Title: Particle Physics Lecture

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Collection: Particle Physics

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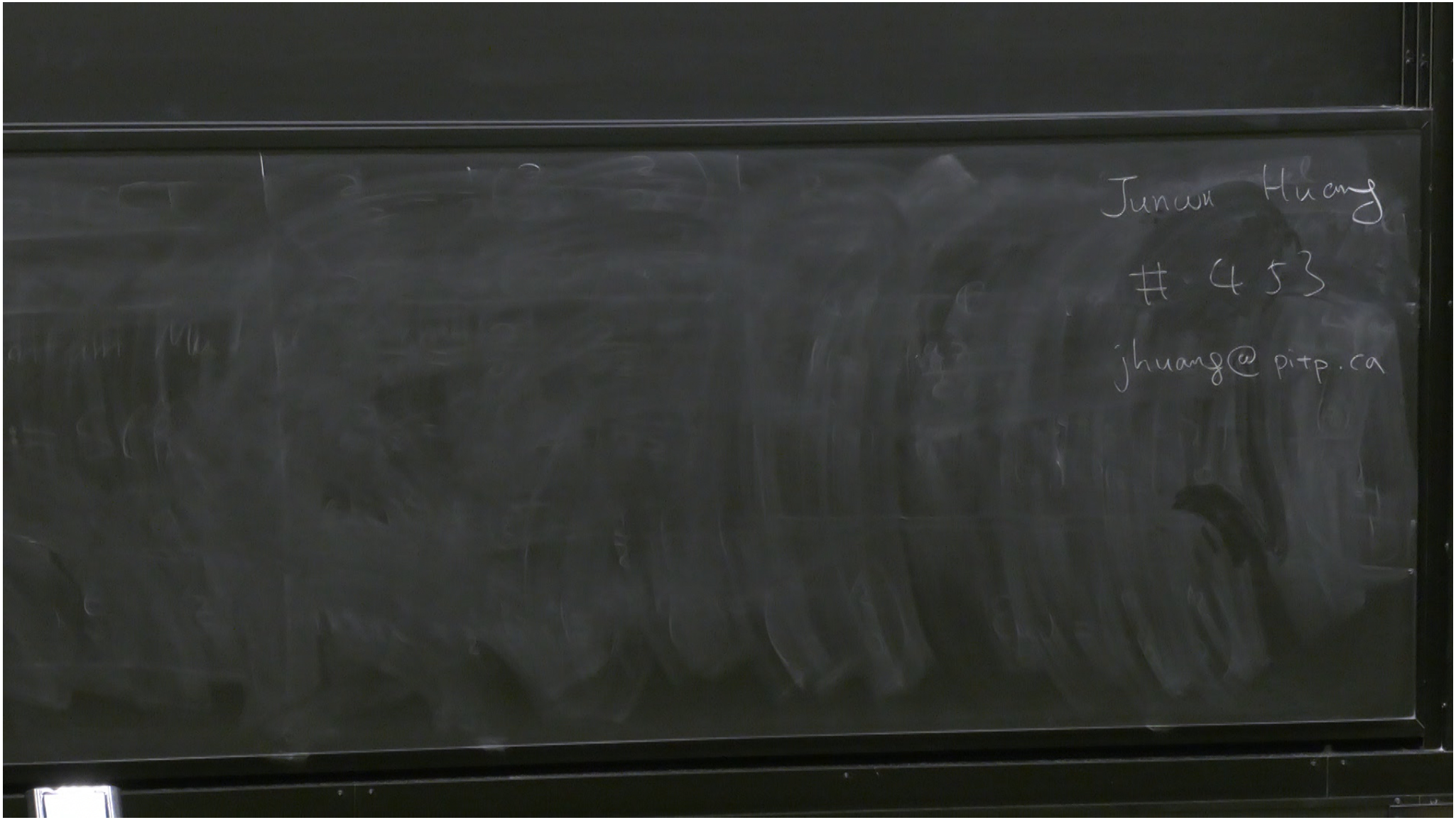
7. Thermal History of our Universe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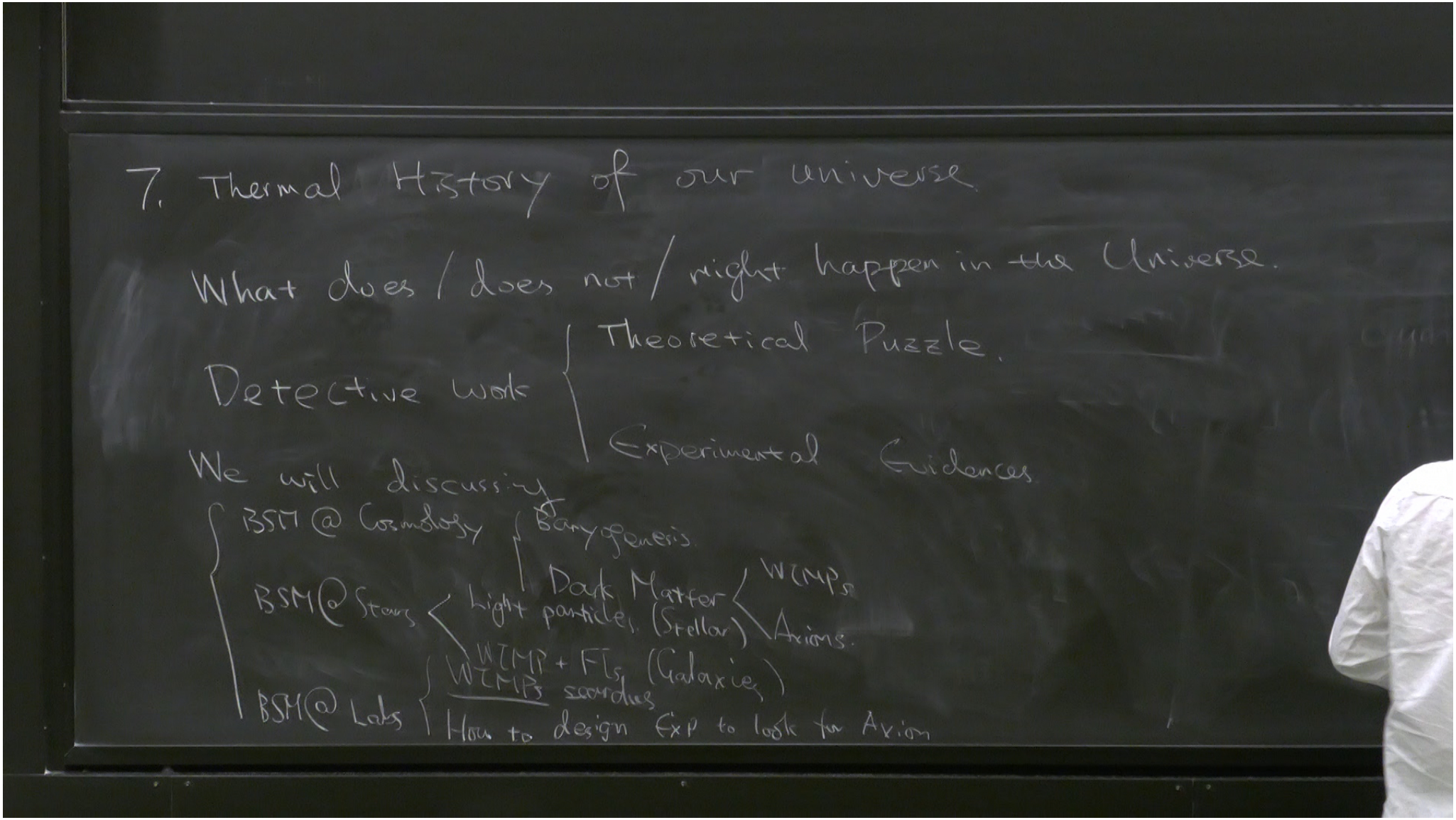
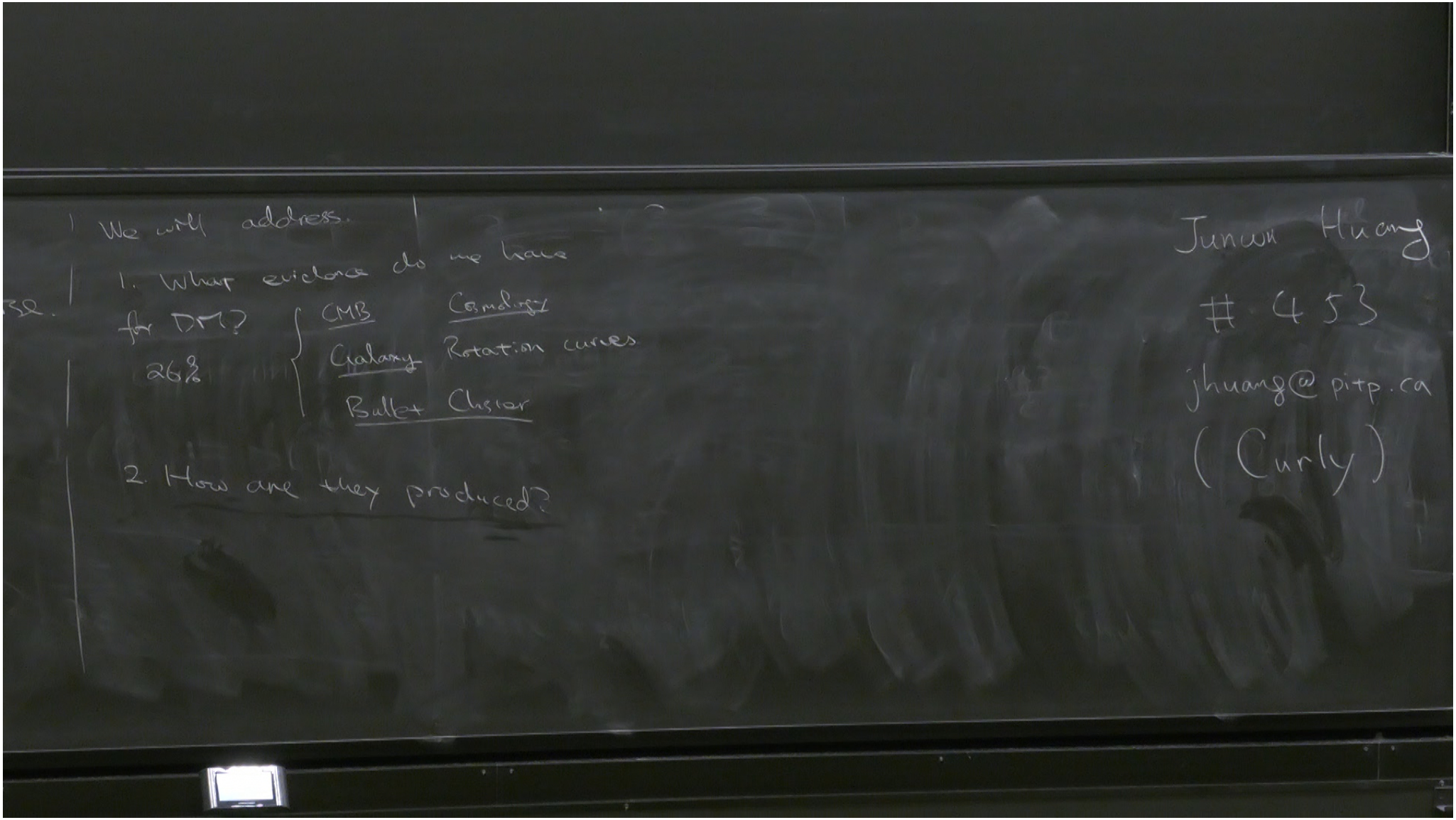

7. Thermal History of our Universe
What does / does not / might happen in the Universe.
Detective work
Theoretical Puzzle.
Experimental Evidences
We will discuss:
BSM @ Cosmology
Baryogenesis
BSM @ Stars
Dark Matter
light particles (Stellar)
WIMPs
Axions.
BSM @ Labs
WIMP + FIs (Galaxies)
WIMPs searches
How to design Exp to look for Axion


We will address.
1. What evidence do we have for DM?
26%
CMB
Cosmology
Galaxy
Rotation curves
Bullet Cluster
2. How are they produced?
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(Curly)

We will address.

1. What evidence do we have for DM?
   - 26%
   - CMB — Cosmology
   - Galaxy — Rotation curves
   - Bullet Cluster
2. How are they produced?
3. What species/particles can be dark matter?
4. How to search for them?
5. Find the correct (obs) constraint?
6. How to optimize my search?
7. Model Building?

Disclaimer $\hbar = c = k_B = 1$

$\pi = 3 = 4 = 1$, $4\pi = 10$

H_0 ---- M_{Pl}

10^{-33}eV 10^{18}GeV

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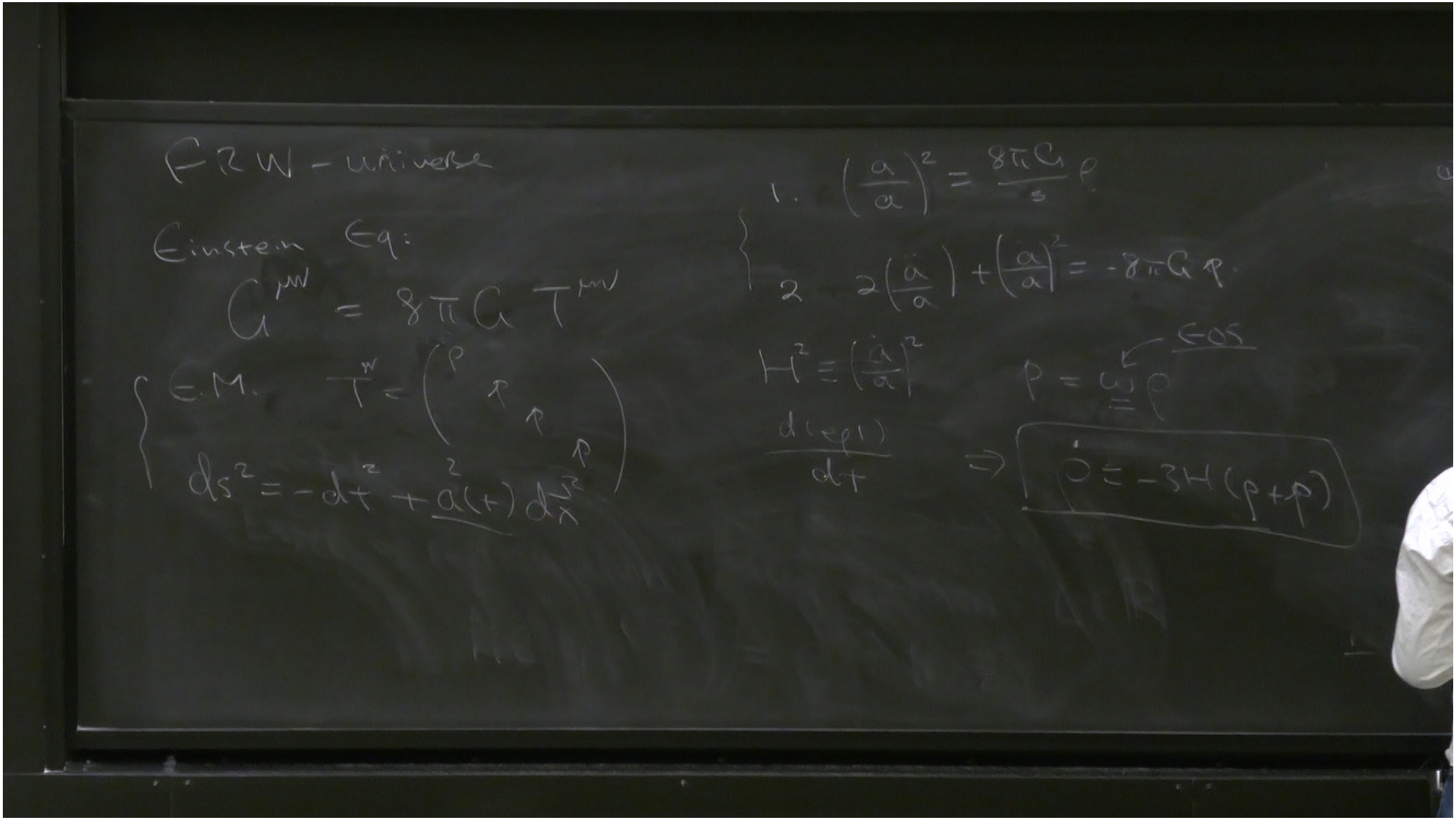
(Curly)


FRW - universe
Einstein Eq:
$G^{\mu\nu} = 8\pi G\, T^{\mu\nu}$
E.M. $T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$
$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$
1. $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$
2. $2\left(\frac{\ddot{a}}{a}\right) + \left(\frac{\dot{a}}{a}\right)^2 = -8\pi G p$
$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2$
EOS
$p = \omega\rho$
$\frac{d(\rho a^3)}{dt} \Rightarrow \dot{\rho} = -3H(\rho + p)$

① Radiation domination.

$\rho_r \sim T^4$, $p = \frac{1}{3}\rho$

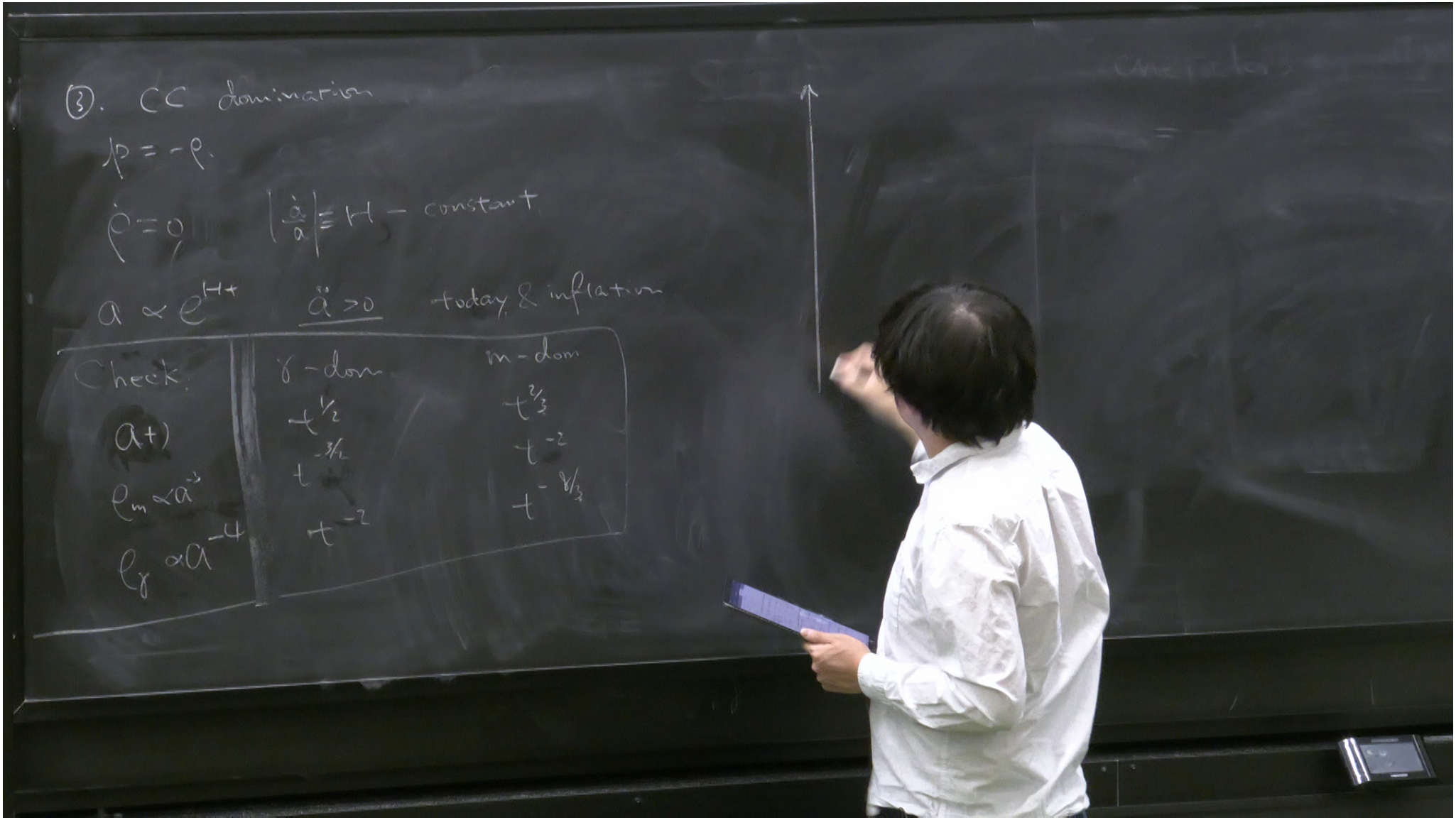
t and a increase. $e \downarrow$ $T \propto \frac{1}{a} \downarrow$

$H^2 \sim \frac{\rho}{M_{pl}^2} \downarrow$ Universe expand.

as it cools down $a \propto t^{1/2}$; $\ddot{a} < 0$

② Matter Domination

$p = 0$ $\rho = m \cdot n \sim m T^3 \propto a^{-3}$


③. CC domination
$p = -\rho$
$\dot{\rho} = 0$
$\left|\frac{\dot{a}}{a}\right| \equiv H$ – constant
$a \propto e^{Ht}$
$\ddot{a} > 0$
today & inflation
Check:
$a(t)$
$\rho_m \propto a^{-3}$
$\rho_\gamma \propto a^{-4}$
γ-dom
$t^{1/2}$
$t^{-3/2}$
t^{-2}
m-dom
$t^{2/3}$
t^{-2}
$t^{-8/3}$

③. CC domination

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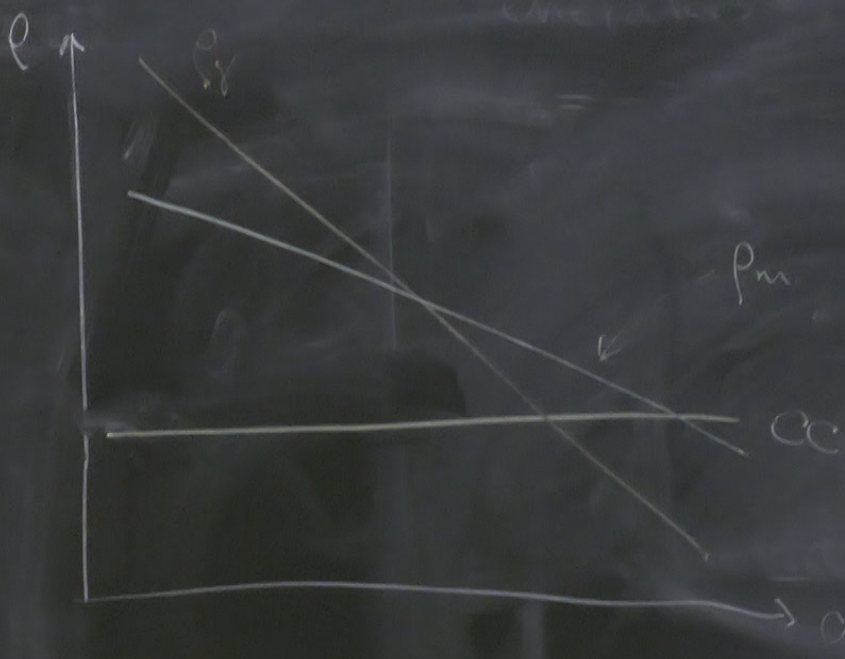
$a(t)$	$t^{1/2}$	$t^{2/3}$
$\rho_m \propto a^{-3}$	$t^{-3/2}$	t^{-2}
$\rho_\gamma \propto a^{-4}$	t^{-2}	$t^{-8/3}$



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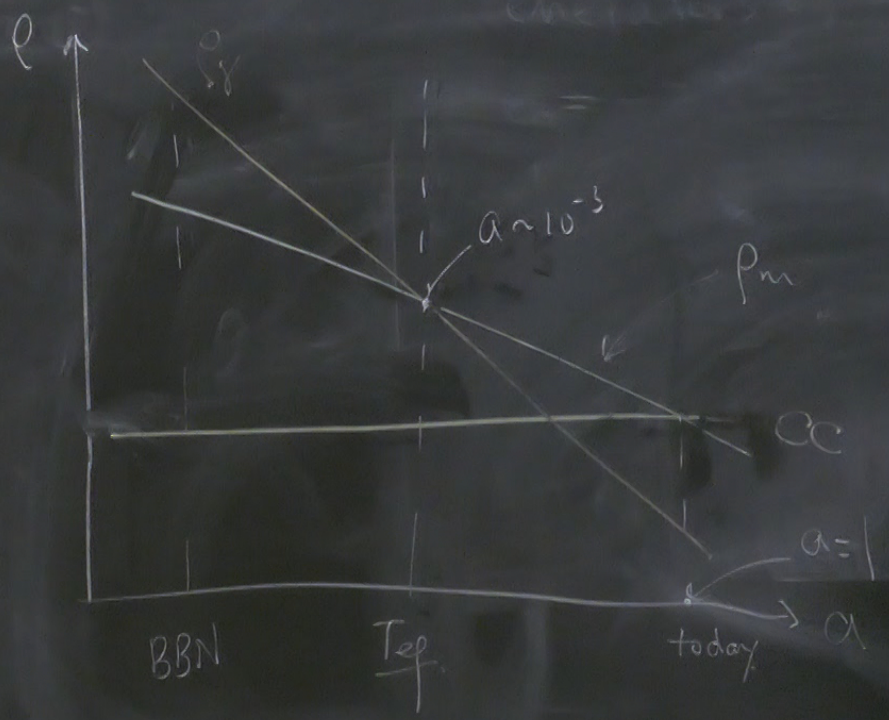

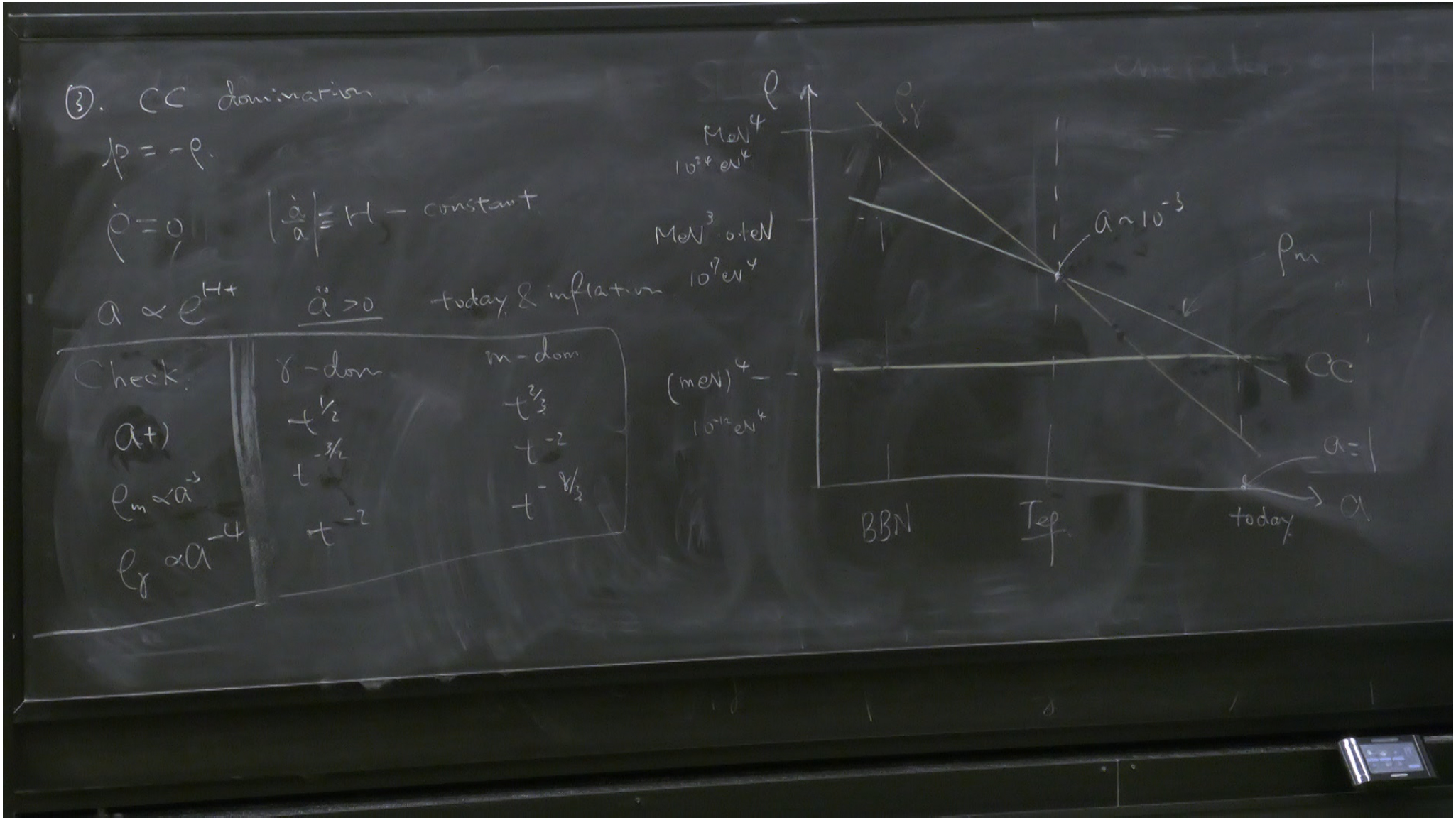
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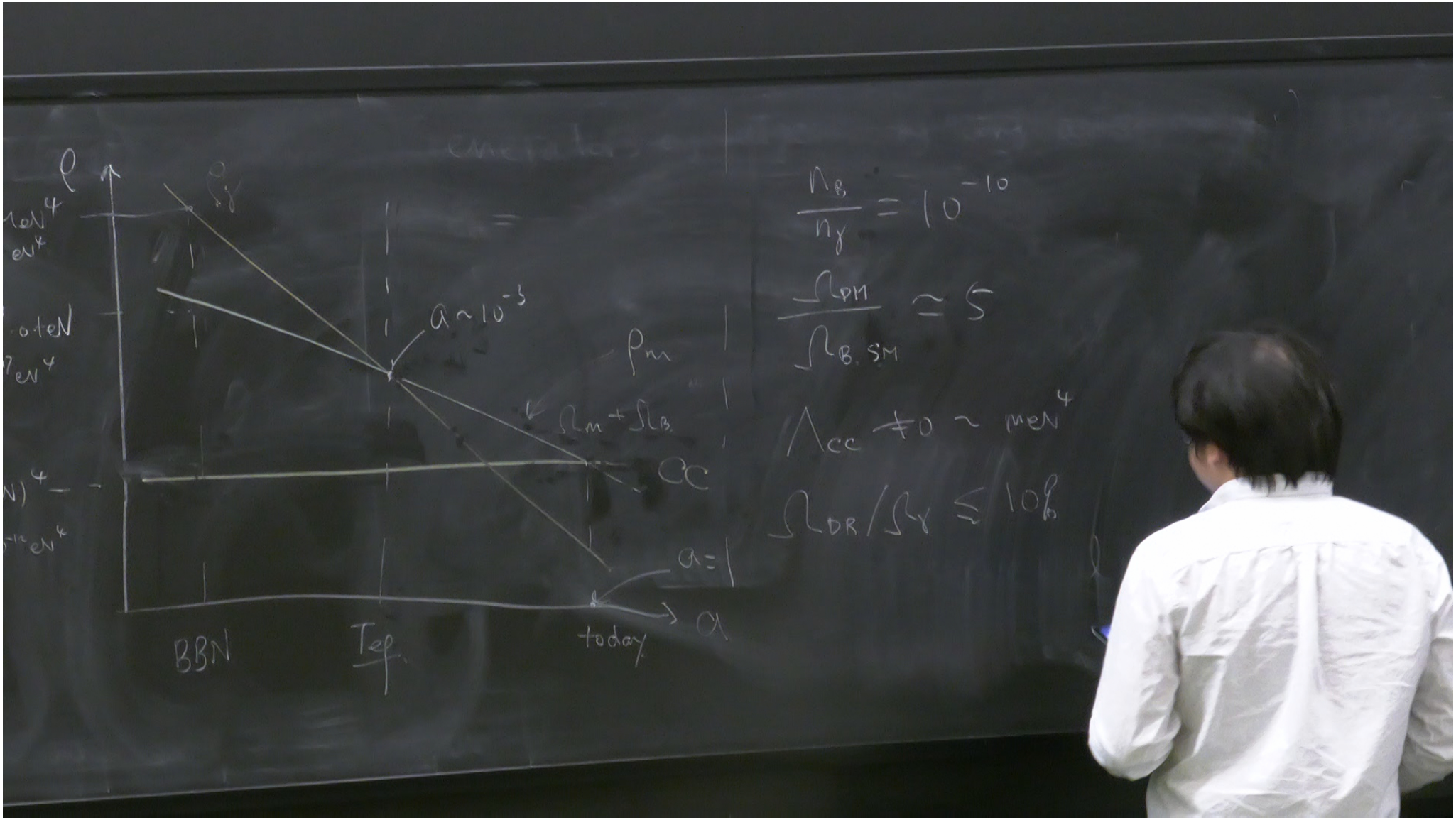
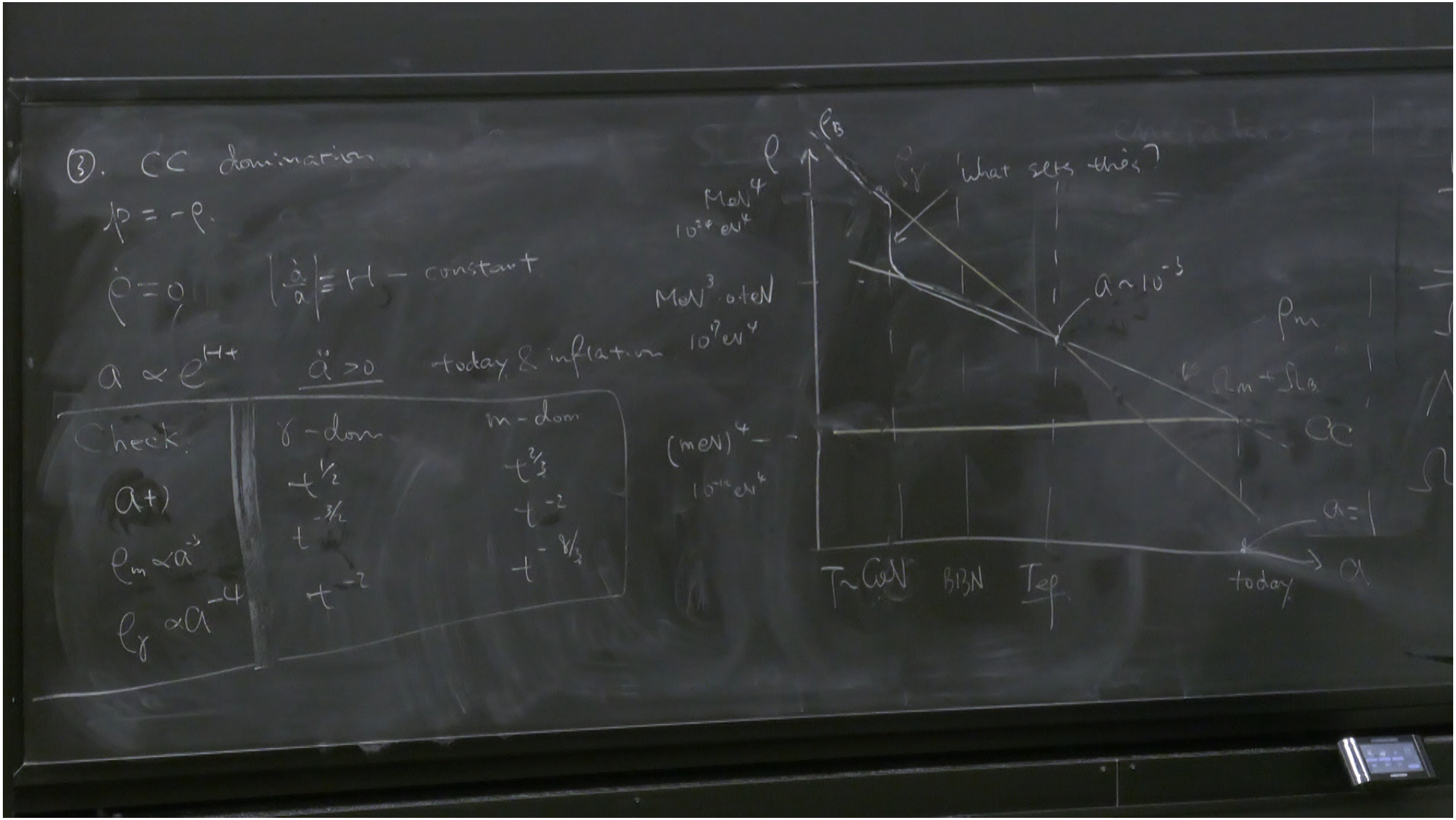
$t^{1/2}$
$t^{-3/2}$
t^{-2}
m-dom
$t^{2/3}$
t^{-2}
$t^{-8/3}$
ρ
ρ_γ
ρ_m
CC
$a \sim 10^{-5}$
$a = 1$
a
BBN
Eq.
today
MeV^4
10^{24} eV^4
MeV$^3 \cdot 0.1$eV
10^{17}eV^4
$(m_e$eV$)^4$
10^{-12}eV^4


ρ
ρ_γ
$a \sim 10^{-3}$
ρ_m
$\Omega_m + \Omega_B$
Λ_{CC}
$a = 1$
a
BBN
Eq.
today
$\frac{n_B}{n_\gamma} = 10^{-10}$
$\frac{\Omega_{DM}}{\Omega_{B,SM}} \simeq 5$
$\Lambda_{CC} \neq 0 \sim meV^4$
$\Omega_{DR}/\Omega_\gamma \leq 10\%$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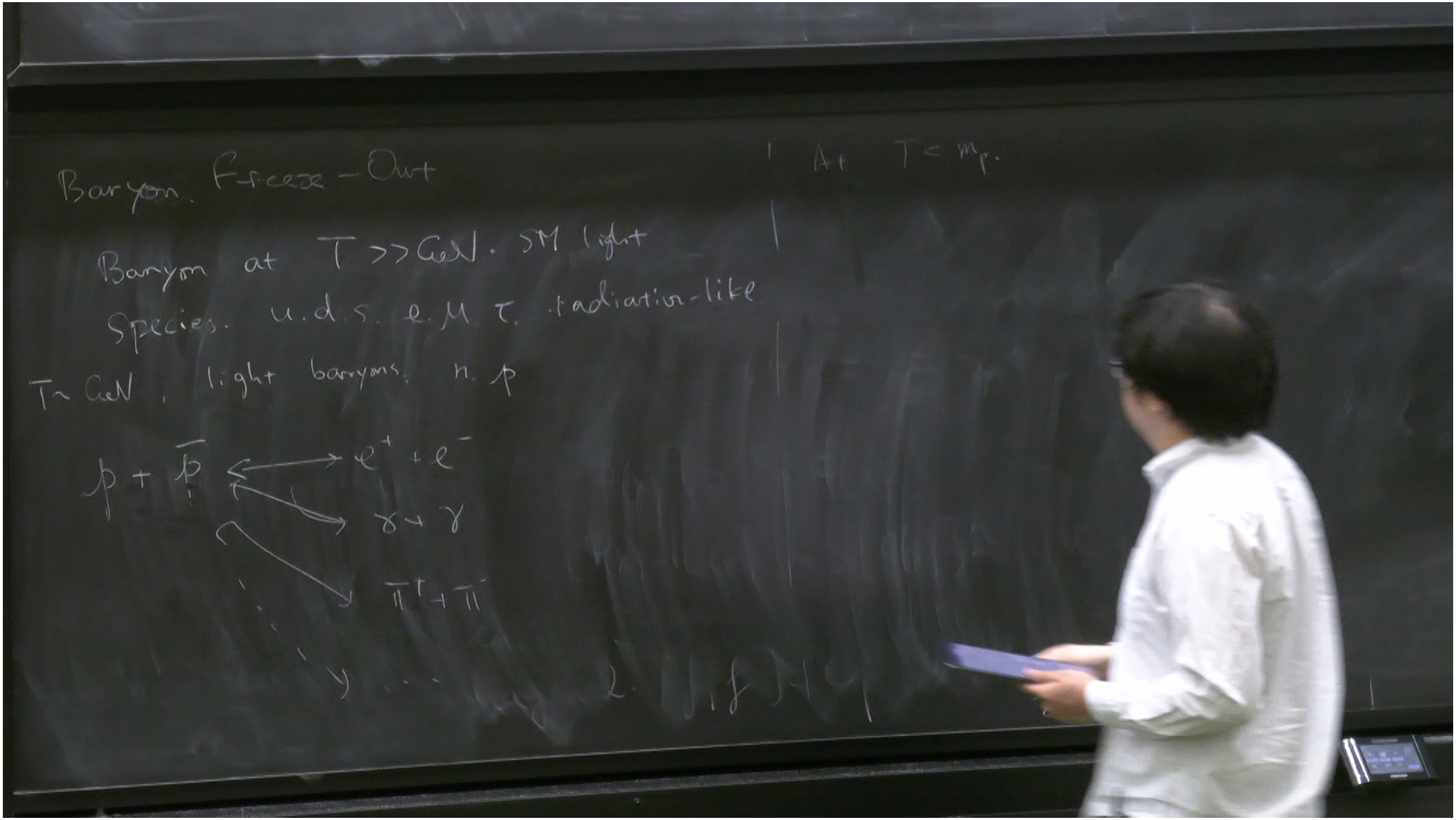
$t^{1/2}$
$t^{-3/2}$
t^{-2}
m-dom
$t^{2/3}$
t^{-2}
$t^{-8/3}$
ρ
ρ_B
ρ_γ
what sets this?
$a \sim 10^{-3}$
ρ_m
$\rho_m + \rho_B$
CC
$a = 1$
today
a
$T \sim$ GeV
BBN
Teq
MeV^4
10^{24} eV^4
MeV^3 0.1eV
10^{17} eV^4
(meV)^4
10^{-12} eV^4


Baryon Freeze-Out
At $T < m_p$.
Baryon at $T >> GeV$. SM light
Species. u.d.s. e.μ.τ. radiation-like
$T \sim GeV$, light baryons: n. p
$p + \bar{p}$
$e^+ + e^-$
$\gamma + \gamma$
$\pi^+ + \pi^-$

Baryon Freeze-Out

Baryon at $T \gg$ GeV. SM light species. u.d.s.e.μ.τ. radiation-like

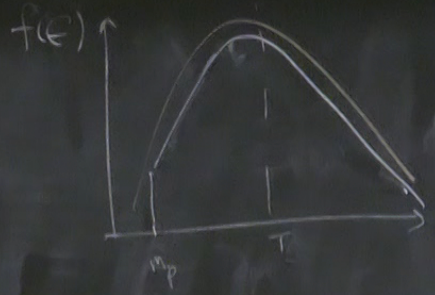
$T \sim$ GeV, light baryons: n, p

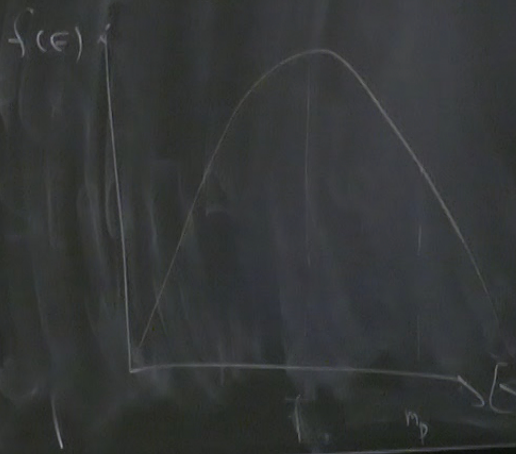
$p + \bar{p} \rightleftarrows e^+ + e^-$

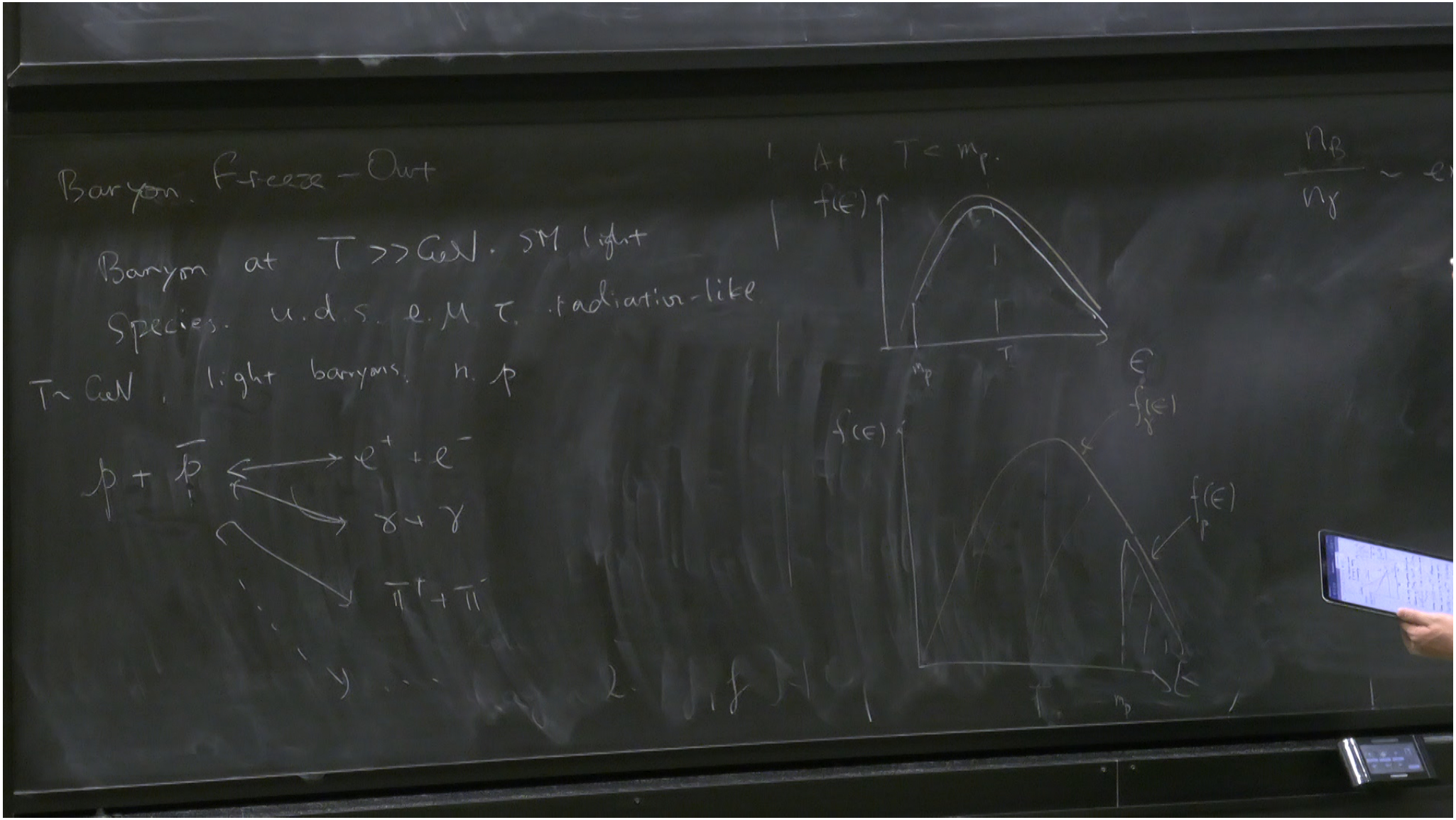
$\gamma + \gamma$

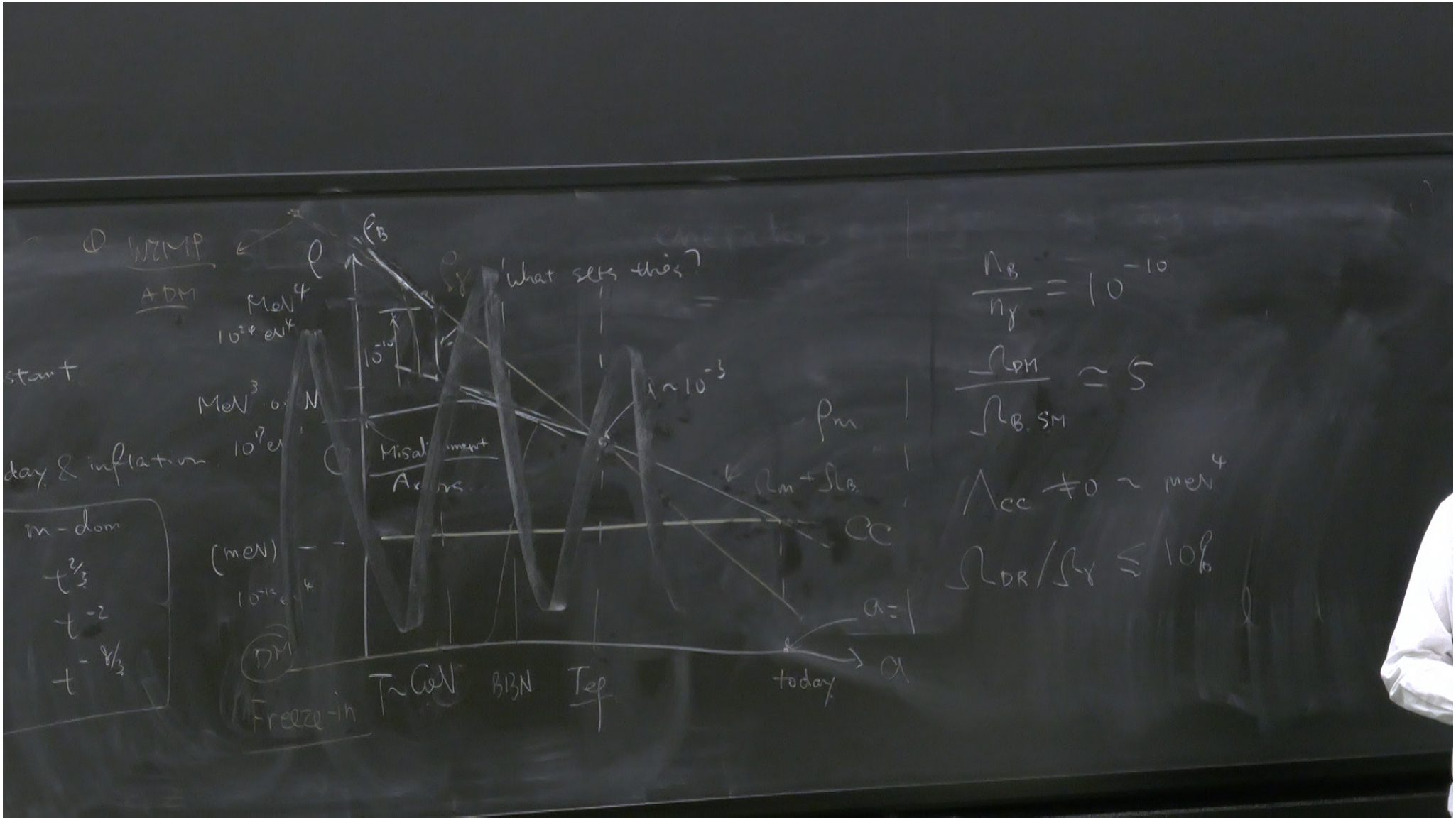
$\pi^+ + \pi^-$

At $T < m_p$.






Baryon Freeze-Out
Baryon at T >> GeV. SM light
species. u.d.s.e.μ.τ. radiation-like
T~GeV, light baryons: n, p
p + p̄
e⁺ + e⁻
γ + γ
π⁺ + π⁻
At T < m_p.
f(ε)
m_p
T
ε
f_γ(ε)
f_p(ε)
n_B / n_γ


WIMP
ADM
MeV^4
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Misalignment
Freeze-in
T~MeV
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what sets this?
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ρ_m
ρ_m + ρ_B
Λ_CC ≠ 0 ~ meV^4
Ω_DR/Ω_γ ≤ 10%
Ω_DM / Ω_B,SM ≃ 5
n_B/n_γ = 10^-10