Stable cold polar molecules

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JILA, NIST and University of Colorado

Correlated States in Degenerate Atomic Gases, KITP, April 25, 2007

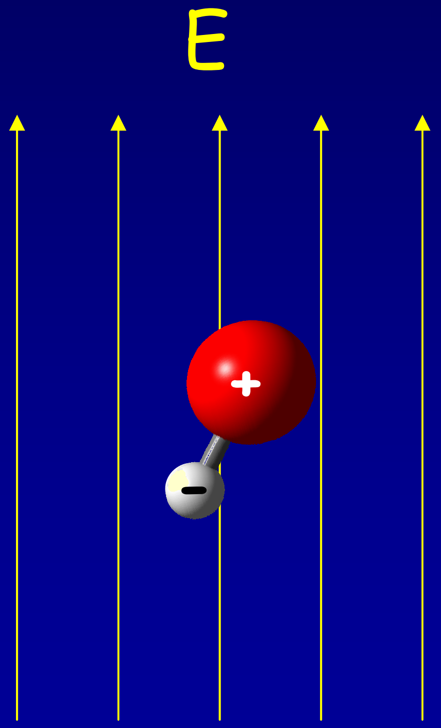
$ Funding $

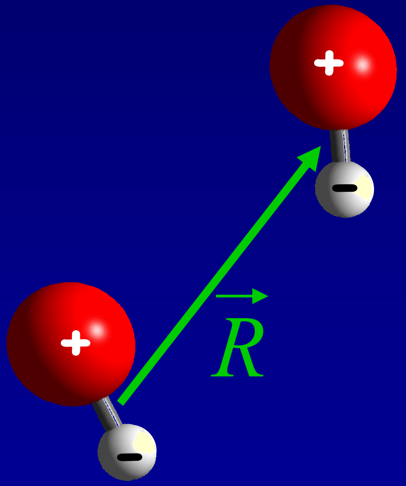
DOE, NIST, NSF

Why ultracold molecules?

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

Electric dipole moments: Orientation is a big deal !



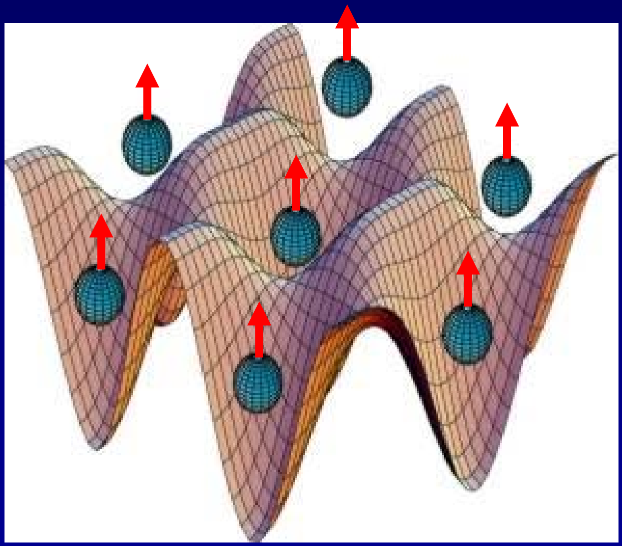


A. Avdeenkov and J. L. Bohn,
Phys. Rev. Lett. **90**, 043006 (2003).

Manifested at or below μK temperatures

Ultracold molecules: quantum physics

- Quantum information
  (strong dipolar interactions, long coherence time)
- Quantum degeneracy (e.g. BEC)
  (anisotropic interactions)
- Dipolar phase transition
  (Condensed matter system)

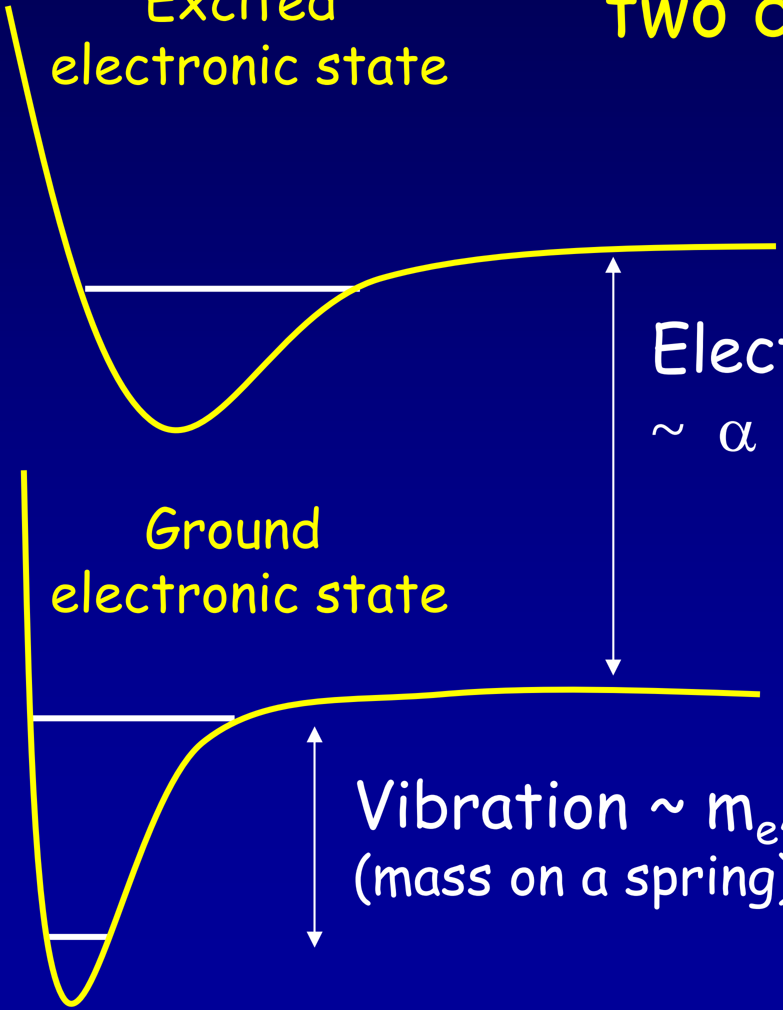


DeMille, Phys. Rev. Lett. **88**, 067901 (2002).
Griesmaier, Werner, Hensler, Stuhler, Pfau, Phys. Rev. Lett. **94**, 160401 (2005).
Micheli, Brennen, Zoller, Nature Physics **2**, 341 (2006). Hans Peter Büchler's talk

Ultracold molecules: Test fundamental principles

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

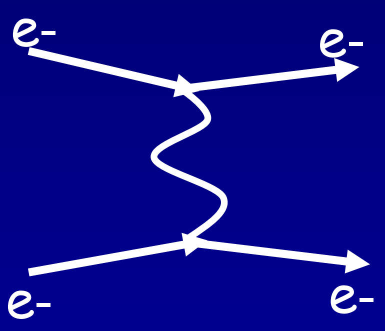
One system,
two different fundamental forces!



Electronic
$\sim \alpha$

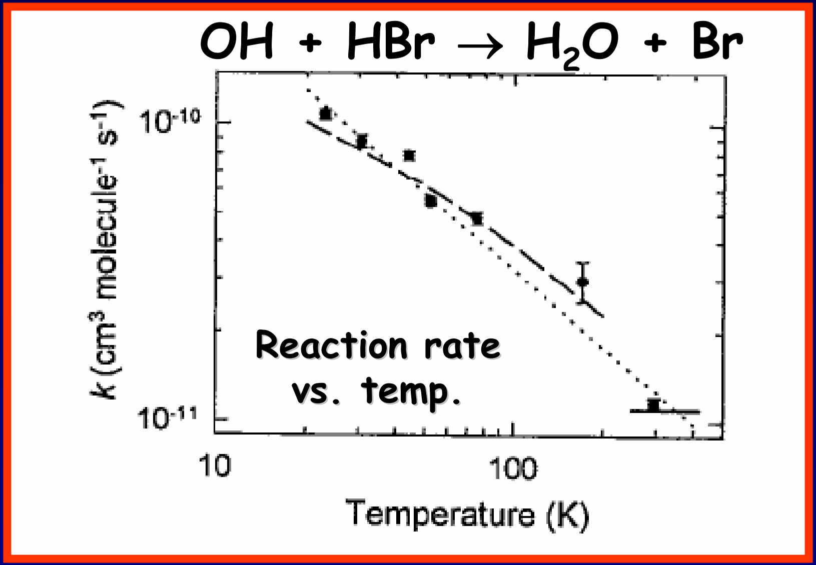
Vibration ~ m_e/m_p
(mass on a spring)

QED

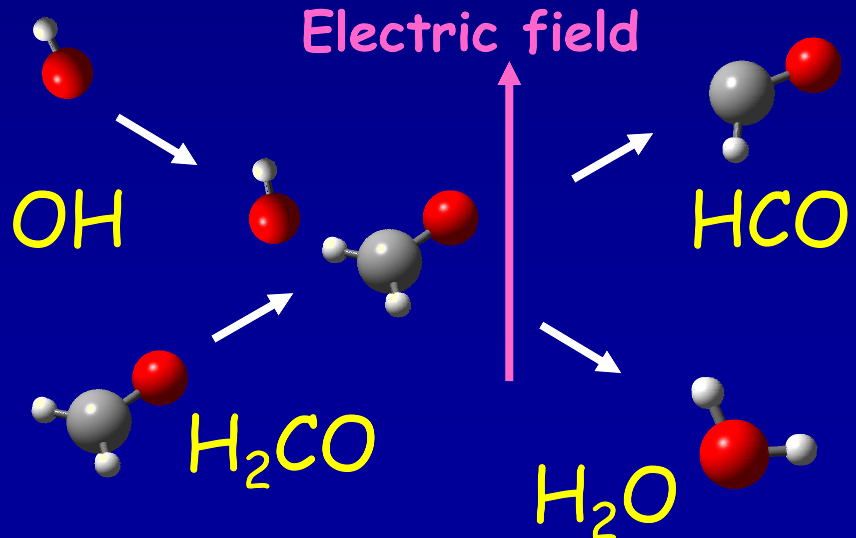


Strong interactions

Ultracold molecules: Precision Chemistry



Stereo-Chemistry

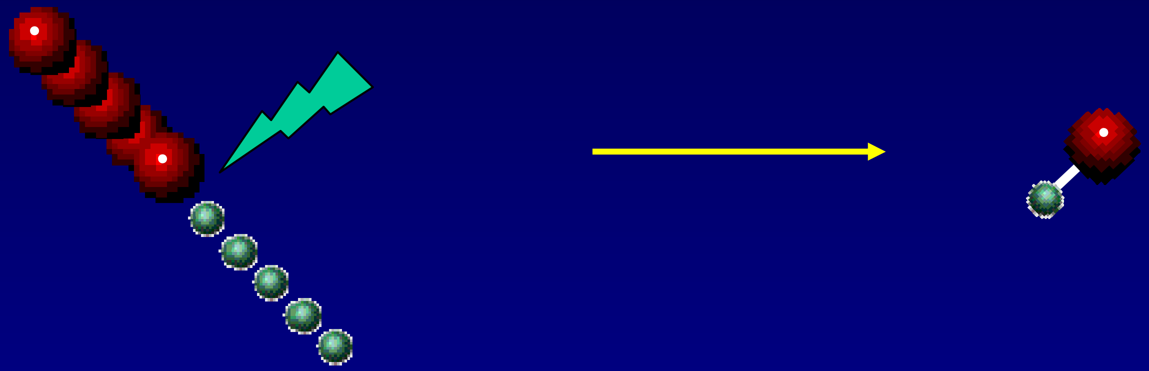


Controlled molecular collisions
Ultracold chemical reactions

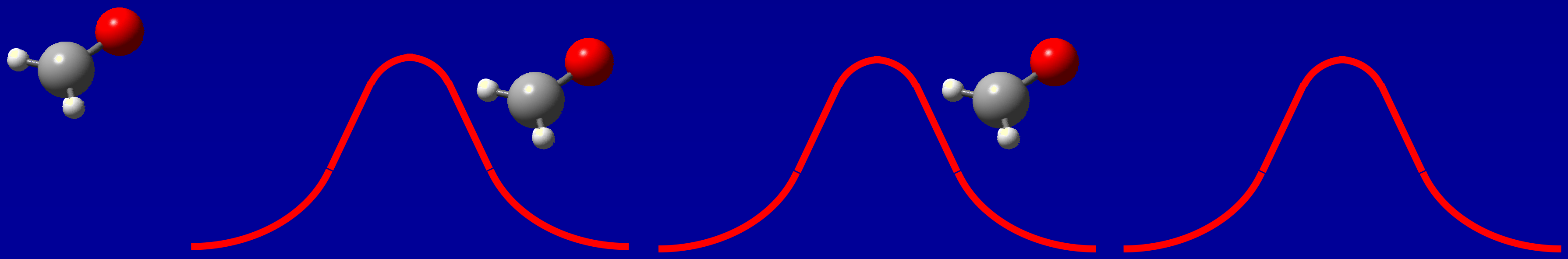
- Molecules in single quantum states, under precise control, for internal & external motions
- Unprecedented study of fundamentally important reactions (Dial the rates): $OH + HBr$, $OH + H_2CO$, $CN + O_2$, $OH + NO$, $OH + OH$, $CN + NH_3$, $OH + H$
- Higher reaction rate at lower temperature (10 K,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

Ways to make cold polar molecules

- **Start from ultracold atoms & pair them (Magneto-Photo-association)**



- **Start from ground-state molecules (Direct cooling of molecules)**

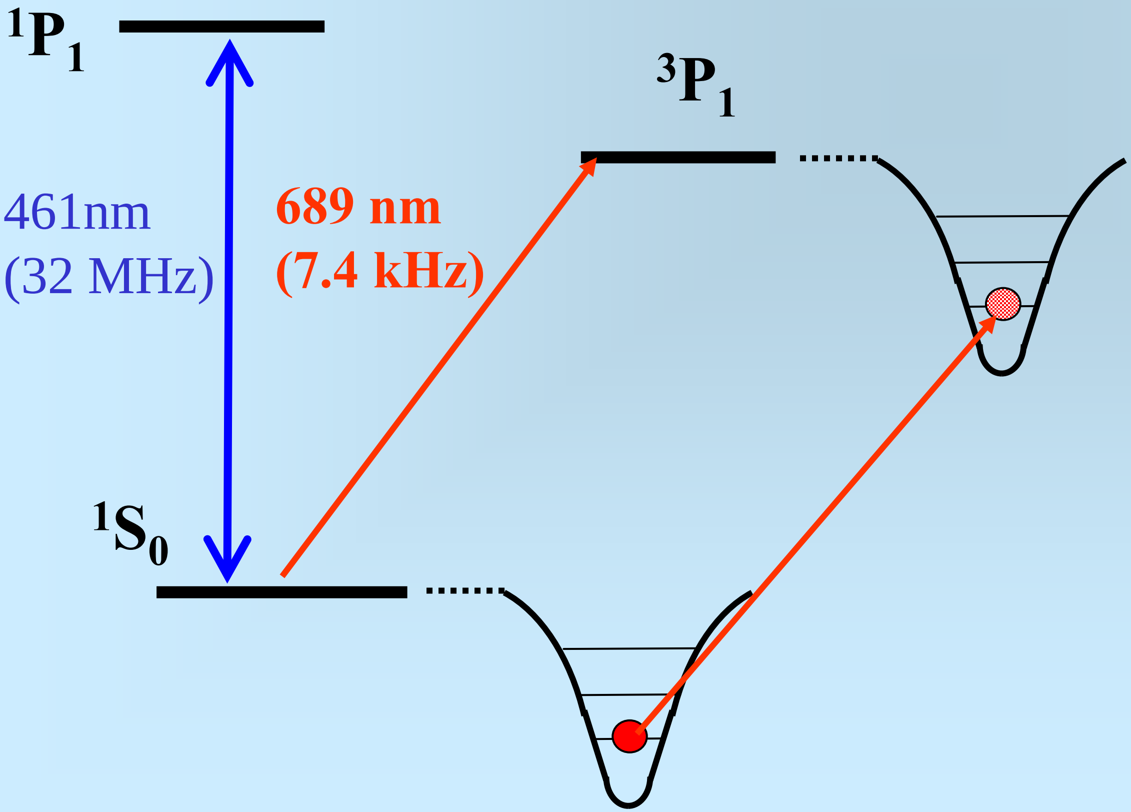


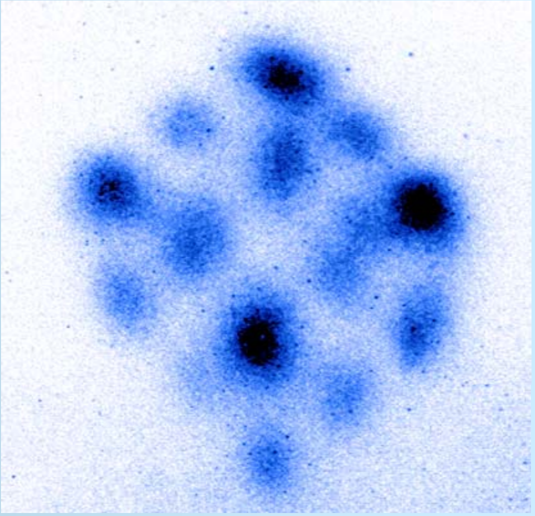
Cool Alkaline Earth – Strontium

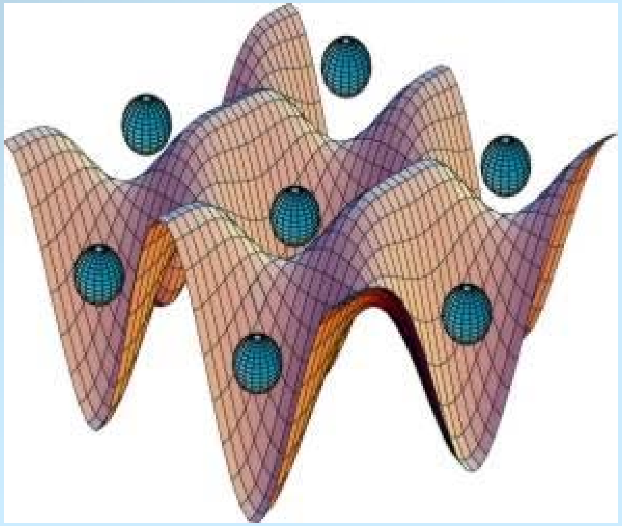
Boyd, Zelevinsky, Ludlow, Foreman, Blatt, Ido, Ye, Science 314, 1430 (2006).
Boyd, Ludlow, Blatt, Foreman, Ido, Zelevinsky, Ye, PRL 98, 083002 (2007).

T ~ 0.5 photon recoil
~ 220 nK

Recoil-free
Potentials matched to < 10^{-15}
Extreme spectral resolution



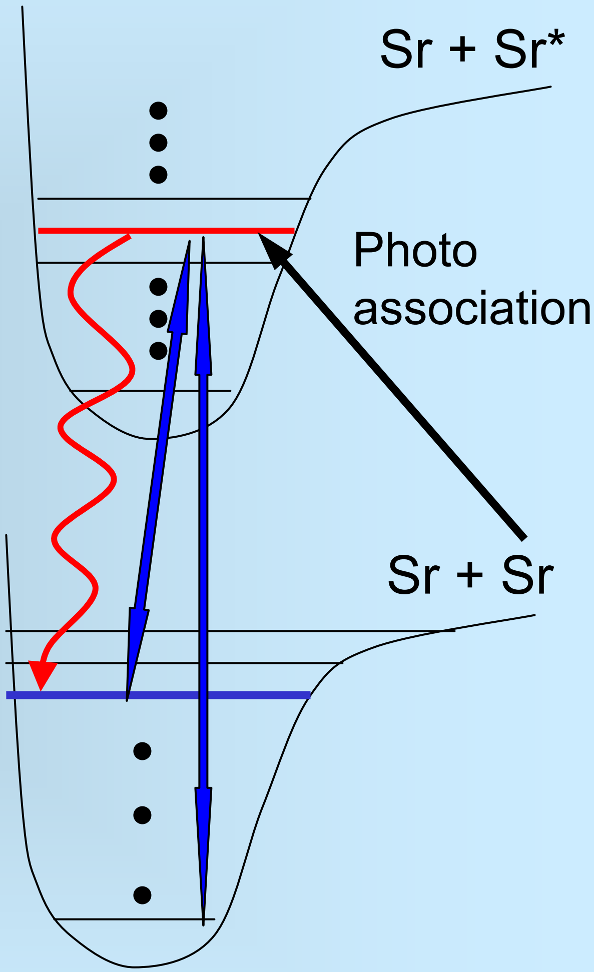




Ultracold Sr_2 Molecules in Lattice

Zelevinsky, Boyd, Ludlow, Ido, Ye, Ciurylo, Naidon, Julienne, PRL 96, 203201 (2006).

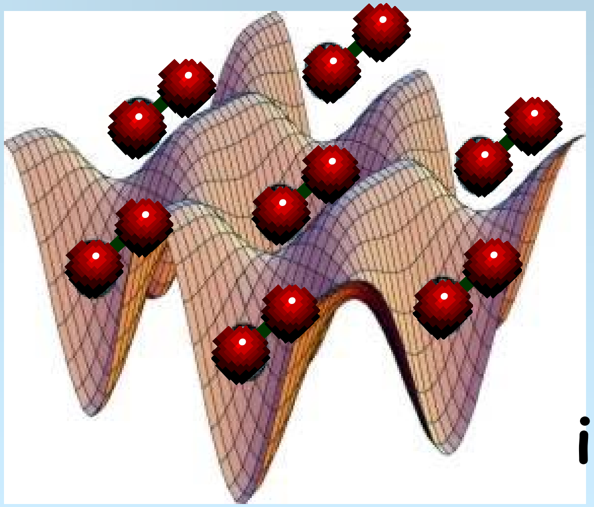
- Narrow lines
  - – All bound states are resolved
- Favorable decay to electronic ground state
- Control of atomic collision with minimum loss



Raman transition for ground state production

Theory:

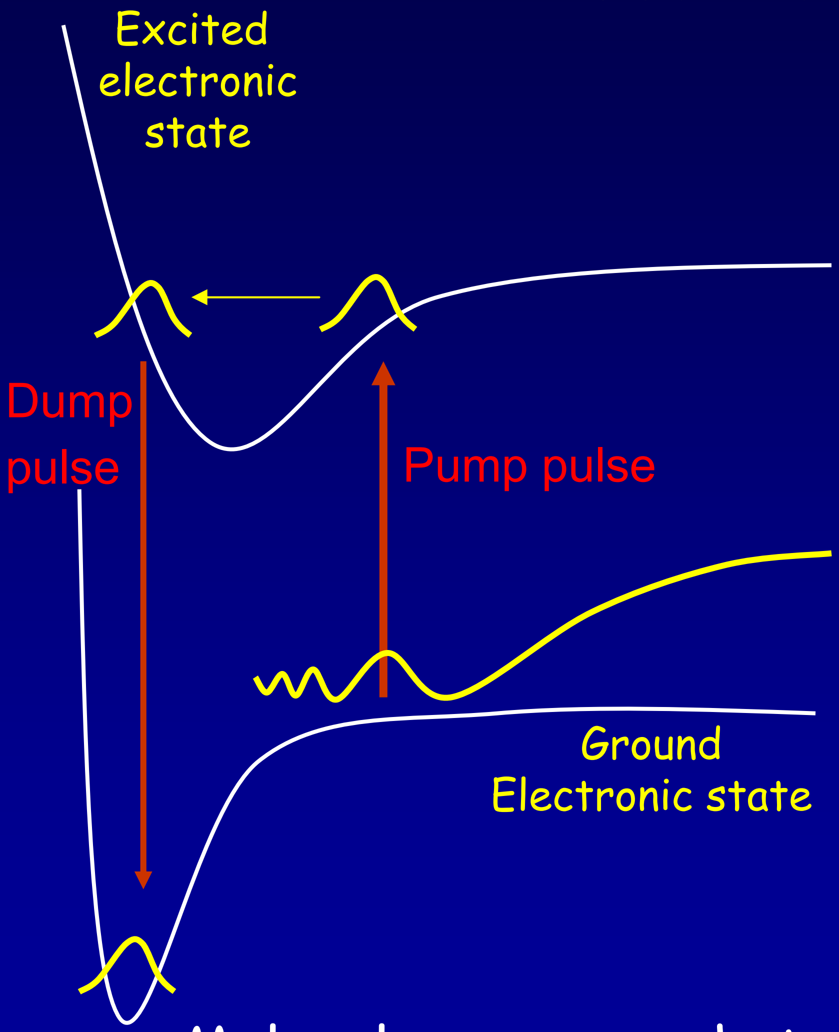
P. Julienne
S. Kotochigova



Polar molecules KRb in collaboration with D. Jin

Photo-Association via Coherent Accumulation of Pulses

Pe'er, Shapiro, Stowe, Shapiro, Ye, Phys. Rev. Lett. 98, 113004 (2007).



The problem – overlap

Molecular wave-packet dynamics bridge the overlap mismatch

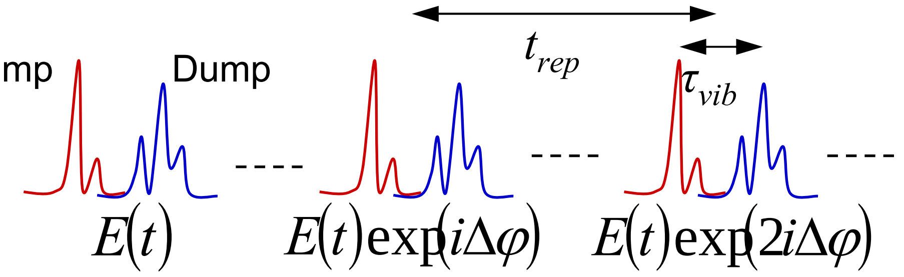
Coherent accumulations resolve single quantum state

Making cold molecules with comb

Why pulse-train ?

Two inherent time scales:
molecular vibration & atomic coherence

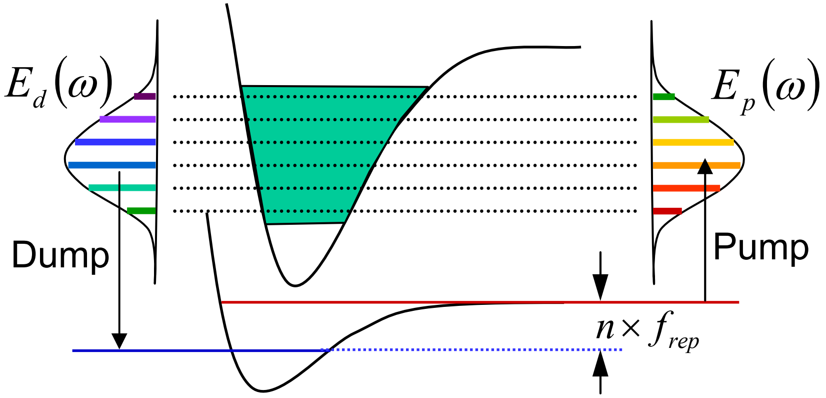
Time Domain picture



Pulse shaping:

- Positive chirp: "one way ticket"
- Robust to energy fluctuations
- Avoid ionization/dissociation

Frequency domain picture

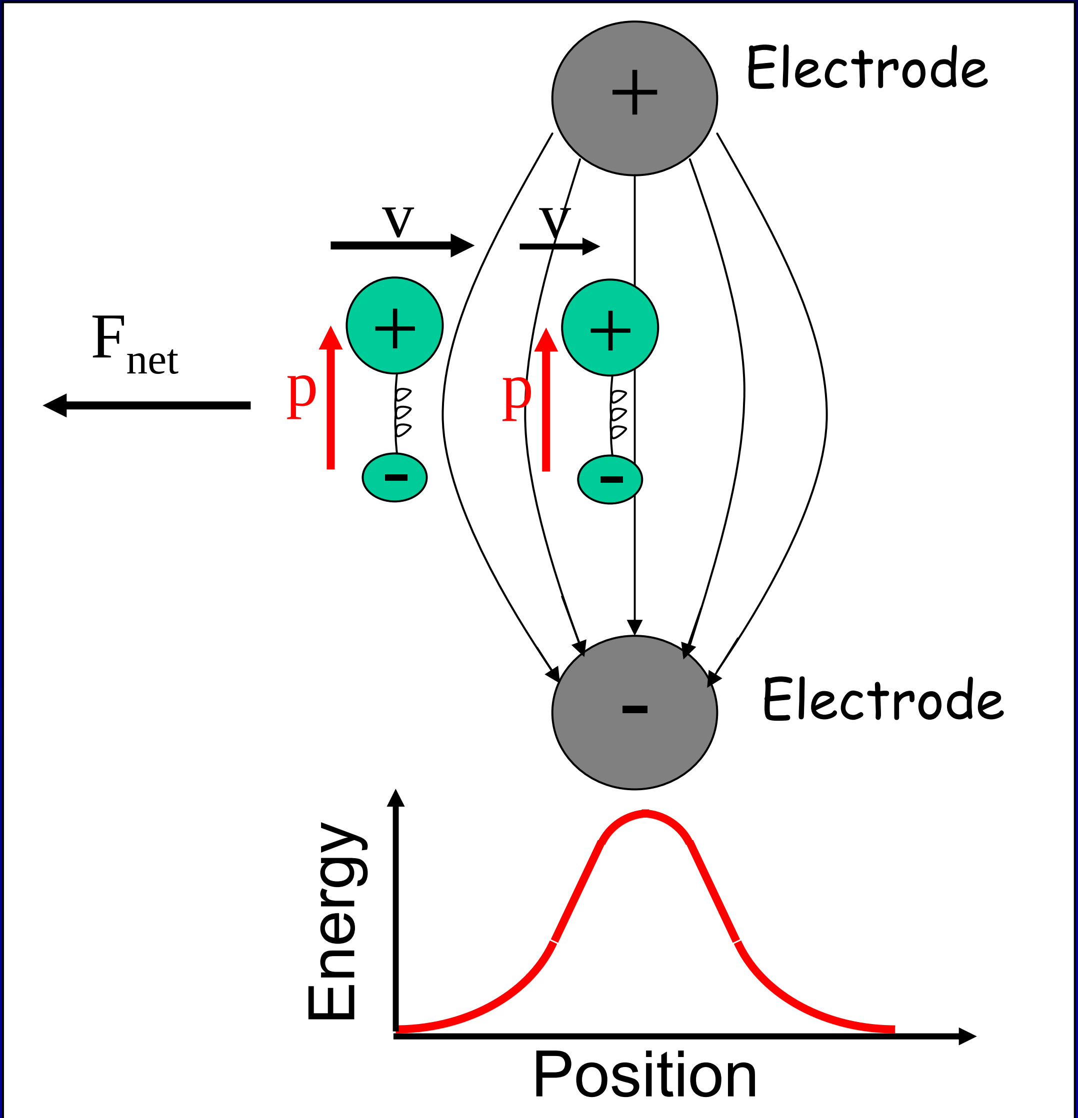


Coherent accumulation:
Weak field interaction
for strong field effects

Coherent control of single pulses – Coarse resolution (vibration).
Coherent accumulation of pulses – Fine resolution (rotation, hyperfine)

Stark deceleration

Direct manipulation of ground state molecules



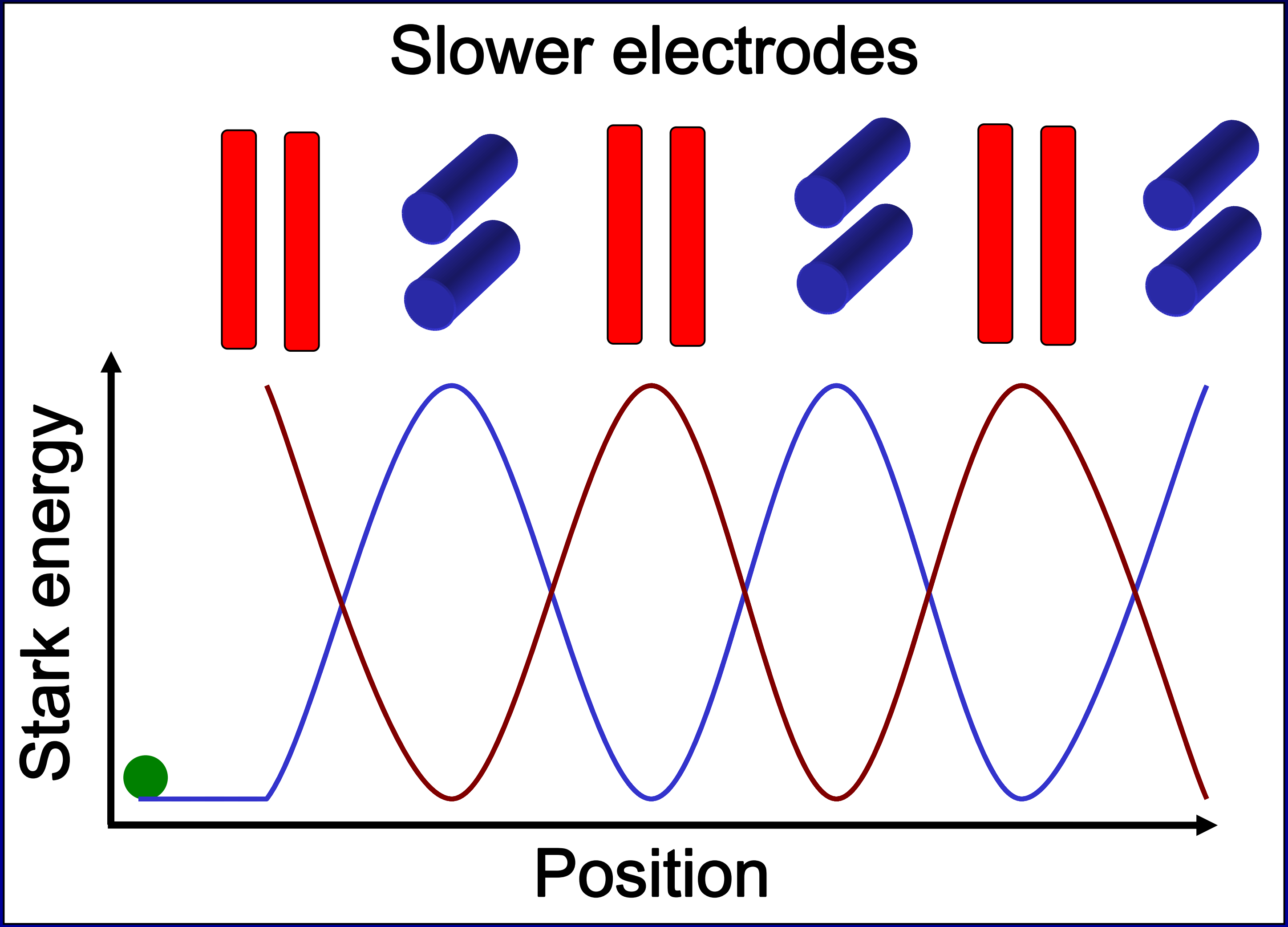
Initial cooling important (supersonic jets: single internal quantum state; external temp. ~ 1 K in a moving frame)

Phase space selection (~ 10 mK)

Applicable to a large variety of molecules

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

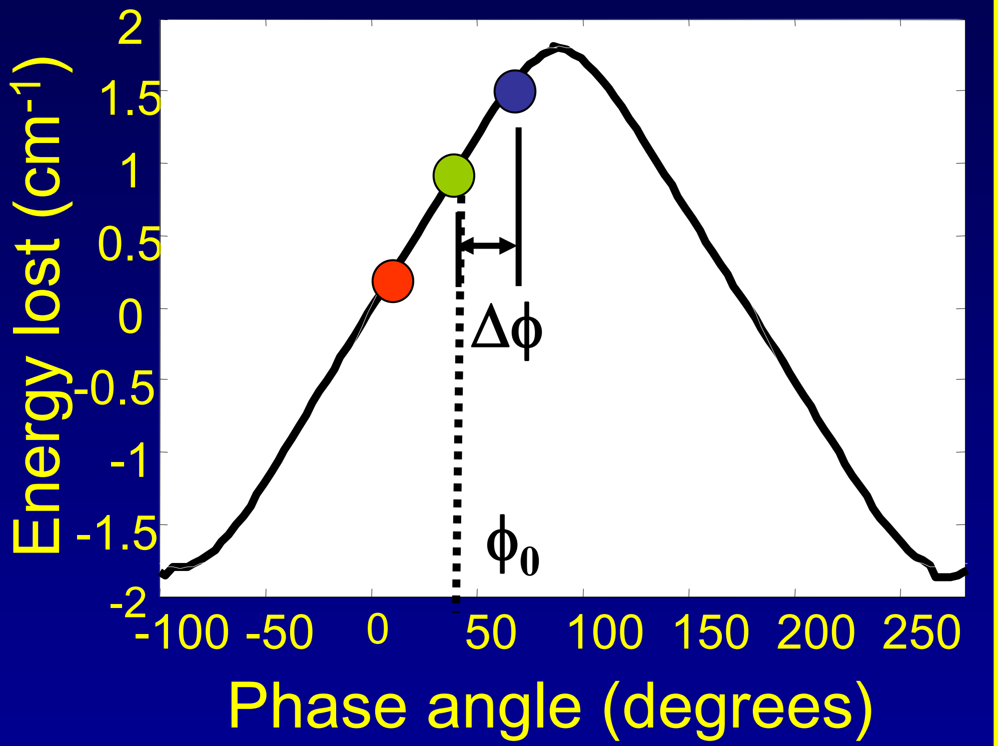
Stark Decelerator



Mathematical description of slowing

Hudson, Bochinski, Lewandowski, Ye, Eur. Phys. J. D **31**, 351 (2004).

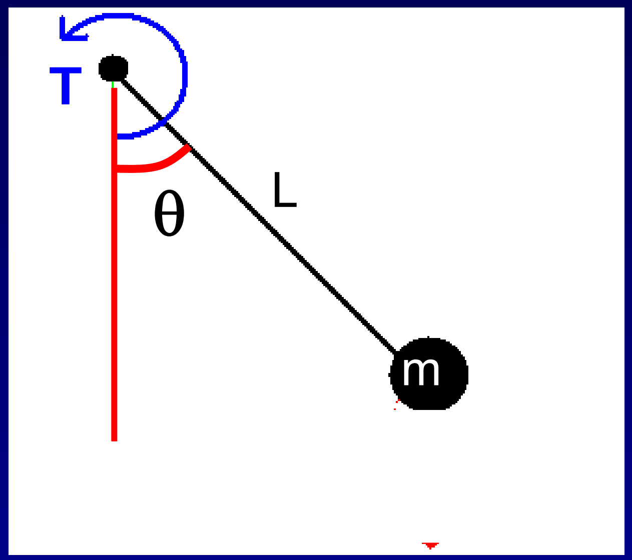
Change in kinetic energy



$$\frac{d^2\Delta\phi}{dt^2} + \frac{\pi W}{mL^2}\left[\sin(\phi_0 + \Delta\phi) - \sin\phi_0\right] = 0$$

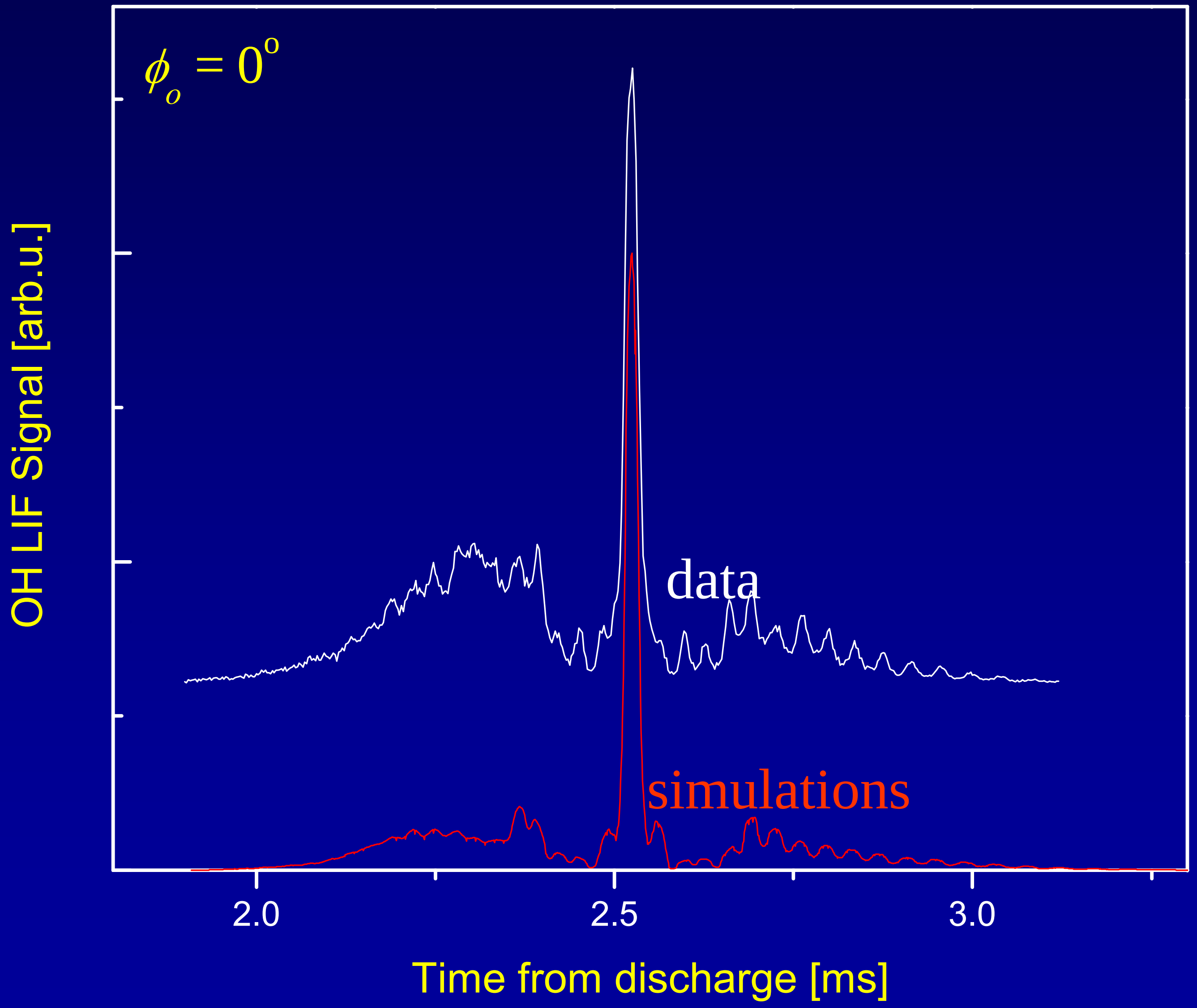
Equilibrium position

Pendulum driven by constant torque



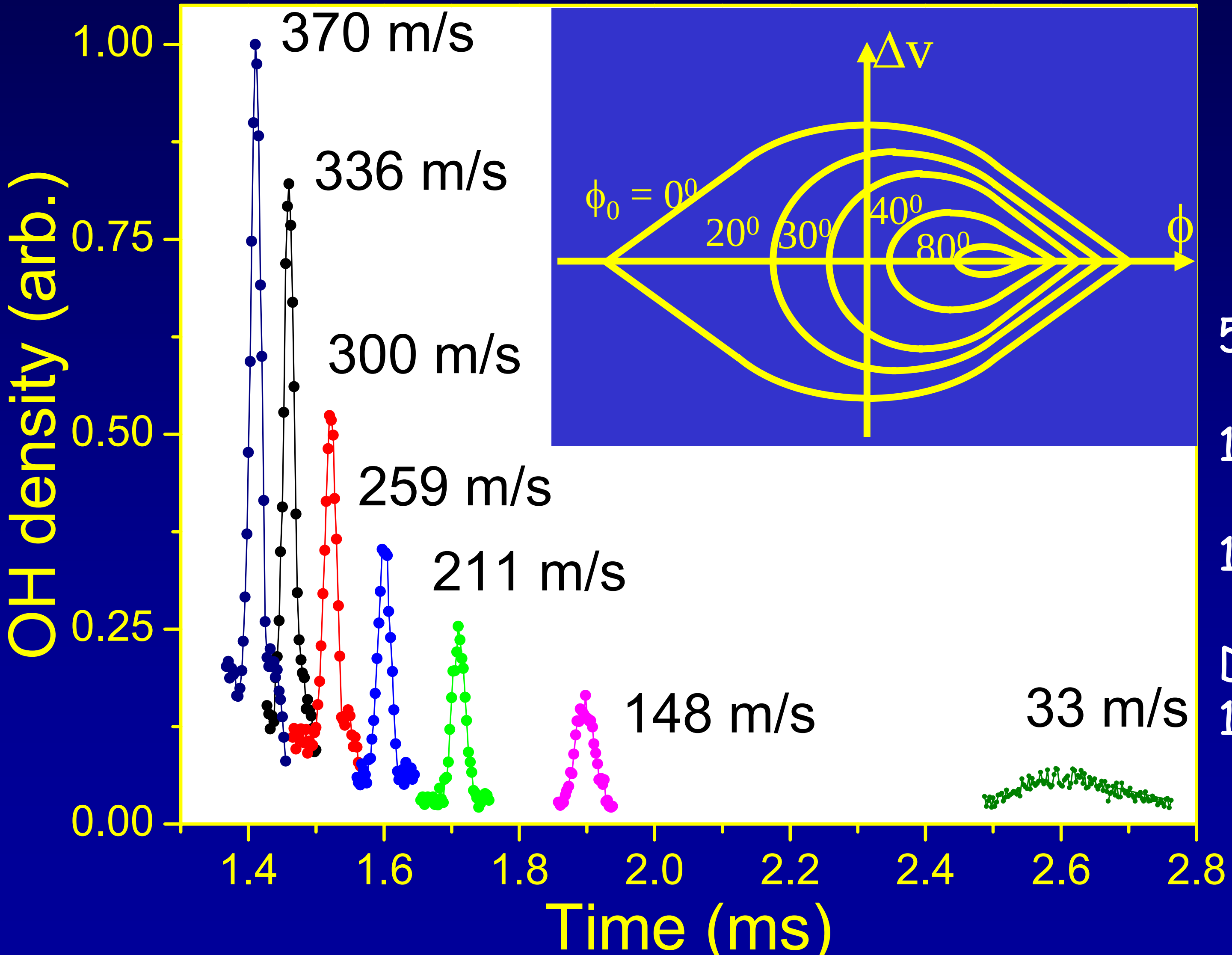
$$\frac{d^2\theta}{dt^2} - \left[\frac{g}{L} Sin(\theta) - \frac{T}{mL^2}\right] = 0$$

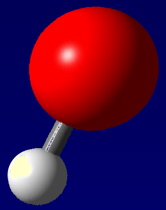
Experiment & Theory



Cold OH molecules

Bochinski, Hudson, Lewandowski, Meijer, Ye, Phys. Rev. Lett. **91**, 243001 (2003).
Bochinski, Hudson, Lewandowski, Ye, Phys. Rev. A **70**, 043410 (2004).





550 m/s to rest

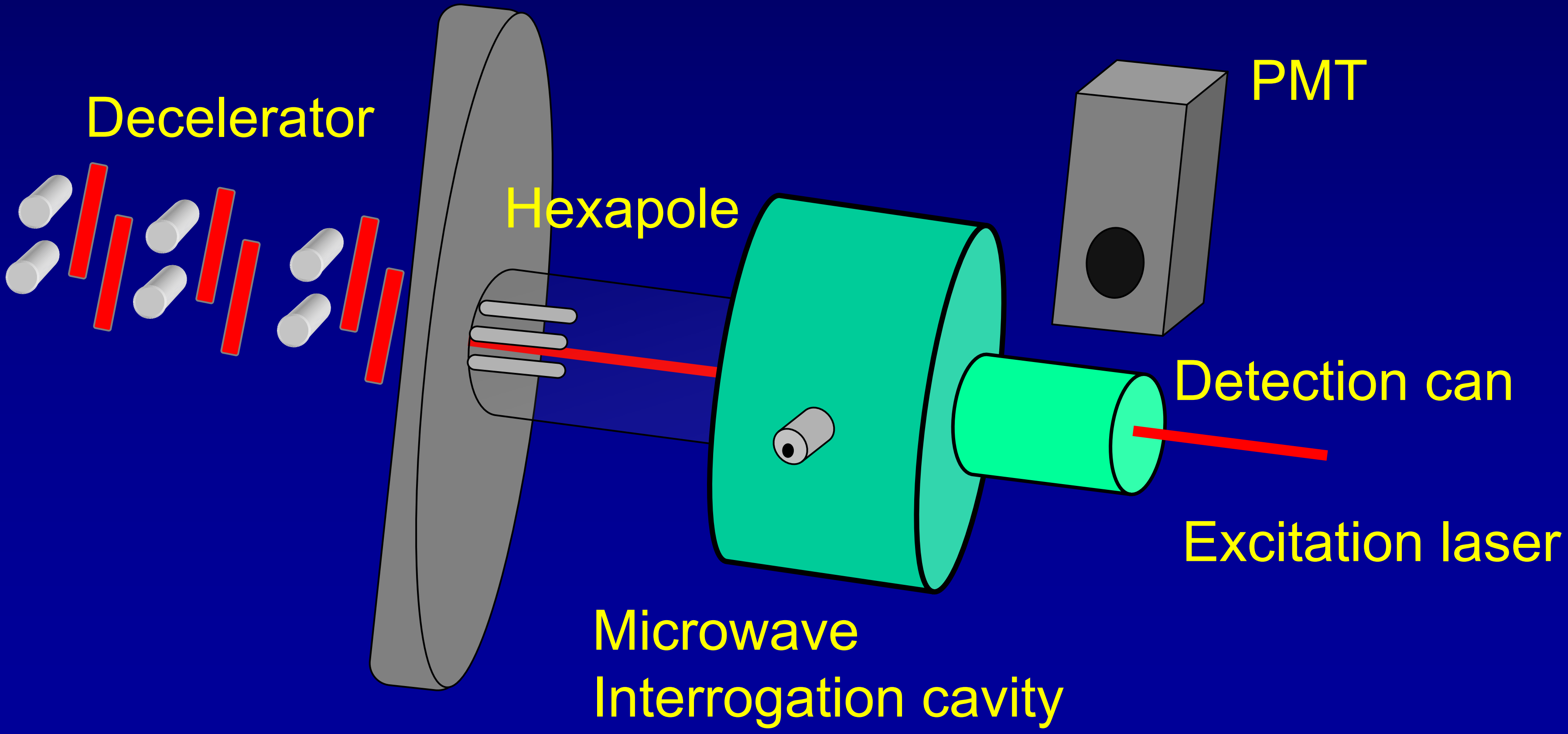
1 K to 10 mK

10^4 – 10^6 molecules

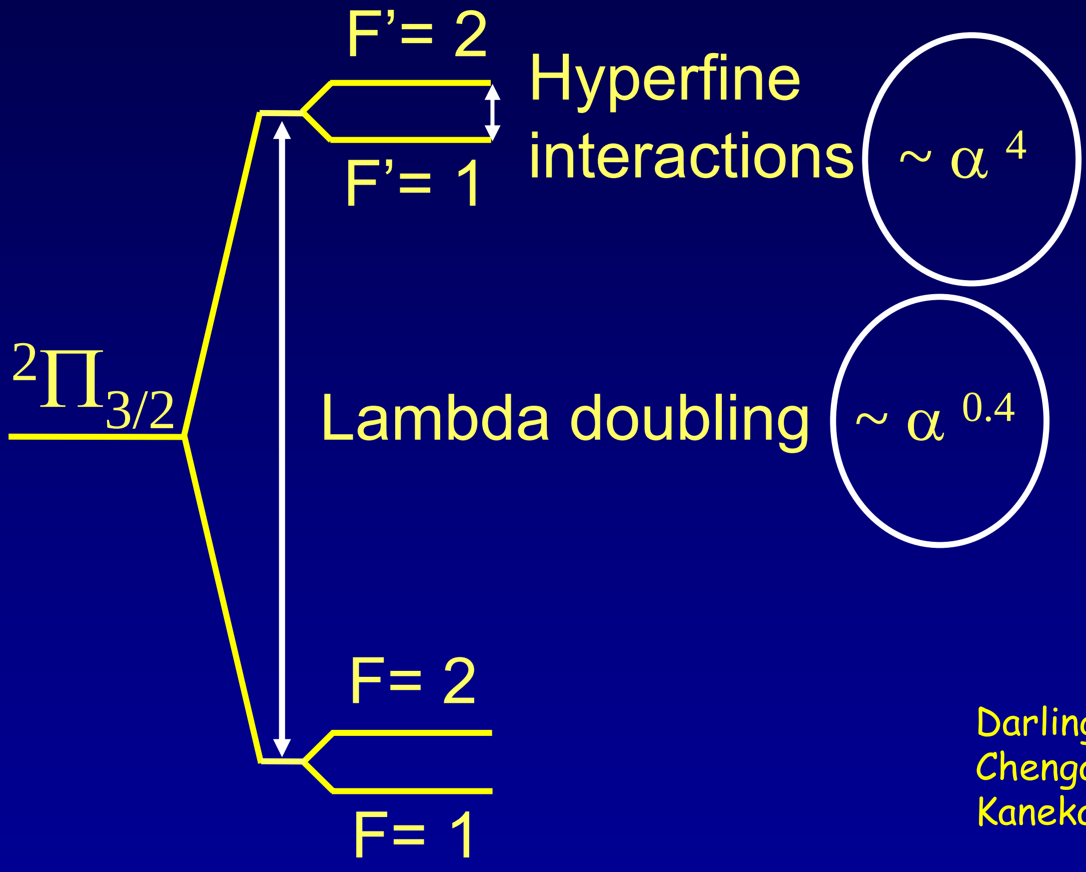
Density:
10^5 – 10^7 /cm^3

Cold molecule based precision spectroscopy

- Rabi or Ramsey interrogation
- High resolution and precision
- Systematic evaluations



Cold OH molecules to constrain $\dot{\alpha}$



F'= 2

Hyperfine interactions $\sim \alpha^{4}$

F'= 1

$^{2}\Pi_{3/2}$

Lambda doubling $\sim \alpha^{0.4}$

F= 2

F= 1

OH megamasers

High redshift $z > 1$

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).

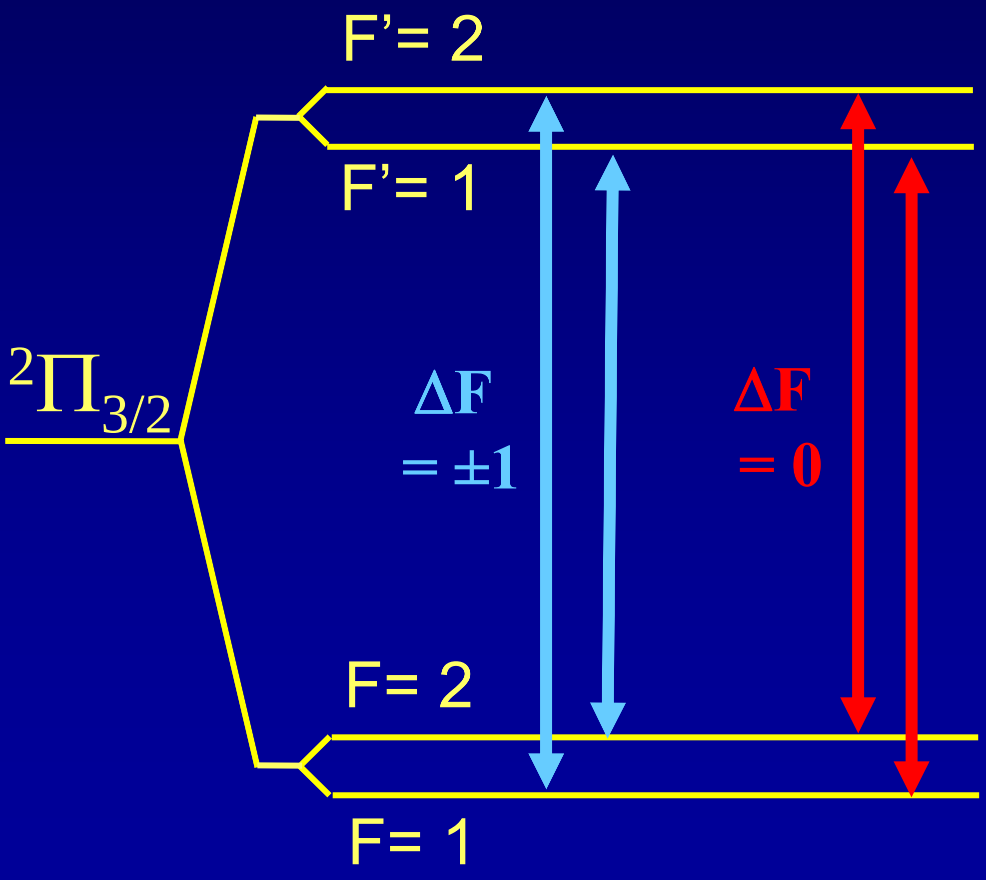
Multiple transitions from the same gas cloud
(Self check on systematics)

Precision measurement of OH ground structure

Measurement accuracy for all four lines: 4 – 10 Hz

Hudson, Lewandowski, Sawyer, Ye PRL 96, 143004 (2006).
Lev, Meyer, Hudson, Sawyer, Bohn, Ye, PRA 74, 061402 (2006).

- SUM (2 satellites) = SUM (2 main lines)
- Satellites calibrate B
- Observed satellites conjugate



F'= 2

F'= 1

$^2\Pi_{3/2}$

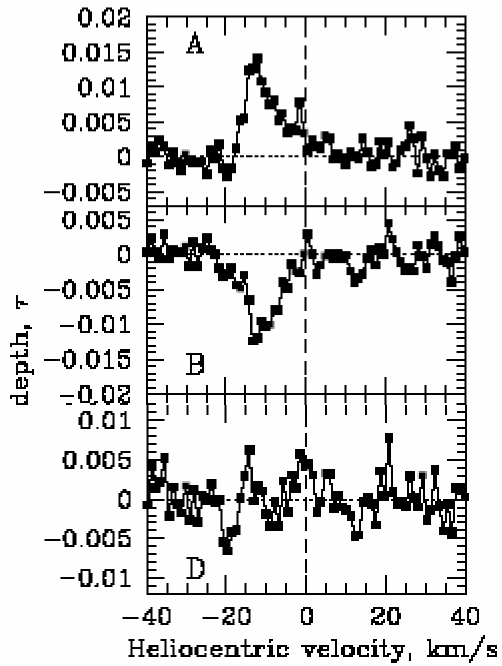
$\Delta F = \pm 1$

$\Delta F = 0$

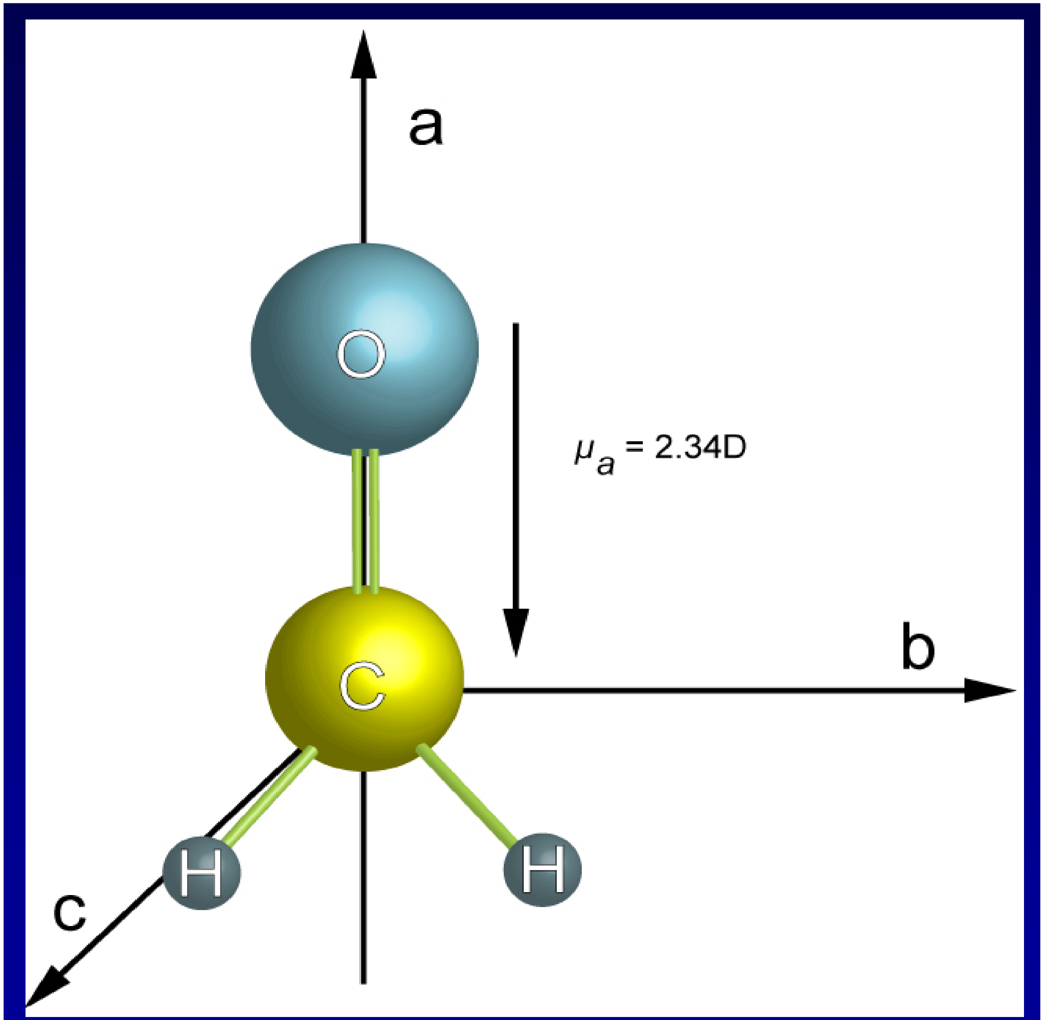
F= 2

F= 1

Kanekar *et al.*, PRL 93, 051302 (2004).



Cold Chemical Reactions



H_2CO – near symmetric rotor:

Formaldehyde (H_2CO):

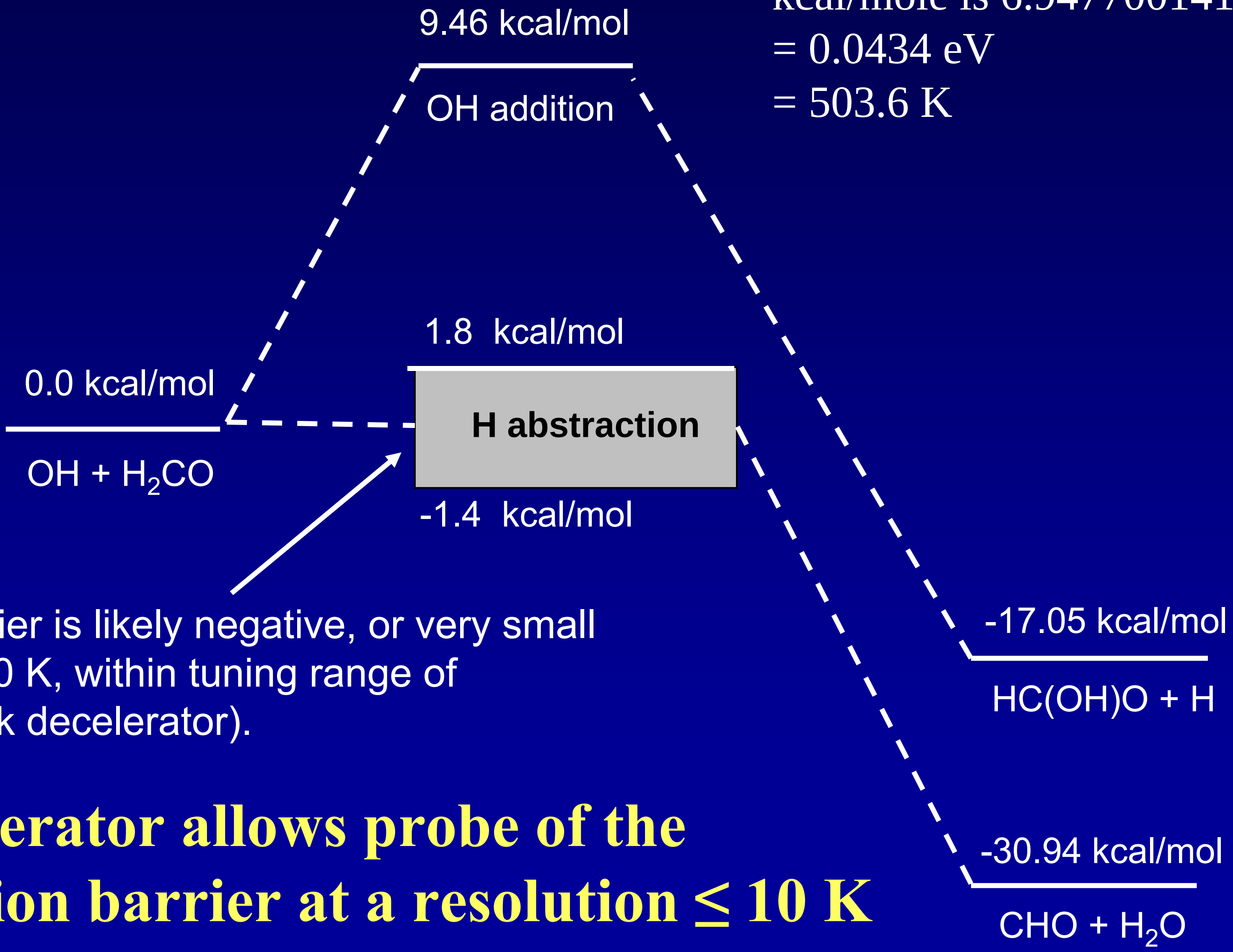
Bring this most general class of molecules to rest in laboratory

H_2CO - OH:
Fundamental reaction dynamics

Atmospheric chemistry
Combustion dynamics
Pollutant monitoring

OH + H_2CO reaction pathways

kcal/mole is $6.947700141 \times 10^{-21}$ J
= 0.0434 eV
= 503.6 K



9.46 kcal/mol

OH addition

1.8 kcal/mol

0.0 kcal/mol

OH + H_2CO

H abstraction

-1.4 kcal/mol

-17.05 kcal/mol

HC(OH)O + H

-30.94 kcal/mol

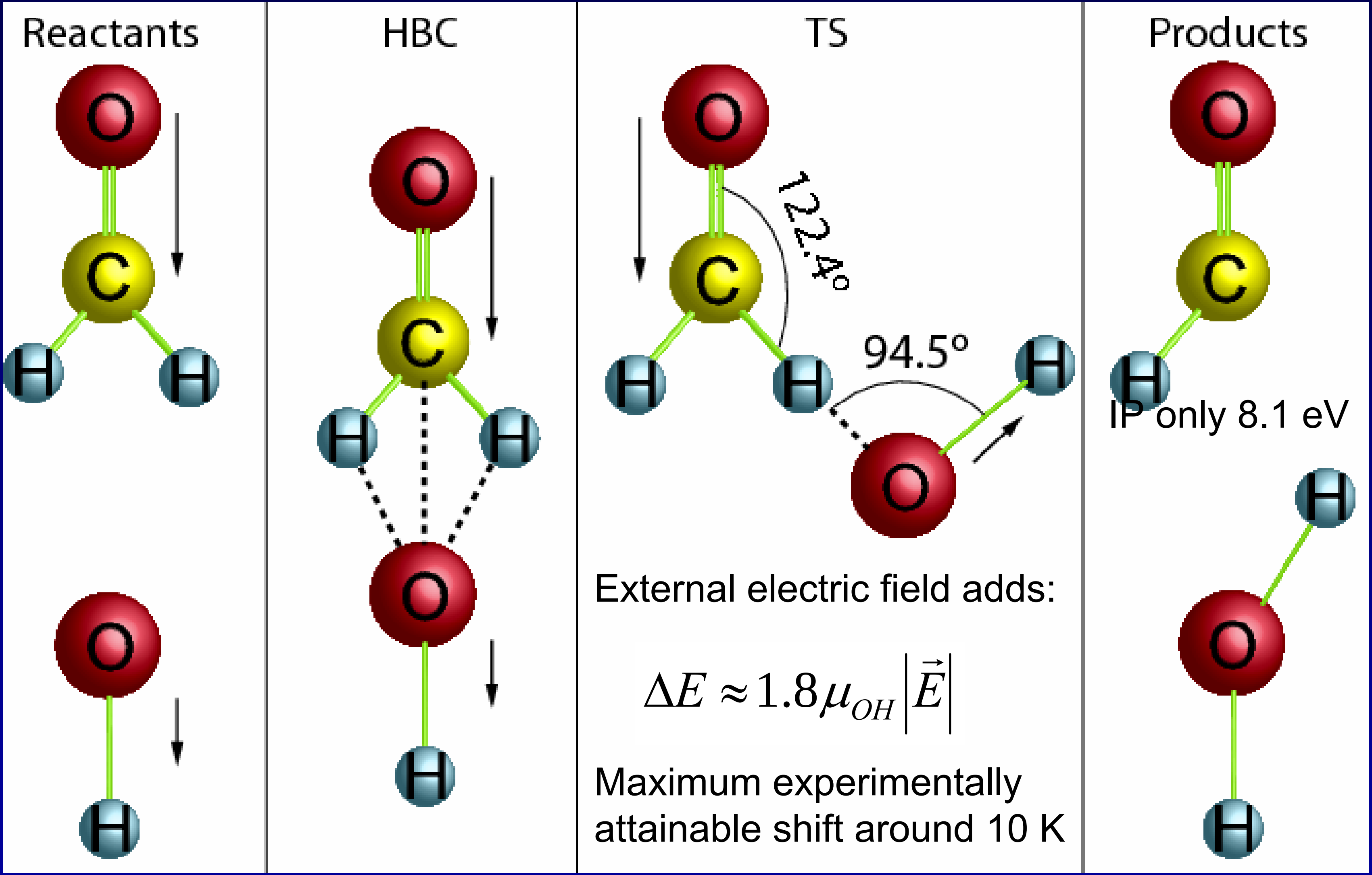
CHO + H_2O

Barrier is likely negative, or very small (~ 60 K, within tuning range of Stark decelerator).

Decelerator allows probe of the reaction barrier at a resolution ≤ 10 K

External electric field tunes reaction barrier

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



IP only 8.1 eV

External electric field adds:

$$\Delta E \approx 1.8\mu_{OH}\left|\vec{E}\right|$$

Maximum experimentally attainable shift around 10 K

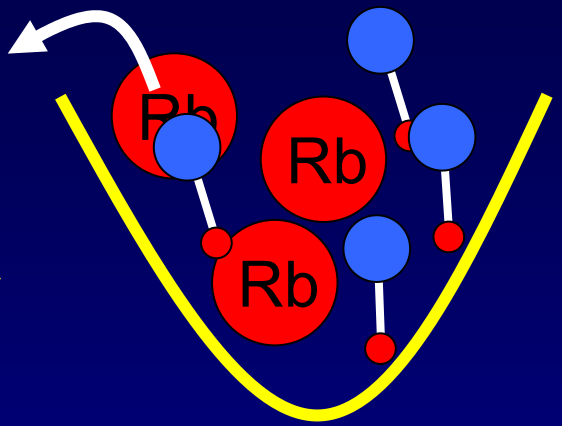
Control of cold chemical reactions; Unique dipolar interaction dynamics

A pressing requirement

Enhancement of the phase space density of cold molecules!

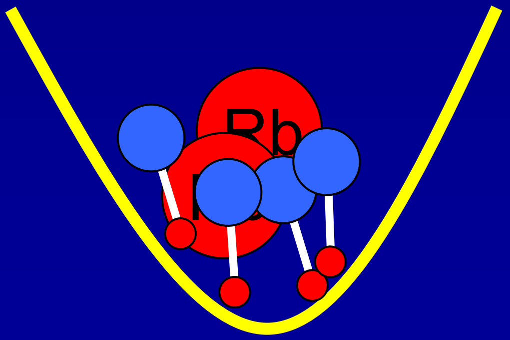
Sympathetic cooling in a trap

Molecules and atoms co-located in a trap.



Selectively remove highest energy Rb atoms.

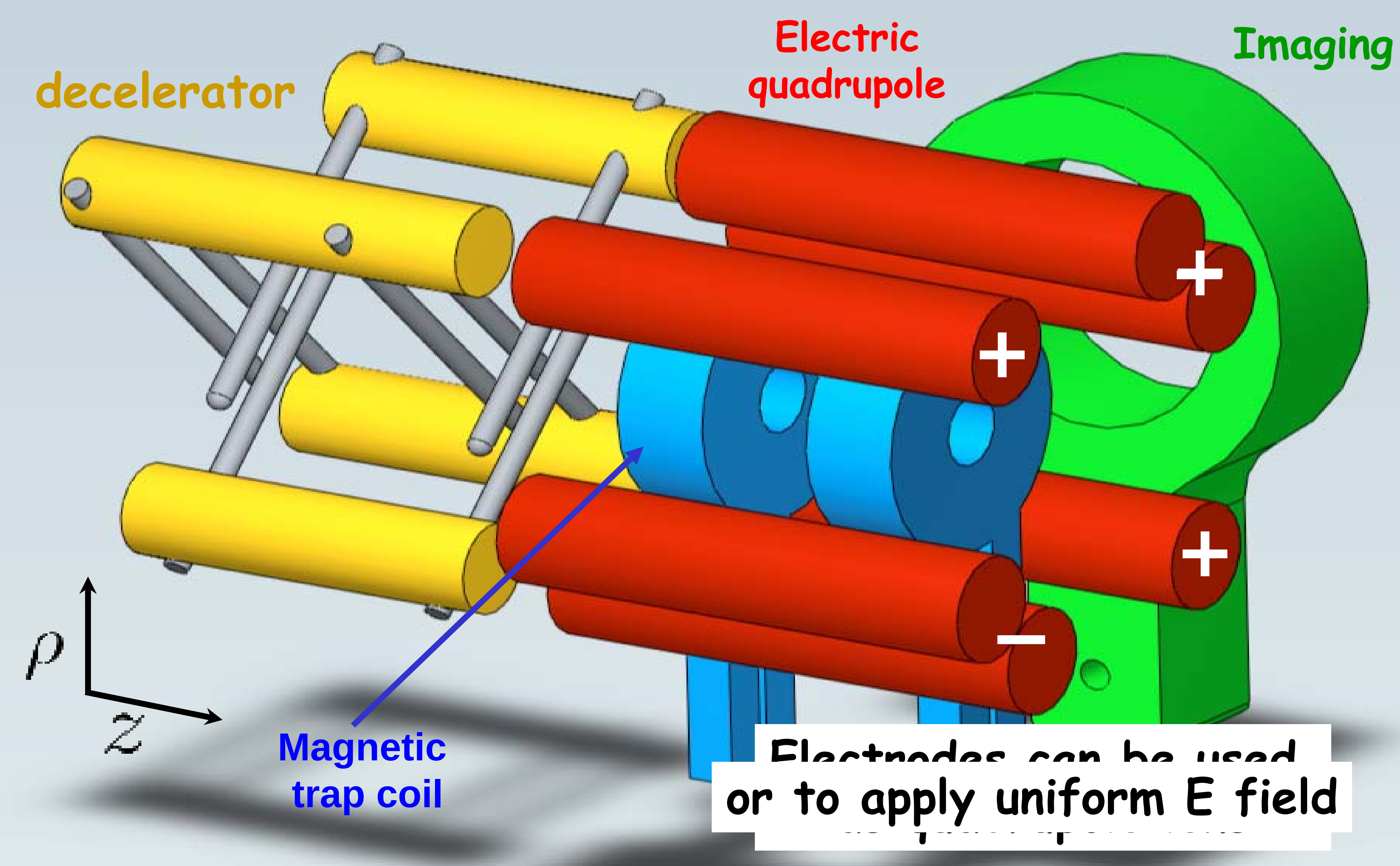
Atoms and molecules rethermalize, through collisions, to a lower temperature.



Requires favorable collision rates

Jeremy Hutson's talk (Friday)

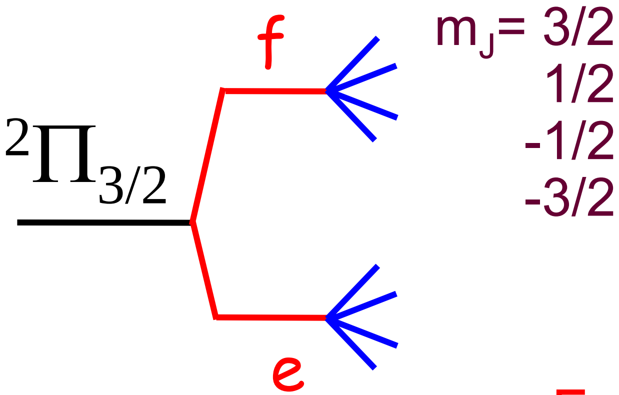
Magnetic trapping of OH

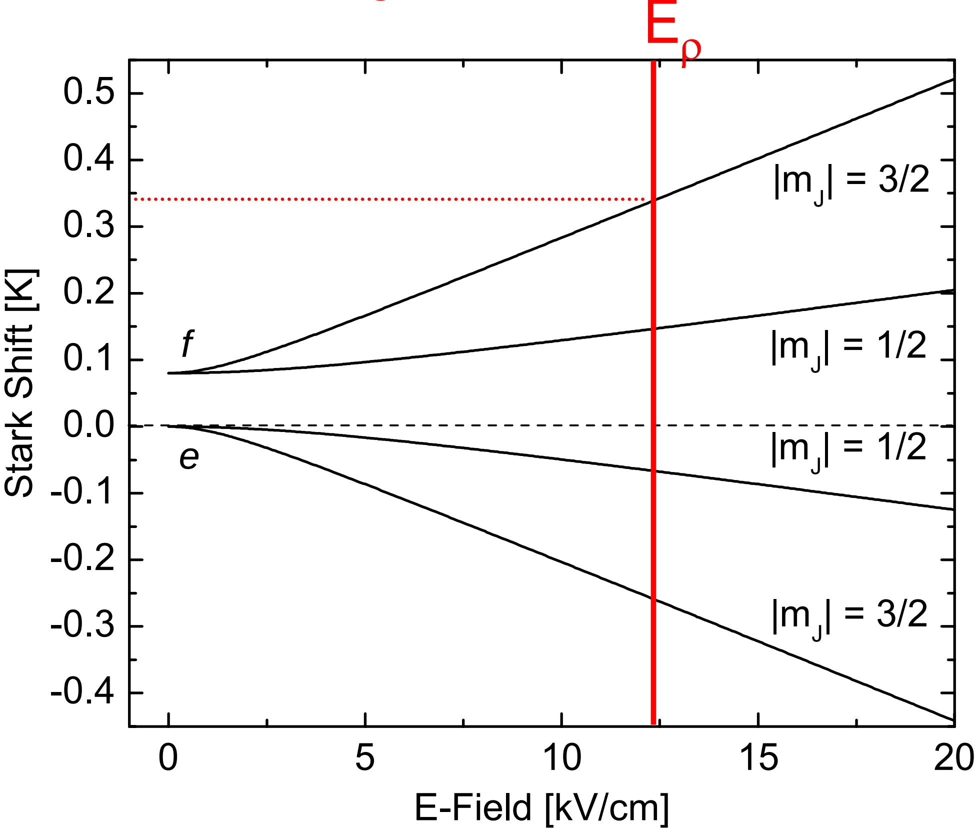


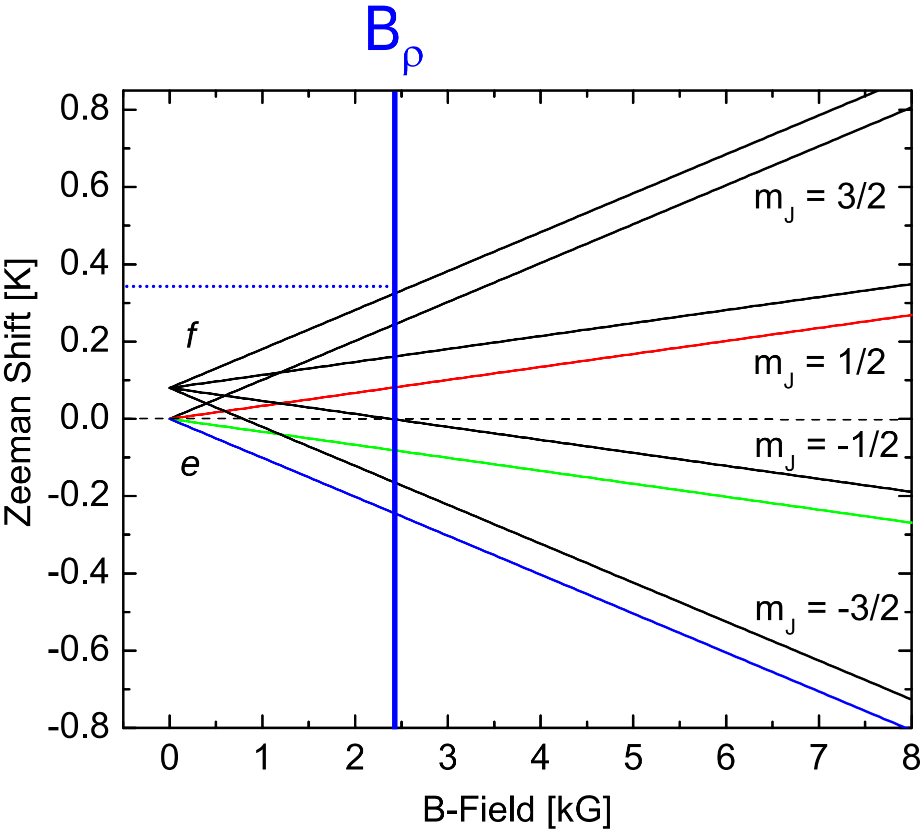
Electrodes can be used

or to apply uniform E field

OH Stark and Zeeman effects



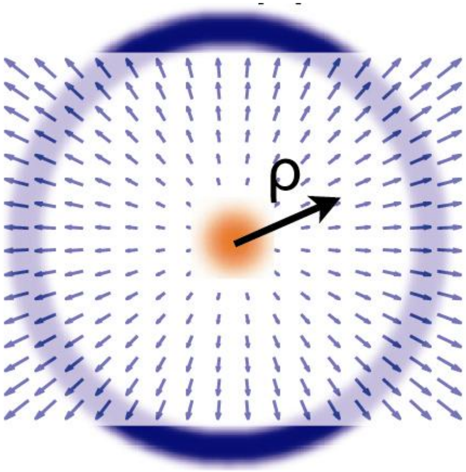




R. Krems' Talk Friday

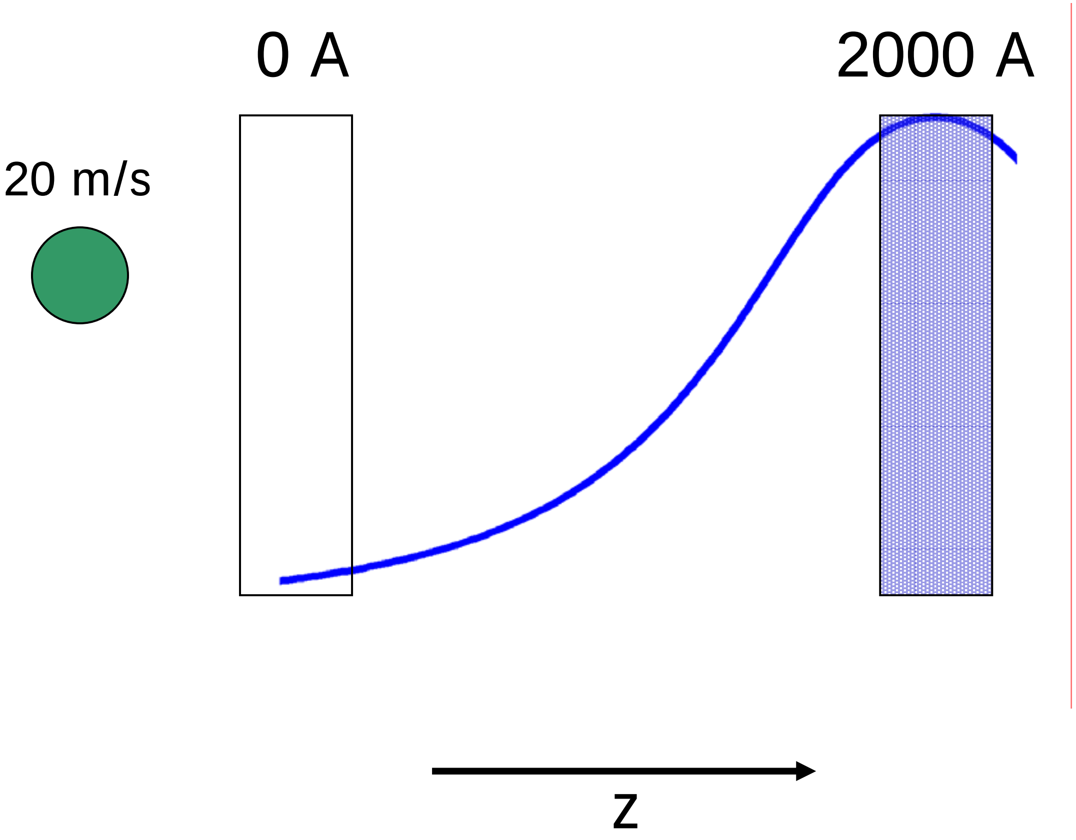
Trapping Scheme

End view



Magnetic
Quadrupole

Side view

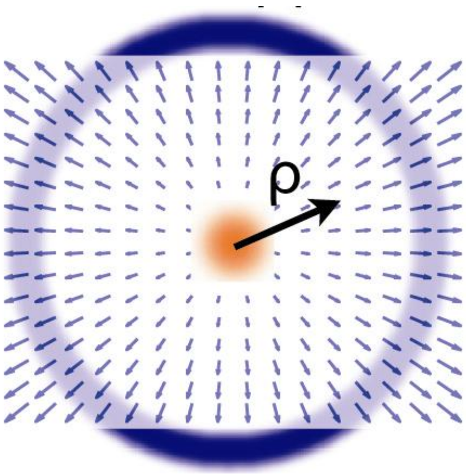


Trapping Scheme

End view

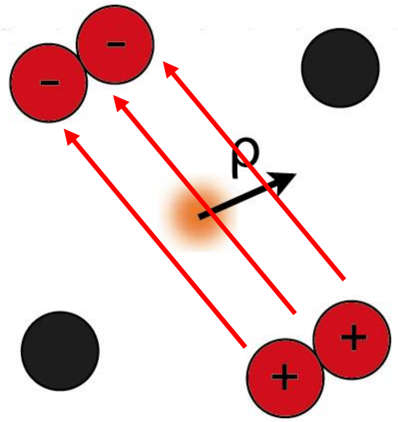
Side view

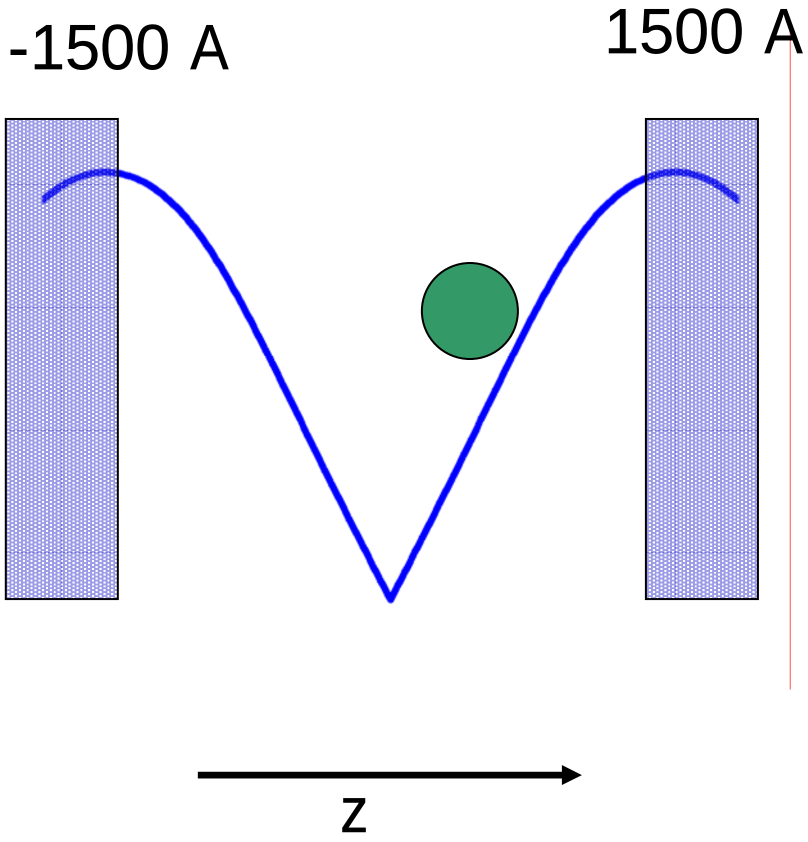
Magnetic
Quadrupole



Uniform
Electric Field

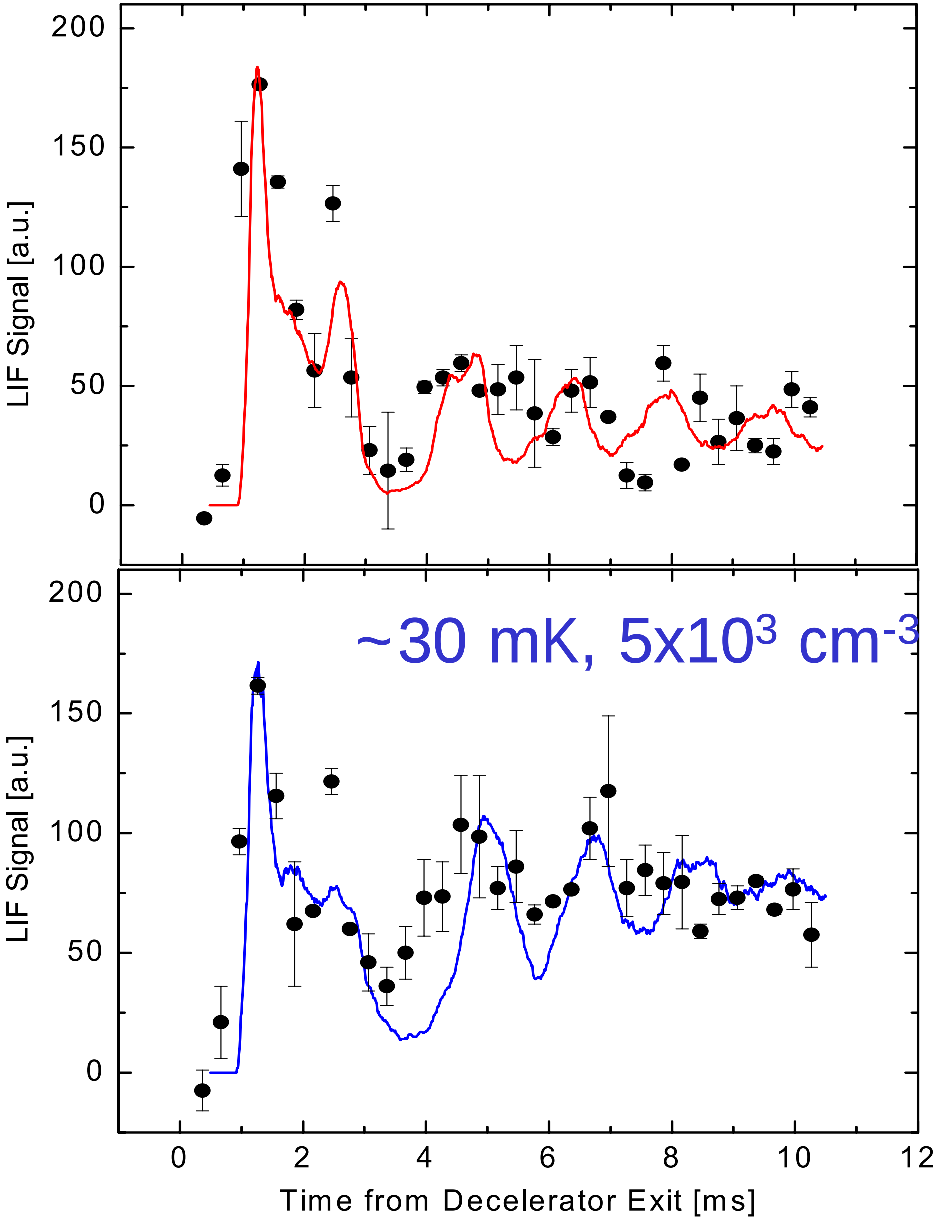
Electric
Quadrupole





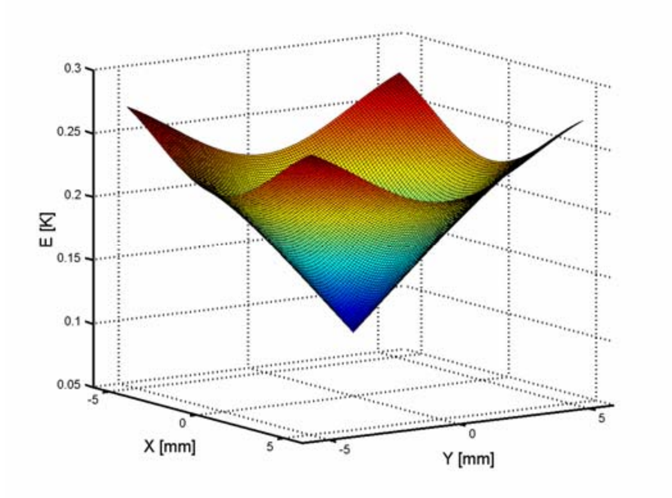
Trap dynamics

Sawyer, Lev, Hudson, Stuhl, Lara, Bohn, Ye, physics/0702146, PRL in press (2007).

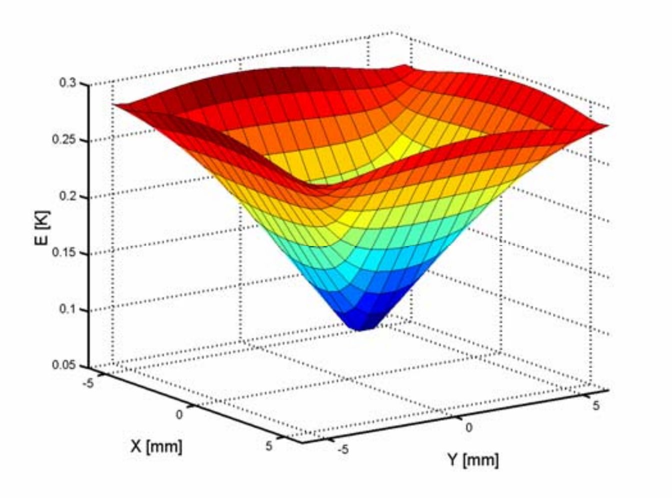


~30 mK, 5×10^3 cm^{-3}

Quadrupole
B

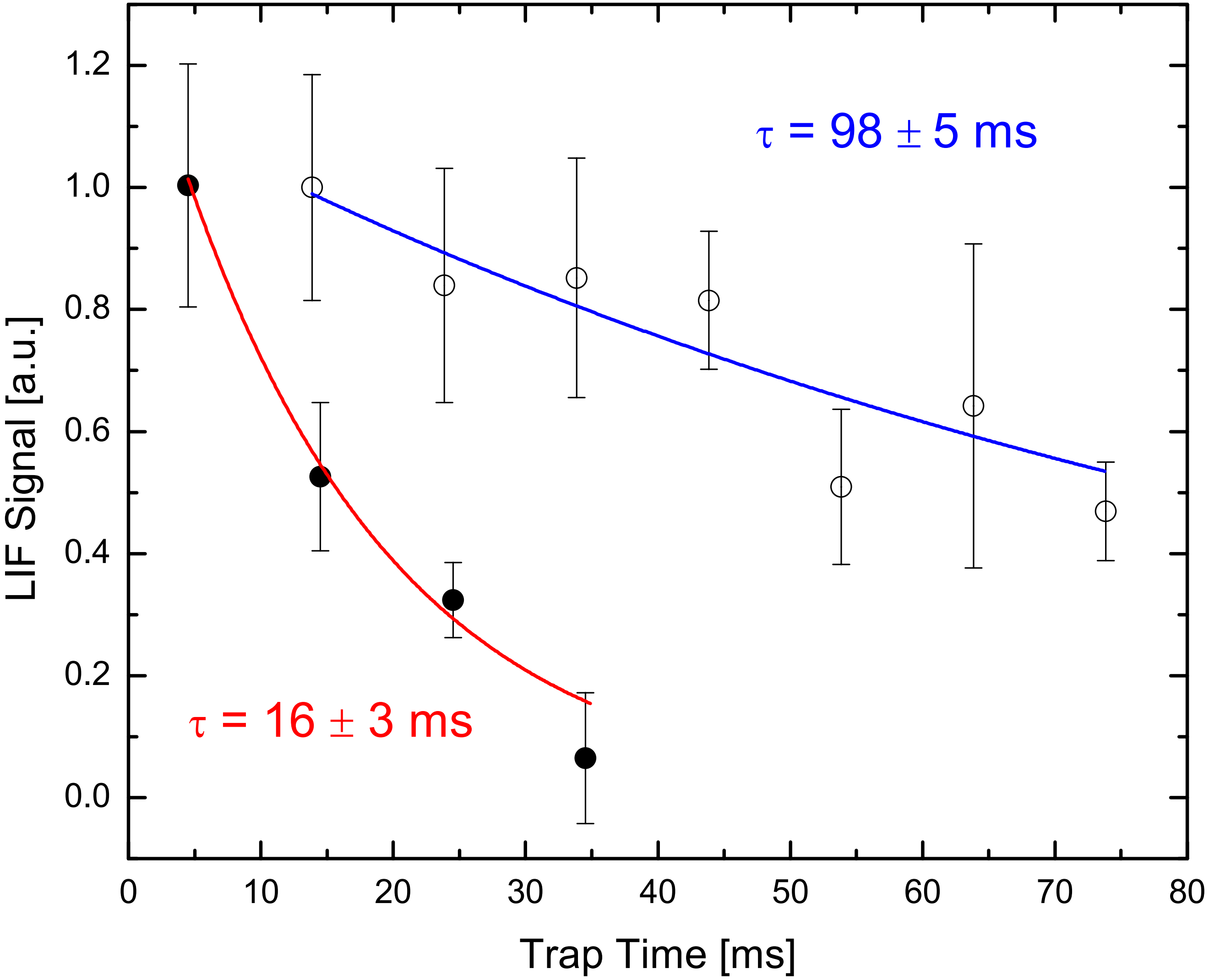


Quadrupole
E, B



OH - N_2 collisions

Collision-limited lifetimes



1×10^{-6} Torr N_2
20 ± 5 ms;

4×10^{-8} Torr N_2
500 ± 100 ms

OH - N_2
cross section:

500 ± 100 $Å^2$

Soon to study dipolar collisions!

Special thanks

http://jilawww.colorado.edu/YeLabs

Ultracold Sr & Sr$_2$

M. Boyd
A. Ludlow
S. Blatt
Dr. T. Zelevinsky
Dr. G. Campbell
Dr. T. Zanon

Cold Polar Molecules

B. Sawyer
Dr. B. Lev
B. Stuhl

Dr. S. Ospelkaus

Femtosecond comb & quantum control

S. Foreman
M. Thorpe
D. Hudson
D. Yost
M. Stowe
Dr. T. Schibli
Dr. A. Pe’er

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P. Julienne, S. Kotochigova (NIST)
M. Shapiro, E. Shapiro (UBC)