Title: Probing the electron-proton mass ratio variation with AMO systems

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Abstract:


Probing the electron-proton mass ratio variation with AMO systems
by Robin Côté
New Ideas in Low-Energy Tests
of Fundamental Physics
Thursday June 19, 2014

University of Connecticut

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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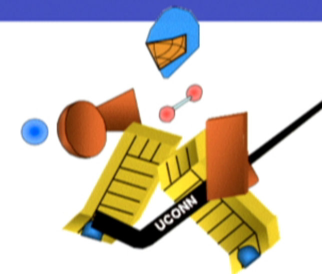
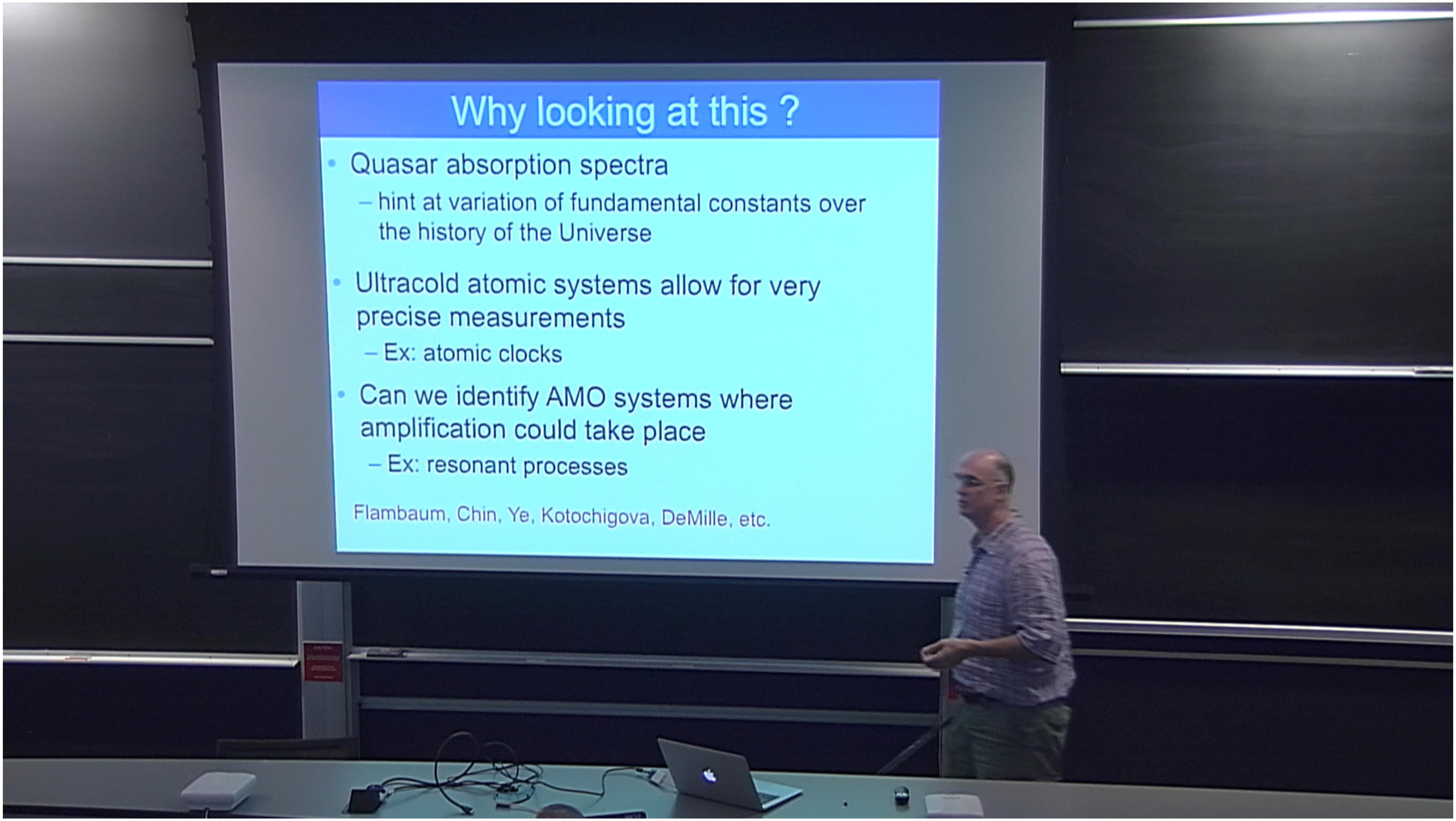
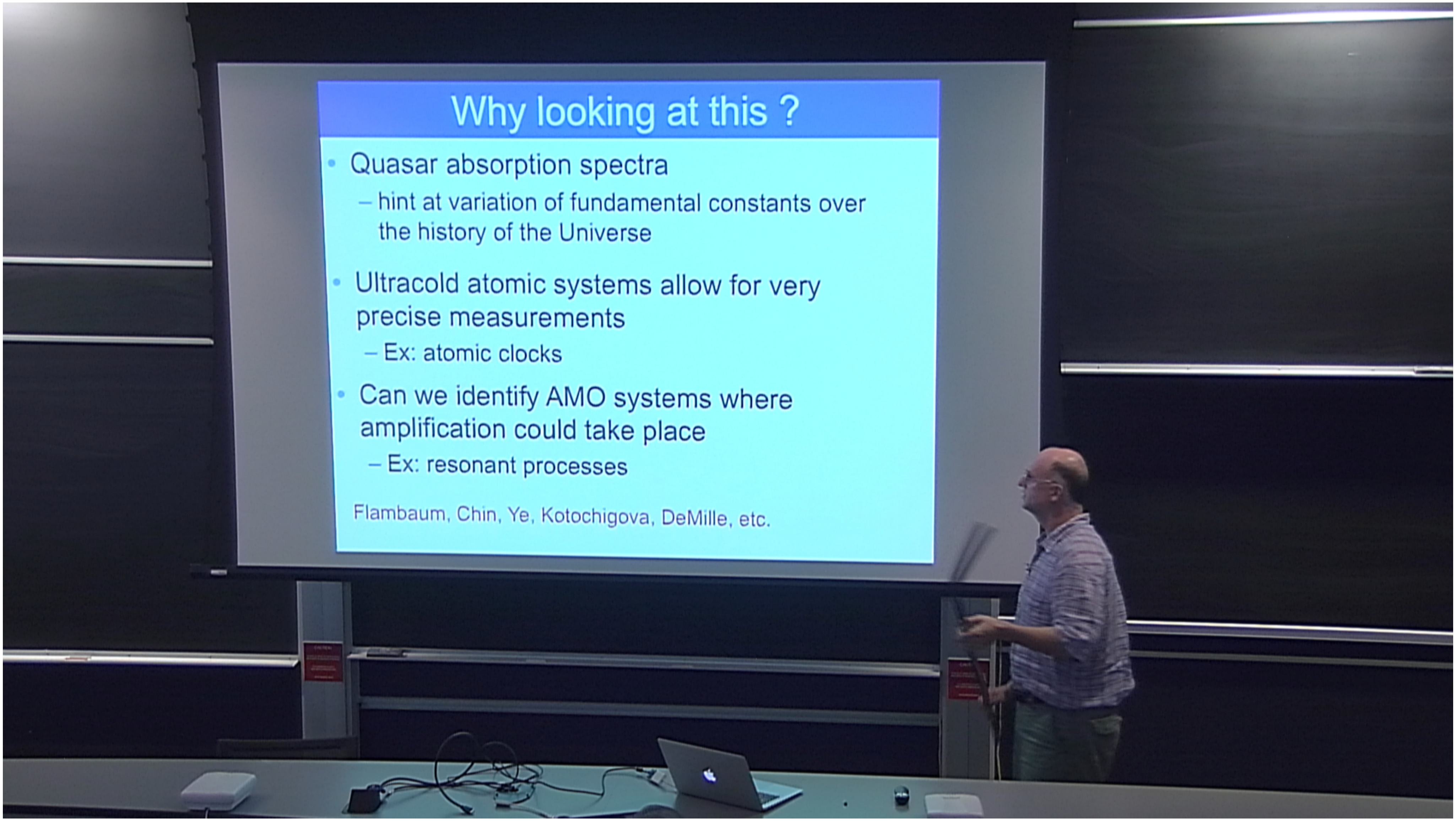
Outline



- Introduction/motivations
- Photoassociation
- Feshbach resonance: FOPA
- Link to variation of mass-ratio
  - Treatment of simple example
  - Other systems
- Other approaches …
- Conclusions


Why looking at this ?
Quasar absorption spectra
– hint at variation of fundamental constants over the history of the Universe
Ultracold atomic systems allow for very precise measurements
– Ex: atomic clocks
Can we identify AMO systems where amplification could take place
– Ex: resonant processes
Flambaum, Chin, Ye, Kotochigova, DeMille, etc.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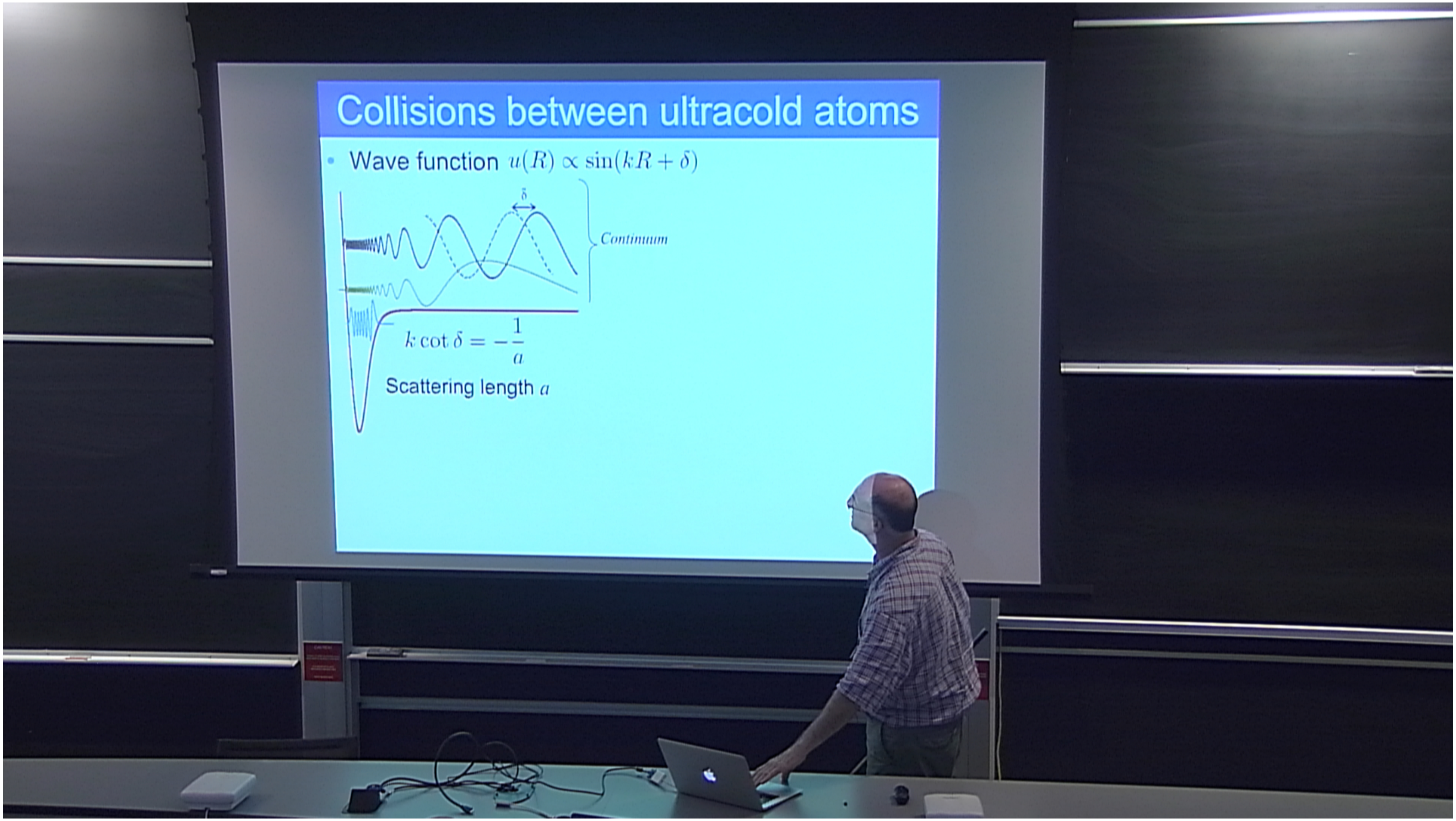
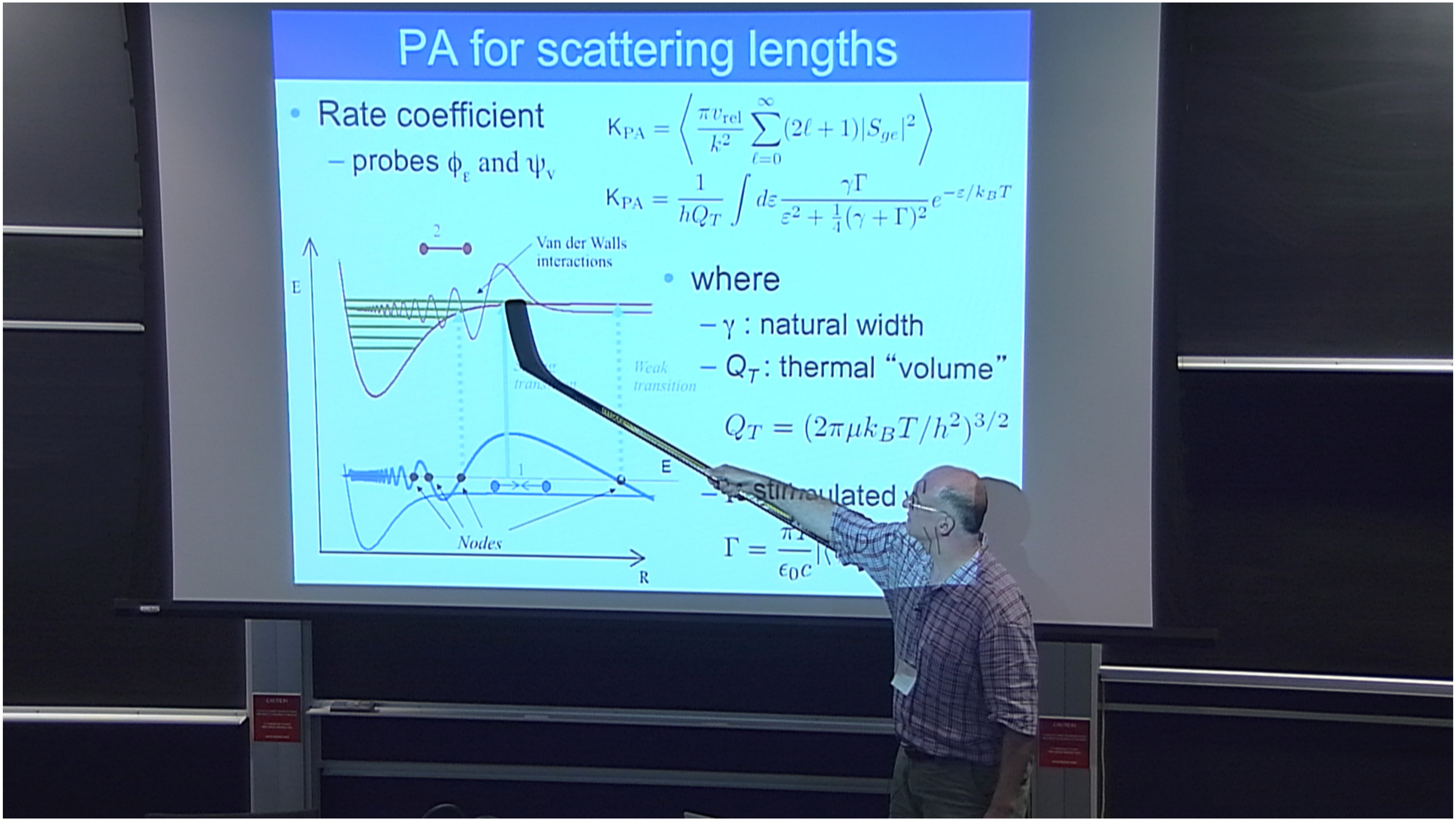
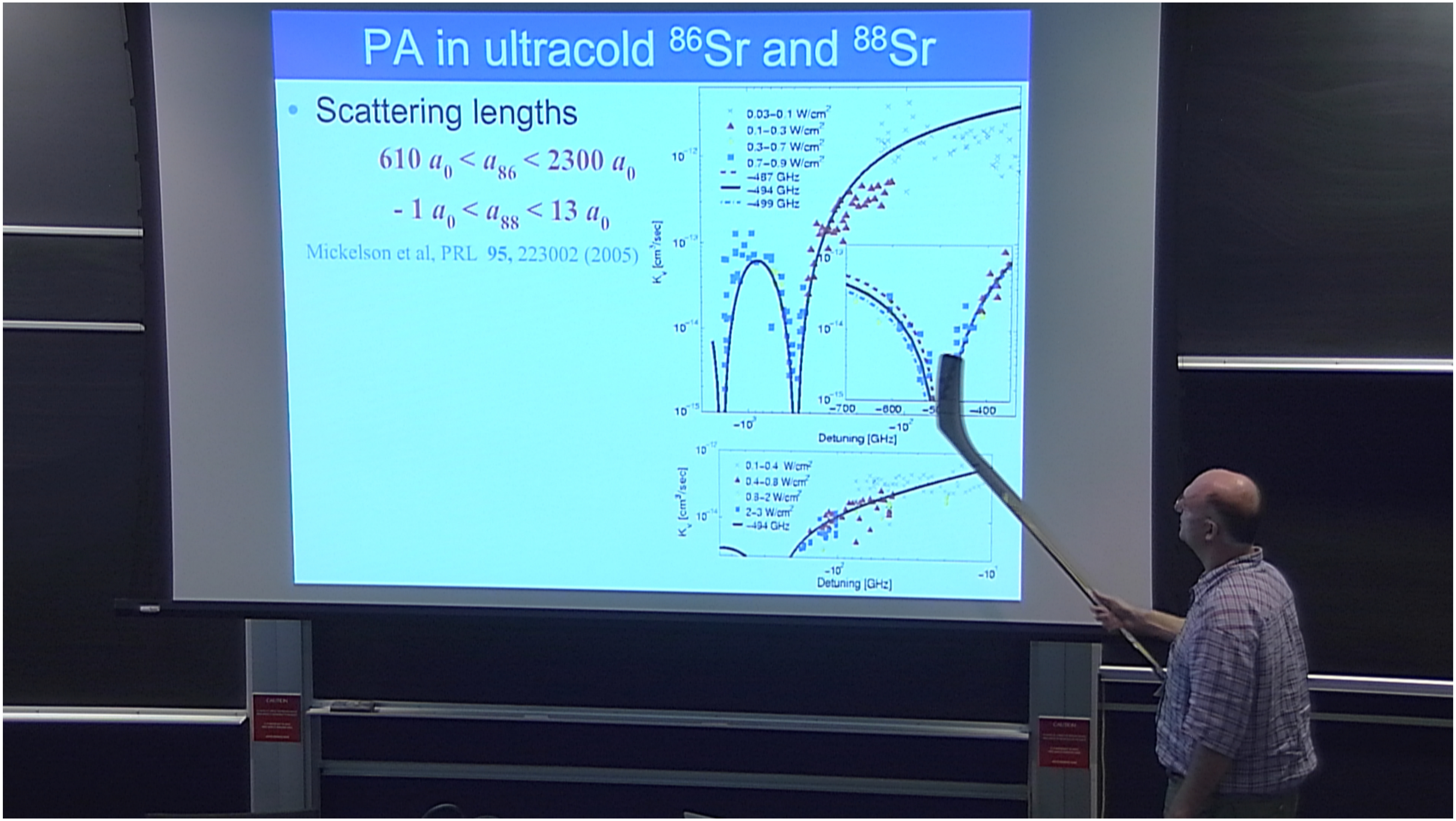
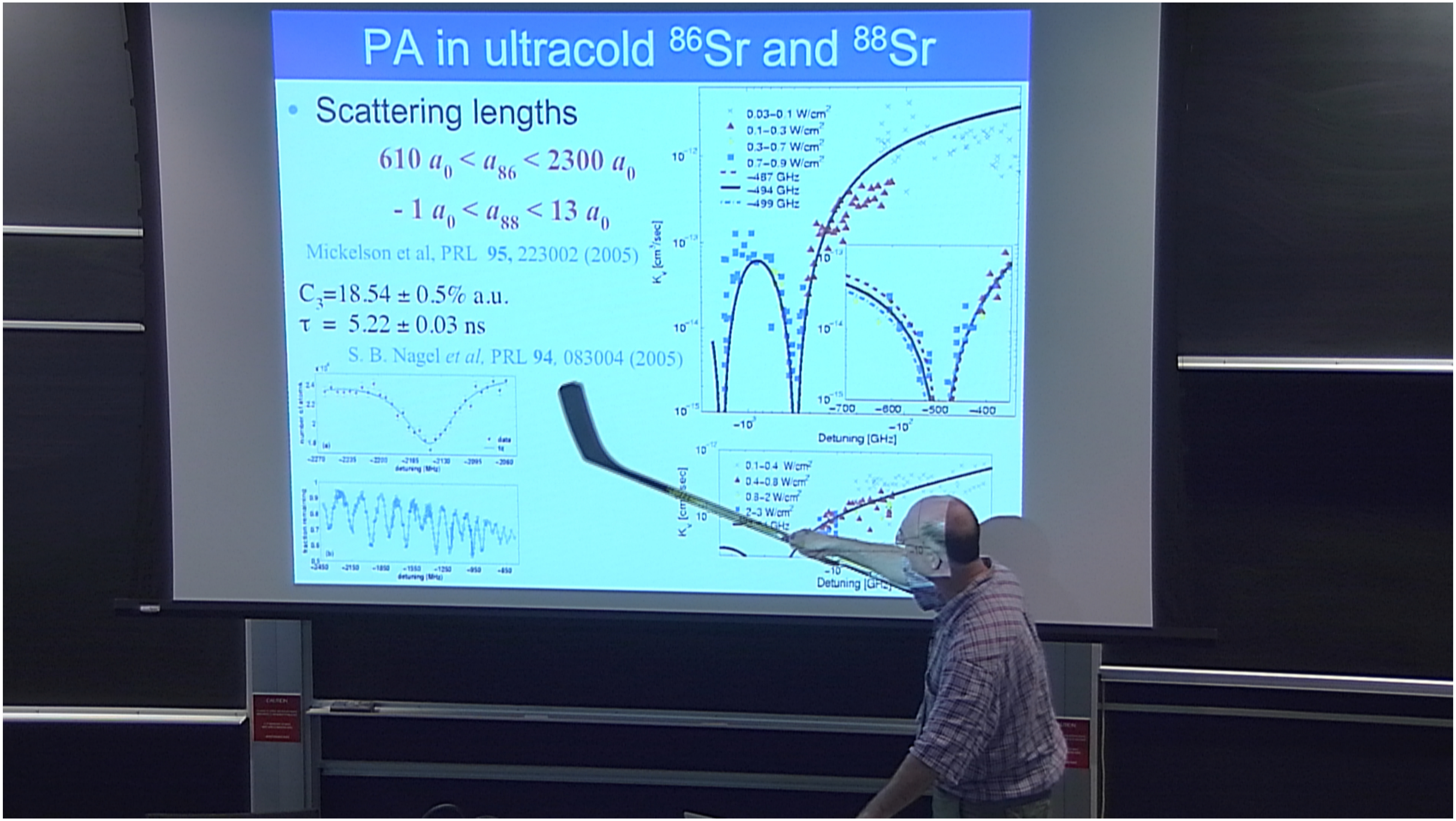


Collisions between ultracold atoms
Wave function $u(R) \propto \sin(kR + \delta)$
δ
Continuum
$k \cot \delta = -\frac{1}{a}$
Scattering length a


PA for scattering lengths
Rate coefficient
– probes φ_ε and ψ_v
$K_{PA} = \left\langle \frac{\pi v_{rel}}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1)|S_{ge}|^2 \right\rangle$
$K_{PA} = \frac{1}{hQ_T} \int d\varepsilon \frac{\gamma\Gamma}{\varepsilon^2 + \frac{1}{4}(\gamma+\Gamma)^2} e^{-\varepsilon/k_B T}$
Van der Walls interactions
E
Weak transition
Nodes
R
where
– γ : natural width
– Q_T : thermal “volume”
$Q_T = (2\pi\mu k_B T/h^2)^{3/2}$



PA in ultracold 86Sr and 88Sr
Scattering lengths
610 a0 < a86 < 2300 a0
- 1 a0 < a88 < 13 a0
Mickelson et al, PRL 95, 223002 (2005)
0.03–0.1 W/cm2
0.1–0.3 W/cm2
0.3–0.7 W/cm2
0.7–0.9 W/cm2
−487 GHz
−494 GHz
−499 GHz
Detuning [GHz]
0.1–0.4 W/cm2
0.4–0.8 W/cm2
0.8–2 W/cm2
2–3 W/cm2
−494 GHz
Detuning [GHz]


PA in ultracold 86Sr and 88Sr
Scattering lengths
610 a0 < a86 < 2300 a0
- 1 a0 < a88 < 13 a0
Mickelson et al, PRL 95, 223002 (2005)
C3=18.54 ± 0.5% a.u.
τ = 5.22 ± 0.03 ns
S. B. Nagel et al, PRL 94, 083004 (2005)
0.03–0.1 W/cm2
0.1–0.3 W/cm2
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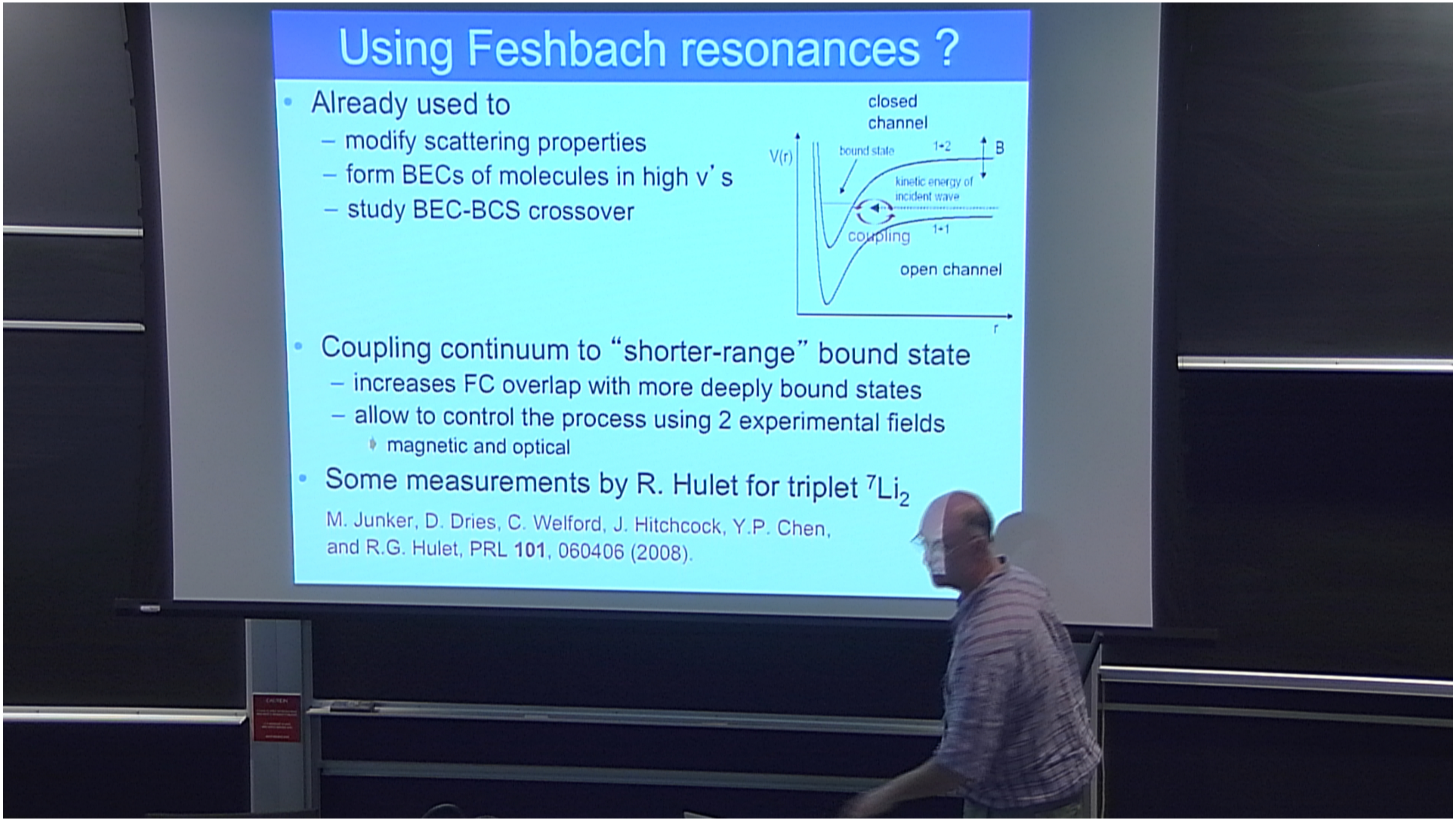
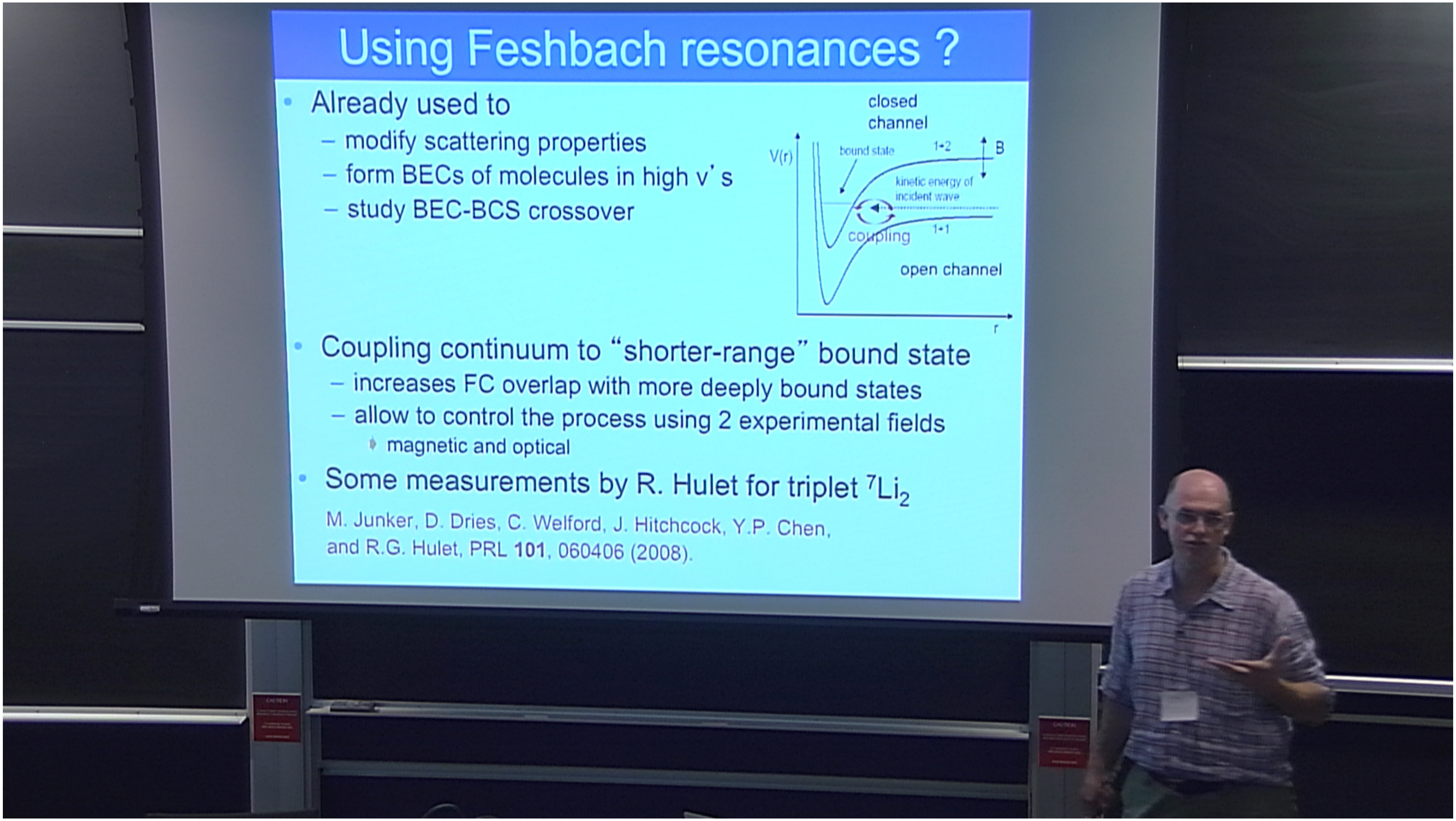

Using Feshbach resonances ?
Already used to
– modify scattering properties
– form BECs of molecules in high v's
– study BEC-BCS crossover
closed channel
V(r)
bound state
1+2
B
kinetic energy of incident wave
coupling
1+1
open channel
r
Coupling continuum to "shorter-range" bound state
– increases FC overlap with more deeply bound states
– allow to control the process using 2 experimental fields
magnetic and optical
Some measurements by R. Hulet for triplet $^7Li_2$
M. Junker, D. Dries, C. Welford, J. Hitchcock, Y.P. Chen, and R.G. Hulet, PRL 101, 060406 (2008).


Using Feshbach resonances ?
Already used to
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V(r)
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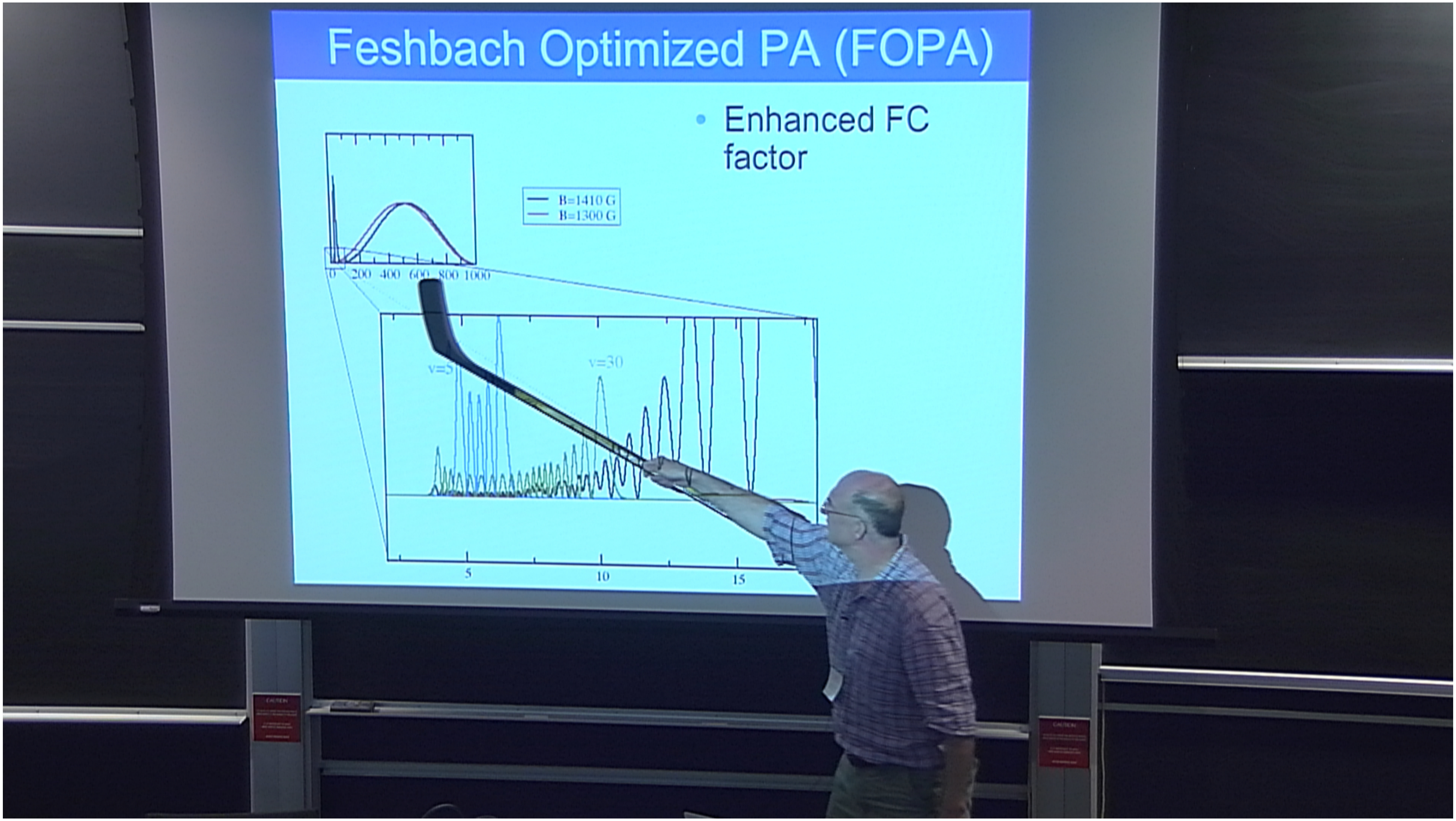
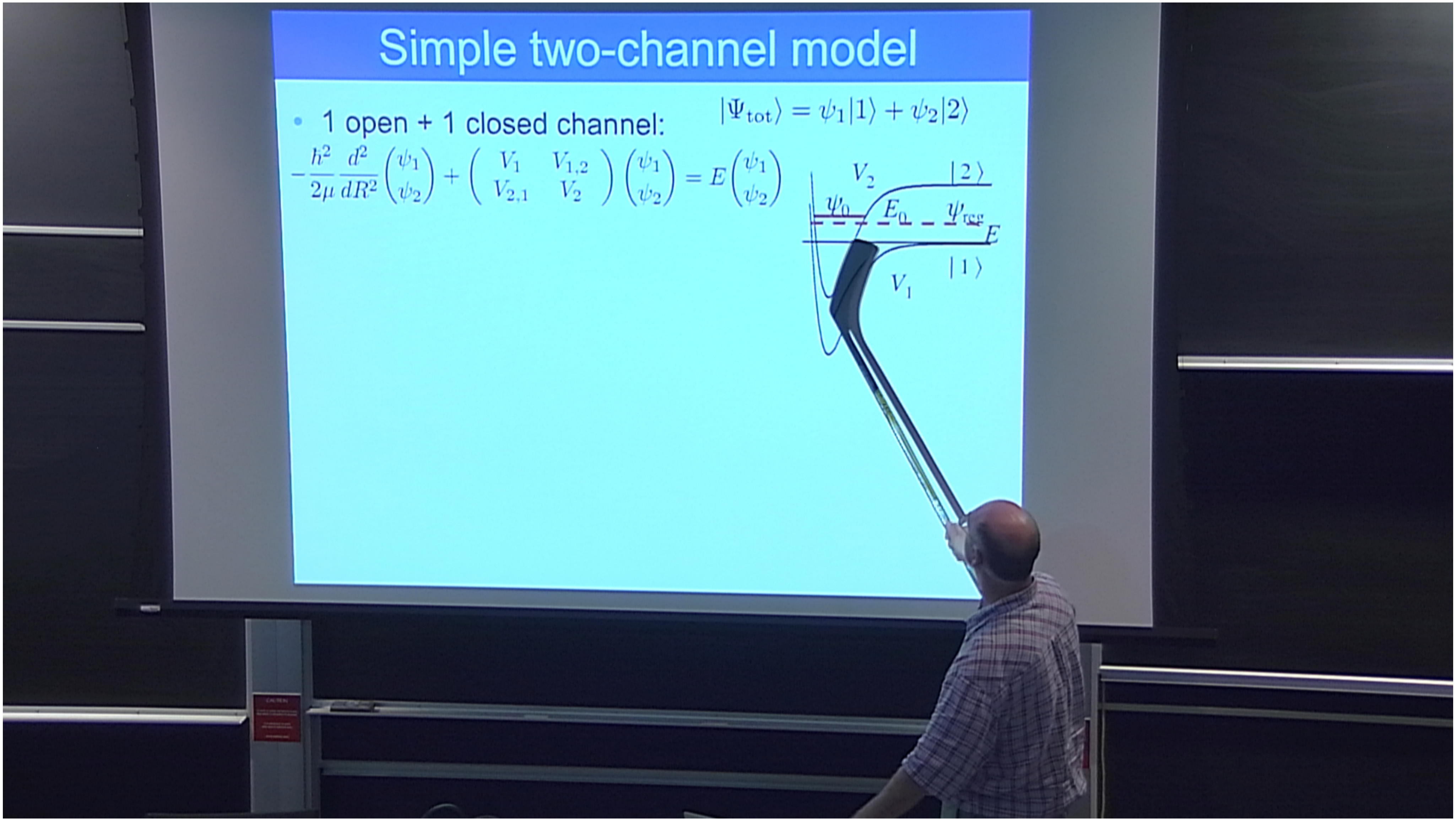
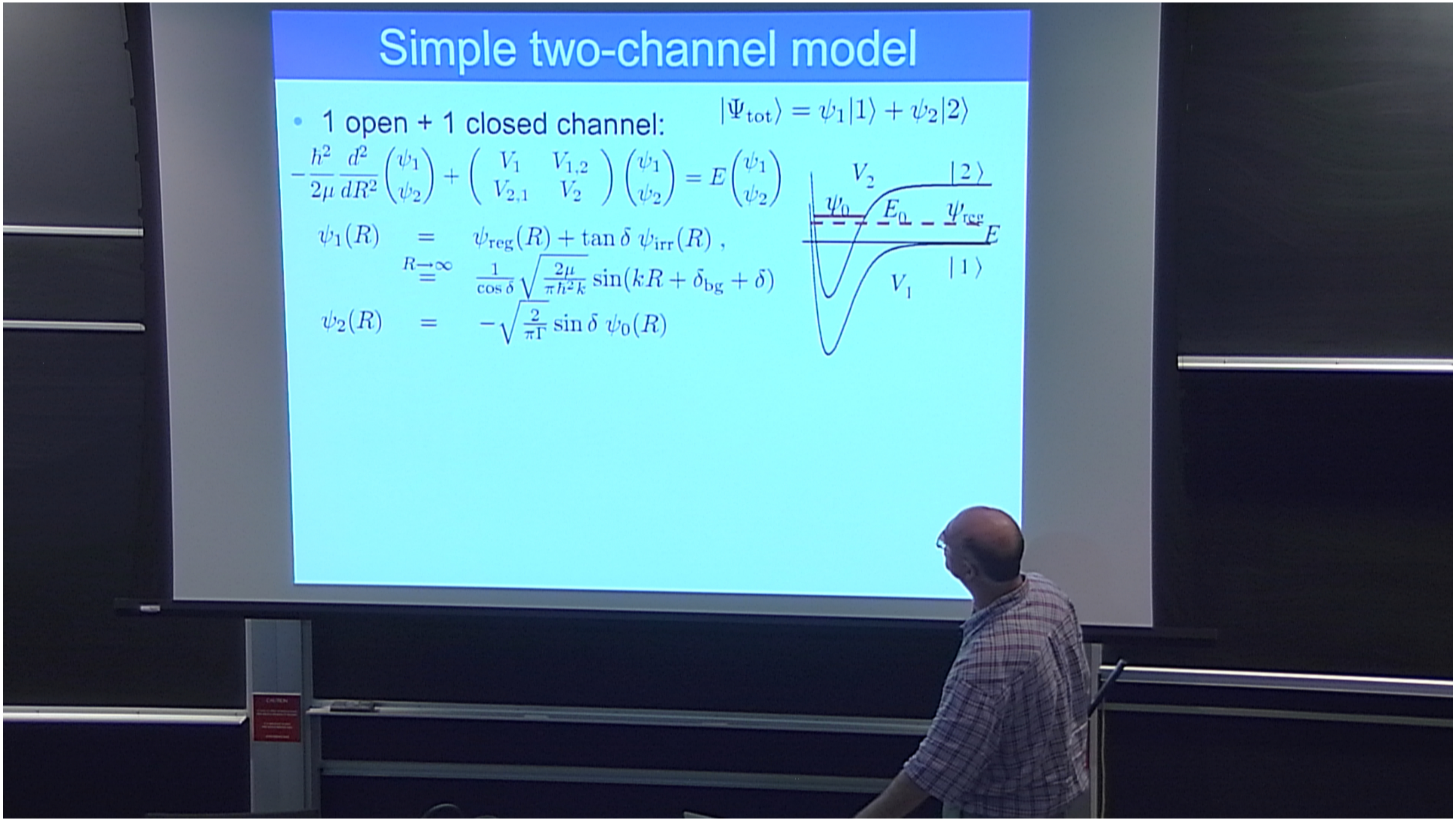

Feshbach Optimized PA (FOPA)
• Enhanced FC factor
B=1410 G
B=1300 G
0 200 400 600 800 1000
v=5
v=30
5
10
15


Simple two-channel model
1 open + 1 closed channel:
$|\Psi_{\rm tot}\rangle = \psi_1|1\rangle + \psi_2|2\rangle$
$-\frac{\hbar^2}{2\mu}\frac{d^2}{dR^2}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} + \begin{pmatrix} V_1 & V_{1,2} \\ V_{2,1} & V_2 \end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = E\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$
V_2
$|2\rangle$
ψ_0
E_0
E
$|1\rangle$
V_1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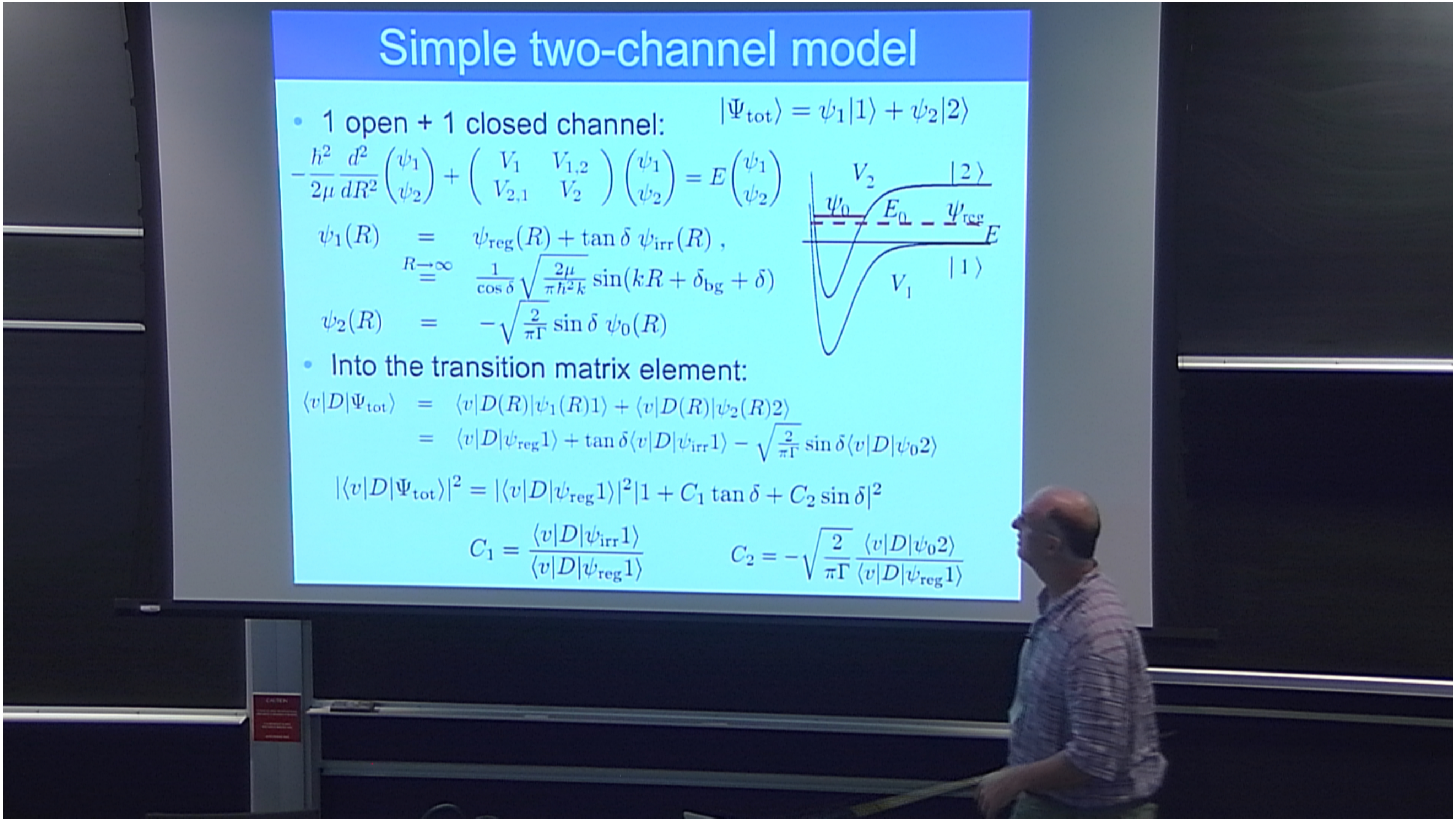
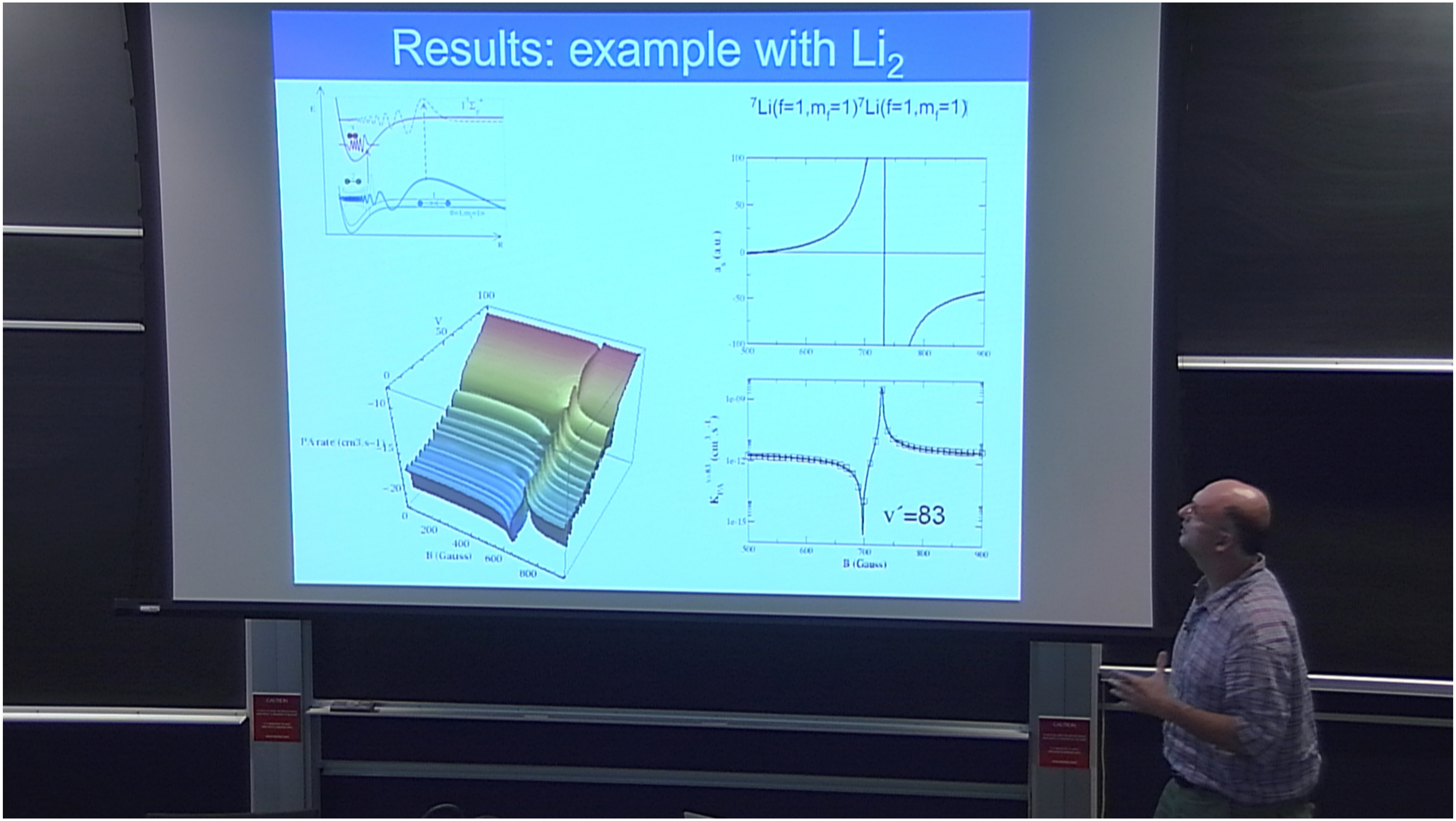
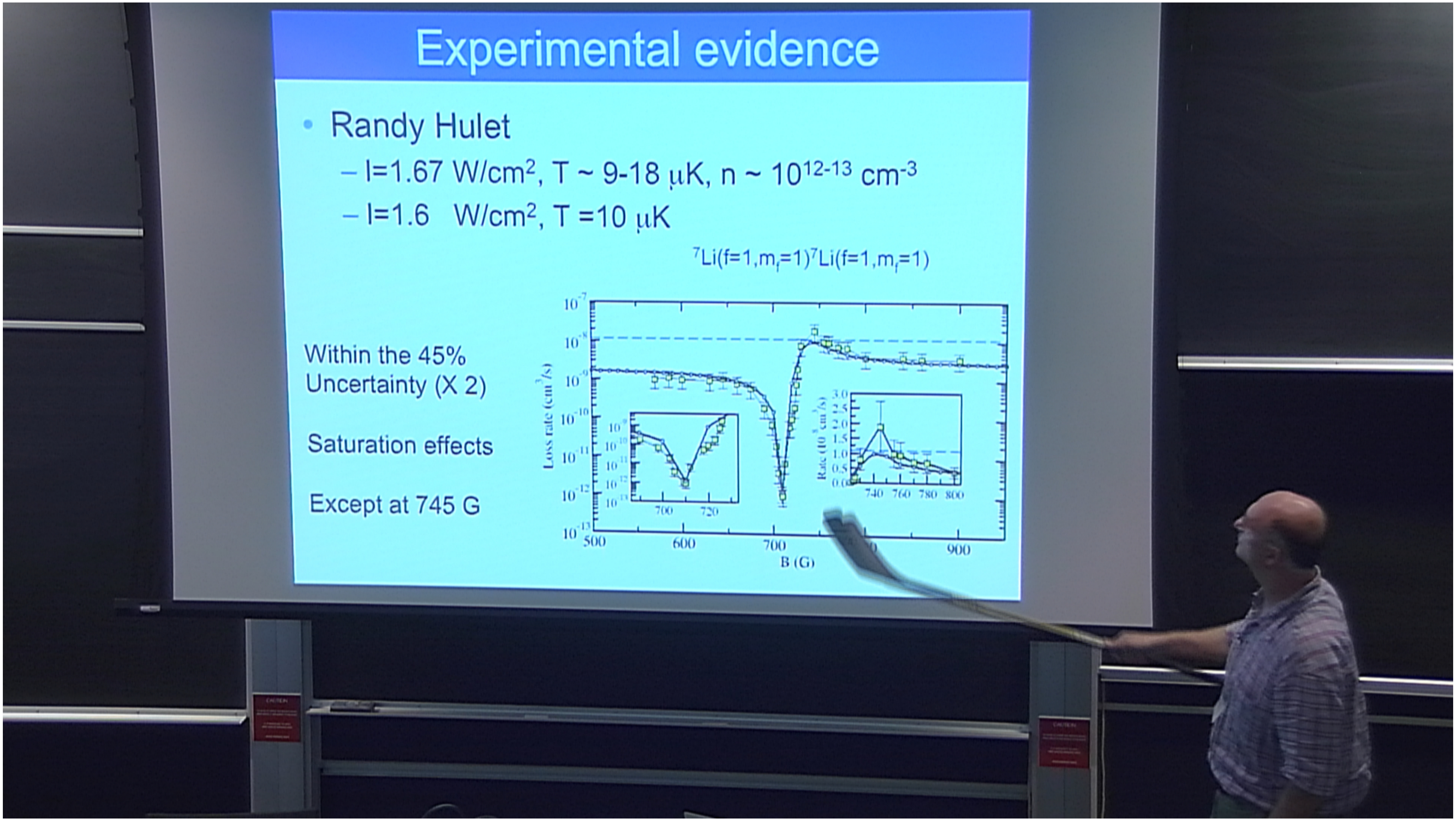
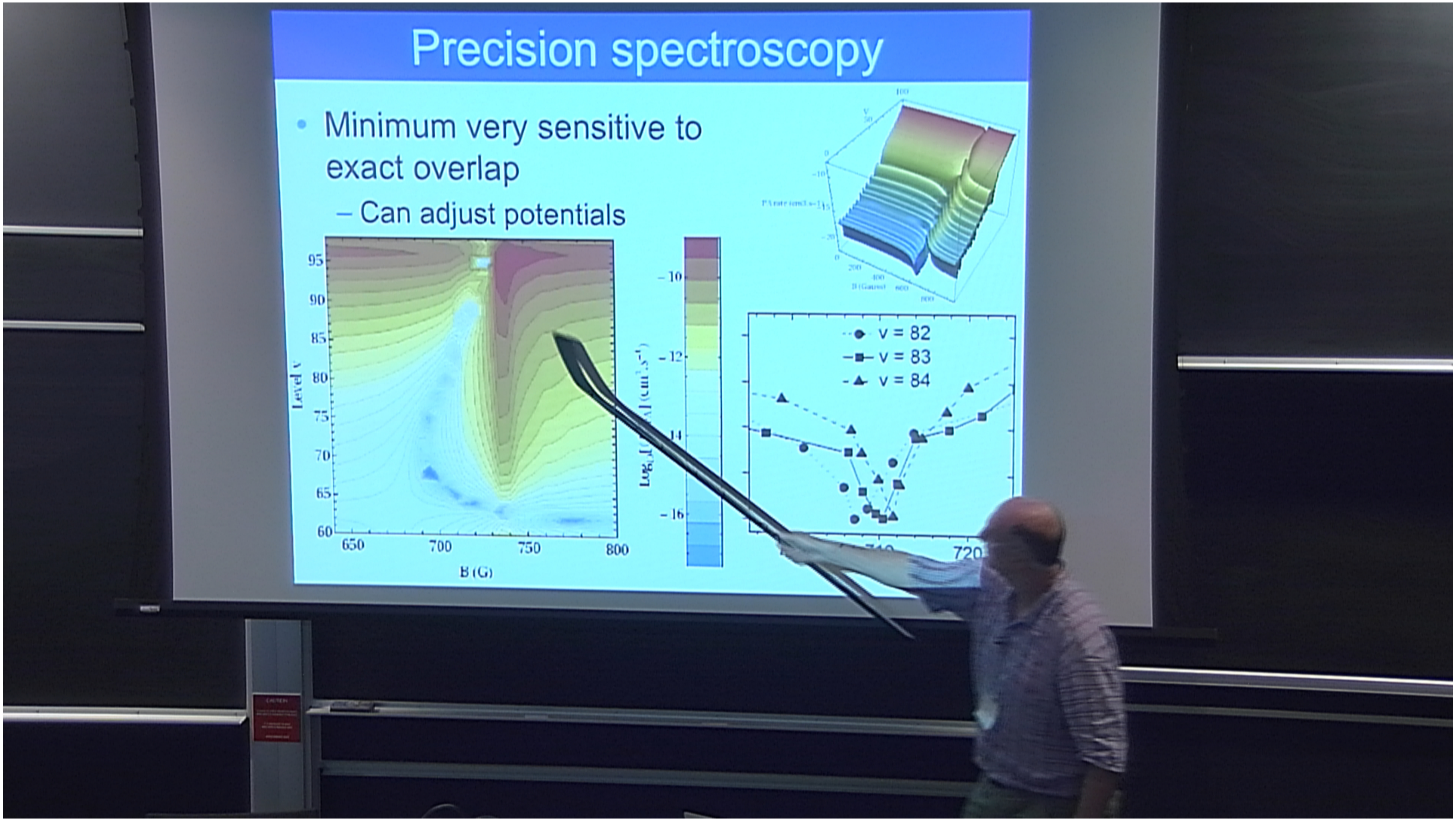
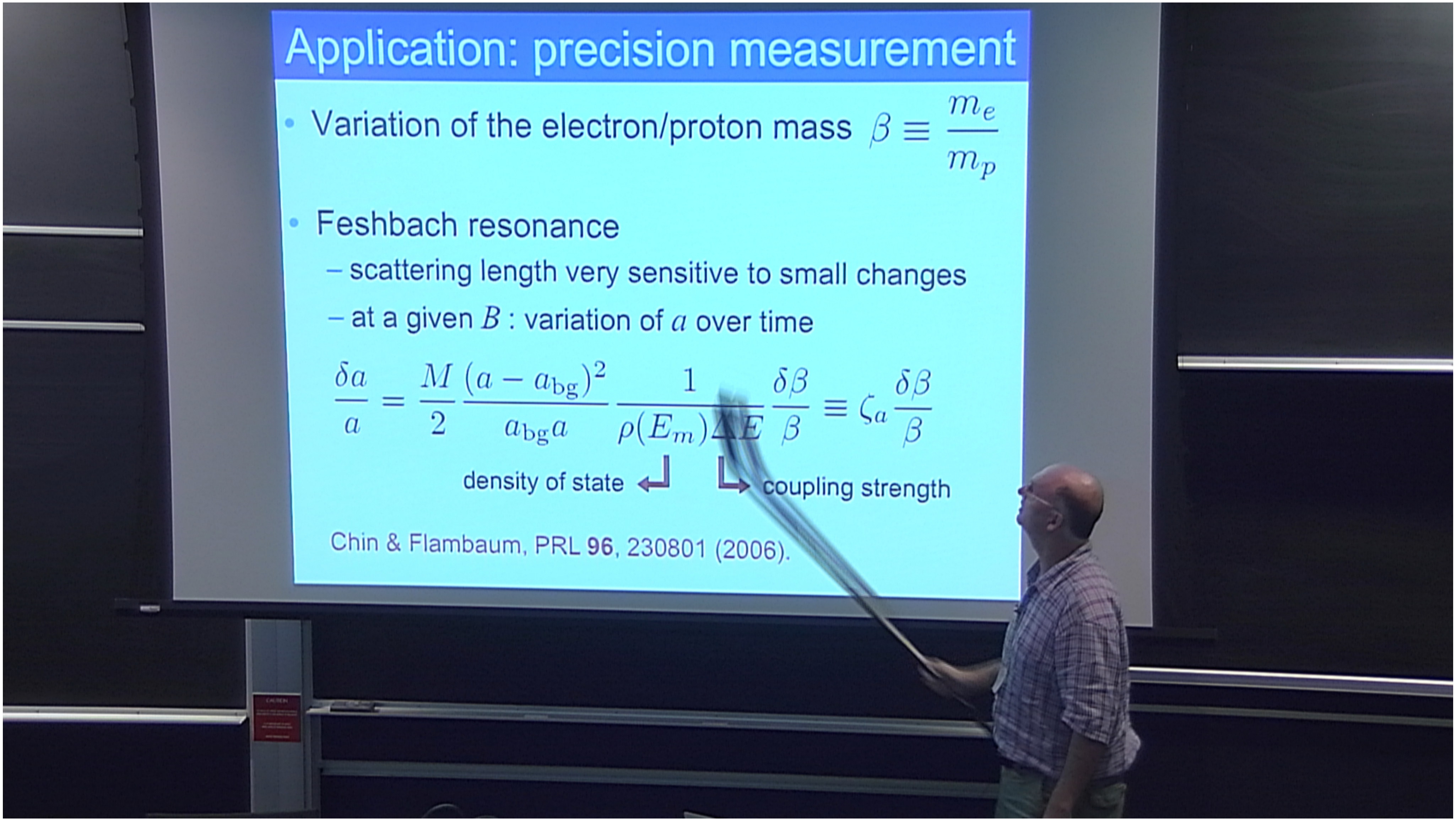
$\psi_1(R) = \psi_{\mathrm{reg}}(R) + \tan\delta\,\psi_{\mathrm{irr}}(R)\,,$
$\overset{R\to\infty}{=} \frac{1}{\cos\delta}\sqrt{\frac{2\mu}{\pi\hbar^2 k}}\sin(kR + \delta_{\mathrm{bg}} + \delta)$
$\psi_2(R) = -\sqrt{\frac{2}{\pi\Gamma}}\sin\delta\,\psi_0(R)$
V_2
$|2\rangle$
ψ_0
E_0
ψ_{reg}
E
$|1\rangle$
V_1

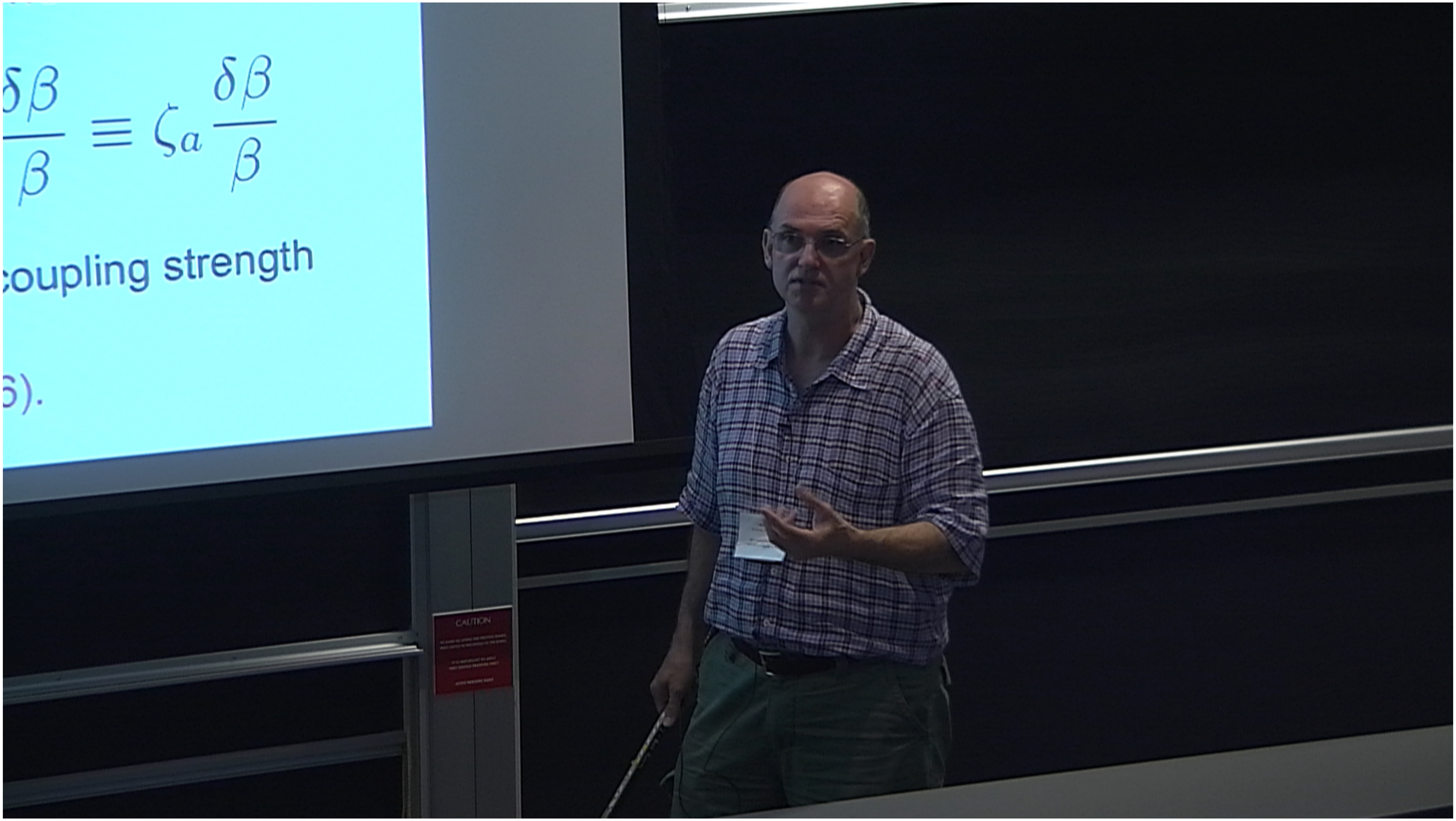

Simple two-channel model
• 1 open + 1 closed channel:
$|\Psi_{\rm tot}\rangle = \psi_1|1\rangle + \psi_2|2\rangle$
$-\frac{\hbar^2}{2\mu}\frac{d^2}{dR^2}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} + \begin{pmatrix} V_1 & V_{1,2} \\ V_{2,1} & V_2\end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = E\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix}$
$\psi_1(R) = \psi_{\rm reg}(R) + \tan\delta\;\psi_{\rm irr}(R)\,,$
$\overset{R\to\infty}{=} \frac{1}{\cos\delta}\sqrt{\frac{2\mu}{\pi\hbar^2 k}}\sin(kR + \delta_{\rm bg} + \delta)$
$\psi_2(R) = -\sqrt{\frac{2}{\pi\Gamma}}\sin\delta\;\psi_0(R)$
V_2
$|2\rangle$
ψ_0
E_0
$\psi_{\rm reg}$
E
$|1\rangle$
V_1
• Into the transition matrix element:
$\langle v|D|\Psi_{\rm tot}\rangle = \langle v|D(R)|\psi_1(R)1\rangle + \langle v|D(R)|\psi_2(R)2\rangle$
$= \langle v|D|\psi_{\rm reg}1\rangle + \tan\delta\langle v|D|\psi_{\rm irr}1\rangle - \sqrt{\frac{2}{\pi\Gamma}}\sin\delta\langle v|D|\psi_0 2\rangle$
$|\langle v|D|\Psi_{\rm tot}\rangle|^2 = |\langle v|D|\psi_{\rm reg}1\rangle|^2|1 + C_1\tan\delta + C_2\sin\delta|^2$
$C_1 = \frac{\langle v|D|\psi_{\rm irr}1\rangle}{\langle v|D|\psi_{\rm reg}1\rangle}$
$C_2 = -\sqrt{\frac{2}{\pi\Gamma}}\frac{\langle v|D|\psi_0 2\rangle}{\langle v|D|\psi_{\rm reg}1\rangle}$

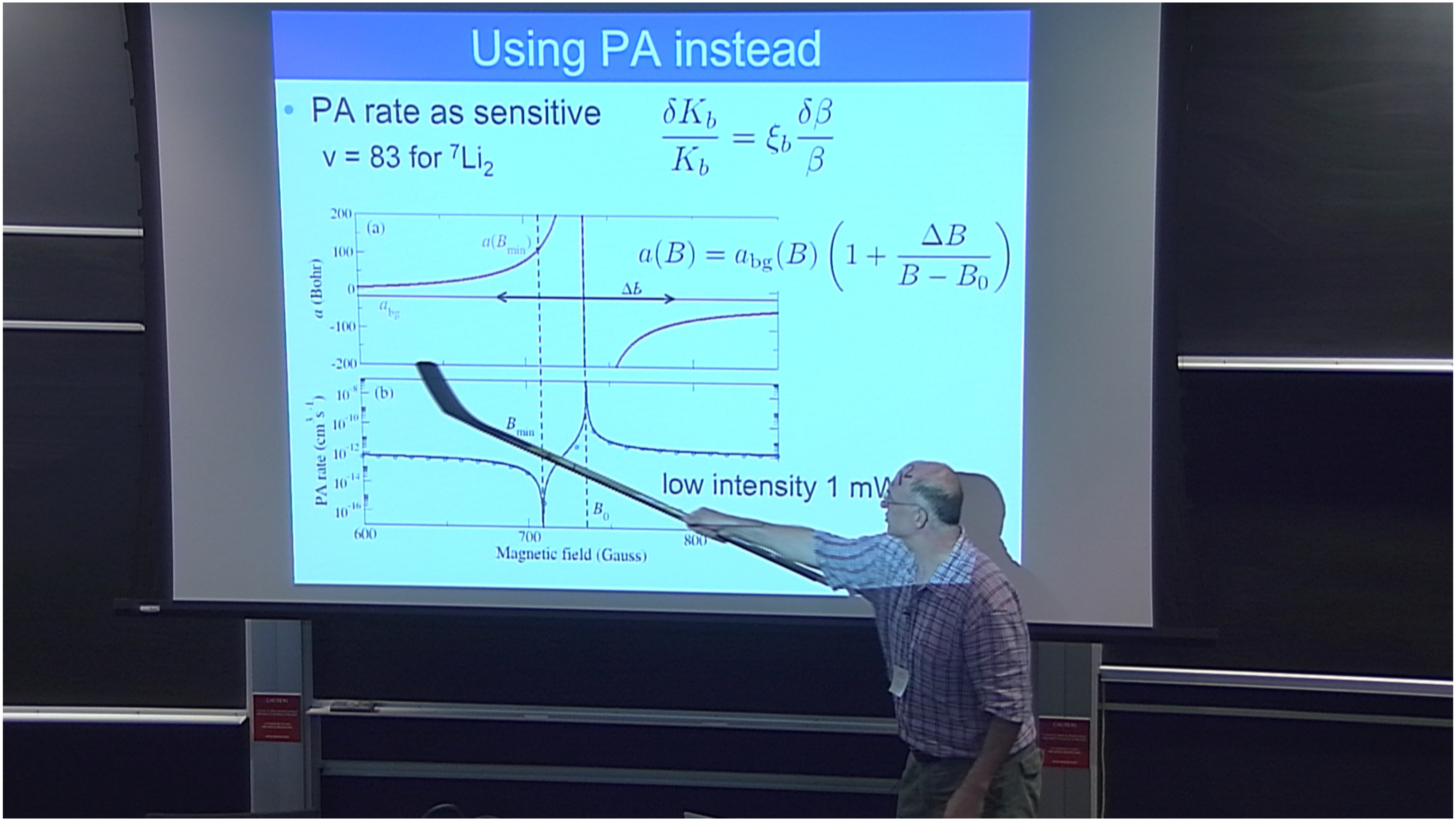

Results: example with Li$_2$
^{7}Li(f=1,m$_f$=1)^{7}Li(f=1,m$_f$=1)
PA rate (cm3.s-1)
B (Gauss)
v´=83
B (Gauss)


Experimental evidence
Randy Hulet
– I=1.67 W/cm2, T ~ 9-18 μK, n ~ 1012-13 cm-3
– I=1.6 W/cm2, T =10 μK
7Li(f=1,mf=1)7Li(f=1,mf=1)
Within the 45% Uncertainty (X 2)
Saturation effects
Except at 745 G
Loss rate (cm3/s)
B (G)
Rate (10-9 cm3/s)

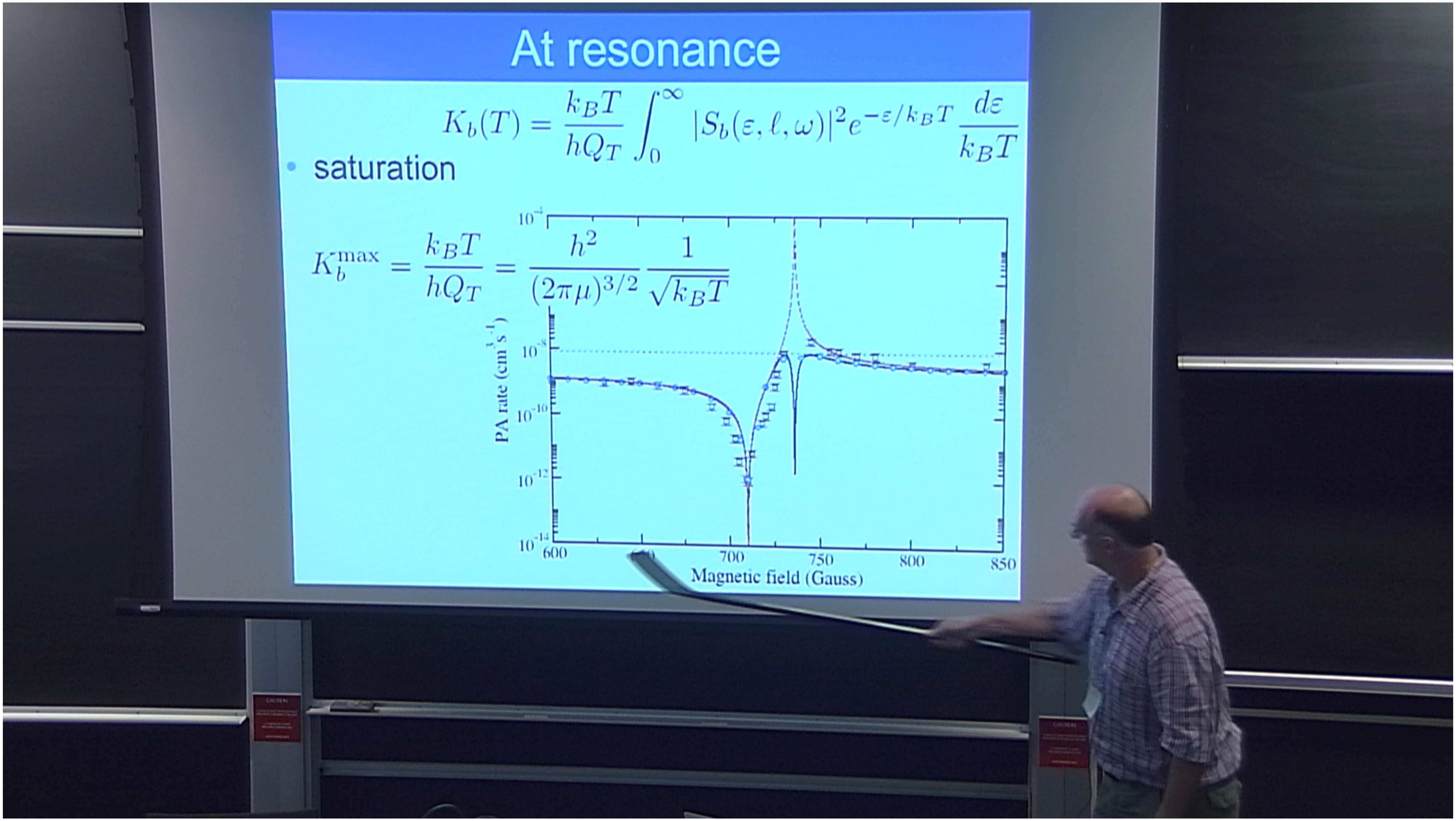

Precision spectroscopy
Minimum very sensitive to exact overlap
– Can adjust potentials
Level v
B (G)
650
700
750
800
−10
−12
−16
v = 82
v = 83
v = 84
720

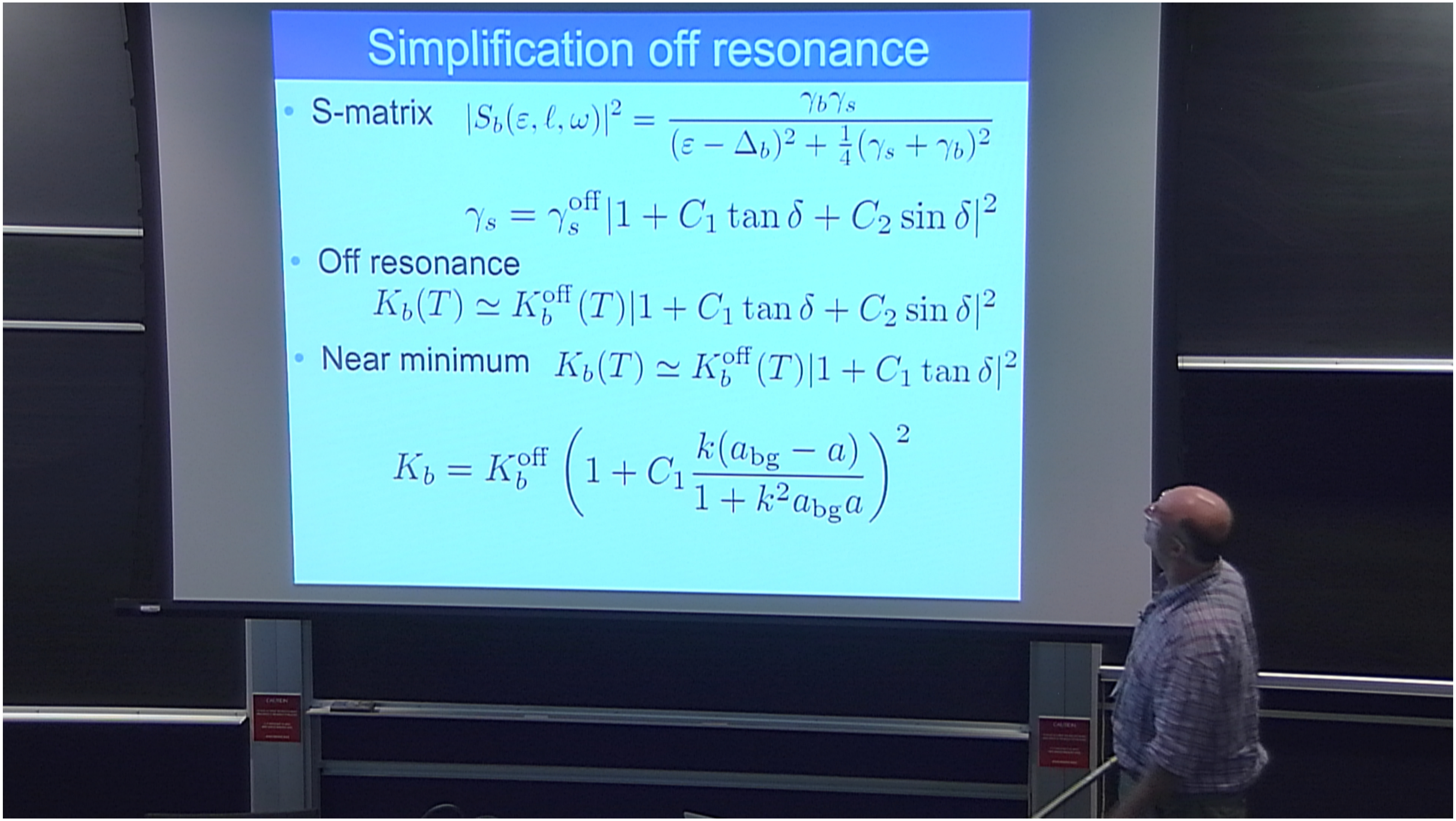

Application: precision measurement
Variation of the electron/proton mass $\beta \equiv \frac{m_e}{m_p}$
Feshbach resonance
– scattering length very sensitive to small changes
– at a given B : variation of a over time
$\frac{\delta a}{a} = \frac{M}{2} \frac{(a - a_{\rm bg})^2}{a_{\rm bg} a} \frac{1}{\rho(E_m)\Delta E} \frac{\delta\beta}{\beta} \equiv \zeta_a \frac{\delta\beta}{\beta}$
density of state
coupling strength
Chin & Flambaum, PRL **96**, 230801 (2006).

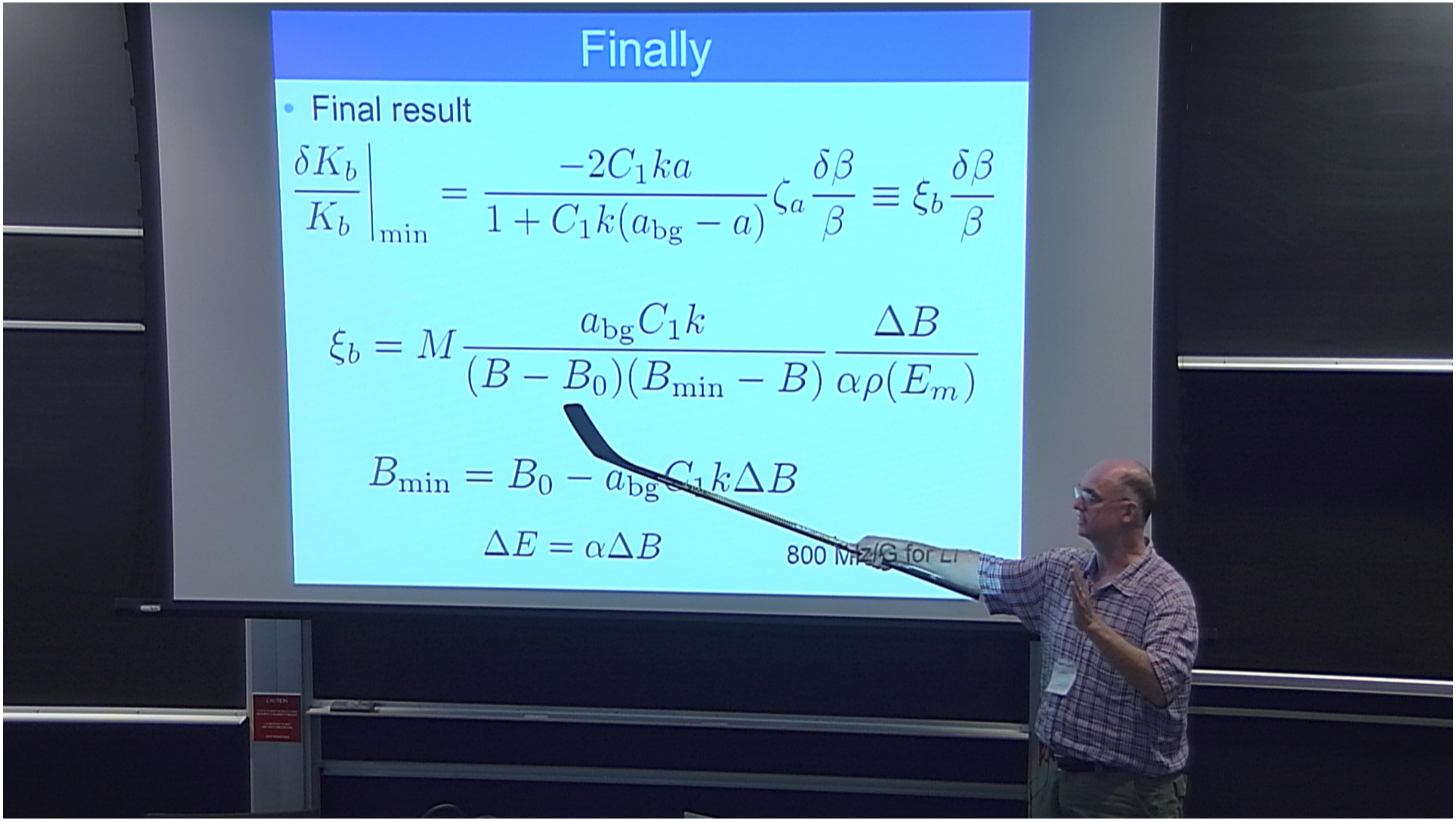

coupling strength
6).
CAUTION

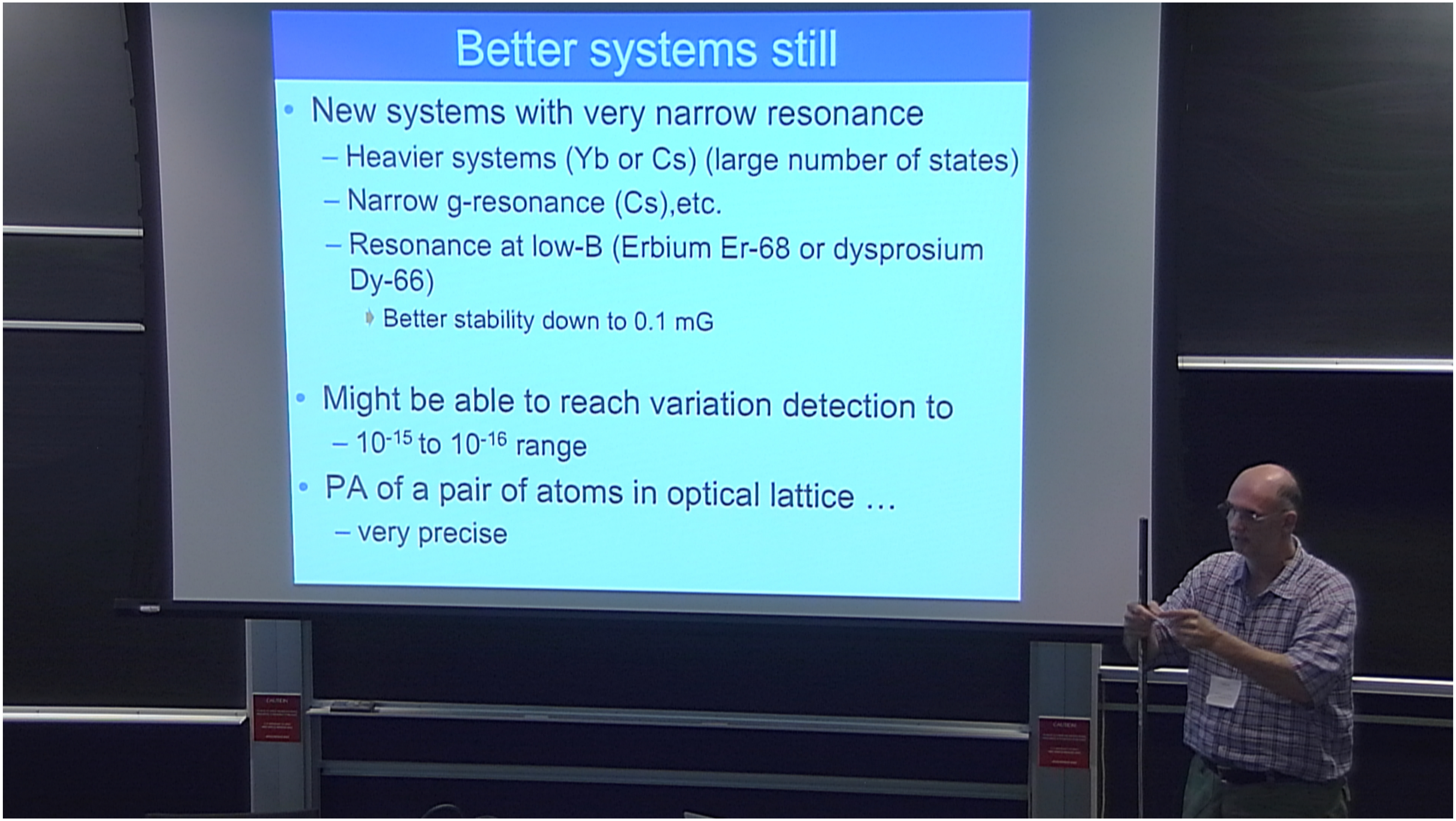


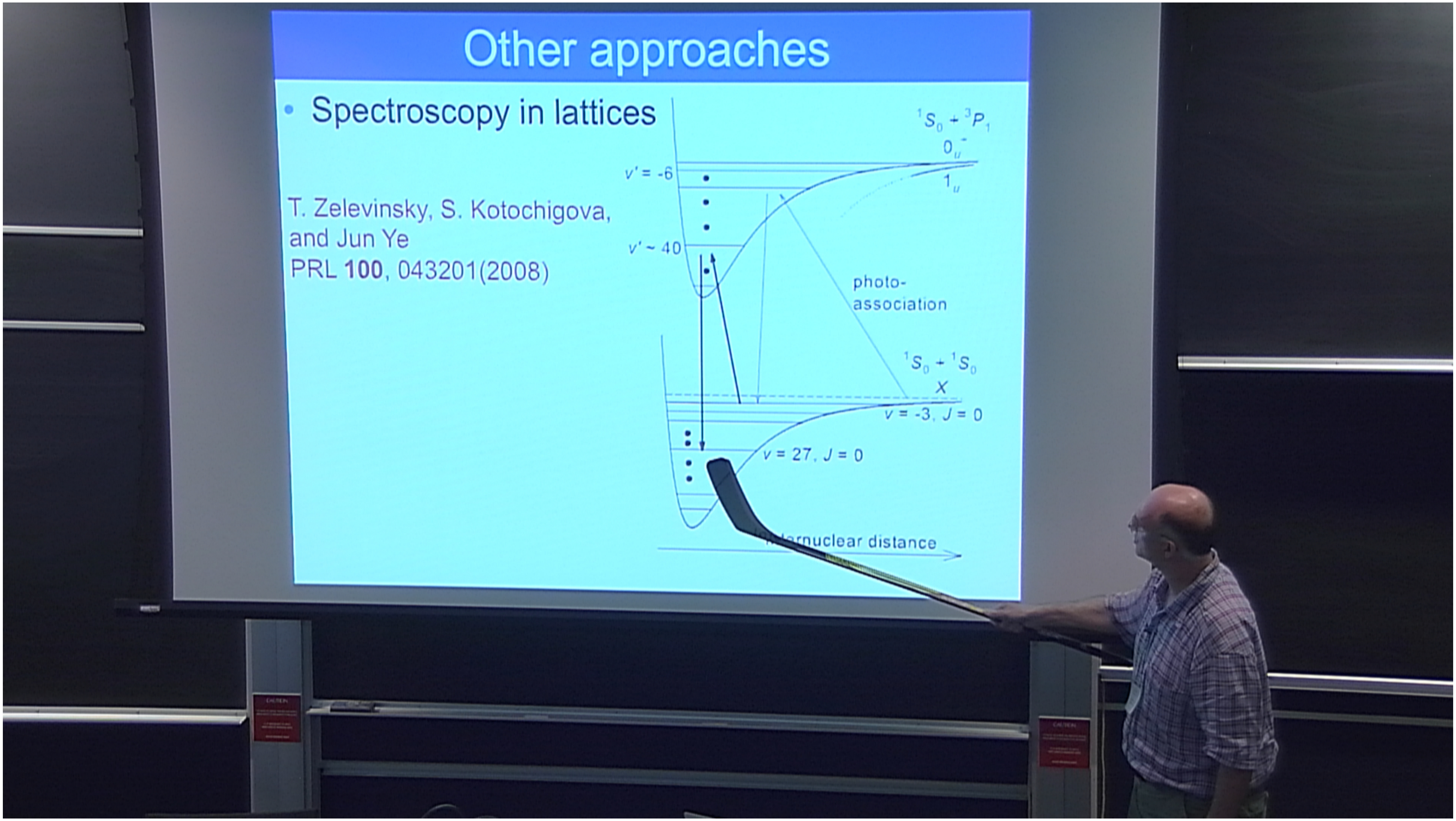
Using PA instead
PA rate as sensitive
v = 83 for $^7Li_2$
$\frac{\delta K_b}{K_b} = \xi_b \frac{\delta\beta}{\beta}$
$a(B) = a_{bg}(B)\left(1 + \frac{\Delta B}{B - B_0}\right)$
low intensity 1 mW
(a)
(b)
a (Bohr)
PA rate
Magnetic field (Gauss)

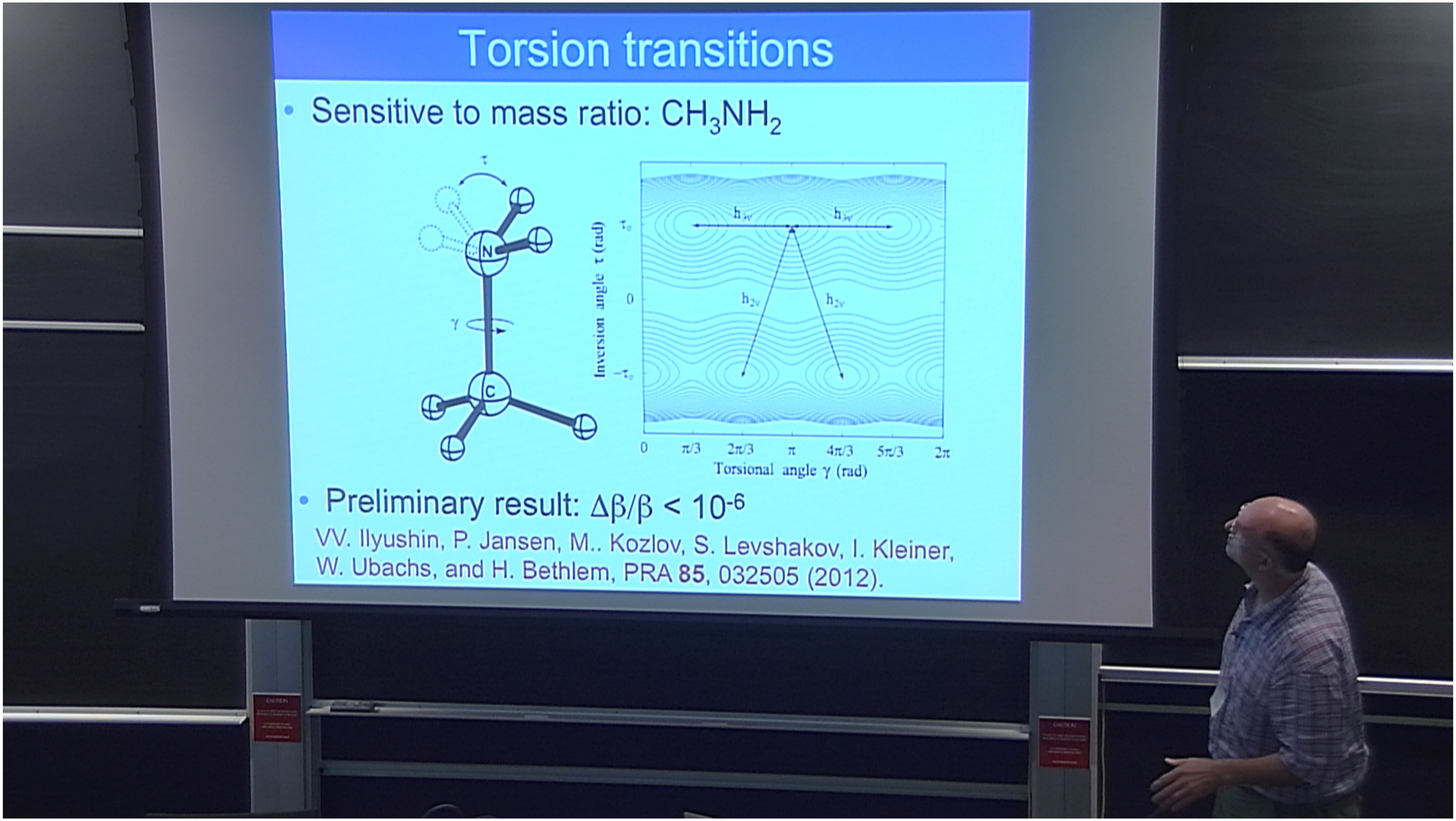

At resonance
$K_b(T) = \frac{k_B T}{h Q_T} \int_0^\infty |S_b(\varepsilon, \ell, \omega)|^2 e^{-\varepsilon/k_B T} \frac{d\varepsilon}{k_B T}$
saturation
$K_b^{\max} = \frac{k_B T}{h Q_T} = \frac{h^2}{(2\pi\mu)^{3/2}} \frac{1}{\sqrt{k_B T}}$
PA rate (cm^3 s^{-1})
Magnetic field (Gauss)
600
700
750
800
850
10^{-8}
10^{-10}
10^{-12}
10^{-14}

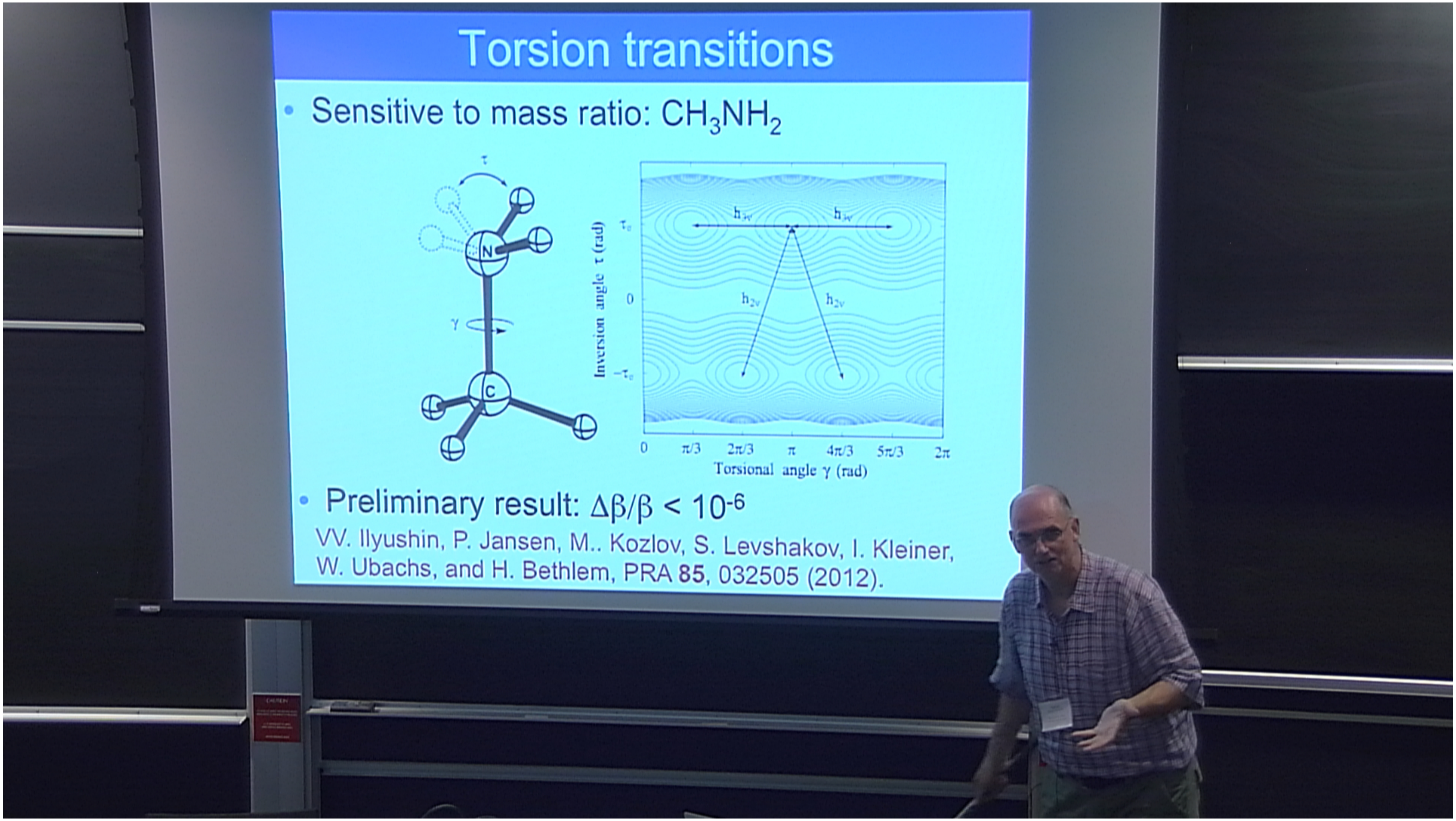

Simplification off resonance
• S-matrix $|S_b(\varepsilon, \ell, \omega)|^2 = \frac{\gamma_b \gamma_s}{(\varepsilon - \Delta_b)^2 + \frac{1}{4}(\gamma_s + \gamma_b)^2}$
$\gamma_s = \gamma_s^{\rm off} |1 + C_1 \tan\delta + C_2 \sin\delta|^2$
• Off resonance
$K_b(T) \simeq K_b^{\rm off}(T) |1 + C_1 \tan\delta + C_2 \sin\delta|^2$
• Near minimum $K_b(T) \simeq K_b^{\rm off}(T) |1 + C_1 \tan\delta|^2$
$K_b = K_b^{\rm off} \left(1 + C_1 \frac{k(a_{\rm bg} - a)}{1 + k^2 a_{\rm bg} a}\right)^2$


Finally
Final result
$\left.\frac{\delta K_b}{K_b}\right|_{\rm min} = \frac{-2C_1 ka}{1+C_1k(a_{\rm bg}-a)}\zeta_a\frac{\delta\beta}{\beta} \equiv \xi_b\frac{\delta\beta}{\beta}$
$\xi_b = M\frac{a_{\rm bg}C_1k}{(B-B_0)(B_{\rm min}-B)}\frac{\Delta B}{\alpha\rho(E_m)}$
$B_{\rm min} = B_0 - a_{\rm bg}C_1k\Delta B$
$\Delta E = \alpha\Delta B$
800 MHz/G for Li


Better systems still
New systems with very narrow resonance
– Heavier systems (Yb or Cs) (large number of states)
– Narrow g-resonance (Cs),etc.
– Resonance at low-B (Erbium Er-68 or dysprosium Dy-66)
Better stability down to 0.1 mG
Might be able to reach variation detection to
– 10-15 to 10-16 range
PA of a pair of atoms in optical lattice …
– very precise


Other approaches
Spectroscopy in lattices
T. Zelevinsky, S. Kotochigova, and Jun Ye
PRL 100, 043201(2008)
1S0 + 3P1
0u+
1u
v' = -6
v' ~ 40
photo-association
1S0 + 1S0
X
v = -3, J = 0
v = 27, J = 0
internuclear distance


Torsion transitions
Sensitive to mass ratio: CH3NH2
τ
N
γ
C
Inversion angle τ (rad)
τ0
0
−τ0
h3v
h3v
h2v
h2v
0
π/3
2π/3
π
4π/3
5π/3
2π
Torsional angle γ (rad)
Preliminary result: Δβ/β < 10-6
VV. Ilyushin, P. Jansen, M.. Kozlov, S. Levshakov, I. Kleiner,
W. Ubachs, and H. Bethlem, PRA 85, 032505 (2012).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Sensitive to mass ratio: CH3NH2
τ
N
γ
C
Inversion angle τ (rad)
Torsional angle γ (rad)
0
π/3
2π/3
π
4π/3
5π/3
2π
h3v
h2v
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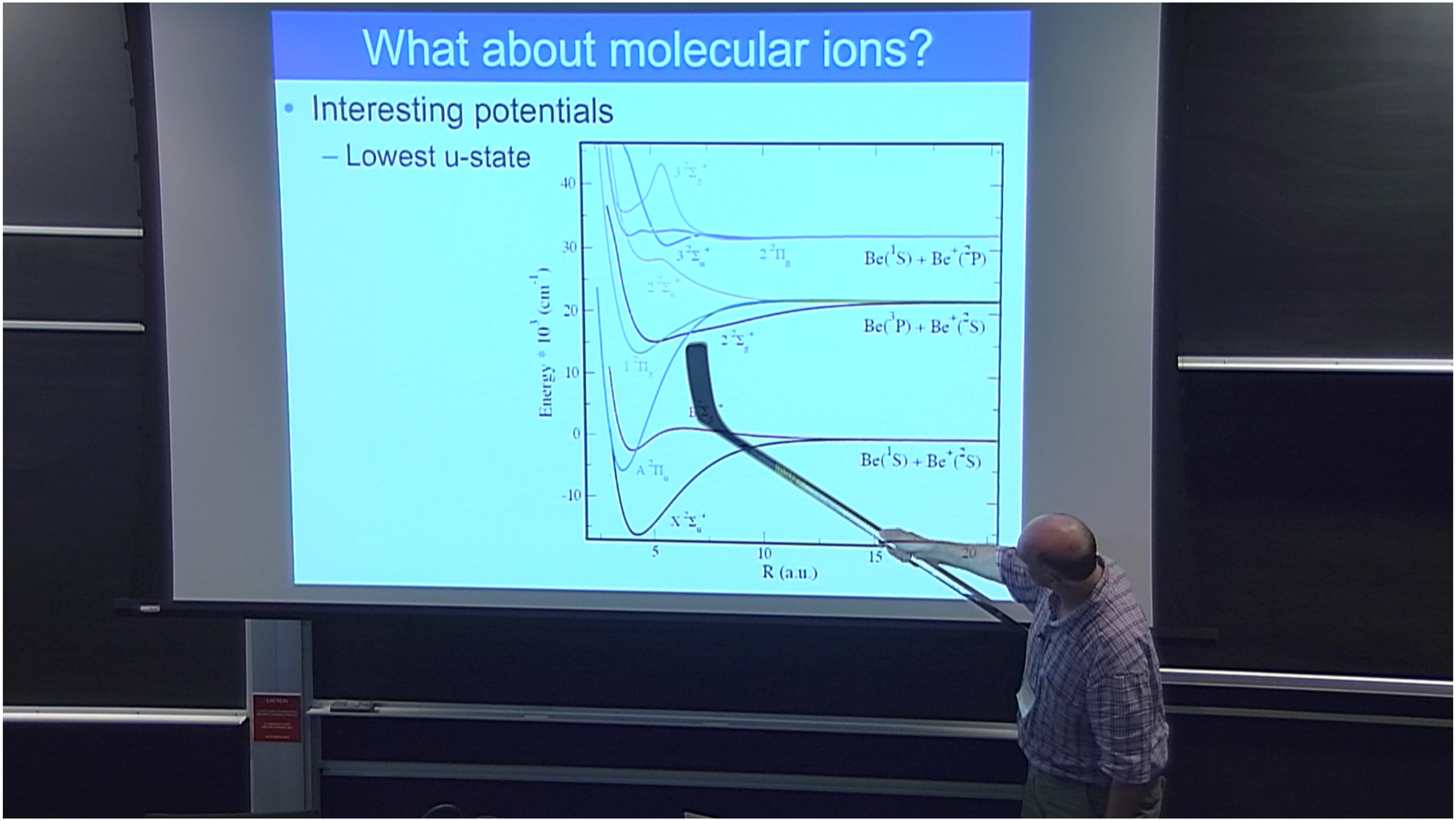
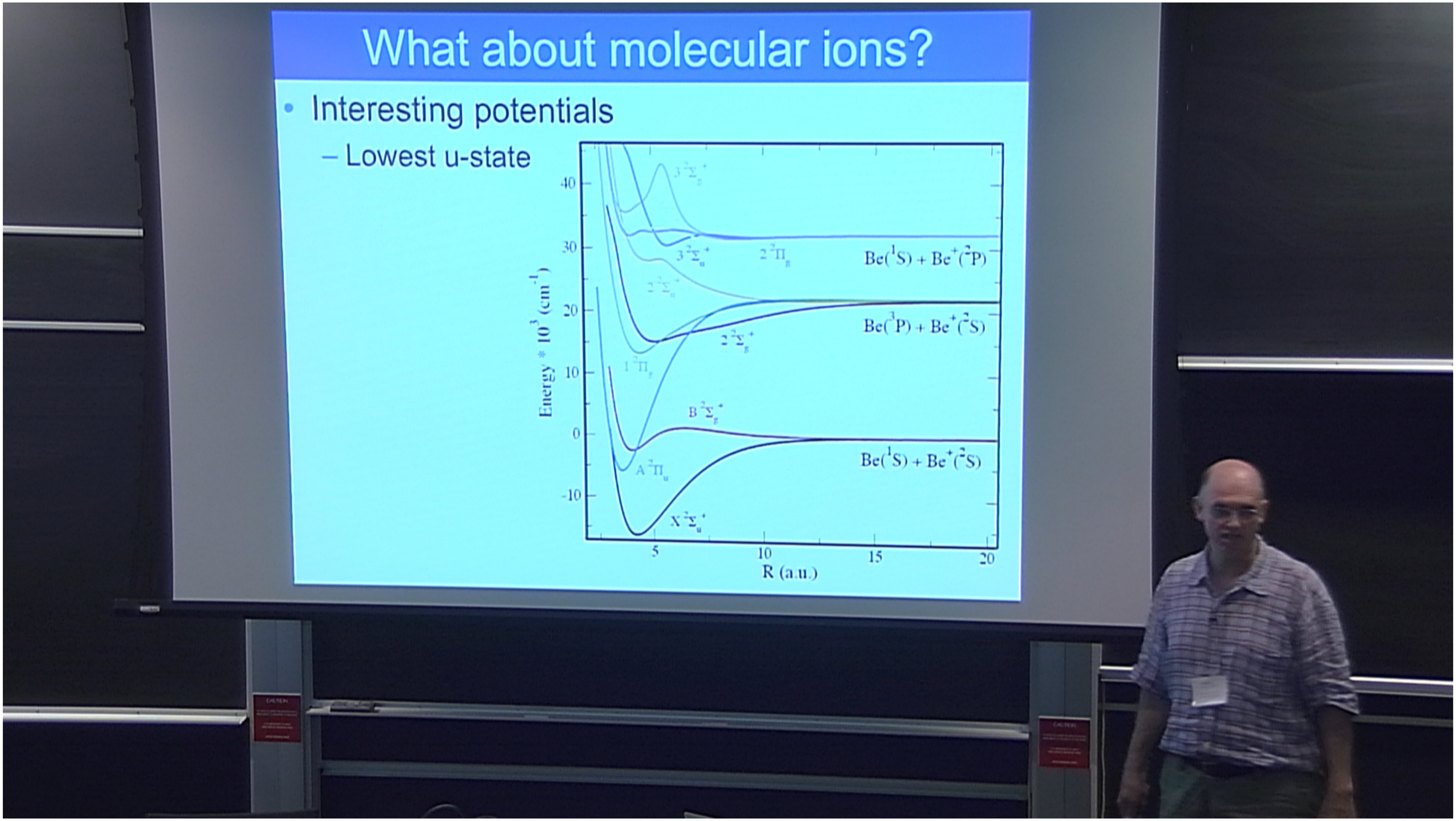
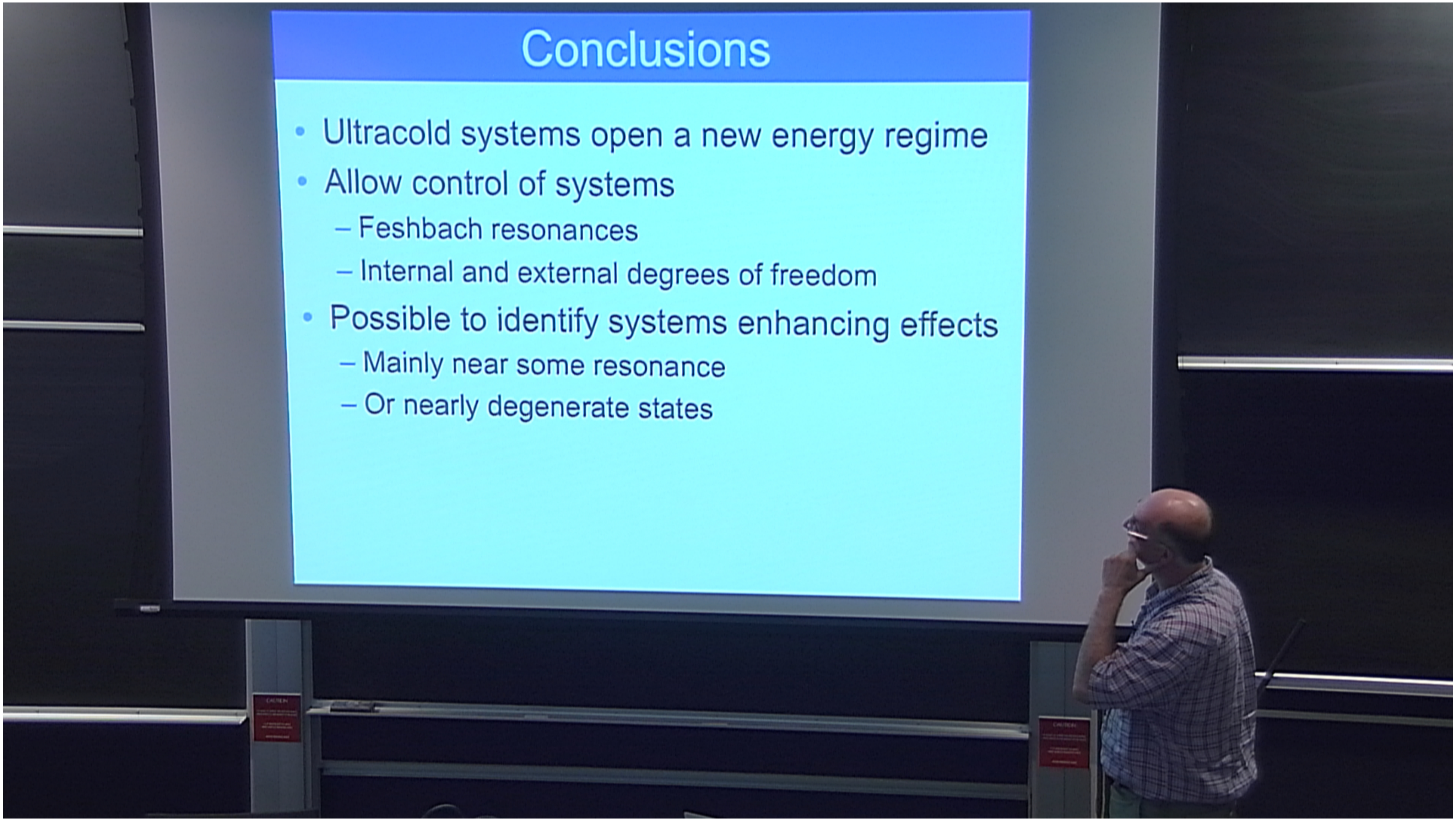

What about molecular ions?
Interesting potentials
– Lowest u-state
Energy * 10^3 (cm^-1)
R (a.u.)
Be(1S) + Be+(2P)
Be(3P) + Be+(2S)
Be(1S) + Be+(2S)
X 2Σu+
A 2Πu
1 2Πg
2 2Σg+
2 2Πg
3 2Σu+
3 2Σg+


What about molecular ions?
• Interesting potentials
– Lowest u-state
Energy * 10^3 (cm^-1)
R (a.u.)
Be(1S) + Be+(2P)
Be(3P) + Be+(2S)
Be(1S) + Be+(2S)
40
30
20
10
0
-10
5
10
15
20


Conclusions
Ultracold systems open a new energy regime
Allow control of systems
– Feshbach resonances
– Internal and external degrees of freedom
Possible to identify systems enhancing effects
– Mainly near some resonance
– Or nearly degenerate states