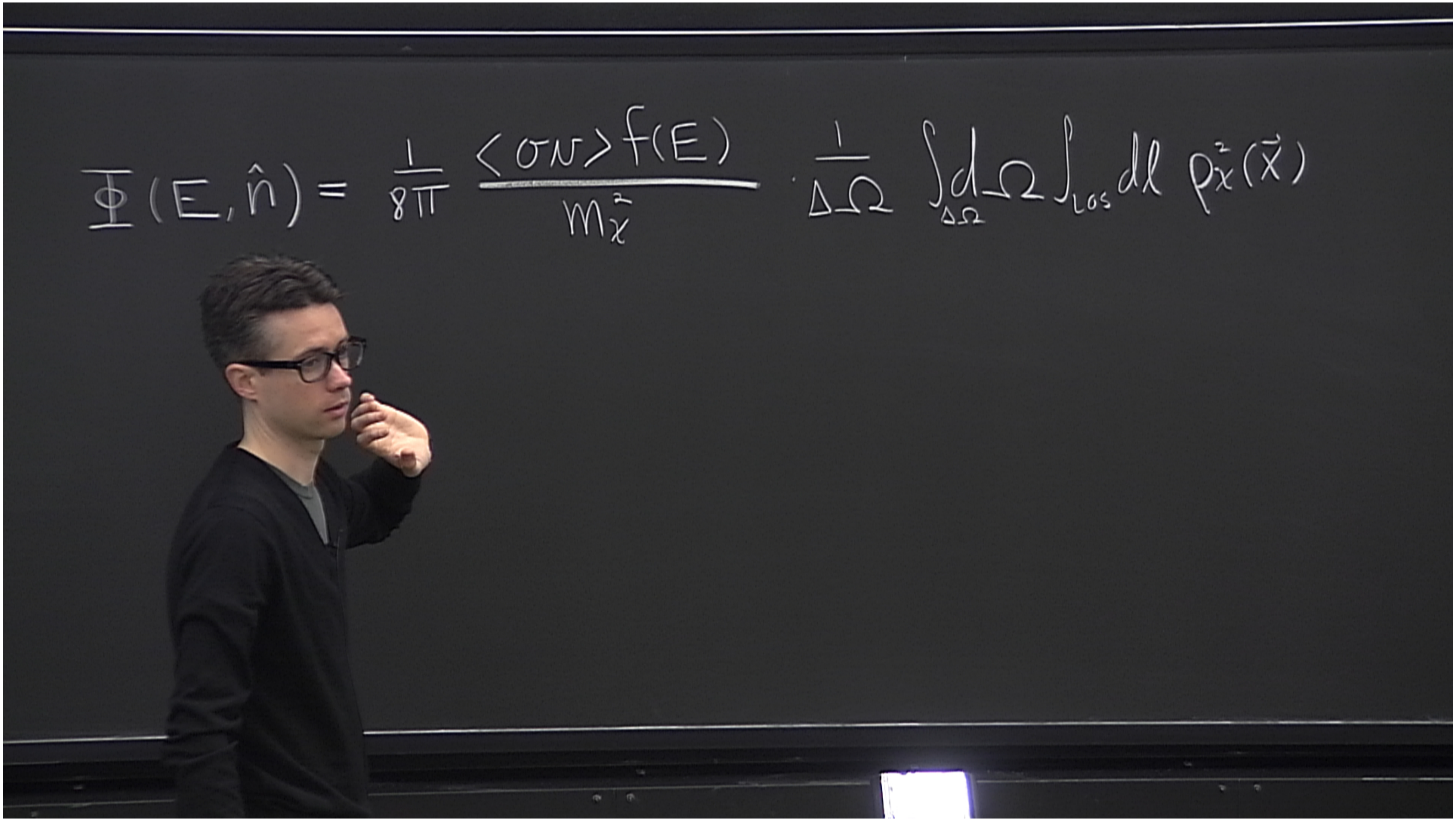
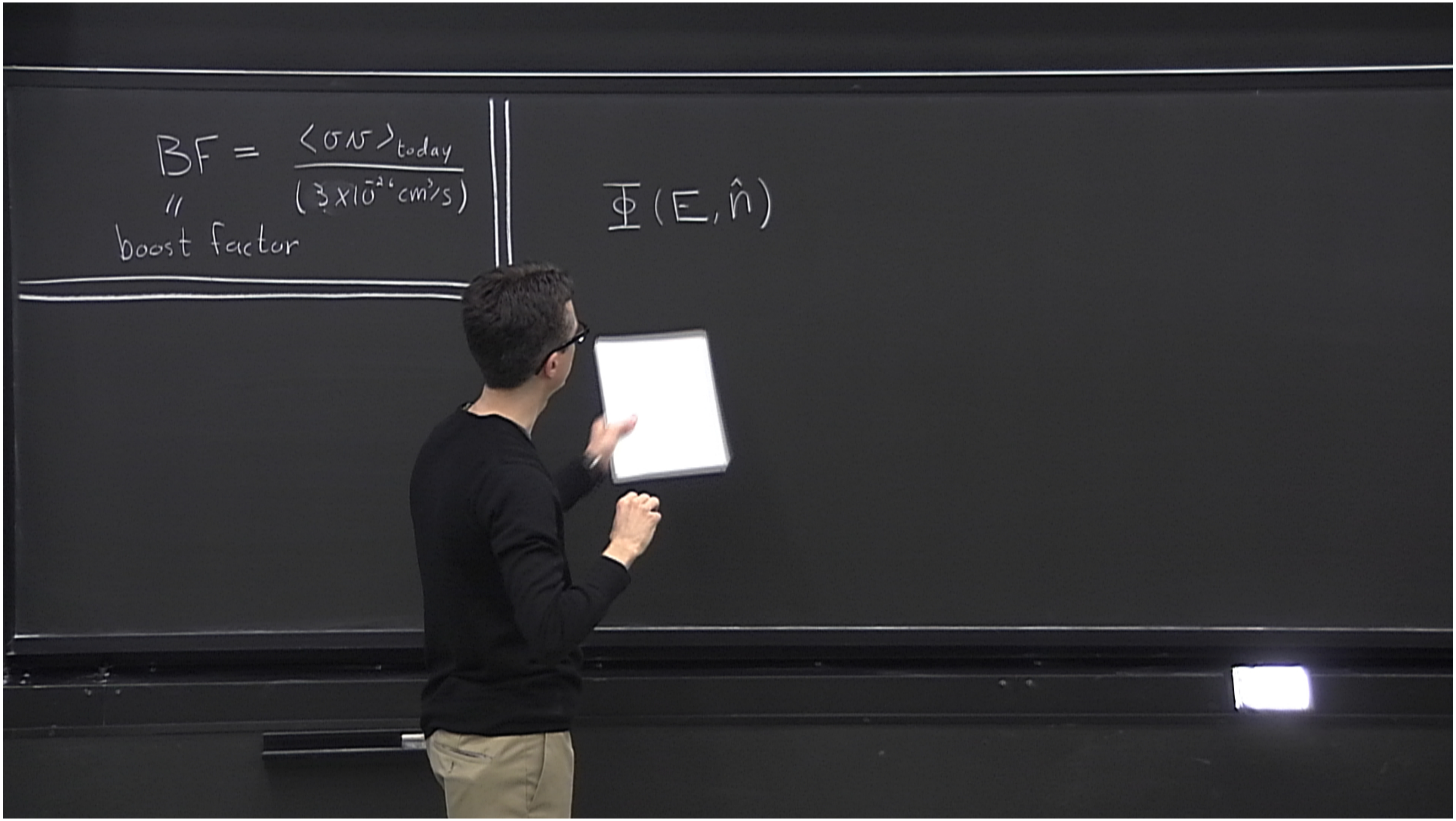
Title: Explorations in Particle Theory - Lecture 12

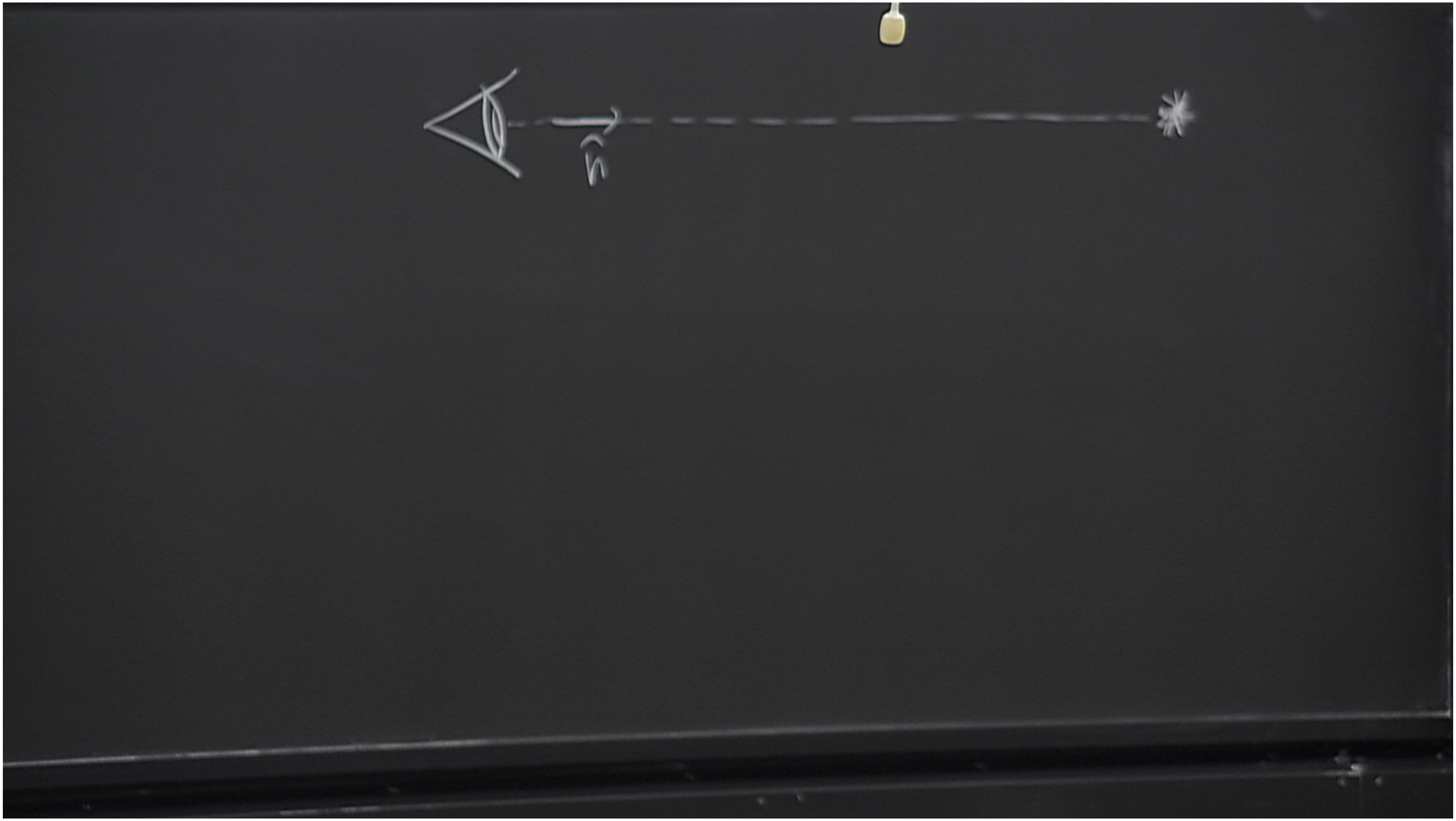
Date: Apr 18, 2012 09:00 AM

URL: http://pirsa.org/12040016

Abstract:


$\Phi(E,\hat{n}) = \frac{1}{8\pi}\frac{\langle \sigma v \rangle f(E)}{m_\chi^2} \cdot \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl\, \rho_\chi^2(\vec{x})$


BF = ⟨σv⟩today / (3×10^-26 cm^3/s)
= boost factor
Φ(E, n̂)



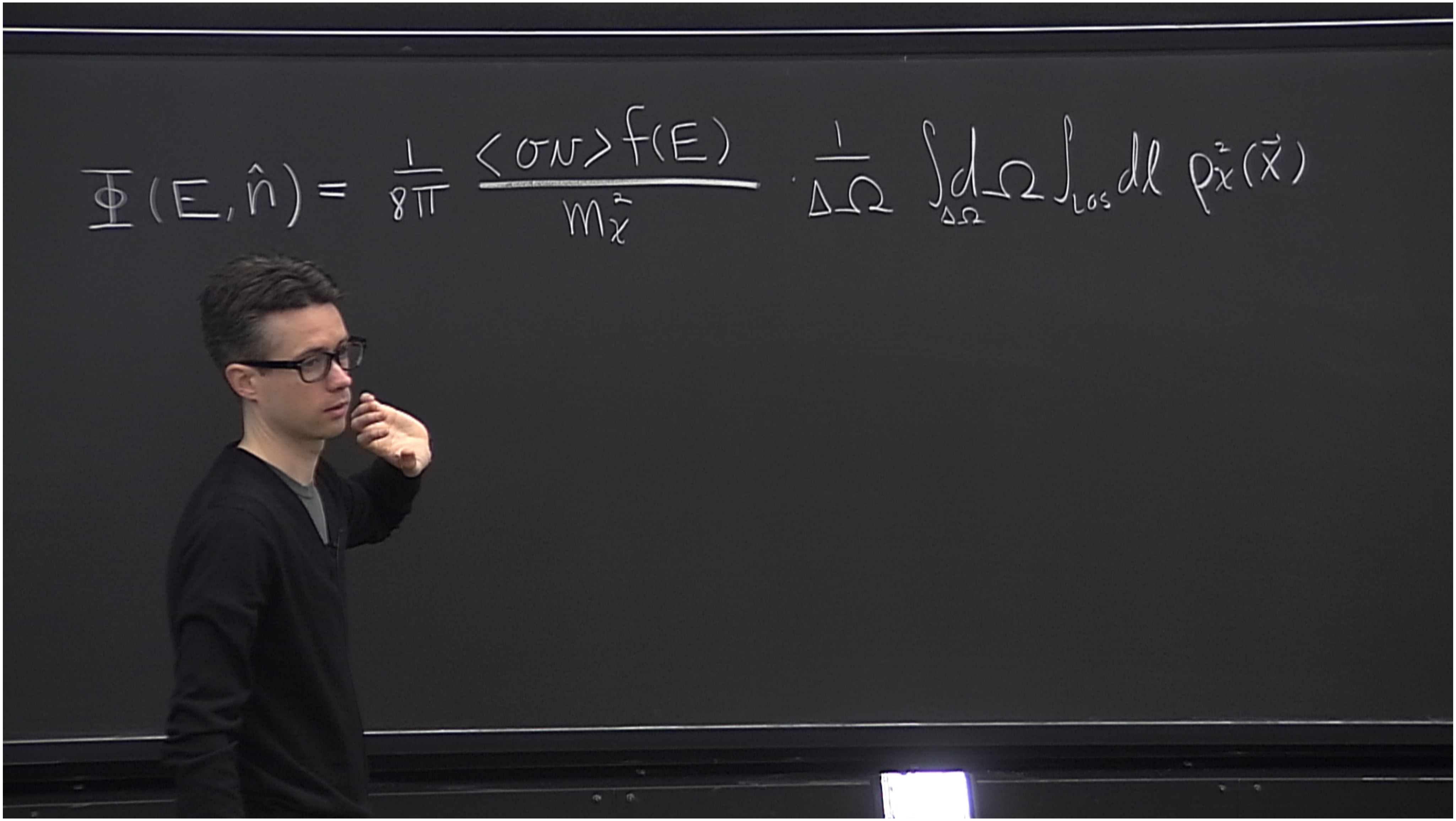
$\hat{n}$

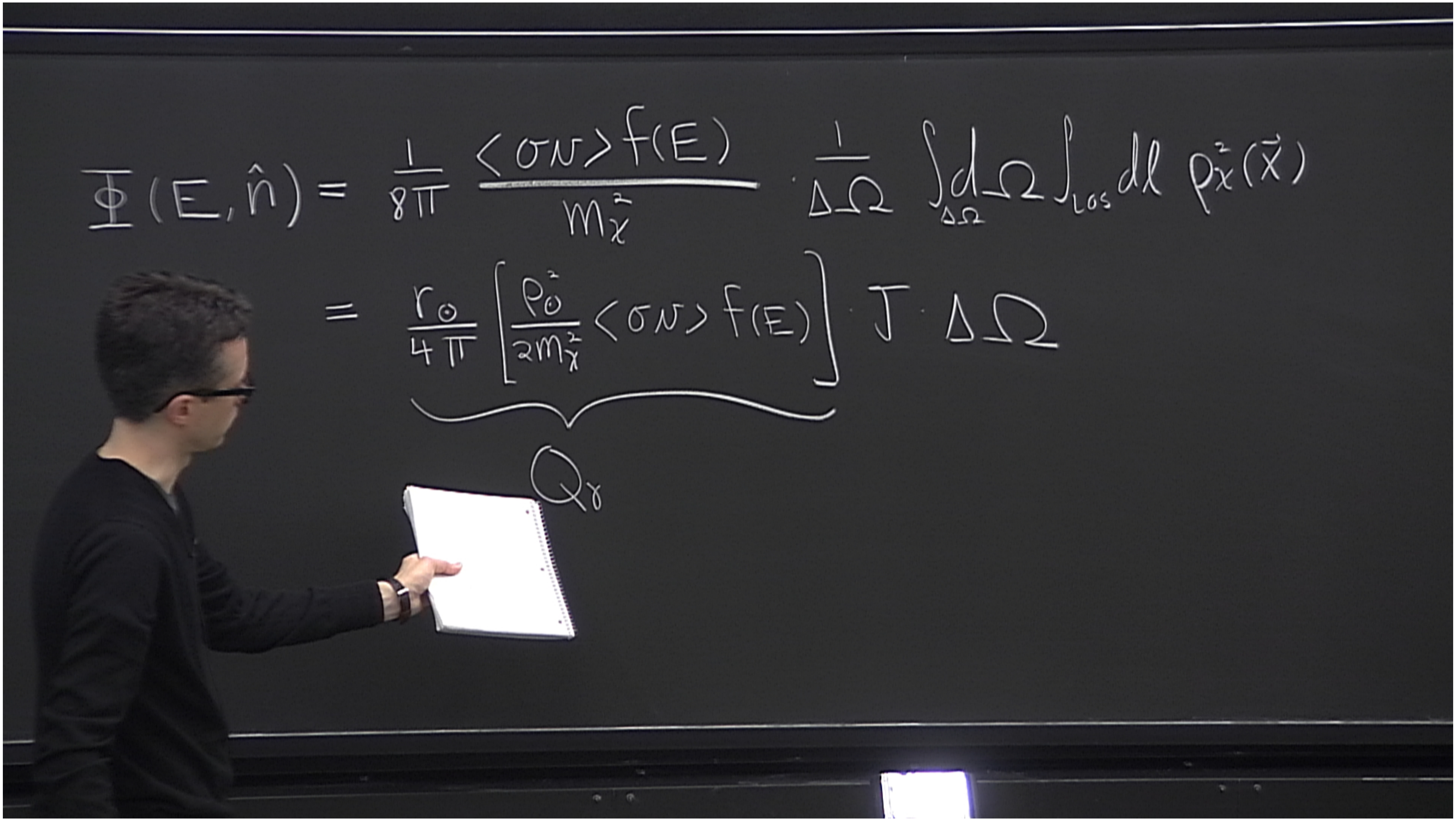
$$BF = \frac{\langle \sigma v \rangle_{today}}{(3 \times 10^{-26}\ \mathrm{cm^3/s})}$$

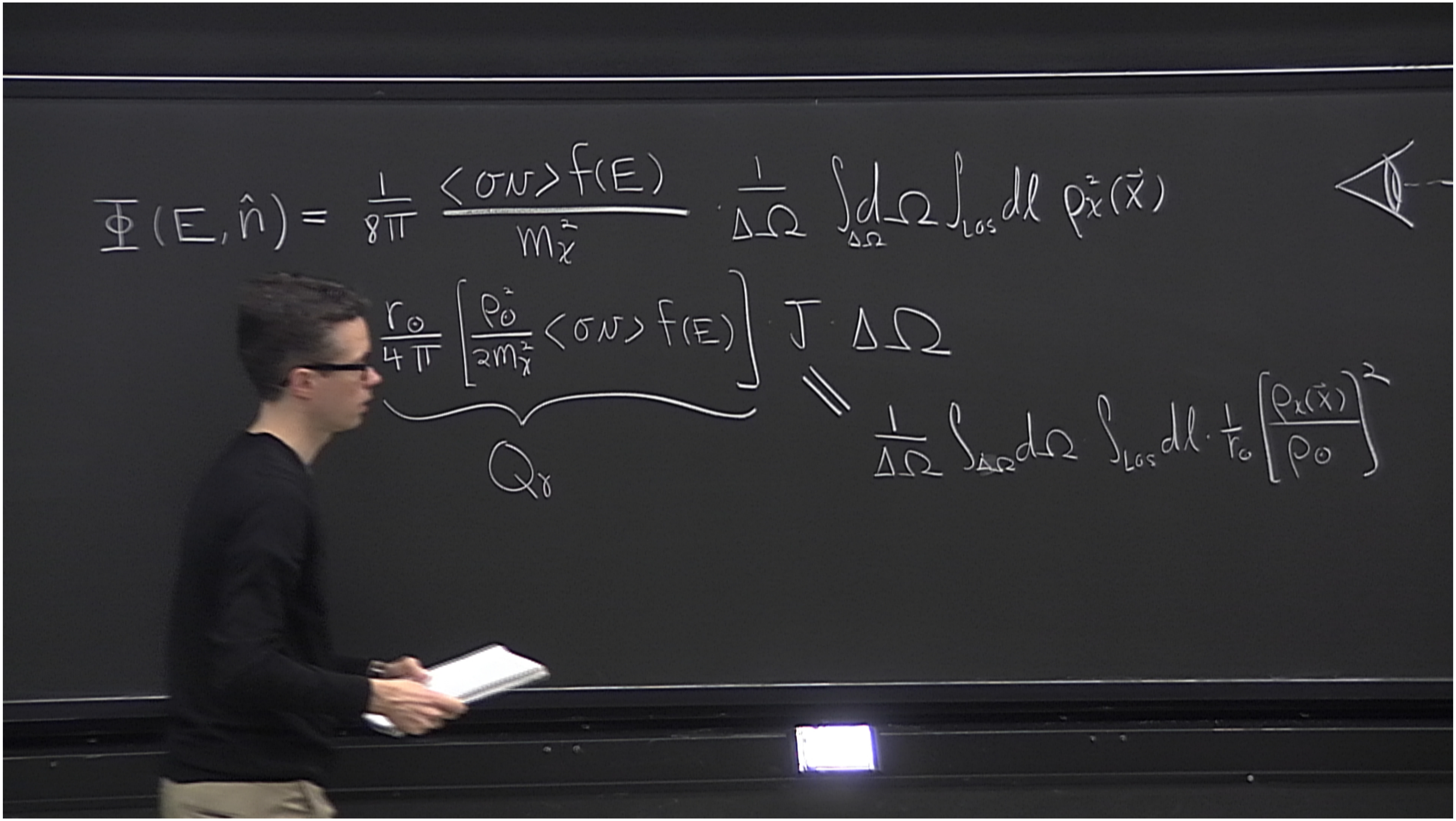
$\shortparallel$

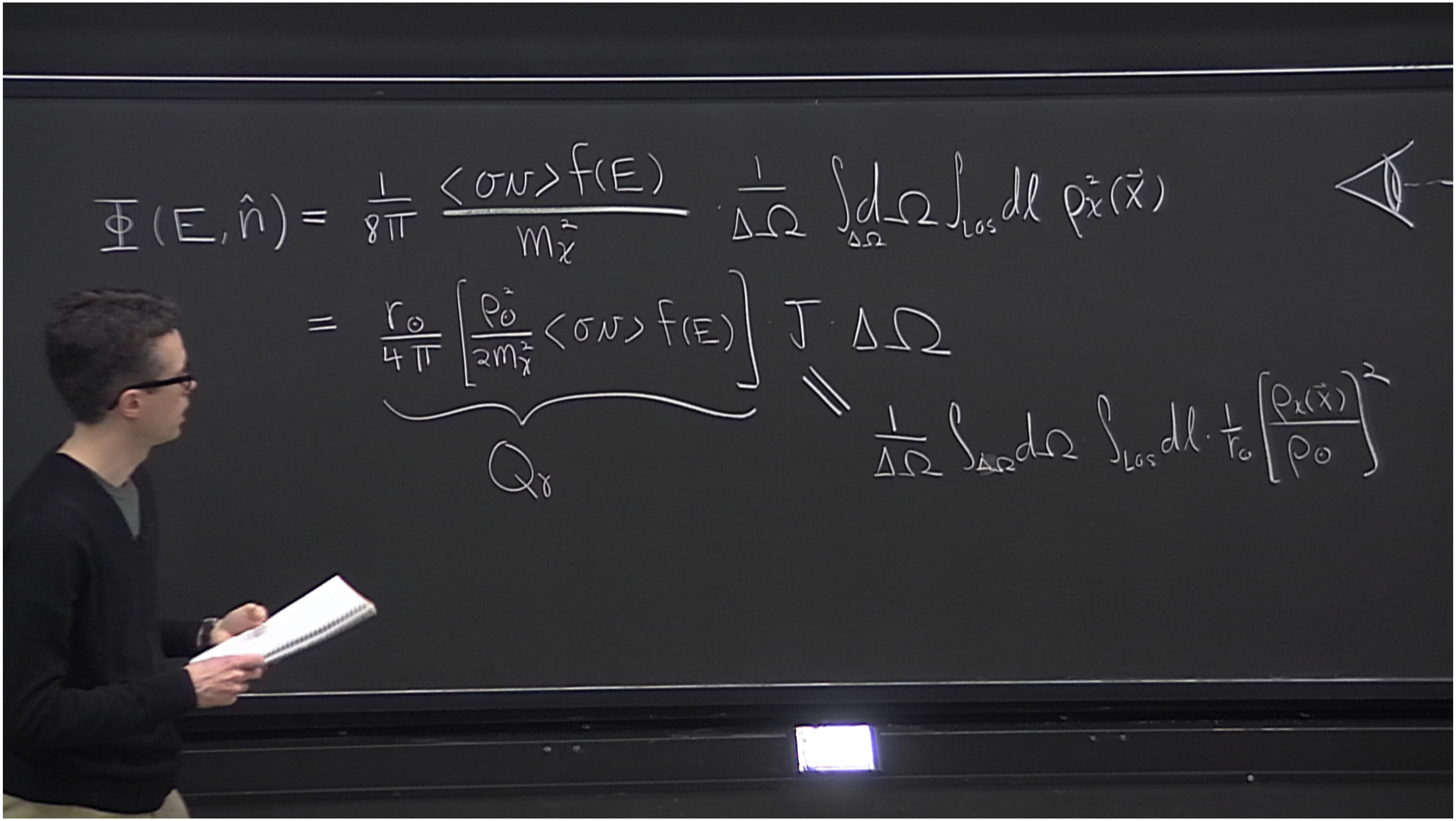
boost factor

$$\Phi(E, \hat{n}) = \frac{1}{8\pi} \frac{\langle \sigma v \rangle f(E)}{m_\chi^2}$$


$\Phi(E,\hat{n}) = \frac{1}{8\pi}\frac{\langle \sigma v\rangle f(E)}{m_\chi^2} \cdot \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl\, \rho_\chi^2(\vec{x})$


$\Phi(E,\hat{n}) = \frac{1}{8\pi}\frac{\langle\sigma v\rangle f(E)}{m_\chi^2}\cdot\frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega\int_{LOS} dl\,\rho_\chi^2(\vec{x})$
$= \underbrace{\frac{r_\odot}{4\pi}\left[\frac{\rho_\odot^2}{2m_\chi^2}\langle\sigma v\rangle f(E)\right]}_{Q_\gamma}\cdot J\cdot\Delta\Omega$

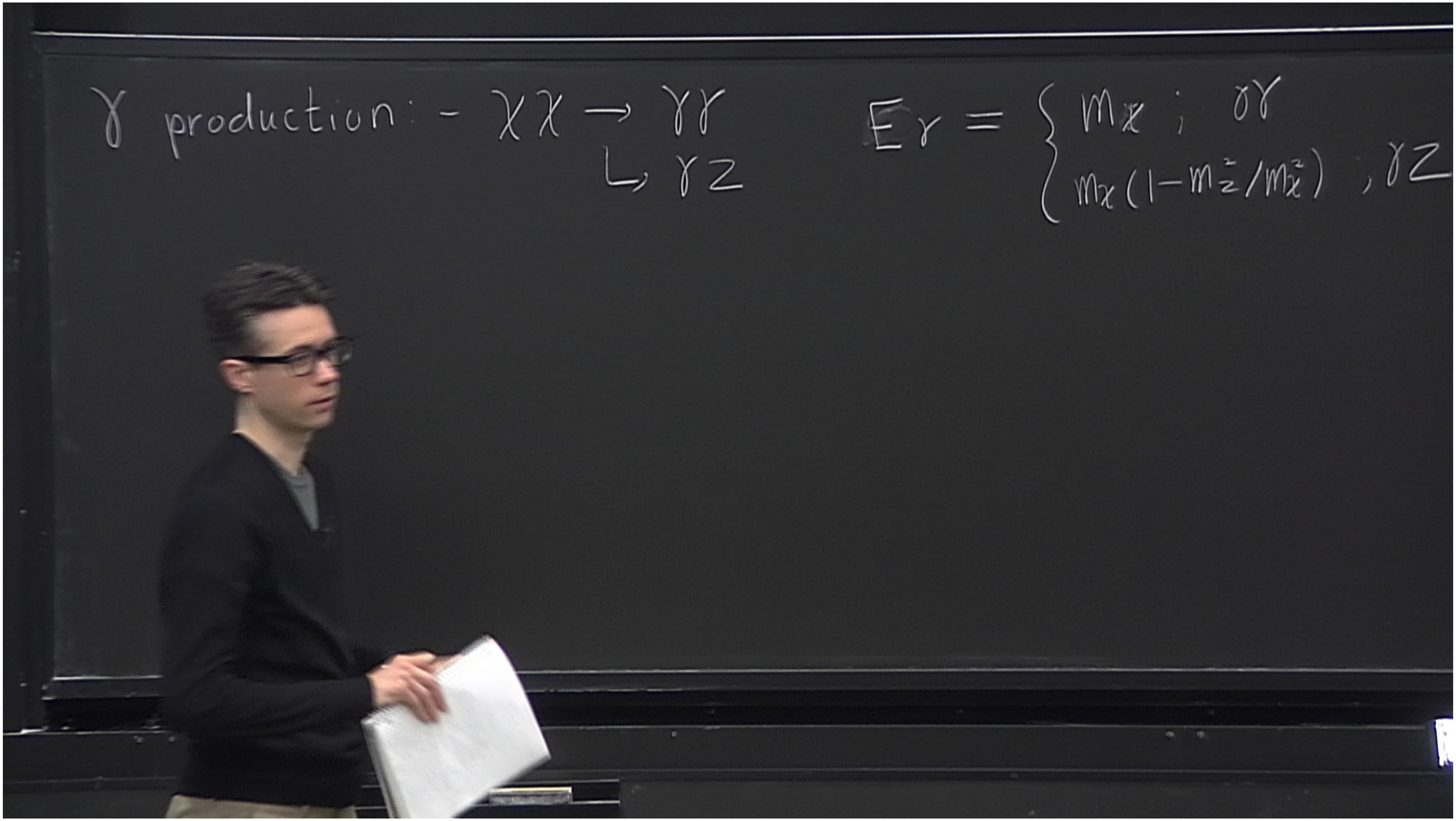

$\Phi(E,\hat{n}) = \frac{1}{8\pi}\frac{\langle\sigma v\rangle f(E)}{m_\chi^2}\cdot\frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl\, \rho_\chi^2(\vec{x})$
$\underbrace{\frac{r_\odot}{4\pi}\left[\frac{\rho_\odot^2}{2m_\chi^2}\langle\sigma v\rangle f(E)\right]}_{Q_\gamma} \cdot J \cdot \Delta\Omega$
$J = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl \cdot \frac{1}{r_\odot}\left[\frac{\rho_\chi(\vec{x})}{\rho_\odot}\right]^2$

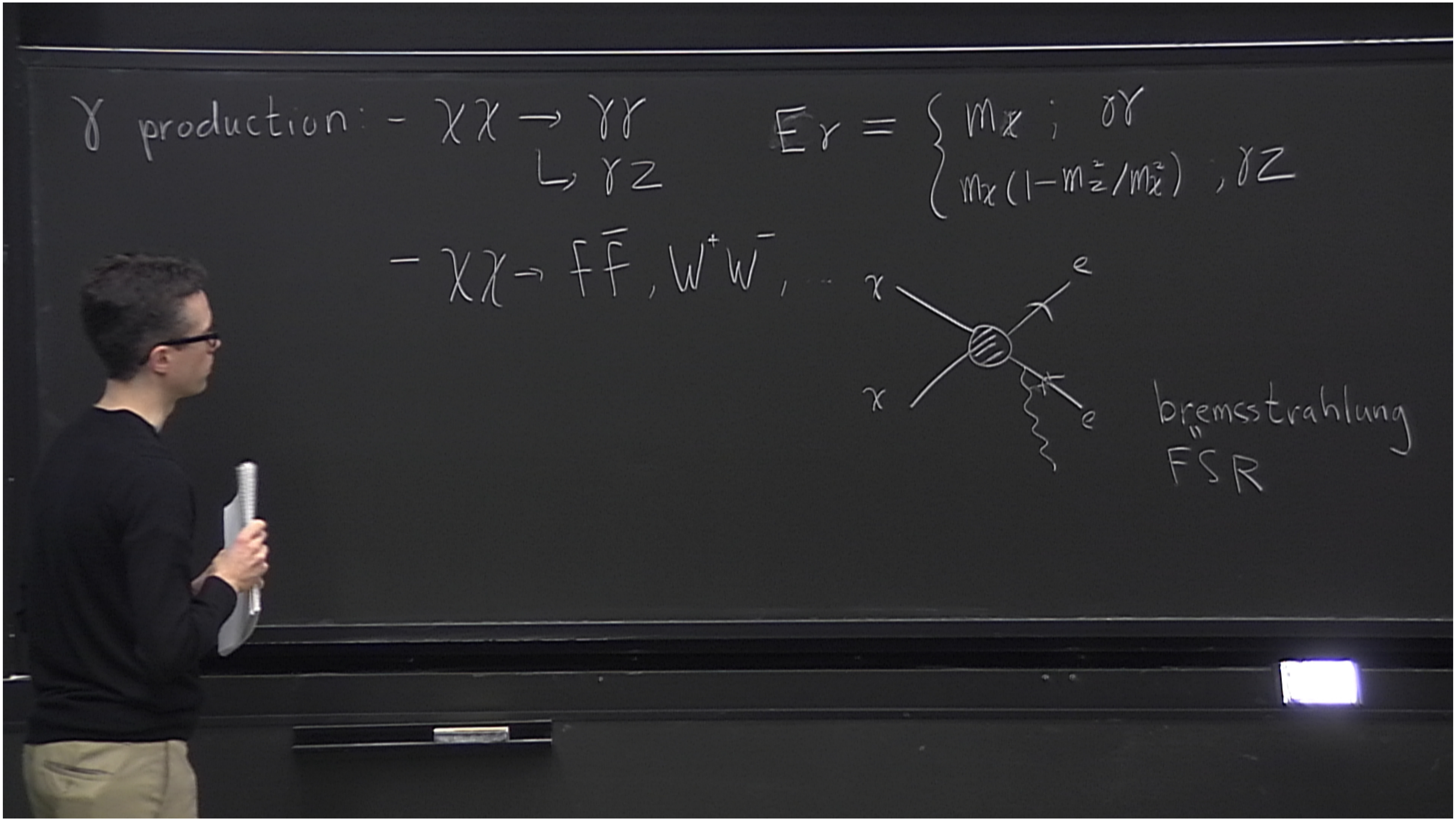

$\Phi(E,\hat{n}) = \frac{1}{8\pi} \frac{\langle \sigma v \rangle f(E)}{m_\chi^2} \cdot \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{LOS} dl\, \rho_\chi^2(\vec{x})$
$= \underbrace{\frac{r_\odot}{4\pi} \left[\frac{\rho_\odot^2}{2m_\chi^2} \langle \sigma v \rangle f(E) \right]}_{Q_\gamma} \cdot J \cdot \Delta\Omega$
$J = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{LOS} dl \cdot \frac{1}{r_\odot} \left[\frac{\rho_\chi(\vec{x})}{\rho_\odot} \right]^2$

$$\Phi(E,\hat{n}) = \frac{1}{8\pi}\frac{\langle \sigma v\rangle f(E)}{m_\chi^2}\cdot\frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl\, \rho_\chi^2(\vec{x})$$

$$= \underbrace{\frac{r_\odot}{4\pi}\left[\frac{\rho_\odot^2}{2m_\chi^2}\langle \sigma v\rangle f(E)\right]}_{Q_\gamma} \cdot J \cdot \Delta\Omega$$

$$J = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_{LOS} dl \cdot \frac{1}{r_\odot}\left[\frac{\rho_\chi(\vec{x})}{\rho_\odot}\right]^2$$


γ production: - $\chi\chi \to \gamma\gamma$
$\hookrightarrow \gamma Z$
$E_\gamma = \begin{cases} m_\chi \; ; & \gamma\gamma \\ m_\chi(1 - m_Z^2/m_\chi^2) \; ; & \gamma Z \end{cases}$


γ production: - $\chi\chi \to \gamma\gamma$
$\hookrightarrow \gamma Z$
$E_\gamma = \begin{cases} m_\chi \ ; \ \gamma\gamma \\ m_\chi(1 - m_Z^2/m_\chi^2) \ ; \gamma Z \end{cases}$
- $\chi\chi \to f\bar{f}, W^+W^-, \ldots$
χ
χ
e
e
bremsstrahlung
"
FSR

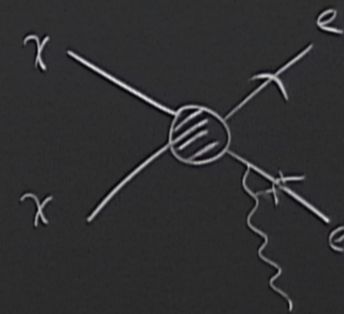
γ production: $- \; \chi\chi \to \gamma\gamma$

$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \gamma Z$

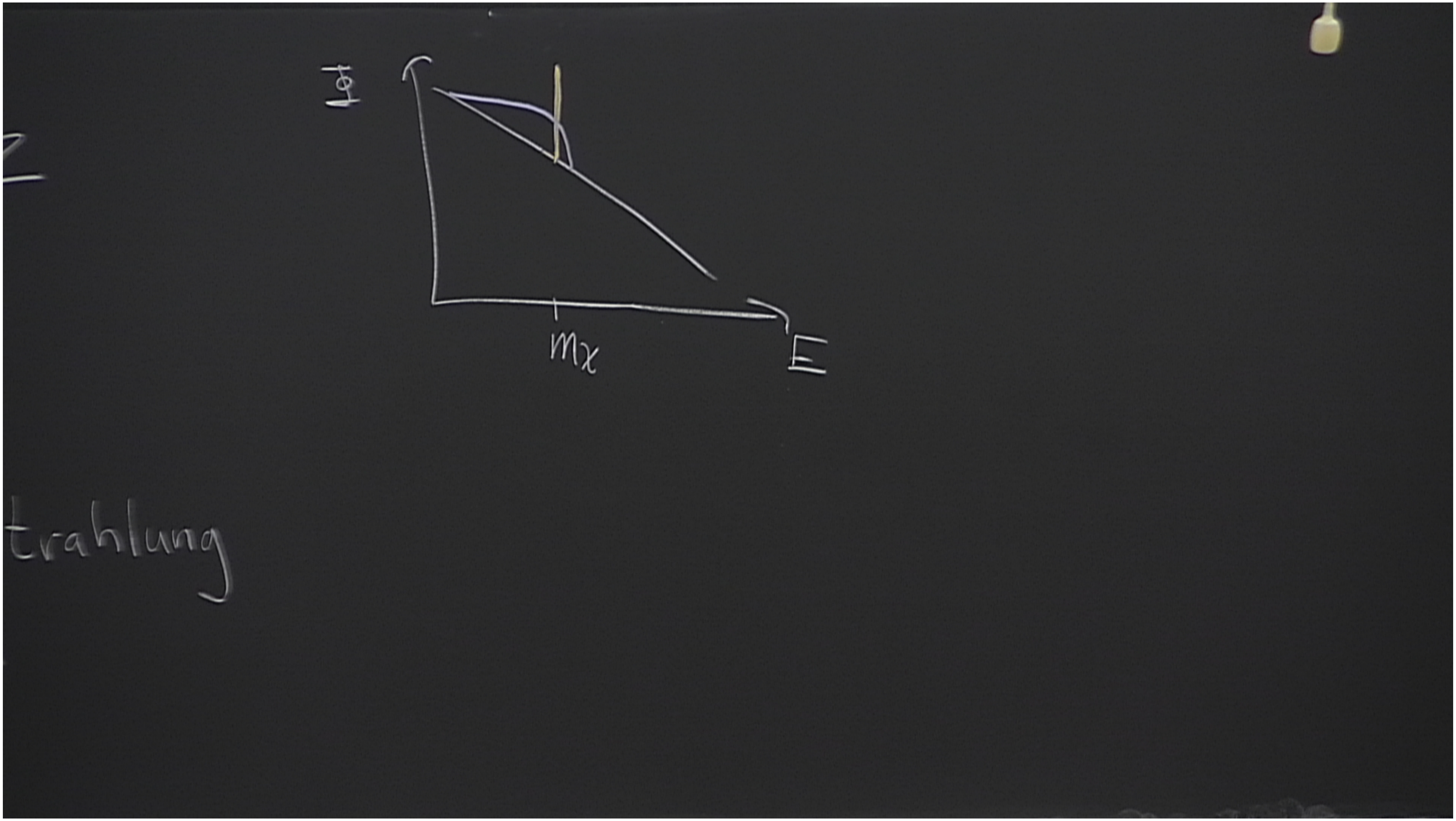
$$E_\gamma = \begin{cases} m_\chi \; ; & \gamma\gamma \\ m_\chi (1 - m_Z^2/m_\chi^2) \; ; & \gamma Z \end{cases}$$

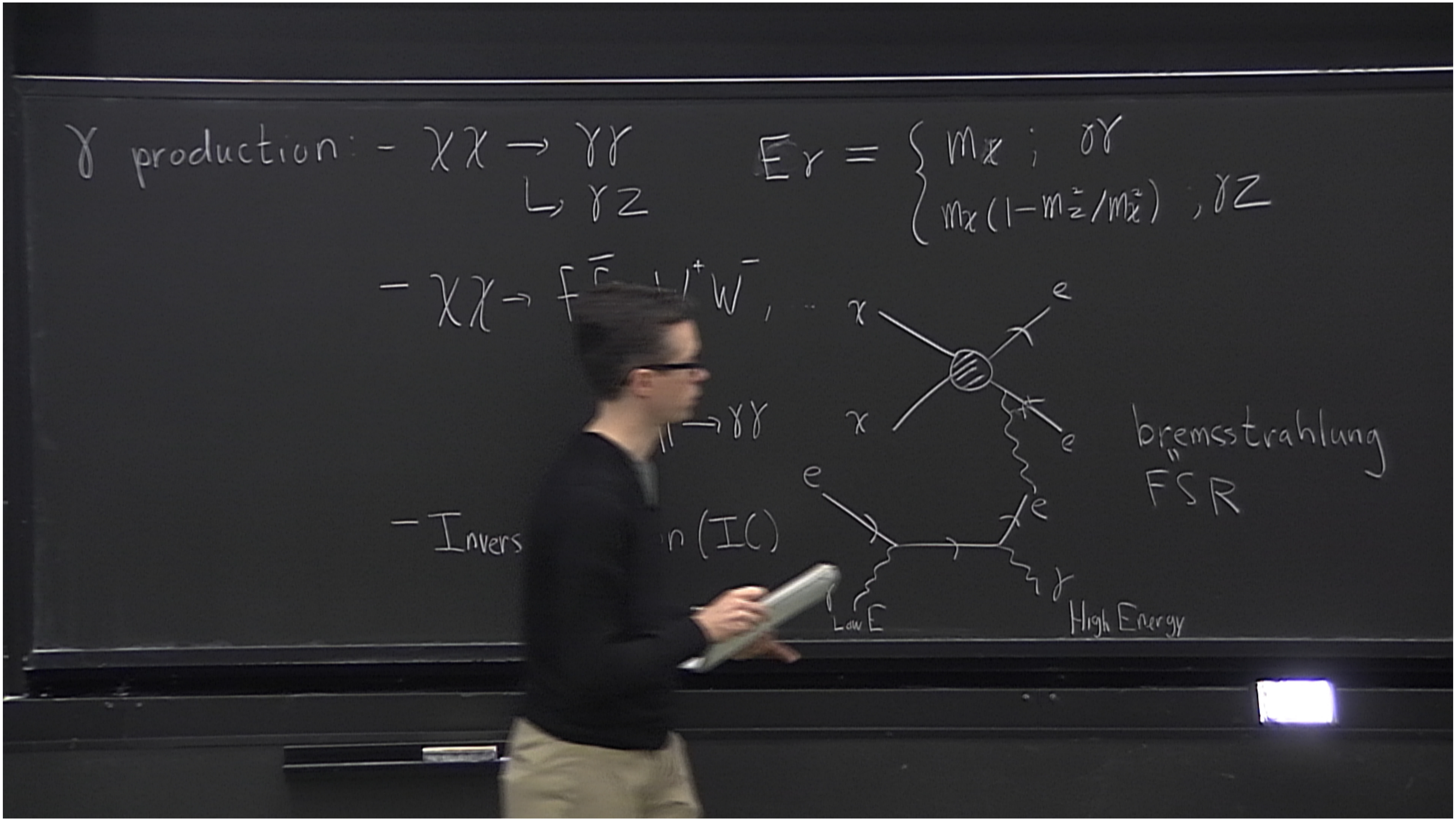
$- \; \chi\chi \to f\bar{f}, W^+W^-, \ldots$

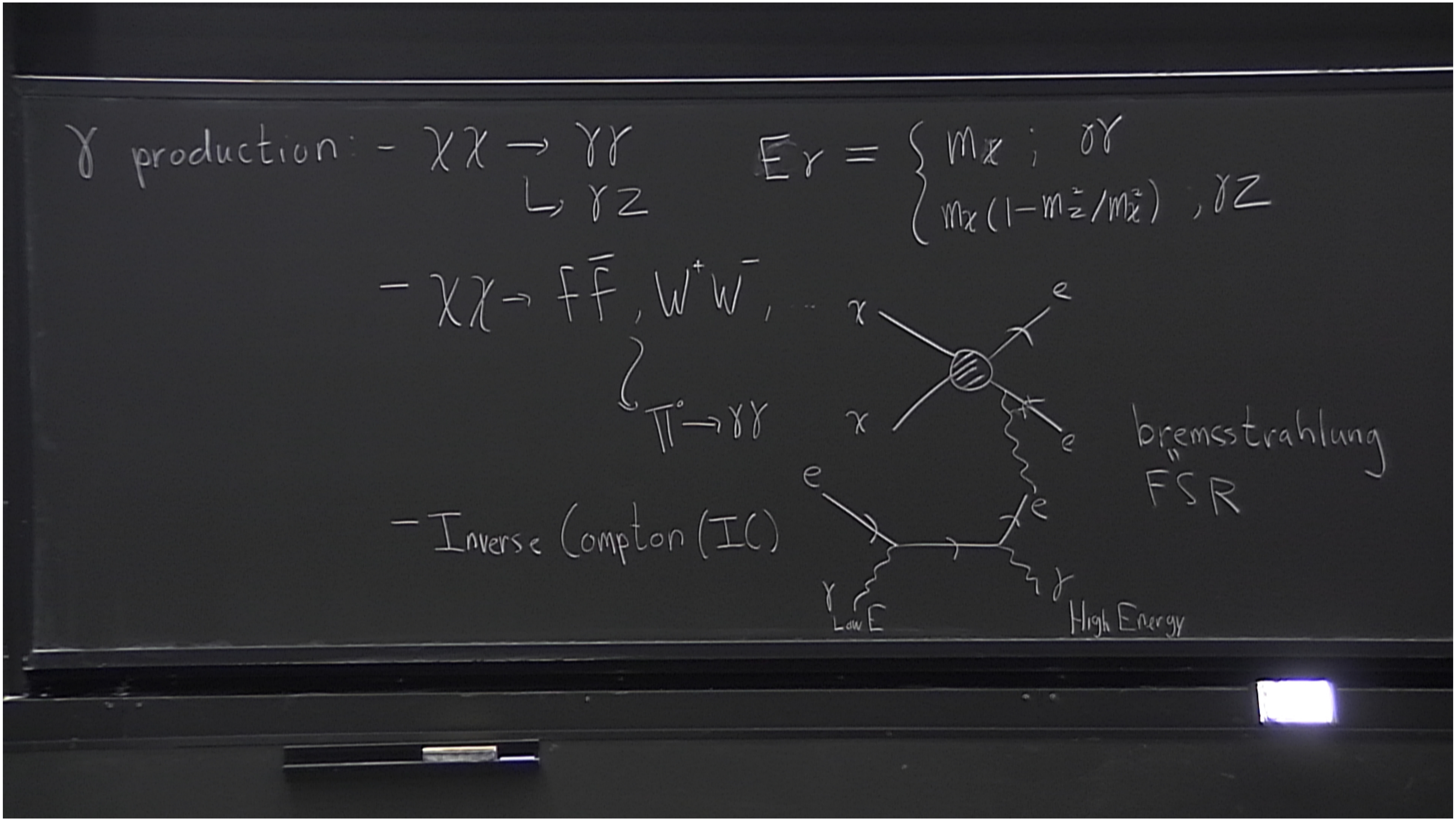
$\quad \hookrightarrow \pi^0 \to \gamma\gamma$

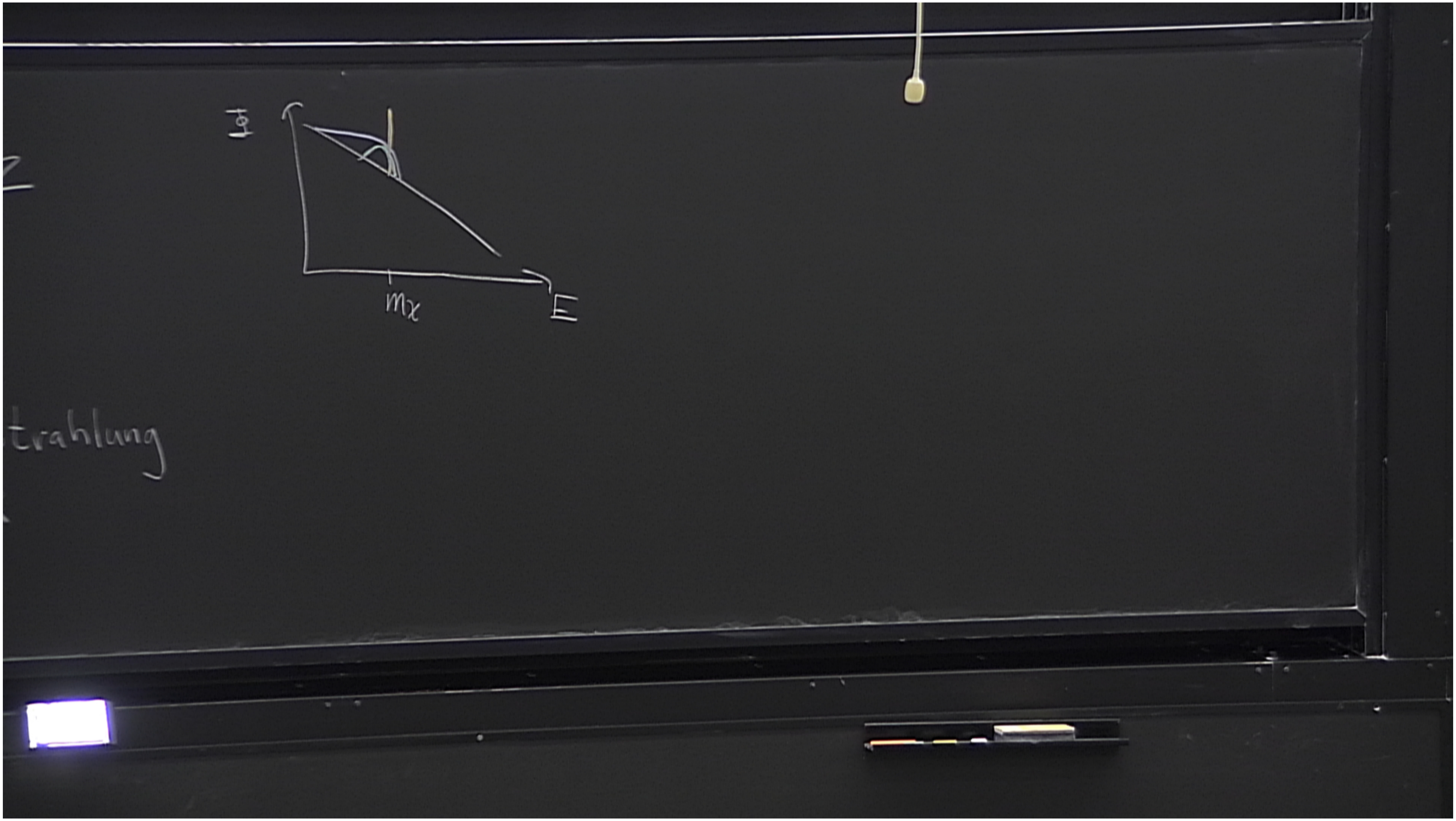


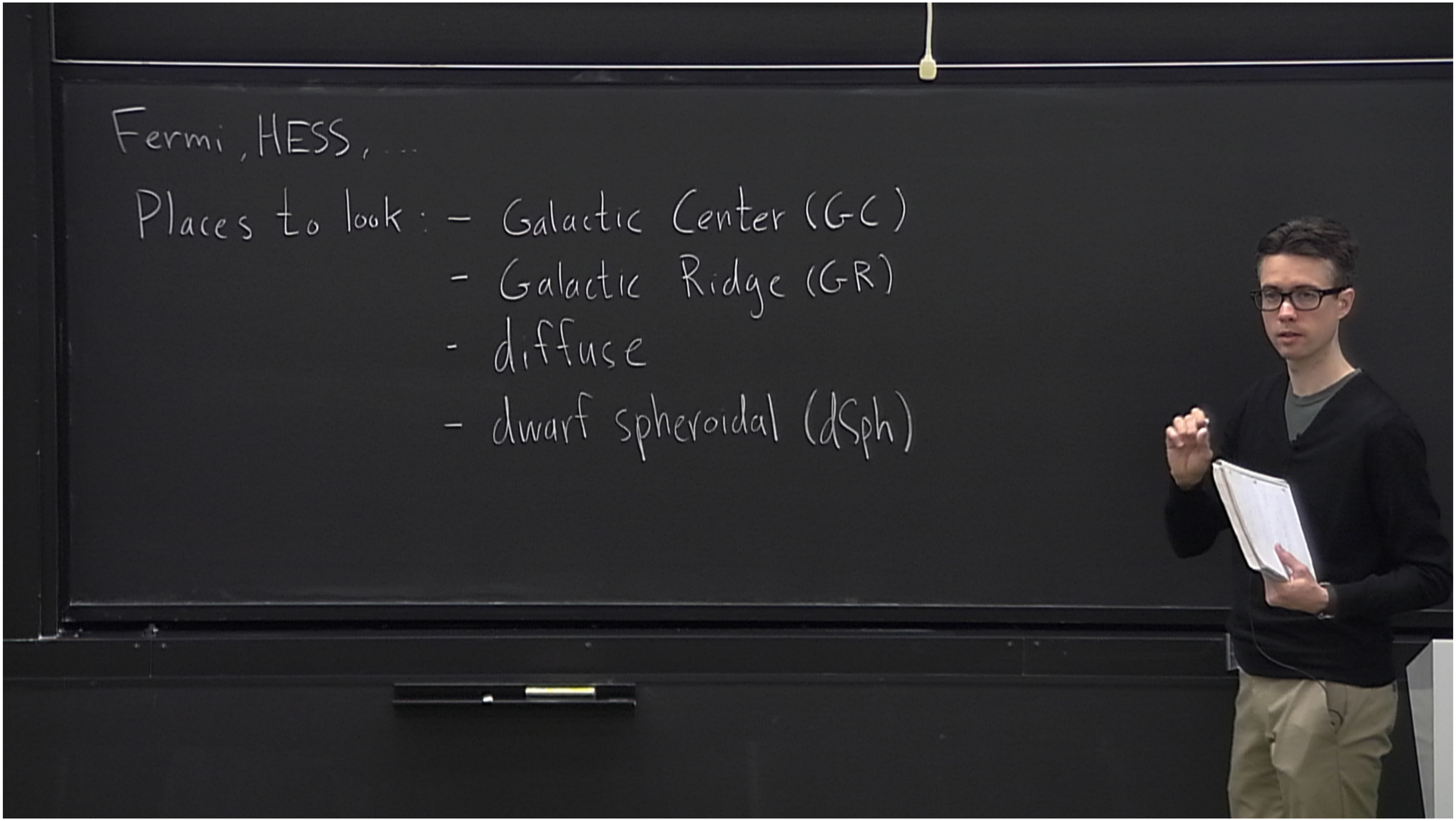
bremsstrahlung
"FSR"

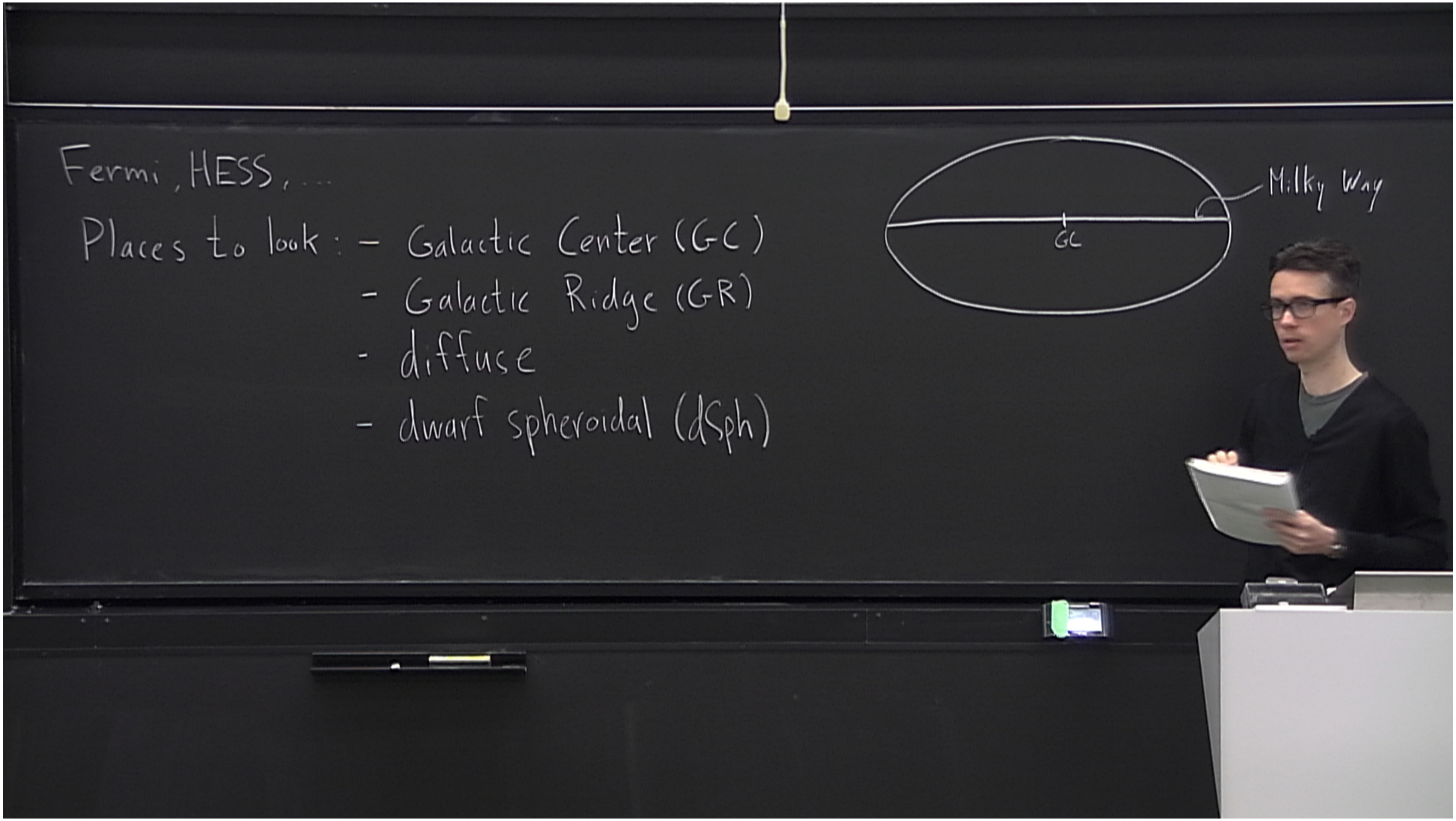

Φ
mχ
E
trahlung

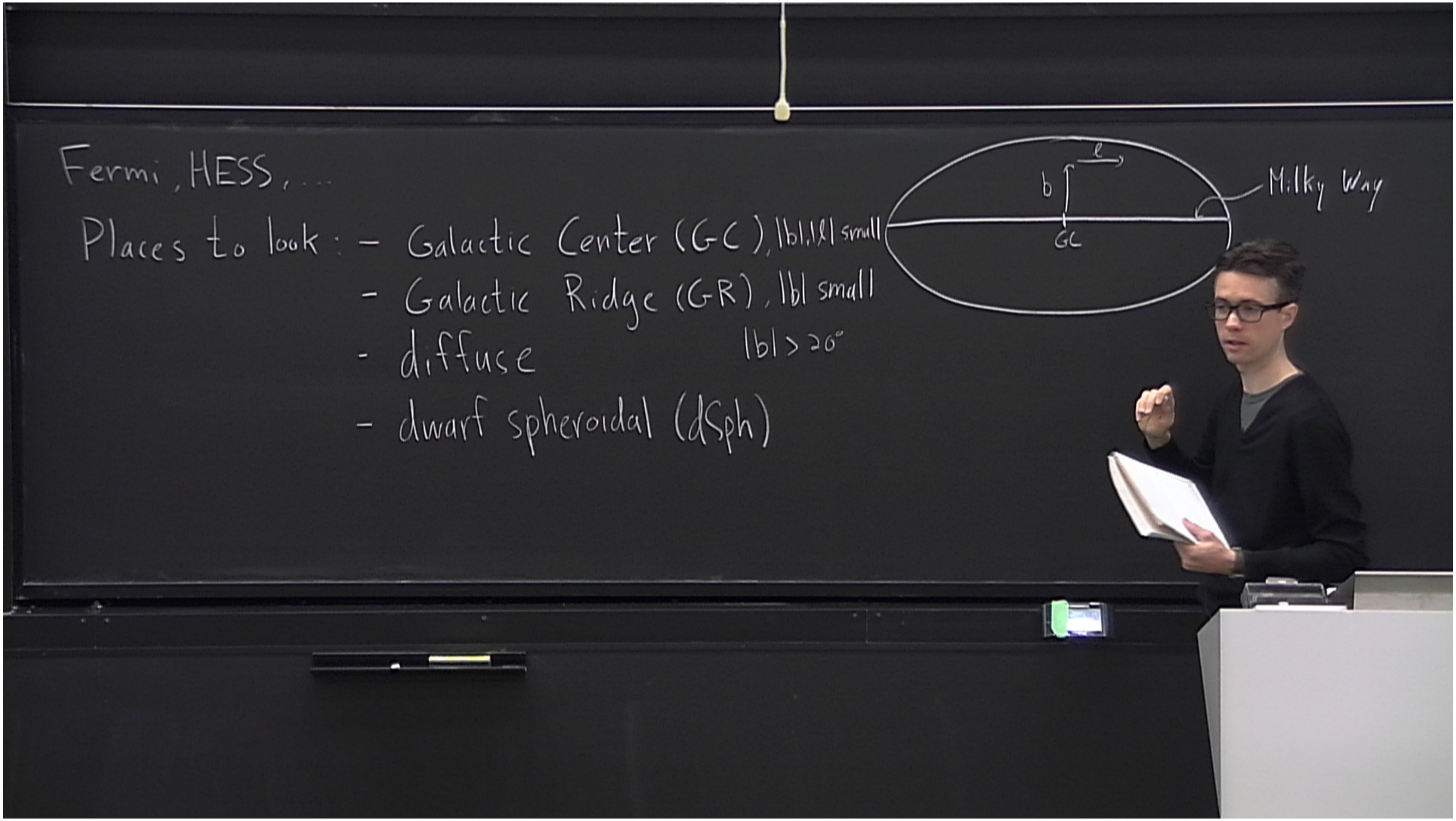

γ production: - χχ → γγ
↳ γZ
Eγ = mχ ; γγ
mχ(1 − mZ²/mχ²) ; γZ
- χχ →
χ
χ
e
e
bremsstrahlung
"
FSR
e
e
- Invers
n (IC)
γ
γ
Low E
High Energy

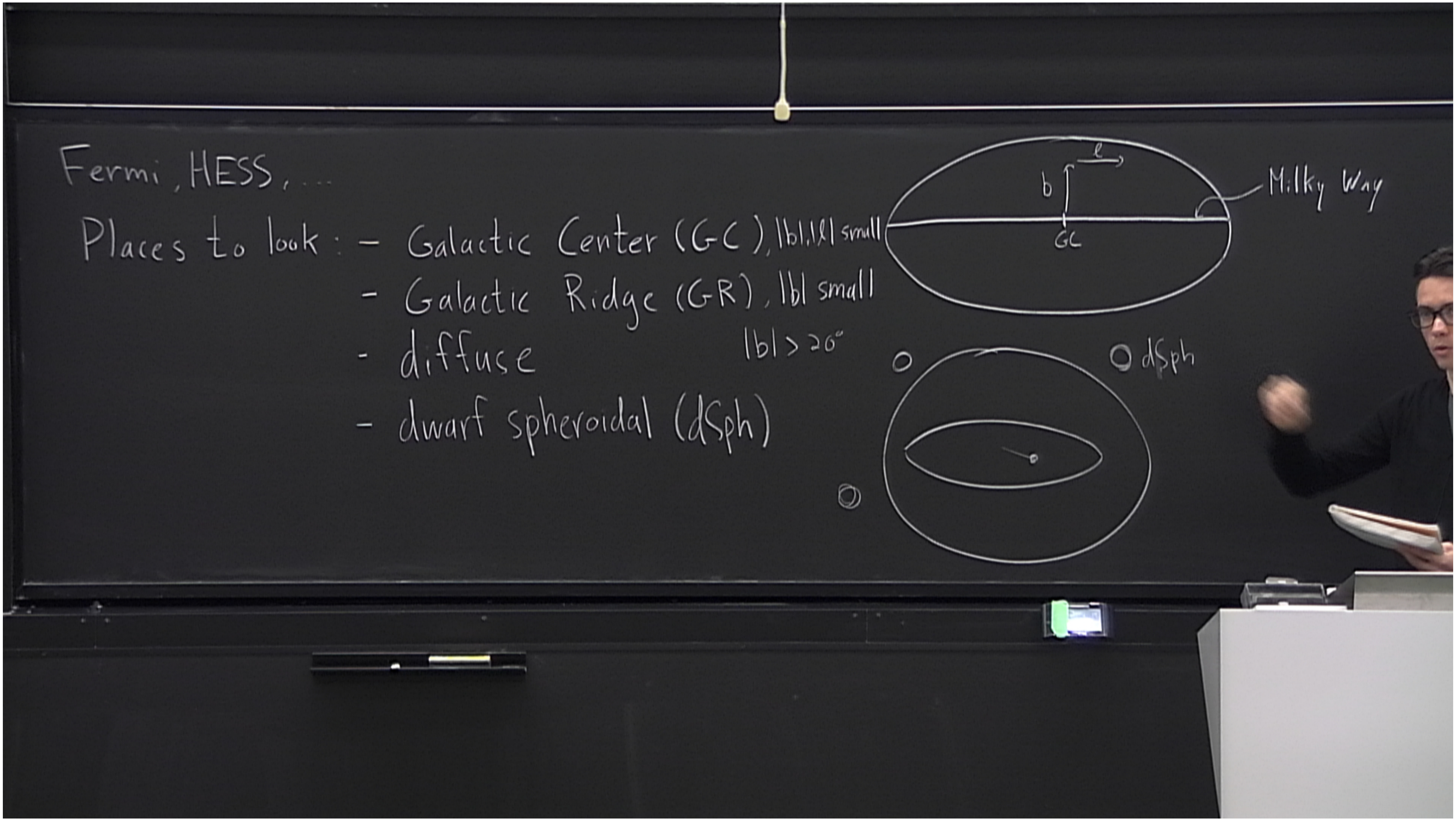

γ production: - $\chi\chi \to \gamma\gamma$
$\hookrightarrow \gamma Z$
$E_\gamma = \begin{cases} m_\chi ; & \gamma\gamma \\ m_\chi(1 - m_Z^2/m_\chi^2) ; & \gamma Z \end{cases}$
- $\chi\chi \to f\bar{f}, W^+W^-, \ldots$
$\pi^0 \to \gamma\gamma$
χ
χ
e
e
bremsstrahlung
"
FSR
- Inverse Compton (IC)
e
e
γ
Low E
γ
High Energy

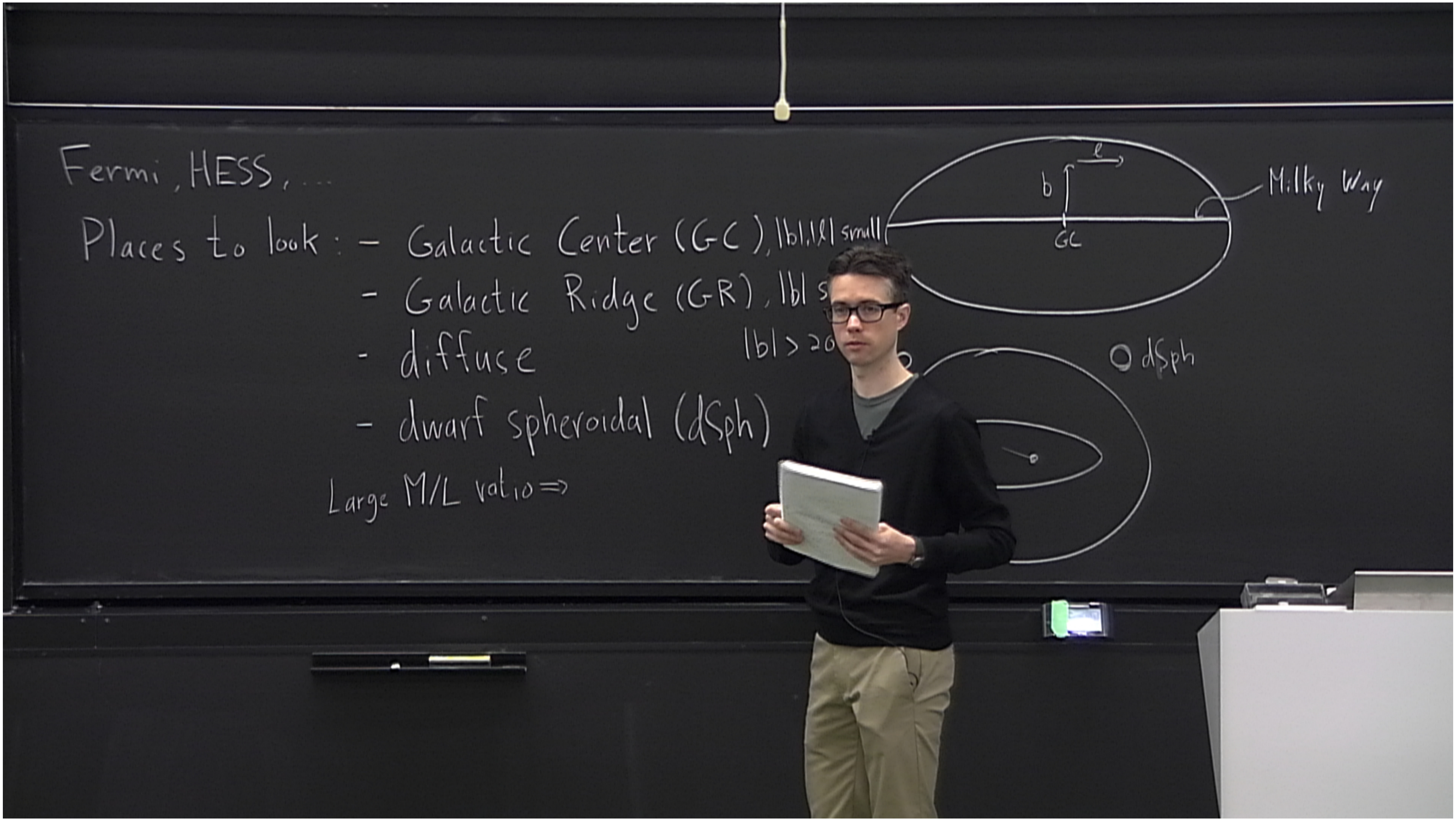

mχ
E
trahlung

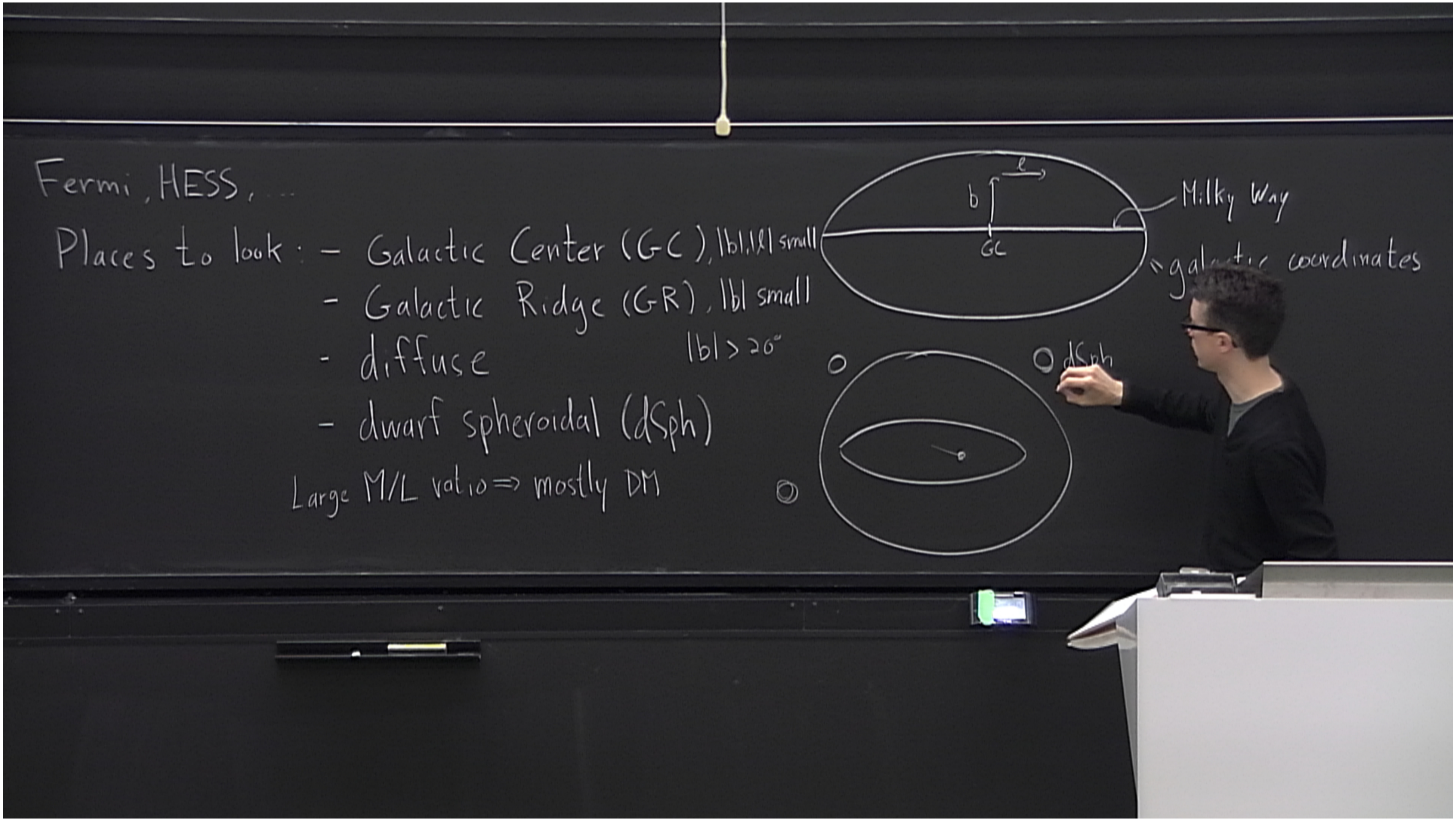

Fermi, HESS, ...
Places to look: - Galactic Center (GC)
- Galactic Ridge (GR)
- diffuse
- dwarf spheroidal (dSph)

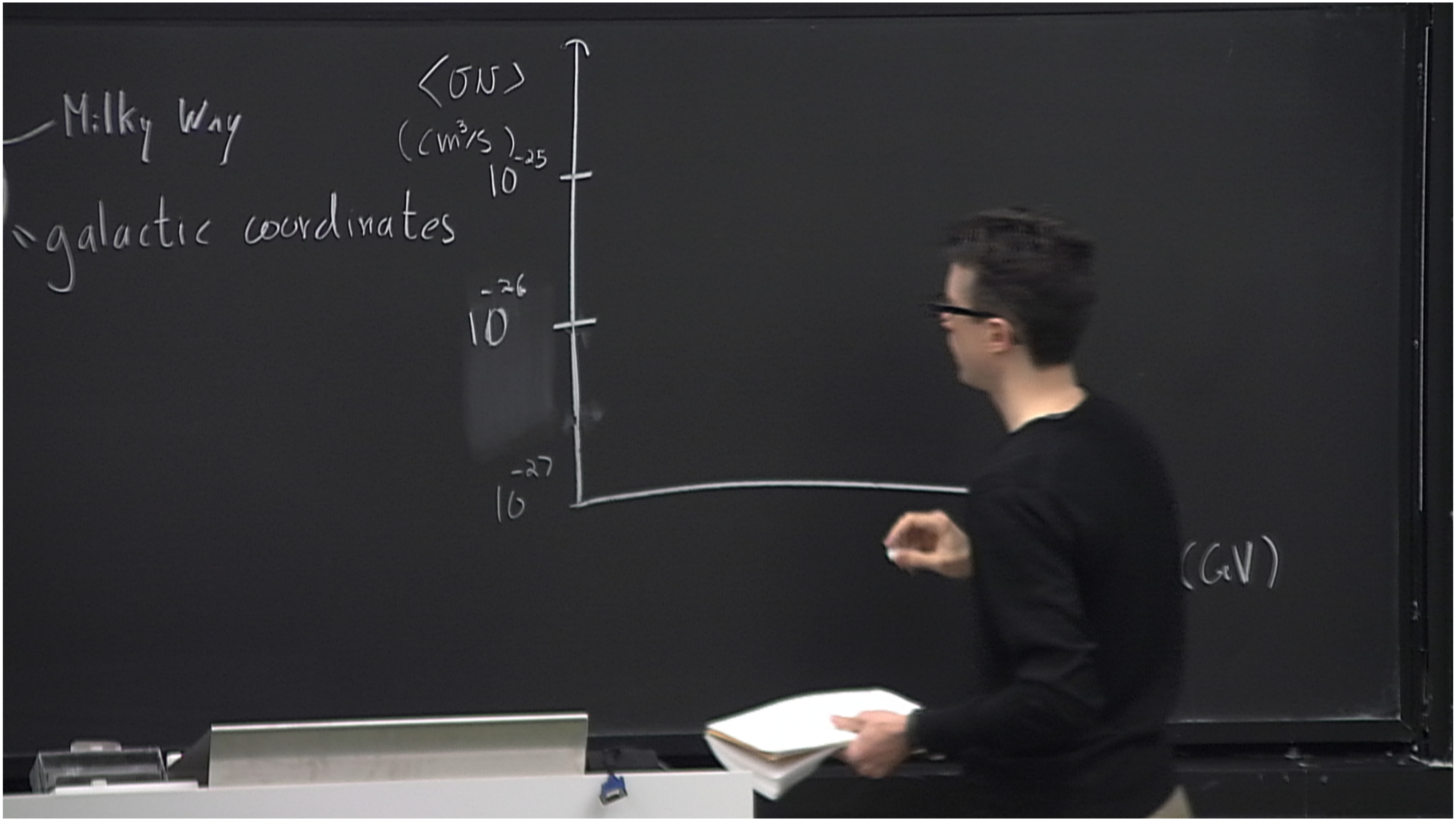

Fermi, HESS, ...
Places to look: - Galactic Center (GC)
- Galactic Ridge (GR)
- diffuse
- dwarf spheroidal (dSph)
Milky Way
GC

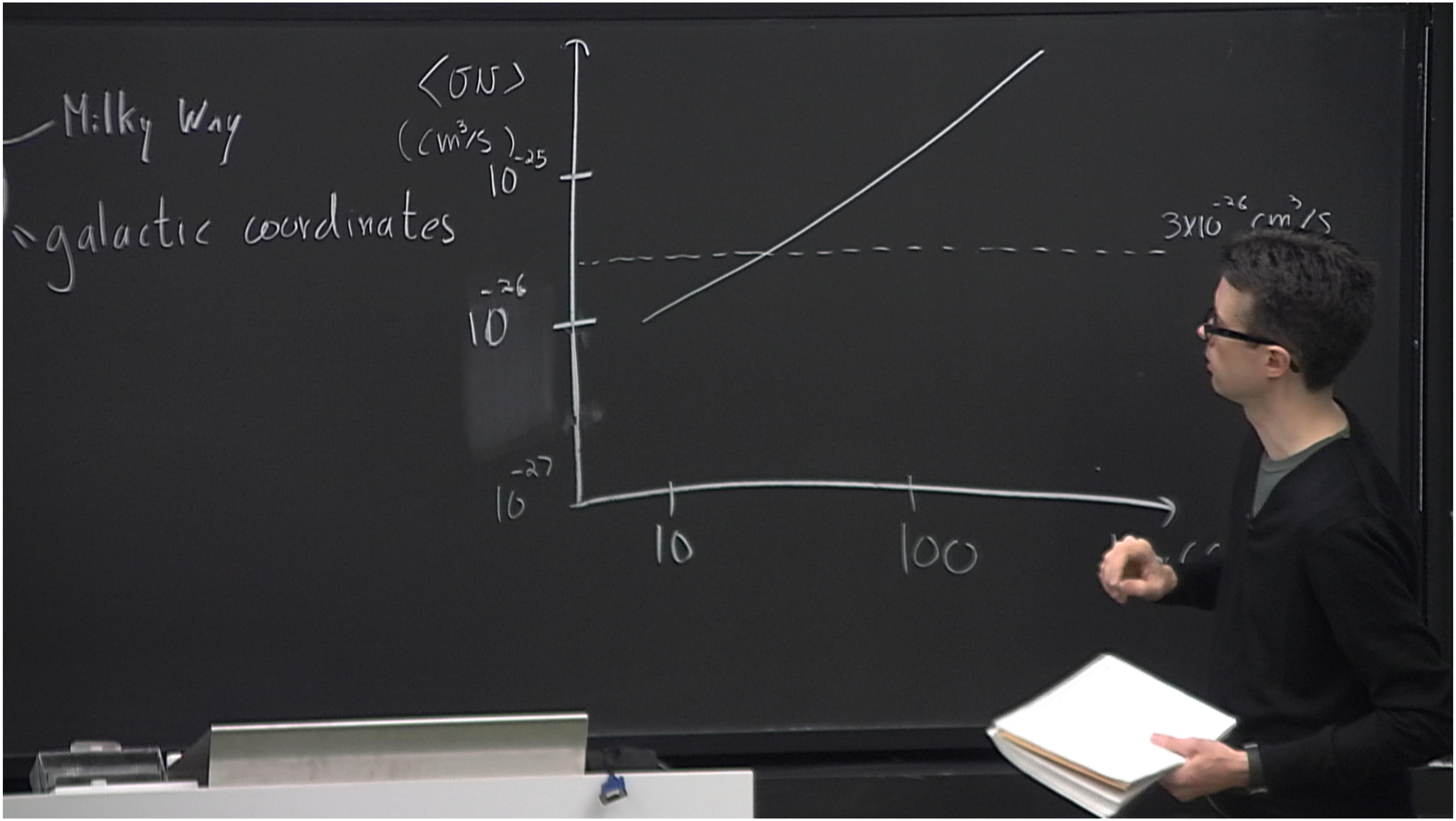

Fermi, HESS, ...
Places to look: - Galactic Center (GC), |b|,|ℓ| small
- Galactic Ridge (GR), |b| small
- diffuse |b| > 20°
- dwarf spheroidal (dSph)
ℓ
b
GC
Milky Way


Fermi, HESS, ...
Places to look: - Galactic Center (GC), |b|,|ℓ| small
- Galactic Ridge (GR), |b| small
- diffuse
|b| > 20°
- dwarf spheroidal (dSph)
ℓ
b
GC
Milky Way
dSph


Fermi, HESS, ...
Places to look: - Galactic Center (GC), |b|,|ℓ| small
- Galactic Ridge (GR), |b|
- diffuse
|b| > 20
- dwarf spheroidal (dSph)
Large M/L ratio ⇒
Milky Way
b
ℓ
GC
dSph

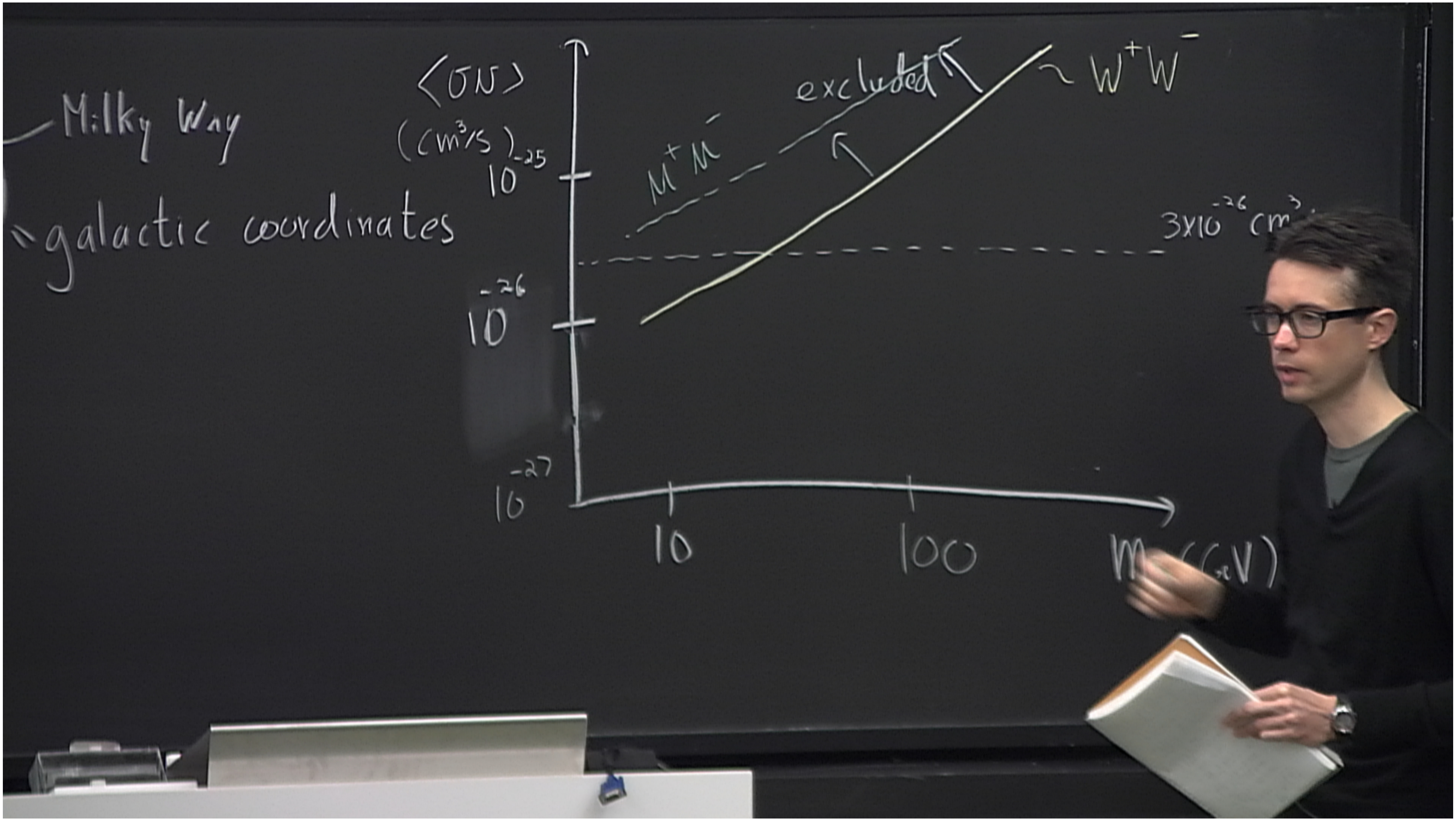

Fermi, HESS, ...
Places to look: - Galactic Center (GC), |b|,|ℓ| small
- Galactic Ridge (GR), |b| small
- diffuse
|b| > 20°
- dwarf spheroidal (dSph)
Large M/L ratio ⇒ mostly DM
ℓ
b
GC
Milky Way
coordinates
dSph

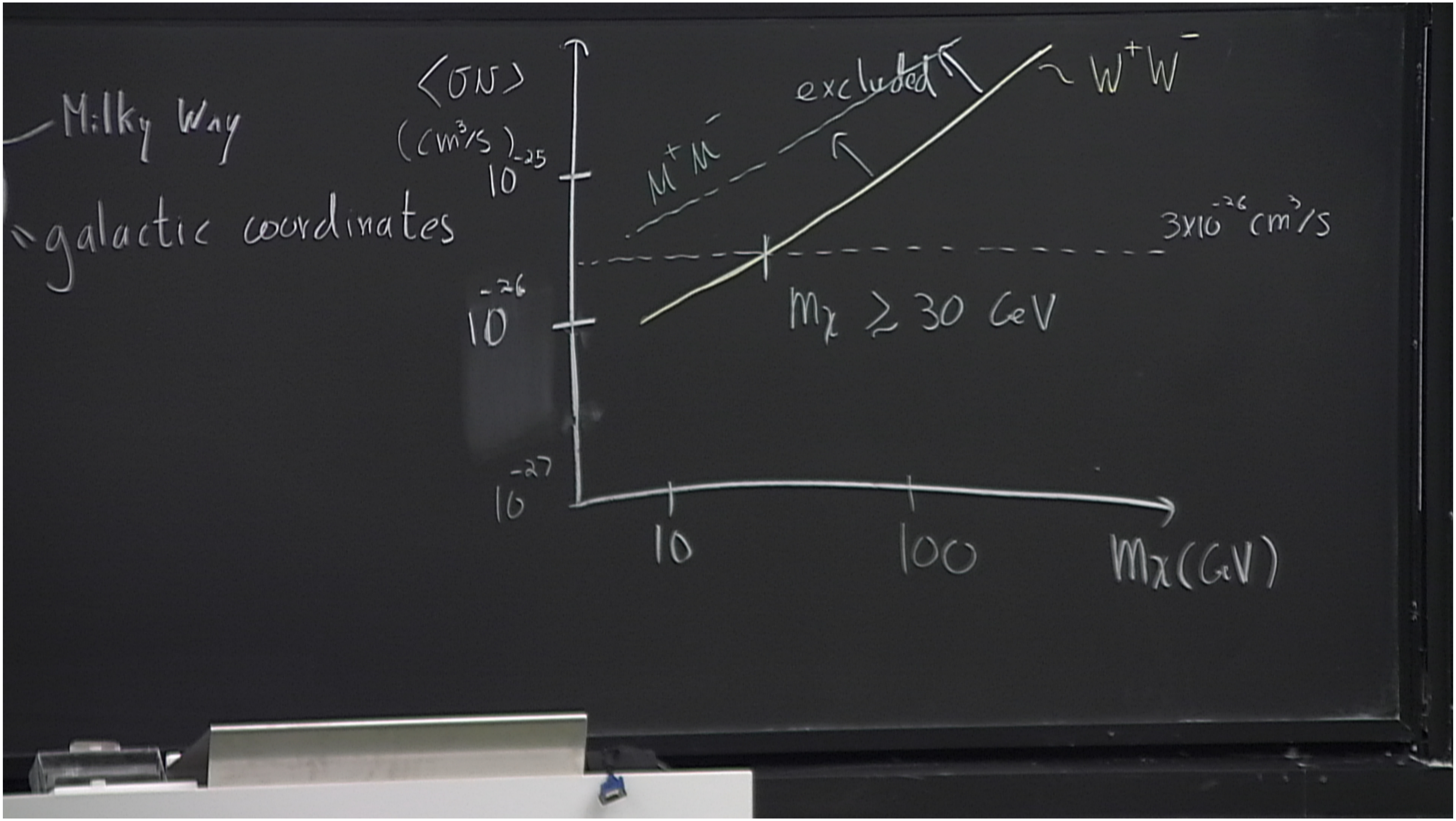

Milky Way
galactic coordinates
⟨σv⟩
(cm³/s)
10⁻²⁵
10⁻²⁶
10⁻²⁷
(GeV)

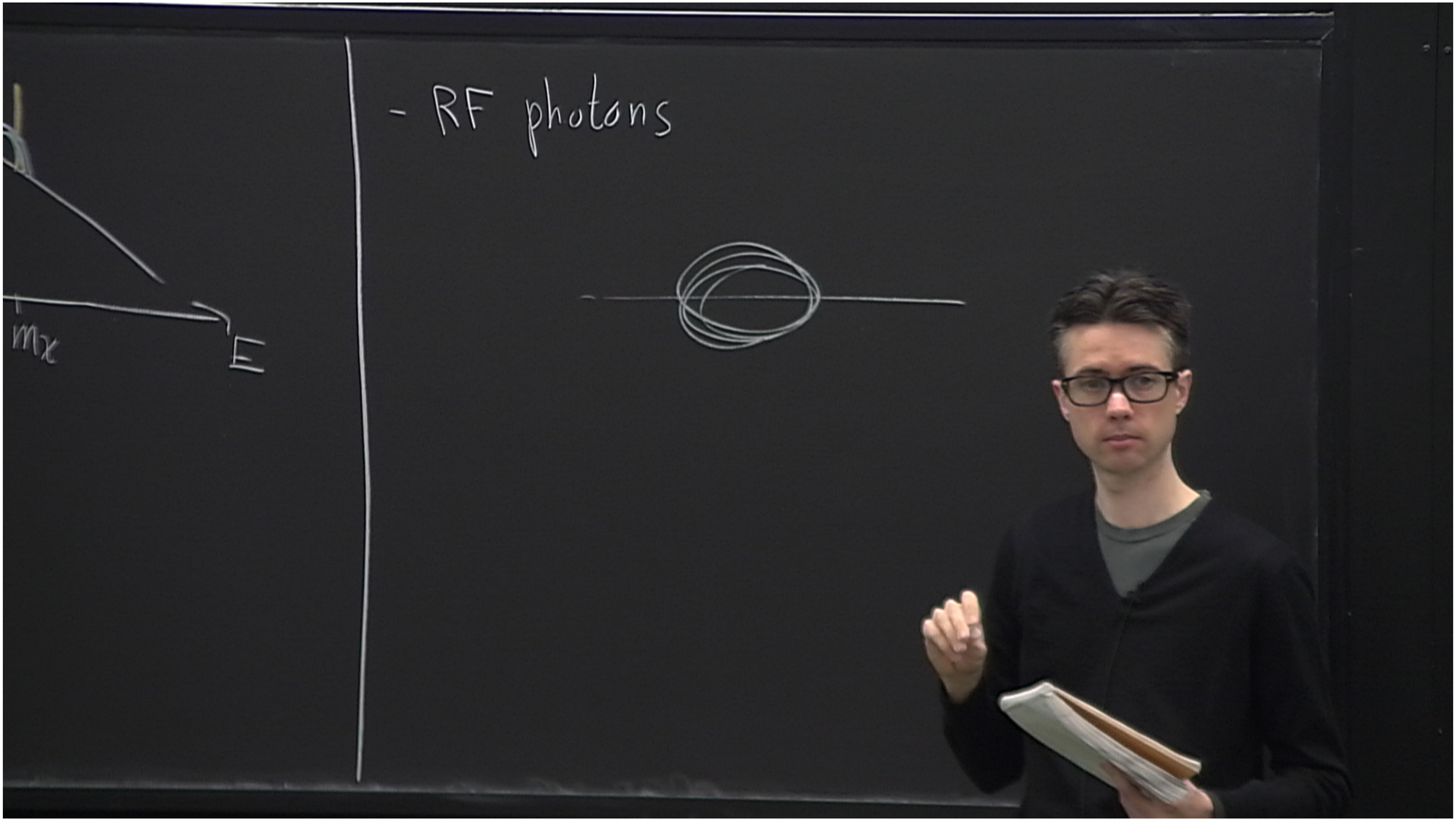


Milky Way
galactic coordinates
⟨σv⟩
(cm³/s)
10⁻²⁵
10⁻²⁶
10⁻²⁷
3x10⁻²⁶ cm³/s
10
100

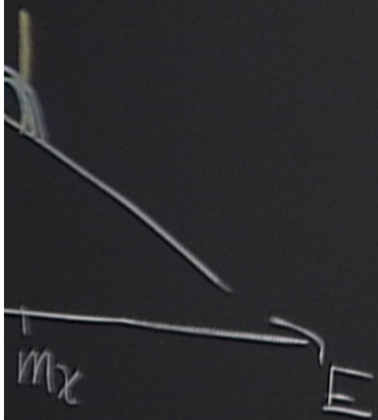
Milky Way
galactic coordinates
⟨σv⟩
(cm³/s)
10⁻²⁵
10⁻²⁶
10⁻²⁷
excluded
3x10⁻²⁶ cm³/s
10
100
mχ(GeV)


Milky Way
galactic coordinates
⟨σv⟩
(cm³/s)
10^{-25}
10^{-26}
10^{-27}
excluded
$\mu^+\mu^-$
W^+W^-
3×10^{-26} cm³
10
100

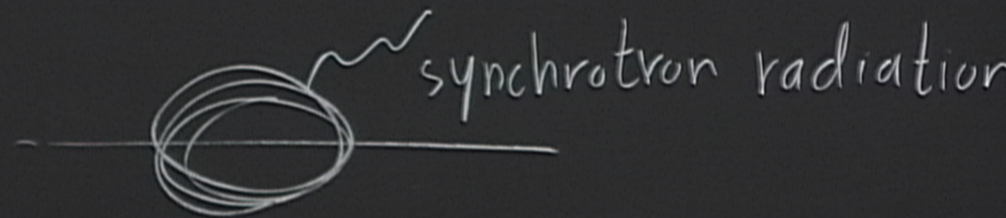

Milky Way
galactic coordinates
$\langle \sigma v \rangle$
(cm^3/s)
10^{-25}
10^{-26}
10^{-27}
excluded
$\sim W^+W^-$
$\mu^+\mu^-$
$3 \times 10^{-26}\ cm^3/s$
$m_\chi \gtrsim 30$ GeV
10
100
m_χ (GeV)

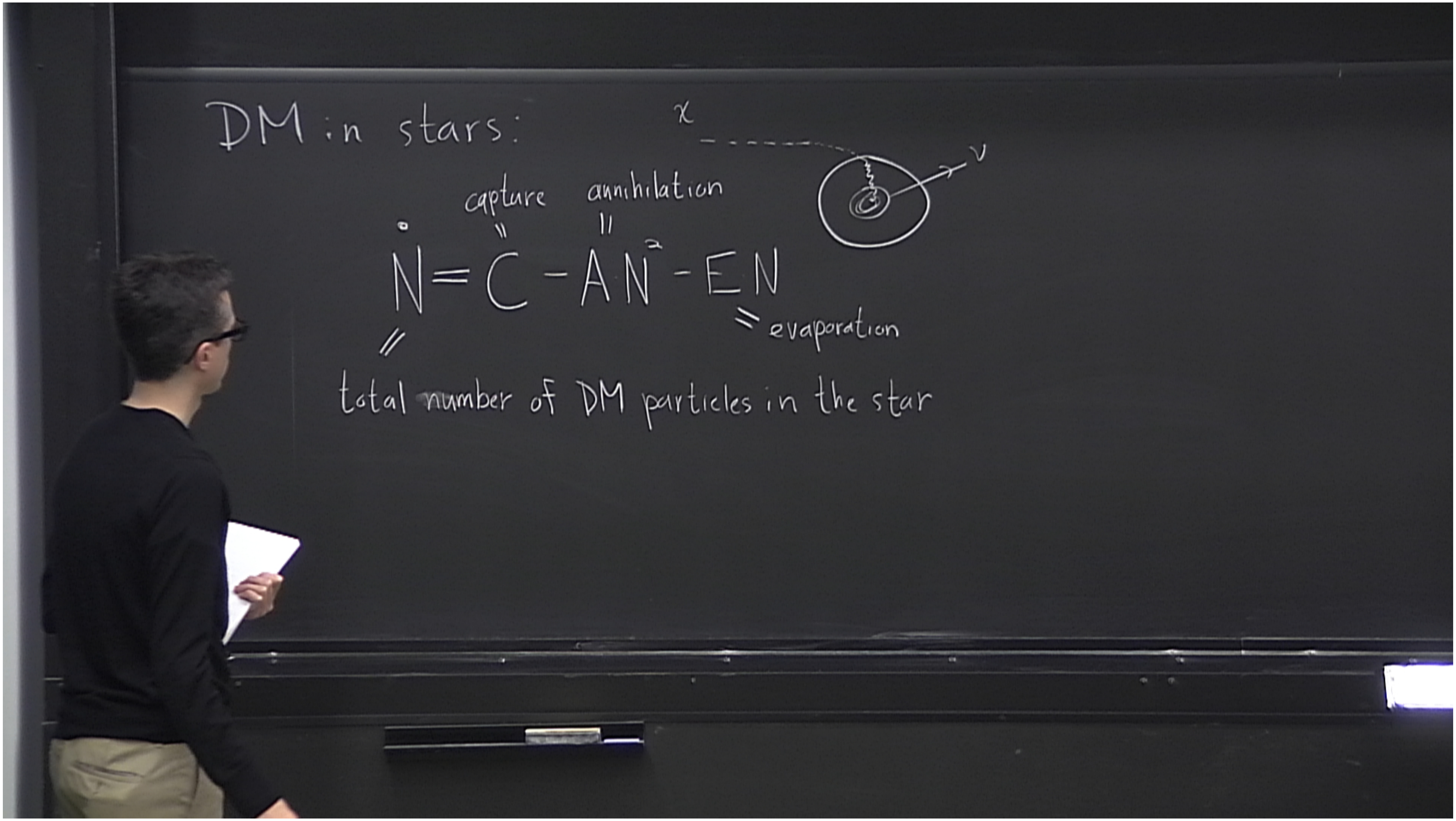


- RF photons
m_χ
E



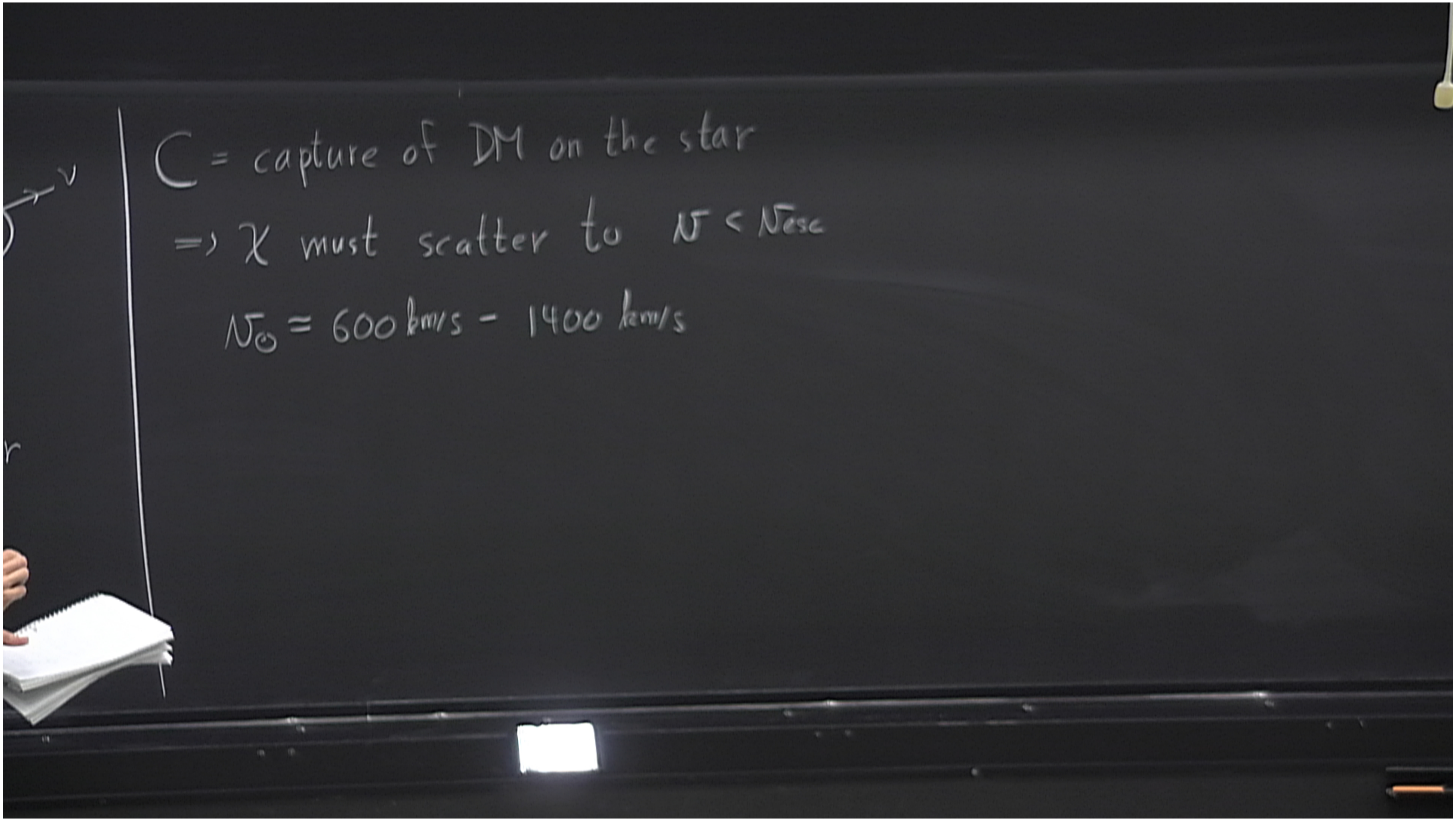
\- RF photons




DM in stars:
χ
ν
capture
annihilation
$\dot{N} = C - AN^2 - EN$
evaporation
total number of DM particles in the star

C = capture of DM on the star

$\Rightarrow \chi$ must scatter to $v < v_{esc}$

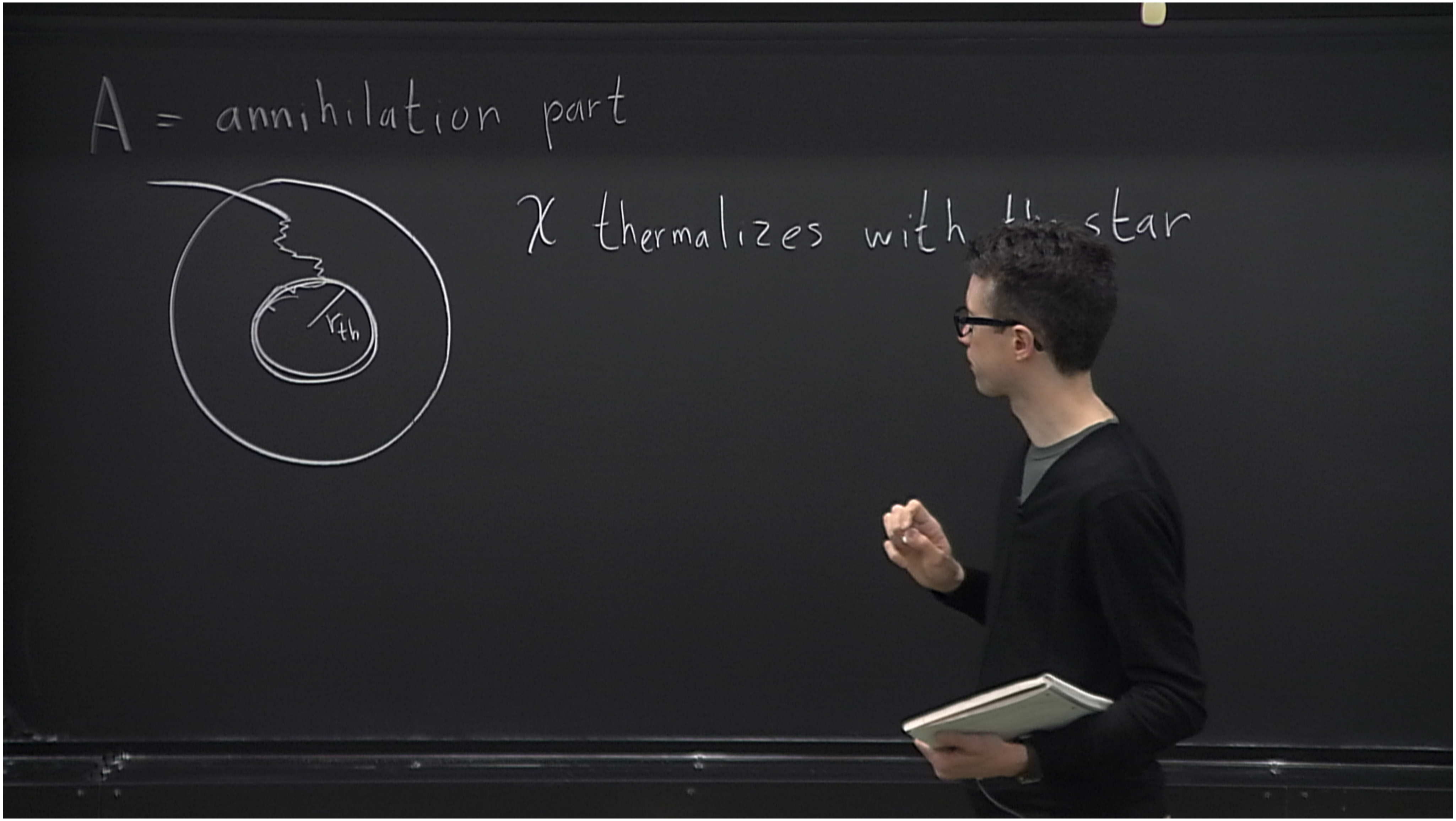

C = capture of DM on the star
=> χ must scatter to v < v_esc
v_⊙ ≃ 600 km/s - 1400 km/s

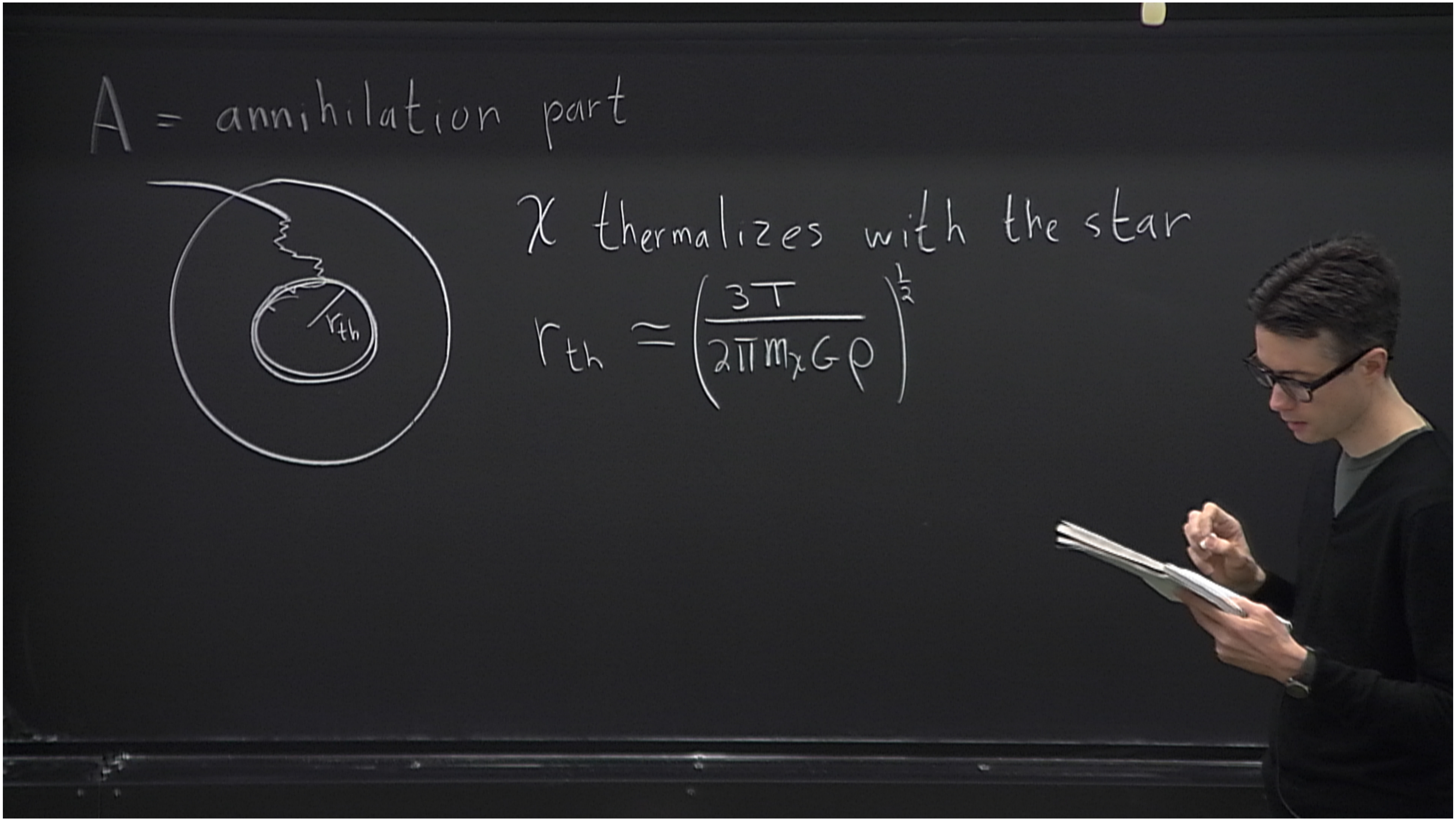
C = capture of DM on the star

$\Rightarrow \chi$ must scatter to $v < v_{esc}$

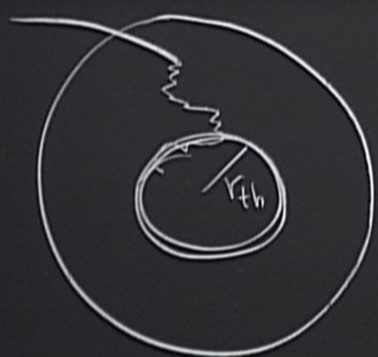
$$v_\odot = 600\ \mathrm{km/s} - 1400\ \mathrm{km/s}$$

$$C_\odot \simeq \left(10^{23}\, s^{-1}\right)\left(\frac{\rho_\chi}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\sigma_p^{SD}}{10^{-40}\ \mathrm{cm^2}}\right)\left(\frac{270\ \mathrm{km/s}}{v_c}\right), \text{ if H dominates}$$


A = annihilation part
r th
χ thermalizes with
star

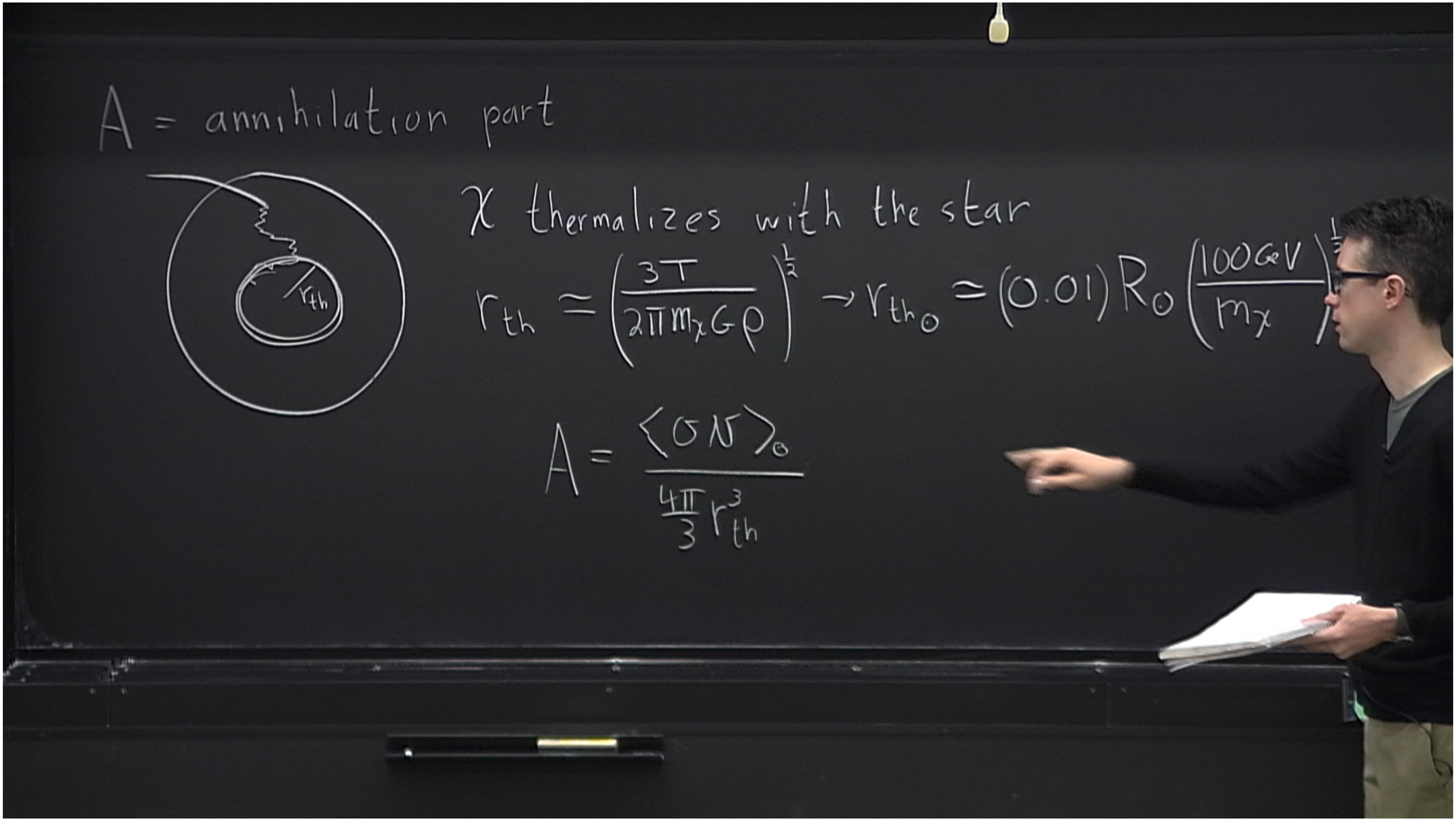

A = annihilation part
r_{th}
χ thermalizes with the star
$r_{th} \simeq \left(\frac{3T}{2\pi m_\chi G \rho}\right)^{\frac{1}{2}}$

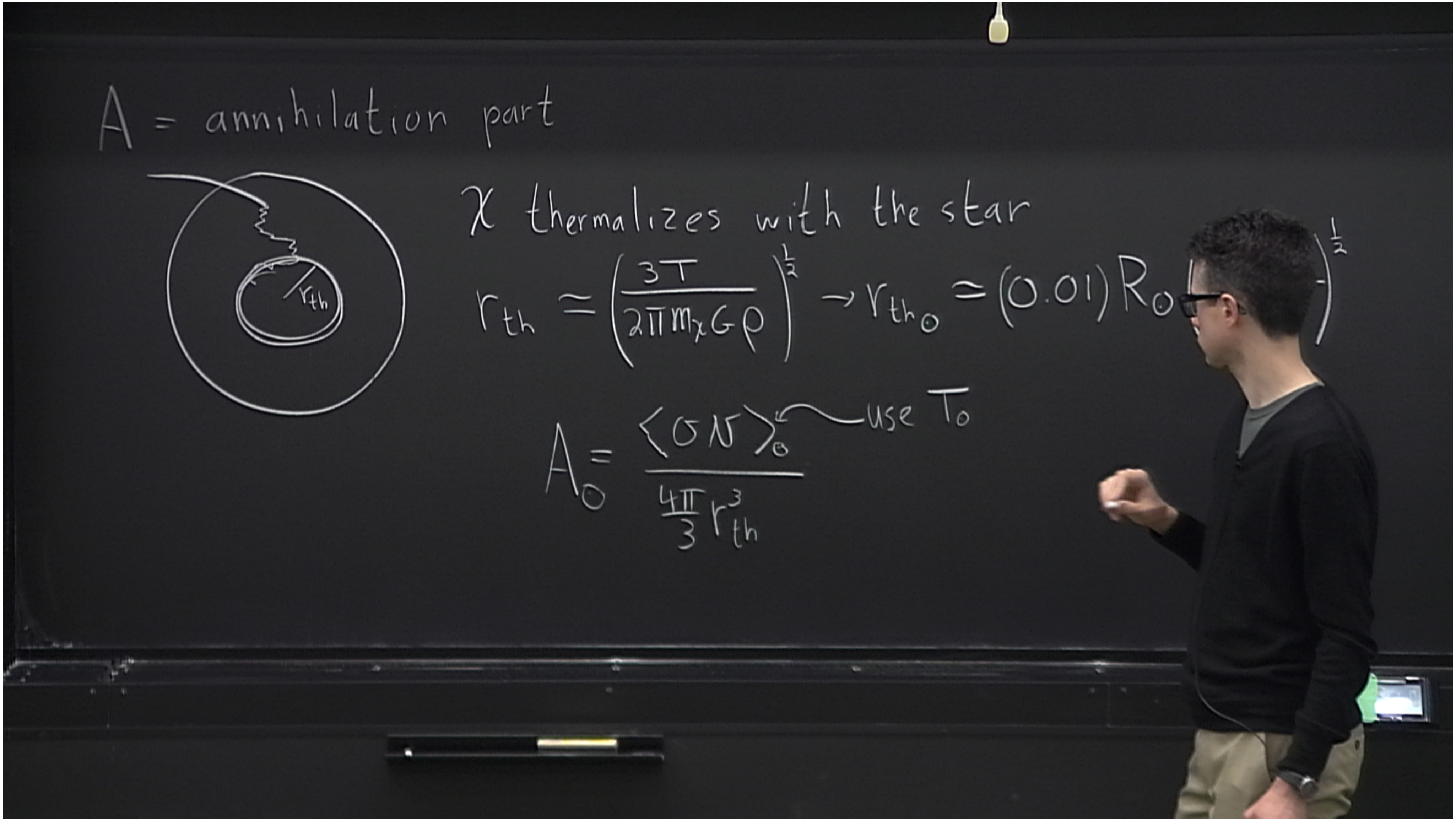
A = annihilation part



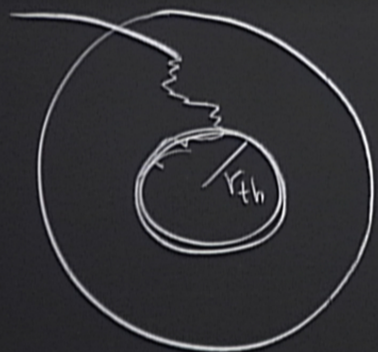
χ thermalizes with the star

$$r_{th} \simeq \left(\frac{3T}{2\pi m_\chi G \rho}\right)^{\frac{1}{2}} \rightarrow r_{th_\odot} \simeq (0.01) R_\odot \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}$$


A = annihilation part
r_th
χ thermalizes with the star
r_th ≃ (3T / 2π m_χ G ρ)^(1/2) → r_th⊙ ≃ (0.01) R⊙ (100 GeV / m_χ)^(1/2)
A = ⟨σv⟩⊙ / (4π/3 r_th^3)


A = annihilation part
r_{th}
χ thermalizes with the star
$r_{th} \simeq \left(\frac{3T}{2\pi m_\chi G\rho}\right)^{\frac{1}{2}} \to r_{th_\odot} \simeq (0.01) R_\odot$
$A_\odot = \frac{\langle \sigma v \rangle_\odot}{\frac{4\pi}{3} r_{th}^3}$
use $T_\odot$

A = annihilation part



χ thermalizes with the star

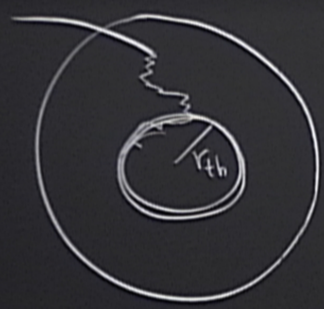
$$r_{th} \simeq \left(\frac{3T}{2\pi m_\chi G\rho}\right)^{\frac{1}{2}} \rightarrow r_{th_\odot} \simeq (0.01) R_\odot \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}$$

$$A_\odot = \frac{\langle \sigma v \rangle_\odot}{\frac{4\pi}{3} r_{th}^3}$$

use T_0 (at core)

$v \sim 10^{-3}$

A = annihilation part



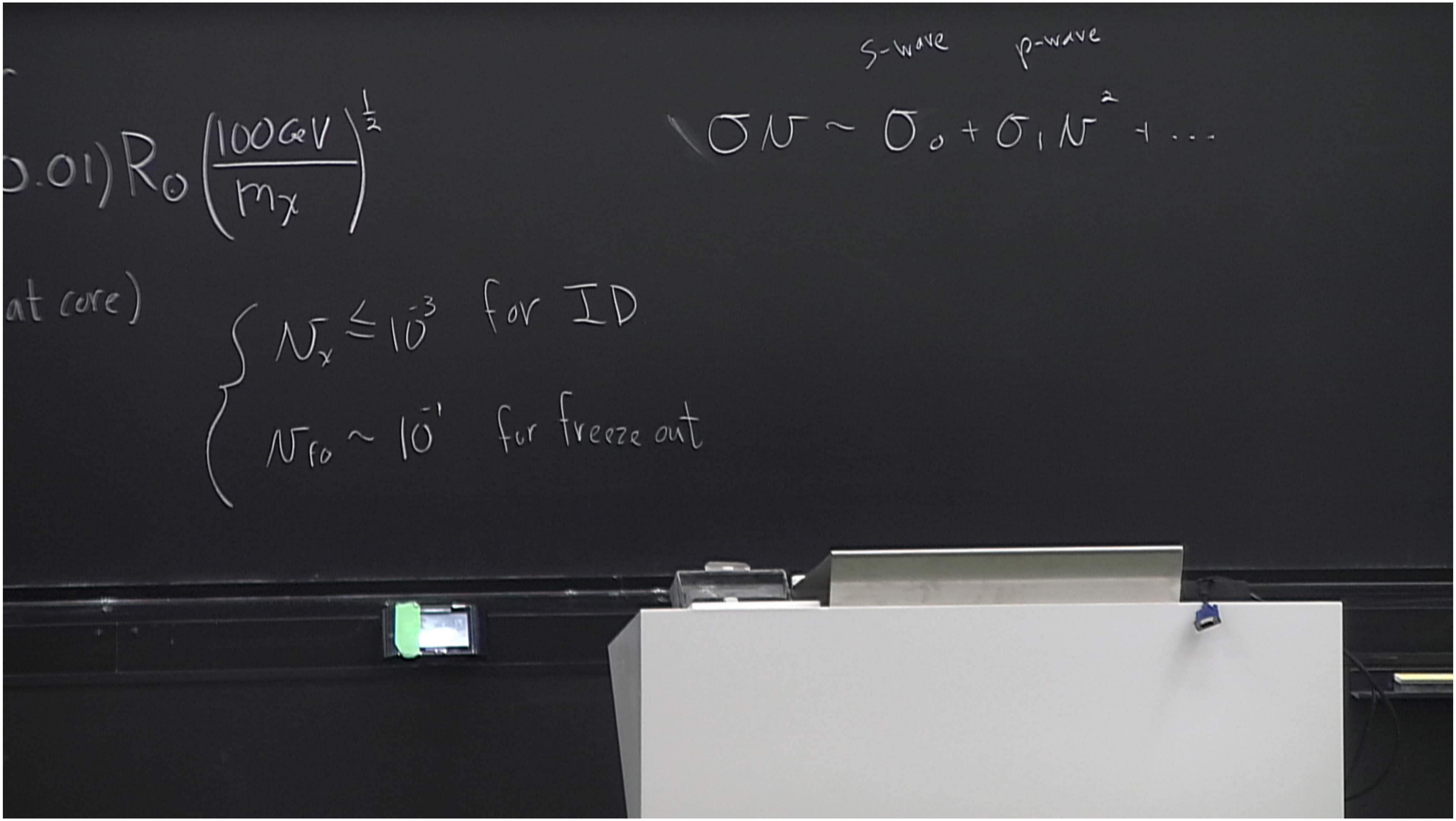
χ thermalizes with the star

$$r_{th} \simeq \left(\frac{3T}{2\pi m_\chi G \rho}\right)^{\frac{1}{2}} \rightarrow r_{th_\odot} \simeq (0.01) R_\odot \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}$$

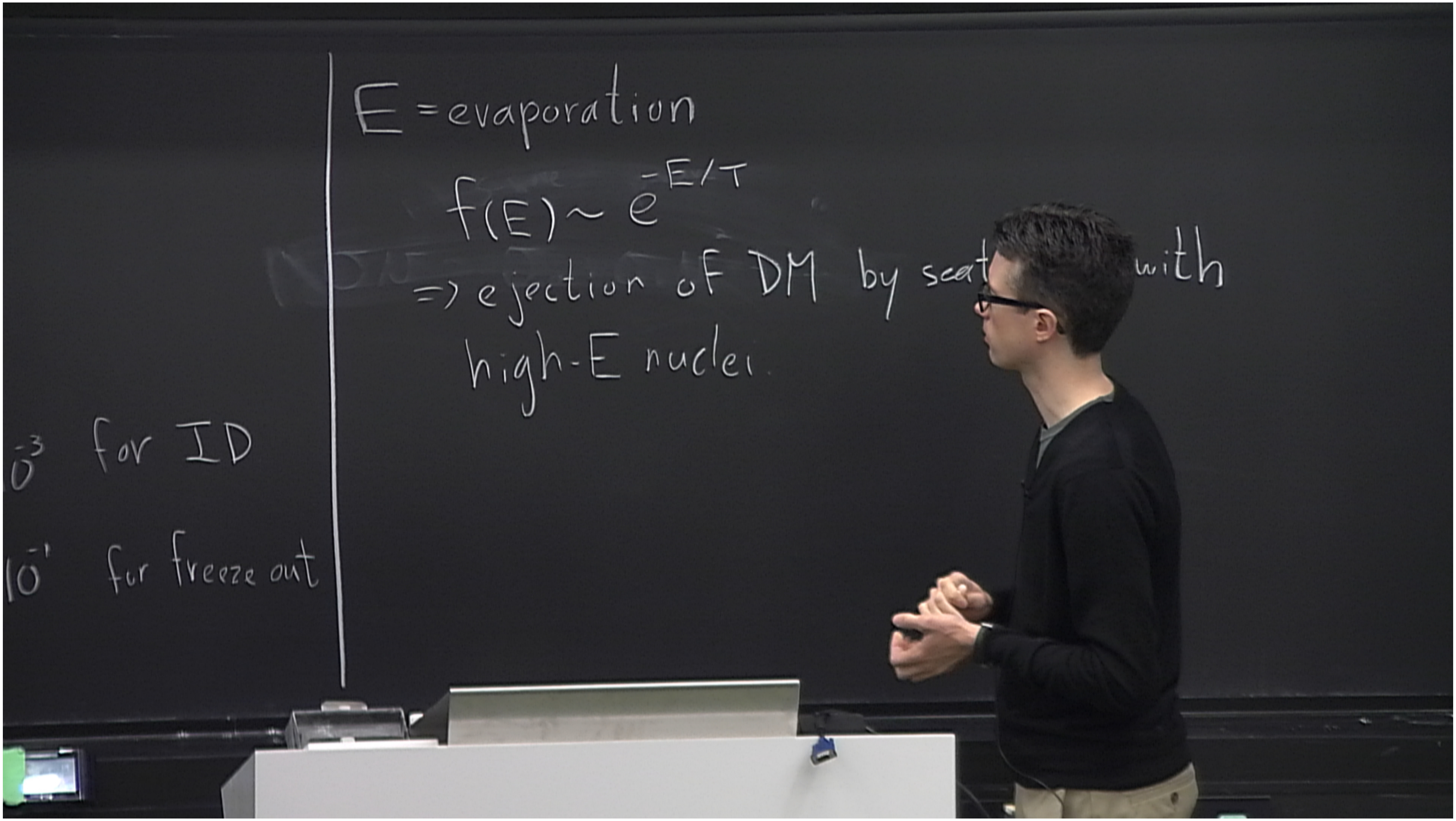
$$A_\odot = \frac{\langle \sigma v \rangle_\odot}{\frac{4\pi}{3} r_{th}^3}$$

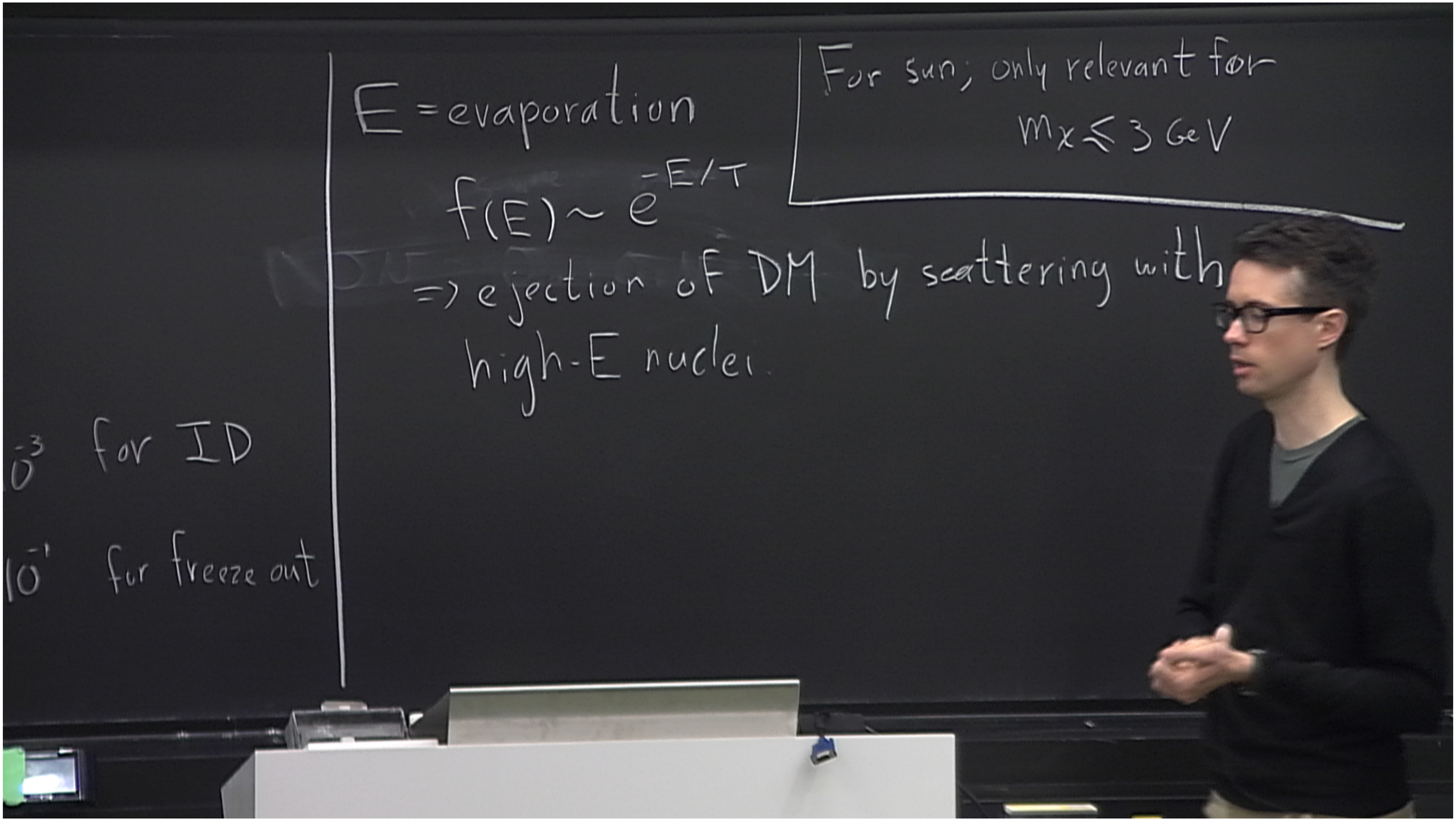
$\langle \sigma v \rangle_\odot$ — use $T_\odot$ (at core)

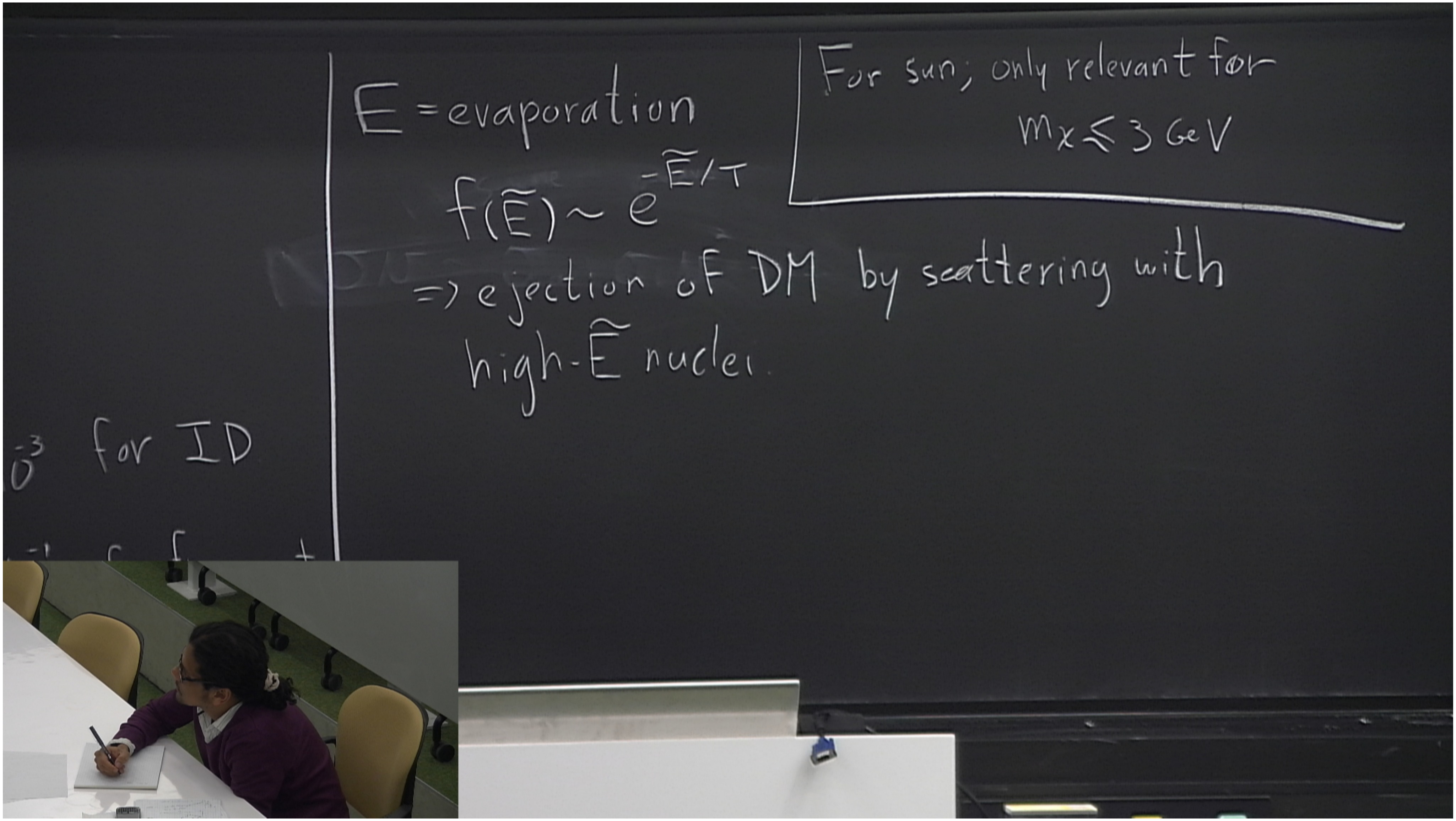
$$\begin{cases} v_\chi \lesssim 10^{-3} & \text{for ID} \\ v_{fo} \sim 10^{-1} & \text{for freeze out} \end{cases}$$

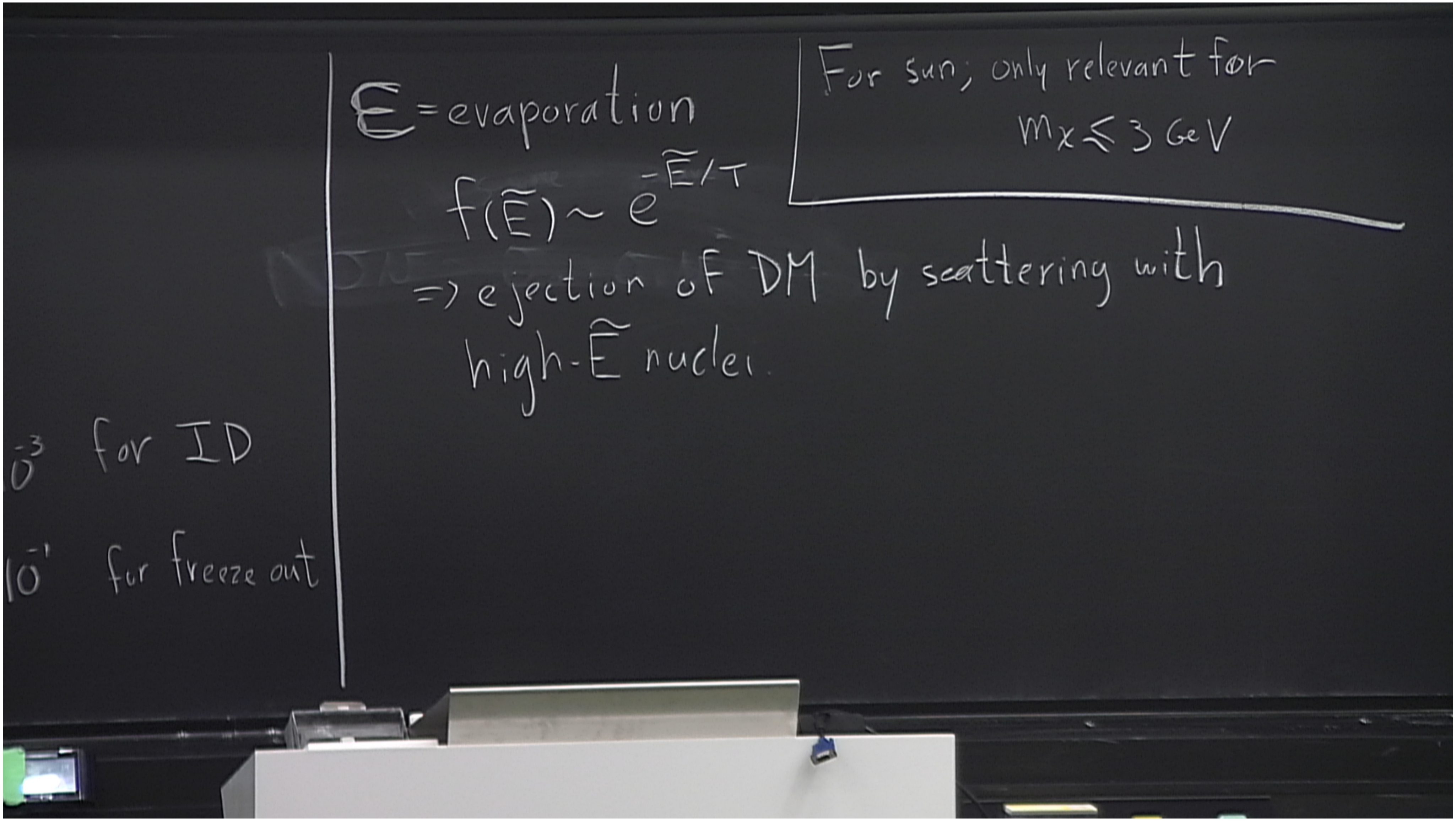

s-wave p-wave
$\sigma v \sim \sigma_0 + \sigma_1 v^2 + \dots$
$.01) R_\odot \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}$
at core)
$v_\chi \leq 10^{-3}$ for ID
$v_{fo} \sim 10^{-1}$ for freeze out

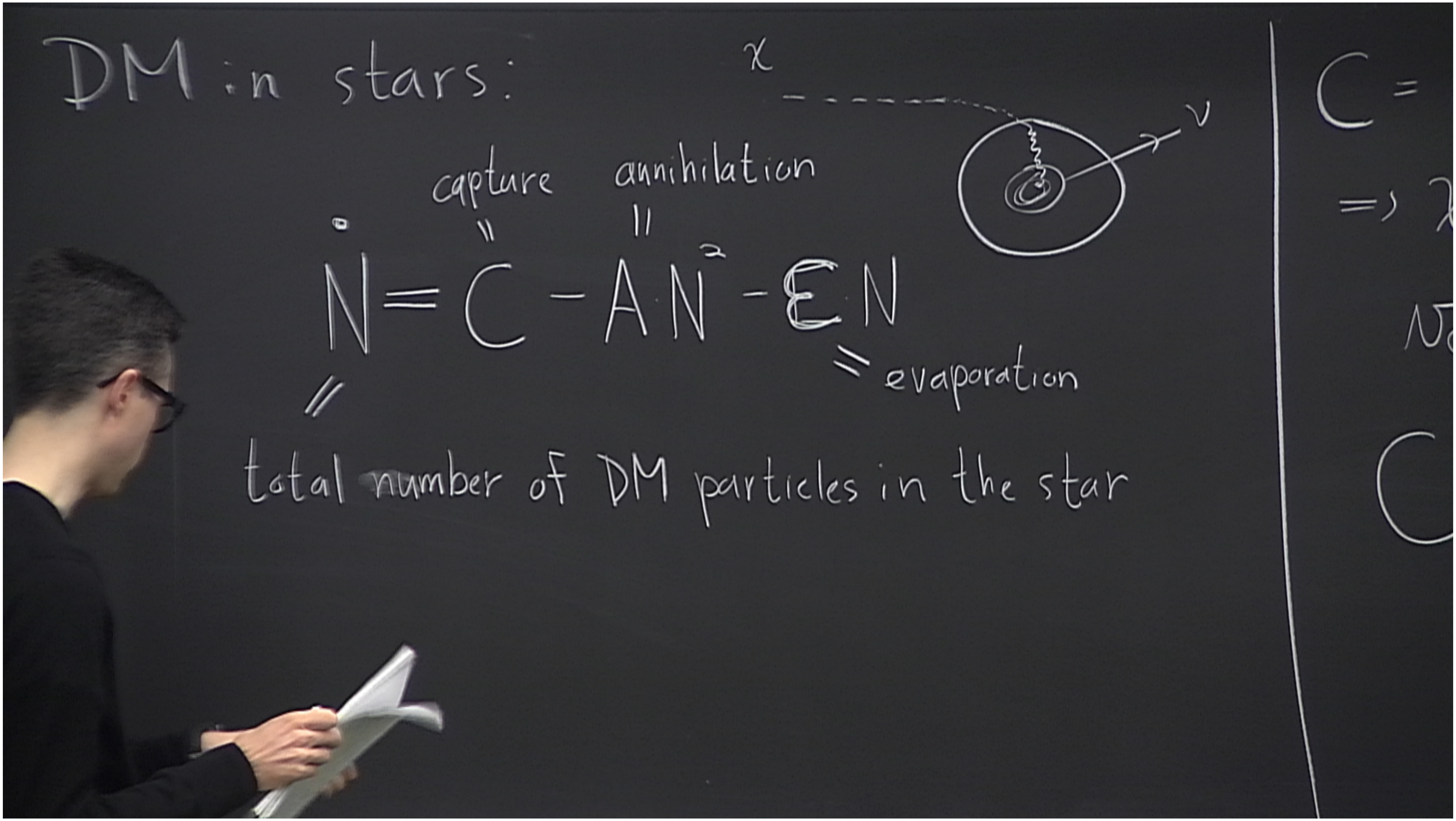

E = evaporation
f(E) ~ e^{-E/T}
10^{-3} for ID
10^{-1} for freeze out

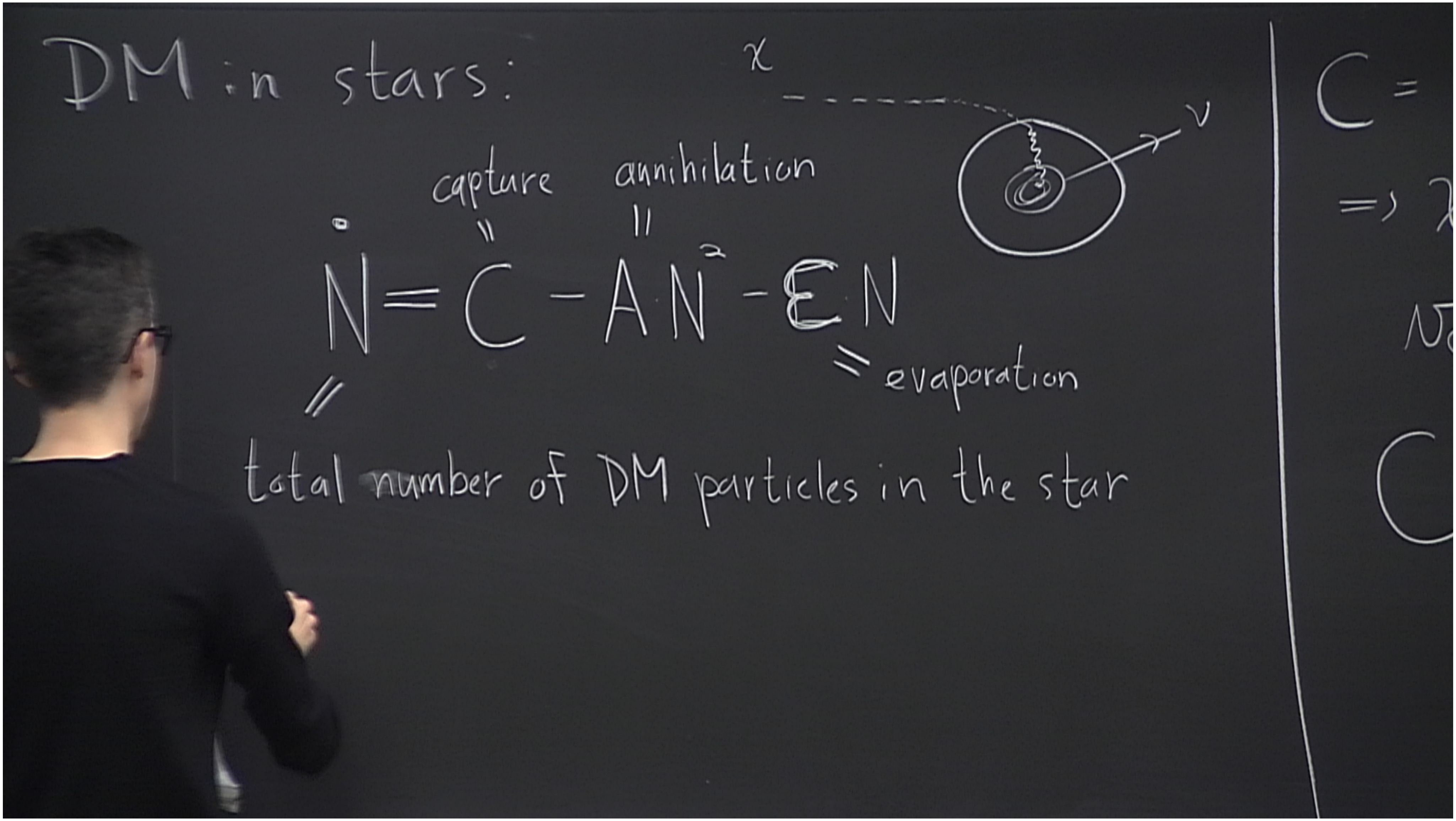

E = evaporation
f(E) ~ e^{-E/T}
=> ejection of DM by
with
high-E nuclei
for ID
for freeze out

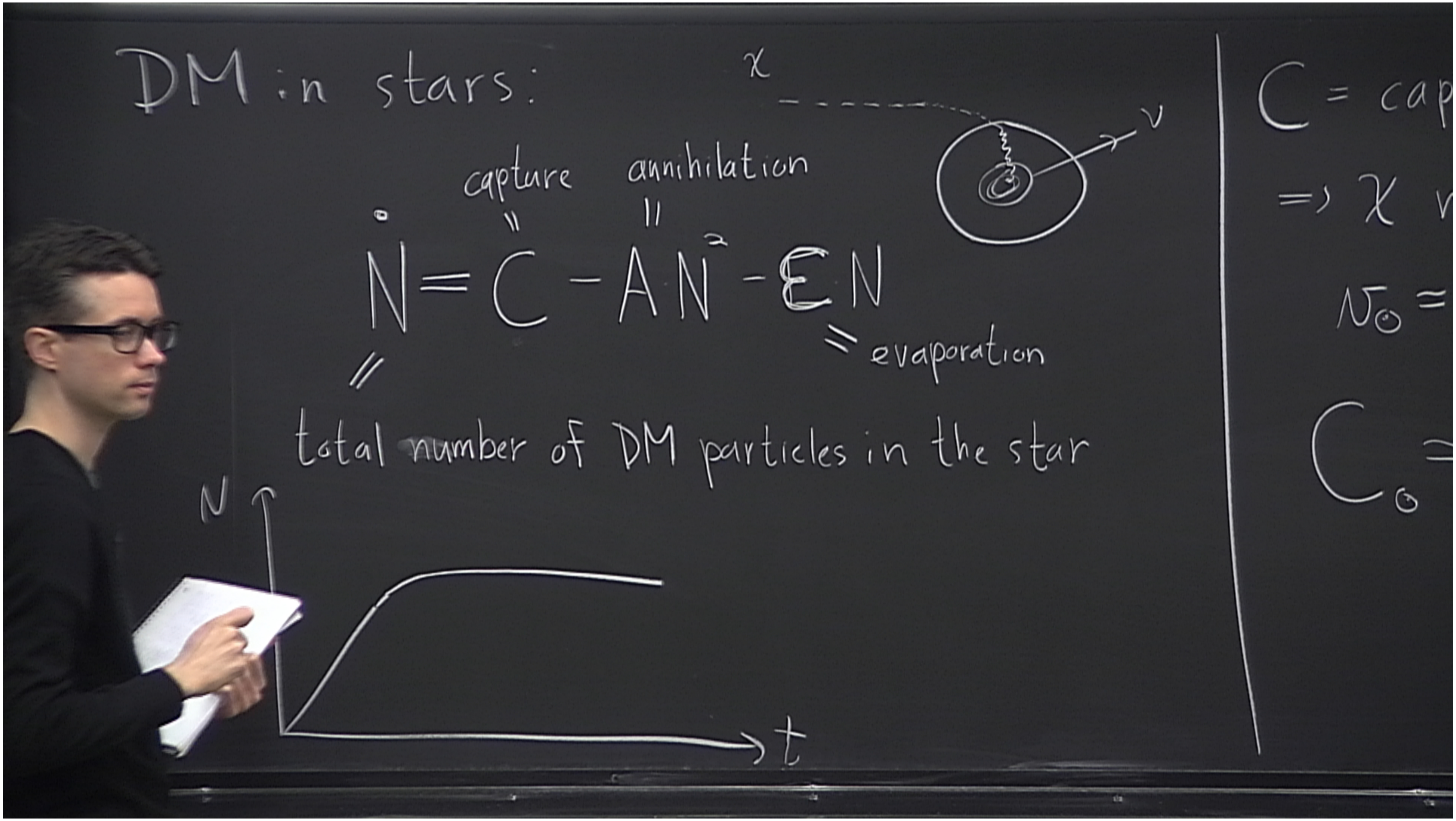

For sun; only relevant for
$m_\chi \lesssim 3$ GeV
E = evaporation
$f(E) \sim e^{-E/T}$
=> ejection of DM by scattering with
high-E nuclei.
for ID
10^{-1} for freeze out


E = evaporation
$f(\tilde{E}) \sim e^{-\tilde{E}/T}$
=> ejection of DM by scattering with
high-$\tilde{E}$ nuclei.
For sun; only relevant for
$m_\chi \lesssim 3$ GeV
for ID


$\mathcal{E}$ = evaporation
$f(\tilde{E}) \sim e^{-\tilde{E}/T}$
$\Rightarrow$ ejection of DM by scattering with
high-$\tilde{E}$ nuclei.
For sun; only relevant for
$m_\chi \lesssim 3$ GeV
0^{-3} for ID
10^{-1} for freeze out

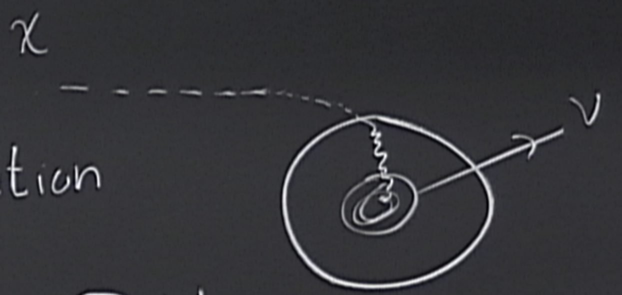

DM in stars:
χ
ν
capture
annihilation
Ṅ = C − A N² − E N
evaporation
total number of DM particles in the star
C =

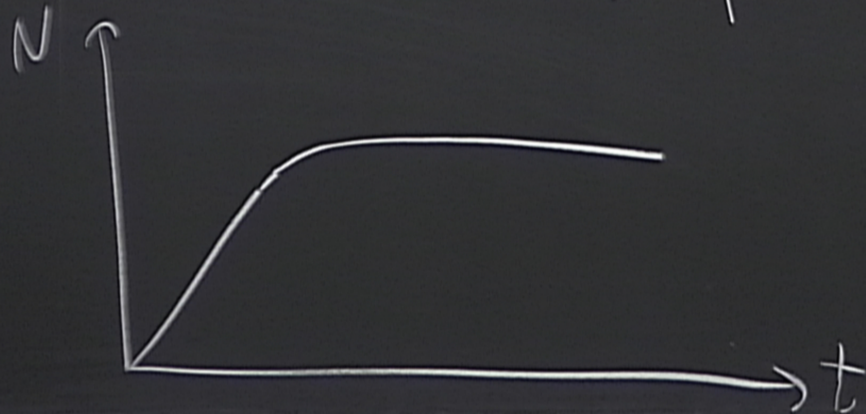

DM in stars:
χ
ν
capture
annihilation
$\dot{N} = C - A N^2 - \mathcal{E} N$
evaporation
total number of DM particles in the star
$C =$
$\Rightarrow \chi$


DM in stars:
χ
ν
capture
annihilation
$\dot{N} = C - A N^2 - \varepsilon N$
evaporation
total number of DM particles in the star
N
t
C = cap
$\Rightarrow \chi$
$N_\odot \approx$
$C_\odot$ =

DM in stars:

$$\underset{\text{total number of DM particles in the star}}{\dot{N}} = \overset{\text{capture}}{C} - \overset{\text{annihilation}}{A} N^2 - \underset{\text{evaporation}}{\mathcal{E}} N$$





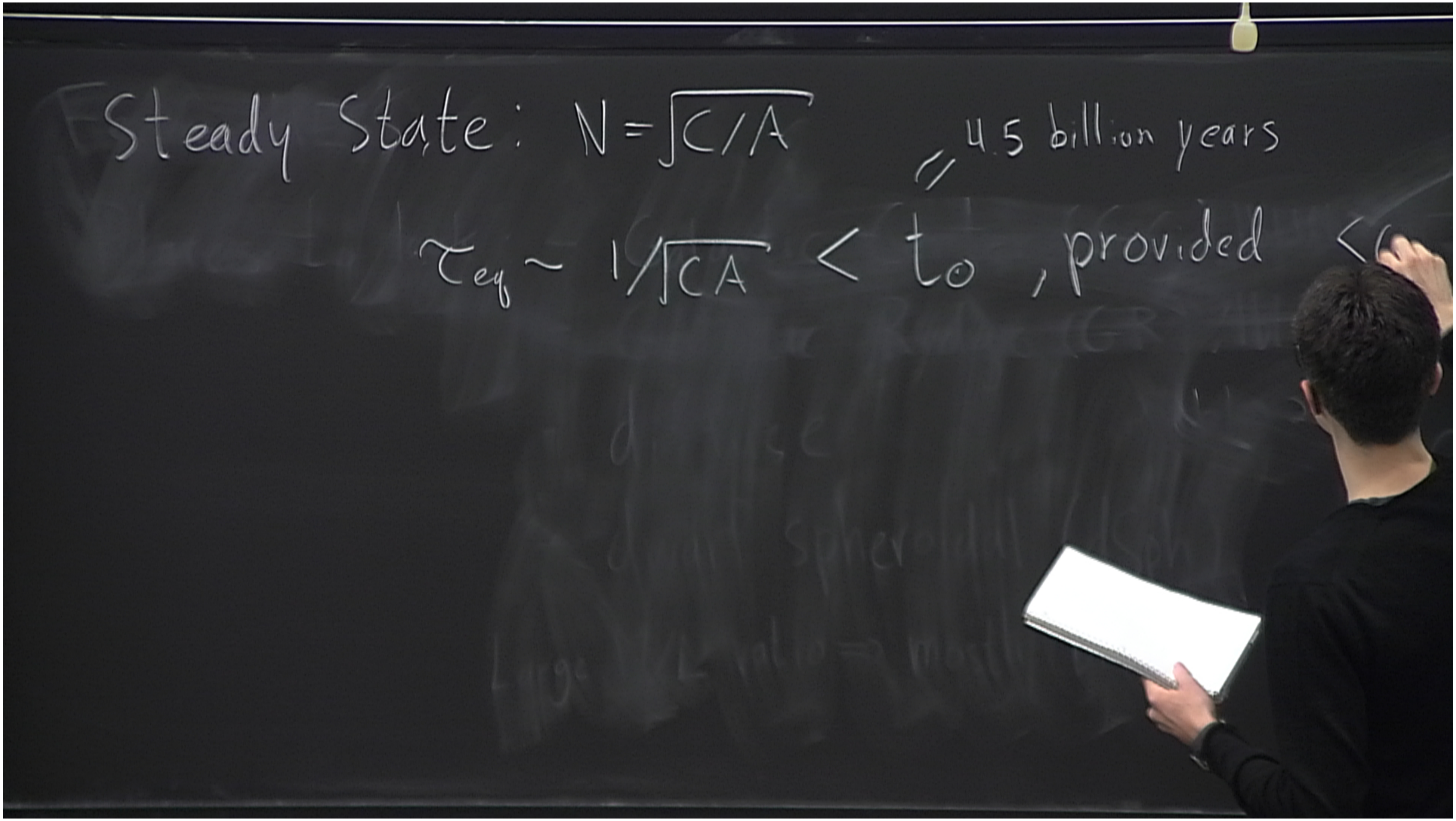
C = cap

$\Rightarrow \chi$ r

$N_\odot =$

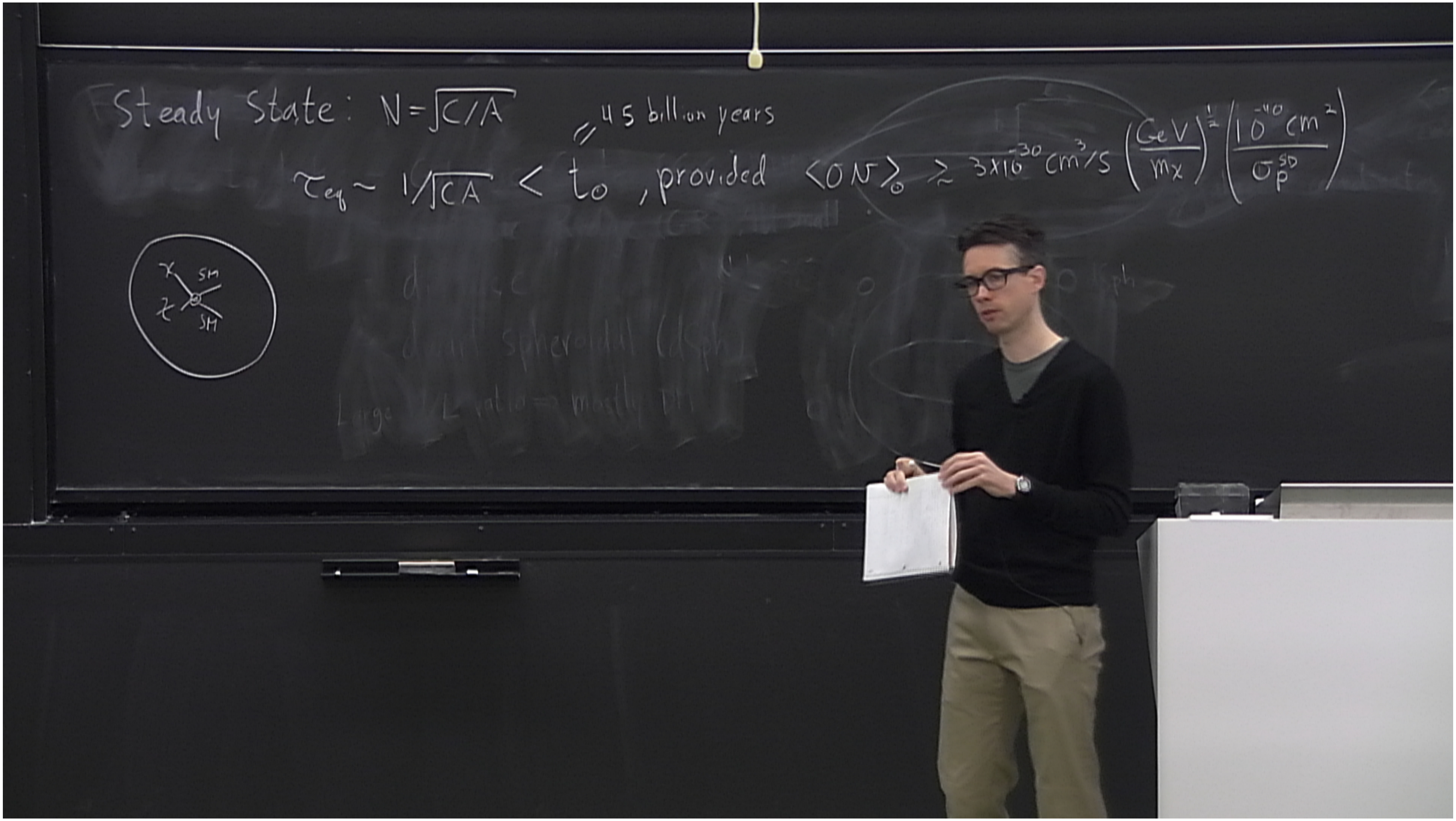
$C_\odot =$

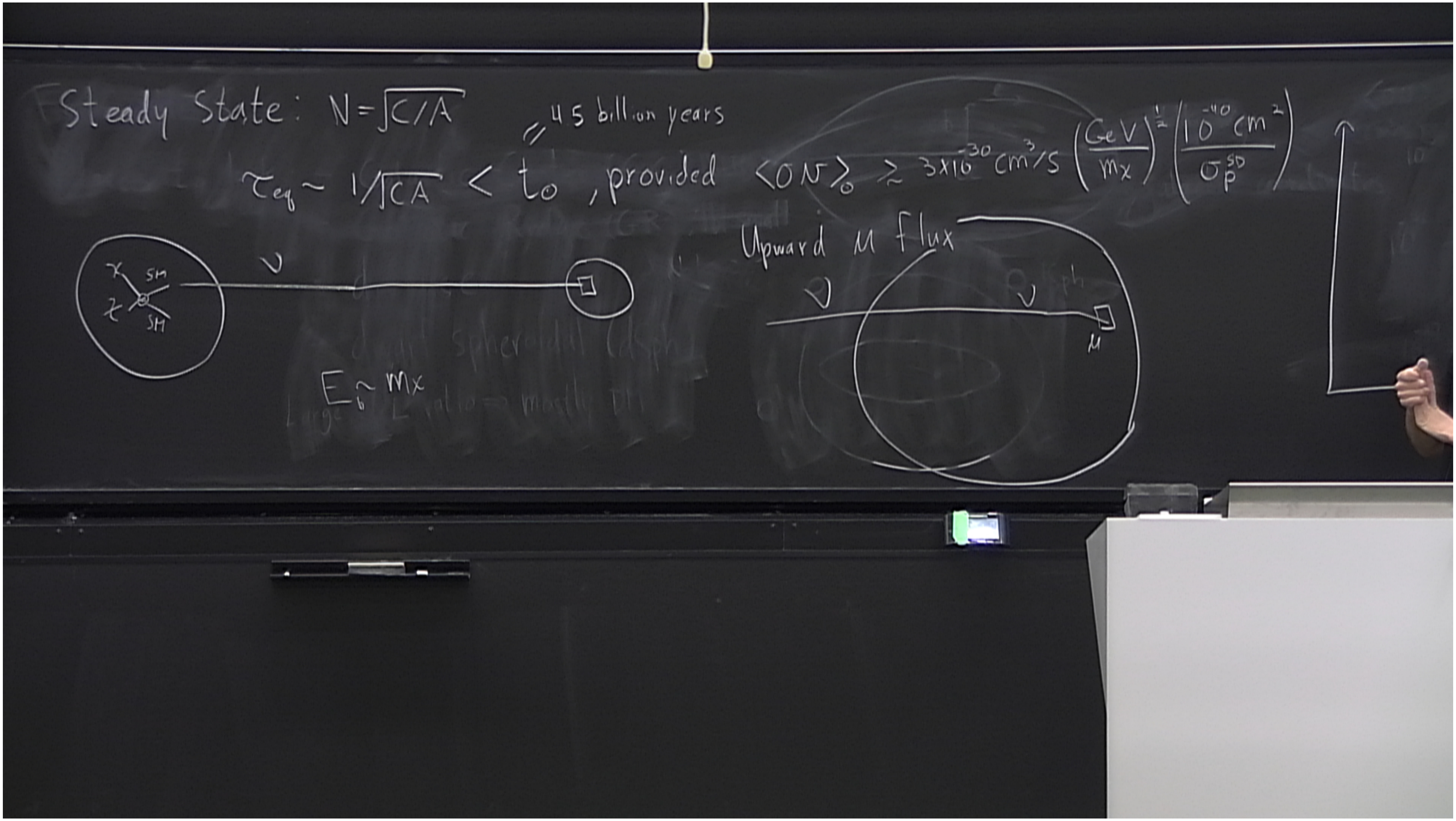

Steady State: $N = \sqrt{C/A}$

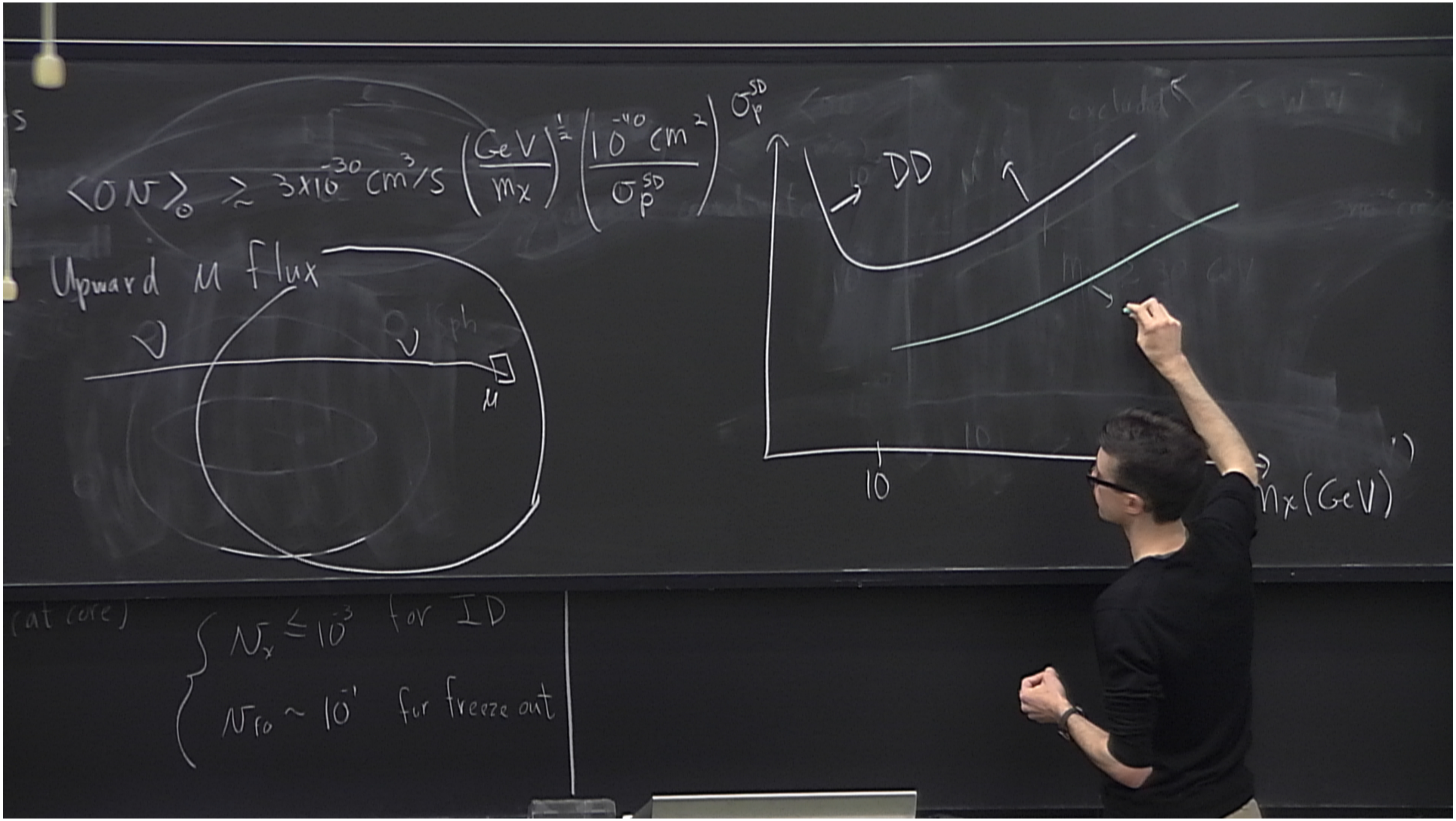

Steady State: $N = \sqrt{C/A}$
$\simeq$ 4.5 billion years
$\tau_{eq} \sim 1/\sqrt{CA} < t_\odot$, provided

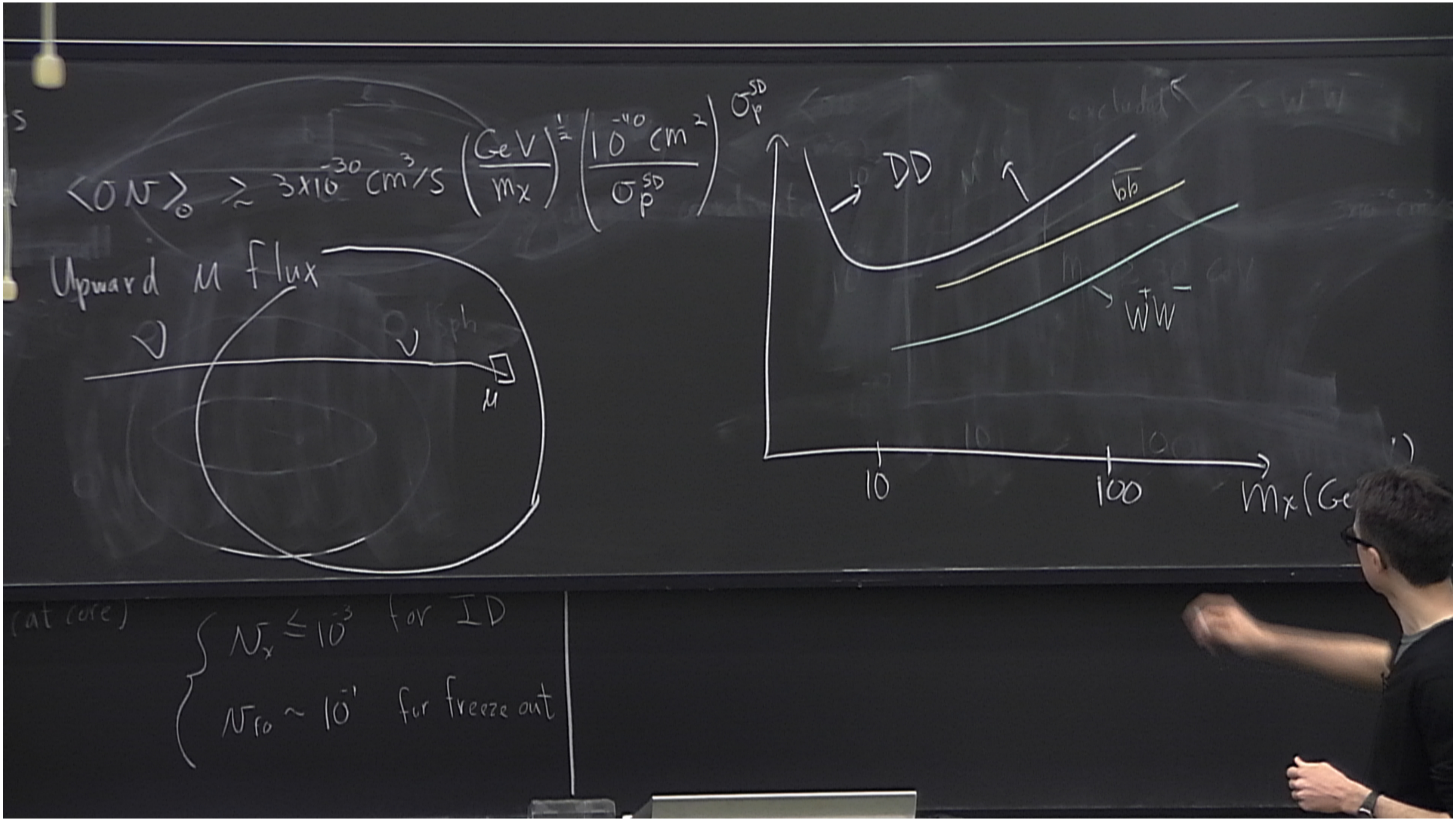
Steady State: $N = \sqrt{C/A}$

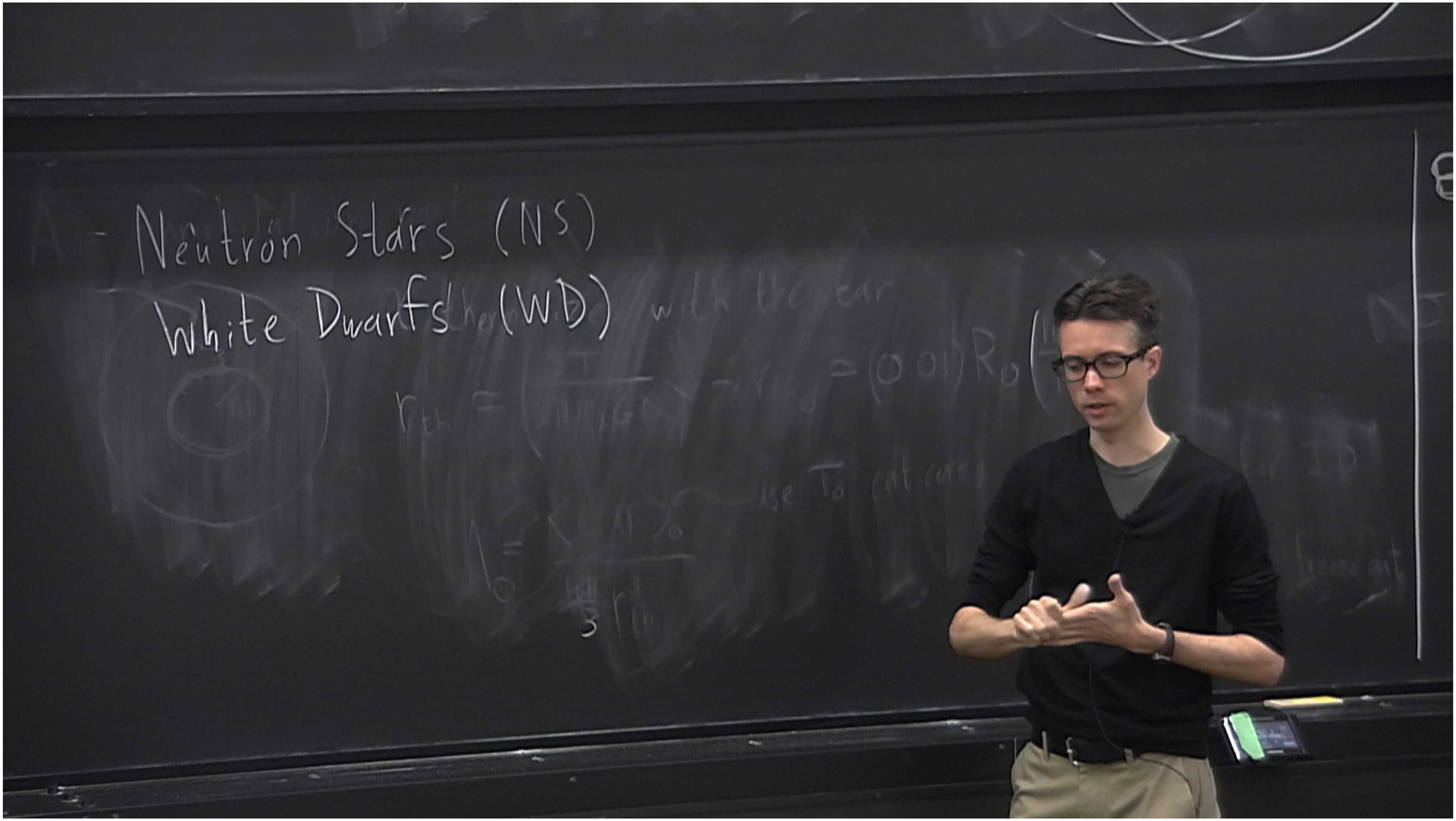
$$\tau_{eq} \sim 1/\sqrt{CA} < \stackrel{\simeq\ 4.5\text{ billion years}}{t_0}\ , \text{provided } \langle \sigma v \rangle_0 \gtrsim 3\times10^{-30}\,\mathrm{cm}^3/\mathrm{s}\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}\left(\frac{10^{-40}\,\mathrm{cm}^2}{\sigma_p^{SD}}\right)$$

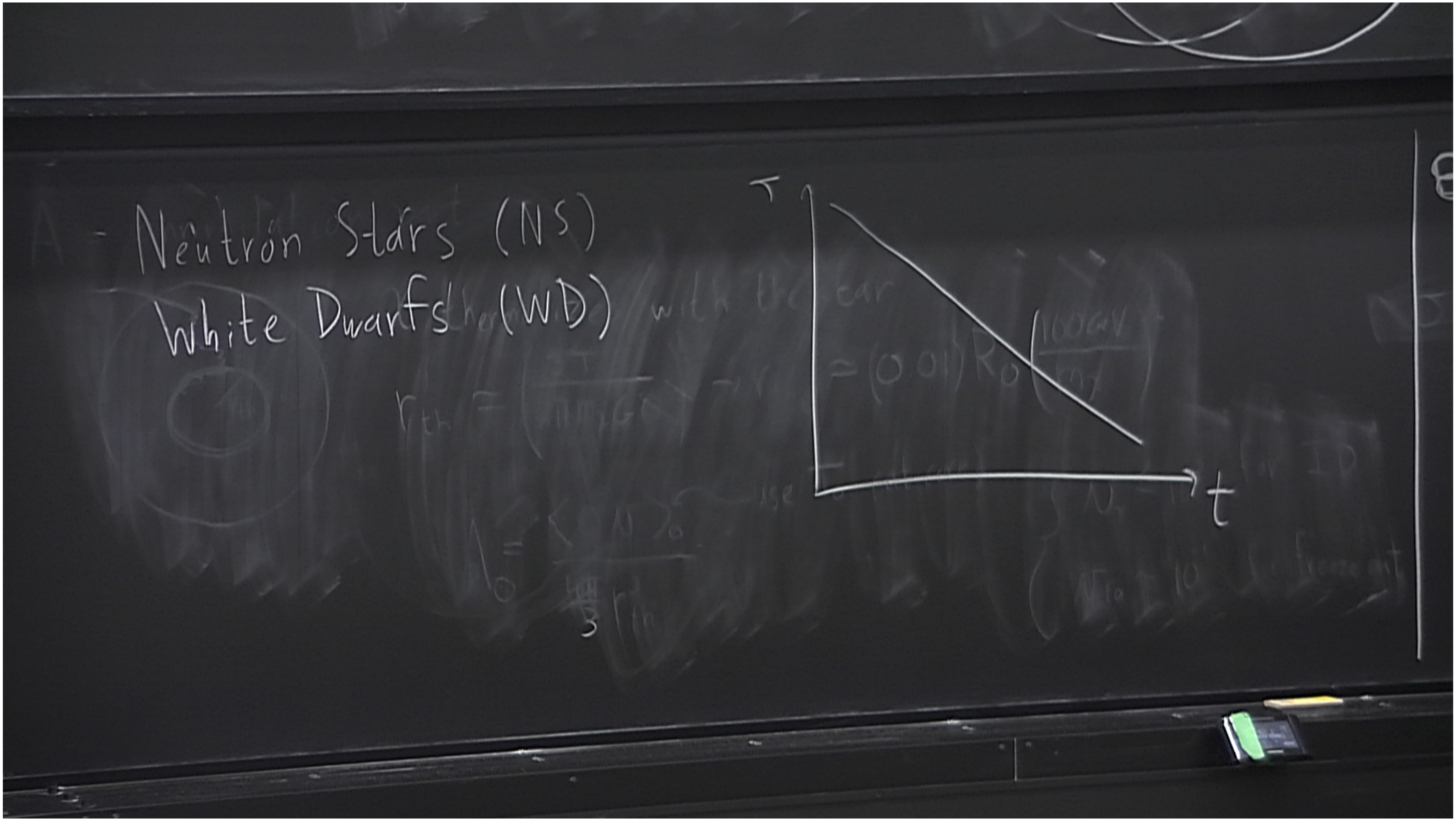

Steady State: N = √C/A
4.5 billion years
τeq ~ 1/√CA < t0 , provided ⟨σv⟩0 ≳ 3x10^-30 cm^3/s (GeV/mχ)^1/2 (10^-40 cm^2/σp^SD)
χ
SM
SM


Steady State: N = √(C/A)
≃ 4.5 billion years
τ_eq ~ 1/√(CA) < t_⊙ , provided ⟨σv⟩_⊙ ≳ 3x10^-30 cm^3/s (GeV/m_χ)^1/2 (10^-40 cm^2/σ_p^SD)
χ
SM
ν
Upward μ flux
ν
μ
E_ν ≃ m_χ

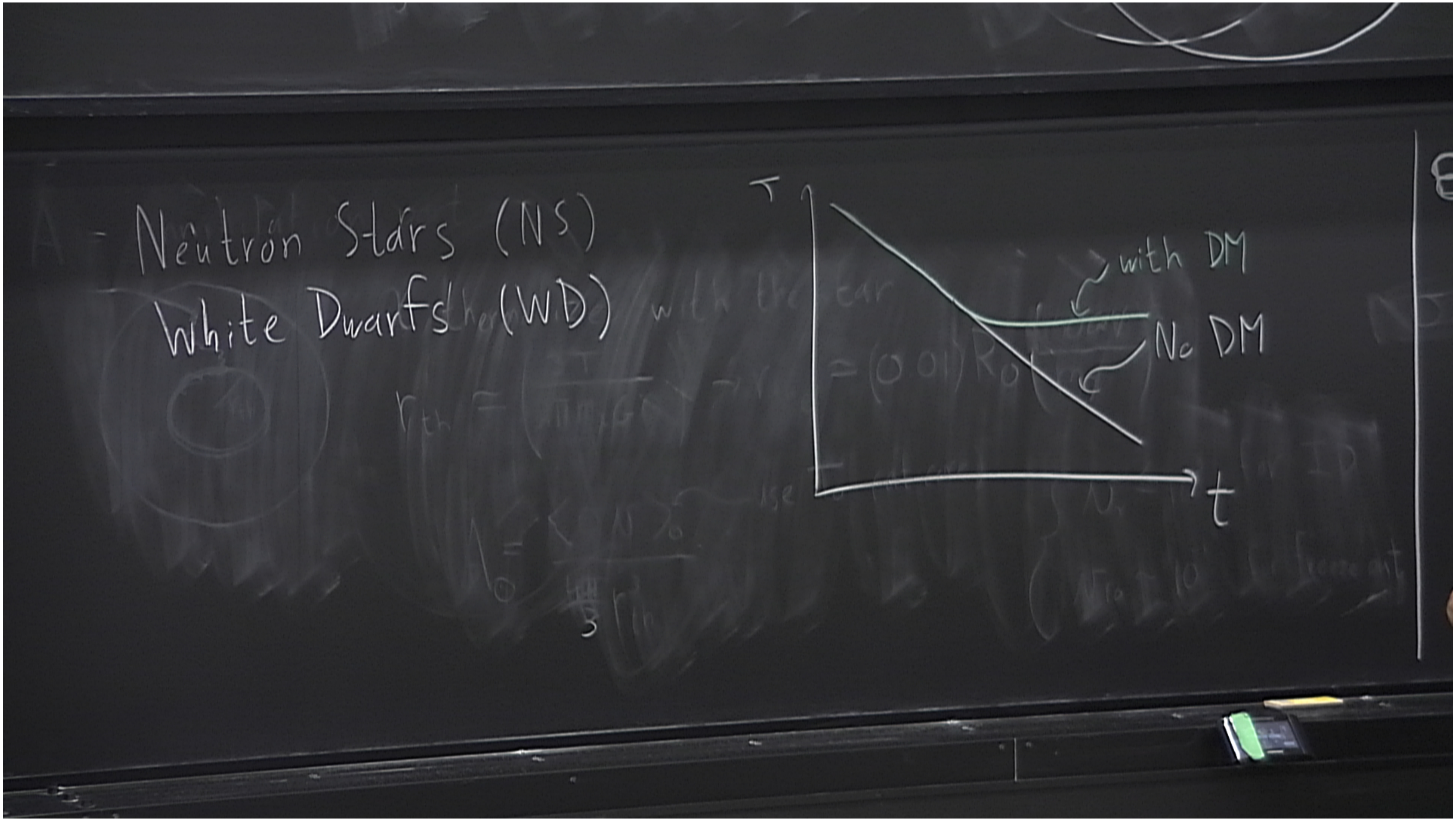

⟨σv⟩₀ ≳ 3x10^-30 cm^3/s (GeV/mχ)^1/2 (10^-40 cm^2/σp^SD) σp^SD
Upward μ flux
ν
ν
μ
DD
10
mχ(GeV)
(at core)
Nχ ≤ 10^-3 for ID
Nfo ~ 10^-1 for freeze out

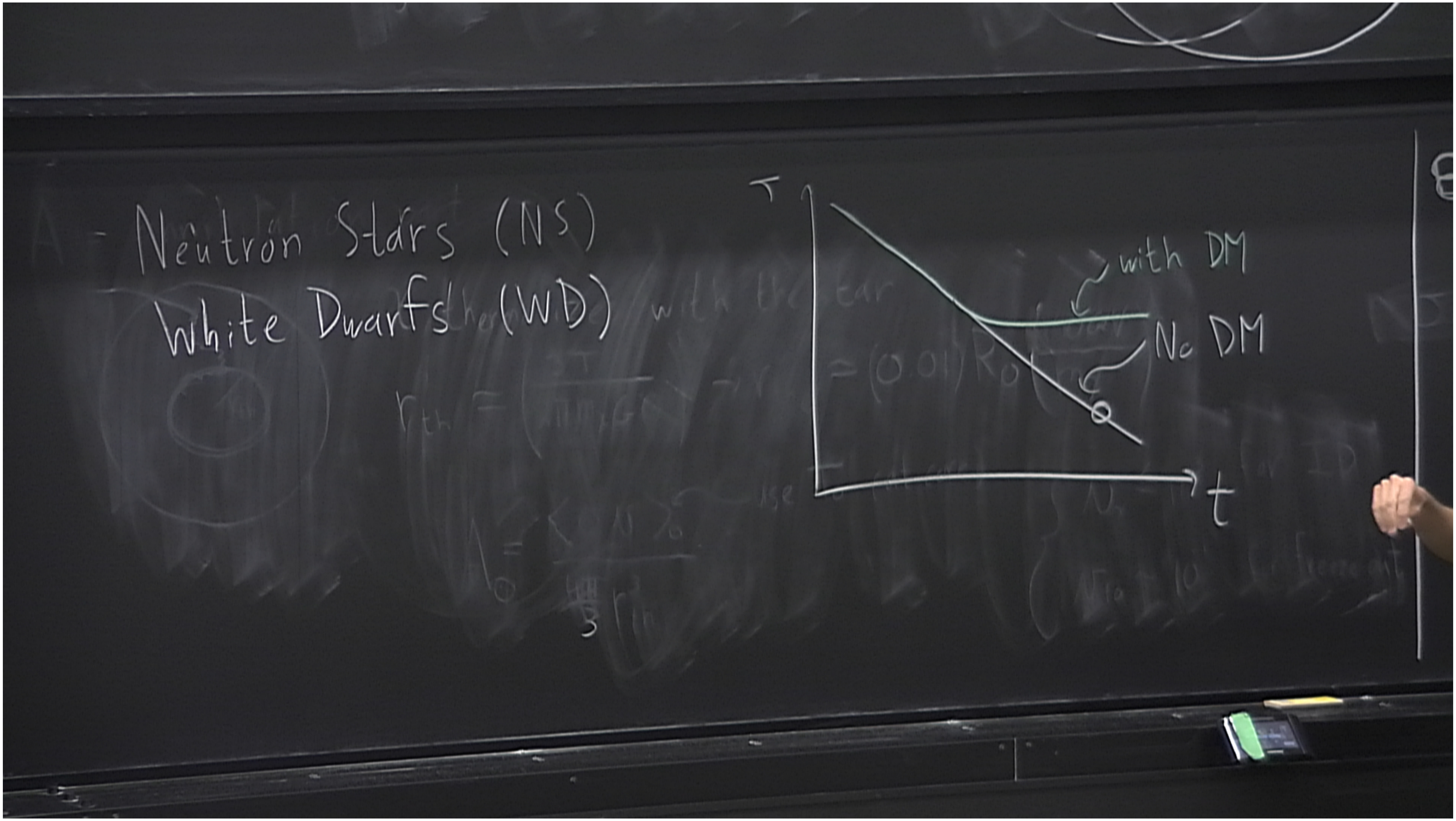

$\langle \sigma v \rangle_\odot \gtrsim 3\times10^{-30}\,\mathrm{cm^3/s}\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{\frac{1}{2}}\left(\frac{10^{-40}\,\mathrm{cm}^2}{\sigma_p^{SD}}\right)\sigma_p^{SD}$
Upward μ flux
ν
ν
μ
DD
$b\bar{b}$
W^+W^-
10
100
m_χ (Ge
(at core)
$N_\chi \leq 10^{-3}$ for ID
$N_{FO} \sim 10^{-1}$ for freeze out


Neutron Stars (NS)
White Dwarfs (WD)



- Neutron Stars (NS)
White Dwarfs (WD)
T
t


- Neutron Stars (NS)
White Dwarfs (WD)
T
t
with DM
No DM


- Neutron Stars (NS)
White Dwarfs (WD)
T
with DM
No DM
t