

Trapped molecules are the best

Steven Hoekstra for NL-eEDM team, Les Houches, 1-6 March 2026

General strategy **with points of attention**

- Motivation clear: new physics is out there to discover! **Many sources that need disentangling**
- Many interesting nuclei to choose from, guided by theory **A moving target - theory crucial**
- Huge enhancements through molecular structure **Spectroscopy and quantum chemistry**
- Recipe: **Once an approach is chosen, change takes (additional) resources**
 - step 1: Form molecules **in sufficient quantity, and be able to handle them**
 - step 2: Collect many of them in one spot for some time **they fly away: cooling and control**
 - step 3: Do the measurement! **push statistics and control all systematics at same level**

Comparing different approaches

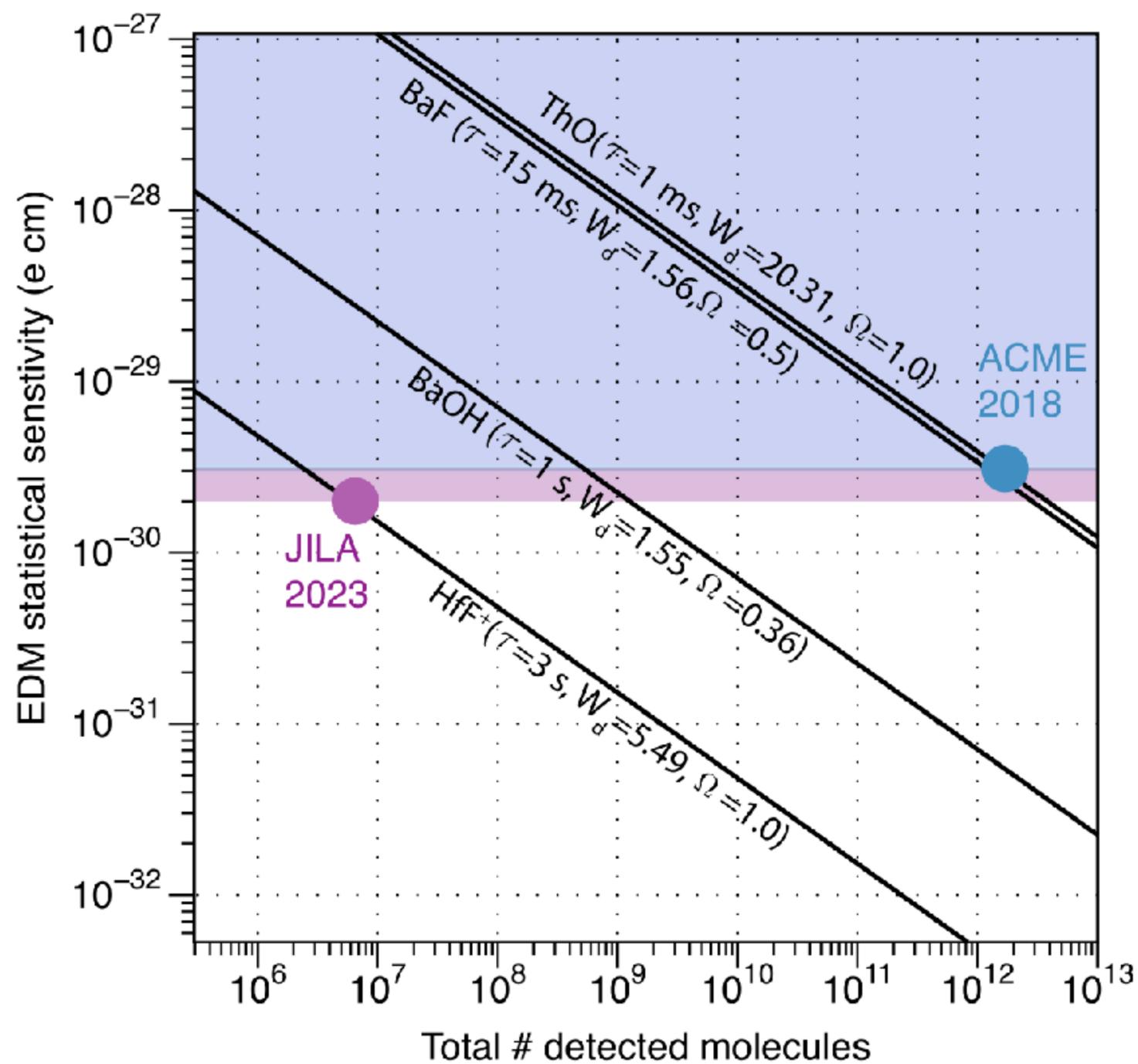


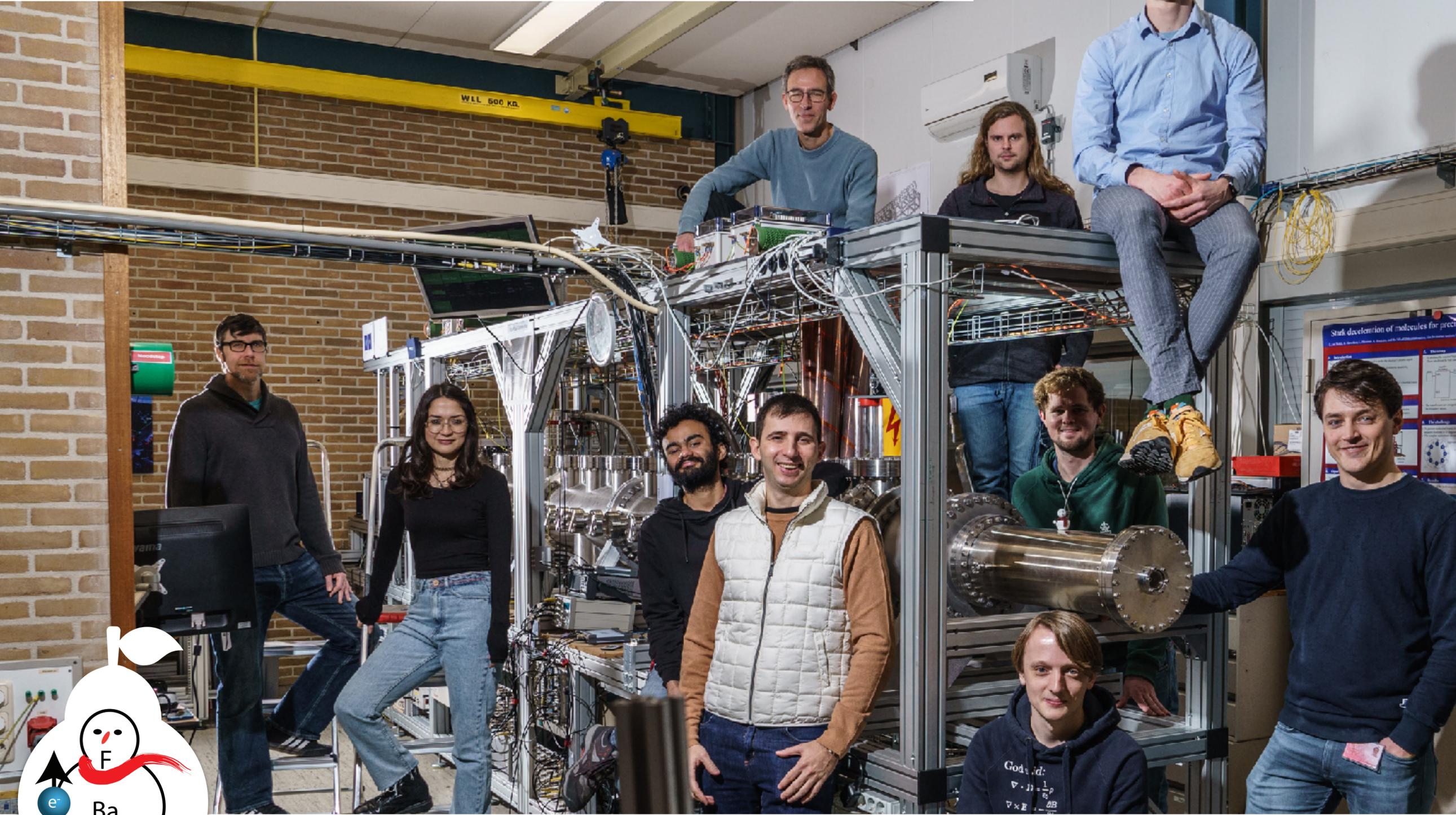
FIG. 1. Overview of statistical sensitivity of different experimental platforms. Each line corresponds to a combination of τ , $|\langle \Omega \rangle|$ and W_d [in units of $10^{24} h \text{ Hz}/(e \text{ cm})$] which is typical for a given molecule species. The dots represent the two most recent experimental results [6,7], taking into account only statistical uncertainty. The blue and purple shaded regions are excluded by the ThO and HfF⁺ experiments, respectively. The $\langle \Omega \rangle$ value for not fully polarized BaOH is calculated in Sec. III B. It can be seen that our target sensitivity of $10^{-30} e \text{ cm}$ can be reached with $N_p = 5 \times 10^9$ BaOH molecules at the shot noise limit.

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

Our approach

- Form a complete team: AMO experimentalists, quantum chemistry, particle physics theory

Teamwork at the intersection of particle physics,
precision laser spectroscopy and quantum chemistry!



Current team:

Particle physics theory

- Jordy de Vries
- Rob Timmermans
- Heleen Mulder
- Lemonia Gialidi

Quantum chemistry

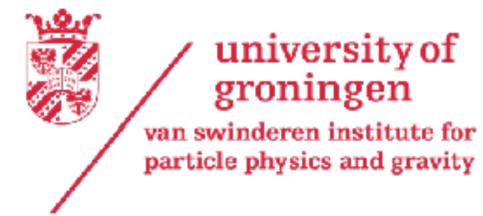
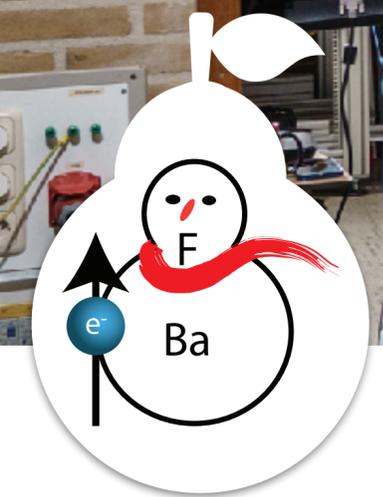
- Anastasia Borschevsky
- Lukas Pastecka
- Agustin Aucar
- Eiffion Prinsen

Precision experiments

- Steven Hoekstra (PI)
- Lorenz Willmann
- Rick Bethlem
- Steve Jones
- Wim Ubachs
- Lucas van Sloten
- Jelmer Levenga
- Bastiaan Nijman
- Joost van Hofslot
- Bart Schellenberg
- Ties Fikkers
- Nithesh Balasubramanian
- Izabella Thompson
- Marianne Westerhof
- William Miyahira
- Iason Arzinos

Technical staff

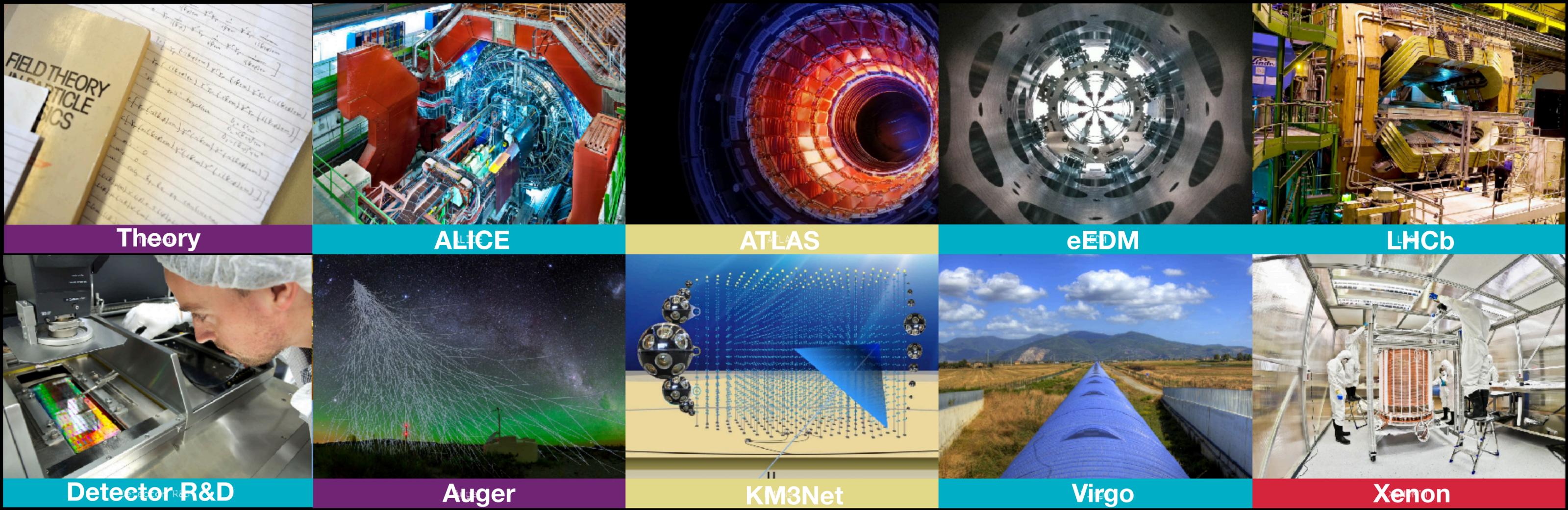
- Leo Huisman
- Oliver Böll
- Robert Datema
- Nikhef workshops



Our approach

- Form a complete team: AMO experimentalists, quantum chemistry, particle physics theory
- Find a stable supporting environment that appreciates physics impact and timescales

NL-eEDM: A Nikhef research programme started in 2017...



Dutch National Institute for (astro)Particle Physics

...using molecules and lasers

Our approach

- Form a complete team: AMO experimentalists, quantum chemistry, particle physics theory
- Find a stable supporting environment that appreciates physics impact and timescales
- Build up a research program that gradually works towards increased sensitivity

The eEDM program

Minimize statistical uncertainty

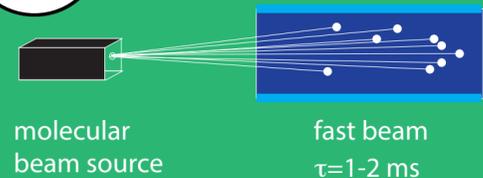
1

$$S \propto$$

$$E \tau \sqrt{N}$$



2017-2025



Phase 1
Fast beam of BaF molecules

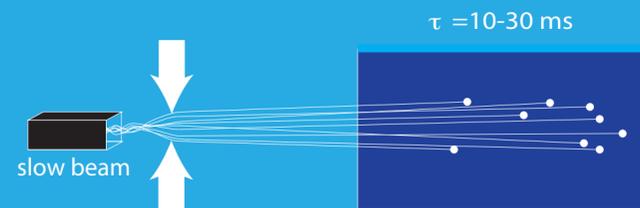
Heavy polar molecules give a high sensitivity to new physics

Slow and cold beams provide a long interaction time

Using entanglement enables linear scaling with the number of molecules

2023-2028

Phase 2
Slow and cold molecular beam



Demonstrate an all-optical superposition state creation

Slow beams push magnetic field sensitivity to the limit

Polyatomic molecules provide co-magnetometer states

Theory framework: connect eEDM experiments to high-energy particle physics

2023-2030

Phase 3
Fountain, Trap
Better molecules



2025-2035

Phase 4
Beyond the quantum limit

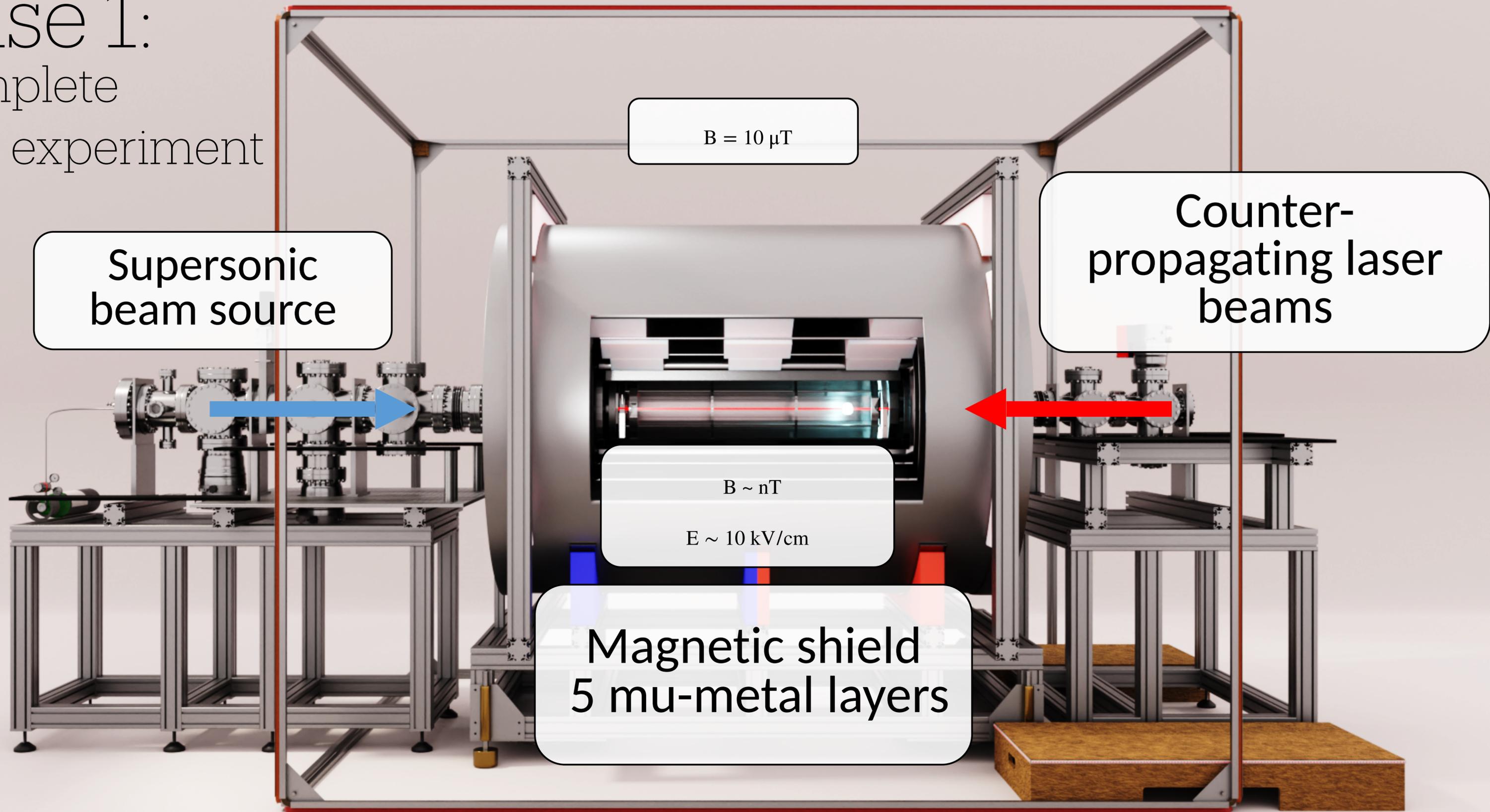


Control systematic effects

Status update BaF eEDM

Phase 1

Phase 1: A complete eEDM experiment



Supersonic
beam source

$B = 10 \mu\text{T}$

Counter-
propagating laser
beams

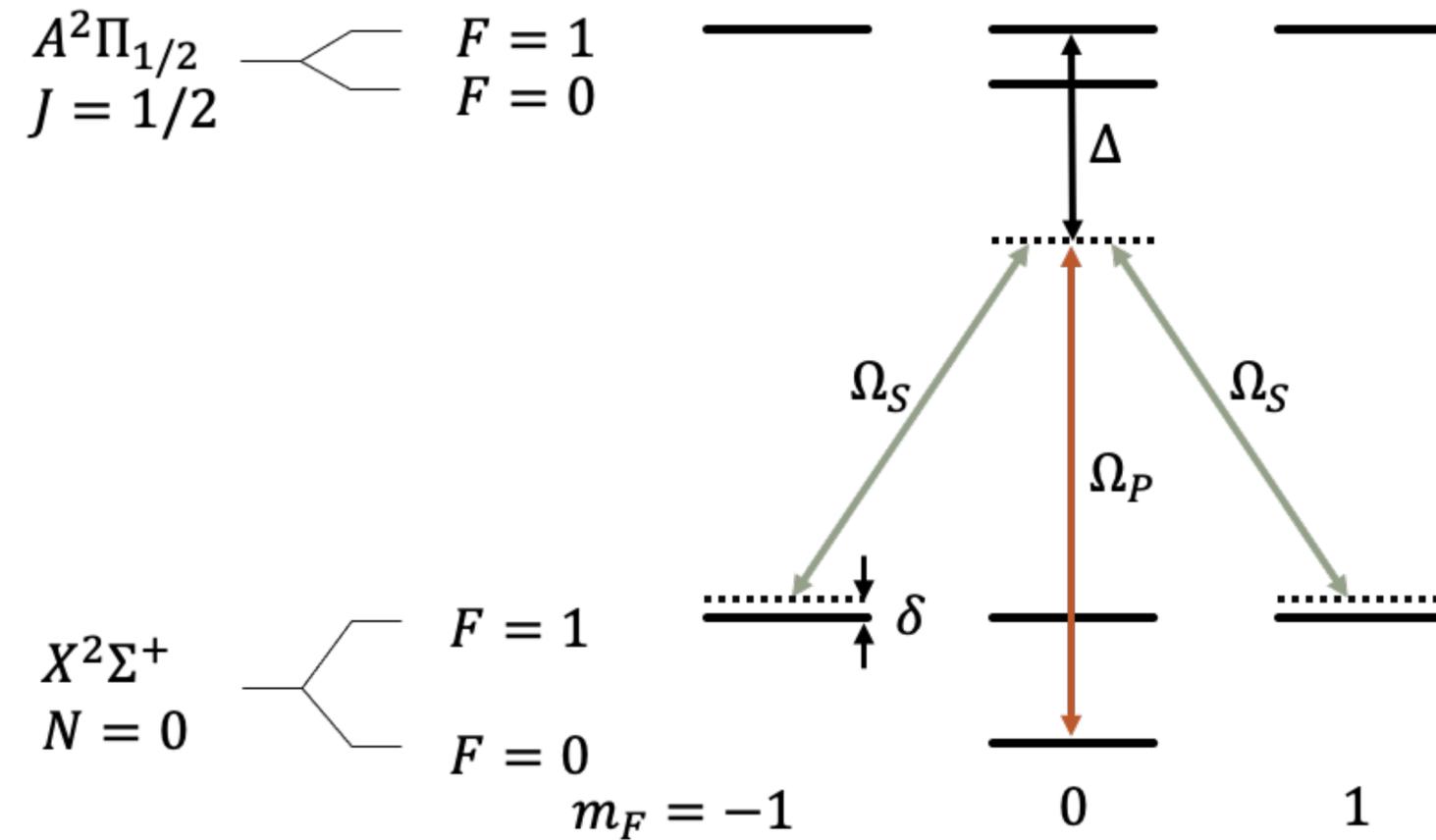
$B \sim \text{nT}$
 $E \sim 10 \text{ kV/cm}$

Magnetic shield
5 mu-metal layers

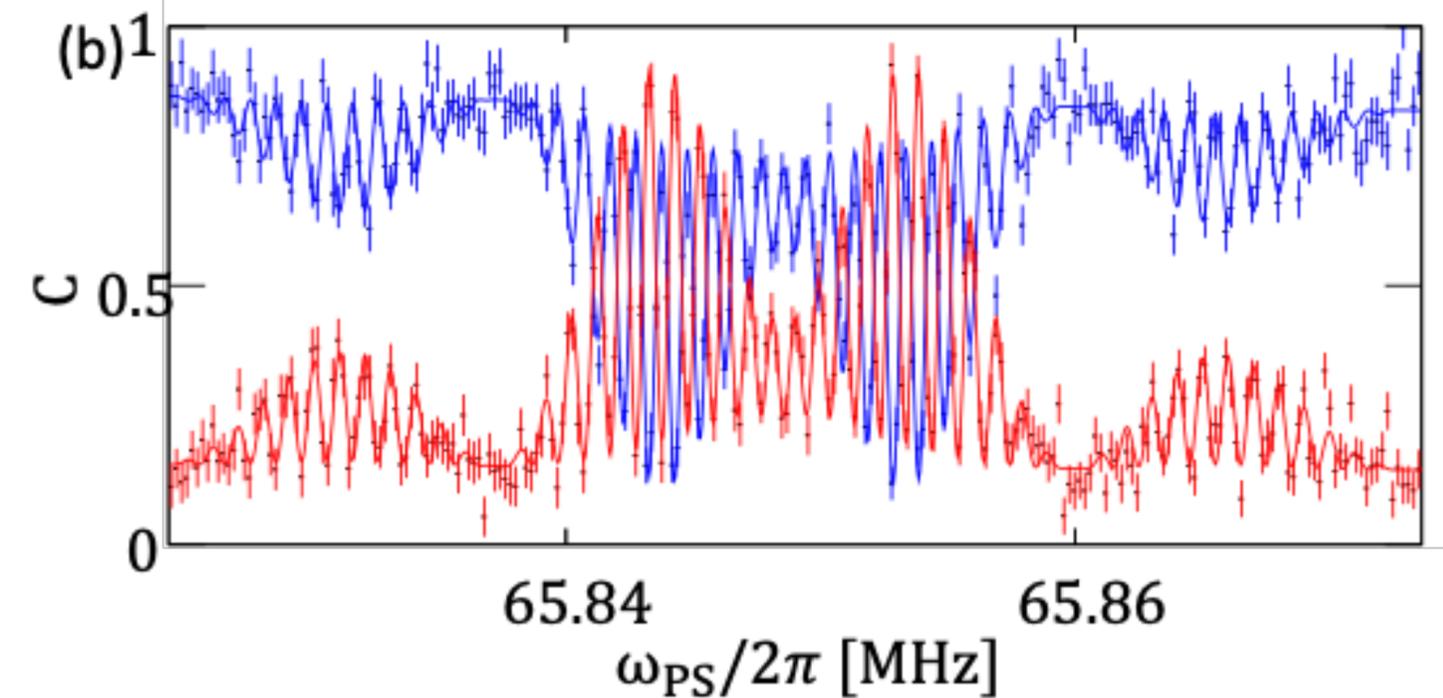
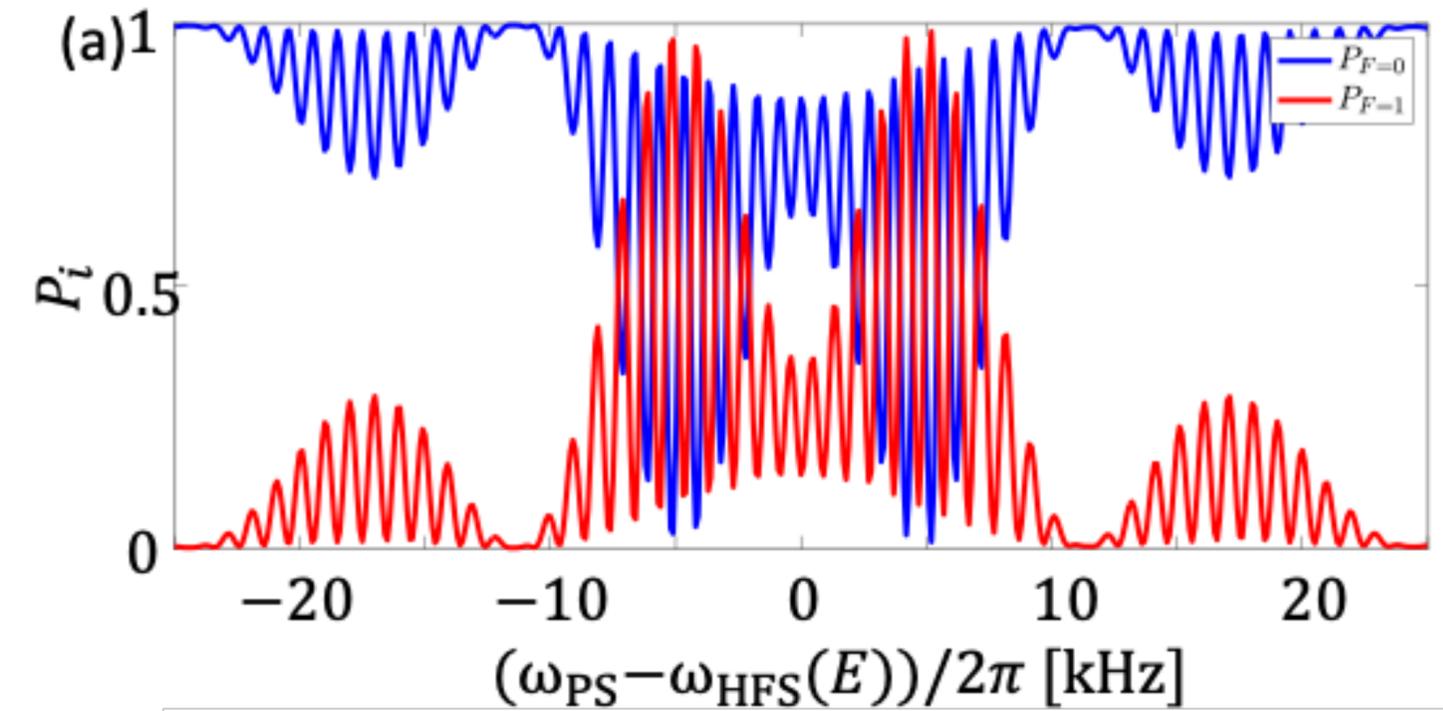


Ramsey interferometry

A. Boeschoten et al., Phys. Rev. A 110, L010801 (2024)



Optical Bloch equations



Ramsey interferometry

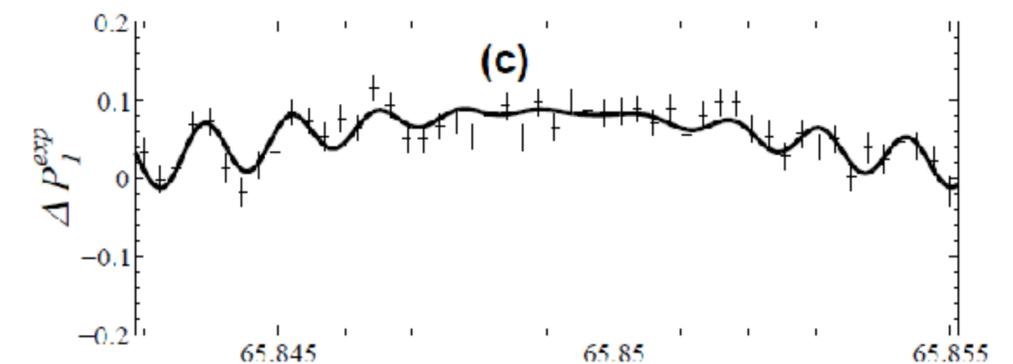
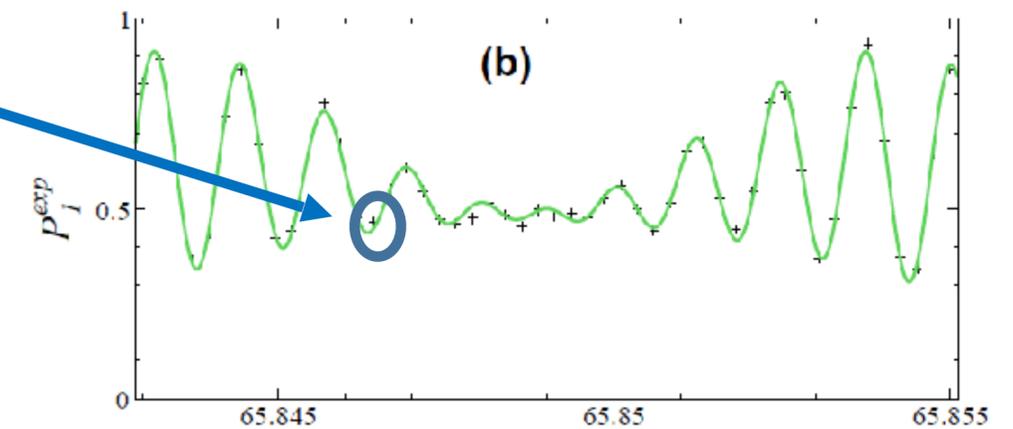
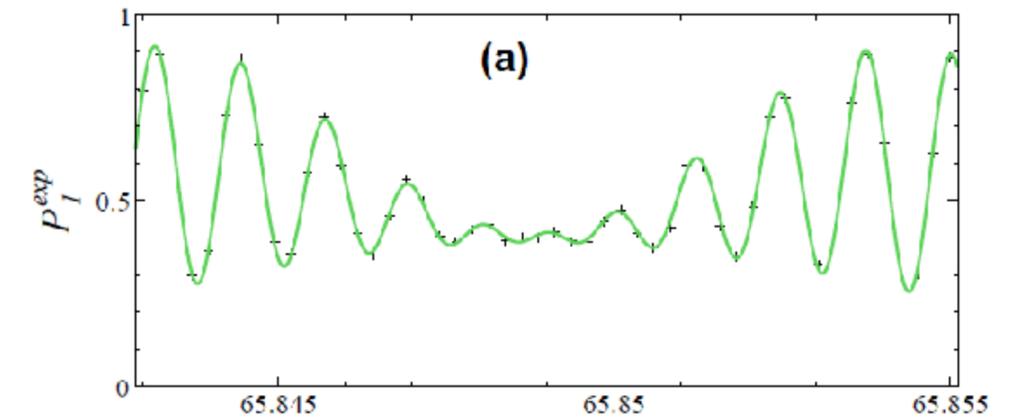
A. Boeschoten et al., Phys. Rev. A 110, L010801 (2024)

In one measurement:

- Symmetric experiment
 - Reversal of field directions
 - Essential step for EDM sensitivity
- Different velocity classes (typically 5)
 - Detuning Δ , Rabi Frequencies Ω
 - Field gradients
- Hyperfine Detuning δ (typically 50)
 - Electric Field E, field gradients

Single state of machine

$$P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$$



Gives ~200 different independent states of the machine, all sensitive to EDM

Essential for limit on systematics

Statistics and Systematics

Boeschoten et al (NL-eEDM collaboration), arXiv:2601.21781

Item	Phase 1
Molecular Beam Source	
Source type	supersonic [29]
Brightness (molecules/sr/pulse)	3.3×10^9
Repetition rate (Hz)	10
Forward velocity (m/s)	600 ± 30
Laser Cooling	
Transverse cooling	1
Rotational cooling	1
Spin Precession Parameters	
Electric Field (kV/cm)	2
Polarization factor $P(E_{\text{ext}})$	0.16
Precession Time (ms)	1
Precession fraction	0.9
Interference contrast	0.9
Fluorescence Detection	
Signal n_{sp}	1
Light collection	0.02
Quantum efficiency	0.07
Average photon rate (s^{-1})	200
Statistical sensitivity ($e \text{ cm day}^{-1}$)	5×10^{-25}

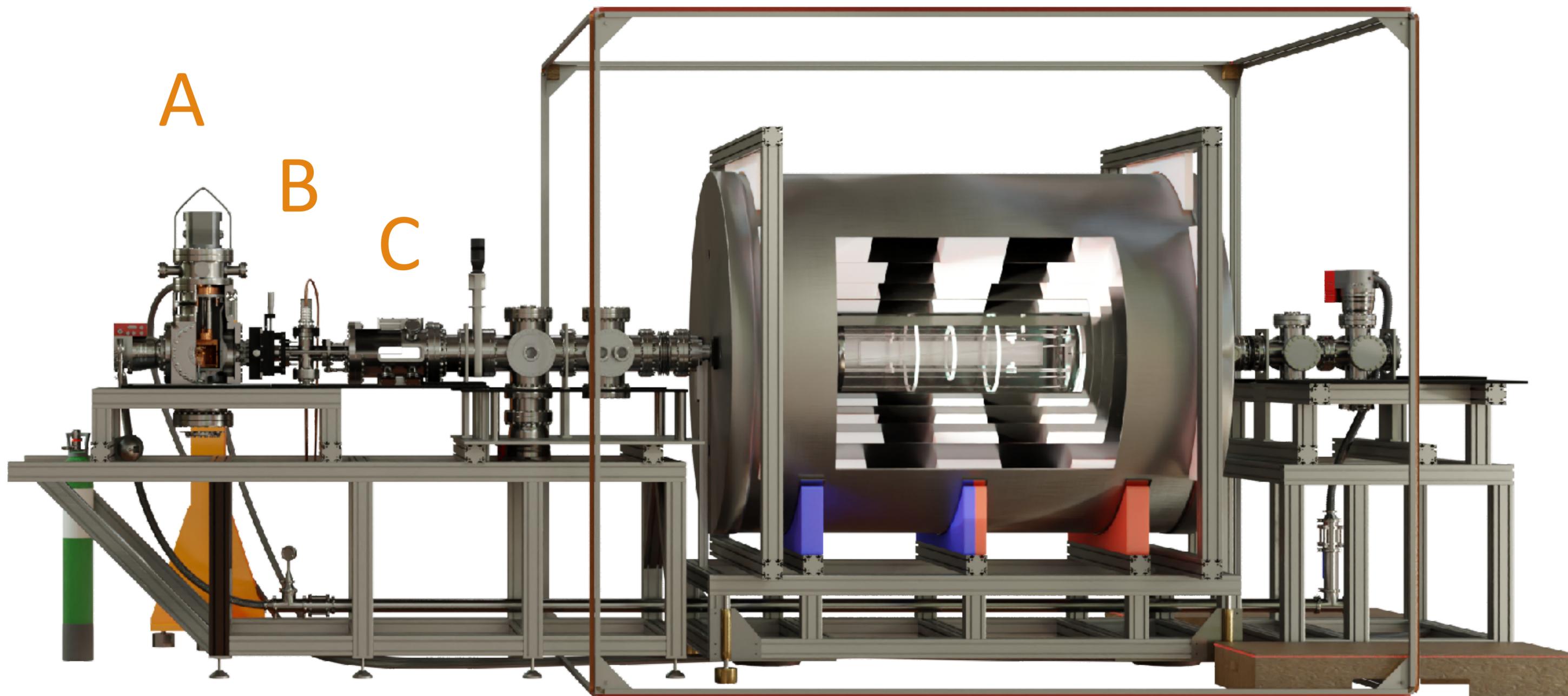
Statistics and Systematics

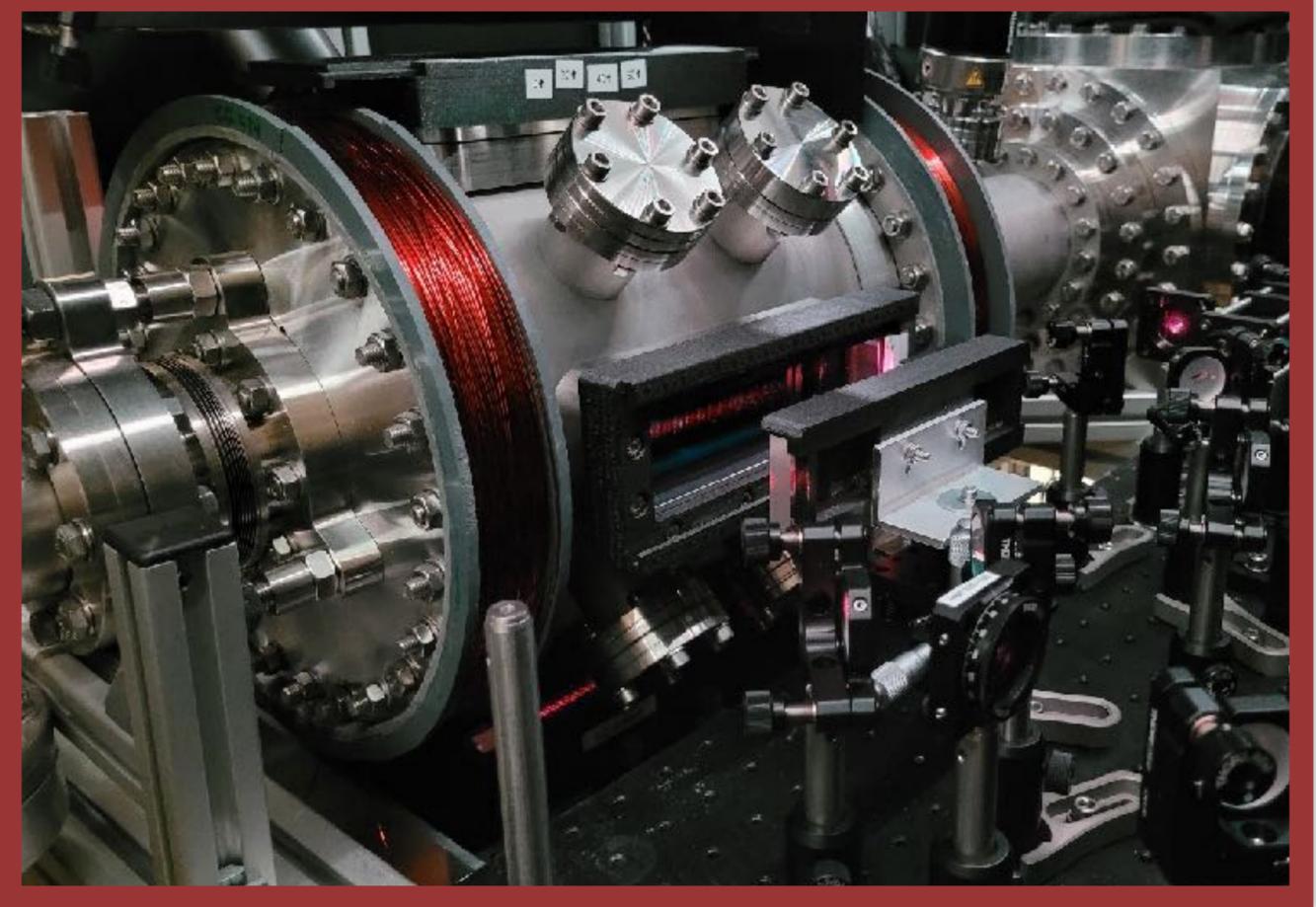
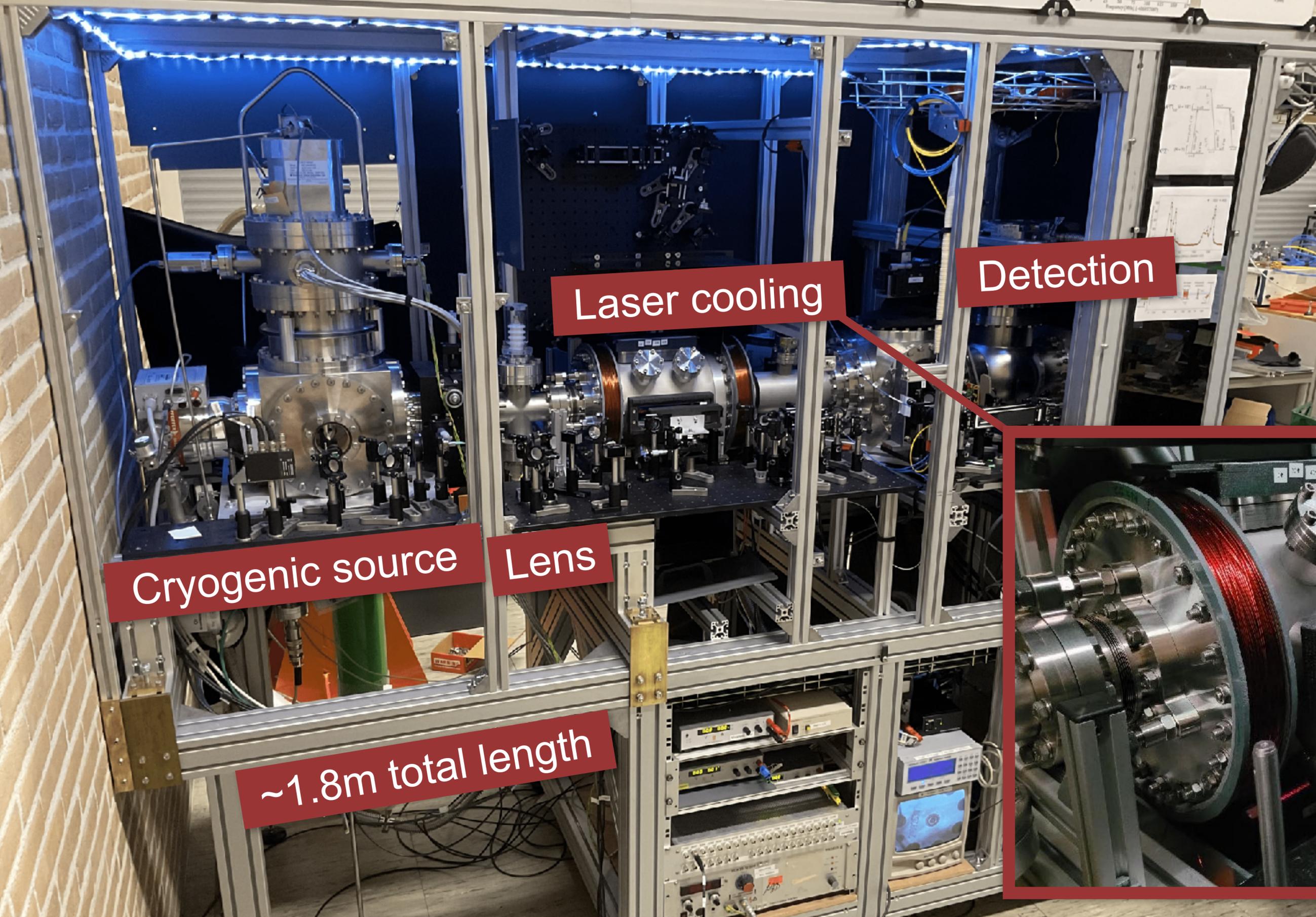
Boeschoten et al (NL-eEDM collaboration), arXiv:2601.21781

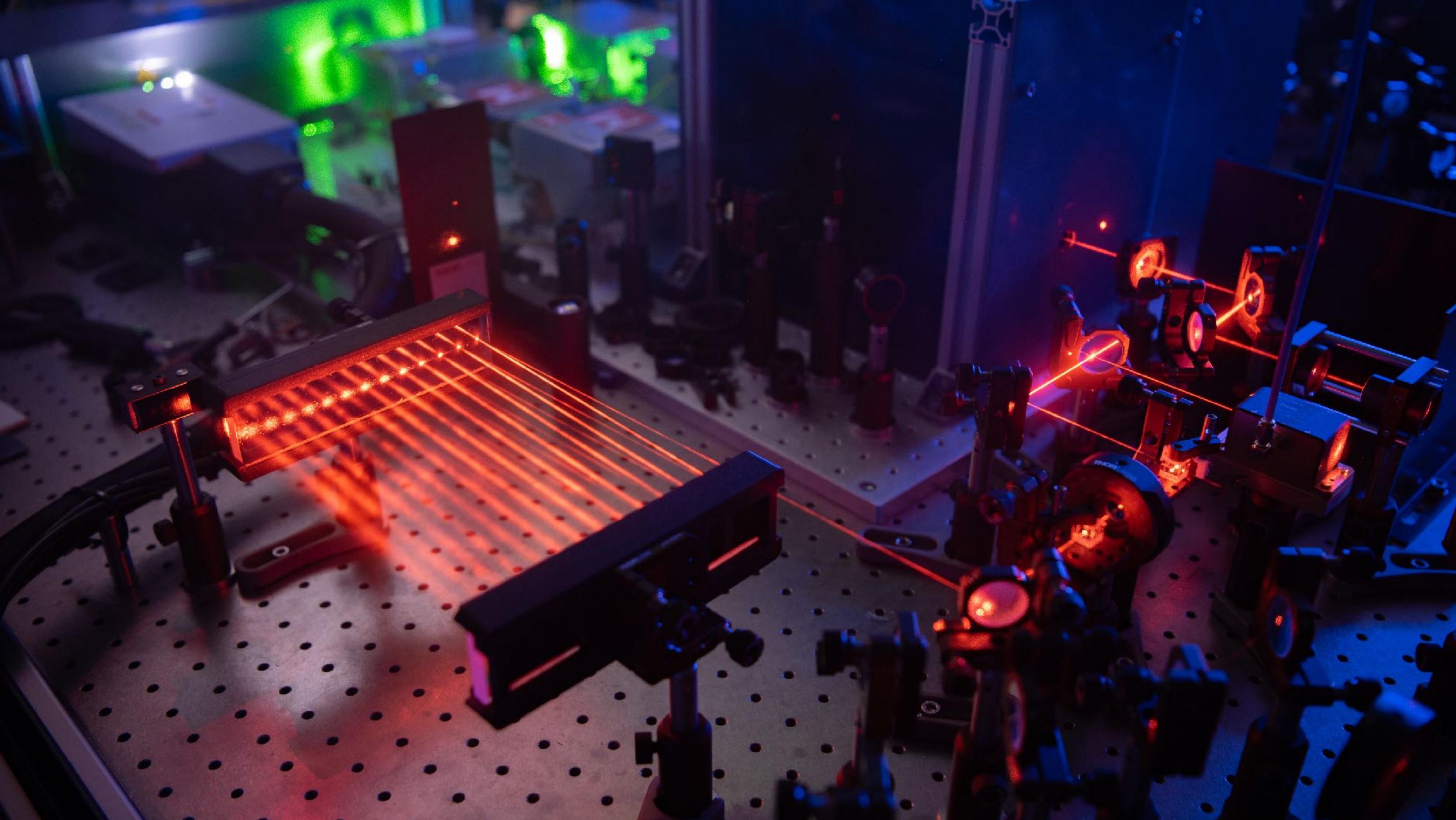
Item	Phase 1	Phase 2	Comment
Molecular Beam Source			
Source type	supersonic [29]	cryogenic buffer gas [36]	
Brightness (molecules/sr/pulse)	3.3×10^9	1×10^{11}	in $N = 0$
Repetition rate (Hz)	10	20	
Forward velocity (m/s)	600 ± 30	200 ± 30	velocity (m/s $\pm 1\sigma$ spread)
Laser Cooling			
Transverse cooling	1	200	gain hexapole and laser cooling
Rotational cooling	1	10	gain optical pumping
Spin Precession Parameters			
Electric Field (kV/cm)	2	10	
Polarization factor $P(E_{\text{ext}})$	0.16	0.53	resulting from larger field strength
Precession Time (ms)	1	3	Due to reduced velocity
Precession fraction	0.9	0.3	Due to length of molecular pulse
Interference contrast	0.9	0.9	
Fluorescence Detection			
Signal n_{sp}	1	1.5	Change detection via $\Pi_{3/2}$ to $D^2\Sigma^+$ state
Light collection	0.02	0.20	Solid angle of light collection
Quantum efficiency	0.07	0.80	Change from PMT to APD
Average photon rate (s^{-1})	200	2×10^9	
Statistical sensitivity ($e \text{ cm day}^{-1}$)	5×10^{-25}	2×10^{-29}	

Phase 2

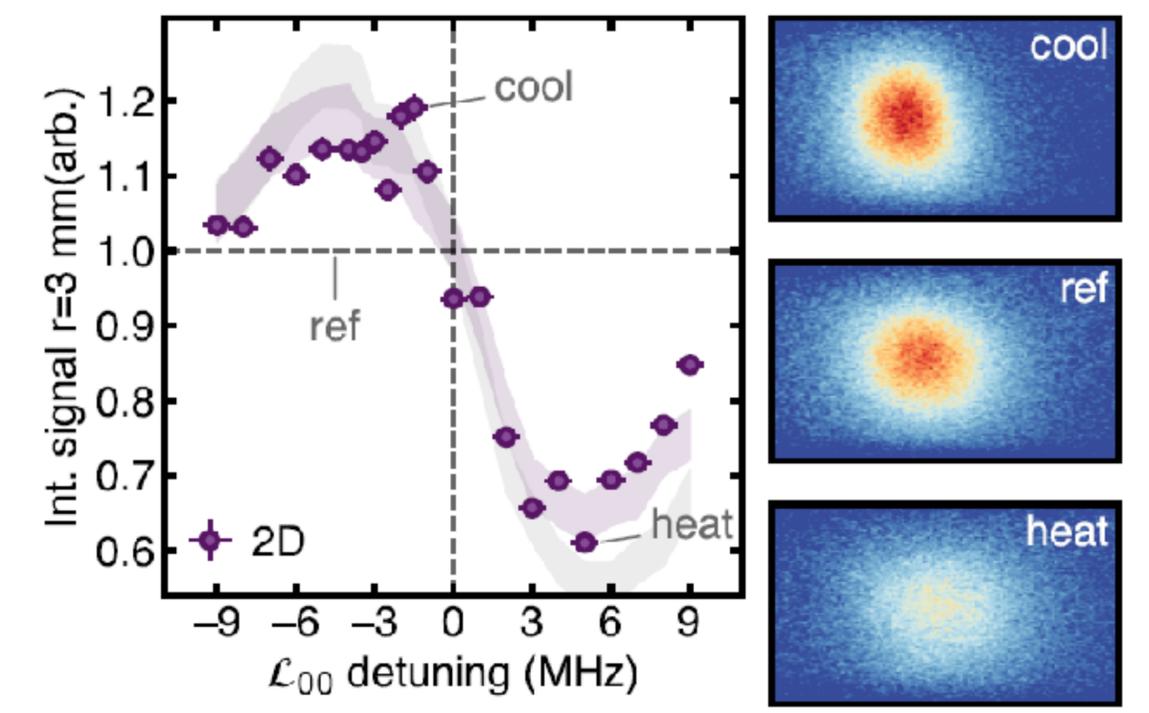
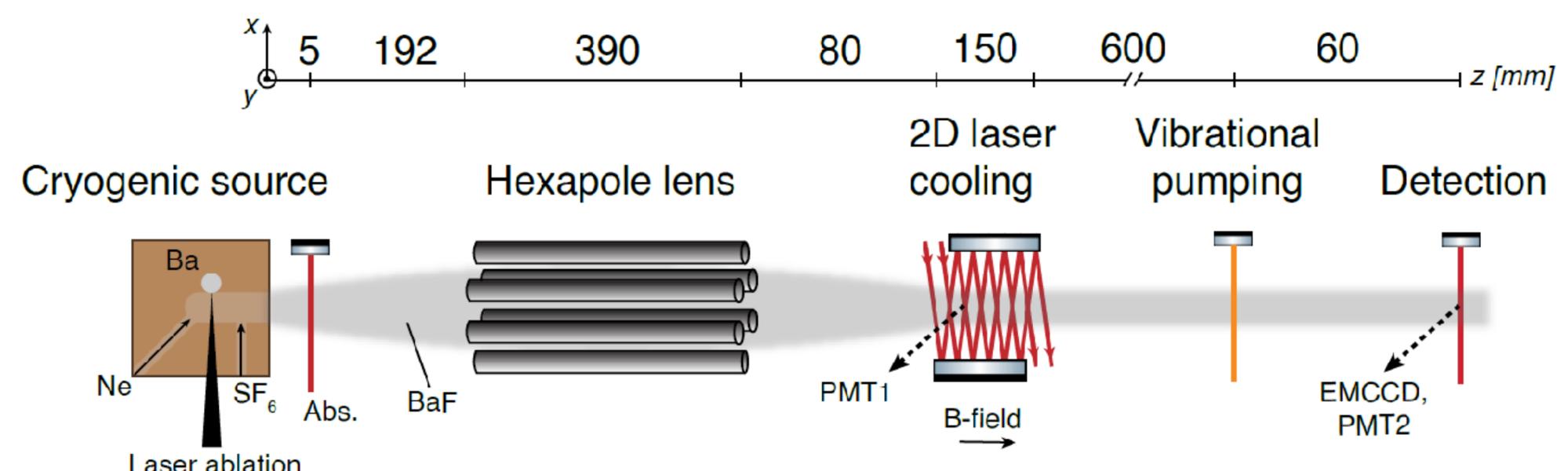
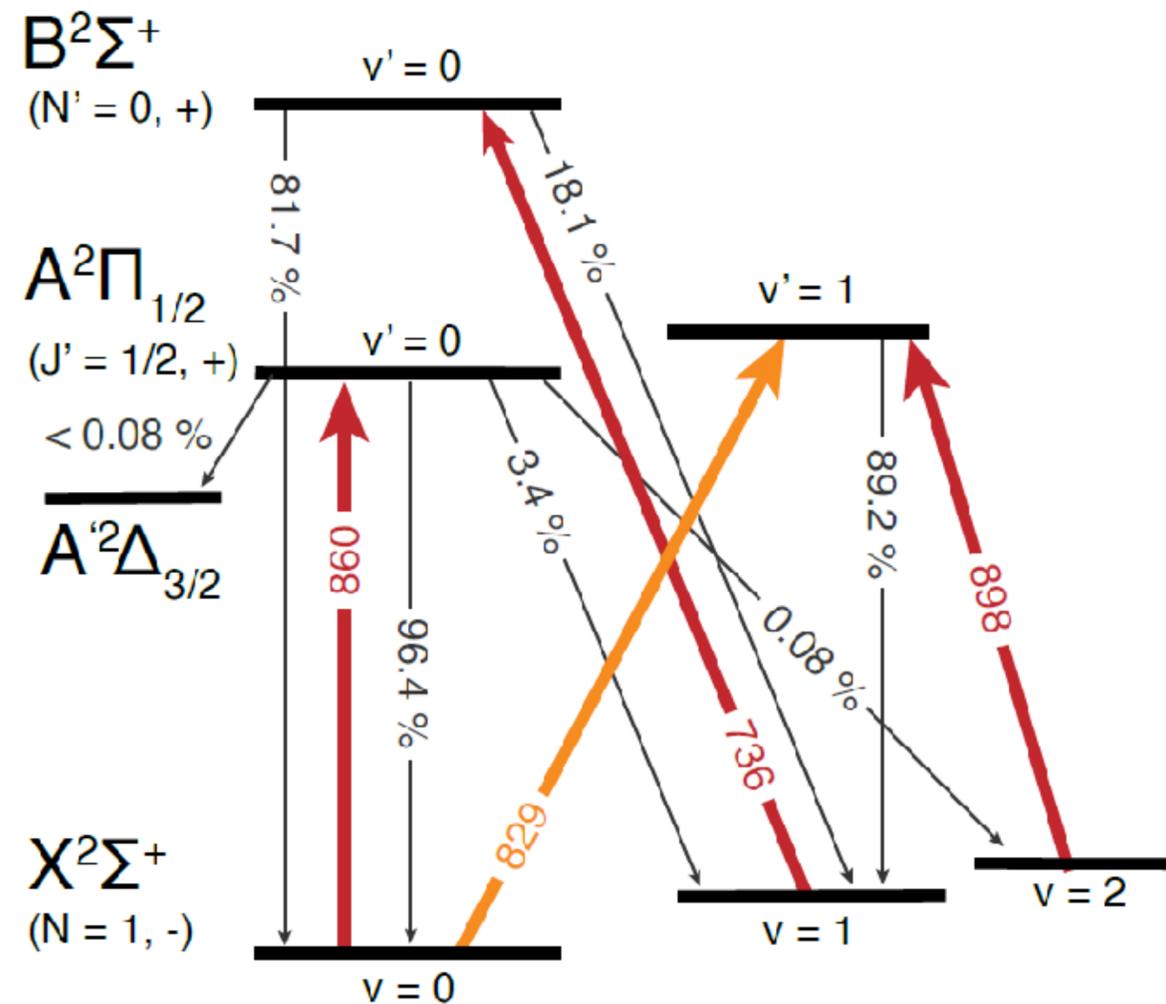
A slow and very intense BaF molecular beam







Combining hexapole lens and 2D laser cooling

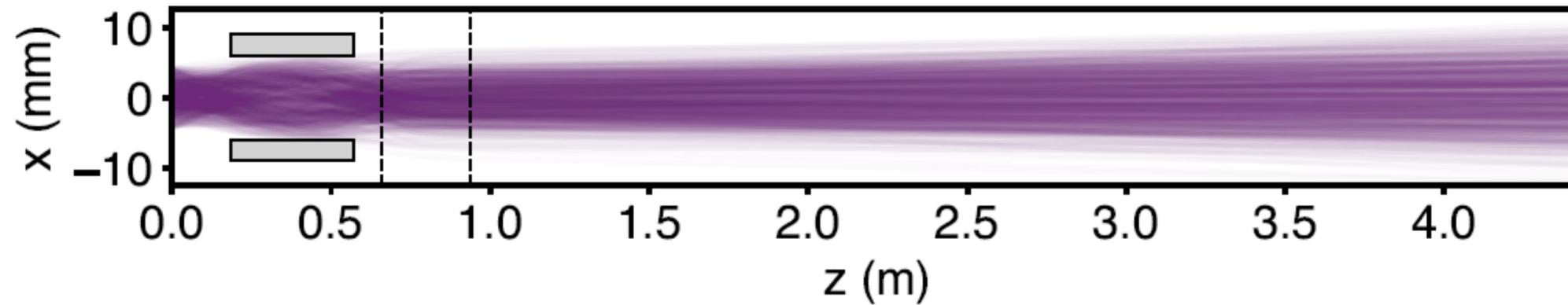


Hexapole:

A. Touwen et al, New Journal of Physics, vol. 26, p. 073054 (2024)

J. van Hofslot et al, Comm. Physics 9, 40 (2026)

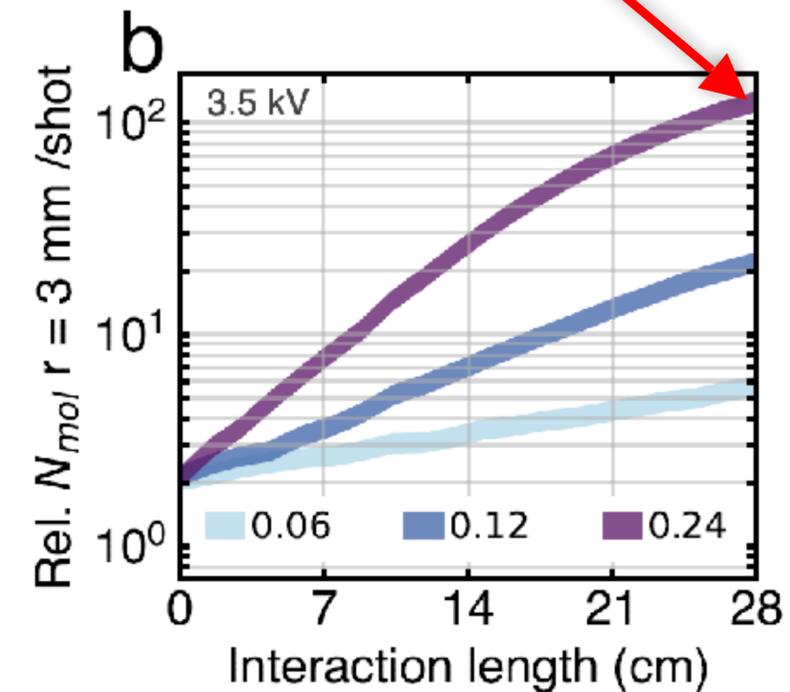
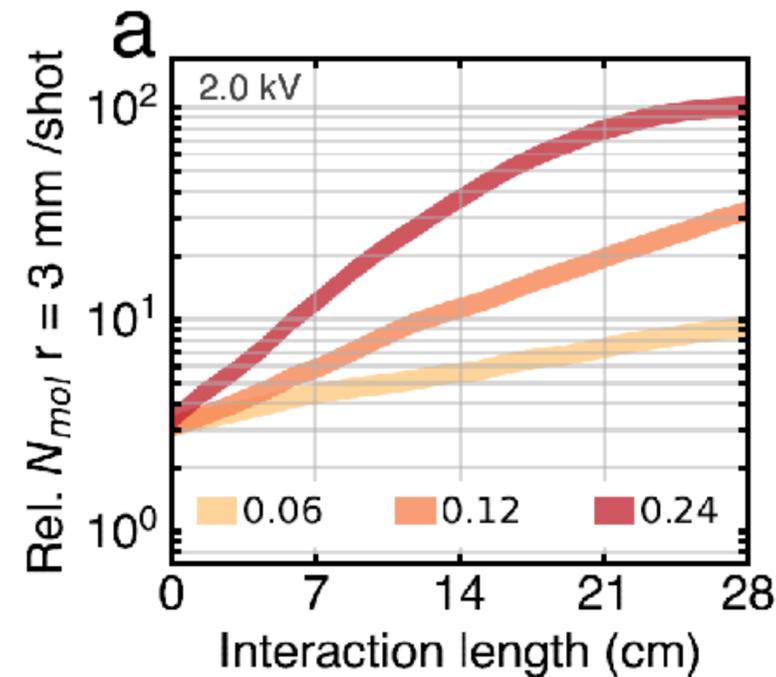
Extrapolating downstream gain in molecule flux

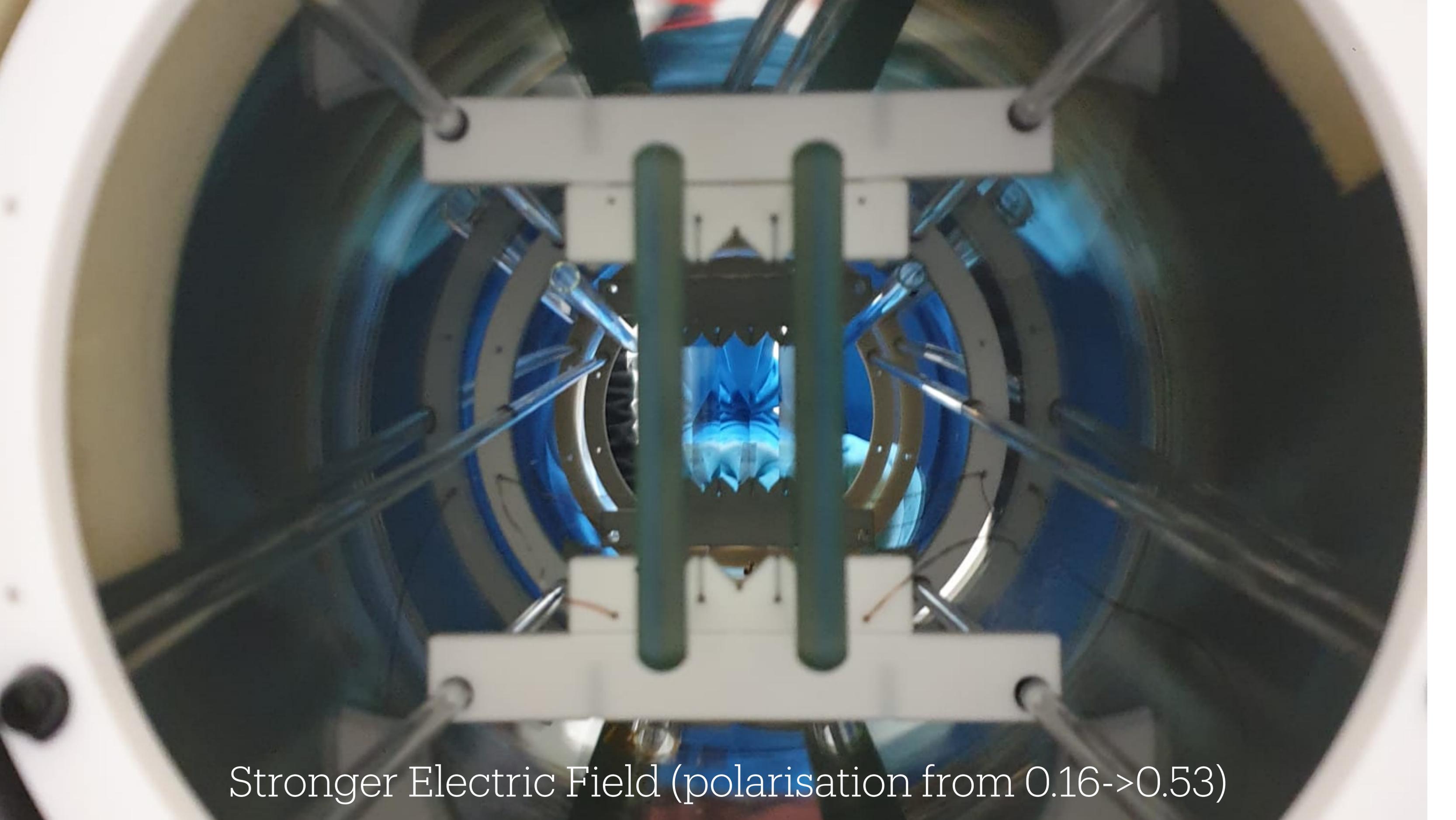


Lens-laser cooling effect depends on:

- State preparation
- Lens focusing strength
- Scattering rate
- Interaction time

Factor 100 gain in downstream molecule flux possible!

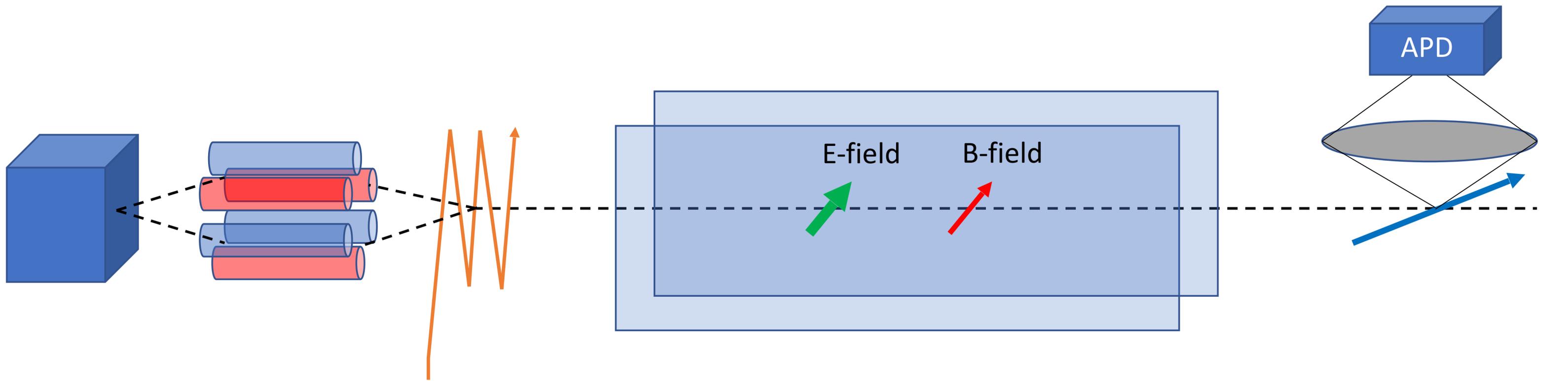




Stronger Electric Field (polarisation from 0.16->0.53)

Phase 2

Improved detection: solid angle 2% \rightarrow 20%, detector efficiency: 7% \rightarrow 80%



Cryosource

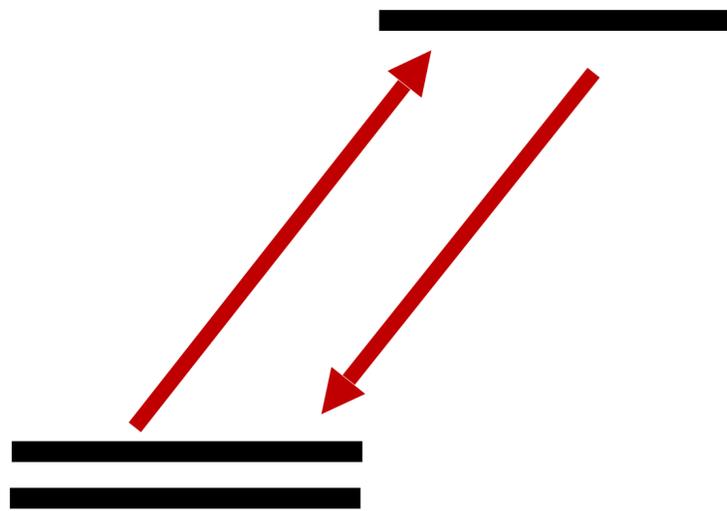
Lens

2D laser cooling

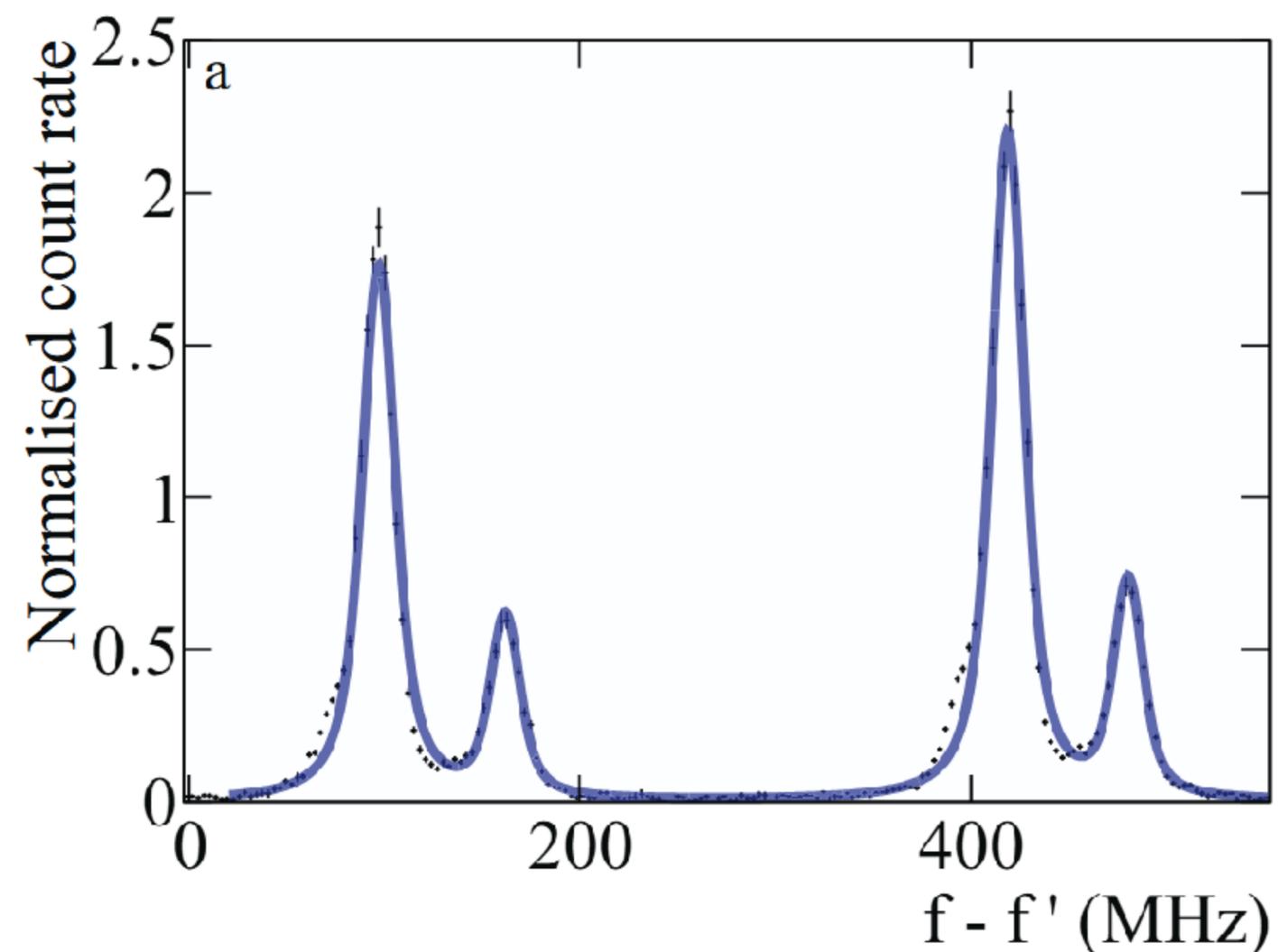
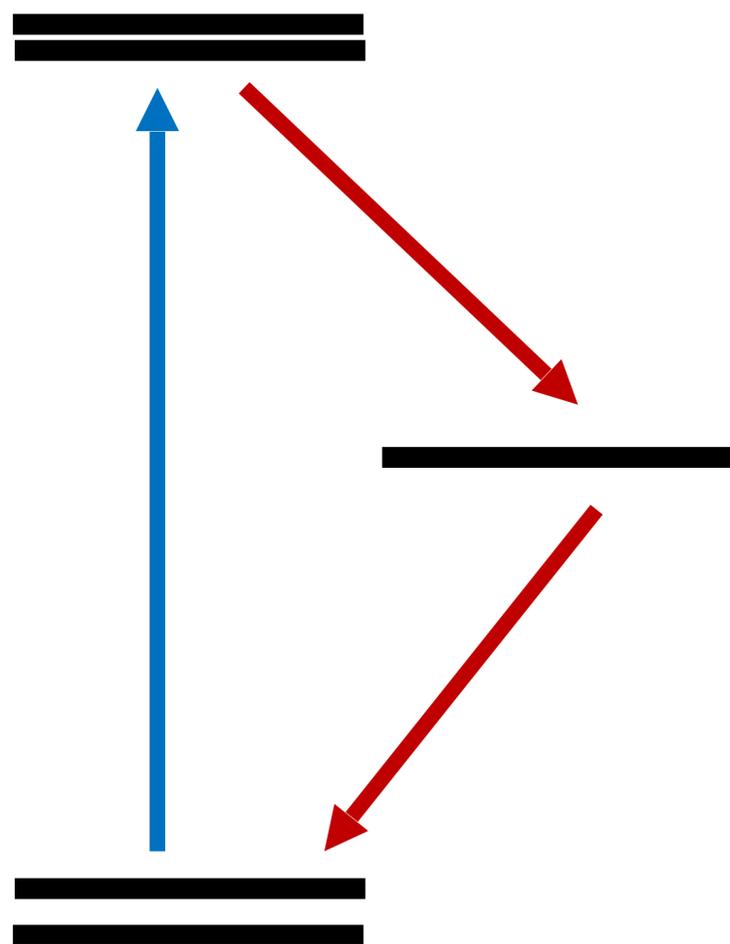
Interaction region

Detection / readout

Caveat: Background laser light



Caveat: Background laser light



Solution: Background-free scheme

Phase 3

Trapping polyatomic molecules

Phys. Rev. A 111, 062815 (2025) with Nick Hutzler and Arian Jadbabaie

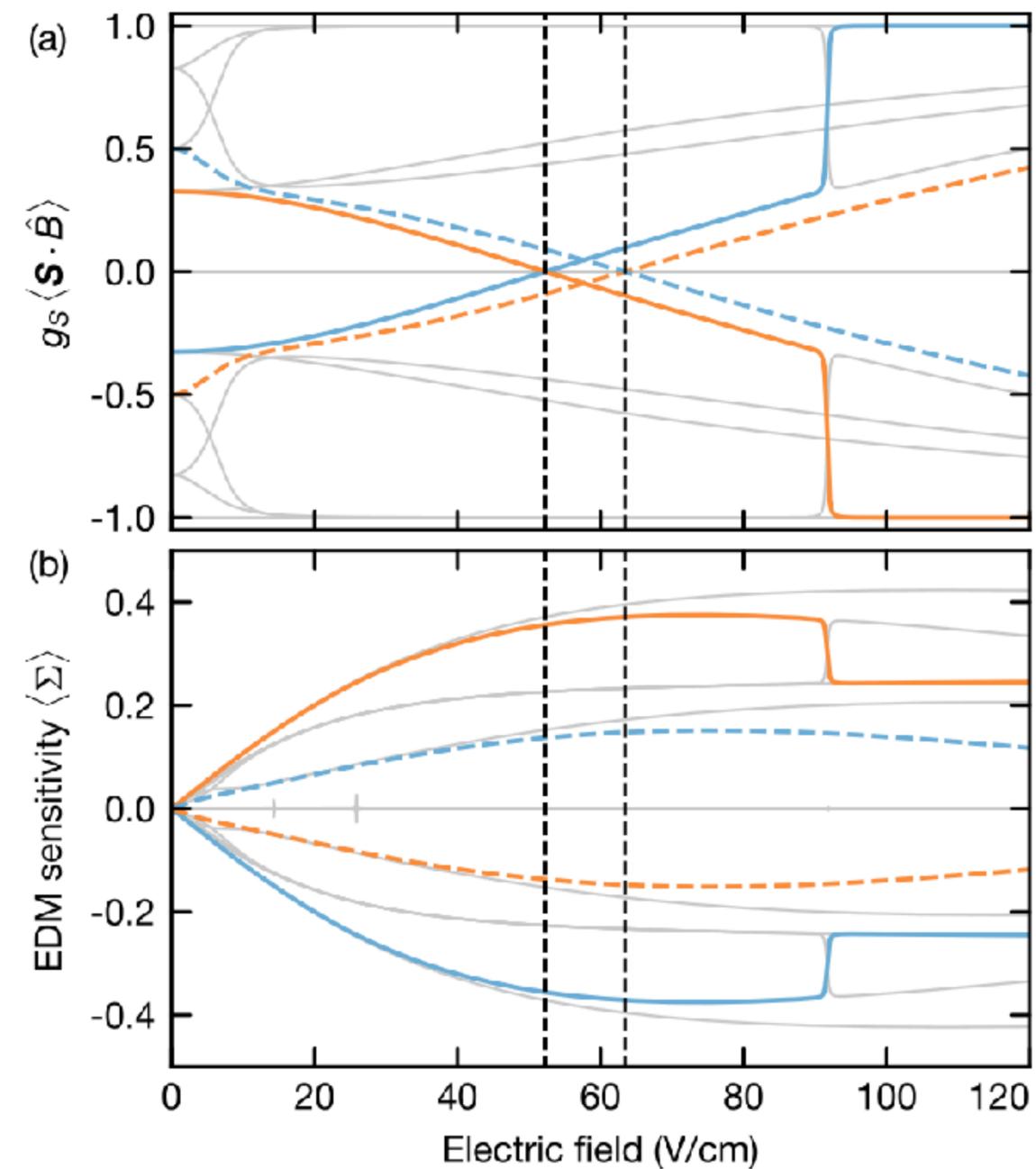
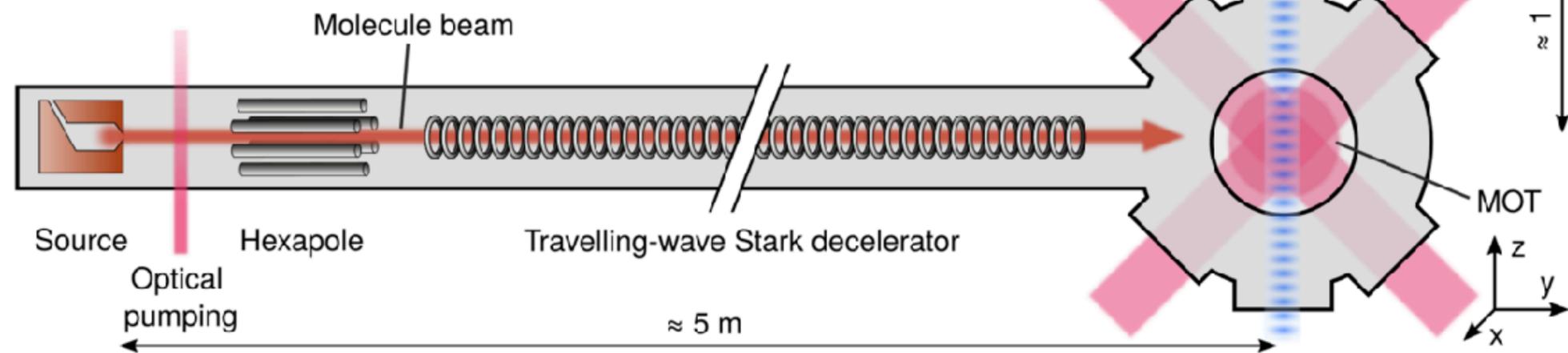
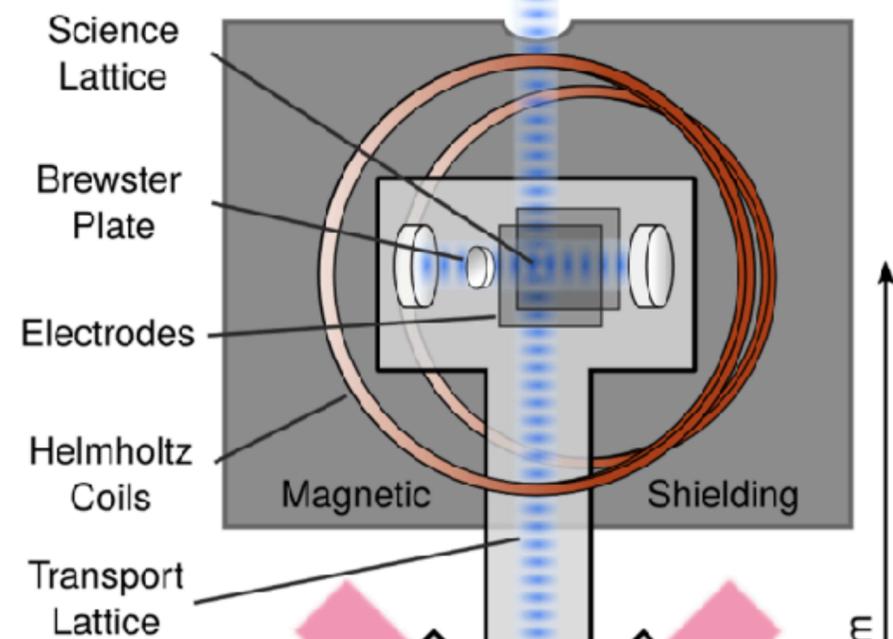
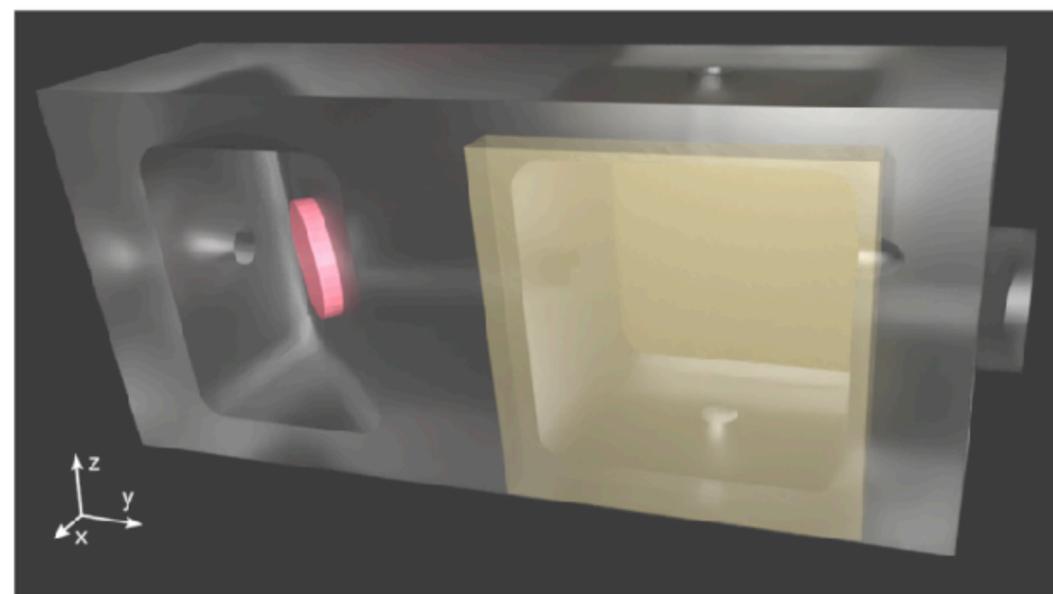


FIG. 5. Dependence of (a) the electron spin magnetic moment $g_S \langle \mathbf{S} \cdot \hat{\mathbf{B}} \rangle$, with $\hat{\mathbf{B}}$ being the unit vector in the direction of the applied magnetic field), and (b) the state EDM sensitivity $\langle \Sigma \rangle$, on the electric field. The solid and dashed lines denote the $|N = 1, J = 1/2^+, F = 1, m_F = \pm 1\rangle$ and $|N = 1, J = 3/2^+, F = 2, m_F = \pm 1\rangle$ state pairs, respectively, and the blue and orange lines denote $m_F = +1$ and $m_F = -1$ states. The gray curves represent other states in the $N = 1$ manifold. The vertical dashed lines indicate the position of the g-factor zero crossings.

Phase 3

BaOH production and characterisation

Fikkers, Balasubramanian et al, New J. Phys. 28, 023202 (2026)

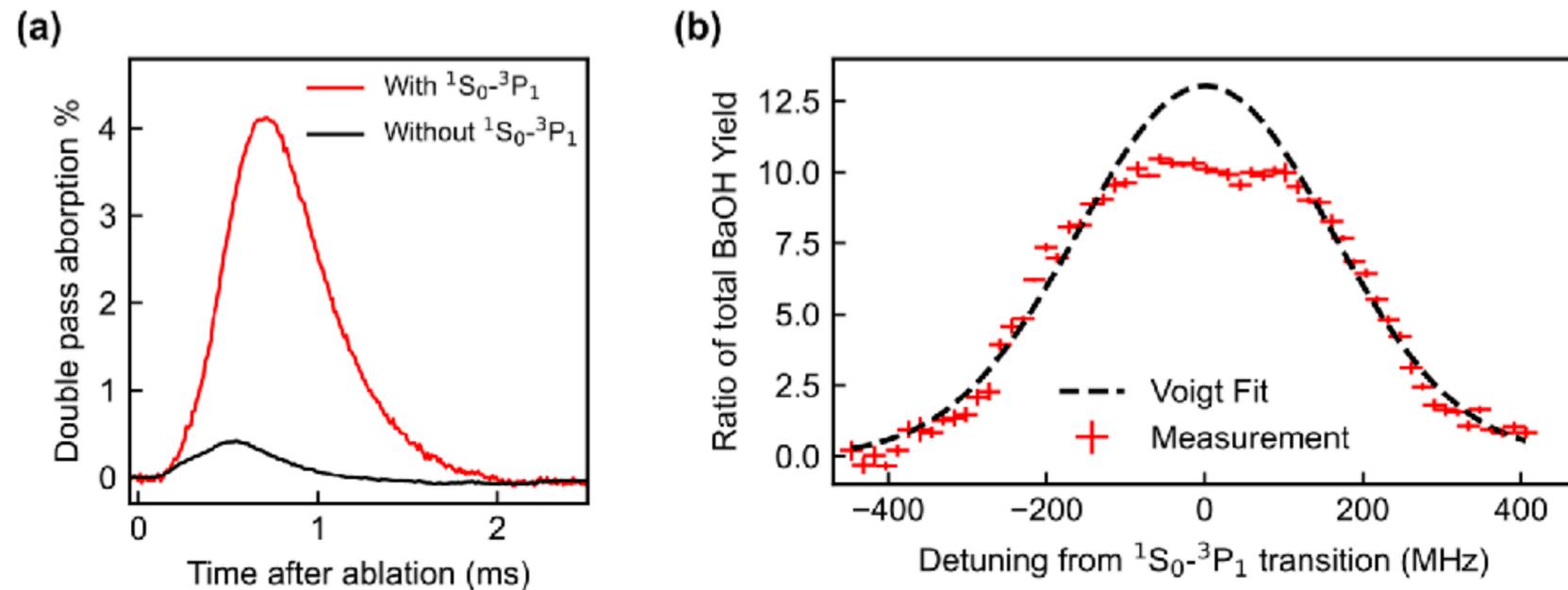
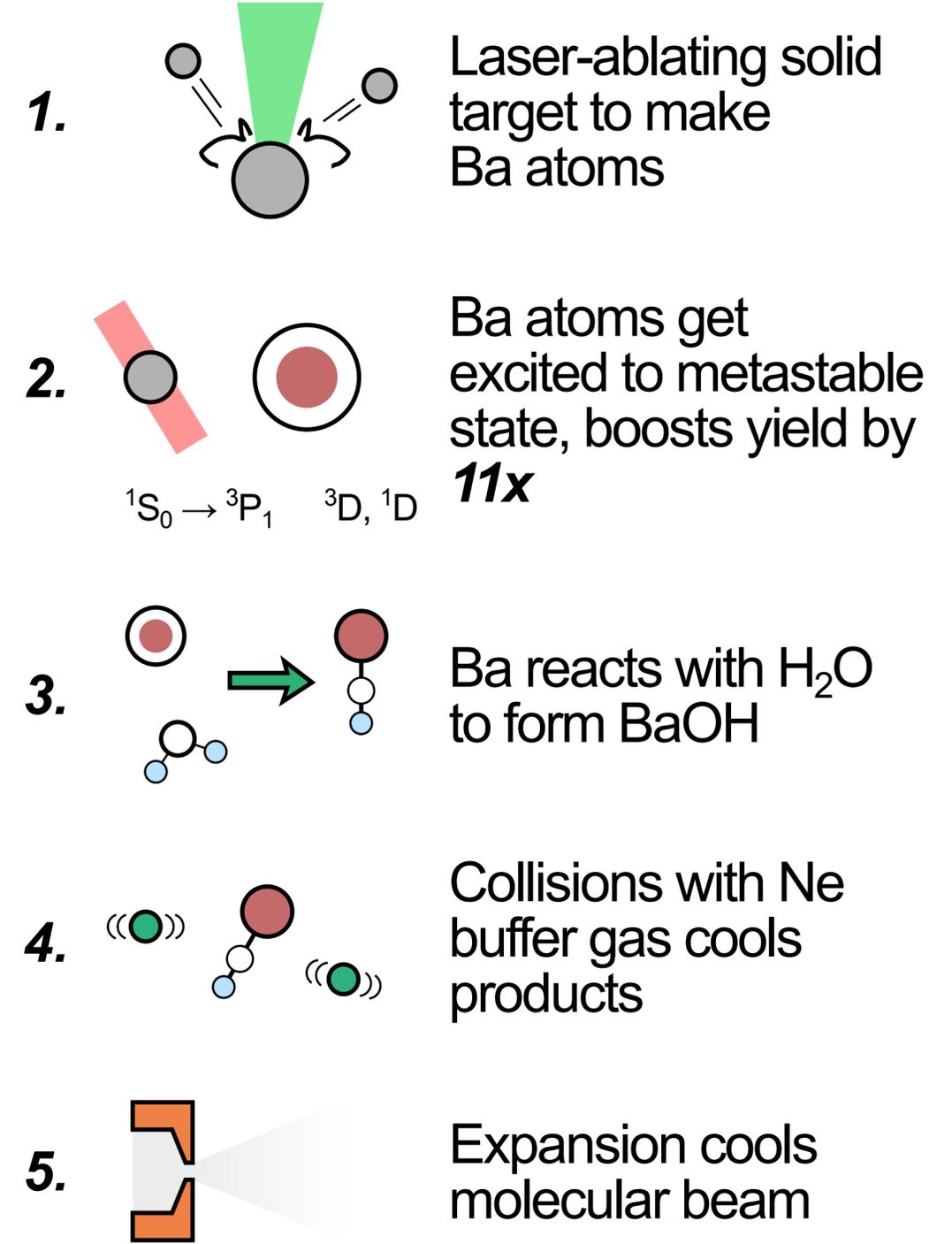


Figure 3. Increased yield of BaOH as a result of the excitation of atomic barium. **(a)** Time-of-flight curves seen from double pass absorption when absorption laser is locked to the $^S R_{21}(1)$ transition between $\tilde{A}^2\Pi_{3/2} - \tilde{X}^2\Sigma_{1/2}$ in the vibrational ground state, with (in red) and without (in black) enhancement laser close to the $^1S_0 - ^3P_1$ resonance. **(b)** The enhancement factor (ratio of the OD integrated over the length of the pulse) as a function of the detuning from the barium $^1S_0 - ^3P_1$ transition. The enhancement factor saturates to a value around 10 when we are within 200 MHz of the resonance.



Phase 3

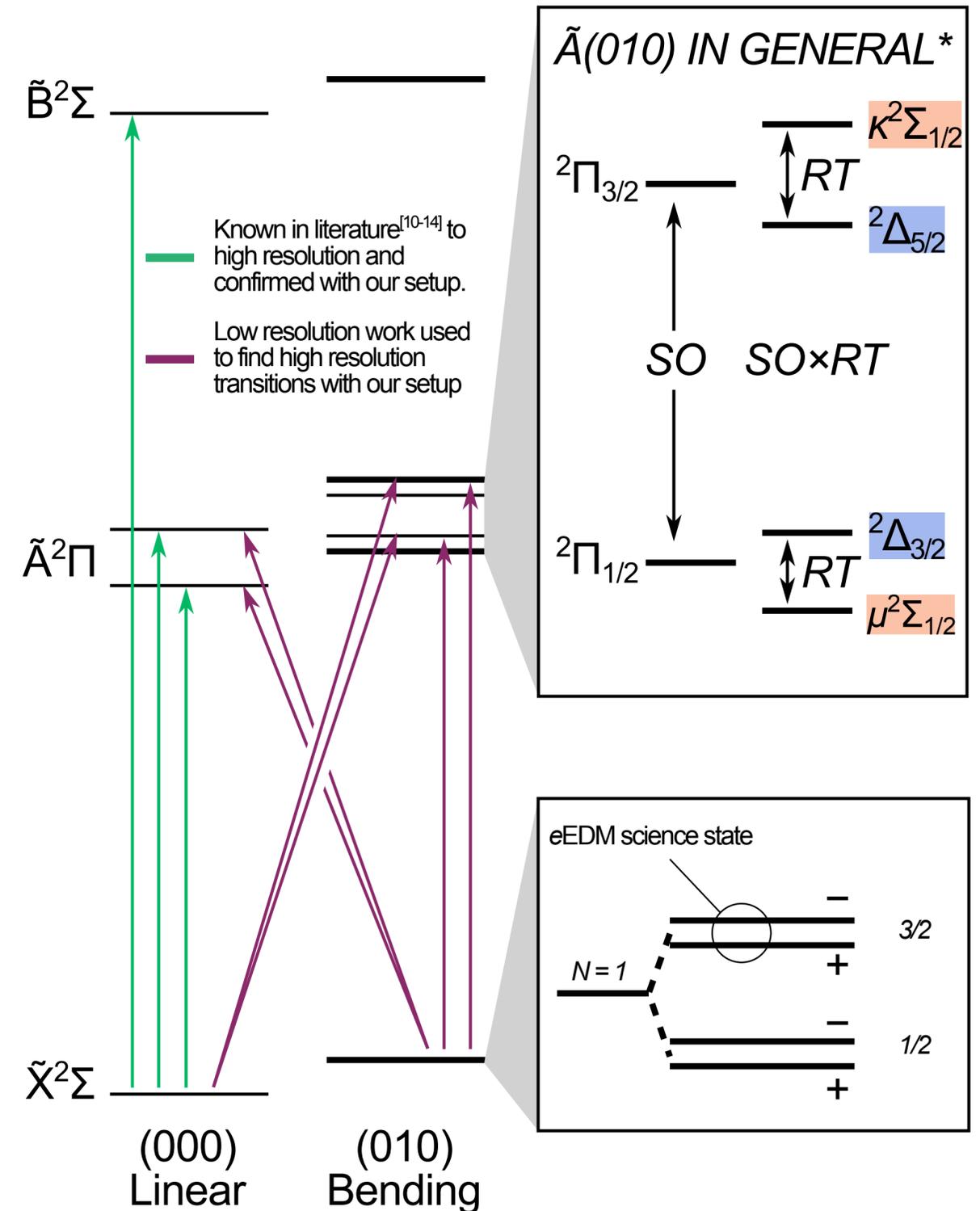
BaOH production and characterisation

Characterisation of molecular structure

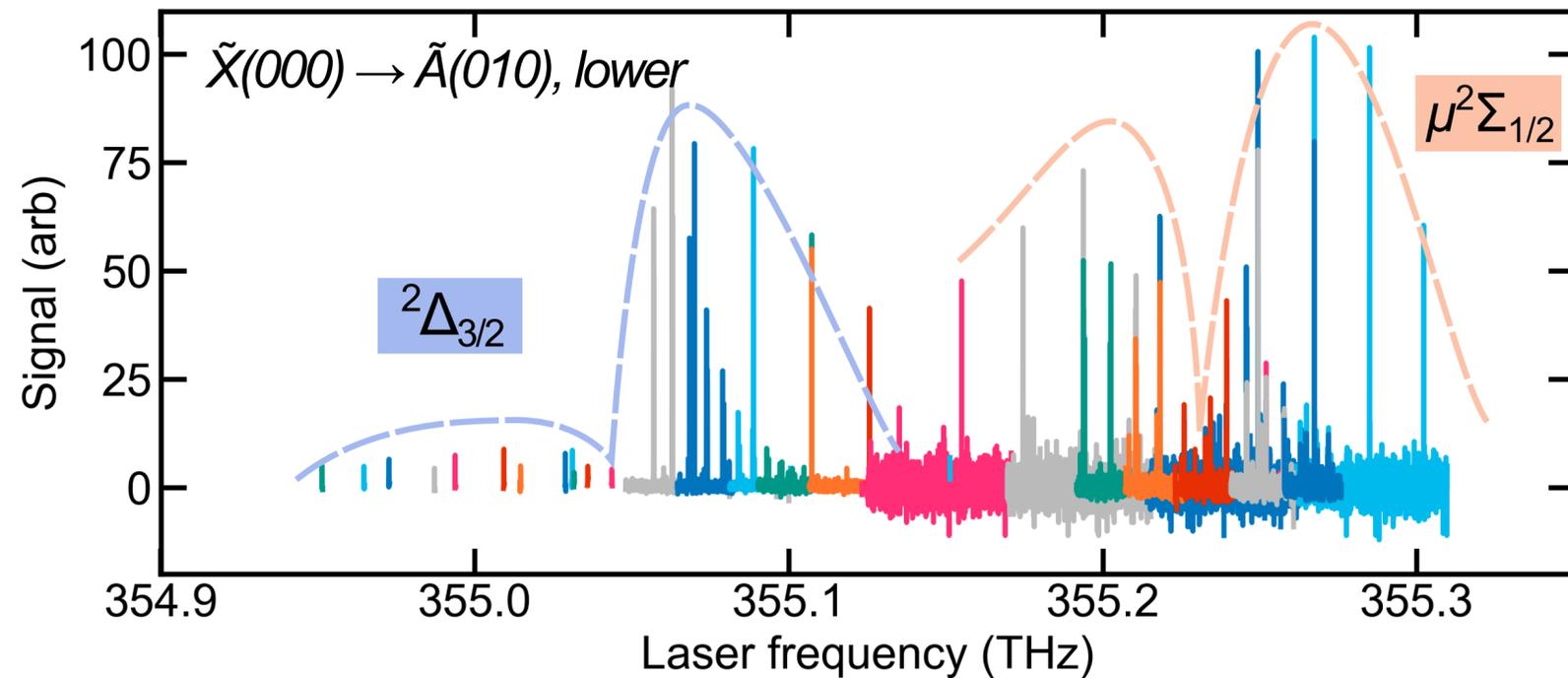
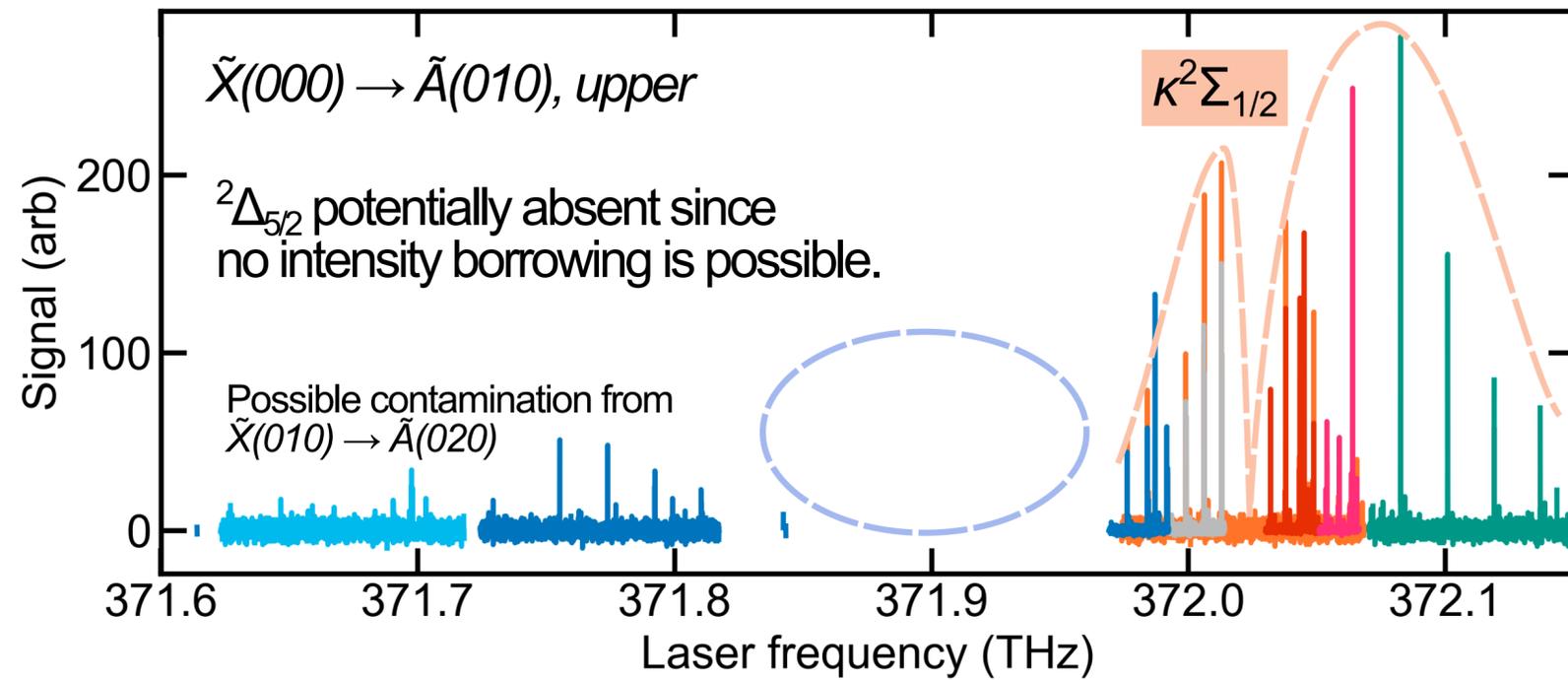
Suffered from frozen water supply lines @10 K, now fixed

Found efficient detection scheme

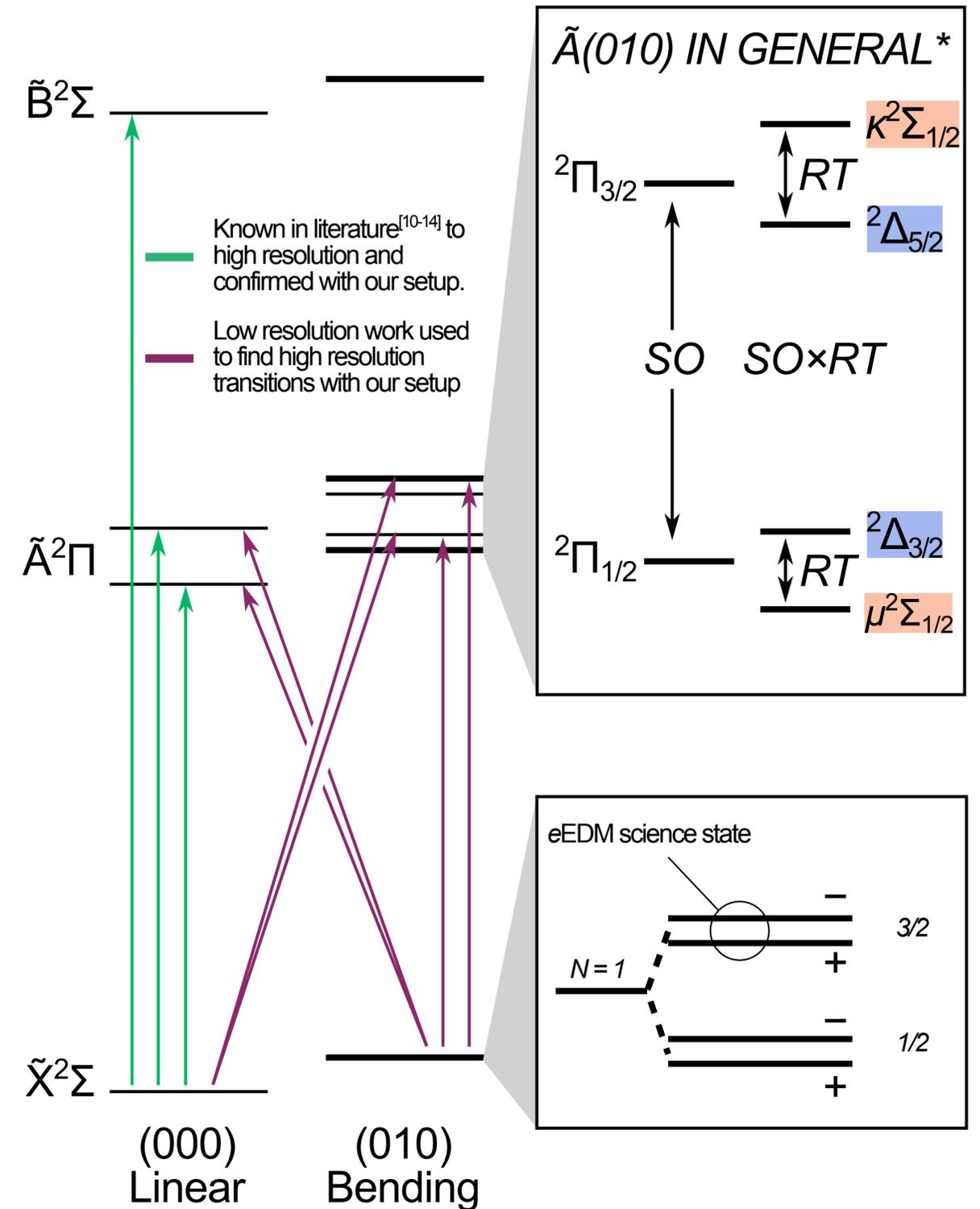
Pumping from linear to bent eEDM state



Phase 3



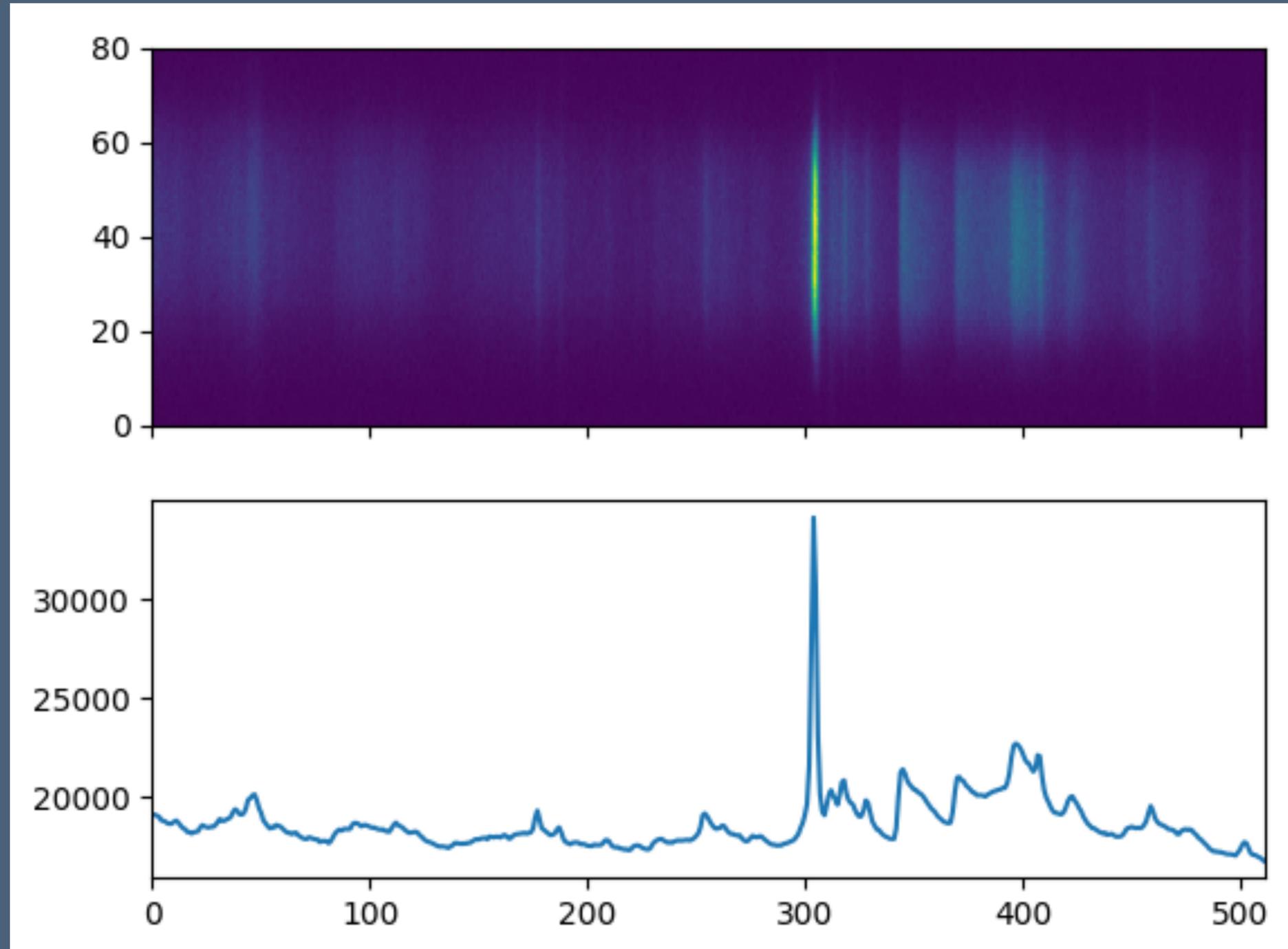
*Preliminary analysis indicates that BaOH does not follow "typical" A-state ordering as found in linear triatomics



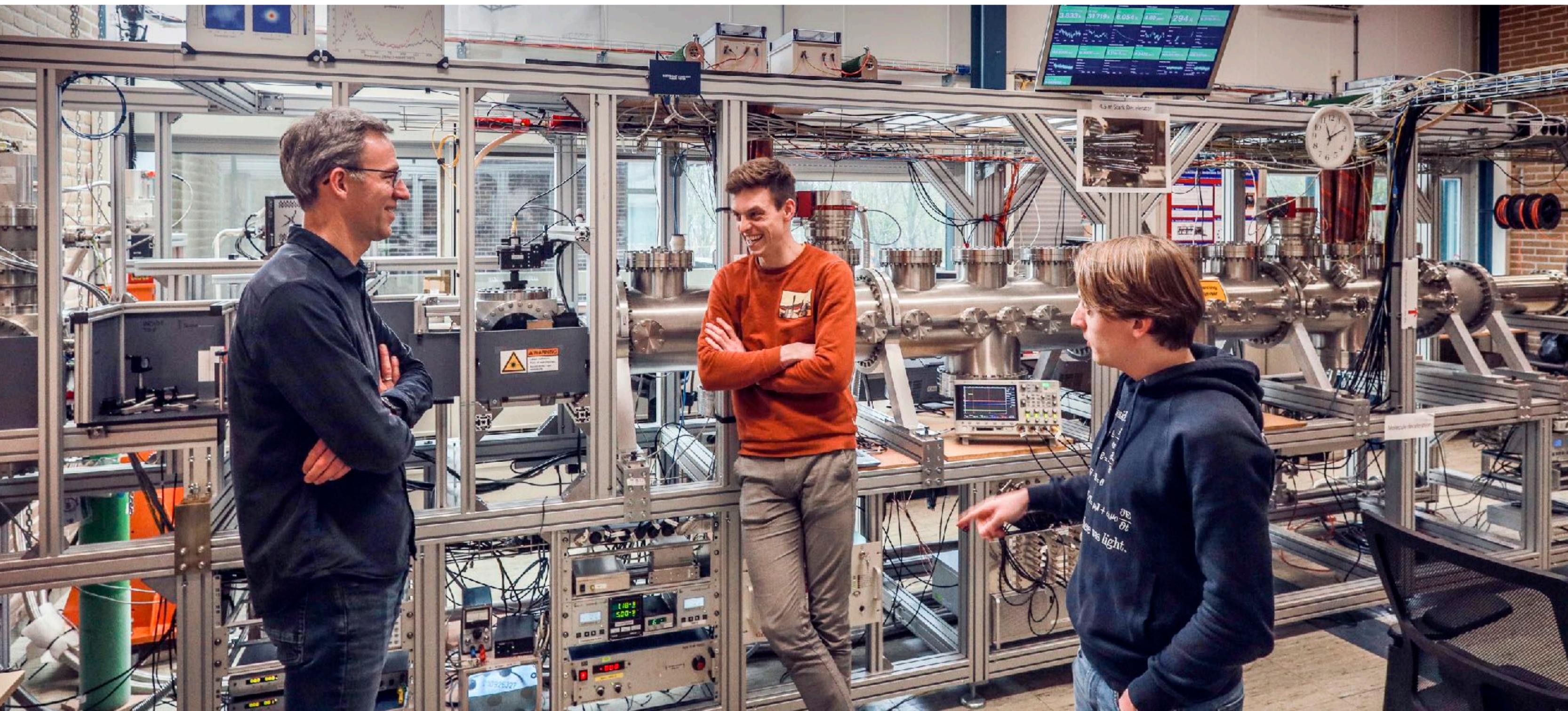
Phase 3

BaOH production and characterisation

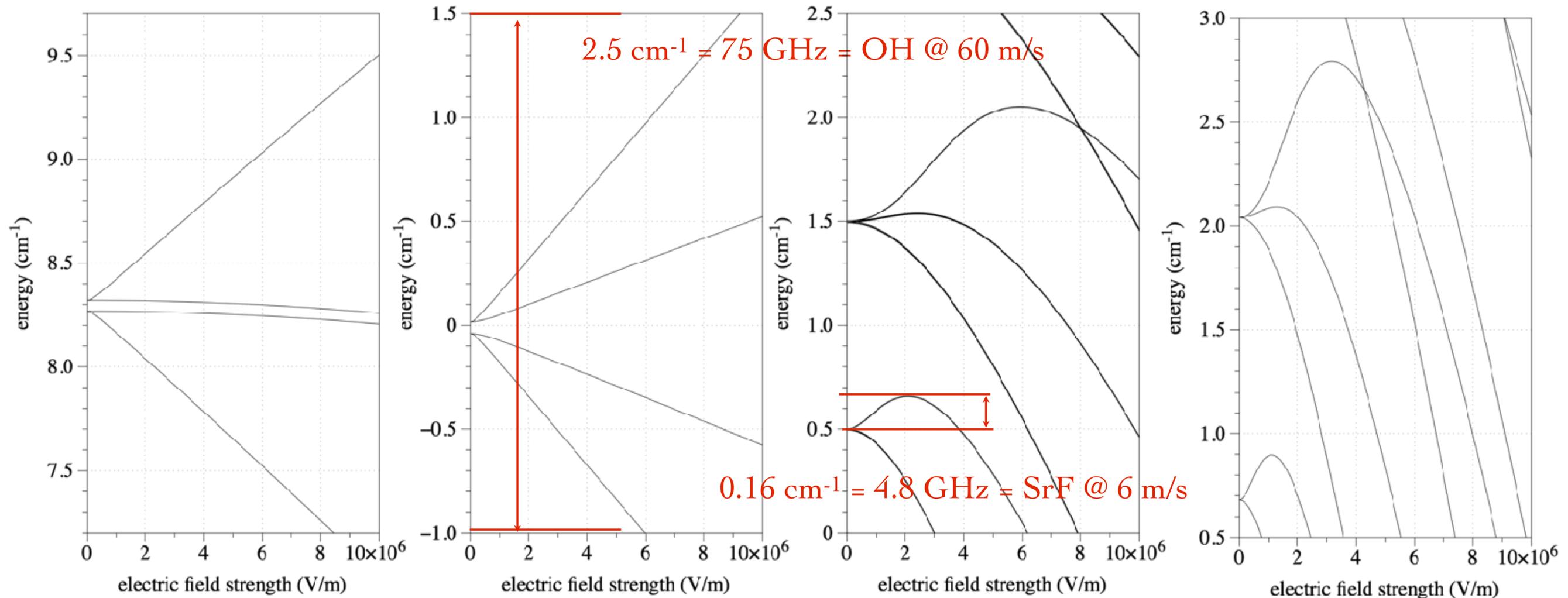
Implementing dispersed fluorescence
to determine branching ratios
for optimal laser cooling scheme



Molecule deceleration



Use Stark shift to decelerate



ND₃

OH

SrF, BaF

SrO

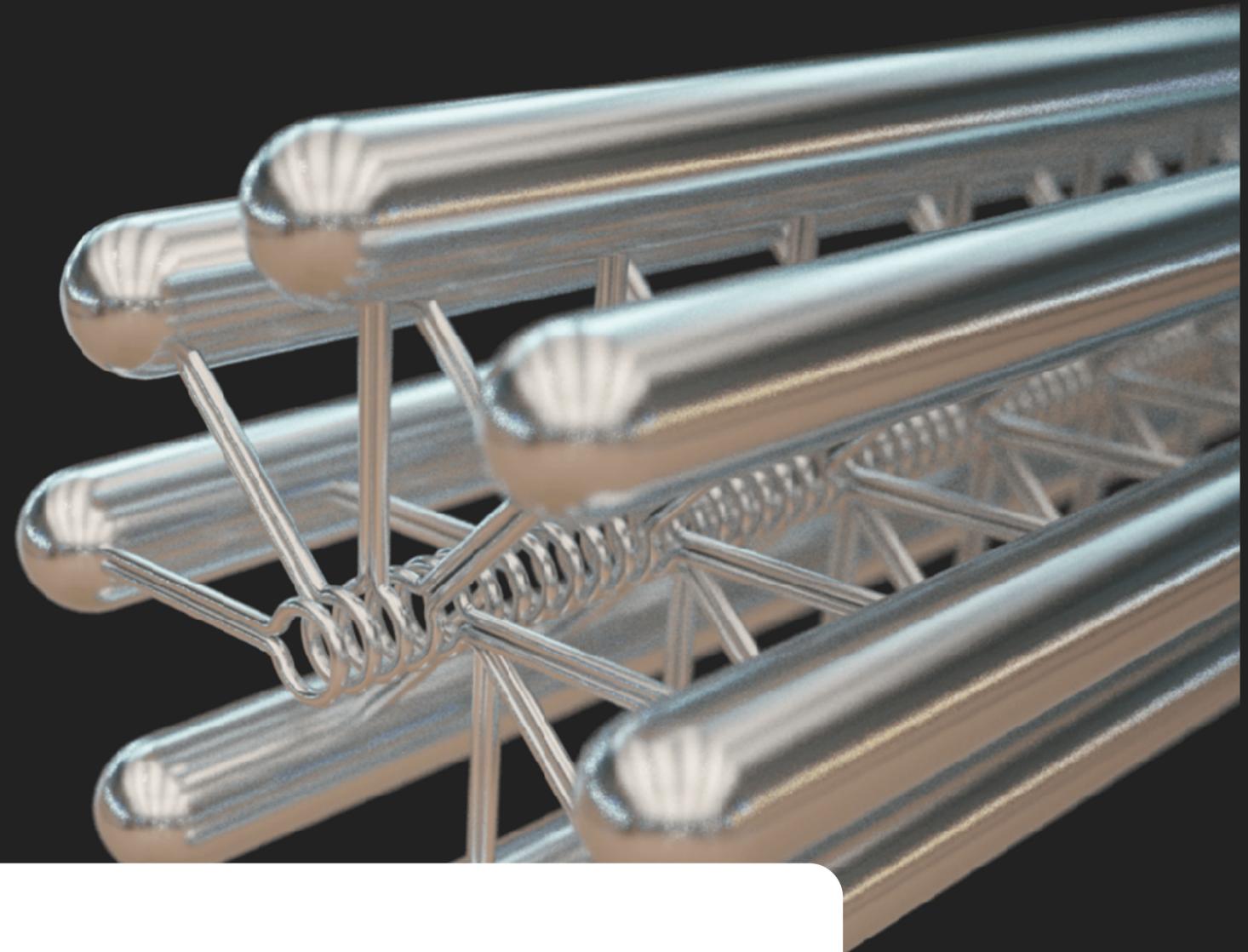
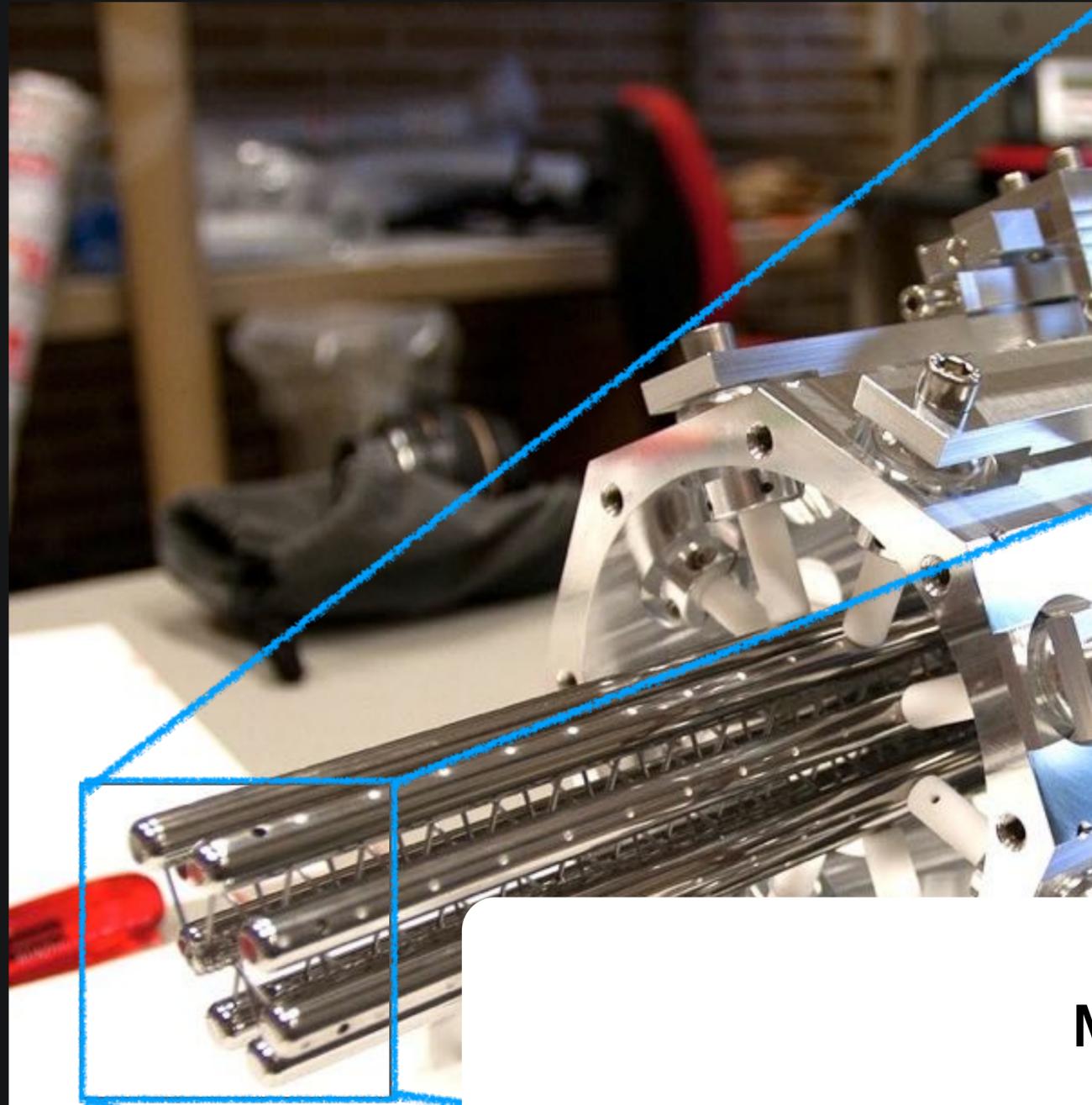
Challenge: extend this technique to heavier species

Deceleration, trapping, collision studies, lifetime measurements

Demonstrated for light molecules: OH, CO, NH₃, NH

Science 313 5793 (2006), PRL 98 133001 (2007), PRL 110 133003 (2013)

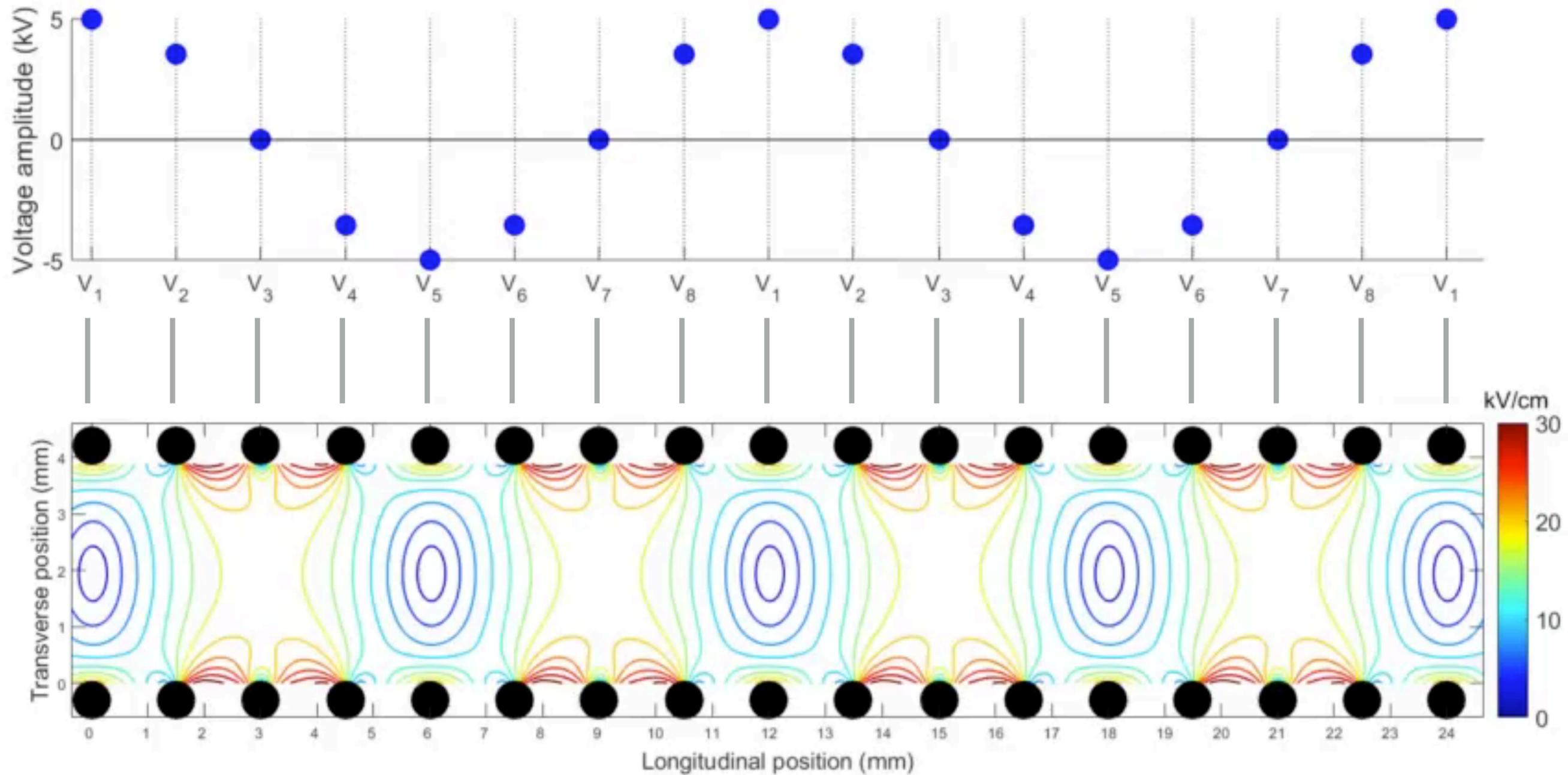
Traveling-wave decelerator: deliver molecules to the trap



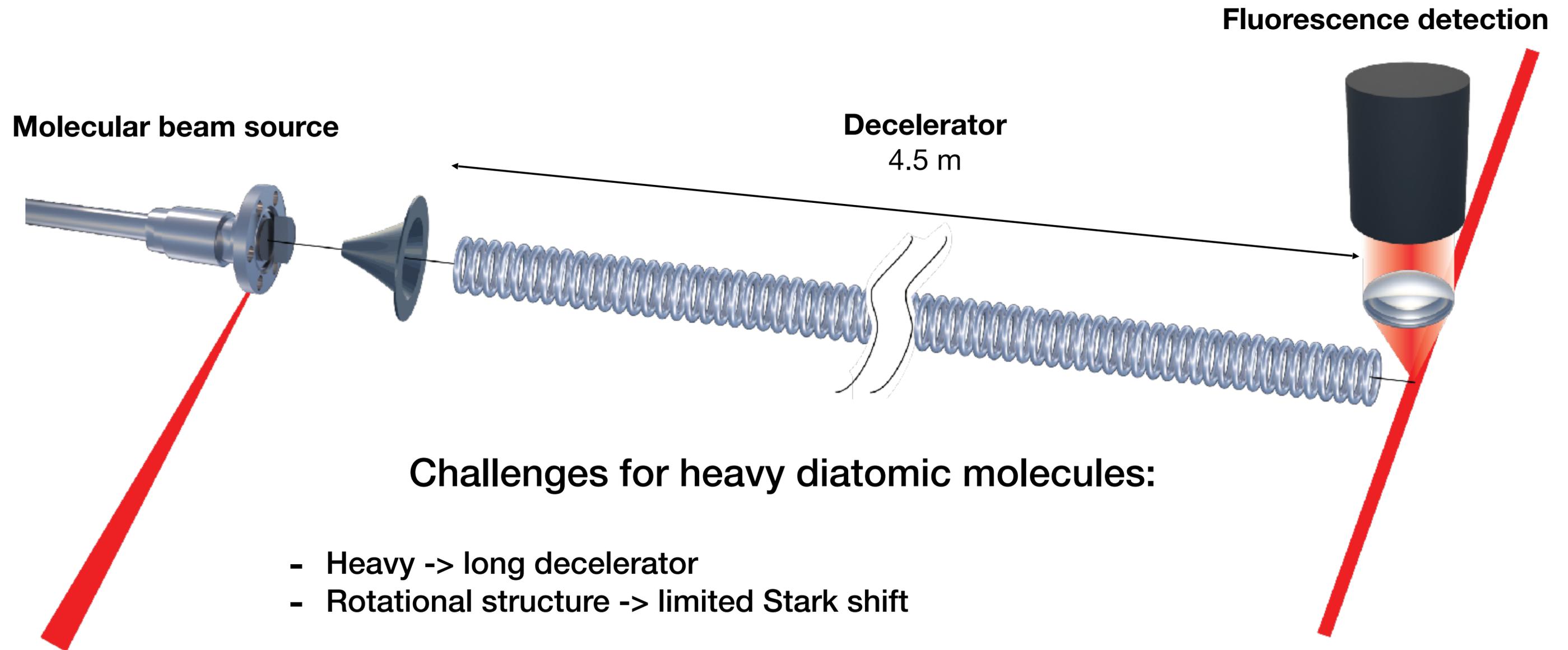
Main aims:

- Capture as many molecules as possible from molecular beam
- Bring average beam velocity from ~ 190 to ~ 10 m/s
- Maintain N during deceleration

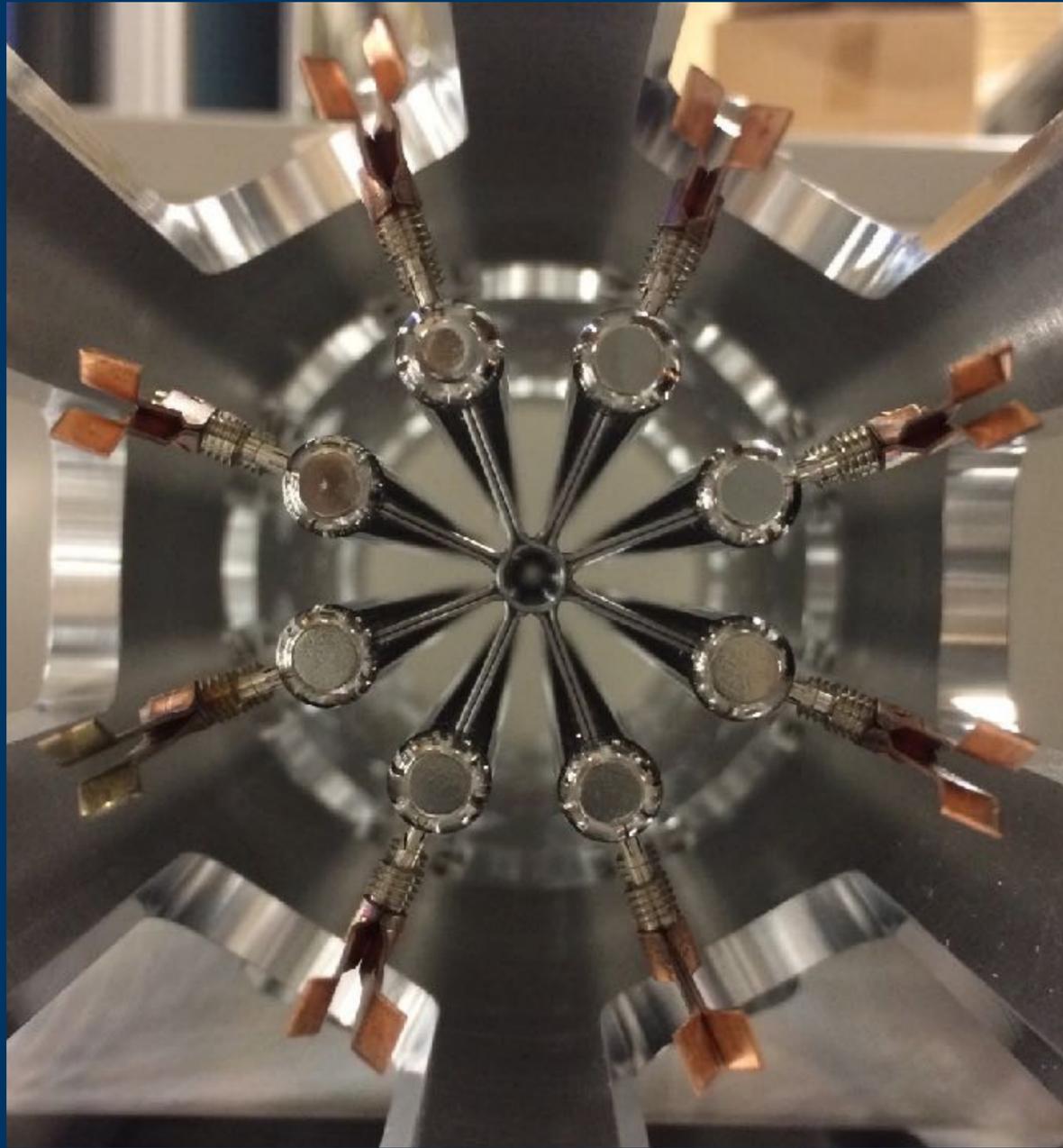
Traveling-wave decelerator



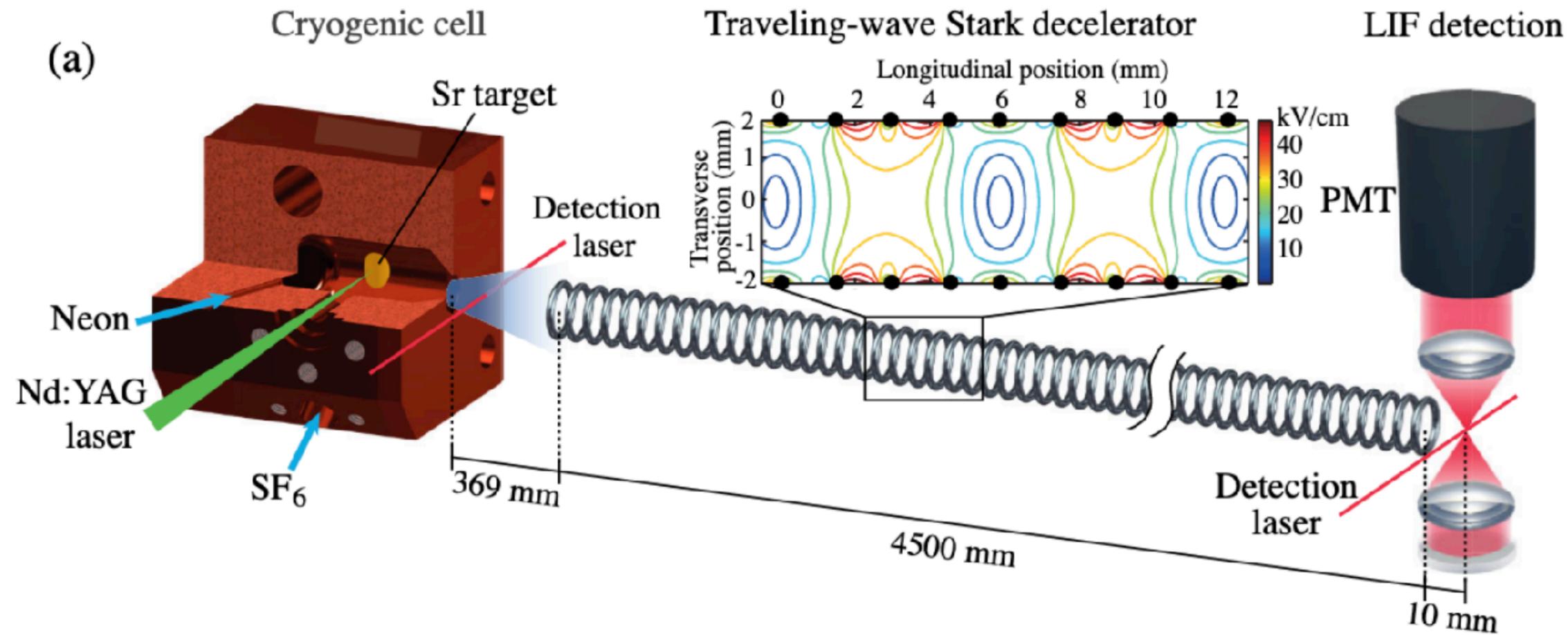
Traveling-wave decelerator



Modular traveling-wave decelerator



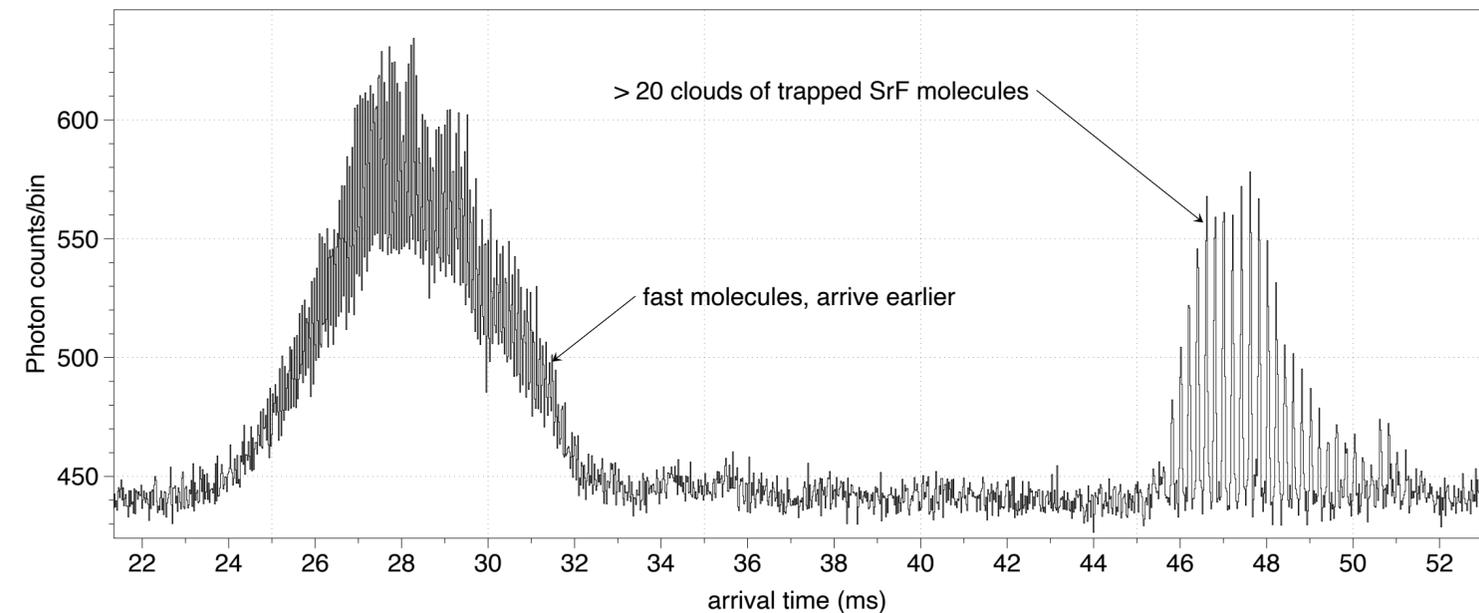
Molecule deceleration



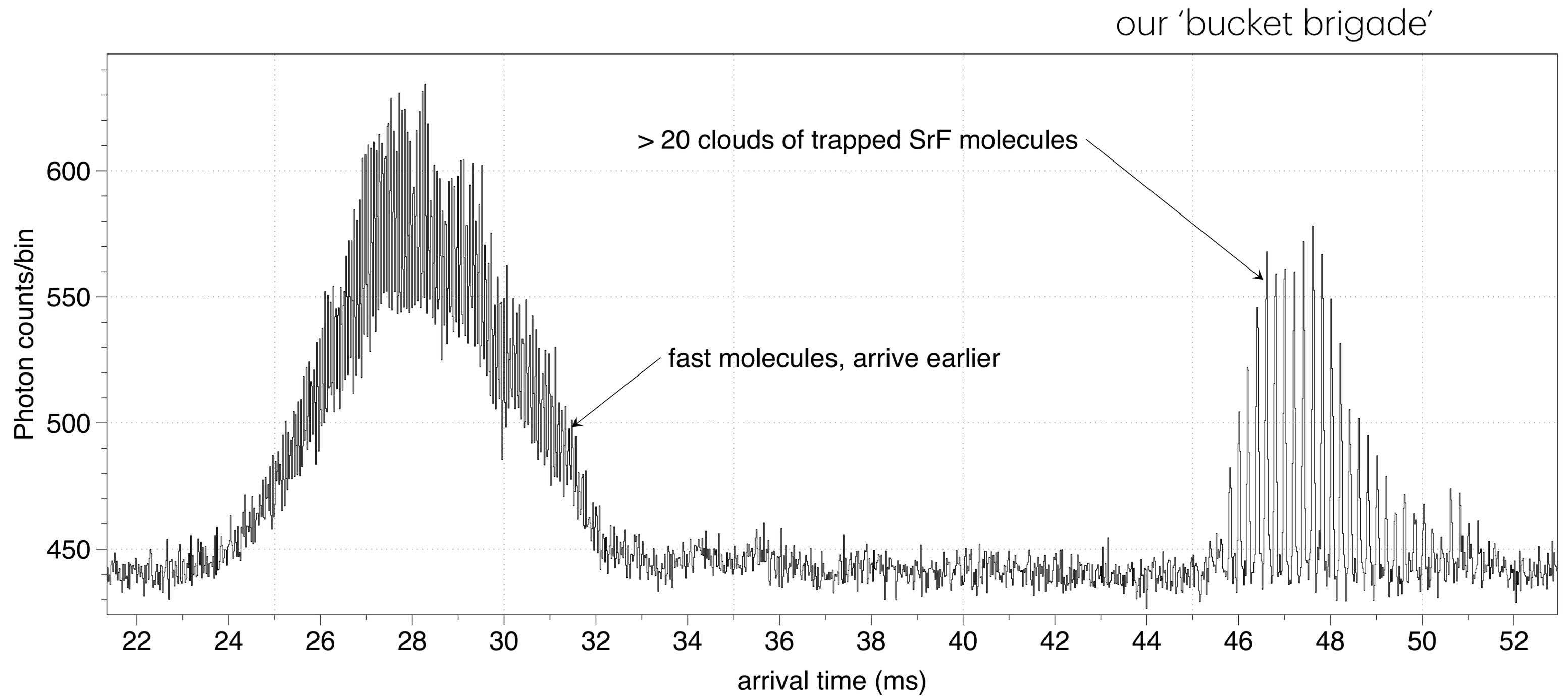
Traveling traps keep molecules together

SrF decelerated, brought to standstill

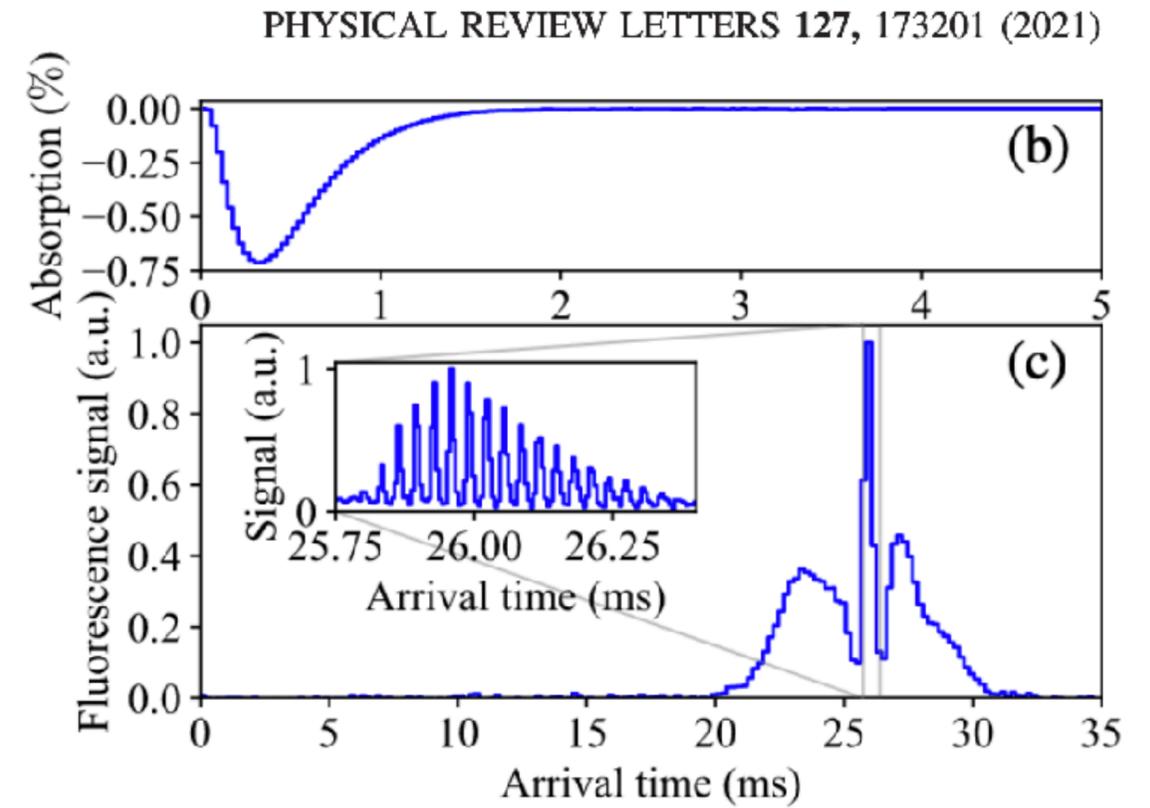
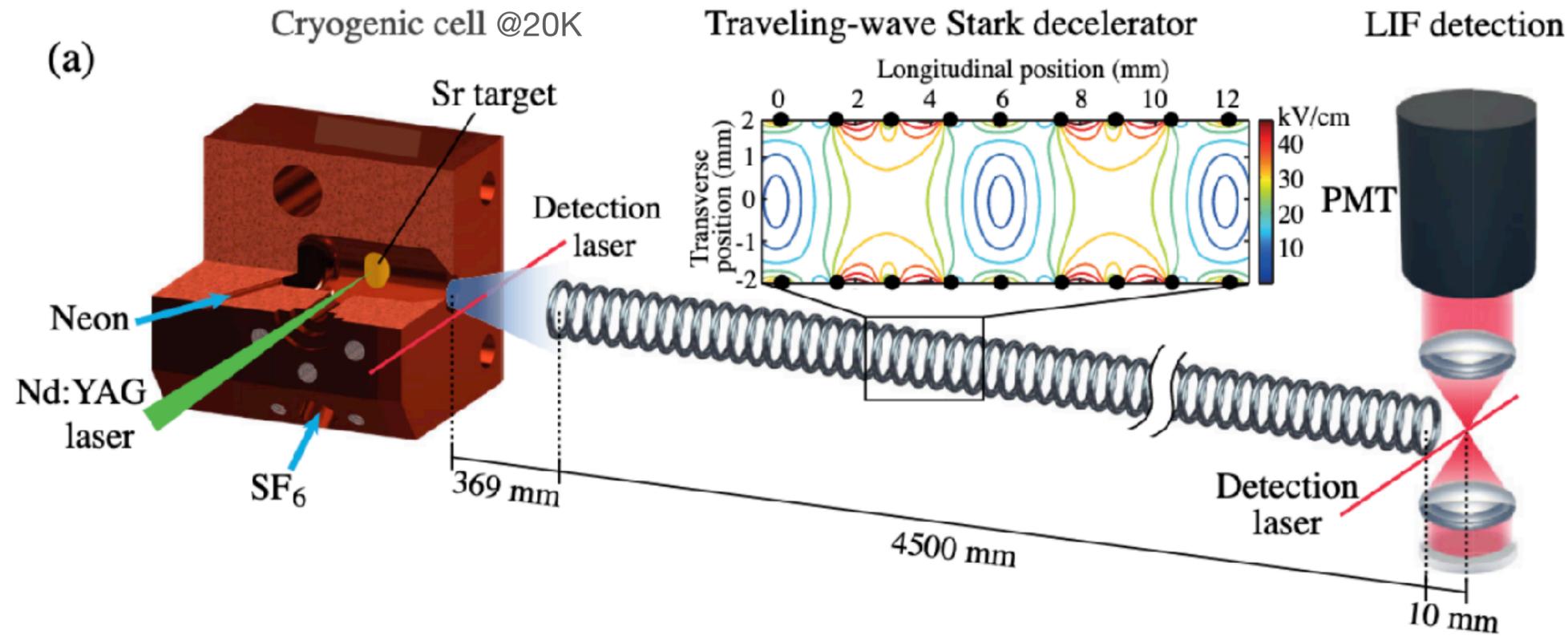
Aggarwal et al, PRL **127**, 173201 (2021)



Molecule deceleration



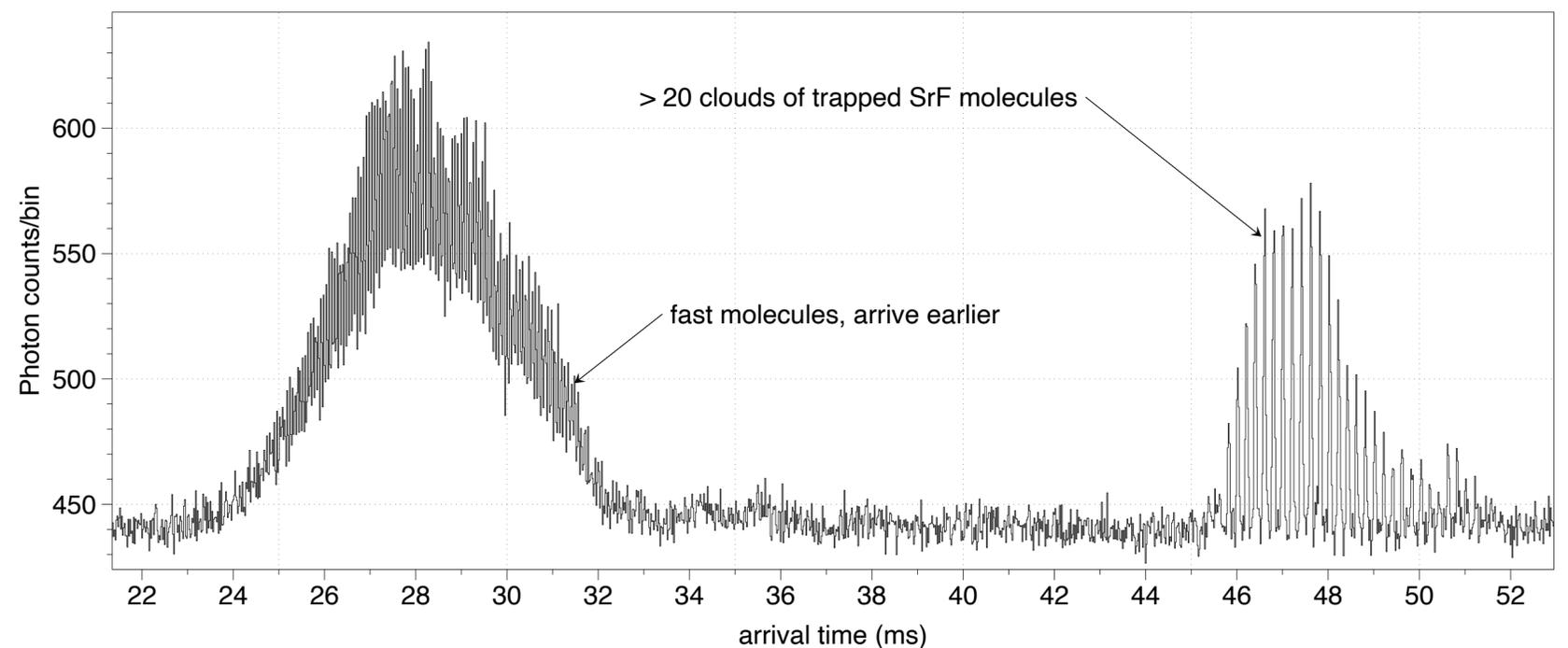
Molecule deceleration



Traveling traps keep molecules together

SrF brought to standstill

BaF, BaOH work in progress
had to upgrade electronics



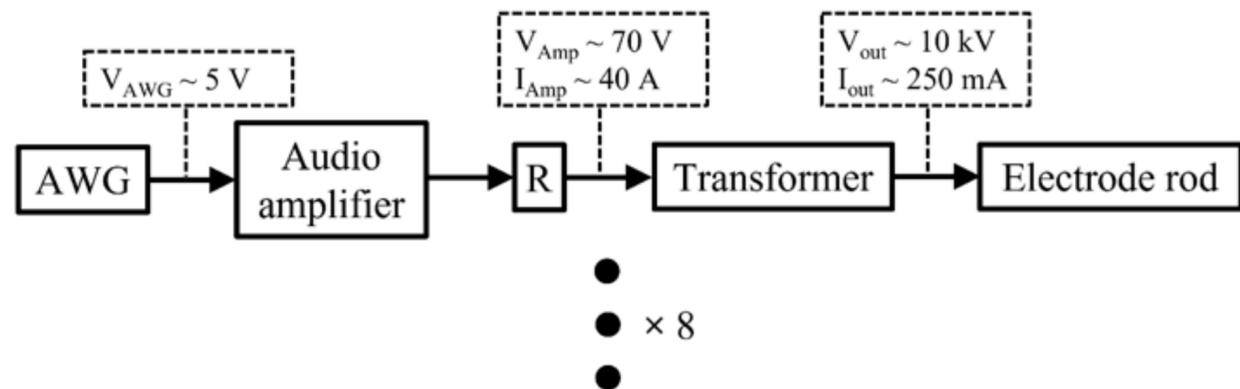


FIG. 4: Schematic overview of the setup. The sequence is repeated for each channel. The dashed boxes show approximate values for the voltage and current amplitudes in that location of the setup when using a test load of 200 pF at 10 kV at the starting frequency of 16.7 kHz. For clarity, the capacitive coupling between adjacent channels and between each channel and ground is not shown.

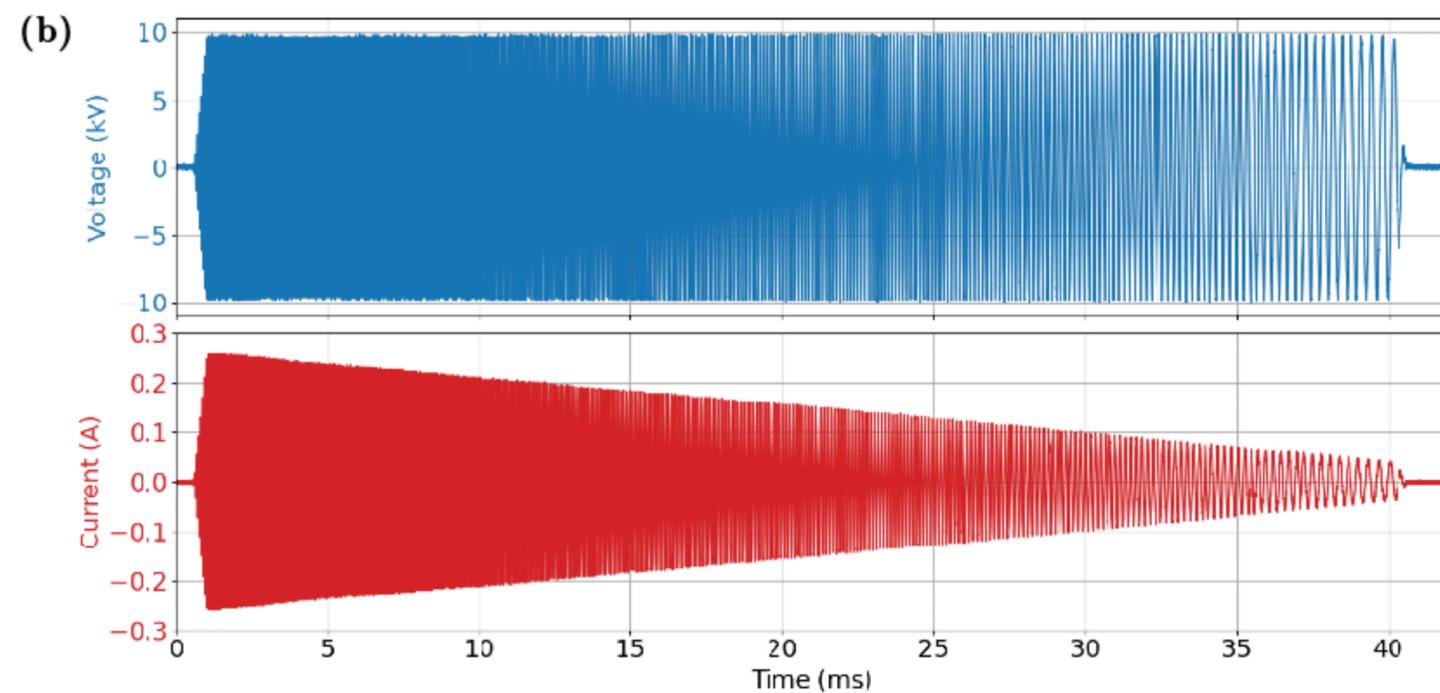
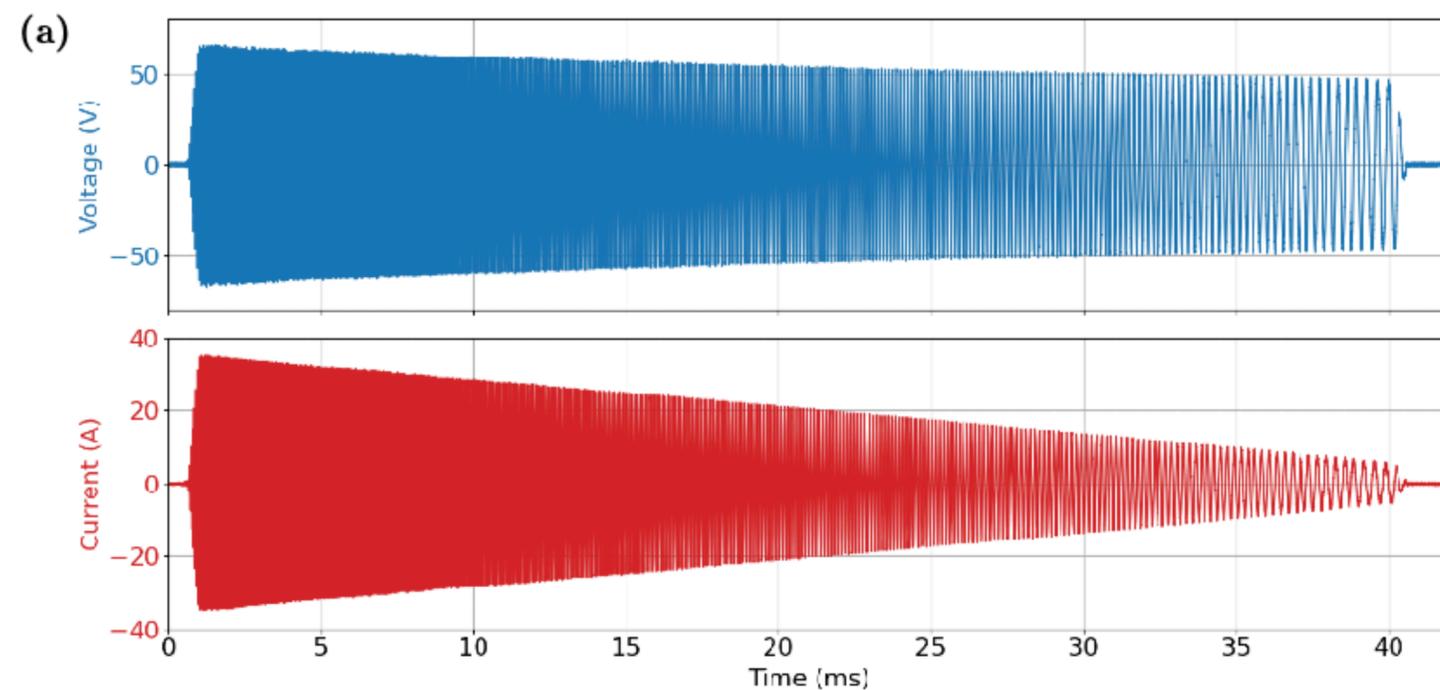
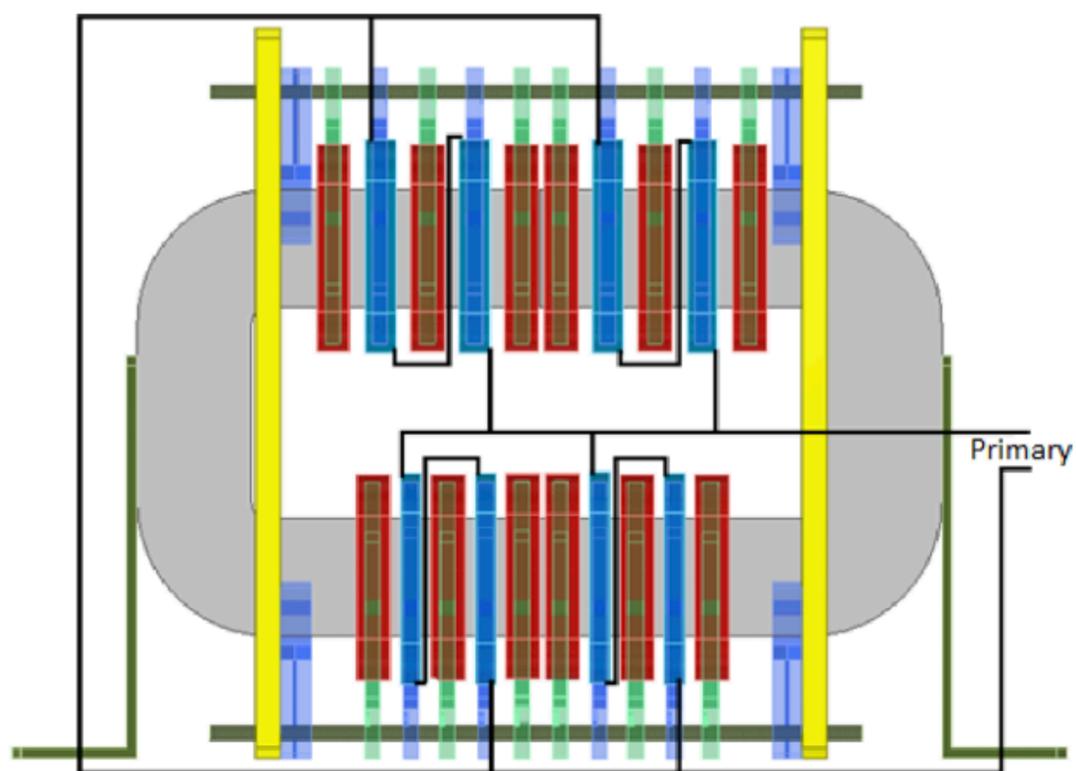


FIG. 13: (a) Voltage across the transformer's input terminals and the corresponding current, and (b) the output voltage and corresponding current of a single encapsulated transformer driven by a frequency sweep from 16.7 kHz to 2.5 kHz in 40 ms on a 200 pF test load. The input waveform is optimized using the feedback system.

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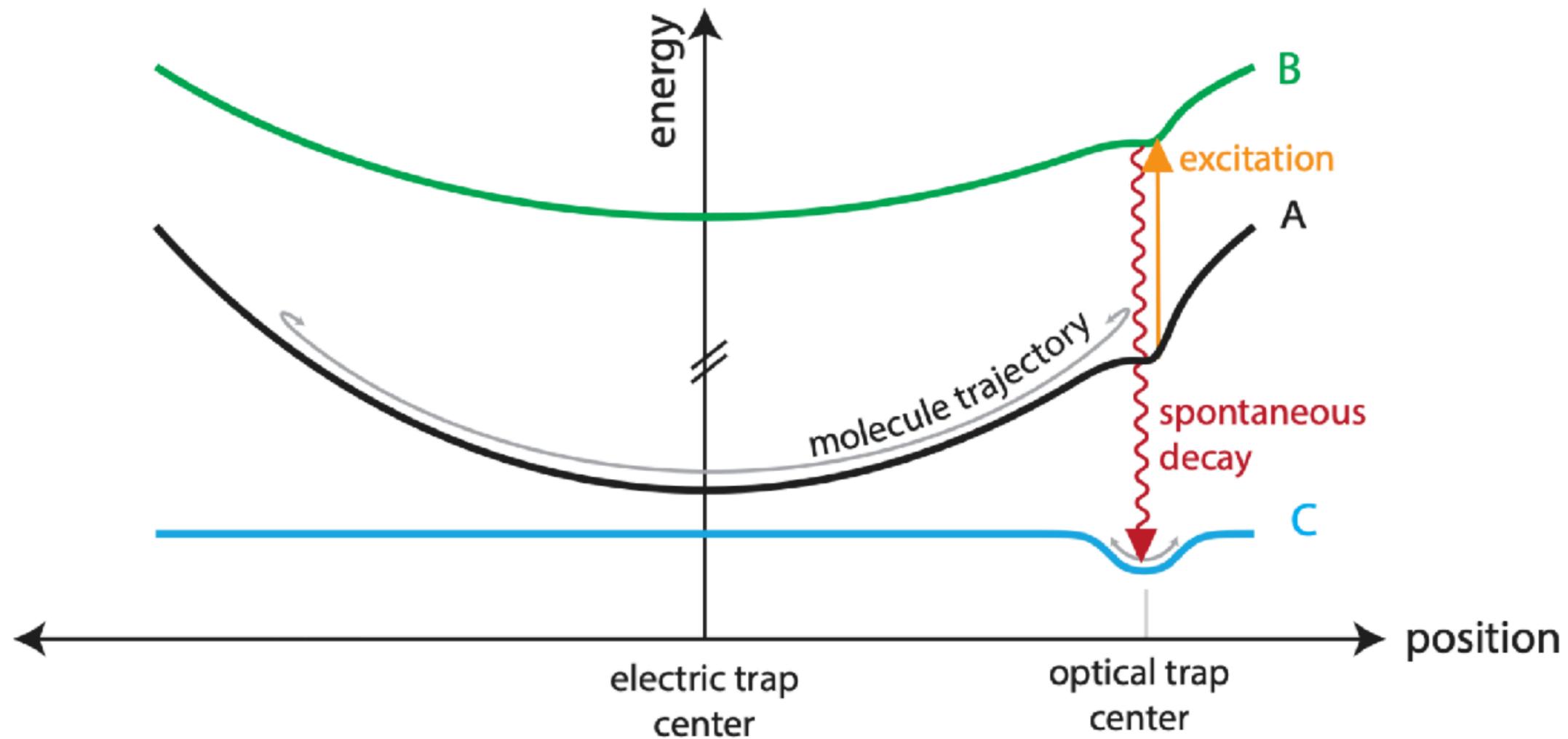
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Phase 3

Trapping polyatomic molecules

Single-photon loading idea



Conclusions

Completed proof-of-principle eEDM measurements (phase 1)

Upgrading to reach $\sim 10^{-30}$ e.cm sensitivity (phase 2)

Good progress towards optically trapped molecules (phase 3)



Great workshop to learn new things, share our expertise, and make new friends!