Title: Dark Sector Theory

Speakers:

Collection: TRISEP 2023

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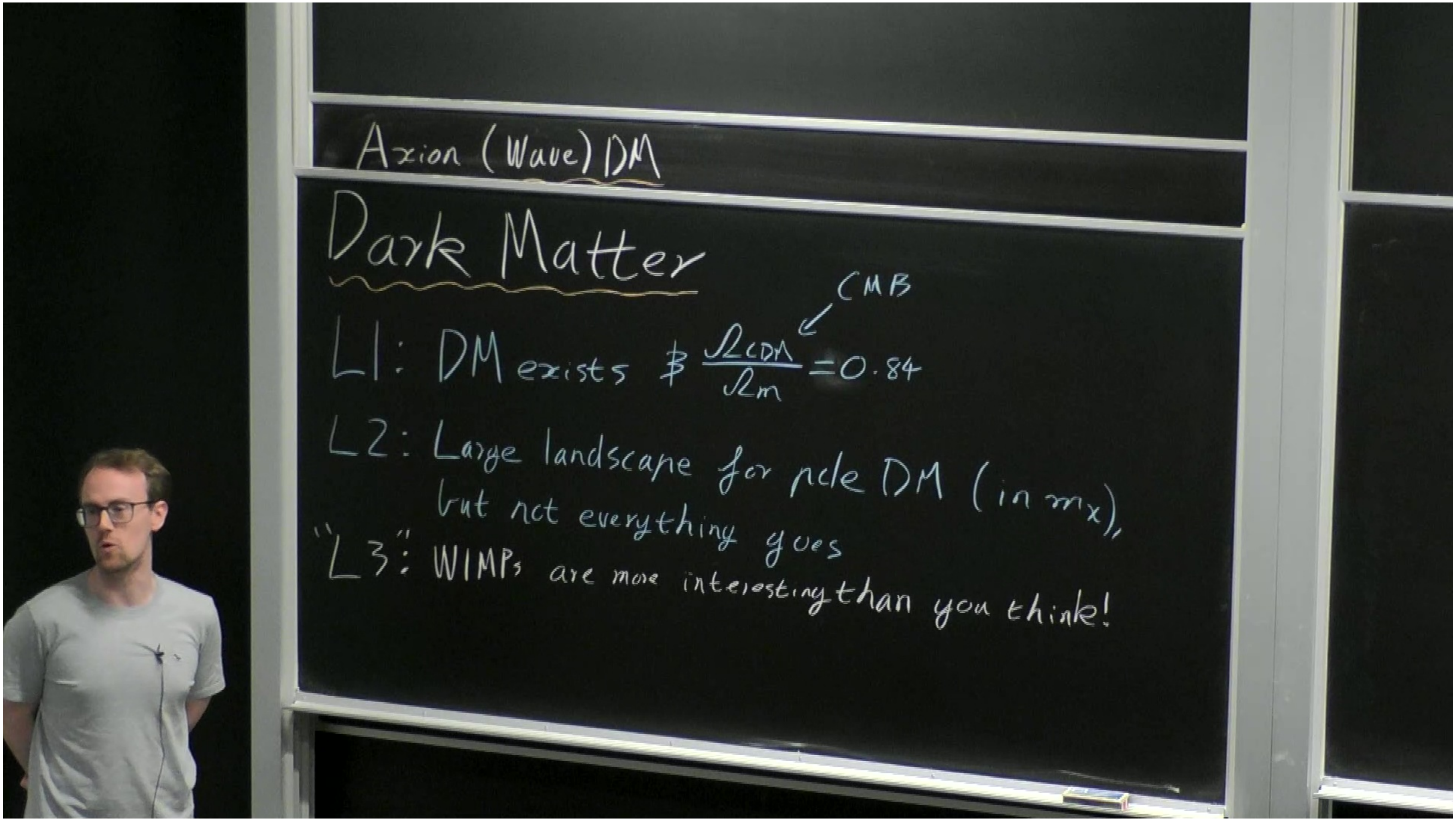
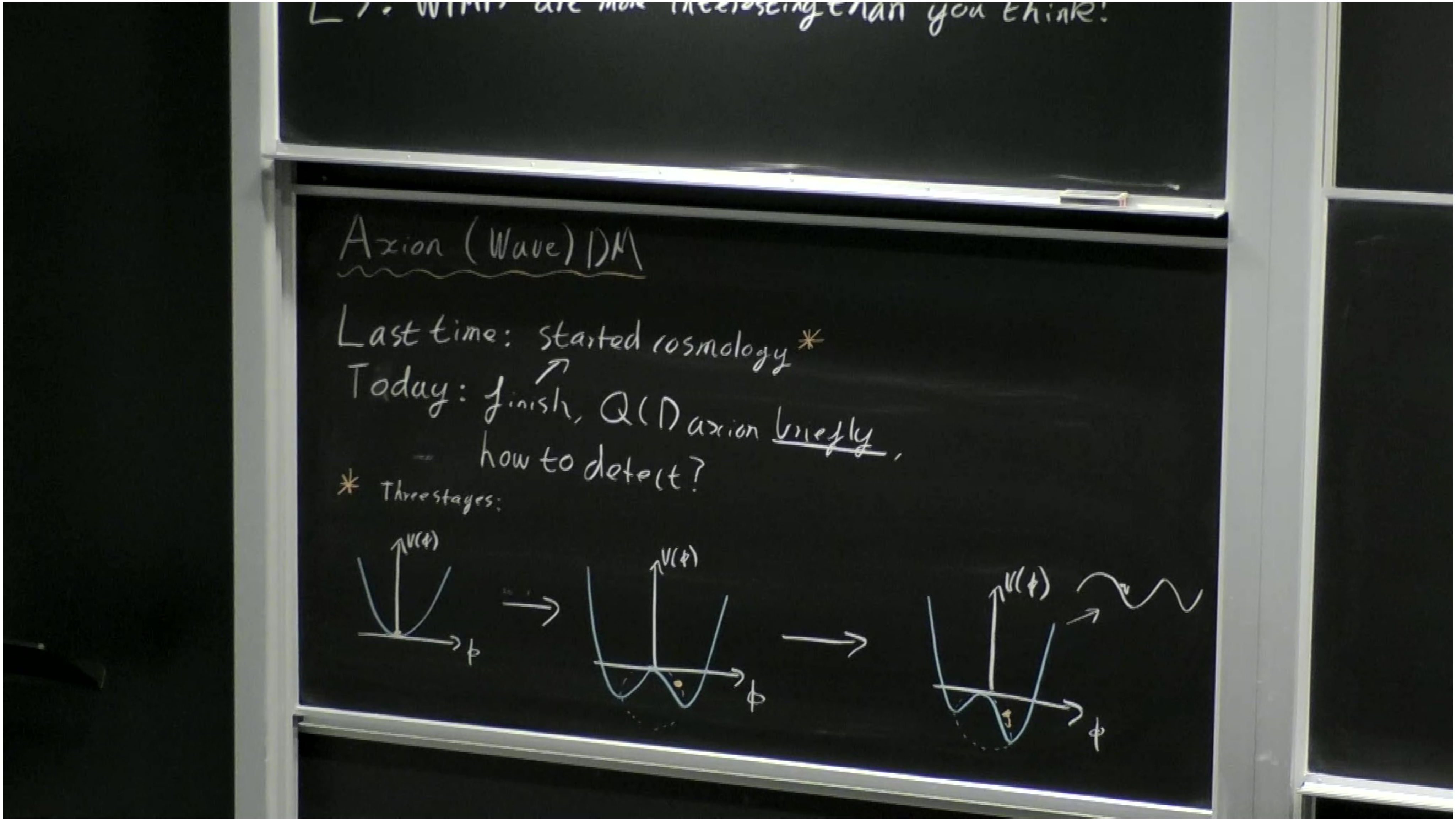
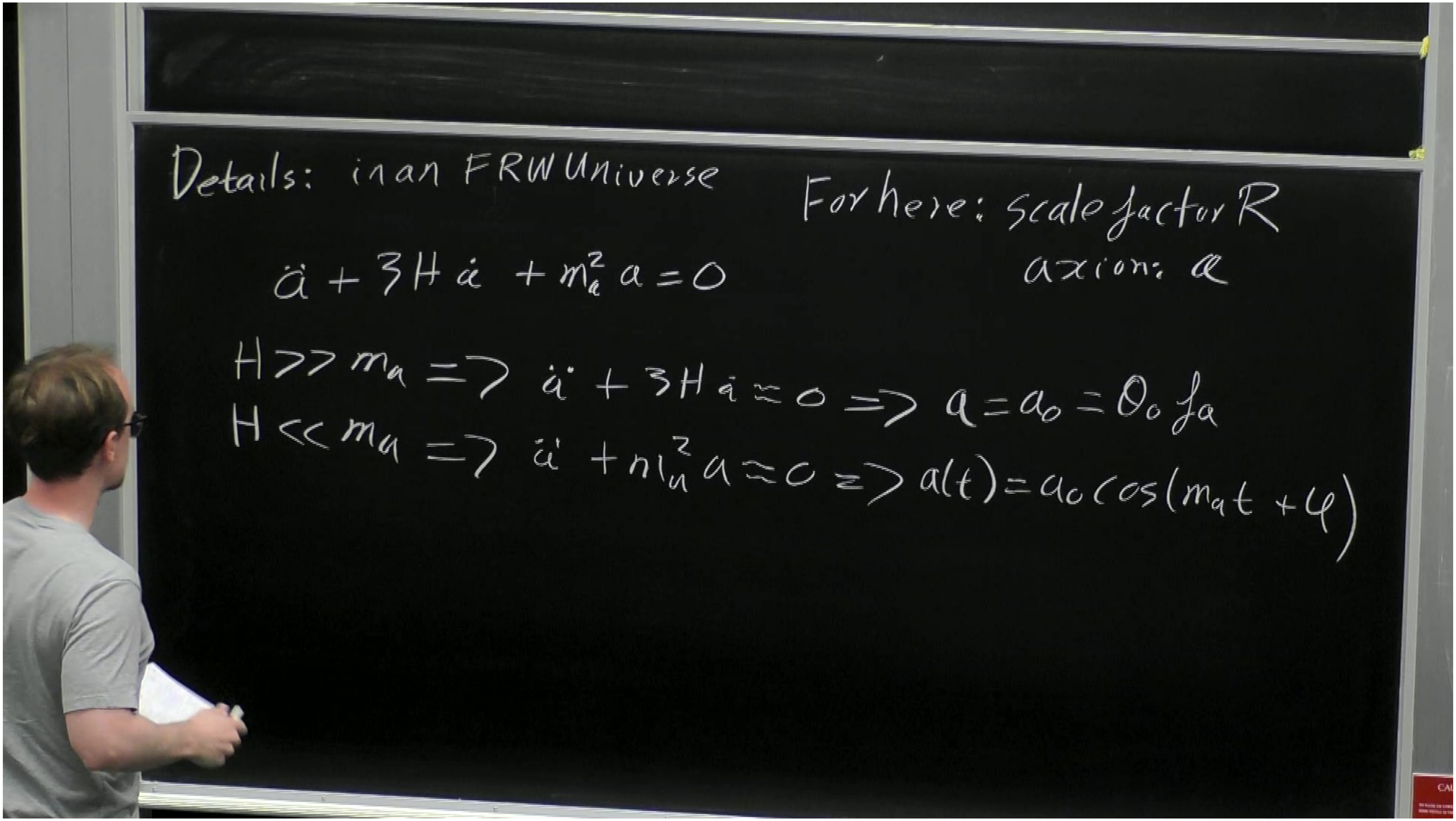
URL: https://pirsa.org/23060073


Axion (Wave) DM
Dark Matter
CMB
L1: DM exists ∋ ΩCDM / Ωm = 0.84
L2: Large landscape for pcle DM (in mx), but not everything goes
"L3": WIMPs are more interesting than you think!


Axion (Wave) DM
Last time: started cosmology *
Today: finish, QCD axion briefly,
how to detect?
* Three stages:
V(ϕ)
ϕ
V(ϕ)
ϕ
V(ϕ)
ϕ


Details: in an FRW Universe
For here: scale factor R
axion: a
$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$
$H \gg m_a \Rightarrow \ddot{a} + 3H\dot{a} \simeq 0 \Rightarrow a = a_0 = \theta_0 f_a$
$H \ll m_a \Rightarrow \ddot{a} + m_a^2 a \simeq 0 \Rightarrow a(t) = a_0 \cos(m_a t + \varphi)$

$H \gg m_a \Rightarrow \ddot{a} + 3H\dot{a} \simeq 0 \Rightarrow a = a_0 = \theta_0 f_a$

$H \ll m_a \Rightarrow \ddot{a} + m_a^2 a \simeq 0 \Rightarrow a(t) = a_0 \cos(m_a t + \varphi)$

Use WKB, ansatz $a(t) = A(t)\cos(m_a t + \varphi)$

Ex: slowly varying $A(t)$, $A \propto R^{-3/2}$

Recall: $\rho \propto a^2 \propto R^{-3} \Rightarrow$ exactly what CDM does

QCD Axion "Briefly" $\Rightarrow$ "QCD Axion Precisely" (Cortona+

Strong CP problem

$$\mathcal{L}_{QCD} \supset -\Theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$\Rightarrow$ neutron EDM ✗ $\Rightarrow \Theta < 10^{-10}$

Why?

$$\mathcal{L}_a = \frac{1}{2}(\partial a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

pion mass, decay

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u+m_d)^2}\sin^2\left(\frac{a}{2f_a} - \frac{\theta}{2}\right)}$$

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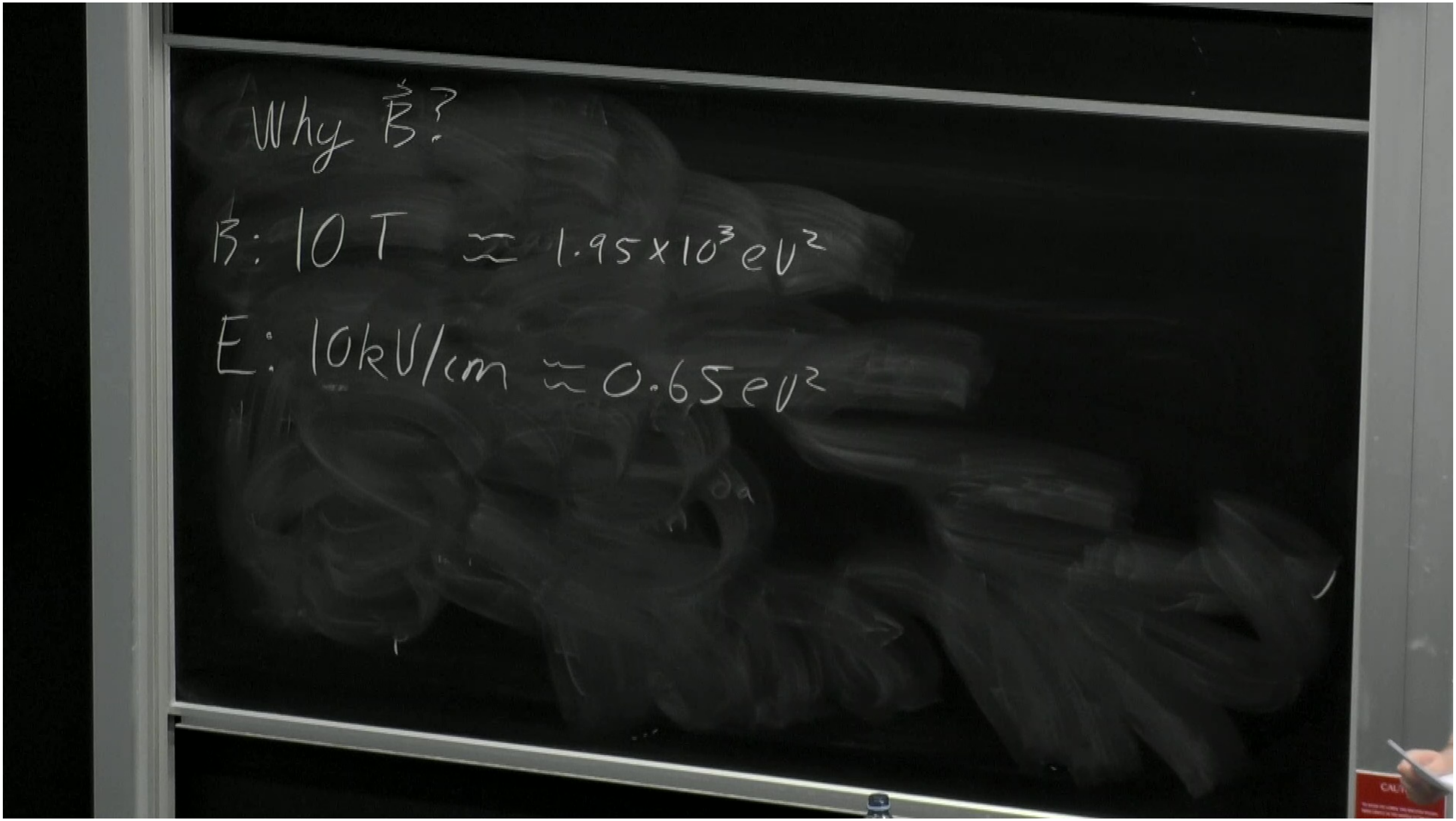
$$\mathcal{L}_a \supset -\frac{1}{2} \underbrace{\left(\overbrace{\frac{m_u m_d}{(m_u + m_d)^2}}^{\simeq \frac{1}{4}} \cdot \frac{m_\pi^2 f_\pi^2}{f_a^2} \right)}_{m_a^2} a^2$$

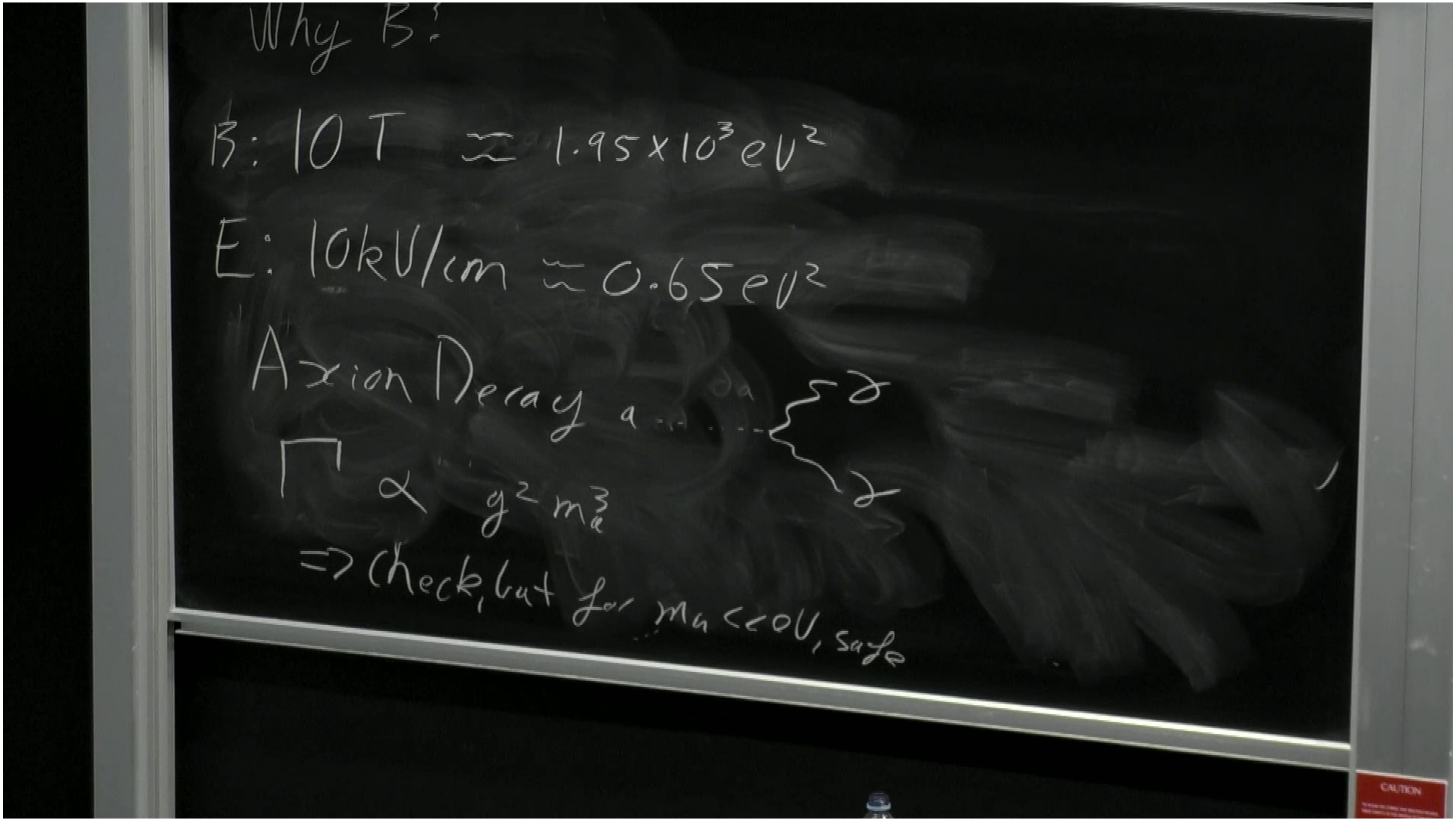
$$m_a f_a \simeq m_\pi f_\pi \Rightarrow f_a < M_{Pl} \Rightarrow m_a > 10^{-12}\,\text{eV}$$

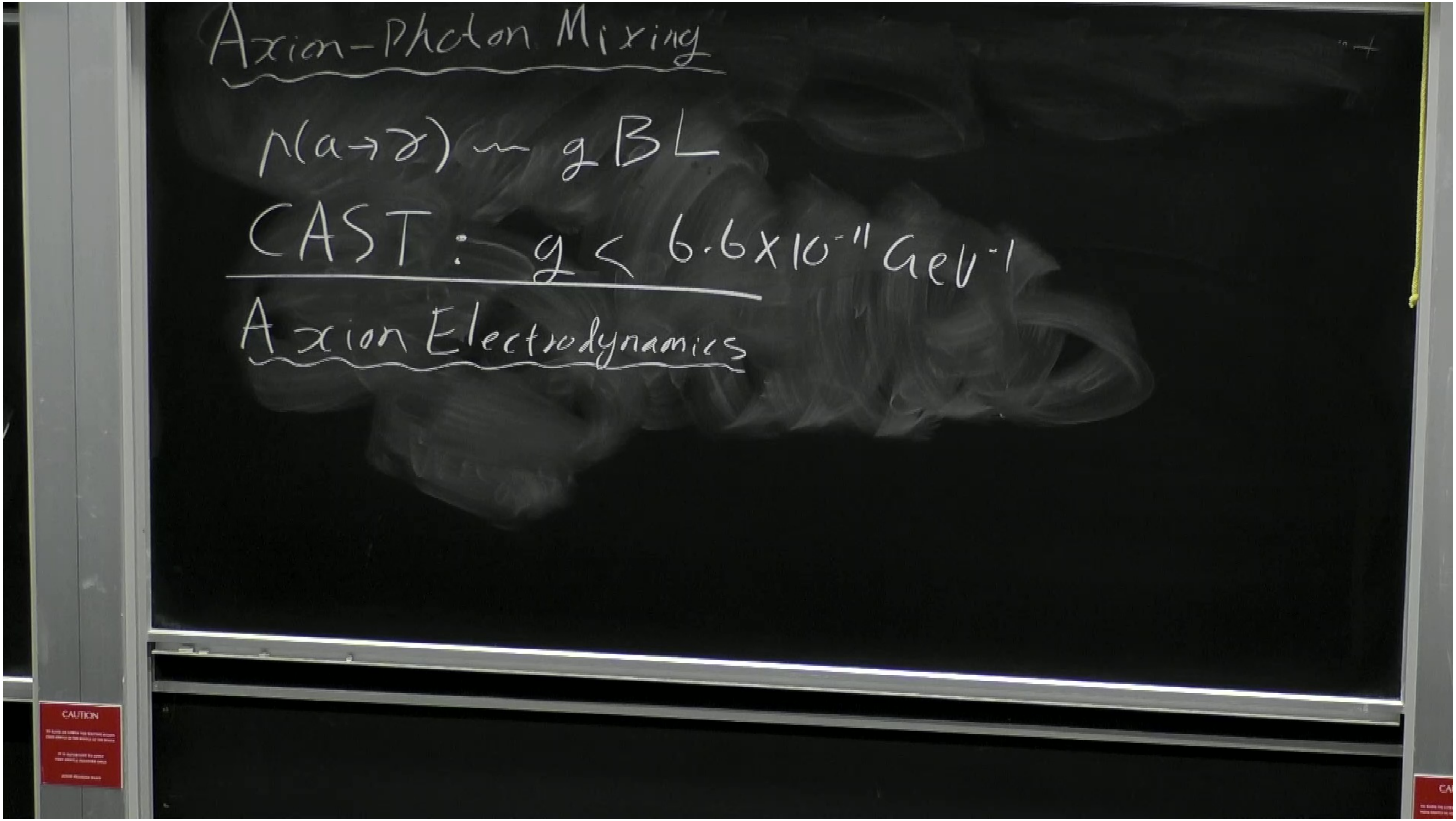
Axion Detection

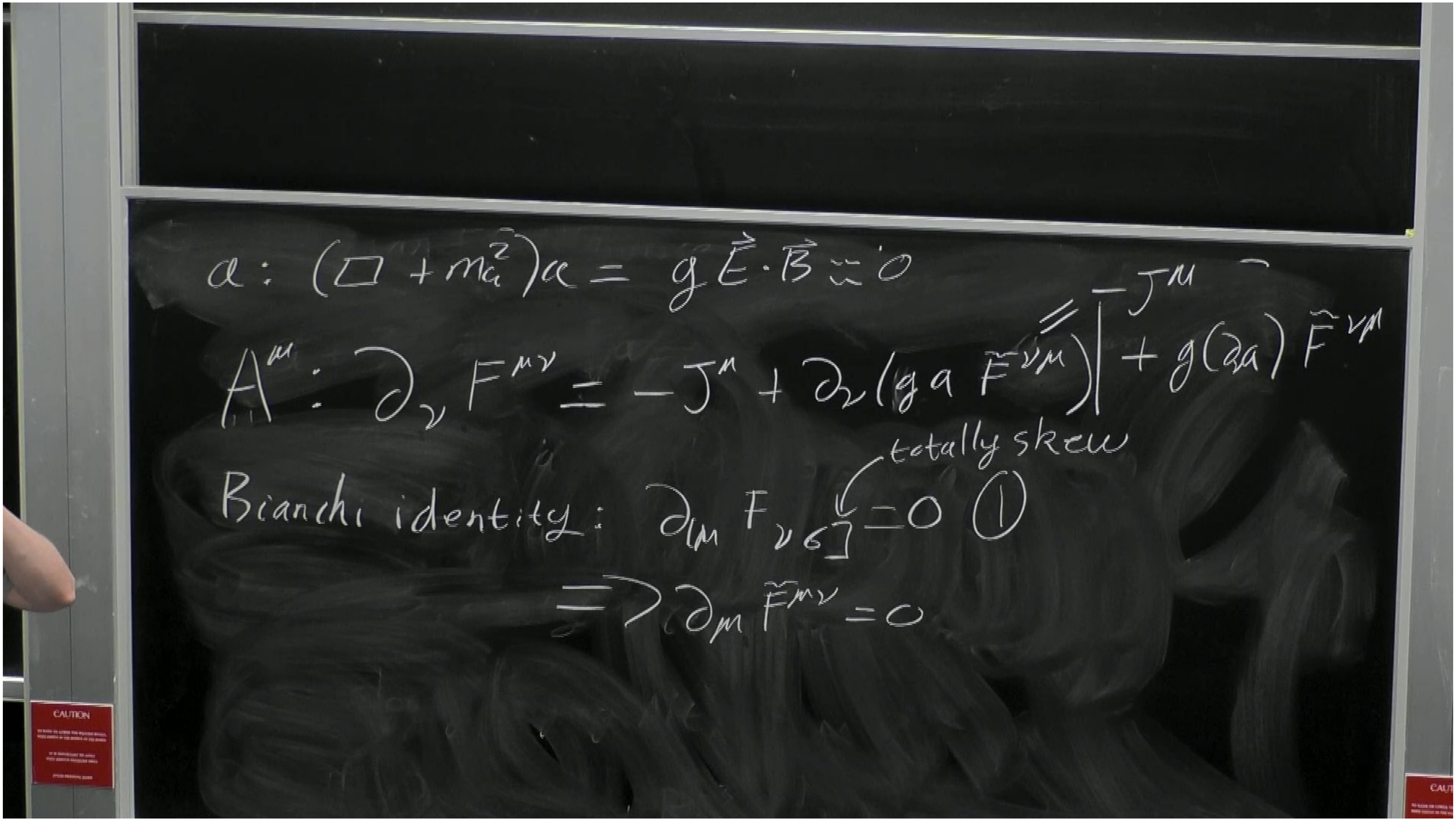
$$\mathcal{L} \supset -\frac{1}{4} \underbrace{g_{a\gamma\gamma}}_{\text{dim}=\text{"}-1\text{"}} \underbrace{a F^{\mu\nu}\tilde{F}_{\mu\nu}}_{\text{dim}-5} = g_{a\gamma\gamma}\, a\, \vec{E}\cdot\vec{B}$$

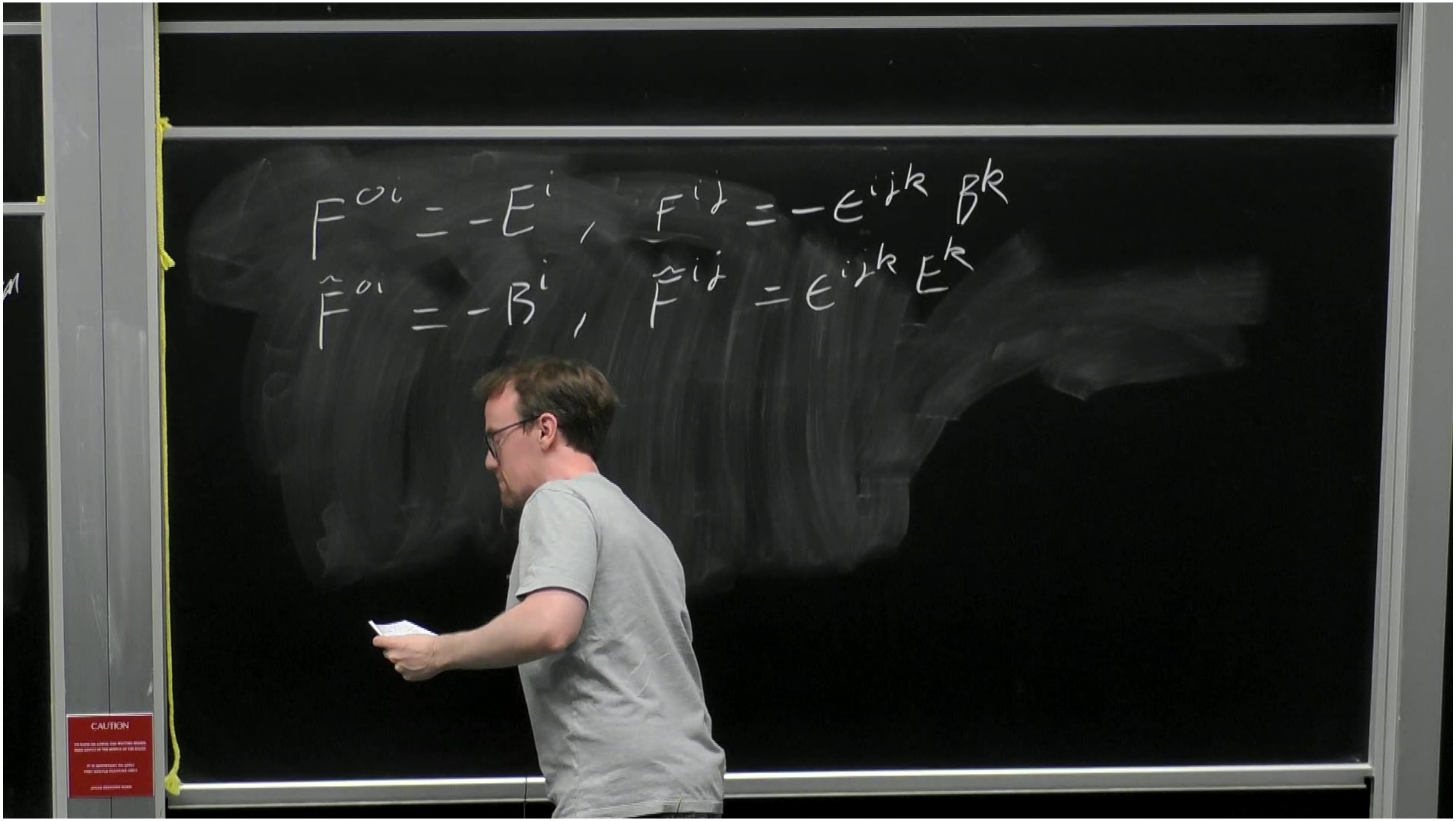
$$g \simeq \mathcal{O}(1)\times \frac{\alpha}{2\pi f_a} \simeq \frac{\alpha\, m_a}{2\pi m_\pi f_\pi}$$

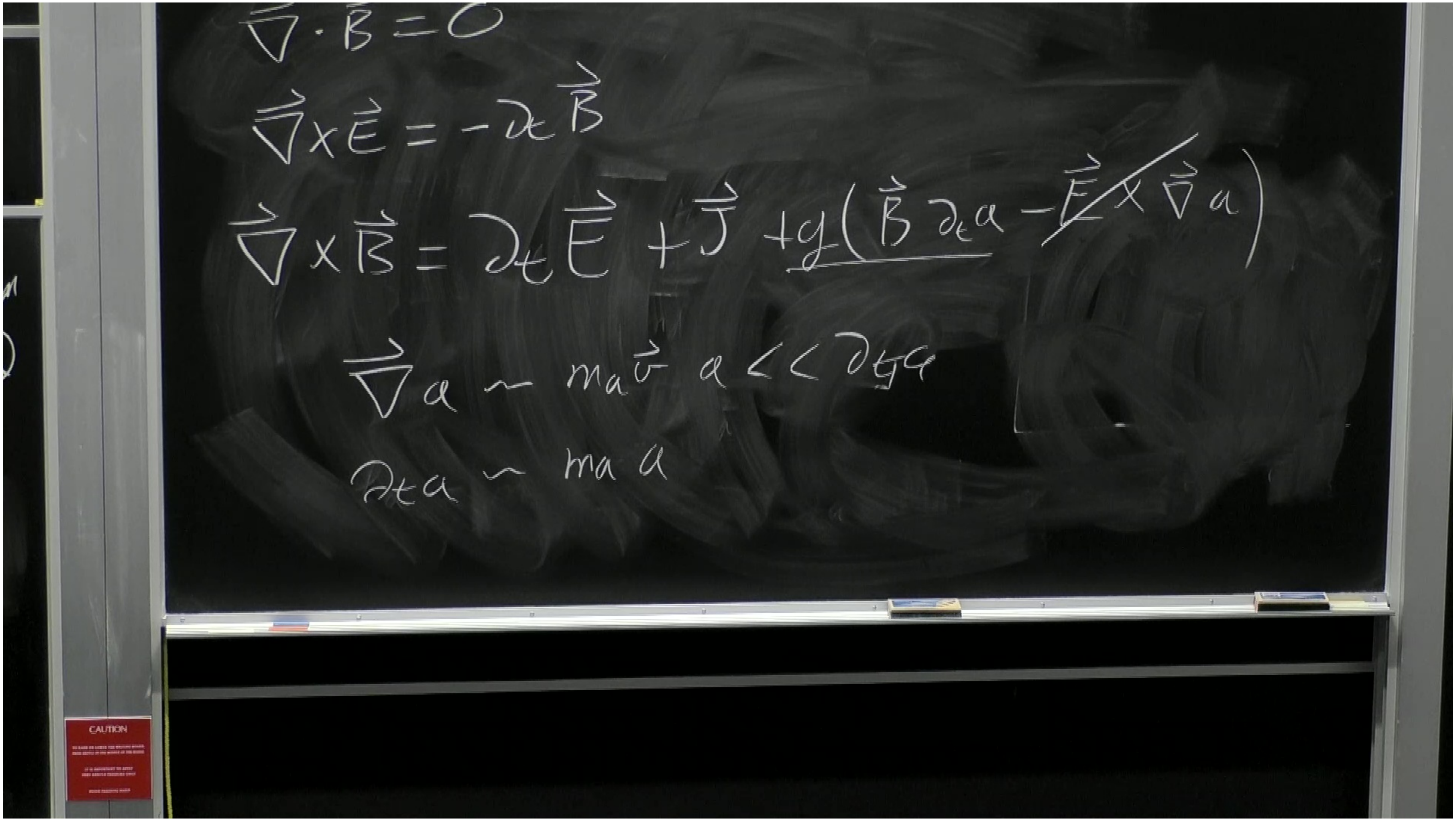

Why $\vec{B}$?
B: 10 T $\simeq$ 1.95×10³ eV²
E: 10kV/cm $\simeq$ 0.65 eV²

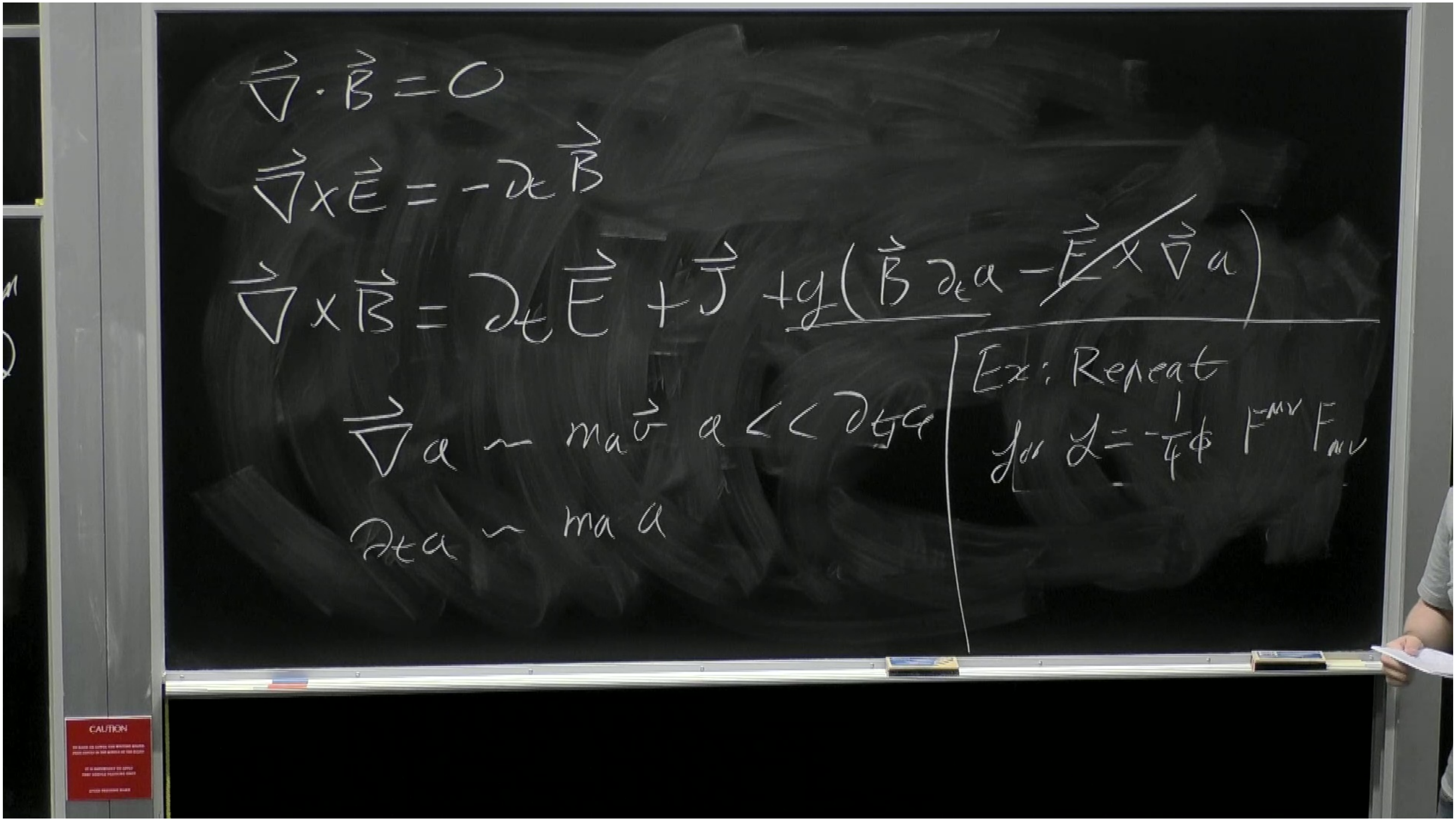

Why B?
B: 10 T ≃ 1.95×10³ eV²
E: 10kV/cm ≃ 0.65 eV²
Axion Decay
Γ ∝ g² m_a³
⇒ Check, but for m_a << eV, safe

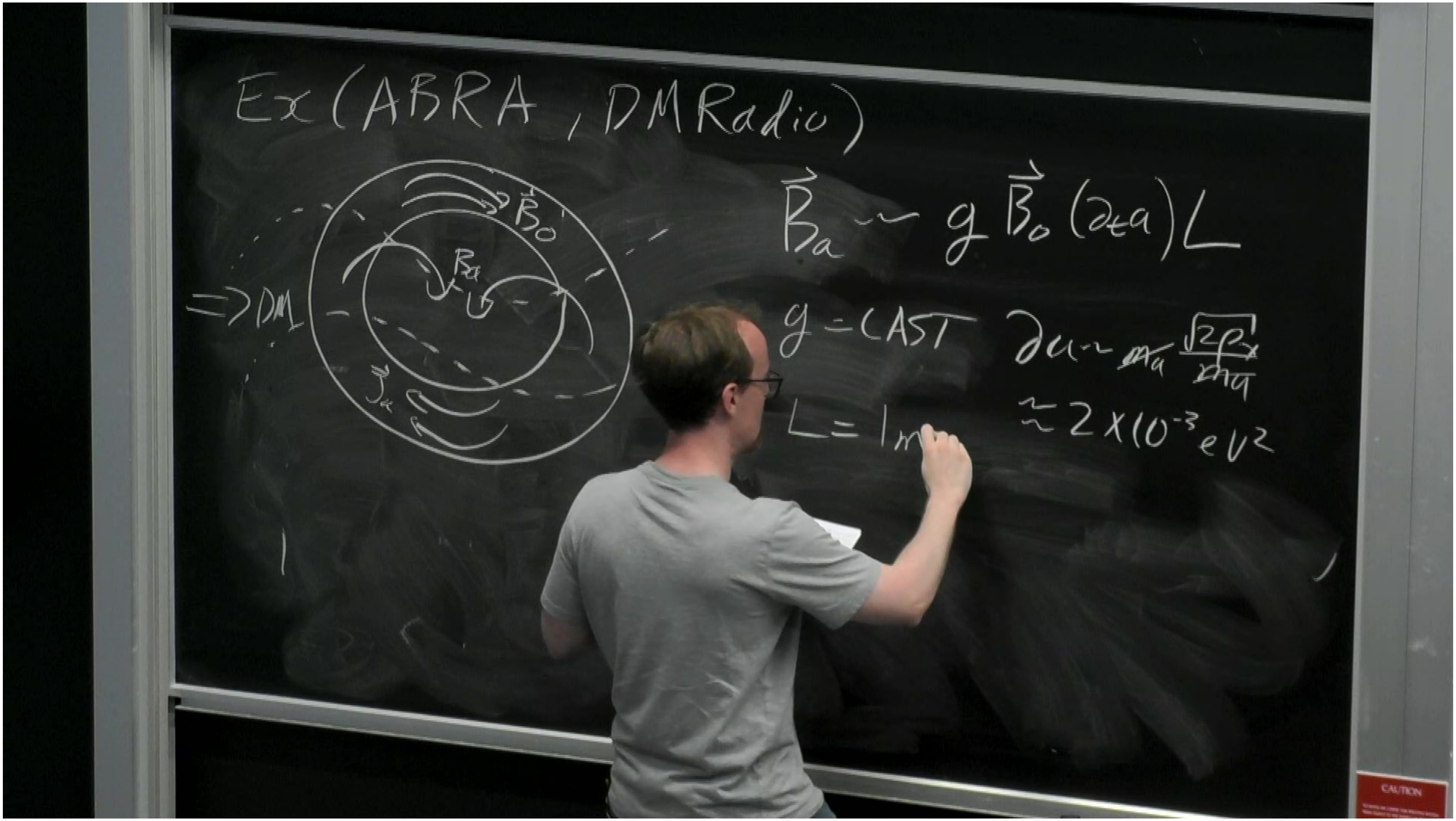

Axion-Photon Mixing
P(a→γ) ~ gBL
CAST: g < 6.6x10^-11 GeV^-1
Axion Electrodynamics
CAUTION

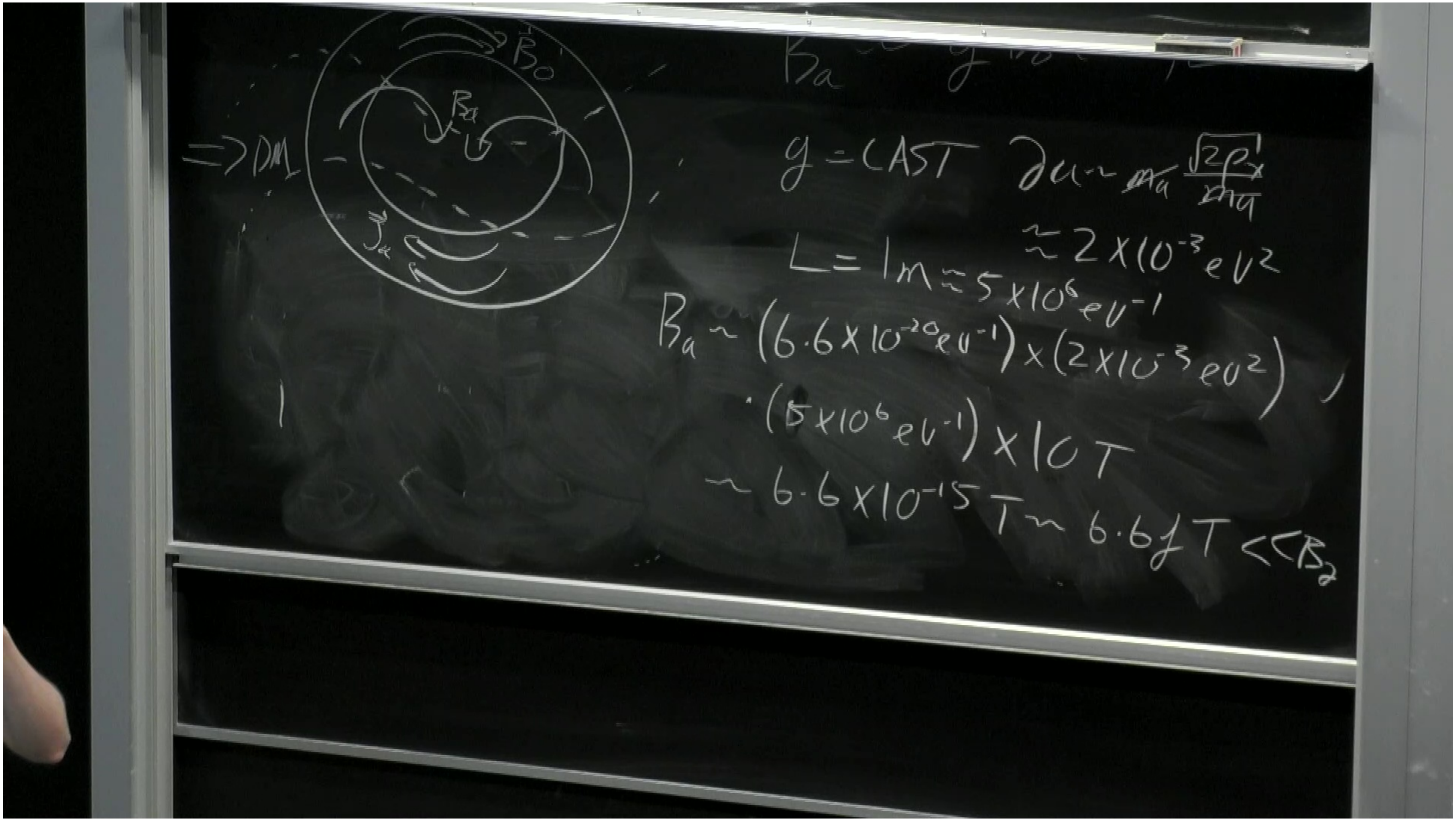

$a: (\Box + m_a^2) a = g \vec{E}\cdot\vec{B} \neq 0$
$A^\mu: \partial_\nu F^{\mu\nu} = -J^\mu + \partial_\nu (g a \tilde{F}^{\nu\mu}) = -J^\mu + g(\partial a)\tilde{F}^{\nu\mu}$
totally skew
Bianchi identity: $\partial_{[\mu} F_{\nu\sigma]} = 0$ ①
$\Rightarrow \partial_\mu \tilde{F}^{\mu\nu} = 0$

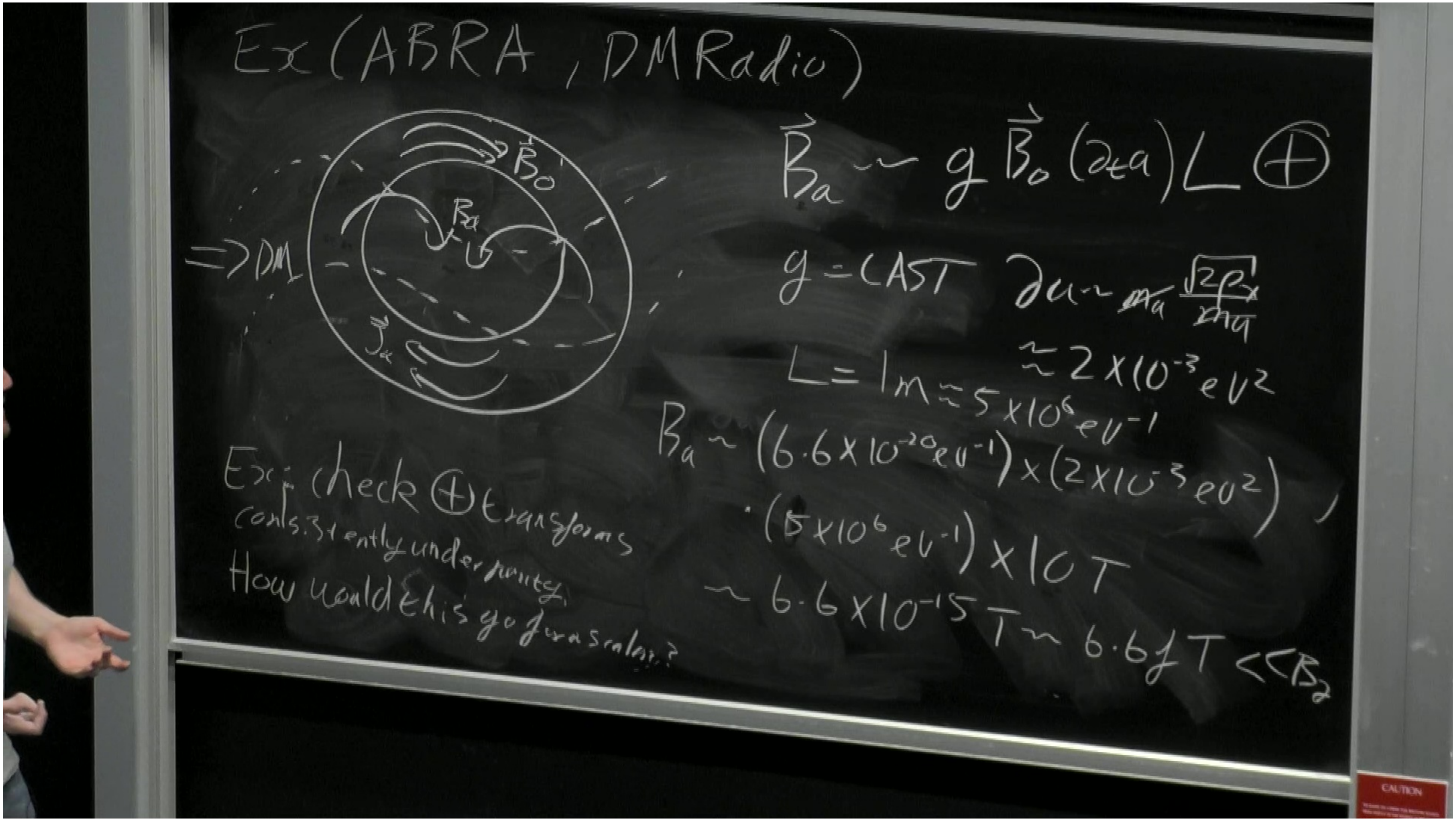

$F^{0i} = -E^i$, $F^{ij} = -\epsilon^{ijk} B^k$
$\hat{F}^{0i} = -B^i$, $\hat{F}^{ij} = \epsilon^{ijk} E^k$
CAUTION


$\vec\nabla \cdot \vec B = 0$
$\vec\nabla \times \vec E = -\partial_t \vec B$
$\vec\nabla \times \vec B = \partial_t \vec E + \vec J + g(\vec B \partial_t a - \vec E \times \vec\nabla a)$
$\vec\nabla a \sim m_a \vec v\, a << \partial_t a$
$\partial_t a \sim m_a a$
CAUTION


$\vec{\nabla}\cdot\vec{B}=0$
$\vec{\nabla}\times\vec{E}=-\partial_t\vec{B}$
$\vec{\nabla}\times\vec{B}=\partial_t\vec{E}+\vec{J}+g(\vec{B}\,\partial_t a-\vec{E}\times\vec{\nabla}a)$
$\vec{\nabla}a\sim m_a\vec{v}\,a \ll \partial_t a$
$\partial_t a\sim m_a a$
Ex: Repeat
for $\mathcal{L}=-\frac{1}{4}\phi F^{\mu\nu}F_{\mu\nu}$


Ex (ABRA, DMRadio)
DM
g = CAST
L = 1m
≃ 2×10⁻³ eV²


⇒ DM
B0
Ba
Ja
g = CAST
∂a ~ √(2ρχ)/ma
≈ 2×10^-3 eV^2
L = 1m ≈ 5×10^6 eV^-1
Ba ~ (6.6×10^-20 eV^-1) × (2×10^-3 eV^2)
· (5×10^6 eV^-1) × 10 T
~ 6.6×10^-15 T ~ 6.6 fT << B0


Ex (ABRA, DMRadio)
$\vec{B}_0$
B_a
J_{eff}
$\Rightarrow$ DM
$\vec{B}_a \sim g \vec{B}_0 (\partial_t a) L$ ⊕
$g = $ CAST
$\partial_t a \sim m_a \frac{\sqrt{2\rho_x}}{m_a} \simeq 2 \times 10^{-3}\, eV^2$
$L = 1m \simeq 5 \times 10^6\, eV^{-1}$
$B_a \sim (6.6 \times 10^{-20} eV^{-1}) \times (2 \times 10^{-3} eV^2) \cdot (5 \times 10^6 eV^{-1}) \times 10\, T$
$\sim 6.6 \times 10^{-15}\, T \sim 6.6\, fT \ll B_0$
Ex: check ⊕ transforms consistently under parity.
How would this go for a scalar?