Laser cooled molecules and their applications to fundamental physics

Radioactive molecules virtual meeting, June 28th 2021

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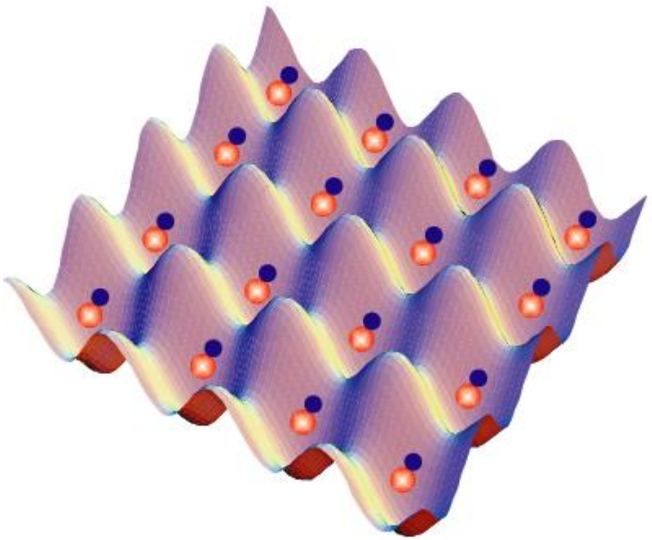
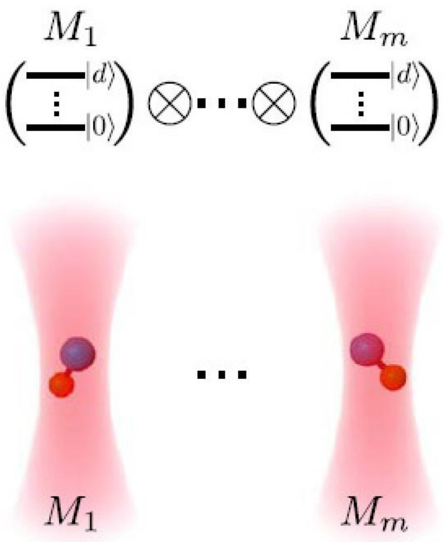
Centre for Cold Matter
Imperial College London

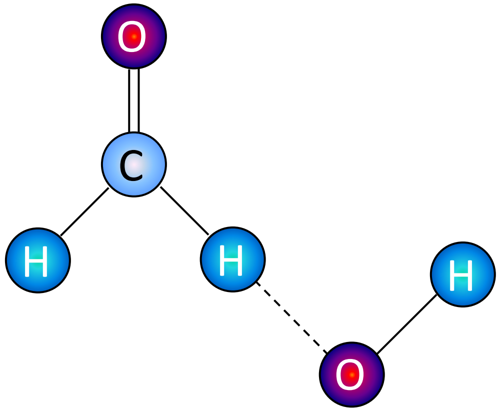
Applications of ultracold molecules



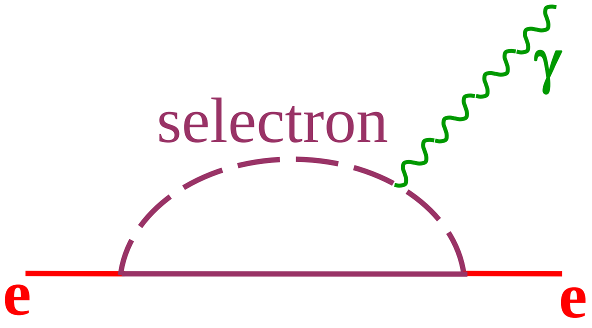
Many-body quantum physics



Quantum information processing



Quantum chemistry



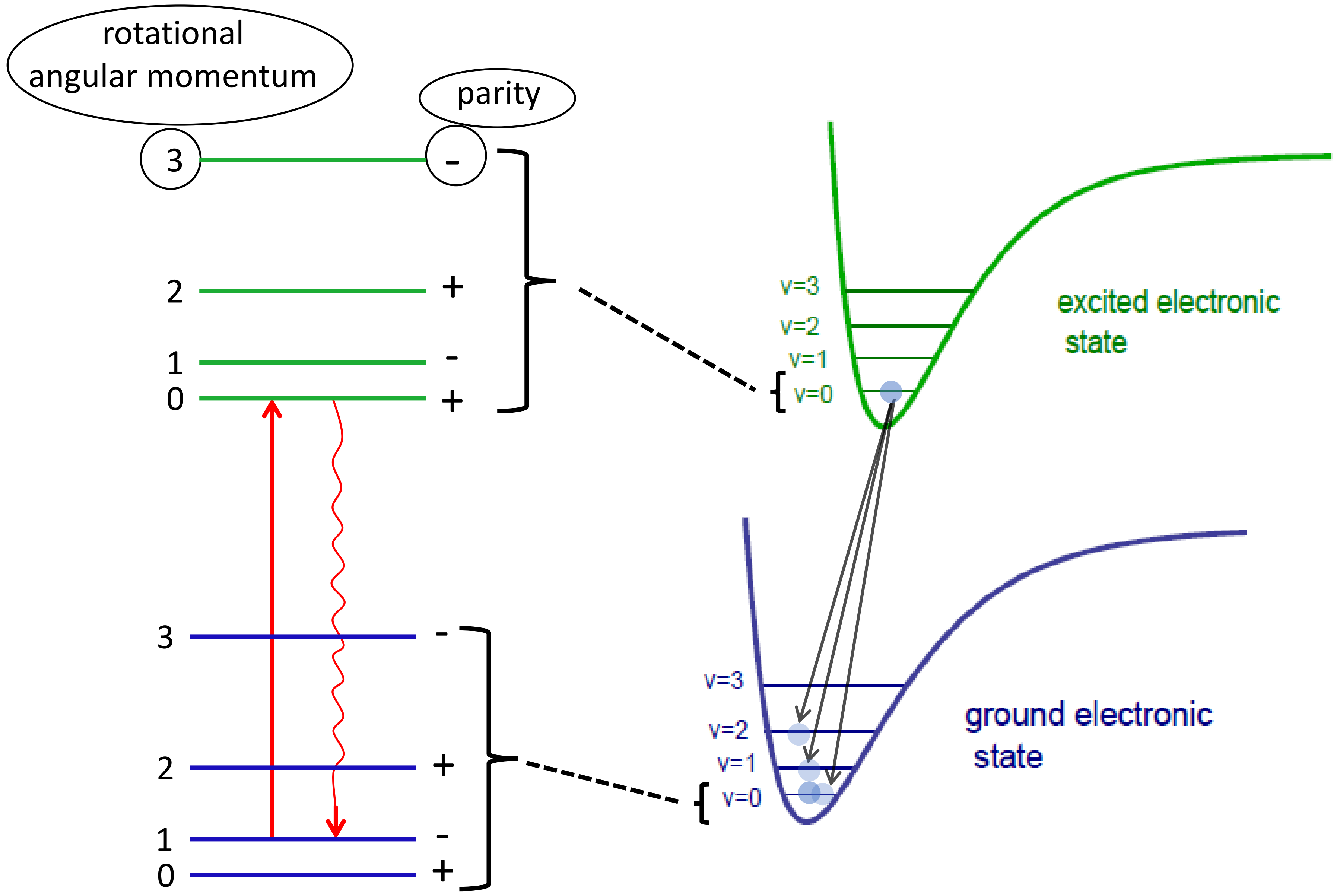
Tests of fundamental physics

- Measuring electron EDM & other T-violating physics
- Searching for varying fundamental constants
- Measuring parity violation in nuclei
- Measuring parity violation in chiral molecules
- Searching for fifth forces

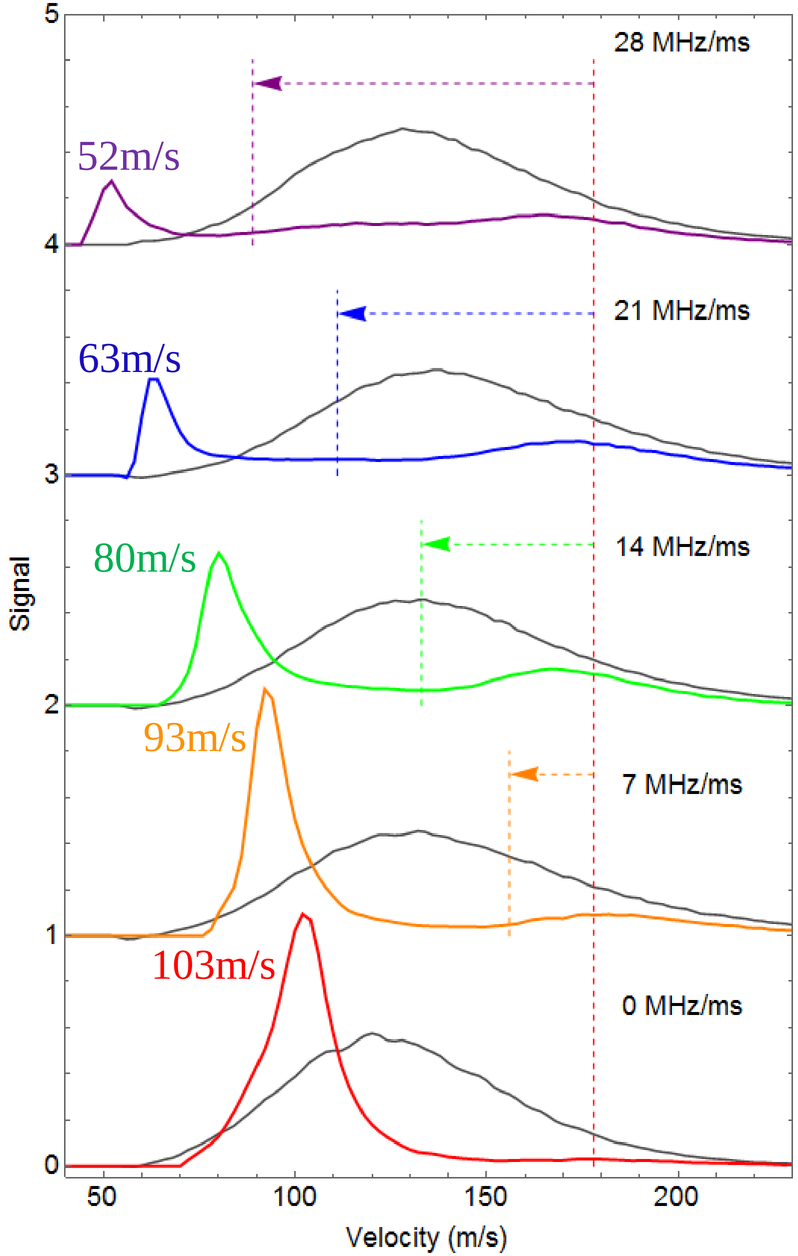
The world of laser-cooled molecules

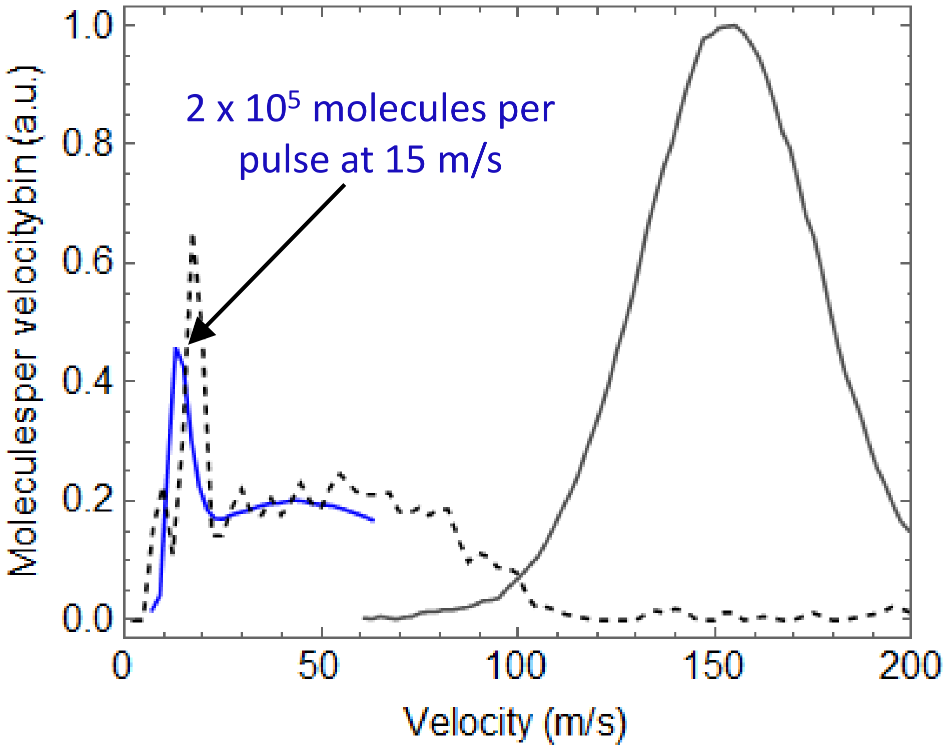
SrF – Yale / Chicago (DeMille)
CaF – London (Tarbutt)
CaF – Harvard (Doyle)
YO – JILA (Ye)
YbF – London (Tarbutt)
BaH – Columbia (Zelevinsky)
AlF – Berlin (Truppe)
AlCl – Connecticut (McCarron)
CH – Connecticut (McCarron)
AlCl – UC Riverside (Hemmerling)
BaF – Nanjing (Yan)
CaF – Hannover (Ospelkaus)
BaF – Stuttgart (Langen)
BaF – Groningen (Hoekstra)
SrOH – Harvard (Doyle)
CaOH – Harvard (Doyle)
YbOH – Harvard (Doyle)
$CaOCH_3$ – Harvard (Doyle)
YbOH – Caltech (Hutzler)

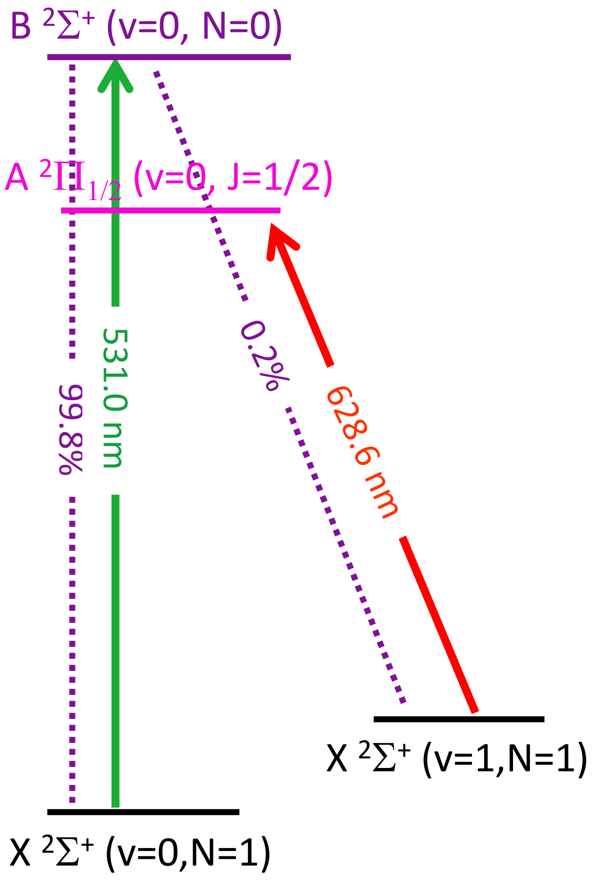
How to apply laser cooling to molecules



Radiation-pressure slowing of CaF molecules



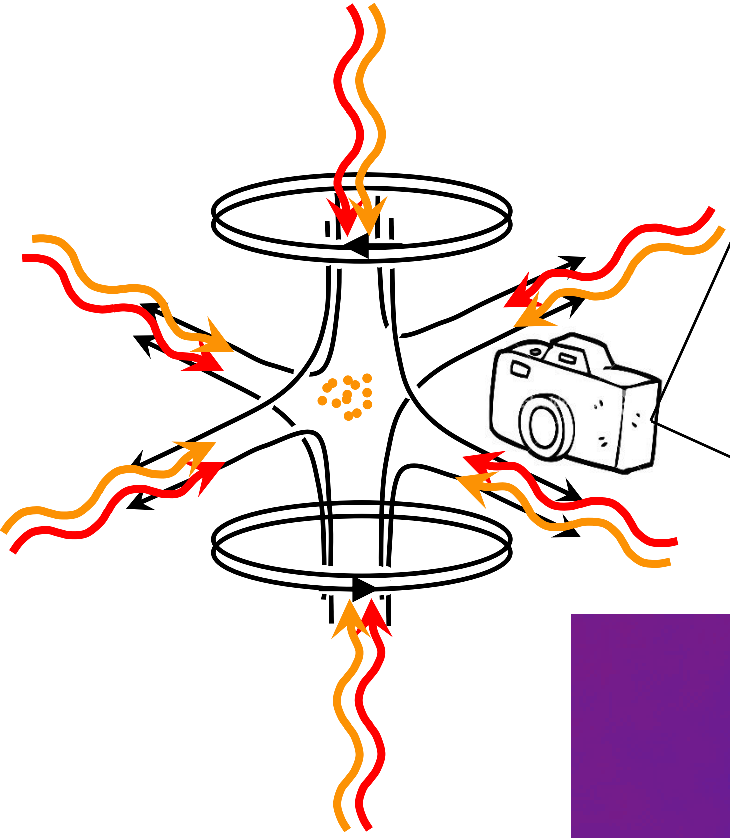




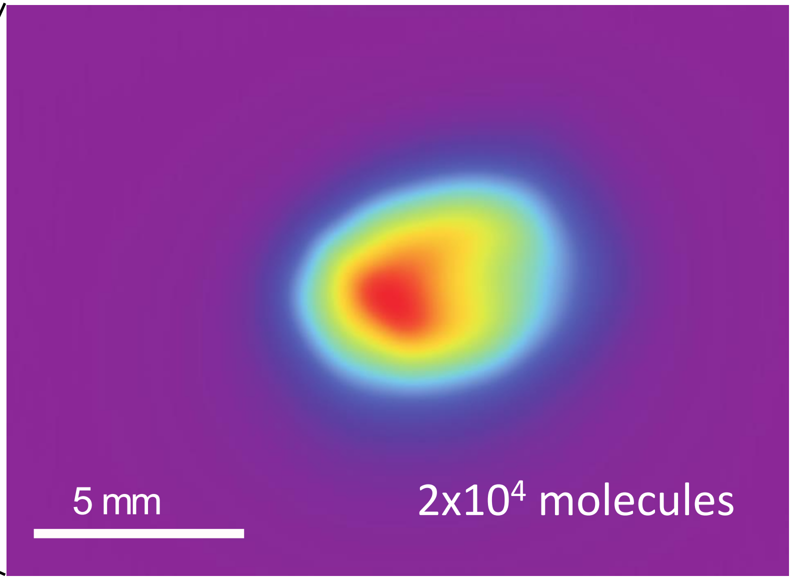
S. Truppe et al., New J. Phys. **19**, 022001 (2017)

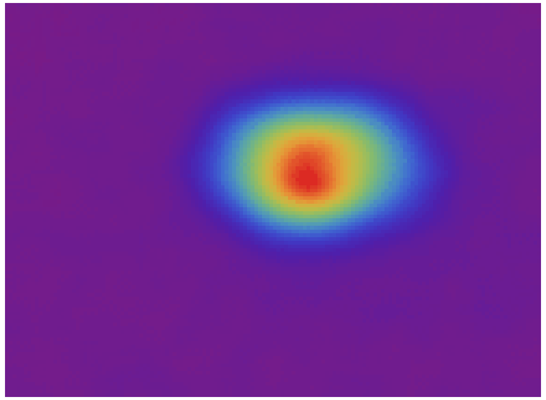
Magneto-optical trap of CaF molecules

606.3 nm + 628.6 nm
+ 628.1 nm + 627.7nm

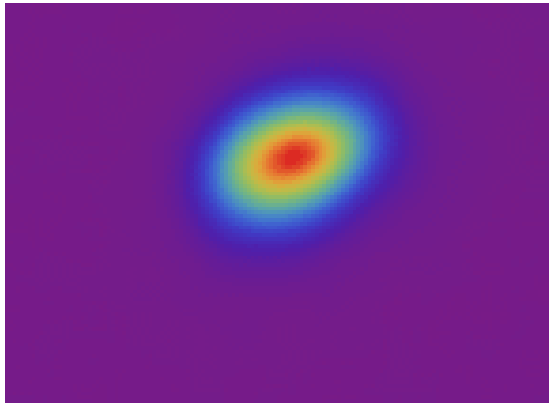


(red-detuned)

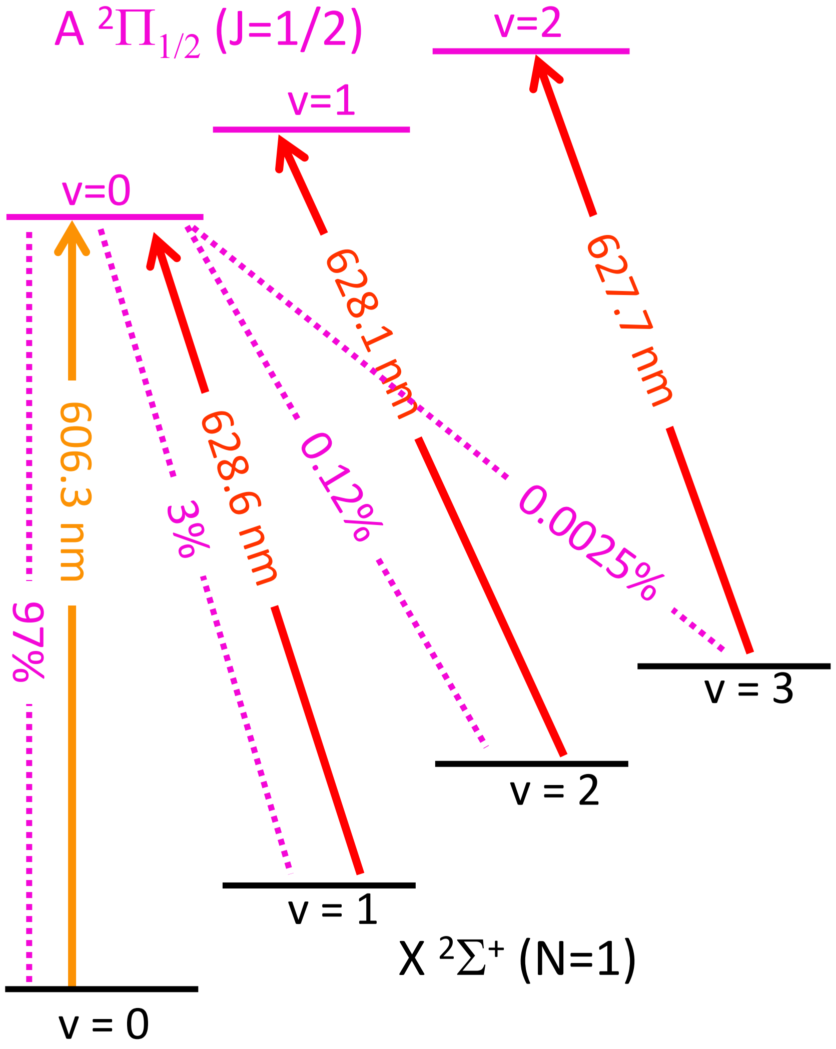




Oscillation frequency: 100 Hz

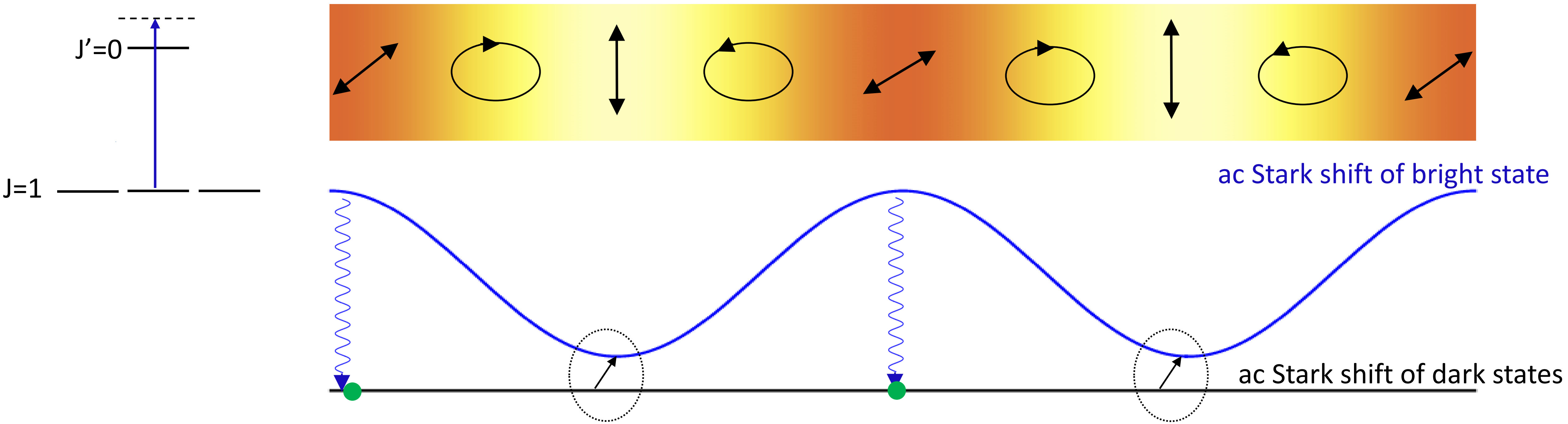


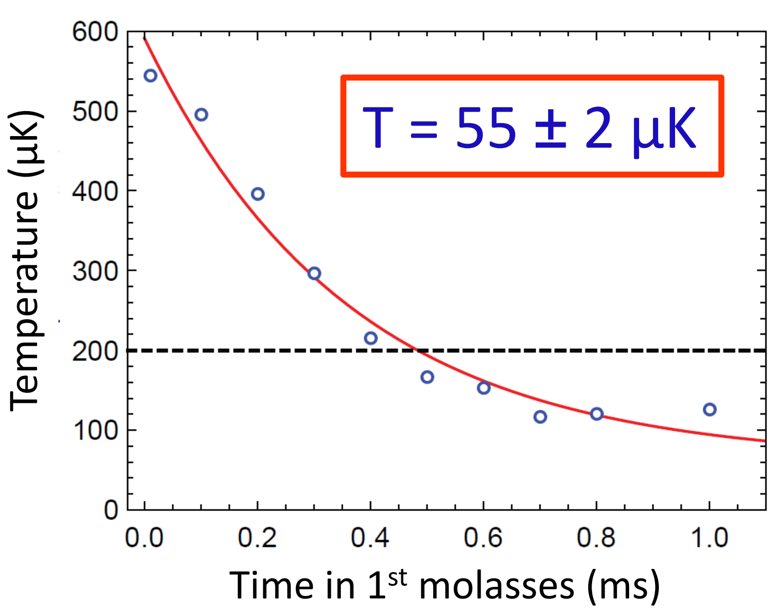
Temperature: 1 – 10 mK

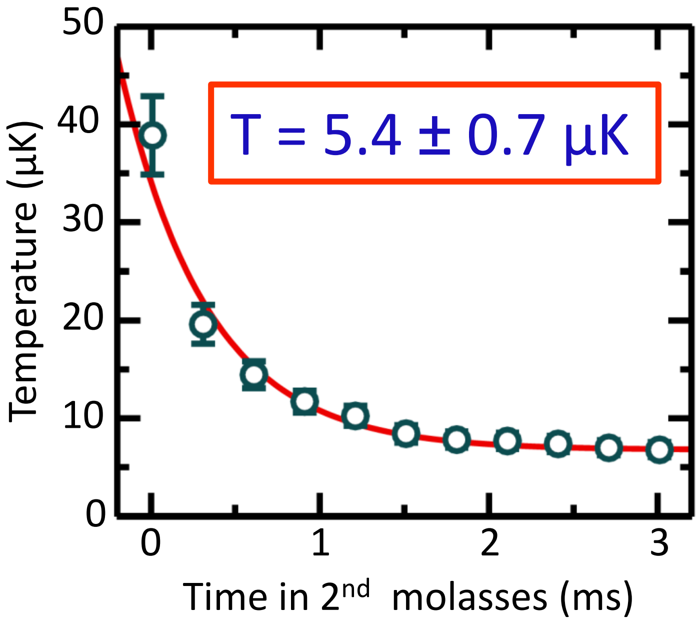


H. Williams et al., New J. Phys. **19**, 113035 (2017)

Sub-Doppler cooling

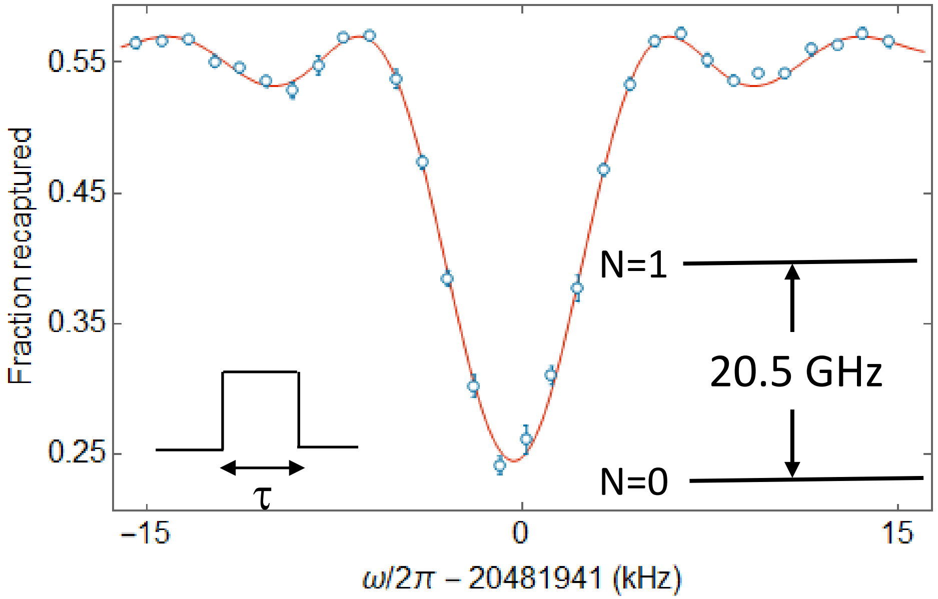


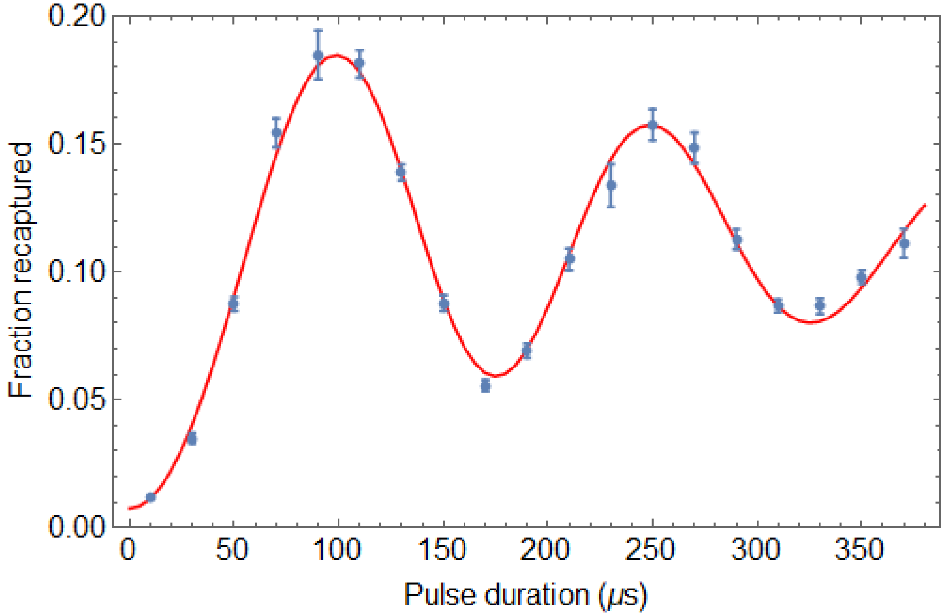


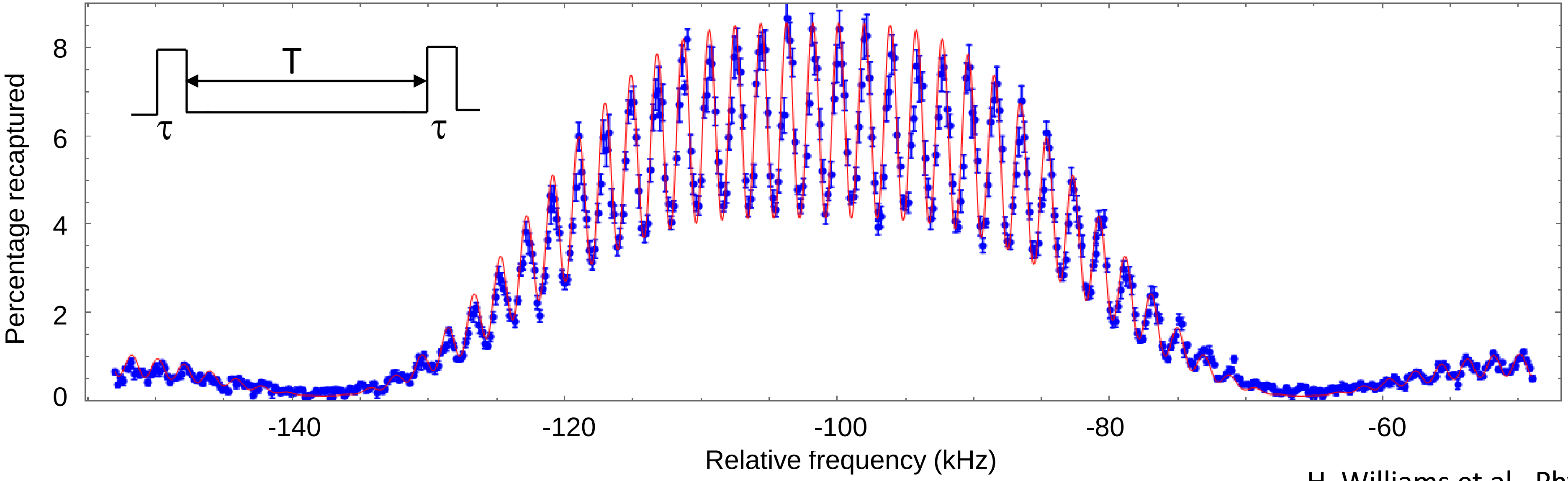


S. Truppe et al., Nature Physics, **13,** 1173 (2017)
L. Caldwell et al., Phys. Rev. Lett. **123**, 033202 (2019)

Coherent control

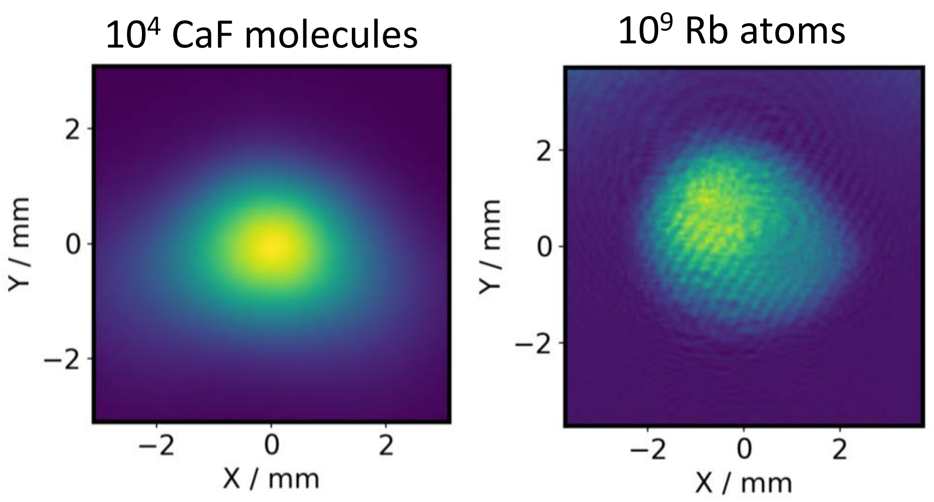






H. Williams et al., Phys. Rev. Lett. **120**, 163201 (2018)
J. A. Blackmore et. al. Quantum Sci. Technol. **4**, 014010 (2019)
L. Caldwell et al, Phys. Rev. Lett. **124**, 063001 (2020)

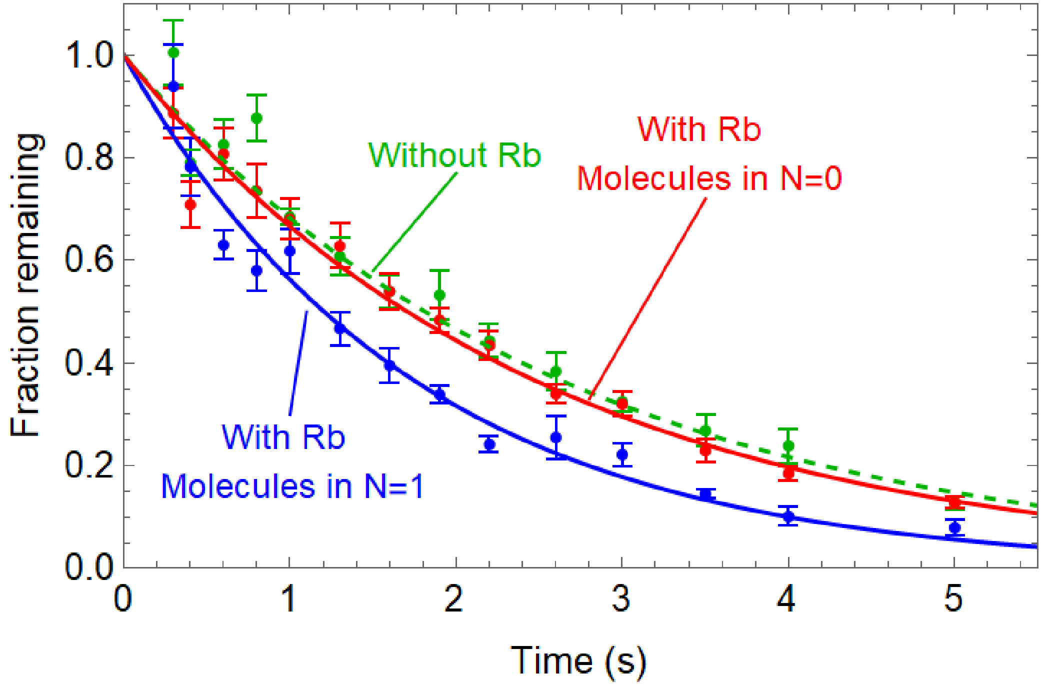
Mixtures of laser-cooled molecules and atoms



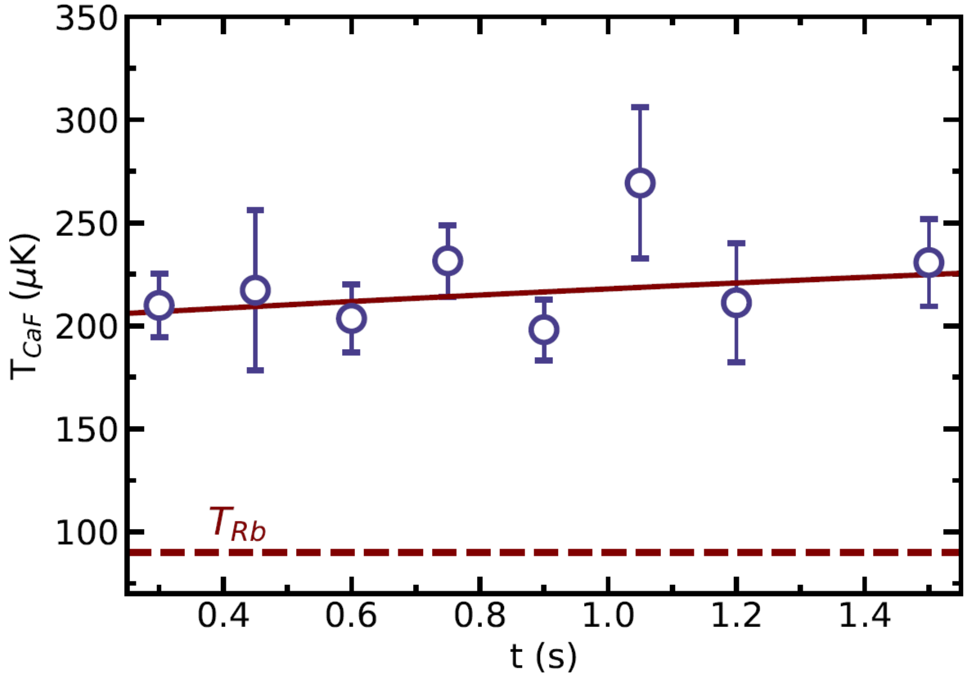
At a collision energy near 100 μK, we find:

- $k_2 = (6.6 \pm 1.5) \times 10^{-11}$ cm^3 s^{-1} for molecules in N=1
- Fast! Attributed to rotation-changing collisions
- $k_2 < 5.8 \times 10^{-12}$ cm^3 s^{-1} (95% CL) for molecules in N=0
- Spin relaxation is much slower
- $\sigma_{elastic} < 1.3 \times 10^{-11}$ cm^2 (95% CL)

Collisions in a magnetic trap

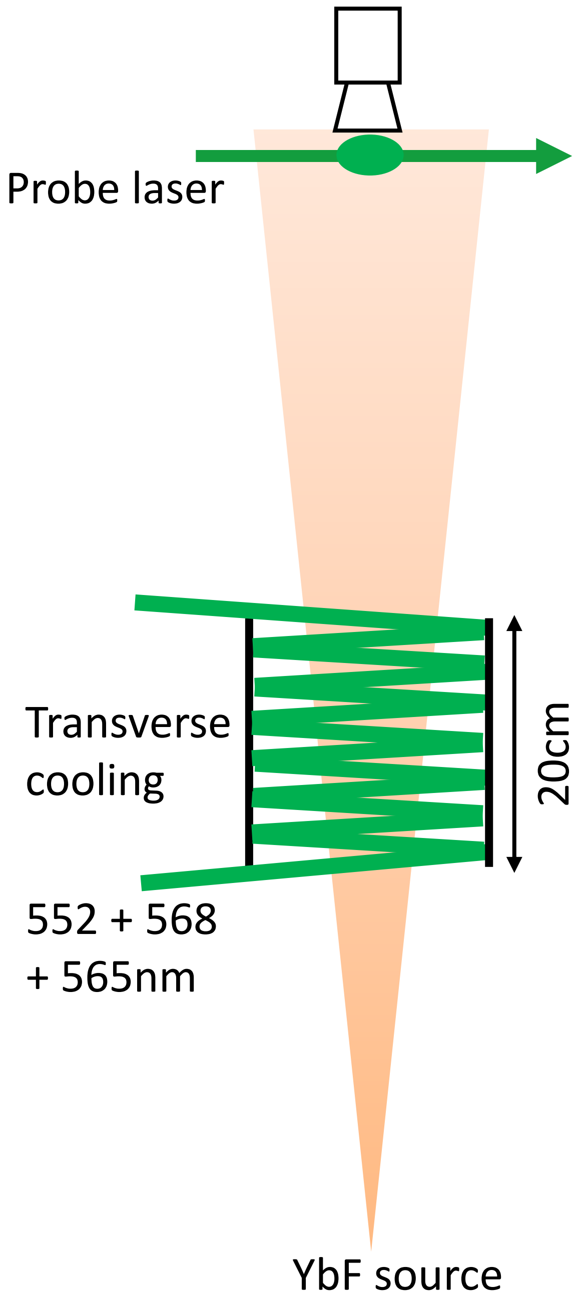


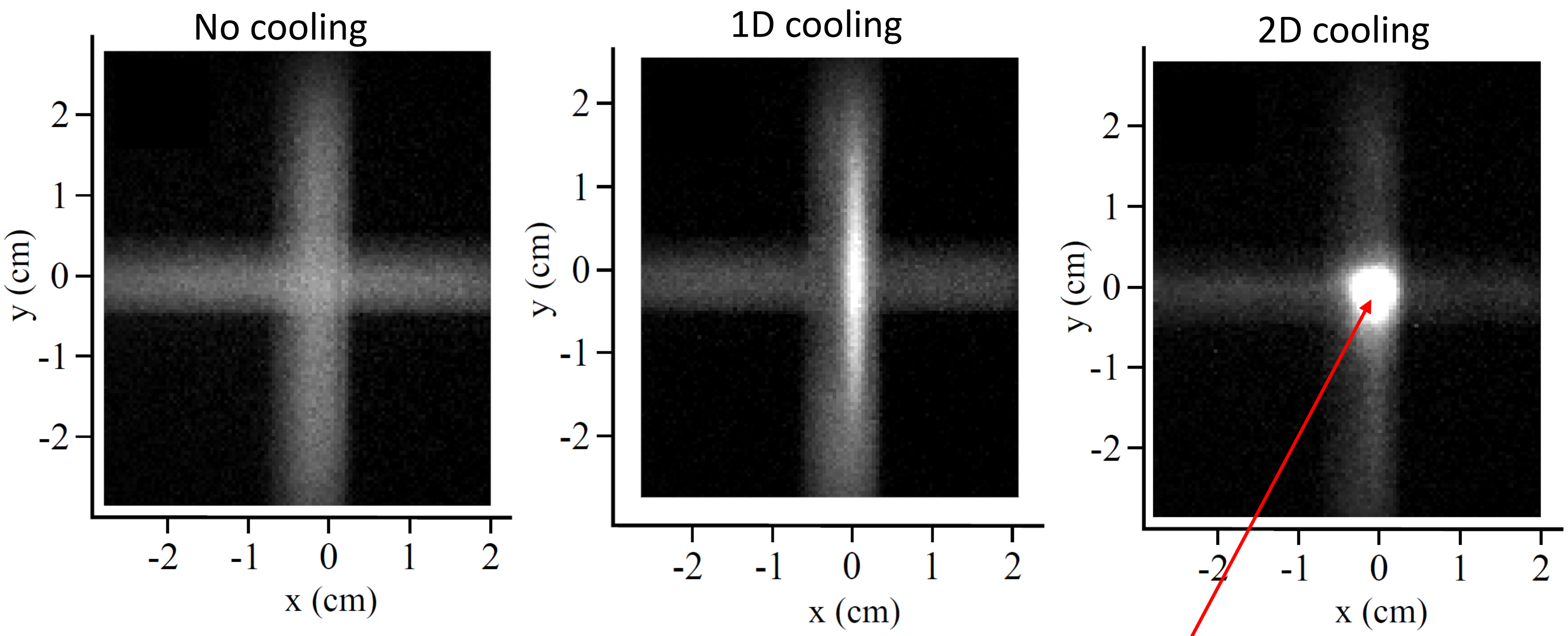
No thermalization between species…yet

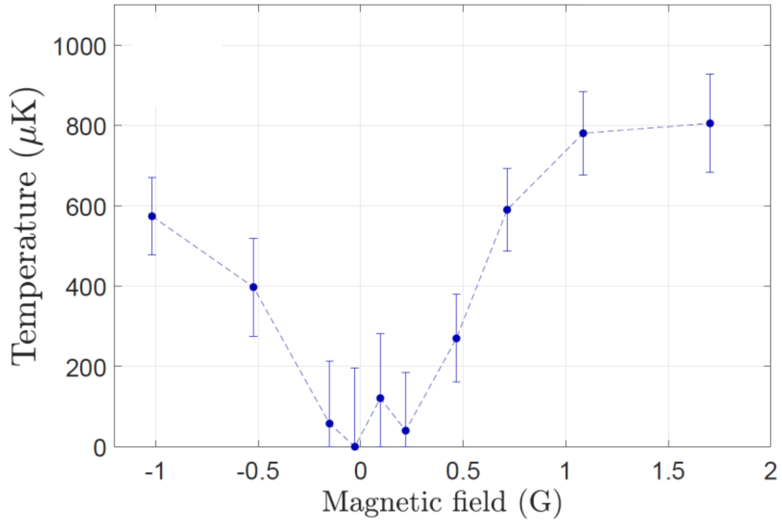


S. Jurgilas et al, Phys. Rev. Lett. **126**, 153401 (2021)

Ultracold YbF for measuring electron electric dipole moment





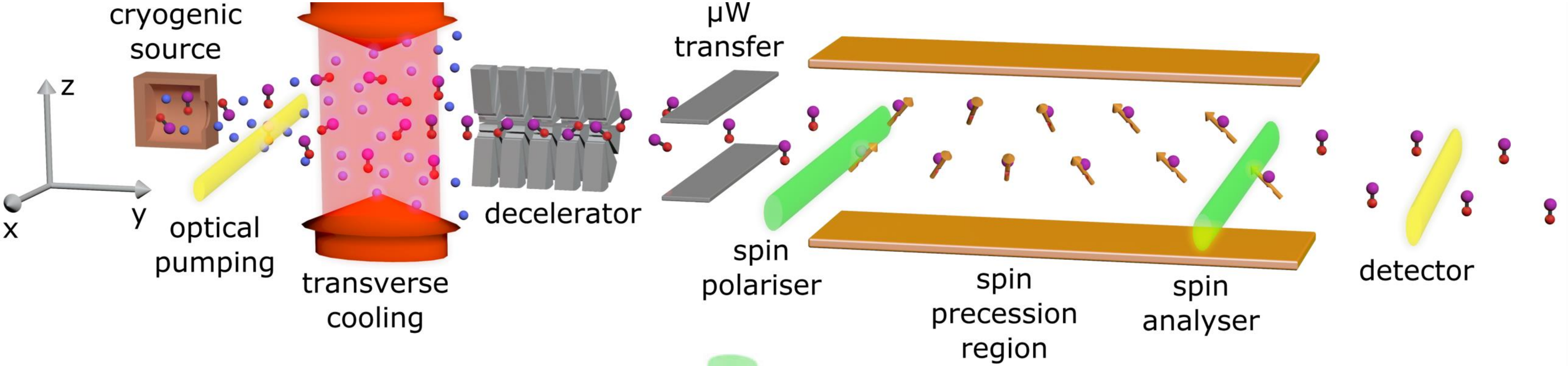


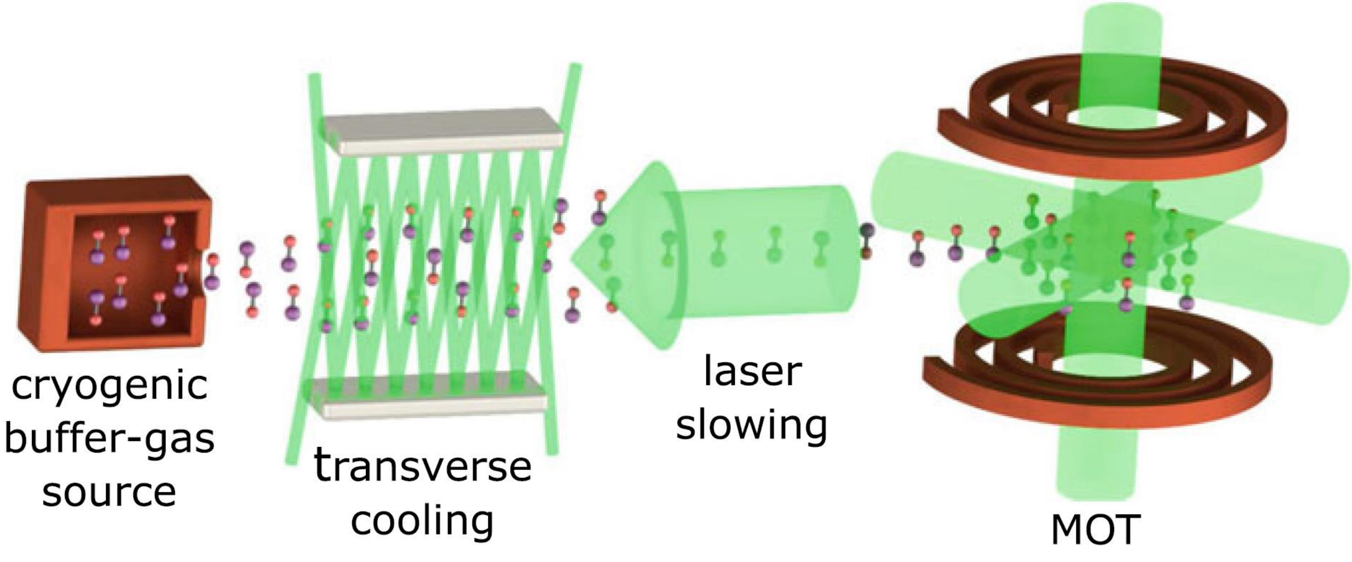
About 10^6 molecules per shot below 200 μK

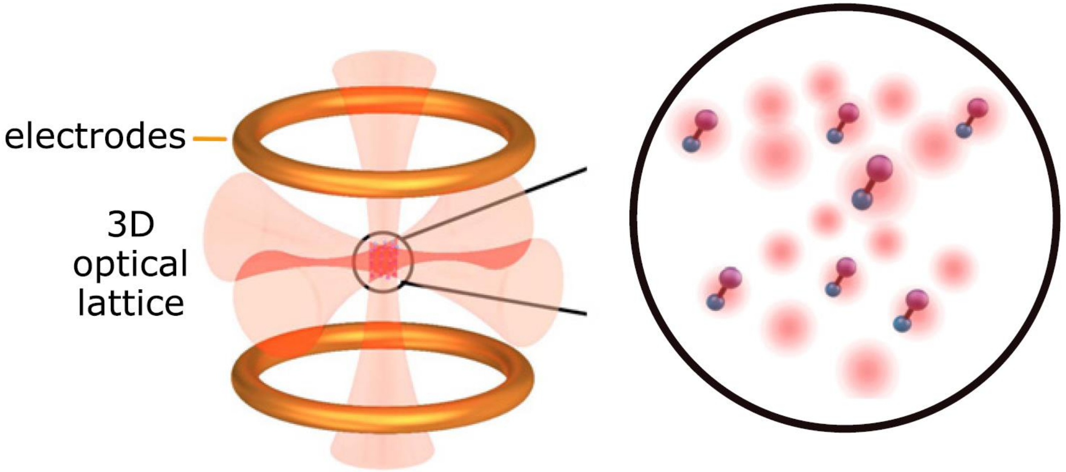
Beam brightness increased by at least a factor 300

J. Lim et al., Phys. Rev. Lett. **120**, 123201 (2018); X. Alauze et al., arXiv:2104.06194 (2021)

Ways to measure eEDM using ultracold YbF

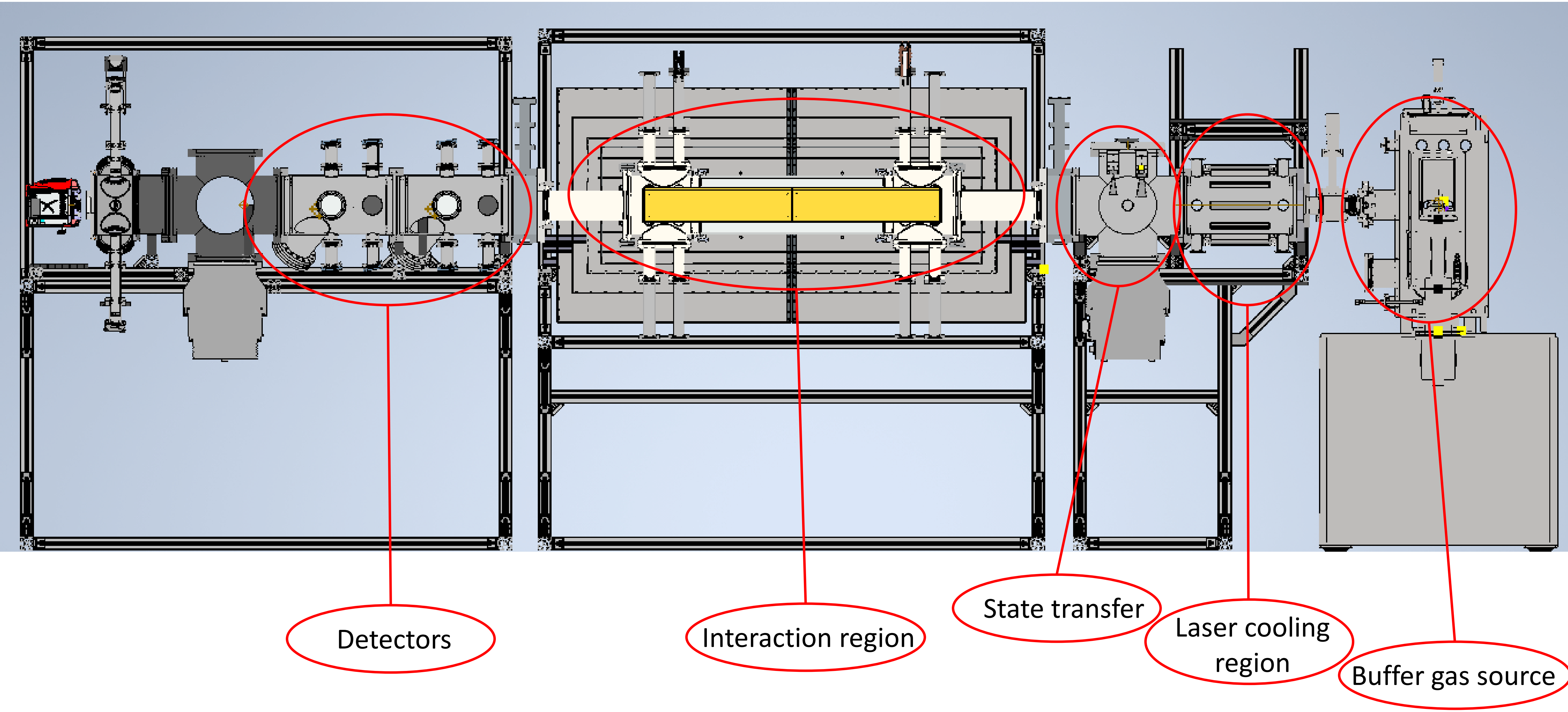






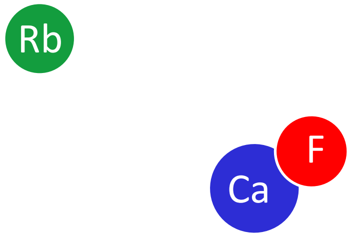
N. J. Fitch et. al. Quantum Sci. Technol. **6**, 014006 (2021)

Experiment to measure eEDM using ultracold YbF

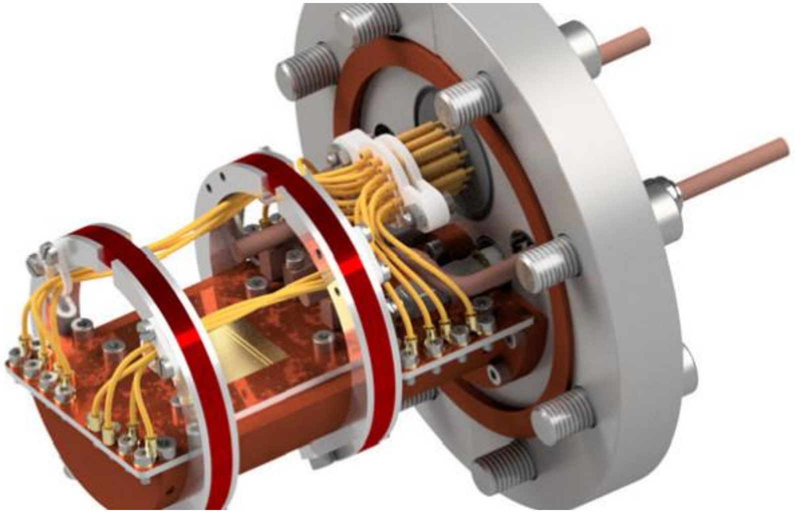


- Immediate aim: demonstrate statistical sensitivity of 10^{-30} e.cm in a day

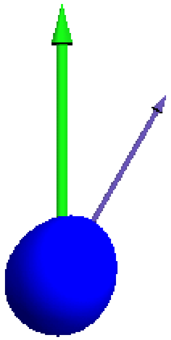
Current directions



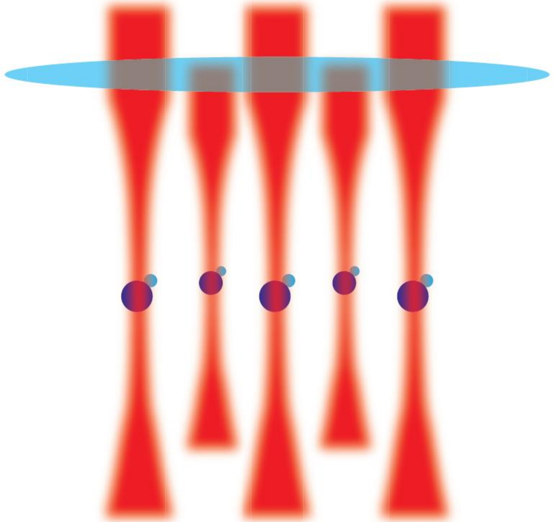
Sympathetic and evaporative cooling



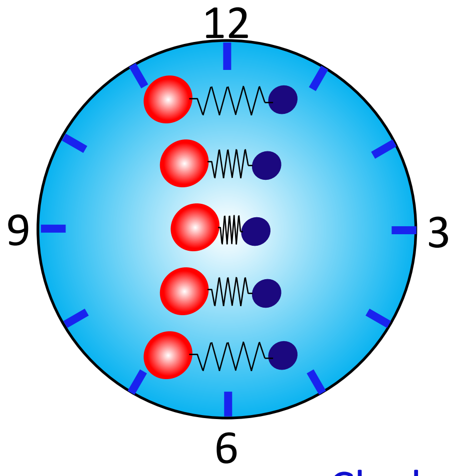
Molecule chip



Measuring EDM with ultracold molecules

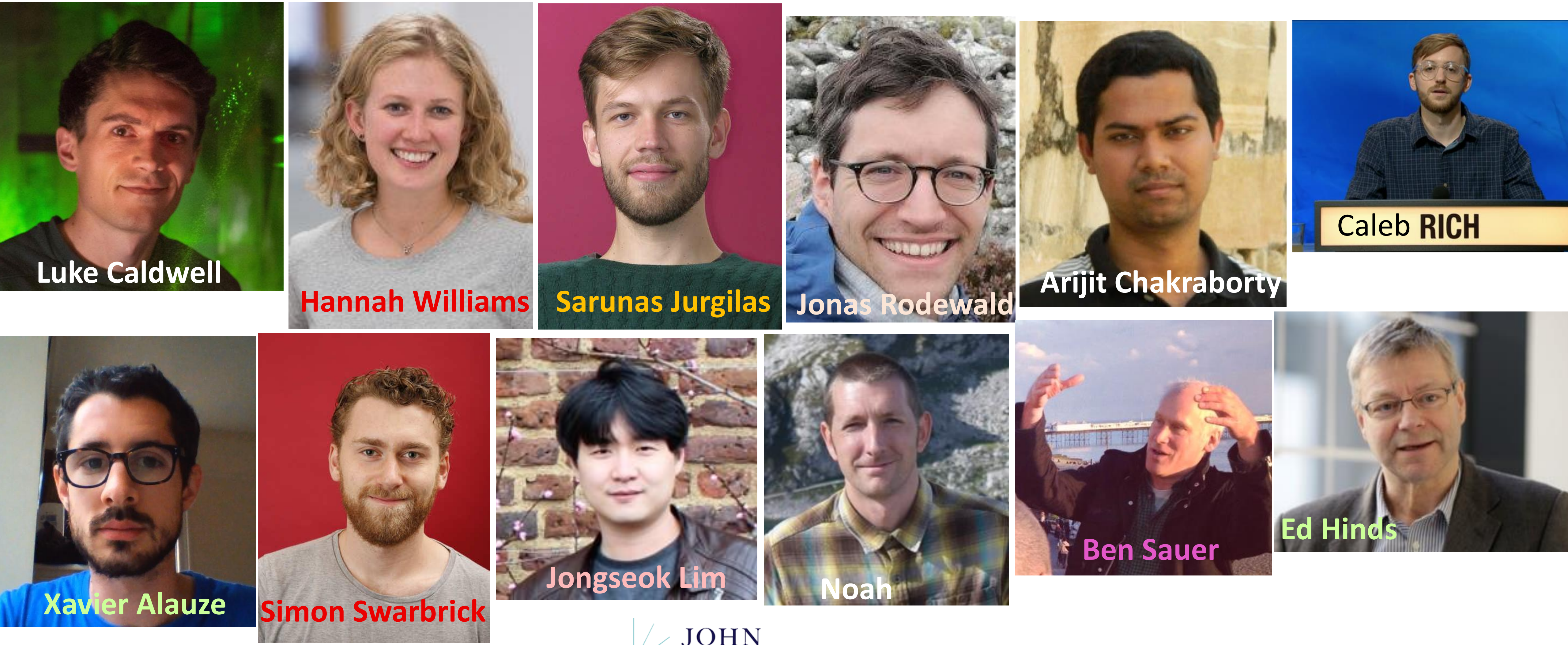


Single molecules in tweezer trap arrays



Clock

Thanks



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