Title: Search for new physics in atoms: cosmic PNC and variation of alpha

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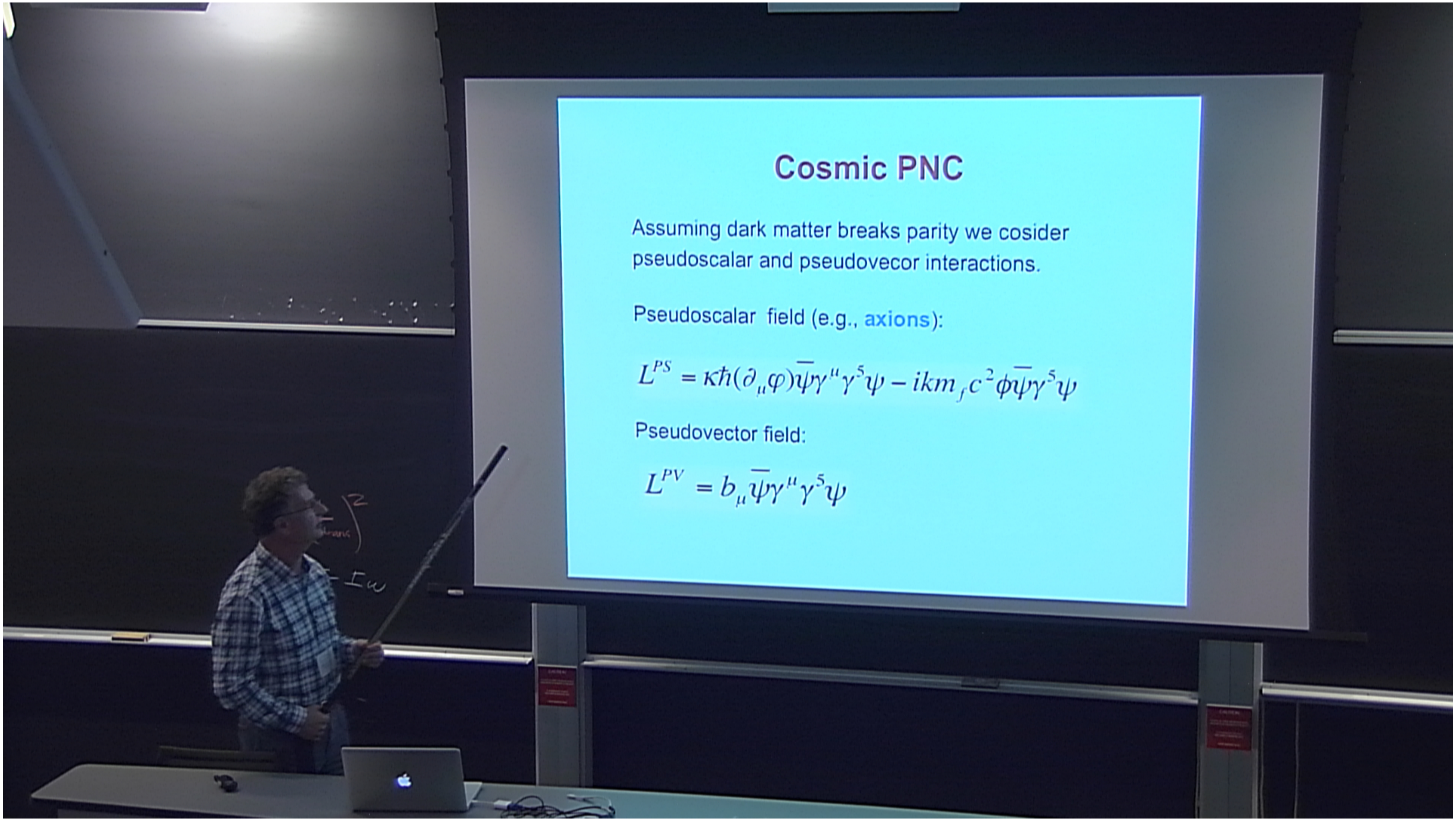
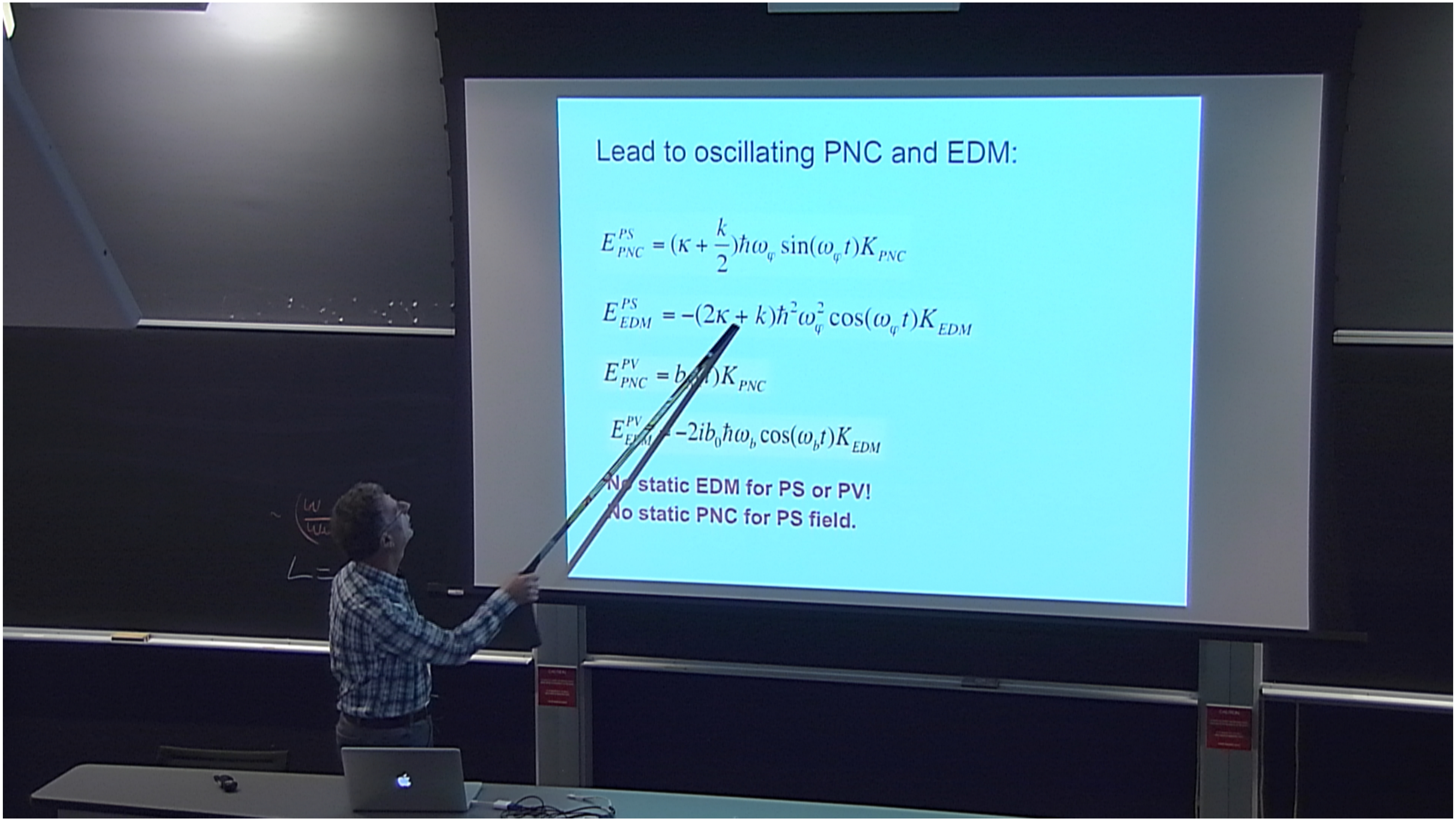
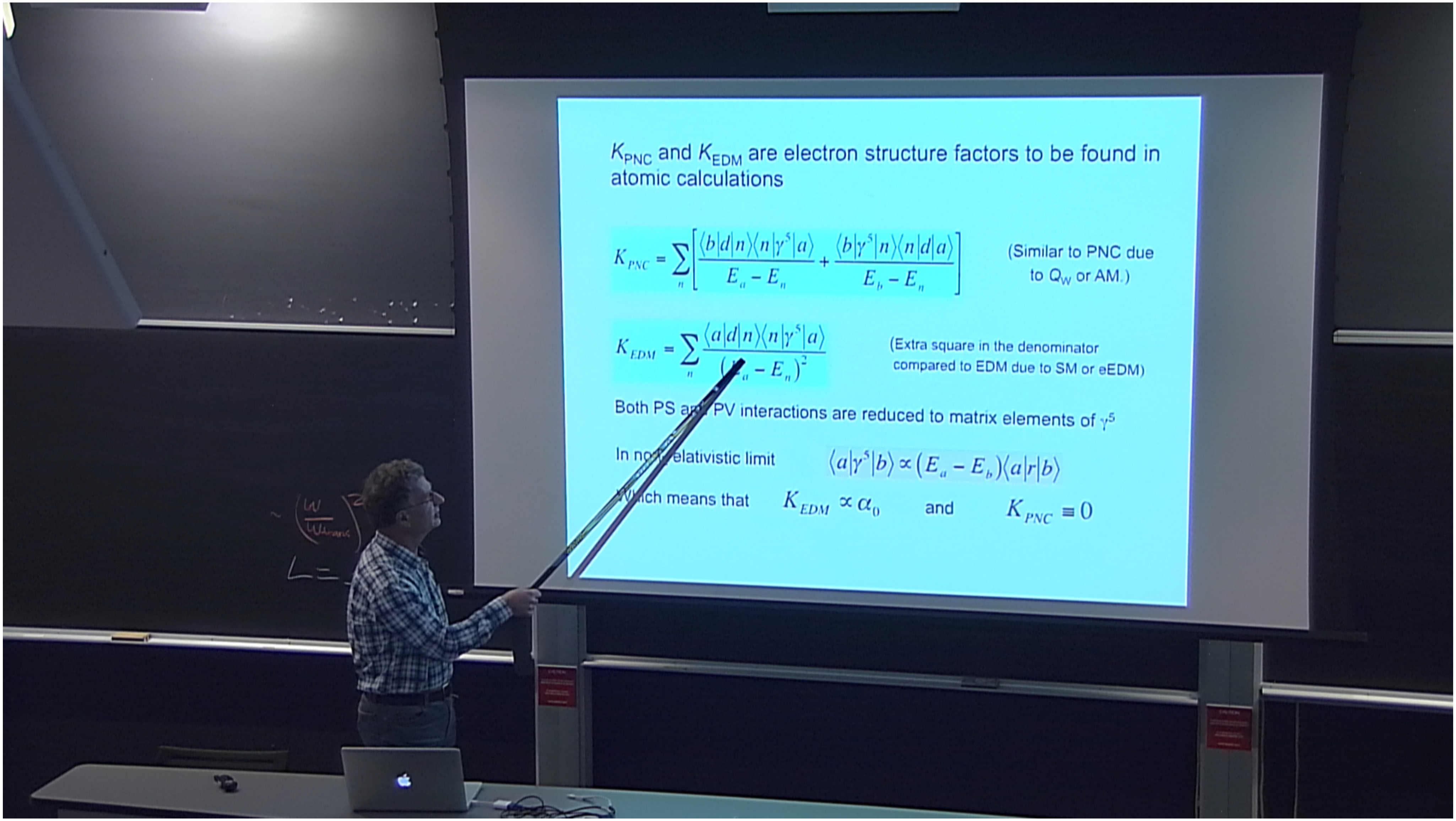
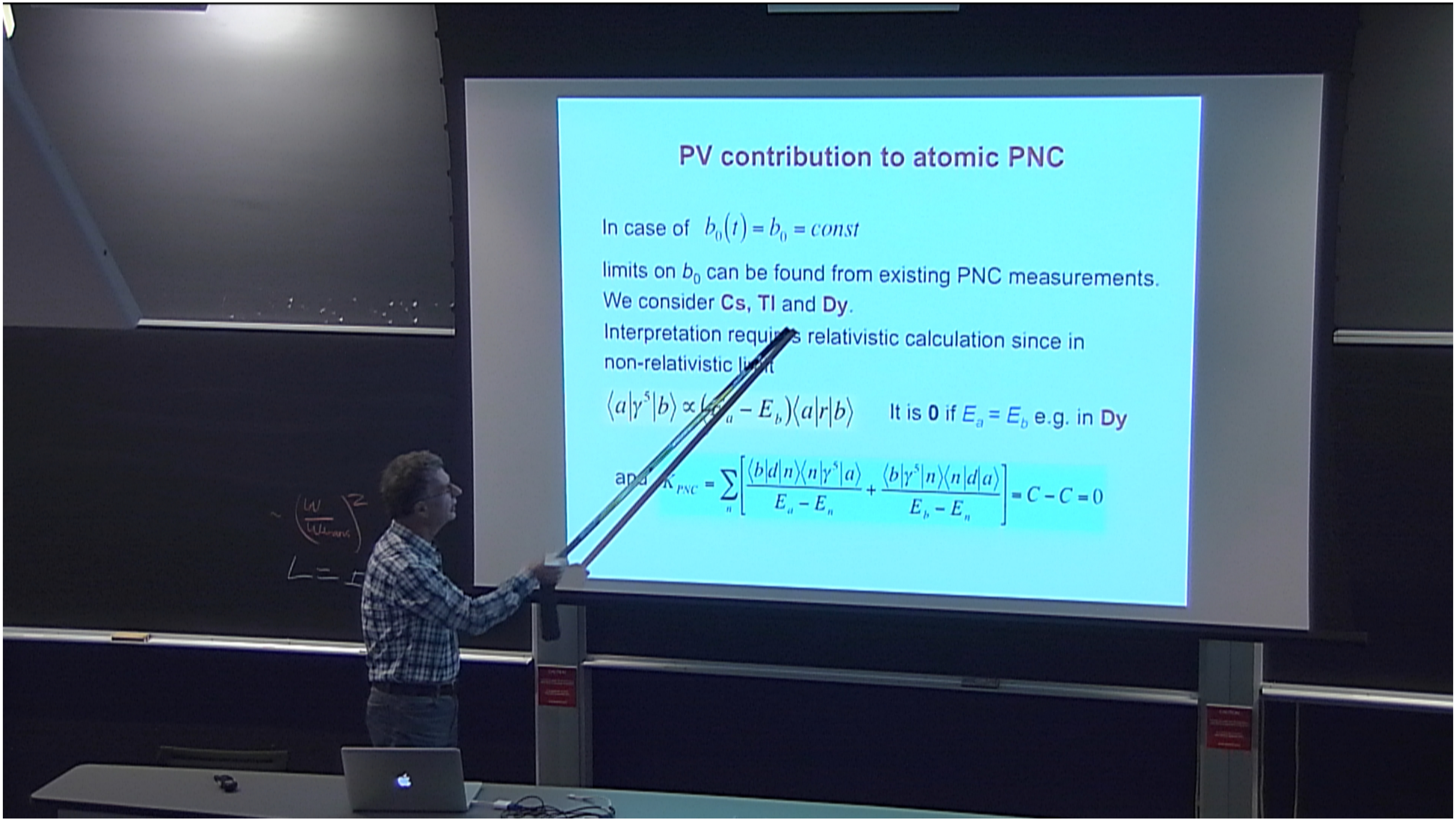
Abstract: We consider pseudo-scalar and pseudo-vector interaction of atomic electrons with hypothetical dark matter particles (e.g., axions). These interactions lead to oscillating atomic parity non-conserving (PNC) amplitudes and/or oscillating electric dipole moments (EDM). In static
 limit for PNC, existing atomic PNC experiments can be used to constrain time component of the pseudo-vector field.

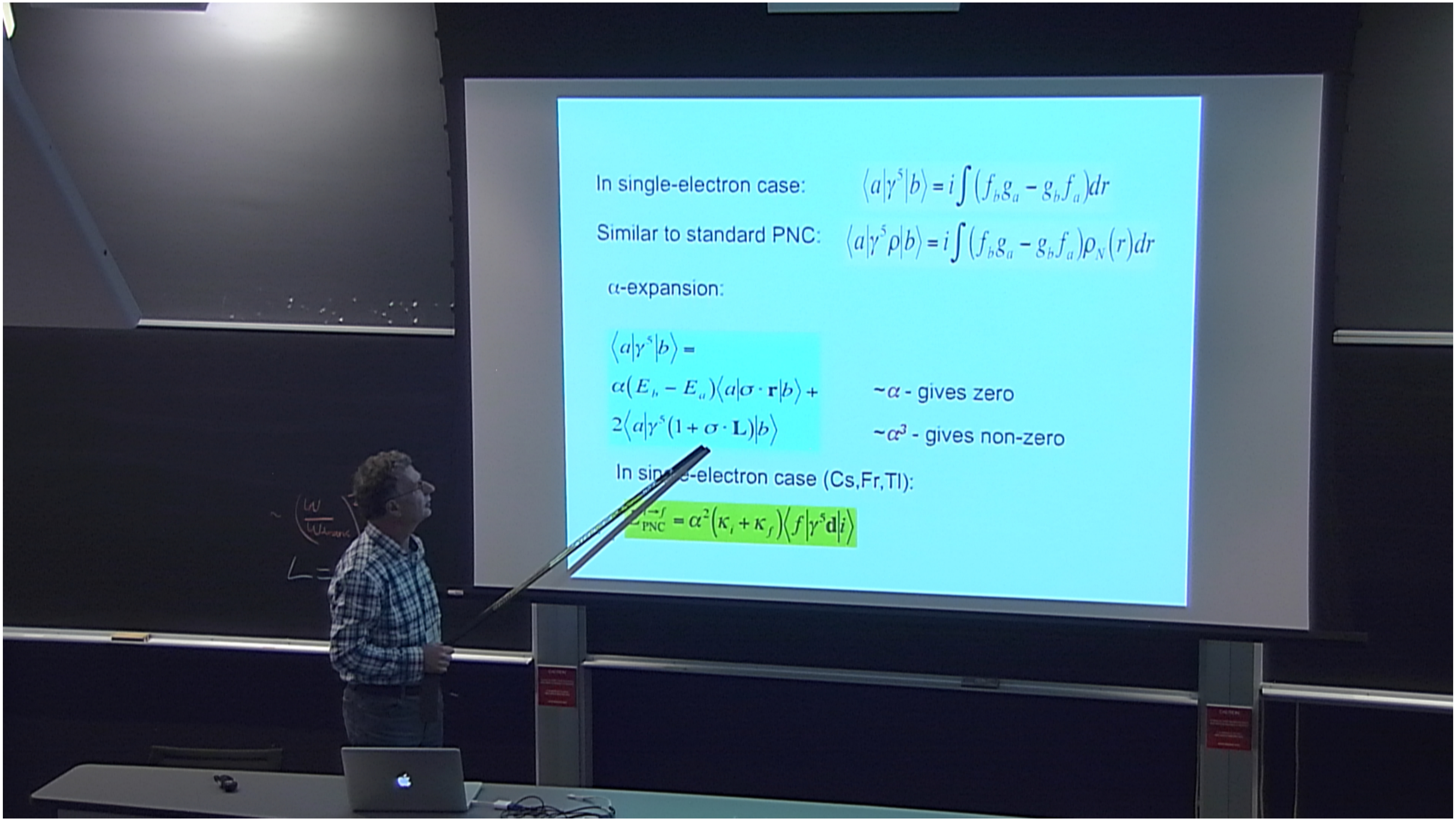
 Possible variation of fundamental constants is suggested by theories unifying gravity with other interactions. Evidence of the space/time variation of the fine structure constant alpha is found in
 the quasar absorption spectra. Optical transitions in highly charged ions can be used as sensitive tools for studying time variation of alpha in laboratory.

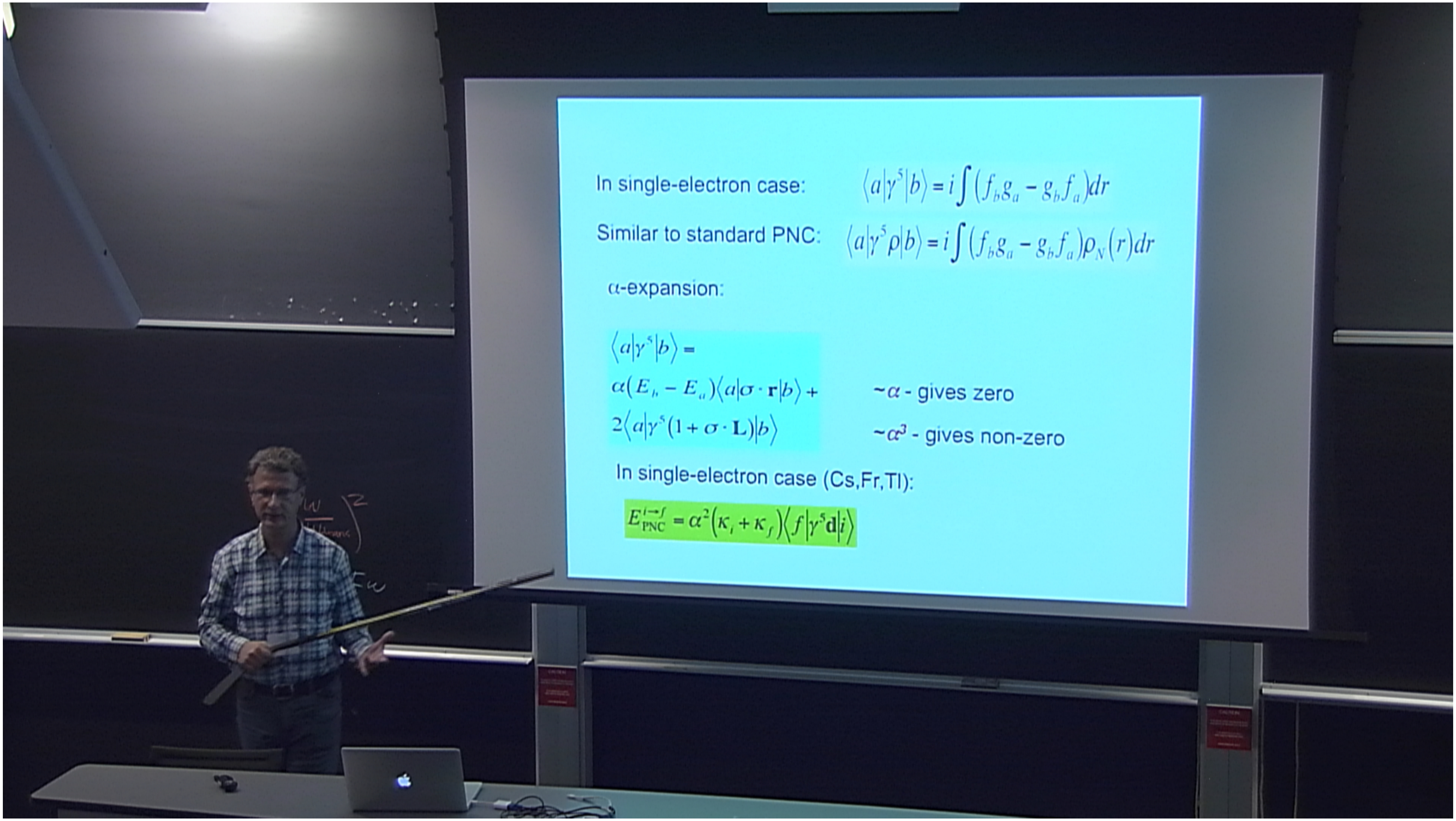

Cosmic PNC
Assuming dark matter breaks parity we cosider pseudoscalar and pseudovecor interactions.
Pseudoscalar field (e.g., axions):
$L^{PS} = \kappa\hbar(\partial_\mu\varphi)\overline{\psi}\gamma^\mu\gamma^5\psi - ikm_f c^2\phi\overline{\psi}\gamma^5\psi$
Pseudovector field:
$L^{PV} = b_\mu\overline{\psi}\gamma^\mu\gamma^5\psi$


Lead to oscillating PNC and EDM:
$E^{PS}_{PNC} = (\kappa + \frac{k}{2})\hbar\omega_{\varphi}\sin(\omega_{\varphi}t)K_{PNC}$
$E^{PS}_{EDM} = -(2\kappa + k)\hbar^2\omega^2_{\varphi}\cos(\omega_{\varphi}t)K_{EDM}$
$E^{PV}_{PNC} = b(t)K_{PNC}$
$E^{PV}_{EDM} = -2ib_0\hbar\omega_b\cos(\omega_b t)K_{EDM}$
No static EDM for PS or PV!
No static PNC for PS field.


K_{PNC} and K_{EDM} are electron structure factors to be found in atomic calculations
$K_{PNC} = \sum_n \left[\frac{\langle b|d|n\rangle\langle n|\gamma^5|a\rangle}{E_a - E_n} + \frac{\langle b|\gamma^5|n\rangle\langle n|d|a\rangle}{E_b - E_n} \right]$
(Similar to PNC due to Q_W or AM.)
$K_{EDM} = \sum_n \frac{\langle a|d|n\rangle\langle n|\gamma^5|a\rangle}{(E_a - E_n)^2}$
(Extra square in the denominator compared to EDM due to SM or eEDM)
Both PS a PV interactions are reduced to matrix elements of γ^5
In no elativistic limit $\langle a|\gamma^5|b\rangle \propto (E_a - E_b)\langle a|r|b\rangle$
ich means that $K_{EDM} \propto \alpha_0$ and $K_{PNC} \equiv 0$


PV contribution to atomic PNC
In case of $b_0(t) = b_0 = const$
limits on b_0 can be found from existing PNC measurements.
We consider Cs, Tl and Dy.
Interpretation requires relativistic calculation since in
non-relativistic limit
$\langle a|\gamma^5|b\rangle \propto (E_a - E_b)\langle a|r|b\rangle$
It is 0 if $E_a = E_b$ e.g. in Dy
and $K_{PNC} = \sum_n \left[\frac{\langle b|d|n\rangle\langle n|\gamma^5|a\rangle}{E_a - E_n} + \frac{\langle b|\gamma^5|n\rangle\langle n|d|a\rangle}{E_b - E_n} \right] = C - C = 0$


In single-electron case: $\langle a|\gamma^5|b\rangle = i\int (f_b g_a - g_b f_a)dr$
Similar to standard PNC: $\langle a|\gamma^5\rho|b\rangle = i\int (f_b g_a - g_b f_a)\rho_N(r)dr$
α-expansion:
$\langle a|\gamma^5|b\rangle =$
$\alpha(E_b - E_a)\langle a|\sigma\cdot\mathbf{r}|b\rangle +$
$2\langle a|\gamma^5(1+\sigma\cdot\mathbf{L})|b\rangle$
~α - gives zero
~α³ - gives non-zero
e-electron case (Cs,Fr,Tl):
$= \alpha^2(\kappa_i + \kappa_f)\langle f|\gamma^5\mathbf{d}|i\rangle$



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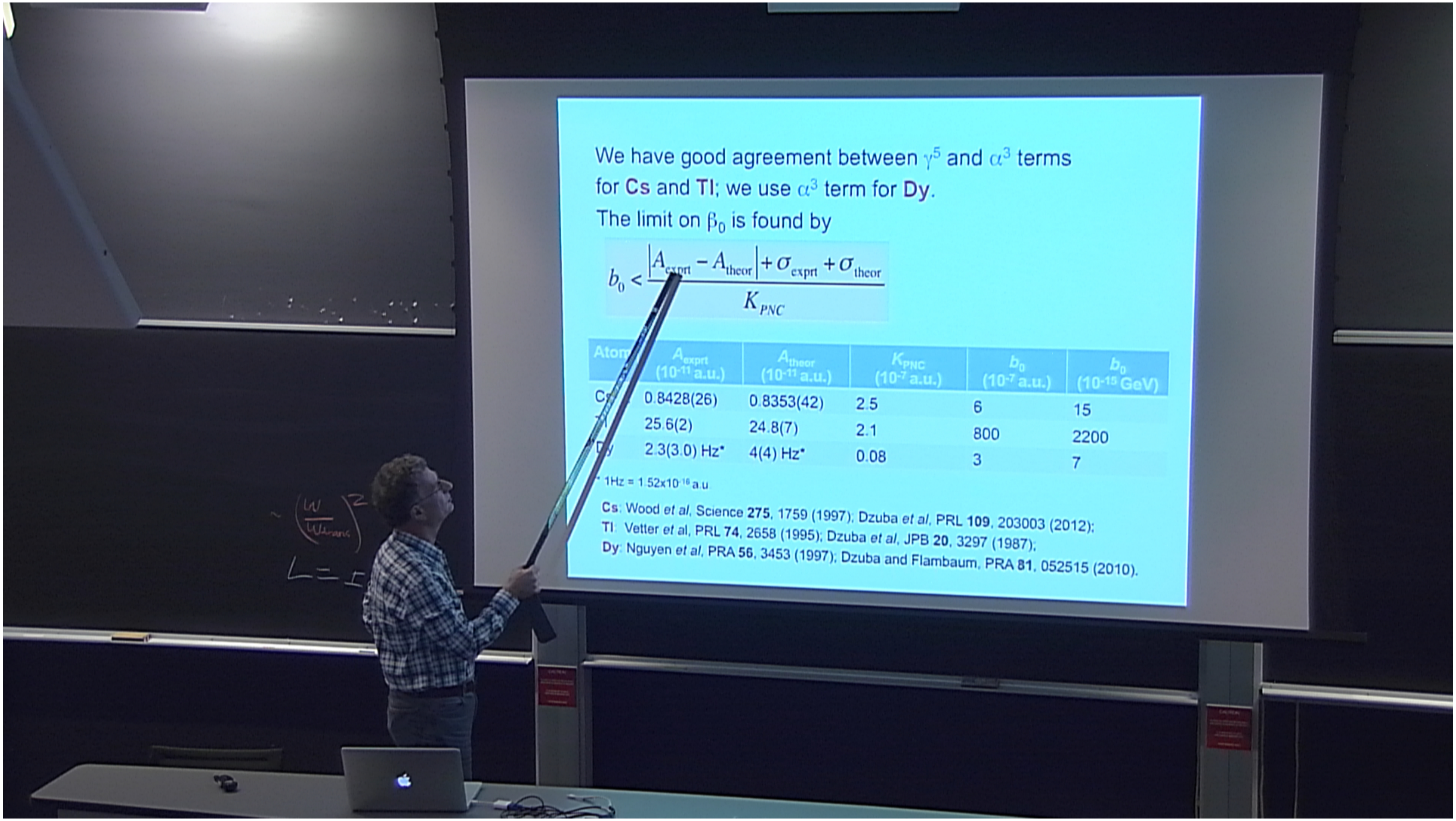
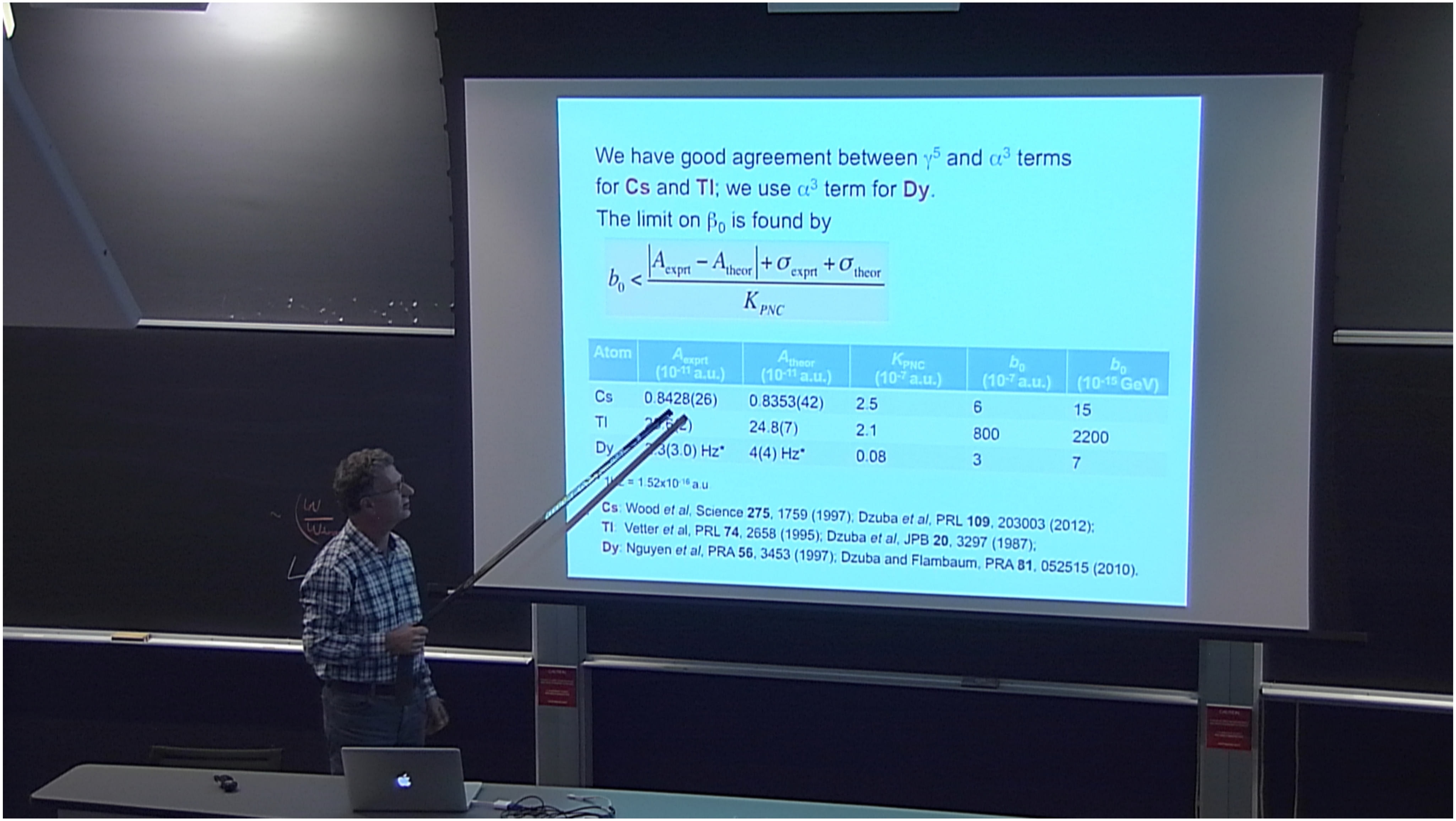
$\alpha(E_b - E_a)\langle a|\sigma\cdot\mathbf{r}|b\rangle +$
$2\langle a|\gamma^5(1+\sigma\cdot\mathbf{L})|b\rangle$
$\sim\alpha$ - gives zero
$\sim\alpha^3$ - gives non-zero
In single-electron case (Cs,Fr,Tl):
$E_{\mathrm{PNC}}^{i\to f} = \alpha^2(\kappa_i + \kappa_f)\langle f|\gamma^5\mathbf{d}|i\rangle$


We have good agreement between γ^5 and α^3 terms
for **Cs** and **Tl**; we use α^3 term for **Dy**.
The limit on β_0 is found by
$$b_0 < \frac{|A_{exprt} - A_{theor}| + \sigma_{exprt} + \sigma_{theor}}{K_{PNC}}$$
Atom
A_{exprt} (10^{-11} a.u.)
A_{theor} (10^{-11} a.u.)
K_{PNC} (10^{-7} a.u.)
b_0 (10^{-7} a.u.)
b_0 (10^{-15} GeV)
0.8428(26) 0.8353(42) 2.5 6 15
25.6(2) 24.8(7) 2.1 800 2200
Dy 2.3(3.0) Hz* 4(4) Hz* 0.08 3 7
* 1Hz = 1.52x10^{-16} a.u
Cs: Wood *et al*, Science **275**, 1759 (1997); Dzuba *et al*, PRL **109**, 203003 (2012);
Tl: Vetter *et* al, PRL **74**, 2658 (1995); Dzuba *et al*, JPB **20**, 3297 (1987);
Dy: Nguyen *et al*, PRA **56**, 3453 (1997); Dzuba and Flambaum, PRA **81**, 052515 (2010).


We have good agreement between γ5 and α3 terms
for Cs and Tl; we use α3 term for Dy.
The limit on β0 is found by
b0 < (|Aexprt − Atheor| + σexprt + σtheor) / KPNC
Atom
Aexprt (10-11 a.u.)
Atheor (10-11 a.u.)
KPNC (10-7 a.u.)
b0 (10-7 a.u.)
b0 (10-15 GeV)
Cs 0.8428(26) 0.8353(42) 2.5 6 15
Tl 24.8(7) 2.1 800 2200
Dy 4(4) Hz* 0.08 3 7
= 1.52x10-16 a.u
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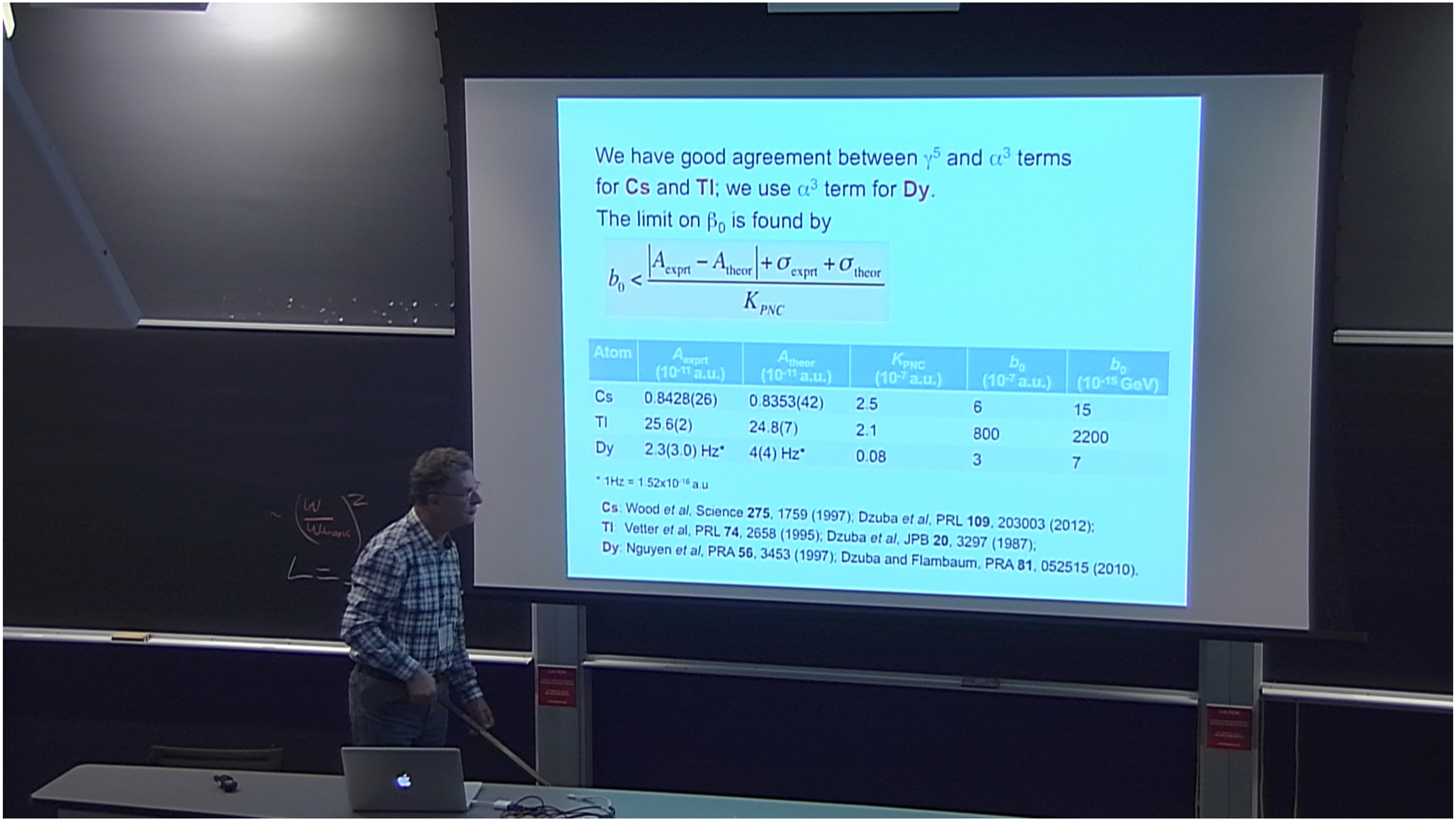
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The limit on β_0 is found by
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Atom | A_{exprt} (10^{-11} a.u.) | A_{theor} (10^{-11} a.u.) | K_{PNC} (10^{-7} a.u.) | b_0 (10^{-7} a.u.) | b_0 (10^{-15} GeV)
Cs | 0.8428(26) | 0.8353(42) | 2.5 | 6 | 15
Tl | 25.6(2) | 24.8(7) | 2.1 | 800 | 2200
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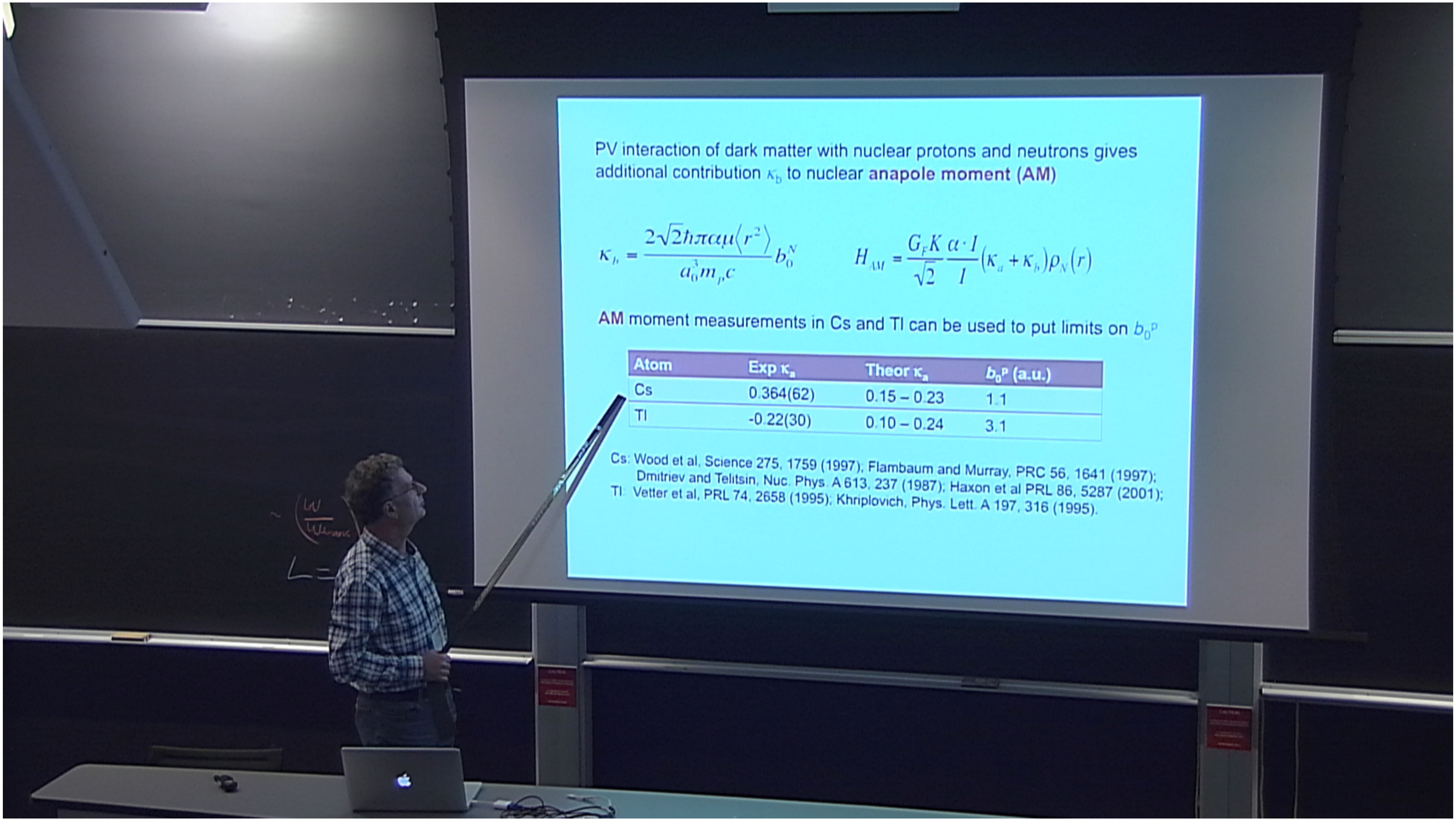
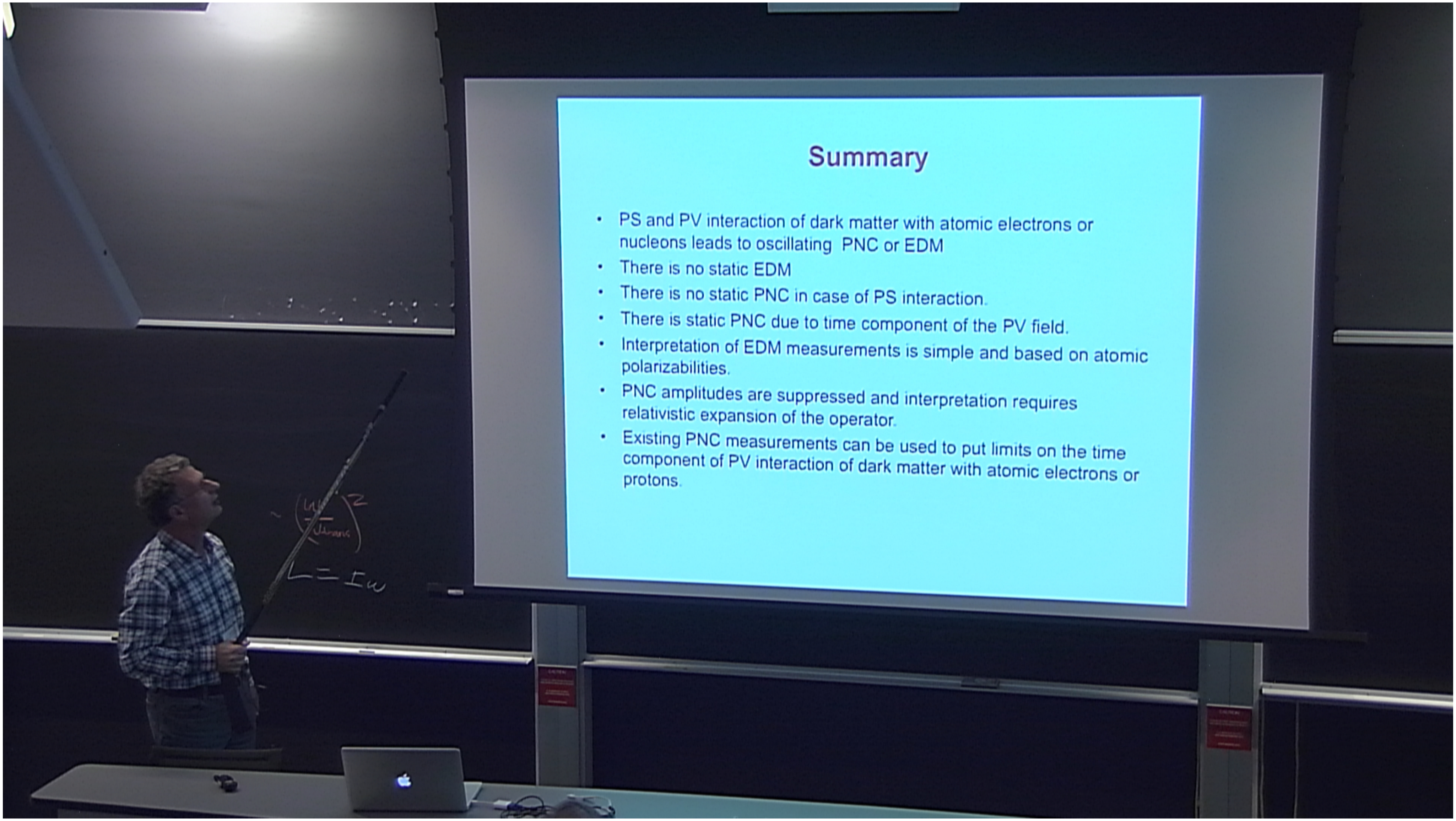
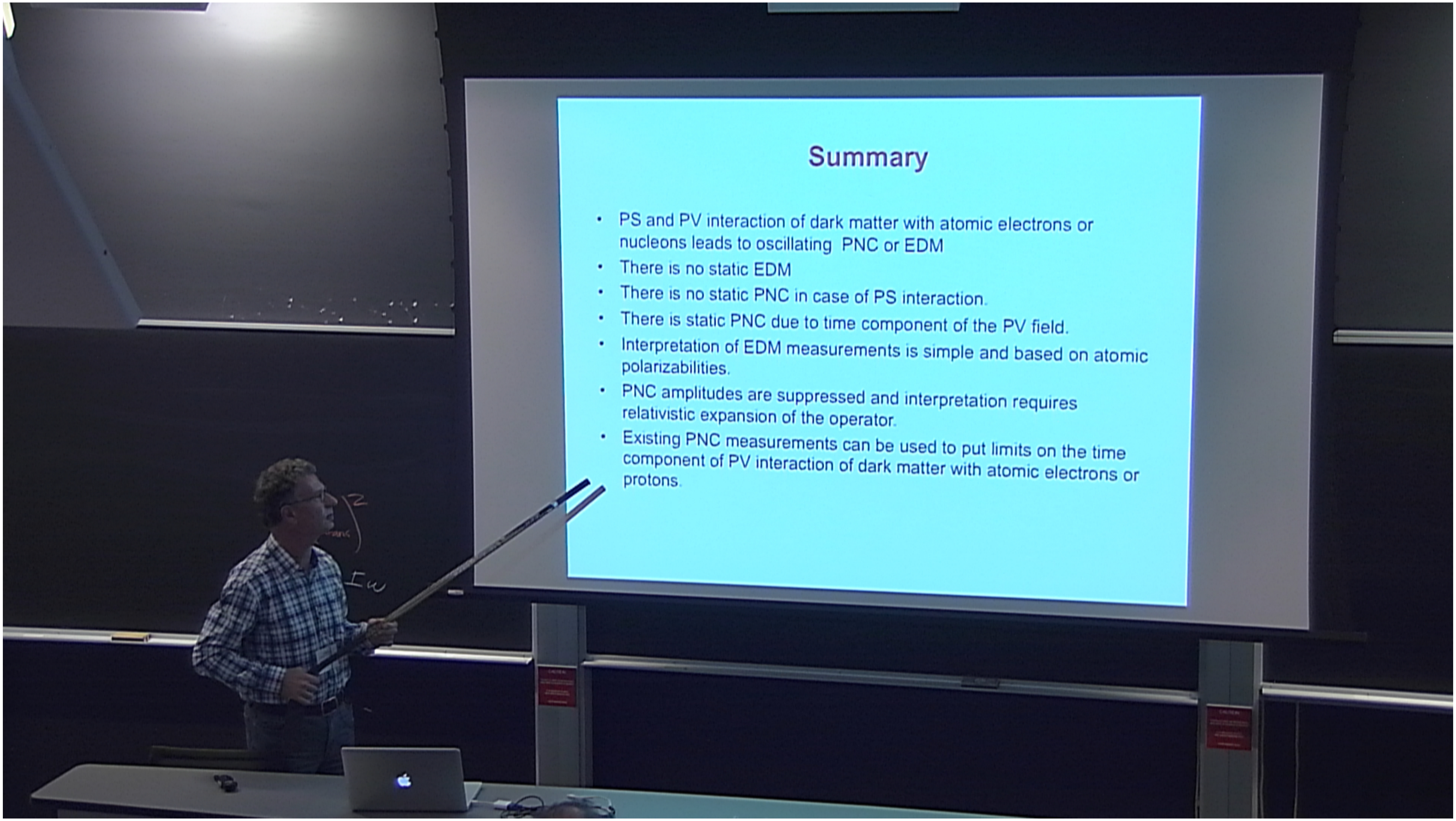

PV interaction of dark matter with nuclear protons and neutrons gives
additional contribution κ_b to nuclear anapole moment (AM)
$\kappa_b = \frac{2\sqrt{2}\hbar\pi\alpha\mu\langle r^2\rangle}{a_0^3 m_p c} b_0^N$
$H_{AM} = \frac{G_F K}{\sqrt{2}} \frac{\alpha \cdot I}{I} (\kappa_a + \kappa_b)\rho_N(r)$
AM moment measurements in Cs and Tl can be used to put limits on b_0^p
Atom
Exp κ_a
Theor κ_a
b_0^p (a.u.)
Cs
0.364(62)
0.15 – 0.23
1.1
Tl
-0.22(30)
0.10 – 0.24
3.1
Cs: Wood et al, Science 275, 1759 (1997); Flambaum and Murray, PRC 56, 1641 (1997);
Dmitriev and Telitsin, Nuc. Phys. A 613, 237 (1987); Haxon et al PRL 86, 5287 (2001);
Tl: Vetter et al, PRL 74, 2658 (1995); Khriplovich, Phys. Lett. A 197, 316 (1995).


Summary
• PS and PV interaction of dark matter with atomic electrons or nucleons leads to oscillating PNC or EDM
• There is no static EDM
• There is no static PNC in case of PS interaction.
• There is static PNC due to time component of the PV field.
• Interpretation of EDM measurements is simple and based on atomic polarizabilities.
• PNC amplitudes are suppressed and interpretation requires relativistic expansion of the operator.
• Existing PNC measurements can be used to put limits on the time component of PV interaction of dark matter with atomic electrons or protons.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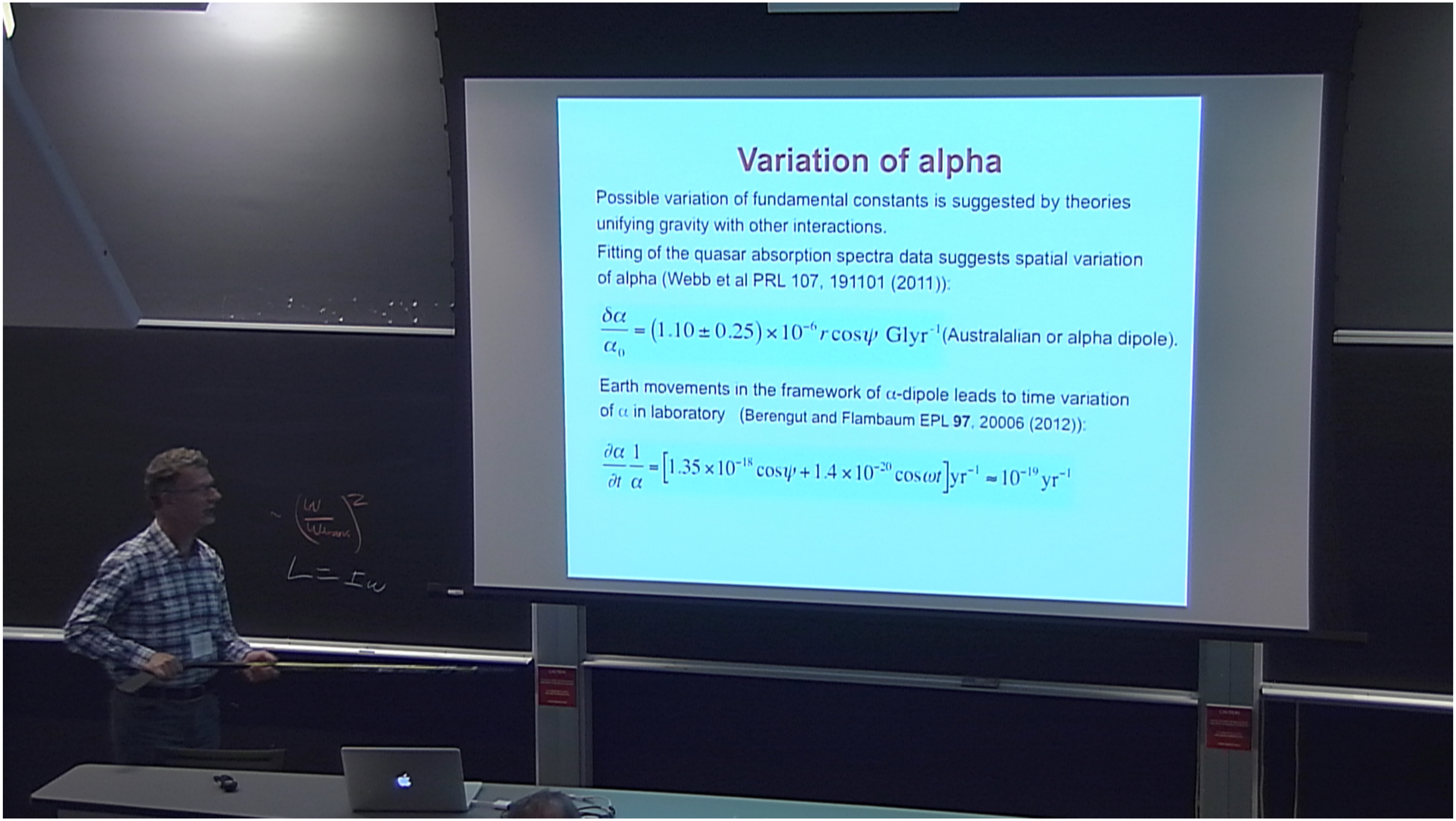
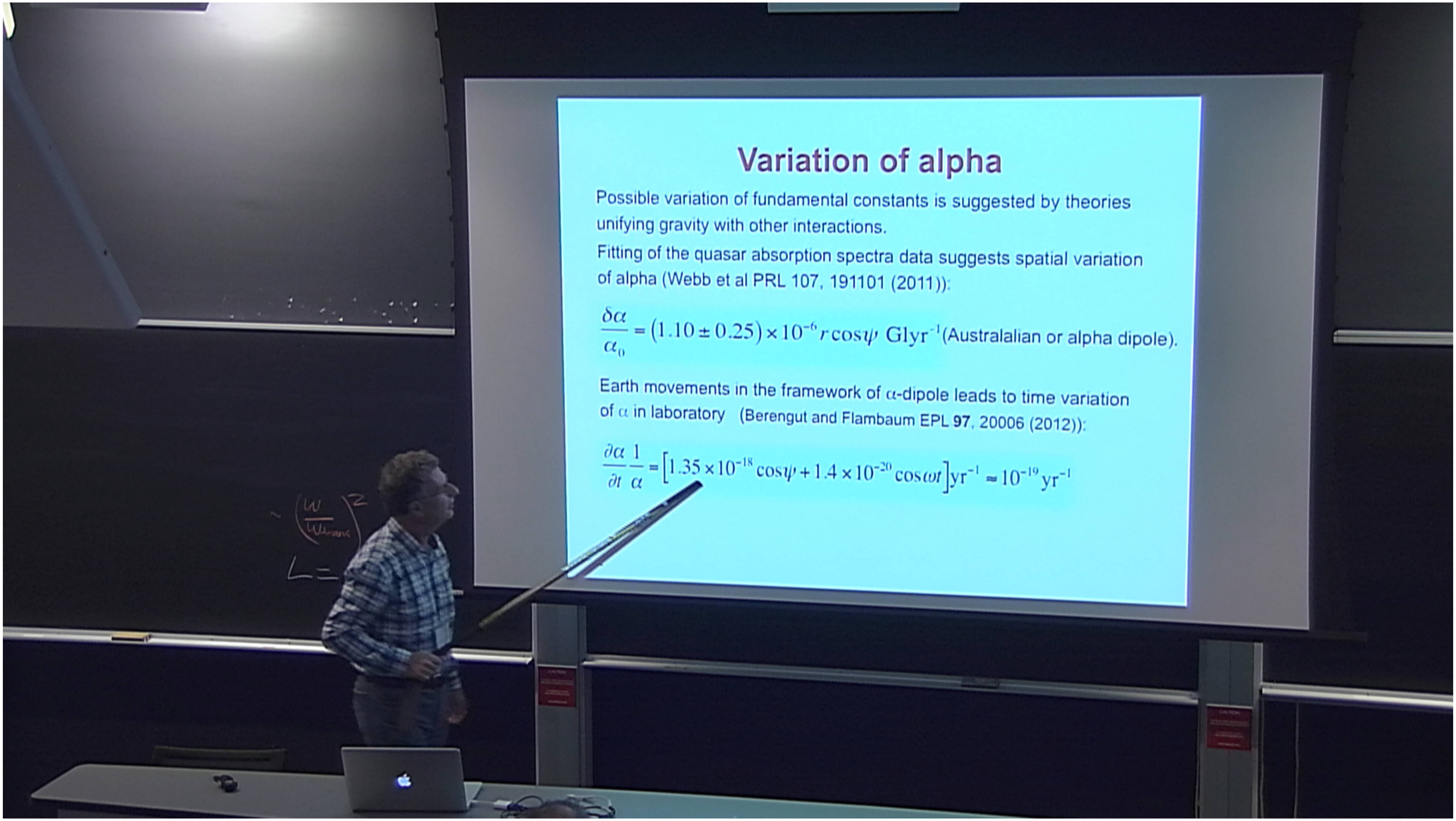

Variation of alpha
Possible variation of fundamental constants is suggested by theories unifying gravity with other interactions.
Fitting of the quasar absorption spectra data suggests spatial variation of alpha (Webb et al PRL 107, 191101 (2011)):
$\frac{\delta\alpha}{\alpha_0} = (1.10 \pm 0.25) \times 10^{-6} r \cos\psi \ \mathrm{Glyr}^{-1}$ (Australalian or alpha dipole).
Earth movements in the framework of α-dipole leads to time variation of α in laboratory (Berengut and Flambaum EPL **97**, 20006 (2012)):
$\frac{\partial\alpha}{\partial t}\frac{1}{\alpha} = \left[1.35 \times 10^{-18} \cos\psi + 1.4 \times 10^{-20} \cos\omega t\right] \mathrm{yr}^{-1} \approx 10^{-19} \mathrm{yr}^{-1}$
$L = I\omega$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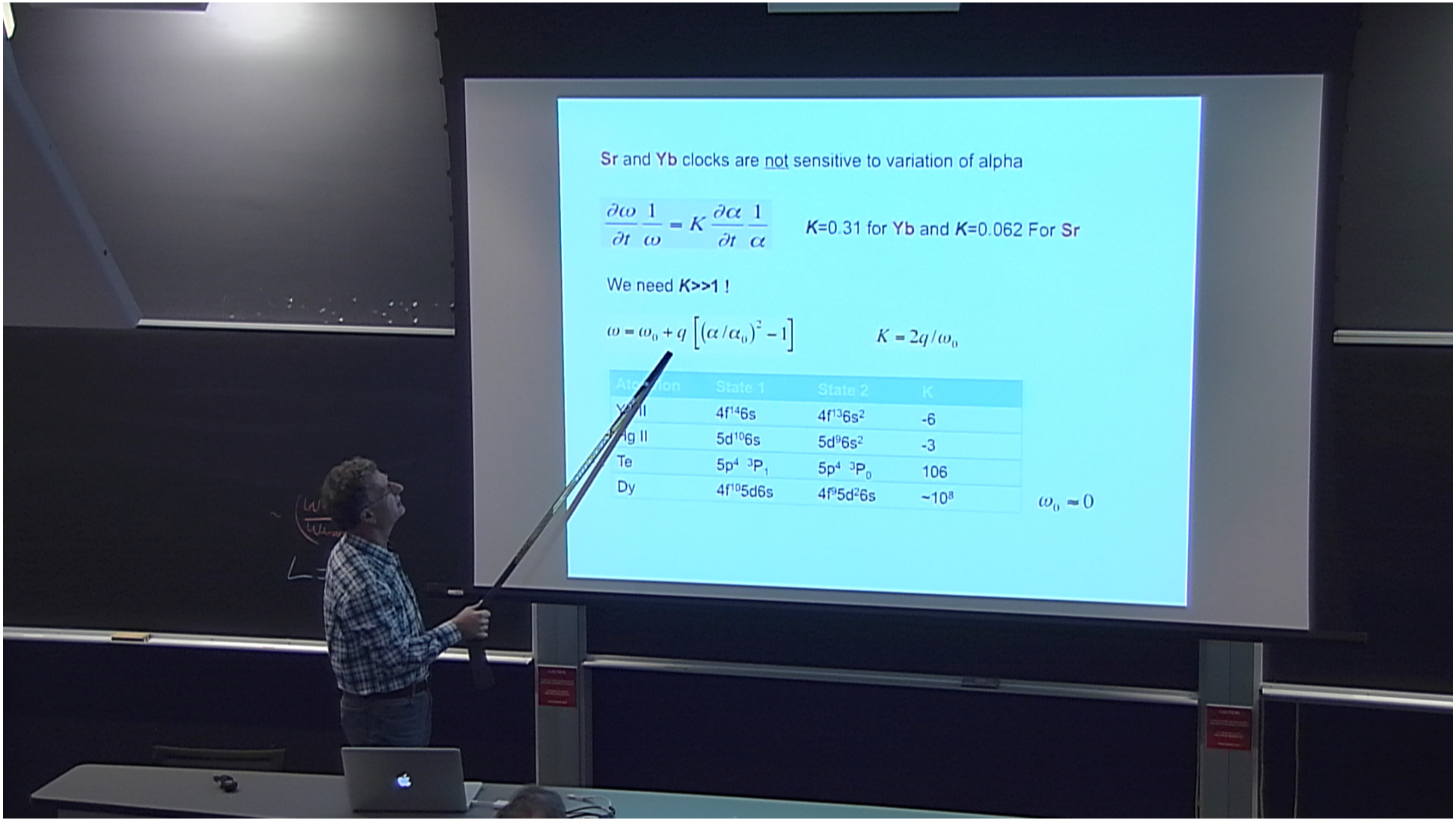
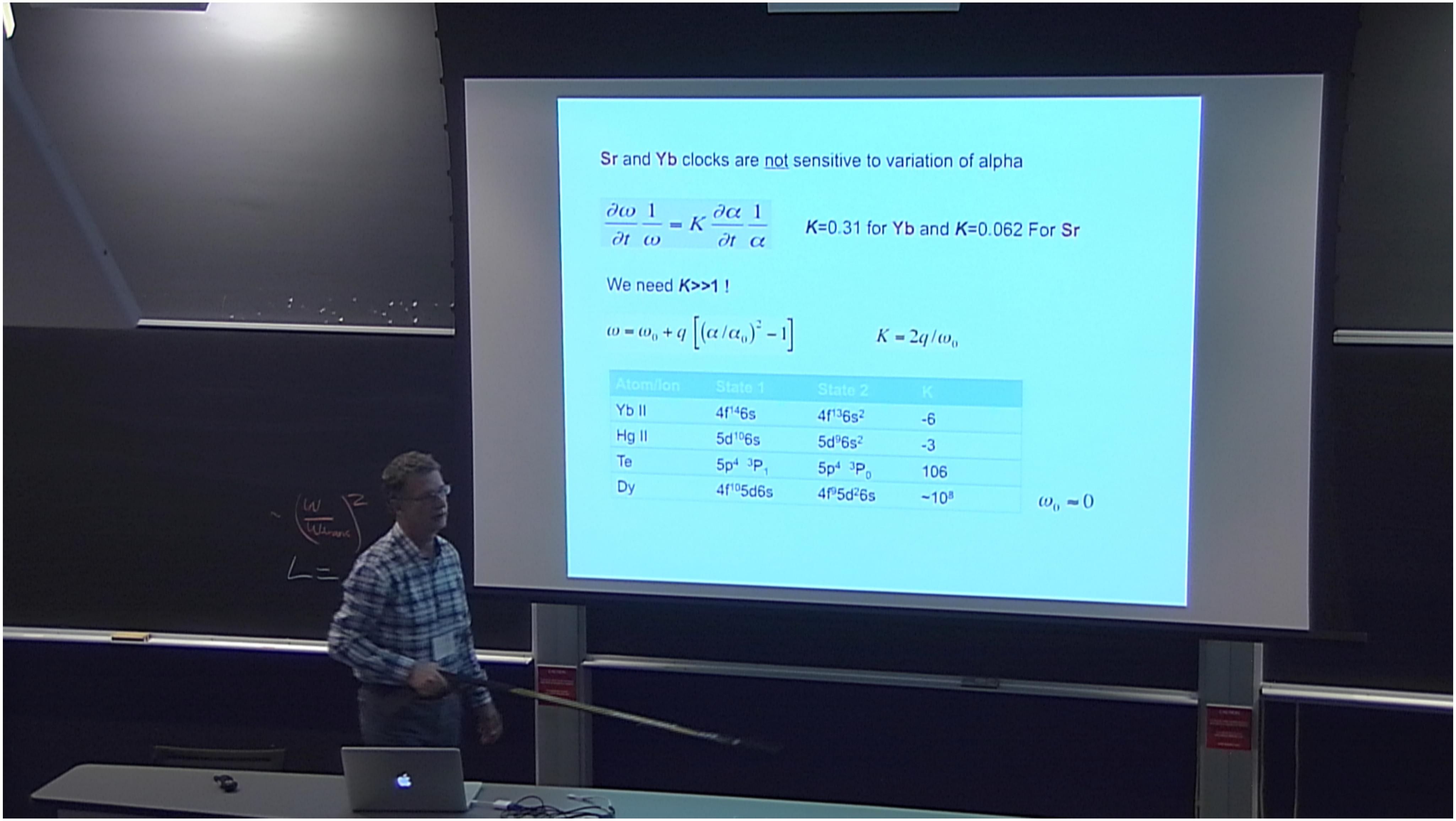

Sr and Yb clocks are not sensitive to variation of alpha
$\frac{\partial\omega}{\partial t}\frac{1}{\omega} = K\frac{\partial\alpha}{\partial t}\frac{1}{\alpha}$
K=0.31 for Yb and K=0.062 For Sr
We need K>>1 !
$\omega = \omega_0 + q\left[(\alpha/\alpha_0)^2 - 1\right]$
$K = 2q/\omega_0$
State 1
State 2
K
4f^{14}6s
4f^{13}6s^2
-6
5d^{10}6s
5d^{9}6s^2
-3
Te
5p^4 $^3P_1$
5p^4 $^3P_0$
106
Dy
4f^{10}5d6s
4f^{9}5d^{2}6s
~10^8
$\omega_0 \approx 0$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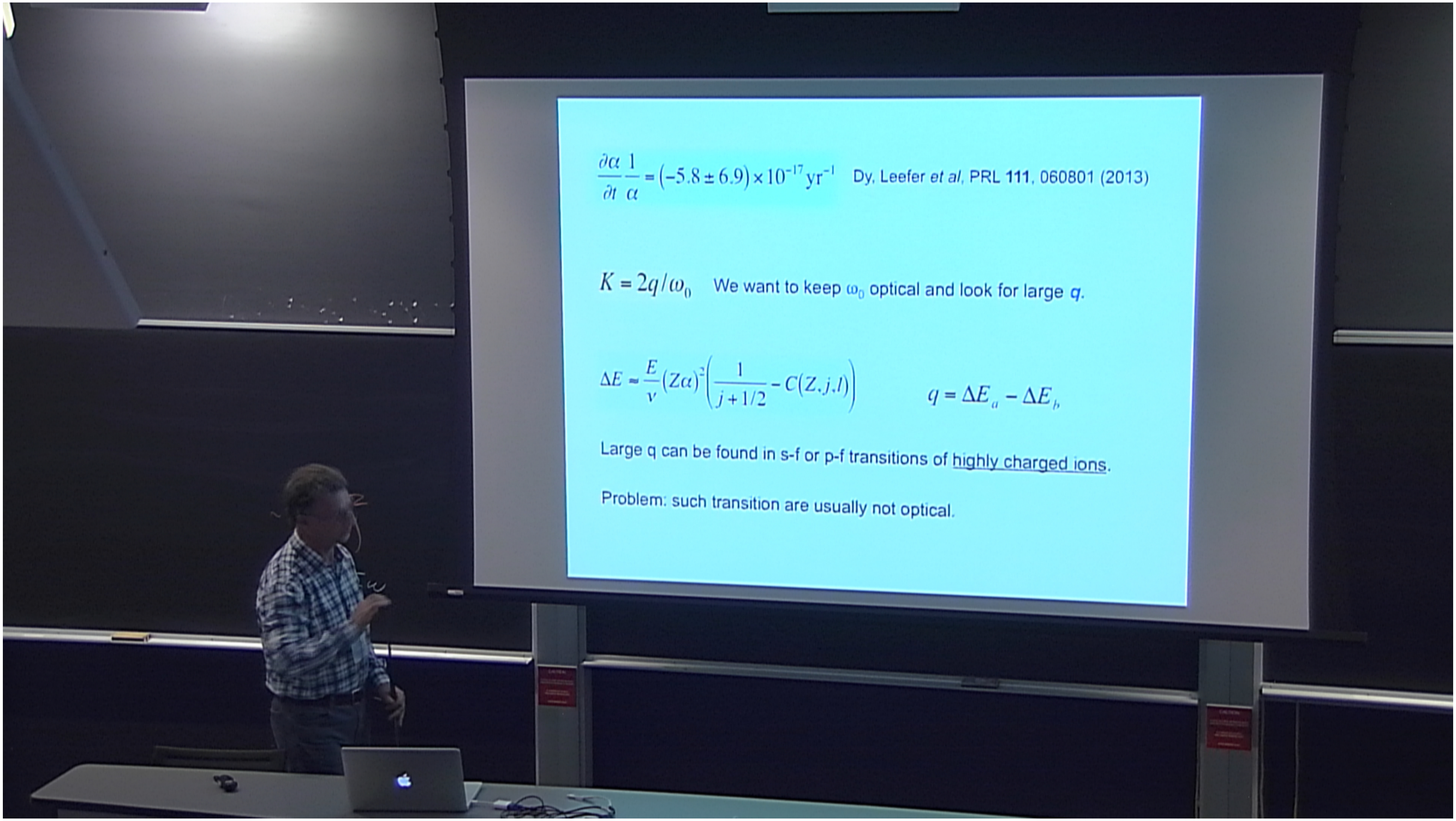
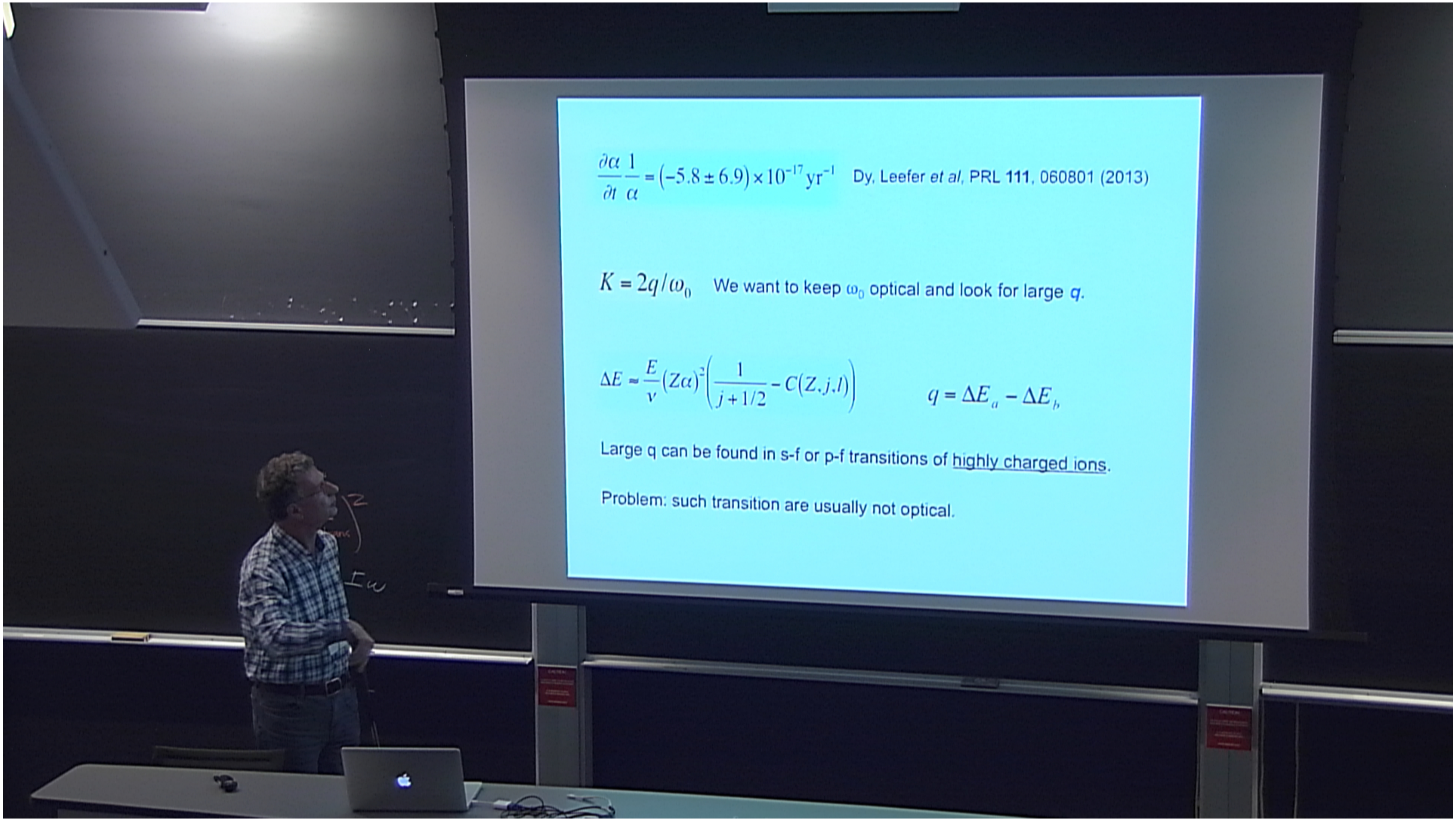
Atom/Ion State 1 State 2 K
Yb II 4f^14 6s 4f^13 6s^2 -6
Hg II 5d^10 6s 5d^9 6s^2 -3
Te 5p^4 3P_1 5p^4 3P_0 106
Dy 4f^10 5d6s 4f^9 5d^2 6s ~10^8
$\omega_0 \approx 0$


$\frac{\partial\alpha}{\partial t}\frac{1}{\alpha} = (-5.8 \pm 6.9) \times 10^{-17}\,\mathrm{yr}^{-1}$ Dy, Leefer *et al*, PRL **111**, 060801 (2013)
$K = 2q/\omega_0$ We want to keep ω_0 optical and look for large ***q***.
$\Delta E \approx \frac{E}{\nu}(Z\alpha)^2\left(\frac{1}{j+1/2} - C(Z,j,l)\right)$
$q = \Delta E_a - \Delta E_b$
Large q can be found in s-f or p-f transitions of highly charged ions.
Problem: such transition are usually not optical.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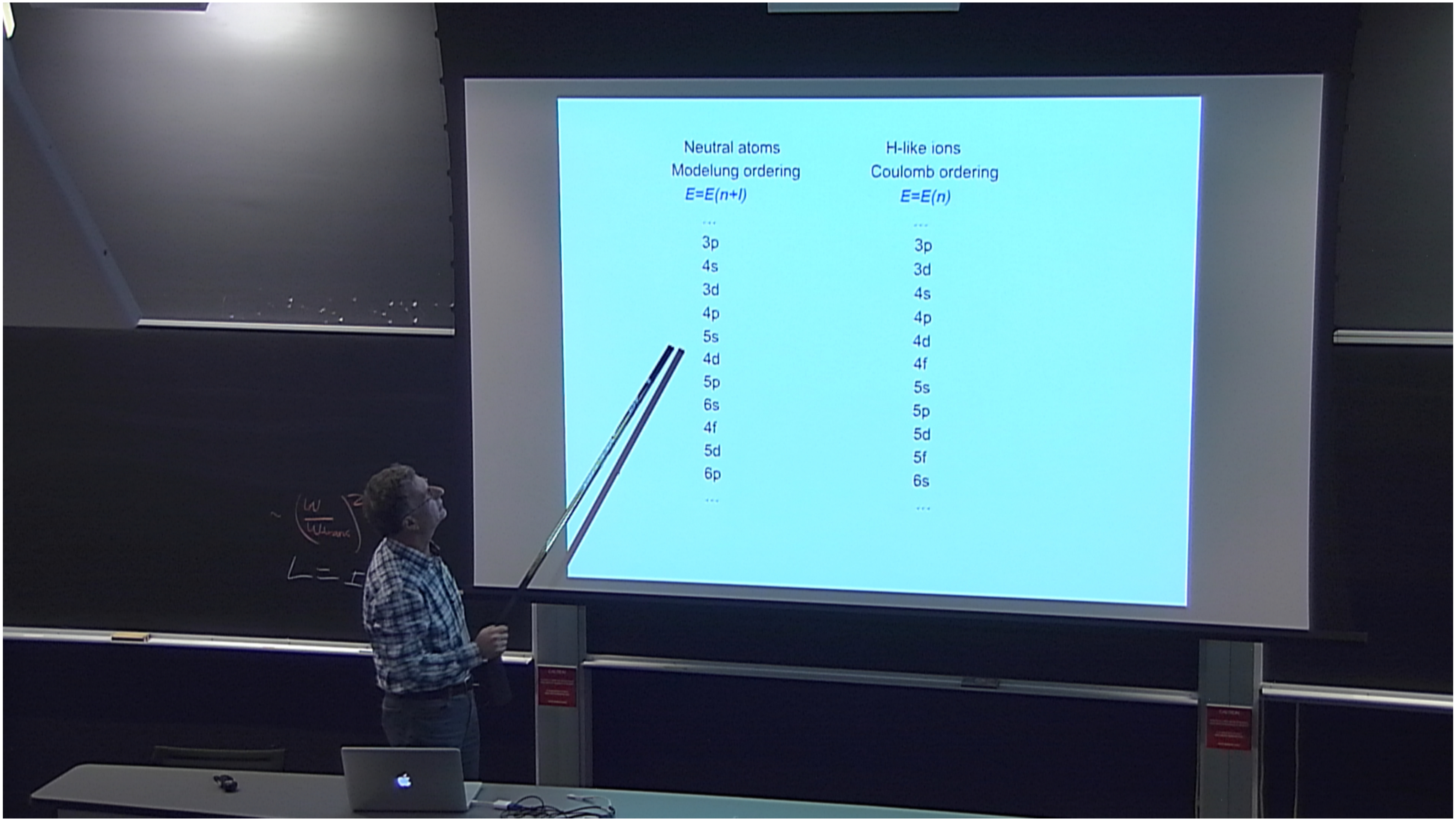
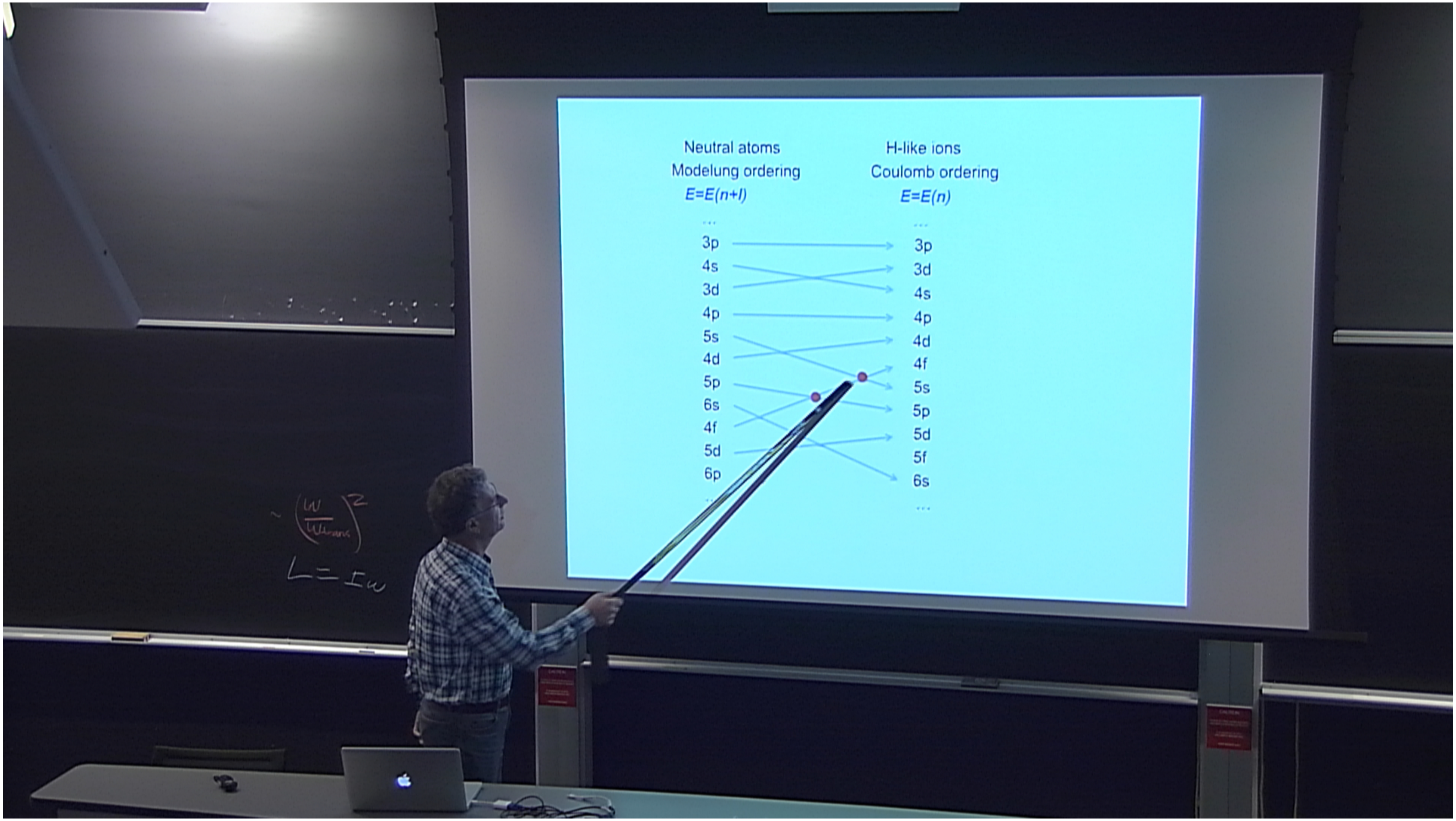

Neutral atoms
Modelung ordering
E=E(n+l)
...
3p
4s
3d
4p
5s
4d
5p
6s
4f
5d
6p
...
H-like ions
Coulomb ordering
E=E(n)
...
3p
3d
4s
4p
4d
4f
5s
5p
5d
5f
6s
...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E=E(n)
3p
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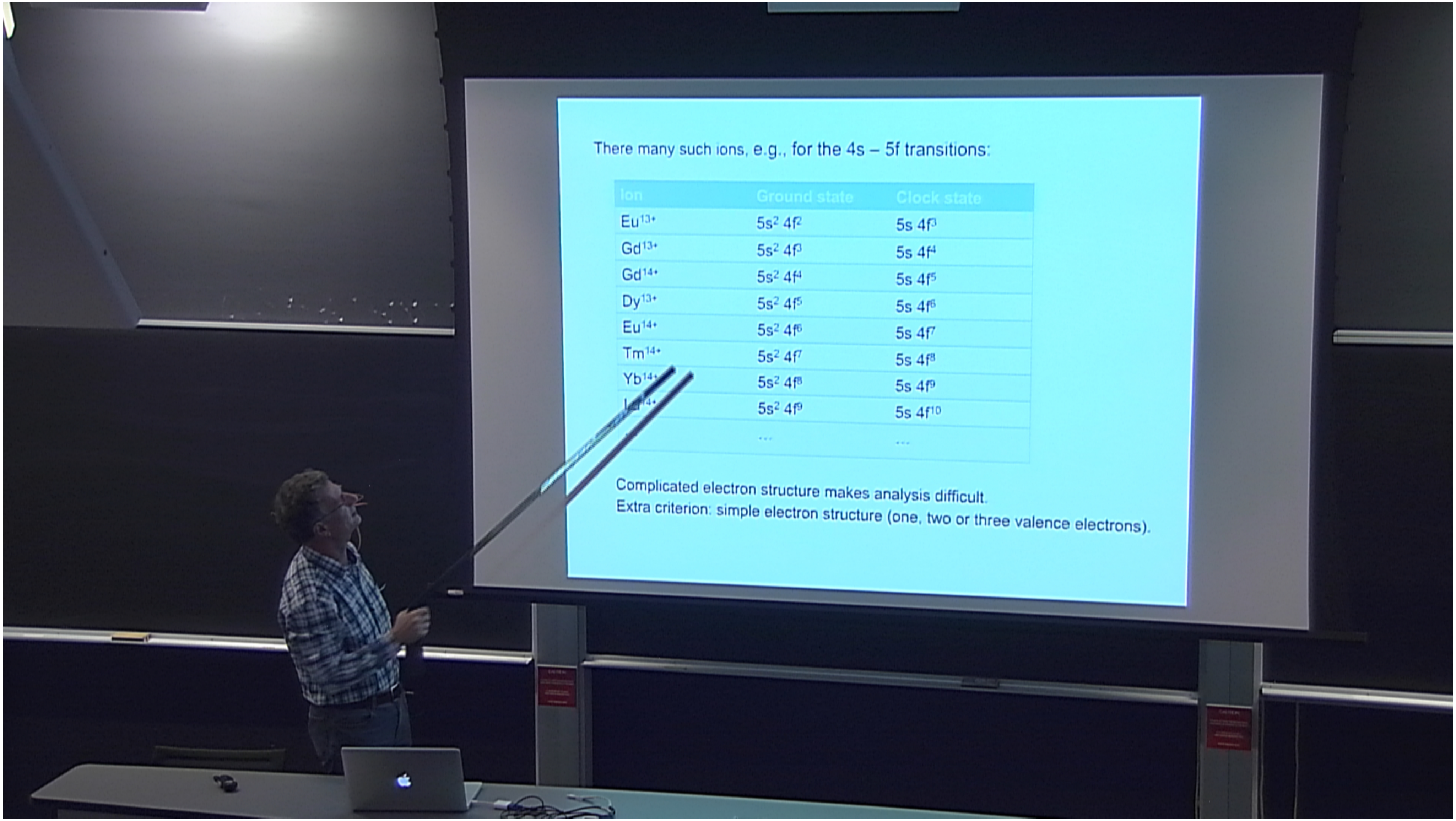
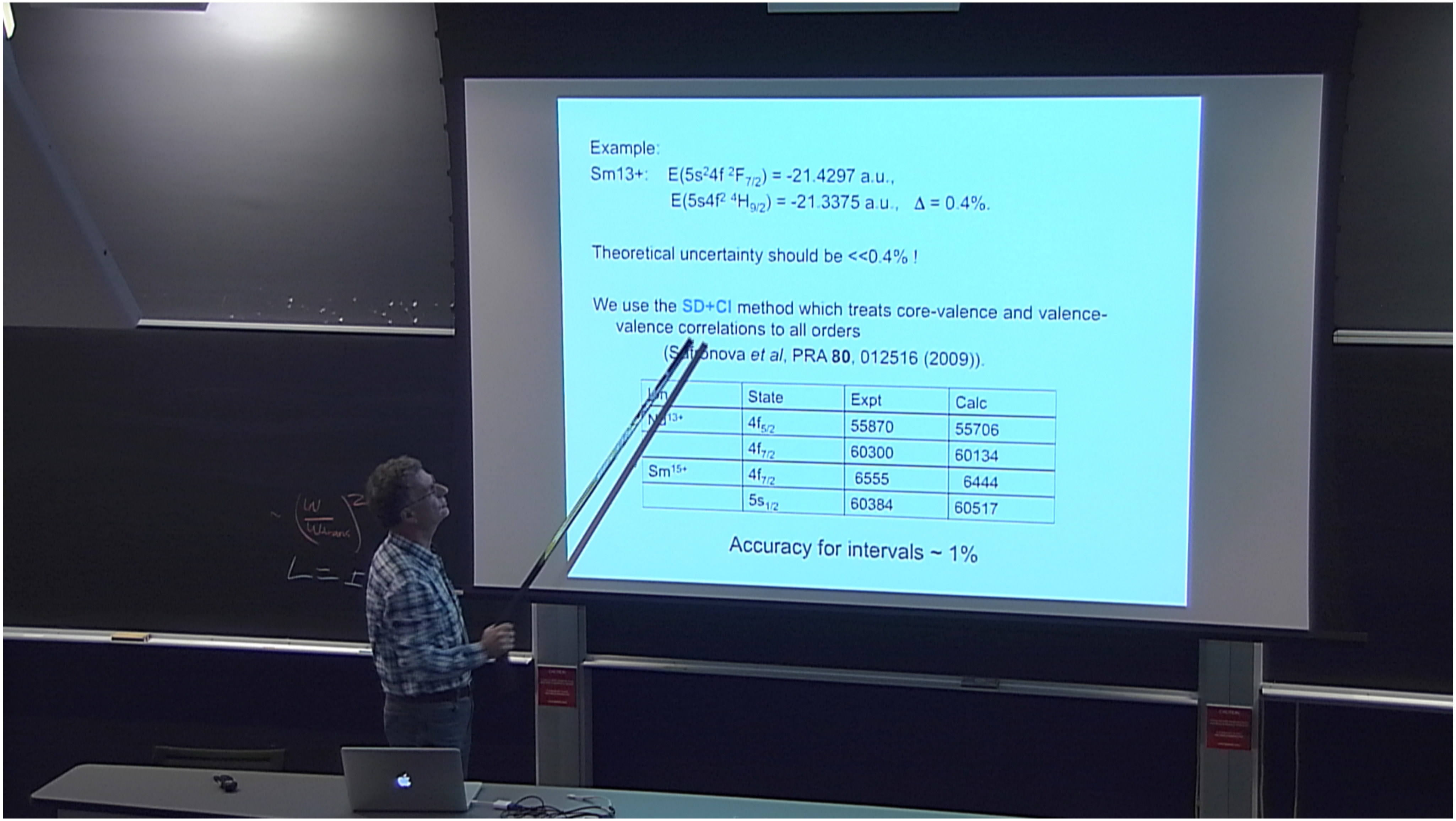
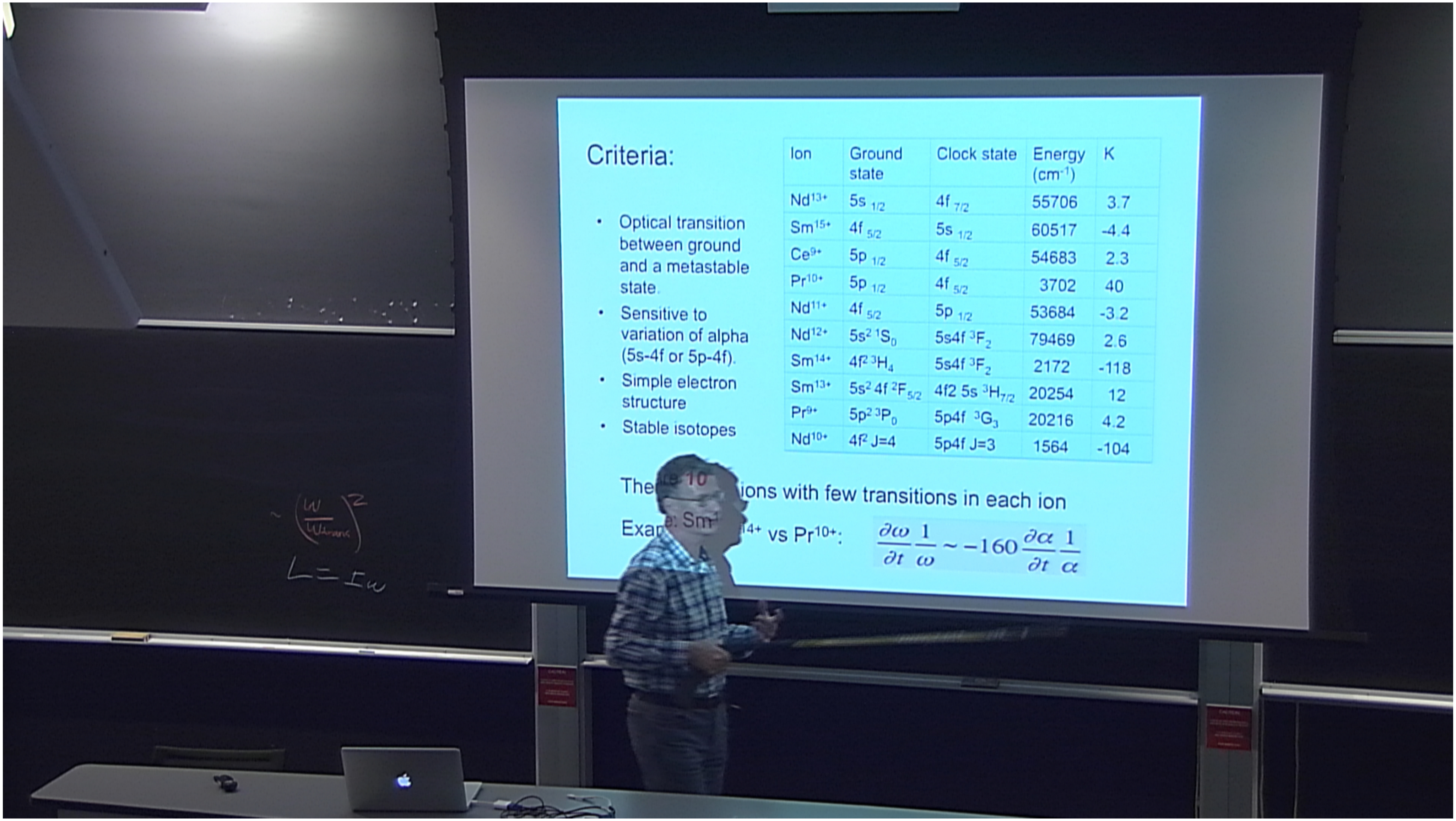
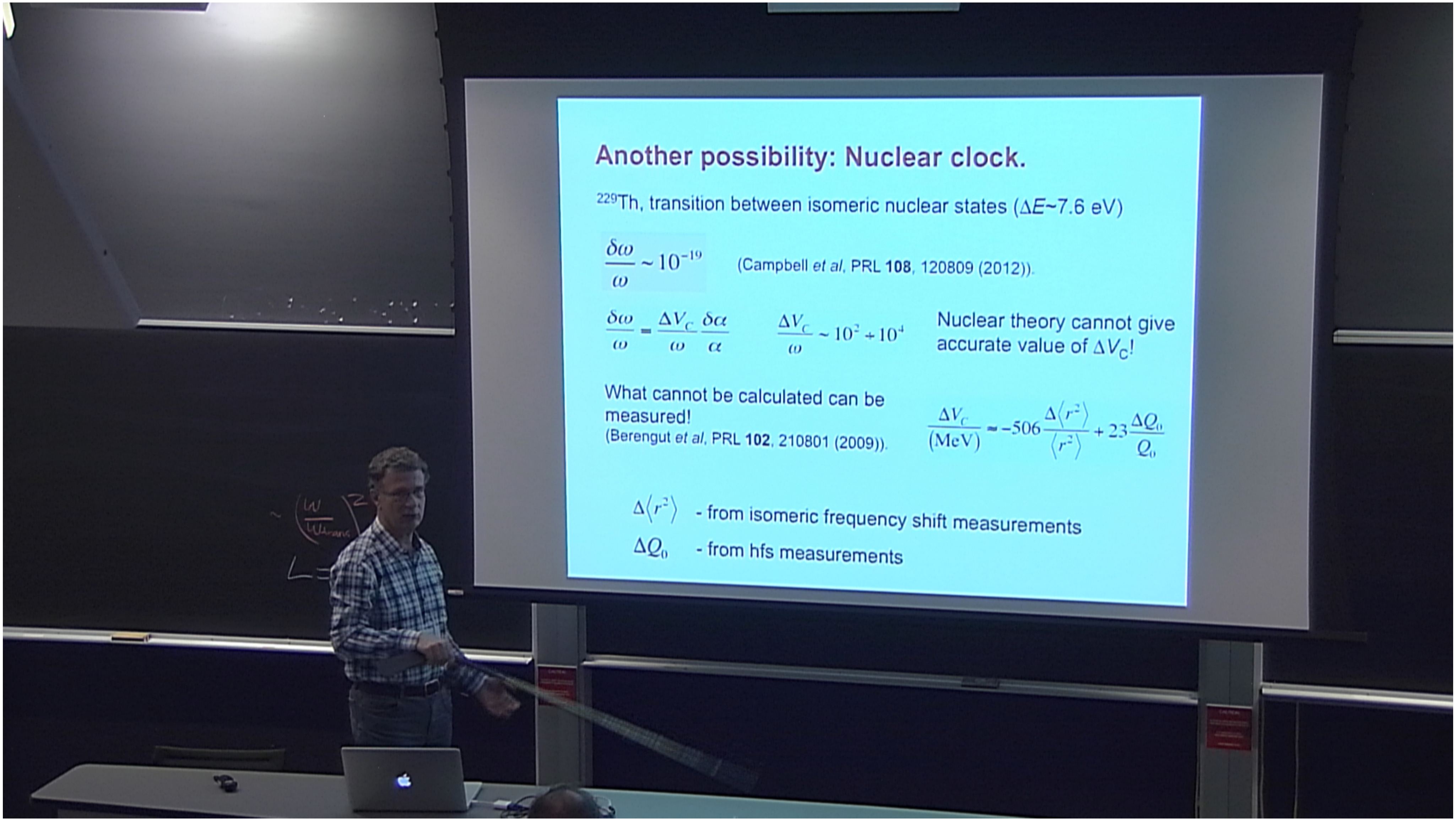
5s
4d
5p
6s
4f
5d
6p
3p
3d
4s
4p
4d
4f
5s
5p
5d
5f
6s
L = Iω


There many such ions, e.g., for the 4s – 5f transitions:
Ion
Ground state
Clock state
Eu13+ 5s2 4f2 5s 4f3
Gd13+ 5s2 4f3 5s 4f4
Gd14+ 5s2 4f4 5s 4f5
Dy13+ 5s2 4f5 5s 4f6
Eu14+ 5s2 4f6 5s 4f7
Tm14+ 5s2 4f7 5s 4f8
Yb14+ 5s2 4f8 5s 4f9
5s2 4f9 5s 4f10
…
…
Complicated electron structure makes analysis difficult.
Extra criterion: simple electron structure (one, two or three valence electrons).


Example:
Sm13+: E(5s²4f ²F7/2) = -21.4297 a.u.,
E(5s4f² ⁴H9/2) = -21.3375 a.u., Δ = 0.4%.
Theoretical uncertainty should be <<0.4% !
We use the SD+CI method which treats core-valence and valence-valence correlations to all orders
et al, PRA 80, 012516 (2009)).
State
Expt
Calc
4f5/2 55870 55706
4f7/2 60300 60134
Sm15+ 4f7/2 6555 6444
5s1/2 60384 60517
Accuracy for intervals ~ 1%


Criteria:
Optical transition between ground and a metastable state.
Sensitive to variation of alpha (5s-4f or 5p-4f).
Simple electron structure
Stable isotopes
Ion | Ground state | Clock state | Energy (cm-1) | K
Nd13+ | 5s 1/2 | 4f 7/2 | 55706 | 3.7
Sm15+ | 4f 5/2 | 5s 1/2 | 60517 | -4.4
Ce9+ | 5p 1/2 | 4f 5/2 | 54683 | 2.3
Pr10+ | 5p 1/2 | 4f 5/2 | 3702 | 40
Nd11+ | 4f 5/2 | 5p 1/2 | 53684 | -3.2
Nd12+ | 5s2 1S0 | 5s4f 3F2 | 79469 | 2.6
Sm14+ | 4f2 3H4 | 5s4f 3F2 | 2172 | -118
Sm13+ | 5s2 4f 2F5/2 | 4f2 5s 3H7/2 | 20254 | 12
Pr9+ | 5p2 3P0 | 5p4f 3G3 | 20216 | 4.2
Nd10+ | 4f2 J=4 | 5p4f J=3 | 1564 | -104
The
10
ions with few transitions in each ion
Exa
Sm
14+ vs Pr10+:
$\frac{\partial\omega}{\partial t}\frac{1}{\omega} \sim -160\frac{\partial\alpha}{\partial t}\frac{1}{\alpha}$
L = Iω


Another possibility: Nuclear clock.
^{229}Th, transition between isomeric nuclear states (ΔE~7.6 eV)
$\frac{\delta\omega}{\omega} \sim 10^{-19}$
(Campbell *et al*, PRL **108**, 120809 (2012)).
$\frac{\delta\omega}{\omega} = \frac{\Delta V_C}{\omega}\frac{\delta\alpha}{\alpha}$
$\frac{\Delta V_C}{\omega} \sim 10^2 \div 10^4$
Nuclear theory cannot give accurate value of ΔV_C!
What cannot be calculated can be measured!
(Berengut *et al*, PRL **102**, 210801 (2009)).
$\frac{\Delta V_C}{(\mathrm{MeV})} \approx -506\frac{\Delta\langle r^2\rangle}{\langle r^2\rangle} + 23\frac{\Delta Q_0}{Q_0}$
$\Delta\langle r^2\rangle$ - from isomeric frequency shift measurements
ΔQ_0 - from hfs measurements