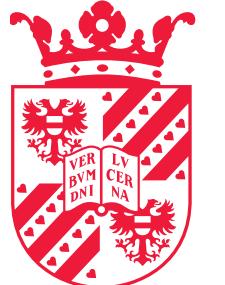
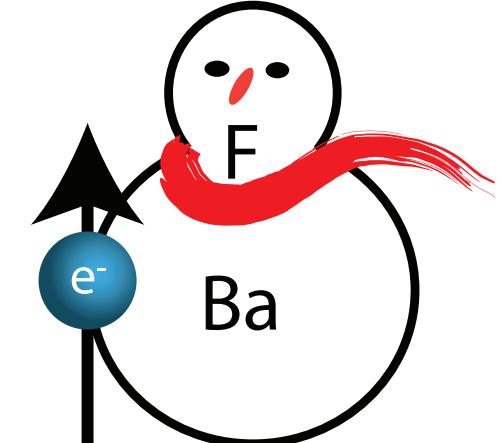
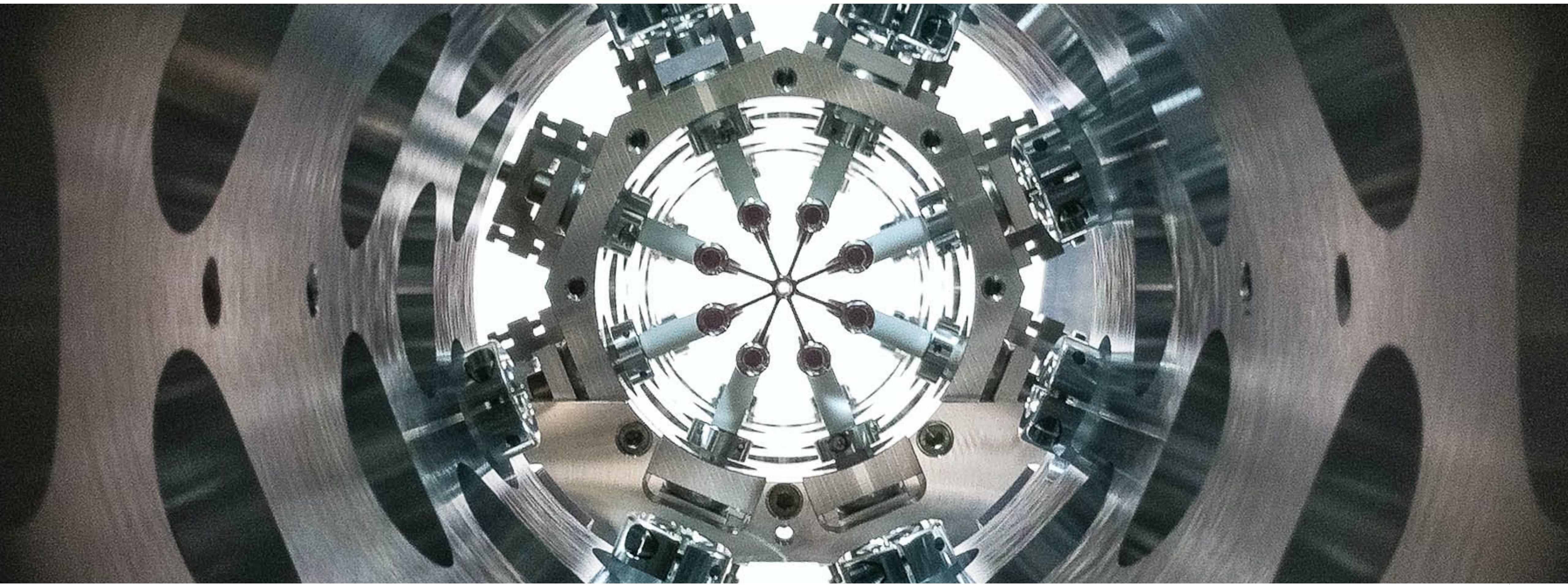


Tabletop particle physics: Measuring the electron-EDM with cold molecules

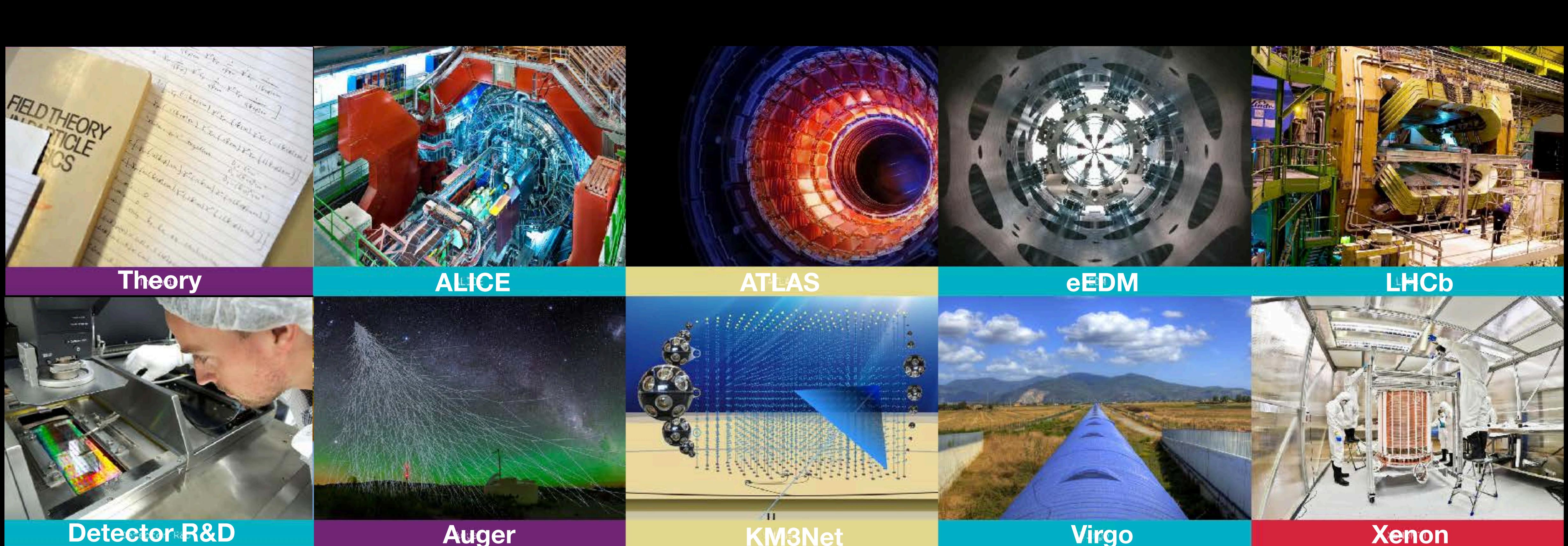


university of
groningen
van swinderen institute for
particle physics and gravity

Nikhef
Dutch National Institute for (astro)Particle Physics

VU
VRIJE
UNIVERSITEIT
AMSTERDAM

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



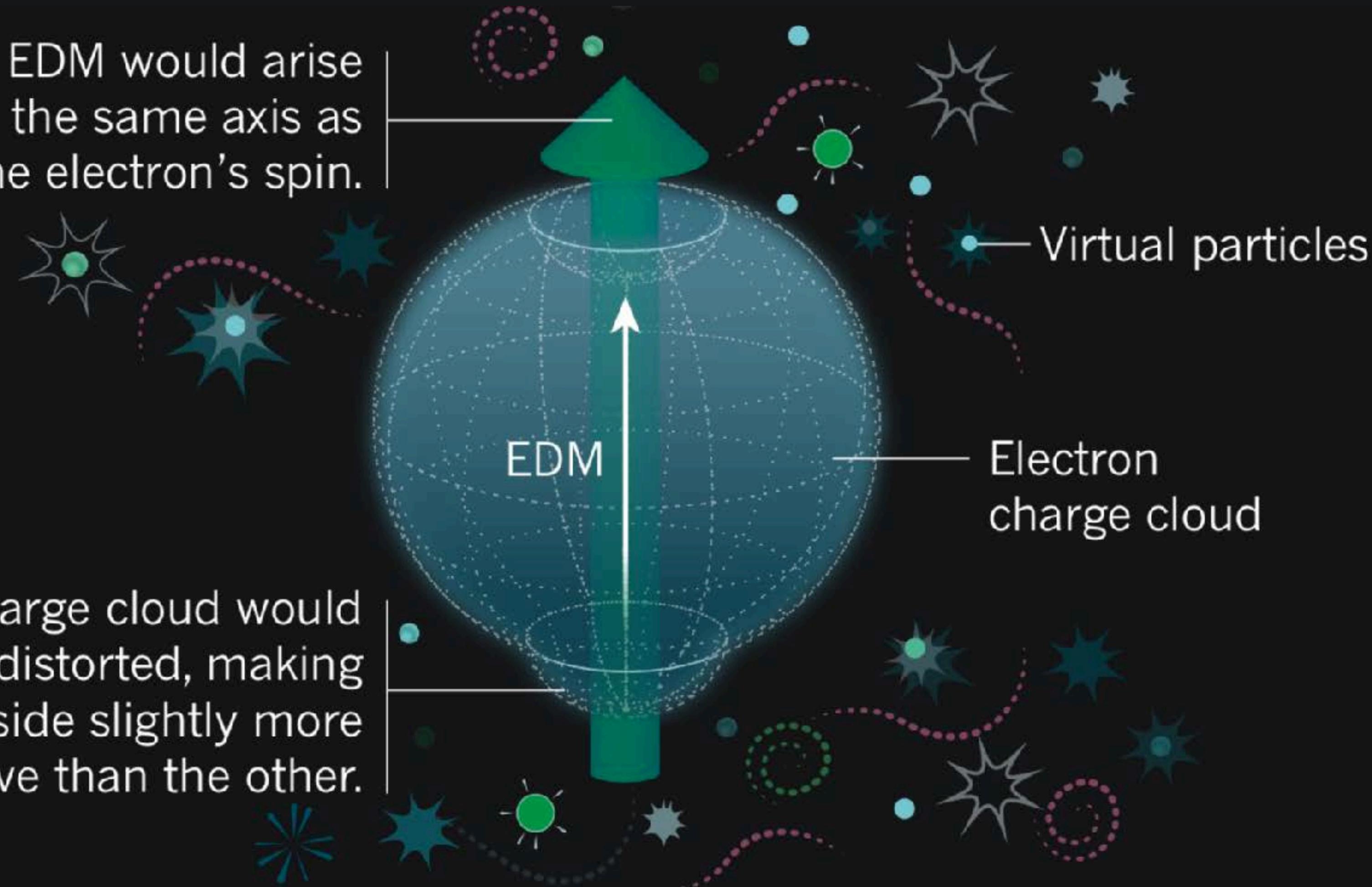
Dutch National Institute for (astro)Particle Physics

...using molecules and lasers!

Is the electron round?

The Electric Dipole Moment of the electron (eEDM)

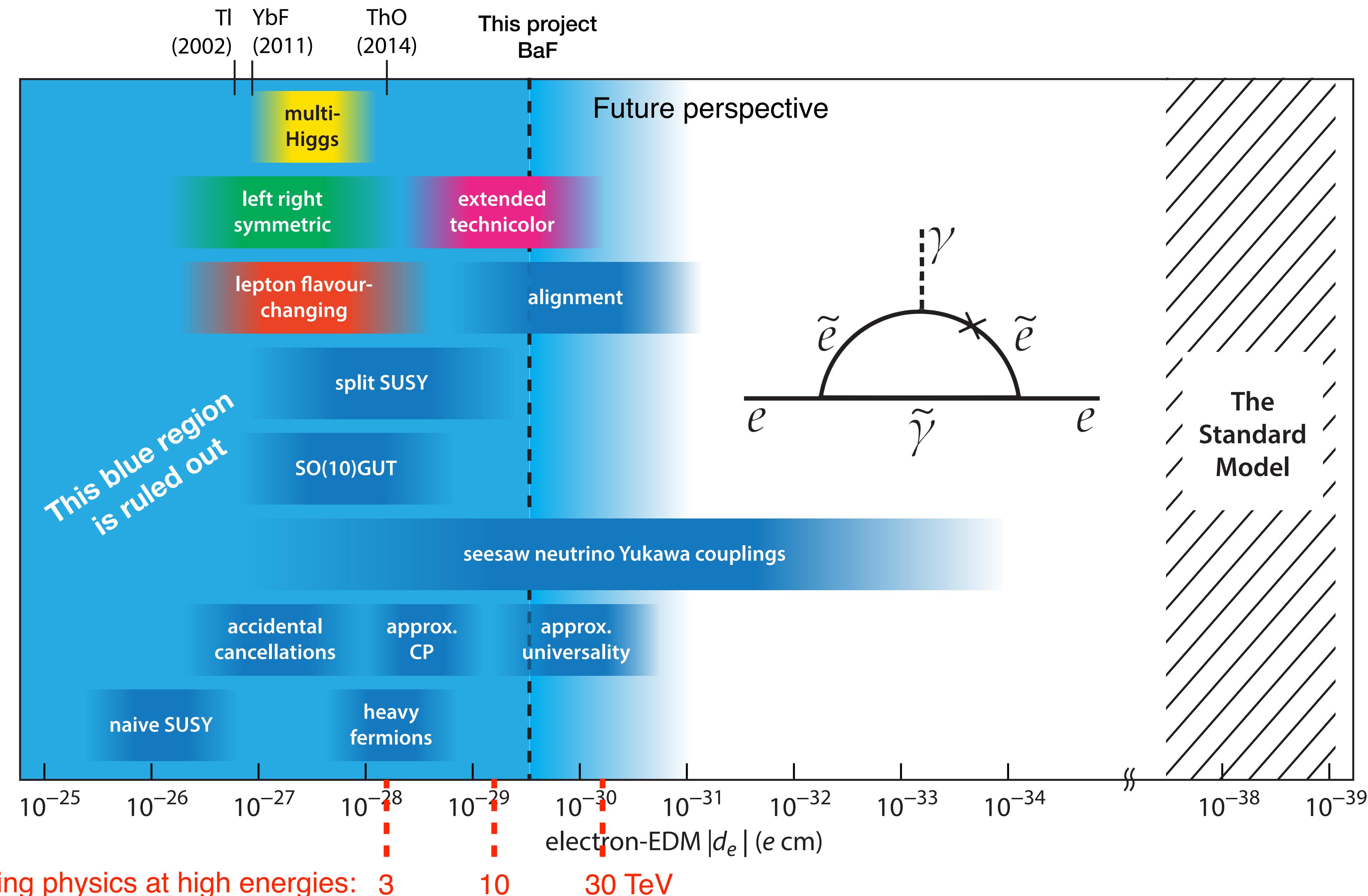
An EDM would arise along the same axis as the electron's spin.



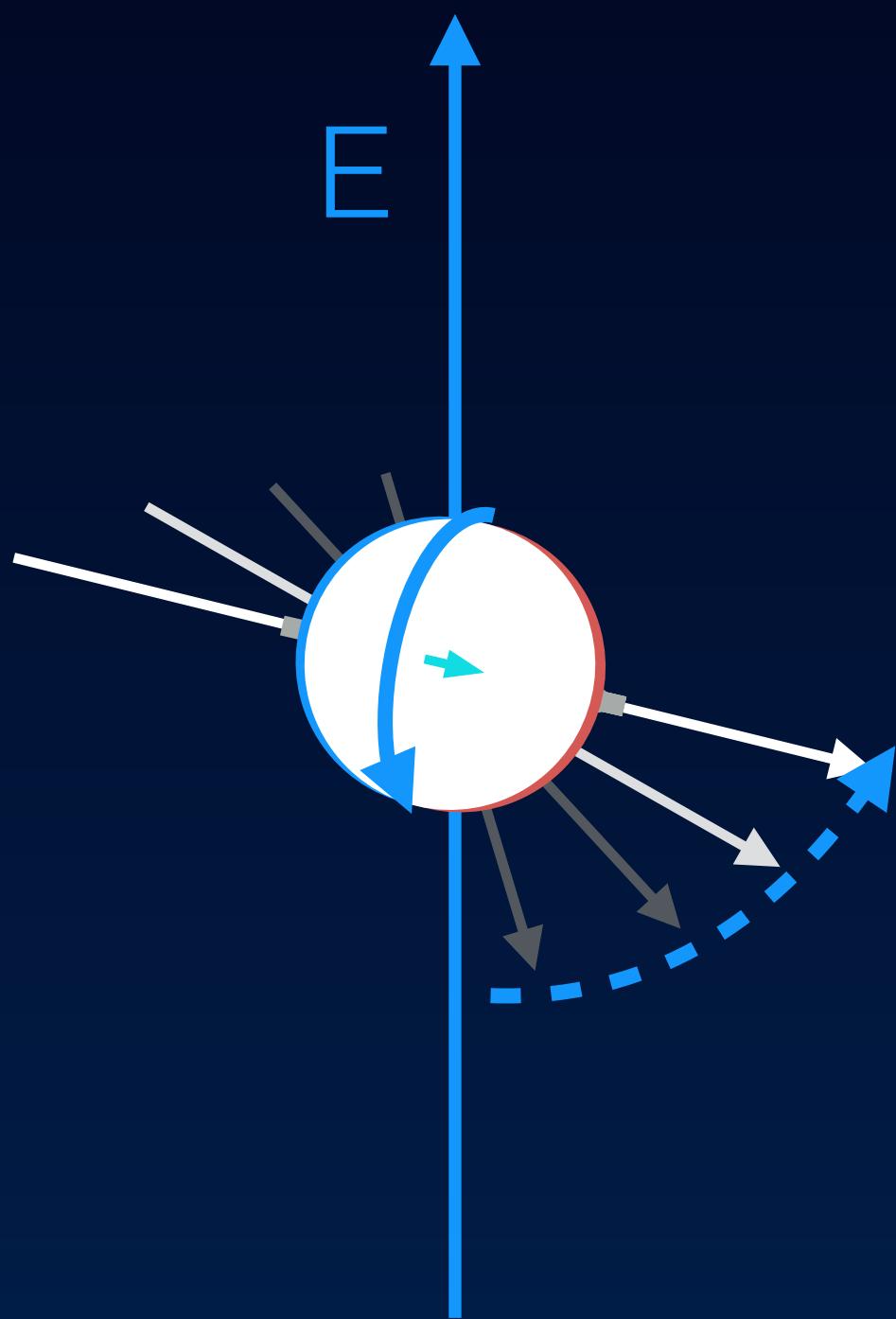
The charge cloud would be distorted, making one side slightly more negative than the other.

an eEDM violates time-reversal symmetry

The Standard Model has problems: it can not explain matter-antimatter asymmetry.
electron-EDM experiments test the extensions that aim to fix this problem!

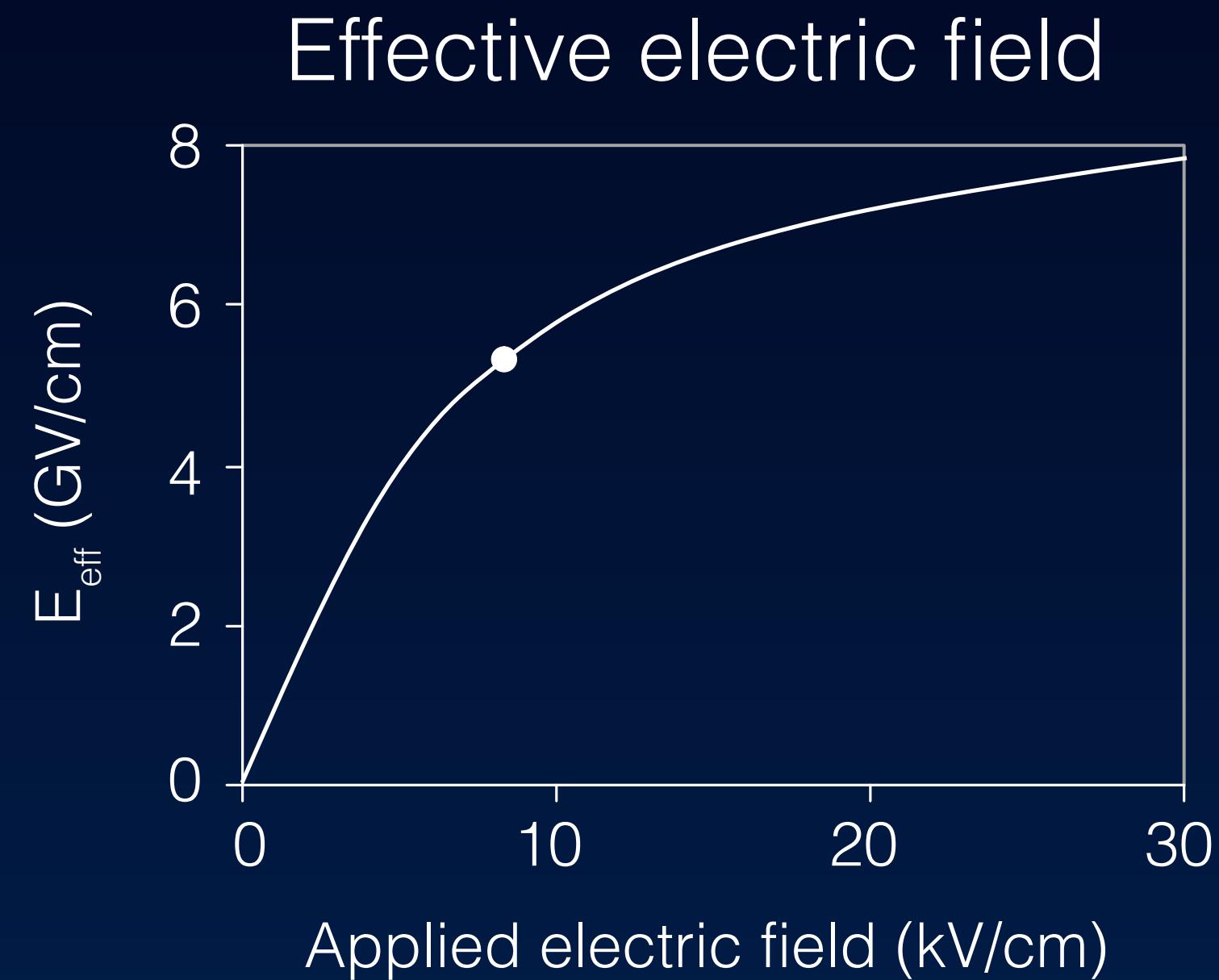
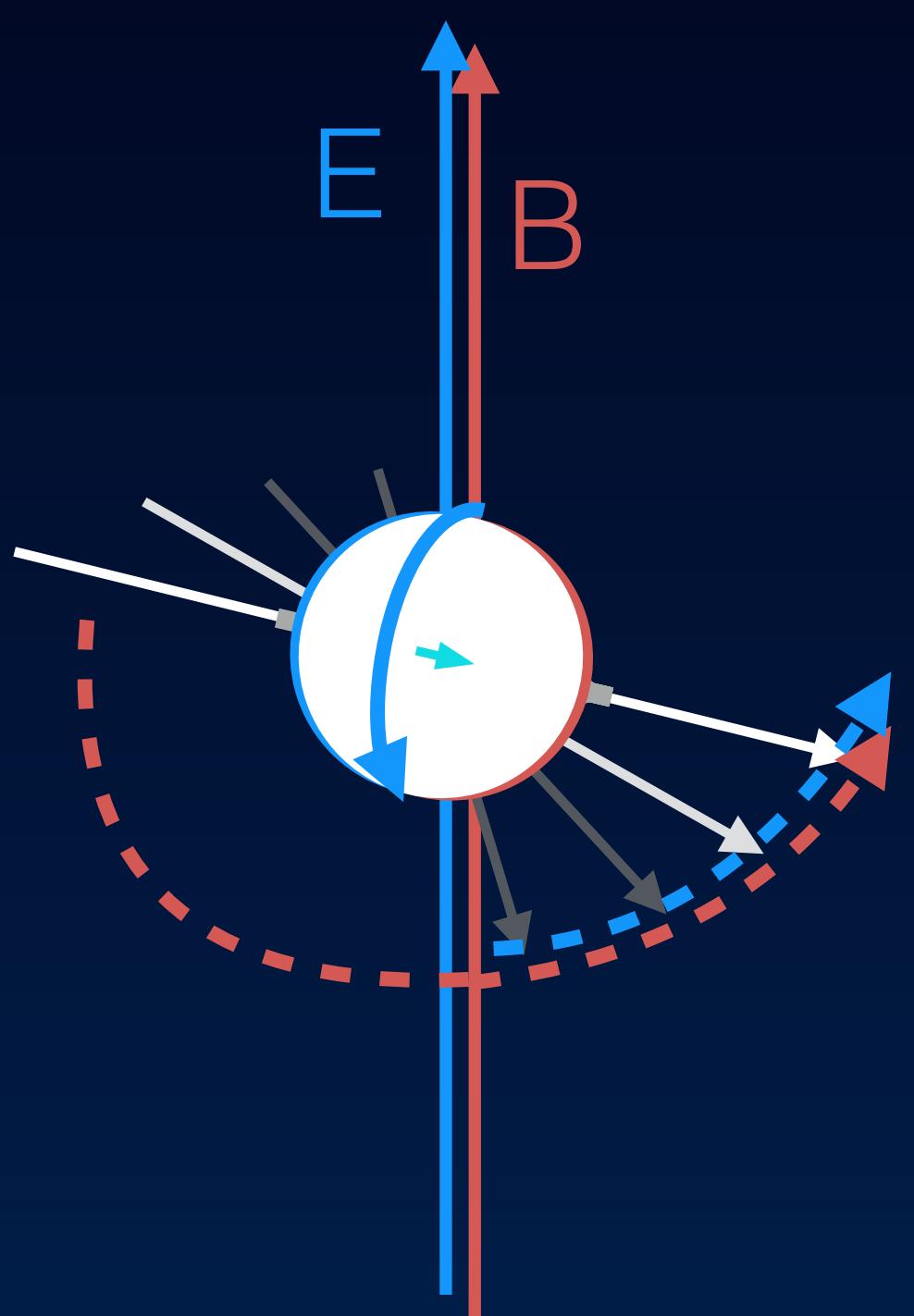


How to measure a dipole moment?



precession!

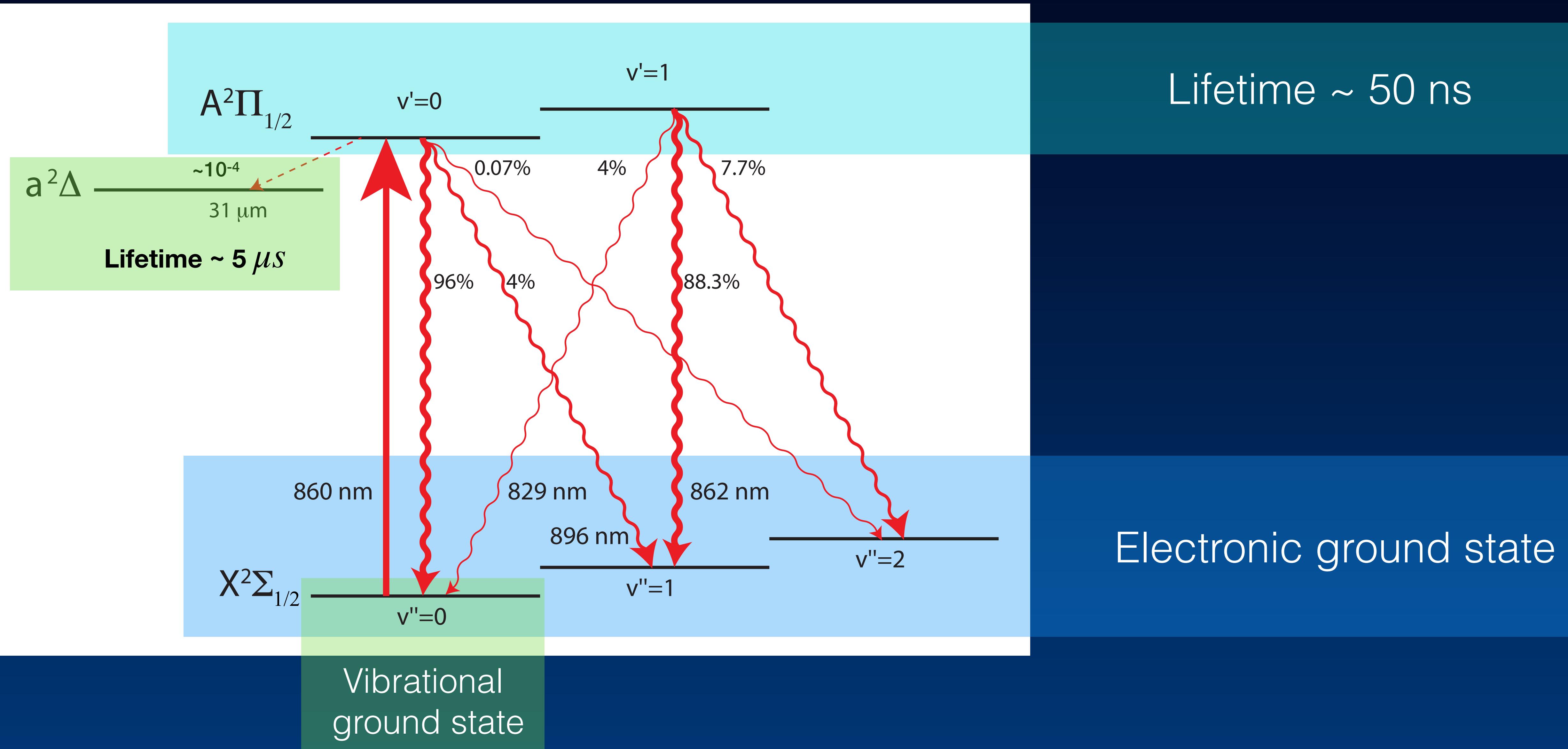
However, electron also has
magnetic dipole moment
(and charge!)



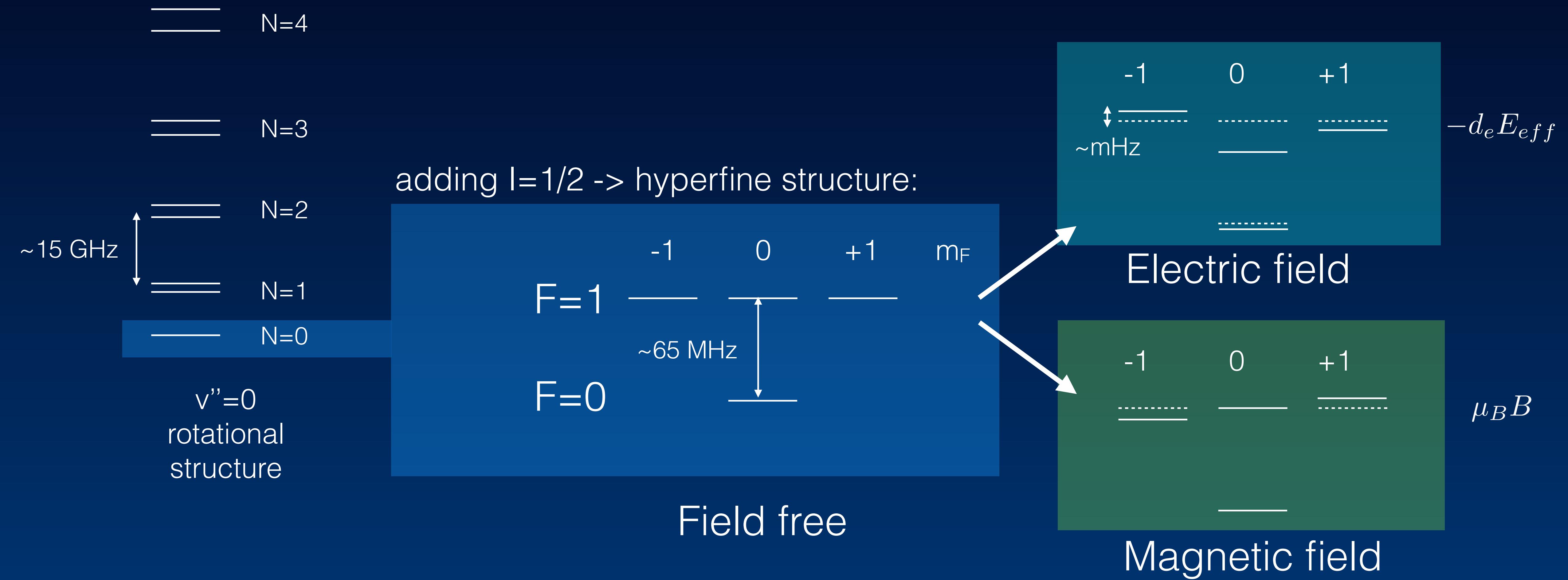
Solution:
use electron embedded
in a polar molecule!
We have selected BaF

Enhances E
Shields B

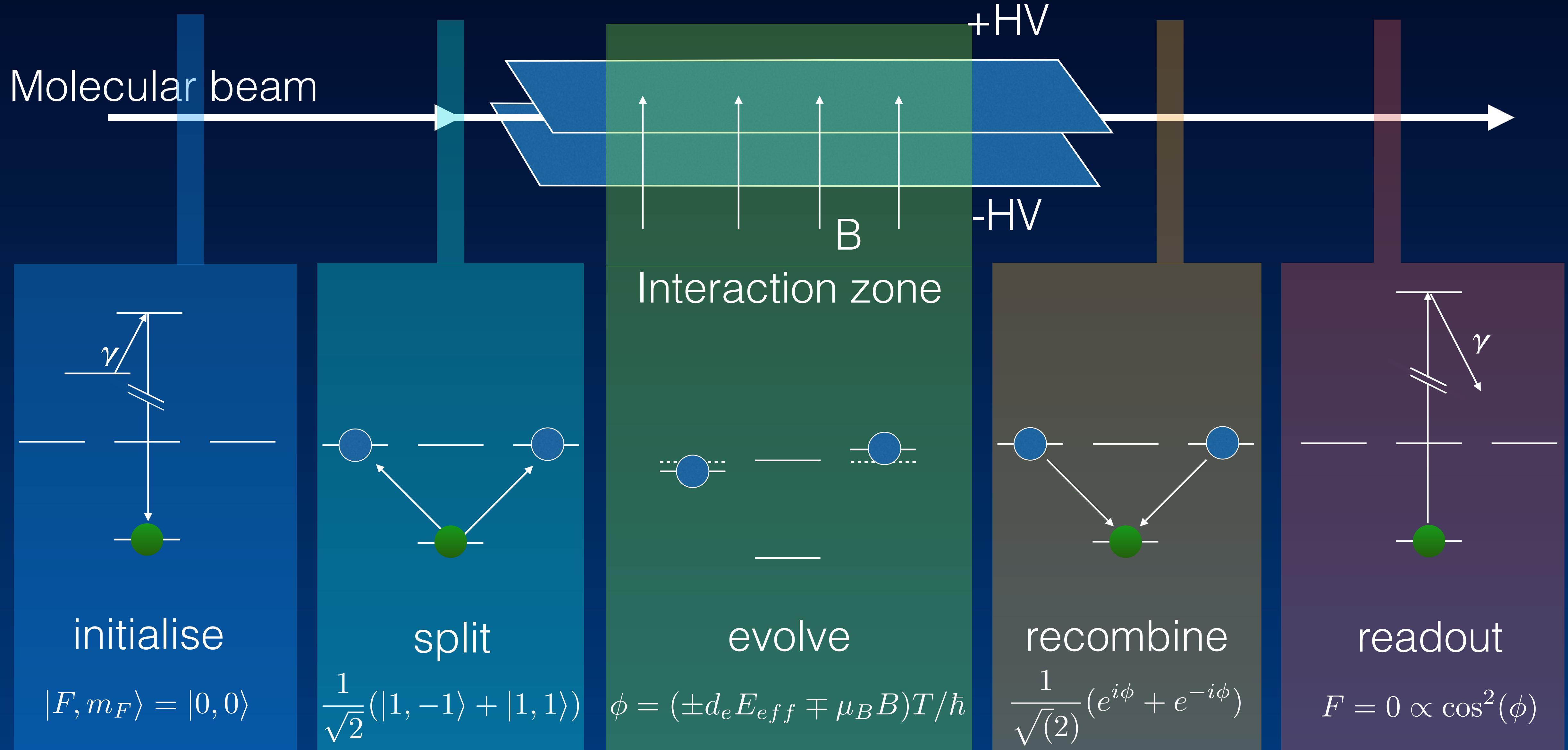
How the electron-EDM measurement is done with BaF molecules



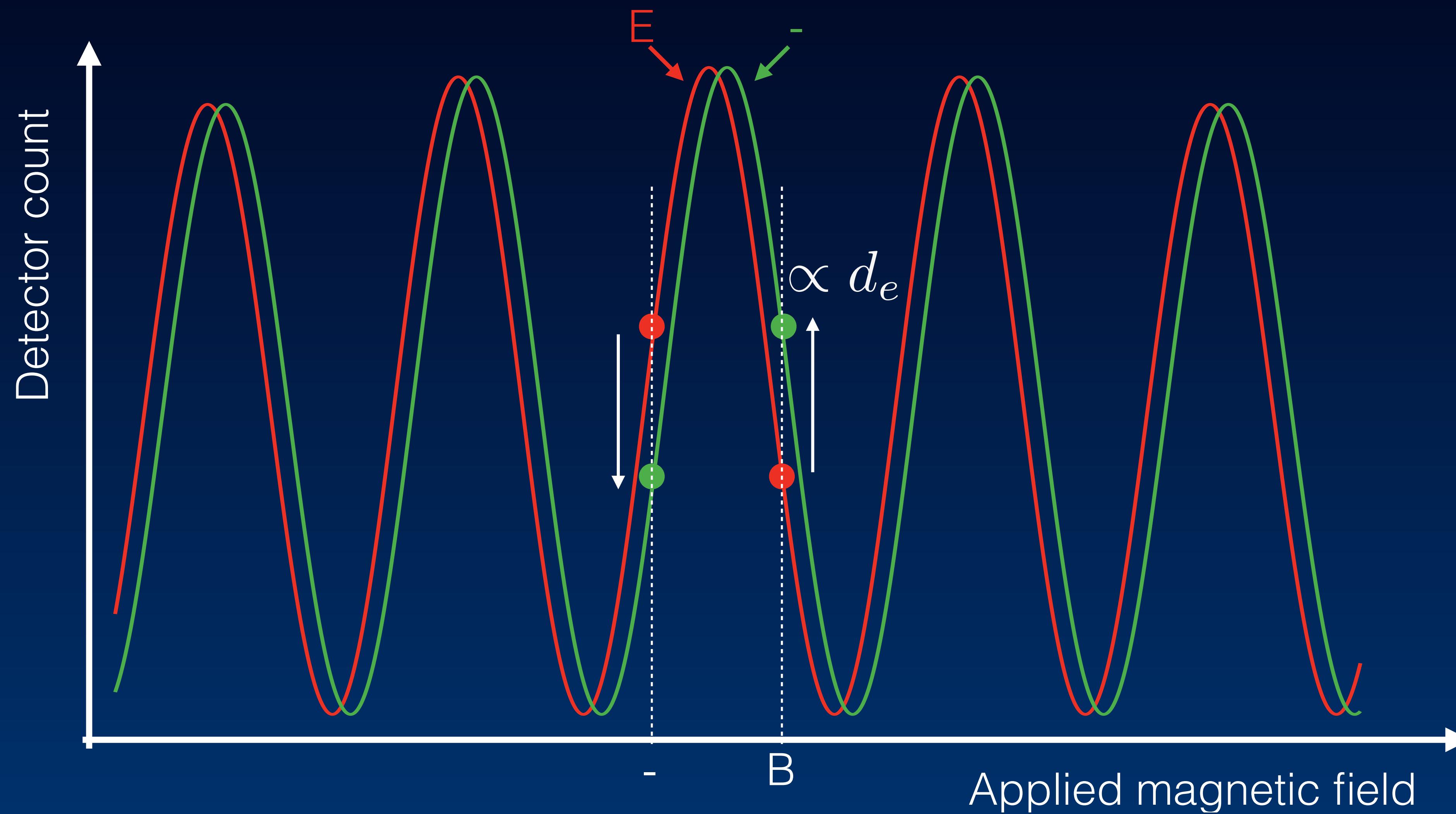
Energy level structure of the BaF molecule



How to read out small energy shifts: spin interferometer



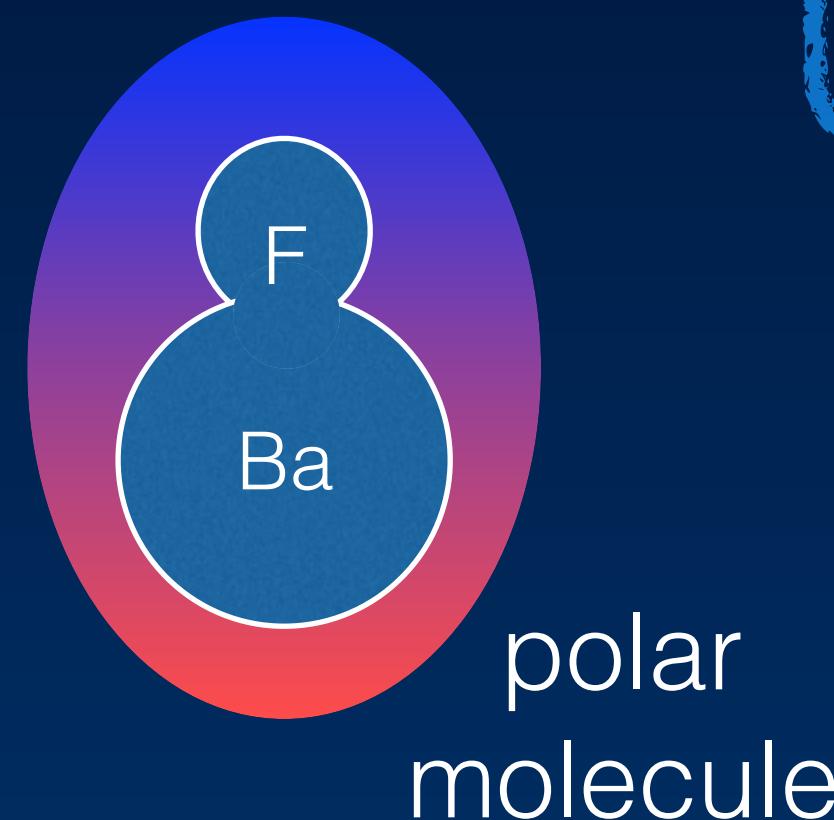
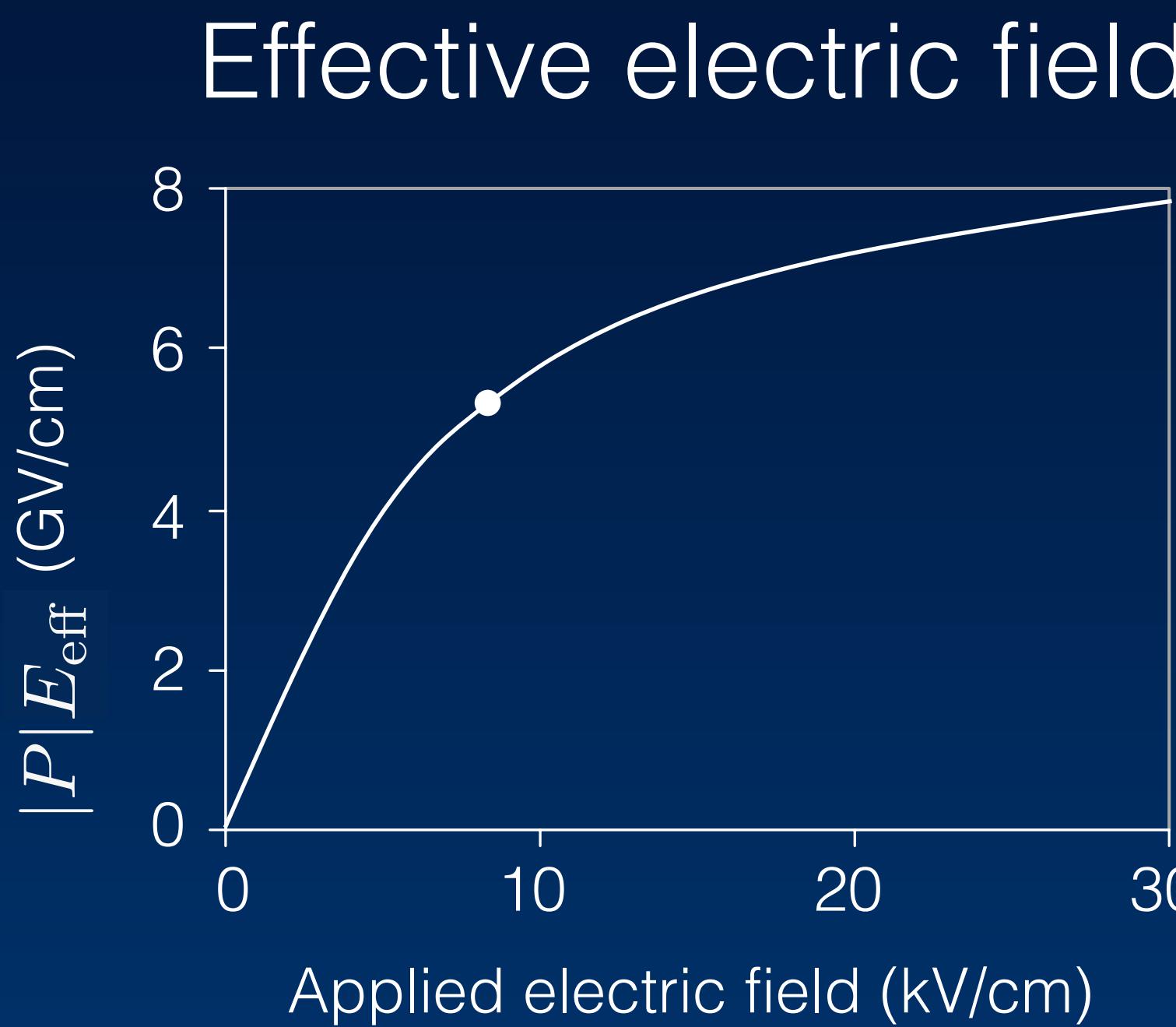
Interferometer phase $\phi = (\pm d_e E_{eff} \mp \mu_B B)T/\hbar$



Increasing the eEDM sensitivity

Measure shift of molecular energy level
that correlates with electric field direction reversal

$$\text{statistical error: } \sigma_d = \frac{\hbar}{e} \frac{1}{2|P|E_{\text{eff}}\tau\sqrt{\dot{N}T}}$$

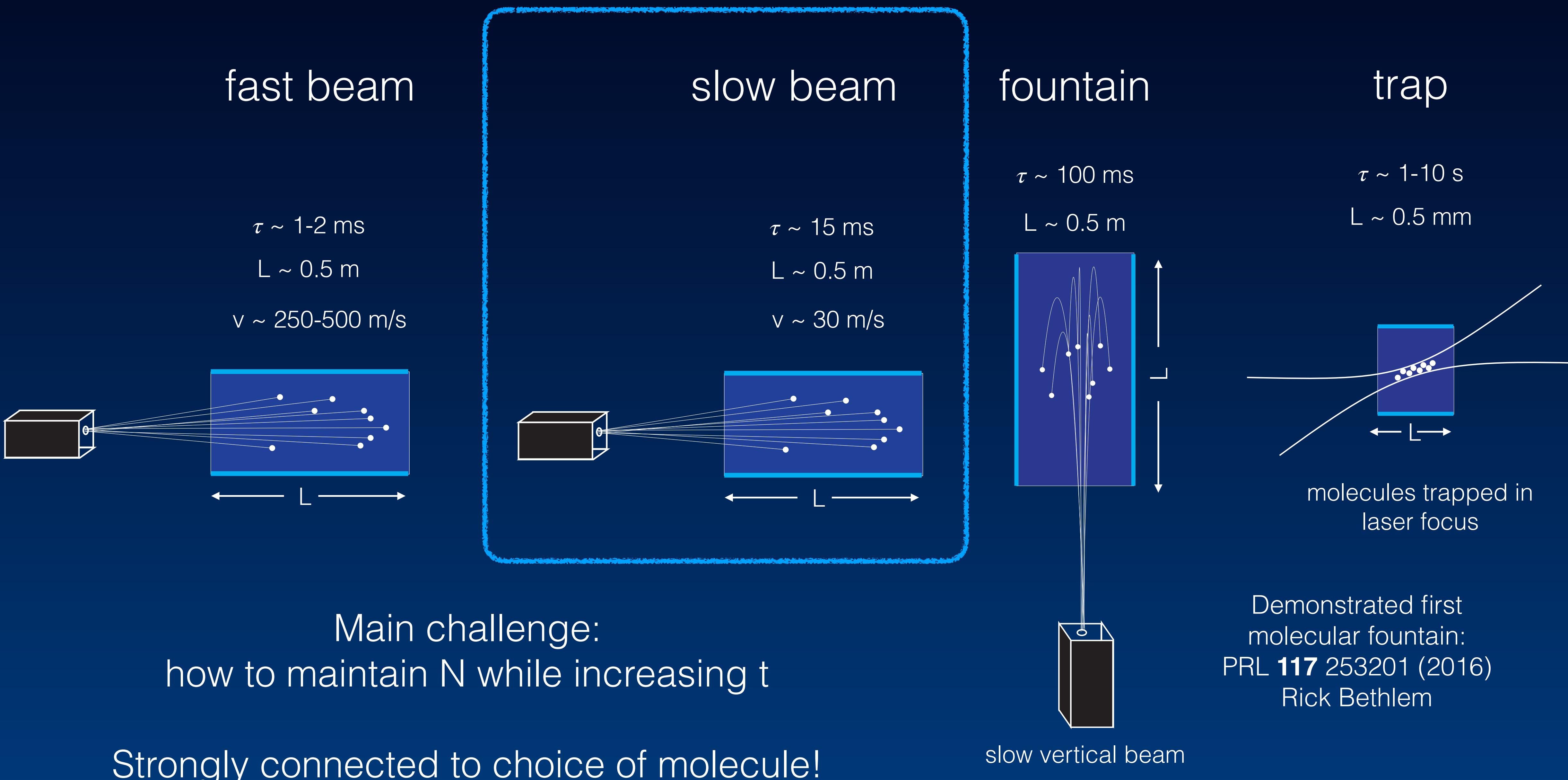


Cold Molecules

Number of detected molecules

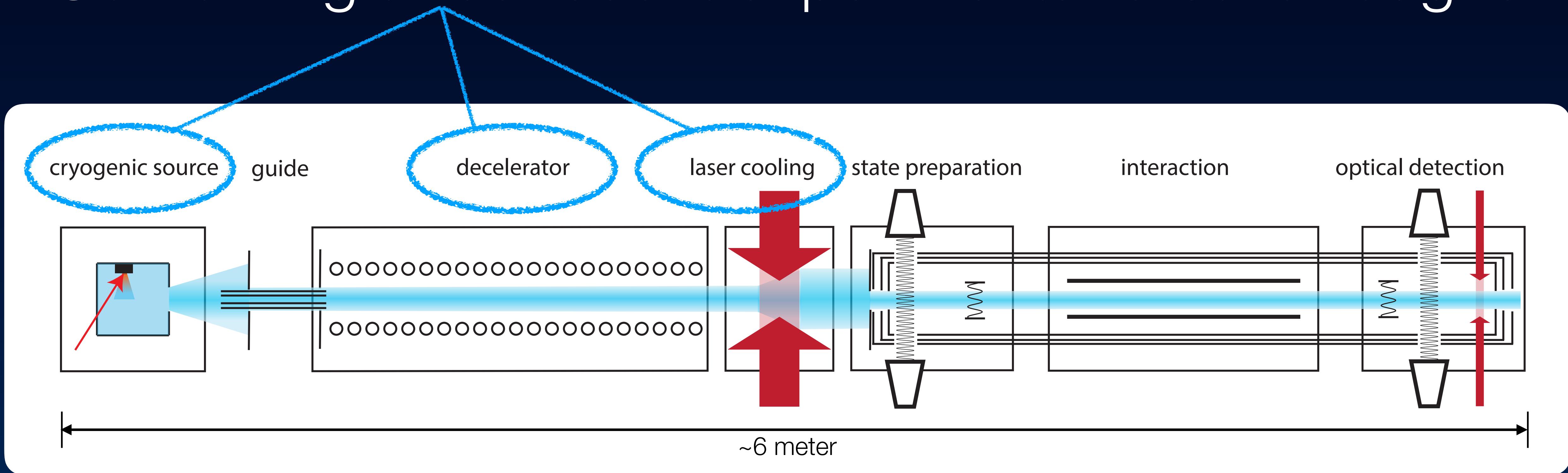
Coherent interaction time

Towards longer coherent interaction times



Our approach:

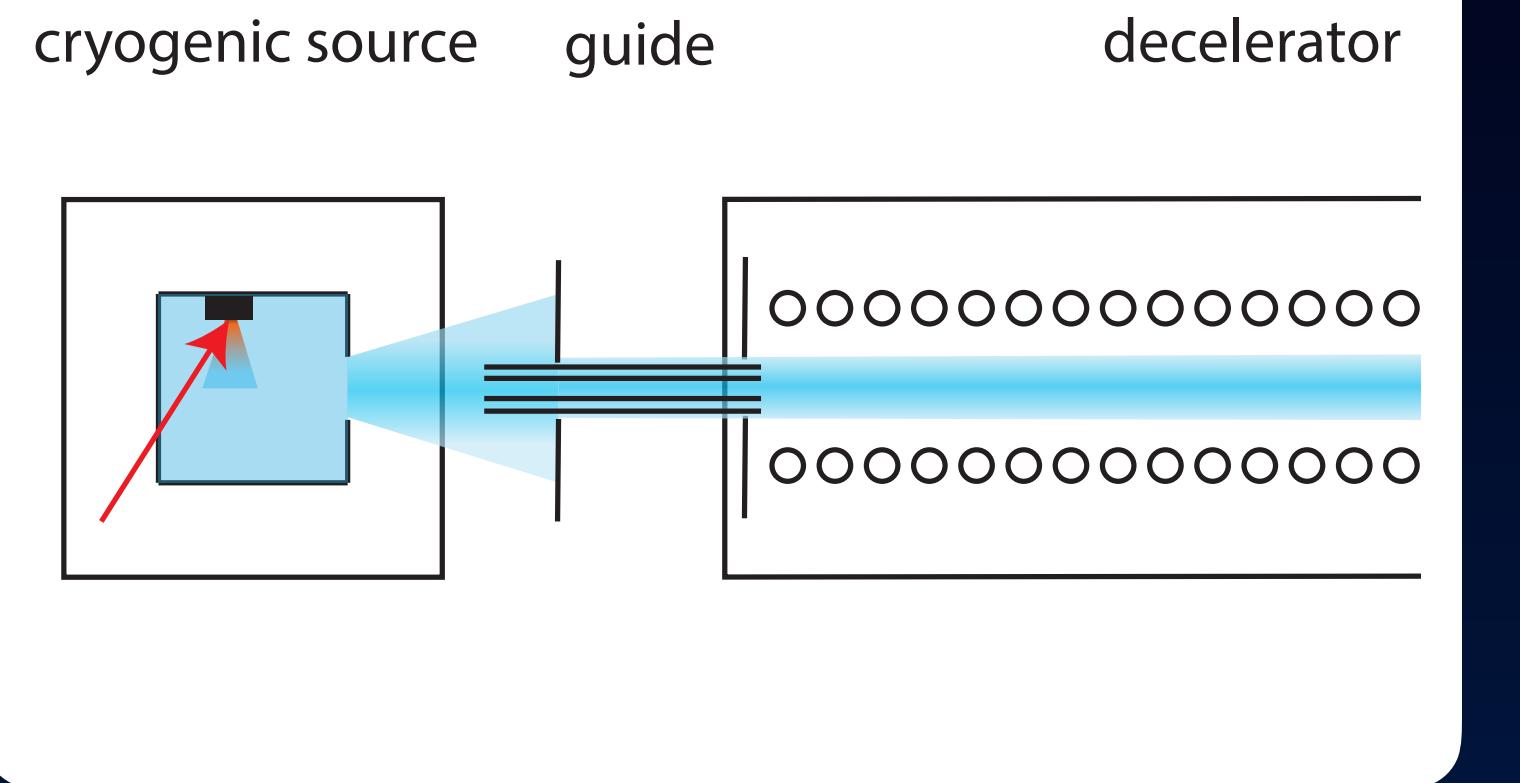
Combining three recent experimental breakthroughs



Using BaF molecules, we can create a very **intense, slow and cold** beam

We aim for $5 \cdot 10^{-30}$ e.cm in the first generation of the experiment

Published paper with full details of proposal: Eur. Phys. J. D **72**:197 (2018)



Molecular beams

Supersonic

Aims:

- Intense, fast beam (~ 600 m/s)
- Very short pulse
- Use to test lasers systems, state manipulation and interaction zone

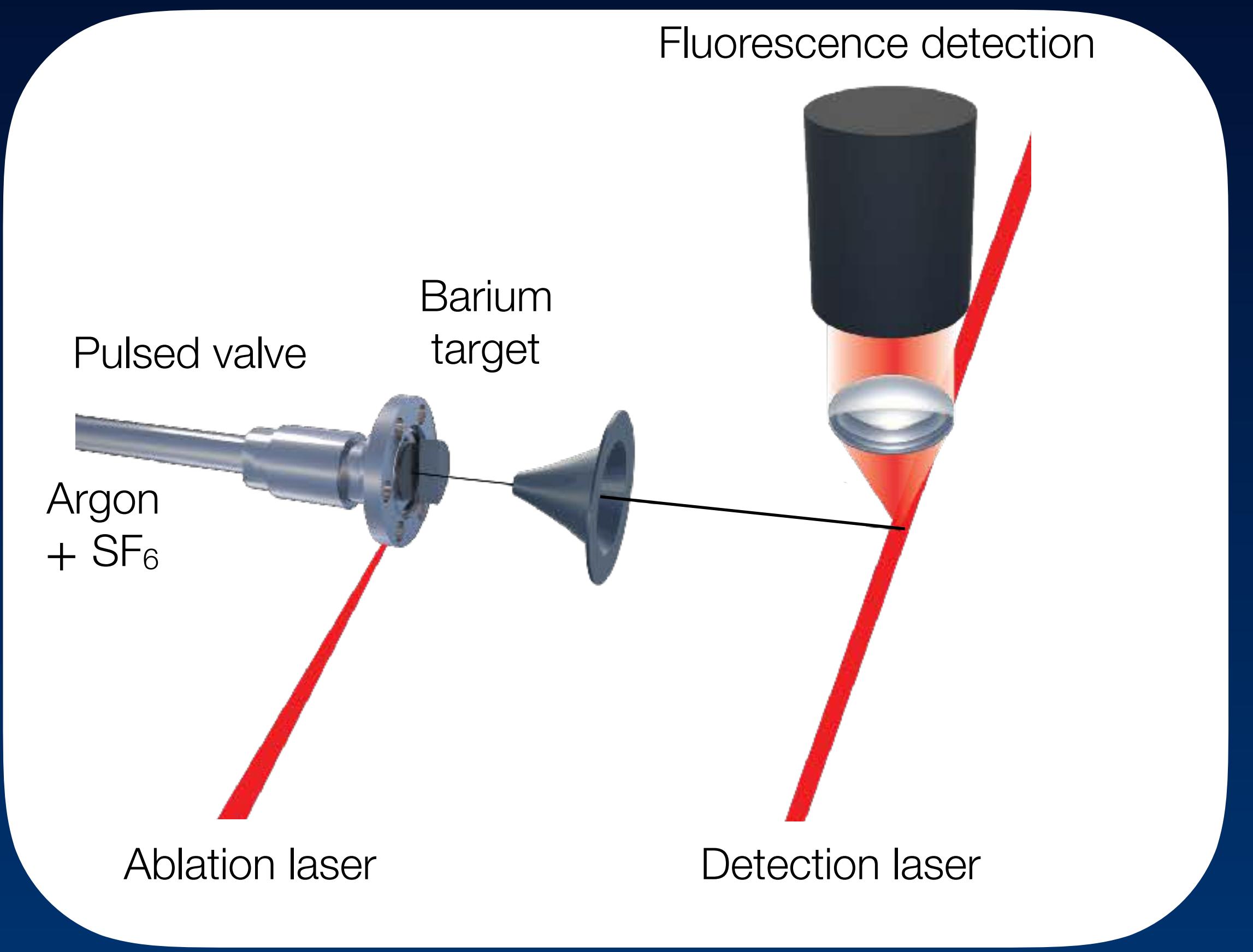
Cryogenic

Aims:

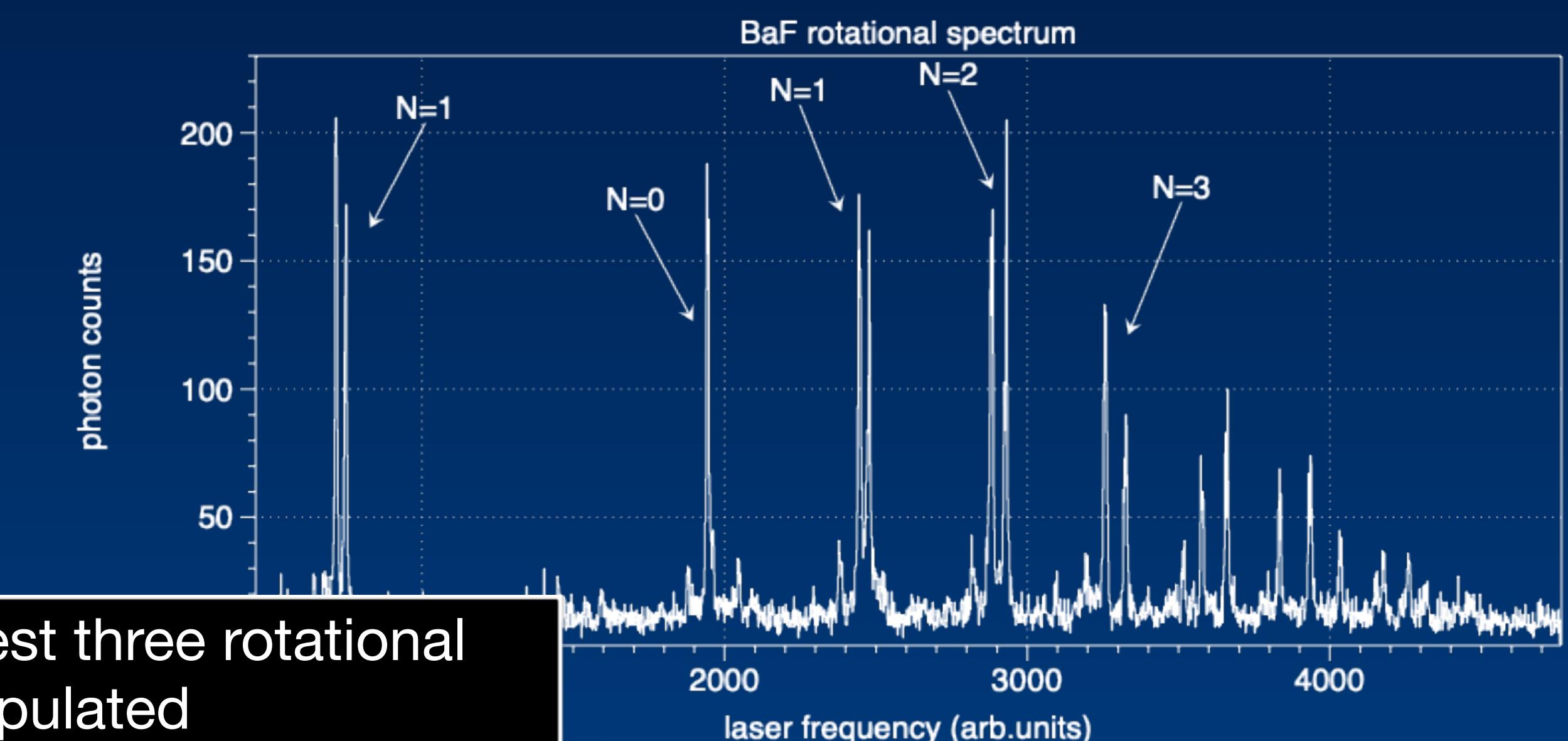
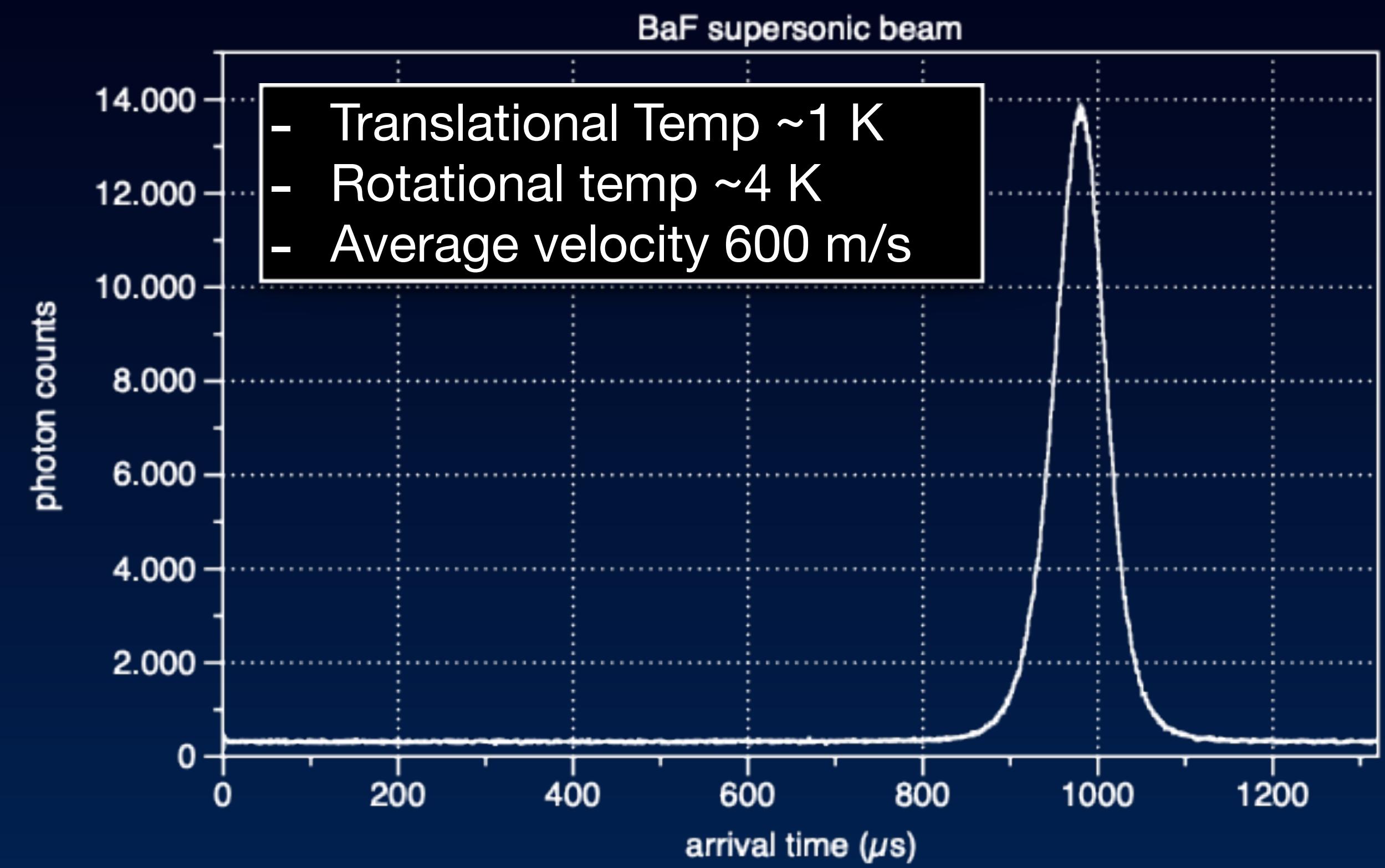
- Intense, slow beam (~ 180 m/s)
- High N: 4×10^9 /shot in the desired state
- Use for eEDM measurement



Supersonic beam



Aggarwal et al, the NL-eEDM collaboration,
Phys. Rev. A 100, 052503 (2019)

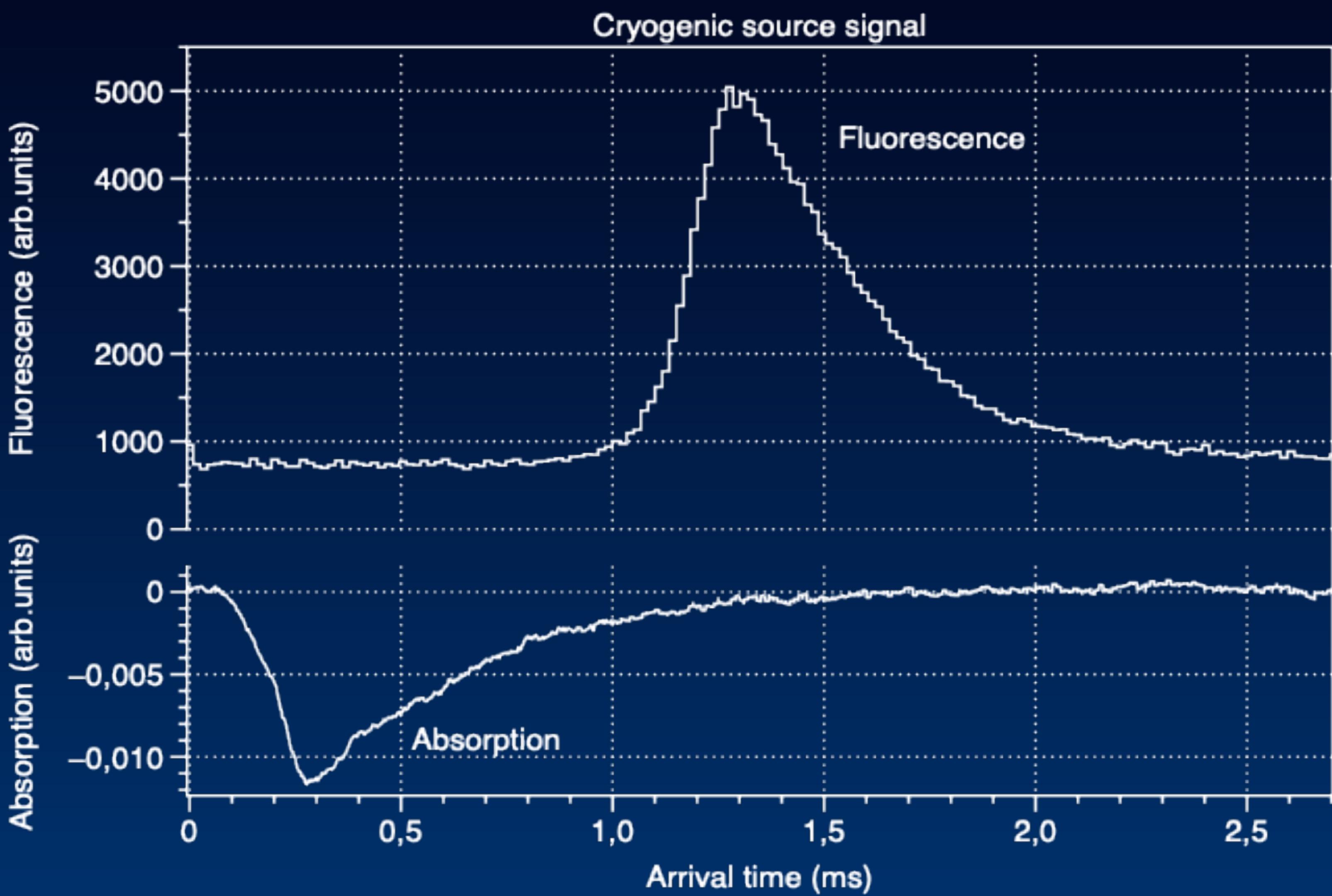


Only lowest three rotational states populated

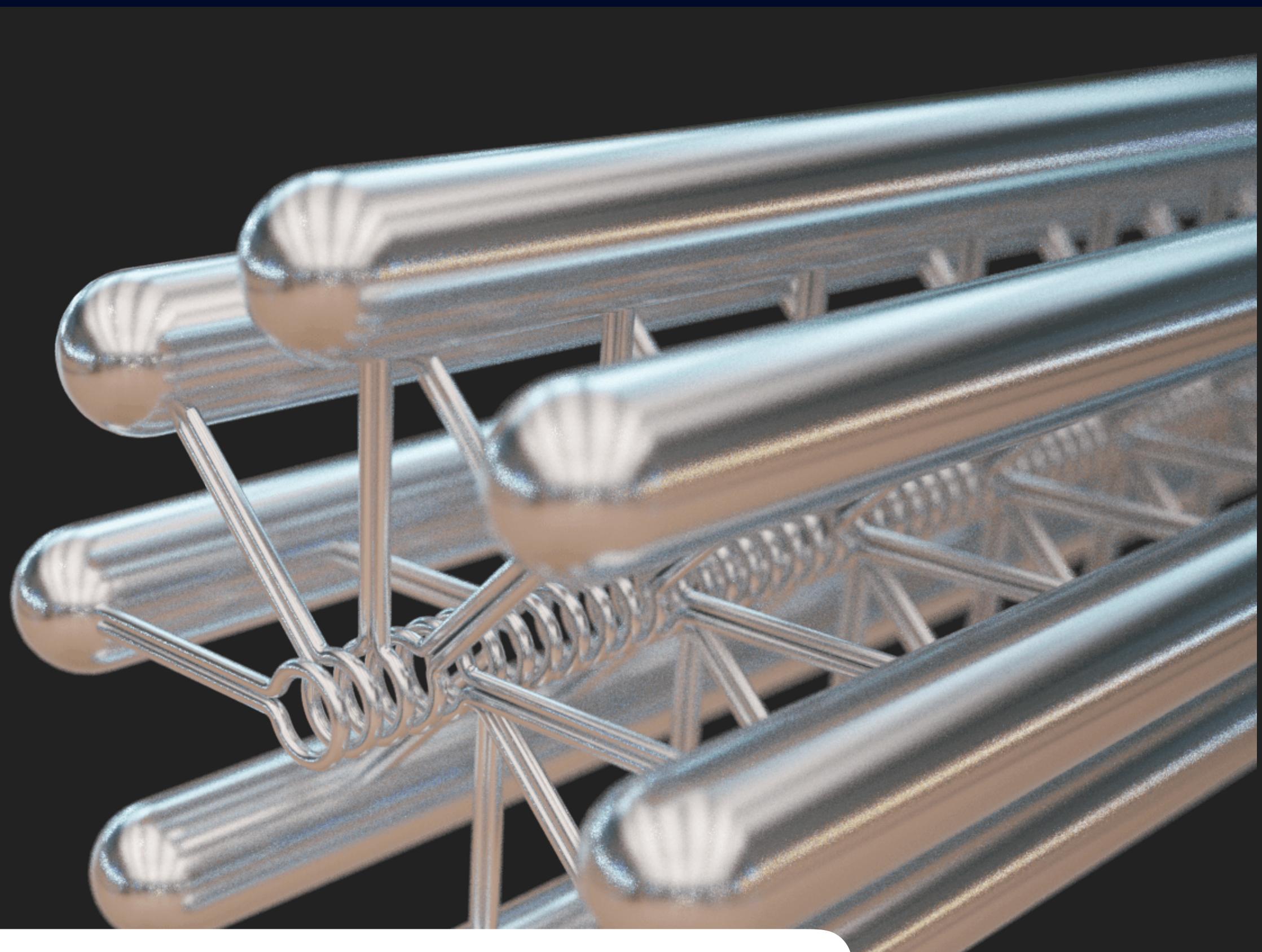
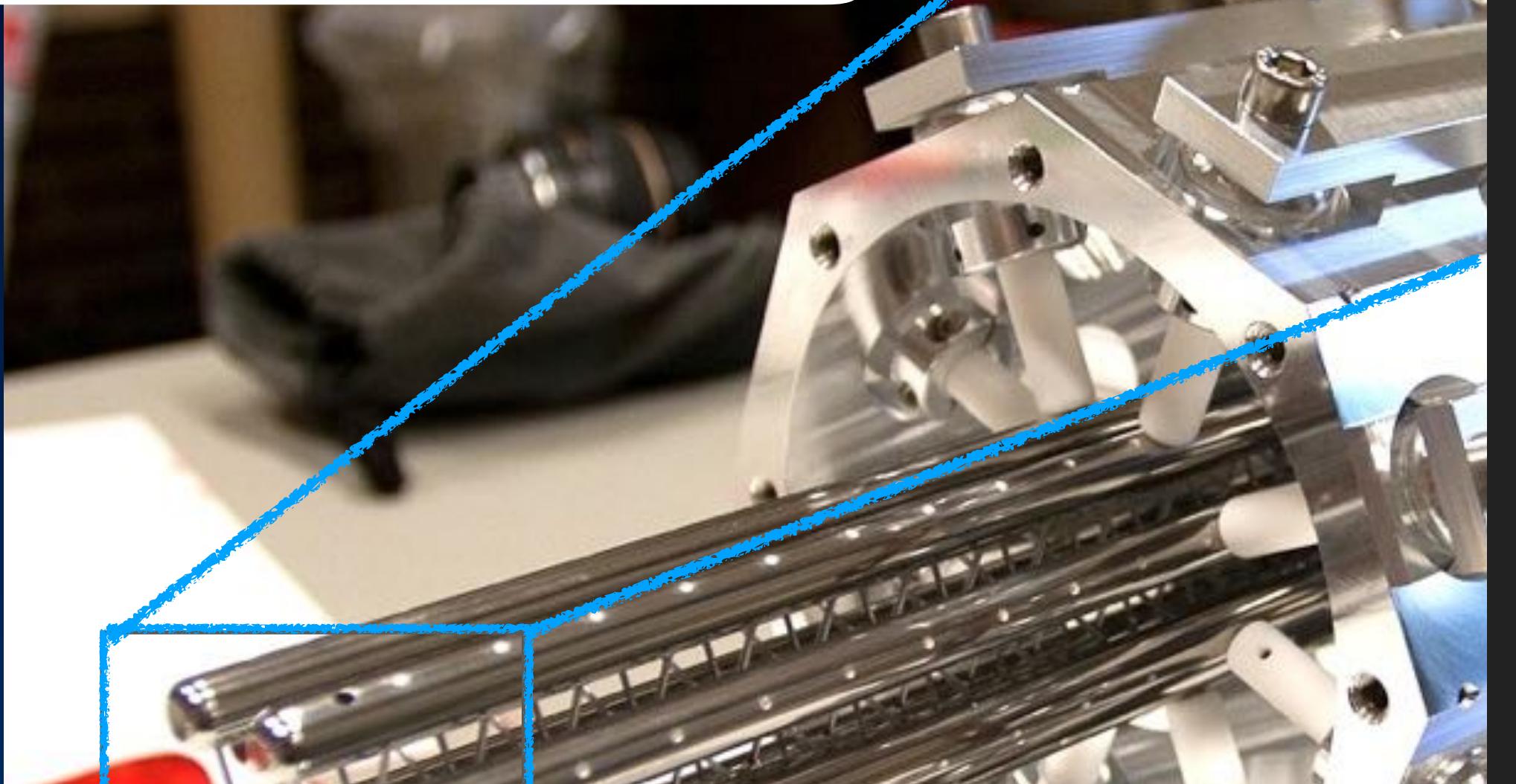
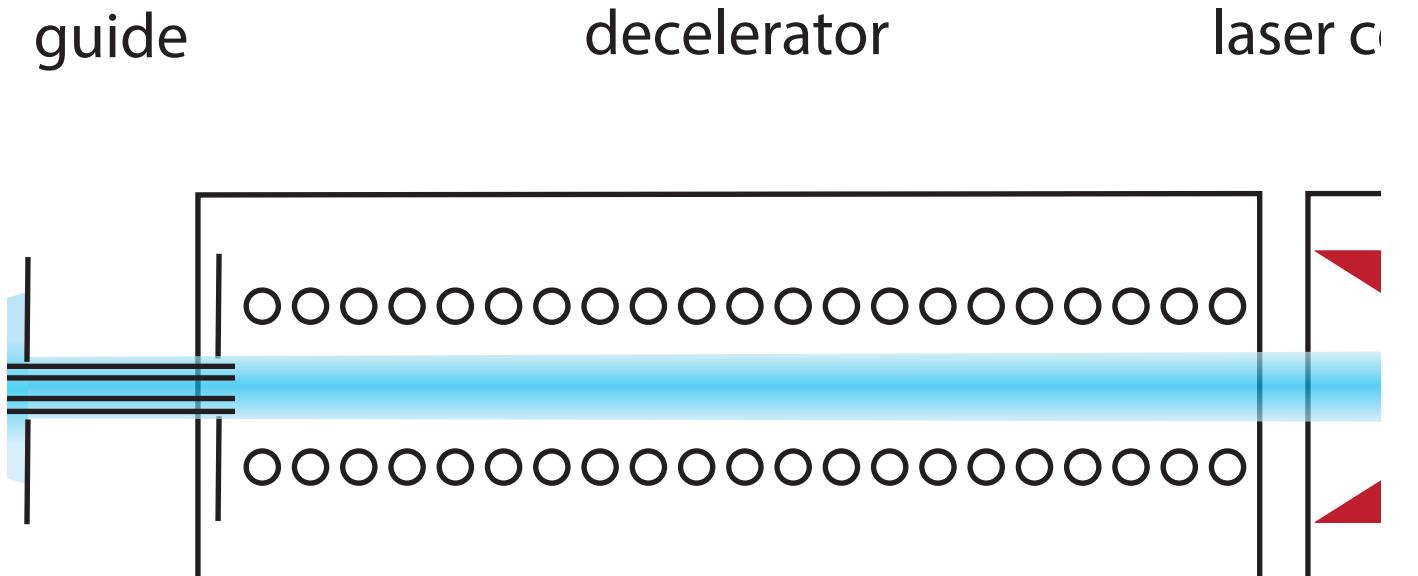
Cryogenic beam is operational!

Cryogenic beam

- Evaporating SrF_2 salt target
- Neon carrier gas
- Absorption, 1 cm from cell
- Fluorescence, 30 cm from cell
- Translational Temp $\sim 10 \text{ K}$
- Velocity 150-200 m/s



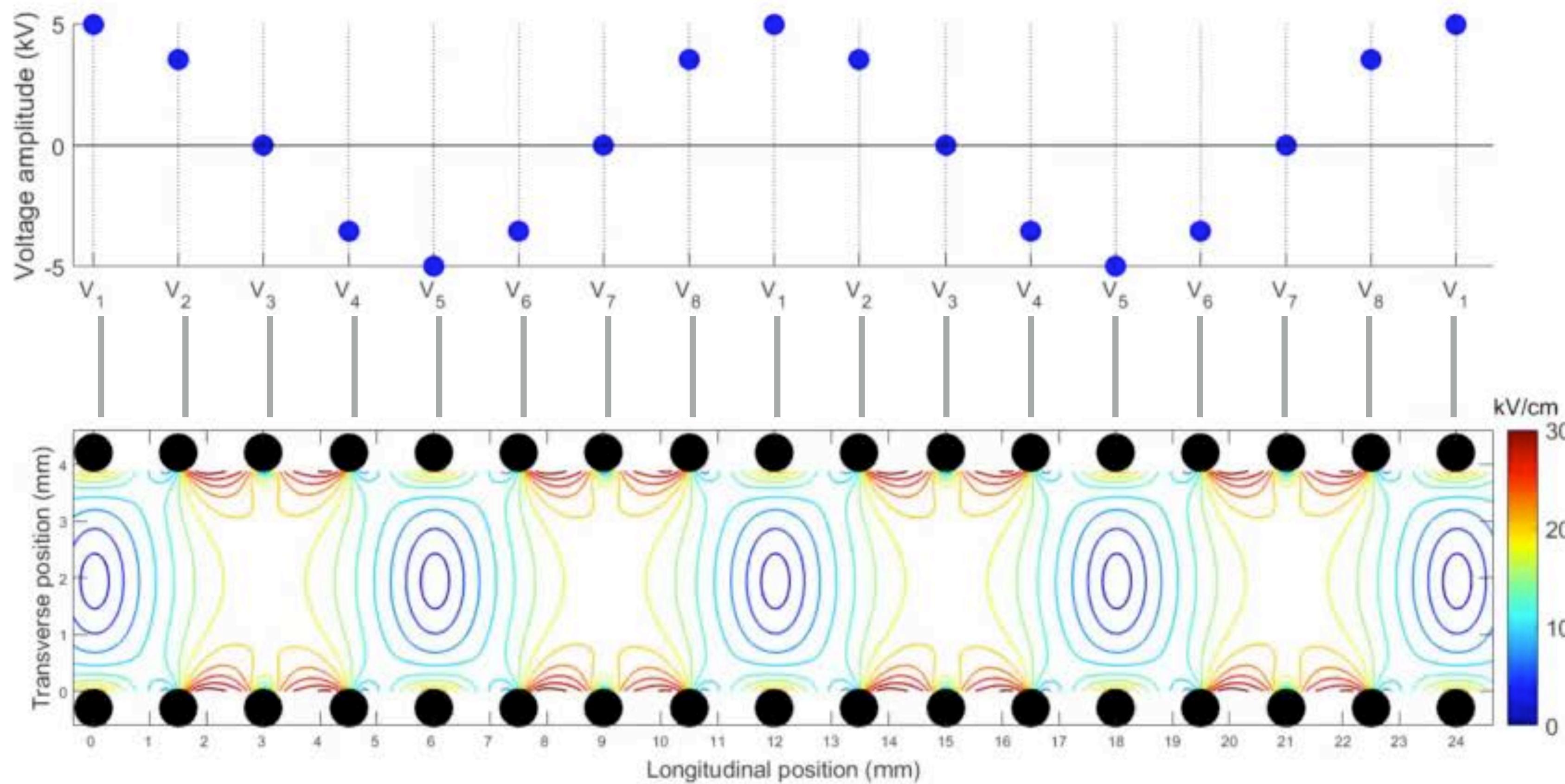
Traveling-wave decelerator



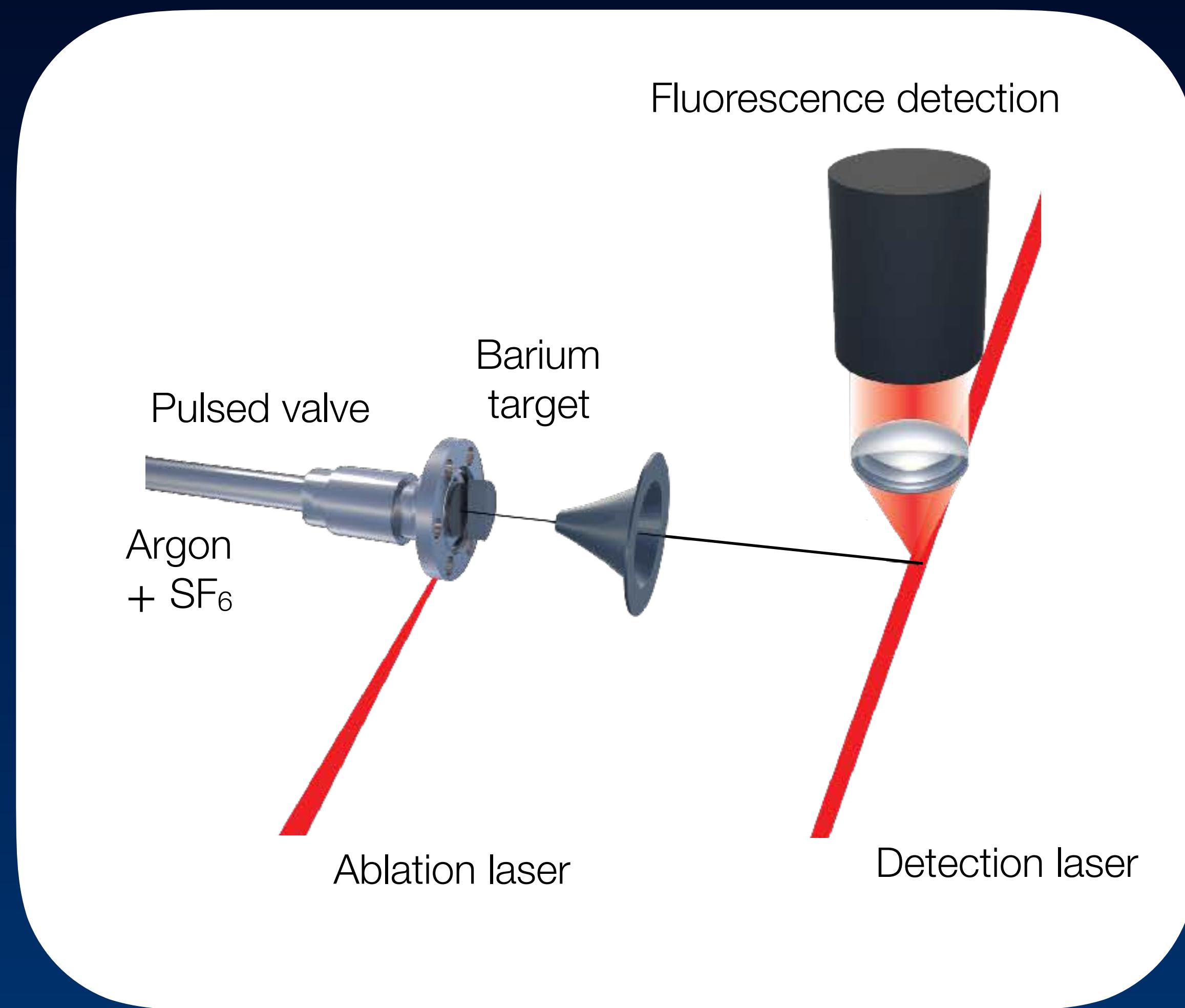
Main aims:

- Capture as many molecules as possible from cryogenic beam
- Bring average beam velocity from ~180 to ~30 m/s
- Keep all molecules during deceleration

Traveling-wave decelerator



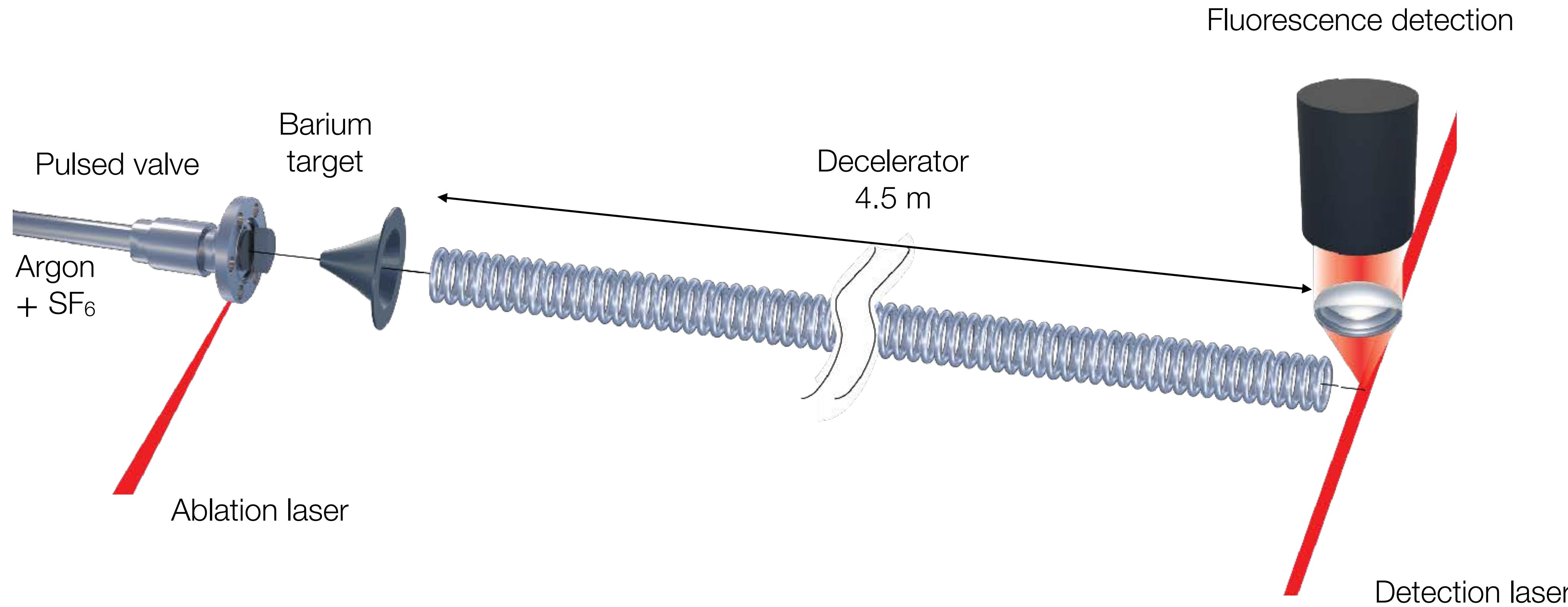
Traveling-wave decelerator



Traveling-wave decelerator



Traveling-wave decelerator



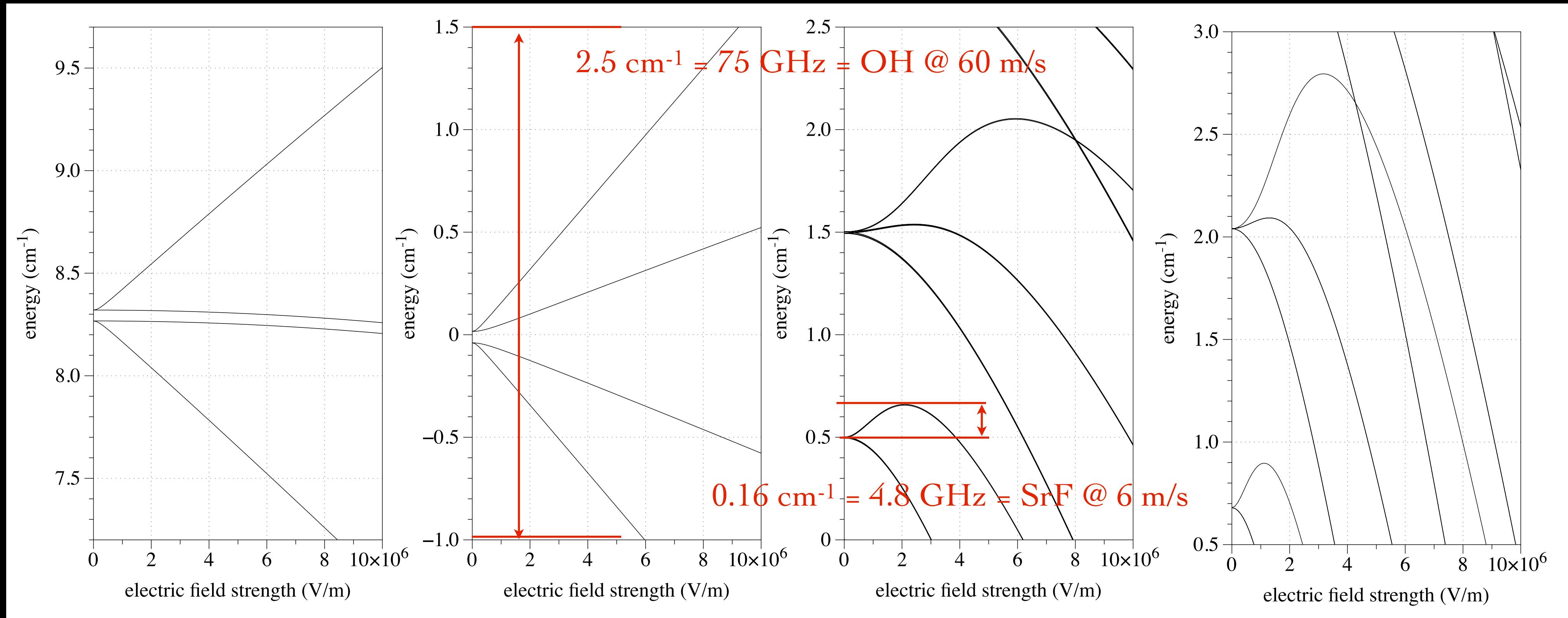
Challenges for heavy diatomic molecules:

Heavy → long decelerator
Rotational structure → limited Stark shift

Challenge: Stark curves of heavy diatomic molecules

Limited force, because only low fields can be used.

At higher fields, the trajectories in the decelerator become unstable.



ND₃

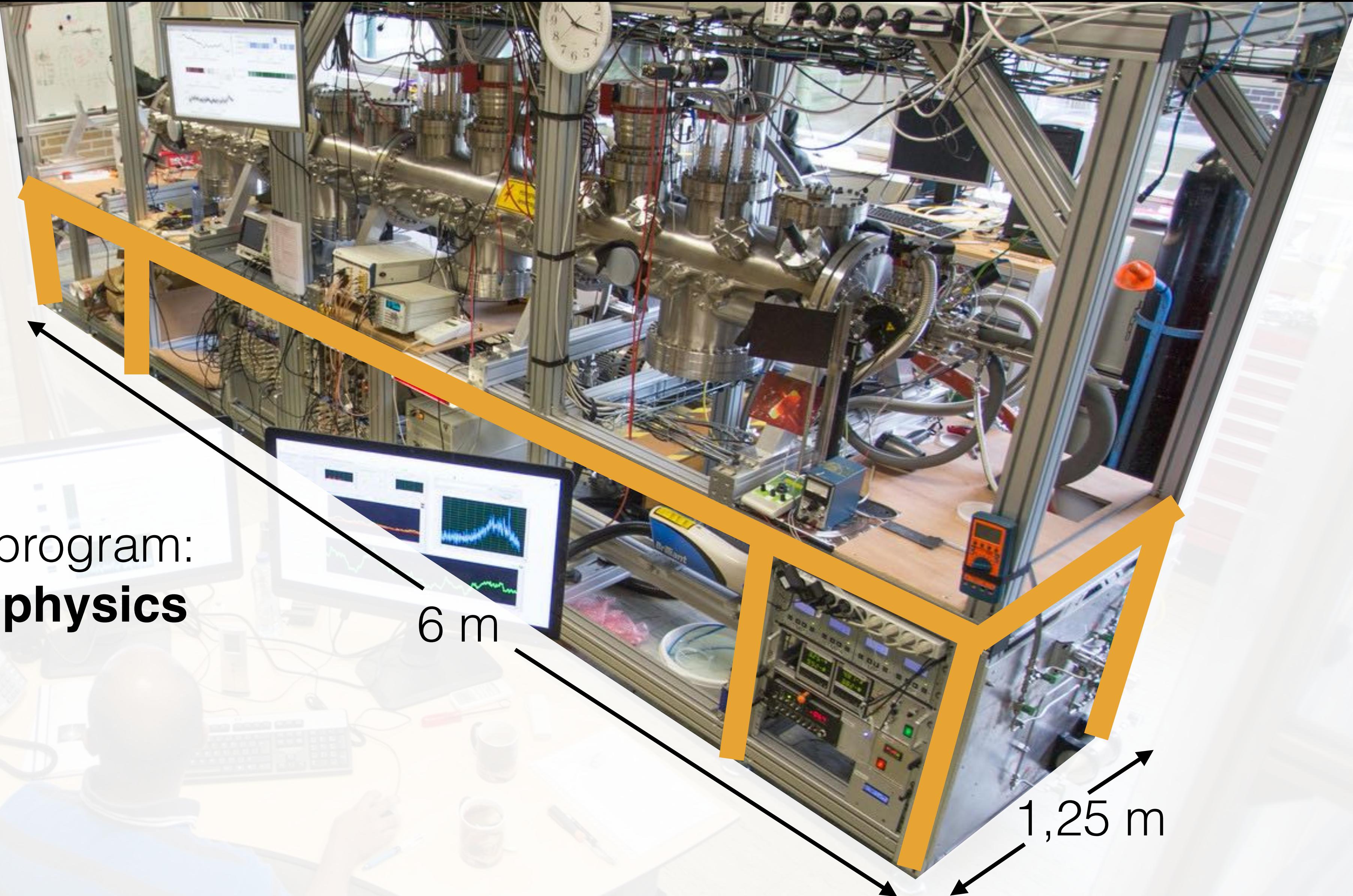
OH ²Π_{3/2}

SrF ²Σ
3.5 Debye

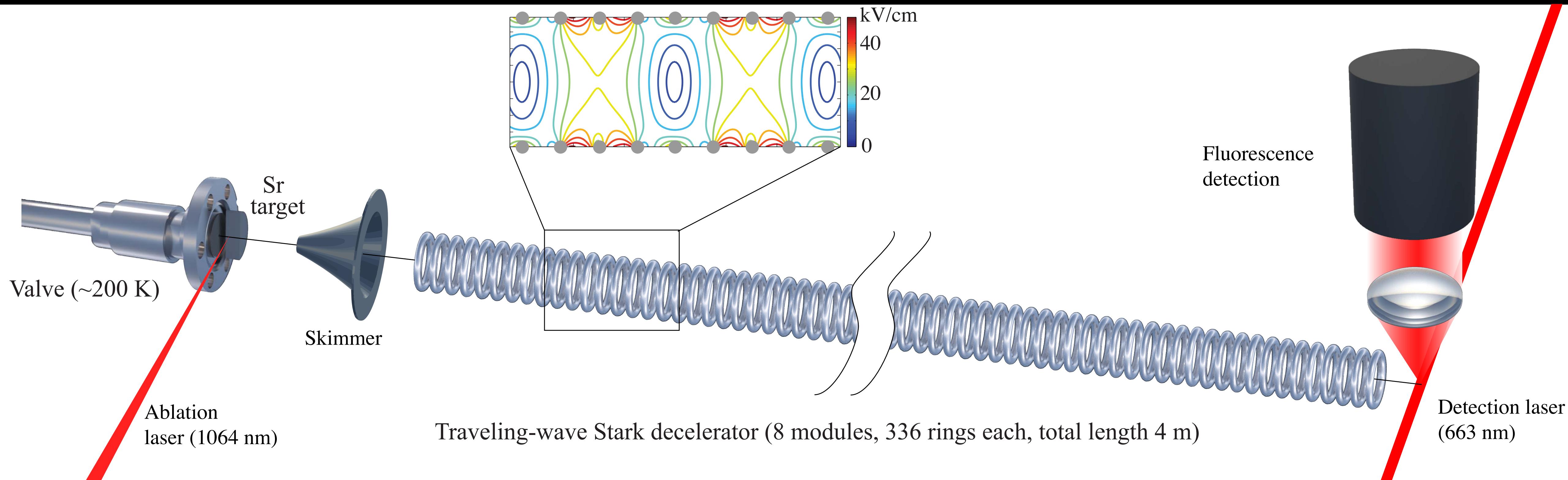
SrO ¹Σ

Limited force: -> a long decelerator

Traveling-wave decelerator has been built and works!

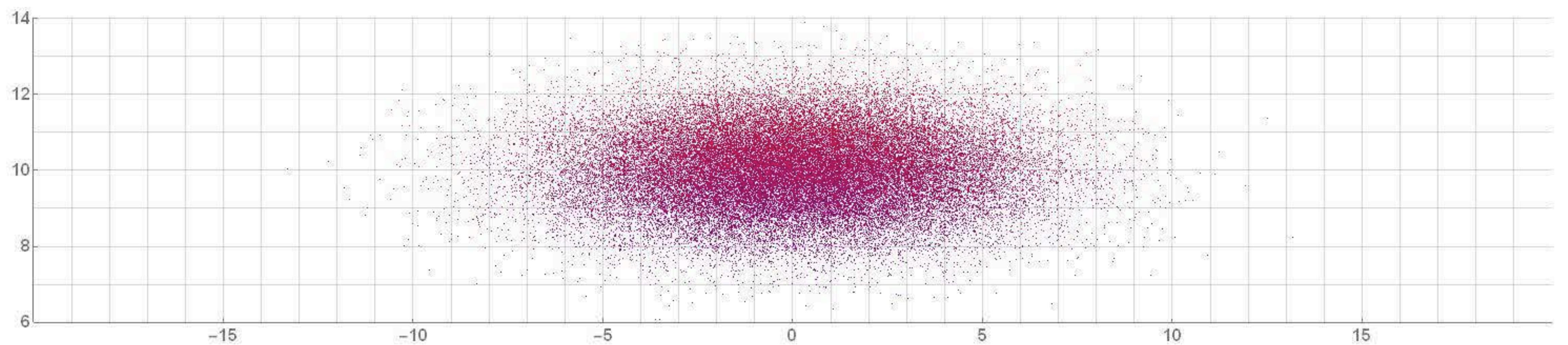


Schematic picture of the setup

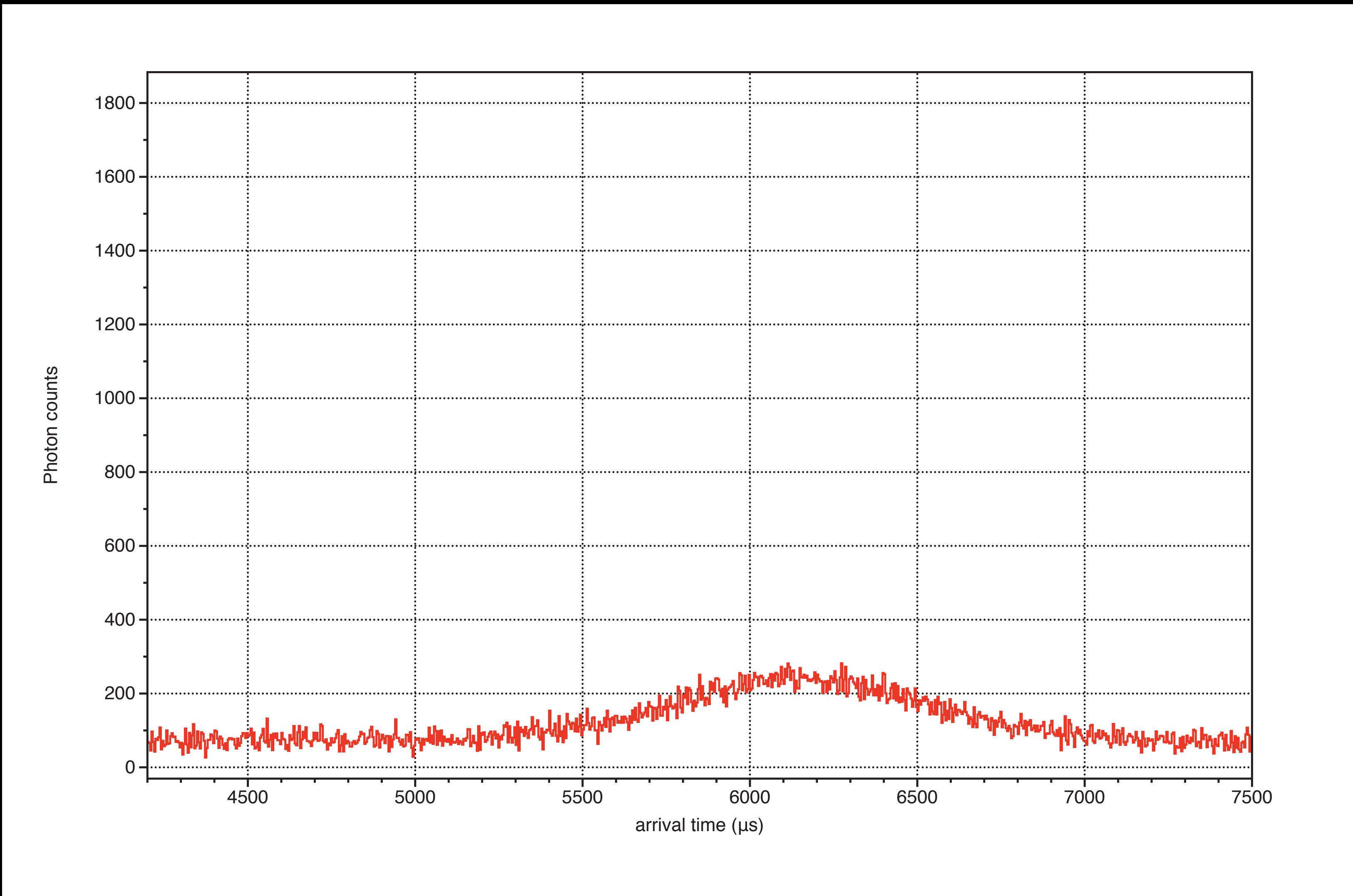


velocity, m/s

$t = 0.0 \text{ s}$



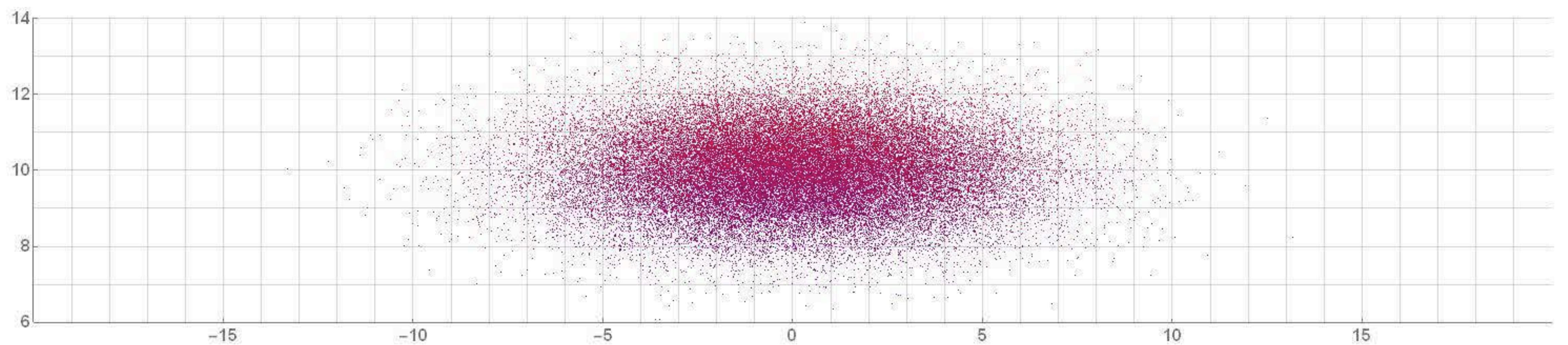
DC guiding



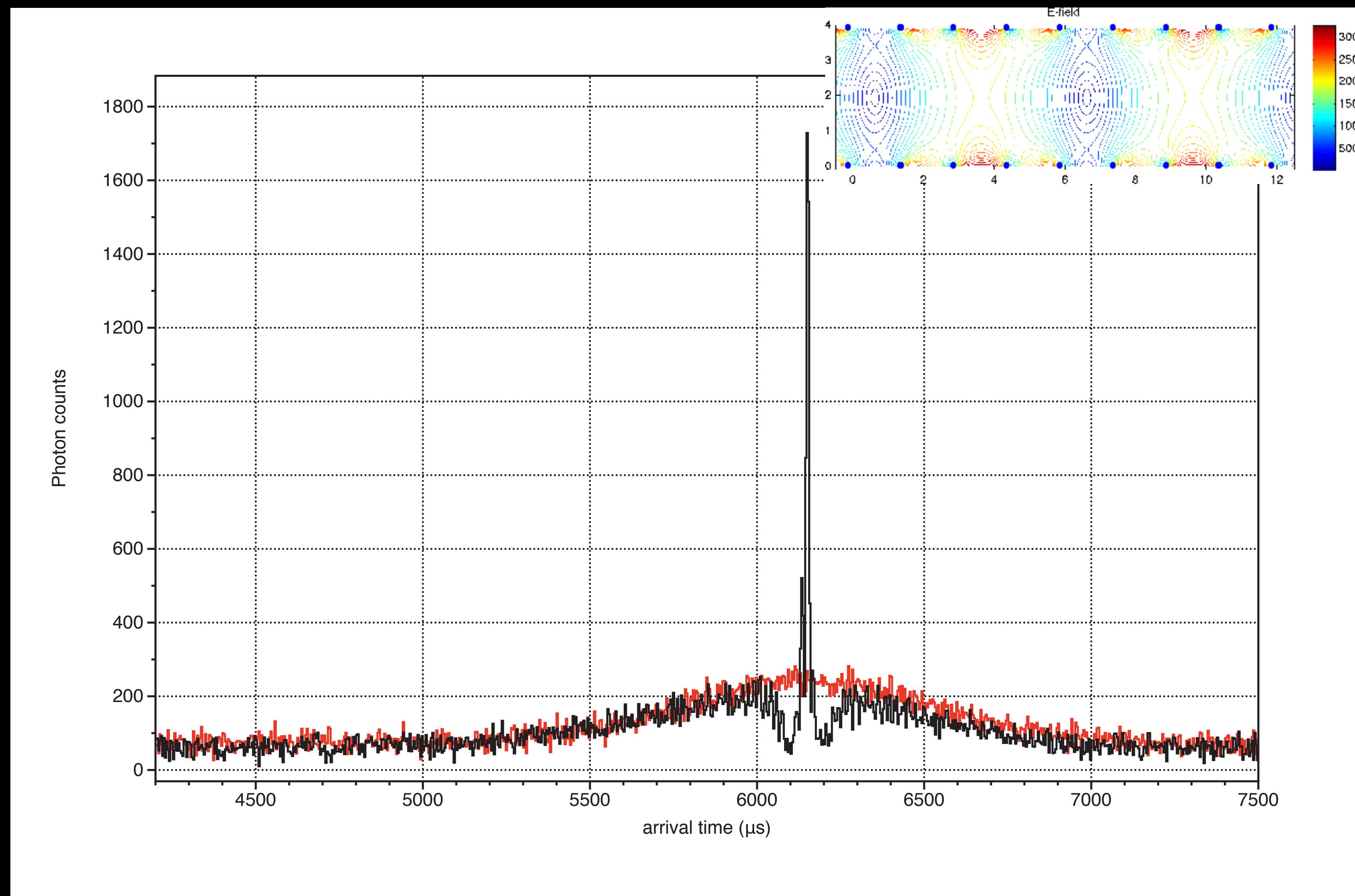
time-of-flight profile

velocity, m/s

$t = 0.0 \text{ s}$

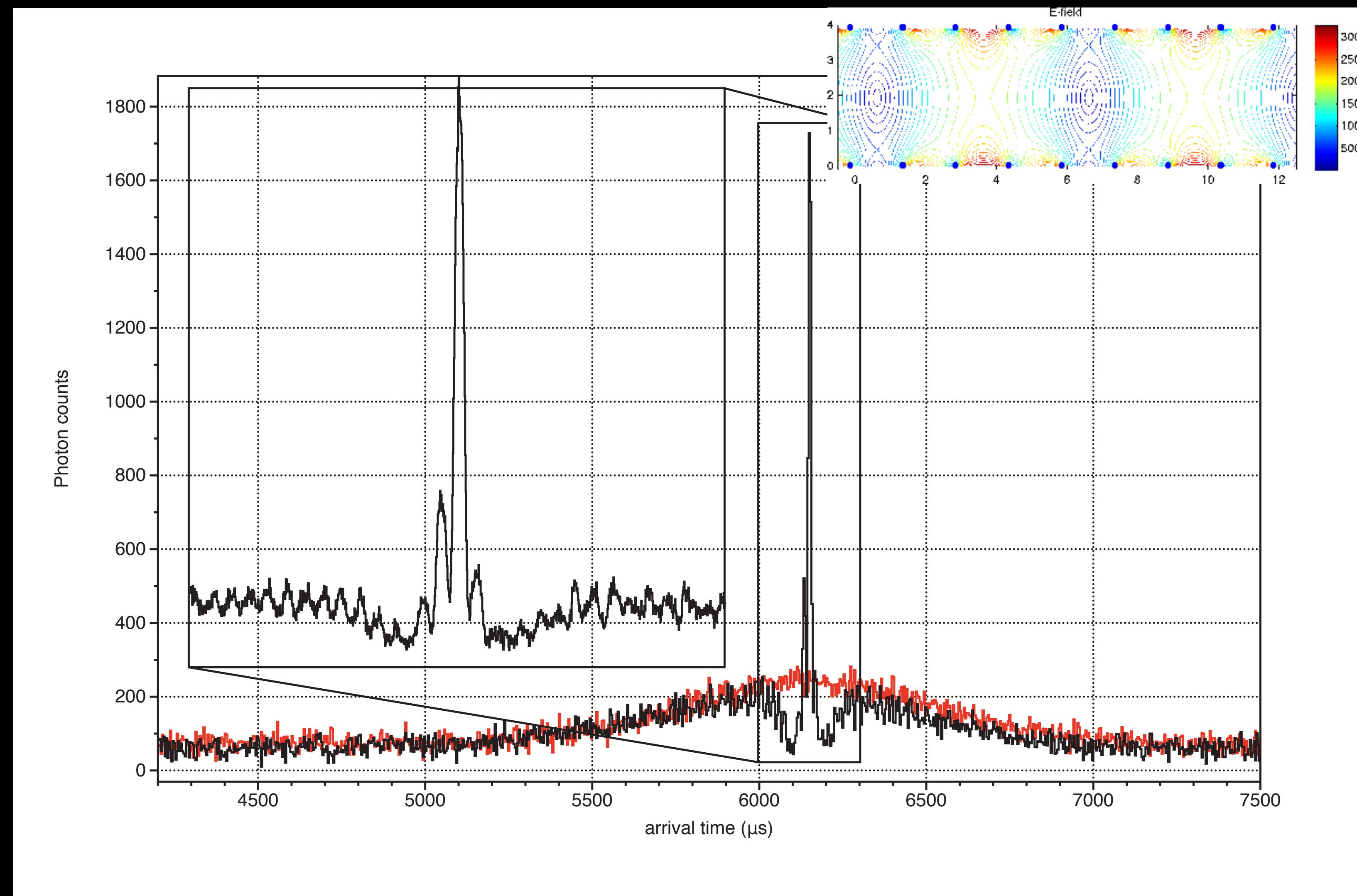


AC guiding



time-of-flight profile

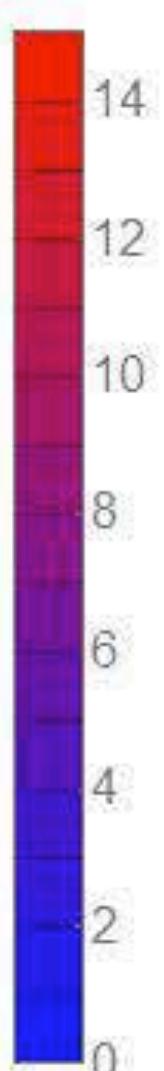
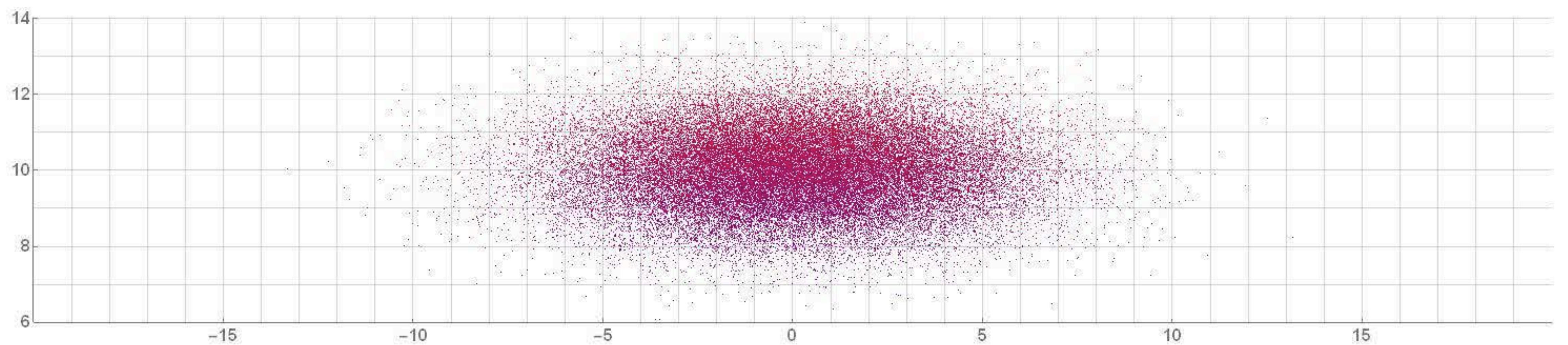
AC guiding



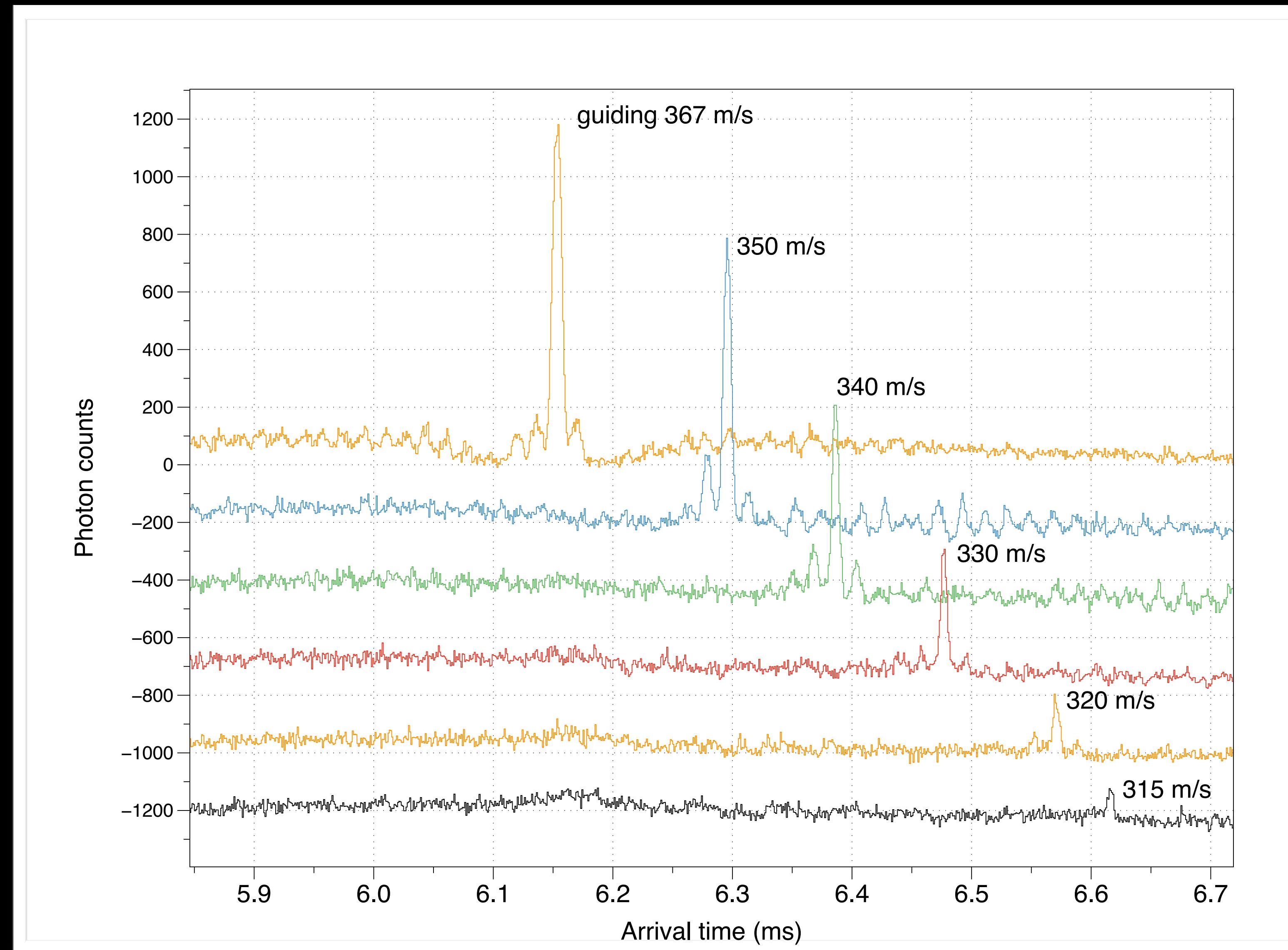
time-of-flight profile

velocity, m/s

$t = 0.0 \text{ s}$

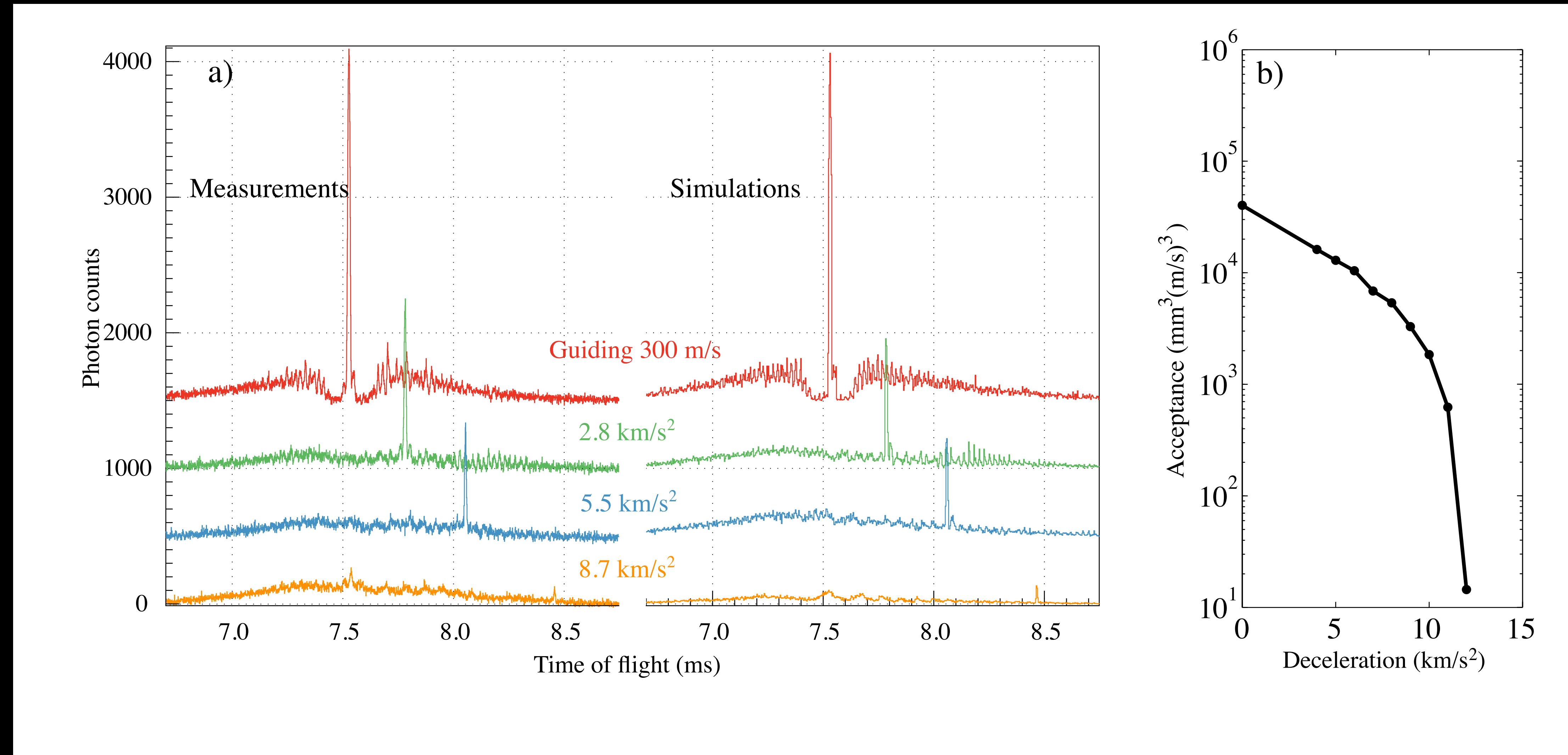


Deceleration of SrF from a room-temperature valve



Decelerator length: 2 m

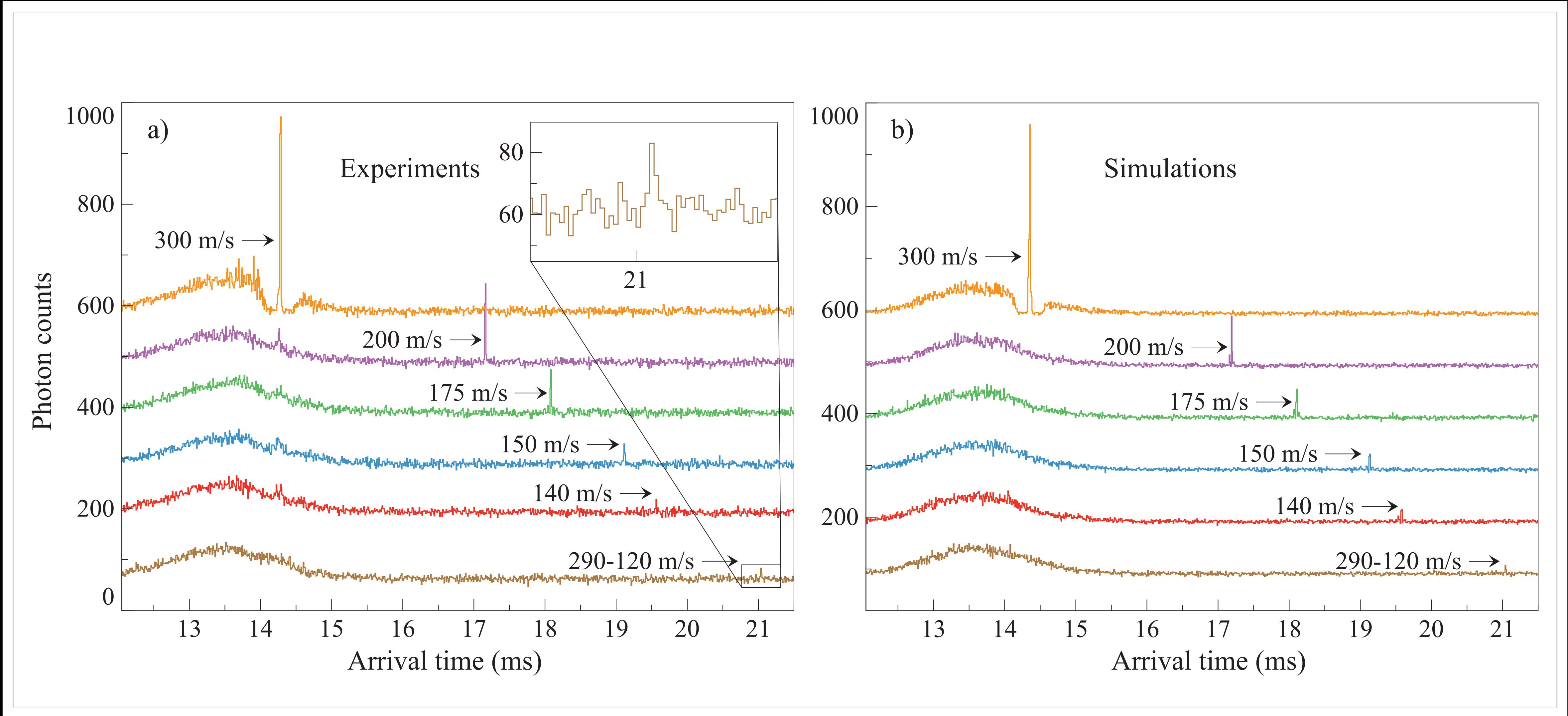
Decrease of acceptance with deceleration strength just as expected:



J. E. van den Berg et al, JMS (2014)

A decelerator of length 4.5 meter will have a 10% transmission efficiency

Deceleration of SrF from a cooled valve

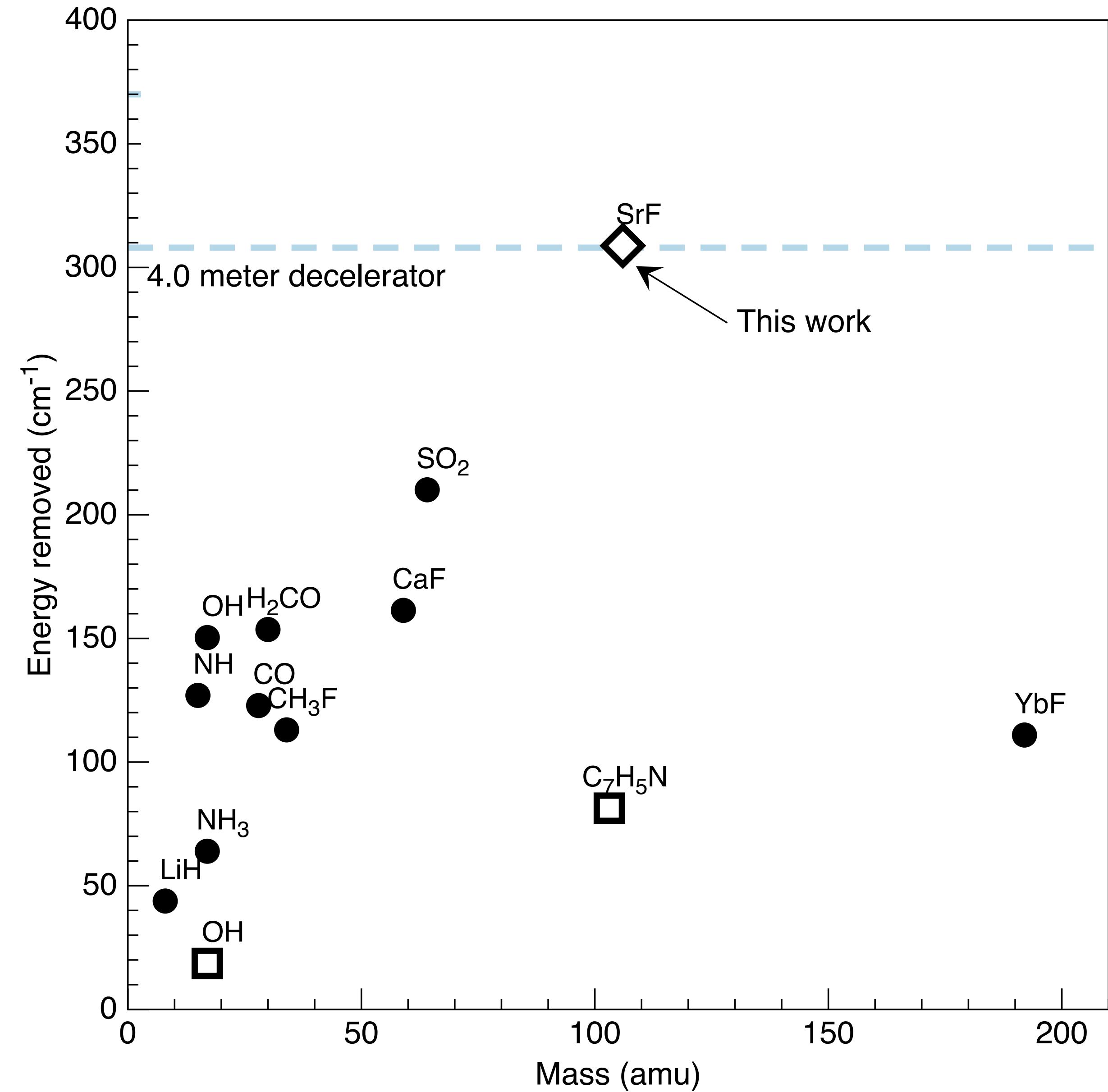


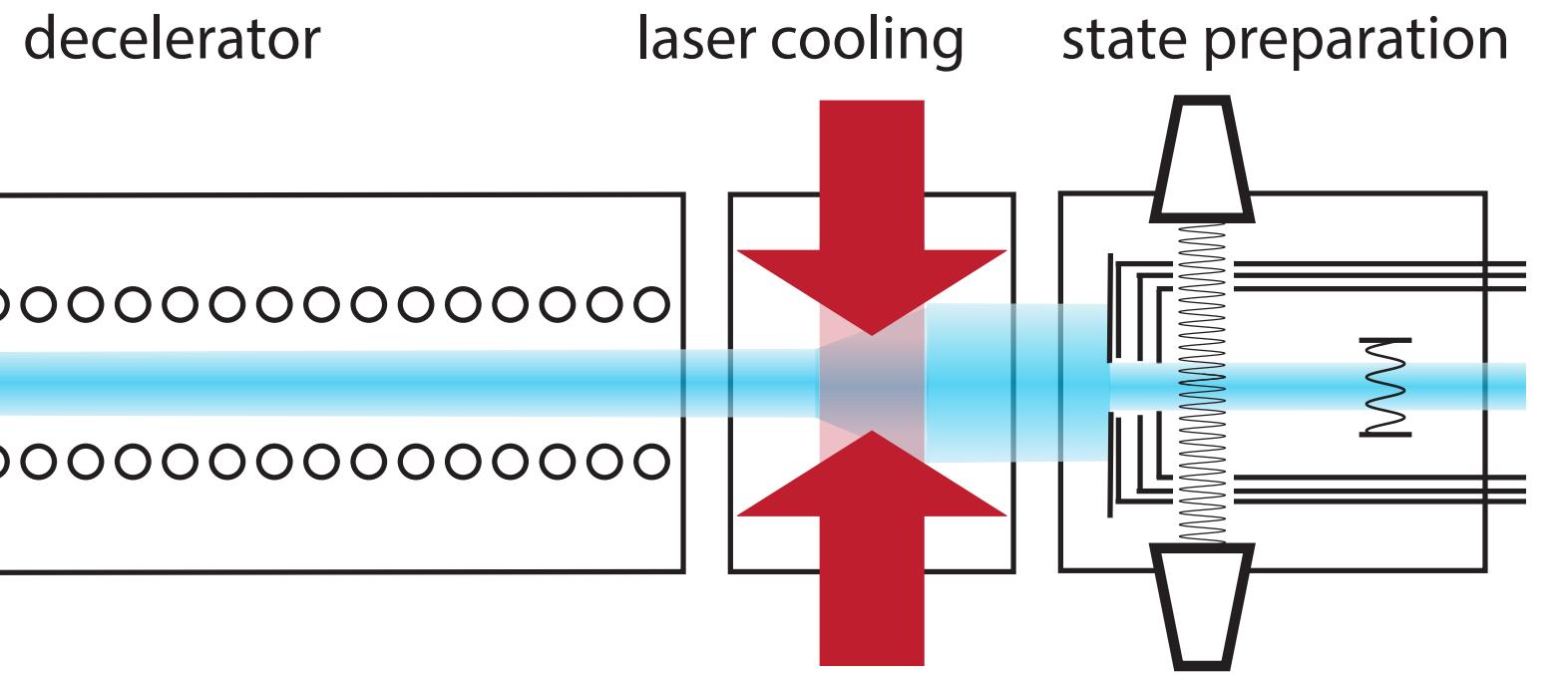
Decelerator length: 4 m

85% of the energy of the molecules is removed!

Curren status:

- 4,5 m decelerator operational
- Working towards stopping SrF
- 2 Cryogenic sources operational





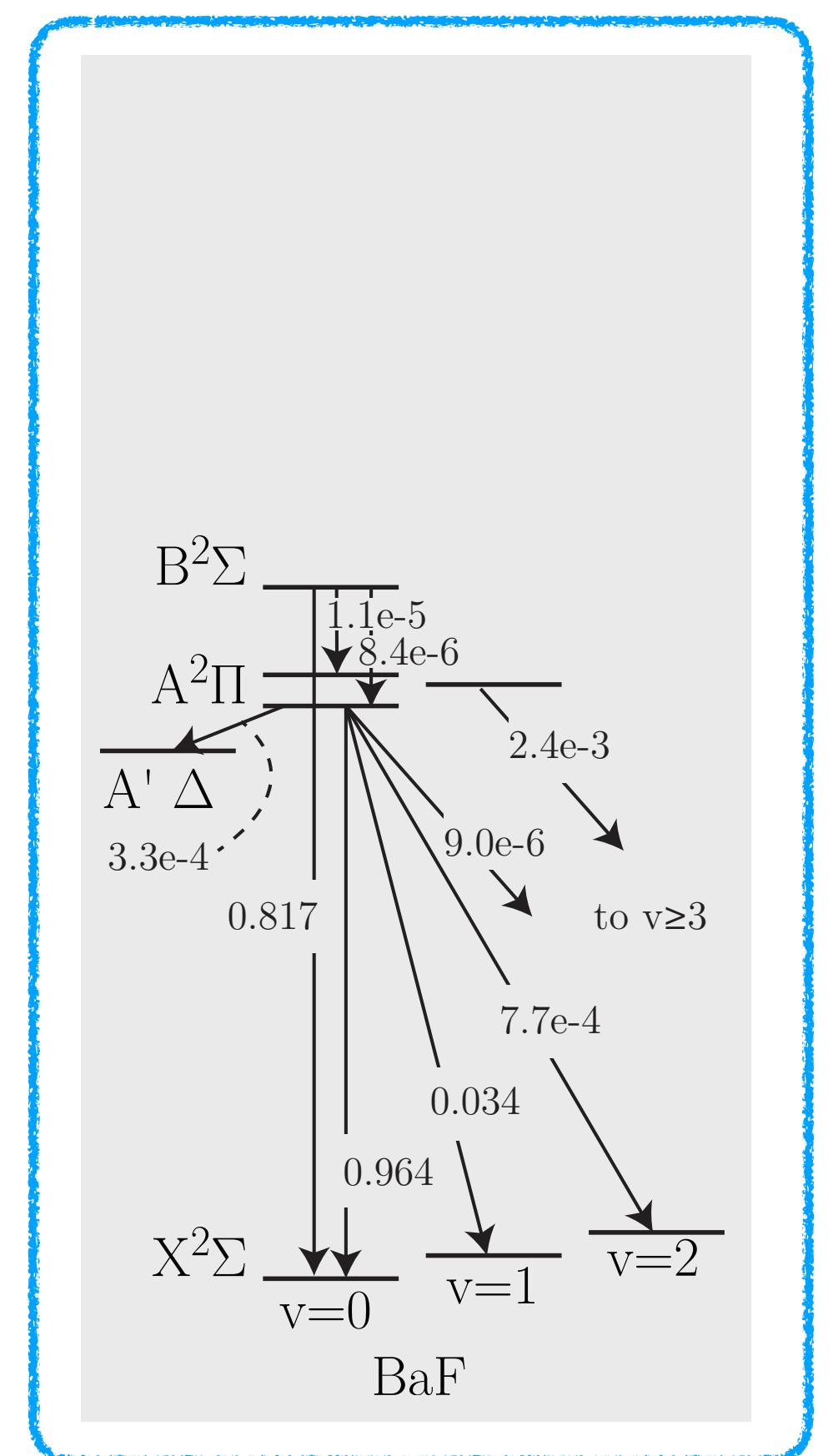
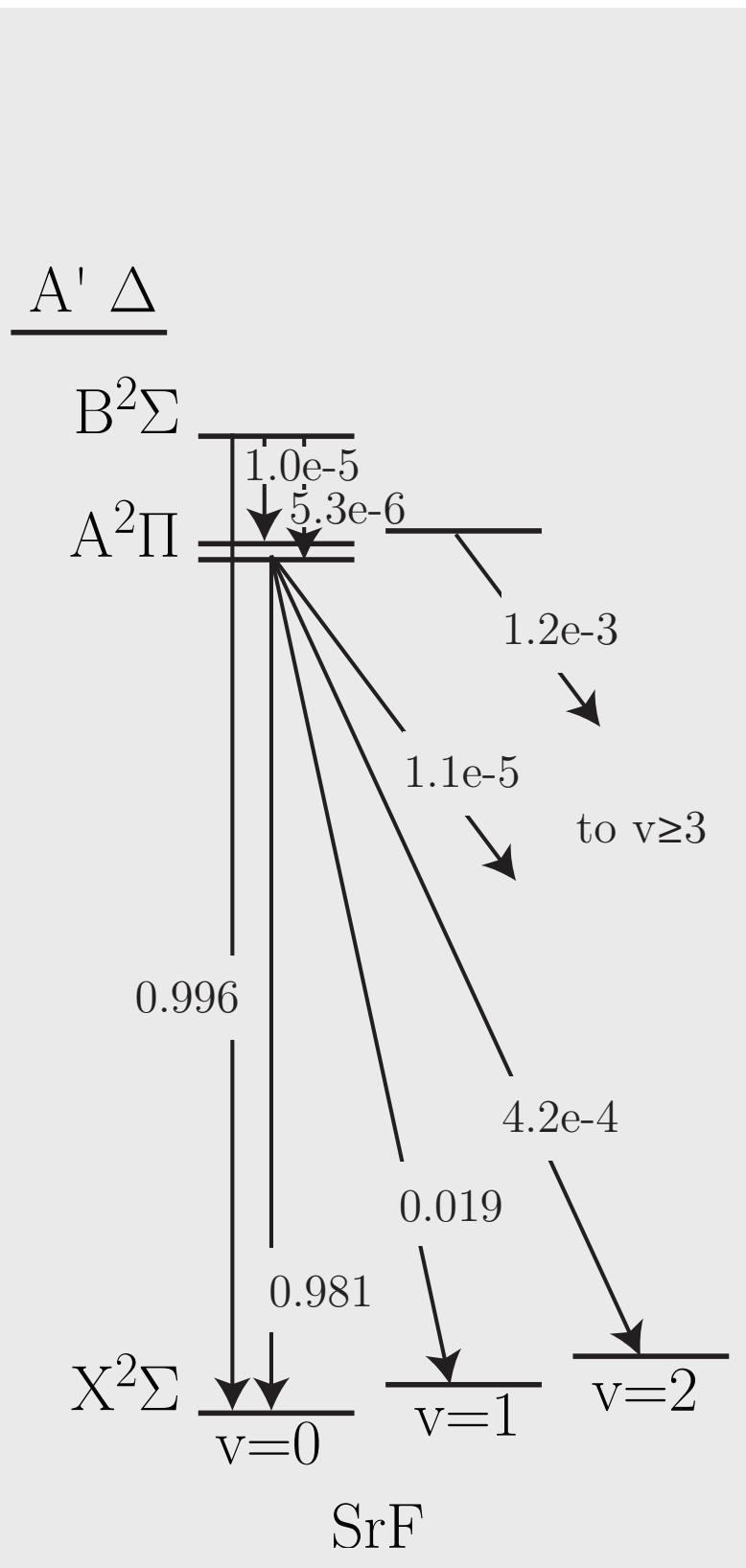
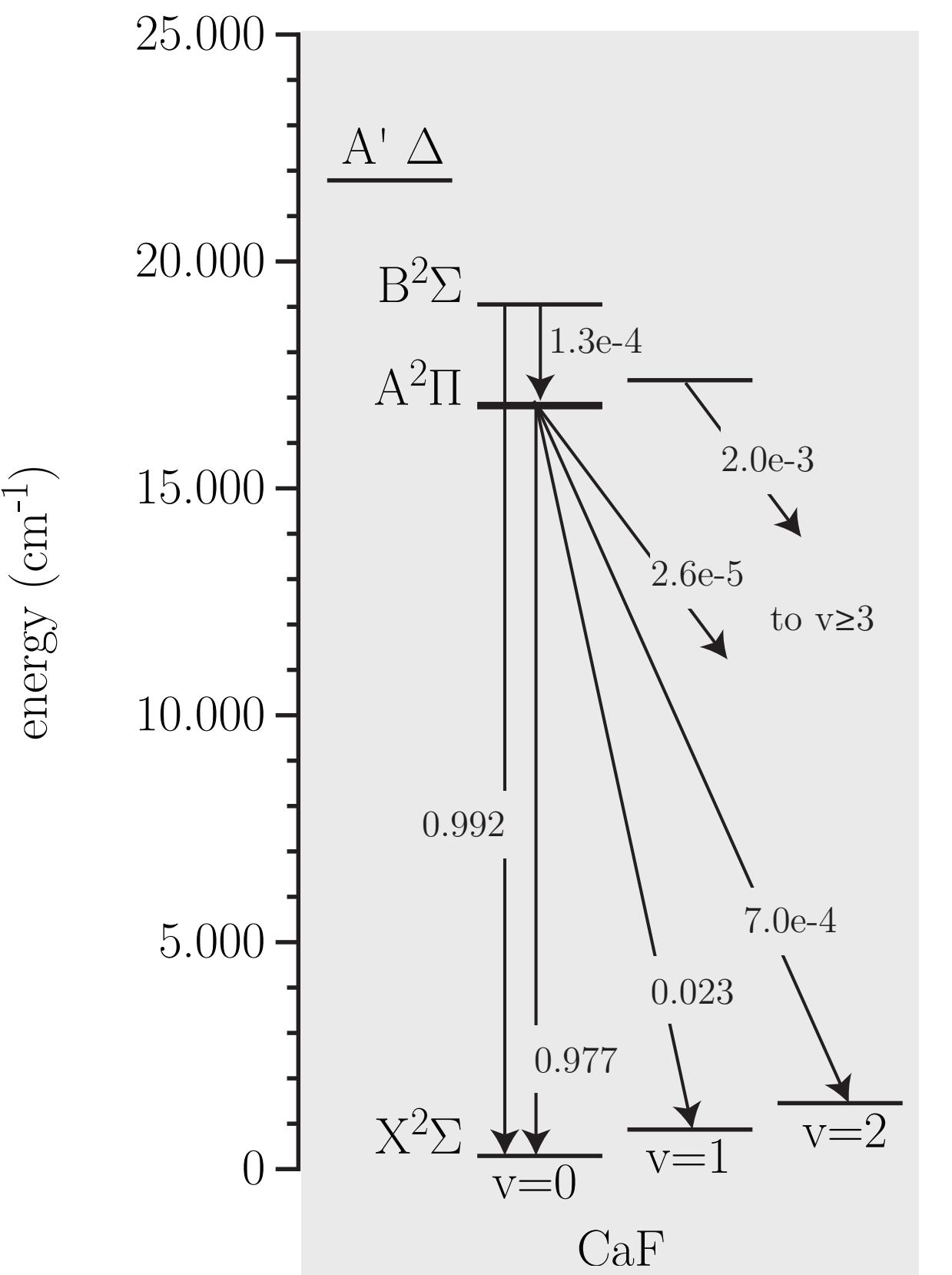
Aim:

- Stop the slow beam from transverse spreading

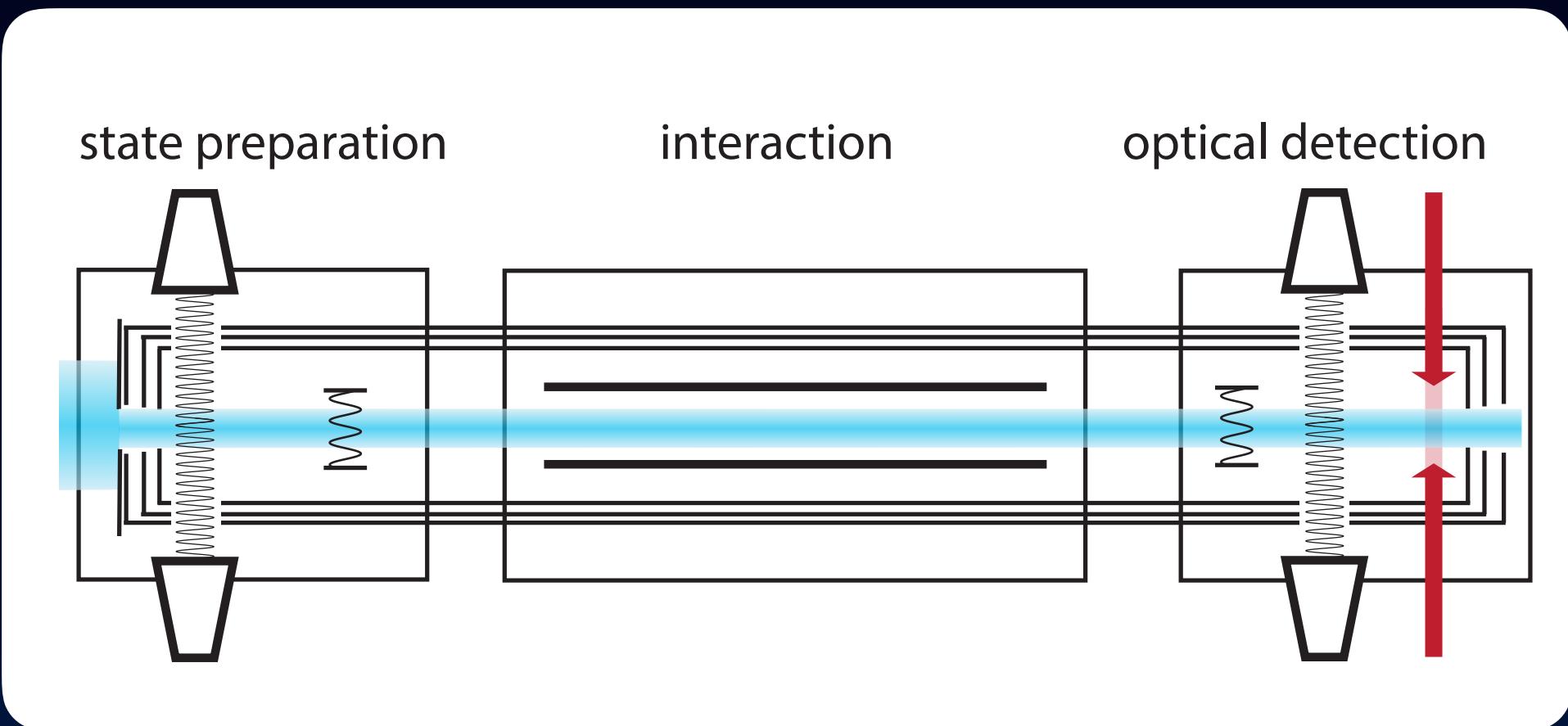
Status:

- Laser system has been set up
- Calculated properties of BaF molecule
- Setting up experiments now!

Laser cooling of molecules

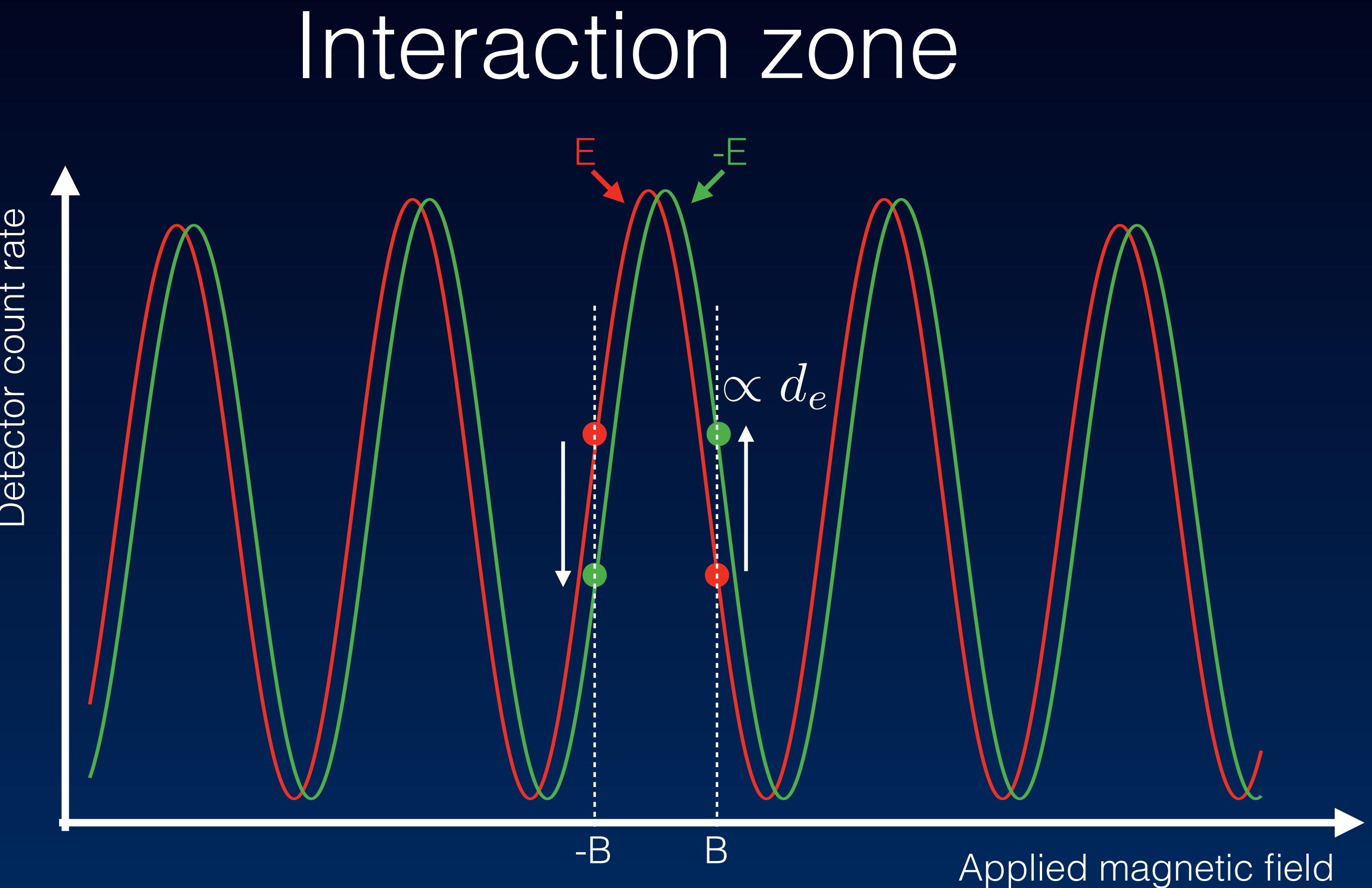


Decay ratio's for BaF sufficient for rapid (2 ms, 2000 photons) transverse laser cooling



Aim:

- Polarise the molecules using a strong electric field, while providing a very stable, uniform and weak magnetic field
- Longer interaction time results in more stringent requirements on the magnetic field ($\pi/4$ B-field is 600 pT = 6 microG)

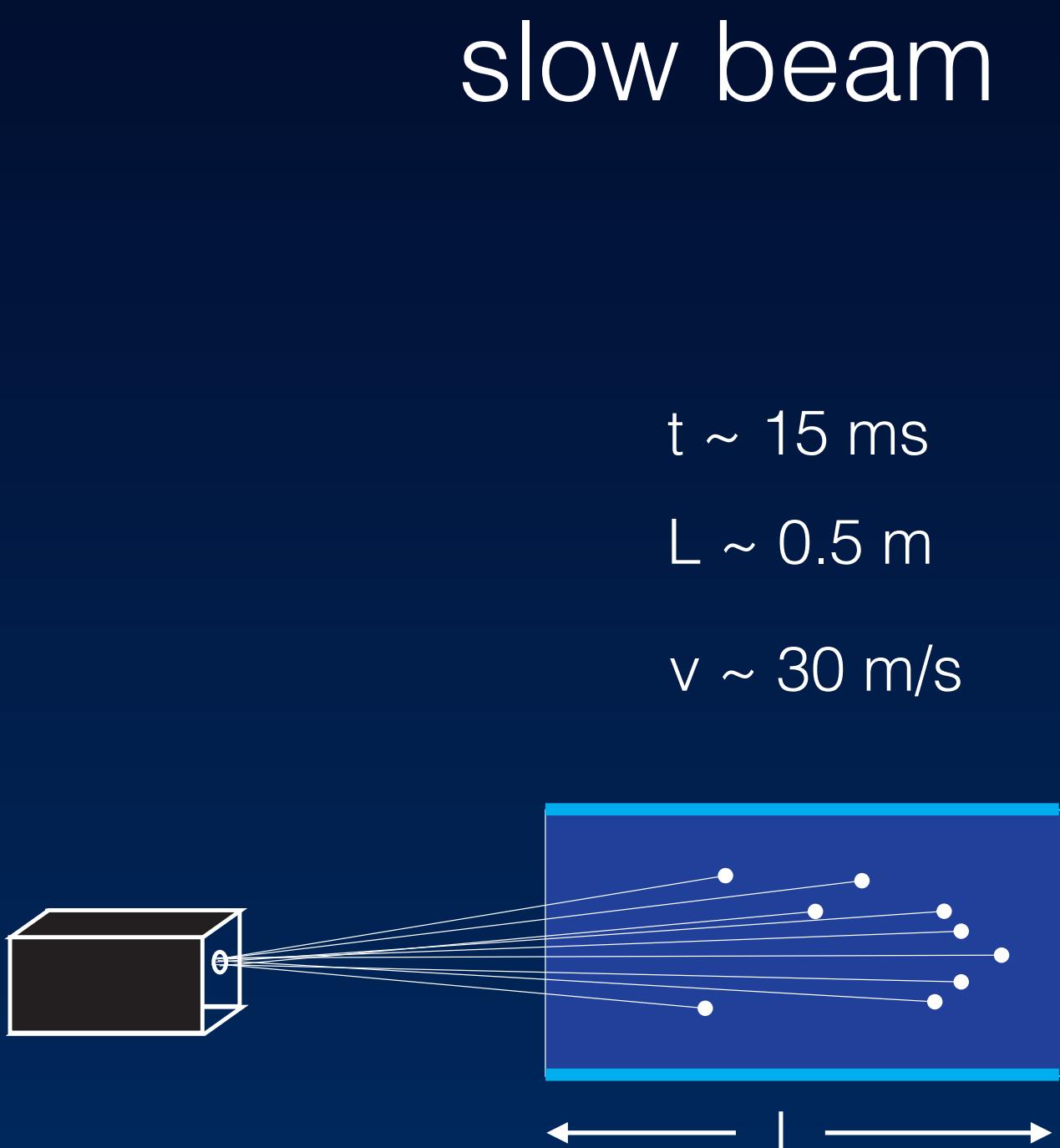
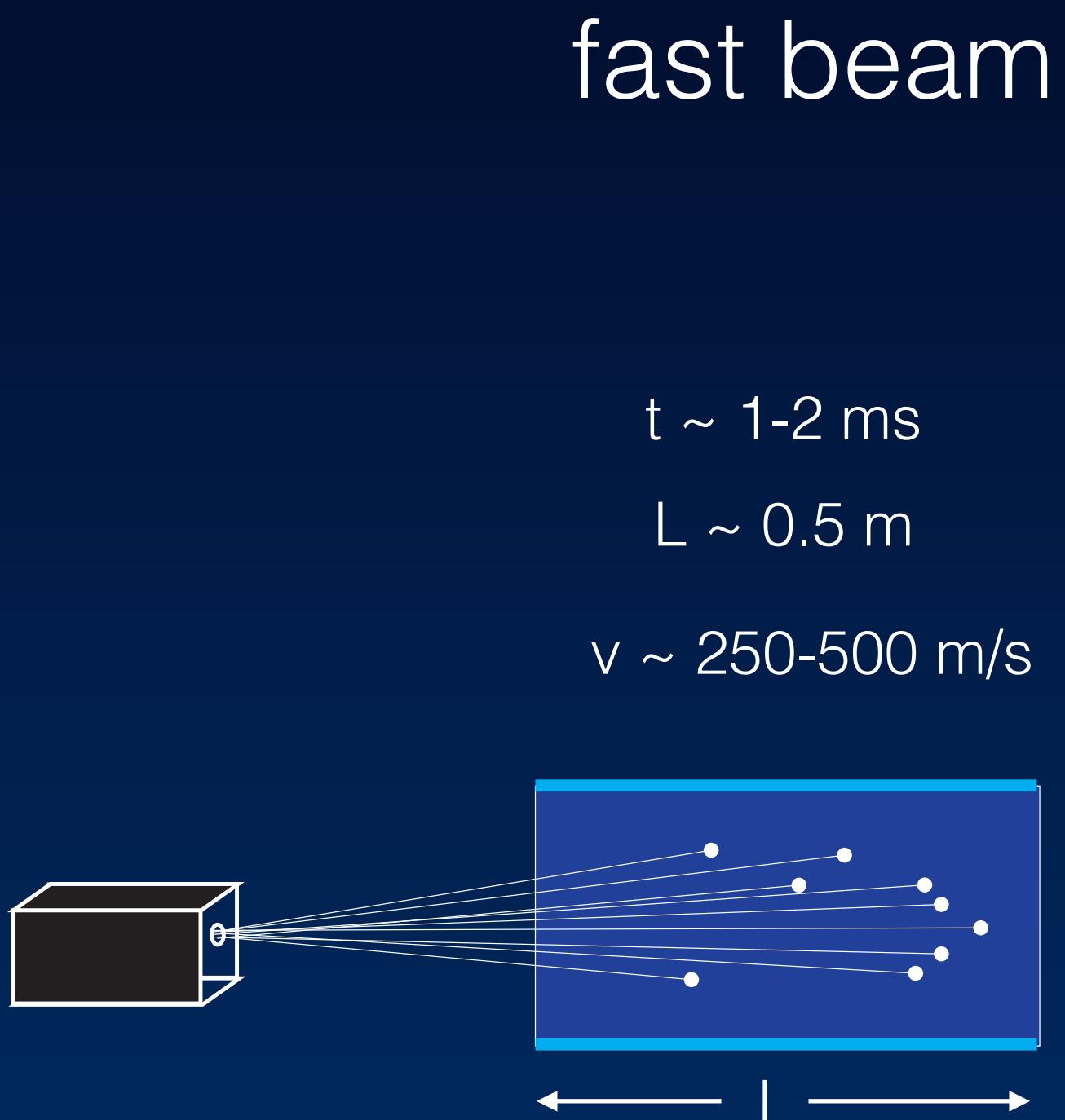


Status:

- Magnetic shielding almost complete and delivered
- Performing a study dedicated to systematic effects

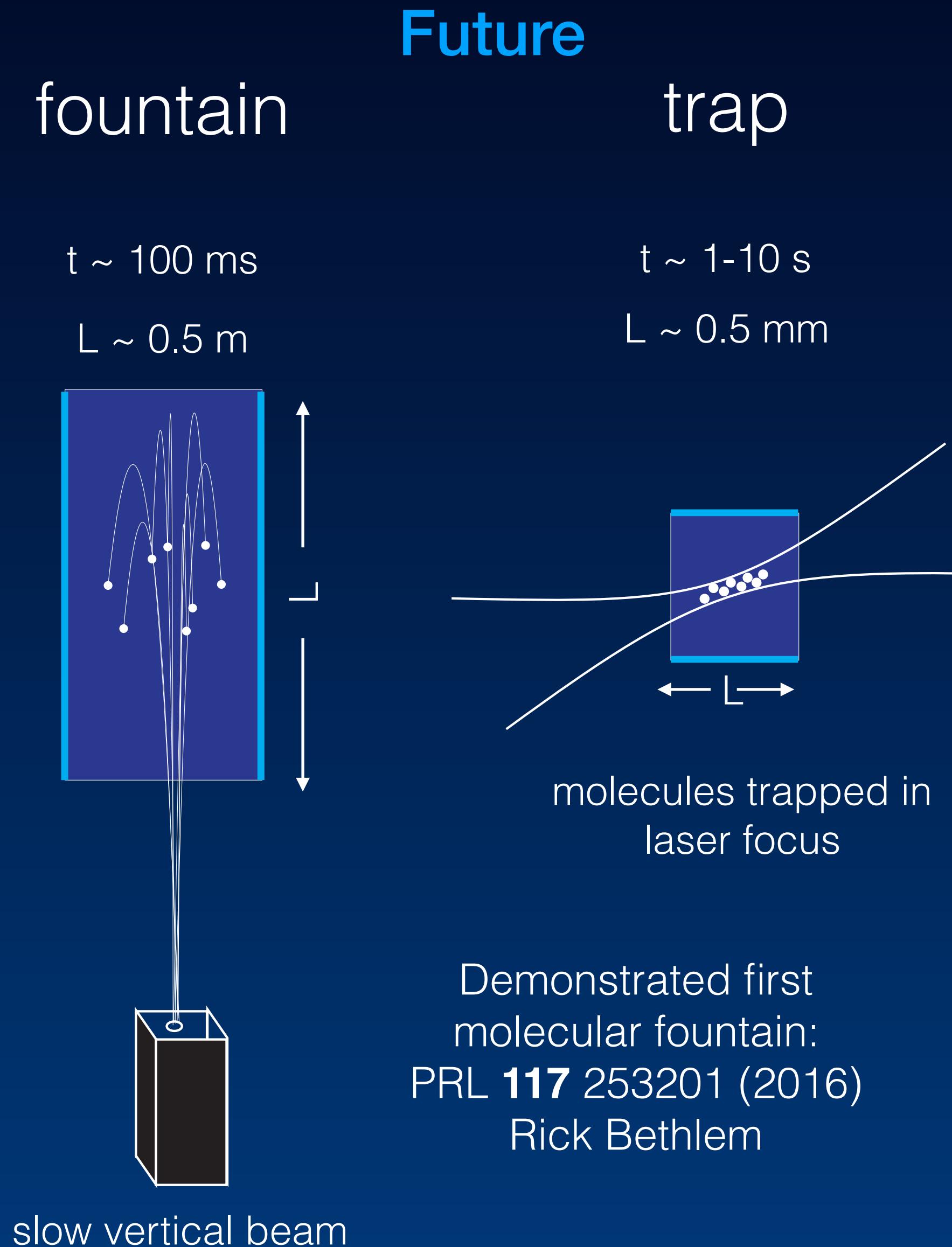
$$\text{Interferometer phase } \phi = (\pm d_e E_{eff} \mp \mu_B B) T / \hbar$$

Future: towards longer coherent interaction times



Main challenge:
how to maintain N while increasing t

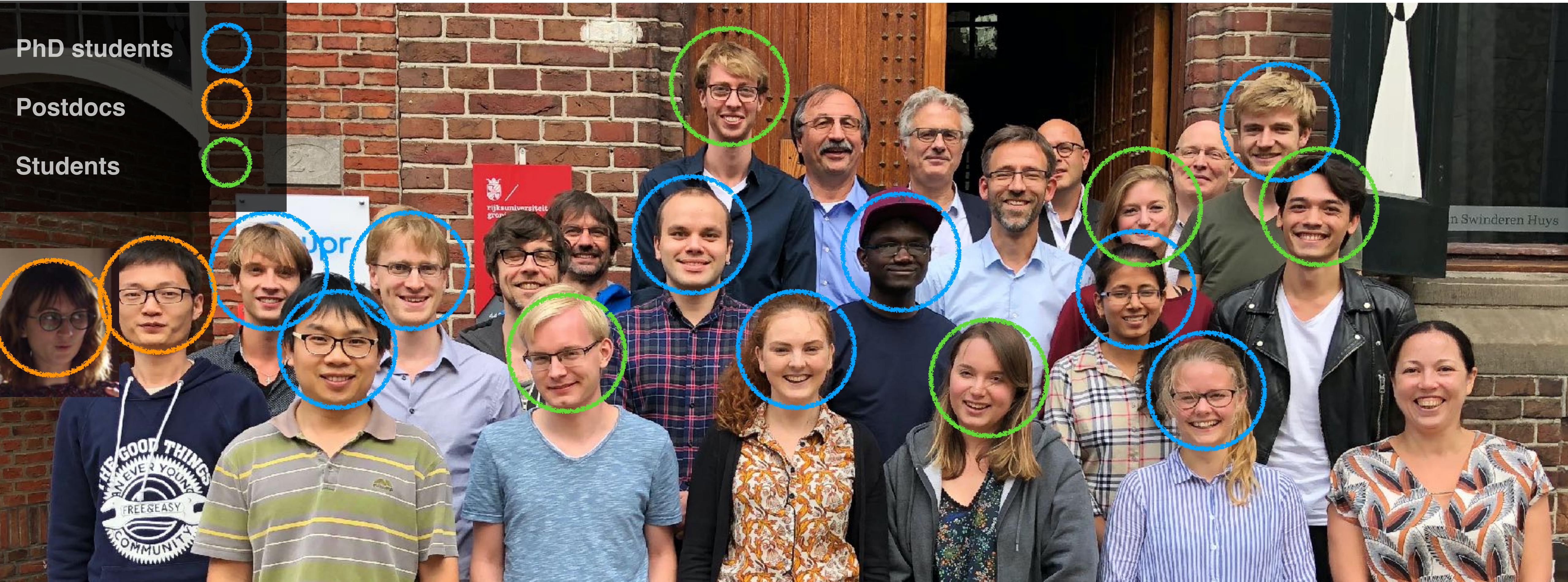
Strongly connected to choice of molecule!



NL-eEDM: the team

postdoc and tenure track
position open!

PhD students
Postdocs
Students



university of
groningen
van swinderen institute for
particle physics and gravity

Nikhef

Dutch National Institute for (astro)Particle Physics

VU

VRIJE
UNIVERSITEIT
AMSTERDAM

Thank you!

Numbers

Table 1. The estimate of the number of molecules that can be detected per repetition of the experiment. We aim to run the experiment at 10 Hz.

Item	Number	Units	Resulting # mol./shot
Source	10^{13}	Molecules/shot	
	0.005	Extraction efficiency from buffer gas cell	
	0.24	Fraction in $v = 0$, $N = 2$	5×10^{10} from source; 4×10^9 in desired state,
	0.3	Fraction in low-field seeking states	$v_{\text{long}} = (180 \pm 50) \text{ m/s}$, $v_{\text{trans}} = \pm 30 \text{ m/s}$.
Decelerator	0.002	Fraction in velocity acceptance	
	0.3	Fraction in spatial acceptance	
	0.7	Efficiency of deceleration relative to guiding	2×10^6 , $v_{\text{long}} = (30 \pm 6) \text{ m/s}$, $v_{\text{trans}} = \pm 5 \text{ m/s}$.
Laser cooling	0.8	Laser cooling efficiency	
	0.7	State transfer efficiency	9×10^5 , $v_{\text{long}} = (30 \pm 6) \text{ m/s}$, $v_{\text{trans}} = \pm 0.2 \text{ m/s}$.
Interaction zone	0.8	Transmission and state transfer efficiency	
	1.0	Detection efficiency	7×10^5