Progress on Zeeman slowing of CaF

Timo Poll, Julius Niederstucke, Paul Kaebert, Supeng Xu, Mirco Siercke, and Silke Ospelkaus
Institut für Quantenoptik, Leibniz Universität Hannover

Introduction and Summary

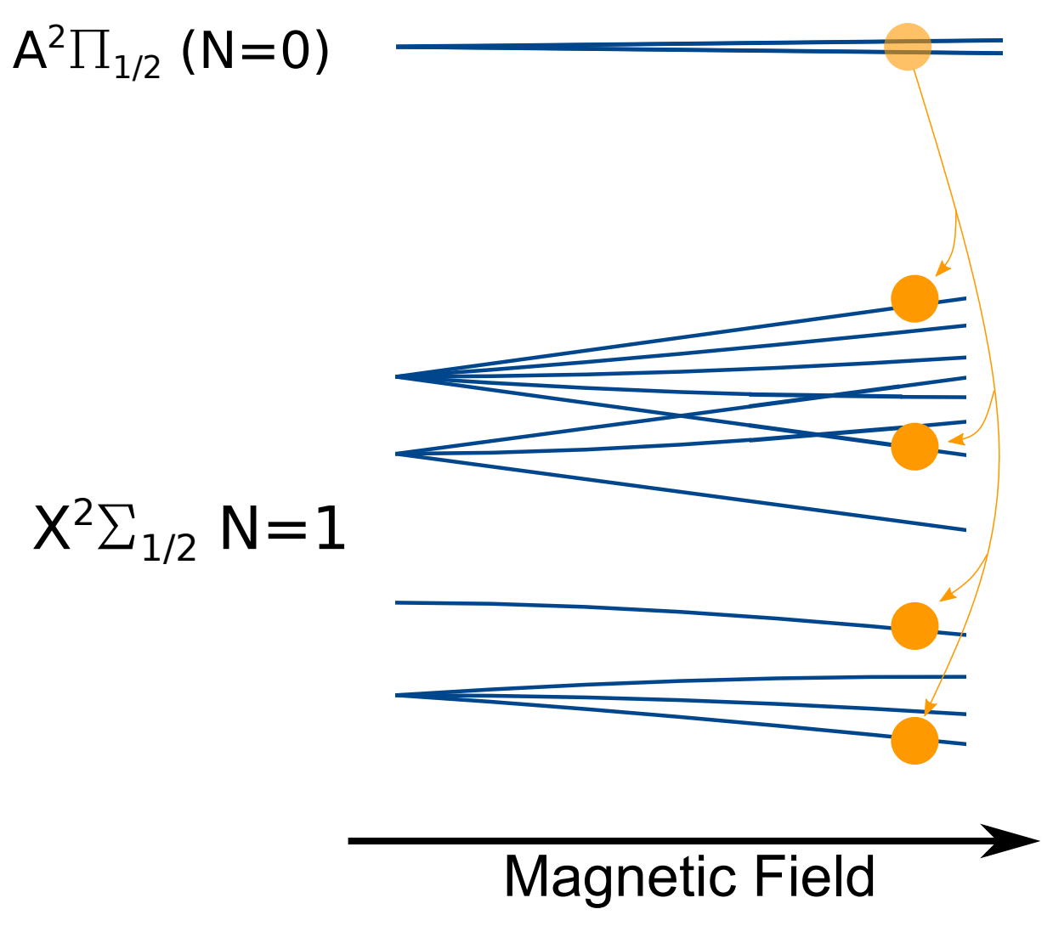
Recently, great progress has been made in direct laser cooling of molecules to temperatures close to absolute zero [1,2]. However, experiments are limited by the number of molecules that can be captured from molecular beams using typical laser-based trapping methods [3,4]. In Petzold et al. 2018 [5], we proposed to transfer Zeeman deceleration to laser-coolable molecules and thus substantially increase the number of molecules that can be captured by e.g. magneto-optical traps. Here, we now present our characterisation of the Zeeman force for CaF molecules, Kaebert et al. 2021[6]. We find excellent agreement of the force with an optical Bloch equation model. This shows that the generated force profile can compress the initial molecular velocity distribution from a standard buffer gas cell to the velocity required for trapping in a magneto-optical trap (MOT). We present the current status of our experiment as well as theoretical work on engineering the sub-Doppler force in molecular dual frequency MOTs for CaF molecules.

Zeeman slowing scheme

Problem with molecular Zeeman slowing

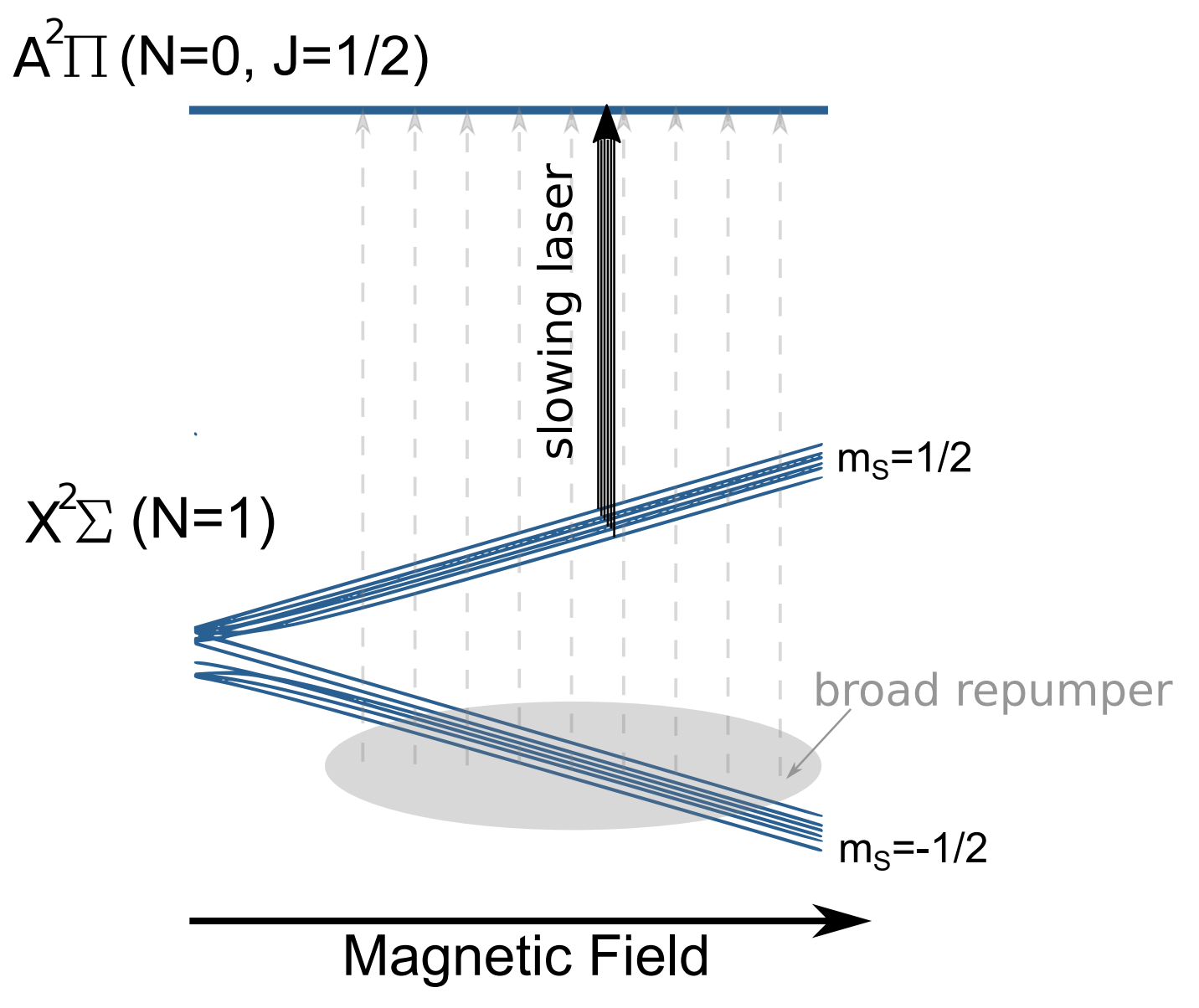
- rotational branching in molecules is mitigated by driving a J→J-1 transition, but there is no closed cycling in the magnetic sublevels as in comparison to a classical J→J+1 transition

→ traditional Zeeman Slower is not possible!



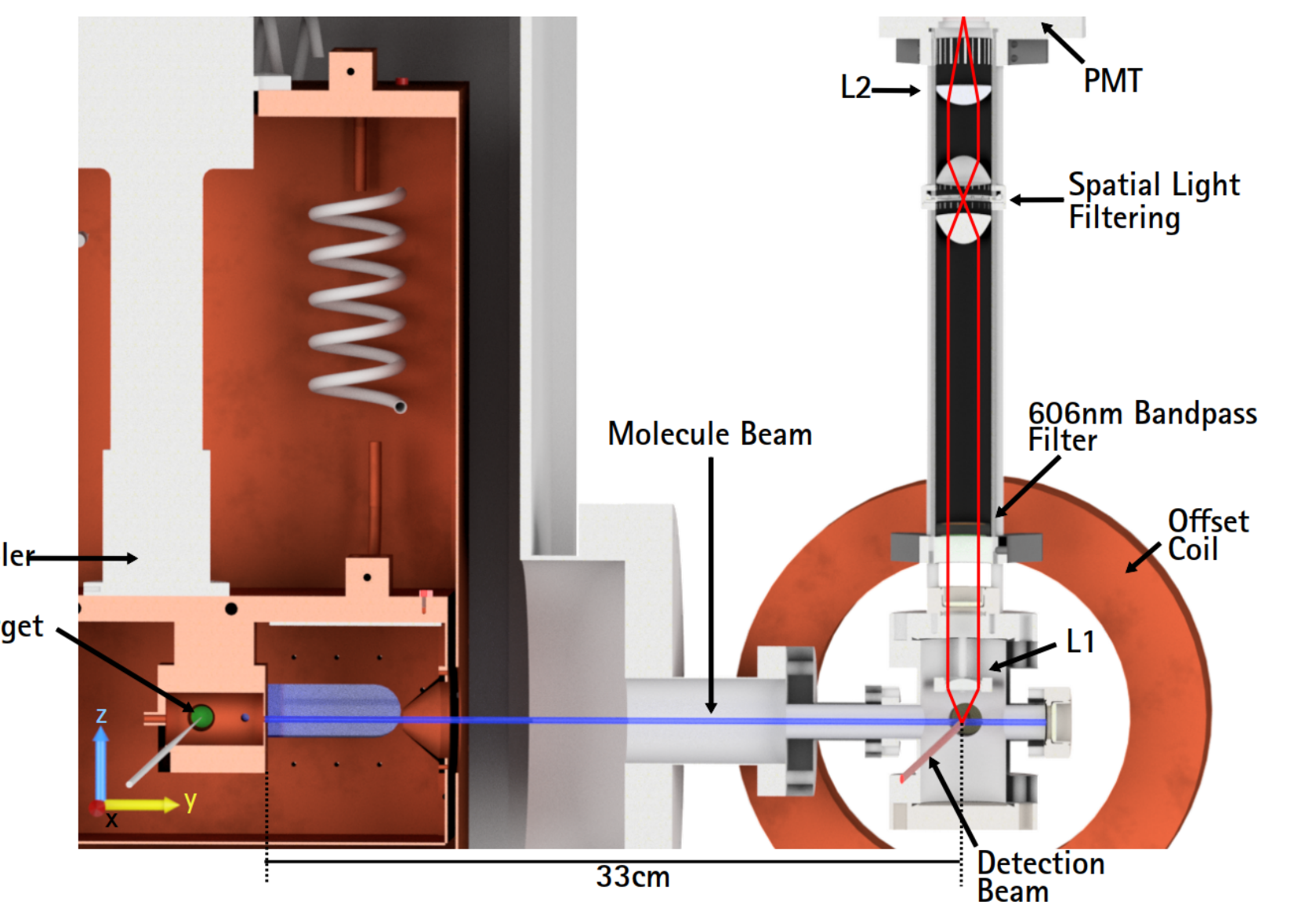
Our Solution: Type II Zeeman slower

- working in Paschen-Back regime simplifies energy shifts
- 6 frequency laser drives the levels with m_S=1/2 to the excited state
- this transition works as the slowing transition, it is magnetically tunable to compensate the changing Doppler shift during slowing
- the m_S=−1/2 levels, which experience the opposite magnetic field dependence, are repumped by a frequency broadened laser
  - → system behaves equivalent to a Zeeman Slower
  - → Laser far detuned (>200MHz)
    - → continuous loading of MOT possible



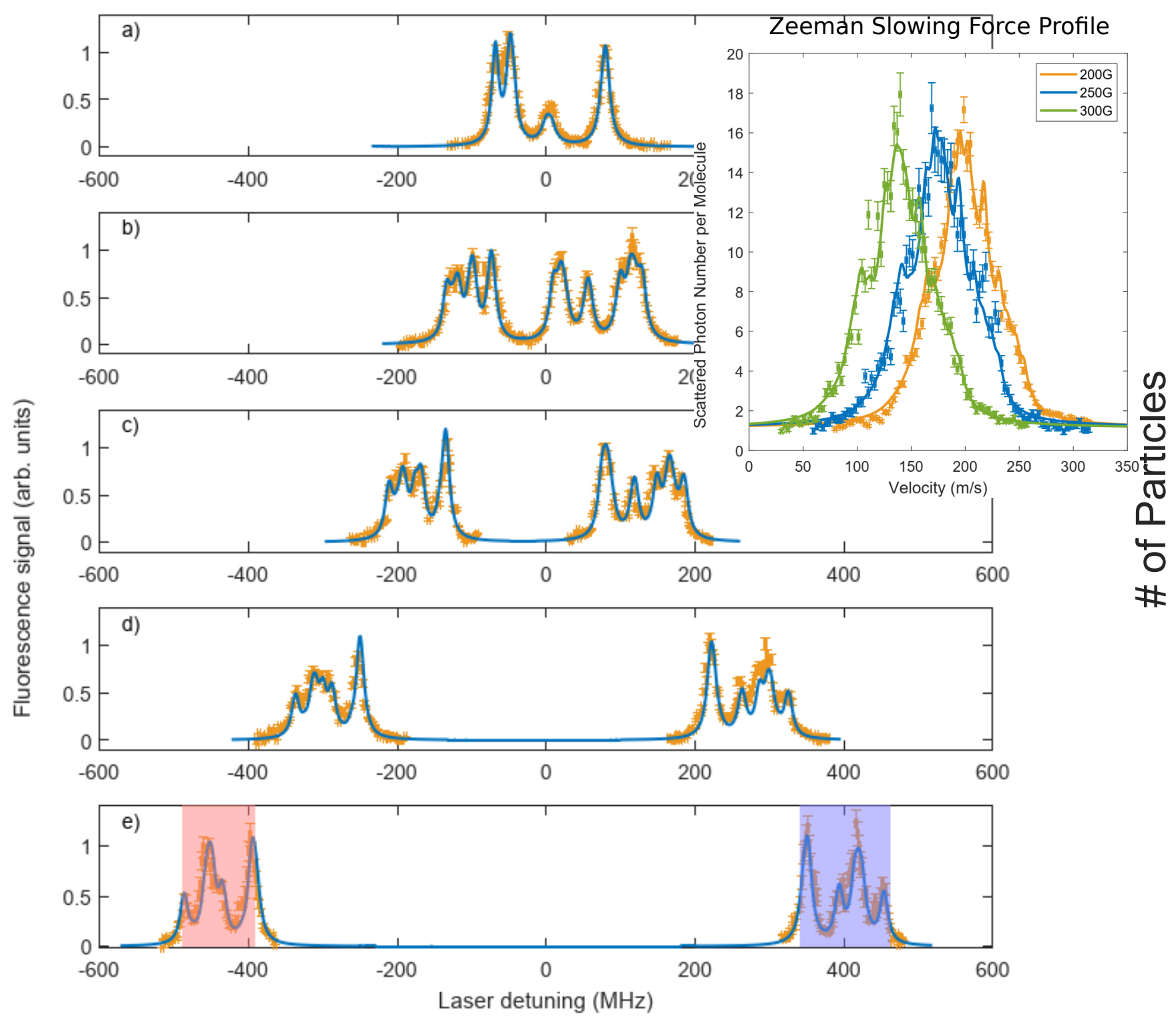
Characterizing the Zeeman Slowing Force in the Paschen-Back Regime

Experimental setup



- Molecules from Laser ablation in Buffer gas cell
- Up to 300 G by pair of coils at the imaging region
- Light induced fluorescence (LIF) is imaged by PMT
- Detection/Repump laser transverse to molecule beam

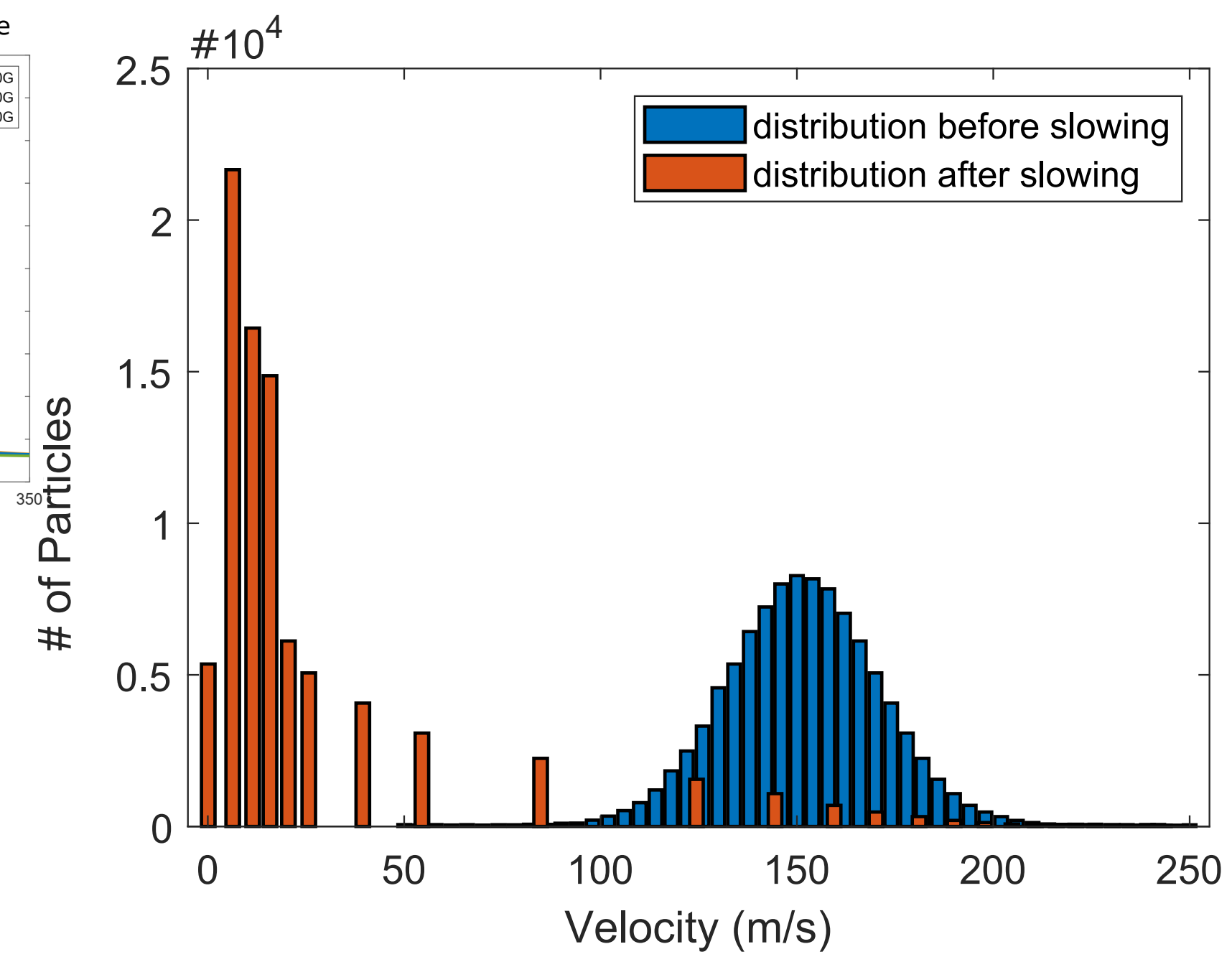
LIF Spectrum of CaF in various B Fields



- LIF Spectrum excellently fits the rate equation model

→ Accurate theoretical prediction of transition strenghts and relative transition frequencies

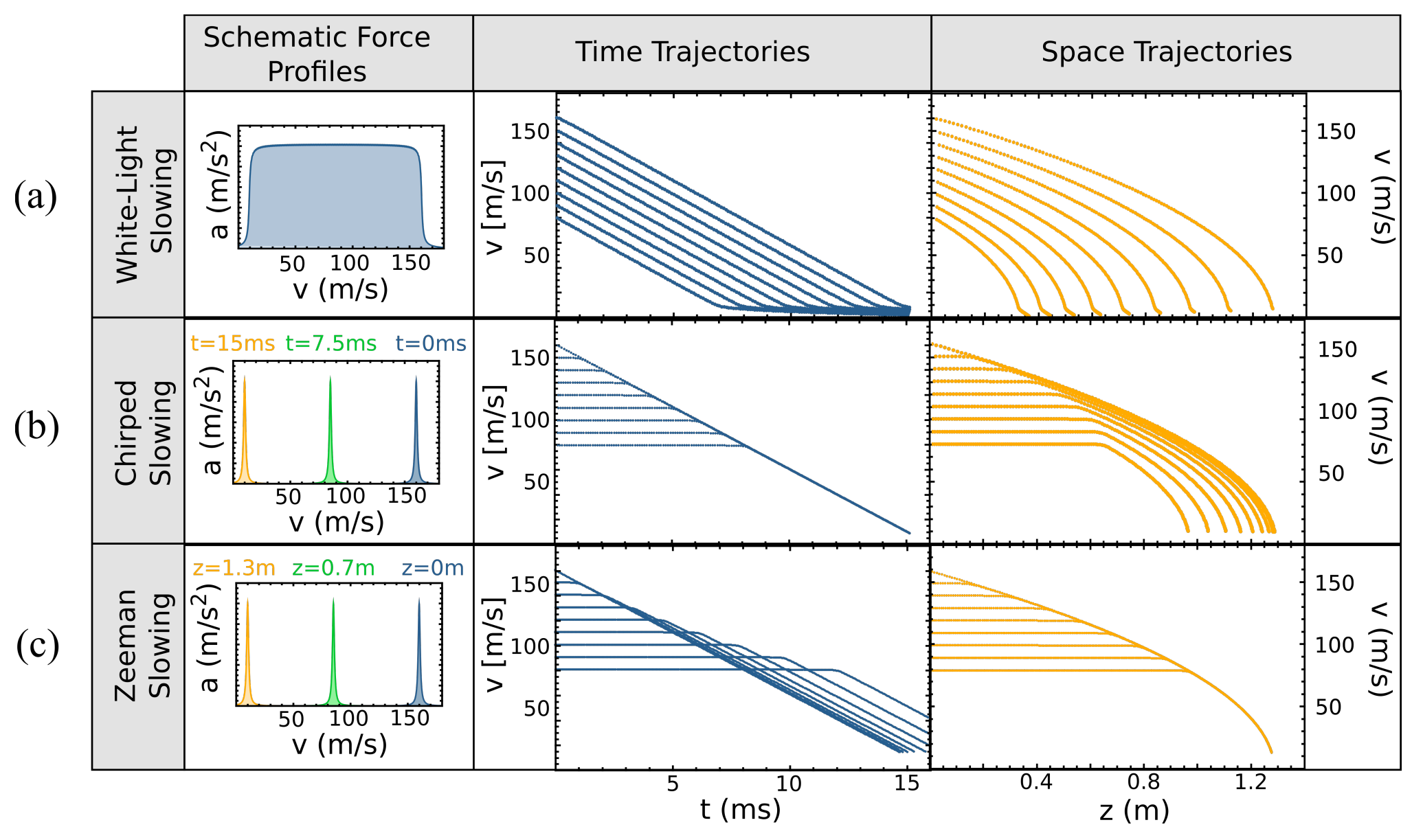
Simulation of velocity distribution



- Measured force profiles now used in 1D simulation of velocity distribution

→ force profiles narrow and high enough for efficient slowing and compression

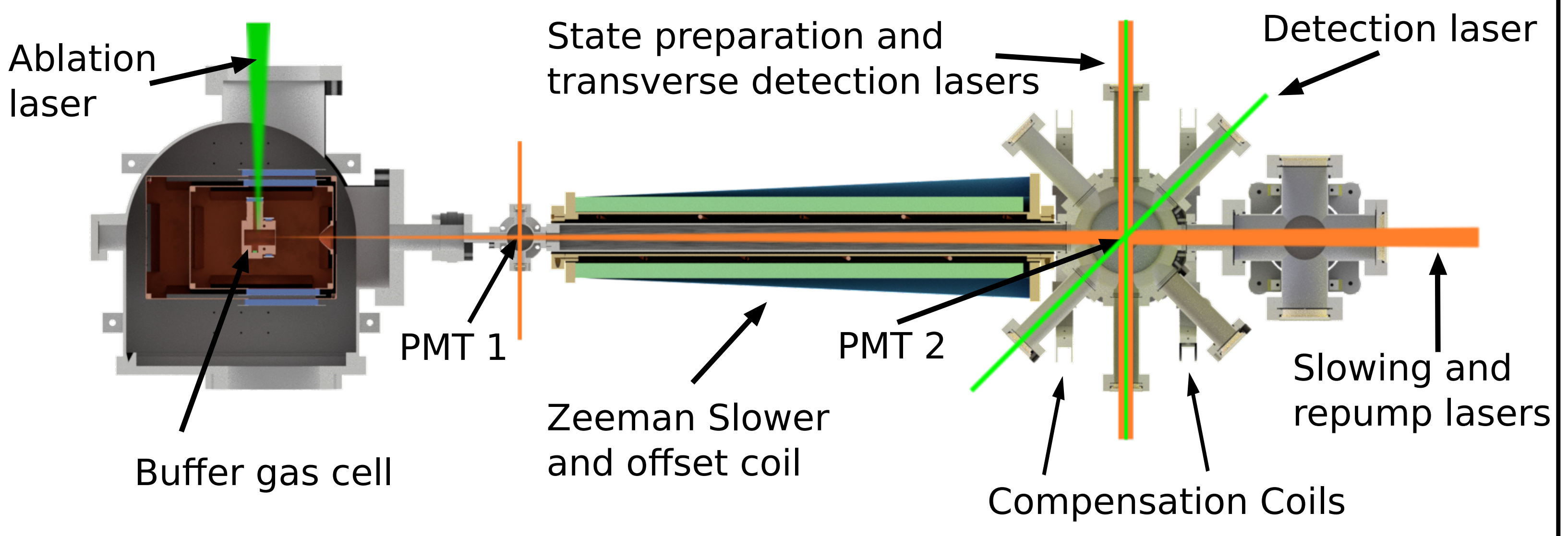
Comparison to other slowing techniques



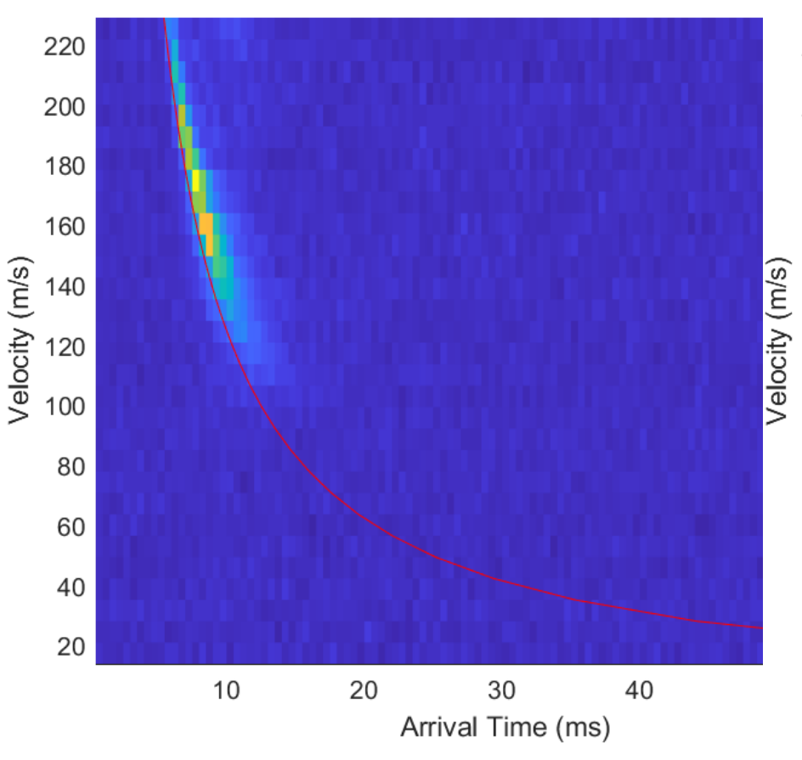
- Only Zeeman Slowing accumulates at one point in space

→ continuous MOT loading possible

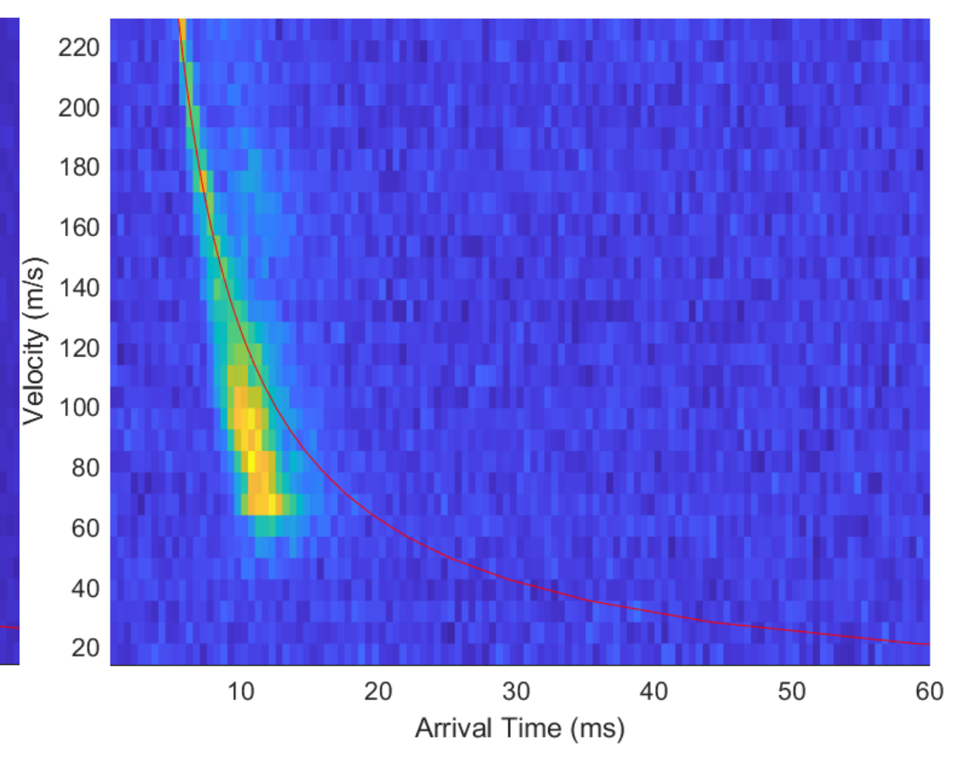
Experimental Setup & First Test



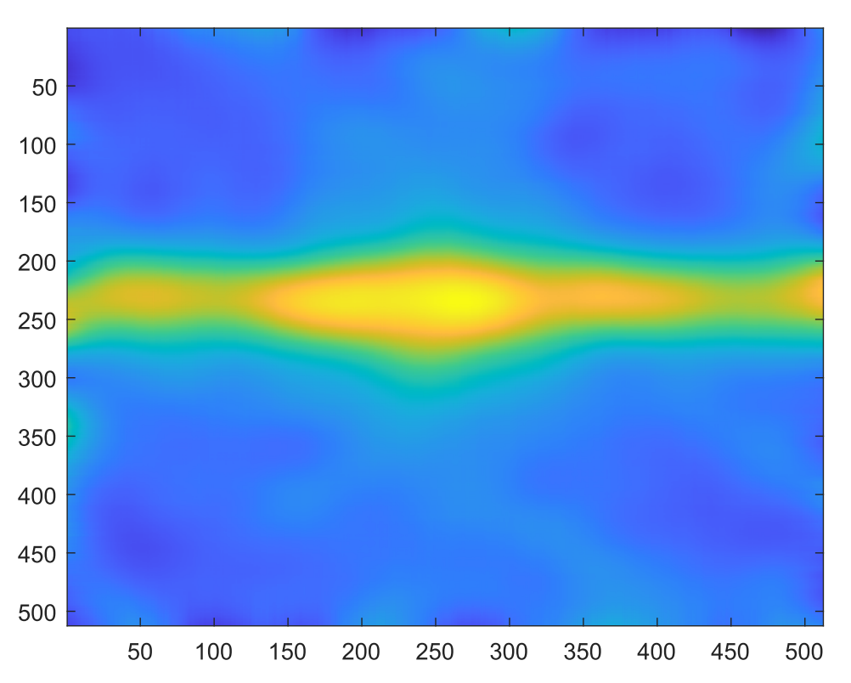
unslowed



slowed

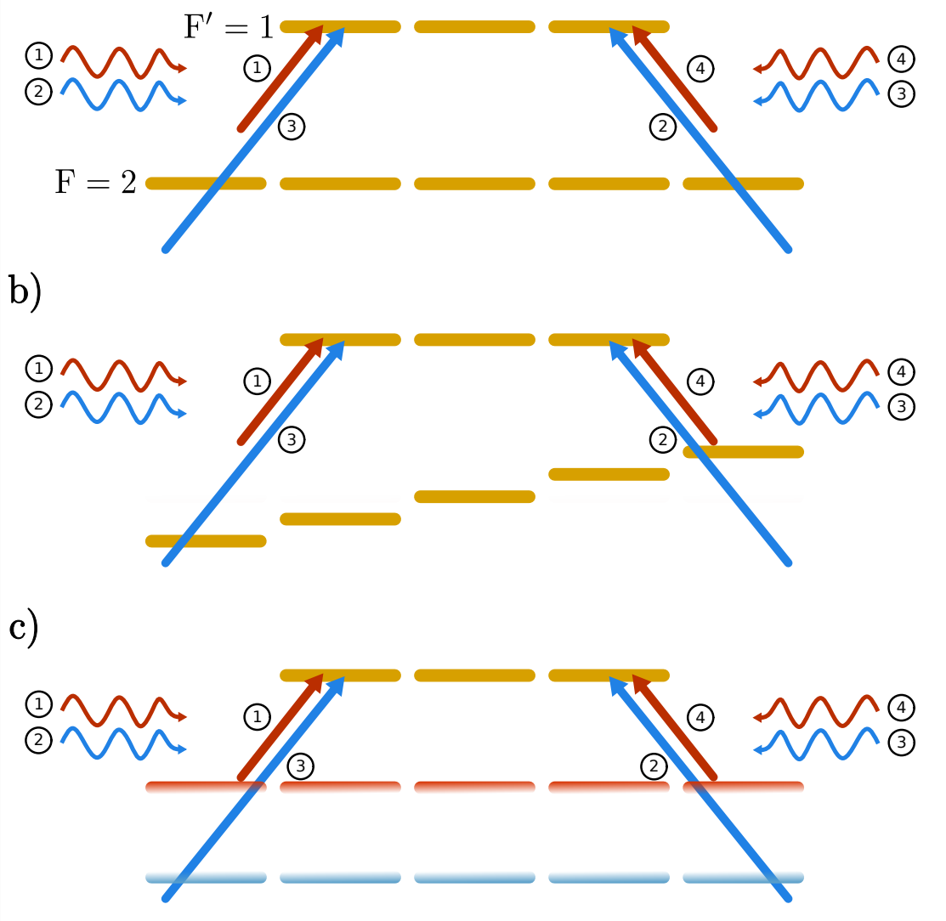


beam on camera



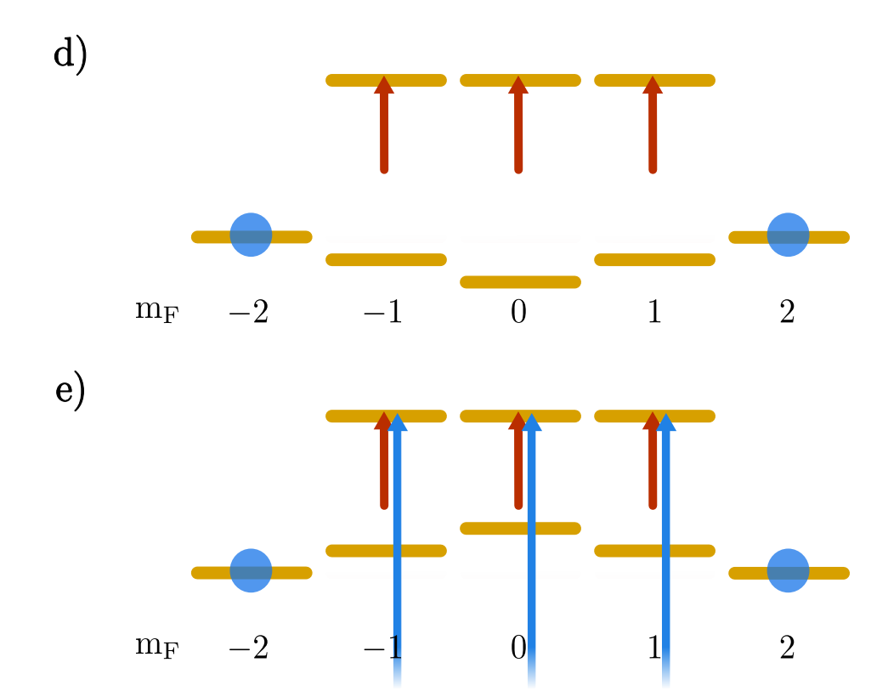
Engineering the Sub-Doppler Force in MOTs

1D MOT Laser Configuration for a *F* = 2 to *F'* = 1 System



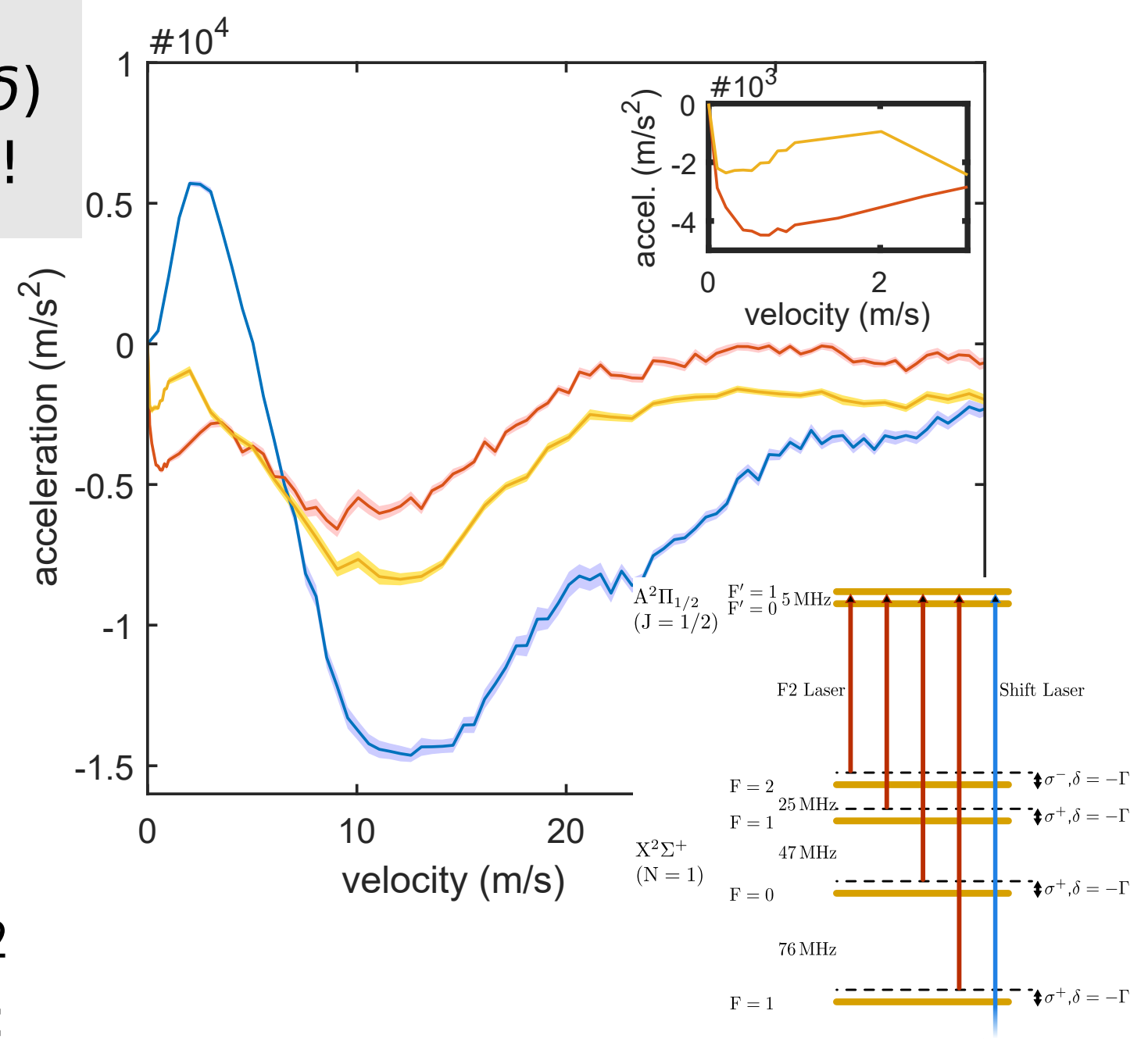
- a) Dual frequency Type-II MOT for magnetic restoring force: Blue detuned laser ③ is σ^+ polarized, red detuned laser ④ is σ^- polarized
- b) Molecule moves right (higher field): ③ & ④ are closer to resonance than ① & ② → net restoring force to left (b)
- c) Lasers ① & ② see blue shifted ground levels, ③ & ④ see red shifted. ④ sooner resonant than ②.

Control
Doppler forces (*Scattering rate ~ I/δ²*)
and
sub-Doppler forces (*AC Stark shift ~ I/δ*)
independently by *I, δ* or *adding lasers*!



- d) AC Stark shift & pumping into $m_F = \pm 2$ in red-detuned cork-screw pol. molasses: Slow/centered molecules 'roll down potential' → Sub-Doppler heating
- e) Reversing sign of AC Stark shift by adding a blue detuned, equally polarized laser.

3D simulation based on optical Bloch equations for a CaF MOT scheme



- Blue curve: 4 laser component, dual frequency MOTs used to date
- Red (yellow) curve: blue-detuned shift laser added with F = 2 laser polarization (reversed). Sub-Doppler cooling below 3 m/s

References

[1] Barry, J. F., Shuman, E. S., Norrgard, E. B., & DeMille, D. (2012). *Laser radiation pressure slowing of a molecular beam.* Physical Review Letters, 108(10), 103002.
[2] Wu, Y., Burau, J. J., Mehling, K., Ye, J. & Ding, S. (2021). *High Phase-Space Density of Laser-Cooled Molecules in an Optical Lattice.* Physical Review Letters, 127, 263201.
[3] Truppe, S., Williams, H. J., Hambach, M., Caldwell, L., Fitch, N. J., Hinds, E. A., ... & Tarbutt, M. R. (2017). *Molecules cooled below the Doppler limit.* Nature Physics, 13(12), 1173.
[4] Anderegg, L., Augenbraun, B. L., Chae, E., Hemmerling, B., Hutzler, N. R., Ravi, A., ... & Doyle, J. M. (2017). *Radio frequency magneto-optical trapping of CaF with high density.* Physical review letters, 119(10), 103201.
[5] Petzold, M., Kaebert, P., Gersema, P., Siercke, M., & Ospelkaus, S. (2018). *A Zeeman slower for diatomic molecules.* New Journal of Physics, 20(4), 042001.
[6] Kaebert, P., Stepanove, M., Poll, T., Petzold, M., Xu, S., Siercke, M., & Ospelkaus, S. (2021). *Characterizing the Zeeman slowing force for 40Ca19F molecules.* New Journal of Physics, 23, 093013.

Gefördert durch
DFG Deutsche Forschungsgemeinschaft