

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>

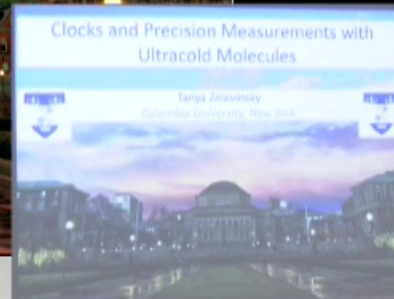
Abstract: Significant advancements in our understanding of the physical world have been driven by increasingly precise atomic spectroscopy. The level of accessible precision entered a new realm with the advent of laser cooling and trapping. Now we can extend the ultrahigh spectroscopic precision, or 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

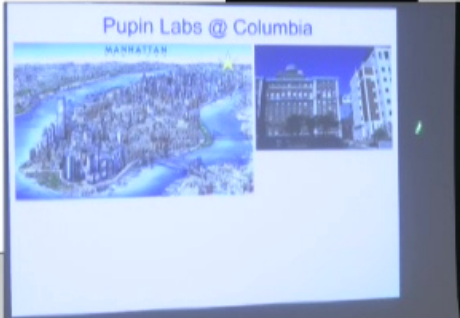
Clocks and Precision Measurements with Ultracold Molecules



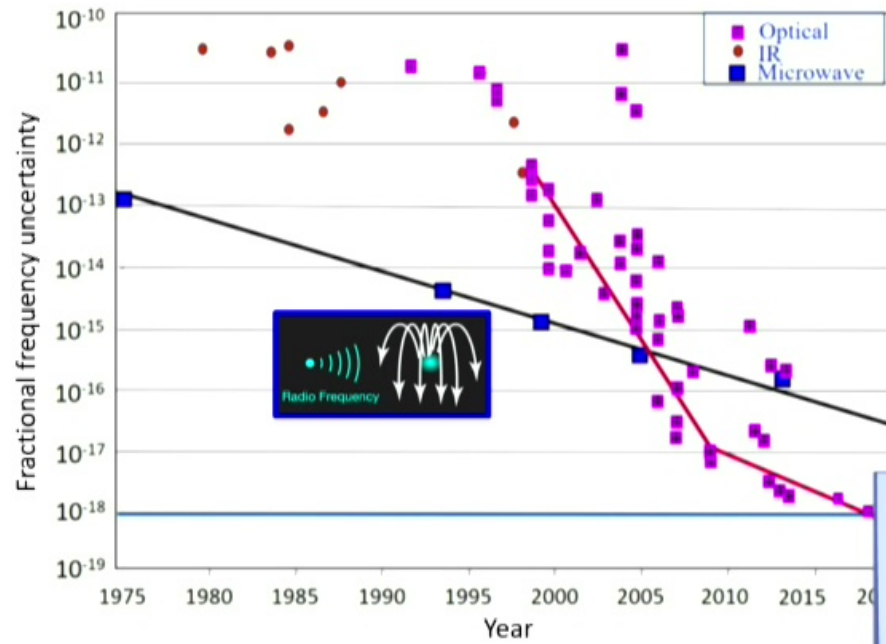
Tanya Zelevinsky
Columbia University, New York



Pupin Labs @ Columbia

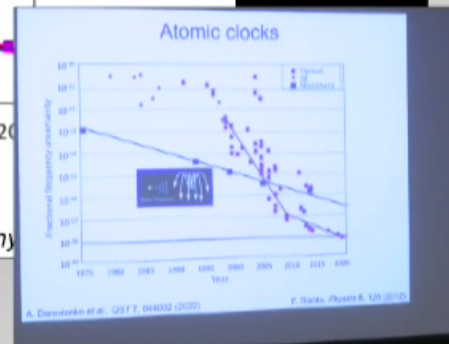


Atomic clocks

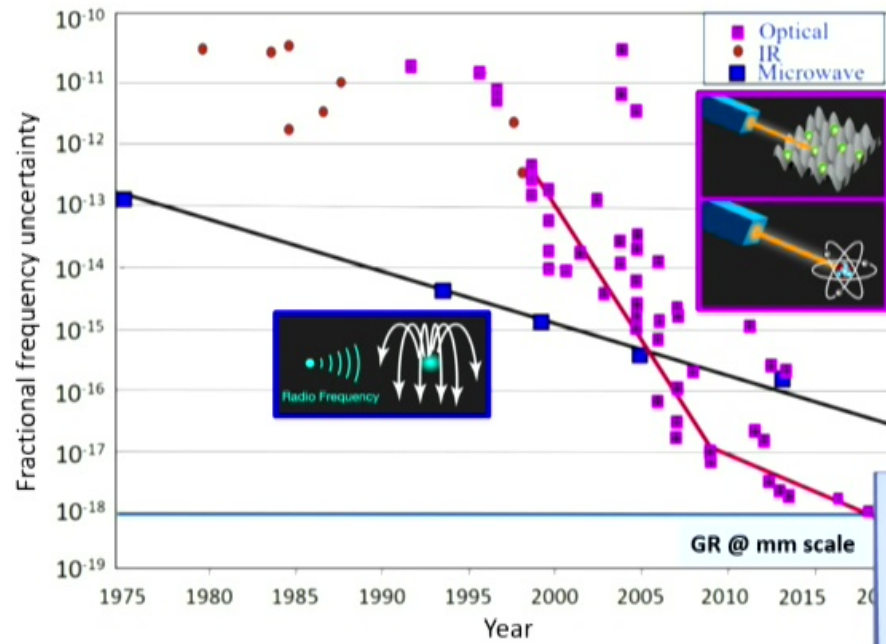


A. Derevianko *et al.*, QST 7, 044002 (2022)

F. Riehle, *Phys*

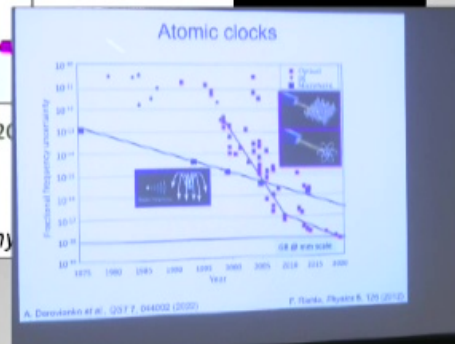


Atomic clocks



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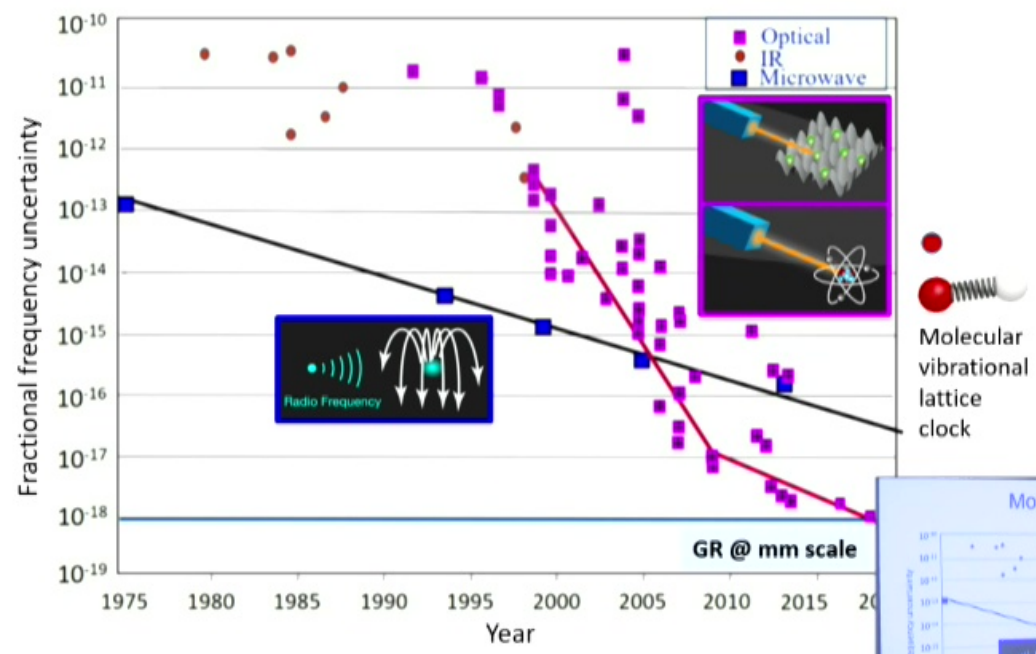
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A. Derevianko *et al.*, QST 7, 044002 (2022)

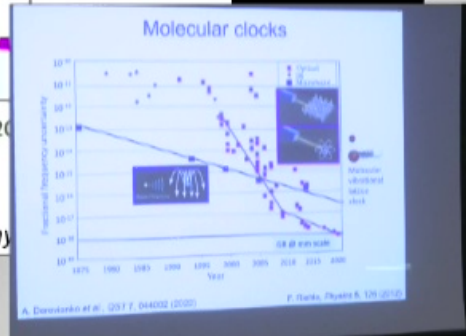
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Molecular clocks



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

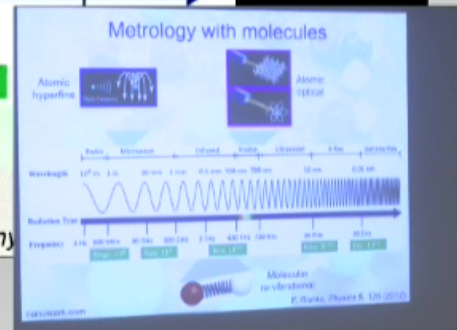
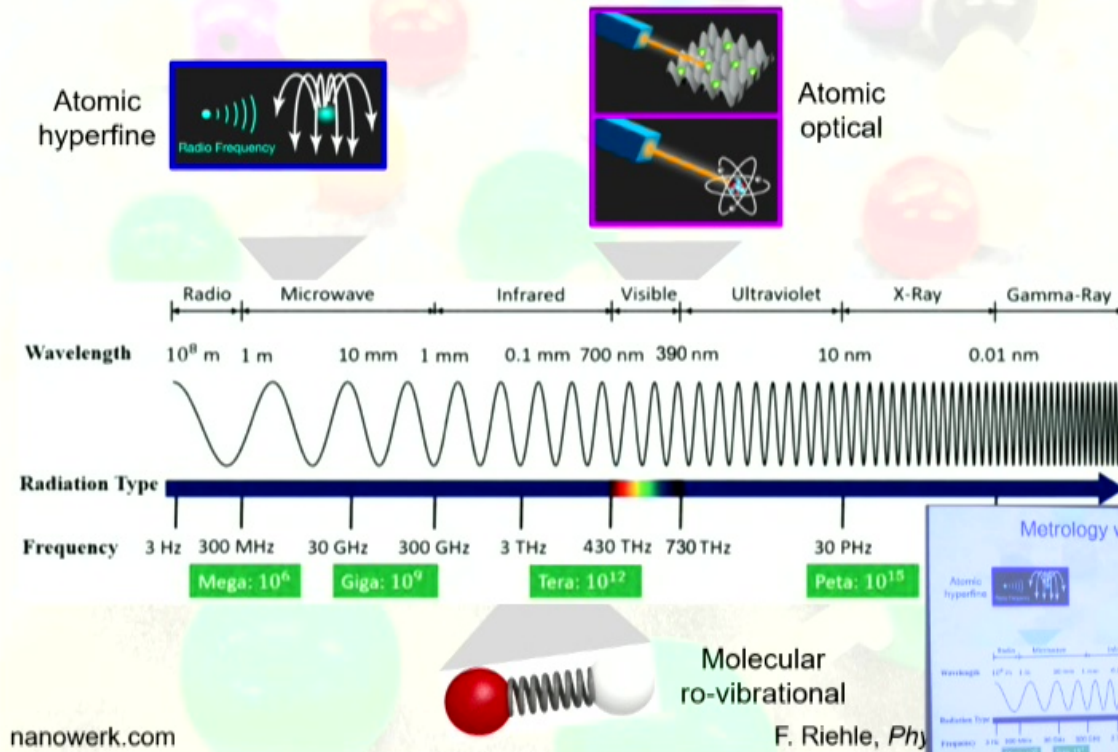
F. Riehle, *Phy*



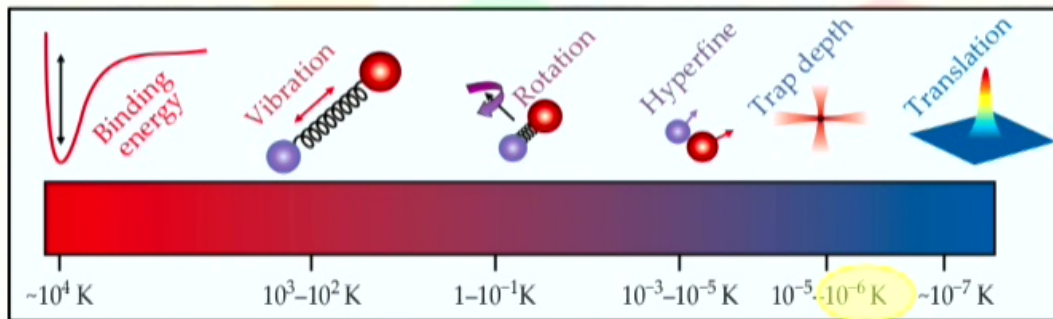
A. Derevianko *et al.*, QST 7, 044002 (2022)

F. Riehle, *Phys*

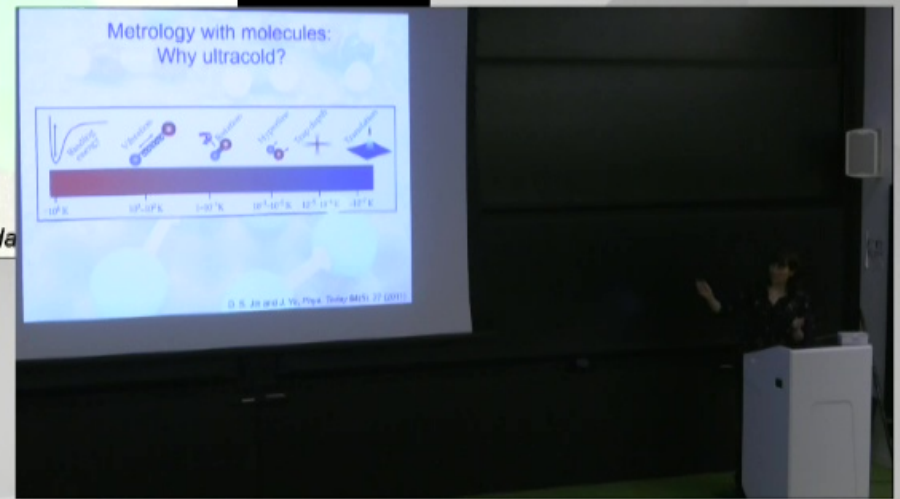
Metrology with molecules



Metrology with molecules: Why ultracold?

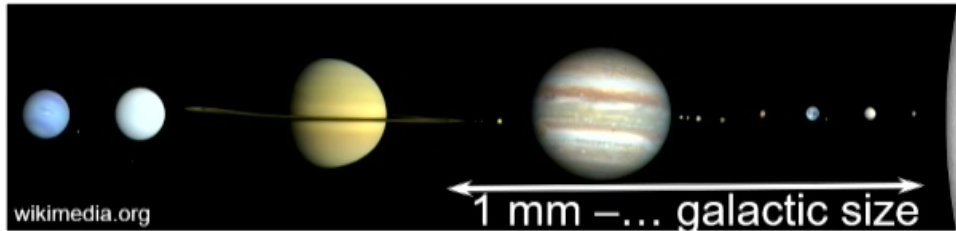


D. S. Jin and J. Ye, *Phys. Today*

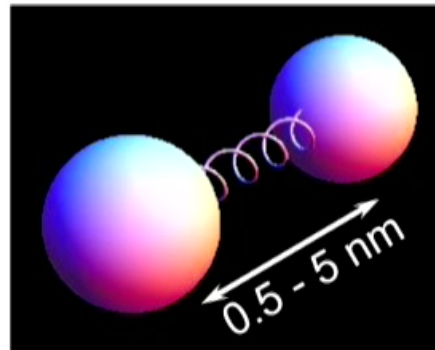


Science with molecular clocks

Newtonian gravity at large scales: Well-understood

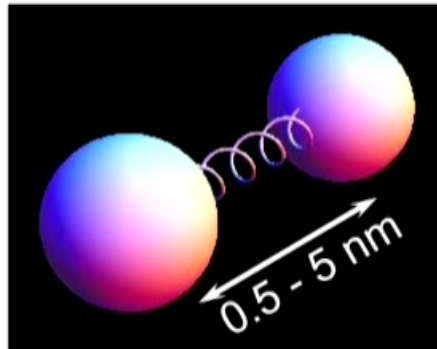


Gravity at nanometer scales: Nearly unknown



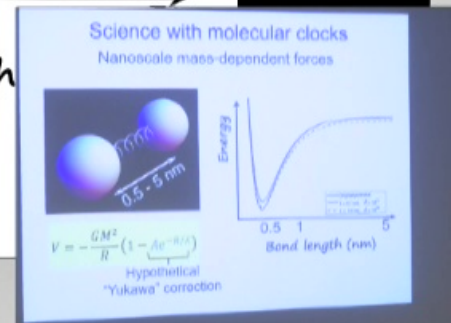
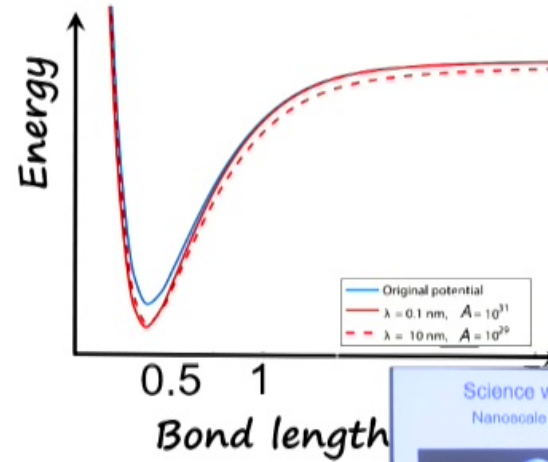
Science with molecular clocks

Nanoscale mass-dependent forces



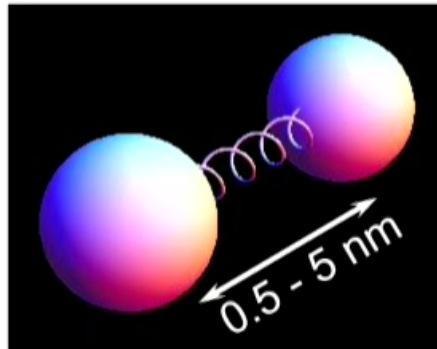
$$V = -\frac{GM^2}{R} \left(1 - \underbrace{Ae^{-R/\lambda}} \right)$$

Hypothetical
"Yukawa" correction



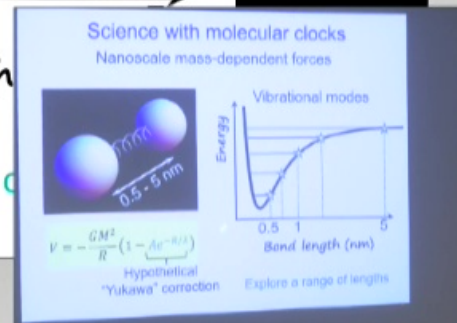
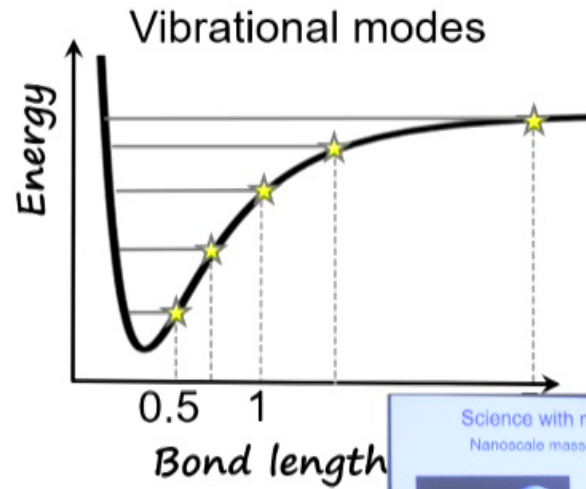
Science with molecular clocks

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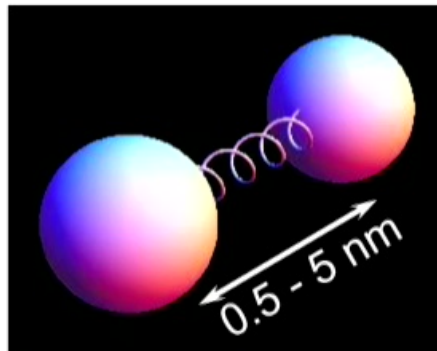
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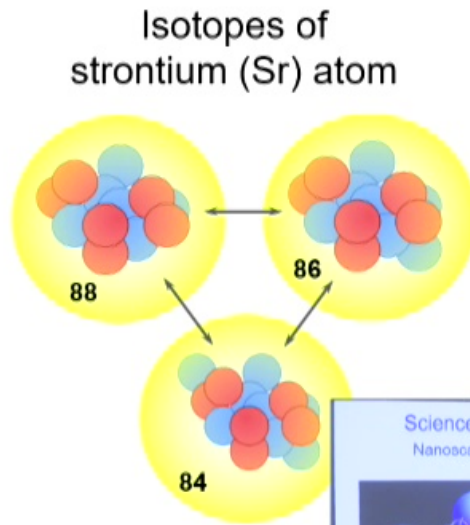
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Nanoscale mass-dependent forces

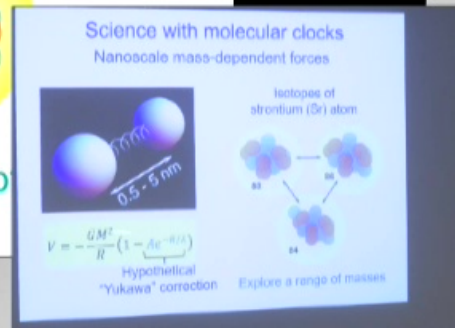


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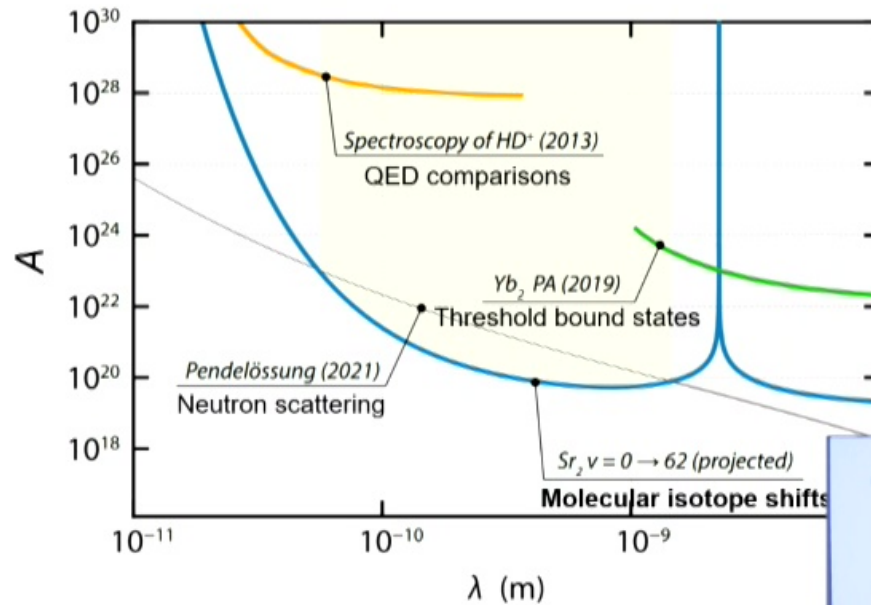


Explore a range of



“5th force” with molecular clock

New approach: Vibrational isotope shifts in nonpolar diatomic molecules

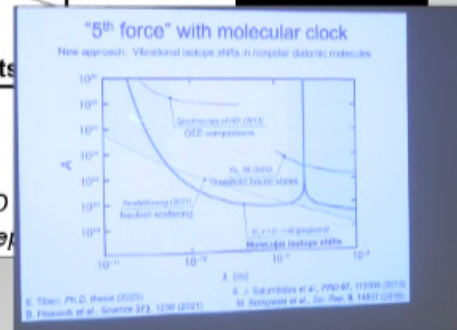


E. Tiberi, *Ph.D. thesis* (2023)

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

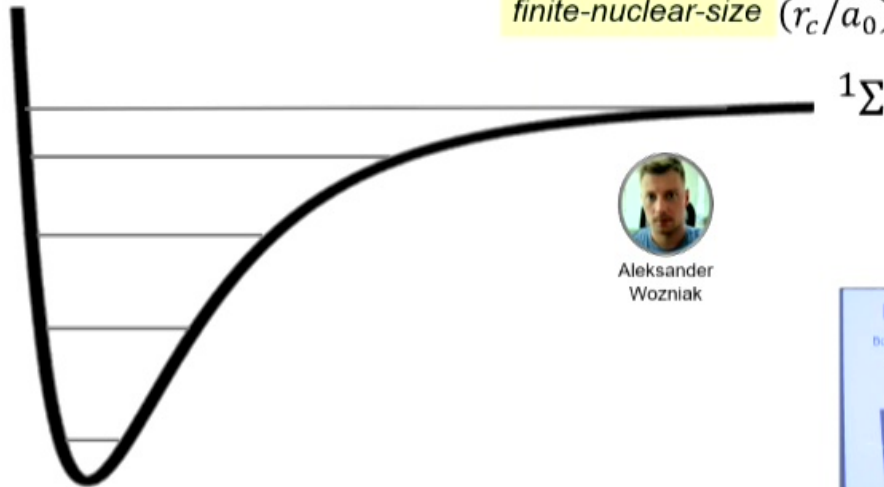
adiabatic
nonadiabatic
relativistic, QED
finite-nuclear-size

$$\mu = \frac{m_e}{Am_p}$$

$$\mu^2$$

$$\alpha^2 \mu, \alpha^3 \mu$$

$$(r_c/a_0)^2$$



Aleksander Wozniak



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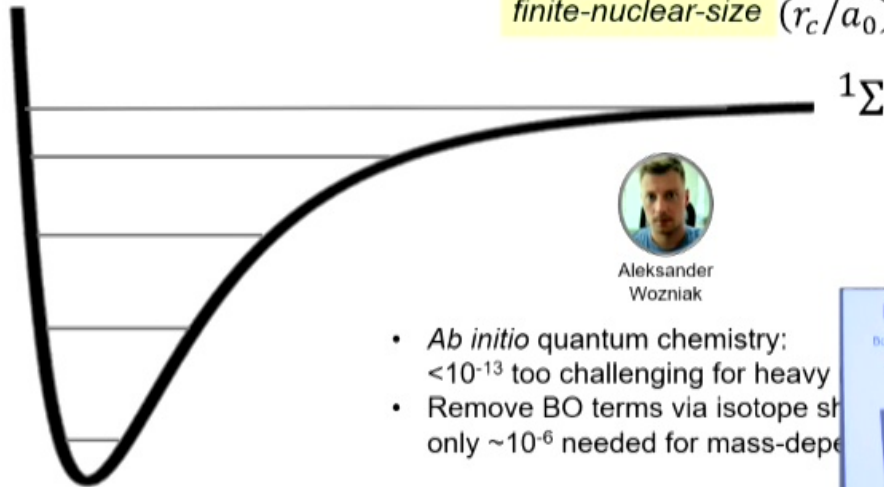
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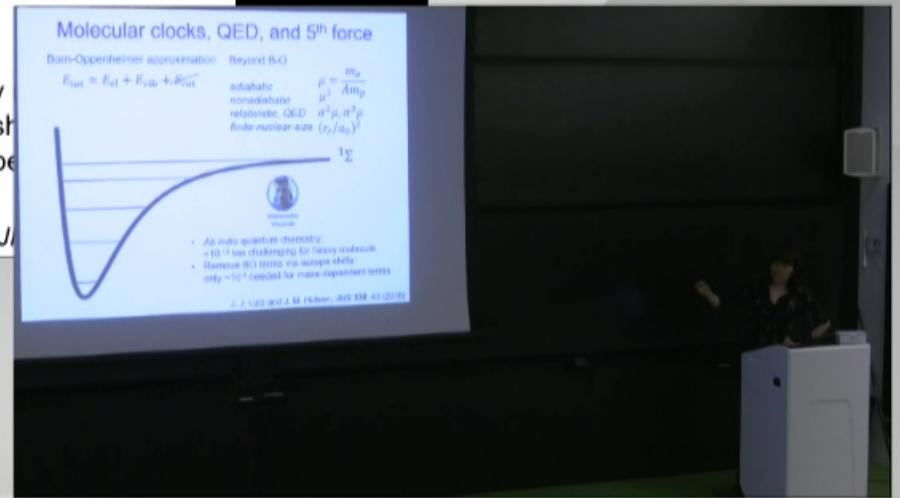
$$(r_c/a_0)^2$$



Aleksander Wozniak

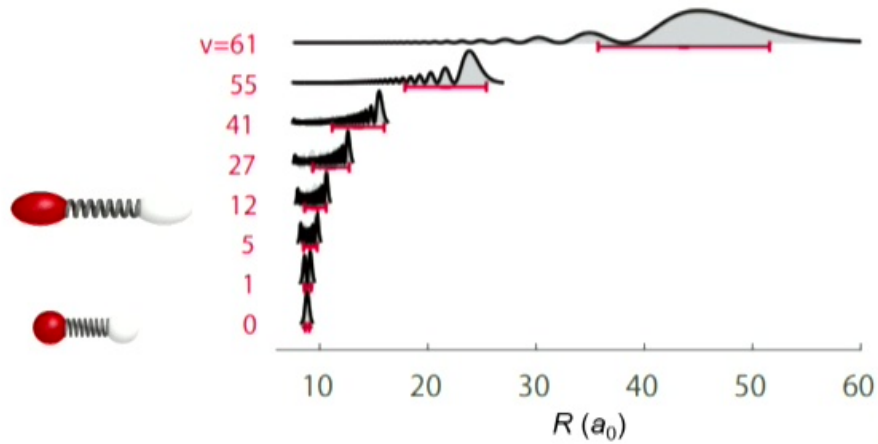
- *Ab initio* quantum chemistry: $<10^{-13}$ too challenging for heavy
- Remove BO terms via isotope shift only $\sim 10^{-6}$ needed for mass-dep

J. J. Lutz and J. M. Hutson, *J. Chem. Phys.* 128, 124301 (2008)

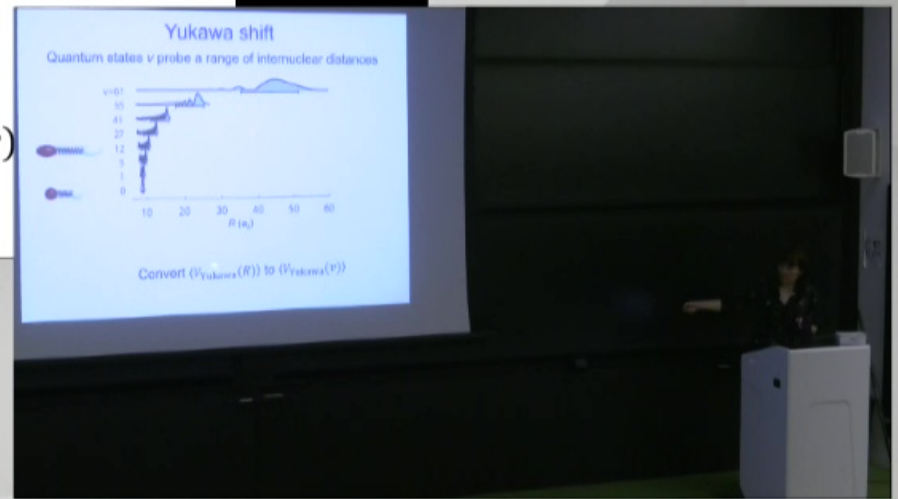


Yukawa shift

Quantum states v probe a range of internuclear distances

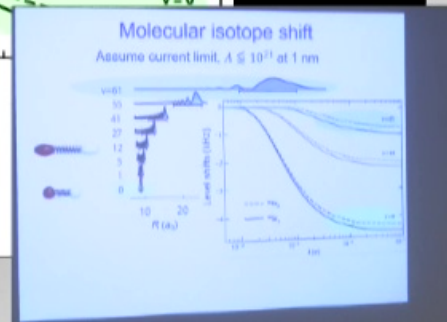
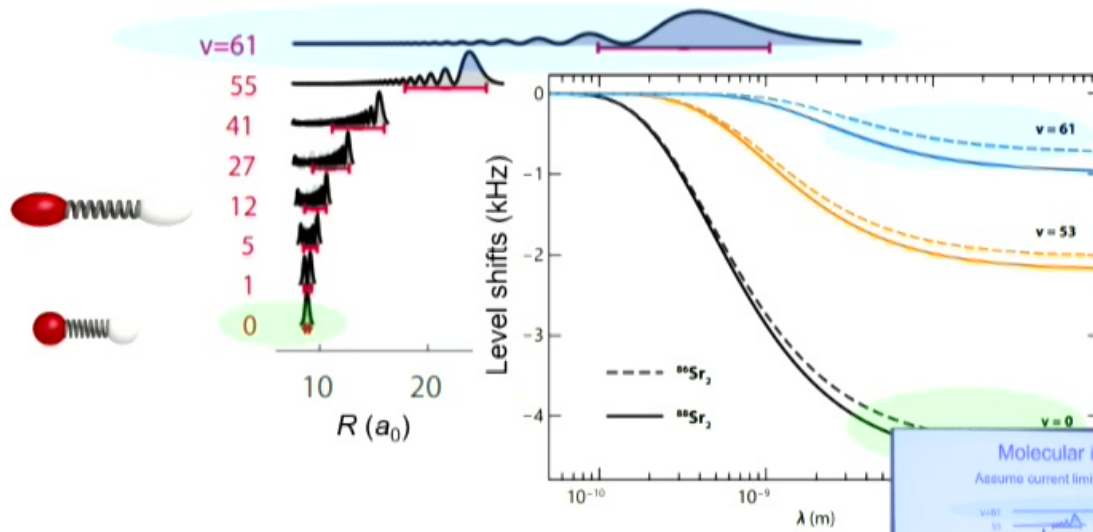


Convert $\langle V_{\text{Yukawa}}(R) \rangle$ to $\langle V_{\text{Yukawa}}(v) \rangle$



Molecular isotope shift

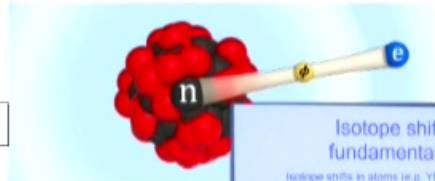
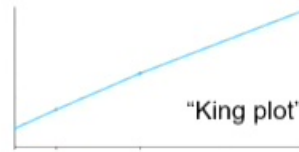
Assume current limit, $A \approx 10^{21}$ at 1 nm



Isotope shifts as test of fundamental interactions

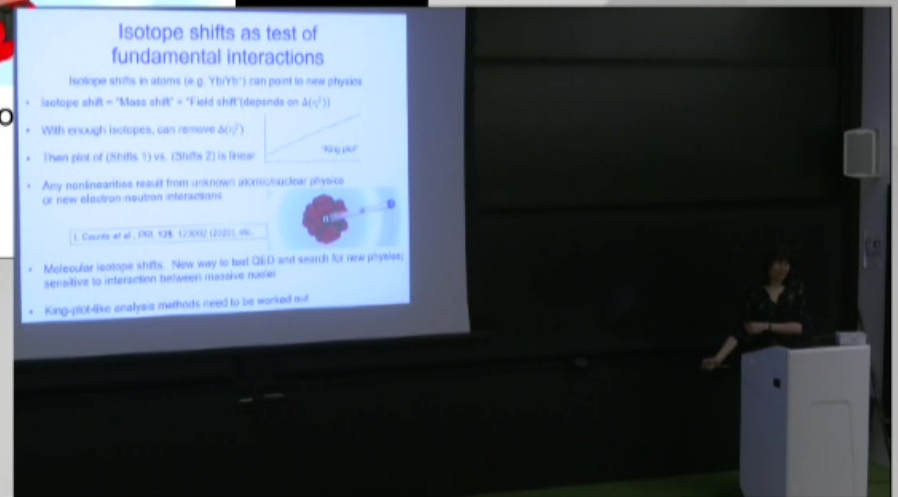
Isotope shifts in atoms (e.g. Yb/Yb⁺) can point to new physics

- 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 for 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

Helium-like, laser-coolable

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IIIA 4A	15 IIIA 5A	16 VIA 6A	17 VIA 7A	18 VIIIA 8A												
1 H Hydrogen 1.008	2 He Helium 4.003	3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948												
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 84.96												
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29												
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]												
87 Fr Francium 223.021	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [285]	111 Rg Roentgenium [286]	112 Cn Copernicium [285]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Uup Ununpentium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]												
89 La Lanthanum 138.905	90 Ce Cerium 140.115	91 Pr Praseodymium 140.908	92 Nd Neodymium 144.24	93 Pm Promethium [145]	94 Sm Samarium 150.36	95 Eu Europium 151.964	96 Gd Gadolinium 157.25	97 Tb Terbium 158.925	98 Dy Dysprosium 162.50	99 Ho Holmium 164.930	100 Er Erbium 167.26	101 Tm Thulium 168.934	102 Yb Ytterbium [173]	103 Lu Lutetium [175]	104 Hf Hafnium [178]	105 Ta Tantalum [180]	106 W Tungsten [184]	107 Re Rhenium [187]	108 Os Osmium [190]	109 Ir Iridium [192]	110 Pt Platinum [195]	111 Au Gold [197]	112 Hg Mercury [201]	113 Tl Thallium [205]	114 Pb Lead [207]	115 Bi Bismuth [209]	116 Po Polonium [209]	117 At Astatine [210]	118 Rn Radon [222]
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [260]	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [285]	111 Rg Roentgenium [286]	112 Cn Copernicium [285]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Uup Ununpentium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

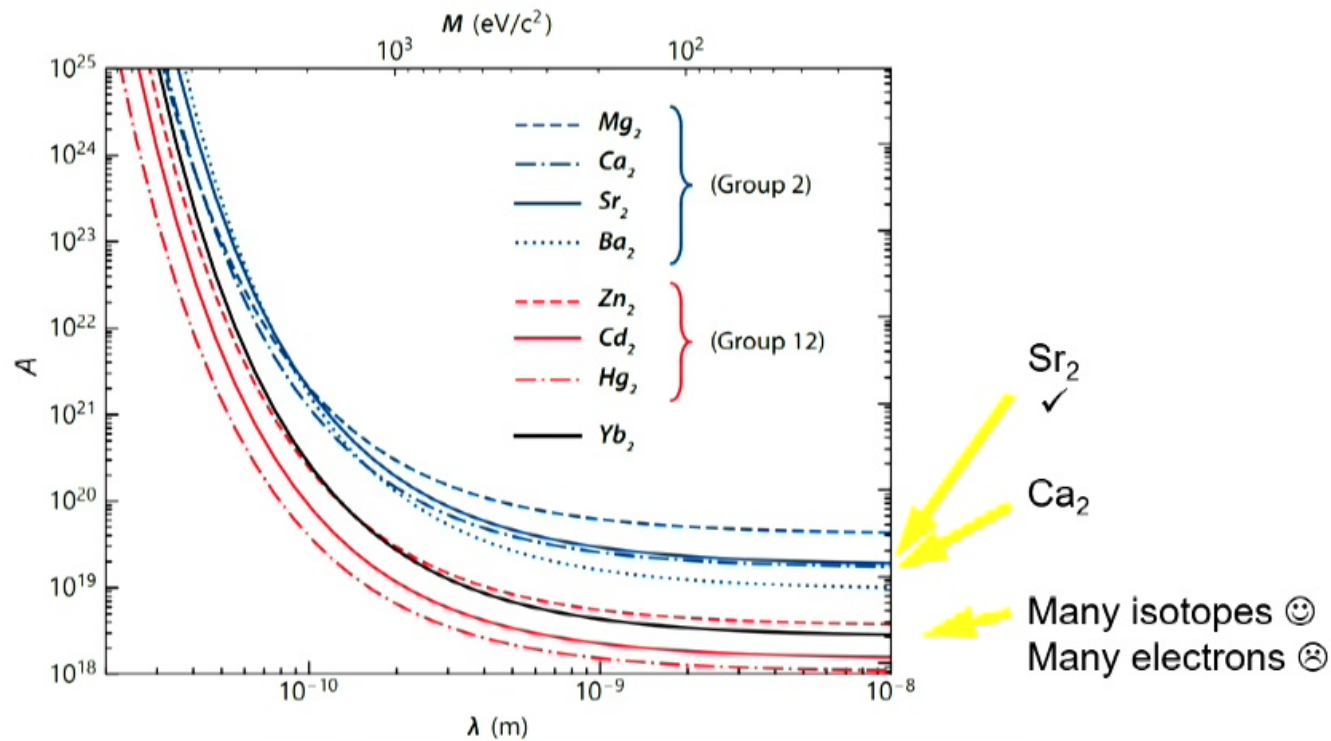
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Beyond B-O

adiabatic

nonadiabatic

relativistic, QED

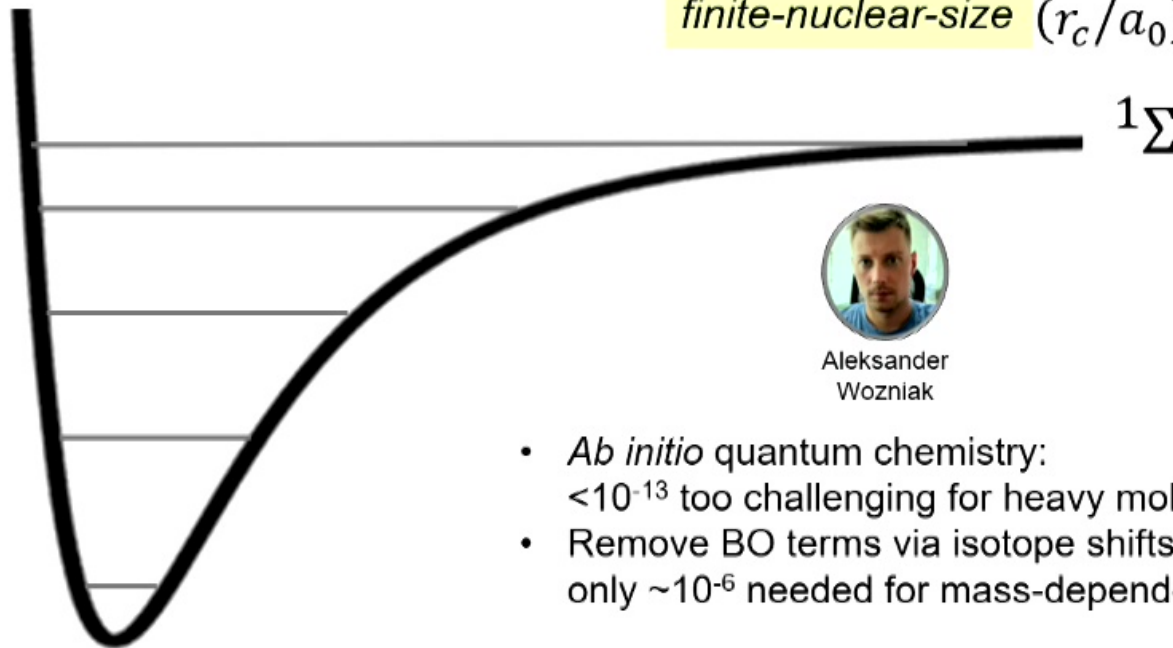
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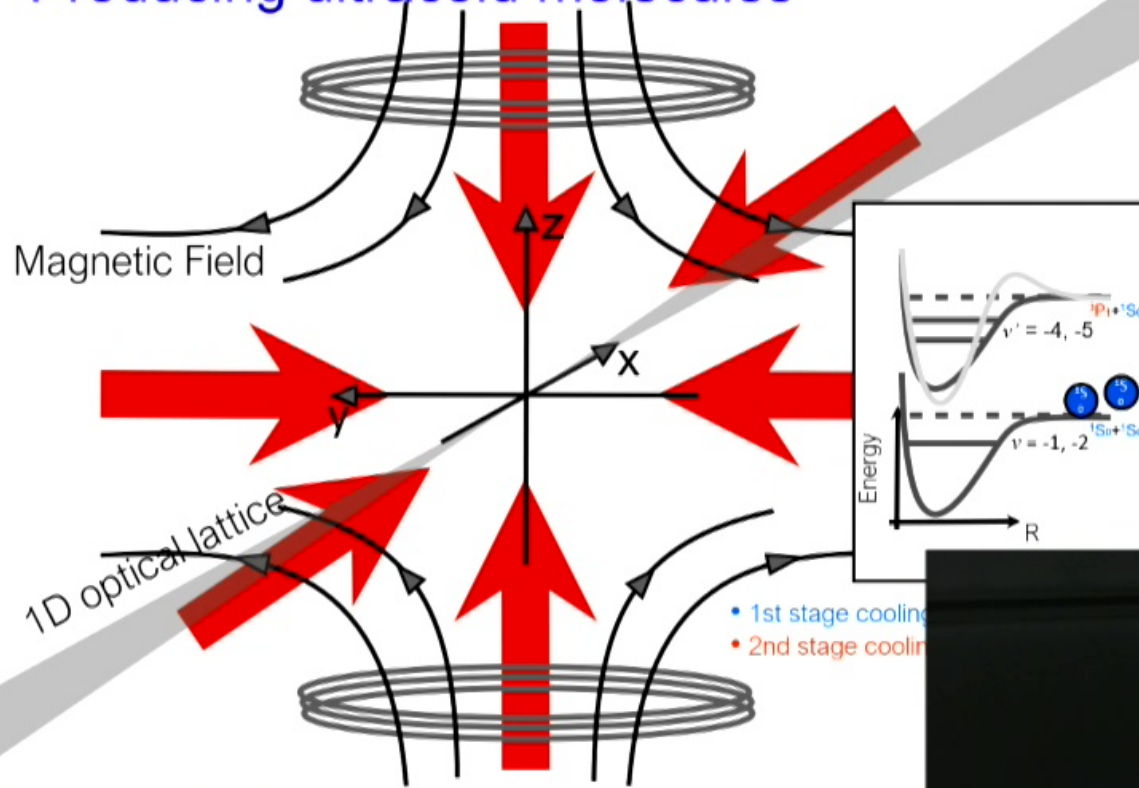


Aleksander
Wozniak

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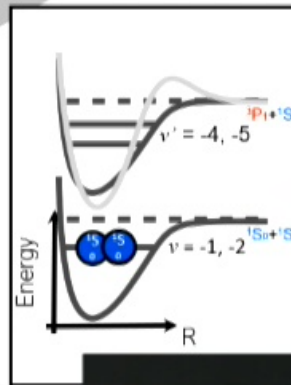
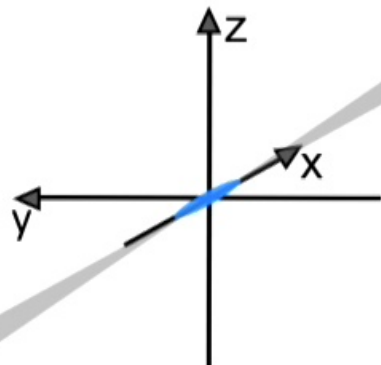
J. J. Lutz and J. M. Hutson, *JMS* **330**, 43 (2016)

Producing ultracold molecules



Producing ultracold molecules

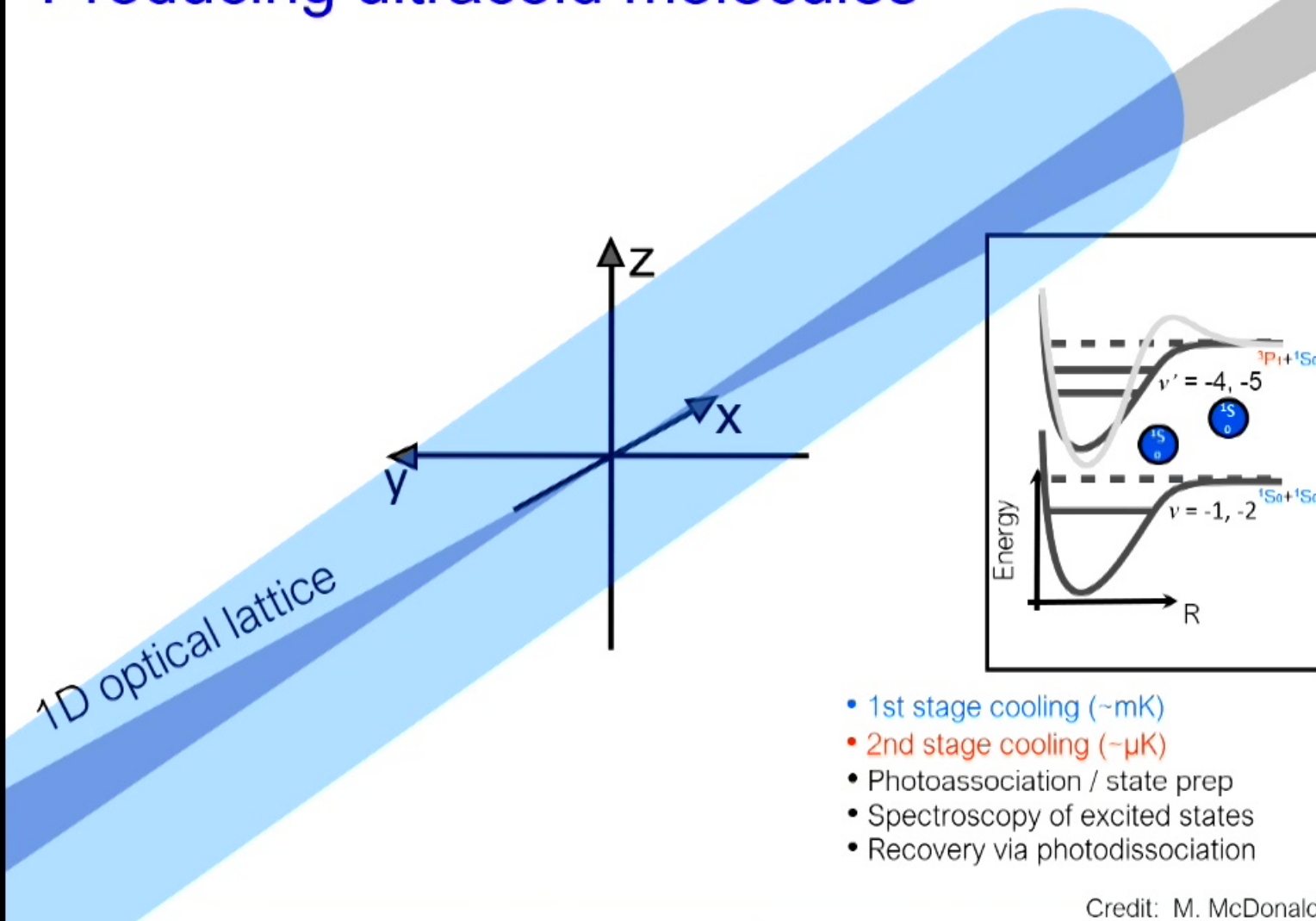
1D optical lattice



- 1st stage cooling
- 2nd stage cooling
- Photoassociation



Producing ultracold molecules



Ultracold photodissociation

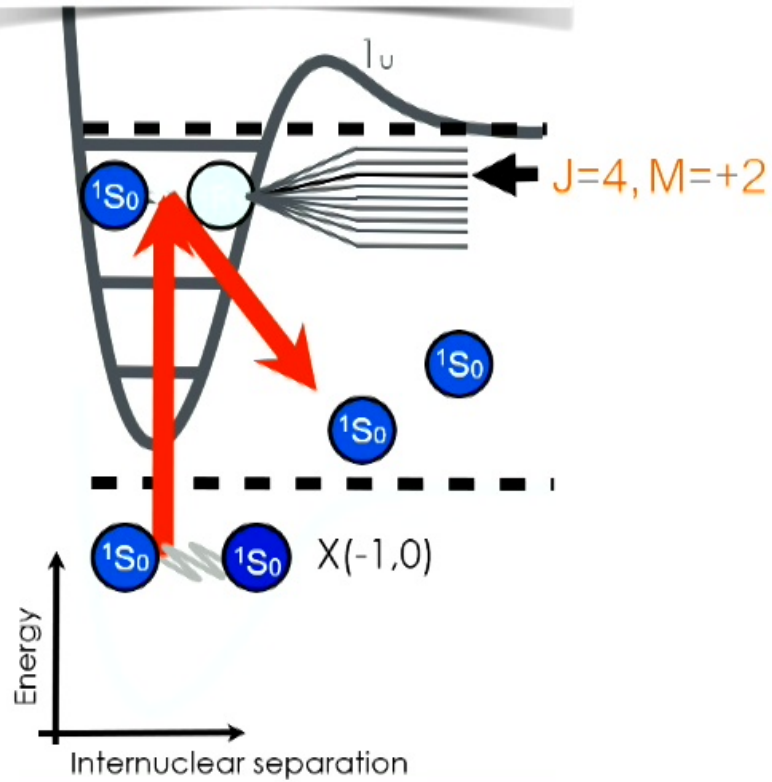
LETTER

DOI:10.1038/nature16514

Photodissociation of ultracold diatomic strontium molecules with quantum state control

M. McDonald¹, B.H. McGuire¹, J. Apellbeck¹, C. H. Lee¹, I. Majewska¹, S. Mozyrsky¹ & T. Zelanin¹

122 | NATURE | VOL 535 | 7 JULY 2016



Credit: M. McDonald

Ultracold photodissociation

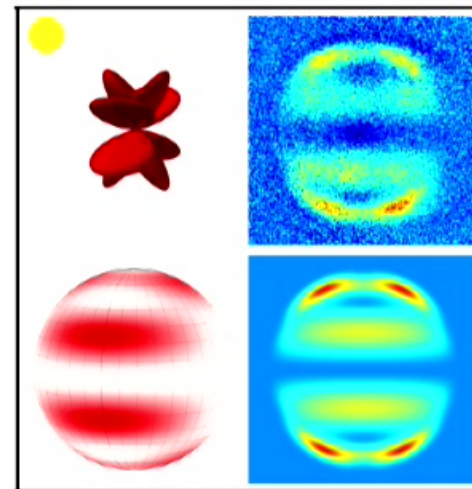
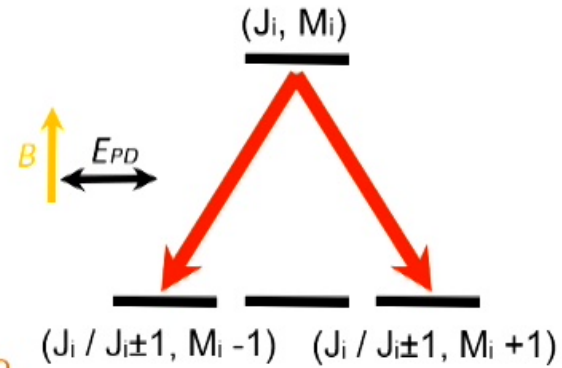
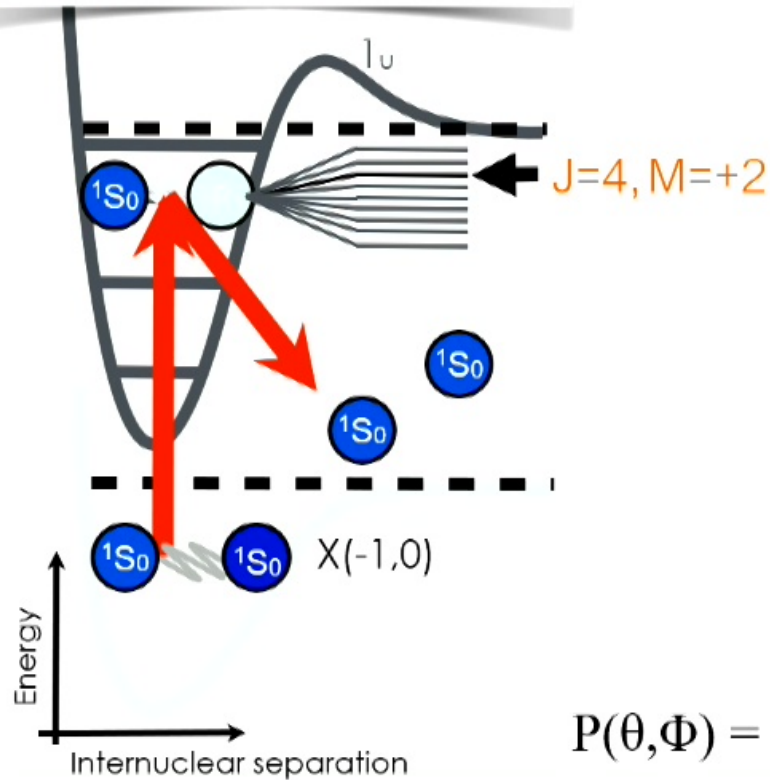
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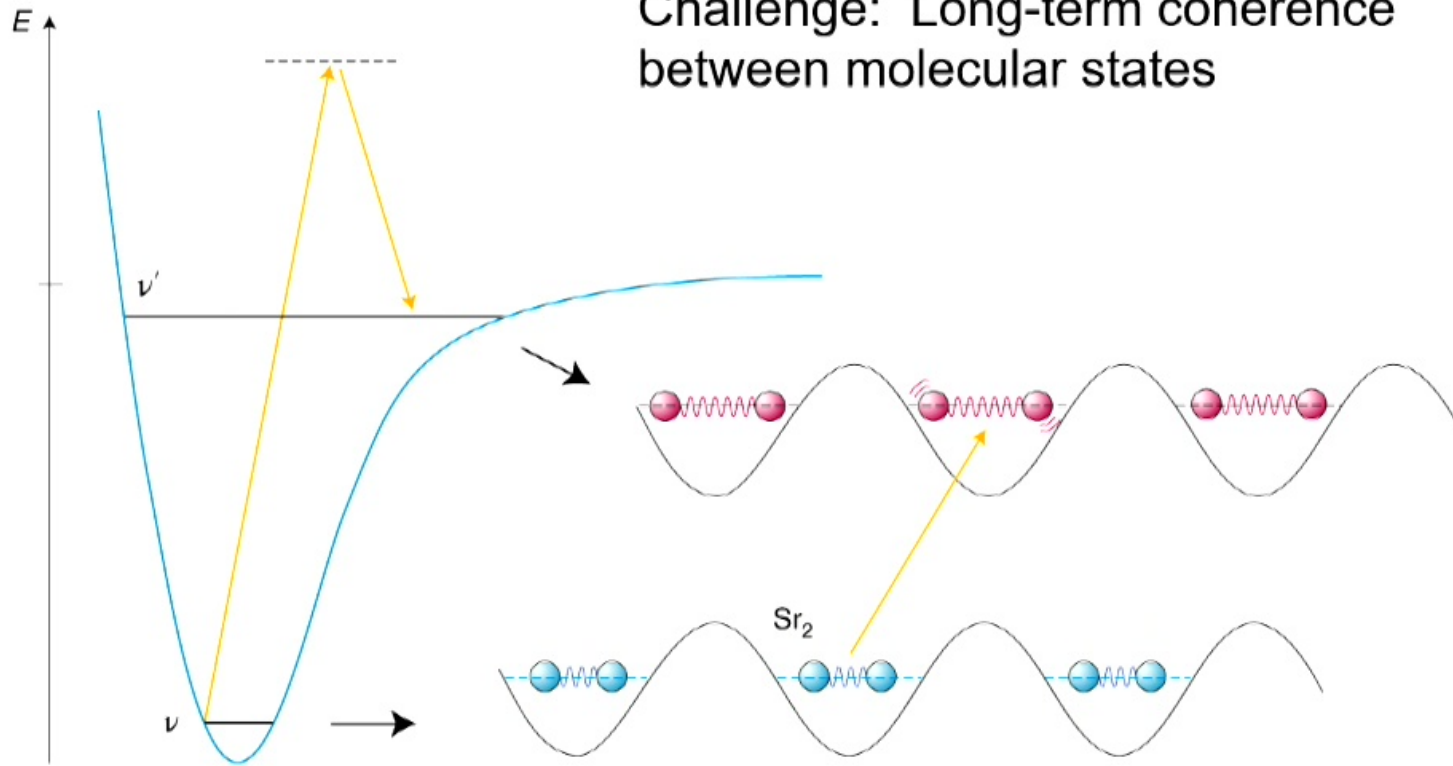


$$P(\theta, \Phi) = |\sqrt{R} \cdot Y_4^1(\theta, \Phi) + \sqrt{1-R} \cdot e^{i\delta} Y_4^3(\theta, \Phi)|^2$$

Credit: M. McDonald

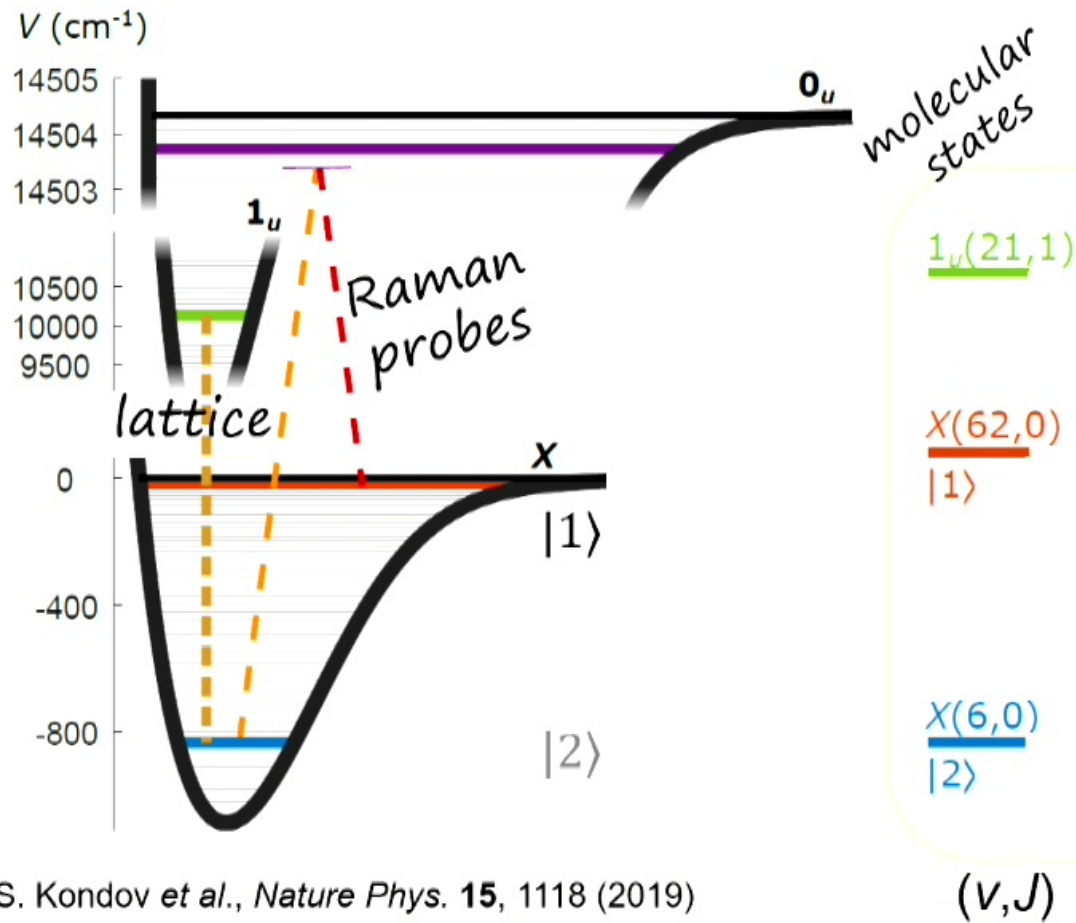
Molecular lattice clock

Challenge: Long-term coherence between molecular states



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

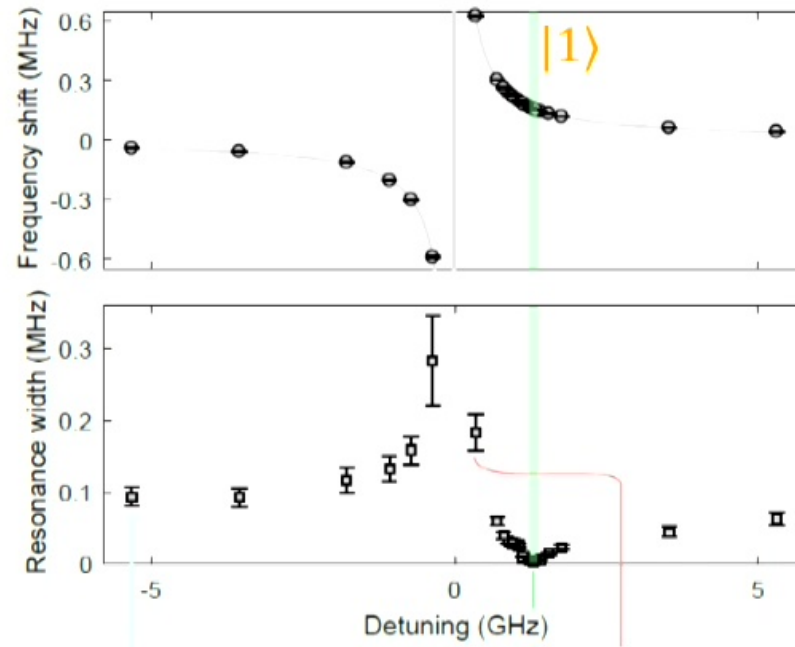
“Magic” lattice trap



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

(v, J)

Enhanced coherence in magic lattice

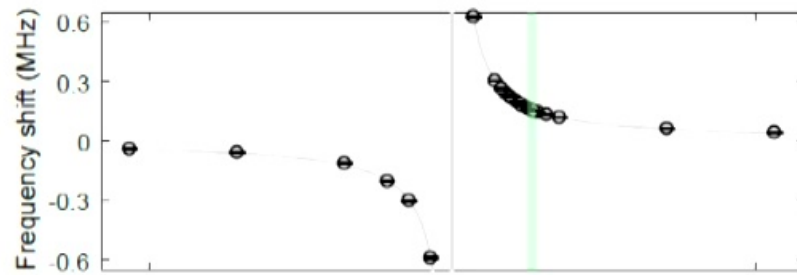


Energy of $|2\rangle$

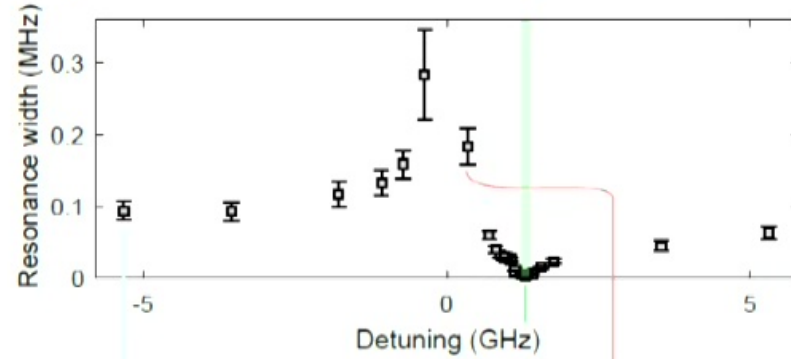
Clock resonance linewidth

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

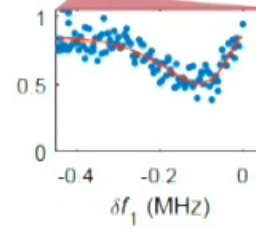
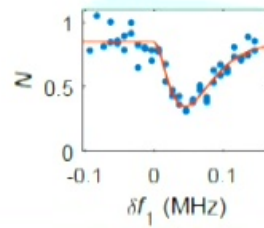
Enhanced coherence in magic lattice



Energy of $|2\rangle$



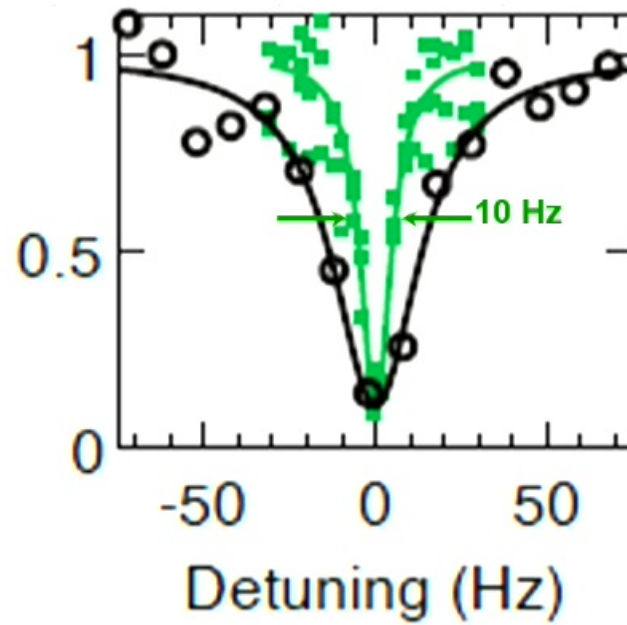
Clock resonance linewidth



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

Narrow vibrational clock resonance

Coherence $10^4\times$



$$Q = 3 \times 10^{12}$$

$$Q (\text{intrinsic}) > 10^{26}$$

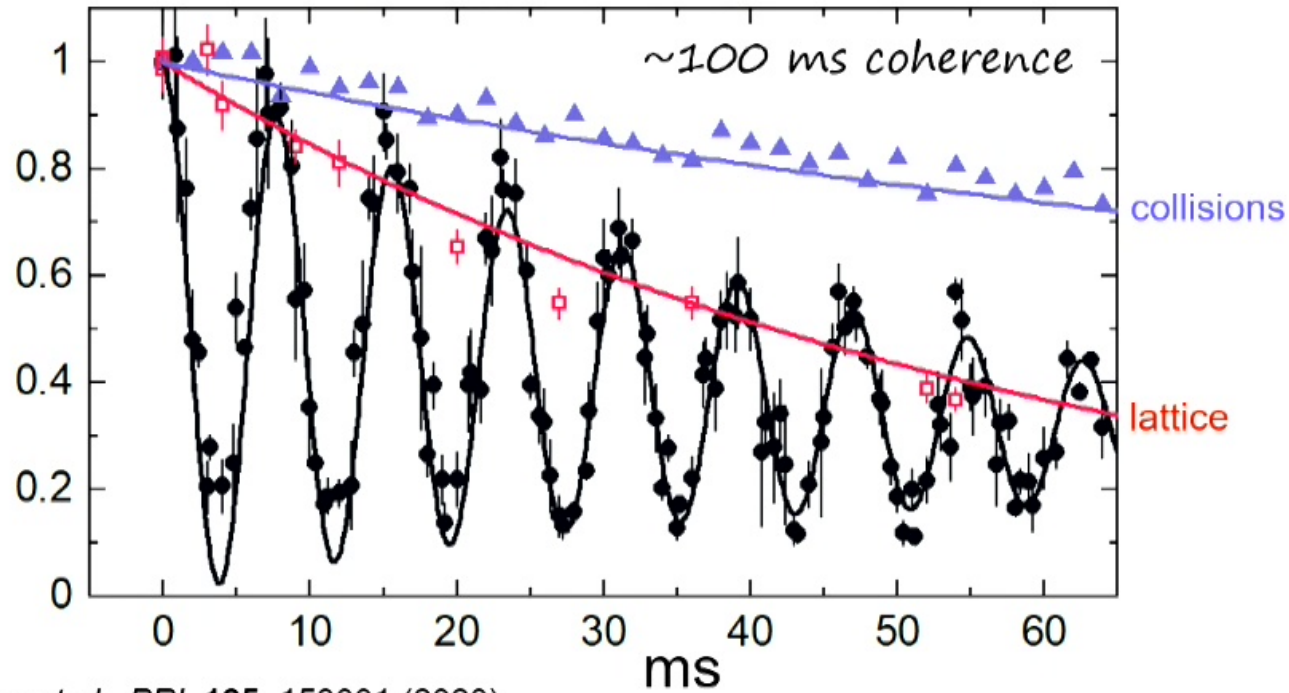
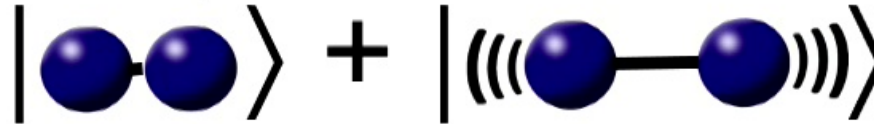
K. H. Leung et al., *Phys. Rev. X* 13, 011047 (2023)

Rabi oscillations

Tightly-to-weakly-bound molecules

$V = 4$

$V = 62$



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

Clock precision

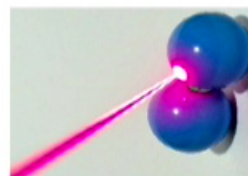
Systematic effects:

What can cause the clock frequency to shift?

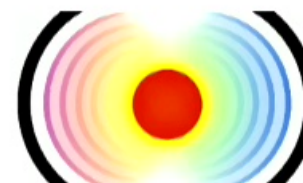
- Lattice laser light



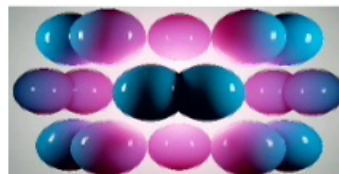
- Probe laser light



- Blackbody radiation



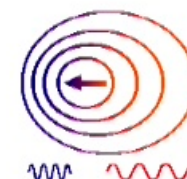
- Collisions



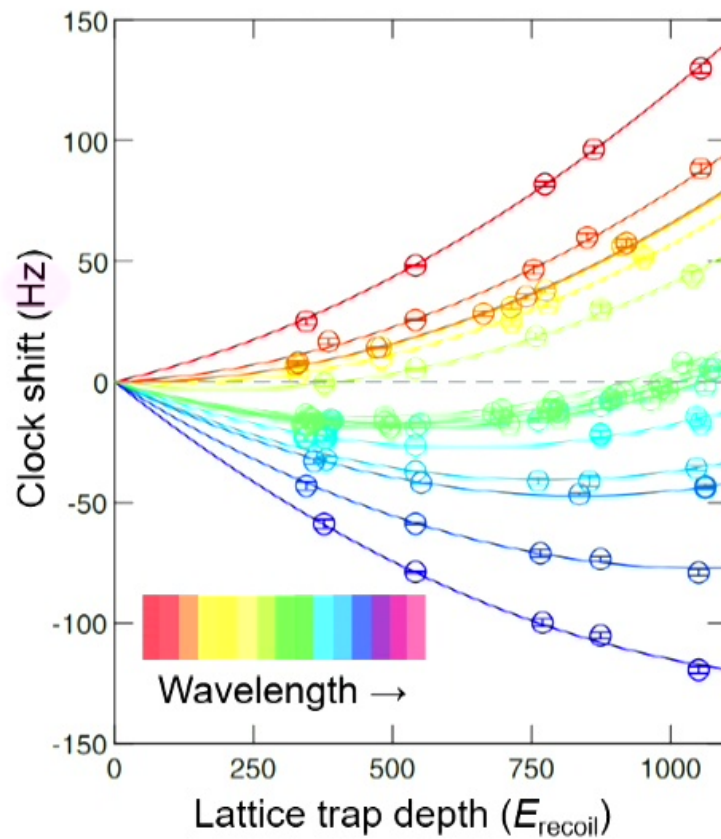
- Magnetic fields



- Doppler shifts

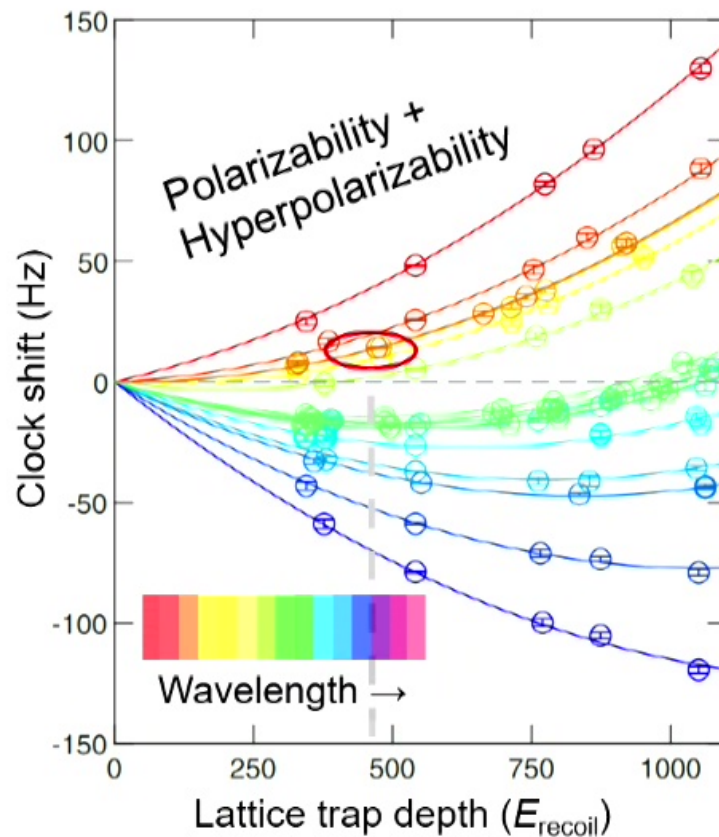


Lattice light shift: Zoom in

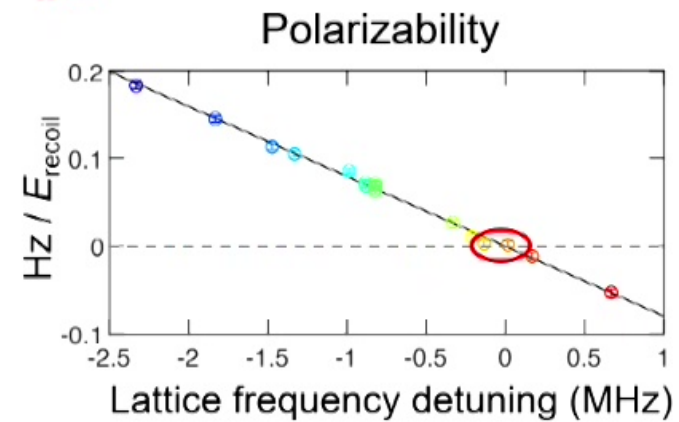


K. H. Leung *et al.*, *Phys. Rev. X* 13, 011047 (2023)

Observe vibrational hyperpolarizability

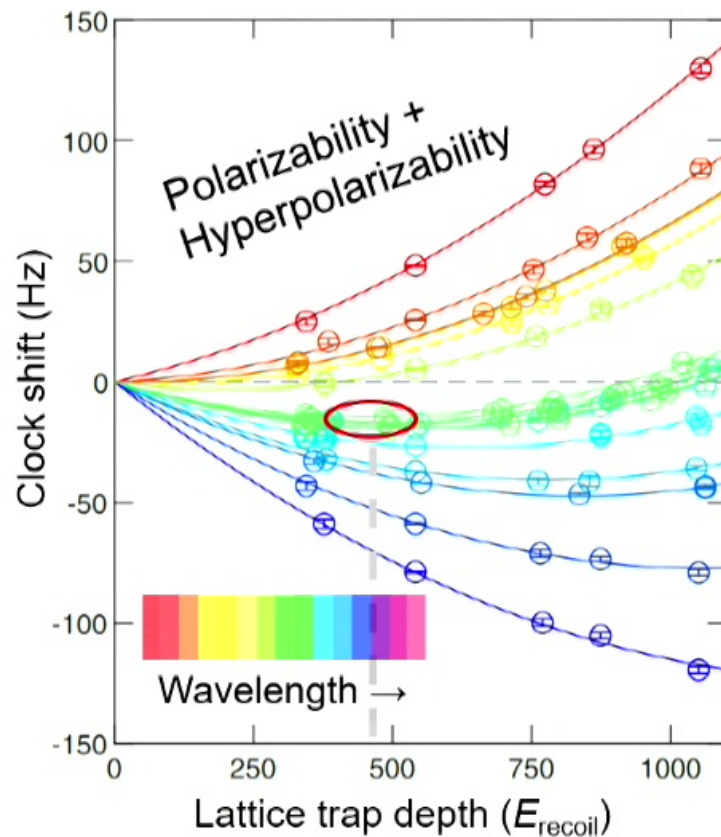


operationally
non-magic
lattice...

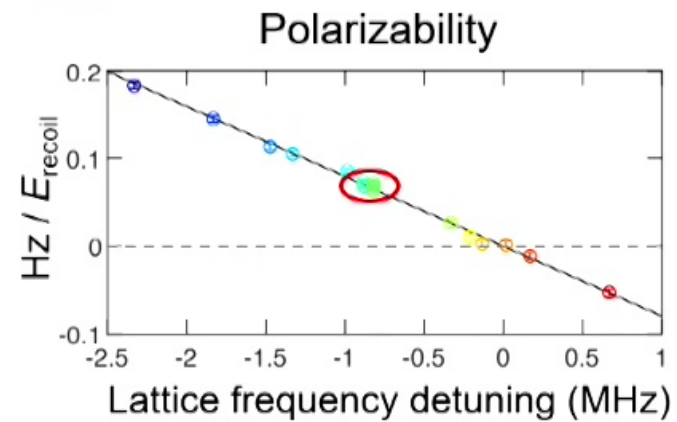


K. H. Leung *et al.*, *Phys. Rev. X* 13, 011047 (2023)

Effectively magic lattice



operationally
magic
lattice



$\sim 4 \times 10^{-14}$ uncertainty,
dominant contributor

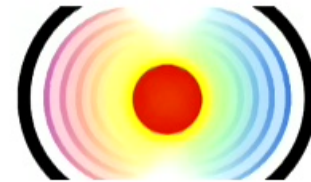
K. H. Leung *et al.*, *Phys. Rev. X* 13, 011047 (2023)

Clock precision

Systematic effects:

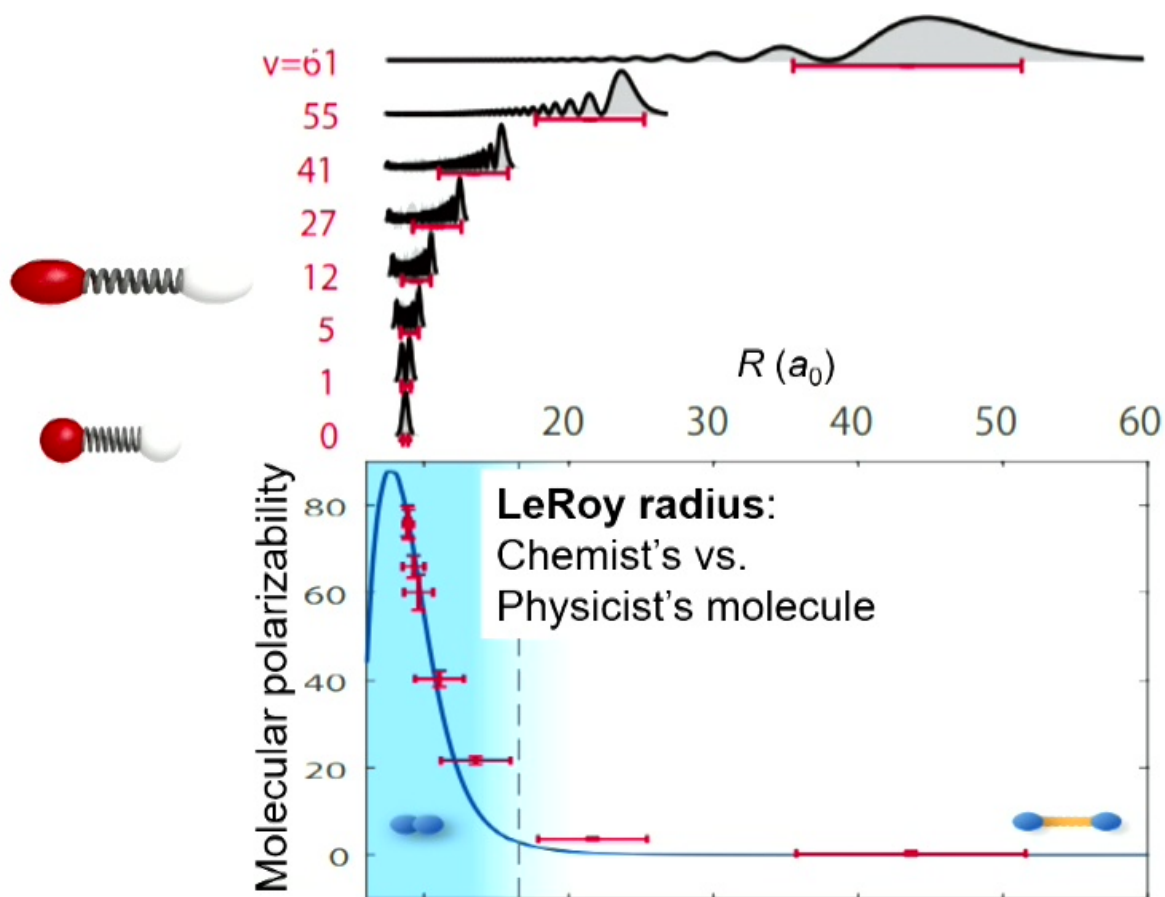
What can cause the clock frequency to shift?

- Blackbody radiation



Far-infrared polarizabilities

Response of vibrating molecule to BBR

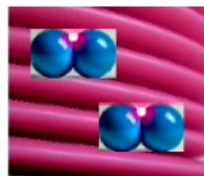


Clock precision

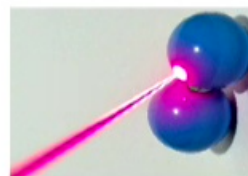
Systematic effects:

What can cause the clock frequency to shift?

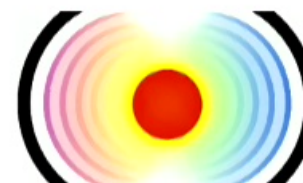
- Lattice laser light



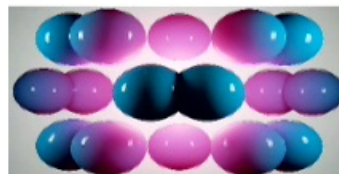
- Probe laser light



- Blackbody radiation



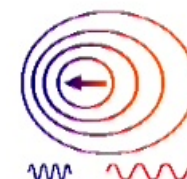
- Collisions



- Magnetic fields

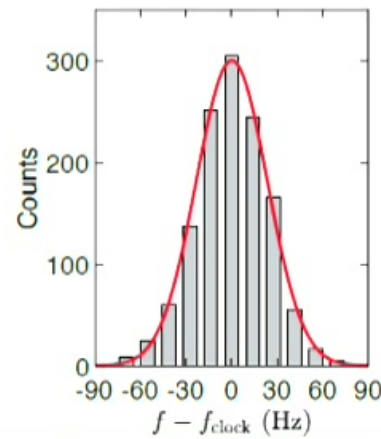
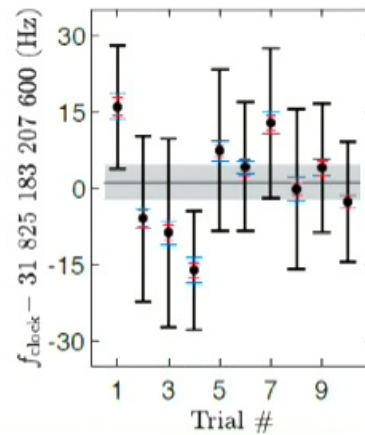
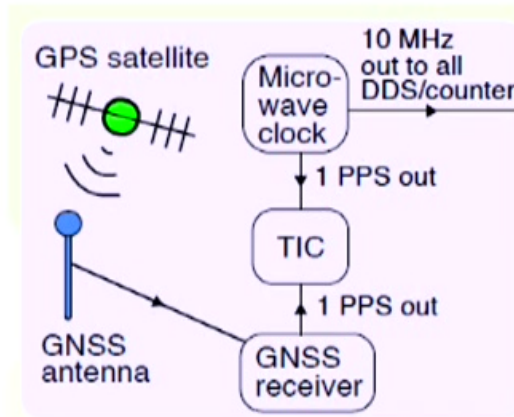


- Doppler shifts



Absolute clock measurement

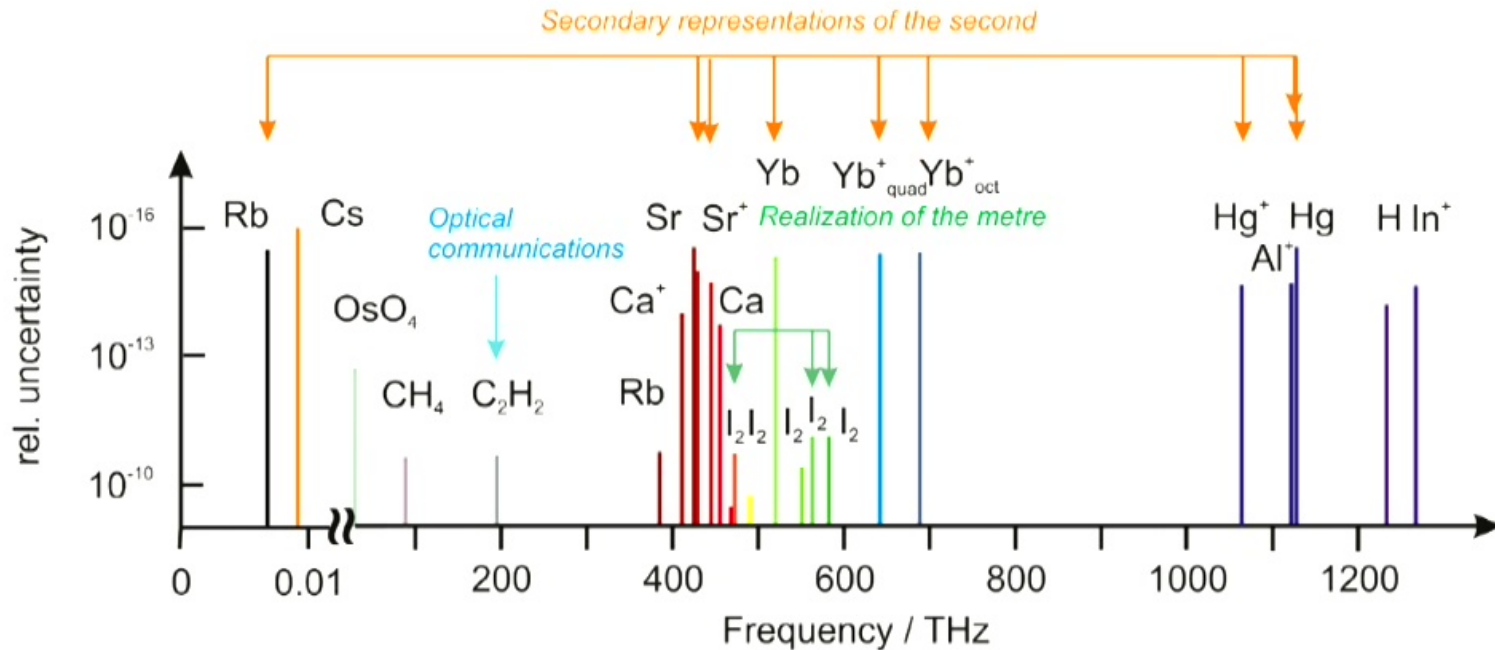
Comparison to Cs atomic time standard



1×10^{-13} uncertainty

Atomic and molecular frequency standards

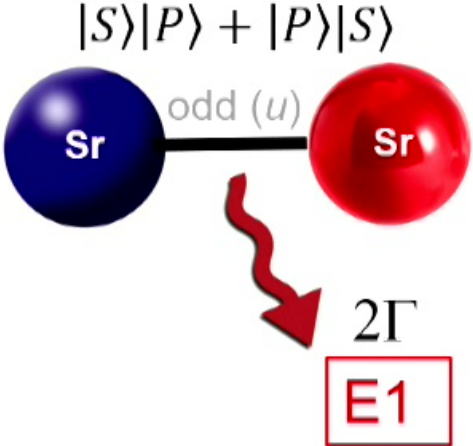
Primary and secondary



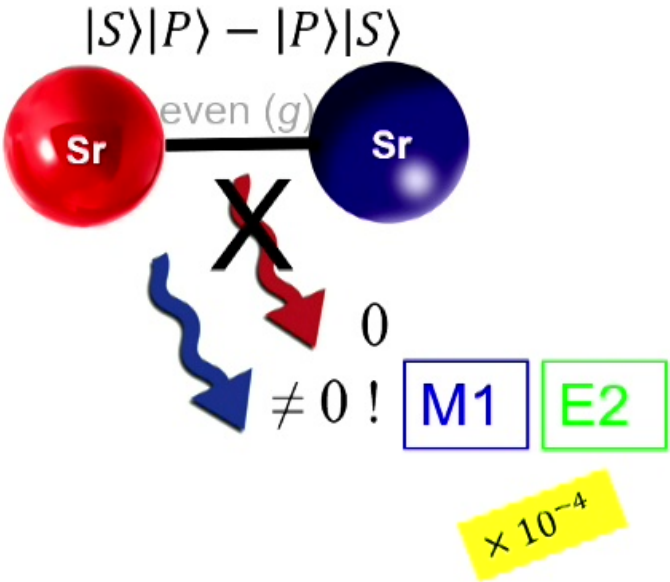
F. Riehle *et al.*, *Metrologia* **55**, 188 (2018)

Optical molecular clocks

Superradiant



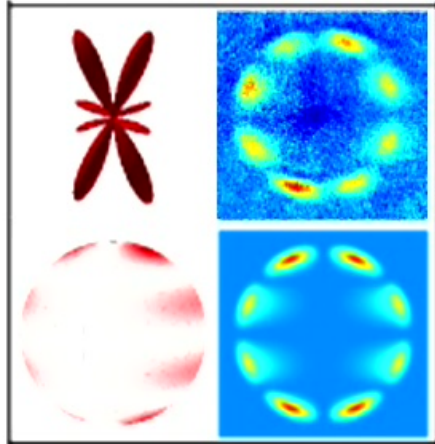
Subradiant



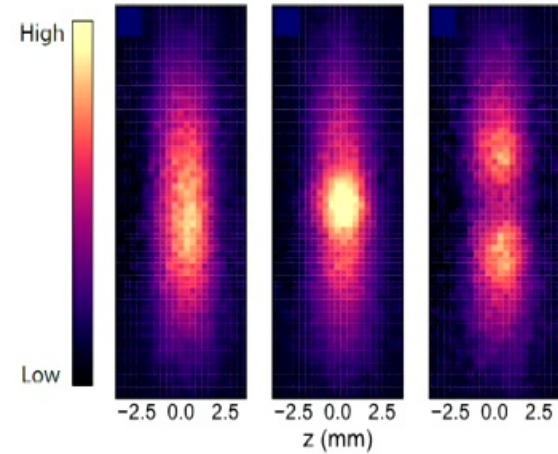
B. McGuyer *et al.*, *Nature Phys.* **11**, 32 (2015)

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

