# Towards Fermionic Ground State Molecules with Strong Dipolar Interactions


Jennifer Schloss, Jee Woo Park, Qingyang Wang, Sebastian Will, and Martin Zwierlein

Massachusetts Institute of Technology, Room 26-268, 77 Massachusetts Avenue, Cambridge, MA 02139


## Motivation

Using ultracold atoms, atomic physicists study matter at temperatures where **quantum statistics dominates** and Bose-Einstein condensates or fermionic superfluids form.

More complex than atoms, **molecules** have more internal degrees of freedom and can have long-range electric dipole interactions. **Bringing molecules into the ultracold regime** opens many new opportunities for observing and controlling physics that is unachievable with atoms.

Owing to their **complex internal states**, molecules cannot be made ultracold using standard atom cooling techniques. To create a quantum degenerate gas of molecules, we cool atoms and then bind them into molecules using the powerful tools of **Feshbach resonances** and **coherent two-photon population transfer**.

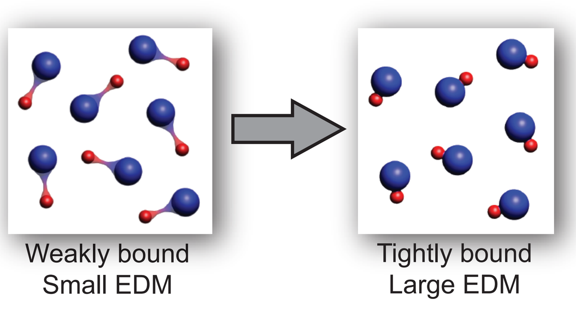
Our group is preparing the first ever **chemically stable Fermi gas of dipolar molecules in their absolute ground state**. Using these molecules, we aim to explore exciting new physics including **novel phases of matter** as well as **quantum simulation, quantum information, and quantum chemistry**.

## NaK molecules

### Why $^{23}Na^{40}K$?

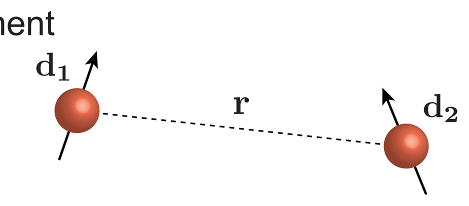
- Strong interaction between $^{23}Na$ and $^{40}K$ makes it possible to form molecules
- Fermions: subject to Pauli exclusion principle, Fermi statistics
- Promising new form of quantum matter!

### Why ground-state $^{23}Na^{40}K$?




- Chemically stable
  NaK + NaK ↛ $Na_2$ + $K_2$
  Long lifetime in trap!
- Large electric dipole moment
  2.72 Debye (5x larger than KRb)
- Ground state = larger dipole moment

Long-range, anisotropic, dipolar interactions dominate many-body physics!

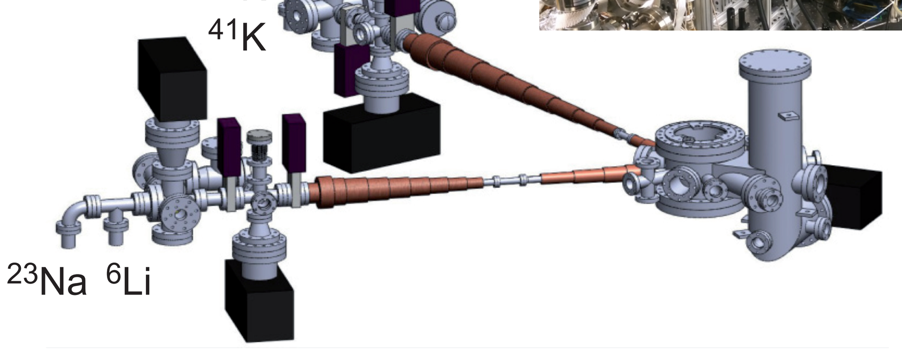



$$V_{dd} = \frac{1}{4\pi\epsilon_0}\frac{\mathbf{d}_1\cdot\mathbf{d}_2 - 3(\mathbf{d}_1\cdot\hat{\mathbf{r}})(\mathbf{d}_2\cdot\hat{\mathbf{r}})}{r^3}$$

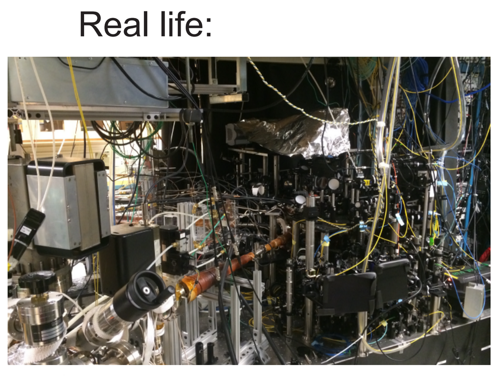
## The LiNaK apparatus

- Multi-species atom cooling and trapping
- Configured for $^6Li$, $^{23}Na$, $^{39}K$, $^{40}K$, and $^{41}K$
- Flexible apparatus allows study of Bose-Bose, Bose-Fermi, and Fermi-Fermi mixtures.

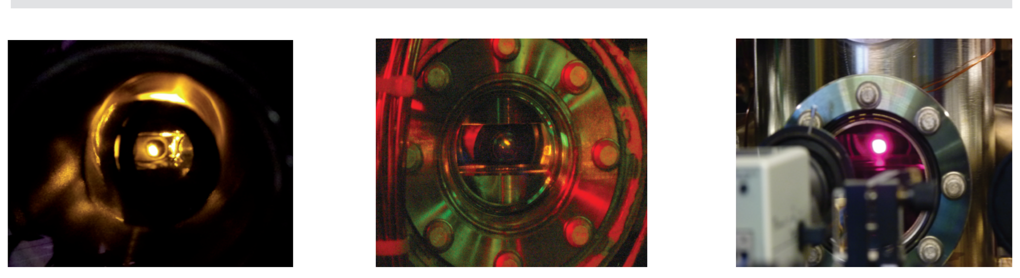
### Design




Real life:



### Multi-species laser cooling



$^{23}Na$ (589 nm) $^{40}K$ (767 nm) $^6Li$ (671 nm)

## Funding

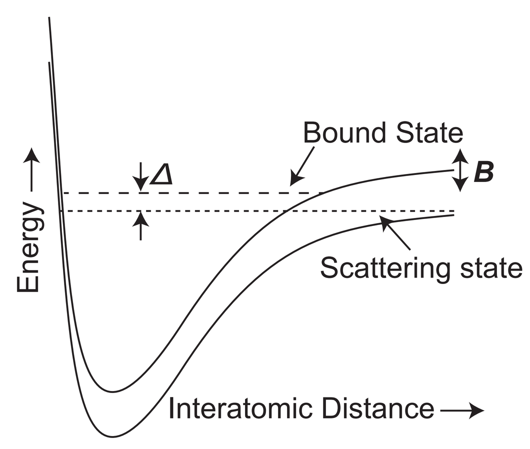

National Science Foundation (NSF), AFOSR - MURI, Alfred P. Sloan Foundation, DARPA - OLE, Hertz Foundation

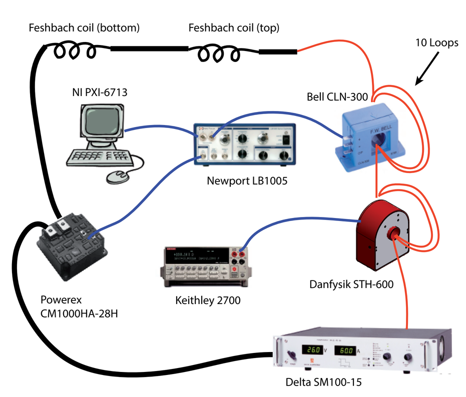

## Ultracold Feshbach molecules of NaK

see Wu et al., PRL 109, 085301 [arXiv:1206.5023 (2012)]

### Tune interaction strength between Na and K using a magnetic field

- Bring atoms into resonance with a weakly-bound "Feshbach molecule" state



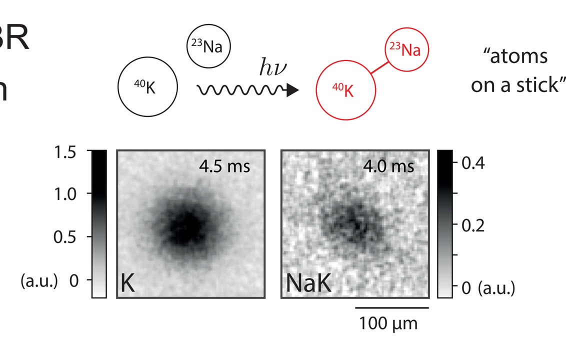



B-field stabilization schematic

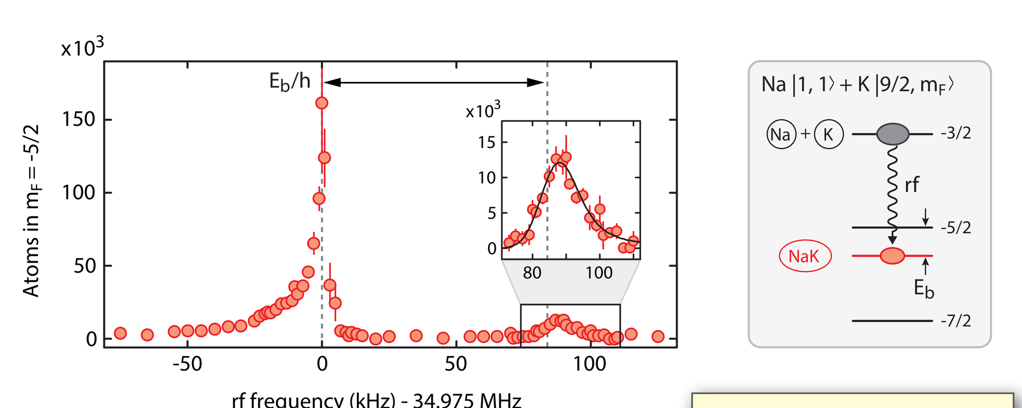
- Requires stable, variable applied magnetic field

### RF association of weakly bound fermionic Feshbach molecules

- RF association close to FBR at ~140 G and ~30 G width
- Direct imaging of loosely bound molecules at high magnetic field
- About 15% conversion efficiency of $^{40}K$



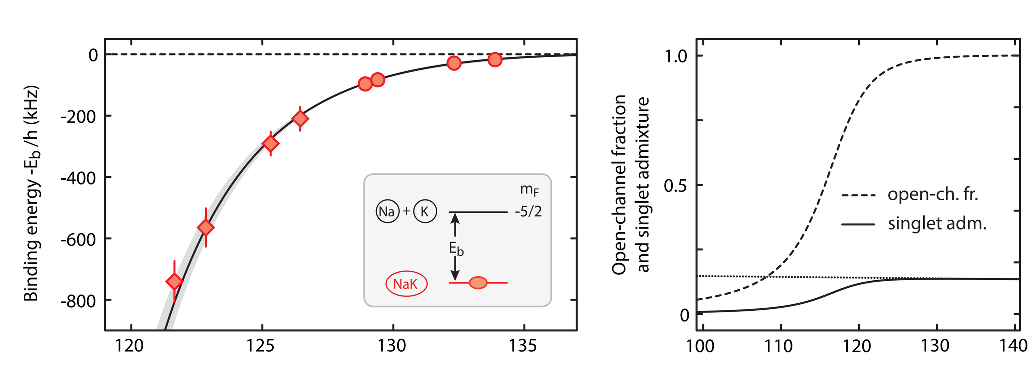

### Association spectrum (B = 129.4 G)




$E_b = h \times 84(6)$ kHz
$T = 260$ (40) nK

- Lineshape of molecule peak: $\Gamma_{\mathrm{mol}}(\nu) \propto \mathcal{F}(h\nu - E_b)p(h\nu - E_b)$
  with Franck-Condon factor: $\mathcal{F}(\epsilon) \propto (1+\epsilon/E_b)^{-2}$
  and probability density: $p(\epsilon) = \rho(\epsilon)\lambda_M^3 \exp\left(-\frac{\mu}{M}\frac{\epsilon}{k_B T}\right)$

### Binding energy $E_b$ versus magnetic field




$B_0$ = 139.7(2.1) G
$\Delta B$ = 29(2) G

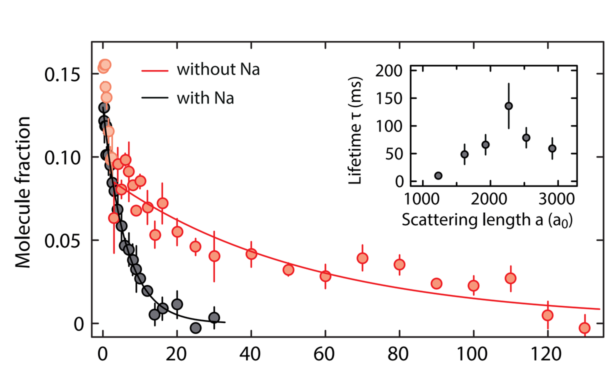
- Open-channel character over ~25 G
- Molecules have mixed singlet-triplet character

### Lifetime of fermionic Feshbach molecules

- Minimal loss rate:

$$\beta = \frac{1}{n_A \tau} = 8(2)\times 10^{-12}\,\frac{\mathrm{cm}^3}{s}$$

Loss rate an order of magnitude smaller than for KRb.



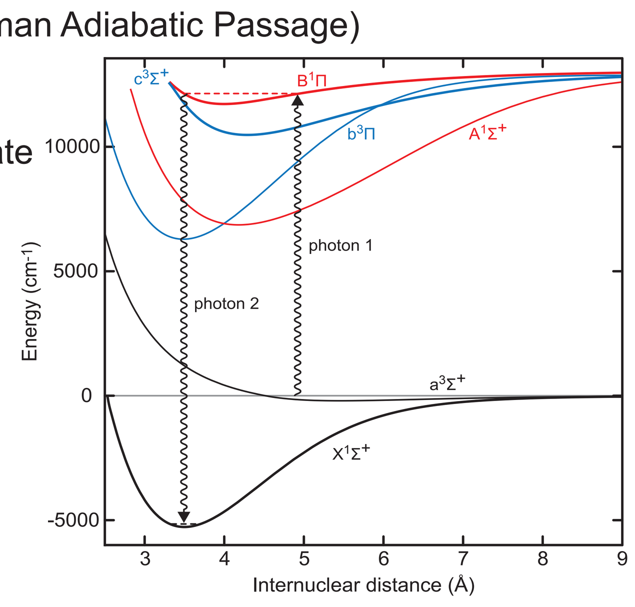

Lifetime τ > 100 ms close to resonance!

## Towards dipolar ground state molecules

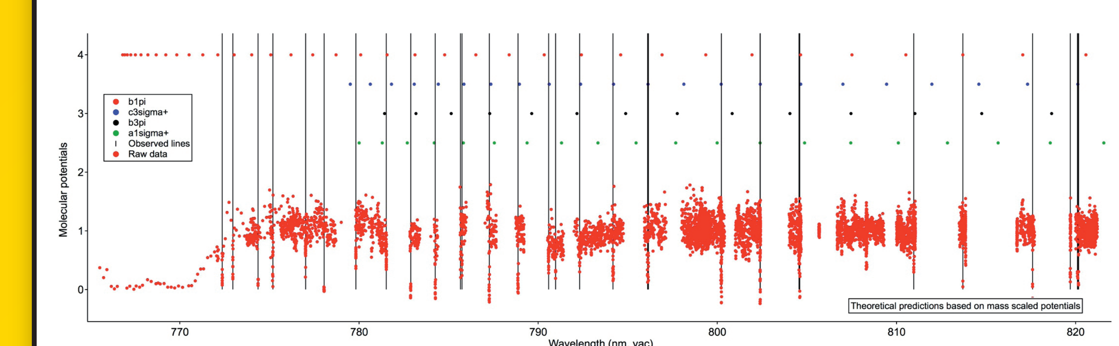
### Two-photon transfer to the molecular ground state

STIRAP (STImulated Raman Adiabatic Passage)

- Coherent pathway to rovibrational ground state mediated by an electronic excited state
- Requires Raman laser system with phase lock between two vastly different frequencies



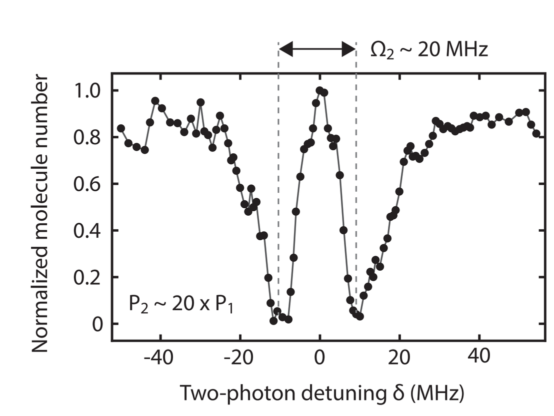

### Photoassociation spectroscopy: Finding the intermediate state



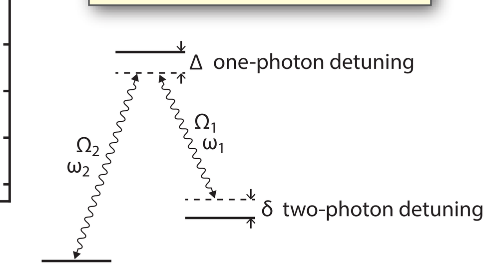
- Predictions (vertical lines) based on mass-scaled NaK potentials
- Identify most of the observed lines based on prediction
- Good candidates for STIRAP to the singlet ground state require large Frank-Condon overlap & singlet-triplet mixing (spin-orbit coupling between B1Π & $c^3\Sigma^+$)

### Two-photon spectroscopy: Exploring the ground state potentials

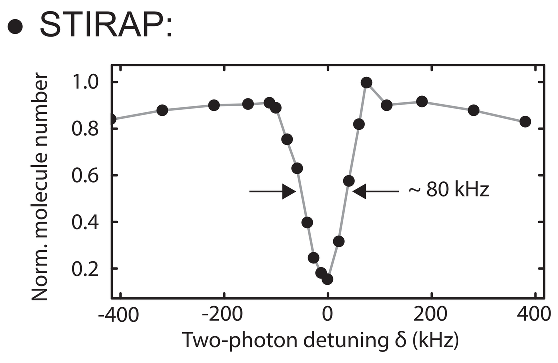
- Diode lasers, Ti:Sapph, and dye lasers set up for spectroscopy
- Autler-Townes splitting: Strong coupling laser between a lower-lying vibrational level ($v$ = -2) in $a^3\Sigma^+$ and the intermediate state in $c^3\Sigma^+$ induces a splitting of the intermediate state:



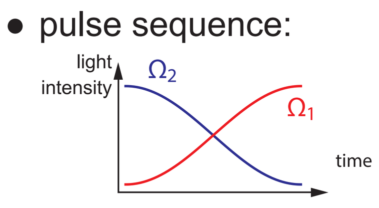

Very strong coupling achievable!




- STIRAP:




- pulse sequence:

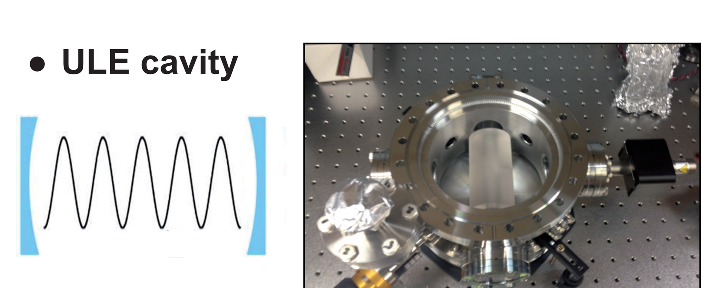



- one-photon detuning: Δ ~ 40 MHz

## Establishing phase coherence

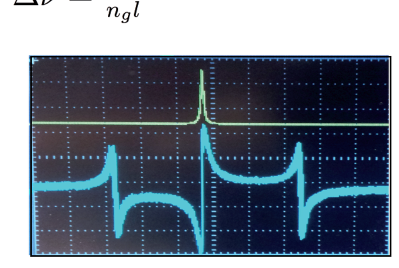
### Two techniques: Frequency comb and ultra-low expansion cavity

- **ULE cavity**



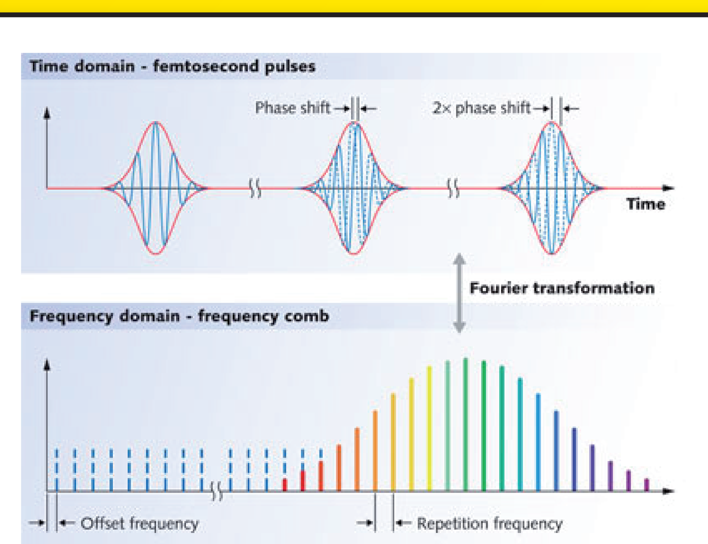
FSR: $\Delta\nu = \frac{c}{n_g l}$

- Lock both lasers to a stable reference cavity



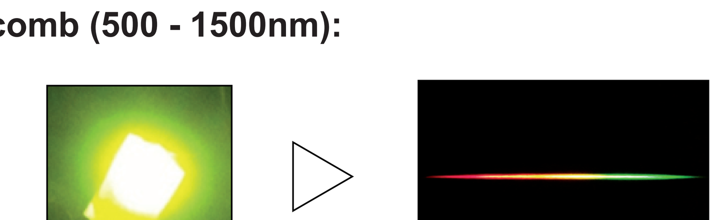
- ULE cavity under vacuum and maintained near zero-point of thermal expansion coefficient
- Pound-Drever-Hall locking scheme

- **Frequency comb (500 - 1500nm):**




http://www.laserfocusworld.com/content/dam/lfw/print-articles/2012/01/1201LFW08f1.jpg

- Pulsed laser comprising discretely spaced frequencies spanning more than an optical octave
- Lock slave lasers to different comb teeth
- Use slave lasers (dye, Ti:Sapph, and/or diode lasers) to transfer molecules to absolute ground state



- Phase lock between master and slave lasers:

sub-kHz linewidth!