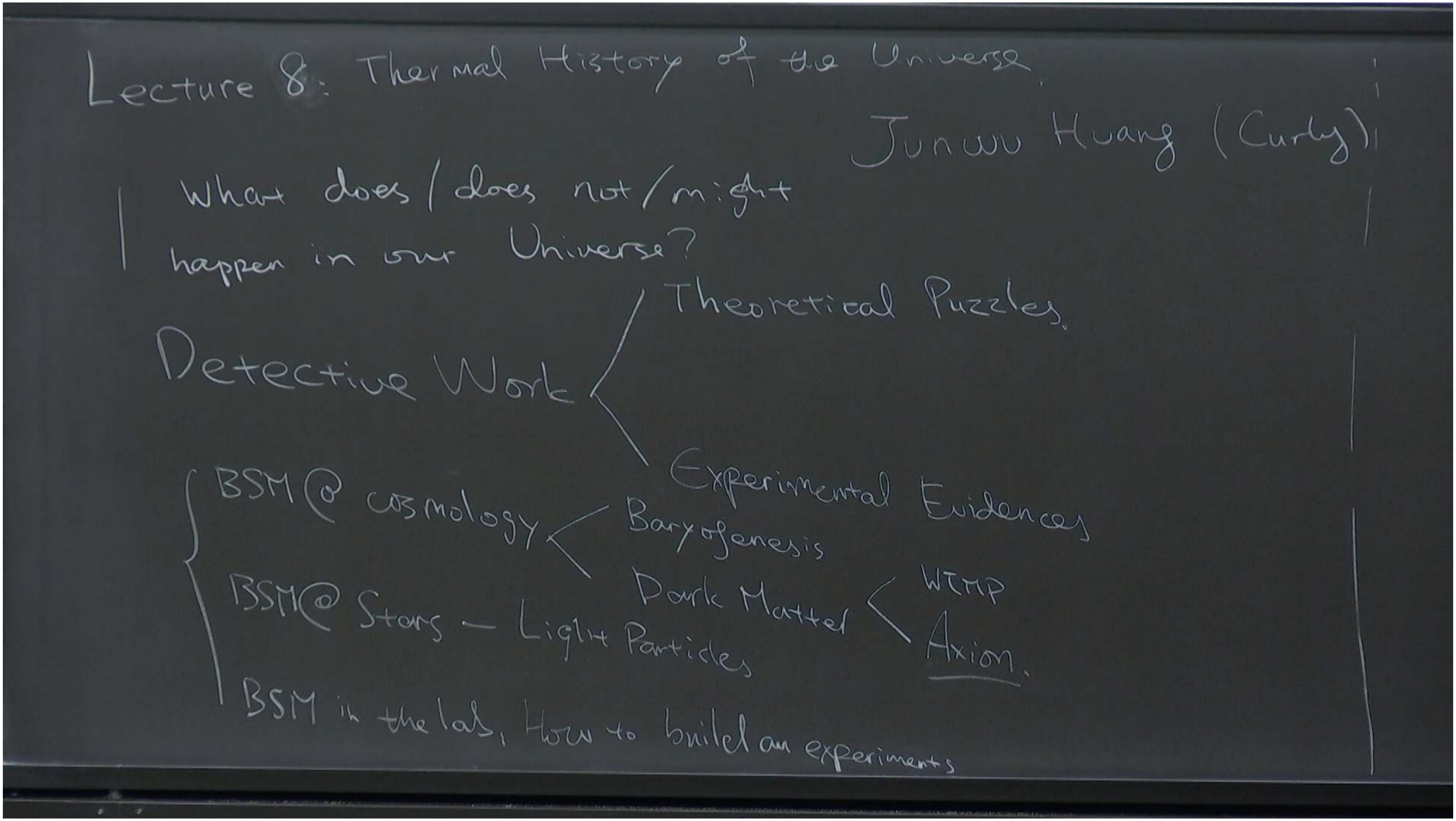
Title: Particle Physics Lecture - 230320

Speakers: Junwu Huang

Collection: Particle Physics (2022/2023)

Date: March 20, 2023 - 11:30 AM

URL: https://pirsa.org/23030063


Lecture 8: Thermal History of the Universe.
Junwu Huang (Curly)
What does / does not / might happen in our Universe?
Detective Work
Theoretical Puzzles.
Experimental Evidences
BSM @ cosmology
Baryogenesis
Dark Matter
WIMP
Axion.
BSM @ Stars — Light Particles
BSM in the lab, How to build an experiments

f the Universe.

Junwu Huang (Curly)

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Matter < WIMP, Axion.

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FRW. universe:

Einstein Eq: $G^{\mu\nu} = 8\pi G\, T^{\mu\nu}$

with EM tensor $T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$

metric: $ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2$

1. $\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\rho$ $\quad H^2 \equiv \left(\frac{\dot a}{a}\right)^2$

2. $2\left(\frac{\ddot a}{a}\right) + \left(\frac{\dot a}{a}\right)^2 = -8\pi G p$

$\frac{d(\text{eq }1)}{dt} \Rightarrow \dot\rho = -3H(\rho + p)$

$p = \omega\rho$

① Ra

verse:

$G^{\mu\nu} = 8\pi G\, T^{\mu\nu}$ $\qquad T^{\mu\nu} g_{\mu\nu}$

tensor: $T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}$

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$2\left(\frac{\ddot a}{a}\right) + \left(\frac{\dot a}{a}\right)^2 = -8\pi G p$

$\Rightarrow \dot\rho = -3H(\rho + p)$

① Radiation: $\rho_\gamma \sim T^4 \qquad p = \frac{1}{3}\rho$

$t \uparrow, \quad \dot\rho < 0 \rightarrow \rho \downarrow \rightarrow T \downarrow$

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$t \uparrow, \quad \dot{\rho} < 0 \to \rho \downarrow \to T \downarrow$

$H^2 \sim \frac{\rho}{M_{pl}^2} \sim \frac{T^4}{M_{pl}^2} \downarrow$ universe size. $\sim \frac{1}{H}$ is increasing.

$a(t) \propto t^{1/2}$

② Matter Domination. $\underline{\rho_m = m \cdot n} \sim m T^3. \quad p = 0 \ (w = 0)$

$t \uparrow \quad \dot{\rho} < 0 \to \rho \downarrow$

$H^2 = \frac{\rho}{M_{pl}^2} \sim \frac{m T^3}{M_{pl}^2} \downarrow$ universe expanding.

③ CC domination $w = -1 \quad p = -\rho$

$\dot{\rho} = 0 \Rightarrow \rho = \Lambda_{cc} \quad H^2 = \frac{\rho}{M_{pl}^2} = \text{constant}$

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$\frac{\dot{a}}{a} = \text{constant} \Rightarrow a \propto \exp^{Ht}$

$a(t) \propto t^{1/2}$

$= \left(\frac{\dot{a}}{a}\right)^2$

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$T^{\mu\nu} g_{\mu\nu}$

$p \quad p$

$= \left(\frac{\dot a}{a}\right)^2$

ρ

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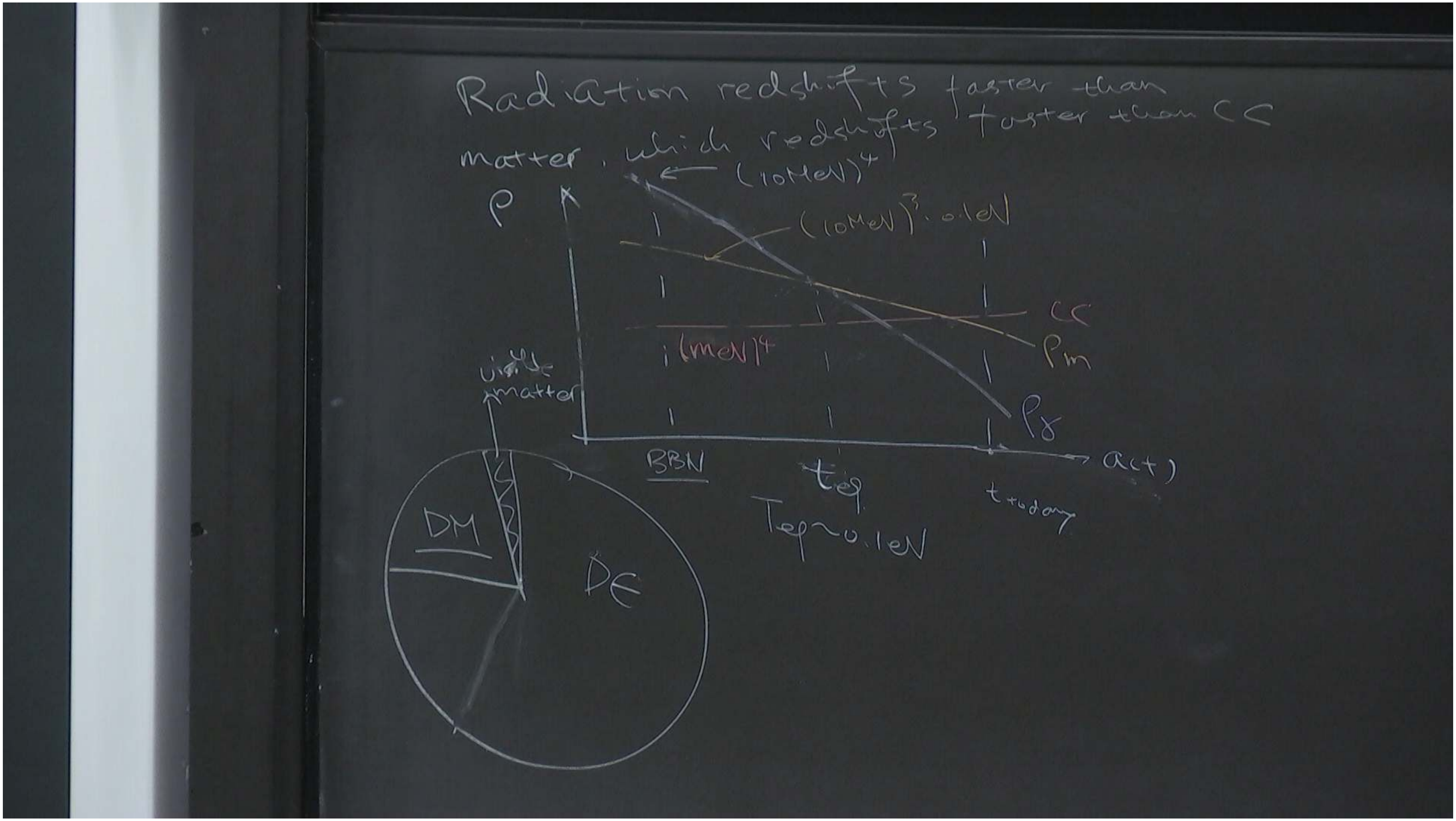
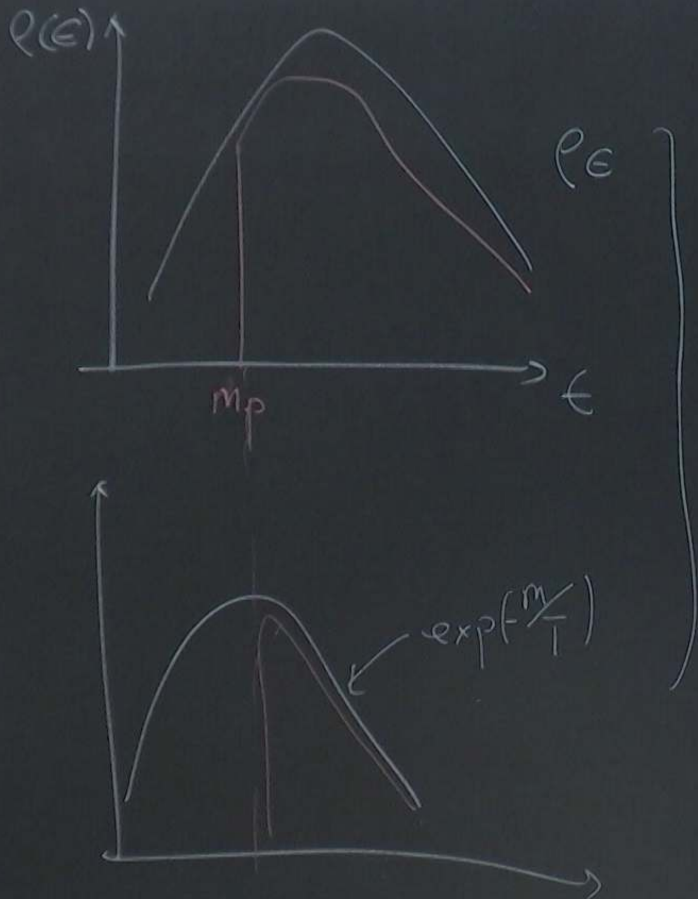

Radiation redshifts faster than matter, which redshifts faster than CC
(10MeV)^4
ρ
(10MeV)^3 · 0.1eV
CC
(meV)^4
ρm
visible matter
ργ
BBN
teq
Teq ~ 0.1eV
ttoday
a(t)
DM
DE

CC

Measurement that points to BSM.

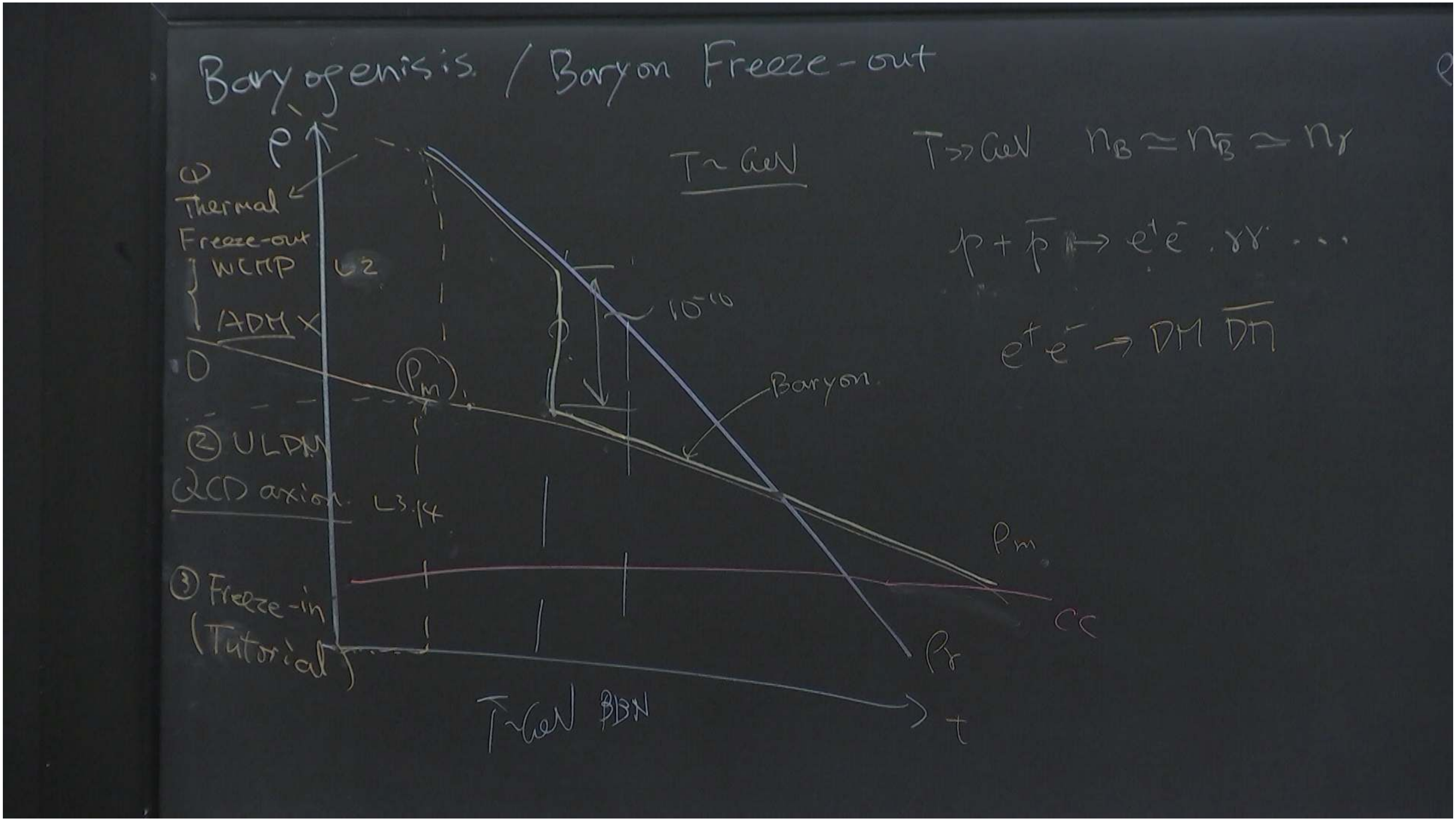
$n_B/n_\gamma \simeq 10^{-10}$ $\quad \dfrac{\Omega_{DM}}{\Omega_{SM}} \simeq 5$ $\quad \Lambda_{cc} \neq 0$

$\Omega_{DR}/\Omega_{SM} \lesssim 10\%$



$$\Rightarrow \frac{n_B + n_{\bar{B}}}{n_\gamma} \propto \exp(-m/T)$$

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} = \text{constant} = 10^{-10}$$


Baryogenisis / Baryon Freeze-out
T ~ GeV
T >> GeV $n_B \simeq n_{\bar{B}} \simeq n_\gamma$
$p + \bar{p} \leftrightarrow e^+e^-, \gamma\gamma \ldots$
$e^+e^- \to DM\ \overline{DM}$
10^{-10}
Baryon
① Thermal Freeze-out
WIMP L2
ADM X
② ULDM
QCD axion L3, 14
③ Freeze-in
(Tutorial)
ρ_m
ρ_γ
CC
T ~ GeV BBN
t