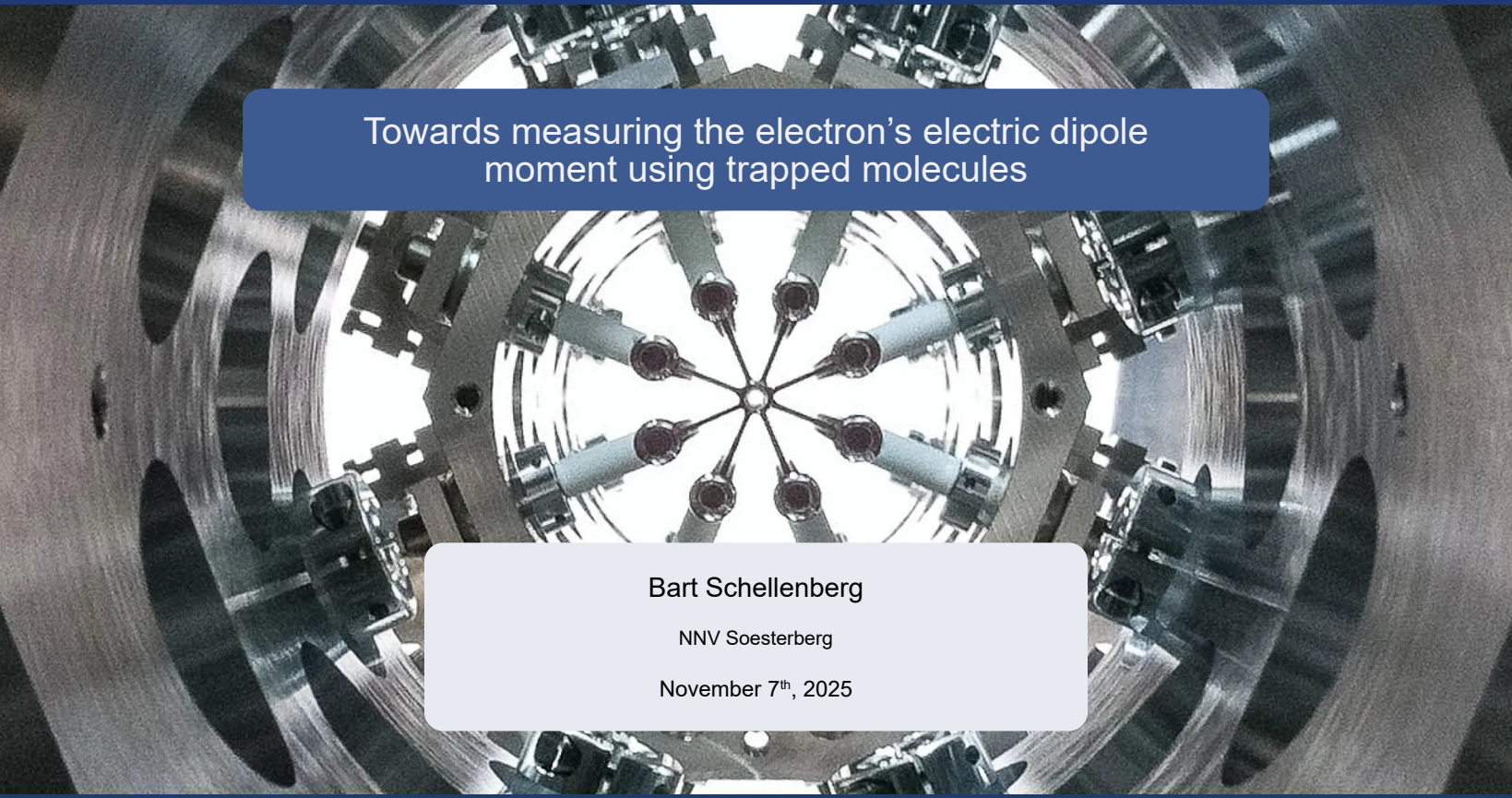


Towards measuring the electron's electric dipole moment using trapped molecules

Bart Schellenberg

NNV Soesterberg

November 7th, 2025

university of groningen | Nikhef | VU Vrije Universiteit Amsterdam | University of Amsterdam | NWO

NL-eEDM collaboration

Particle Physics

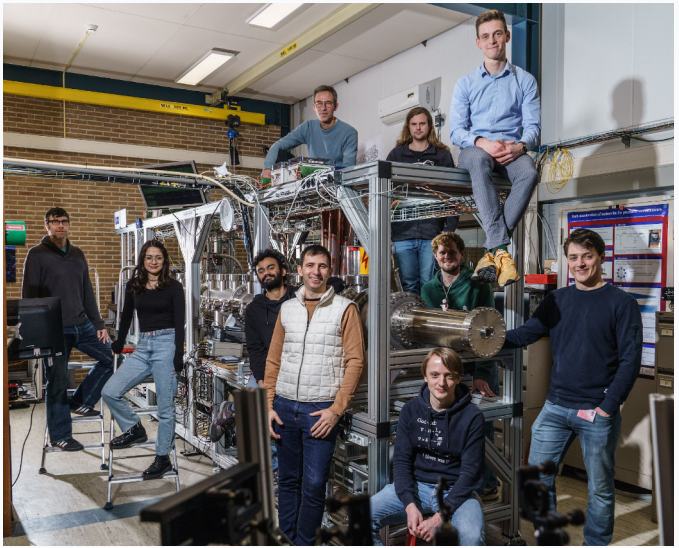
Jordy de Vries
Heleen Mulder
Rob Timmermans

Quantum Chemistry

Anastasia Borschevsky
Lukáš Pašteka
Agustín Aucar
Eifion Prinsen

Experiments

Steven Hoekstra
Hendrick Bethlem
Lorenz Willman
Steven Jones
Wim Ubachs
Joost van Hofslot
Jelmer Levenga
Bastiaan Nijman
Ties Fikkers
Lucas van Sloten
Bart Schellenberg
Nithesh Balasubramanian
Izabella Thompson
Jason Arzinos
Marianne Westerhof



eEDM as a probe for BSM theories

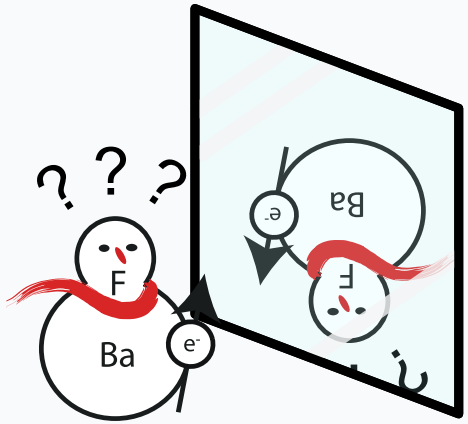
The EDM of a fundamental particle describes a CP violating interaction.

At $\mathcal{O}^{d=6}$

$$H_{\text{eEDM}} = 2d_e \vec{S} \cdot \vec{E}$$

pseudo-vector vector

CP violation in SM insufficient to explain observed matter-anti-matter asymmetry.



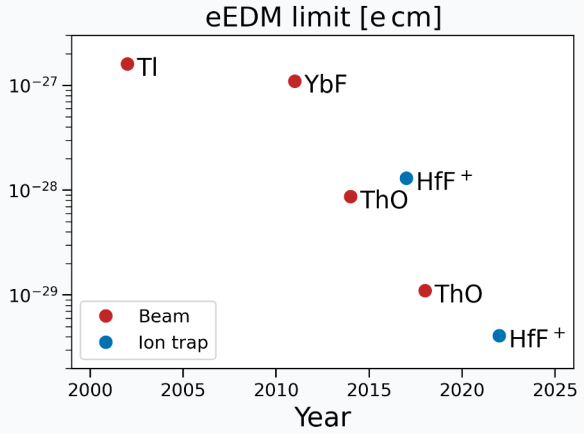
eEDM as a probe for BSM theories

Measure shift in molecular energy that correlates with electric field reversal.

Shot-noise-limited sensitivity:

$$\sigma = \frac{\hbar}{2\,|\Omega|\,W_d\,\tau\,\sqrt{N_p}}$$

- state-dependent factor
- heavy, polar molecule
- interaction time
- number of molecules



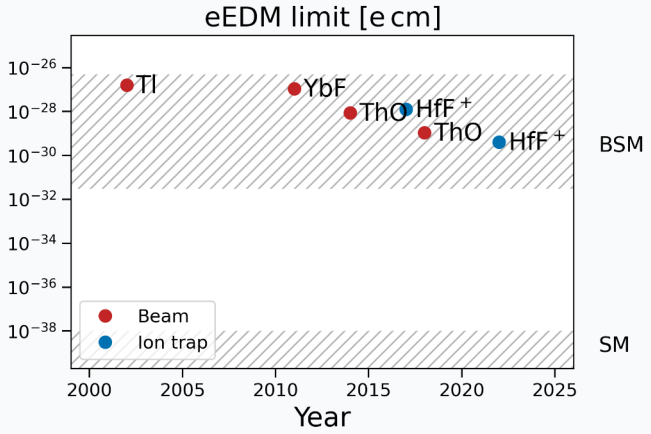
eEDM as a probe for BSM theories

Measure shift in molecular energy that correlates with electric field reversal.

Shot-noise-limited sensitivity:

$$\sigma = \frac{\hbar}{2\,|\Omega|\,W_d\,\tau\,\sqrt{N_p}}$$

- state-dependent factor
- heavy, polar molecule
- interaction time
- number of molecules



eEDM as a probe for BSM theories

Measure shift in molecular energy that correlates with electric field reversal.

Shot-noise-limited sensitivity:

$$\sigma = \frac{\hbar}{2\,|\Omega|\,W_d\,\tau\,\sqrt{N_p}}$$

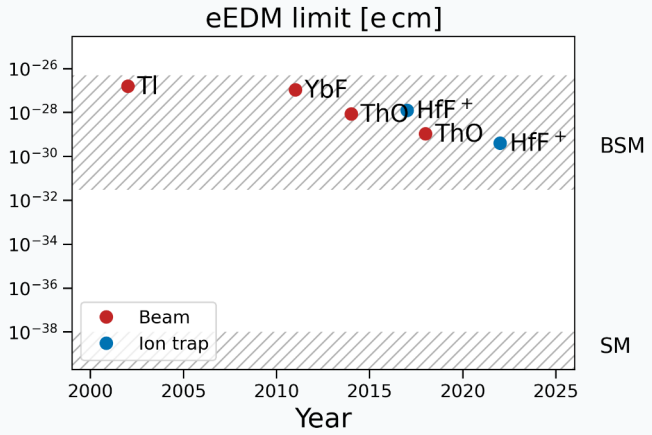
state-dependent factor

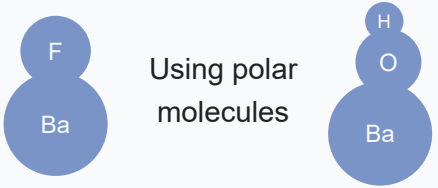
heavy, polar molecule

interaction time

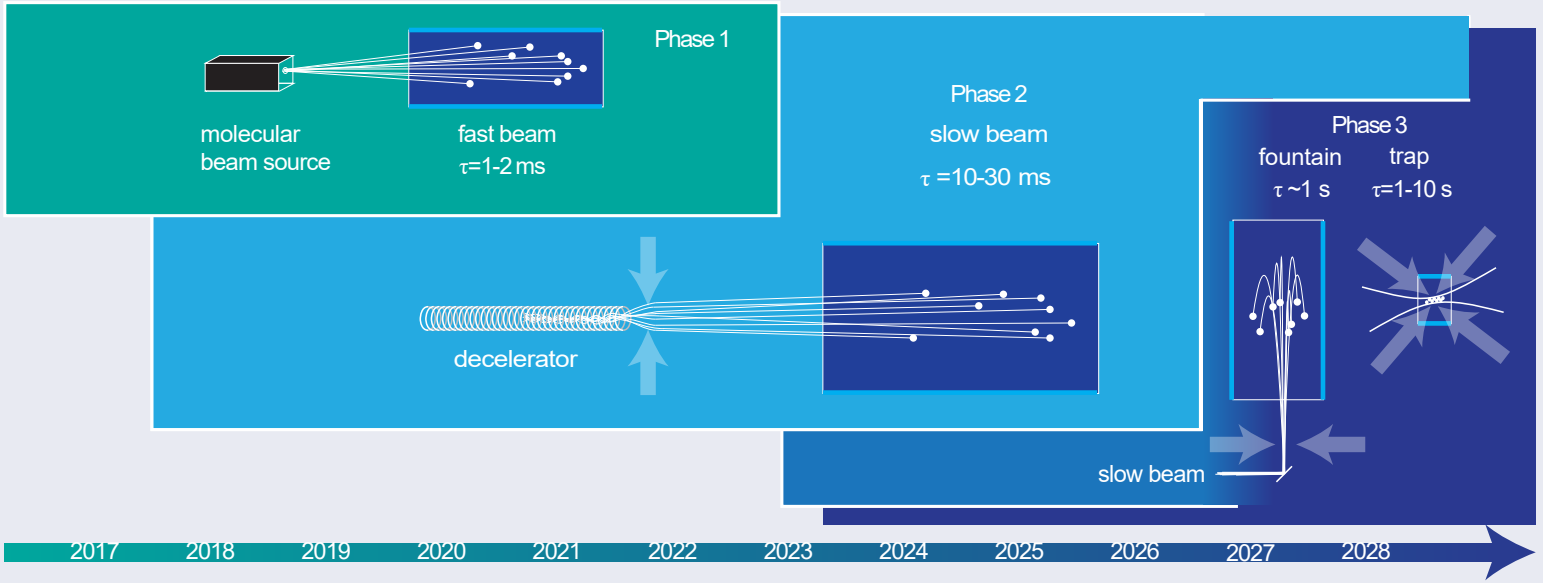
number of molecules

Can we increase τ, even if that means sacrificing N_p ?





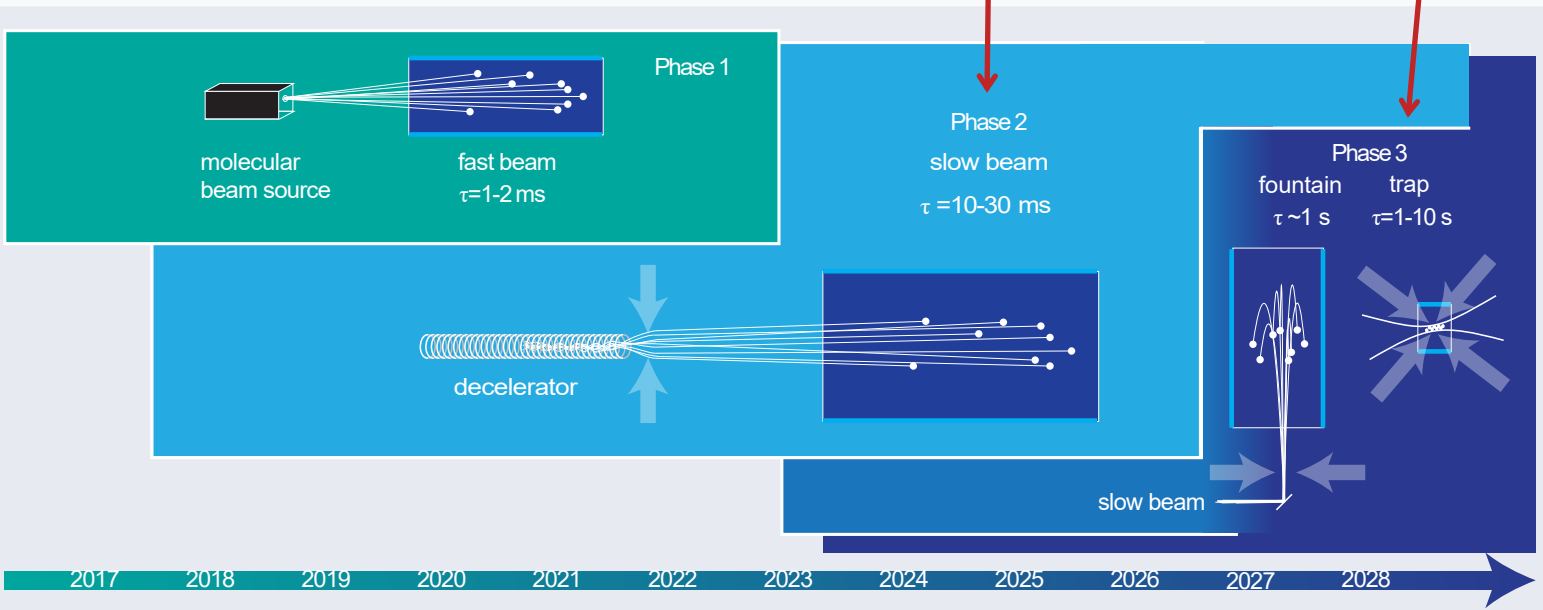
The NL-eEDM experiment



The NL-eEDM experiment

Talk by Bastiaan Nijman:
"Background free detection of BaF for eEDM searches"
(15:20)

This talk



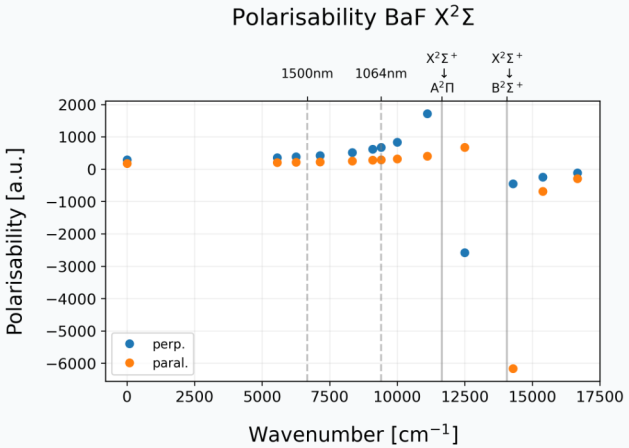
How to make an optical trap

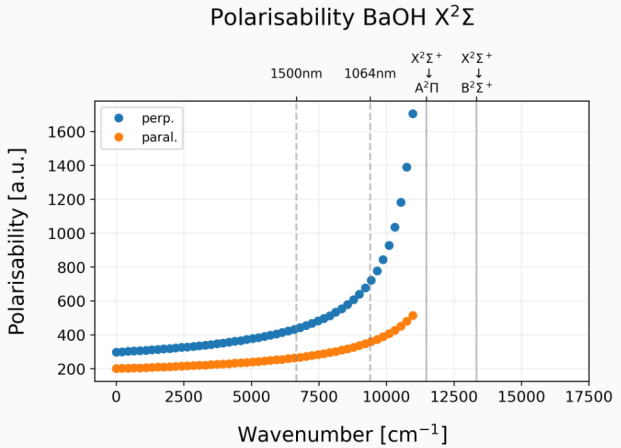
Understanding how molecules interact with light.

$$\Delta E \approx -\frac{1}{4}\,\alpha\,\mathcal{E}^2$$

optical field

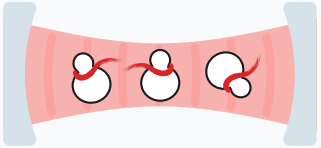
polarisability





Prinsen et al. arXiv:2510.19564
Schellenberg et al. arXiv:2507.17521

Lattice Trap



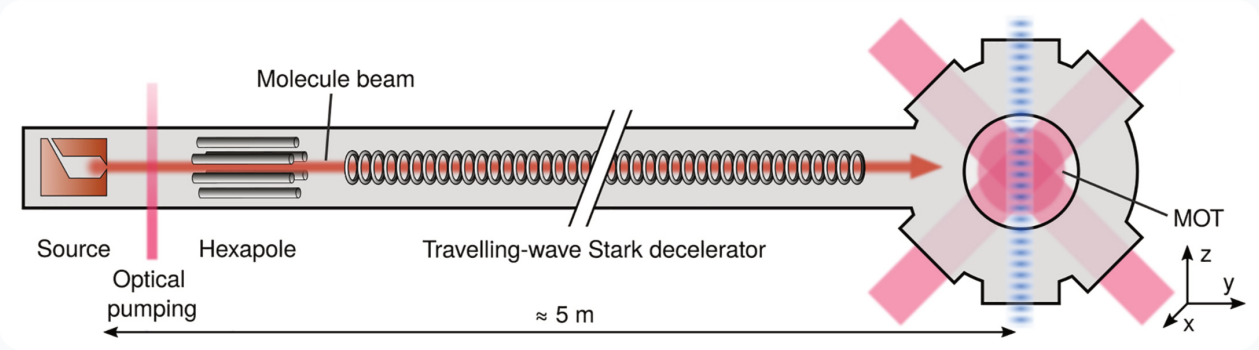
Power	~ 10 W
Waist	~ 150 μm
Depth	~ 10 mK
Wavelength	1064 nm

From source:

- ~ 10^8 molecules
- Velocity: ~ 150 - 200 m/s
- Temperature: ~ 5 - 20 K
- Volume: ~ cm^3

→ **Cooling required**

Sketch of potential loading setup



Production

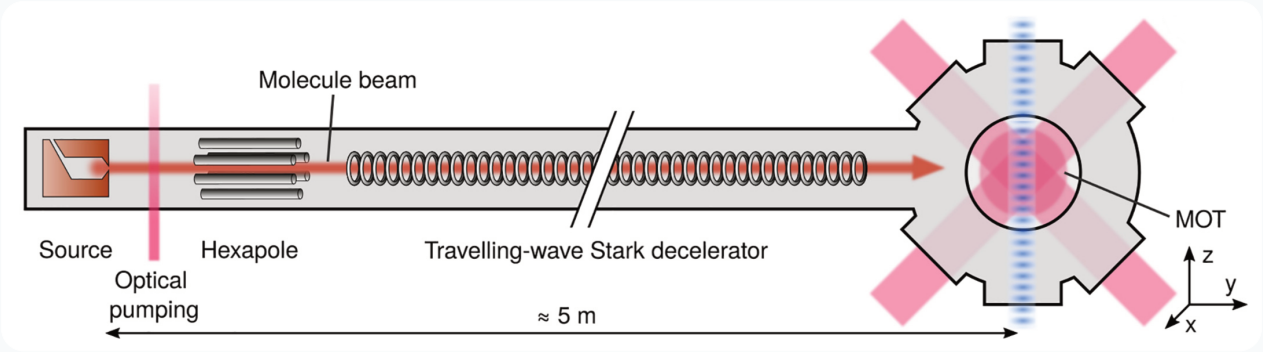
Cooling

Trapping

Bause et al. Phys. Rev. A 111, 062815 (2025)

Sketch of potential loading setup

Possible, but very challenging



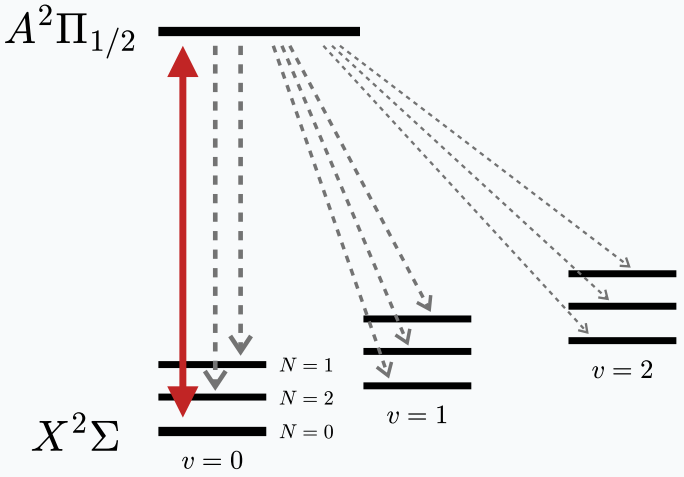
Production

Cooling

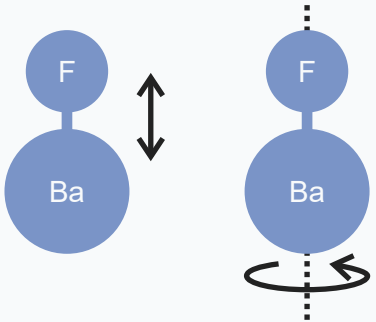
Trapping

Bause et al. Phys. Rev. A 111, 062815 (2025)

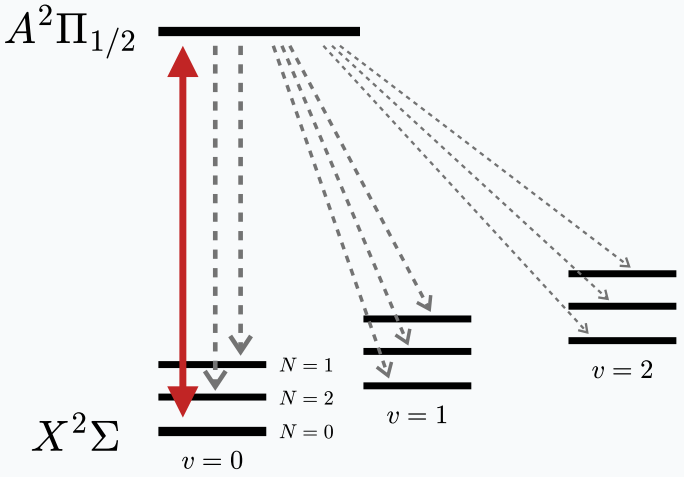
Laser cooling



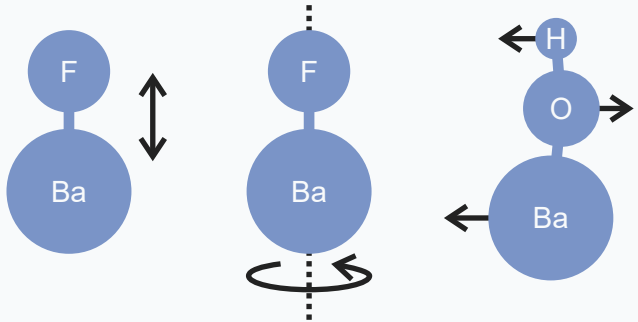
$$H = H_{\text{electronic}} + H_{\text{vibration}} + \\ + H_{\text{rotation}} + H_{\text{fine}} + H_{\text{hyperfine}}$$



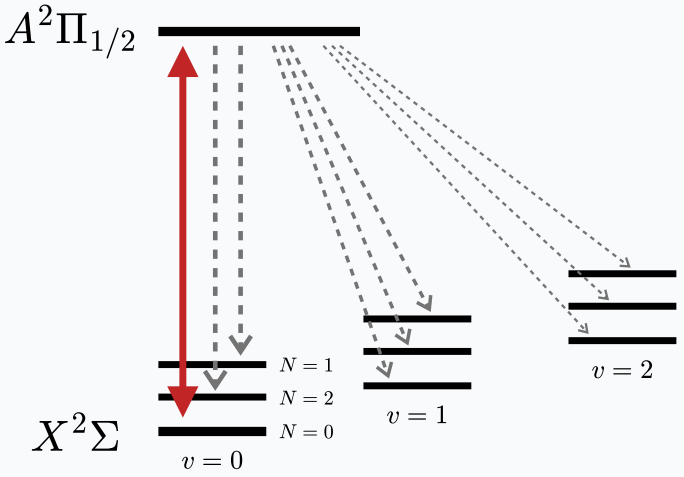
Laser cooling



$$H = H_{\text{electronic}} + H_{\text{vibration}} + H_{\text{bending}} + \\ + H_{\text{rotation}} + H_{\text{fine}} + H_{\text{hyperfine}}$$

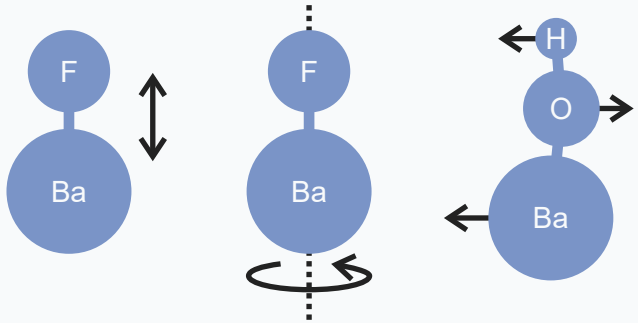


Laser cooling



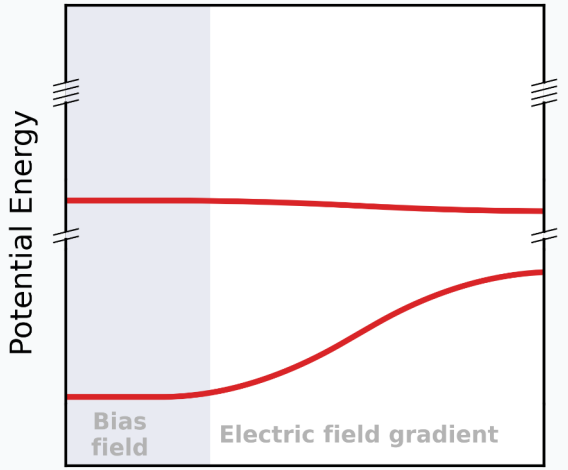
$$H = H_{\text{electronic}} + H_{\text{vibration}} + H_{\text{bending}} + \\ + H_{\text{rotation}} + H_{\text{fine}} + H_{\text{hyperfine}}$$

~ 5-10 lasers to keep cycle closed for BaF MOT



Single-photon trap loading

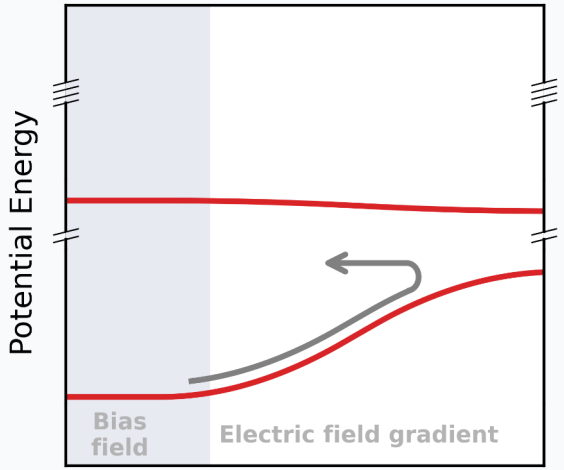
Exploiting state dependent potentials



Schellenberg et al. arXiv:2507.17521

Exploiting state dependent potentials

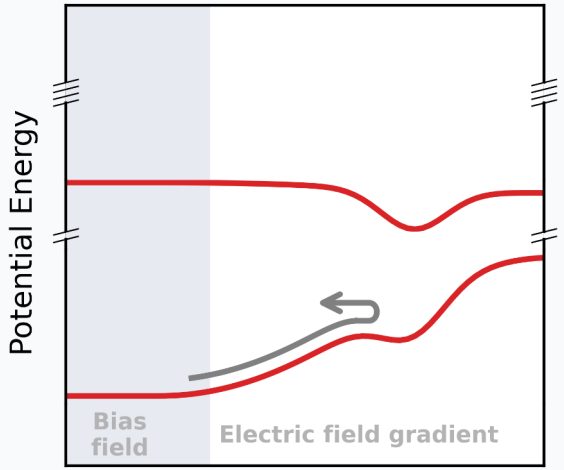
$|1\rangle$ Molecules fly into potential barrier and are reflected.



Schellenberg et al. arXiv:2507.17521

Exploiting state dependent potentials

$|1\rangle$ Molecules fly into potential barrier and are reflected.
Optical trap is placed at the turning point.



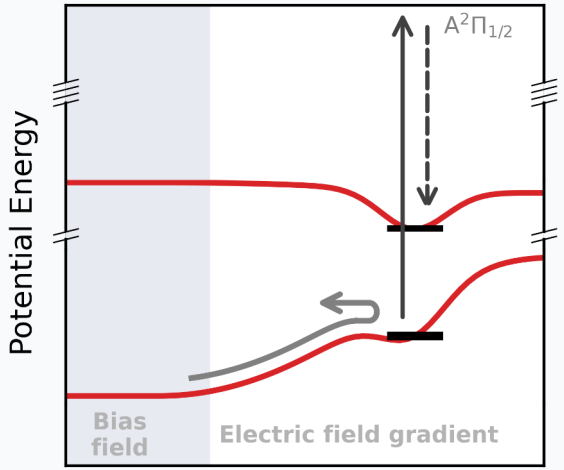
Schellenberg et al. arXiv:2507.17521

Exploiting state dependent potentials

$|1\rangle$ Molecules fly into potential barrier and are reflected.
Optical trap is placed at the turning point.

$|2\rangle$ Molecules are excited when their kinetic energy is minimal.

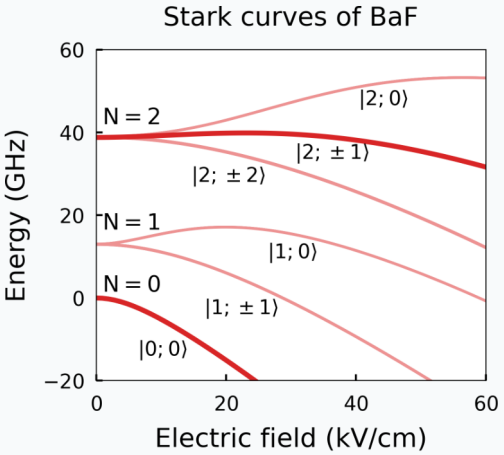
$|3\rangle$ Spontaneous decay to trapped state, whose coupling to E is small.



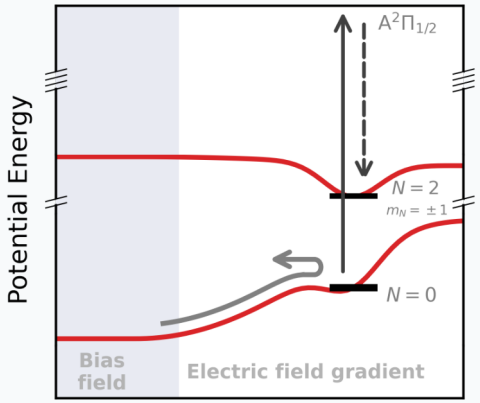
Schellenberg et al. arXiv:2507.17521

Exploiting state dependent potentials

Trap loading without optical cycling.



Rotational structure common in linear molecules.



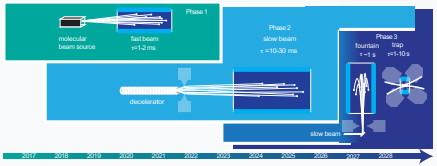
Estimated Performance (using Stark decelerator)			
Trap depth	7.3 mK	Capture rate	~ 0.04 %
Lifetime	~ 1 second	Number in trap	~ 880

Schellenberg et al. arXiv:2507.17521

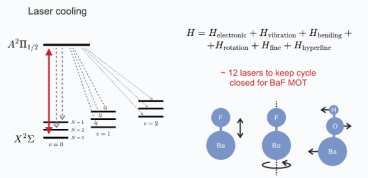
Conclusion

Summary

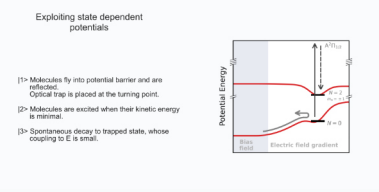
Traps offer longer interaction time



Cooling is challenging



Investigating alternative routes

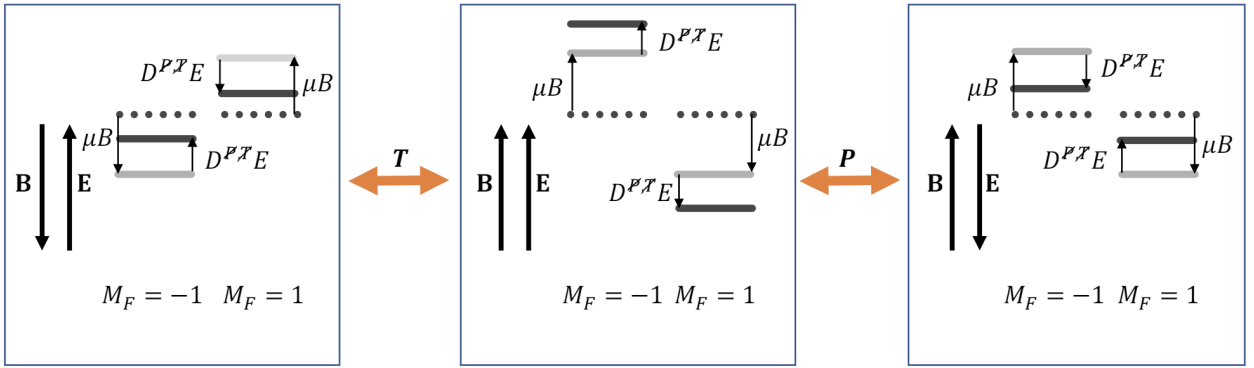


Backup slides

eEDM as a probe for BSM theories

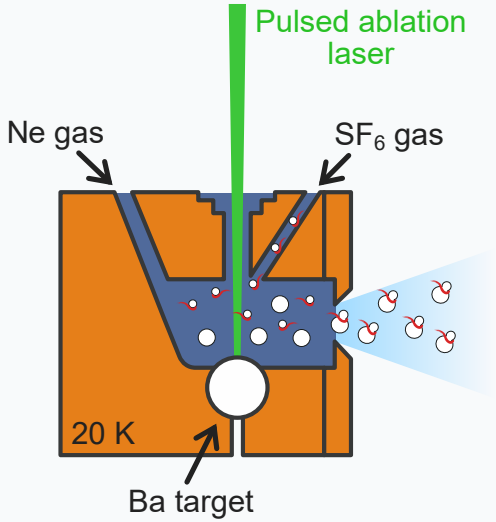
Molecular energy levels: $H = \ldots - \vec{\mu} \cdot \vec{B} - \vec{D}^{P,T} \cdot \vec{E}$

Levels shift in E and B field:



Measuring Ramsey interference between hyperfine M_F levels.

Figure adapted from A. Boeschoten (2023) [PhD thesis]



Output:

150 - 200 m/s

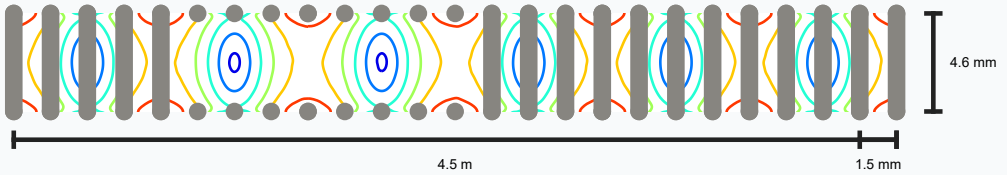
5 - 20 K

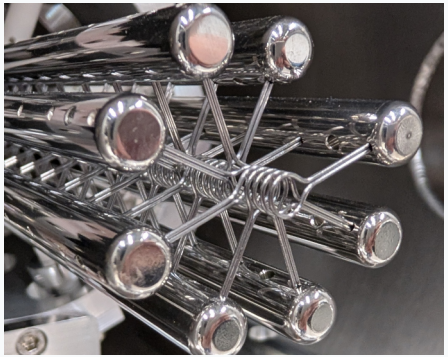
~10^8 molecules

Work by:
* Ties Fikkers
* Nithesh Balasubramanian

(Longitudinal) Stark deceleration

3D moving electrostatic traps to decelerate molecules





Output:

0 - 30 m/s

500 mK

~10^6 molecules

Work by:
* Lucas van Sloten
* Marianne Westerhof