Title: Axion-induced effects and topological defect dark matter detection schemes

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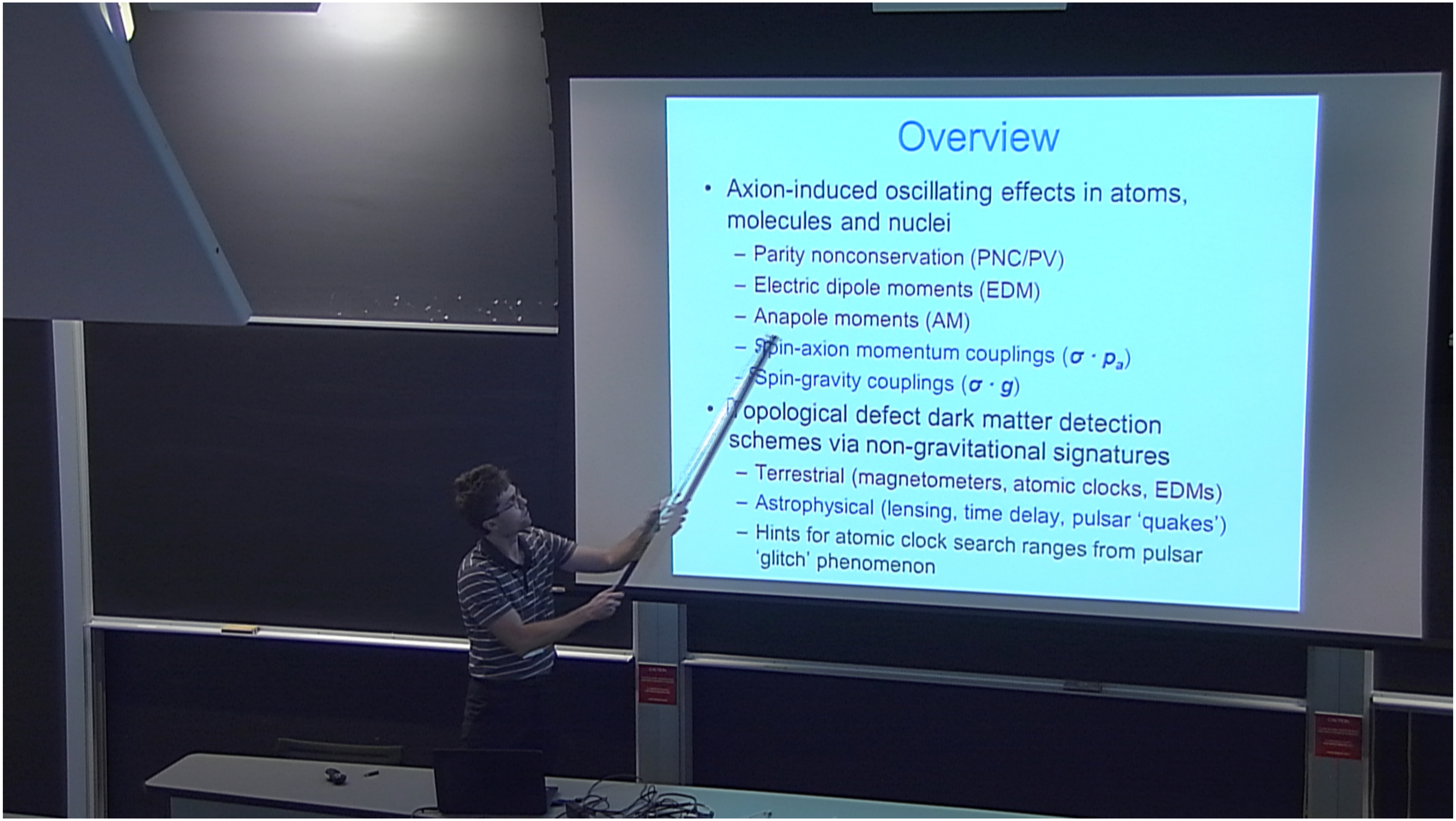
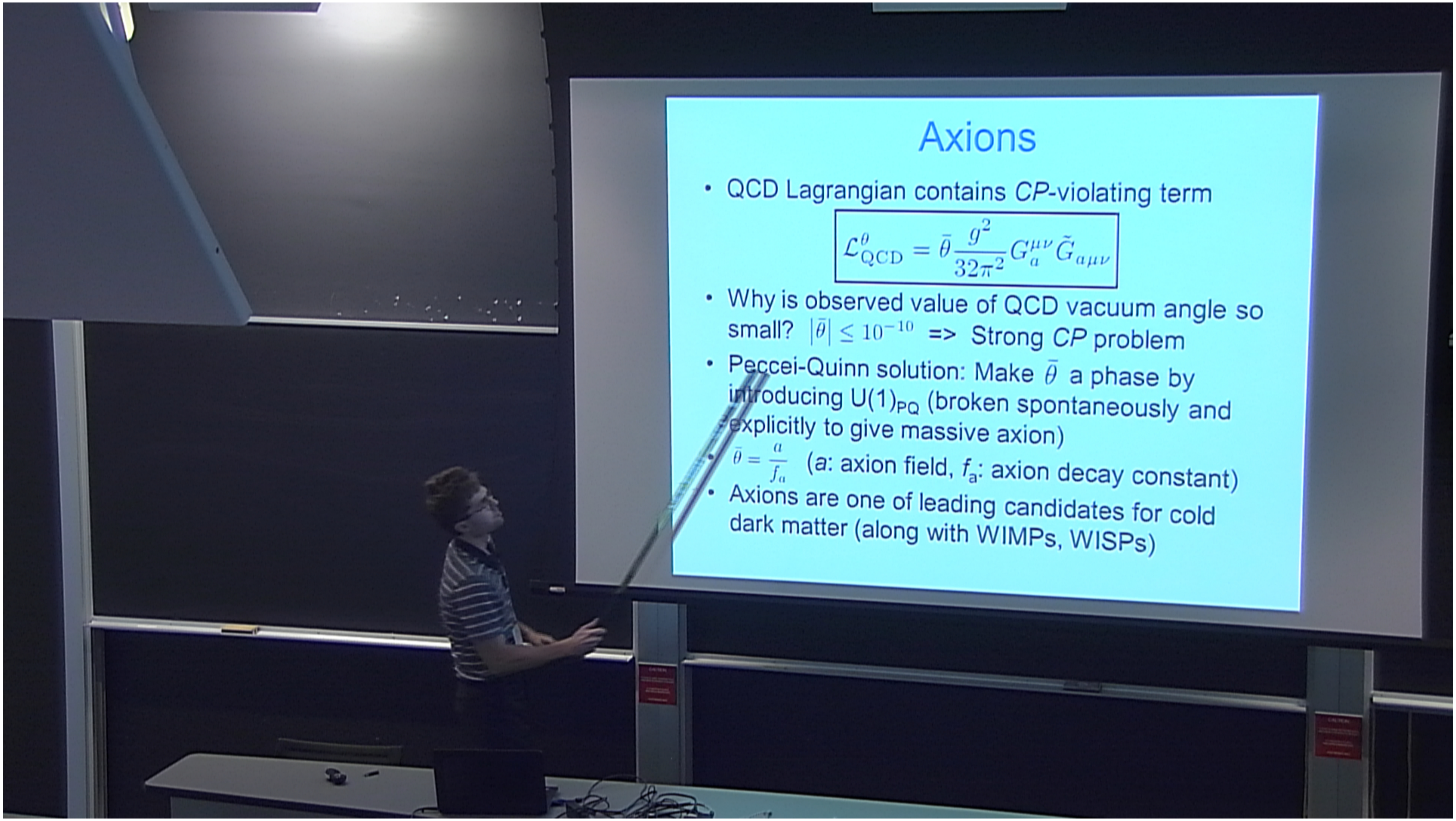
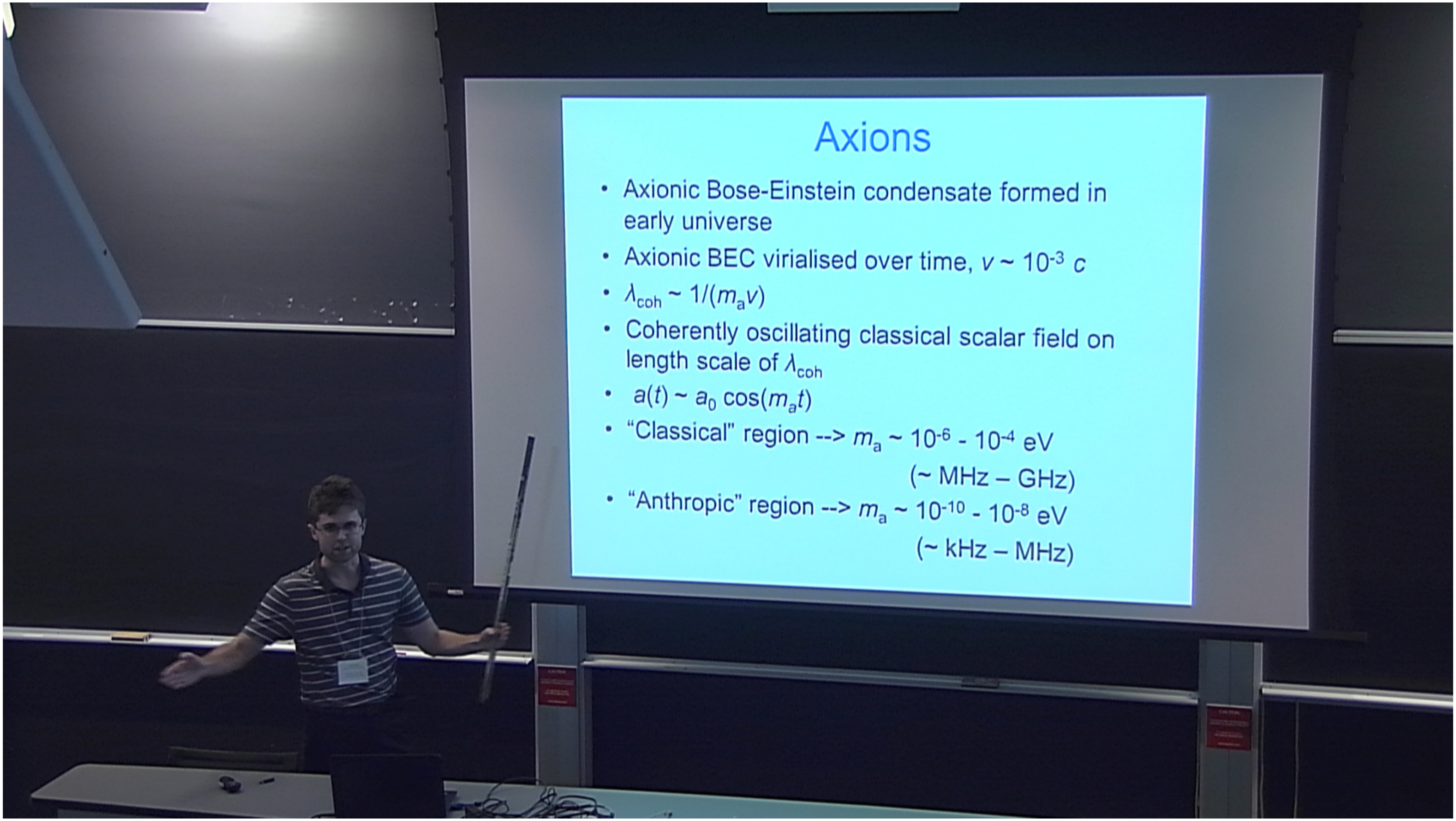
Abstract: <span>We discuss new observable effects of axionic dark matter in atoms, molecules and nuclei. We show that the interaction of an axion field, or in general a pseudoscalar field, with the axial-vector current generated by an electron through a derivative-type coupling can give rise to a time-dependent mixing of opposite-parity states in atomic and molecular systems. Likewise, the analogous interaction of an axion field with the axial-vector current generated by a nucleon can give rise to time-dependent mixing of opposite-parity states in nuclear systems. This mixing can induce oscillating electric dipole moments, oscillating parity nonconservation effects and oscillating anapole moments in such systems. By adjusting the energy separation between the opposite-parity states of interest to match the axion mass energy, axion-induced experimental observables can be enhanced by many orders of magnitude. Oscillating atomic electric dipole moments can also be generated by axions through hadronic mechanisms, namely the P,T-violating nucleon-nucleon interaction and through the axion-induced electric dipole moments of valence nucleons, which comprise the nuclei. The axion field is modified by Earthâ€™s gravitational field. The interaction of the spin of either an electron or nucleon with this modified axion field leads to axion-induced observable effects. These effects, which are of the form g â€¢ Ïƒ, differ from the axion-wind effect, which has the form pa â€¢ Ïƒ.

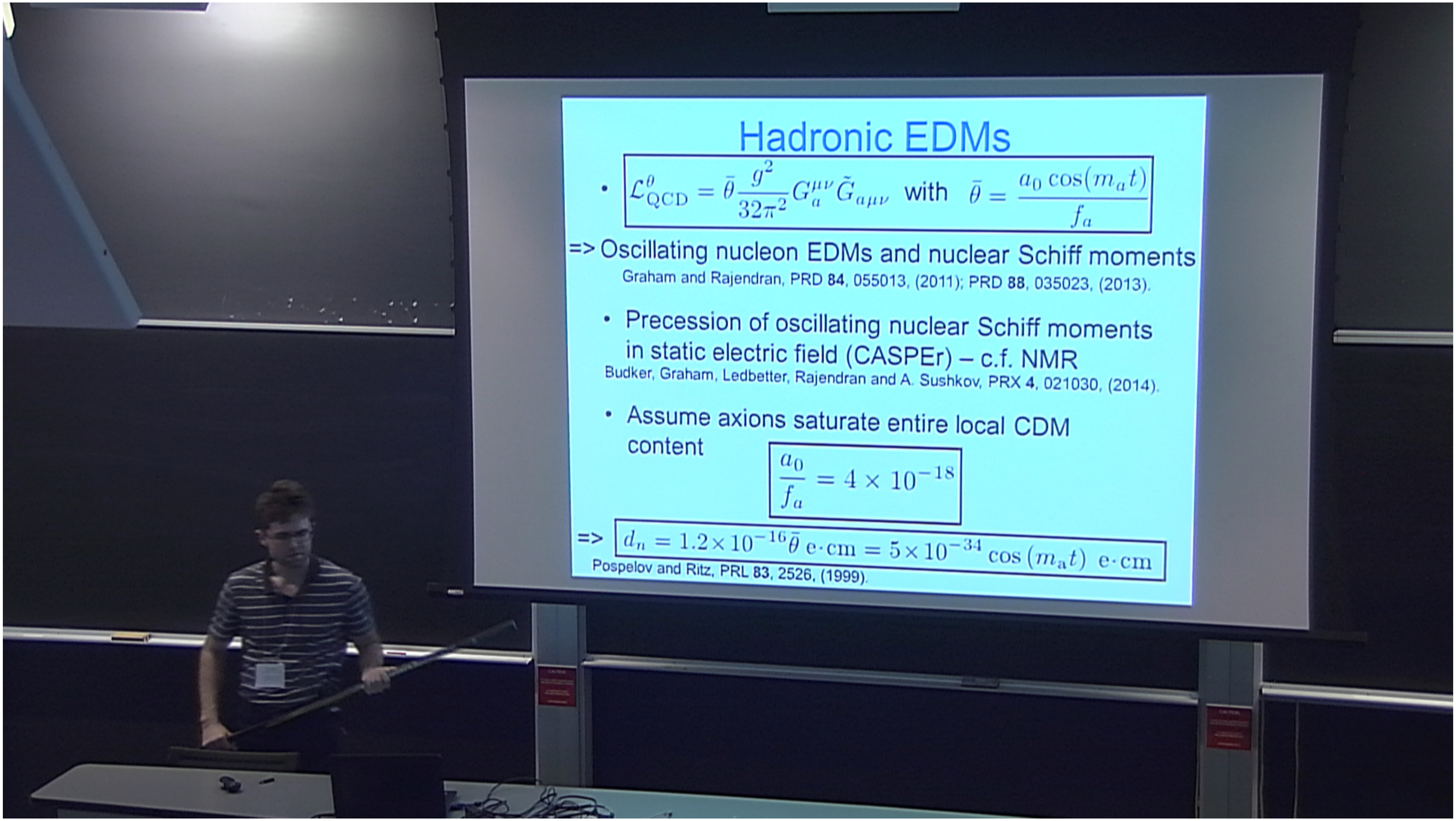
We also propose schemes for the detection of topological defect dark matter using pulsars and other luminous extraterrestrial systems via non-gravitational signatures. The dark matter field, which makes up a defect, may interact with standard model particles, including quarks and the photon, resulting in the alteration of their masses. When a topological defect passes through a pulsar, its mass, radius and internal structure may be altered, resulting in a pulsar `quake'. A topological defect may also function as a cosmic dielectric material with a frequency-dependent index of refraction, which would give rise to the time delay of a periodic extraterrestrial light or radio signal, and the dispersion of a light or radio source in a similar manner to an optical lens. The biggest advantage of such astrophysical observations over recently proposed terrestrial detection methods is the much higher probability of a defect been found in the vast volumes of outer space compared with one passing through Earth itself.

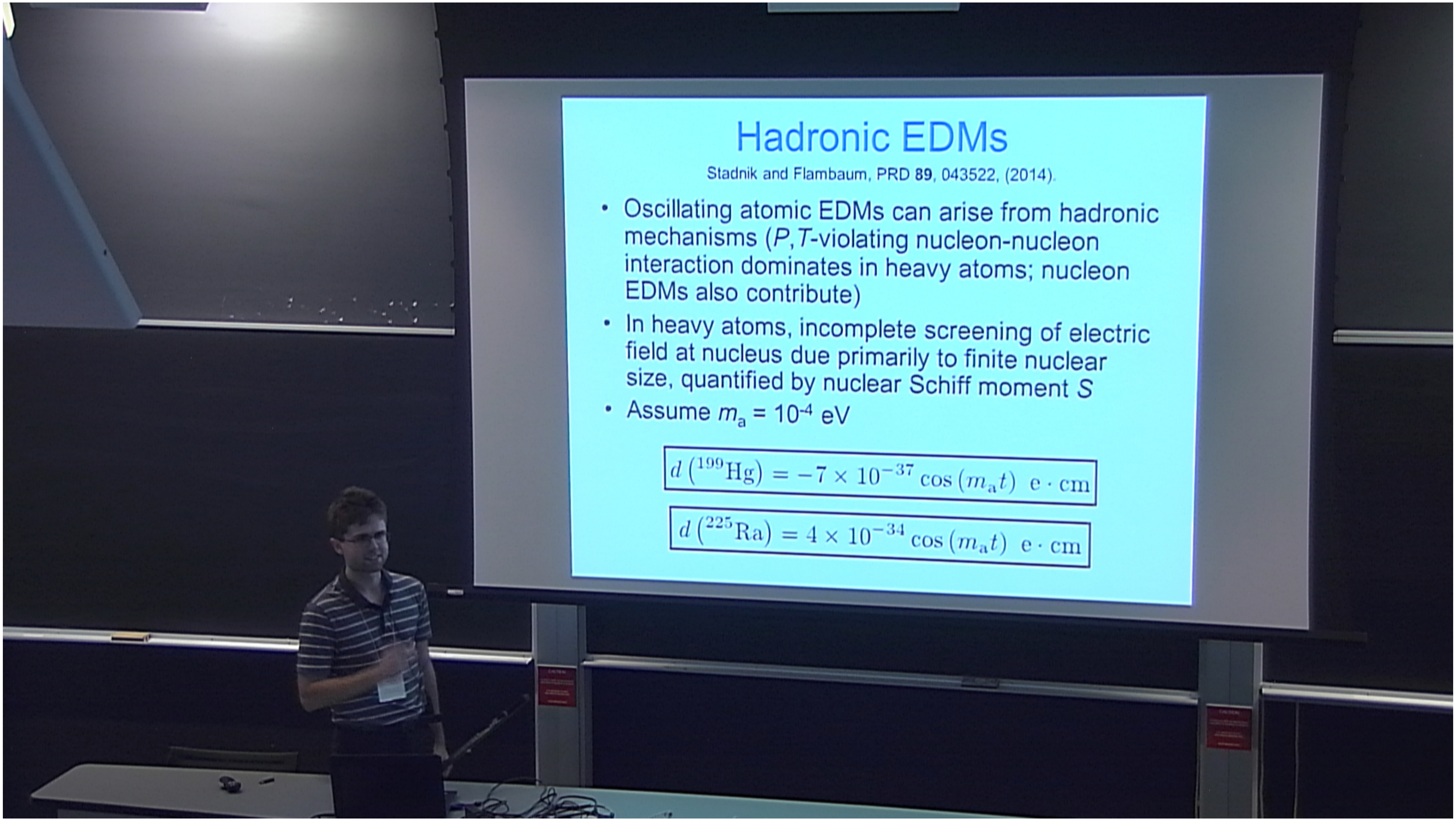
References: (1) Phys. Rev. D 89, 043522 (2014).
(2) arXiv:1404.2723.
(3) arXiv:1405.5337.

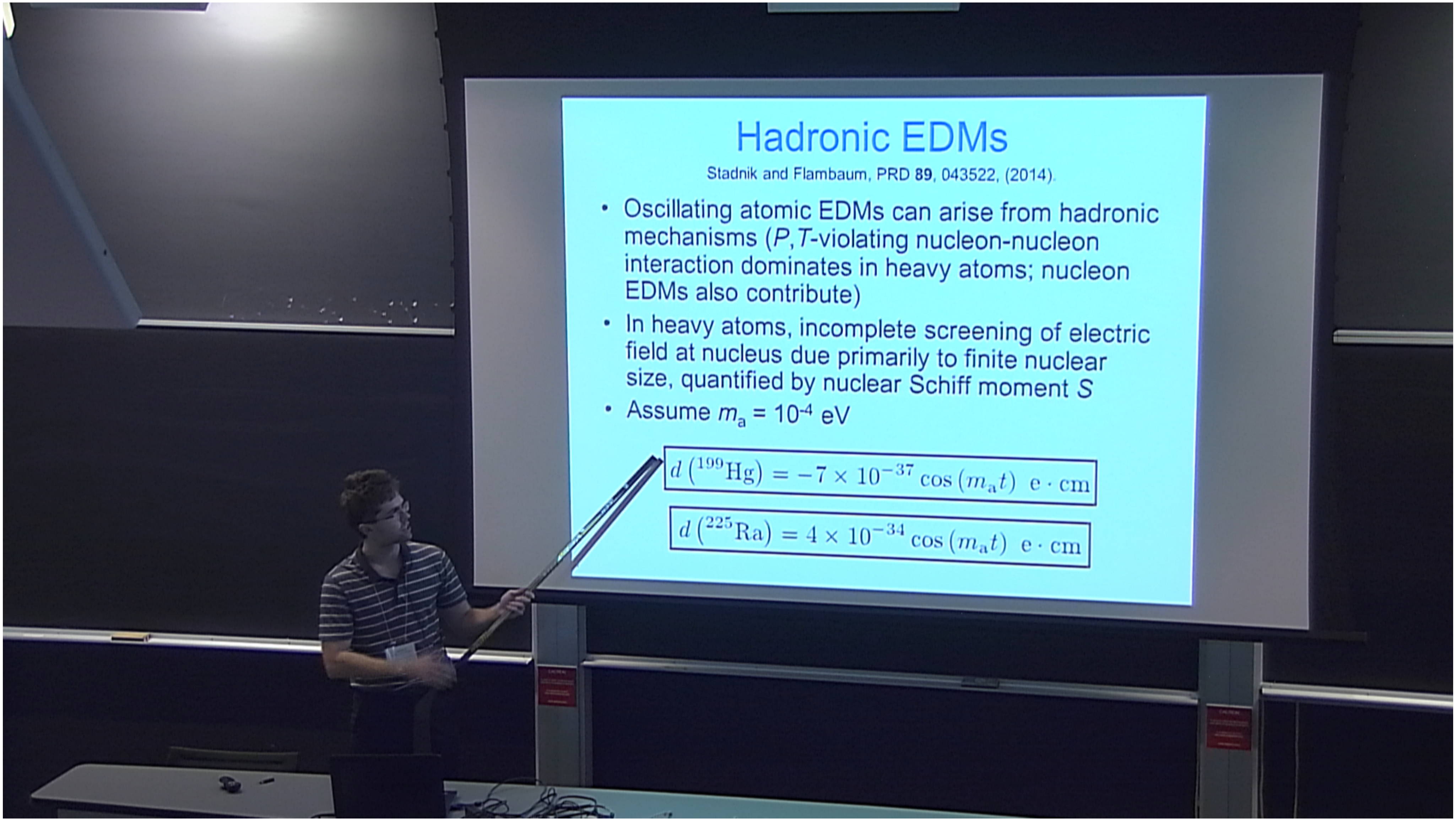

Overview
• Axion-induced oscillating effects in atoms, molecules and nuclei
– Parity nonconservation (PNC/PV)
– Electric dipole moments (EDM)
– Anapole moments (AM)
– Spin-axion momentum couplings ($\sigma \cdot p_a$)
– Spin-gravity couplings ($\sigma \cdot g$)
• opological defect dark matter detection schemes via non-gravitational signatures
– Terrestrial (magnetometers, atomic clocks, EDMs)
– Astrophysical (lensing, time delay, pulsar 'quakes')
– Hints for atomic clock search ranges from pulsar 'glitch' phenomenon


Axions
• QCD Lagrangian contains CP-violating term
$\mathcal{L}^{\theta}_{\rm QCD} = \bar{\theta}\frac{g^2}{32\pi^2}G^{\mu\nu}_{a}\tilde{G}_{a\mu\nu}$
• Why is observed value of QCD vacuum angle so small? $|\bar{\theta}| \leq 10^{-10}$ => Strong CP problem
• Peccei-Quinn solution: Make $\bar{\theta}$ a phase by introducing $U(1)_{PQ}$ (broken spontaneously and explicitly to give massive axion)
• $\bar{\theta} = \frac{a}{f_a}$ (a: axion field, f_a: axion decay constant)
• Axions are one of leading candidates for cold dark matter (along with WIMPs, WISPs)


Axions
• Axionic Bose-Einstein condensate formed in early universe
• Axionic BEC virialised over time, $v \sim 10^{-3}\ c$
• $\lambda_{coh} \sim 1/(m_a v)$
• Coherently oscillating classical scalar field on length scale of λ_{coh}
• $a(t) \sim a_0 \cos(m_a t)$
• "Classical" region --> $m_a \sim 10^{-6}$ - 10^{-4} eV
(~ MHz – GHz)
• "Anthropic" region --> $m_a \sim 10^{-10}$ - 10^{-8} eV
(~ kHz – MHz)


Hadronic EDMs
• $\mathcal{L}^{\theta}_{\rm QCD} = \bar{\theta}\frac{g^2}{32\pi^2} G^{\mu\nu}_a \tilde{G}_{a\mu\nu}$ with $\bar{\theta} = \frac{a_0 \cos(m_a t)}{f_a}$
=> Oscillating nucleon EDMs and nuclear Schiff moments
Graham and Rajendran, PRD 84, 055013, (2011); PRD 88, 035023, (2013).
• Precession of oscillating nuclear Schiff moments in static electric field (CASPEr) – c.f. NMR
Budker, Graham, Ledbetter, Rajendran and A. Sushkov, PRX 4, 021030, (2014).
• Assume axions saturate entire local CDM content
$\frac{a_0}{f_a} = 4 \times 10^{-18}$
=> $d_n = 1.2\times 10^{-16}\bar{\theta}\ {\rm e\cdot cm} = 5\times 10^{-34} \cos(m_{\rm a} t)\ {\rm e\cdot cm}$
Pospelov and Ritz, PRL 83, 2526, (1999).


Hadronic EDMs
Stadnik and Flambaum, PRD 89, 043522, (2014).
• Oscillating atomic EDMs can arise from hadronic mechanisms (P,T-violating nucleon-nucleon interaction dominates in heavy atoms; nucleon EDMs also contribute)
• In heavy atoms, incomplete screening of electric field at nucleus due primarily to finite nuclear size, quantified by nuclear Schiff moment S
• Assume $m_a = 10^{-4}$ eV
$d\left(^{199}\mathrm{Hg}\right) = -7 \times 10^{-37} \cos\left(m_\mathrm{a} t\right)\ \mathrm{e \cdot cm}$
$d\left(^{225}\mathrm{Ra}\right) = 4 \times 10^{-34} \cos\left(m_\mathrm{a} t\right)\ \mathrm{e \cdot cm}$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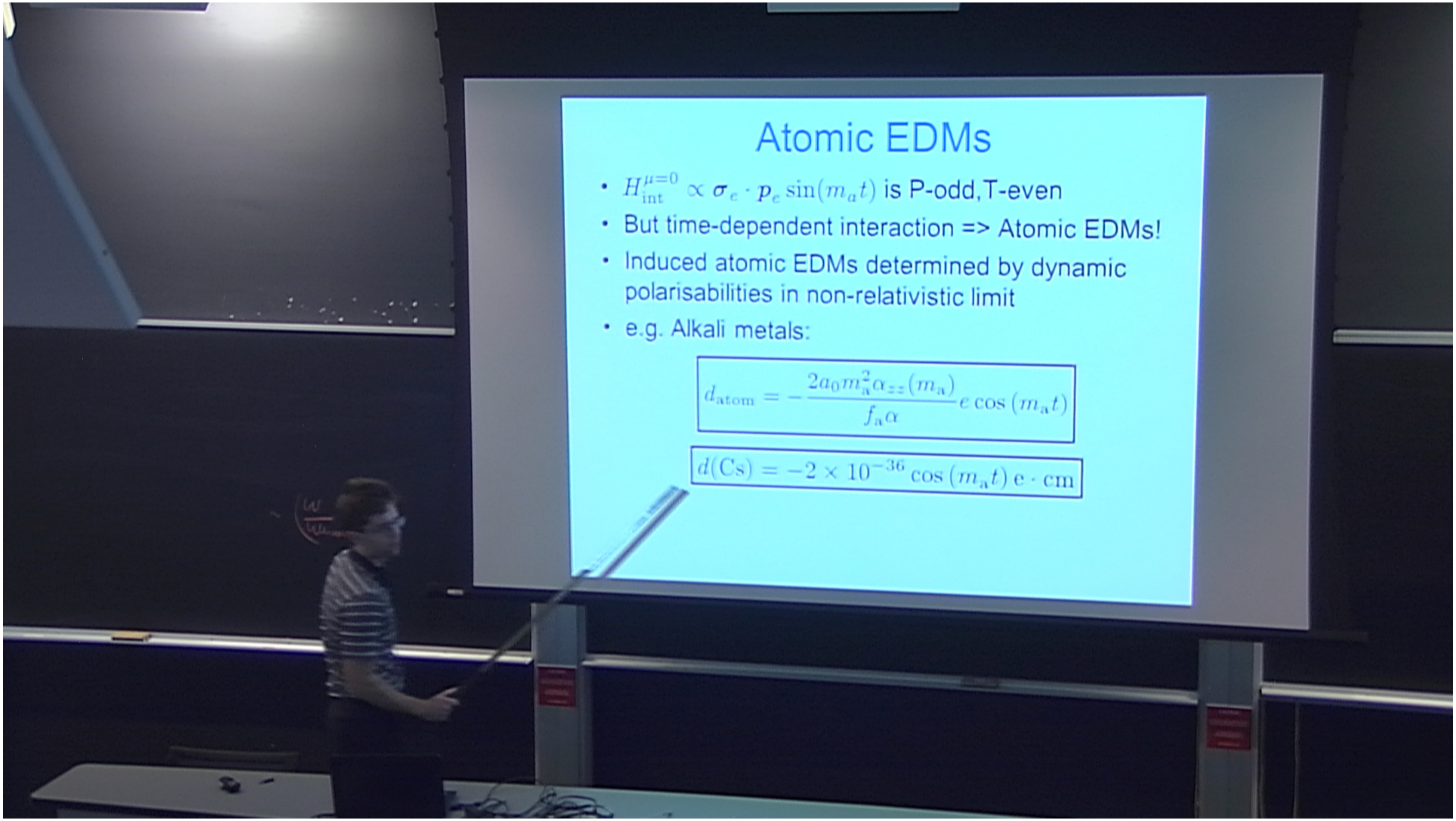
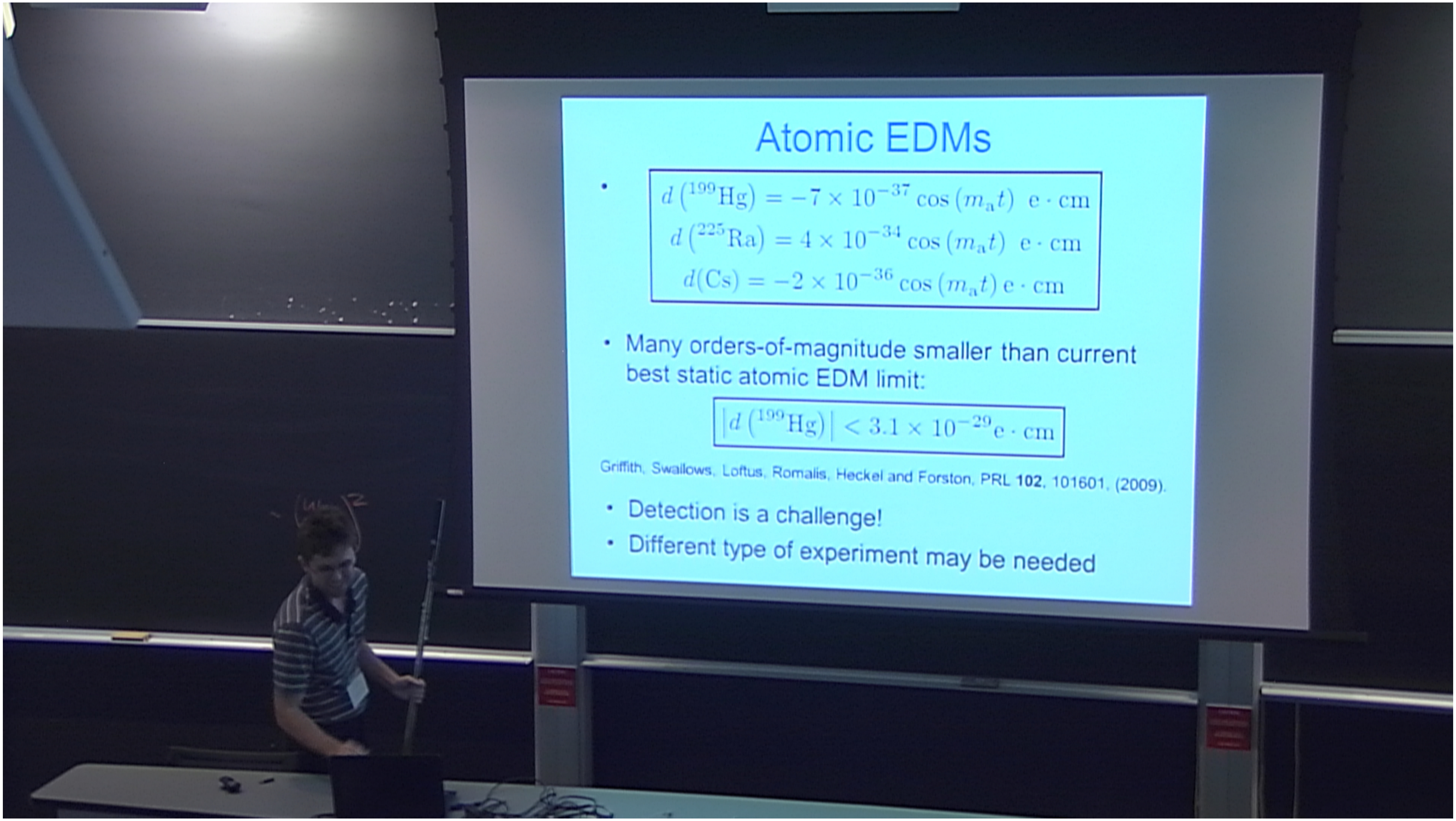

Atomic EDMs
$H_{\rm int}^{\mu=0} \propto \boldsymbol{\sigma}_e \cdot \boldsymbol{p}_e \sin(m_a t)$ is P-odd,T-even
But time-dependent interaction => Atomic EDMs!
Induced atomic EDMs determined by dynamic polarisabilities in non-relativistic limit
e.g. Alkali metals:
$d_{\rm atom} = -\frac{2a_0 m_{\rm a}^2 \alpha_{zz}(m_{\rm a})}{f_{\rm a}\alpha} e \cos(m_{\rm a} t)$
$d({\rm Cs}) = -2 \times 10^{-36} \cos(m_{\rm a} t)\, {\rm e \cdot cm}$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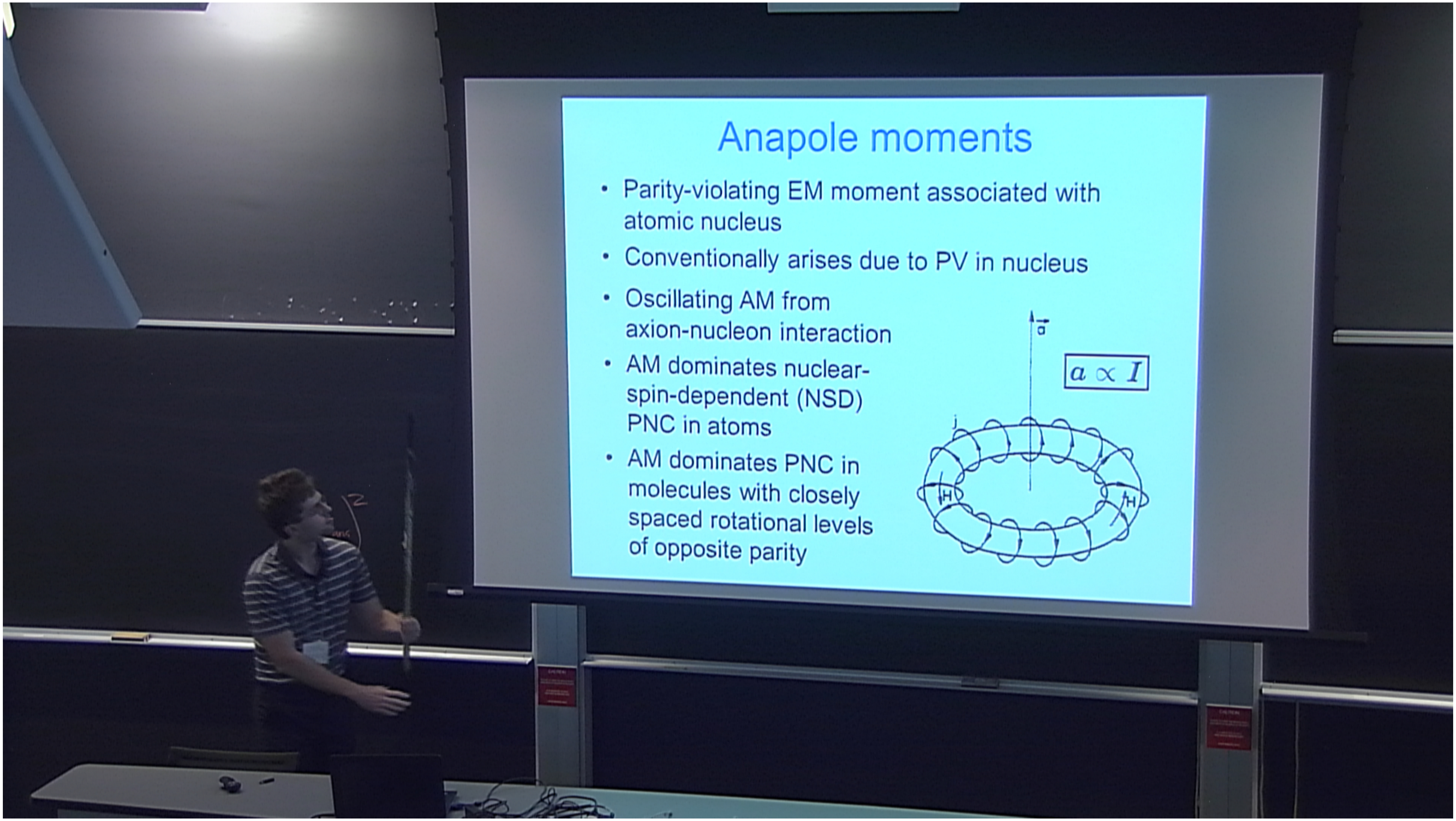
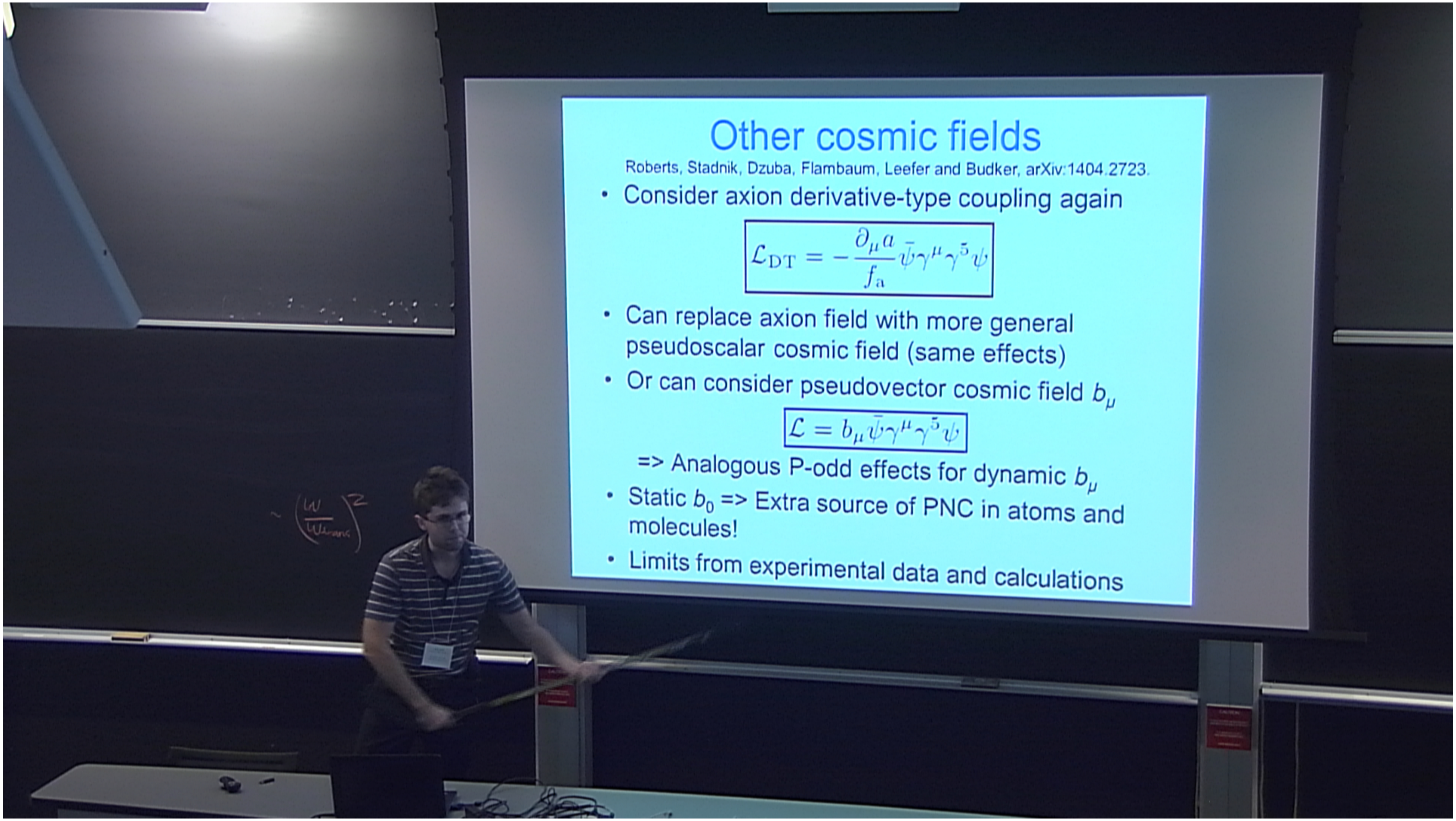
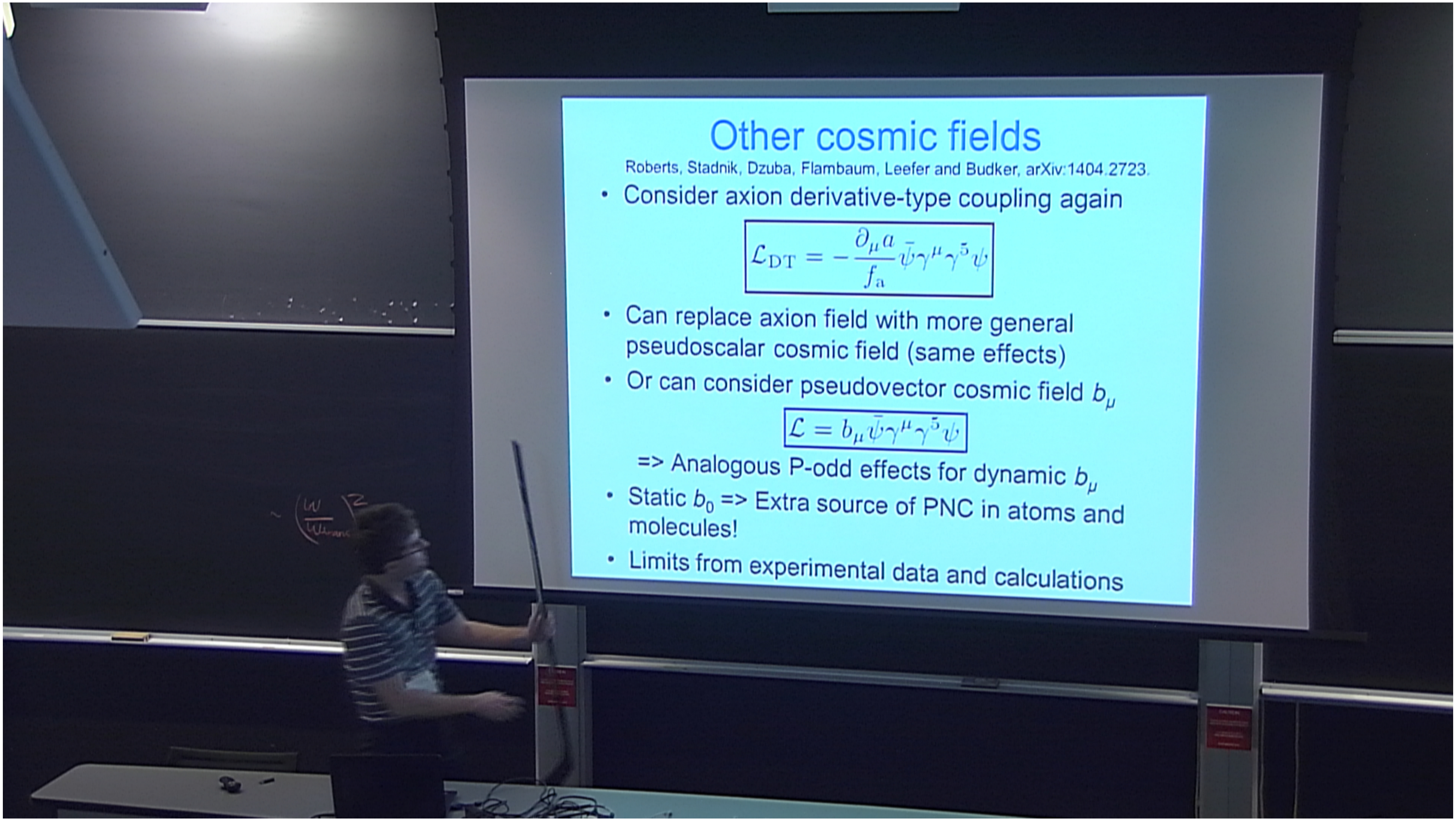
$d(\mathrm{Cs}) = -2 \times 10^{-36} \cos\left(m_a t\right)\ \mathrm{e \cdot cm}$
Many orders-of-magnitude smaller than current best static atomic EDM limit:
$\left|d\left({}^{199}\mathrm{Hg}\right)\right| < 3.1 \times 10^{-29} \mathrm{e \cdot cm}$
Griffith, Swallows, Loftus, Romalis, Heckel and Forston, PRL 102, 101601, (2009).
Detection is a challenge!
Different type of experiment may be needed


Anapole moments
• Parity-violating EM moment associated with atomic nucleus
• Conventionally arises due to PV in nucleus
• Oscillating AM from axion-nucleon interaction
• AM dominates nuclear-spin-dependent (NSD) PNC in atoms
• AM dominates PNC in molecules with closely spaced rotational levels of opposite parity
$a \propto I$
j
H
H


Other cosmic fields
Roberts, Stadnik, Dzuba, Flambaum, Leefer and Budker, arXiv:1404.2723.
• Consider axion derivative-type coupling again
$\mathcal{L}_{\rm DT} = -\frac{\partial_\mu a}{f_{\rm a}} \bar{\psi}\gamma^\mu\gamma^5\psi$
• Can replace axion field with more general pseudoscalar cosmic field (same effects)
• Or can consider pseudovector cosmic field b_μ
$\mathcal{L} = b_\mu \bar{\psi}\gamma^\mu\gamma^5\psi$
=> Analogous P-odd effects for dynamic b_μ
• Static b_0 => Extra source of PNC in atoms and molecules!
• Limits from experimental data and calculations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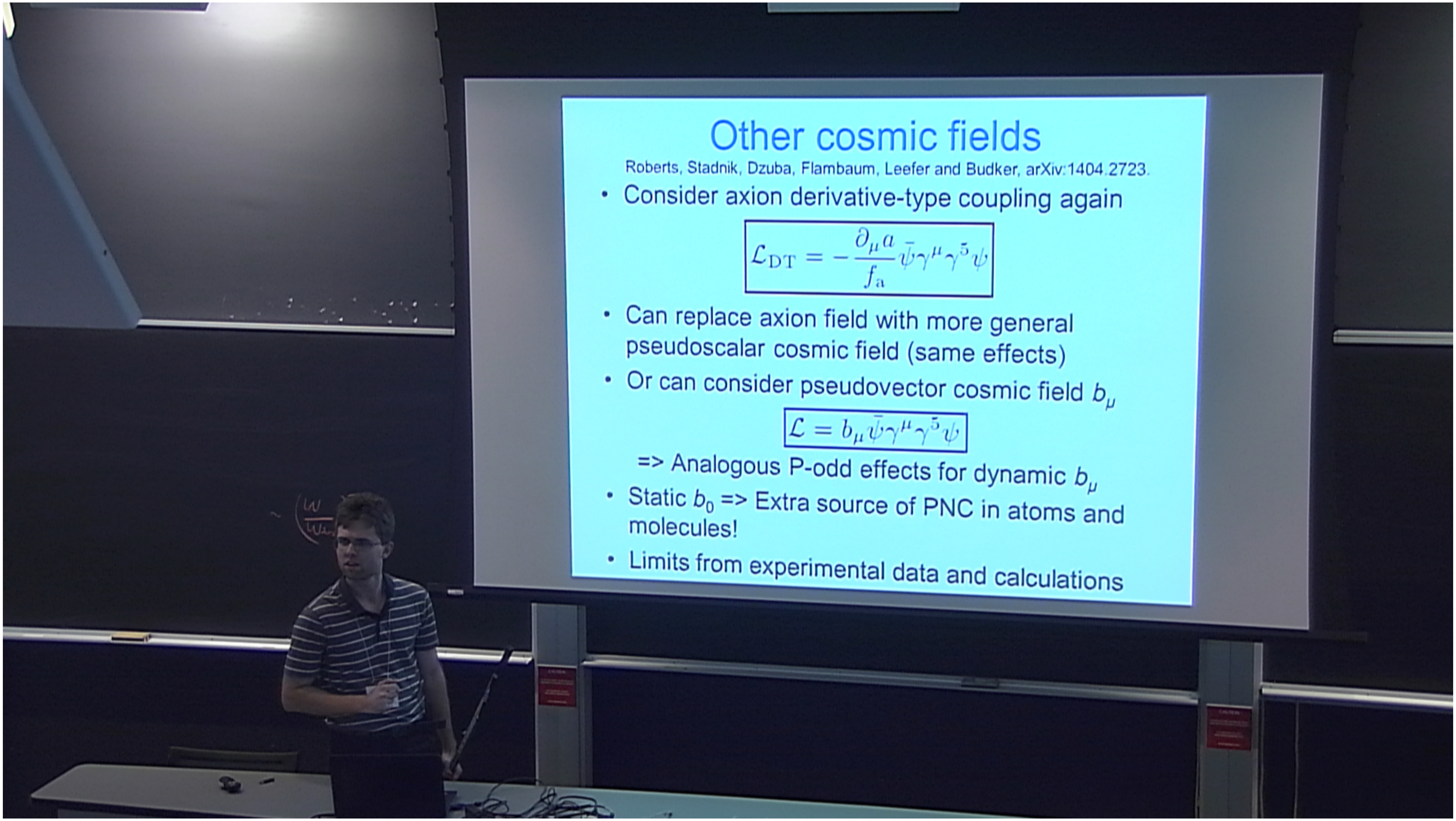
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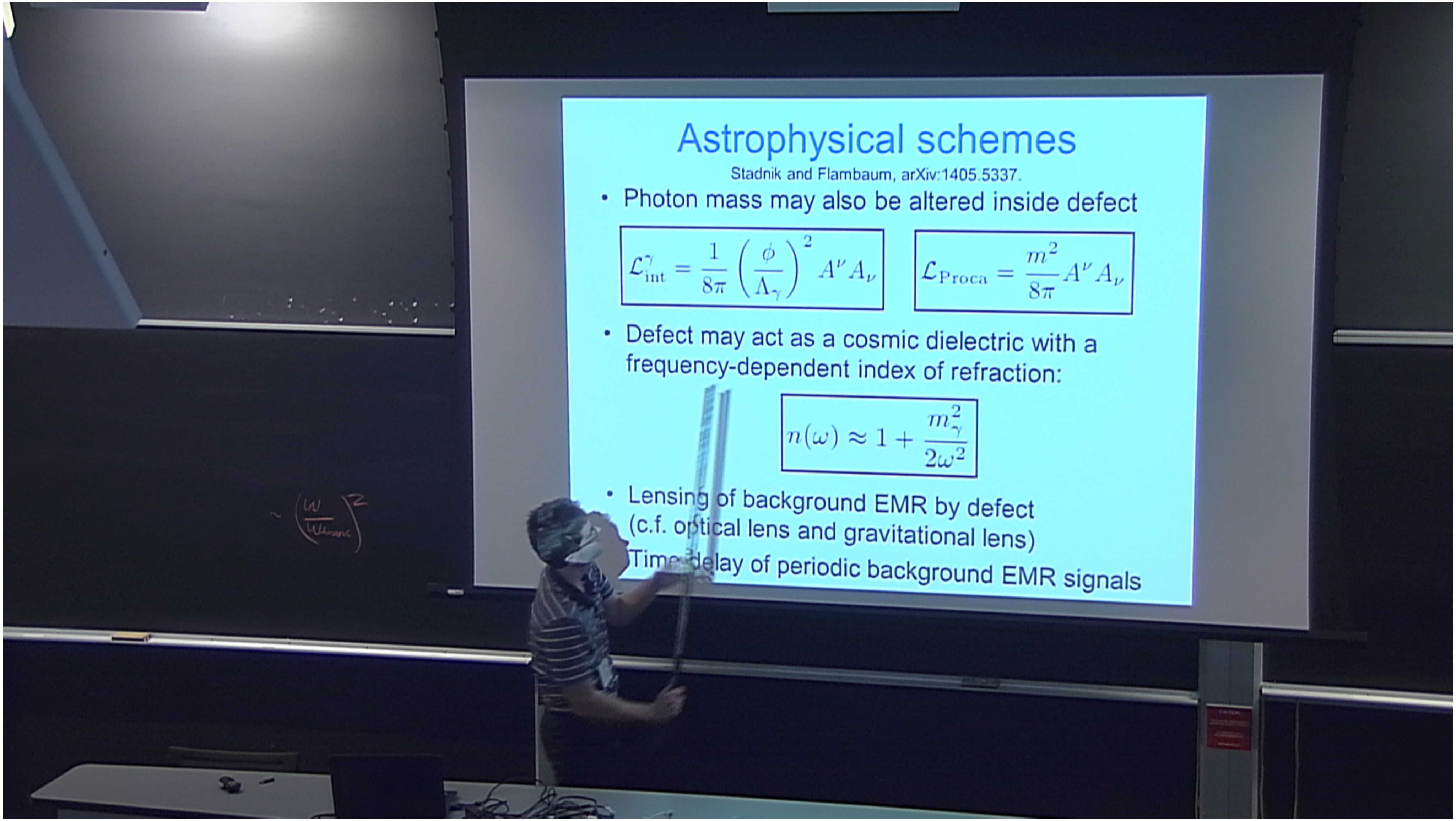
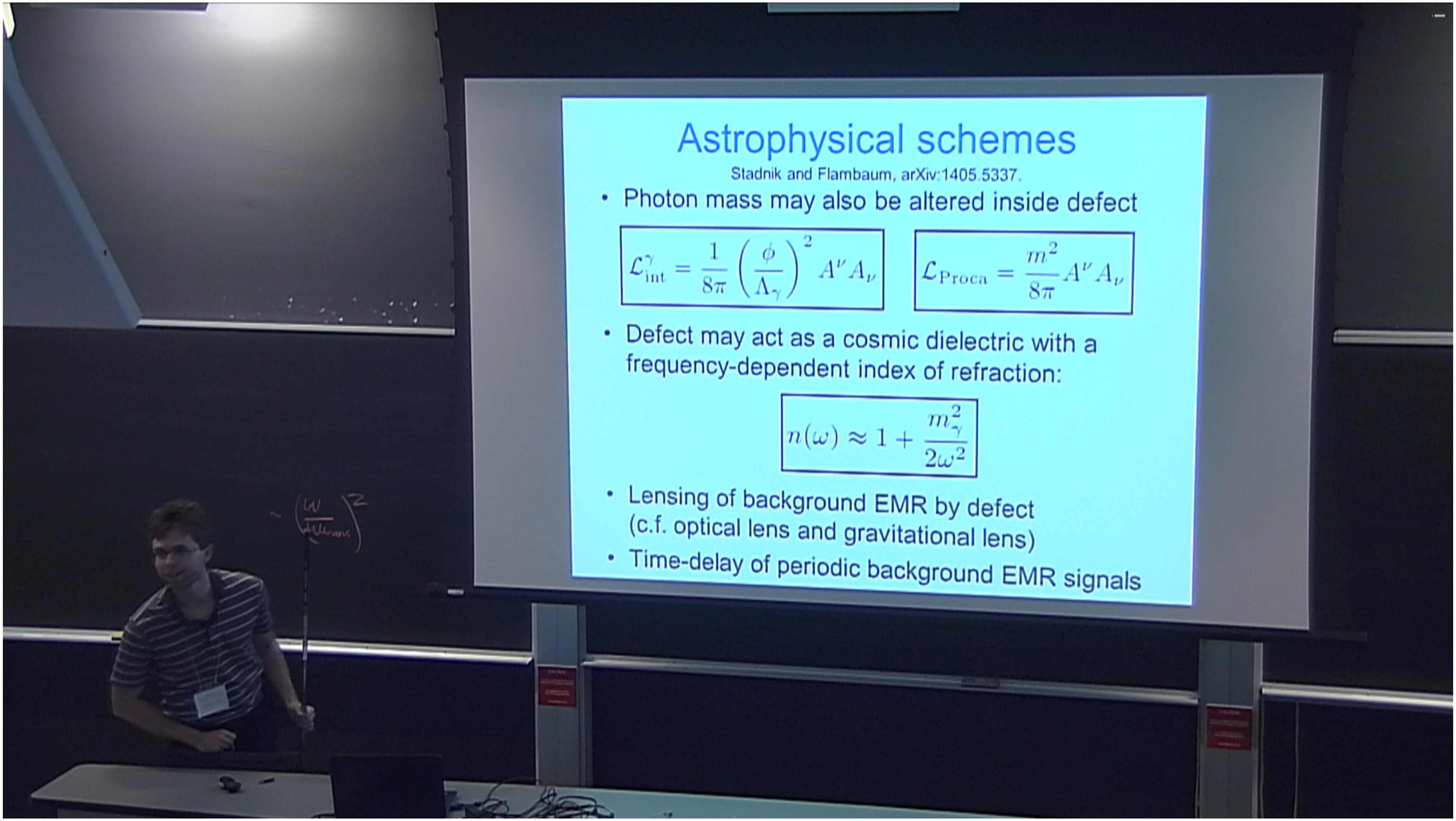

Astrophysical schemes
Stadnik and Flambaum, arXiv:1405.5337.
• Photon mass may also be altered inside defect
$\mathcal{L}_{\mathrm{int}}^{\gamma} = \frac{1}{8\pi}\left(\frac{\phi}{\Lambda_\gamma}\right)^2 A^\nu A_\nu$
$\mathcal{L}_{\mathrm{Proca}} = \frac{m^2}{8\pi} A^\nu A_\nu$
• Defect may act as a cosmic dielectric with a frequency-dependent index of refraction:
$n(\omega) \approx 1 + \frac{m_\gamma^2}{2\omega^2}$
• Lensing of background EMR by defect (c.f. optical lens and gravitational lens)
• Time-delay of periodic background EMR signals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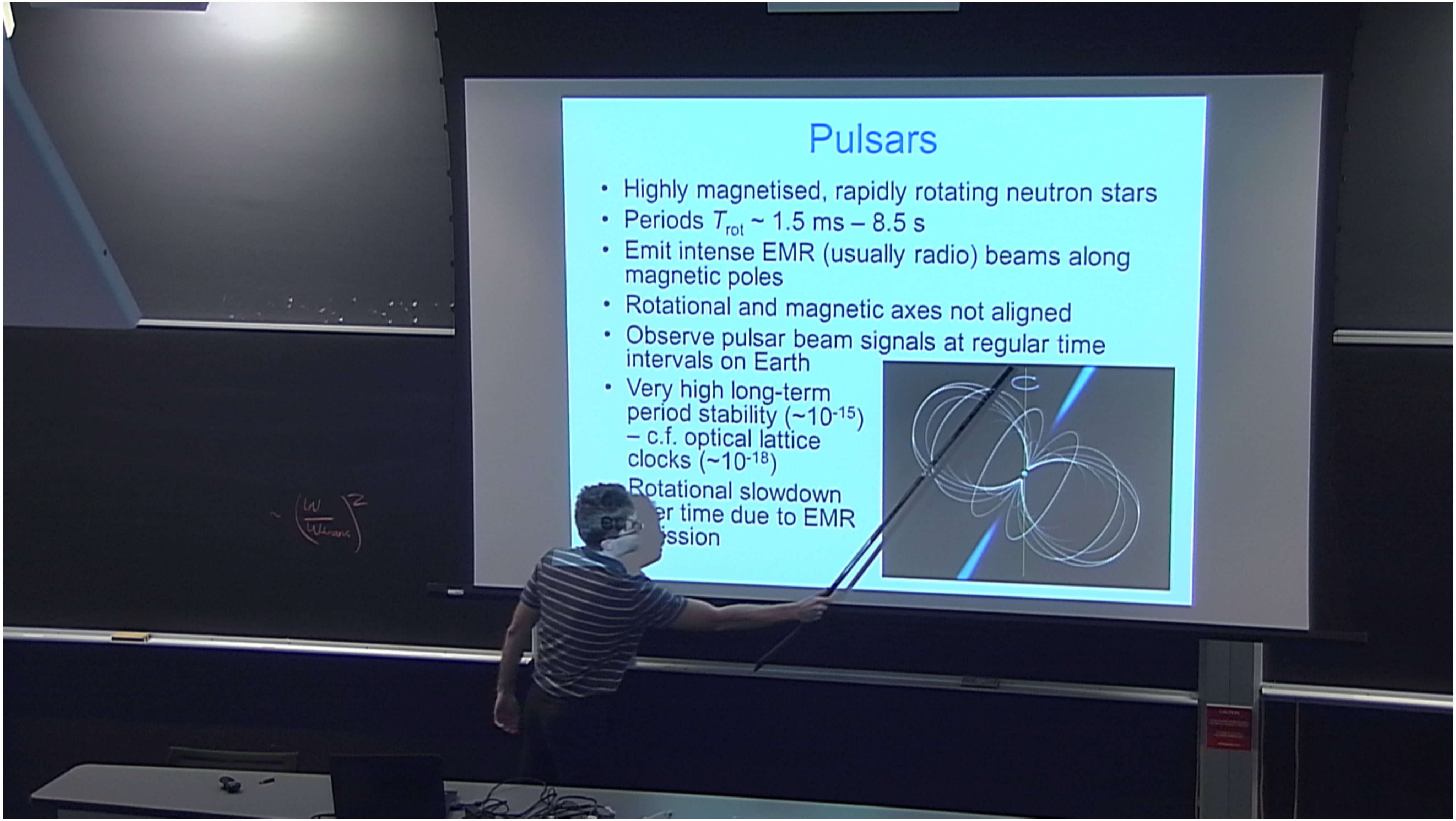
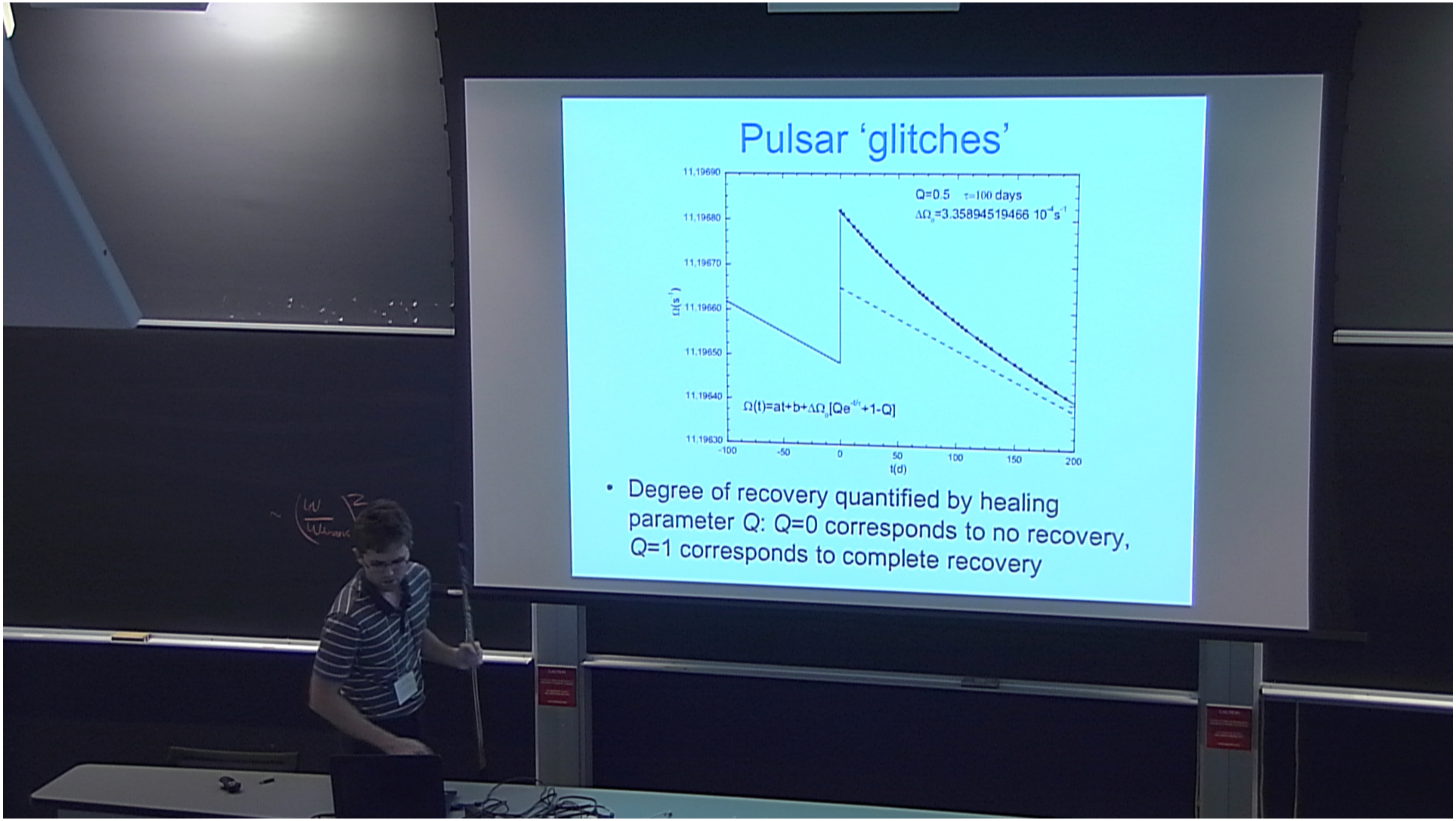
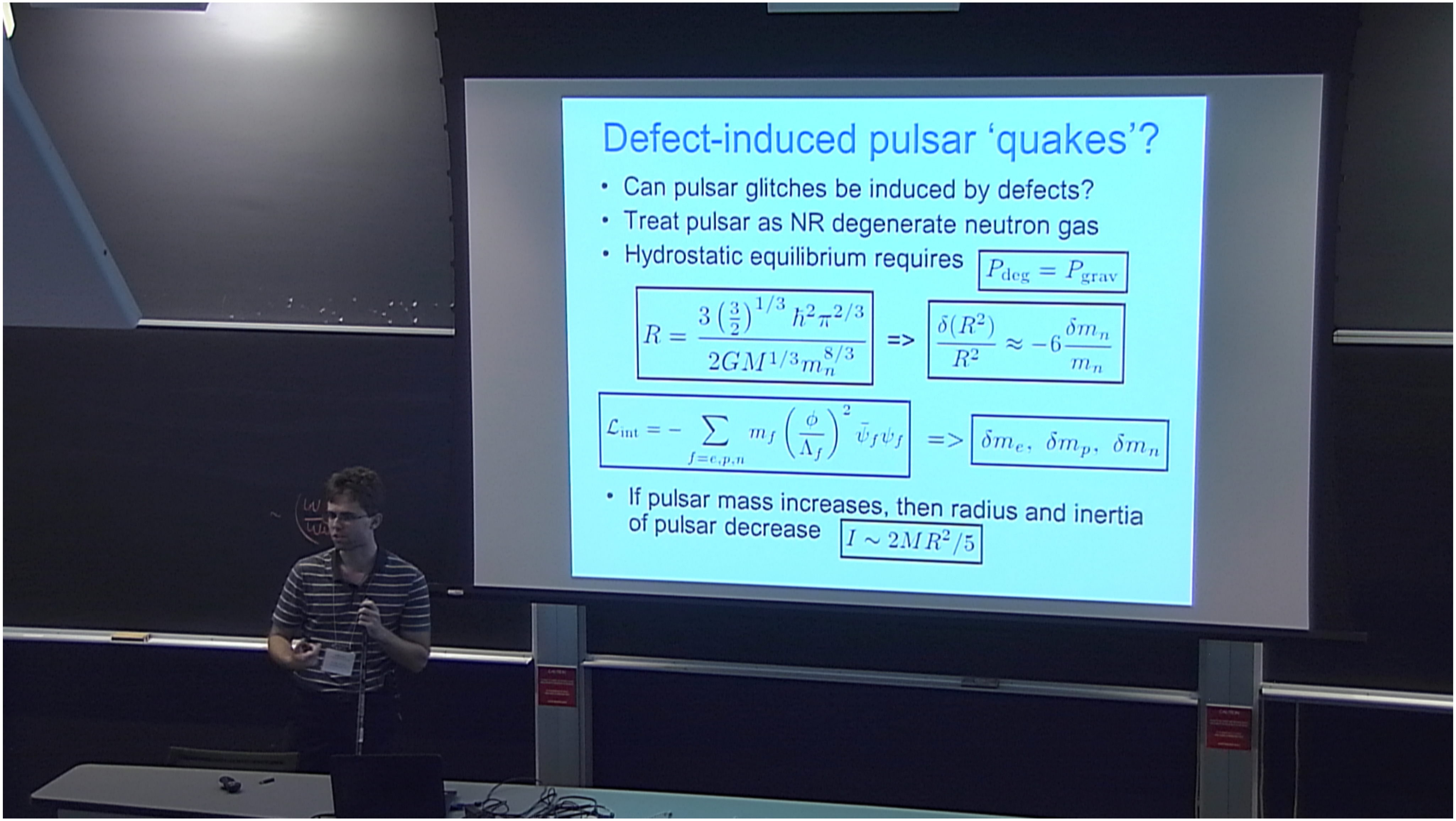
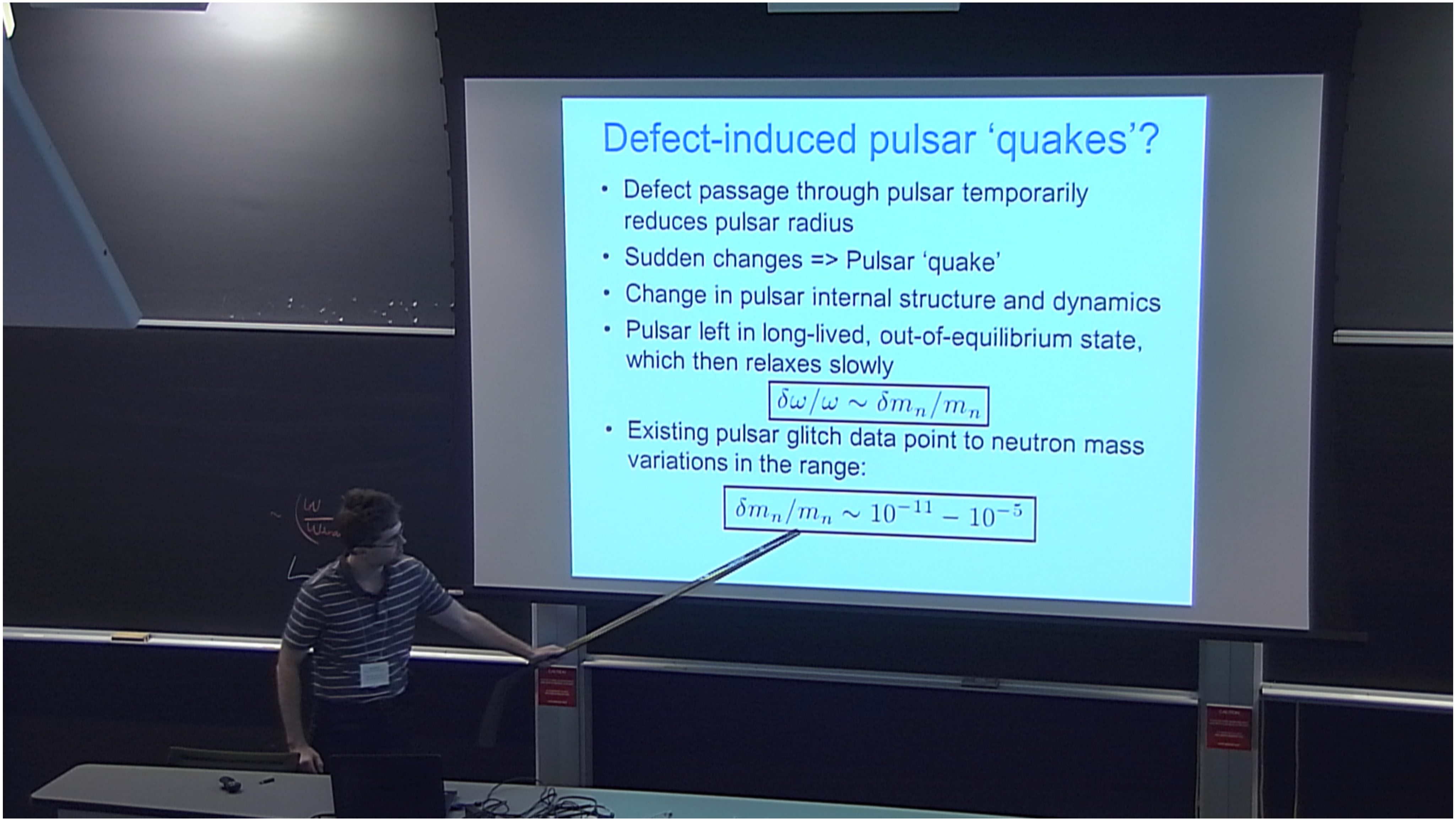
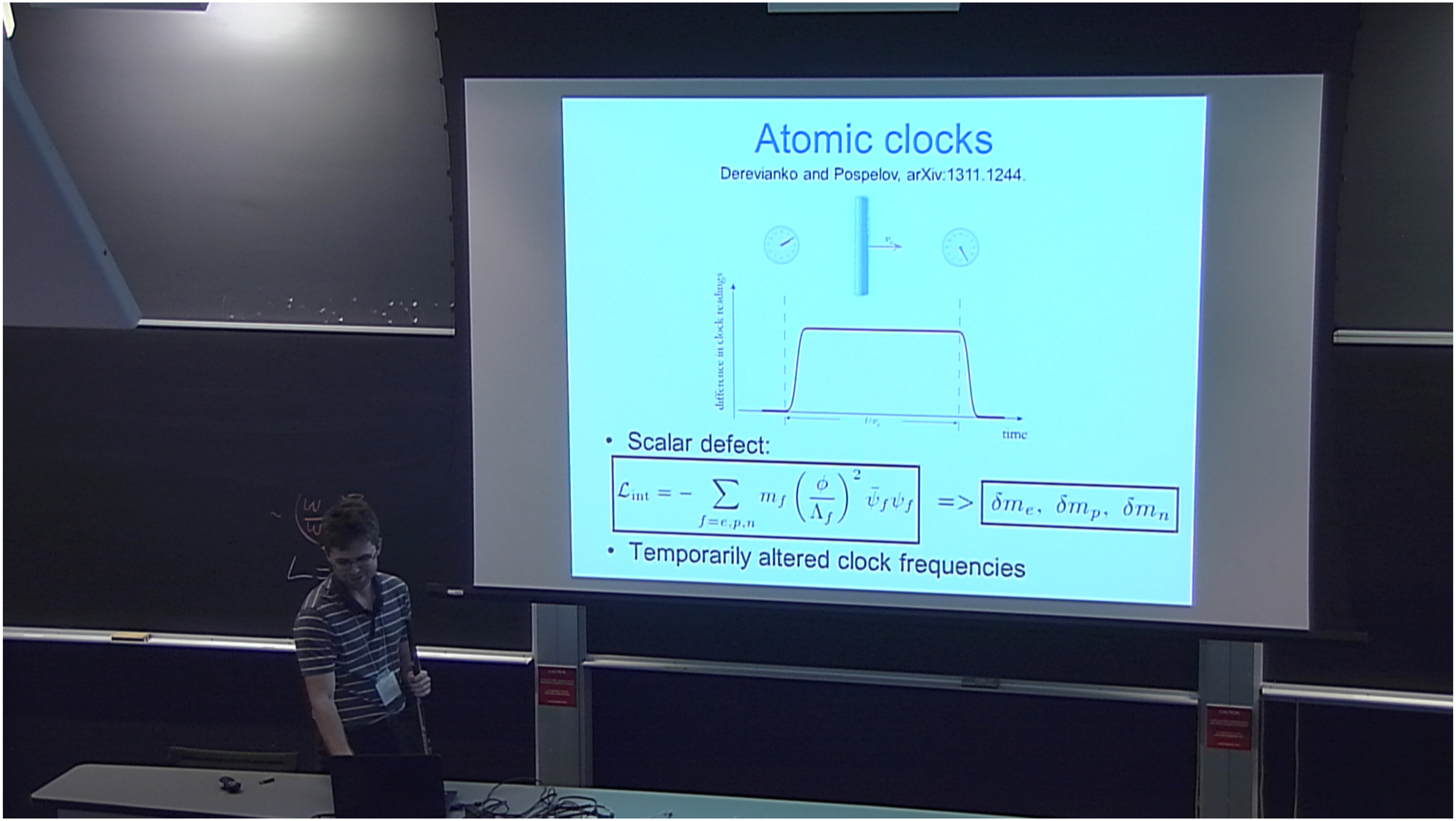
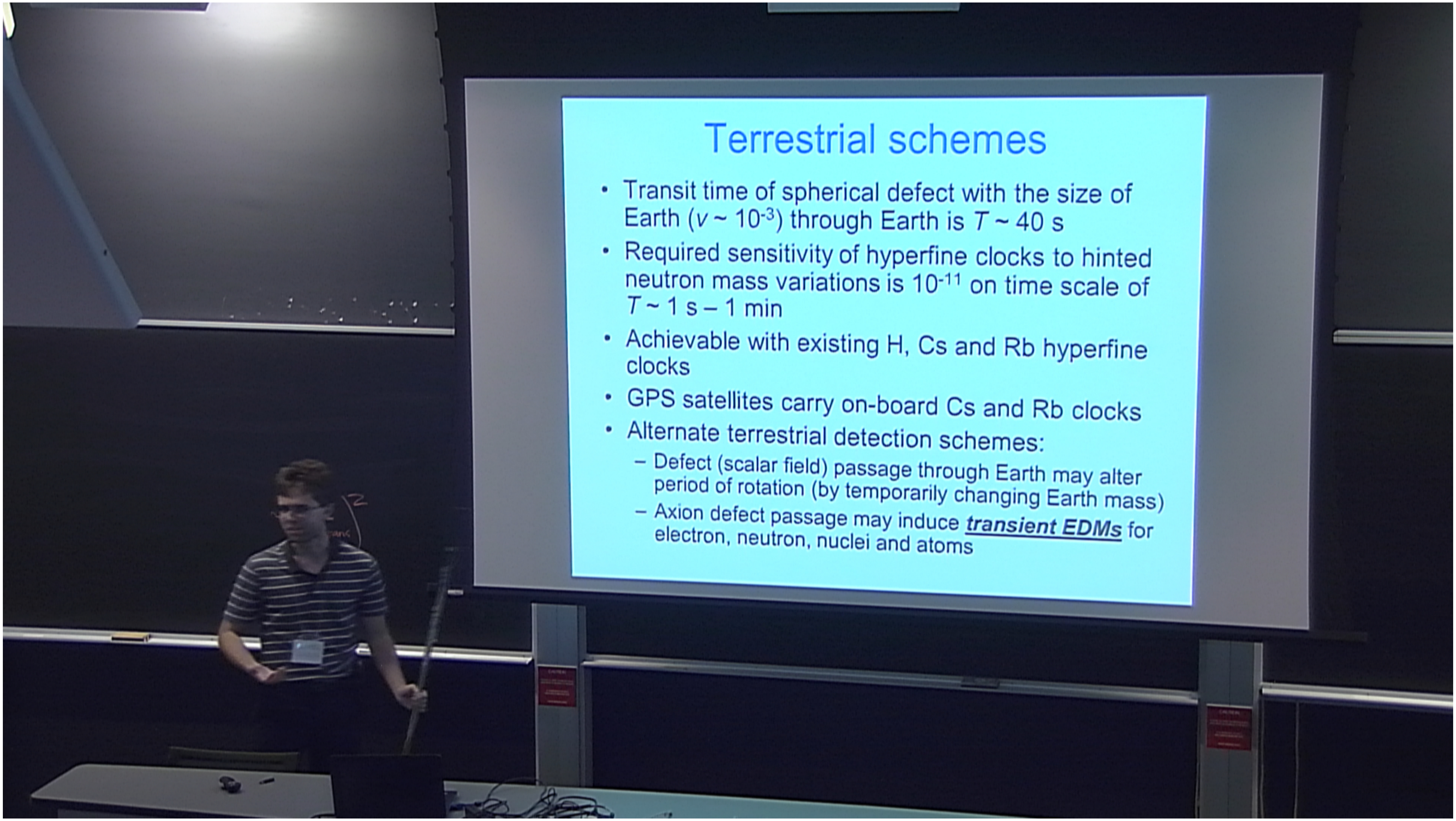

Pulsars
Highly magnetised, rapidly rotating neutron stars
Periods T_{rot} ~ 1.5 ms – 8.5 s
Emit intense EMR (usually radio) beams along magnetic poles
Rotational and magnetic axes not aligned
Observe pulsar beam signals at regular time intervals on Earth
Very high long-term period stability (~10^{-15}) – c.f. optical lattice clocks (~10^{-18})
Rotational slowdown
er time due to EMR
ssion


Pulsar 'glitches'
Q=0.5 τ=100 days
ΔΩ0=3.35894519466 10^-4 s^-1
Ω(t)=at+b+ΔΩ0[Qe^-t/τ+1-Q]
Ω(s^-1)
t(d)
• Degree of recovery quantified by healing parameter Q: Q=0 corresponds to no recovery, Q=1 corresponds to complete recovery


Defect-induced pulsar 'quakes'?
• Can pulsar glitches be induced by defects?
• Treat pulsar as NR degenerate neutron gas
• Hydrostatic equilibrium requires $P_{\rm deg} = P_{\rm grav}$
$R = \frac{3\left(\frac{3}{2}\right)^{1/3} \hbar^2 \pi^{2/3}}{2GM^{1/3} m_n^{8/3}}$ => $\frac{\delta(R^2)}{R^2} \approx -6\frac{\delta m_n}{m_n}$
$\mathcal{L}_{\rm int} = -\sum_{f=e,p,n} m_f \left(\frac{\phi}{\Lambda_f}\right)^2 \bar{\psi}_f \psi_f$ => $\delta m_e,\ \delta m_p,\ \delta m_n$
• If pulsar mass increases, then radius and inertia of pulsar decrease $I \sim 2MR^2/5$


Defect-induced pulsar 'quakes'?
• Defect passage through pulsar temporarily reduces pulsar radius
• Sudden changes => Pulsar 'quake'
• Change in pulsar internal structure and dynamics
• Pulsar left in long-lived, out-of-equilibrium state, which then relaxes slowly
$\delta\omega/\omega \sim \delta m_n/m_n$
• Existing pulsar glitch data point to neutron mass variations in the range:
$\delta m_n/m_n \sim 10^{-11} - 10^{-5}$


Atomic clocks
Derevianko and Pospelov, arXiv:1311.1244.
difference in clock readings
time
• Scalar defect:
$\mathcal{L}_{\rm int} = - \sum_{f=e,p,n} m_f \left(\frac{\phi}{\Lambda_f}\right)^2 \bar{\psi}_f \psi_f$
=>
$\delta m_e,\ \delta m_p,\ \delta m_n$
• Temporarily altered clock frequencies


Terrestrial schemes
• Transit time of spherical defect with the size of Earth ($v \sim 10^{-3}$) through Earth is $T \sim 40$ s
• Required sensitivity of hyperfine clocks to hinted neutron mass variations is 10^{-11} on time scale of $T \sim 1$ s – 1 min
• Achievable with existing H, Cs and Rb hyperfine clocks
• GPS satellites carry on-board Cs and Rb clocks
• Alternate terrestrial detection schemes:
– Defect (scalar field) passage through Earth may alter period of rotation (by temporarily changing Earth mass)
– Axion defect passage may induce transient EDMs for electron, neutron, nuclei and atoms