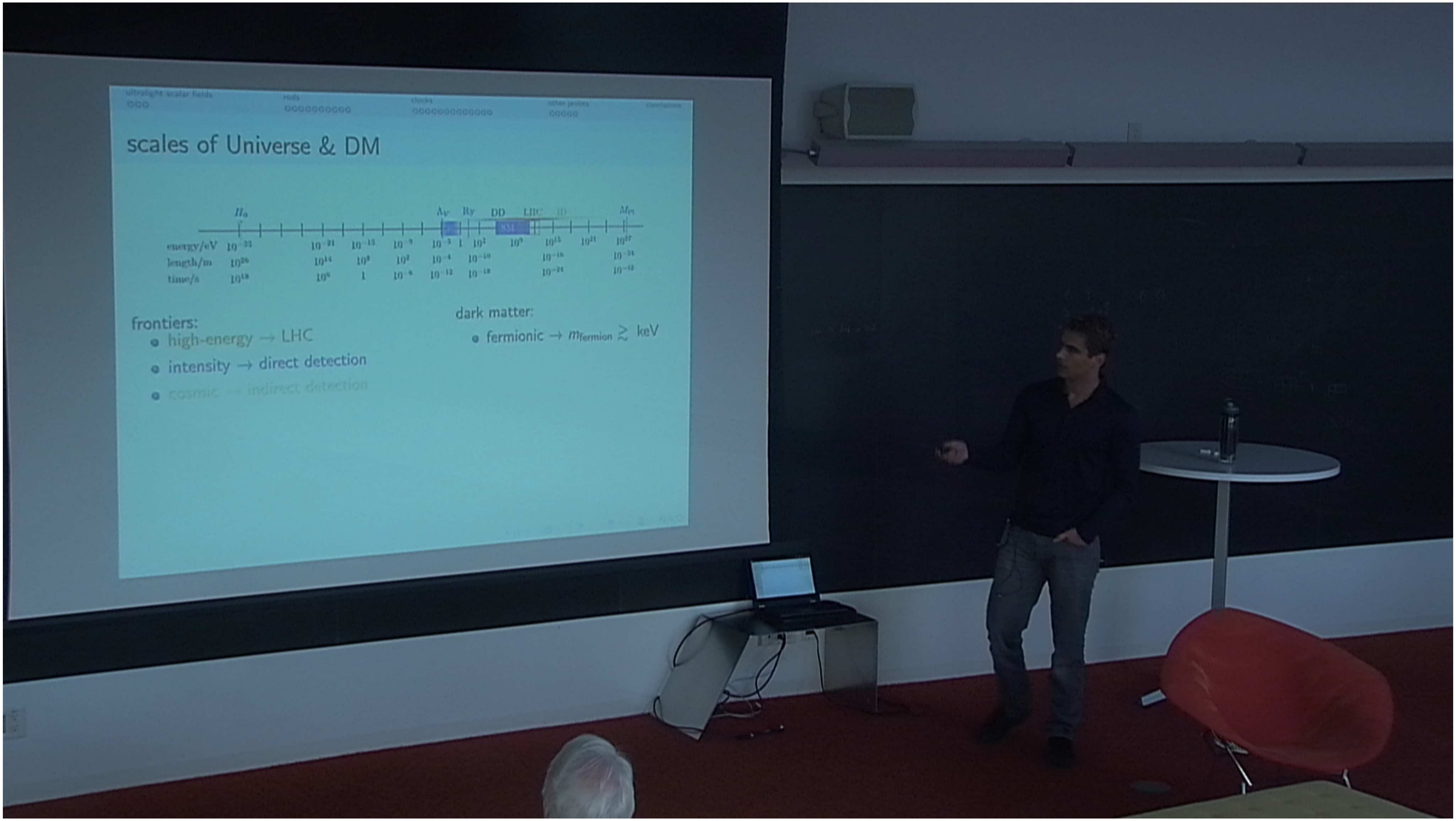
Title: Looking for light scalar dark matter with rods and clocks

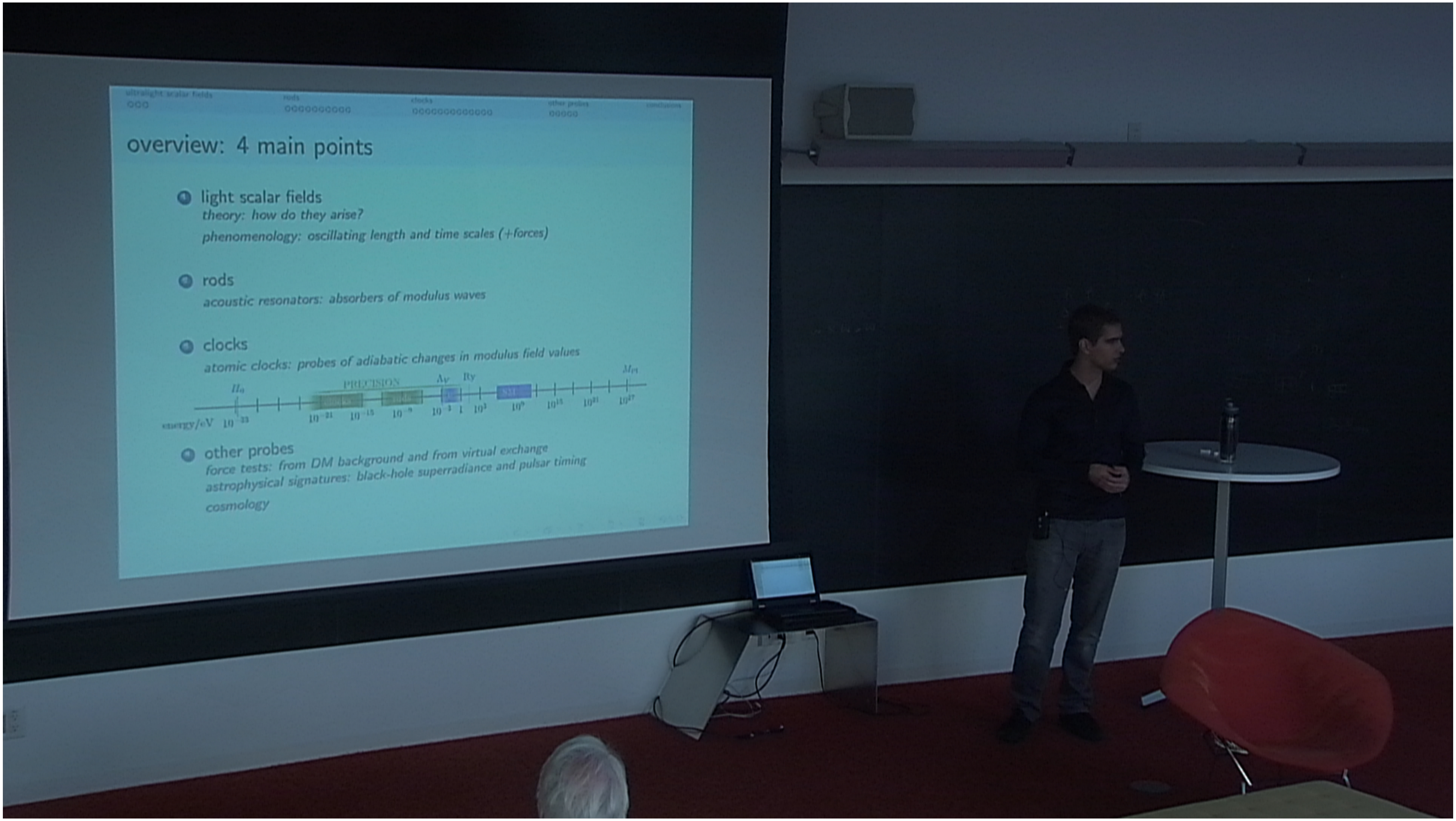
Date: Feb 05, 2016 12:30 PM

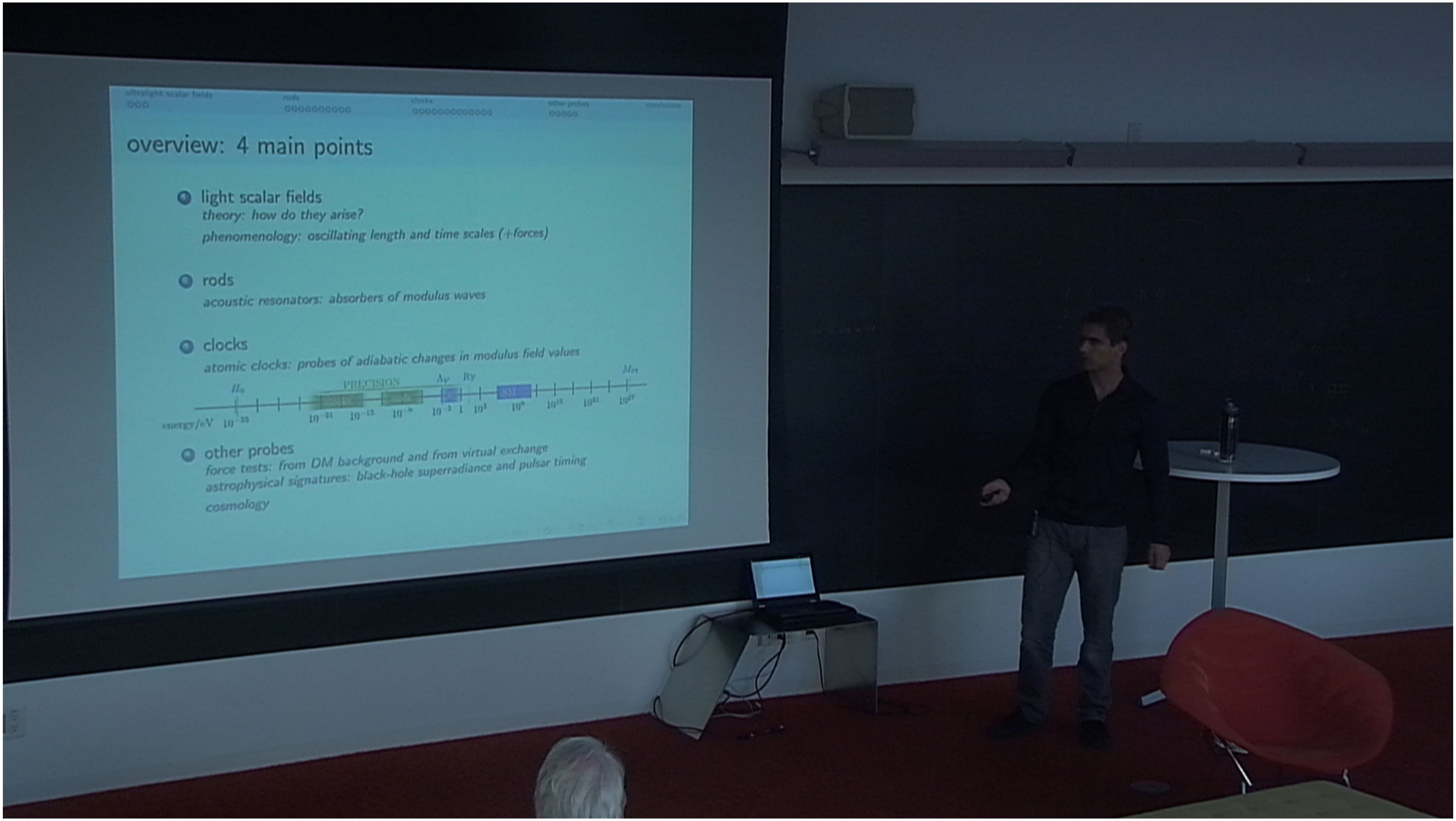
URL: http://pirsa.org/16020099

Abstract: <p>If the dark matter is made up of a bosonic particle, it can be ultralight, with a mass potentially much below 1 eV. Well-known DM candidates of this type include pseudoscalars like the QCD axion, and vectors such as hidden photons kinetically mixed with the Standard Model. Moduli, even-parity scalars with nonderivative couplings to the SM, can also be light dark matter. I will show that they cause tiny fractional oscillations of SM parameters, such as the electron mass and the fine-structure constant, in turn modulating length and time scales of atoms. Rods and clocks, used in gedanken experiments in relativity, have since transformed into actual precision instruments. The size of acoustic resonators and the frequency of optical clocks can now be measured to 1 part in 10^22 and 10^18, respectively, and thus constitute sensitive probes of moduli. </p>

<p>In this talk, I will give an overview of the parameter space of modulus dark matter, and discuss the sensitivity of the proposed experiments compared to existing constraints from fifth-force tests.</p>


scales of Universe & DM
energy/eV
length/m
time/s
frontiers:
high-energy → LHC
intensity → direct detection
cosmic → indirect detection
dark matter:
fermionic → m_fermion ≳ keV


ultralight scalar fields
rods
clocks
other probes
conclusions
overview: 4 main points
light scalar fields
theory: how do they arise?
phenomenology: oscillating length and time scales (+forces)
rods
acoustic resonators: absorbers of modulus waves
clocks
atomic clocks: probes of adiabatic changes in modulus field values
PRECISION
energy/eV
other probes
force tests: from DM background and from virtual exchange
astrophysical signatures: black-hole superradiance and pulsar timing
cosmology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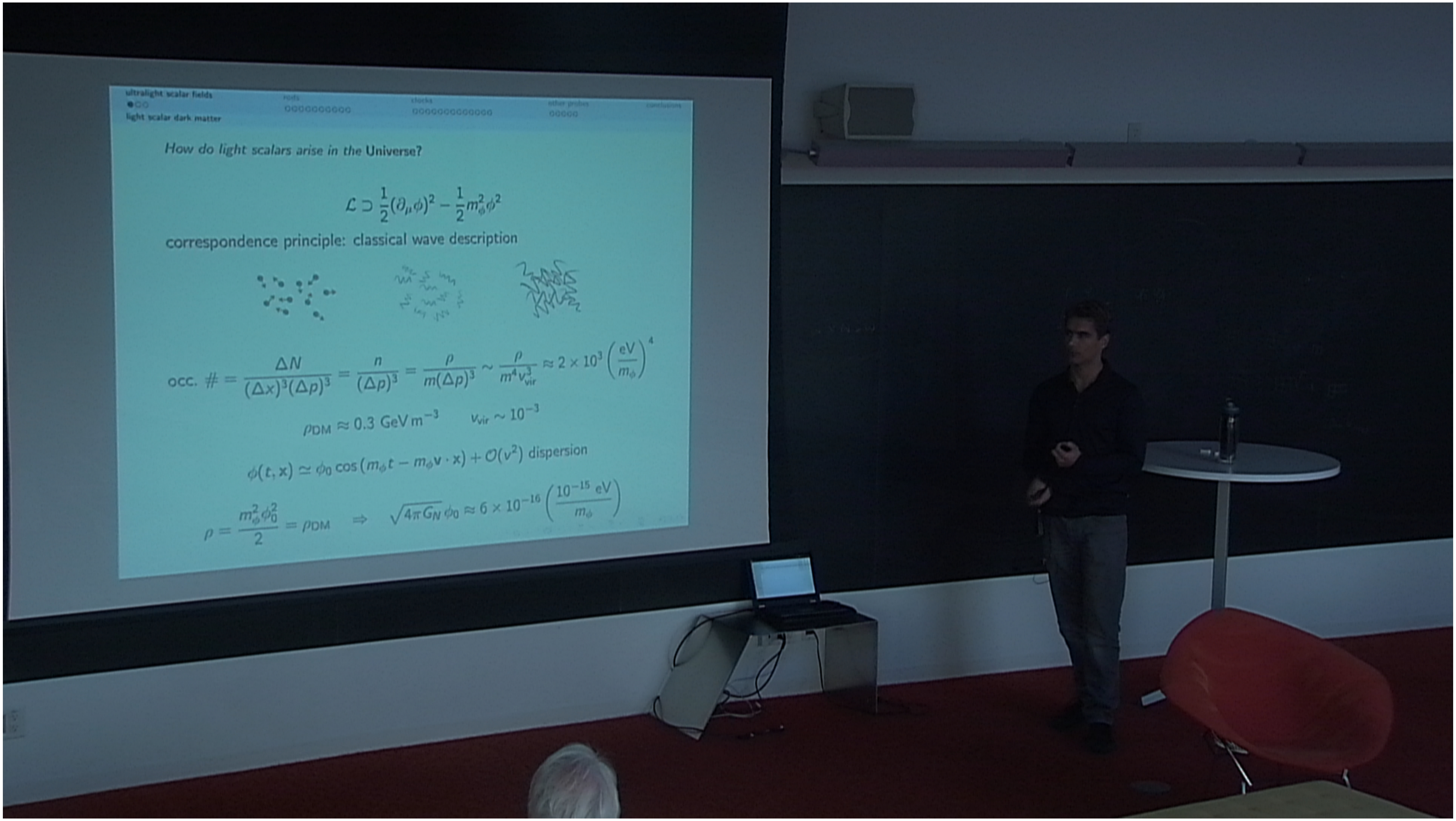
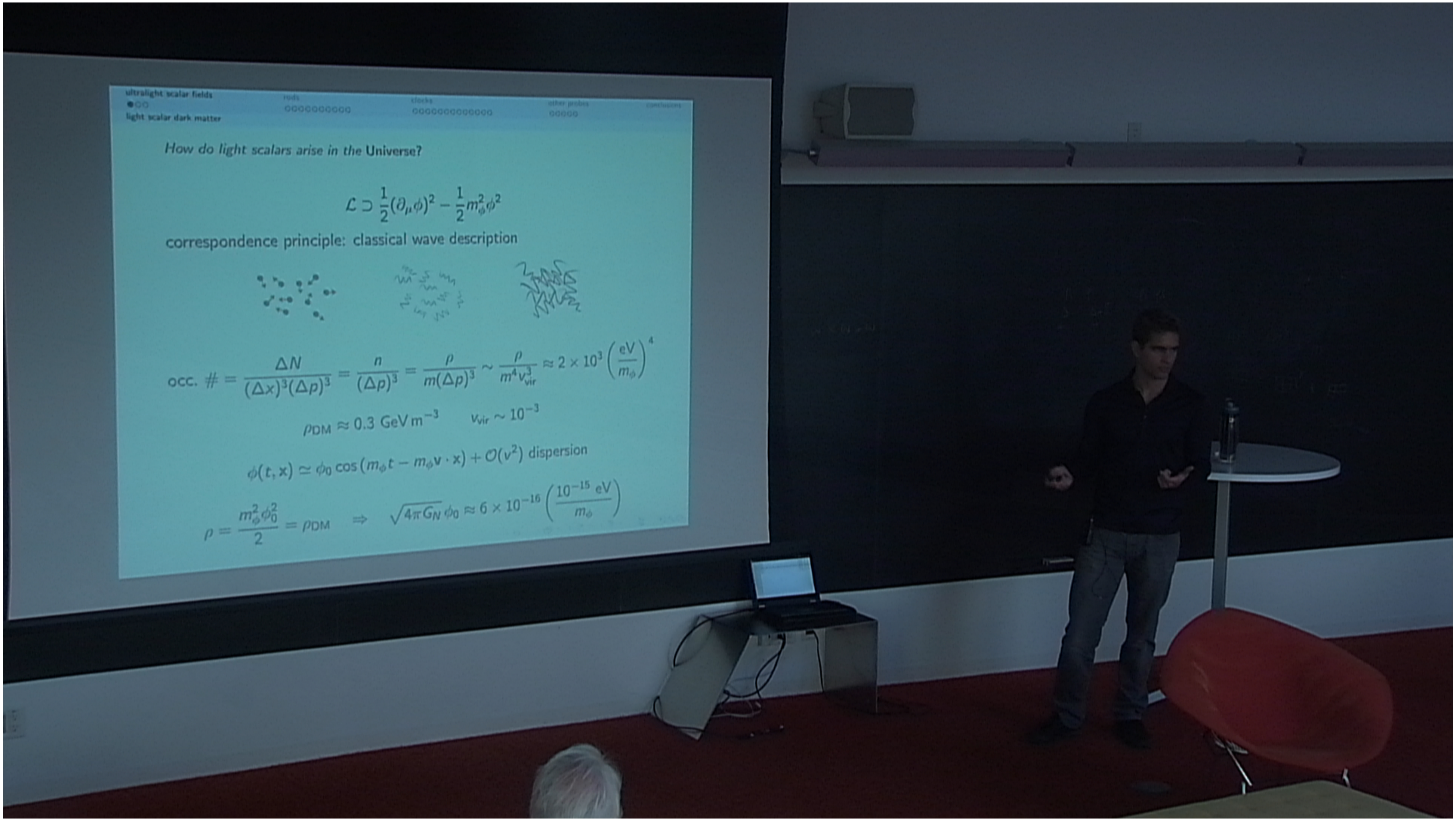

ultralight scalar fields
light scalar dark matter
How do light scalars arise in the Universe?
$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2$
correspondence principle: classical wave description
occ. $\# = \frac{\Delta N}{(\Delta x)^3 (\Delta p)^3} = \frac{n}{(\Delta p)^3} = \frac{\rho}{m(\Delta p)^3} \sim \frac{\rho}{m^4 v_{vir}^3} \approx 2 \times 10^3 \left(\frac{\mathrm{eV}}{m_\phi}\right)^4$
$\rho_{DM} \approx 0.3\ \mathrm{GeV\,m^{-3}}$ $v_{vir} \sim 10^{-3}$
$\phi(t, \mathbf{x}) \simeq \phi_0 \cos(m_\phi t - m_\phi \mathbf{v} \cdot \mathbf{x}) + \mathcal{O}(v^2)$ dispersion
$\rho = \frac{m_\phi^2 \phi_0^2}{2} = \rho_{DM} \Rightarrow \sqrt{4\pi G_N}\,\phi_0 \approx 6 \times 10^{-16} \left(\frac{10^{-15}\ \mathrm{eV}}{m_\phi}\right)$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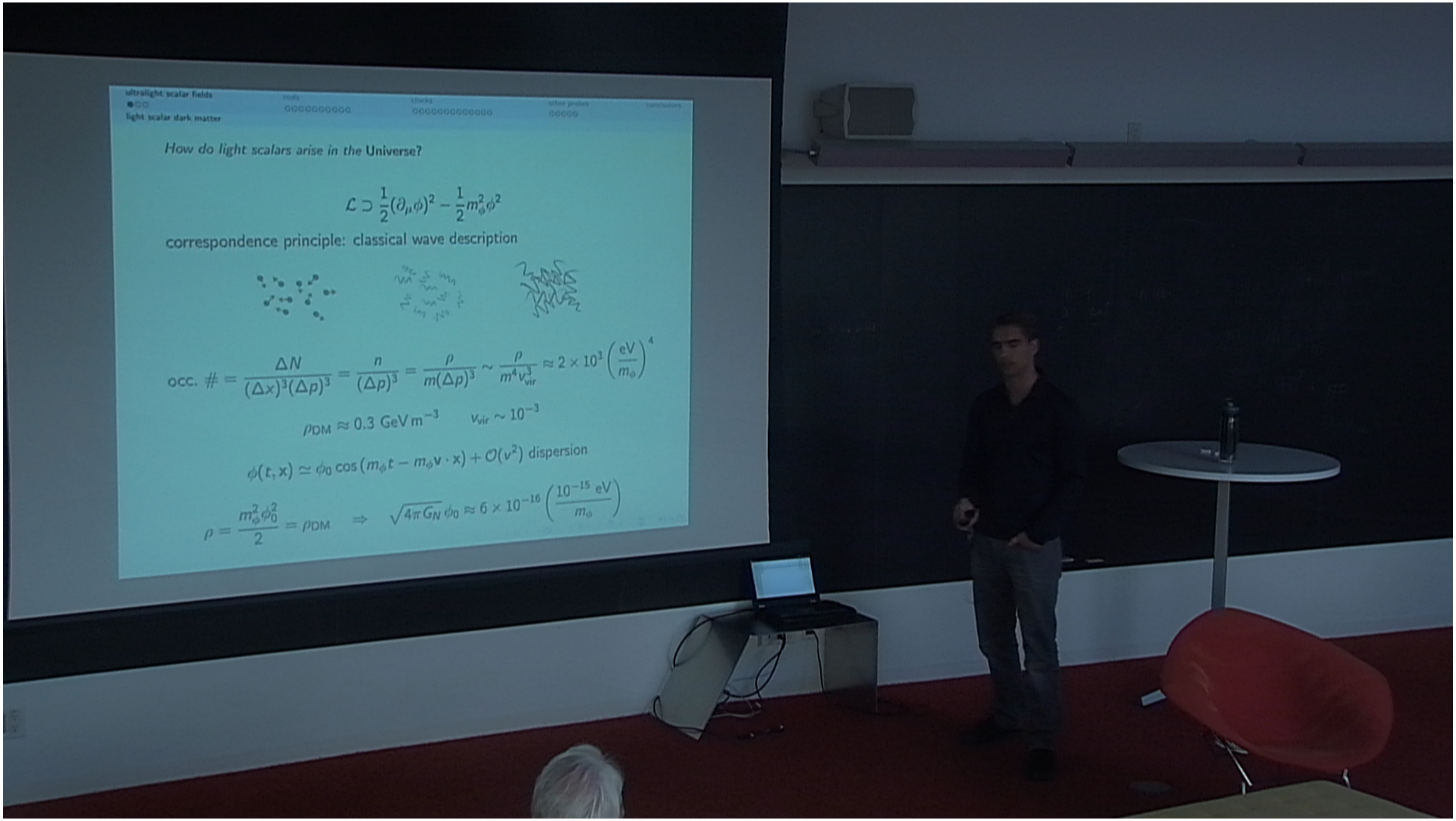
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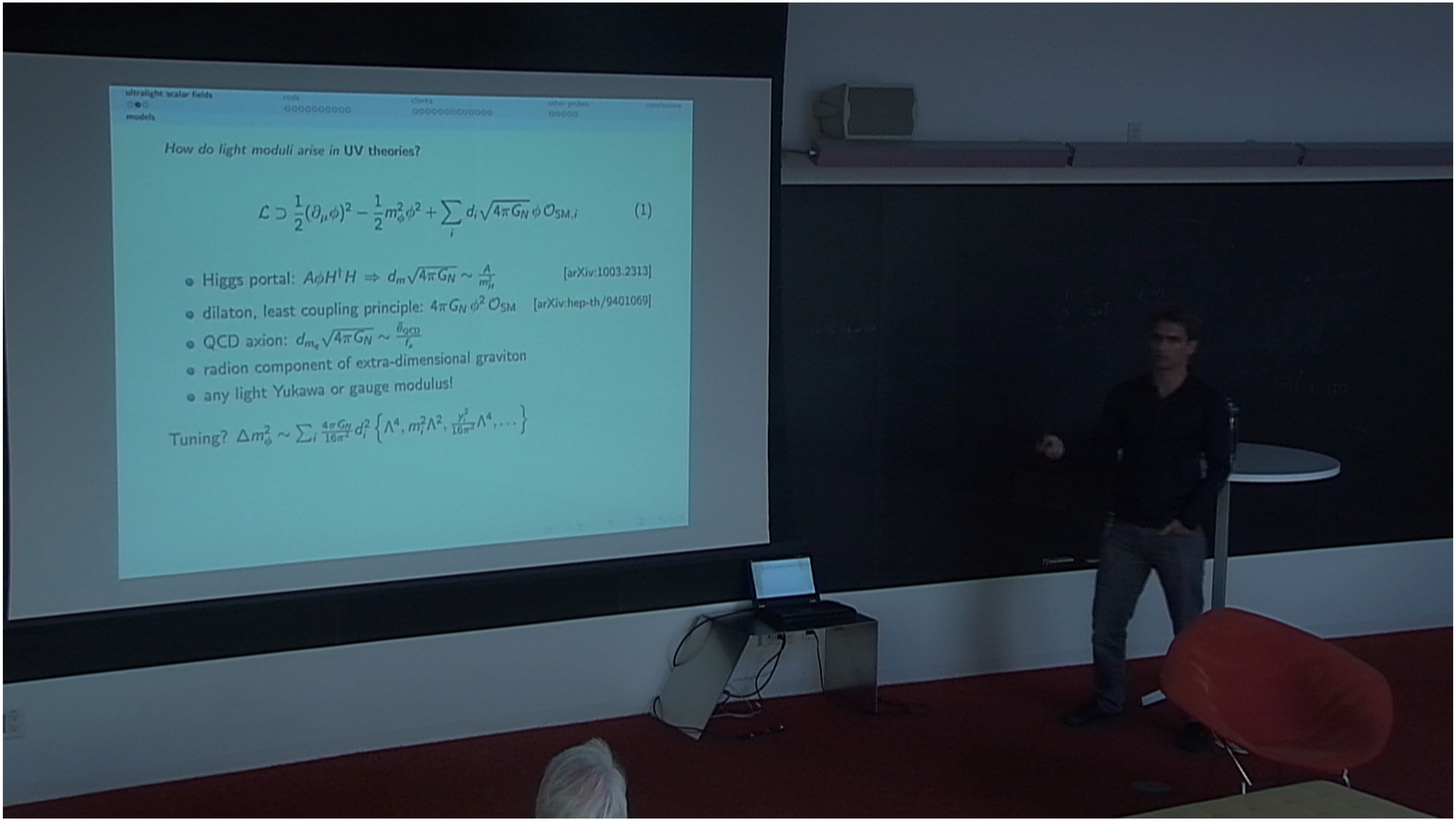
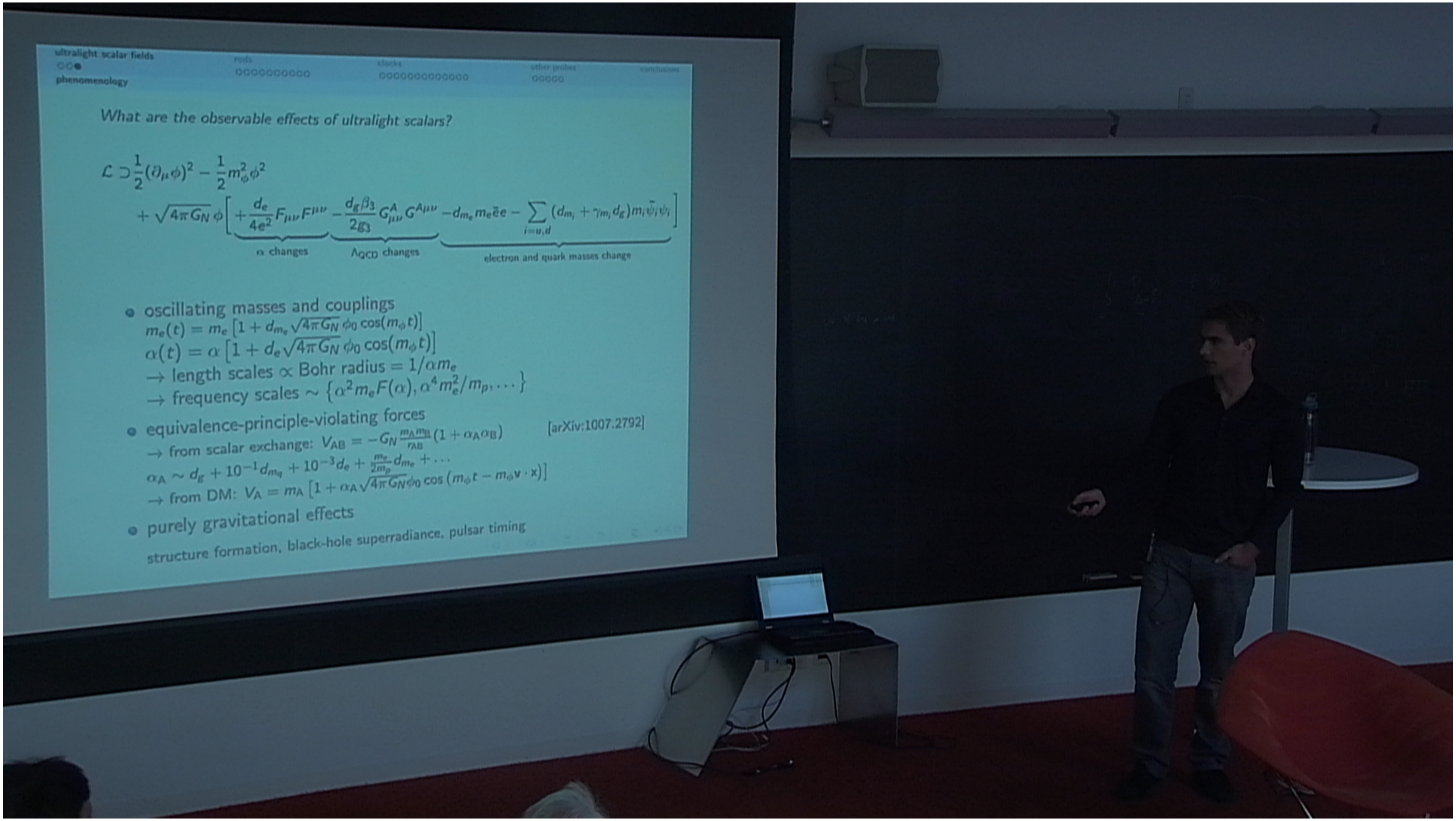
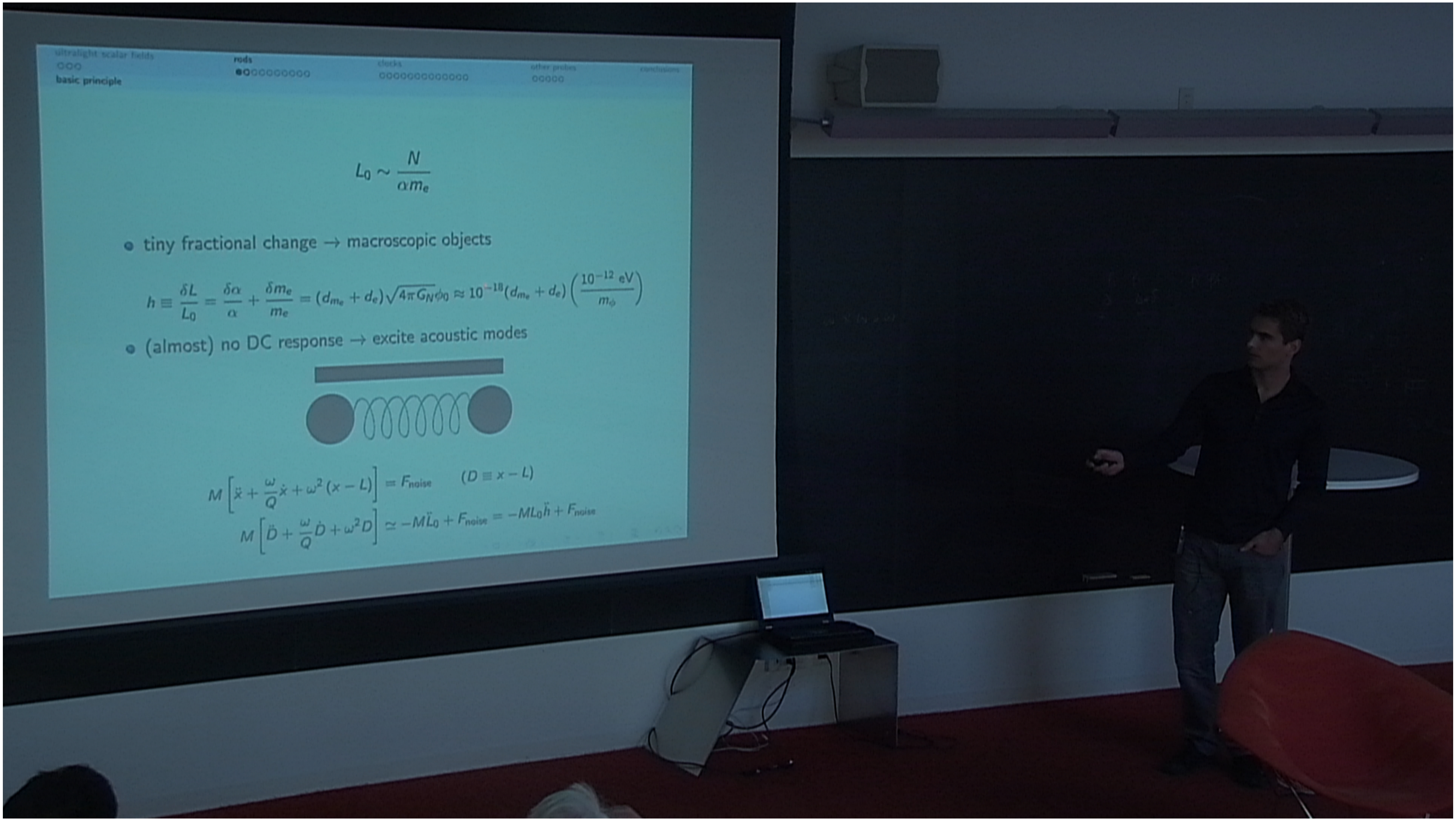

ultralight scalar fields
models
clocks
How do light moduli arise in UV theories?
$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 \phi^2 + \sum_i d_i \sqrt{4\pi G_N}\, \phi\, \mathcal{O}_{SM,i} \quad (1)$$
Higgs portal: $A\phi H^\dagger H \Rightarrow d_m \sqrt{4\pi G_N} \sim \frac{A}{m_H^2}$ [arXiv:1003.2313]
dilaton, least coupling principle: $4\pi G_N \phi^2 \mathcal{O}_{SM}$ [arXiv:hep-th/9401069]
QCD axion: $d_{m_q} \sqrt{4\pi G_N} \sim \frac{\bar{\theta}_{QCD}}{f_a}$
radion component of extra-dimensional graviton
any light Yukawa or gauge modulus!
Tuning? $\Delta m_\phi^2 \sim \sum_i \frac{4\pi G_N}{16\pi^2} d_i^2 \left\{\Lambda^4, m_i^2 \Lambda^2, \frac{y_i^2}{16\pi^2}\Lambda^4, \dots\right\}$


ultralight scalar fields
phenomenology
rods
clocks
other probes
conclusions
What are the observable effects of ultralight scalars?
$\mathcal{L} \supset \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + \sqrt{4\pi G_N}\,\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - d_{m_e}m_e\bar{e}e - \sum_{i=u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$
α changes
Λ_{QCD} changes
electron and quark masses change
oscillating masses and couplings
$m_e(t) = m_e\left[1 + d_{m_e}\sqrt{4\pi G_N}\,\phi_0\cos(m_\phi t)\right]$
$\alpha(t) = \alpha\left[1 + d_e\sqrt{4\pi G_N}\,\phi_0\cos(m_\phi t)\right]$
→ length scales ∝ Bohr radius $= 1/\alpha m_e$
→ frequency scales $\sim \{\alpha^2 m_e F(\alpha), \alpha^4 m_e^2/m_p, \dots\}$
equivalence-principle-violating forces
[arXiv:1007.2792]
→ from scalar exchange: $V_{AB} = -G_N\frac{m_A m_B}{r_{AB}}(1+\alpha_A\alpha_B)$
$\alpha_A \sim d_g + 10^{-1}d_{m_q} + 10^{-3}d_e + \frac{m_e}{2m_p}d_{m_e} + \dots$
→ from DM: $V_A = m_A\left[1 + \alpha_A\sqrt{4\pi G_N}\phi_0\cos(m_\phi t - m_\phi \mathbf{v}\cdot\mathbf{x})\right]$
purely gravitational effects
structure formation, black-hole superradiance, pulsar timing


ultralight scalar fields
basic principle
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other probes
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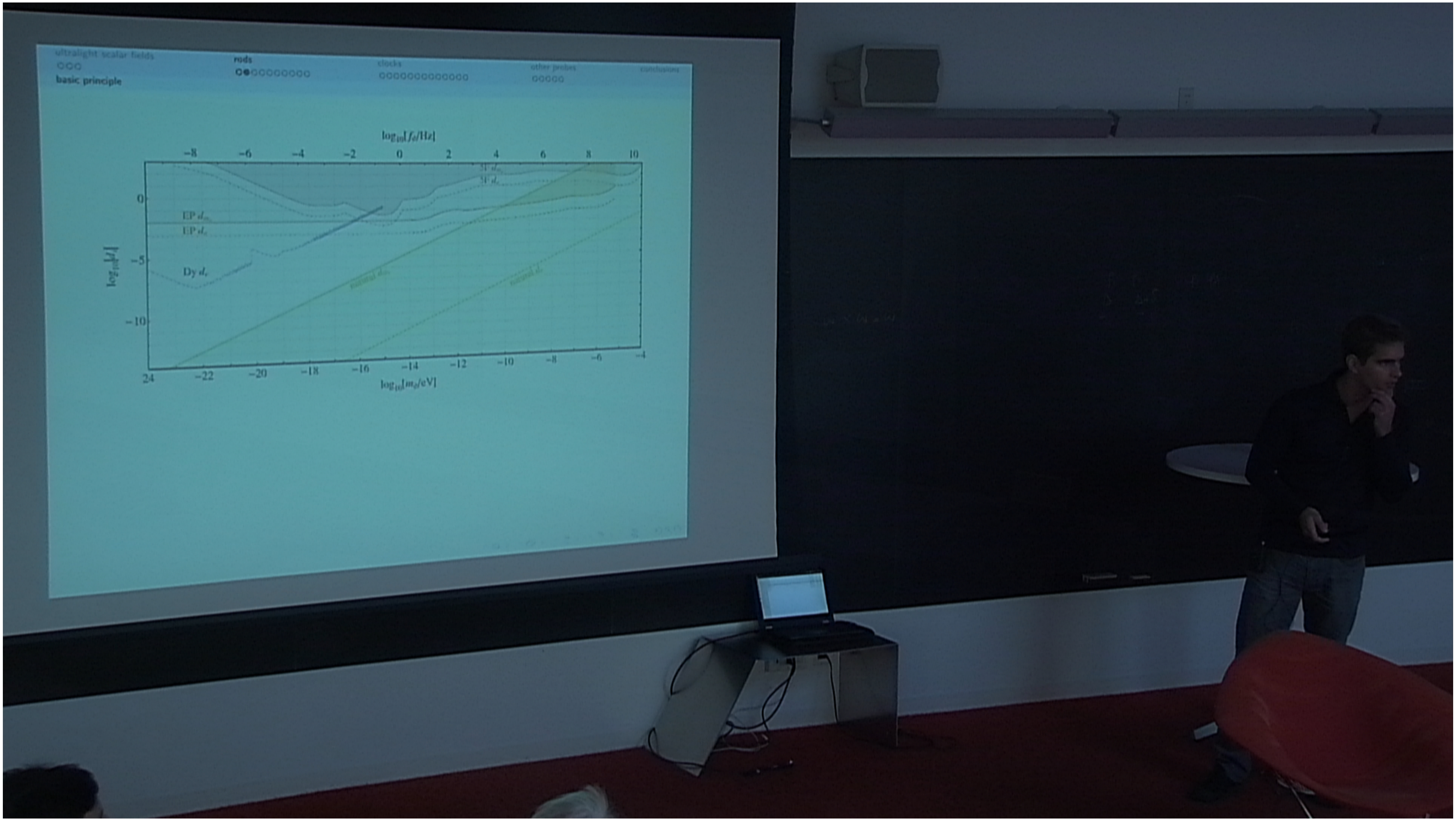
$L_0 \sim \frac{N}{\alpha m_e}$
tiny fractional change → macroscopic objects
$h \equiv \frac{\delta L}{L_0} = \frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e} = (d_{m_e} + d_e)\sqrt{4\pi G_N}\phi_0 \approx 10^{-18}(d_{m_e} + d_e)\left(\frac{10^{-12}\ \mathrm{eV}}{m_\phi}\right)$
(almost) no DC response → excite acoustic modes
$M\left[\ddot{x} + \frac{\omega}{Q}\dot{x} + \omega^2(x - L)\right] = F_{\mathrm{noise}}$ $(D \equiv x - L)$
$M\left[\ddot{D} + \frac{\omega}{Q}\dot{D} + \omega^2 D\right] \simeq -M\ddot{L}_0 + F_{\mathrm{noise}} = -ML_0\ddot{h} + F_{\mathrm{noise}}$


ultralight scalar fields
basic principle
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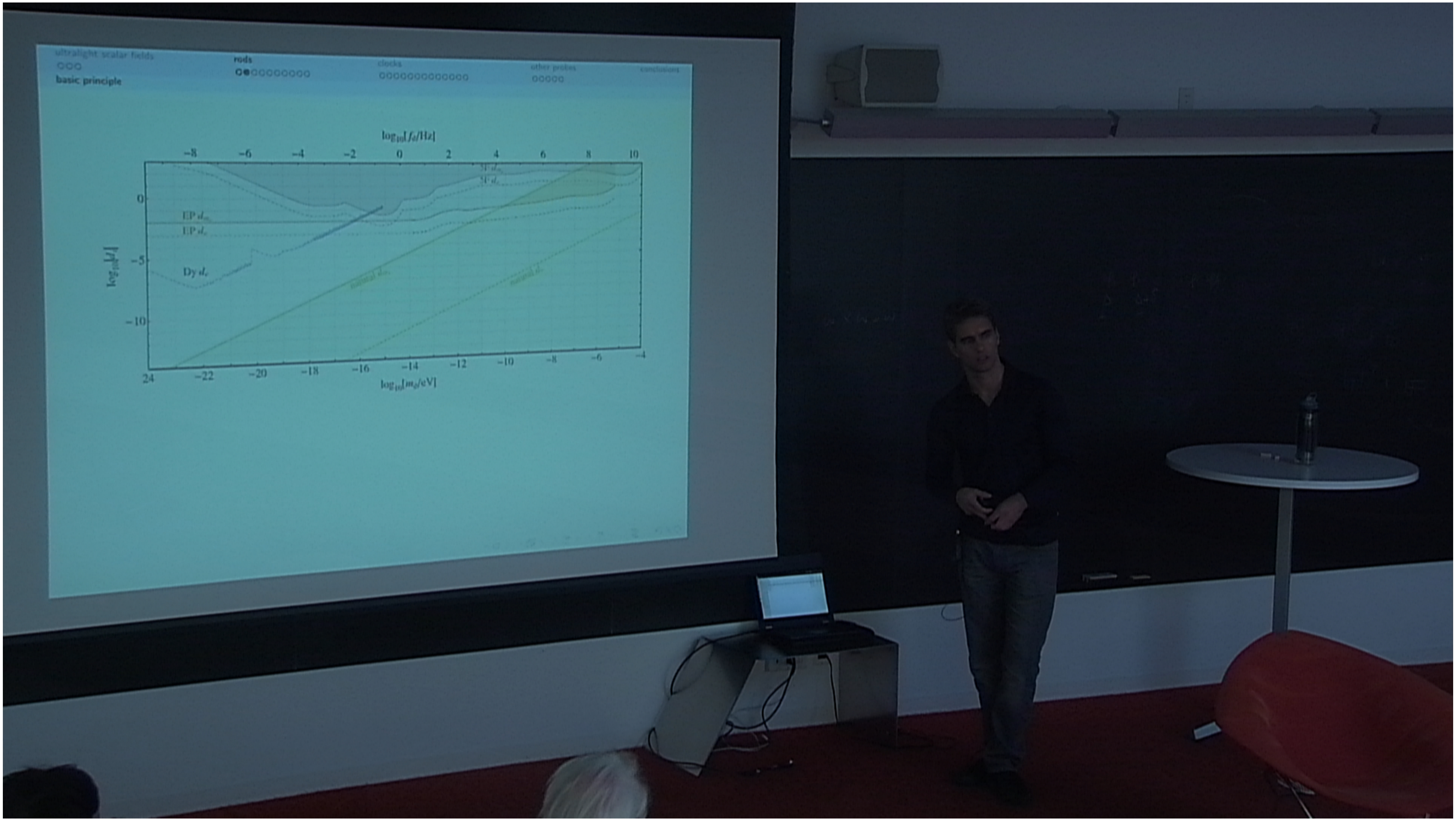
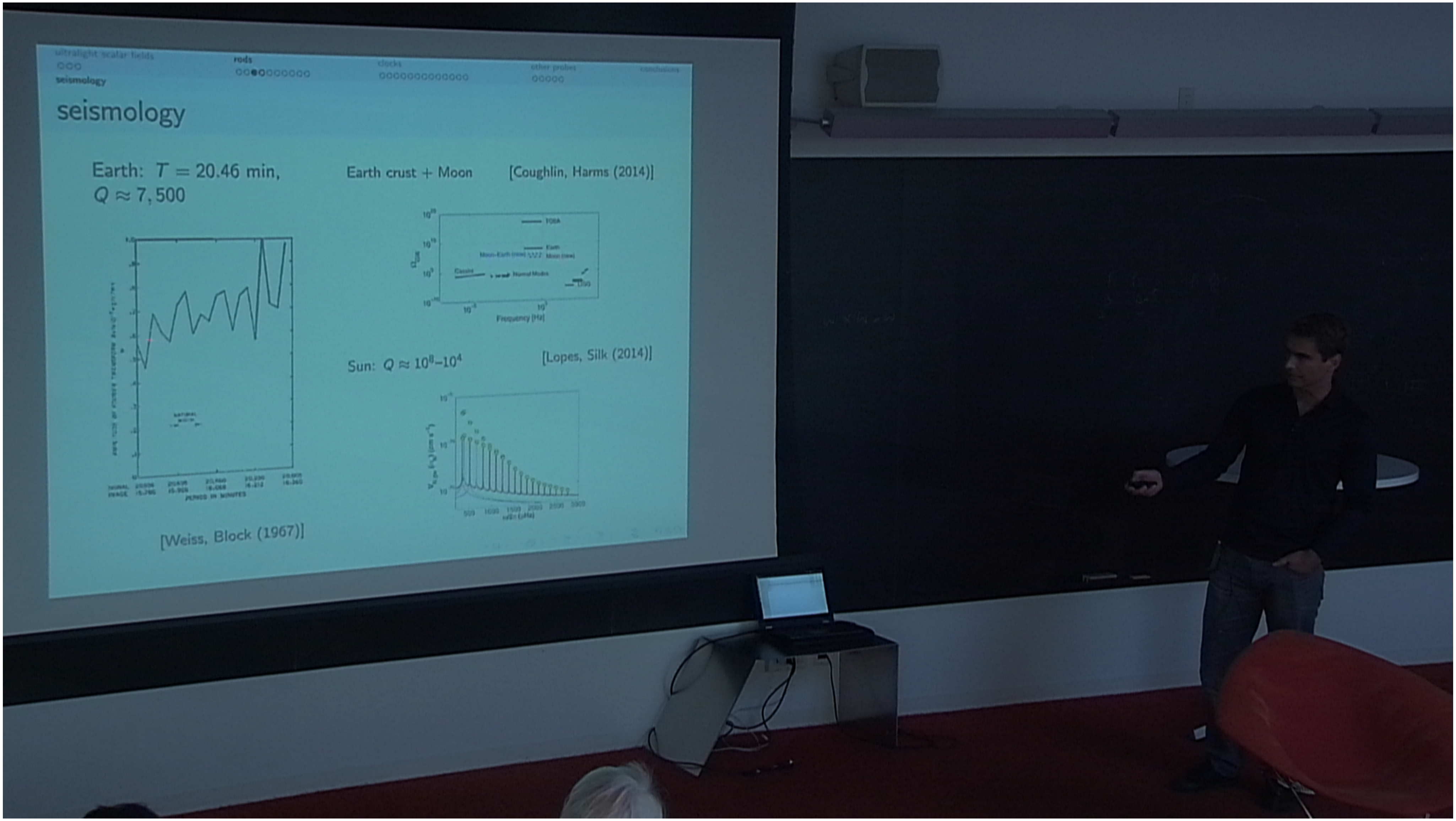
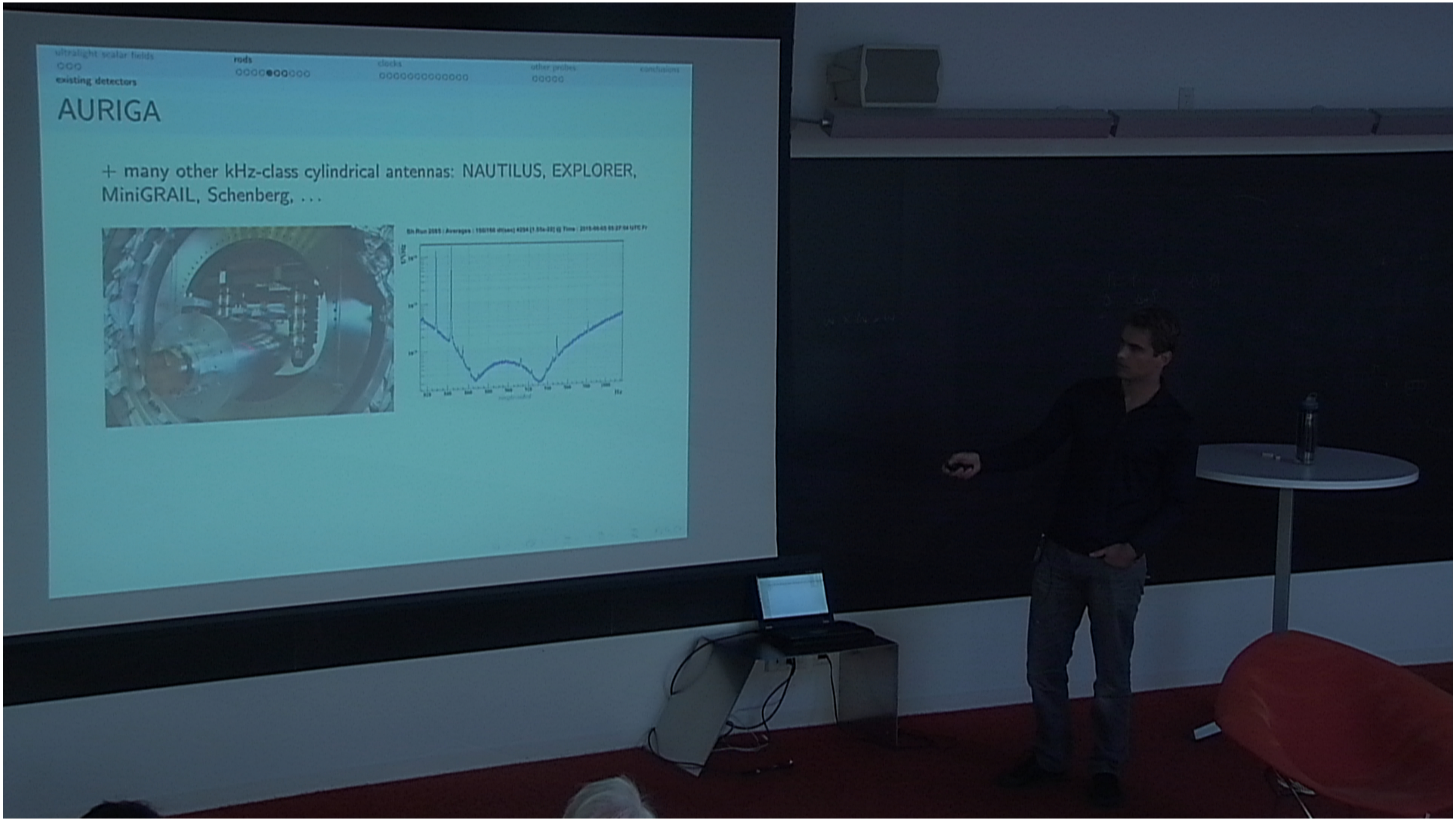
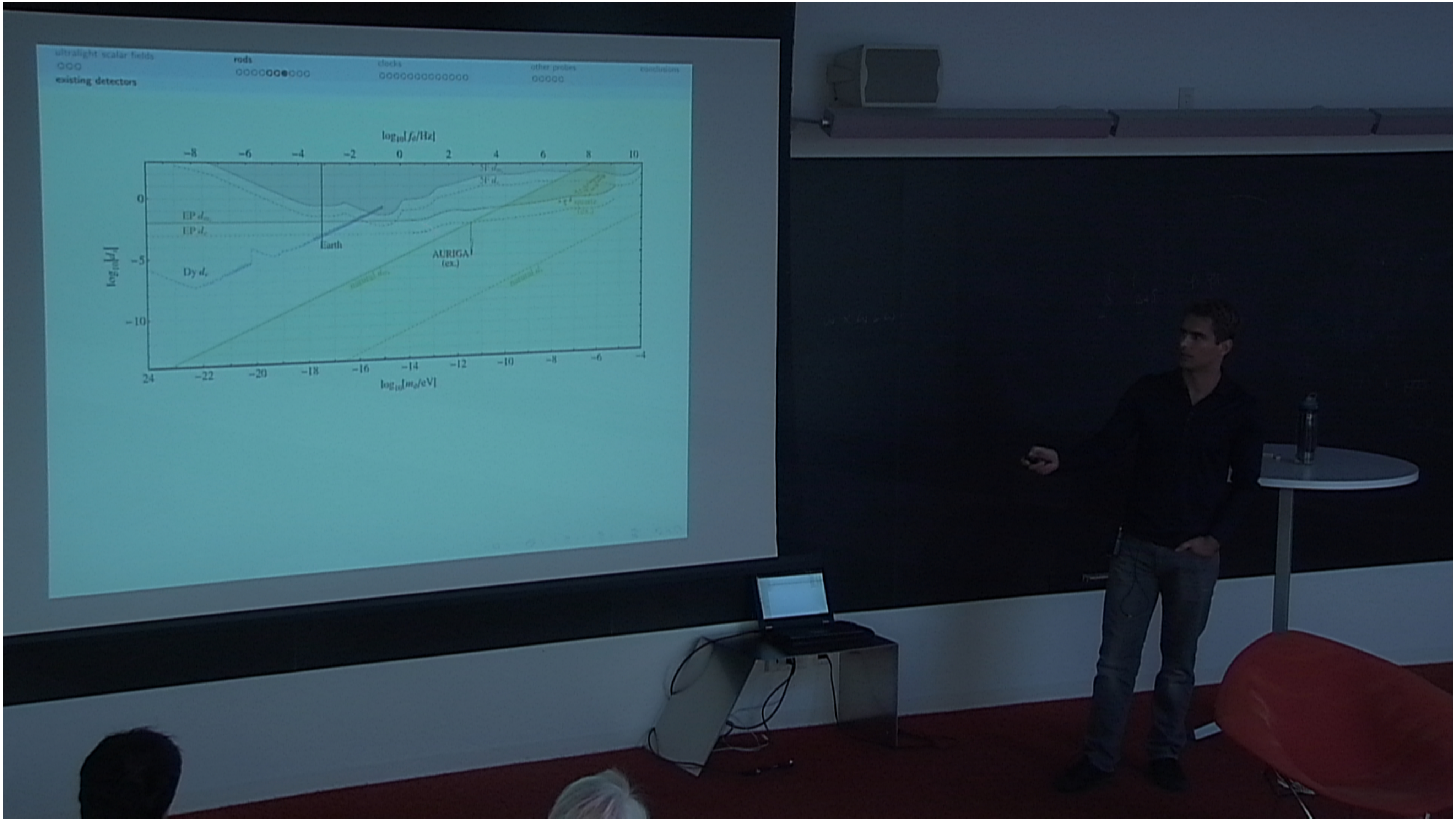
conclusions
$\log_{10}[f_\phi/\mathrm{Hz}]$
EP d_{m_e}
EP d_e
Dy d_e
$\log_{10}[d]$
$\log_{10}[m_\phi/\mathrm{eV}]$



rods
basic principle
$\log_{10}[f_\phi/\mathrm{Hz}]$
EP d_{m_e}
EP d_e
Dy d_e
$\log_{10}|d|$
$\log_{10}[m_\phi/\mathrm{eV}]$


seismology
Earth: $T = 20.46$ min, $Q \approx 7,500$
[Weiss, Block (1967)]
Earth crust + Moon
[Coughlin, Harms (2014)]
Frequency [Hz]
Sun: $Q \approx 10^8$–10^4
[Lopes, Silk (2014)]


ultralight scalar fields
existing detectors
rods
clocks
other probes
conclusions
AURIGA
+ many other kHz-class cylindrical antennas: NAUTILUS, EXPLORER, MiniGRAIL, Schenberg, . . .



ultralight scalar fields
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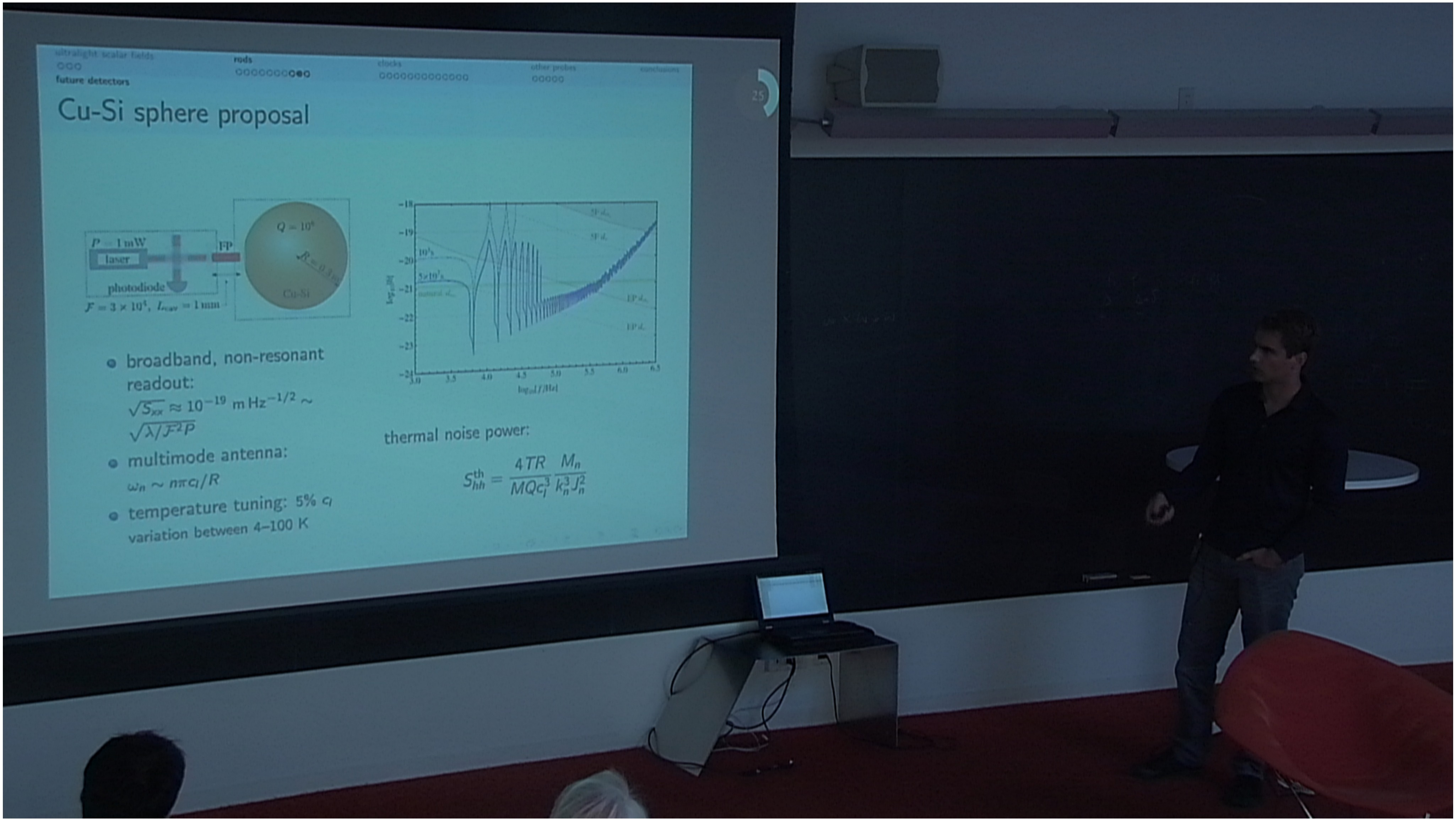
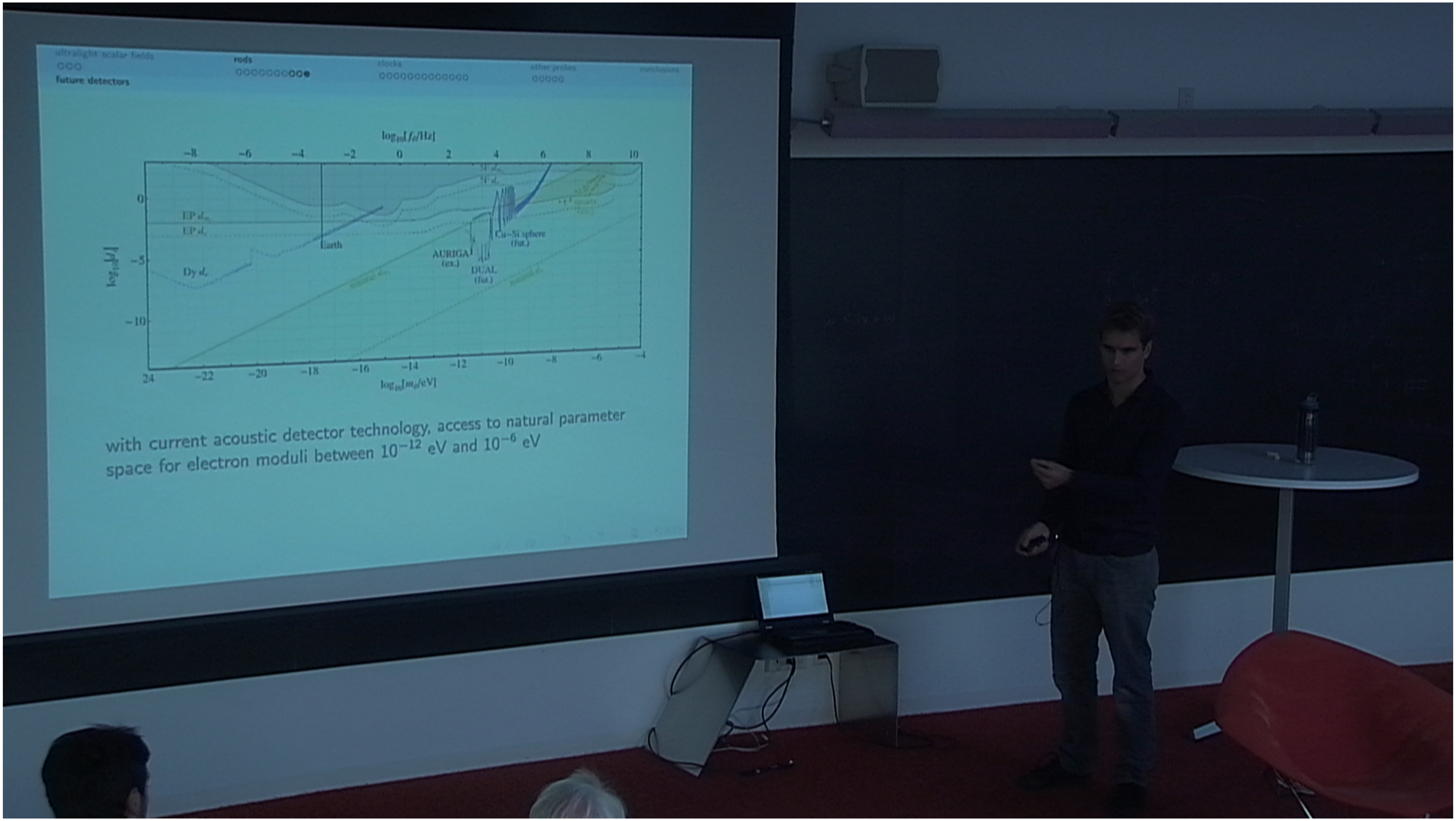
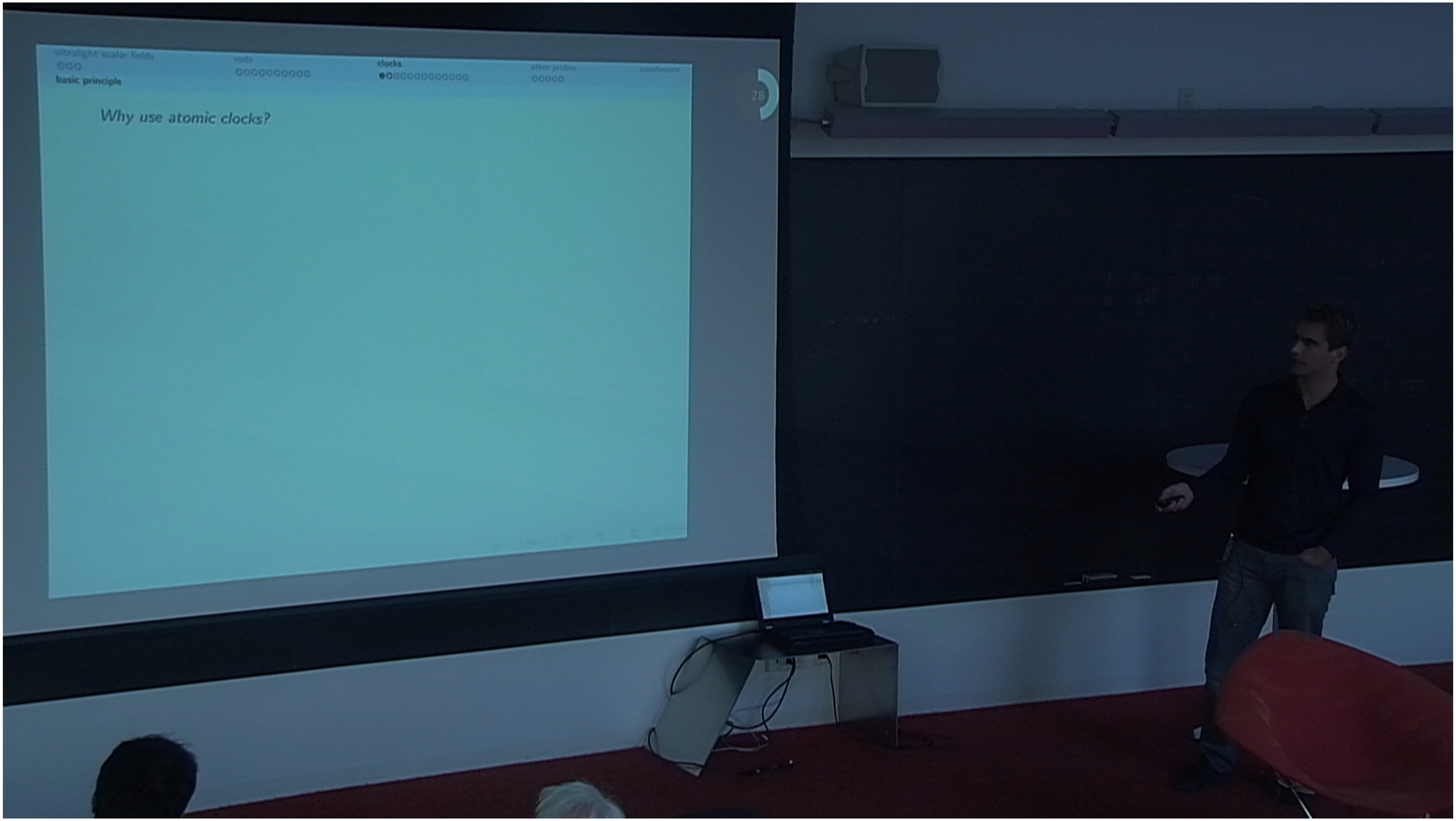
$\log_{10}[f_\phi/\text{Hz}]$
EP d_{m_e}
EP d_e
Dy d_e
Earth
AURIGA
(ex.)
$\log_{10}[m_\phi/\text{eV}]$


future detectors
Cu-Si sphere proposal
P = 1 mW
laser
photodiode
FP
Cu-Si
broadband, non-resonant readout: $\sqrt{S_{xx}} \approx 10^{-19}$ m Hz$^{-1/2}$ $\sim \sqrt{\lambda/\mathcal{F}^2 P}$
multimode antenna: $\omega_n \sim n\pi c_l/R$
temperature tuning: 5% c_l variation between 4–100 K
thermal noise power:
$S_{hh}^{\rm th} = \frac{4TR}{MQc_l^3}\frac{M_n}{k_n^3 J_n^2}$


future detectors
log10[fφ/Hz]
EP dme
EP de
Earth
Dy de
AURIGA (ex.)
DUAL (fut.)
Cu–Si sphere (fut.)
log10[mφ/eV]
with current acoustic detector technology, access to natural parameter space for electron moduli between 10^−12 eV and 10^−6 eV



ultralight scalar fields
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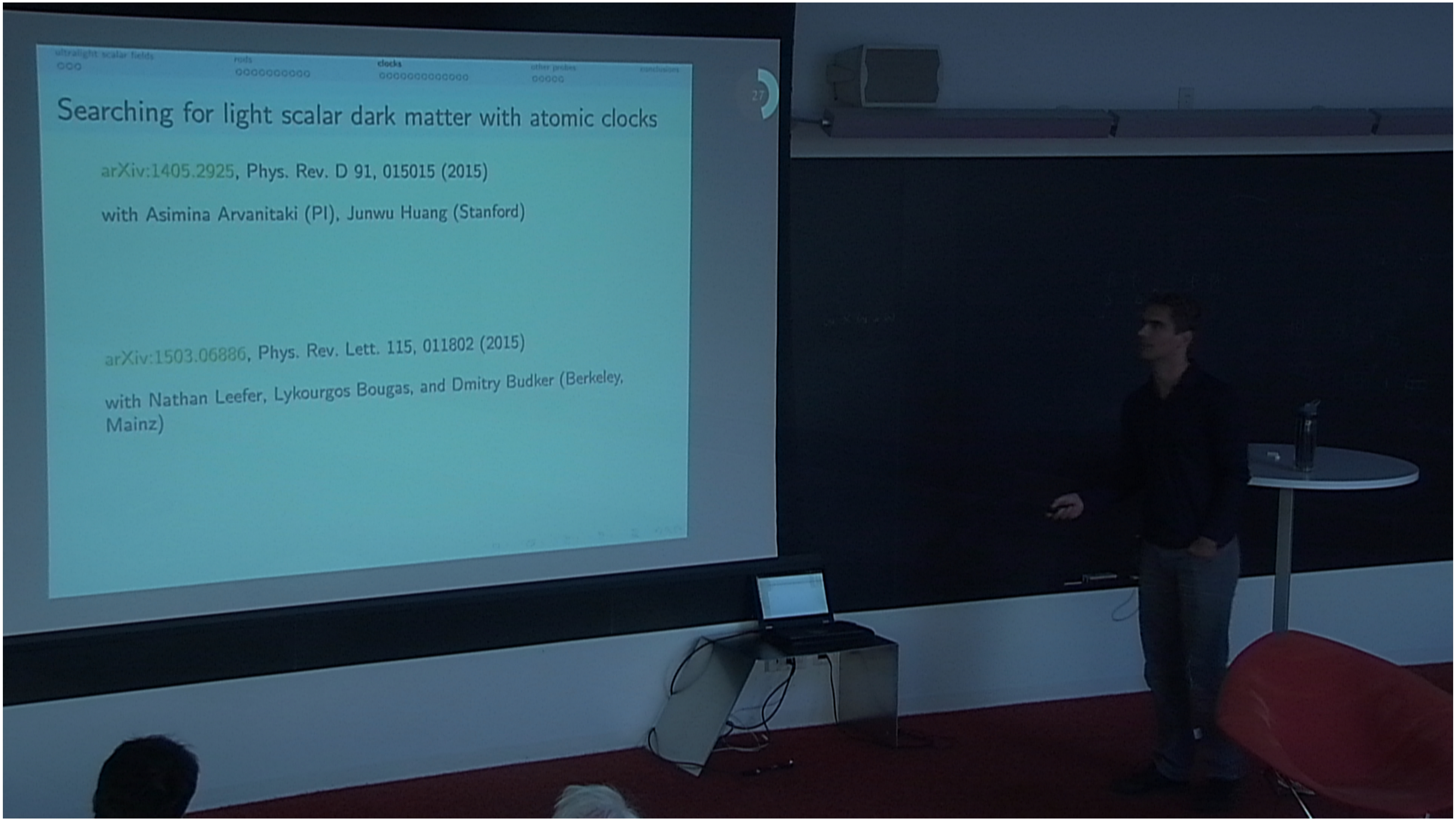
Why use atomic clocks?
28



ultralight scalar fields
rods
clocks
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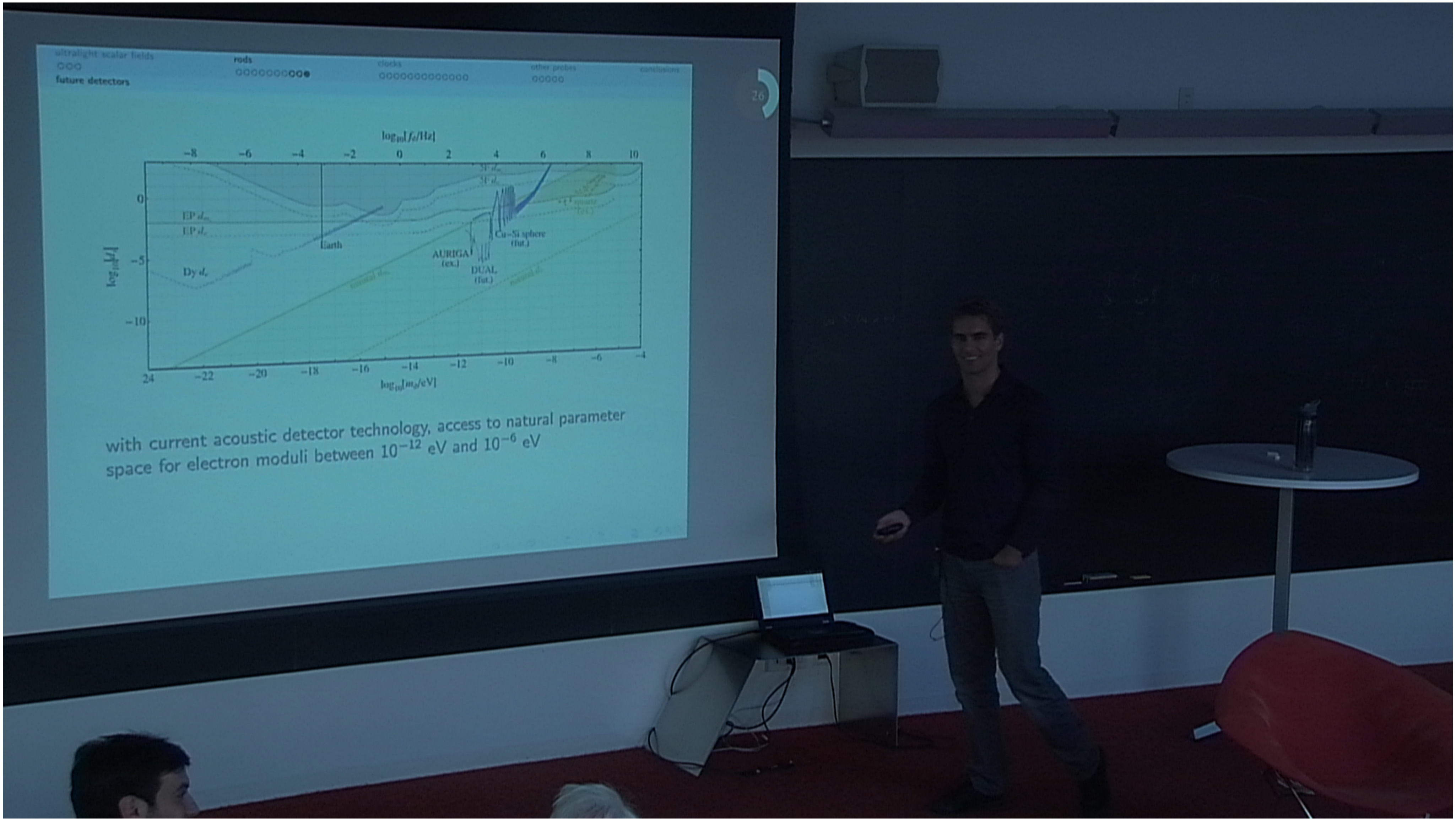
conclusions
Searching for light scalar dark matter with atomic clocks
arXiv:1405.2925, Phys. Rev. D 91, 015015 (2015)
with Asimina Arvanitaki (PI), Junwu Huang (Stanford)
arXiv:1503.06886, Phys. Rev. Lett. 115, 011802 (2015)
with Nathan Leefer, Lykourgos Bougas, and Dmitry Budker (Berkeley, Mainz)


future detectors
$\log_{10}[f_\phi/\mathrm{Hz}]$
EP d_{m_e}
EP d_e
Dy d_e
Earth
AURIGA (ex.)
DUAL (fut.)
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$\log_{10}[m_\phi/\mathrm{eV}]$
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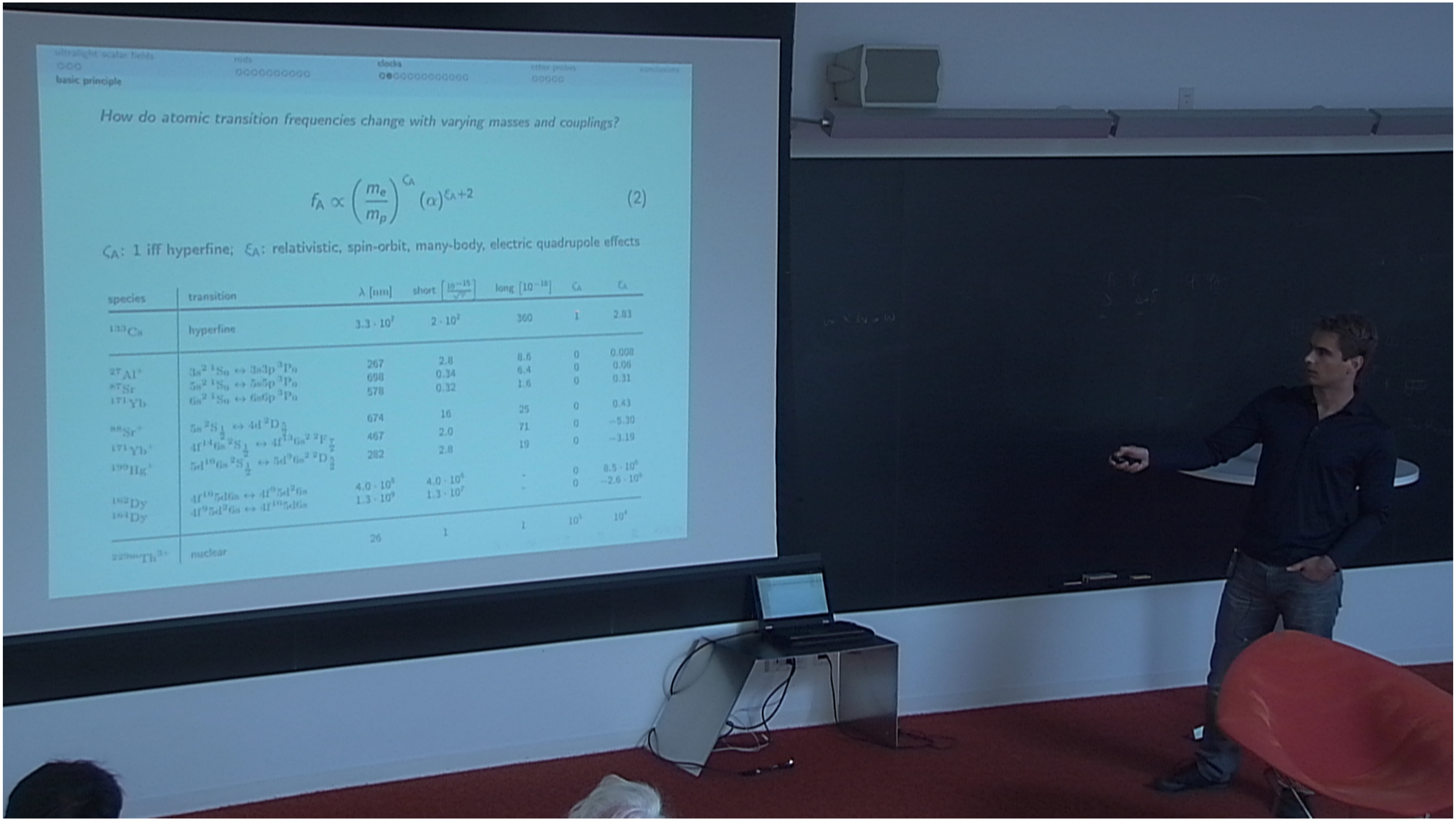
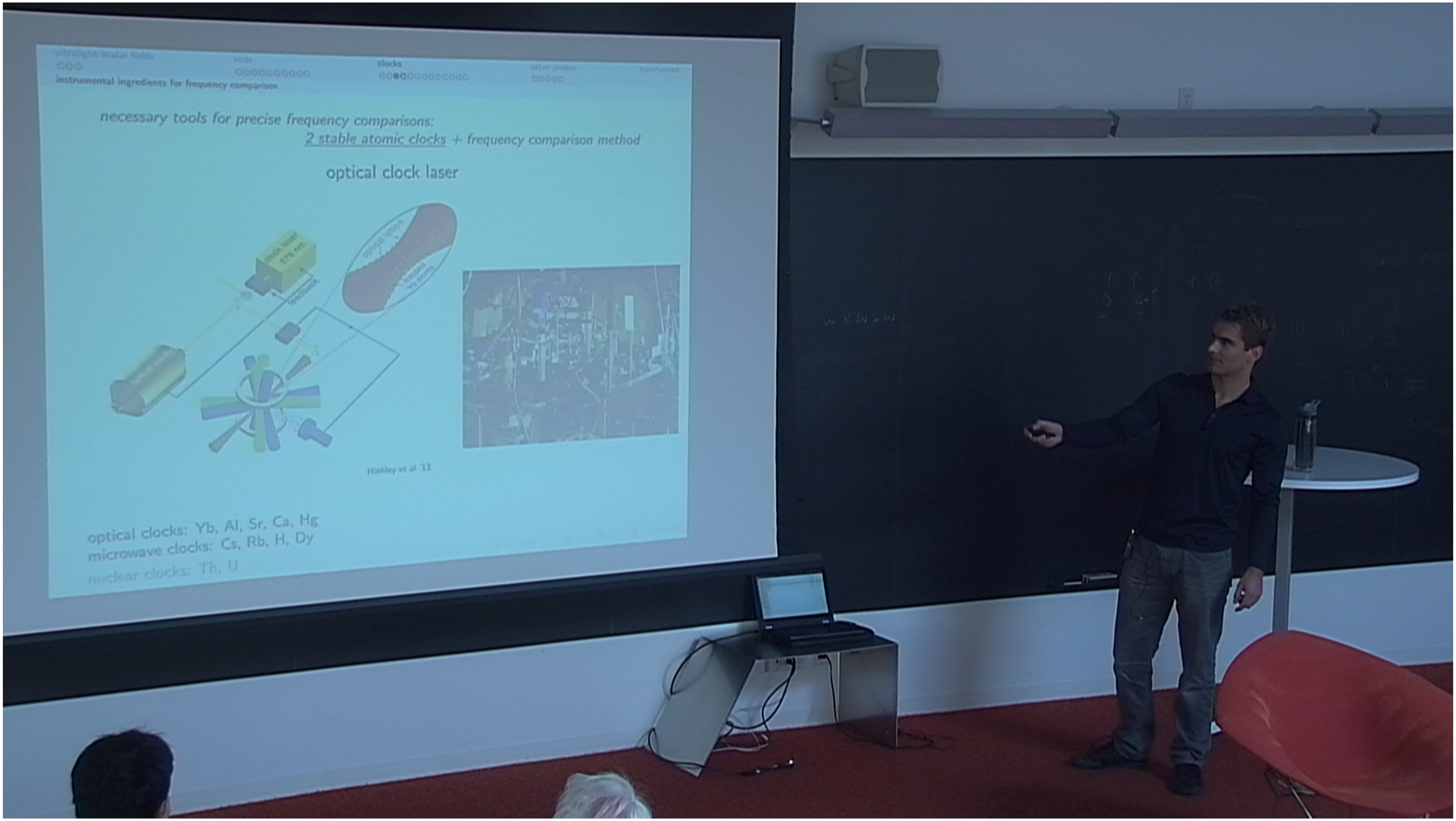
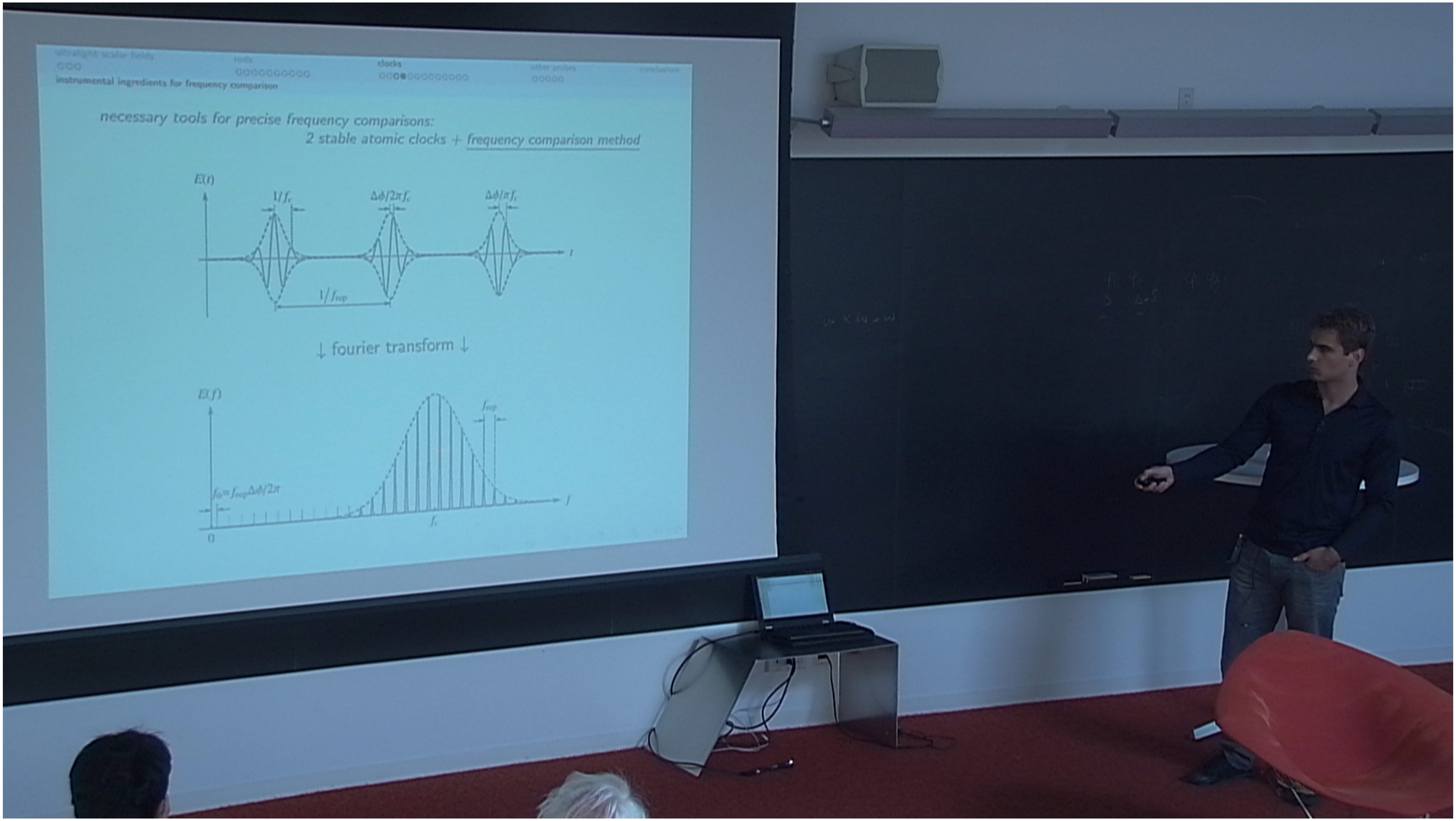
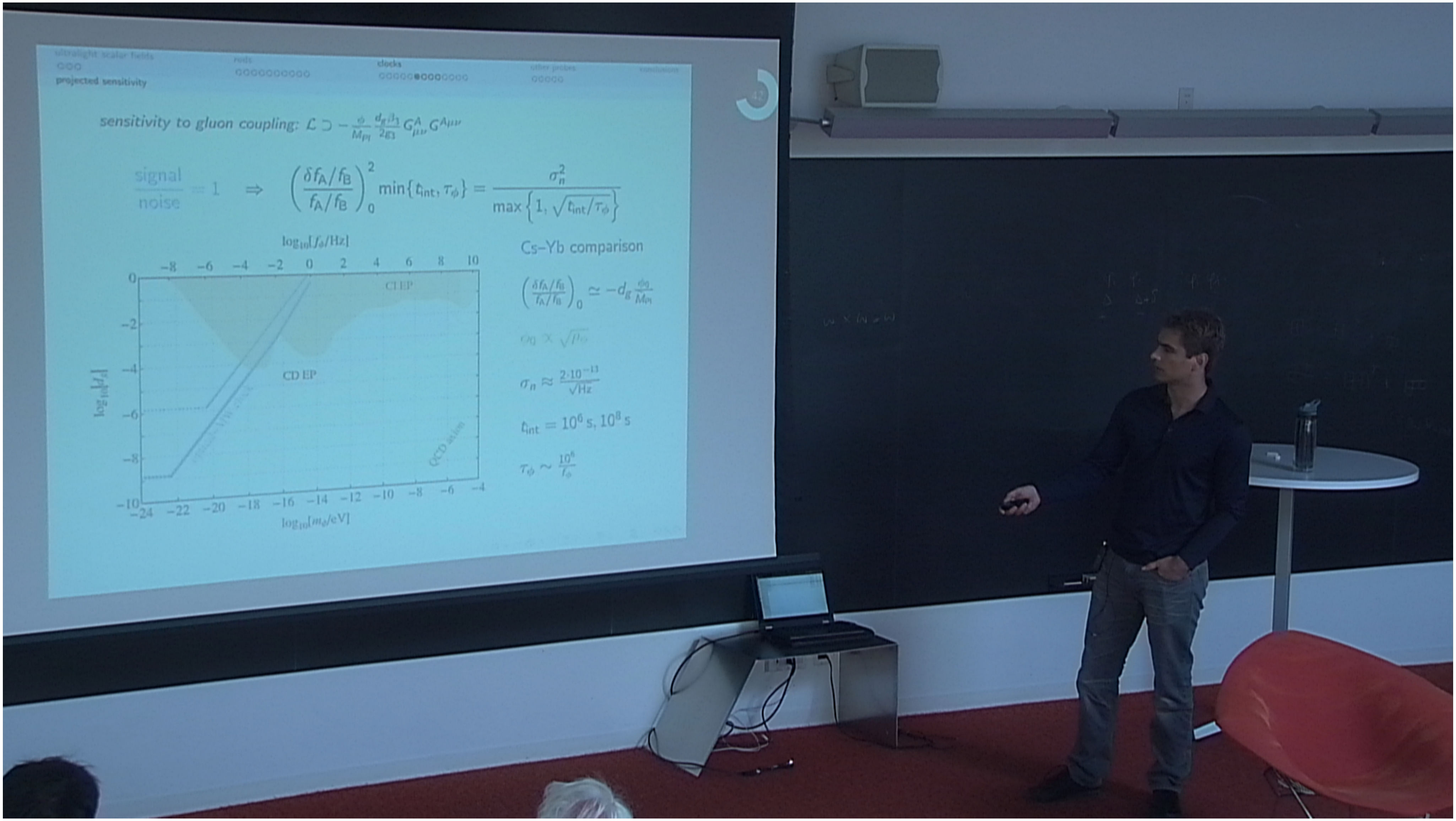

basic principle
clocks
How do atomic transition frequencies change with varying masses and couplings?
$f_A \propto \left(\frac{m_e}{m_p}\right)^{\zeta_A} (\alpha)^{\xi_A+2}$ (2)
ζ_A: 1 iff hyperfine; ξ_A: relativistic, spin-orbit, many-body, electric quadrupole effects
species | transition | λ [nm] | short | long [10^-18] | ζA | ξA
133Cs | hyperfine | 3.3 · 10^7 | 2 · 10^2 | 360 | 1 | 2.83
27Al+ | 3s2 1S0 ↔ 3s3p 3P0 | 267 | 2.8 | 8.6 | 0 | 0.008
87Sr | 5s2 1S0 ↔ 5s5p 3P0 | 698 | 0.34 | 6.4 | 0 | 0.06
171Yb | 6s2 1S0 ↔ 6s6p 3P0 | 578 | 0.32 | 1.6 | 0 | 0.31
88Sr+ | 674 | 16 | 25 | 0 | 0.43
171Yb+ | 467 | 2.0 | 71 | 0 | −5.30
199Hg+ | 282 | 2.8 | 19 | 0 | −3.19
162Dy | 4f10 5d6s ↔ 4f9 5d2 6s | 4.0 · 10^8 | 4.0 · 10^6 | 0 | 8.5 · 10^6
164Dy | 4f9 5d2 6s ↔ 4f10 5d6s | 1.3 · 10^9 | 1.3 · 10^7 | 0 | −2.6 · 10^6
229mTh3+ | nuclear | 26 | 1 | 1 | 10^5 | 10^4

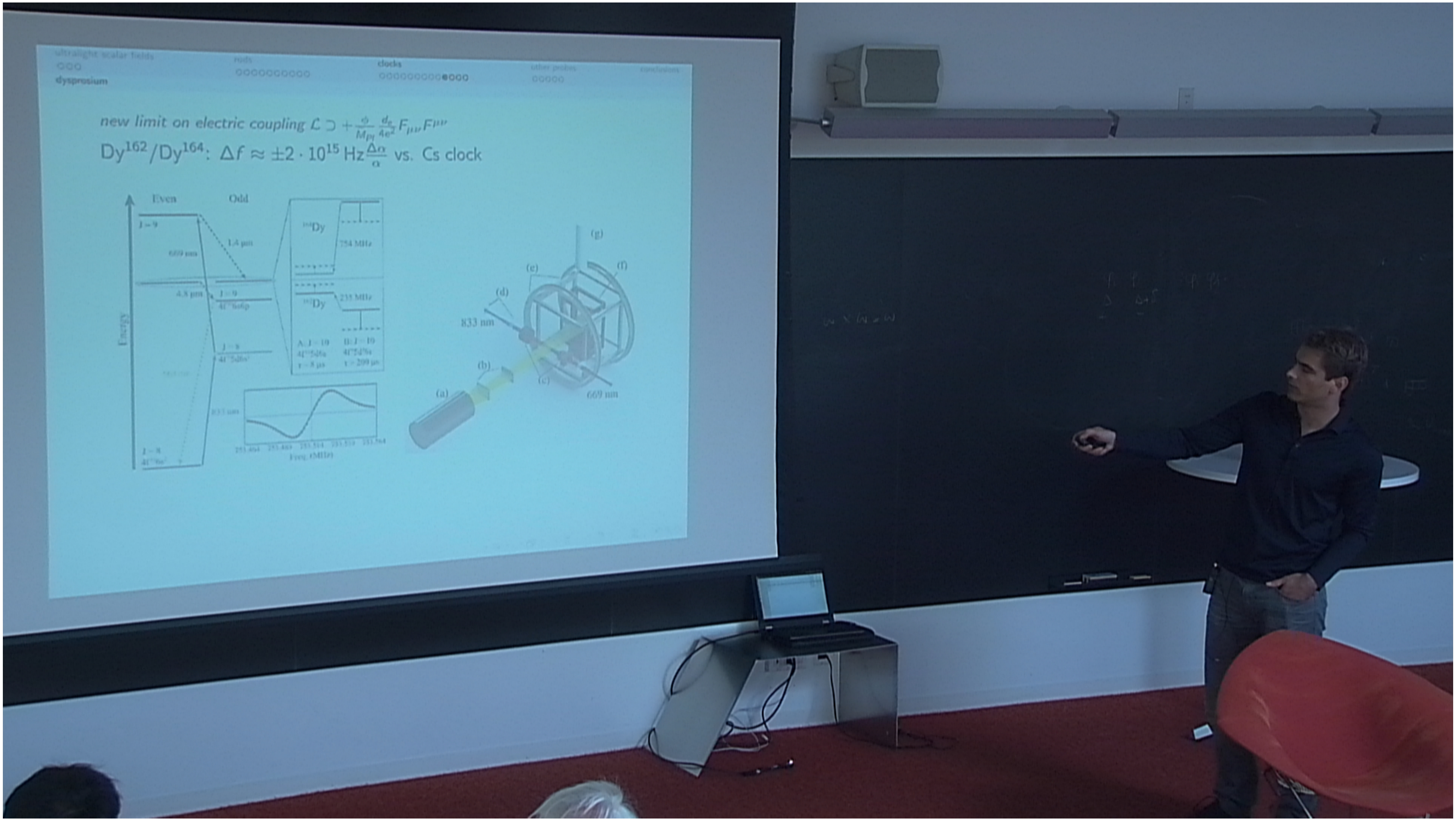


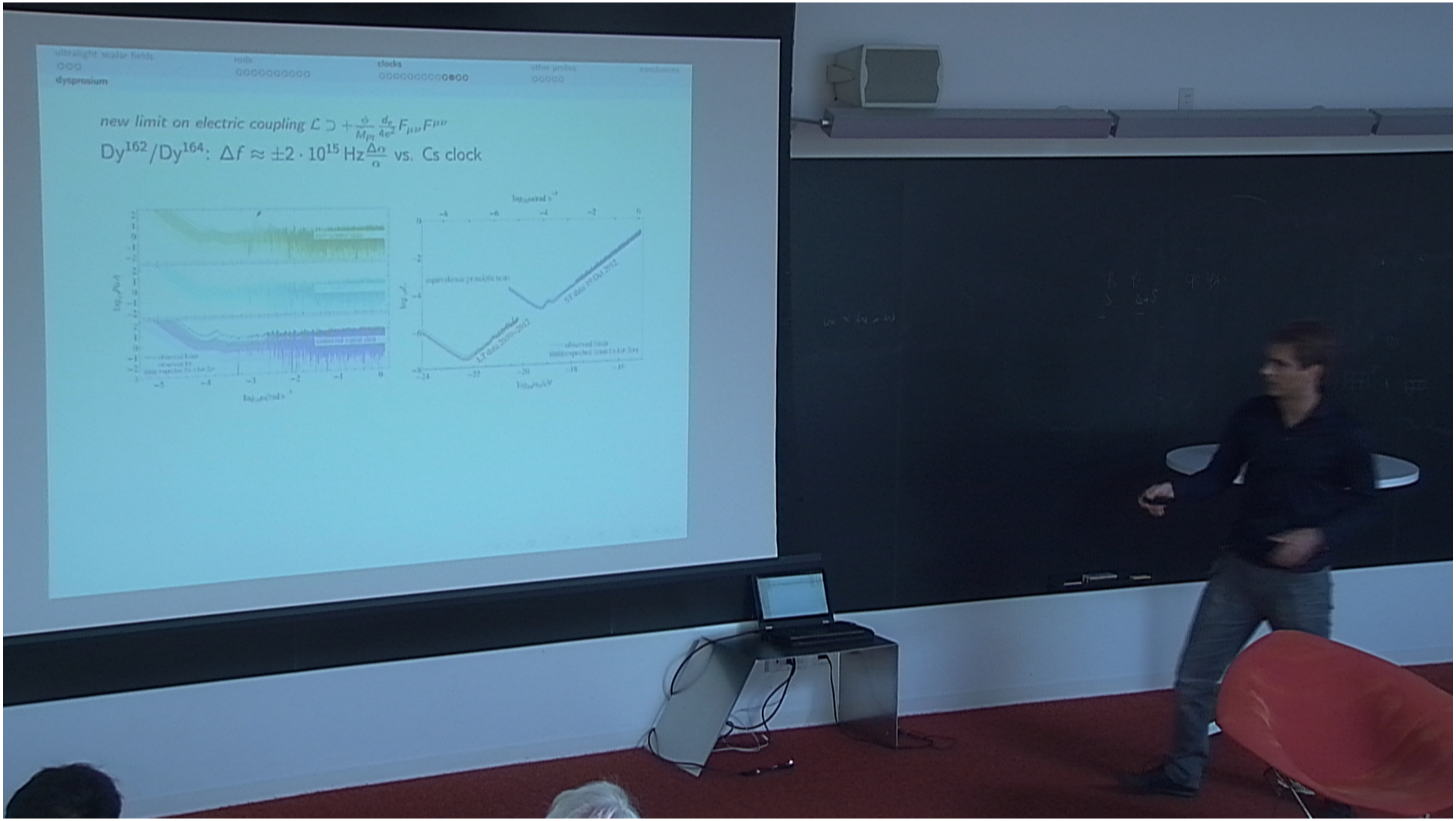
ultralight scalar fields
clocks
instrumental ingredients for frequency comparison
necessary tools for precise frequency comparisons:
2 stable atomic clocks + frequency comparison method
optical clock laser
clock laser
578 nm
feedback
optical lattice
trapped
Yb atoms
Hinkley et al '13
optical clocks: Yb, Al, Sr, Ca, Hg
microwave clocks: Cs, Rb, H, Dy
nuclear clocks: Th, U

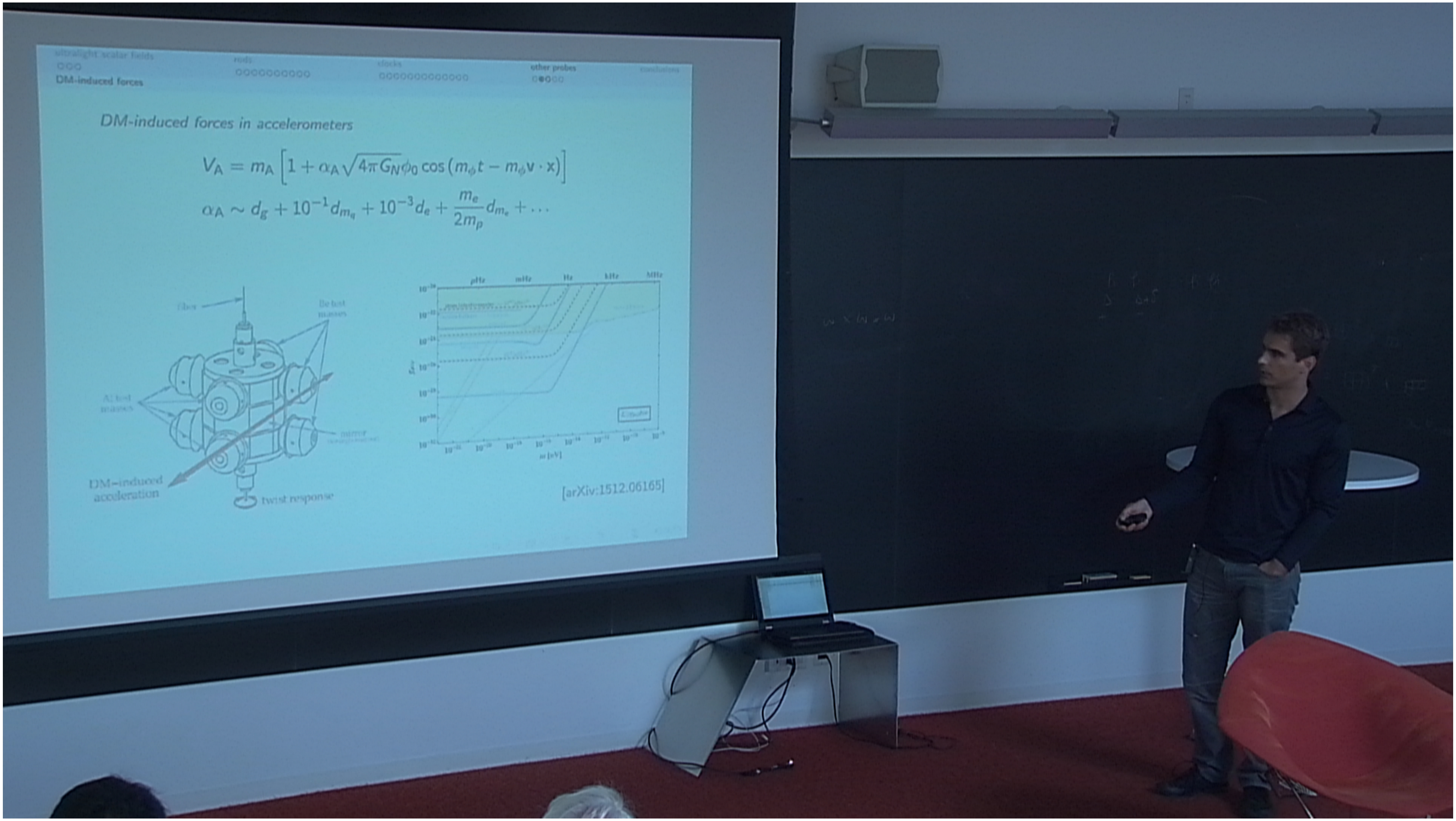

clocks
instrumental ingredients for frequency comparison
necessary tools for precise frequency comparisons:
2 stable atomic clocks + frequency comparison method
E(t)
1/f_c
Δφ/2πf_c
Δφ/πf_c
t
1/f_rep
↓ fourier transform ↓
E(f)
f_rep
f_0 = f_rep Δφ/2π
f
f_c
0



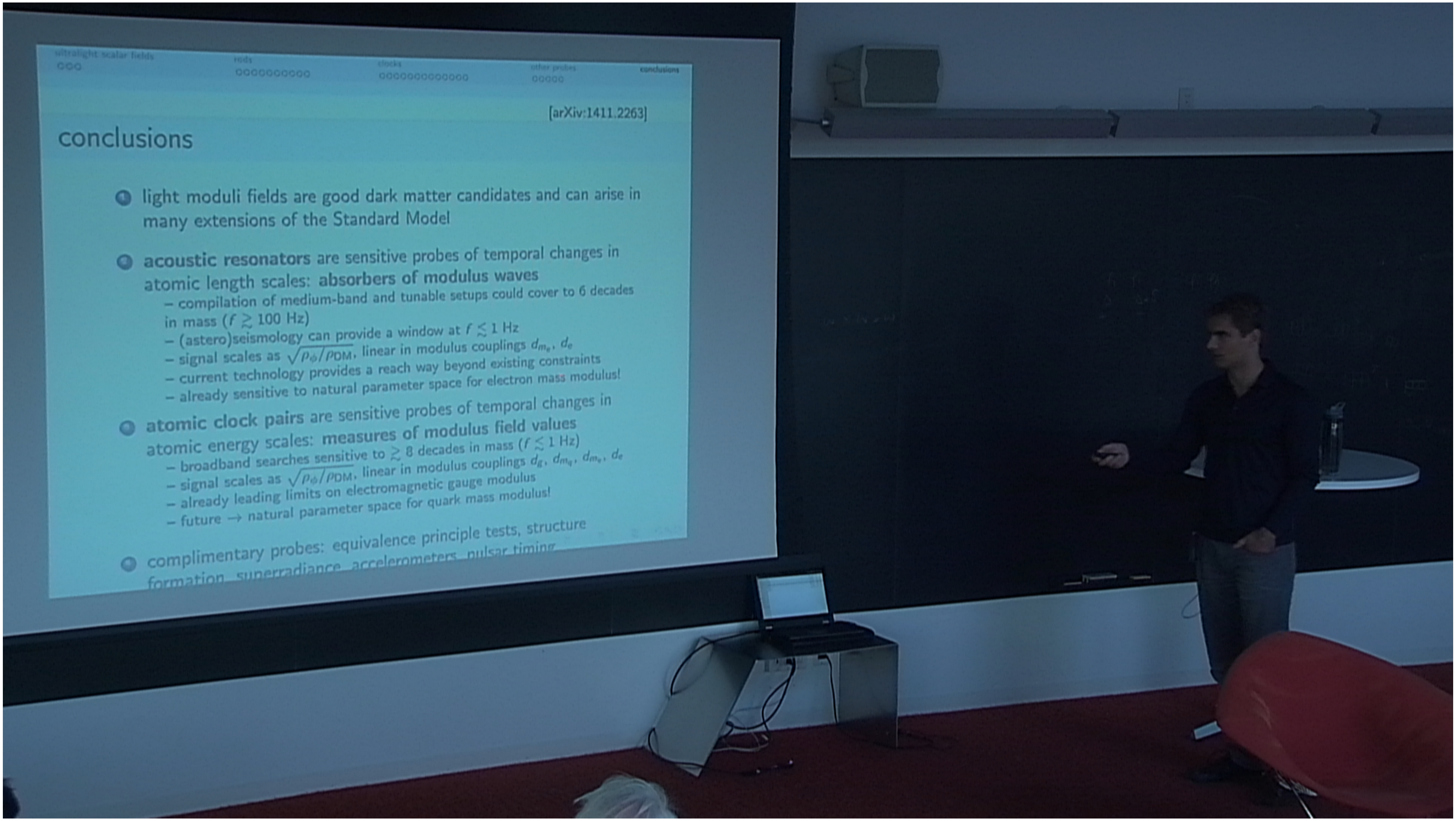
sensitivity to gluon coupling: $\mathcal{L} \supset -\frac{\phi}{M_{Pl}} \frac{d_g \beta_3}{2 g_3} G^A_{\mu\nu} G^{A\mu\nu}$
$\frac{\text{signal}}{\text{noise}} = 1 \Rightarrow \left(\frac{\delta f_A / f_B}{f_A / f_B}\right)_0^2 \min\{t_{int}, \tau_\phi\} = \frac{\sigma_n^2}{\max\left\{1, \sqrt{t_{int}/\tau_\phi}\right\}}$
Cs–Yb comparison
$\left(\frac{\delta f_A / f_B}{f_A / f_B}\right)_0 \simeq -d_g \frac{\phi_0}{M_{Pl}}$
$\sigma_n \approx \frac{2 \cdot 10^{-13}}{\sqrt{Hz}}$
$t_{int} = 10^6$ s, 10^8 s
$\tau_\phi \sim \frac{10^6}{f_\phi}$
CI EP
CD EP
QCD axion

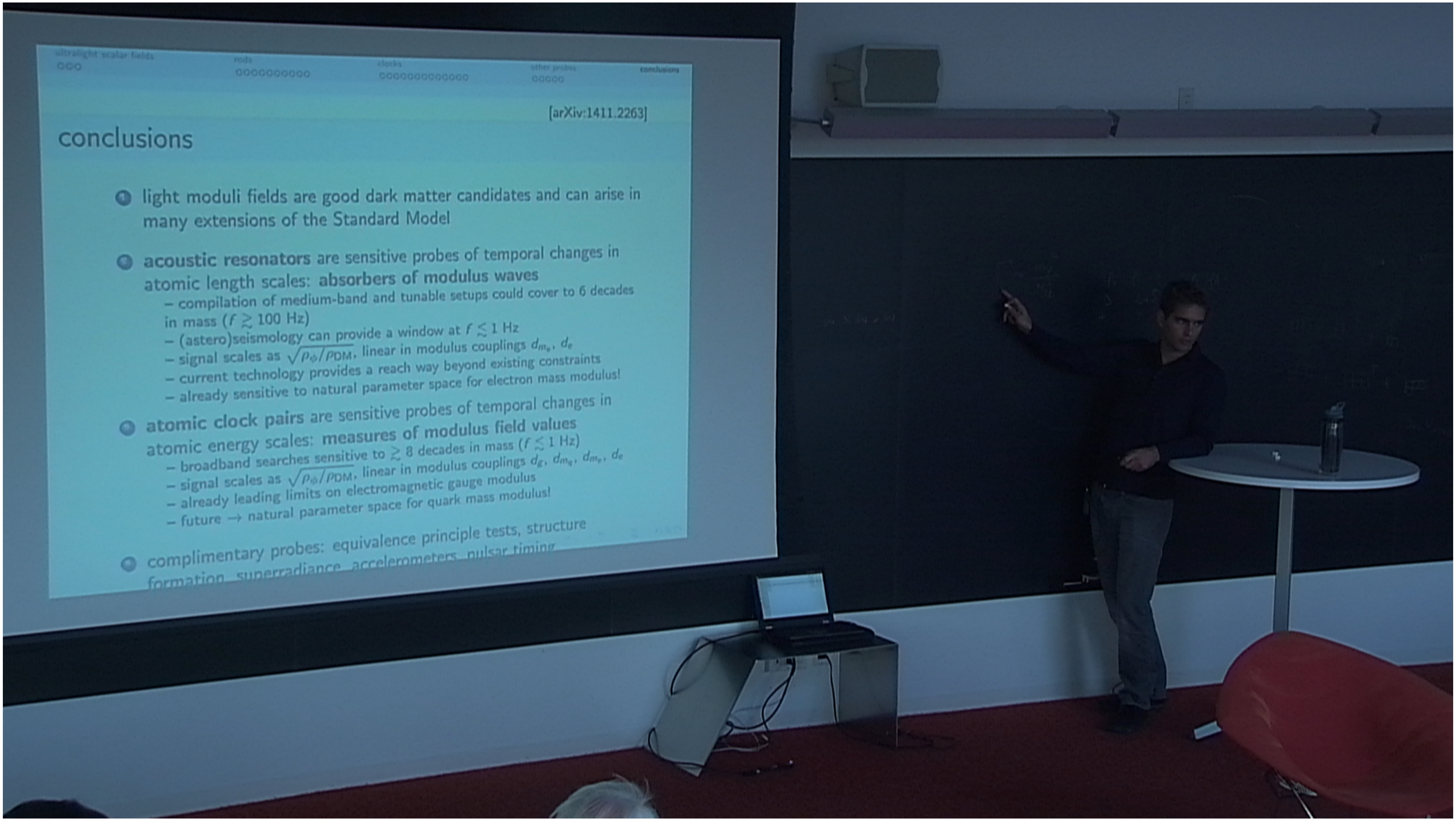

dysprosium
clocks
new limit on electric coupling $\mathcal{L} \supset +\frac{\phi}{M_{Pl}} \frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu}$
Dy^{162}/Dy^{164}: $\Delta f \approx \pm 2 \cdot 10^{15}\,\mathrm{Hz}\frac{\Delta\alpha}{\alpha}$ vs. Cs clock
Even
Odd
Energy
833 nm
669 nm


clocks
dysprosium
new limit on electric coupling $\mathcal{L} \supset +\frac{\phi}{M_{Pl}}\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu}$
Dy^{162}/Dy^{164}: $\Delta f \approx \pm 2 \cdot 10^{15}\,\mathrm{Hz}\frac{\Delta\alpha}{\alpha}$ vs. Cs clock



DM-induced forces
other probes
DM-induced forces in accelerometers
$V_A = m_A \left[1 + \alpha_A \sqrt{4\pi G_N}\phi_0 \cos(m_\phi t - m_\phi \mathbf{v}\cdot\mathbf{x})\right]$
$\alpha_A \sim d_g + 10^{-1} d_{m_q} + 10^{-3} d_e + \frac{m_e}{2m_p} d_{m_e} + \dots$
DM-induced acceleration
twist response
[arXiv:1512.06165]


ultralight scalar fields
rods
clocks
other probes
conclusions
[arXiv:1411.2263]
conclusions
light moduli fields are good dark matter candidates and can arise in many extensions of the Standard Model
acoustic resonators are sensitive probes of temporal changes in atomic length scales: **absorbers of modulus waves**
– compilation of medium-band and tunable setups could cover to 6 decades in mass ($f \gtrsim 100$ Hz)
– (astero)seismology can provide a window at $f \lesssim 1$ Hz
– signal scales as $\sqrt{\rho_\phi/\rho_{DM}}$, linear in modulus couplings d_{m_e}, d_e
– current technology provides a reach way beyond existing constraints
– already sensitive to natural parameter space for electron mass modulus!
atomic clock pairs are sensitive probes of temporal changes in atomic energy scales: **measures of modulus field values**
– broadband searches sensitive to $\gtrsim 8$ decades in mass ($f \lesssim 1$ Hz)
– signal scales as $\sqrt{\rho_\phi/\rho_{DM}}$, linear in modulus couplings d_g, d_{m_q}, d_{m_e}, d_e
– already leading limits on electromagnetic gauge modulus
– future → natural parameter space for quark mass modulus!
complimentary probes: equivalence principle tests, structure


[arXiv:1411.2263]
conclusions
light moduli fields are good dark matter candidates and can arise in many extensions of the Standard Model
acoustic resonators are sensitive probes of temporal changes in atomic length scales: absorbers of modulus waves
– compilation of medium-band and tunable setups could cover to 6 decades in mass ($f \gtrsim 100$ Hz)
– (astero)seismology can provide a window at $f \lesssim 1$ Hz
– signal scales as $\sqrt{\rho_\phi/\rho_{DM}}$, linear in modulus couplings d_{m_e}, d_e
– current technology provides a reach way beyond existing constraints
– already sensitive to natural parameter space for electron mass modulus!
atomic clock pairs are sensitive probes of temporal changes in atomic energy scales: measures of modulus field values
– broadband searches sensitive to $\gtrsim 8$ decades in mass ($f \lesssim 1$ Hz)
– signal scales as $\sqrt{\rho_\phi/\rho_{DM}}$, linear in modulus couplings d_g, d_{m_q}, d_{m_e}, d_e
– already leading limits on electromagnetic gauge modulus
– future → natural parameter space for quark mass modulus!
complimentary probes: equivalence principle tests, structure