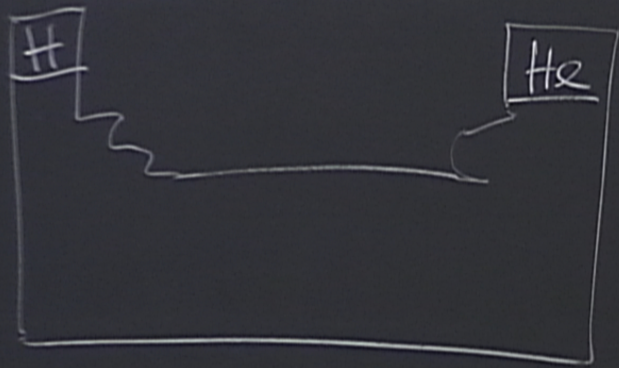
Title: PSI 2015/2016 Cosmology - Lecture 6

Date: Feb 08, 2016 11:30 AM

URL: http://pirsa.org/16020056

Abstract:

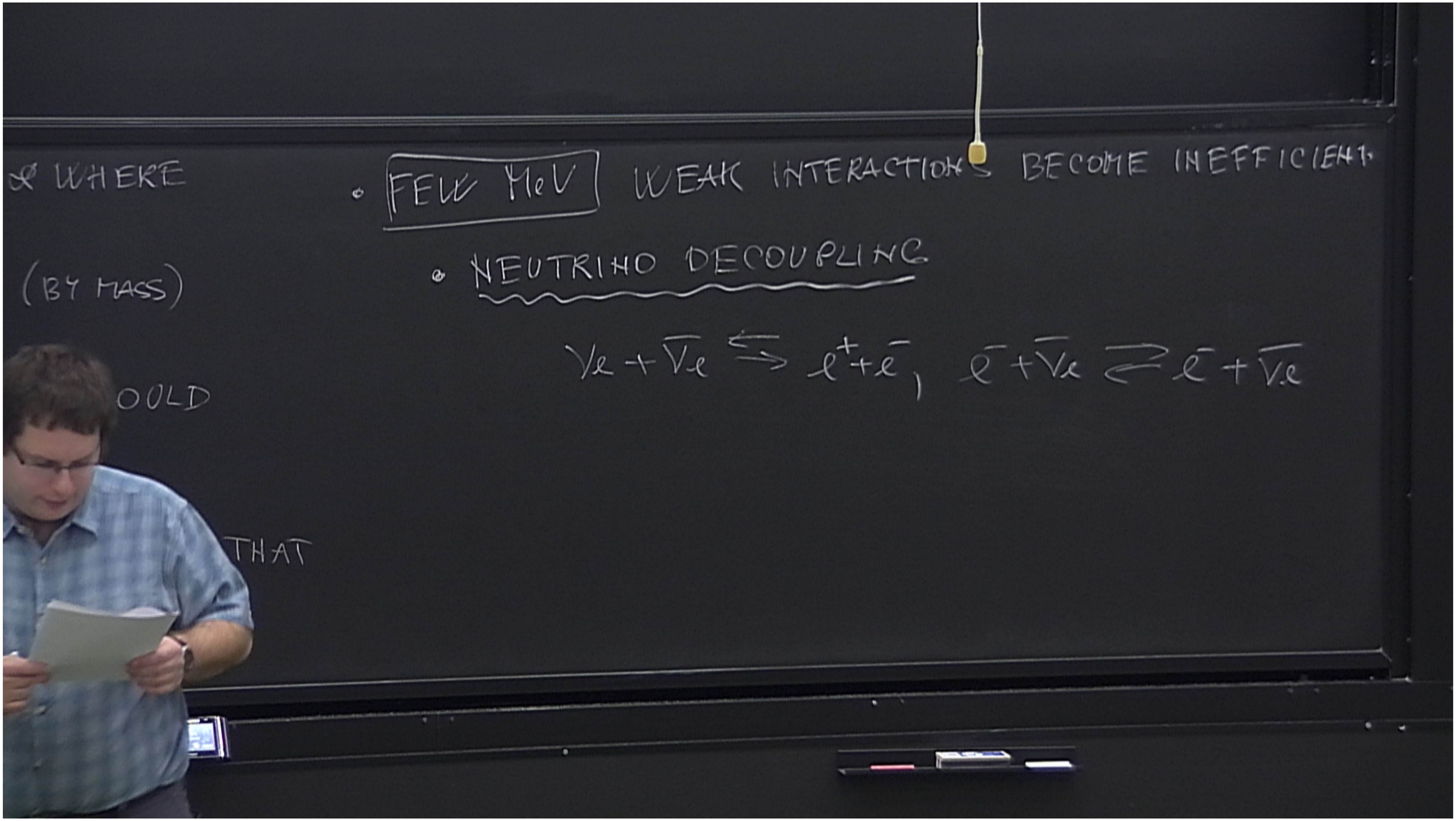


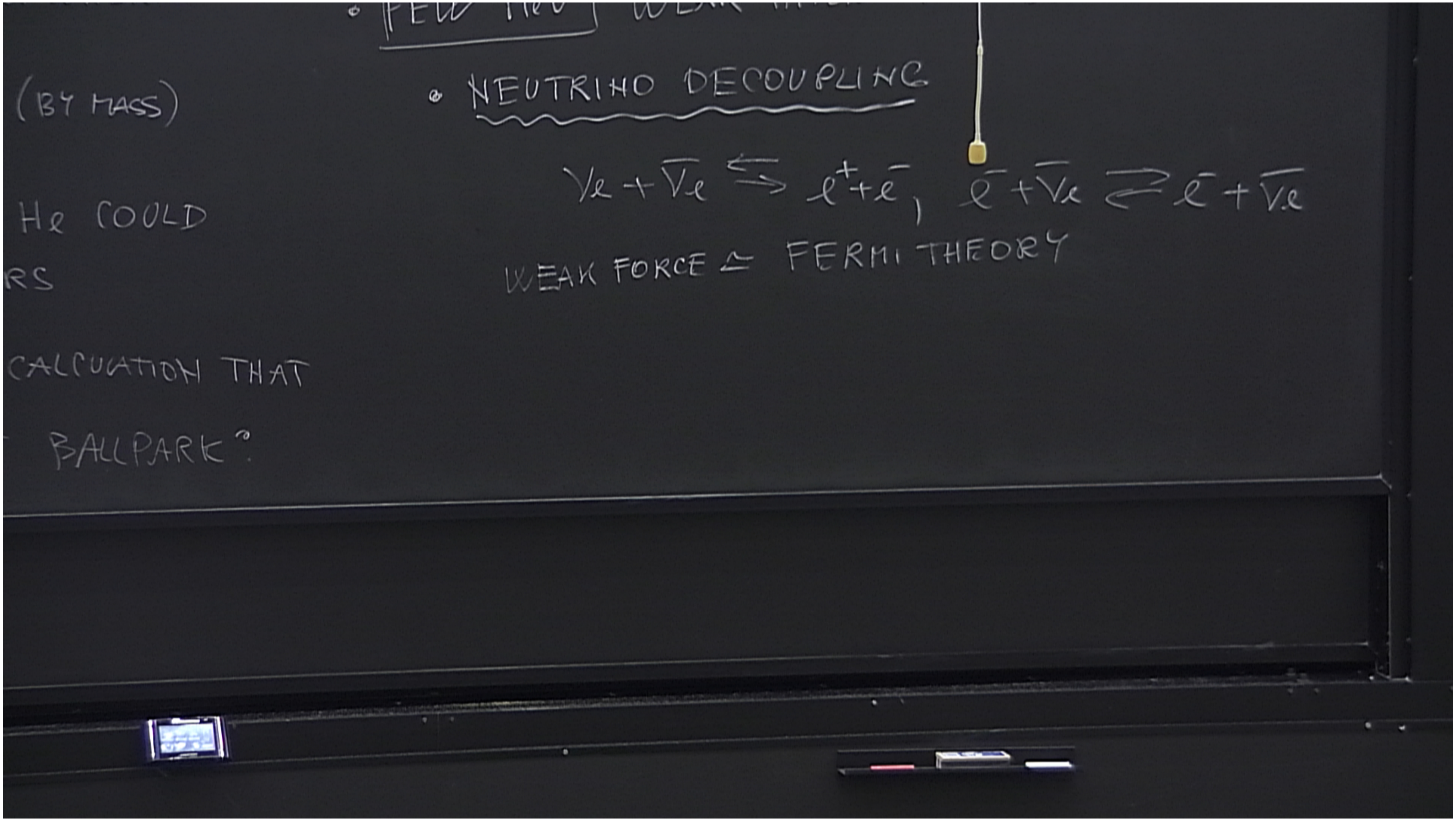
WANT TO EXPLAIN WHEN & WHERE PRODUCED:

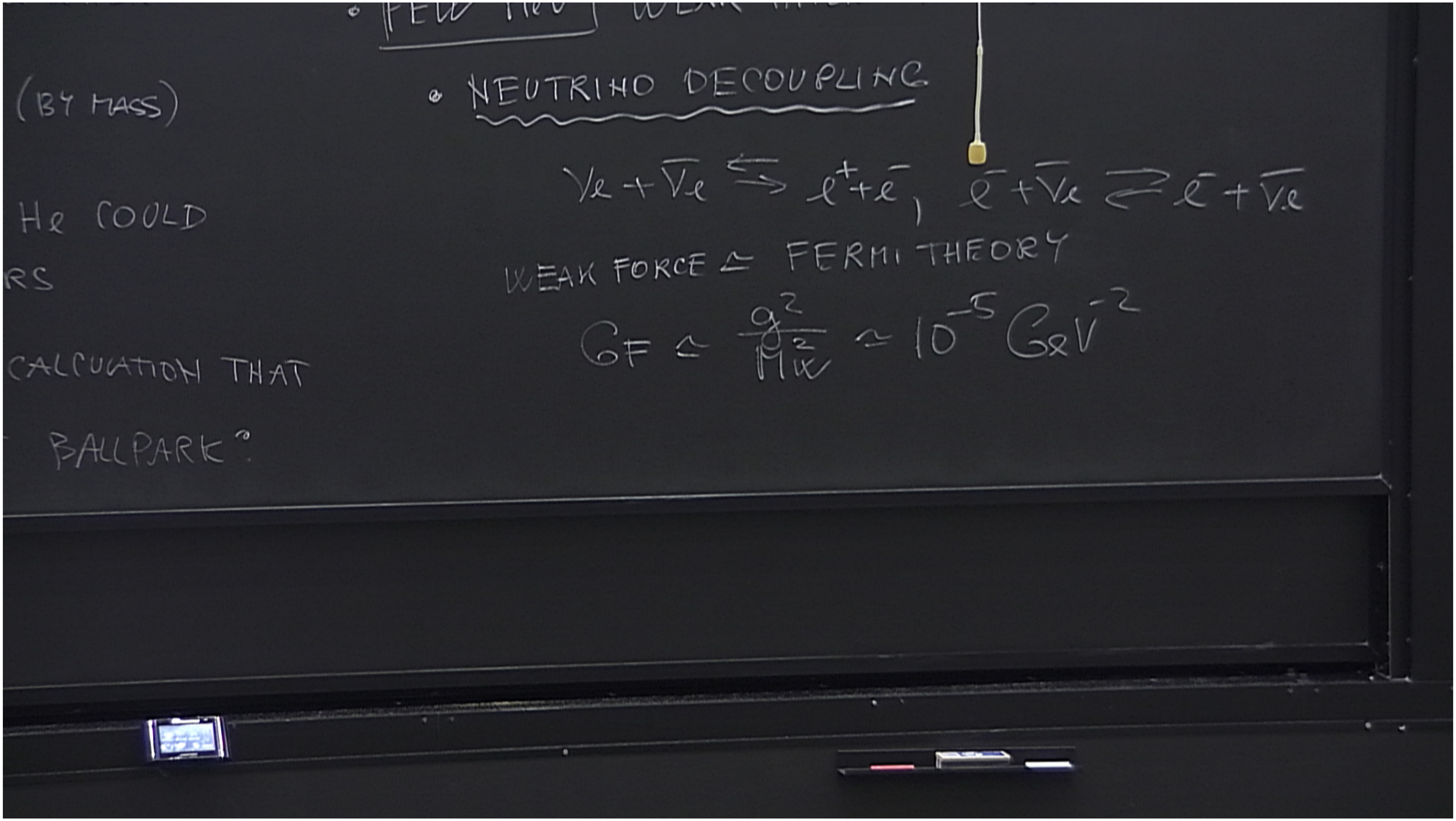
75% H

25% He (BY MASS)

- ONLY LESS THAN 1% OF He COULD HAVE BEEN FUSED IN STARS
- BACK OF THE ENVELOPE CALCULATION THAT BBN GIVES RIGHT BALLPARK?


& WHERE
(BY MASS)
OULD
THAT
• FEW MeV WEAK INTERACTIONS BECOME INEFFICIENT.
• NEUTRINO DECOUPLING
$\nu_e + \bar{\nu}_e \rightleftarrows e^+ + e^-$, $e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$


(BY MASS)
He COULD
RS
CALCULATION THAT
BALLPARK?
NEUTRINO DECOUPLING
$\nu_e + \bar{\nu}_e \leftrightarrows e^+ + e^-$, $e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$
WEAK FORCE ≃ FERMI THEORY


(BY MASS)
He COULD
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CALCUATION THAT
BALLPARK?
• NEUTRINO DECOUPLING
$\nu_e + \bar{\nu}_e \leftrightarrows e^+ + e^-$, $e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$
WEAK FORCE ≃ FERMI THEORY
$G_F \simeq \frac{g^2}{M_W^2} \simeq 10^{-5}\,GeV^{-2}$

• NEUTRINO DECOUPLING

(BY MASS)

He COULD

RS

CALCULATION THAT

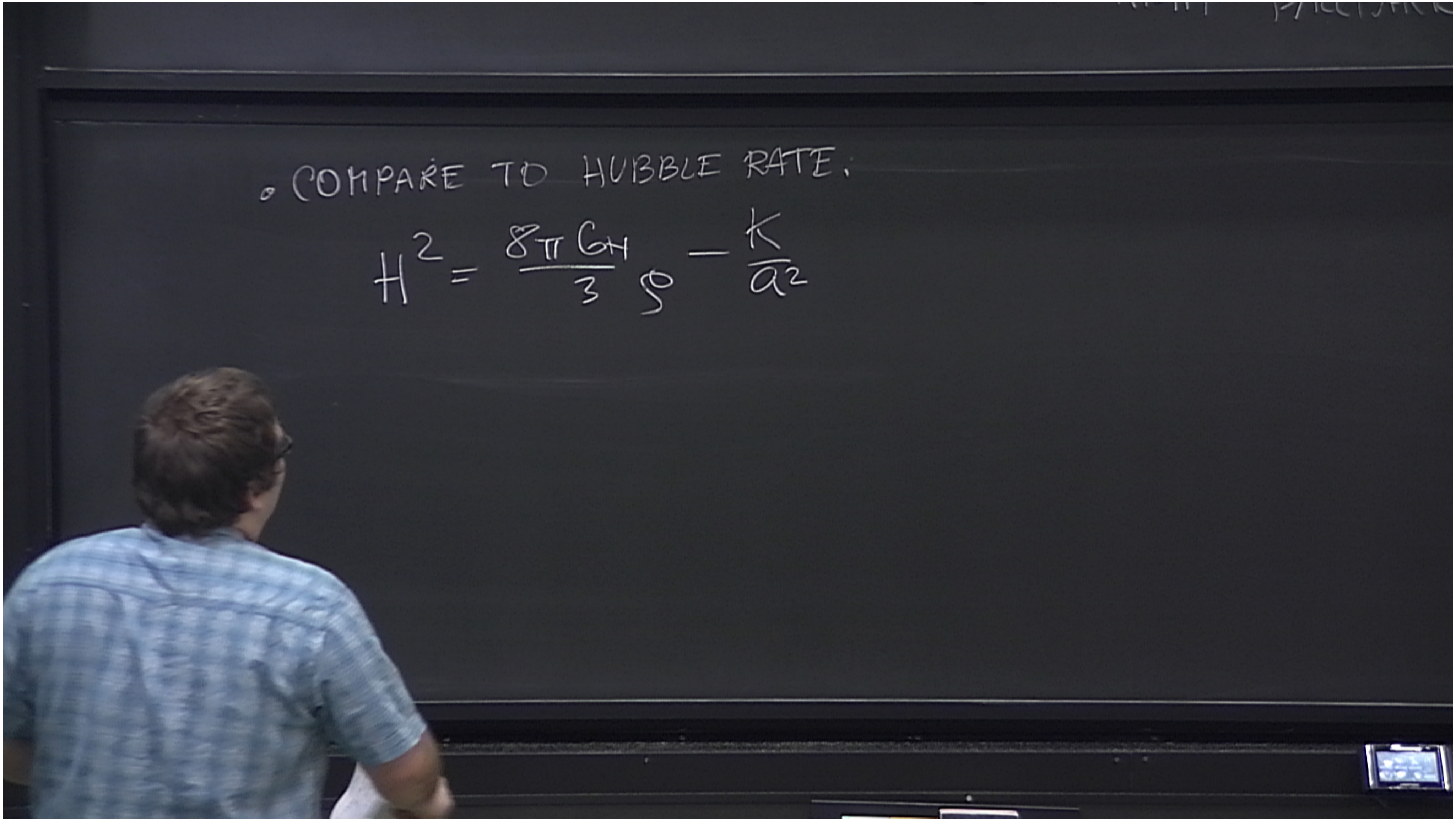
BALLPARK?

$$\nu_e + \bar{\nu}_e \leftrightarrows e^+ + e^-, \quad e^- + \bar{\nu}_e \rightleftarrows e^- + \bar{\nu}_e$$

WEAK FORCE $\simeq$ FERMI THEORY

$$G_F \simeq \frac{g^2}{M_W^2} \simeq 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\Rightarrow \Gamma \sim G_F^2 T^5$$


COMPARE TO HUBBLE RATE:
$H^2 = \frac{8\pi G_N}{3}\rho - \frac{K}{a^2}$

- COMPARE TO HUBBLE RATE:

$$H^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{k}{a^2}} = \left| \, G_N = \frac{1}{M_{Pl}^2} \, \right|$$

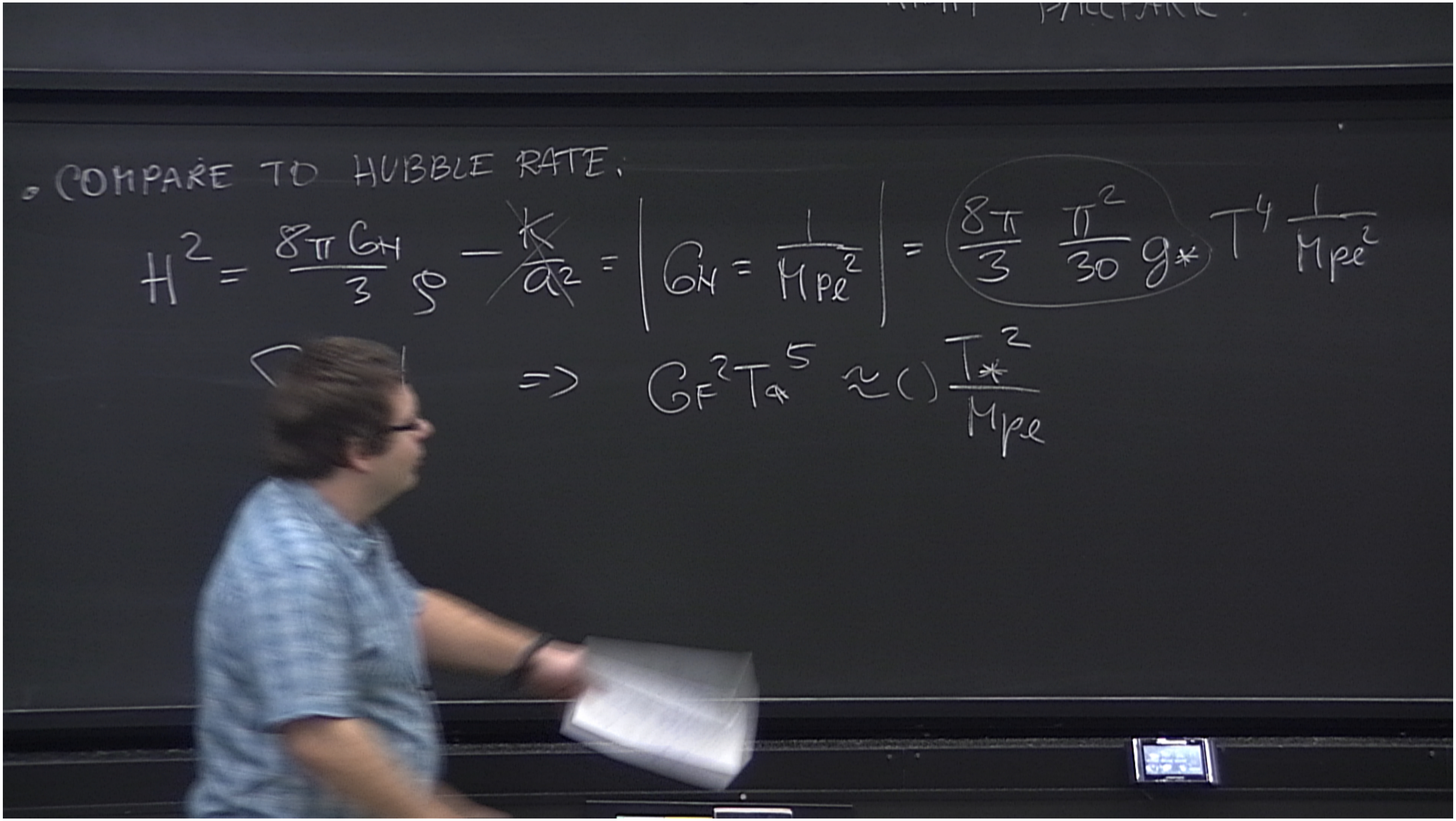
- COMPARE TO HUBBLE RATE.

$$H^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{k}{a^2}} = \left| G_N = \frac{1}{M_{Pl}^2} \right| = \frac{8\pi}{3}\frac{\pi^2}{30} g_* T^4 \frac{1}{M_{Pl}^2}$$

- COMPARE TO HUBBLE RATE.

$$H^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{k}{a^2}} = \left| G_N = \frac{1}{M_{pl}^2} \right| = \frac{8\pi}{3}\frac{\pi^2}{30} g_* T^4 \frac{1}{M_{pl}^2}$$

$$\Gamma \simeq H \quad \Rightarrow \quad G_F^2 T_*^5 \simeq \frac{T_*^2}{M_{pl}}$$

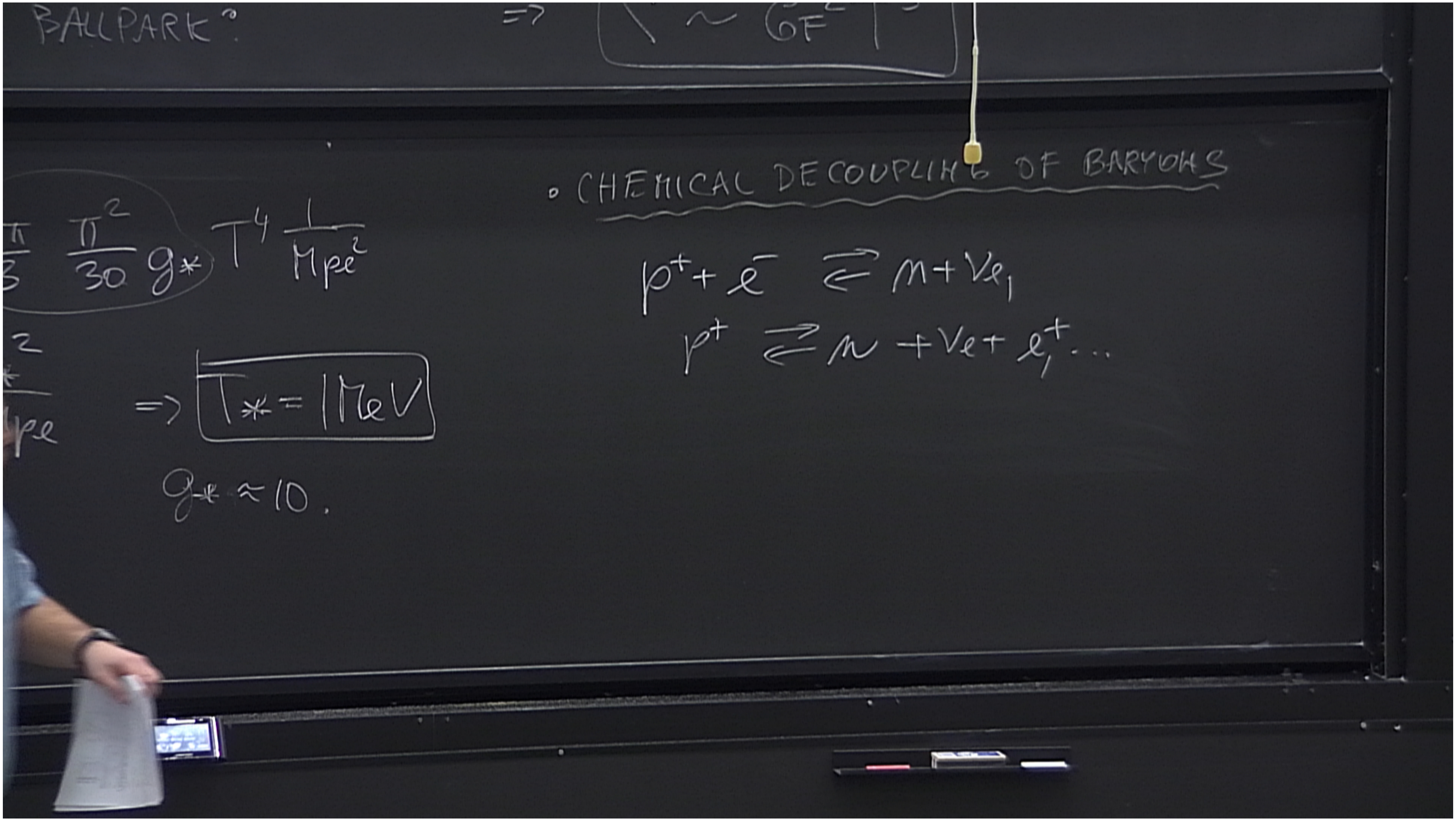

• COMPARE TO HUBBLE RATE.
$H^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{k}{a^2}} = \left| G_N = \frac{1}{M_{pl}^2} \right| = \frac{8\pi}{3}\frac{\pi^2}{30} g_* T^4 \frac{1}{M_{pl}^2}$
$\Rightarrow G_F^2 T_*^5 \approx (\,) \frac{T_*^2}{M_{pl}}$

OMPARE TO HUBBLE RATE.

$$H^2 = \frac{8\pi G_N}{3}\rho - \cancel{\frac{K}{a^2}} = \left| G_N = \frac{1}{M_{pl}^2} \right| = \frac{8\pi}{3}\,\frac{\pi^2}{30}\,g_*\,T^4\,\frac{1}{M_{pl}^2}$$

$$\Gamma \simeq H \quad \Rightarrow \quad G_F^2 T_*^5 \simeq (\,)\,\frac{T_*^2}{M_{pl}} \quad \Rightarrow \quad \boxed{T_* = 1\,\mathrm{MeV}}$$

$g_* \simeq 10.$


BALLPARK?
• CHEMICAL DECOUPLING OF BARYONS
$p^+ + e^- \rightleftarrows n + \nu_e$,
$p^+ \rightleftarrows n + \nu_e + e^+$, ...
$\frac{\pi^2}{30} g_* T^4 \frac{1}{M_{pl}^2}$
$T_* = 1\,\mathrm{MeV}$
$g_* \approx 10$.

BALLPARK?

$\Rightarrow \boxed{\Gamma \sim G_F^2 T^5}$

$\frac{\pi}{3} \quad \frac{\pi^2}{30} g_* T^4 \frac{1}{M_{pl}^2}$

$\Rightarrow \boxed{T_* = 1\,\text{MeV}}$

$g_* \approx 10.$

- CHEMICAL DECOUPLING OF BARYONS

$$p^+ + e^- \rightleftarrows n + \nu_e,$$

$$p^+ \rightleftarrows n + \nu_e + e^+, \ldots$$

$\Rightarrow$ NEUTRONS FREEZE OUT
(IF NO LONGER EFFICIENT)

$\frac{\ }{30} g_* \quad M_{pl}^2$

$\Rightarrow \boxed{T_* = 1\,\mathrm{MeV}}$

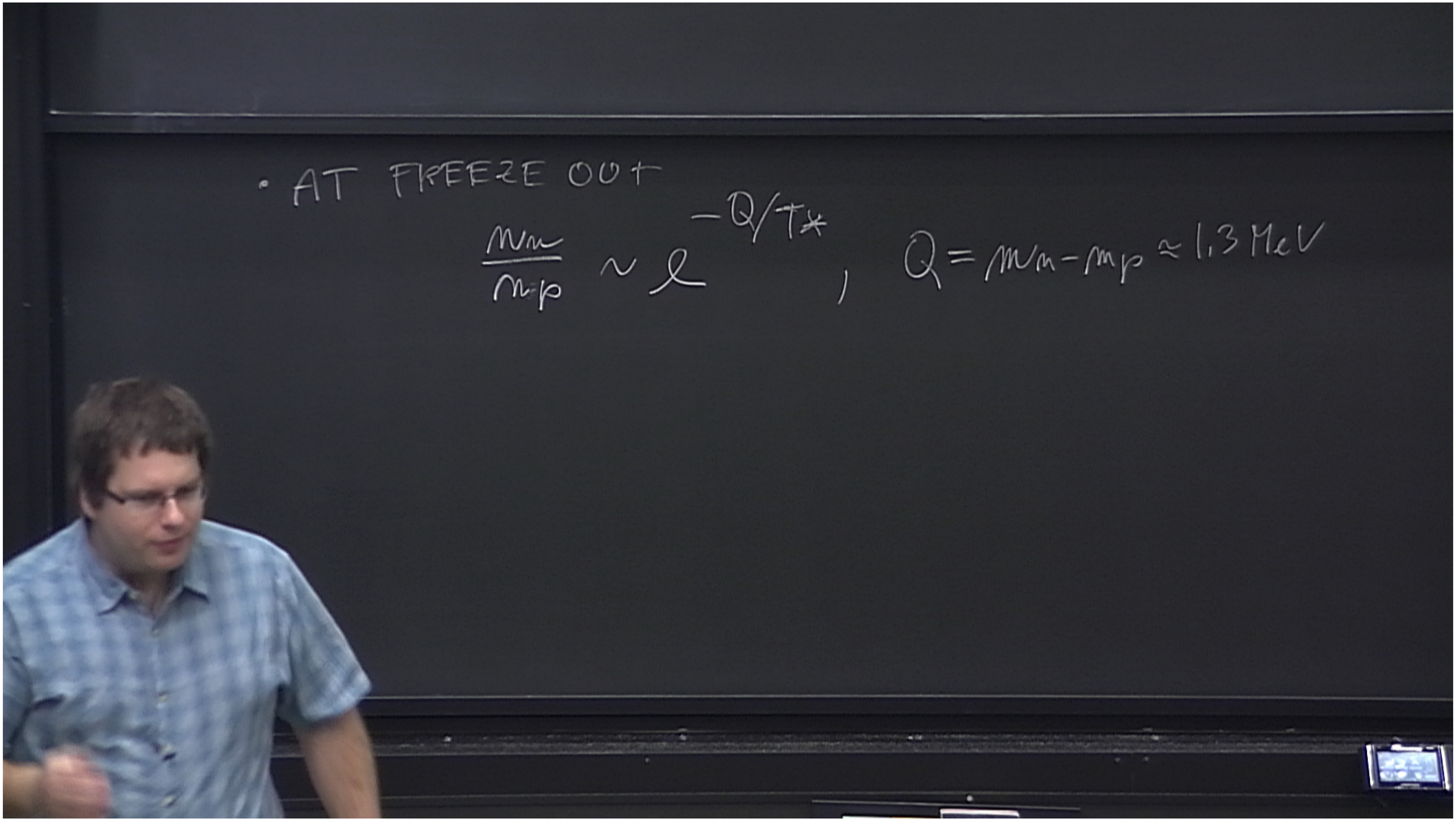
$g_* \approx 10.$

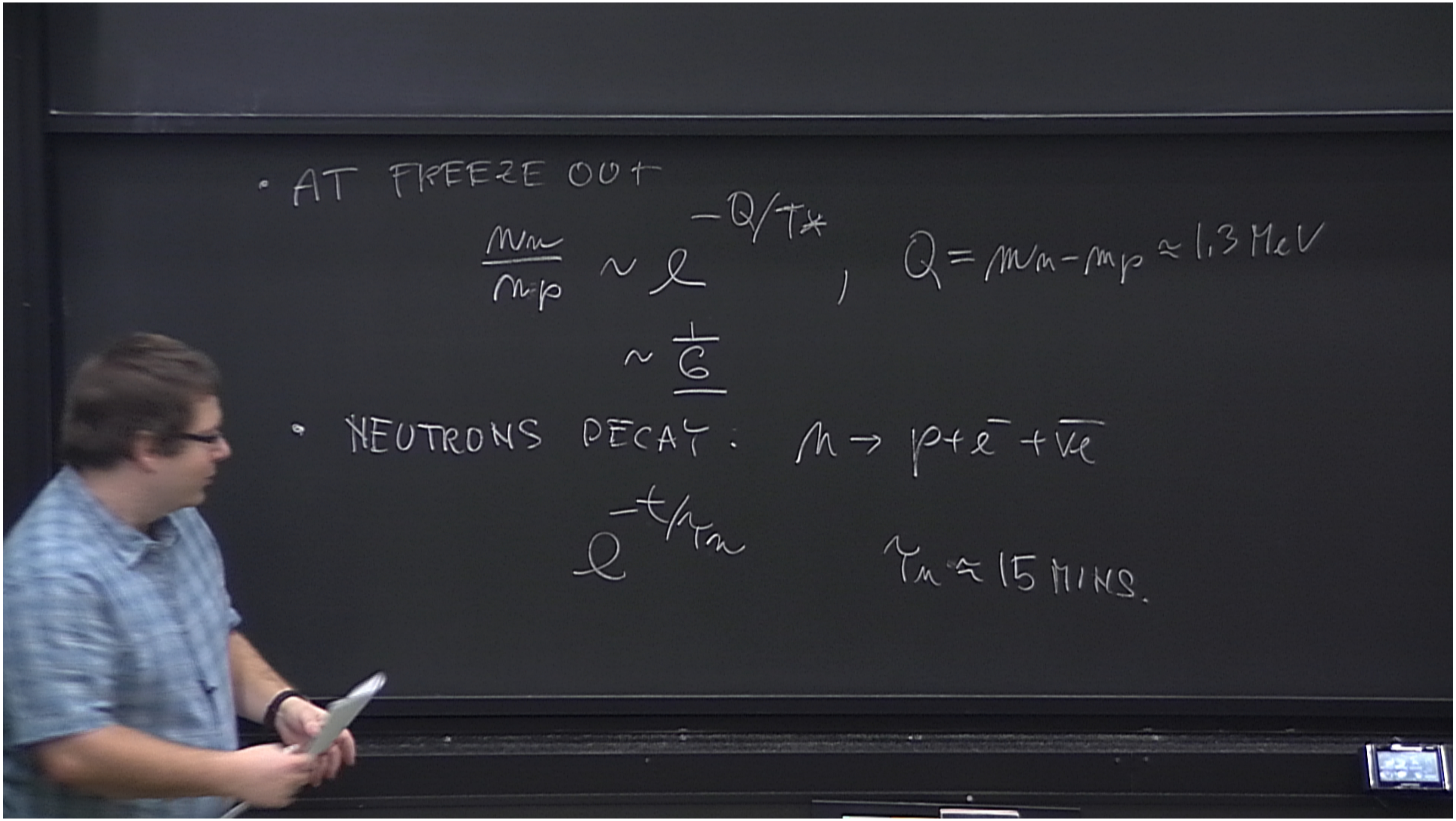
$p^+ + e^- \rightleftarrows n + \nu_e,$

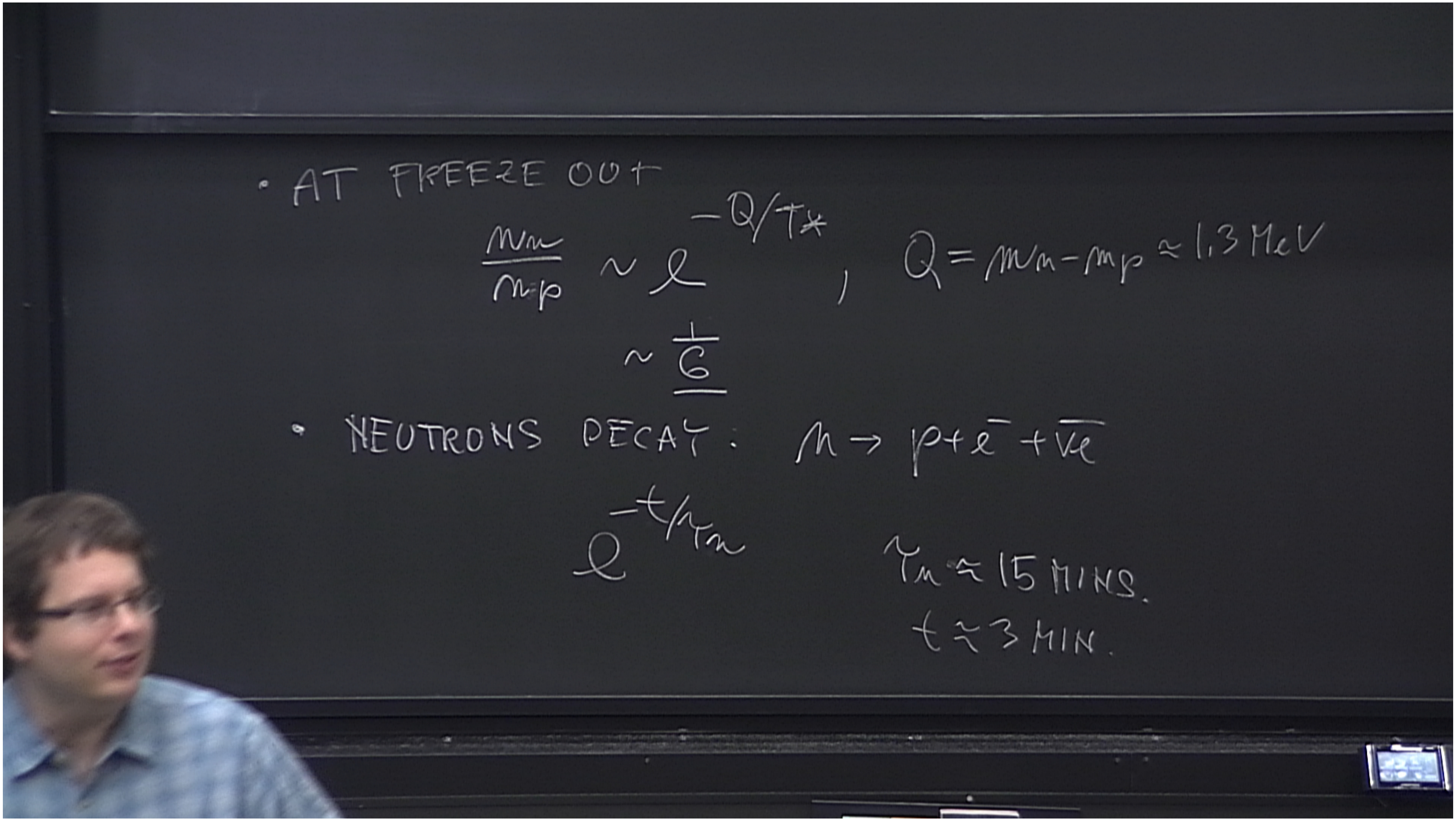
$p^+ \rightleftarrows n + \nu_e + e^+, \ldots$

$\Rightarrow$ NEUTRONS FREEZE OUT
(IF NO LONGER EFFICIENT)

$\boxed{T_* = 0.8\,\mathrm{MeV}}$


• AT FREEZE OUT
$\frac{m_n}{m_p} \sim e^{-Q/T_*}$, $Q = m_n - m_p \simeq 1.3$ MeV


• AT FREEZE OUT
$\frac{m_n}{m_p} \sim e^{-Q/T_*}$, $Q = m_n - m_p \approx 1.3$ MeV
$\sim \frac{1}{6}$
• NEUTRONS DECAY : $n \to p + e^- + \bar{\nu}_e$
e^{-t/τ_n}
$\tau_n \approx 15$ MINS.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$t \simeq 3$ MIN.

• AT FREEZE OUT

$$\frac{n_n}{n_p} \sim e^{-Q/T_*}, \quad Q = m_n - m_p \approx 1.3\text{ MeV}$$

$$\sim \frac{1}{6}$$

• NEUTRONS DECAY: $n \to p + e^- + \bar{\nu}_e$

$$e^{-t/\tau_n}$$

$\tau_n \approx 15$ MINS.

$t \approx 3$ MIN.

$$\boxed{T_{*} = 0.8 \text{ MeV}}$$

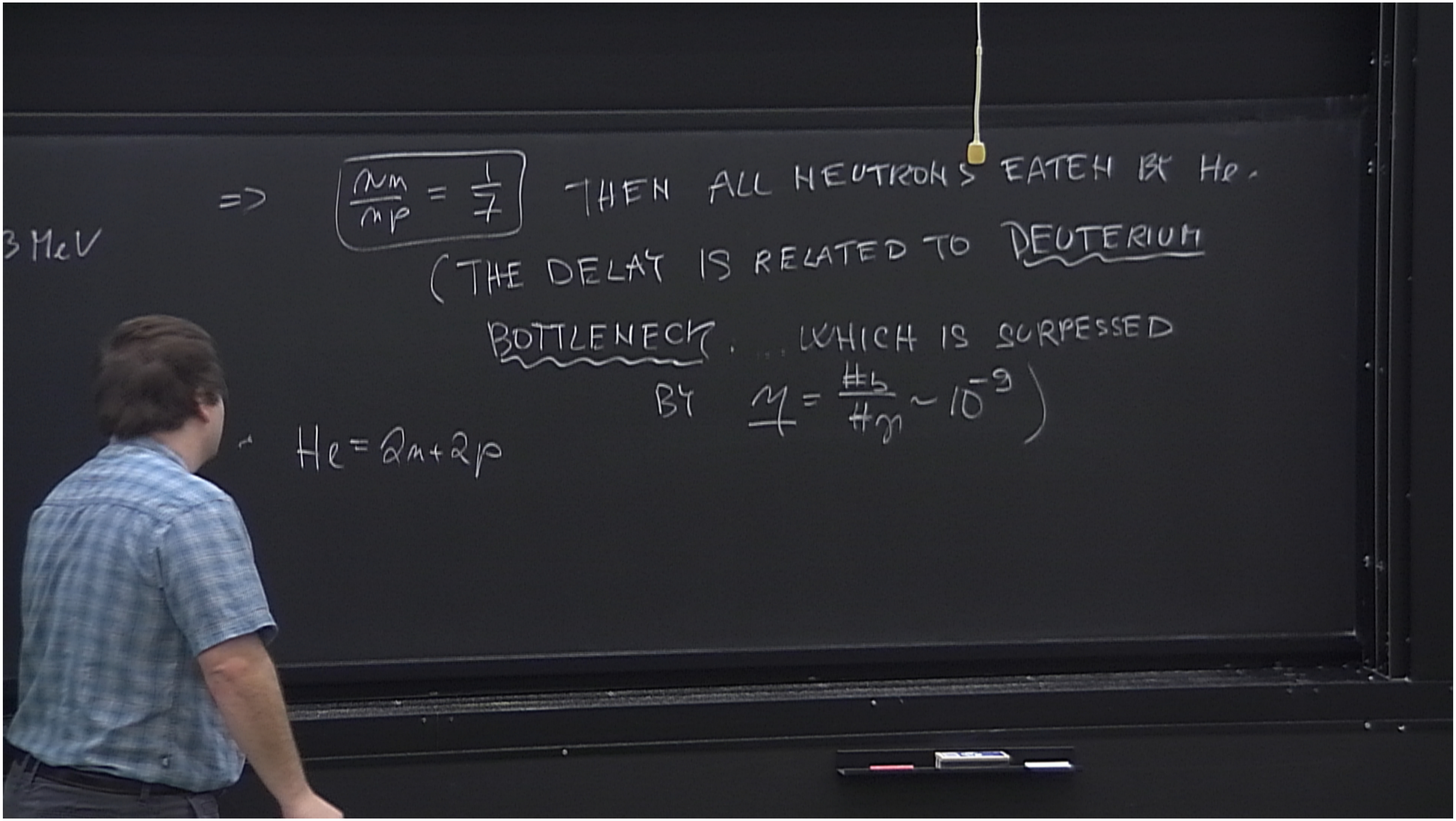
3 MeV

$\Rightarrow$ $\boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.

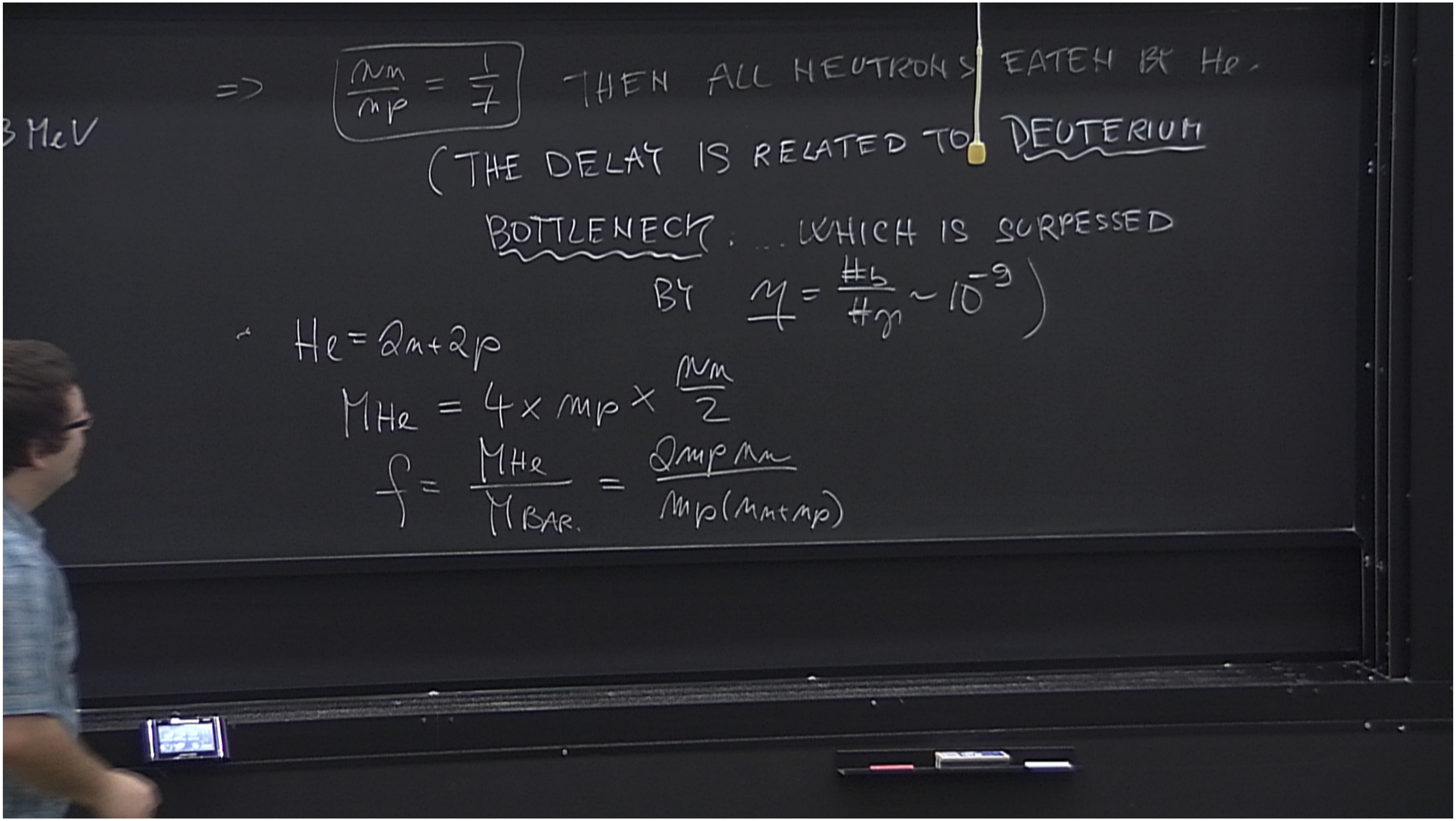
(THE DELAY IS RELATED TO <u>DEUTERIUM</u>

<u>BOTTLENECK</u>; ... WHICH IS SURPESSED

BY $\eta = \frac{\#b}{\#\gamma} \sim 10^{-9}$)



3 MeV
=> $\boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.
(THE DELAY IS RELATED TO DEUTERIUM
BOTTLENECK ... WHICH IS SURPESSED
BY $\eta = \frac{\#b}{\#\gamma} \sim 10^{-9}$)
$He = 2n + 2p$



MeV
$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.
(THE DELAY IS RELATED TO DEUTERIUM
BOTTLENECK ... WHICH IS SURPESSED
BY $\eta = \frac{\# b}{\# \gamma} \sim 10^{-9}$)
$He = 2n + 2p$
$M_{He} = 4 \times m_p \times \frac{n_n}{2}$
$f = \frac{M_{He}}{M_{BAR.}} = \frac{2 m_p n_n}{m_p (n_n + n_p)}$

3 MeV

$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.

(THE DELAY IS RELATED TO DEUTERIUM BOTTLENECK ... WHICH IS SURPESSED BY $\eta = \frac{\#b}{\#\gamma} \sim 10^{-9}$)

He = 2n + 2p

$$M_{He} = 4 \times m_p \times \frac{n_n}{2}$$

$$f = \frac{M_{He}}{M_{BAR.}} = \frac{2 m_p n_n}{m_p (n_n + m_p)} = \frac{2}{1+7} = \frac{1}{4}$$

.. 25% He

3 MeV

$\Rightarrow$ $\boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.

(THE DELAY IS RELATED TO DEUTERIUM BOTTLENECK ... WHICH IS SURPRESSED BY $\eta = \frac{\#_b}{\#_\gamma} \sim 10^{-9}$)

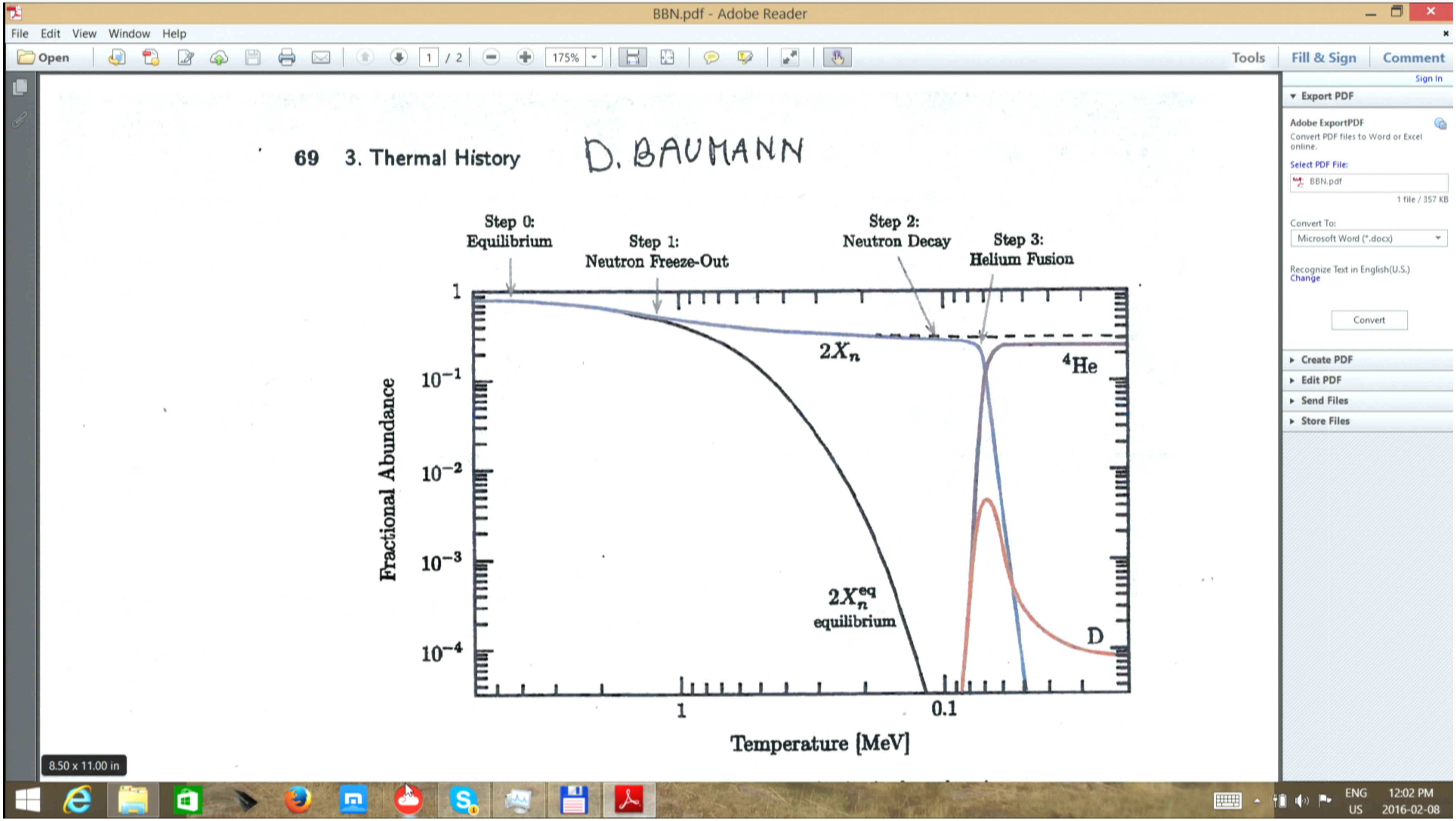
$He = 2n + 2p$

$$\frac{M_{He}}{V} = 4 \times m_p \times \frac{n_n}{2}$$

$$f = \frac{M_{He}}{M_{BAR.}} = \frac{2 m_p n_n}{m_p(n_n + n_p)} = \frac{2}{1+7} = \frac{1}{4} \;..\; 25\%\ He$$

- BBN .. TEST OF FUNDAMENTAL PHYSICS.

g_*, τ_n, η, G_N, G_F, ...


BBN.pdf - Adobe Reader
69 3. Thermal History
D. BAUMANN
Step 0:
Equilibrium
Step 1:
Neutron Freeze-Out
Step 2:
Neutron Decay
Step 3:
Helium Fusion
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Fractional Abundance
$2X_n$
^{4}He
$2X_n^{eq}$
equilibrium
D
1
0.1
Temperature [MeV]
8.50 x 11.00 in
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Select PDF File:
BBN.pdf
1 file / 357 KB
Convert To:
Microsoft Word (*.docx)
Recognize Text in English(U.S.)
Change
Convert
Create PDF
Edit PDF
Send Files
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Tools
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Comment
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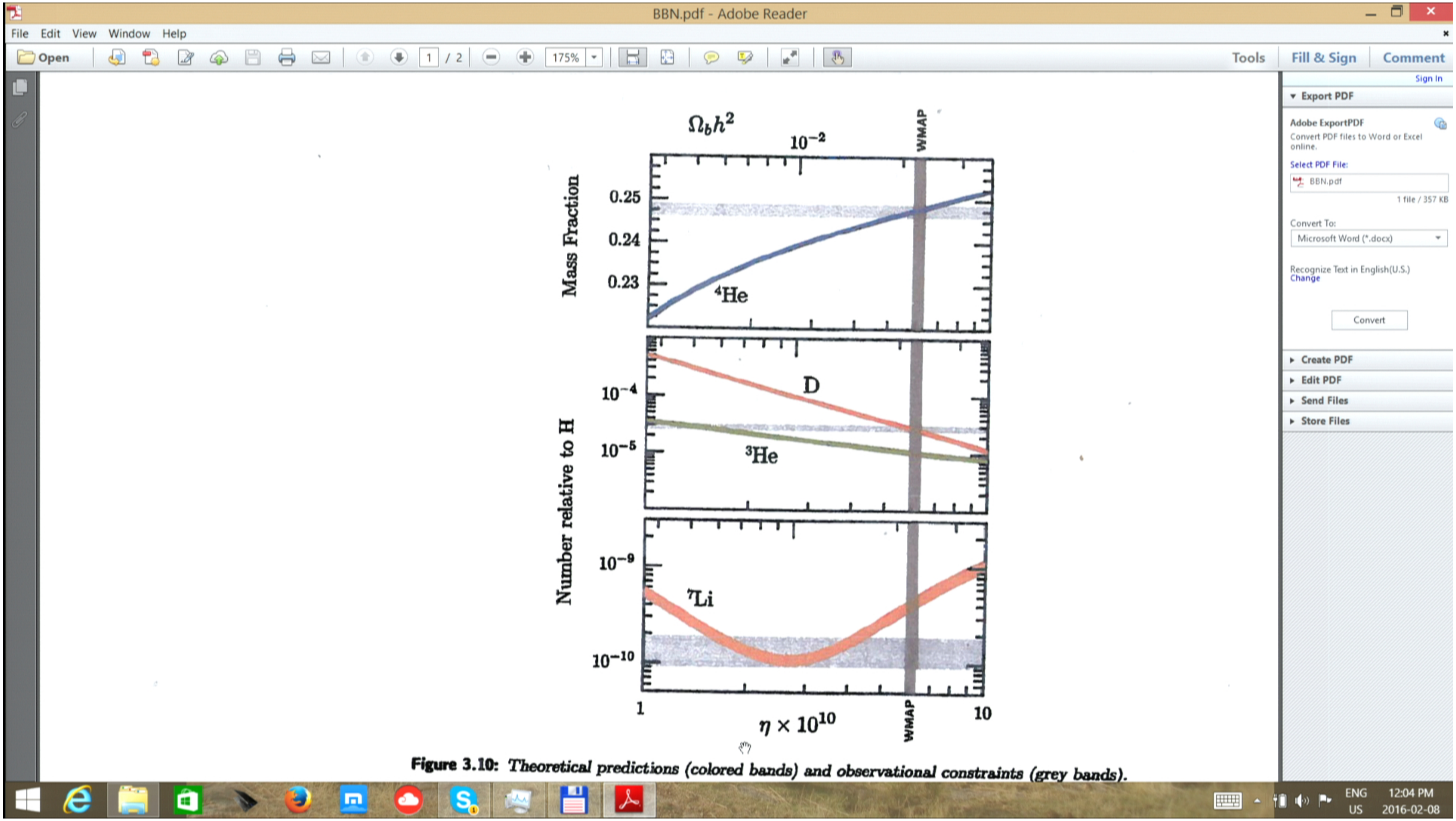


Figure 3.10: *Theoretical predictions (colored bands) and observational constraints (grey bands).*

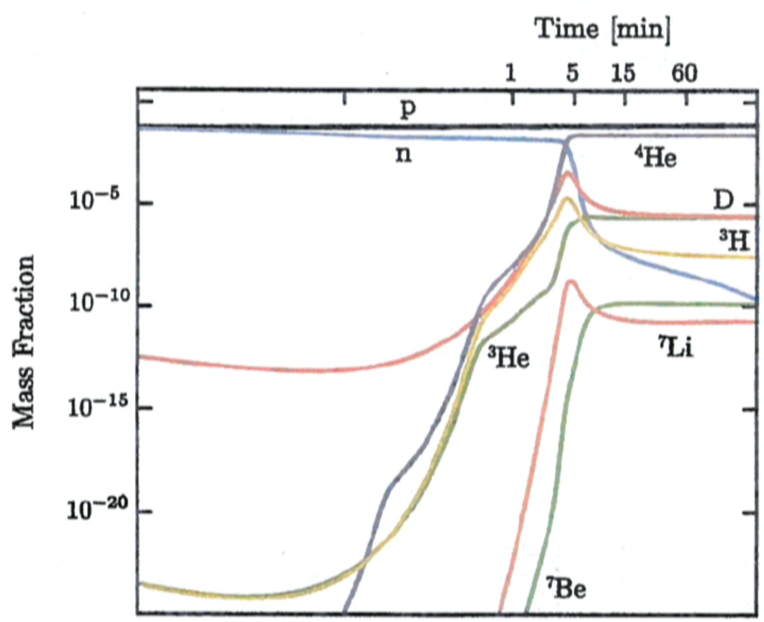
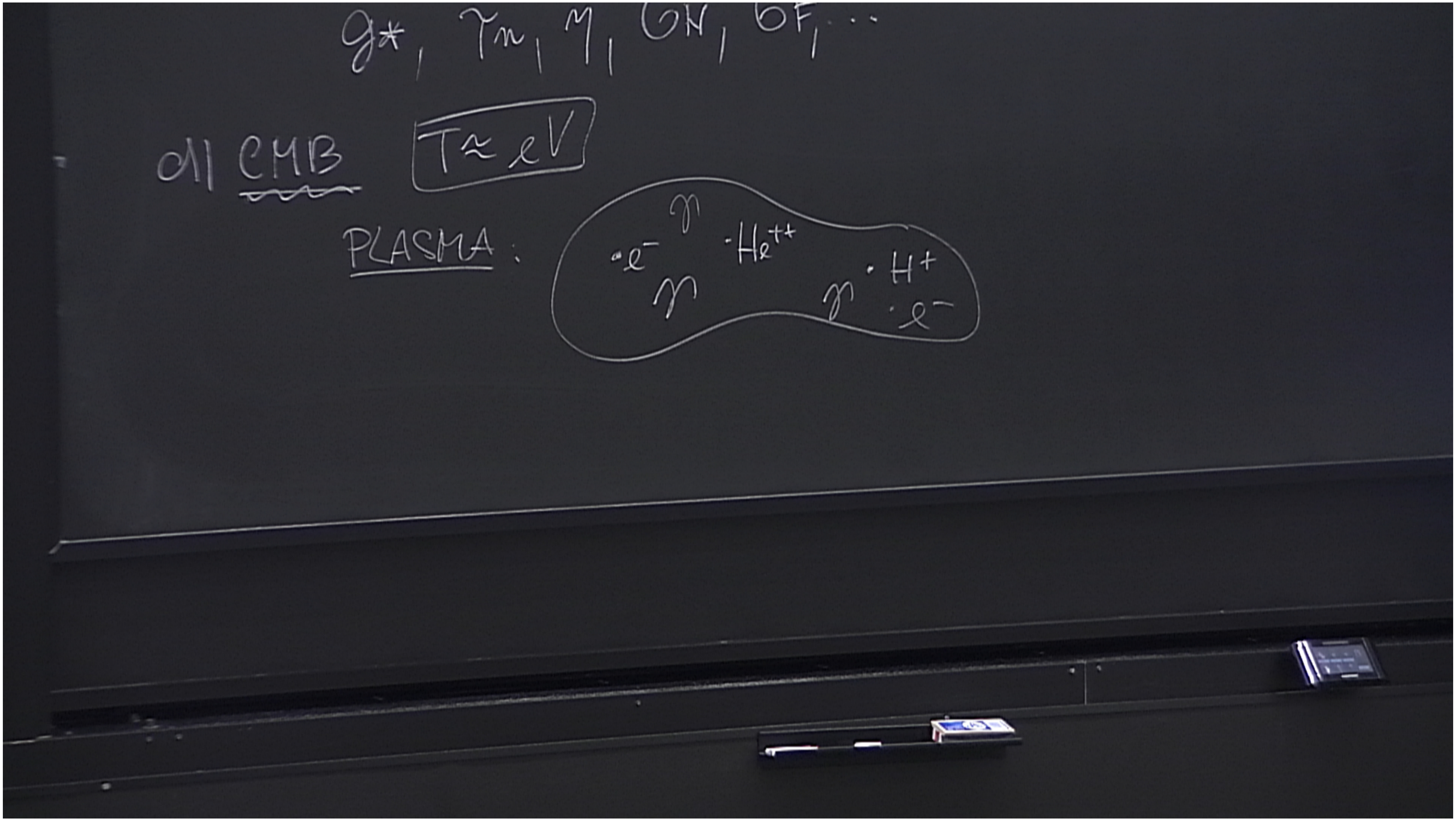
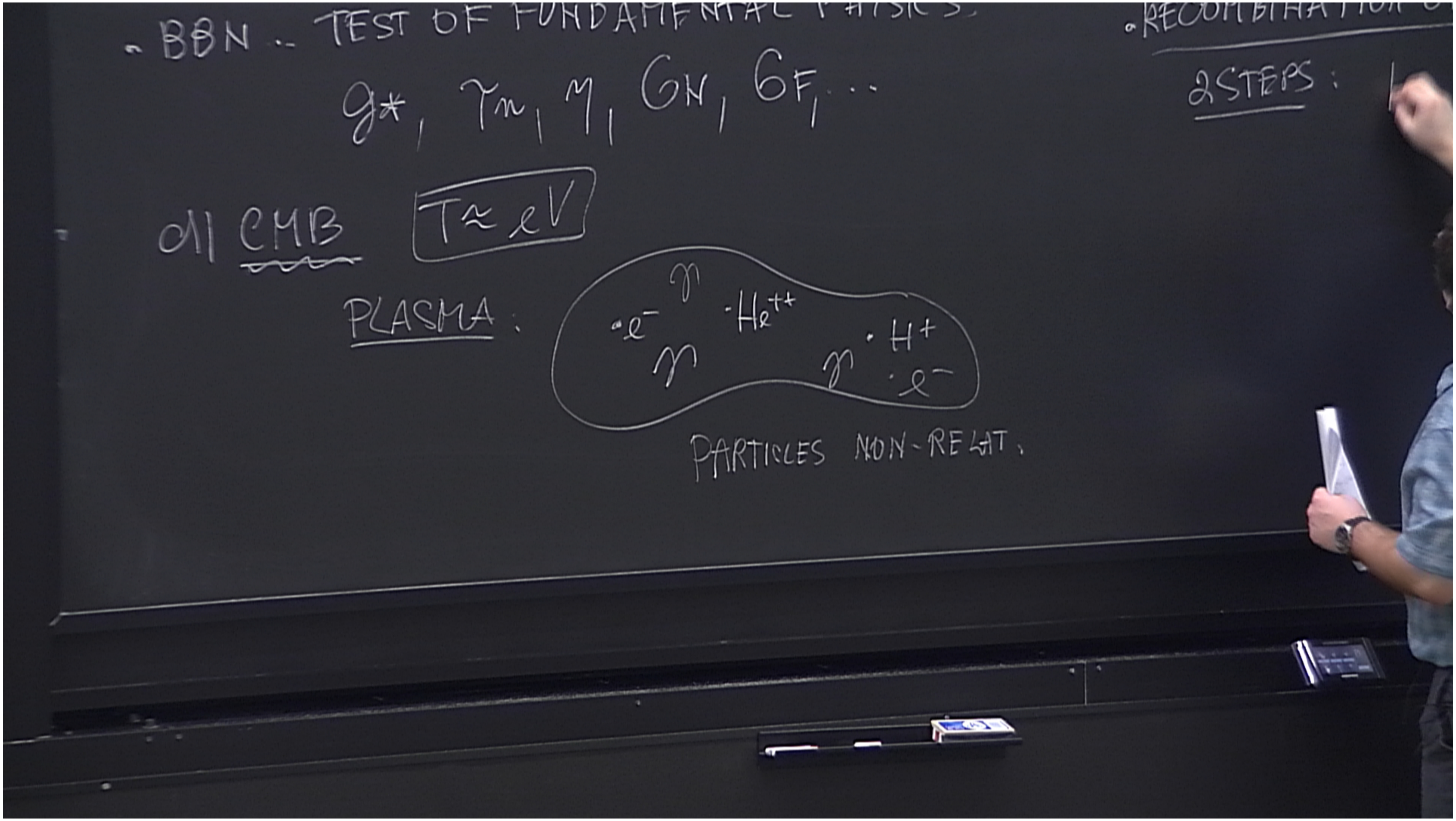
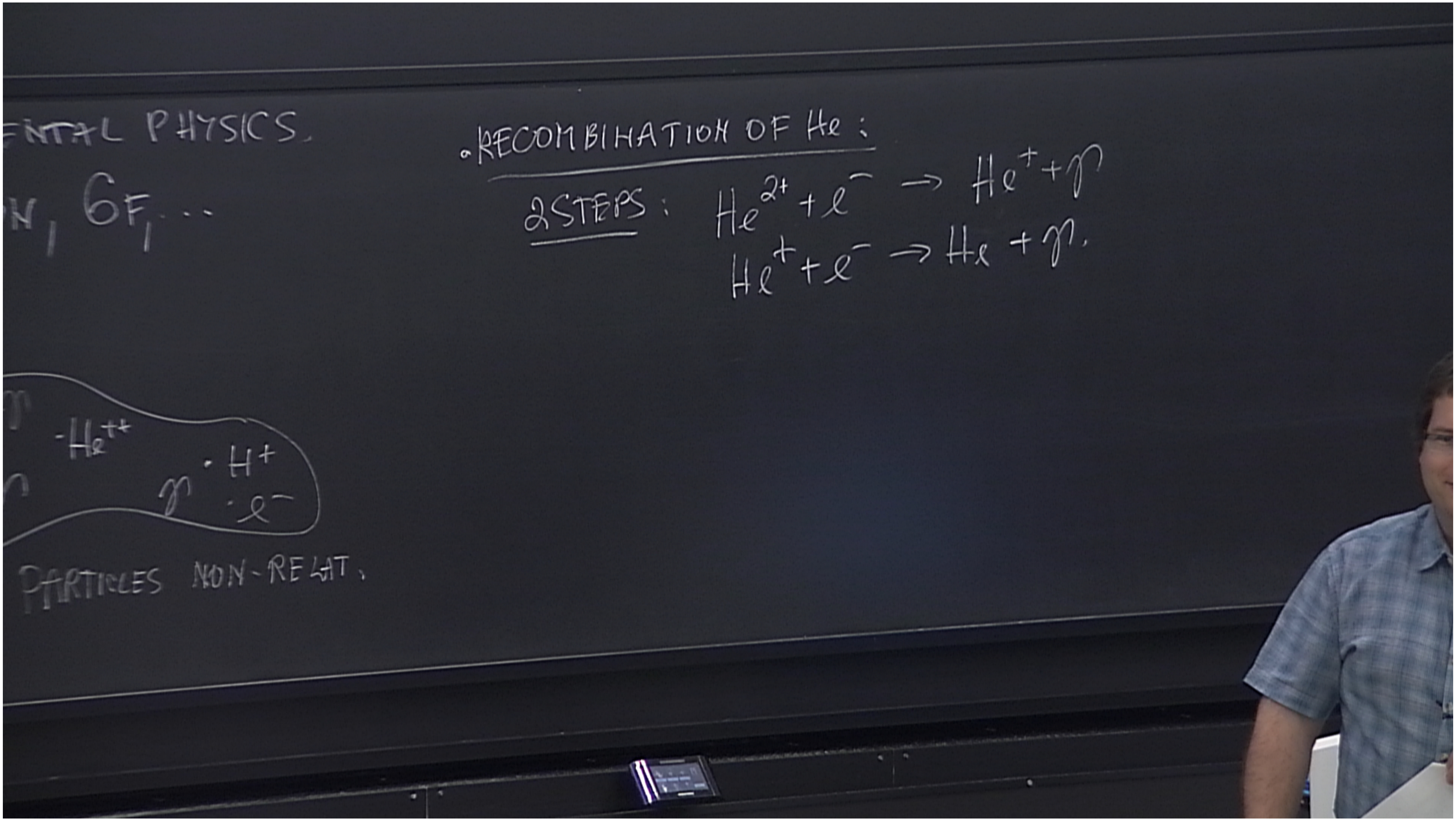


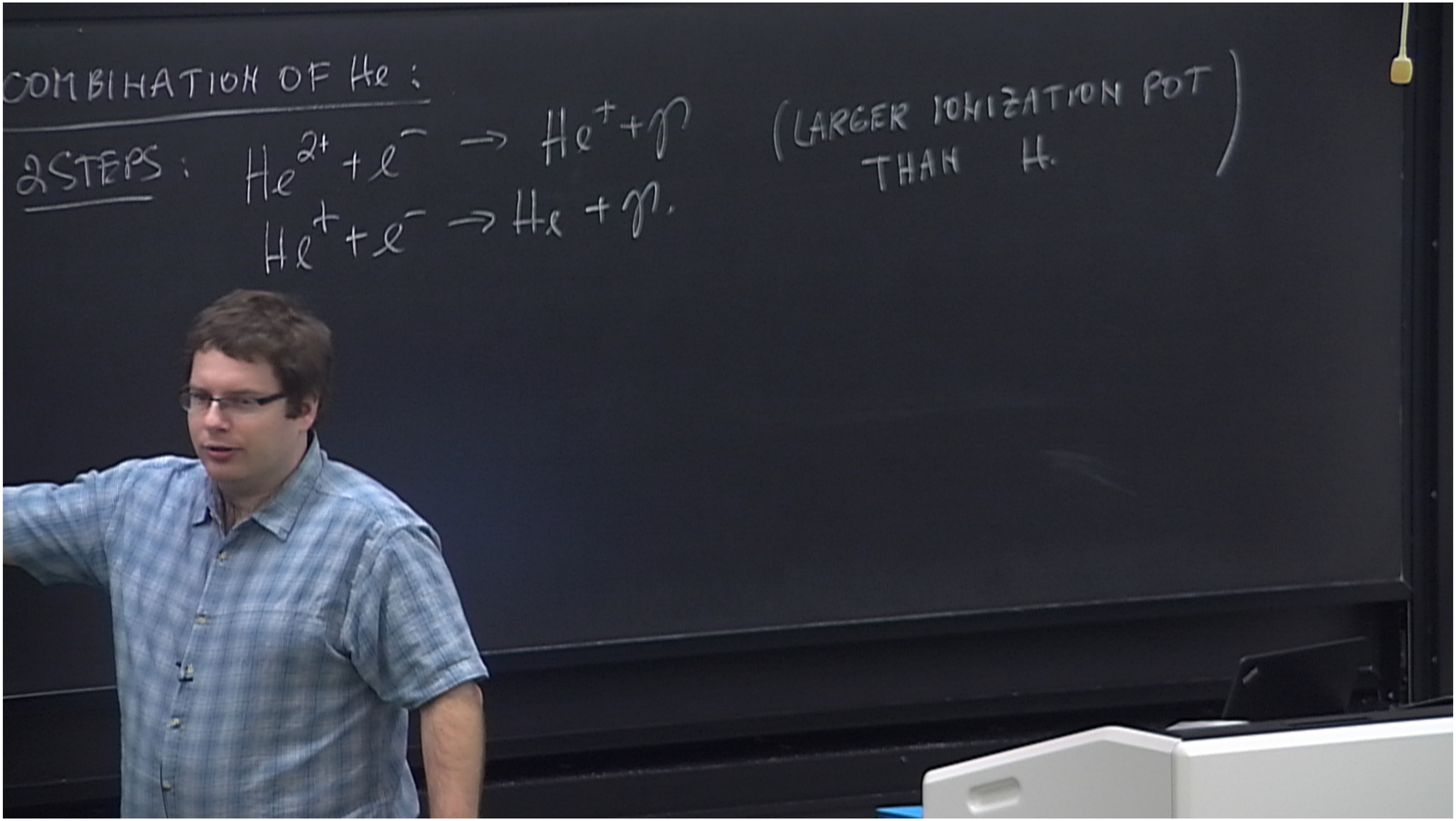
Figure 3.11: *Numerical results for the evolution of light element abundances.*

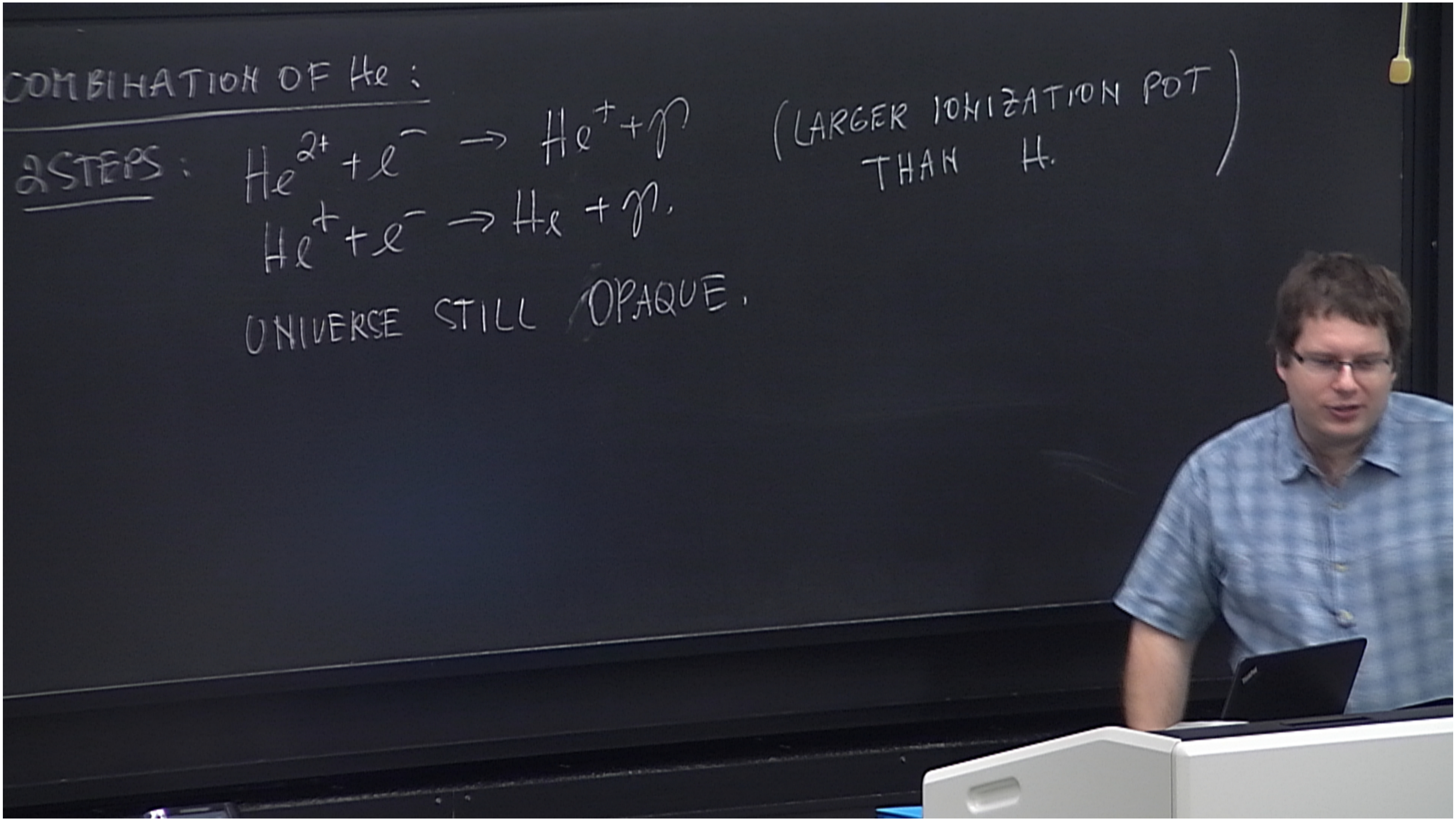
The shape of the curves in fig. 3.11 can easily be understood: The abundance of ^{4}He increases with increasing η as nucleosythesis starts earlier for larger baryon density. D and ^{3}He are burnt by fusion, thus their abundances decrease as η increases. Finally, ^{7}Li is destroyed by protons at low η with an efficiency that increases with η. On the other hand, its precursor ^{7}Be is produced

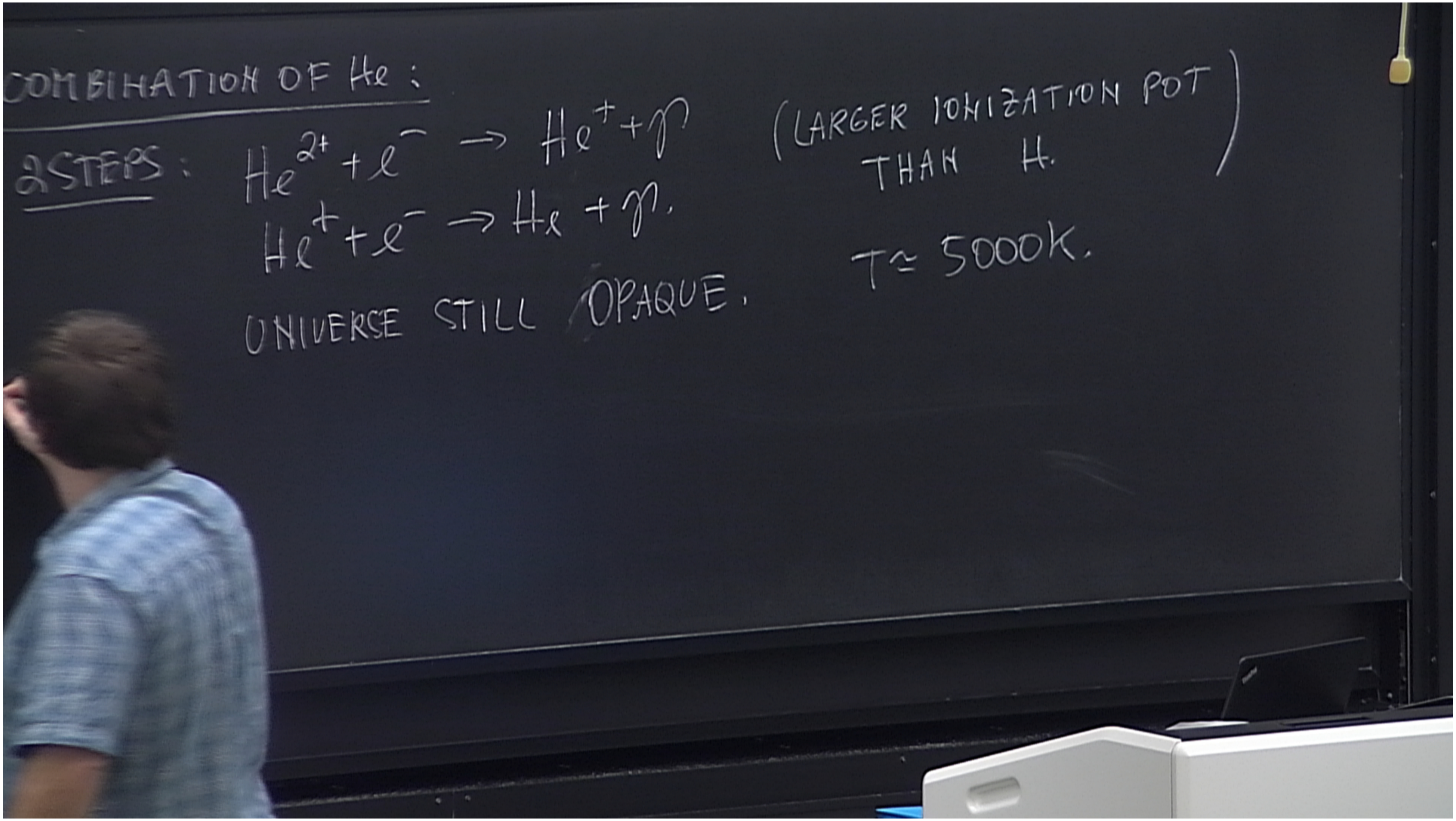

g_*, τ_n, η, G_N, G_F, ...
a) CMB
$\boxed{T \approx eV}$
PLASMA:
e^- γ He^{++}
γ H^+
γ e^-

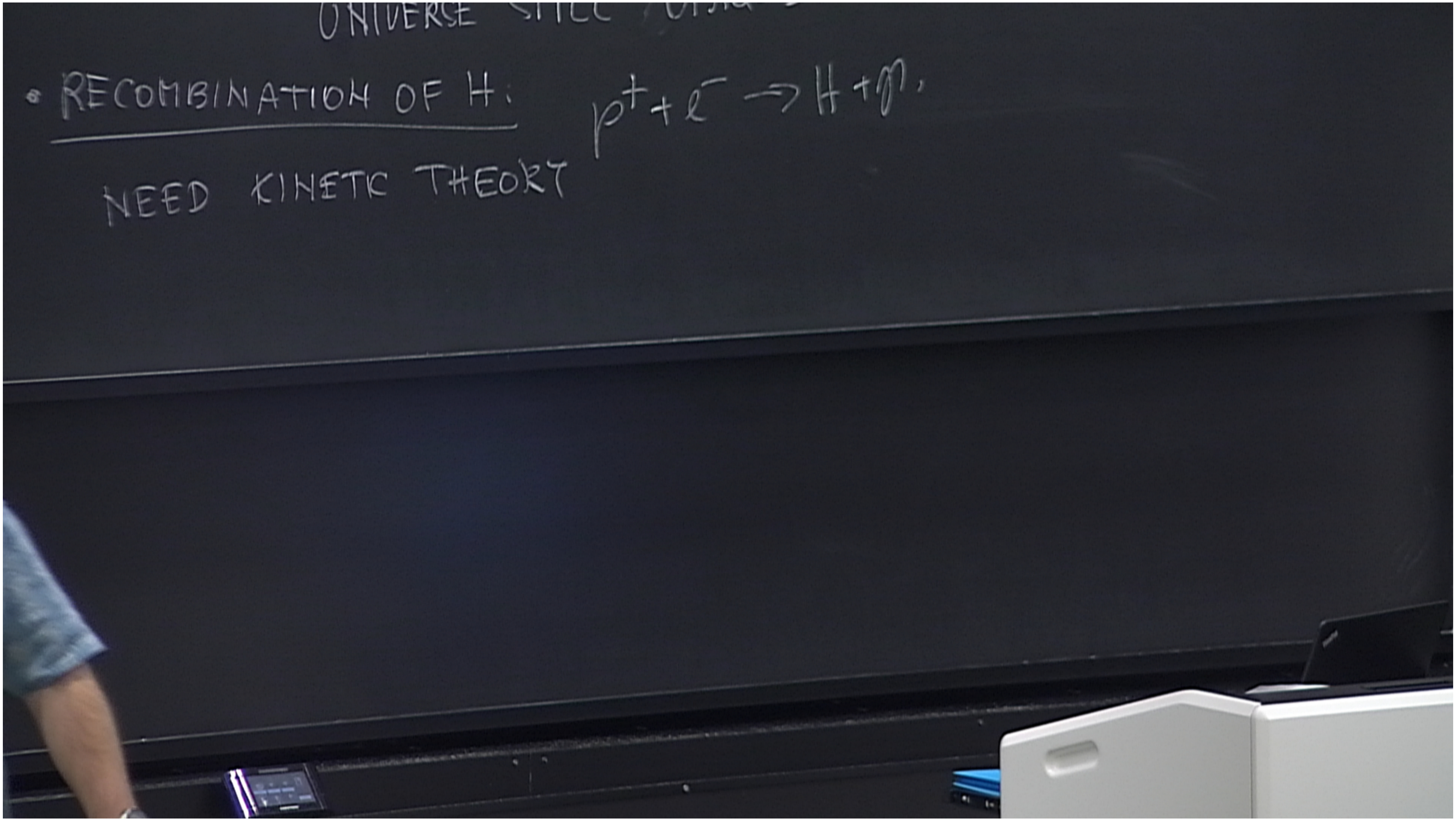

• BBN .. TEST OF FUNDAMENTAL PHYSICS:
g_*, τ_n, η, G_N, G_F, ...
c) CMB
$T \approx eV$
PLASMA:
e^-
γ
He^{++}
γ
γ
H^+
e^-
PARTICLES NON-RELAT.
2STEPS:


ENTAL PHYSICS.
RECOMBINATION OF He :
2 STEPS : $He^{2+} + e^{-} \rightarrow He^{+} + \gamma$
$He^{+} + e^{-} \rightarrow He + \gamma$.
He^{++}
H^{+}
e^{-}
PARTICLES NON-RELAT.


COMBINATION OF He :
2 STEPS : He2+ + e- → He+ + γ
He+ + e- → He + γ.
(LARGER IONIZATION POT
THAN H.)


OMBINATION OF He :
2 STEPS : $He^{2+} + e^- \rightarrow He^+ + \gamma$
$He^+ + e^- \rightarrow He + \gamma$.
(LARGER IONIZATION POT THAN H.)
UNIVERSE STILL OPAQUE.


COMBINATION OF He :
2 STEPS : $He^{2+} + e^- \rightarrow He^+ + \gamma$
$He^+ + e^- \rightarrow He + \gamma$.
(LARGER IONIZATION POT THAN H.)
$T \simeq 5000K$.
UNIVERSE STILL OPAQUE.



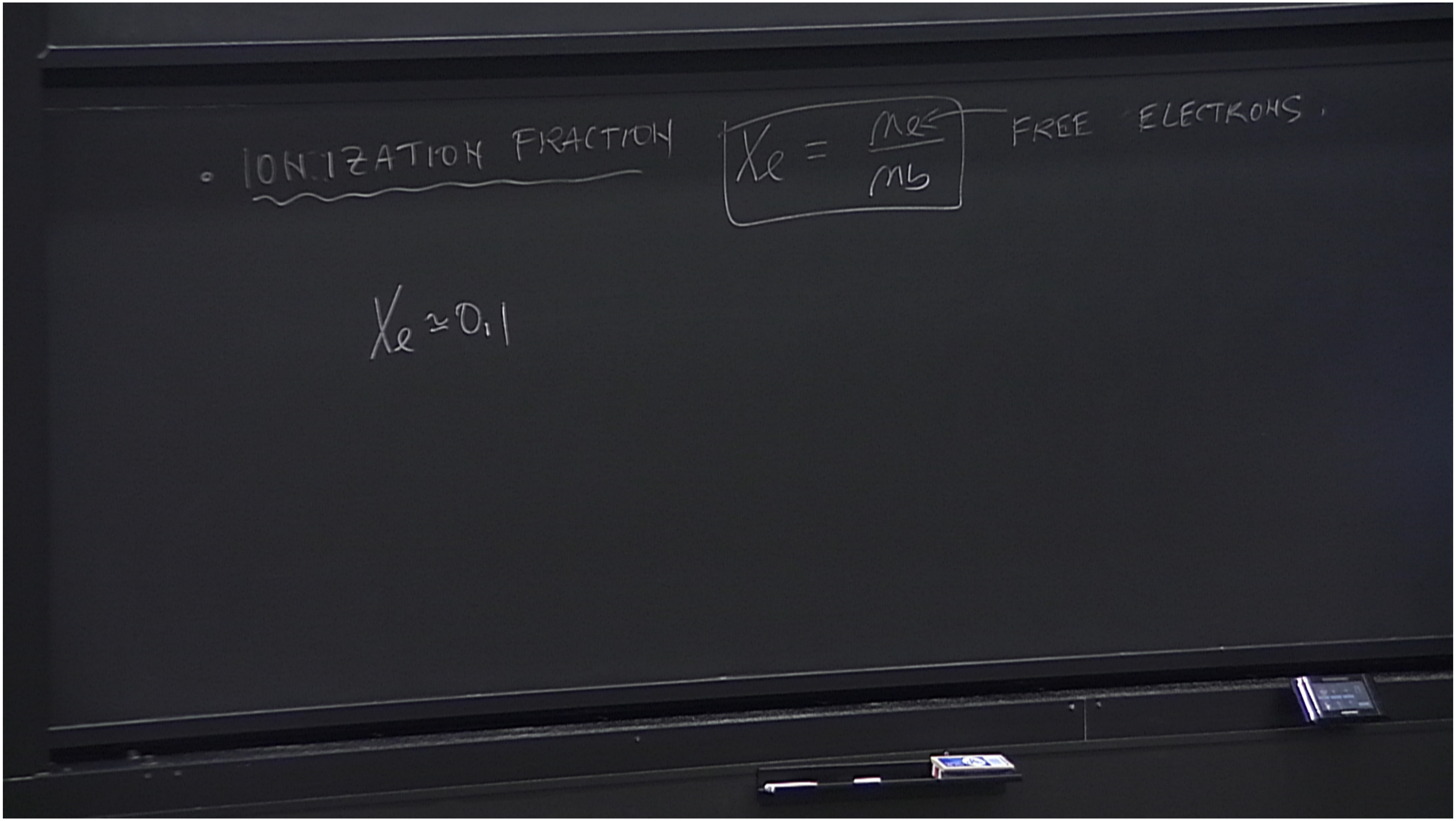
• RECOMBINATION OF H: $p^+ + e^- \to H + \gamma$,
NEED KINETIC THEORY

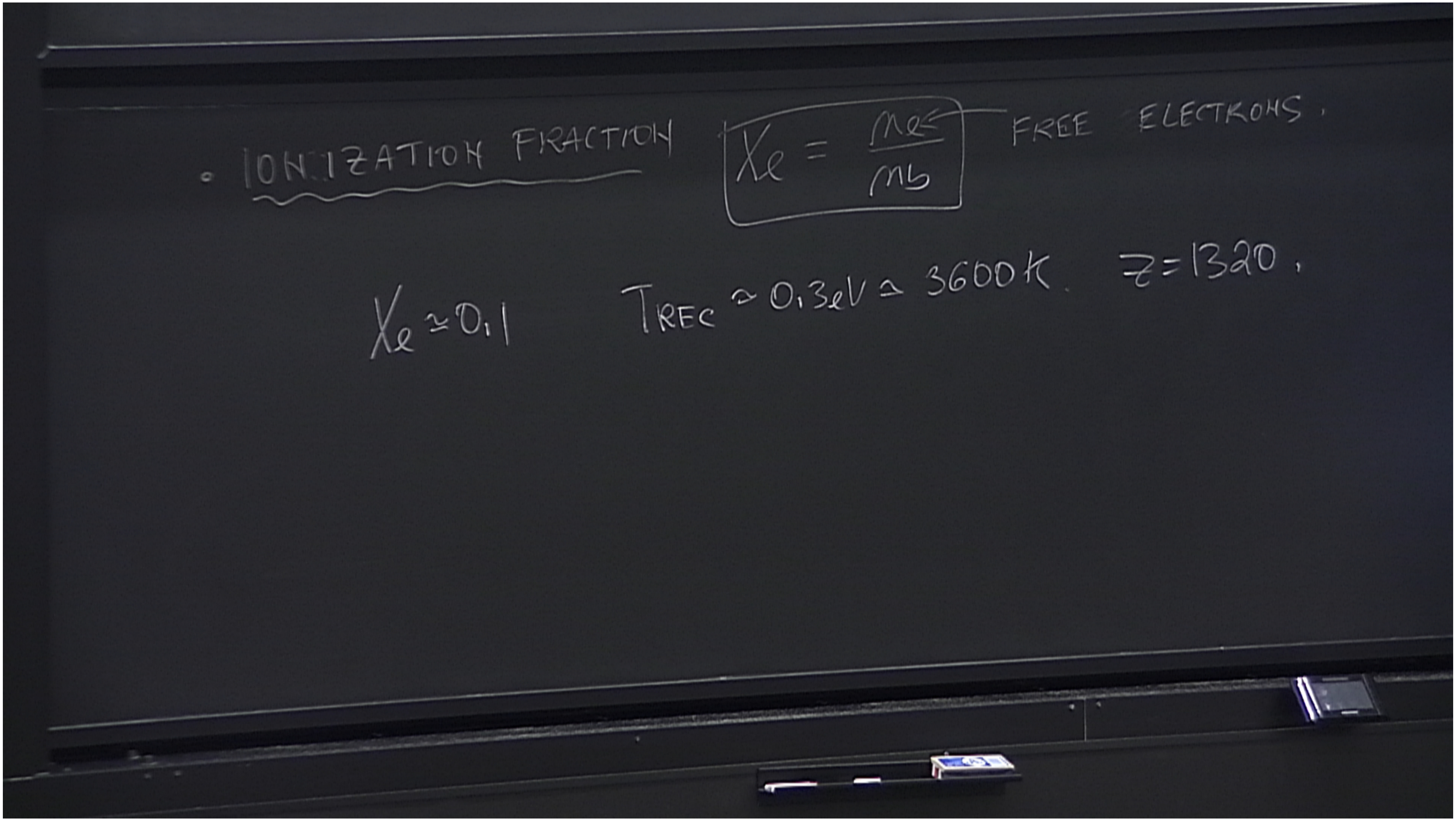
- RECOMBINATION OF H: $p^+ + e^- \to H + \gamma$,

NEED KINETIC THEORY. QUALITATIVE RESULT CAN BE OBTAINED

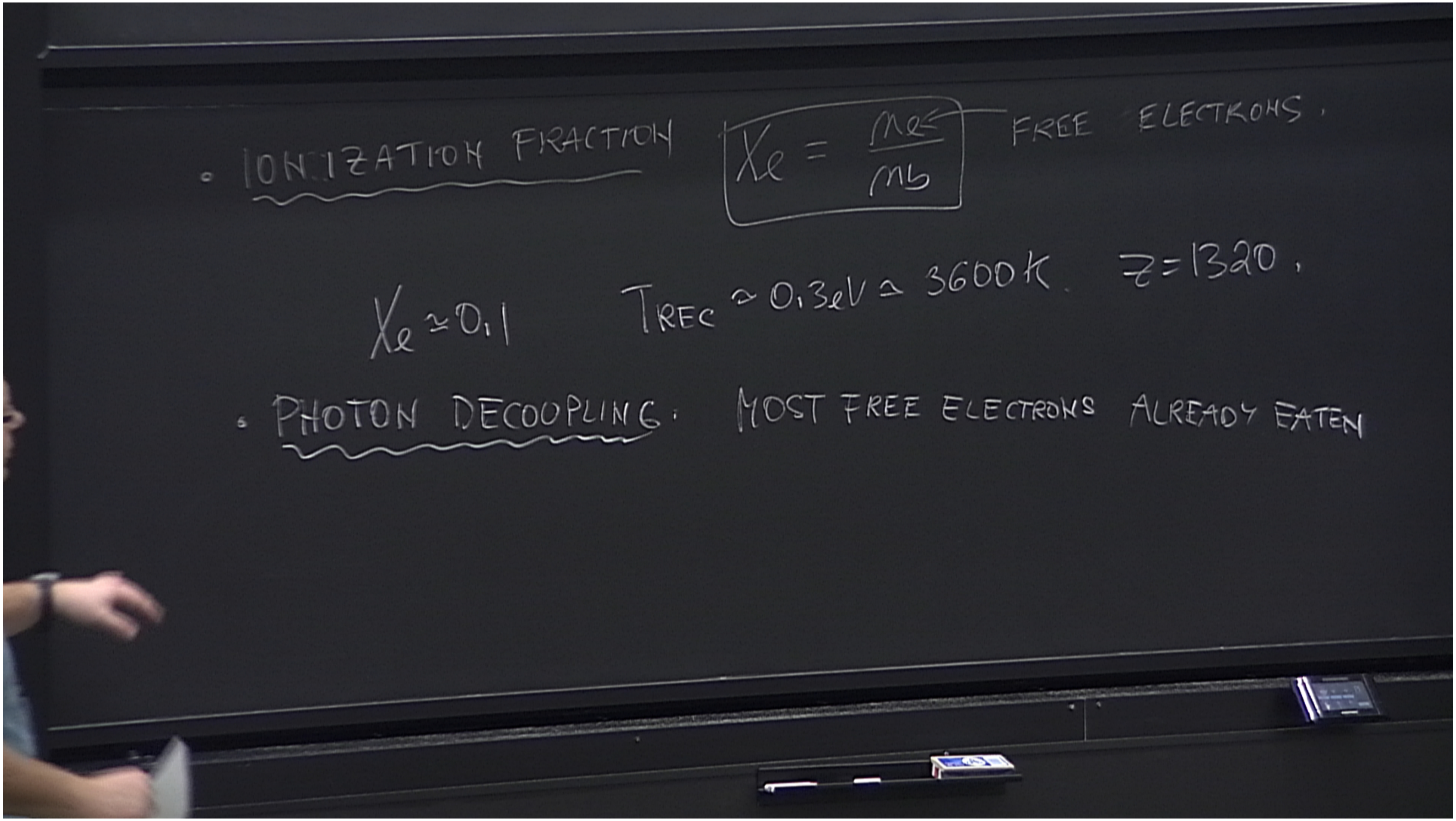
SAHA APPROXIMATION (H2)

- IONIZATION FRACTION $\boxed{X_e = \frac{n_e}{n_b}}$ FREE ELECTRONS.


• IONIZATION FRACTION
$\boxed{X_e = \frac{n_e}{n_b}}$
FREE ELECTRONS.
$X_e \simeq 0.1$



• IONIZATION FRACTION
$\boxed{X_e = \frac{n_e}{n_b}}$
FREE ELECTRONS.
$X_e \simeq 0.1$
$T_{REC} \simeq 0.3\,eV \simeq 3600K$.
$z = 1320$,

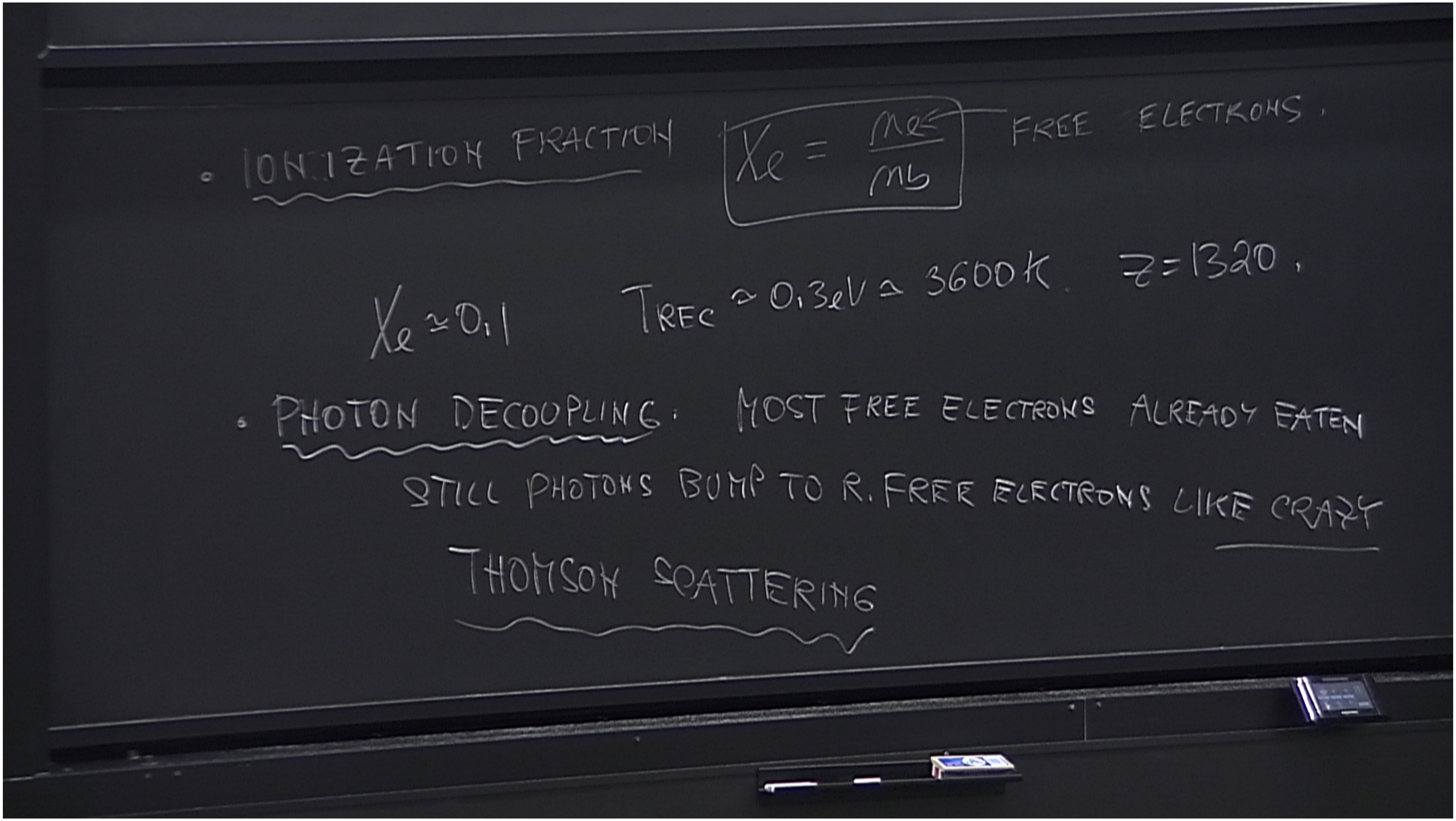

• IONIZATION FRACTION
$X_e = \frac{n_e}{n_b}$
FREE ELECTRONS.
$X_e \simeq 0.1$
$T_{REC} \simeq 0.3eV \simeq 3600K$.
$z = 1320$.
• PHOTON DECOUPLING: MOST FREE ELECTRONS ALREADY EATEN

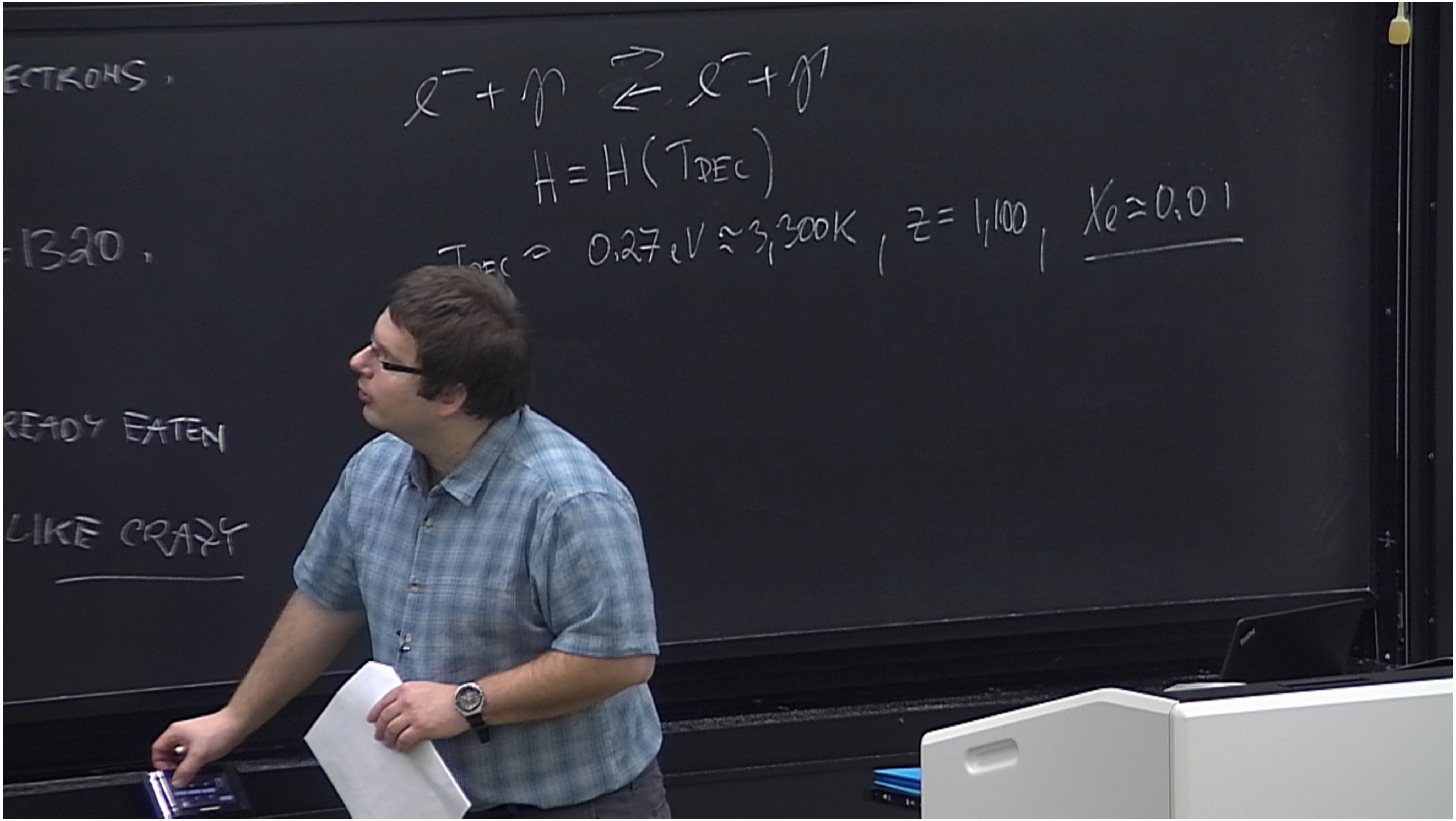
- IONIZATION FRACTION $\boxed{X_e = \frac{n_e}{n_b}}$ FREE ELECTRONS.

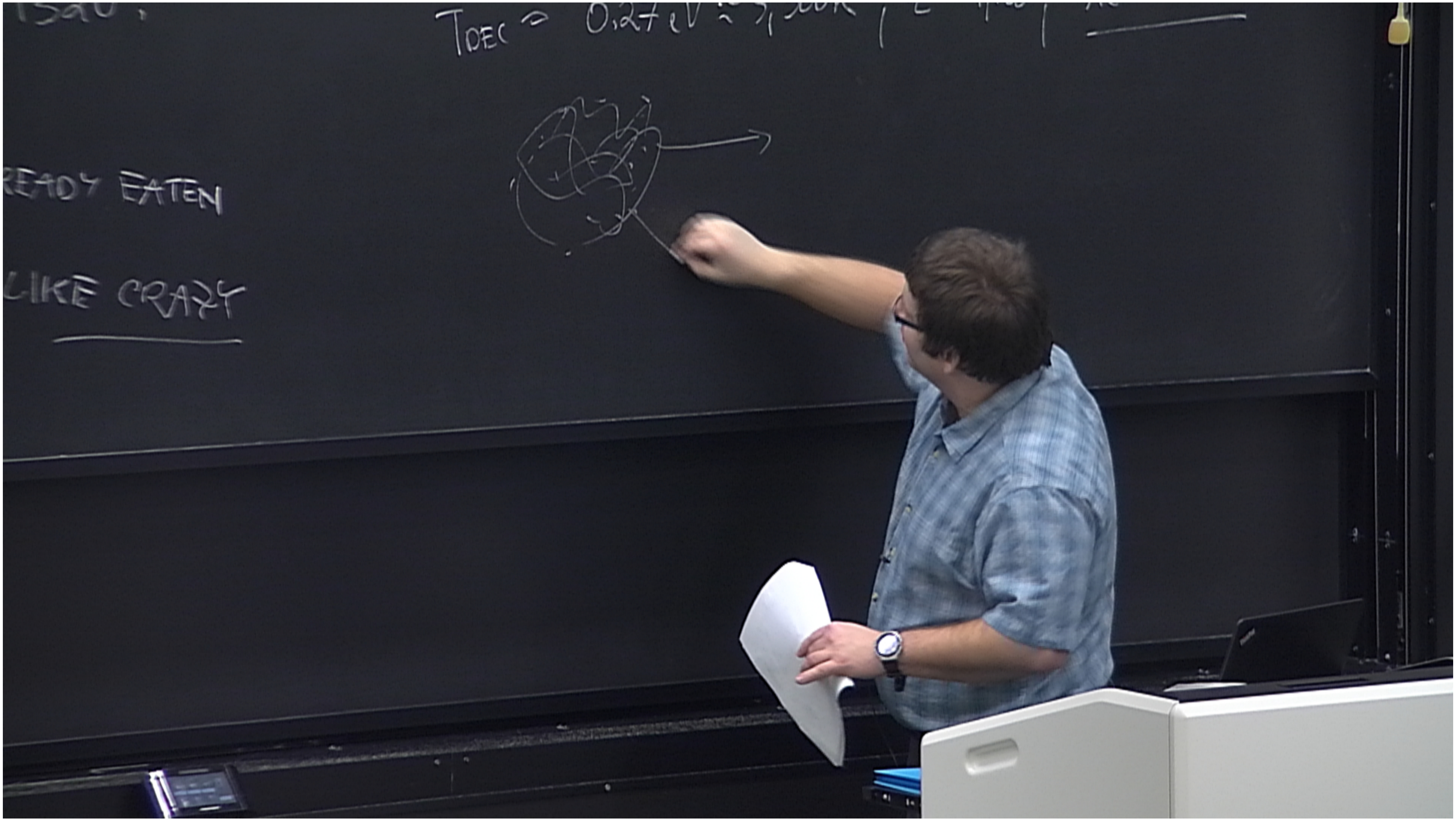
$X_e \simeq 0.1$ $T_{REC} \simeq 0.3\,eV \simeq 3600K$. $z = 1320$.

- PHOTON DECOUPLING: MOST FREE ELECTRONS ALREADY EATEN

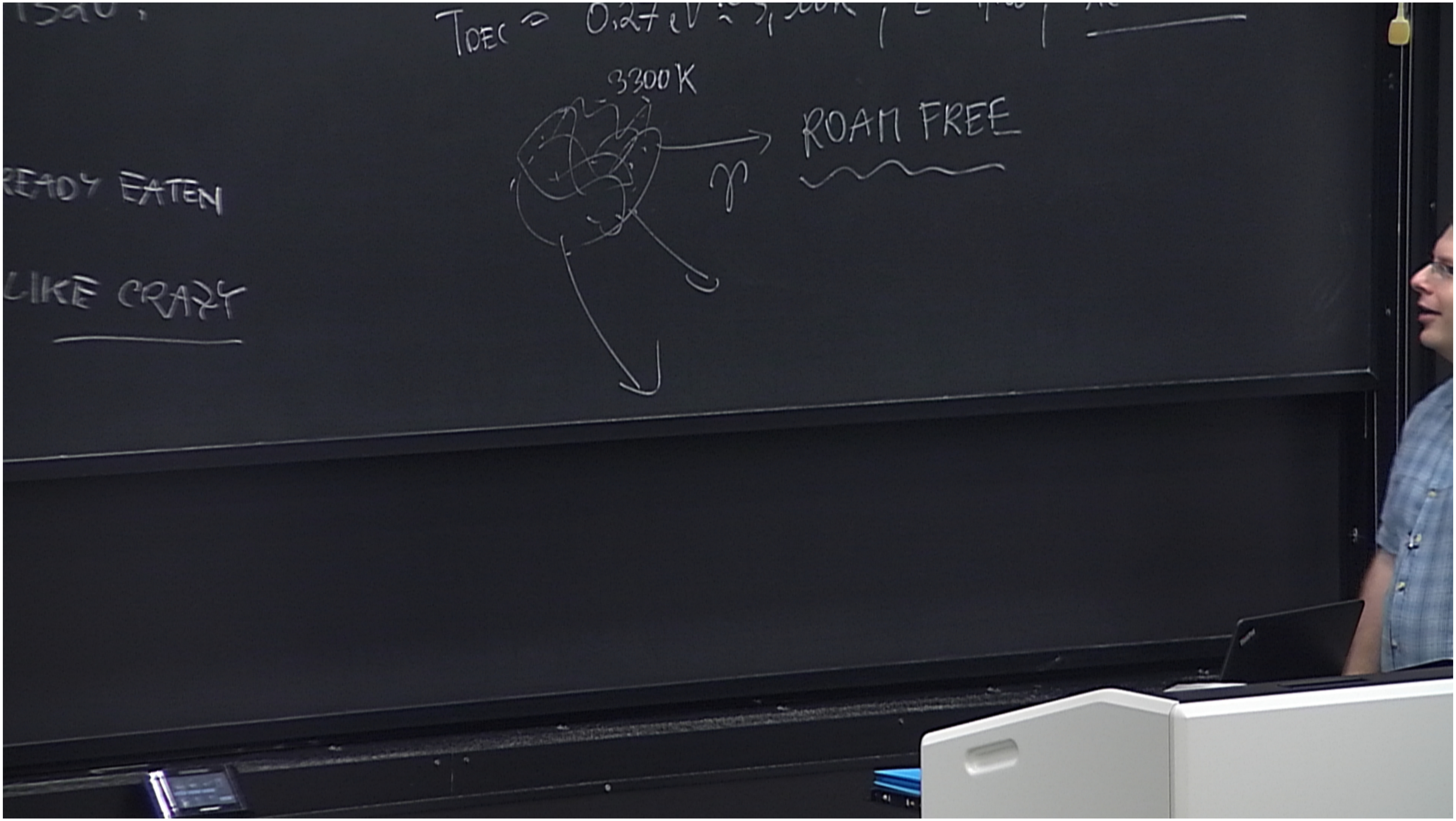
STILL PHOTONS BUMP TO R. FREE ELECTRONS LIKE CRAZY

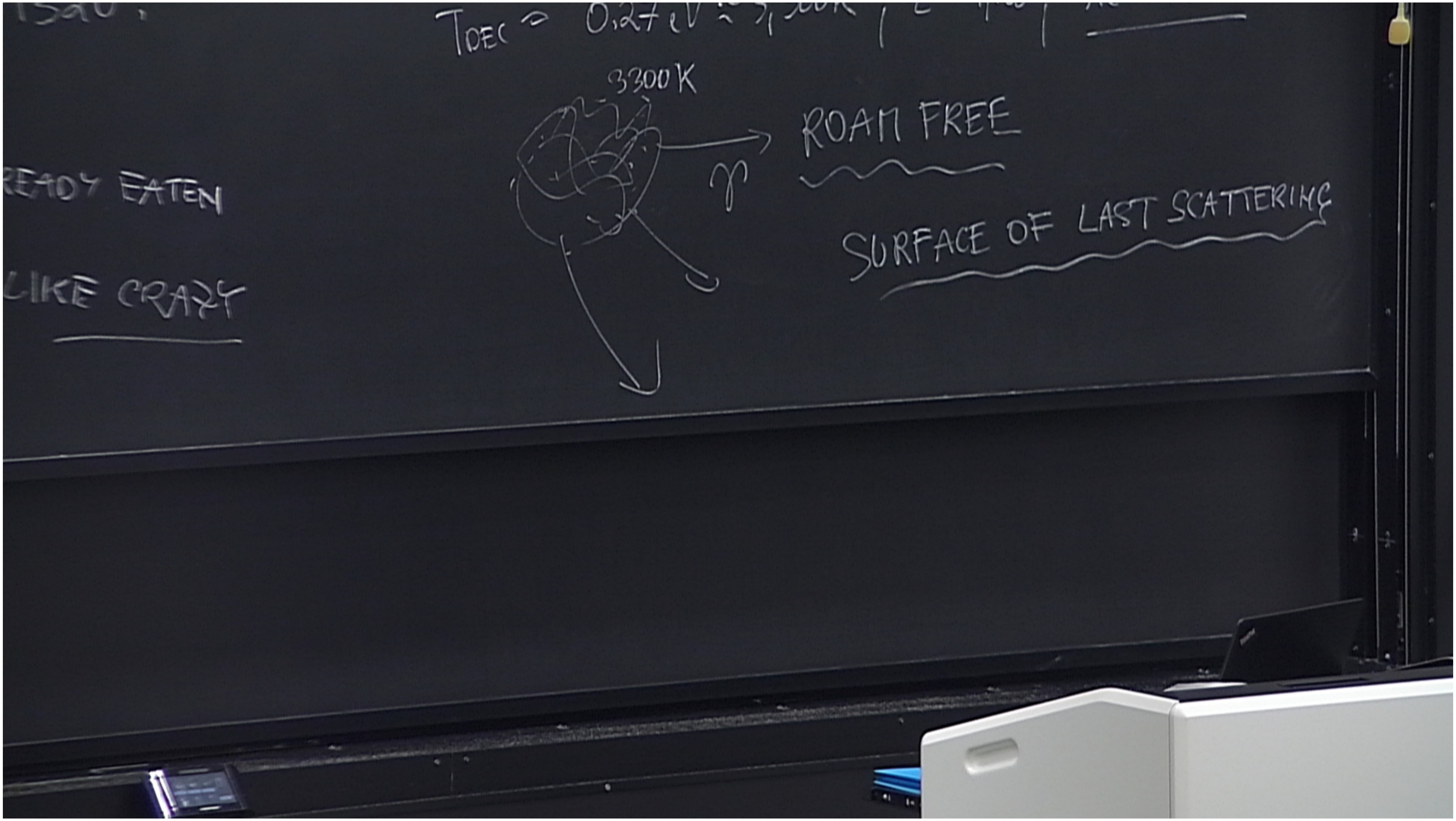

IONIZATION FRACTION
Xe = ne/nb FREE ELECTRONS.
Xe ≃ 0.1 TREC ≃ 0.3eV ≃ 3600K. z = 1320.
PHOTON DECOUPLING: MOST FREE ELECTRONS ALREADY EATEN
STILL PHOTONS BUMP TO R. FREE ELECTRONS LIKE CRAZY
THOMSON SCATTERING

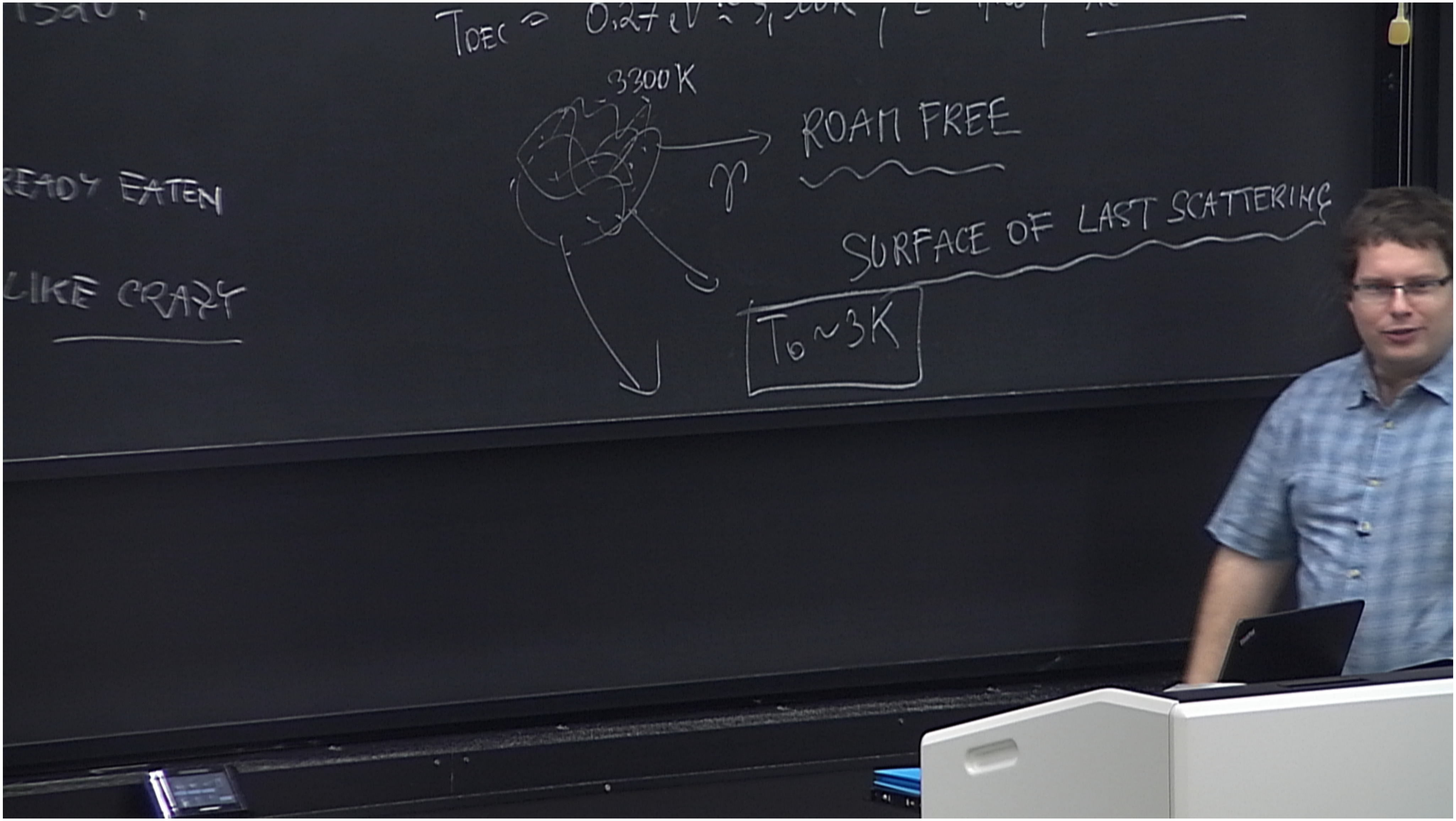

ECTRONS.
=1320.
READY EATEN
LIKE CRAZY
e⁻ + γ ⇄ e⁻ + γ
H = H(T_DEC)
T_DEC ≃ 0.27 eV ≃ 3,300K, z = 1,100, Xe ≃ 0.01

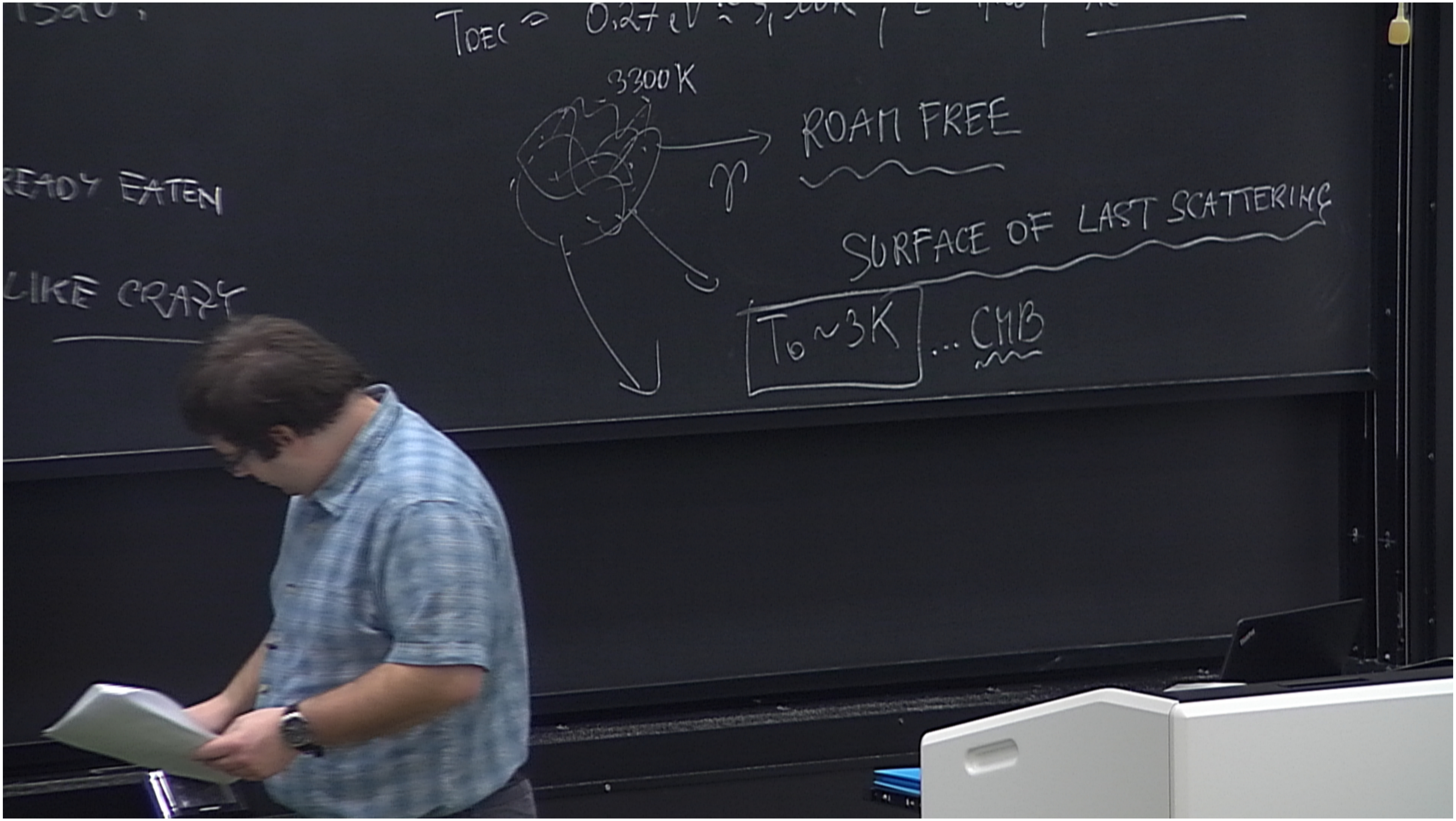


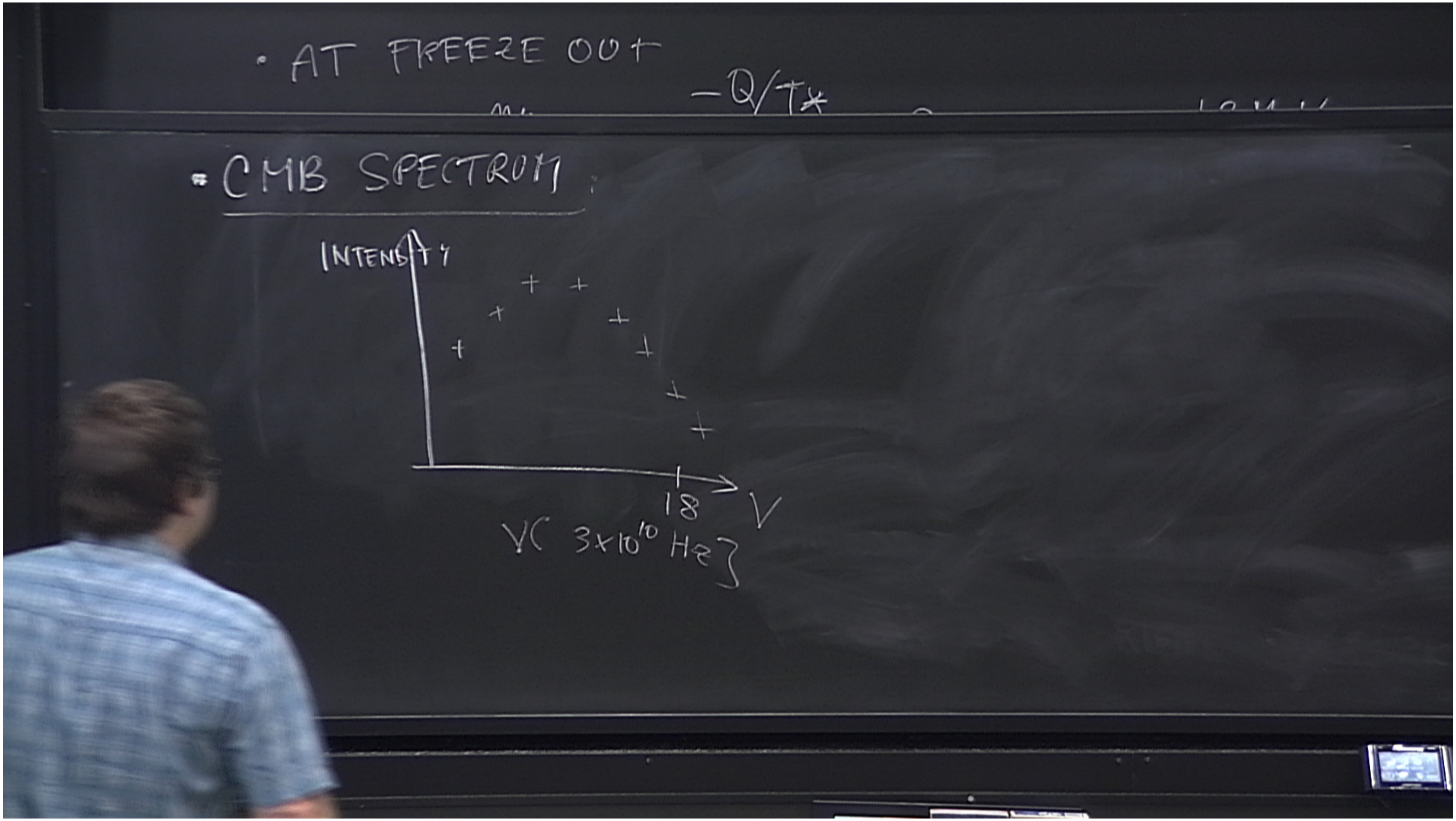
READY EATEN
LIKE CRAZY

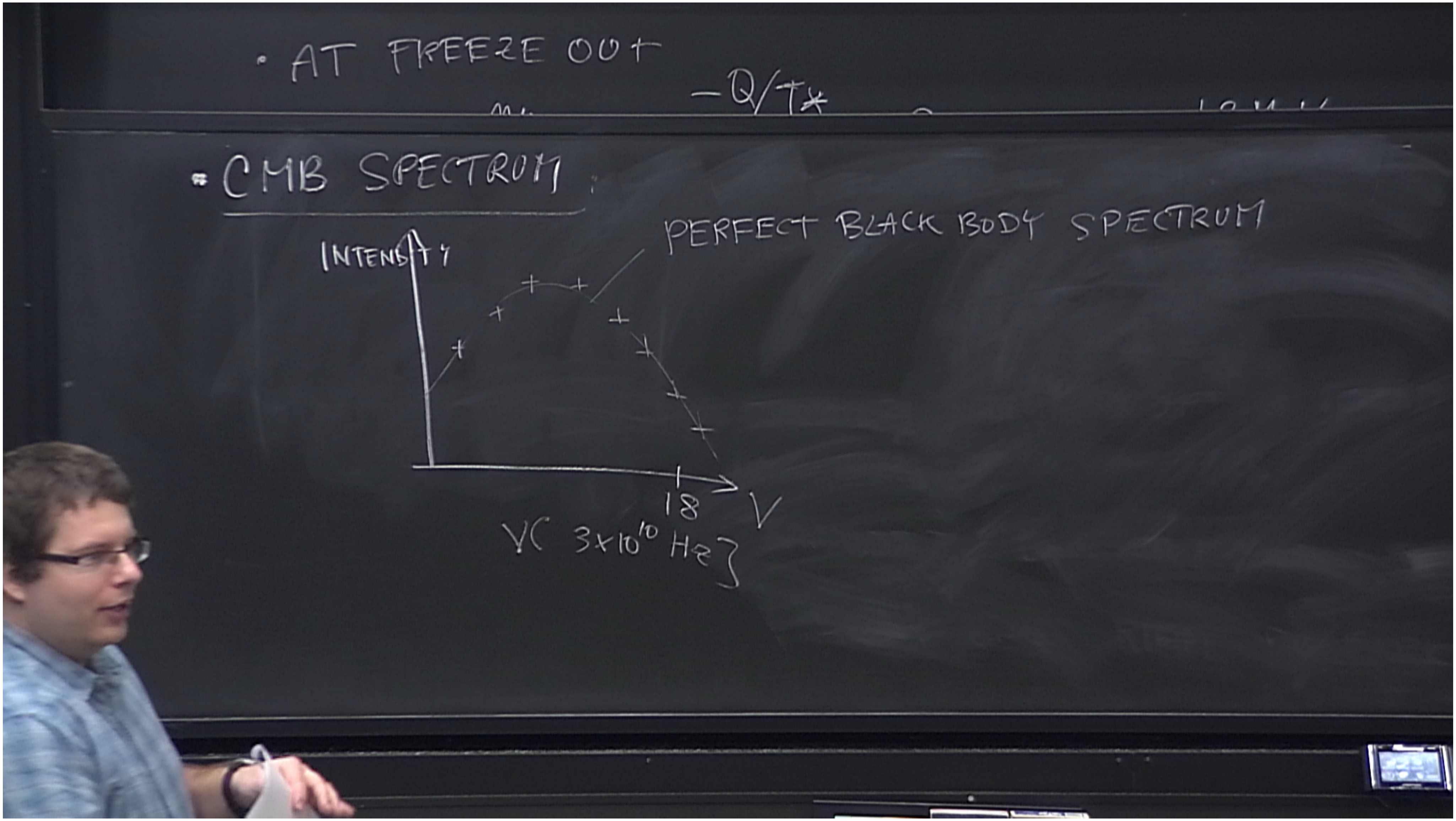

TDEC ≈ 0.27 eV
3300 K
ROAM FREE
γ
EADY EATEN
LIKE CRAZY

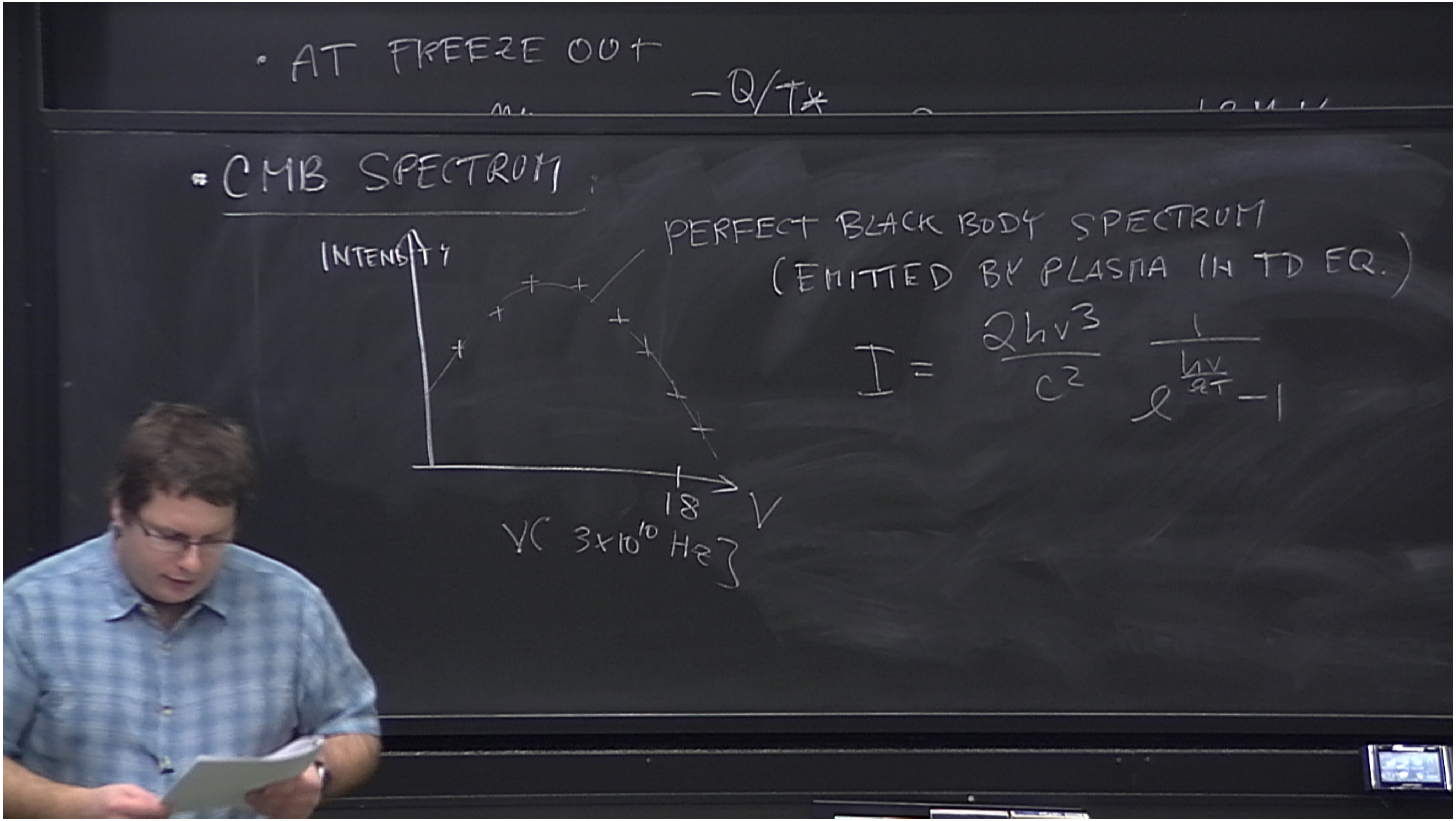

T_DEC ≈ 0.27 eV
3300 K
ROAM FREE
γ
SURFACE OF LAST SCATTERING
READY EATEN
LIKE CRAZY


3300 K
ROAM FREE
γ
READY EATEN
LIKE CRAZY
SURFACE OF LAST SCATTERING
T0 ~ 3K


READY EATEN
LIKE CRAZY
3300 K
ROAM FREE
SURFACE OF LAST SCATTERING
T0 ~ 3K ... CMB


• AT FREEZE OUT
−Q/T*
• CMB SPECTRUM :
INTENSITY
18
ν
ν(3×10^10 Hz}

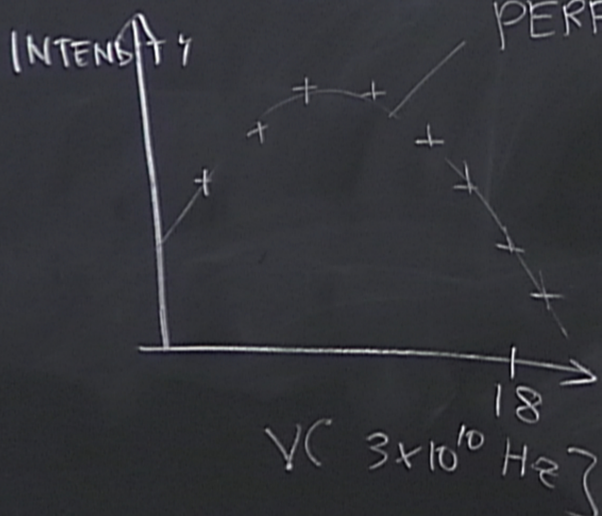

• AT FREEZE OUT
$-Q/T_*$
• CMB SPECTRUM:
PERFECT BLACK BODY SPECTRUM
INTENSITY
18
ν
ν [3×10^{10} Hz]


• AT FREEZE OUT
−Q/T*
• CMB SPECTRUM:
PERFECT BLACK BODY SPECTRUM
(EMITTED BY PLASMA IN TD EQ.)
I = 2hν³/c² · 1/(e^{hν/kT} − 1)
INTENSITY
18
ν
ν [3×10¹⁰ Hz]

- AT FREEZE OUT

$-Q/T_*$

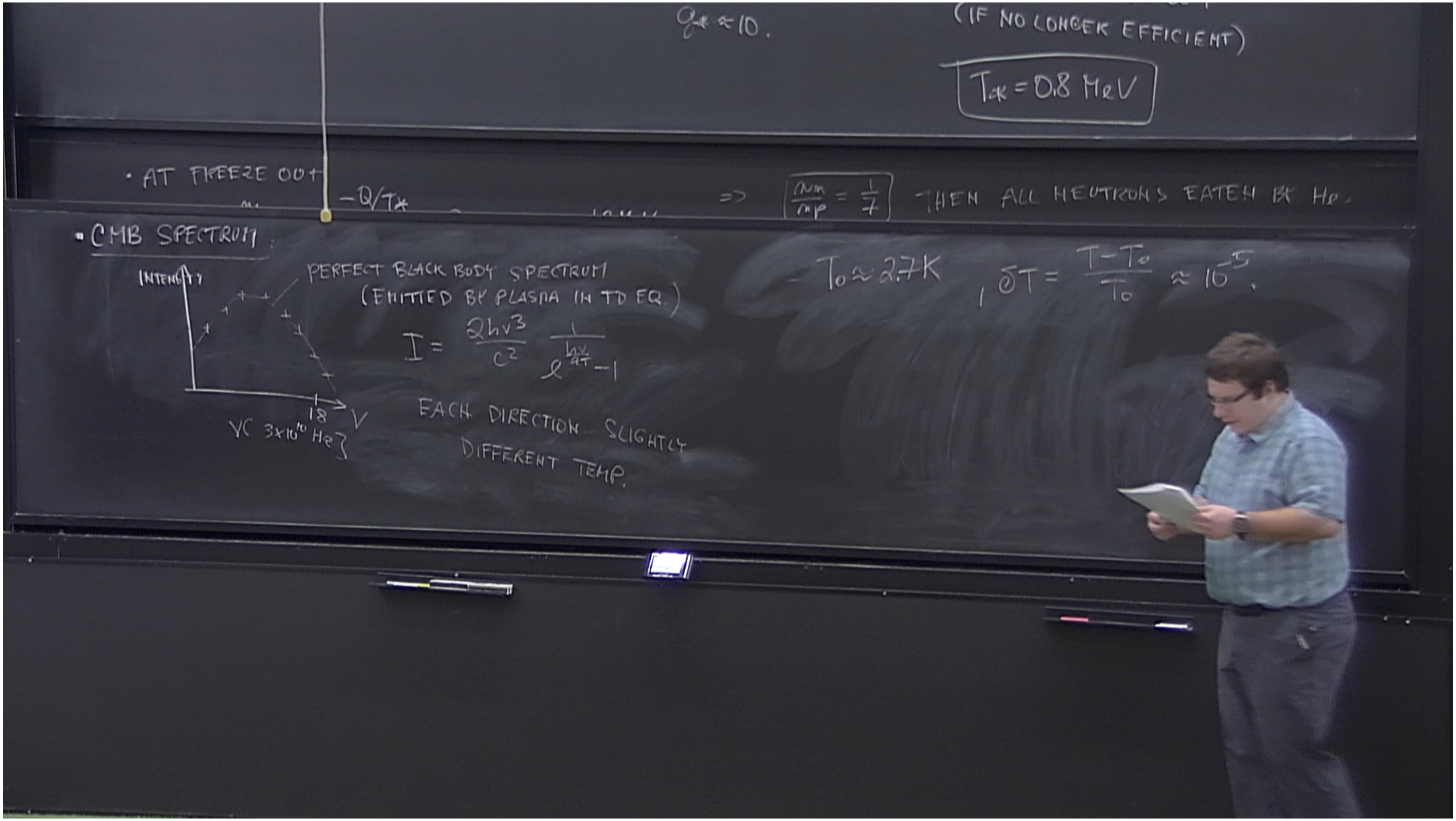
- CMB SPECTRUM:

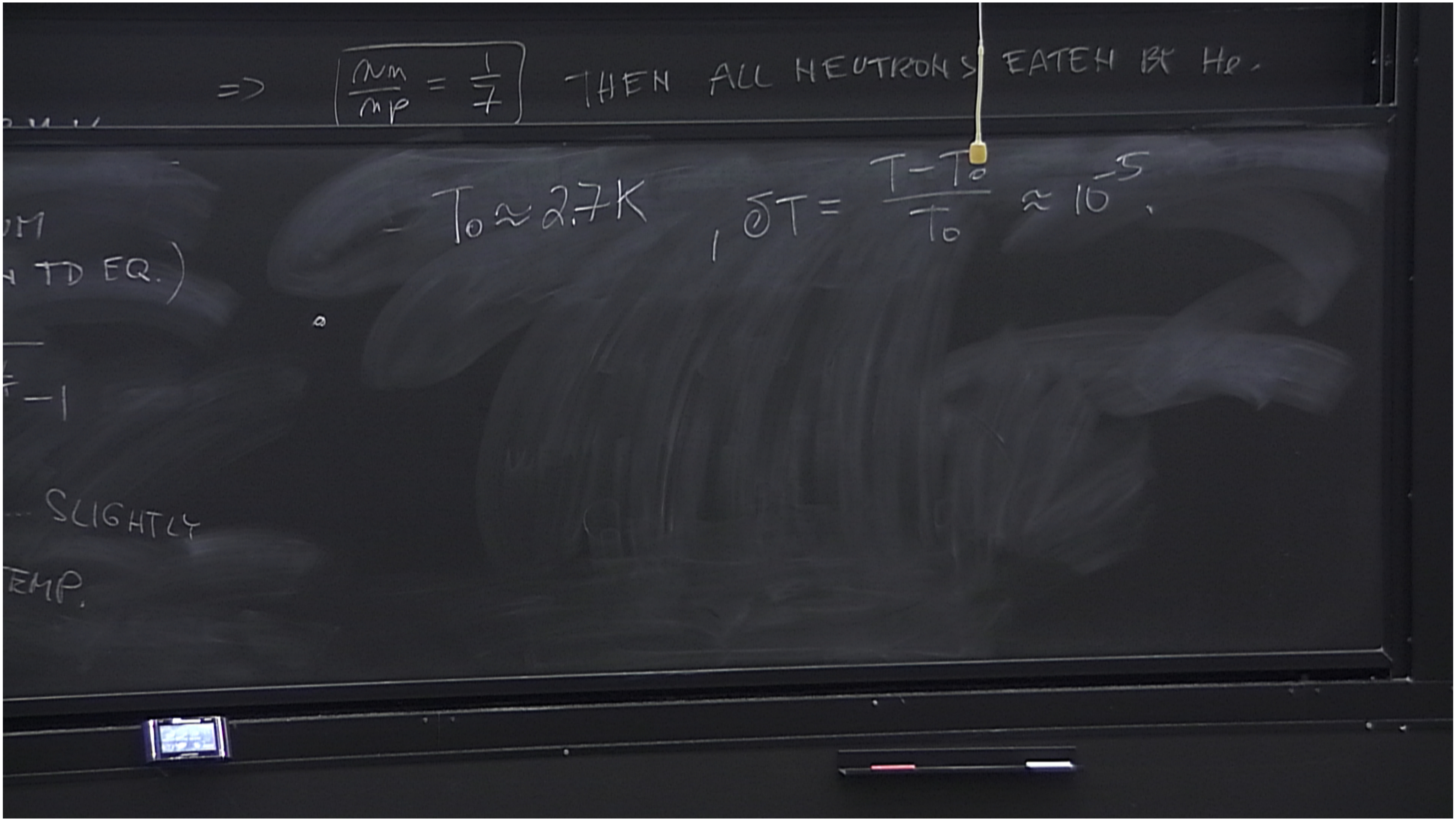


PERFECT BLACK BODY SPECTRUM
(EMITTED BY PLASMA IN TD EQ.)

$$I = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

EACH DIRECTION... SLIGHTLY DIFFERENT TEMP.


(IF NO LONGER EFFICIENT)
T* = 0.8 MeV
• AT FREEZE OUT
THEN ALL NEUTRONS EATEN BY He.
• CMB SPECTRUM
INTENSITY
PERFECT BLACK BODY SPECTRUM
(EMITTED BY PLASMA IN TD EQ.)
T0 ≈ 2.7K
δT = (T − T0)/T0 ≈ 10^-5
I = (2hν^3/c^2) 1/(e^(hν/kT) − 1)
EACH DIRECTION SLIGHTLY
DIFFERENT TEMP.



$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.
$T_0 \approx 2.7K$, $\delta T = \frac{T - T_0}{T_0} \approx 10^{-5}$.
TD EQ.)
SLIGHTLY

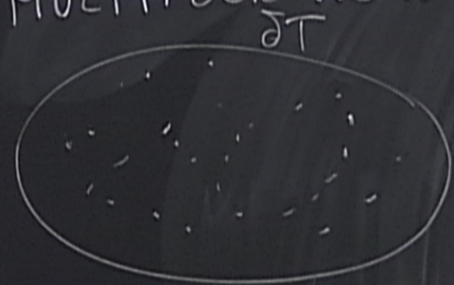
$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.

...M

...N TD EQ.)

$T_0 \approx 2.7K$, $\delta T = \frac{T - T_0}{T_0} \approx 10^{-5}$.

- MULTIPOLE MOMENTS



... SLIGHTLY

...EMP.

$\Rightarrow \boxed{\frac{n_n}{n_p} = \frac{1}{7}}$ THEN ALL NEUTRONS EATEN BY He.

UM

TD EQ.)

$T_0 \approx 2.7K$, $\delta T = \frac{T - T_0}{T_0} \approx 10^{-5}$.

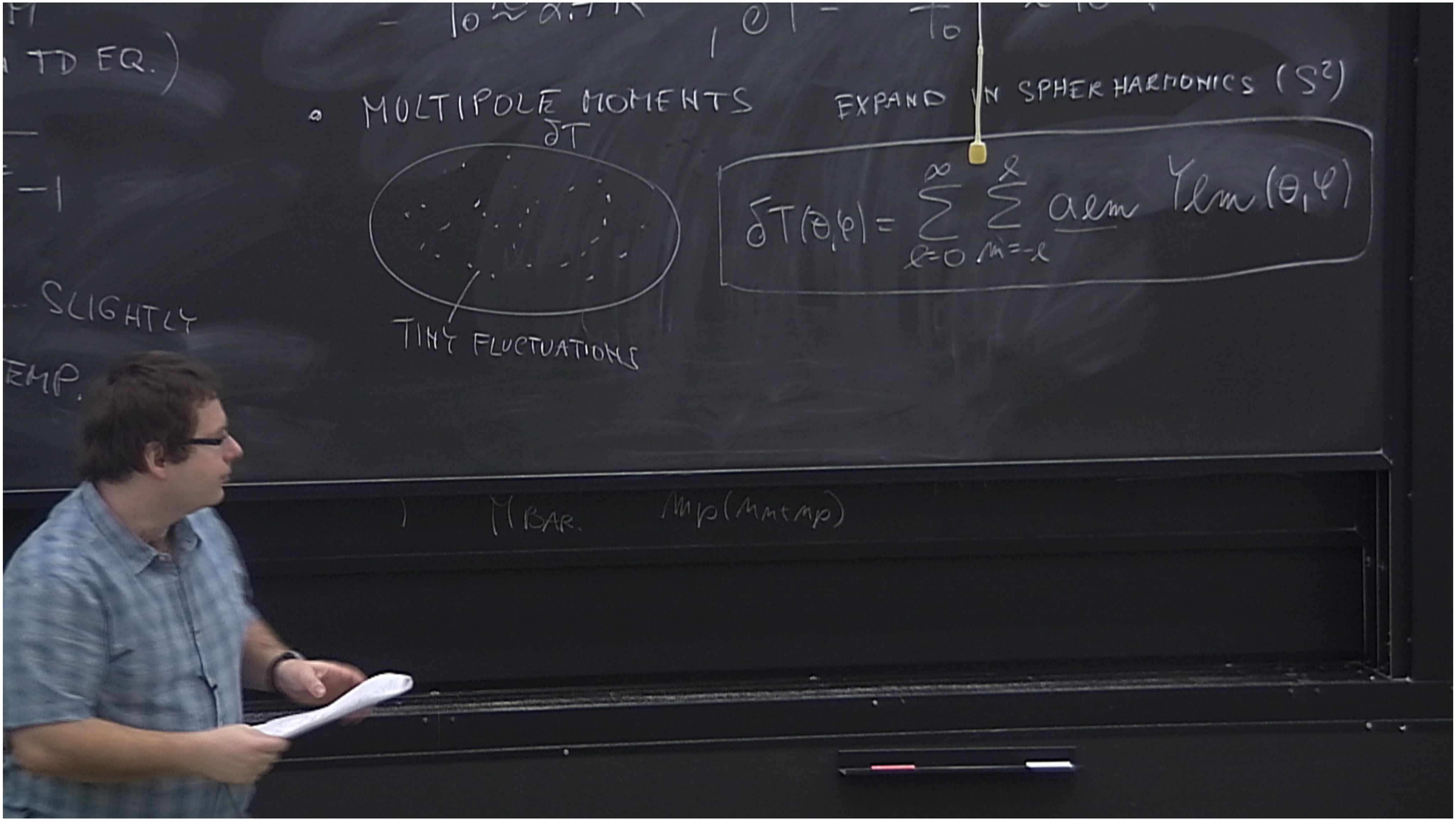
- MULTIPOLE MOMENTS

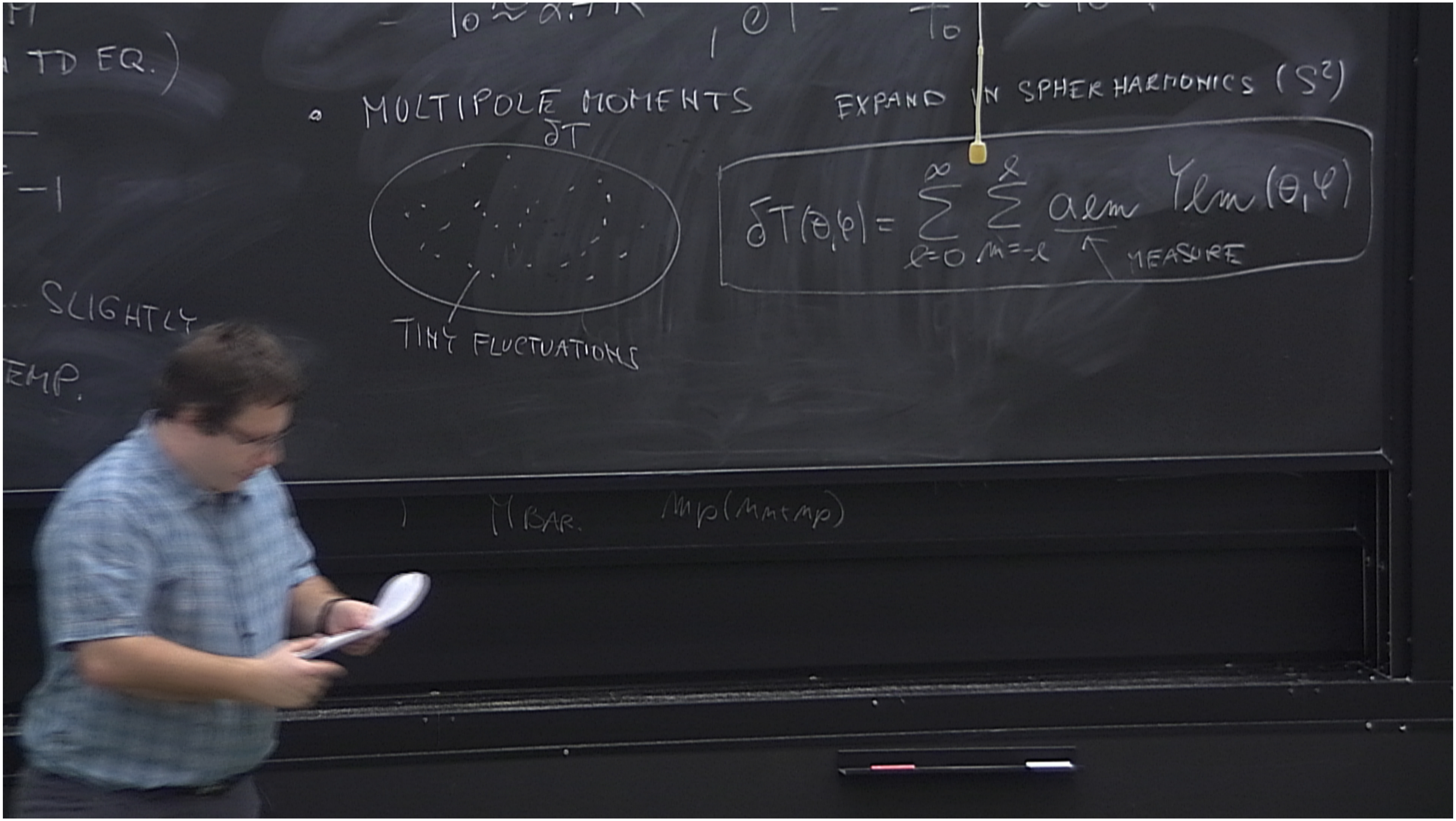
δT

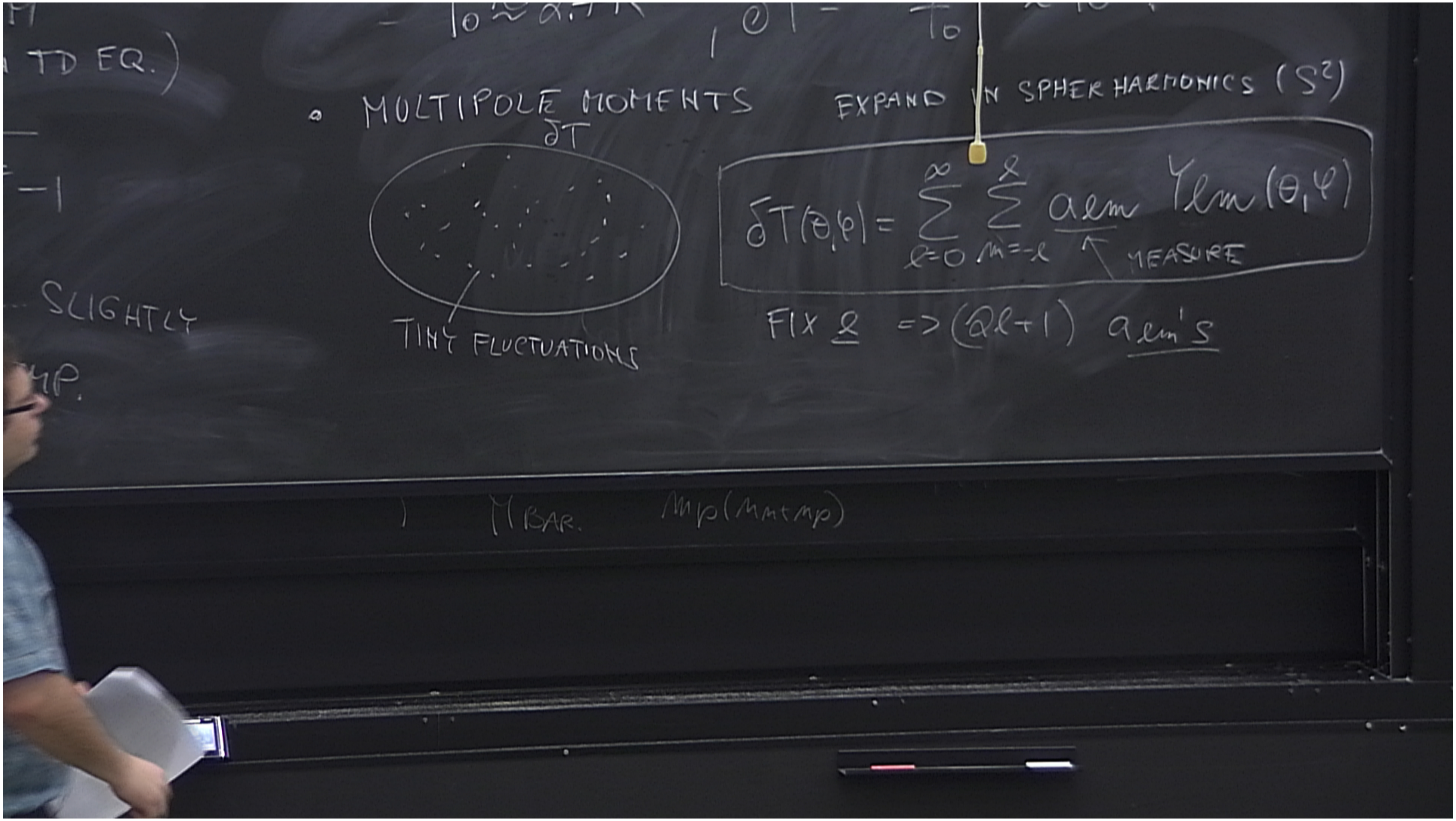
TINY FLUCTUATIONS

SLIGHTLY

EMP.


TD EQ.)
MULTIPOLE MOMENTS
δT
TINY FLUCTUATIONS
SLIGHTLY
EXPAND IN SPHER HARMONICS (S²)
δT(θ,φ) = Σ_{ℓ=0}^{∞} Σ_{m=-ℓ}^{ℓ} a_{ℓm} Y_{ℓm}(θ,φ)
M BAR.


TD EQ.)
MULTIPOLE MOMENTS
EXPAND IN SPHER HARMONICS (S^2)
δT
$\delta T(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$
MEASURE
SLIGHTLY
TINY FLUCTUATIONS
EMP.
M BAR.
$m_p(m_n+m_p)$


TD EQ.)
MULTIPOLE MOMENTS
δT
TINY FLUCTUATIONS
SLIGHTLY
EXPAND IN SPHER HARMONICS (S^2)
$\delta T(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$
MEASURE
FIX ℓ => $(2\ell+1)$ $a_{\ell m}$'s
M BAR.

-1

... SLIGHTLY

EMP.

TINY FLUCTUATIONS

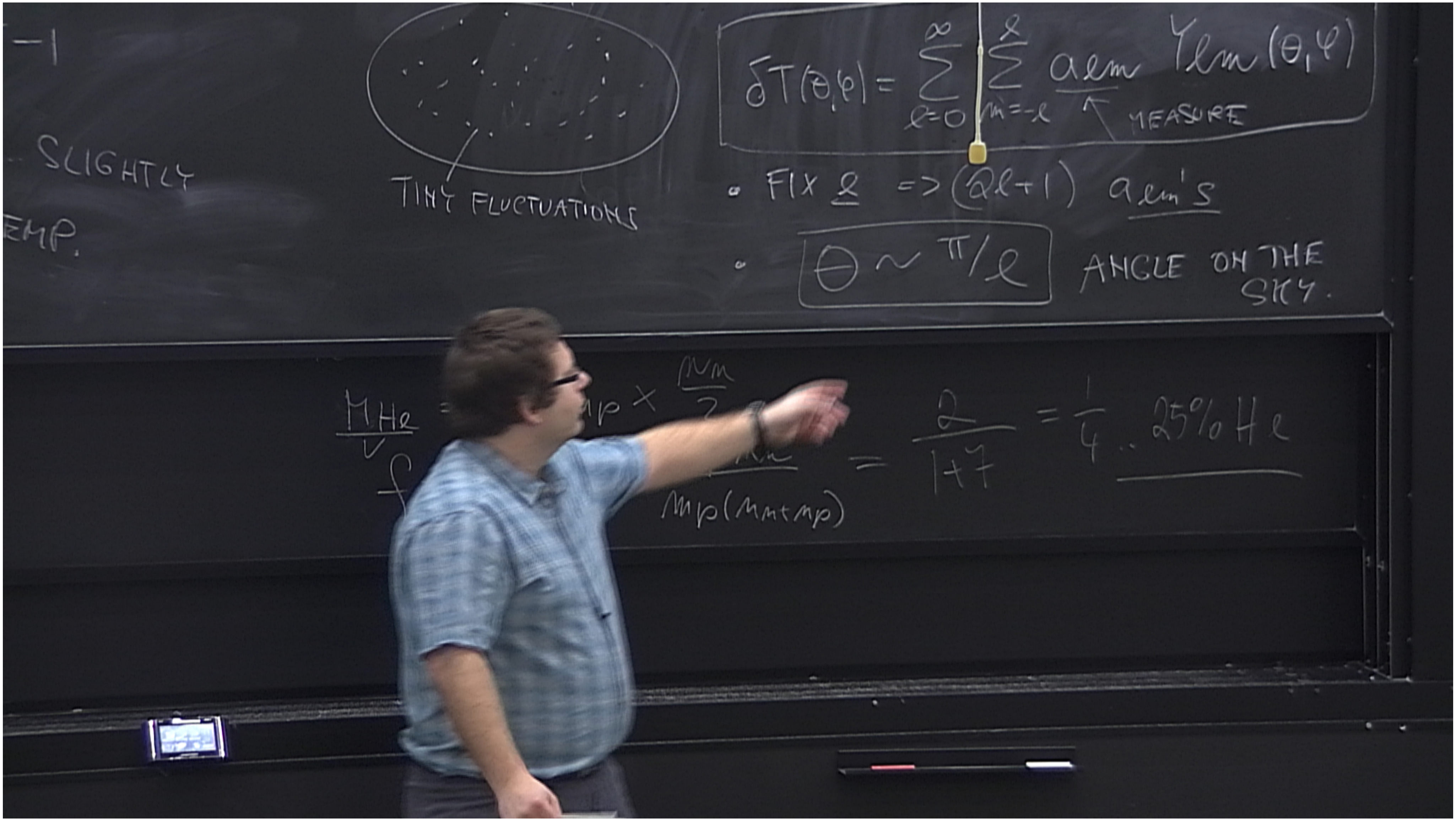
$$\boxed{\delta T(\theta,\varphi) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m}\, Y_{\ell m}(\theta,\varphi)}$$

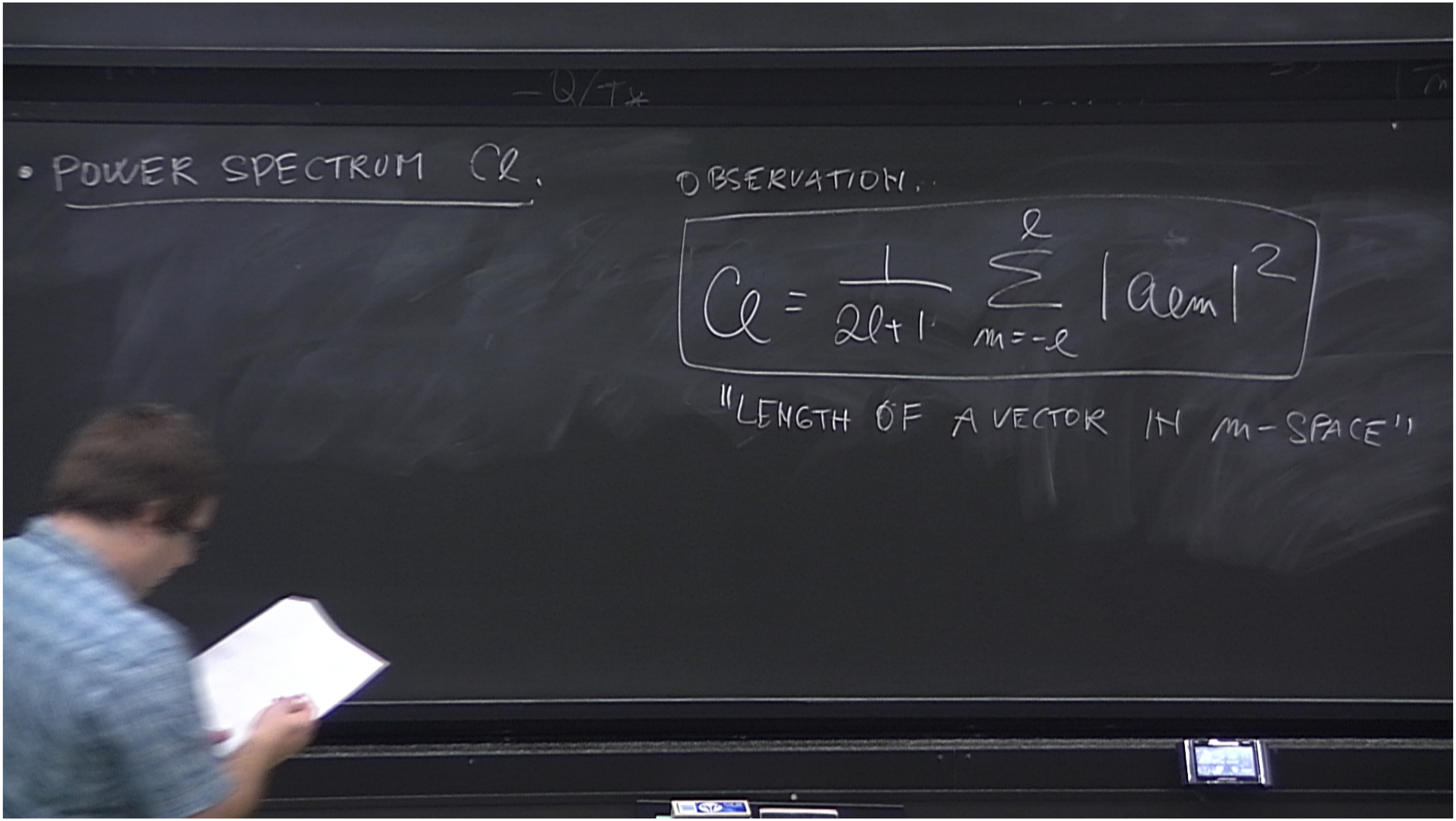
MEASURE

- FIX ℓ $\Rightarrow$ $(2\ell+1)$ $a_{\ell m}$'s
- $\boxed{\Theta \sim \pi/\ell}$

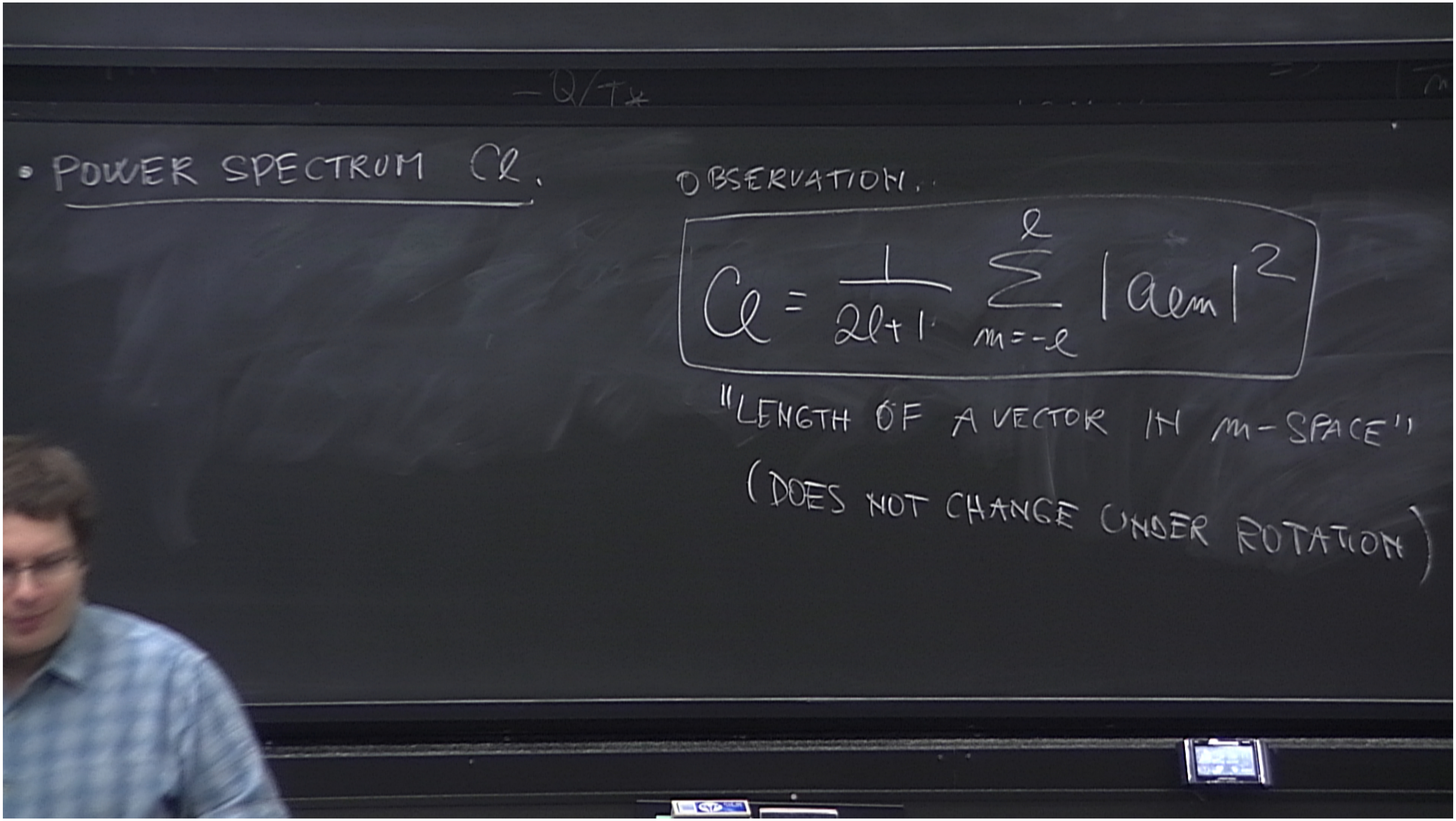
$$\frac{M_{He}}{V} = 4 \times m_p \times \frac{n_n}{2}$$

$$f = \frac{M_{He}}{M_{BAR.}} = \frac{2 m_p n_n}{m_p(n_n + n_p)} = \frac{2}{1+7} = \frac{1}{4} \;..\; \underline{25\%\ He}$$


SLIGHTLY
TINY FLUCTUATIONS
δT(θ,φ) = Σ Σ alm Ylm(θ,φ)
MEASURE
FIX l => (2l+1) alm's
θ ~ π/l
ANGLE ON THE SKY.
25% He

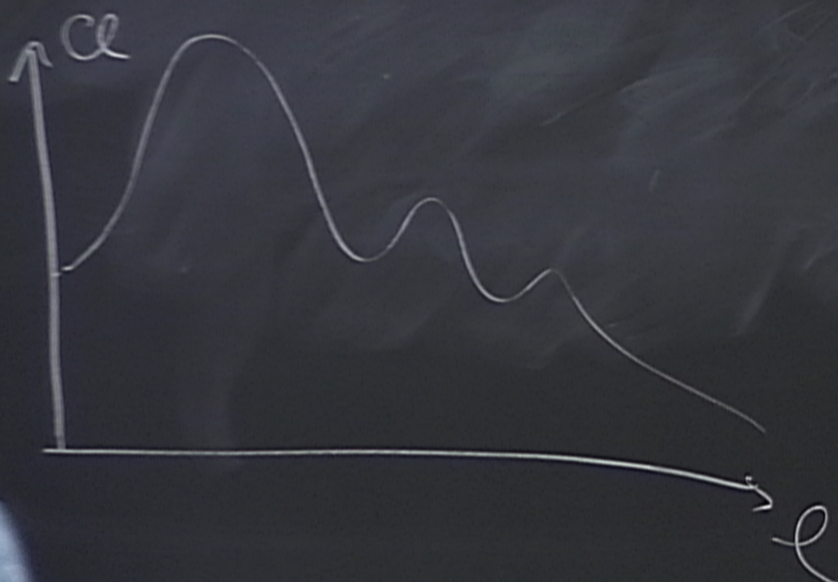


• POWER SPECTRUM C_ℓ.
OBSERVATION.
$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$
"LENGTH OF A VECTOR IN m-SPACE"



• POWER SPECTRUM C_ℓ.
OBSERVATION.
$$\boxed{C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$
"LENGTH OF A VECTOR IN m-SPACE"
(DOES NOT CHANGE UNDER ROTATION)

- POWER SPECTRUM C_ℓ.



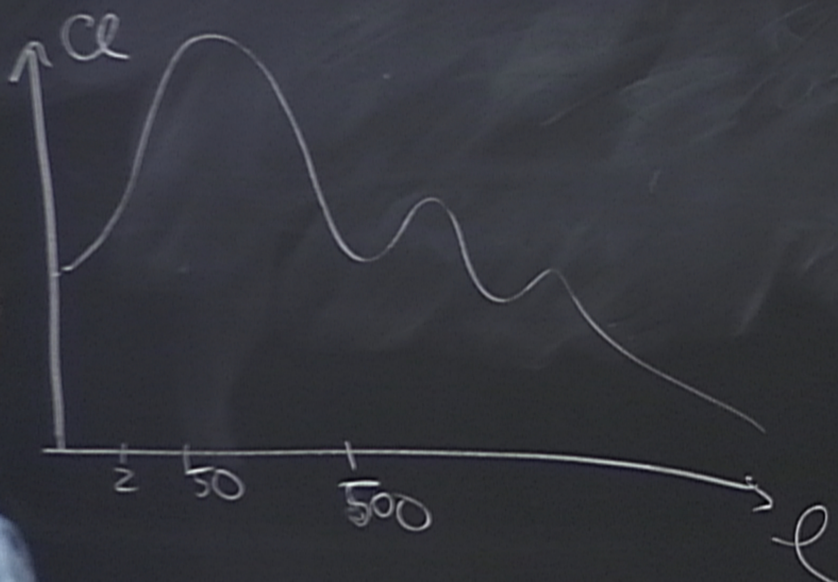
OBSERVATION:

$$\boxed{C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

"LENGTH OF A VECTOR IN m-SPACE"

(DOES NOT CHANGE UNDER ROTATION)

- POWER SPECTRUM C_ℓ.



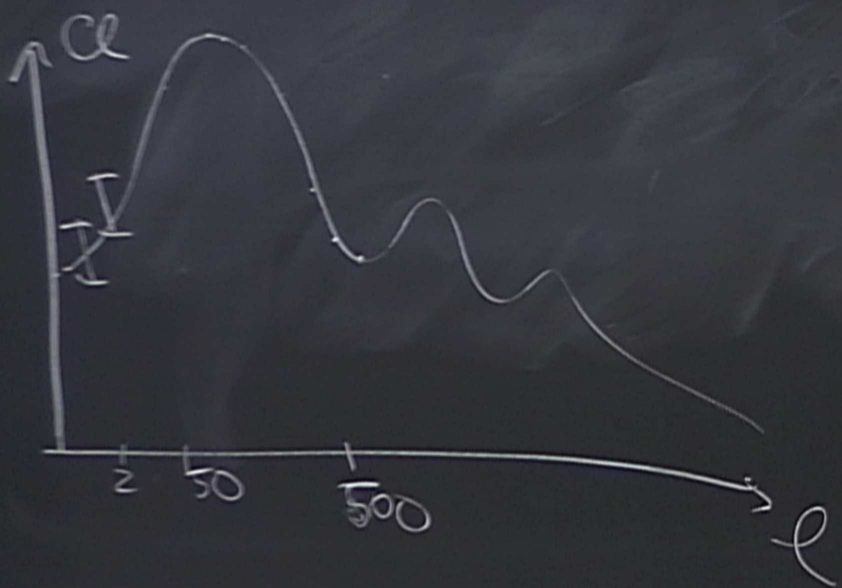
OBSERVATION.

$$\boxed{C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

"LENGTH OF A VECTOR IN m-SPACE"

(DOES NOT CHANGE UNDER ROTATION)

- POWER SPECTRUM C_ℓ.



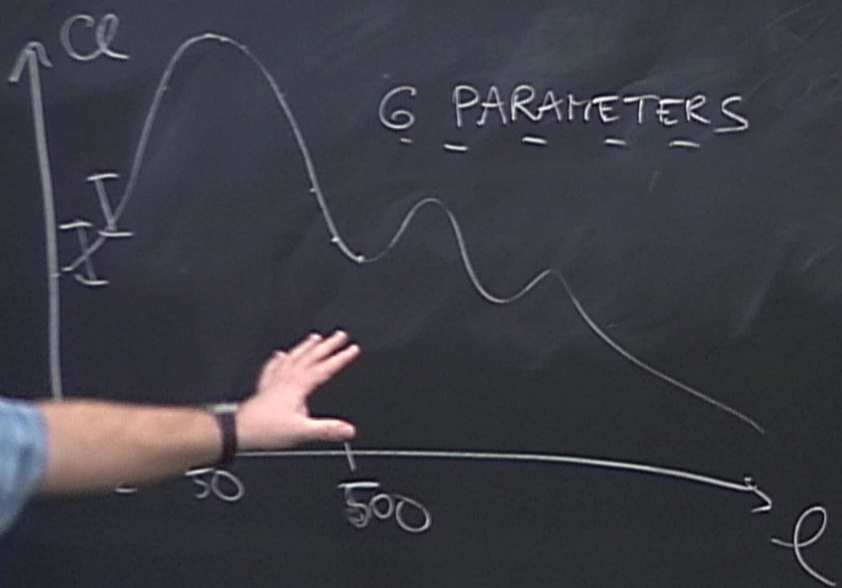
OBSERVATION.

$$\boxed{C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

"LENGTH OF A VECTOR IN m-SPACE"

(DOES NOT CHANGE UNDER ROTATION)

• POWER SPECTRUM C_ℓ.

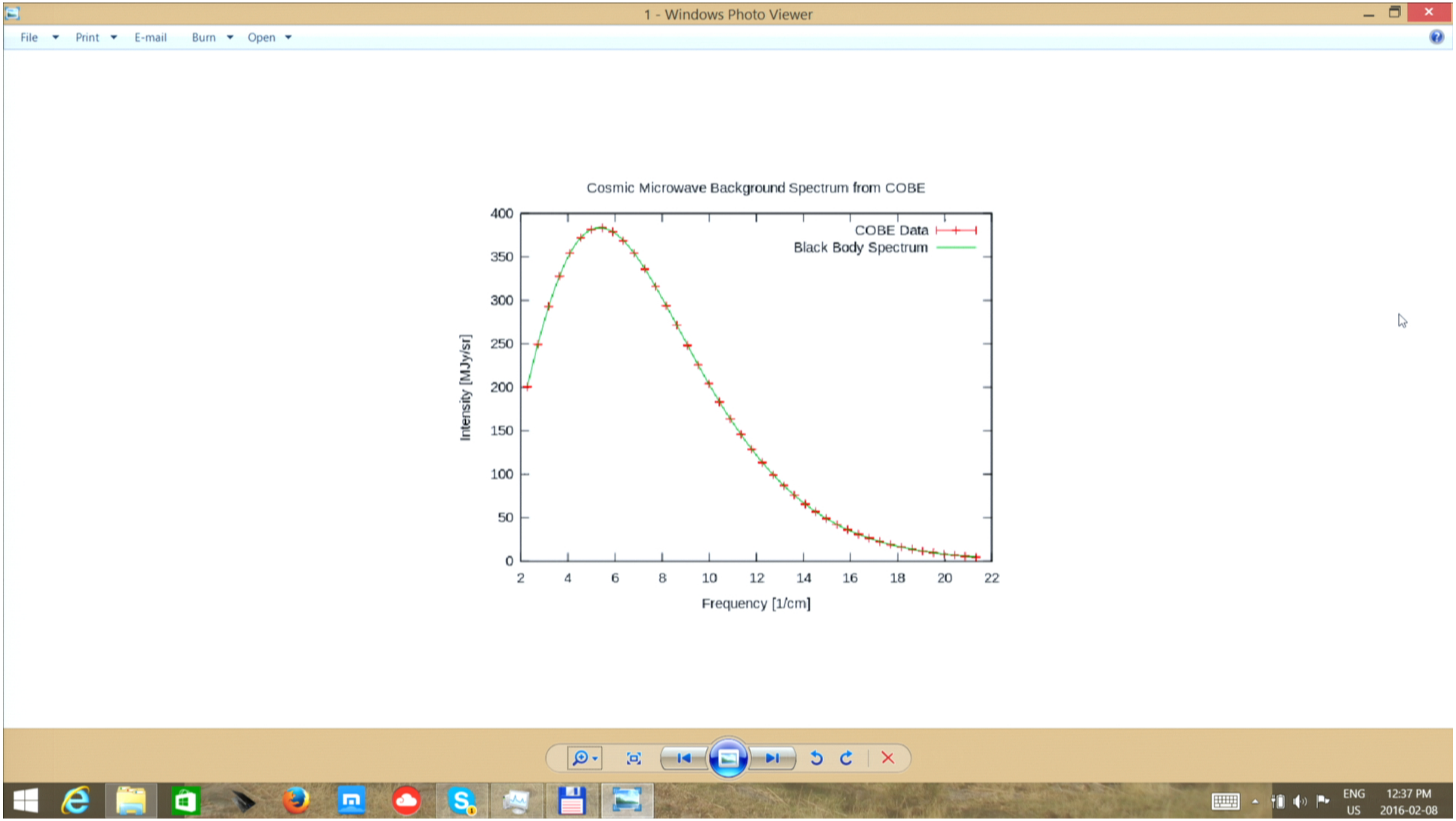


OBSERVATION:

$$\boxed{C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

"LENGTH OF A VECTOR IN m-SPACE"

(DOES NOT CHANGE UNDER ROTATION)


1 - Windows Photo Viewer
File
Print
E-mail
Burn
Open
Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
Frequency [1/cm]
400
350
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250
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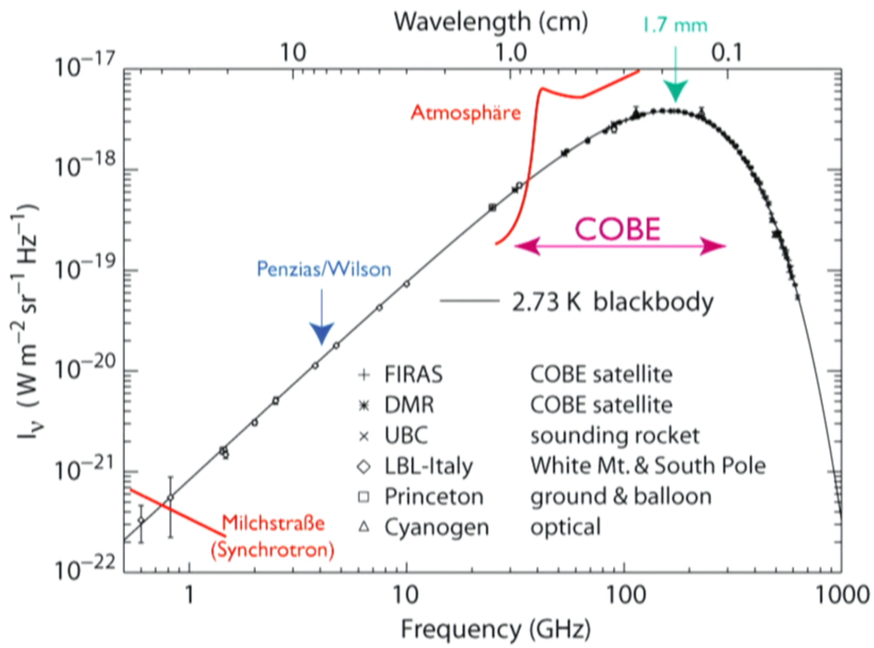
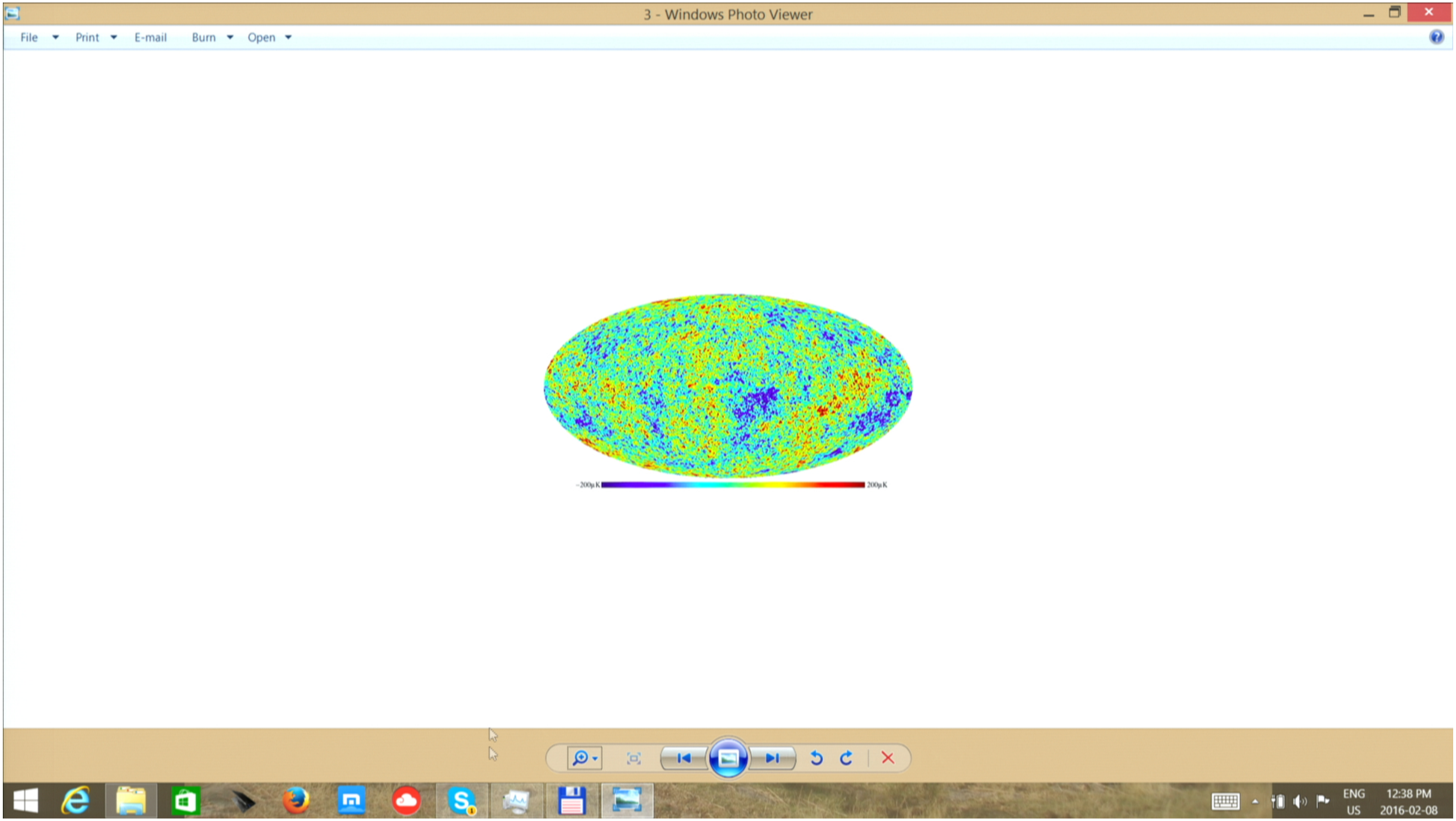
2016-02-08


Wavelength (cm)
1.7 mm
10
1.0
0.1
Atmosphäre
COBE
Penzias/Wilson
2.73 K blackbody
FIRAS COBE satellite
DMR COBE satellite
UBC sounding rocket
LBL-Italy White Mt. & South Pole
Princeton ground & balloon
Cyanogen optical
Milchstraße
(Synchrotron)
I_ν (W m^{-2} sr^{-1} Hz^{-1})
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
1
10
100
1000
Frequency (GHz)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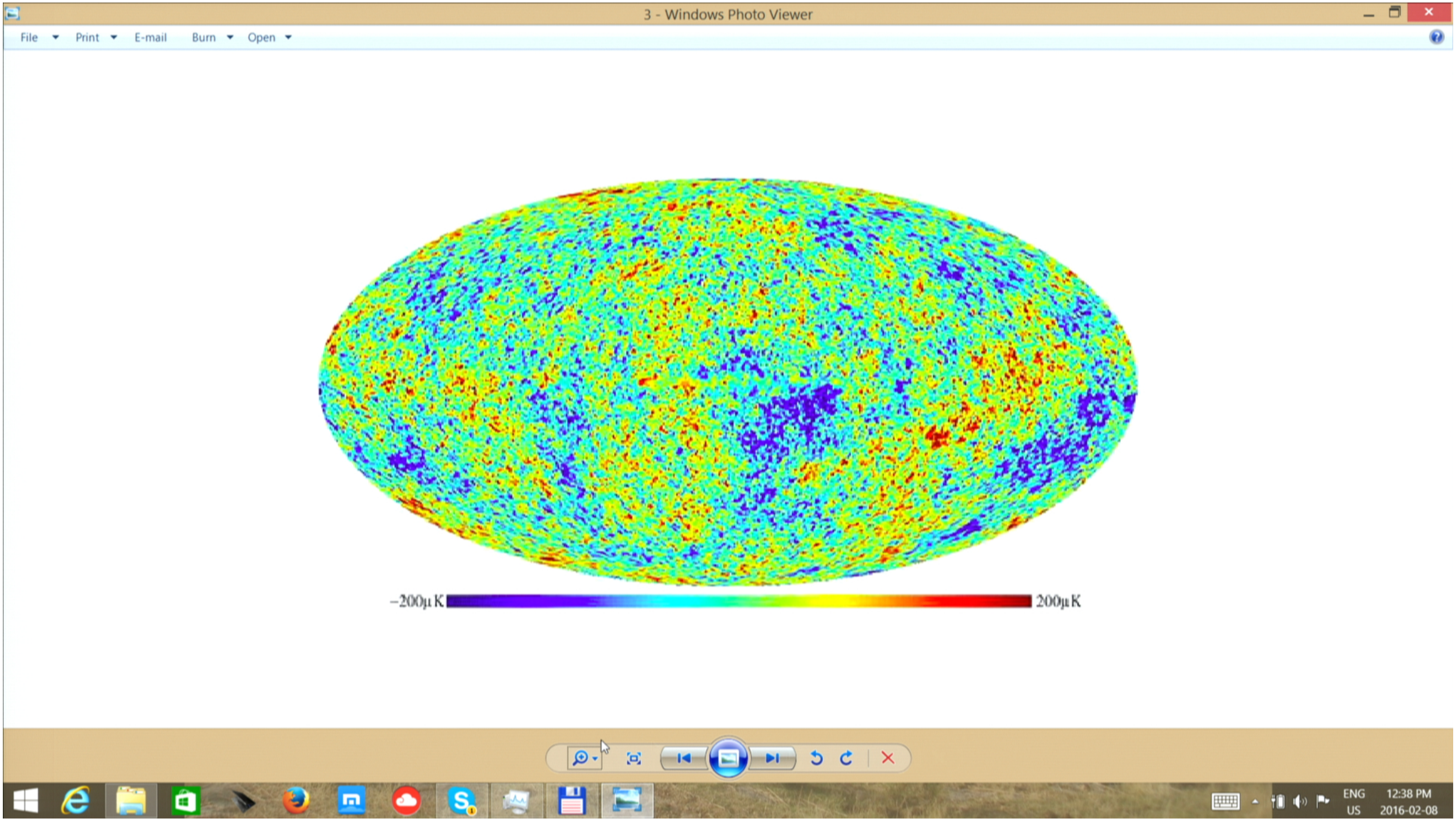
2016-02-08


3 - Windows Photo Viewer
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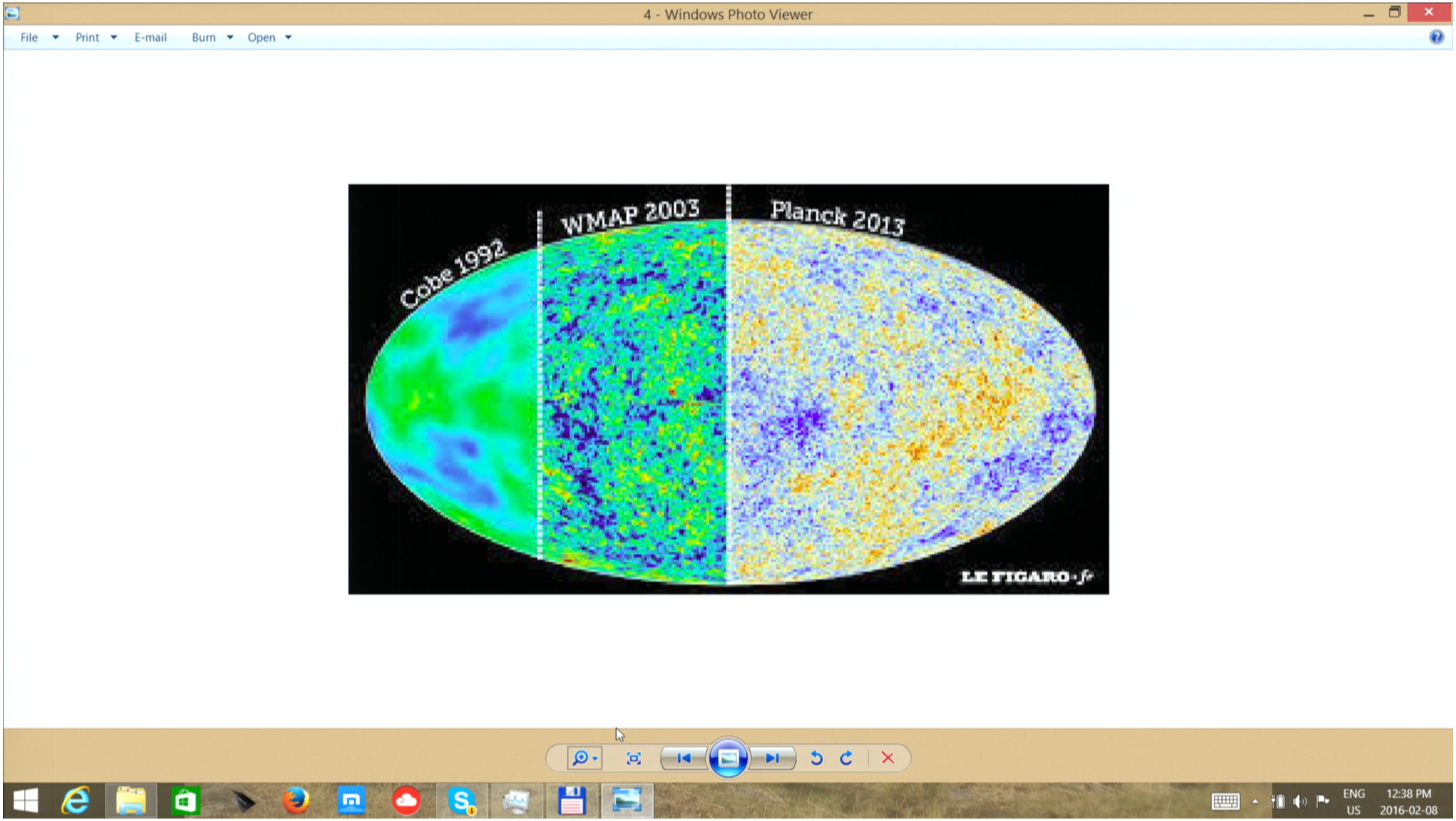
4 - Windows Photo Viewer
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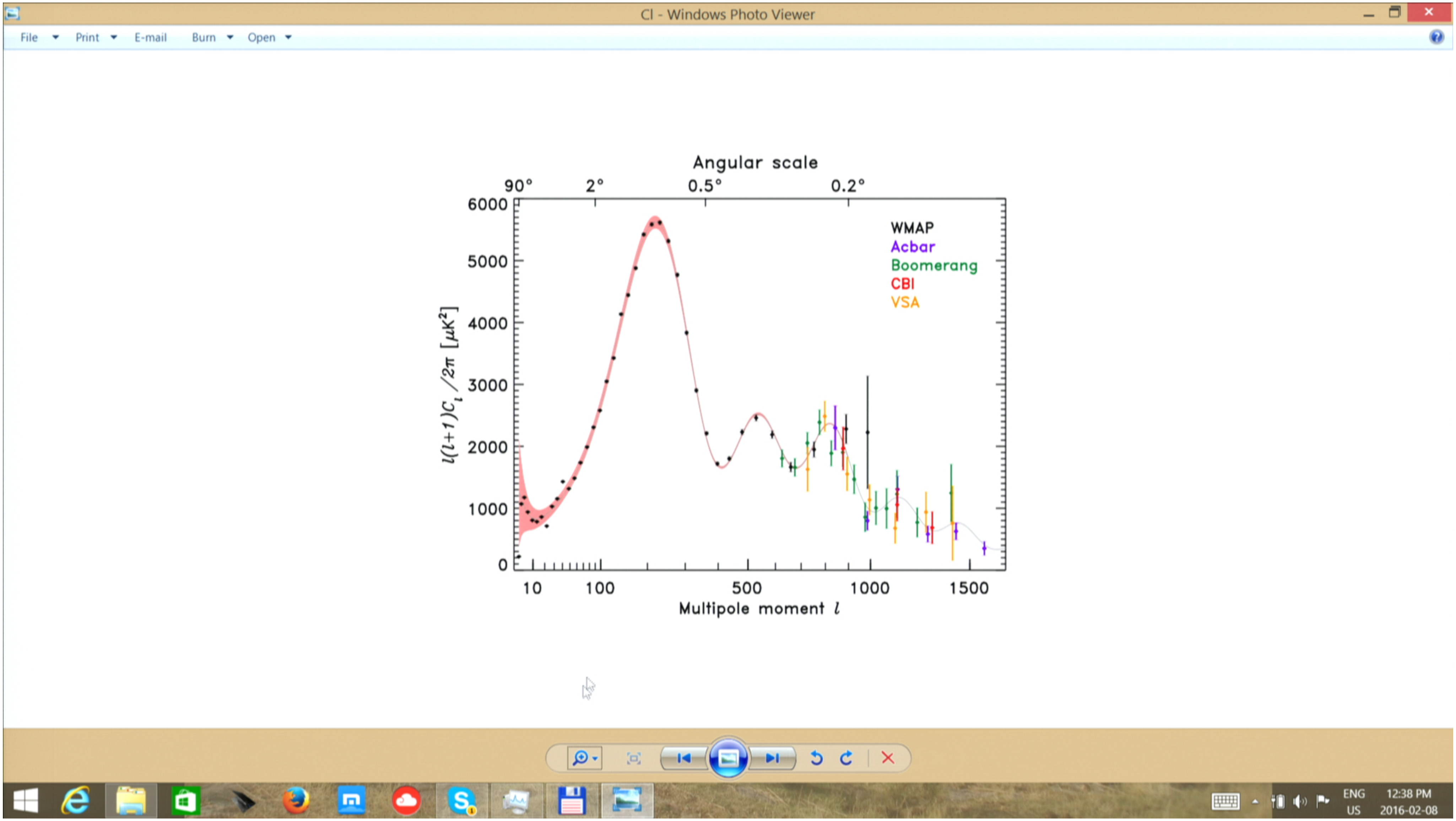
2016-02-08


Cl - Windows Photo Viewer
File
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Burn
Open
Angular scale
90°
2°
0.5°
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3000
2000
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$l(l+1)C_l\,/2\pi\ [\mu K^2]$
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CBI
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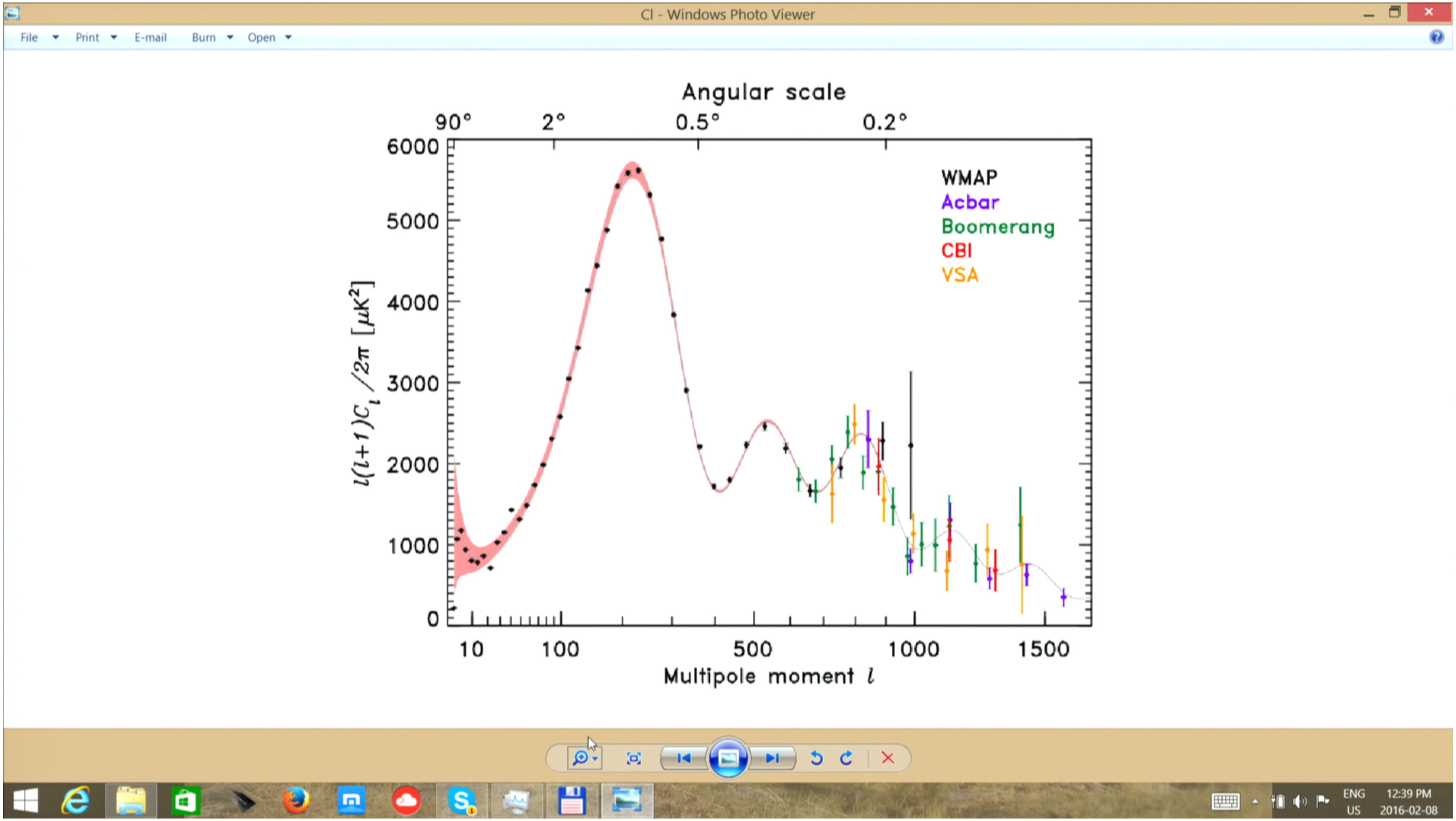
2016-02-08


Cl - Windows Photo Viewer
File Print E-mail Burn Open
Angular scale
90° 2° 0.5° 0.2°
6000
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Multipole moment l
$l(l+1)C_l/2\pi\ [\mu K^2]$
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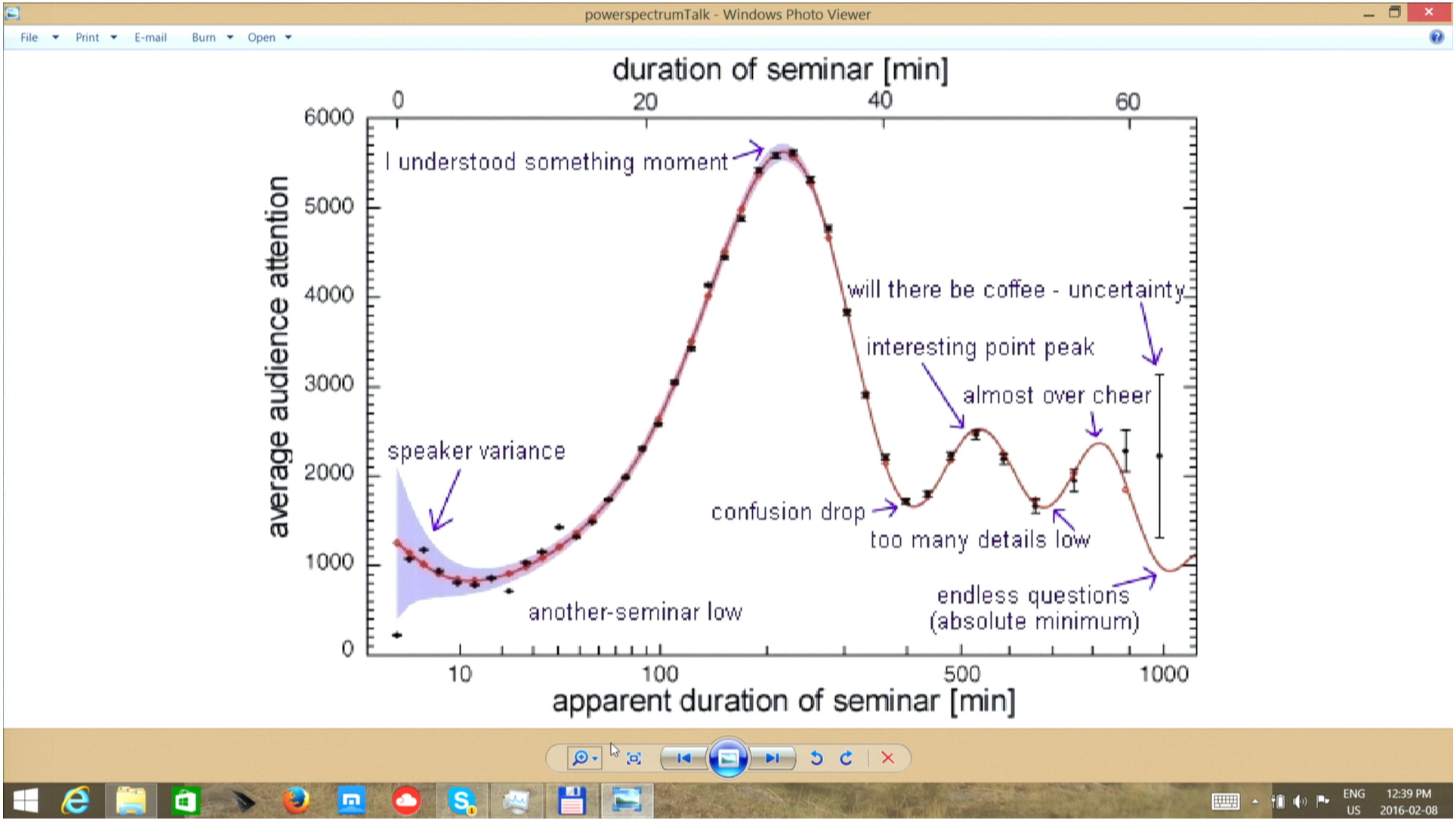
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duration of seminar [min]
0
20
40
60
6000
5000
4000
3000
2000
1000
0
average audience attention
I understood something moment
will there be coffee - uncertainty
interesting point peak
almost over cheer
speaker variance
confusion drop
too many details low
another-seminar low
endless questions
(absolute minimum)
10
100
500
1000
apparent duration of seminar [min]
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2016-02-08