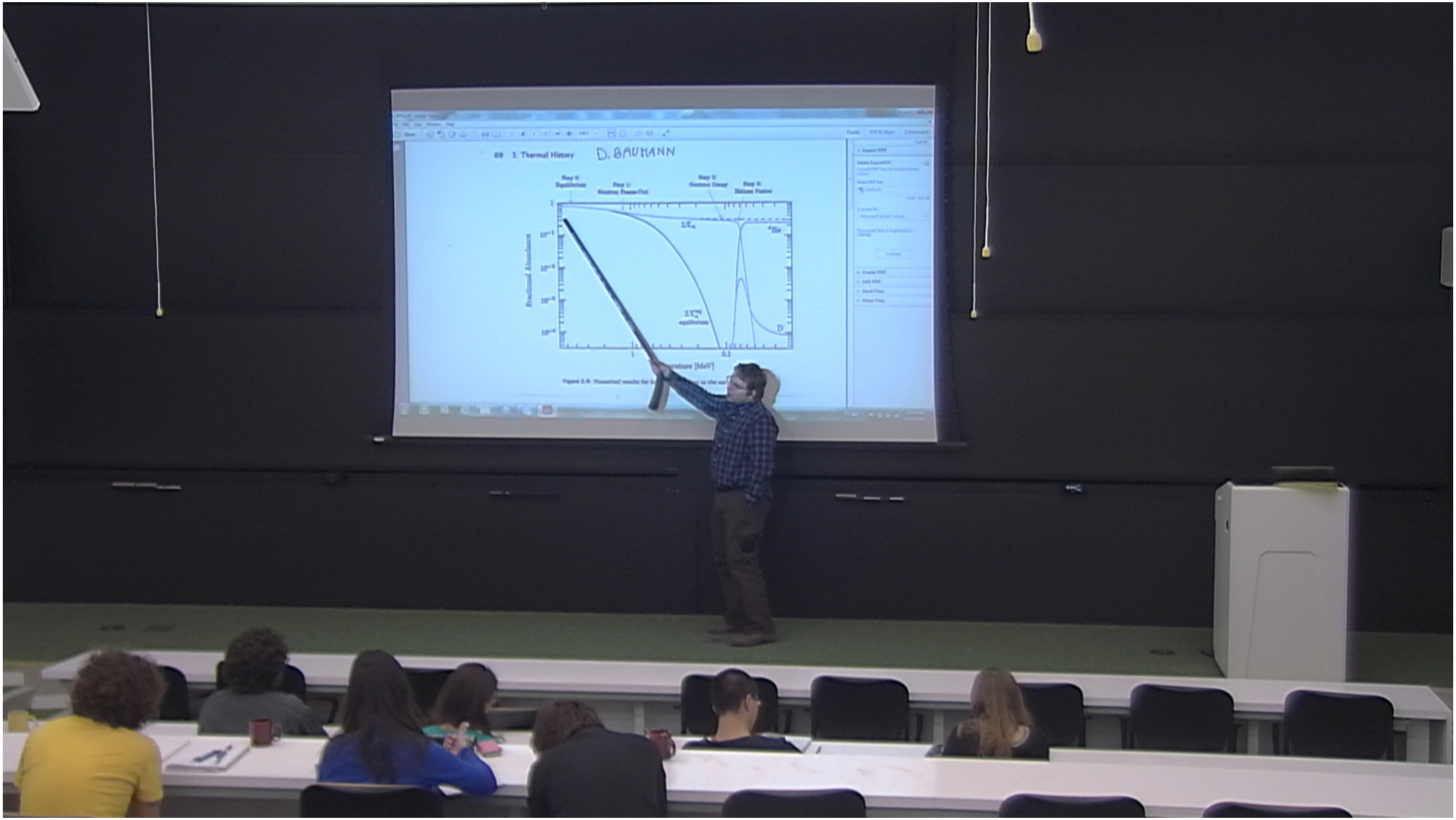
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Abstract:


09 3. Thermal History
D. BAUMANN
Step 0: Equilibrium
Step 1: Neutron Freeze-Out
Step 2: Neutron Decay
Step 3: Helium Fusion
Fractional Abundance
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$2X_n$
^4He
$2X_n^{eq}$
equilibrium
D
1
0.1
Temperature [MeV]

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 D. BAUMANN

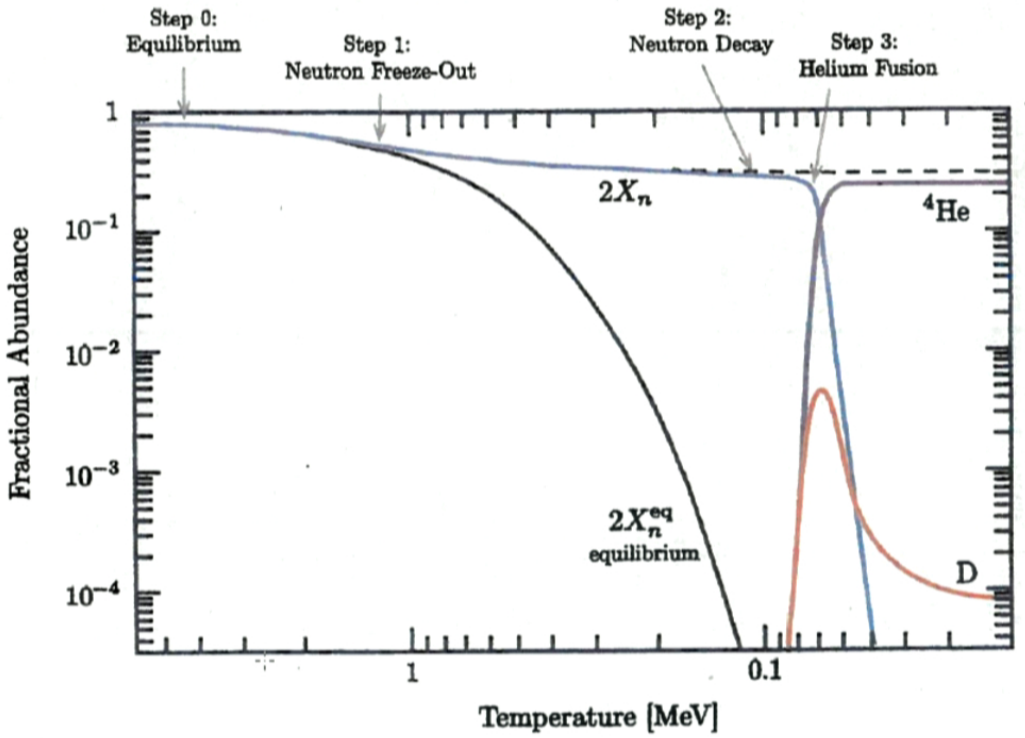


Figure 3.9: *Numerical results for helium production in the early universe.*

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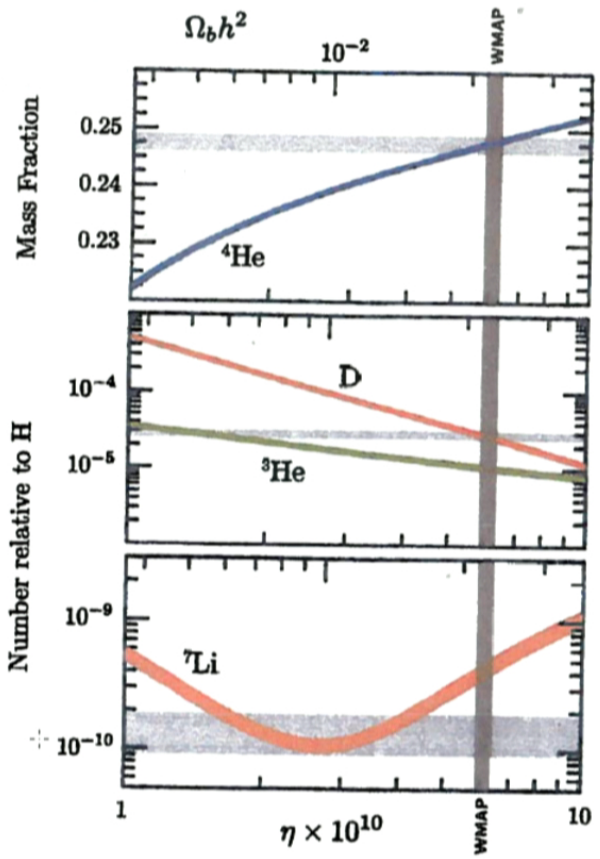


Figure 3.10: *Theoretical predictions (colored bands) and observational constraints (grey bands).*

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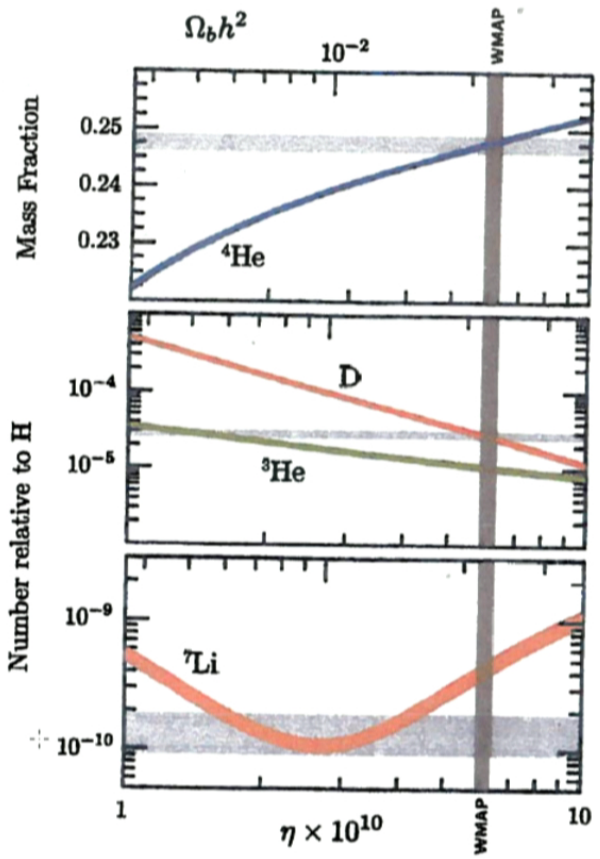
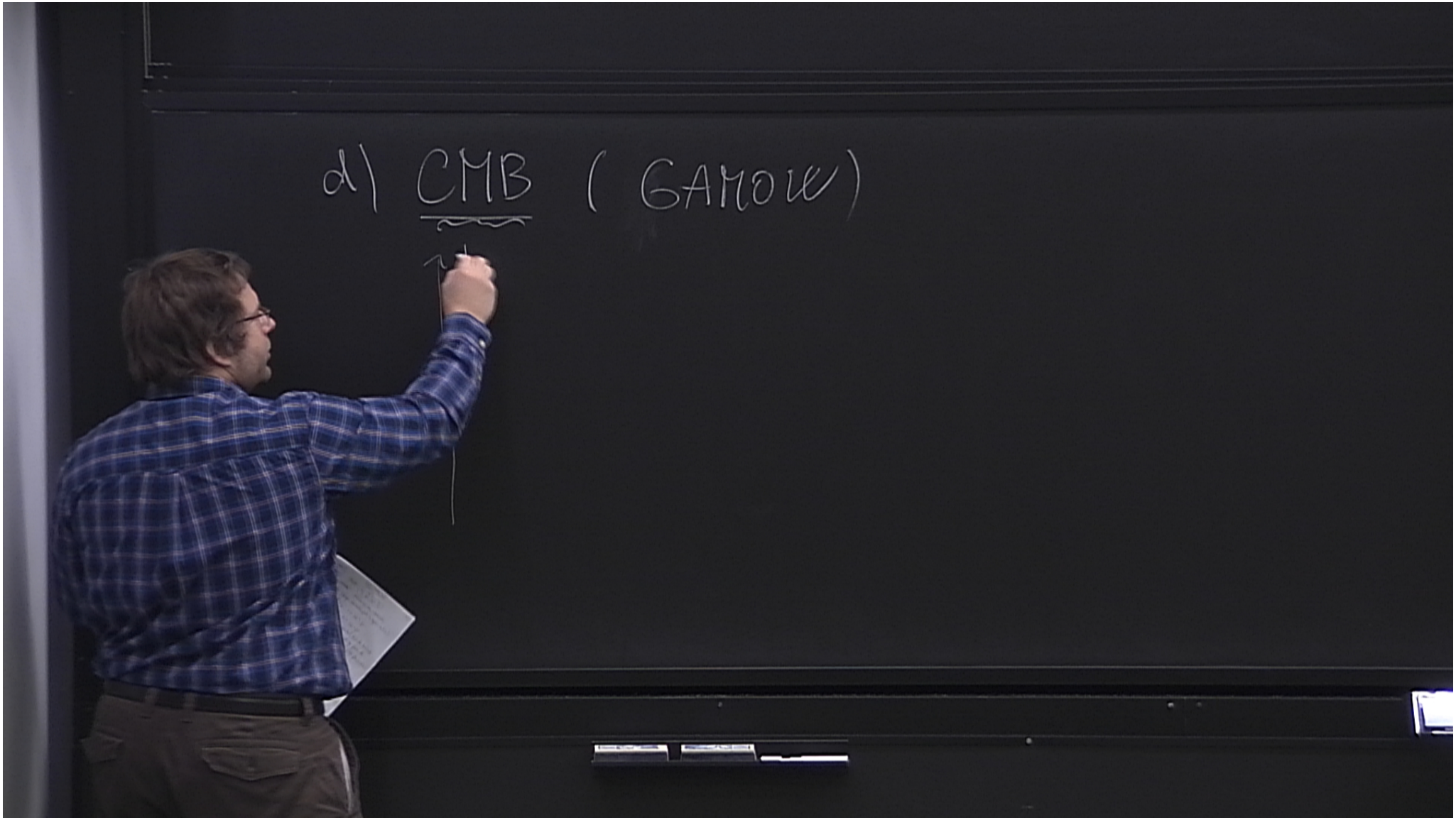
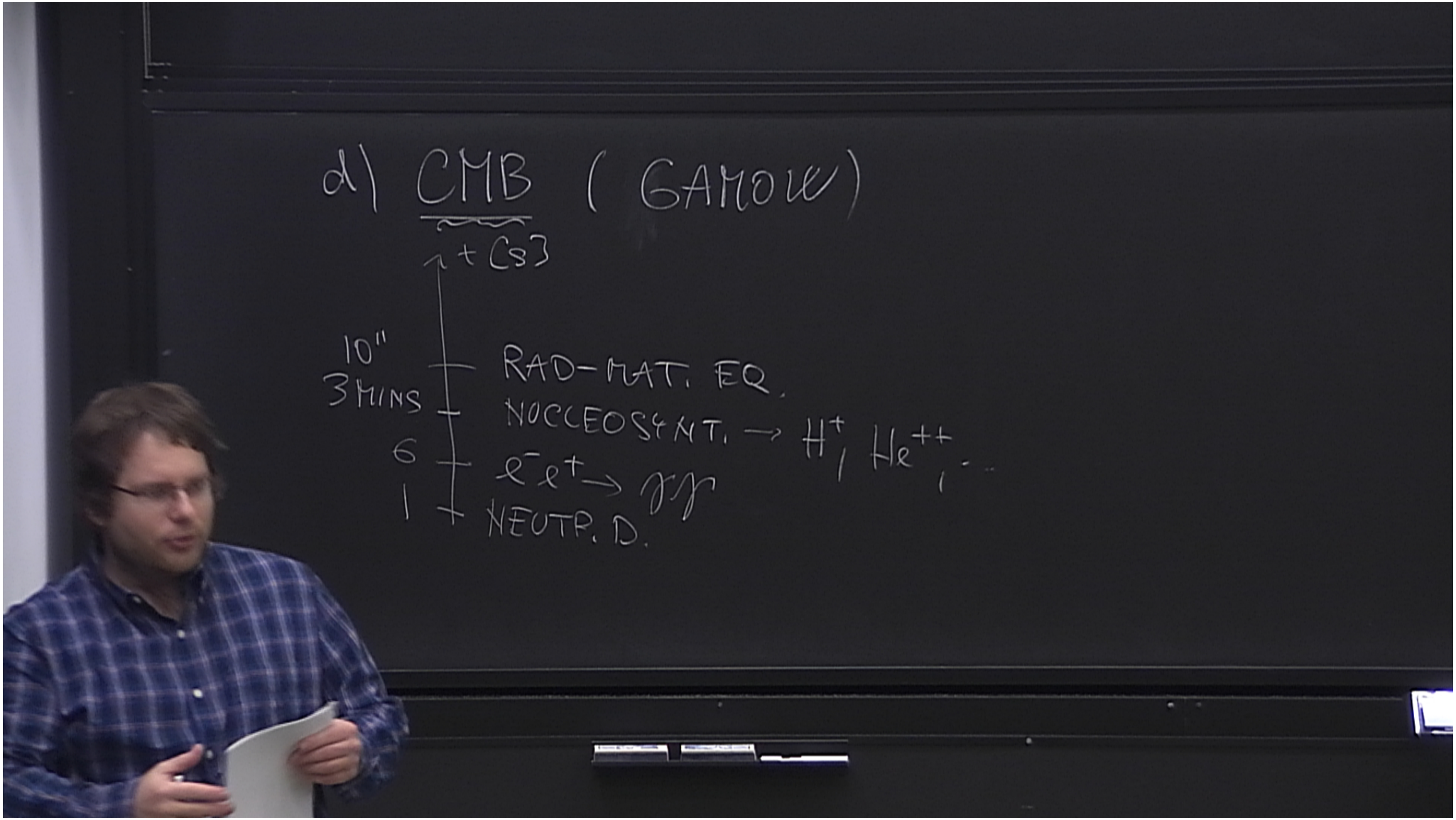
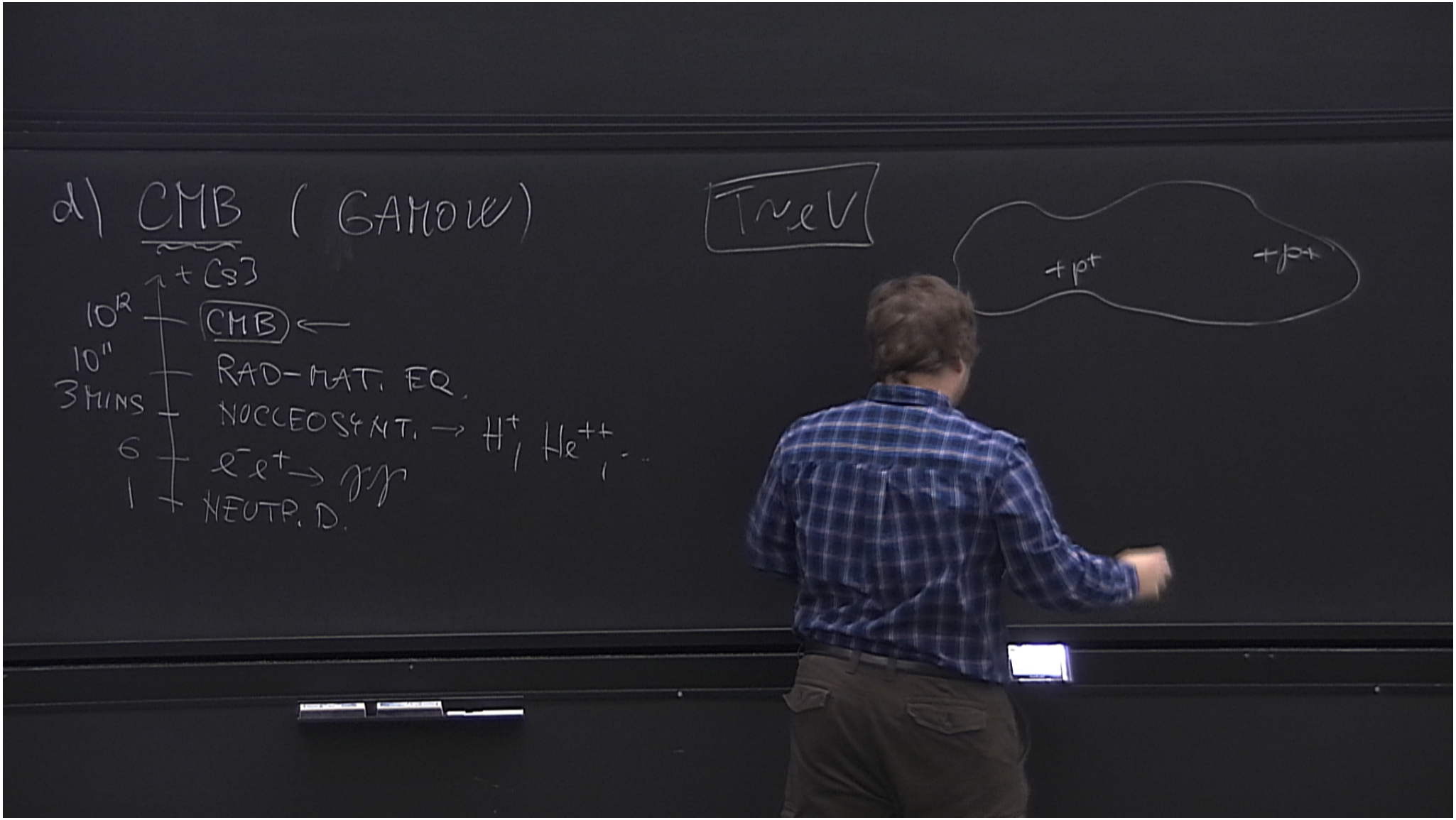


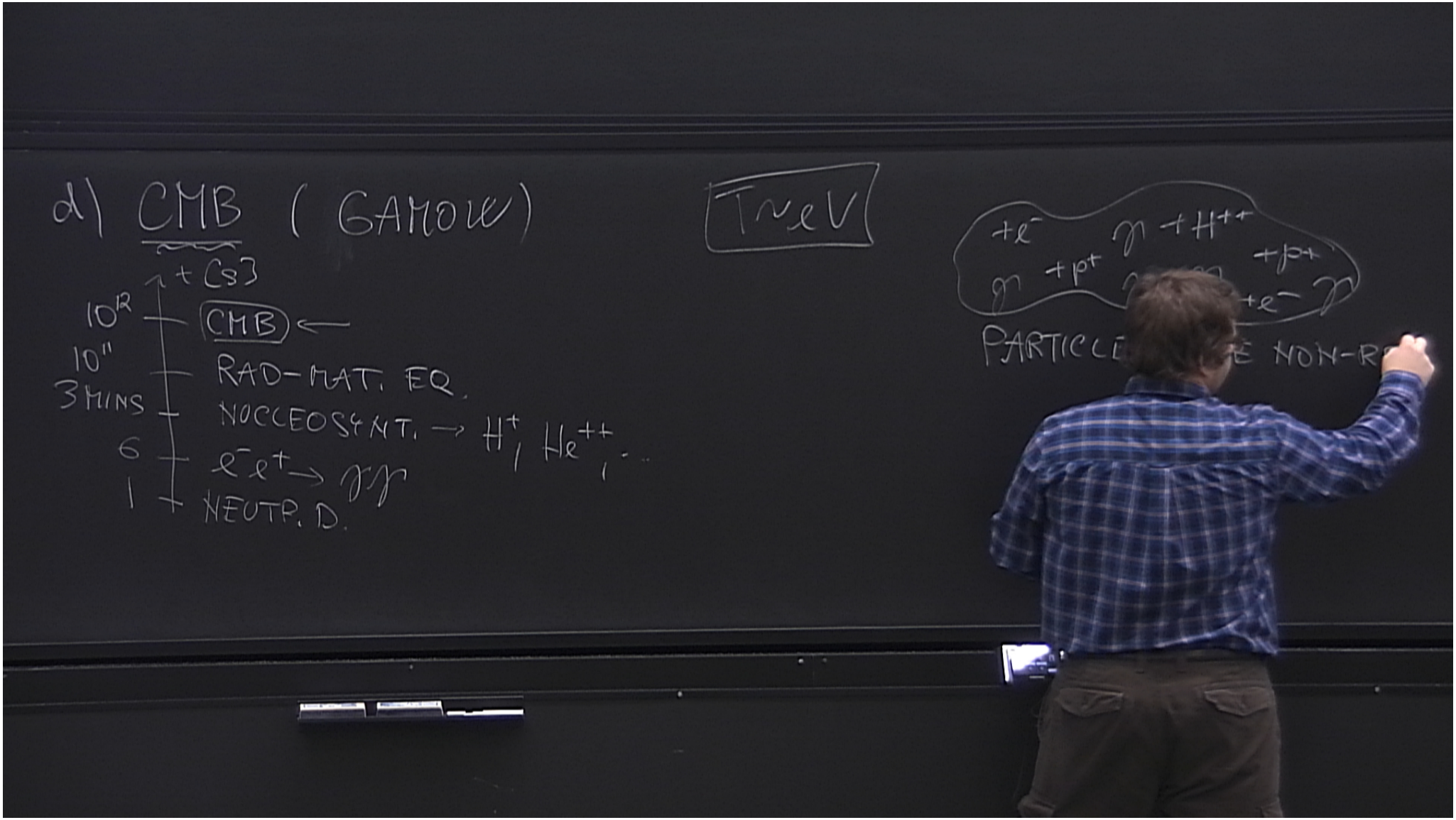
Figure 3.10: *Theoretical predictions (colored bands) and observational constraints (grey bands).*

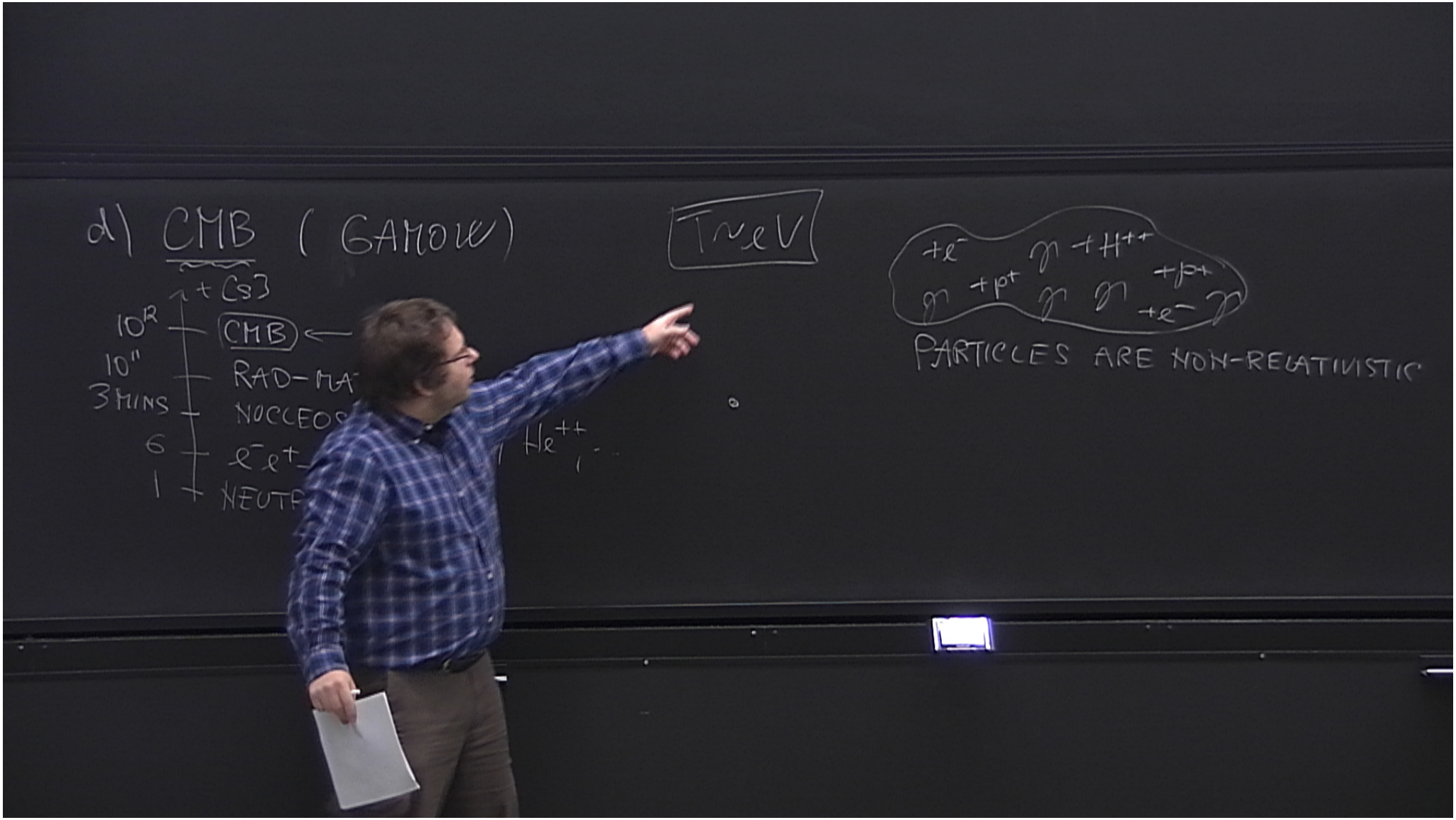
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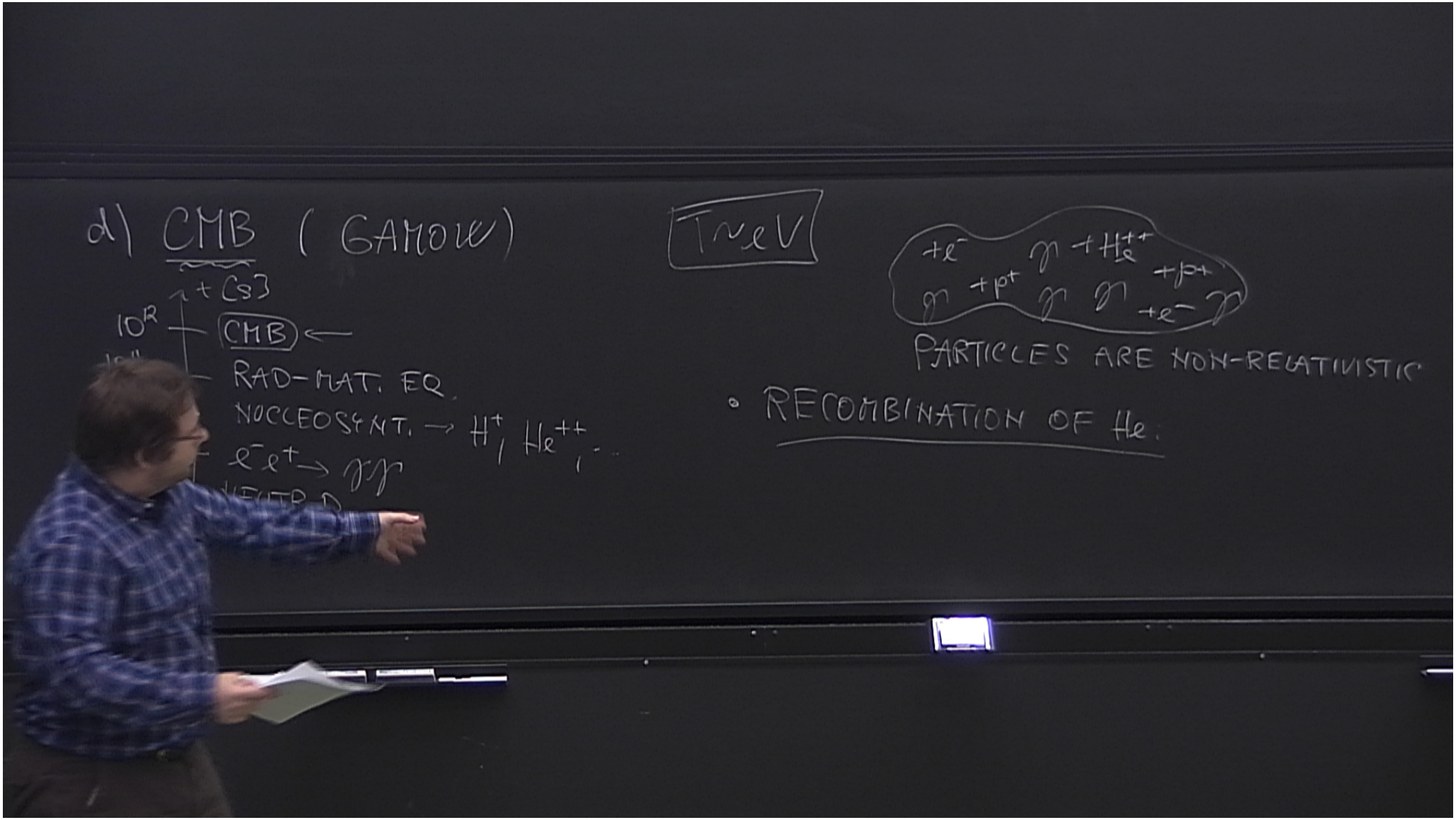

d) CMB (GAMOW)

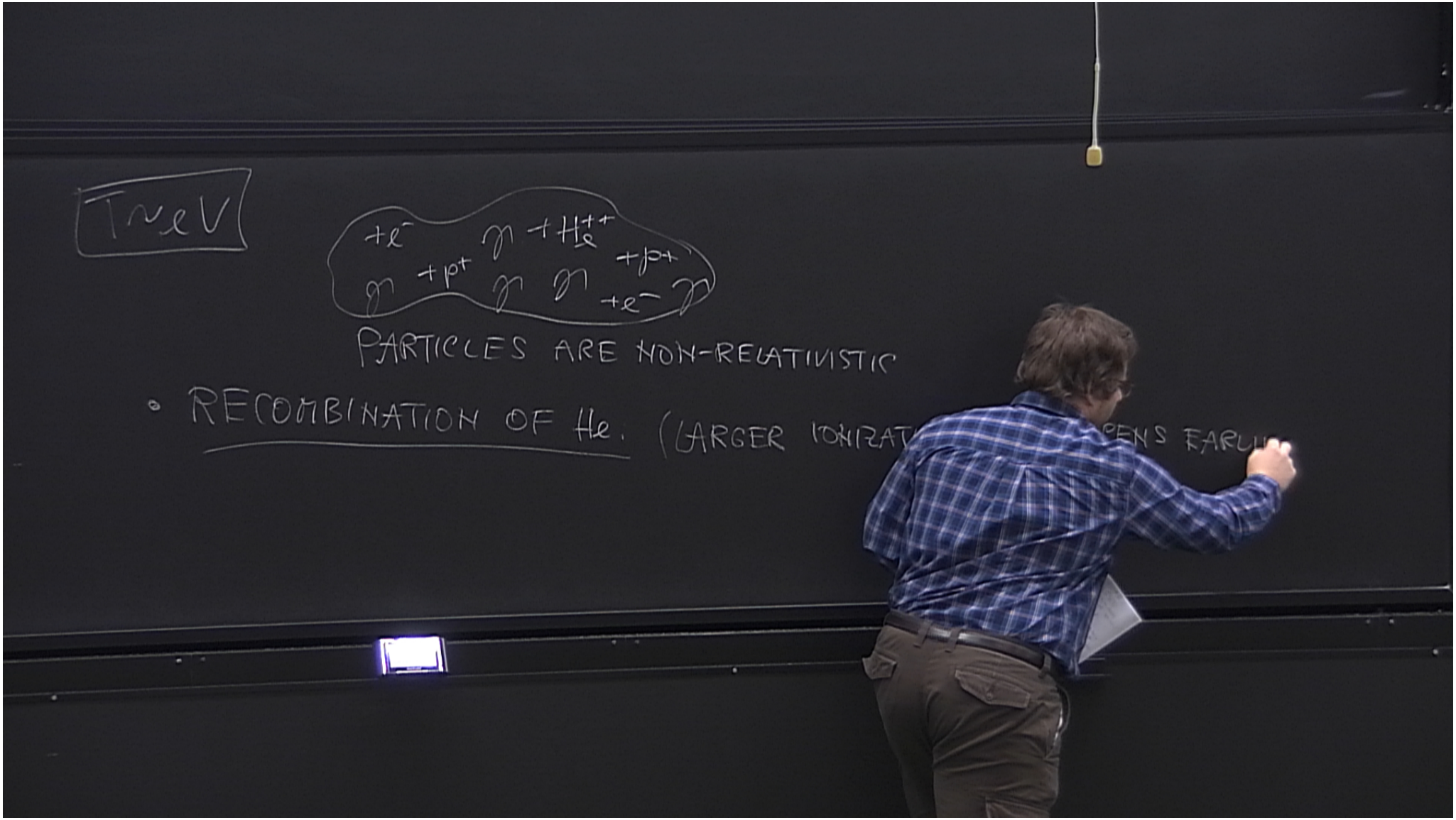

d) CMB (GAMOW)
t [s]
10"
3 MINS
6
1
RAD-MAT. EQ.
NUCLEOSYNT. → H+, He++, ...
e- e+ → γγ
NEUTR. D.

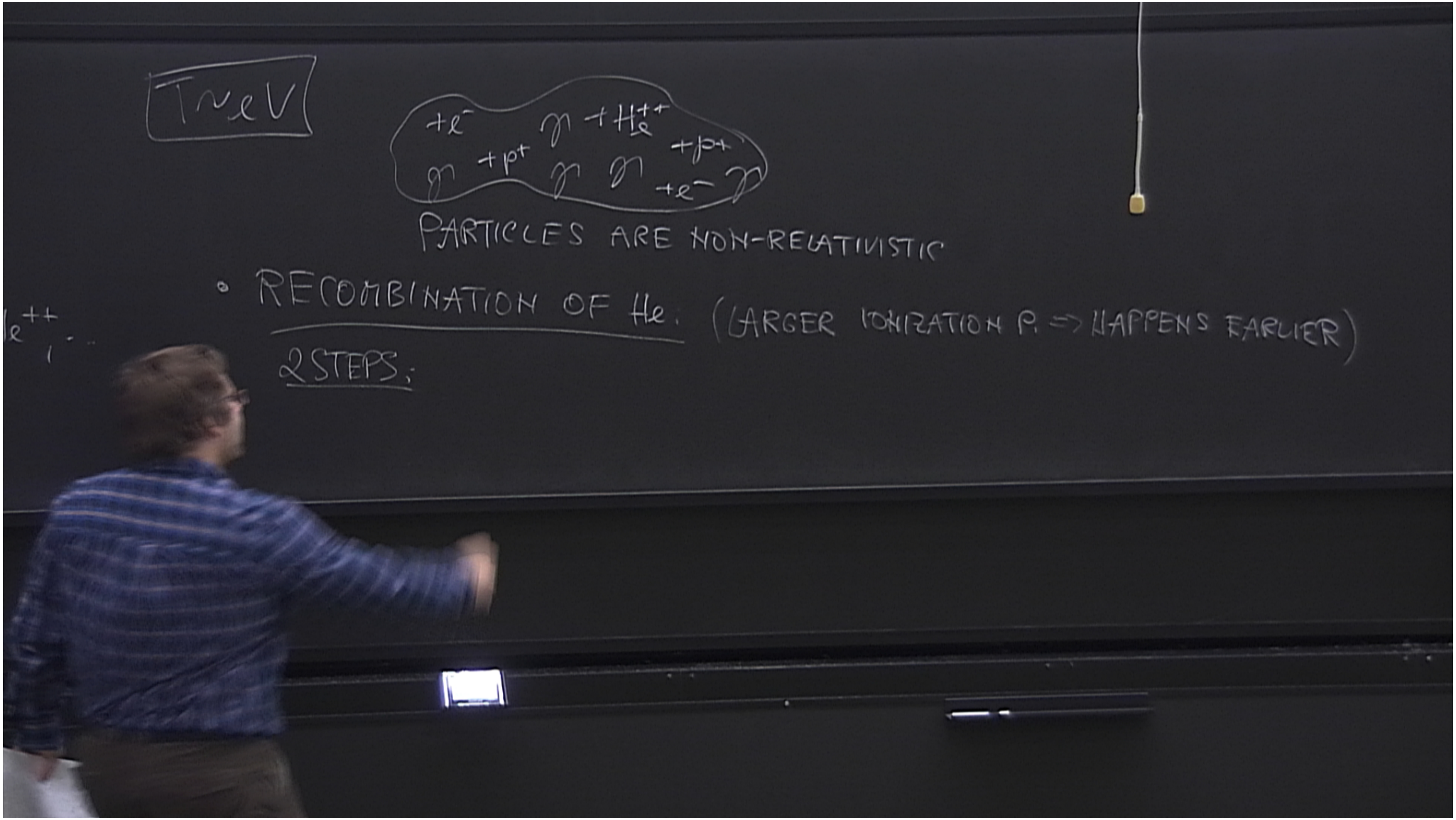

d) CMB (GAMOW)
+ Cs3
10^{12}
CMB ←
10"
RAD-MAT. EQ.
3 MINS
NUCLEOSYNT. → H^+, He^{++}, ...
6
$e^- e^+ \rightarrow \gamma\gamma$
1
NEUTR. D.
T ≈ eV
+ p^+
+ p^+

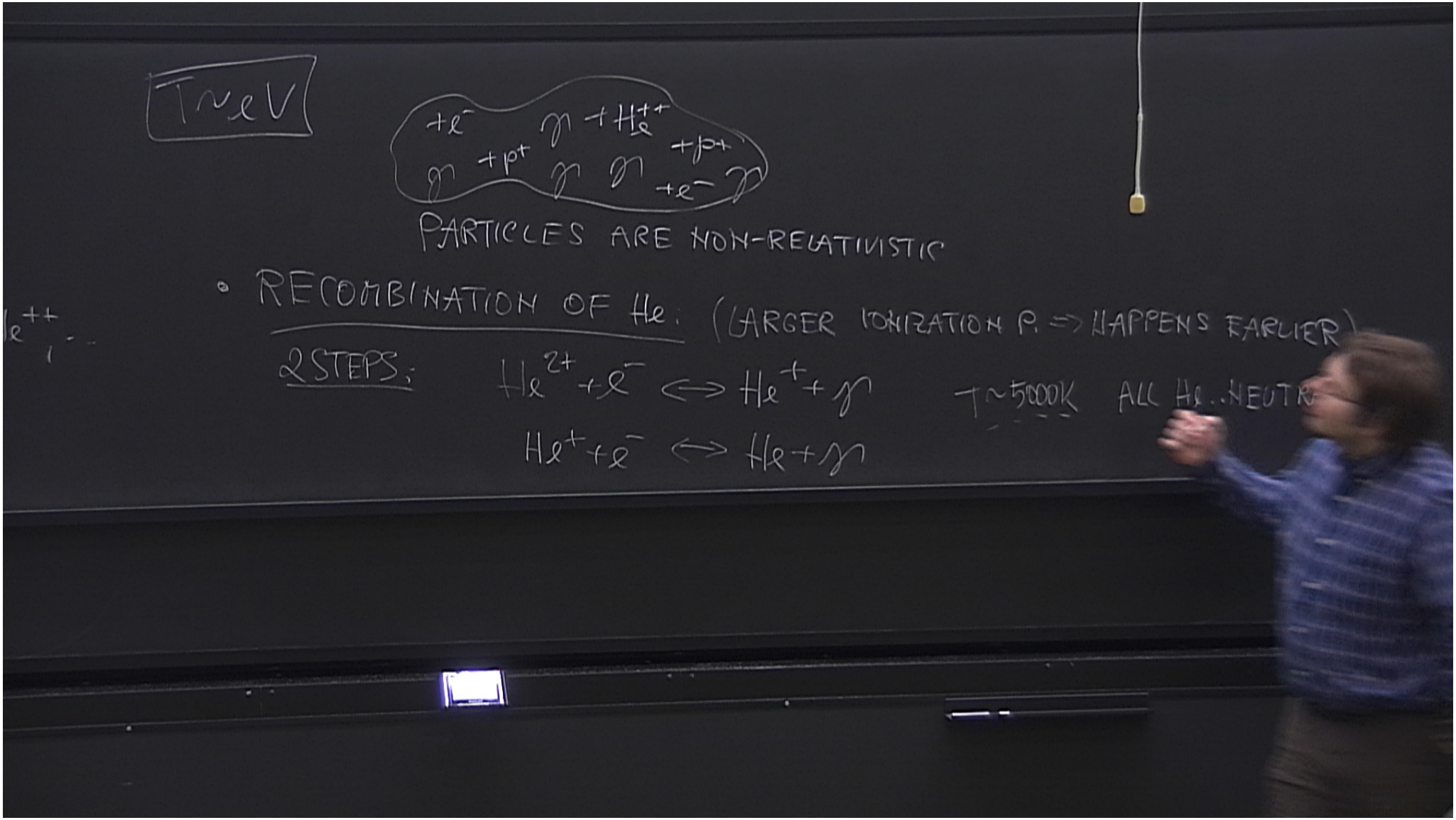

d) CMB (GAMOW)
1eV
+Cs3
10^{12}
CMB ←
10"
RAD-MAT. EQ.
3 MINS
NUCLEOSYNT. → H^+, He^{++}, ...
6
$e^- e^+ \rightarrow \gamma\gamma$
1
NEUTR. D.
$+e^-$
$\gamma + H^{++}$
$+p^+$
$\gamma + p^+$
$+e^-$
PARTICLE
NON-R

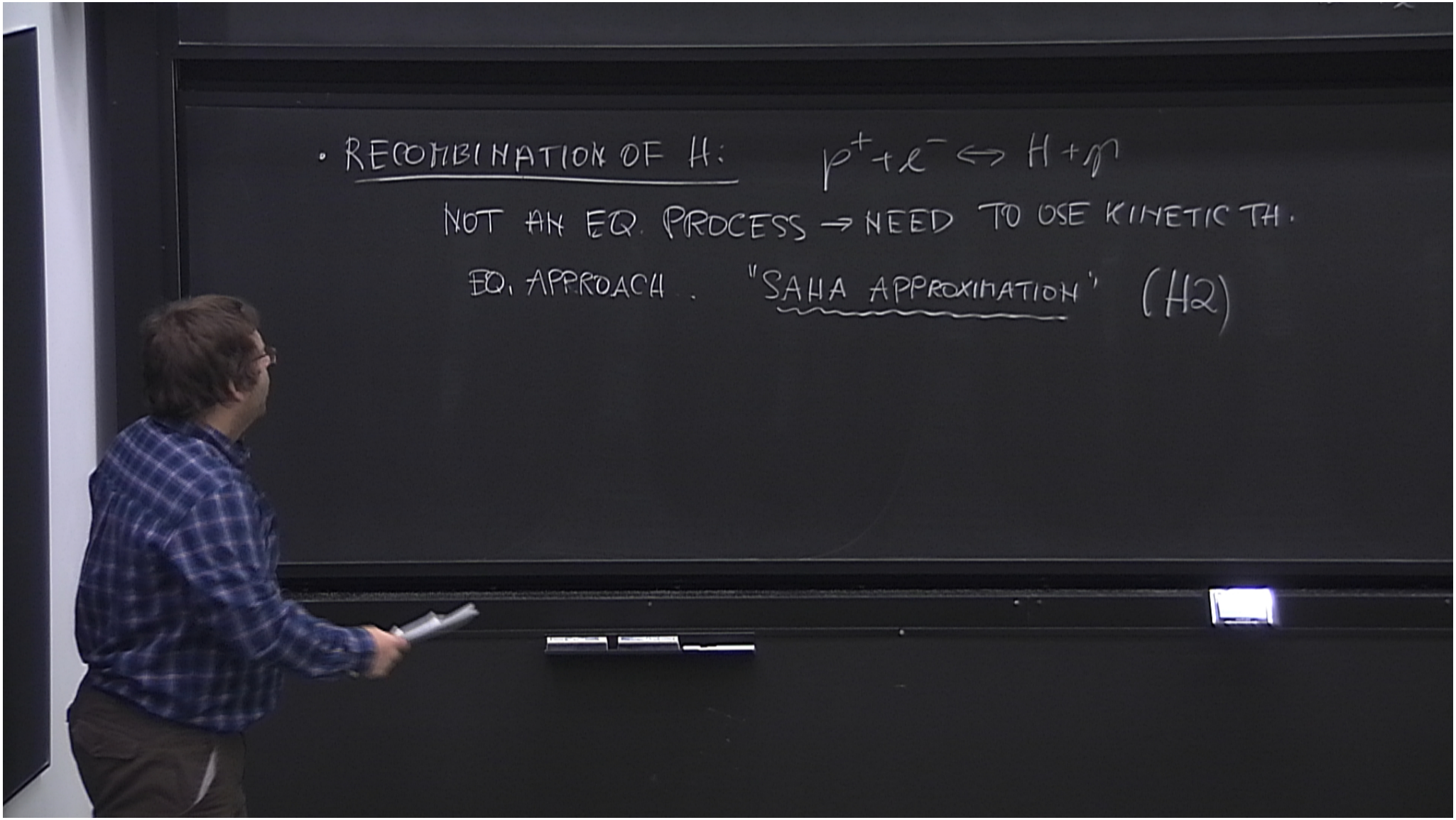

d) CMB (GAMOW)
1 eV
+ Cs3
10^{12}
CMB
10"
RAD-MA
3 MINS
NUCLEOS
6
$e^- e^+$
1
NEUTR
He^{++}
$+e^-$ γ $+H^{++}$
γ $+p^+$ γ γ $+p^+$
$+e^-$ γ
PARTICLES ARE NON-RELATIVISTIC

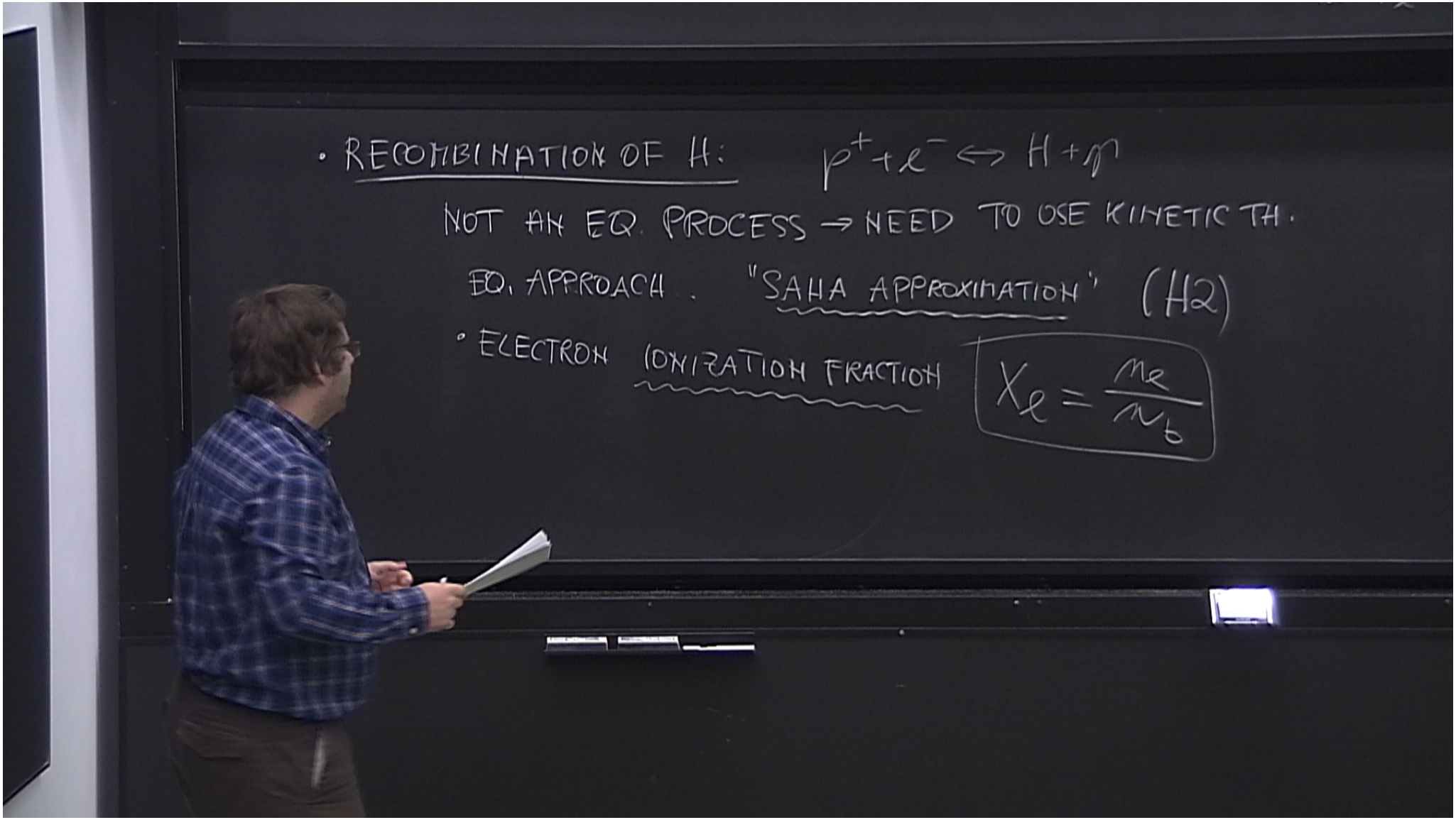

d) CMB (GAMOW)
1 eV
+Cs3
10^2
CMB
RAD-MAT. EQ.
NUCLEOSYNT. → H^+, He^{++}, ...
$e^- e^+ \rightarrow \gamma\gamma$
$+e^-$ γ $+He^{++}$ $+p^+$
γ $+p^+$ γ γ $+e^-$ γ
PARTICLES ARE NON-RELATIVISTIC
• RECOMBINATION OF He:

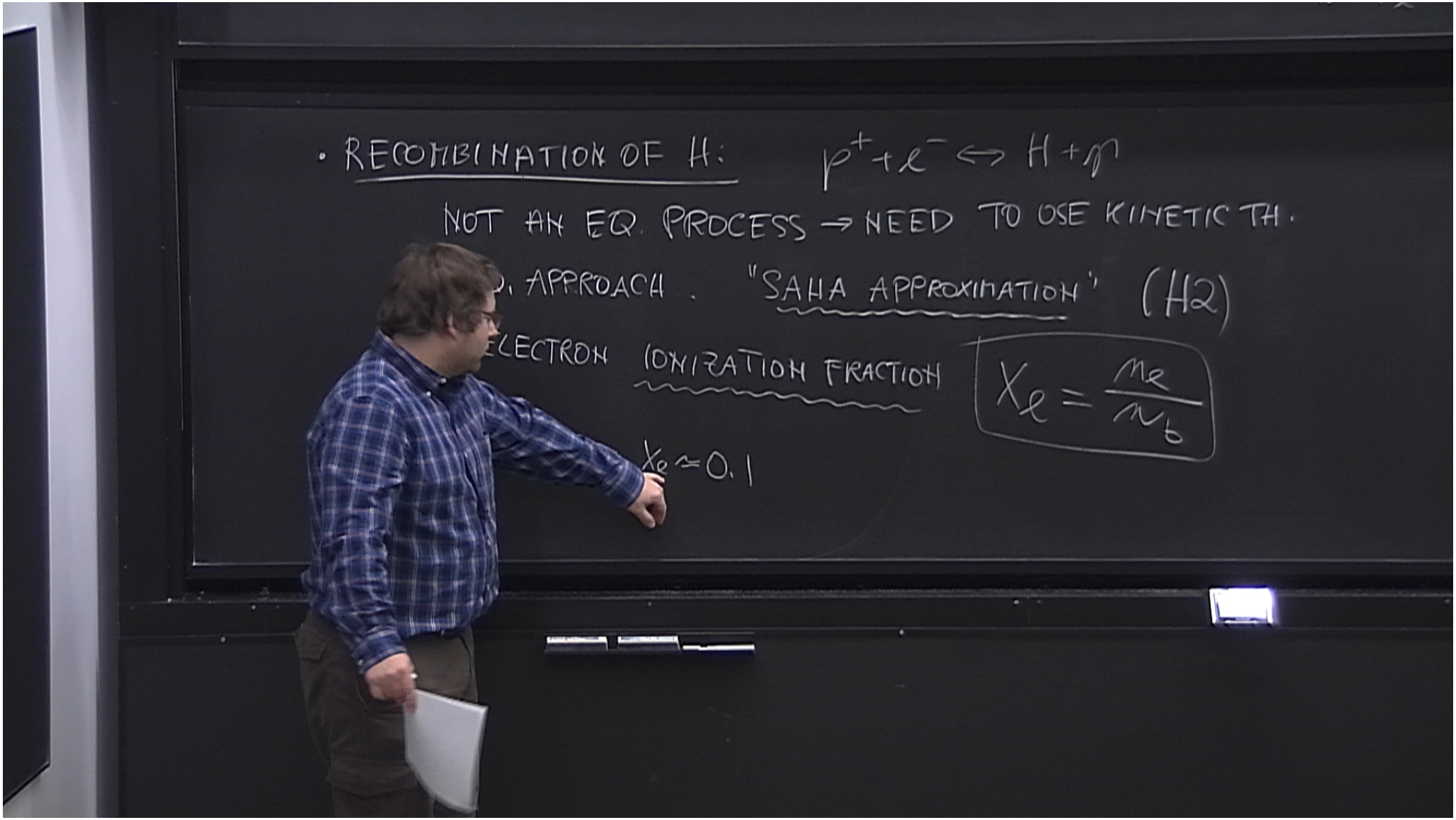

TreV
PARTICLES ARE NON-RELATIVISTIC
• RECOMBINATION OF He.

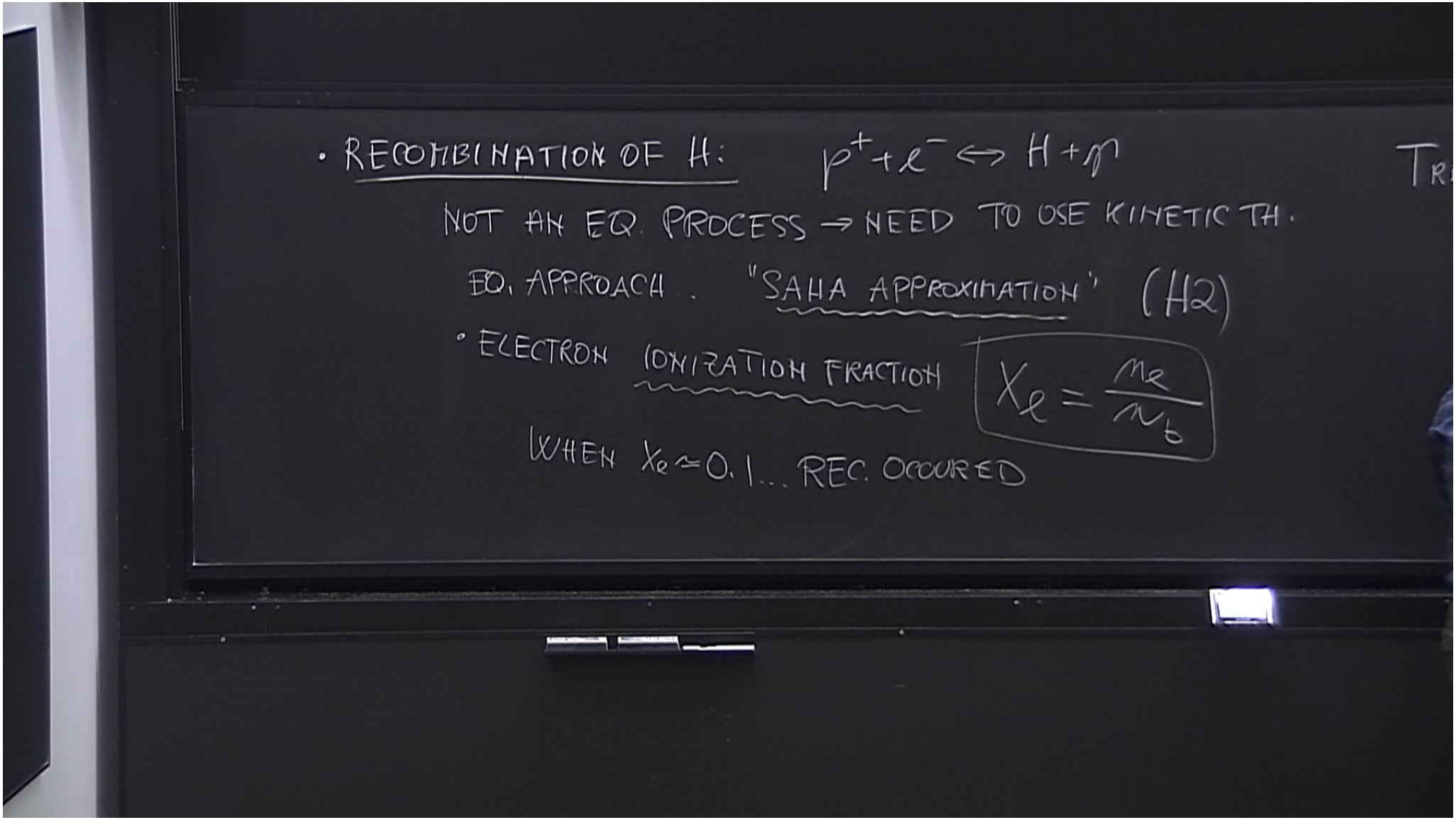

T≈eV
PARTICLES ARE NON-RELATIVISTIC
• RECOMBINATION OF He: (LARGER IONIZATION P. => HAPPENS EARLIER)
2 STEPS:

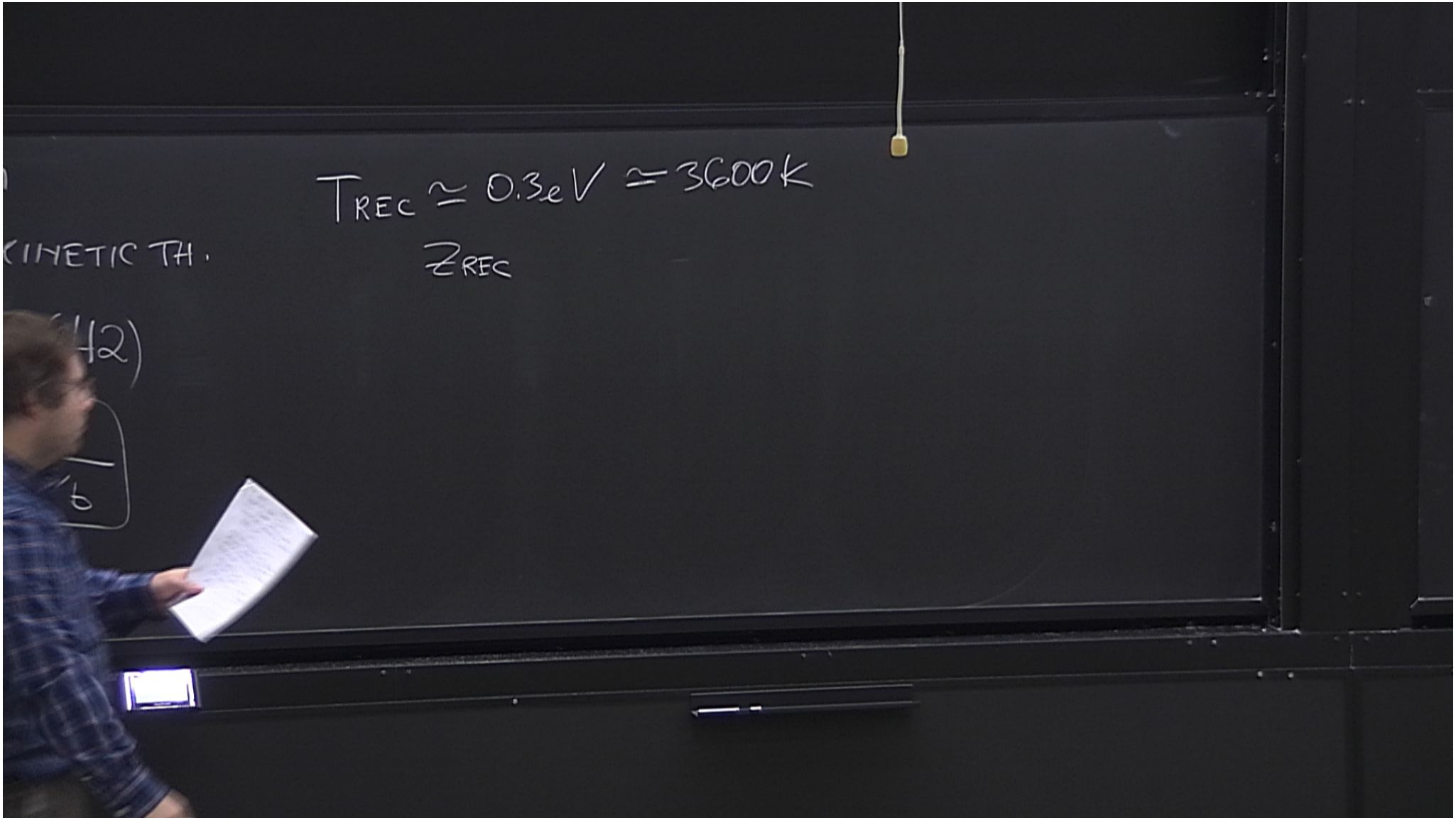

T≈1eV
PARTICLES ARE NON-RELATIVISTIC
• RECOMBINATION OF He: (LARGER IONIZATION P. ⇒ HAPPENS EARLIER)
2STEPS:
T≈5000K ALL He..NEUTR

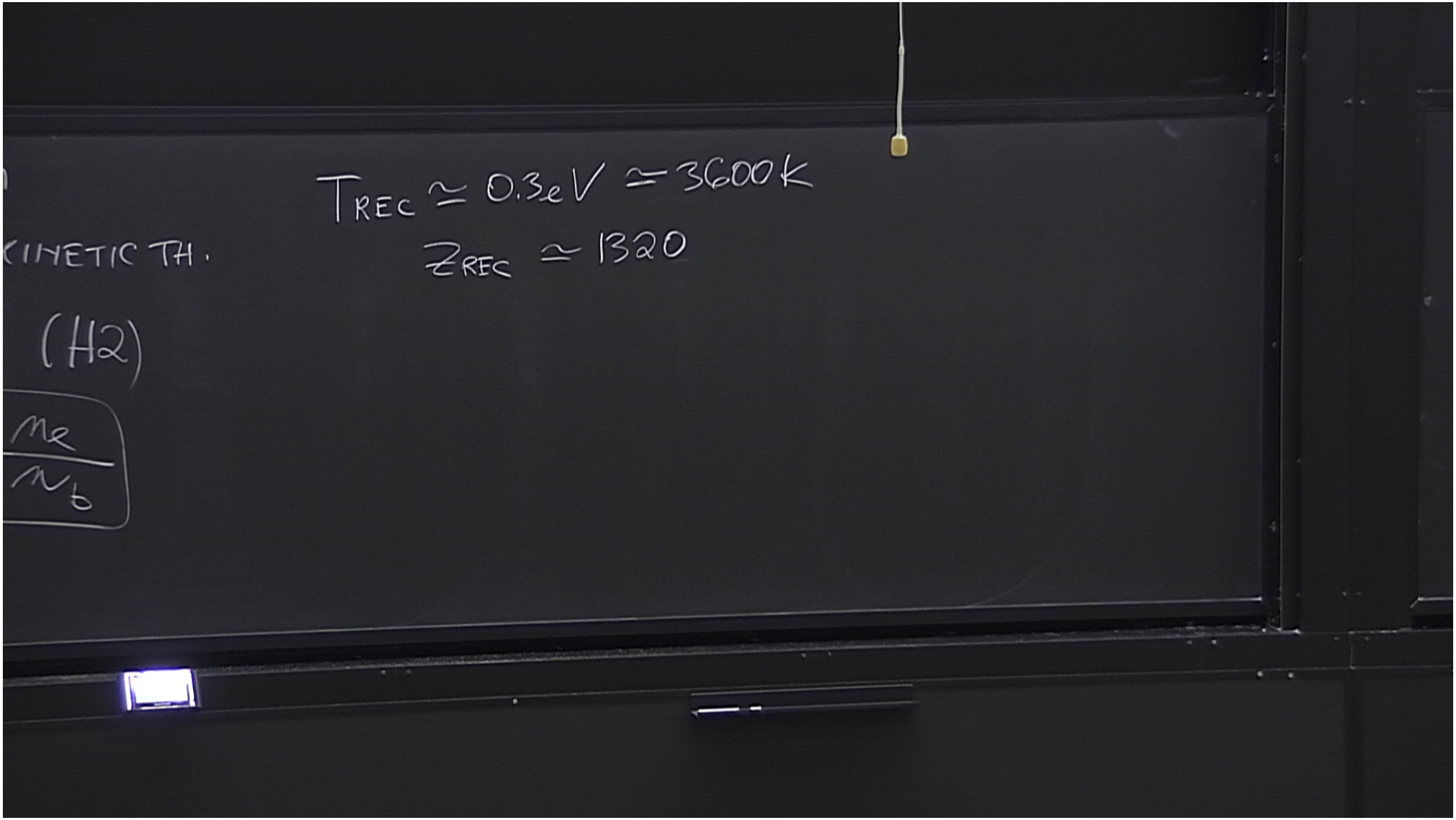

• RECOMBINATION OF H: $p^+ + e^- \leftrightarrow H + \gamma$
NOT AN EQ. PROCESS → NEED TO USE KINETIC TH.
EQ. APPROACH. "SAHA APPROXIMATION" (H2)

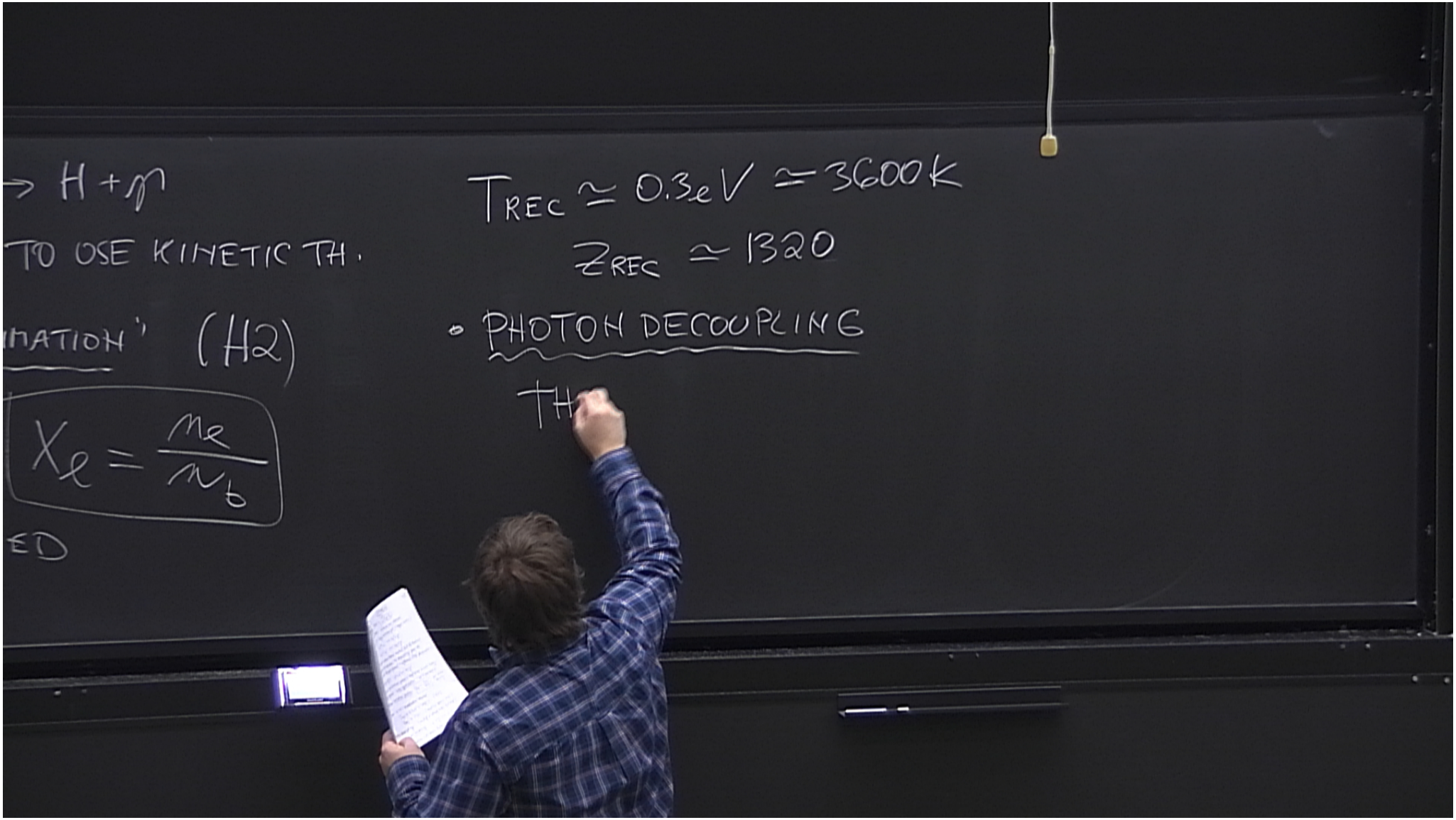

• RECOMBINATION OF H: $p^+ + e^- \leftrightarrow H + \gamma$
NOT AN EQ. PROCESS → NEED TO USE KINETIC TH.
EQ. APPROACH . "SAHA APPROXIMATION" (H2)
• ELECTRON IONIZATION FRACTION $X_e = \frac{n_e}{n_b}$

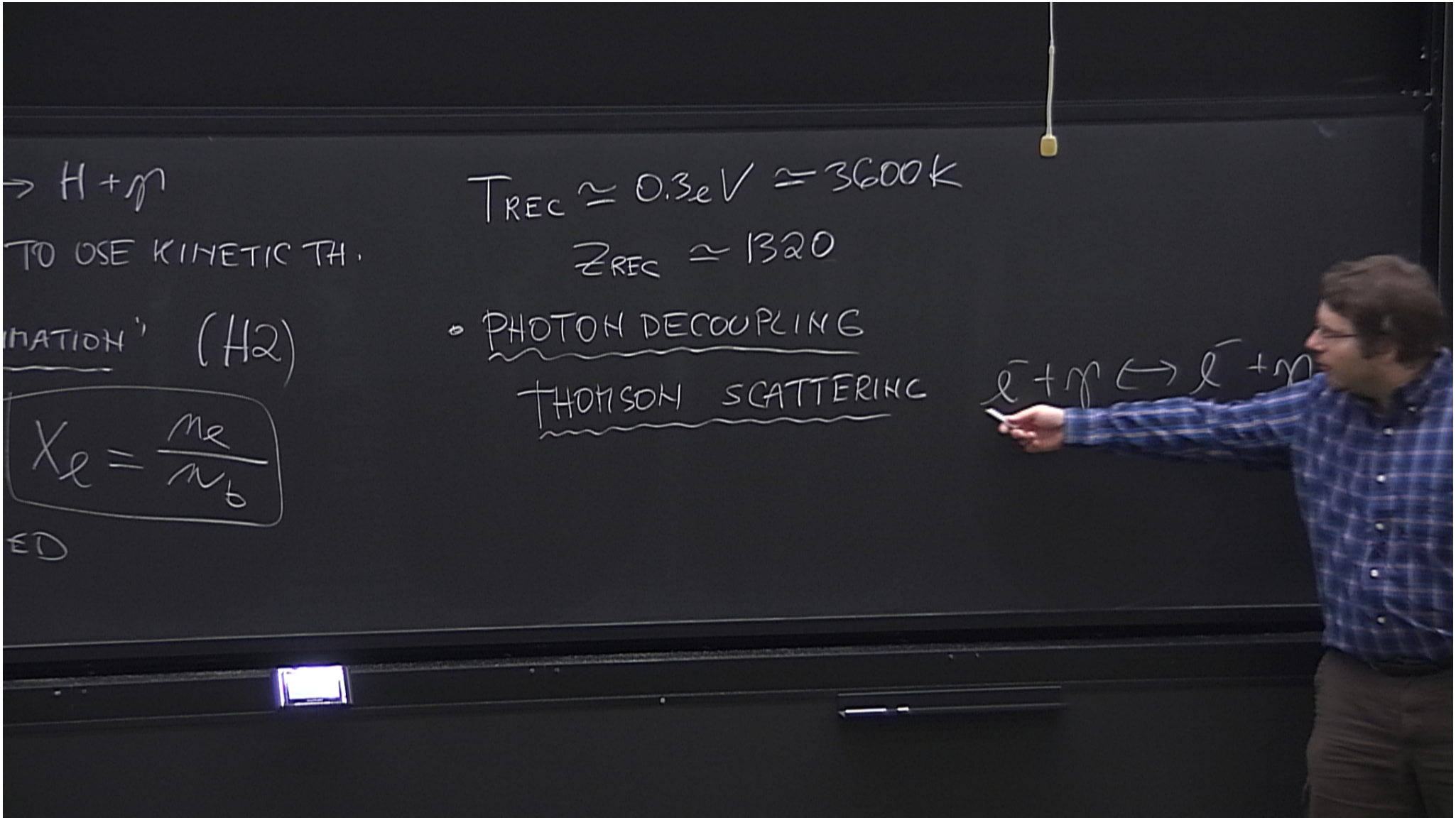

• RECOMBINATION OF H: $p^+ + e^- \leftrightarrow H + \gamma$
NOT AN EQ. PROCESS → NEED TO USE KINETIC TH.
APPROACH . "SAHA APPROXIMATION" (H2)
ELECTRON IONIZATION FRACTION
$X_e = \frac{n_e}{n_b}$
$X_e \simeq 0.1$

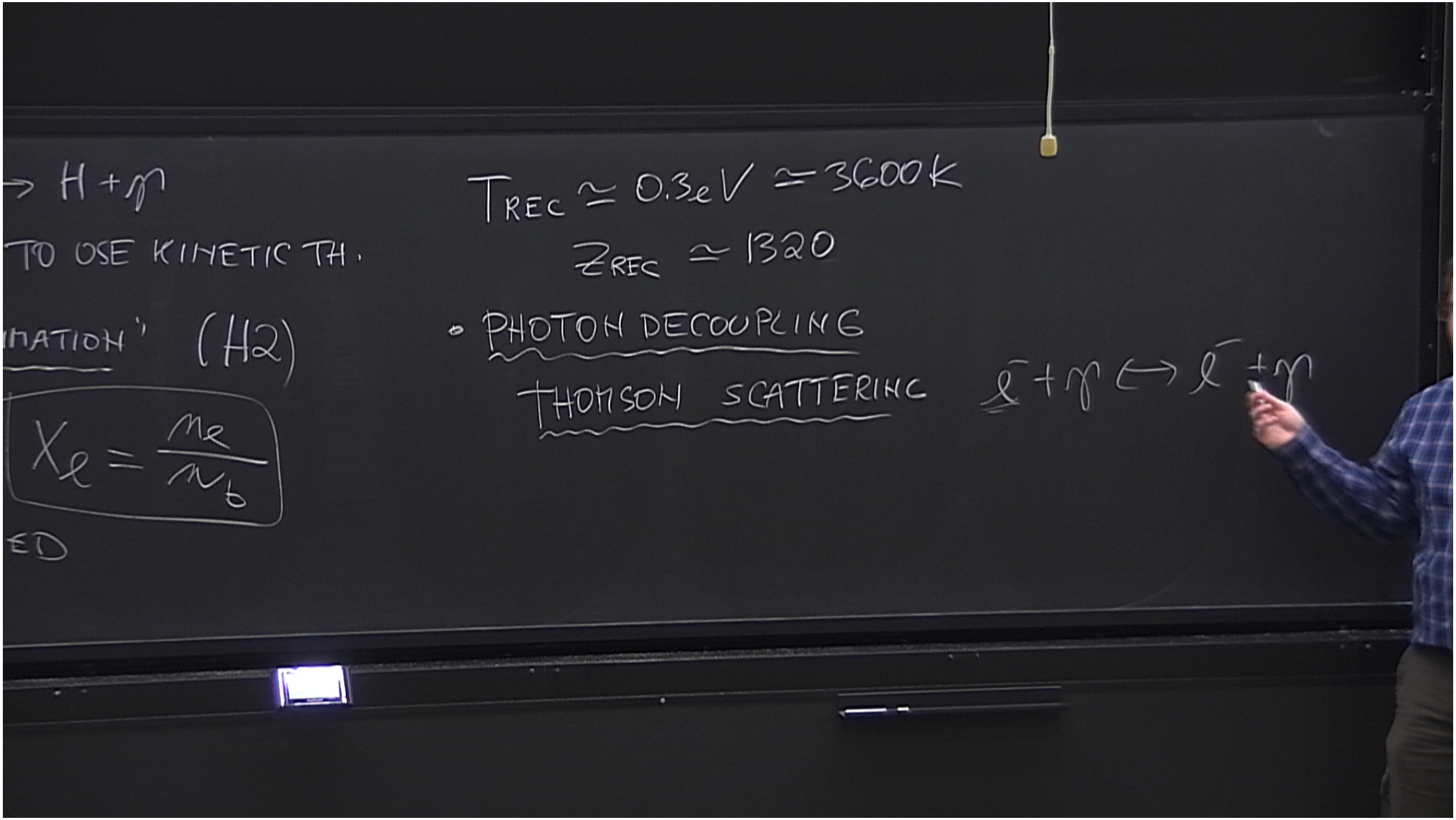

• RECOMBINATION OF H: $p^+ + e^- \leftrightarrow H + \gamma$
NOT AN EQ. PROCESS → NEED TO USE KINETIC TH.
EQ. APPROACH. "SAHA APPROXIMATION" (H2)
• ELECTRON IONIZATION FRACTION $X_e = \frac{n_e}{n_b}$
WHEN $X_e \simeq 0.1$... REC. OCCURED

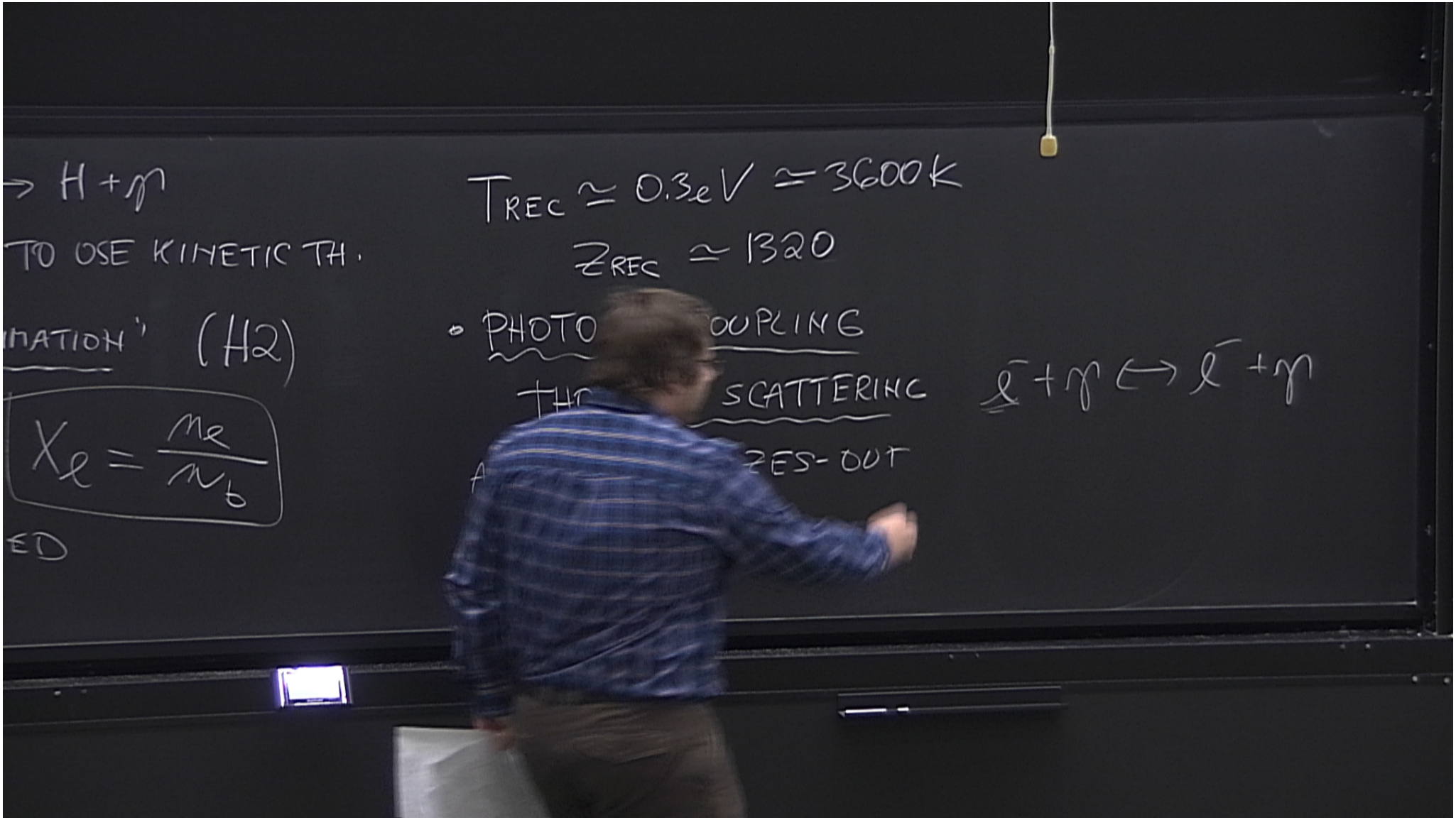

$T_{REC} \simeq 0.3eV \simeq 3600K$
z_{REC}
KINETIC TH.
(42)

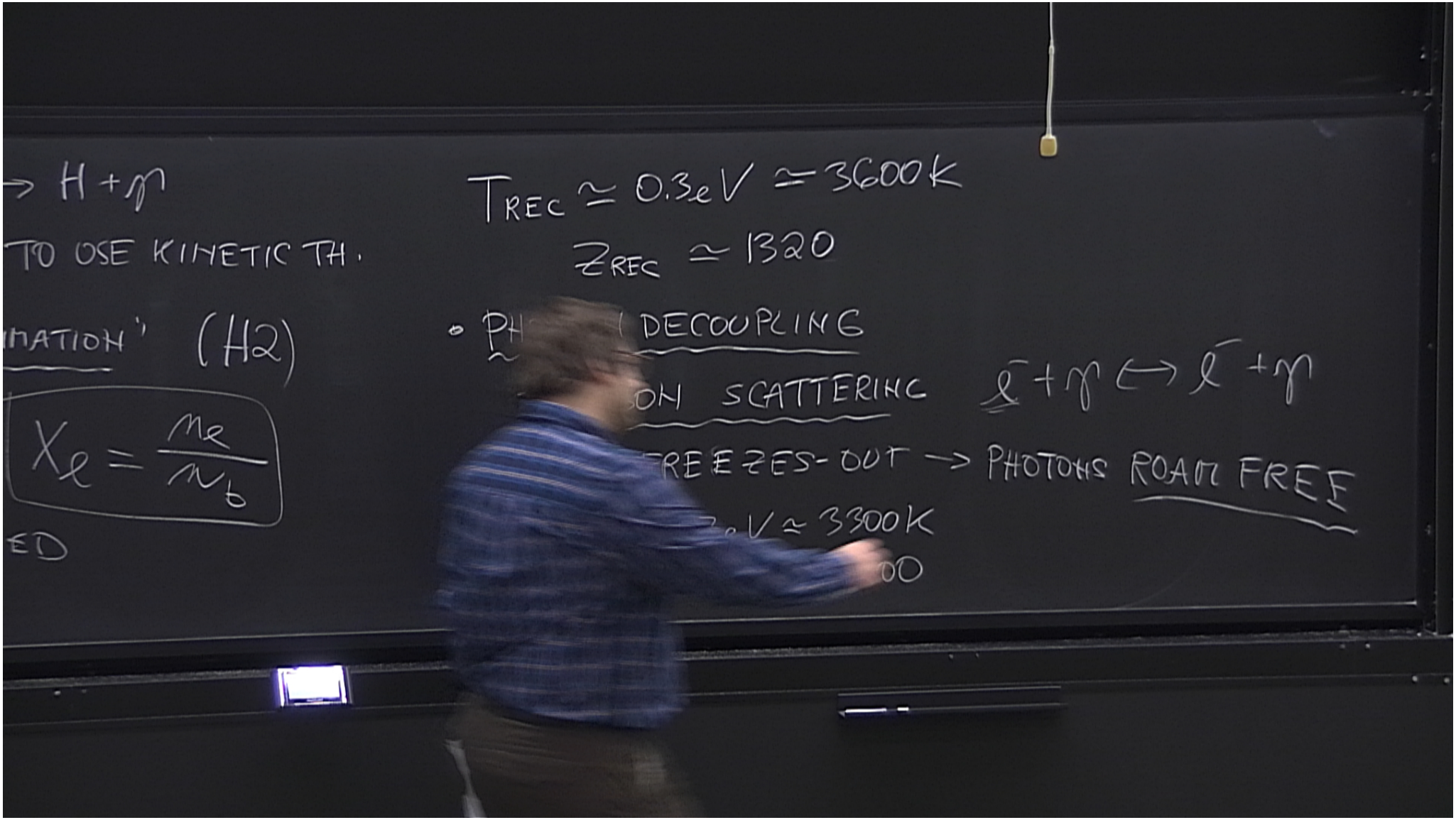

$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
KINETIC TH.
(H2)
$\frac{n_e}{n_b}$

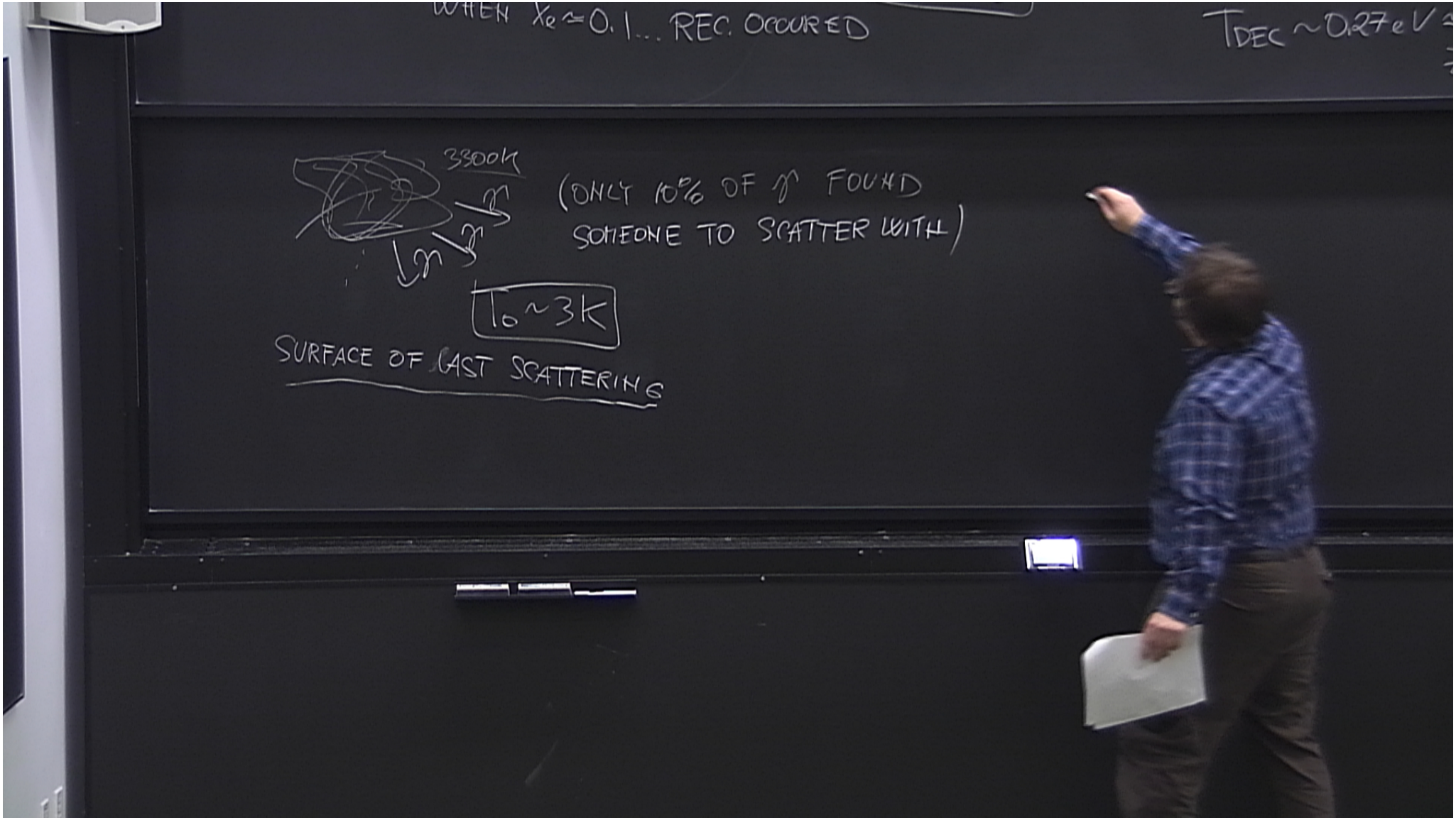

→ H + p
TO USE KINETIC TH.
MATION' (H2)
$X_e = \frac{n_e}{n_b}$
ED
$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
• PHOTON DECOUPLING
TH

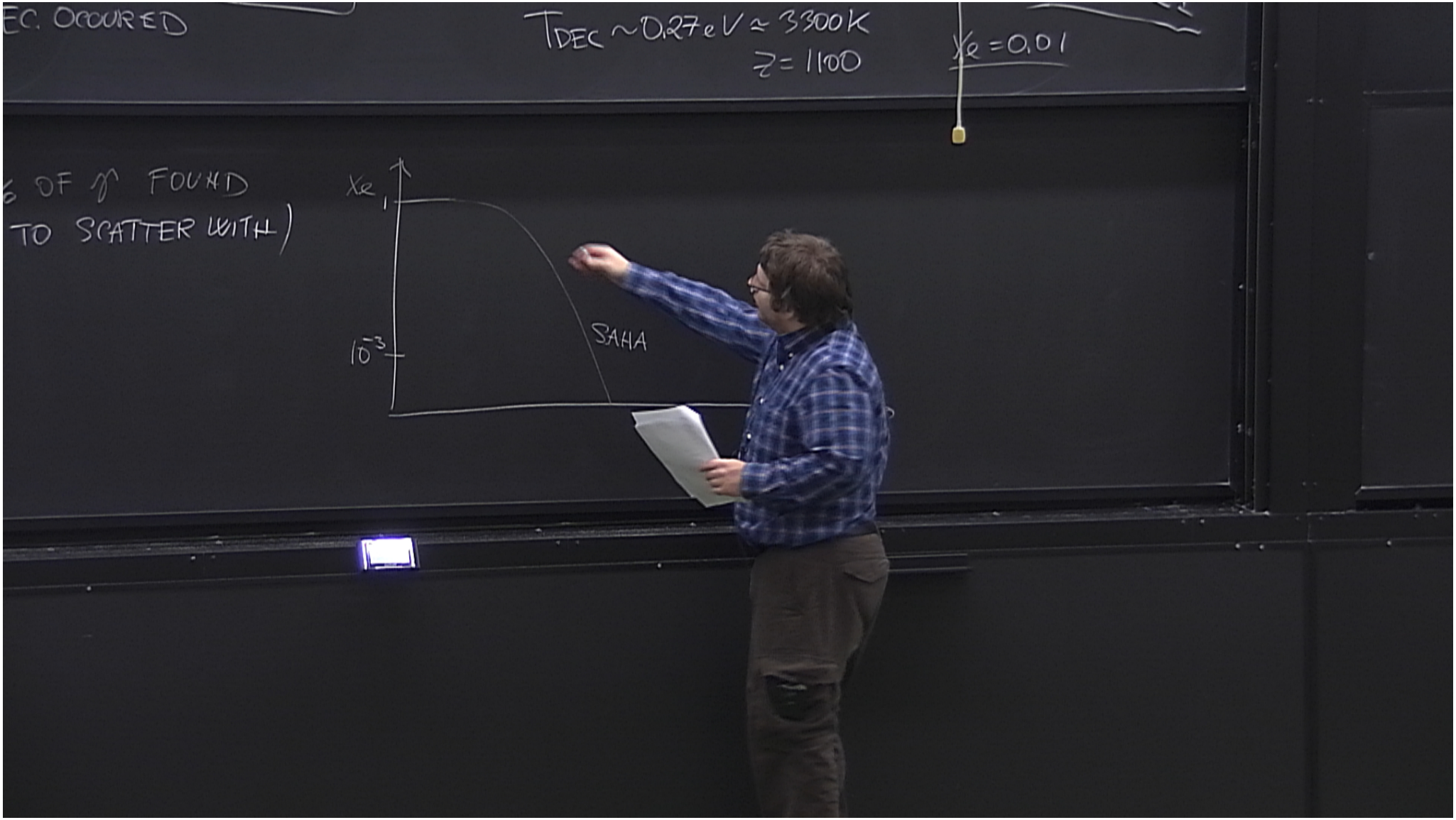

→ H + γ
TO USE KINETIC TH.
MATION' (H2)
$X_e = \frac{n_e}{n_b}$
ED
$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
• PHOTON DECOUPLING
THOMSON SCATTERING
$e^- + \gamma \leftrightarrow e^- +$

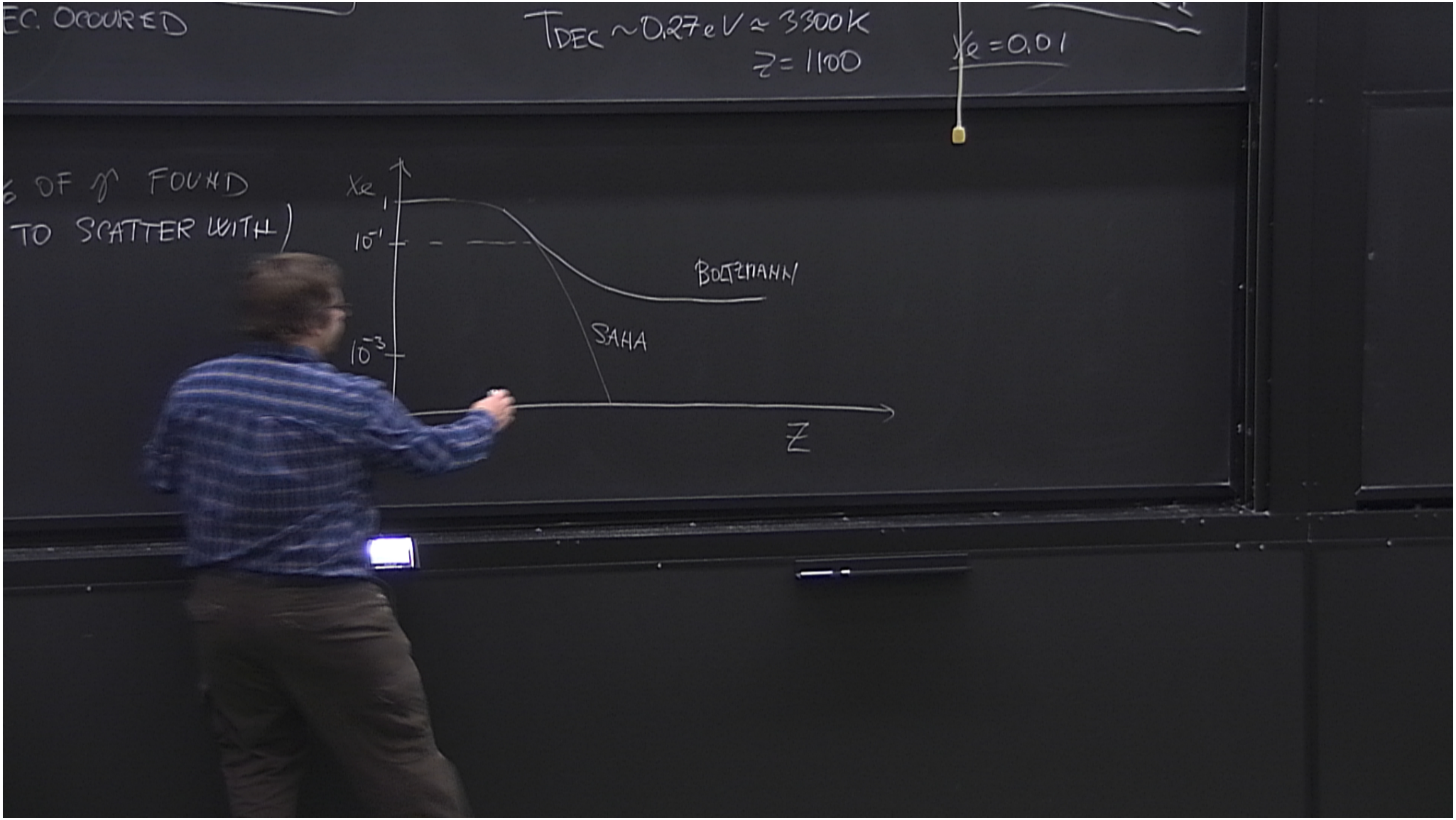

→ H + γ
TO USE KINETIC TH.
MATION' (H2)
$X_e = \frac{n_e}{n_b}$
ED
$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
• PHOTON DECOUPLING
THOMSON SCATTERING
$e^- + \gamma \leftrightarrow e^- + \gamma$


→ H + γ
TO USE KINETIC TH.
MATION' (H2)
$X_e = \frac{n_e}{n_b}$
ED
$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
• PHOTO OUPLING
SCATTERING
$e^- + \gamma \leftrightarrow e^- + \gamma$
ES- OUT


→ H + γ
TO USE KINETIC TH.
MATION' (H2)
$X_e = \frac{n_e}{n_b}$
ED
$T_{REC} \simeq 0.3eV \simeq 3600K$
$z_{REC} \simeq 1320$
DECOUPLING
ON SCATTERING
$e^- + \gamma \leftrightarrow e^- + \gamma$
REEZES-OUT → PHOTONS ROAM FREE
V ≃ 3300K
00


WHEN $X_e \simeq 0.1$... REC. OCCURED
$T_{DEC} \sim 0.27 eV$
3300K
(ONLY 10% OF γ FOUND SOMEONE TO SCATTER WITH)
$T_0 \sim 3K$
SURFACE OF LAST SCATTERING


EC. OCCURED
$T_{DEC} \sim 0.27\,eV \simeq 3300\,K$
$z = 1100$
$x_e = 0.01$
OF γ FOUND
TO SCATTER WITH)
x_e
1
10^{-3}
SAHA


EC. OCCURED
$T_{DEC} \sim 0.27\,eV \simeq 3300K$
$z = 1100$
$x_e = 0.01$
OF γ FOUND
TO SCATTER WITH)
x_e
1
10^{-1}
10^{-3}
BOLTZMANN
SAHA
z

EC. OCCURED

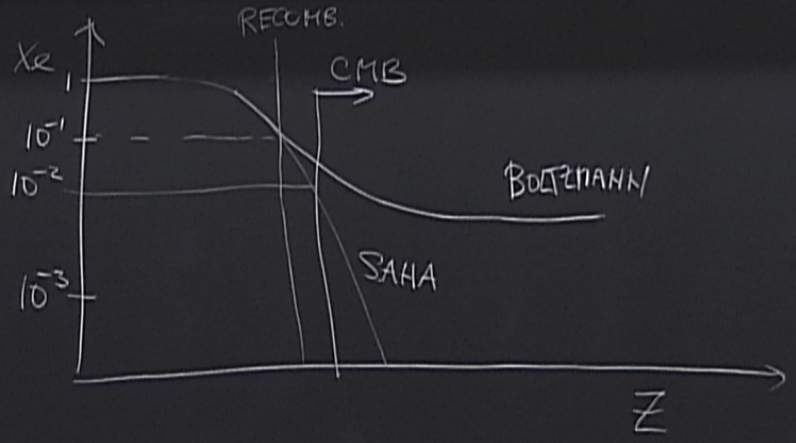
$T_{DEC} \sim 0.27\,eV \simeq 3300\,K$

$z = 1100$

$x_e = 0.01$

OF γ FOUND

TO SCATTER WITH)



EC. OCCURED

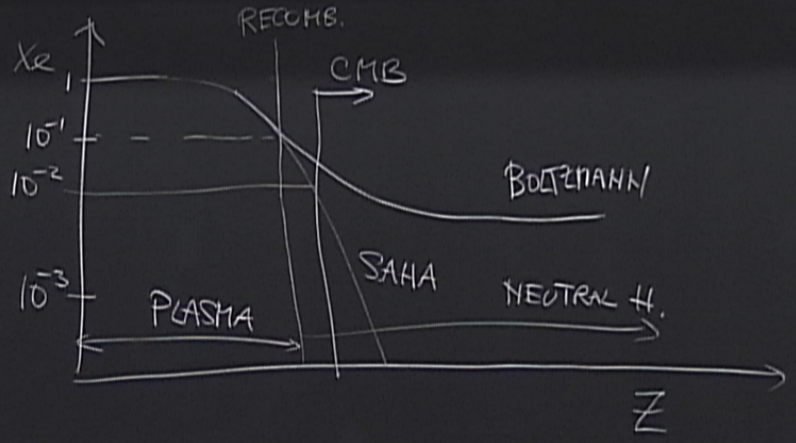
$T_{DEC} \sim 0.27\,eV \simeq 3300\,K$

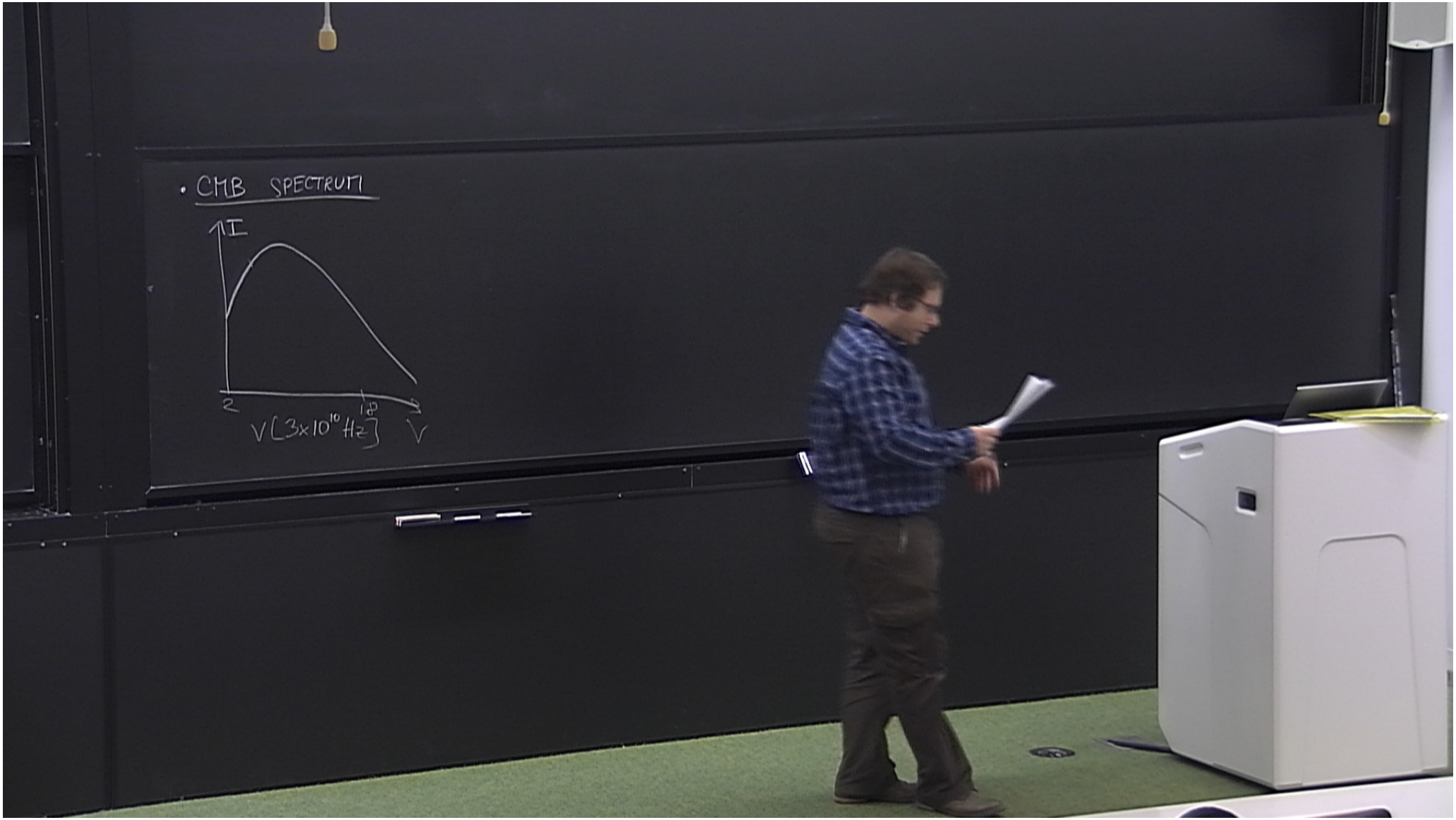
$z = 1100$

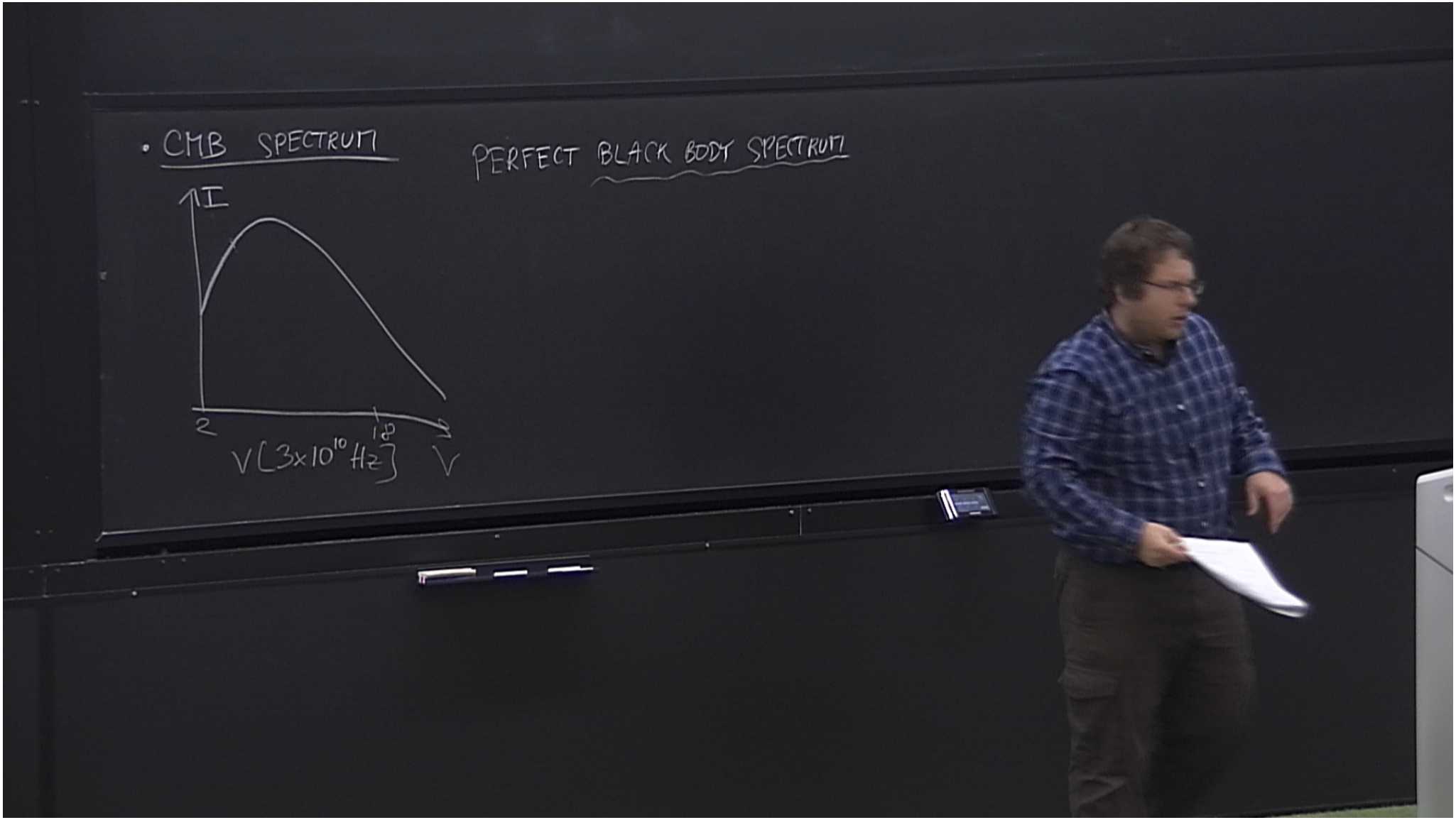
$x_e = 0.01$

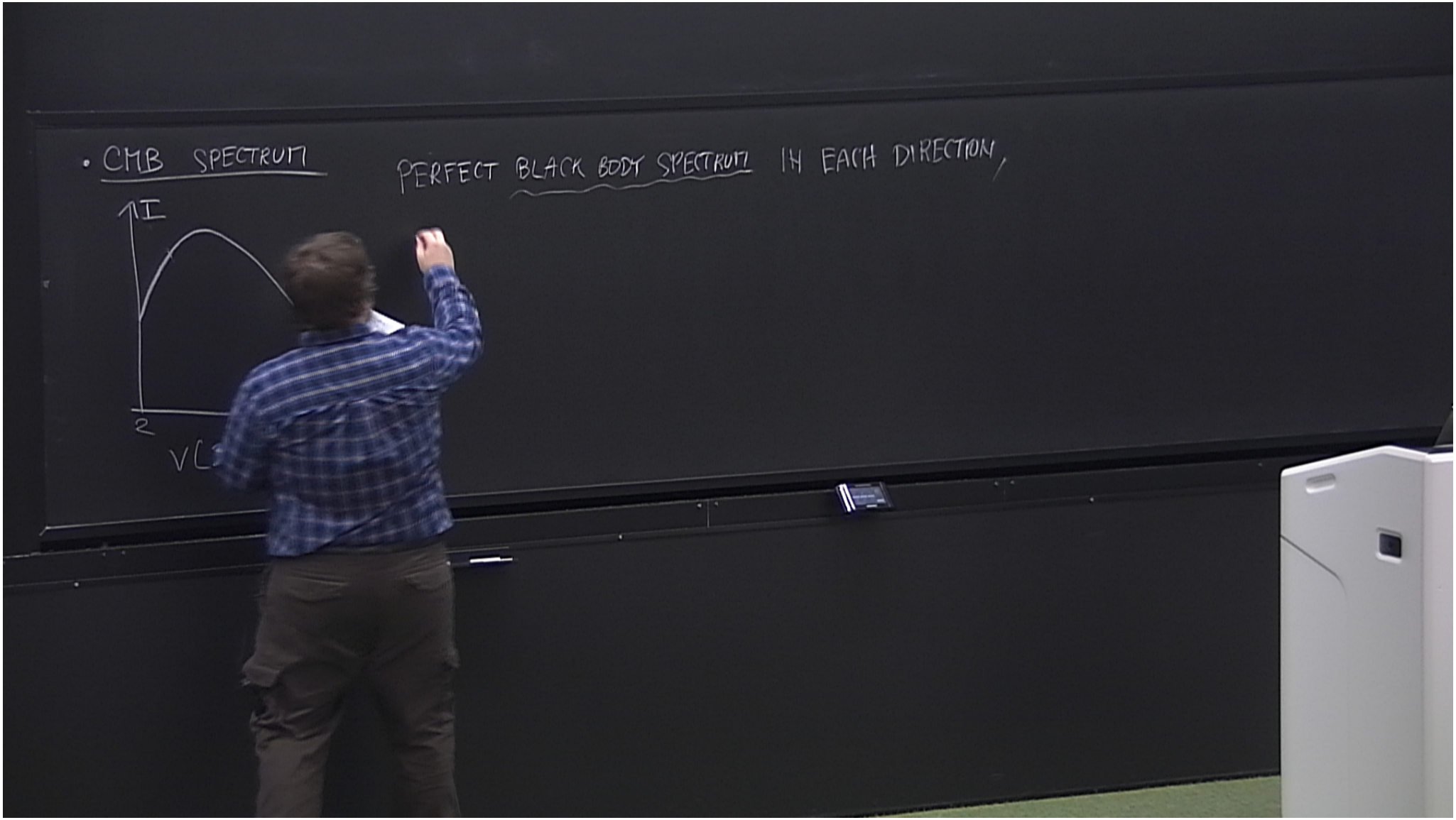
OF γ FOUND

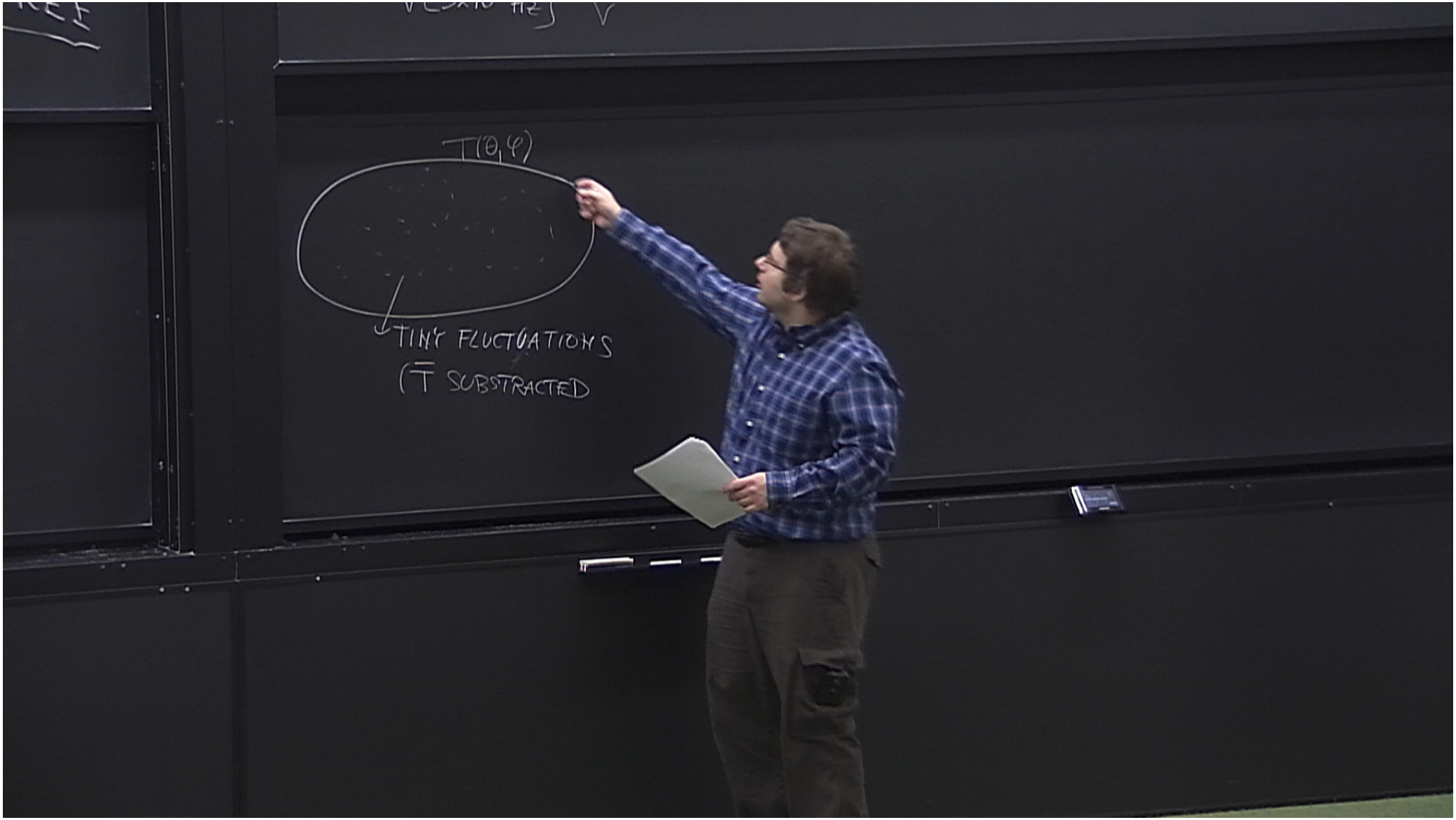
TO SCATTER WITH)

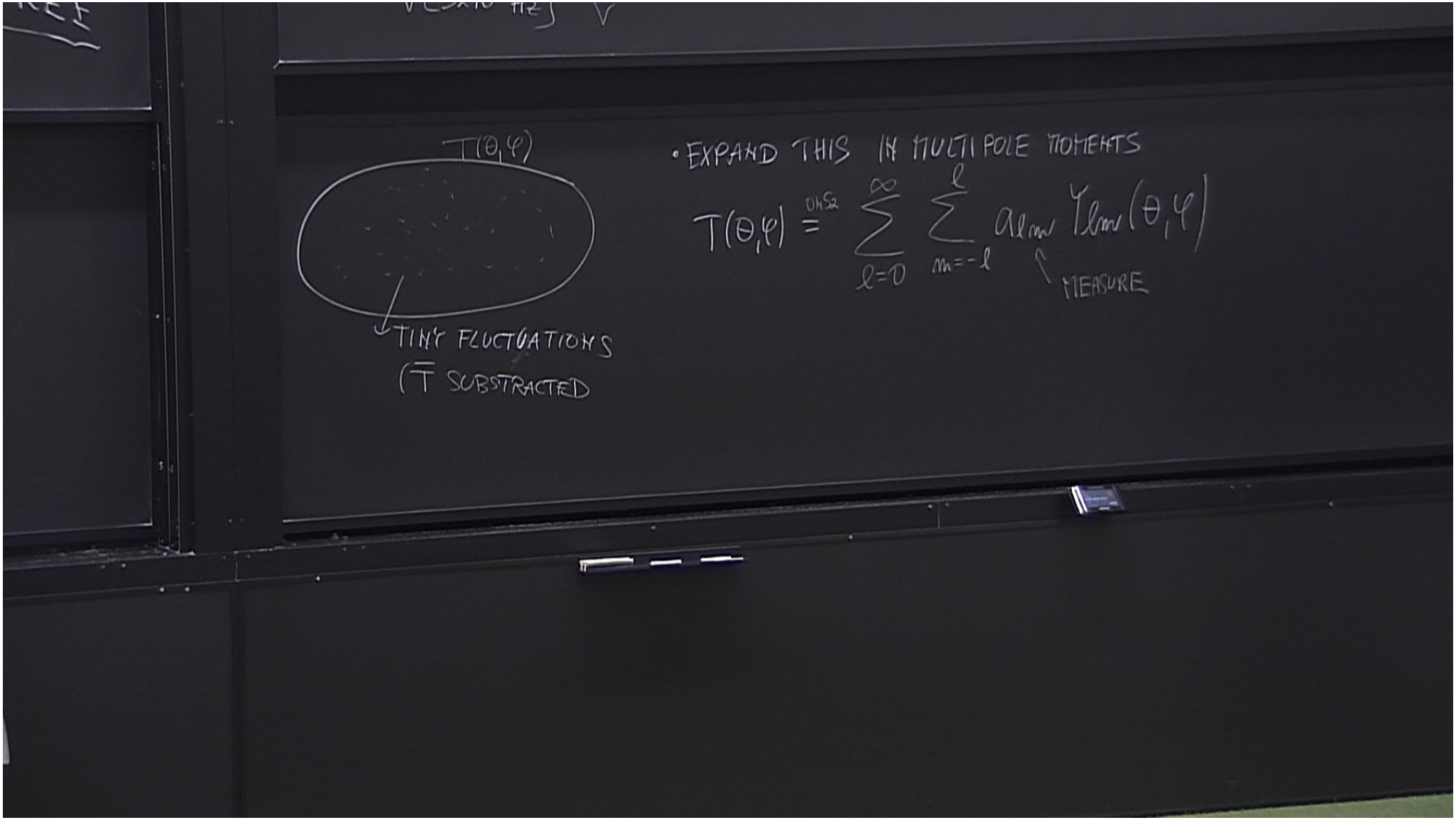


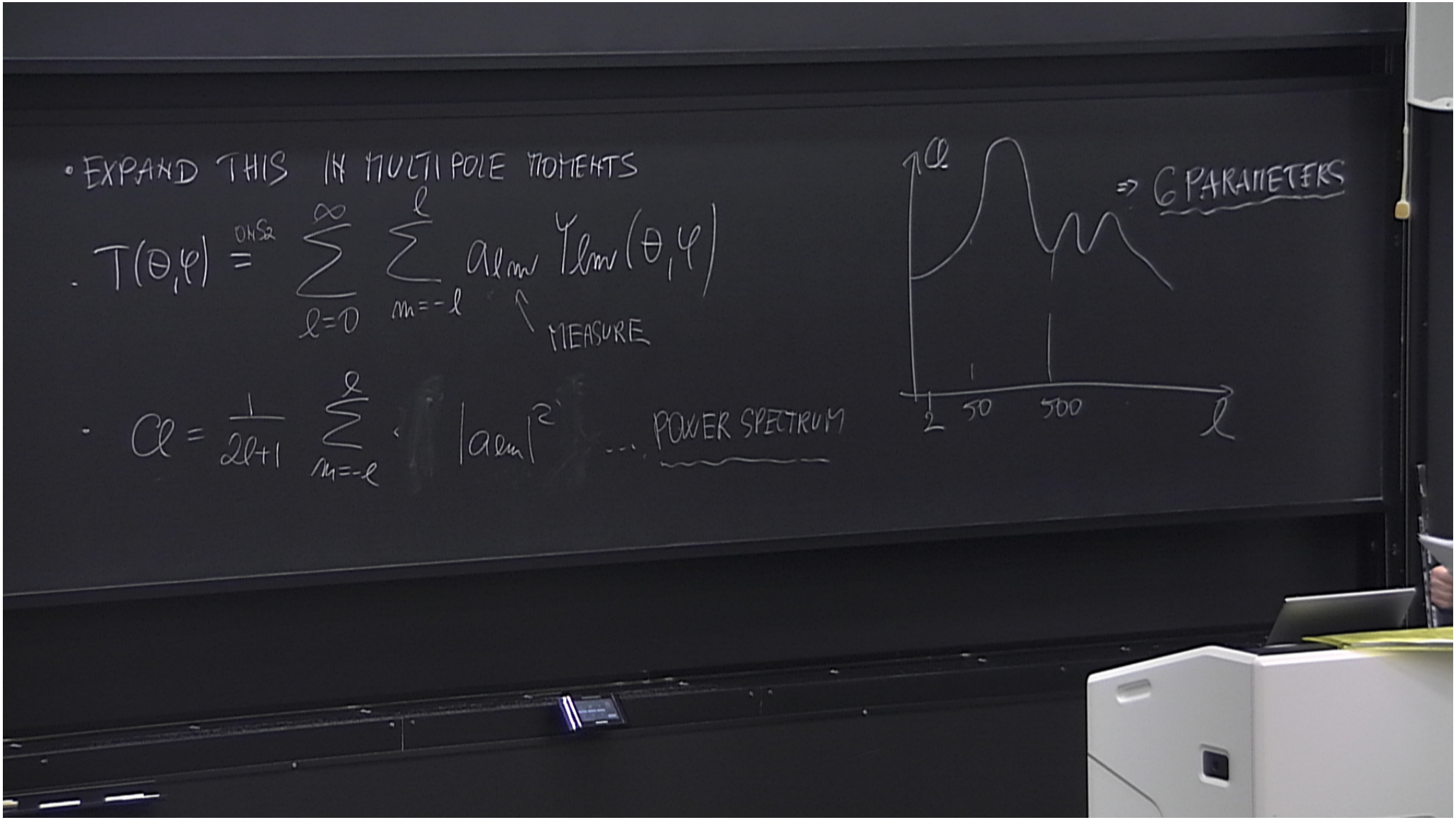

• CMB SPECTRUM
I
2
1.5
1
ν [3×10^10 Hz]
ν

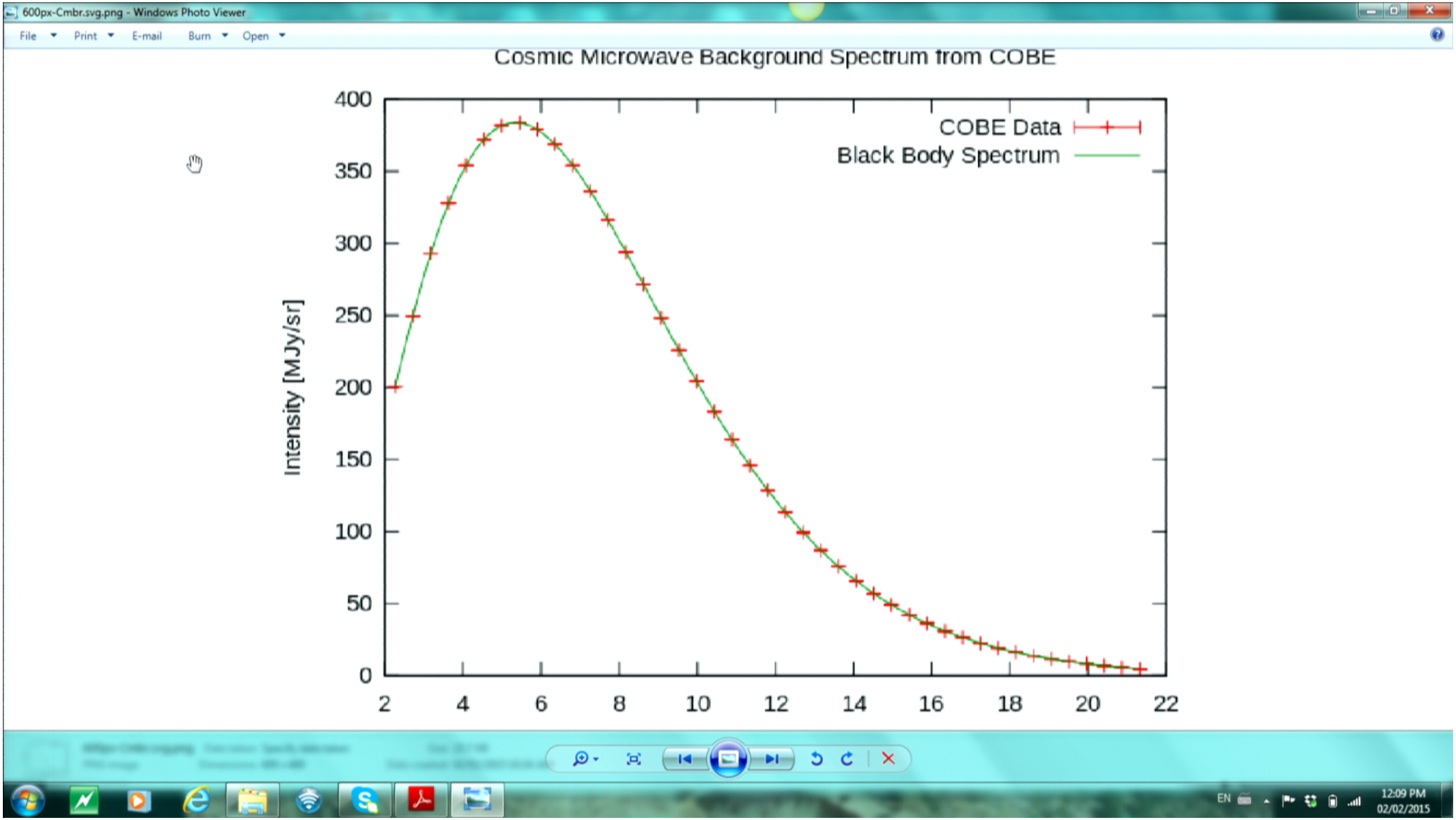

• CMB SPECTRUM
PERFECT BLACK BODY SPECTRUM
I
2
10
ν [3×10^10 Hz]
ν

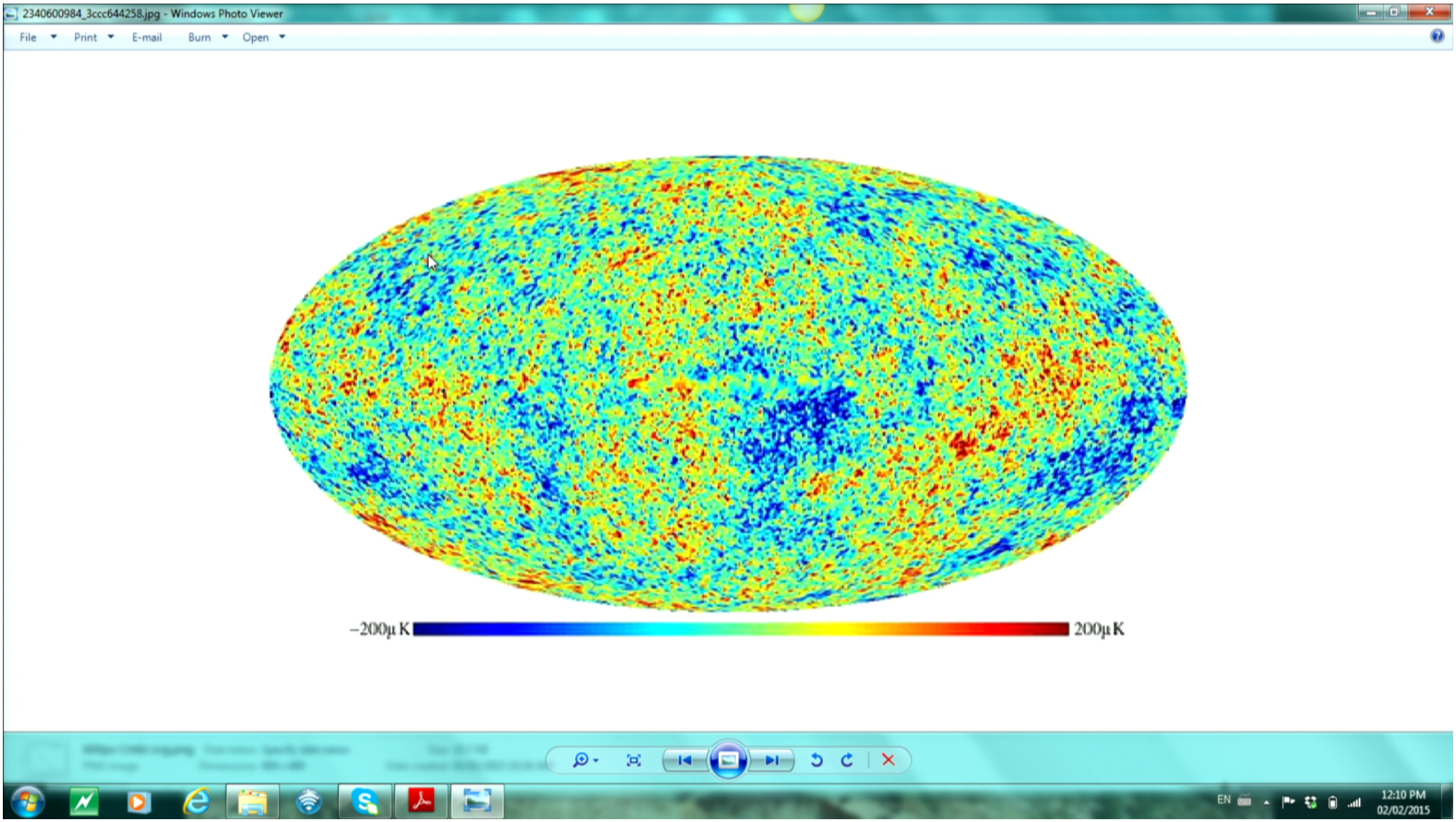

• CMB SPECTRUM
PERFECT BLACK BODY SPECTRUM IN EACH DIRECTION,
I
2
VC

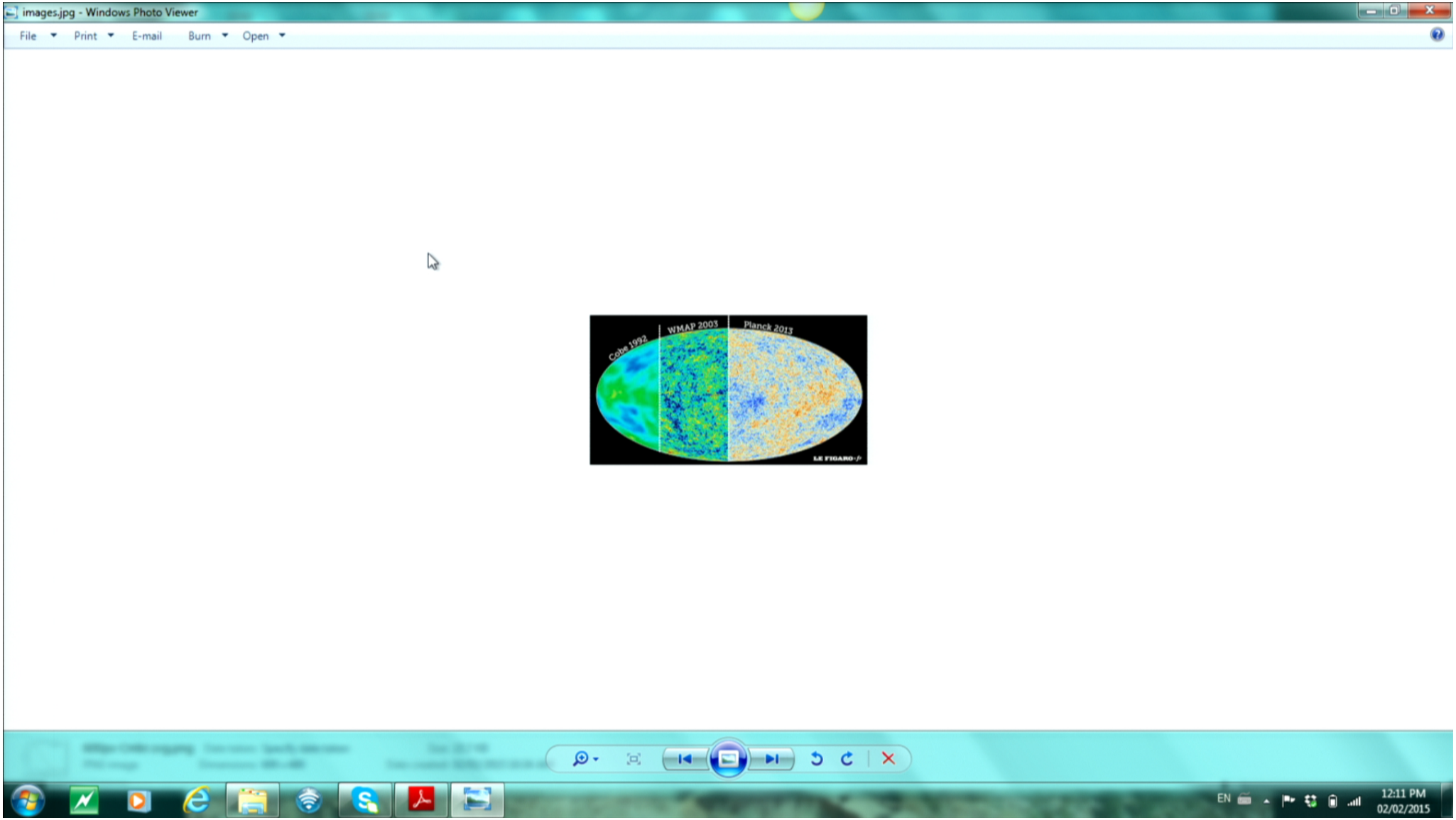

T(θ,φ)
TINY FLUCTUATIONS
(T̄ SUBSTRACTED

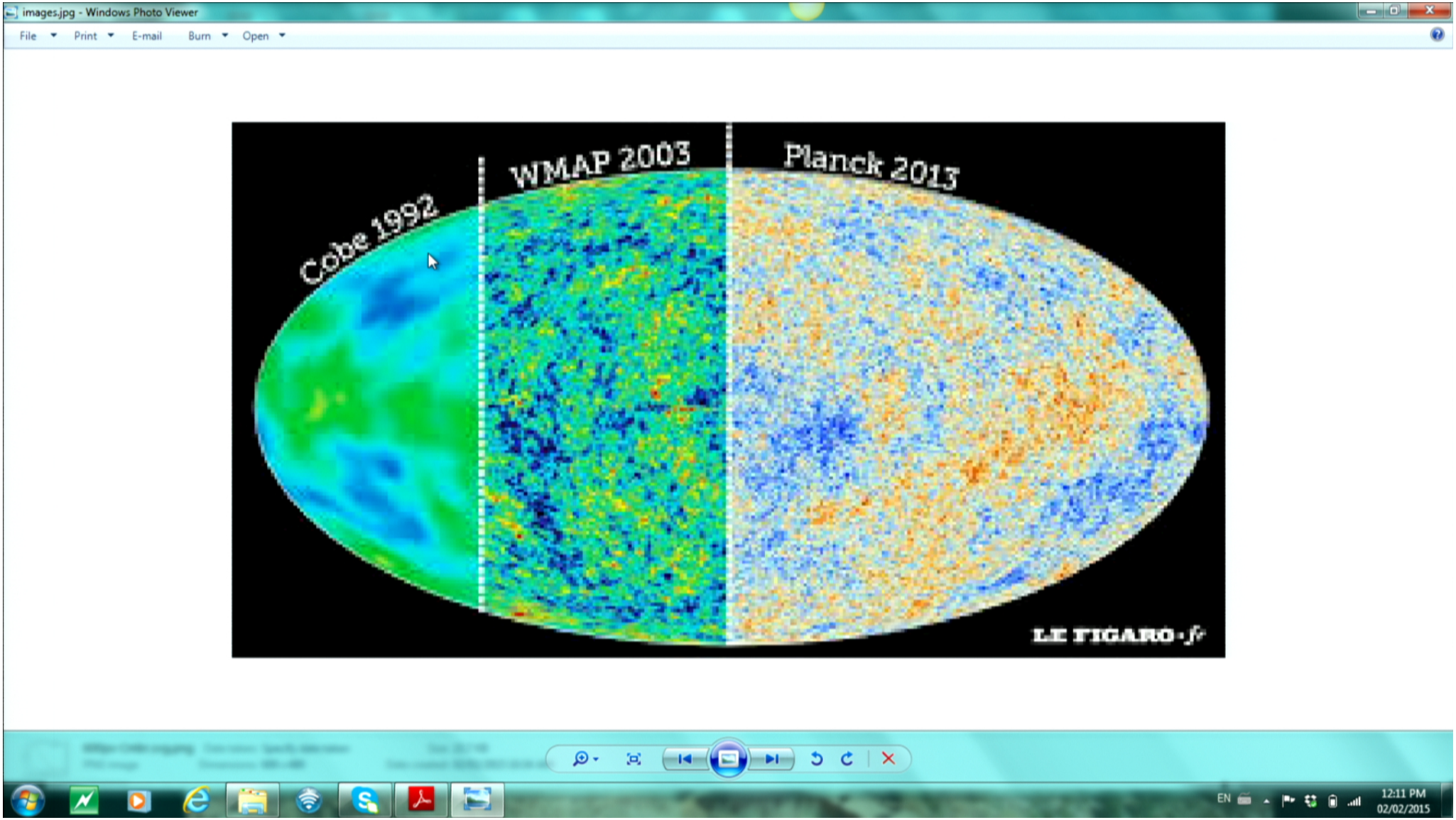

T(θ,φ)
TINY FLUCTUATIONS
($\bar{T}$ SUBSTRACTED
• EXPAND THIS IN MULTIPOLE MOMENTS
$T(\theta,\varphi) \overset{\text{ON } S^2}{=} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$
MEASURE

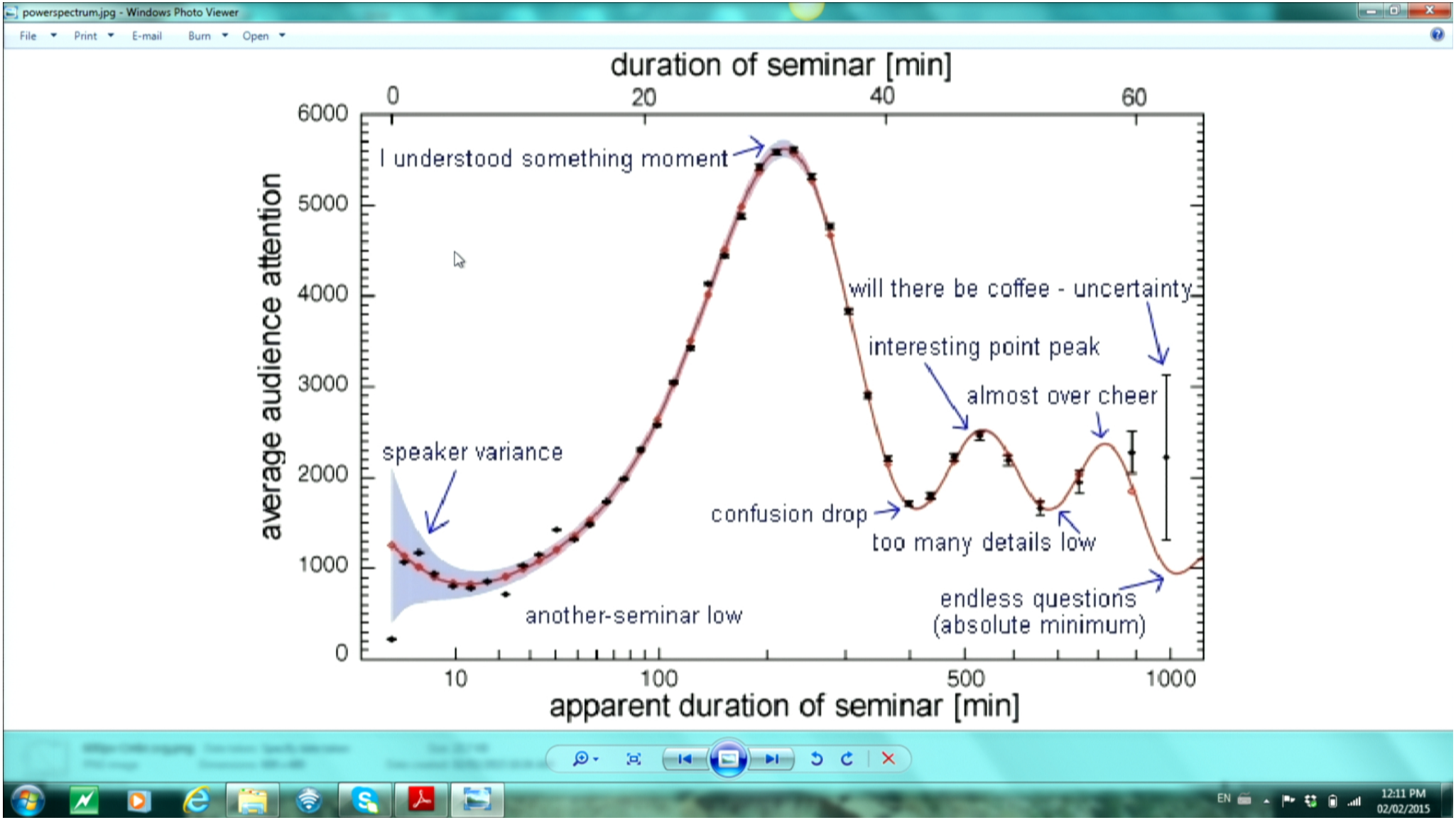

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$T(\theta,\varphi) \overset{\text{ON } S^2}{=} \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$
MEASURE
$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$ ... POWER SPECTRUM
C_ℓ
=> 6 PARAMETERS
2
50
500
ℓ

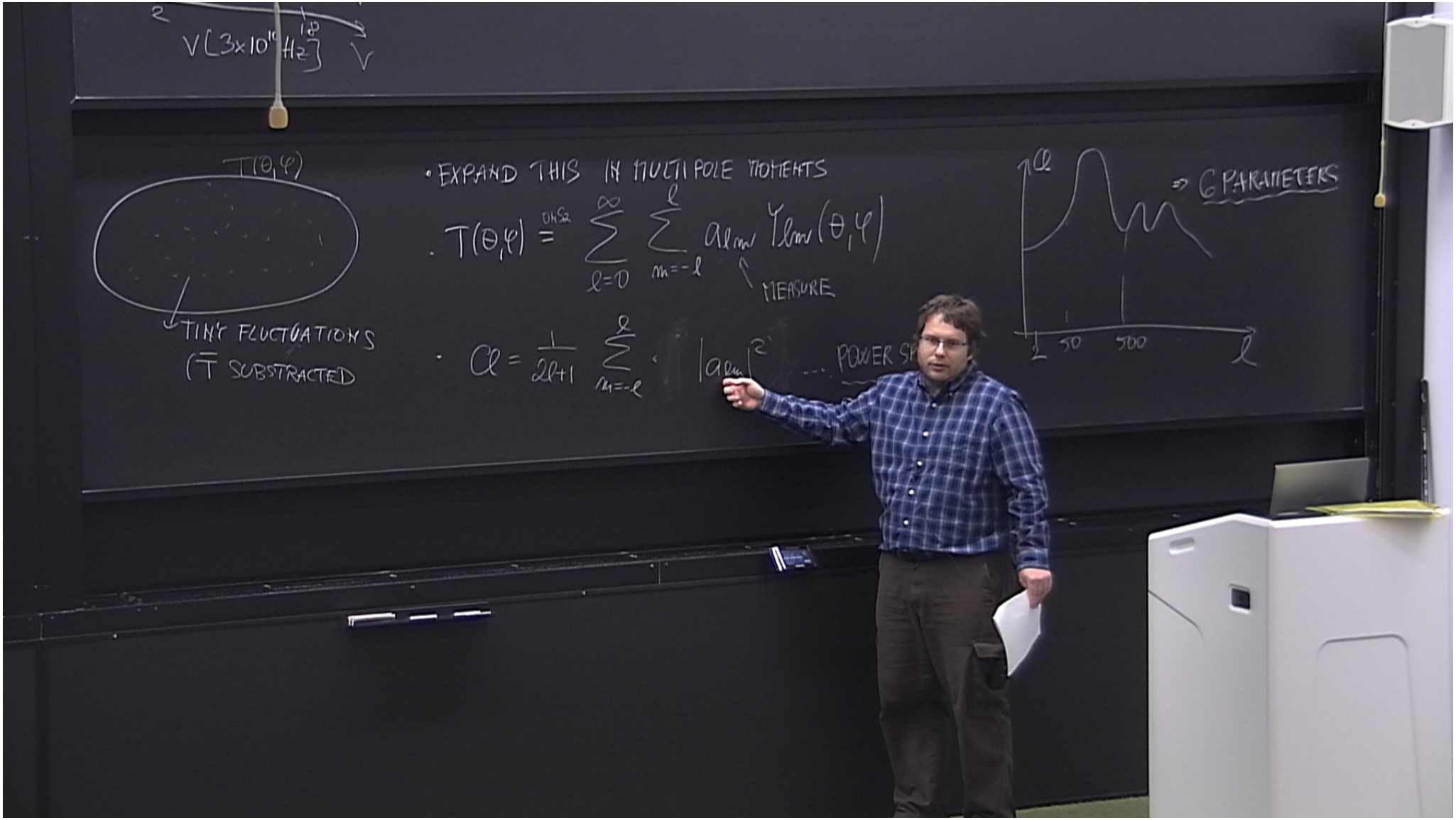

600px-Cmbr.svg.png - Windows Photo Viewer
File
Print
E-mail
Burn
Open
Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
400
350
300
250
200
150
100
50
0
2
4
6
8
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14
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22
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02/02/2015

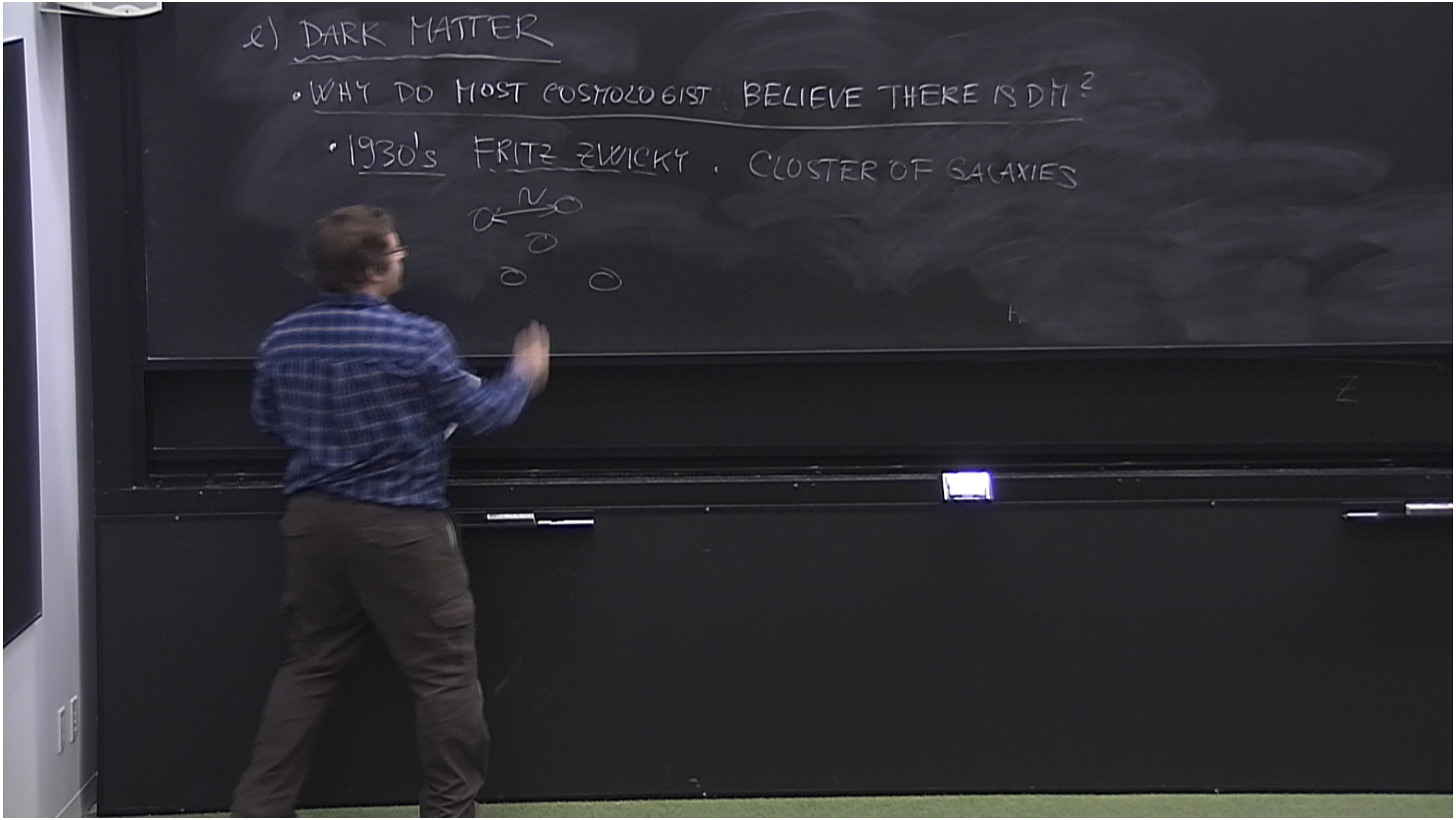

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File
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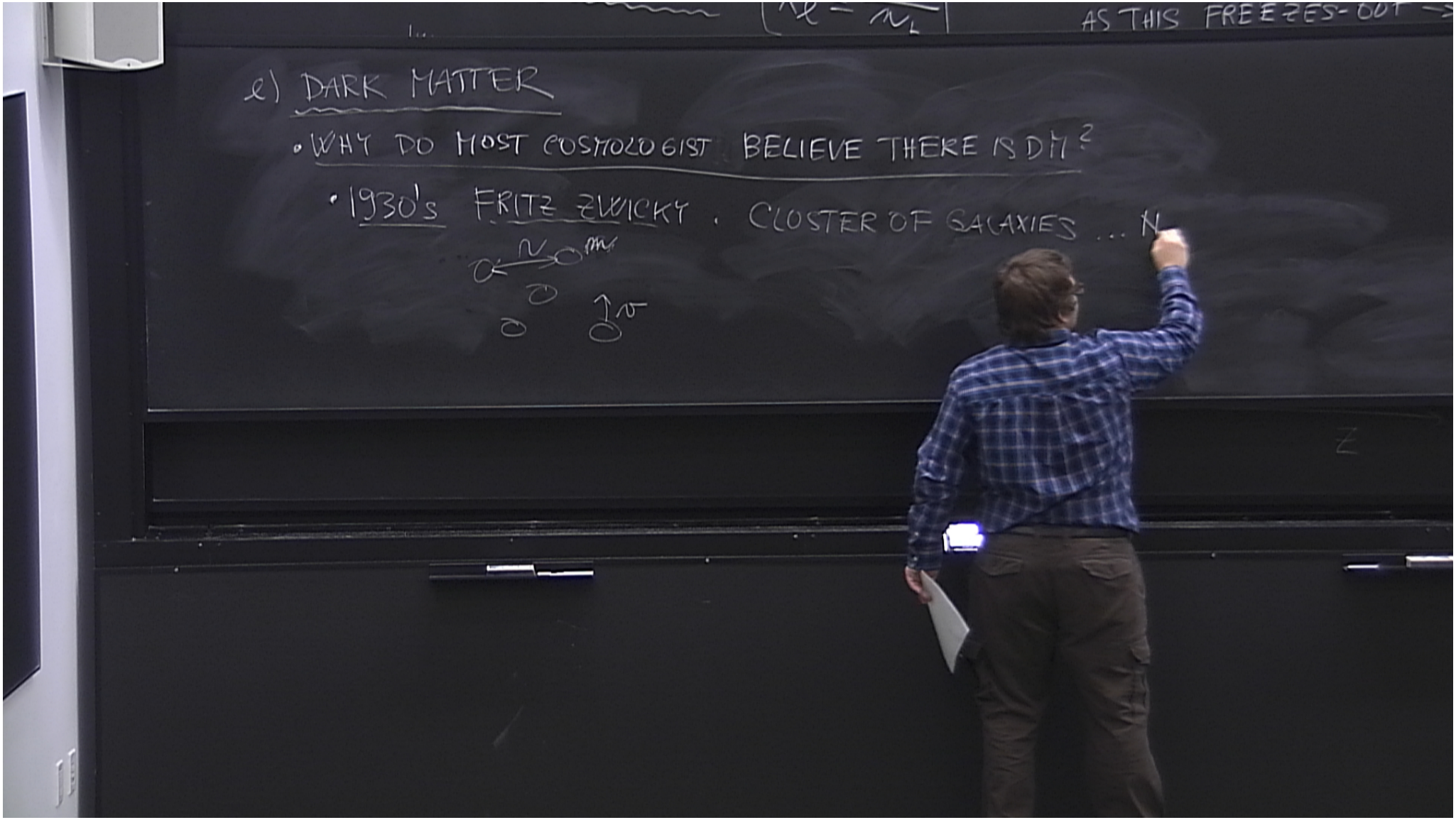

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File
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Burn
Open
Cobe 1992
WMAP 2003
Planck 2013
LE FIGARO.fr
EN
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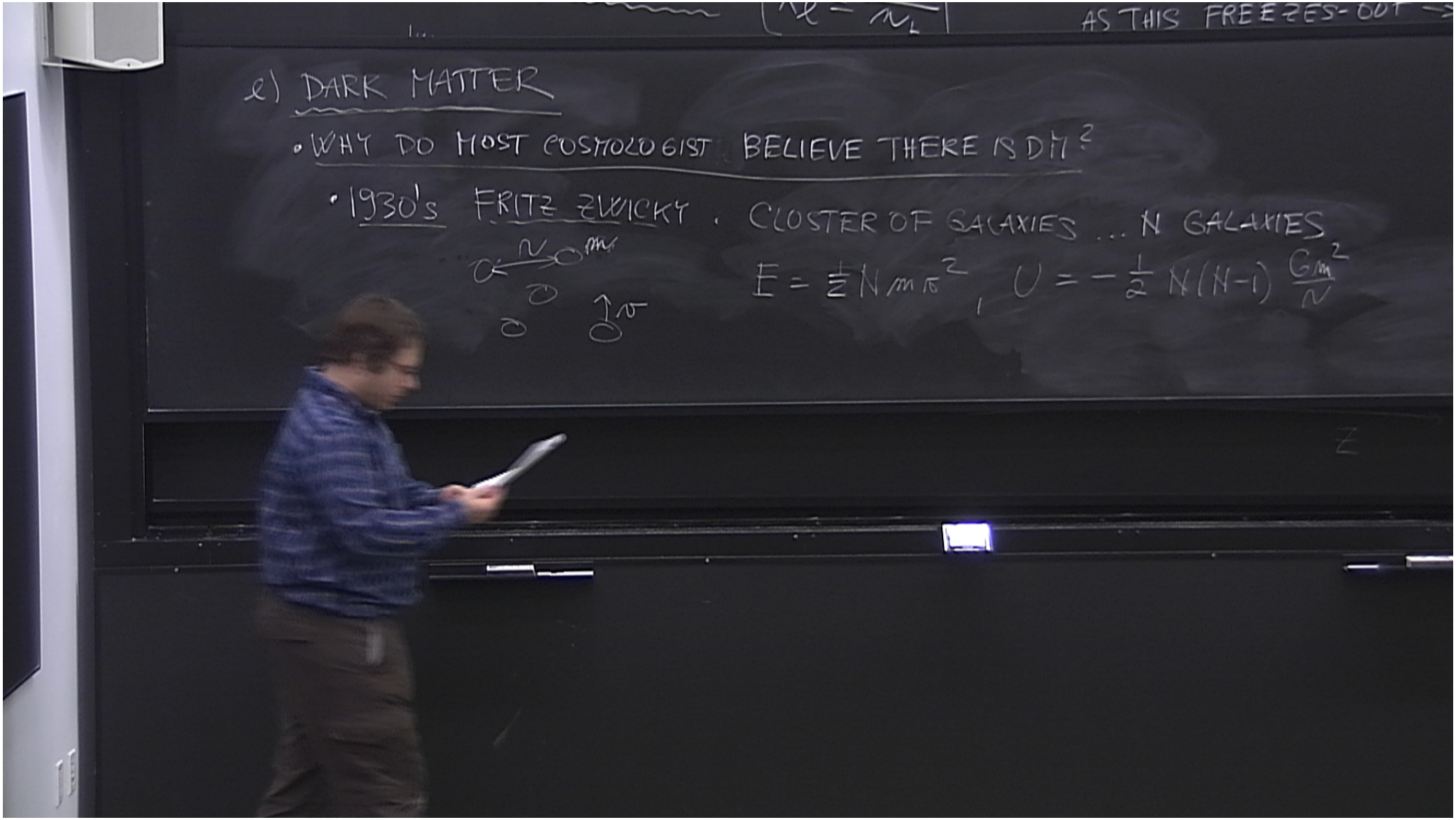

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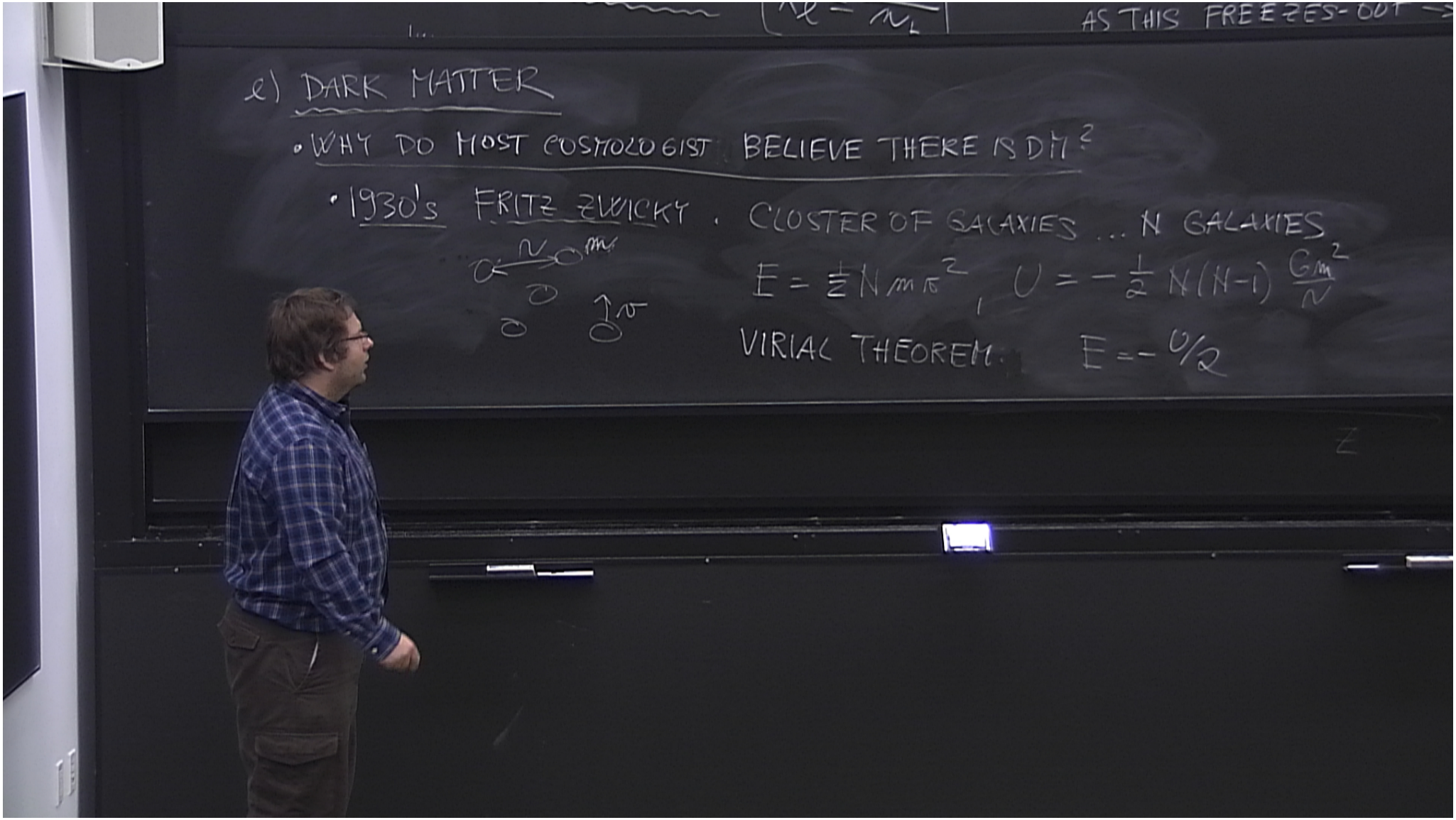

powerspectrum.jpg - Windows Photo Viewer
File
Print
E-mail
Burn
Open
duration of seminar [min]
0
20
40
60
average audience attention
6000
5000
4000
3000
2000
1000
0
I understood something moment
will there be coffee - uncertainty
interesting point peak
almost over cheer
speaker variance
confusion drop
too many details low
endless questions
(absolute minimum)
another-seminar low
10
100
500
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apparent duration of seminar [min]
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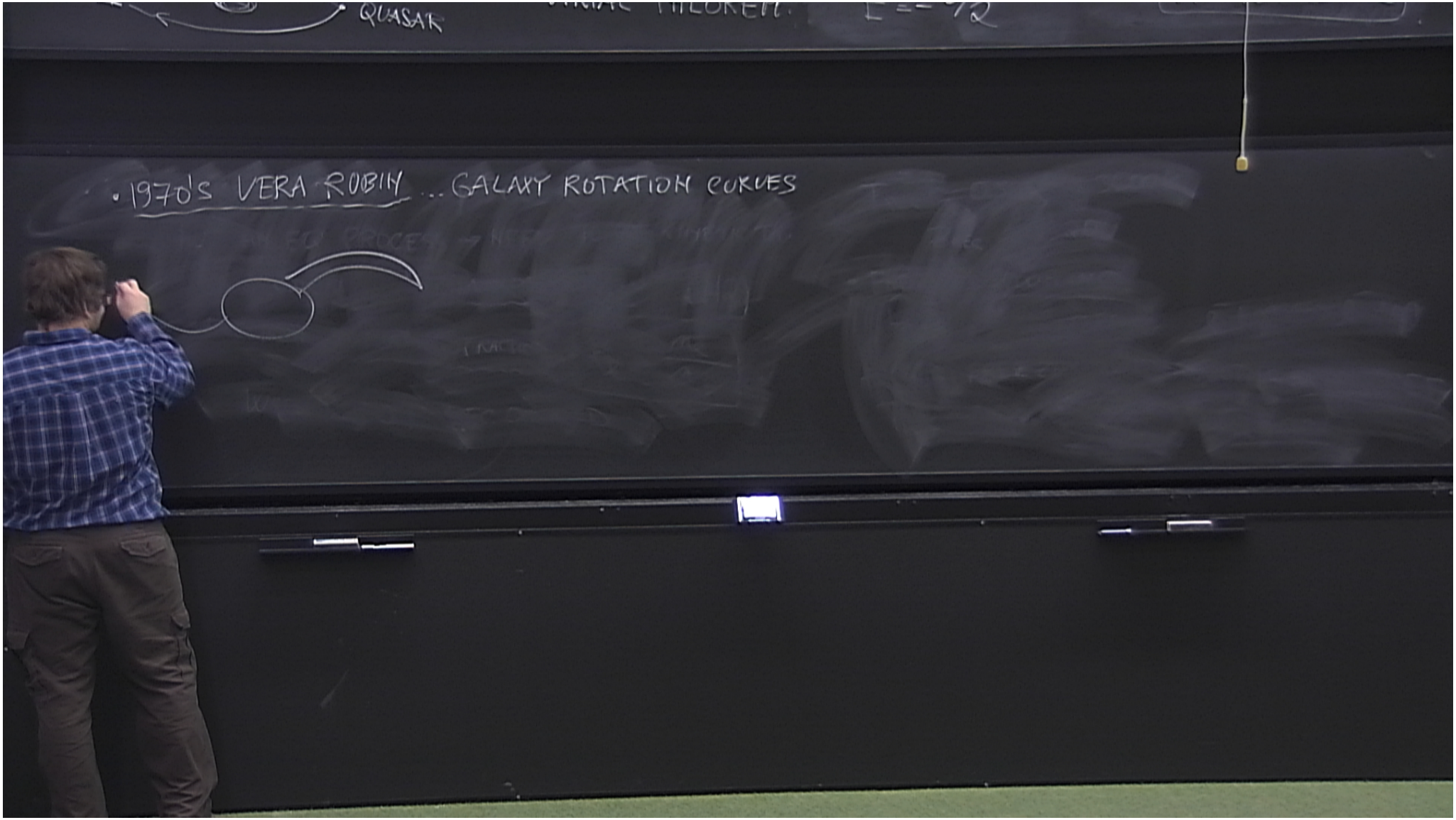

V [3×10^10 Hz]
T(θ,φ)
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POWER SP
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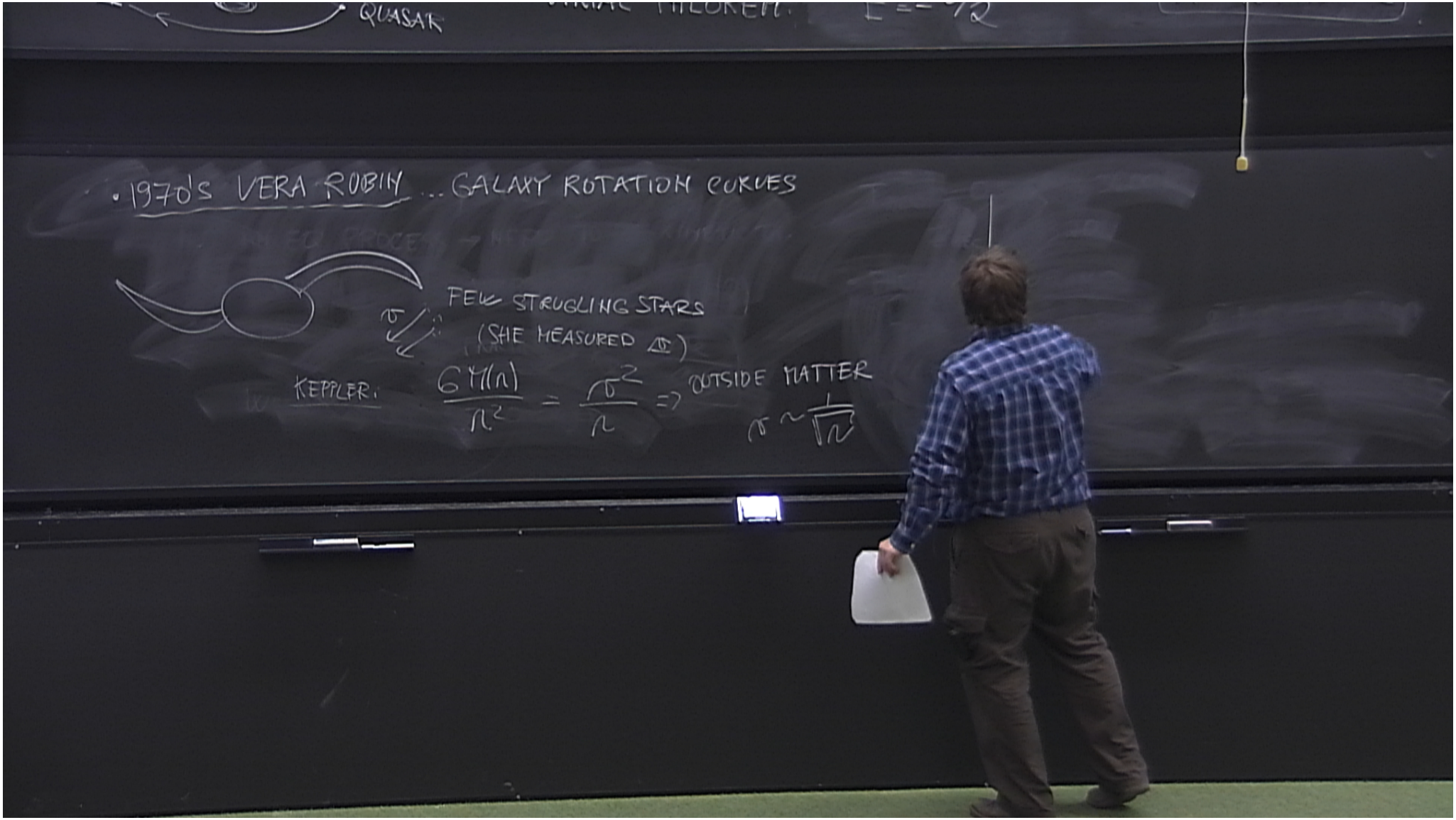

e) DARK MATTER
• WHY DO MOST COSMOLOGIST BELIEVE THERE IS DM?
• 1930's FRITZ ZWICKY . CLUSTER OF GALAXIES
N

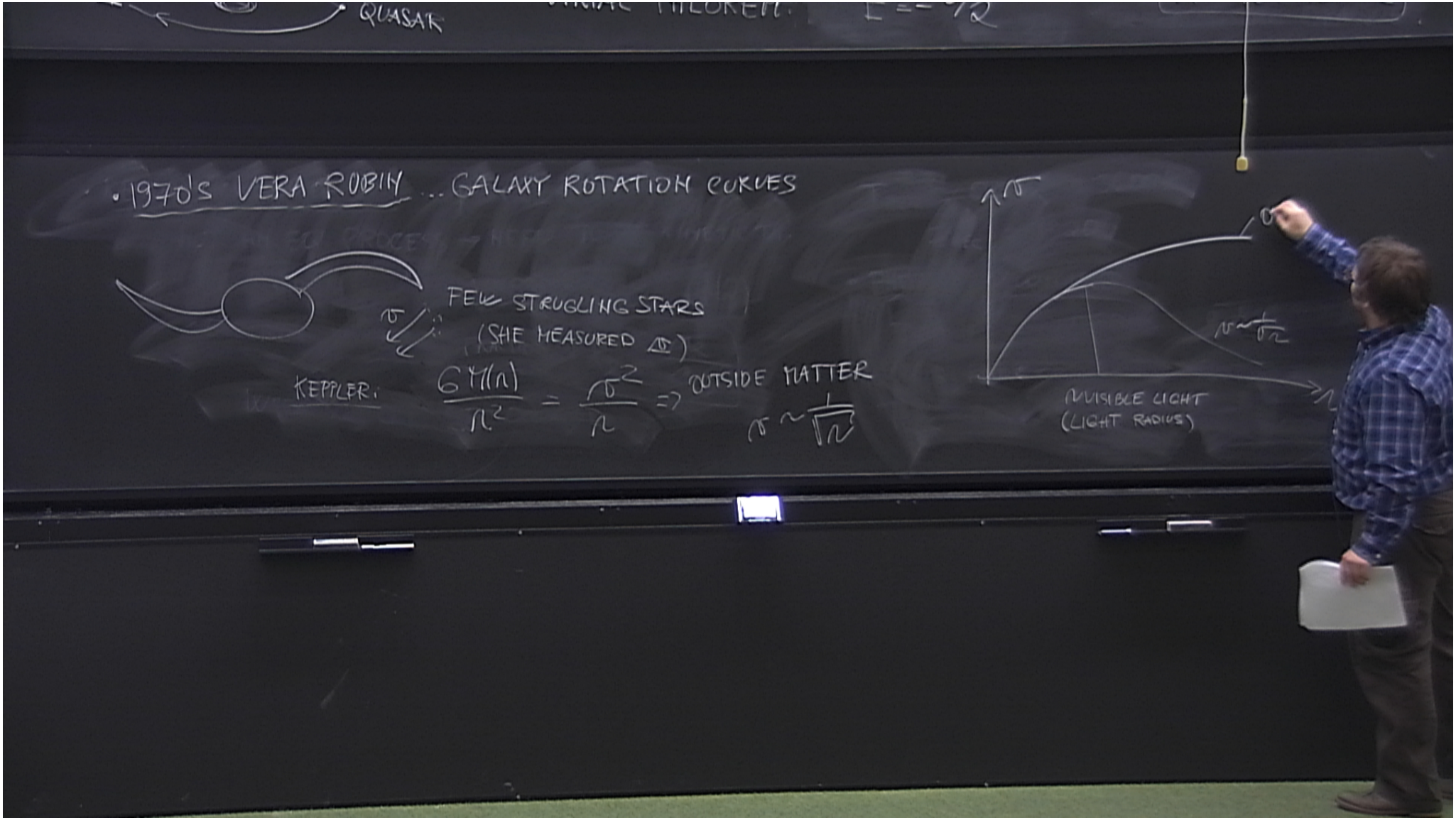

AS THIS FREEZES-OUT
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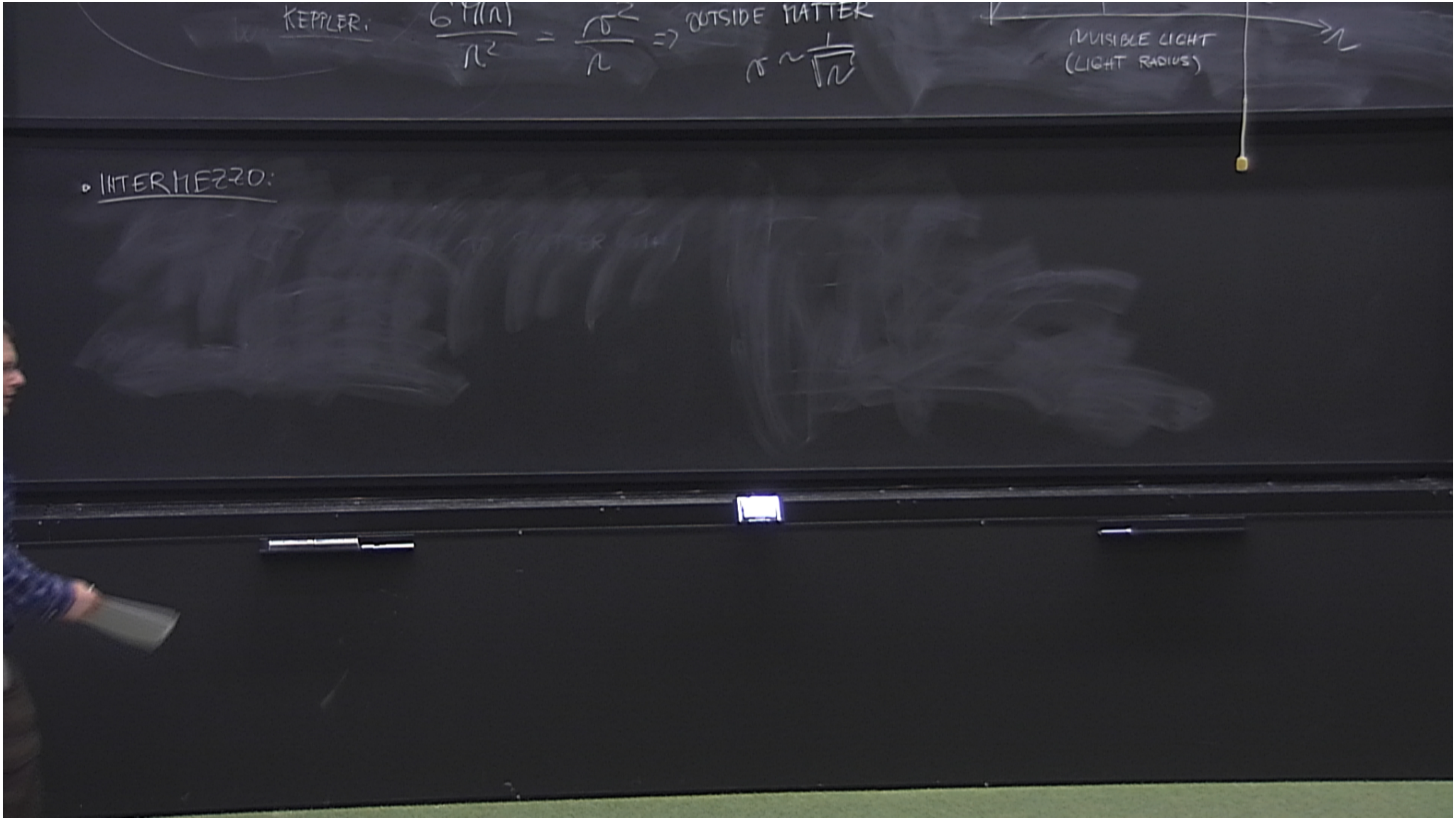

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• 1930's FRITZ ZWICKY . CLOSTER OF GALAXIES ... N GALAXIES
N
m
v
$E = \frac{1}{2} N m v^2$, $U = -\frac{1}{2} N(N-1) \frac{G m^2}{N}$

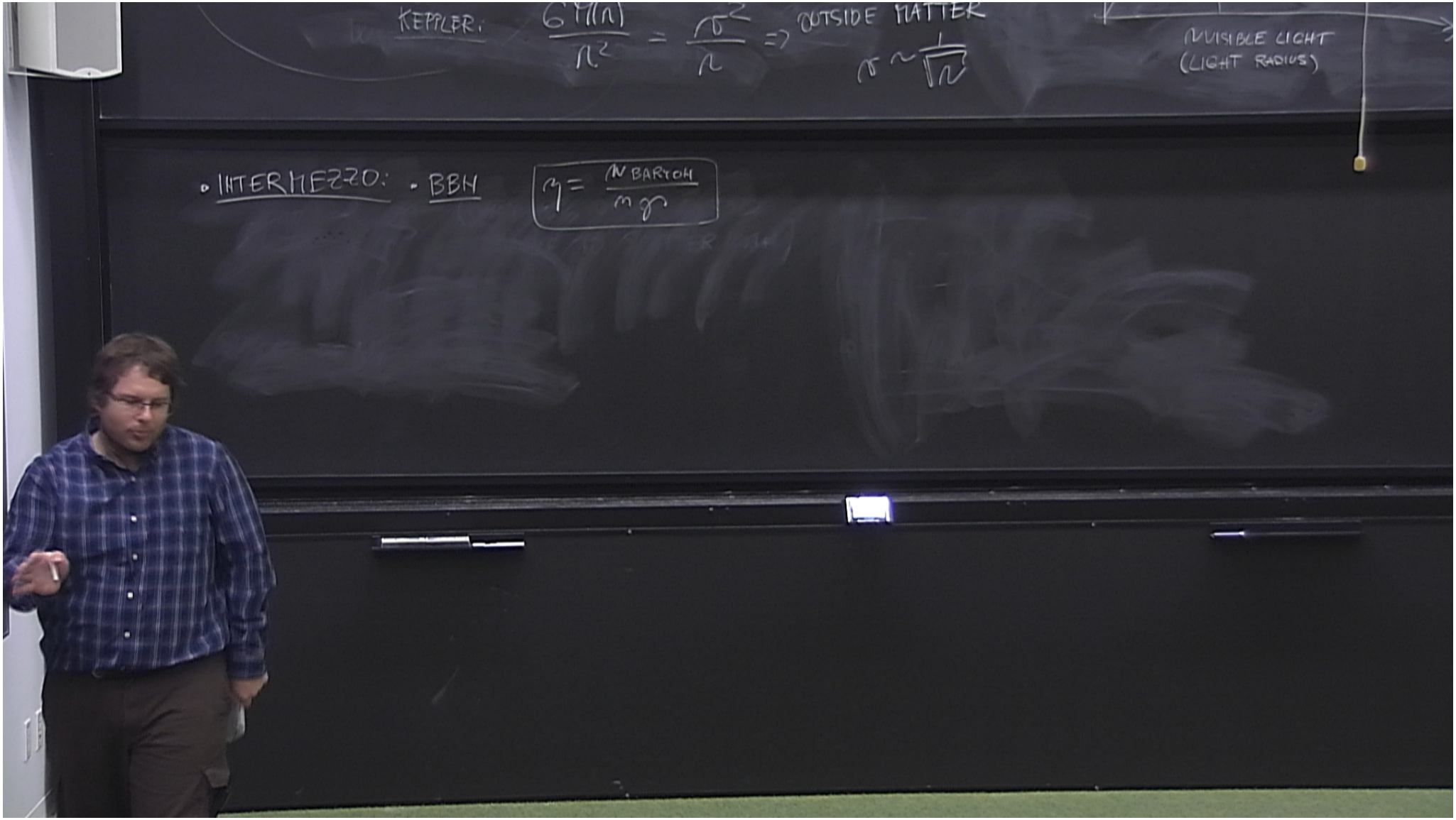

AS THIS FREEZES-OUT
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m
$E = \frac{1}{2} N m \sigma^2$, $U = -\frac{1}{2} N(N-1) \frac{G m^2}{N}$
VIRIAL THEOREM: $E = -U/2$

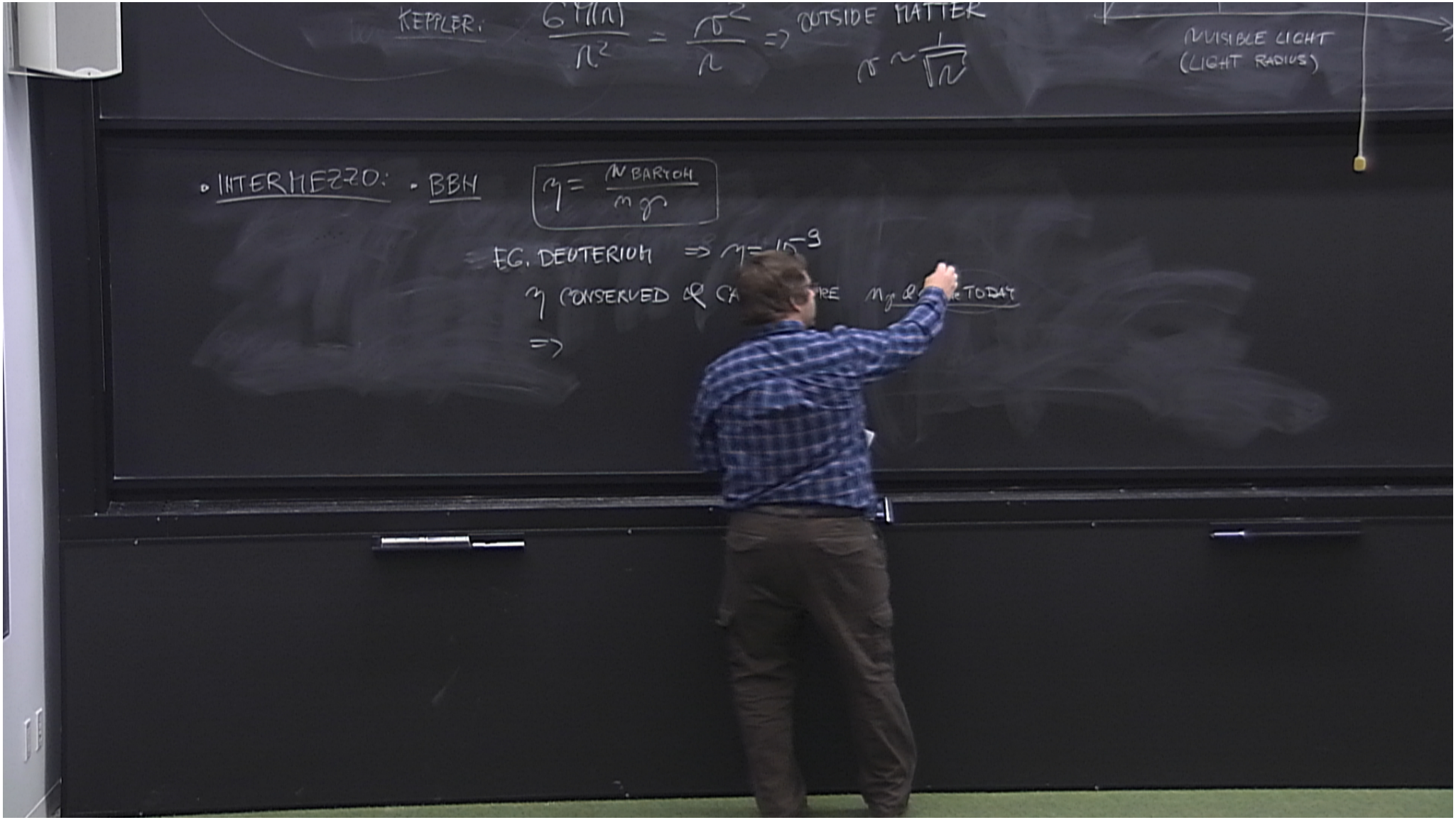

QUASAR
• 1970's VERA ROBIN ... GALAXY ROTATION CURVES

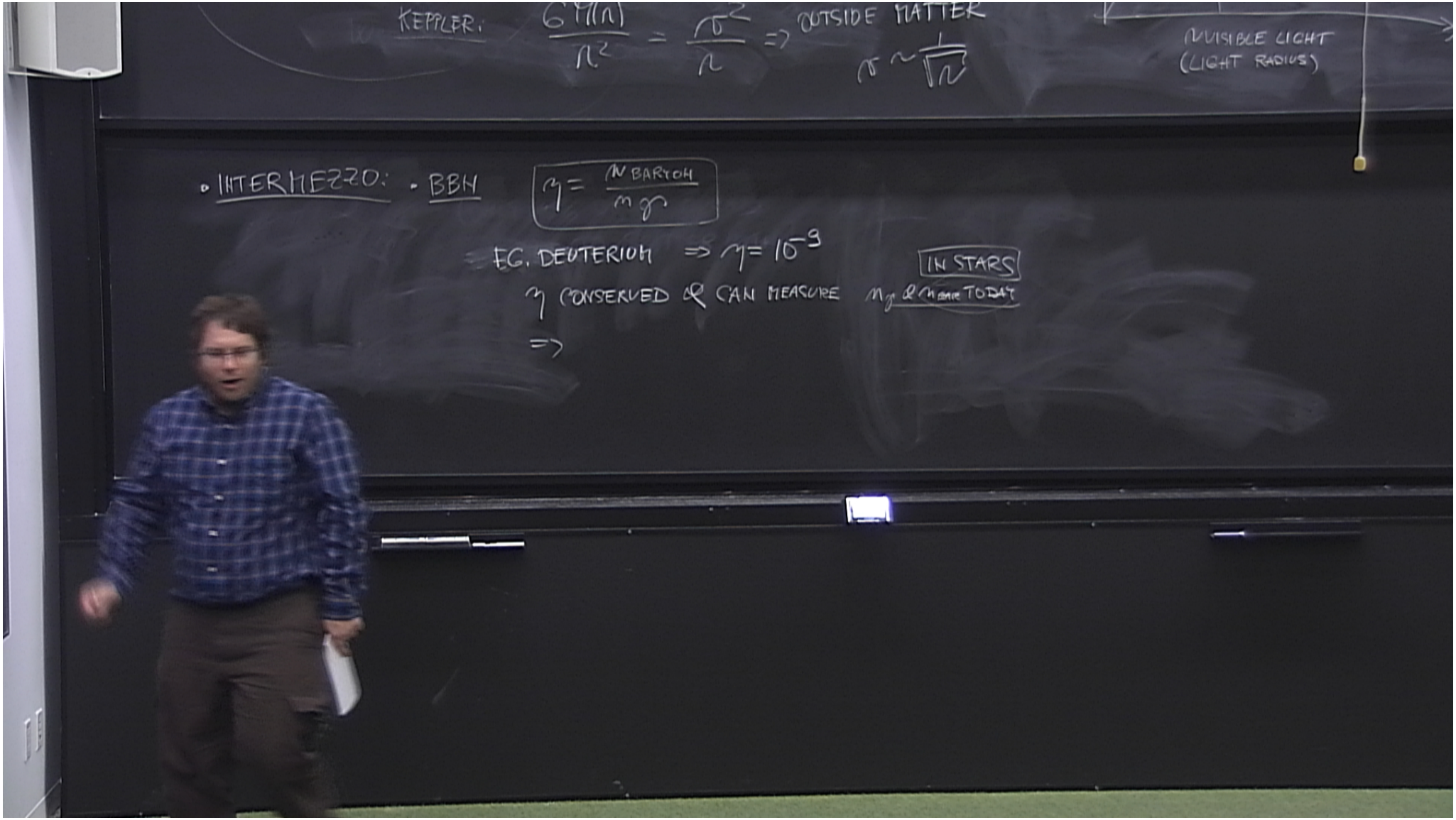

QUASAR
• 1970's VERA RUBIN ... GALAXY ROTATION CURVES
FEW STRUGGLING STARS
(SHE MEASURED v)
KEPPLER:
$\frac{GM(r)}{r^2} = \frac{v^2}{r}$ => OUTSIDE MATTER
$v \sim \frac{1}{\sqrt{r}}$

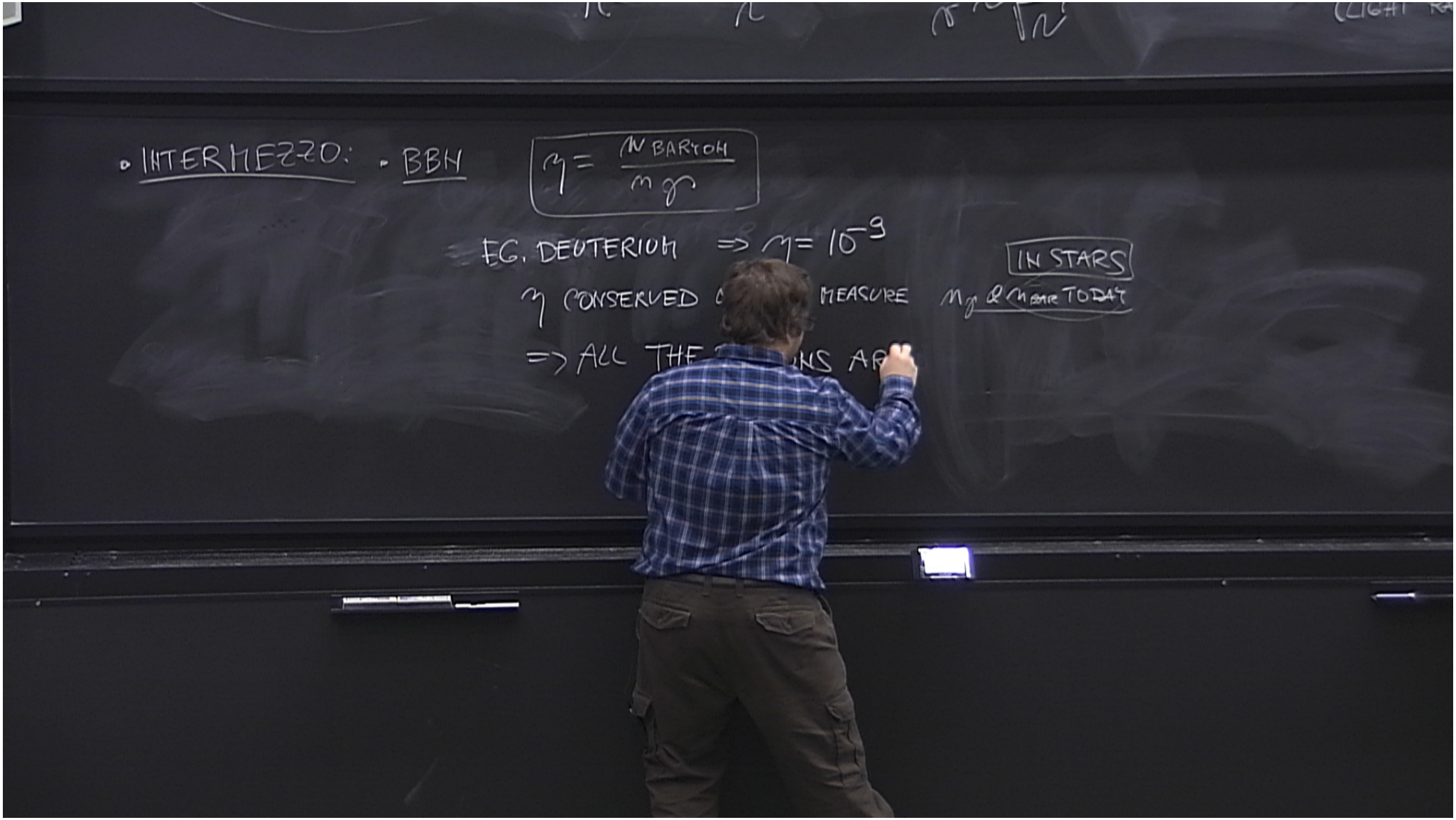

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VISIBLE LIGHT
(LIGHT RADIUS)

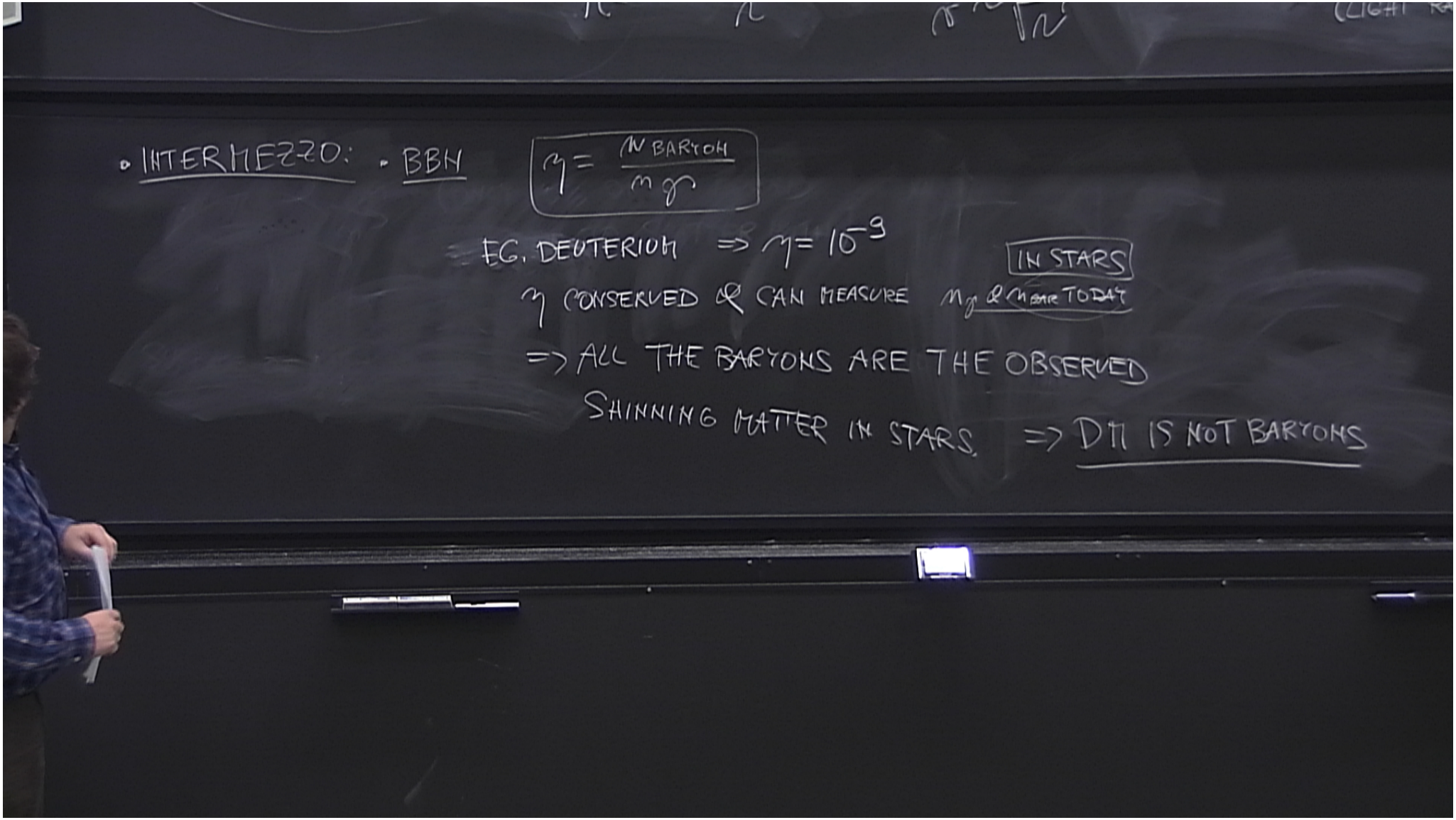

KEPPLER:
OUTSIDE MATTER
INVISIBLE LIGHT
(LIGHT RADIUS)
• INTERMEZZO:

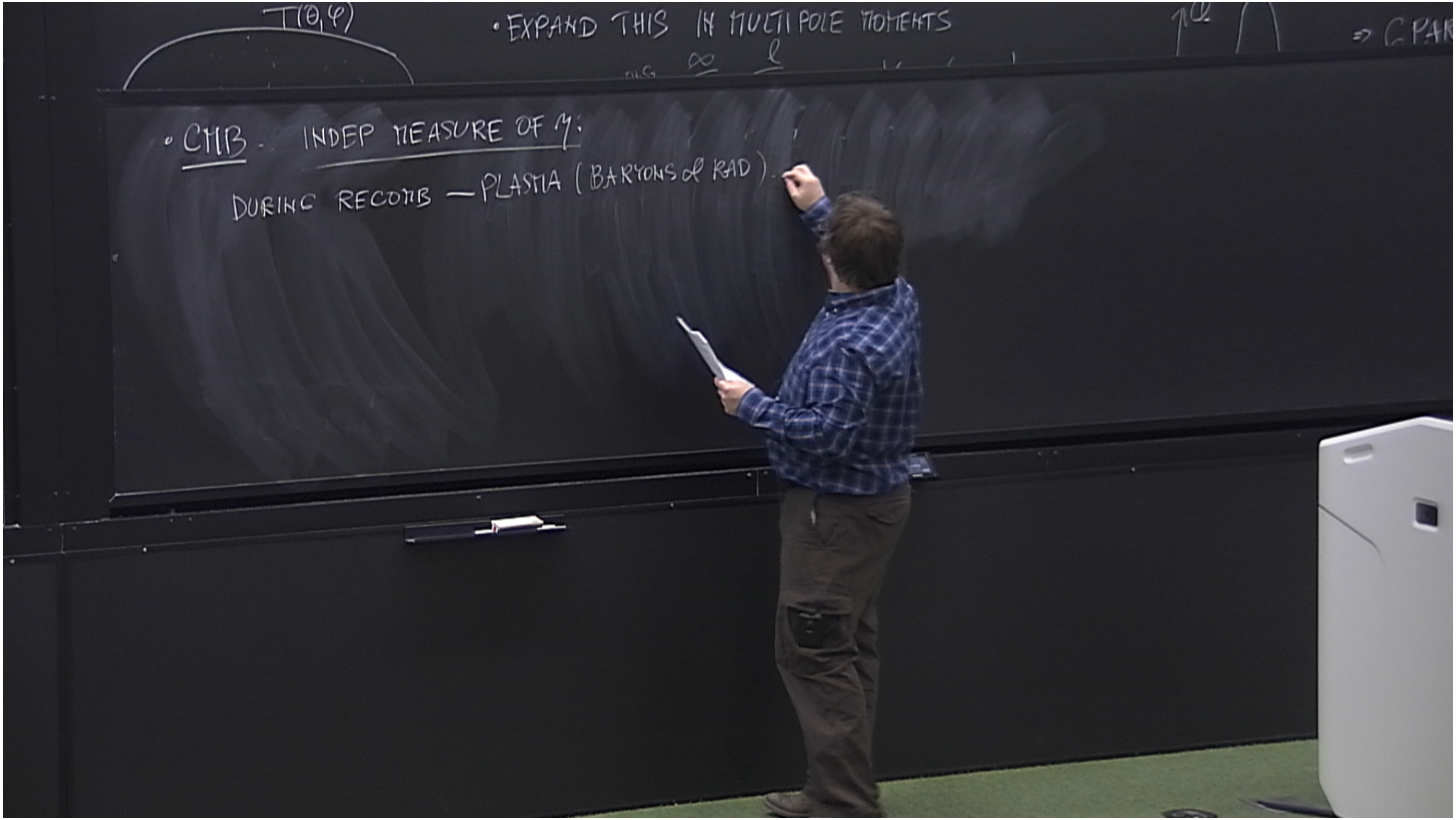

KEPLER:
OUTSIDE MATTER
VISIBLE LIGHT
(LIGHT RADIUS)
• INTERMEZZO: • BBN
η = N BARYON / n γ

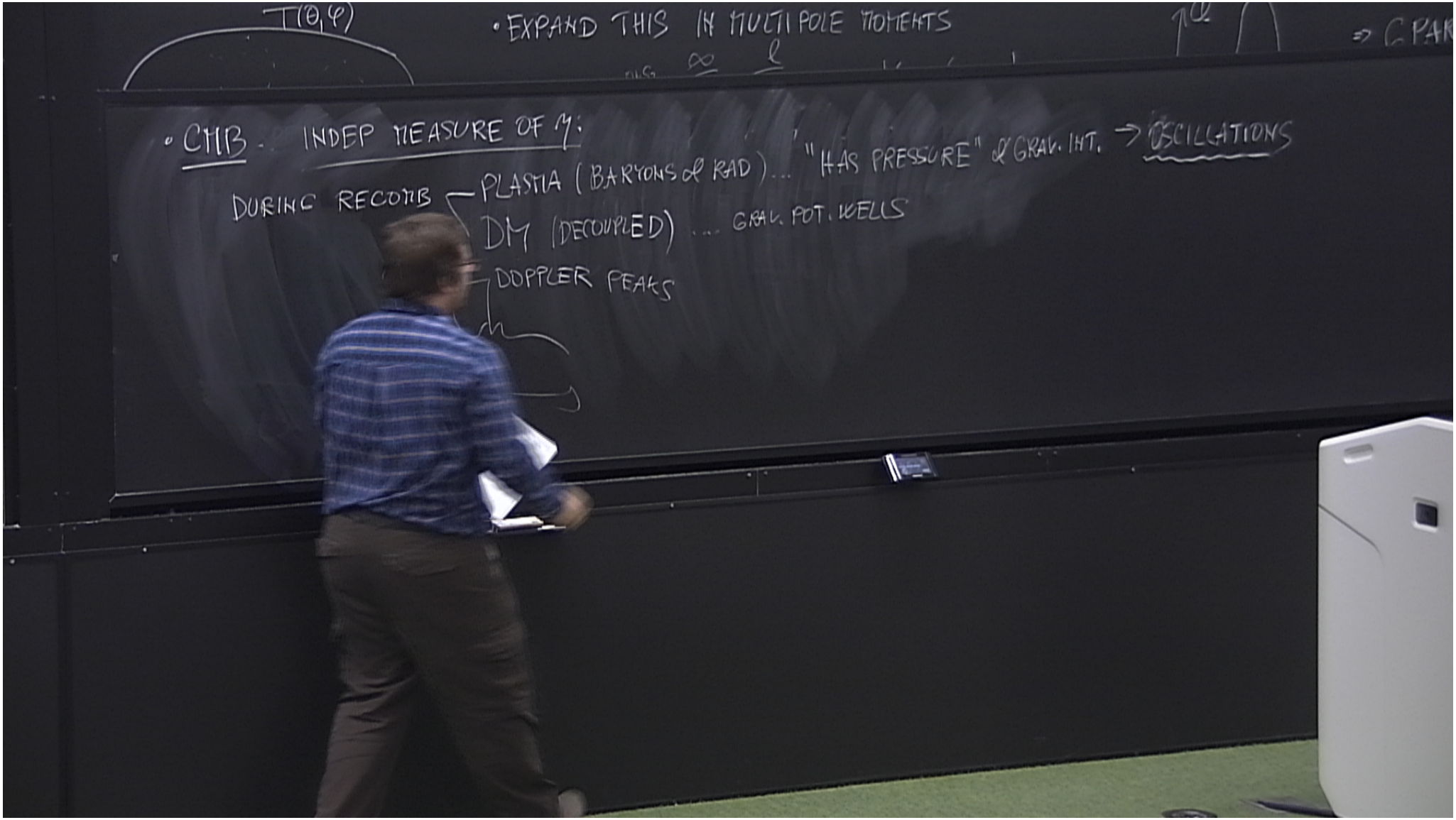

KEPLER:
OUTSIDE MATTER
VISIBLE LIGHT
(LIGHT RADIUS)
• INTERMEZZO: • BBN
EG. DEUTERIUM
CONSERVED
TODAY

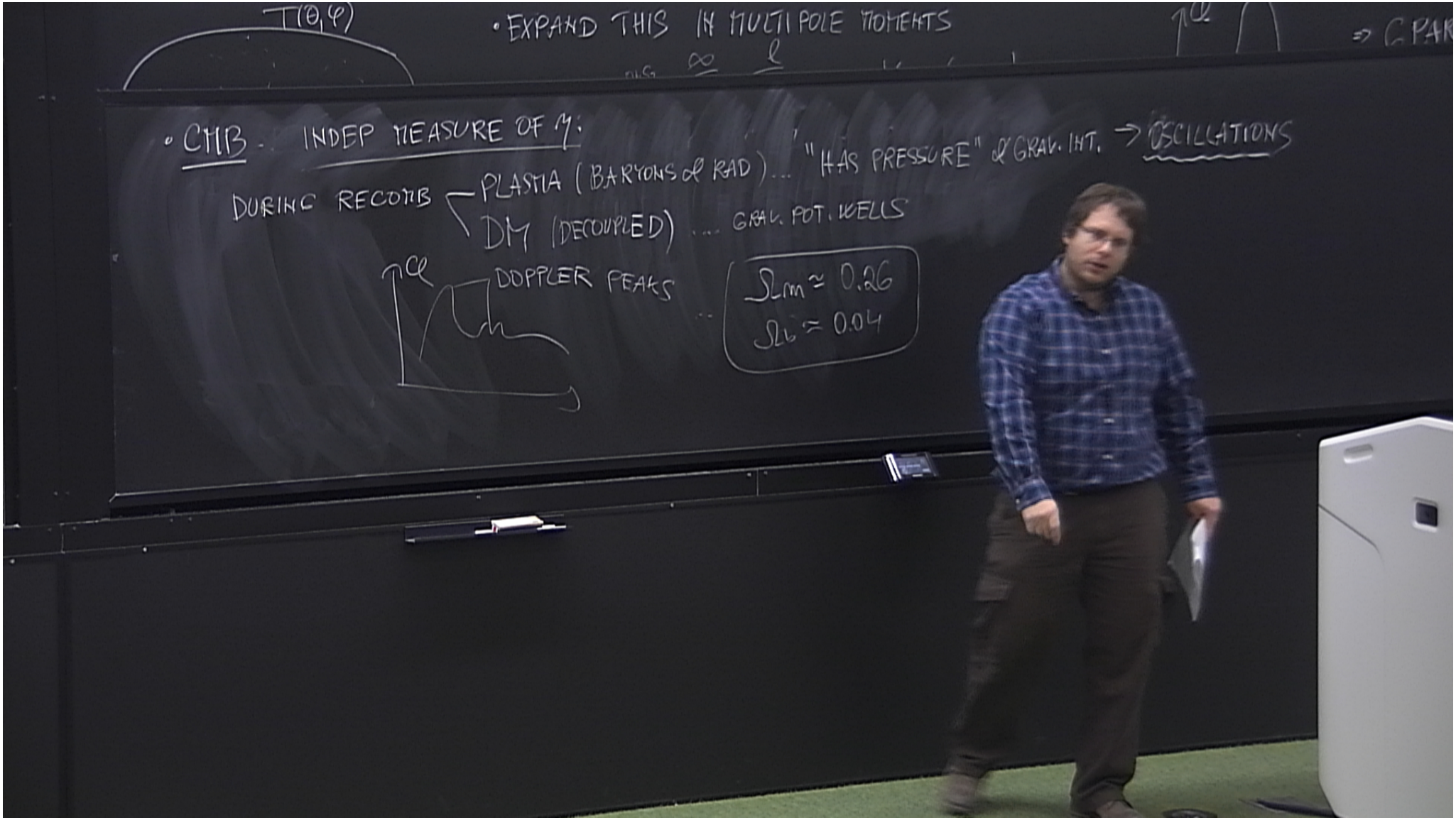

KEPLER:
OUTSIDE MATTER
VISIBLE LIGHT
(LIGHT RADIUS)
• INTERMEZZO: • BBN
EG. DEUTERIUM
IN STARS
TODAY


• INTERMEZZO: • BBN
$\eta = \frac{N_{BARYON}}{N_\gamma}$
EG. DEUTERIUM $\Rightarrow \eta = 10^{-9}$
η CONSERVED
MEASURE
IN STARS
N_γ TODAY
$\Rightarrow$ ALL THE


• INTERMEZZO: • BBN
$\eta = \frac{N_{BARYON}}{n_\gamma}$
EG. DEUTERIUM $\Rightarrow \eta = 10^{-9}$
IN STARS
η CONSERVED & CAN MEASURE n_γ & n_{BARYON} TODAY
$\Rightarrow$ ALL THE BARYONS ARE THE OBSERVED
SHINNING MATTER IN STARS. $\Rightarrow$ DM IS NOT BARYONS


T(θ,φ)
• EXPAND THIS IN MULTIPOLE MOMENTS
• CMB - INDEP MEASURE OF M:
DURING RECOMB — PLASMA (BARYONS & RAD)


T(θ,φ)
• EXPAND THIS IN MULTI POLE MOMENTS
• CMB - INDEP MEASURE OF Ω:
DURING RECOMB
PLASMA (BARYONS & RAD) ... "HAS PRESSURE" & GRAV. INT. → OSCILLATIONS
DM (DECOUPLED) ... GRAV. POT. WELLS
DOPPLER PEAKS


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DM (DECOUPLED) ... GRAV. POT. WELLS
DOPPLER PEAKS
Ωm ≃ 0.26
ΩΛ ≃ 0.04