

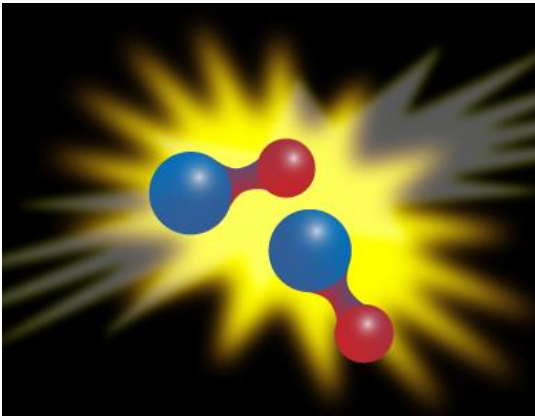
High-Precision Physics and Chemistry with Ultracold Molecules



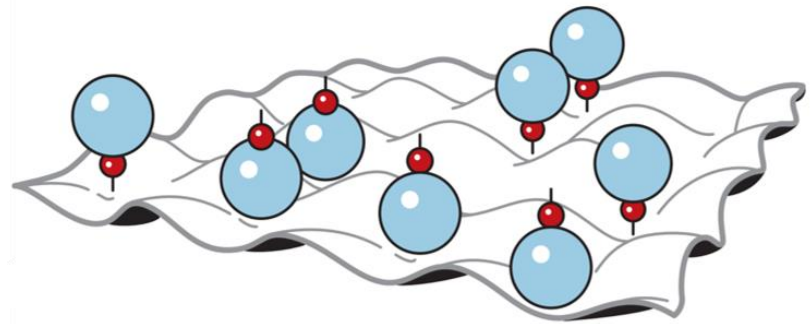
Tanya Zelevinsky
Columbia University, New York



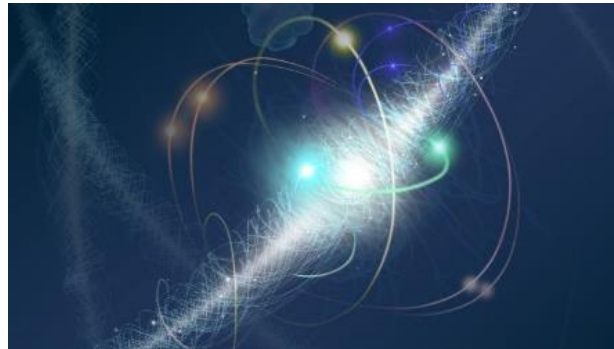
Quantum science with molecules



Fundamental
chemistry

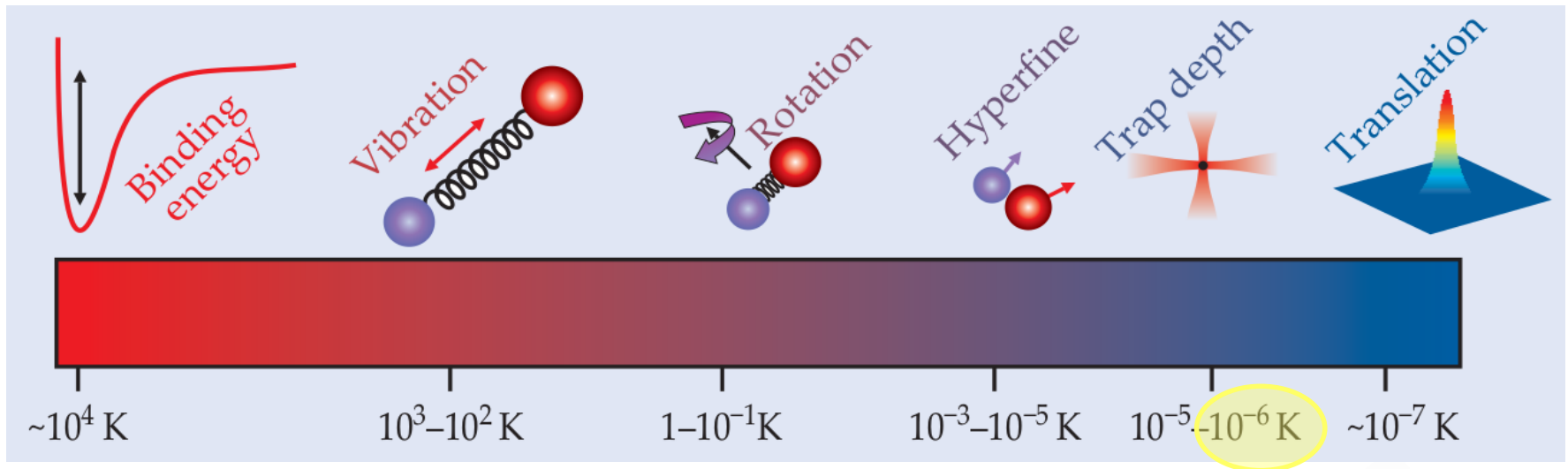


Quantum
materials

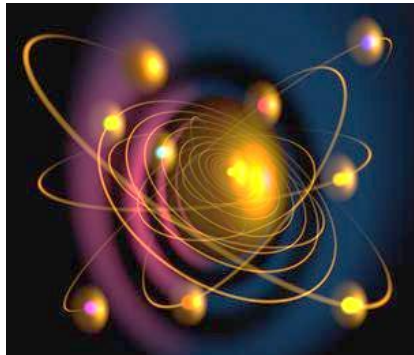


Fundamental
physics

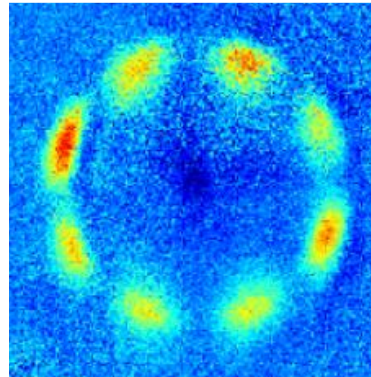
Why ultracold?



Fundamental
metrology

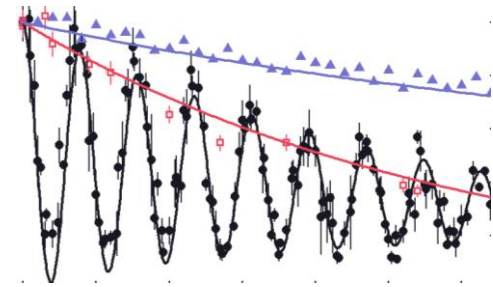


Ultracold
chemistry

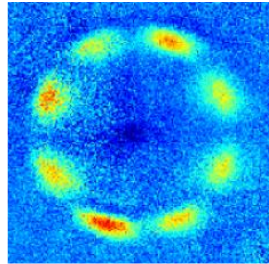


Quantum science with molecules

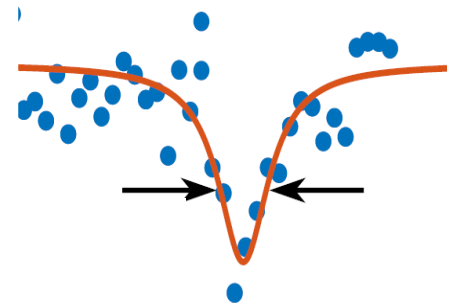
- Can small molecules contribute to our understanding of fundamental forces (“old” and “new” physics)?



- 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

direct cooling

Number
Symbol
Name
Atomic Mass

assembly

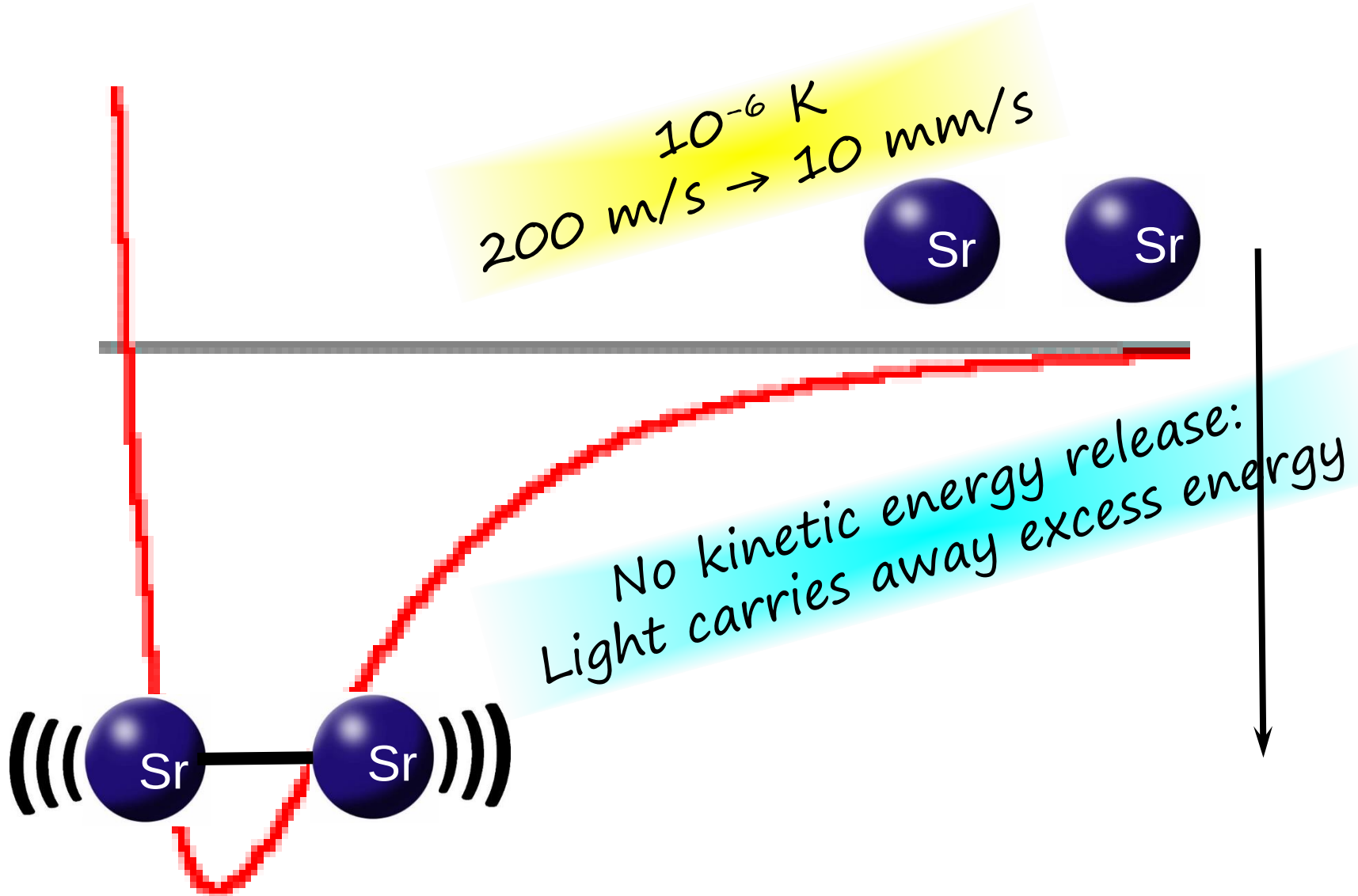
1 H Hydrogen 1.008	2 He Helium 4.003																
3 Li Lithium 6.941	4 Be Beryllium 9.012																
11 Na Sodium 22.990	12 Mg Magnesium 24.305																
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	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 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.293
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanoids	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinoids	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
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 [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Metalloid	Nonmetal	Halogen	Noble Gas	Lanthanoid	Actinoid
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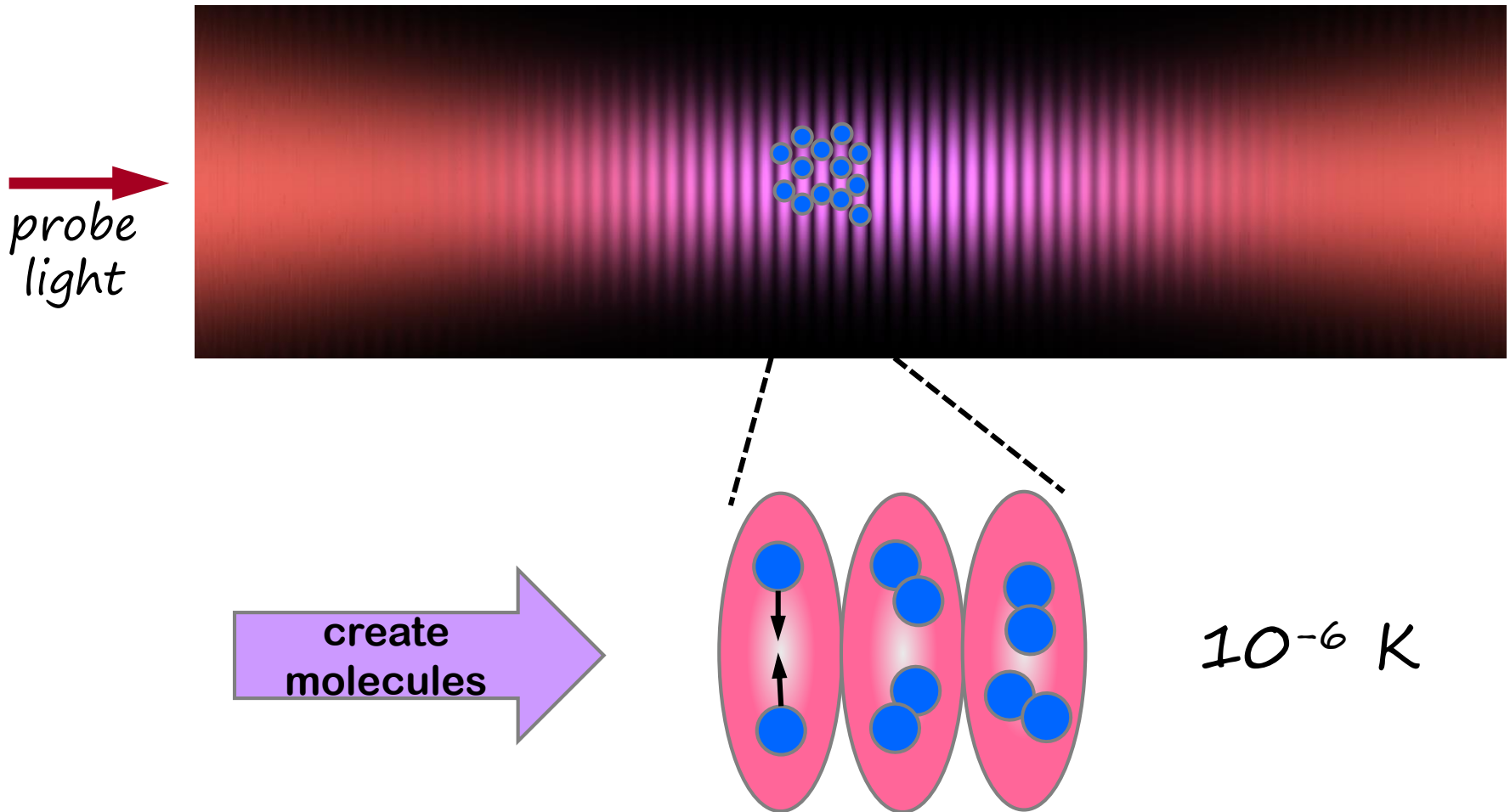
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Ultracold molecule photo-assembly

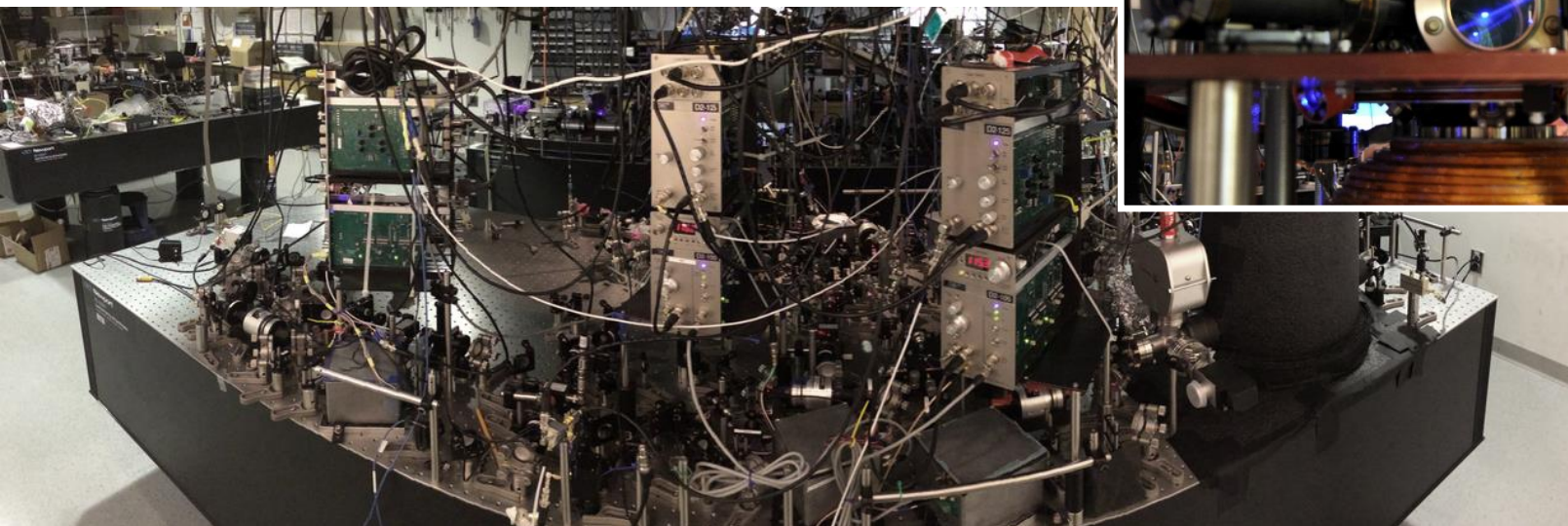
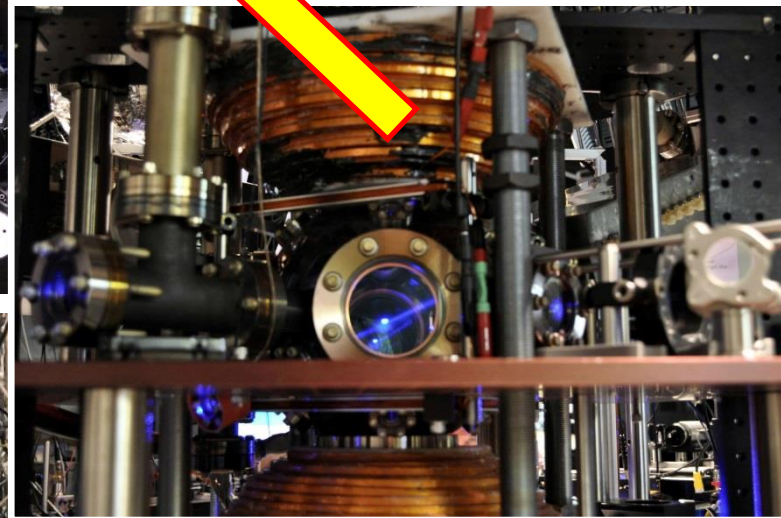
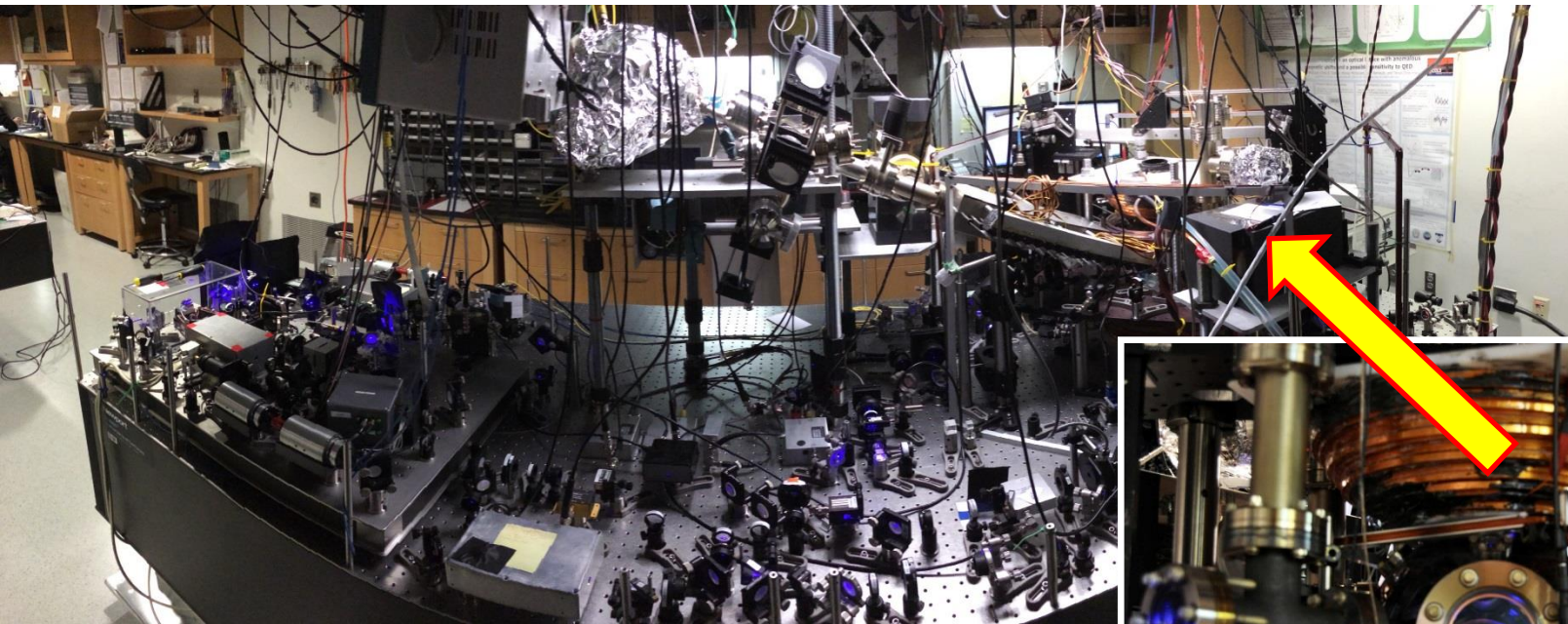


Optical lattice trap

*Standing wave of light
holds atoms or molecules in bright microtraps*

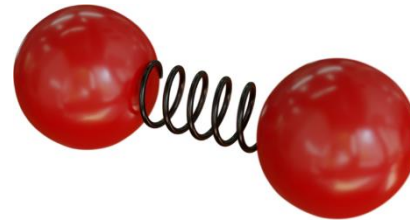
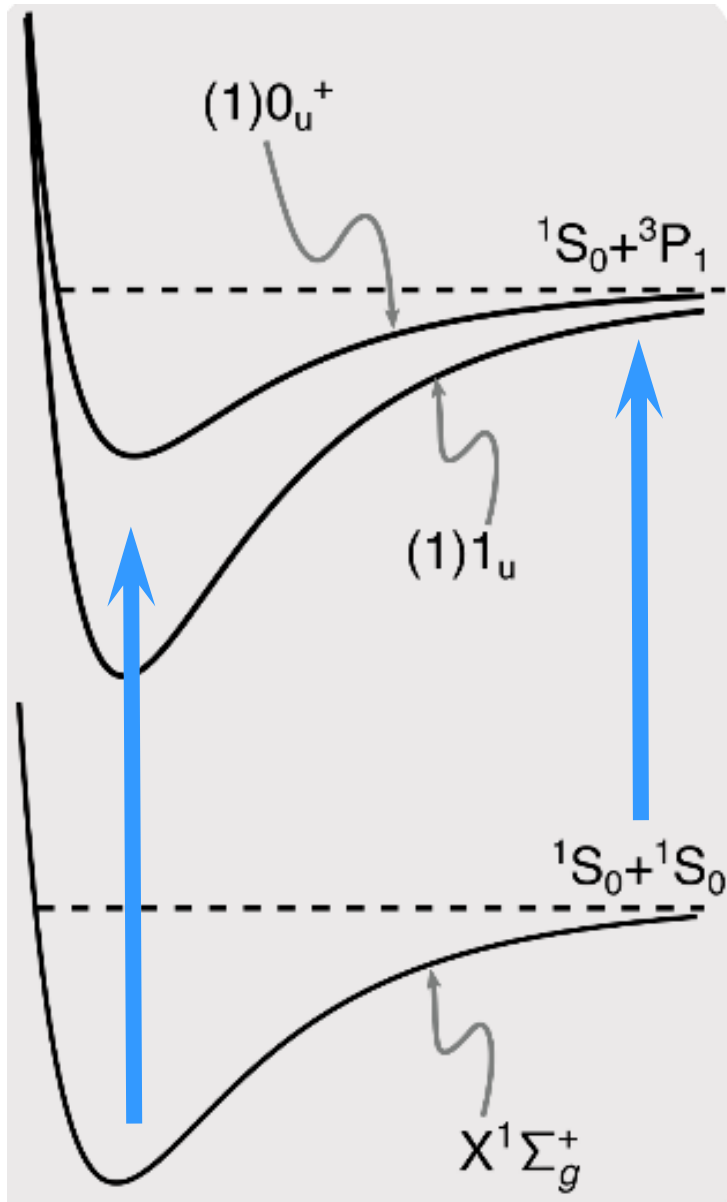


Making ultracold molecules

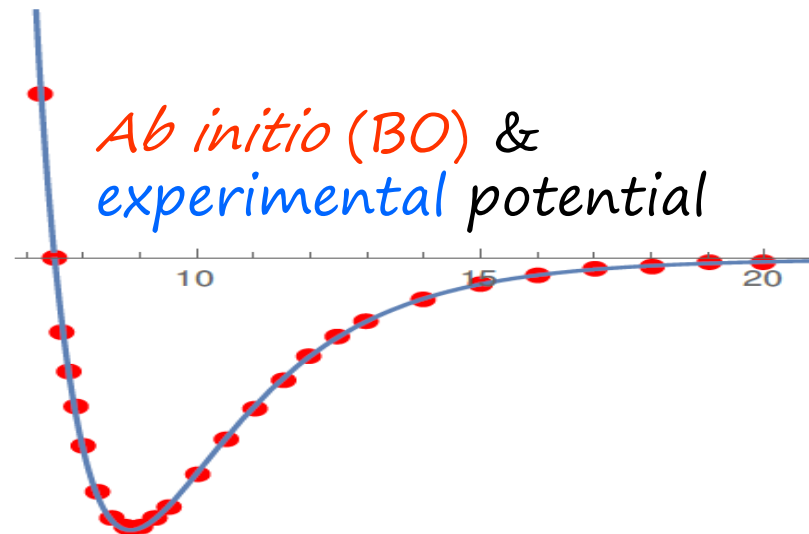


^{88}Sr

Ultracold van der Waals dimers

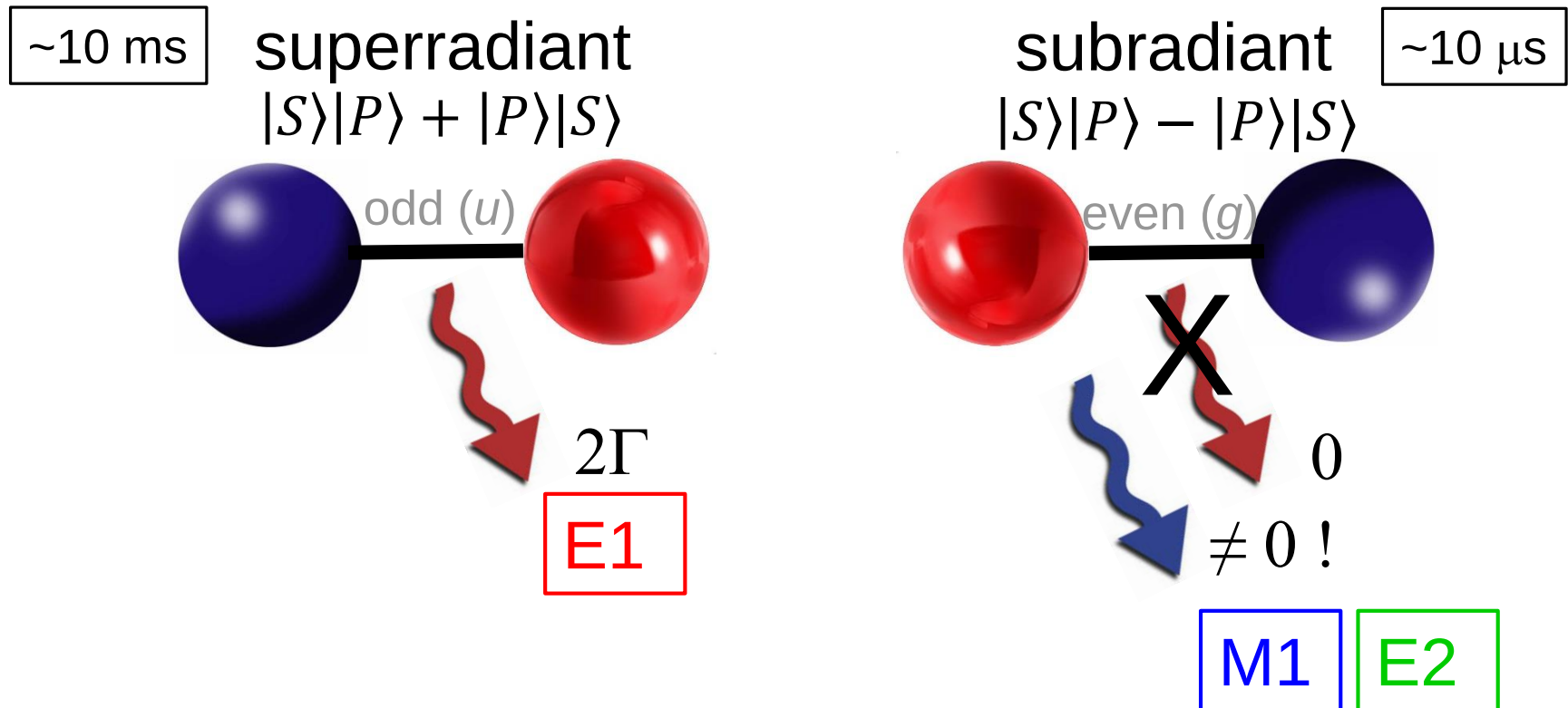
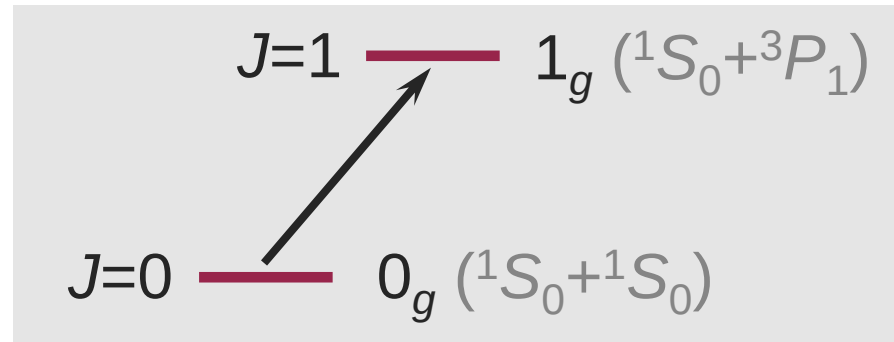


- Singlet-triplet narrow transitions: quantum control
- Spinless ground state: precise metrology & *ab initio*



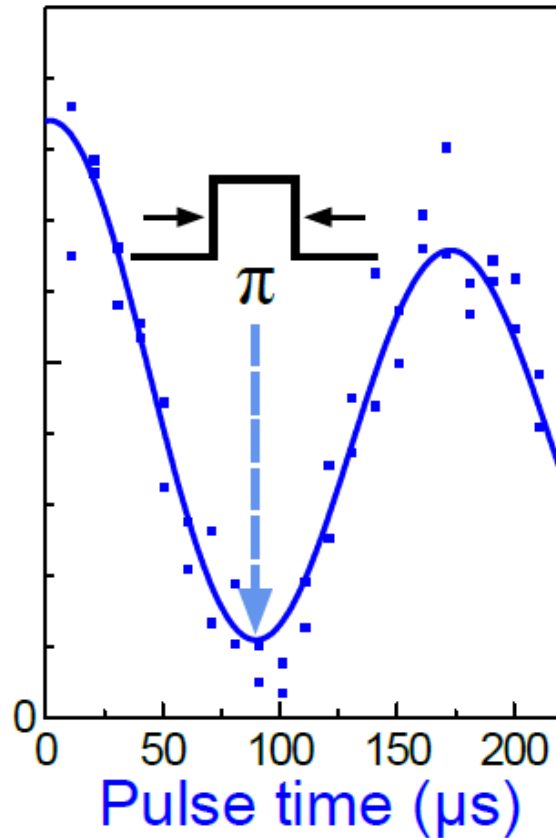
Narrow-line control of molecules

Identical nuclei $\rightarrow$ Inversion symmetry

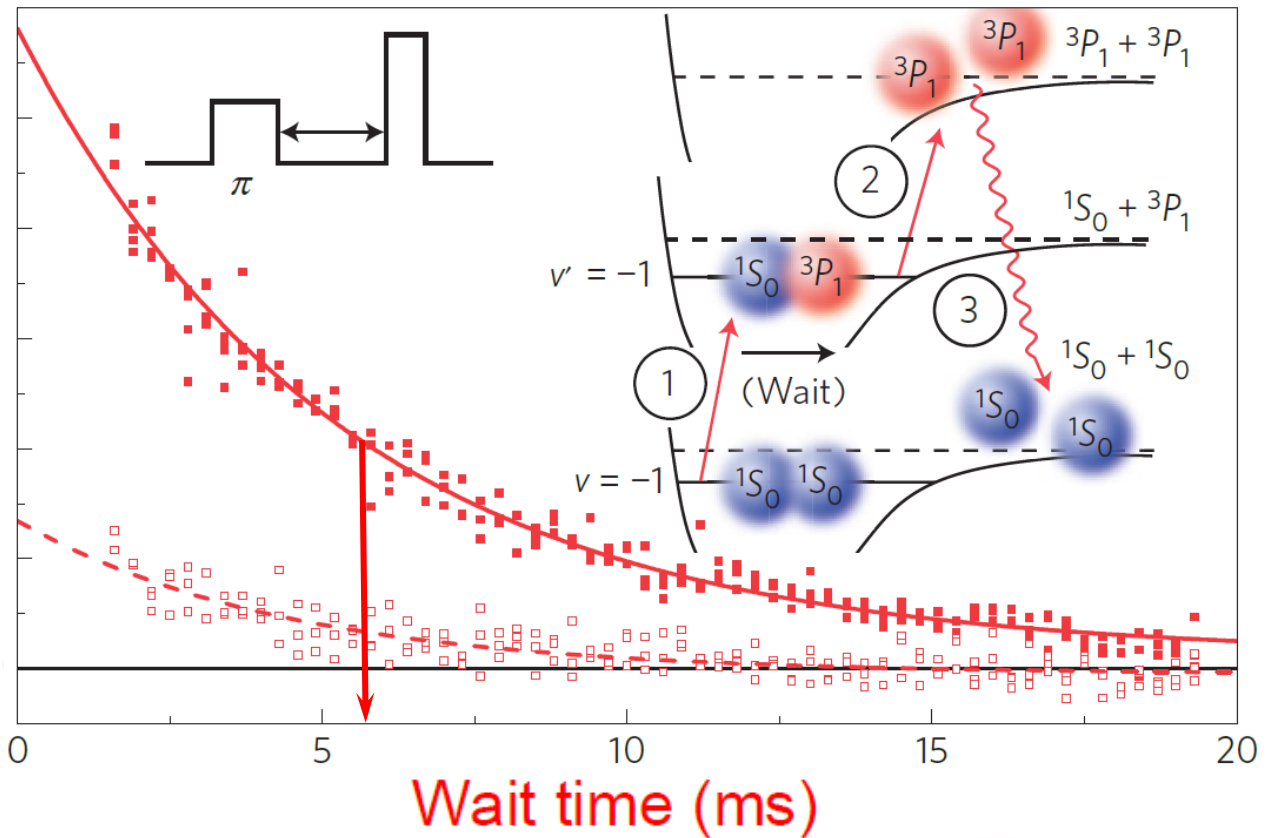


Narrow-line control of molecules

Subradiant states

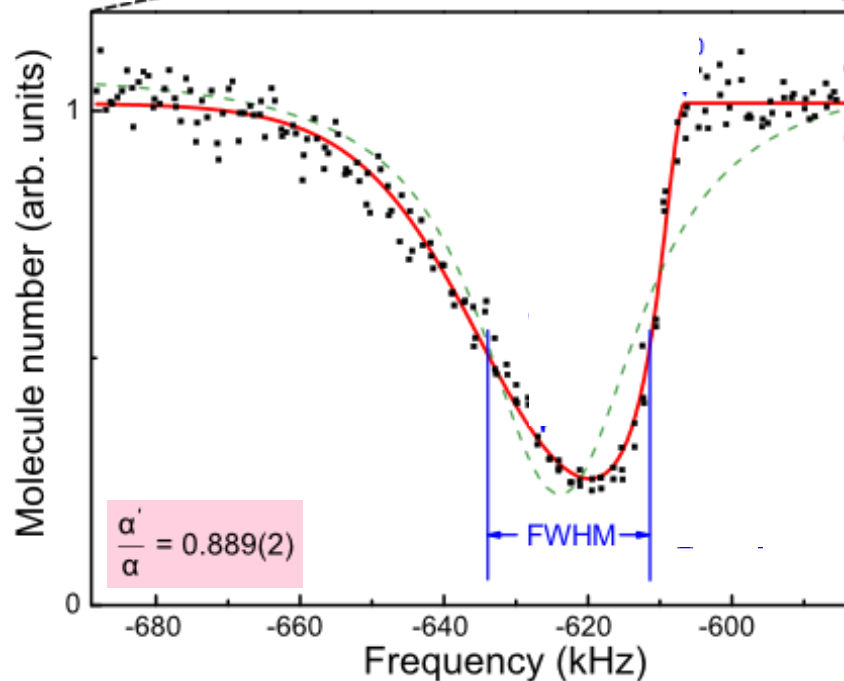
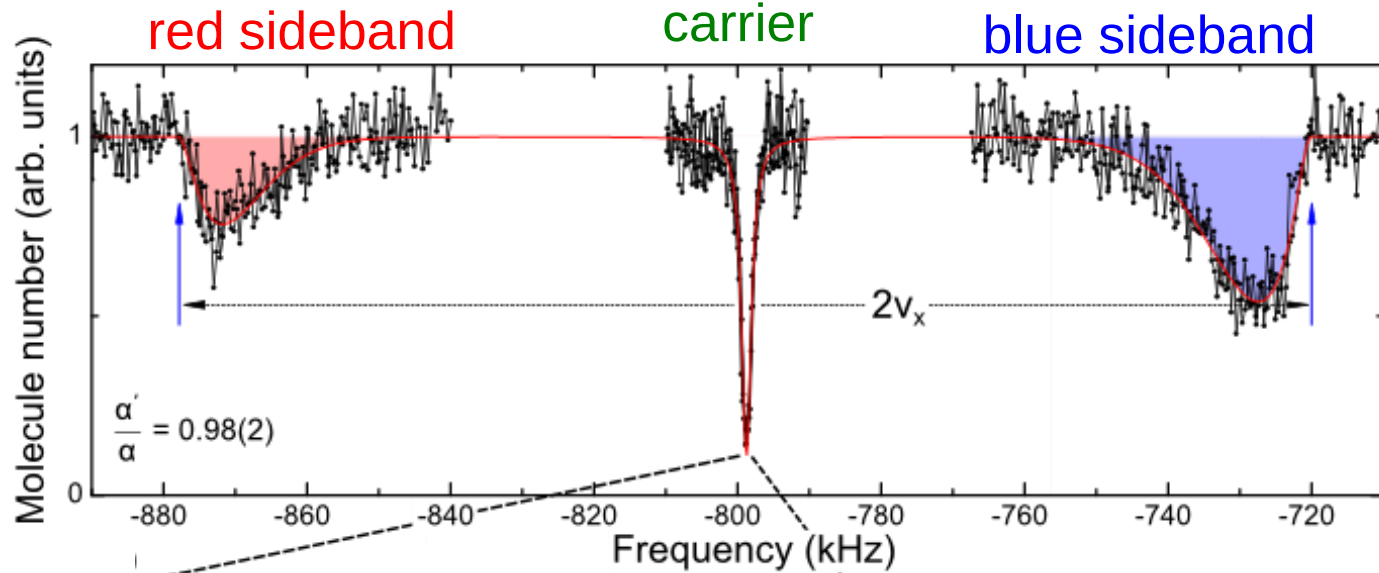


Molecule-light coherence



5.5 ms lifetime

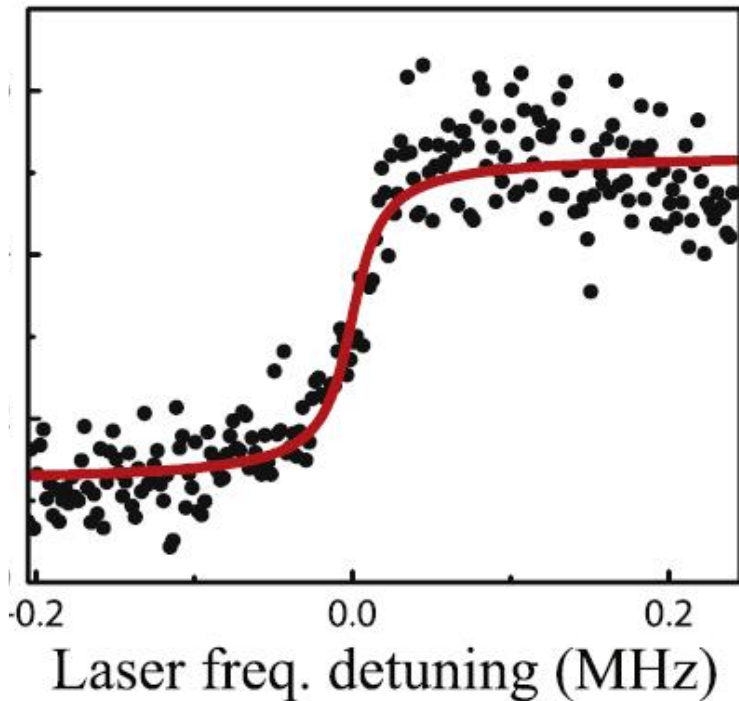
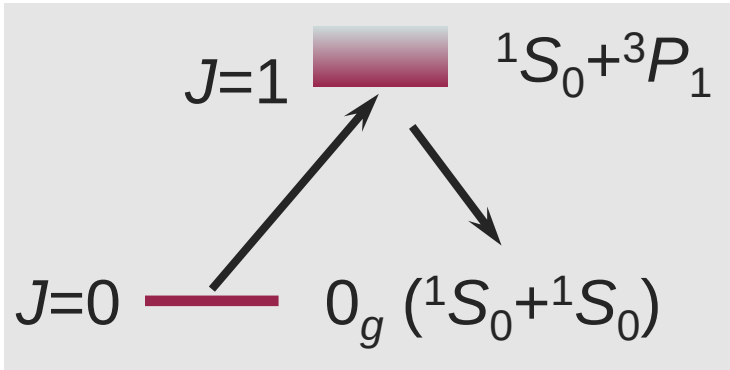
Narrow-line control of molecules



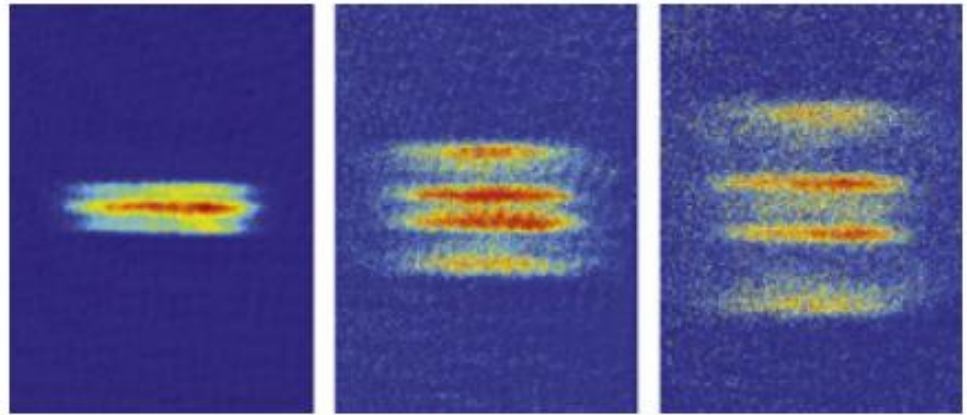
Precise measurements of
sidebands & temperature

Narrow-line control of molecules

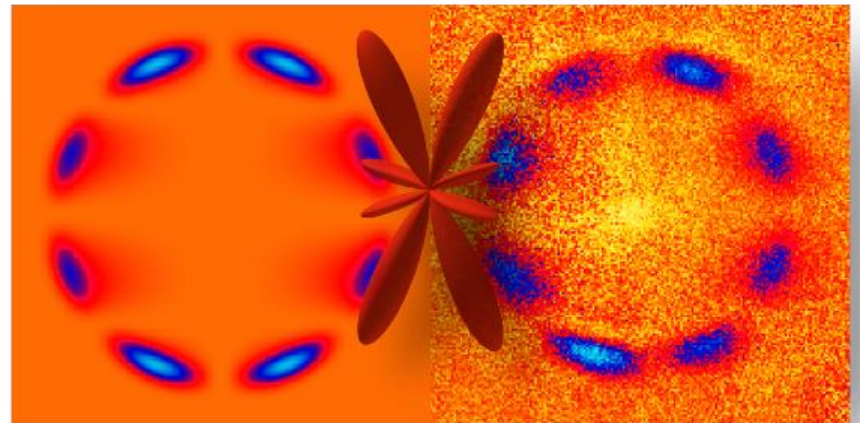
State-resolved photochemistry



Side-view camera

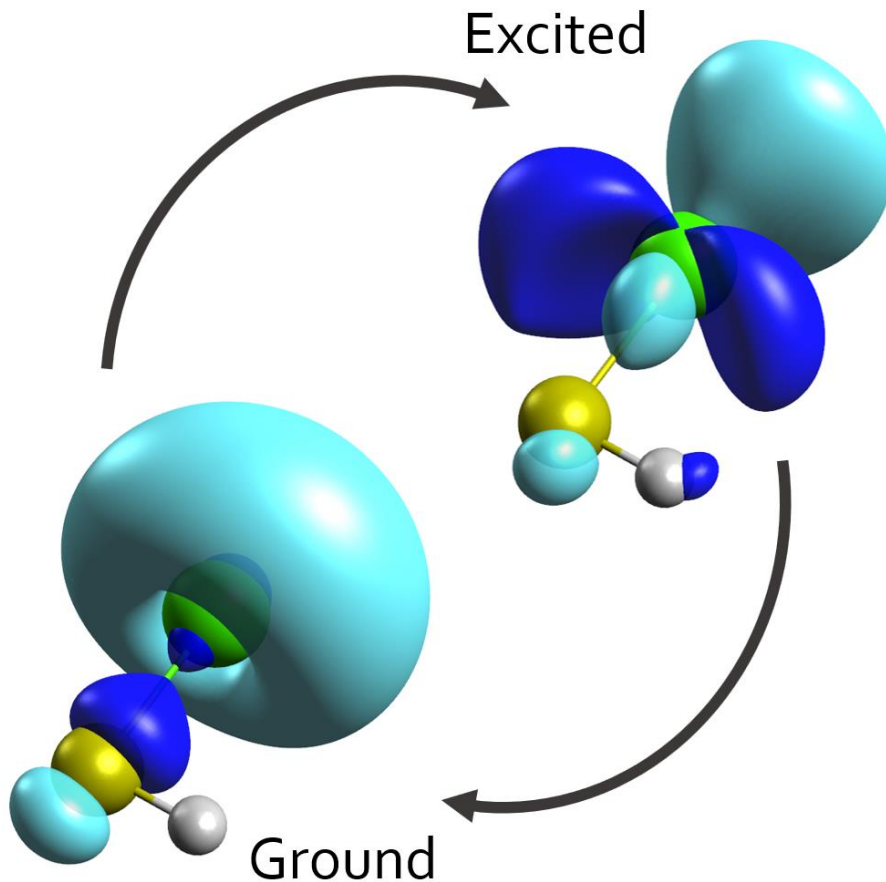


Line-of-sight camera: quantum interference



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



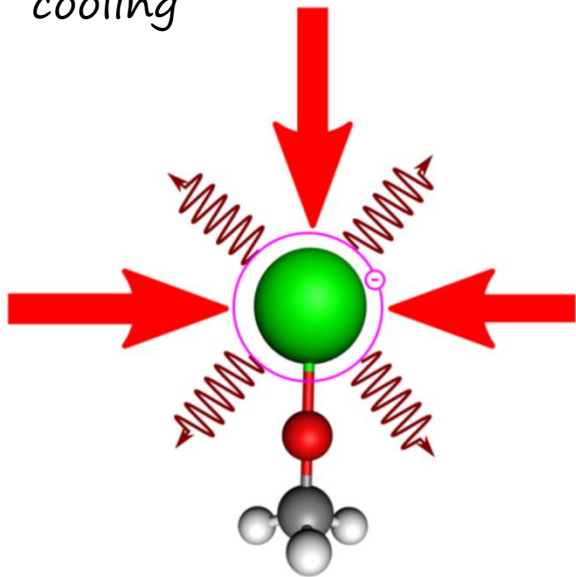
W. M. Keck Foundation
project

Collaboration with:

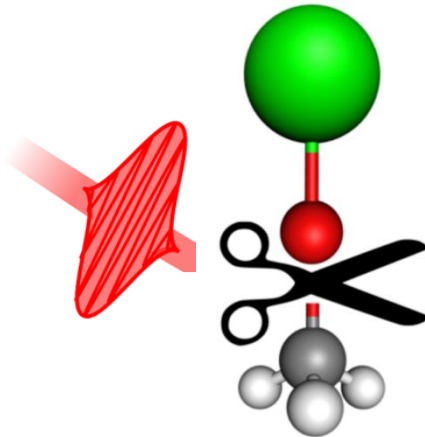


Creating exotic ultracold gases

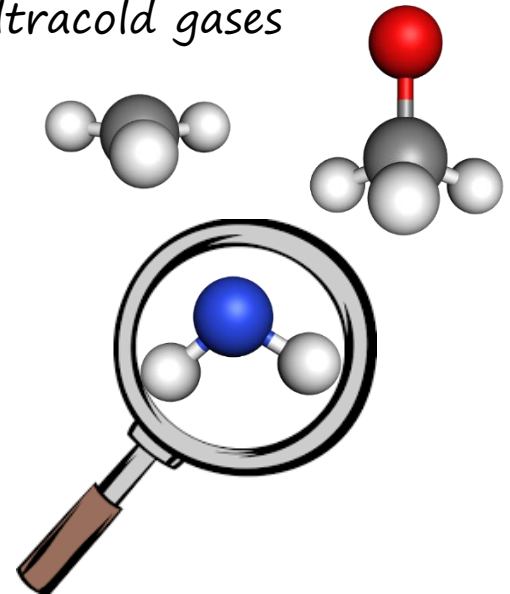
Step 1: Direct laser cooling



Step 2: Precise molecular dissociation



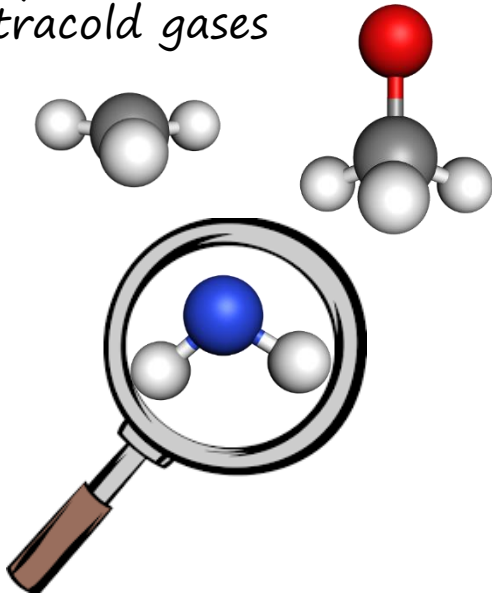
Step 3: Probe exotic ultracold gases



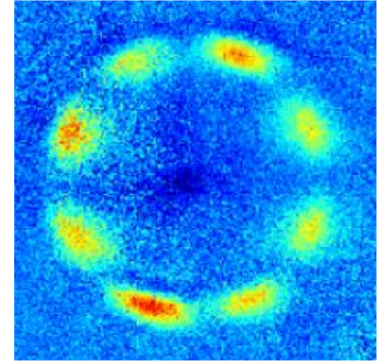
Studying novel ultracold gases

Columbia – Harvard, W. M. Keck

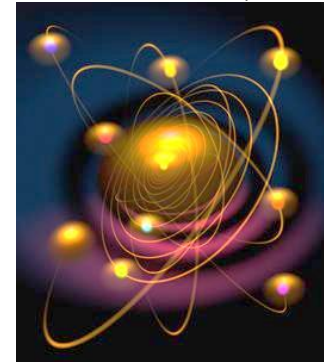
Step 3: Probe novel
ultracold gases



Step 3a:
Ultracold chemistry



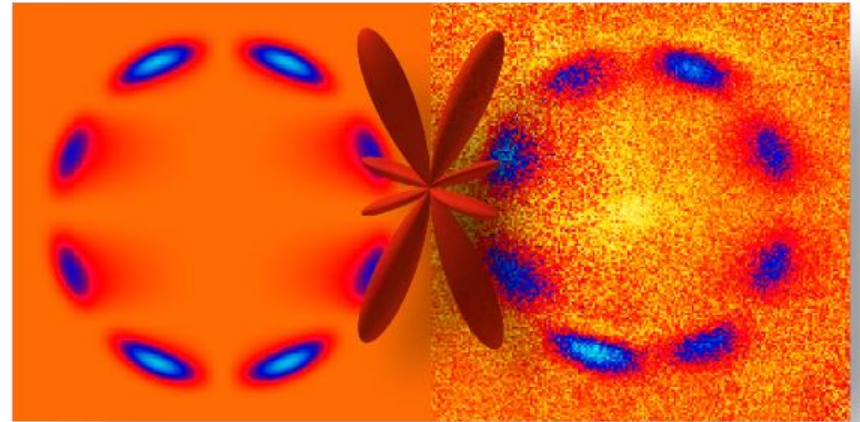
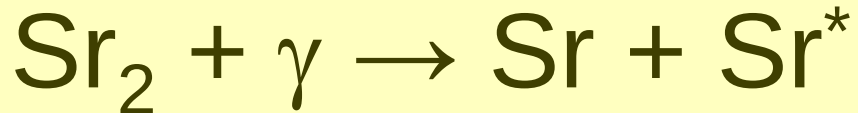
Step 3b:
Fundamental physics



Ultracold photochemistry

Complete quantum state control
of “reverse collision”

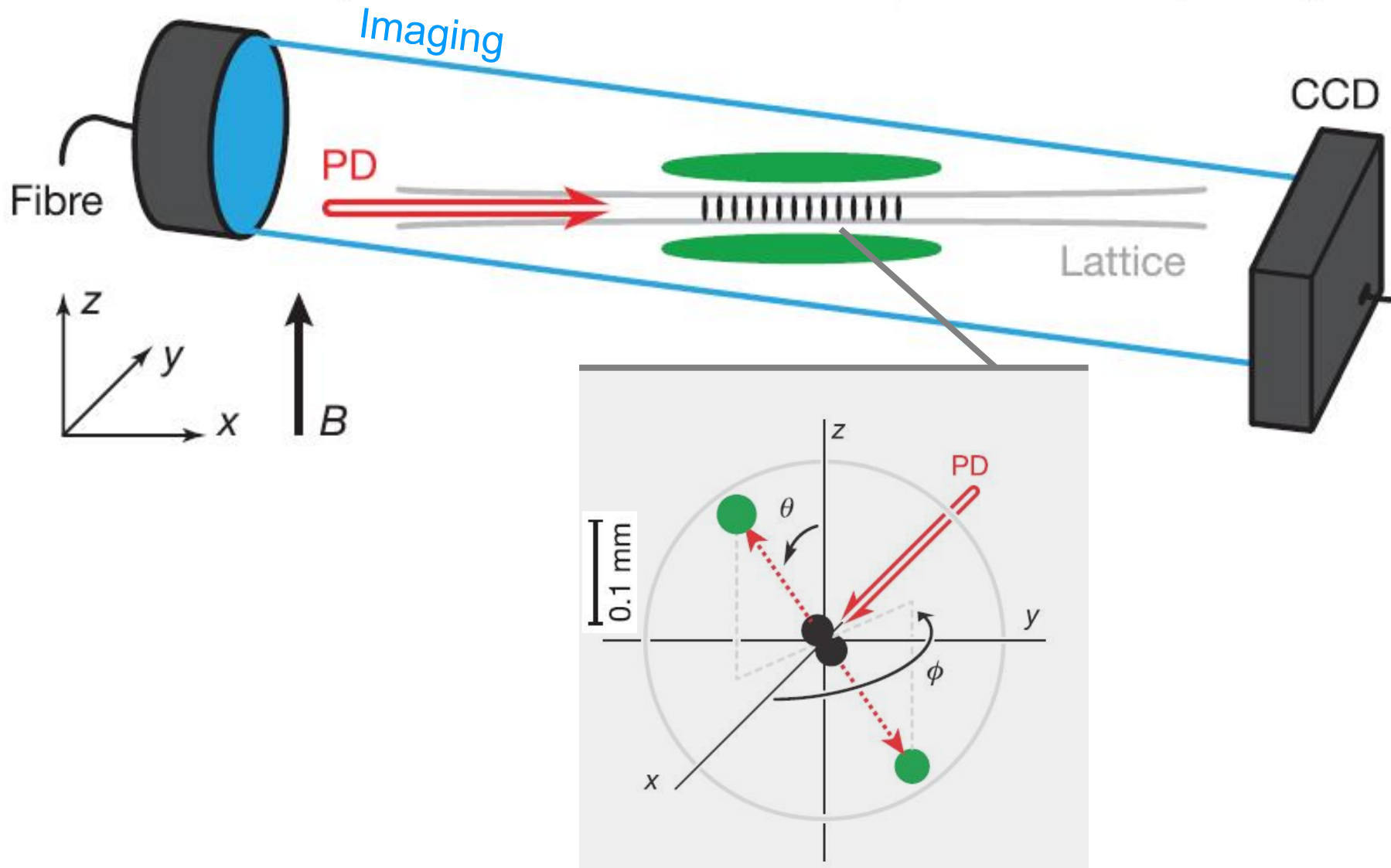
Photodissociation



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

Ultracold Photodissociation

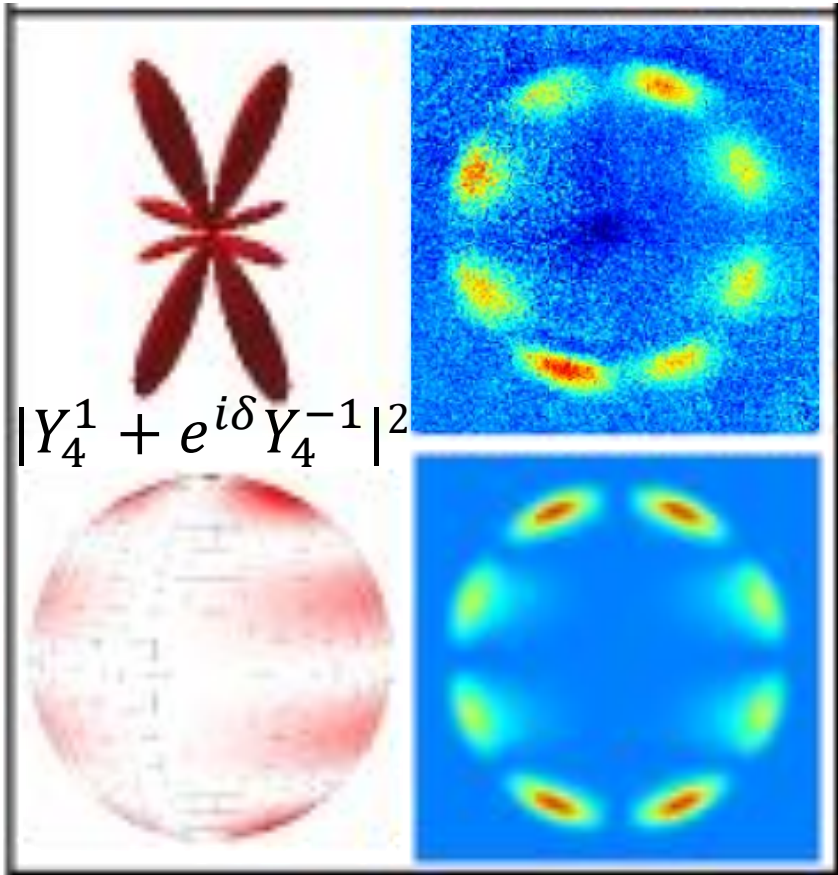
Photofragment angular distribution



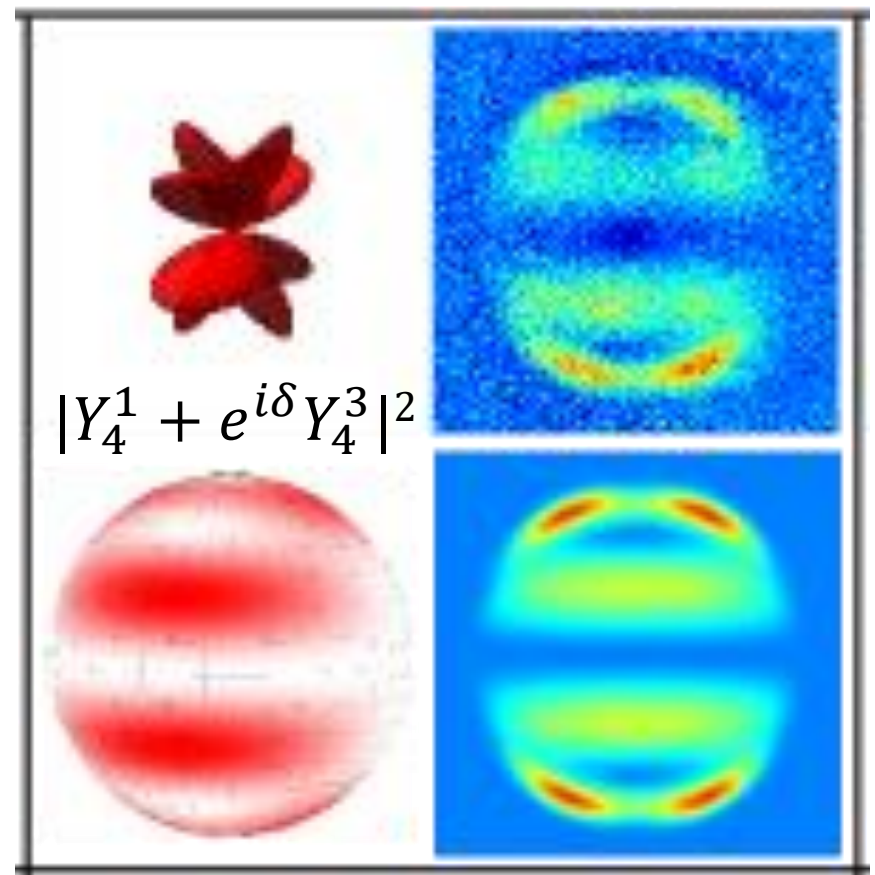
Ultracold Photodissociation

Matter-wave interference

$J = 4; M = \pm 1$



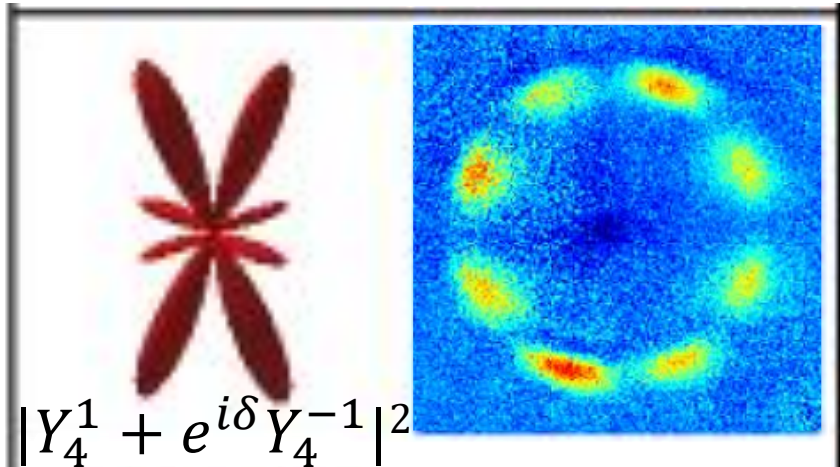
$J = 4; M = 1, 3$



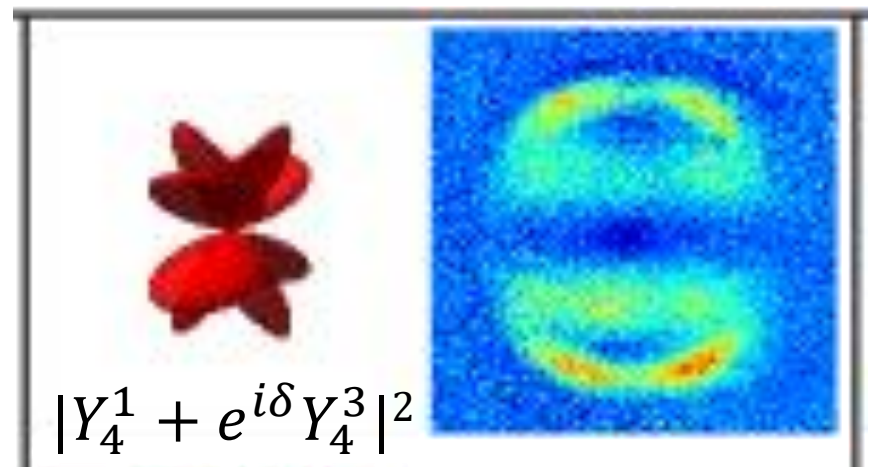
Ultracold Photodissociation

Matter-wave interference

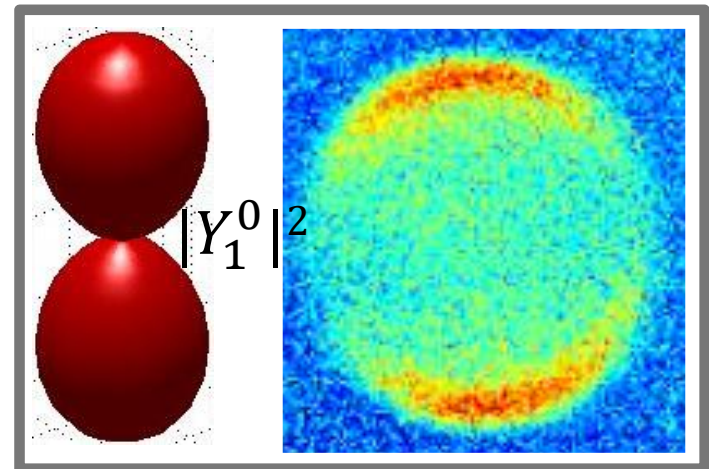
$J = 4; M = \pm 1$



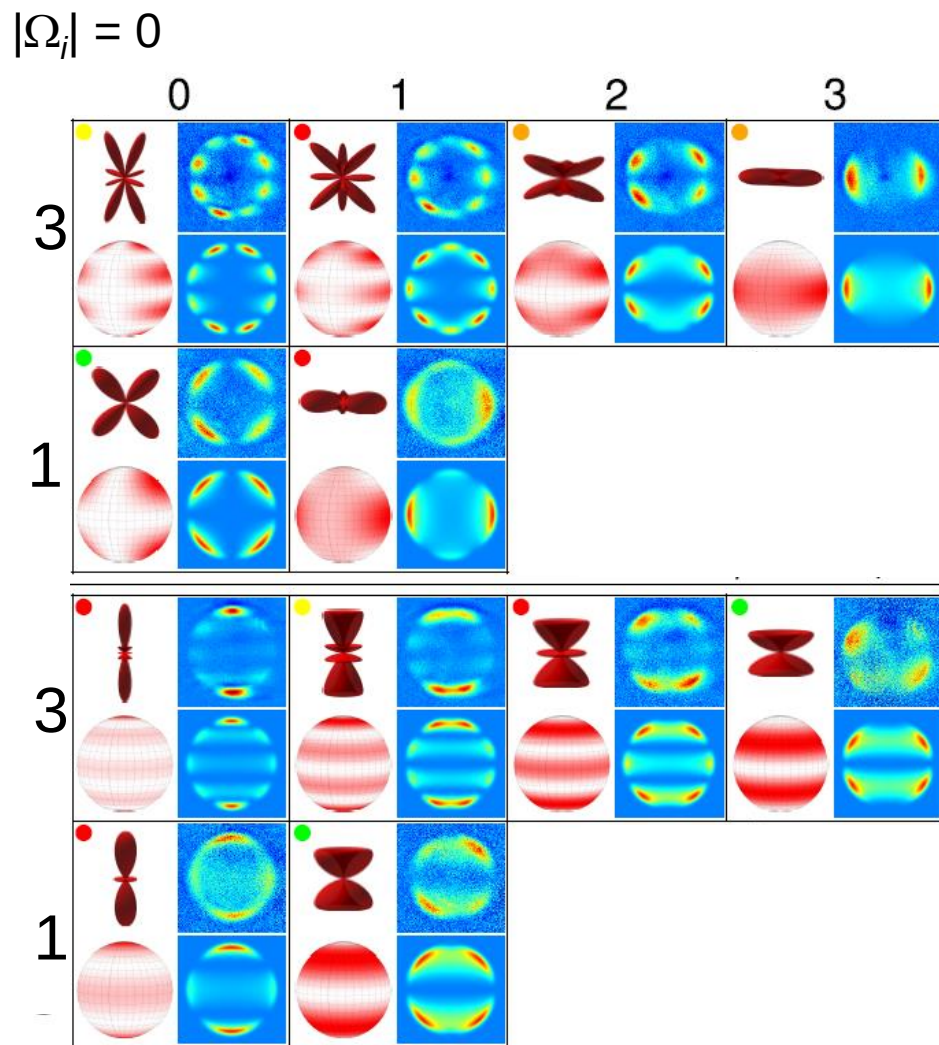
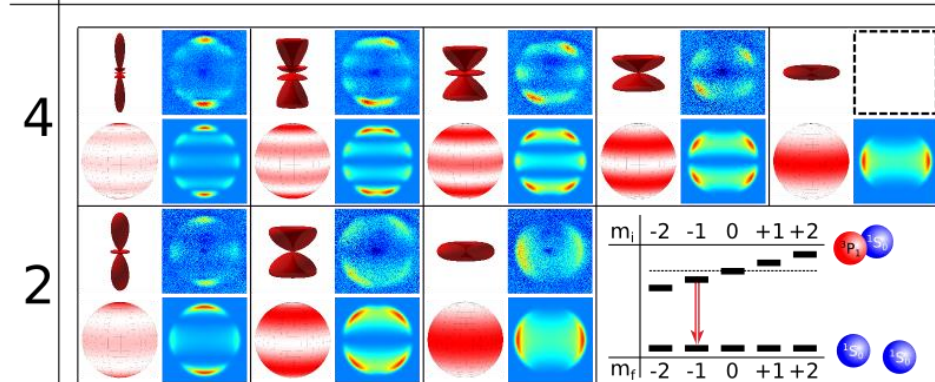
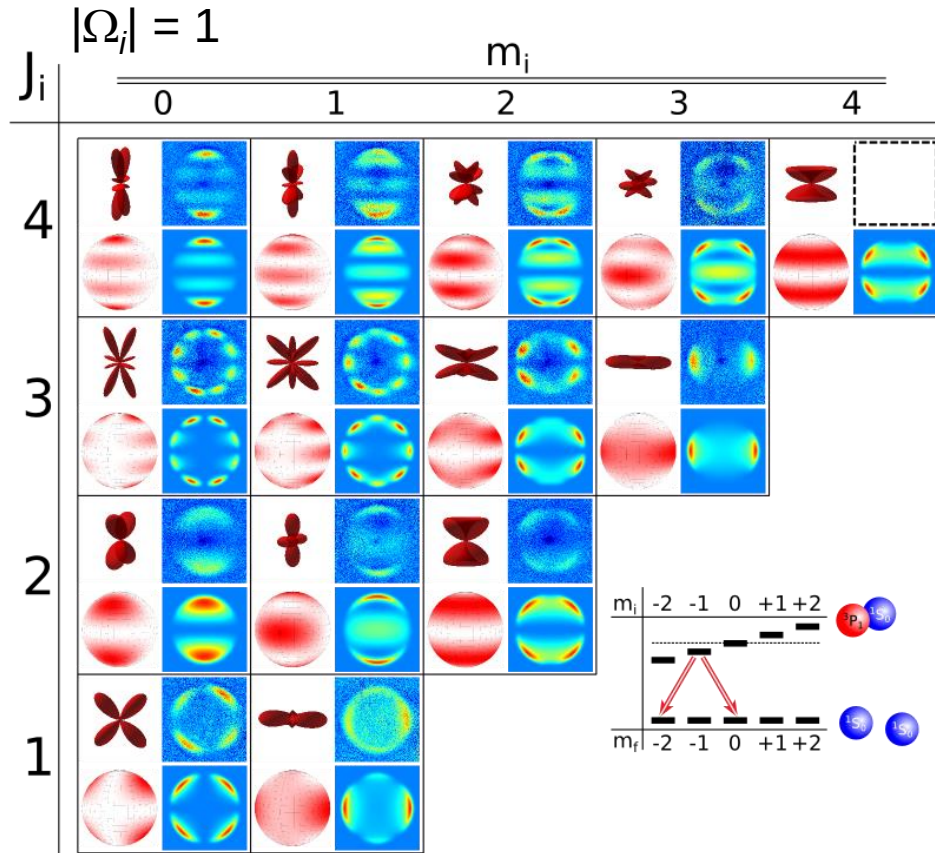
$J = 4; M = 1, 3$



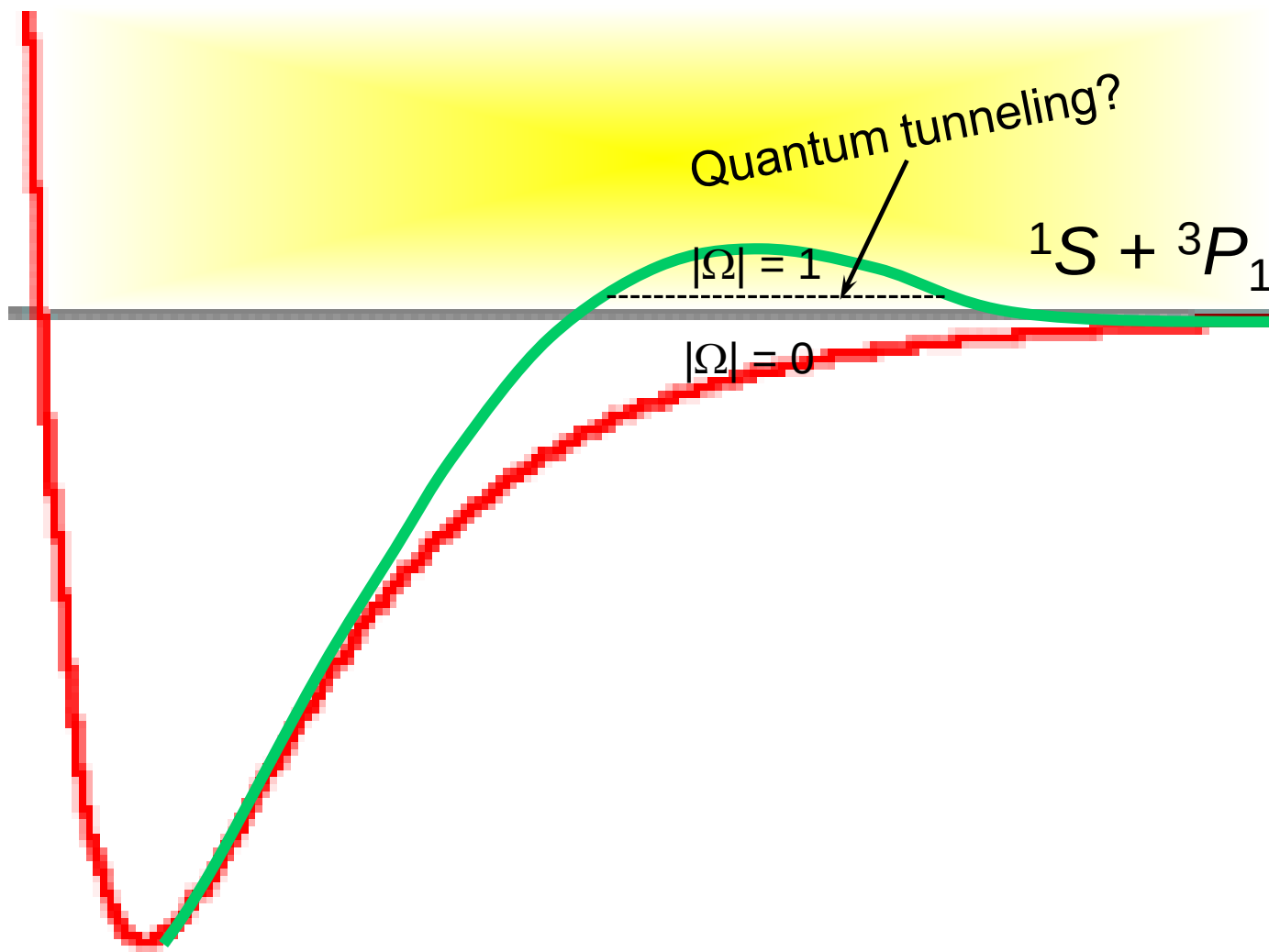
“Classical” fragmentation
of diatomic molecule



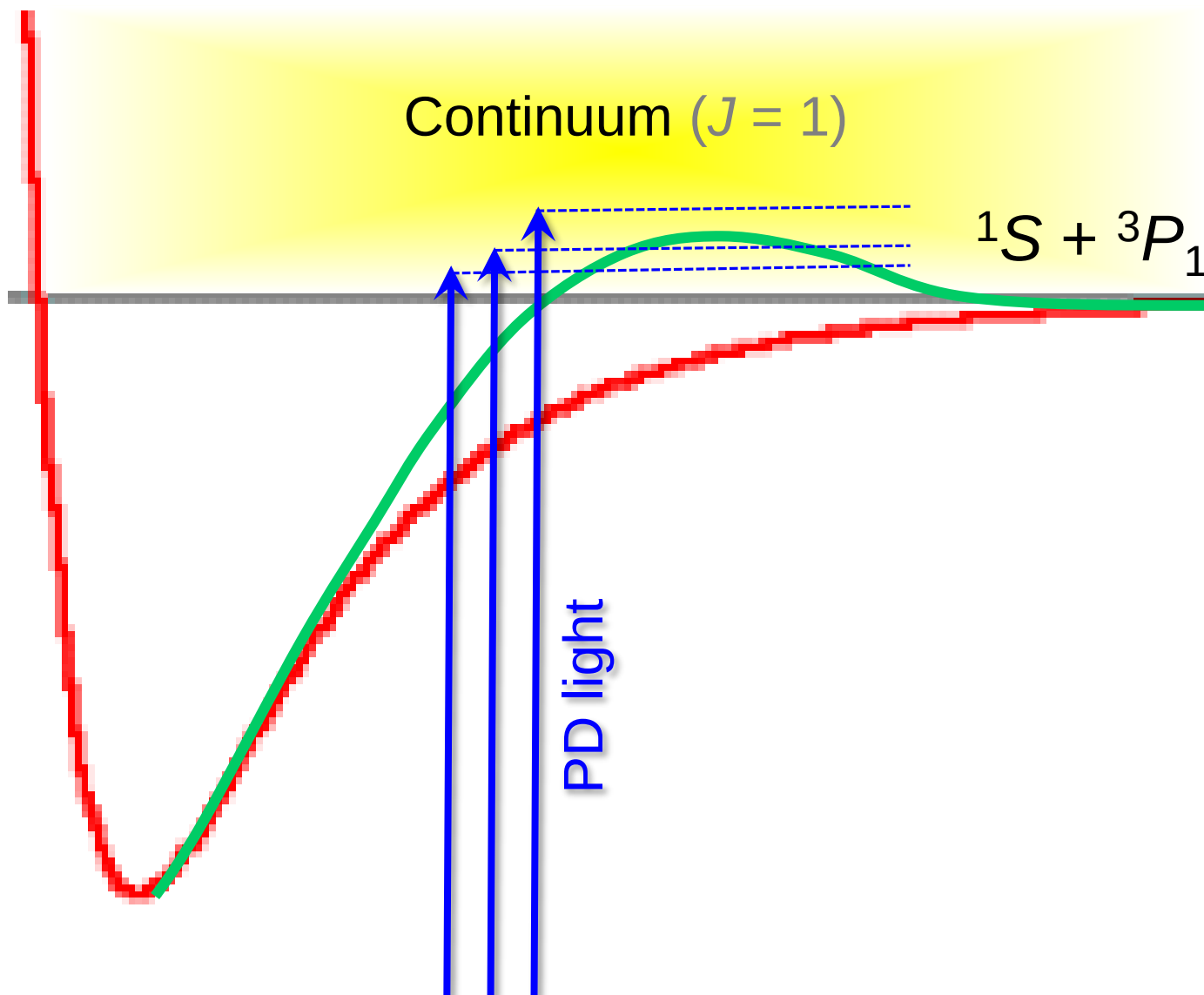
Photofragment Angular Distributions



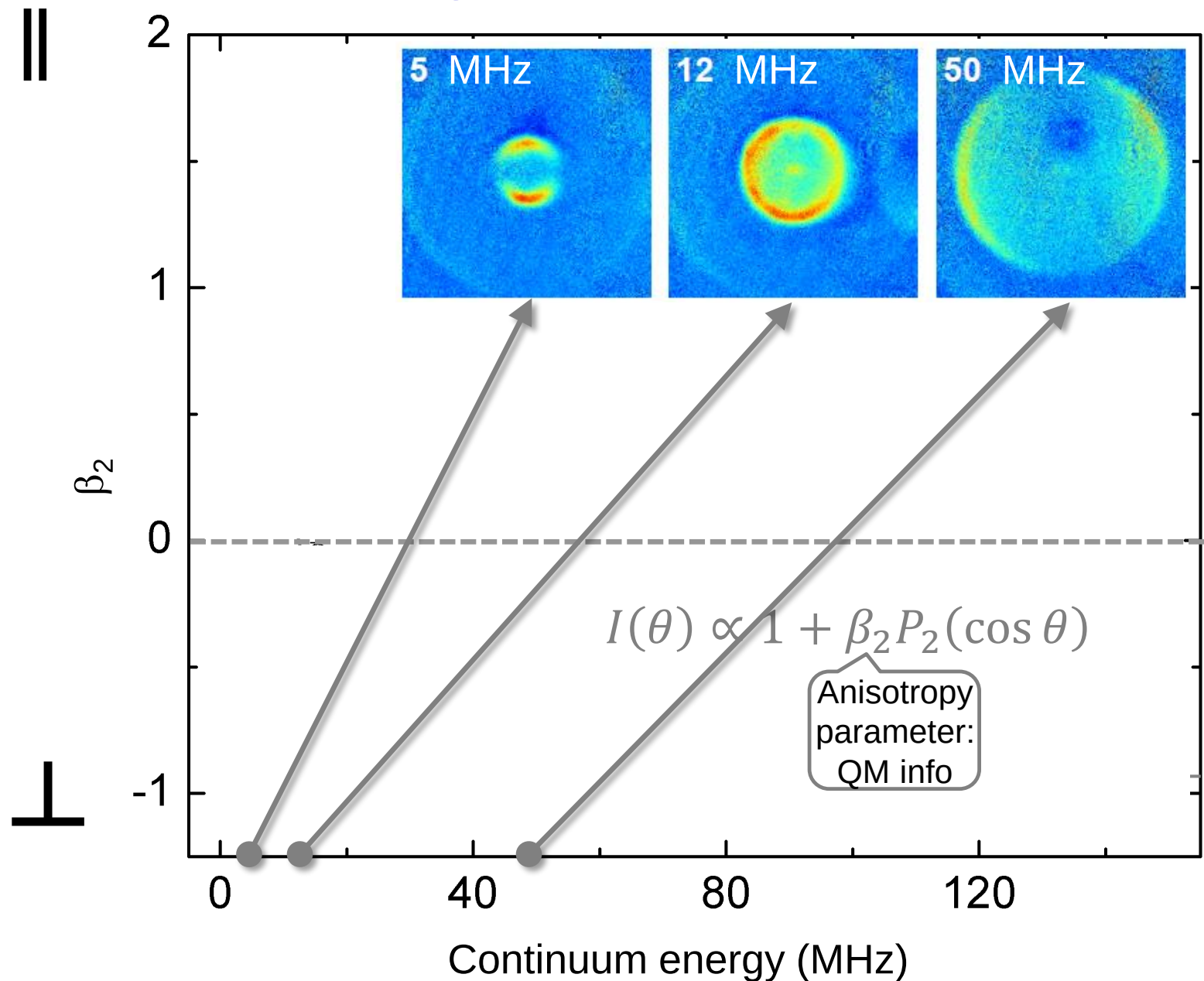
Probing Reaction Barriers



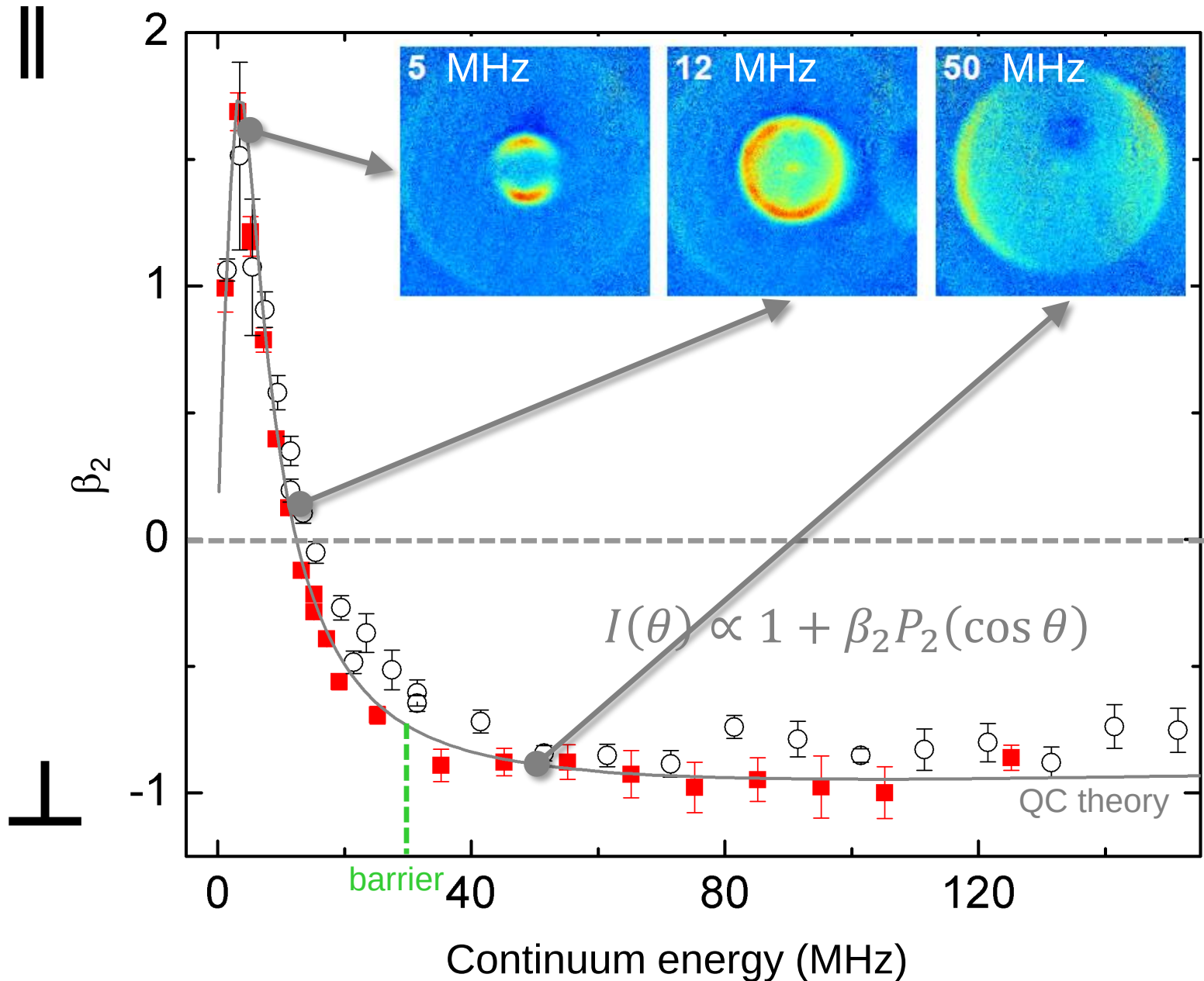
Probing Reaction Barriers



Probing Reaction Barriers



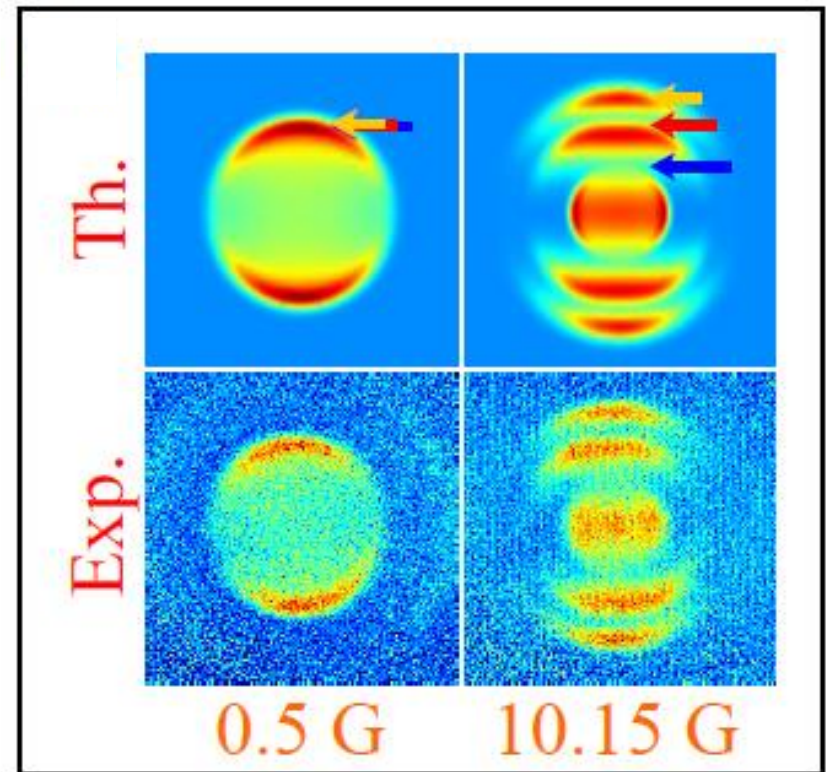
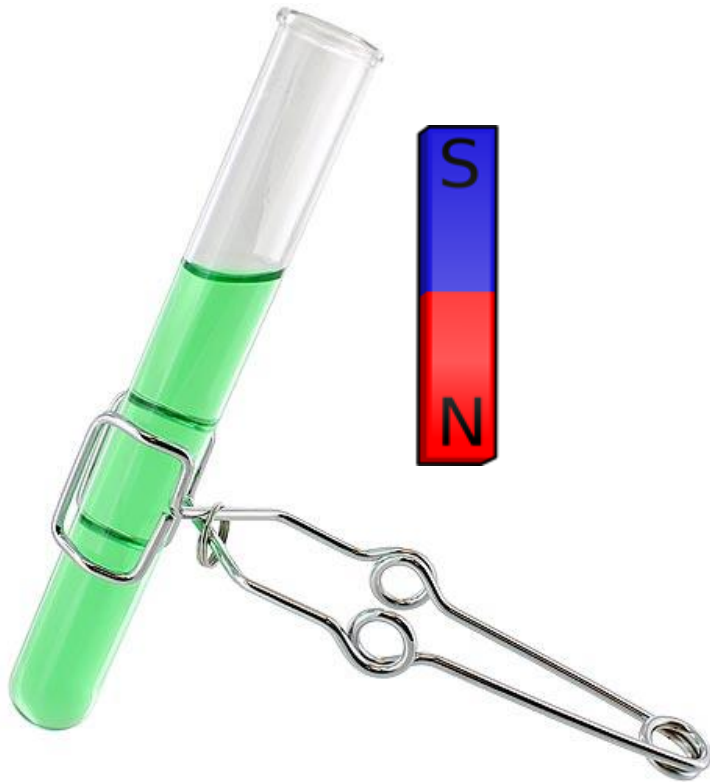
Probing Reaction Barriers



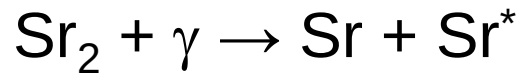
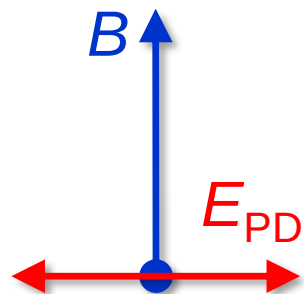
Field Control of Photodissociation

Comparable energies at ~ 1 mK:

- Kinetic
- Barrier
- Zeeman

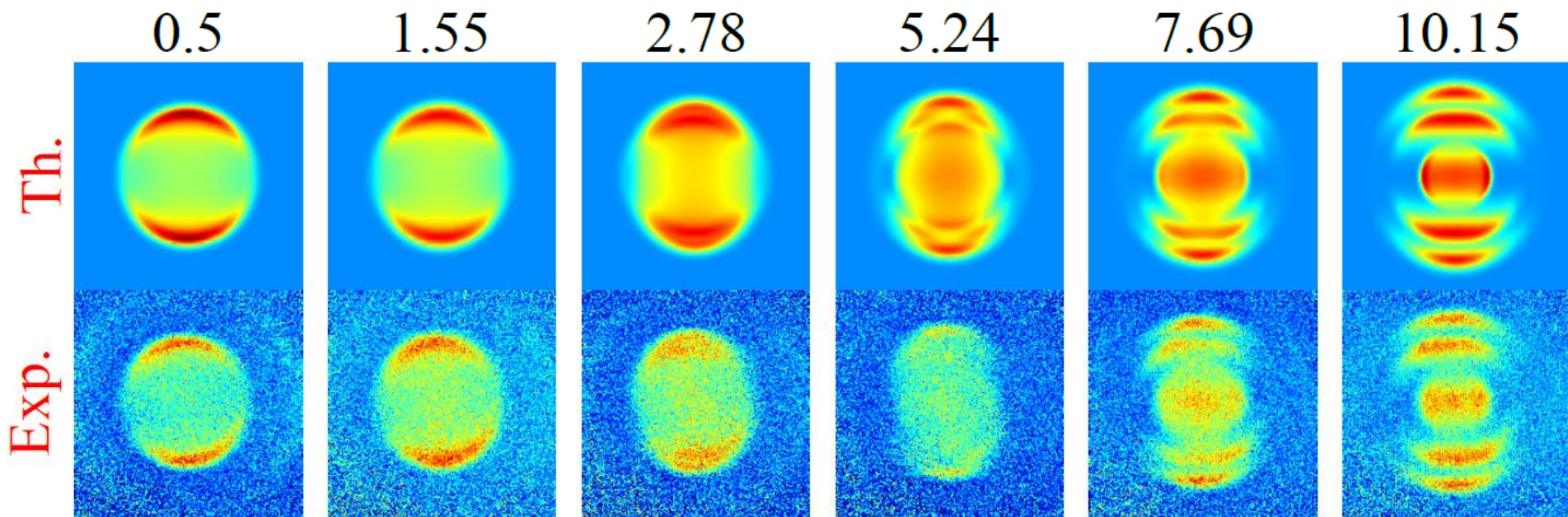


Field Control of Photodissociation



Energy = 30 MHz = 1.5 mK

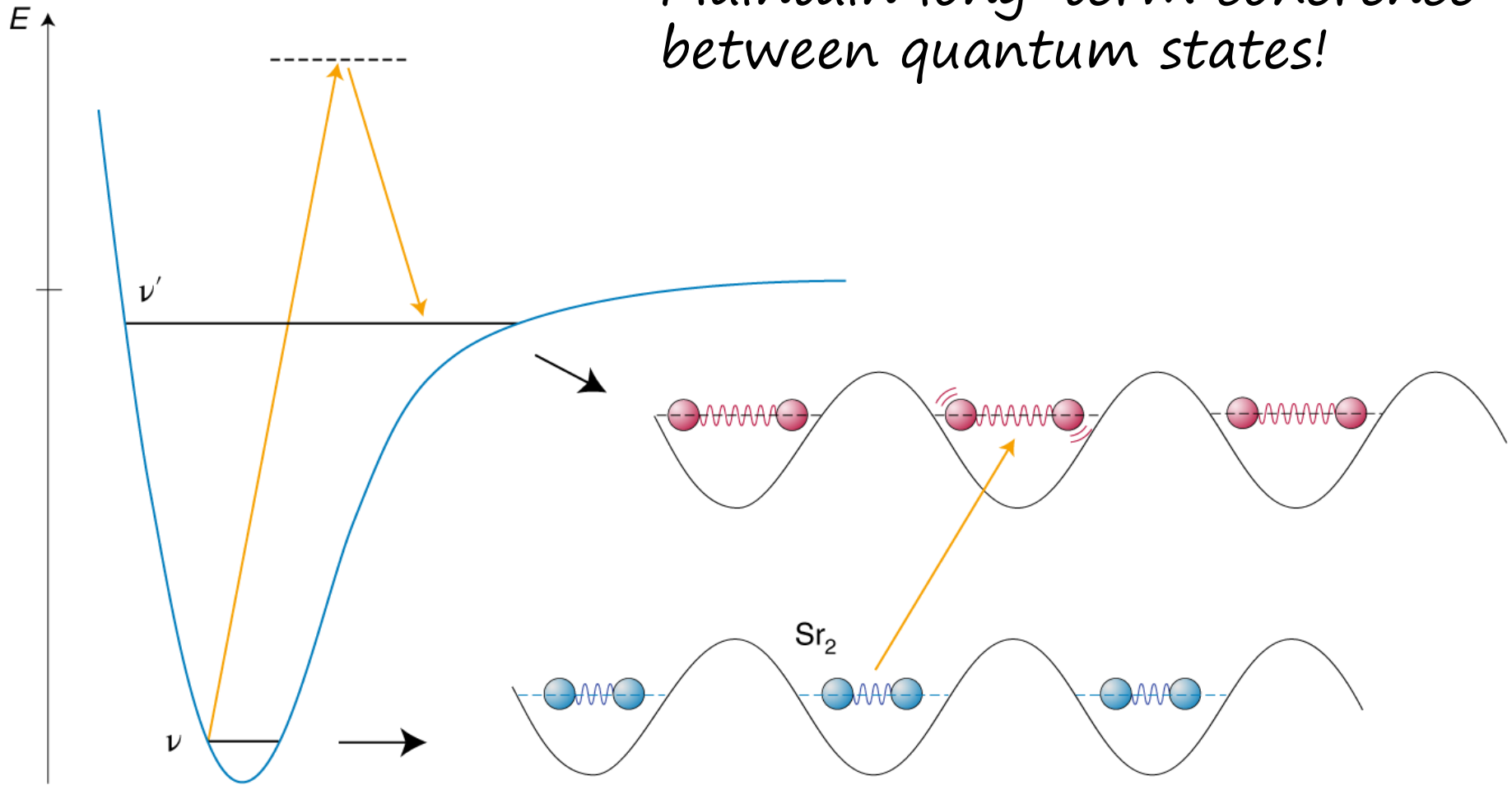
Magnetic Field (G)



Key point: Mixing of partial waves in the continuum

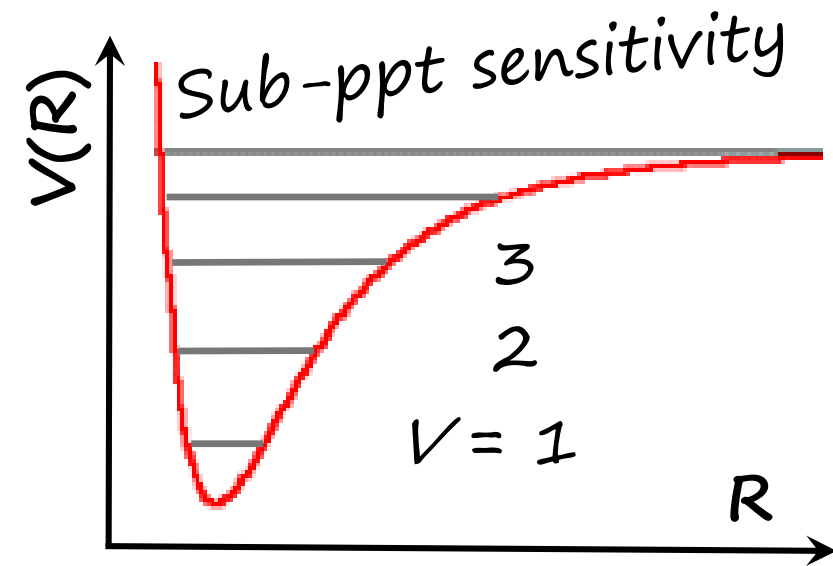
Molecular lattice clock

*Maintain long-term coherence
between quantum states!*

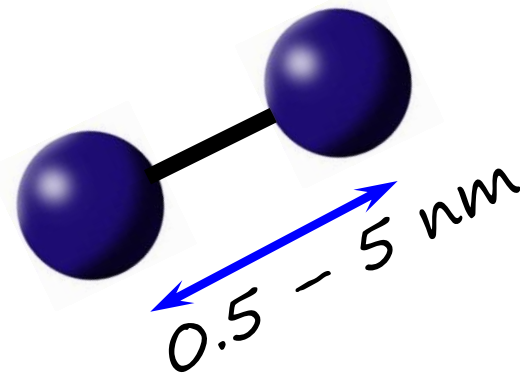


New science with molecular clocks

Interatomic force sensing



Ultrashort-range gravity



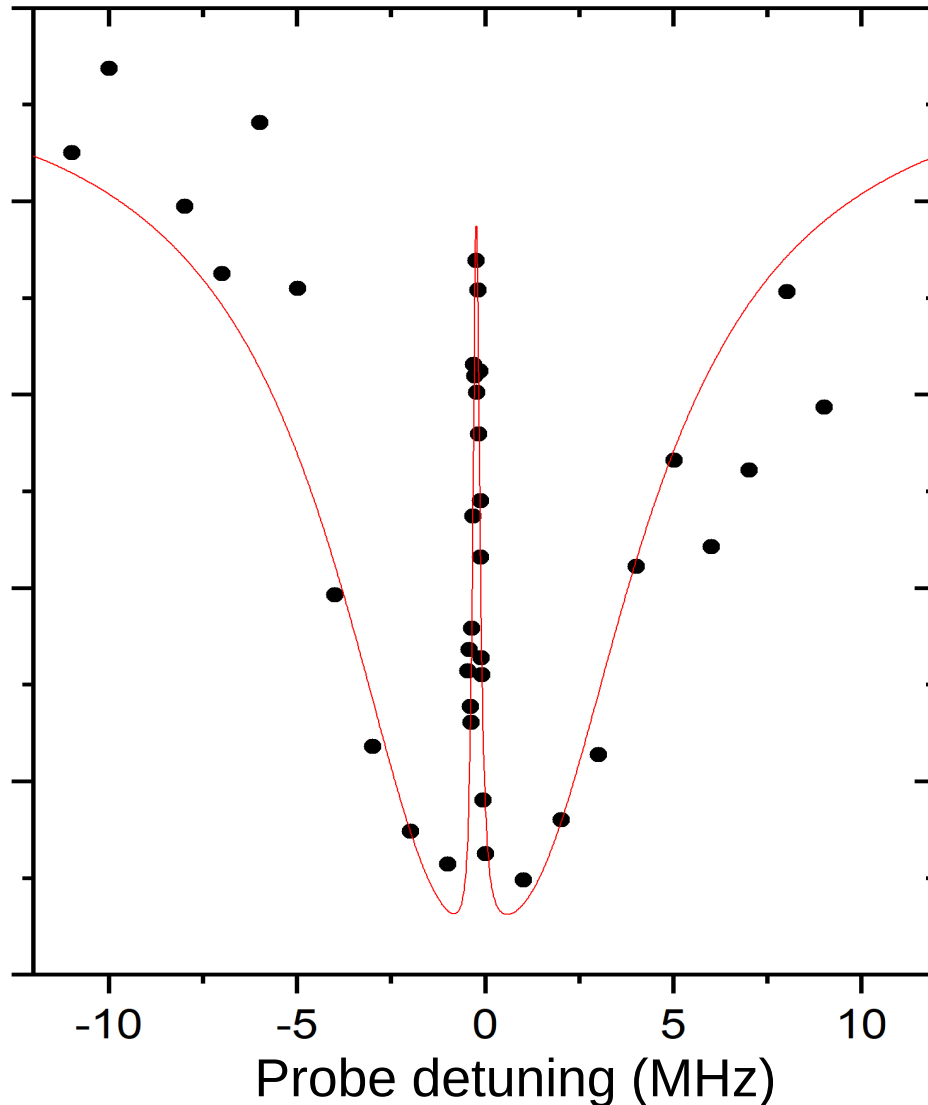
$$V = -\frac{GM^2}{r} (1 + Ae^{-r/\lambda})$$

$$A < 10^{22} !$$

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

Creation of Sr_2 in absolute ground state

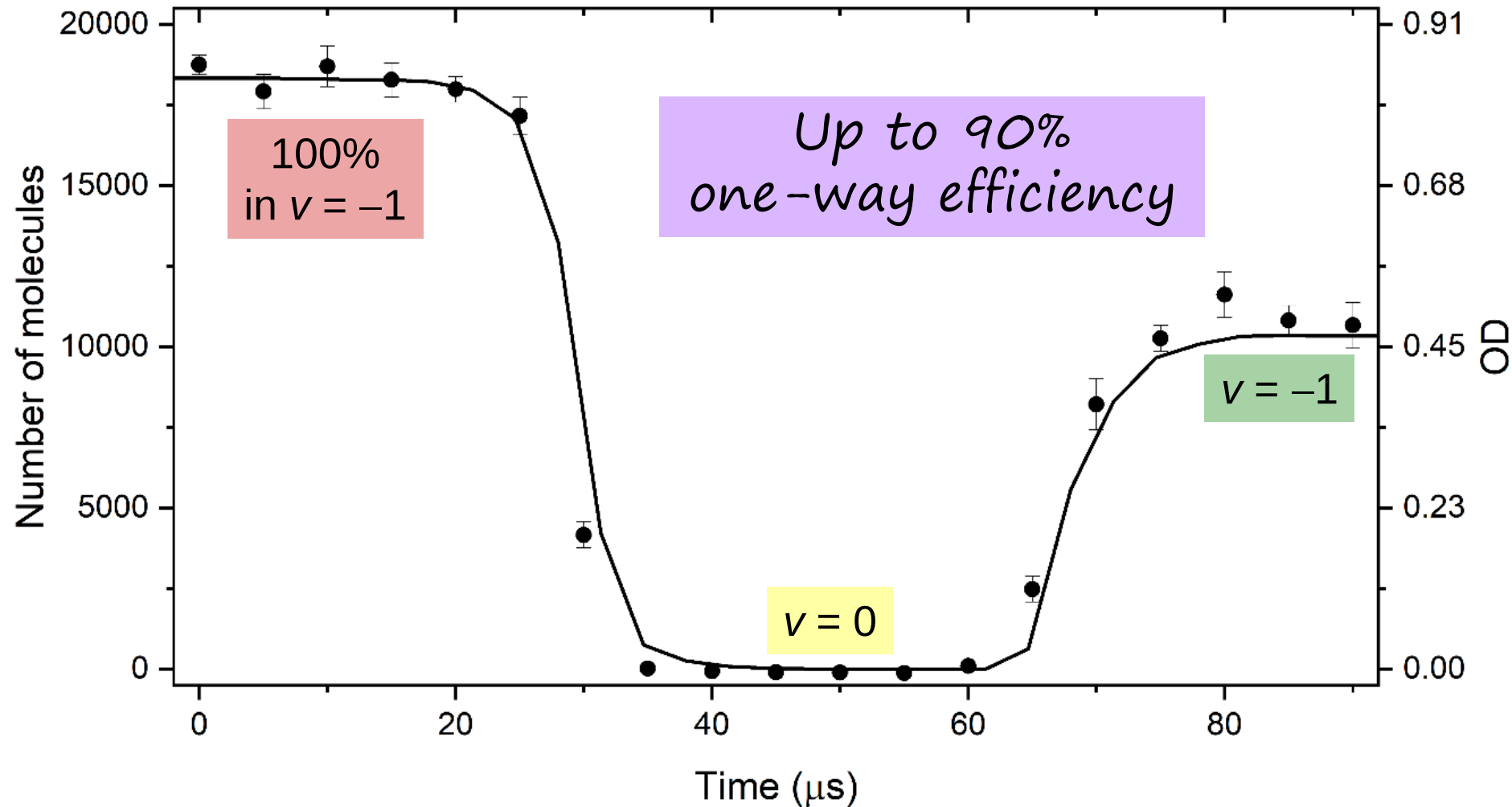
Stimulated Raman adiabatic passage (STIRAP)



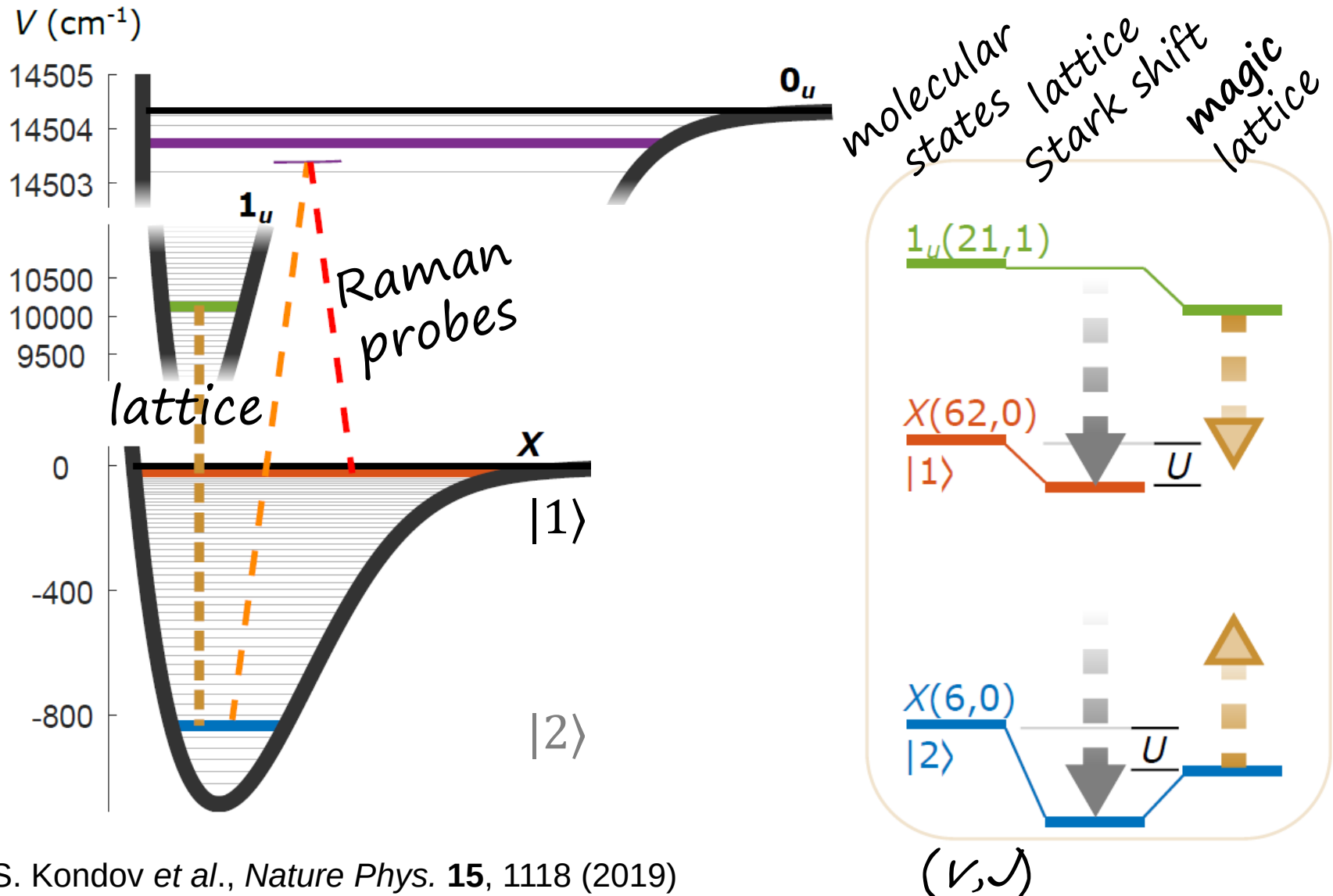
EIT spectrum
across full
potential

Creation of Sr_2 in absolute ground state

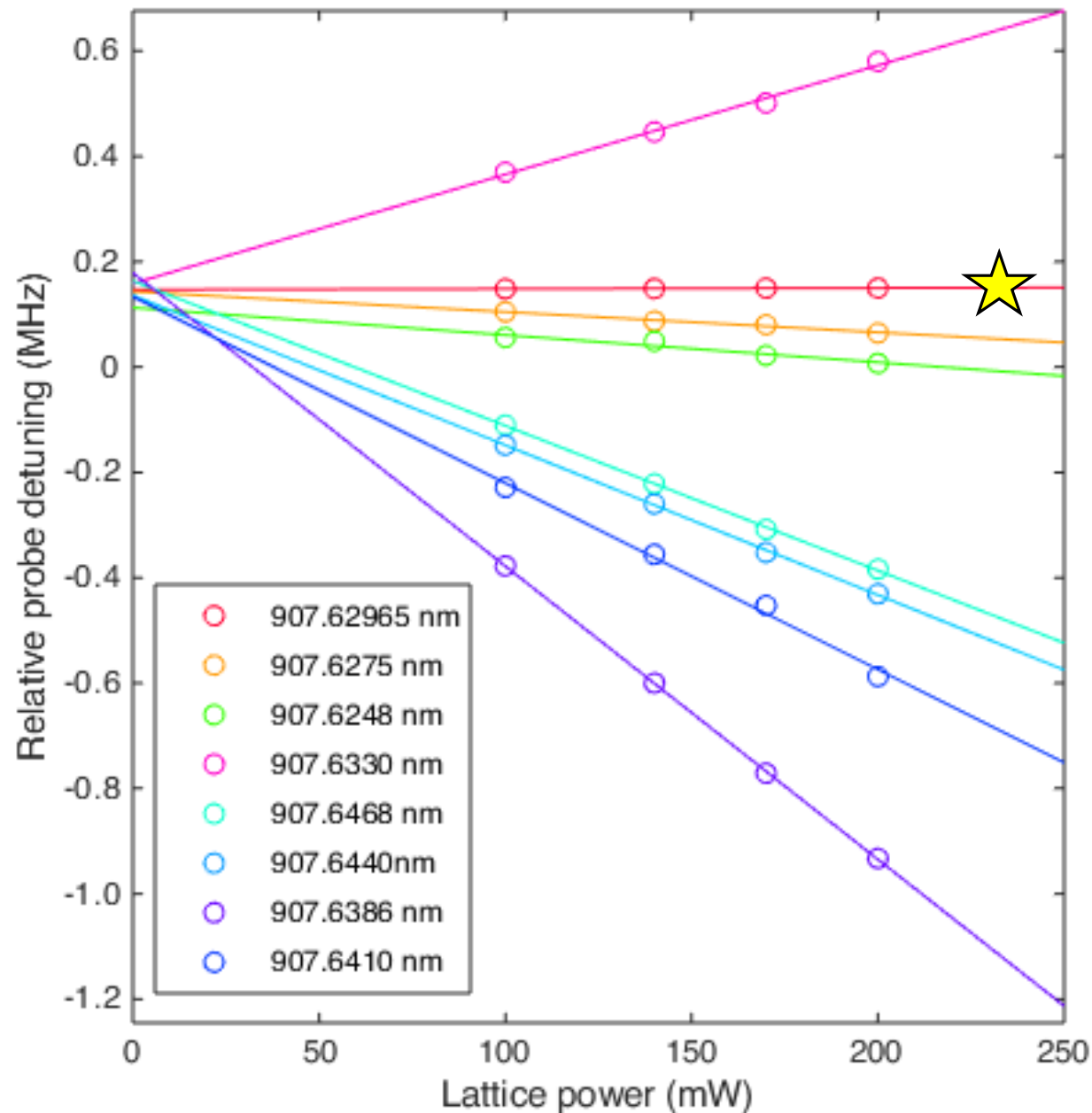
Stimulated Raman adiabatic passage (STIRAP)



Molecular lattice clock

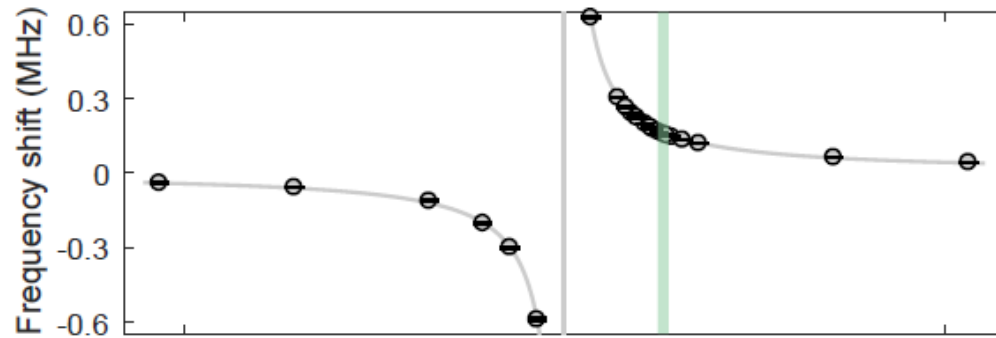


Magic-wavelength lattice

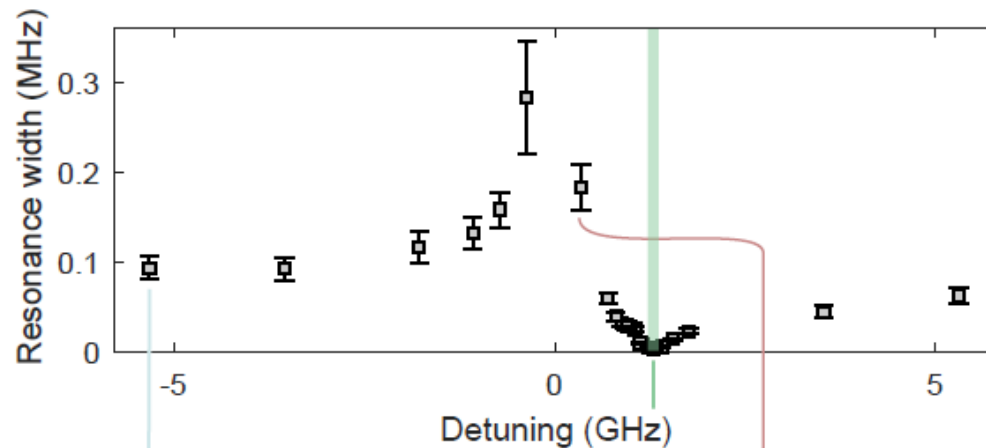


Molecular lattice clock

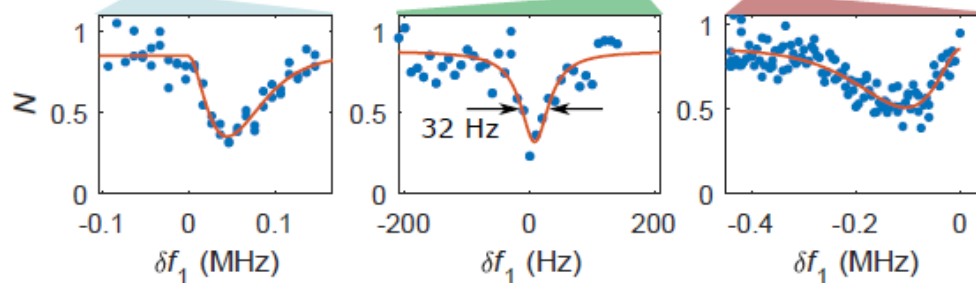
Coherence in magic lattice



*Energy of
 $|2\rangle$*

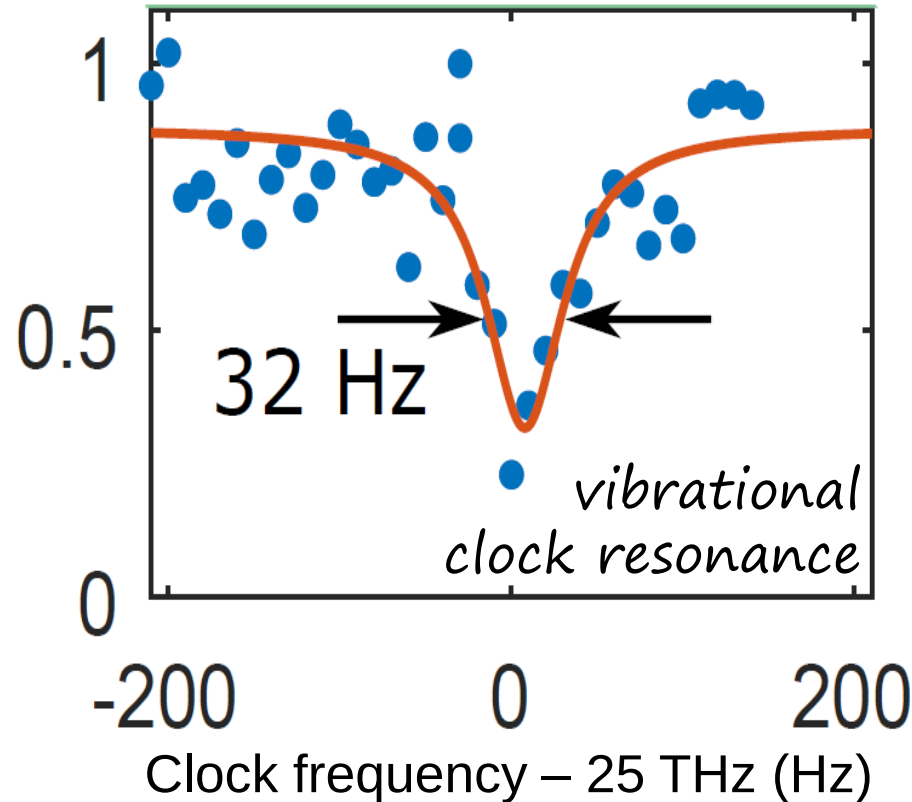


*Clock
resonance
linewidth*



Molecular lattice clock

Coherence in magic lattice : $\times 3,000$!



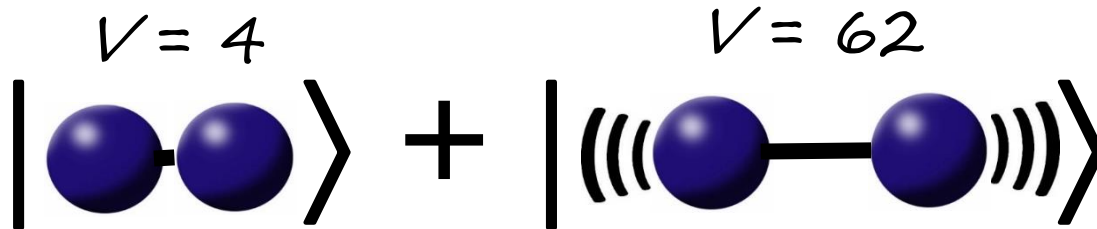
$$Q = 8 \times 10^{11}$$

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

Molecular lattice clock

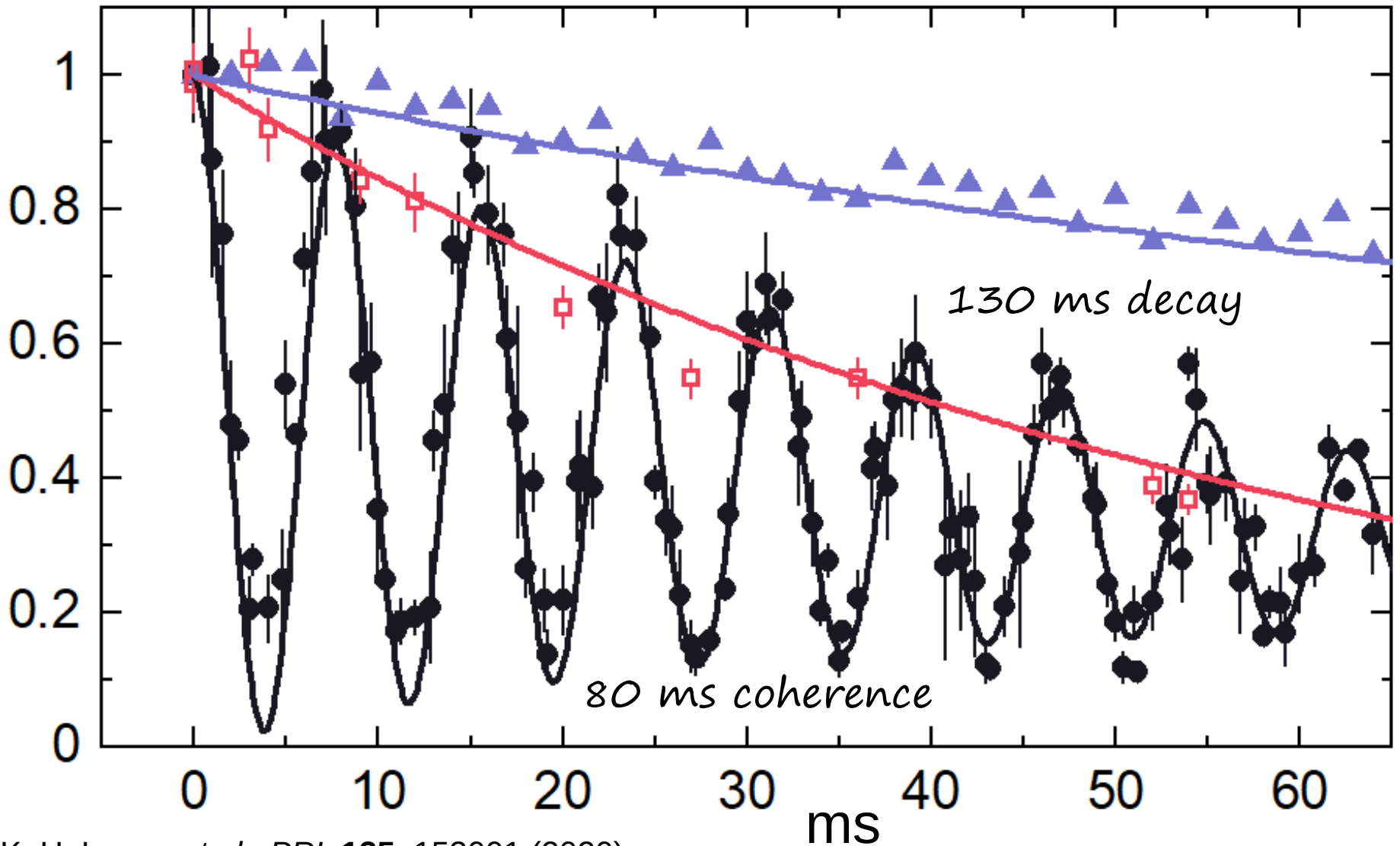
Coherence in magic lattice

Quantum Rabi oscillations



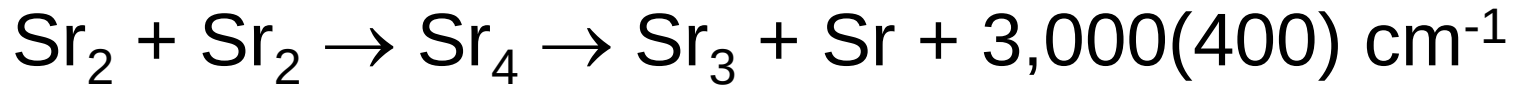
Molecular lattice clock

Coherence in magic lattice

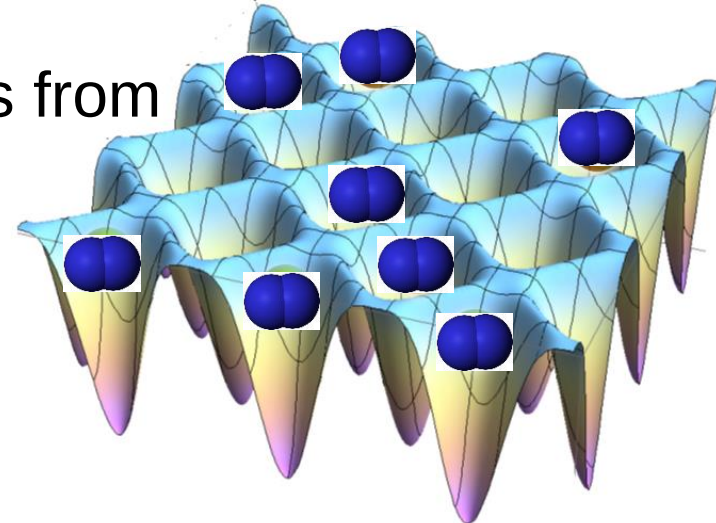
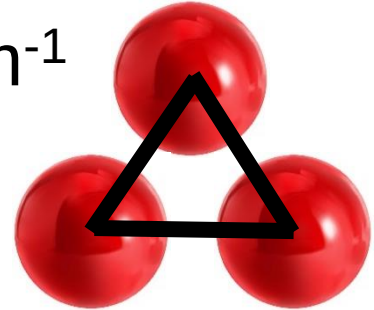


Two-body loss of Sr_2 molecules

Ultracold reactive collisions



- “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



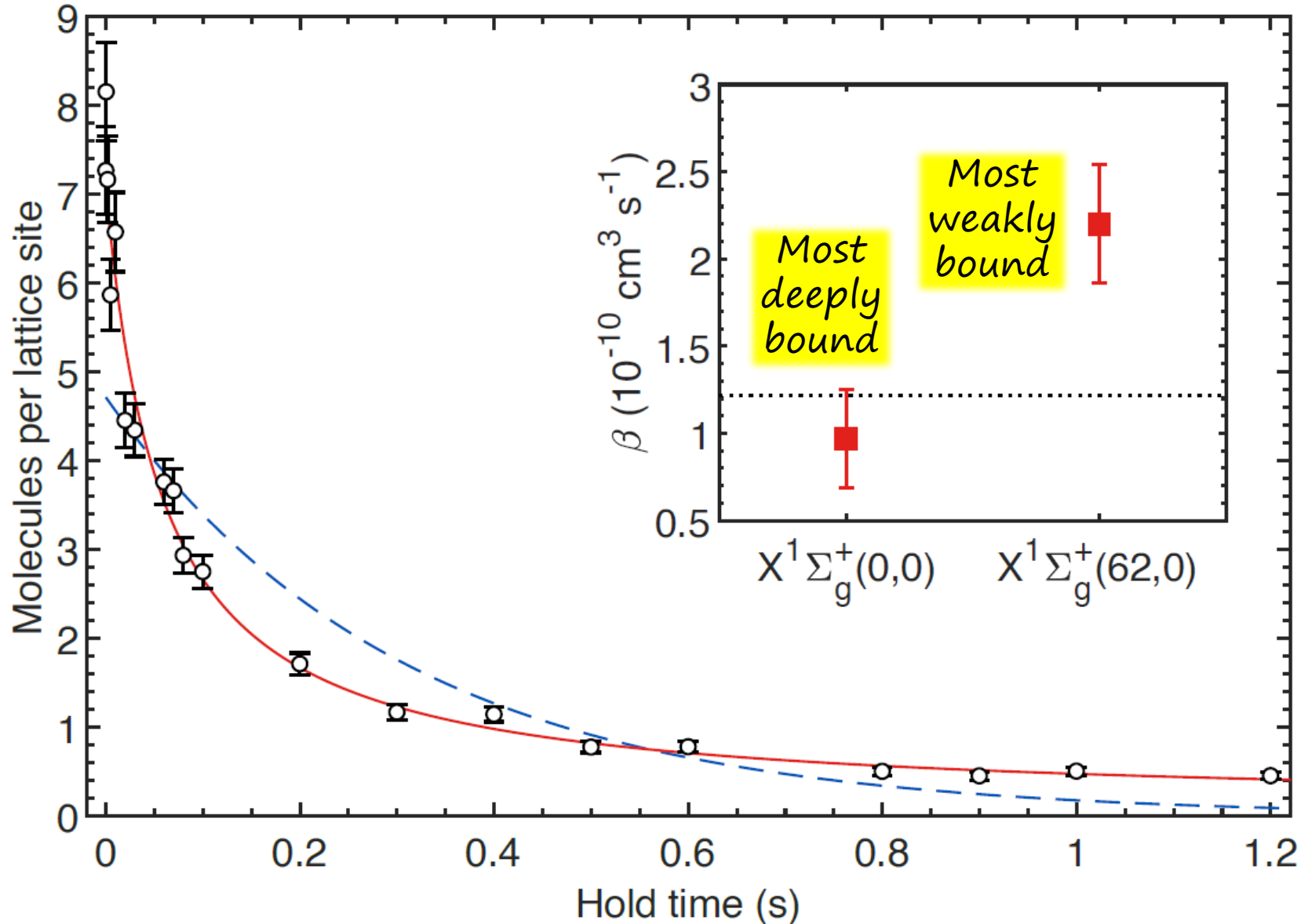
Z. Idziaszek and P. S. Julienne, *PRL* **104**, 113202 (2010)

M. Tomza *et al.*, *PRA* **88**, 050701(R) (2013)

P. S. Żuchowski and J. M. Hutson, *PRA* **81**, 060703(R) (2010)

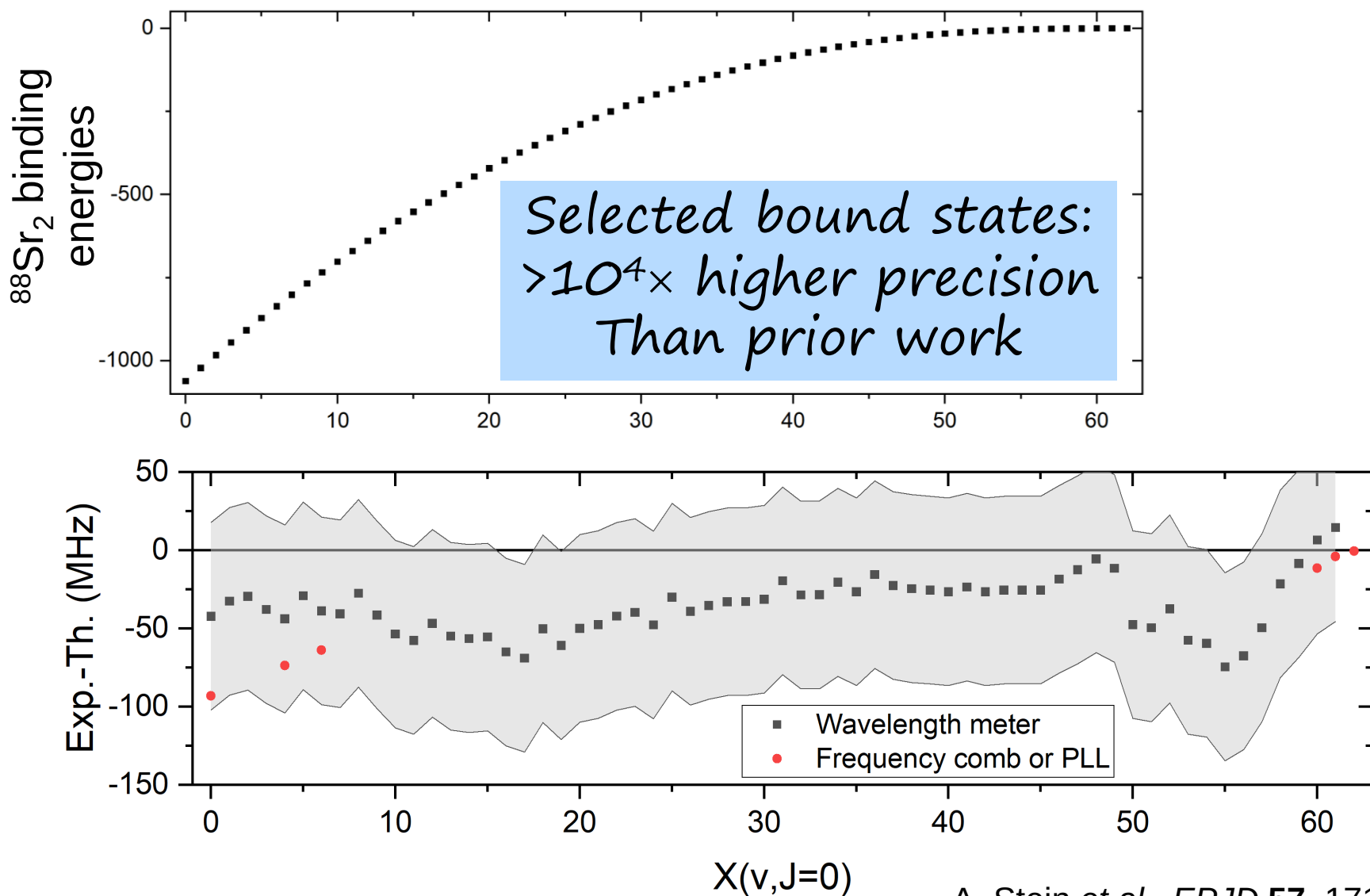
Ultracold Sr_2 reactive collisions

Molecule loss rates are independent of vibrational state



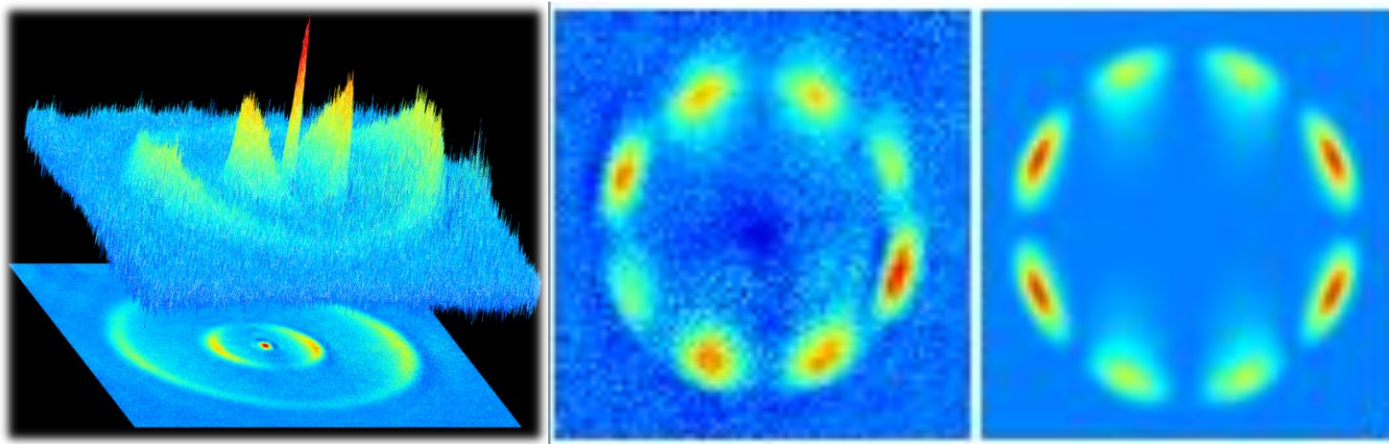
High-precision vibrational spectrum

Autler-Townes spectroscopy of van der Waals force



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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