e\bar{e}$ annihilation
0.1 MeV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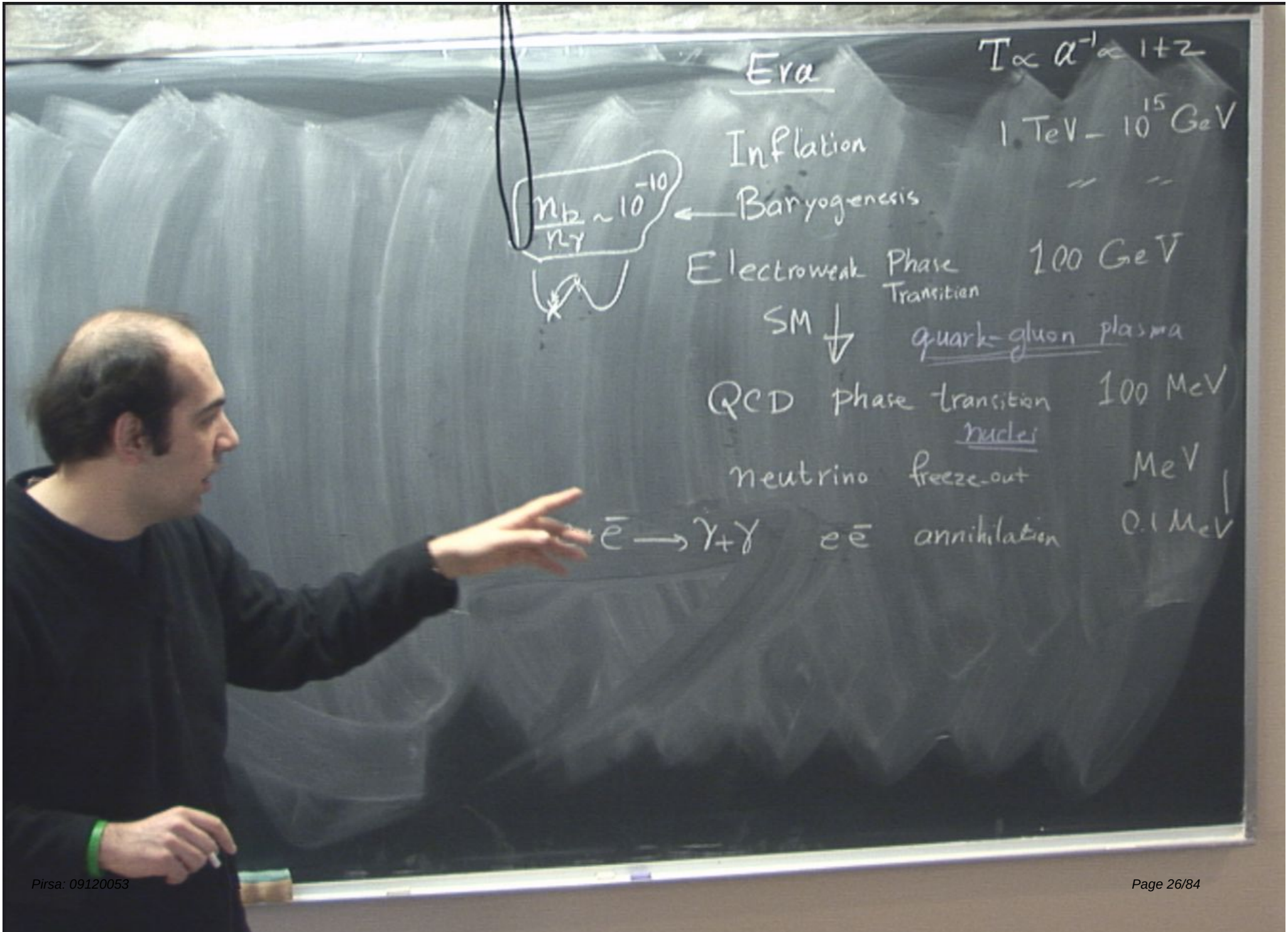
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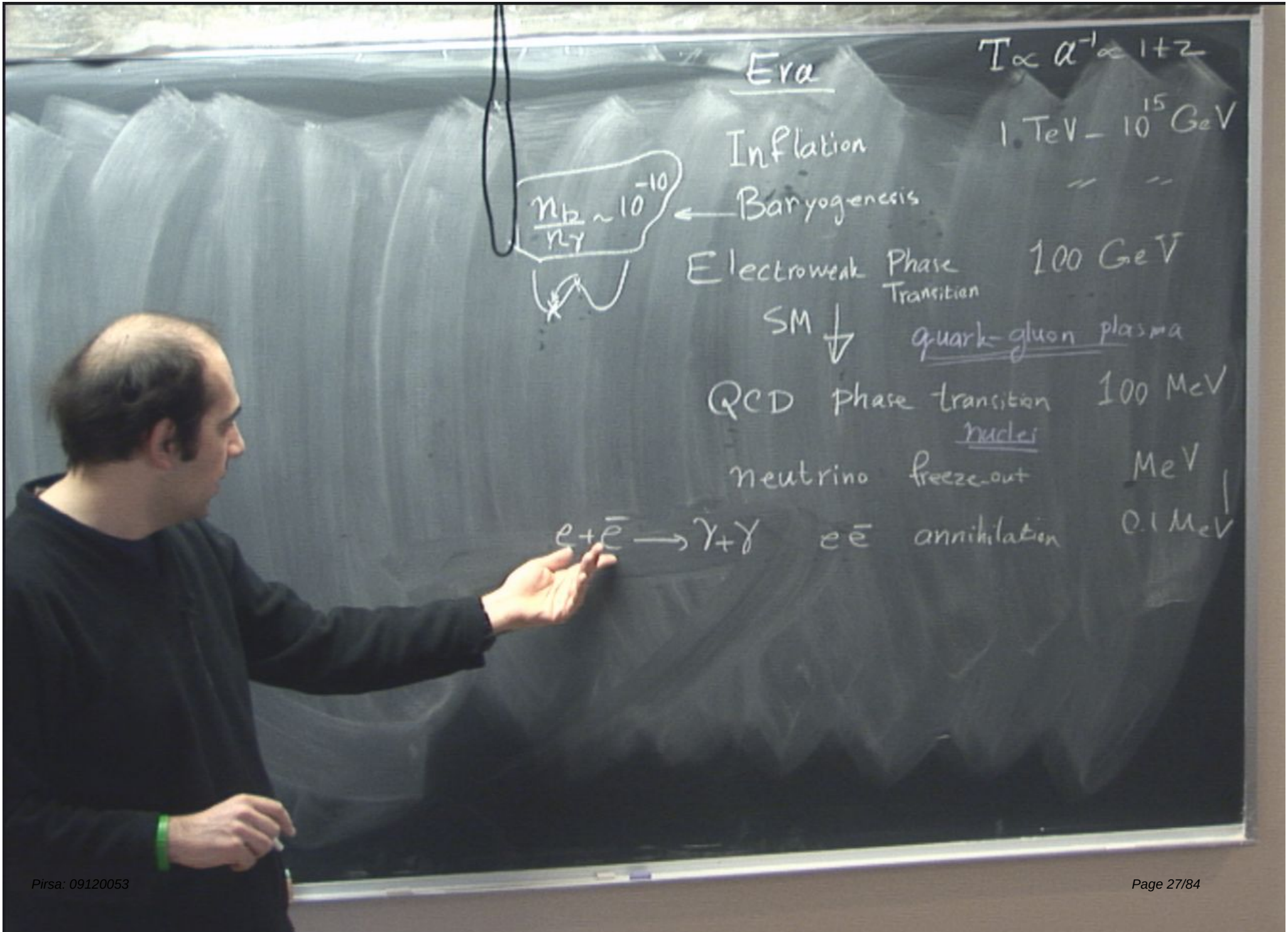
100 MeV
nuclei
neutrino freeze-out
MeV
$e\bar{e} \longrightarrow \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV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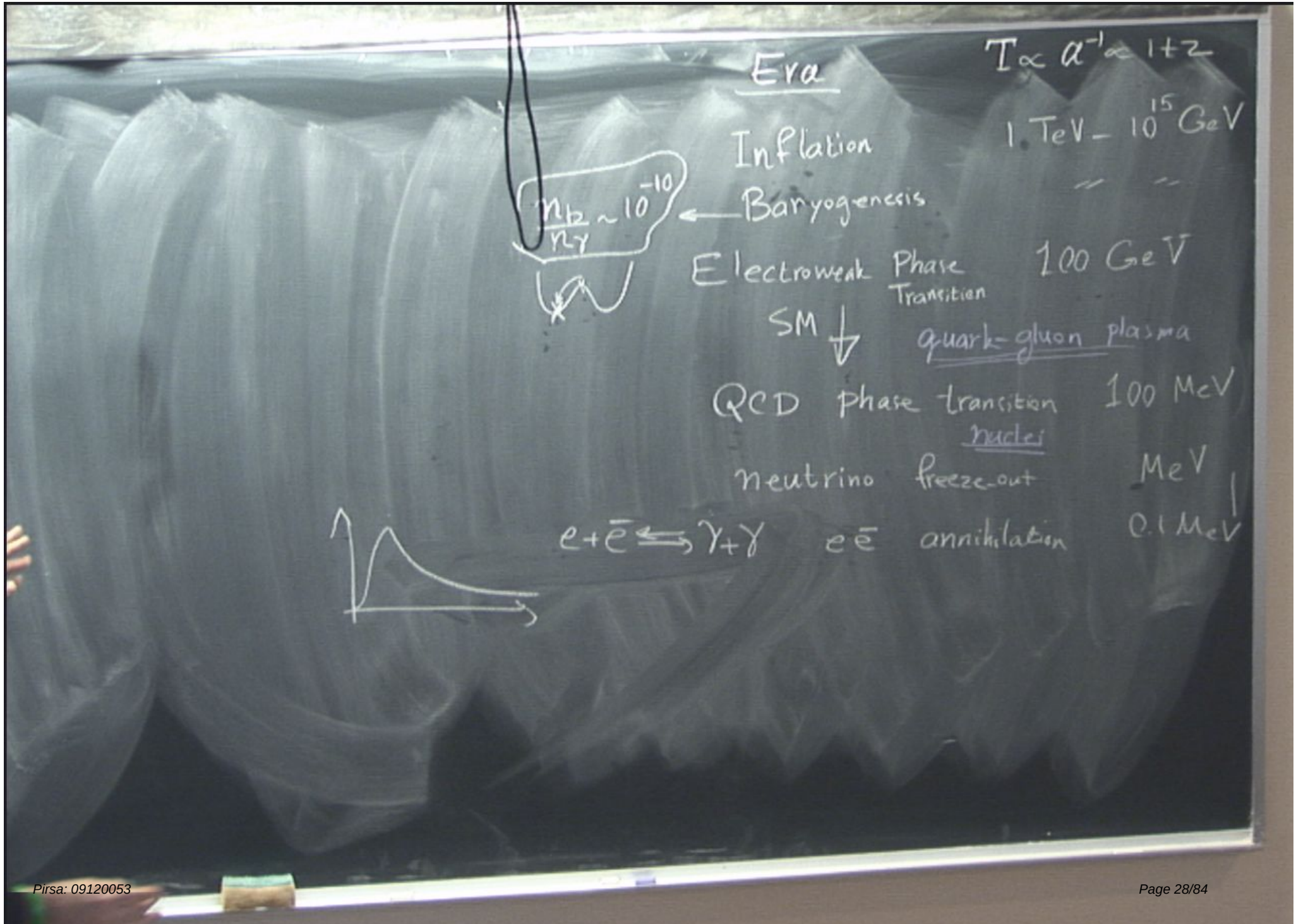
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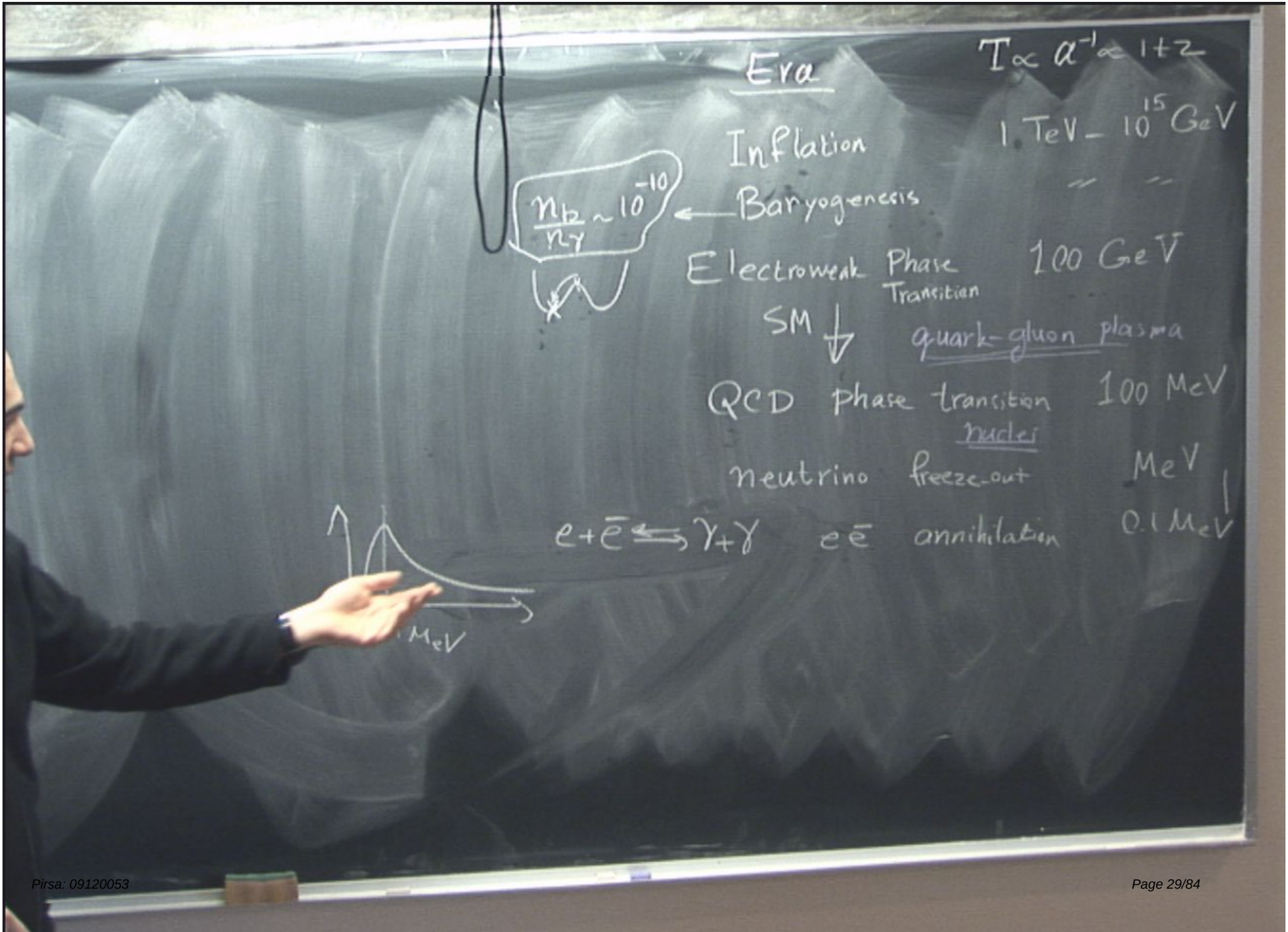
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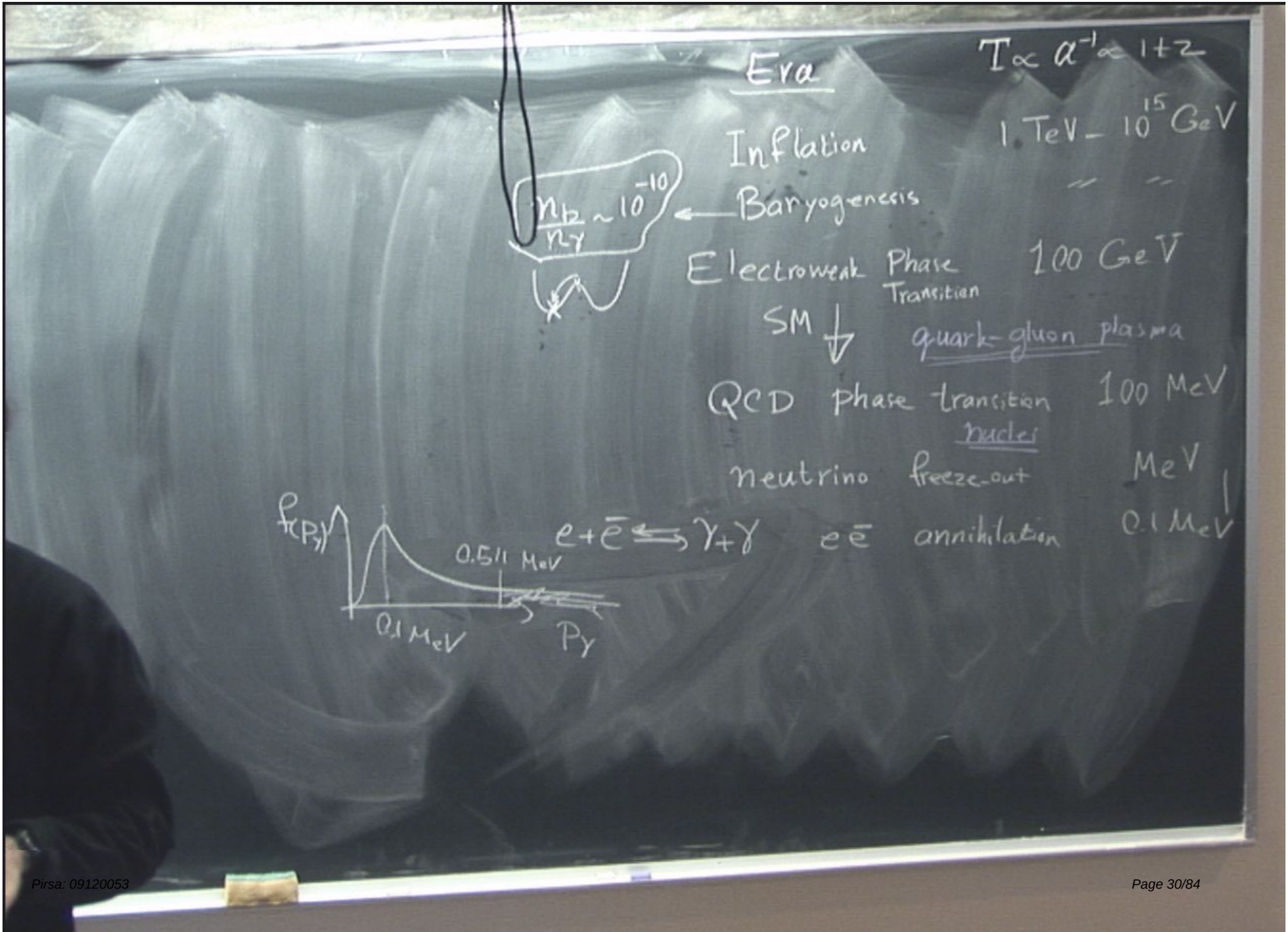
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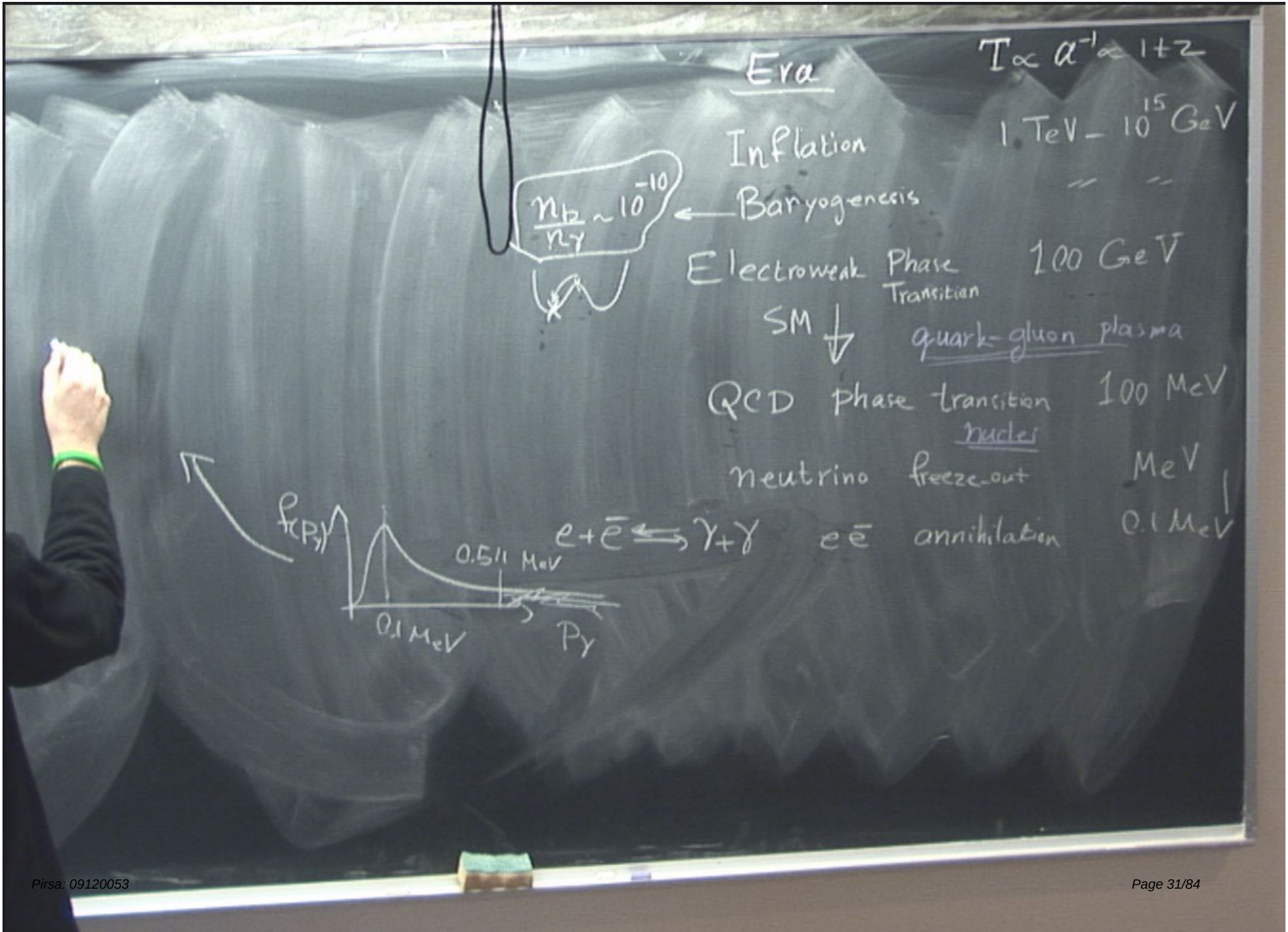
MeV
$e+\bar{e} \rightleftharpoons \gamma+\gamma$
$e\bar{e}$ annihilation
0.1 MeV
$f(p_\gamma)$
0.511 MeV
0.1 MeV
p_γ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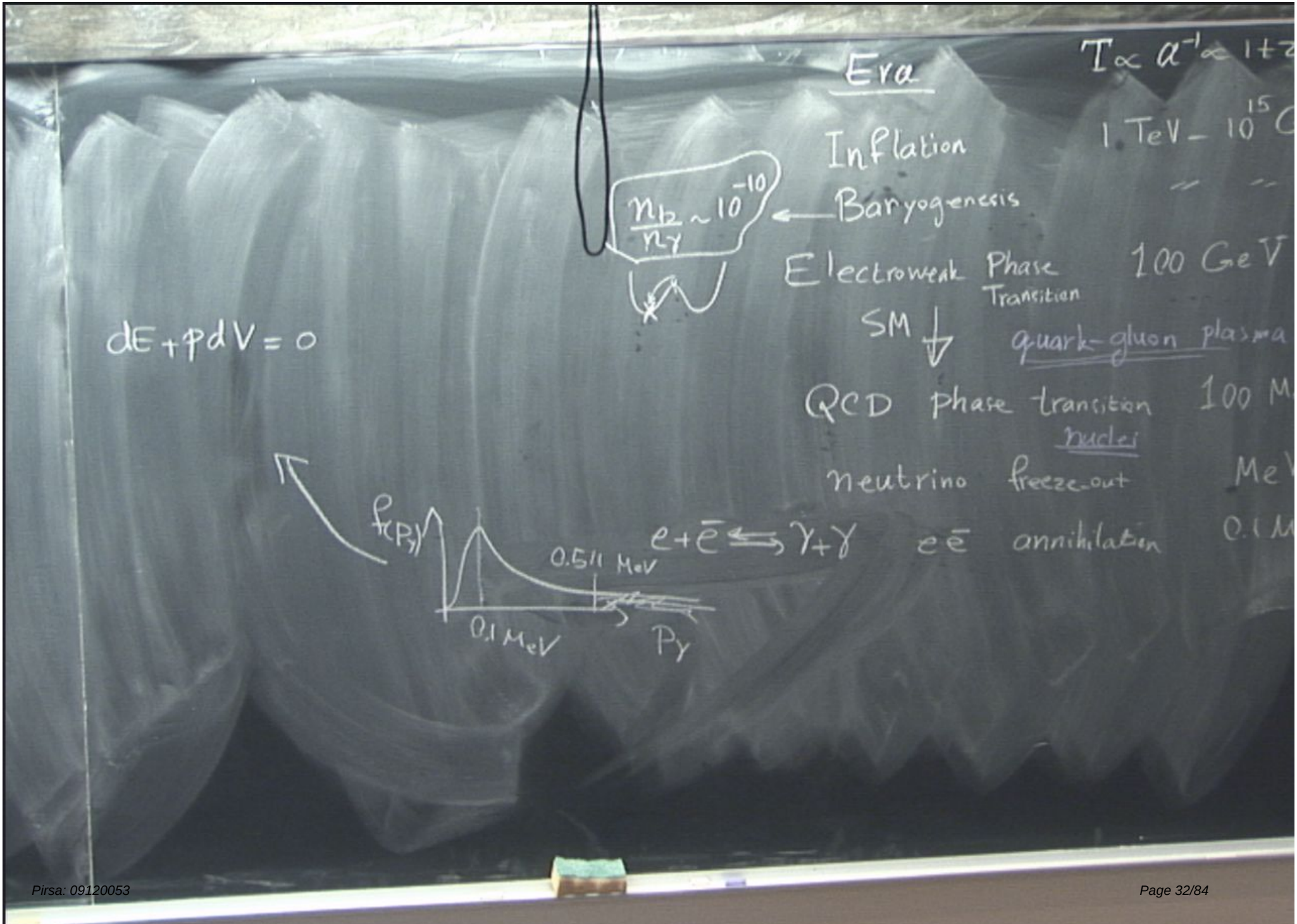
Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} G
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV
$dE + pdV = 0$
SM
quark-gluon plasma
QCD phase transition
100 M
nuclei
neutrino freeze-out
MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
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$f(p_\gamma)$
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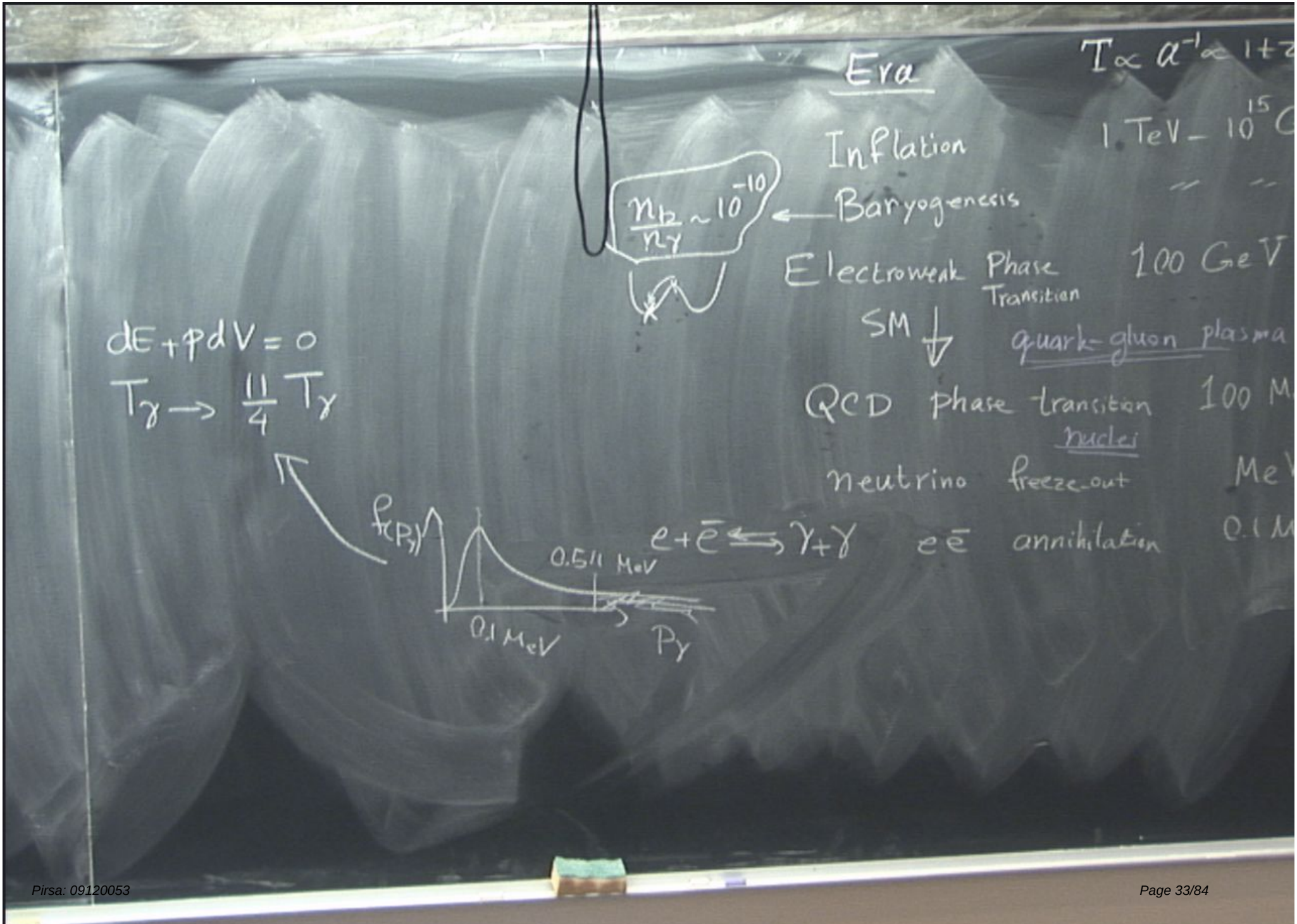
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Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
$dE + pdV = 0$
$T_\gamma \rightarrow \frac{11}{4} T_\gamma$
QCD phase transition
100 M
nuclei
neutrino freeze-out
Me
$e+\bar{e} \leftrightarrows \gamma+\gamma$
$e\bar{e}$ annihilation
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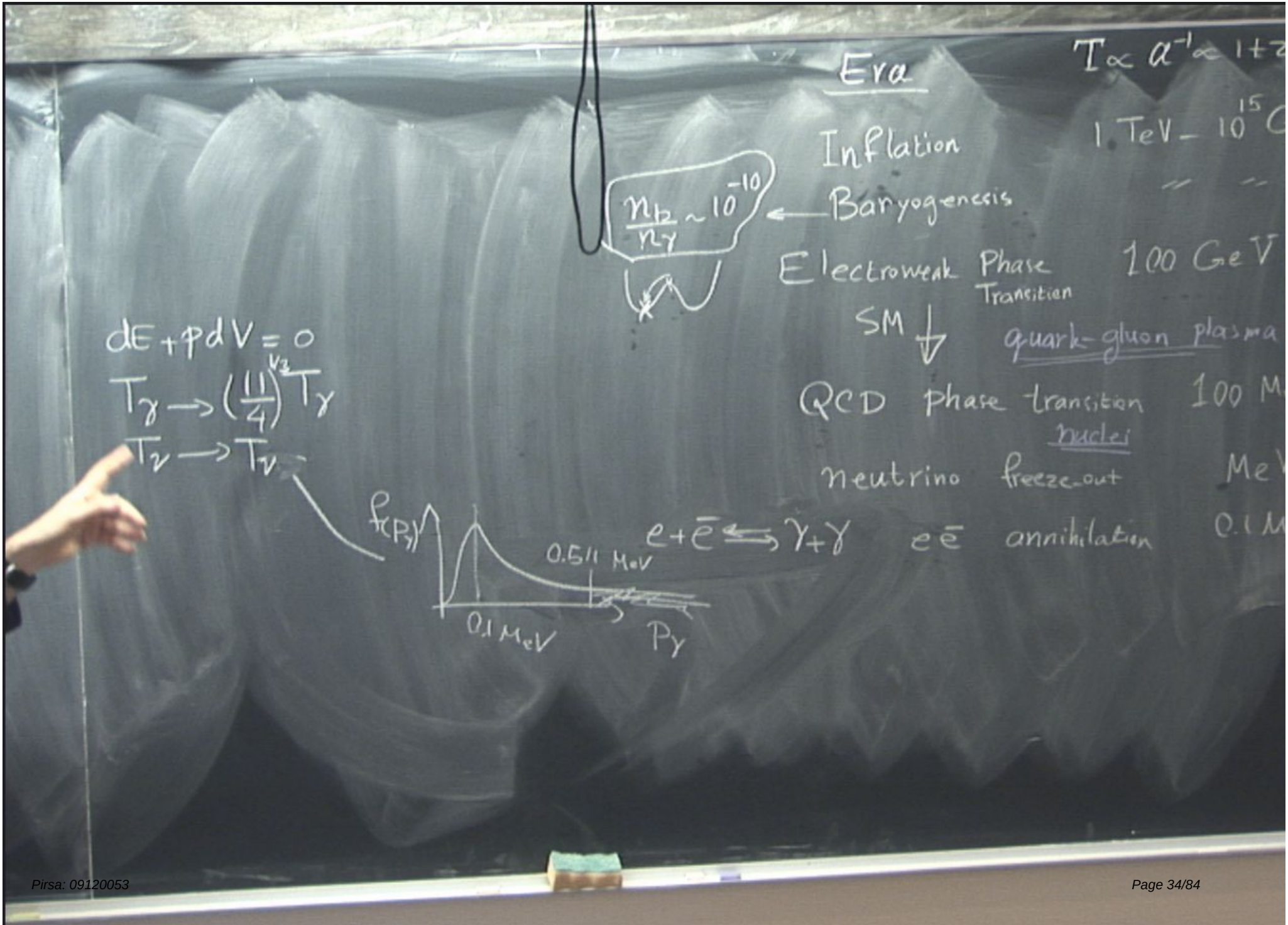
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Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
QCD phase transition
100 M
nuclei
neutrino freeze-out
Me
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 M
$f(p_\gamma)$
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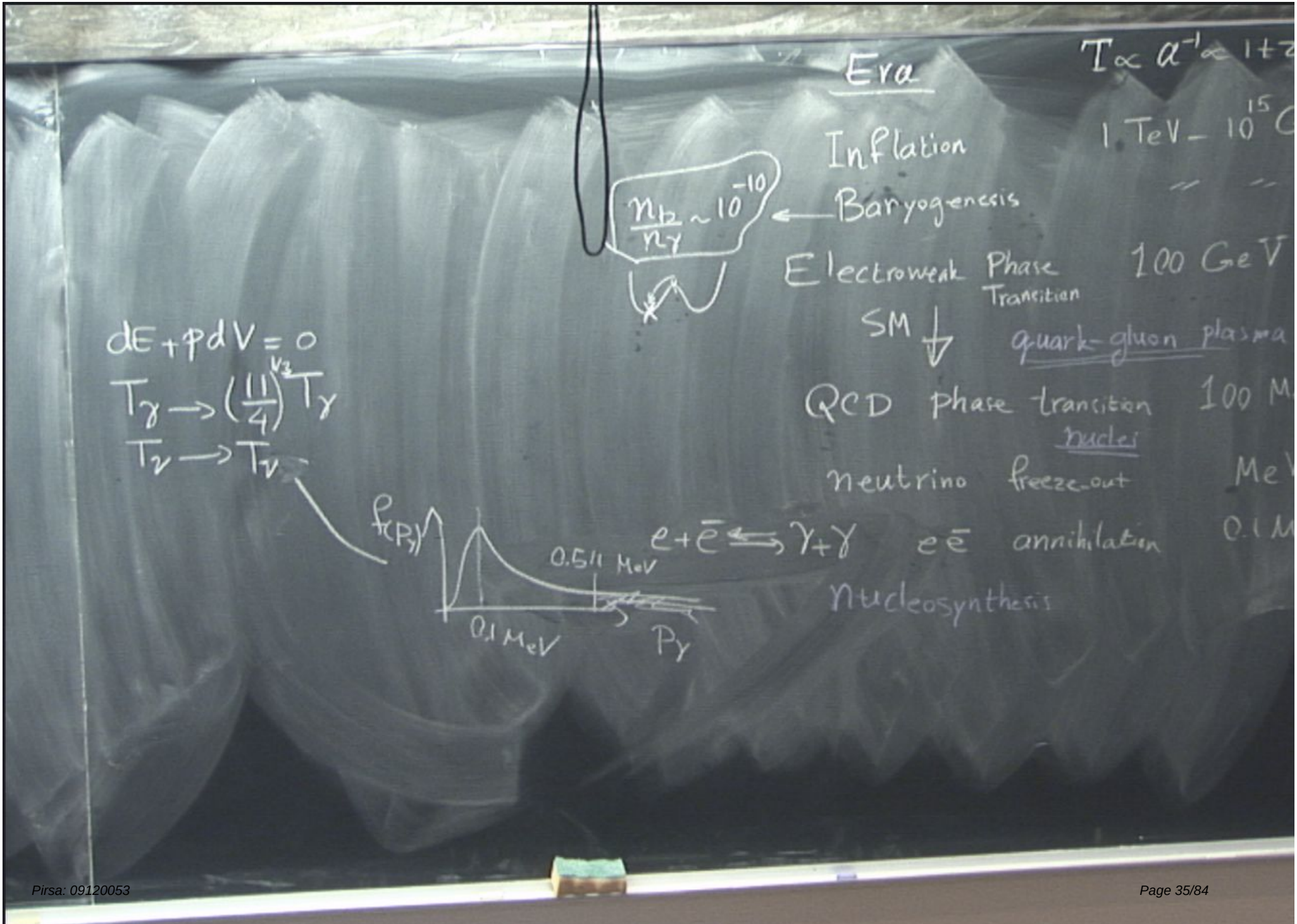
0.1 MeV
p_γ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QCD phase transition
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nuclei
neutrino freeze-out
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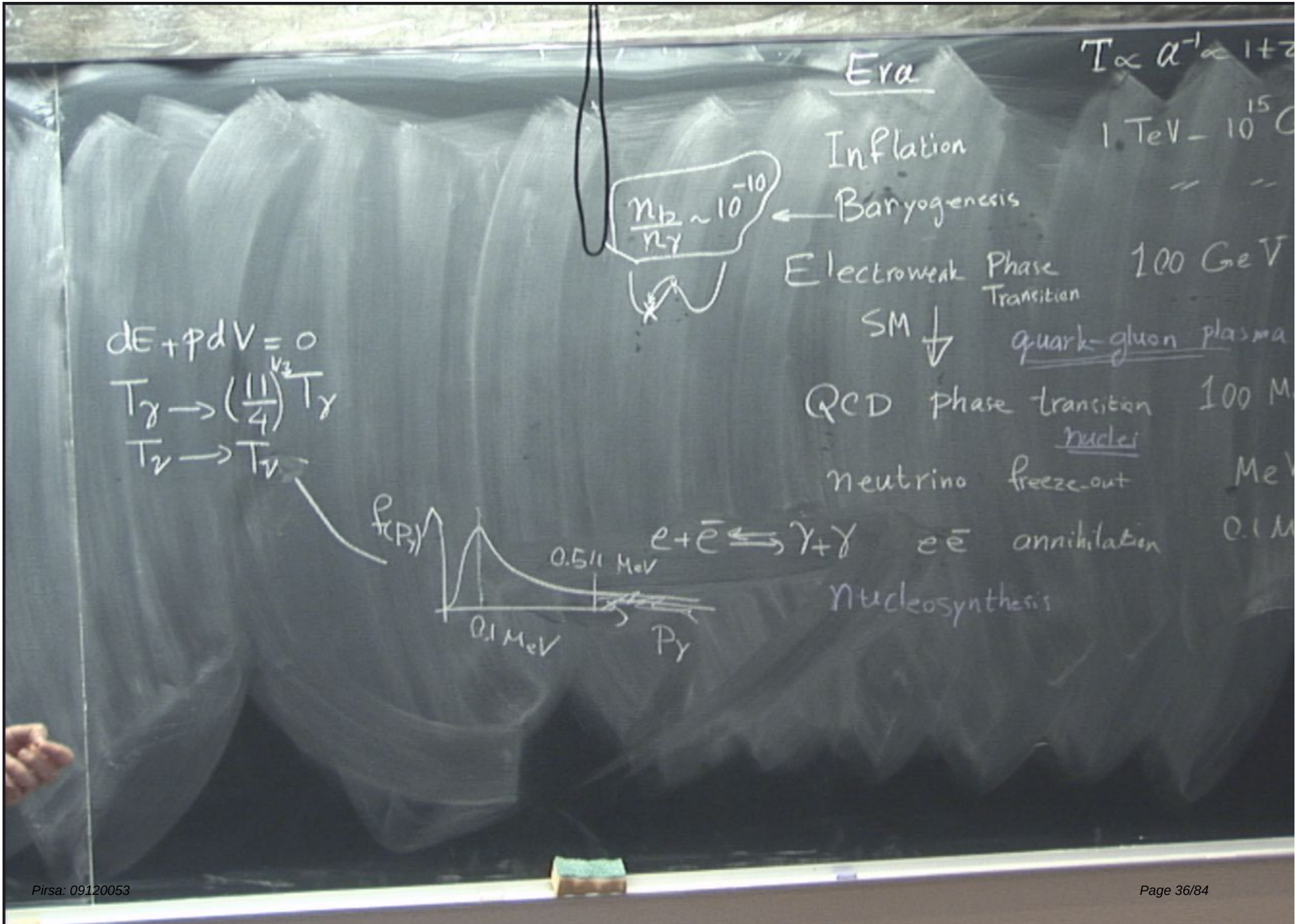
$e+\bar{e} \rightleftharpoons \gamma+\gamma$
$e\bar{e}$ annihilation
0.1 M
$f(p_\gamma)$
0.511 MeV
0.1 MeV
p_γ
nucleosynthesis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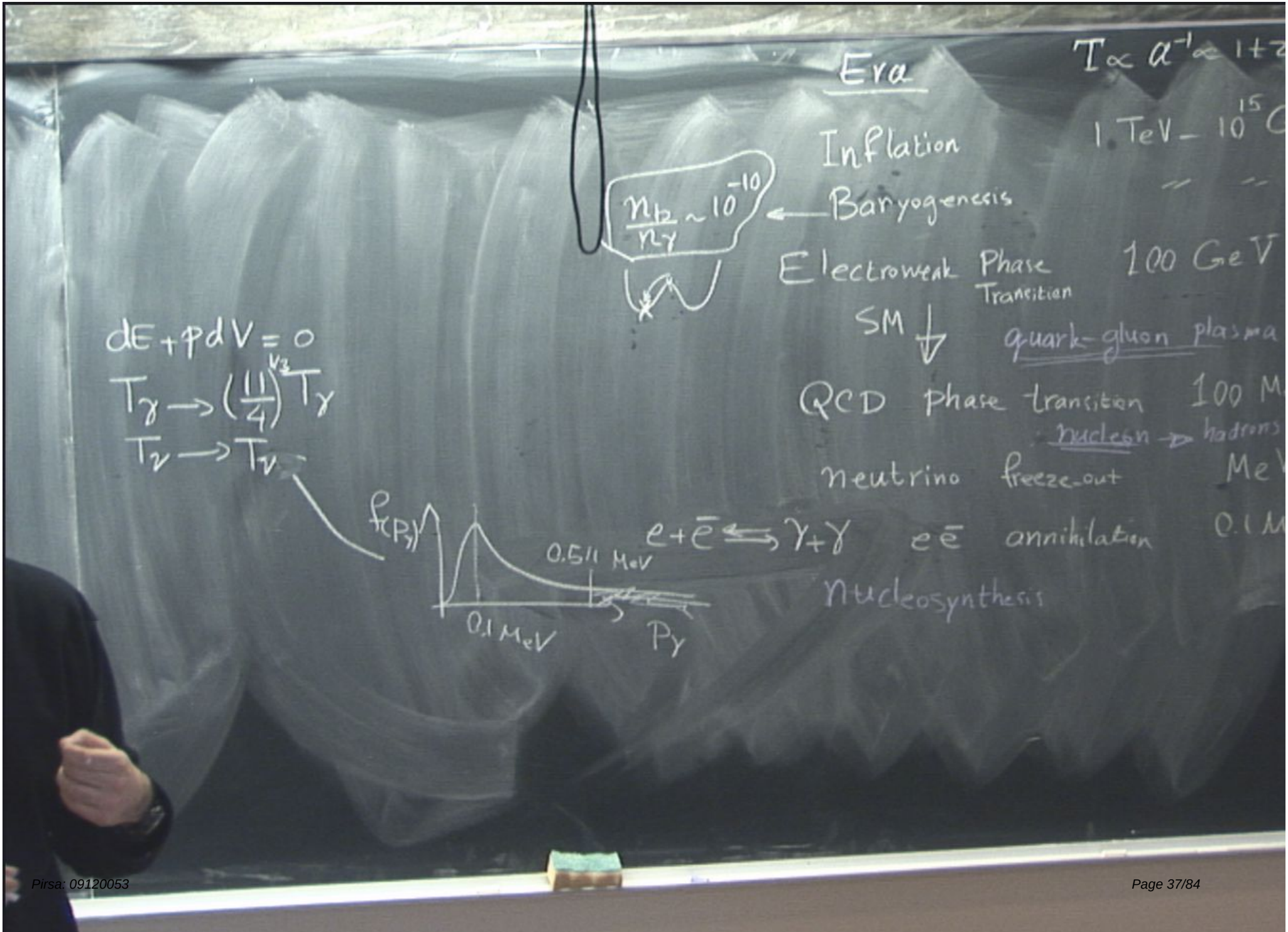
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
$dE + pdV = 0$
$T_\gamma \rightarrow \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \rightarrow T_\nu$
QCD phase transition
100 M
nuclei
neutrino freeze-out
Me
$f(p_\gamma)$
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 M
0.511 MeV
nucleosynthesis
0.1 MeV
p_γ


Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} G
$\frac{n_b}{n_\gamma} \sim 10^{-10}$
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
quark-gluon plasma
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
QCD phase transition
100 M
nucleon → hadrons
neutrino freeze-out
Me
$f(p_\gamma)$
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 M
0.511 MeV
nucleosynthesis
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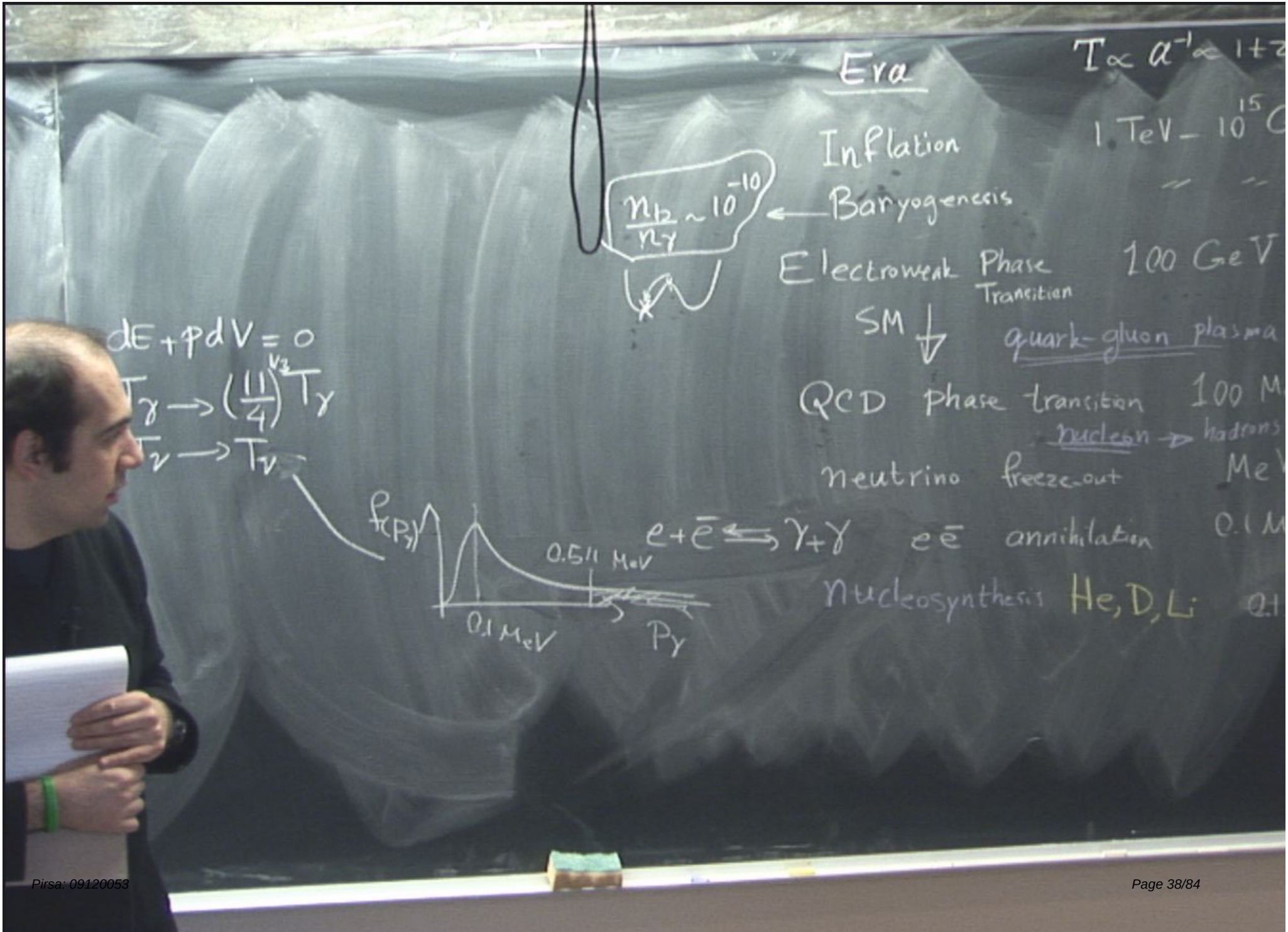
p_γ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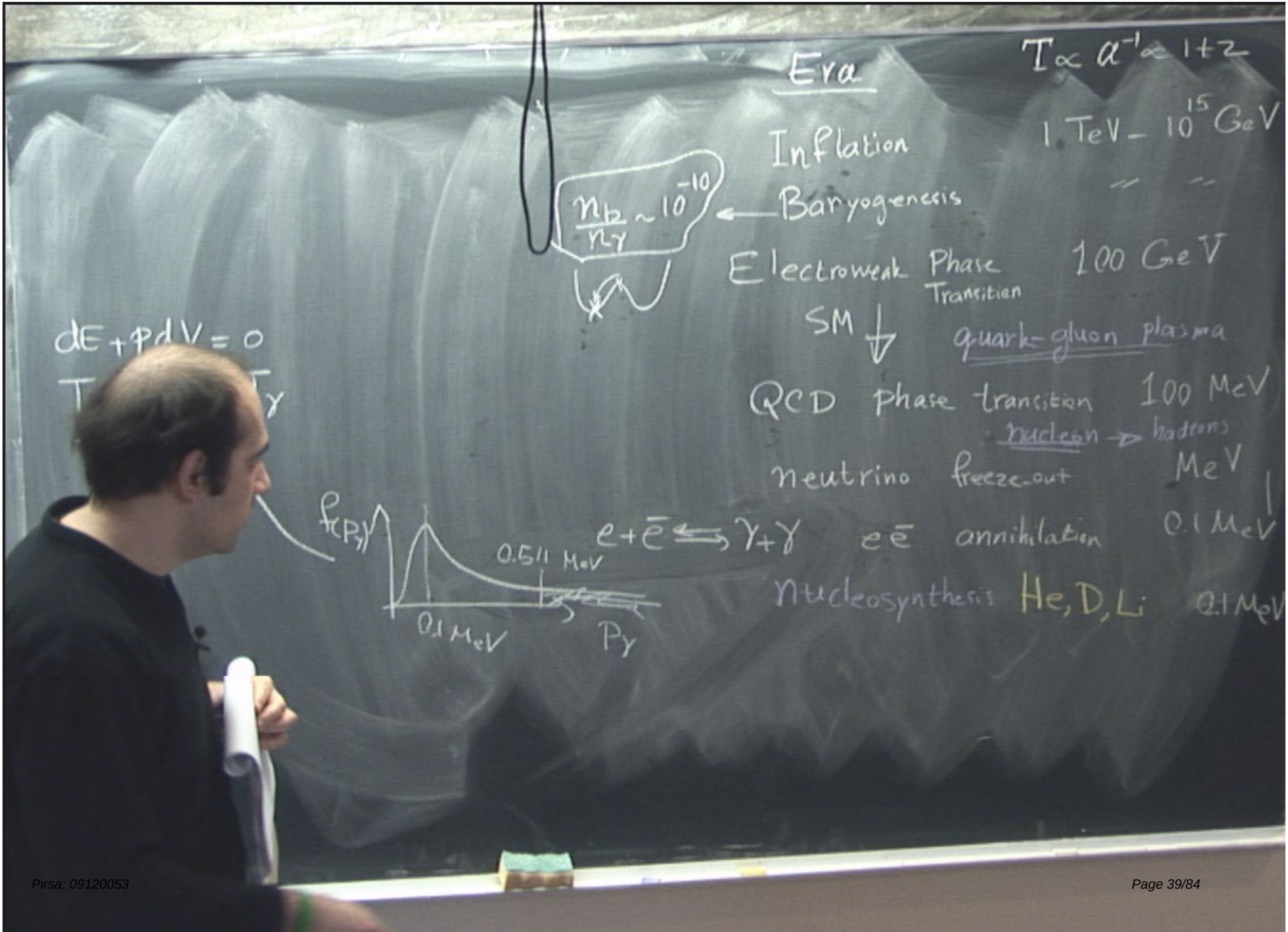
0.1 M
nucleosynthesis
He, D, Li
0.1
0.1 MeV
p_γ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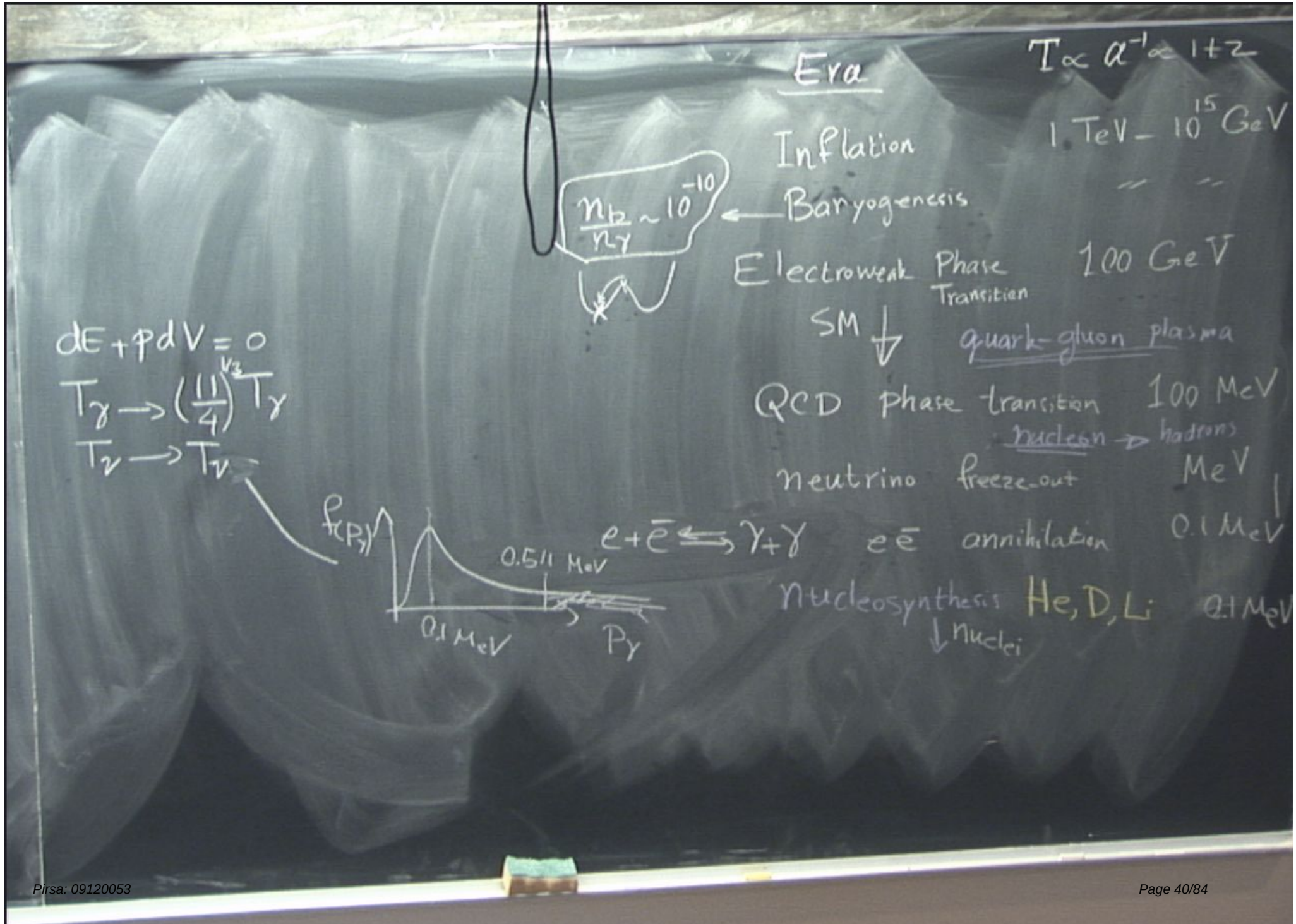
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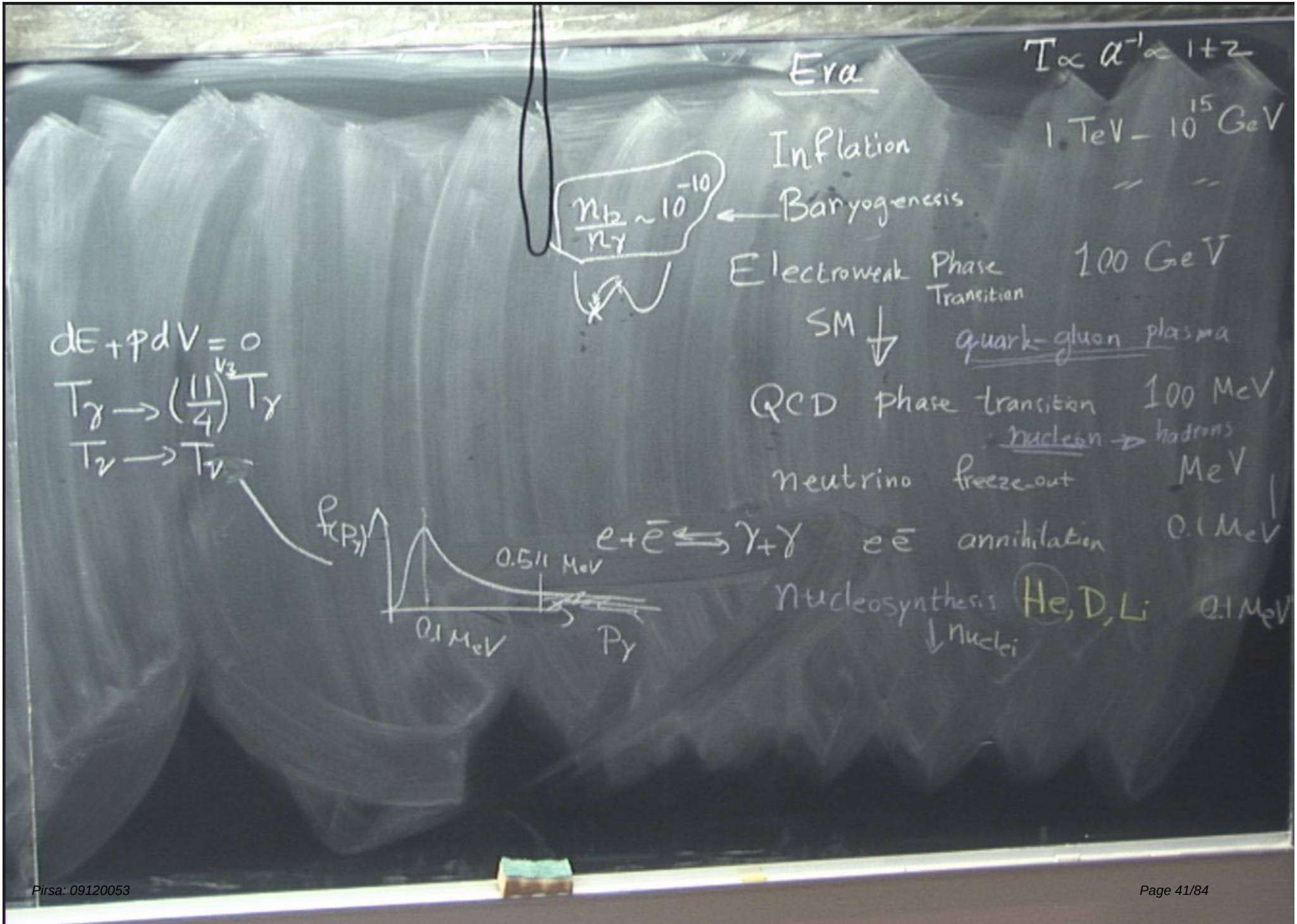
0.1 MeV
p_γ
nucleosynthesis
He, D, Li
0.1 MeV
↓ nuclei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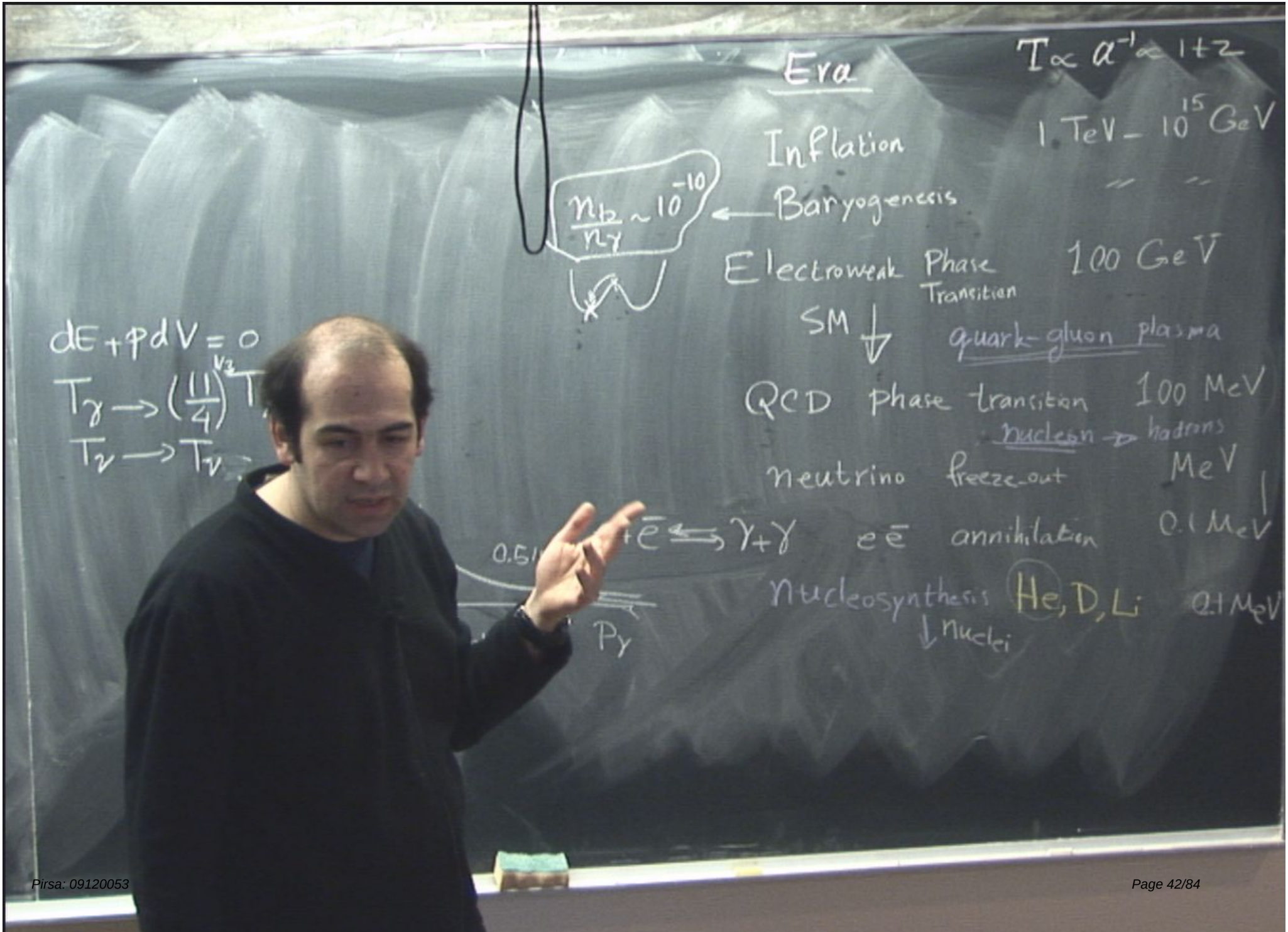
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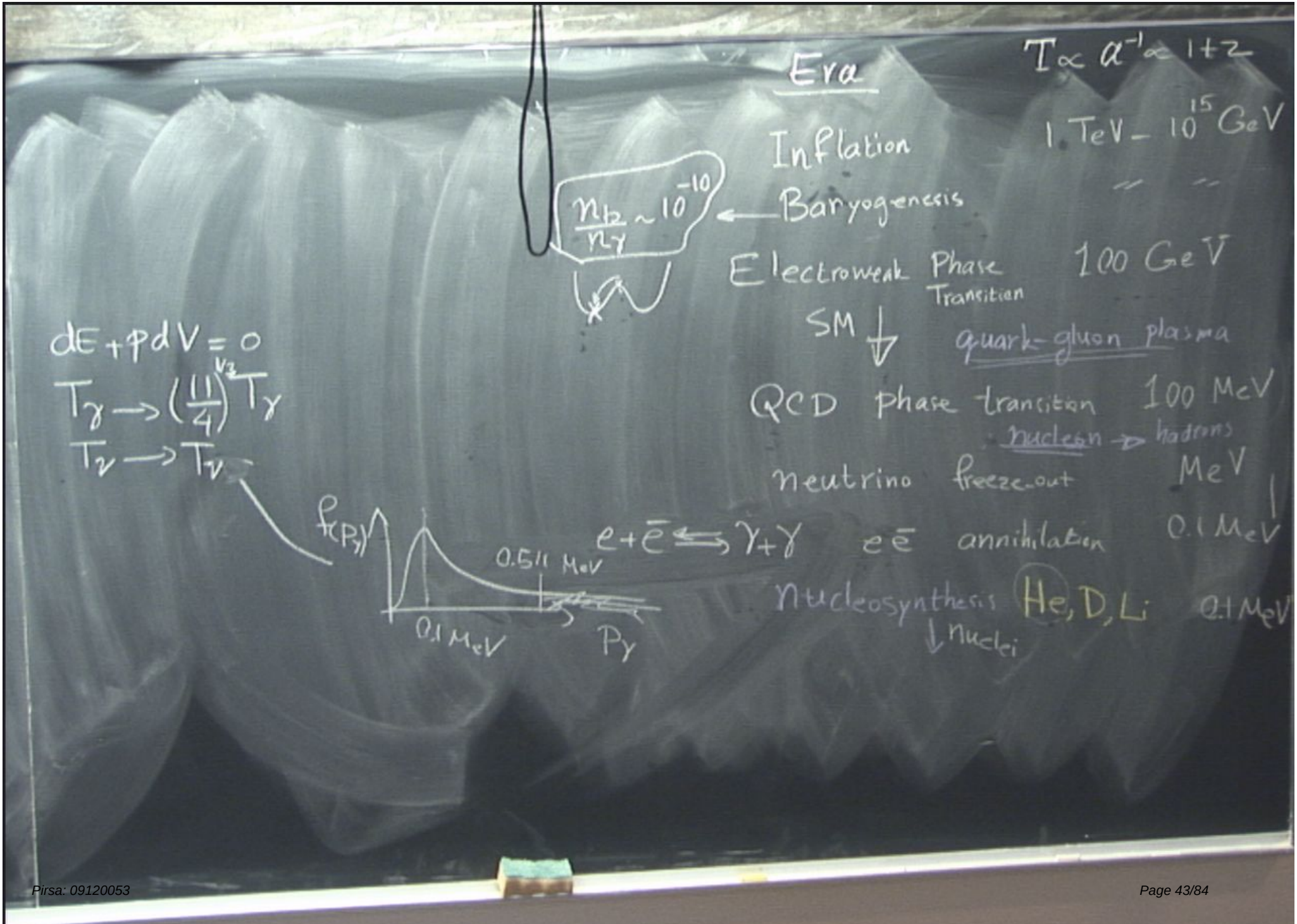
Nucleosynthesis
He, D, Li
0.1 MeV
↓ nuclei
p_γ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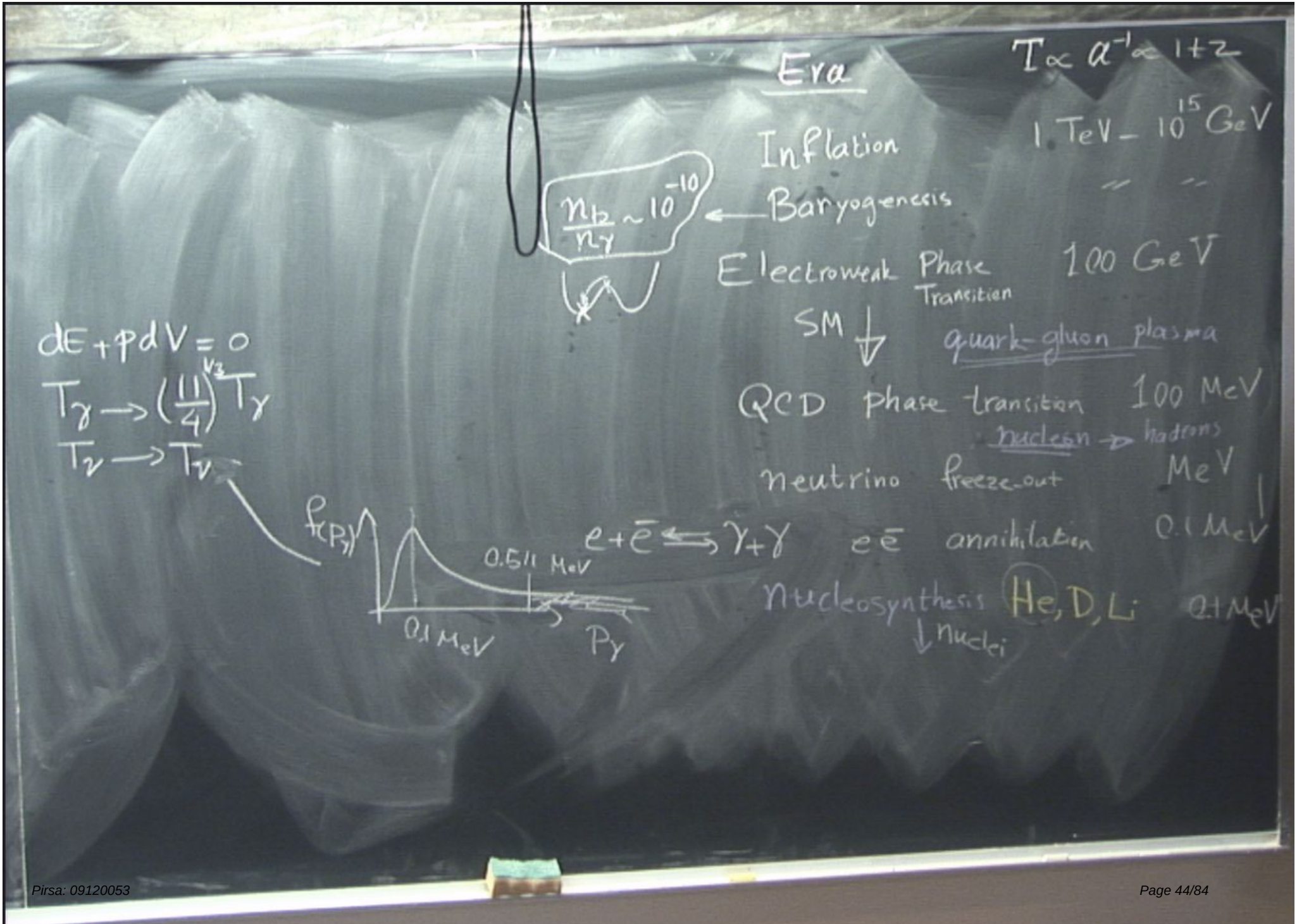
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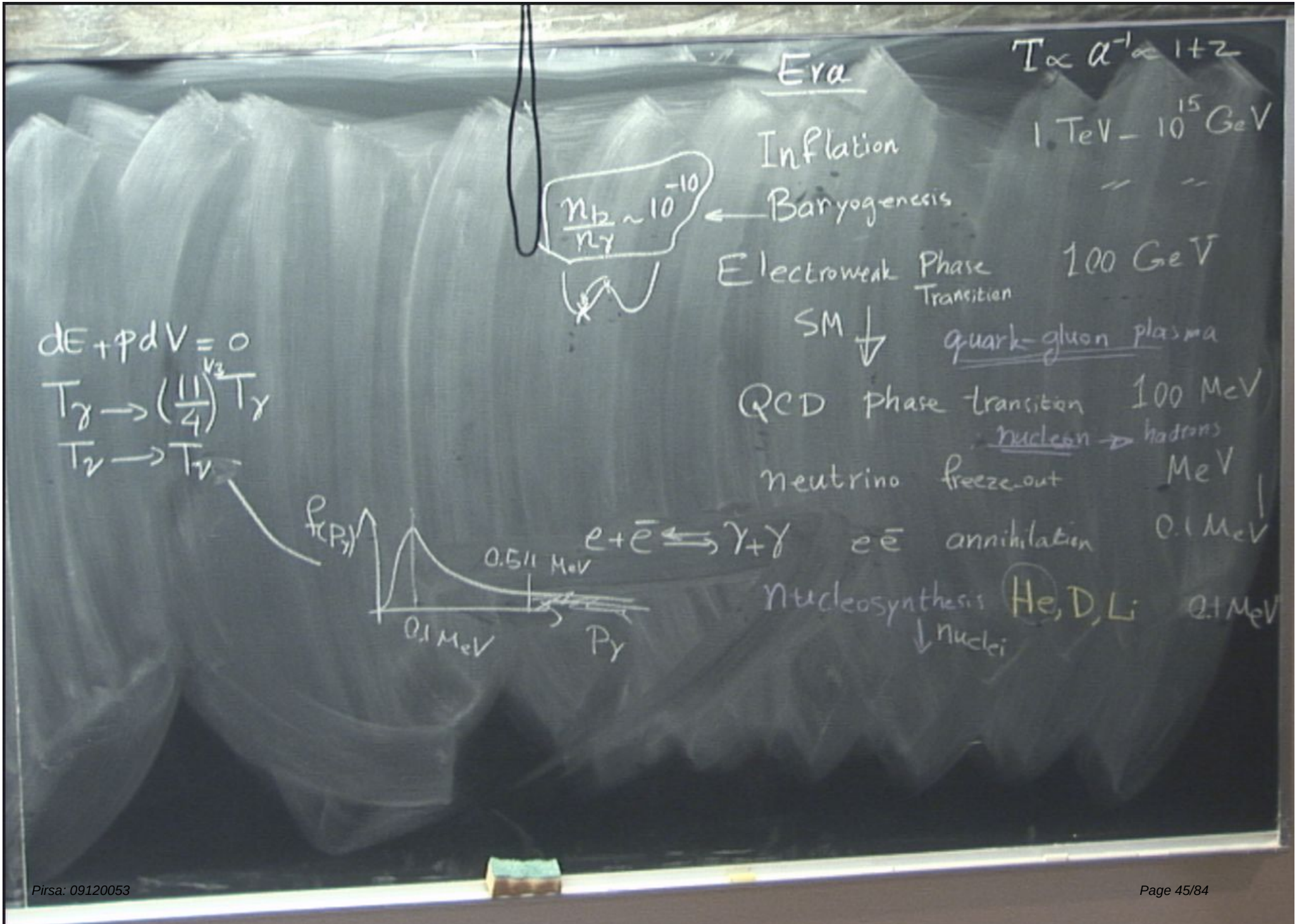
p_γ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$T \propto a^{-1} \propto 1+z$
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1 TeV – 10^{15} GeV
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nucleosynthesis
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0.1 MeV
↓ nuclei
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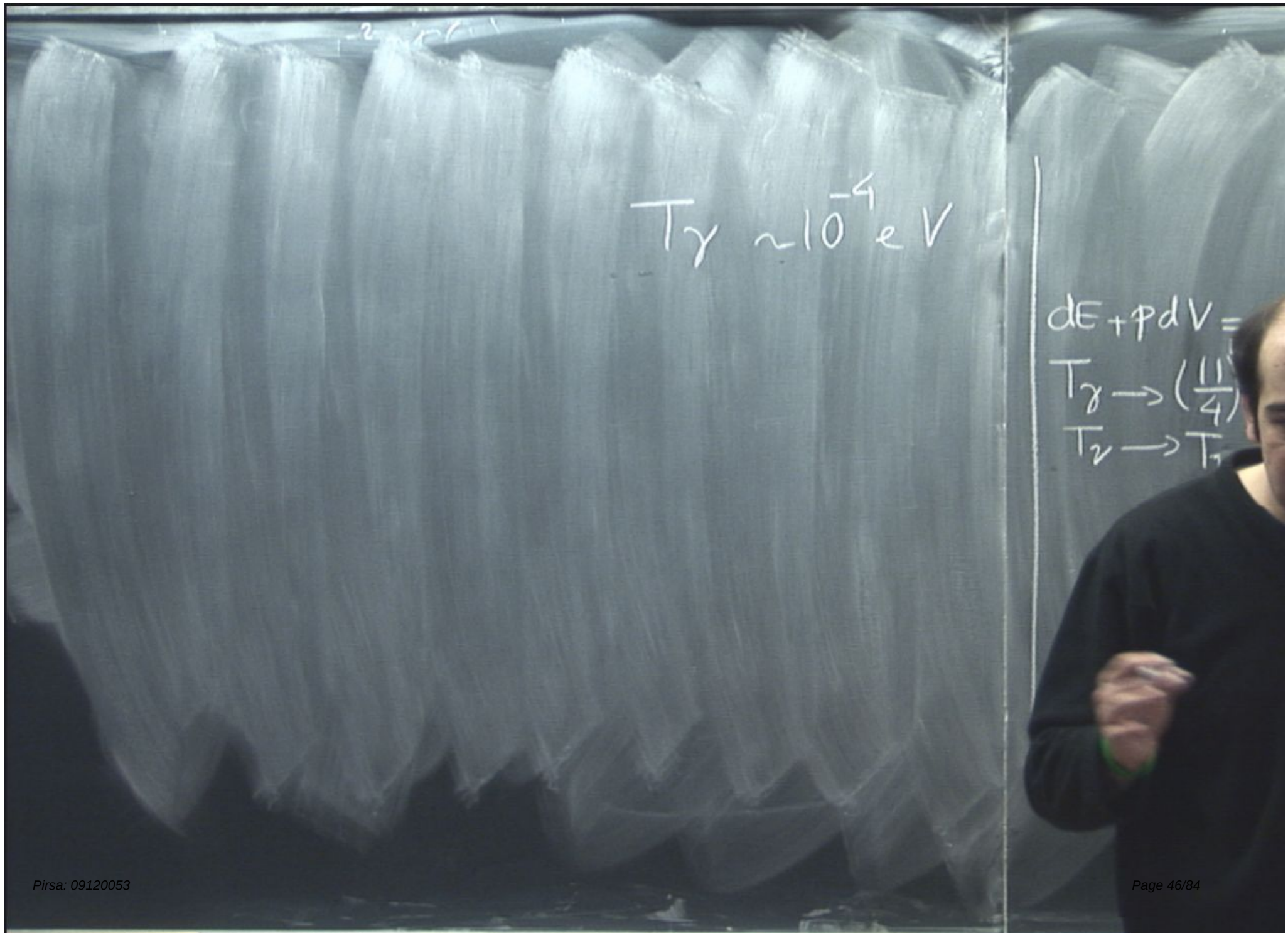
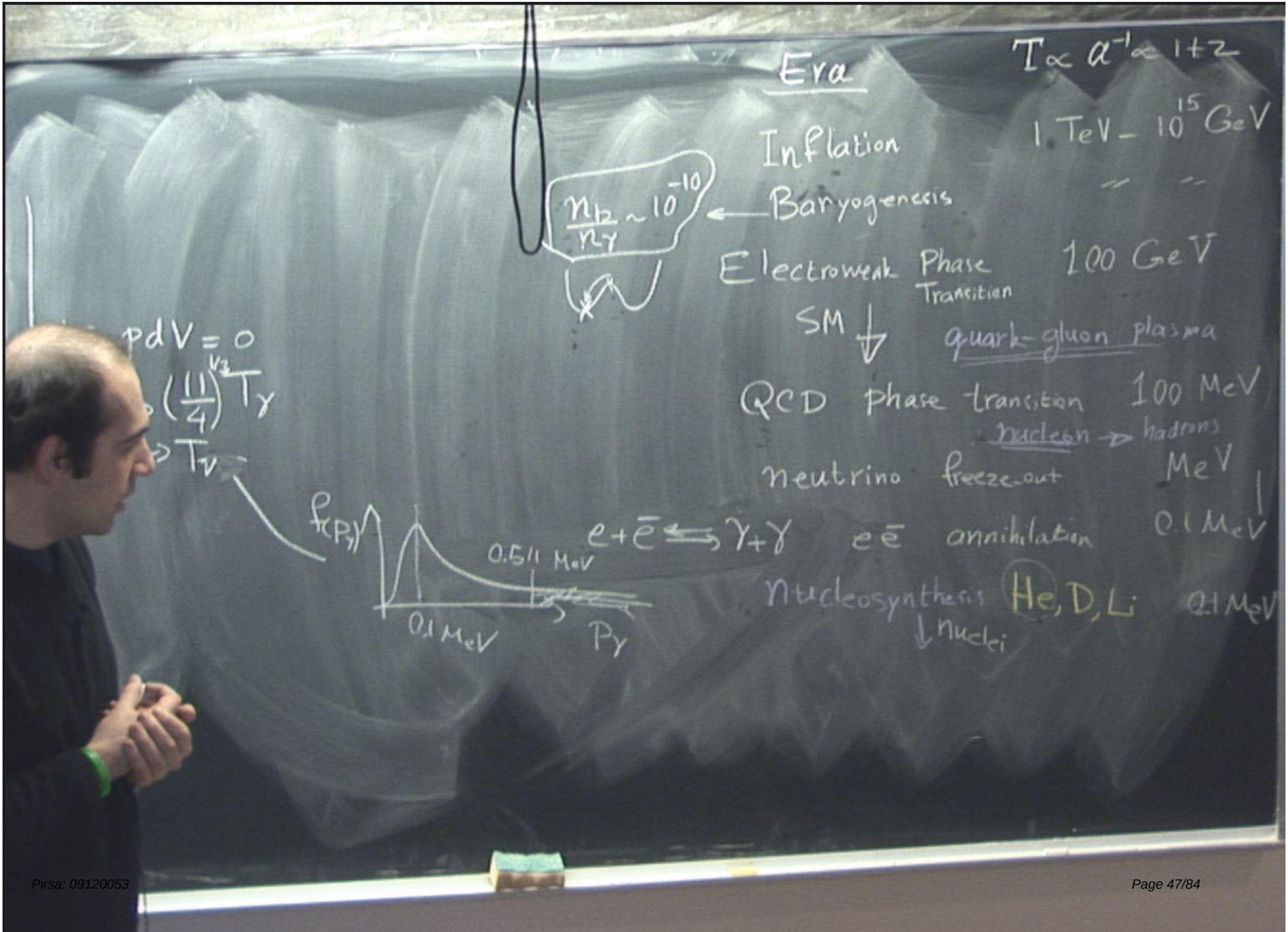
p_γ


$T_\gamma \sim 10^{-4}\,eV$
$dE + p\,dV =$
$T_\gamma \rightarrow \left(\frac{11}{4}\right)$
$T_\nu \rightarrow T_\gamma$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1 TeV – 10^{15} GeV
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Baryogenesis
Electroweak Phase Transition
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quark-gluon plasma
QCD phase transition
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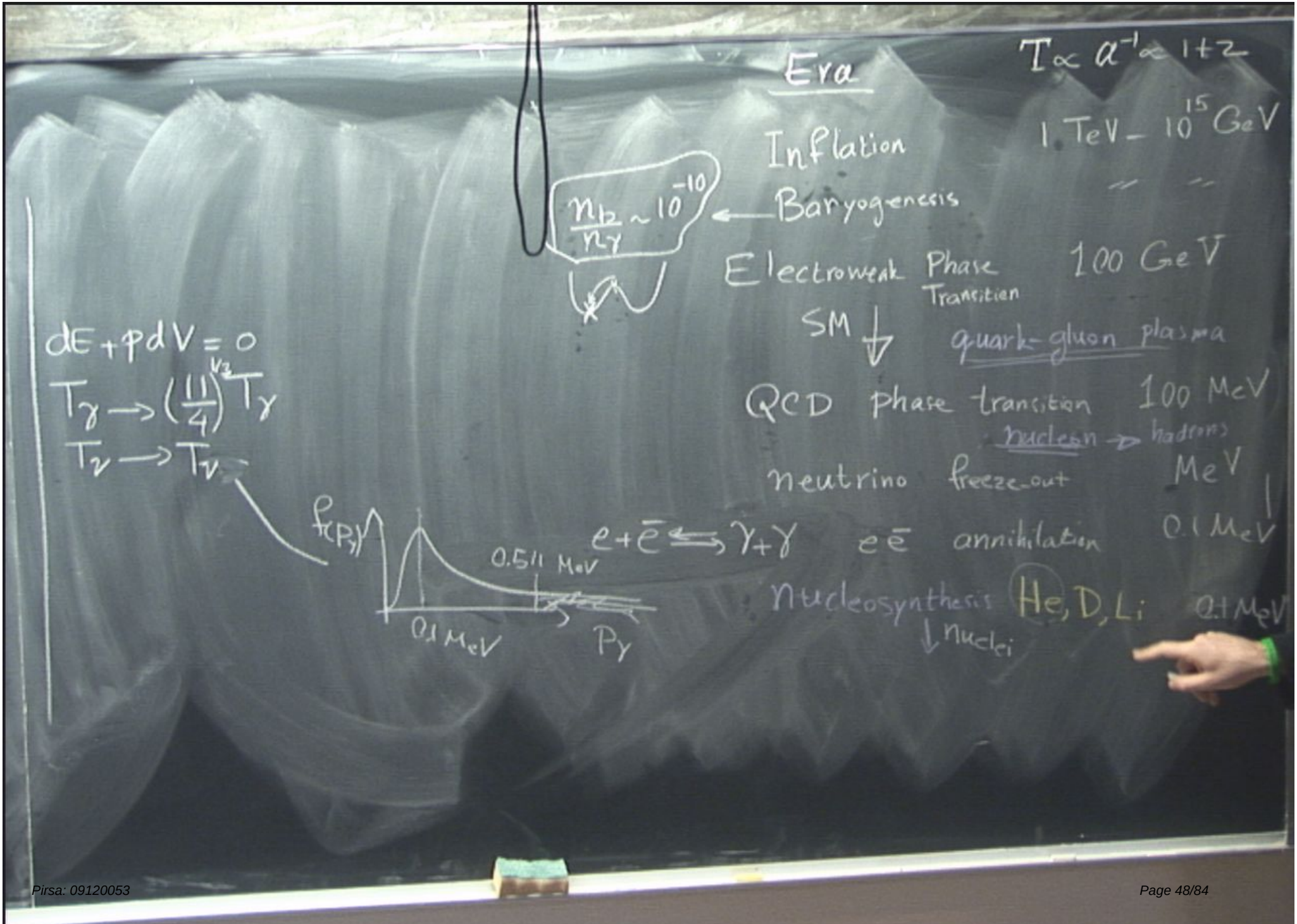
0.1 MeV
0.511 MeV
nucleosynthesis
He, D, Li
0.1 MeV
nuclei
$f(p_\gamma)$
0.1 MeV
p_γ
$pdV = 0$
$\left(\frac{11}{4}\right)^{1/3} T_\gamma$
T_ν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Inflation
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Electroweak Phase Transition
100 GeV
SM
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QCD phase transition
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nucleon → hadrons
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MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
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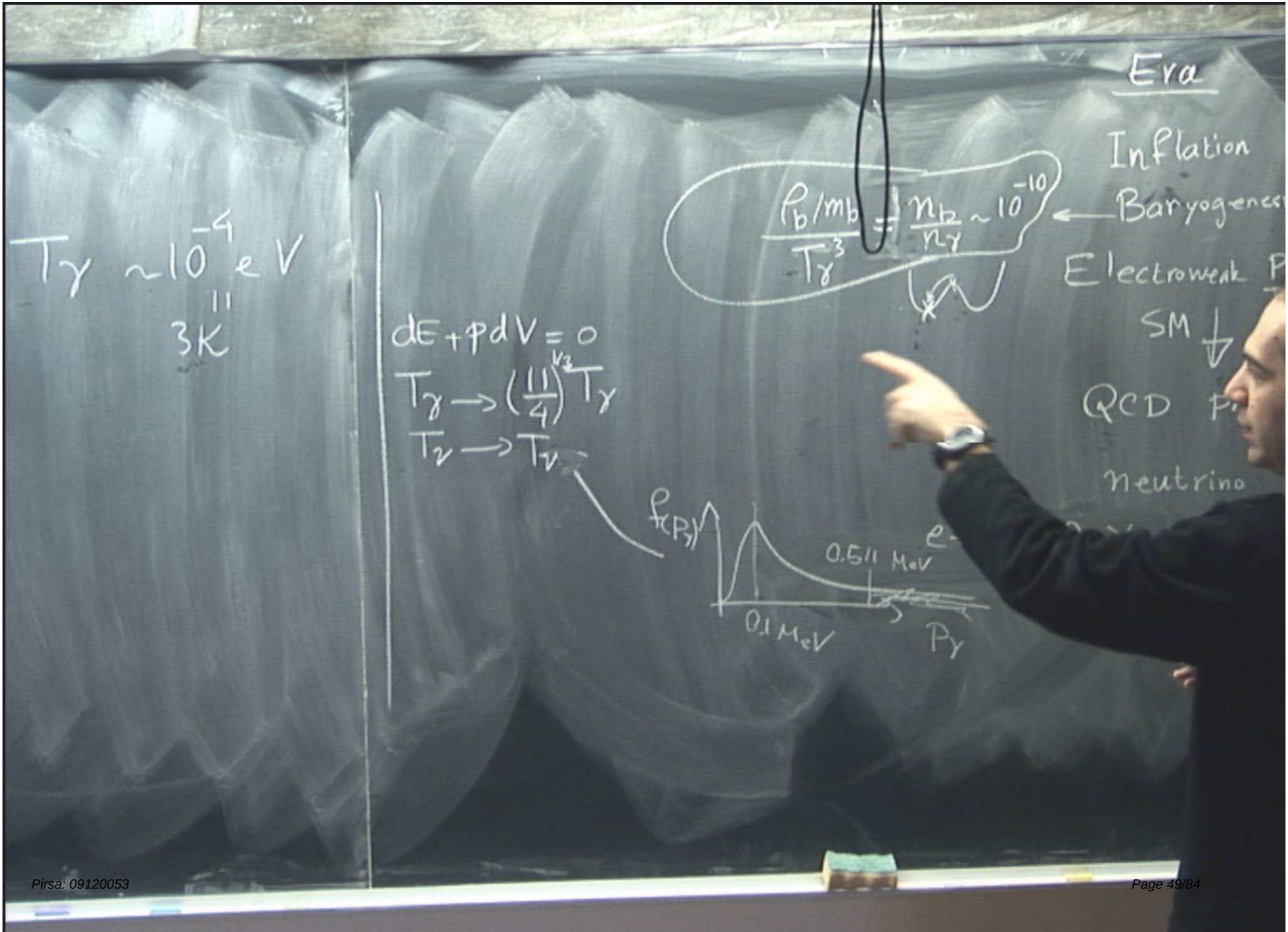
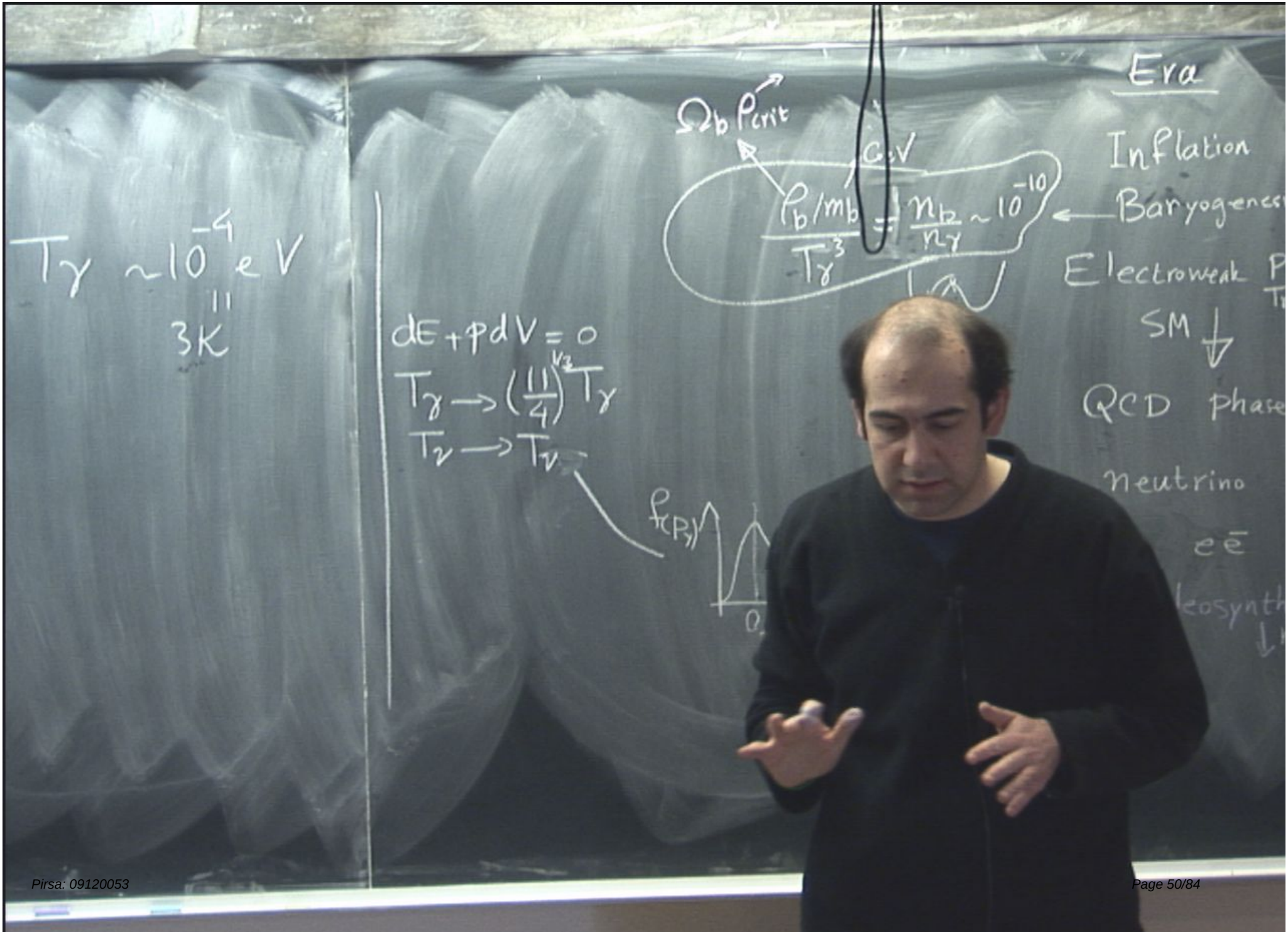
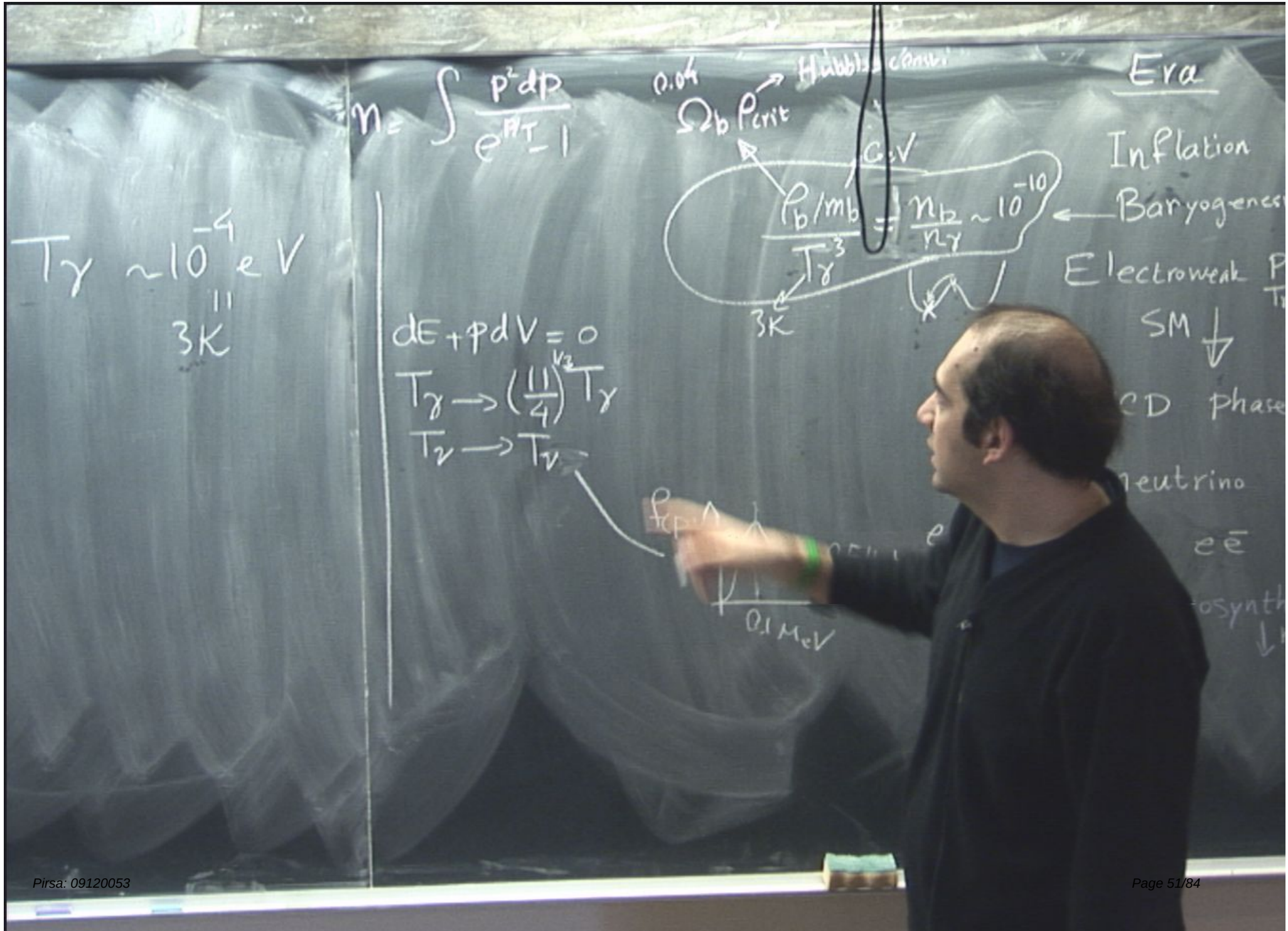
0.1 MeV
0.511 MeV
0.1 MeV
P_γ
nucleosynthesis
He, D, Li
0.1 MeV
↓ nuclei


Era
Inflation
Baryogenesis
Electroweak
SM
QCD
neutrino
$T_\gamma \sim 10^{-4}$ eV
$3K$
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$\frac{p_b/m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
$f(p_\gamma)$
0.511 MeV
0.1 MeV
p_γ


Era
Inflation
Baryogenesis
Electroweak
SM
QCD phase
neutrino
$e\bar{e}$
$T_\gamma \sim 10^{-4}$ eV
3K
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$\Omega_b \rho_{crit}$
GeV
$\frac{\rho_b/m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
$f(p_\gamma)$


Era
Inflation
Baryogenes
Electroweak
SM
CD phase
neutrino
$T_\gamma \sim 10^{-4}$ eV
3K
$dE + p\,dV = 0$
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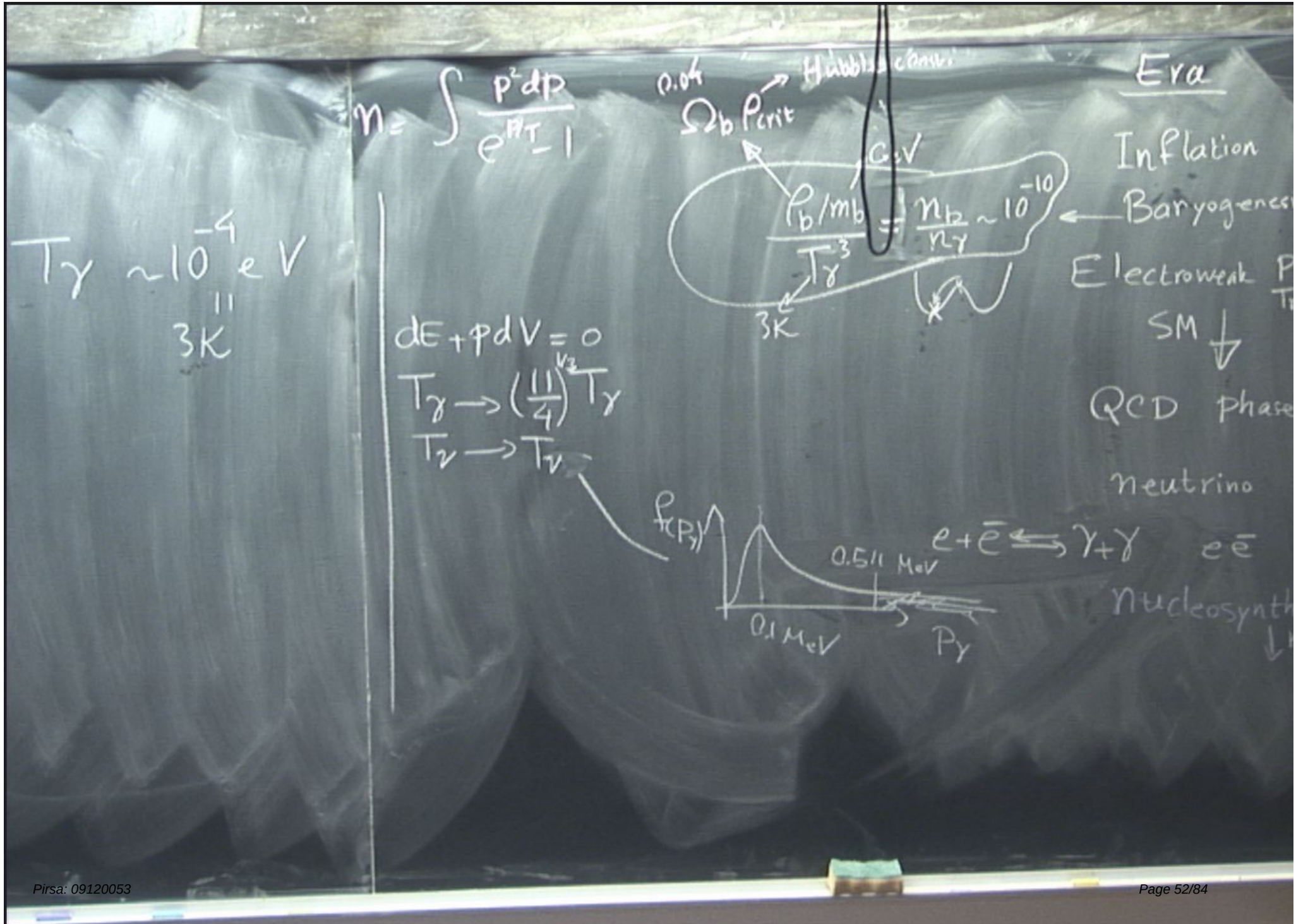
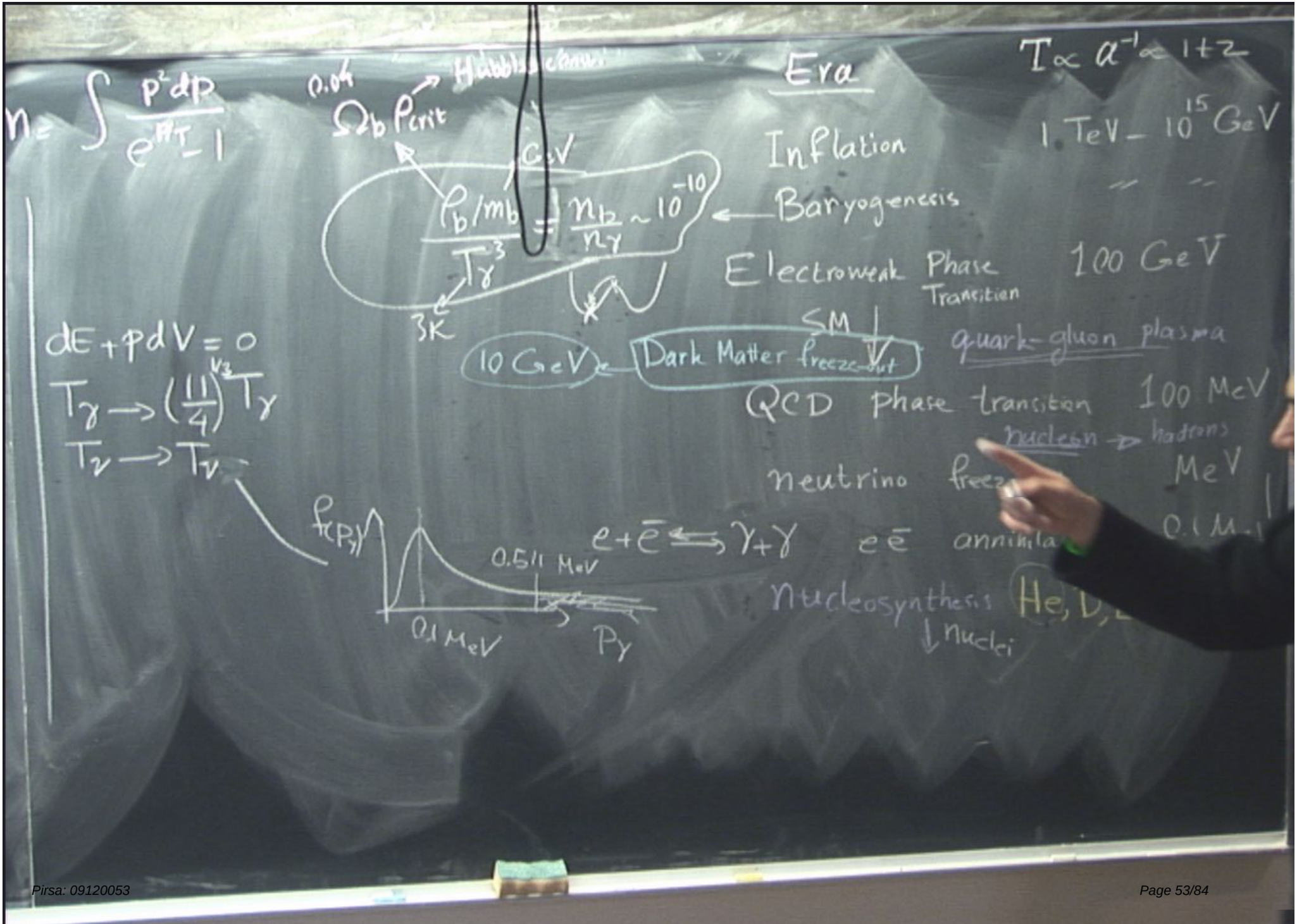
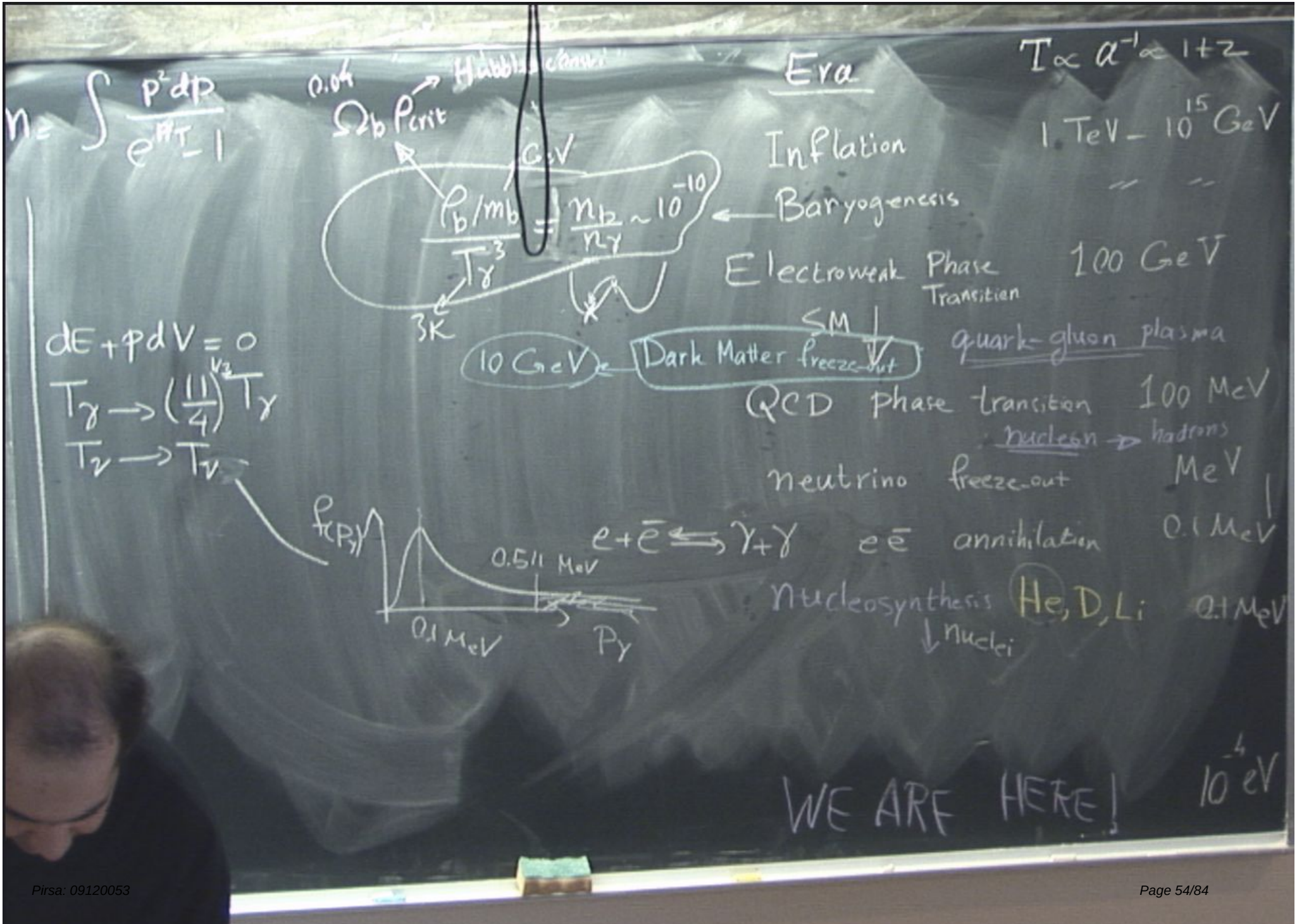
$\frac{\rho_b/m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
0.1 MeV



$T_\gamma \sim 10^{-4}$ eV
3K
$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const.
GeV
$\frac{\rho_b/m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
0.1 MeV
p_γ
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$
Era
Inflation
Baryogenes
Electroweak
SM
QCD phase
neutrino
nucleosynth



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freez
MeV
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
0.1 MeV
p_γ
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihila
Nucleosynthesis He, D,
nuclei


Era
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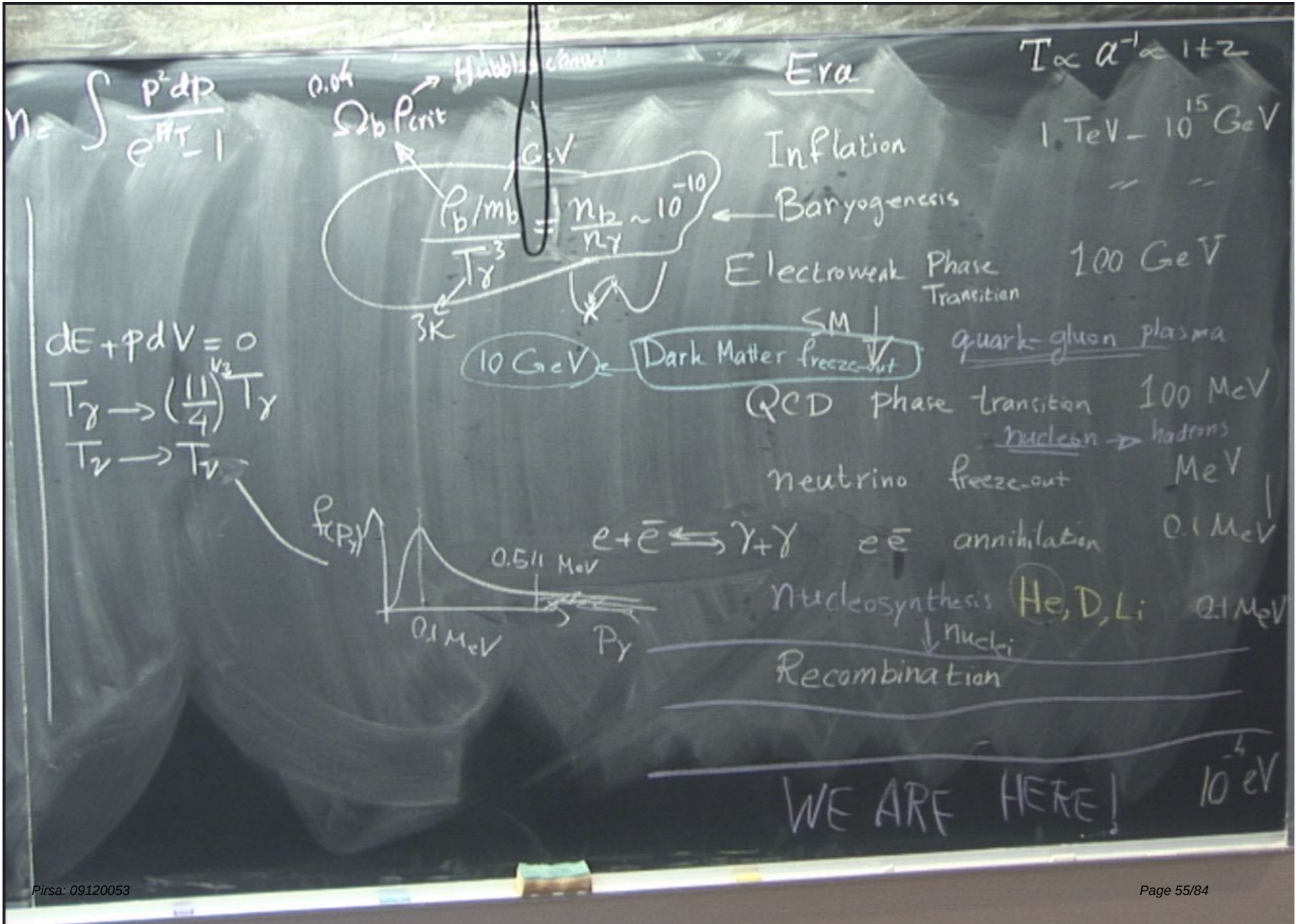
nucleon → hadrons
neutrino freeze-out
MeV
0.1 MeV
nucleosynthesis
He, D, Li
0.1 MeV
nuclei
0.511 MeV
0.1 MeV
WE ARE HERE!
10^{-4} eV


Era
$T \propto a^{-1} \propto 1+z$
$n_\epsilon = \int \frac{p^2 dp}{e^{\frac{p}{kT}} - 1}$
$\Omega_b \rho_{crit}$
0.04
Hubble constant
GeV
$\rho_b/m_b = \frac{n_b}{n_\gamma} \sim 10^{-10}$
T_γ^3
3K
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
$dE + pdV = 0$
$T_\gamma \rightarrow \left(\frac{11}{4}\right)^{1/3} T_\gamma$
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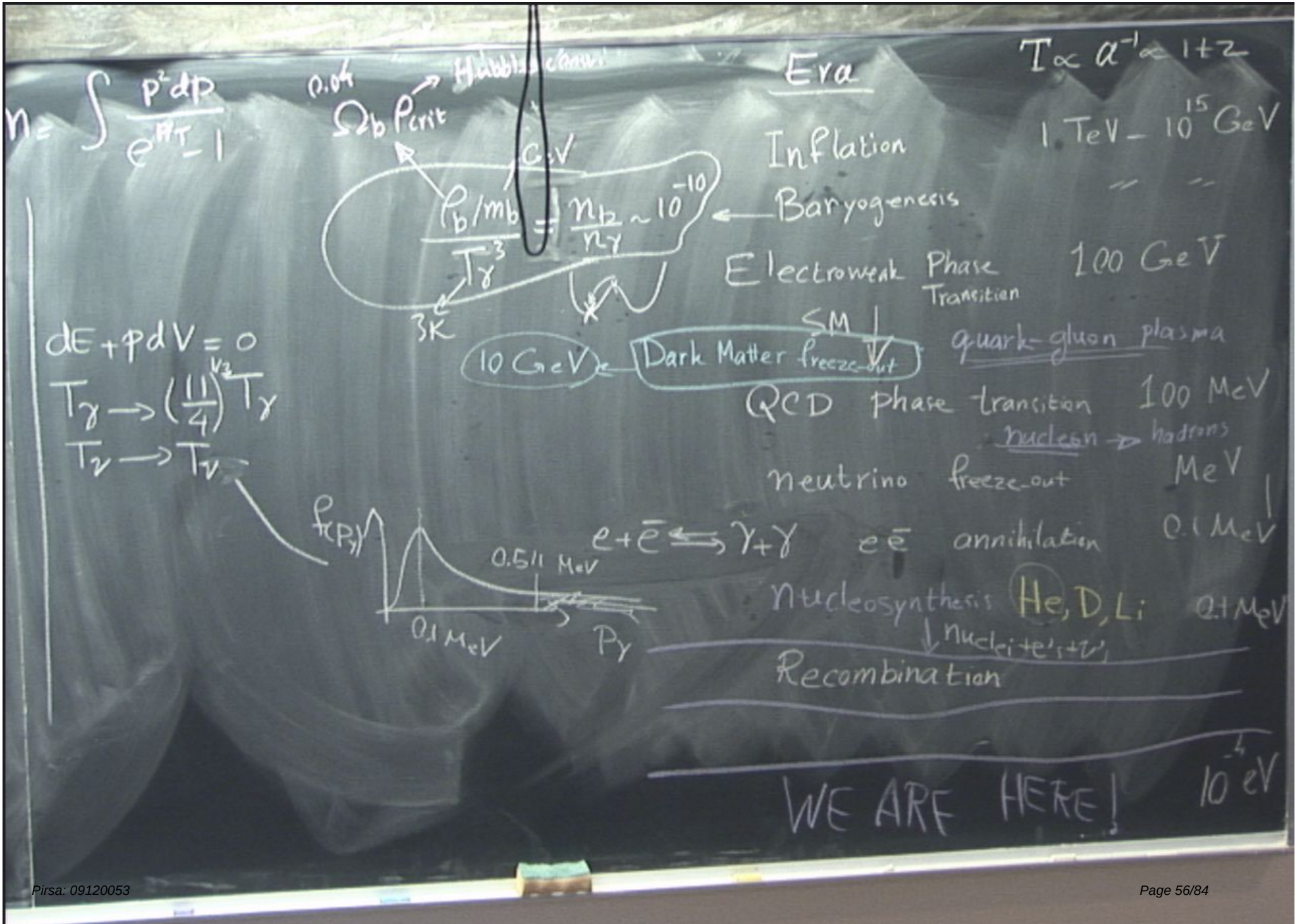
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$f(p_\gamma)$
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
0.511 MeV
0.1 MeV
p_γ
nucleosynthesis
He, D, Li
0.1 MeV
nuclei
Recombination
WE ARE HERE!
10^{-4} eV



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
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$dE + p\,dV = 0$
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0.1 MeV
p_γ
Era
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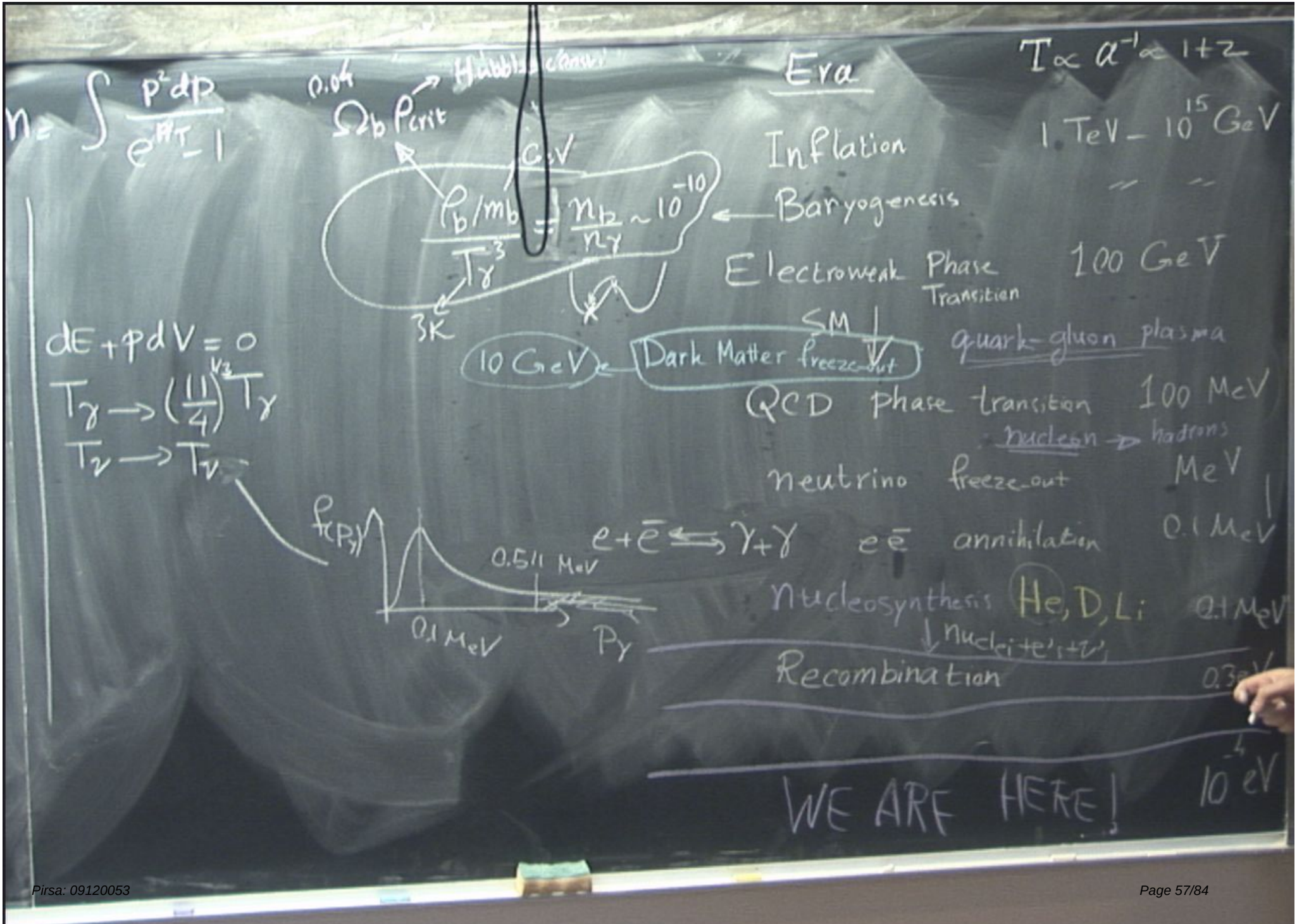
100 GeV
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
Recombination
WE ARE HERE!
10^{-4} eV



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
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$\Omega_b \rho_{crit}$
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p_γ
Era
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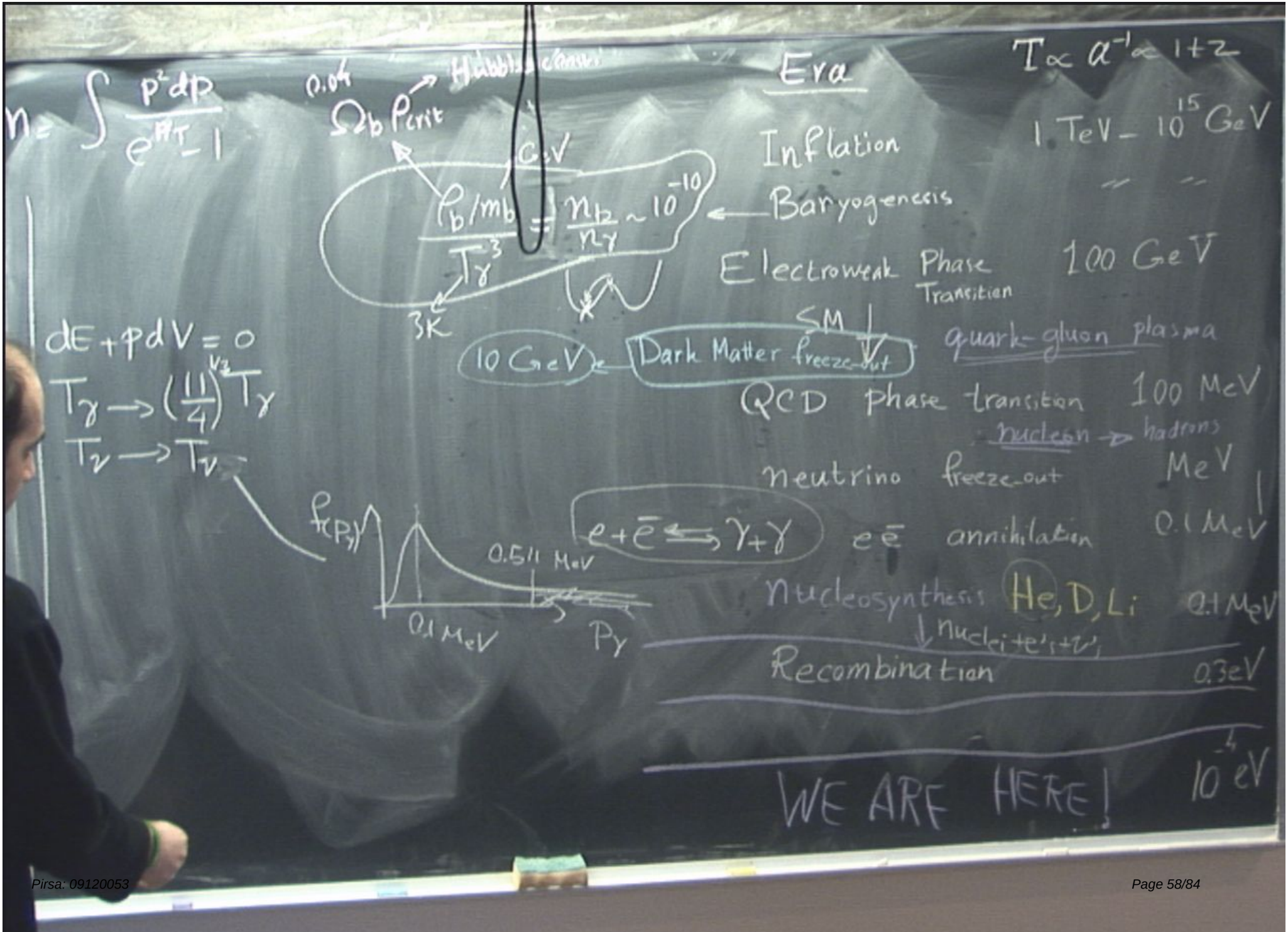
100 GeV
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
Recombination
0.3 eV
WE ARE HERE!
10^{-4} eV


Era
Inflation
Baryogenesis
Electroweak Phase Transition
SM
Dark Matter freeze-out
10 GeV
quark-gluon plasma
QCD phase transition
nucleon → hadrons
neutrino freeze-out
e+ē ⇌ γ+γ
ē annihilation
0.511 MeV
0.1 MeV
nucleosynthesis
He, D, Li
Recombination
0.3eV
WE ARE HERE!
3K
1 TeV – 10^15 GeV
100 GeV
100 MeV
MeV
0.1 MeV
0.1 MeV
10^-4 eV
T ∝ a^-1 ∝ 1+z
dE + pdV = 0
T_γ → (11/4)^1/3 T_γ
T_ν → T_ν
0.04
Ω_b ρ_crit
GeV
ρ_b/m_b / T_γ^3 = n_b/n_γ ~ 10^-10

$n = \int \frac{p^2 dp}{e^{p/T} - 1}$

$\Omega_b \rho_{crit}$ 0.04 Hubble constant

Era

$T \propto a^{-1} \propto 1+z$

Inflation 1 TeV – 10^{15} GeV

Baryogenesis

$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$

Electroweak Phase Transition 100 GeV

3K

SM

Dark Matter freeze-out 10 GeV

quark-gluon plasma

$dE + pdV = 0$

$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$

$T_\nu \to T_\nu$

QCD phase transition 100 MeV

nucleon → hadrons

neutrino freeze-out MeV

$f(p_\gamma)$

$e + \bar{e} \rightleftharpoons \gamma + \gamma$ $e\bar{e}$ annihilation 0.1 MeV

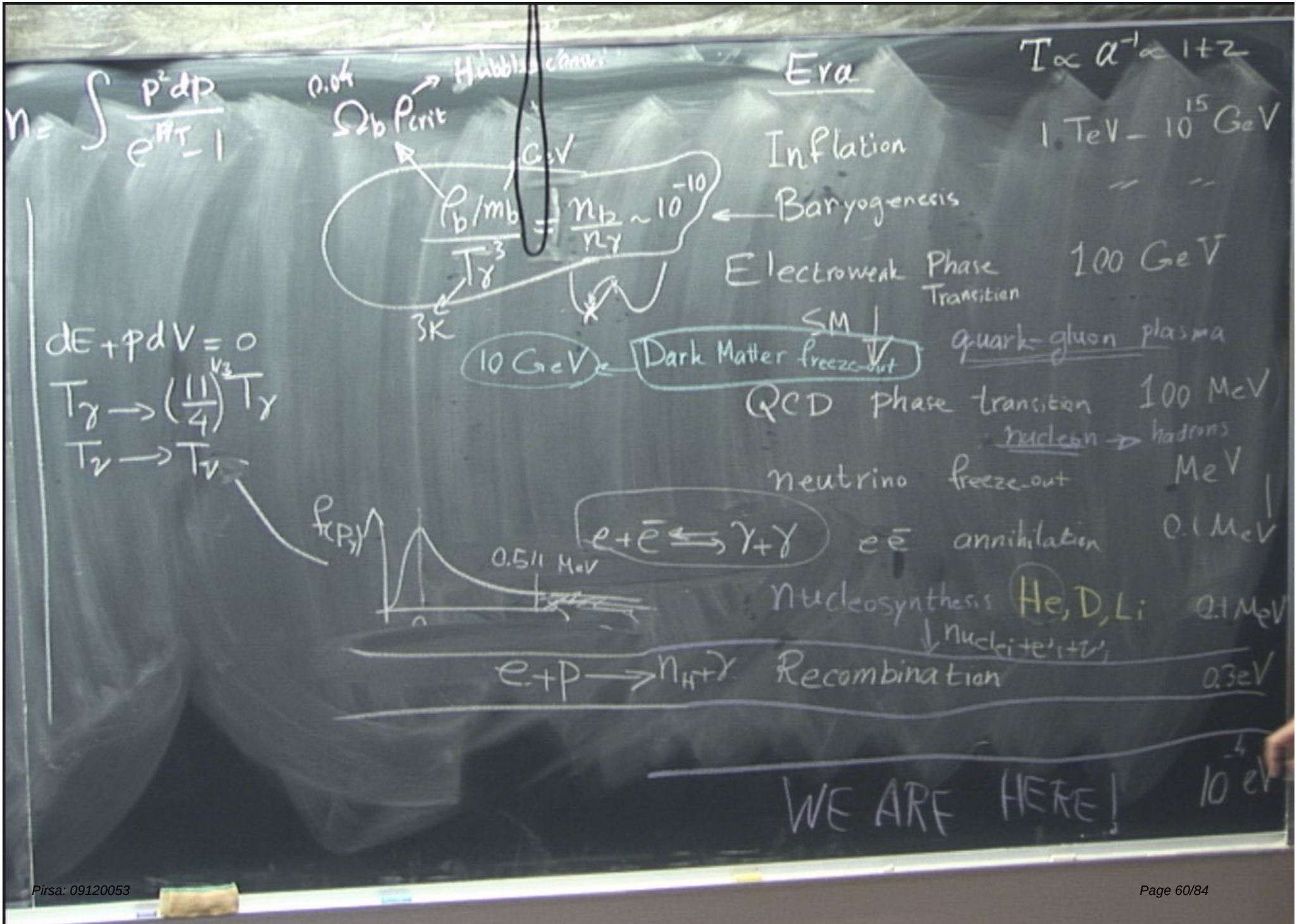
0.511 MeV

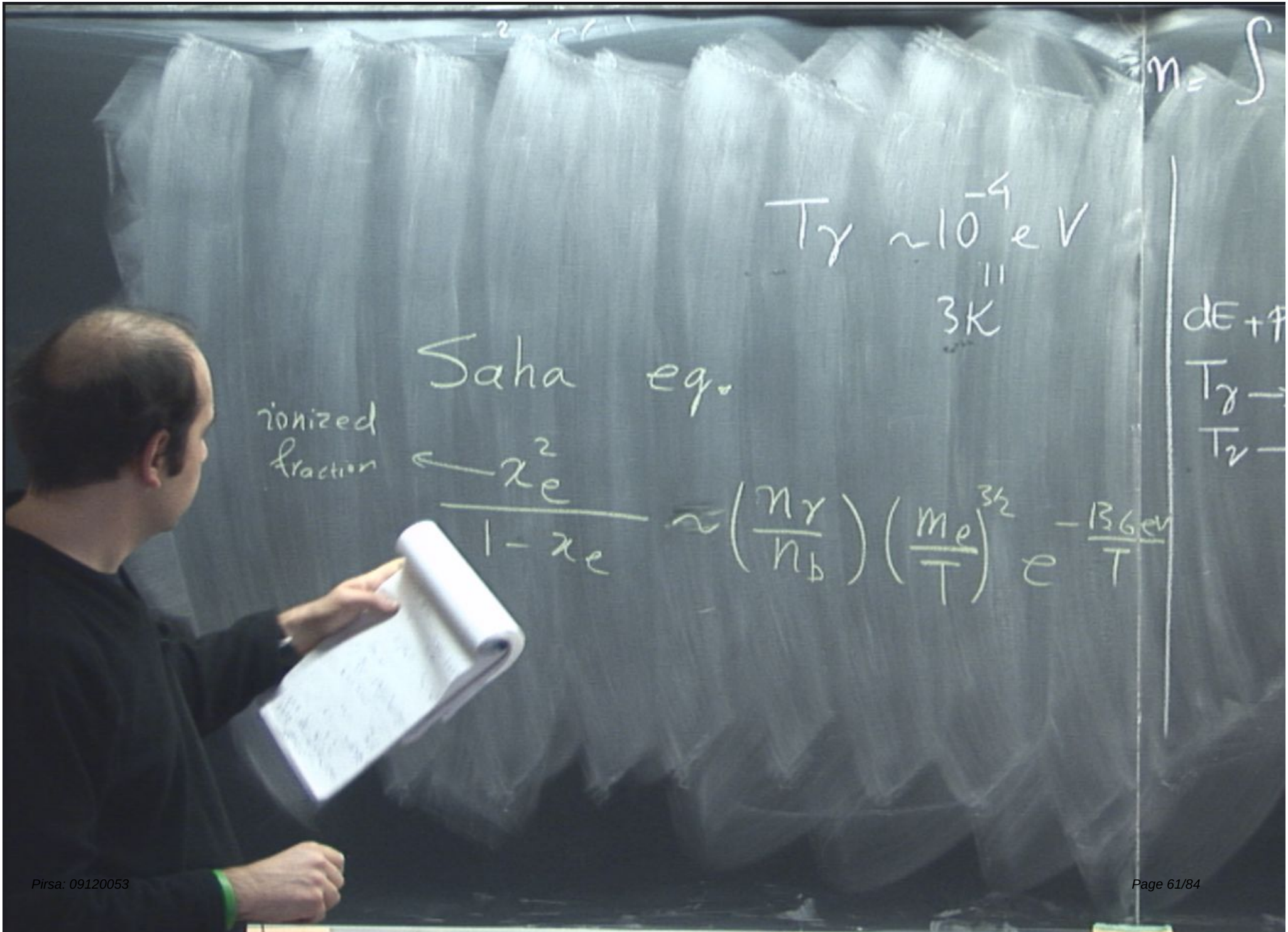
nucleosynthesis He, D, Li 0.1 MeV

↓ nuclei + e^- + ν

$e + p \to n_H + \gamma$ Recombination 0.3eV

WE ARE HERE! 10^{-4} eV


Era
$T \propto a^{-1} \propto 1+z$
$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
$\Omega_b \rho_{crit}$
0.04
Hubble constant
GeV
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
$\rho_b/m_b = n_b \sim 10^{-10}$
T_γ^3
n_γ
3K
Electroweak Phase Transition
100 GeV
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$f(p_\gamma)$
0.511 MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
nucleosynthesis
He, D, Li
0.1 MeV
$\downarrow$ nuclei + e' + ν'
$e + p \to n_H + \gamma$
Recombination
0.3eV
WE ARE HERE!
10^{-4} eV


$T_\gamma \sim 10^{-4}\,eV$
$3K$
Saha eq.
ionized fraction
$\frac{x_e^2}{1-x_e} \approx \left(\frac{n_\gamma}{n_b}\right)\left(\frac{m_e}{T}\right)^{3/2} e^{-\frac{13.6eV}{T}}$

$n = \int$

$T_\gamma \sim 10^{-4}\ eV$

$\parallel$

$3K$

$dE +$

$T_\gamma \rightarrow$

$T_\nu \rightarrow$

Saha eq.

ionized fraction $\leftarrow$

$$\frac{x_e^2}{1 - x_e} \simeq \left(\frac{n_\gamma}{n_b}\right)\left(\frac{m_e}{T}\right)^{3/2} e^{-\frac{13.6\,eV}{T}}$$

$$\boxed{\mu_e + \mu_p = \mu_H}$$

$n = \int \frac{p^2 dp}{e^{p/T} - 1}$

$\Omega_b \rho_{crit}$ 0.04 Hubble constant

$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$ GeV

3K

$dE + p dV = 0$

$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$

$T_\nu \to T_\nu$

$f(p_\gamma)$

0.511 MeV

$e + \bar{e} \rightleftharpoons \gamma + \gamma$

$e + p \rightleftharpoons n_H + \gamma$

Era

$T \propto a^{-1} \propto 1+z$

Inflation — 1 TeV – 10^{15} GeV

Baryogenesis

Electroweak Phase Transition — 100 GeV

SM | Dark Matter freeze-out — 10 GeV

quark-gluon plasma

QCD phase transition — 100 MeV

nucleon → hadrons

neutrino freeze-out — MeV

$e\bar{e}$ annihilation — 0.1 MeV

nucleosynthesis — He, D, Li — 0.1 MeV

↓ nuclei + e^- + ν

Recombination — 0.3 eV

WE ARE HERE! — 10^{-4} eV

$T_\gamma \sim 10^{-4}\ eV$

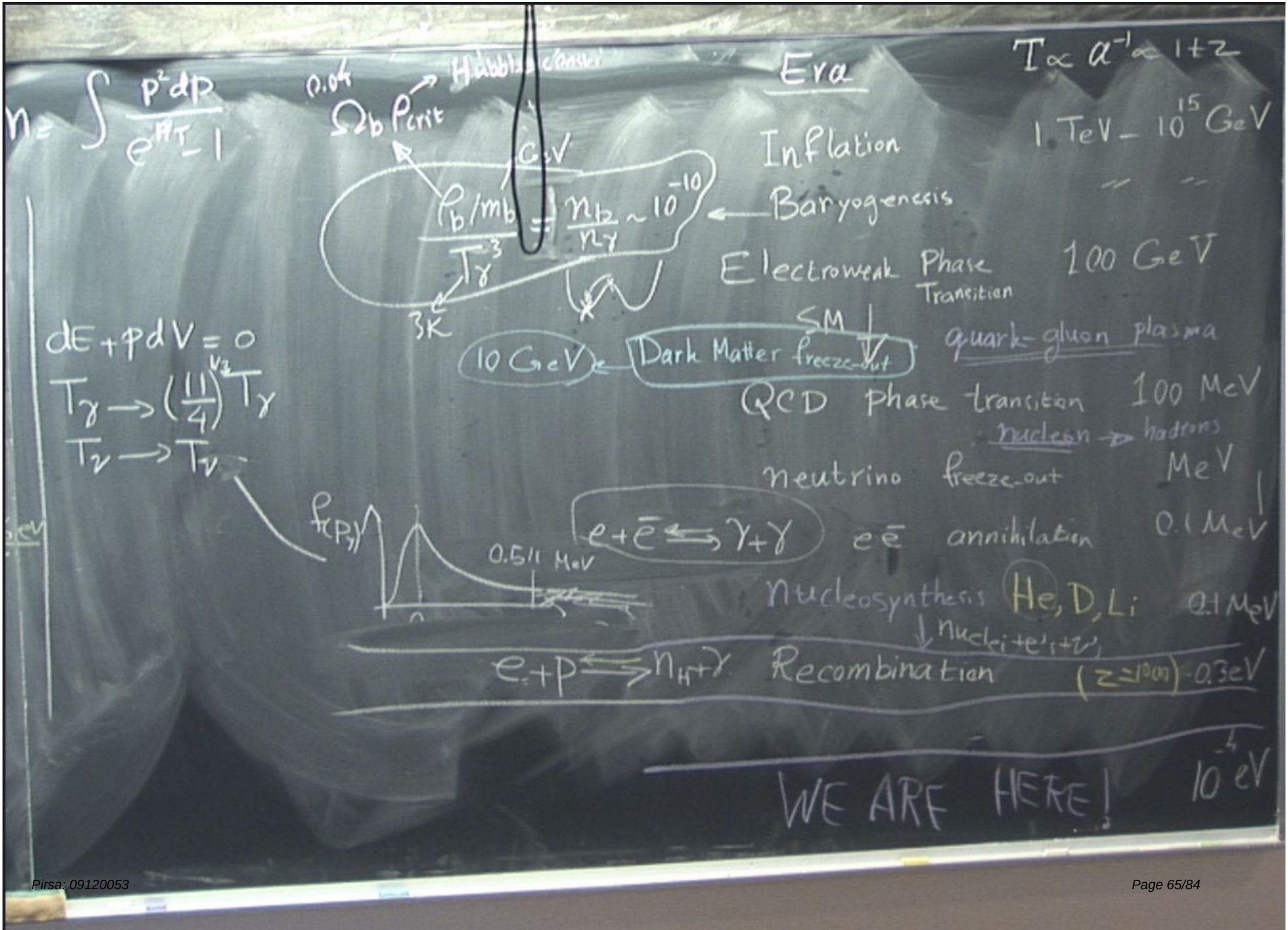
$3K$

Saha eq.

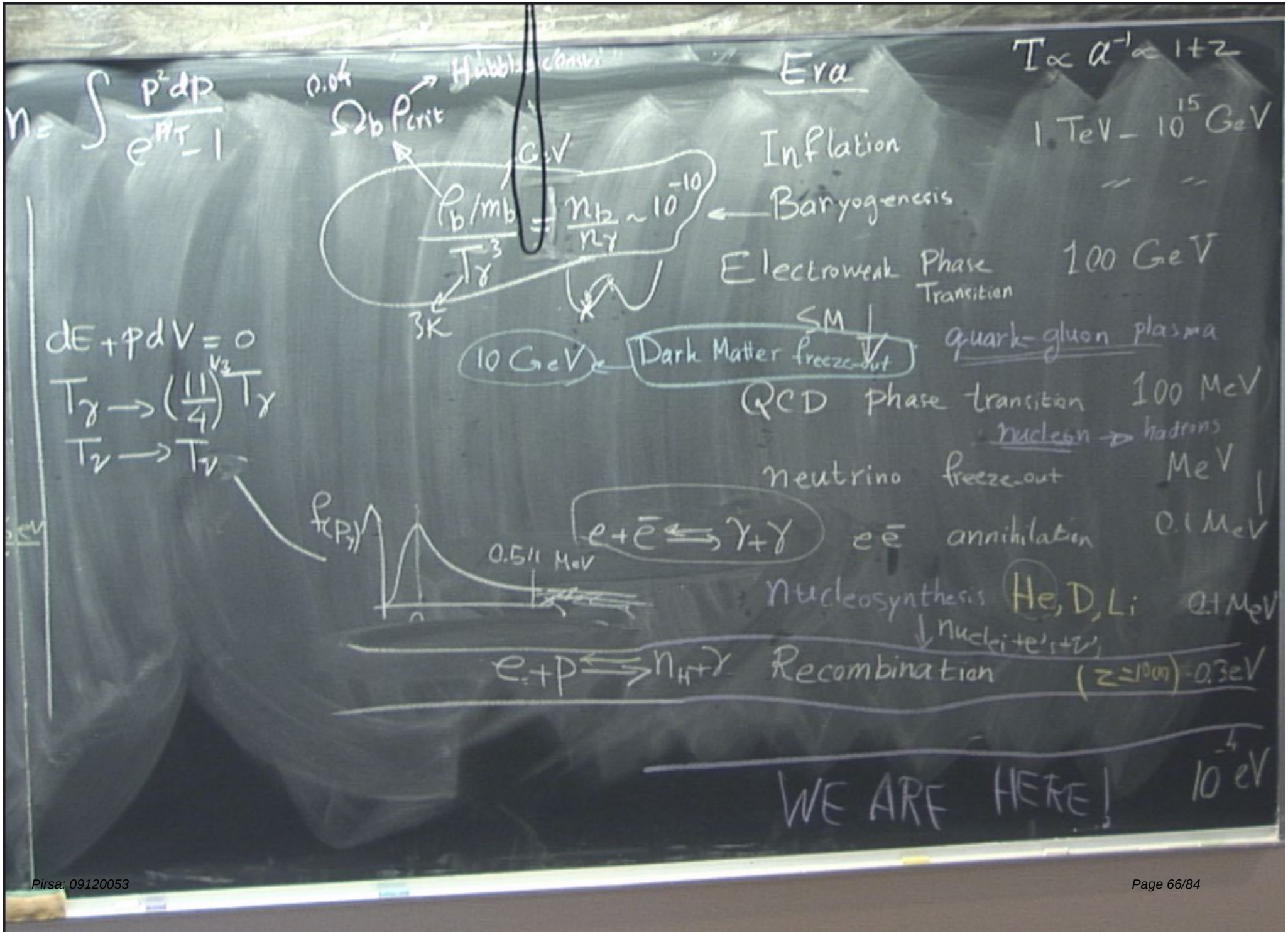
ionized fraction $\leftarrow \dfrac{x_e^2}{1-x_e} \sim \left(\dfrac{n_\gamma}{n_b}\right)\left(\dfrac{m_e}{T}\right)^{3/2} e^{-\frac{B_G e}{T}}$

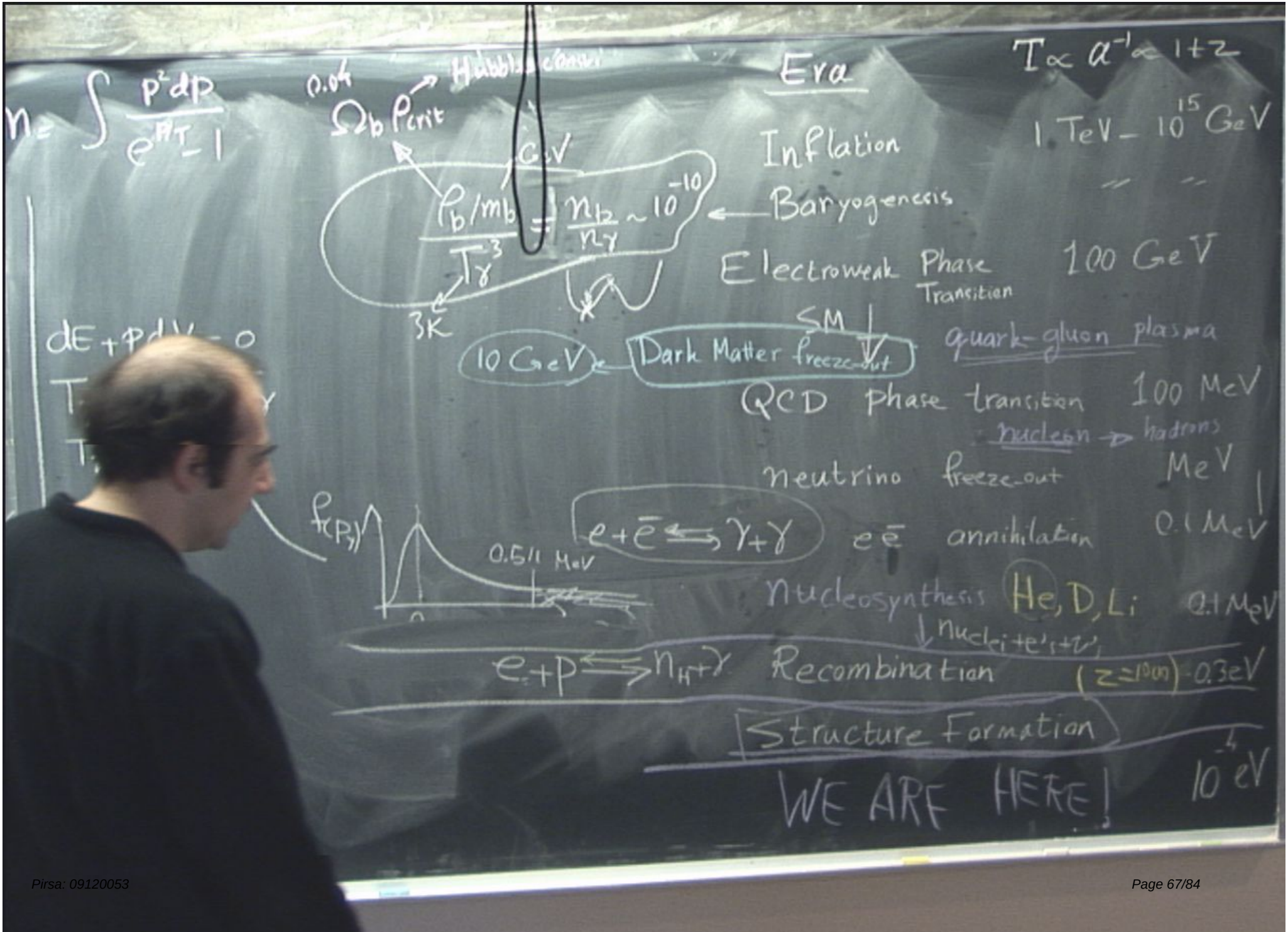
10^{10}

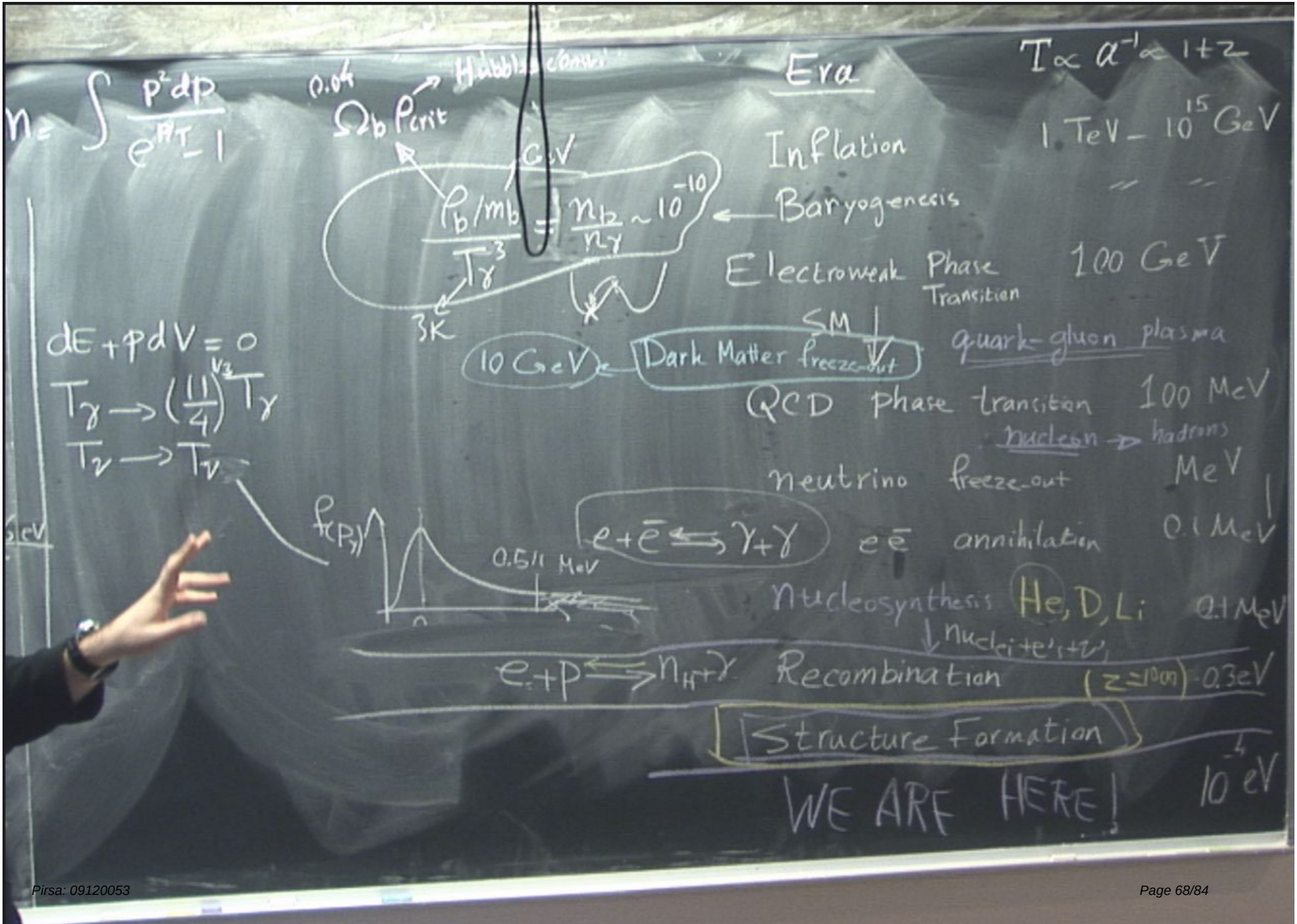
$\mu_e + \mu_p = \mu_H$



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
$e + p \leftrightarrows n_H + \gamma$
Recombination
(z ≃ 1000) 0.3 eV
WE ARE HERE!
10^{-4} eV


Era
$T \propto a^{-1} \propto 1+z$
$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble constant
GeV
$\rho_b/m_b = n_b \sim 10^{-10}$
T_γ^3
$n_{b\gamma}$
3K
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
Dark Matter freeze-out
10 GeV
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
neutrino freeze-out
MeV
$f(p_\gamma)$
0.511 MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
nucleosynthesis
He, D, Li
0.1 MeV
nuclei + e' + ν'
$e^- + p \rightleftharpoons n_H + \gamma$
Recombination
(z ≈ 1000) ~0.3eV
10^{-4} eV
WE ARE HERE!


Era
Inflation
Baryogenesis
Electroweak Phase Transition
100 GeV
SM
Dark Matter freeze-out
10 GeV
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
e+ē ⇌ γ+γ
e ē annihilation
0.1 MeV
0.511 MeV
nucleosynthesis
He, D, Li
0.1 MeV
e⁻+p ⇌ n_H+γ
Recombination
(z=1000) 0.3eV
Structure Formation
WE ARE HERE!
10⁻⁴ eV
3K



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
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100 GeV
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$e + \bar{e} \leftrightarrows \gamma + \gamma$
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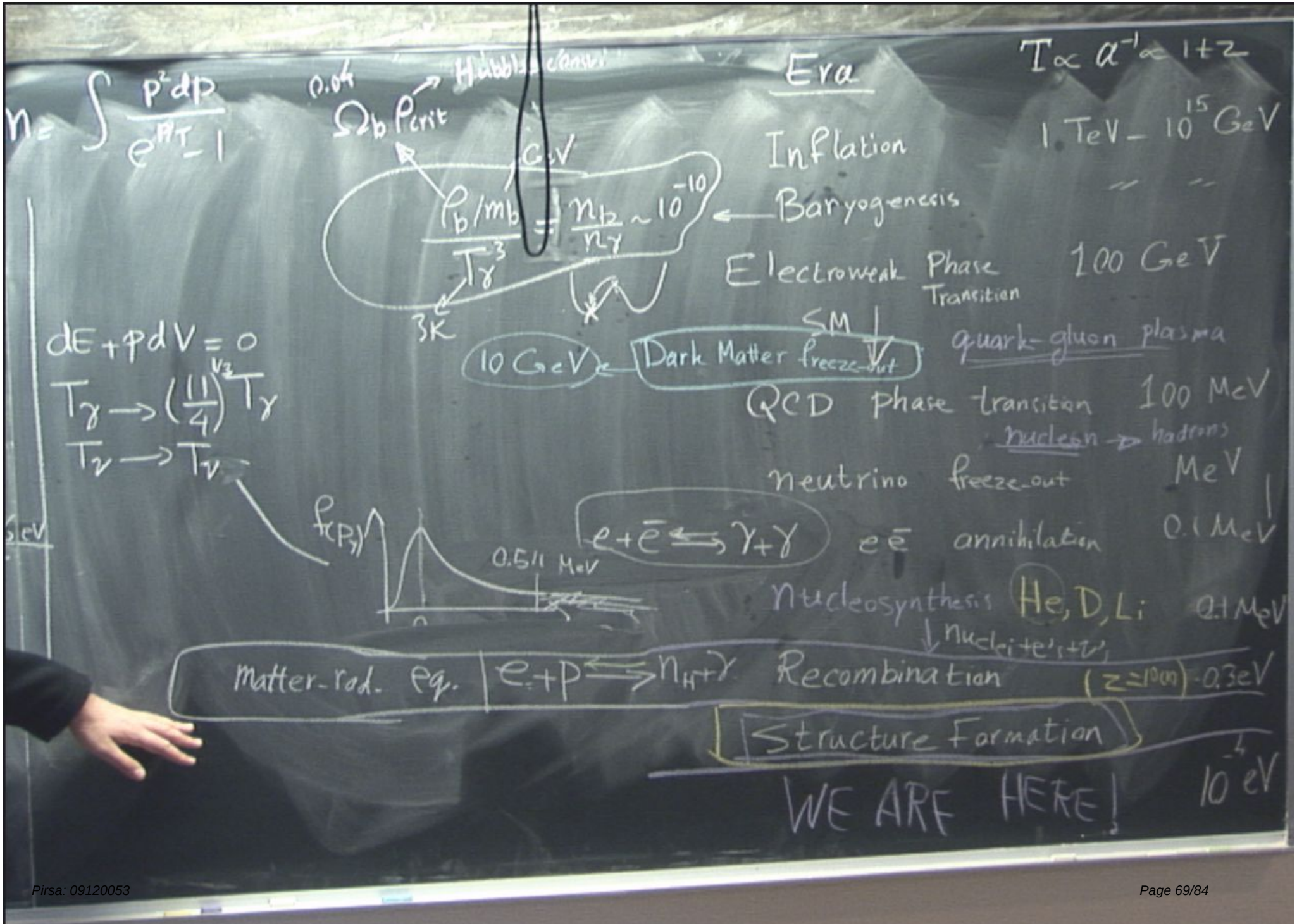
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
$e + p \leftrightarrows n_H + \gamma$
Recombination
(z ≃ 1000) 0.3 eV
Structure Formation
WE ARE HERE!
10^{-4} eV



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
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$T \propto a^{-1} \propto 1+z$
Inflation
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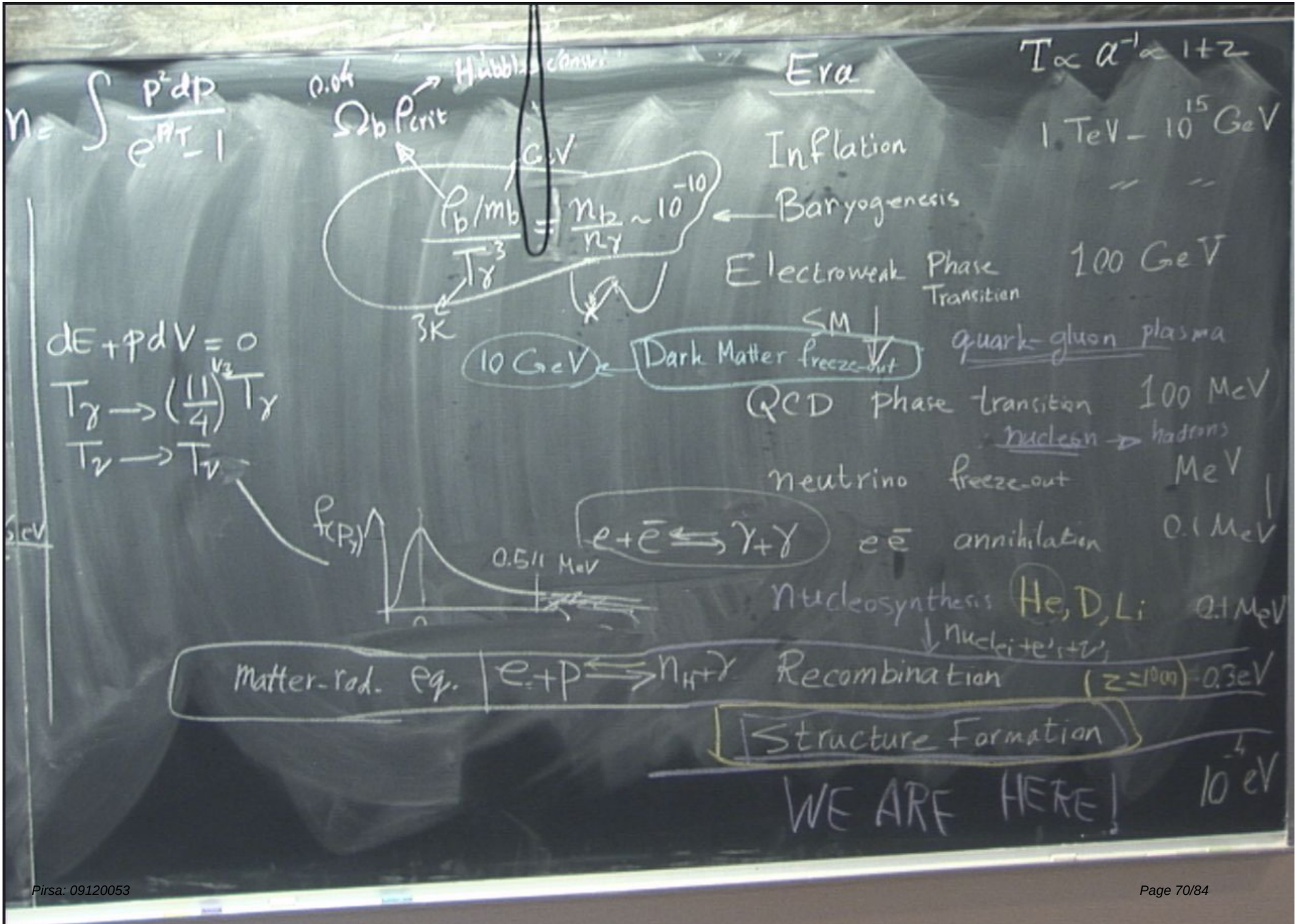
MeV
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
Matter-rad. eq.
$e + p \leftrightarrows n_H + \gamma$
Recombination
(z ≃ 1000) 0.3 eV
Structure Formation
WE ARE HERE!
10^{-4} eV



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const.
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
Era
$T \propto a^{-1} \propto 1+z$
Inflation
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QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
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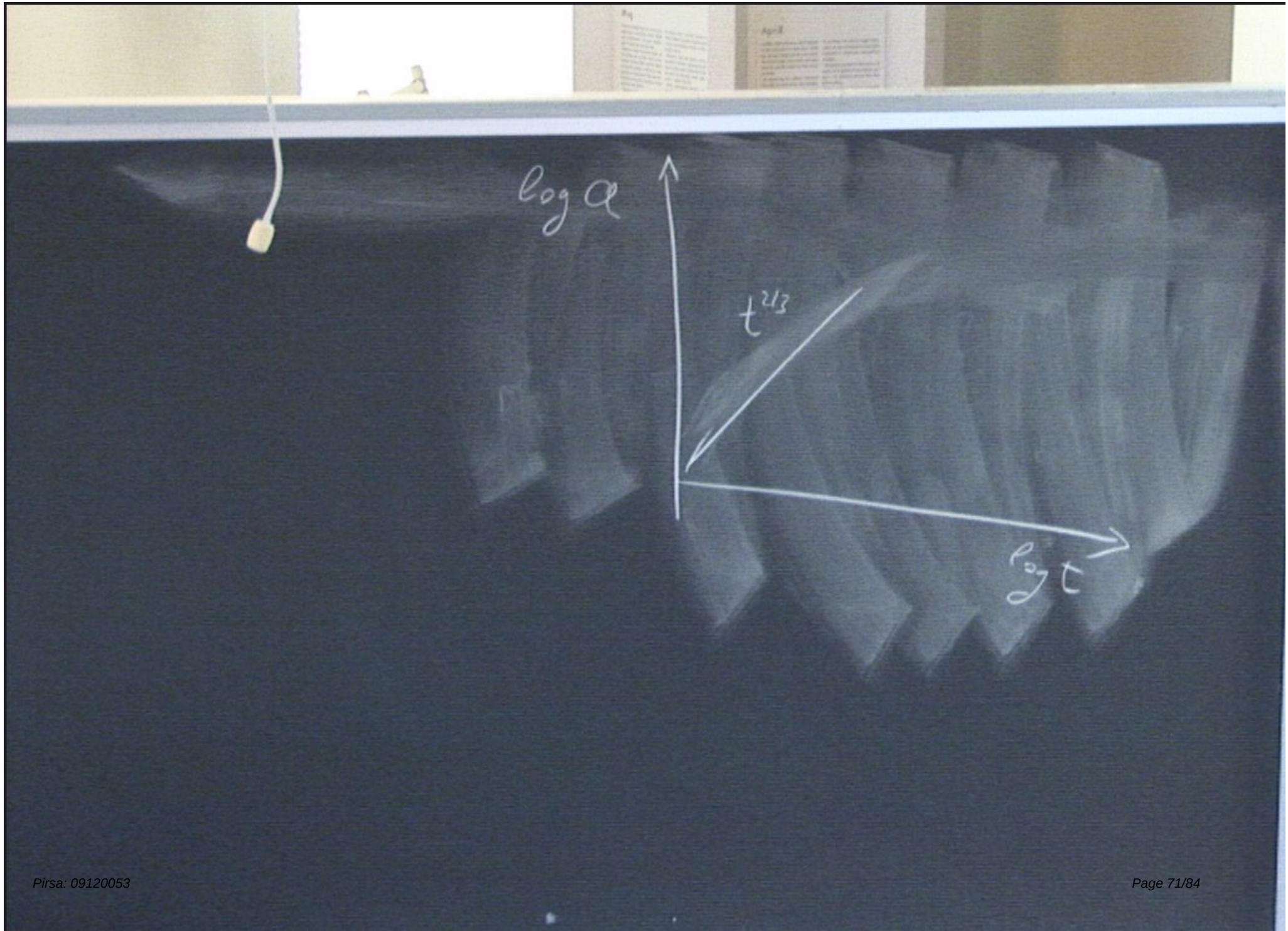
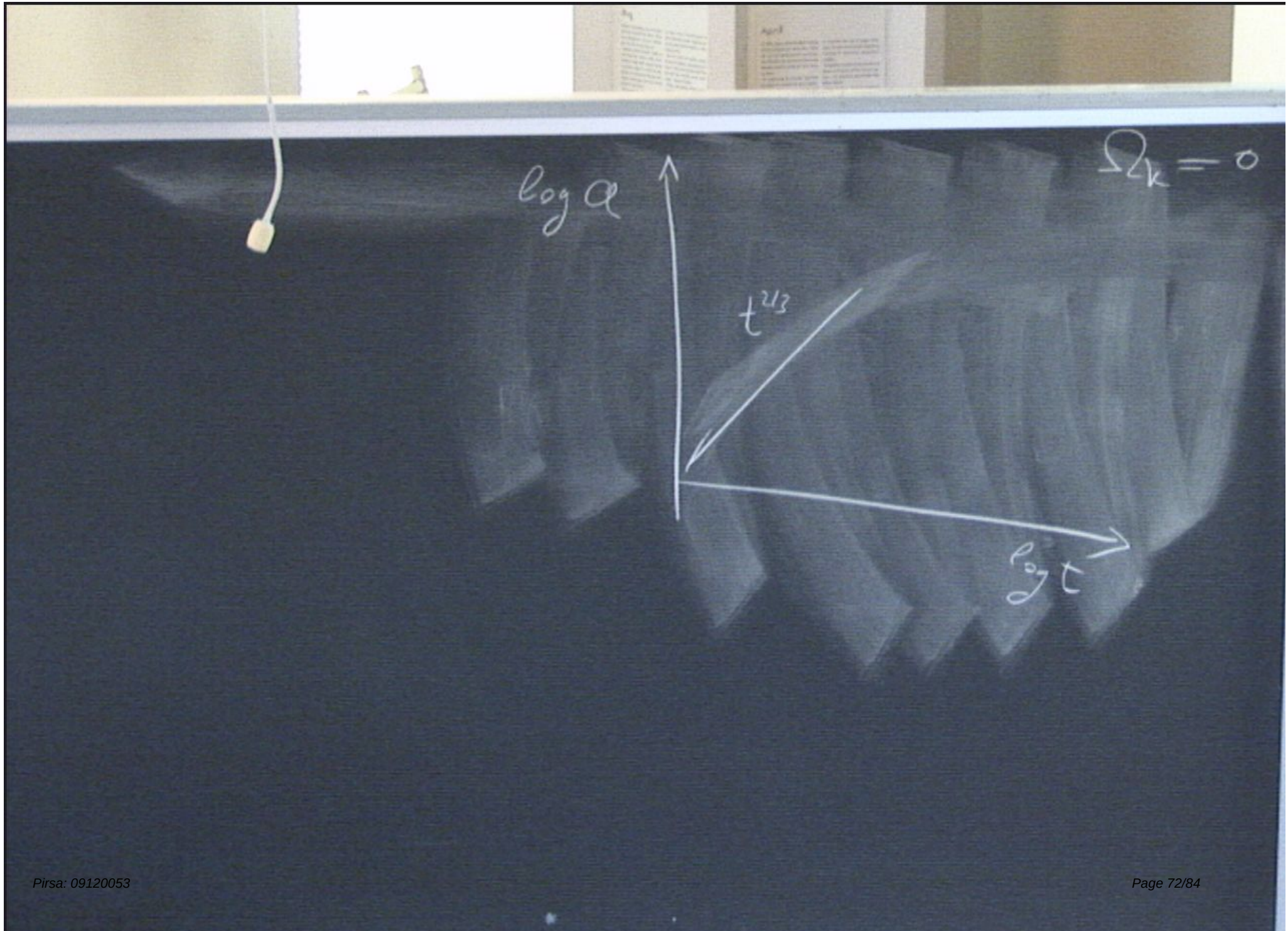
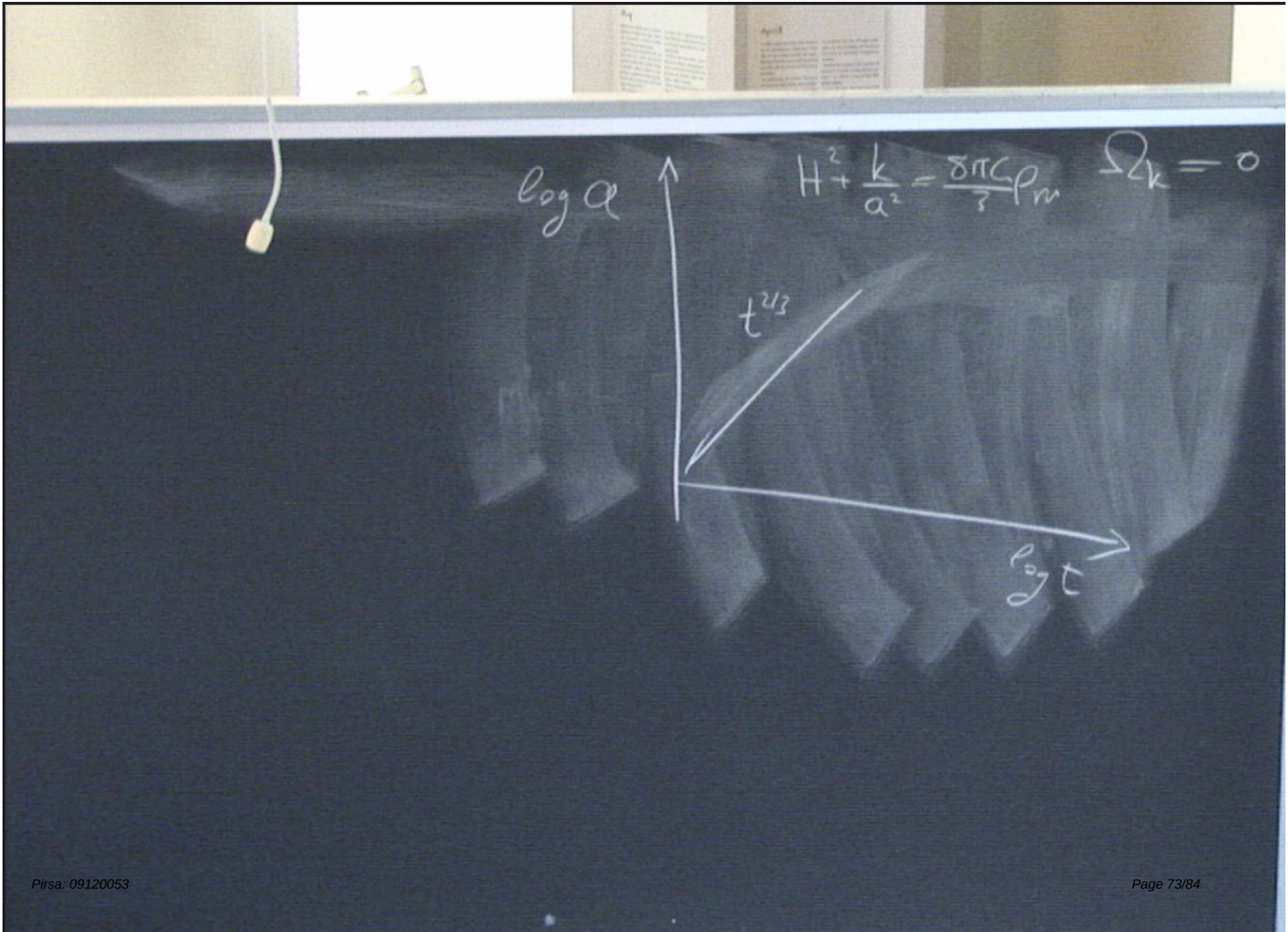
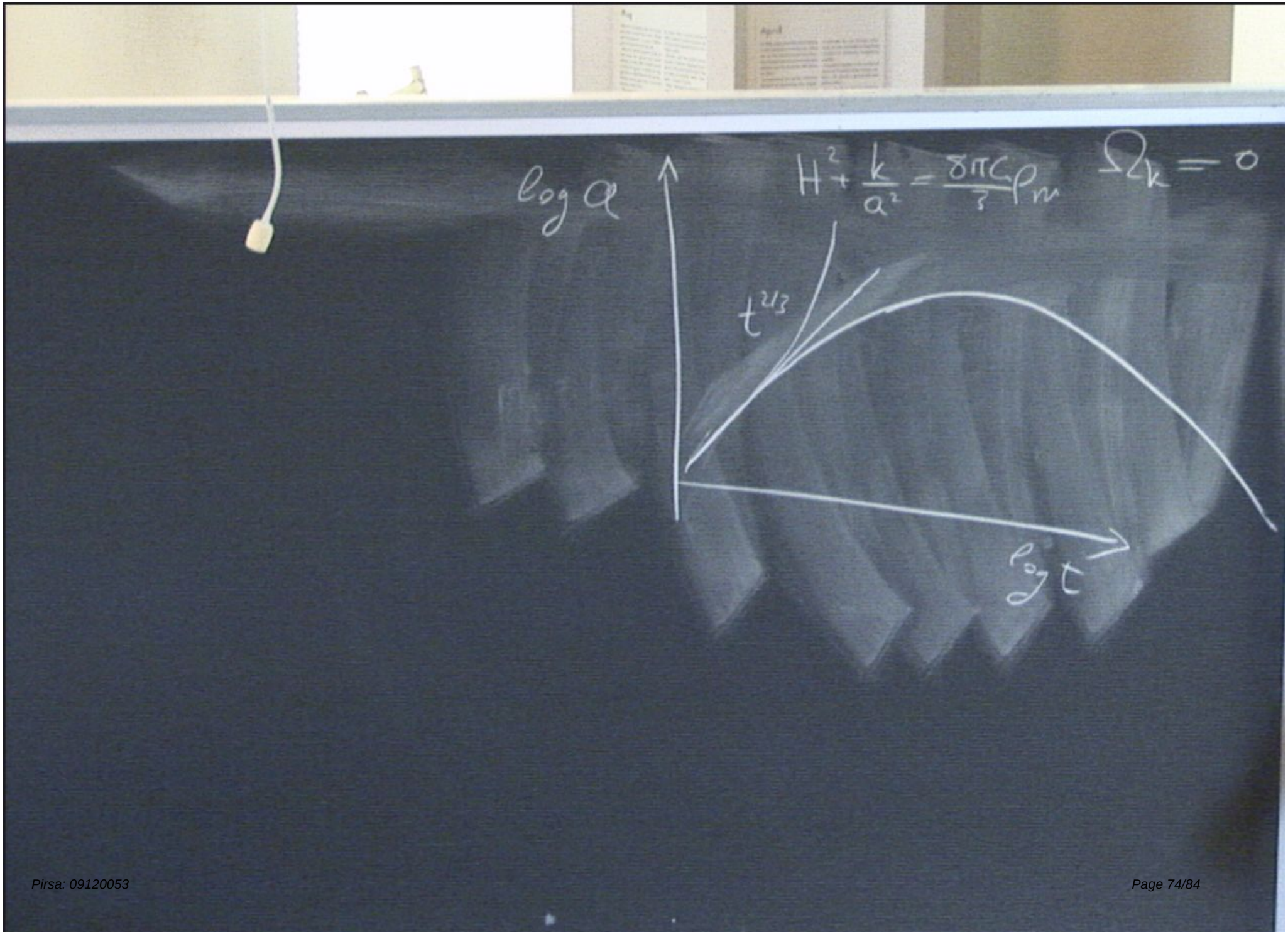
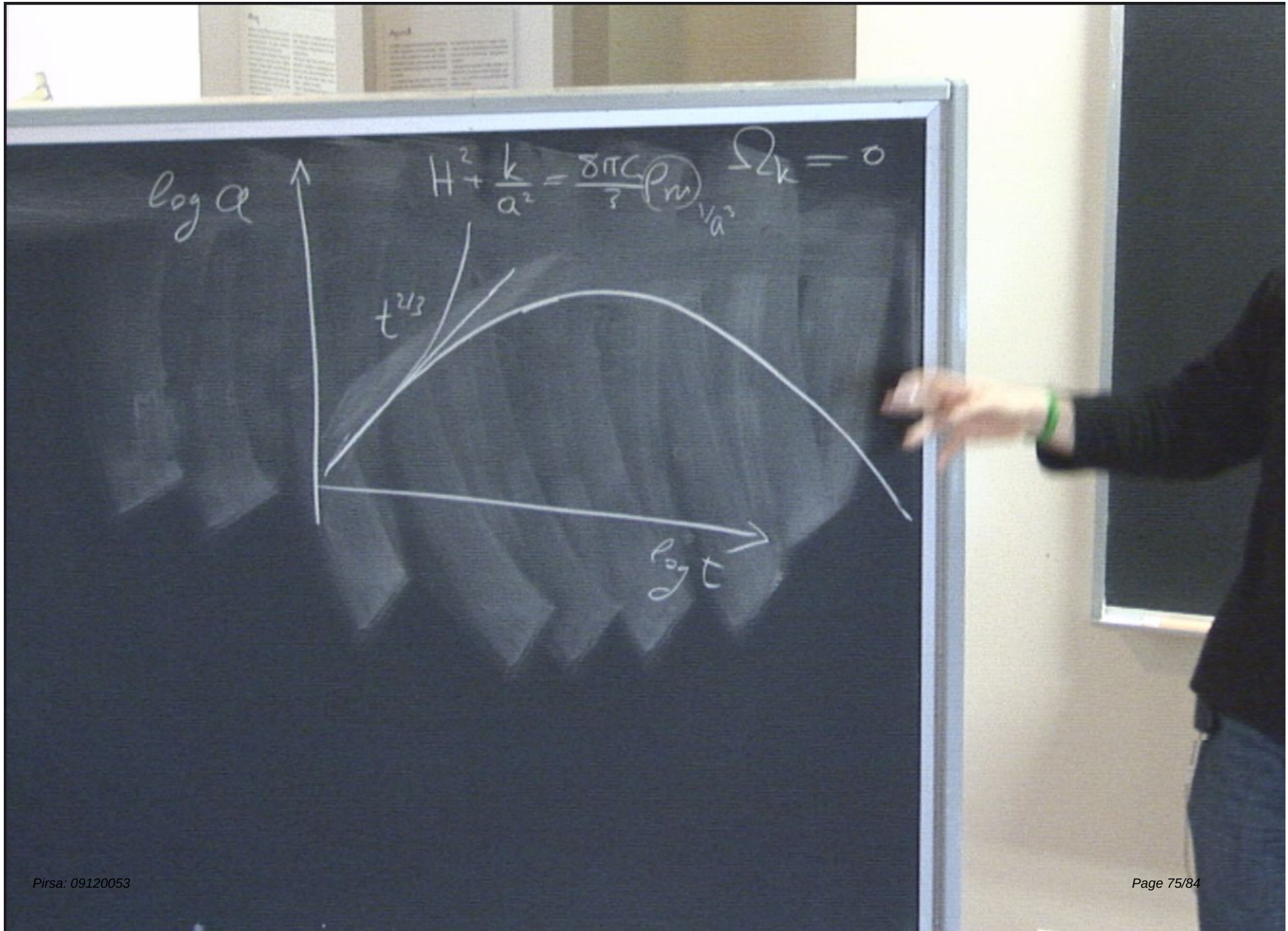
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
matter-rad. eq.
$e + p \leftrightarrows n_H + \gamma$
Recombination
(z ≃ 1000) 0.3 eV
Structure Formation
WE ARE HERE!
10^{-4} eV

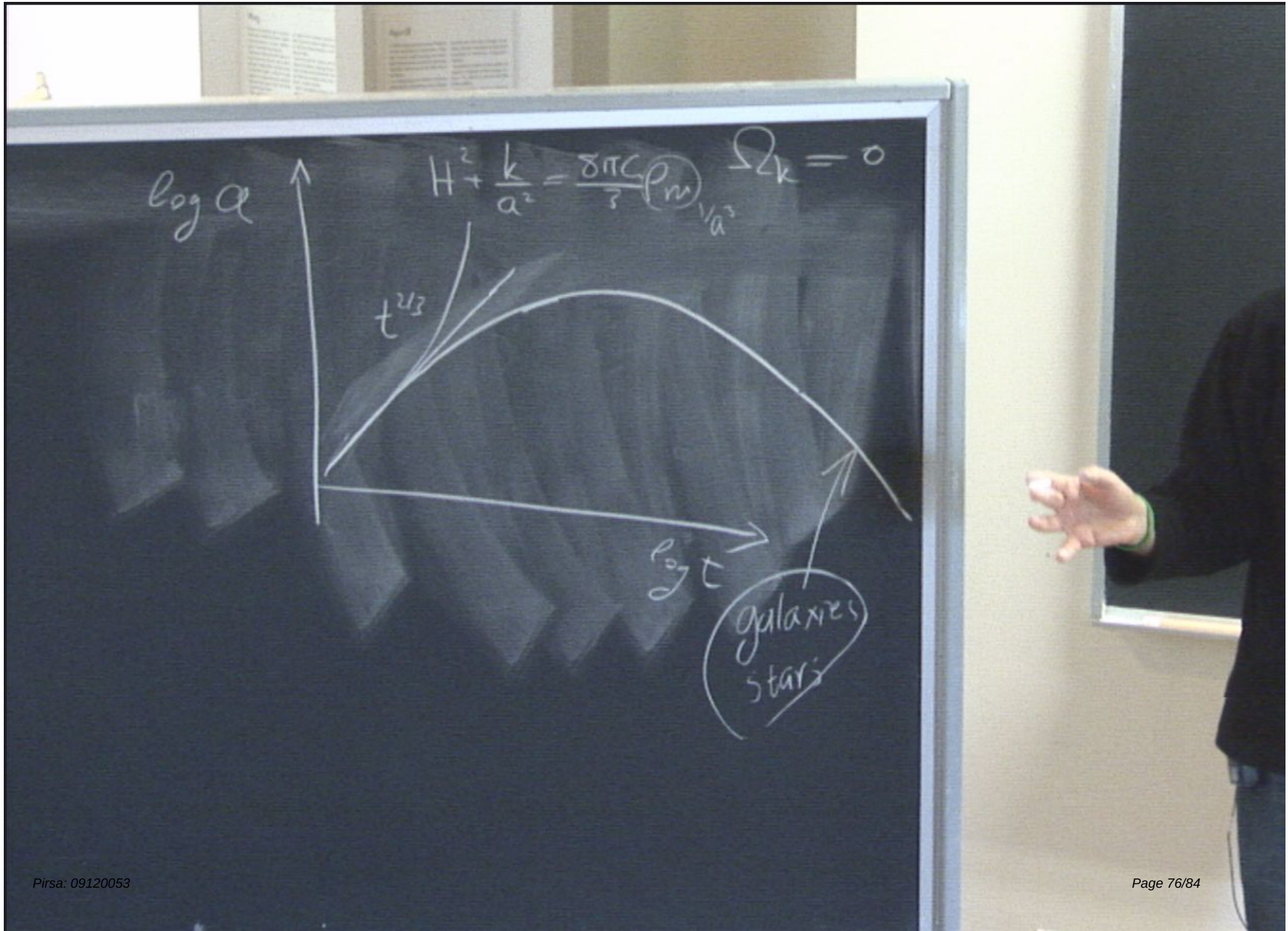

log a
t^{2/3}
log t

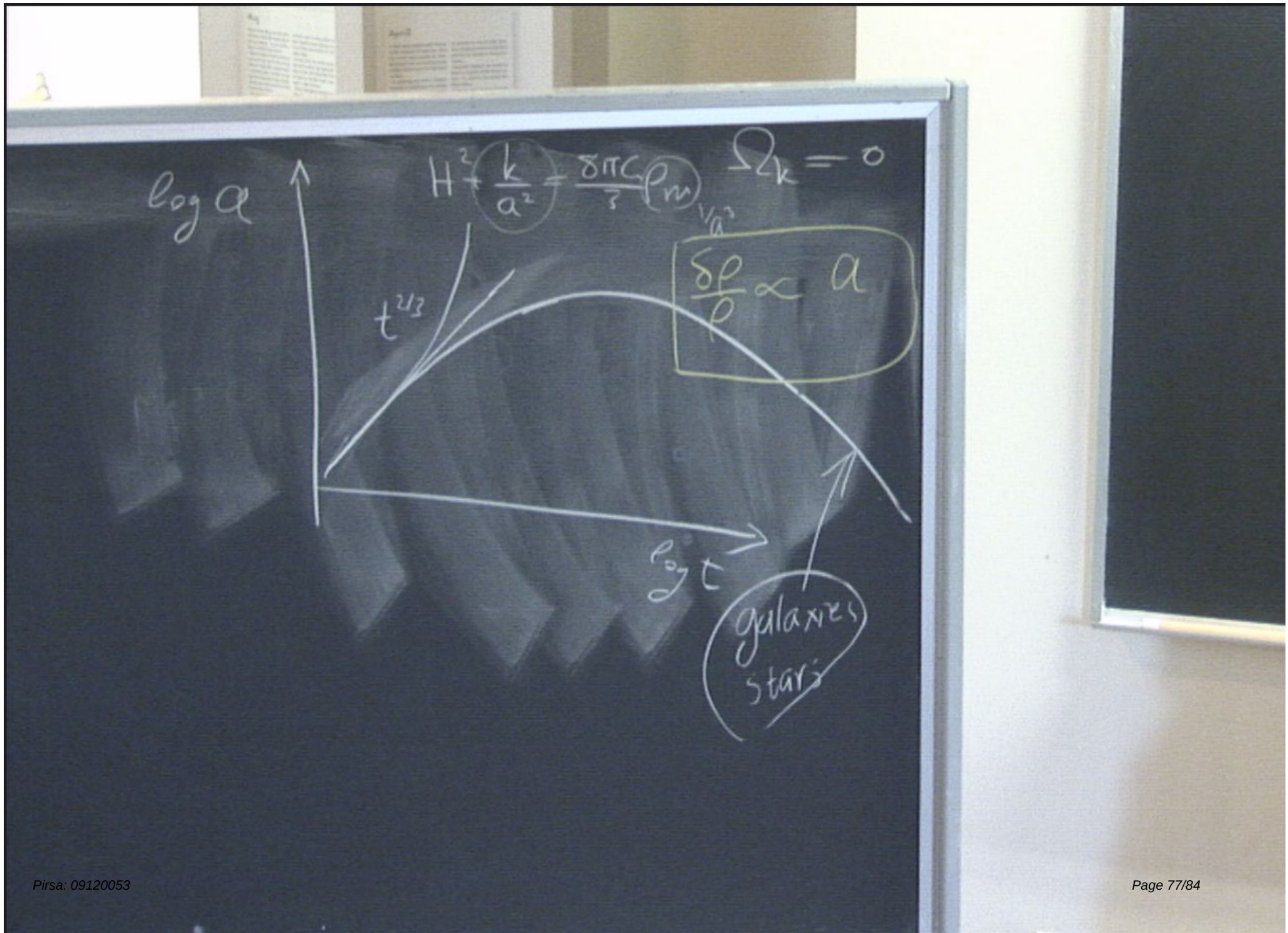

$\Omega_k = 0$
log a
$t^{2/3}$
log t

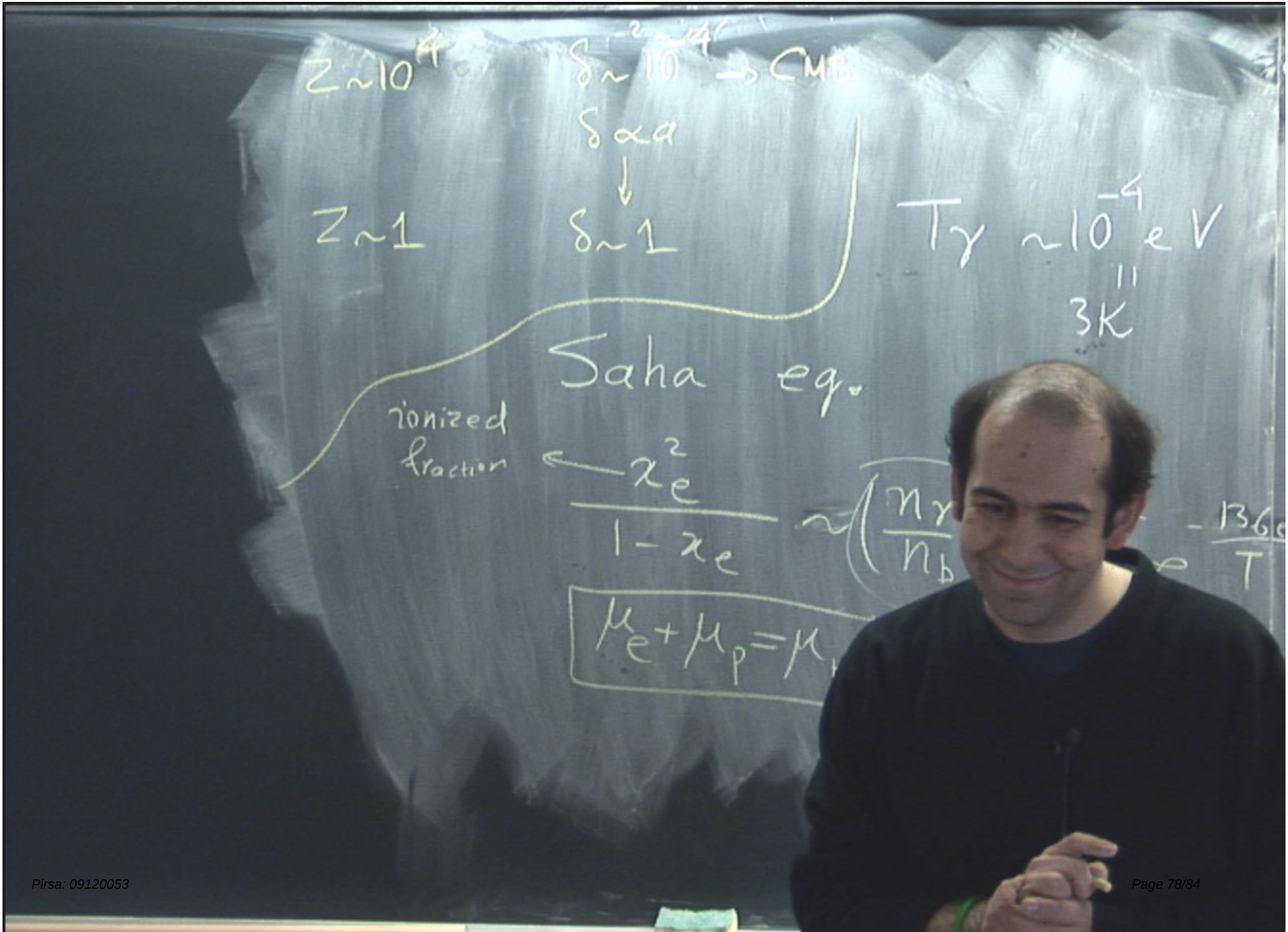

log a
$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_m$
$\Omega_k = 0$
$t^{2/3}$
log t


log a
$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_m$
$\Omega_k = 0$
$t^{2/3}$
log t


log a
$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_m$
$1/a^3$
$\Omega_k = 0$
$t^{2/3}$
log t


log a
$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_m$
$\rho_m \sim 1/a^3$
$\Omega_k = 0$
$t^{2/3}$
log t
galaxies
stars


log a
$H^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho_m$
$\Omega_k = 0$
$1/a^3$
$t^{2/3}$
$\frac{\delta\rho}{\rho} \propto a$
log t
galaxies
stars


Z~10^4
δ~10^-4 → CMB
δ∝a
Z~1
δ~1
Tγ ~10^-4 eV
3K
Saha eq.
ionized fraction
x_e^2 / (1 - x_e)
μ_e + μ_p = μ

$z \sim 10^4$ $\quad \delta \sim 10^{-2} - 10^{-4} \rightarrow$ CMB

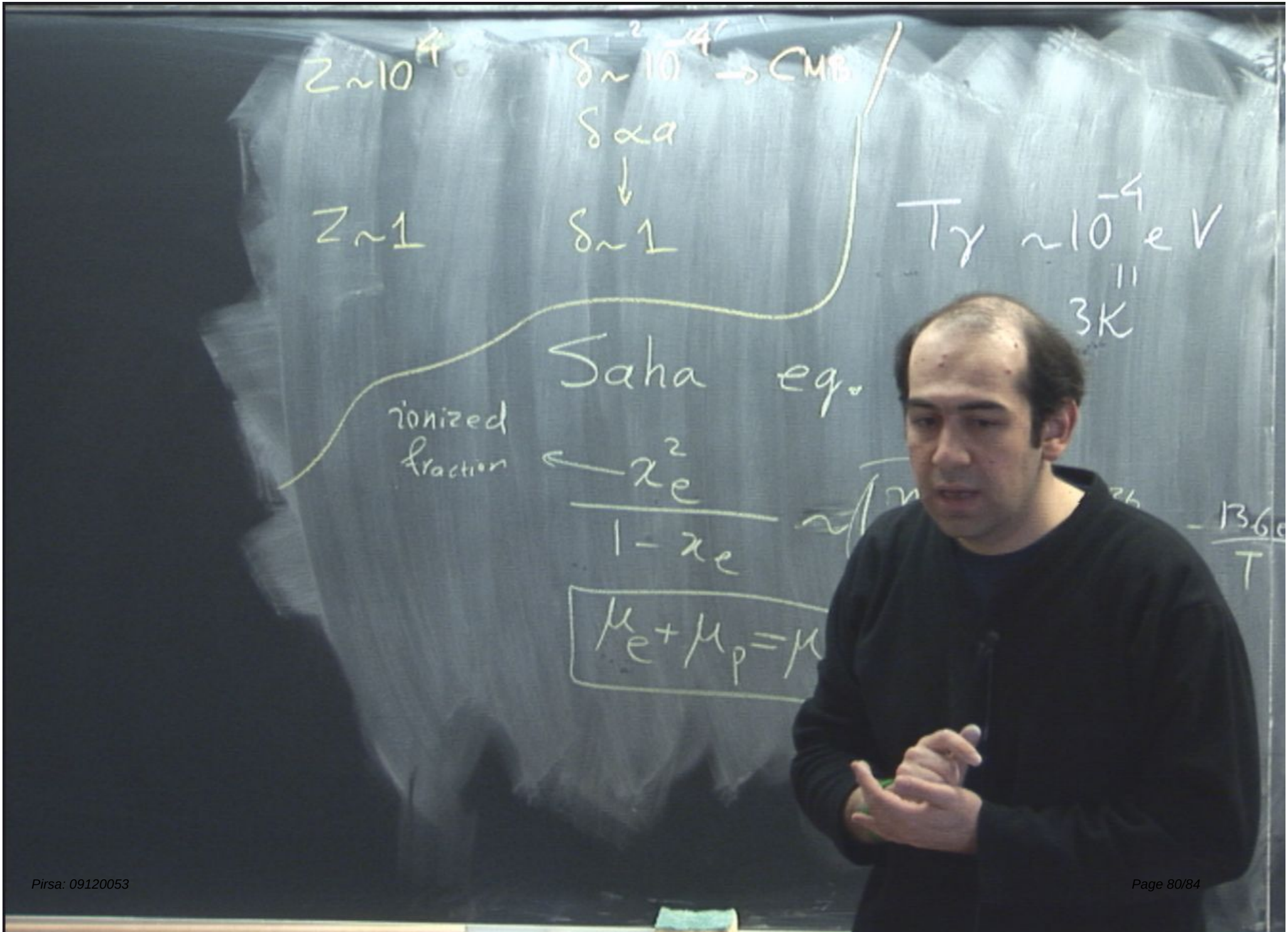
$\delta \propto a$

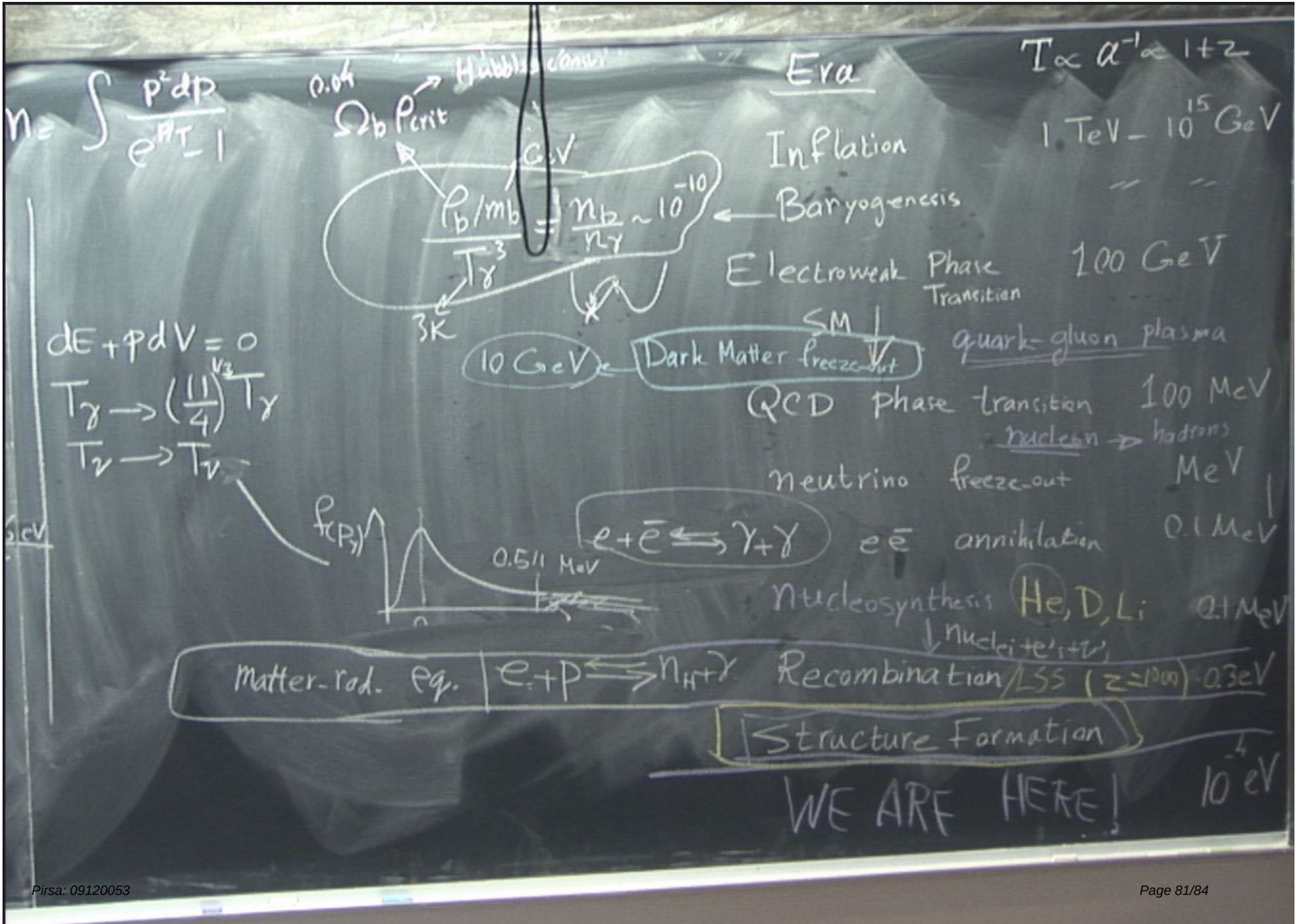
$z \sim 1$ $\quad \delta \sim 1$ $\quad T_\gamma \sim 10^{-4}$ eV $\sim 3K$

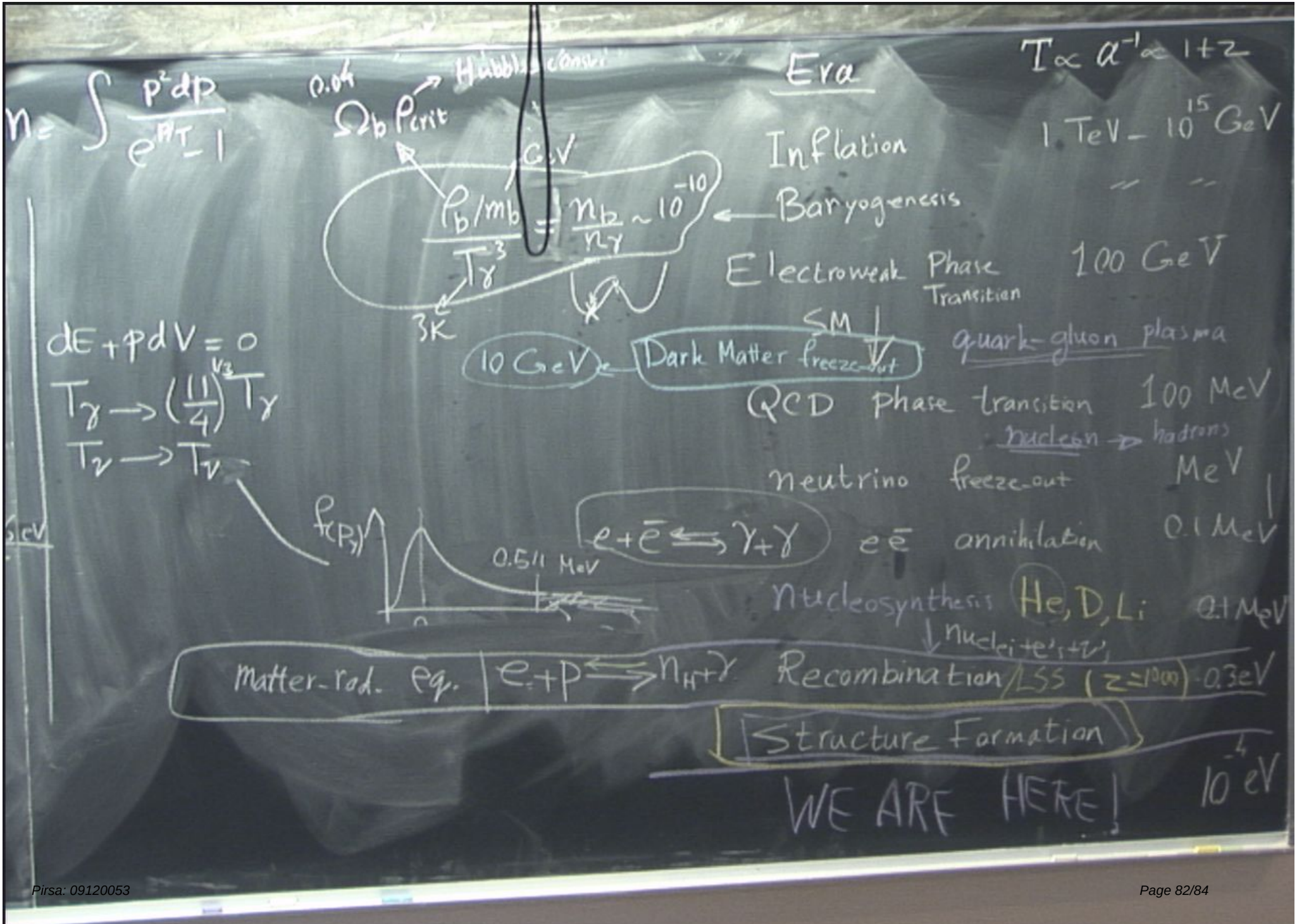
Saha eq.

ionized fraction $\leftarrow \dfrac{x_e^2}{1-x_e} \sim \left(\dfrac{n_\gamma}{n_b}\right)\left(\dfrac{m_e}{T}\right)^{3/2} e^{-\frac{13.6}{T}}$ $\quad 10^{10}$

$\mu_e + \mu_p = \mu_H$


z ~ 10^4
δ ~ 10^-2 → 10^-4 → CMB
δ ∝ a
z ~ 1
δ ~ 1
Tγ ~ 10^-4 eV
3K
Saha eq.
ionized fraction
x_e^2 / (1 - x_e)
μ_e + μ_p = μ


Era
$T \propto a^{-1} \propto 1+z$
$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
$\Omega_b \rho_{crit}$
0.04
Hubble constant
GeV
$\rho_b/m_b = \frac{n_b}{n_\gamma} \sim 10^{-10}$
T_γ^3
3K
Inflation
1 TeV – 10^{15} GeV
Baryogenesis
Electroweak Phase Transition
100 GeV
$dE + pdV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
QCD phase transition
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
0.511 MeV
nucleosynthesis
He, D, Li
0.1 MeV
nuclei + e^- + ν
Matter-rad. eq.
$e^- + p \rightleftharpoons n_H + \gamma$
Recombination/LSS (z=1000)
0.3eV
Structure Formation
WE ARE HERE!
10^{-4} eV


Era
$T \propto a^{-1} \propto 1+z$
$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
$\Omega_b \rho_{crit}$
0.04
Hubble constant
GeV
$\rho_b/m_b = n_b \sim 10^{-10}$
T_γ^3
n_γ
3K
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SM
10 GeV
Dark Matter freeze-out
quark-gluon plasma
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100 MeV
nucleon → hadrons
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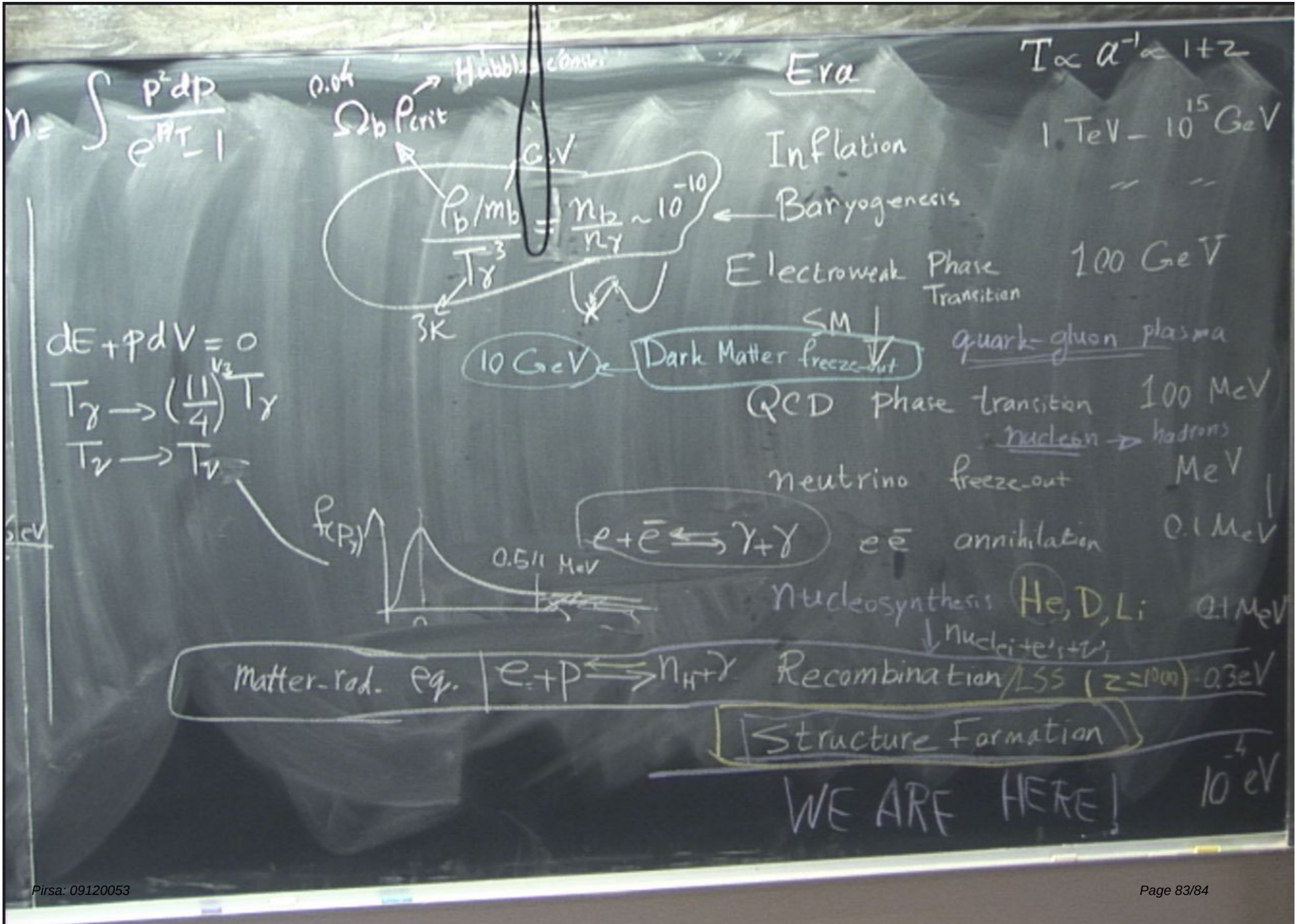
MeV
$f(p_\gamma)$
0.511 MeV
$e + \bar{e} \rightleftharpoons \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
nucleosynthesis
He, D, Li
0.1 MeV
nuclei + e^- + ν
Matter-rad. eq.
$e^- + p \rightleftharpoons n_H + \gamma$
Recombination/LSS (z ≃ 1000)
0.3eV
Structure Formation
WE ARE HERE!
10^{-4} eV



$n = \int \frac{p^2 dp}{e^{p/T} - 1}$
0.04
$\Omega_b \rho_{crit}$
Hubble const
GeV
$\frac{\rho_b / m_b}{T_\gamma^3} = \frac{n_b}{n_\gamma} \sim 10^{-10}$
3K
Era
$T \propto a^{-1} \propto 1+z$
Inflation
1 TeV – 10^{15} GeV
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100 GeV
SM
quark-gluon plasma
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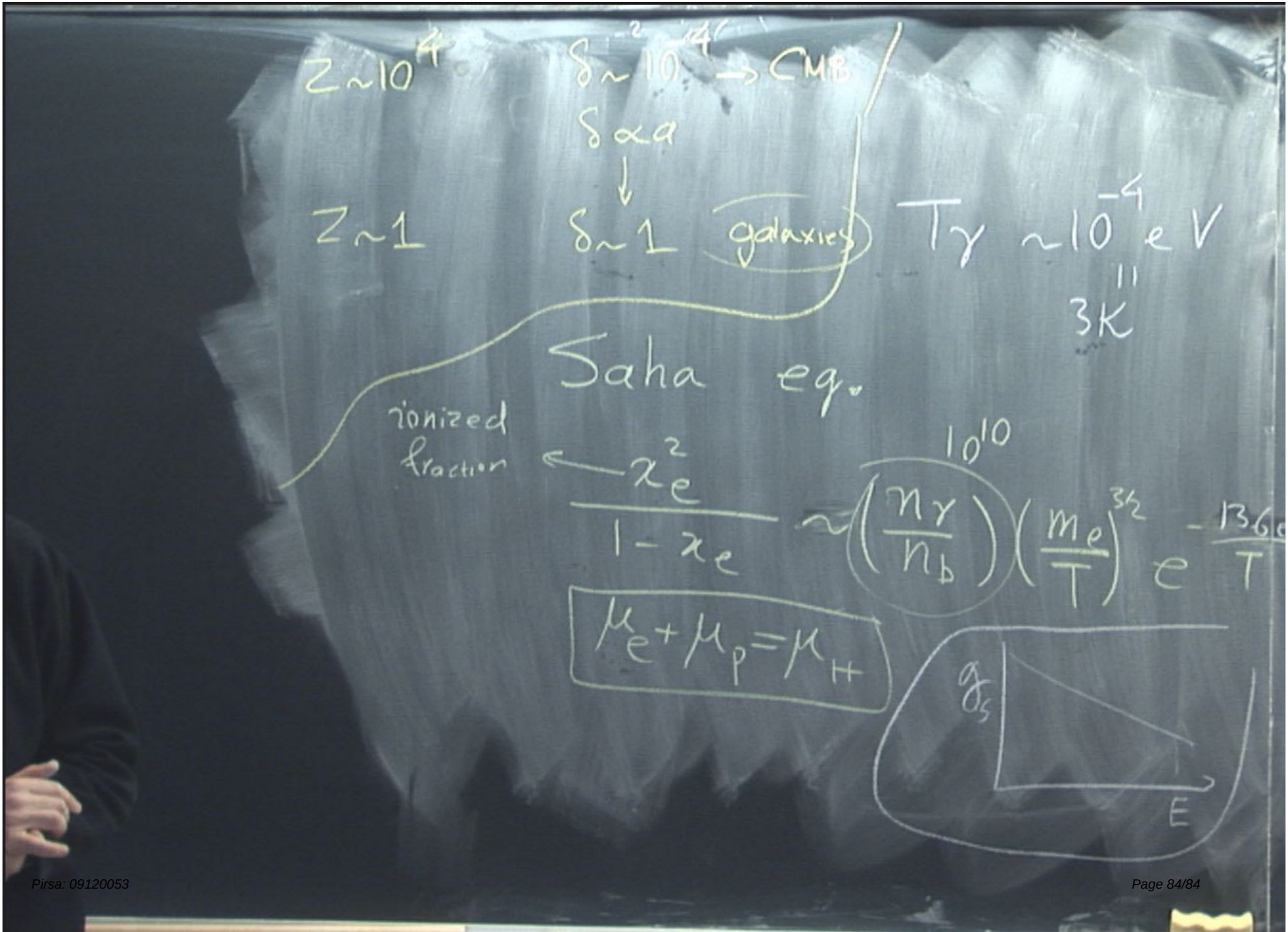
100 MeV
nucleon → hadrons
neutrino freeze-out
MeV
$dE + p\,dV = 0$
$T_\gamma \to \left(\frac{11}{4}\right)^{1/3} T_\gamma$
$T_\nu \to T_\nu$
$f(p_\gamma)$
0.511 MeV
$e + \bar{e} \leftrightarrows \gamma + \gamma$
$e\bar{e}$ annihilation
0.1 MeV
Nucleosynthesis He, D, Li
0.1 MeV
nuclei + e's + ν's
Matter-rad. eq.
$e + p \leftrightarrows n_H + \gamma$
Recombination / LSS ($z \simeq 1000$) 0.3 eV
Structure Formation
WE ARE HERE!
10^{-4} eV


z ~ 10^4
δ ~ 10^-2 → 10^-4 → CMB
δ ∝ a
z ~ 1
δ ~ 1
galaxies
Tγ ~ 10^-4 eV
3K
Saha eq.
ionized fraction
x_e^2 / (1 - x_e) ~ (n_γ / n_b) (m_e / T)^3/2 e^-13.6/T
10^10
μ_e + μ_p = μ_H
g_s
E