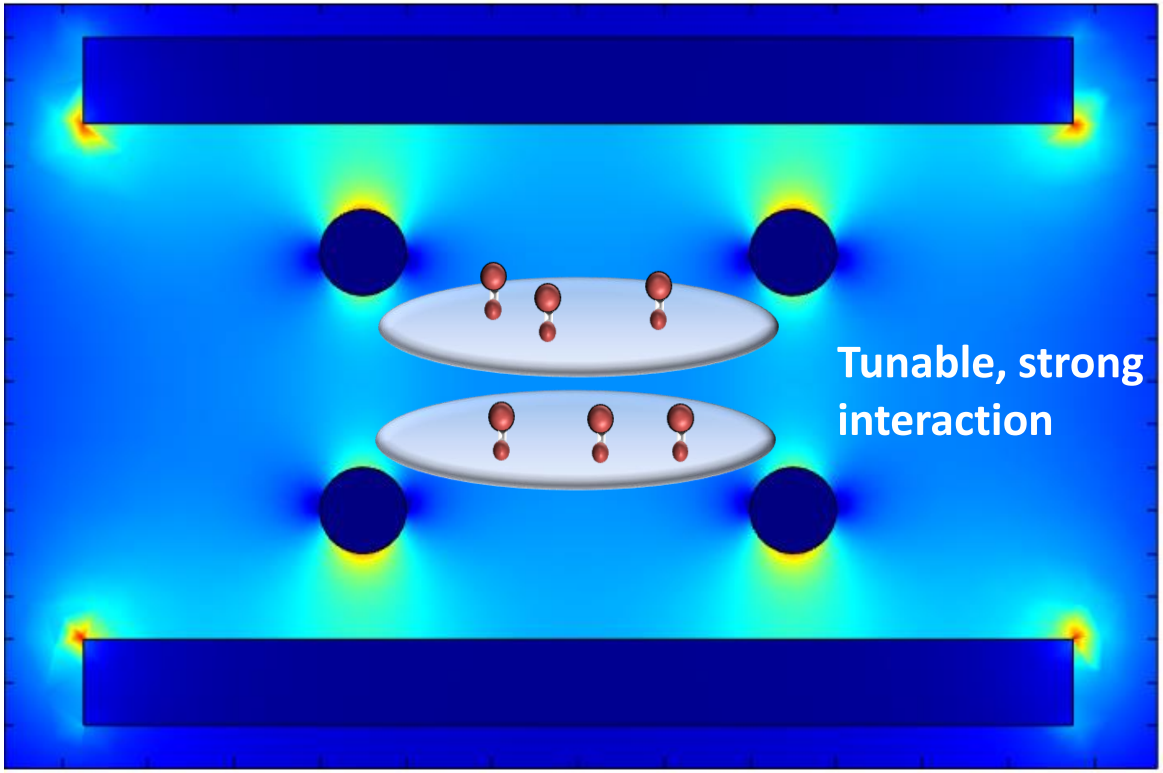
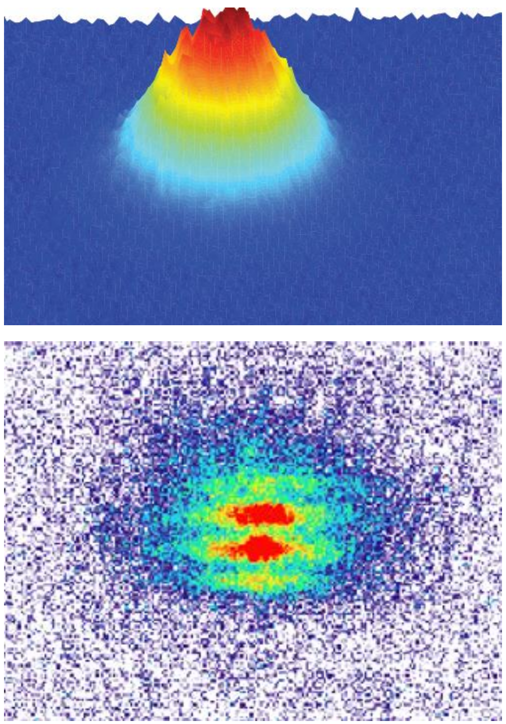
A Fermi gas of polar molecules (from 3D to 2D)

J. Ye
JILA, NIST & Univ. Colorado

Quantum Science Seminar, June 18, 2020

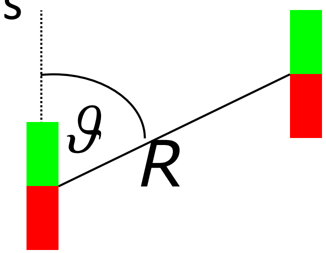




Dipolar quantum systems

- Strongly correlated quantum material
- Dynamics with tunable, long-range interactions

Atomic magnetic dipoles

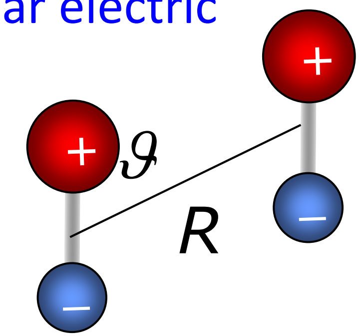


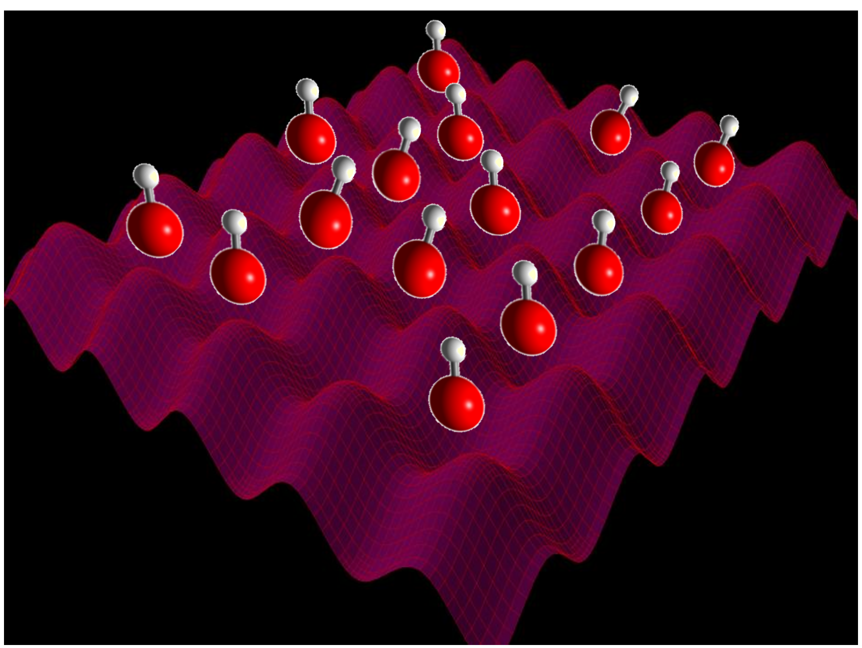
Stuttgart, Innsbruck, Stanford, …

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

Tunable in angle & strength (**E**)

Molecular electric dipoles

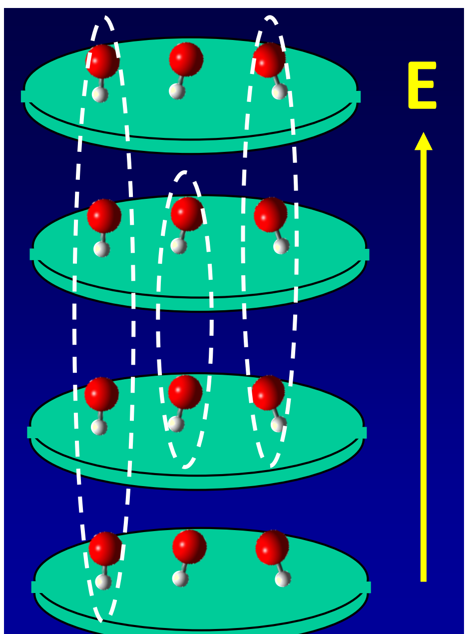




Quantum metrology,

Quantum information

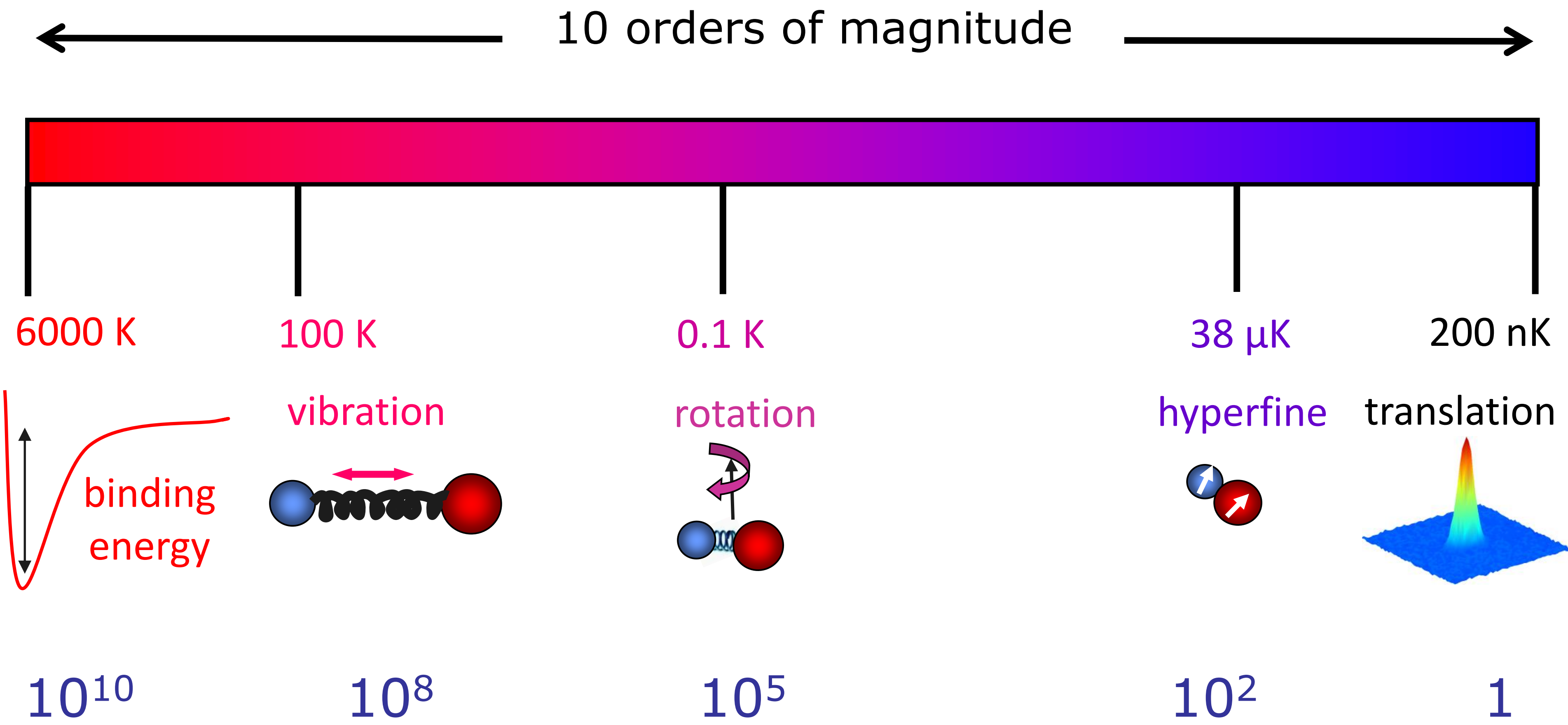
Chemistry



Molecules are complex

Jin & Ye, Physics Today **64**, 27 (2011).

Quantum gas of molecules

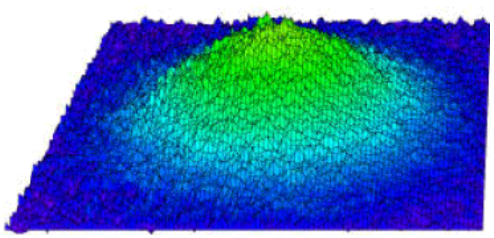


Ultracold polar molecules

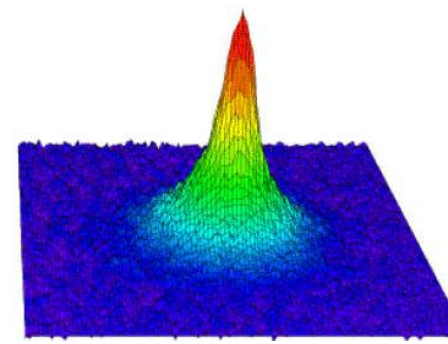
Ni, Ospelkaus, de Miranda, Pe'er, Neyenhuis, Zirbel, Kotochigova, Julienne, Jin, & Ye, Science **322**, 231 (2008).

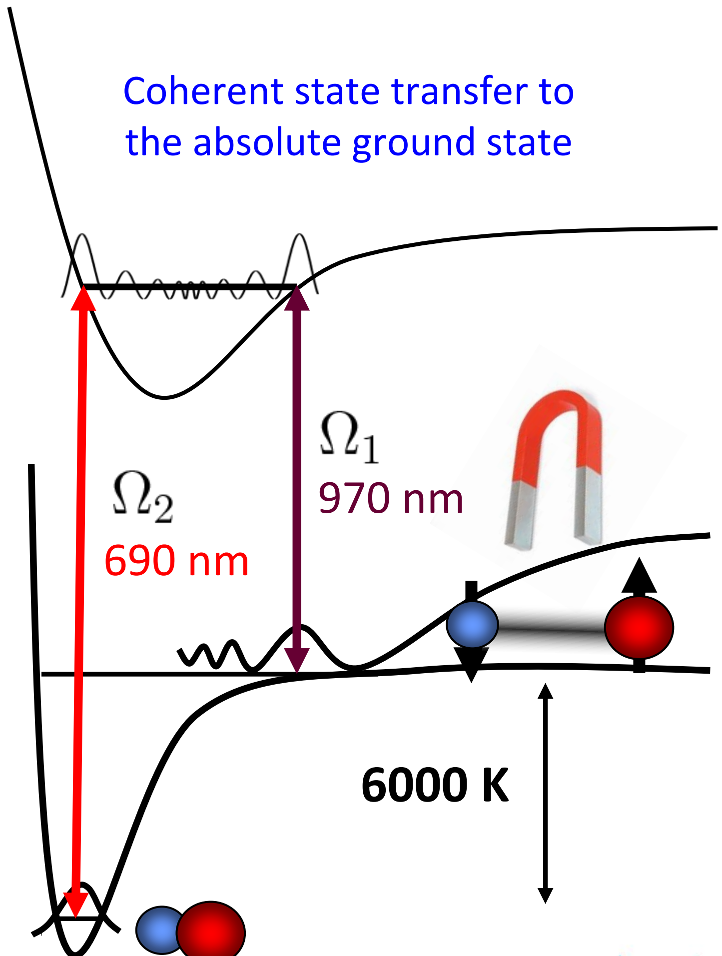
Innsbruck, Durham, MIT, Hong Kong, USTC, MPQ, Harvard, CQT, …

^{40}K Fermions



^{87}Rb Bosons





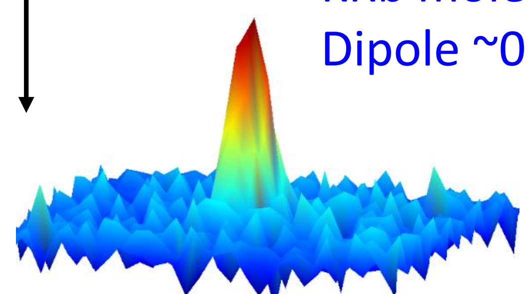
Temperature ~ 200 nK

Density ~$10^{12}/cm^3$

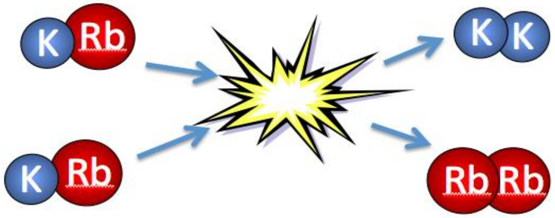
T/T_F ~ 1.4

KRb molecules

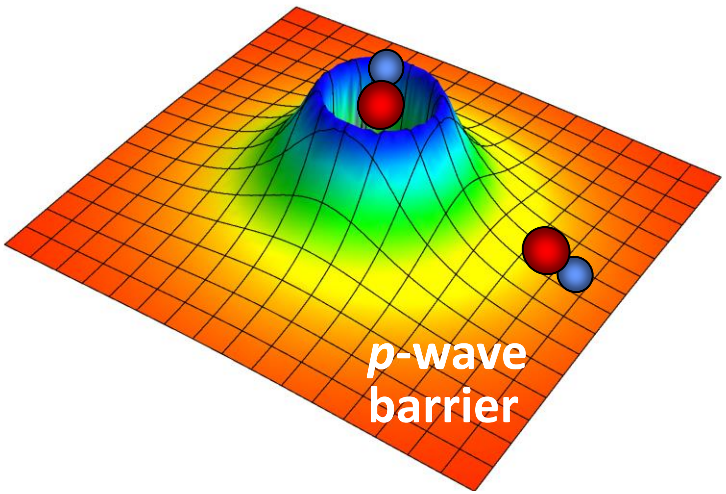
Dipole ~0.5 Debye

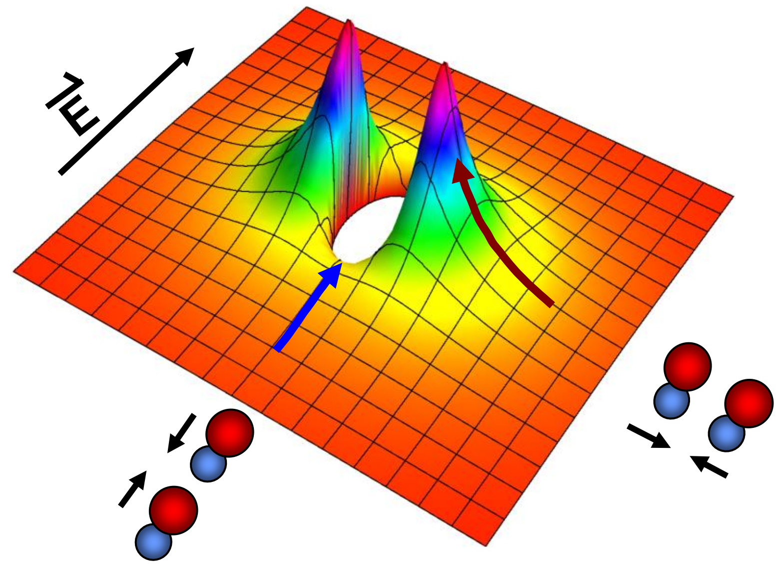


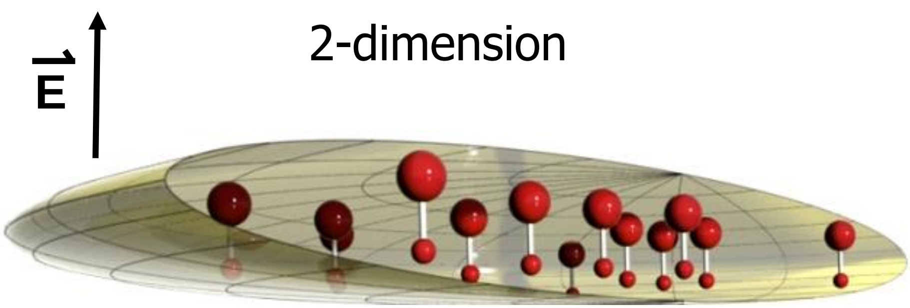
Chemistry in the quantum regime



- Quantum statistics dictate reaction rate
- Single partial wave at threshold
- Dipolar interaction enhances reaction
- Stereo chemistry – geometry matters







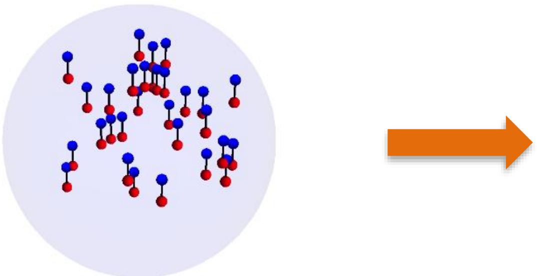
Ospelkaus *et al.*, Science **327**, 853 (2010).

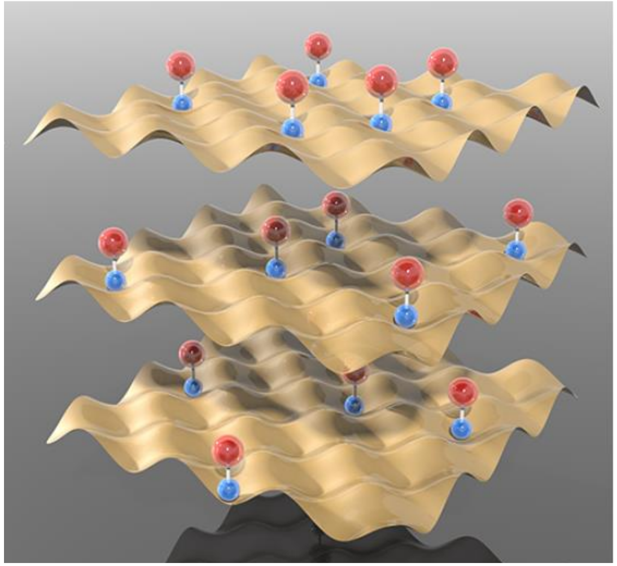
Ni *et al.*, Nature **464**, 1324 (2010).

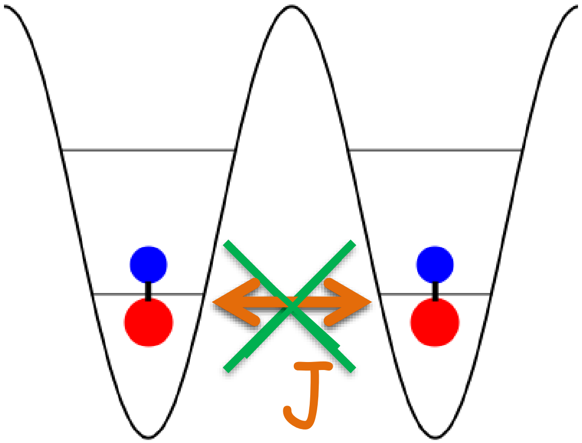
de Miranda *et al.*, Nature Phys. **7**, 502 (2011).

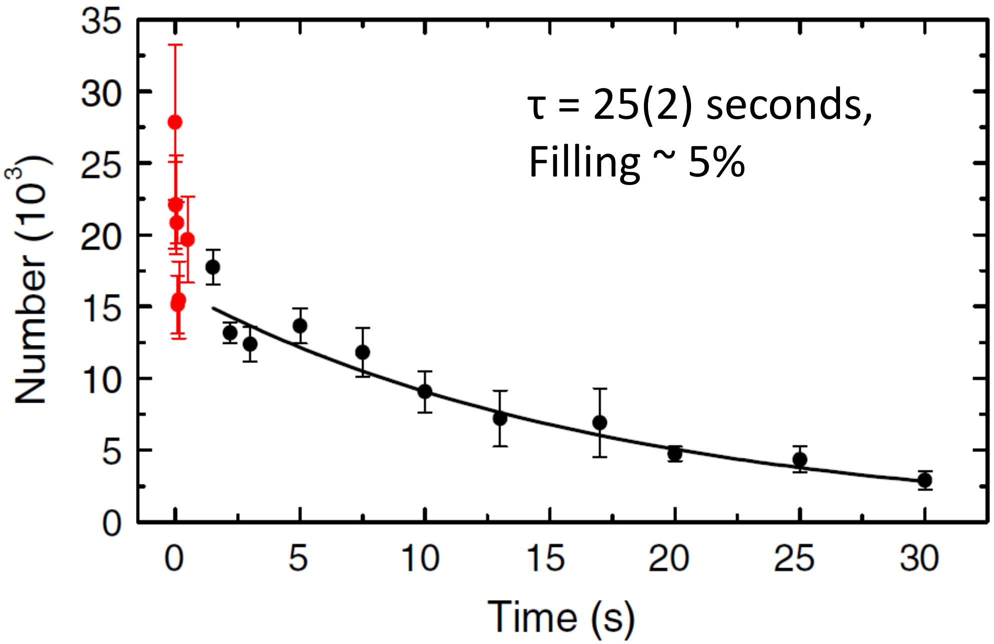
Putting molecules in a 3D lattice

Chotia *et al.*, PRL **108**, 080405 (2012); Zhu *et al.*, PRL **112**, 070404 (2014).





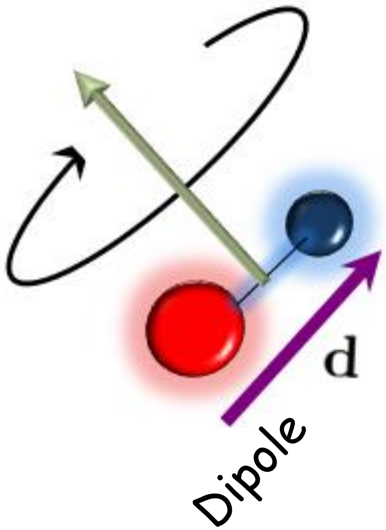




Molecules as dipolar spins

Gorshkov *et al.*, Phys. Rev. Lett. **107**, 115301 (2011).

Rotation → Spin

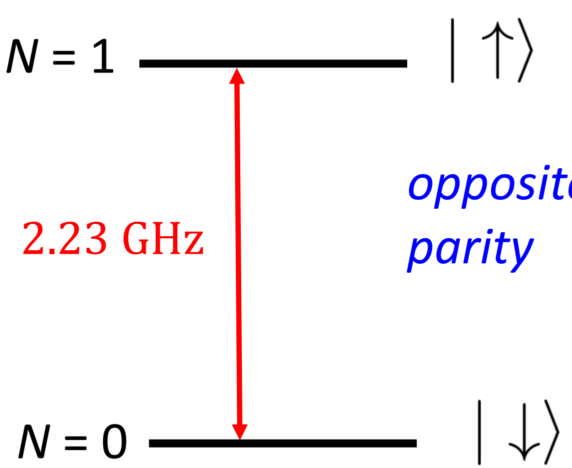


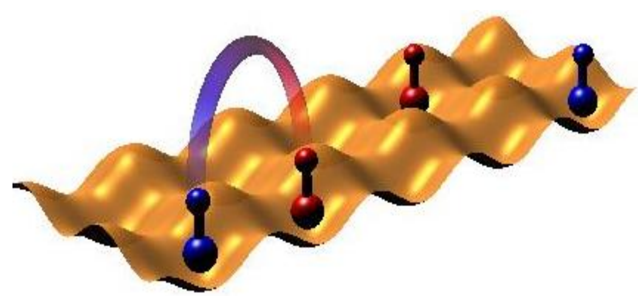
$$H = \sum_{i>j} V_{dd}(\mathbf{r}_i - \mathbf{r}_j)\left[J_z S_i^z S_j^z + \frac{J_\perp}{2}\left(S_i^+ S_j^- + S_i^- S_j^+\right)\right]$$

$$\frac{1 - 3\cos^2\theta_{ij}}{|\mathbf{r}_i - \mathbf{r}_j|^3}$$

Ising $J_z \sim (d_\uparrow - d_\downarrow)^2$

Spin exchange $J_\perp \sim d_{\uparrow\downarrow}^2$ ~ 100 Hz





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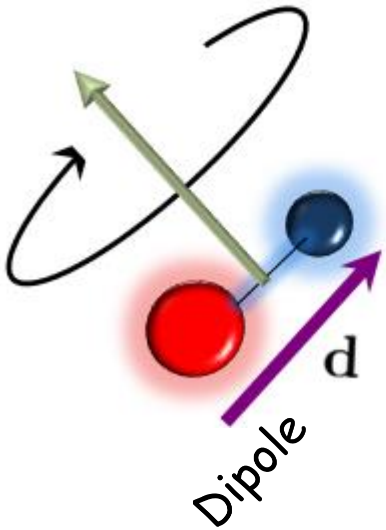

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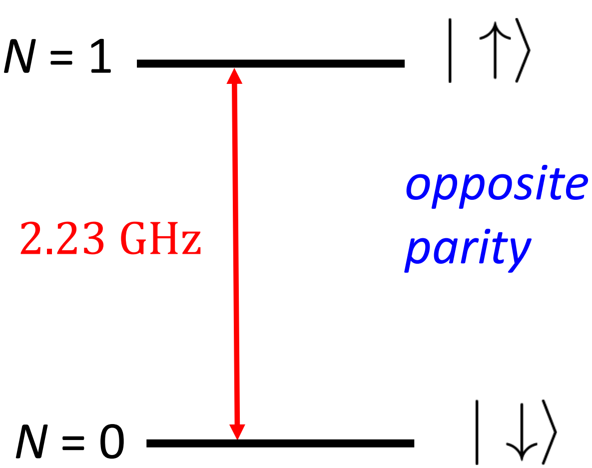
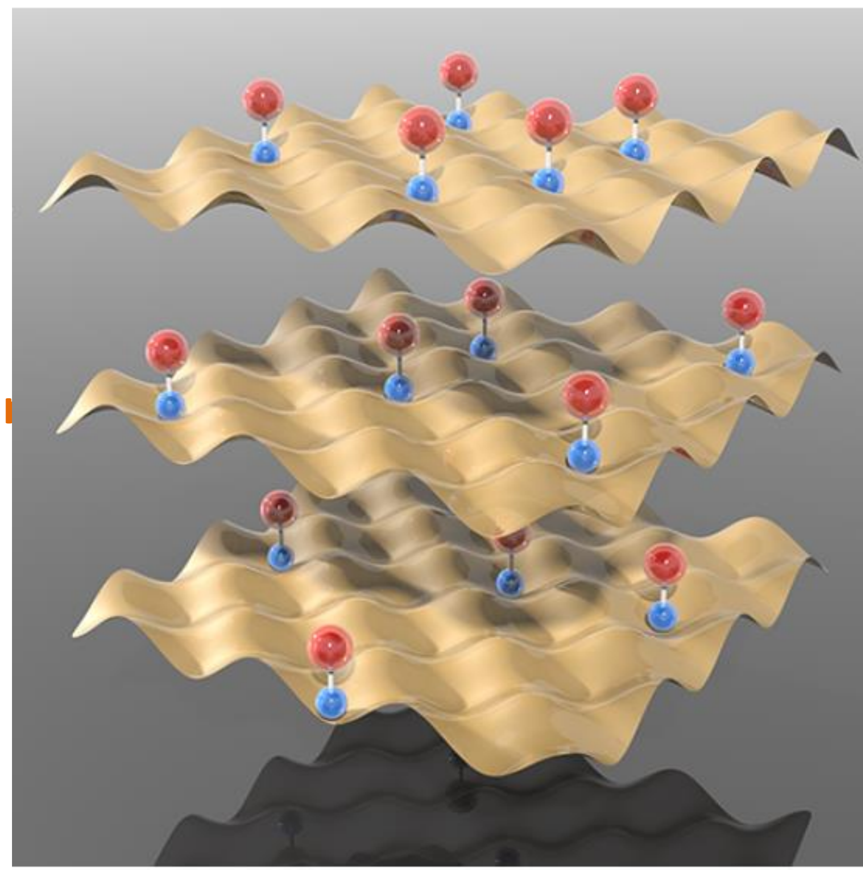
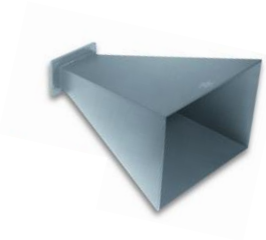


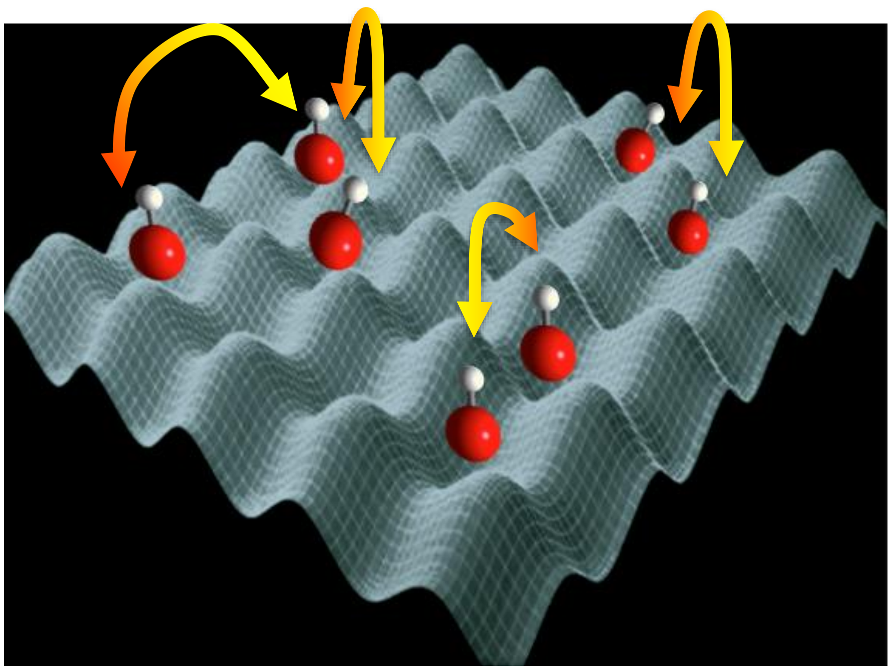
Spi

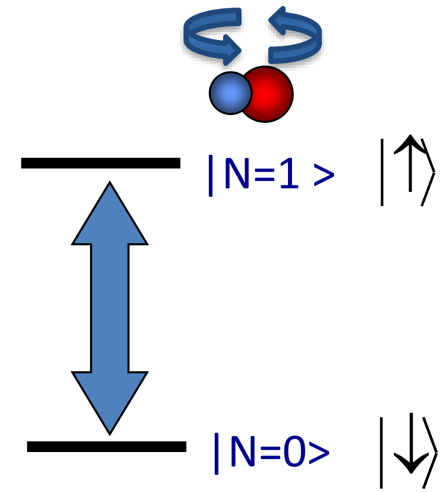


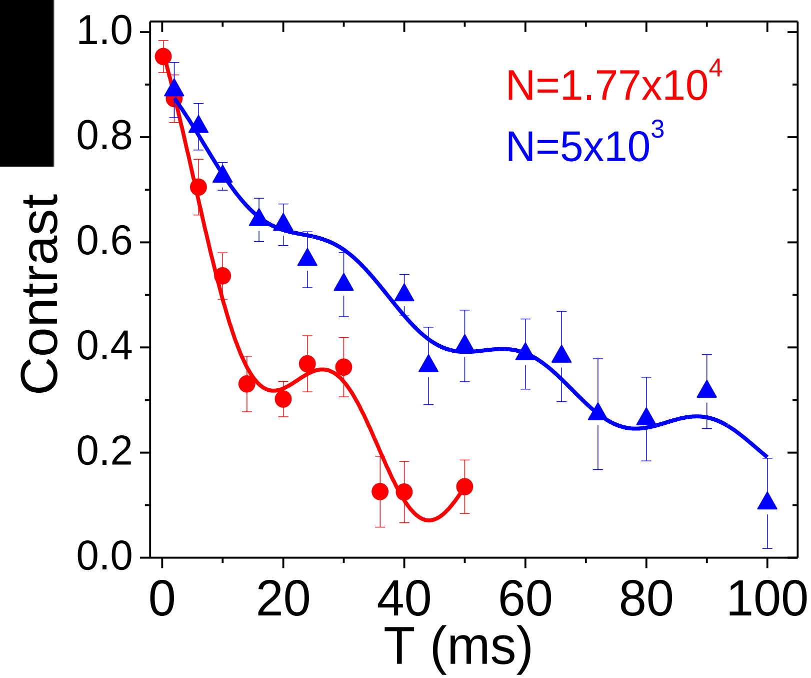
A Dipolar Spin-Lattice Model

B. Yan *et al.*, Nature **501**, 521 (2013).









- Start with N=0. $|\downarrow\rangle$
- Drive a coherent spin superposition. $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right)$
- Probe spin coherence at T. (Ramsey spectroscopy)

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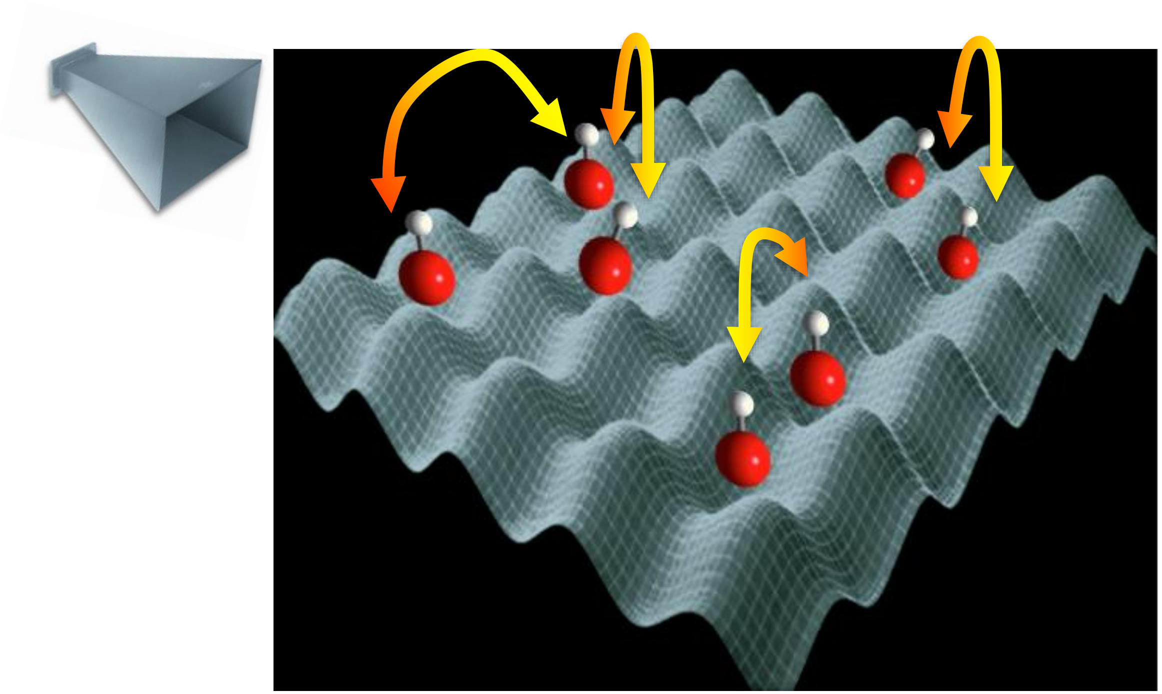

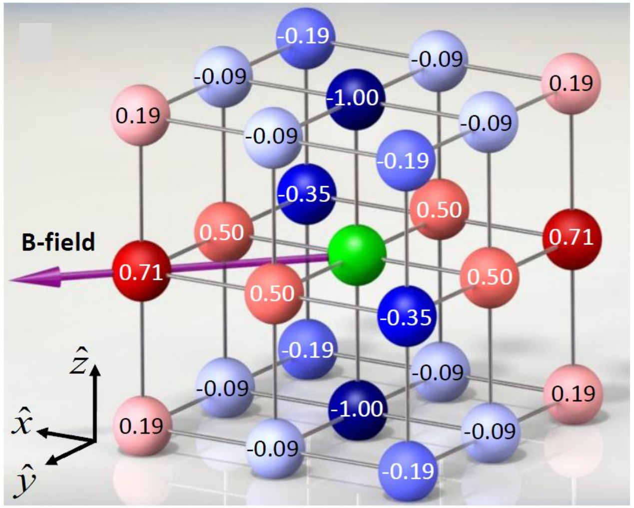

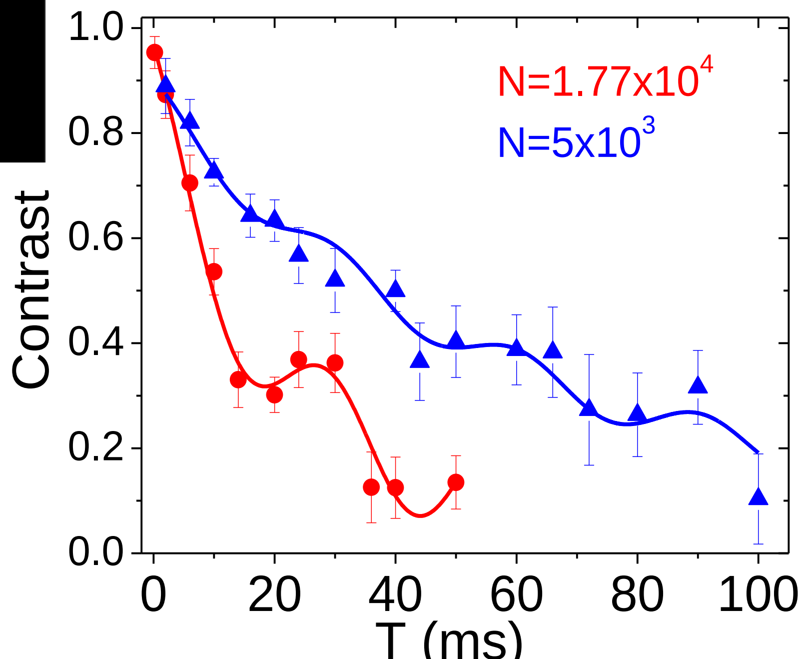

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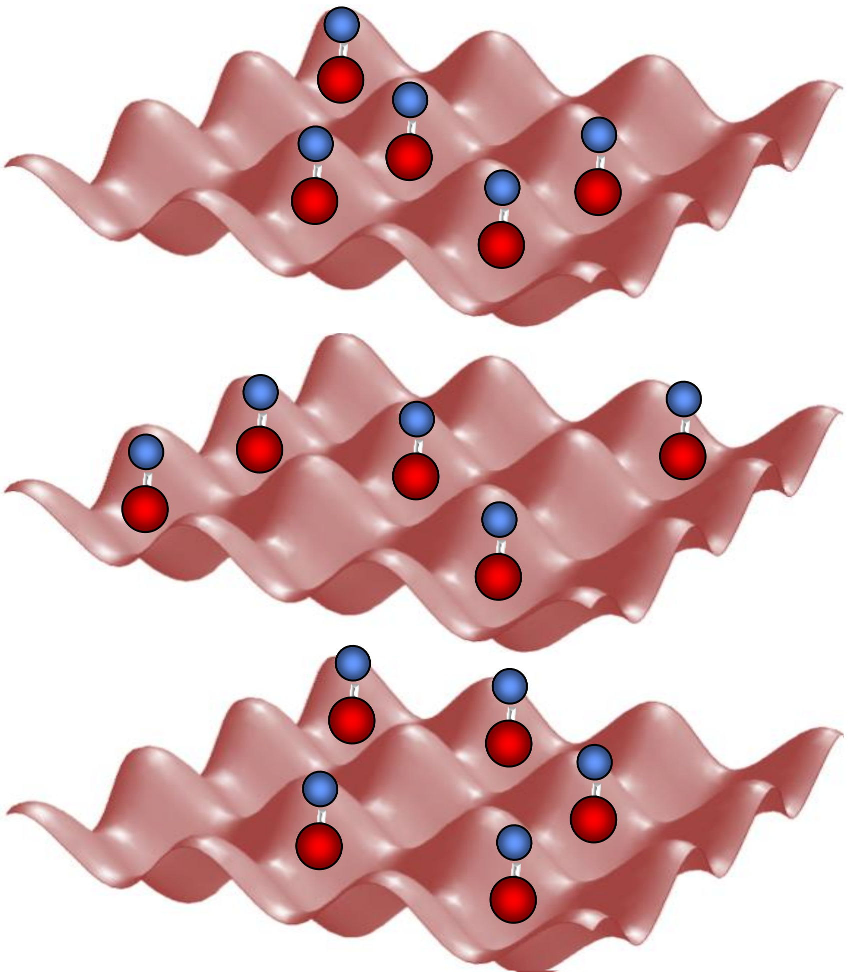
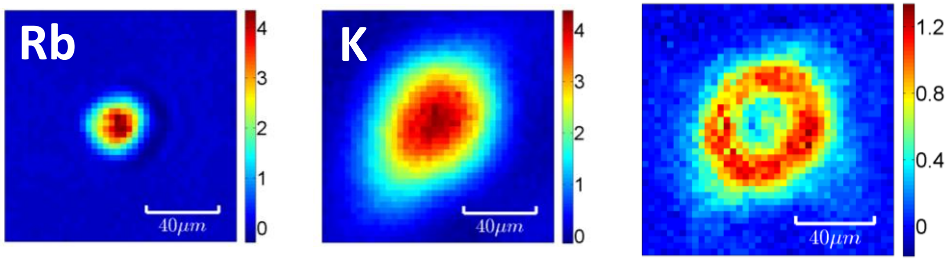
Quantum synthesis of molecular matter

S. Moses *et al.*, Science **350**, 659 (2015).



1. Rb MOTT insulator
2. K fermionic band insulator
3. Magnetic association & STIRAP



Sites with one atom of each species

Dual Mott/band insulator

- "High" density for fermions
- "Low" density for bosons

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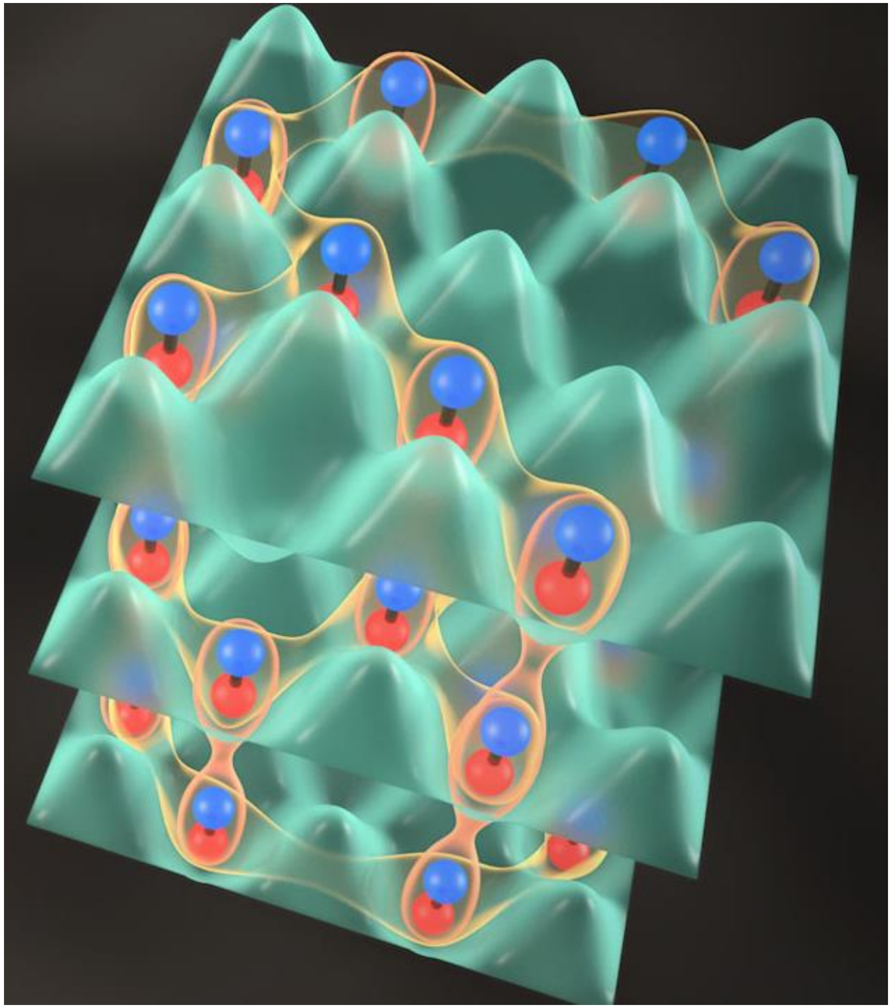
KRb: 1.5 x 10^3, ~25% filling



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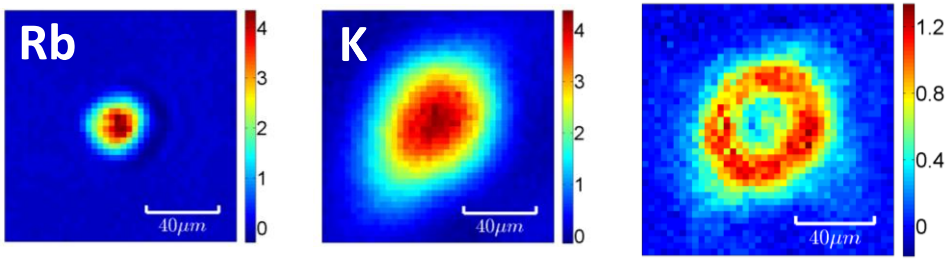

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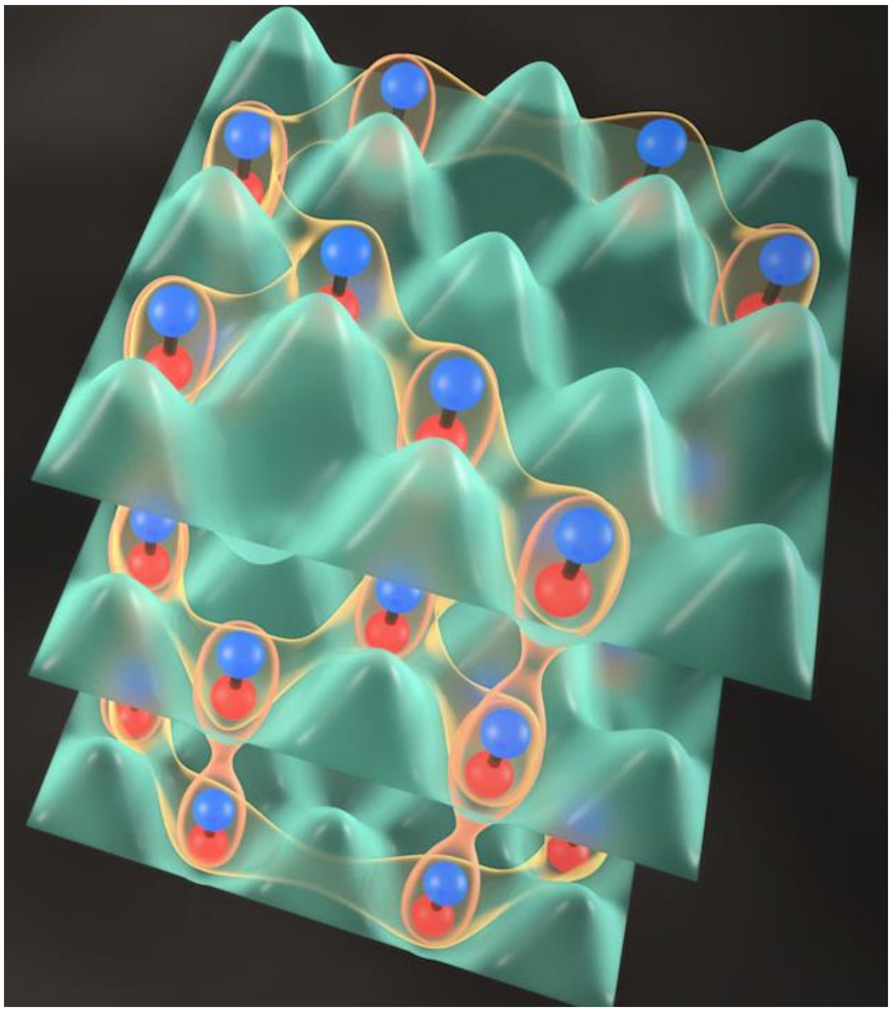
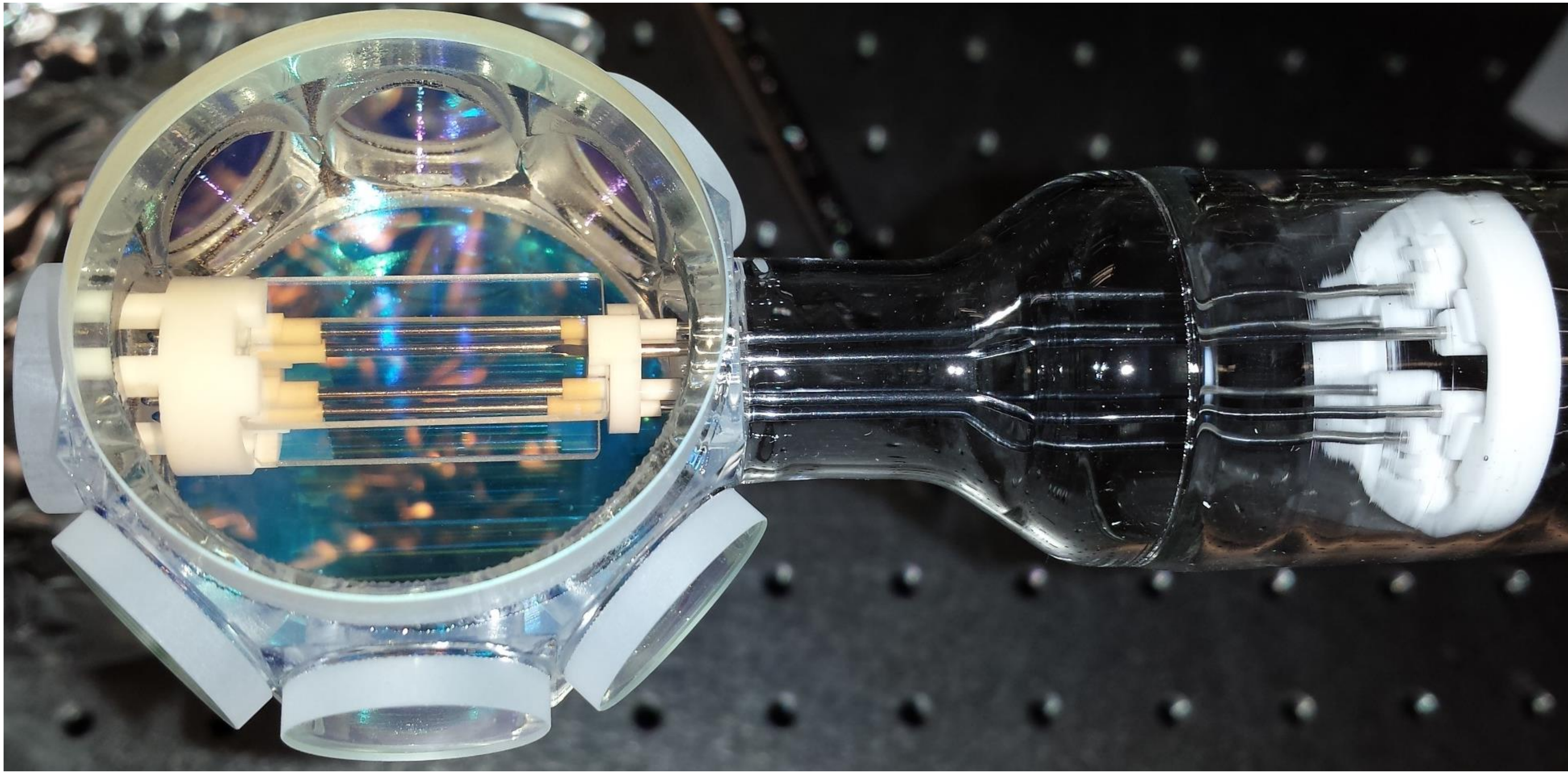
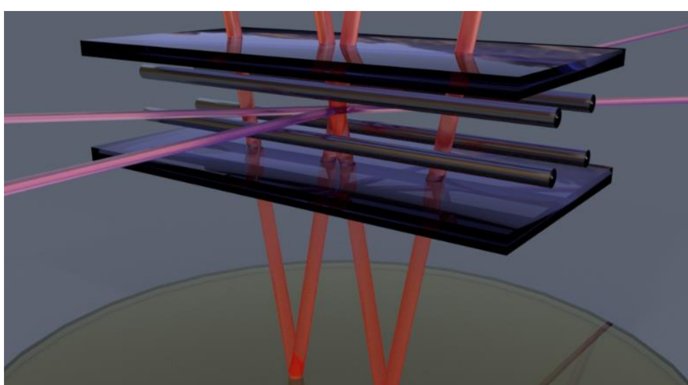
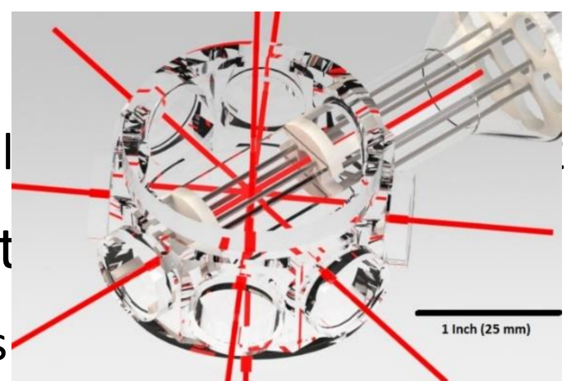
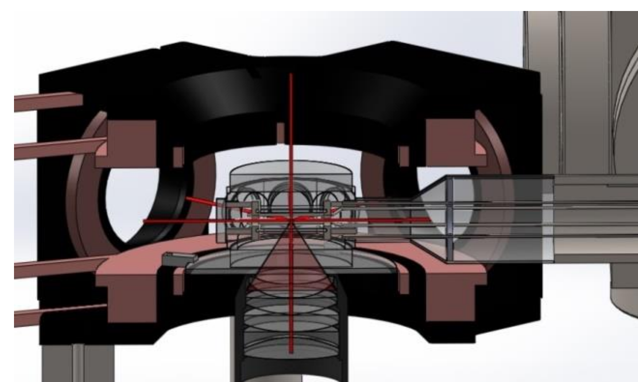


The JILA KRb machine: Generation II



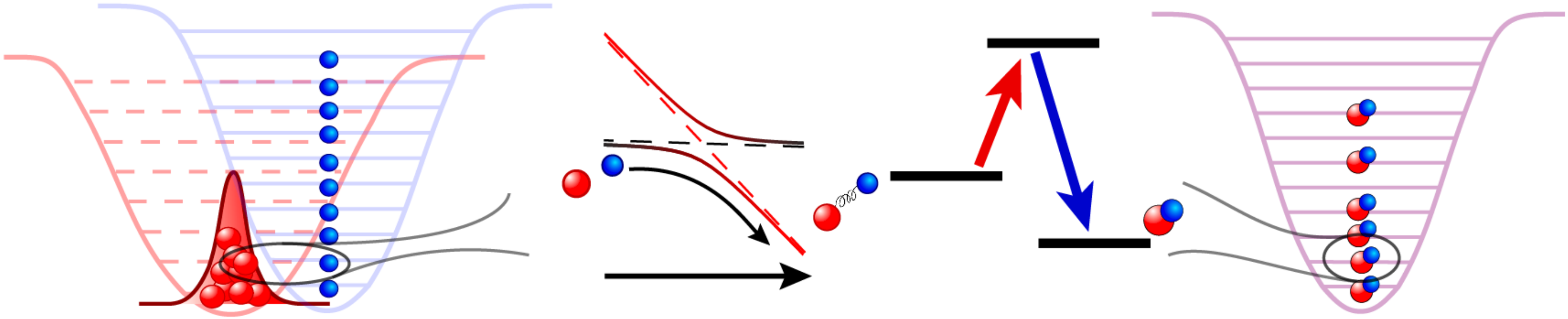






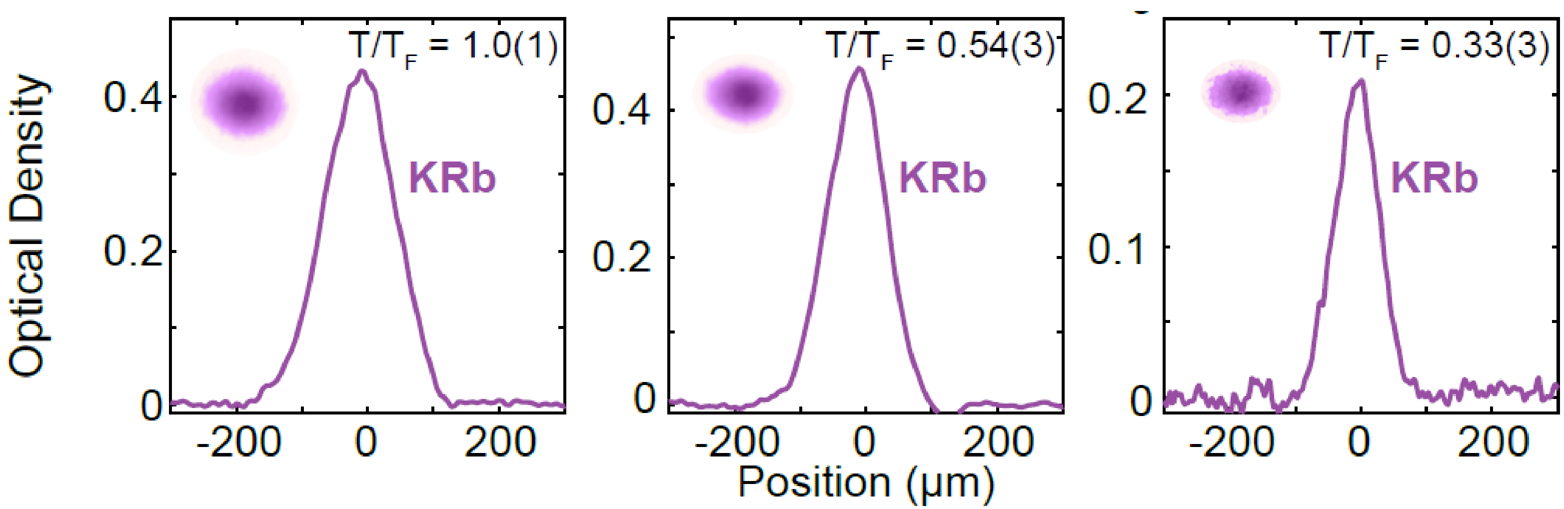
Making a degenerate Fermi gas of molecules

De Marco *et al.*, Science **363**, 853 (2019).

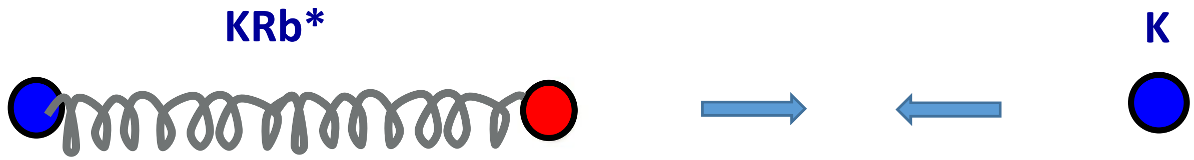


Key advance: make molecules with both Rb & K deeply dengerate

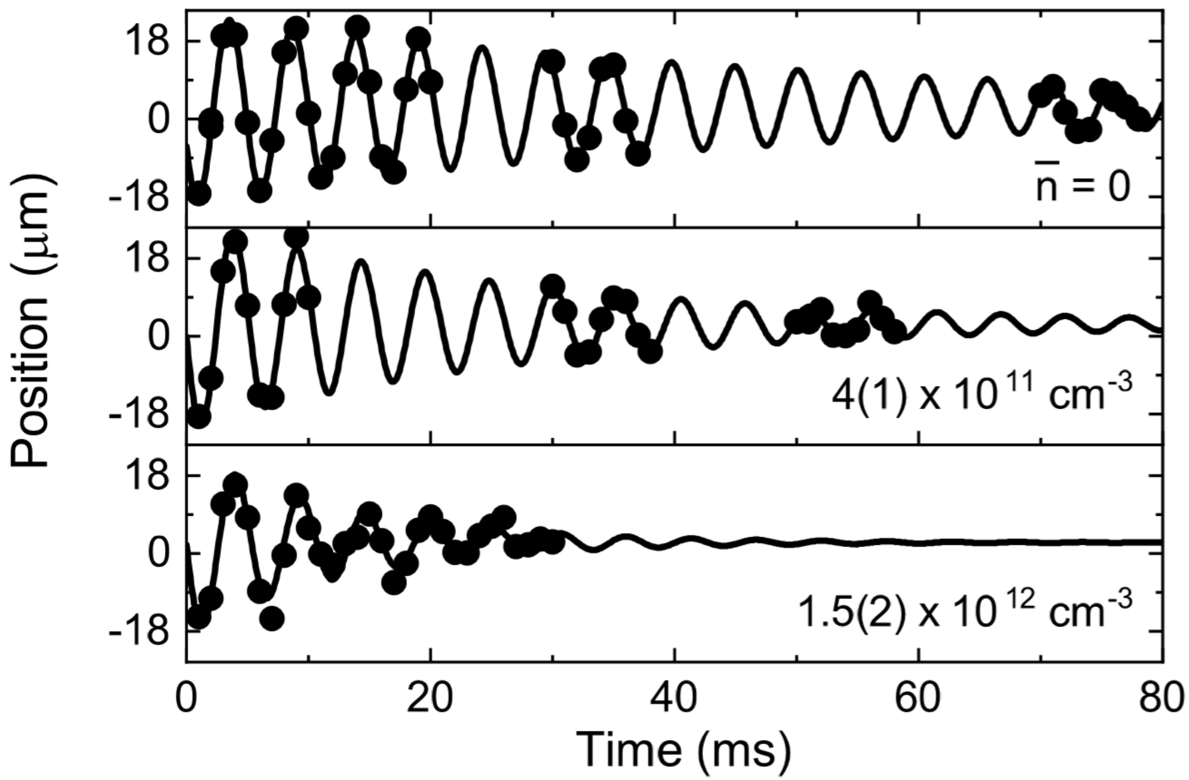
- Lowest $T/T_F = 0.33$
- 3×10^4 molecules



Atom - Molecule thermalization



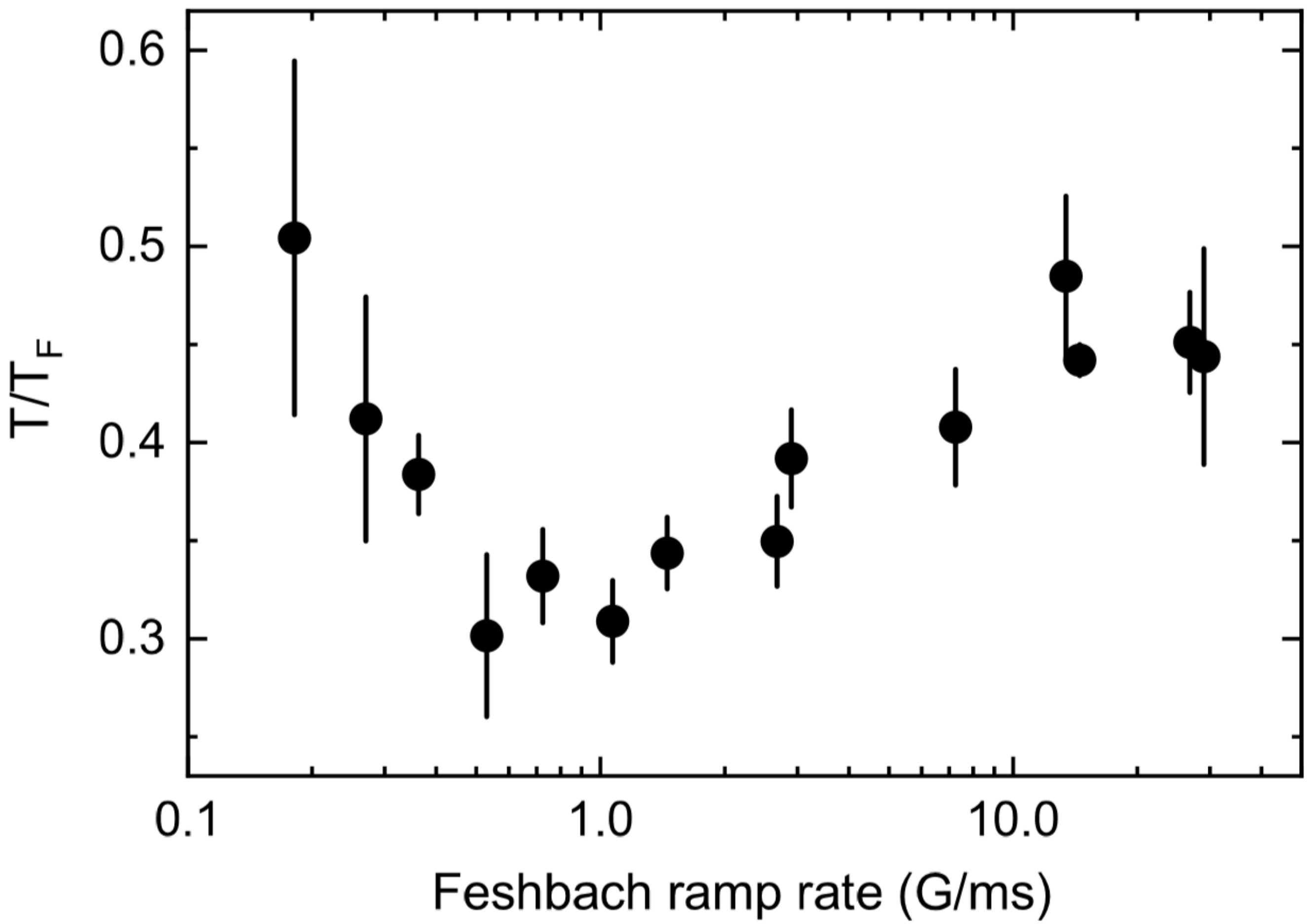
- Produce KRb*, remove remaining Rb
- Excite center of mass oscillation of KRb* but not K
- Scattering length of K + KRb* follows K + Rb



Increase K density n

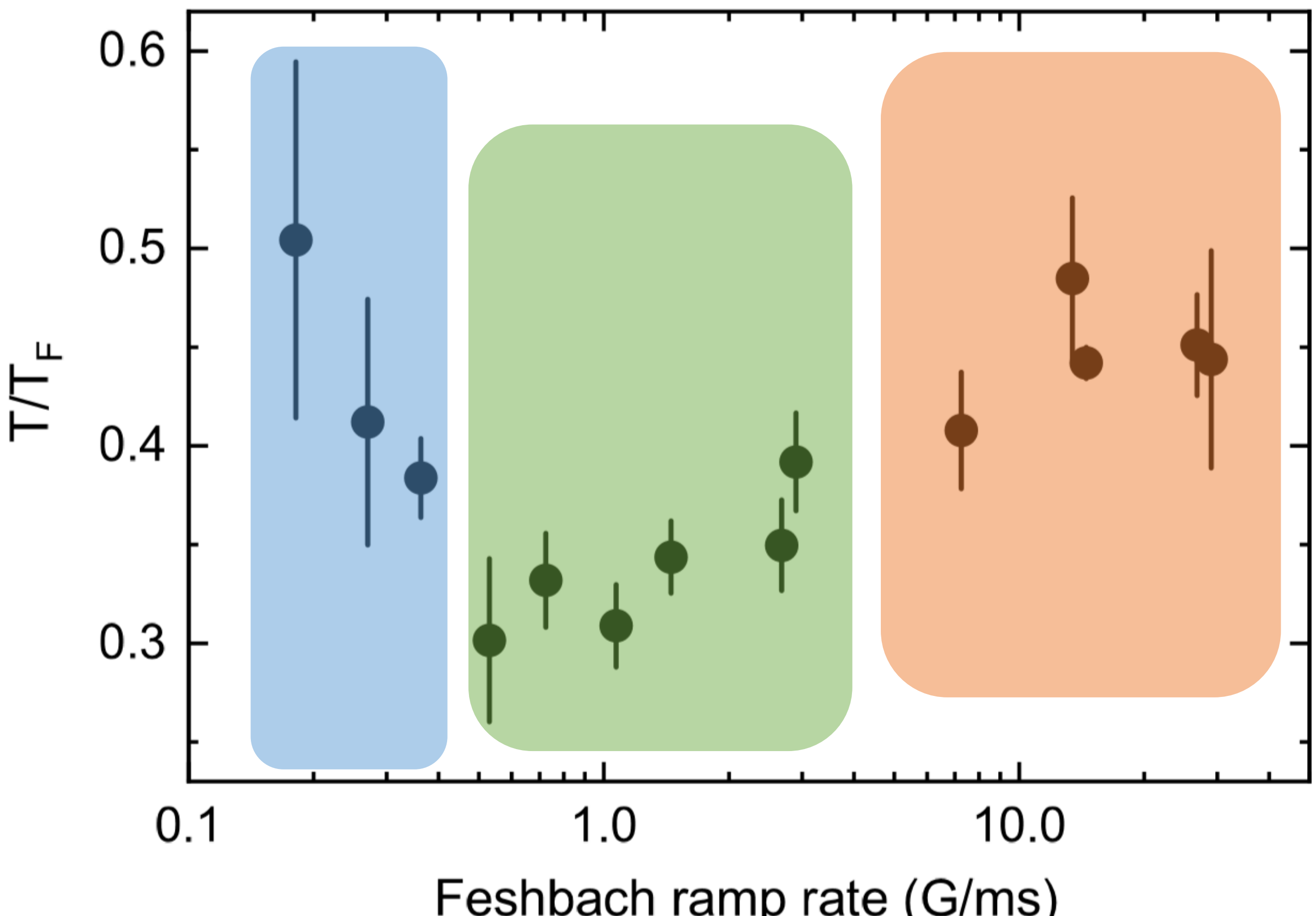
Feshbach Ramp Equilibration

- ~6 elastic collisions during a typical 2 G/ms Feshbach ramp
- Varying Feshbach ramp rate also probes elastic vs inelastic processes



Feshbach Ramp Equilibration

- Slow ramps: dominated by inelastic loss near resonance
- Fast ramps: ramp faster than thermalization rate
- Intermediate speeds: T/T_F reaches a minimum of ~0.3



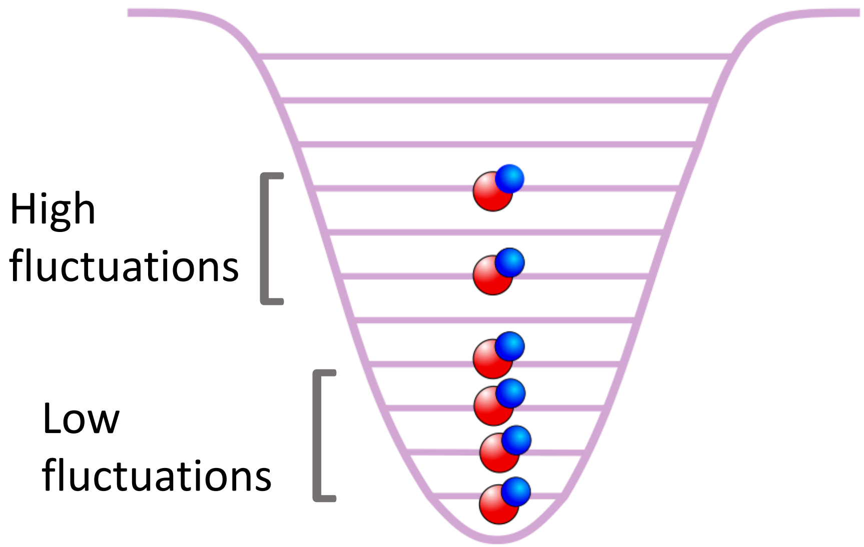
Fluctuation Suppression in Fermi Gases

- Measurement of particle number mean & variance in a subvolume of a Fermi gas
- Direct, local probe of state occupation
- Li degenerate gas (MIT, Zurich)

C. Sanner *et al.*, PRL **105**, 040402 (2010); T. Mueller *et al.*, PRL **105**, 040401 (2010).

Classical gas: $$\frac{\sigma_N^2}{\bar{N}} = 1$$

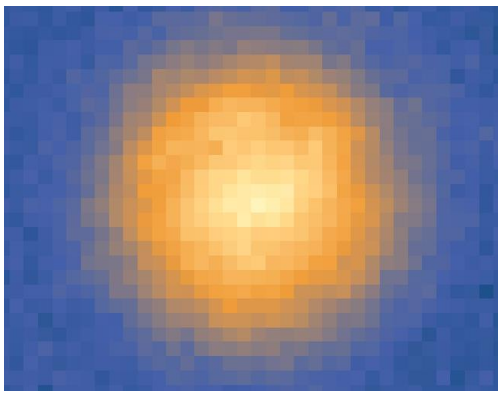
Degenerate gas: $$\frac{\sigma_N^2}{\bar{N}} \propto \frac{T}{T_{\mathrm{F}}} \quad (T \ll T_{\mathrm{F}})$$

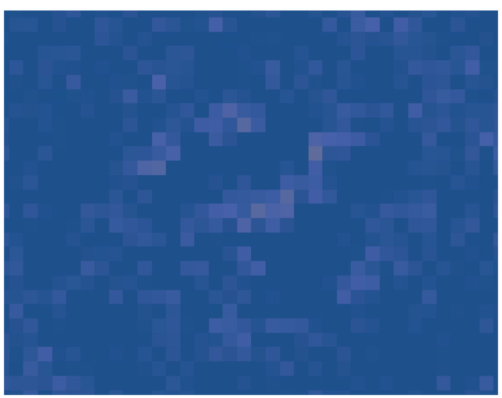


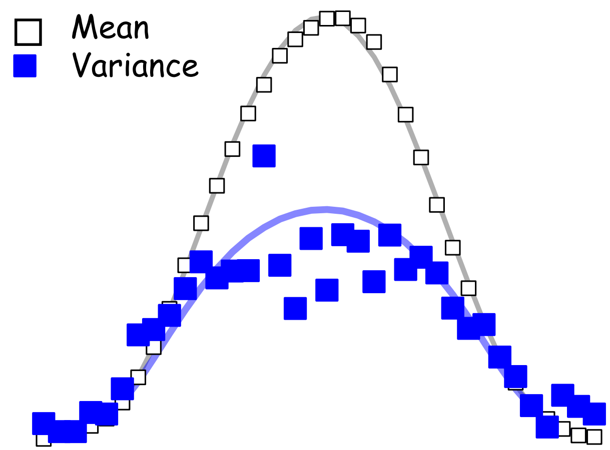
Fluctuation Suppression in Fermi Gases

W. Tobias *et al.*, Phys. Rev. Lett. **124**, 033401 (2020).

- Non-degenerate gas: mean = variance, over entire cloud
- Degenerate gas: increasing suppression of variance near the center







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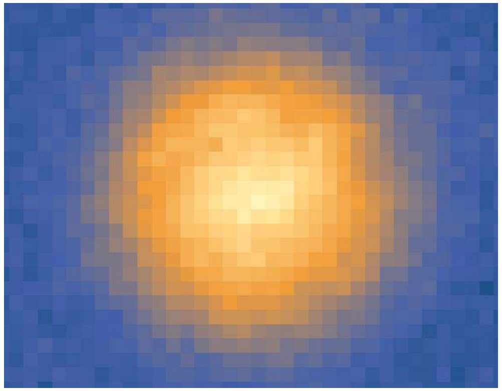
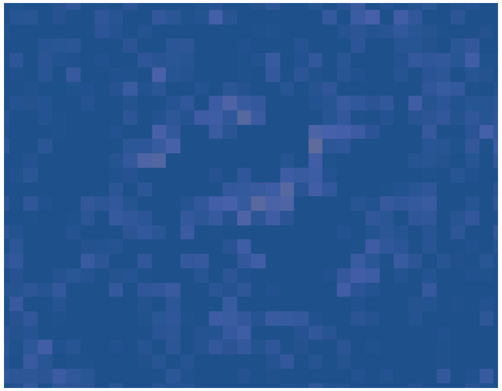
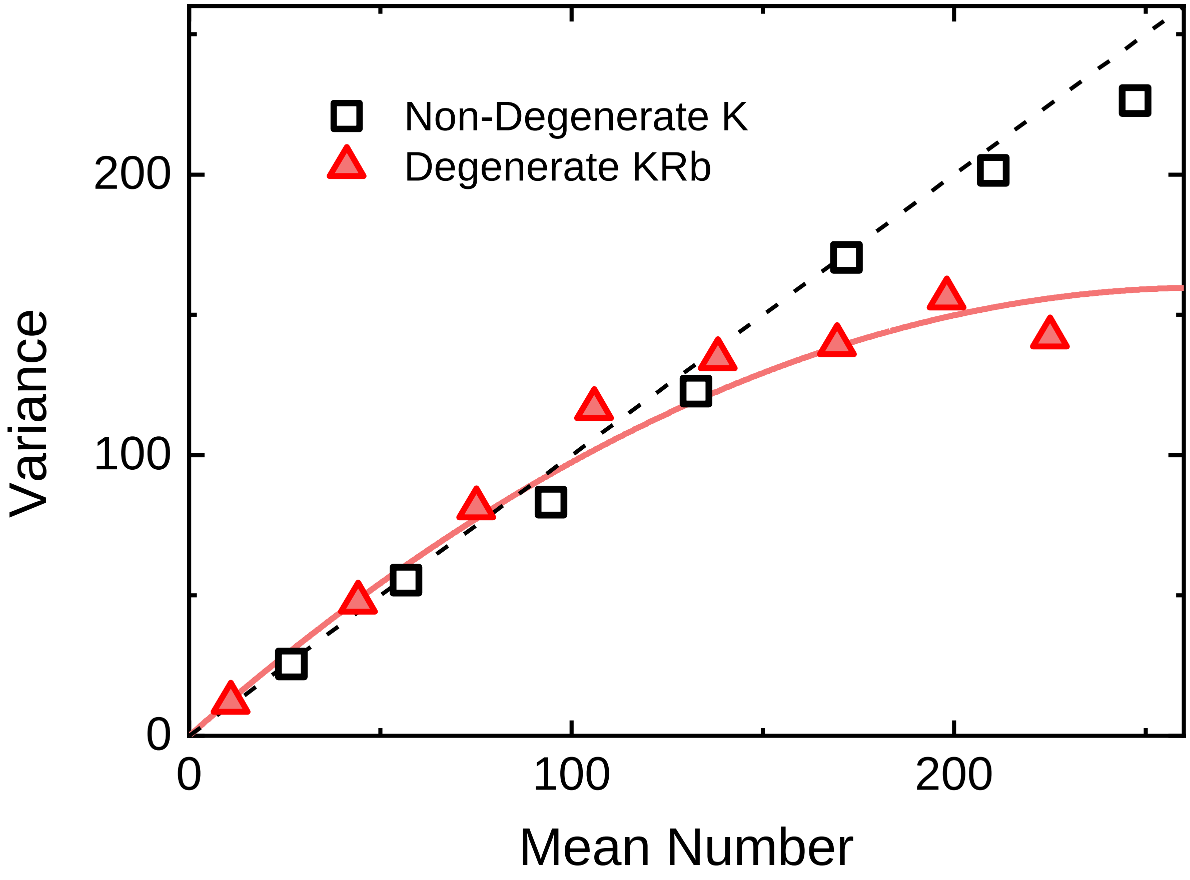


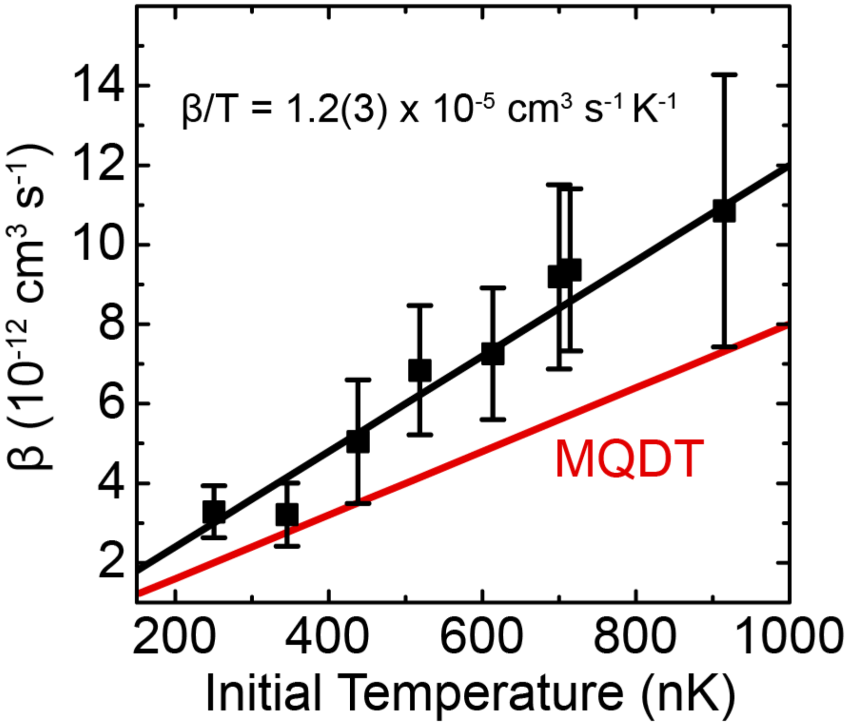




Chemistry near absolute zero

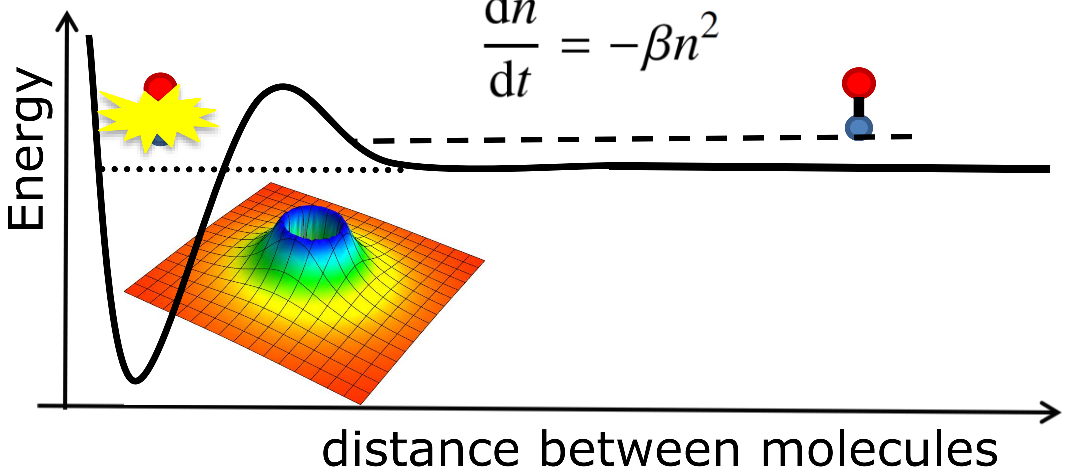
Ospelkaus *et al.*, Science **327**, 853 (2010).

Previous work: $T/T_F \sim 1.4$



β / T = constant

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -\beta n^2$$



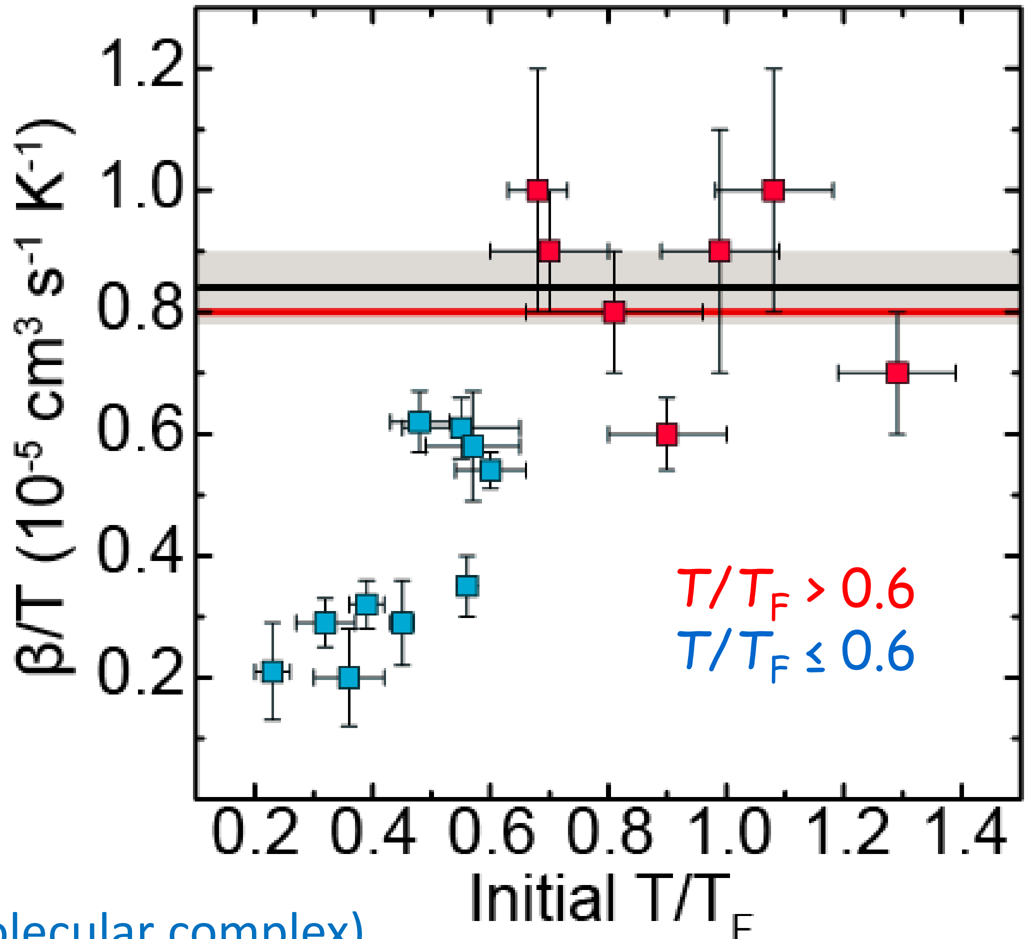
Ni group: Direct detection of K_2Rb_2 intermediate (2019).

Suppression of reaction in degeneracy

De Marco *et al.*, Science **363**, 853 (2019).

Chemical reaction in a degenerate Fermi gas

- For $T/T_F > 0.6$
  - $\beta/T = 0.84(6) \times 10^{-5}$ cm^3 s^{-1} K^{-1}
  - MQDT: $0.8(1) \times 10^{-5}$ cm^3 s^{-1} K^{-1}
- For $T/T_F \leq 0.6$
  - β/T decreases

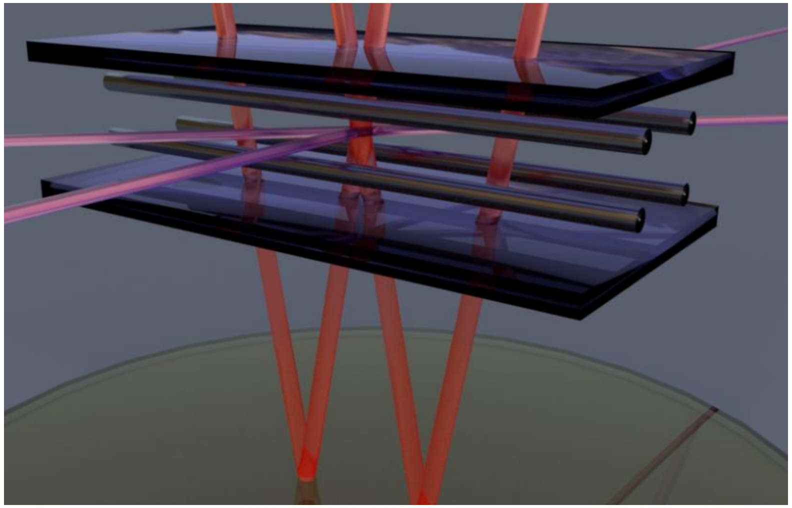


Qi Zhou group: *p*-wave contact

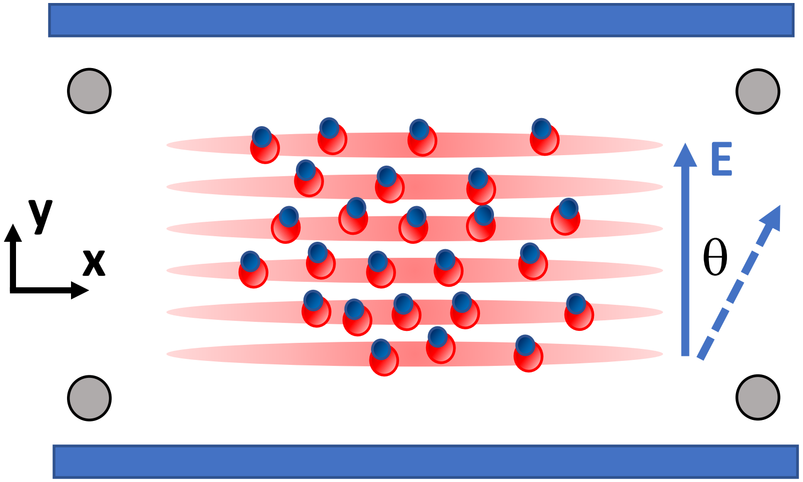
Ana Maria Rey group: Zeno effect (molecular complex)

Polar molecules need precise E-field control

Jacob Covey,
PhD thesis
JILA 2017



- E_{DC}: angle θ, 0 to 15 kV/cm,
- Gradient (x, y): 0 to 8 kV/cm^2; Curvature
- RF for rotational transition (~ 100 kHz Rabi)

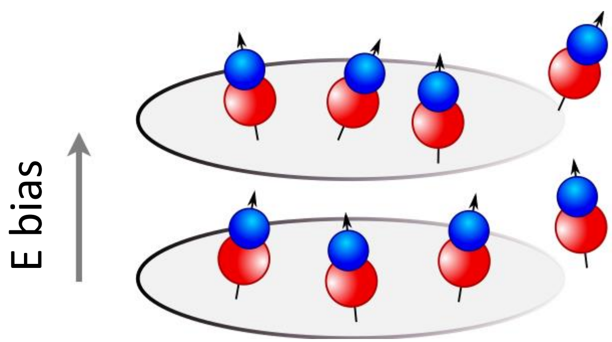


- E-field increases chemical reactivity in 3D
- Counteract this by confining molecules in 2D (repulsive interaction) --> increase ratio of elastic-to-inelastic collisions

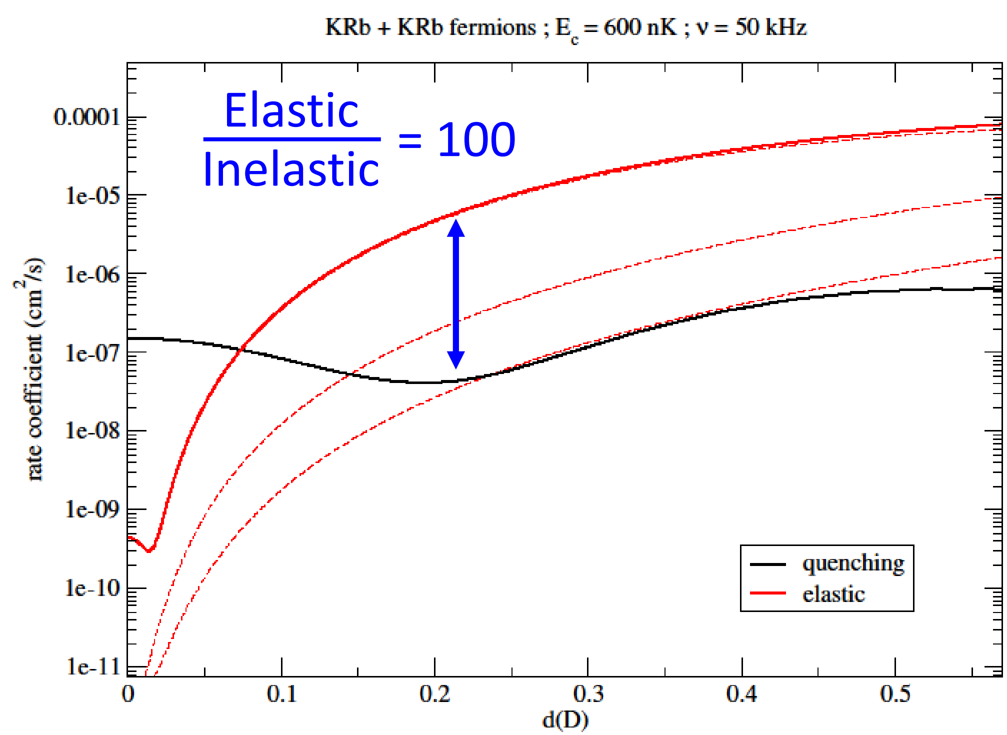
Dipolar physics in 2D

Büchler, Bohn, Demler, Julienne, Lewenstein, Santos, Shlyapnikov, Baranov/Zoller, …

- Suppressed chemical reaction
- Crossover from 3D regime to 2D
- Elastic vs. inelastic scattering of dipoles in 2D
- Dipolar evaporative cooling
- Collective modes (hydrodynamic regime, preliminary)

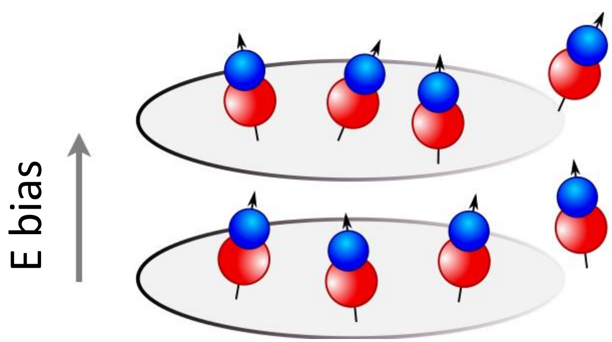


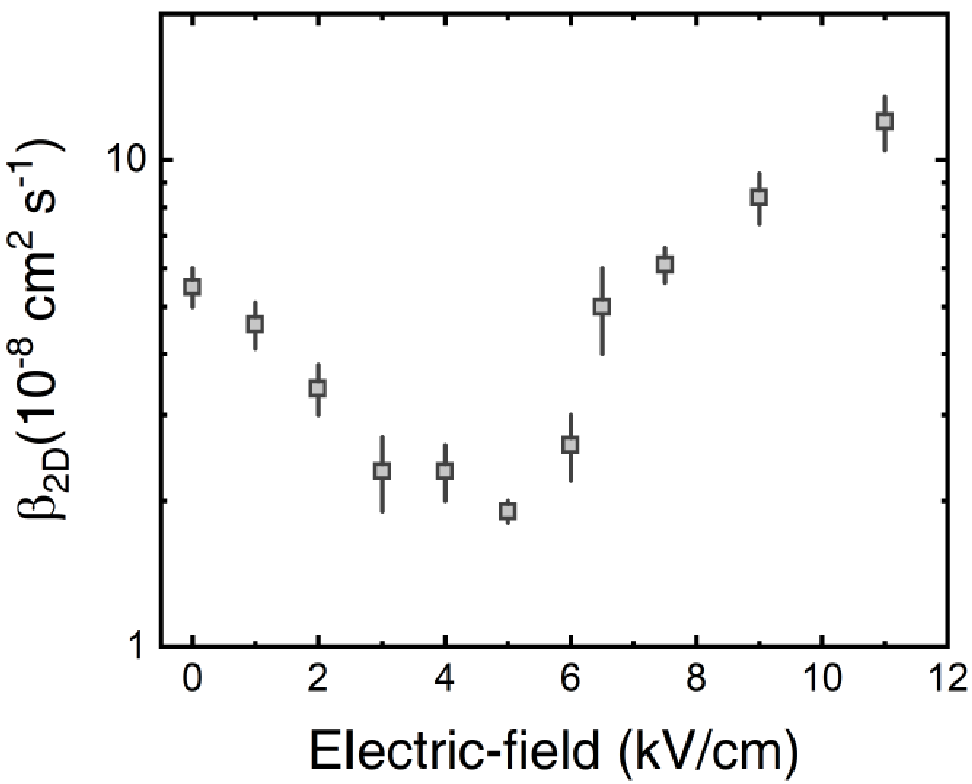
Quéméner & Bohn,
PRA **81**, 060701 (2010) ; **83**, 012705 (2011).



Suppression of inelastic loss in 2D

- For dipole moment of 0.2 D, elastic / inelastic ~100
- Suppression of chemical reaction
- Essential for study of interesting quantum phases





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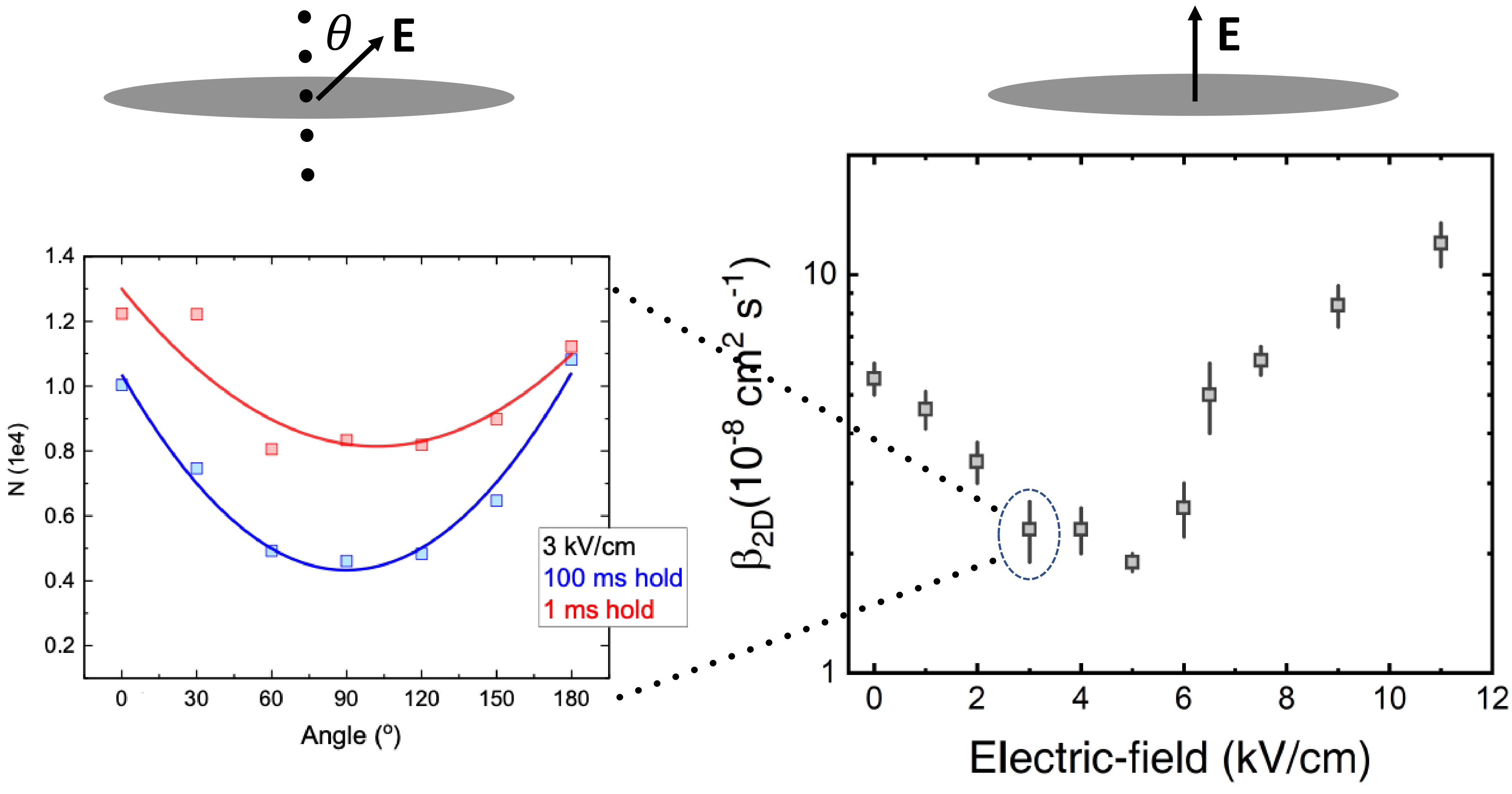
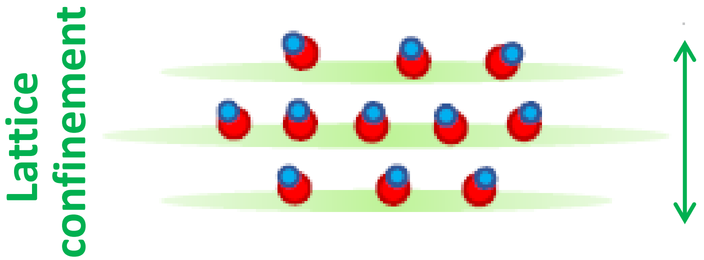
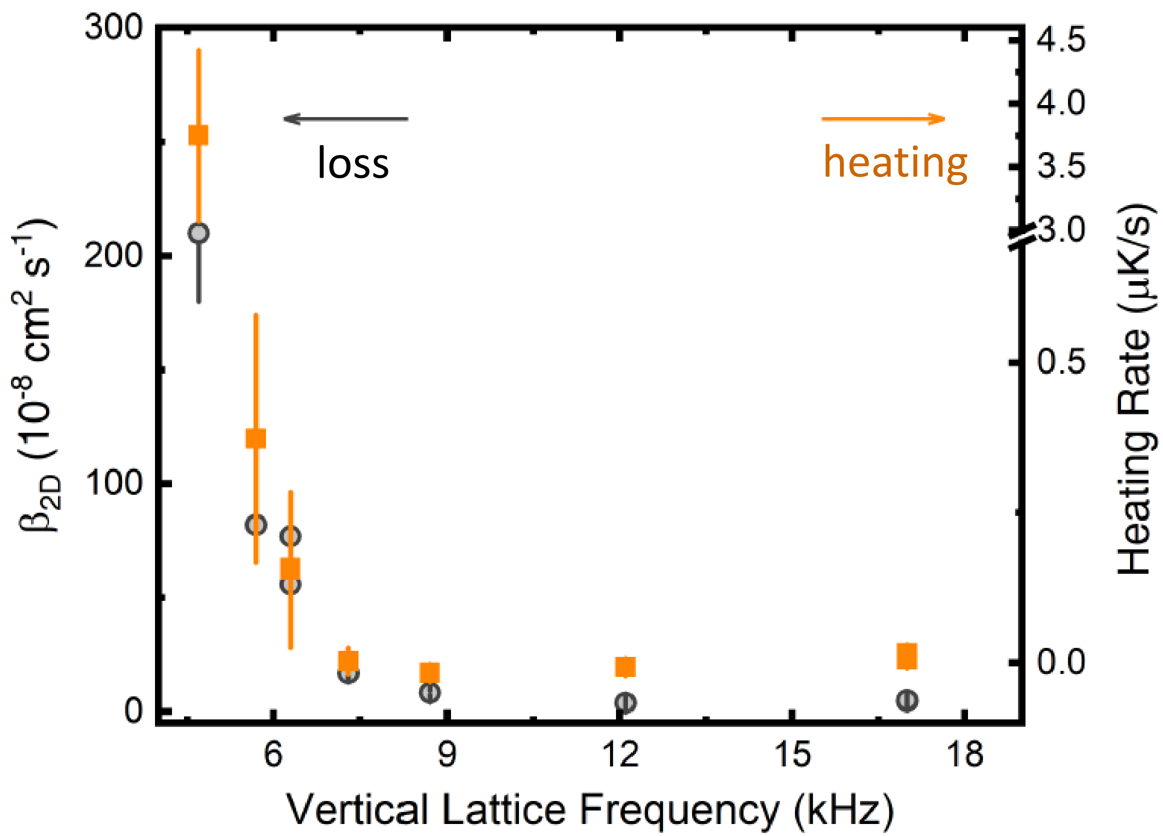


Crossover from 3D to 2D

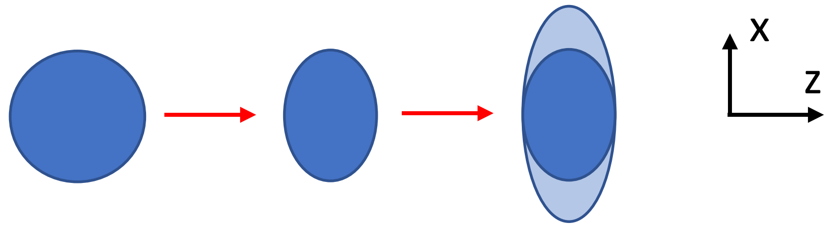
- Suppression of loss → suppression of anti-evaporation heating





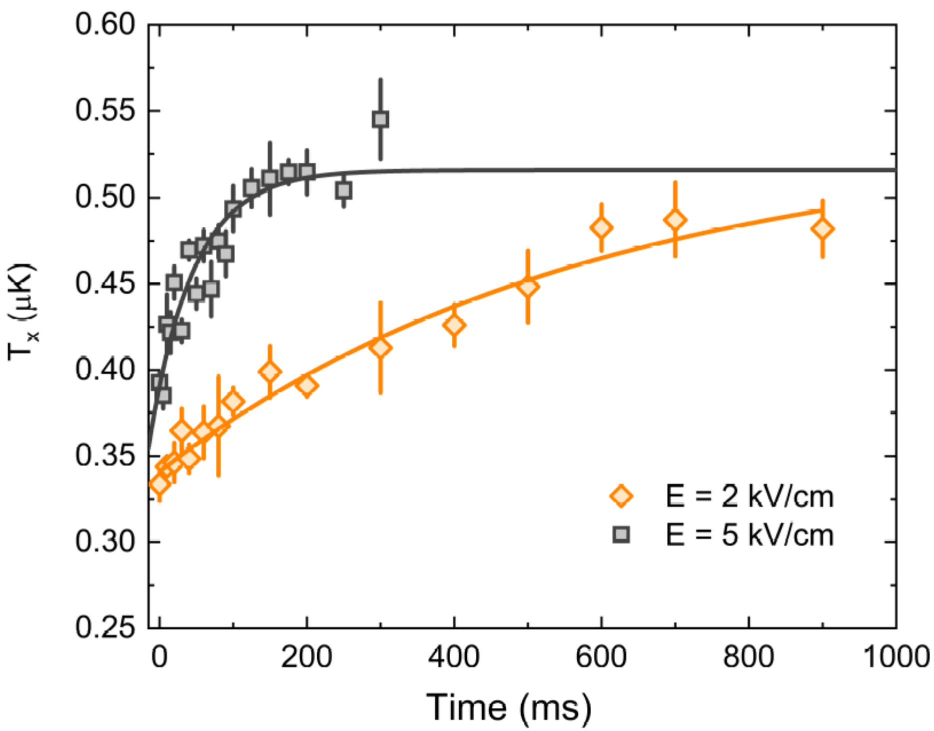
Dipolar thermalization

- Cross dimensional thermalization
- Determine dipolar collision cross-section

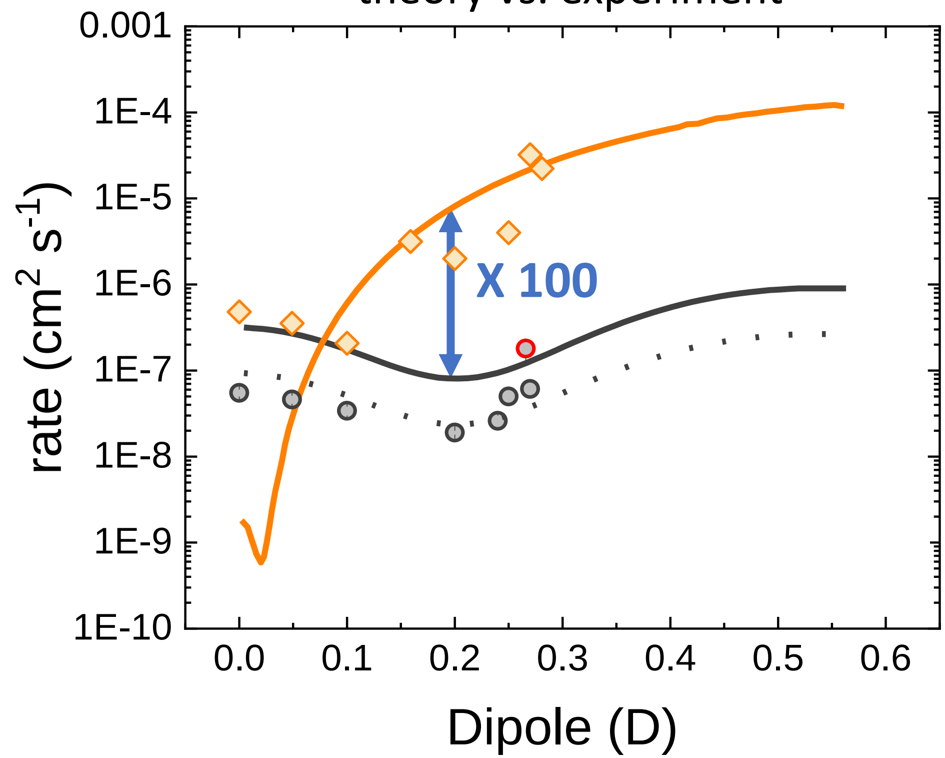


Squeeze along z

Increasing T_x along x ?



theory vs. experiment



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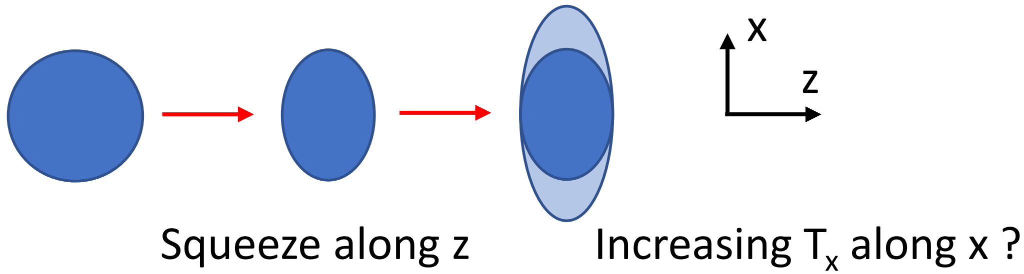
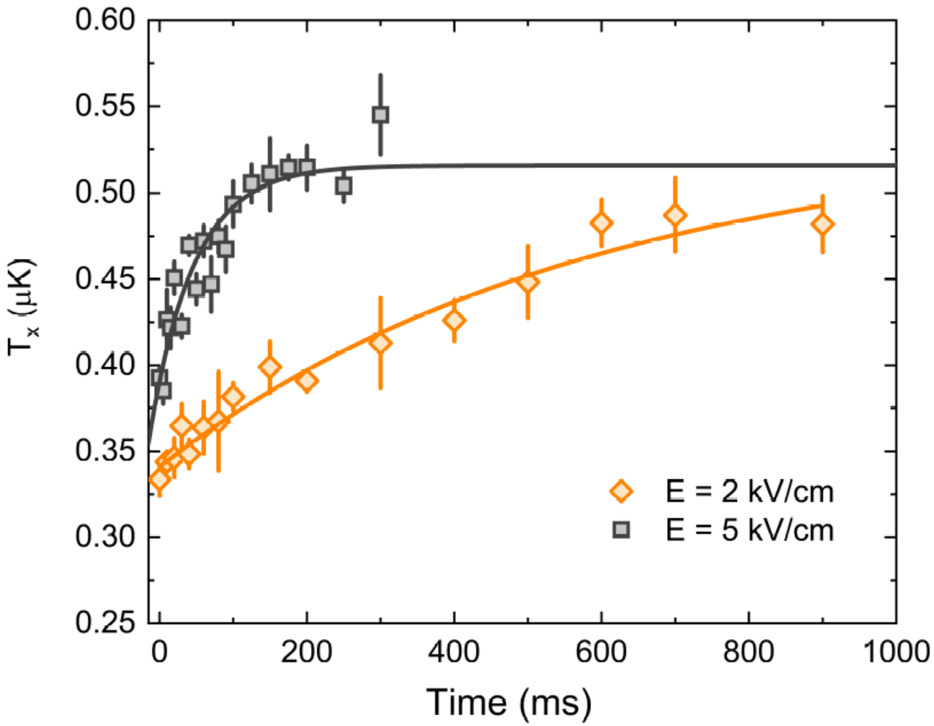
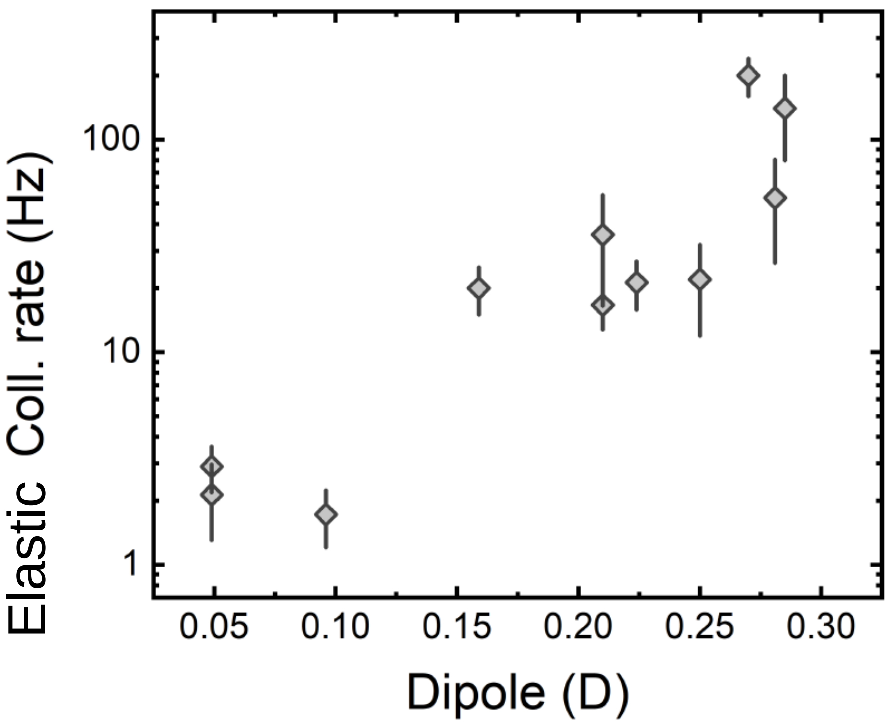
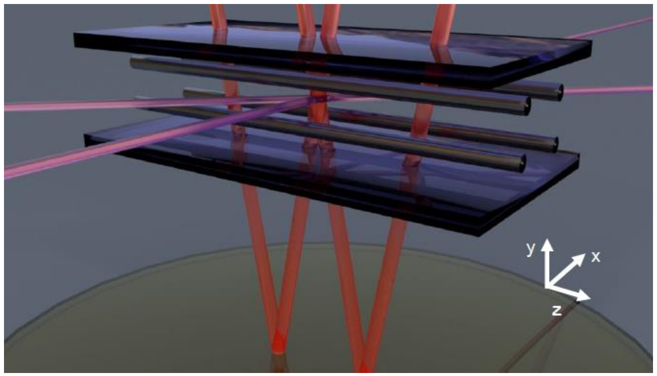


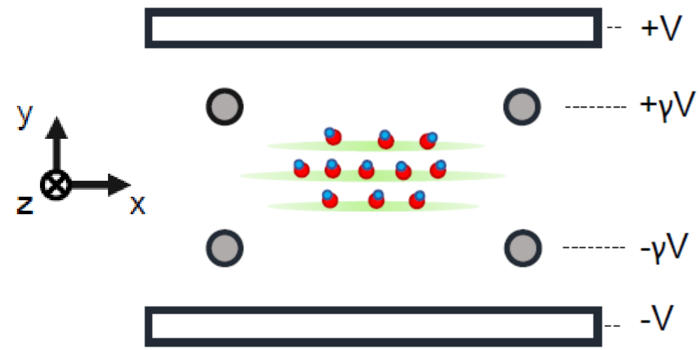


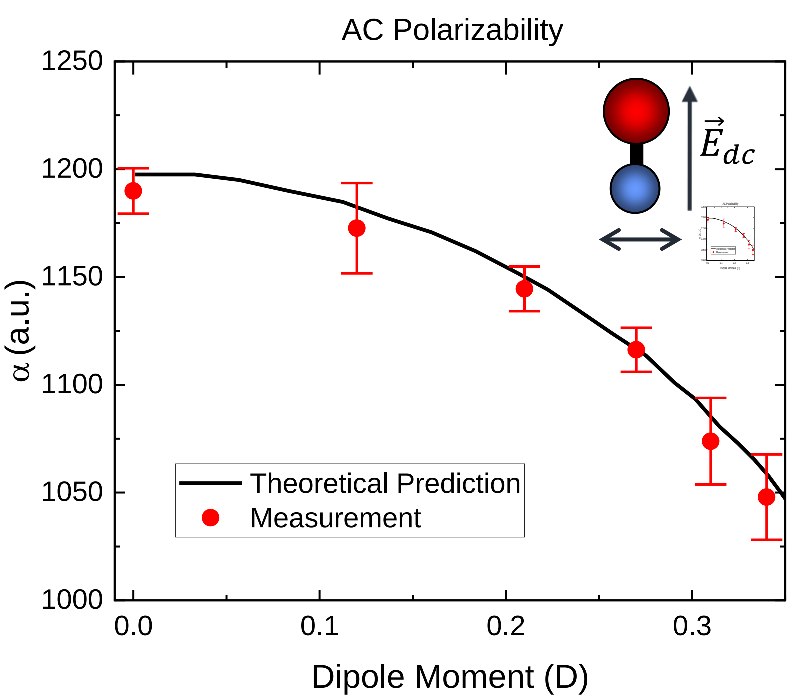


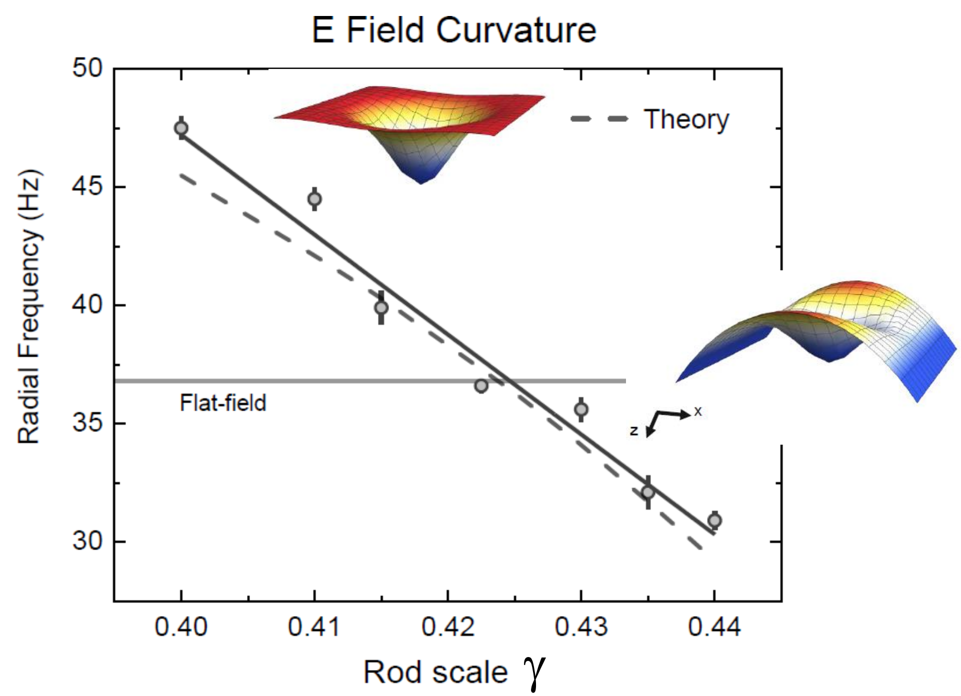
Dipole-assisted Evaporation

- Control of E-field and its gradient
- Favorable collisions, & precise tuning of trap potential



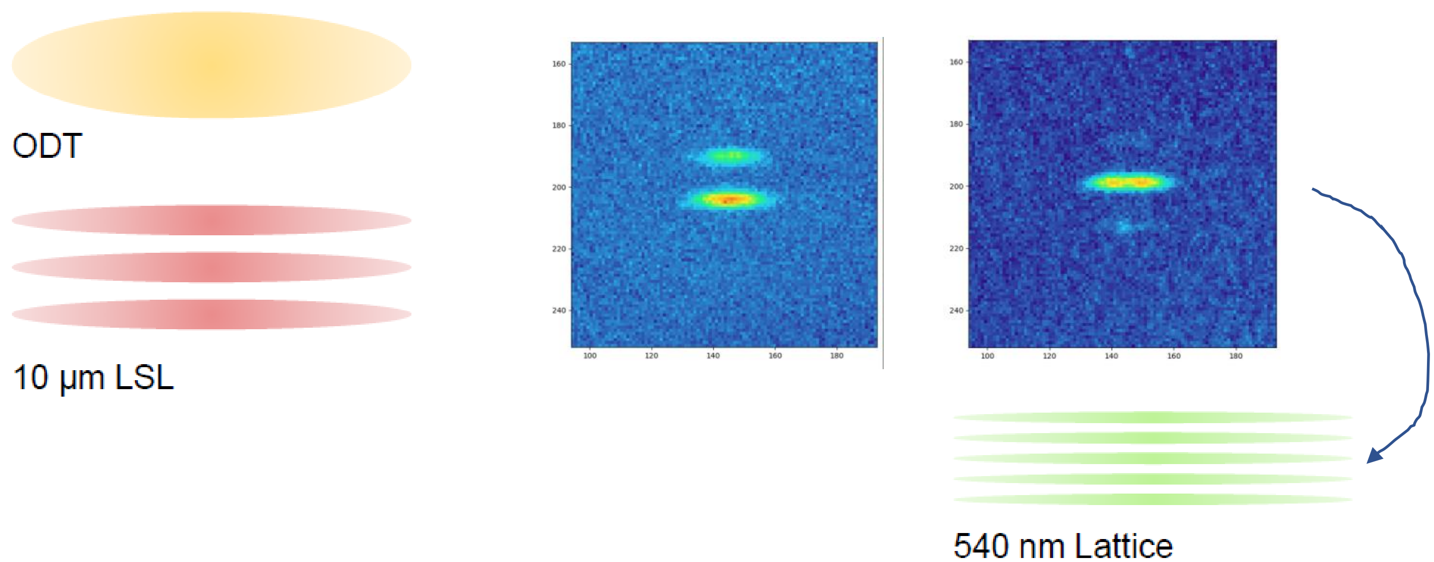




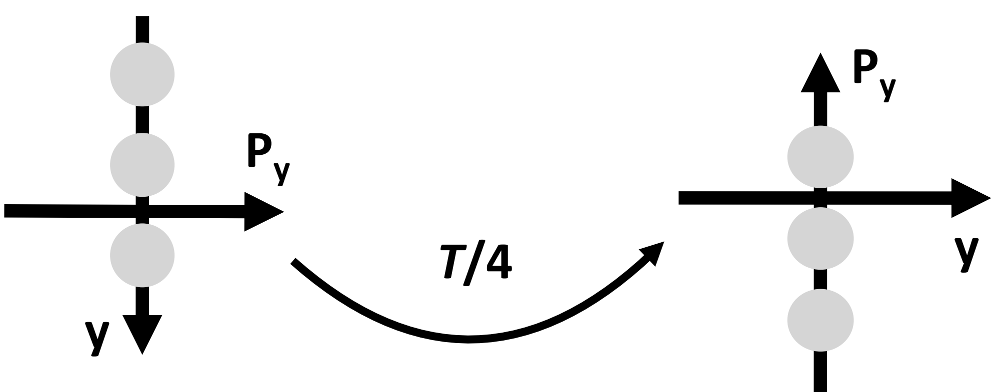


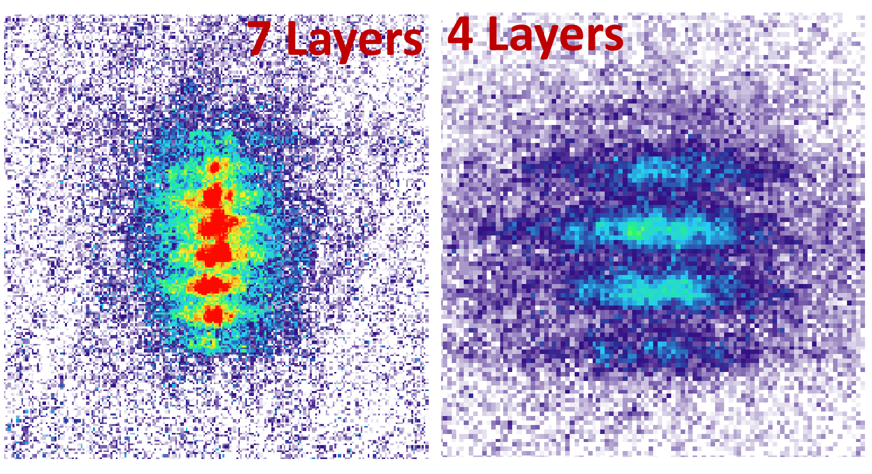
Dipole-assisted Evaporation

- Control and imaging of lattice layers
- Combine a large-spacing lattice and a science lattice



Refocus to image 540 nm layers
inside a dipole trap (period *T*)

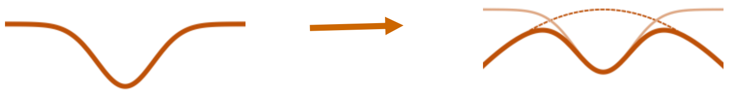




Dipole-assisted Evaporation

- Evaporation sequence

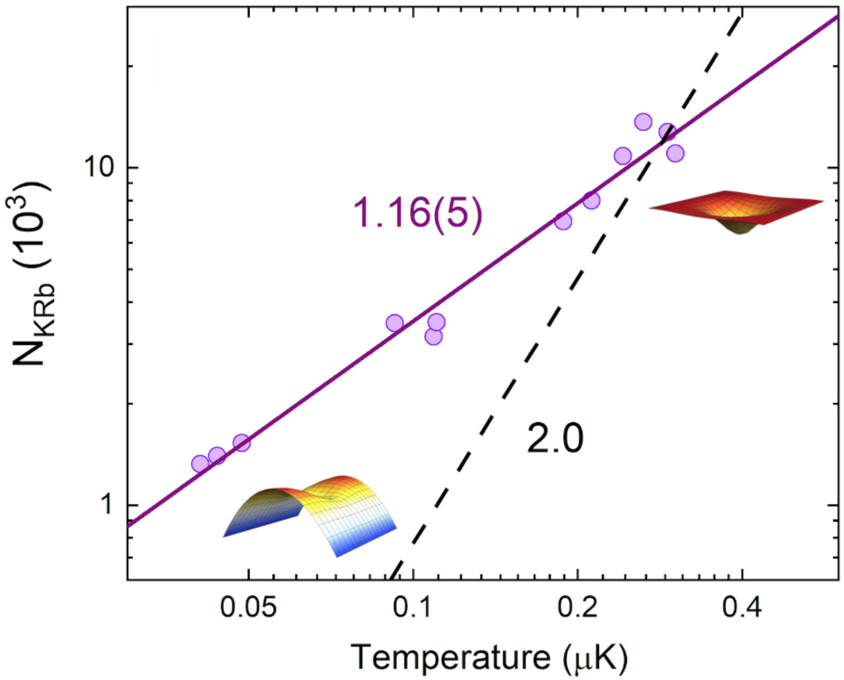
- Create 2D molecules
- Ramp to a target E field (100 ms)
- Increase anti-curvature/ decrease trap depth over a timescale of 500 ms



- Remove anti-trapping and turn off E (200 ms)
- Image molecules

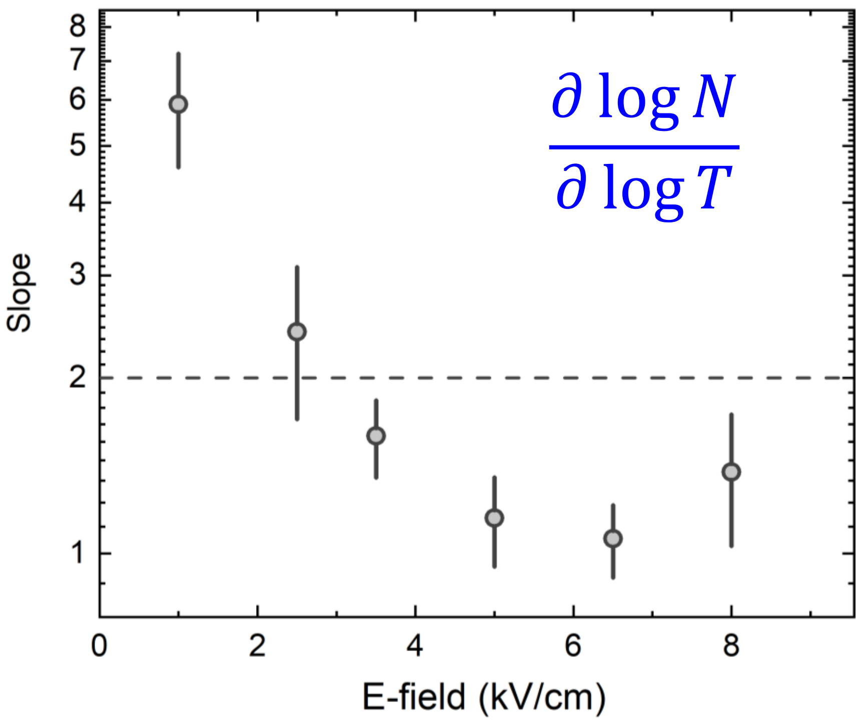
- Criterion for good evaporation:

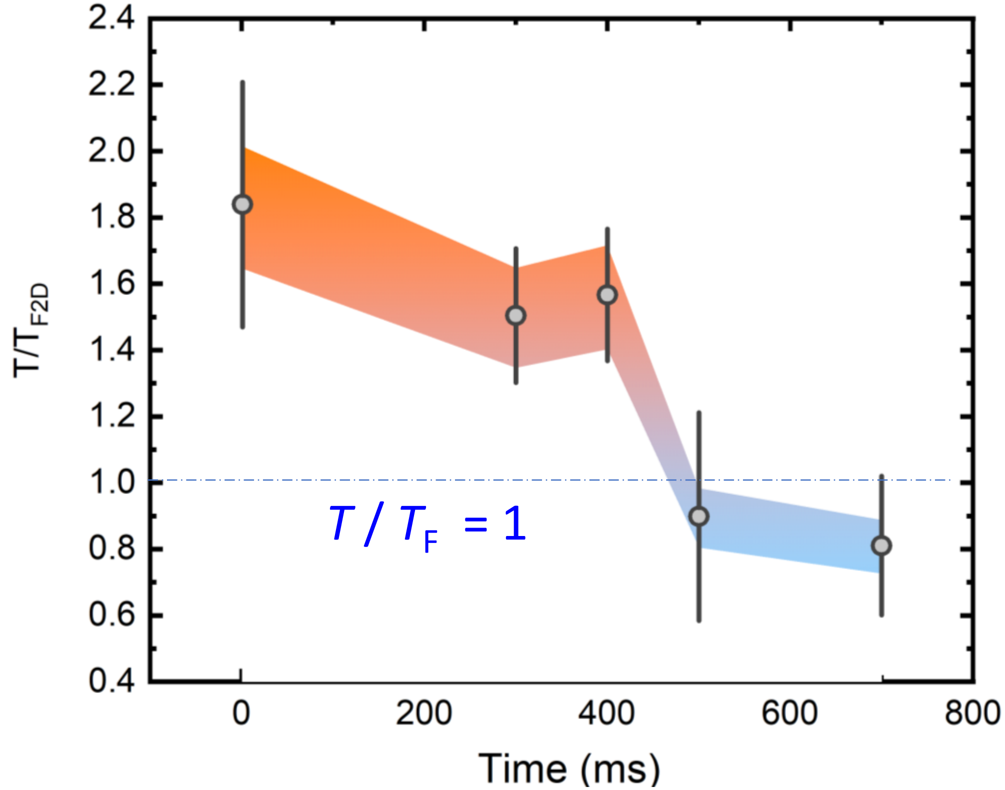
$$\frac{\partial \log N}{\partial \log T} < D = 2$$



Dipole-assisted Evaporation

- Evaporation summary

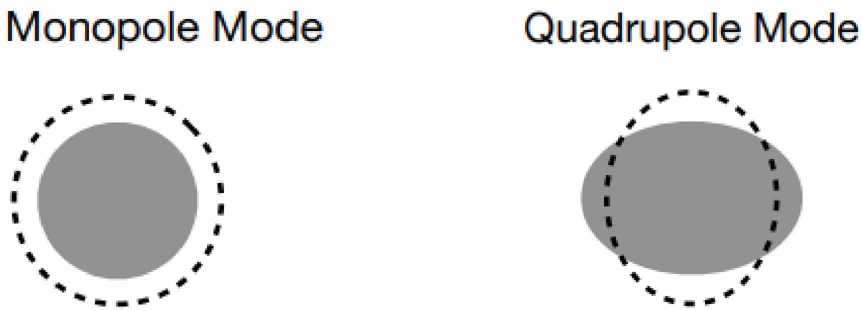


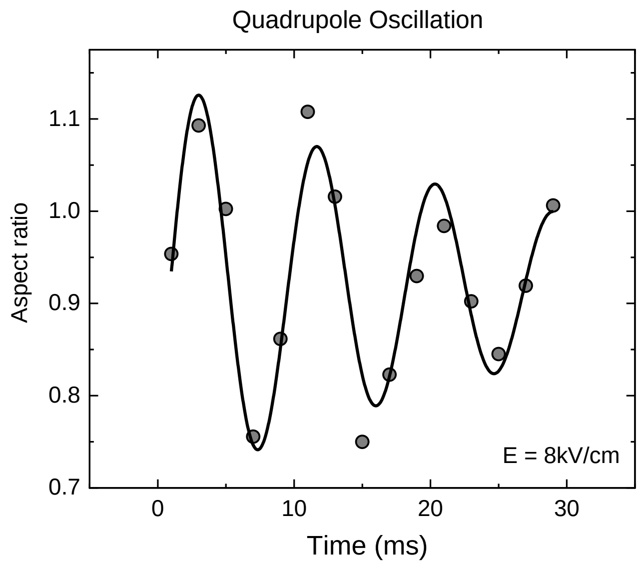


Collisionless to hydrodynamic transition

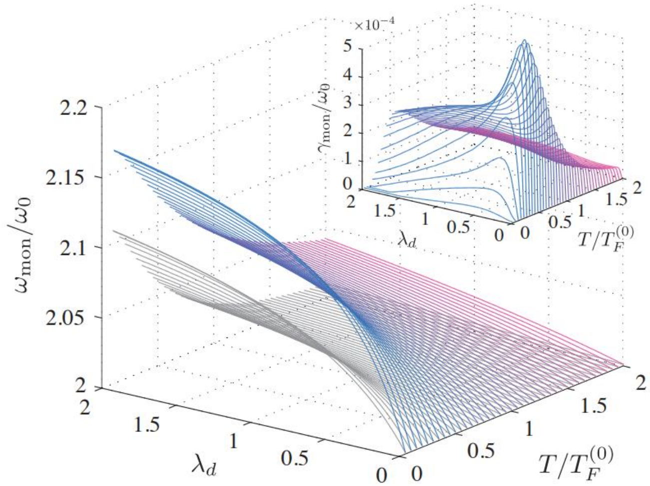
Dynamics of 2D Dipolar Gases Babadi & Demler, PRA 86, 063638 (2012).

- Strong dipole-dipole interactions give rise to collective behavior.
- System behaves *collectively* when interaction is comparable to kinetic energy (*hydrodynamic*)
- The two regimes are distinguished by frequency and damping rate of the fundamental excitations.



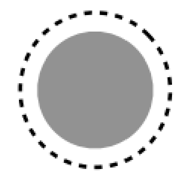


Collisionless to hydrodynamic transition

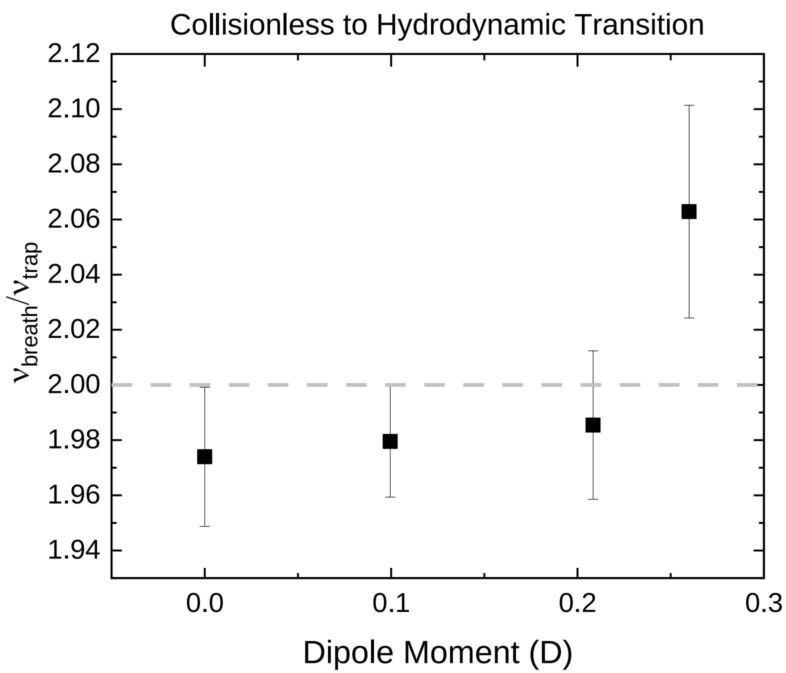


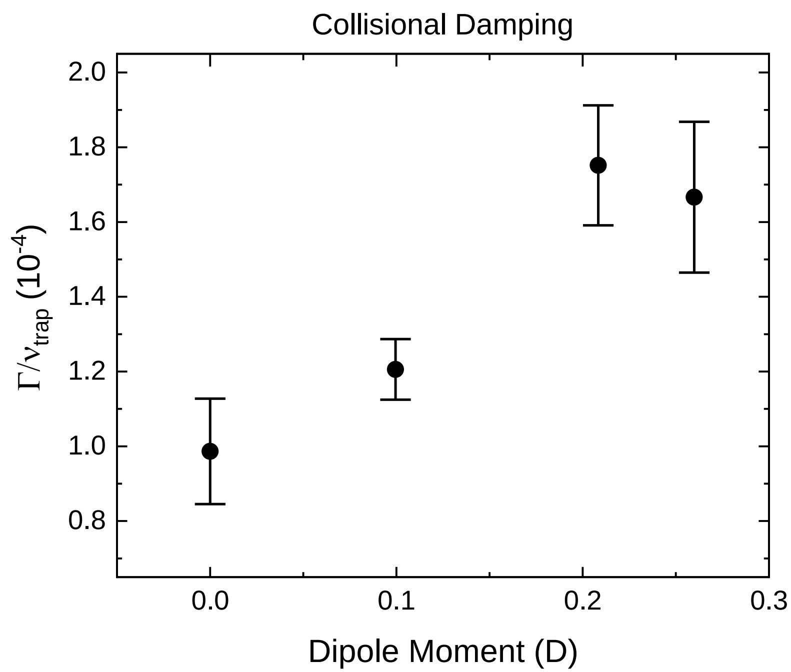
Babadi & Demler, PRA 86, 063638 (2012).

Monopole Mode



Increased oscillation frequency & faster damping





Preliminary

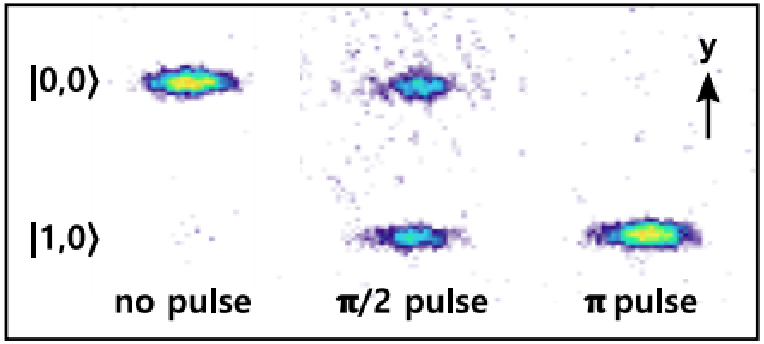
Strongly-interacting dipolar molecular gas in 2D

- Suppressed chemical reactions (dipolar strength, angle dependences)
- Tunable, dominant Elastic Collisions
- Dipole-assisted evaporative cooling
- Collective excitation regimes (Preliminary)

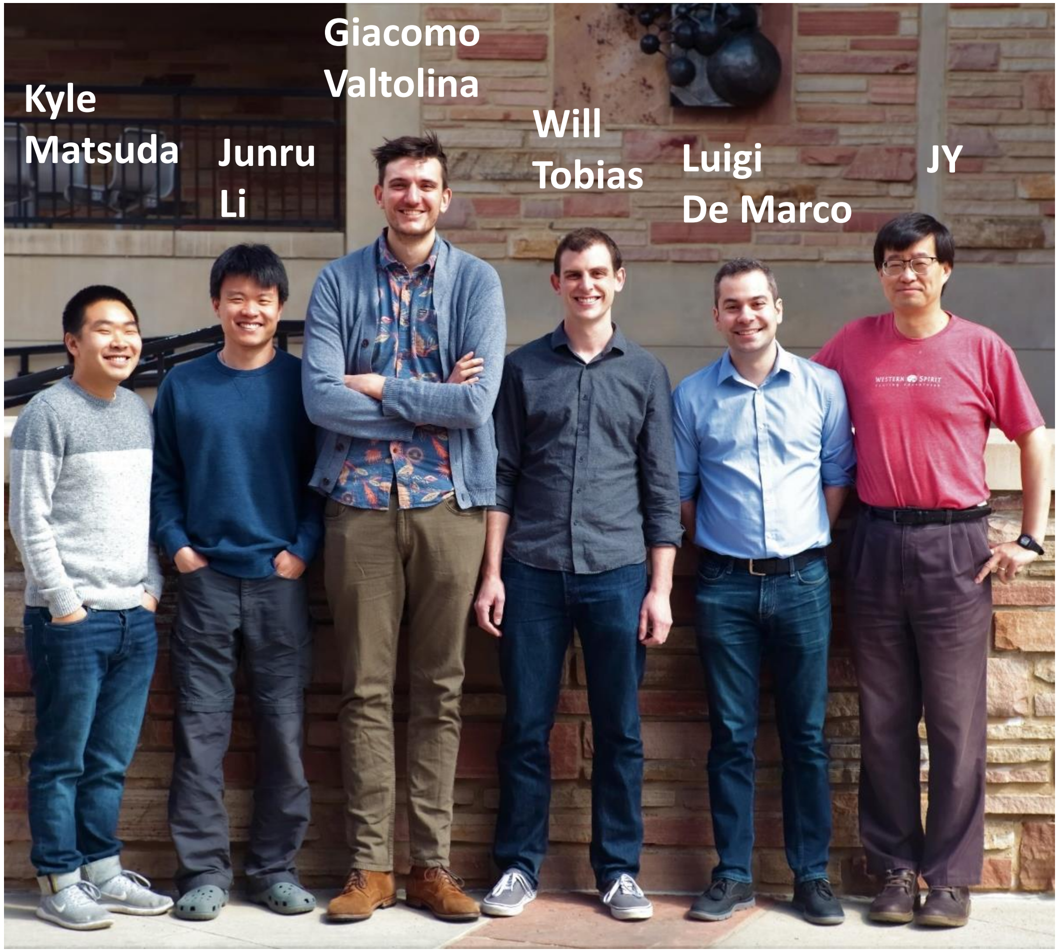
- $T \sim 250$ nK
- $n \sim 1 \times 10^8$ cm^{-2}
- $k_B T / \hbar\omega_\perp \sim 0.25$
- $d \sim 0.3$ Debye
- tunable θ
- $T/T_F \sim 1$

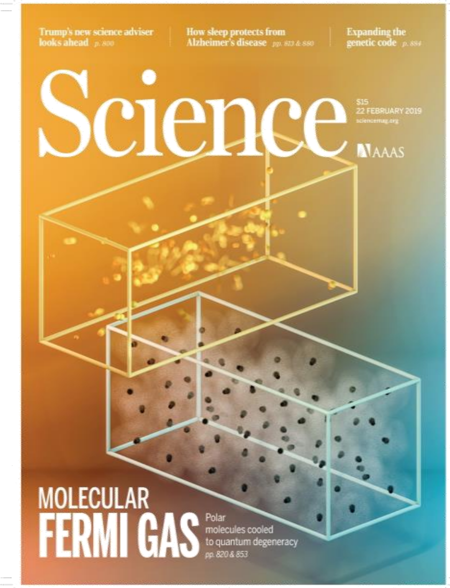
Technical Developments

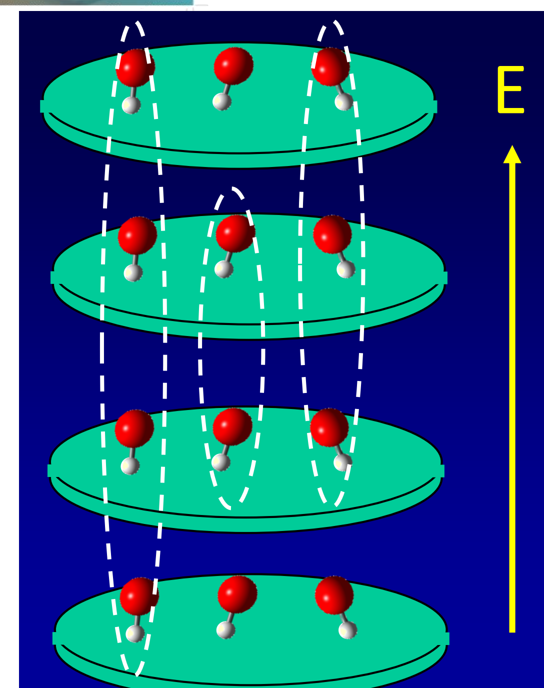
- High density dipolar molecules
- Versatile E-field control, static, dynamic, gradients.
- Stern-Gerlach



Acknowledgement







<u>Theory Collaborations</u>

John Bohn	Paul Julienne
Eugene Demler	Ana Maria Rey
Jose D'Incao	Peter Zoller