Title: Displaced vertices from dark matter freeze-in

Date: May 08, 2015 12:30 PM

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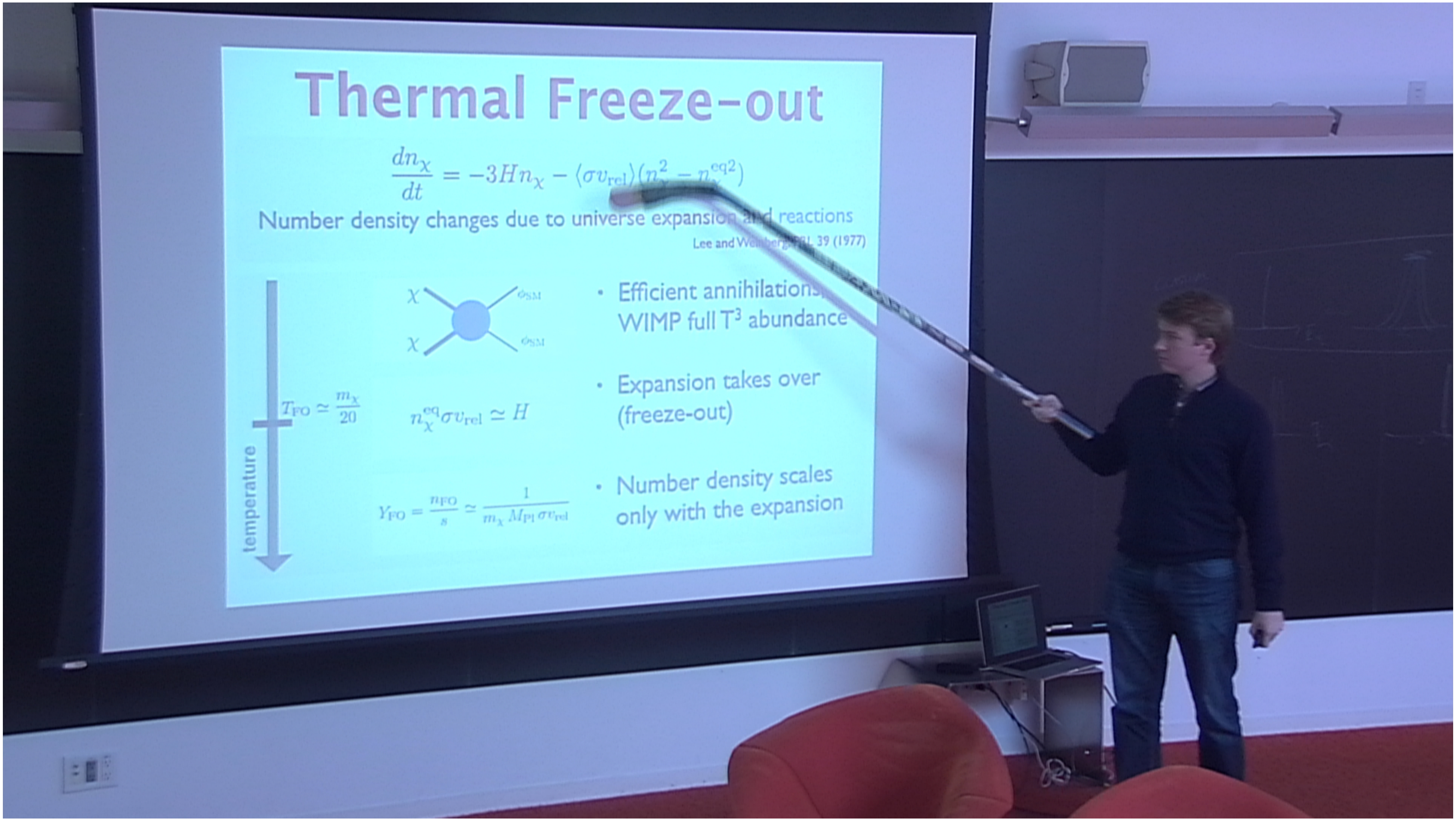
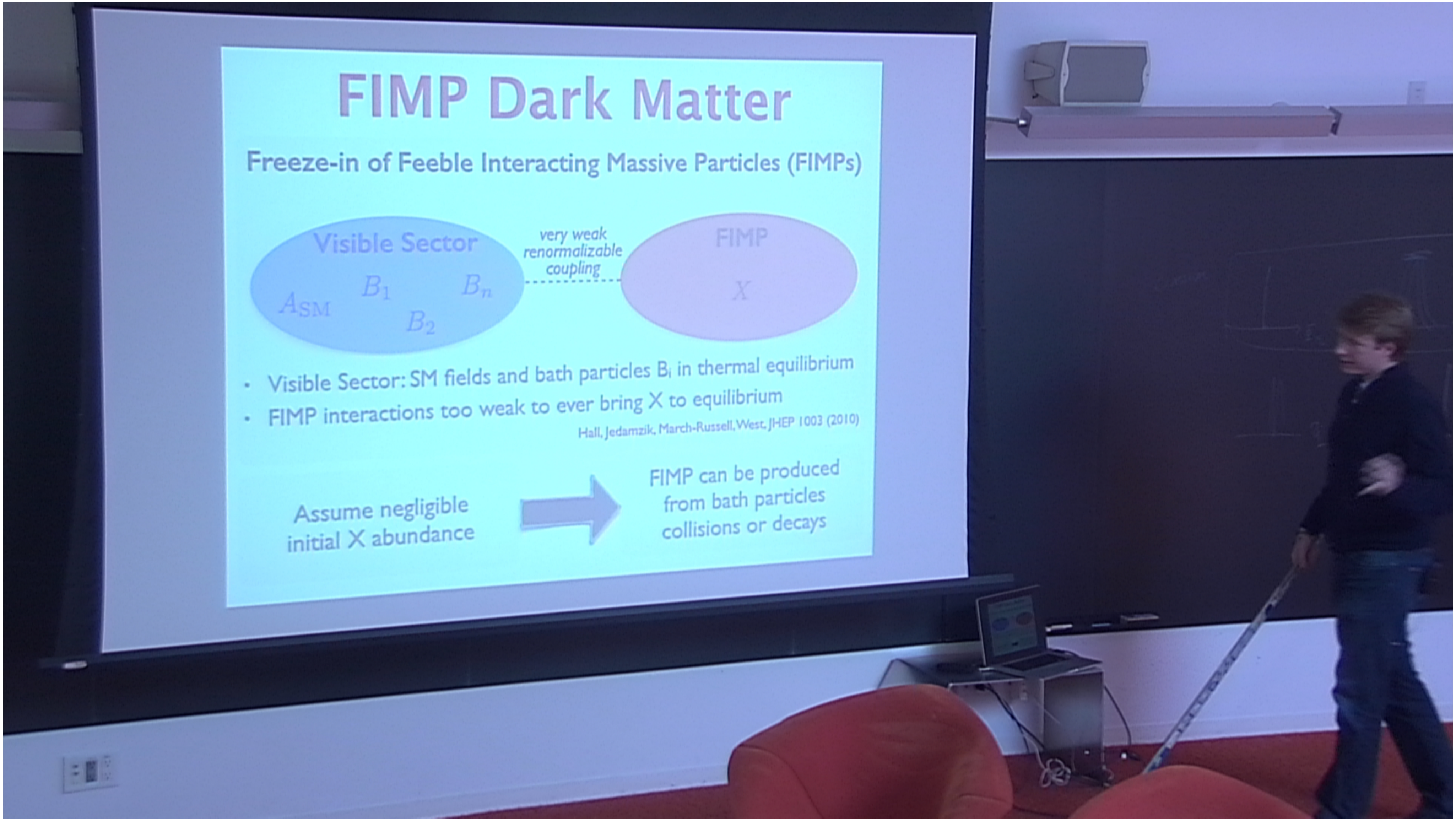
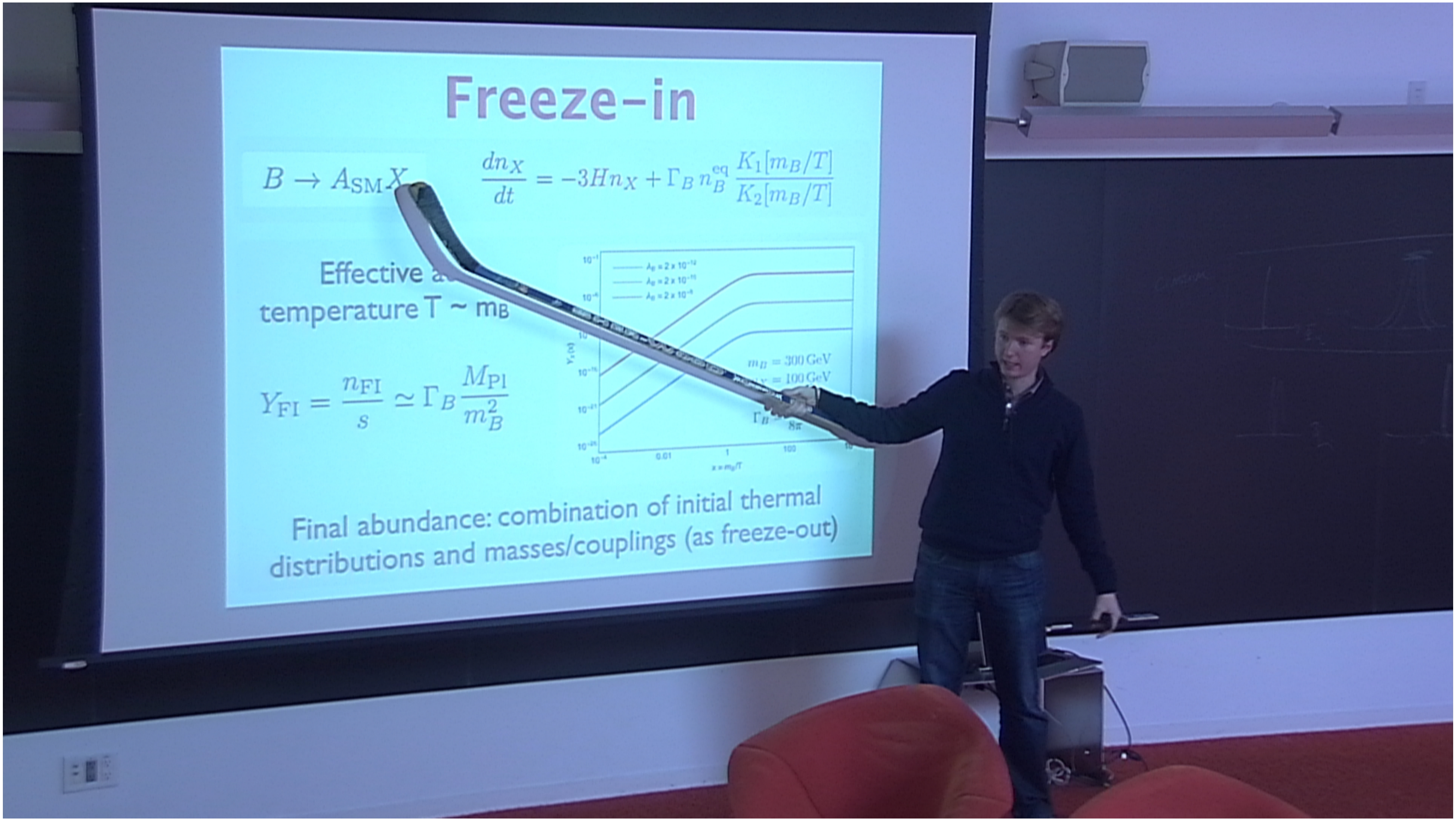
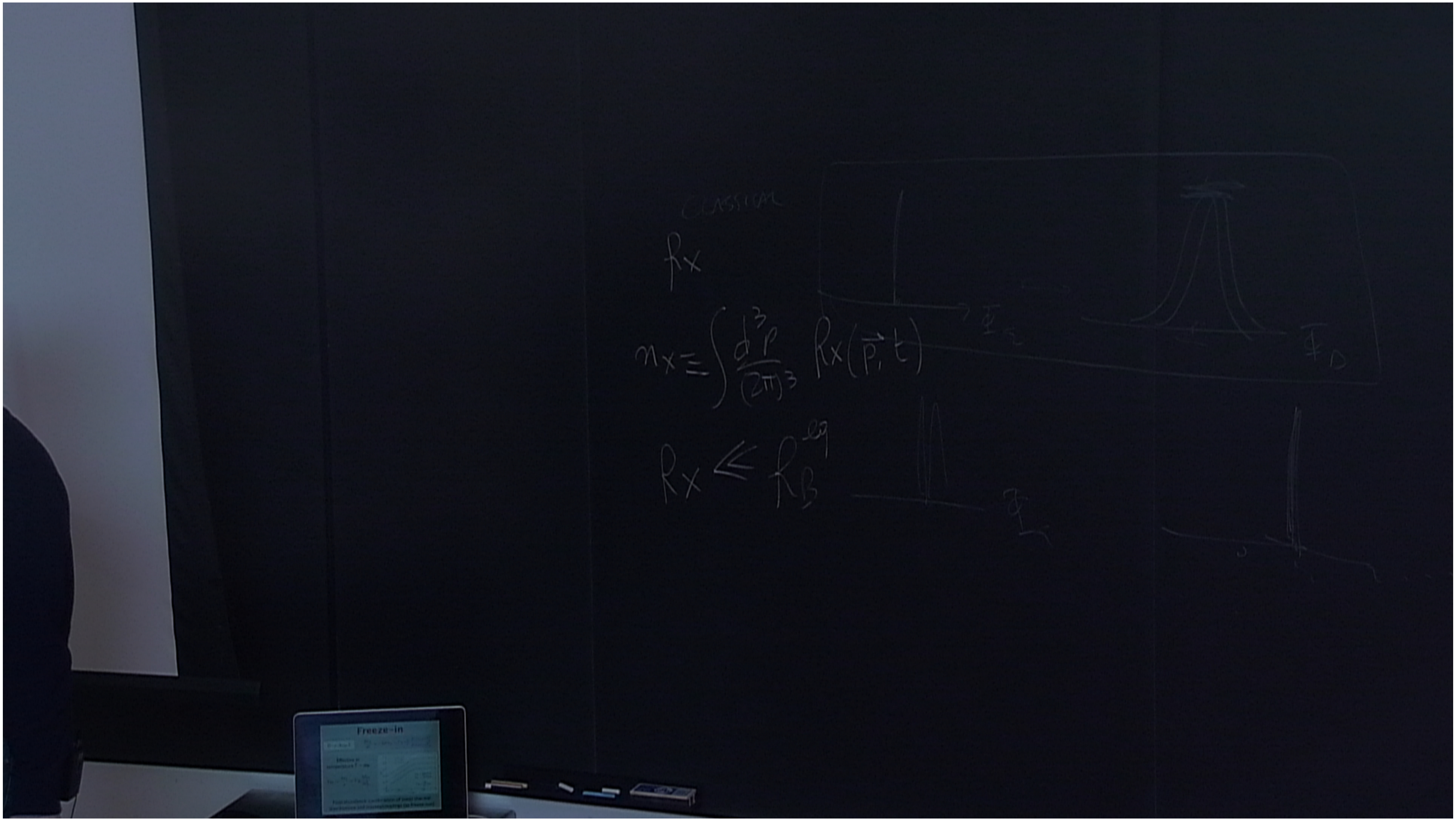
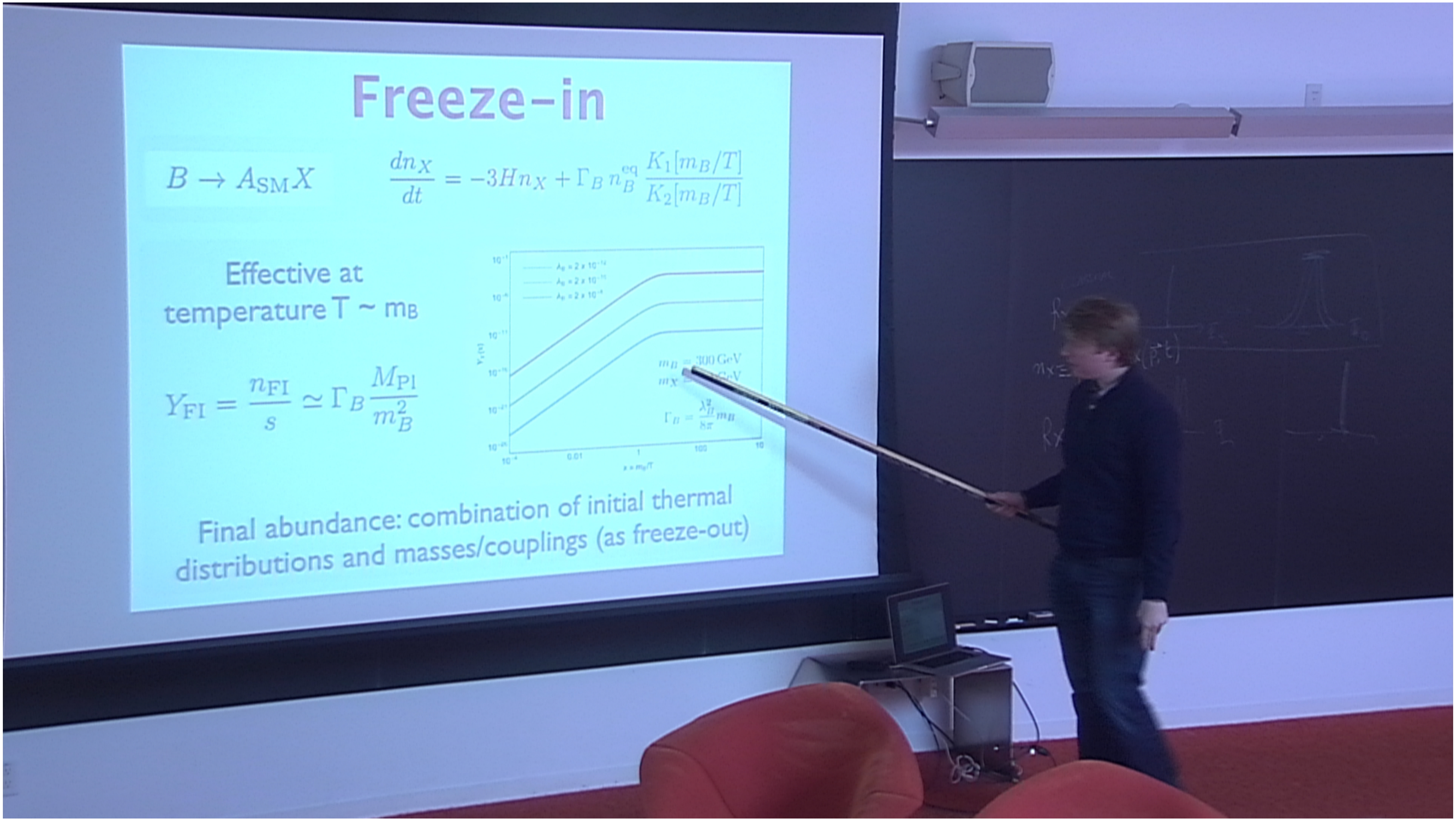
Abstract: <p>
Freeze-in is a general and calculable mechanism for dark matter production in the early universe. Assuming a standard cosmological history, such a framework predicts metastable particles with a lifetime generically too long to observe their decays in a collider environment. In this talk I will report work in progress where we consider alternative cosmologies, where entropy dumped in the primordial Standard Model plasma leads to shorter lifetime for the metastable particles in order to reproduce the observed dark matter density. Famous examples are moduli decays in SUSY theories and inflationary reheating. Remarkably, for a large region of the parameter space the decay lengths are in the displaced vertex range and they can be observable at present and future colliders.</p>

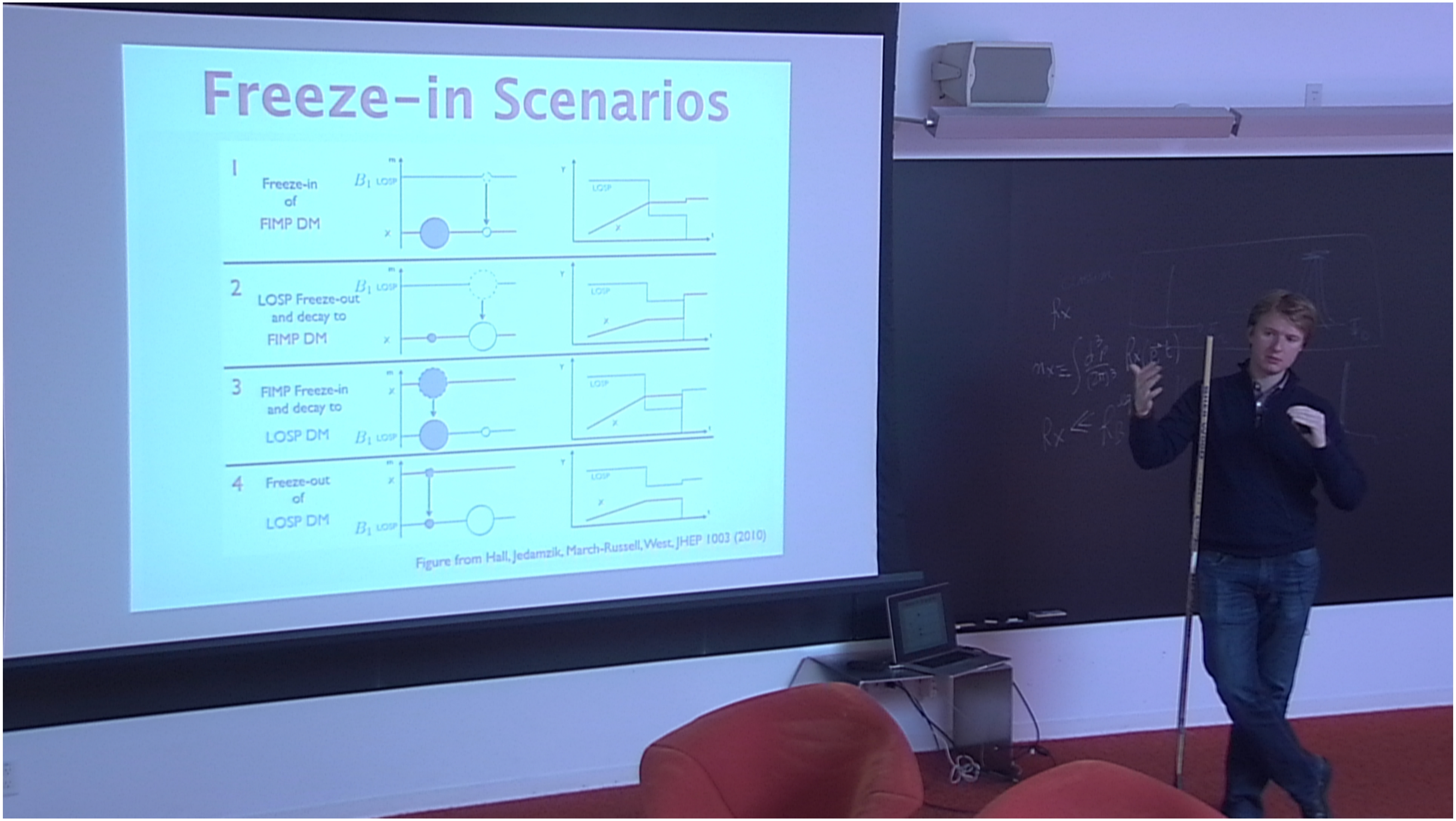

Thermal Freeze-out
$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{\rm rel} \rangle (n_\chi^2 - n_\chi^{\rm eq2})$
Number density changes due to universe expansion and reactions
PRL 39 (1977)
χ
χ
$\phi_{\rm SM}$
$\phi_{\rm SM}$
Efficient annihilations
WIMP full T^3 abundance
$T_{\rm FO} \simeq \frac{m_\chi}{20}$
$n_\chi^{\rm eq} \sigma v_{\rm rel} \simeq H$
Expansion takes over (freeze-out)
temperature
$Y_{\rm FO} = \frac{n_{\rm FO}}{s} \simeq \frac{1}{m_\chi M_{\rm Pl} \sigma v_{\rm rel}}$
Number density scales only with the expansion

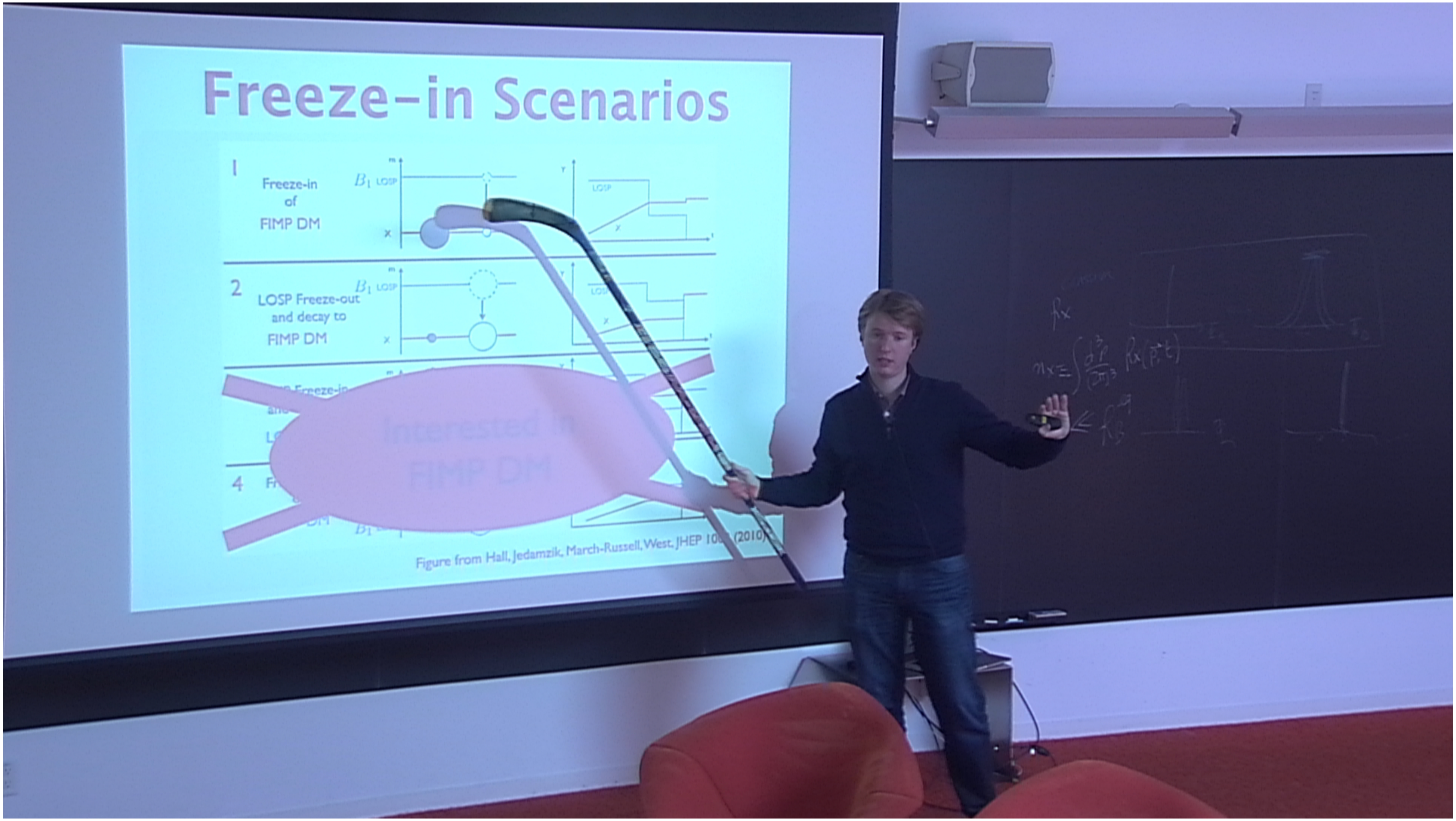

FIMP Dark Matter
Freeze-in of Feeble Interacting Massive Particles (FIMPs)
Visible Sector
A_{SM}
B_1
B_2
B_n
very weak renormalizable coupling
FIMP
X
Visible Sector: SM fields and bath particles B_i in thermal equilibrium
FIMP interactions too weak to ever bring X to equilibrium
Hall, Jedamzik, March-Russell, West, JHEP 1003 (2010)
Assume negligible initial X abundance
FIMP can be produced from bath particles collisions or decays

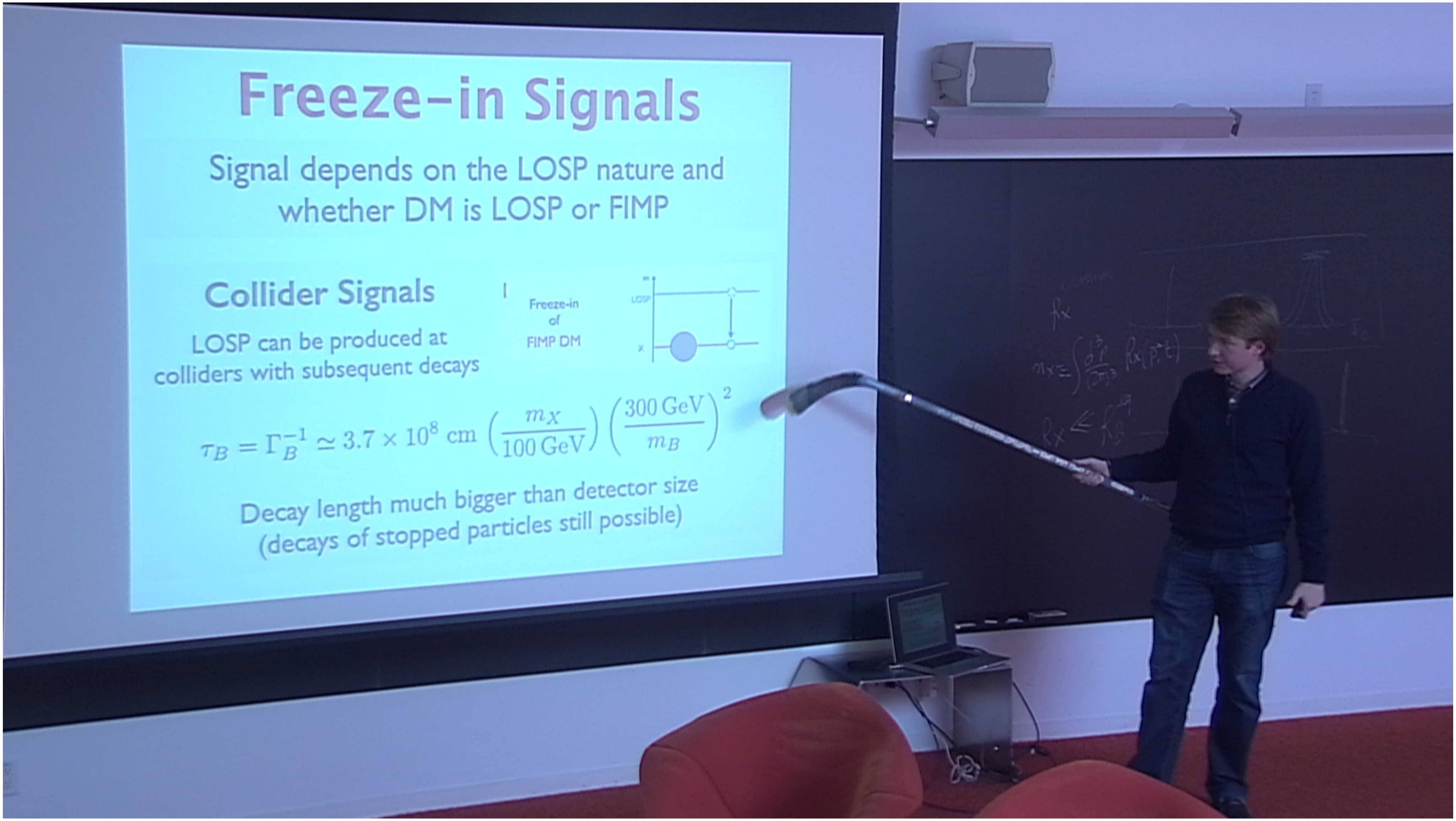

Freeze-in
$B \to A_{SM} X$
$\frac{dn_X}{dt} = -3Hn_X + \Gamma_B n_B^{eq} \frac{K_1[m_B/T]}{K_2[m_B/T]}$
temperature T ~ mB
$Y_{FI} = \frac{n_{FI}}{s} \simeq \Gamma_B \frac{M_{Pl}}{m_B^2}$
$m_B = 300\,\mathrm{GeV}$
Final abundance: combination of initial thermal distributions and masses/couplings (as freeze-out)

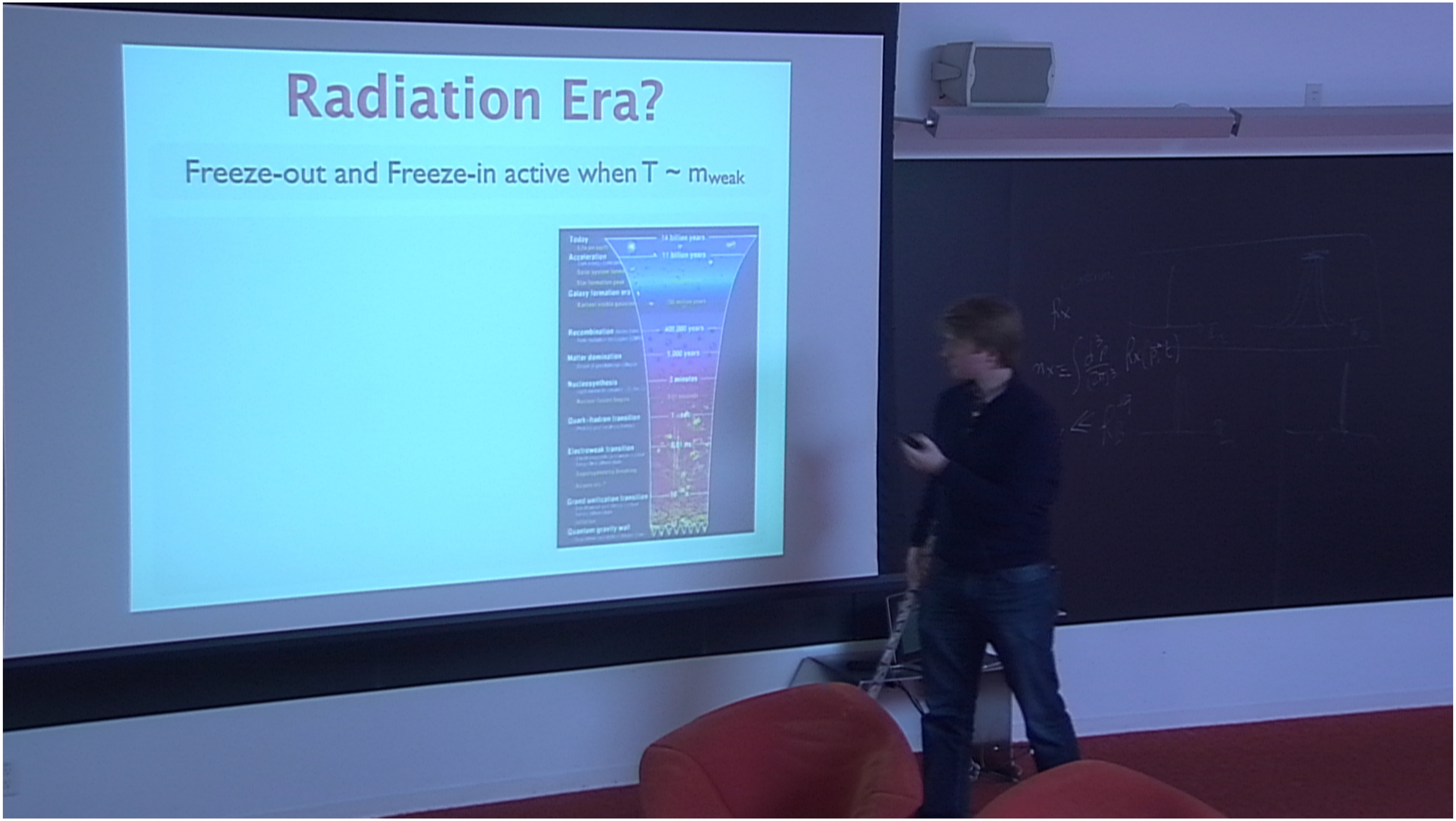

CLASSICAL
f_X
$n_X = \int \frac{d^3p}{(2\pi)^3} f_X(\vec{p}, t)$
$f_X \ll f_B^{eq}$
Freeze-in


Freeze-in
$B \to A_{SM} X$
$\frac{dn_X}{dt} = -3Hn_X + \Gamma_B\, n_B^{eq} \frac{K_1[m_B/T]}{K_2[m_B/T]}$
Effective at temperature T ~ mB
$Y_{FI} = \frac{n_{FI}}{s} \simeq \Gamma_B \frac{M_{Pl}}{m_B^2}$
$m_B = 300$ GeV
$\Gamma_B = \frac{\lambda_B^2}{8\pi} m_B$
Final abundance: combination of initial thermal distributions and masses/couplings (as freeze-out)

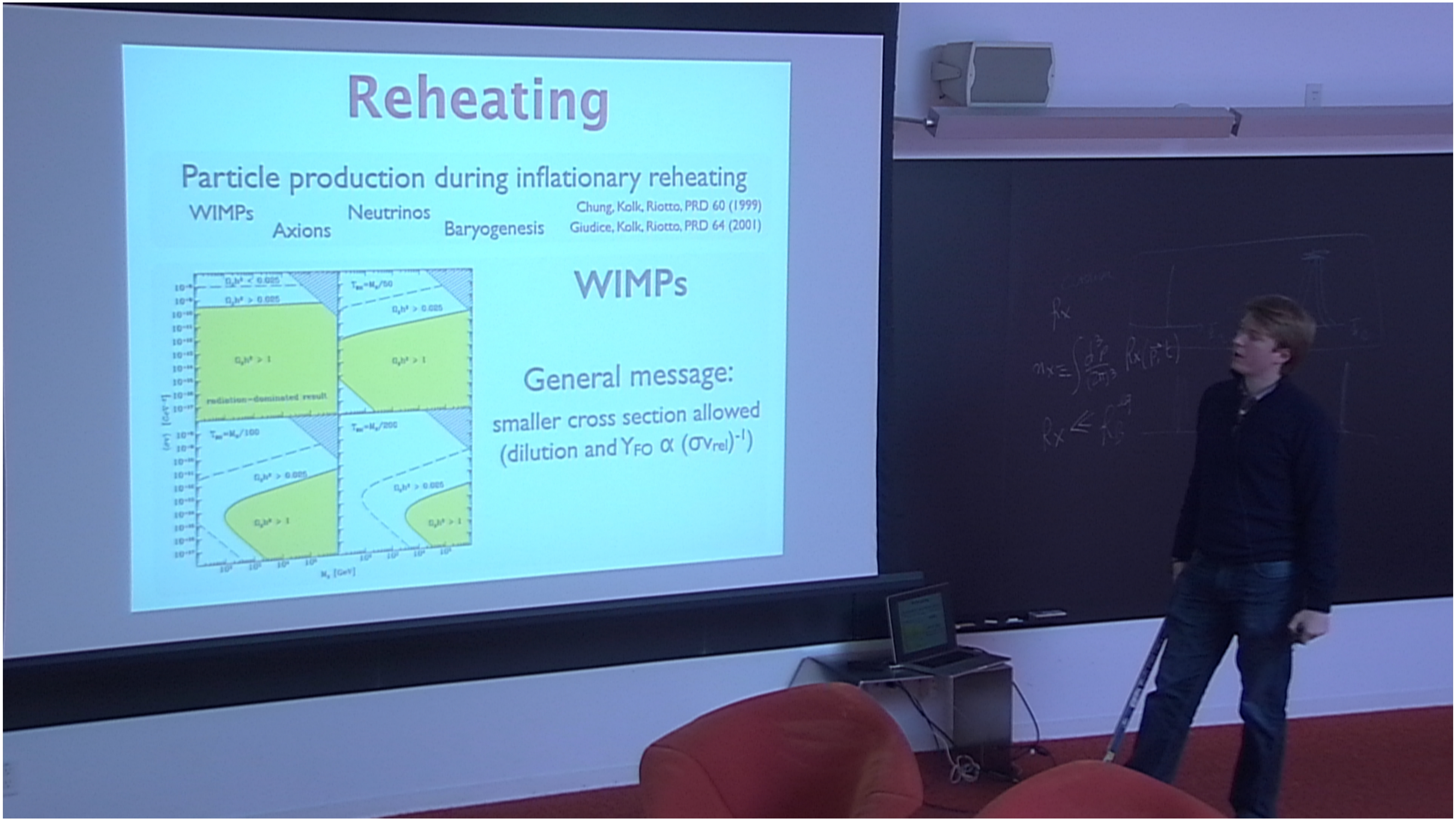

Freeze-in Scenarios
1
Freeze-in of FIMP DM
2
LOSP Freeze-out and decay to FIMP DM
3
FIMP Freeze-in and decay to LOSP DM
4
Freeze-out of LOSP DM
Figure from Hall, Jedamzik, March-Russell, West, JHEP 1003 (2010)

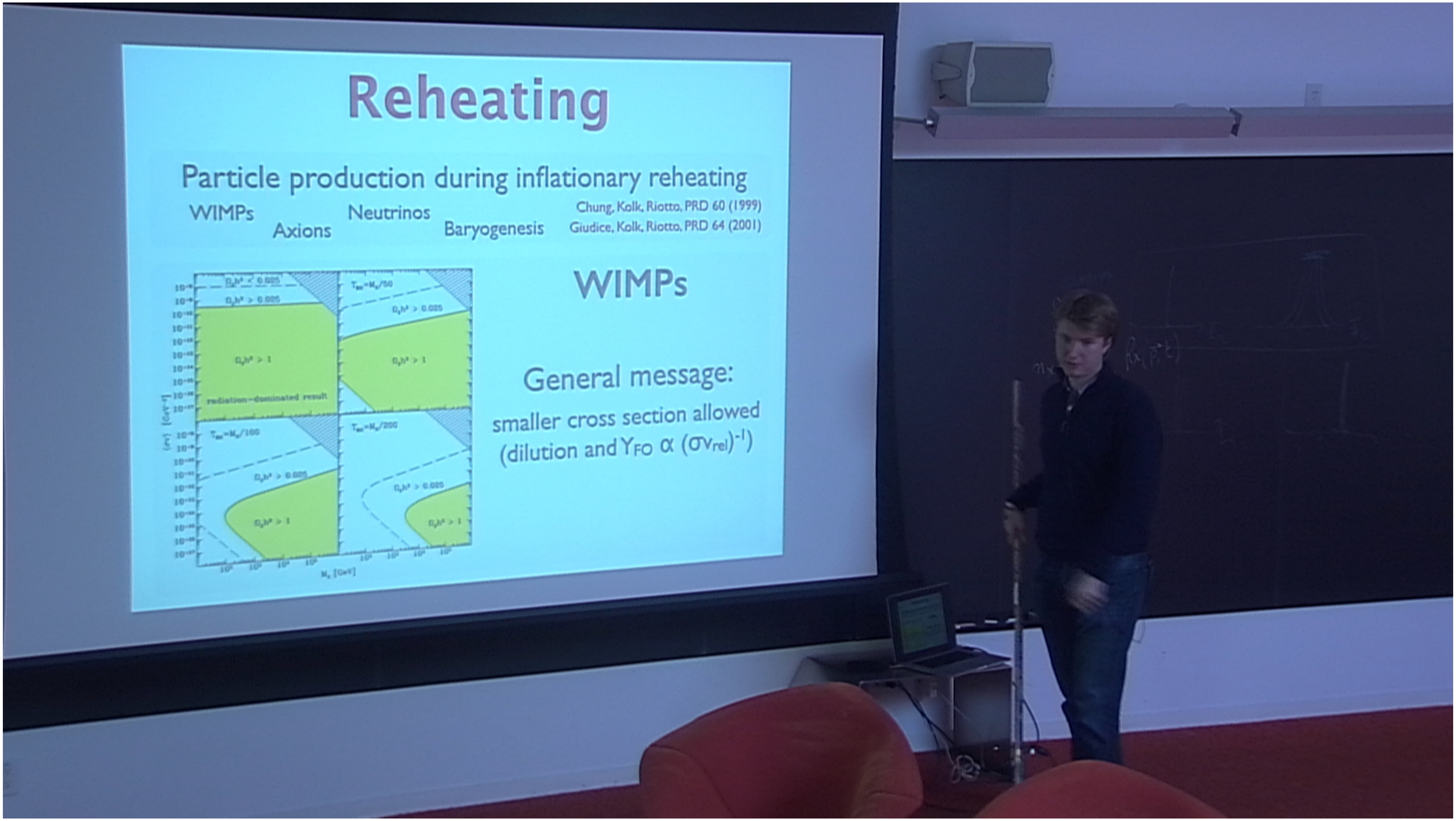

Freeze-in Scenarios
1
Freeze-in of FIMP DM
2
LOSP Freeze-out and decay to FIMP DM
4
Interested in FIMP DM
Figure from Hall, Jedamzik, March-Russell, West, JHEP 10 (2010)


Freeze-in Signals
Signal depends on the LOSP nature and whether DM is LOSP or FIMP
Collider Signals
LOSP can be produced at colliders with subsequent decays
Freeze-in of FIMP DM
LOSP
X
$\tau_B = \Gamma_B^{-1} \simeq 3.7 \times 10^8 \text{ cm} \left(\frac{m_X}{100\,\text{GeV}}\right)\left(\frac{300\,\text{GeV}}{m_B}\right)^2$
Decay length much bigger than detector size
(decays of stopped particles still possible)


Radiation Era?
Freeze-out and Freeze-in active when T ~ m_weak


Radiation Era?
Freeze-out and Freeze-in active when T ~ m_{weak}
Assuming standard cosmology this happens during a radiation dominated era
Today
14 billion years
Acceleration
11 billion years
Galaxy formation era
Recombination
400,000 years
Matter domination
5,000 years
3 minutes
Electroweak transition
Grand unification transition
Quantum gravity wall


Reheating
Particle production during inflationary reheating
WIMPs
Axions
Neutrinos
Baryogenesis
Chung, Kolb, Riotto, PRD 60 (1999)
Giudice, Kolb, Riotto, PRD 64 (2001)
WIMPs
General message:
smaller cross section allowed
(dilution and Y_{FO} α $(\sigma v_{rel})^{-1}$)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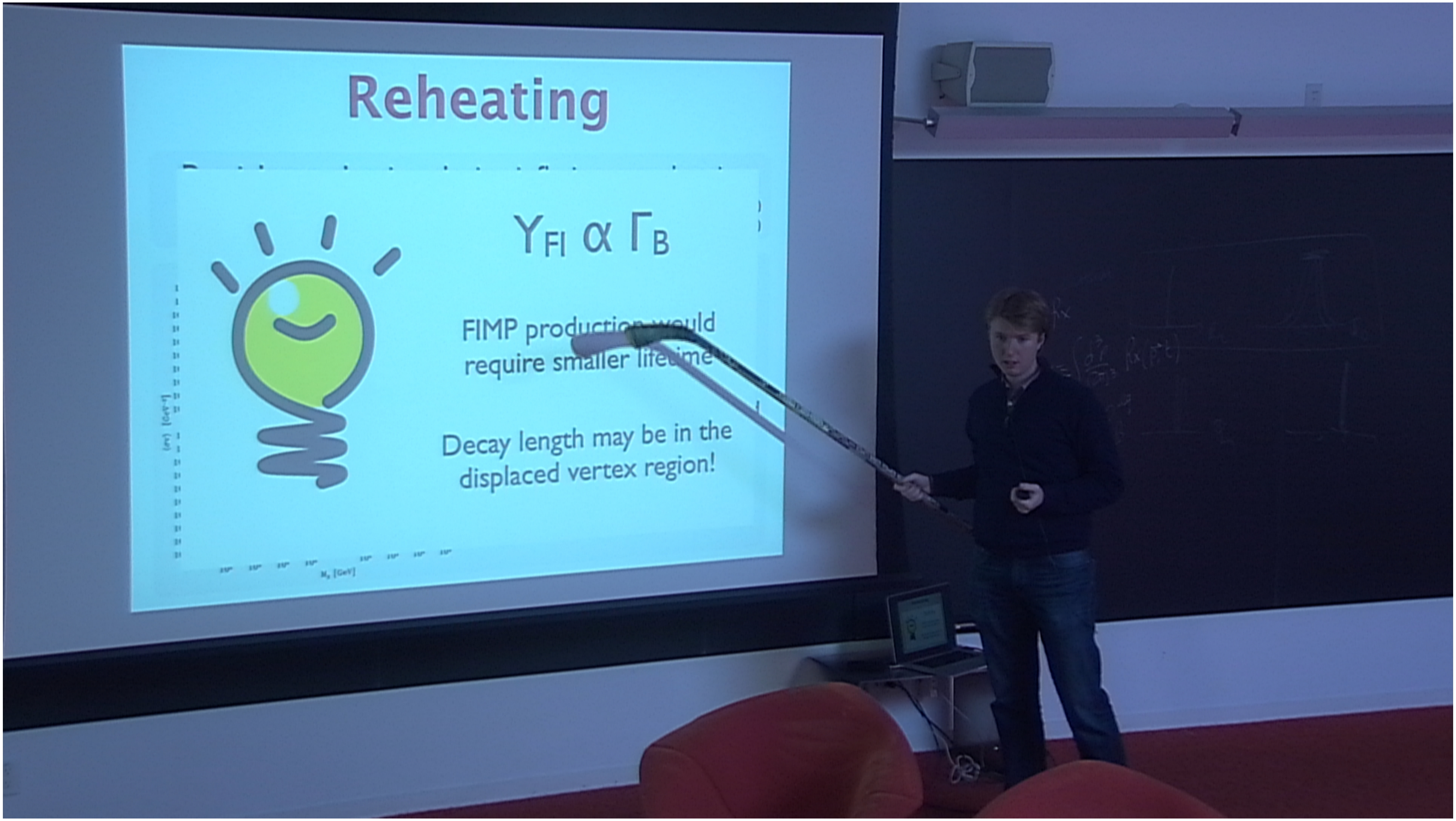
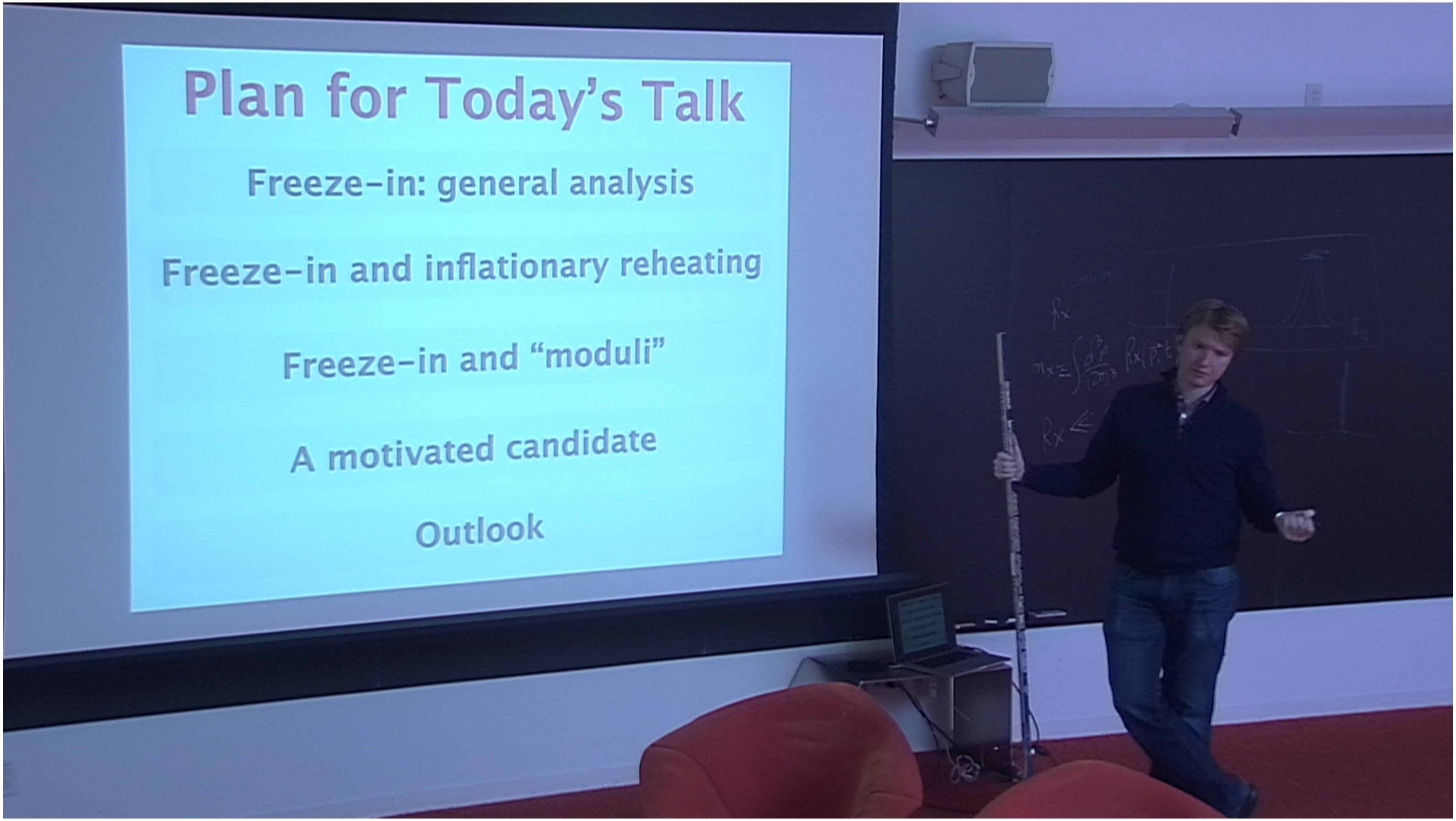
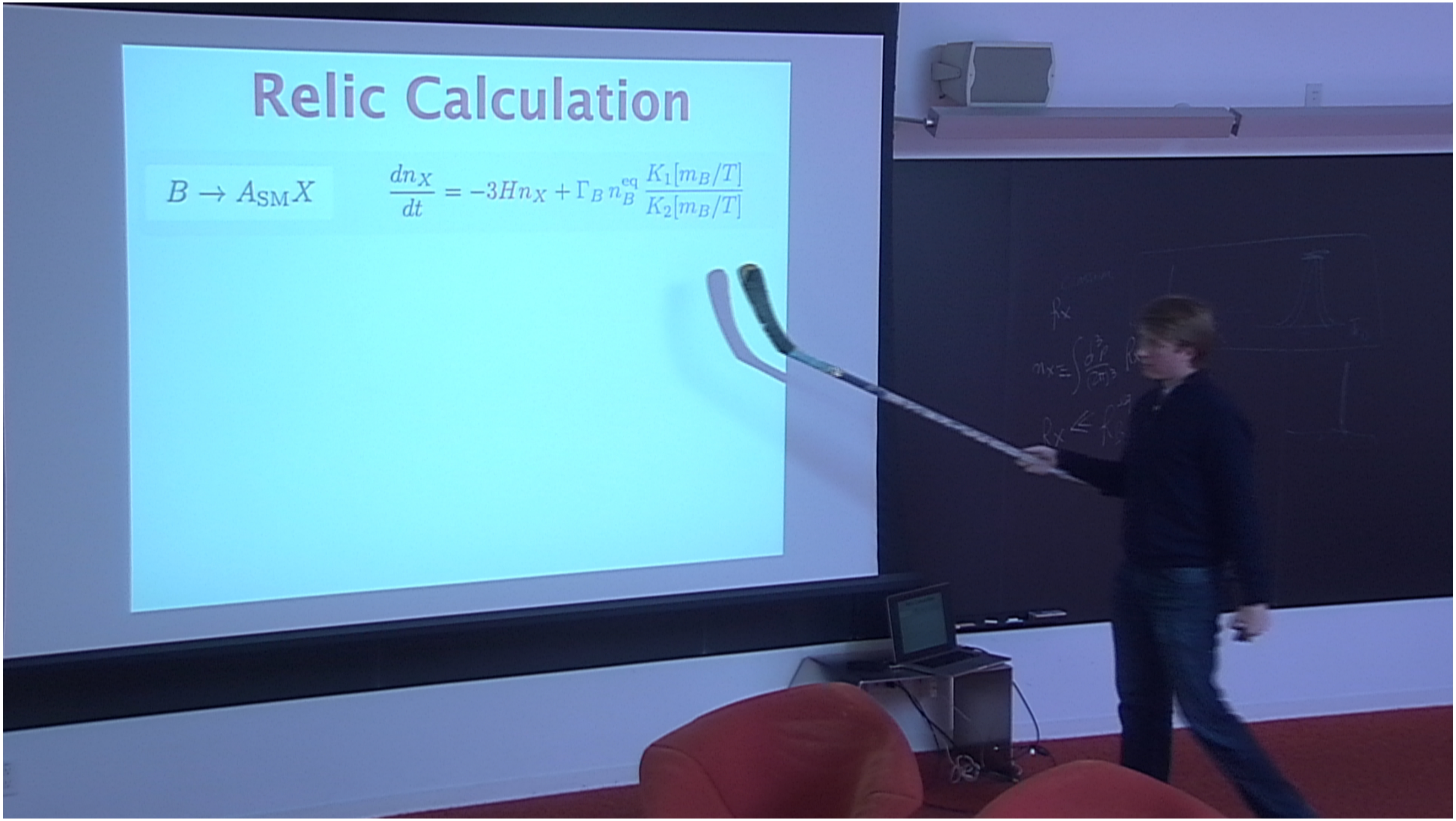
General message:
smaller cross section allowed
(dilution and $Y_{FO} \propto (\sigma v_{rel})^{-1}$)


Reheating
$Y_{FI} \propto \Gamma_B$
FIMP production would
require smaller lifetime
Decay length may be in the
displaced vertex region!


Plan for Today's Talk
Freeze-in: general analysis
Freeze-in and inflationary reheating
Freeze-in and "moduli"
A motivated candidate
Outlook


Relic Calculation
$B \to A_{\rm SM} X$
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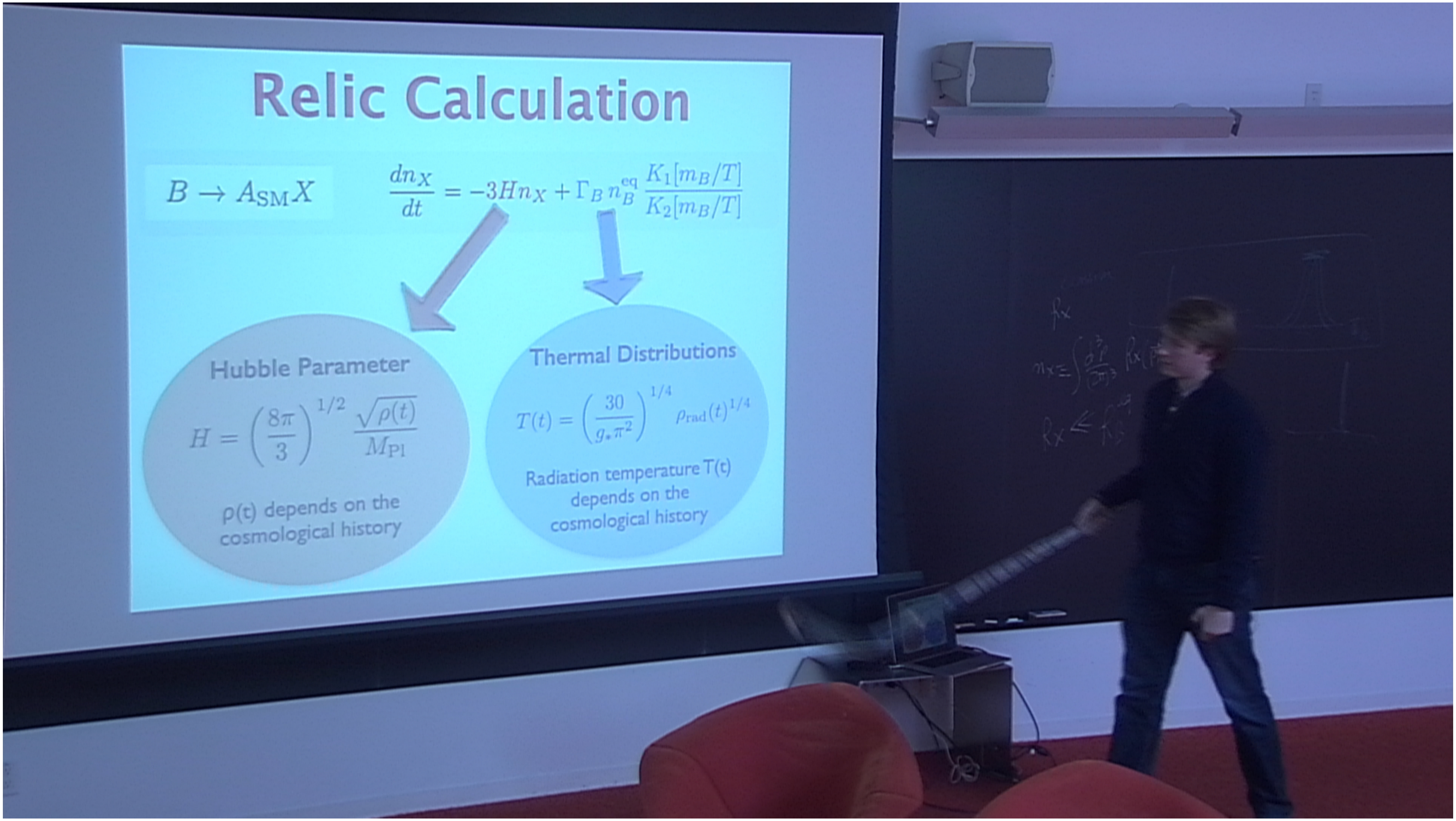
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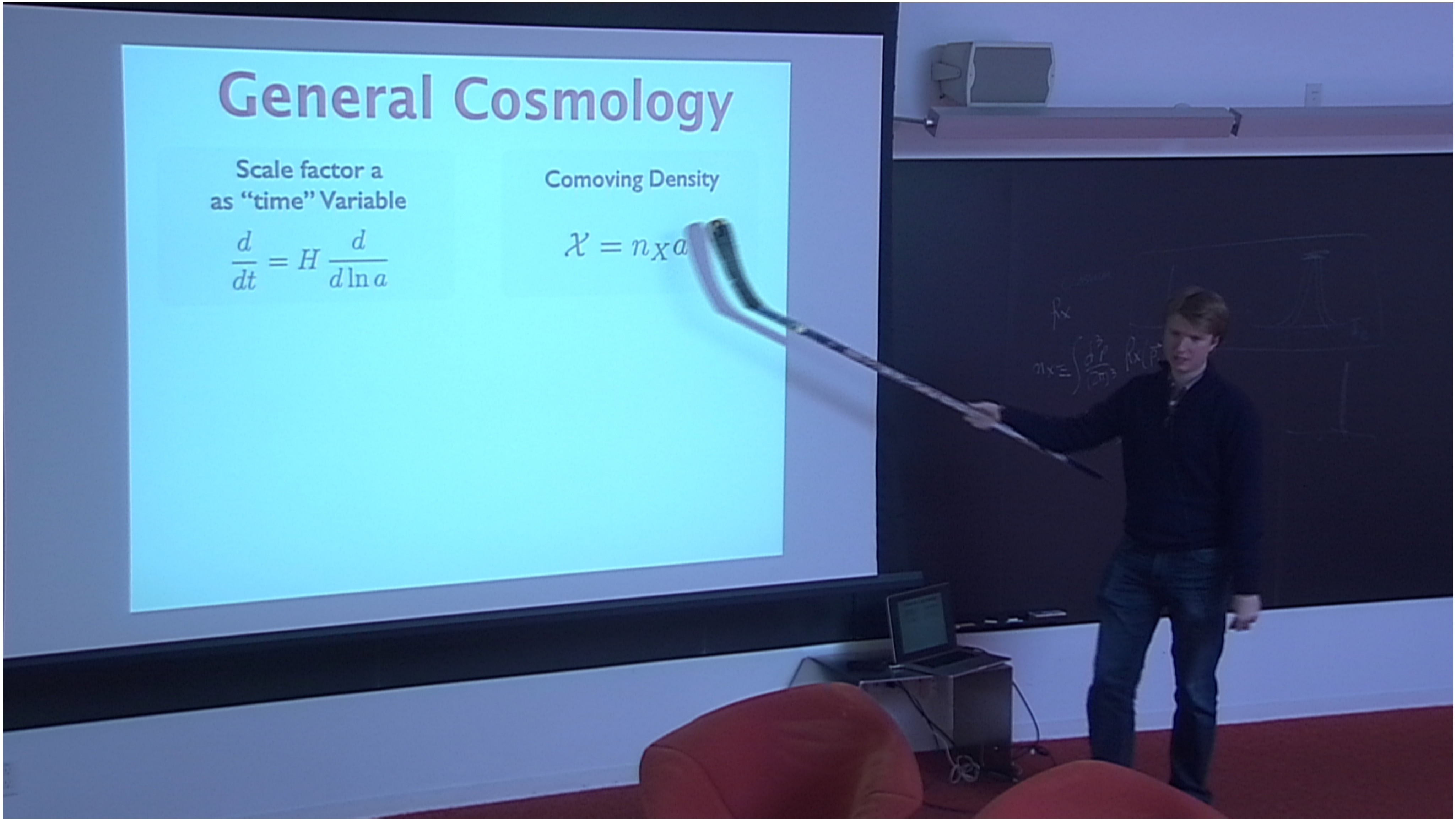
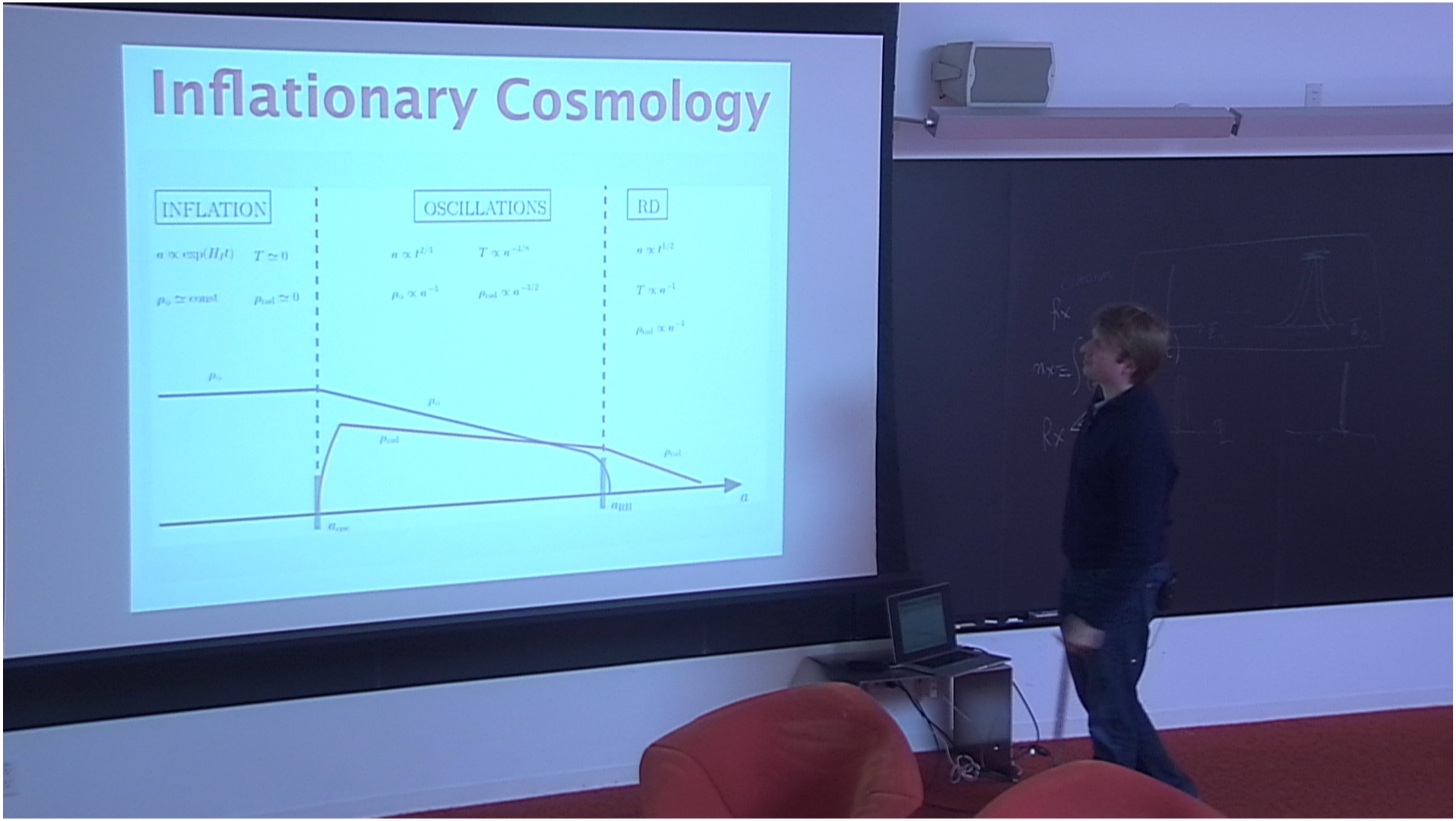
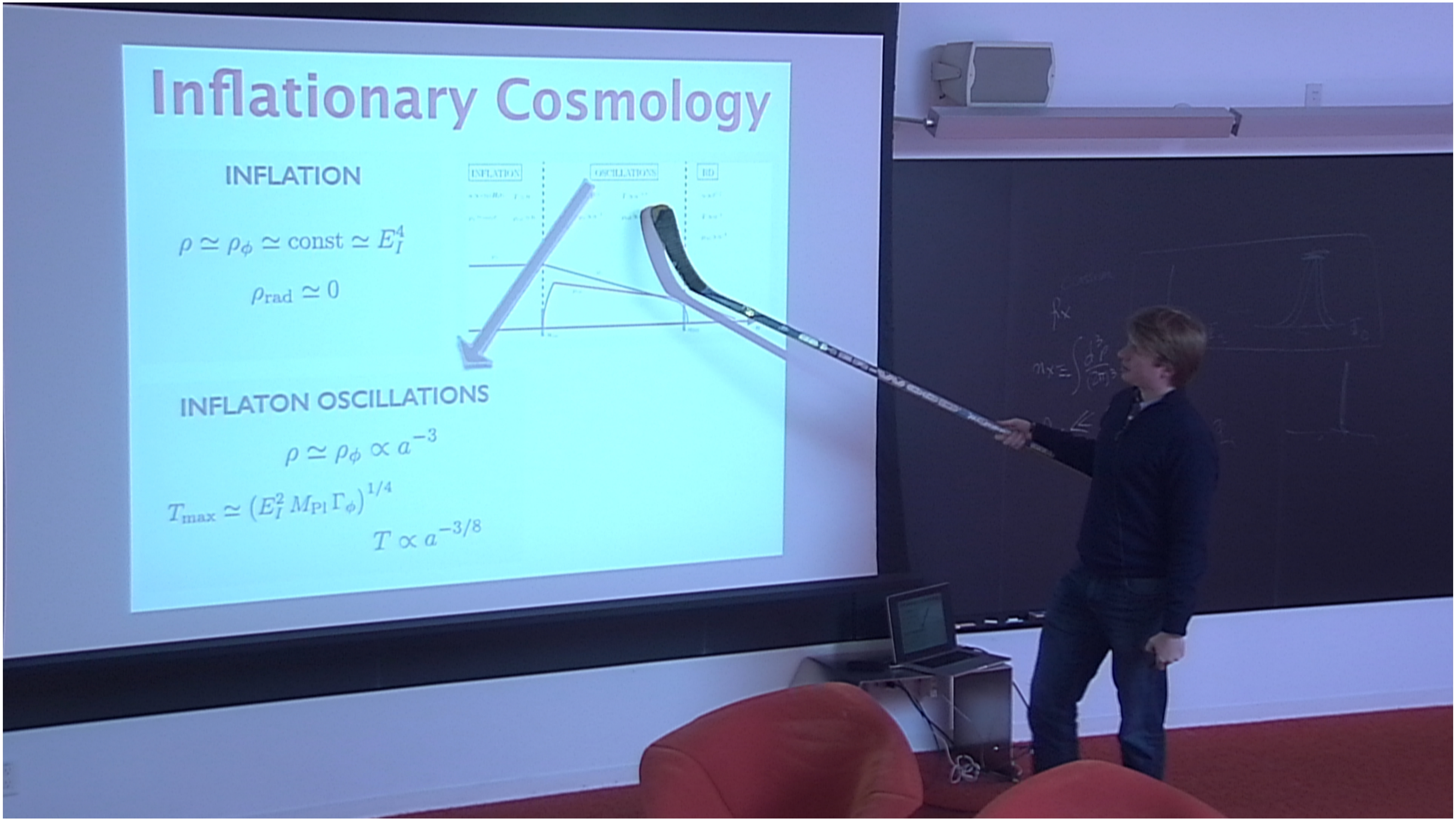
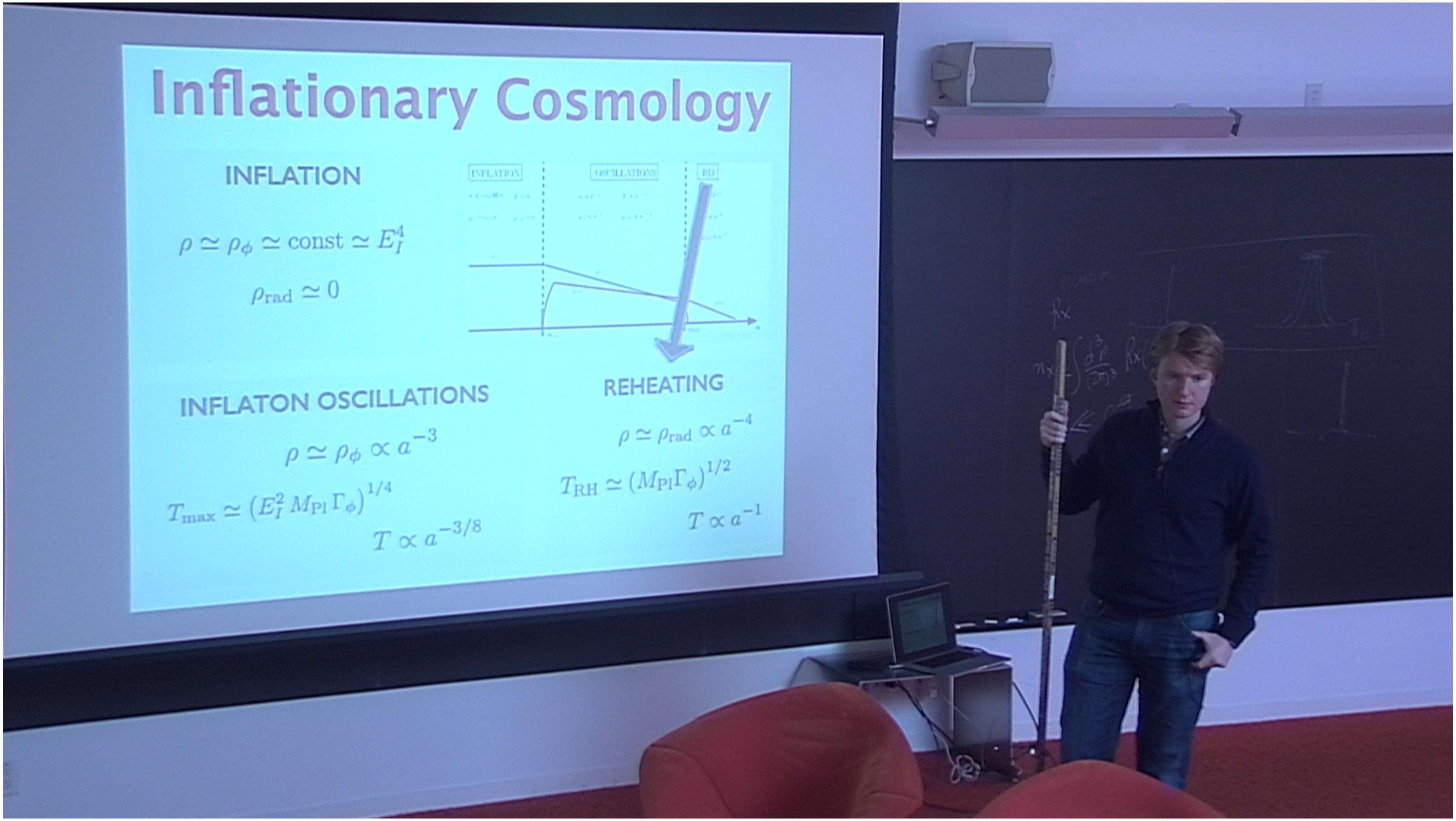
Hubble Parameter
$H = \left(\frac{8\pi}{3}\right)^{1/2} \frac{\sqrt{\rho(t)}}{M_{Pl}}$
ρ(t) depends on the cosmological history
Thermal Distributions
$T(t) = \left(\frac{30}{g_* \pi^2}\right)^{1/4} \rho_{rad}(t)^{1/4}$
Radiation temperature T(t) depends on the cosmological history


General Cosmology
Scale factor a
as "time" Variable
$\frac{d}{dt} = H \frac{d}{d \ln a}$
Comoving Density
$\mathcal{X} = n_\chi a$


Inflationary Cosmology
INFLATION
OSCILLATIONS
RD


Inflationary Cosmology
INFLATION
$\rho \simeq \rho_\phi \simeq \text{const} \simeq E_I^4$
$\rho_{\rm rad} \simeq 0$
INFLATON OSCILLATIONS
$\rho \simeq \rho_\phi \propto a^{-3}$
$T_{\rm max} \simeq (E_I^2 M_{\rm Pl} \Gamma_\phi)^{1/4}$
$T \propto a^{-3/8}$
INFLATION
OSCILLATIONS
RD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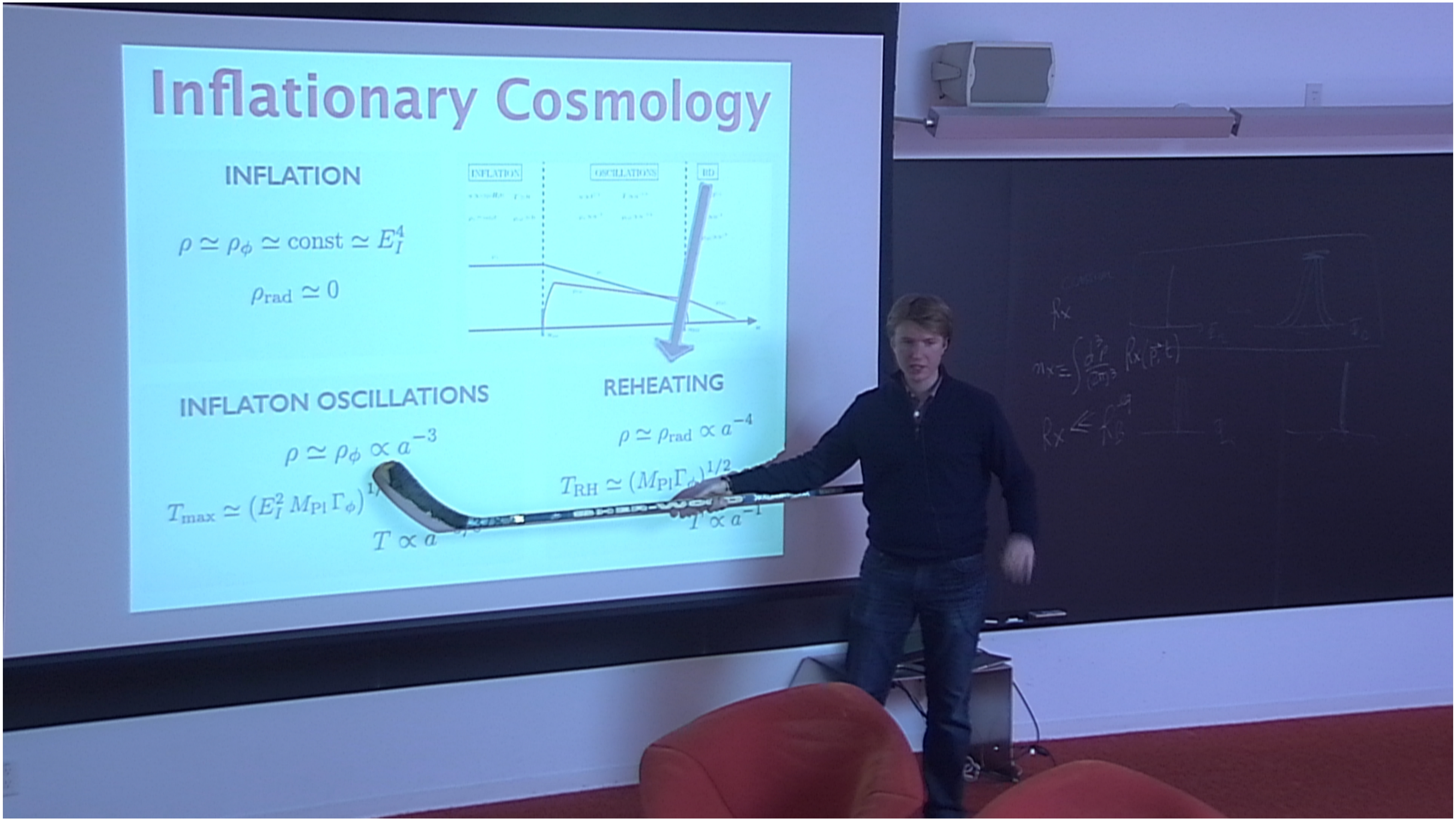
$T \propto a^{-3/8}$
REHEATING
$\rho \simeq \rho_{\mathrm{rad}} \propto a^{-4}$
$T_{\mathrm{RH}} \simeq (M_{\mathrm{Pl}} \Gamma_\phi)^{1/2}$
$T \propto a^{-1}$
INFLATION
OSCILLATIONS
RD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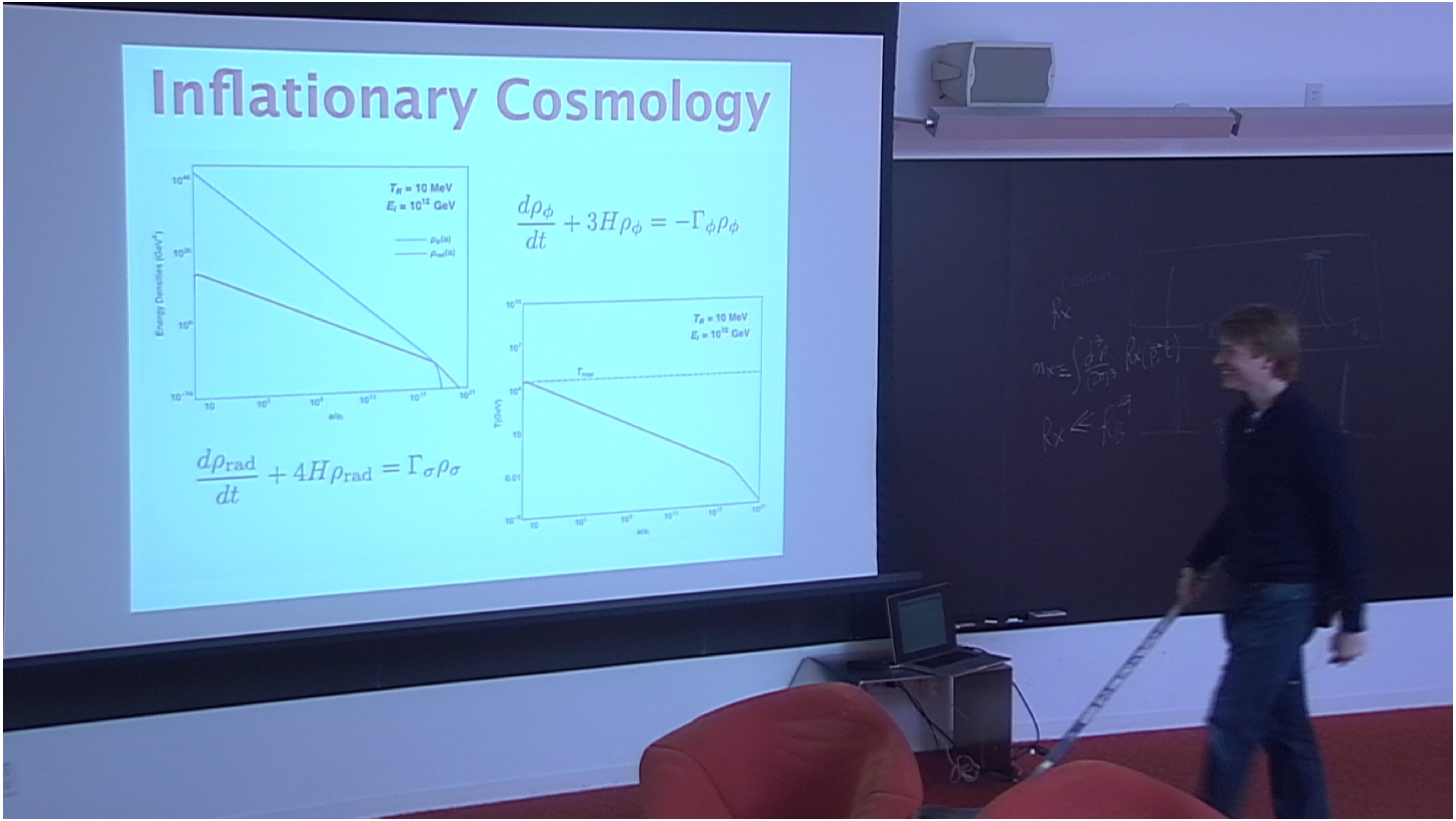
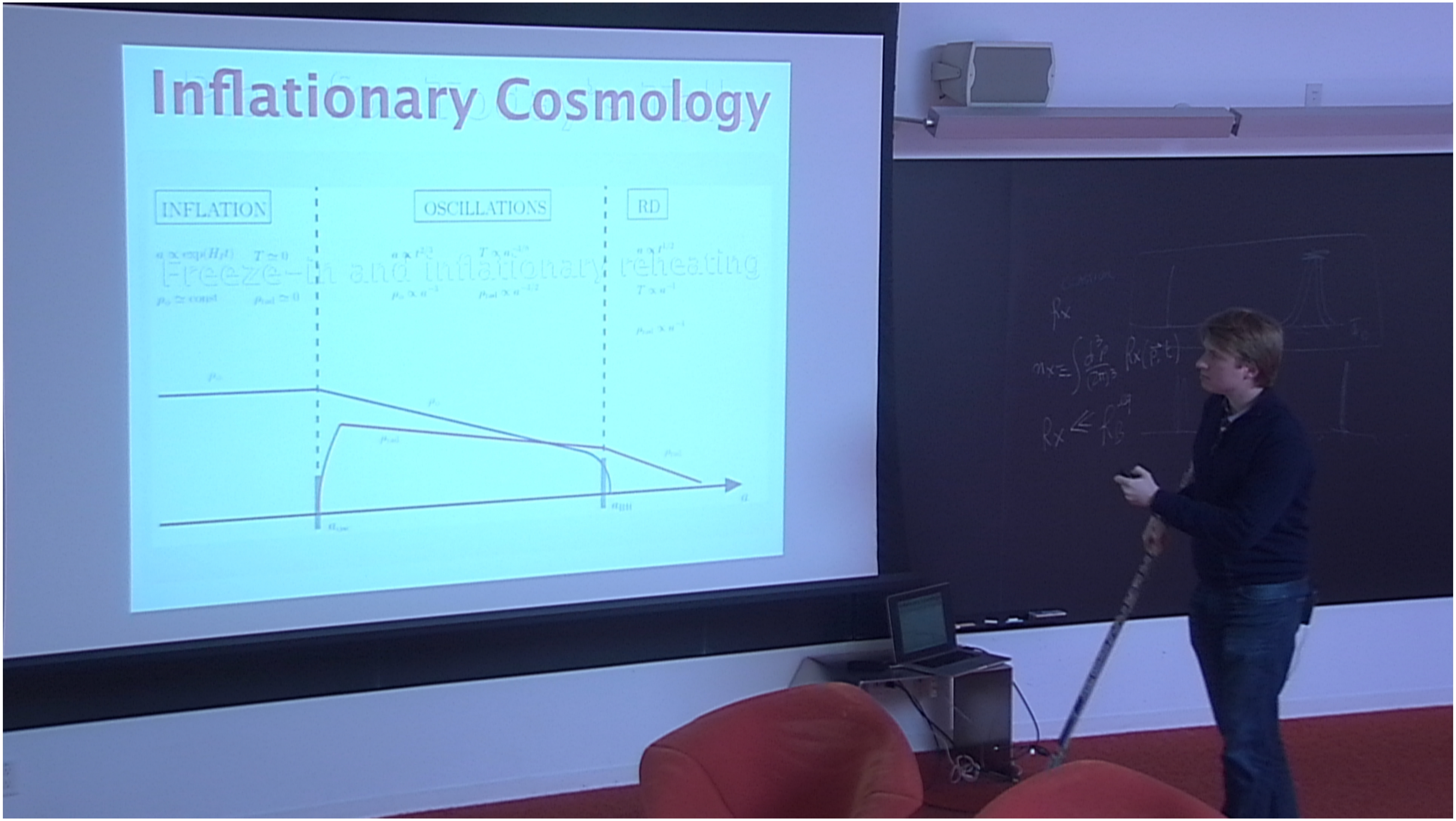
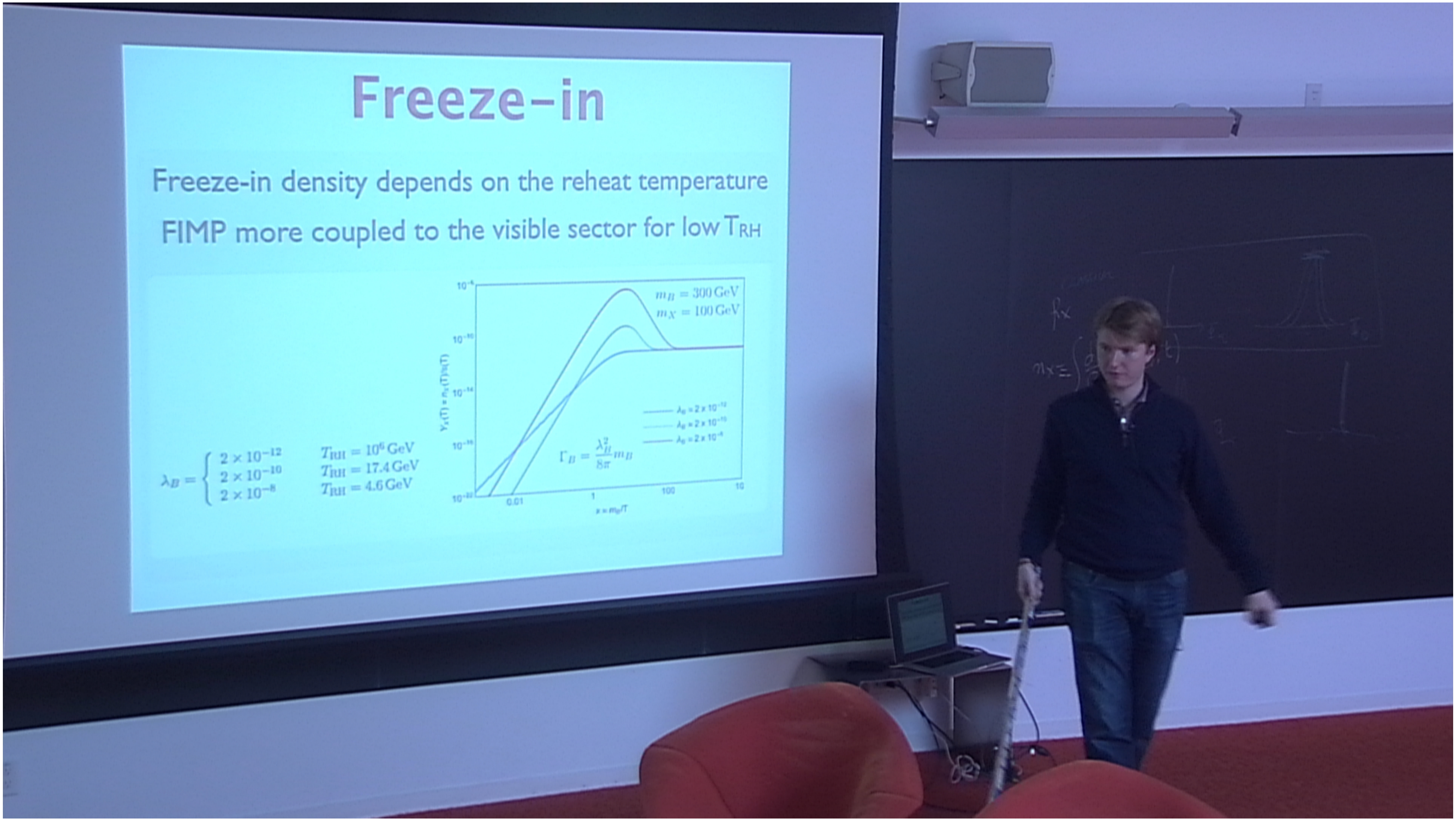
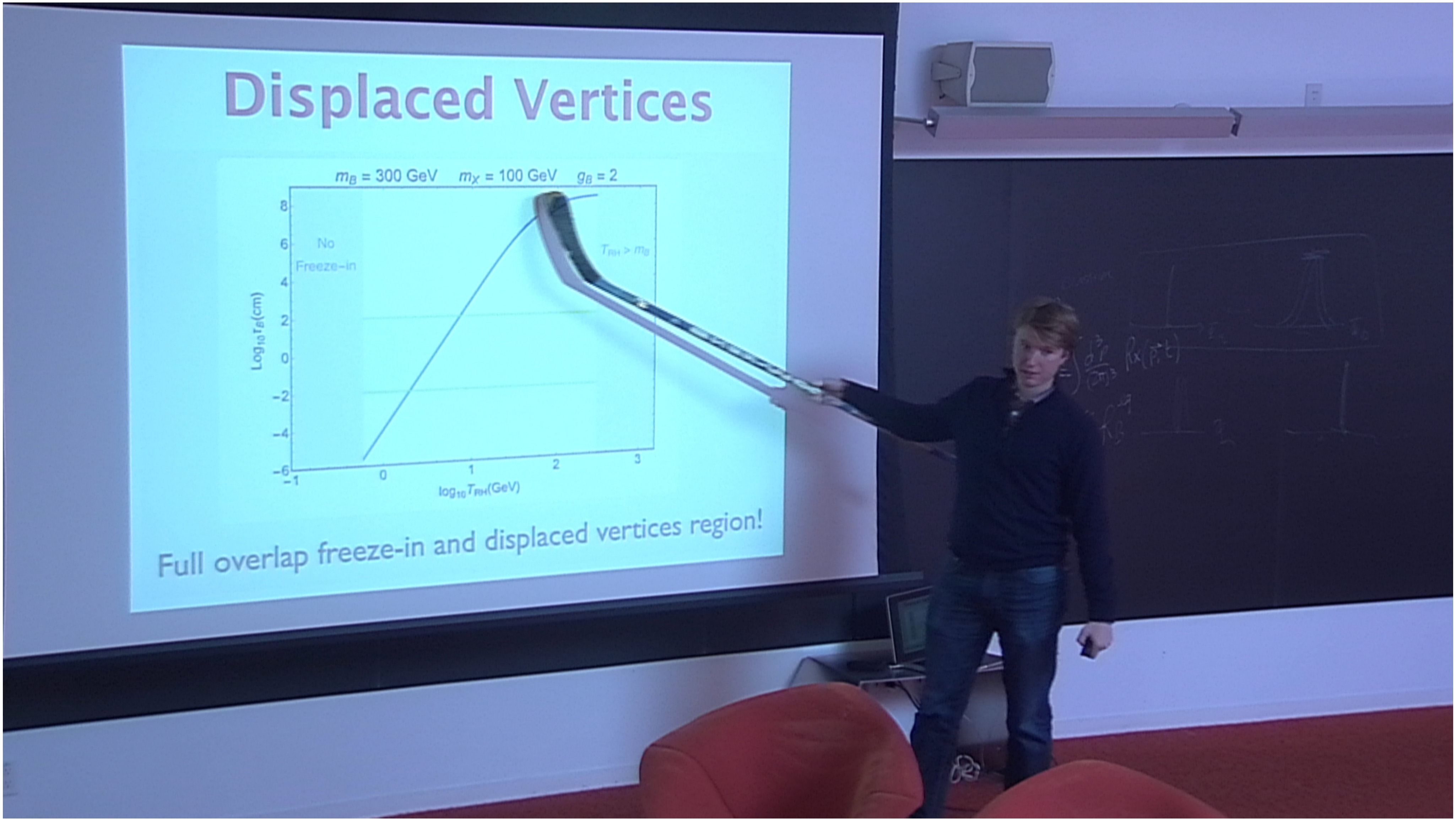
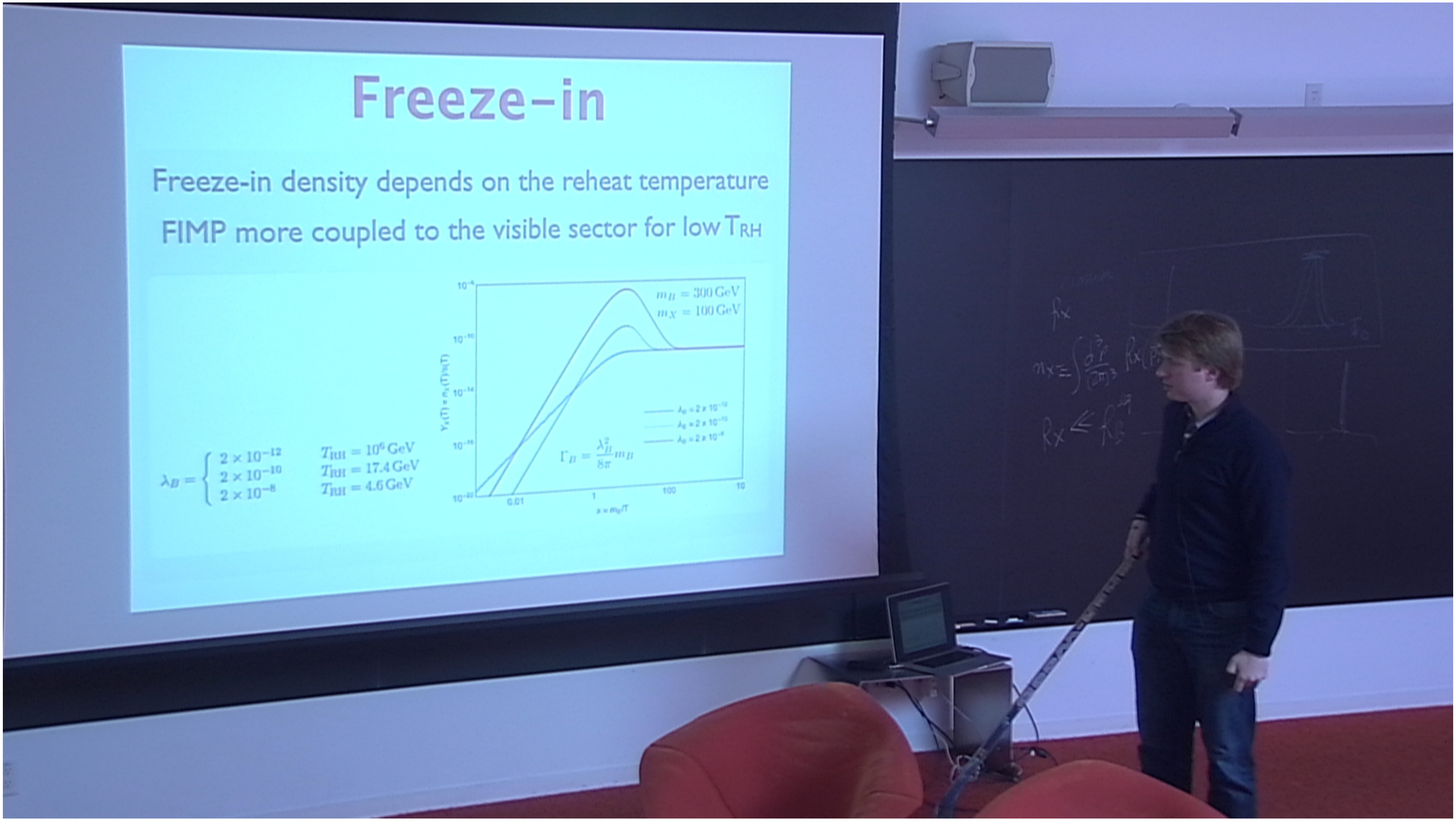

Inflationary Cosmology
T_R = 10 MeV
$E_I = 10^{12}$ GeV
Energy Densities (GeV^4)
a/a_I
$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$
T_R = 10 MeV
$E_I = 10^{12}$ GeV
T_{max}
T(GeV)
a/a_I
$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\sigma \rho_\sigma$

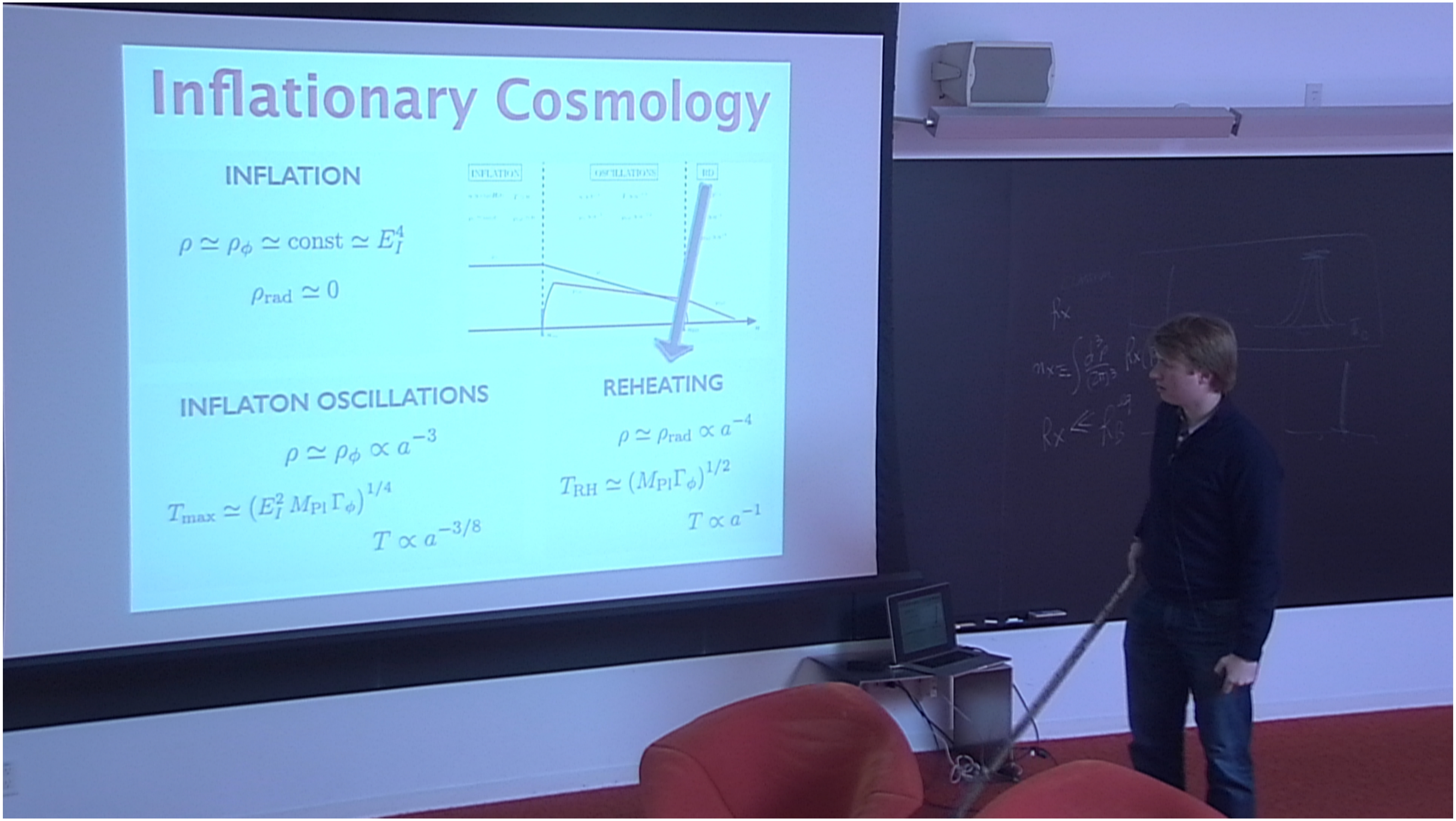


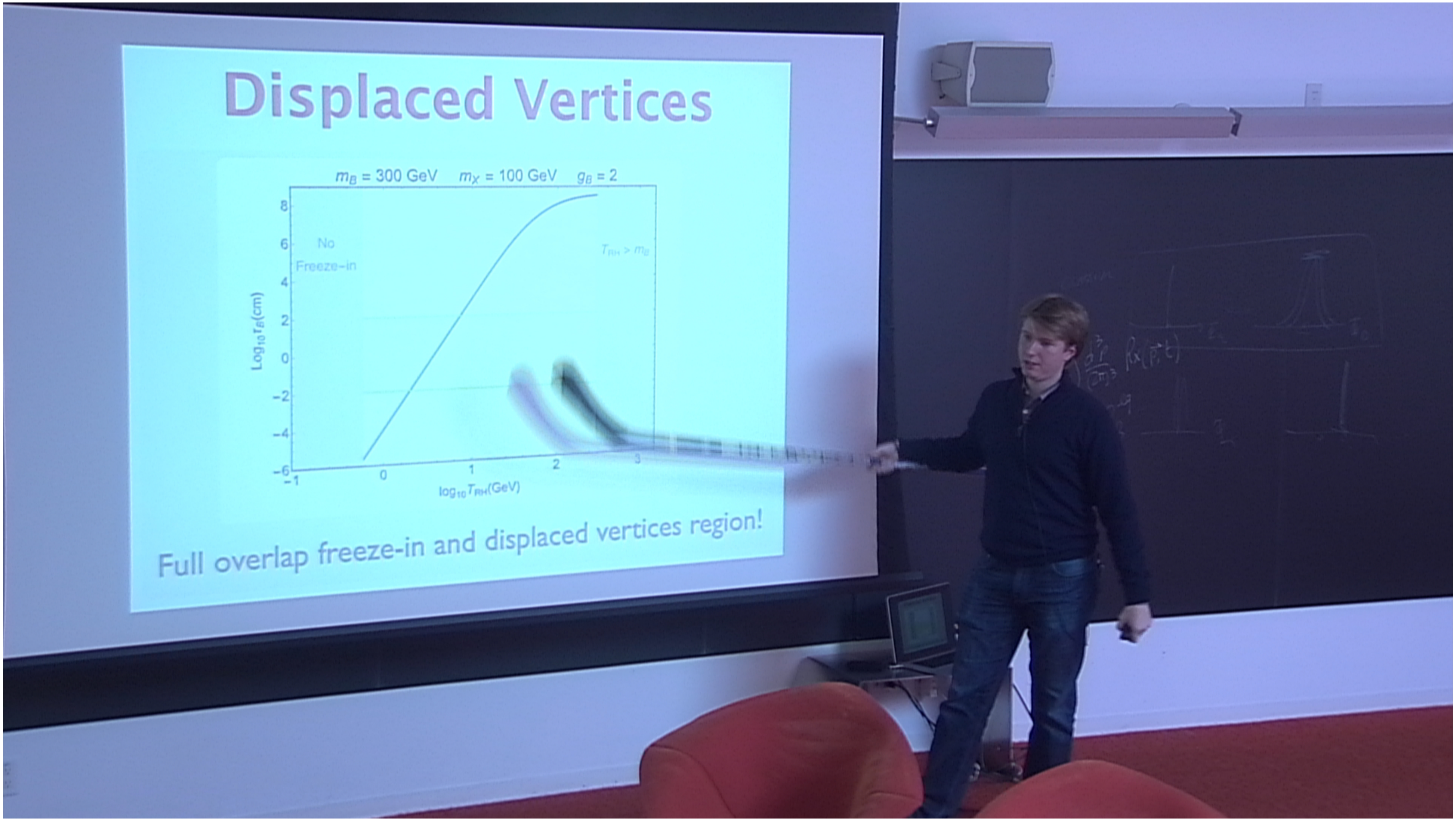
Inflationary Cosmology
INFLATION
OSCILLATIONS
RD
Freeze-in and inflationary reheating

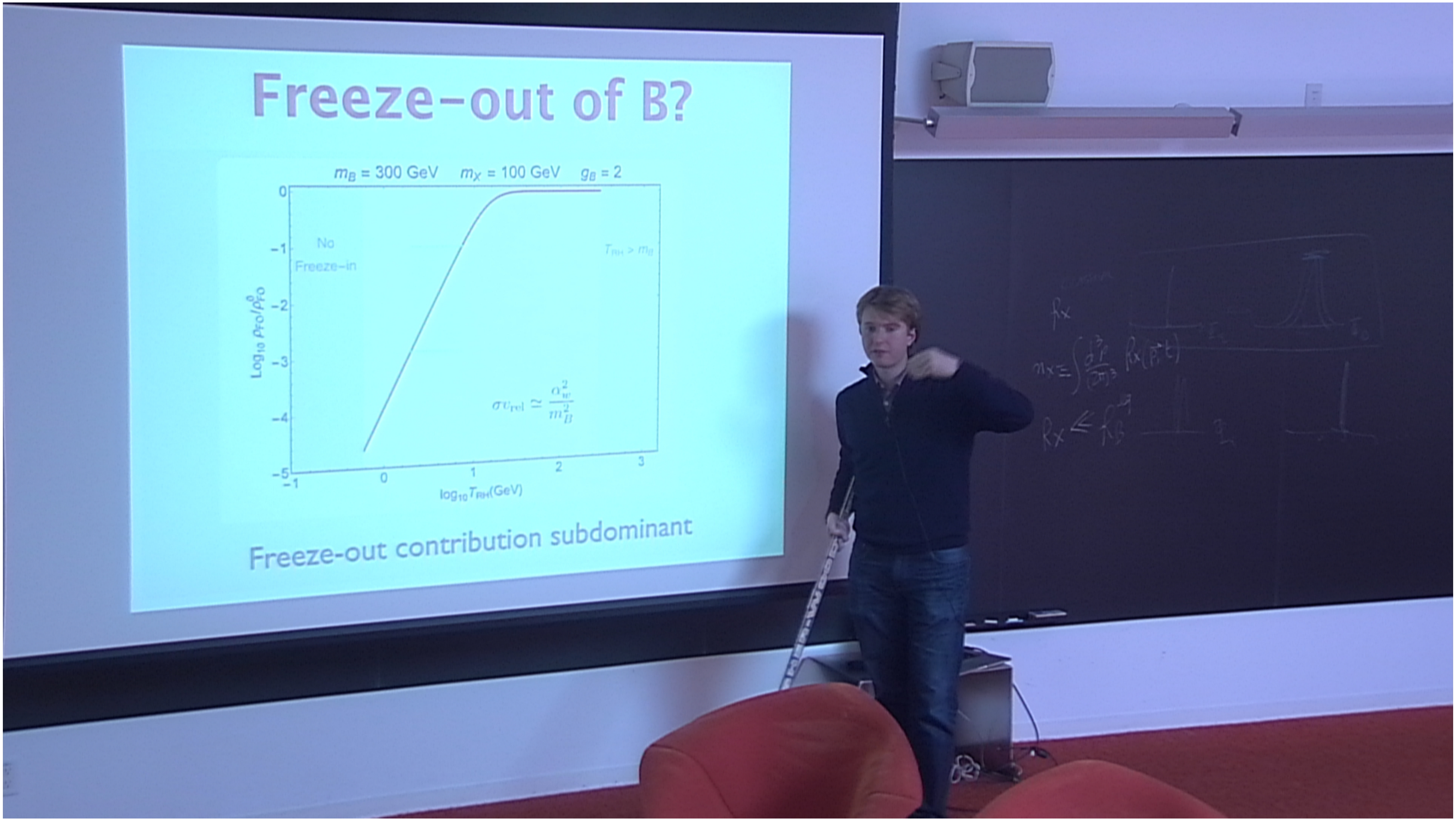

Freeze-in
Freeze-in density depends on the reheat temperature
FIMP more coupled to the visible sector for low T_{RH}
$m_B = 300\,\mathrm{GeV}$
$m_X = 100\,\mathrm{GeV}$
$\Gamma_B = \frac{\lambda_B^2}{8\pi} m_B$
$\lambda_B = \begin{cases} 2\times10^{-12} & T_{RH} = 10^6\,\mathrm{GeV} \\ 2\times10^{-10} & T_{RH} = 17.4\,\mathrm{GeV} \\ 2\times10^{-8} & T_{RH} = 4.6\,\mathrm{GeV} \end{cases}$
0.01
1
100

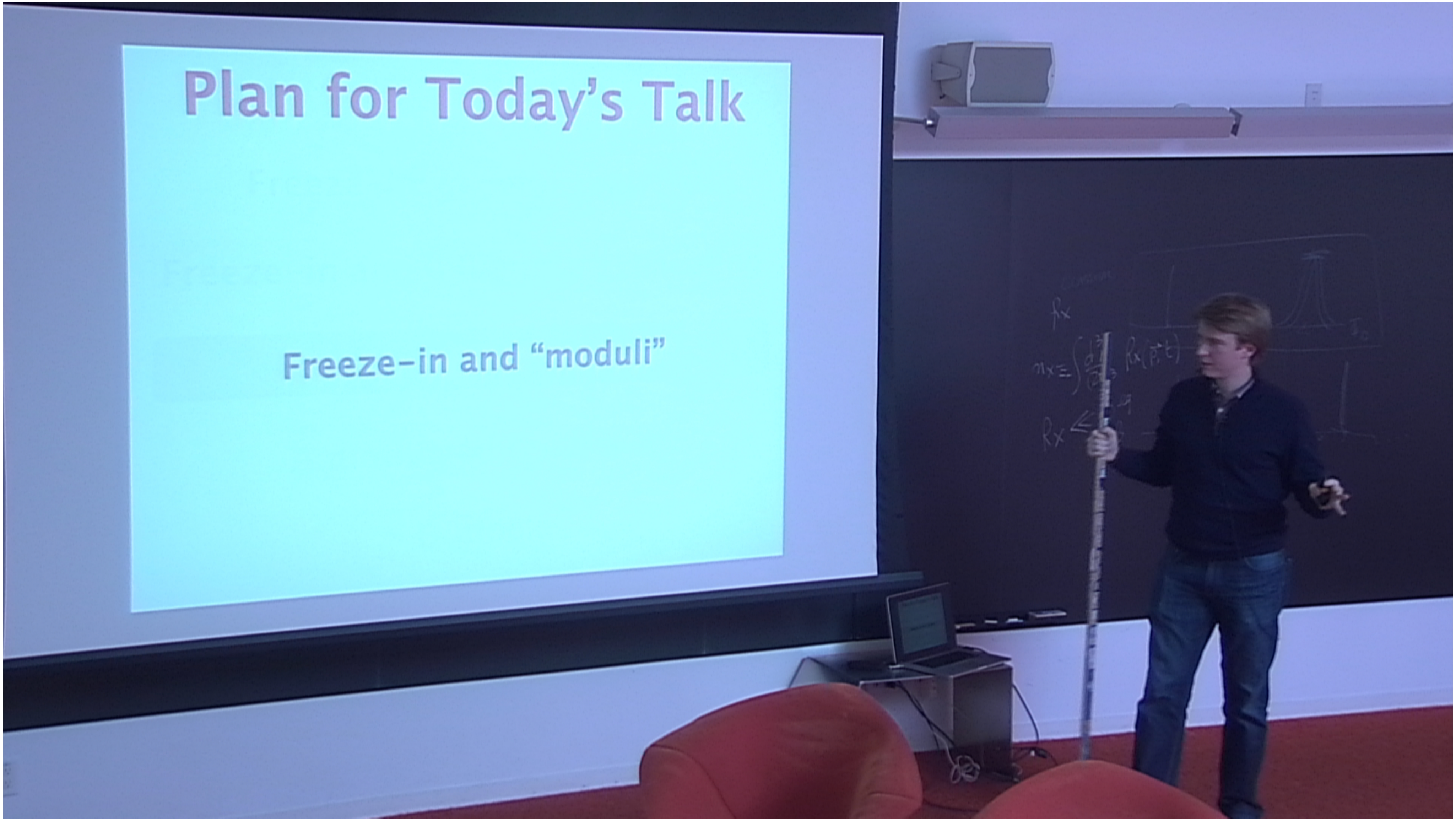

Displaced Vertices
m_B = 300 GeV m_X = 100 GeV g_B = 2
No Freeze-in
$T_{RH} > m_B$
$\mathrm{Log}_{10}\,\tau_B$(cm)
$\log_{10} T_{RH}$(GeV)
Full overlap freeze-in and displaced vertices region!

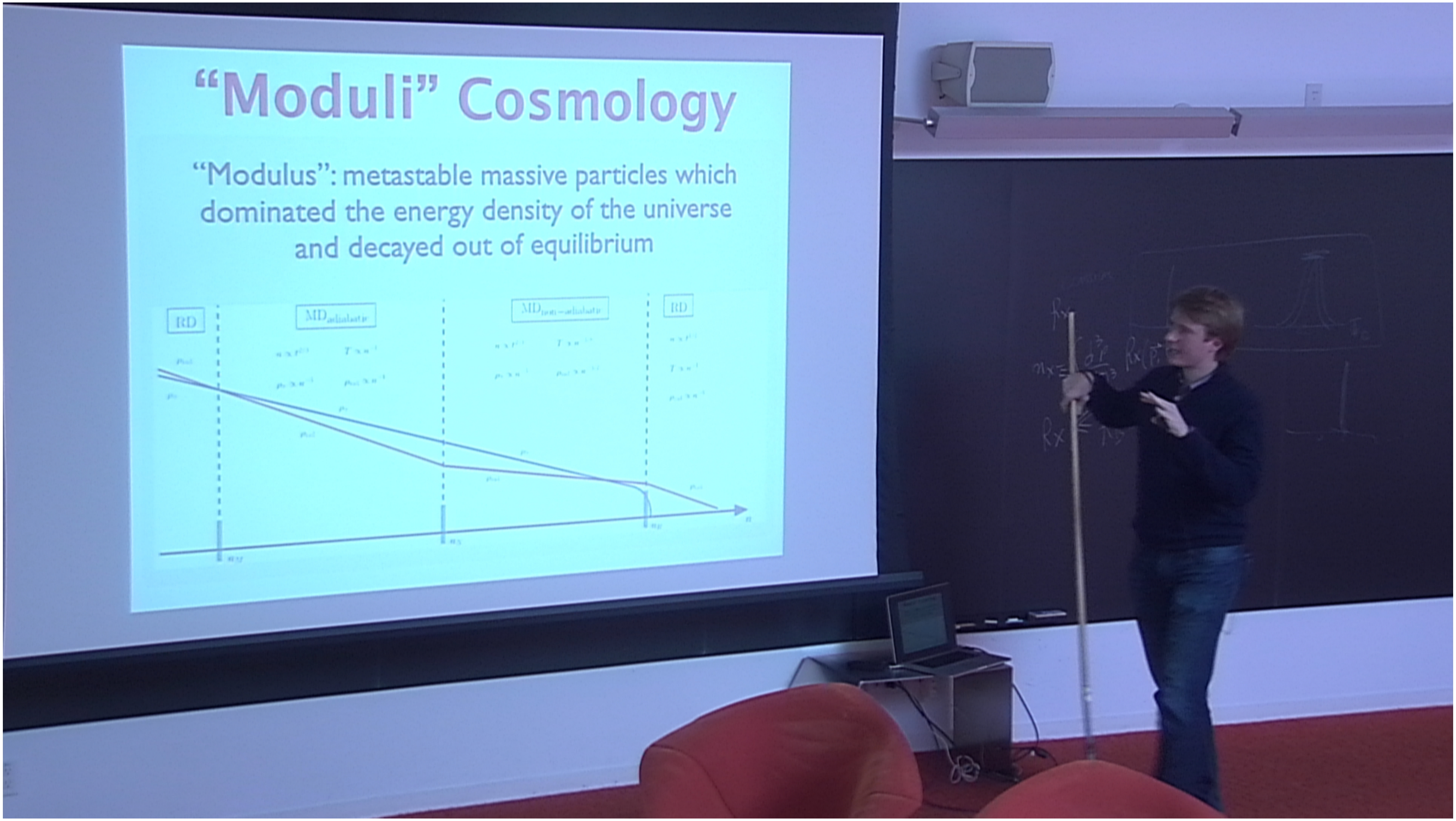

Freeze-in
Freeze-in density depends on the reheat temperature
FIMP more coupled to the visible sector for low T_RH
m_B = 300 GeV
m_X = 100 GeV
λ_B = 2 × 10^-12, 2 × 10^-10, 2 × 10^-8
T_RH = 10^6 GeV
T_RH = 17.4 GeV
T_RH = 4.6 GeV
Γ_B = λ_B^2 / 8π m_B

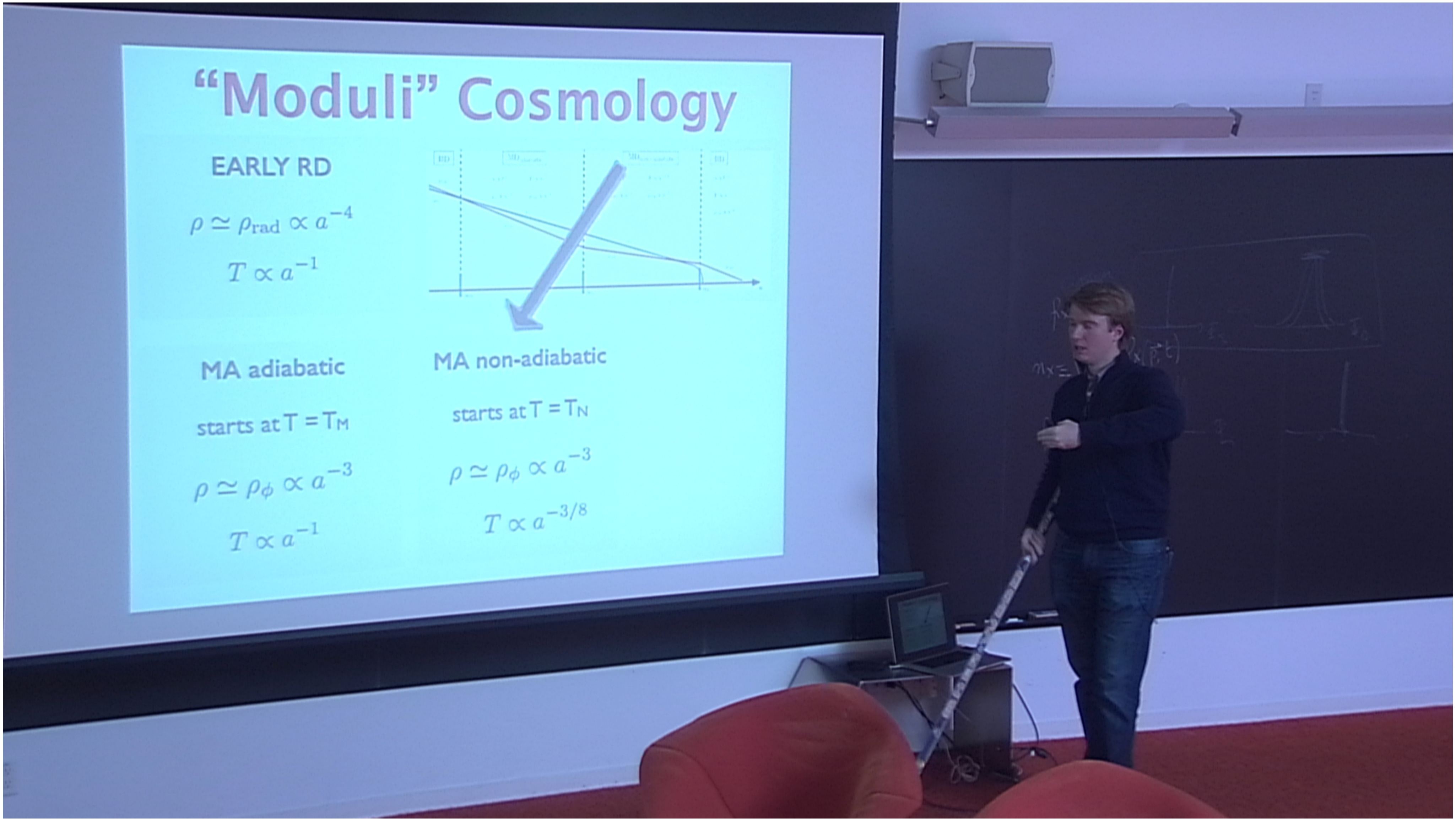

Inflationary Cosmology
INFLATION
$\rho \simeq \rho_\phi \simeq \text{const} \simeq E_I^4$
$\rho_{\rm rad} \simeq 0$
INFLATON OSCILLATIONS
$\rho \simeq \rho_\phi \propto a^{-3}$
$T_{\rm max} \simeq (E_I^2 \, M_{\rm Pl} \, \Gamma_\phi)^{1/4}$
$T \propto a^{-3/8}$
REHEATING
$\rho \simeq \rho_{\rm rad} \propto a^{-4}$
$T_{\rm RH} \simeq (M_{\rm Pl} \Gamma_\phi)^{1/2}$
$T \propto a^{-1}$
INFLATION
OSCILLATIONS
RD

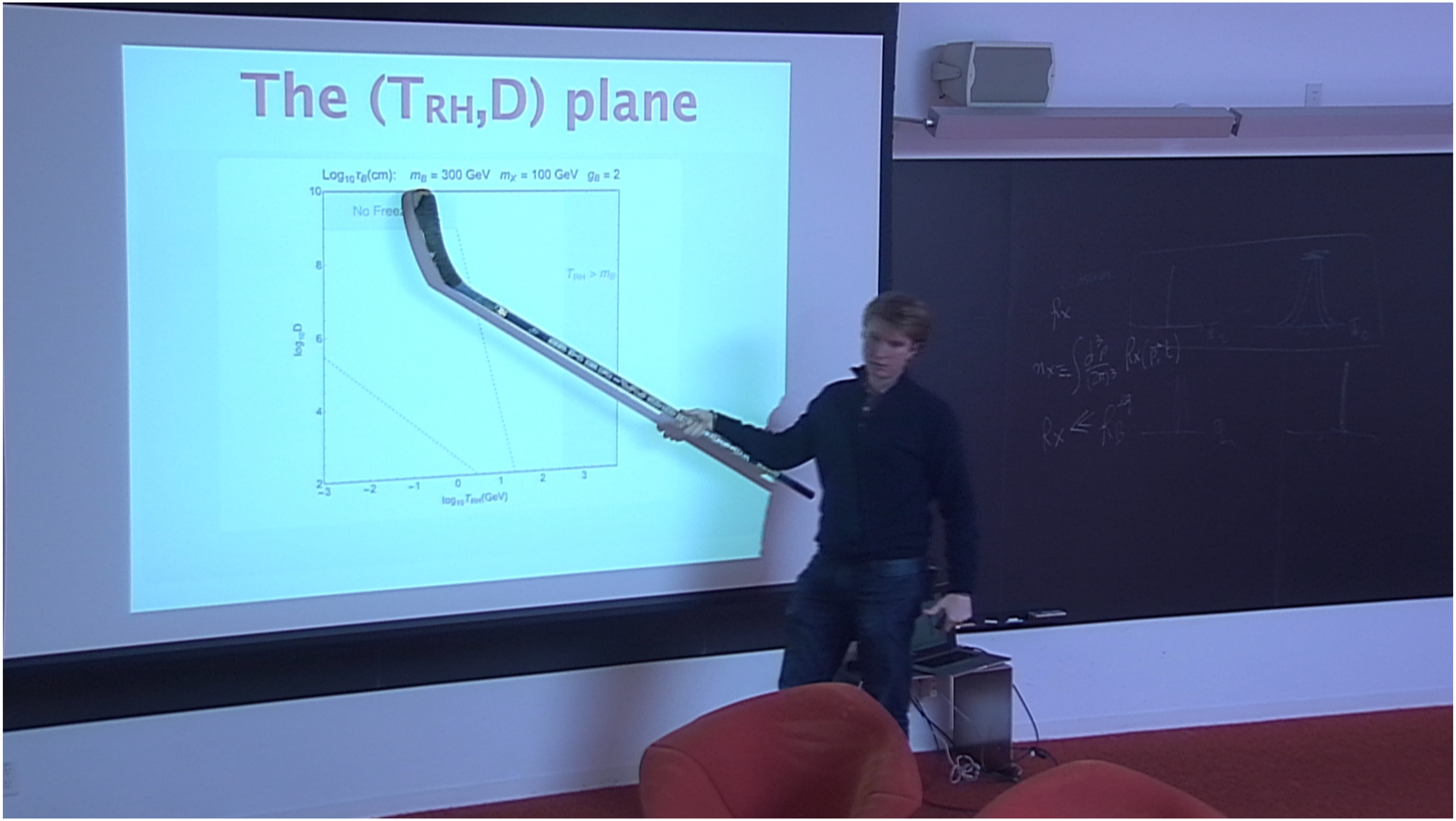

Displaced Vertices
m_B = 300 GeV m_X = 100 GeV g_B = 2
No
Freeze-in
$T_{RH} > m_B$
$\mathrm{Log}_{10}\,\tau_B$(cm)
$\log_{10} T_{RH}$(GeV)
Full overlap freeze-in and displaced vertices region!

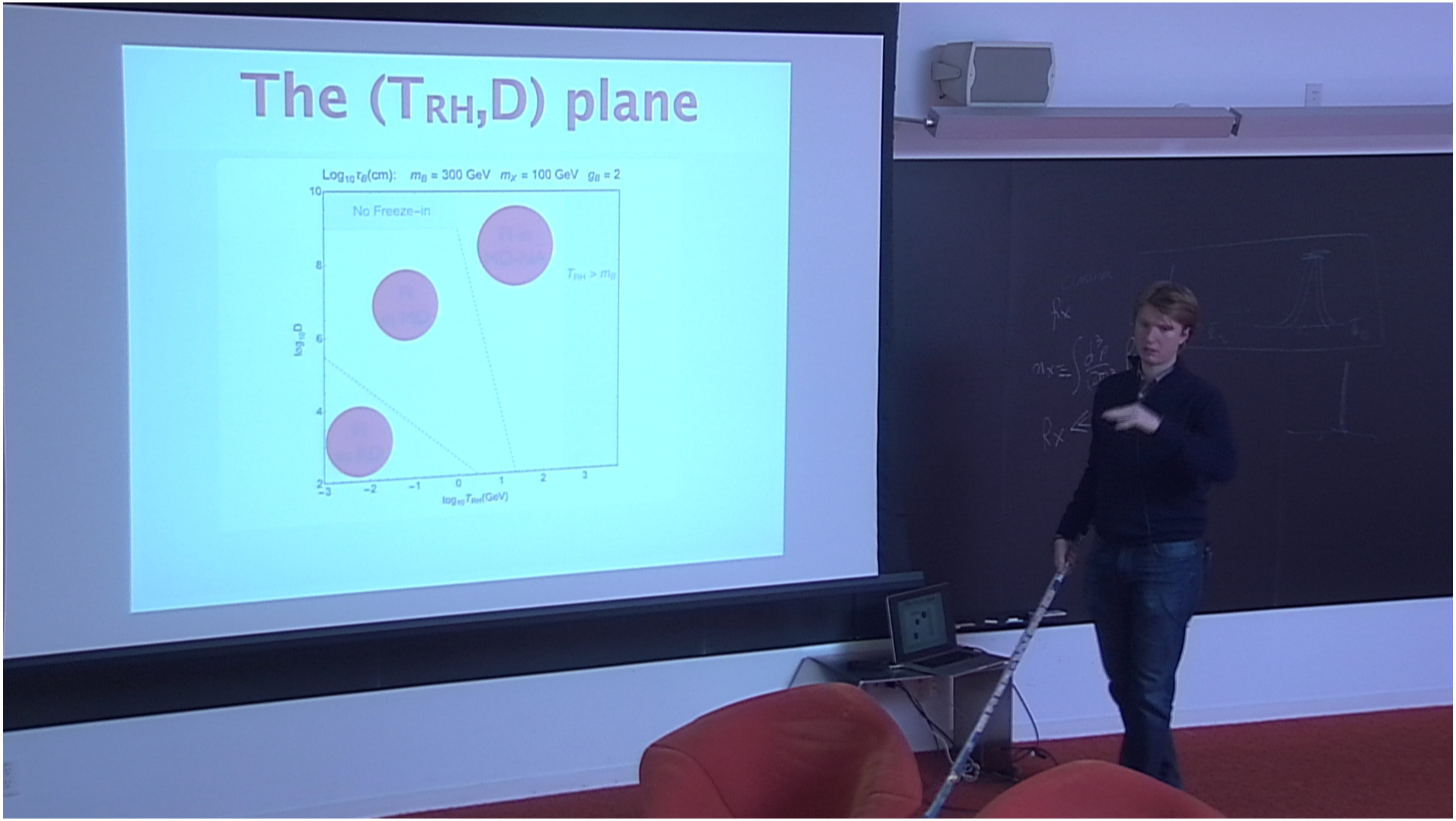

Freeze-out of B?
m_B = 300 GeV m_X = 100 GeV g_B = 2
No
Freeze-in
$T_{RH} > m_B$
$\sigma v_{rel} \simeq \frac{\alpha_w^2}{m_B^2}$
$\mathrm{Log}_{10}\,\rho_{FO}/\rho^0_{FO}$
$\log_{10} T_{RH}$(GeV)
Freeze-out contribution subdominant

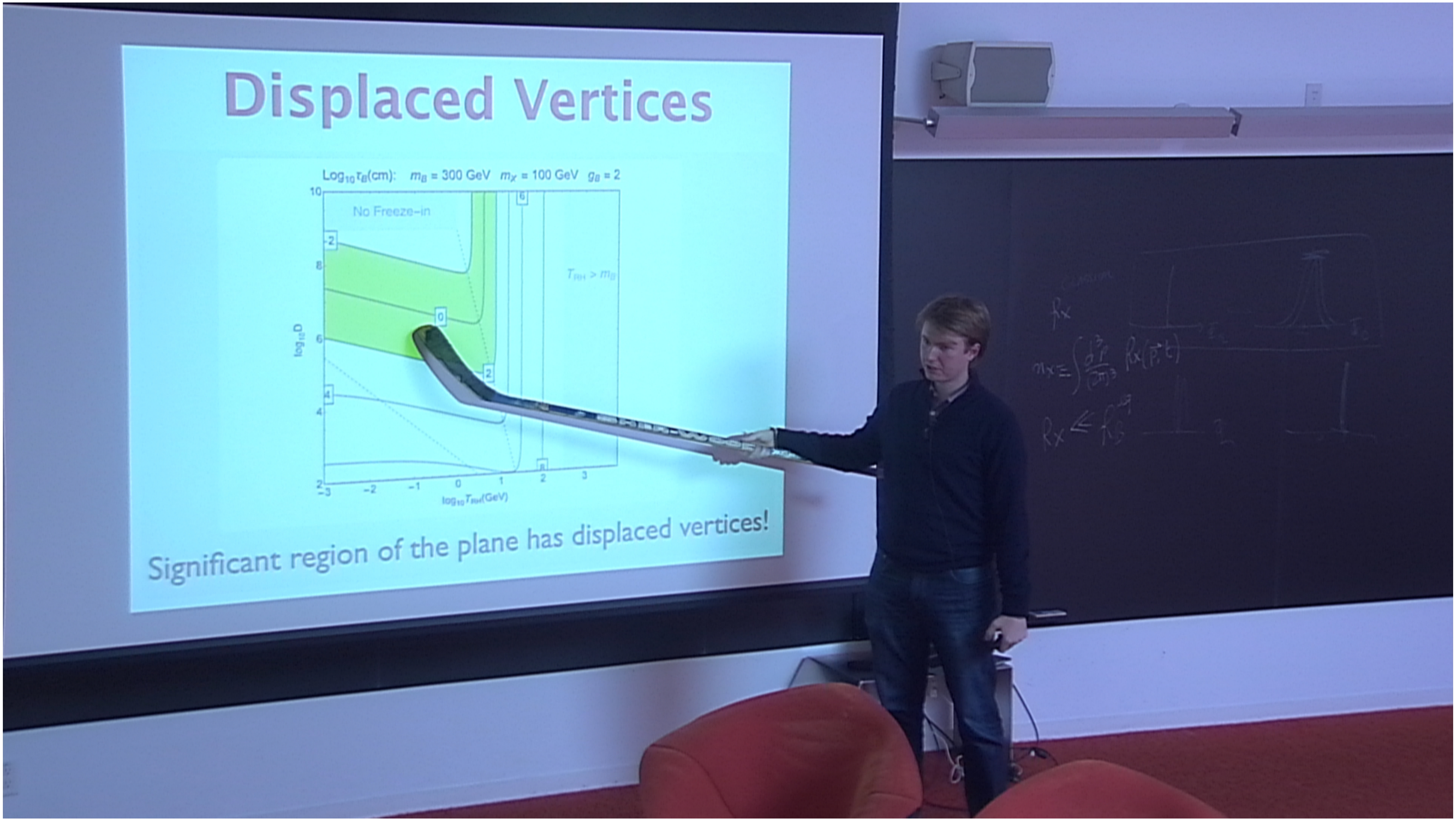

Plan for Today's Talk
Freeze-in and "moduli"

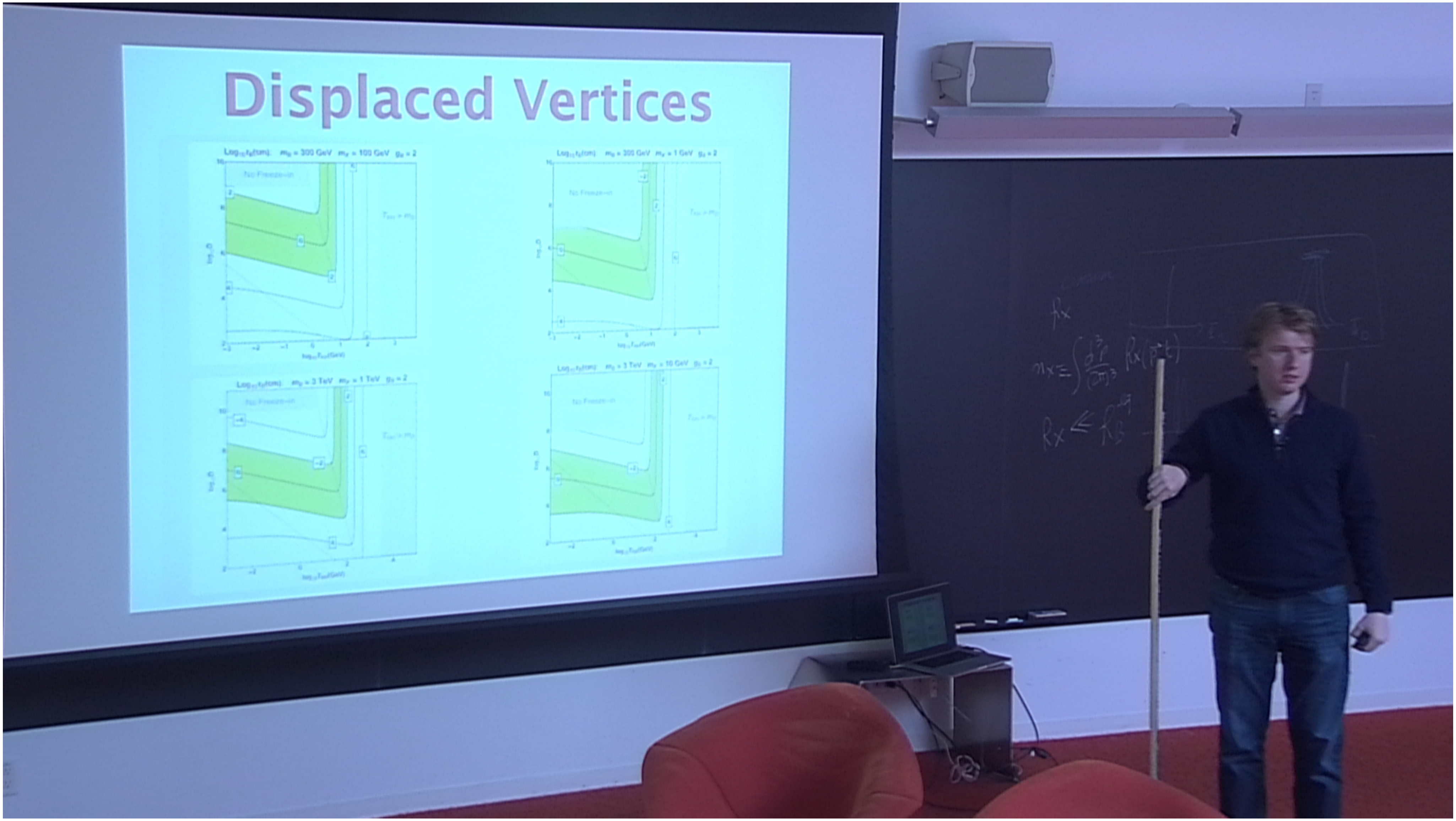

"Moduli" Cosmology
"Modulus": metastable massive particles which dominated the energy density of the universe and decayed out of equilibrium
RD
MD adiabatic
MD non-adiabatic
RD

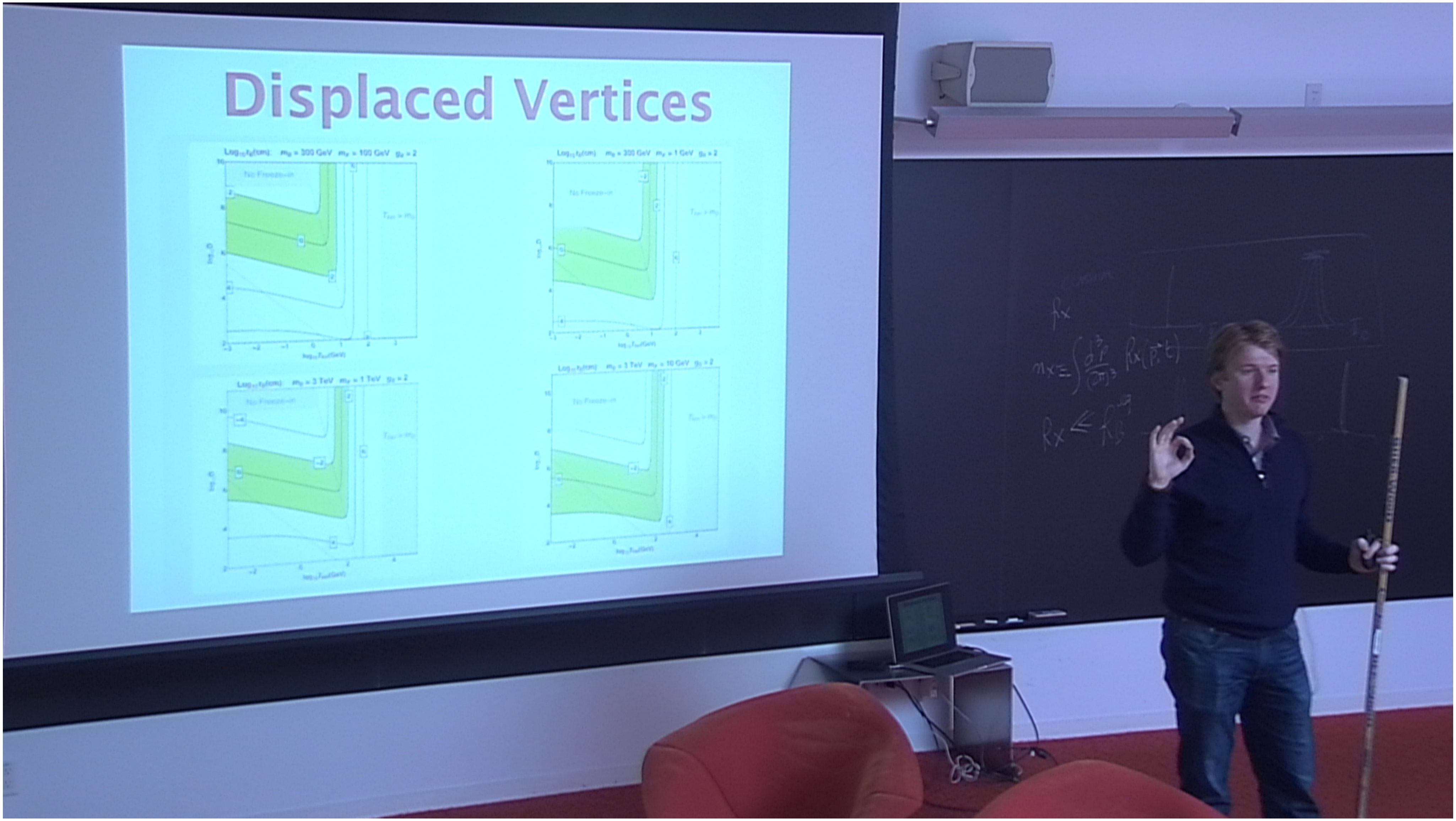

"Moduli" Cosmology
EARLY RD
$\rho \simeq \rho_{\rm rad} \propto a^{-4}$
$T \propto a^{-1}$
MA adiabatic
starts at T = T$_M$
$\rho \simeq \rho_\phi \propto a^{-3}$
$T \propto a^{-1}$
MA non-adiabatic
starts at T = T$_N$
$\rho \simeq \rho_\phi \propto a^{-3}$
$T \propto a^{-3/8}$

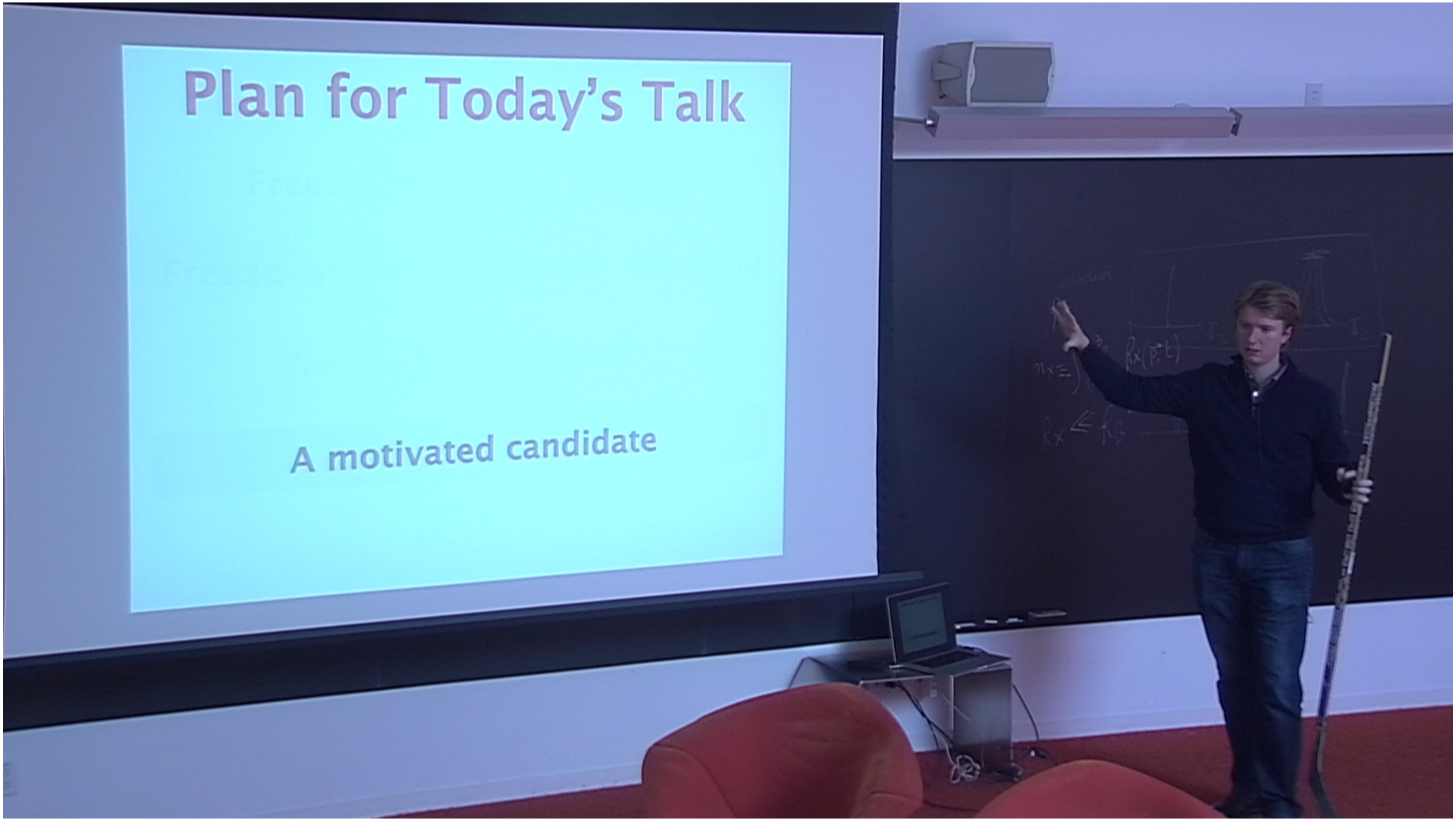

The (T_{RH},D) plane
Log10τB(cm): mB = 300 GeV mX = 100 GeV gB = 2
No Free
TRH > mB
log10D
log10TRH(GeV)

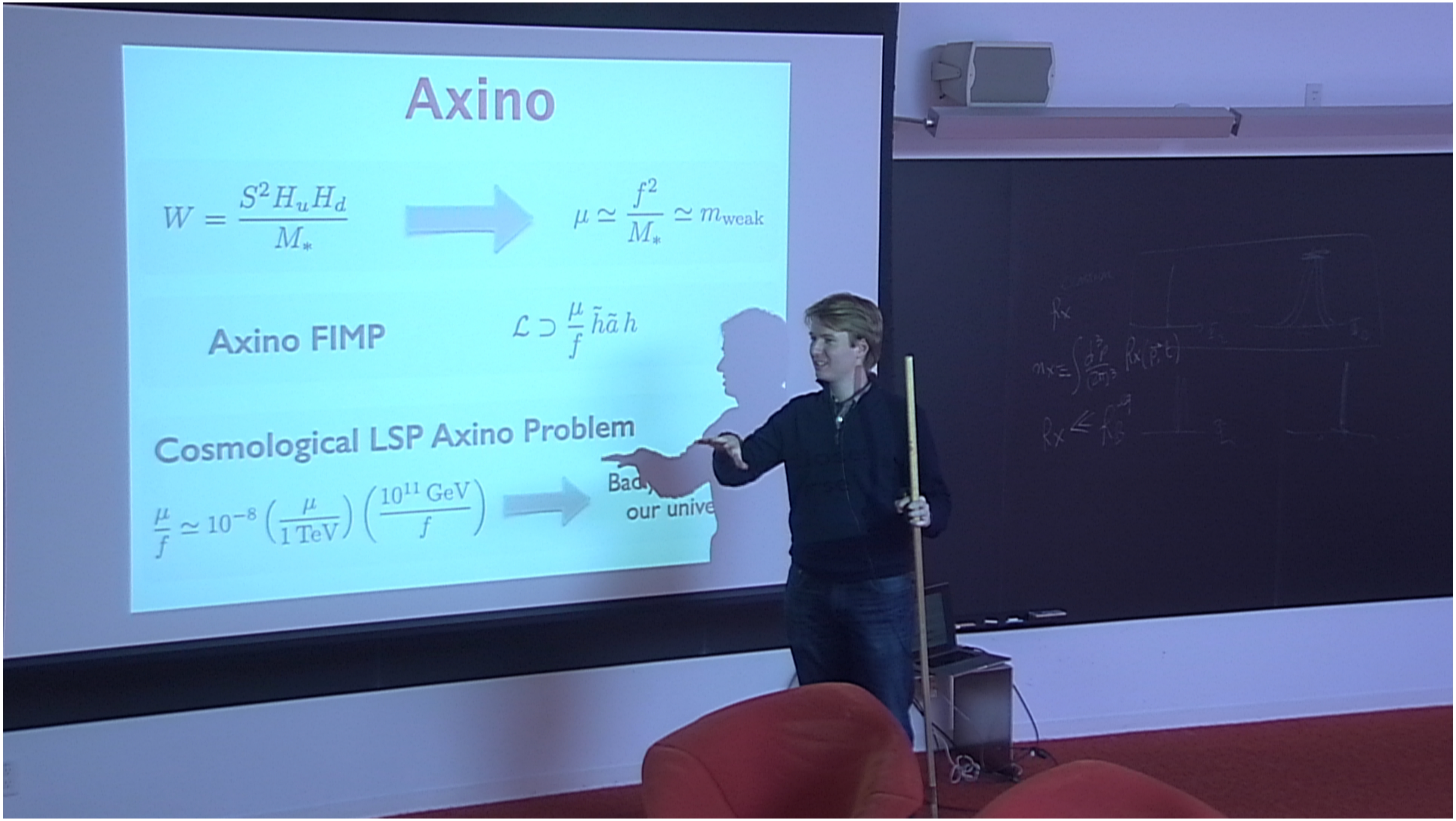

The (T_RH,D) plane
Log10 τB(cm): mB = 300 GeV mX = 100 GeV gB = 2
No Freeze-in
TRH > mB
log10 D
log10 TRH(GeV)

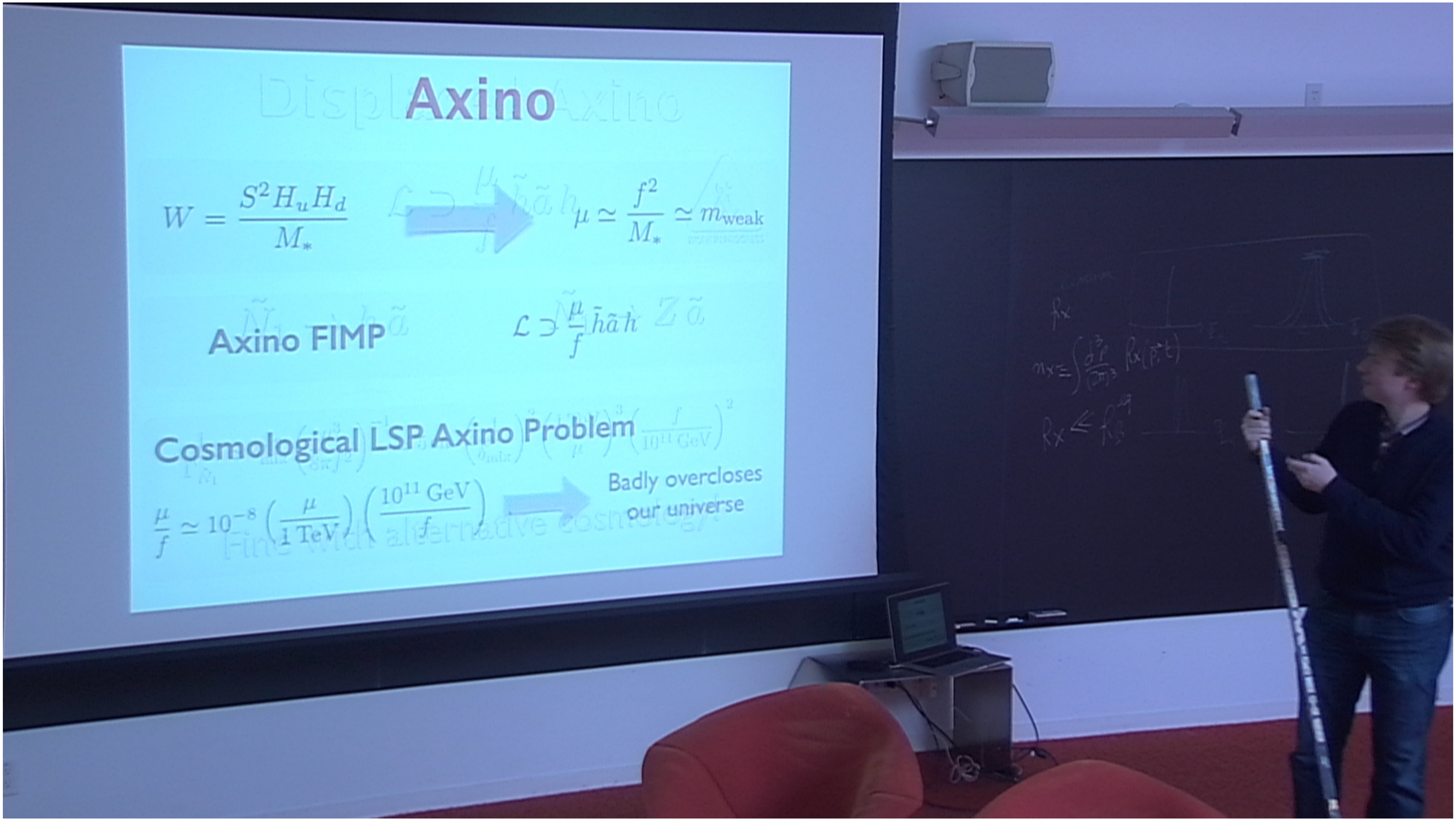

Displaced Vertices
Log10 τB(cm): mB = 300 GeV mX = 100 GeV gB = 2
No Freeze-in
TRH > mB
log10 D
log10 TRH(GeV)
Significant region of the plane has displaced vertices!

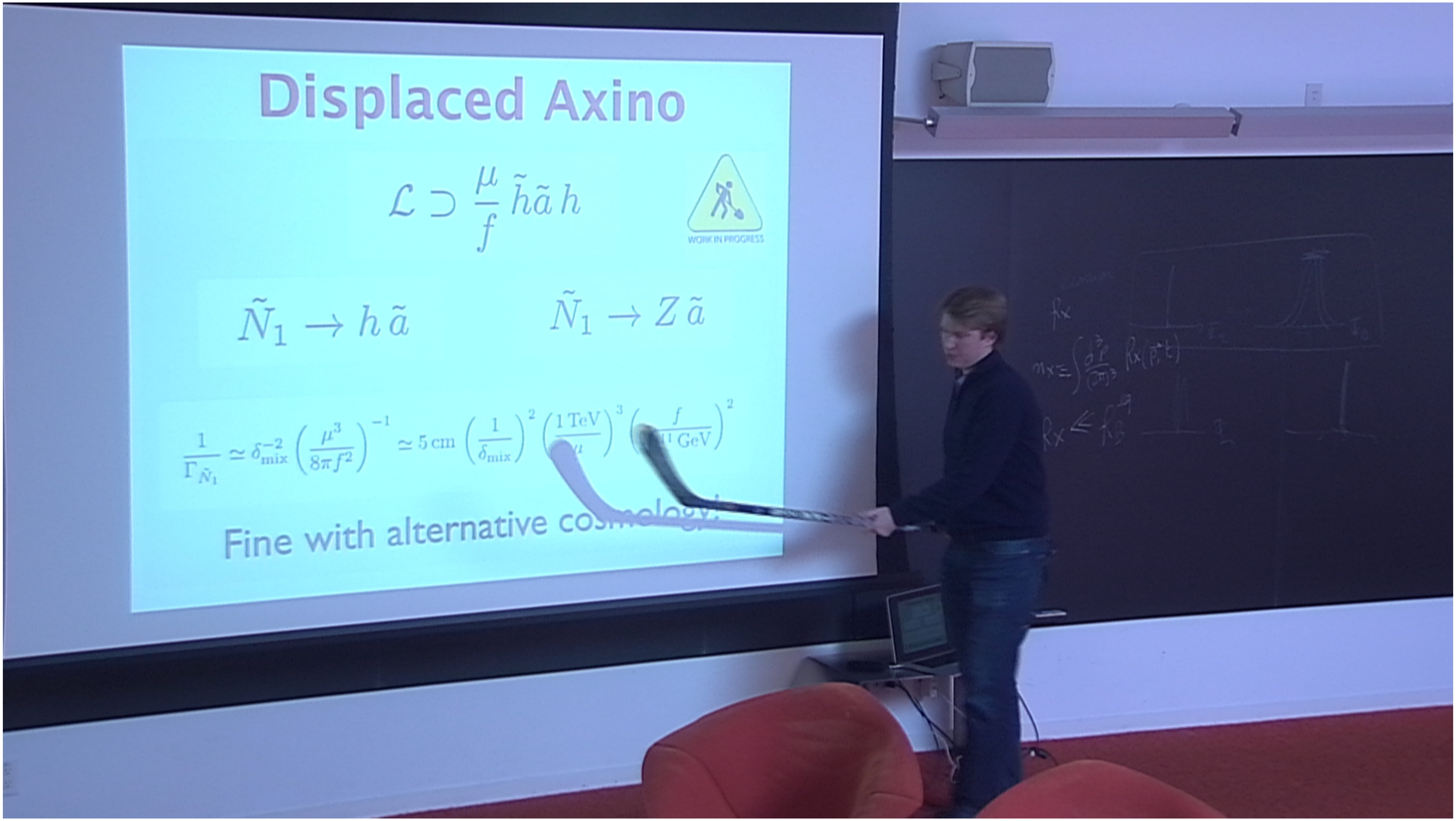

Displaced Vertices
No Freeze-in
No Freeze-in
No Freeze-in
No Freeze-in

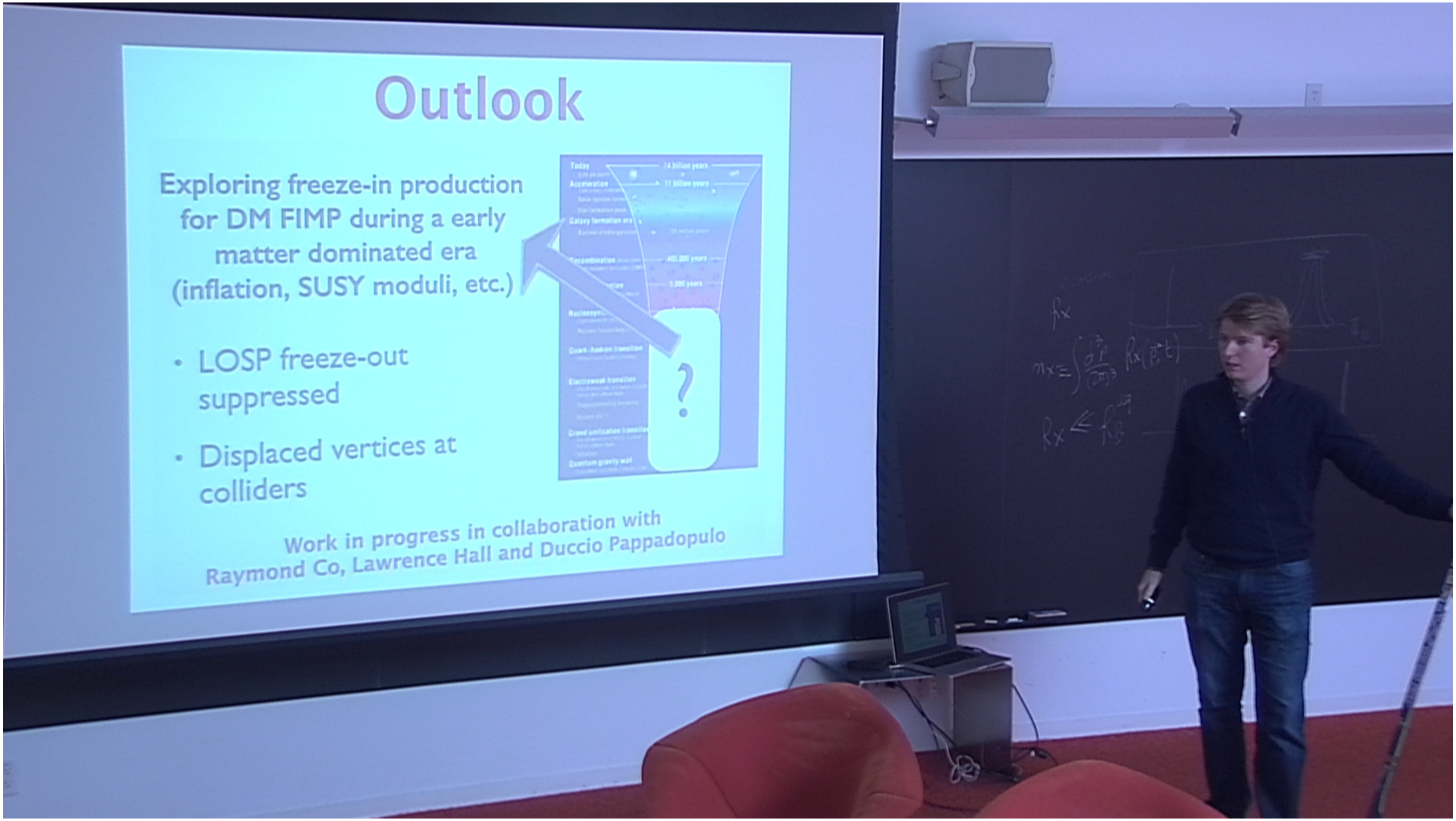

Displaced Vertices


Plan for Today's Talk
A motivated candidate


Axino
$W = \frac{S^2 H_u H_d}{M_*}$
$\mu \simeq \frac{f^2}{M_*} \simeq m_{\rm weak}$
Axino FIMP
$\mathcal{L} \supset \frac{\mu}{f} \tilde{h} \tilde{a} h$
Cosmological LSP Axino Problem
$\frac{\mu}{f} \simeq 10^{-8} \left(\frac{\mu}{1\,{\rm TeV}}\right) \left(\frac{10^{11}\,{\rm GeV}}{f}\right)$
our unive


Axino
$W = \frac{S^2 H_u H_d}{M_*}$
$\mu \simeq \frac{f^2}{M_*} \simeq m_{\rm weak}$
Axino FIMP
$\mathcal{L} \supset \frac{\mu}{f} \tilde{h} \tilde{a} h$
Cosmological LSP Axino Problem
$\frac{\mu}{f} \simeq 10^{-8} \left(\frac{\mu}{1\,\mathrm{TeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f}\right)$
Badly overcloses
our universe


Displaced Axino
$\mathcal{L} \supset \frac{\mu}{f} \tilde{h} \tilde{a} h$
WORK IN PROGRESS
$\tilde{N}_1 \to h \tilde{a}$
$\tilde{N}_1 \to Z \tilde{a}$
$\frac{1}{\Gamma_{\tilde{N}_1}} \simeq \delta_{\rm mix}^{-2} \left(\frac{\mu^3}{8\pi f^2}\right)^{-1} \simeq 5\,{\rm cm} \left(\frac{1}{\delta_{\rm mix}}\right)^2$
Fine with alternative


Outlook
Exploring freeze-in production for DM FIMP during a early matter dominated era (inflation, SUSY moduli, etc.)
• LOSP freeze-out suppressed
• Displaced vertices at colliders
Today
Acceleration
14 billion years
11 billion years
400,000 years
5,000 years
Quark–hadron transition
Electroweak transition
Quantum gravity wall
?
Work in progress in collaboration with
Raymond Co, Lawrence Hall and Duccio Pappadopulo