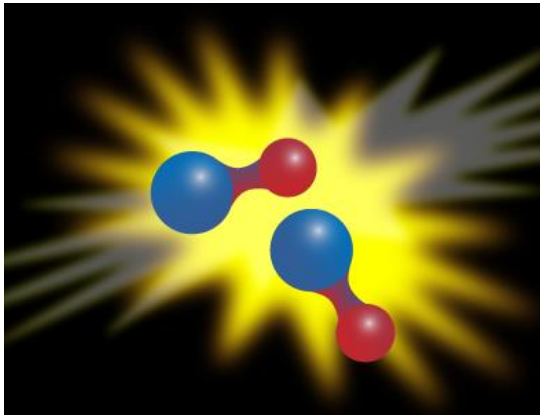
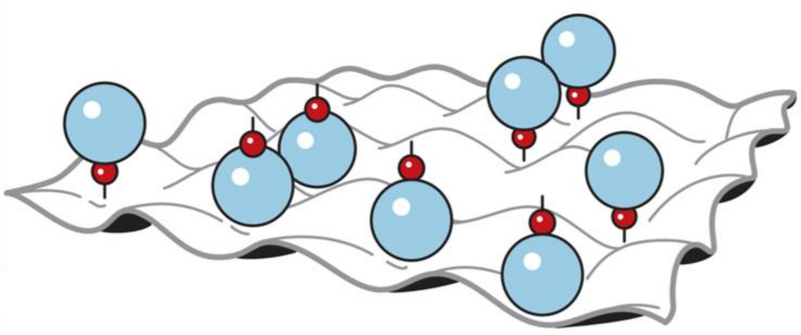
High-Precision Physics and Chemistry with Ultracold Molecules

Tanya Zelevinsky
Columbia University, New York

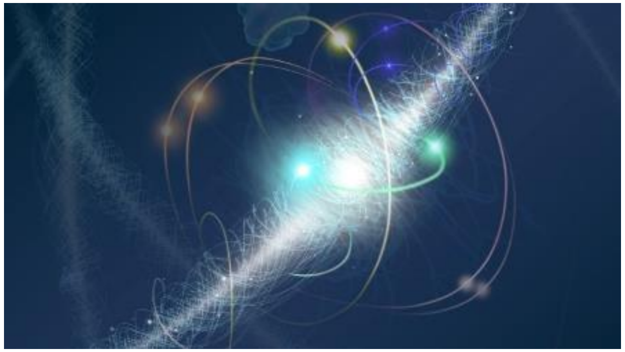
Quantum science with molecules



Fundamental
chemistry



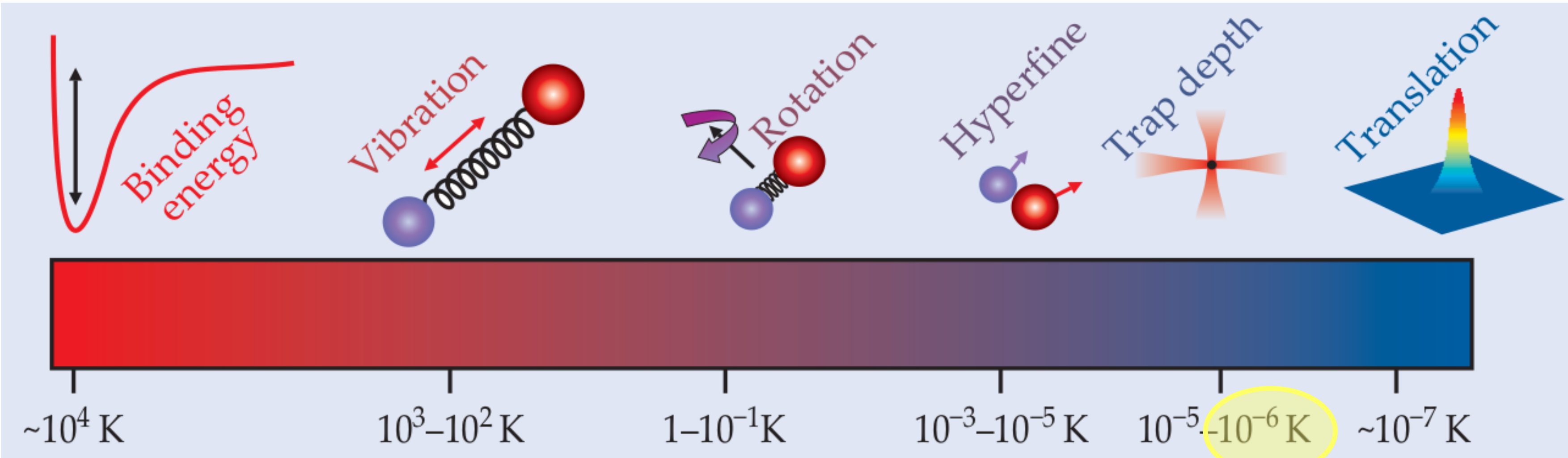
Quantum
materials

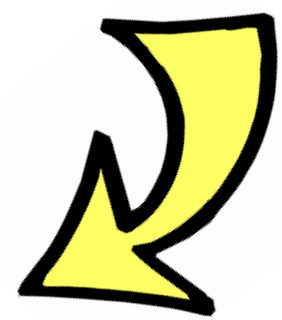


Fundamental
physics

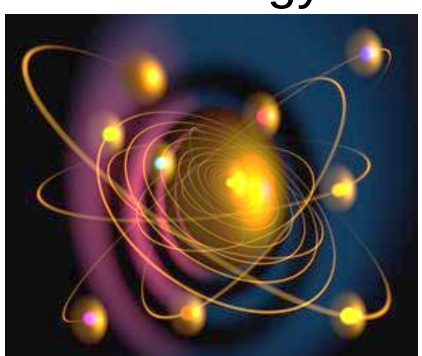
J. L. Bohn *et al*, *Science* **357**, 1002 (2017)

Why ultracold?

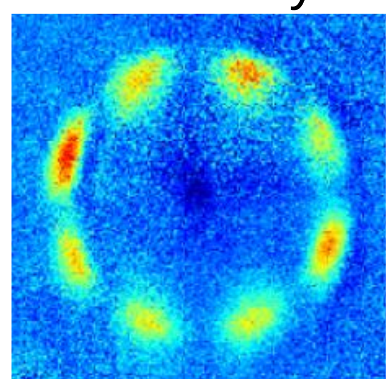




Fundamental metrology



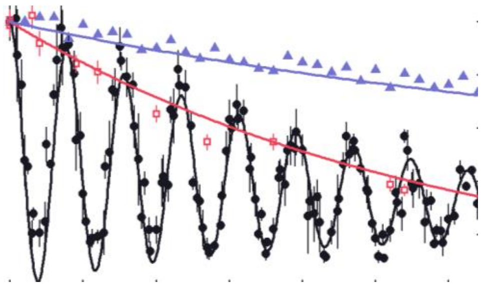
Ultracold chemistry



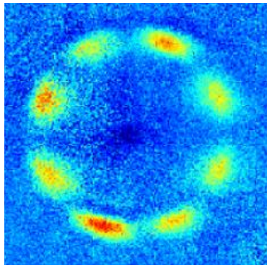
D. S. Jin and J. Ye, *Phys. Today* **64**(5), 27 (2011)

Quantum science with molecules

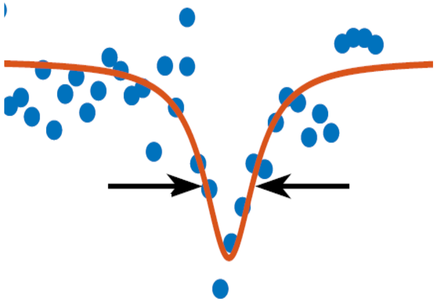
- Can small molecules contribute to our understanding of fundamental forces ("old" and "new" physics)?



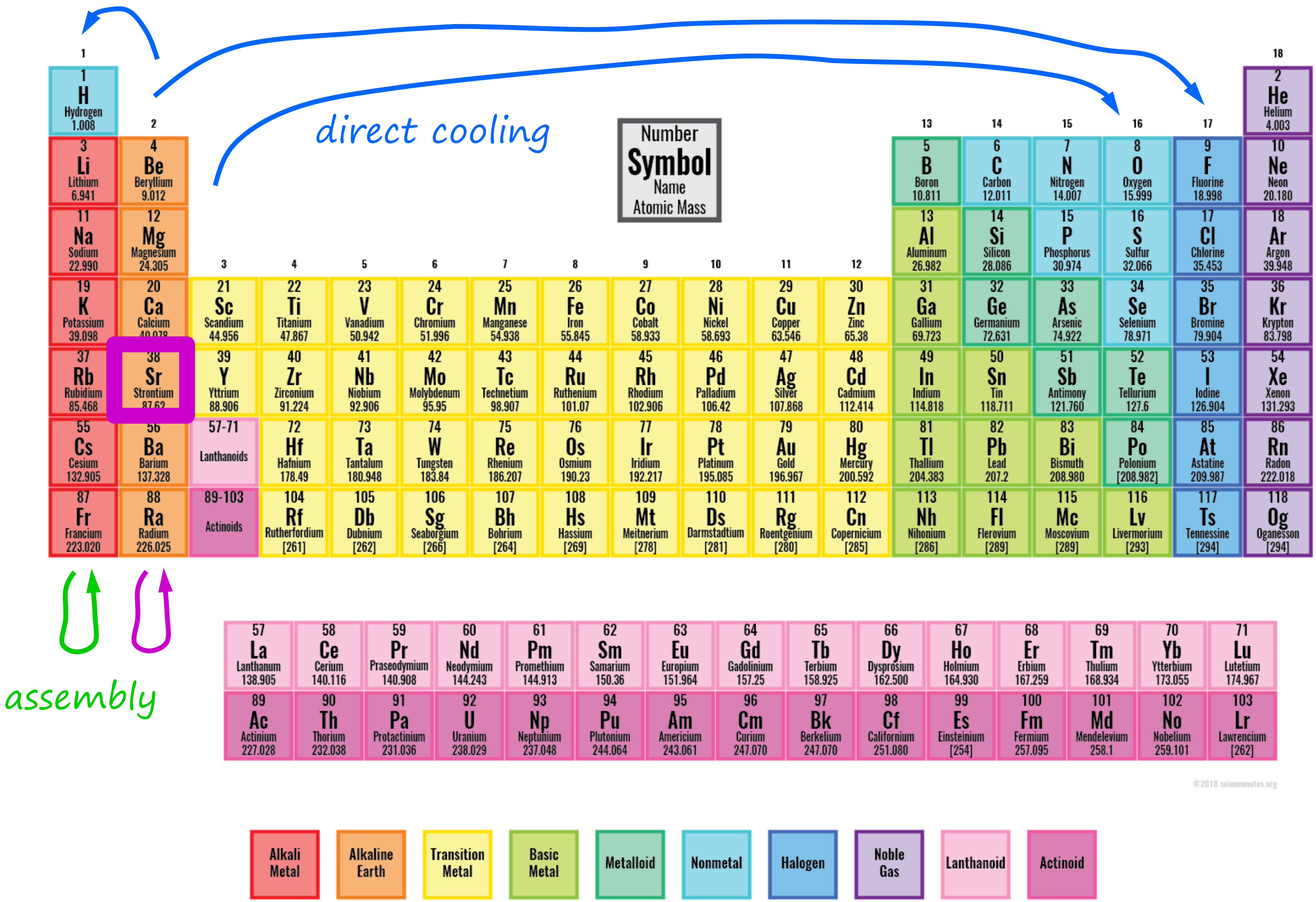
- Is it possible to control these molecules across frequency regimes, and to decouple their internal dynamics from the environment?



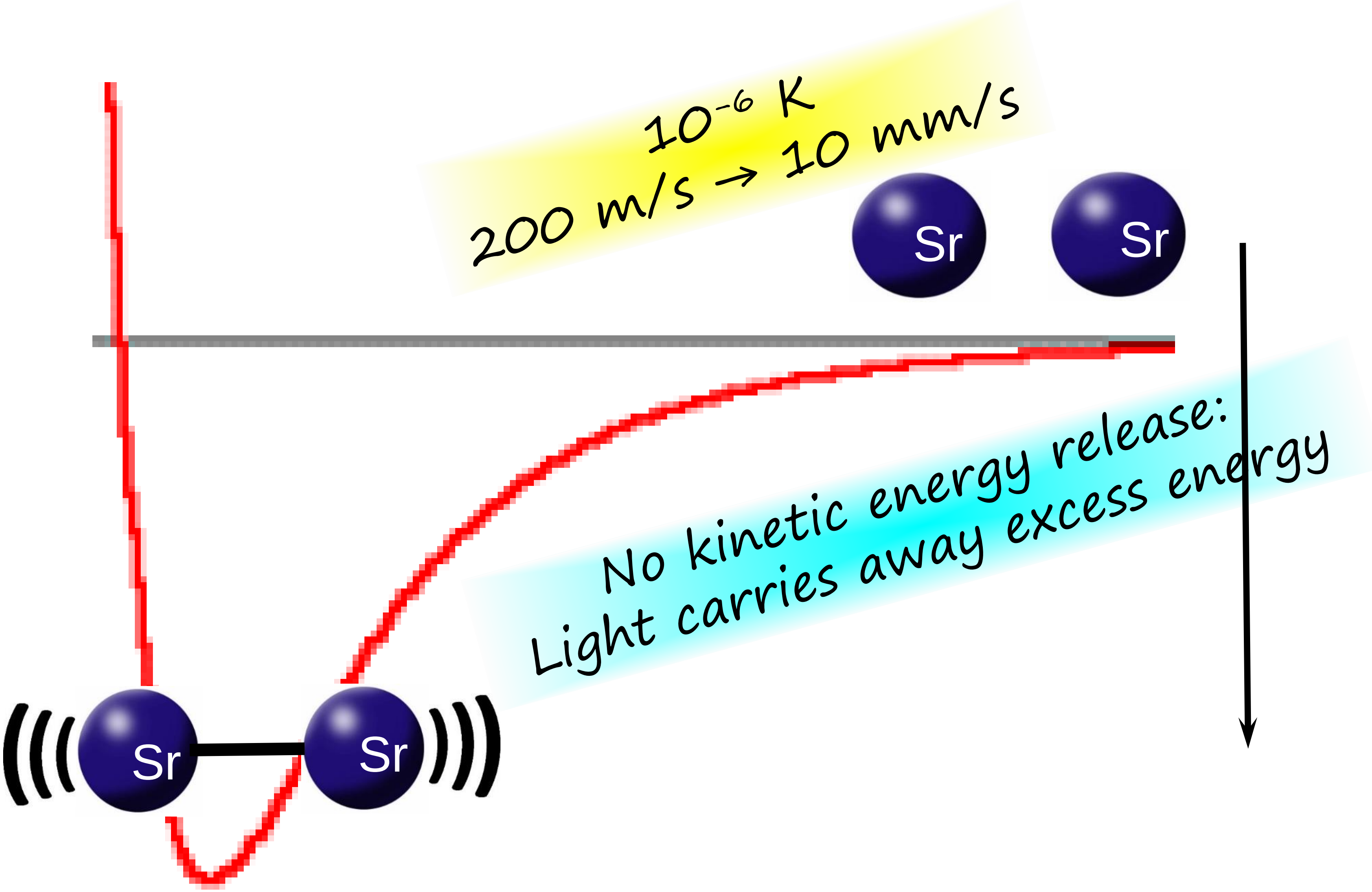
- Is there a metrological advantage for molecular systems?



Producing ultracold molecules

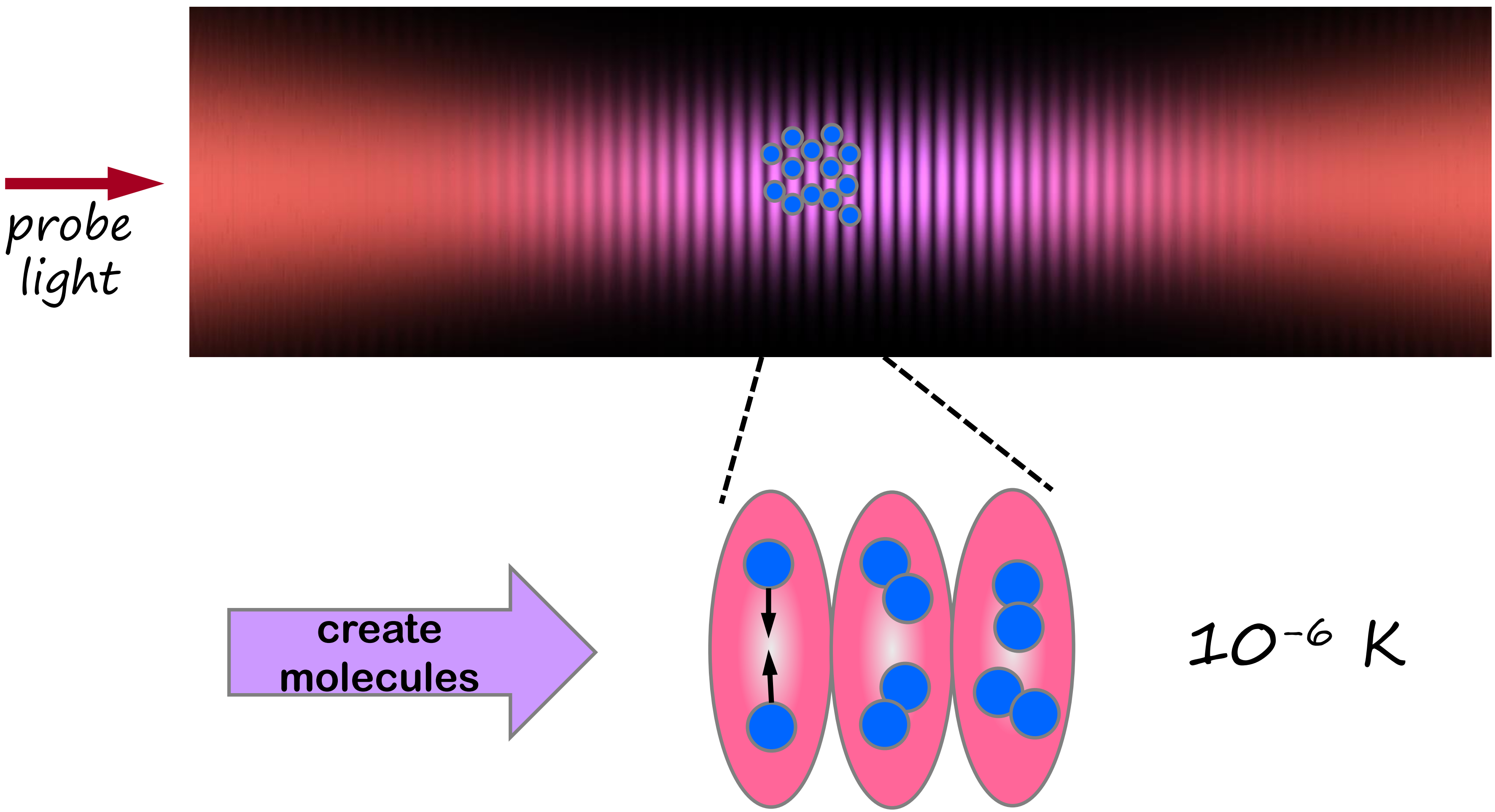


Ultracold molecule photo-assembly



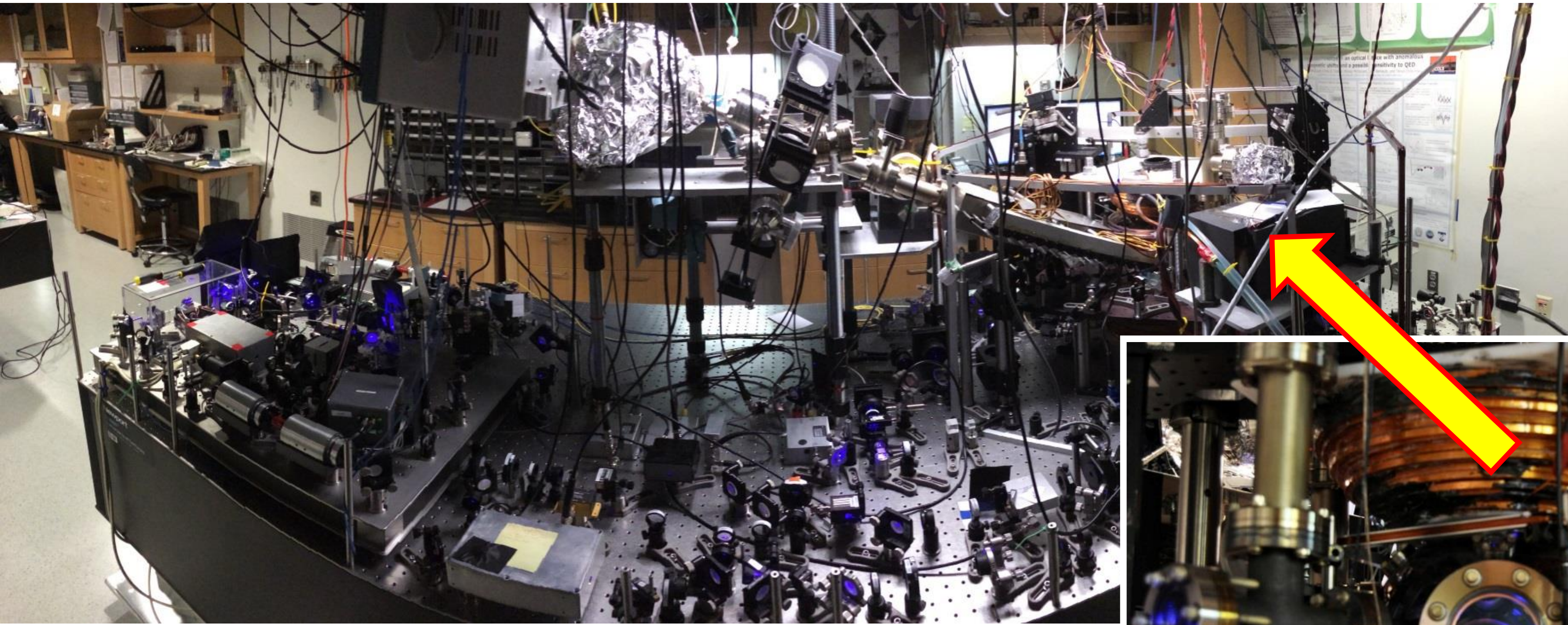
Optical lattice trap

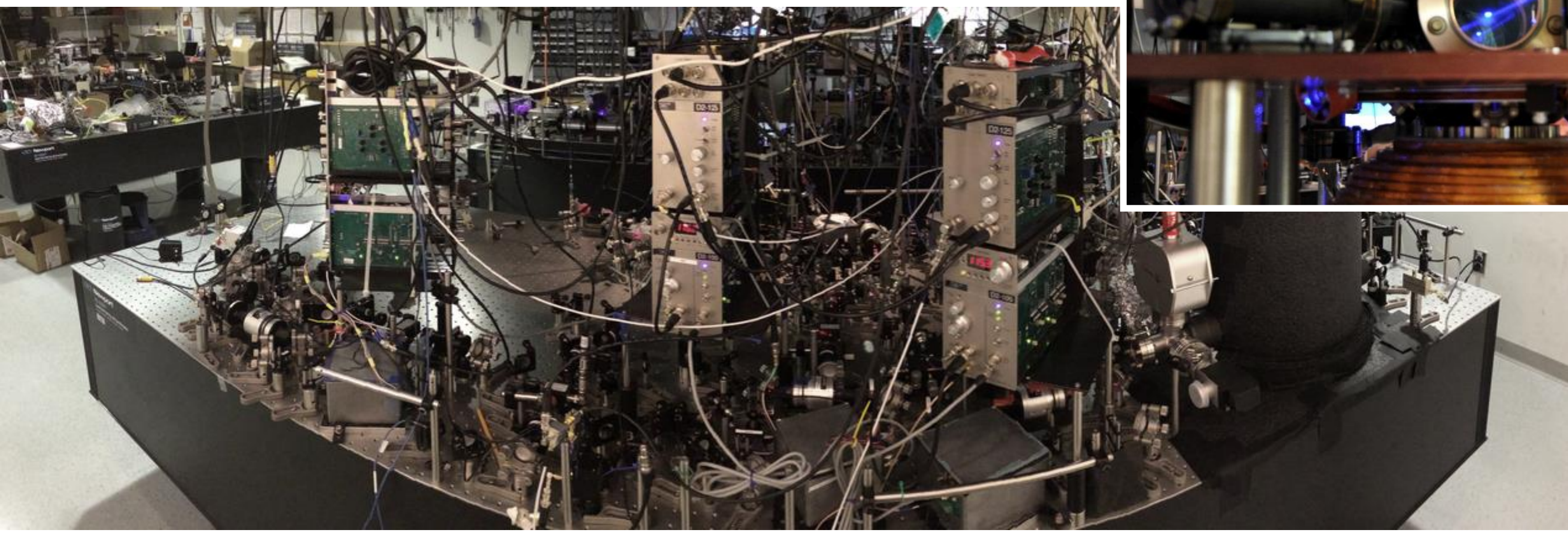
Standing wave of light
holds atoms or molecules in bright microtraps

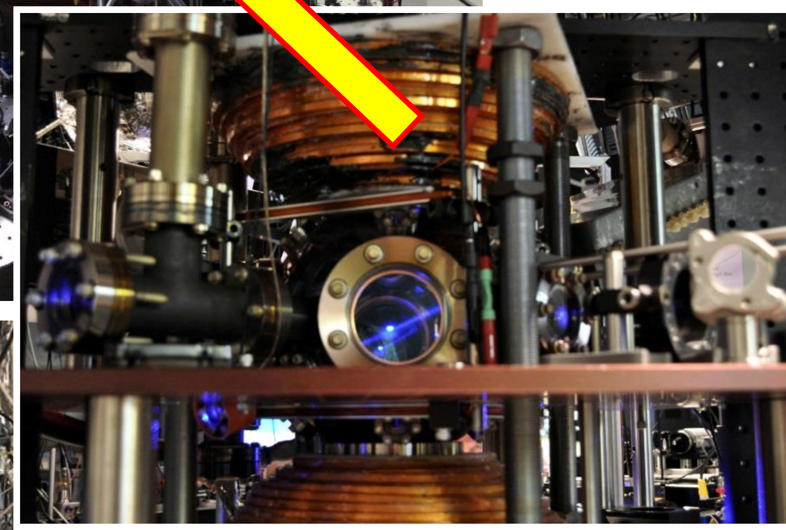


Graphics: S. Blatt

Making ultracold molecules



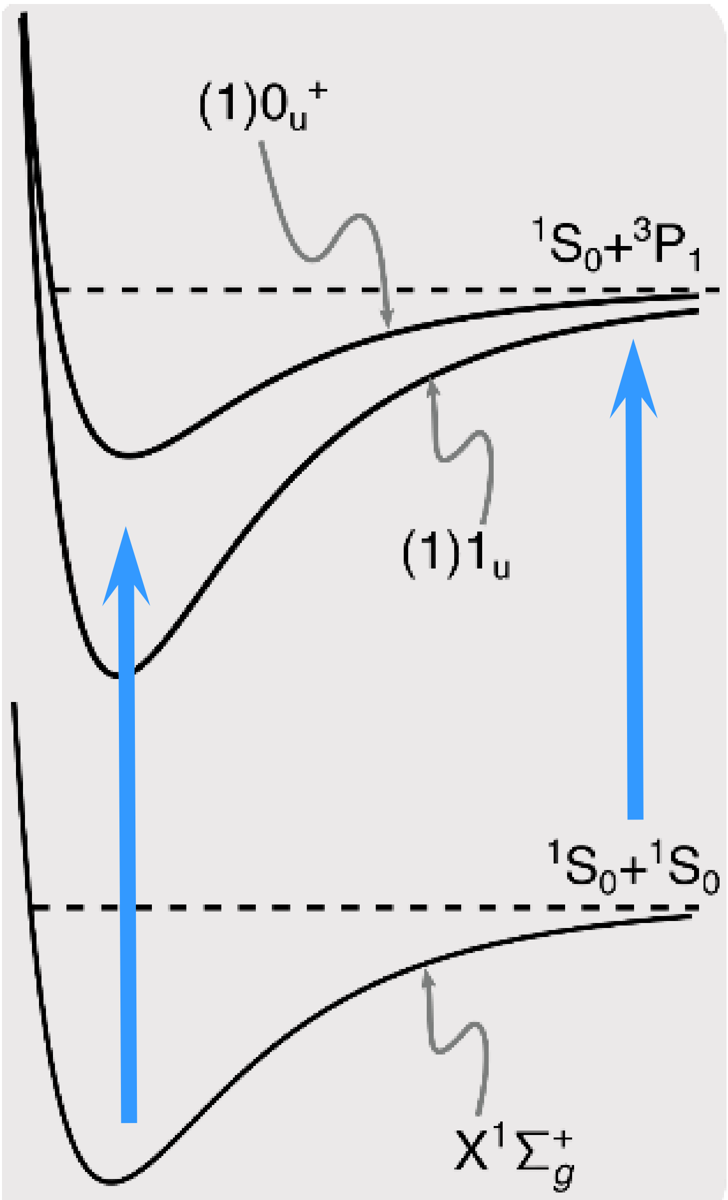


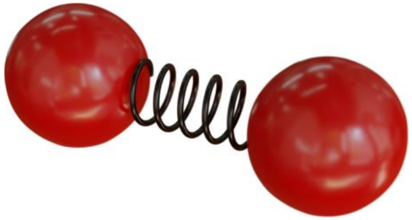


^{88}Sr

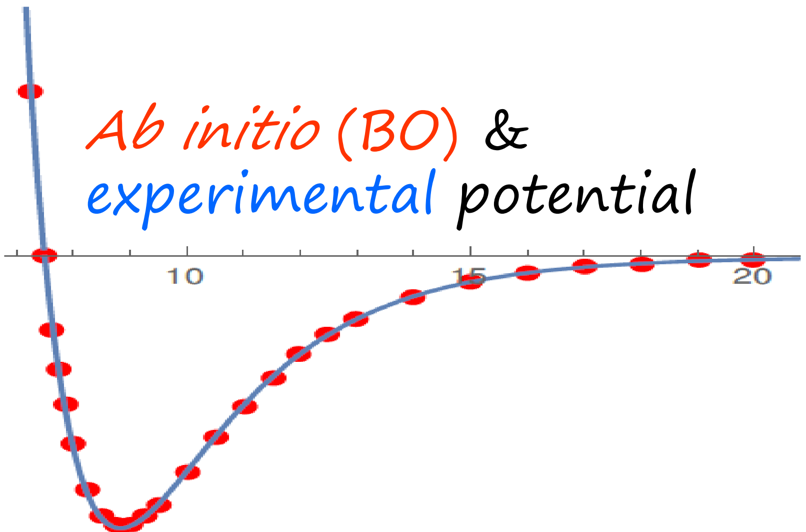
G. Reinaudi *et al*., *PRL* **109**, 115303 (2012)

Ultracold van der Waals dimers





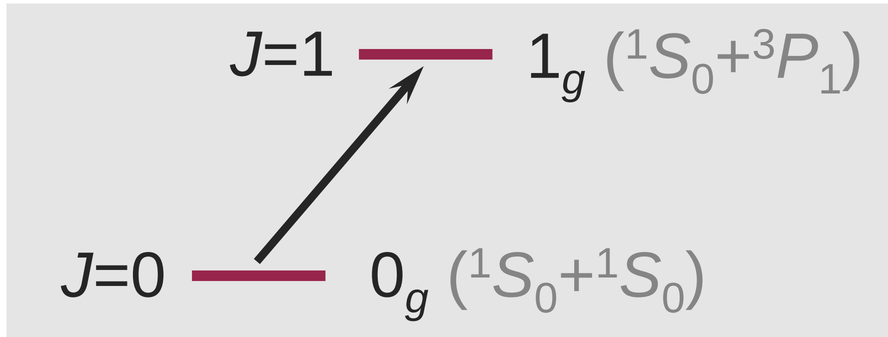
- *Singlet-triplet narrow transitions: quantum control*
- *Spinless ground state: precise metrology & ab initio*

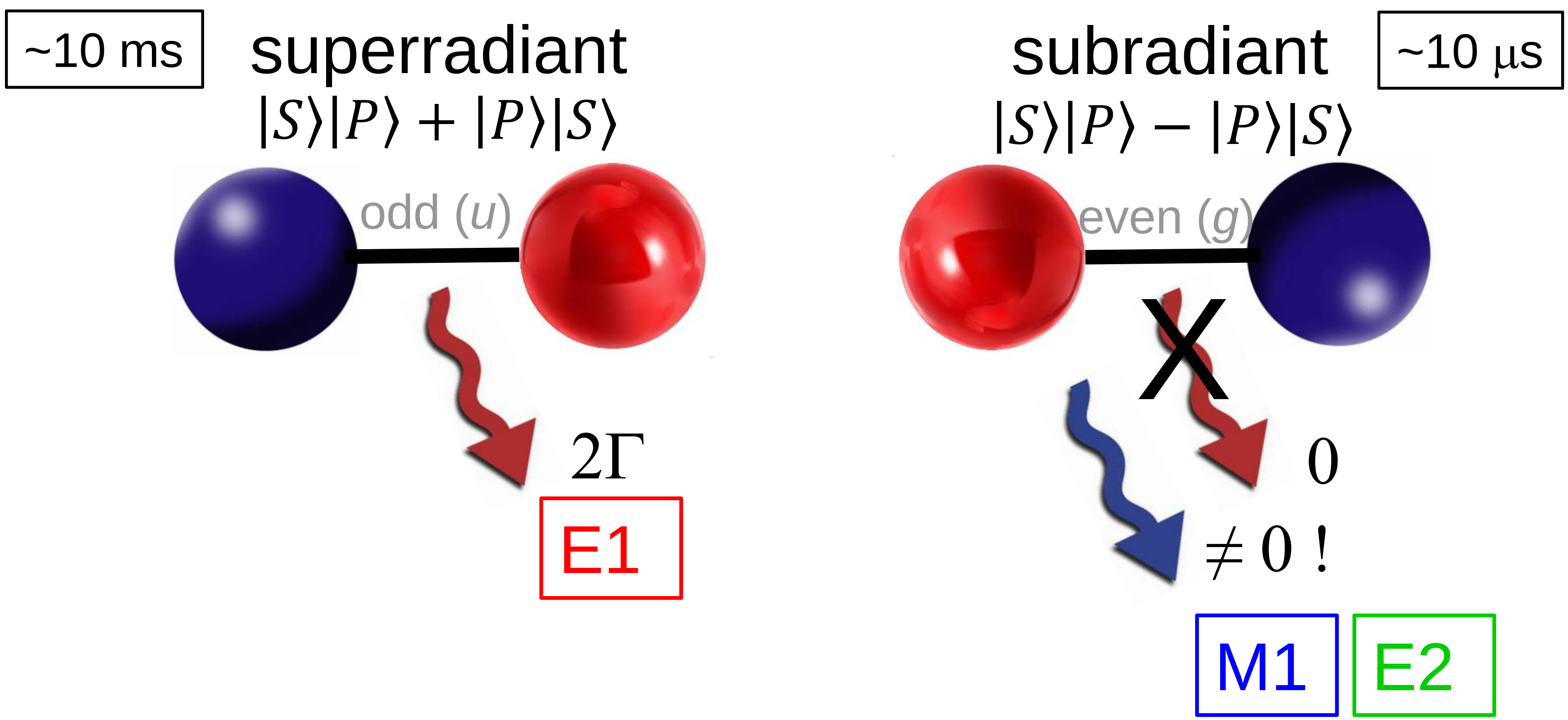


tec-science.com

Narrow-line control of molecules

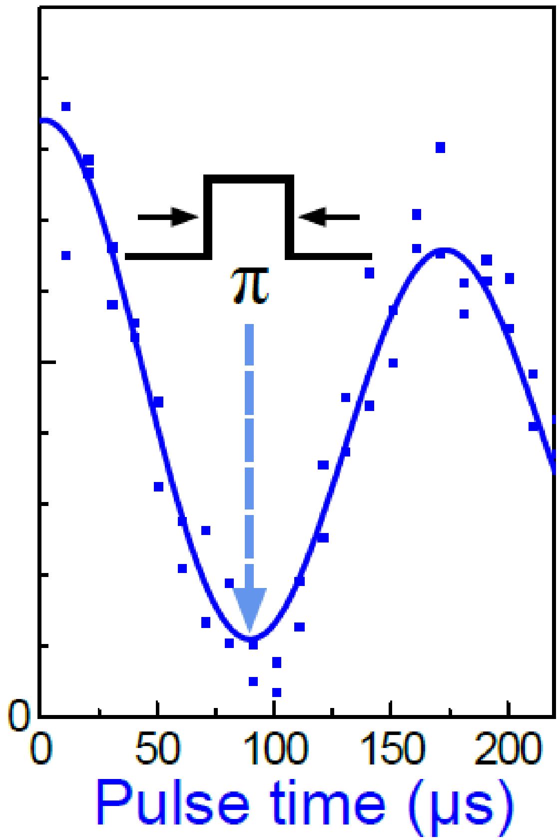
Identical nuclei → Inversion symmetry

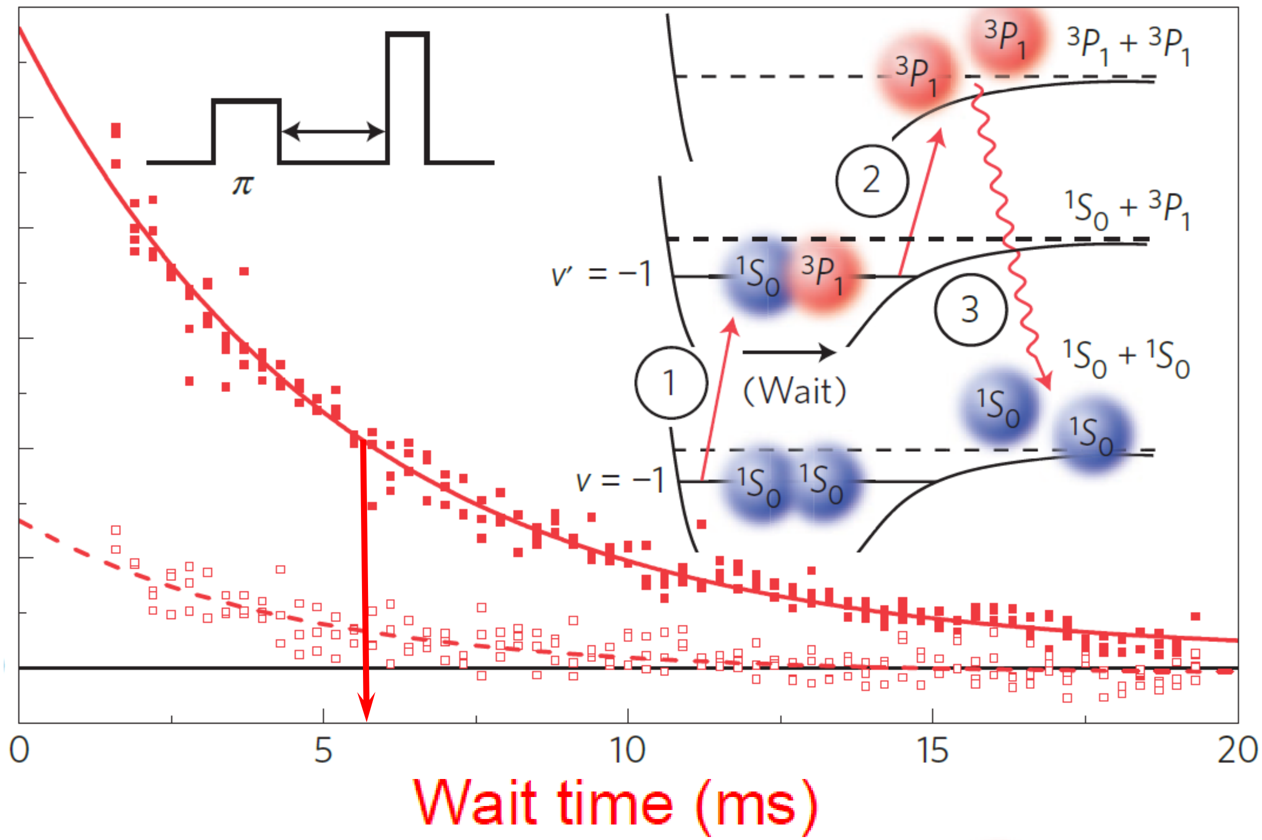




Narrow-line control of molecules

Subradiant states



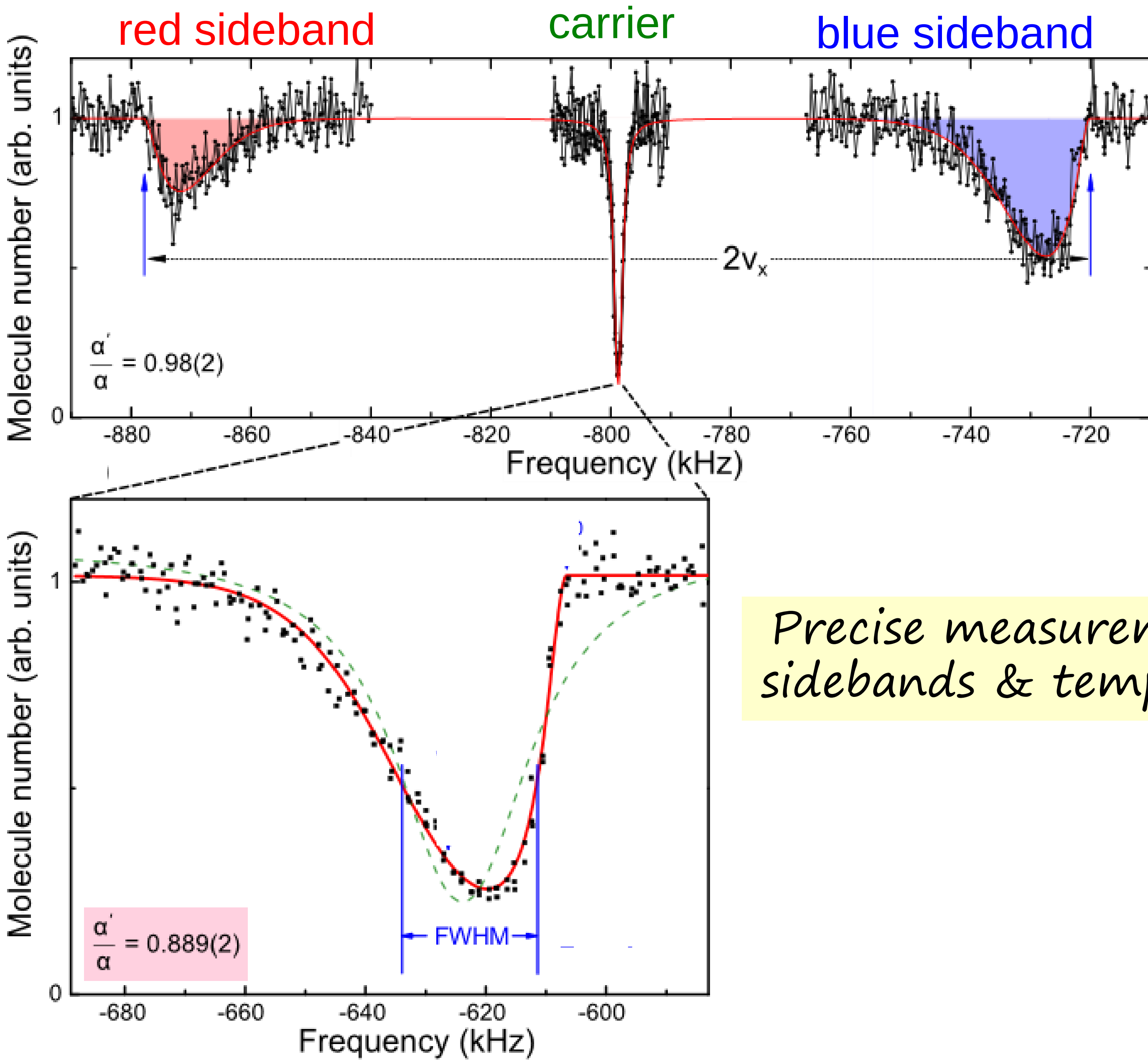


Molecule-light coherence

5.5 ms lifetime

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

Narrow-line control of molecules

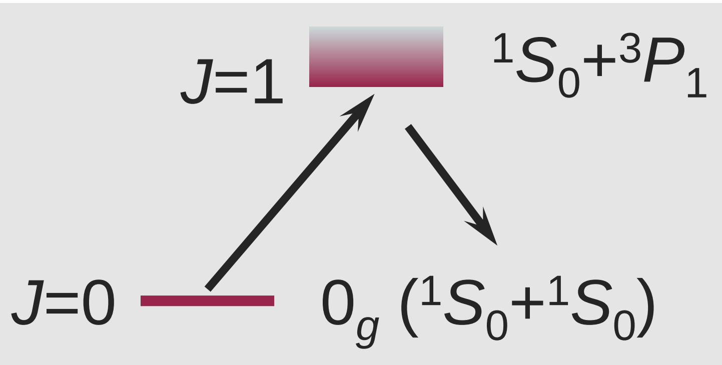


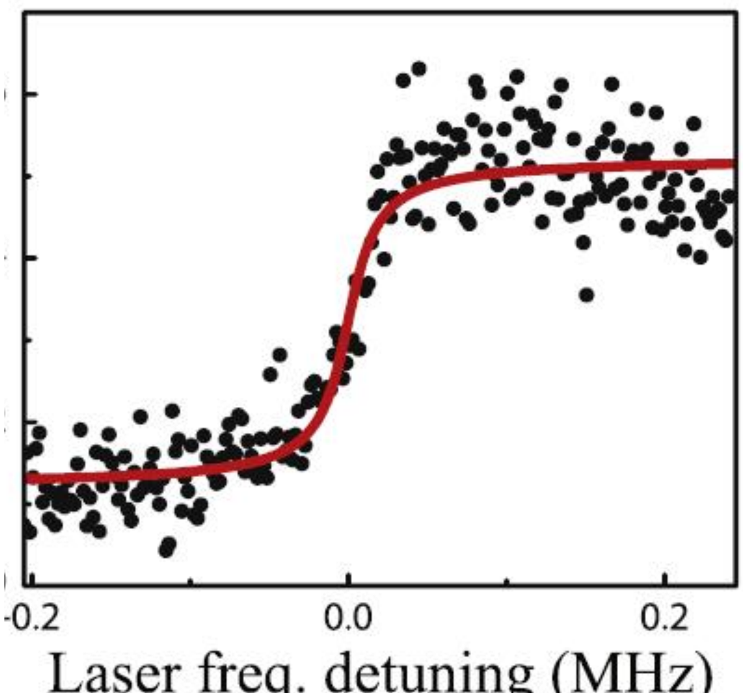
Precise measurements of sidebands & temperature

M. McDonald *et al.*, *PRL* **114**, 023001 (2015)

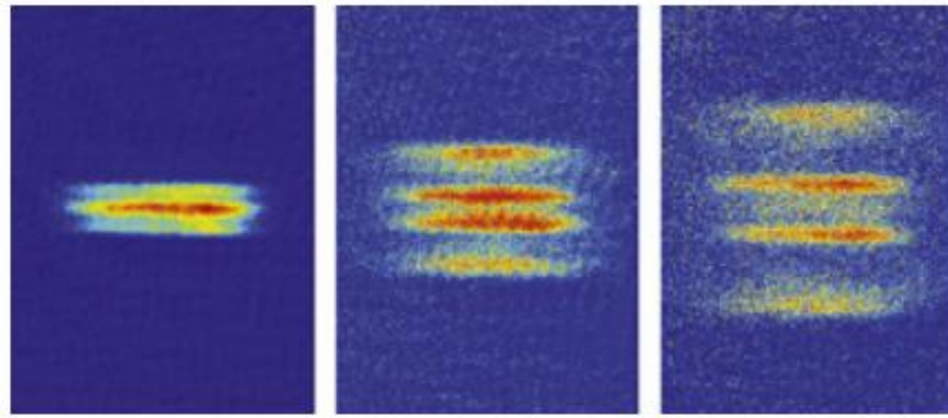
Narrow-line control of molecules

State-resolved photochemistry

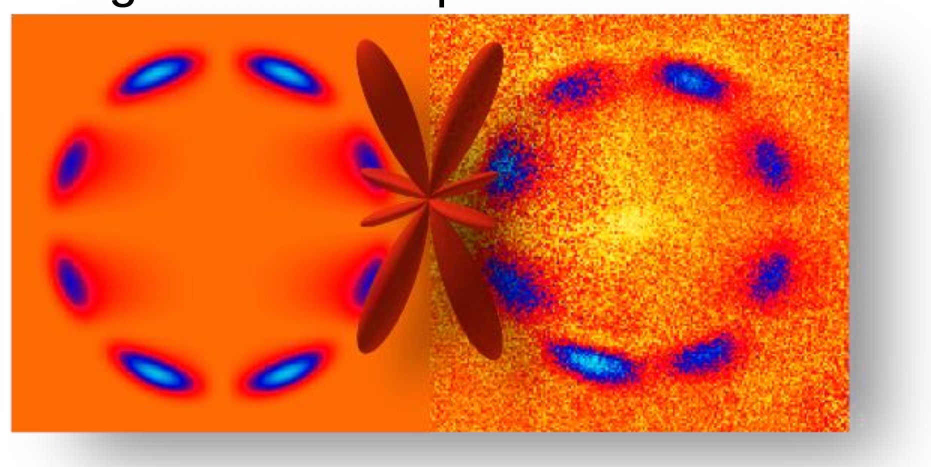




Side-view camera

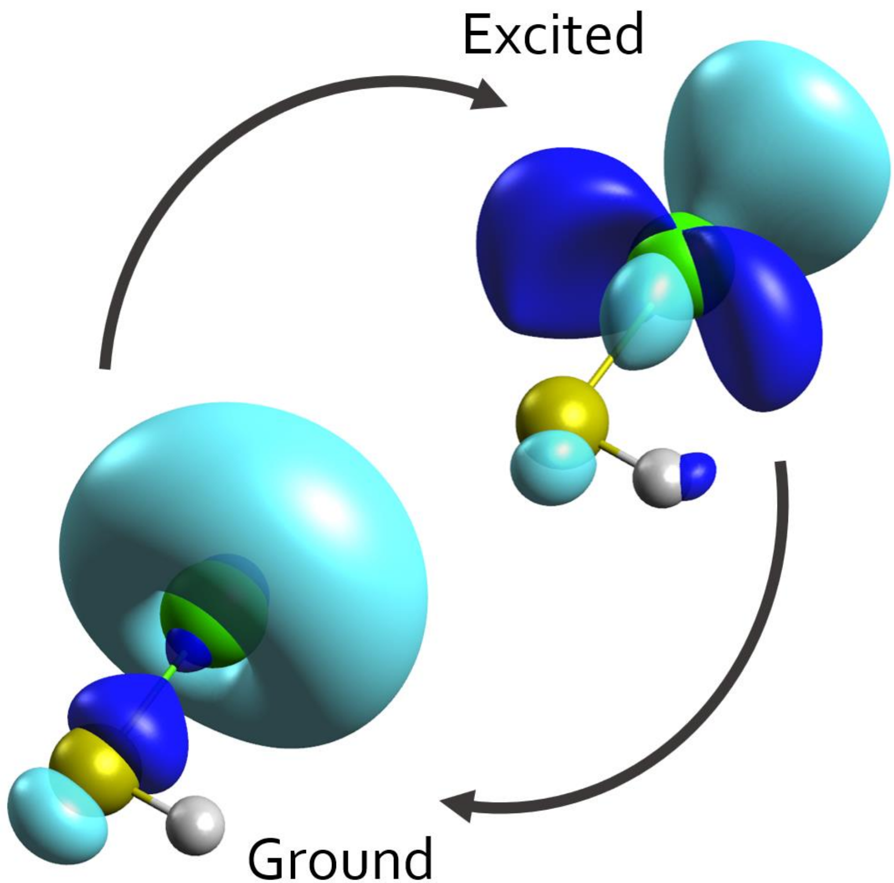


Line-of-sight camera: quantum interference



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

Creation of Ultracold Exotic Gases via Laser Cooling and Precise Dissociation of Molecules

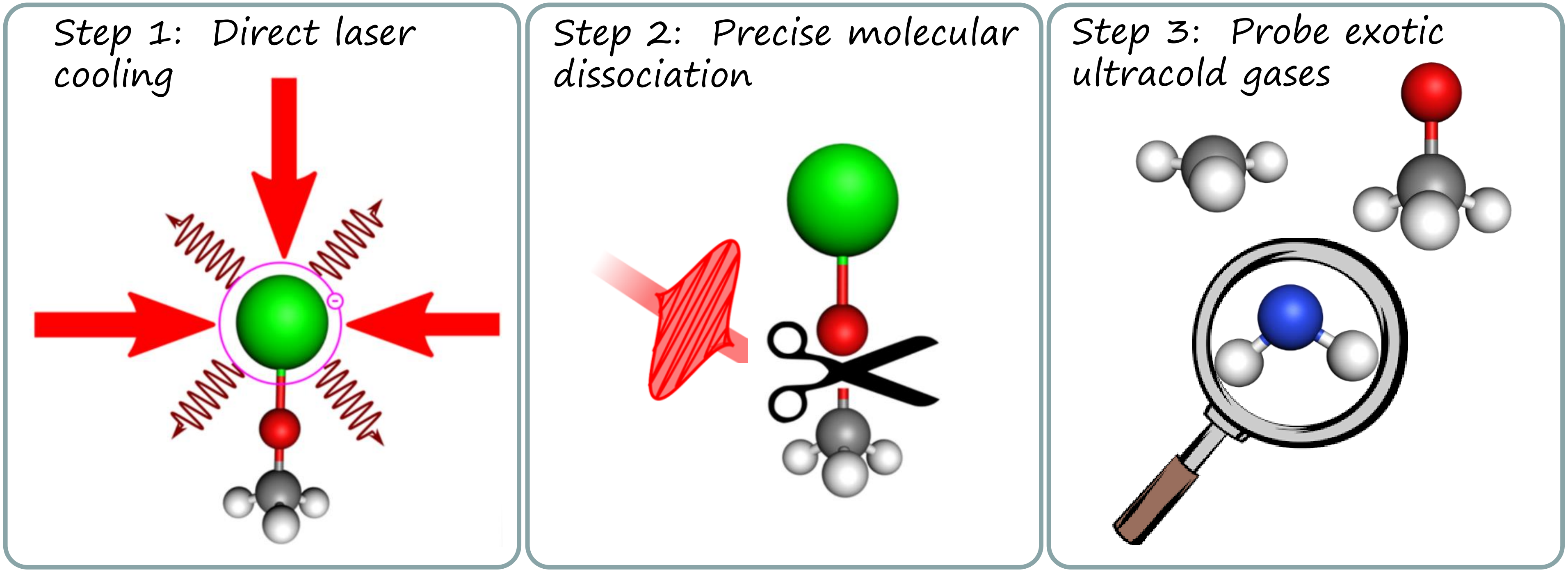


W. M. Keck Foundation project

Collaboration with:

B. L. Augenbraun *et al.*, *Phys. Rev. X* **10**, 031022 (2020)

Creating exotic ultracold gases

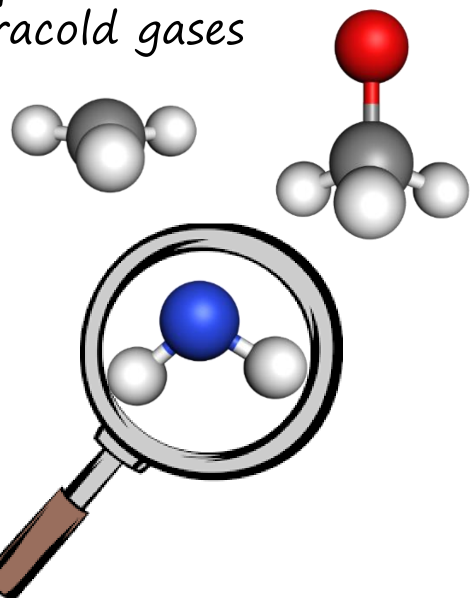


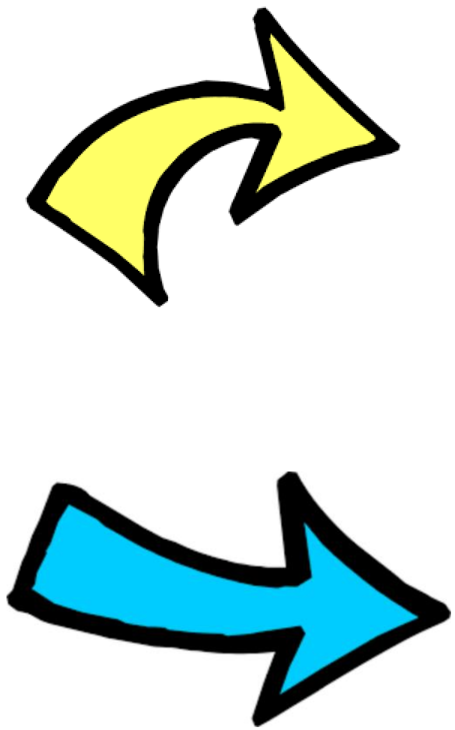
I. C. Lane, *PRA* **92**, 022511 (2015)

Studying novel ultracold gases

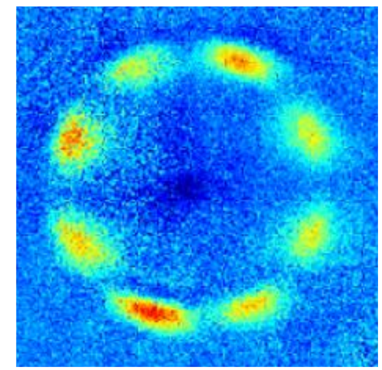
Columbia – Harvard, W. M. Keck

Step 3: Probe novel ultracold gases

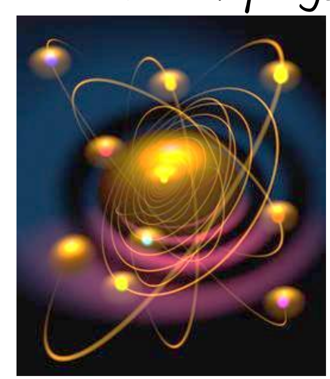




Step 3a: Ultracold chemistry



Step 3b: Fundamental physics

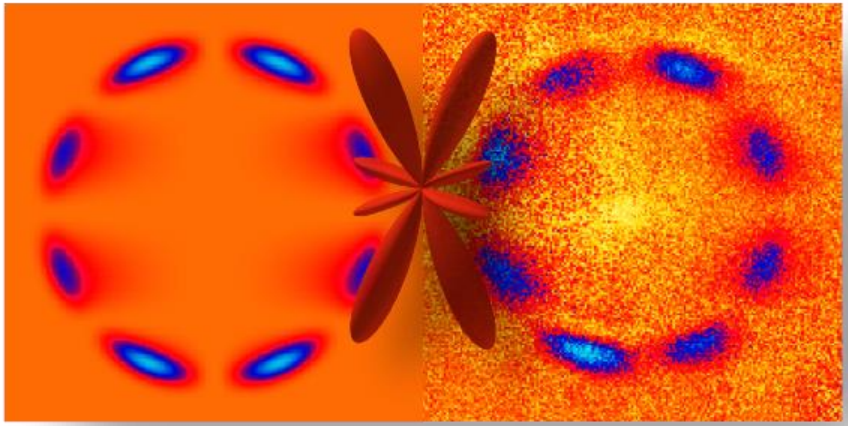


Ultracold photochemistry

Complete quantum state control of "reverse collision"

Photodissociation

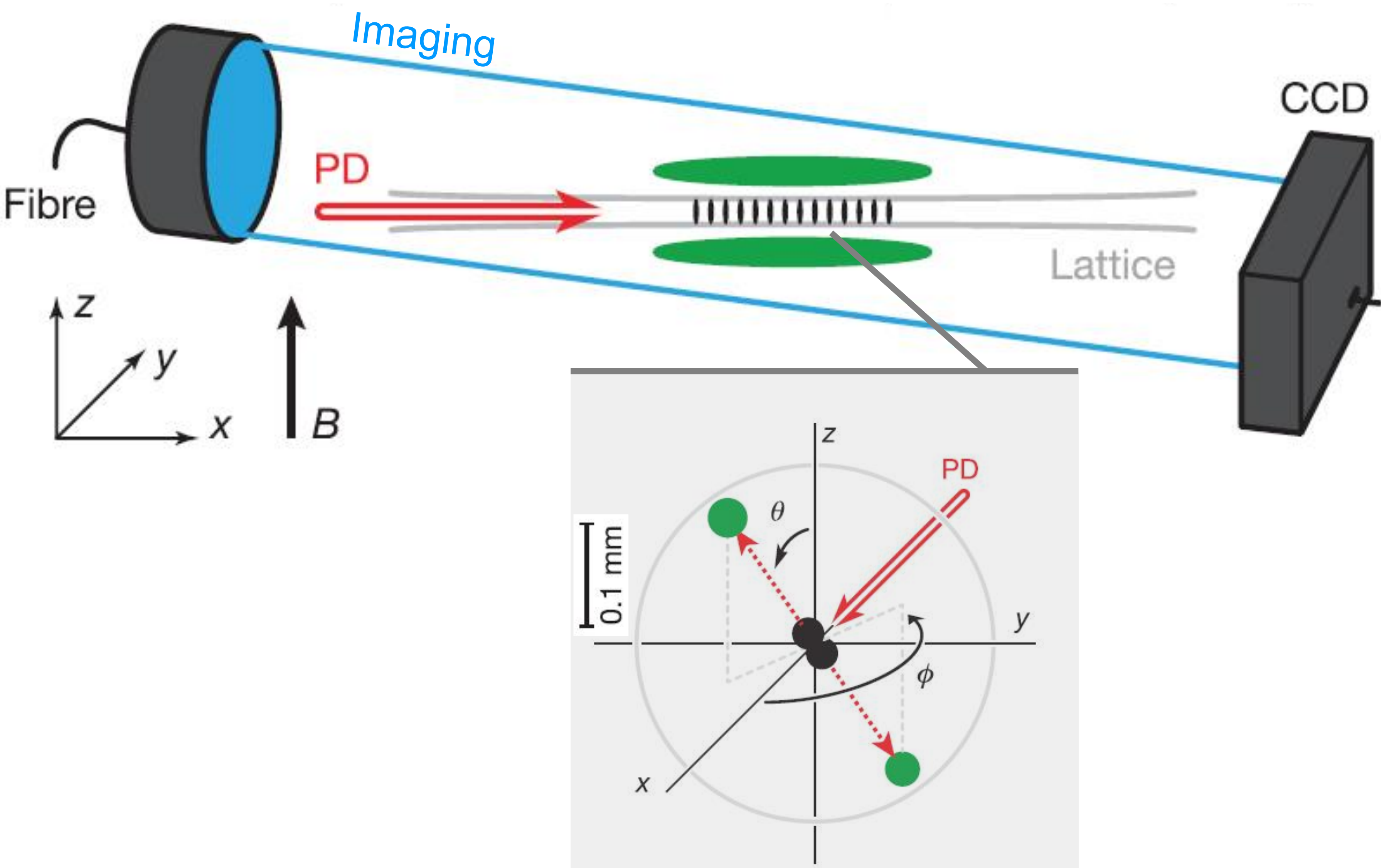
$$Sr_2 + \gamma \rightarrow Sr + Sr^*$$



- Quantum-state selected reactants and products
- Reactions described by matter waves
- High-precision studies of electronic continua

Ultracold Photodissociation

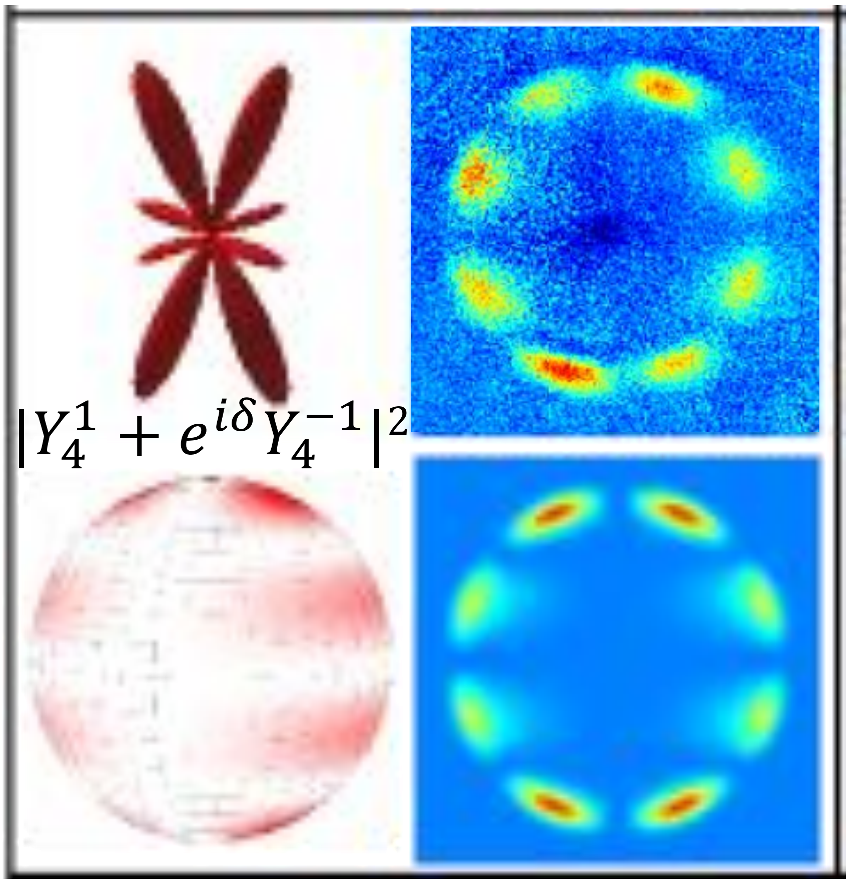
Photofragment angular distribution



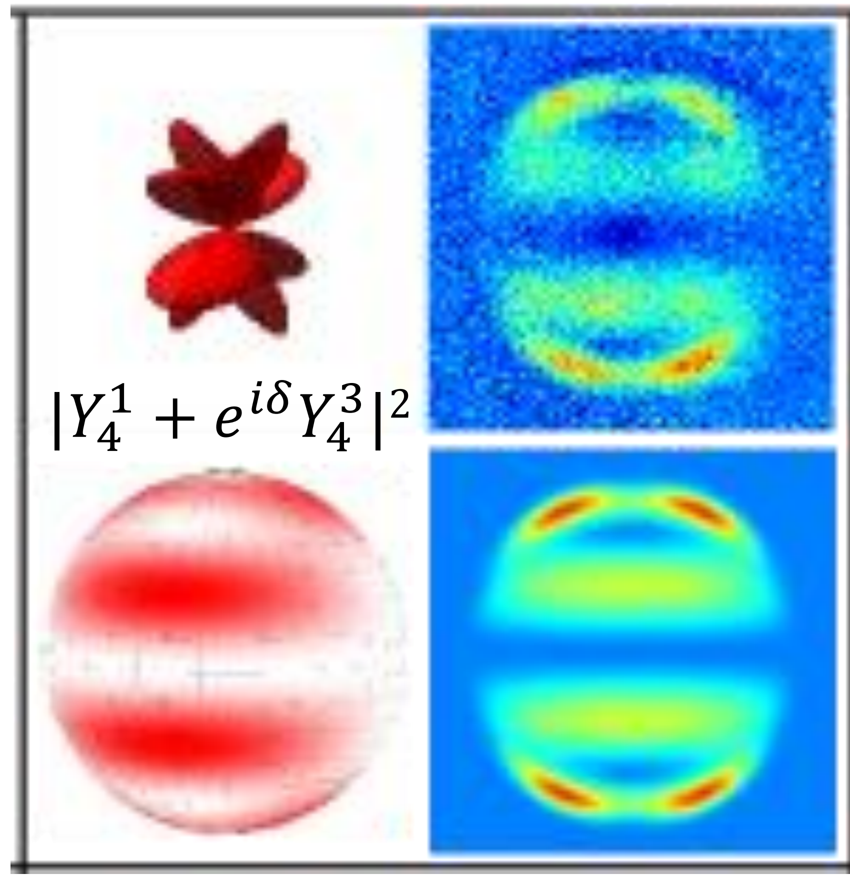
Ultracold Photodissociation

Matter-wave interference

$J = 4; M = \pm 1$



$J = 4; M = 1,3$



M. McDonald *et al*., *Nature* **535**, 122 (2016)

Ultracold Photodissociation

Matter-wave interference

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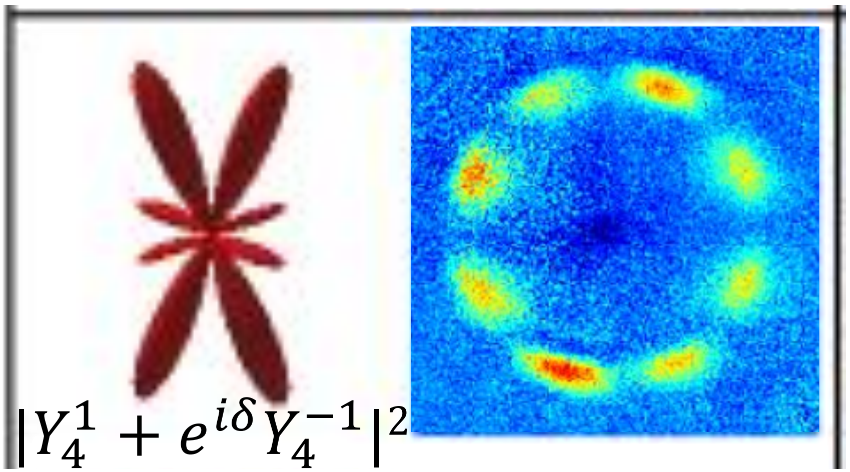
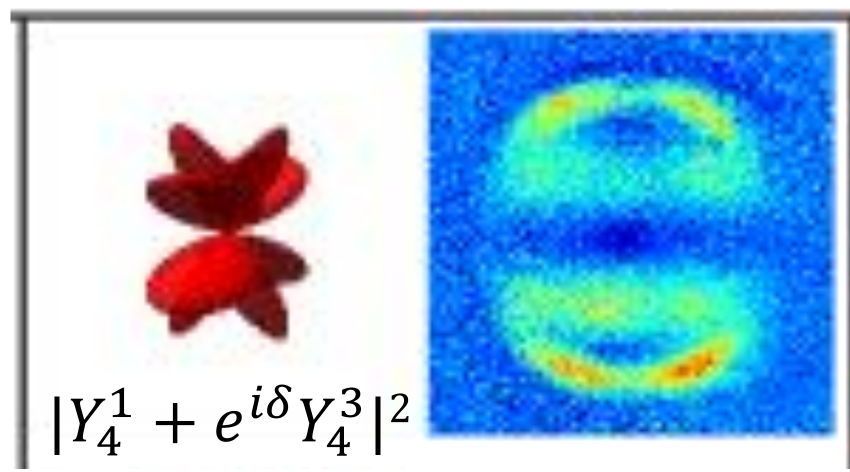
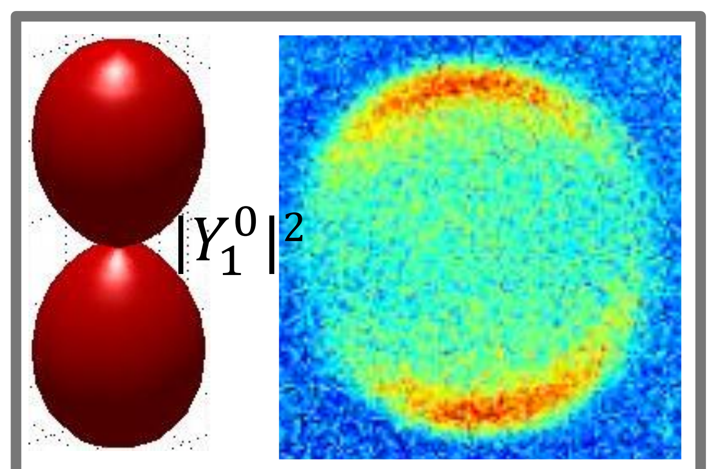


$J = 4; M = 1,3$

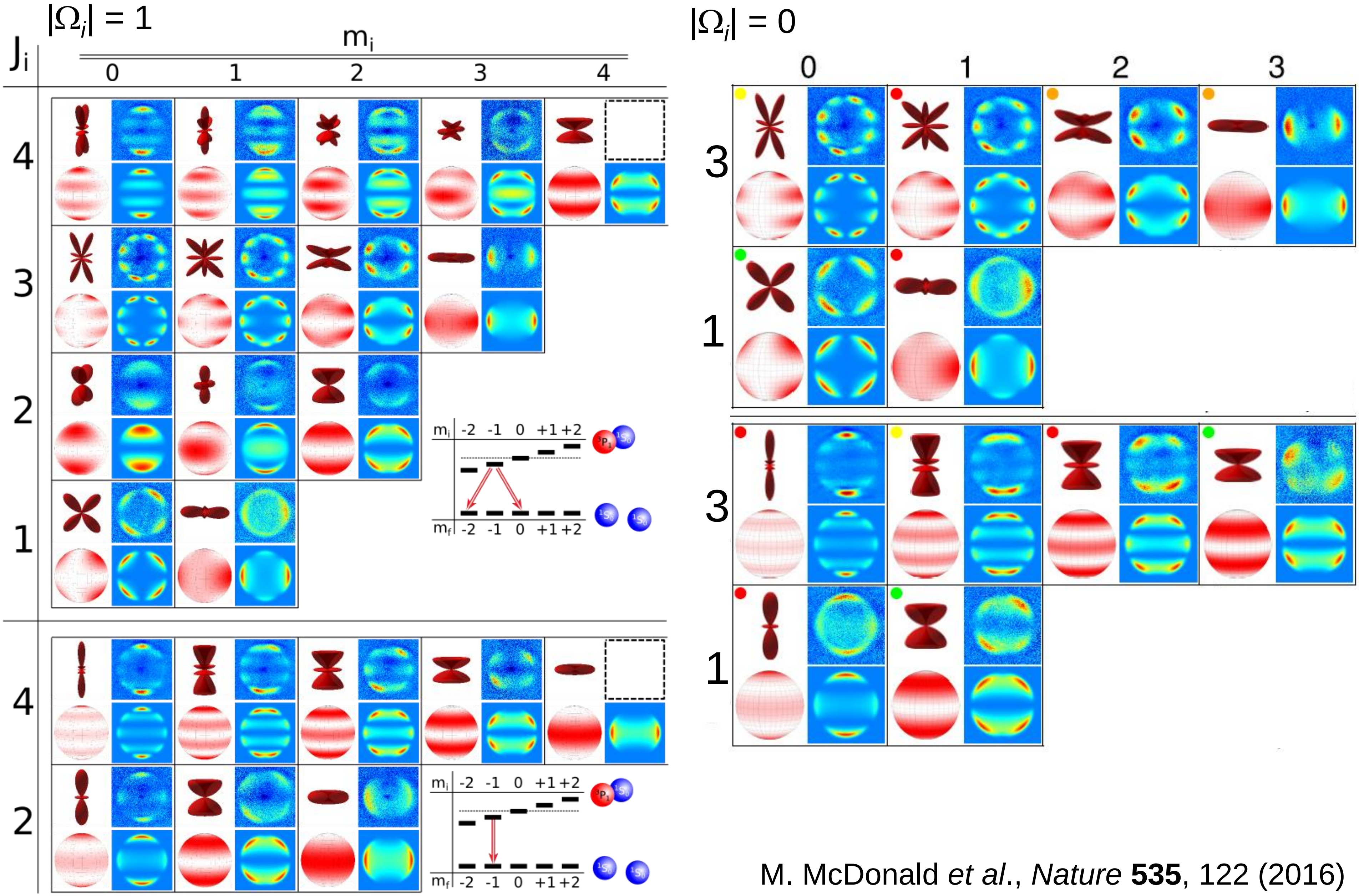


"Classical" fragmentation of diatomic molecule



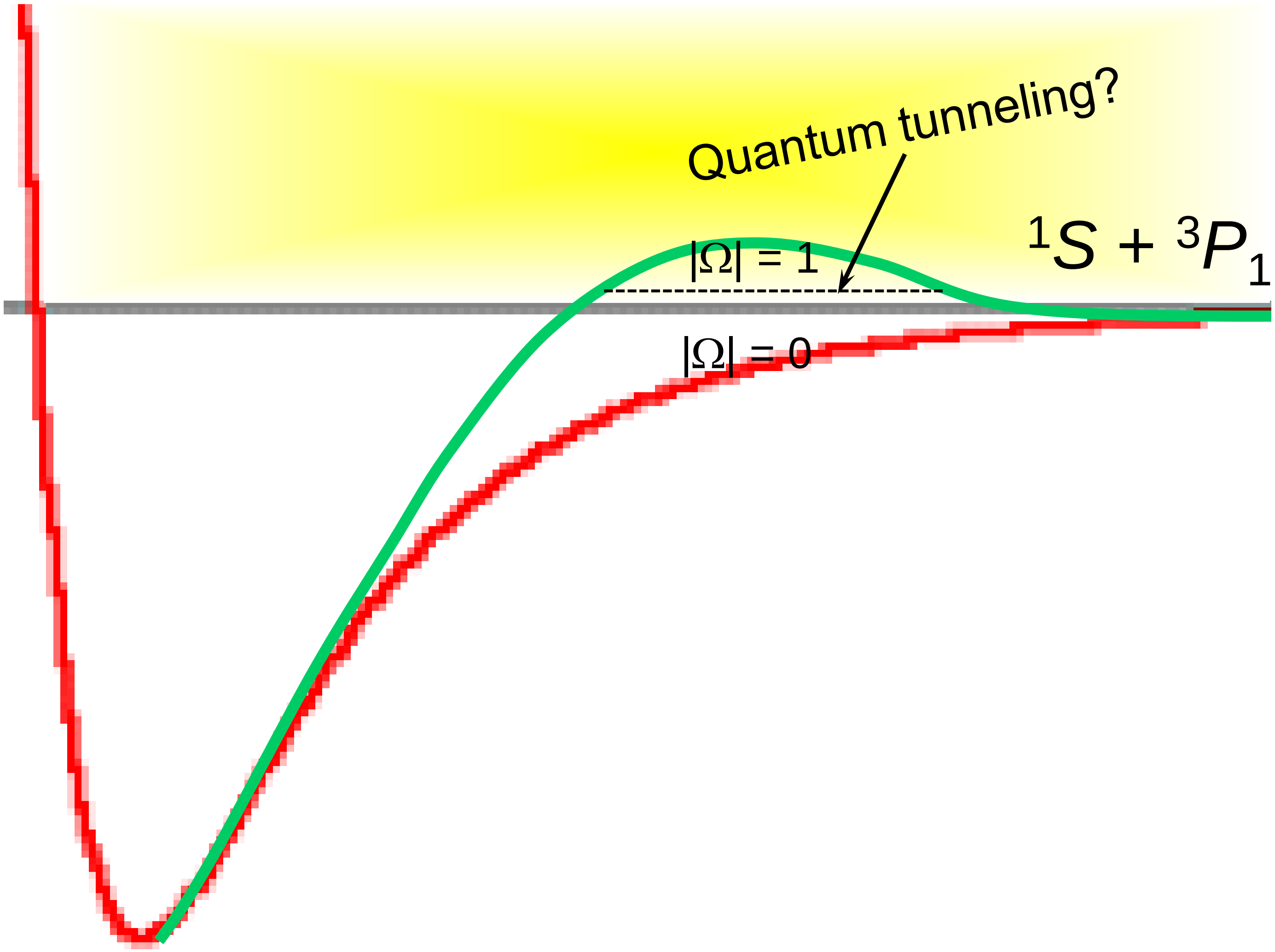
M. McDonald *et al.*, *Nature* **535**, 122 (2016)

Photofragment Angular Distributions

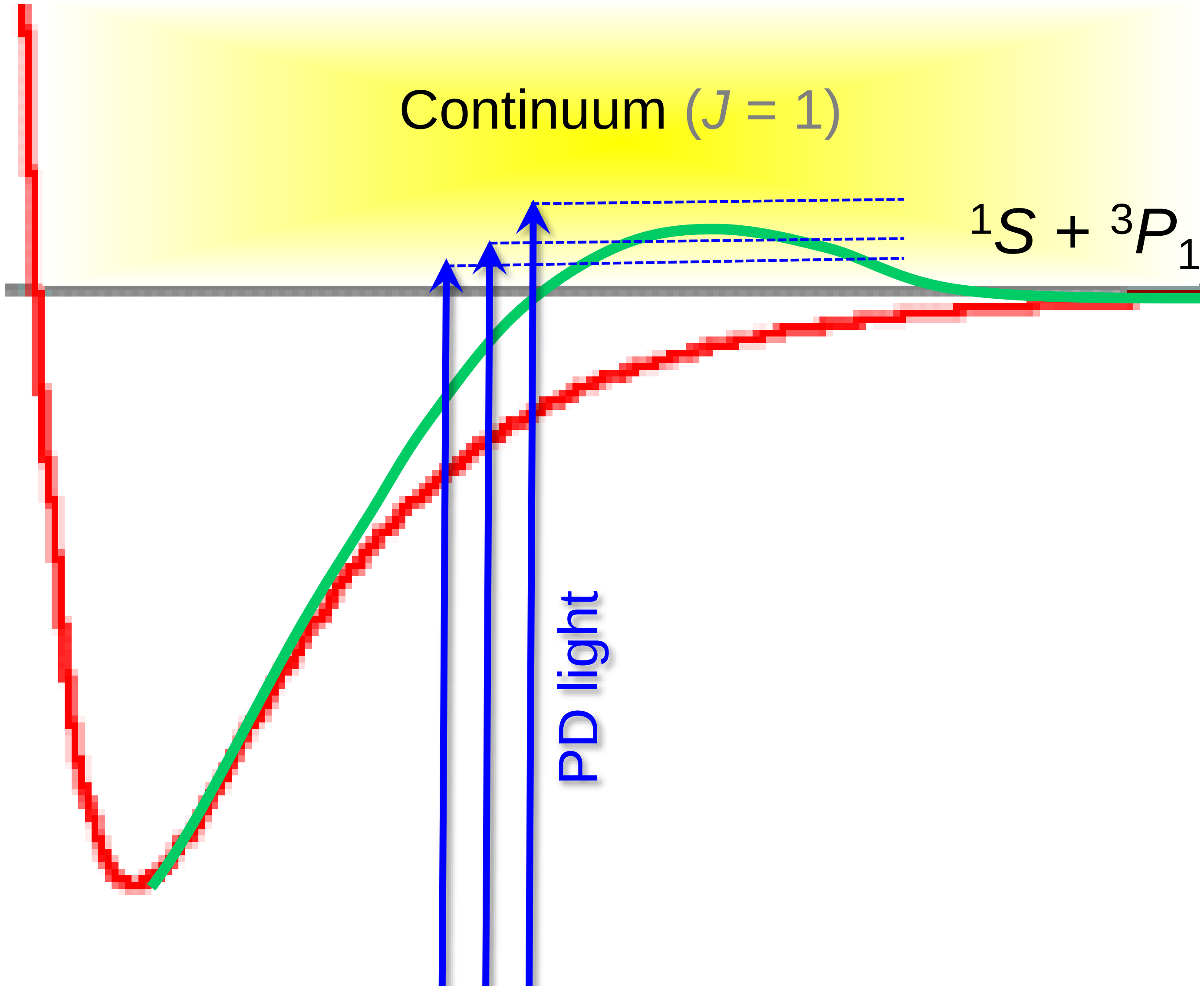


M. McDonald *et al.*, *Nature* **535**, 122 (2016)

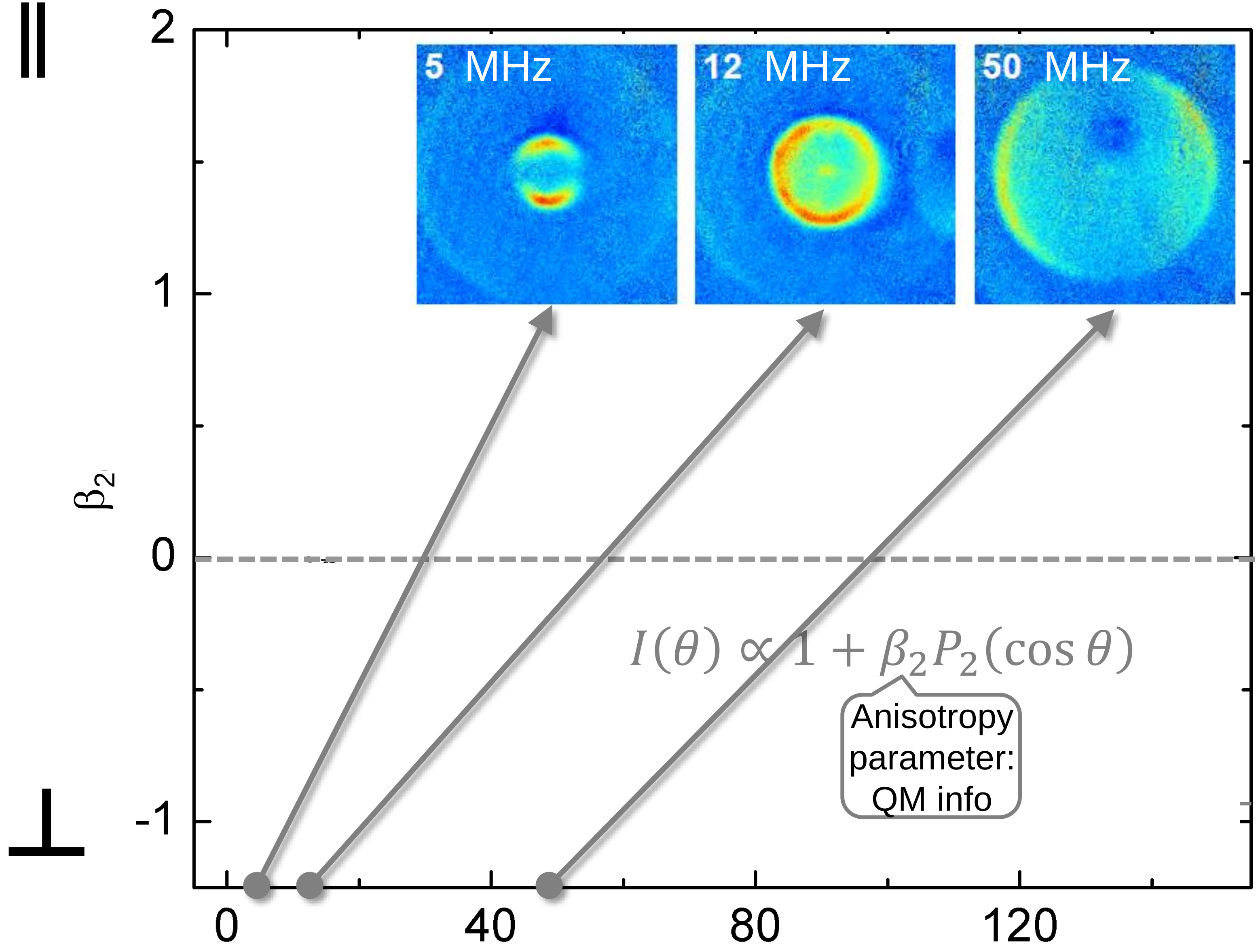
Probing Reaction Barriers



Probing Reaction Barriers

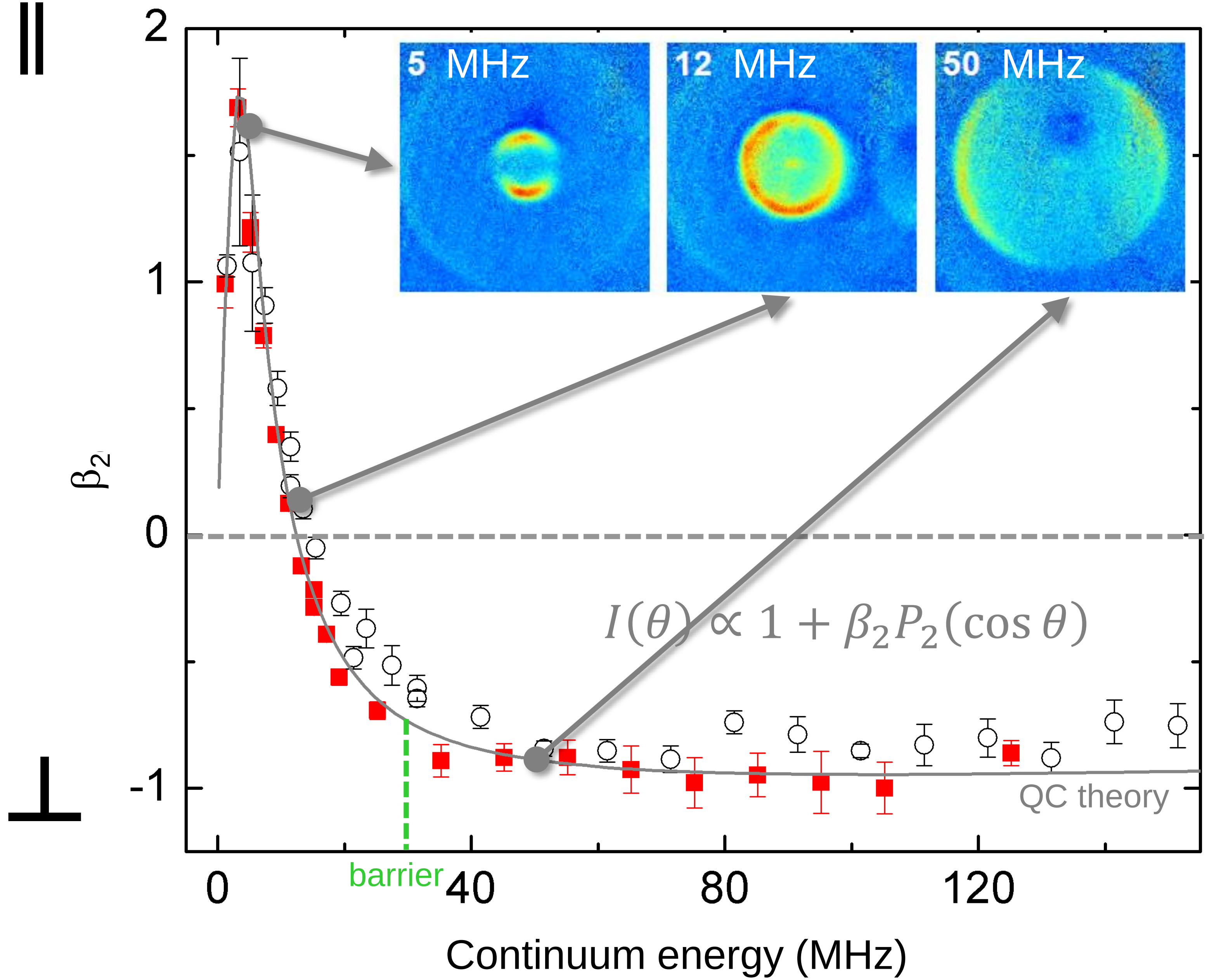


Probing Reaction Barriers



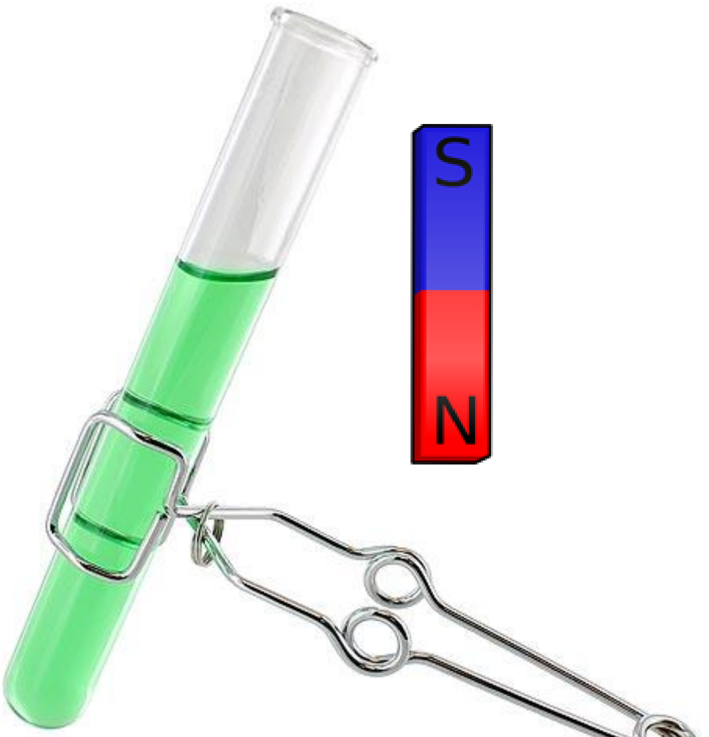
M. McDonald *et al.*, *Nature* **535**, 122 (2016)

Probing Reaction Barriers



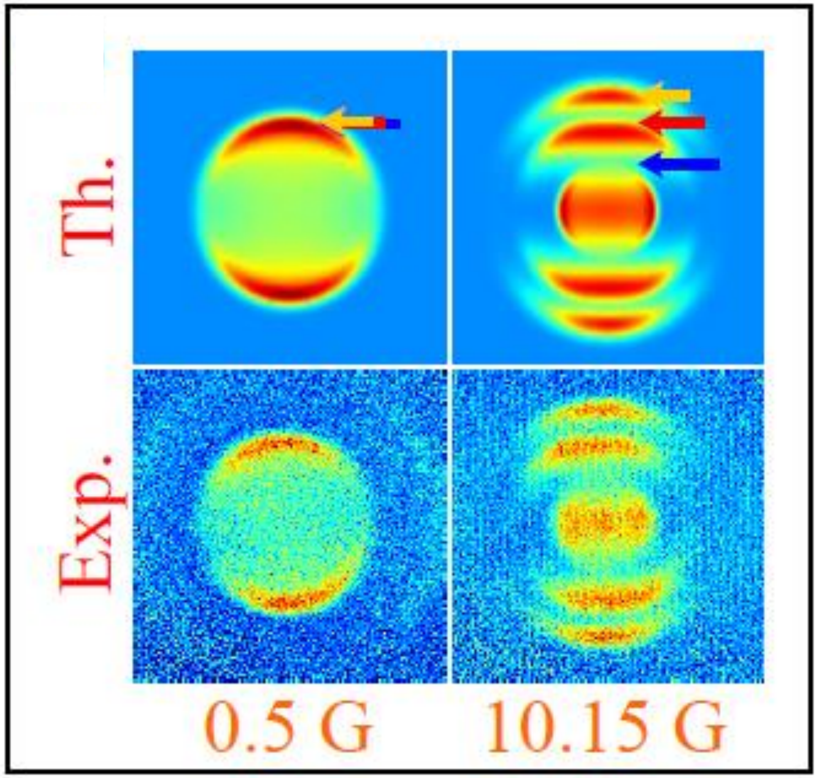
M. McDonald *et al.*, *Nature* **535**, 122 (2016)

Field Control of Photodissociation



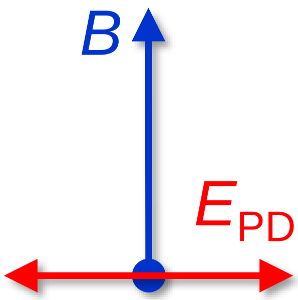
Comparable energies at ~ 1 mK:

- Kinetic
- Barrier
- Zeeman



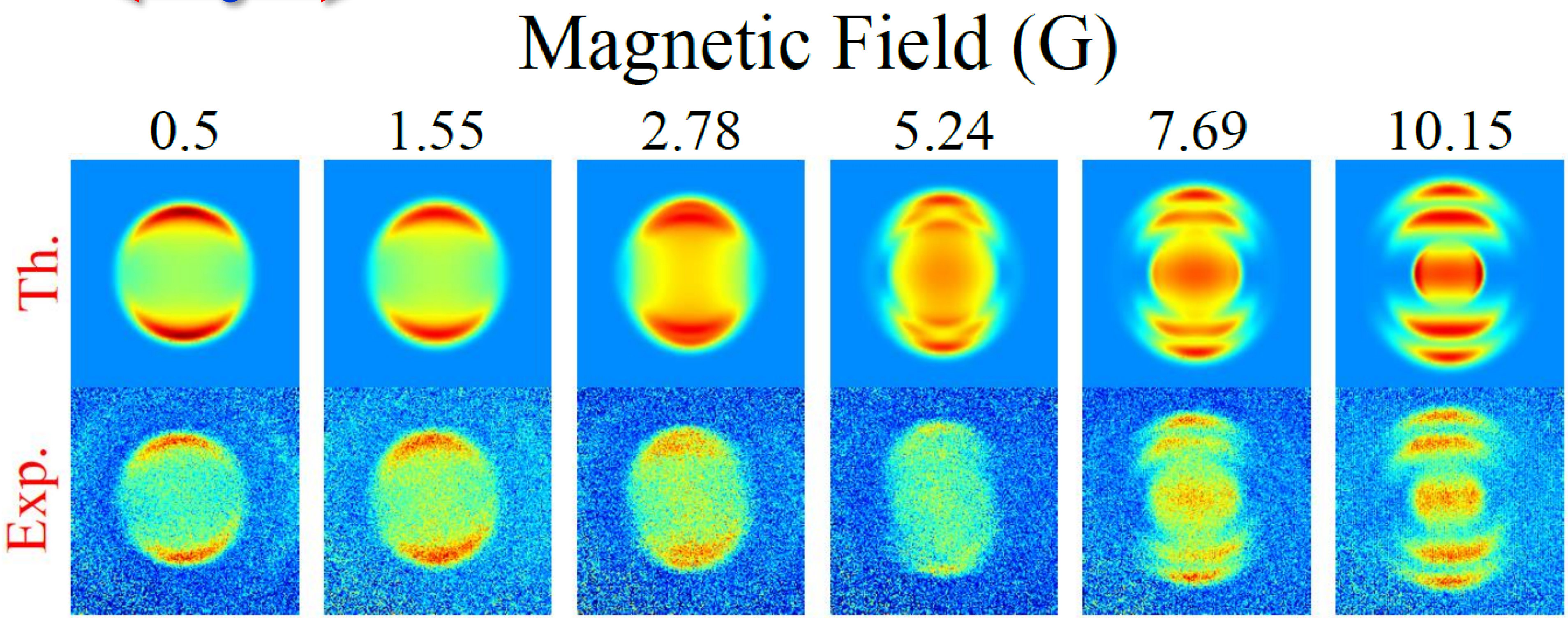
M. McDonald *et al.*, PRL **120**, 033201 (2018)

Field Control of Photodissociation



$$Sr_2 + \gamma \rightarrow Sr + Sr^*$$

Energy = 30 MHz = 1.5 mK

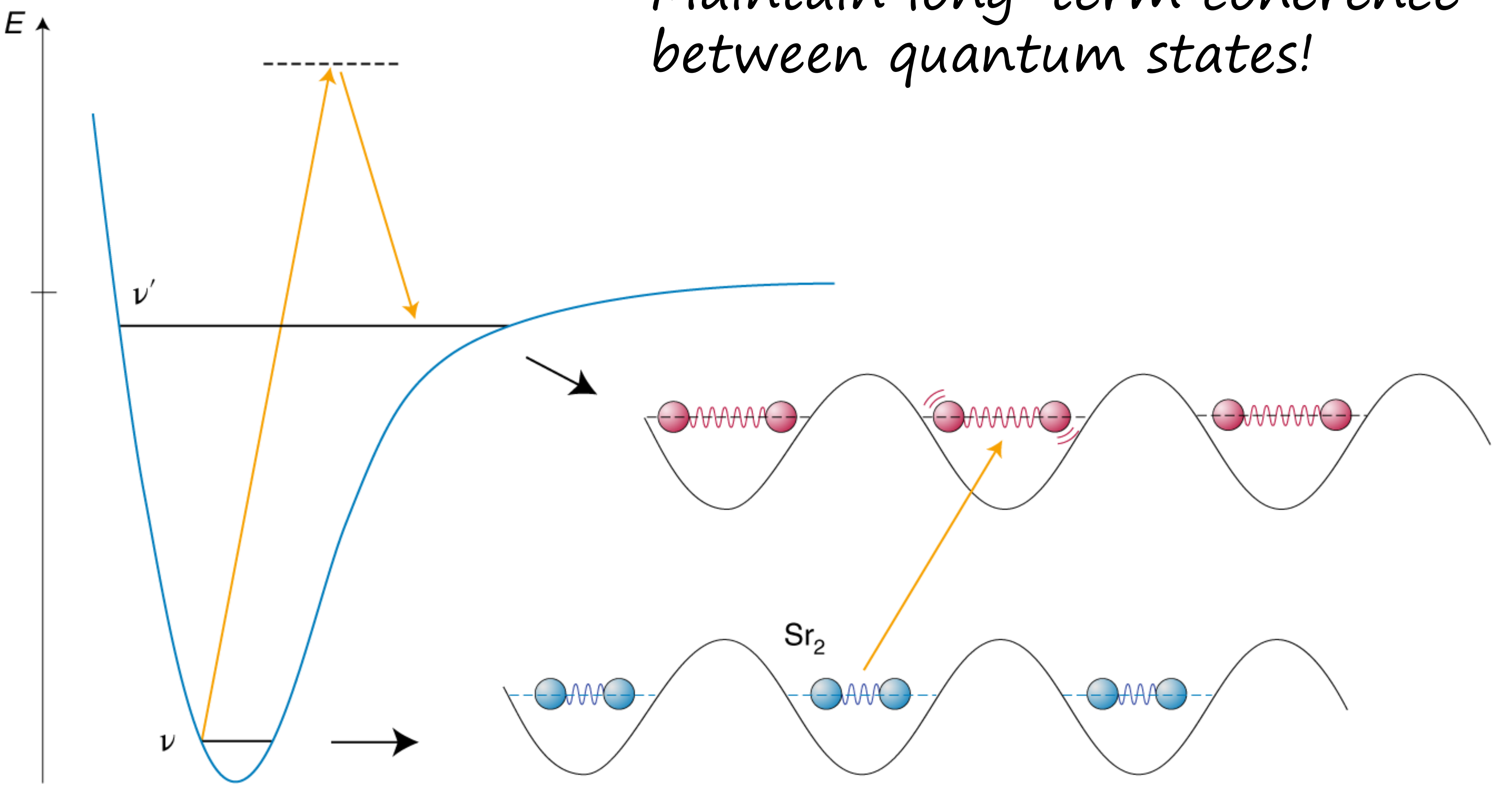


Key point: Mixing of partial waves in the continuum

M. McDonald *et al.*, PRL **120**, 033201 (2018)

Molecular lattice clock

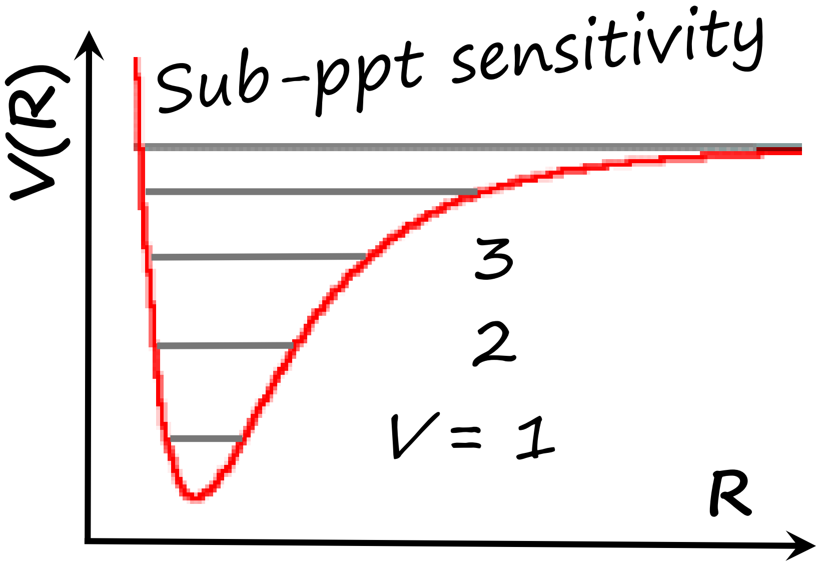
Maintain long-term coherence between quantum states!



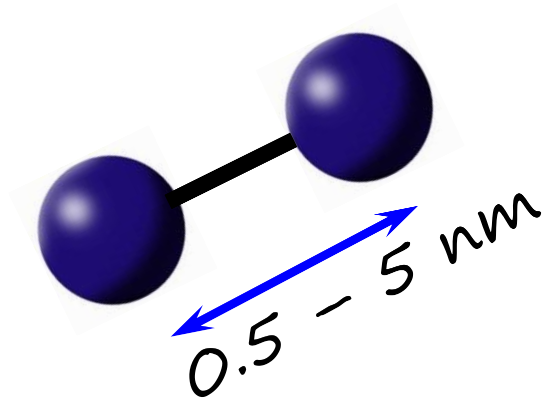
N. Poli, *Nature Phys.* **15**, 1106 (2019)

New science with molecular clocks

Interatomic force sensing



Ultrashort-range gravity



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

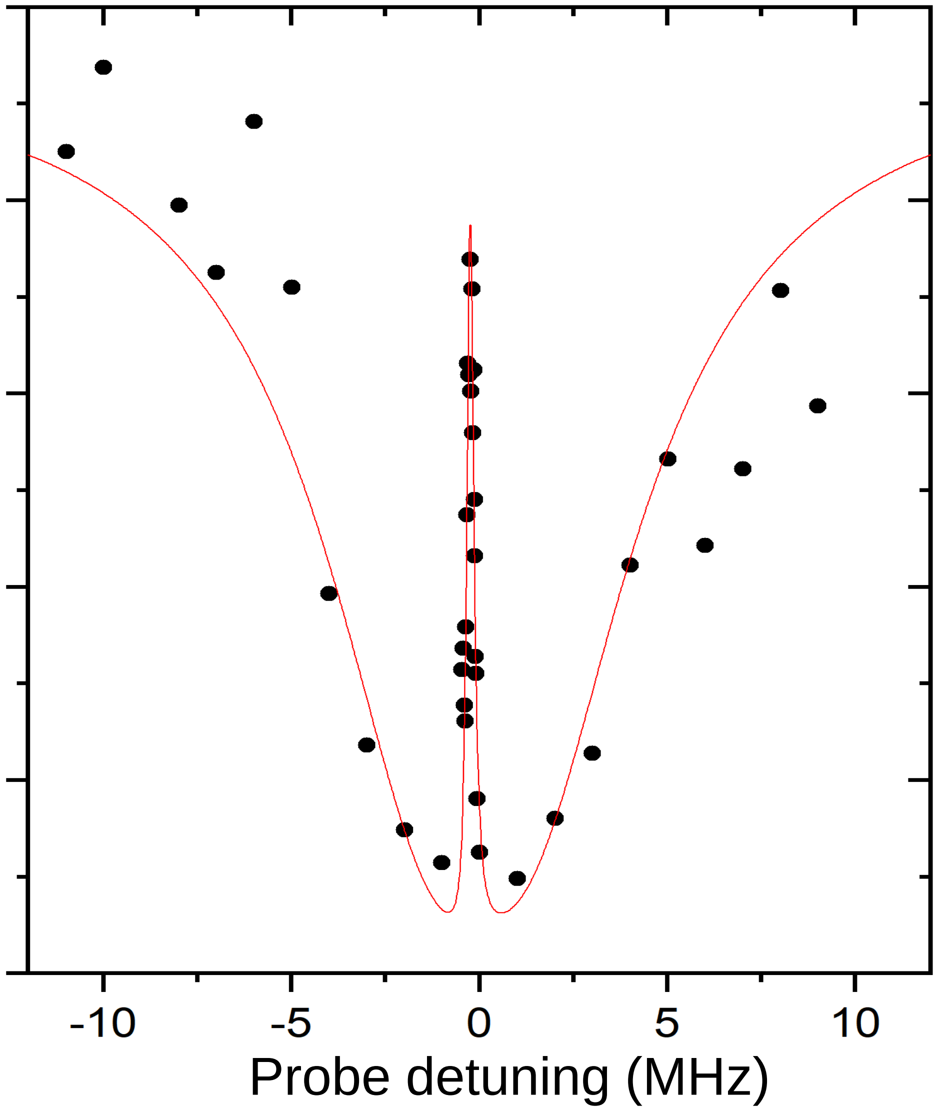
$A < 10^{22}$!

Also THz metrology, $\frac{d}{dt}\left(\frac{m_e}{m_p}\right)$, …

Y. Kamiya *et al.*, *PRL* **114**, 161101 (2015)

Creation of Sr_2 in absolute ground state

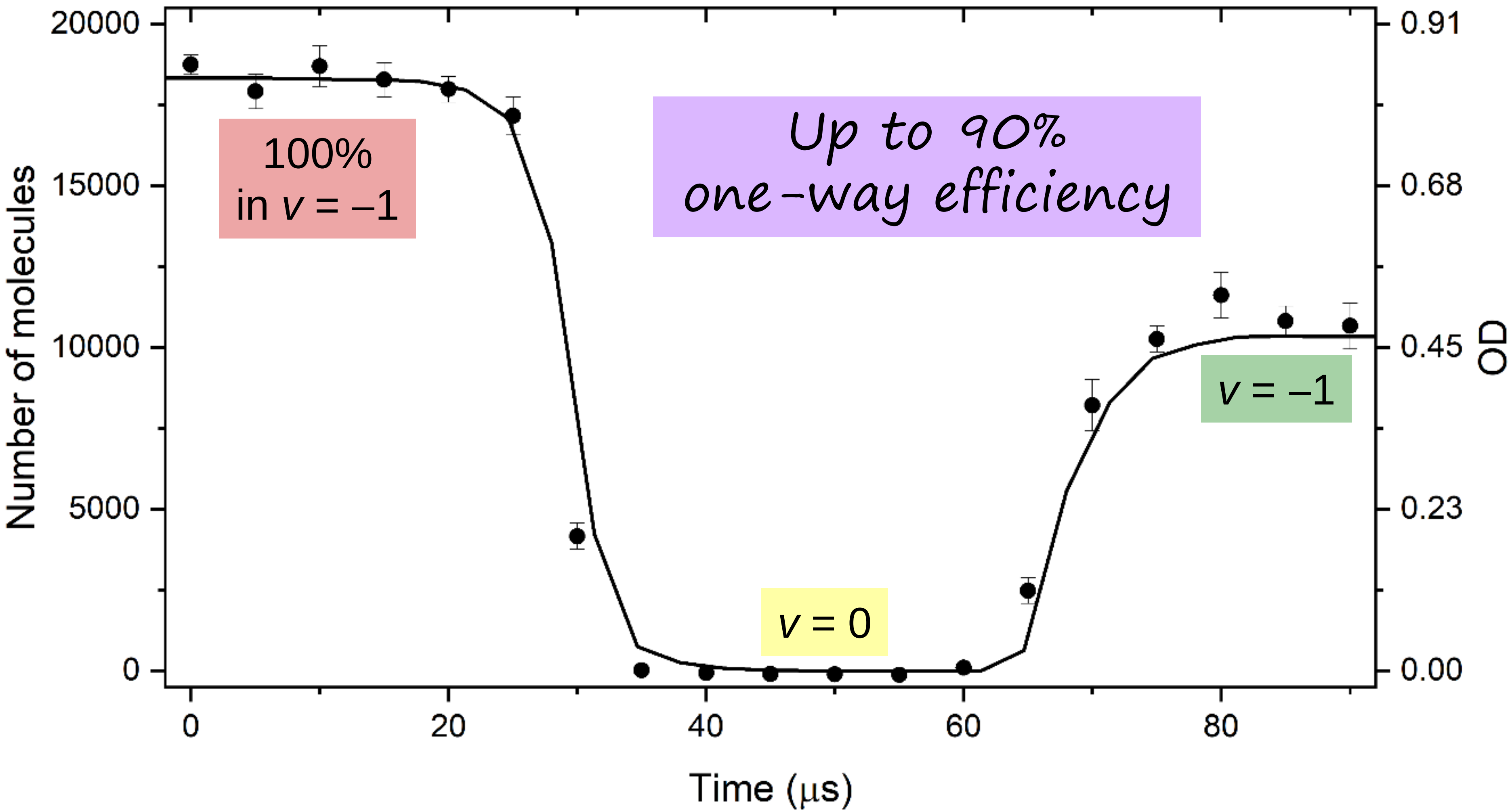
Stimulated Raman adiabatic passage (STIRAP)



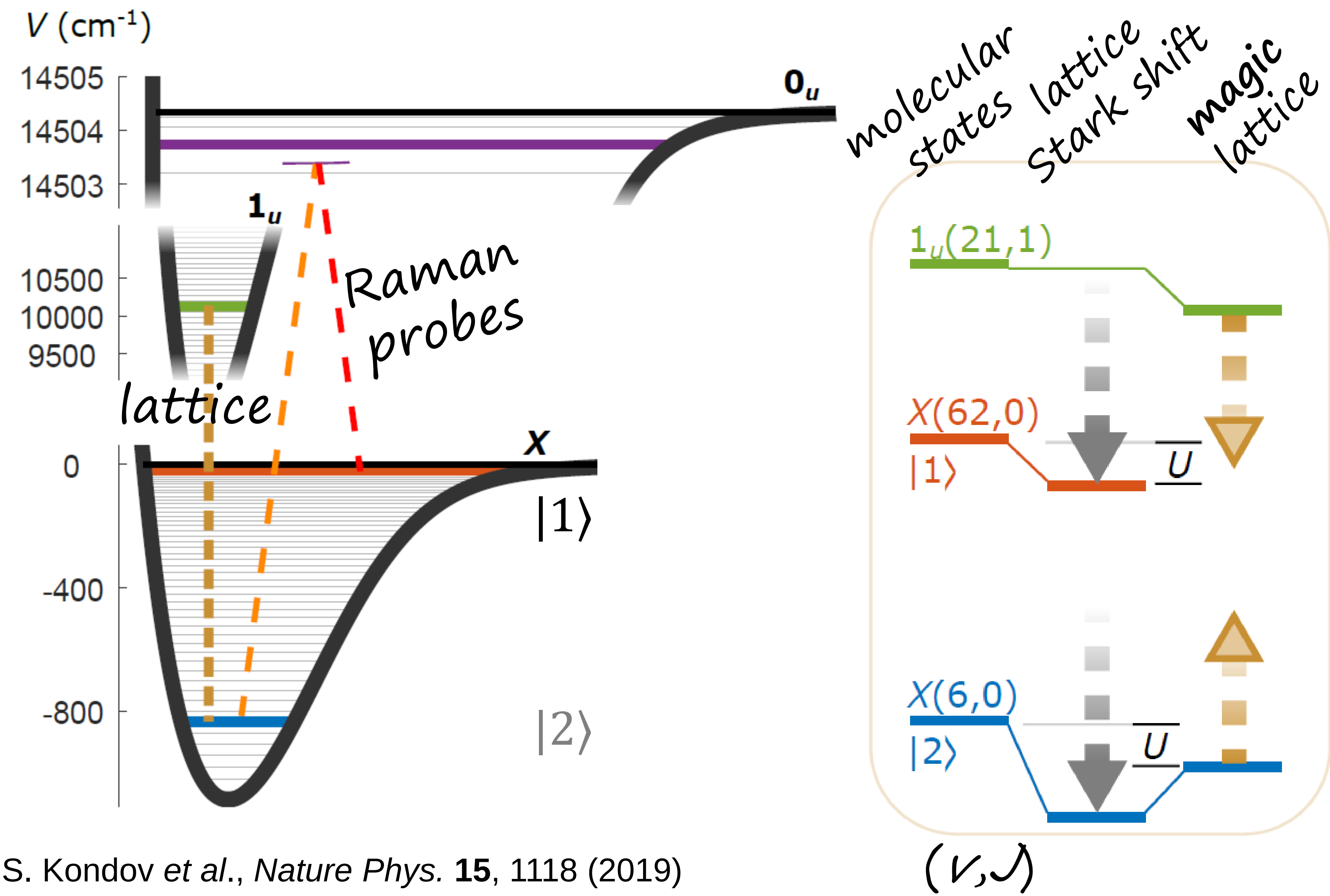
EIT spectrum across full potential

Creation of Sr_2 in absolute ground state

Stimulated Raman adiabatic passage (STIRAP)

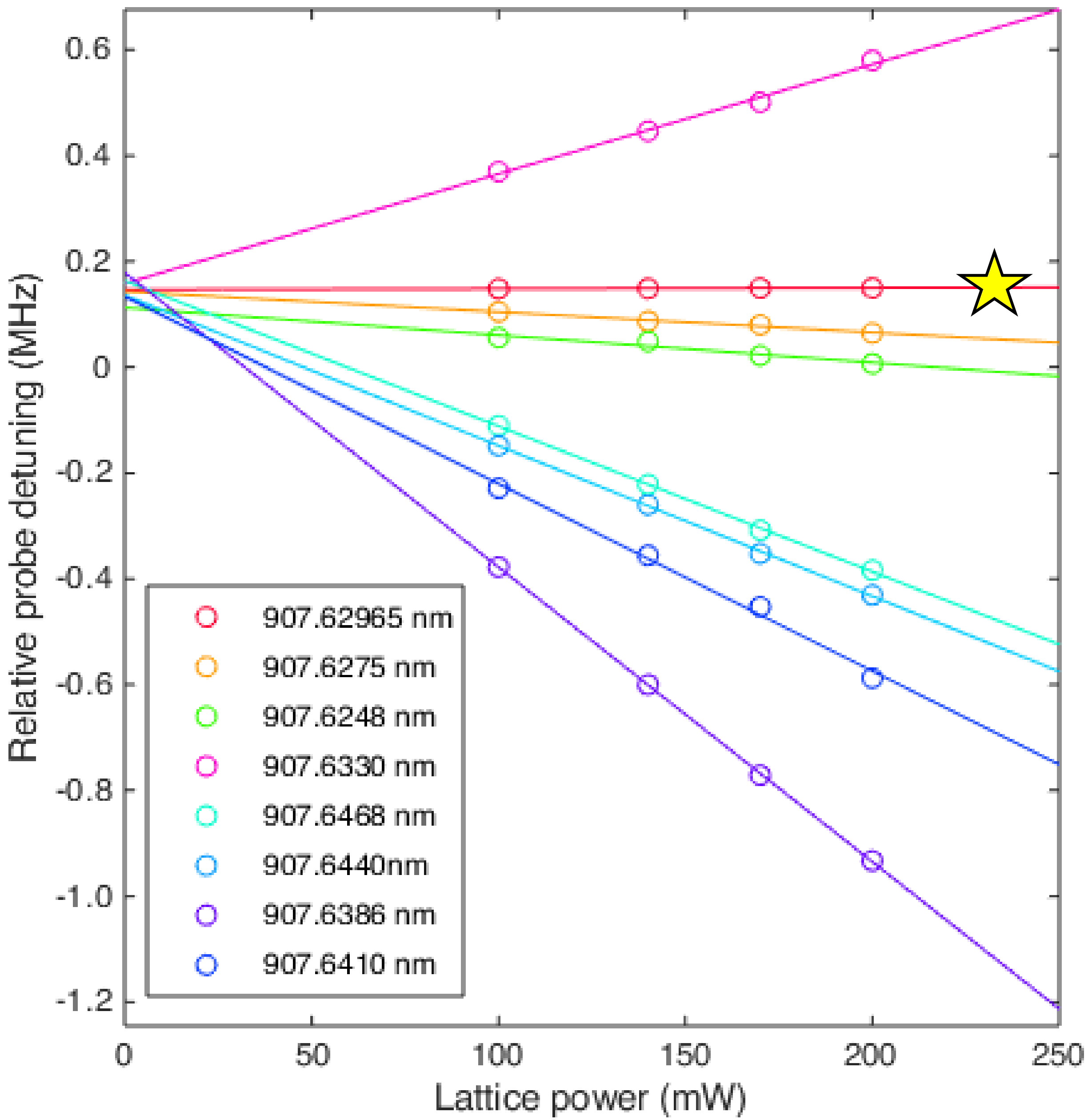


Molecular lattice clock



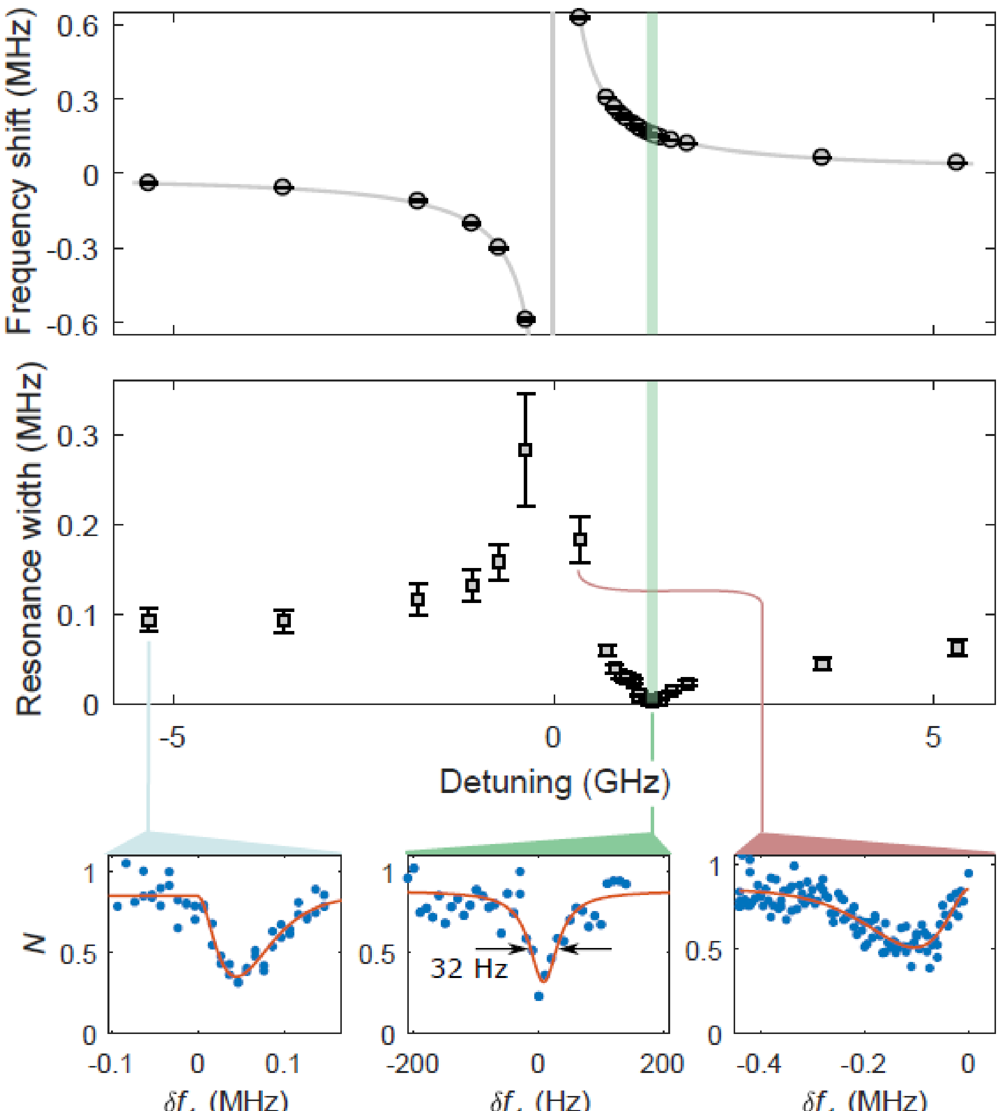
S. S. Kondov *et al.*, *Nature Phys.* **15**, 1118 (2019)

Magic-wavelength lattice



Molecular lattice clock

Coherence in magic lattice



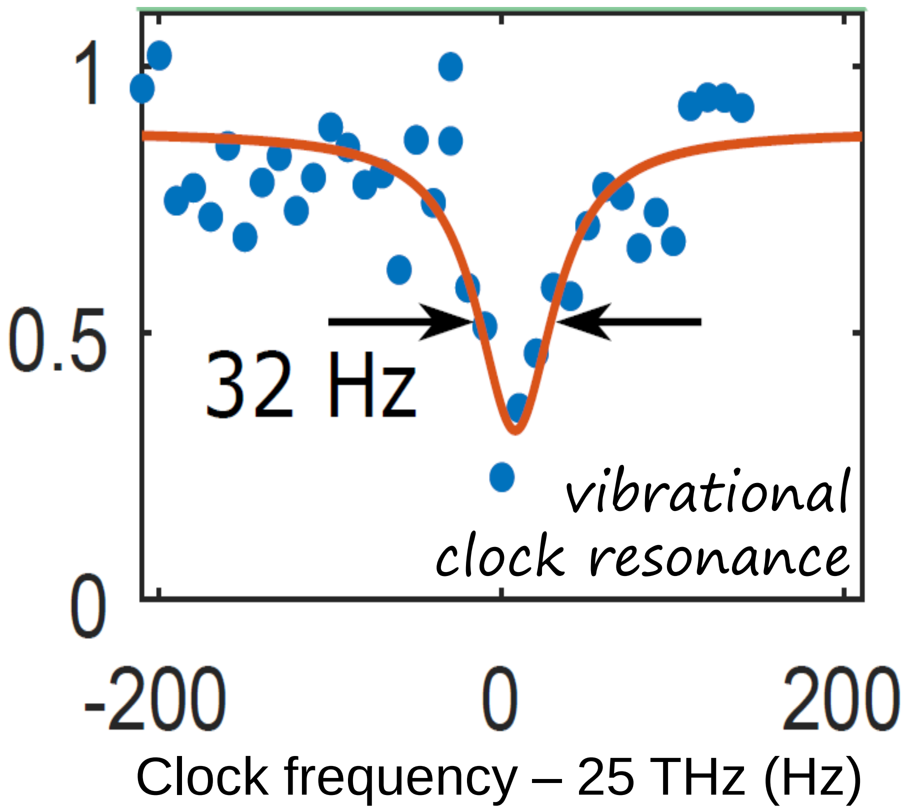
Energy of $|2\rangle$

Clock resonance linewidth

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

Molecular lattice clock

Coherence in magic lattice : ×3,000!



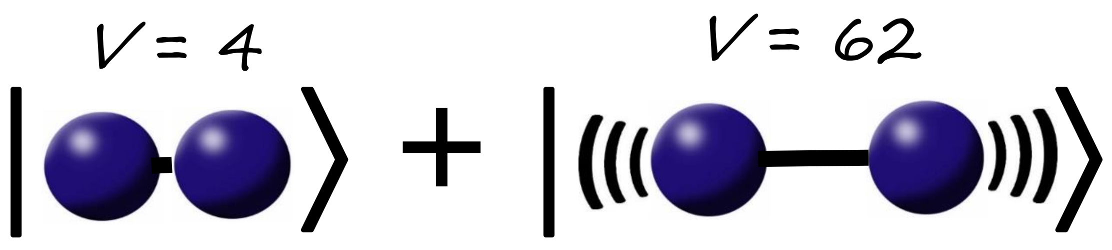
$Q = 8\times10^{11}$ Q (*intrinsic*) $> 10^{26}$

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

Molecular lattice clock

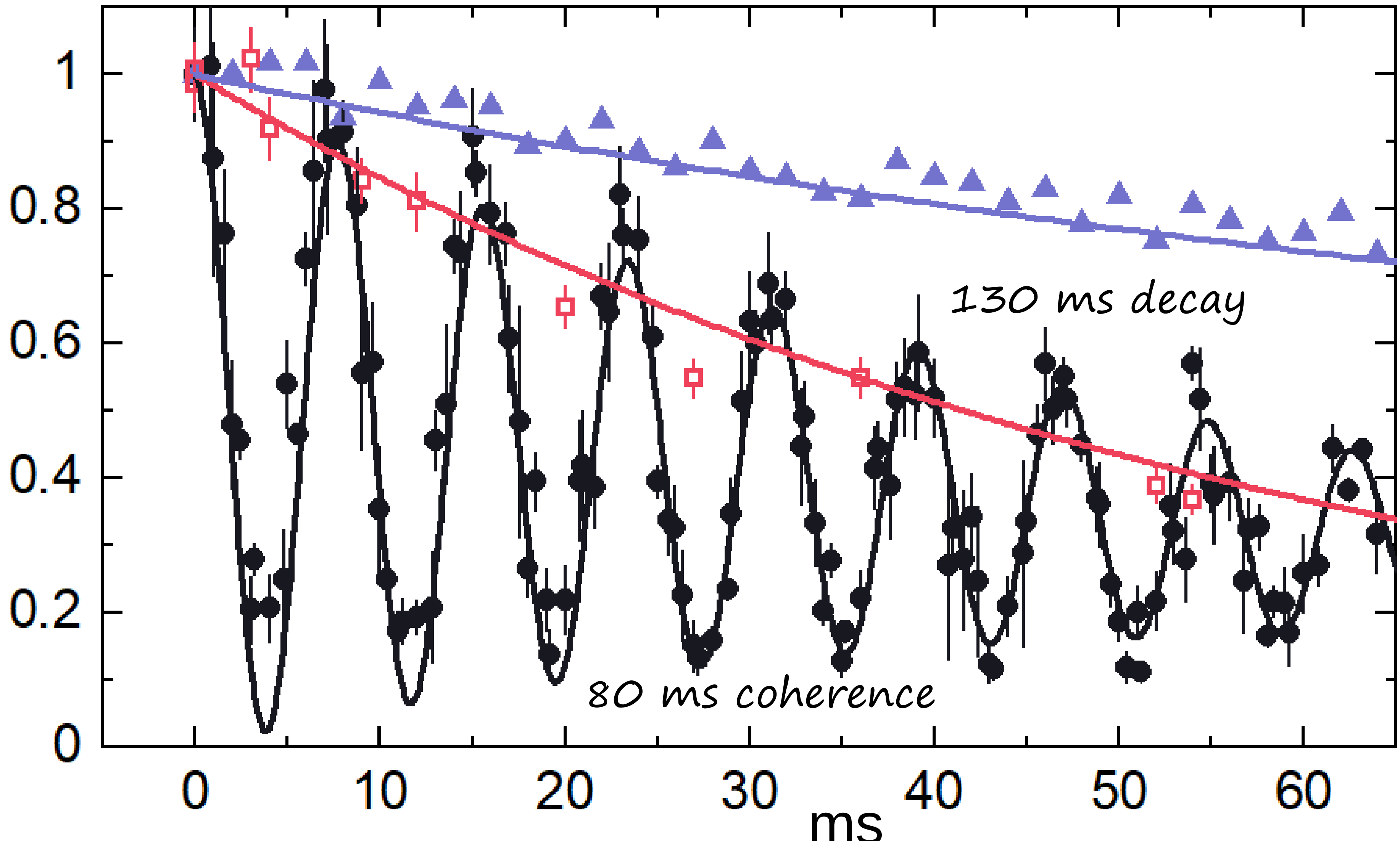
Coherence in magic lattice

Quantum Rabi oscillations



Molecular lattice clock

Coherence in magic lattice

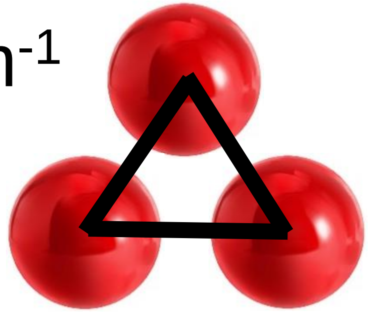


K. H. Leung *et al.*, *PRL* **125**, 153001 (2020)

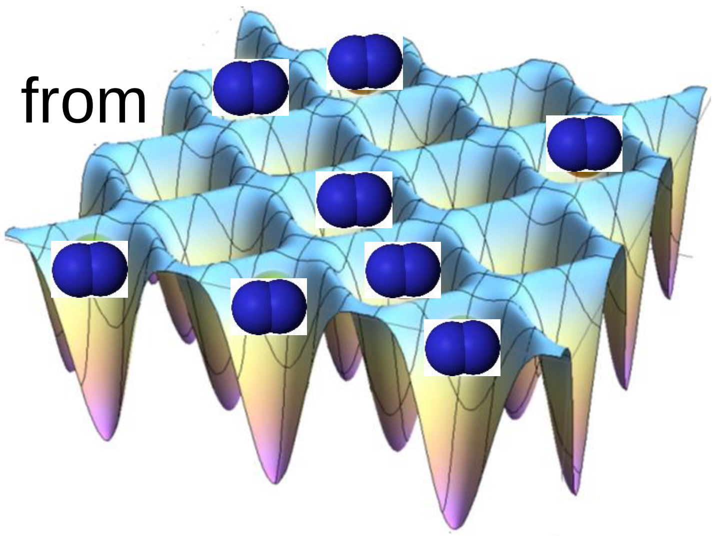
Two-body loss of Sr_2 molecules

Ultracold reactive collisions

$$Sr_2 + Sr_2 \rightarrow Sr_4 \rightarrow Sr_3 + Sr + 3{,}000(400)\ \mathrm{cm}^{-1}$$



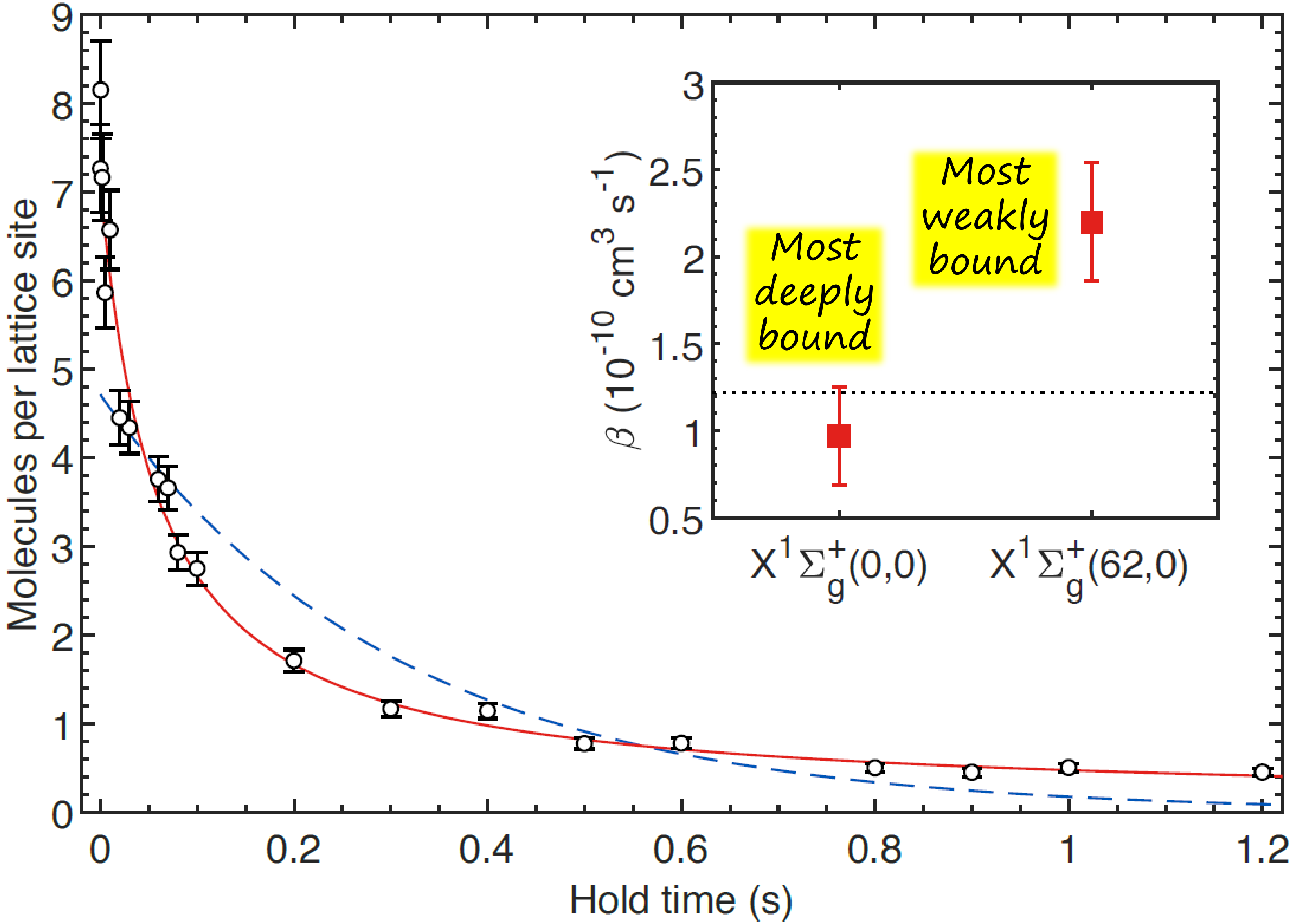
- "Universal" two-body loss rate
- No dependence on vibrational state *v*
- Unknown if Sr_4 complexes live long enough to experience trap-light excitation
- 3D optical lattice can protect molecules from collisions



Z. Idziaszek and P. S. Julienne, *PRL* **104**, 113202 (2010)
M. Tomza *et al.*, *PRA* **88**, 050701(R) (2013)
P. S. Żuchowski and J. M. Hutson, *PRA* **81**, 060703(R) (2010)

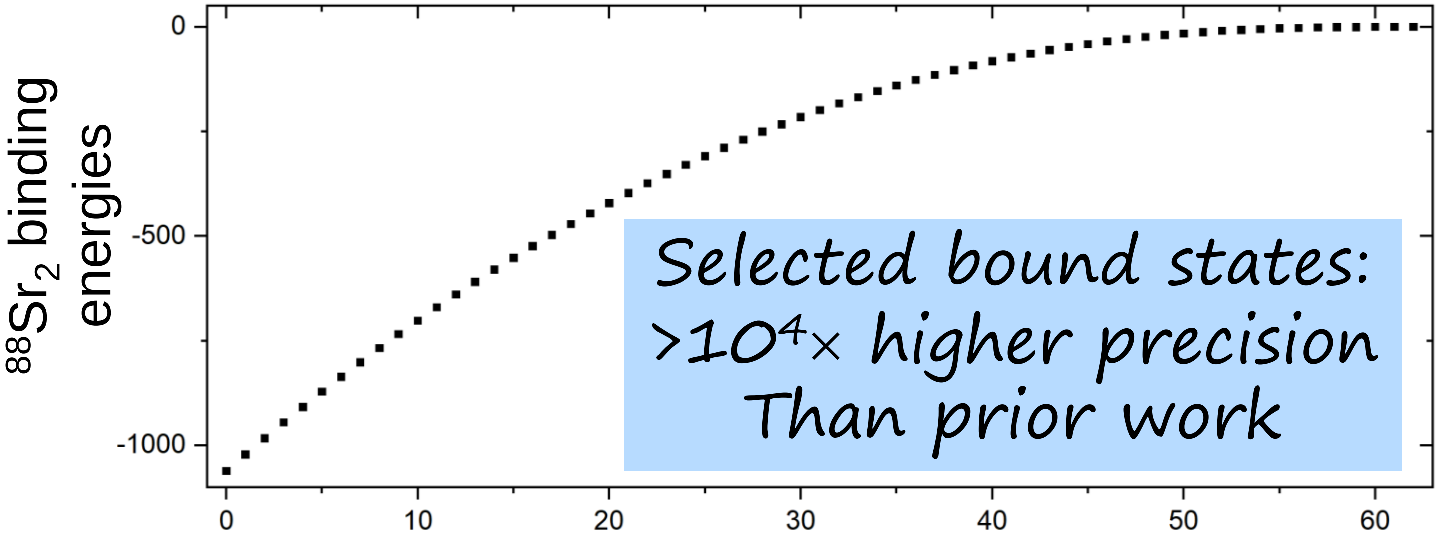
Ultracold Sr_2 reactive collisions

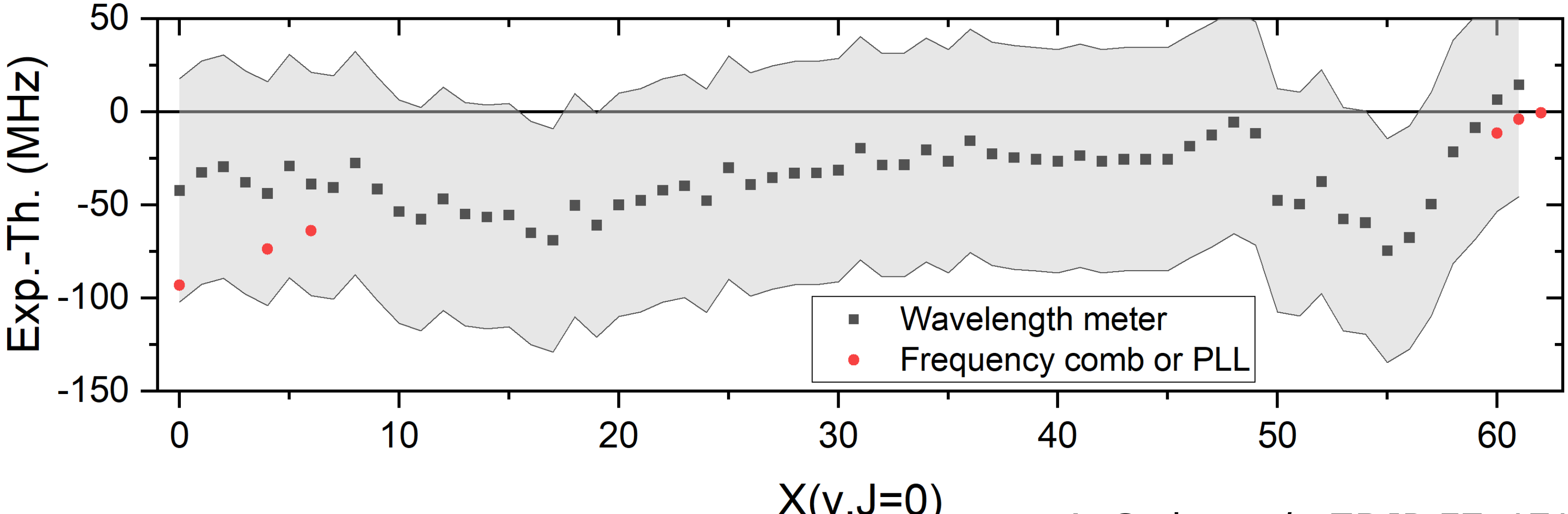
Molecule loss rates are independent of vibrational state



High-precision vibrational spectrum

Autler-Townes spectroscopy of van der Waals force





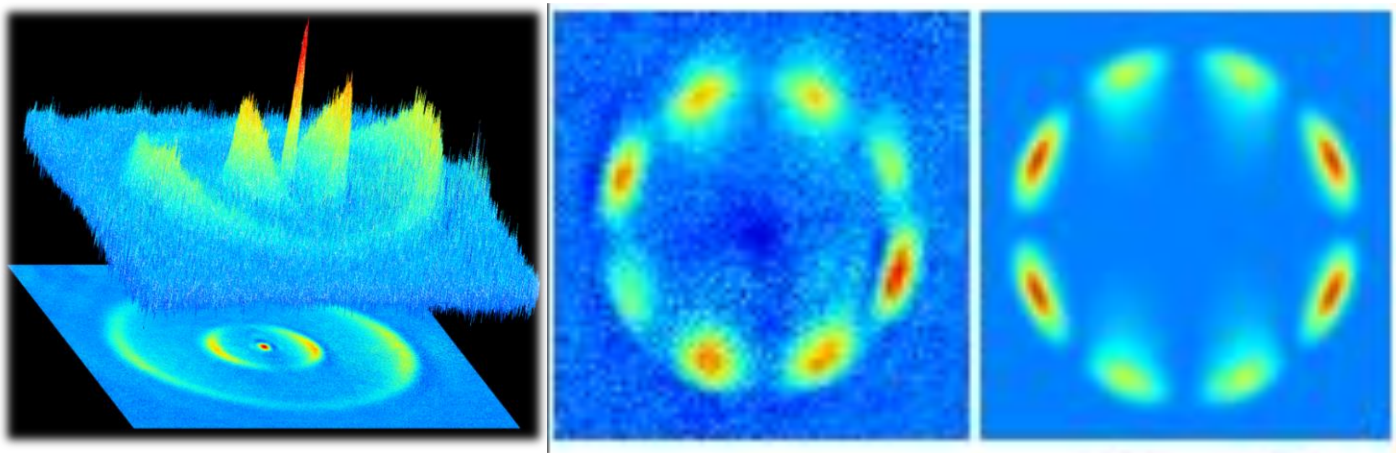
A. Stein *et al.*, *EPJD* **57**, 171 (2010)

Summary

- Ultracold van der Waals molecules

- Photochemistry in the quantum regime
- Field control of reactions

- Molecular lattice clock: $Q \sim 10^{12}$
- ppt interatomic force measurements



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May 27, 2021