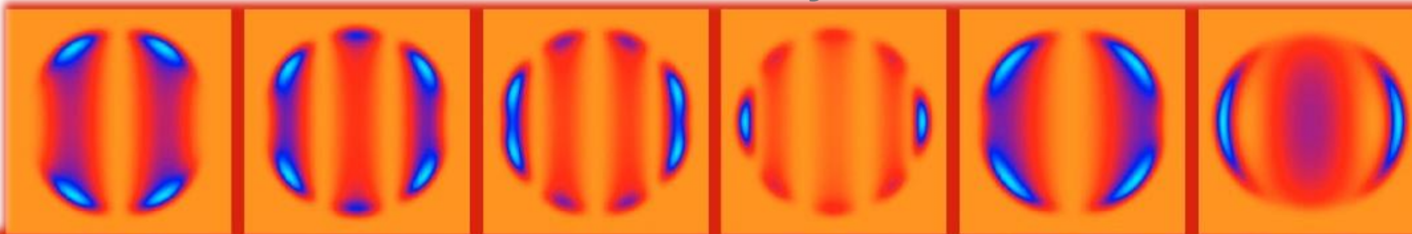
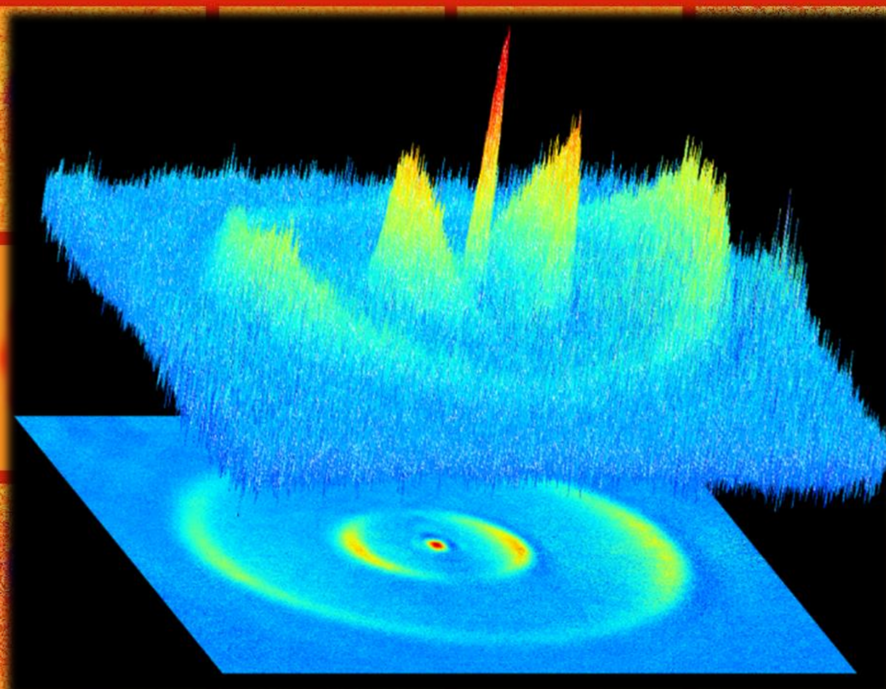
Physics and Chemistry with Diatomic Molecules Near Absolute Zero

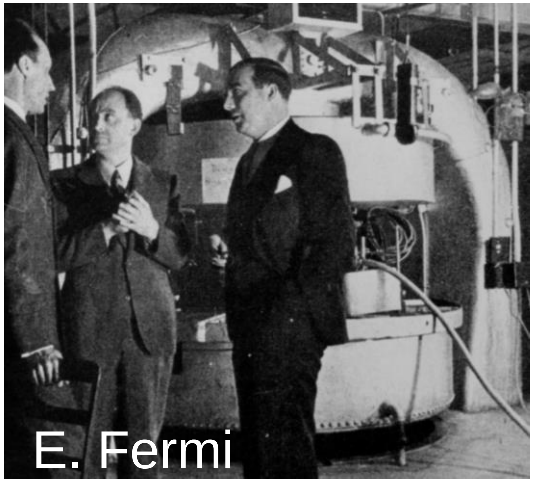
Tanya Zelevinsky & ZLab

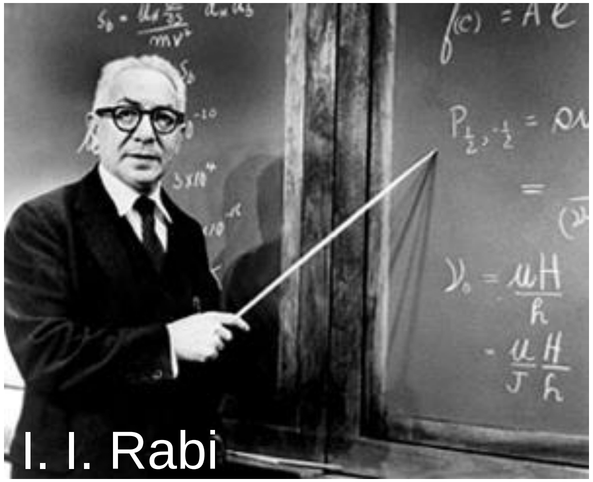
Columbia University, New York



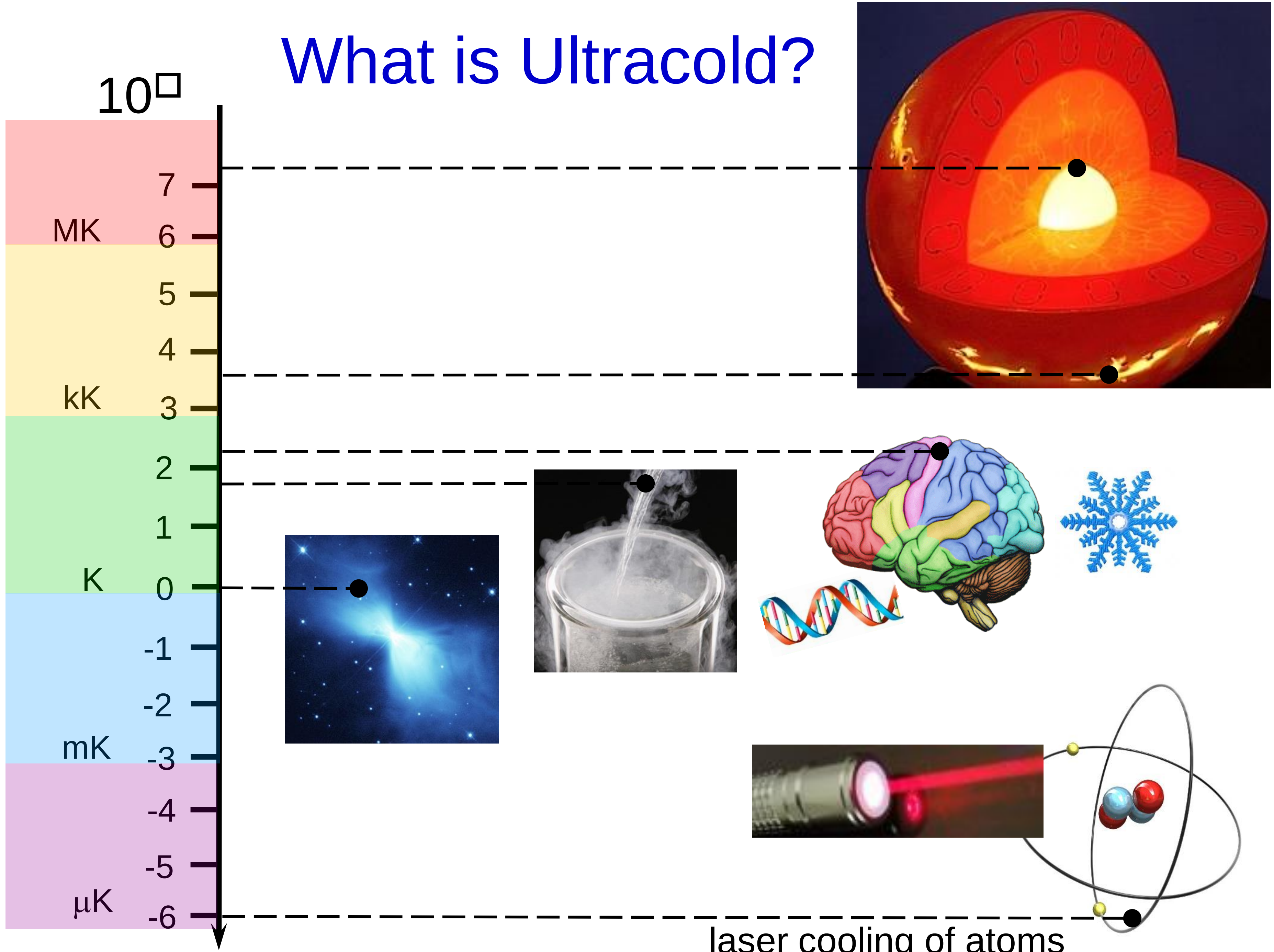


Pupin Labs @ Columbia



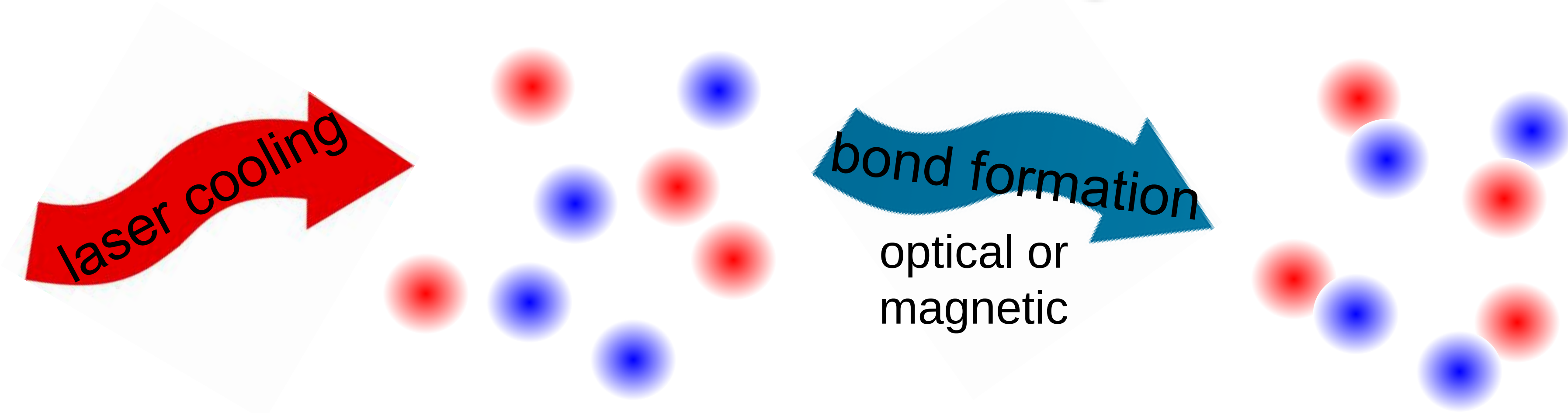


What is Ultracold?



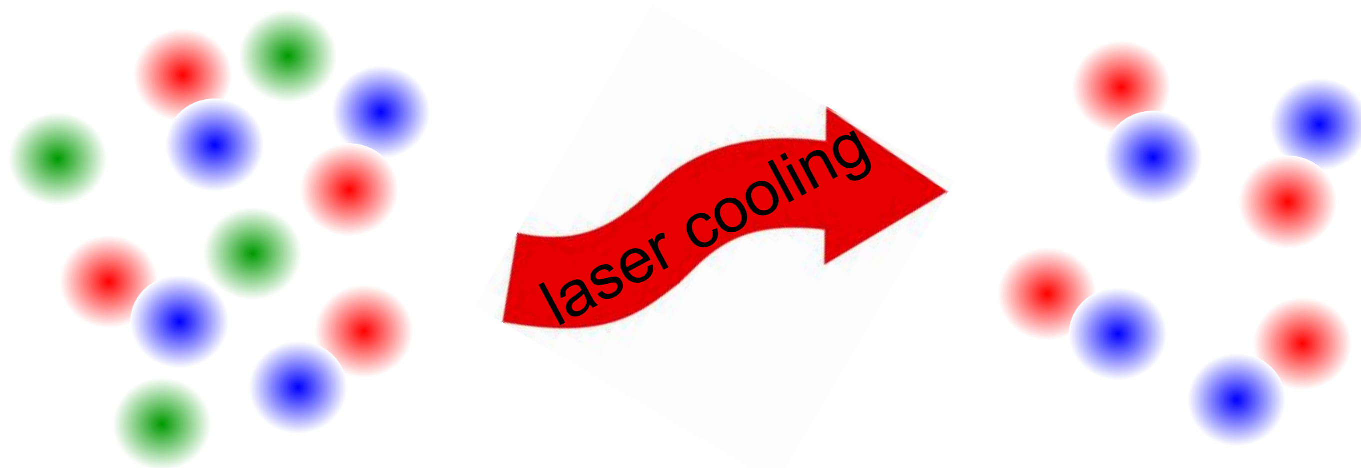
Beyond Cold Atoms

Indirect molecule cooling



Direct molecule cooling

buffer gas
(sympathetic)
cooling



Why Cold Molecules?

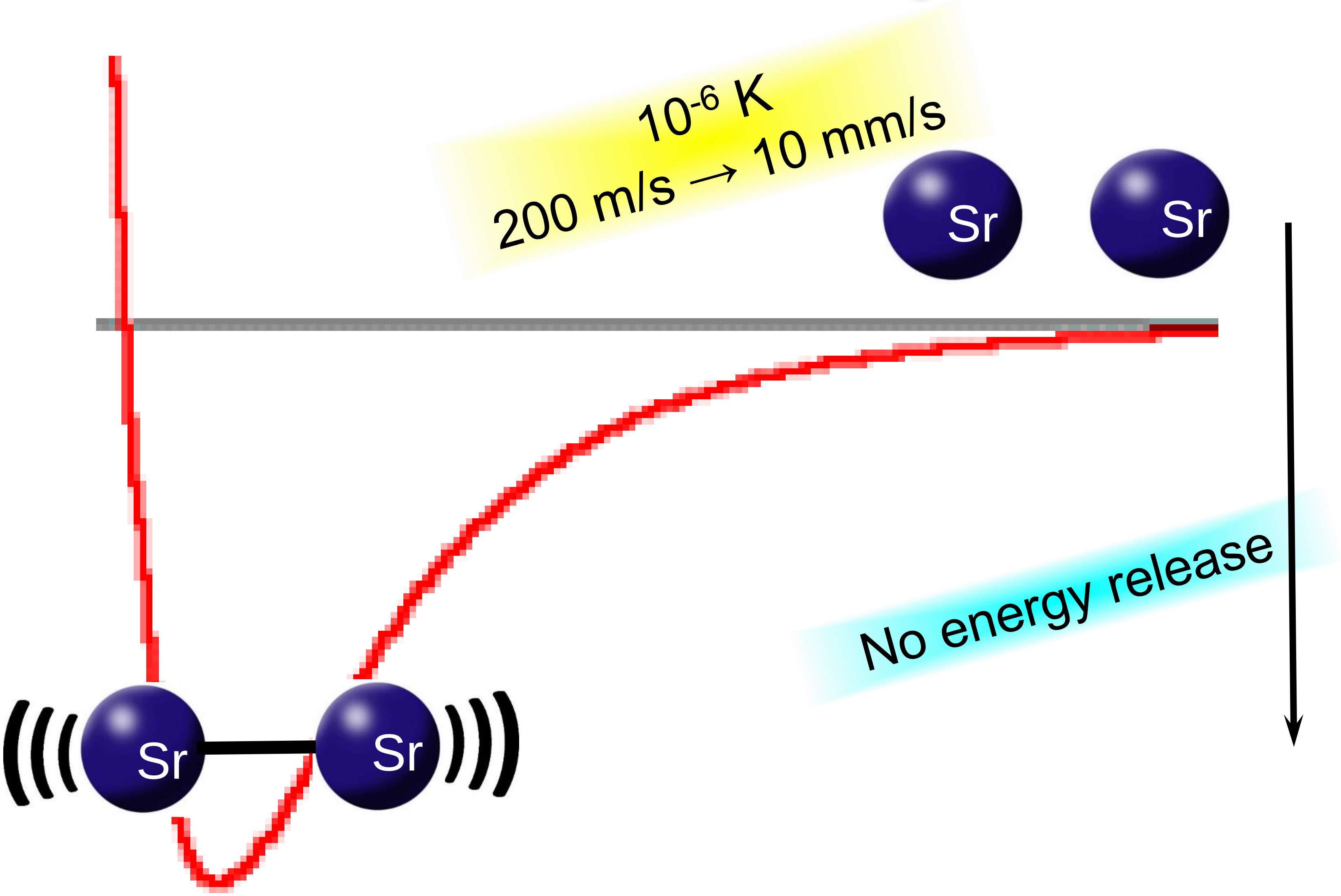
atomic H spectrum

molecular H_2 spectrum

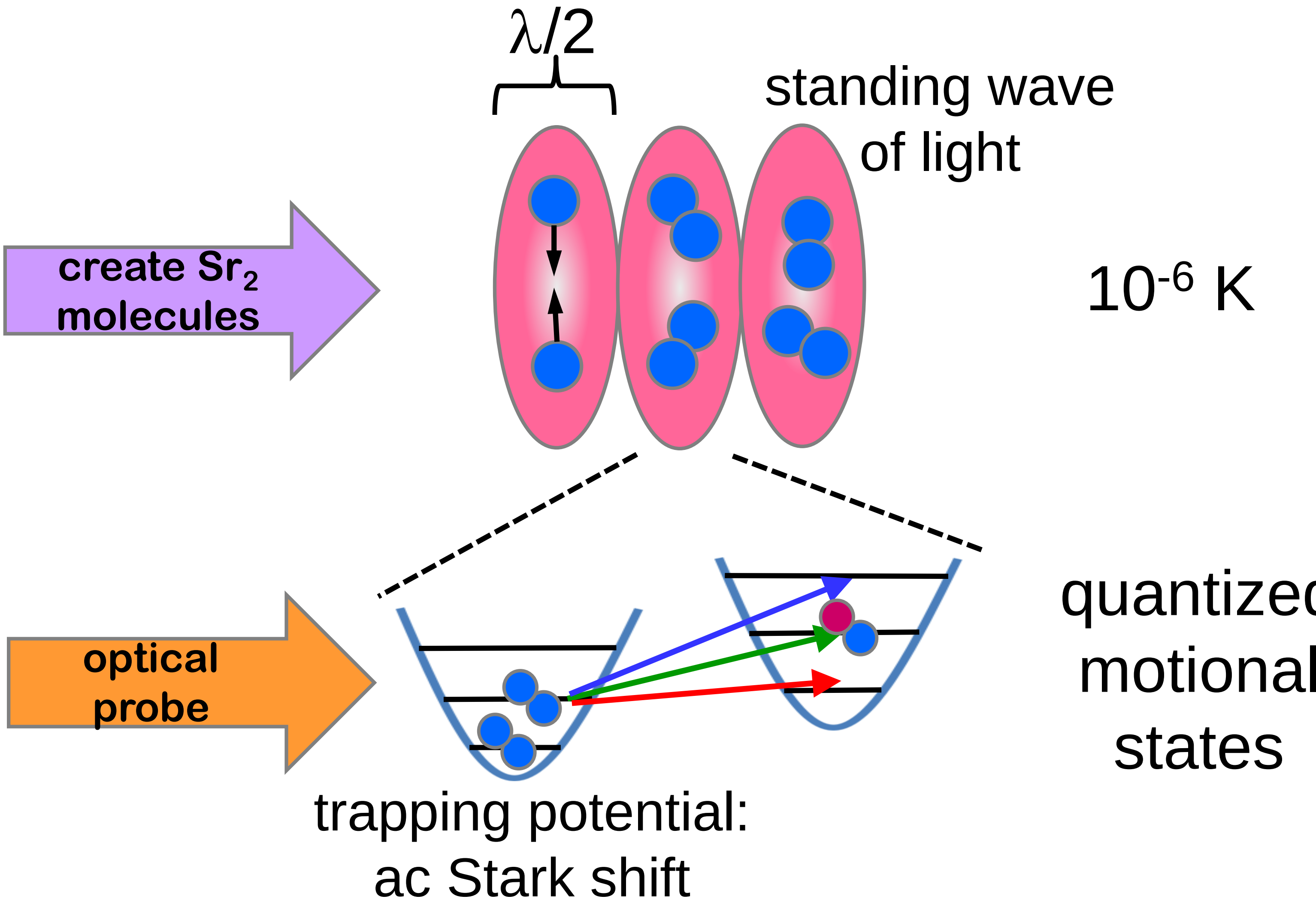
New science
Quantum-state-controlled ultracold chemistry
Dipolar quantum gases & many-body physics
Enhancement of EDMs and parity violation
New physics and “5^{th} force”
Fundamental constants & variations

Ultracold Diatomic Molecules

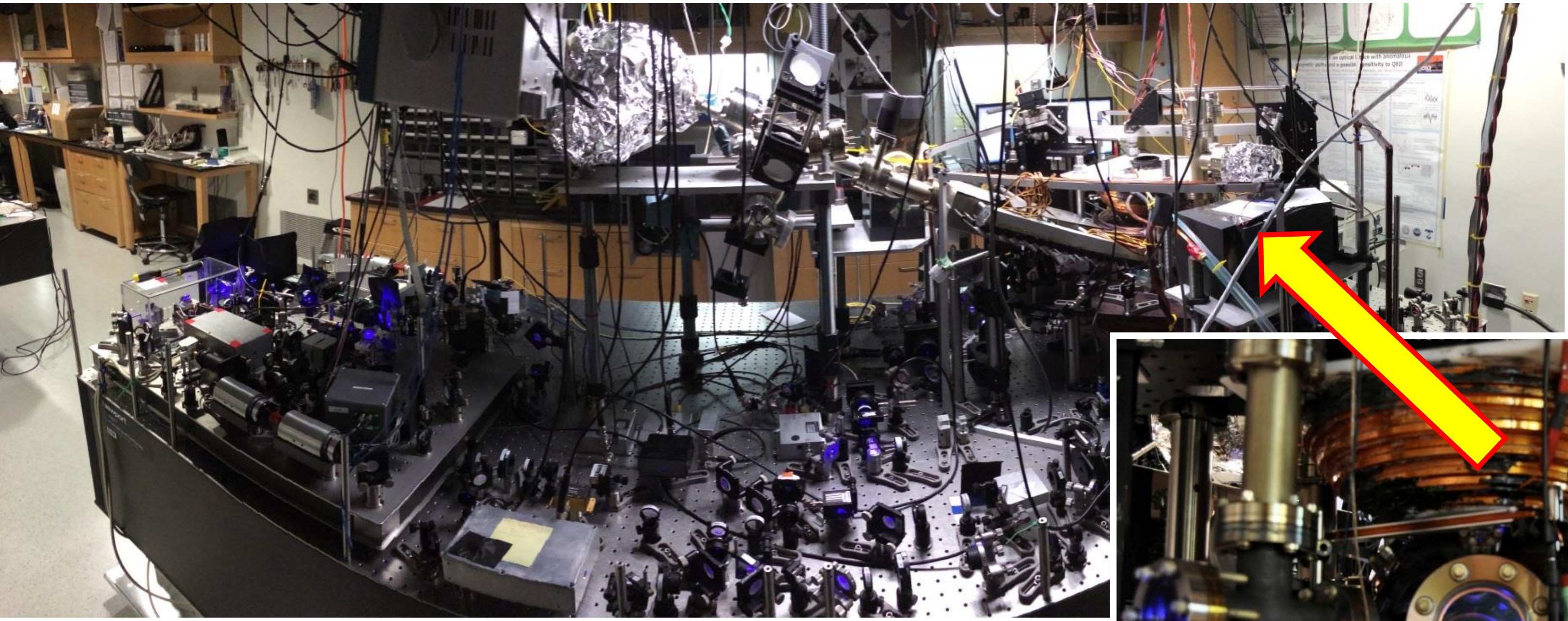
Indirect molecule cooling

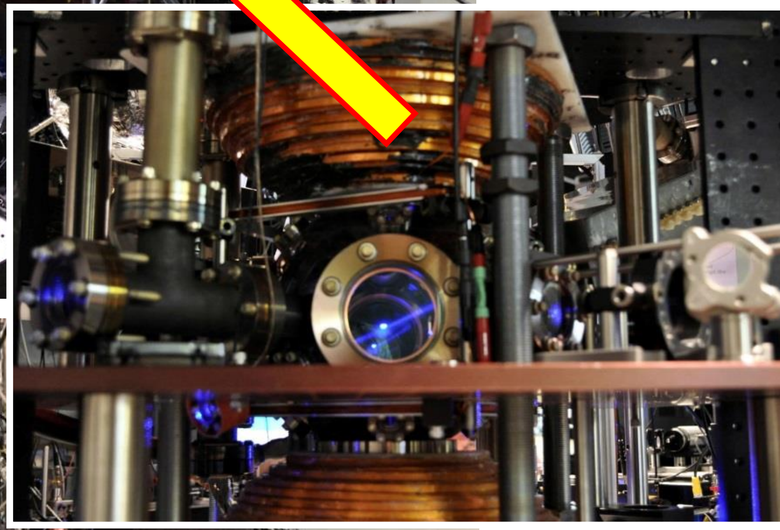


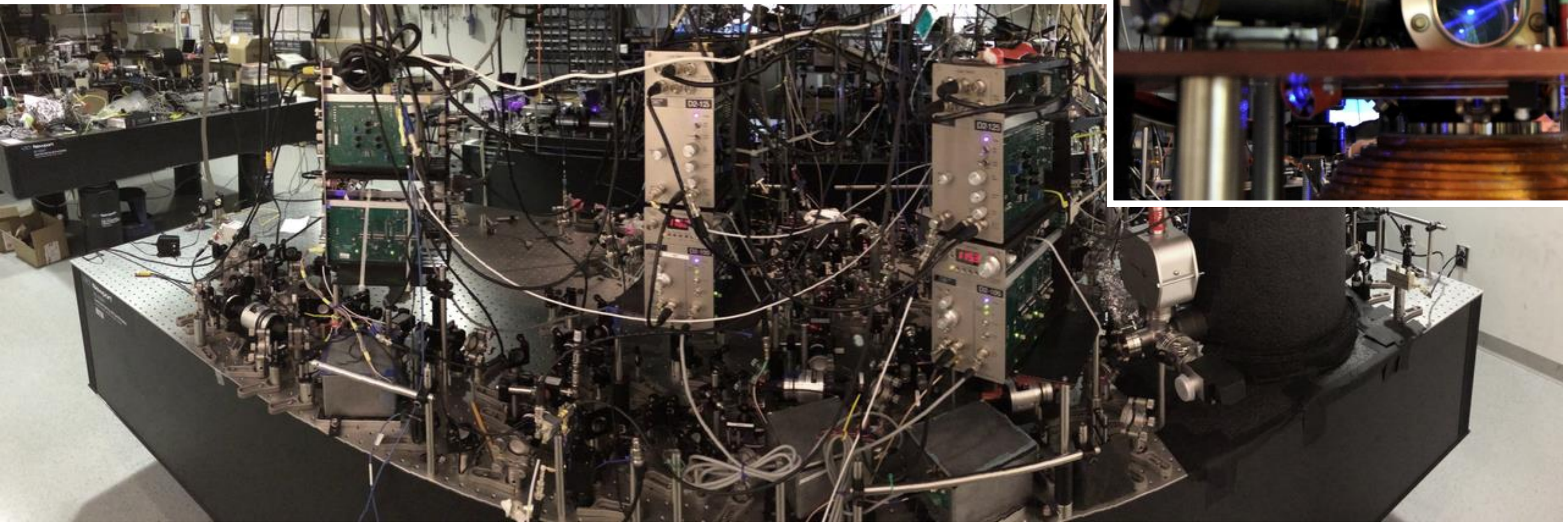
Tight Trapping: Optical Lattice Clocks



Molecular Lattice Clock







^{88}Sr

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

Science with Cold and Ultracold Molecules

- Ultracold chemistry
- Molecular clocks
- Table-top particle physics

Ultracold Chemistry

Quantum-state selected reactants and products

Bimolecular collisions

$$AB + AB \longrightarrow A_2 + B_2$$

Photoassociation

$$A + A + \gamma \longrightarrow A_2^*$$

Photodissociation

$$A_2 + \gamma \longrightarrow A + A^*$$

Ultracold Chemistry

Quantum-state selected reactants and products

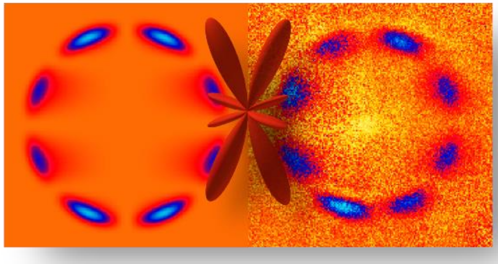
Complete quantum state control of “reverse collision”

Photodissociation

$$A_2 + \gamma \longrightarrow A + A^*$$

Ultracold Chemistry

Quantum-state selected reactants and products



Photodissociation

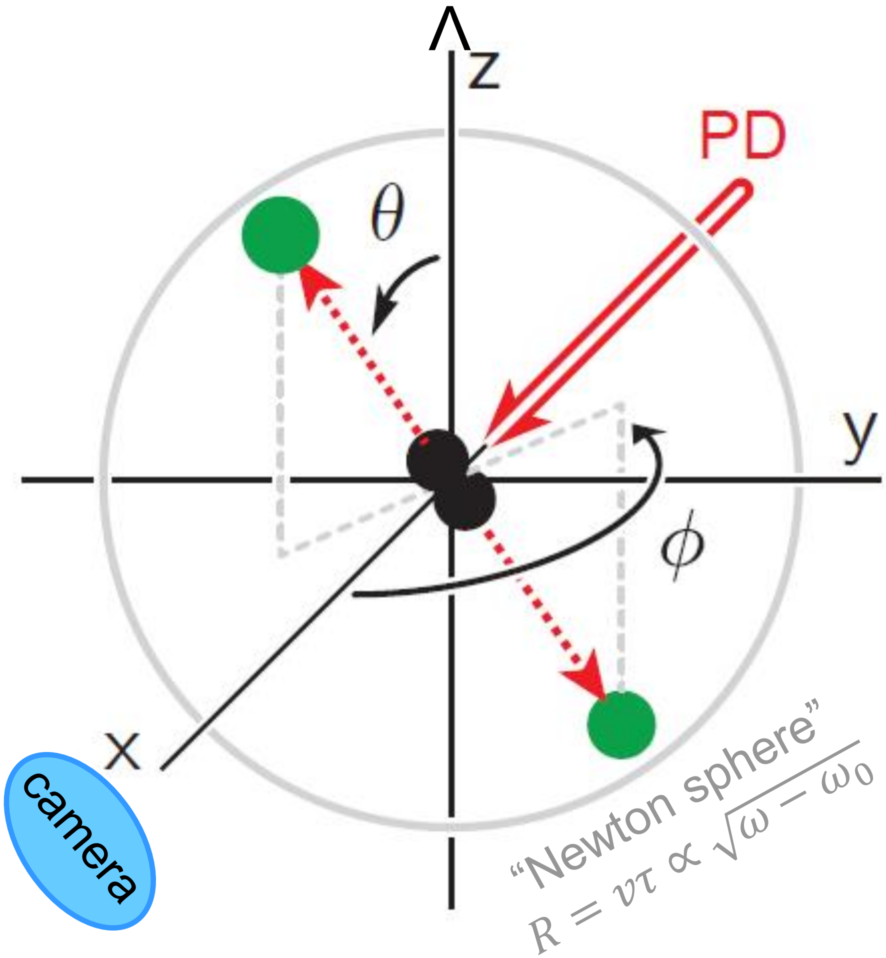
$$Sr_2 + \gamma \rightarrow Sr + Sr^*$$

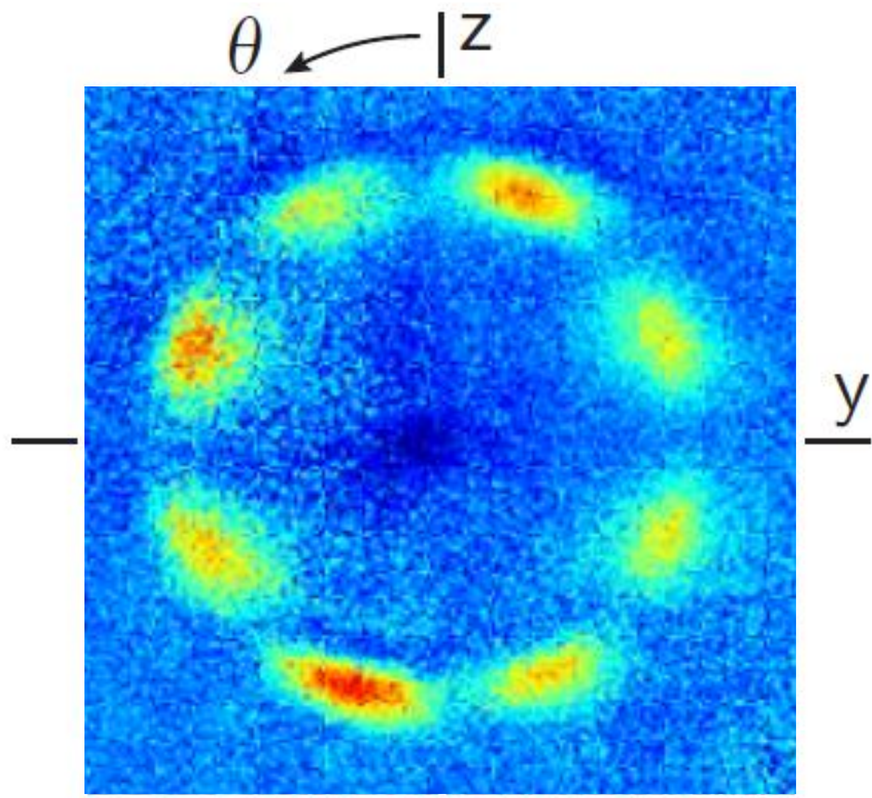
The "hydrogen atom" of ultracold chemistry

- Experiment → first-principles theory → comparison

Ultracold Photodissociation

Photofragment angular distribution

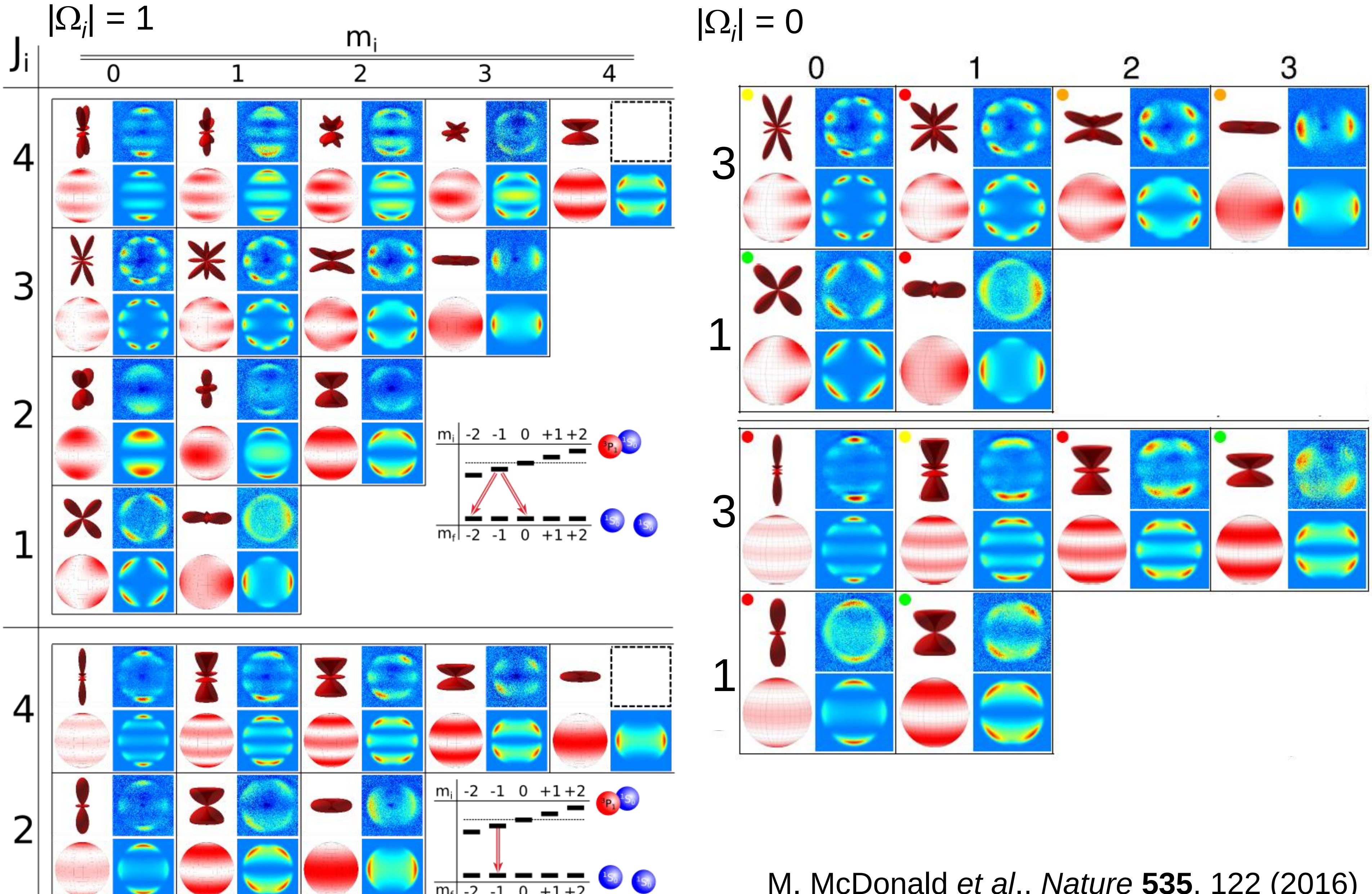




(J = 4; M = ±1)

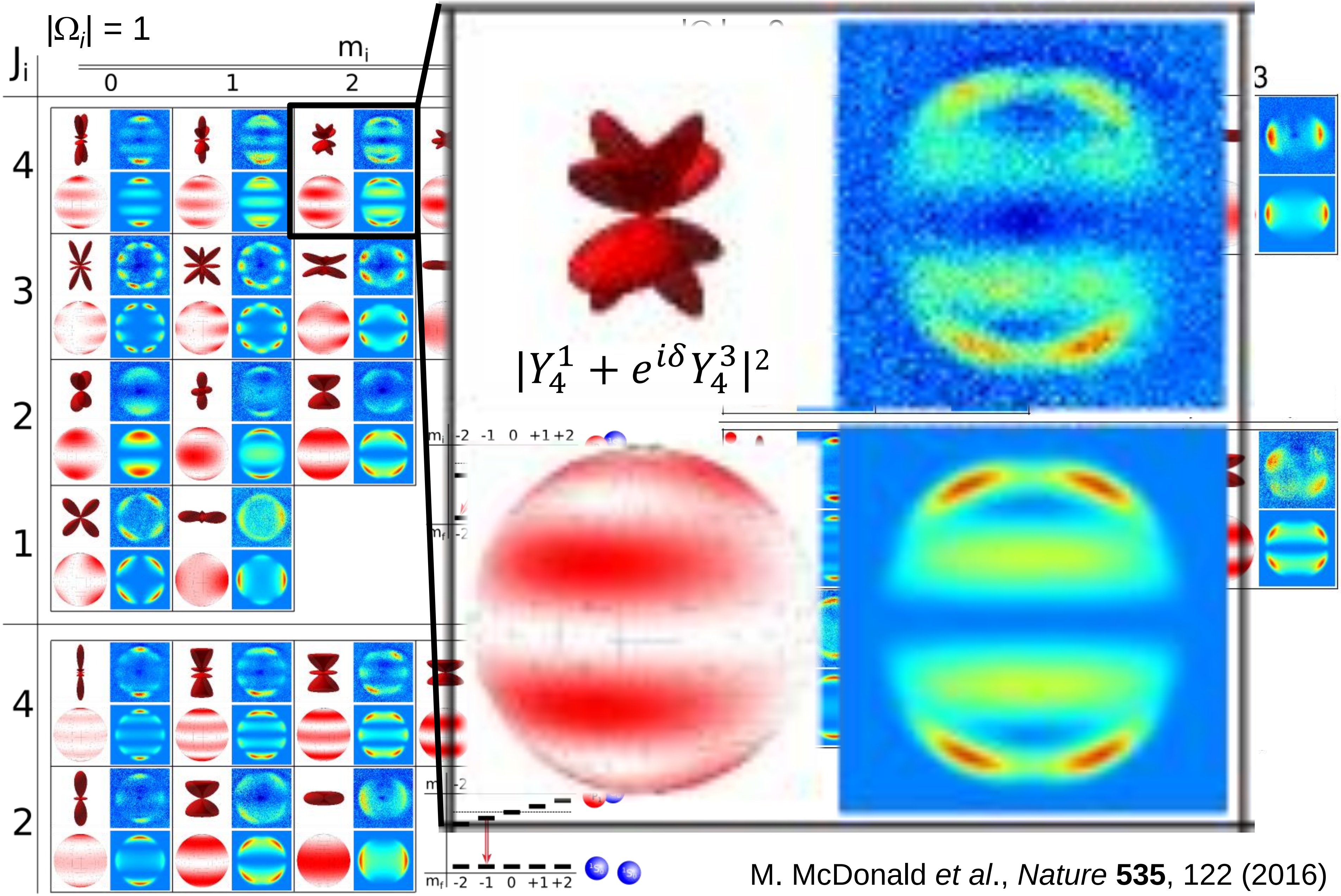
Matter-wave interference→ ϕ dependence!

Photofragment Angular Distributions



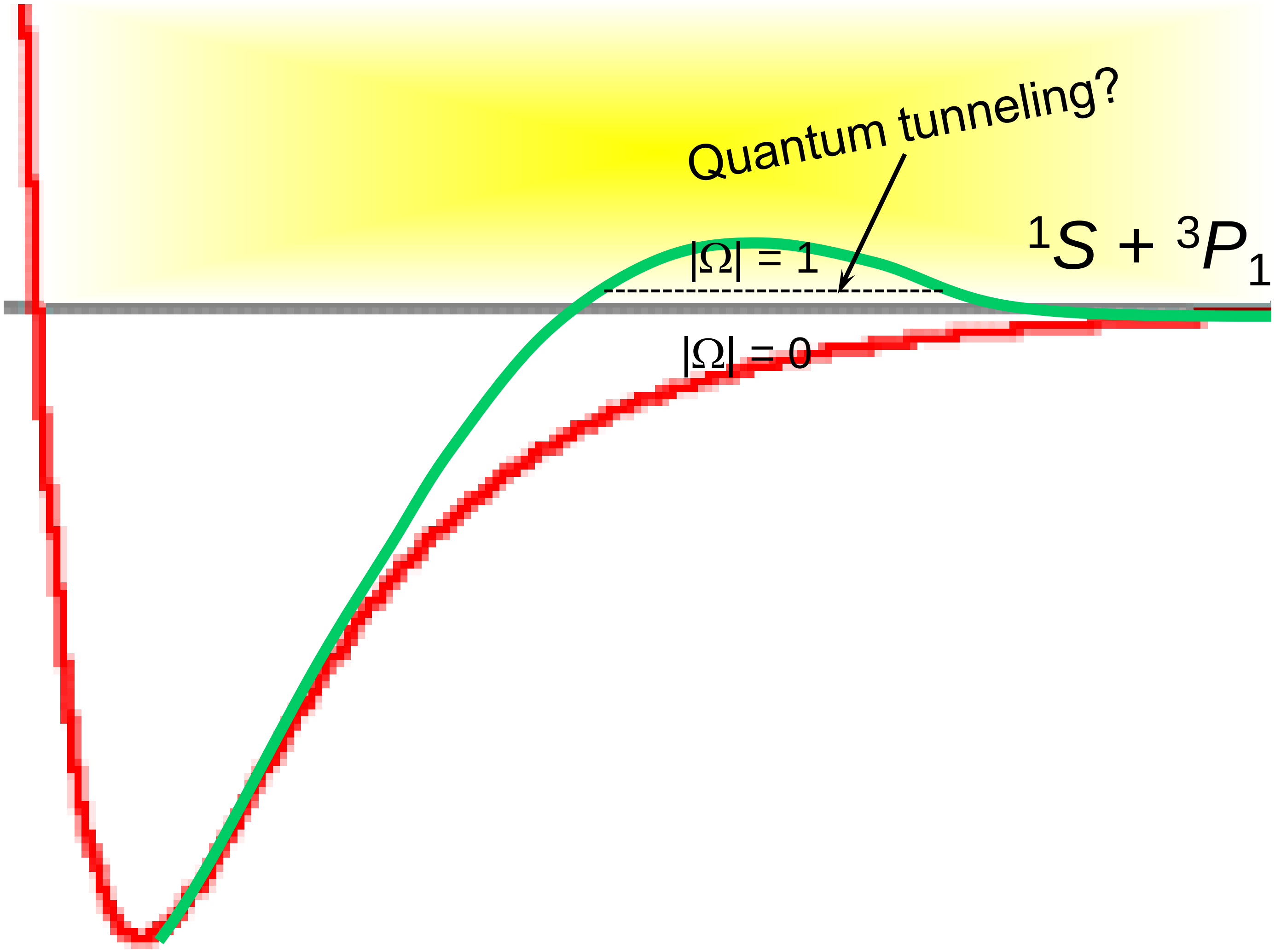
M. McDonald *et al.*, *Nature* **535**, 122 (2016)

Photofragment Angular Distributions



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

Probing Reaction Barriers



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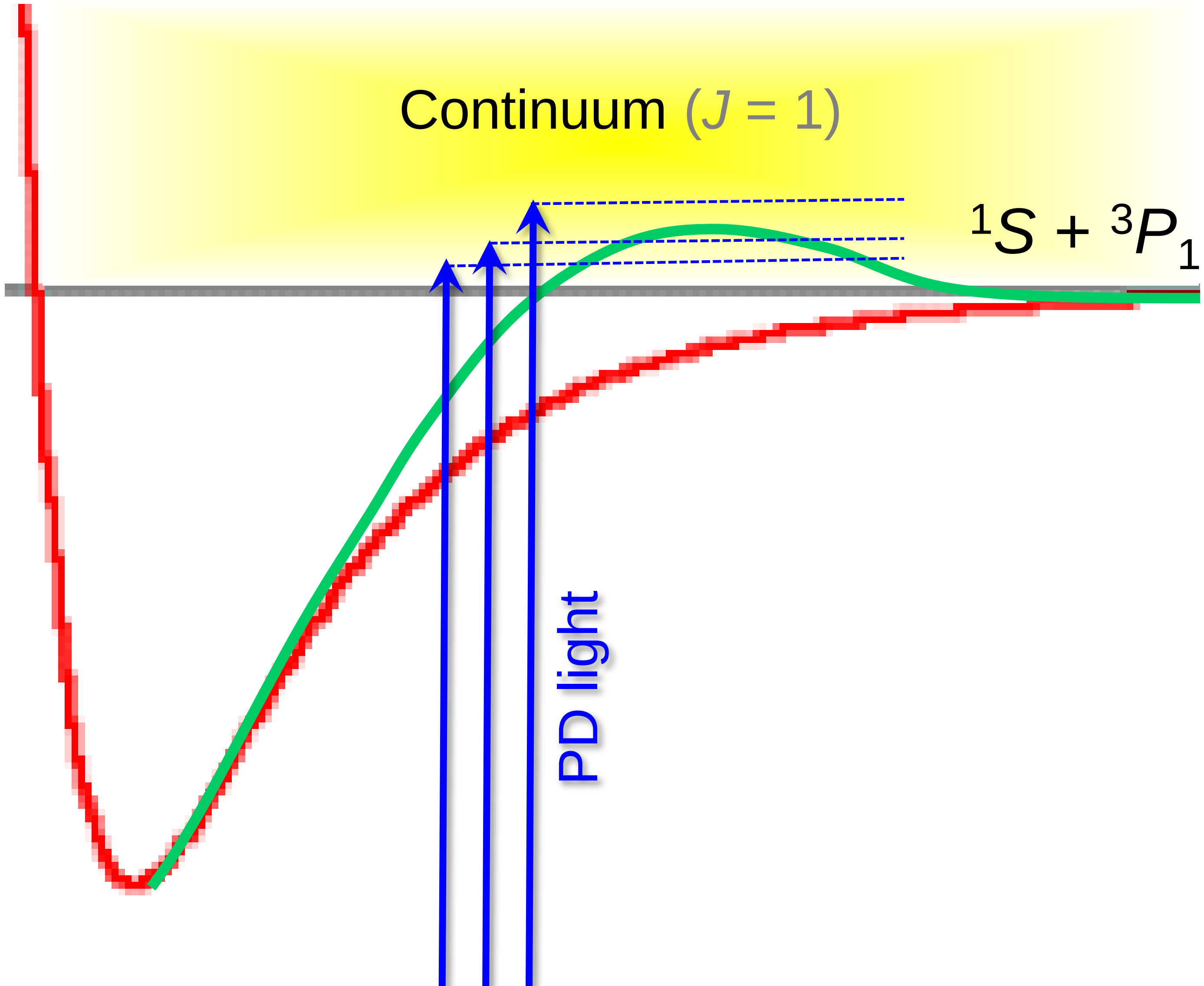
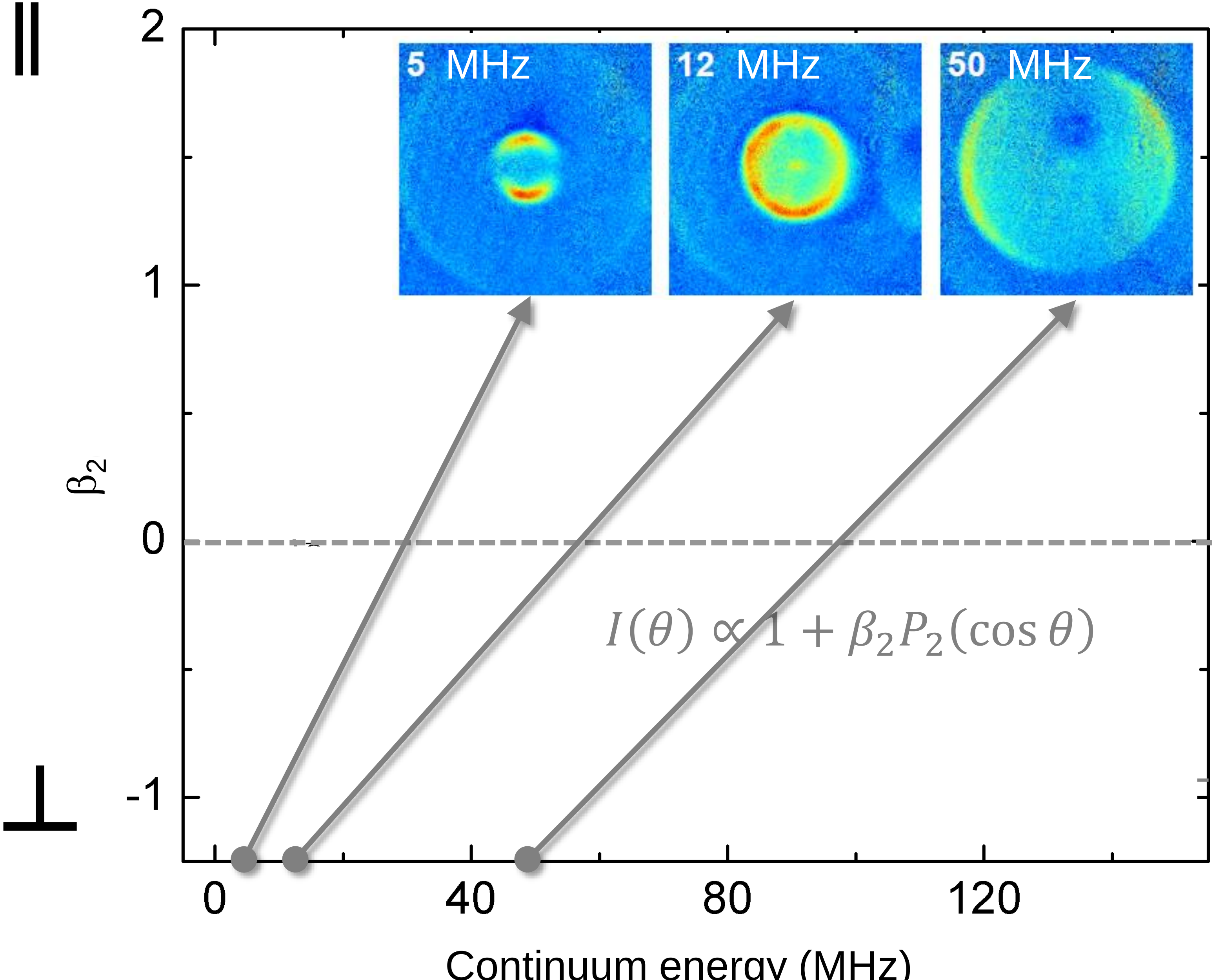


Probing Reaction Barriers



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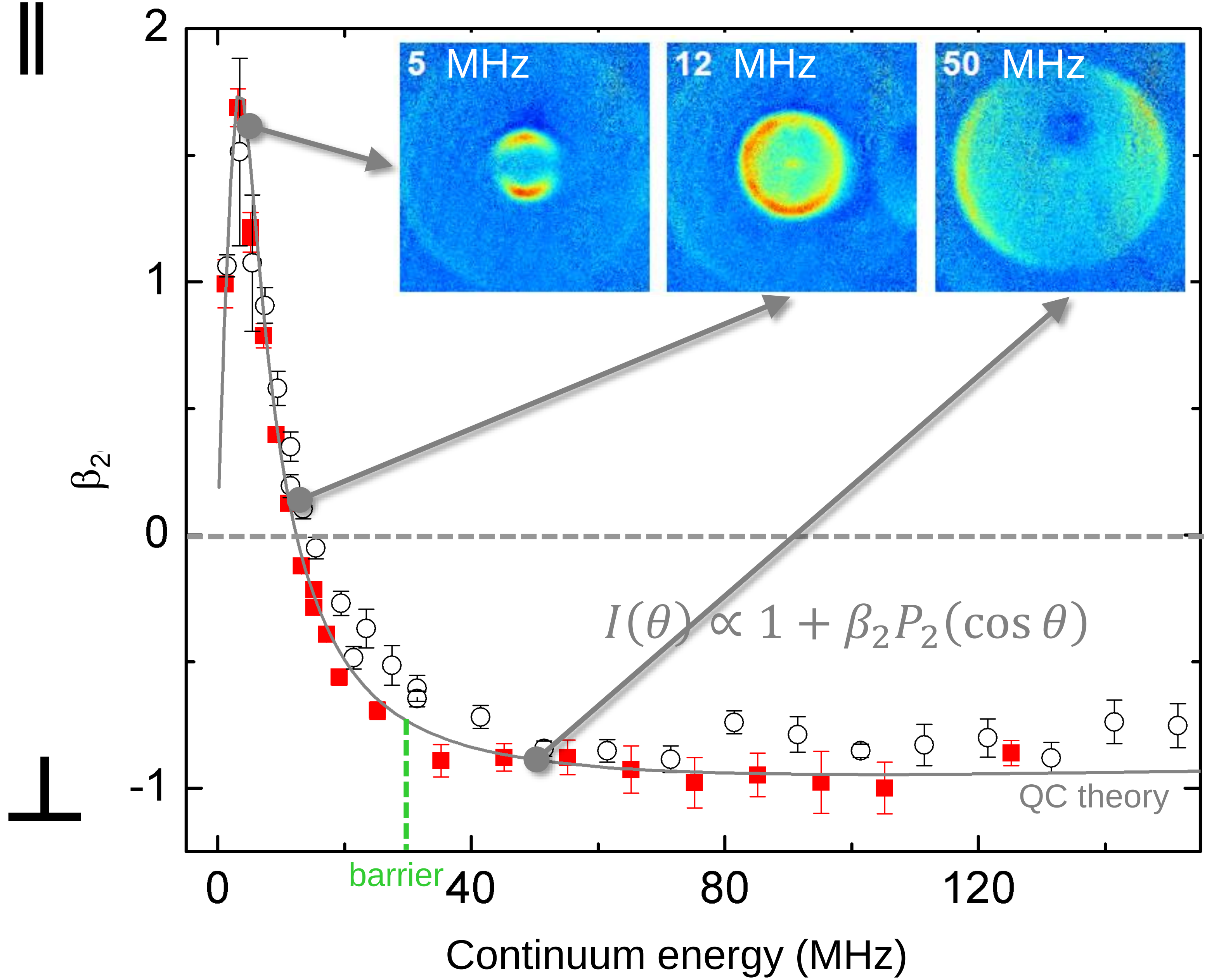
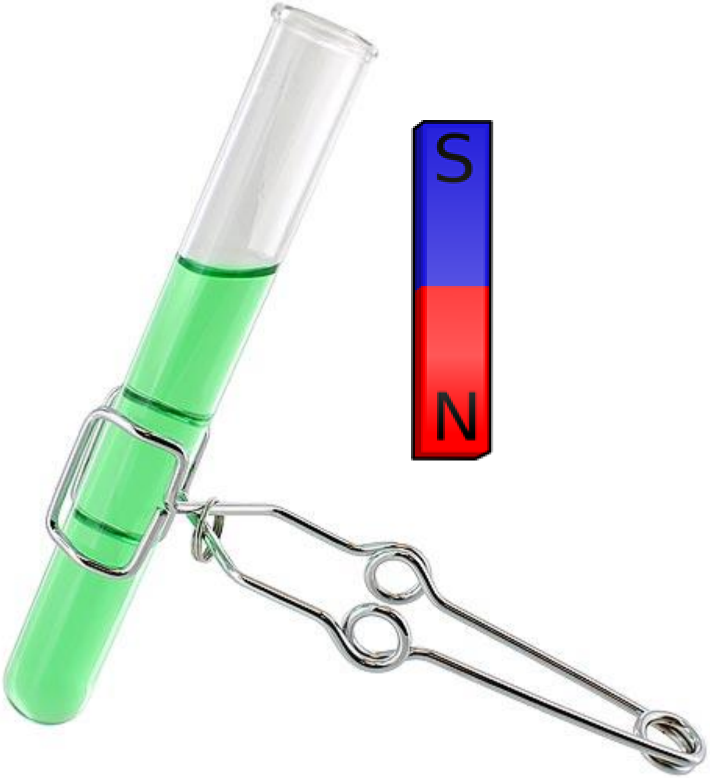
Probing Reaction Barriers



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

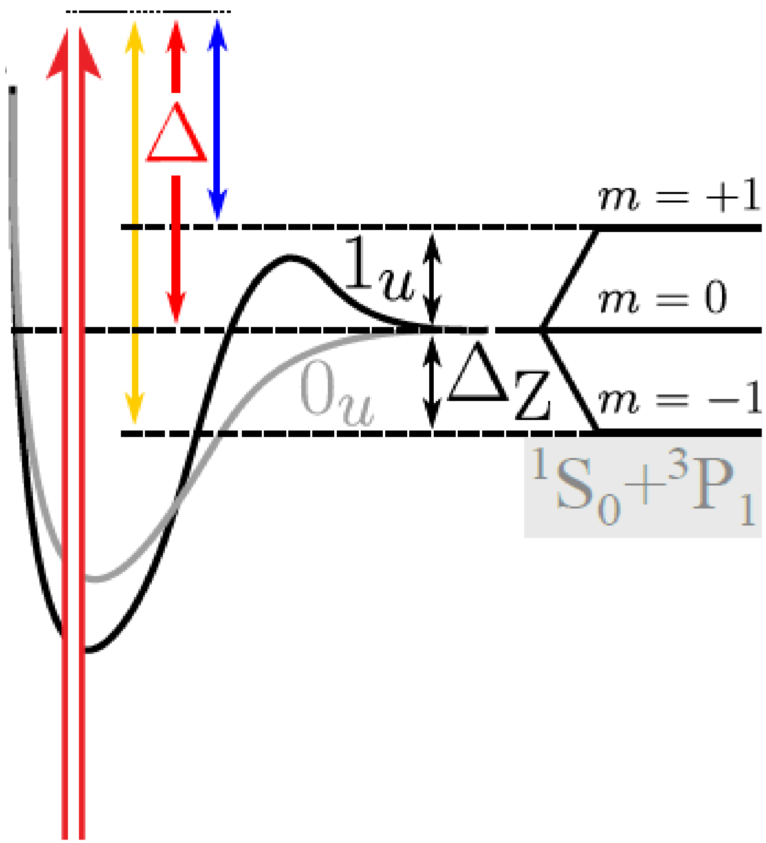
Field Control of Photodissociation



Comparable energies at ~ 1 mK:

- Kinetic
- Barrier
- Zeeman

Field Control of Photodissociation



Comparable energies at ~ 1 mK:

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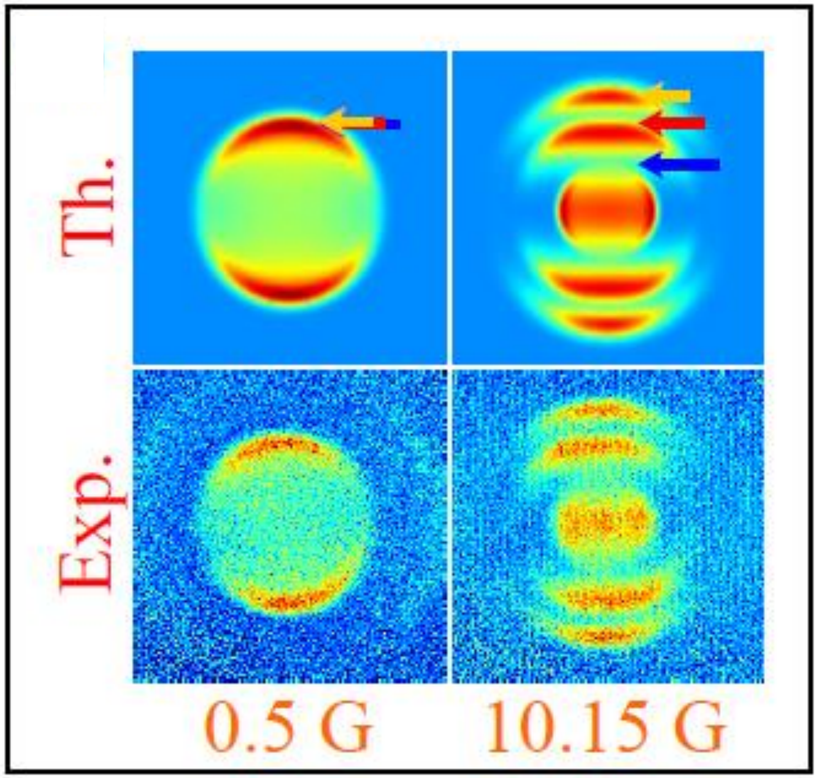
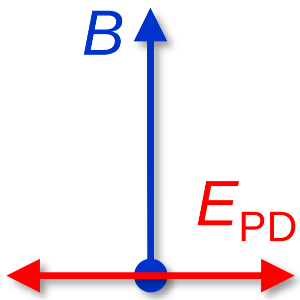


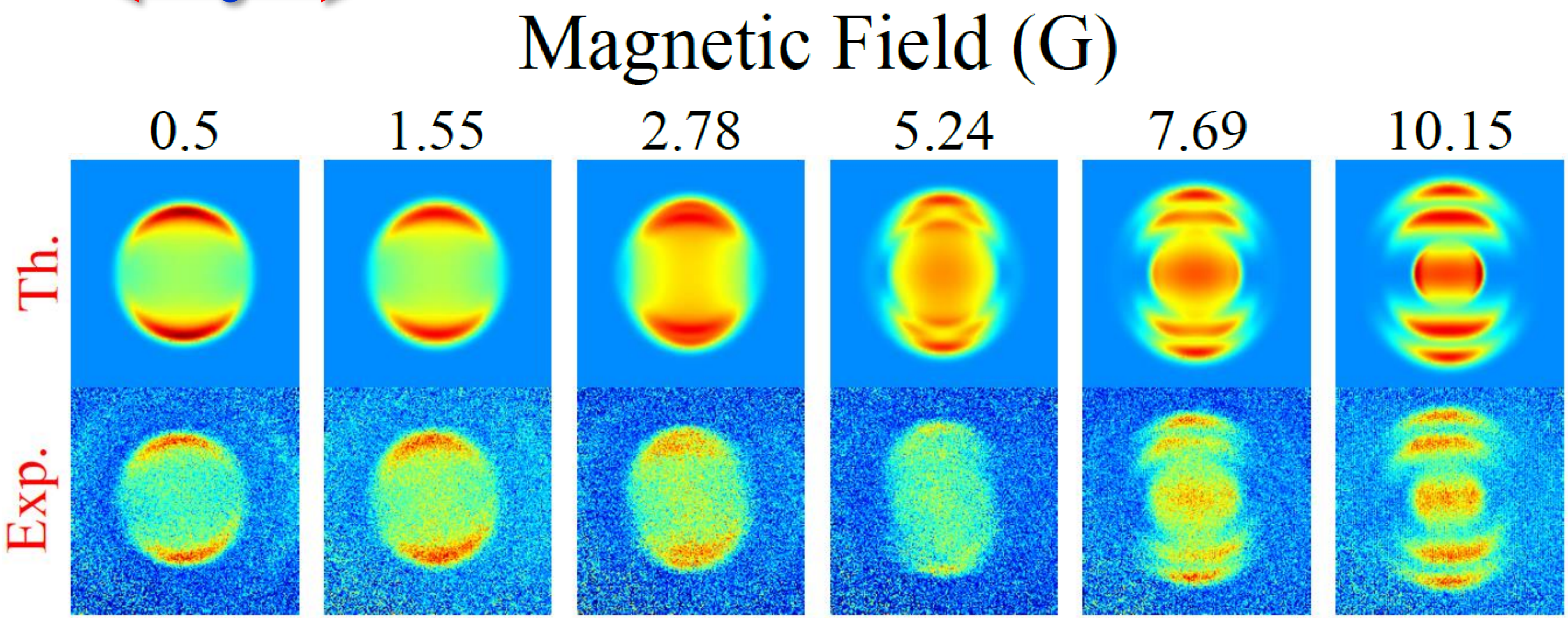
M. McDonald *et al*., PRL, accepted

Field Control of Photodissociation



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

Energy = 30 MHz = 1.5 mK



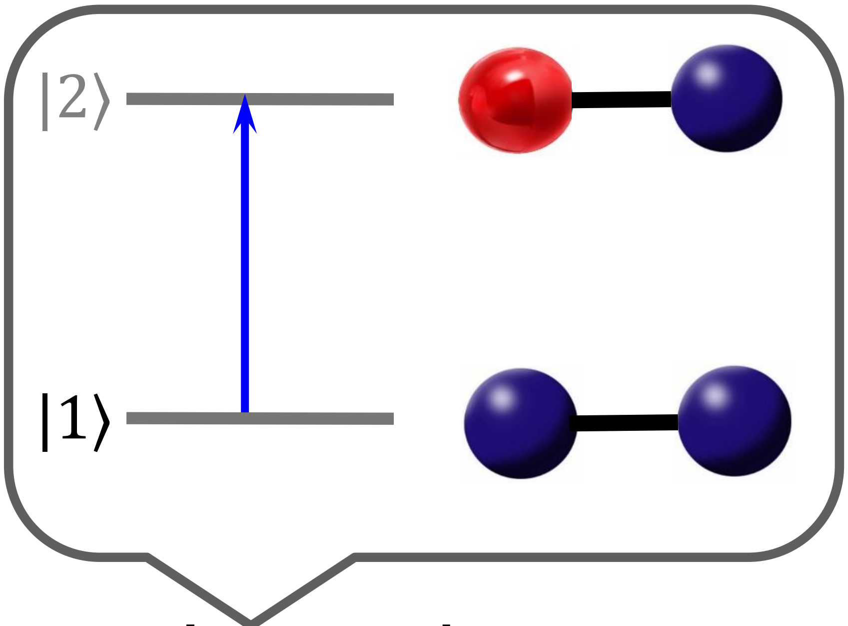
Key point: Mixing of partial waves in the continuum

M. McDonald *et al*., PRL, accepted

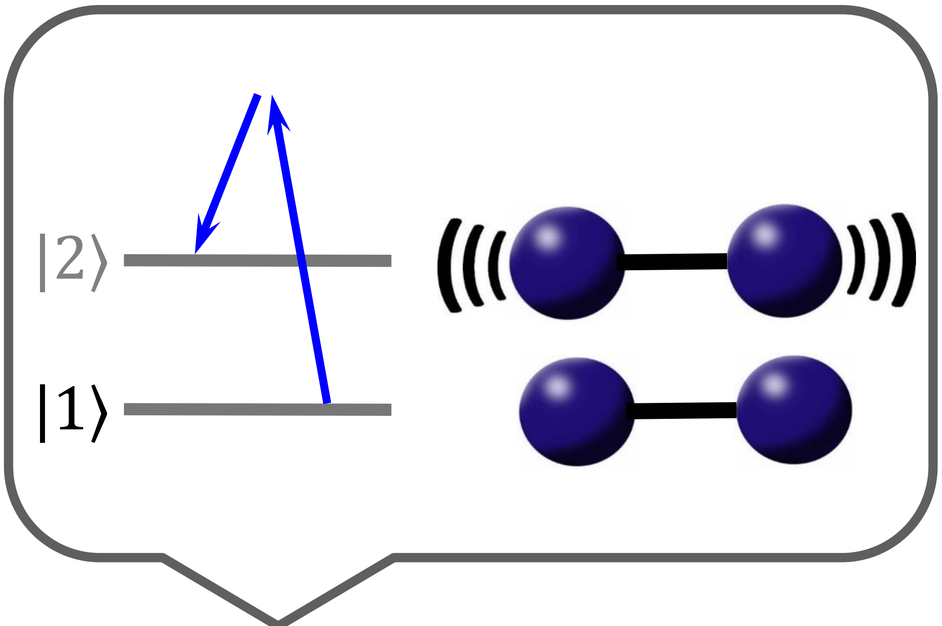
Science with Cold and Ultracold Molecules

- Ultracold chemistry
- Molecular clocks
- Table-top particle physics

Clocks



Electronic



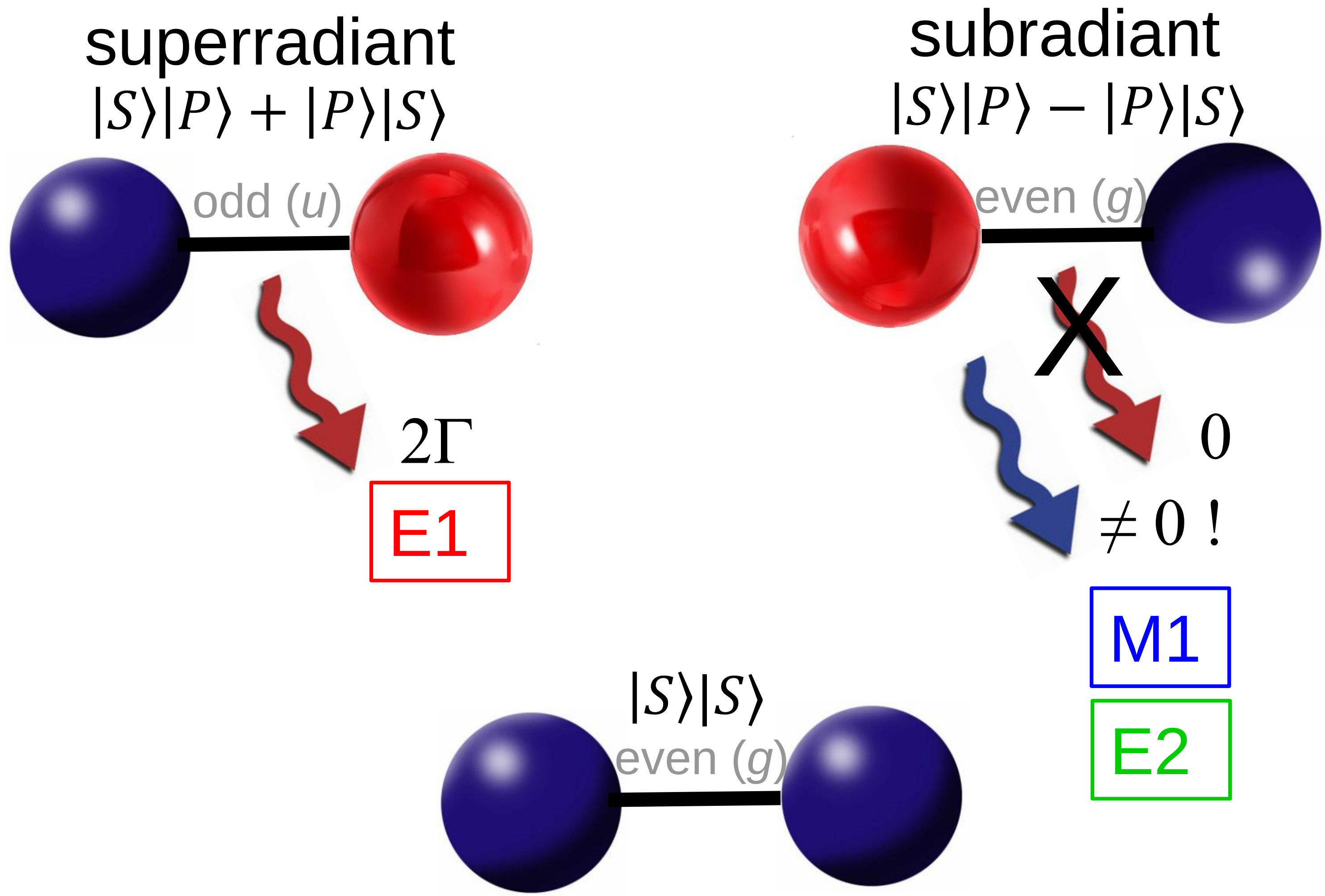
Vibrational

Coherence time of |1⟩+|2⟩ superposition

- Intrinsic
- Trap & environment

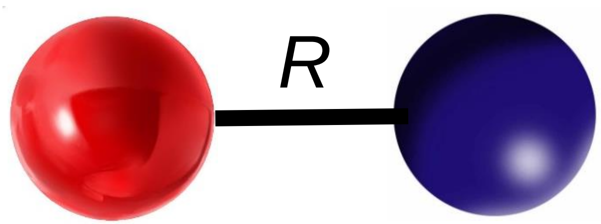
Two-Body Quantum Optics

Identical nuclei → Inversion symmetry



Two-Body Quantum Optics

Subradiance



$$\left|\frac{\mu_{M1}}{\mu_{E1}}\right|^2 \approx \left(\frac{R}{\lambda}\right)^2 \approx 10^{-4}$$

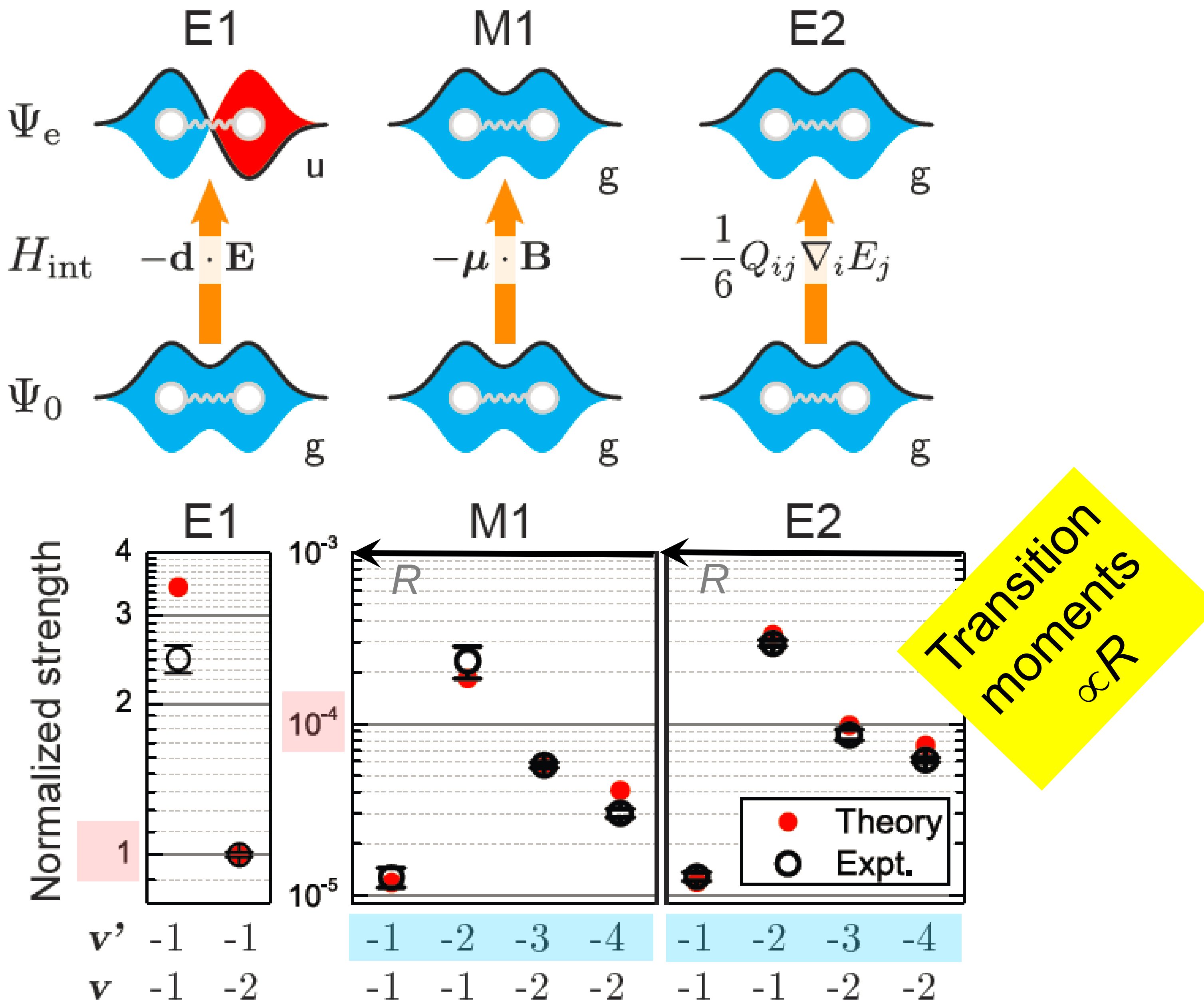
@ $R = 100\ a_0$

Need $10^4\times$ suppression of E1!

→ Molecules ✓

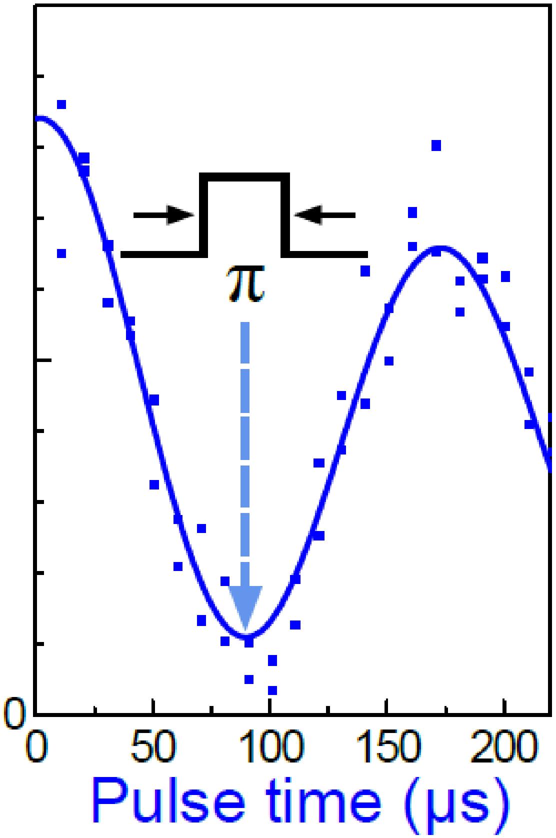
B. Bussery-Honvault and R. Moszynski, *Mol. Phys.* **104**, 2387 (2006)

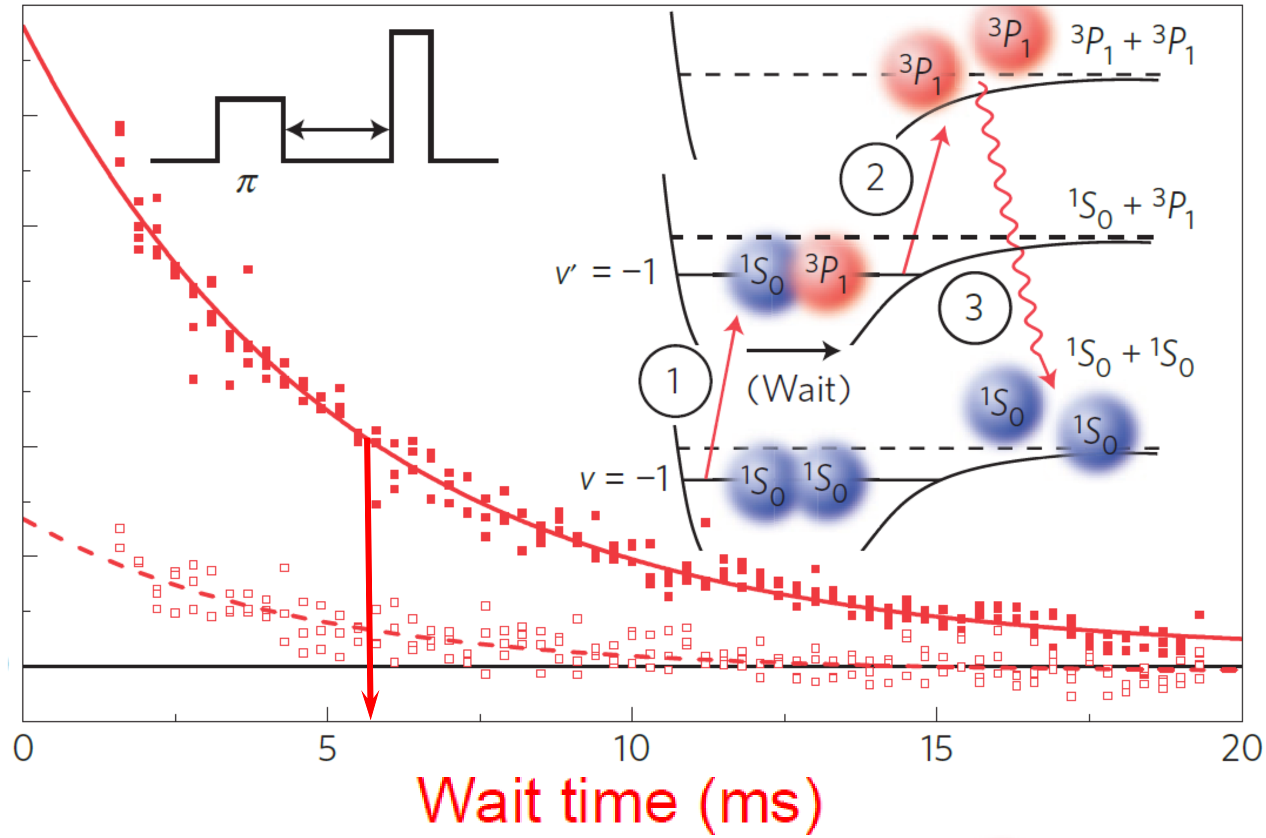
Two-Body Subradiance



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

Subradiant Lifetime

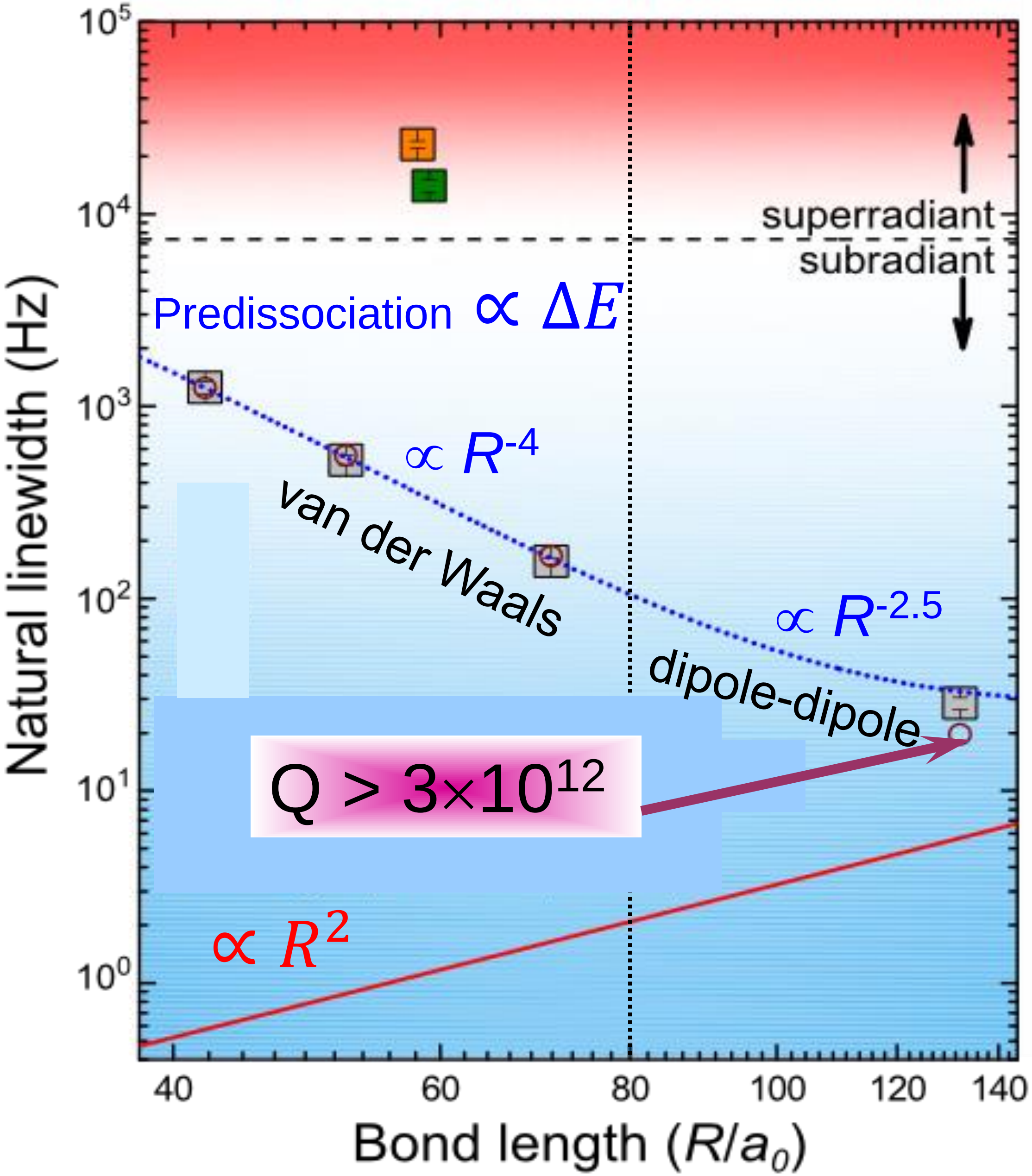




5.5 ms molecule-light coherence time

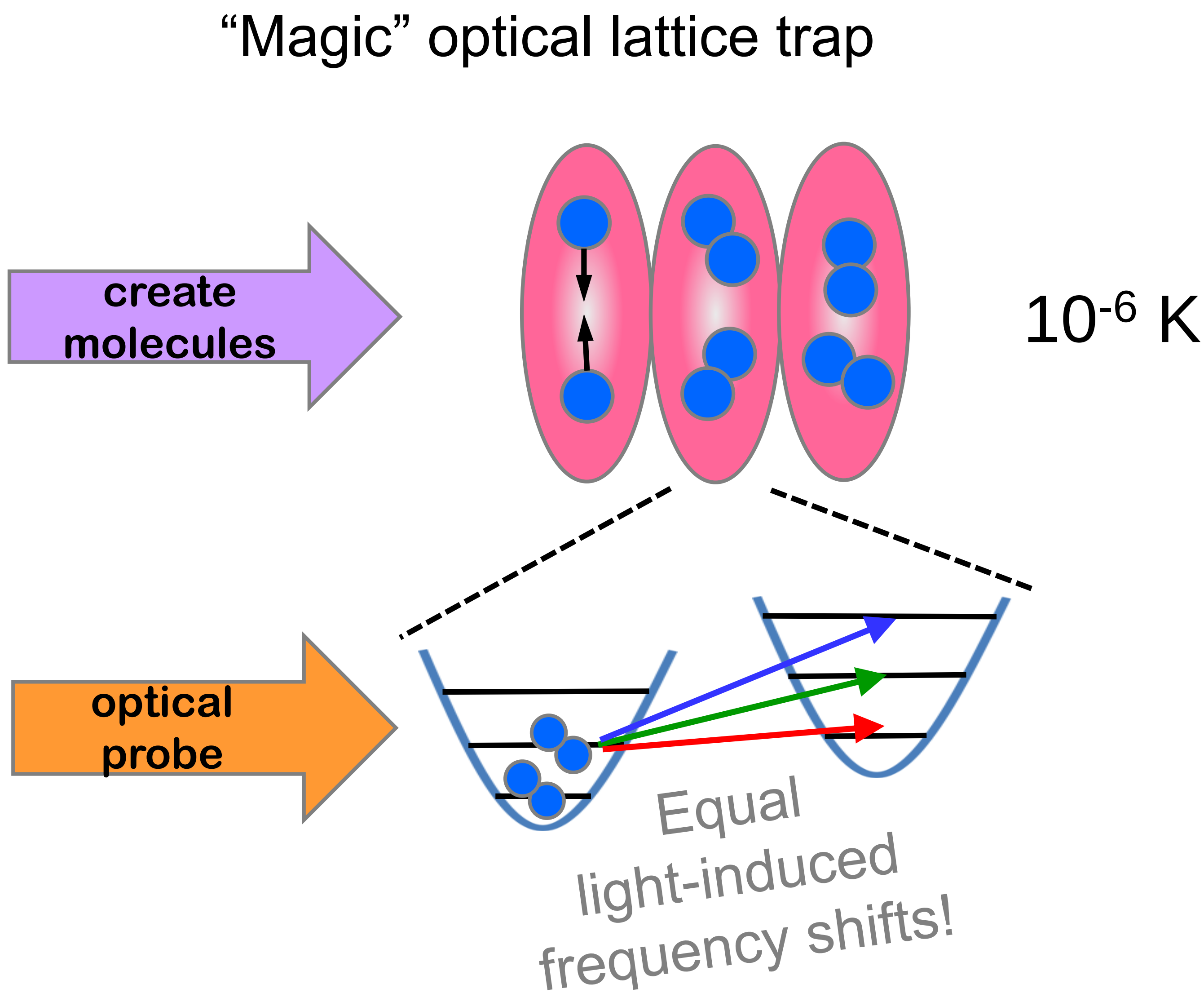
B. McGuyer *et al.*, *Nature Phys.* **11**, 32 (2015)

Two-Body Subradiance



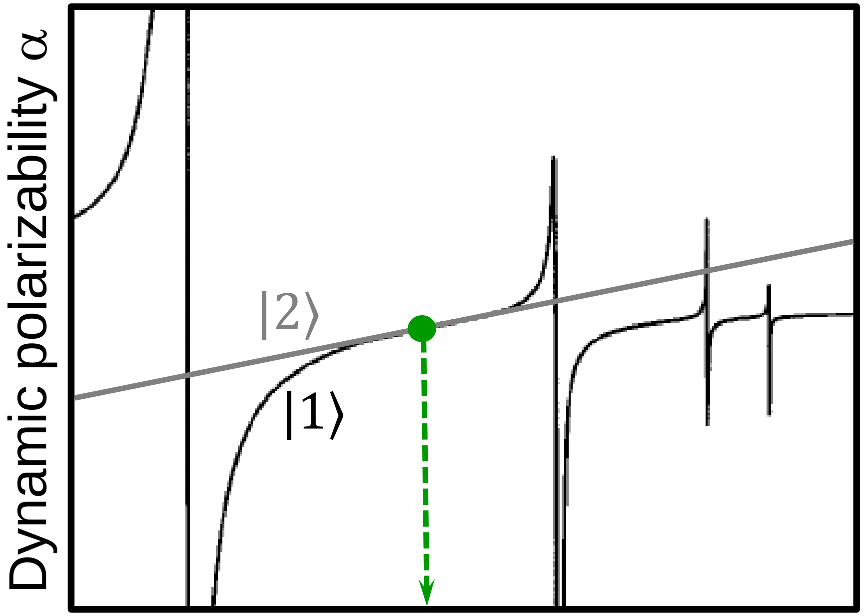
B. McGuyer *et al.*, *Nature Phys.* **11**, 32 (2015)

Trap-Insensitive Spectroscopy



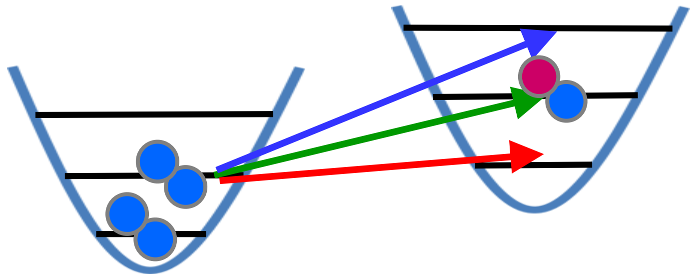
Trap-Insensitive Spectroscopy

"Magic" optical lattice trap

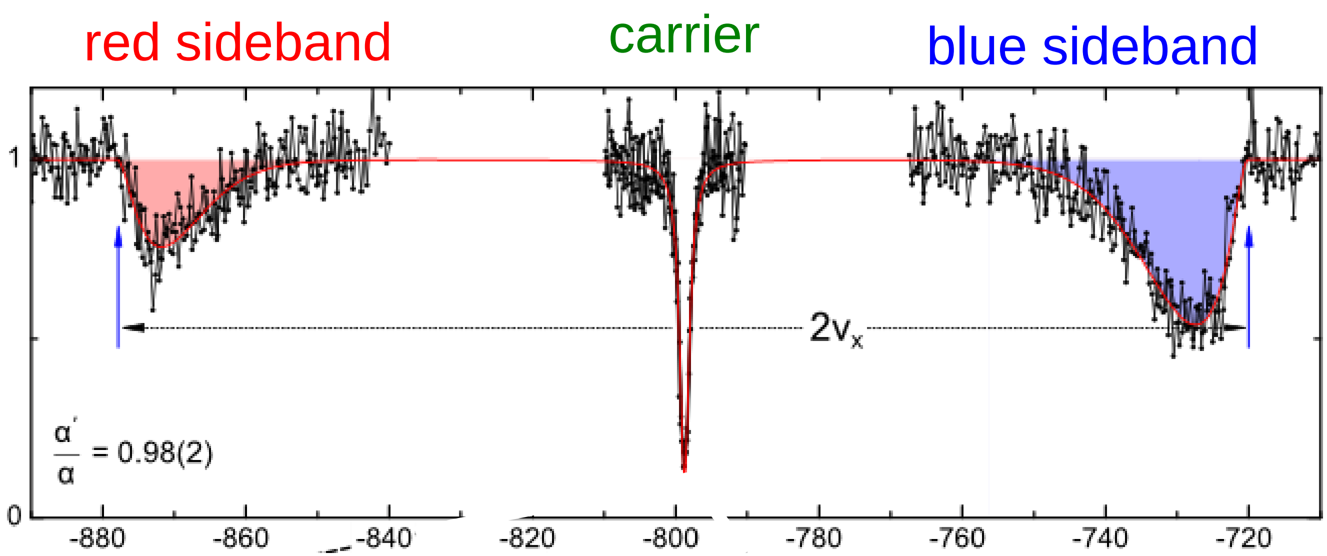


Coherent superposition of |1⟩ + |2⟩ ✓

Trap-Insensitive Spectroscopy

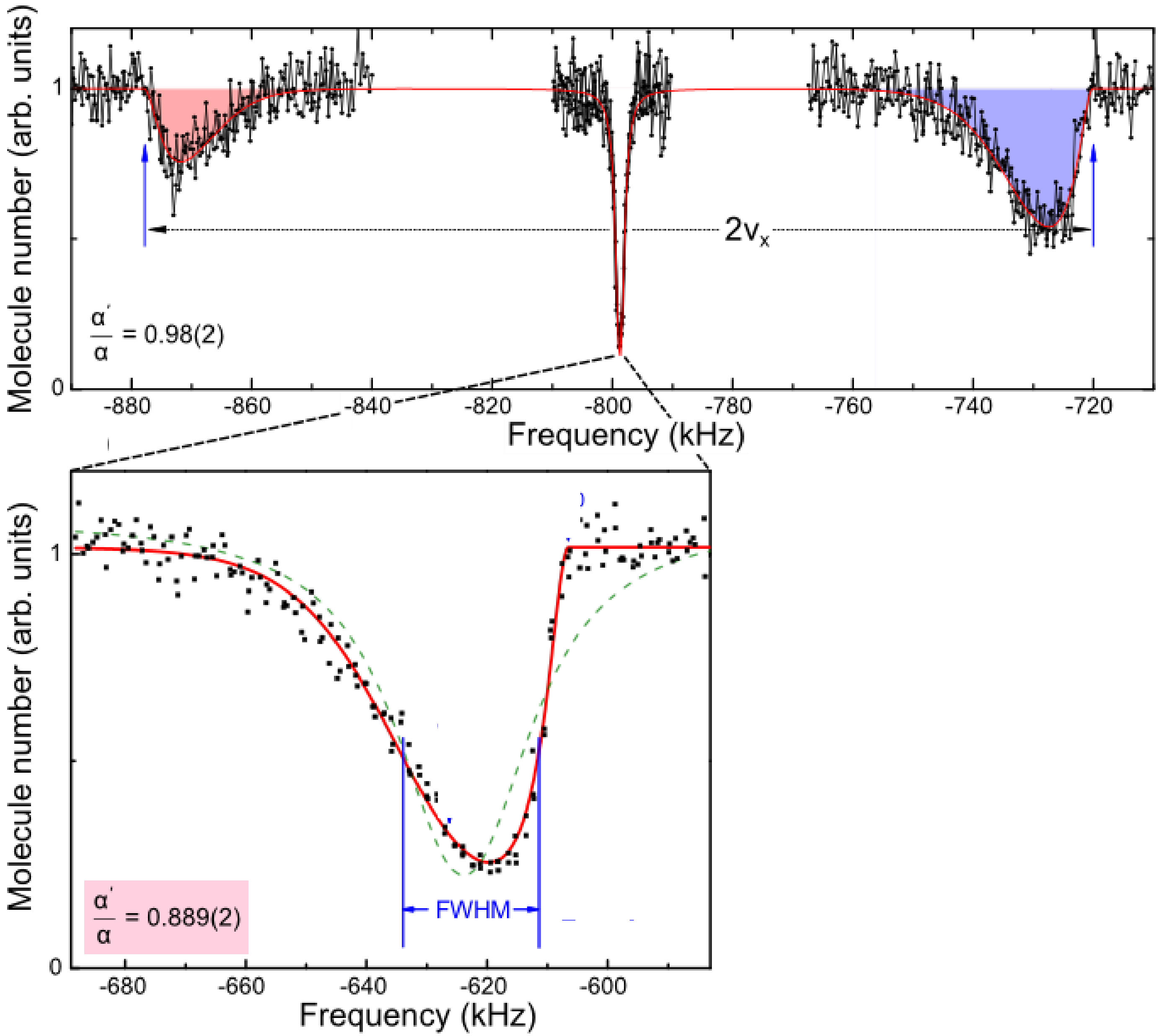


‘Magic’-lattice optical absorption spectrum



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

Trap-Insensitive Spectrosopy



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

Trap-Insensitive Spectroscopy

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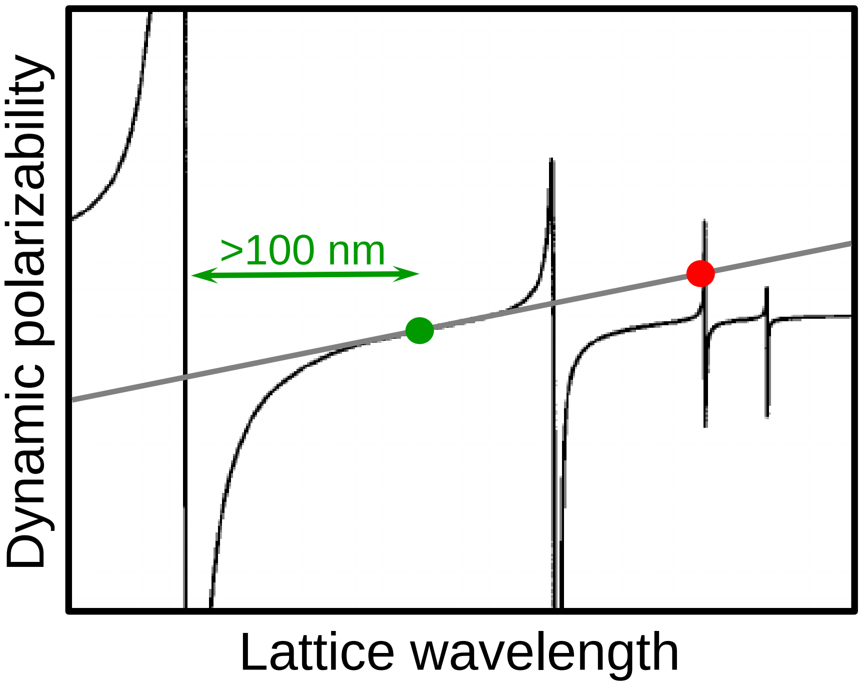
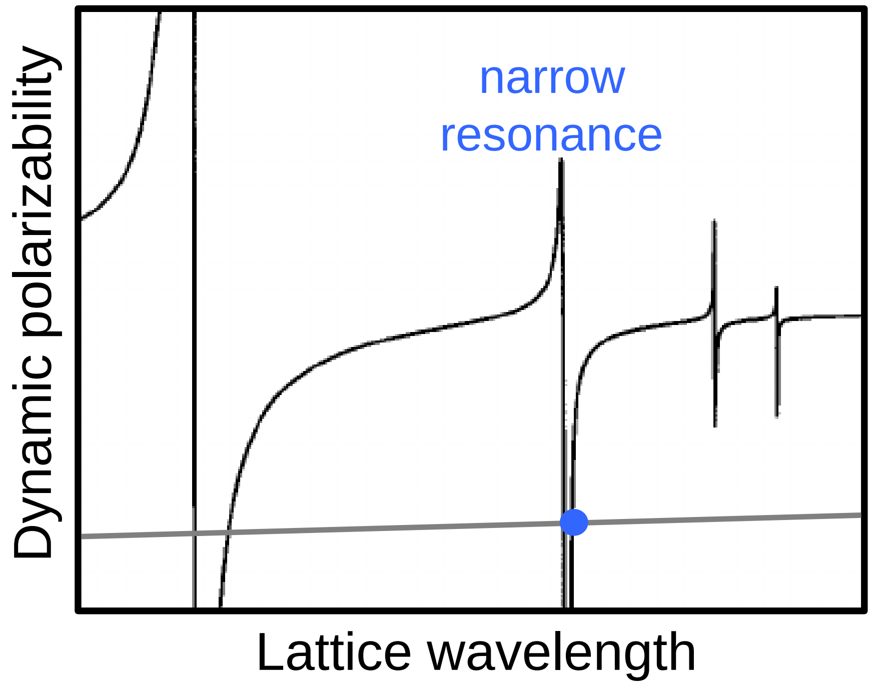


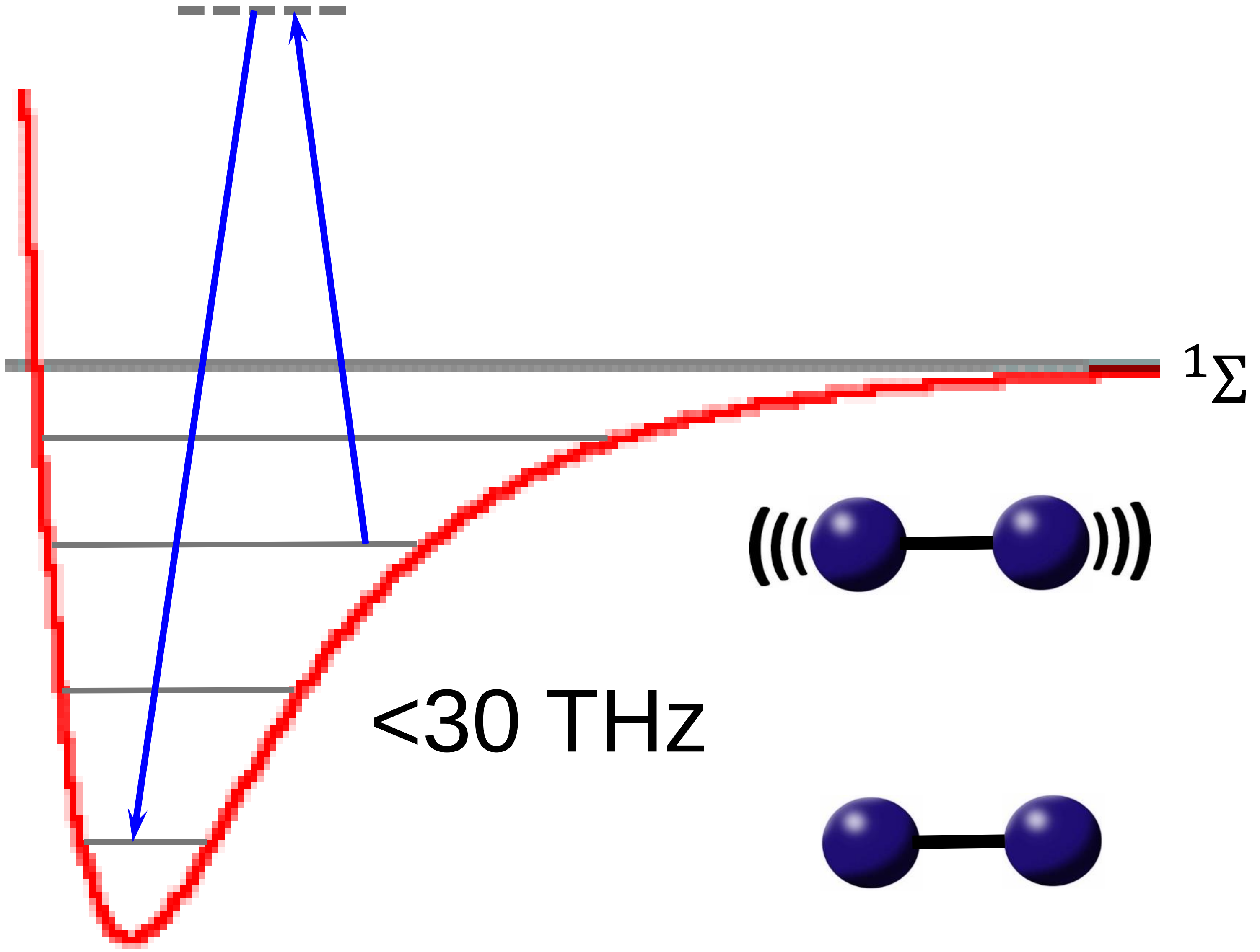


Nonresonant crossing:
Traditional choice; hard to find ☹

Resonant crossing:
Heating/loss

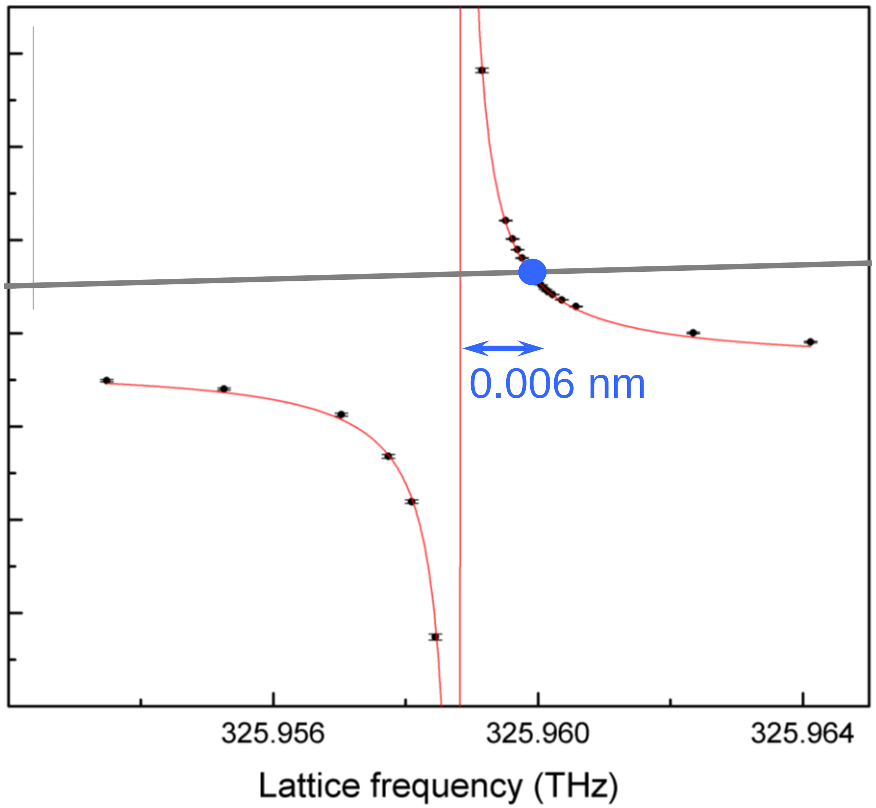
Resonant crossing:
* No heating/loss!
* Easy to find ☺

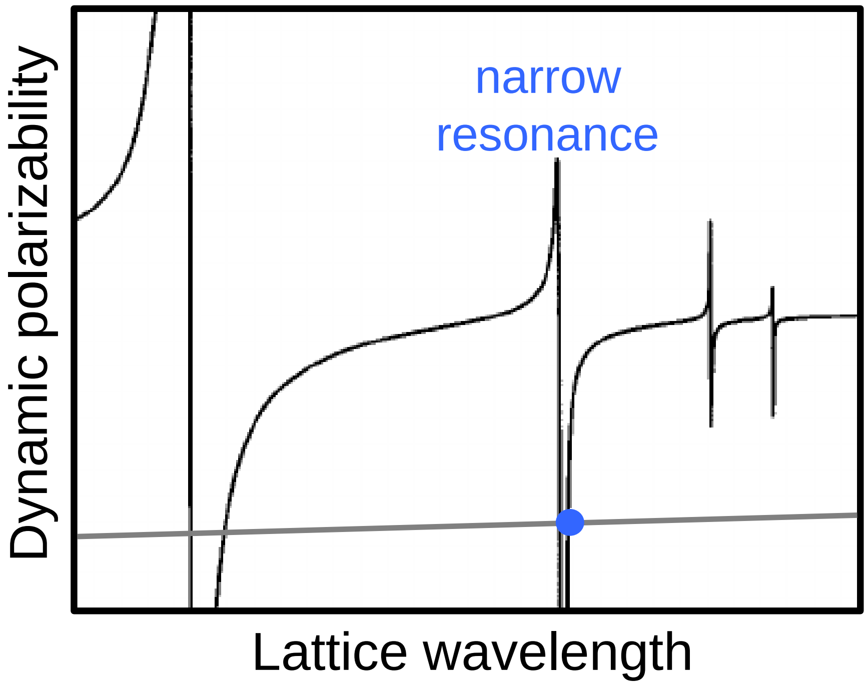
Clock Based on Molecular Vibrations



Trap-Insensitive Spectroscopy

“Magic” optical lattice trap





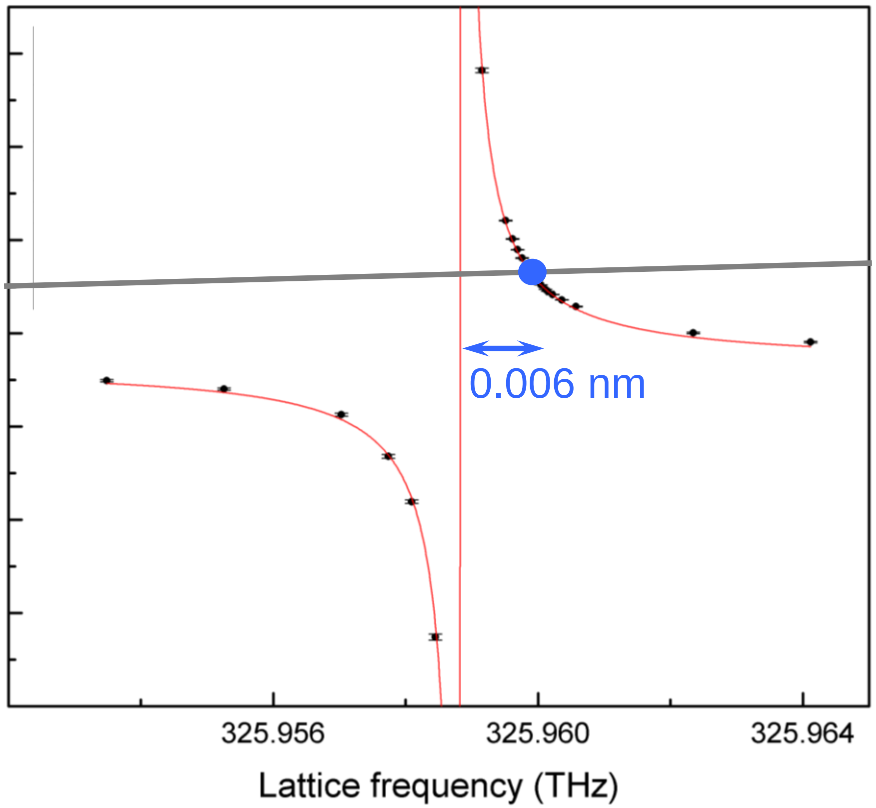
Resonant crossing:

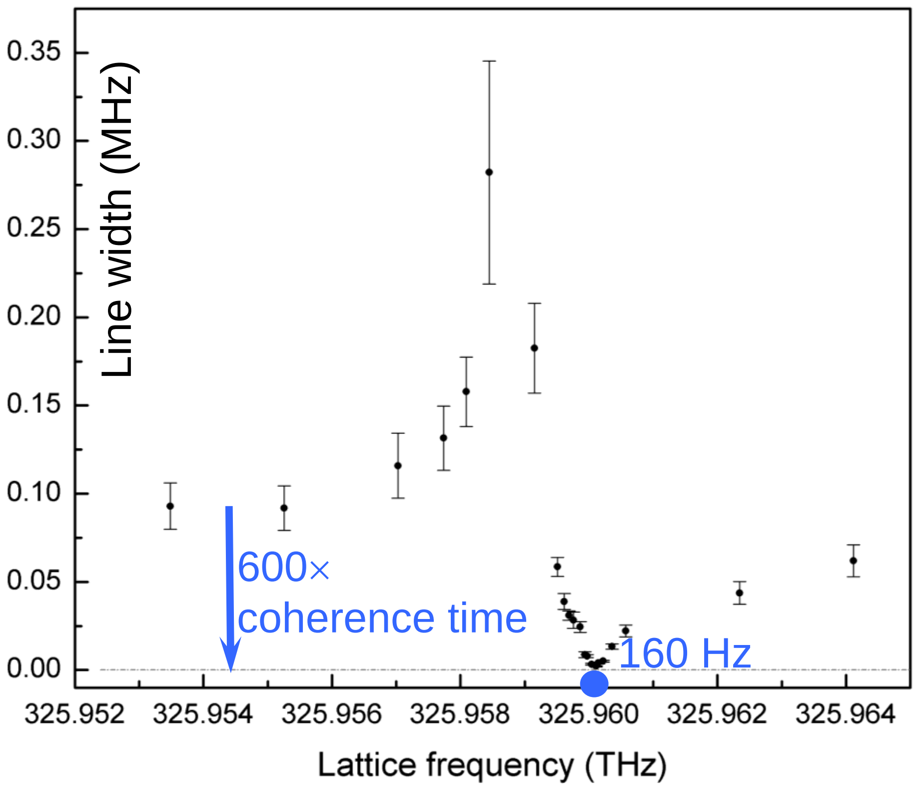
* No heating/loss!

* Easy to find

Trap-Insensitive Spectroscopy

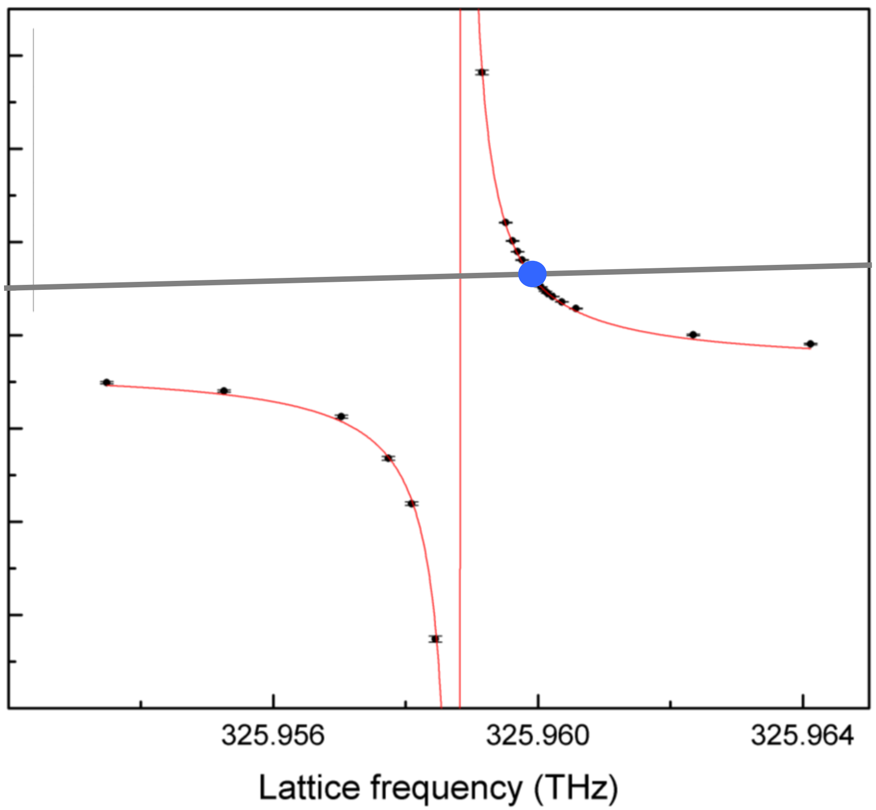
“Magic” optical lattice trap

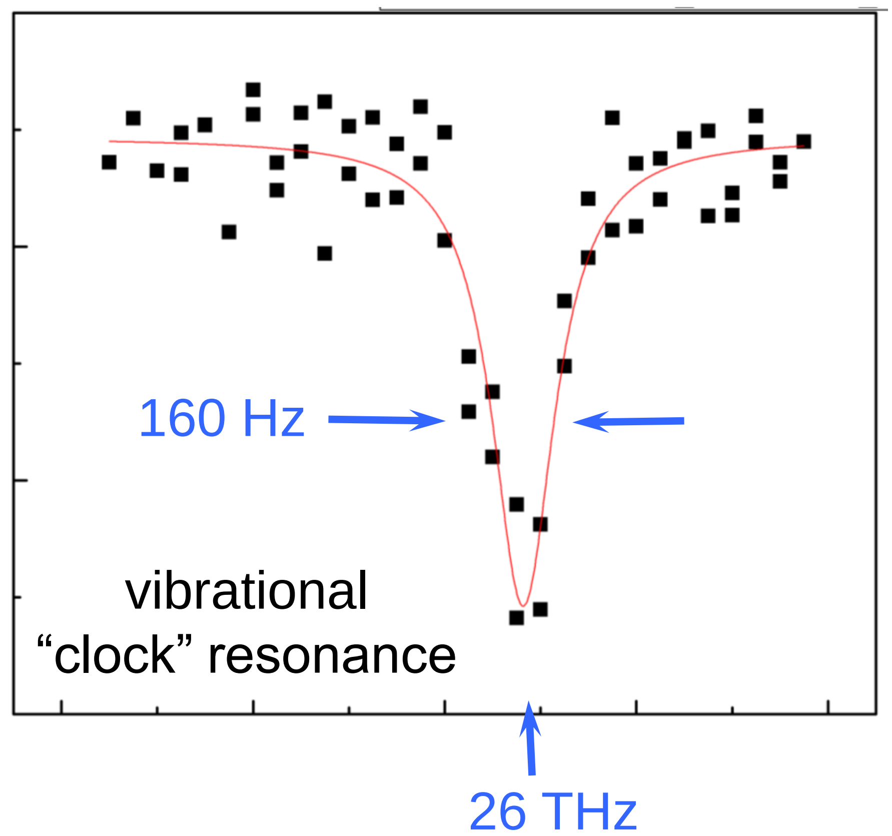




Trap-Insensitive Spectroscopy

"Magic" optical lattice trap



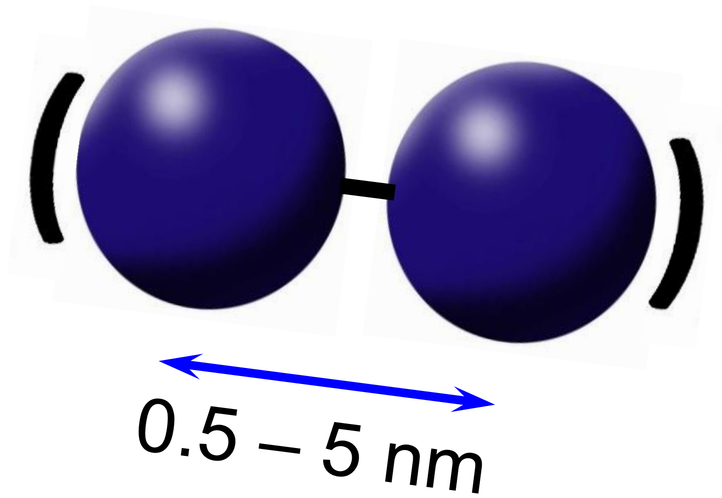


$Q = 2\times10^{11}$
(fiber limited)

Science with Cold and Ultracold Molecules

- Ultracold chemistry
- Molecular clocks
- Table-top particle physics

New Mass-Dependent Forces



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

Yukawa

$A < 10^{21}$
@ 1 nm !

→ Need state-of-the-art measurement of van der Waals interatomic force

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

M. Borkowski *et al.*, arXiv:1612.03842

Molecular QED and 5th force

Born-Oppenheimer approximation

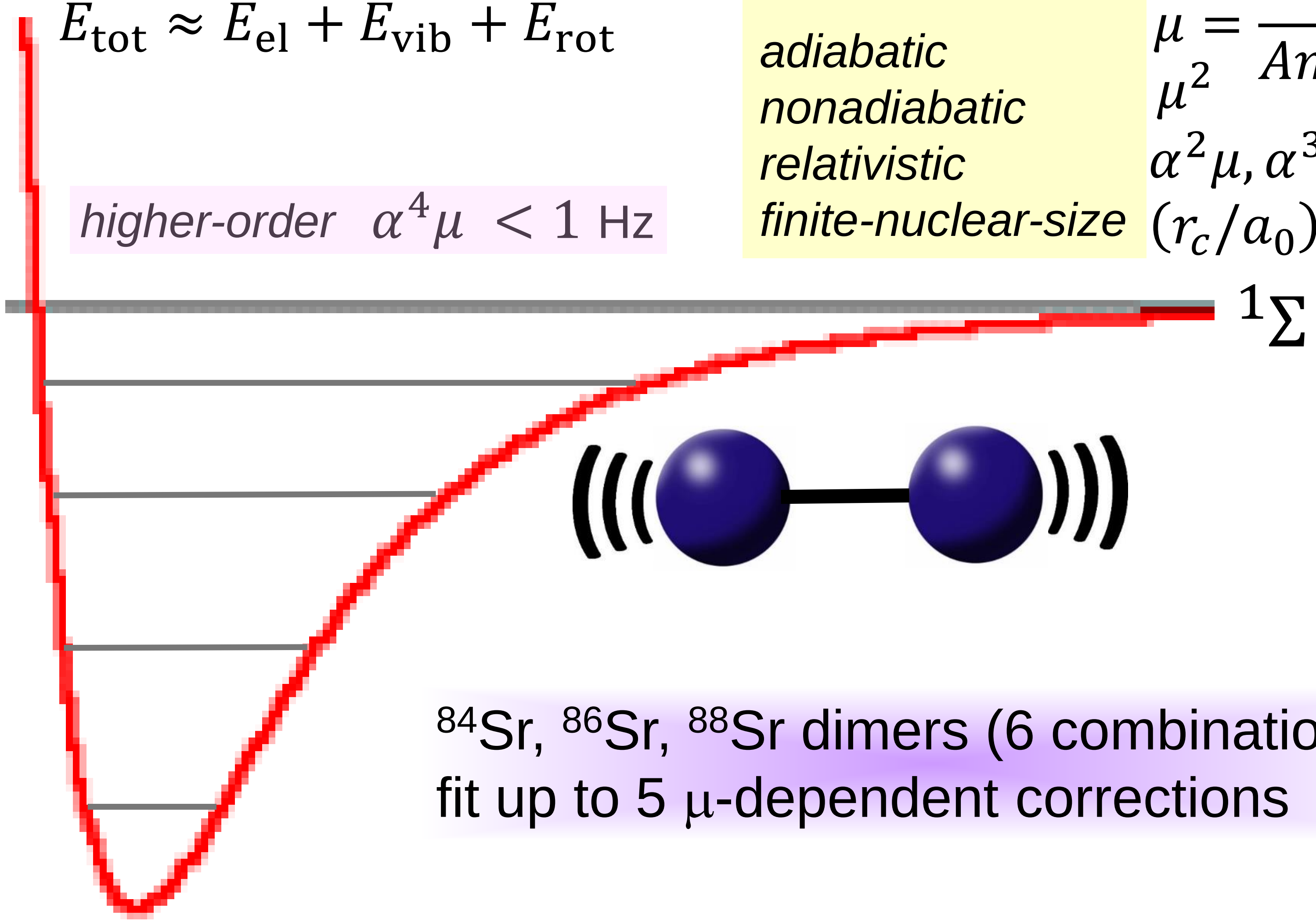
$E_{\mathrm{tot}} \approx E_{\mathrm{el}} + E_{\mathrm{vib}} + E_{\mathrm{rot}}$

higher-order $\alpha^4\mu < 1$ Hz

Beyond B-O

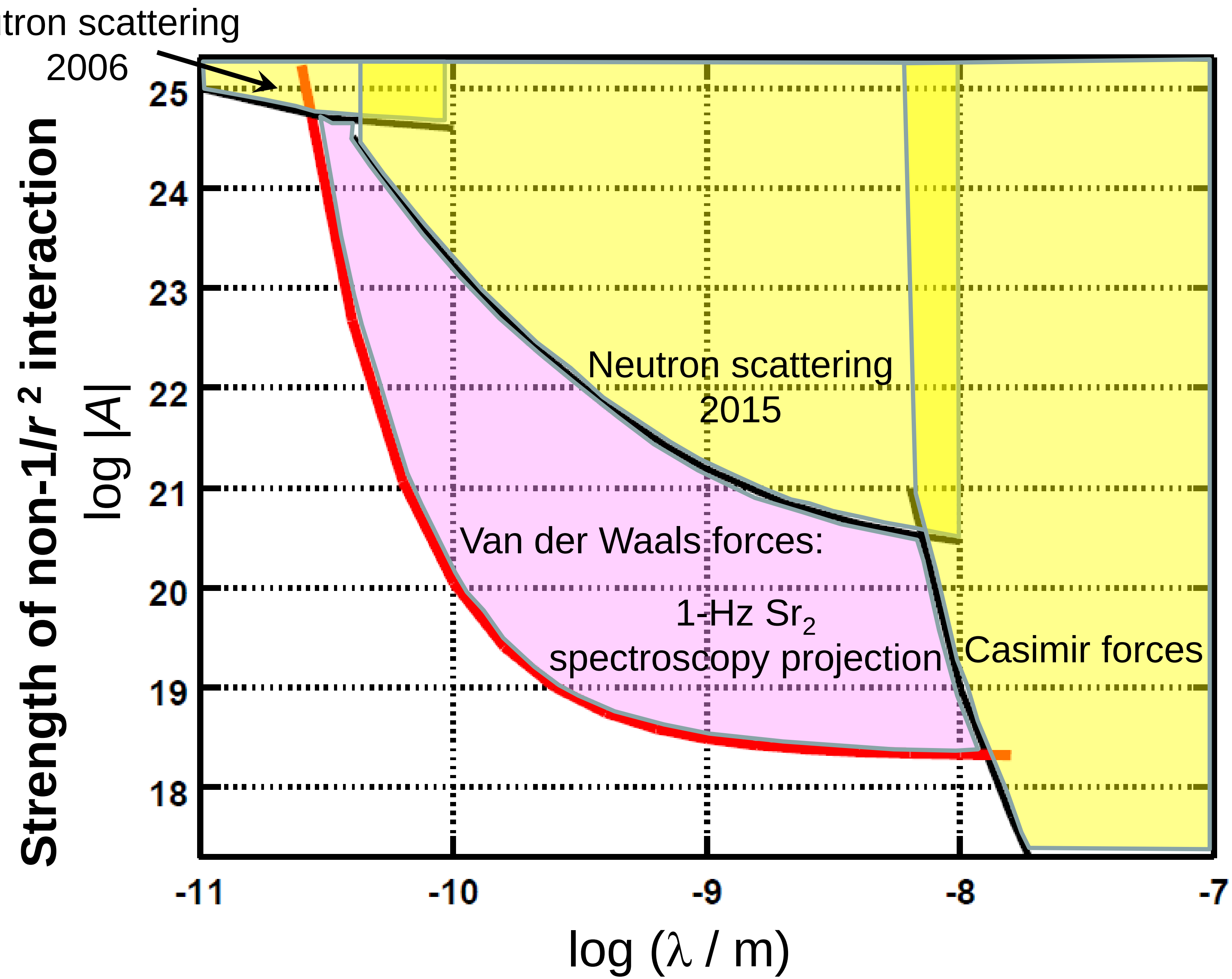
$\mu = \dfrac{m_e}{Am_p}$

adiabatic	μ^2
nonadiabatic	$\alpha^2\mu, \alpha^3\mu$
relativistic	$(r_c/a_0)^2$
finite-nuclear-size	



^{84}Sr, ^{86}Sr, ^{88}Sr dimers (6 combinations): fit up to 5 μ-dependent corrections

Molecular QED and 5th Force



Y. N. Pokotilovski, *Phys. At. Nucl.* **69**, 924 (2006)
Y. Kamiya *et al.*, *PRL* **114**, 161101 (2015)
M. Bordag *et al.*, *Phys. Rep.* **353**, 1 (2001)
M. Borkowski *et al.*, *J. Phys. Conf. Ser.* **810**, 012014 (2017)

Zlab

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**Mickey McDonald:
APS DAMOP
Doctoral Thesis Prize
2017**

Theory:

Robert Moszynski

Iwona Majewska

U. of Warsaw