A Quantum Gas of Polar Molecules

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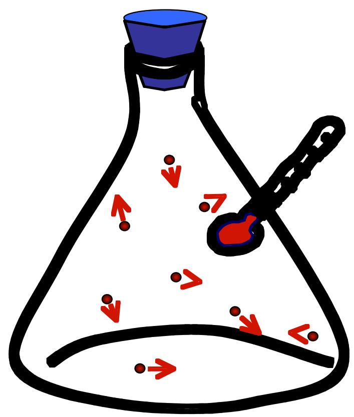
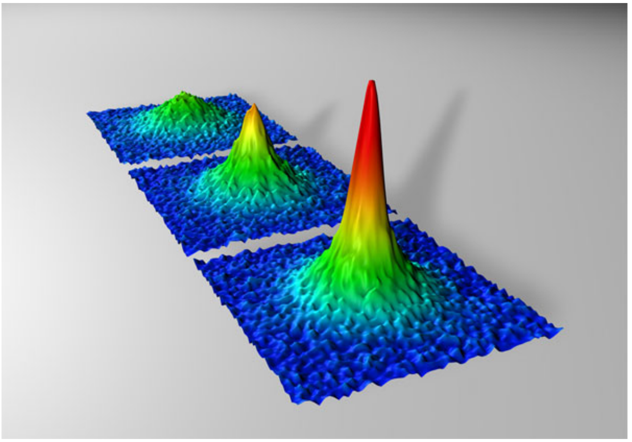
$Keck Foundation, NIST, and NSF$

Ultracold Atomic Quantum Gases



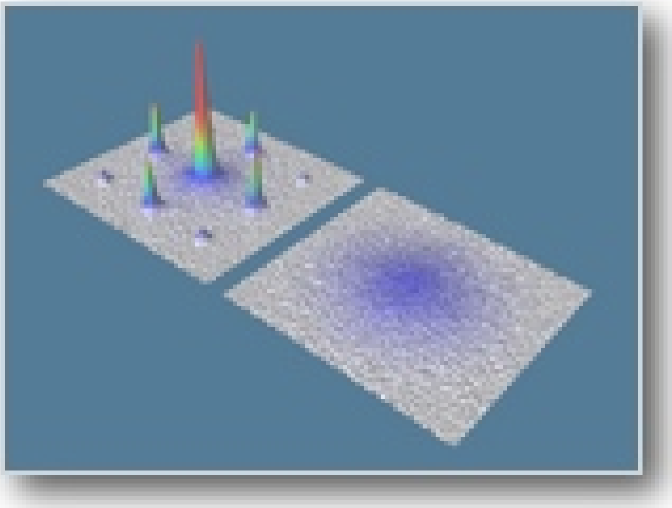
<1 μK

Bose-Einstein Condensation
Degenerate Fermi Gas



strongly correlated systems

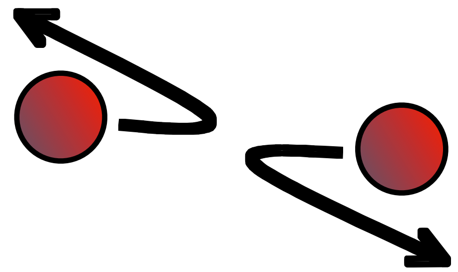
* superfluidity in Fermi gases
* quantum phase transitions with fermions/bosons in optical lattices
* and many more...



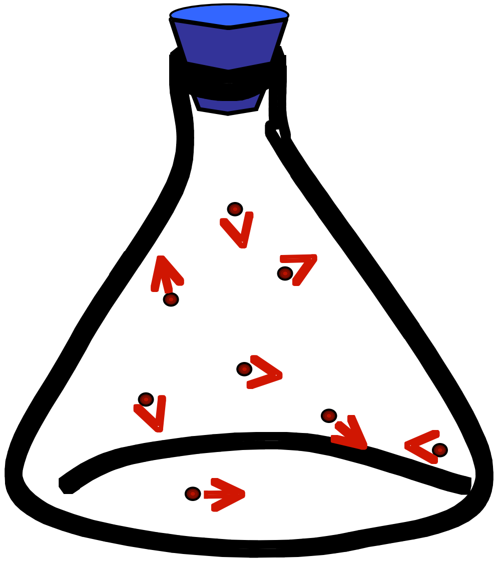
Interactions are Key

Atoms

Contact interactions



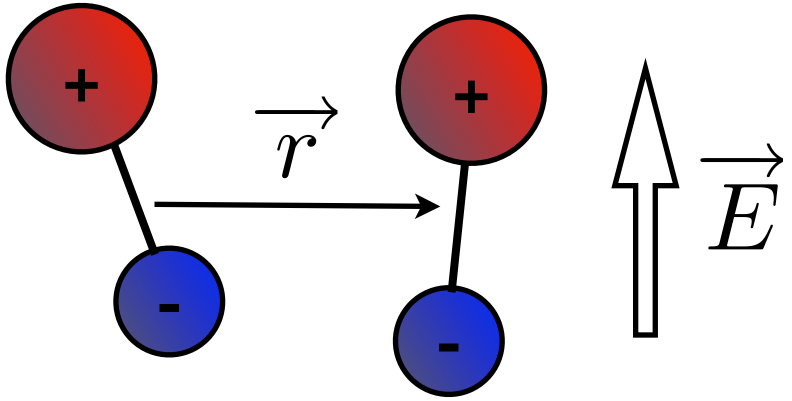
- short range $\delta(R)$
- isotropic



Why Polar Molecules?

dipole-dipole interactions

- anisotropic
- long-range ($1/r^3$)
- tunable dipoles



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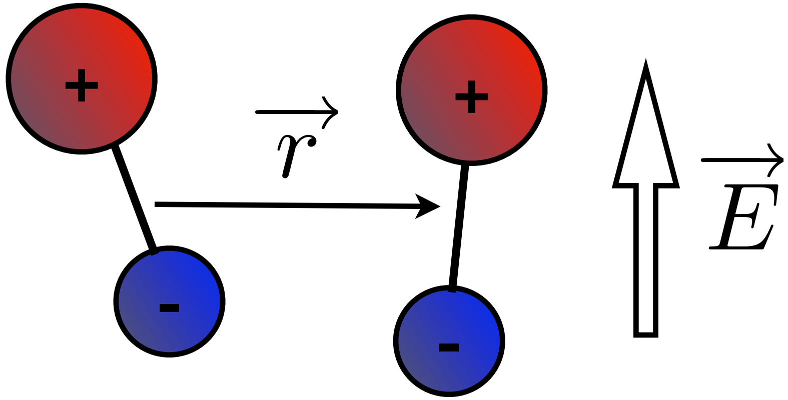

$$\frac{(\text{Debye})^2}{(\text{Bohr magneton})^2} \cdot c^2 = 10^4$$

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anisotropic

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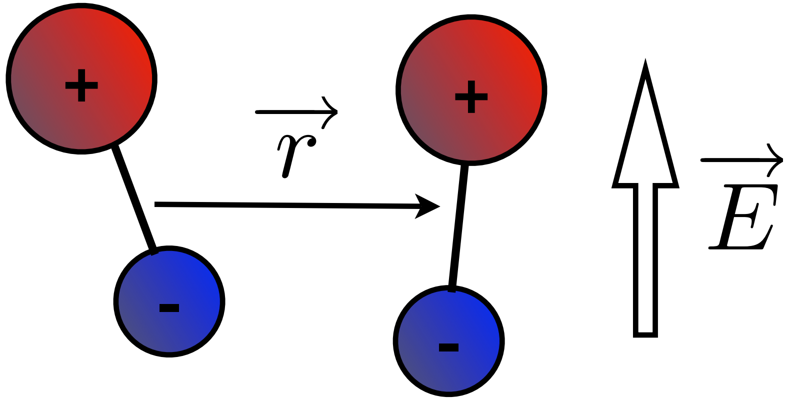
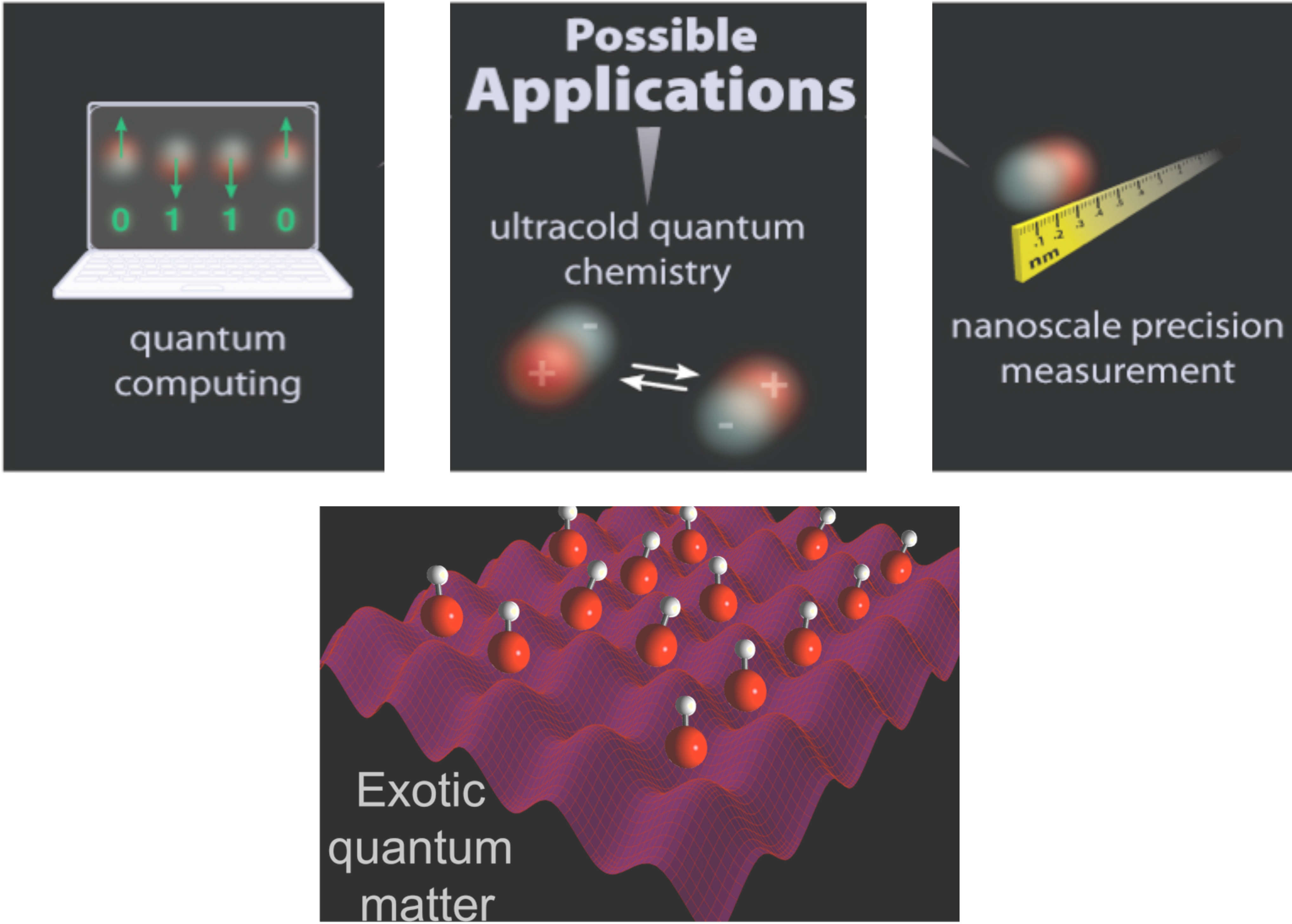


complex internal structure offers new ways of control

$$\frac{(\text{Debye})^2}{(\text{Bohr magneton})^2} \cdot c^2 = 10^4$$


Possible
Applications
0 1 1 0
quantum
computing
ultracold quantum
chemistry
+
-
nm
nanoscale precision
measurement
Exotic
quantum
matter

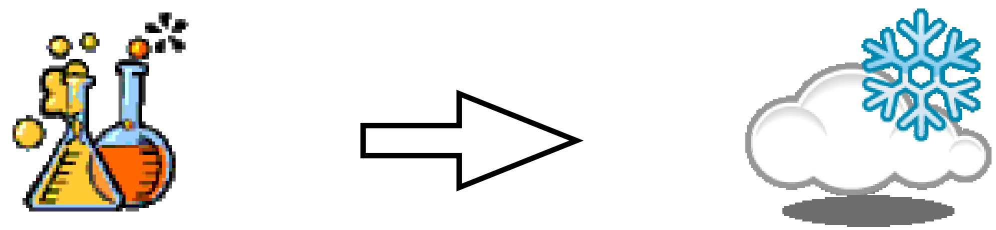
Outline

* challenges
* our approach - coherent transfer
* making ro-vibronic ground-state polar molecules in a single quantum state
* ultracold chemistry and dipolar collisions
* outlook

Status of the quest for a Quantum Gas of Polar Molecules

$$PSD(n\Lambda^3)=10^{-13} \text{ to } 10^{-15}$$

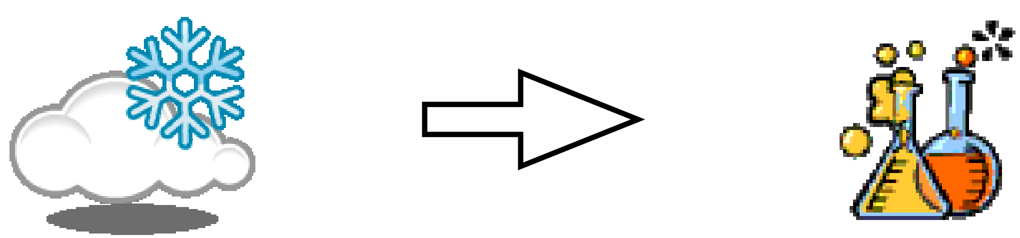
* Direct cooling of molecules (Doyle, Meijer, Ye, Rempe, ...)



mK

make molecules cooling

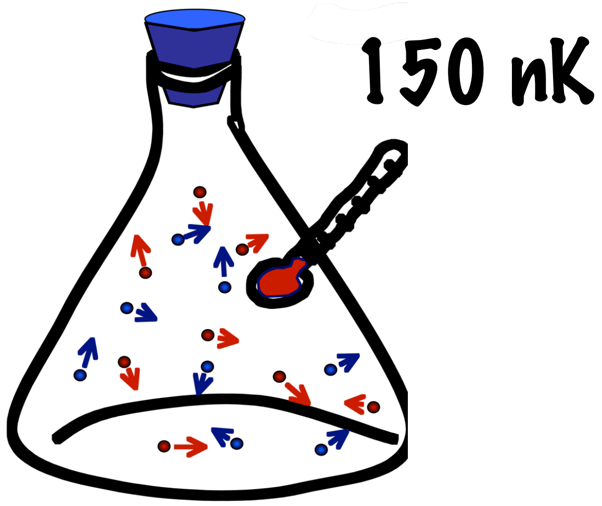
* Photoassociation of ultracold atoms (DeMille, Stwalley, Bigelow, Weidmuller,...)



100μK

cooling make molecules

Starting from Ultracold Atoms

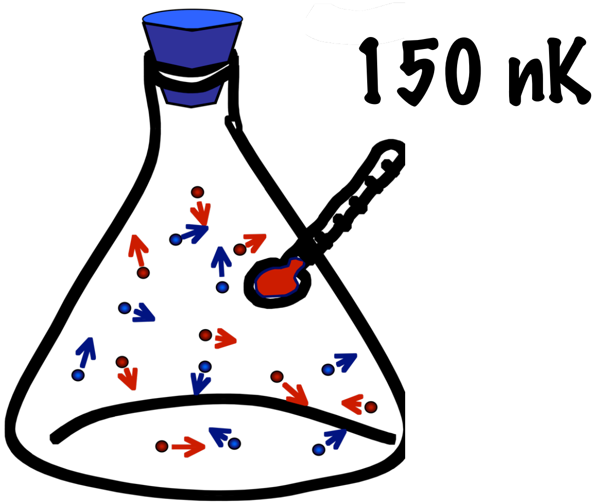


Two types of atoms

Rubidium (boson)

Potassium (fermion)

Starting from Ultracold Atoms

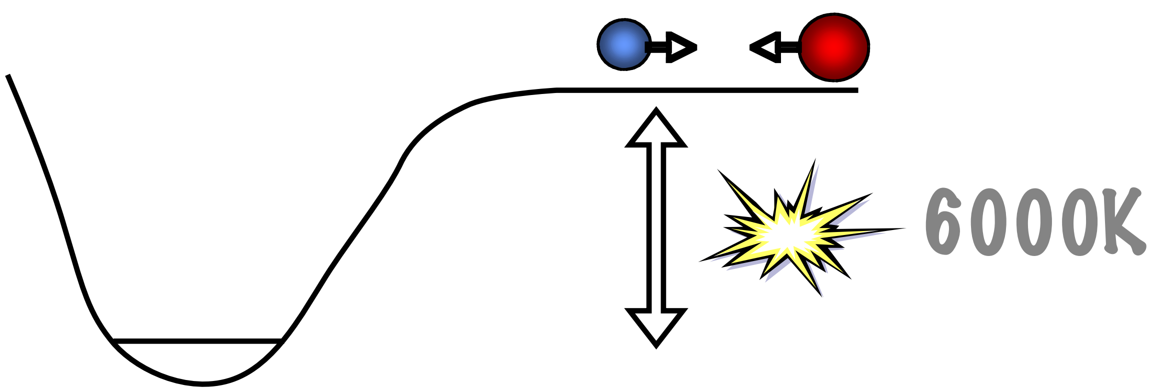


Two types of atoms

Rubidium (boson)

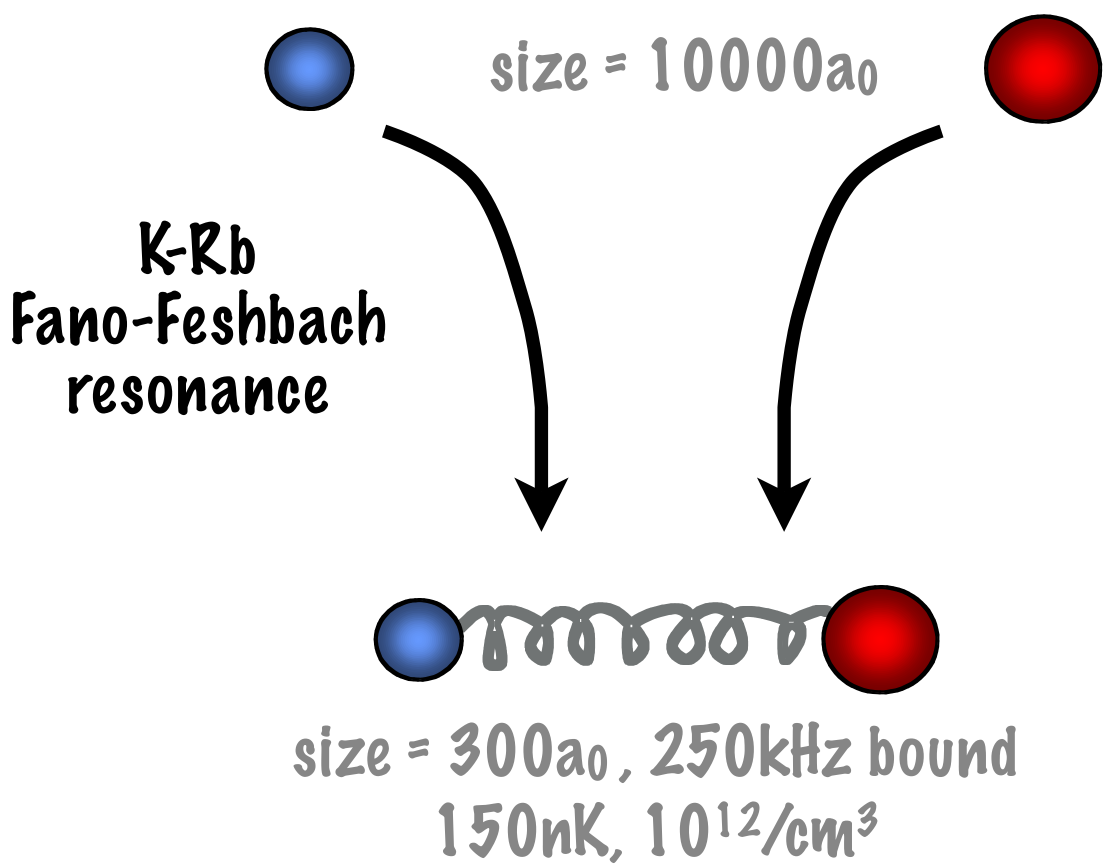
Potassium (fermion)

challenges: efficient molecule creation while staying cold



Making KRb Feshbach Molecules

weakly bound "Feshbach" molecules can be created near a magnetic field tunable atomic scattering resonance



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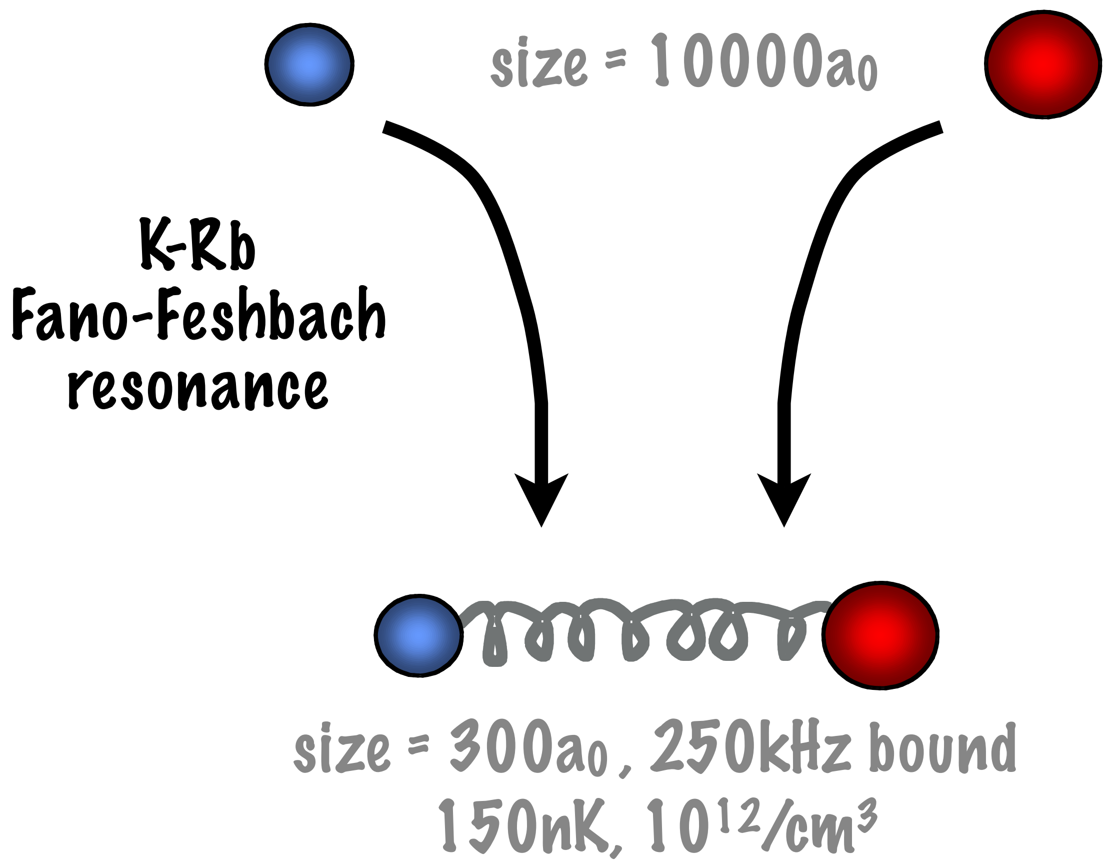

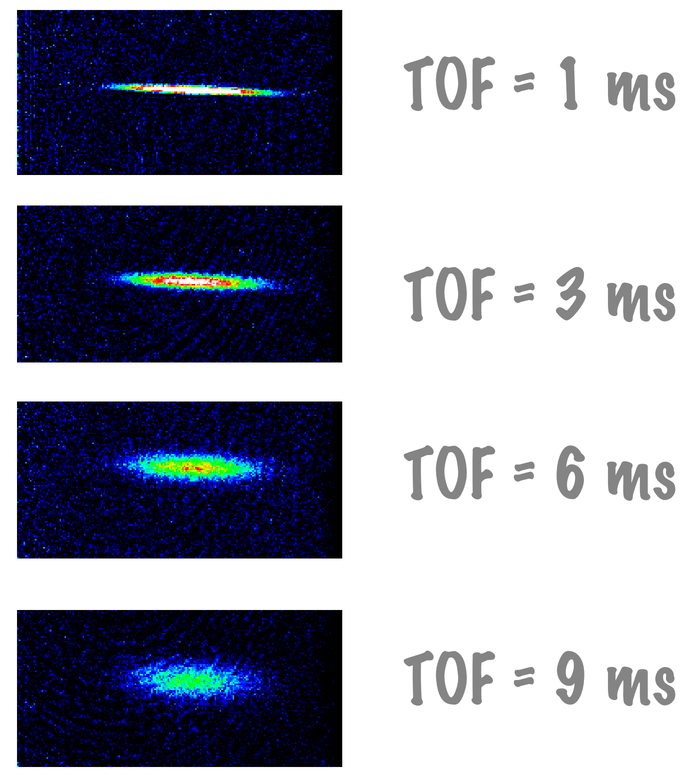

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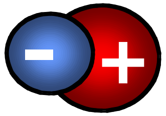
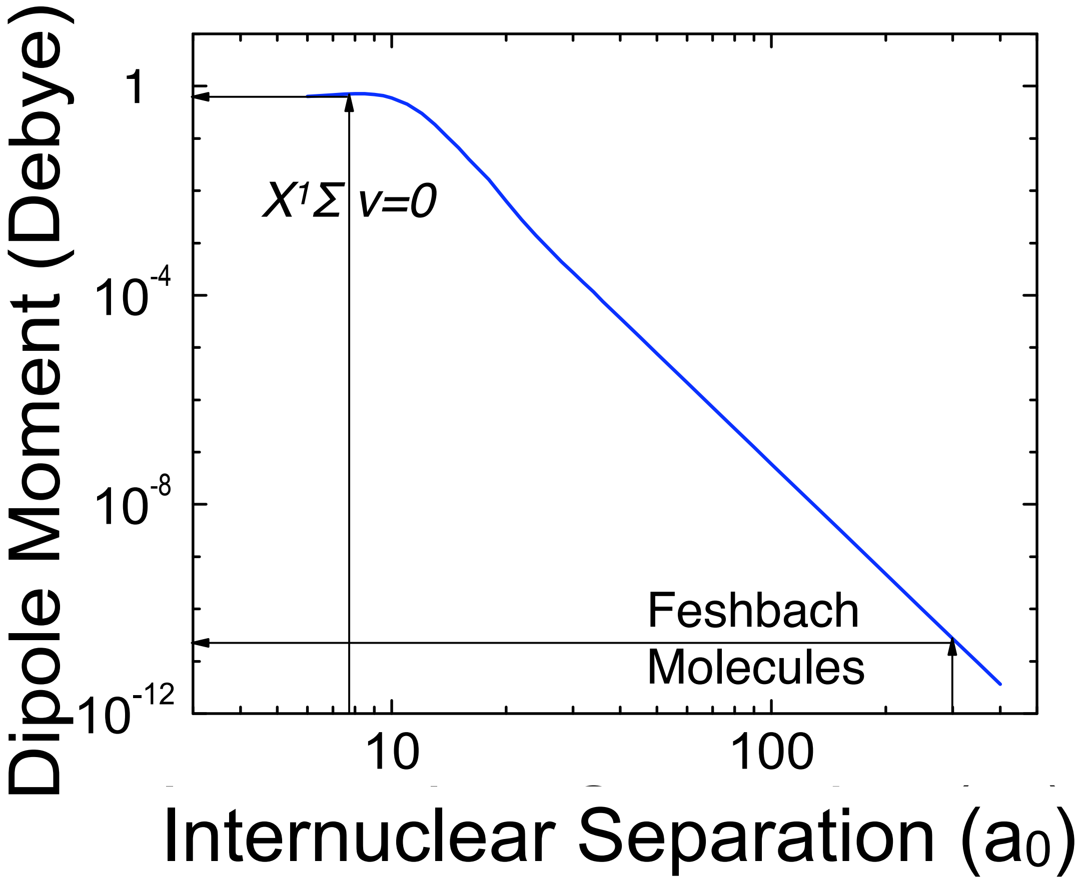
Shrink the Molecules

small, tightly bound, polar molecules

KRb dipole moment

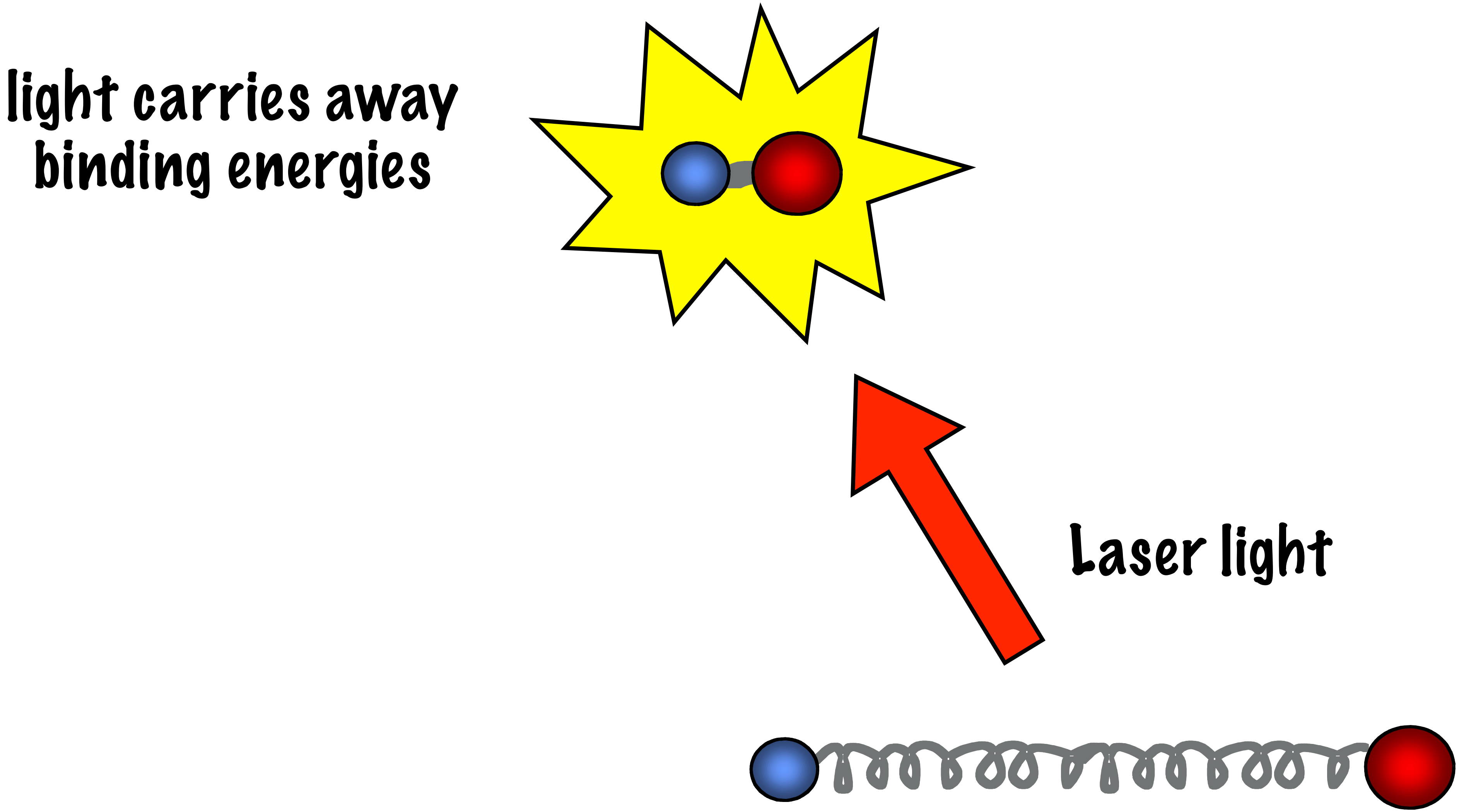




Kotochigova *et al.*, Phys. Rev. A **68**, 022501 (2003)

making molecules Ultracold and Polar

In A Single Internal Quantum State



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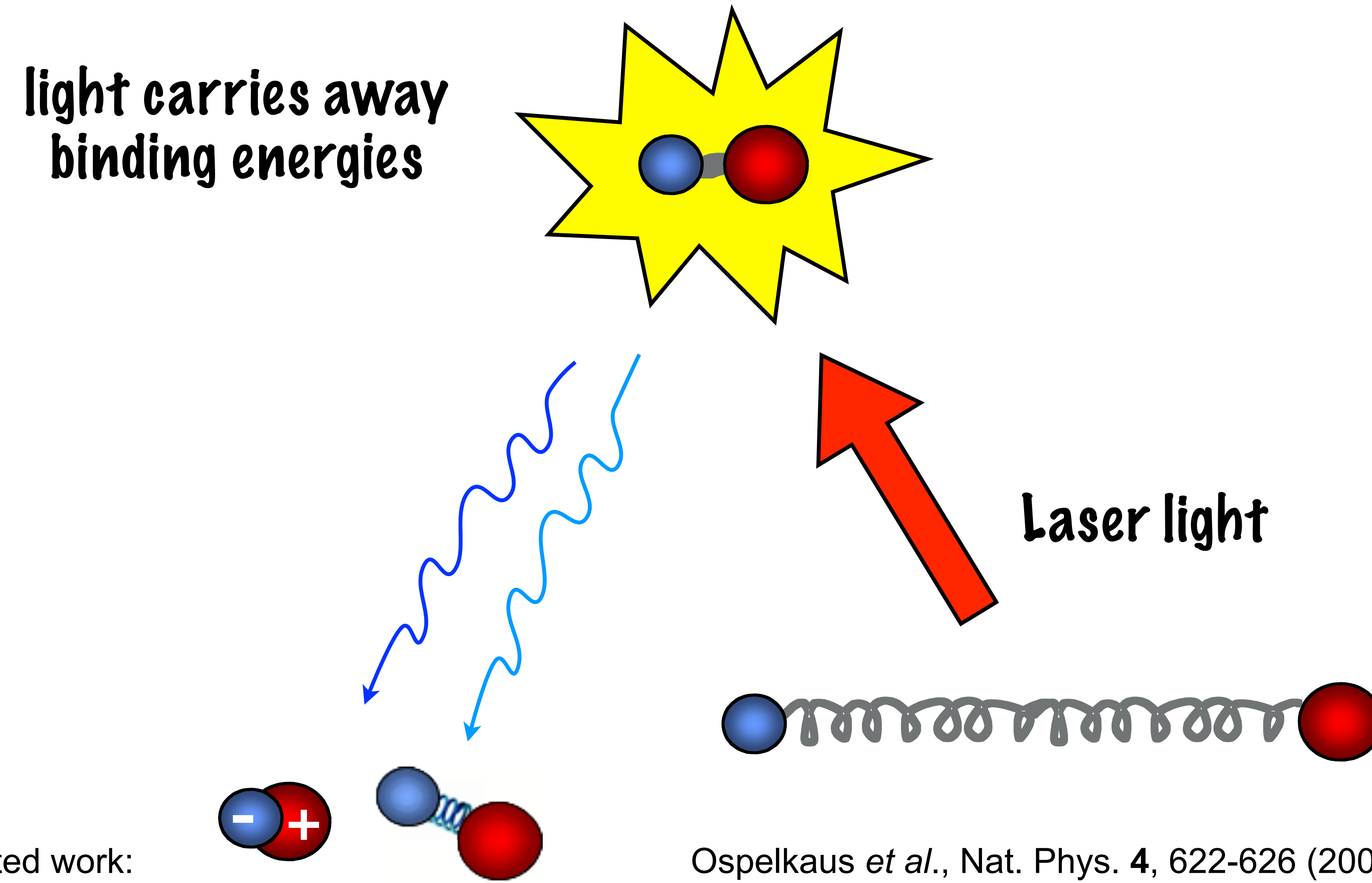

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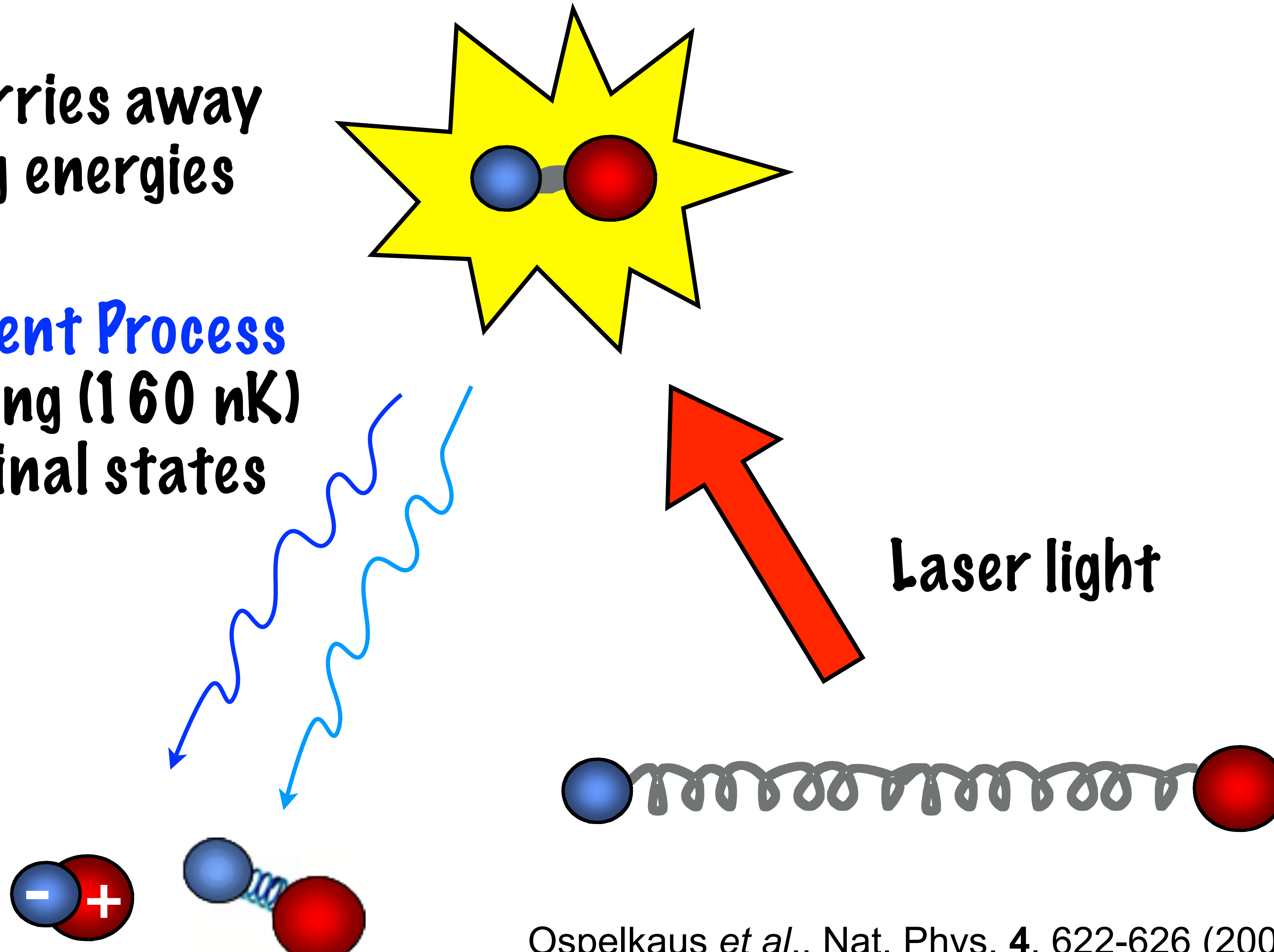
making molecules Ultracold and Polar

In A Single Internal Quantum State

light carries away binding energies

non-Coherent Process
recoil heating (160 nK)
multiple final states



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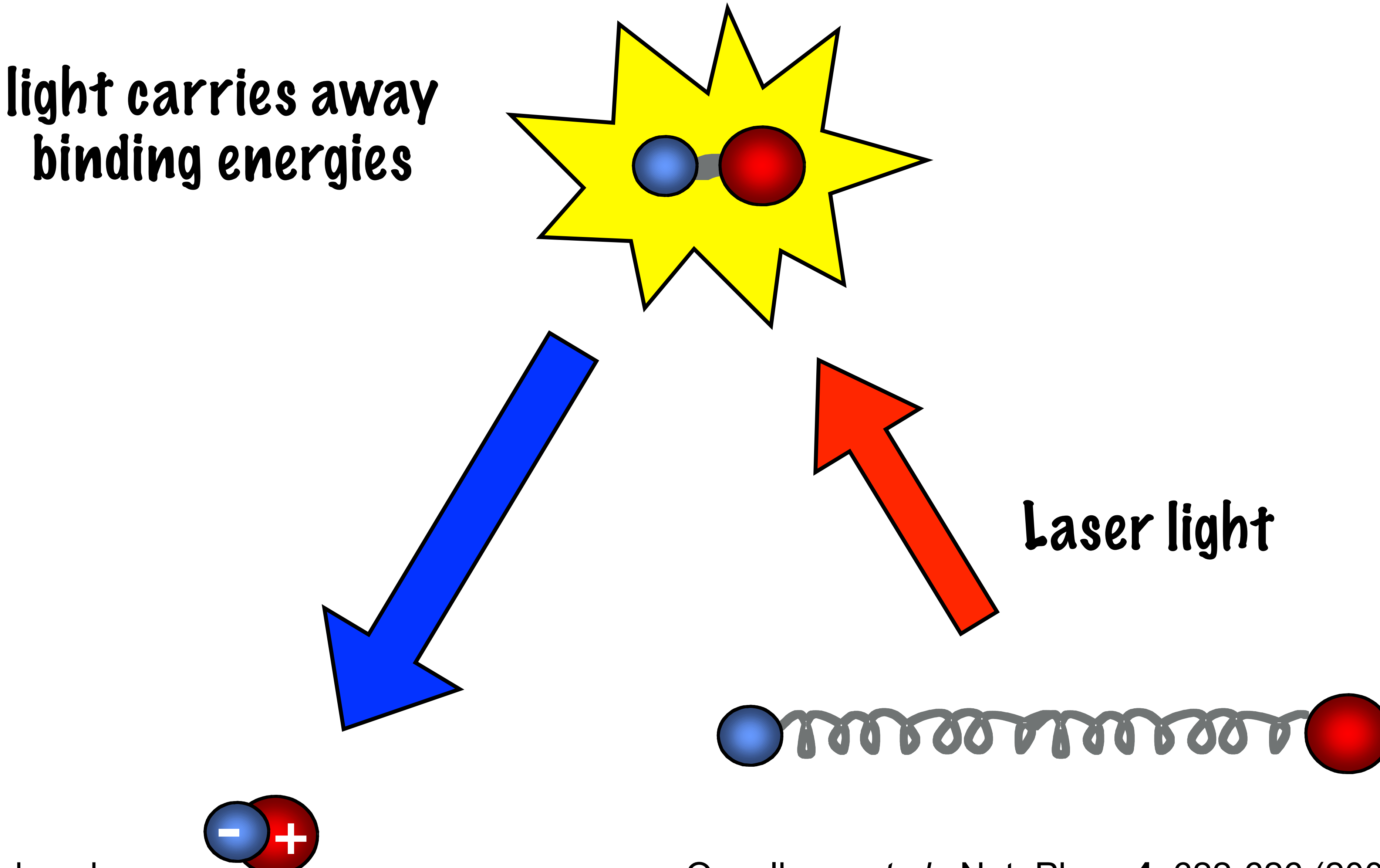

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light carries away
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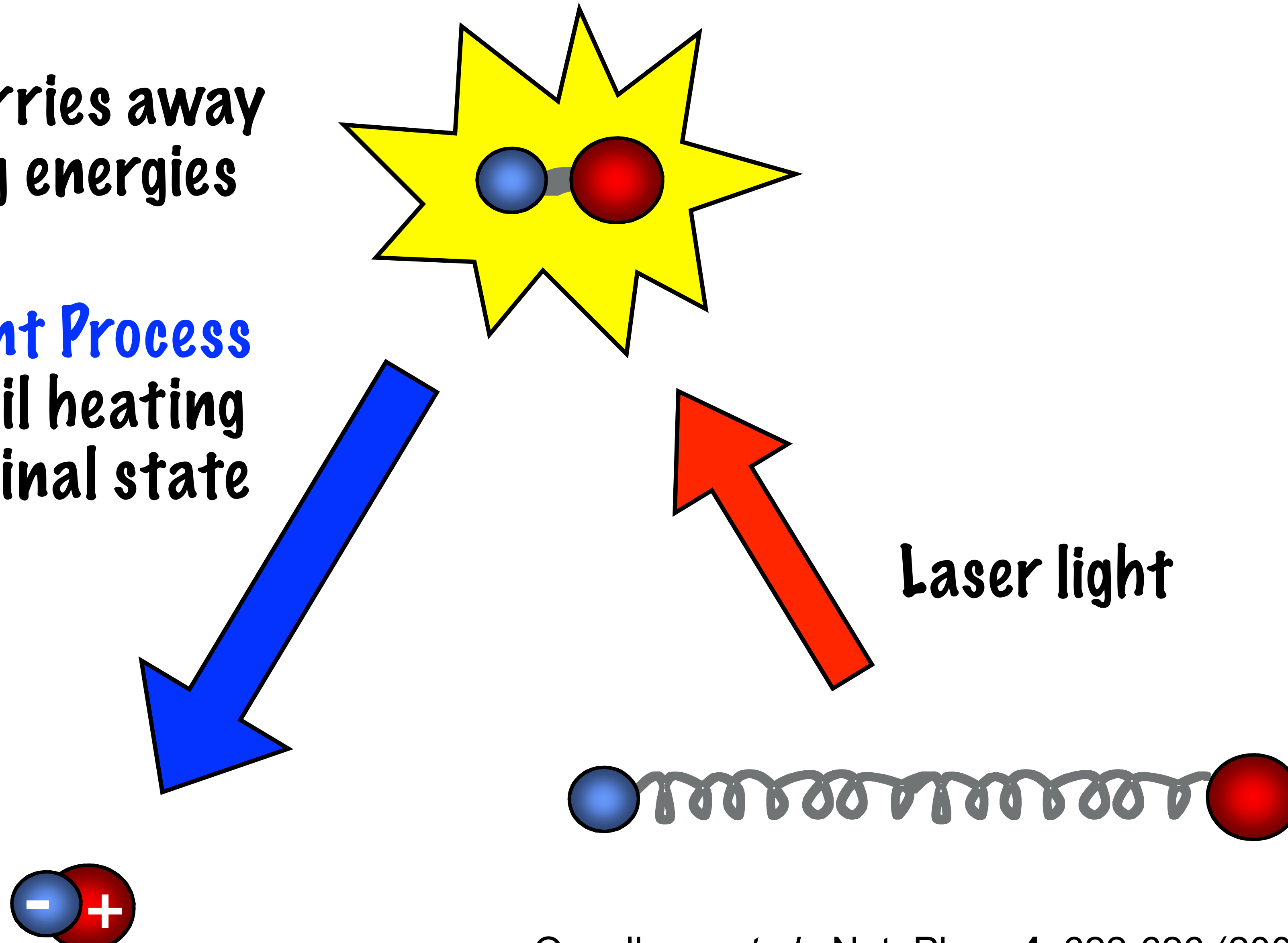
Coherent Process
no recoil heating
single final state



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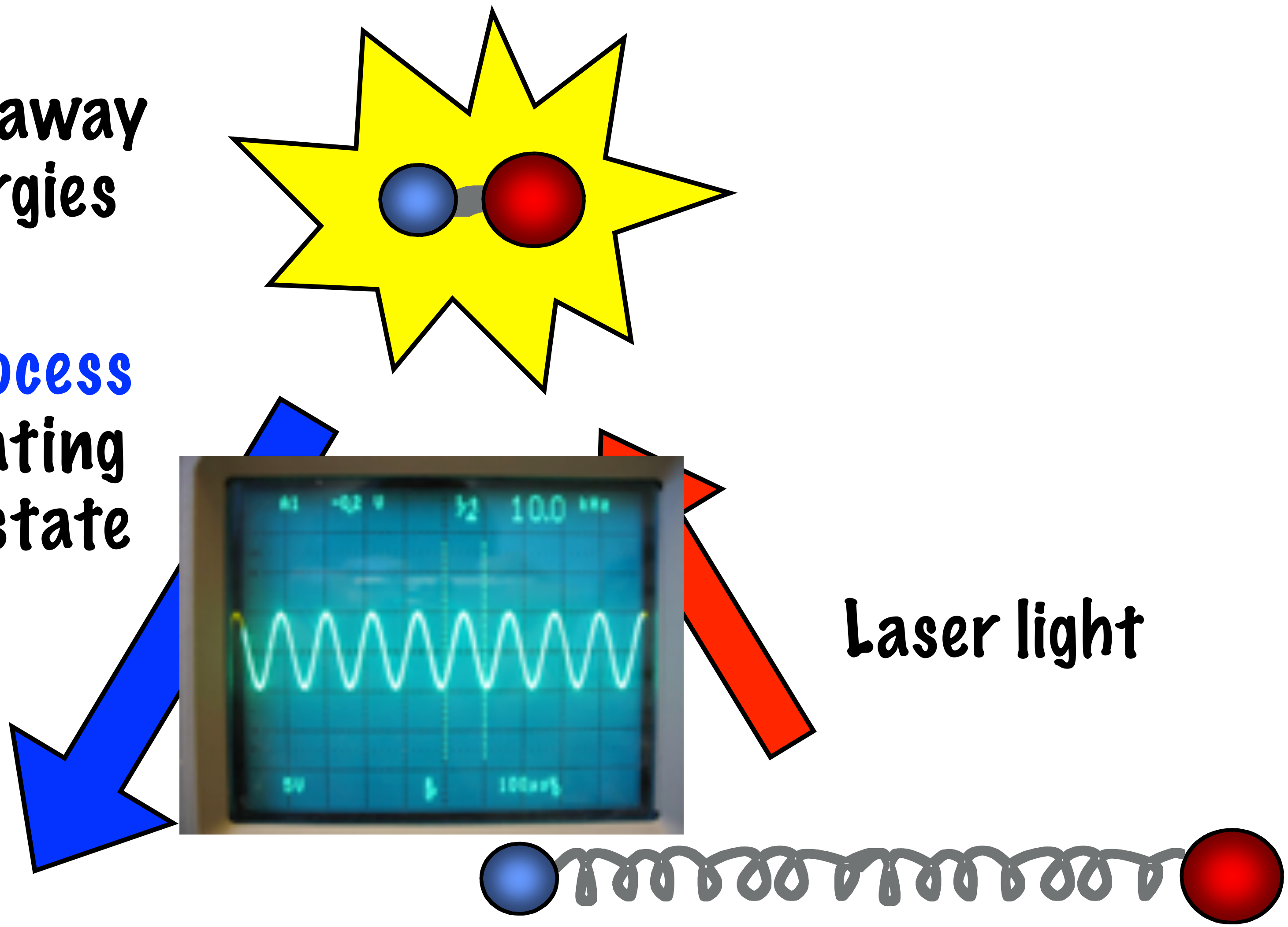
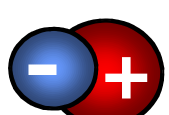


Laser light



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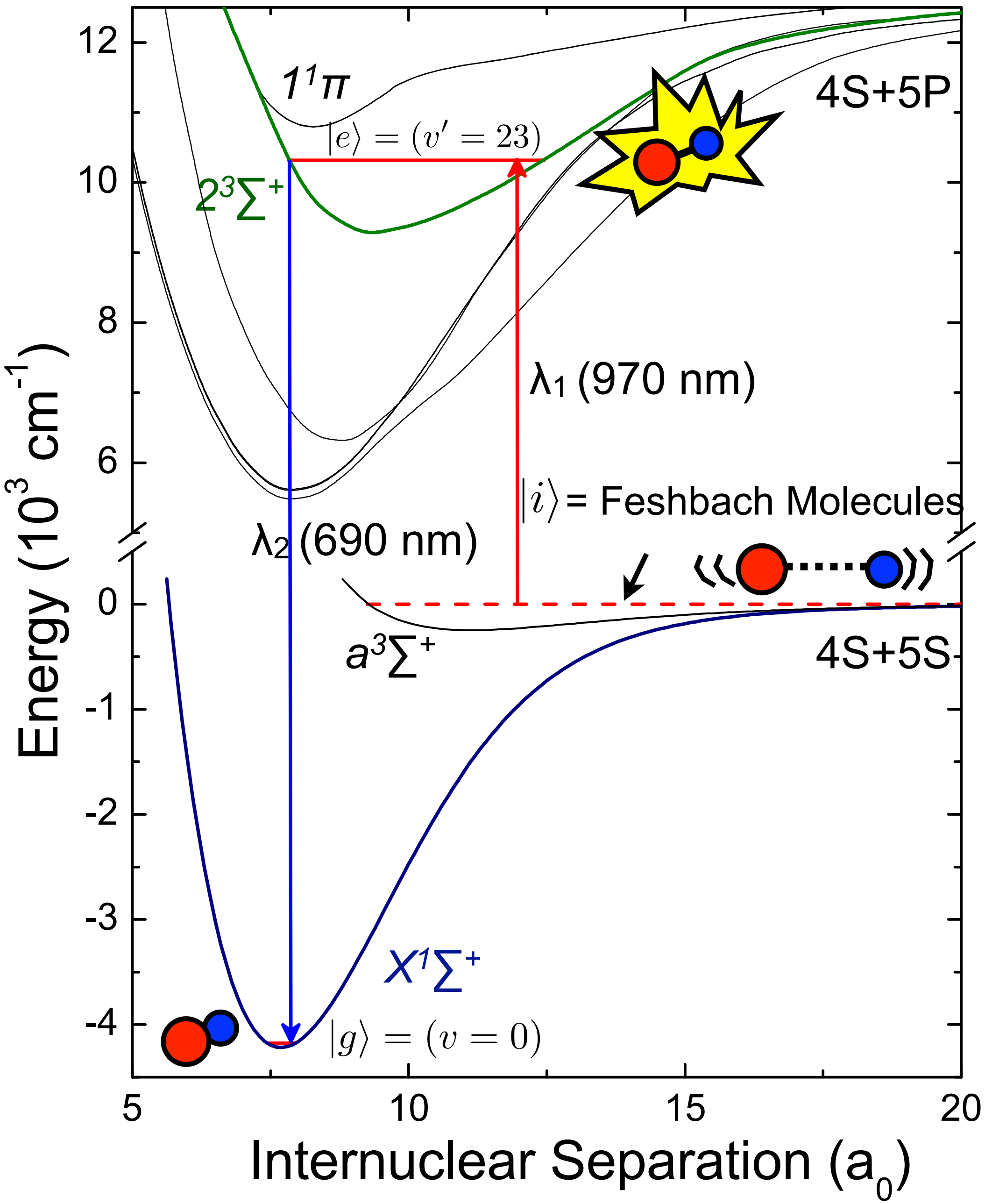
One Magic Bridge



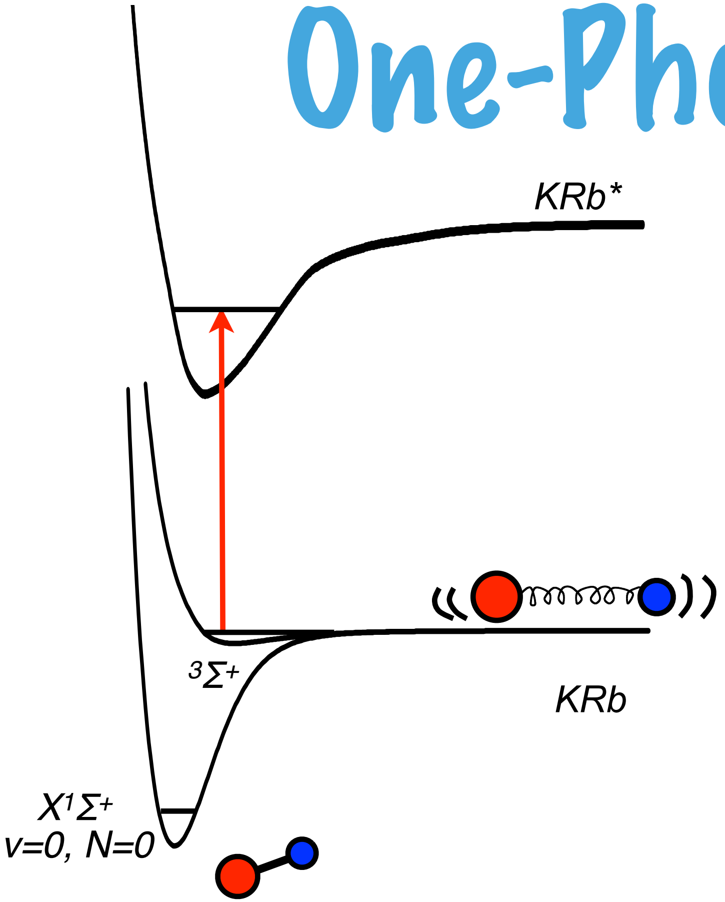
Large Franck-Condon factors

non-trivial triplet-singlet mixing

Ni *et al.*, Science **322**, 231 (2008)

Related photoassociation work:
Sage *et al.*, PRL **94**, 203001 (2005)

One-Photon Spectroscopy



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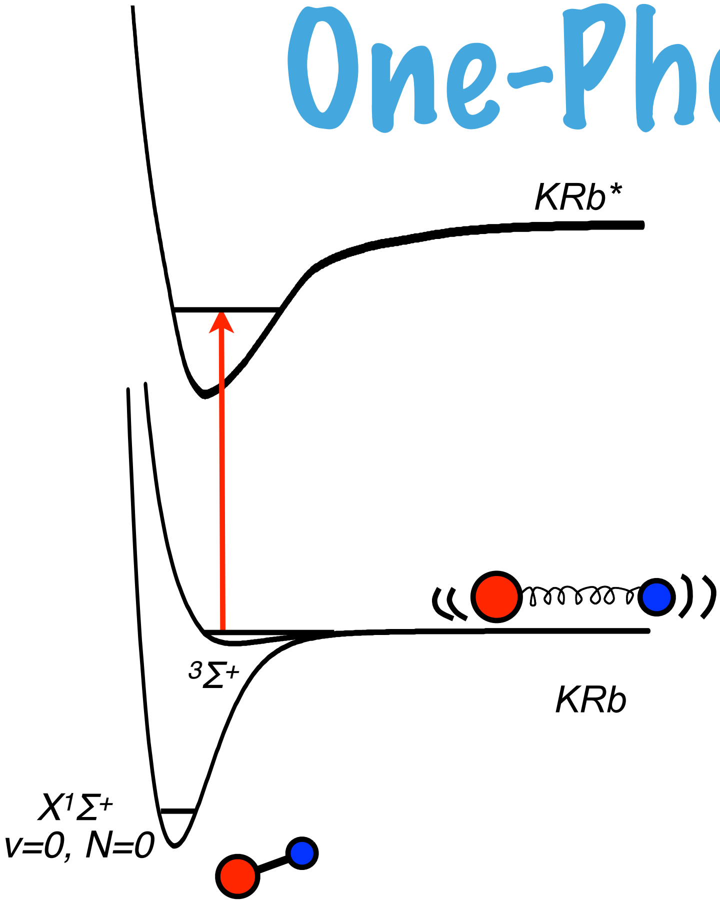

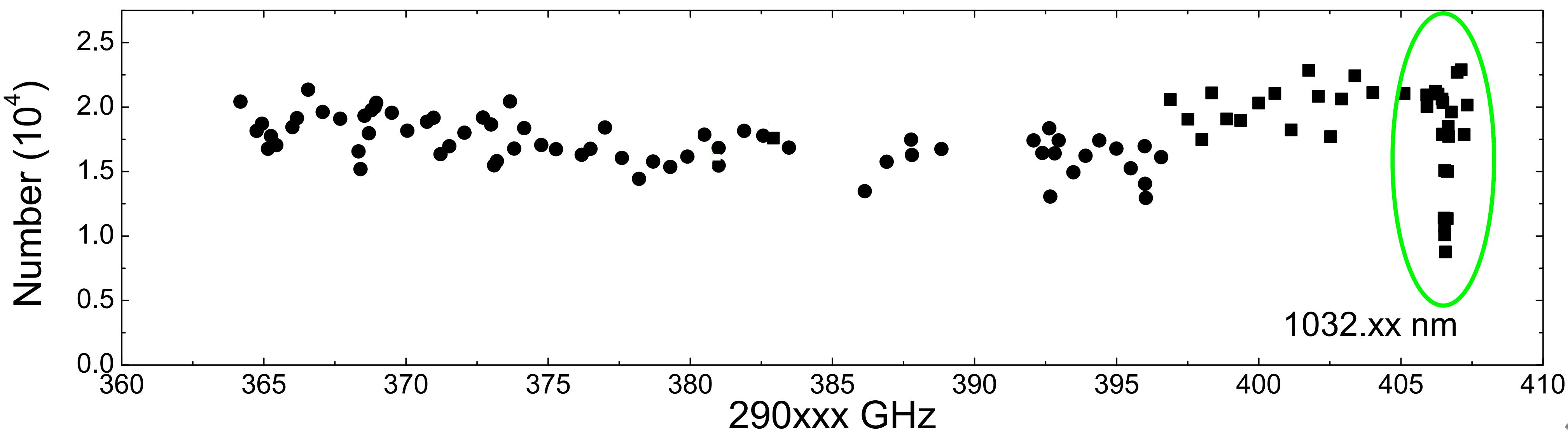

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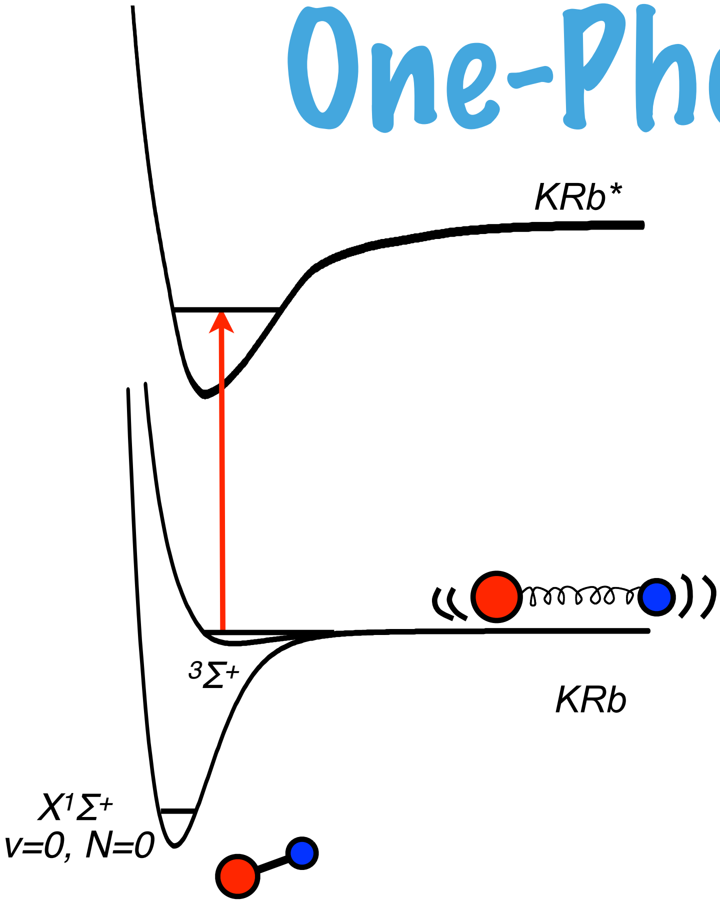

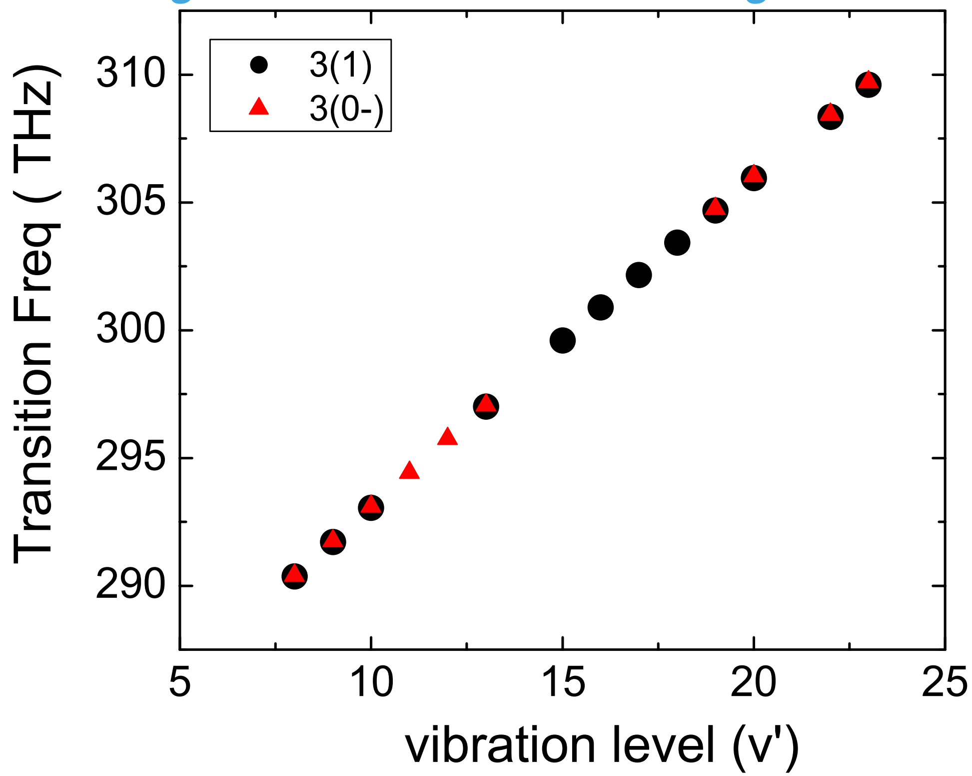

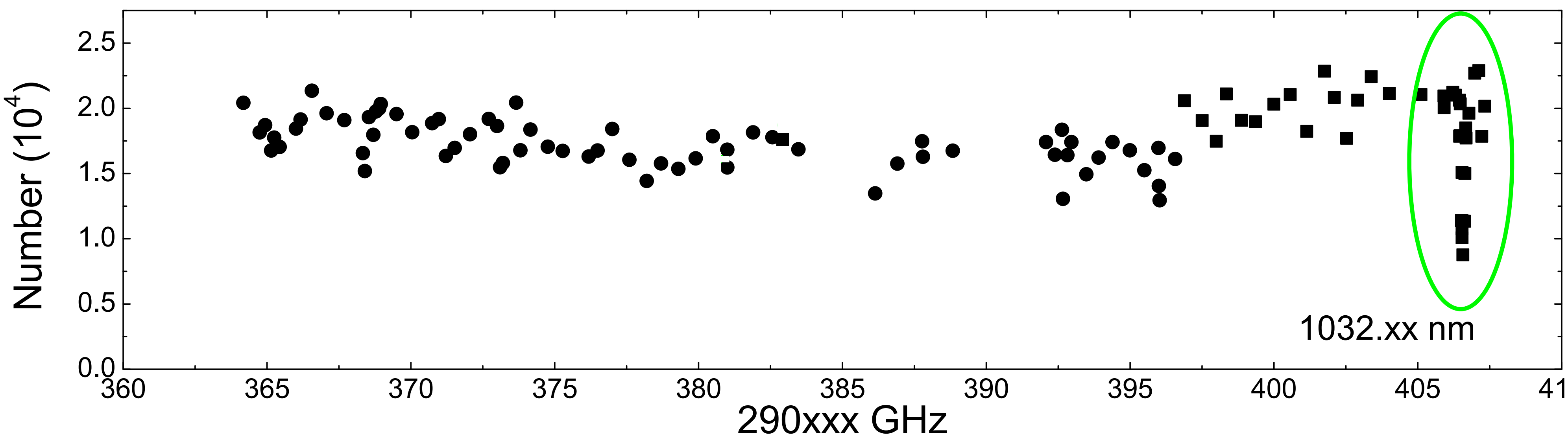

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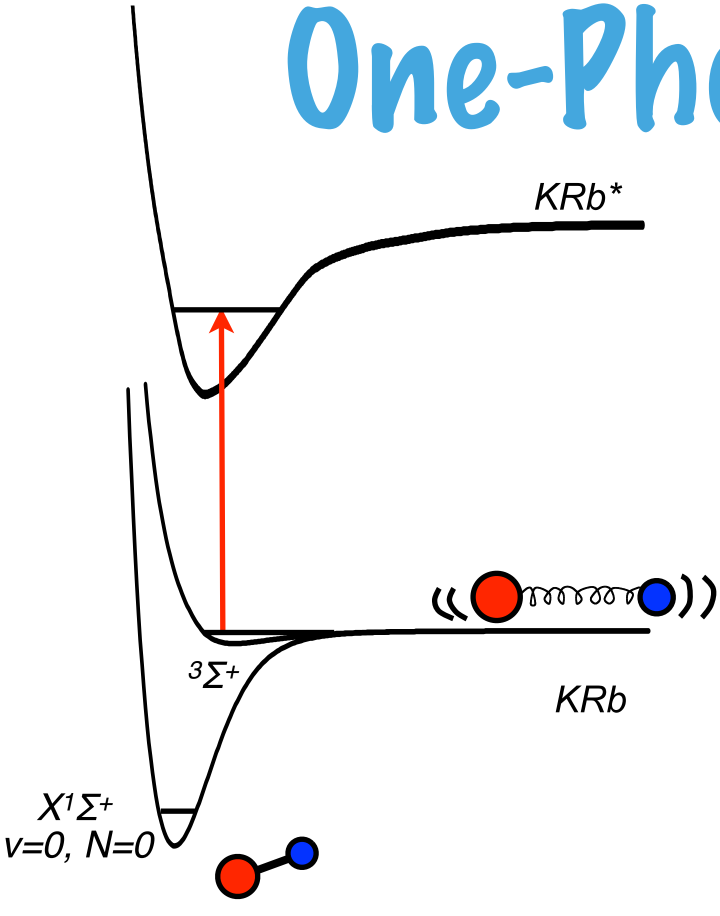
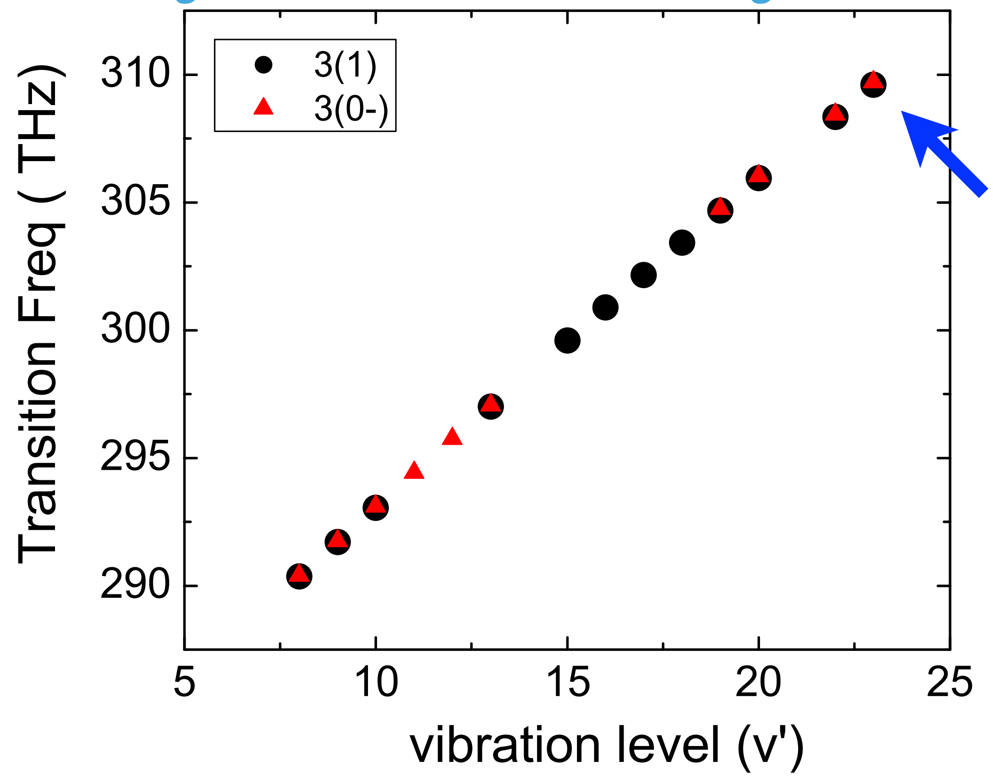
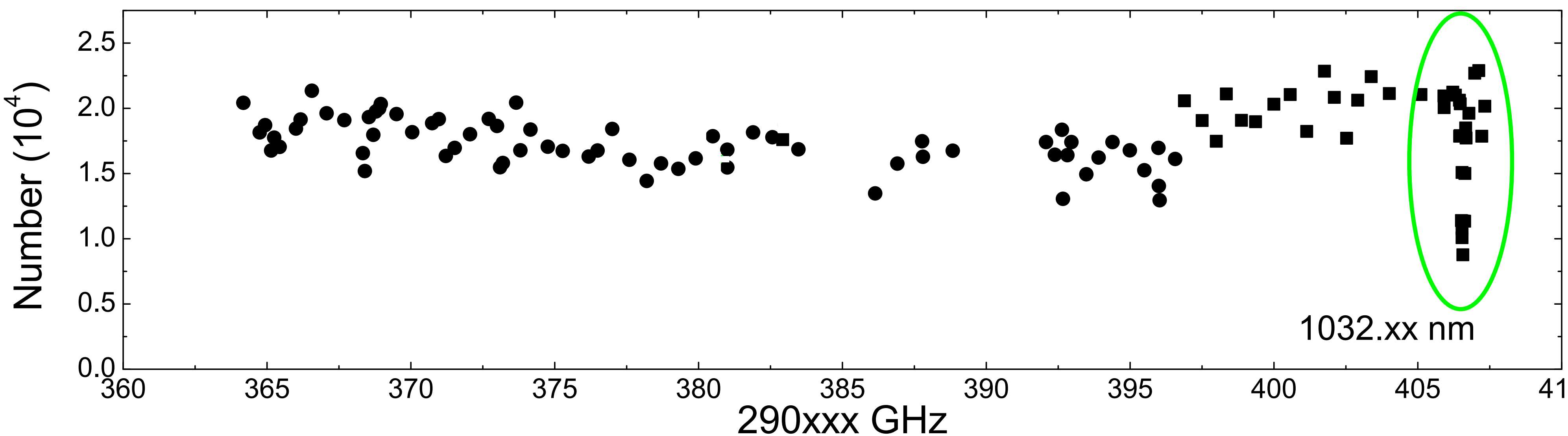
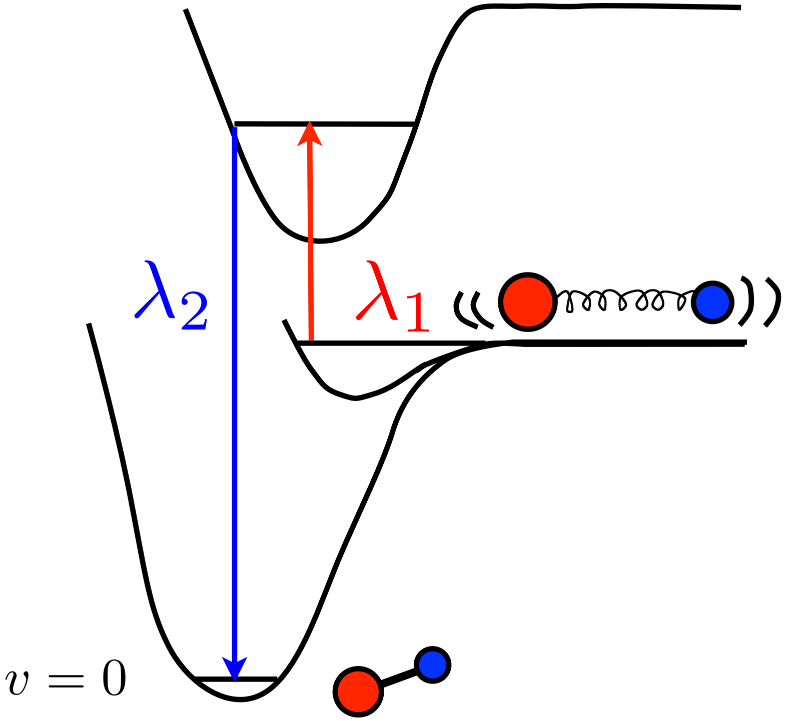




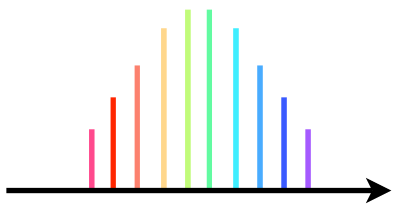


Dark Resonance

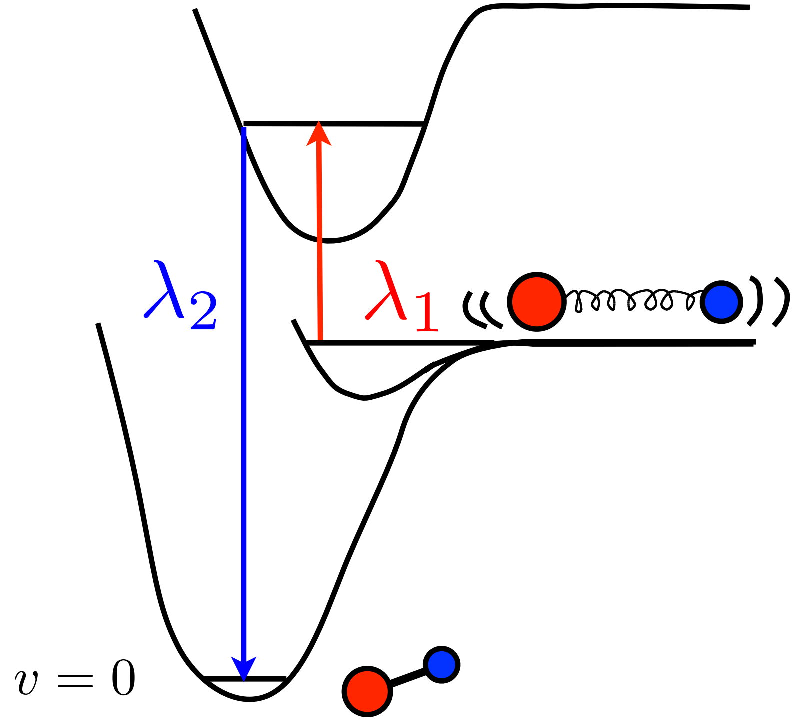


Arimondo and Orriol (1976)

Dark Resonance



bridging 125 THz



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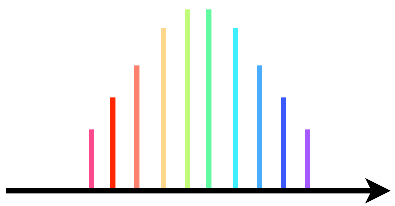

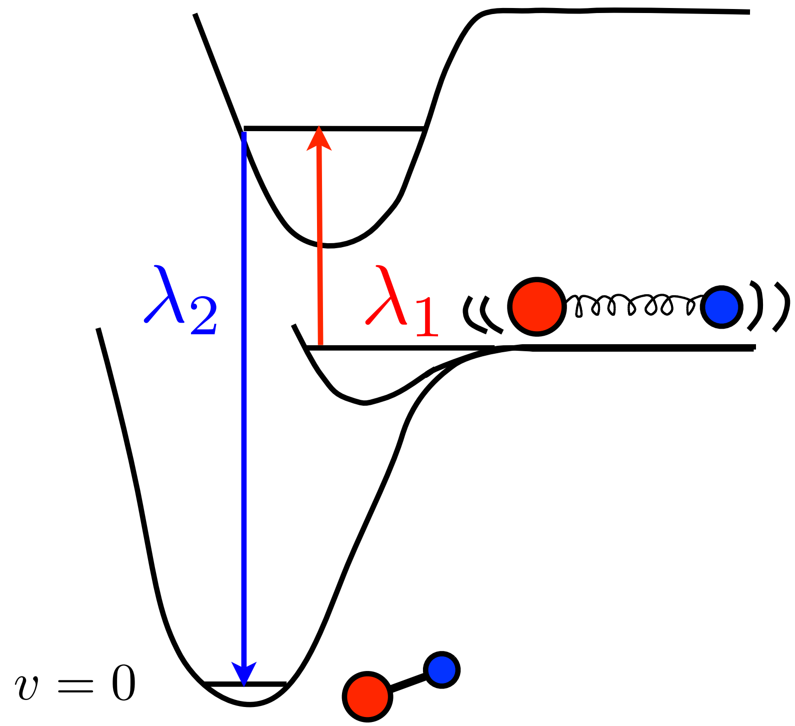

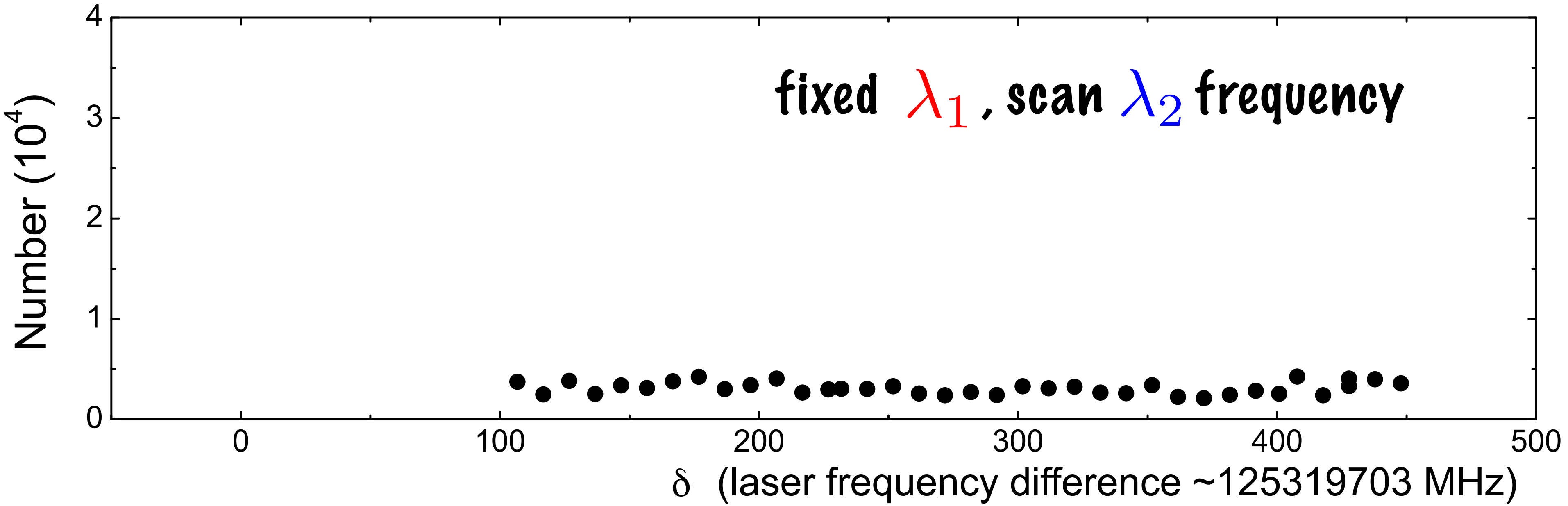

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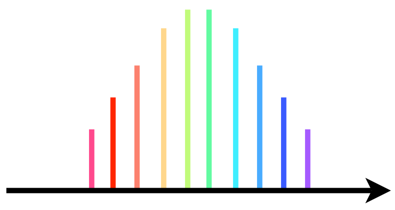

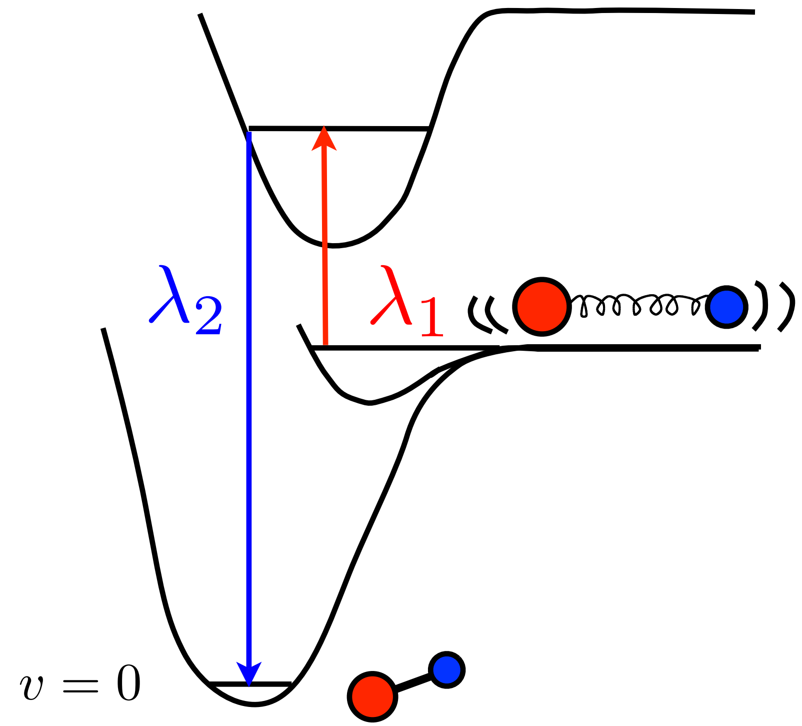

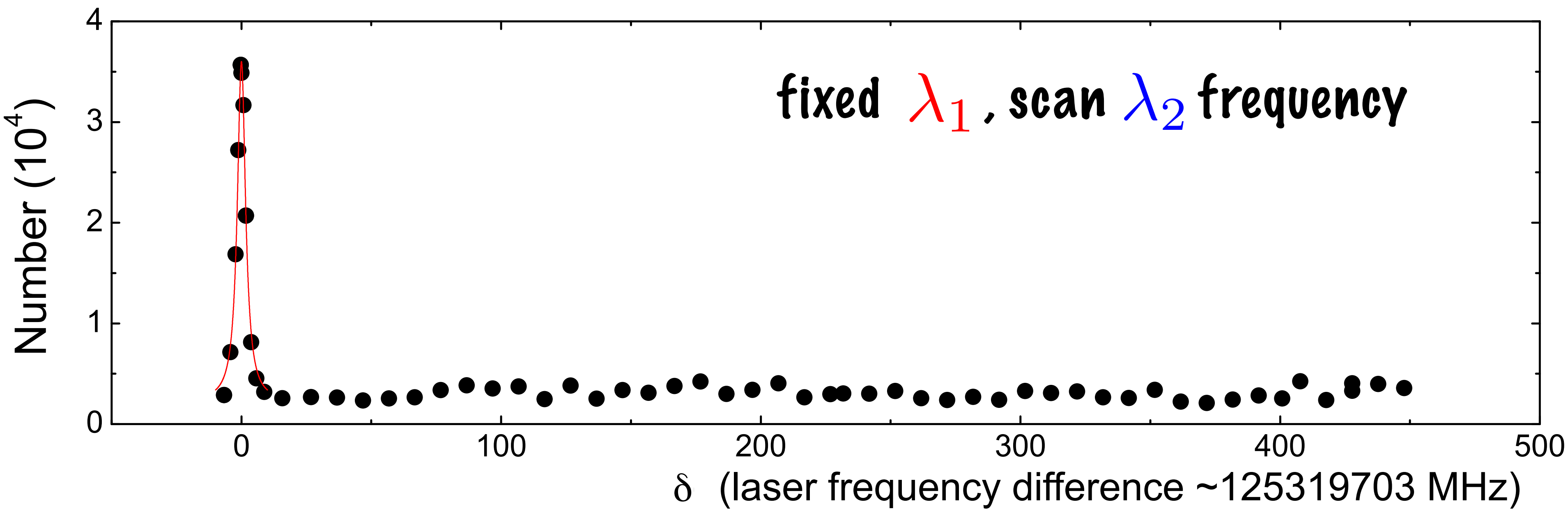

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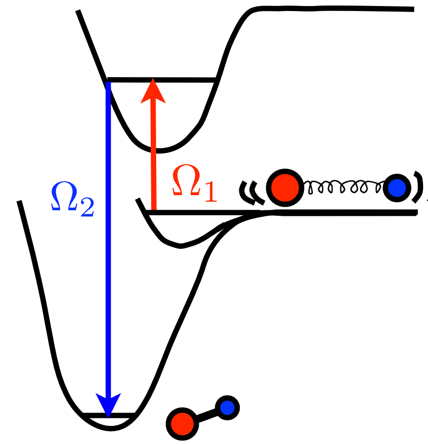
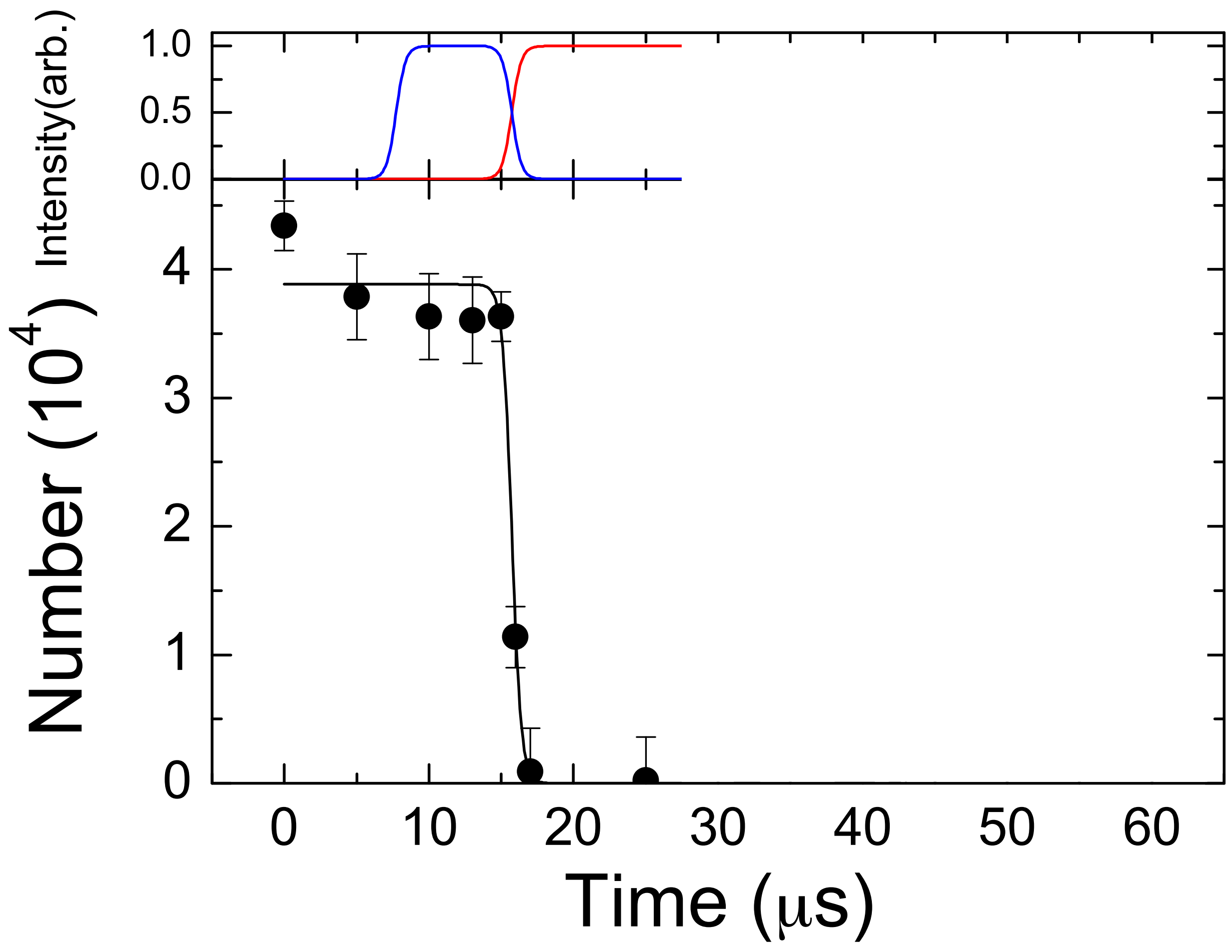
STIRAP

STImulated Raman Adiabatic Passage

4μs one-way transfer



v=0, *N*=0



>80-90% one-way efficiency

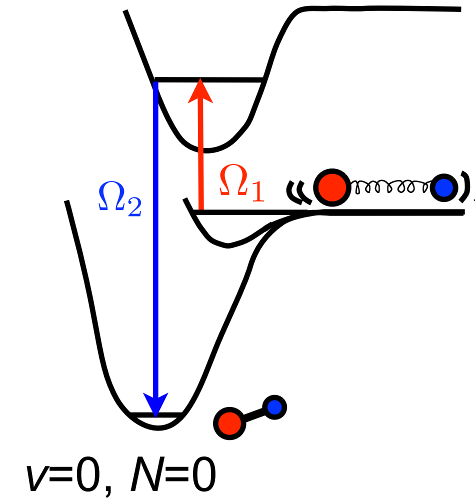
STIRAP review: K. Bergmann et al., RMP **70**, 1003-1025 (1998)

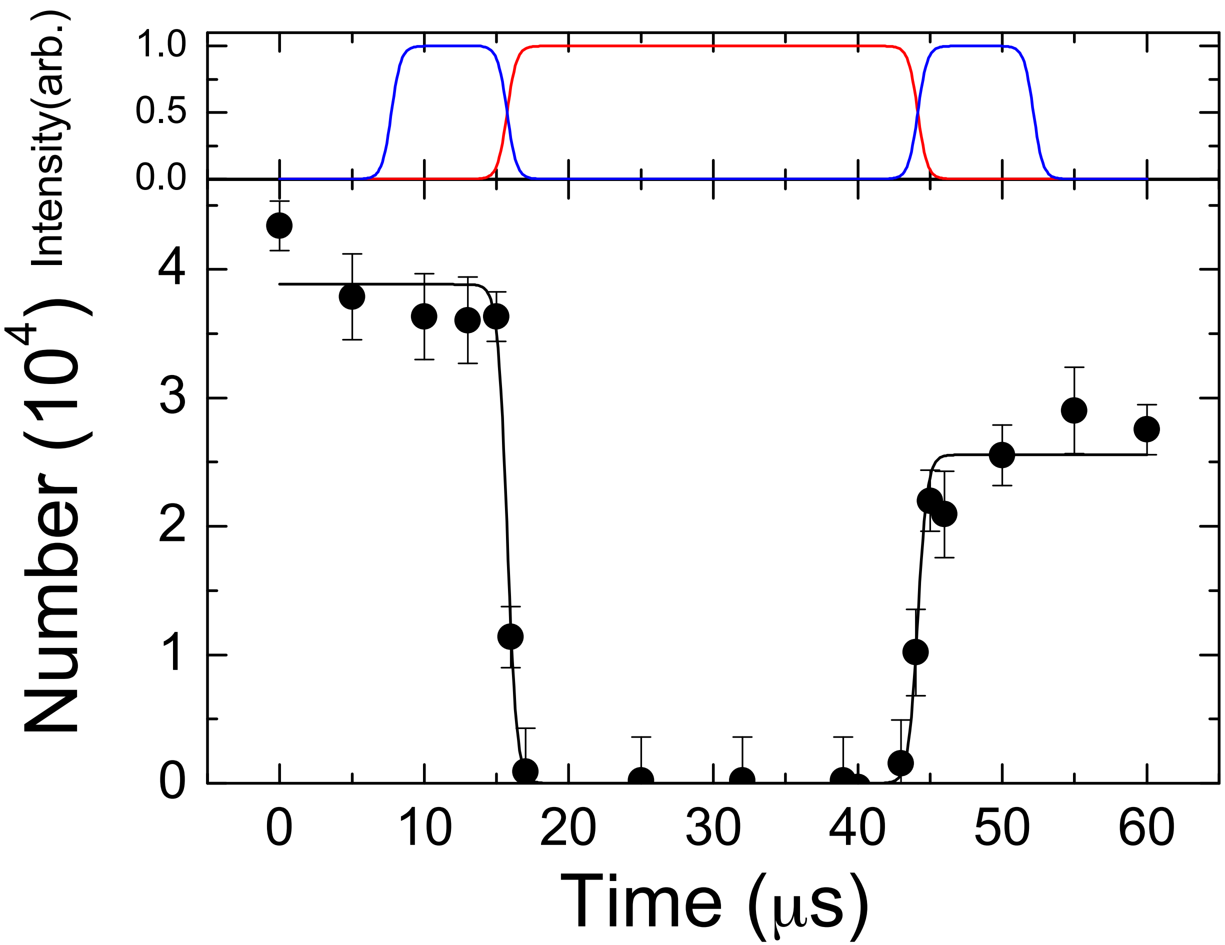
Related work for non-polar molecules, Cs_2 and Rb_2 (Innsbruck, 2008)

STIRAP

STImulated Raman Adiabatic Passage

4μs one-way transfer





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Trapped fermionic molecules

PSD = 0.06

peak density = $10^{12}/cm^3$

temperature = 160 nK

molecules in a single and lowest

rotational, vibrational, and electronic

ground state!

11 orders of magnitude improvement from previous results

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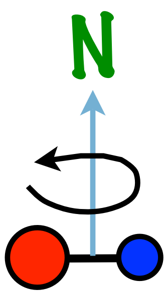
what about hyperfine structure?

Reaching the Lowest Hyperfine State

v=0, N=0, electronic orbital=0, electronic spin =0
but with nuclear spins:

36 total states

N=1



N=0

m_I

m_I+1

Ospelkaus, Ni, Quéméner *et al*. PRL **104**, 030402(2010)

Reaching the Lowest Hyperfine State

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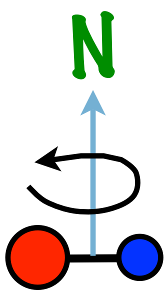
36 total states

>90%   <10% admixture

N=1 mF= m_N-1 + m_I+1 ———— m_N + m_I



strong nuclear electric quadruple interactions

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m_I

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Ospelkaus, Ni, Quéméner *et al*. PRL **104**, 030402(2010)

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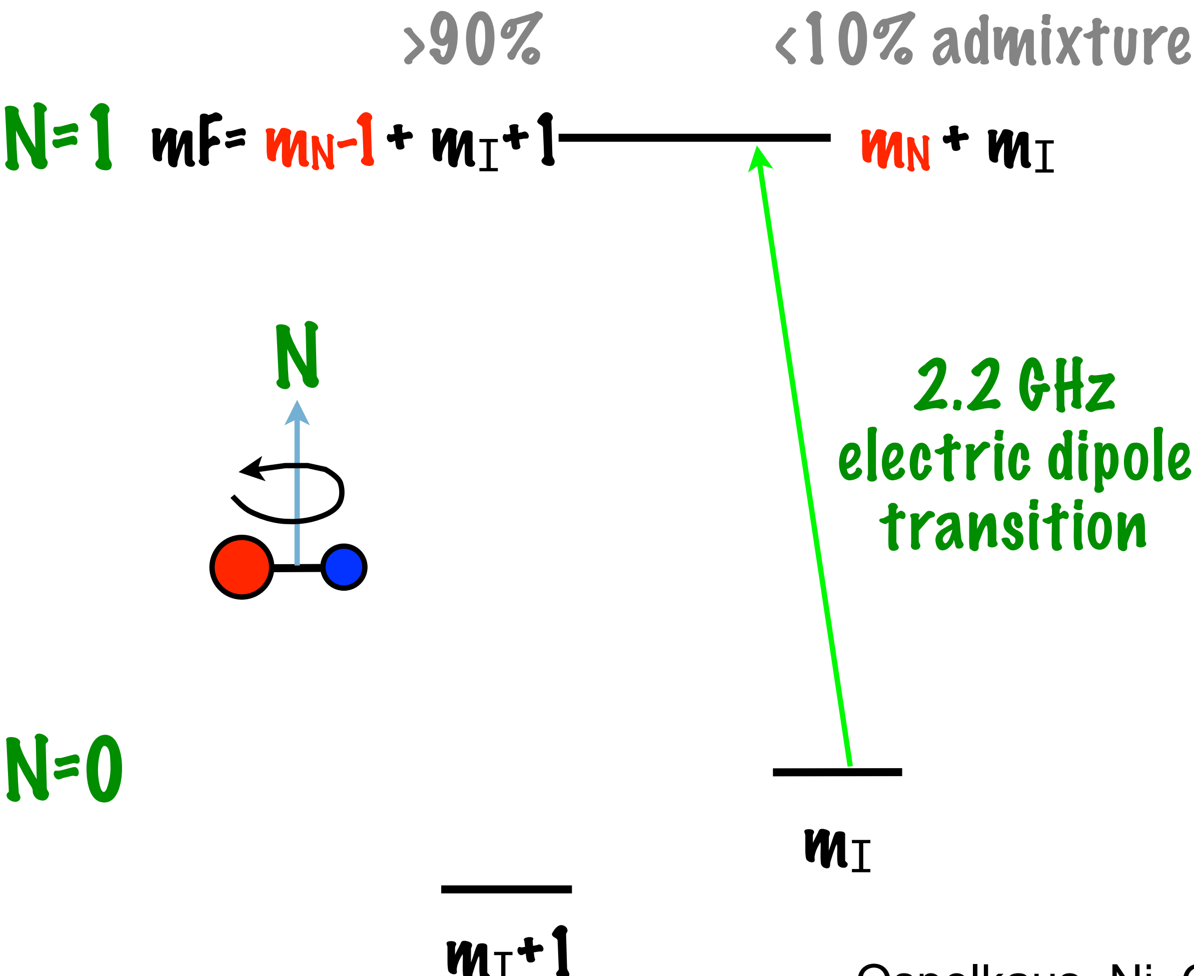

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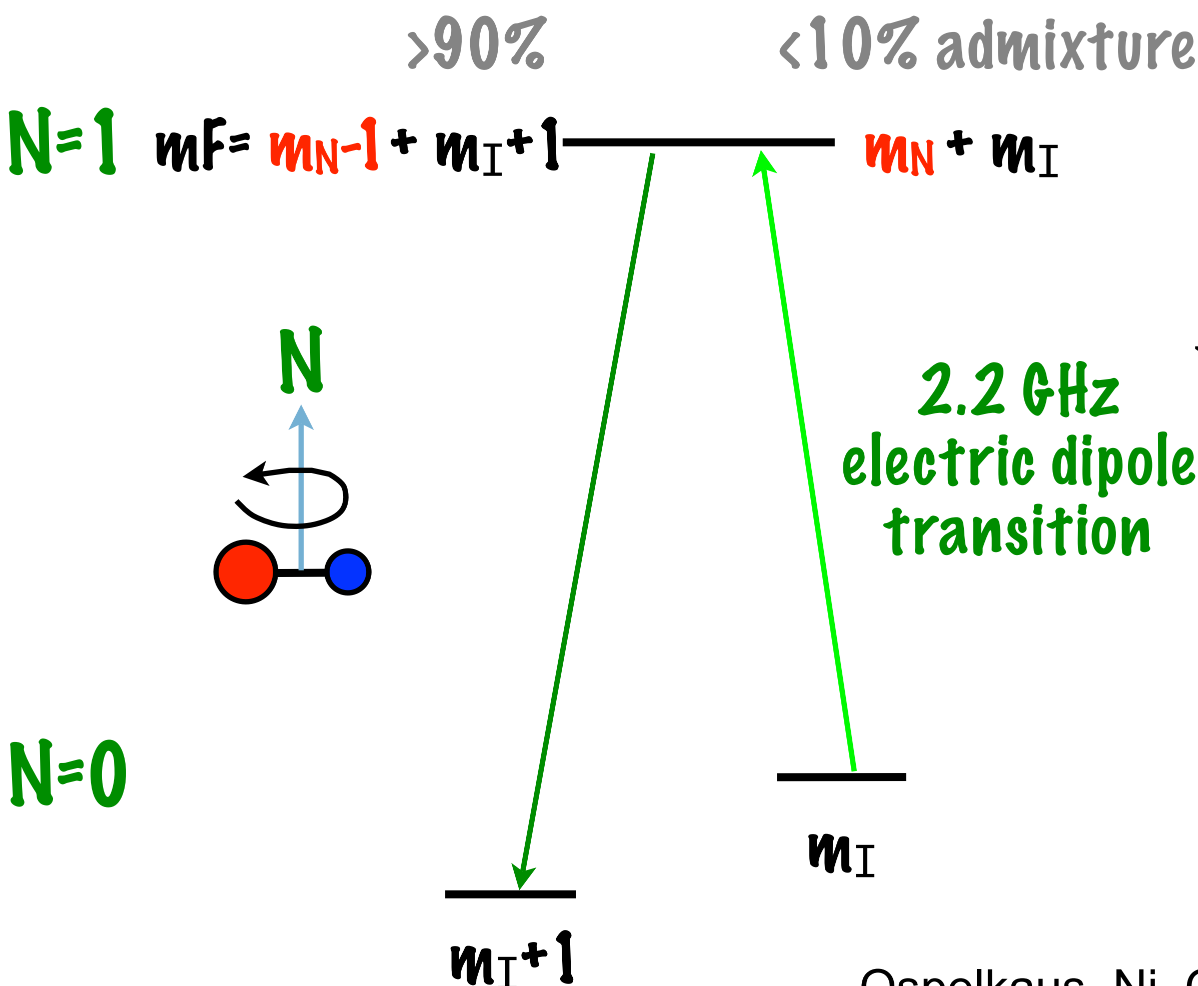
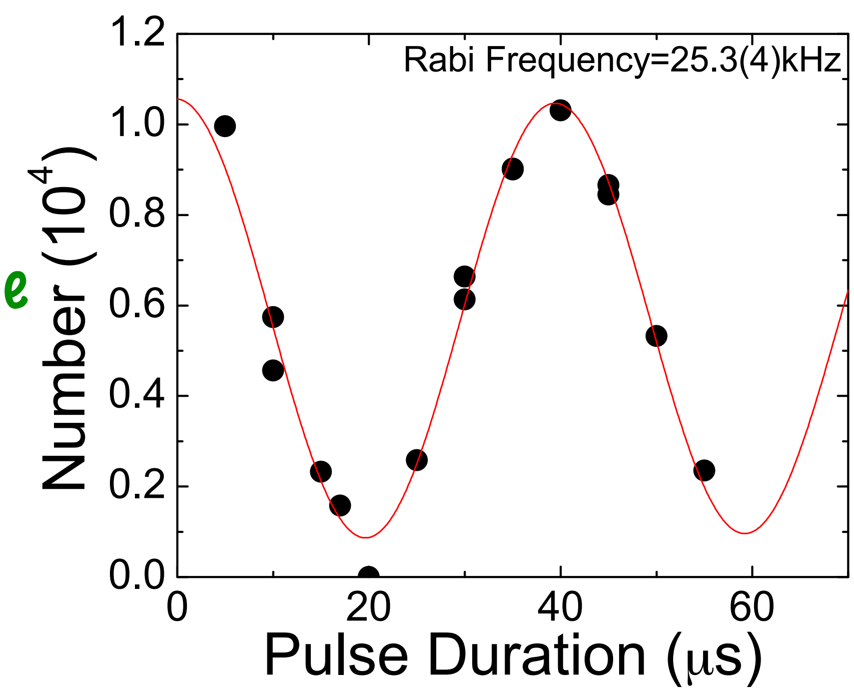




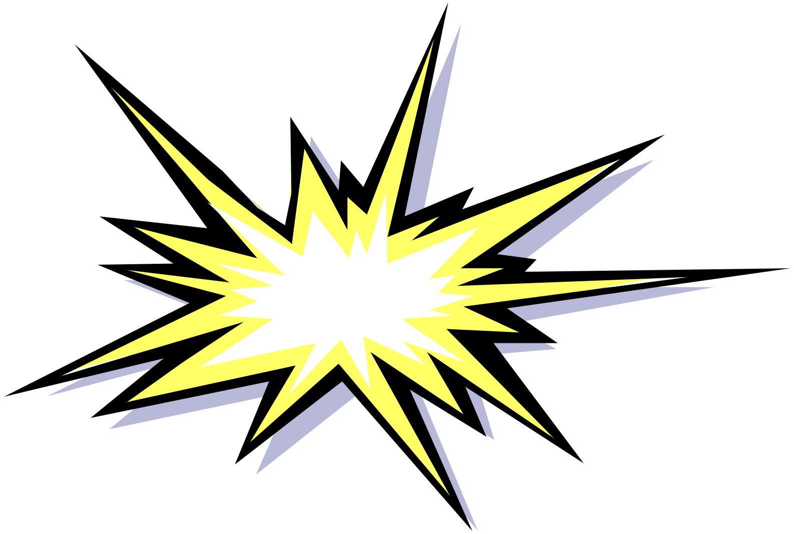
Ospelkaus, Ni, Quéméner *et al*. PRL **104**, 030402(2010)

molecules in the lowest energy state

(electronic, vibrational, rotational, and hyperfine)

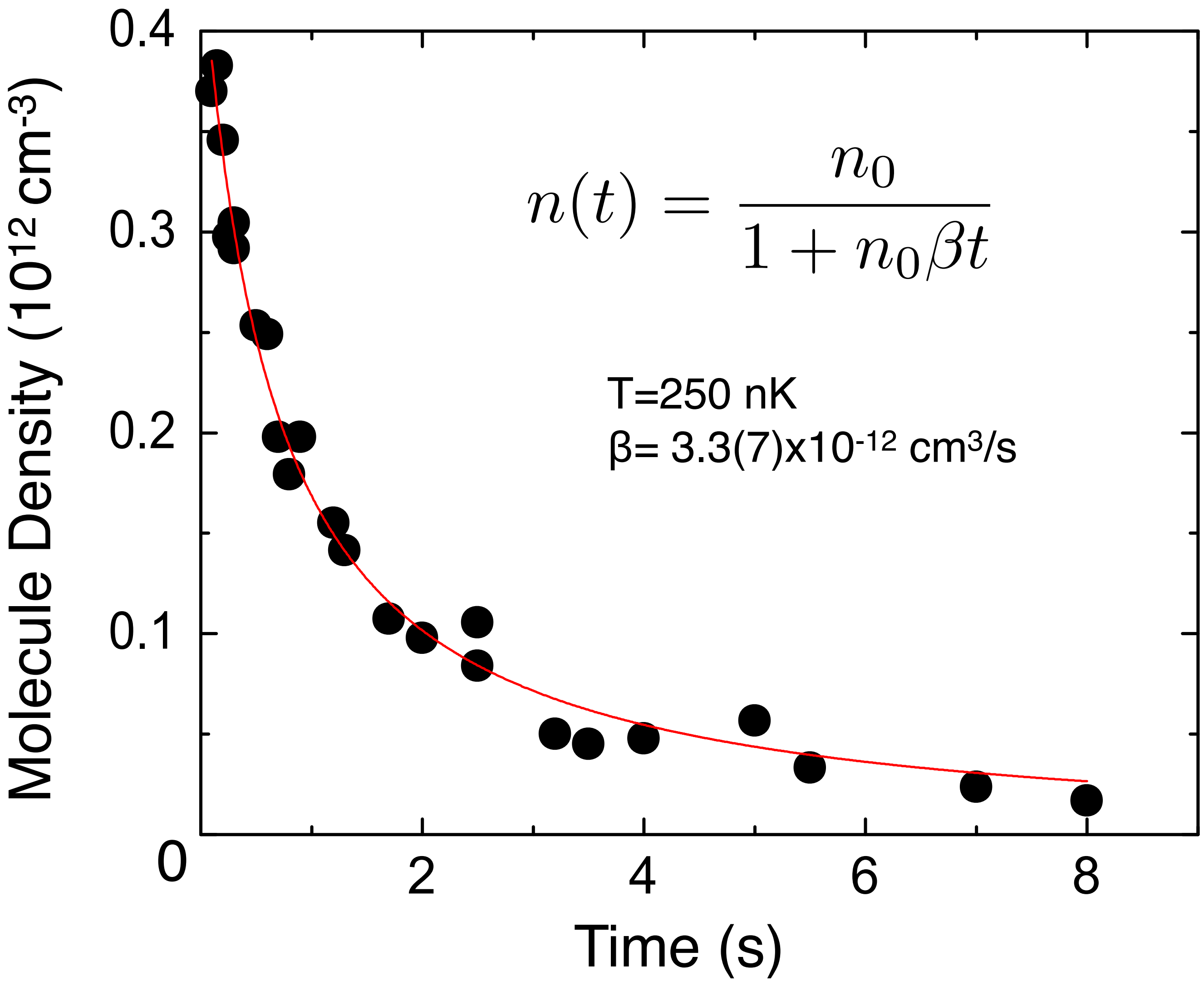
can they decay?

what determines the rate?



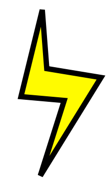
Long-Lived Molecules...

two-body loss $\dot{n}(t) = -\beta n(t)^2$



Ultracold Chemistry?!

possible exothermic reaction

$KRb + KRb \rightarrow K_2 + Rb_2 +$ 

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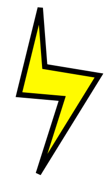
$KRb + KRb \rightarrow K_2 + Rb_2 +$ 

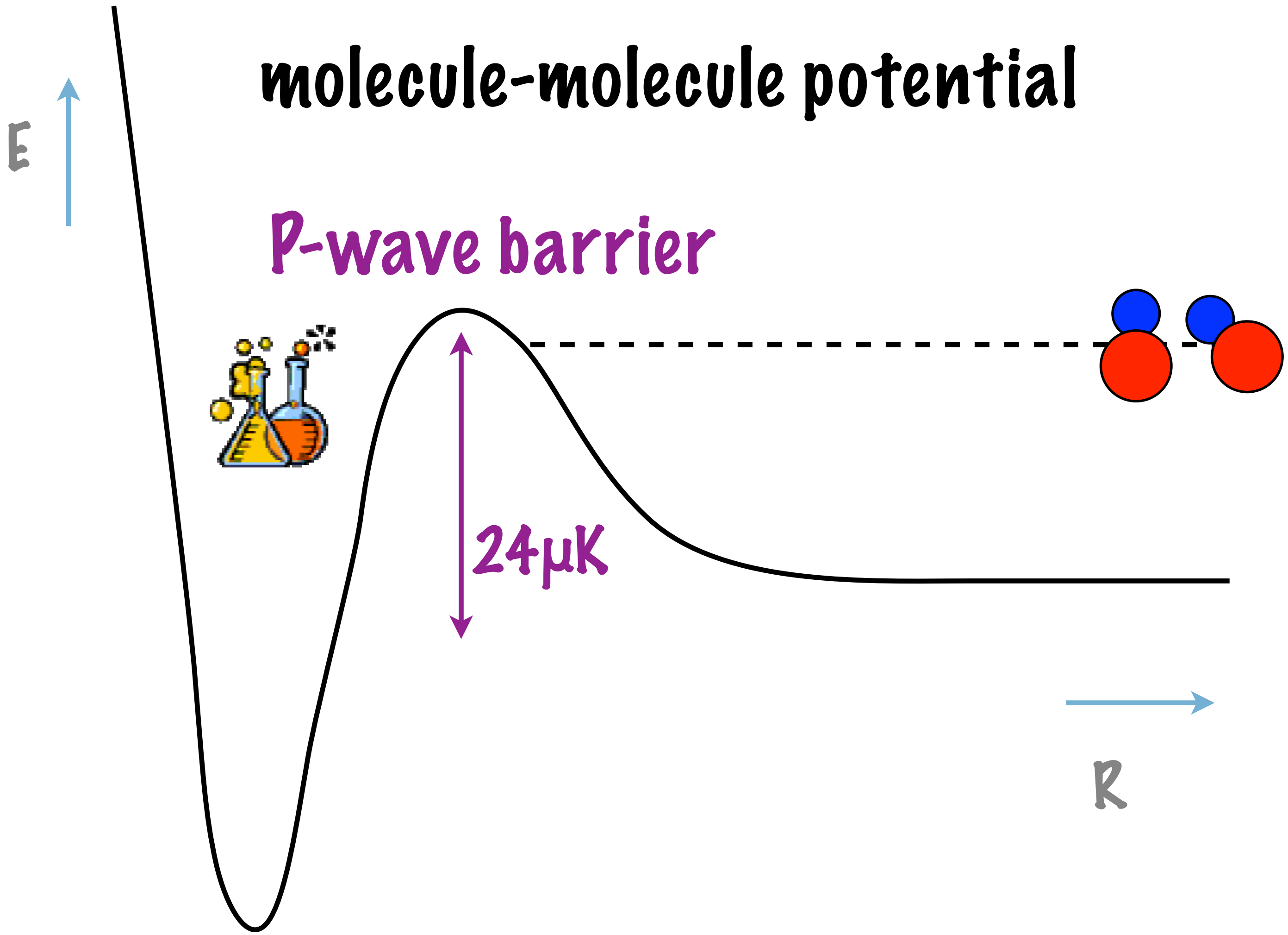
but our molecules are spin-polarized fermions...

collisions should be suppressed at ultralow T

Utracold Fermi Gas of Molecules

Wigner Threshold Law
for inelastic collisions

$\beta \propto T^L$, L=1 (p-wave)



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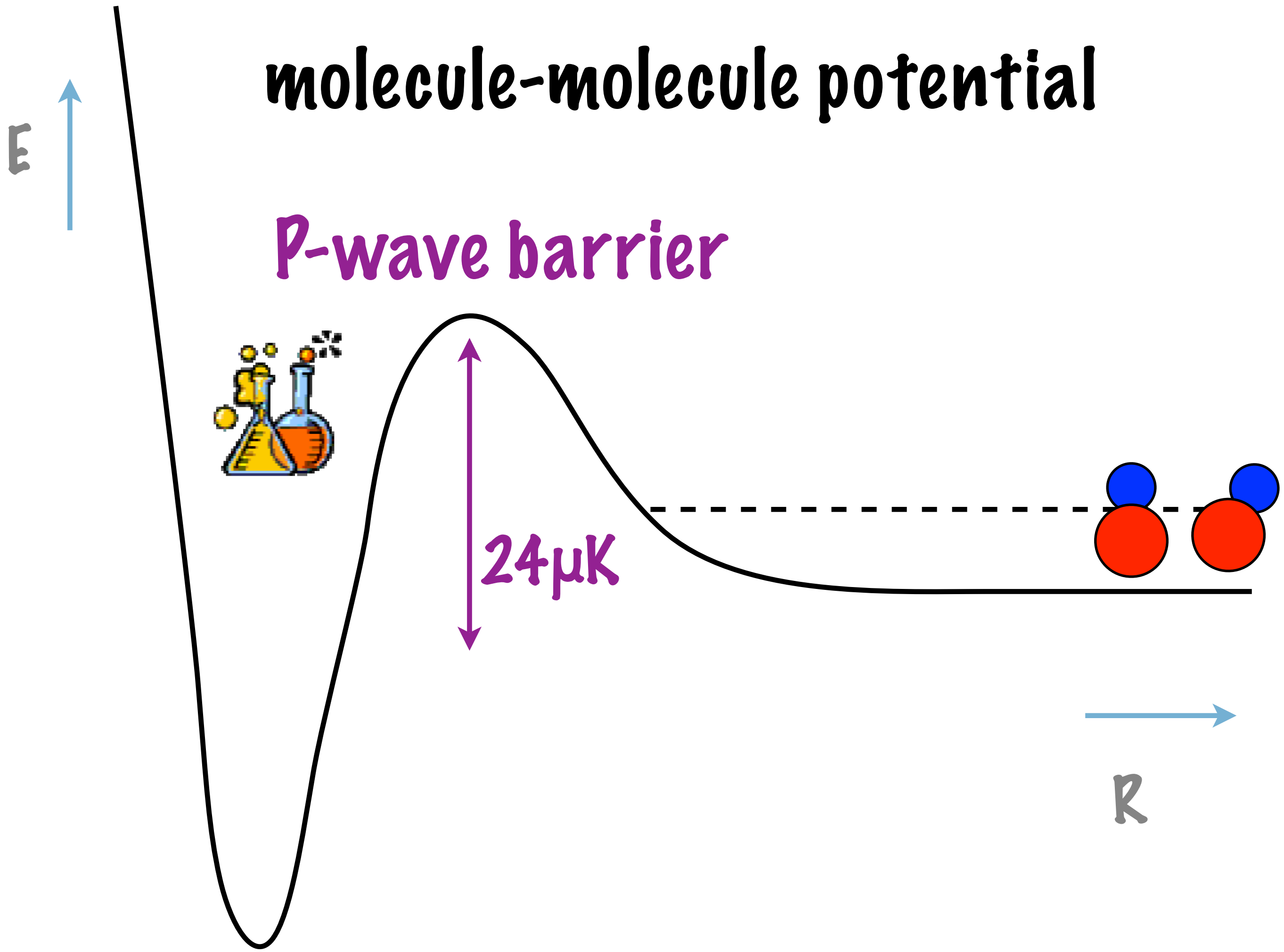
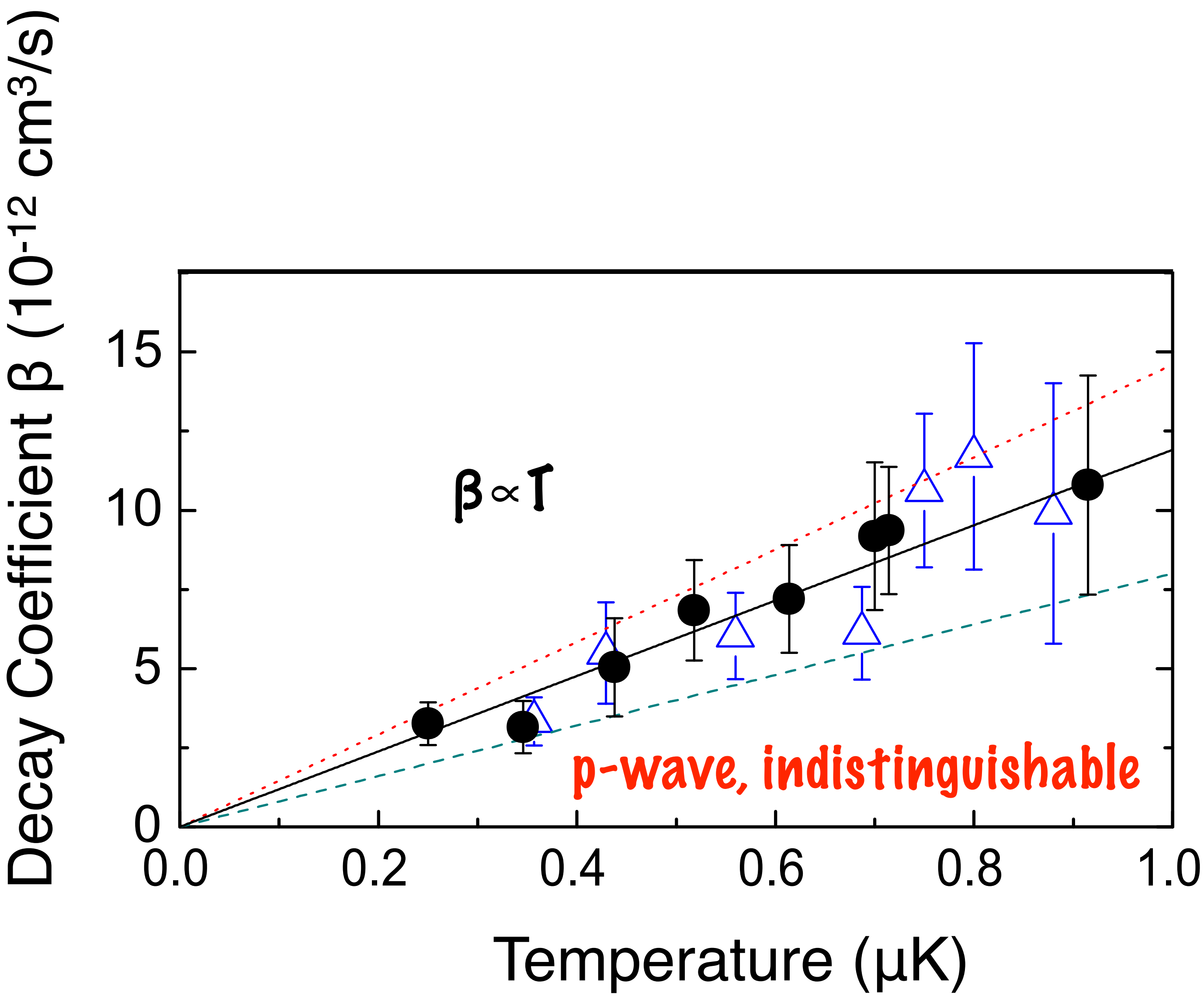
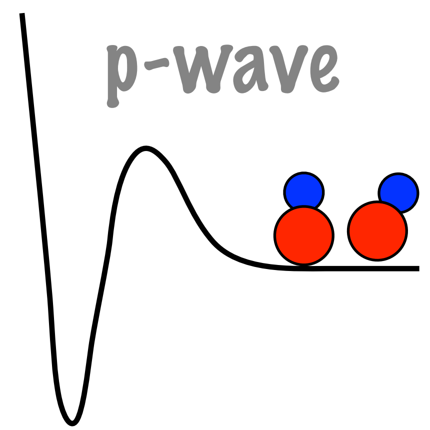


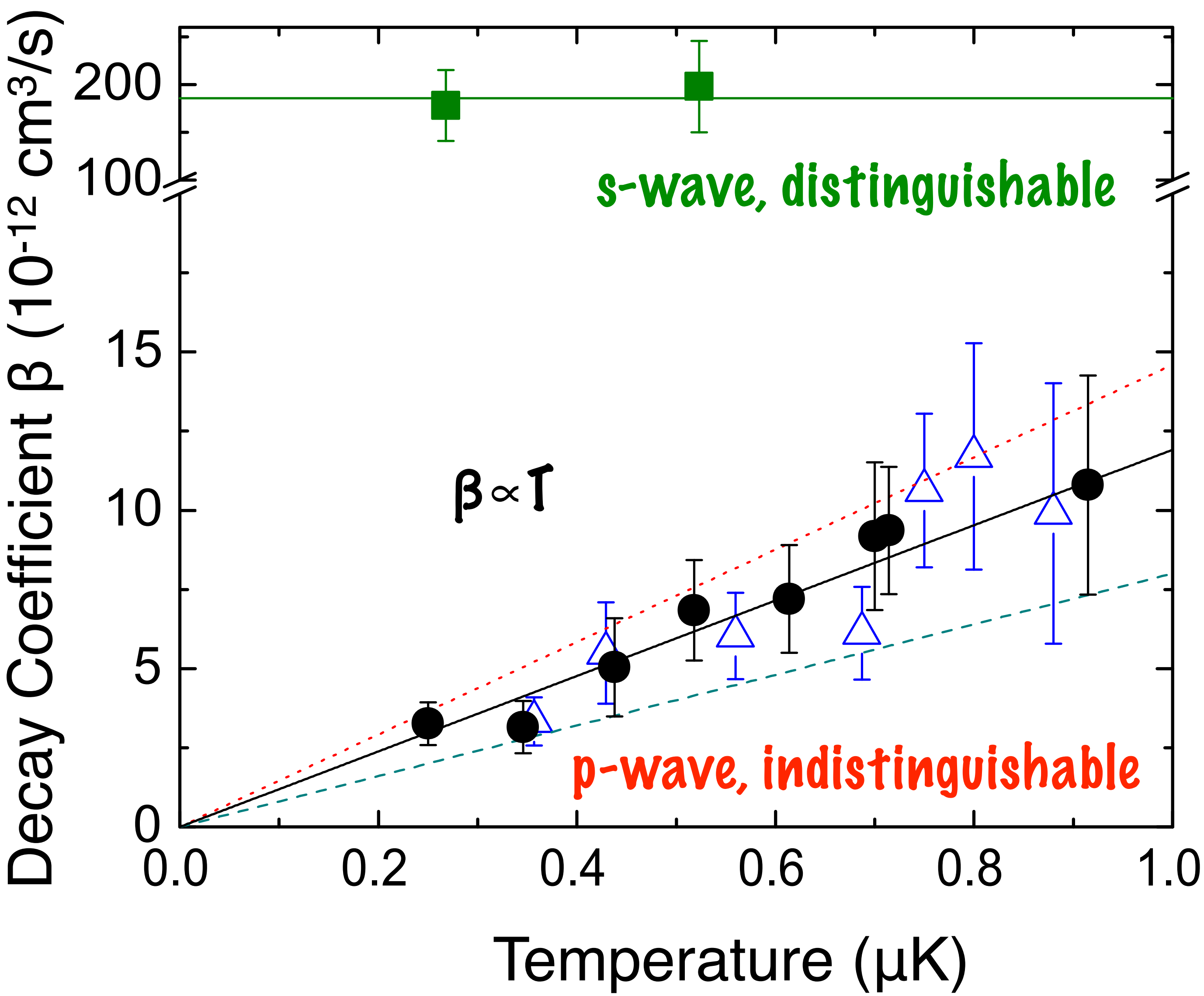
Molecular Inelastic Collisions - Wigner Threshold Law

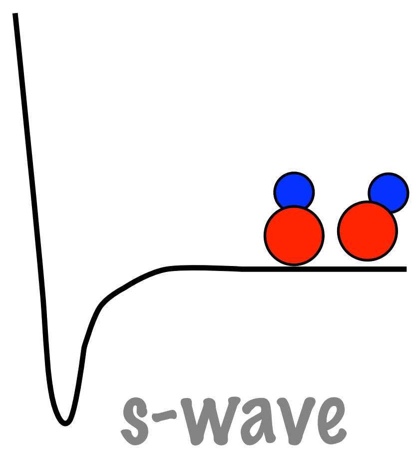




Ospelkaus, Ni *et al.*,
Science **327**, 853 (2010)

Molecular Inelastic Collisions - Wigner Threshold Law

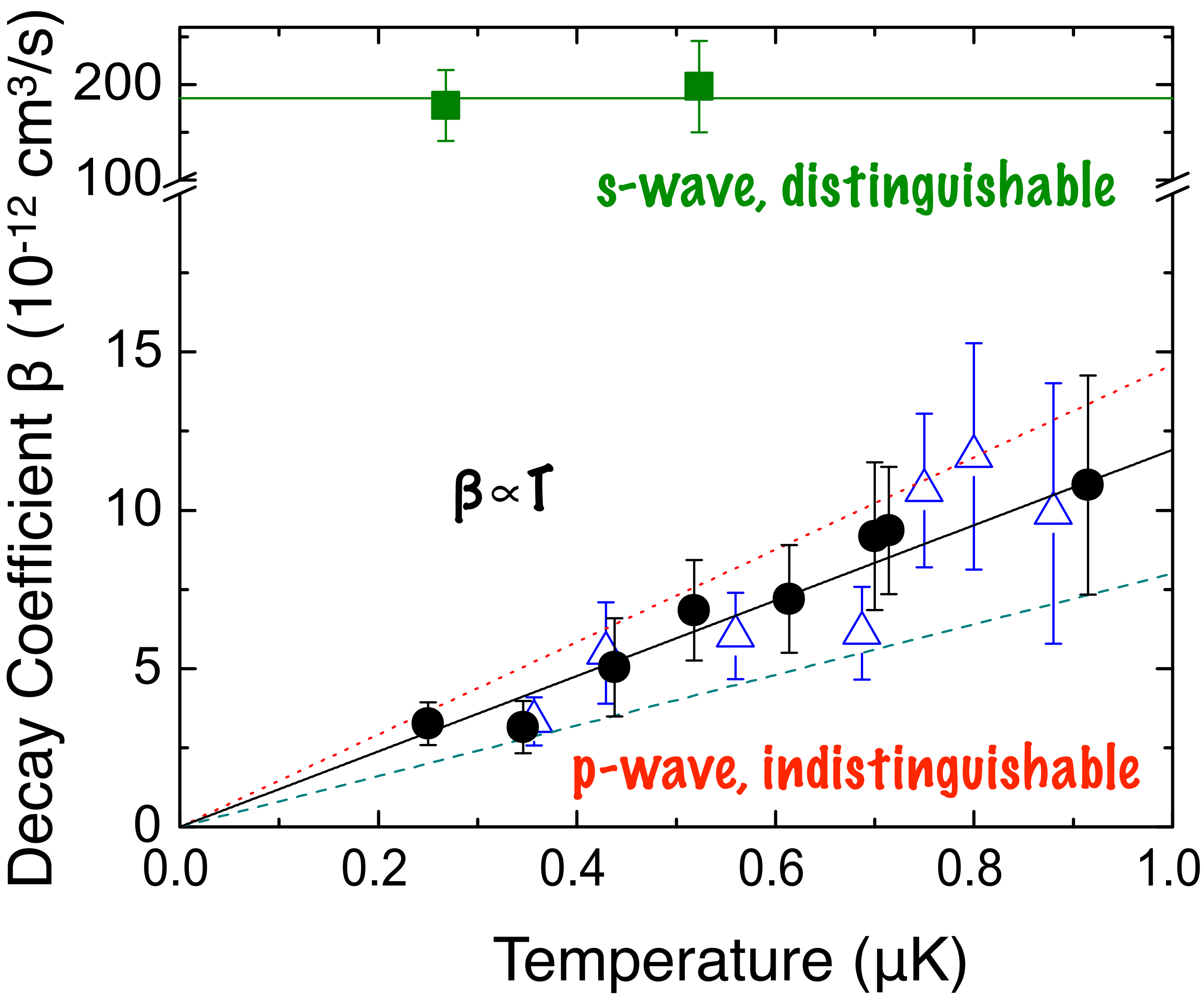


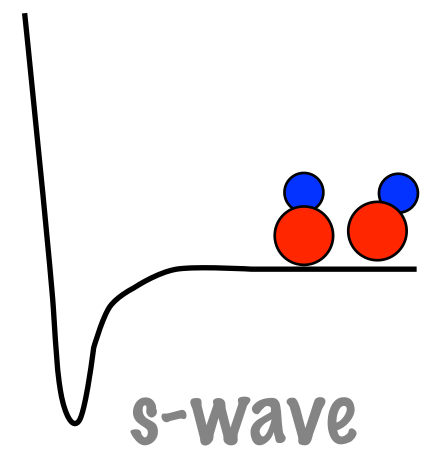


Ospelkaus, Ni *et al.*, Science **327**, 853 (2010)

Molecular Inelastic Collisions - Wigner Threshold Law

Quantum Statistics Controlled Reaction Rates

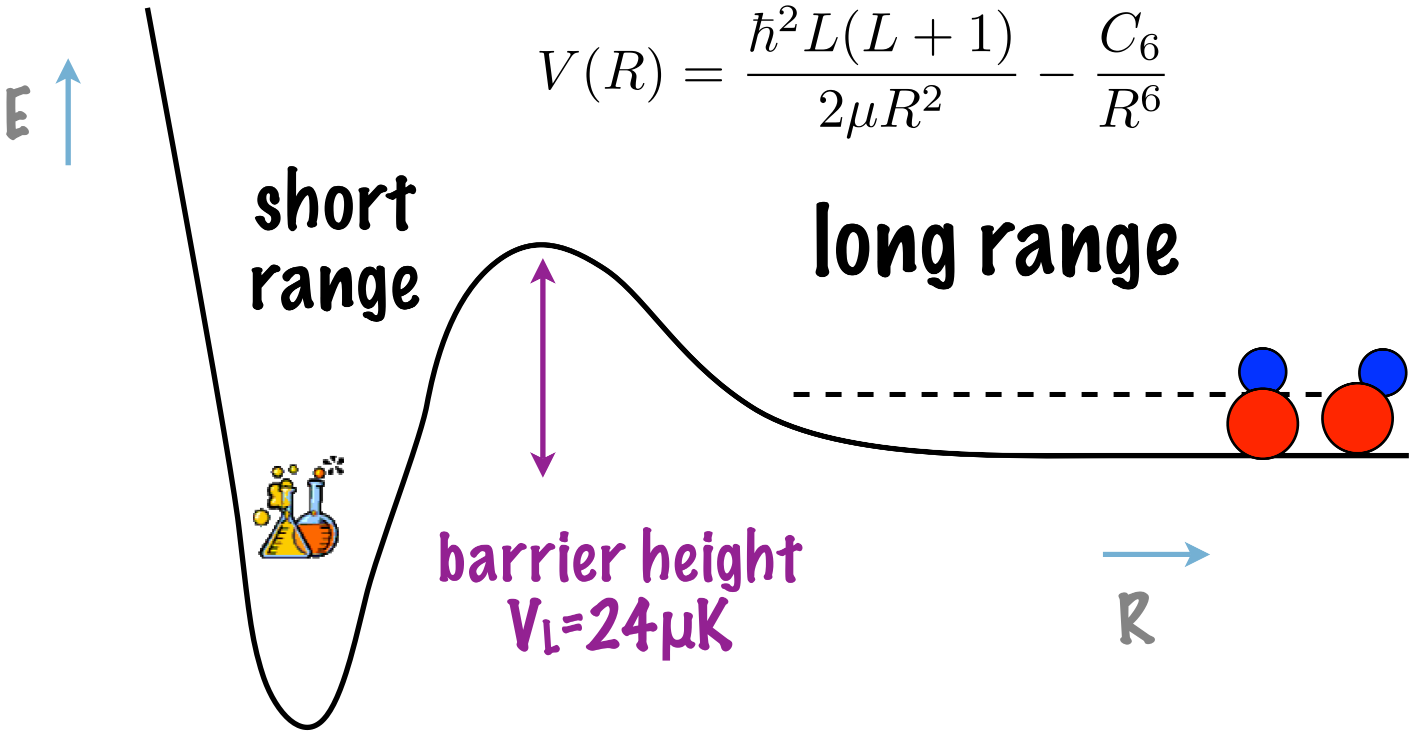




Ospelkaus, Ni *et al.*,
Science **327**, 853 (2010)

"Quantum Threshold" Model

$$V(R) = \frac{\hbar^2 L(L+1)}{2\mu R^2} - \frac{C_6}{R^6}$$



* Short Range: assume unit probability for loss
* Long Range: small probability for tunneling through the barrier (rate can be estimated by the barrier height and collisional energy)

G. Quéméner and J. Bohn, *PRA* **81** 022702 (2010)

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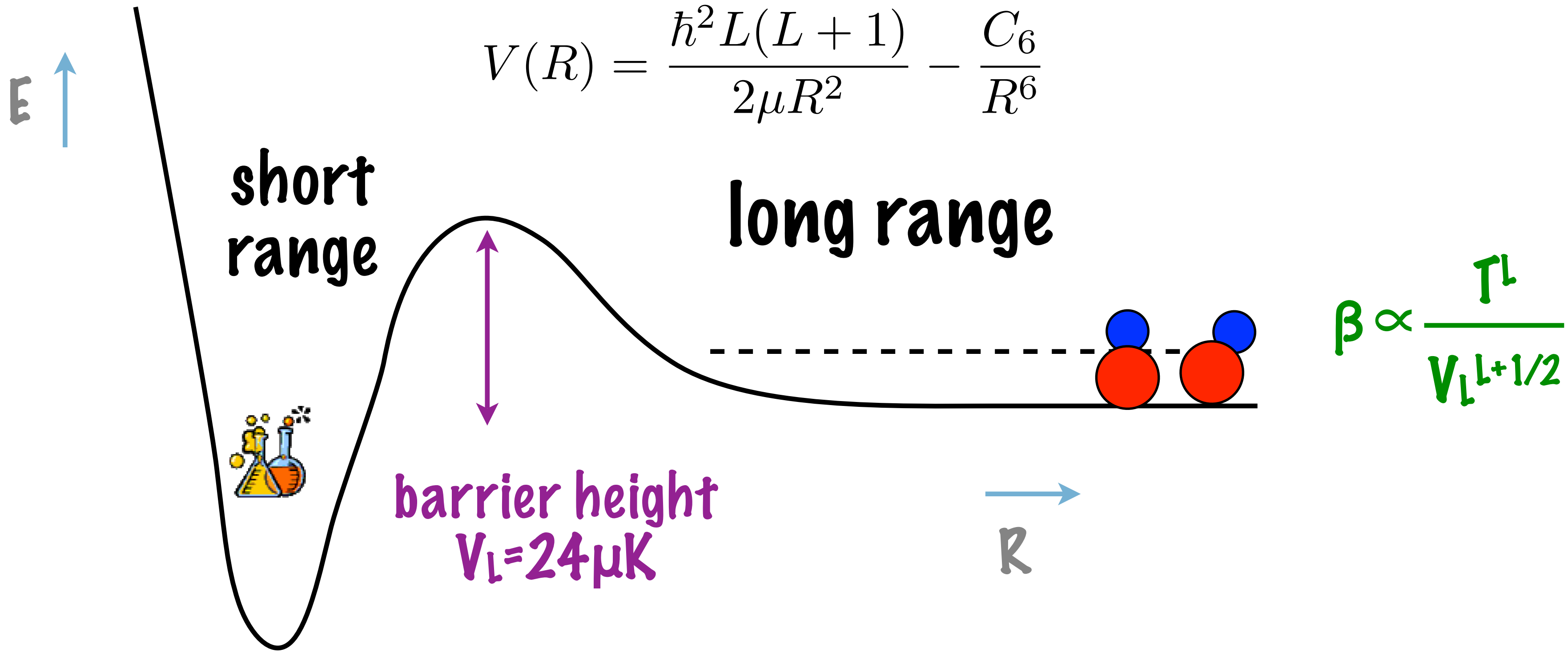

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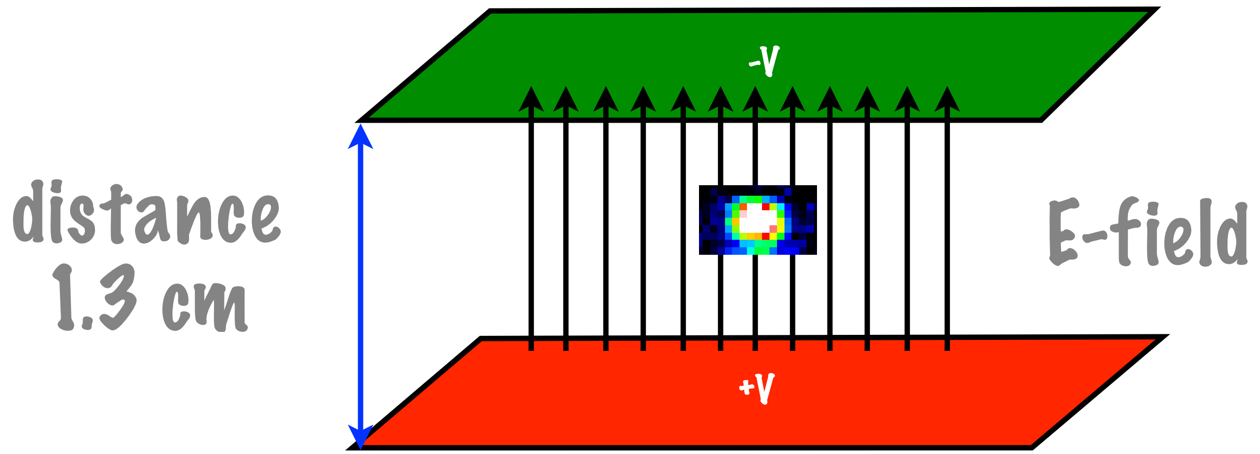
Turn on Electric Field



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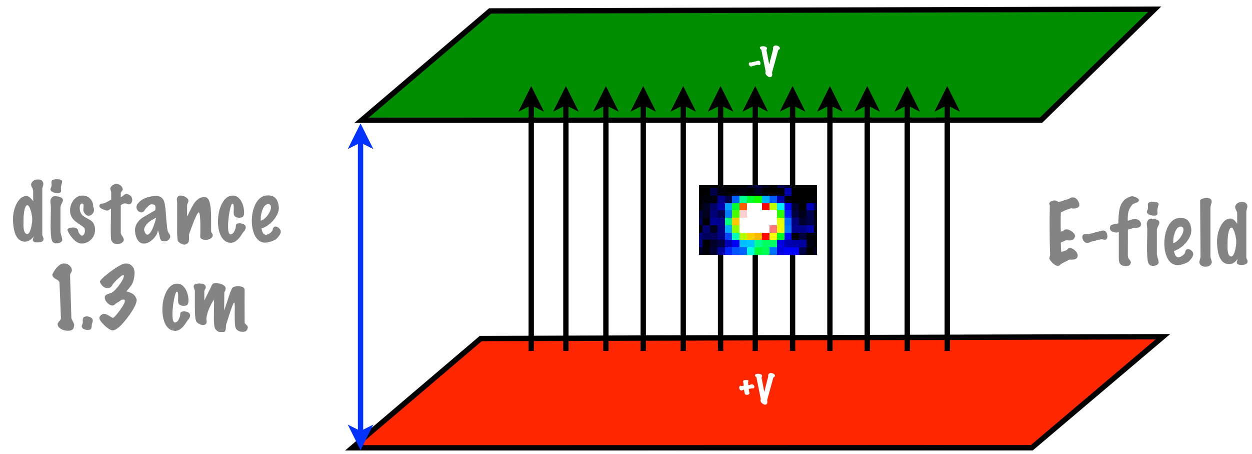
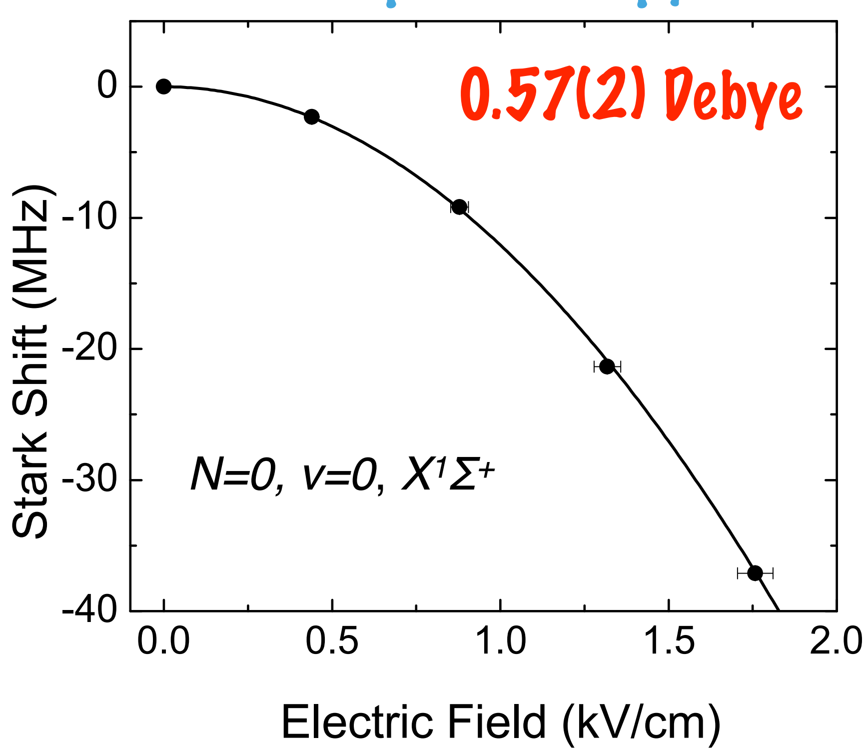


Stark Spectroscopy



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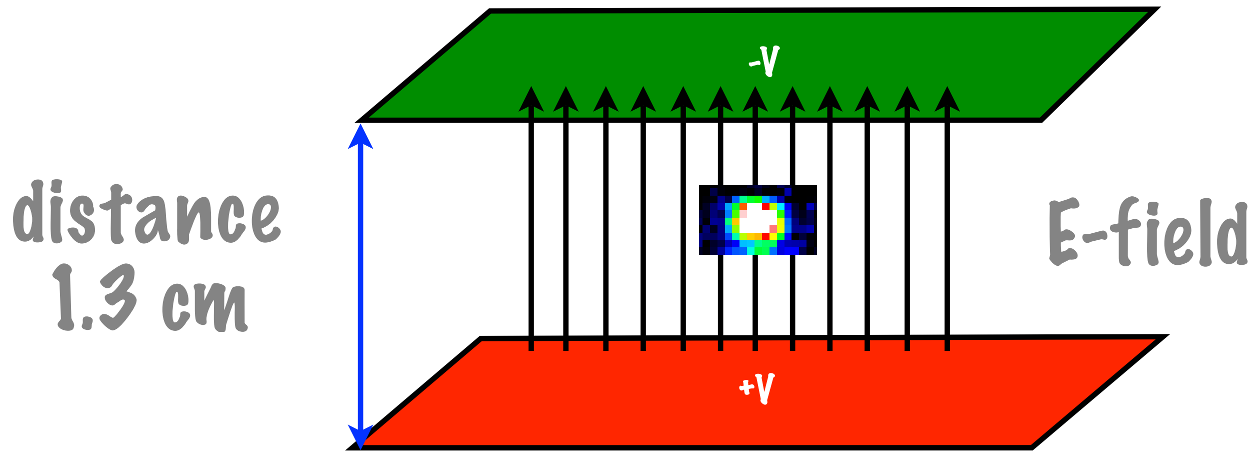
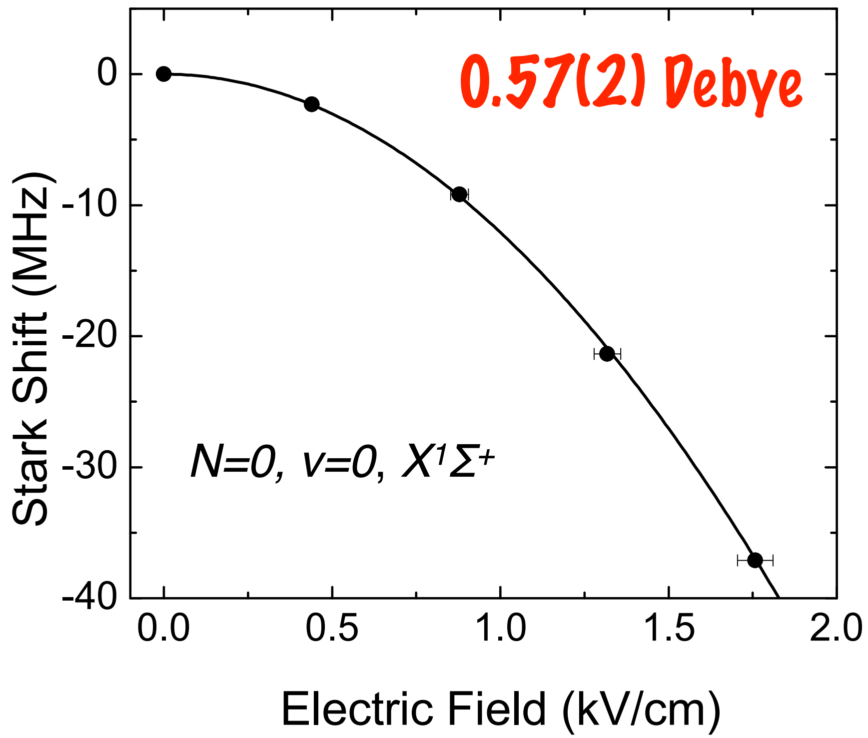
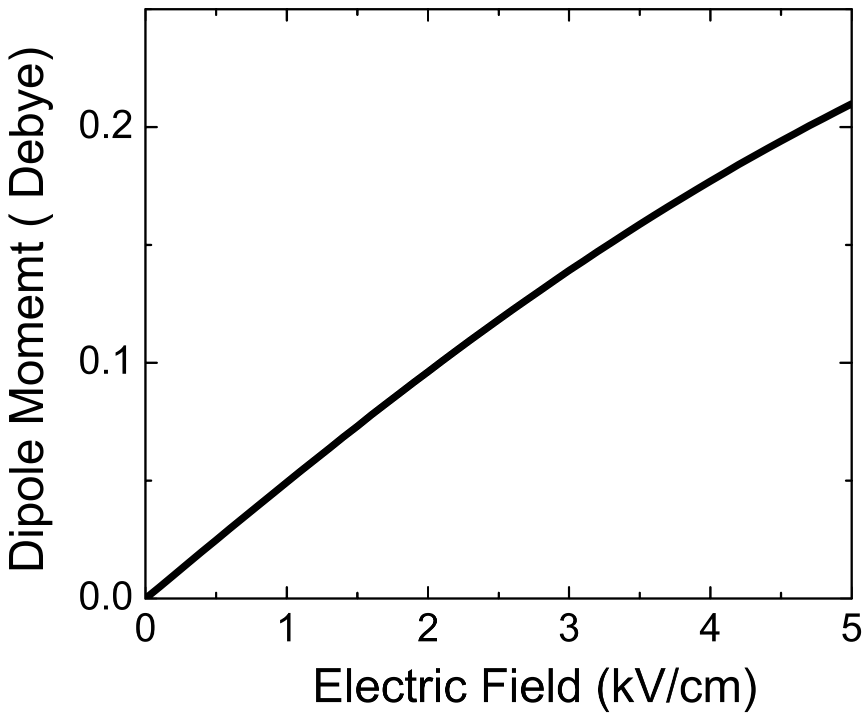


Stark Spectroscopy

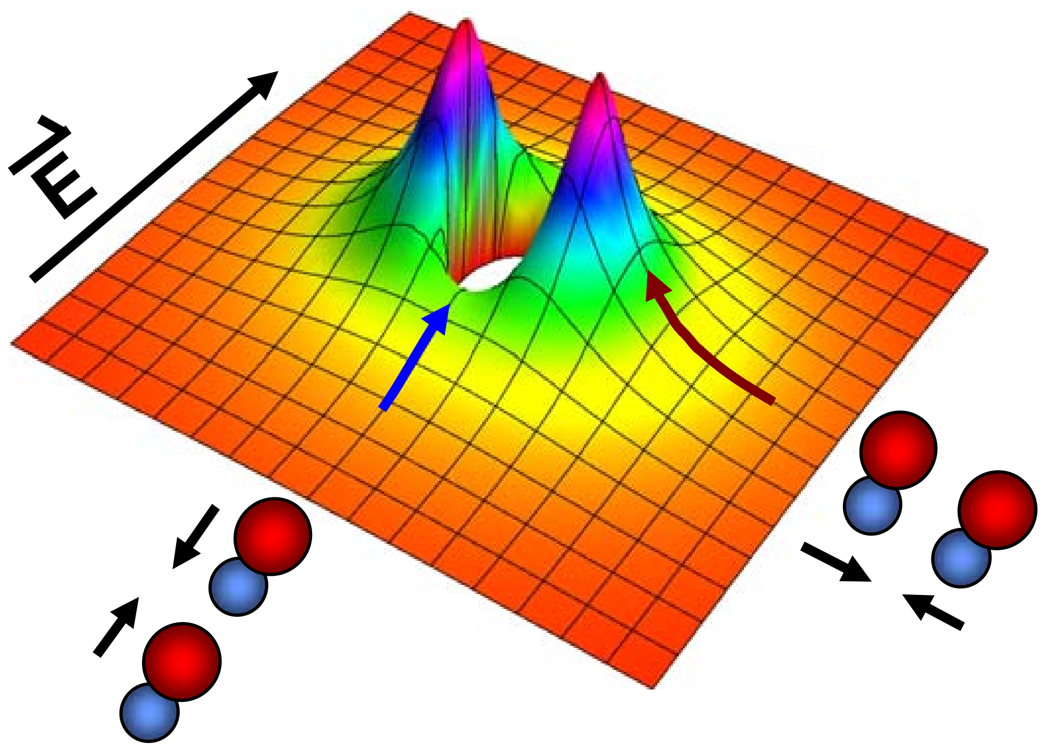


Tuning dipole moment with an E-field



Anisotropy of P-wave Barrier Heights

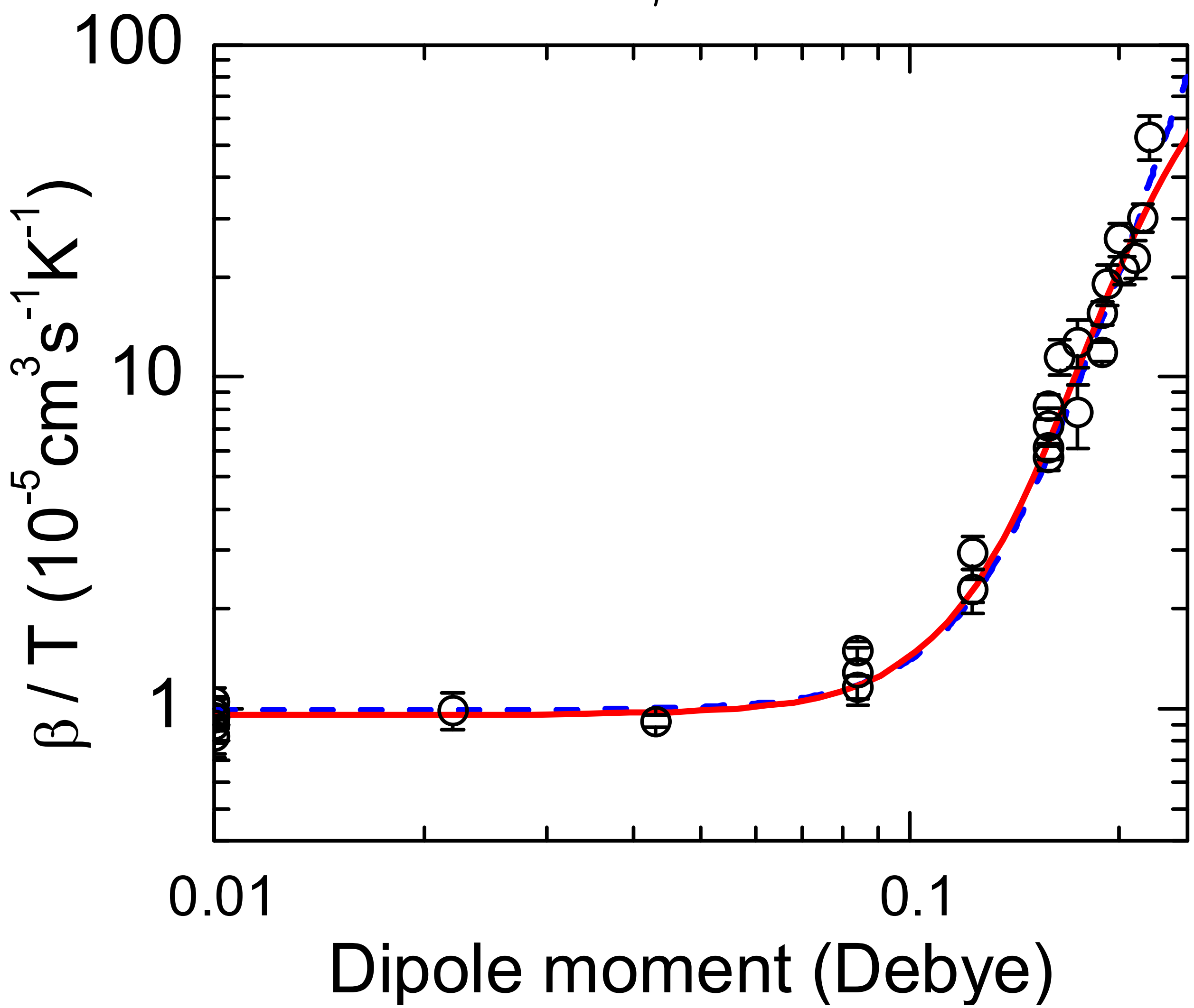
Long-range potential $$V(R) = \frac{\hbar^2 L(L+1)}{2\mu R^2} - \frac{C_6}{R^6} - \frac{C_3}{R^3}$$



collisions in 3D will effectively average over the different channels

Inelastic Dipolar Collisions

$$V(R) = \frac{\hbar^2 L(L+1)}{2\mu R^2} - \frac{C_6}{R^6} - \frac{C_3}{R^3}$$



Theory by Quéméner and Bohn

Ni, Ospelkaus *et al*., Nature **464**, 1324 (2010)

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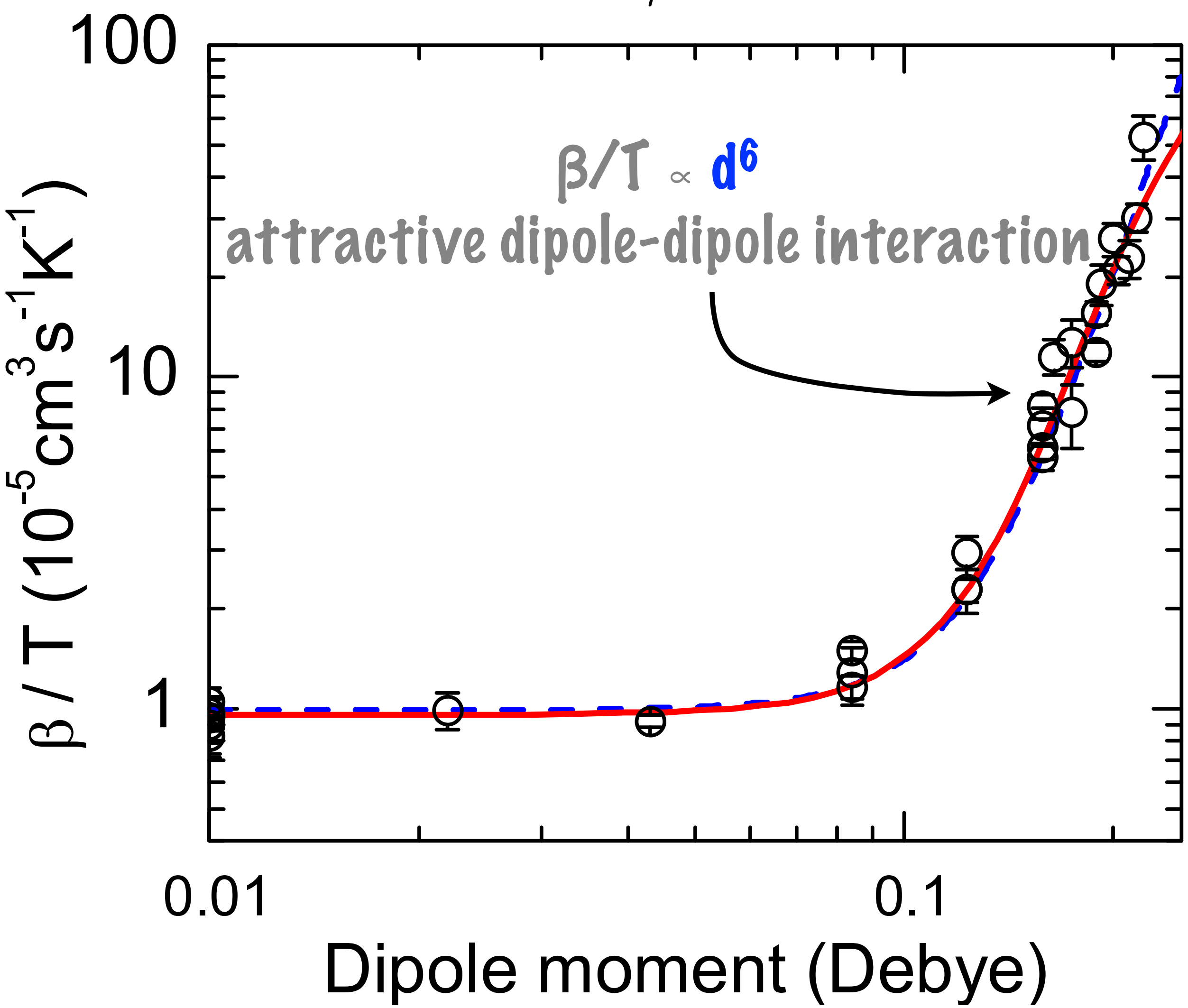

$$\beta \propto \frac{T^L}{V_L^{L+1/2}}$$

Theory by Quéméner and Bohn

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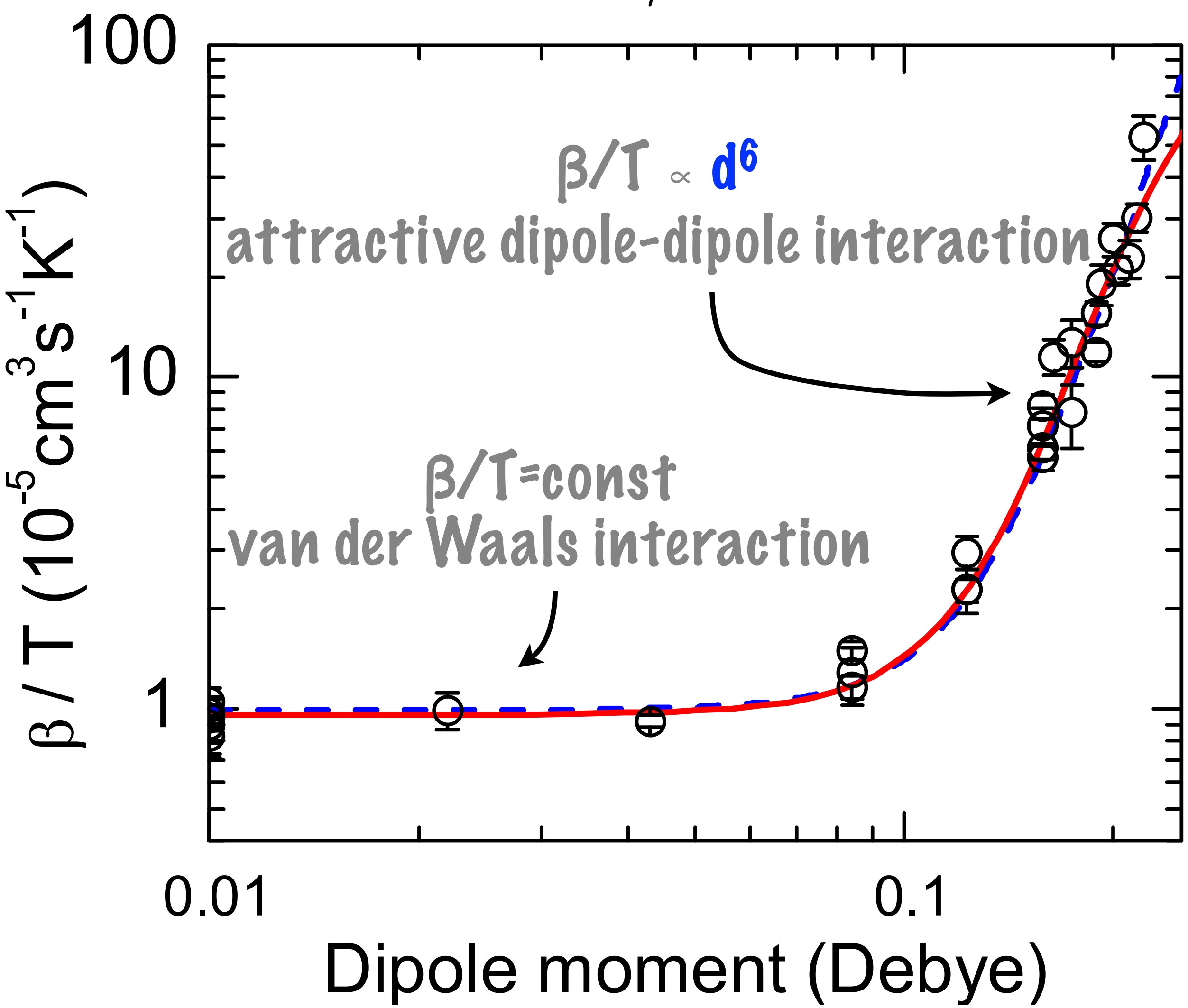


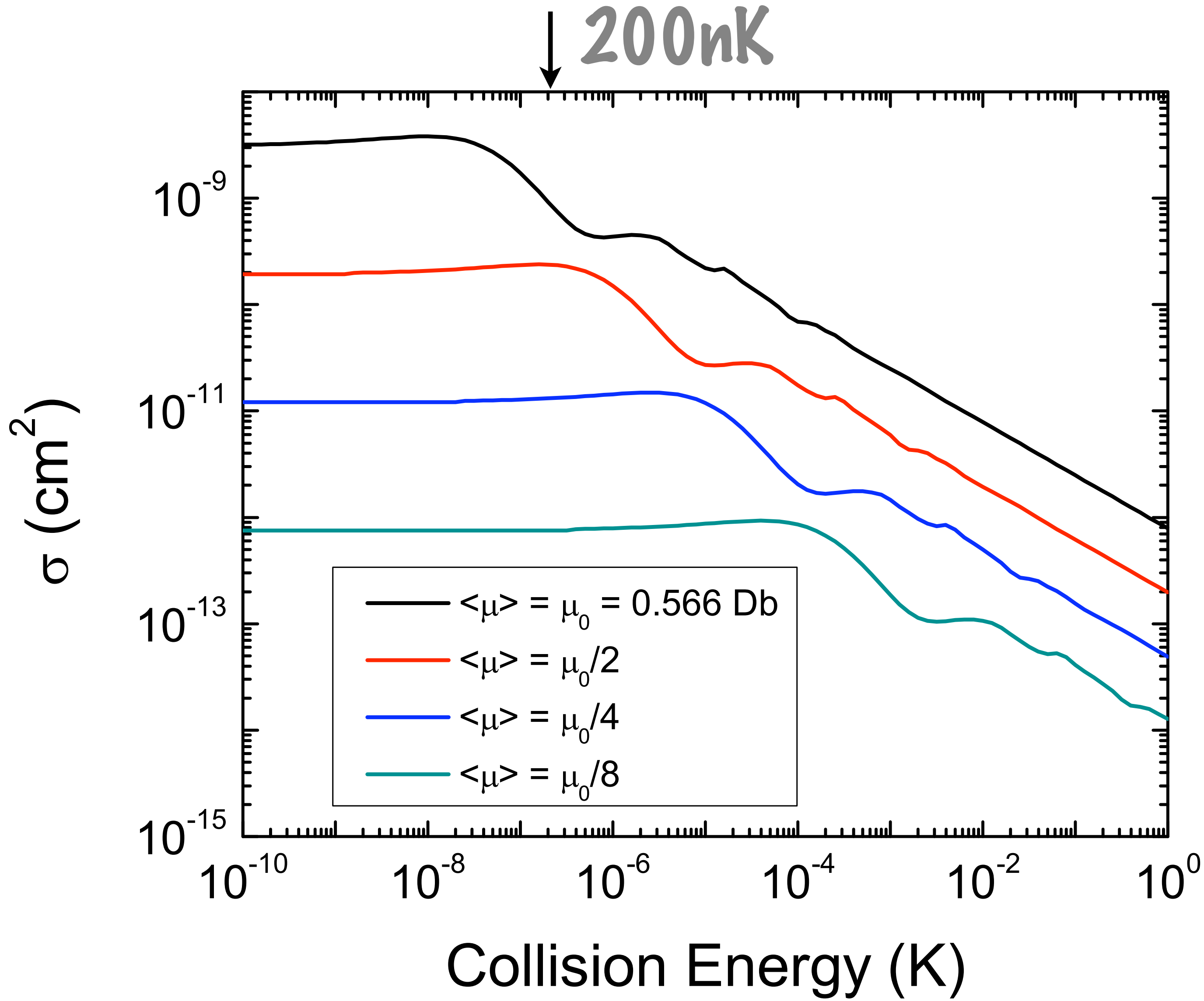
$$\beta \propto \frac{T^L}{V_L^{L+1/2}}$$

Theory by Quéméner and Bohn

Ni, Ospelkaus *et al.*, Nature **464**, 1324 (2010)

what about elastic collisions?

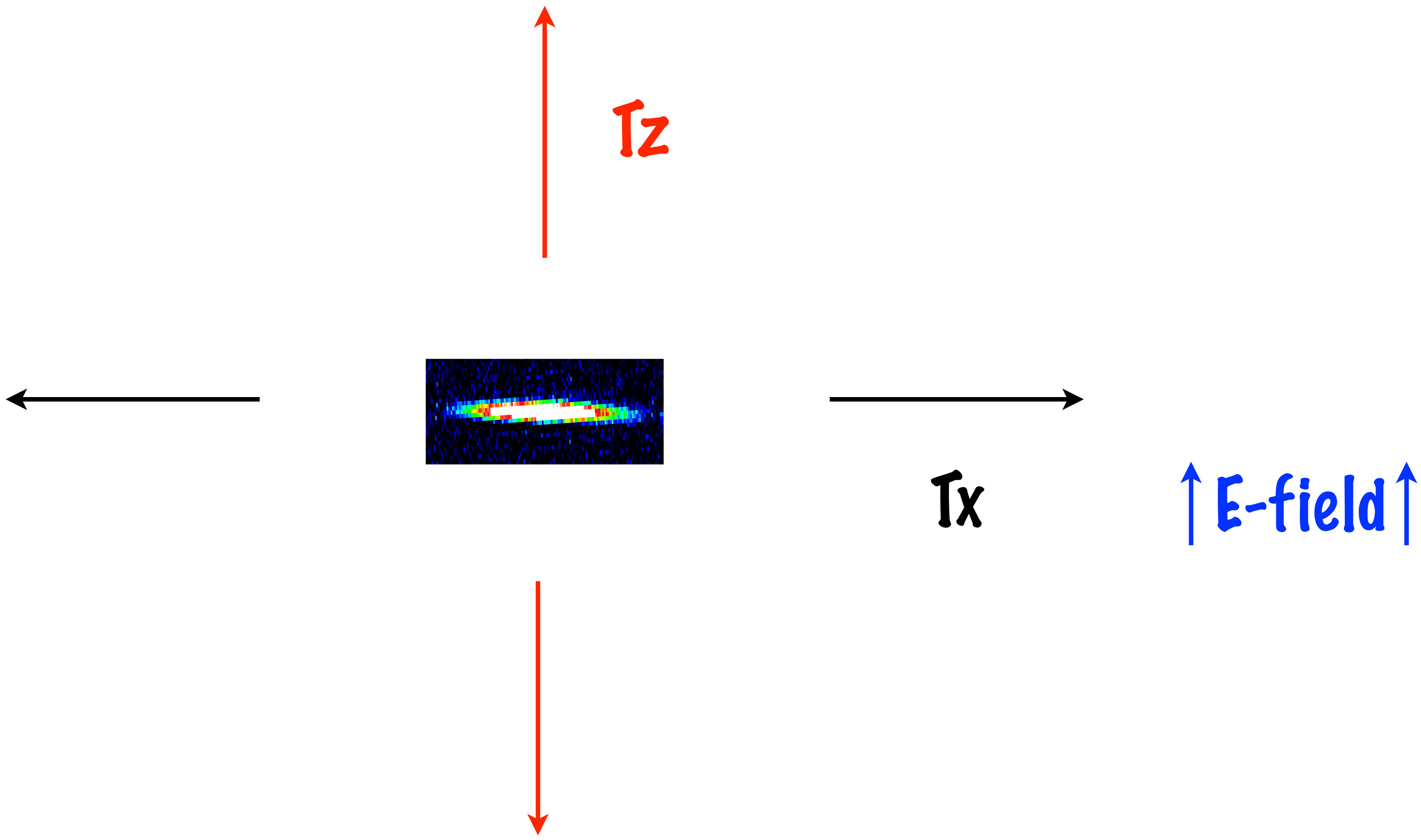
indistinguishable Fermionic KRb elastic collisions



$$\sigma \propto d^4$$

J. Bohn *et al*., New J. Phys. **11,** 055039 (2009)

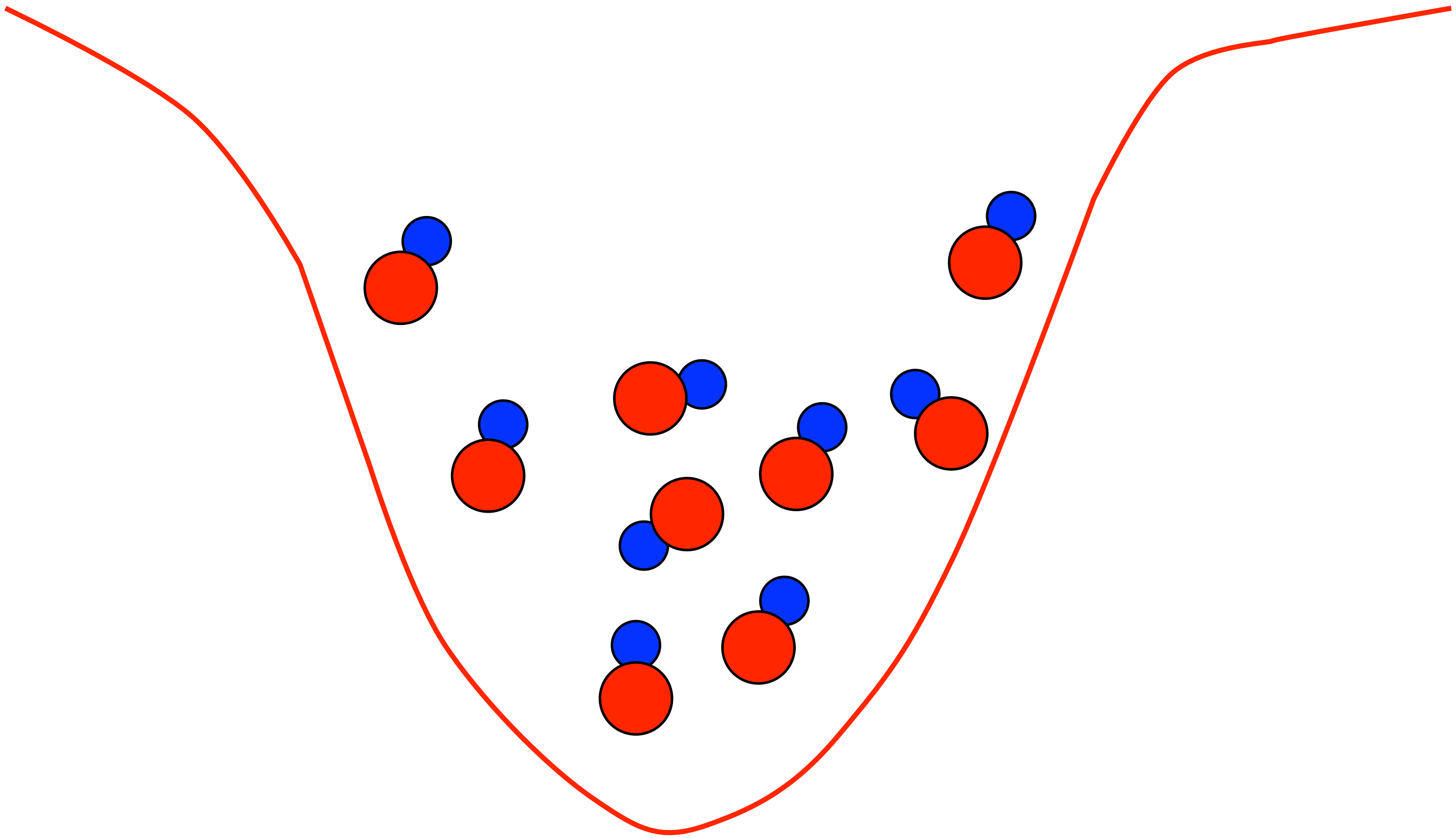
cross-dimension rethermalization



Monroe, Wieman *et al.*, PRL **70,** 414 (1993)

Heating from Inelastic Collisions

$$\dot{n} = -\beta n^2$$



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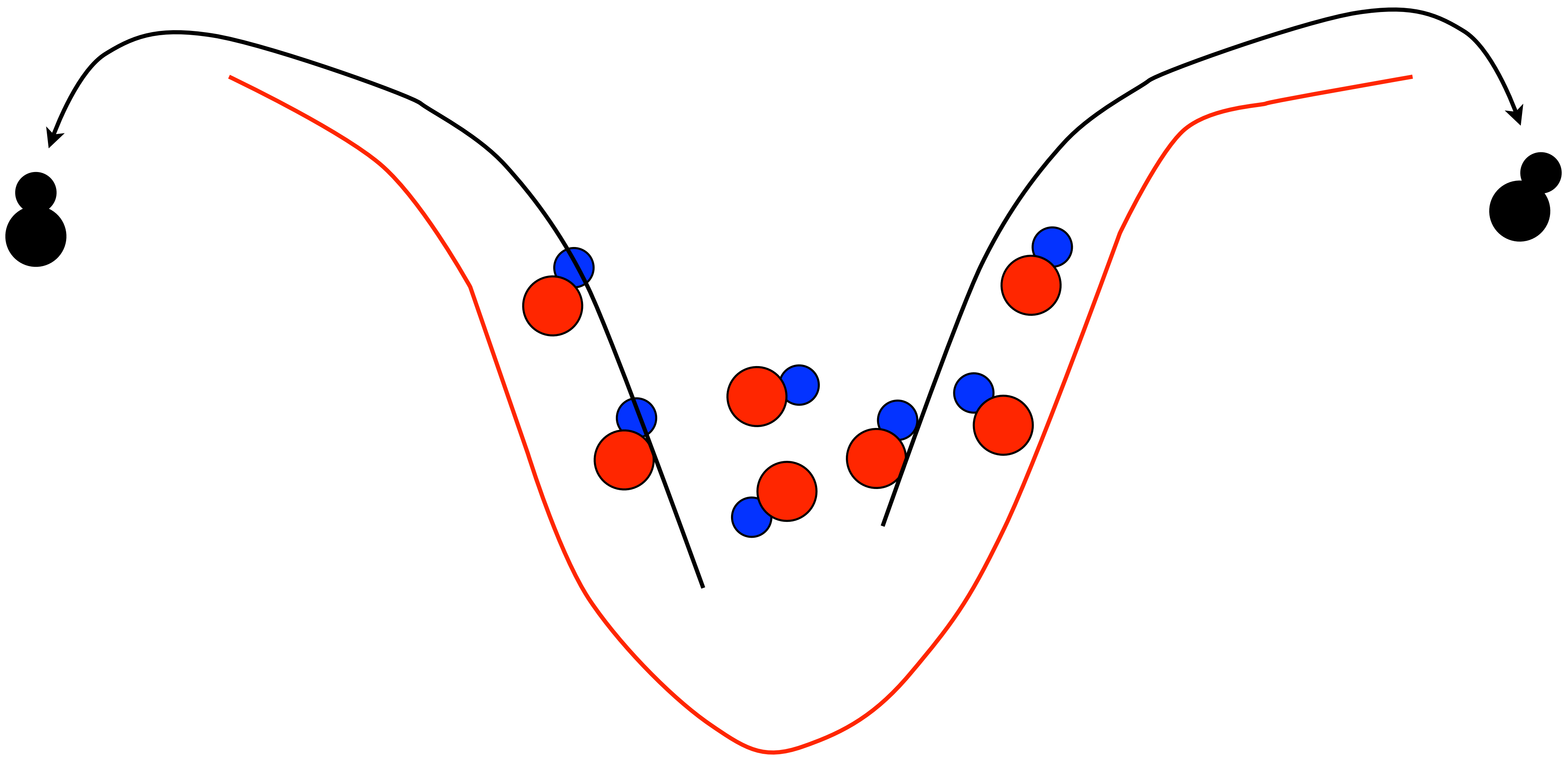
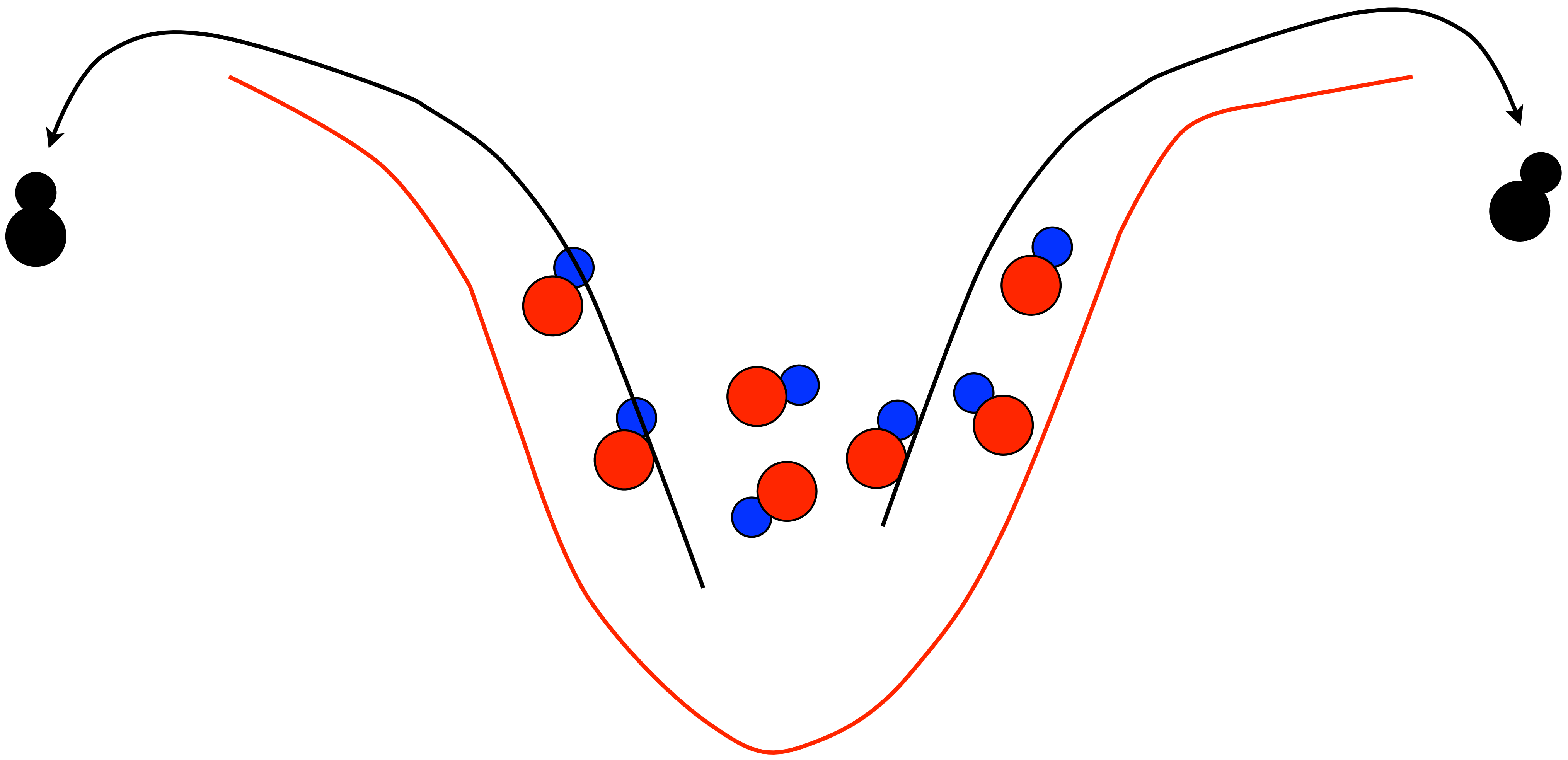


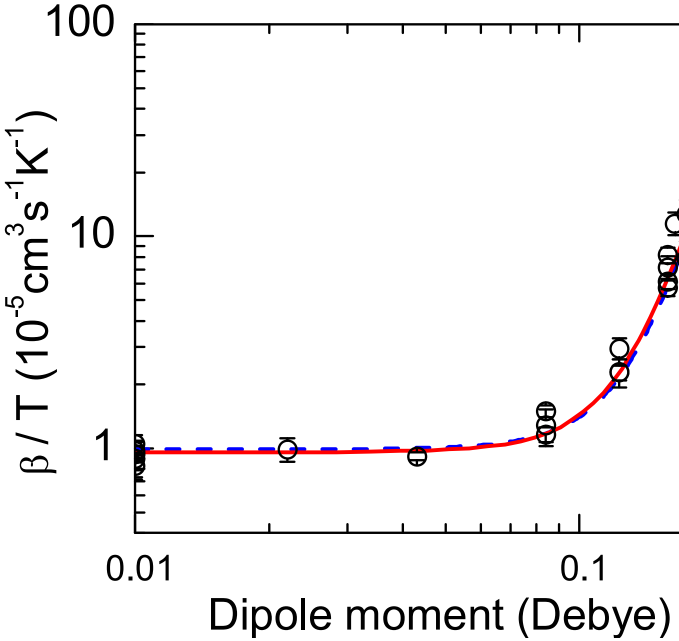
Heating from Inelastic Collisions

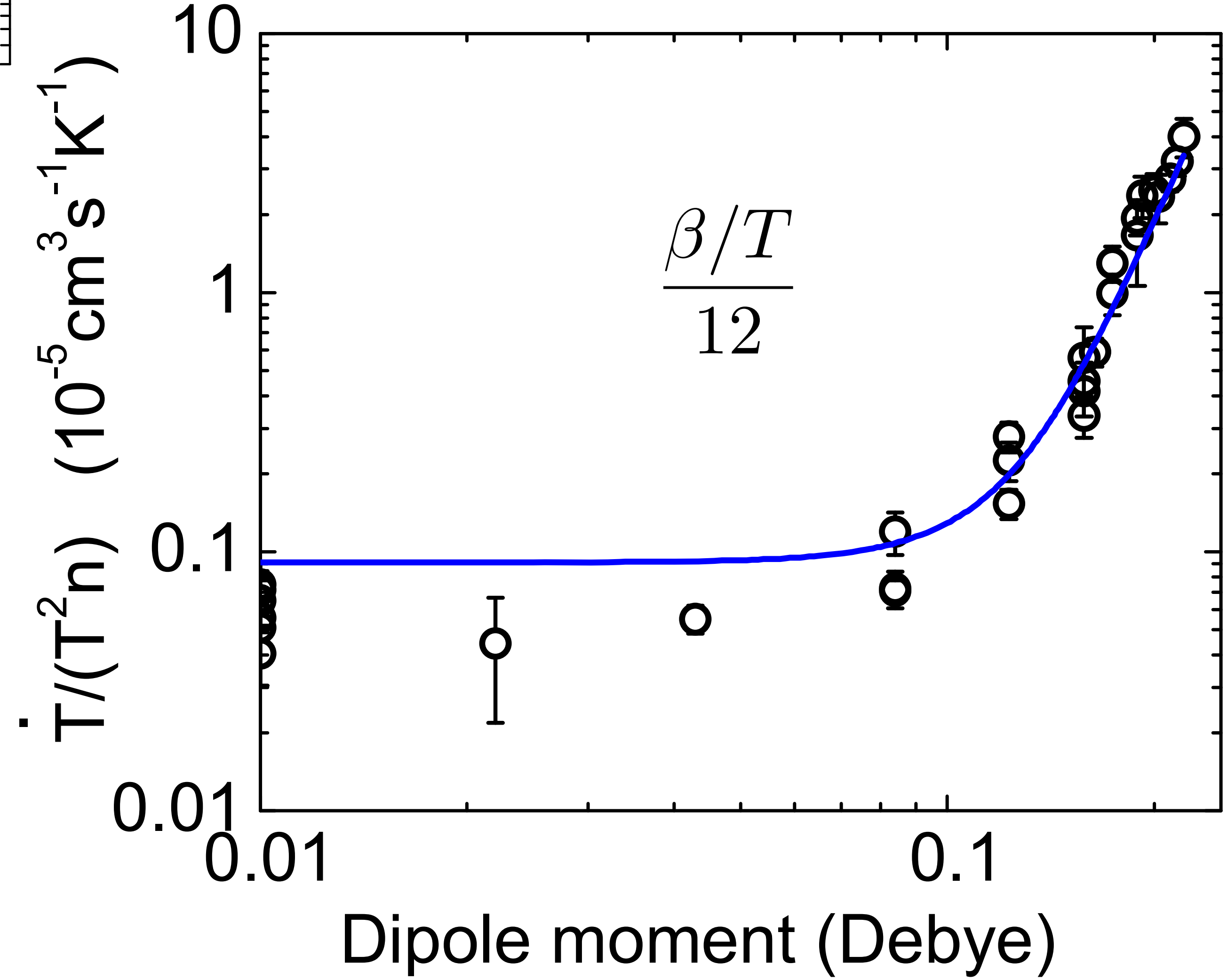
$$\dot{n} = -\beta n^2 = -K \cdot T \cdot n^2$$



Heating

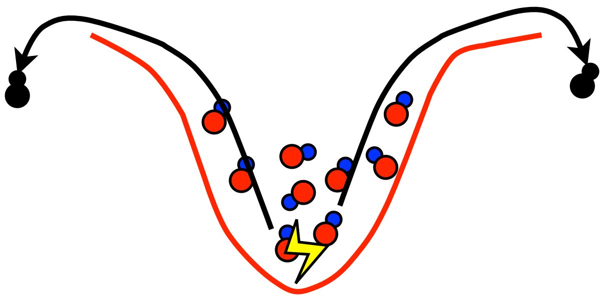
$$T = \frac{(2T_x + T_z)}{3}$$





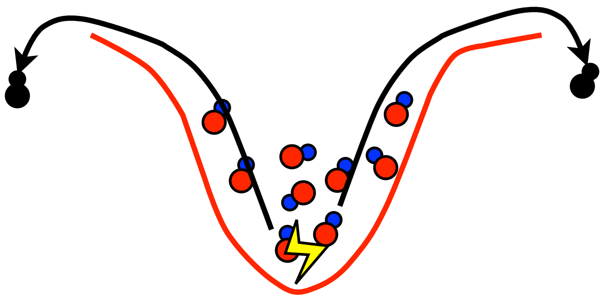
(Anisotropic) Heating or Cooling?

$$\Delta E_z^{m_L=0} = 2k_bT_z - k_bT_z - \frac{\mu}{2}\frac{\int_{-\infty}^{\infty} f(v_z,v_r)v_z^4 dv_z}{\int_{-\infty}^{\infty} f(v_z,v_r)v_z^2 dv_z}$$



(Anisotropic) Heating or Cooling?

$$\Delta E_z^{m_L=0} = \underbrace{2k_bT_z}_{\text{average energy for a pair}} - k_bT_z - \frac{\mu}{2}\frac{\int_{-\infty}^{\infty} f(v_z, v_r)v_z^4 dv_z}{\int_{-\infty}^{\infty} f(v_z, v_r)v_z^2 dv_z}$$



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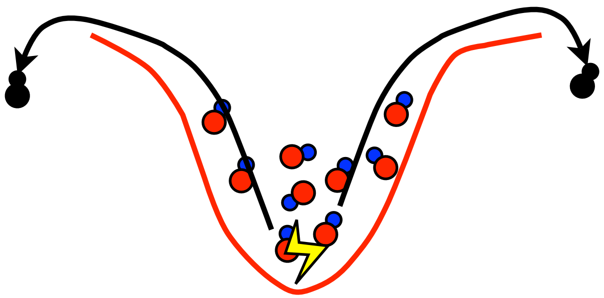

(Anisotropic) Heating or Cooling?

averaging for relative kinetic energy of a pair

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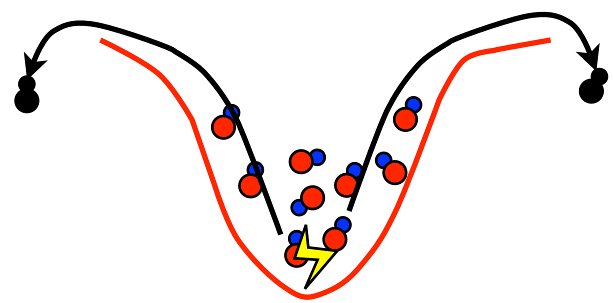

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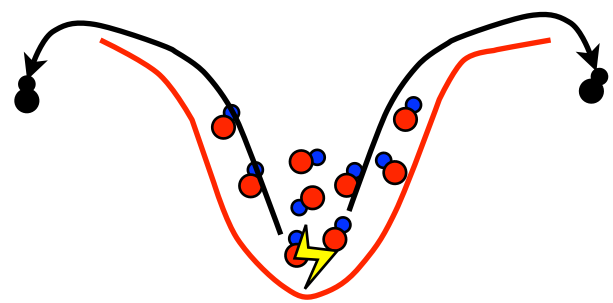
cooling!!



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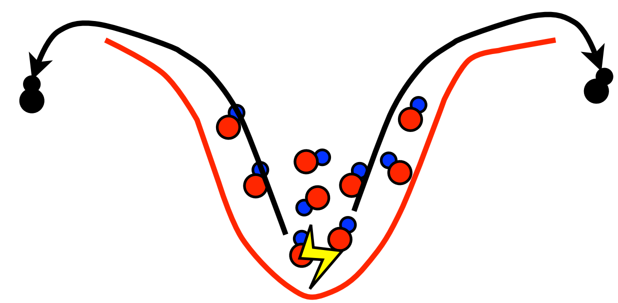
cooling!!

$$\Delta E_x^0 = \frac{1}{2}k_bT_x$$ heating!!

$$\Delta E_z^1 = \frac{1}{2}k_bT_z$$ heating!!

$$\Delta E_x^1 = 0$$ no change



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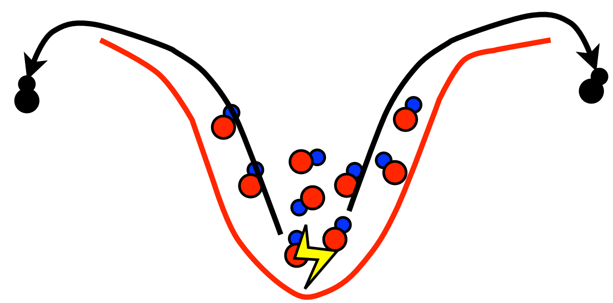

Heating Rate

$$\frac{dT_z}{dt} = \frac{n}{2}(\frac{-1}{2}T_z\beta^0 + \frac{1}{2}T_z\beta^1)$$

$$\frac{dT_x}{dt} = \frac{n}{2}(\frac{1}{2}T_x\beta^0)$$

(Anisotropic) Heating or Cooling?

averaging for relative kinetic energy of a pair

$$\Delta E_z^{m_L=0} = \underbrace{2k_bT_z}_{\text{average energy for a pair}} - \underbrace{k_bT_z}_{\text{average c.m. energy}} - \frac{\mu}{2}\frac{\int_{-\infty}^{\infty} f(v_z,v_r)v_z^4 dv_z}{\underbrace{\int_{-\infty}^{\infty} f(v_z,v_r)v_z^2 dv_z}_{\text{MB distribution,}}} = 2k_bT_z - \frac{5}{2}k_bT_z = -\frac{1}{2}k_bT_z$$

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$$\Delta E_x^0 = \frac{1}{2}k_bT_x$$

heating!!

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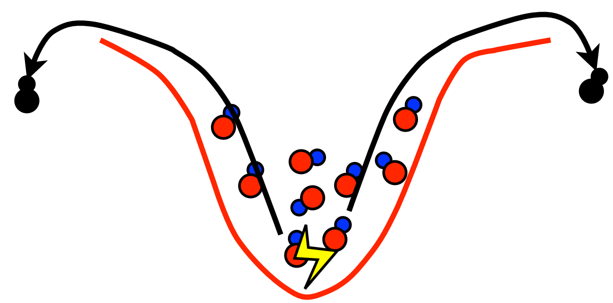
no change

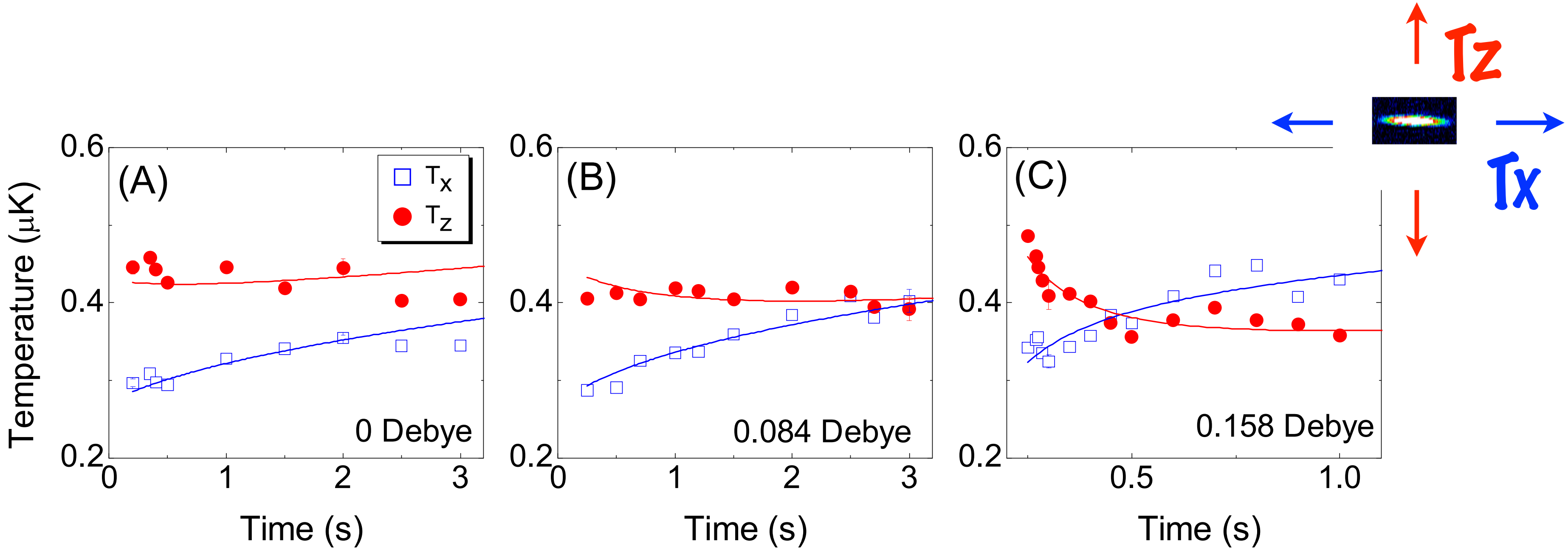


Heating Rate

$$\frac{dT_z}{dt} = \frac{n}{2}\Big(\frac{-1}{2}T_z\underbrace{\beta^0}_{\propto K^0T_z} + \frac{1}{2}T_z\underbrace{\beta^1}_{\propto K^1T_x}\Big)$$

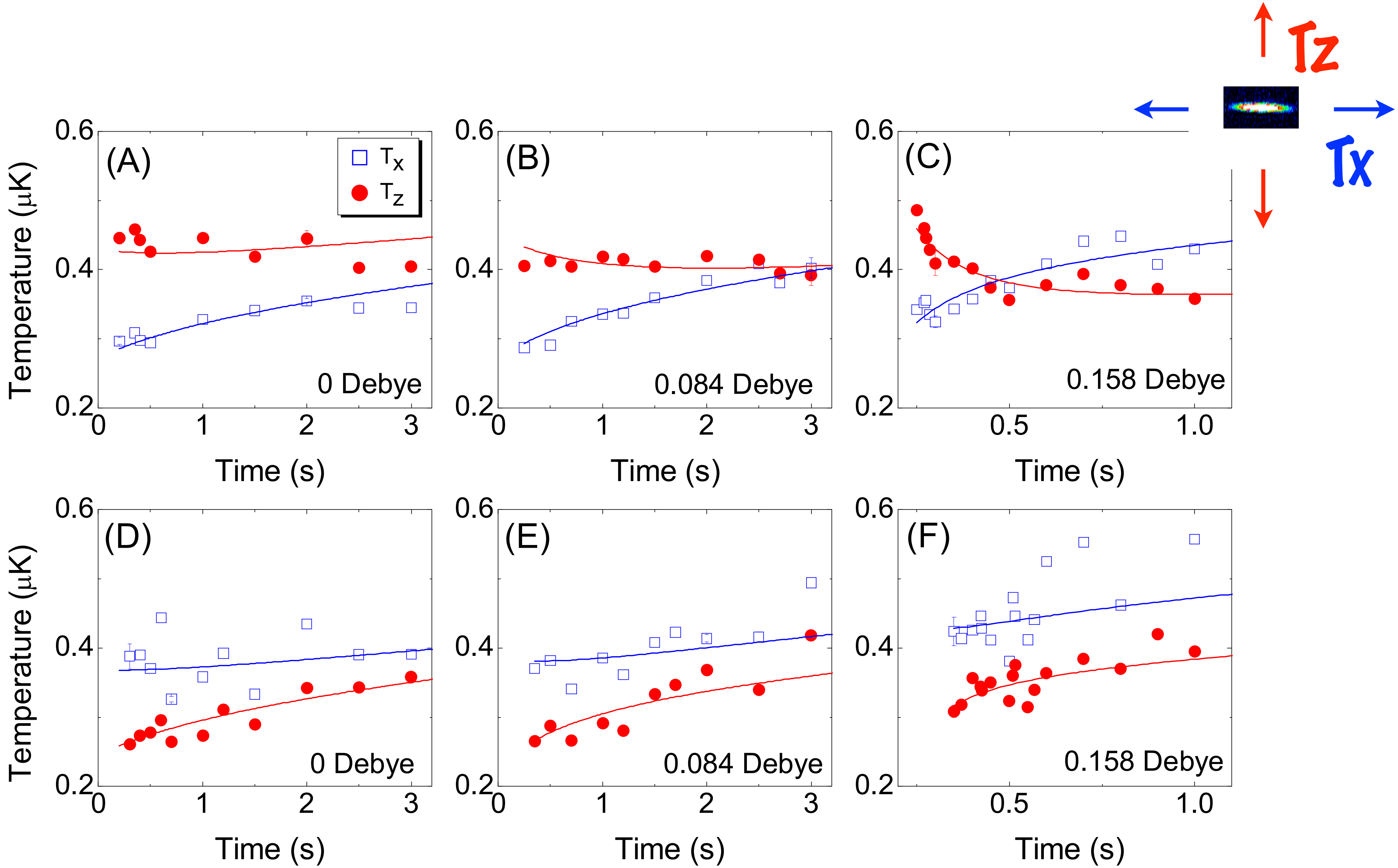
$$\frac{dT_x}{dt} = \frac{n}{2}\Big(\frac{1}{2}T_x\beta^0\Big)$$

Evidence of Anisotropic Dipolar Collisions



Ni, Ospelkaus *et al.*, Nature **464**, 1324 (2010)

Evidence of Anisotropic Dipolar Collisions



Ni, Ospelkaus *et al.*, Nature **464**, 1324 (2010)

Observed anisotropic inelastic collisions, but the heating/cooling effects eclipse elastic rethermalization collisions

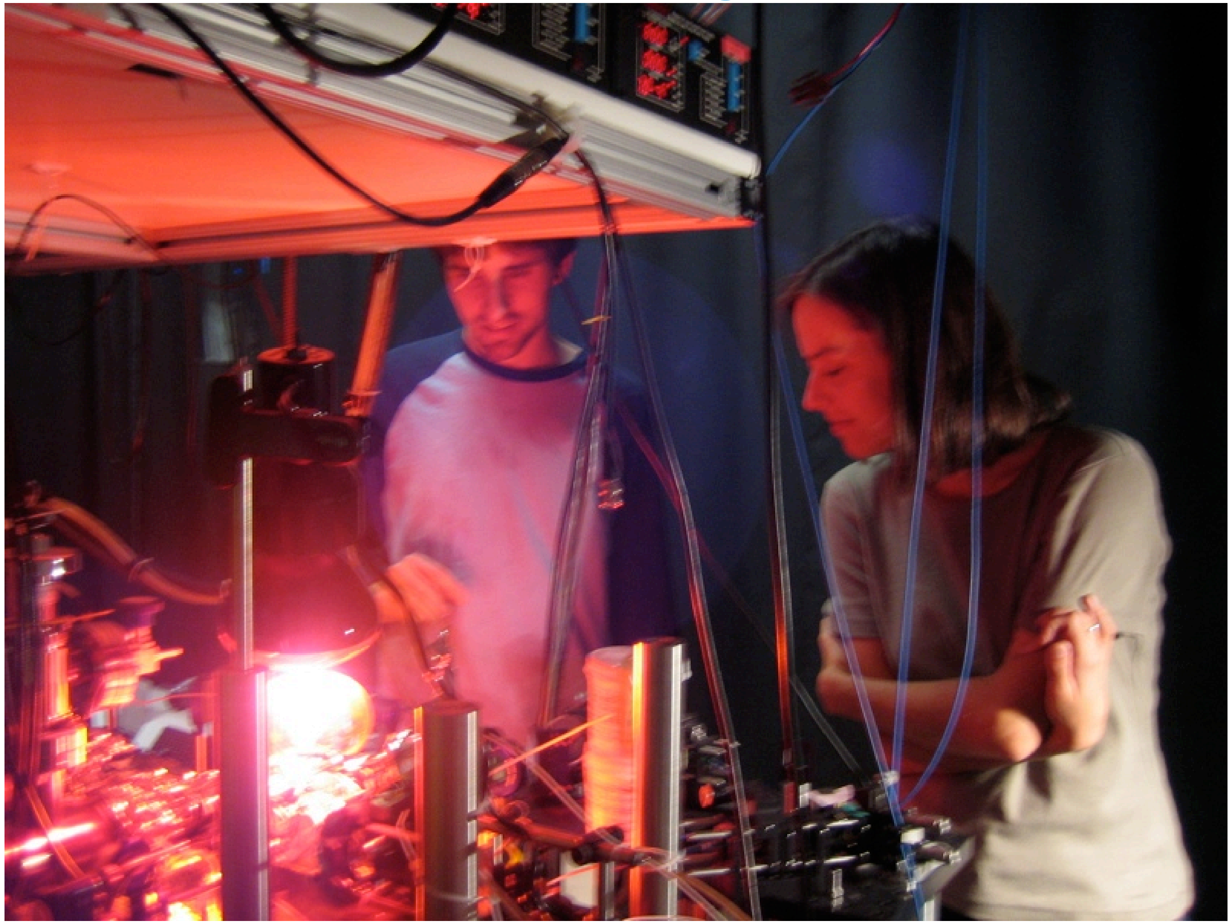
Conclusions

* >90% efficiency, few$\times 10^4$ polar molecules at 160nK. T/T_F=1.4 (PSD 0.06) Peak density $10^{12}/cm^3$
* a general scheme for other bialkali molecules (on-going effort worldwide)
* controlling molecular hyperfine states
* seeing ultracold chemical reactions !!
* exploring long-range and anisotropic dipolar collisions

Outlook

* suppress inelastic collisions in 2D geometry
  (current on-going work in JILA)
* evaporative cooling of molecules
* study of quantum phases

Acknowledgements



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