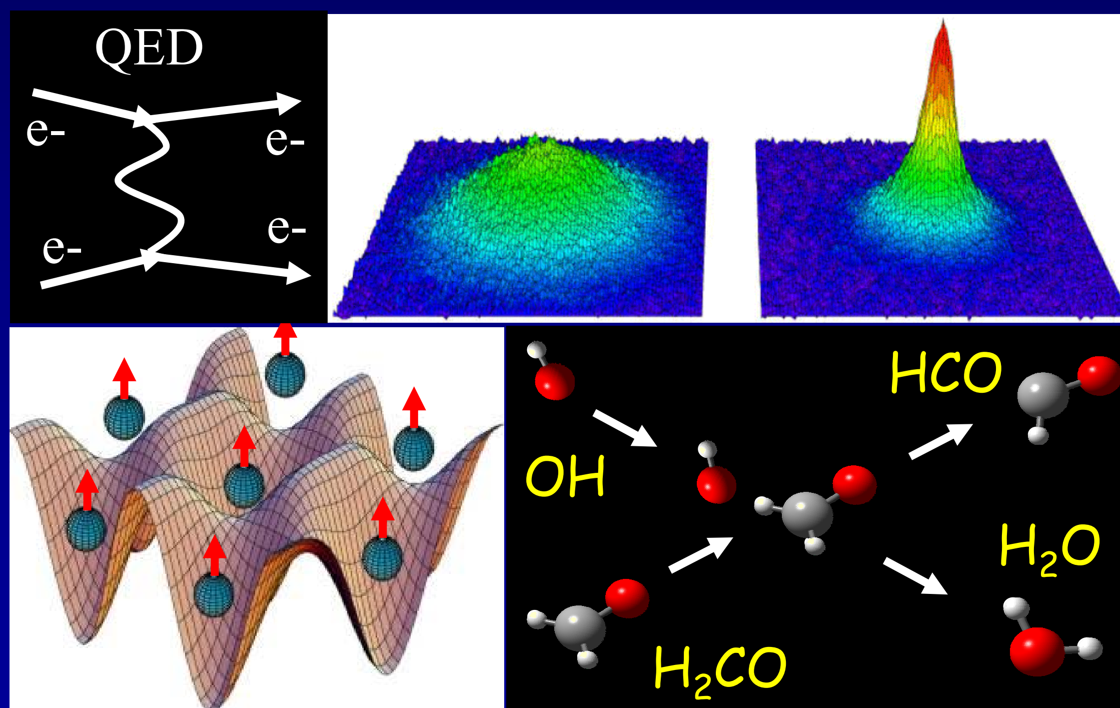
Cold & ultracold molecules – new frontiers

J. Ye, JILA

Michigan Quantum Summer School, Ann Arbor, June 18, 2008

Precision test

Quantum dipolar gas



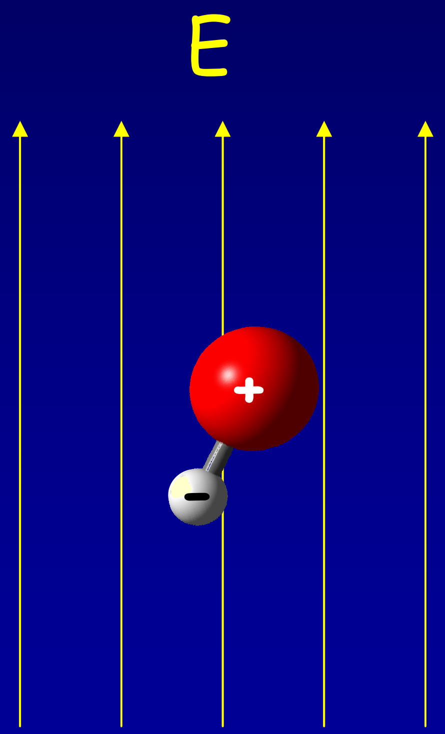
Quantum measurement

Chemical reactions

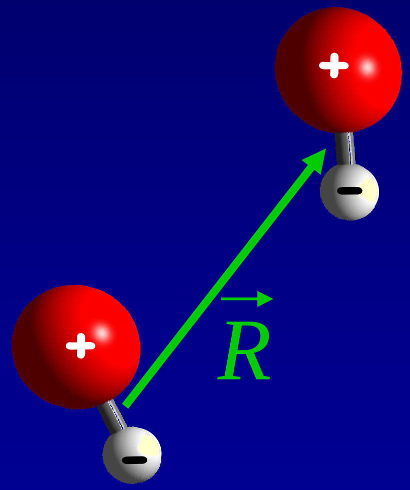
Why ultracold molecules?

J. Doyle *et al.*, Eur. Phys. J. D 31, 149 (2004).

Electric dipole moments: Orientation is a big deal !



A. Avdeenkov and J. L. Bohn,
Phys. Rev. Lett. **90**, 043006 (2003).



Manifested at or below
μK temperatures

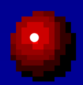
Ultracold molecules – a hard challenge

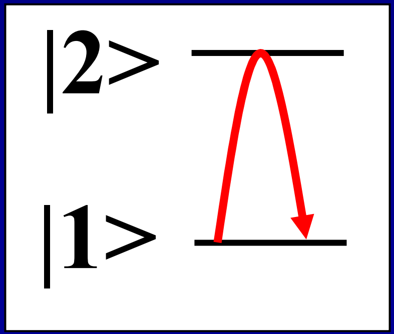
"A diatomic molecule is a molecule with one atom too many!"

– Nobel Laureate Arthur Schawlow, co-inventor of laser and co-founder of laser spectroscopy

"Basketball"

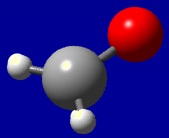
Atoms

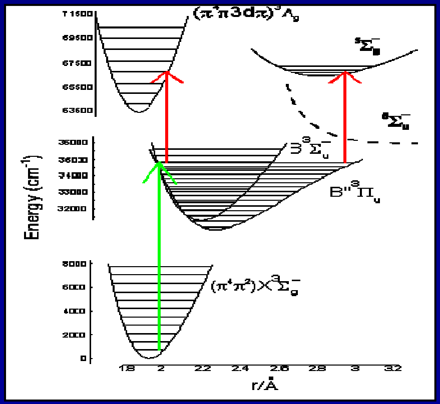




"American football"

Molecules



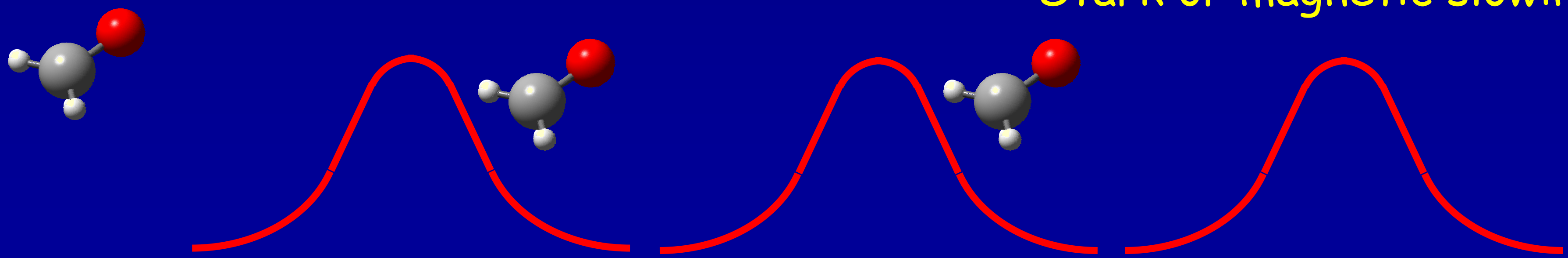


Ways to make cold polar molecules

- Pairing ultracold atoms (Magneto-Photo-association)

- Direct cooling of ground-state molecules

Buffer gas cooling
Stark or magnetic slowing

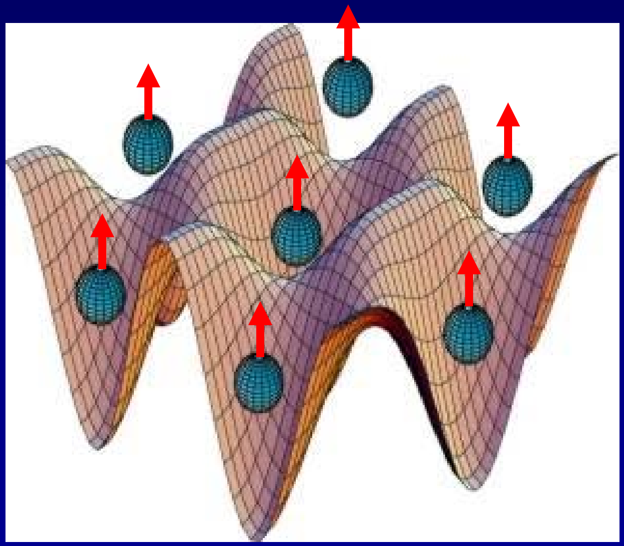


Ultracold molecules: quantum physics

- Quantum information
  (strong dipolar interactions, long coherence time)

- Quantum degeneracy (e.g. BEC)
  (anisotropic interactions)

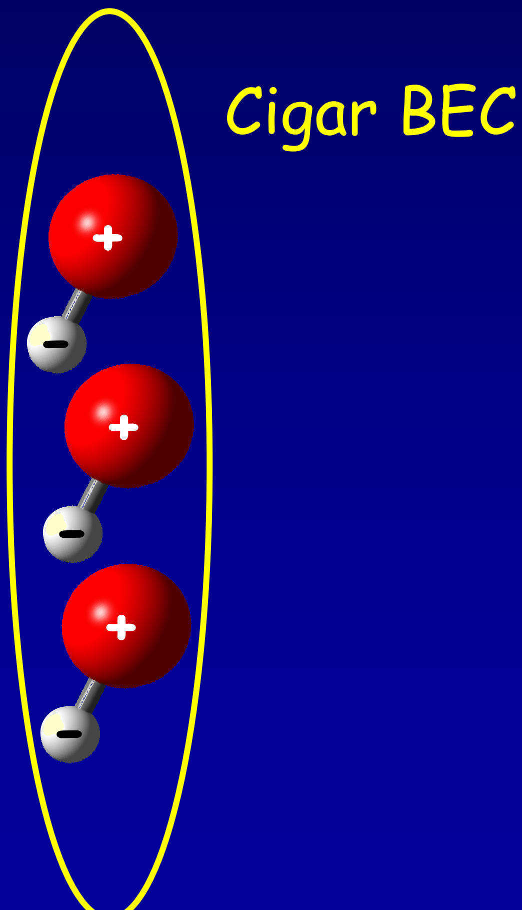
- Dipolar phase transition
  (Condensed matter system)

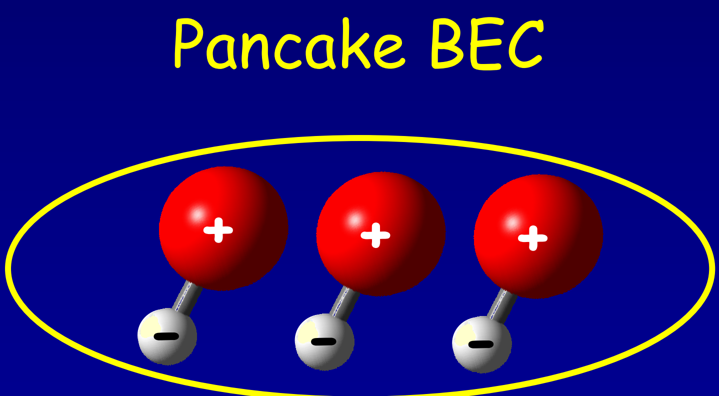


DeMille, Phys. Rev. Lett. **88**, 067901 (2002).
H.P. Buchler *et al*., PRL **98**, 060404 (2007). T. Koch *et al*., Nature Phys. **4**, 218 (2008).
Micheli, Brennen, Zoller, Nature Physics **2**, 341 (2006).

Dipolar quantum gas

- Long range
- Orientation-specific interactions

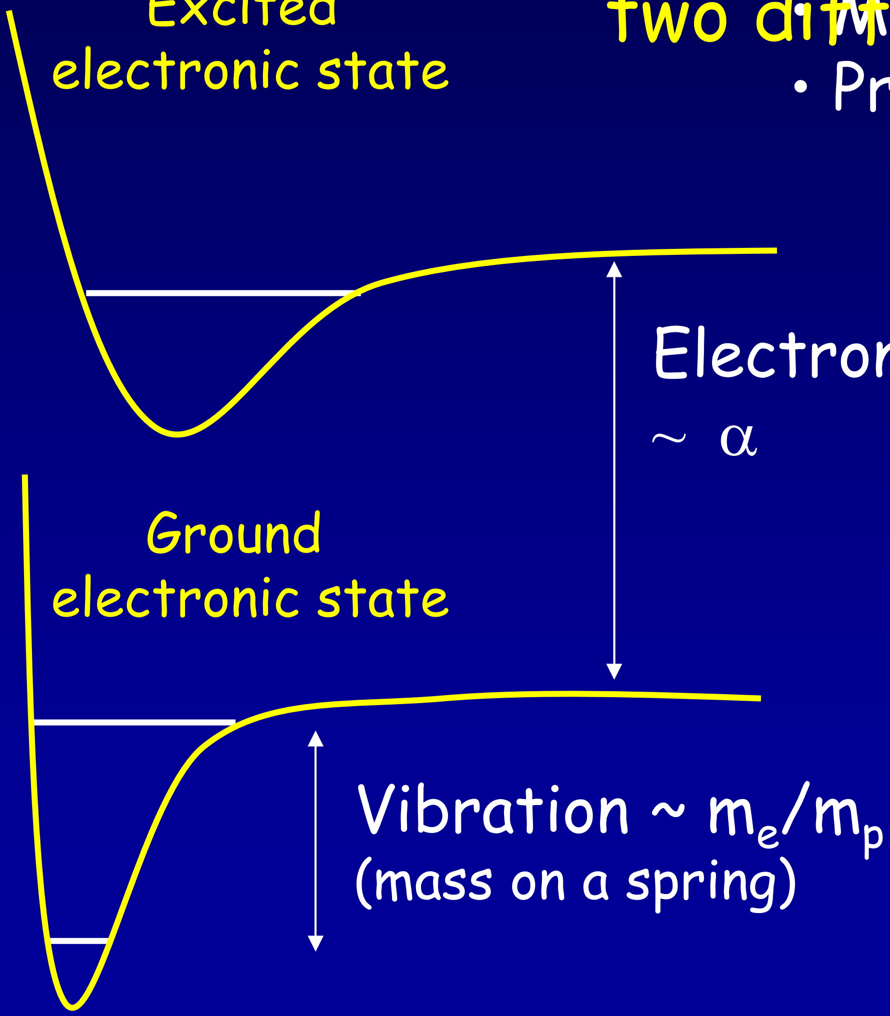


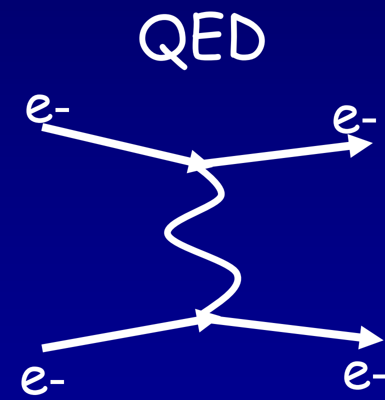


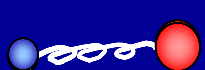
Ultracold molecules: Test fundamental principles

- Ultrahigh resolution spectroscopy
- Standards in wide spectral ranges
- Molecular interferometry
- Precision measurement

One system, two different fundamental forces!

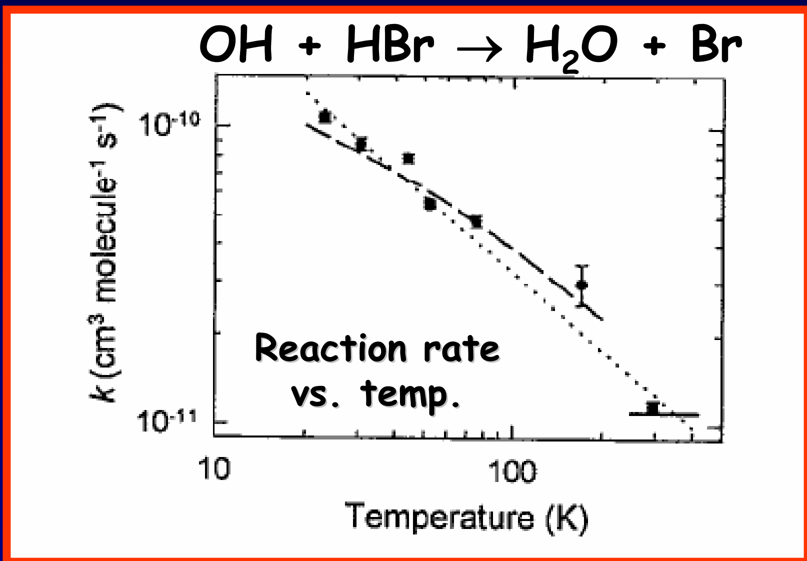




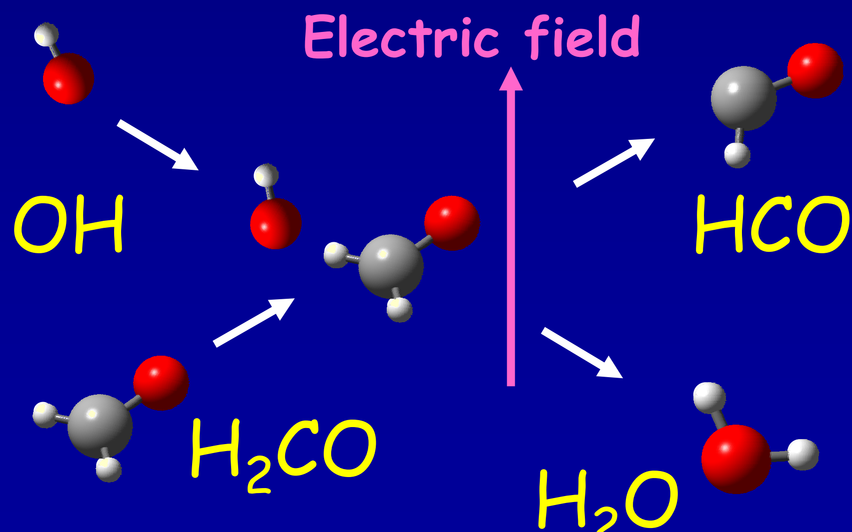


Strong interactions

Ultracold molecules: Precision Chemistry



Stereo-Chemistry



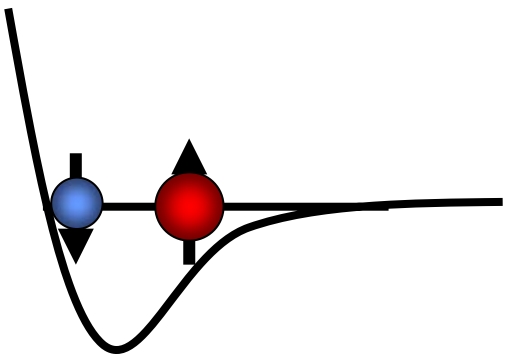
Controlled molecular collisions
Ultracold chemical reactions

- Molecules in single quantum states, under precise control, for internal & external motions
- Unprecedented study of fundamentally important reactions (Dial the rates): OH + HBr, OH + H_2CO, CN + O_2, OH + NO, OH + OH, CN + NH_3, OH + H
- Higher reaction rate at lower temperature (10 K, importance for interstellar chemistry)

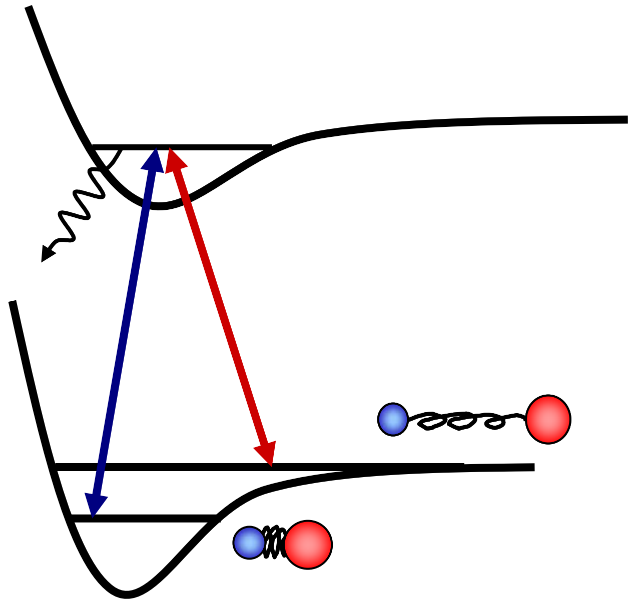
Quantum gas of polar molecules

Towards quantum gas of polar molecules

Feshbach molecule creation + Coherent two-photon state transfer



- Single initial quantum state
- Weakly bound, non-polar

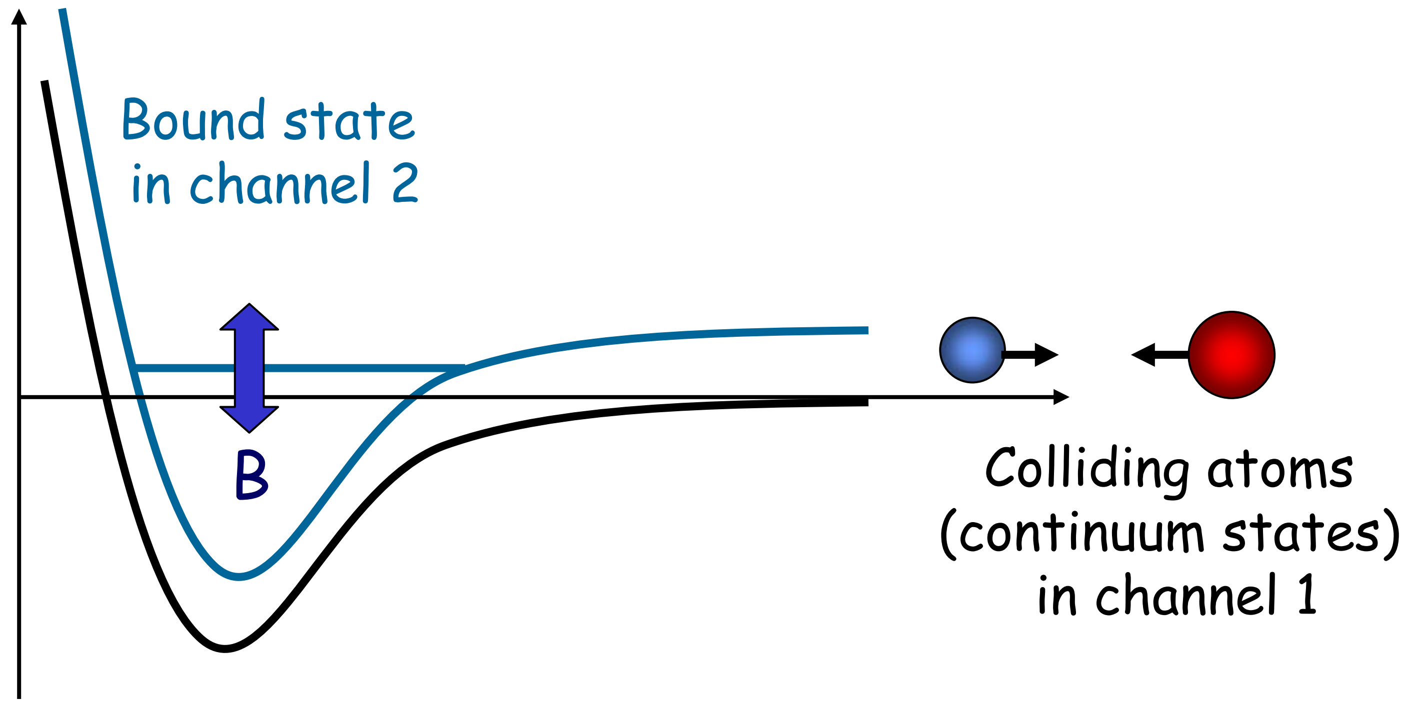


- Single final quantum state
- Deeply bound, polar

→ Dense ultracold deeply bound molecules ($T \sim 100$nK, $n \sim 10^{12}/cm^3$)

Magnetic-field Feshbach resonance

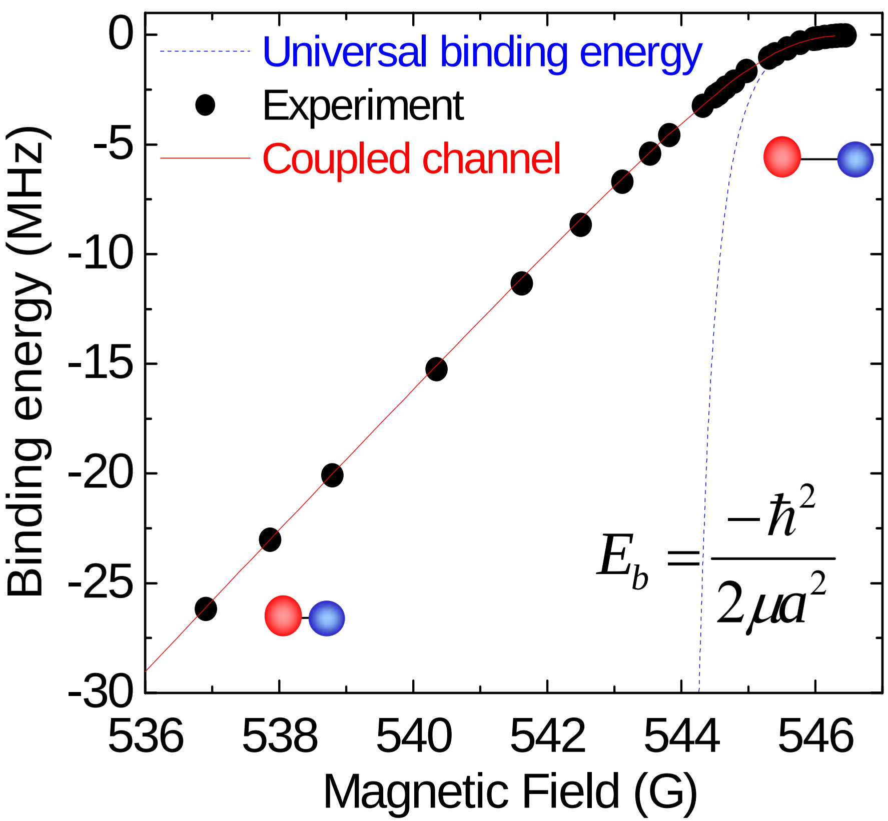
Field-tunable scattering resonance

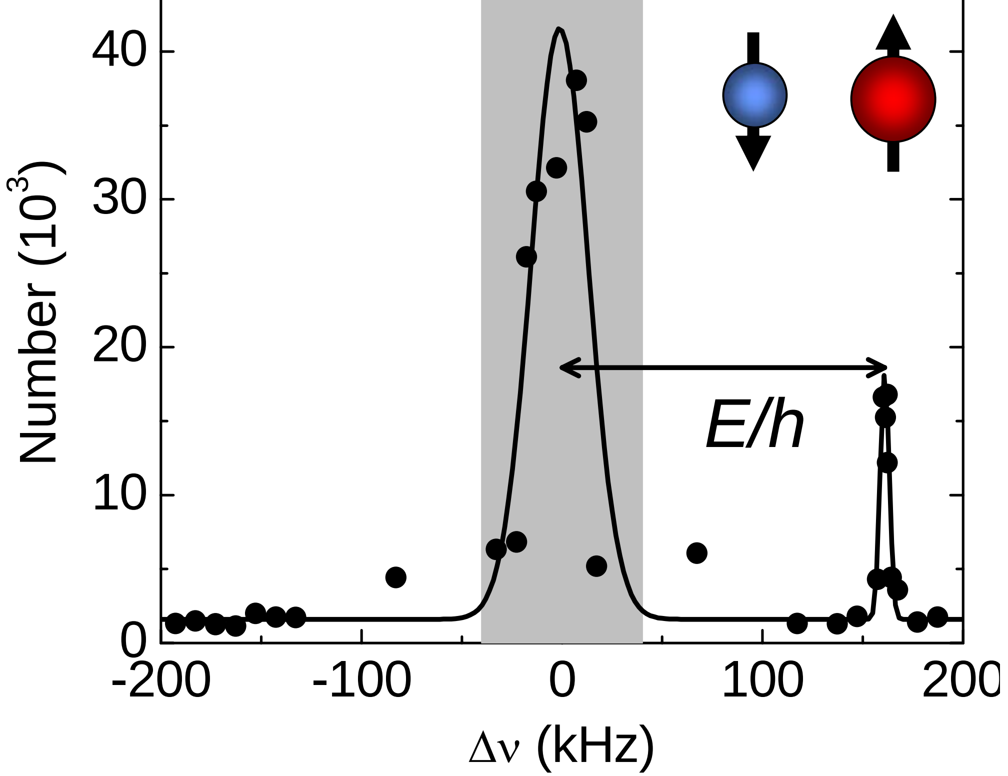


Channels coupled by hyperfine interaction

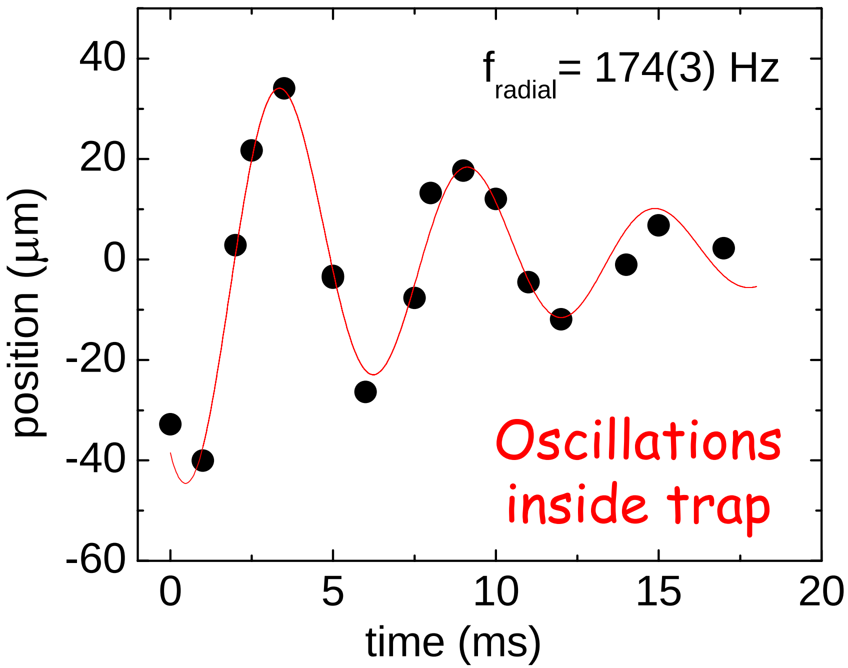
KRb Feshbach molecules

- Near-degenerate mixture of ^{40}K & ^{87}Rb (T ~100 nK)
- RF association of molecules

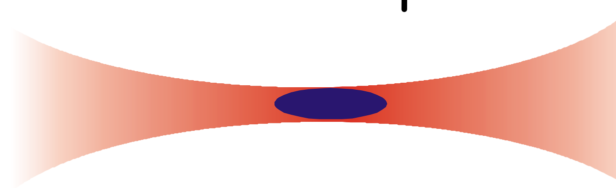




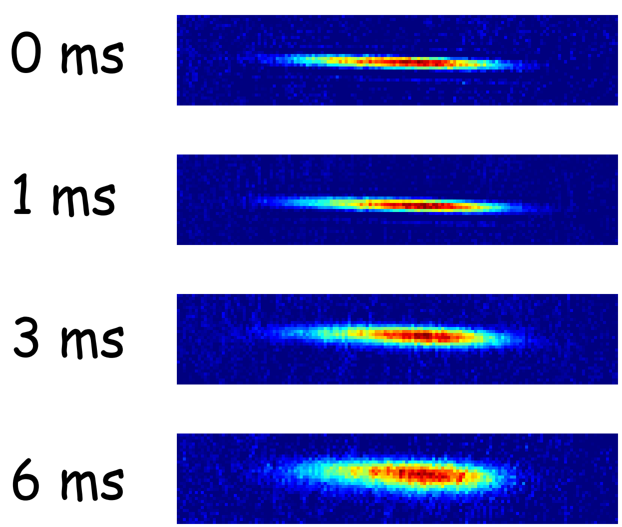
Ultracold trapped KRb



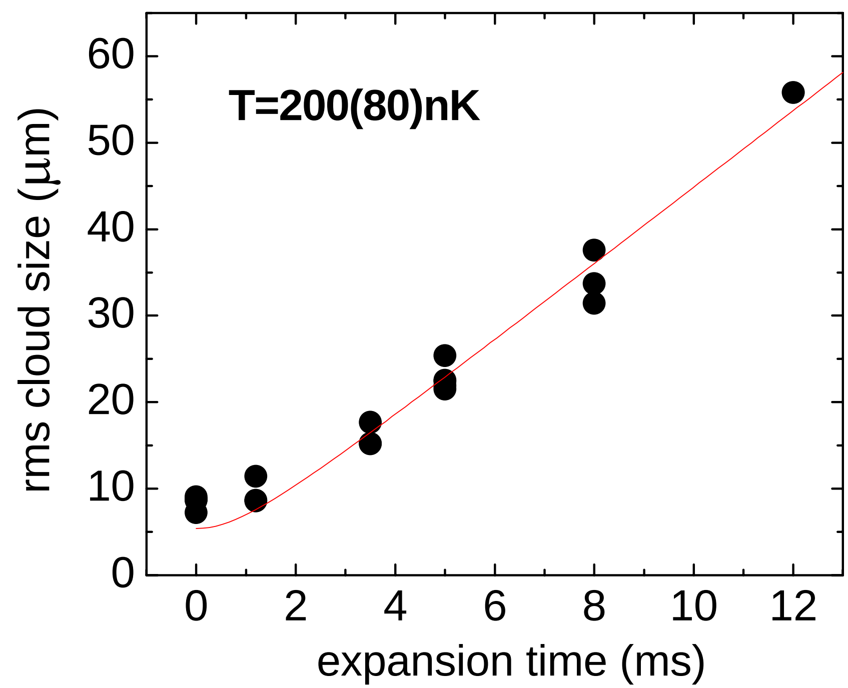
Confined in an optical trap



3 x 10^4 molecules
Density ~$10^{12}/cm^3$



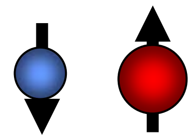
Expansion from the optical trap



Fermionic molecule collisional properties

Zirbel et al., Phys. Rev. Lett. 100, 143201 (2008).

Fermionic ^{40}K

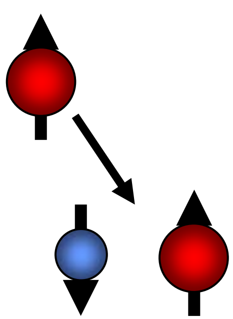


Bosonic ^{87}Rb

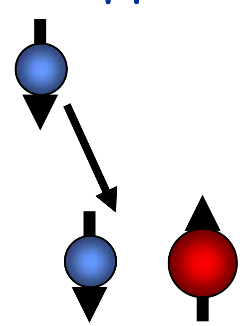
Collisional processes:

- Molecule-molecule collisions → Suppressed at ultralow temperatures (fermionic character)
- Atom-molecule collisions

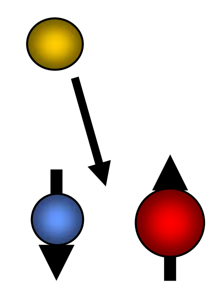
Bosonic enhancement



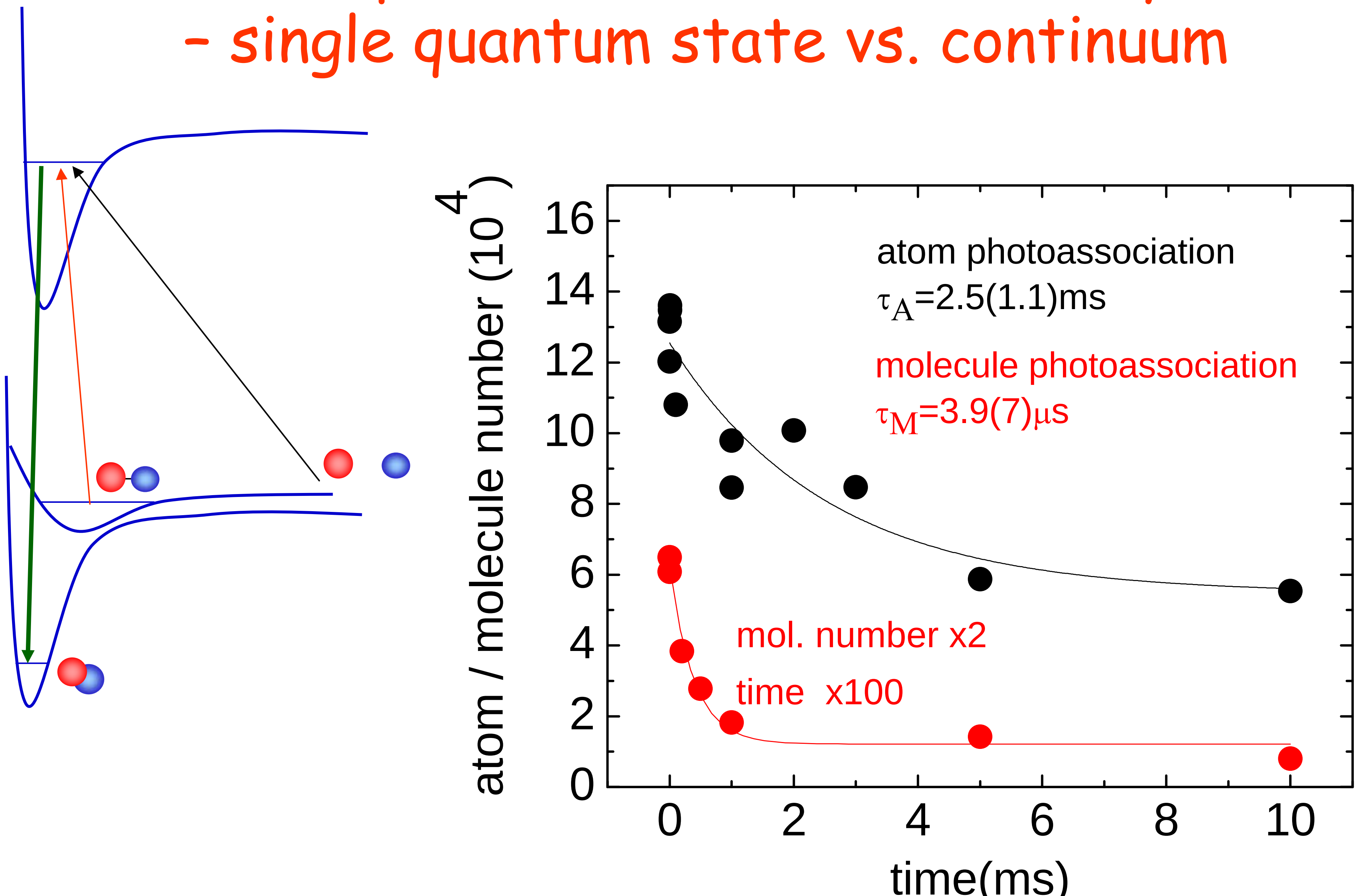
Ferminoic suppression



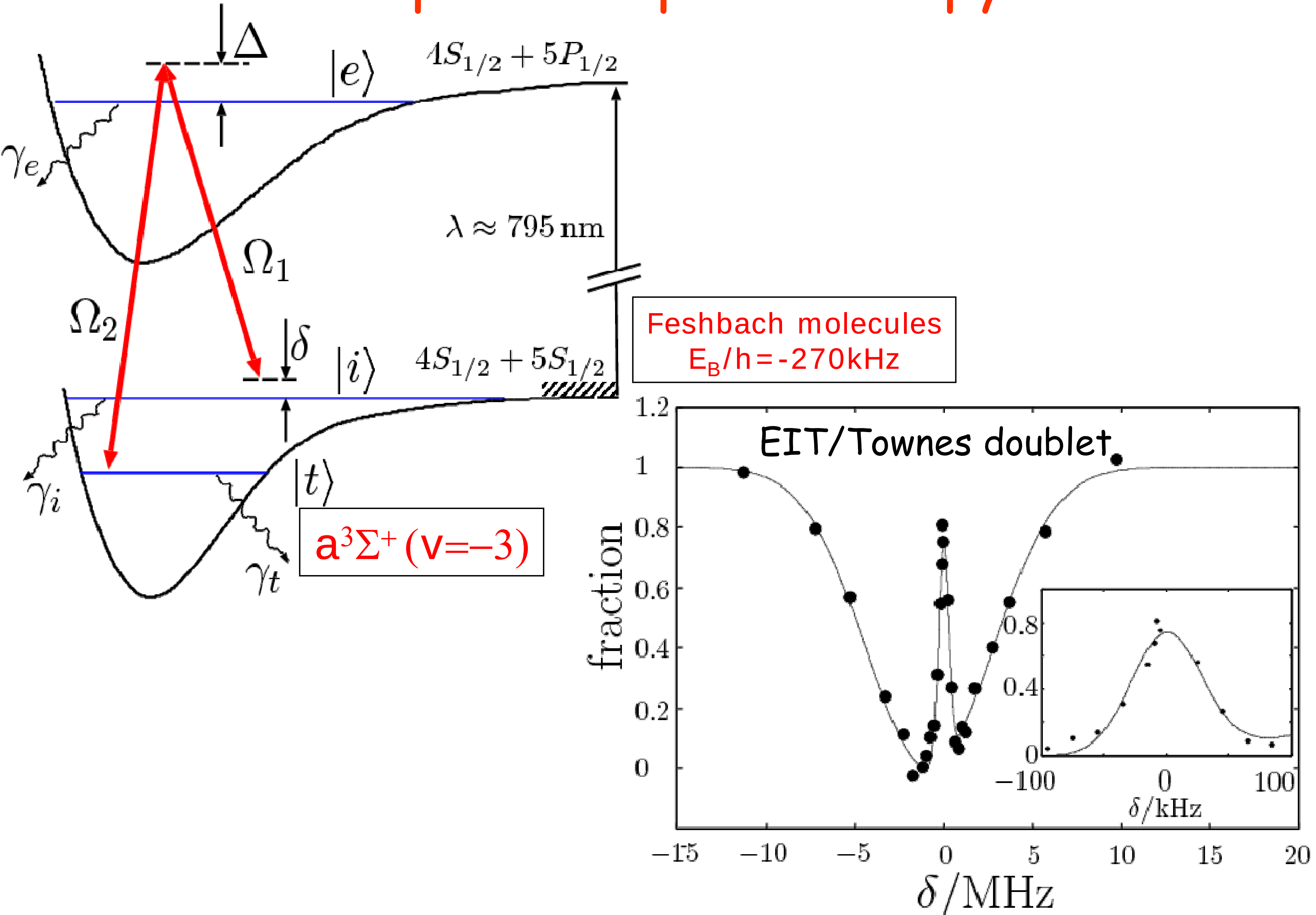
Distinguishable particles



KRb photoassociation efficiency - single quantum state vs. continuum

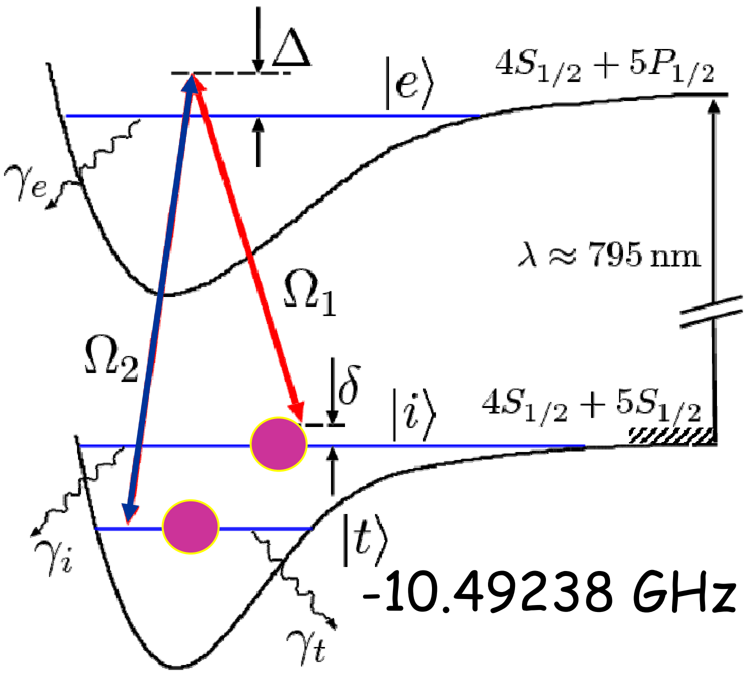


Two photon spectroscopy

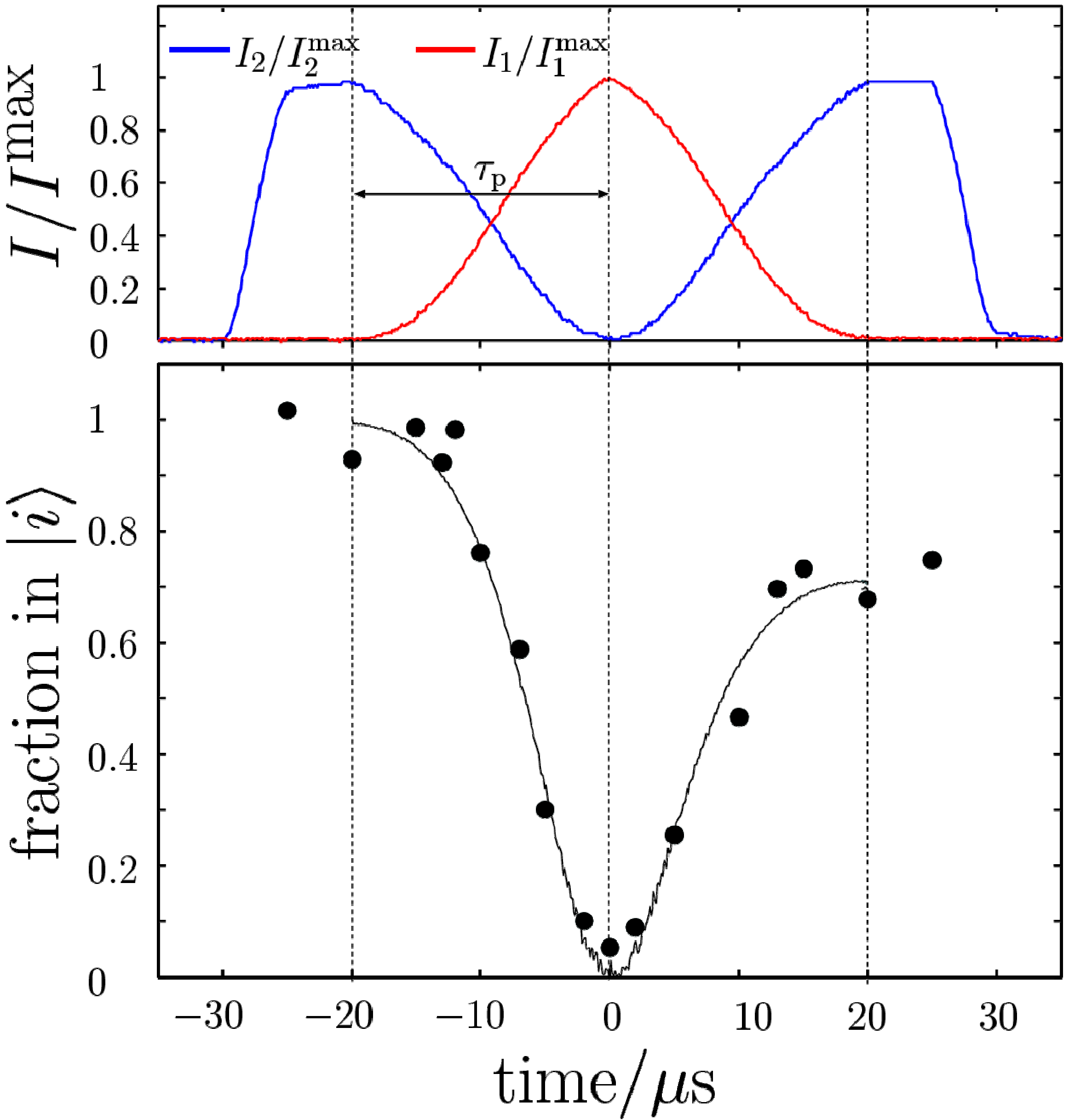


Coherent Transfer - STIRAP

Ospelkaus et al., Nature Physics, in press (2008).

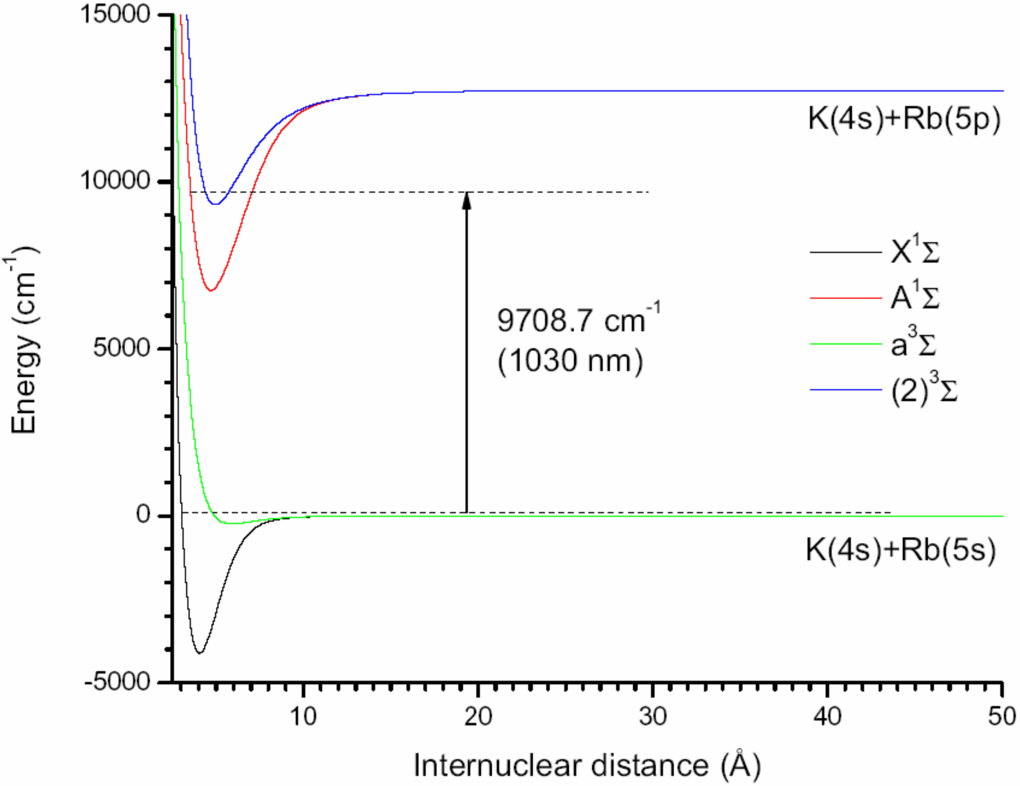


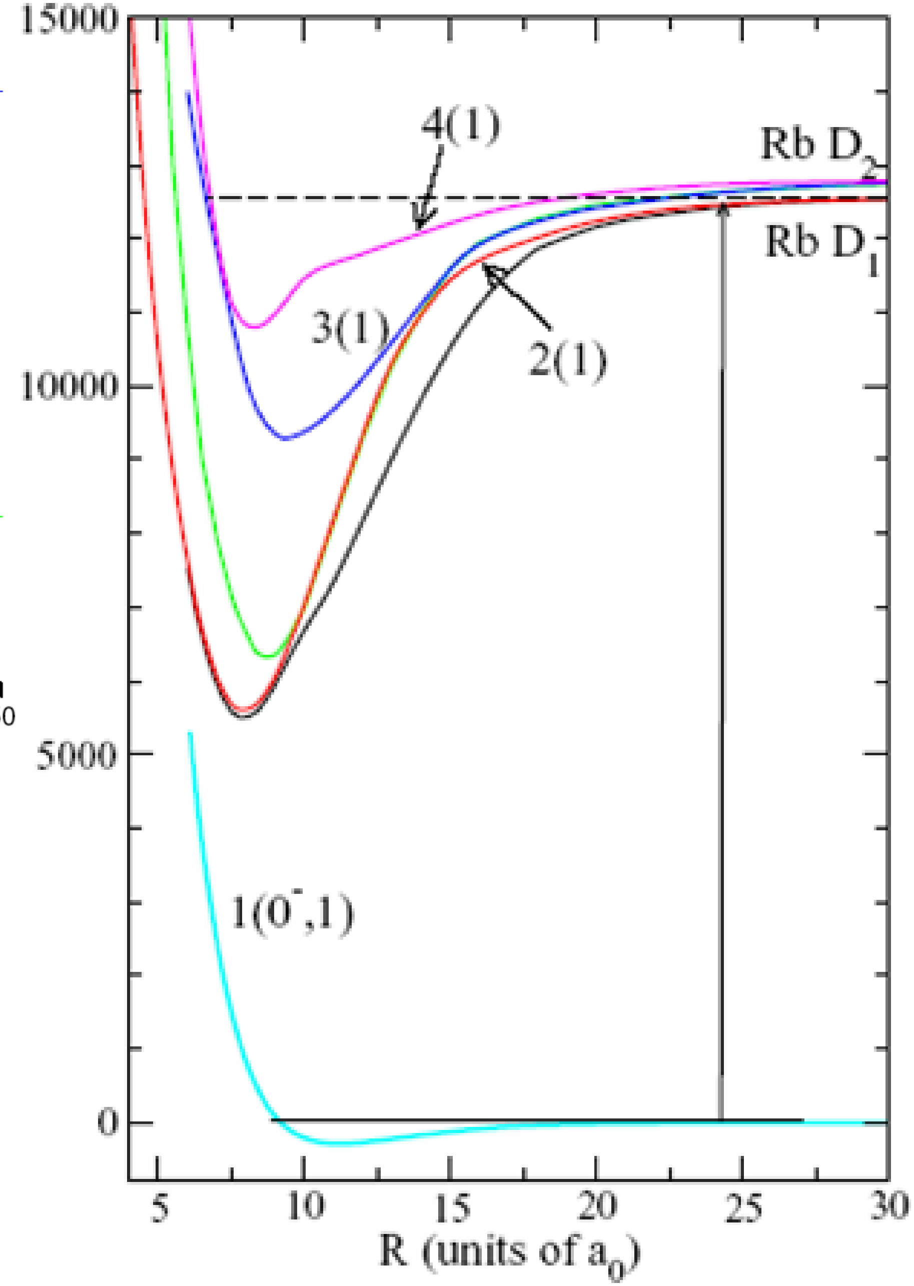
-10.49238 GHz



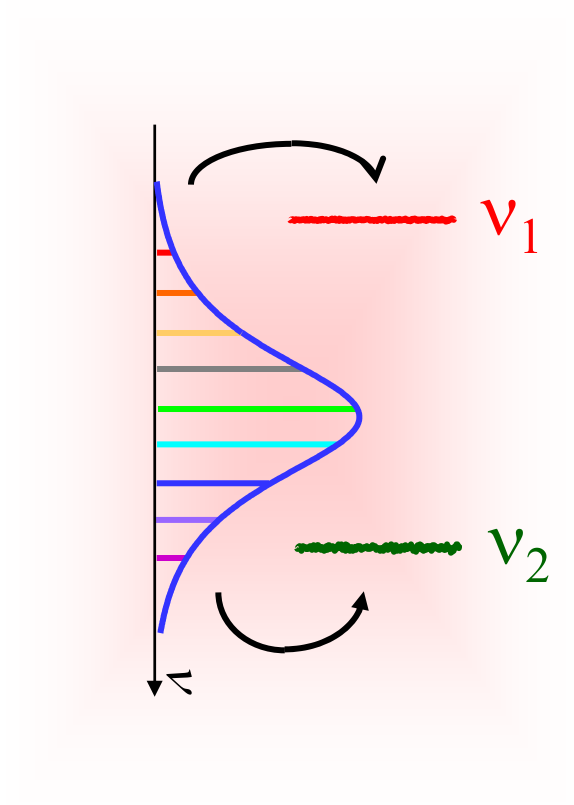
84% transfer efficiency

KRb potentials

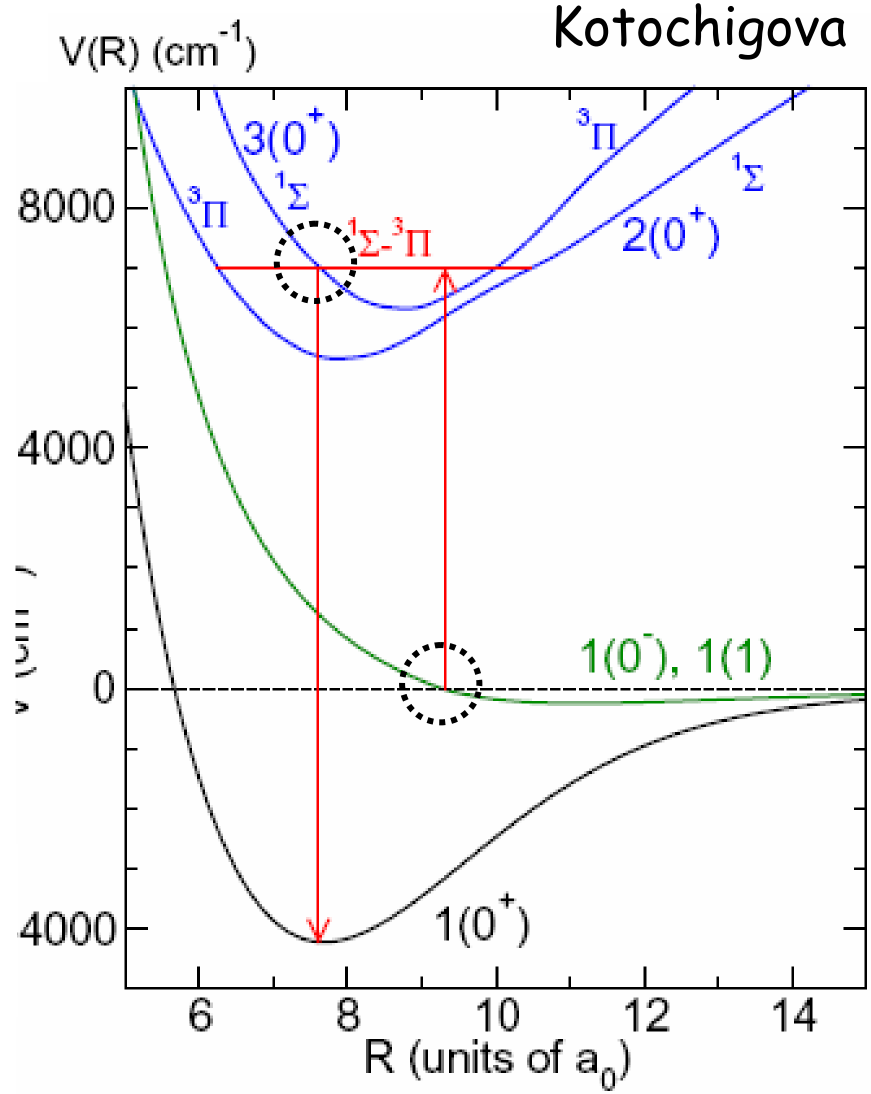




Frequency comb-assisted transfer



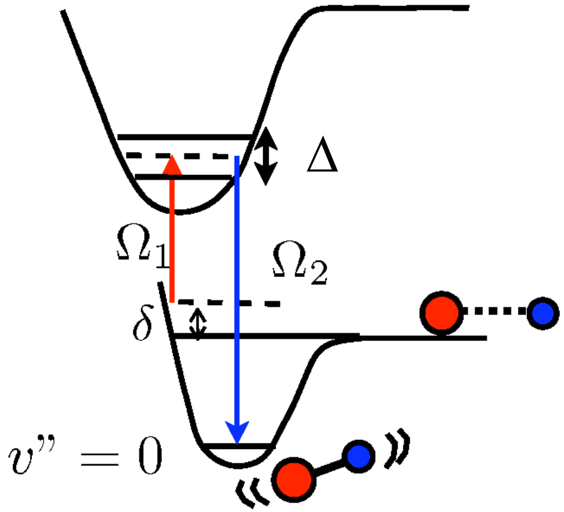
Julienne
Kotochigova



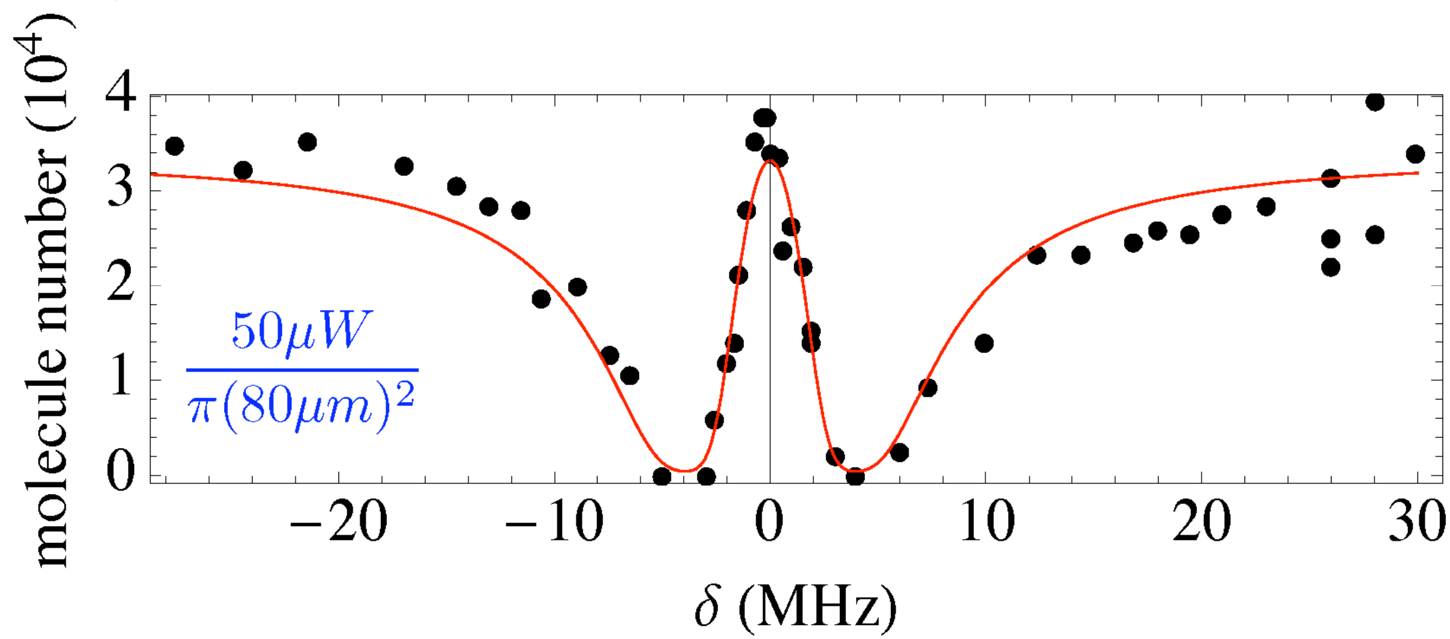
Reaching $A^1\Sigma$ (v=0)

Stwalley, Eur. Phys. J. D 31, 221-225 (2004)

v"=0 Dark Resonance

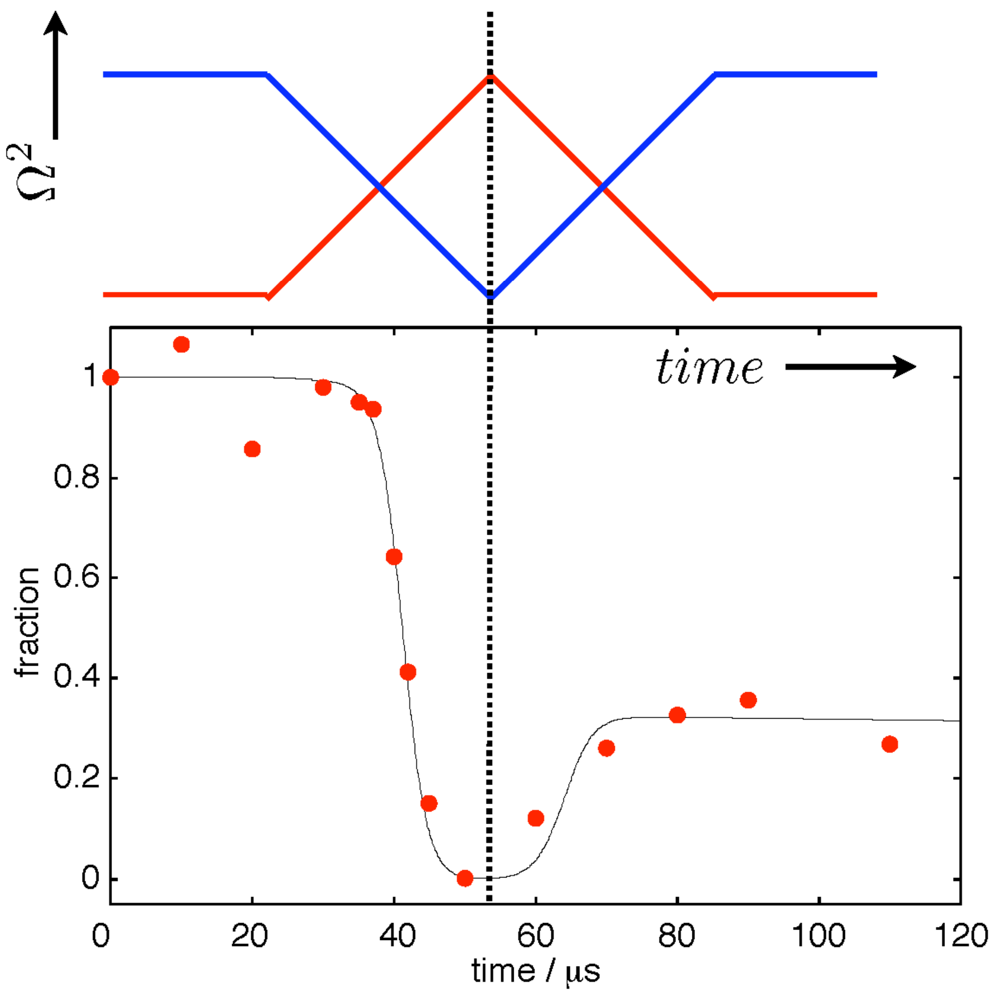


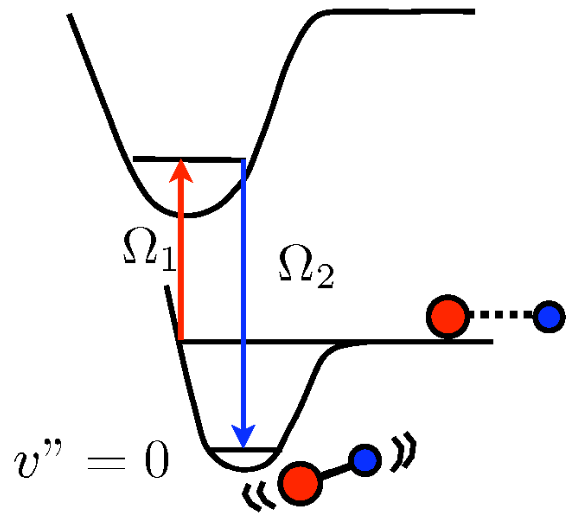
- v=0 binding energy = 7.2 THz
- transition dipole moment= 0.2 ea0



STIRAP

STImulated Raman Adiabatic Passage





Where are we?

Efficient coherent transfer, $>$ 7 THz in a single step

v = 0 (J = 0) in $^3\Sigma$, N = 2 x 10^4, n = $10^{12}/cm^3$,

No heating, 300 nK, $T/T_F = 3$

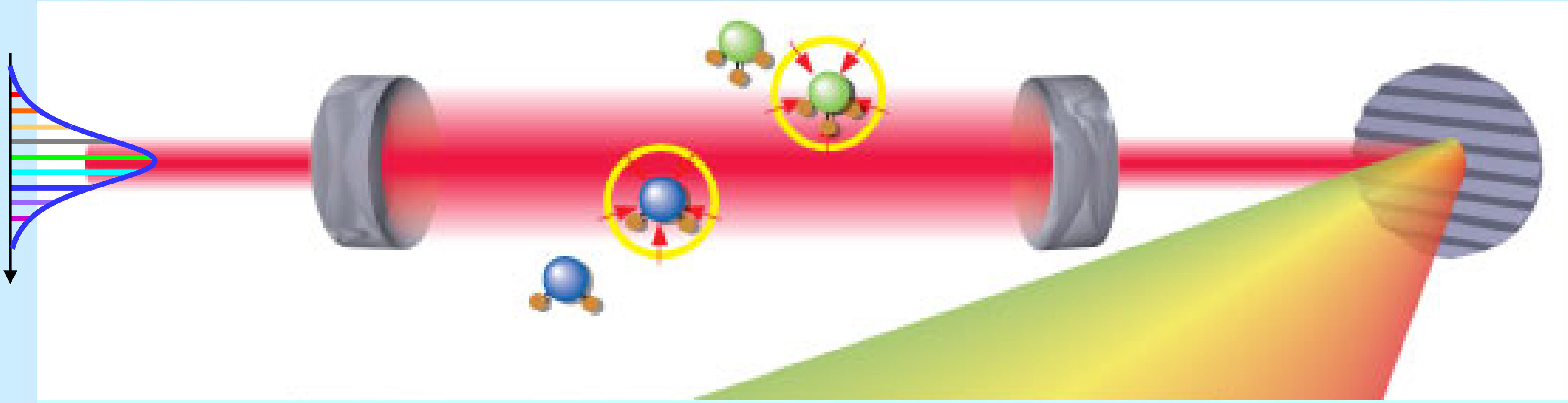
Experimentally observed dipole moment ~0.1 Debye

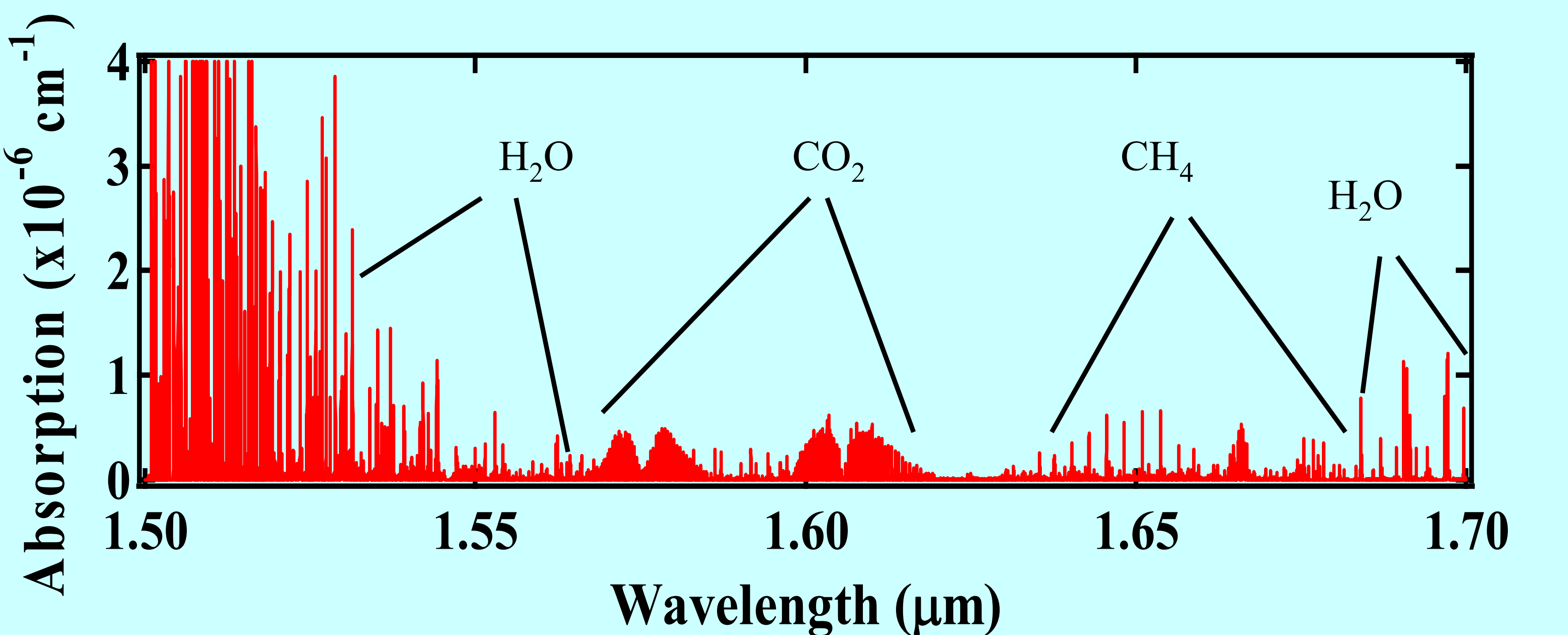
Expect to reach v = 0 in $^1\Sigma$, (120 THz), ~ 1 Debye

Introduce anisotropic & long-range interactions

Frequency comb spectroscopy

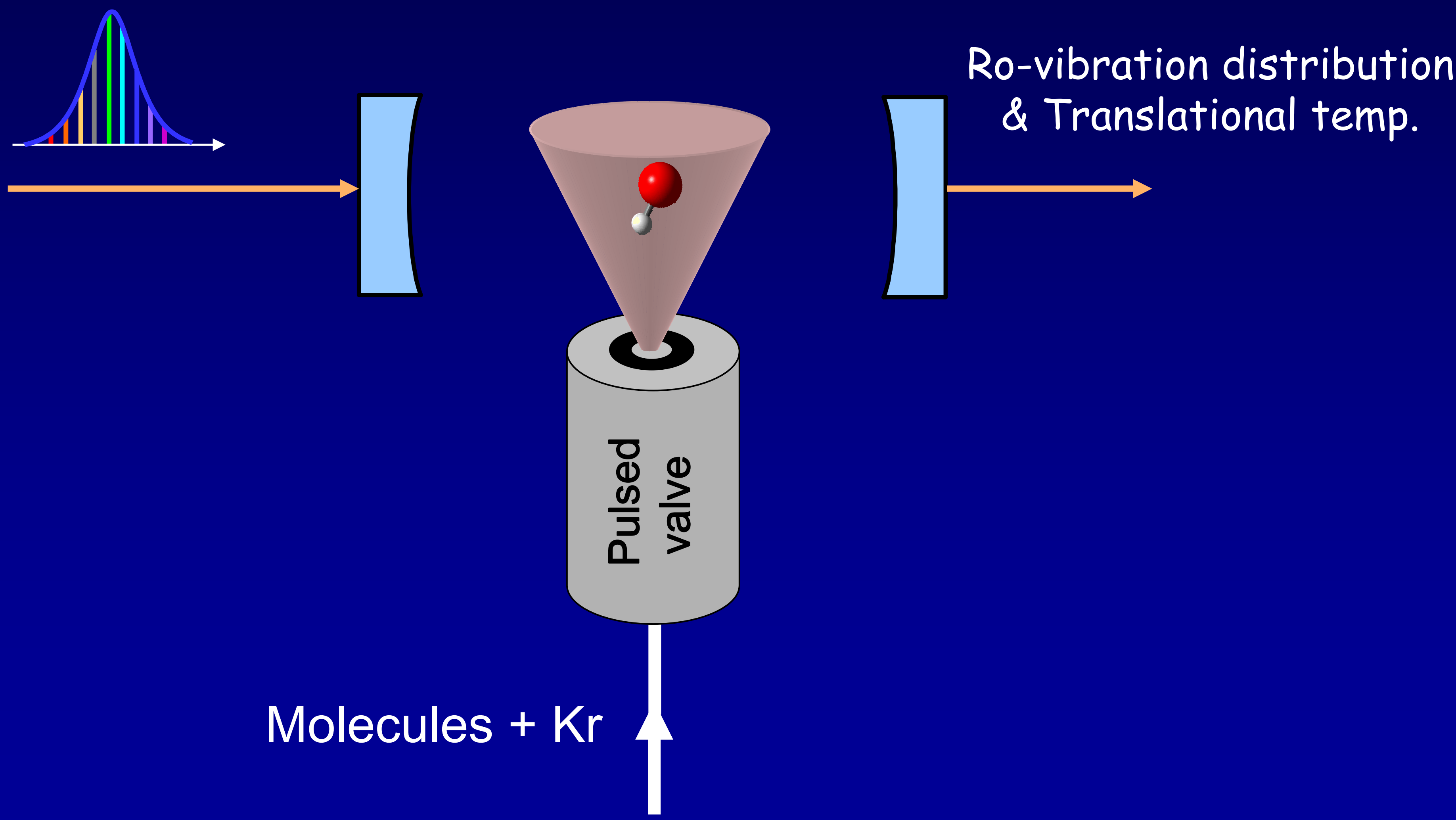
Thorpe *et al.*, Science 311, 1595 (2006); Opt. Exp. <u>16</u>, 2387 (2008).





Tomography of all degrees of freedom

Thorpe and Ye, Appl. Phys. B 91, 397 (2008).

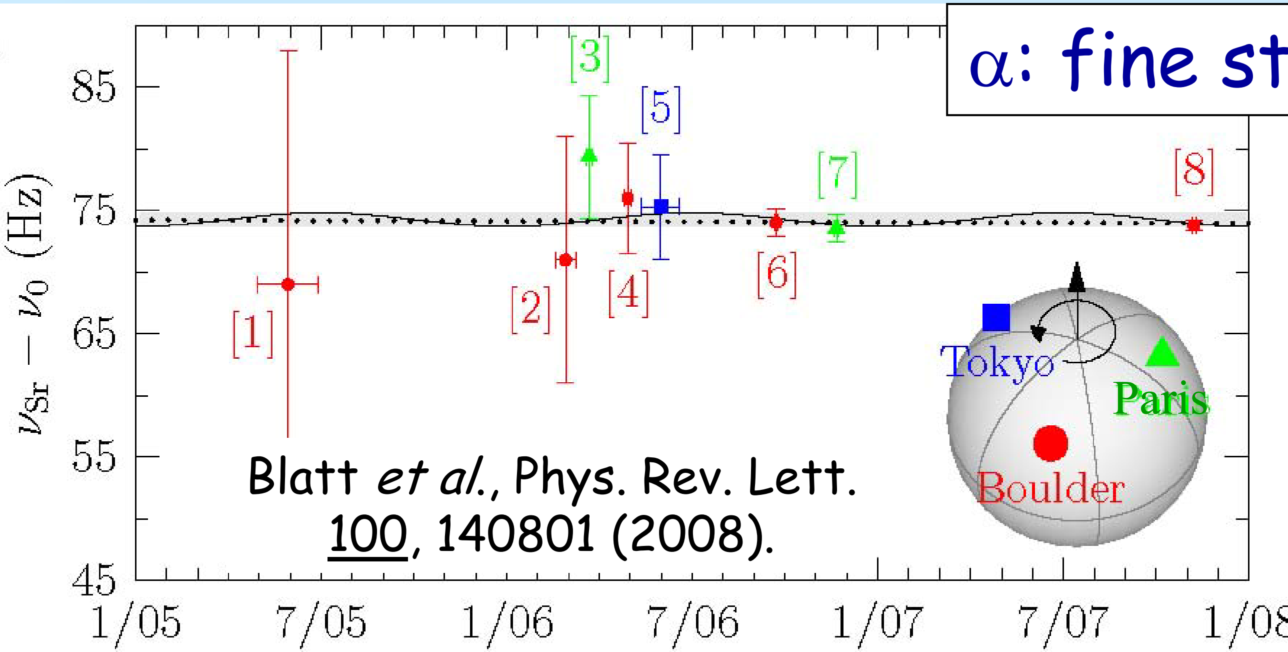


Cold ground-state molecules

(from precision measurement to cold molecular collisions)

Test of fundamental constants

α: fine structure constant



Blatt *et al.*, Phys. Rev. Lett. 100, 140801 (2008).

•Modern epoch

Clock measurements are consistent with zero

$\Delta\alpha/\alpha = -3.3\ (3.0) \times 10^{-16}$/yr

• Early universe

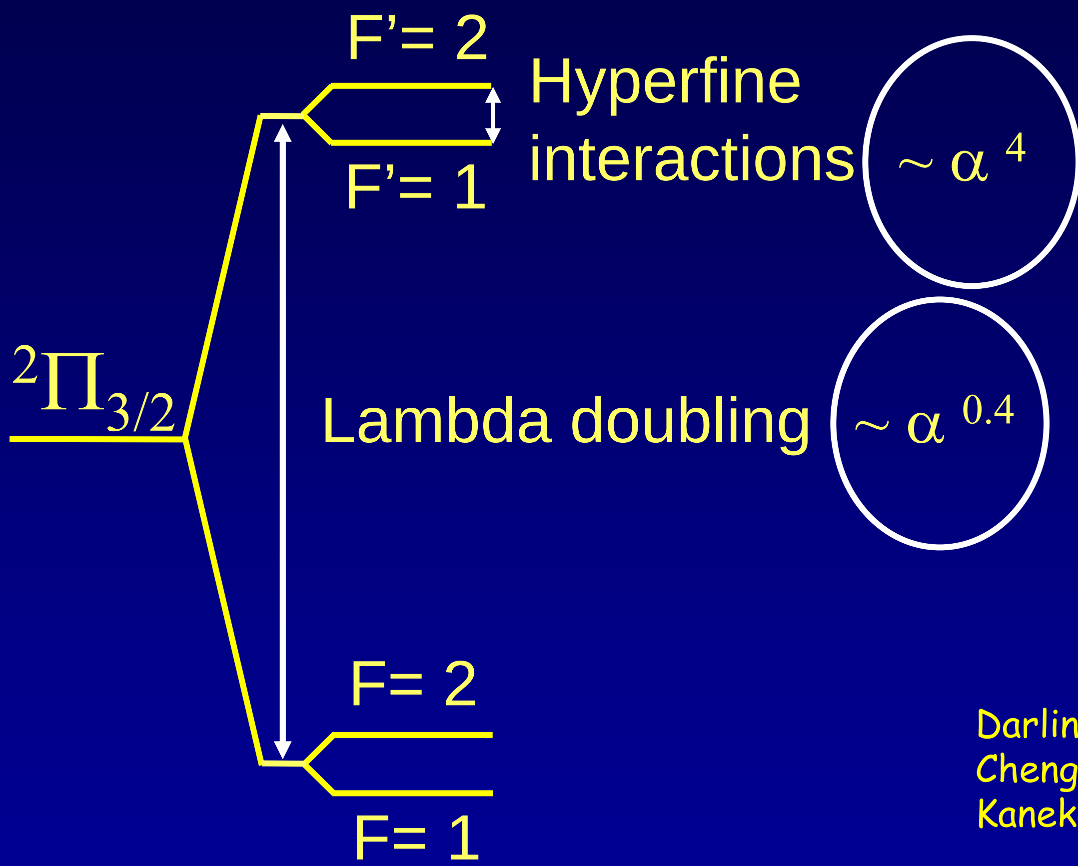
• Not so clear…

Webb *et al.*, PRL 87, 091301 (2001).

Astron. Astrophys. 415, L7 (2004).

– Conflicting results

Cold OH molecules to constrain $\Delta\alpha / \alpha$



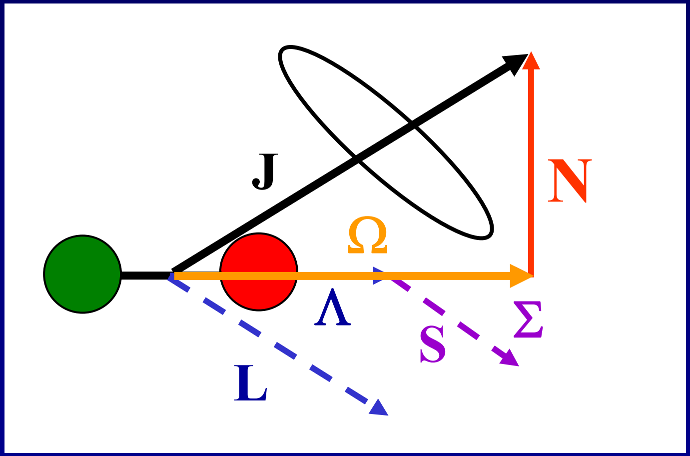
OH megamasers

Darling, Phys. Rev. Lett **91**, 011301 (2003).
Chengalur *et al.*, Phys. Rev. Lett. 91, 241302 (2003).
Kanekar *et al.*, Phys. Rev. Lett. **93**, 051302 (2004).

Multiple transitions from the same gas cloud
(Self check on systematics)

Molecular electronic state labeling

- Heteronuclear diatomic molecules possess only axial symmetry
  - different good quantum numbers than for atoms

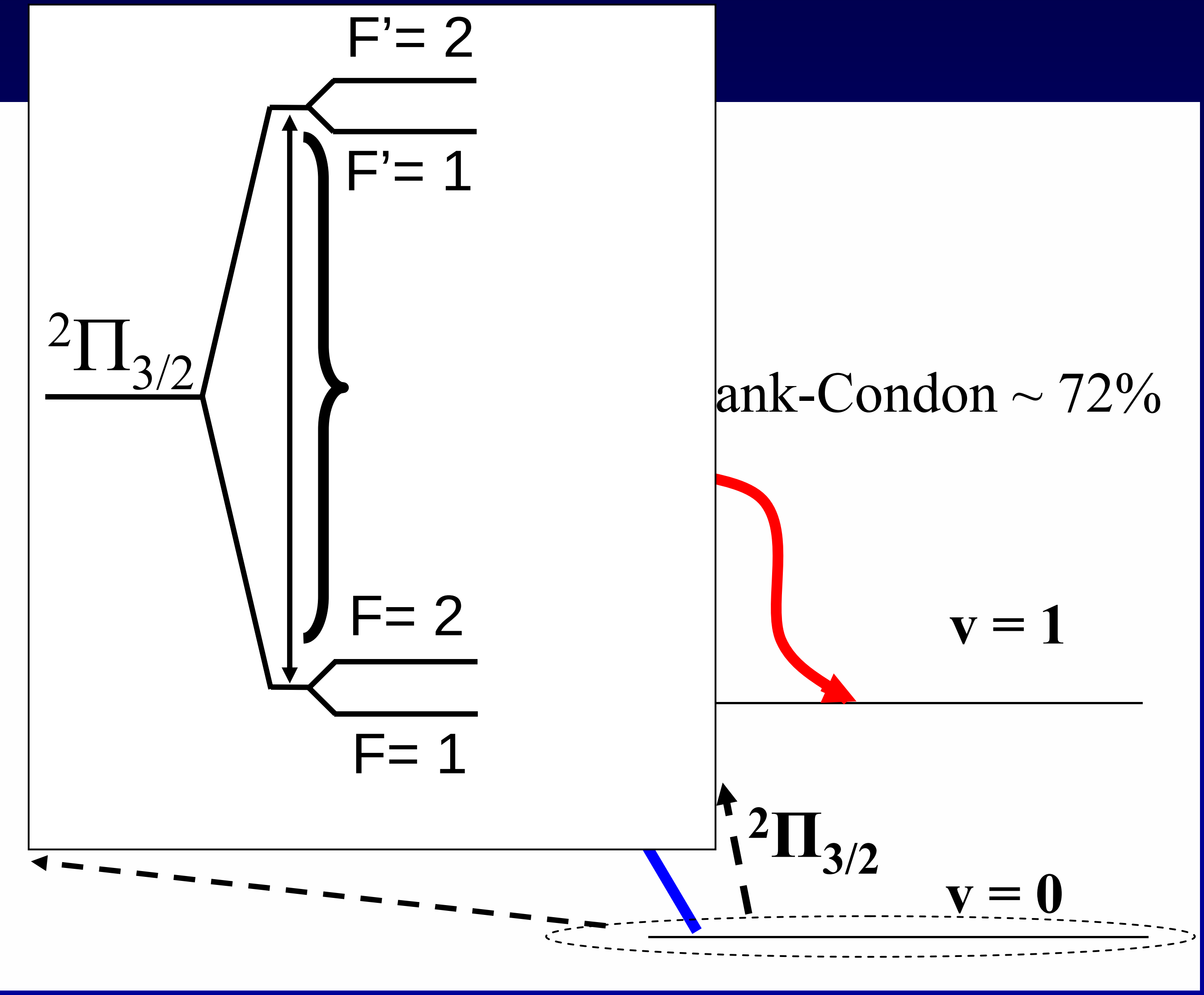


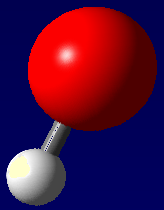
- $\Omega = |\Lambda + \Sigma|$
- $\mathbf{J} = \mathbf{\Omega} + \mathbf{N}$

- Electronic potentials are labeled as $^{2\Sigma+1}\Lambda_{\Omega}$
  - $\Sigma, \Pi, \Delta, \ldots$ states for $\Lambda = 0, 1, 2, \ldots$
  (i.e., $^2\Pi_{3/2}$ state has $\Lambda=1$, $\Sigma=1/2$, $\Omega=3/2$)

- Good quantum #'s are Λ, Σ, Ω, J, m_J (or just Ω, J, m_J)

Basic energy structure of OH



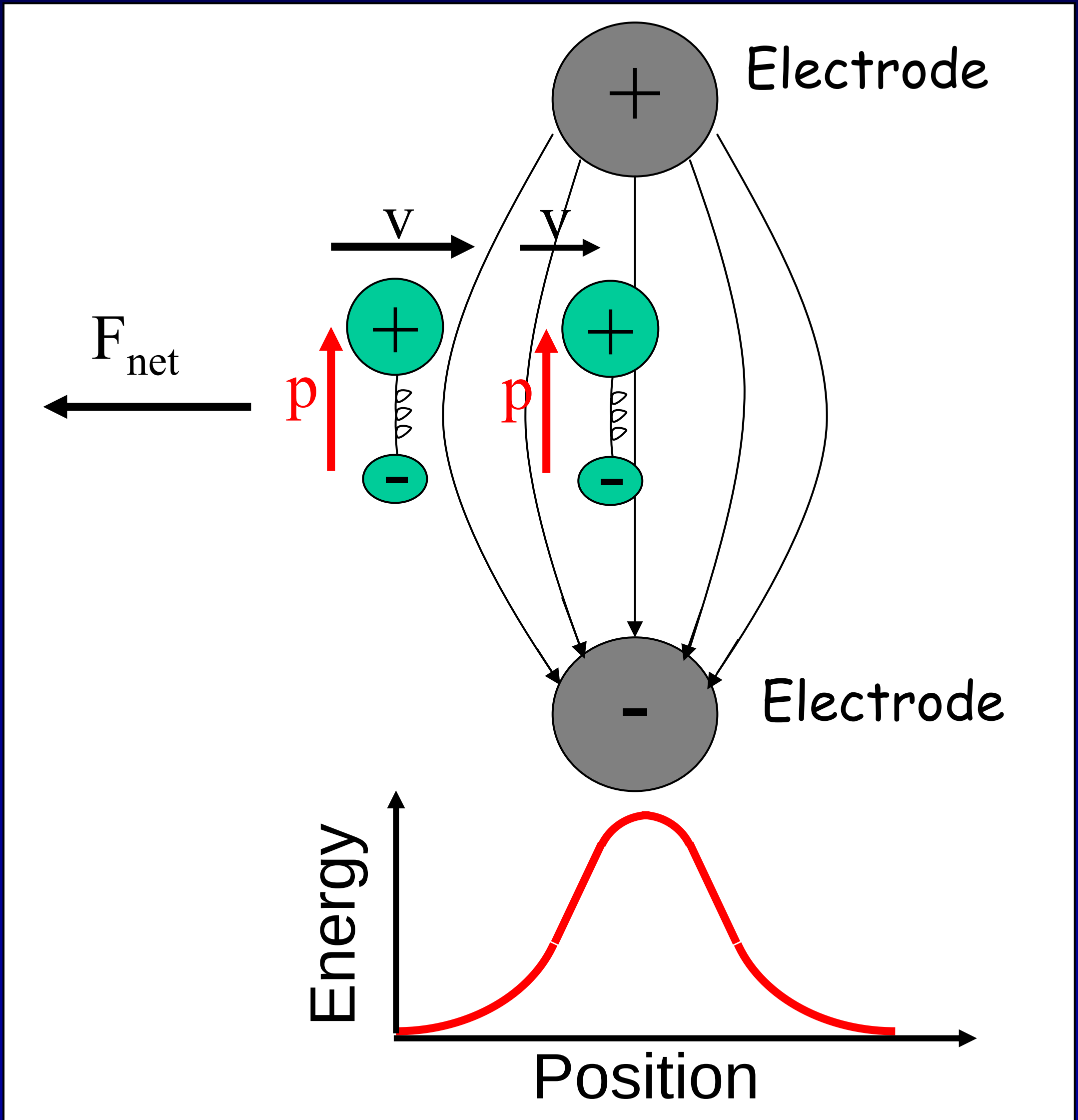


Basics:

- Ground State $^2\Pi_{3/2}$
- λ doublet spacing ~1 GHz
- Electric dipole (1.67 D)
- magnetic moment (μ_B)

Stark deceleration

Direct manipulation of ground state molecules



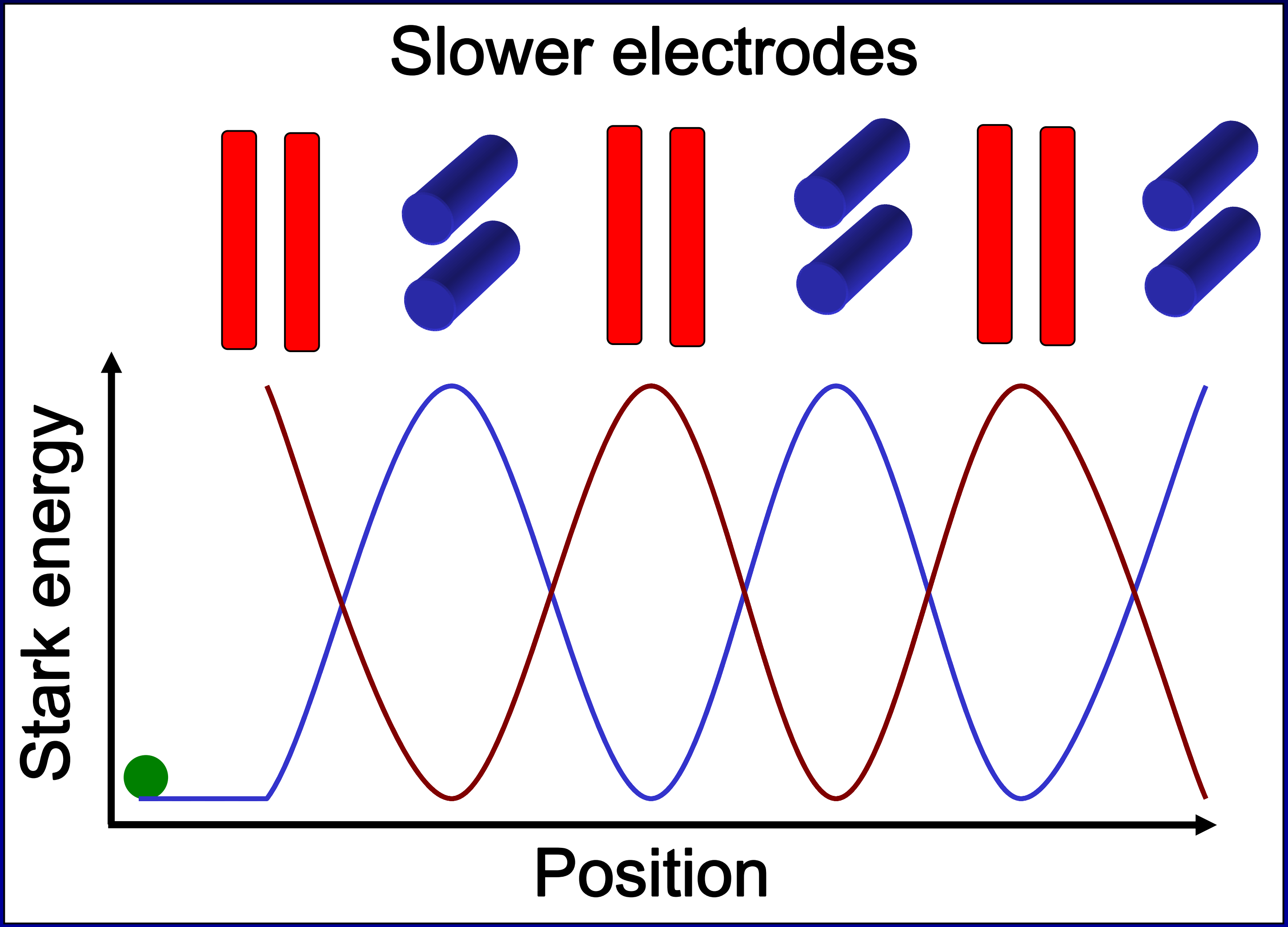
Cooling by supersonic expansion (~ 1 K in a moving frame)

Phase space selection (~ 10 mK)

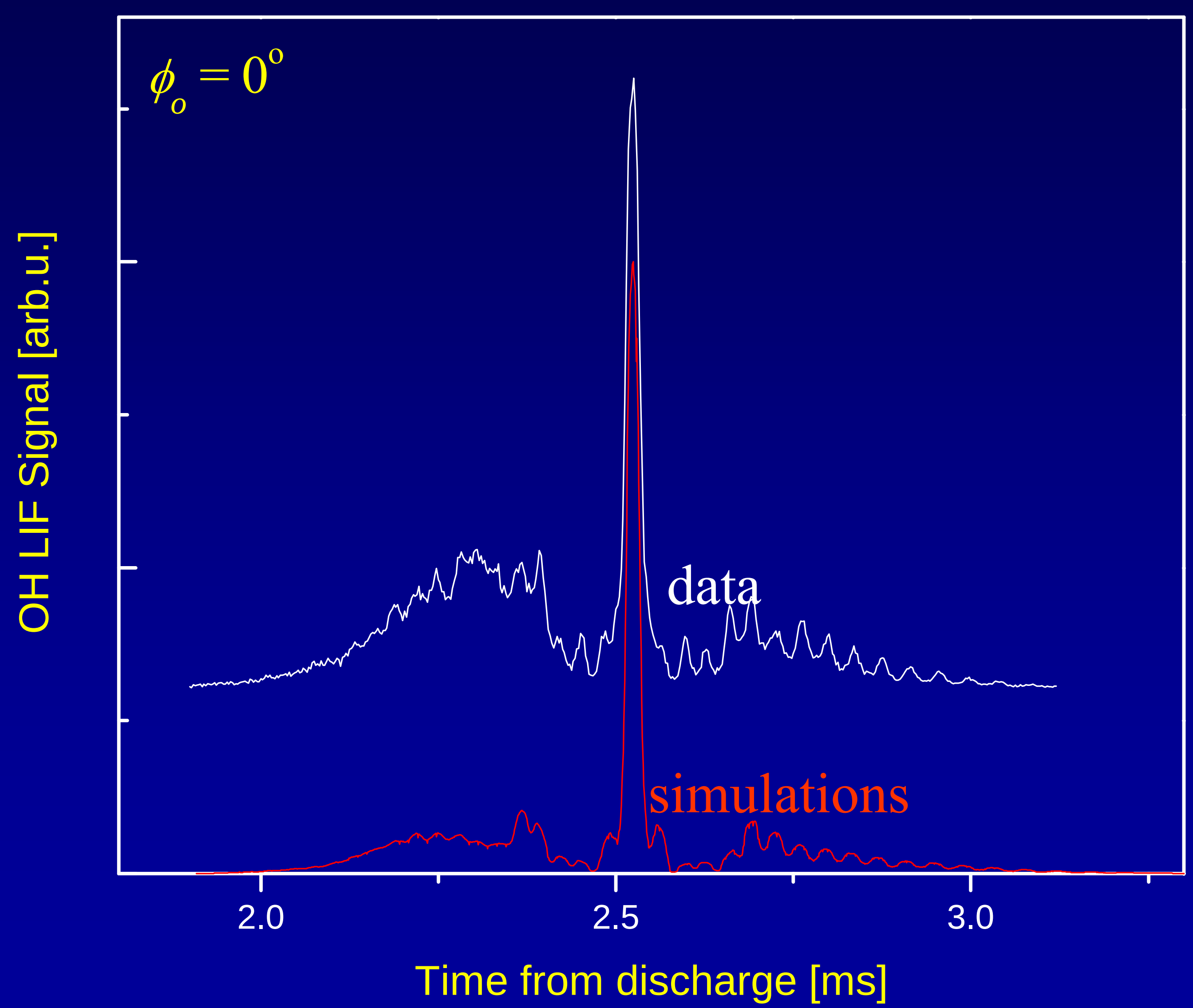
Applicable to a large variety of molecules

Bethlem, Berden, Meijer, Phys. Rev. Lett. 83 1558 (1999).

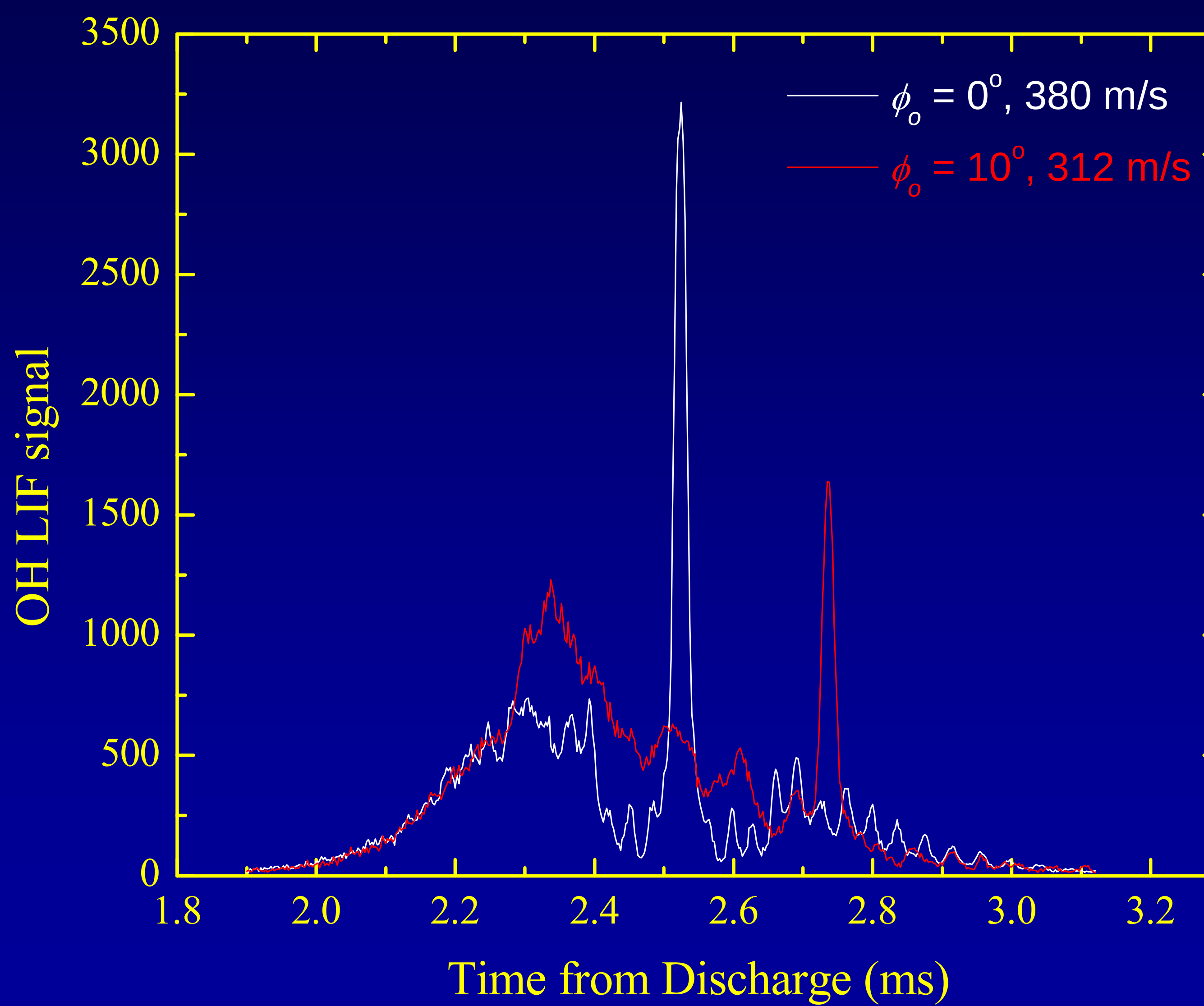
Stark Decelerator



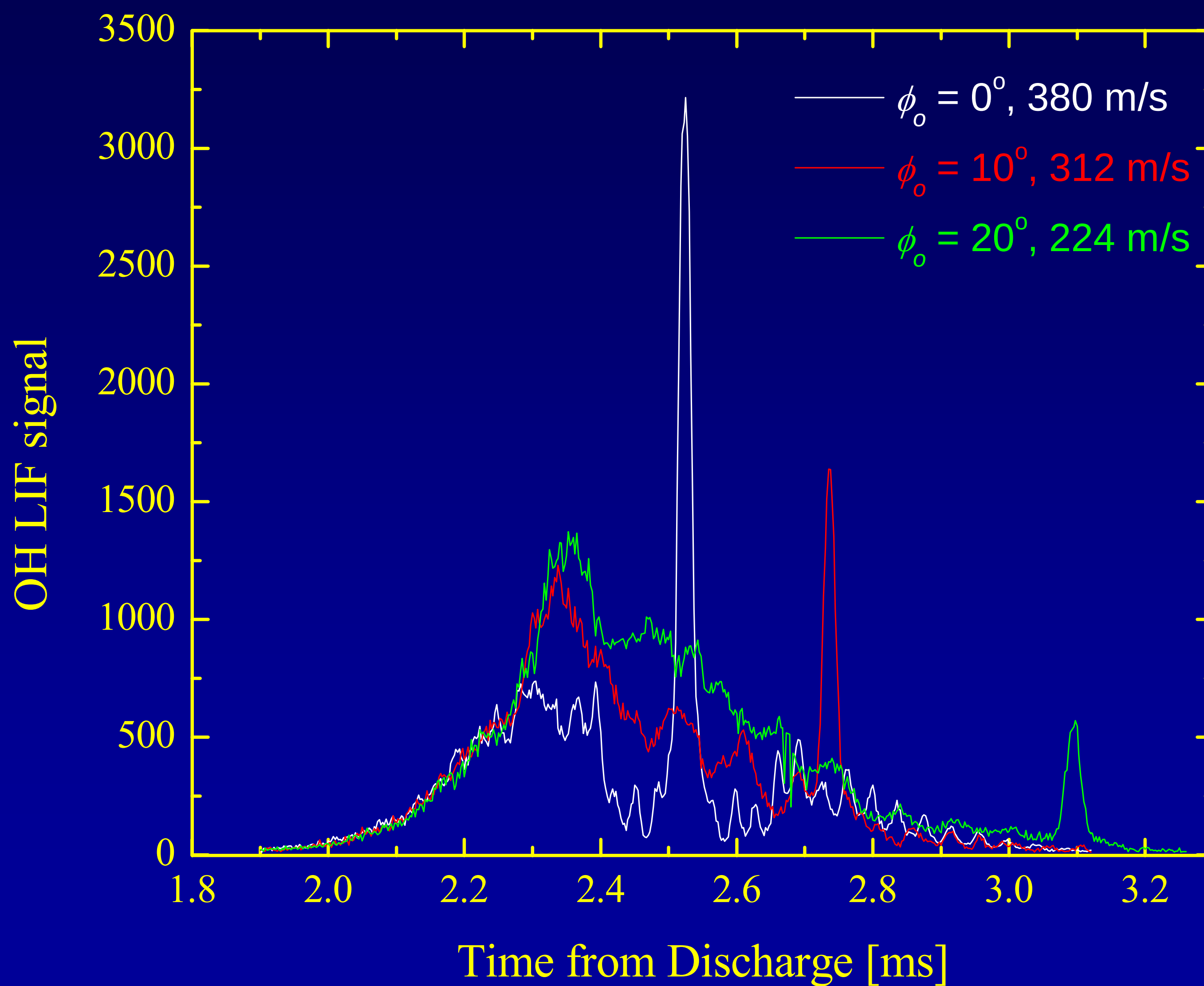
Experiment & Theory



Slowed molecular packet

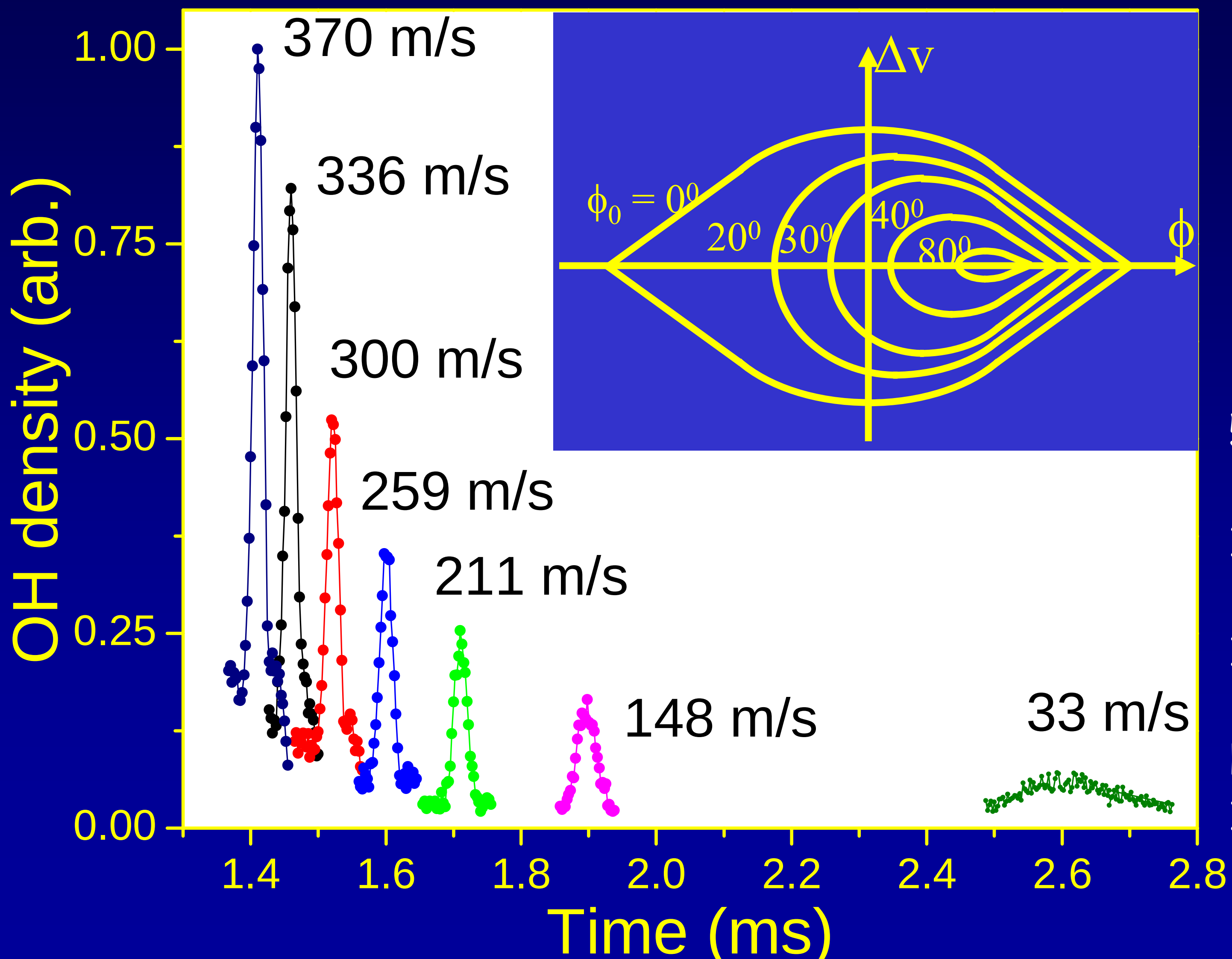


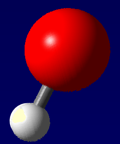
Slowed molecular packet

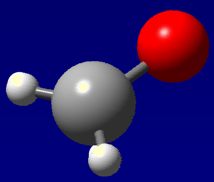


Cold ground-state molecules

Bochinski, Hudson, Lewandowski, Meijer, Ye, Phys. Rev. Lett. **91**, 243001 (2003).
Hudson et al., Phys. Rev. A 73, 063404 (2006).







550 m/s to rest

1 K to 10 mK

10^4 – 10^6 molecules

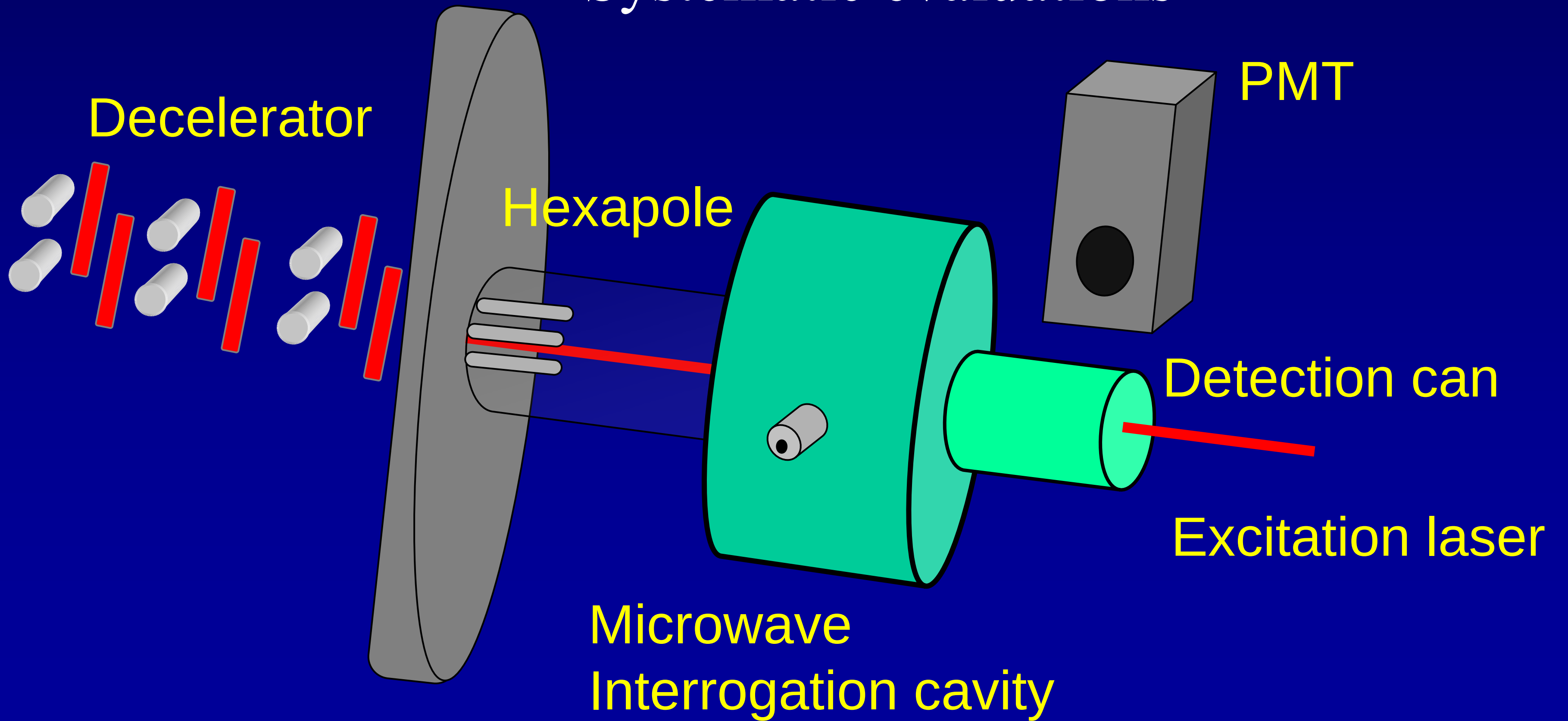
Density:
10^5 – 10^7 /cm^3

Cold molecule based precision spectroscopy

Hudson, Lewandowski, Sawyer, Ye, PRL 96, 143004 (2006).

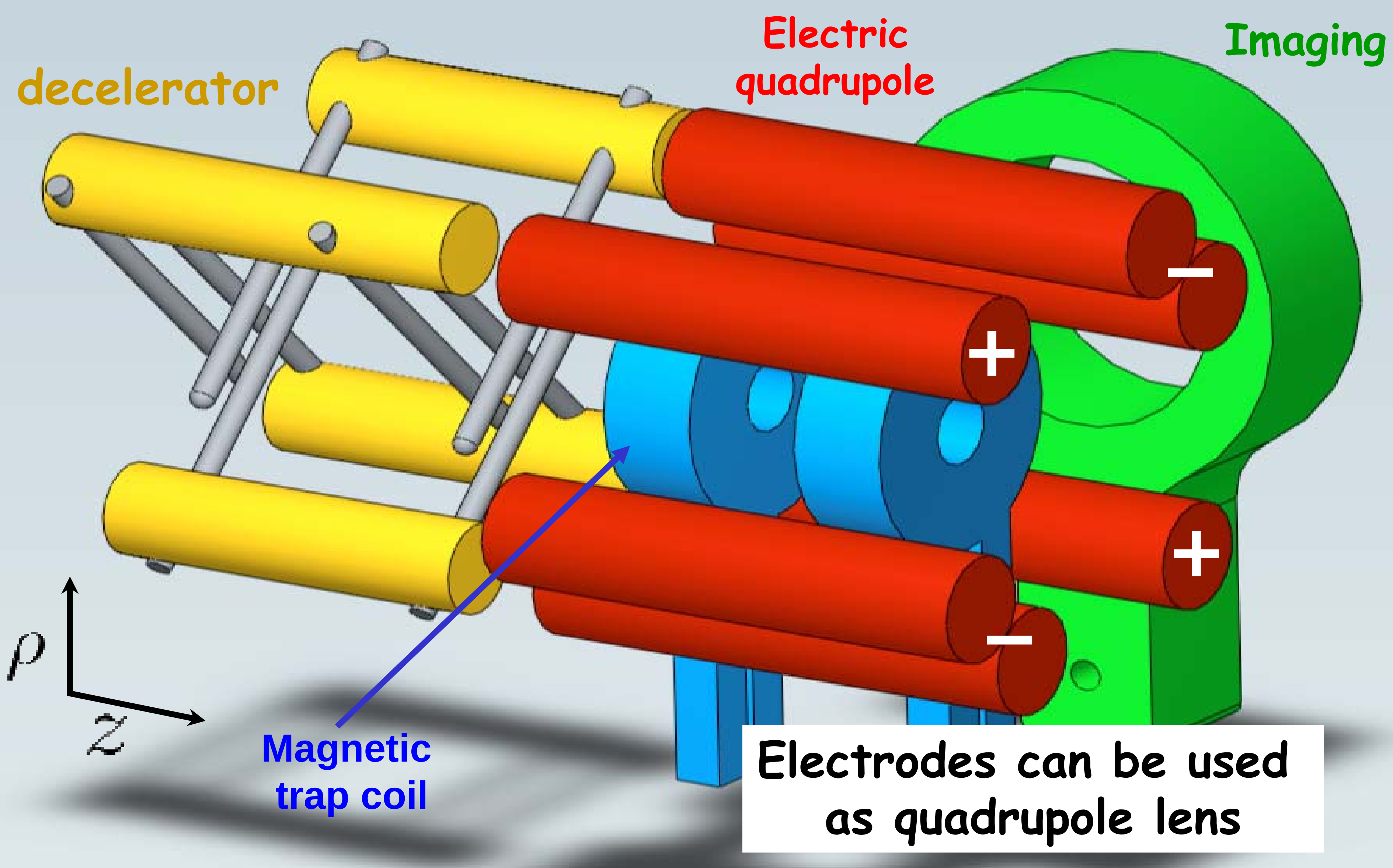
Lev, Meyer, Hudson, Sawyer, Bohn, Ye, PRA 74, 061402 (2006).

- High resolution and precision
- Systematic evaluations



Magnetic trapping of OH

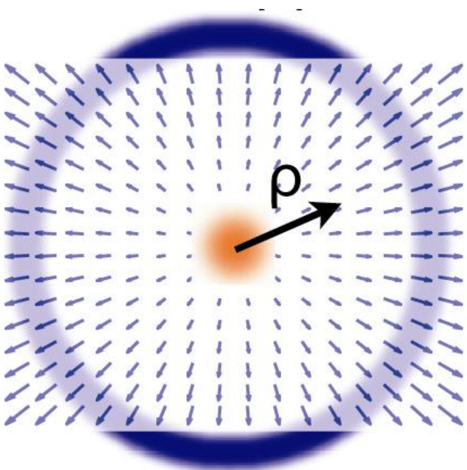
Sawyer, Lev, Hudson, Stuhl, Lara, Bohn, & Ye, Phys. Rev. Lett. 98, 253002 (2007).



Electrodes can be used as quadrupole lens

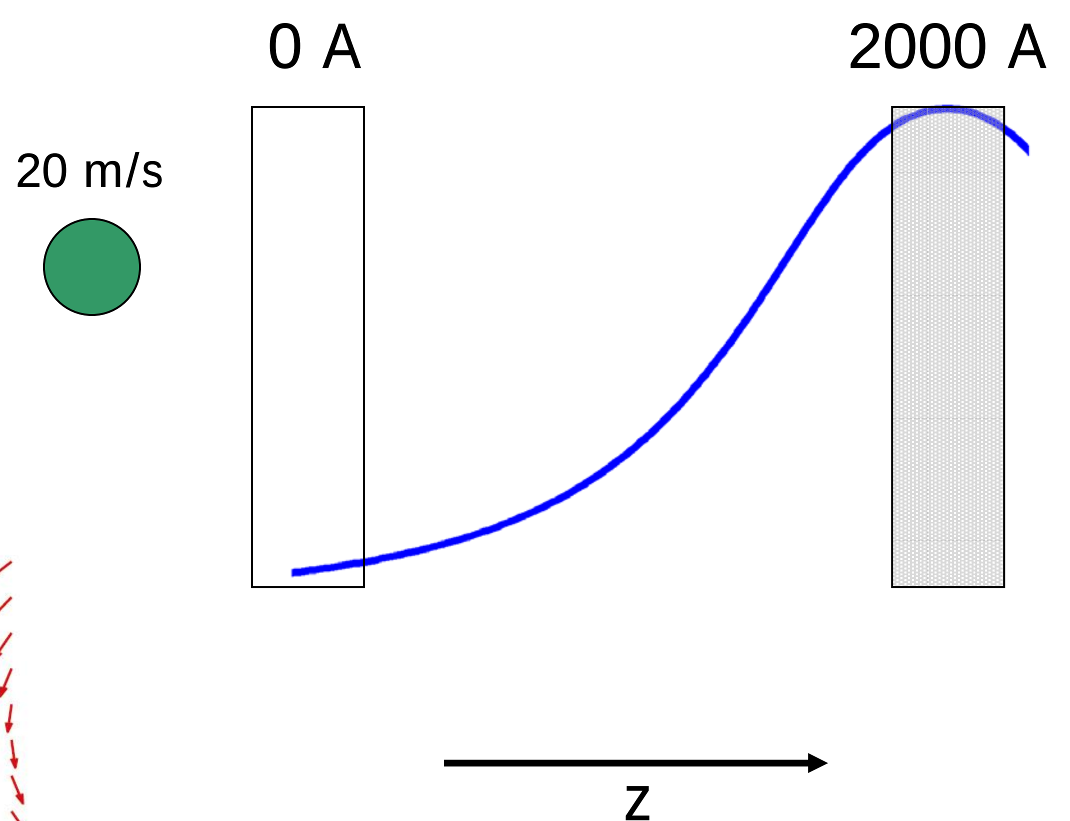
Trapping Scheme

End view

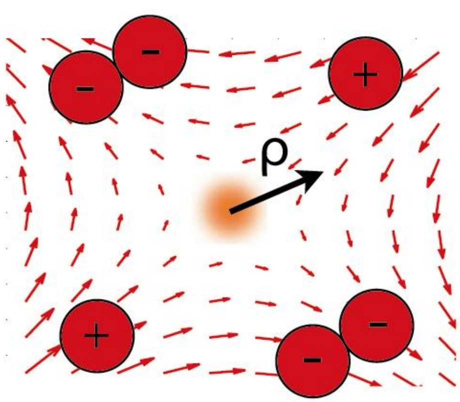


Magnetic
Quadrupole

Side view



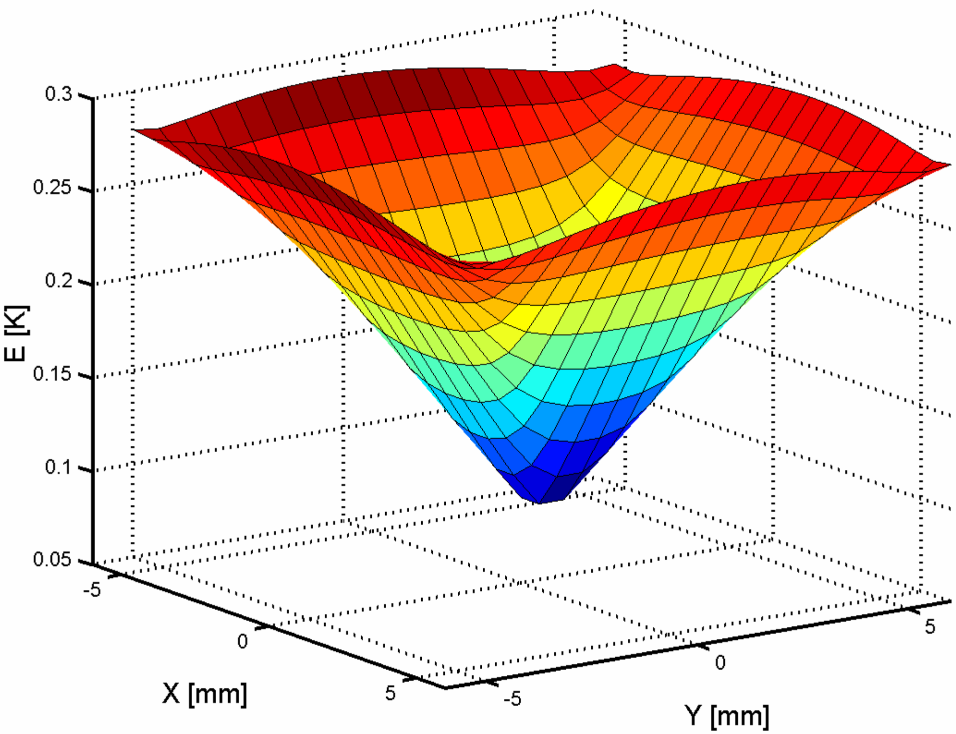
Electric
Quadrupole

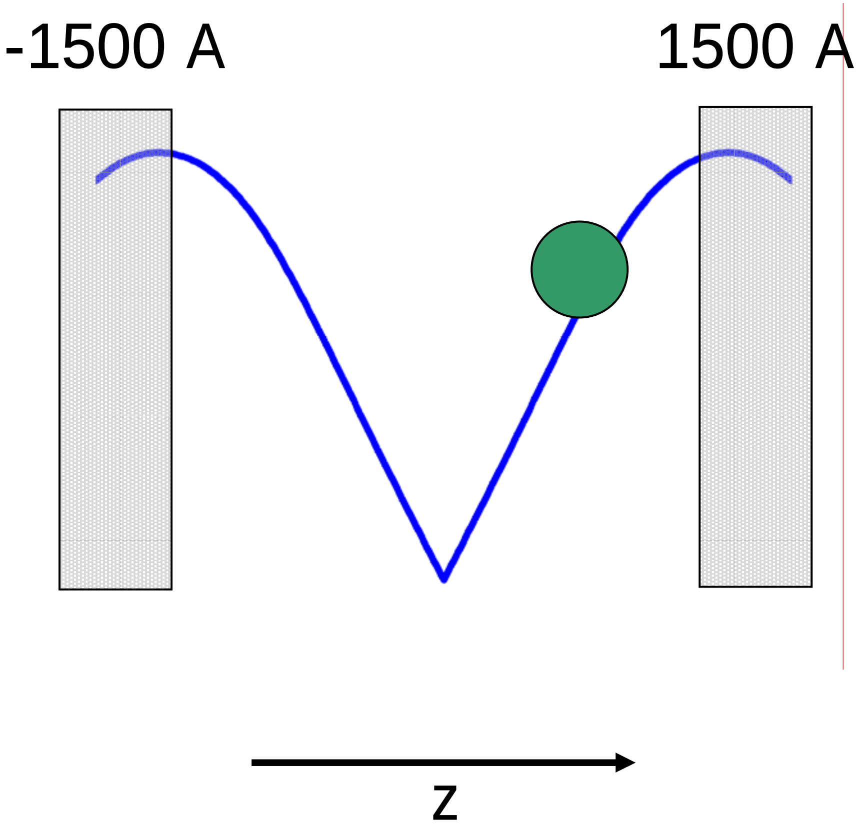


Trapping Scheme

~30 mK, 5×10^3 cm^{-3}

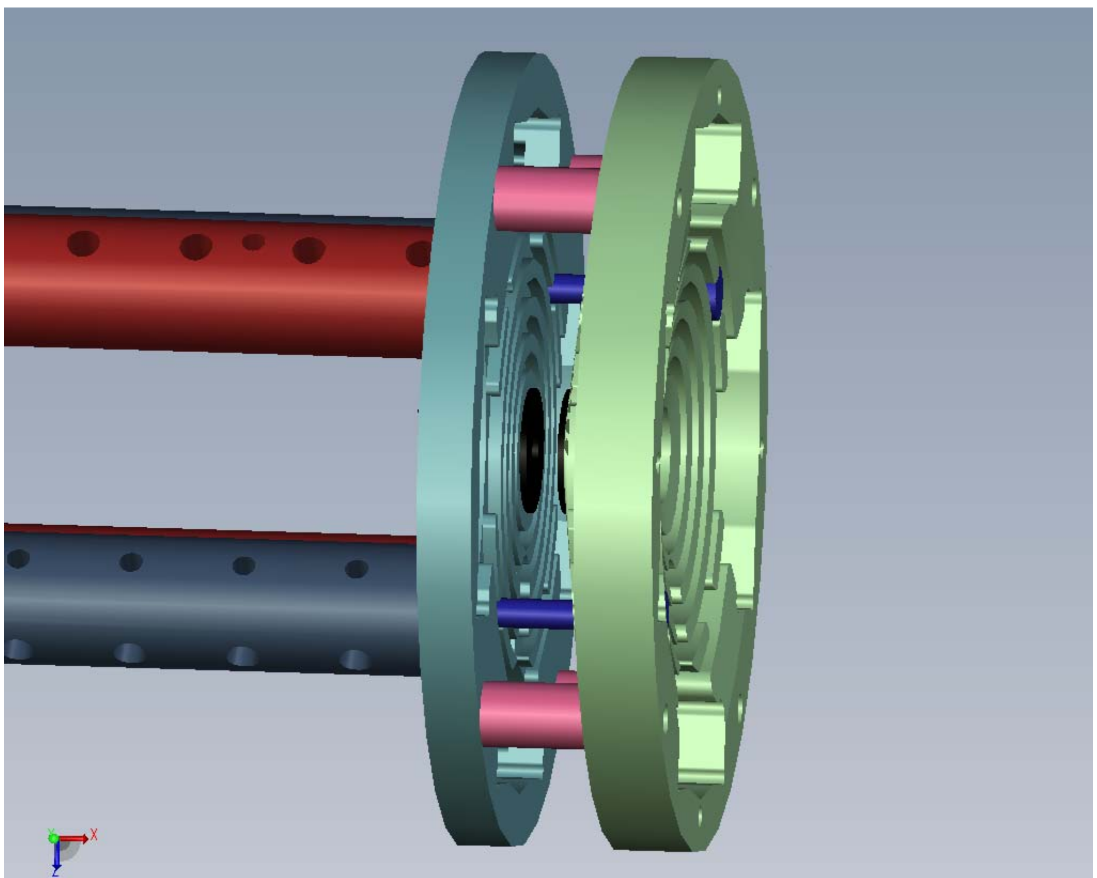
Magnetic Quadrupole + Electric Quadrupole





Permanent-Magnet Trap

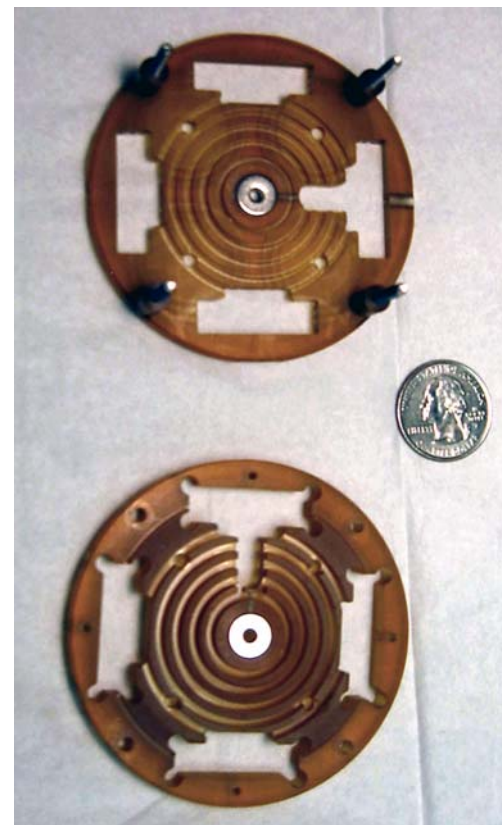
10mm



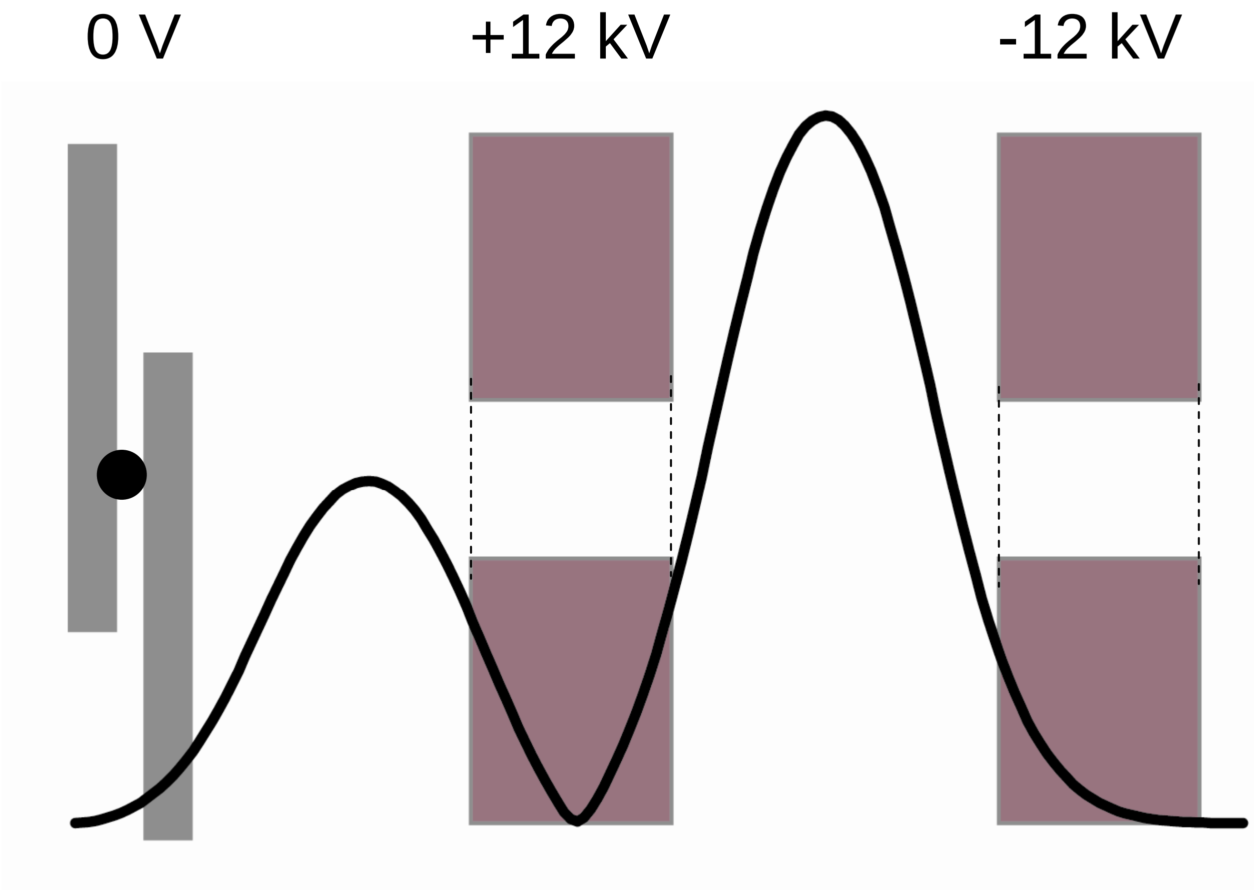
NdFeB (N42SH)

T_{op} = 120^{o}C

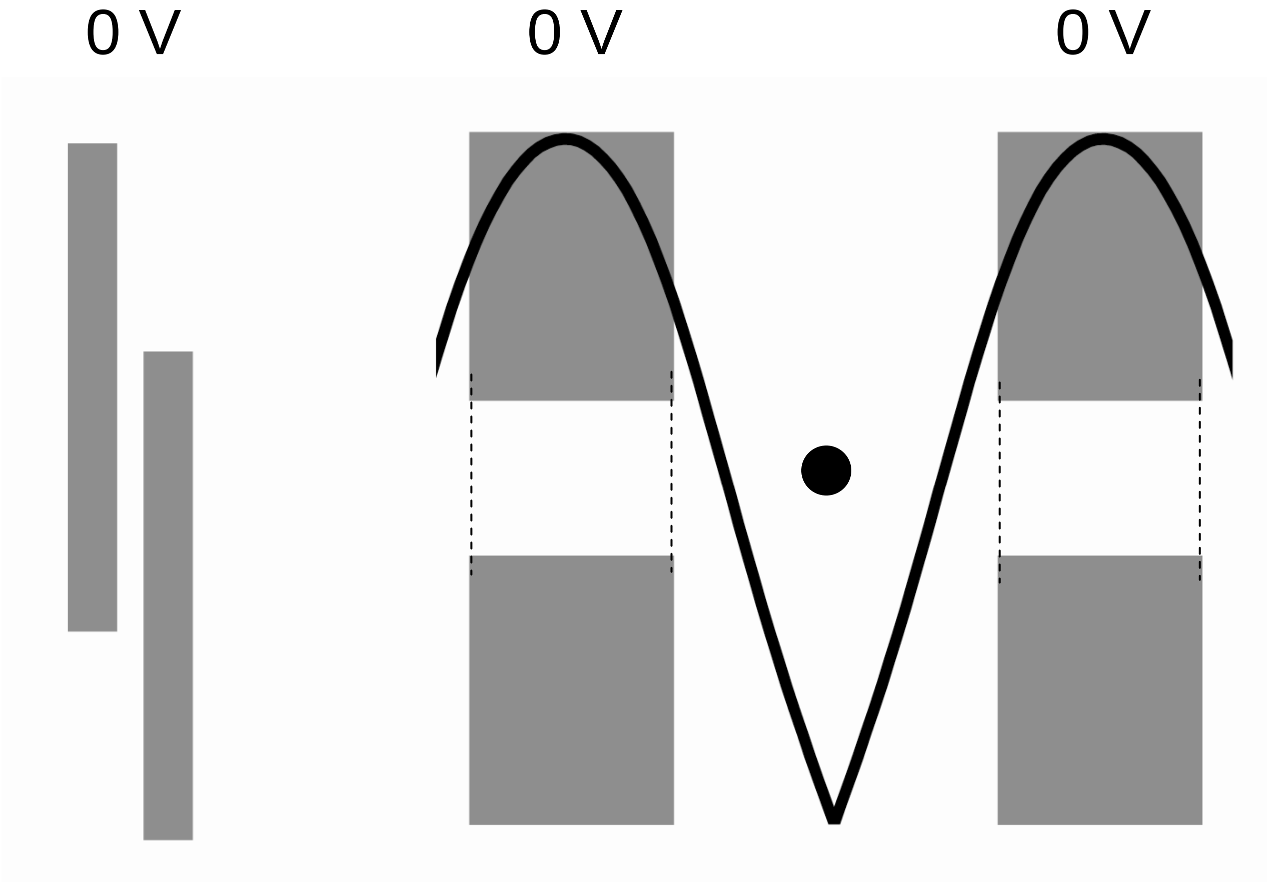
B_{res} = 1.24 T



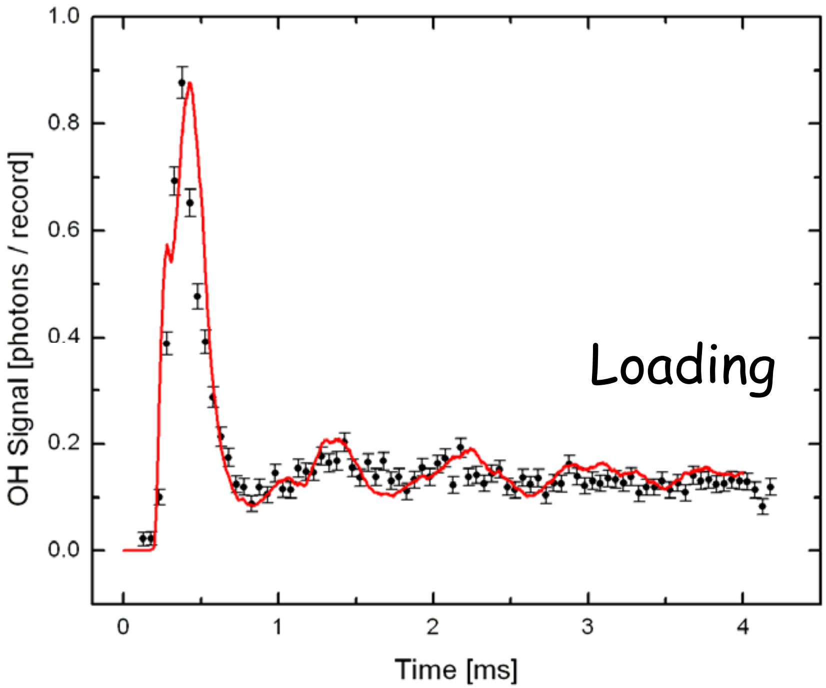
Trap Loading



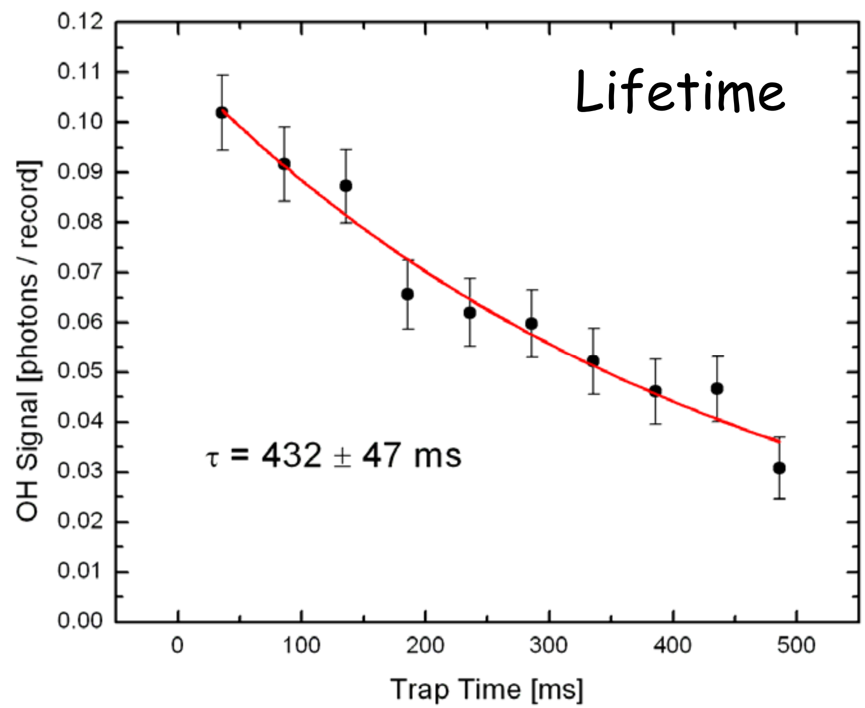
Trap Loading



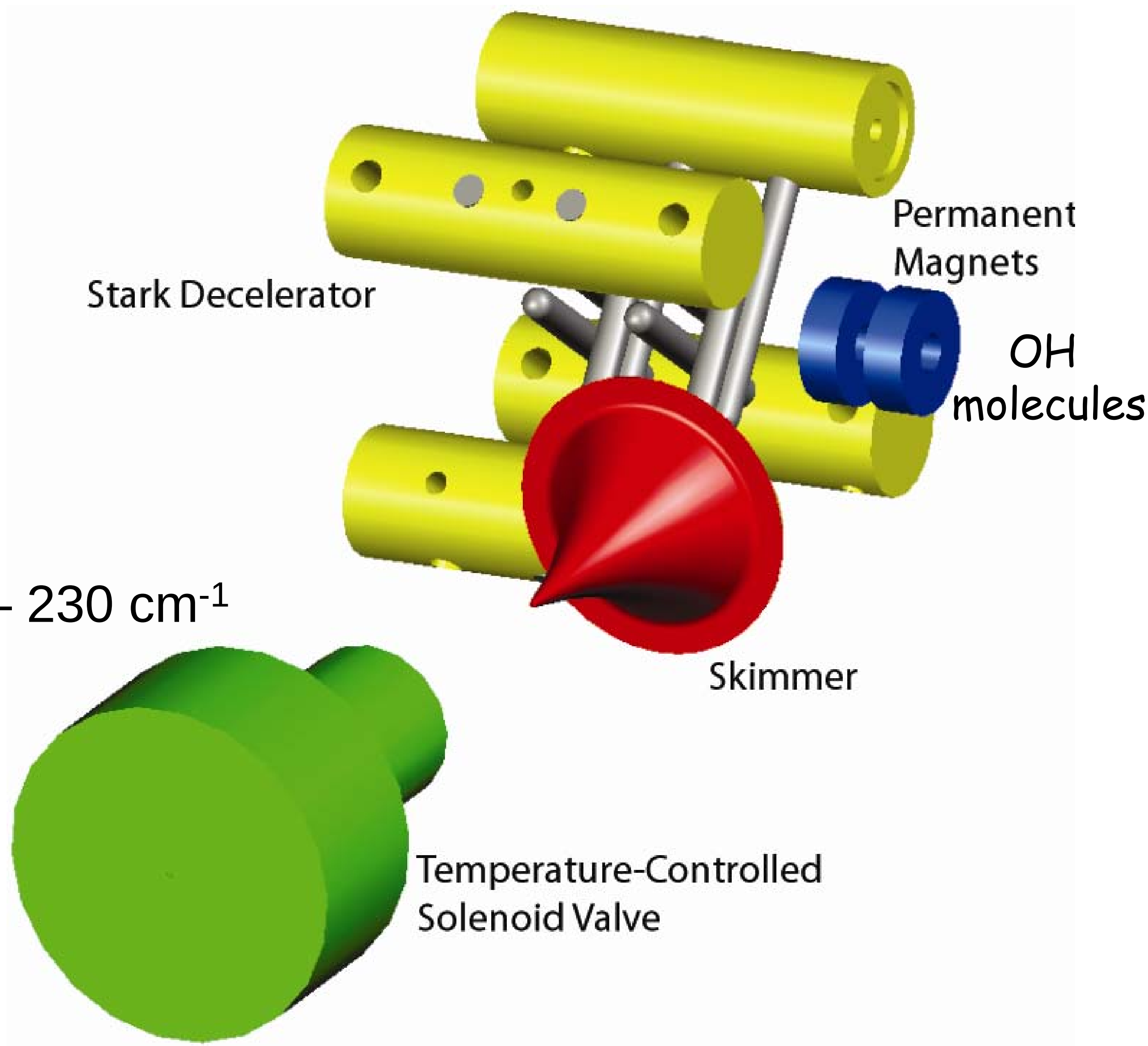
Permanent magnetic trap of OH



~ $2 \times 10^6\ cm^{-3}$
70 mK



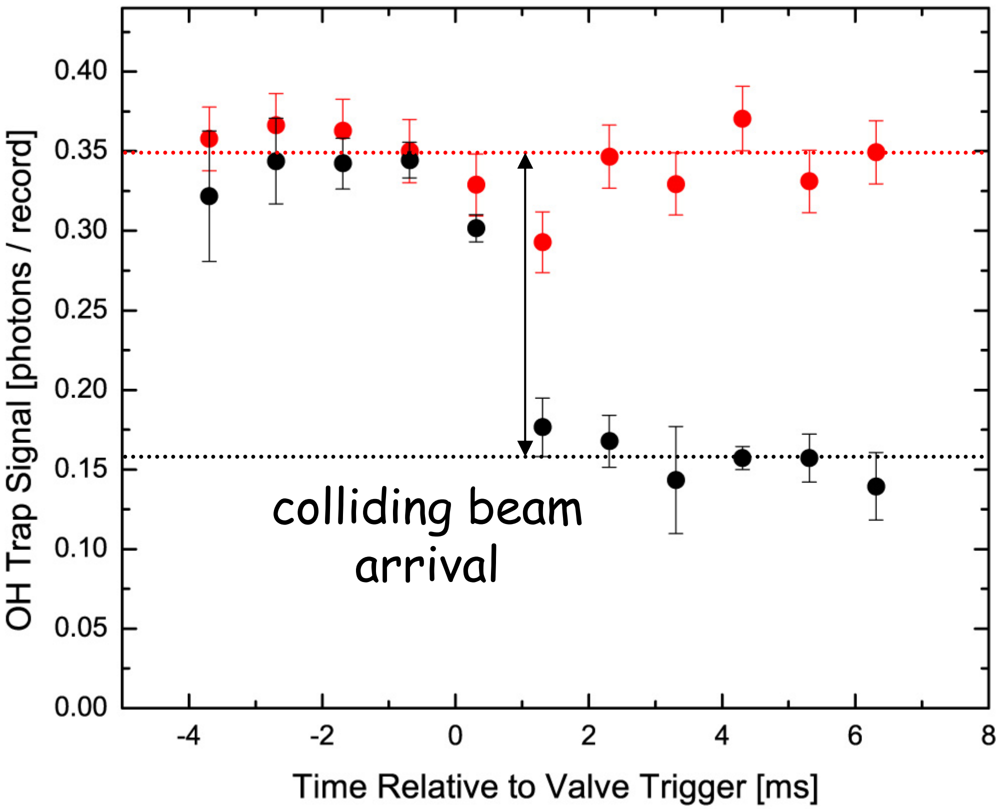
Collision inside a trap



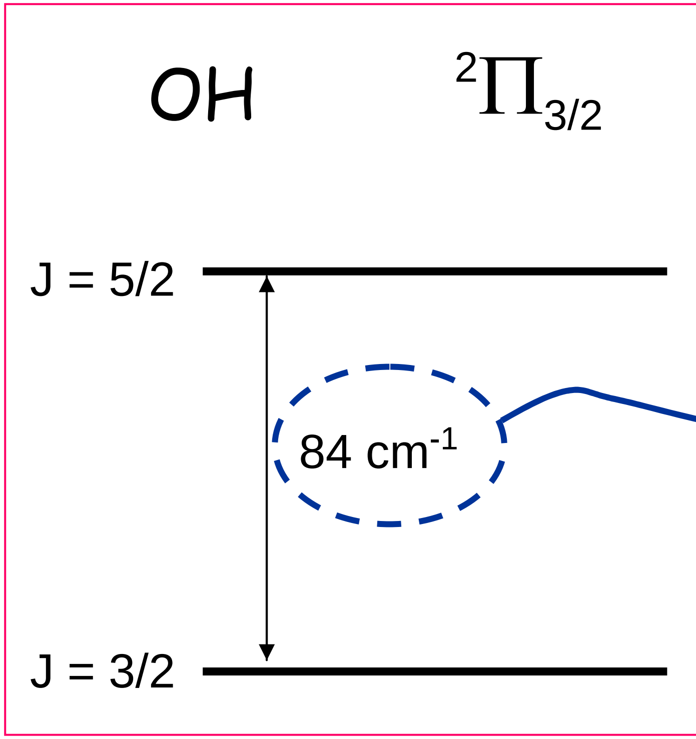
$E_{cm} \sim 60\ cm^{-1} – 230\ cm^{-1}$

Trap Scattering

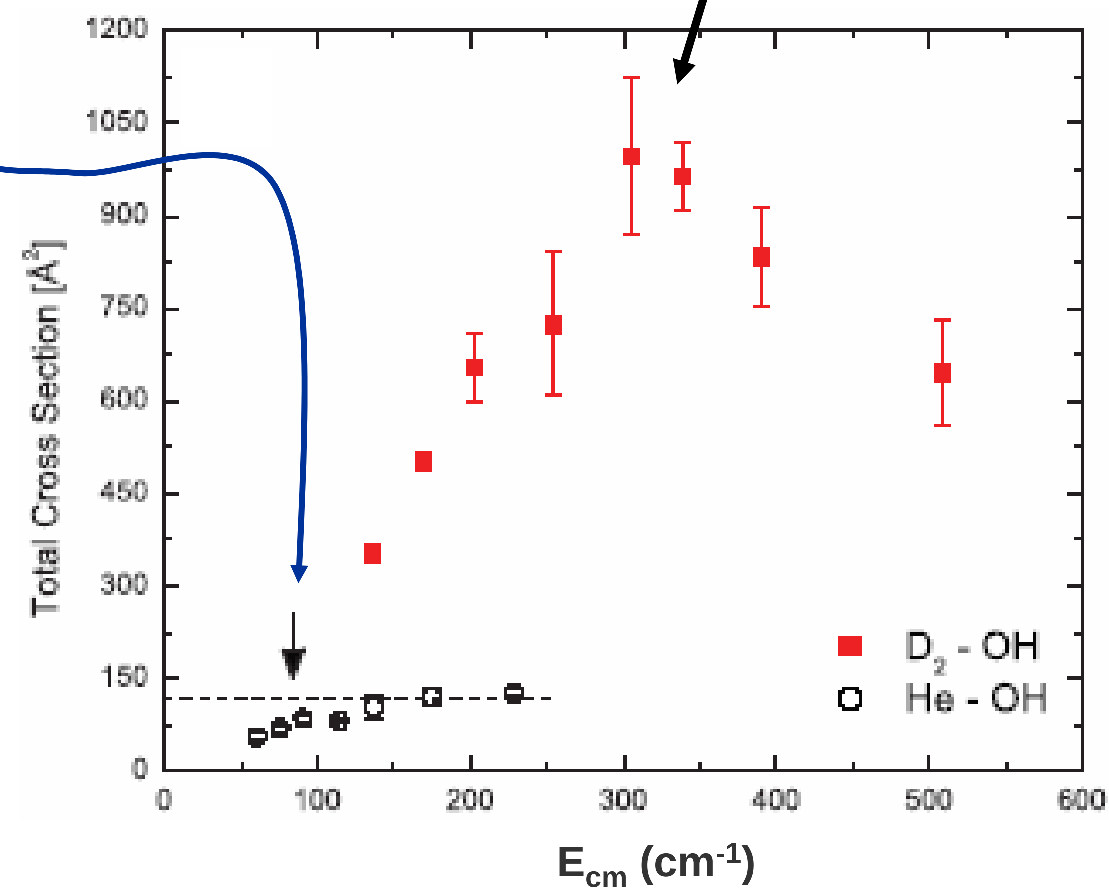
OH – He or OH – D_2



Absolute collision cross sections

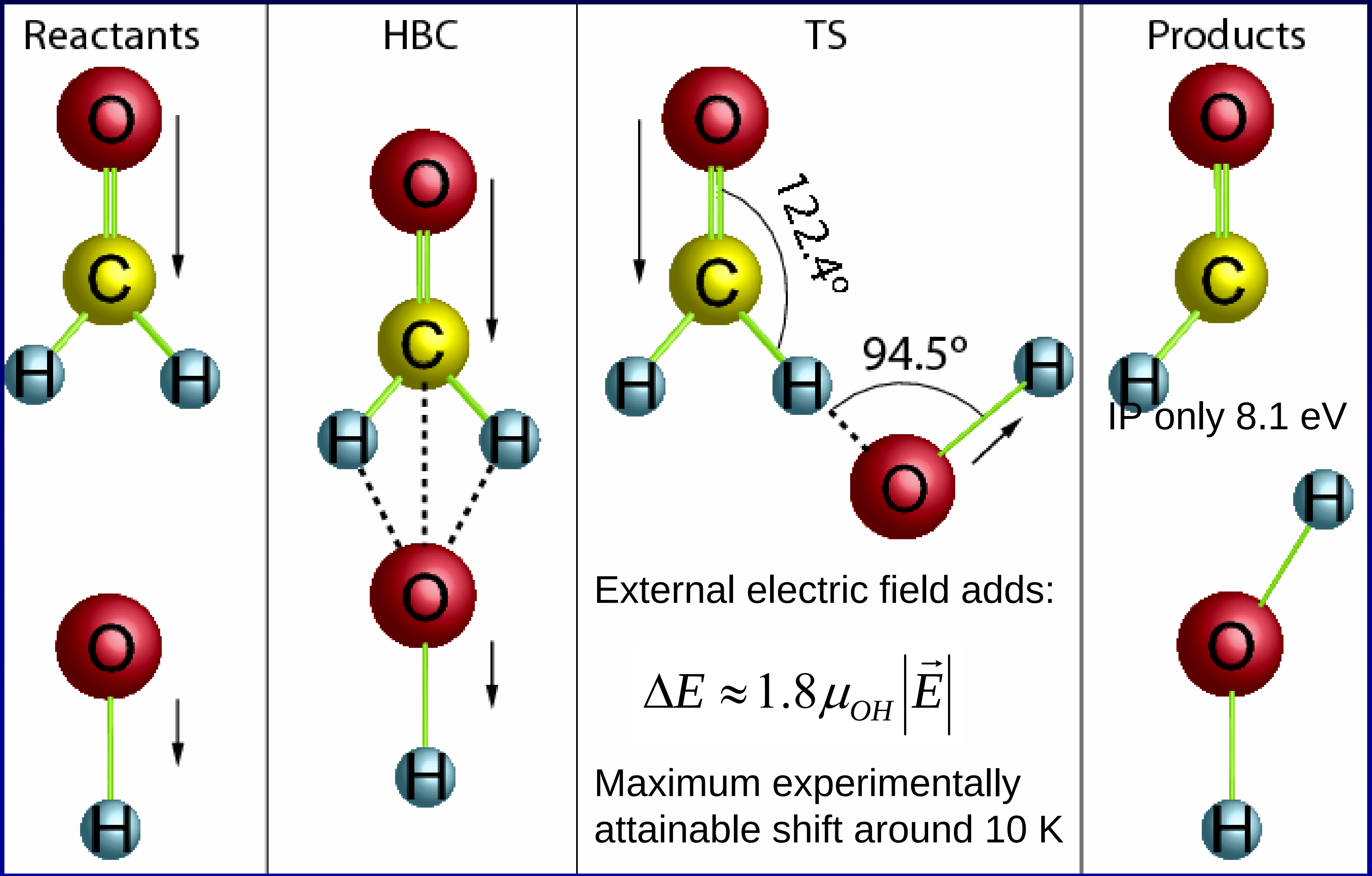


D_2: (1) J = 1 quadrupole moment
(2) J = 1 → J =3 (300 cm^{-1})



External electric field tunes reaction barrier

Hudson, Ticknor, Sawyer, Taatjes, Lewandowski, Bochinski, Bohn, Ye, Phys. Rev. A **73**, 063404 (2006).



Control of cold chemical reactions; Unique dipolar interaction dynamics

Special thanks

OH and H_2CO

B. Sawyer
B. Stuhl
M. Yeo
D. Wang

E. Hudson (Yale)
B. Lev (Illinois)
H. Lewandowski (JILA)
J. Bochinski (NC State)

KRb

S. Ospelkaus
A. Pe'er
K.-K. Ni
J. Zirbel
B. Neyenhuis
M. Miranda

D. S. Jin

D. Jin, J. Bohn (JILA)
P. Julienne (NIST), S. Kotochigova (Temple)
H. Ritsch (Innsbruck)