Title: Clocks and precision measurements with ultracold molecules

Speakers: Tanya Zelevinsky

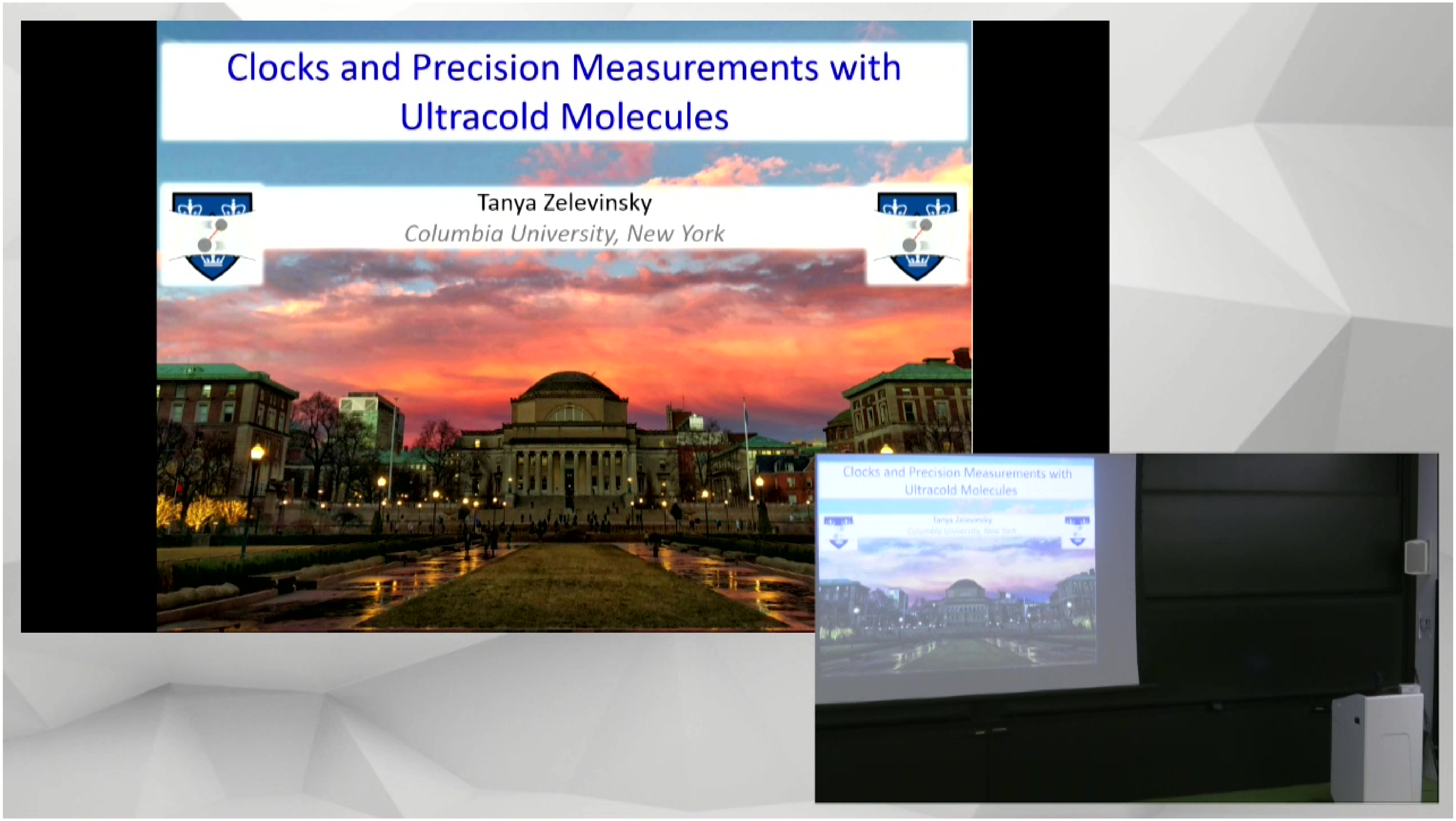
Series: Colloquium

Date: March 13, 2024 - 2:00 PM

URL: https://pirsa.org/24030111

Abstract: Significant advancements in our understanding of the physical world have been driven by increasingly precise atomic spectroscopy. The level of accessible precision entered a new realm with the advent of laser cooling and trapping. Now we can extend the ultrahigh spectroscopic precision, or atomic clock technology, to more complex quantum particles like diatomic molecules. The ability to quantify molecular degrees of freedom, such as nuclear vibrations, with nearly atomic-clock precision illuminates their previously hidden properties. Moreover, it suggests possibilities to leverage this precision for probing fundamental aspects of physical interactions, including enhanced tests of Newtonian gravity at the nanometer scale.

Zoom link



Clocks and Precision Measurements with Ultracold Molecules

Tanya Zelevinsky

Columbia University, New York

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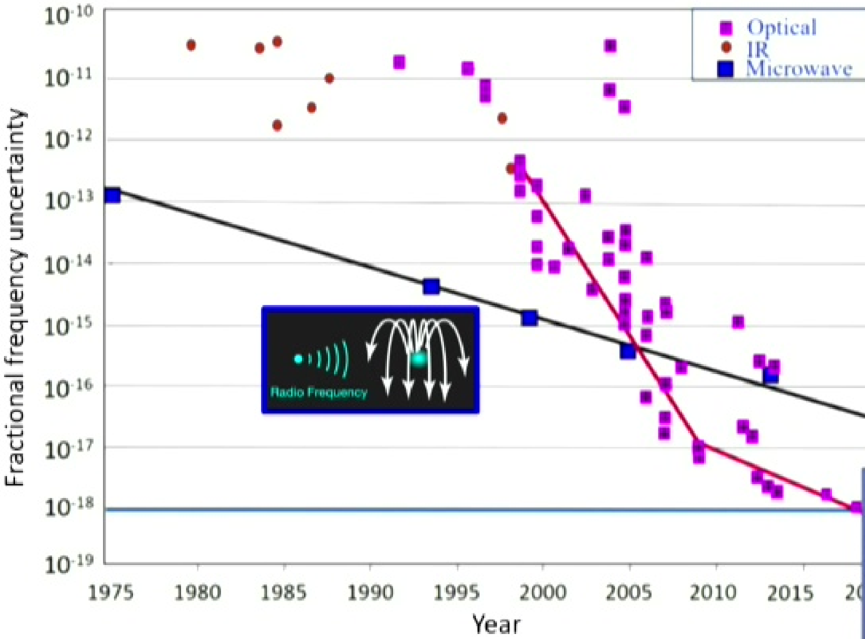
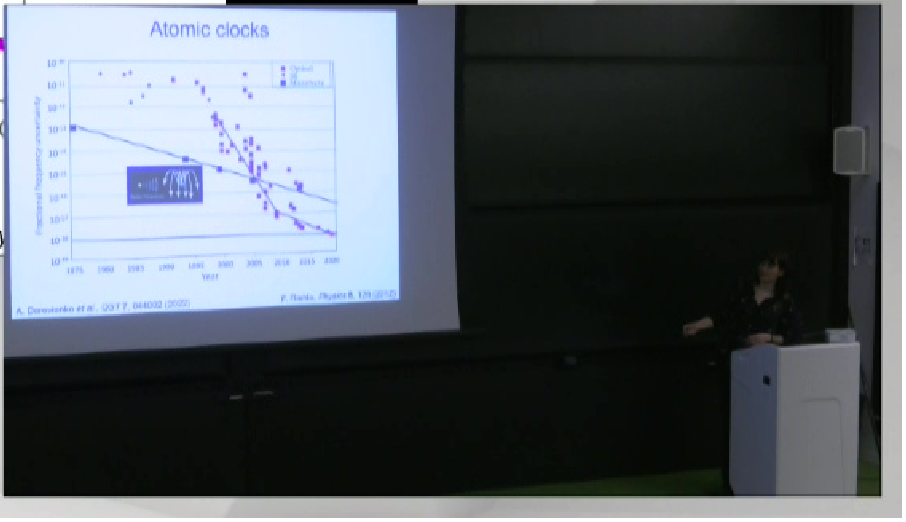
Pupin Labs @ Columbia

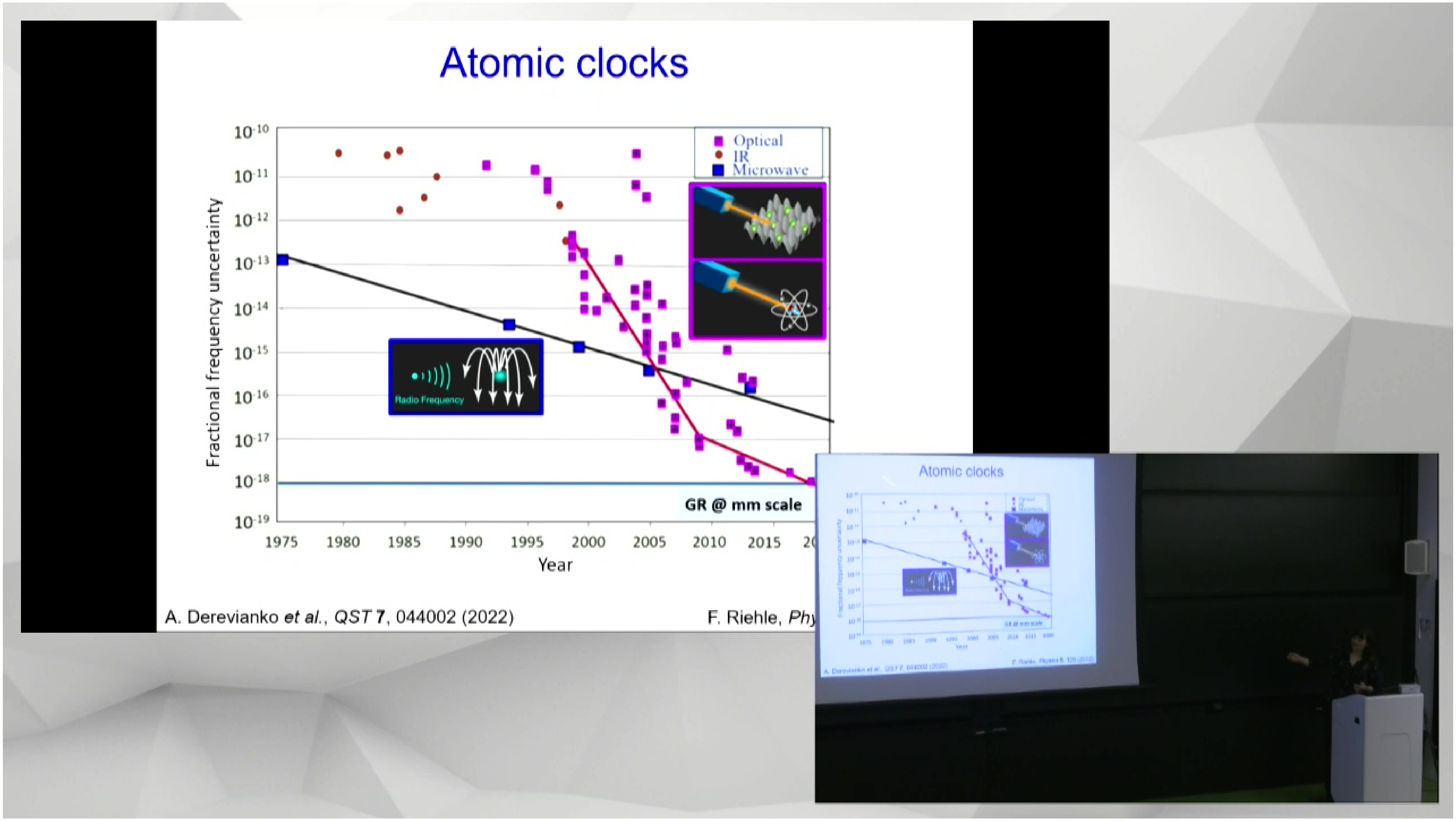
Atomic clocks



A. Derevianko *et al.*, *QST* **7**, 044002 (2022)

F. Riehle, *Phy*





Atomic clocks

A. Derevianko *et al.*, *QST* **7**, 044002 (2022)

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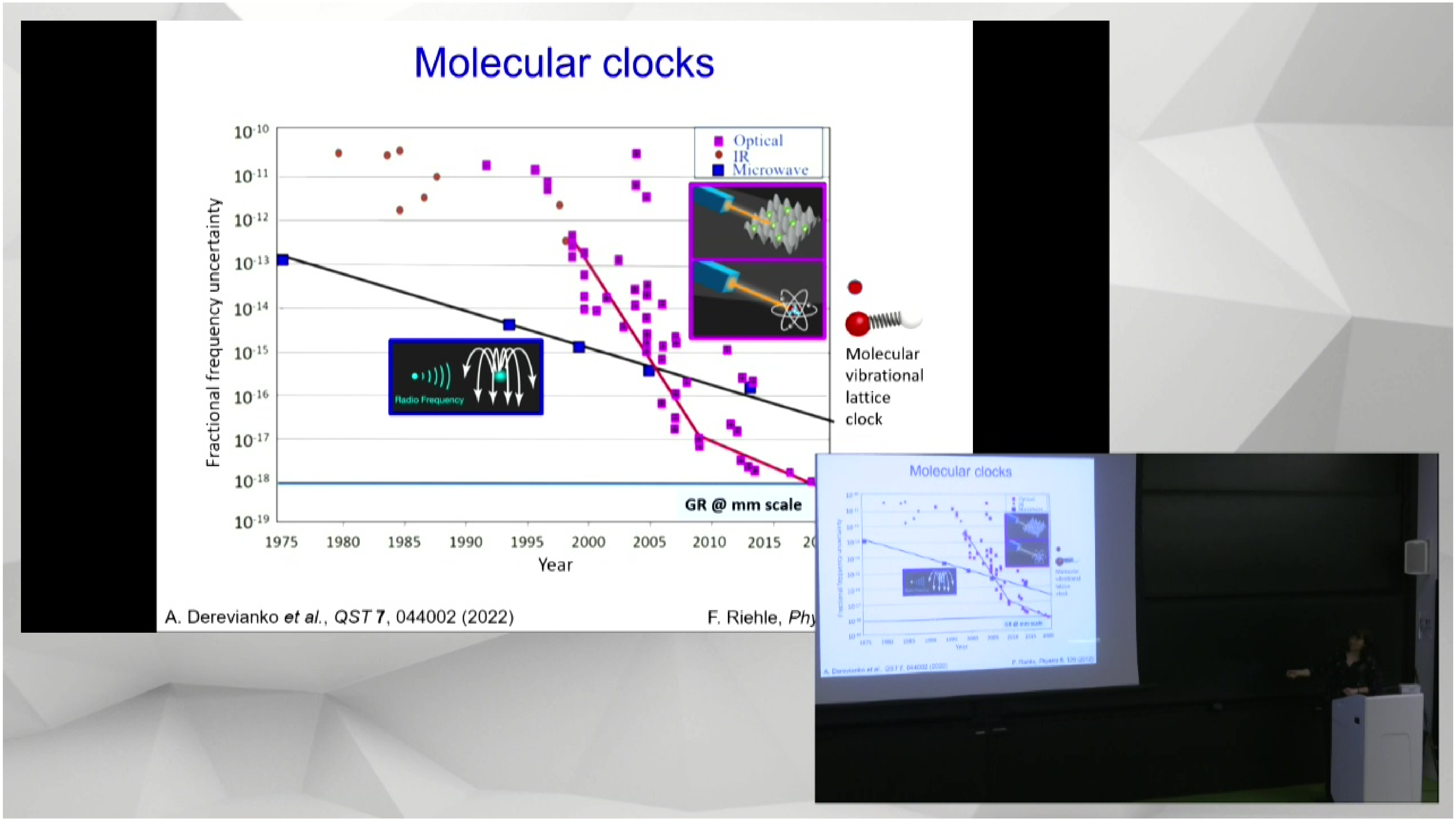
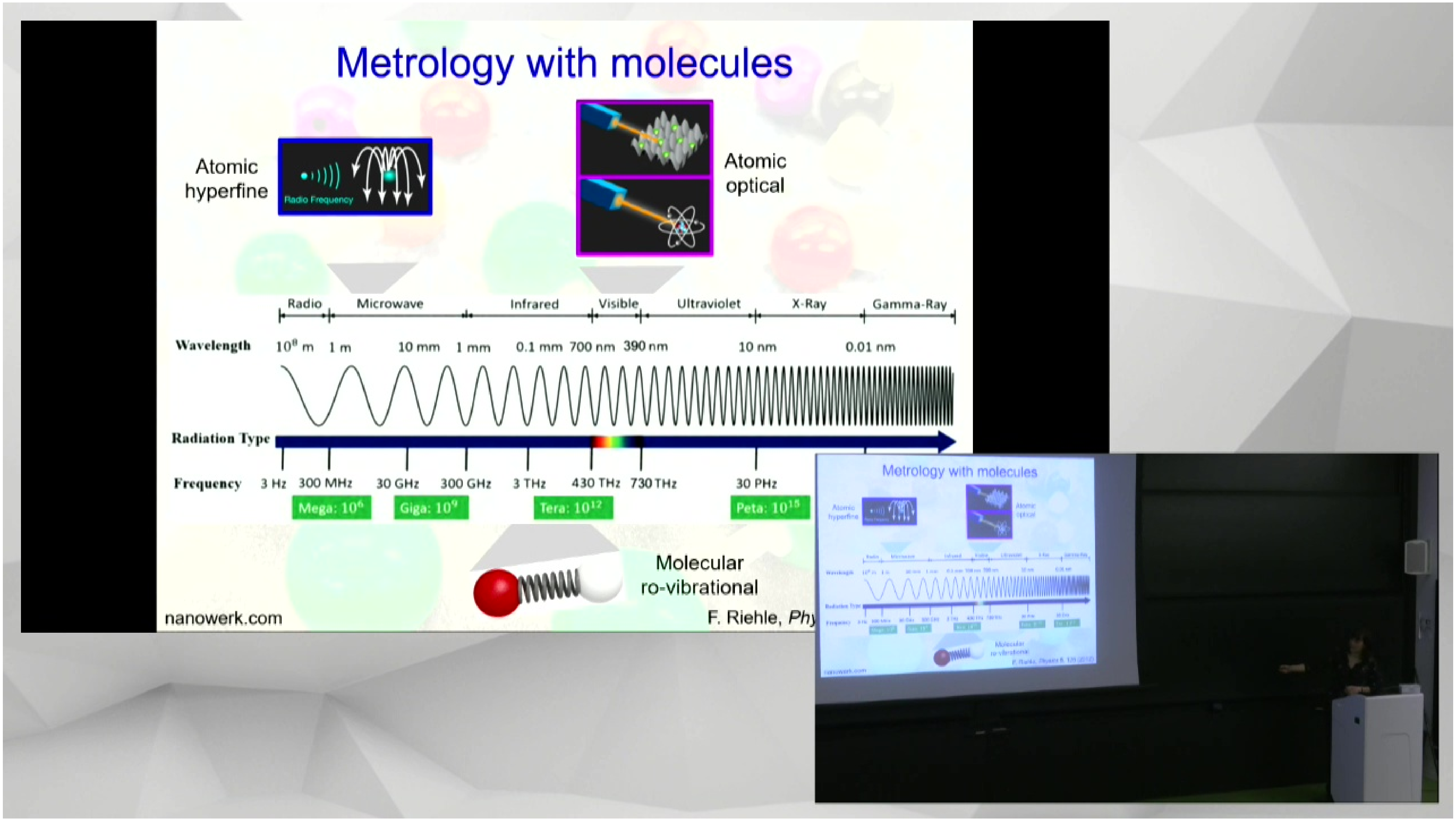
Molecular clocks



Molecular vibrational lattice clock

A. Derevianko *et al.*, *QST* **7**, 044002 (2022)

F. Riehle, *Phy*



Metrology with molecules

Atomic hyperfine

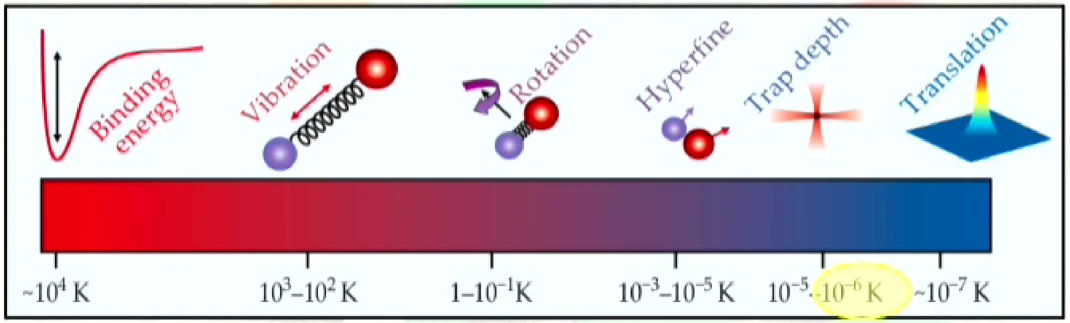
Atomic optical

Molecular ro-vibrational

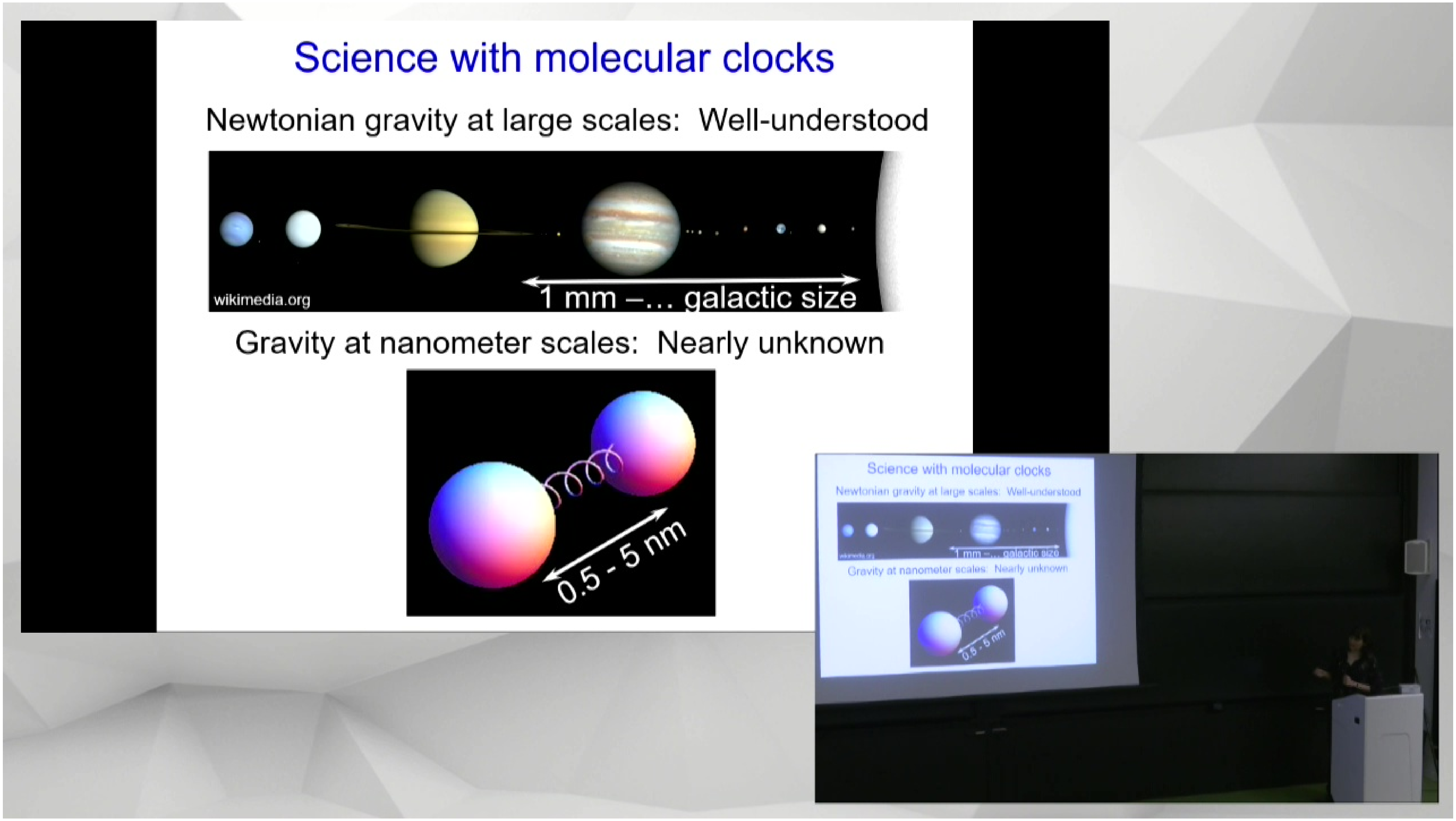
nanowerk.com

F. Riehle, *Phy*

Metrology with molecules:
Why ultracold?



D. S. Jin and J. Ye, *Phys. Toda*



Science with molecular clocks

Newtonian gravity at large scales: Well-understood

Gravity at nanometer scales: Nearly unknown

Science with molecular clocks
Newtonian gravity at large scales: Well-understood
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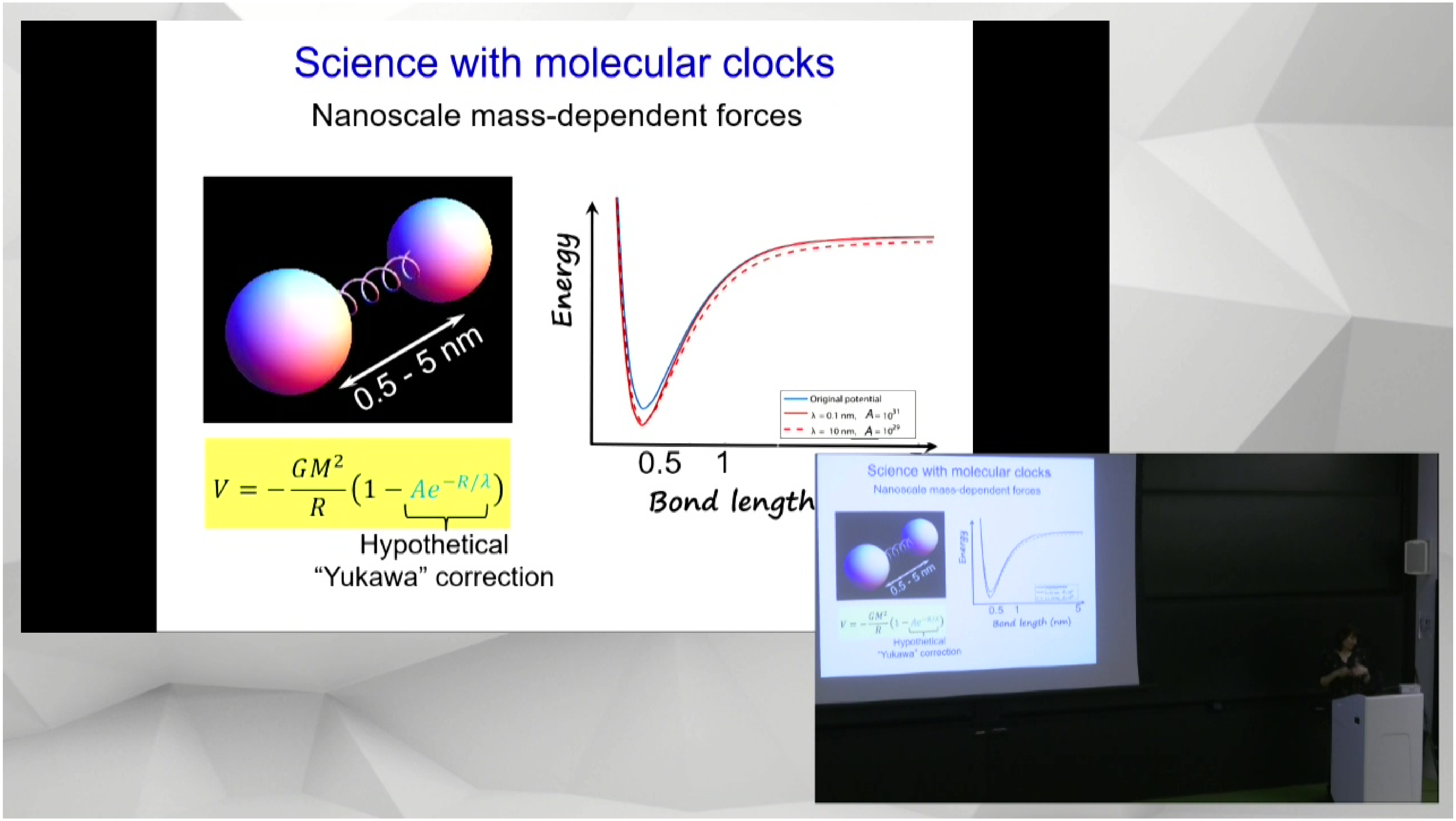


Science with molecular clocks

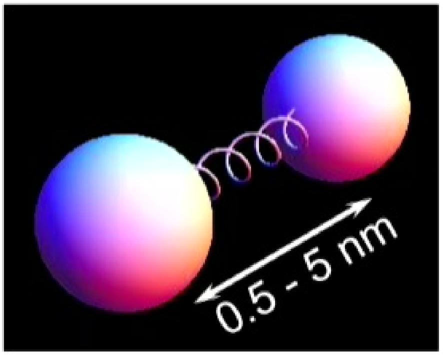
Nanoscale mass-dependent forces

$$V = -\frac{GM^2}{R}\left(1 - \underbrace{Ae^{-R/\lambda}}\right)$$

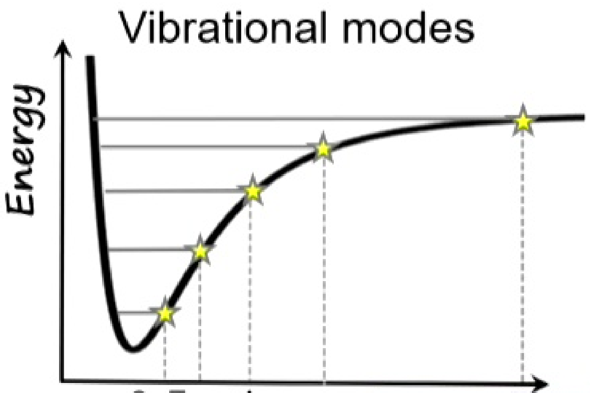
Hypothetical
"Yukawa" correction

Science with molecular clocks

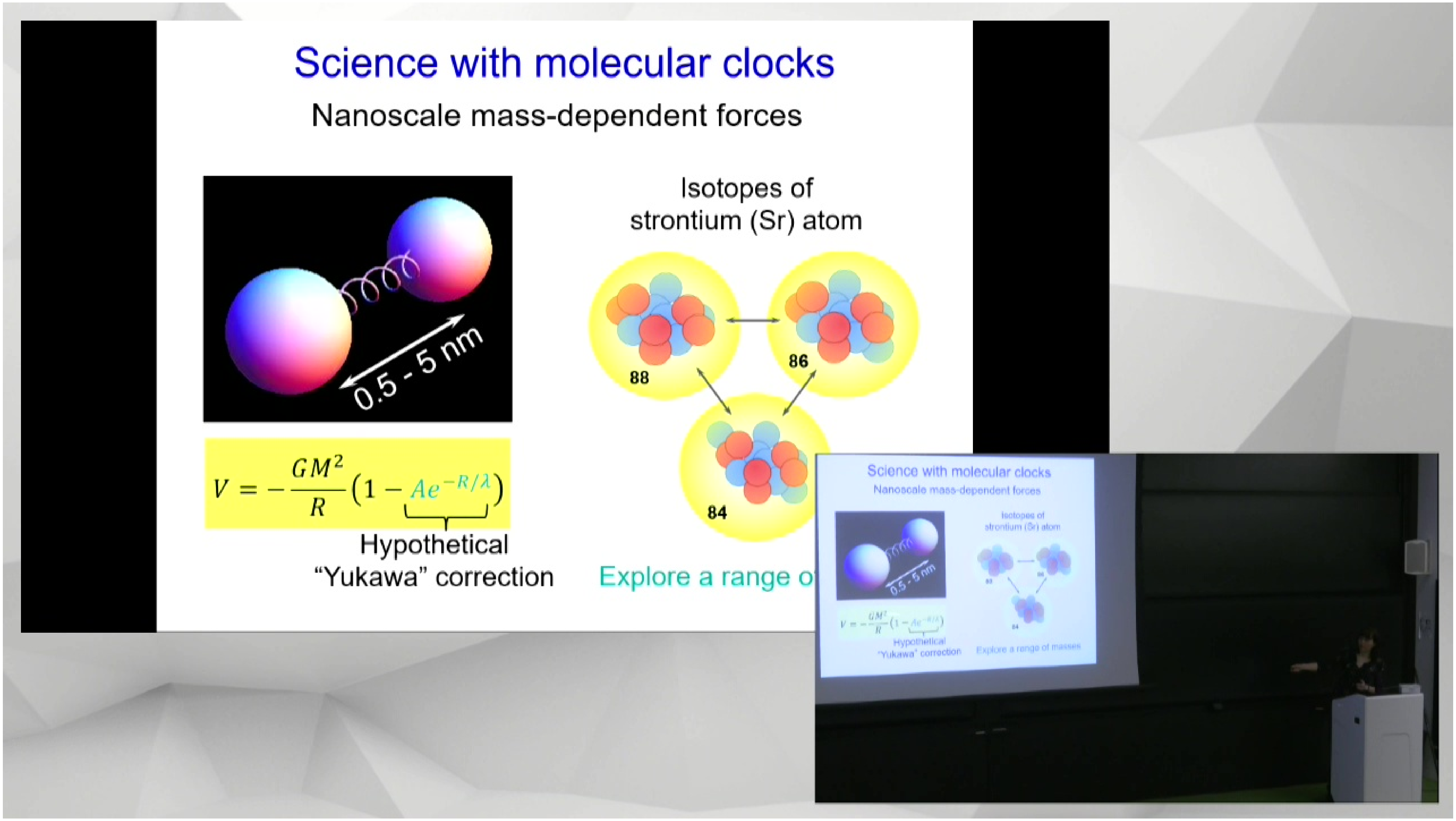
Nanoscale mass-dependent forces



$$V = -\frac{GM^2}{R}\left(1 - \underbrace{Ae^{-R/\lambda}}_{\text{Hypothetical “Yukawa” correction}}\right)$$



Explore a range c



Science with molecular clocks

Nanoscale mass-dependent forces

Isotopes of
strontium (Sr) atom

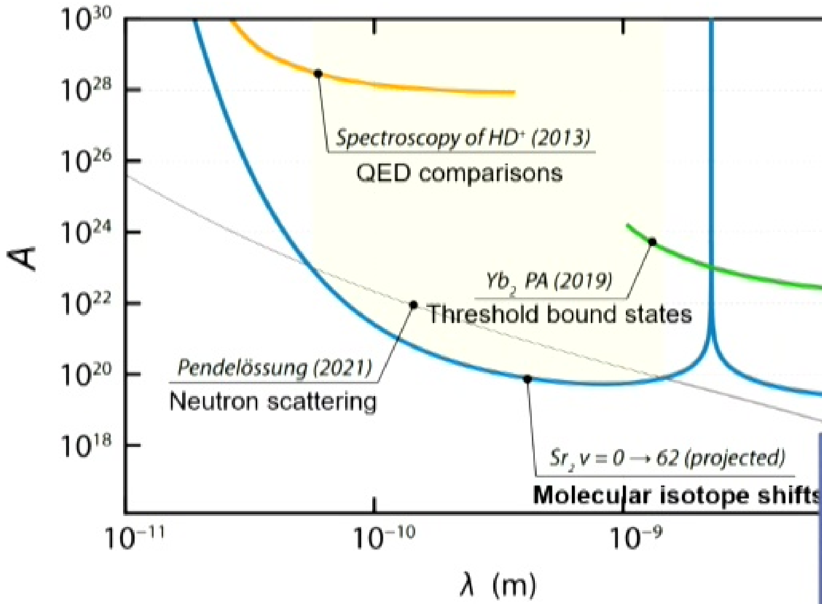
$$V = -\frac{GM^2}{R}\left(1 - \underbrace{Ae^{-R/\lambda}}\right)$$

Hypothetical
“Yukawa” correction

Explore a range o

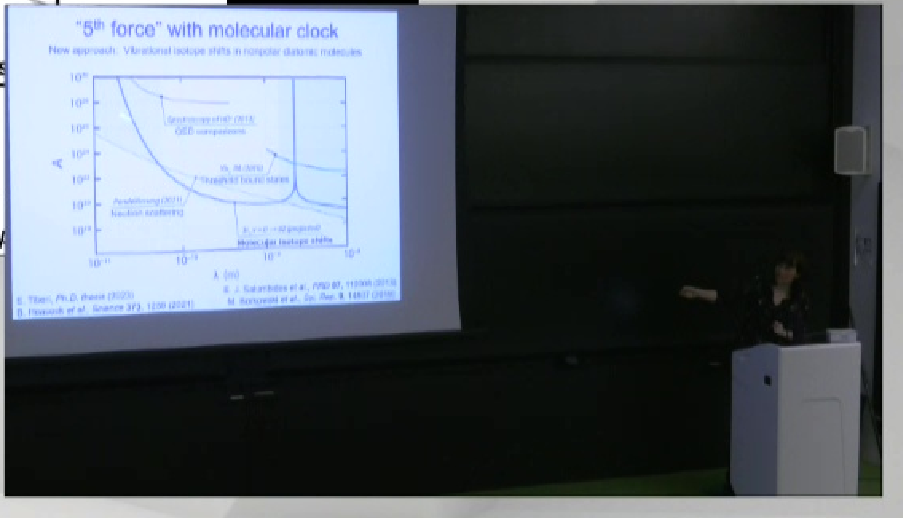
“5th force” with molecular clock

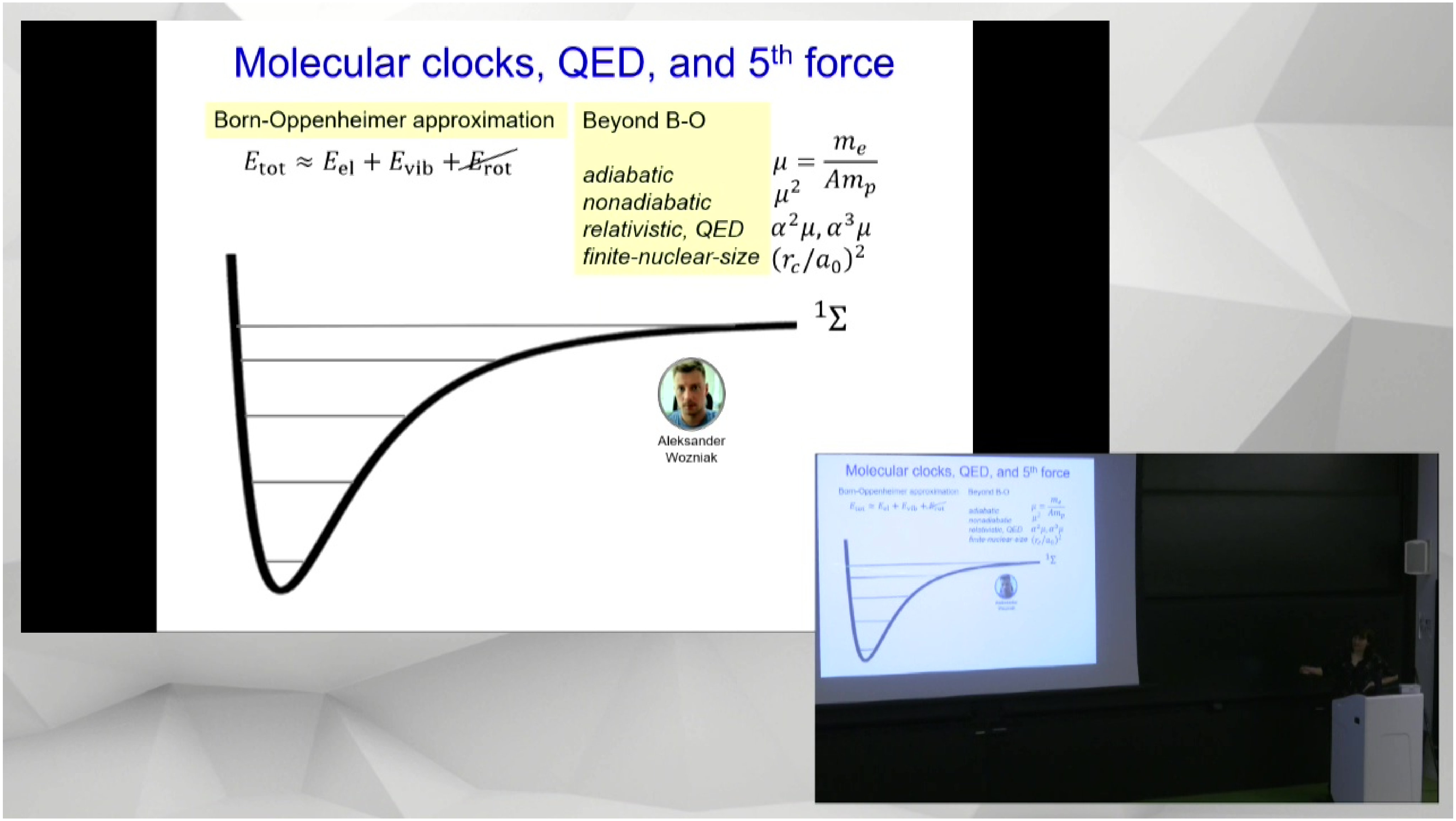
New approach: Vibrational isotope shifts in nonpolar diatomic molecules



E. Tiberi, *Ph.D. thesis* (2023)
B. Heacock *et al.*, *Science* **373**, 1239 (2021)

E. J. Salumbides *et al.*, *PRD*
M. Borkowski *et al.*, *Sci. Rep*





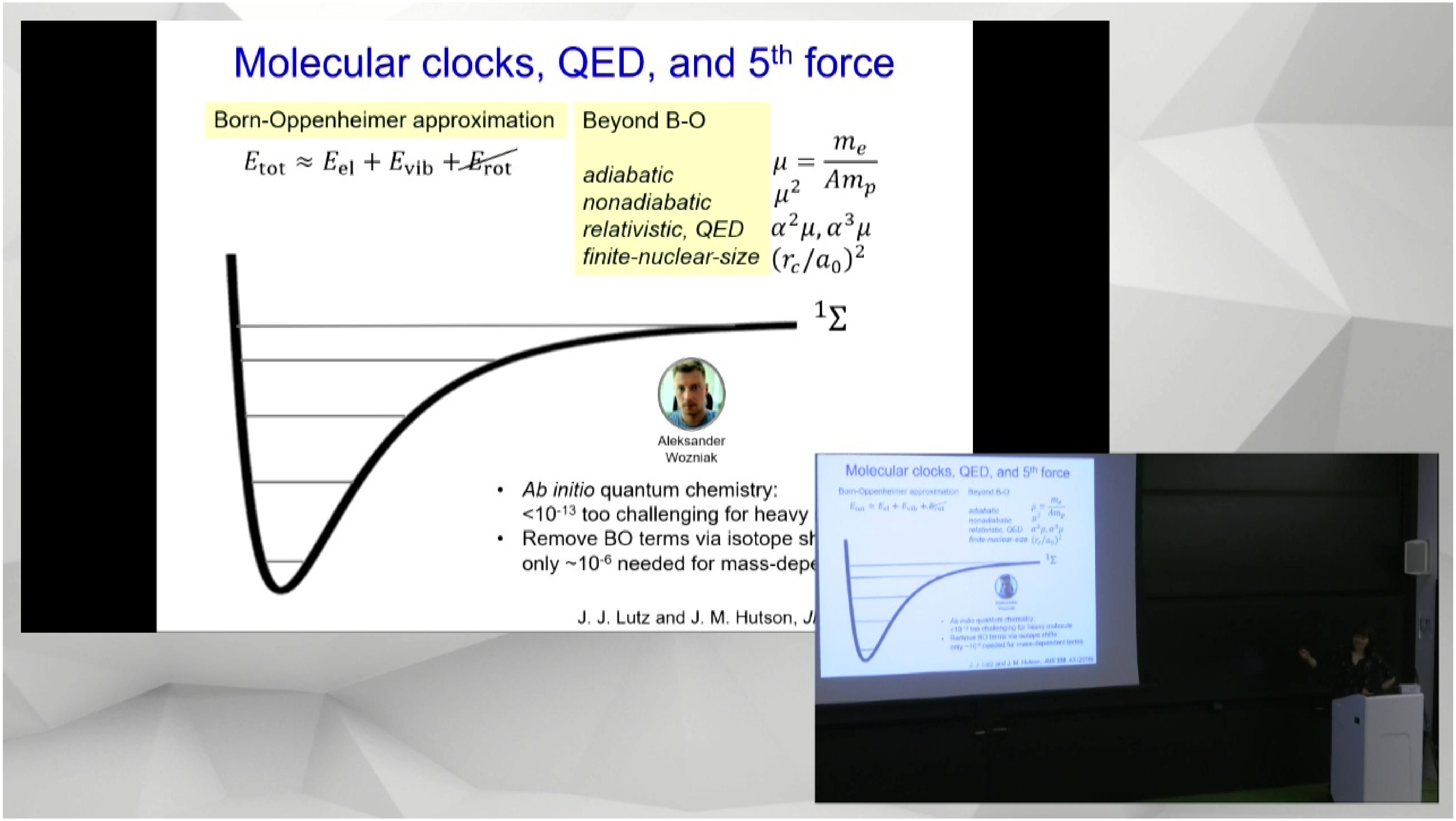
Molecular clocks, QED, and 5th force

Born-Oppenheimer approximation

$$E_{\text{tot}} \approx E_{\text{el}} + E_{\text{vib}} + \cancel{E_{\text{rot}}}$$

Beyond B-O

adiabatic	$\mu = \frac{m_e}{A m_p}$
nonadiabatic	μ^2
relativistic, QED	$\alpha^2\mu, \alpha^3\mu$
finite-nuclear-size	$(r_c/a_0)^2$



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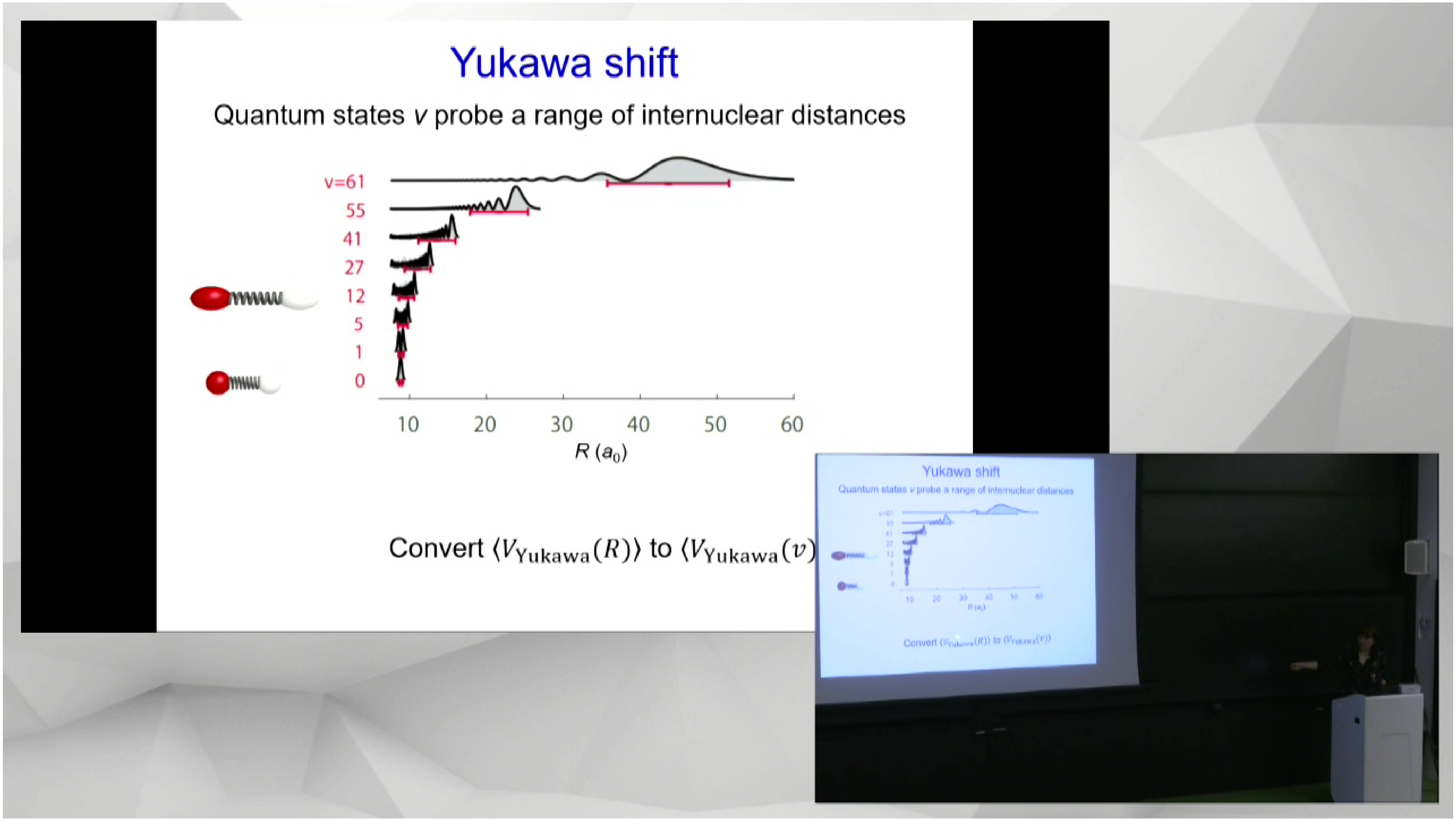
- *Ab initio* quantum chemistry: $<10^{-13}$ too challenging for heavy
- Remove BO terms via isotope sh only $\sim 10^{-6}$ needed for mass-depe

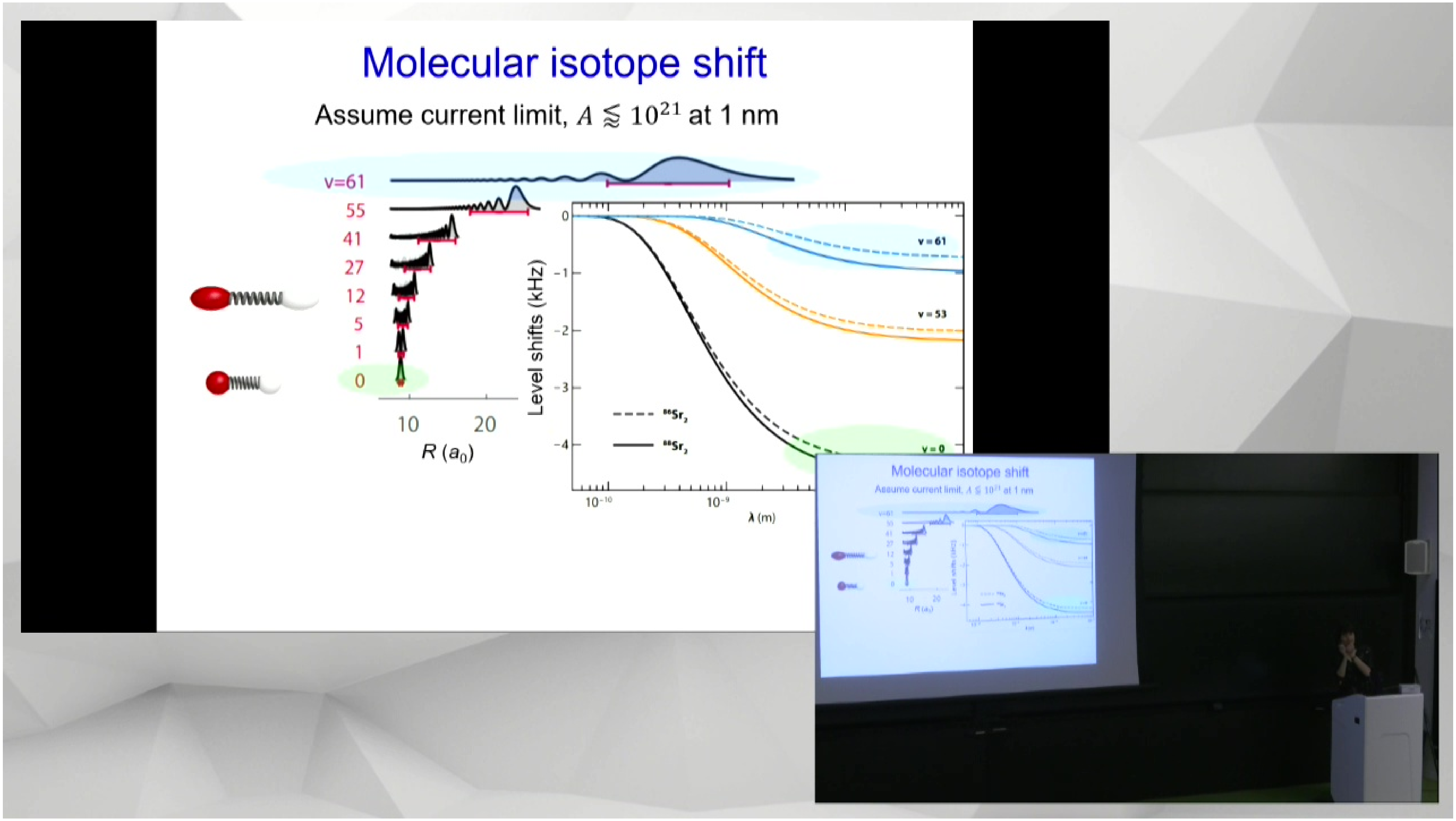
J. J. Lutz and J. M. Hutson, J



Yukawa shift

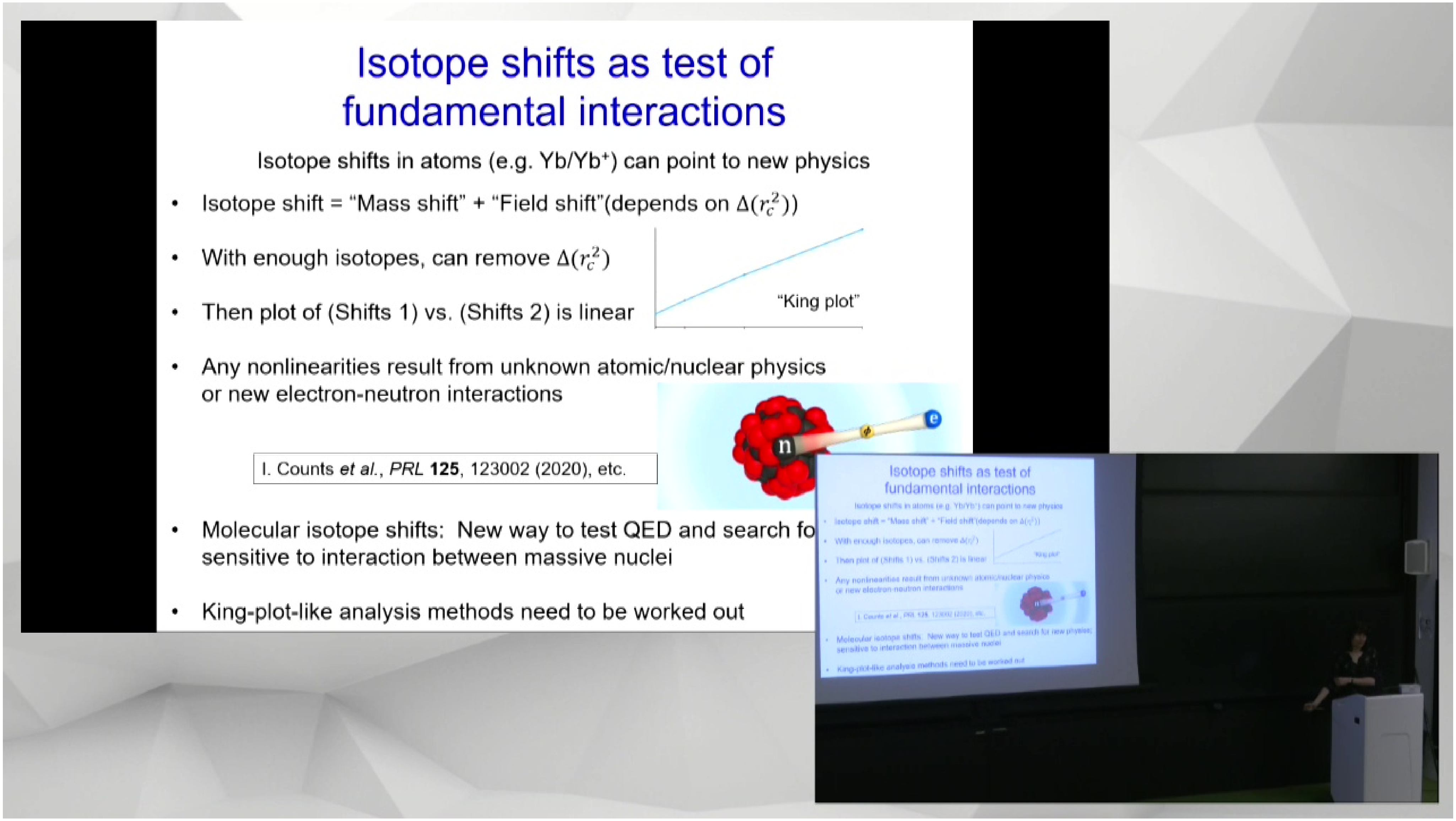
Quantum states *v* probe a range of internuclear distances

Convert $\langle V_{\mathrm{Yukawa}}(R)\rangle$ to $\langle V_{\mathrm{Yukawa}}(v)$



Molecular isotope shift

Assume current limit, $A \lessapprox 10^{21}$ at 1 nm



Isotope shifts as test of fundamental interactions

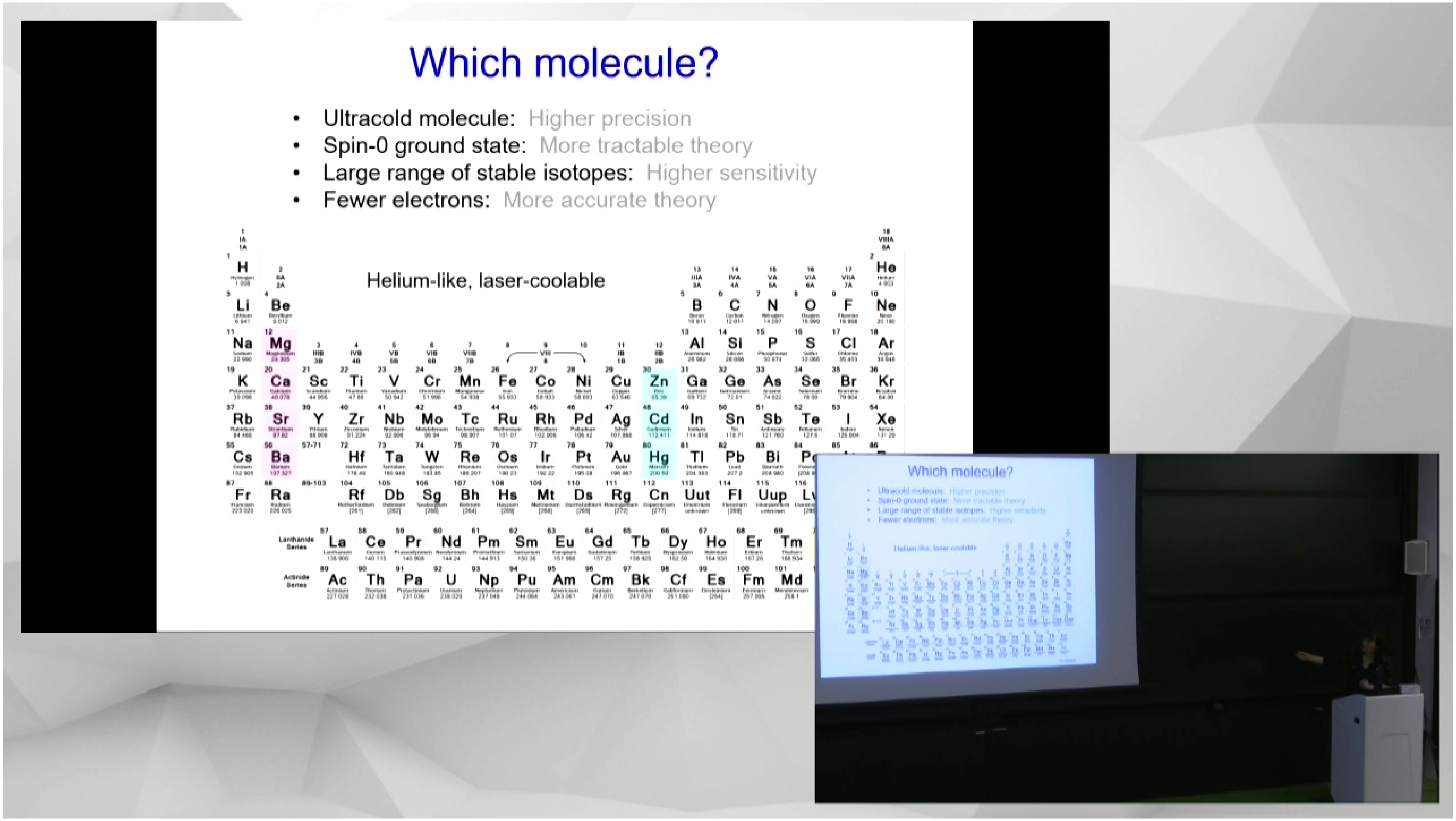
Isotope shifts in atoms (e.g. Yb/Yb⁺) can point to new physics

- Isotope shift = “Mass shift” + “Field shift”(depends on $\Delta(r_c^2)$)
- With enough isotopes, can remove $\Delta(r_c^2)$
- Then plot of (Shifts 1) vs. (Shifts 2) is linear

- Any nonlinearities result from unknown atomic/nuclear physics or new electron-neutron interactions

I. Counts *et al.*, *PRL* **125**, 123002 (2020), etc.

- Molecular isotope shifts: New way to test QED and search fo sensitive to interaction between massive nuclei
- King-plot-like analysis methods need to be worked out



Which molecule?

- Ultracold molecule: Higher precision
- Spin-0 ground state: More tractable theory
- Large range of stable isotopes: Higher sensitivity
- Fewer electrons: More accurate theory

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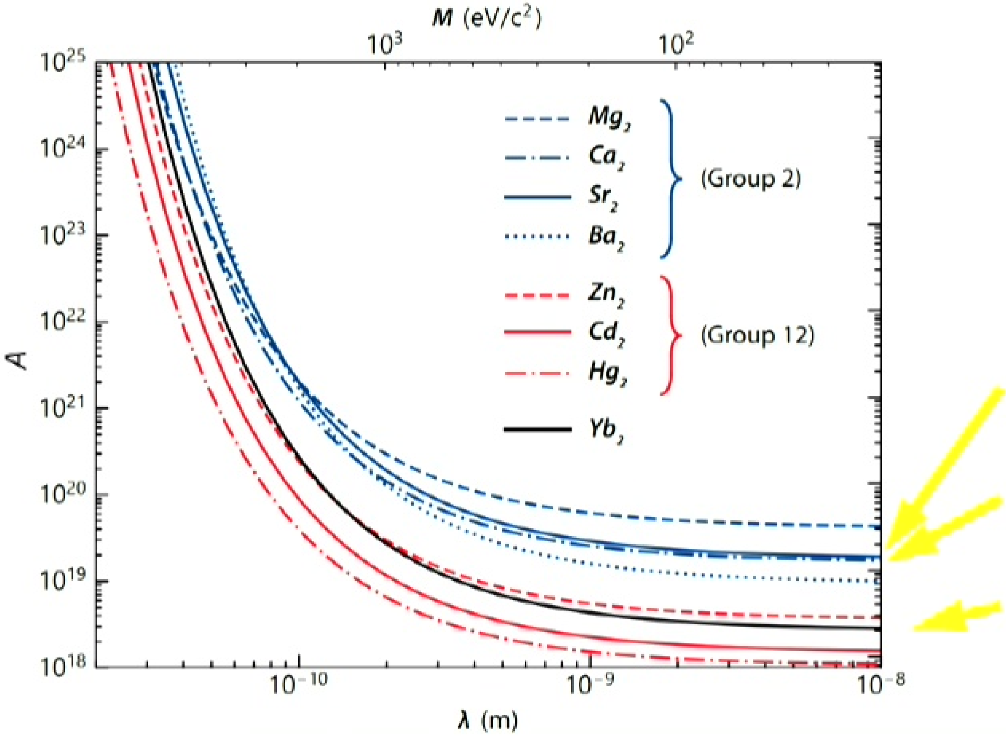

Sr_2 ✓

Ca_2

Many isotopes ☺
Many electrons ☹

Molecular clocks, QED, and 5th force

Born-Oppenheimer approximation

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Beyond B-O

$$\mu = \frac{m_e}{A m_p}$$

adiabatic	μ
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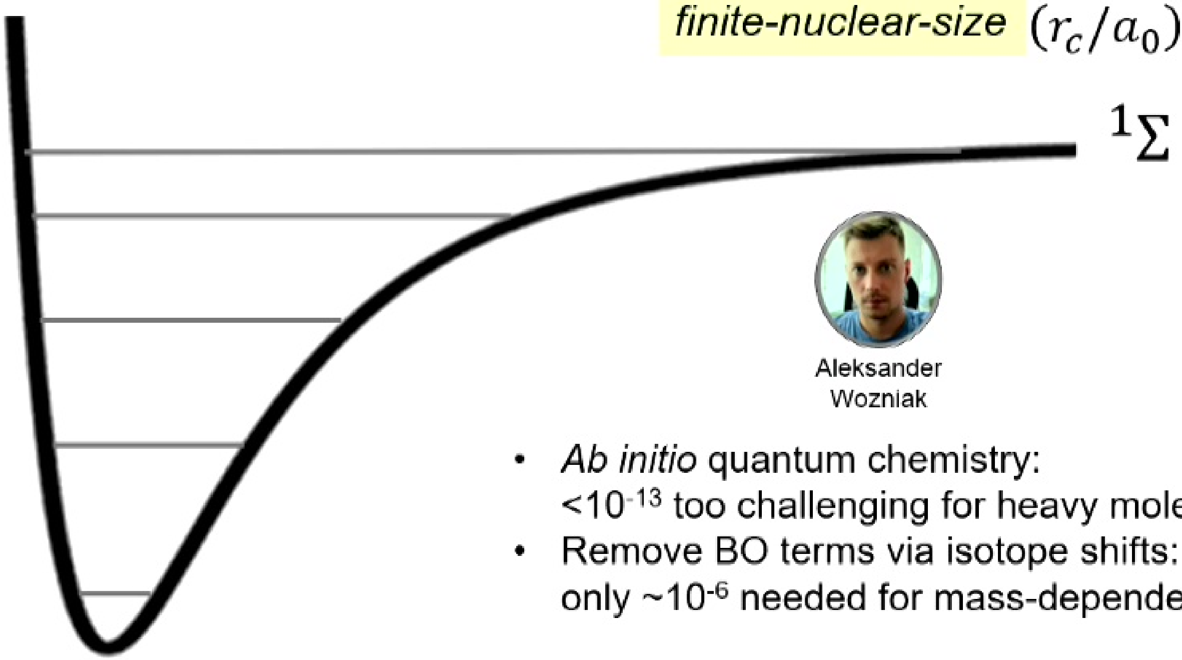
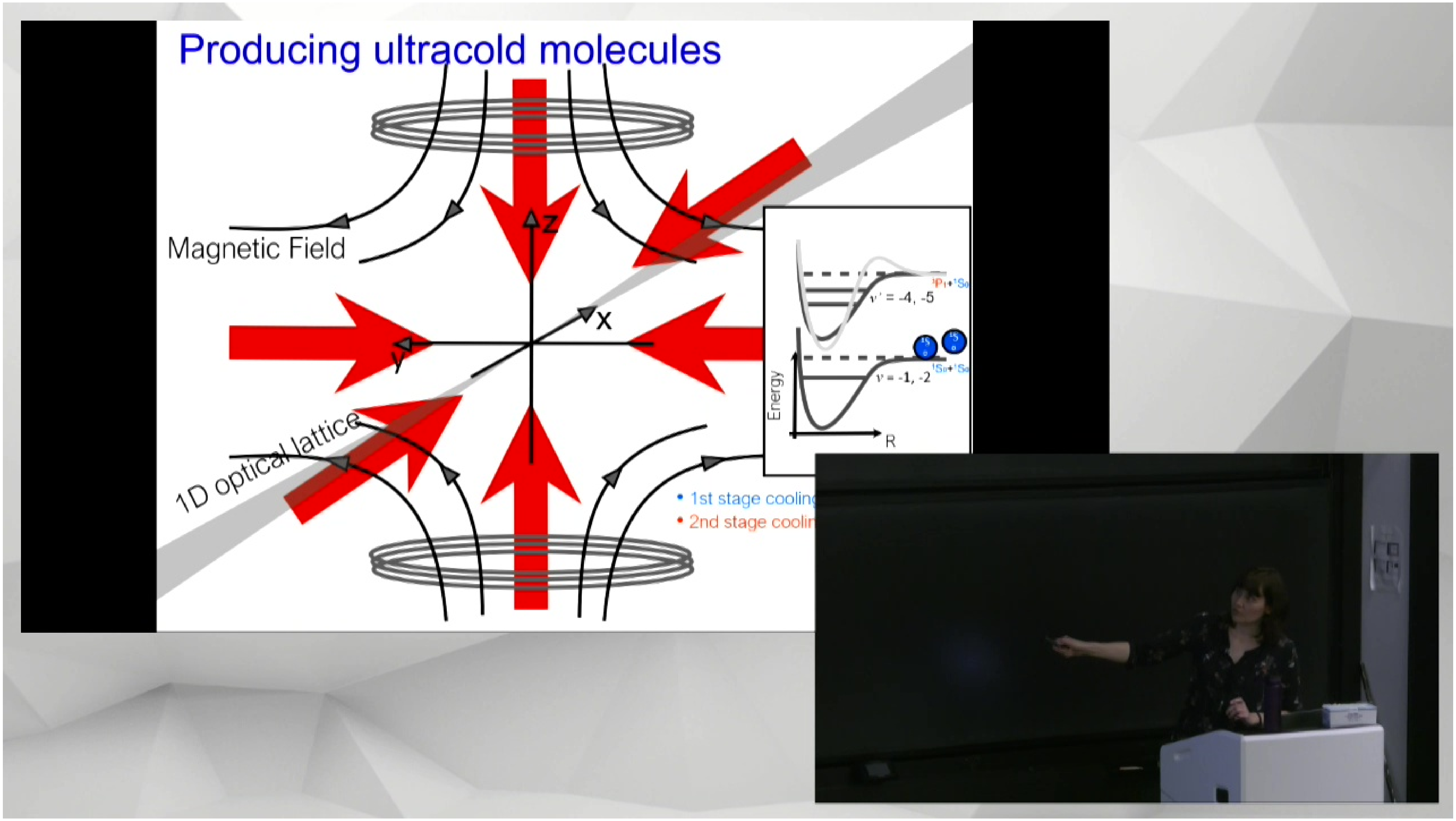


Aleksander Wozniak

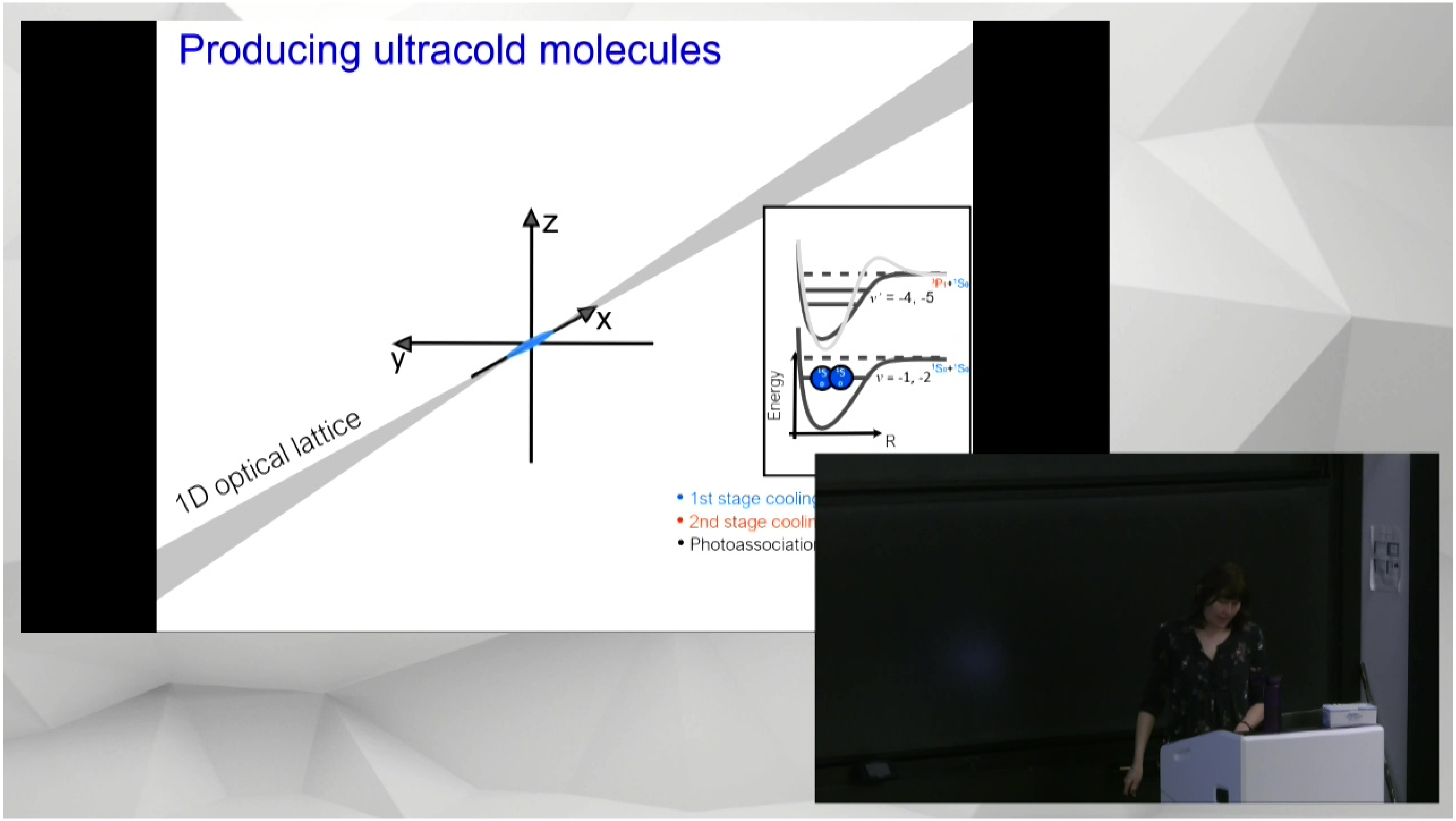
- *Ab initio* quantum chemistry: $<10^{-13}$ too challenging for heavy molecule
- Remove BO terms via isotope shifts: only $\sim 10^{-6}$ needed for mass-dependent terms

J. J. Lutz and J. M. Hutson, *JMS* **330**, 43 (2016)

Producing ultracold molecules



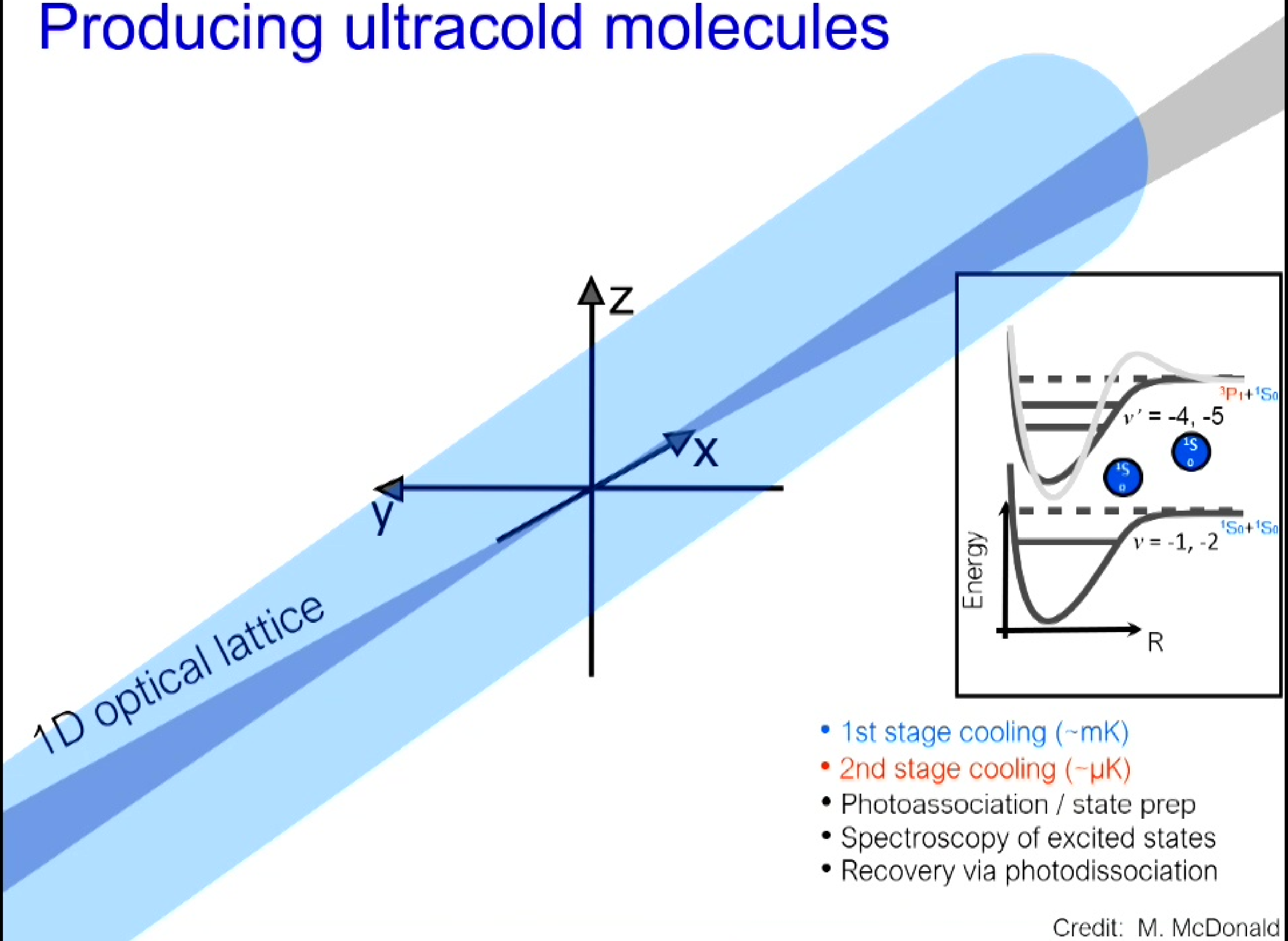
- 1st stage coolin
- 2nd stage coolin



Producing ultracold molecules

- 1st stage coolin
- 2nd stage coolin
- Photoassociatio

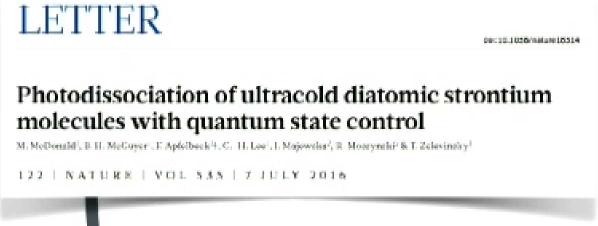
Producing ultracold molecules



- 1st stage cooling (~mK)
- 2nd stage cooling (~μK)
- Photoassociation / state prep
- Spectroscopy of excited states
- Recovery via photodissociation

Credit: M. McDonald

Ultracold photodissociation

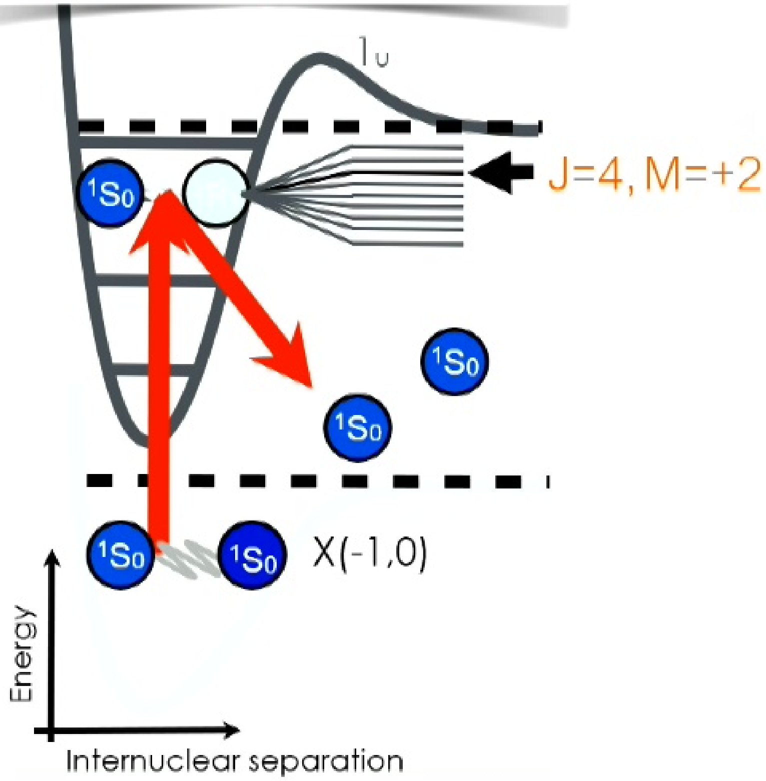


LETTER

Photodissociation of ultracold diatomic strontium molecules with quantum state control

M. McDonald[1], B. H. McGuyer[1], F. Apfelbeck[1,3], C.-H. Lee[1], I. Majewska[2], R. Moszynski[2] & T. Zelevinsky[1]

122 | NATURE | VOL 535 | 7 JULY 2016



Credit: M. McDonald

Ultracold photodissociation

LETTER

doi:10.1038/nature18314

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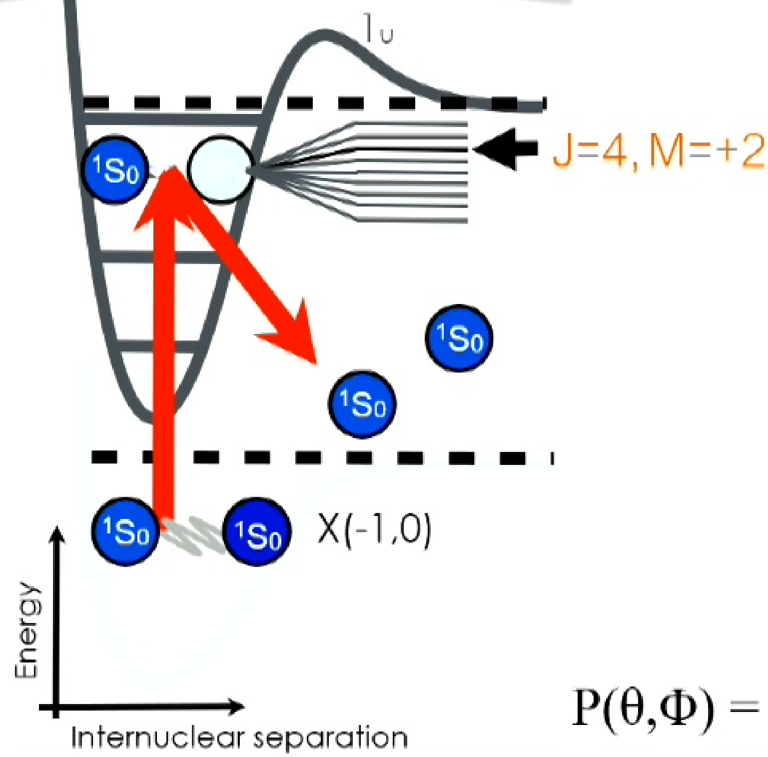
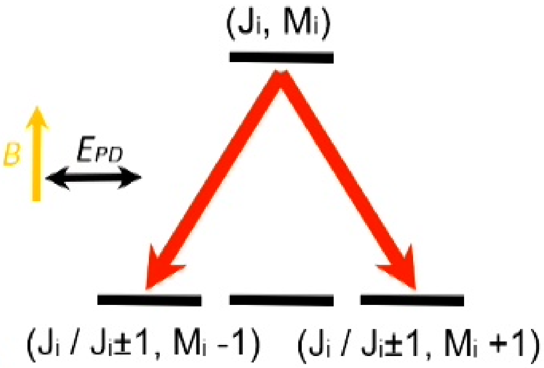
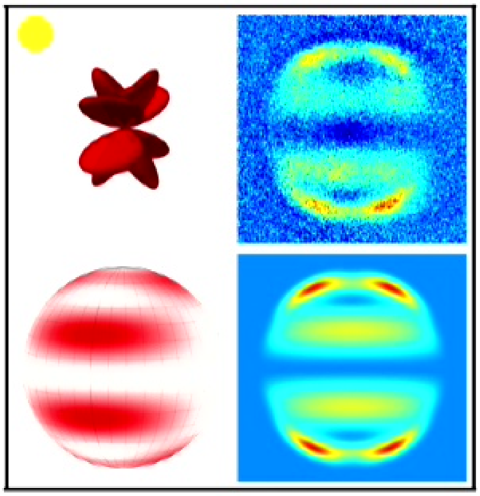




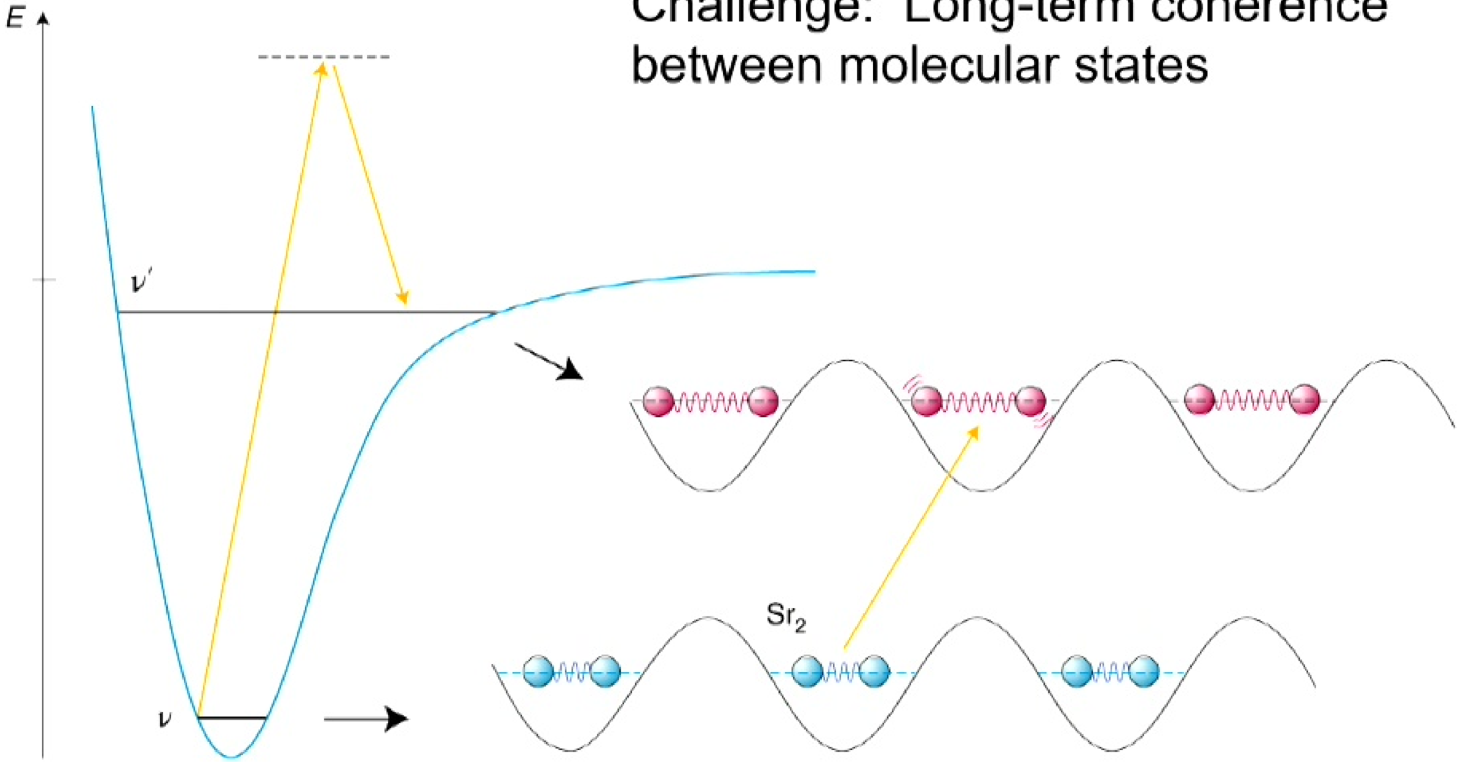


$$P(\theta,\Phi) = |\sqrt{R}\cdot Y_4^1(\theta,\Phi)+\sqrt{1-R}\cdot e^{i\delta}\, Y_4^3(\theta,\Phi)|^2$$

Credit: M. McDonald

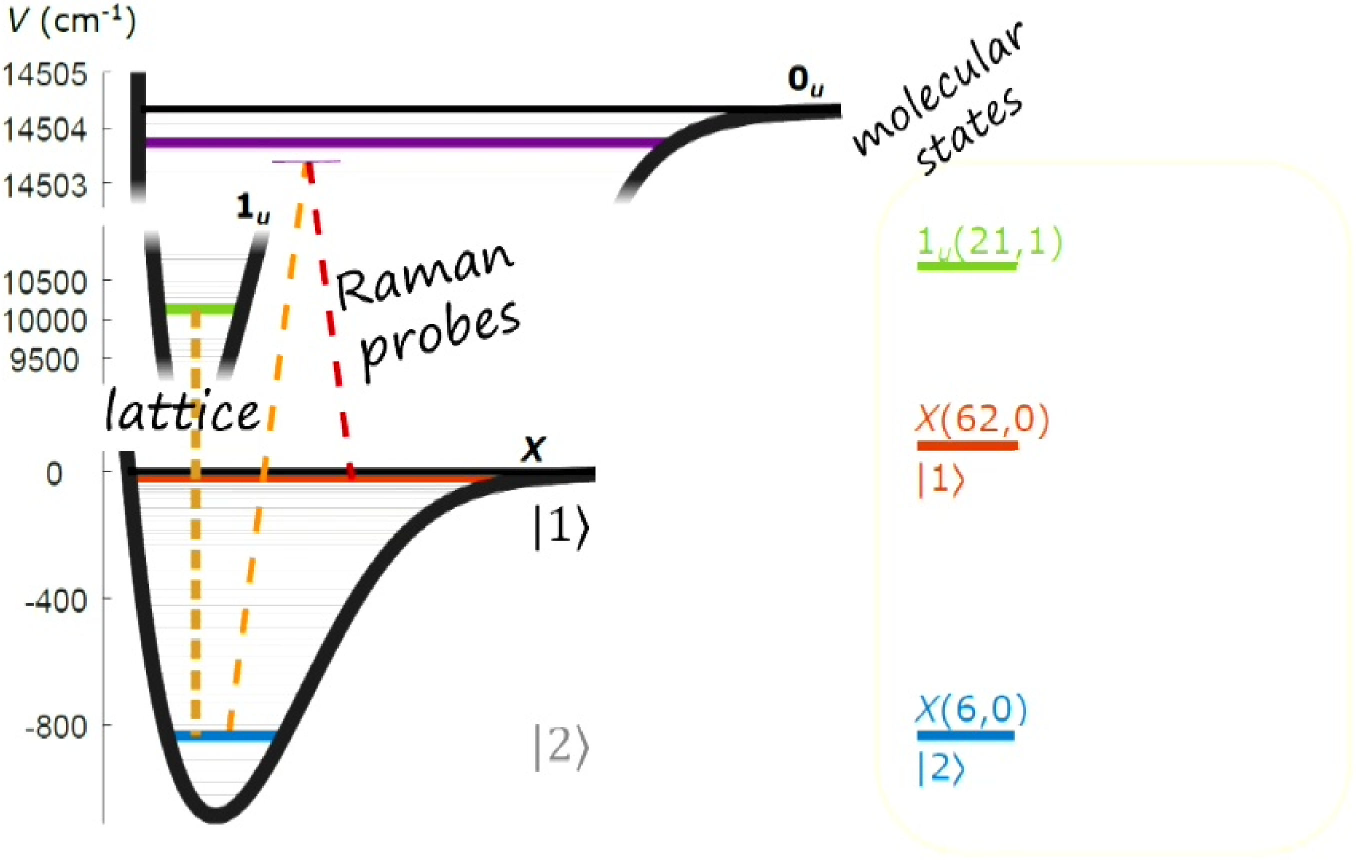
Molecular lattice clock

Challenge: Long-term coherence between molecular states



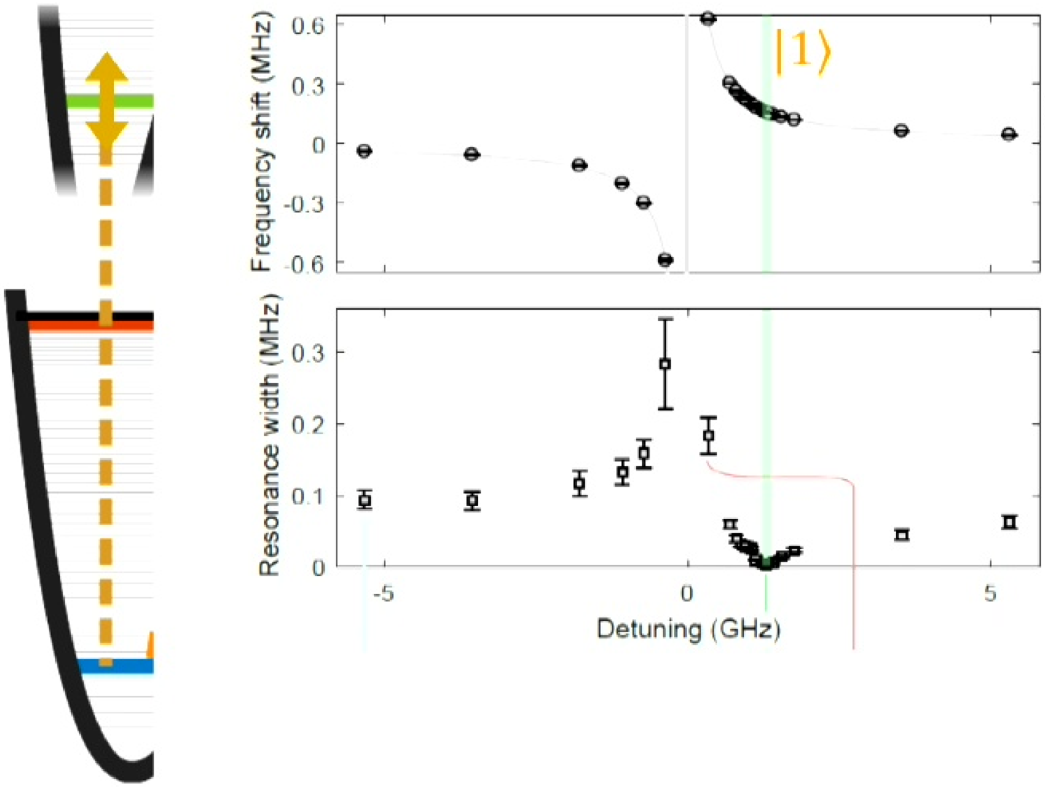
N. Poli, *Nature Phys.* **15**, 1106 (2019)

“Magic” lattice trap



S. S. Kondov *et al.*, *Nature Phys.* **15**, 1118 (2019)

Enhanced coherence in magic lattice

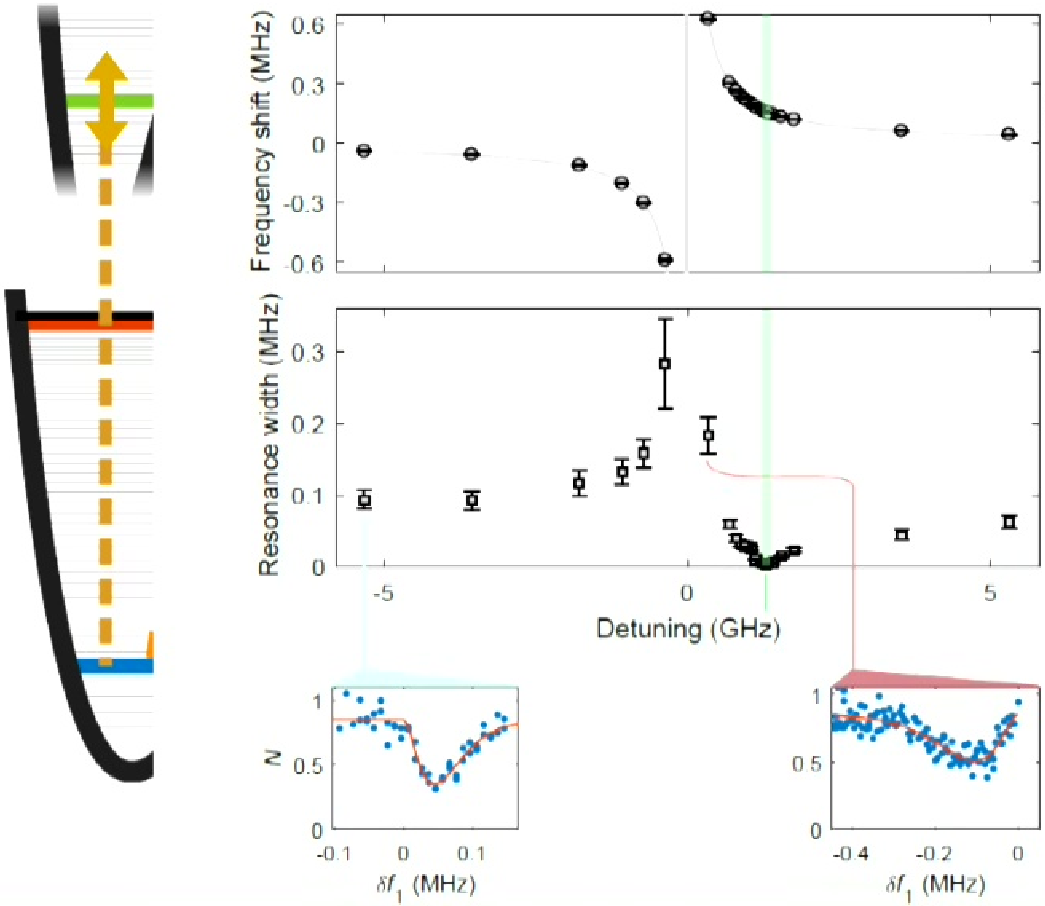


Energy of $|2\rangle$

Clock resonance linewidth

S. S. Kondov *et al.*, *Nature Phys.* **15**, 1118 (2019)

Enhanced coherence in magic lattice



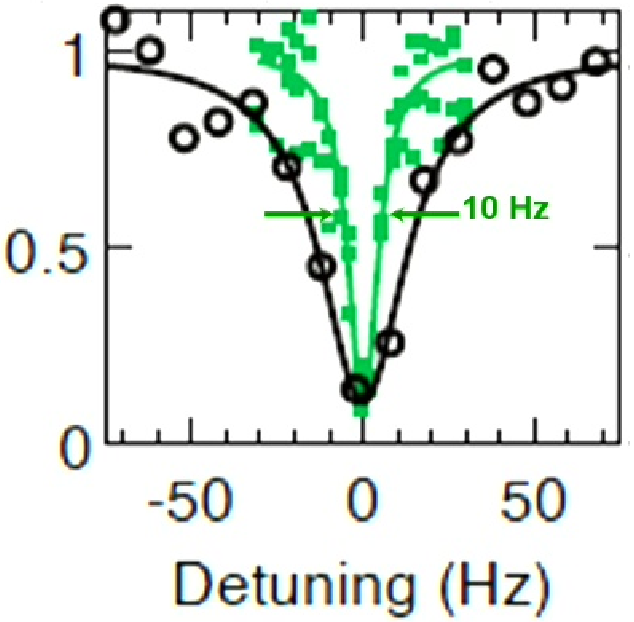
Energy of $|2\rangle$

Clock resonance linewidth

S. S. Kondov *et al.*, *Nature Phys.* **15**, 1118 (2019)

Narrow vibrational clock resonance

Coherence $10^4\times$



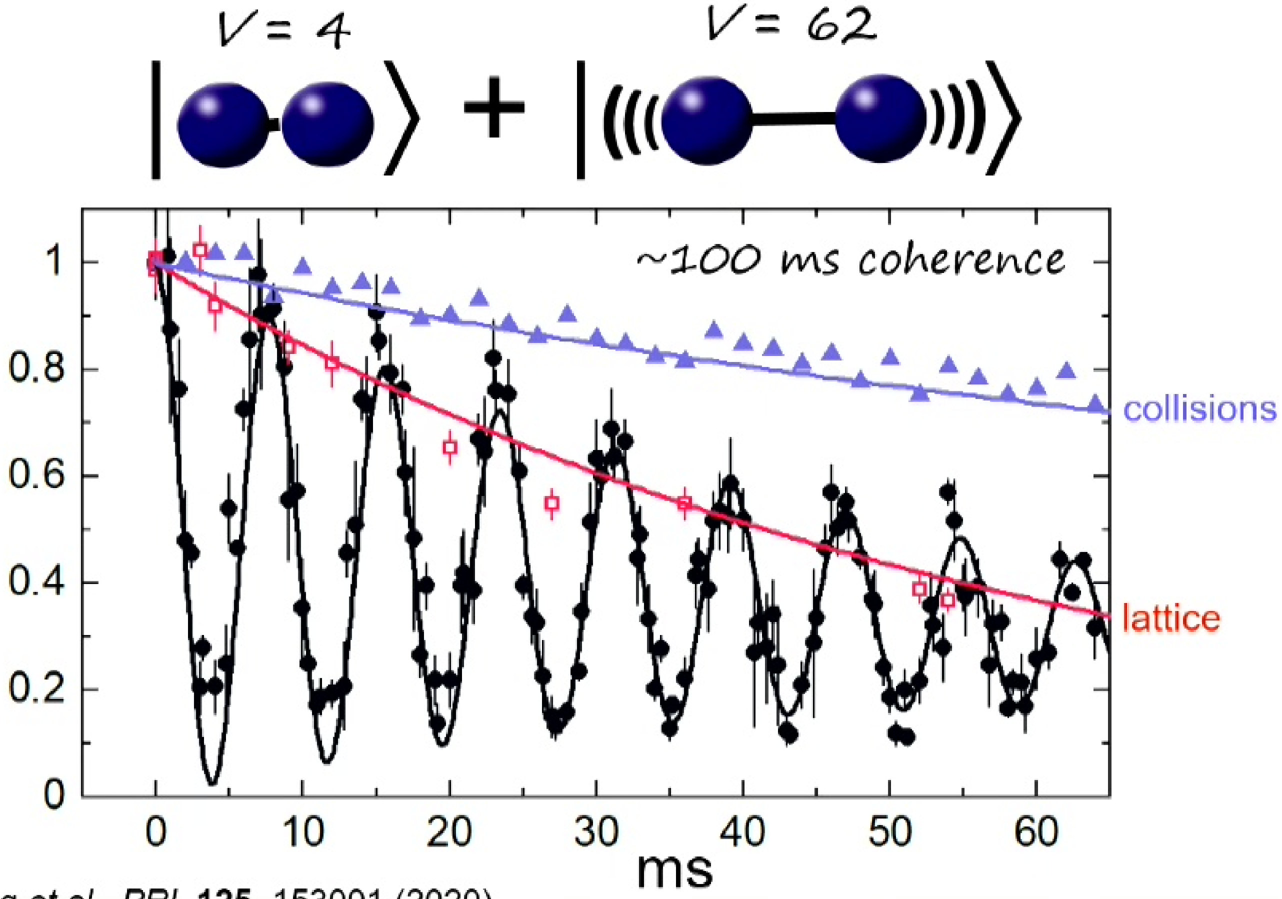
K. H. Leung *et al.*, *Phys. Rev. X 13*, 011047 (2023)

$Q = 3\times10^{12}$

Q (*intrinsic*) $> 10^{26}$

Rabi oscillations

Tightly-to-weakly-bound molecules


V = 4

V = 62

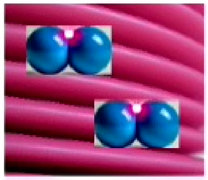
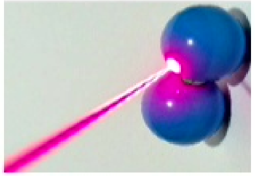
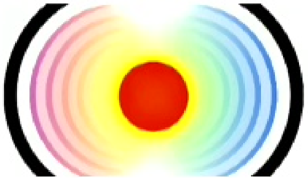
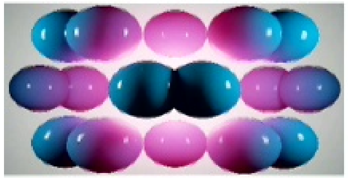
~100 ms coherence

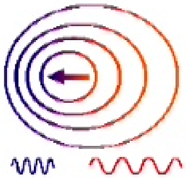
K. H. Leung *et al.*, *PRL* **125**, 153001 (2020)

Clock precision

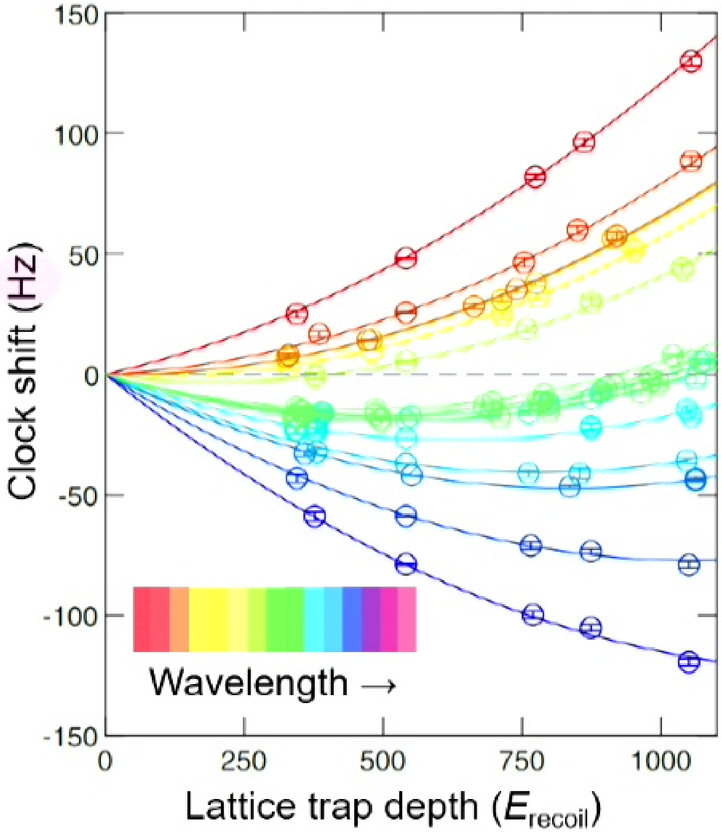
Systematic effects:
What can cause the clock frequency to shift?

- Lattice laser light
- Probe laser light
- Blackbody radiation
- Collisions
- Magnetic fields
- Doppler shifts

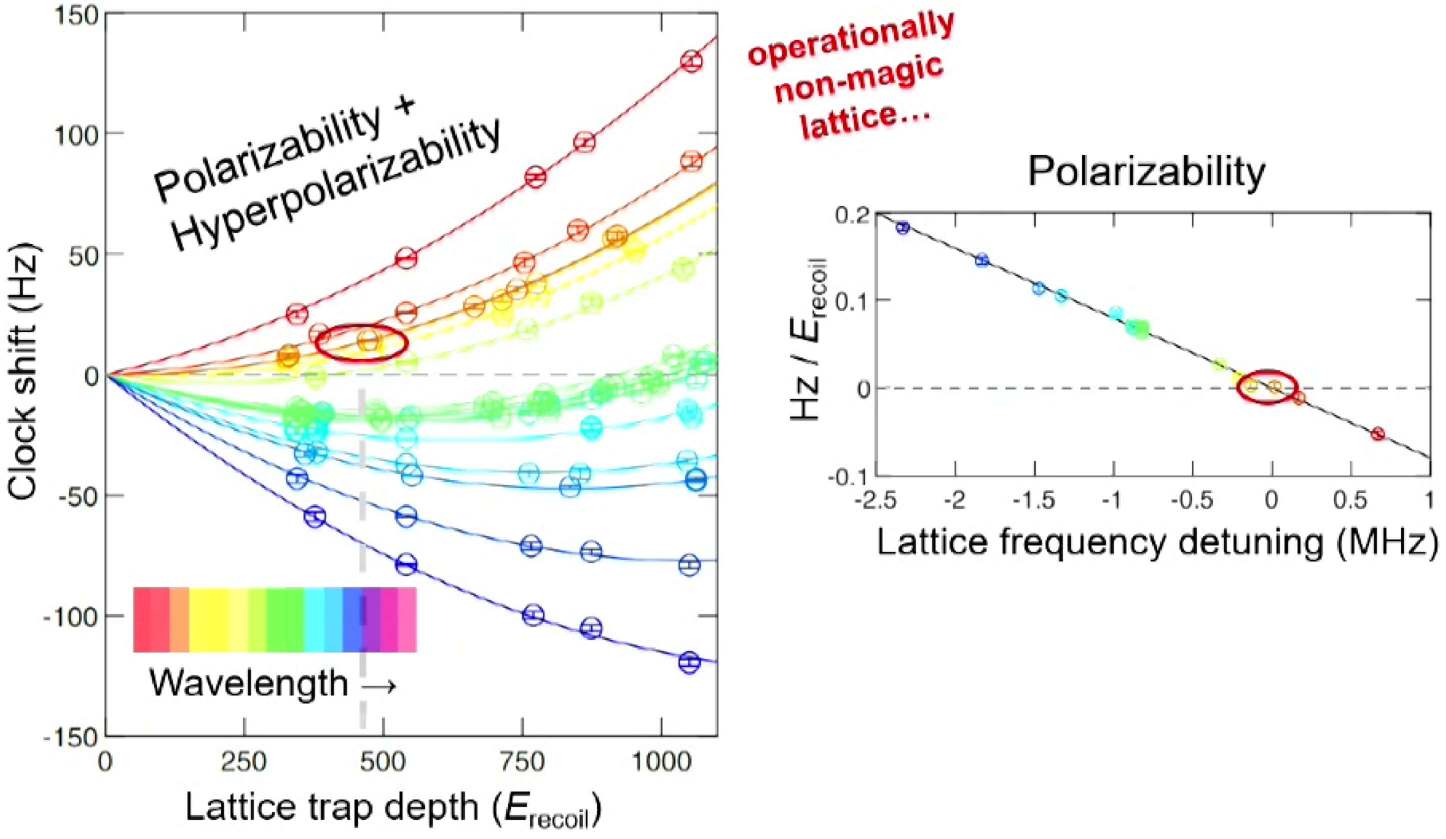


Lattice light shift: Zoom in



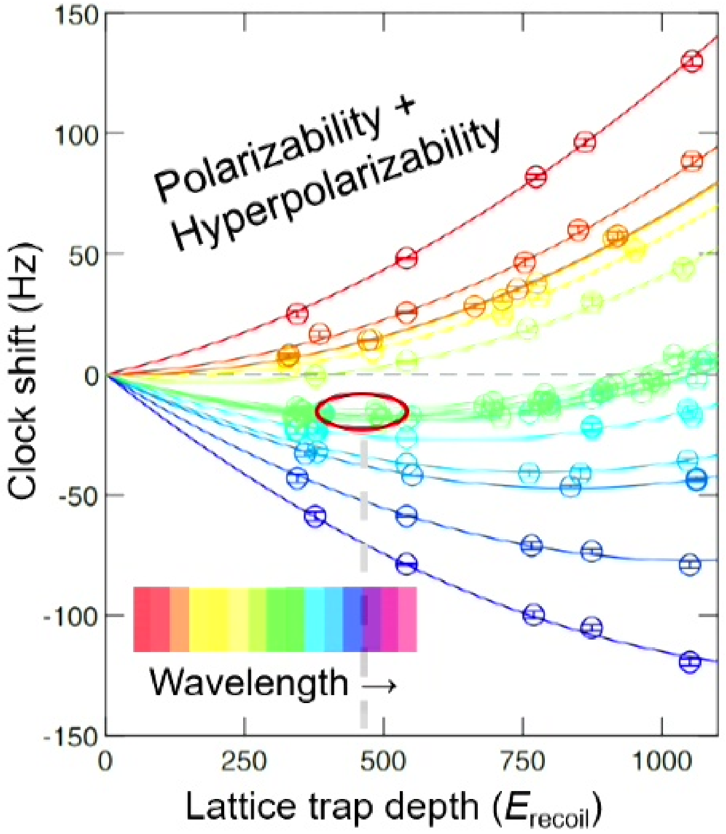
K. H. Leung *et al.*, *Phys. Rev. X 13*, 011047 (2023)

Observe vibrational hyperpolarizability



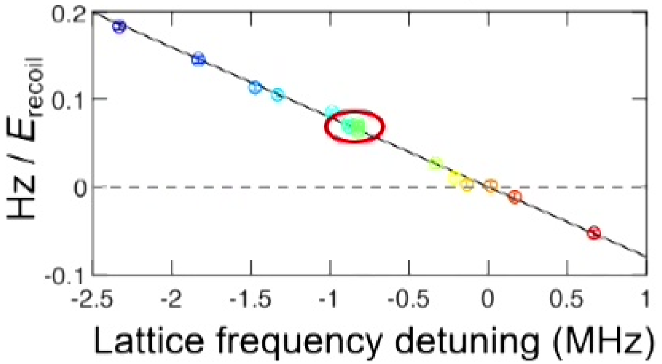
K. H. Leung *et al.*, *Phys. Rev. X 13*, 011047 (2023)

Effectively magic lattice



operationally magic lattice

Polarizability



~4×10^{-14} uncertainty, dominant contributor

K. H. Leung *et al.*, *Phys. Rev. X 13*, 011047 (2023)

Clock precision

Systematic effects:
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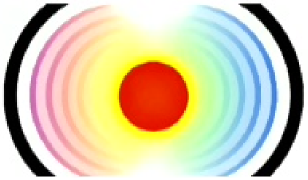
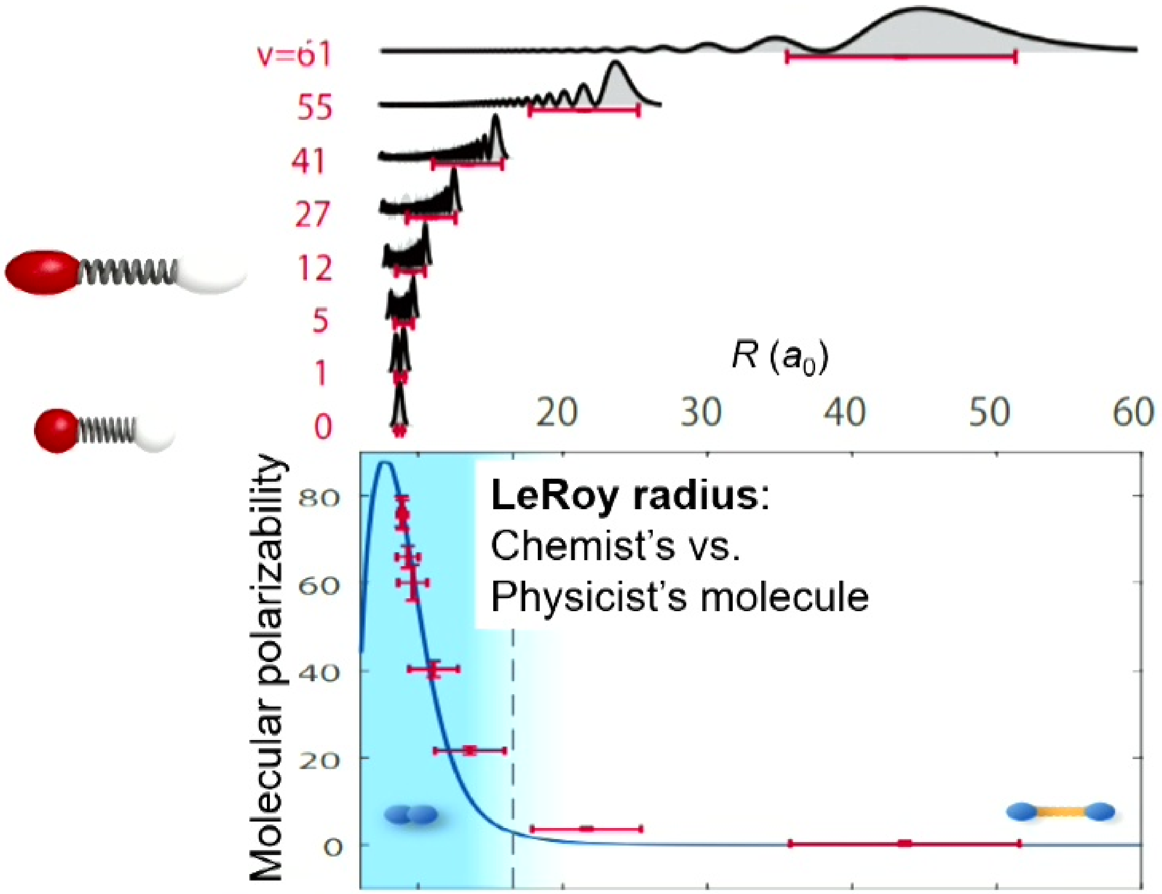
- Blackbody radiation



Far-infrared polarizabilities

Response of vibrating molecule to BBR



LeRoy radius:
Chemist's vs.
Physicist's molecule

Clock precision

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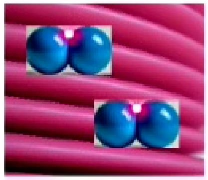
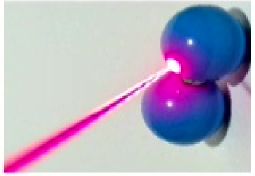
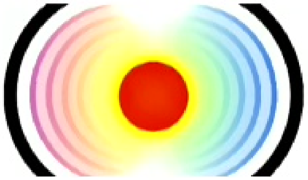


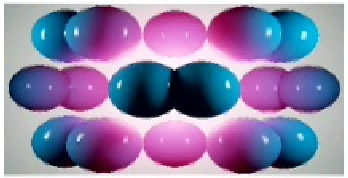
- Probe laser light



- Blackbody radiation

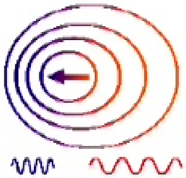


- Collisions



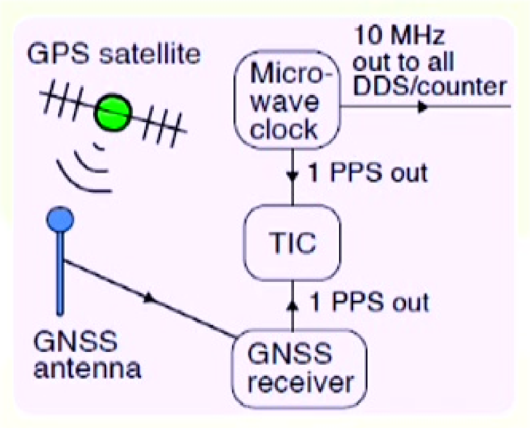
- Magnetic fields

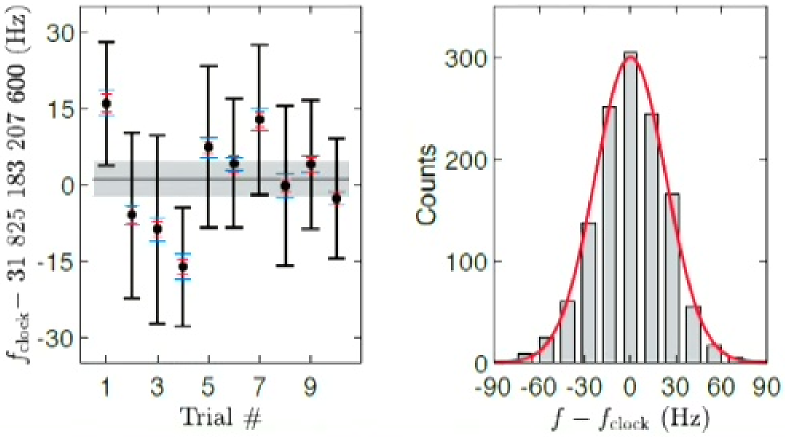
- Doppler shifts



Absolute clock measurement

Comparison to Cs atomic time standard



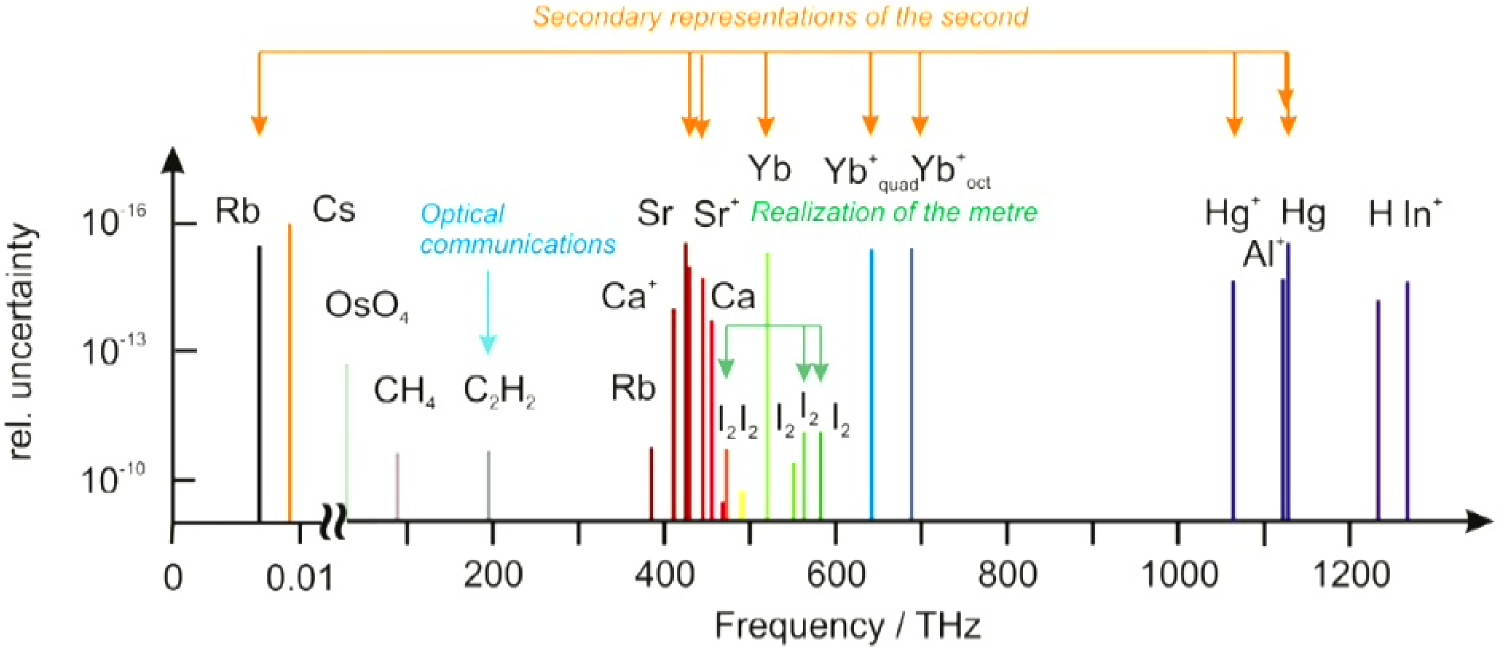


1×10^{-13} uncertainty

K. H. Leung *et al.*, *Phys. Rev. X 13*, 011047 (2023)

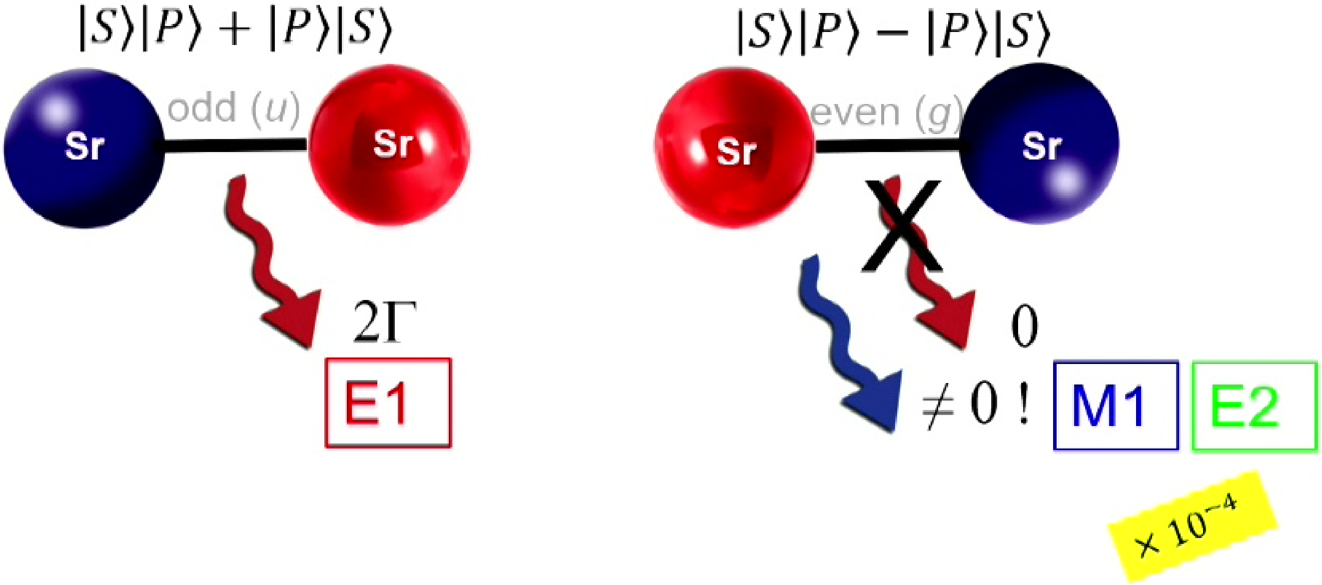
Atomic and molecular frequency standards

Primary and secondary



F. Riehle *et al.*, *Metrologia* **55**, 188 (2018)

Optical molecular clocks



Superradiant

$|S\rangle|P\rangle + |P\rangle|S\rangle$

2Γ

E1

Subradiant

$|S\rangle|P\rangle - |P\rangle|S\rangle$

0

$\neq 0$!

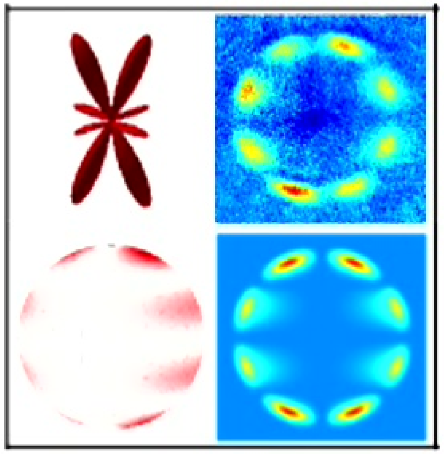
M1 E2

$\times 10^{-4}$

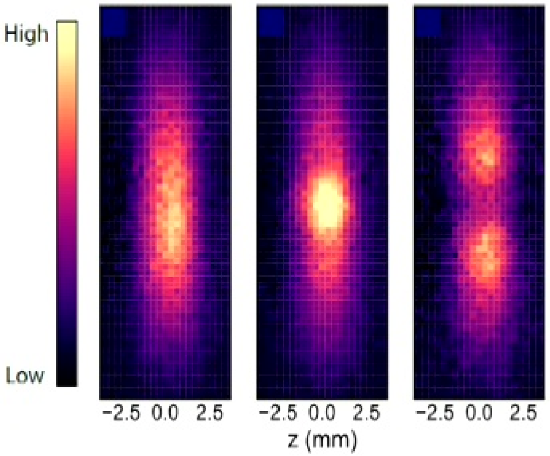
B. McGuyer *et al*., *Nature Phys*. **11**, 32 (2015)

Other projects with cold molecules

Ultracold chemistry and quantum photodissociation



Laser cooling of new bosonic and fermionic molecules (CaH, CaD)



CeNTREX: Proton EDM & fundamental symmetries