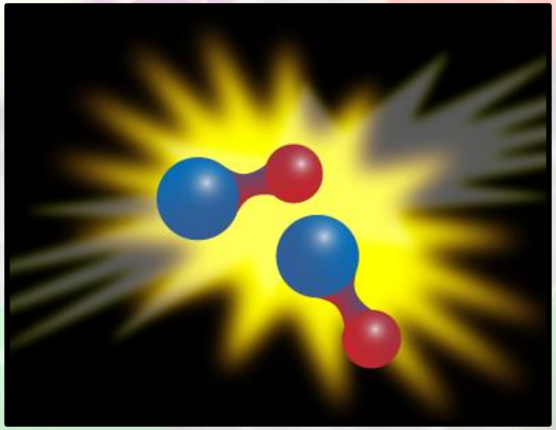
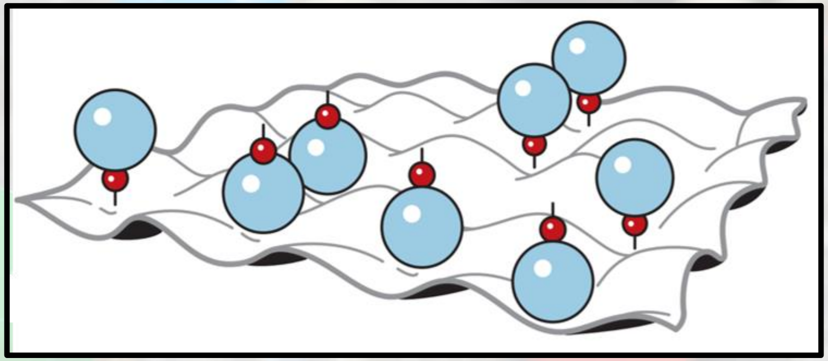
# Molecular Lattice Clocks

Tanya Zelevinsky
*Columbia University, New York*

# Quantum science with molecules



Fundamental
chemistry

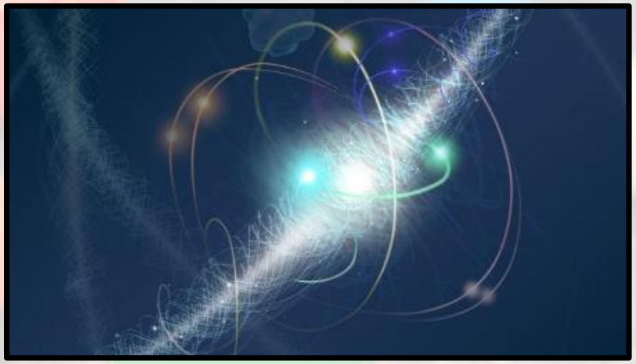


Quantum
materials

**Fundamental**
**physics & metrology**

J. L. Bohn *et al*, *Science* **357**, 1002 (2017)

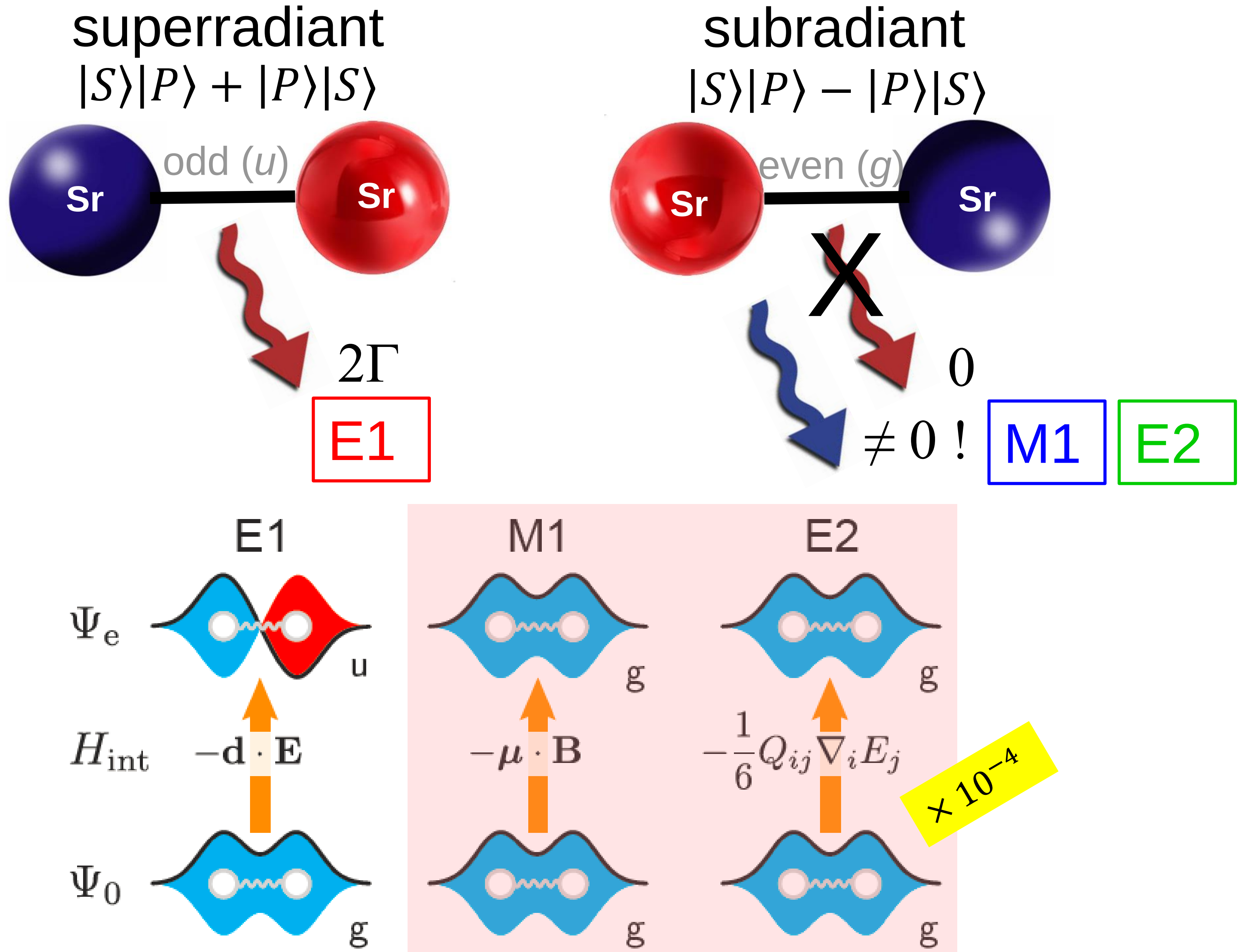
# Quantum science with molecules



## Molecular clocks:
## Limits of precision and coherence with molecular states

- **Metrology with atoms & molecules**
- **Precise measurements of fundamental phenomena**
- **Coherence in optical traps for clocks, qubits, cold chemistry**
- **New level of precision for molecular physics and QED**

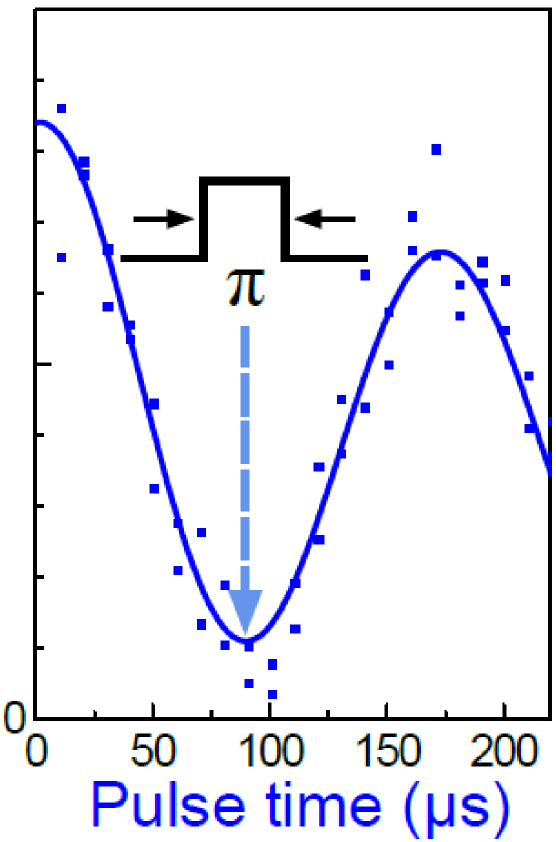
# Two-body subradiant states

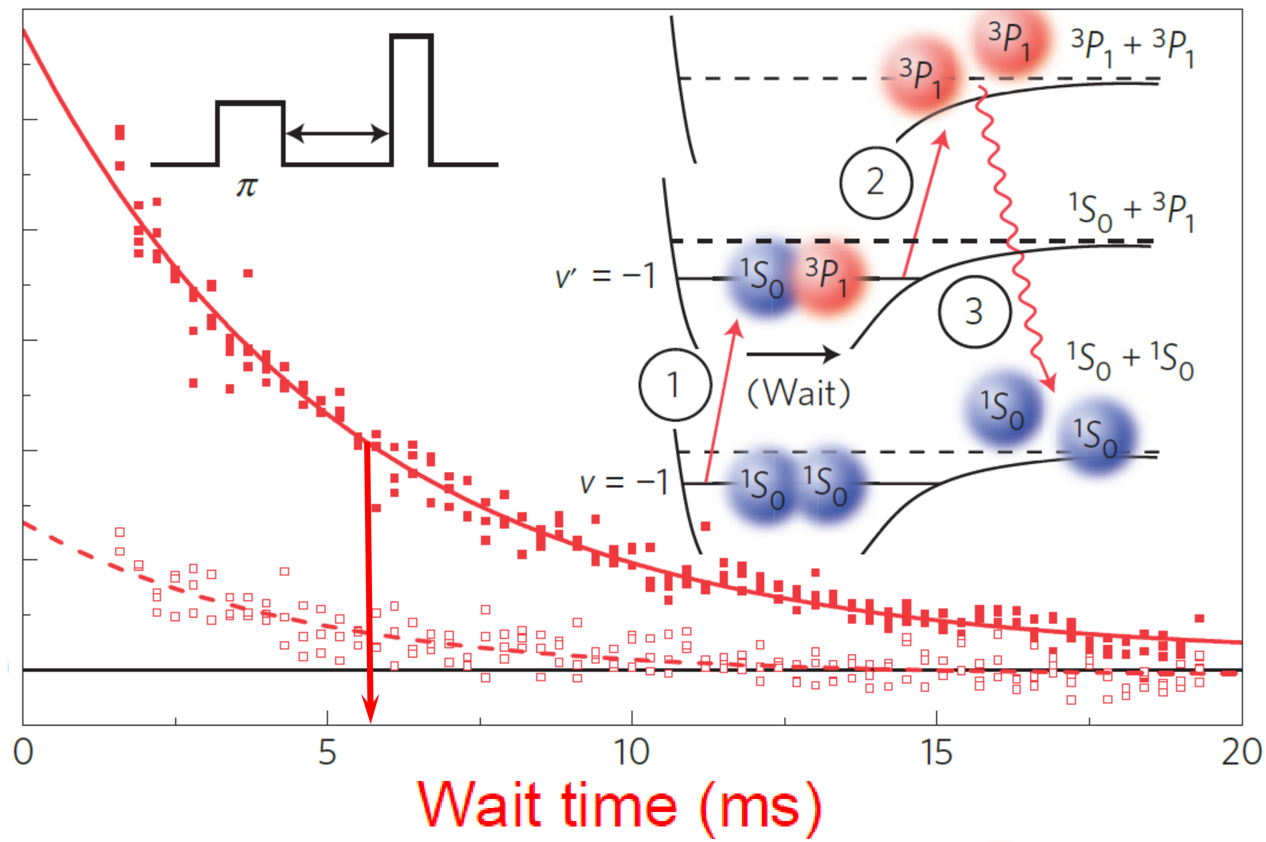



B. McGuyer *et al.*, *Nature Phys.* **11**, 32 (2015)
W. Skomorowski *et al.*, *JCP* **136**, 194306 (2012)

# Two-body subradiant states

Coherent control



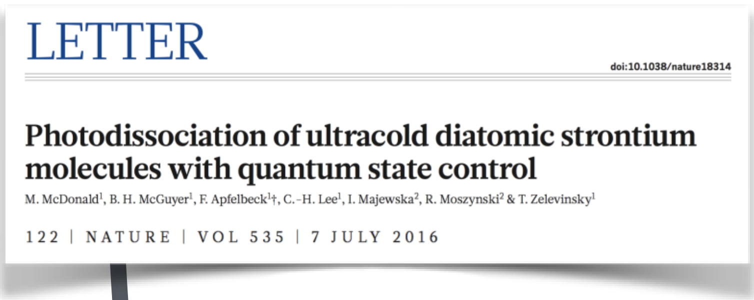




Molecule-light coherence,
$Q>3\times10^{12}$

5.5 ms lifetime

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

# Ultracold photodissociation

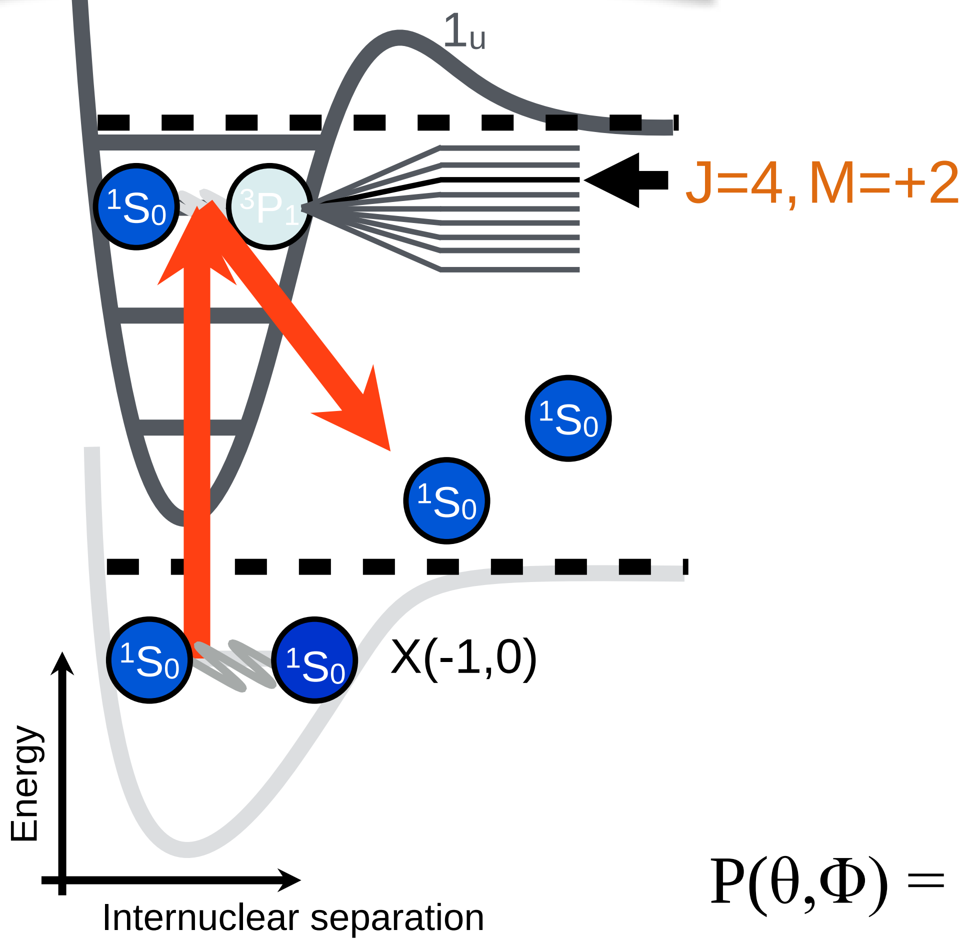

LETTER

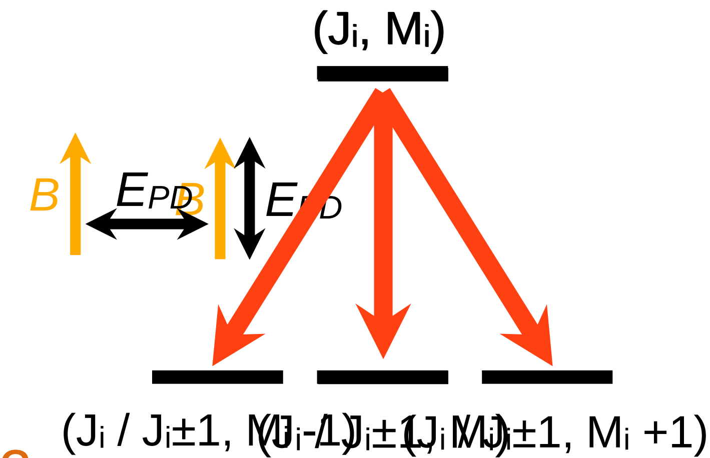
doi:10.1038/nature18314

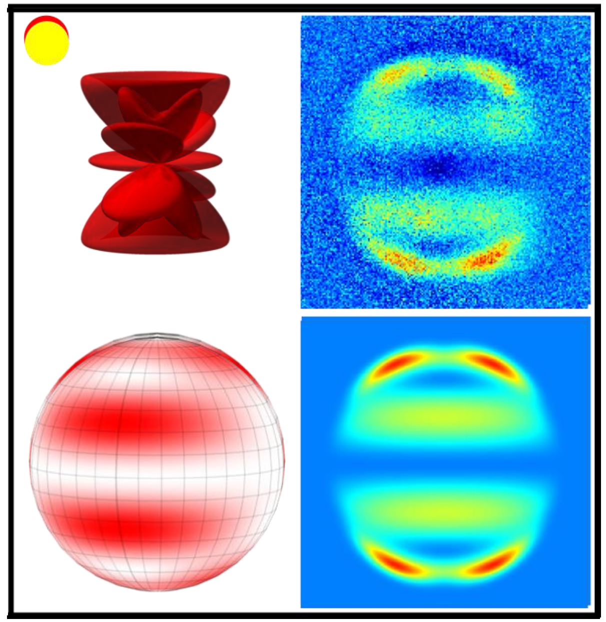
**Photodissociation of ultracold diatomic strontium molecules with quantum state control**

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

122 | NATURE | VOL 535 | 7 JULY 2016



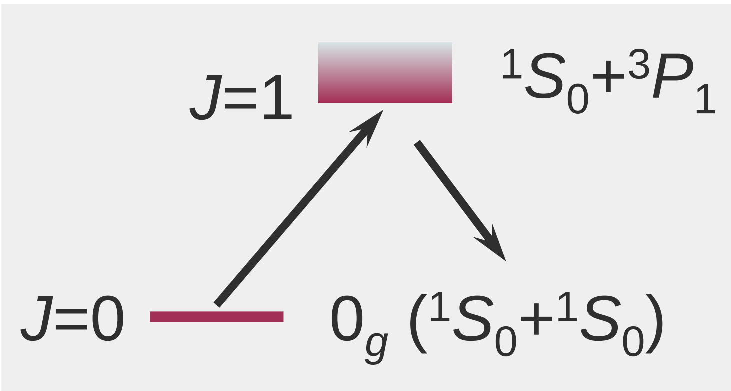



$P(\theta,\Phi) = |\sqrt{R}\,Y_4^2(\theta,\Phi) \ldots Y_4^3(\theta,\Phi)|^2$

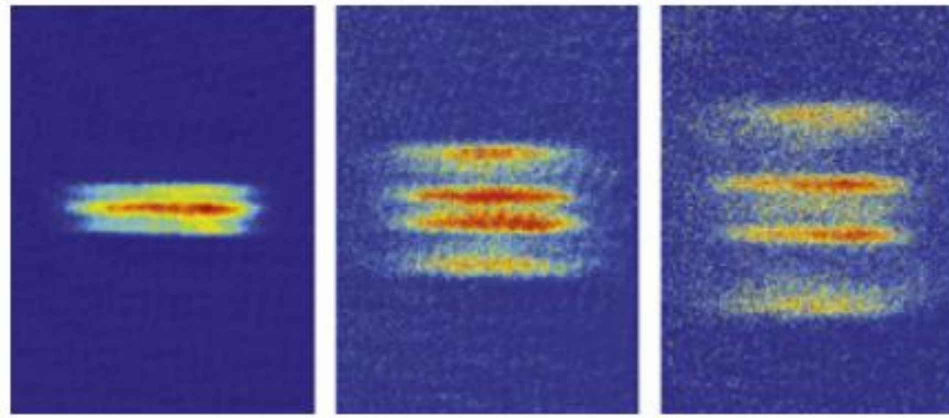
Credit: M. McDonald

# Ultracold photodissociation

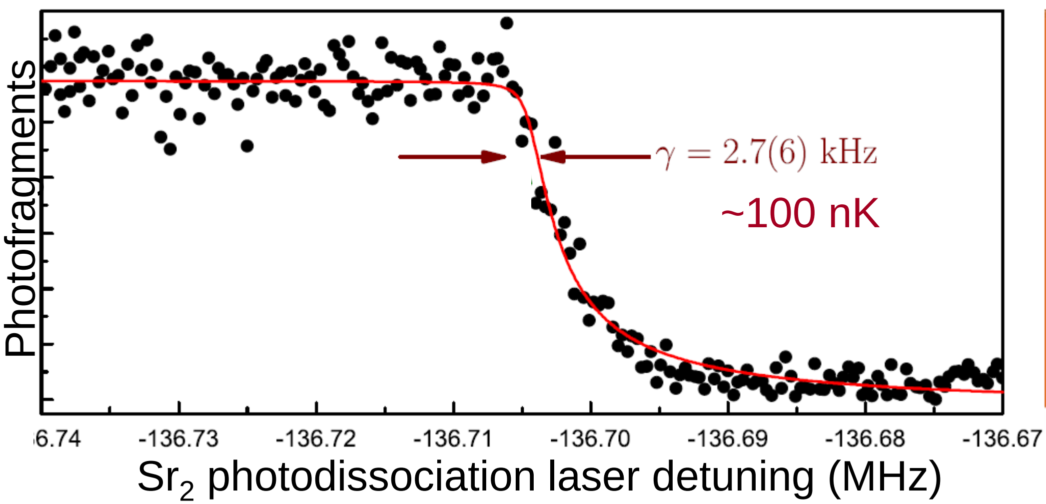
*State-resolved photochemistry*

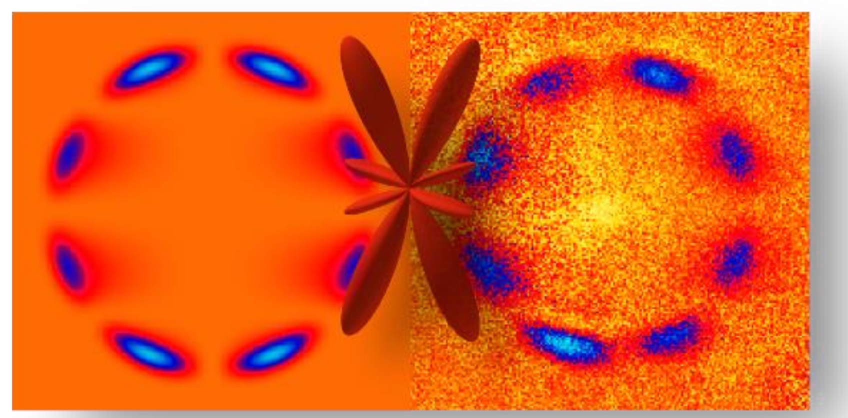



Side-view camera



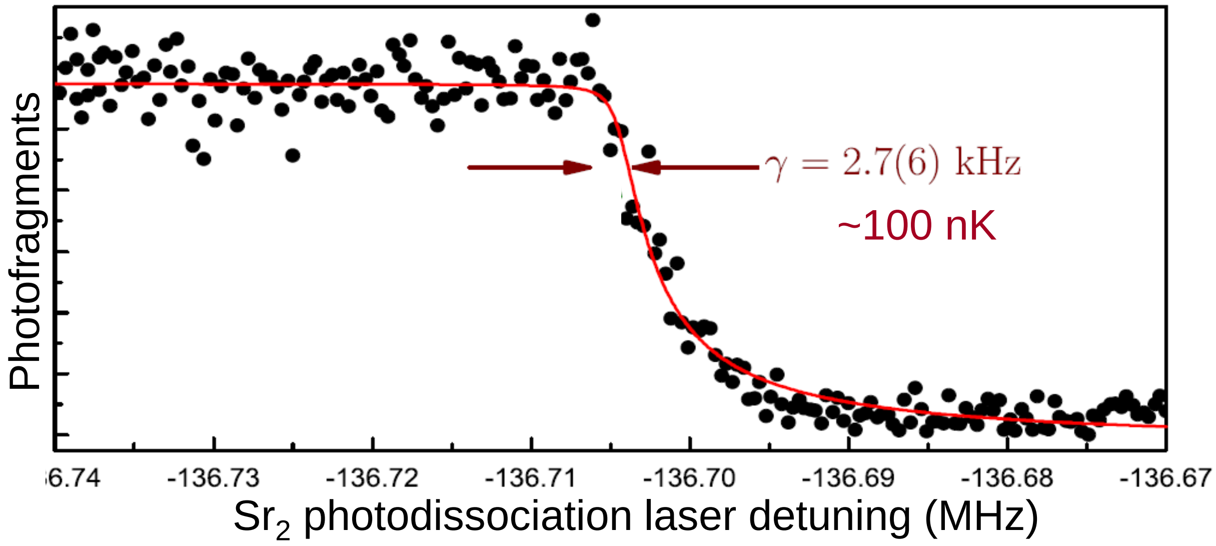
Line-of-sight camera: quantum interference

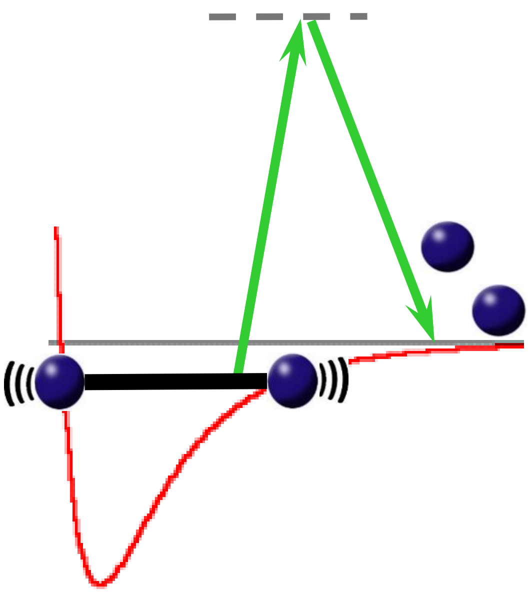


M. McDonald *et al.*, *Nature* **535**, 122 (2016)
B. McGuyer *et al.*, NJP **17**, 055004 (2015)

# Ultracold molecule dissociation



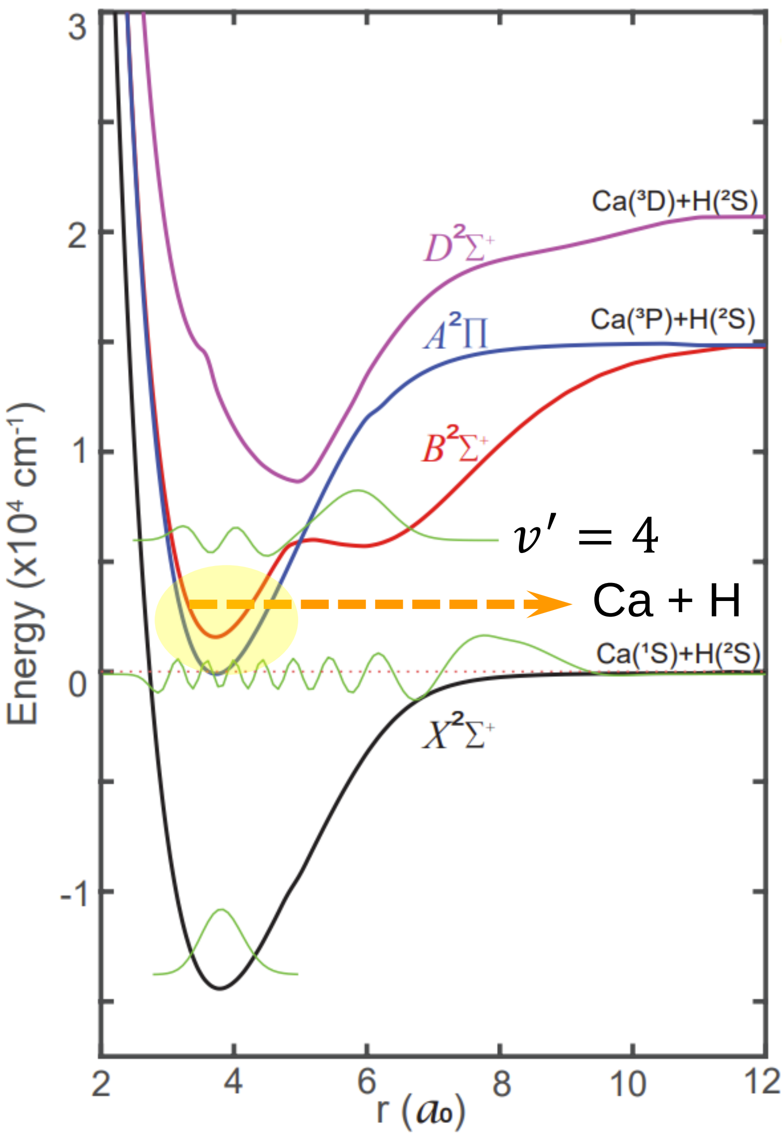
Produce ultracold gases
of photofragments
from precursor molecules?

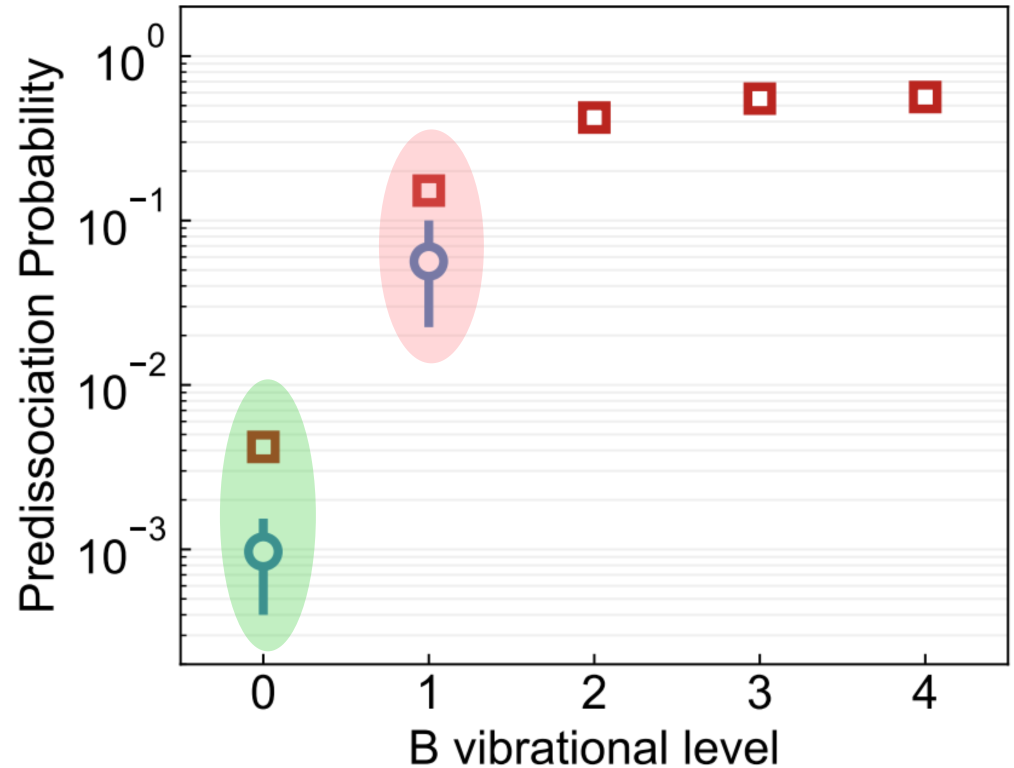
$CaH + \gamma \rightarrow Ca + H$

I. Lane, *PRA* **92**, 022511 (2015)

# Dissociation of CaH molecules

## *Natural predissociation + 3D laser cooling*



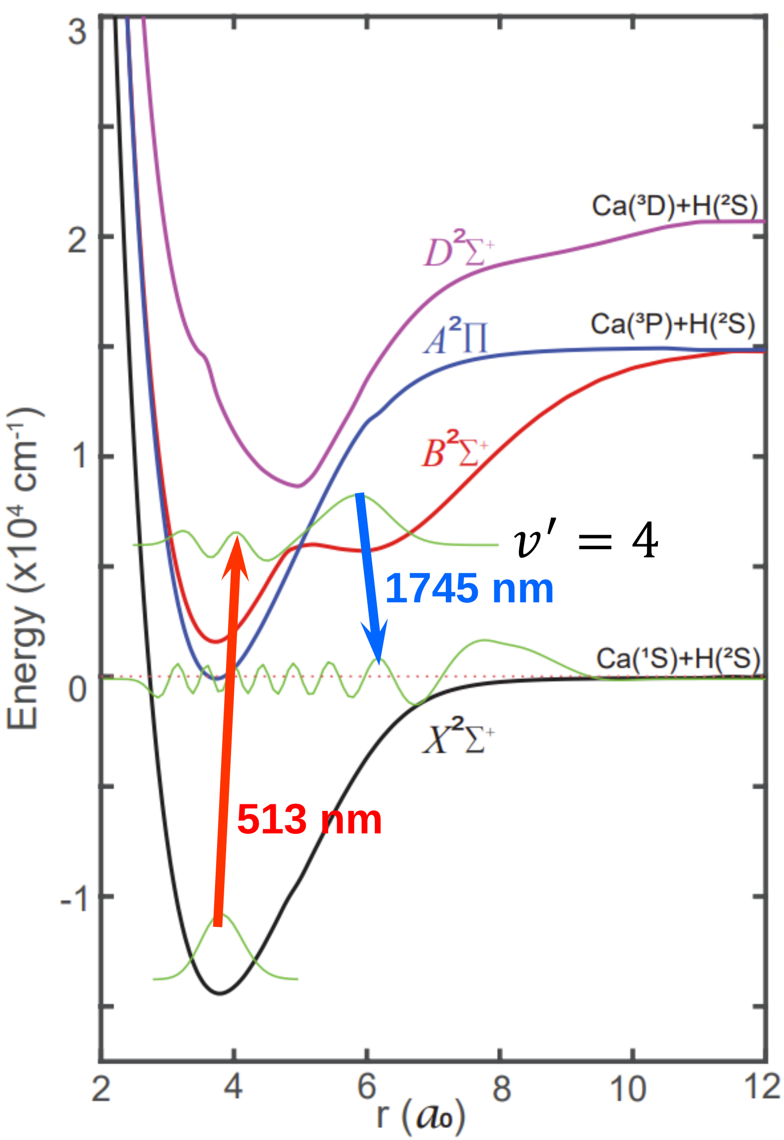



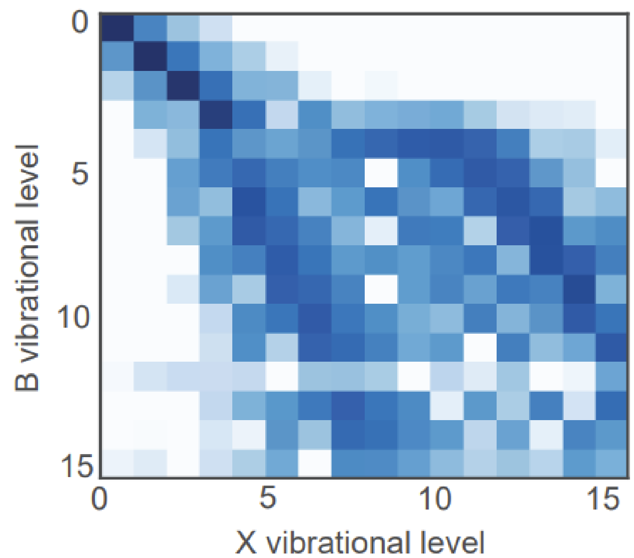

Anastassia Alexandrova Claire Dickerson Daniel Neuhauser Lan Cheng

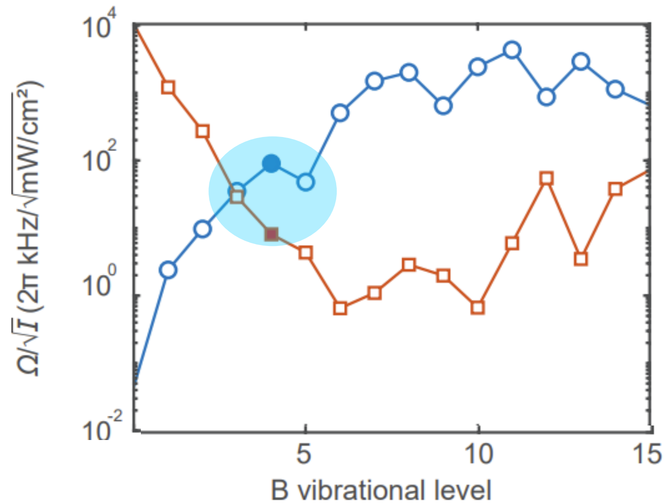
Q. Sun *et al.*, arXiv:2306.01184

# Dissociation of CaH molecules

## *Controlled dissociation*



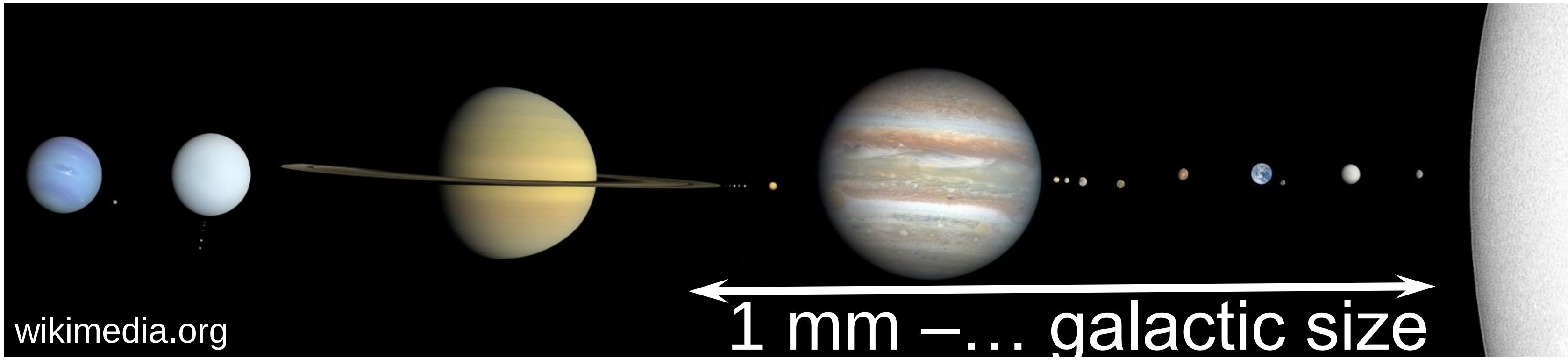



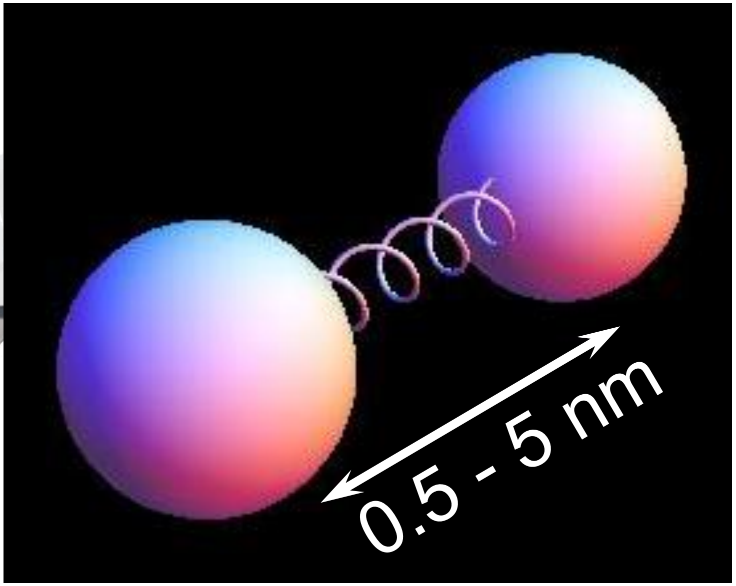

Q. Sun *et al.*, arXiv:2306.01184

# Science with molecular clocks

Newtonian gravity at large scales:  Well-understood

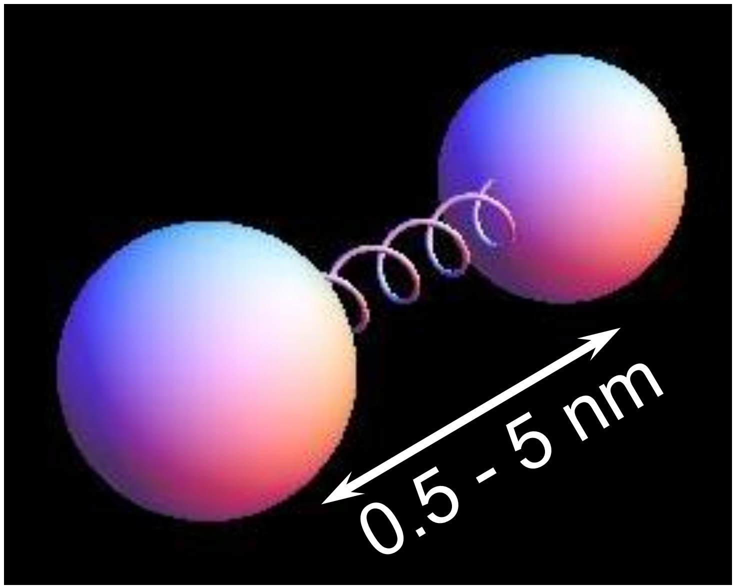



Gravity at nanometer scales:  Nearly unknown



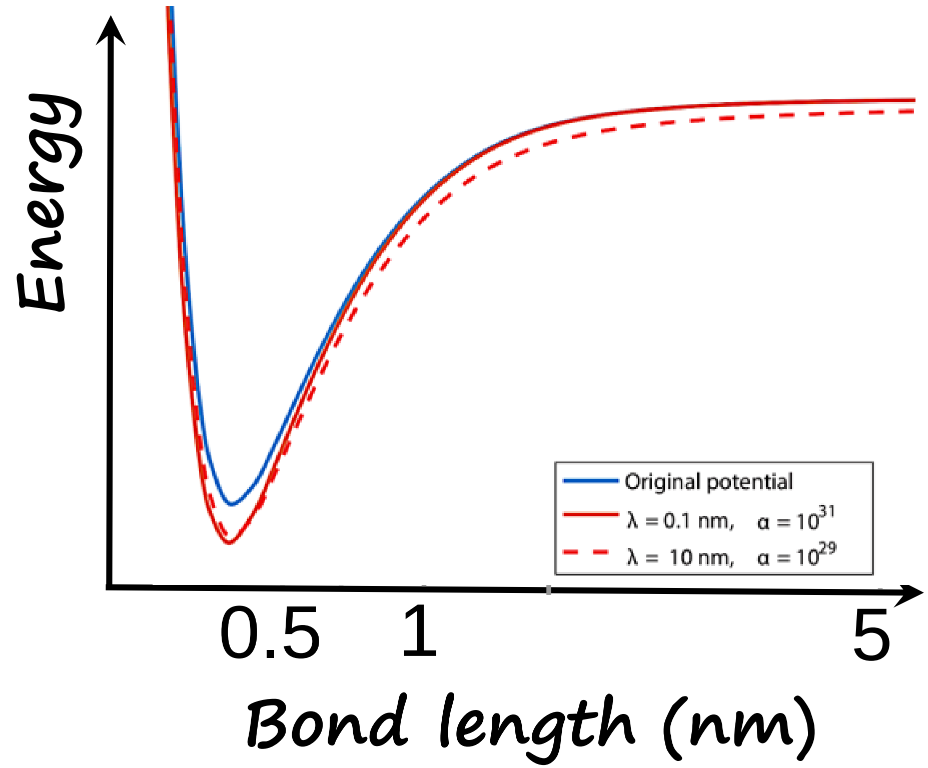
# Science with molecular clocks

## Nanoscale mass-dependent forces



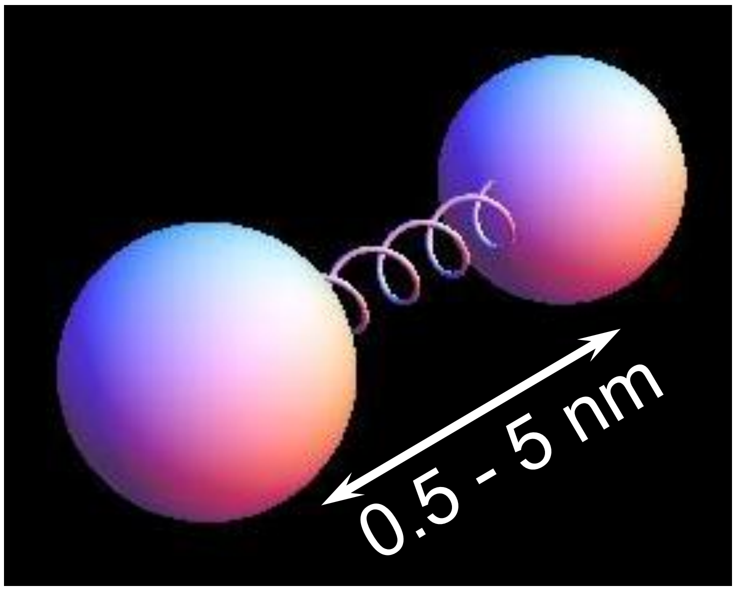

$$V = -\frac{GM^2}{r}\left(1 + Ae^{-r/\lambda}\right)$$

Hypothetical
“Yukawa” correction



# Science with molecular clocks

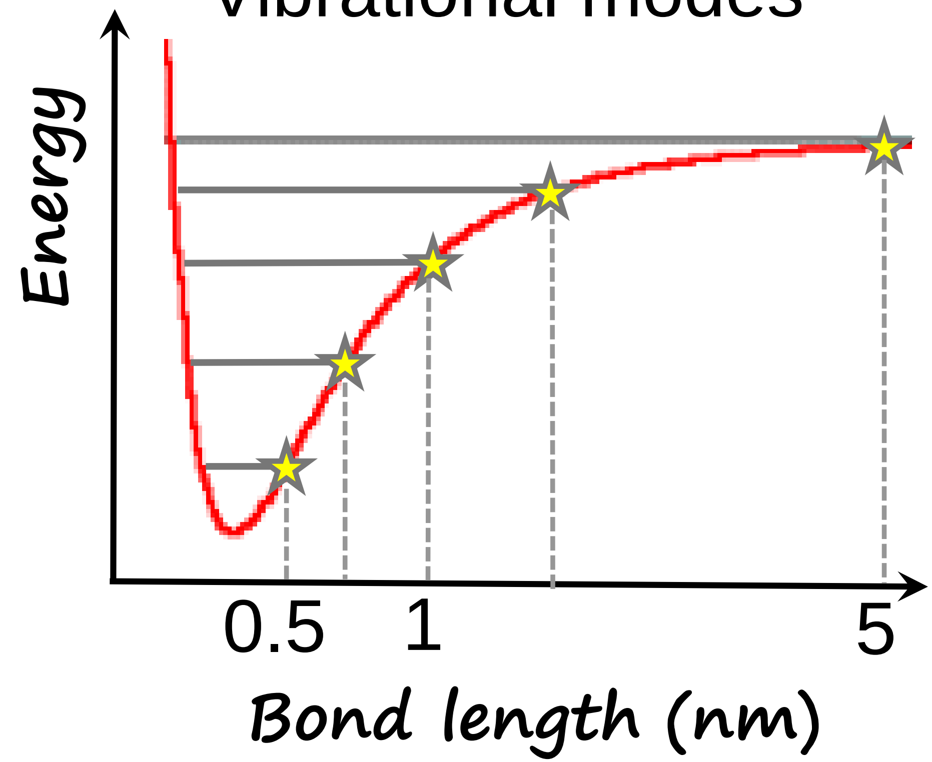
## Nanoscale mass-dependent forces




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

Hypothetical
"Yukawa" correction

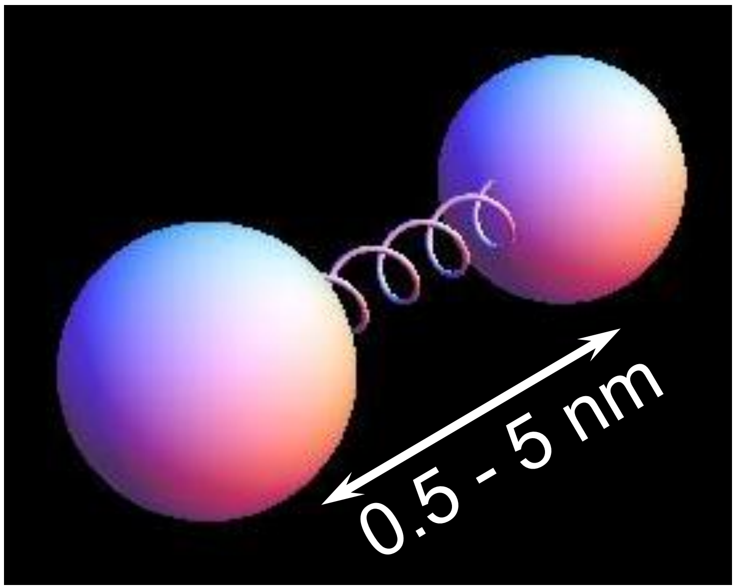
Vibrational modes




Explore a range of lengths

# Science with molecular clocks

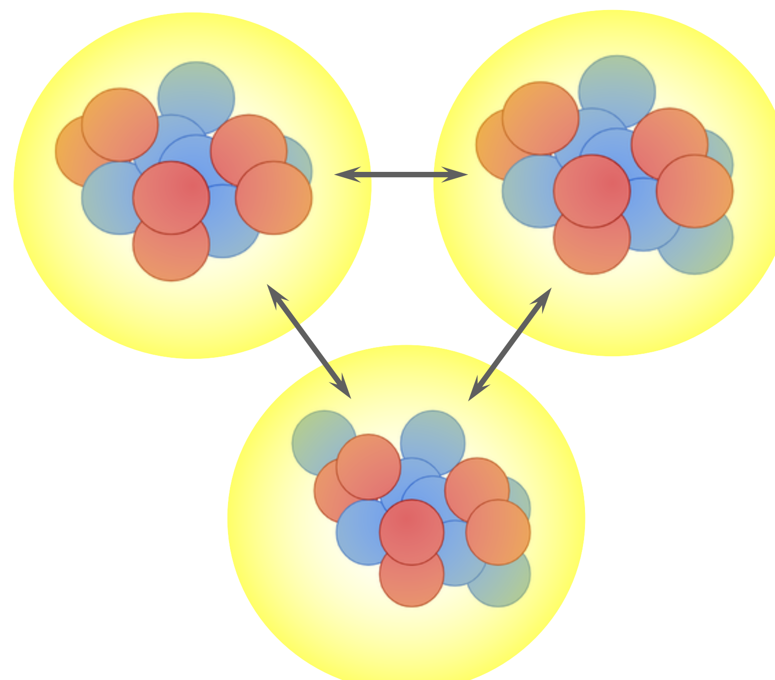
## Nanoscale mass-dependent forces




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

Hypothetical
“Yukawa” correction

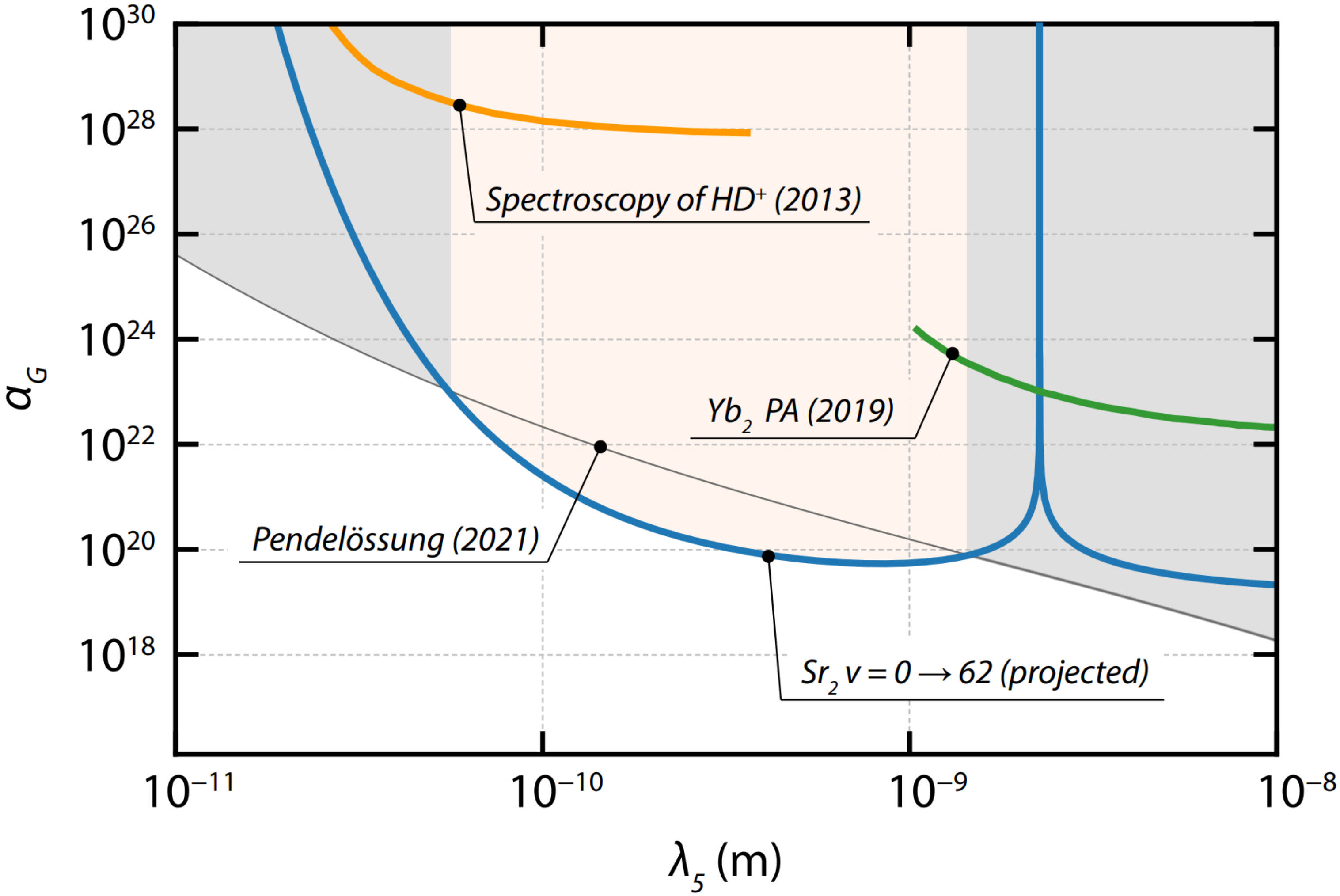
Isotopes
of strontium atom



Explore a range of masses

# $5^{th}$ force with molecular clock

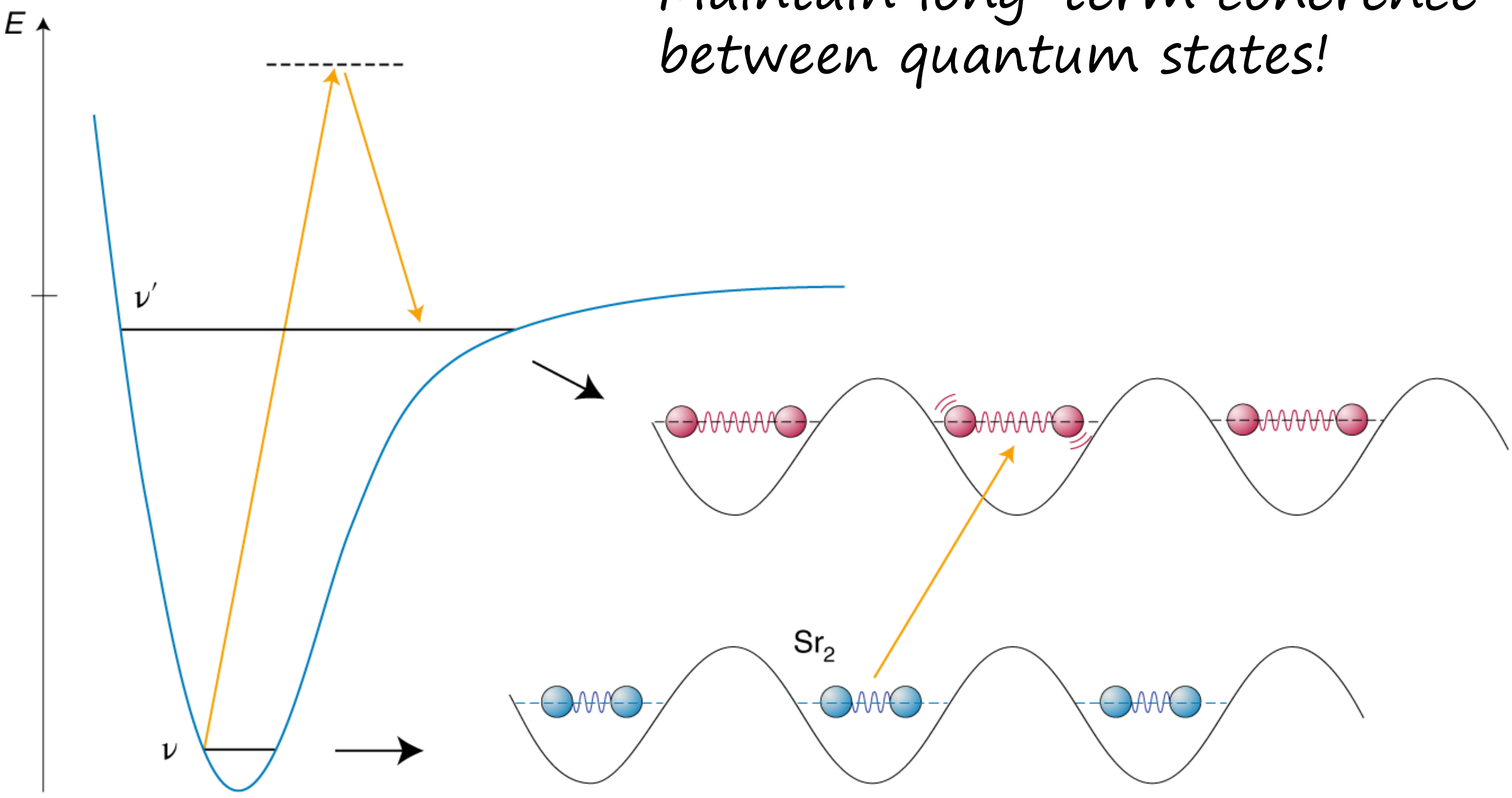
*Current experimental capability*




E. Tiberi, *Ph.D. thesis* (2023)
B. Heacock *et al.*, *Science* **373**, 1239 (2021)
E. J. Salumbides *et al.*, *PRD* **87**, 112008 (2013)
M. Borkowski *et al.*, *Sci. Rep.* **9**, 14807 (2019)

# Molecular lattice clock

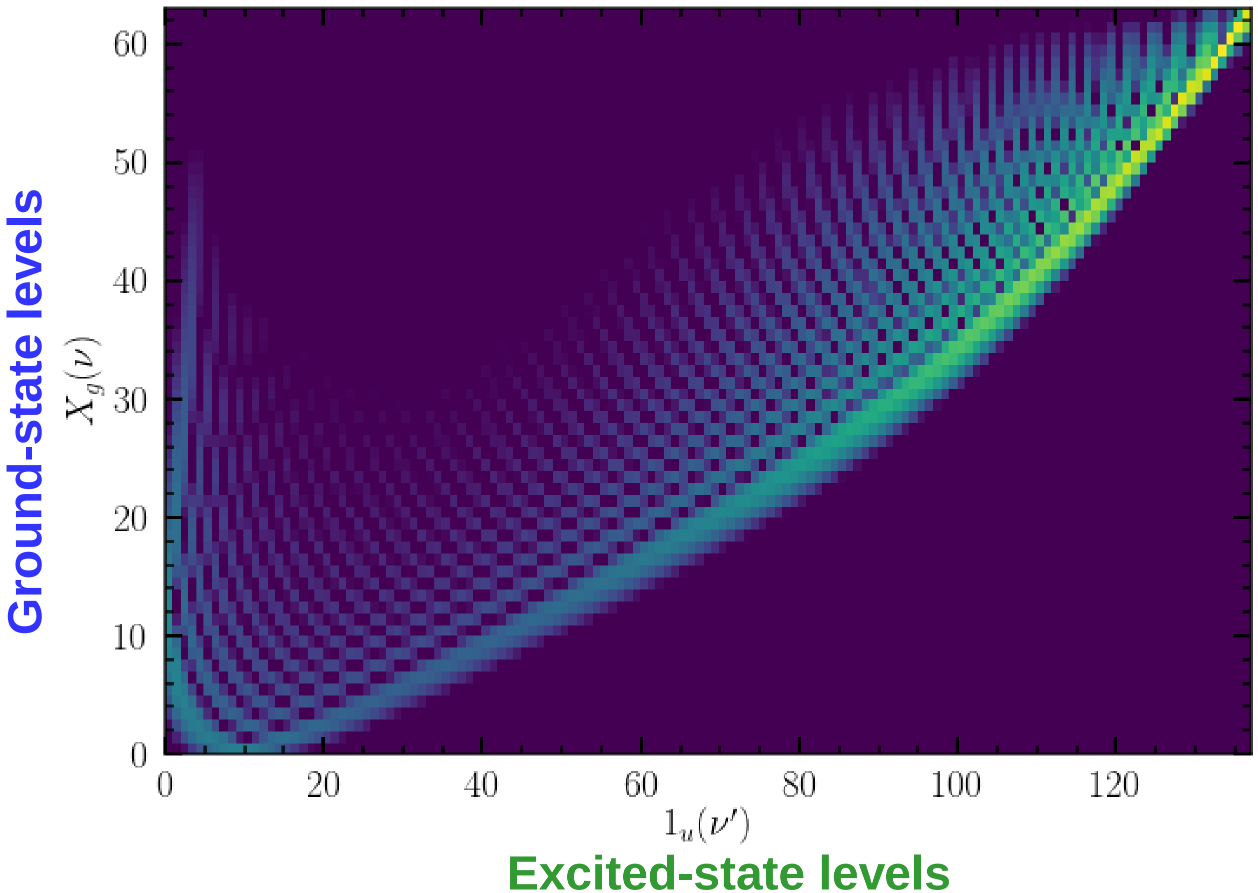
Maintain long-term coherence between quantum states!

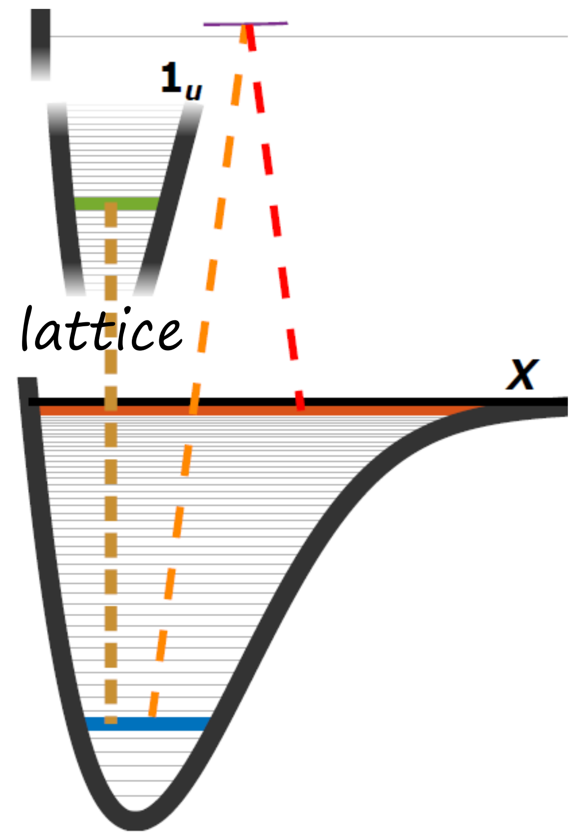



N. Poli, *Nature Phys.* **15**, 1106 (2019)

# Magic wavelengths

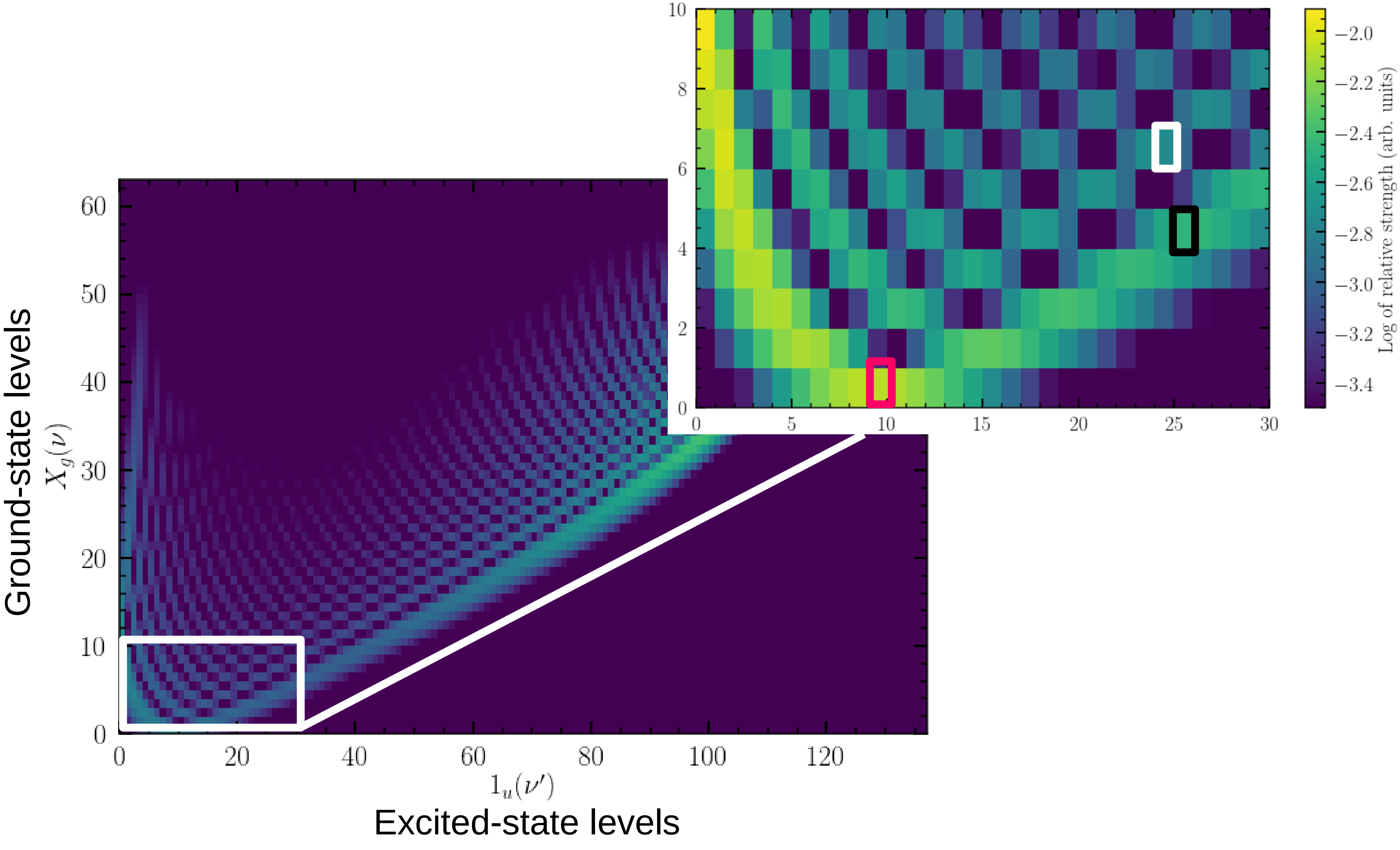
Trap light scattering limits coherence: Choose best λ!



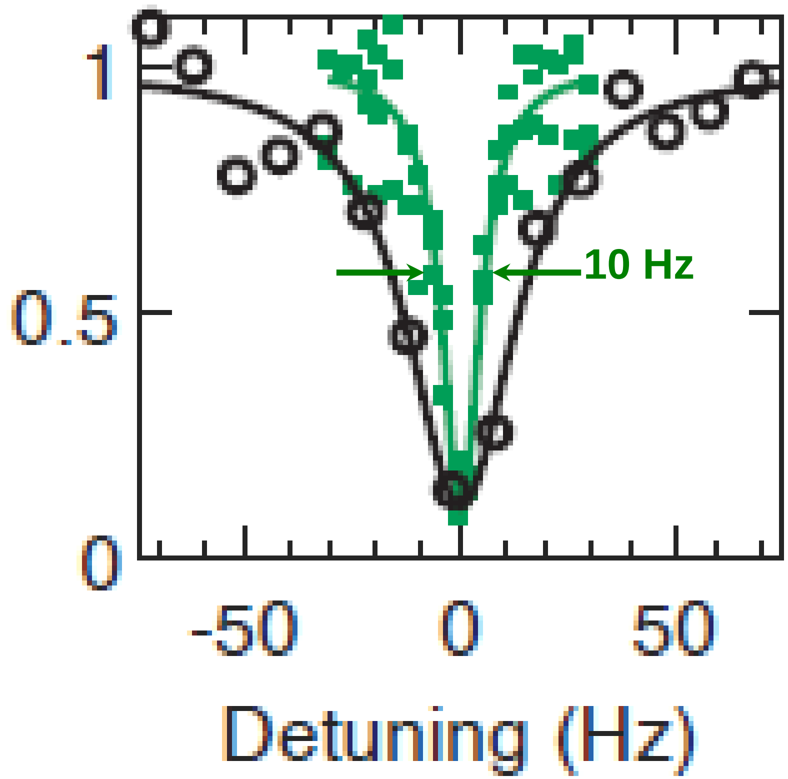
# Magic wavelengths

*Trap light scattering limits coherence: Choose best λ!*



# Molecular lattice clock

*Coherence in magic lattice : ×10⁴!*

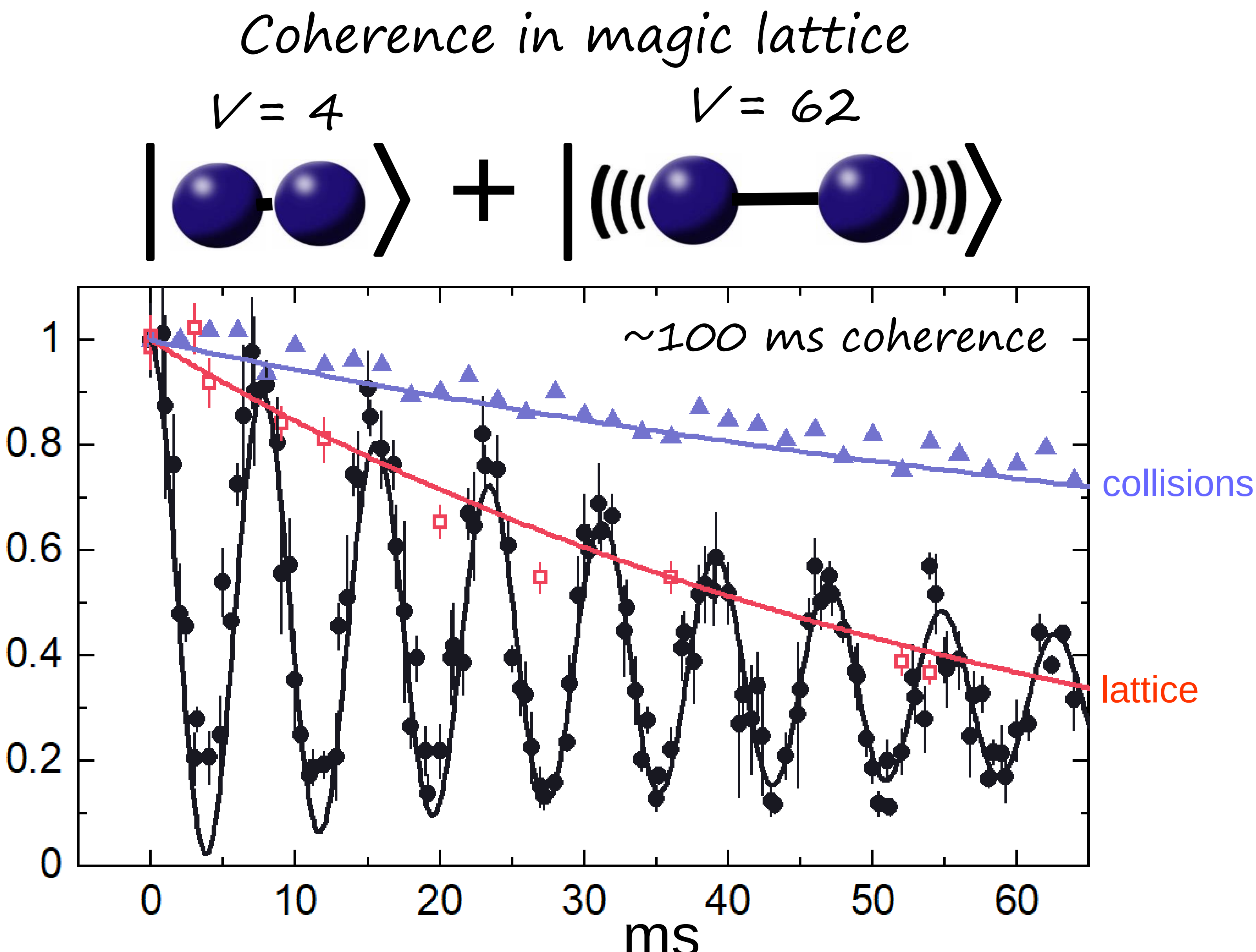



$Q = 3\times10^{12}$

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

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

# Molecular lattice clock




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

# Clock precision & accuracy

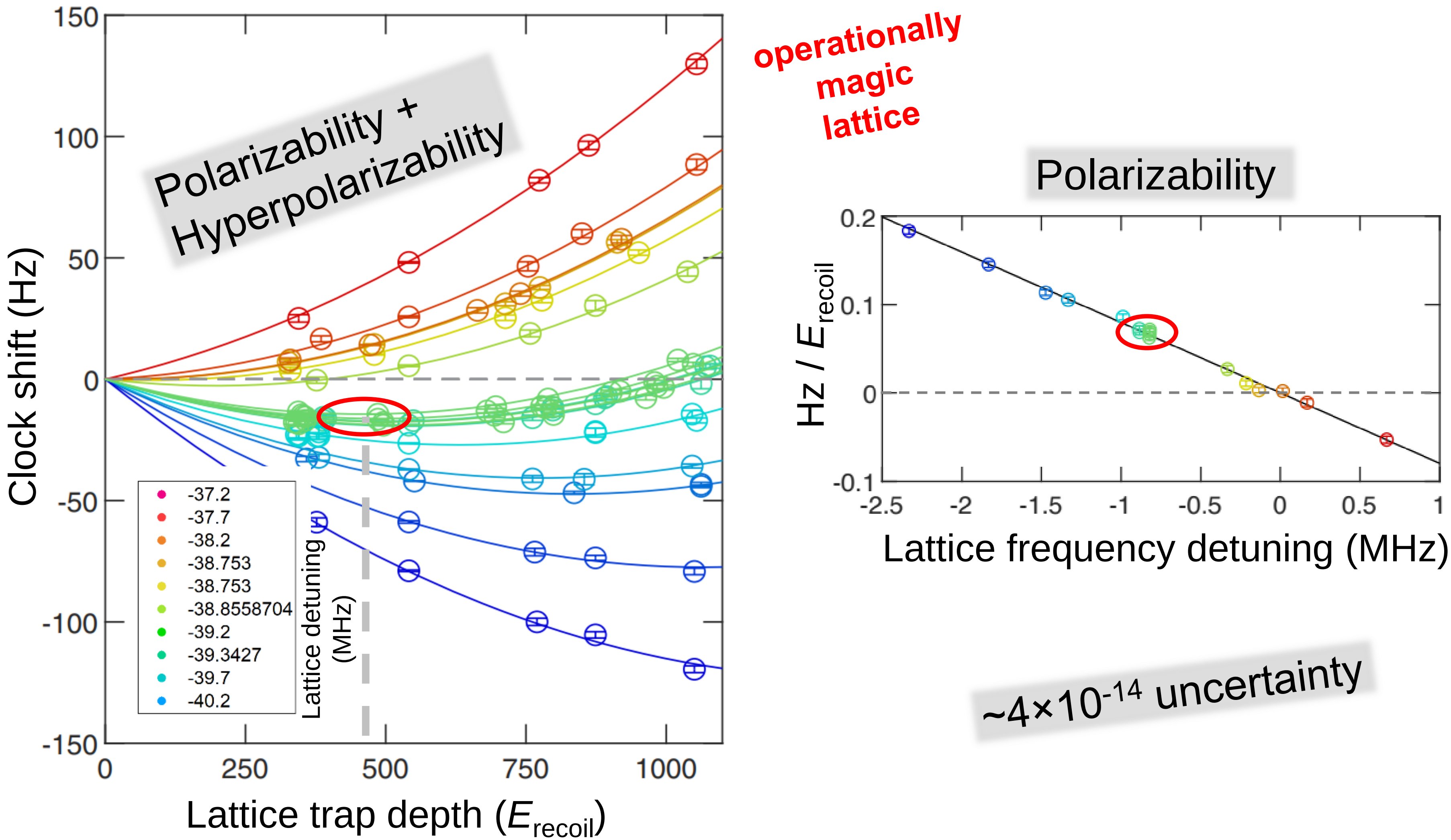
Systematic effects:
What can cause the clock frequency to shift?

$\times \mathbf{10^{-14}}$

| Systematic | Correction | Uncertainty |
|---|---|---|
| Lattice Stark ($E1, M1, E2$) | 100.1 | 3.4 |
| Lattice Stark (hyperpolarizability) | -50.8 | 1.9 |
| Probe Stark (total) | 31.5 | 2.2 |
| BBR | -2.2 | 0.4 × |
| Density | -0.6 | 0.3 |
| Quadratic Zeeman | 0 | 0.05 |
| dc Stark | 0 | $< 0.1$ |
| Doppler and phase chirps | 0 | $< 1$ |
| Lattice tunneling | 0 | $< 0.1$ |
| Line pulling | 0 | $< 0.1$ |
| Scan-and-fit | 0 | $< 0.6$ |
| **Total** | 77.9 | 4.6 |

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

# Clock shifts: Lattice light intensity

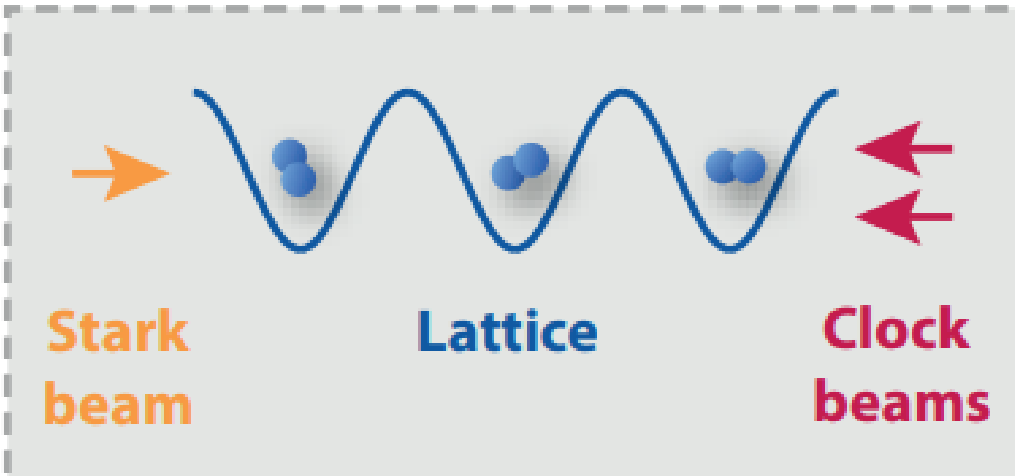



~4×10$^{-14}$ uncertainty

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

# Clock shifts:  BBR

## Purely vibrational BBR shifts?

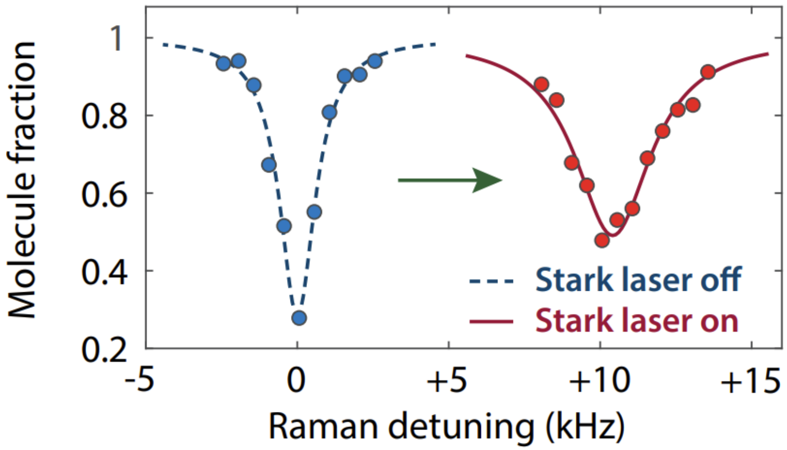


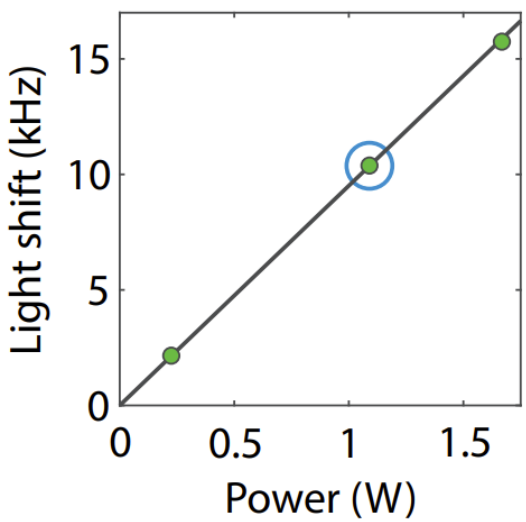

Wojtek Skomorowski

# Molecular polarizabilities

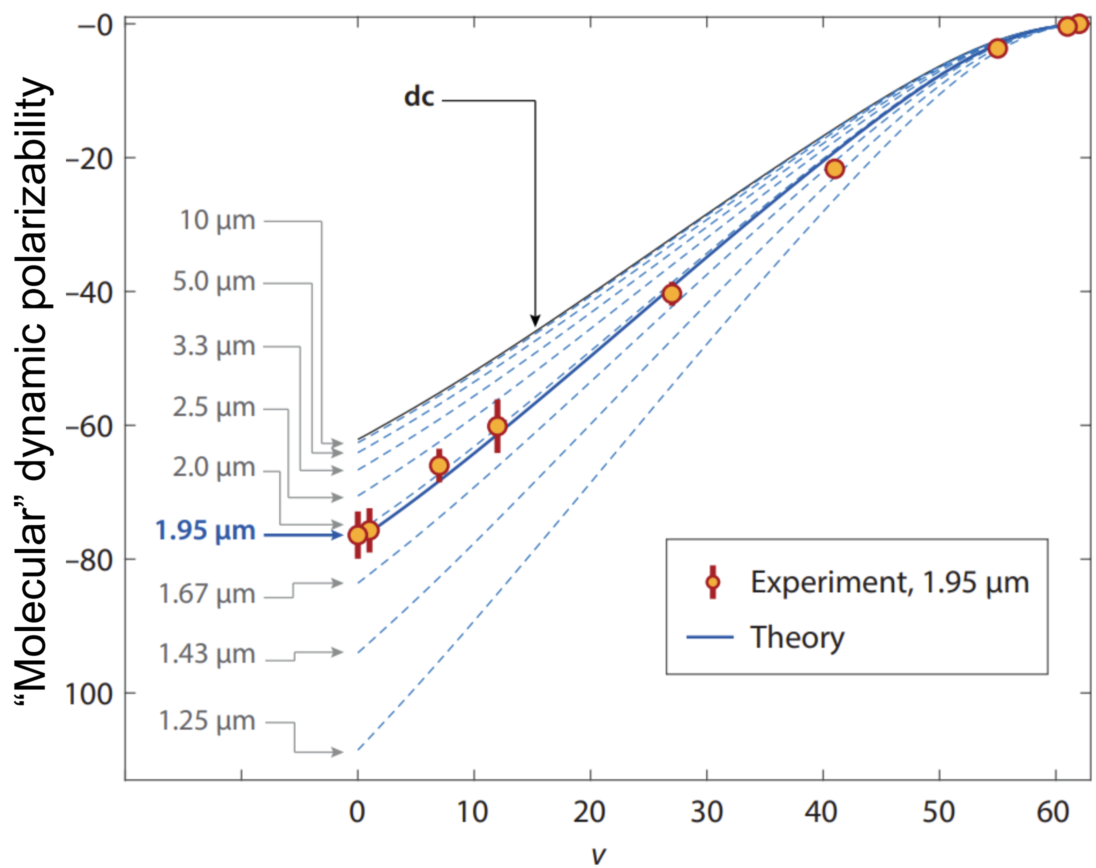
*DC to infrared*

IR Stark shift measurement (2 μm) using clock transitions




IR Stark shifts, all vibrational states: Measurement & calculations




B. Iritani *et al*., arXiv:2306.00981

# Molecular polarizabilities

## *DC to infrared*

IR Stark shifts, all vibrational states:
Measurement & calculations

Net BBR shift:

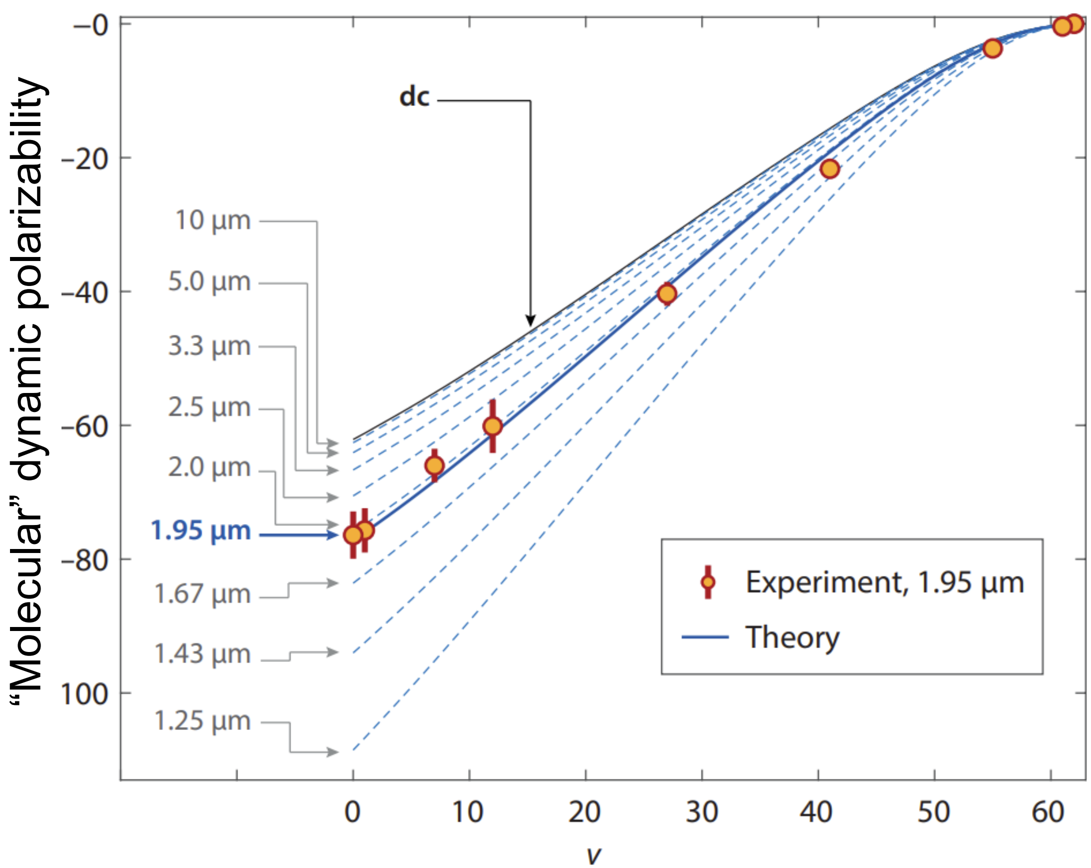
$$\mathcal{O}(10^{-14})$$

BBR shift uncertainty:

$$< 5 \times 10^{-16}$$

Dynamic correction:

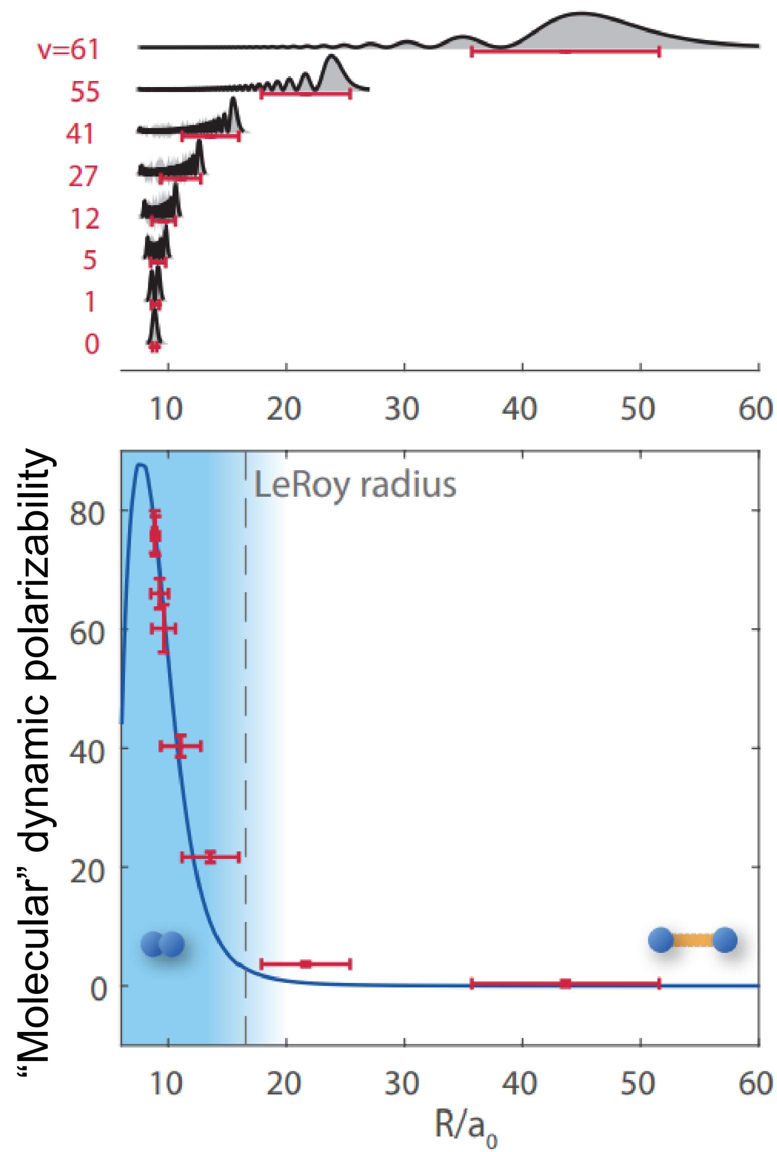
$$\eta \sim 0.5\%$$




B. Iritani *et al*., arXiv:2306.00981

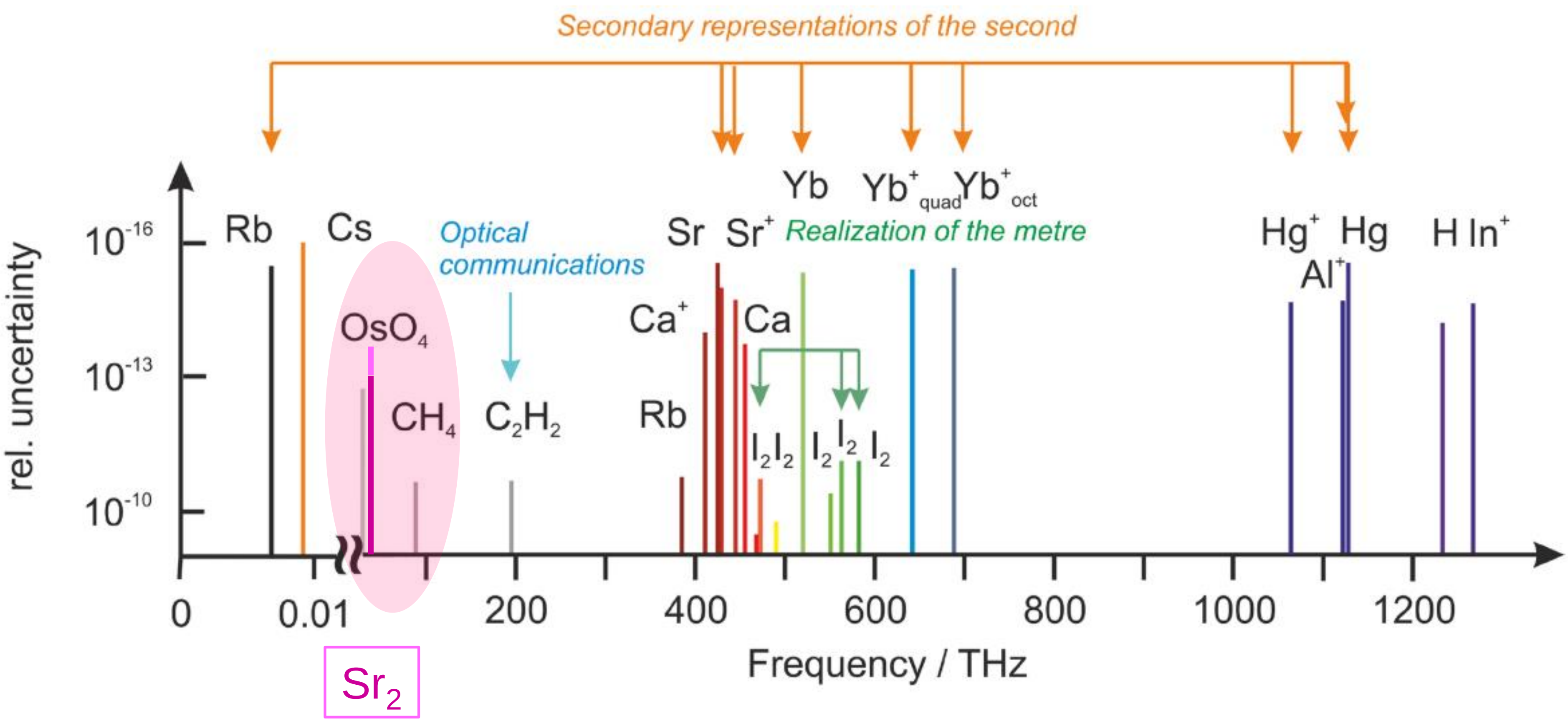
# Molecular polarizabilities

## Physicists' vs. chemists' molecules



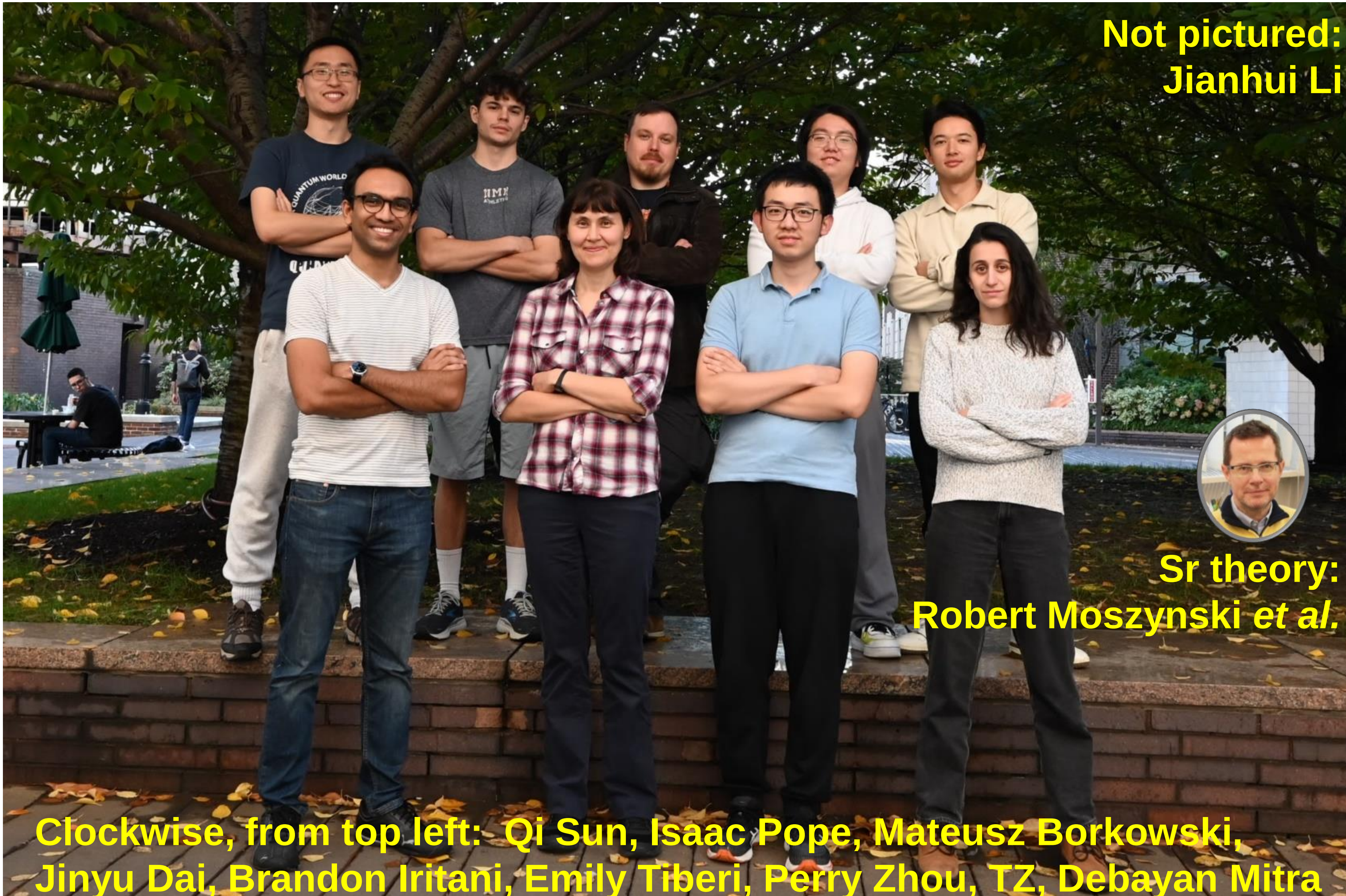
# Frequency standards

2017 recommendations




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

# ZLab


Not pictured:
Jianhui Li
Sr theory:
Robert Moszynski *et al.*
Clockwise, from top left: Qi Sun, Isaac Pope, Mateusz Borkowski,
Jinyu Dai, Brandon Iritani, Emily Tiberi, Perry Zhou, TZ, Debayan Mitra

# Poster presenters

Mateusz Borkowski

**$Sr_2$ lattice clock**
**(Monday #38)**

Eliot Bohr

**Superradiance-enhanced Ramsey spectroscopy**
**(Tuesday #50)**

Sofus L. Kristensen

**Superradiant optical line narrowing**
**(Thursday #108)**

Stefan A. Schäffer

**Coherent control of noise in collective emission**
**(Thursday #109)**