NL-*e*EDM
Measuring the electron-EDM with BaF molecules

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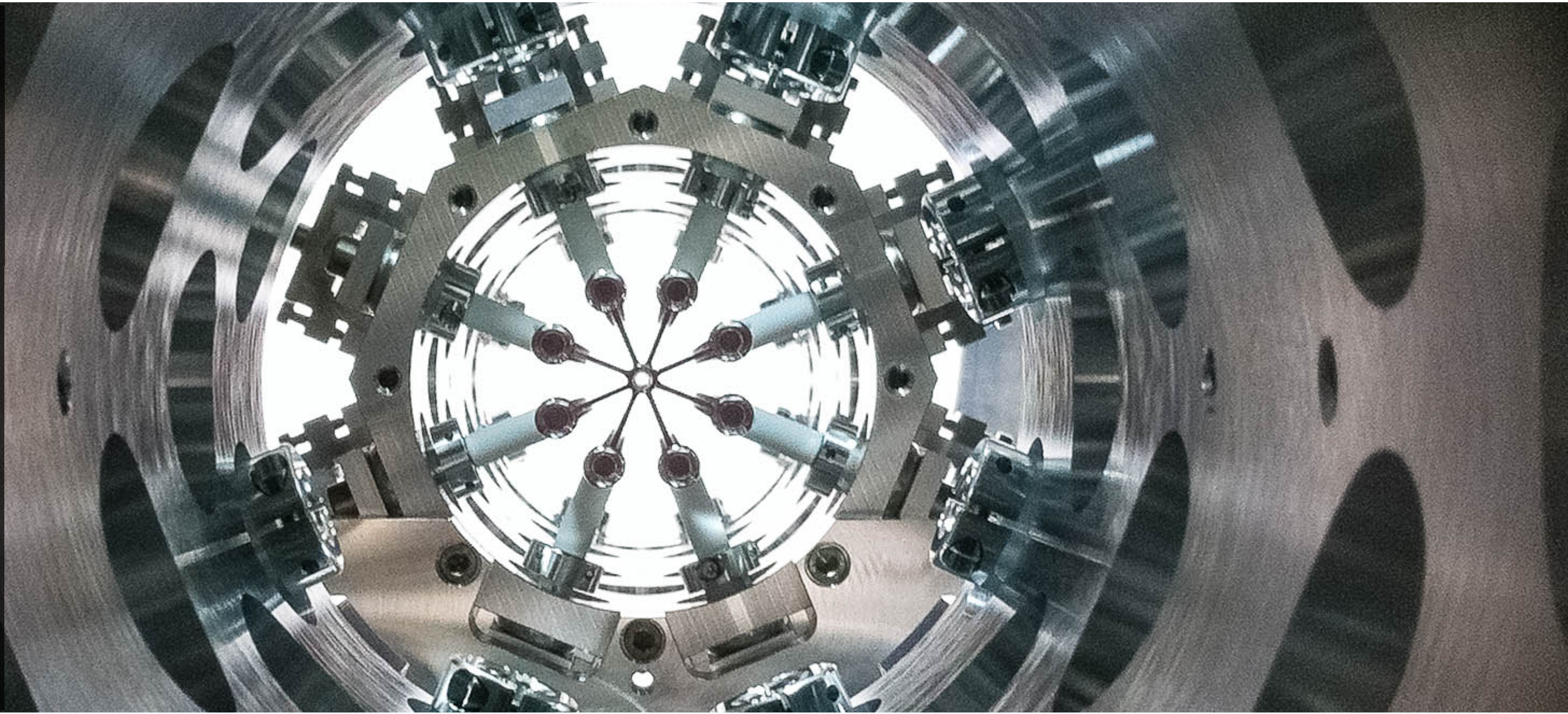

university of groningen
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Nikhef
Dutch National Institute for (astro)Particle Physics

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Is the electron round?

The Electric Dipole Moment of the electron (eEDM)

eEDM violates P, T and CP symmetry (provided CPT holds)

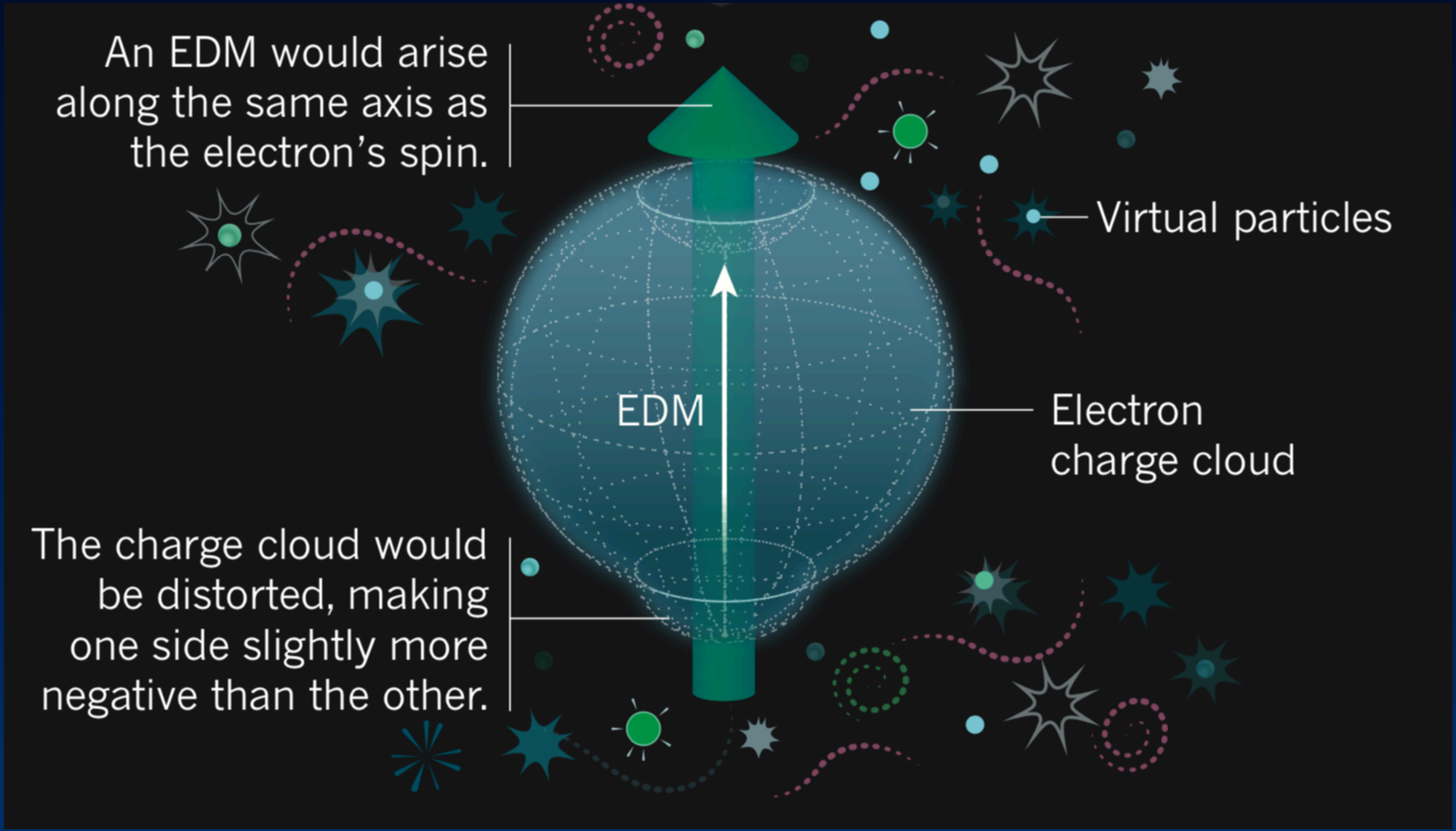
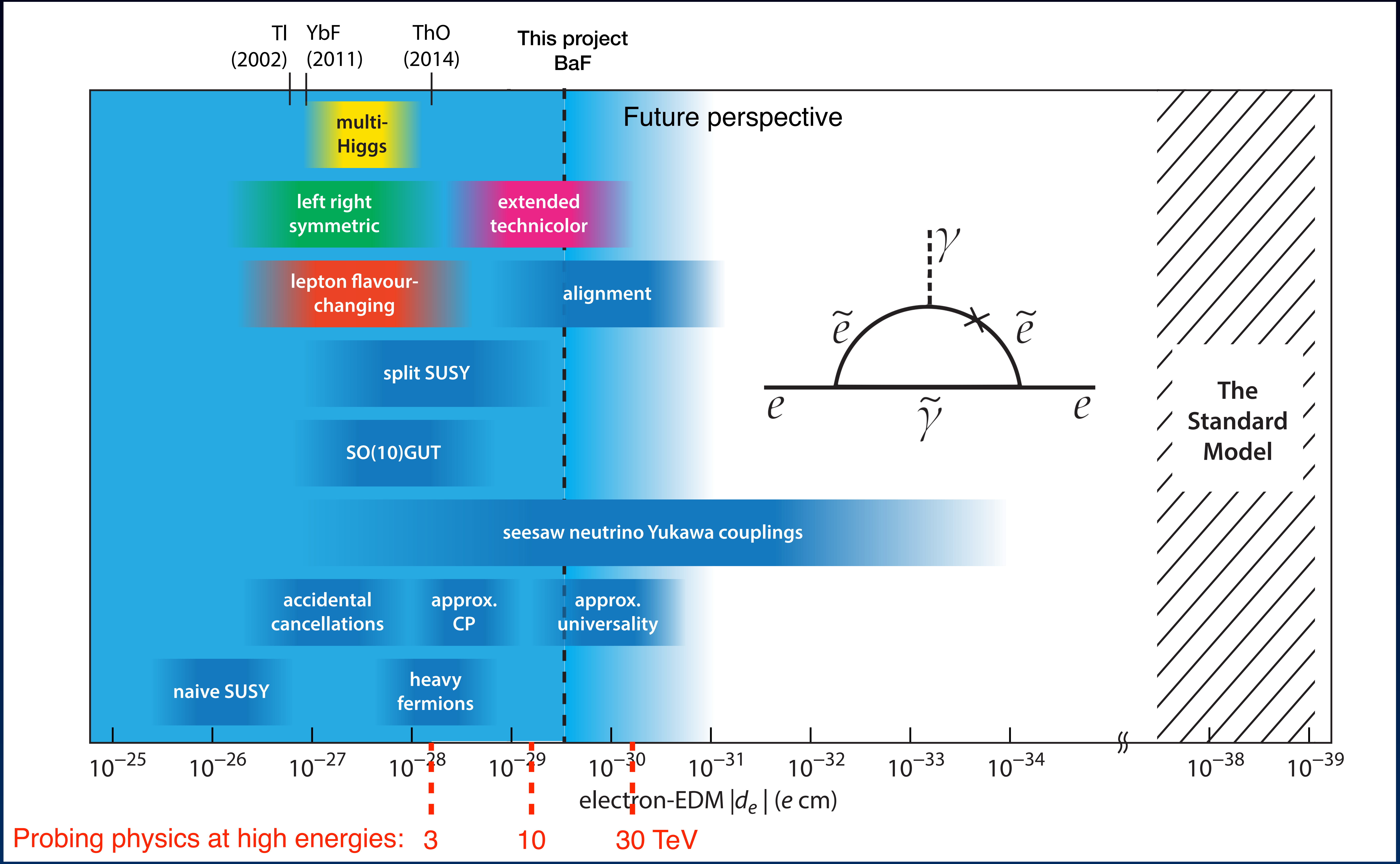
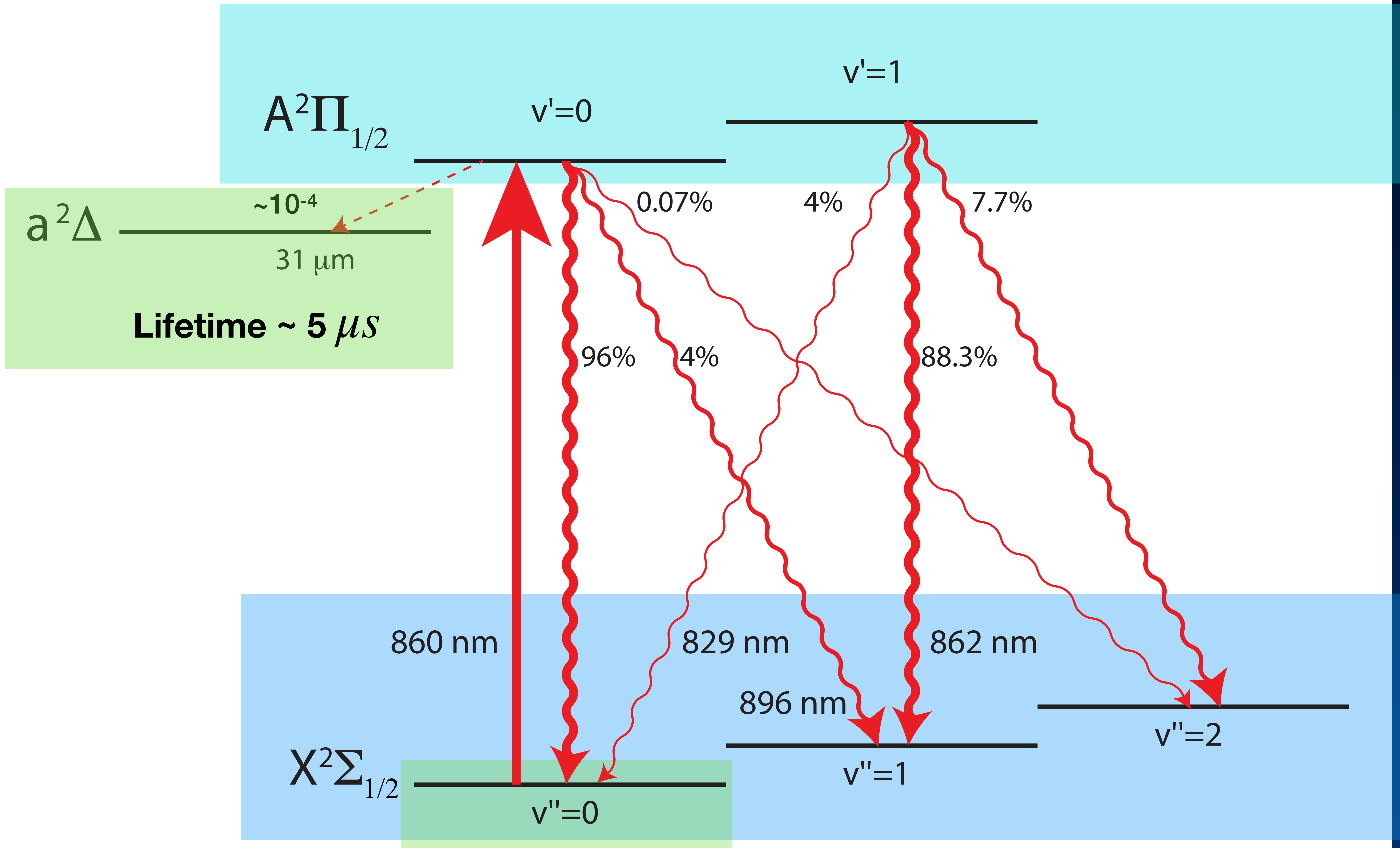


fig: Nature 553, 144 (2018)



Next-generation experiment with **cold molecules**

How the electron-EDM measurement is done with BaF molecules



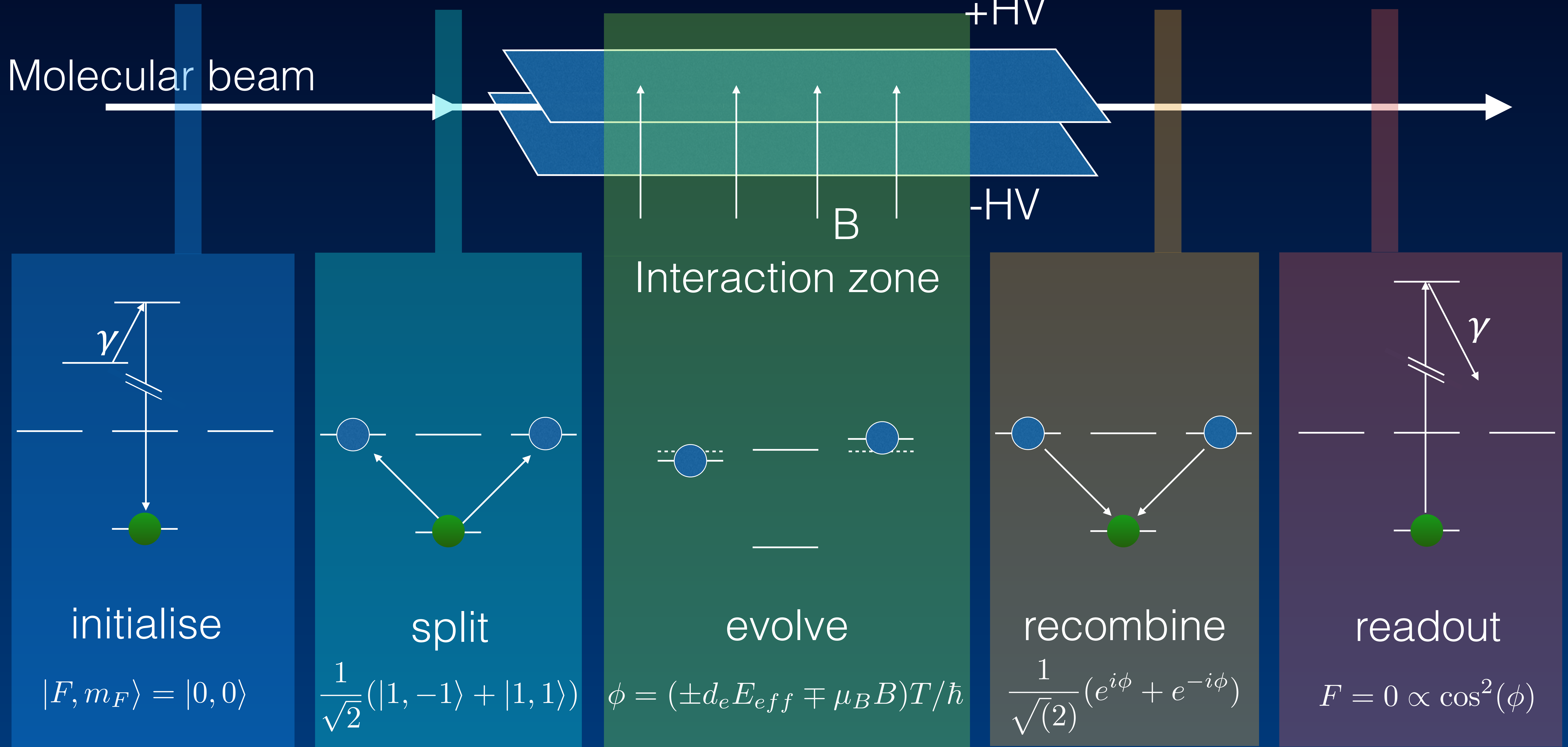
Lifetime ~ 50 ns

Electronic ground state

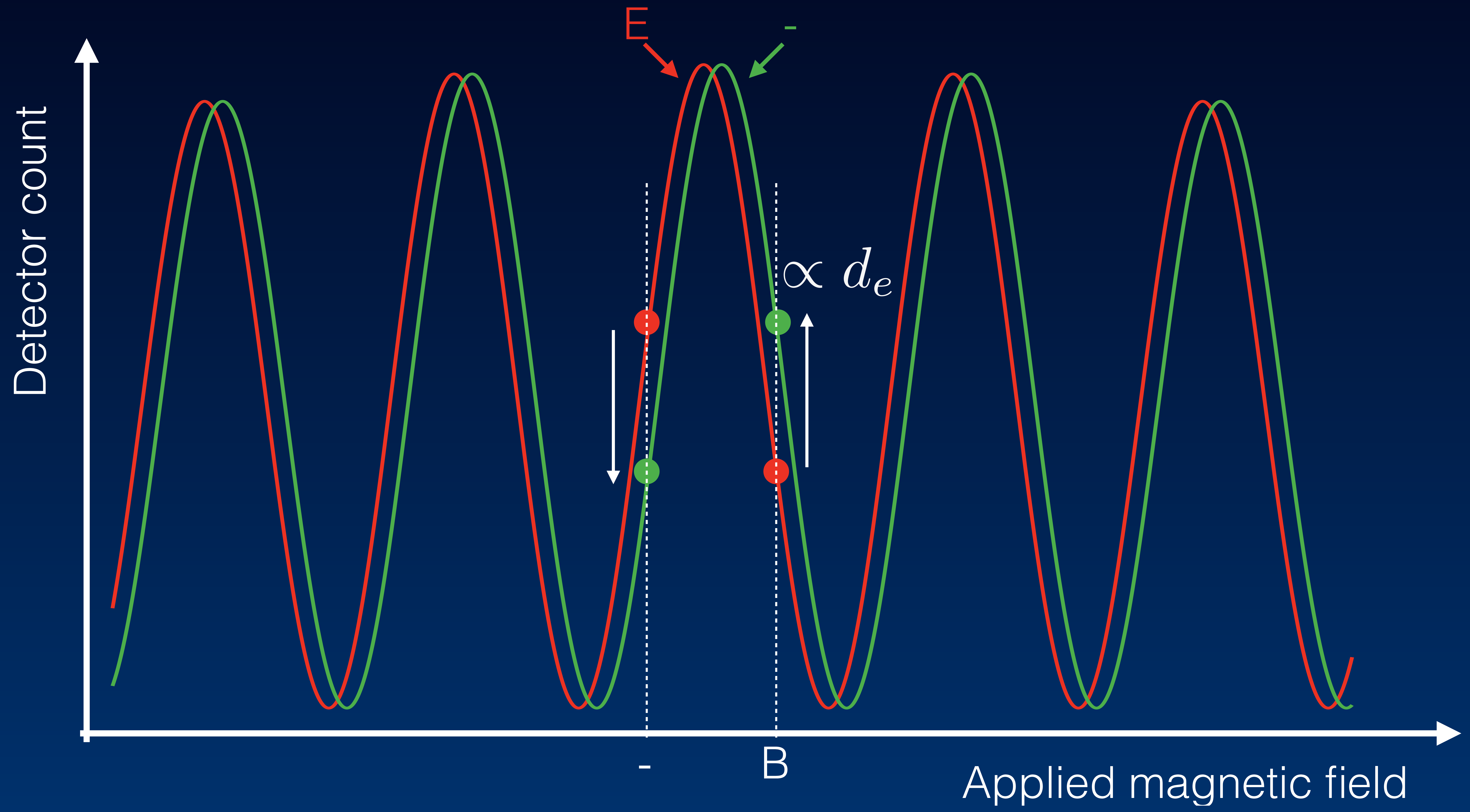
Vibrational ground state

Energy level structure of the BaF molecule

How to read out small energy shifts: spin interferometer



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



after slide by Ed Hinds

Increasing the eEDM sensitivity

Measure energy shift that correlates with electric field direction reversal

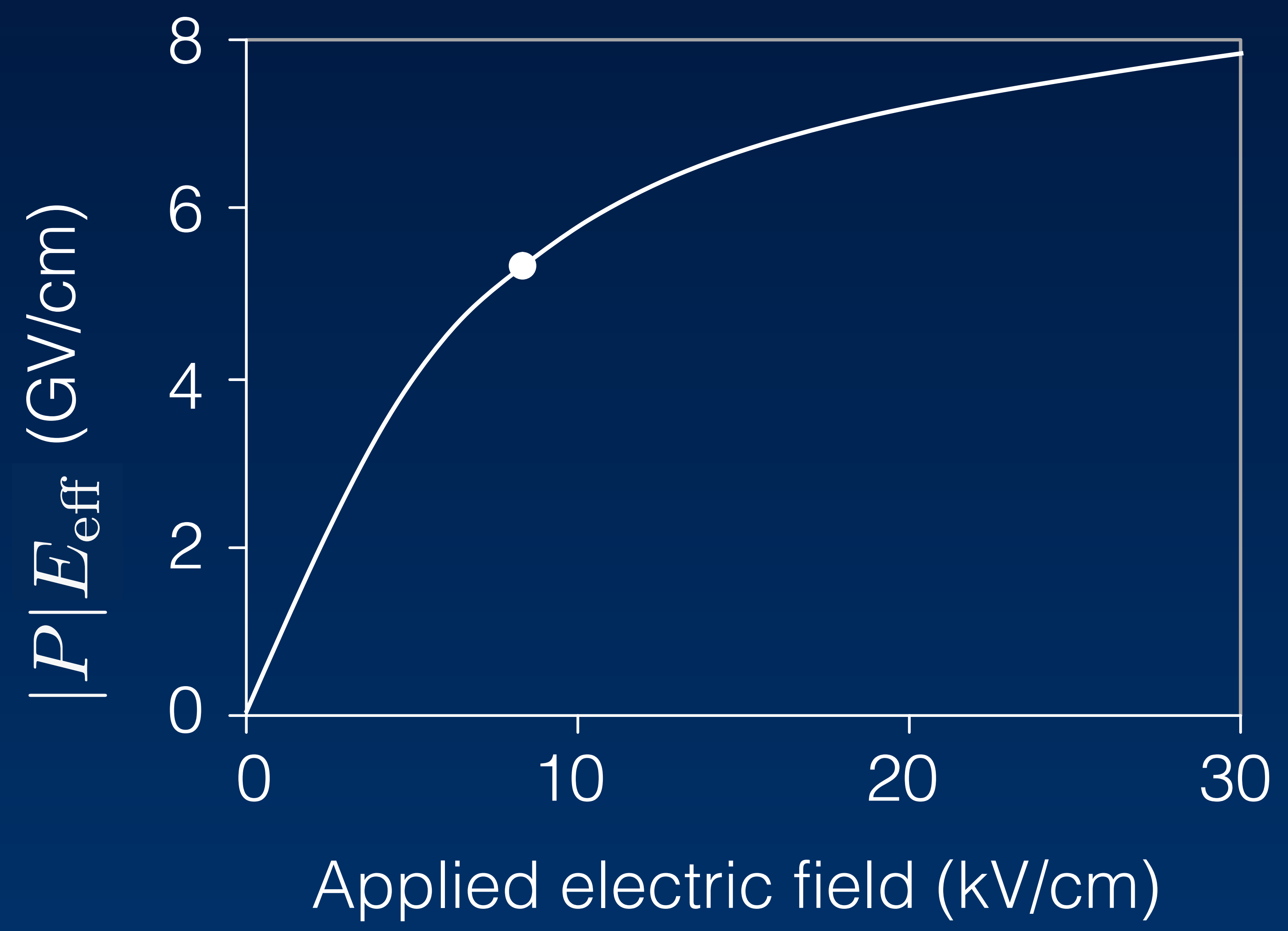
statistical error: $\sigma_d = \frac{\hbar}{e} \frac{1}{2|P|E_{\text{eff}}\tau\sqrt{\dot{N}T}}$

Effective electric field

Cold Molecules

Number of detected molecules

Coherent interaction time



polar molecule

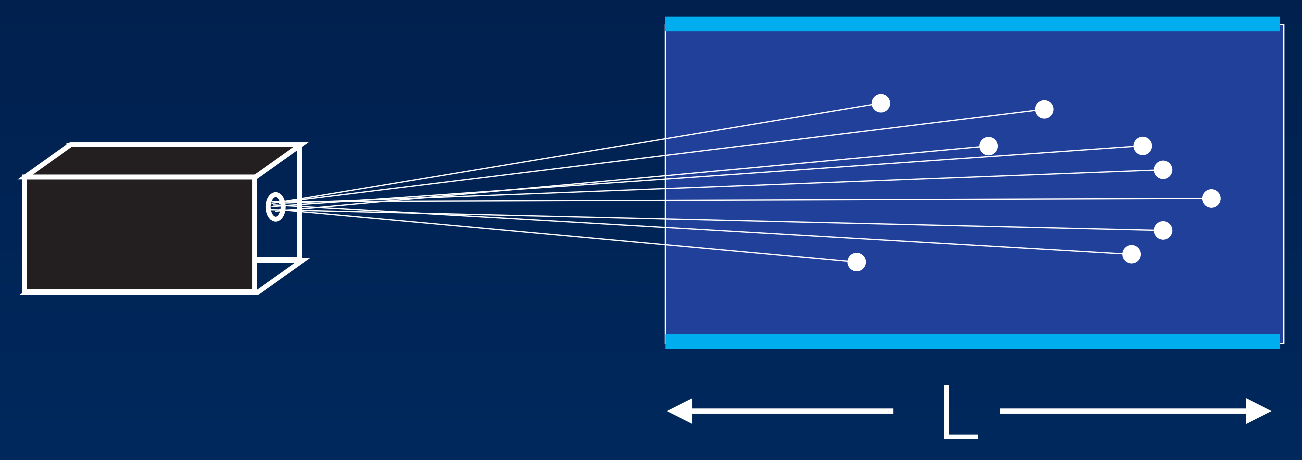
Towards longer coherent interaction times

fast beam

t ~ 1-2 ms

L ~ 0.5 m

v ~ 250-500 m/s

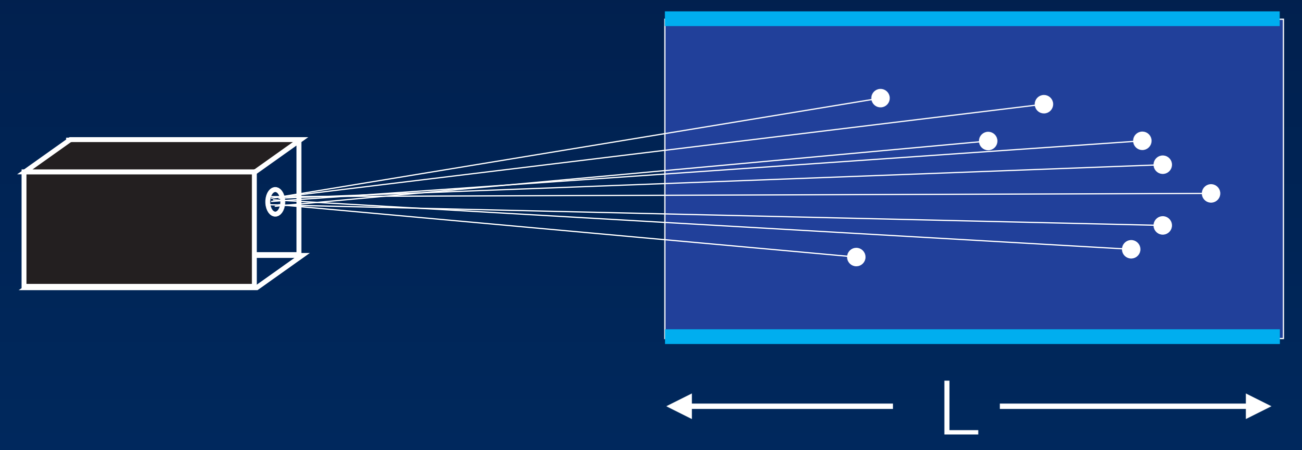


slow beam

t ~ 15 ms

L ~ 0.5 m

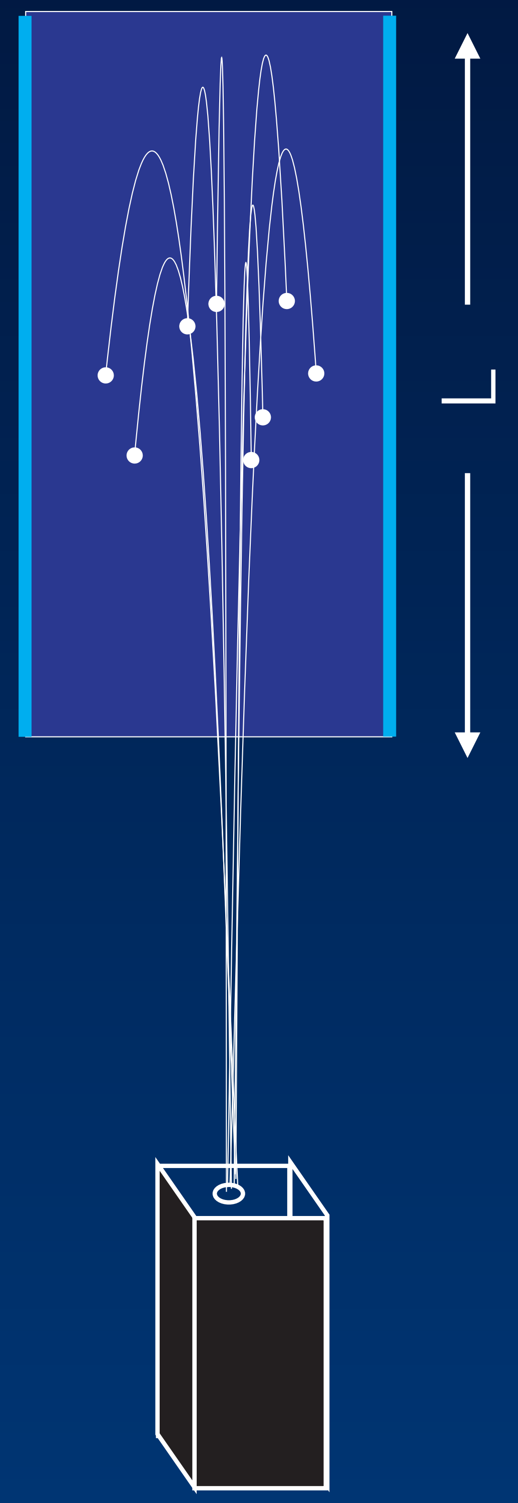
v ~ 30 m/s



fountain

t ~ 100 ms

L ~ 0.5 m

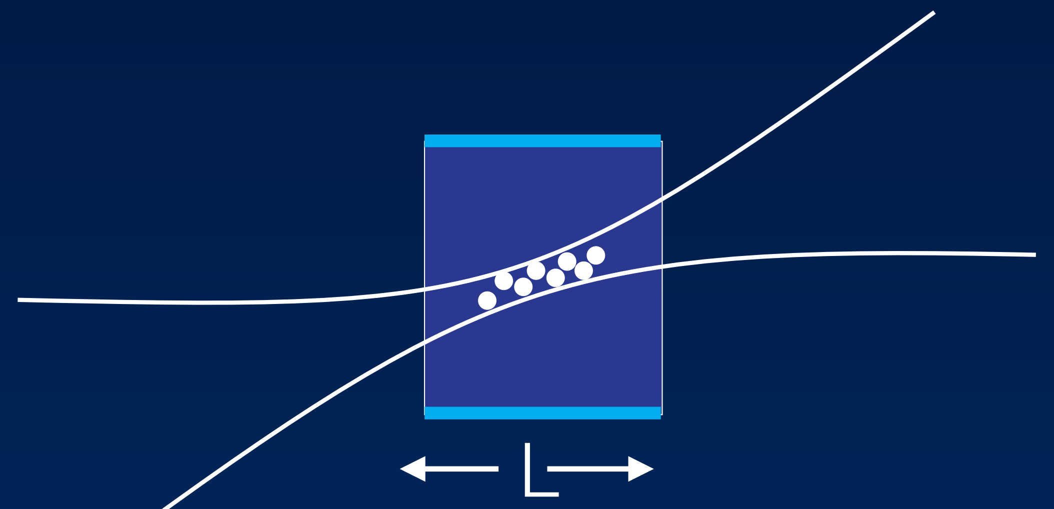


slow vertical beam

trap

t ~ 1-10 s

L ~ 0.5 mm



molecules trapped in laser focus

Demonstrated first molecular fountain:
PRL **117** 253201 (2016)
Rick Bethlem

Main challenge:
how to maintain N while increasing t

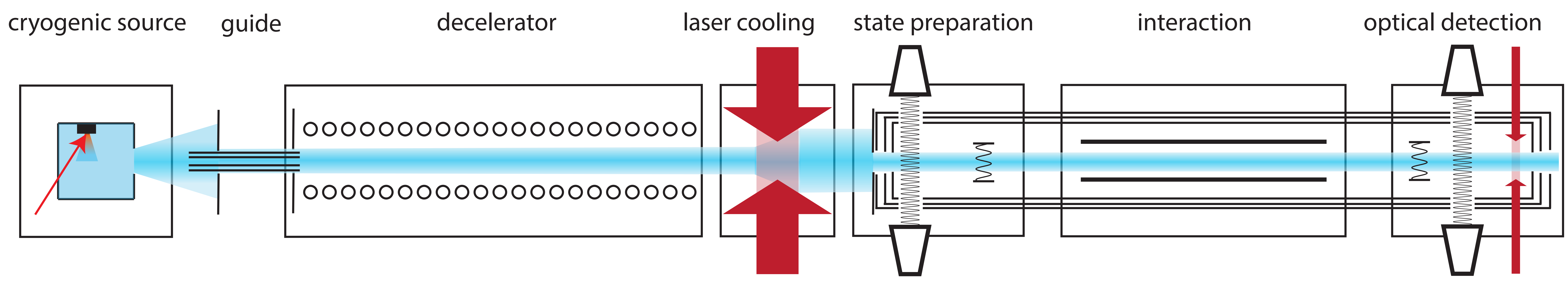
Strongly connected to choice of molecule!

Our approach:

Combining three recent experimental breakthroughs

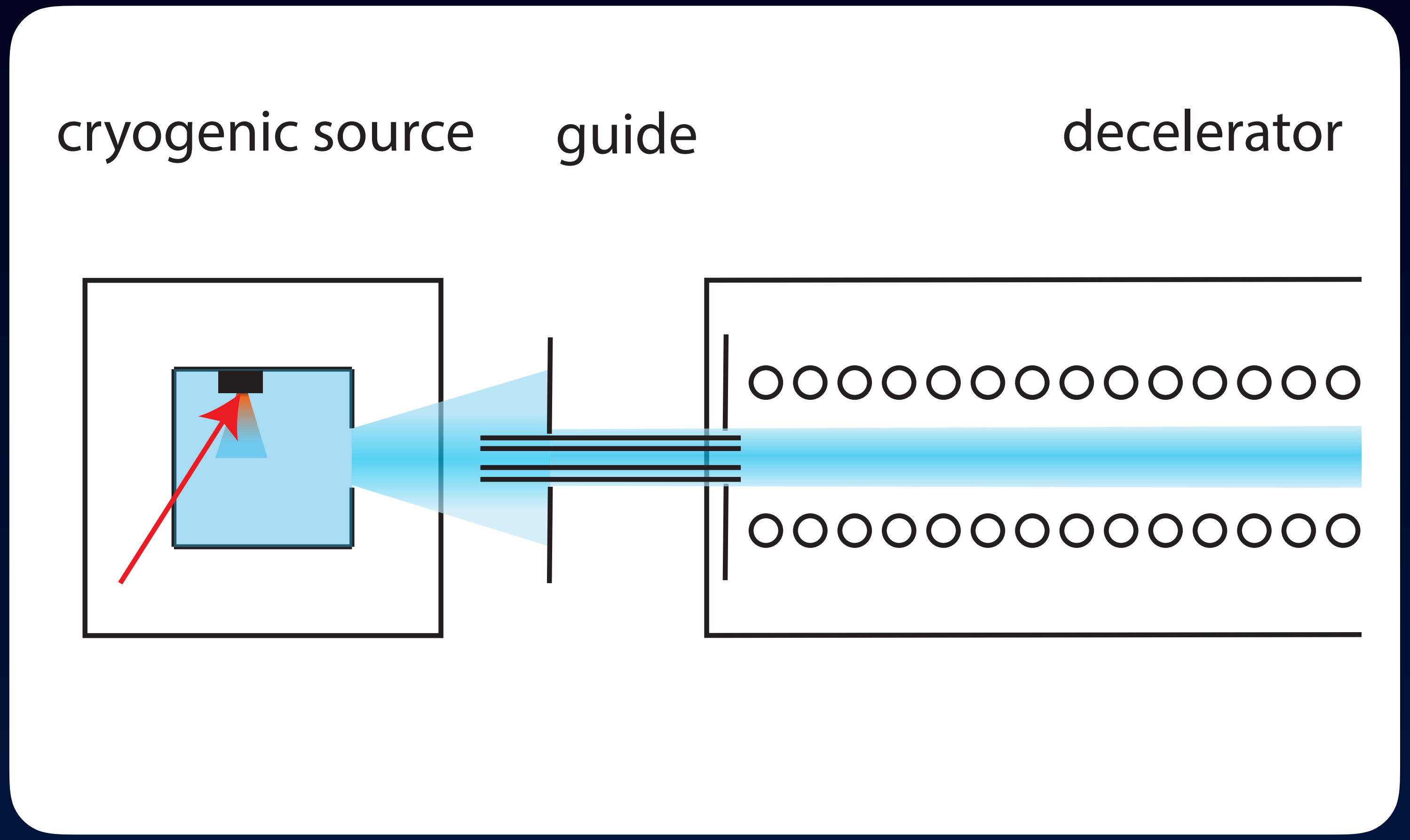
1) Cryogenic source
2) Stark deceleration
3) Molecular laser cooling

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



We aim for 5.10^{-30} e.cm in the first generation of the experiment

Published paper with full details of proposal: EPJD **72**:197 *(2018)*



Molecular beams

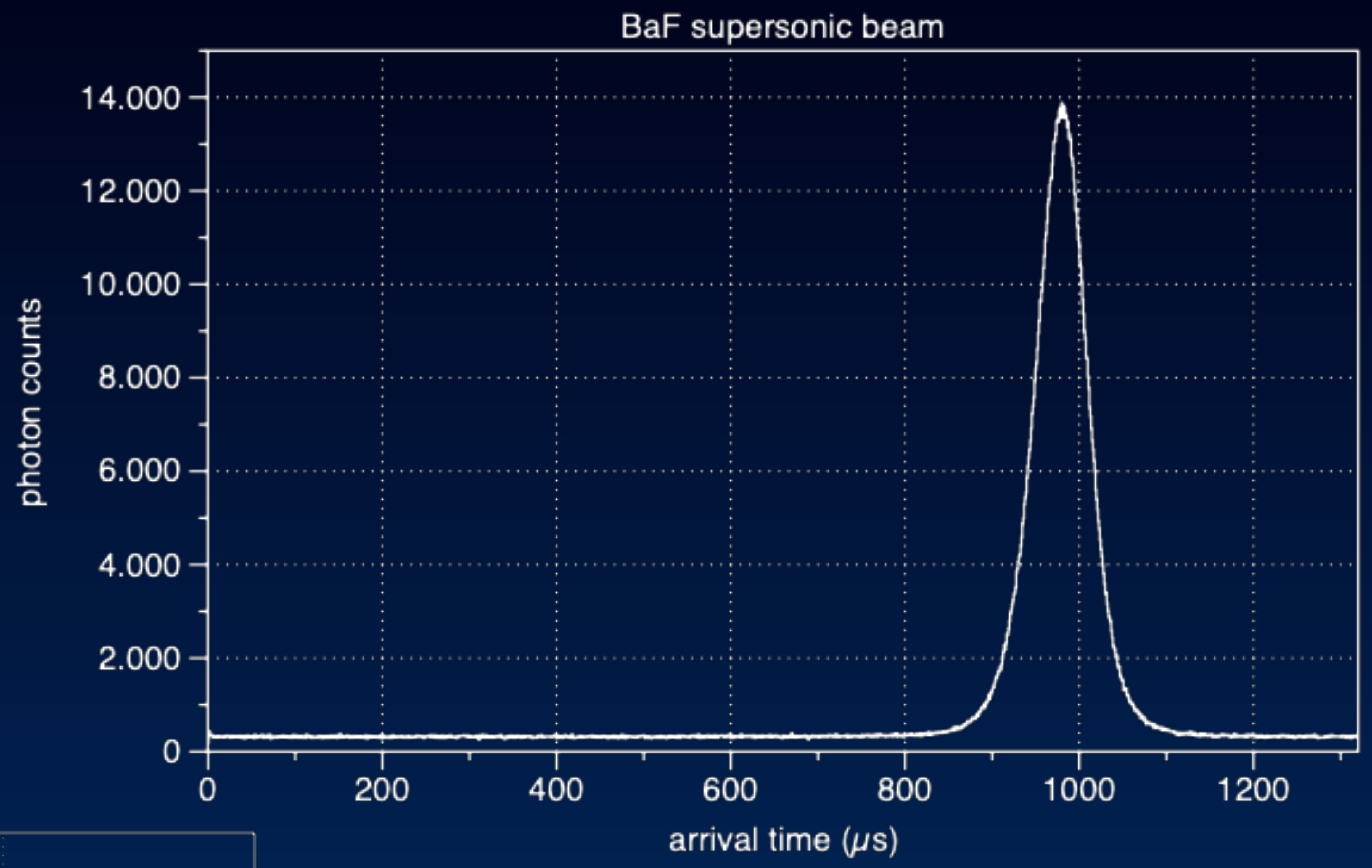
Supersonic

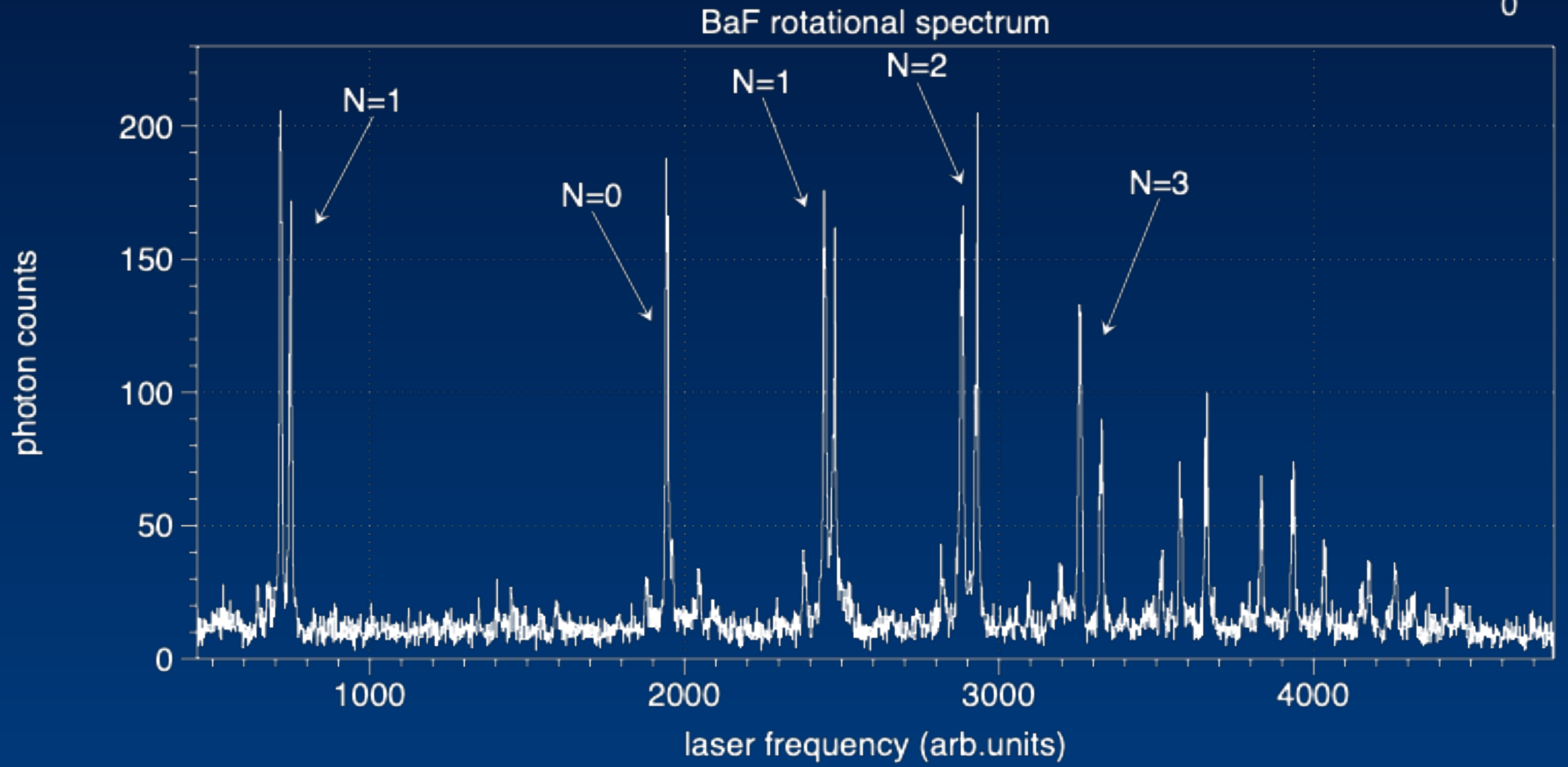
Aims:
- Intense, fast beam (600 m/s)
- Short pulse
- Test lasers systems, state manipulation and interaction zone

Cryogenic

Aims:
- slow, but relatively fast beam (~180 m/s)
- relatively short pulse
- relatively small velocity spread
  - for optimal loading into decelerator
- High N: 4×10^9/shot in the desired state
- Use for eEDM measurement

First BaF results





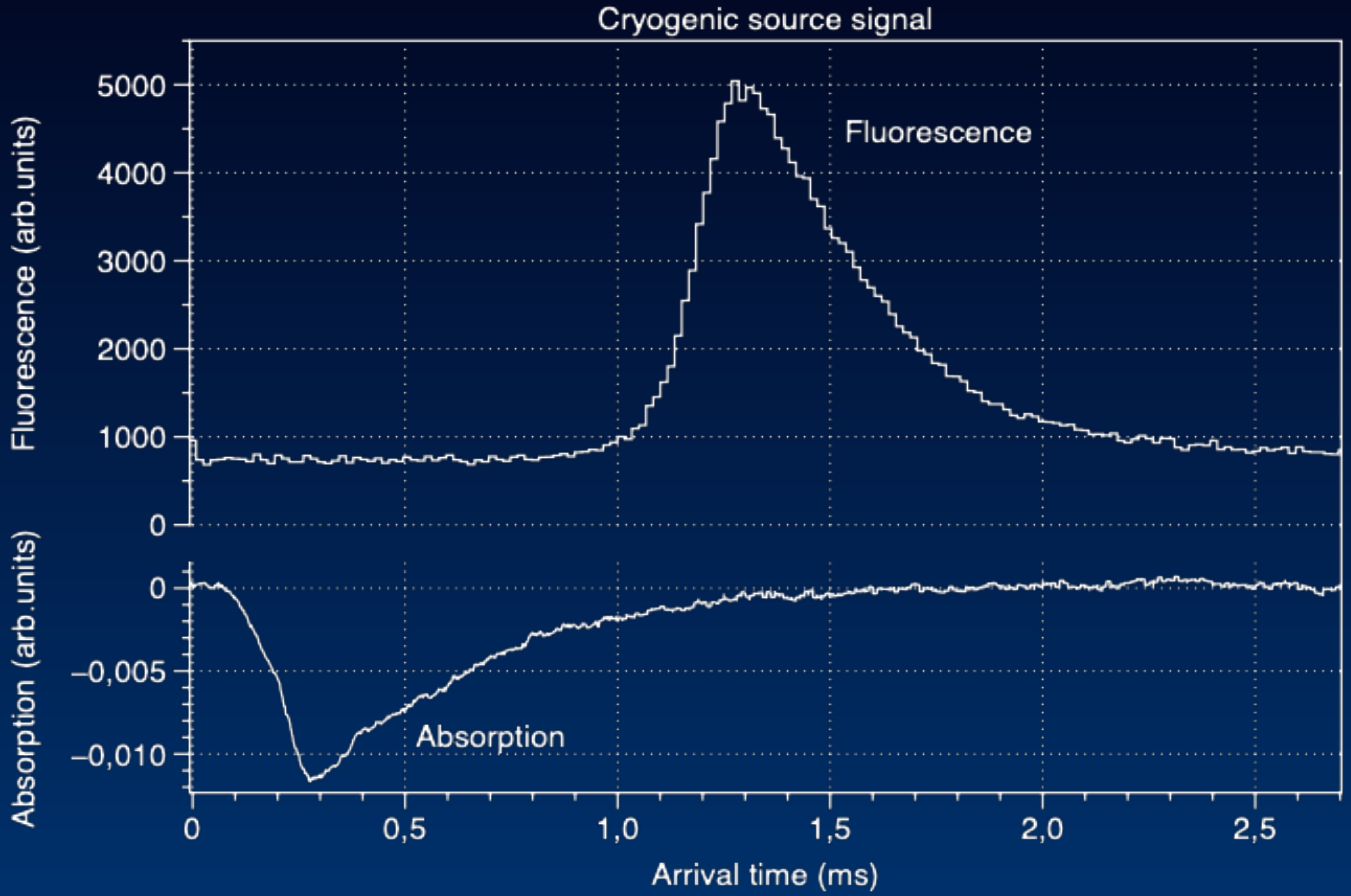
Supersonic beam

- Ablating barium metal target
- Even-Lavie valve
- Argon expansion + SF_6
- Fluorescence detection, 60 cm from valve
- Translational Temp 1-2 K
- Rotational temp ~4 K
- Velocity 600 m/s
- Working on state manipulation

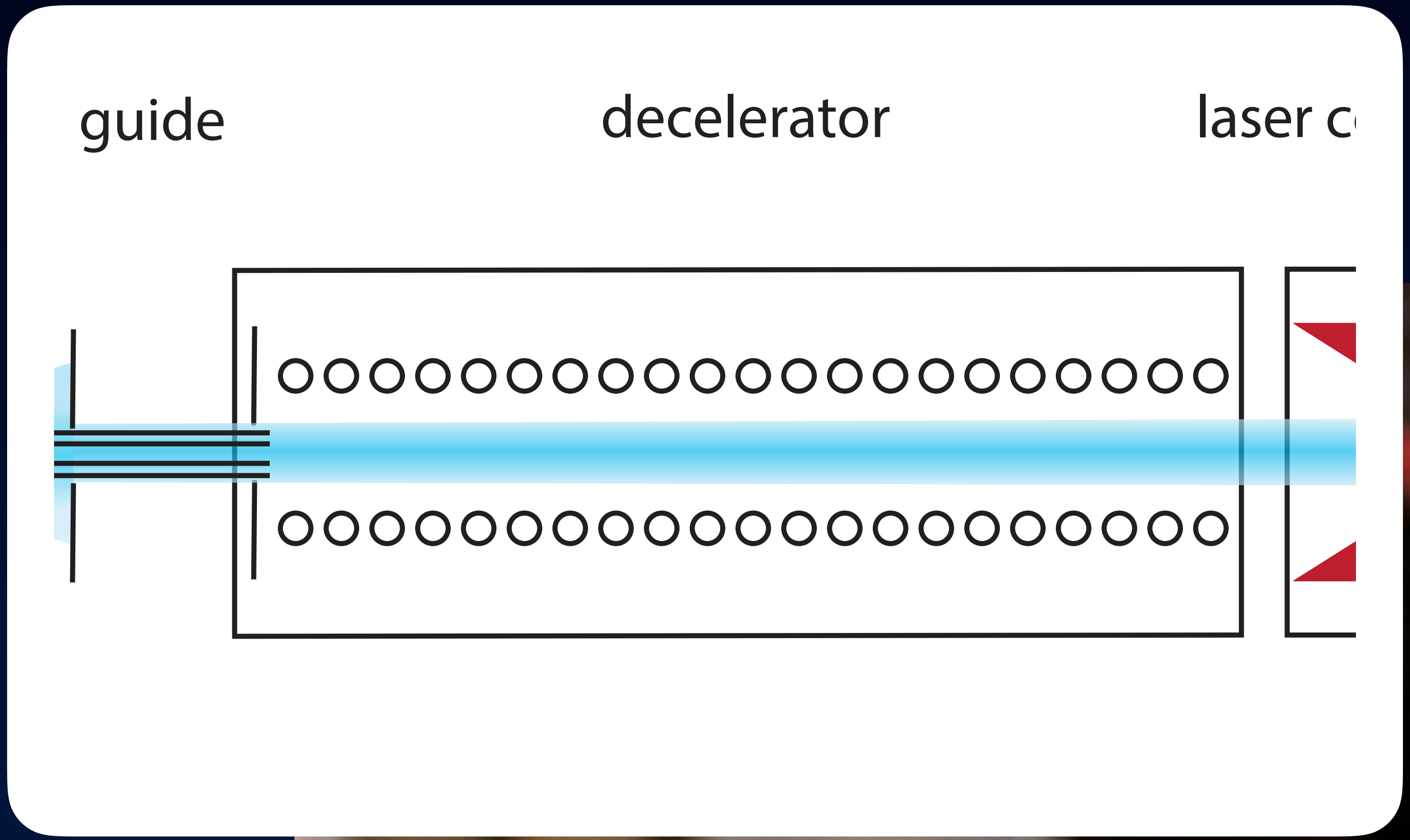
First cryogenic beam results

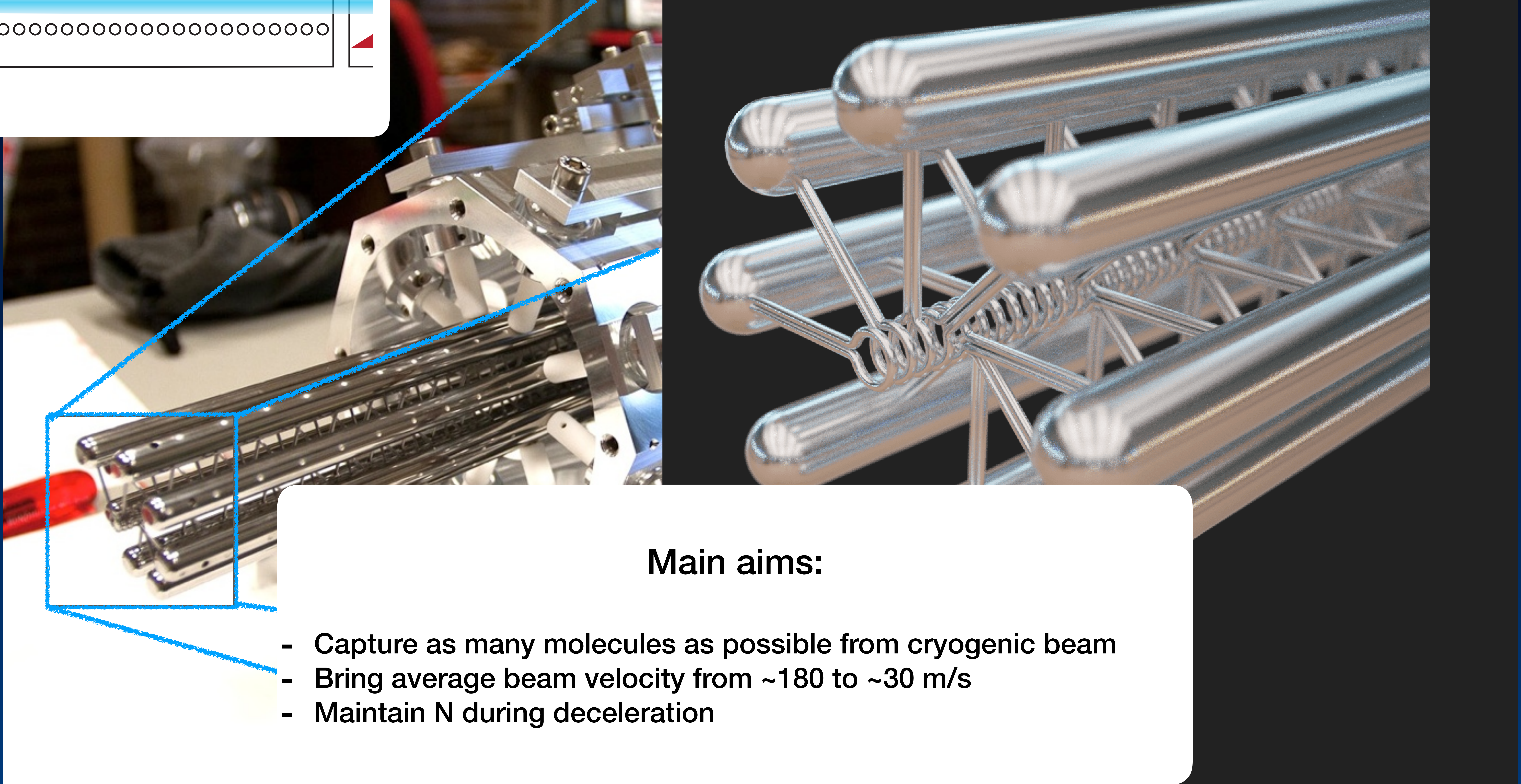
Cryogenic beam

- Ablating SrF_2 salt target
- Imperial college design (Tarbutt, Truppe)
- Neon carrier gas
- Absorption, 1 cm from cell
- Fluorescence, 30 cm from cell
- Translational Temp 10 K
- Velocity 150-200 m/s
- Operating @ 10 Hz



Traveling-wave decelerator

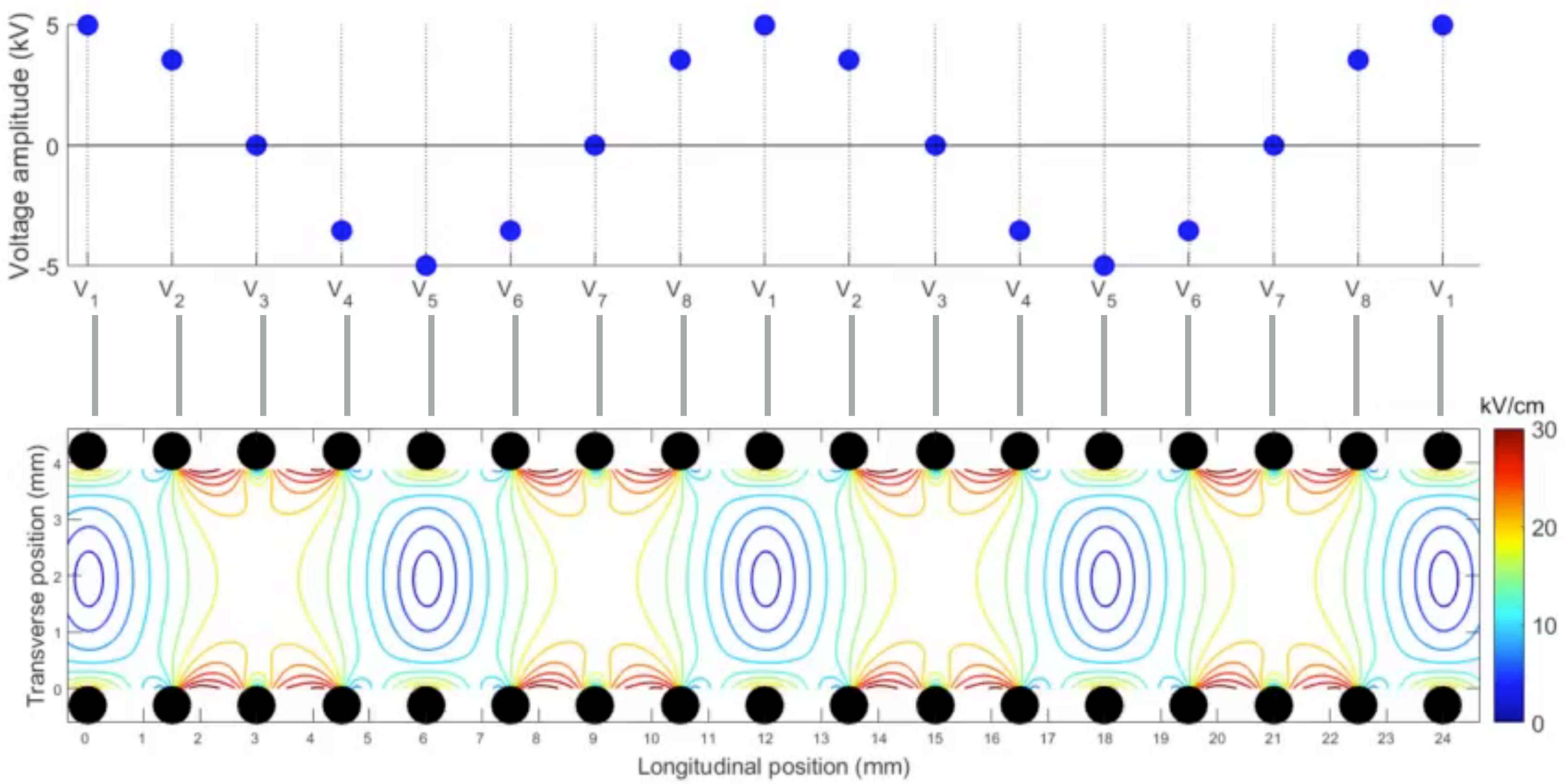




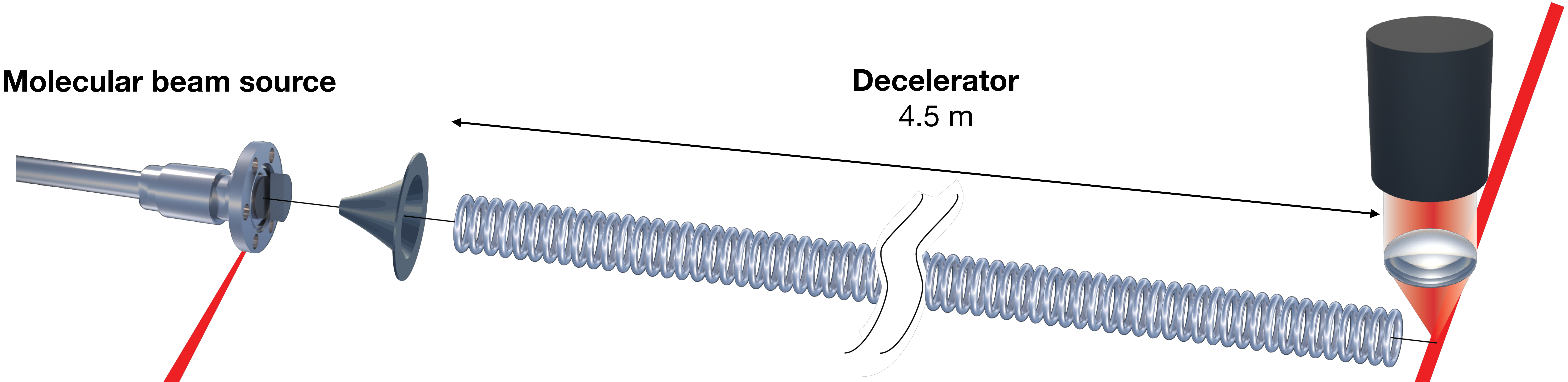
Main aims:

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

Traveling-wave decelerator



Traveling-wave decelerator

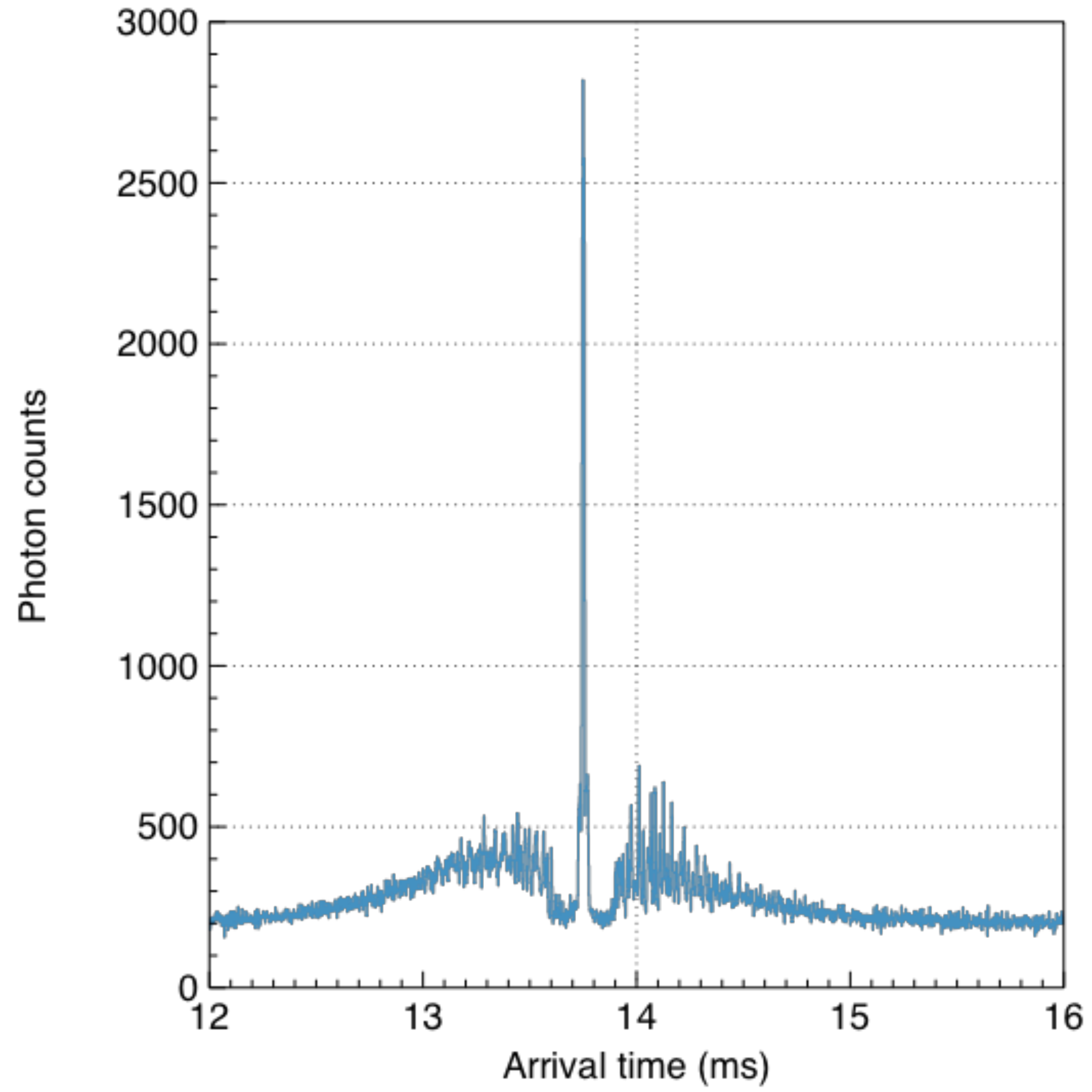


Challenges for heavy diatomic molecules:

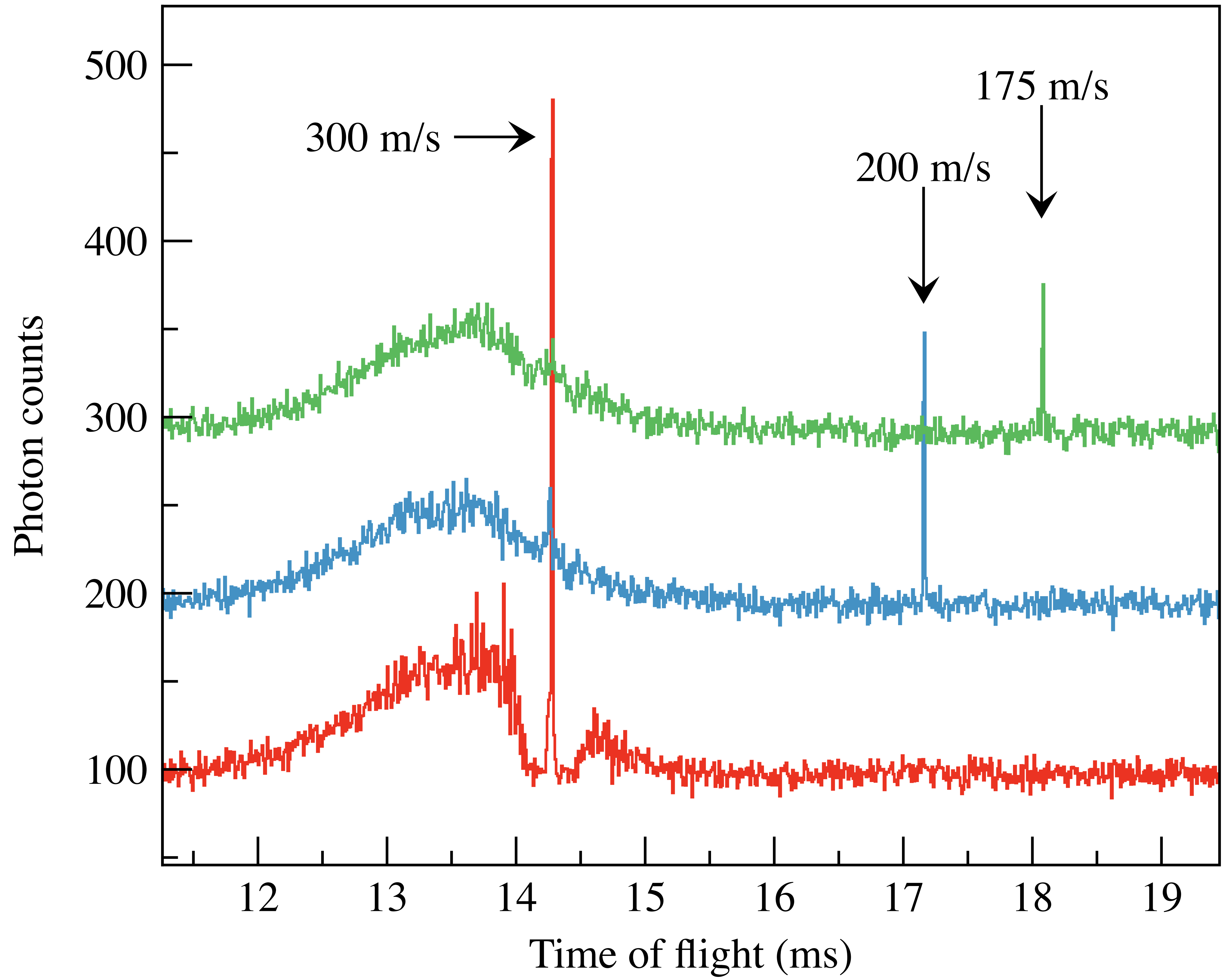
- Heavy -> long decelerator
- Rotational structure -> limited Stark shift

Traveling-wave decelerator

Stark deceleration of SrF ($X^2\Sigma$, N=1)



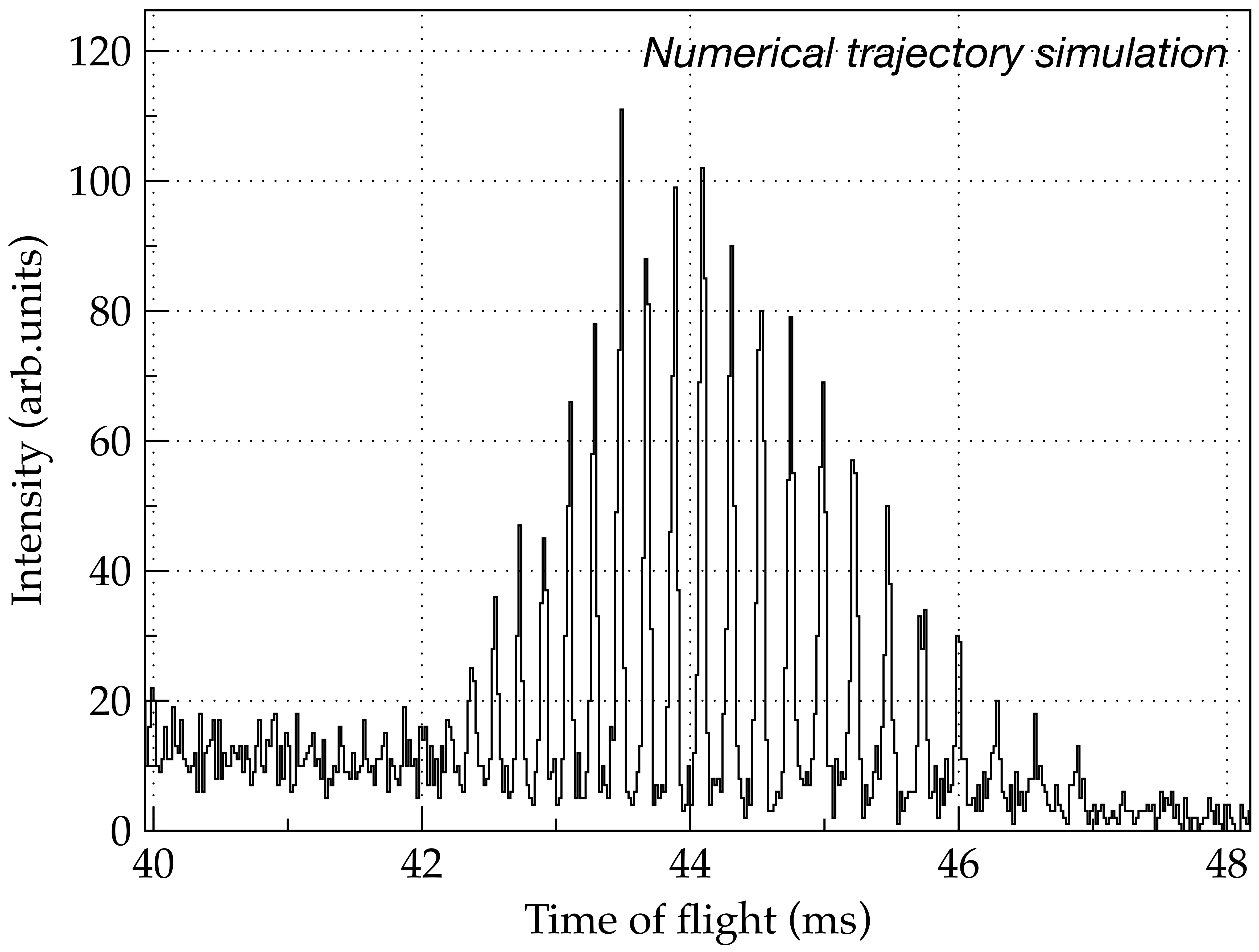
Guiding @ 345 m/s



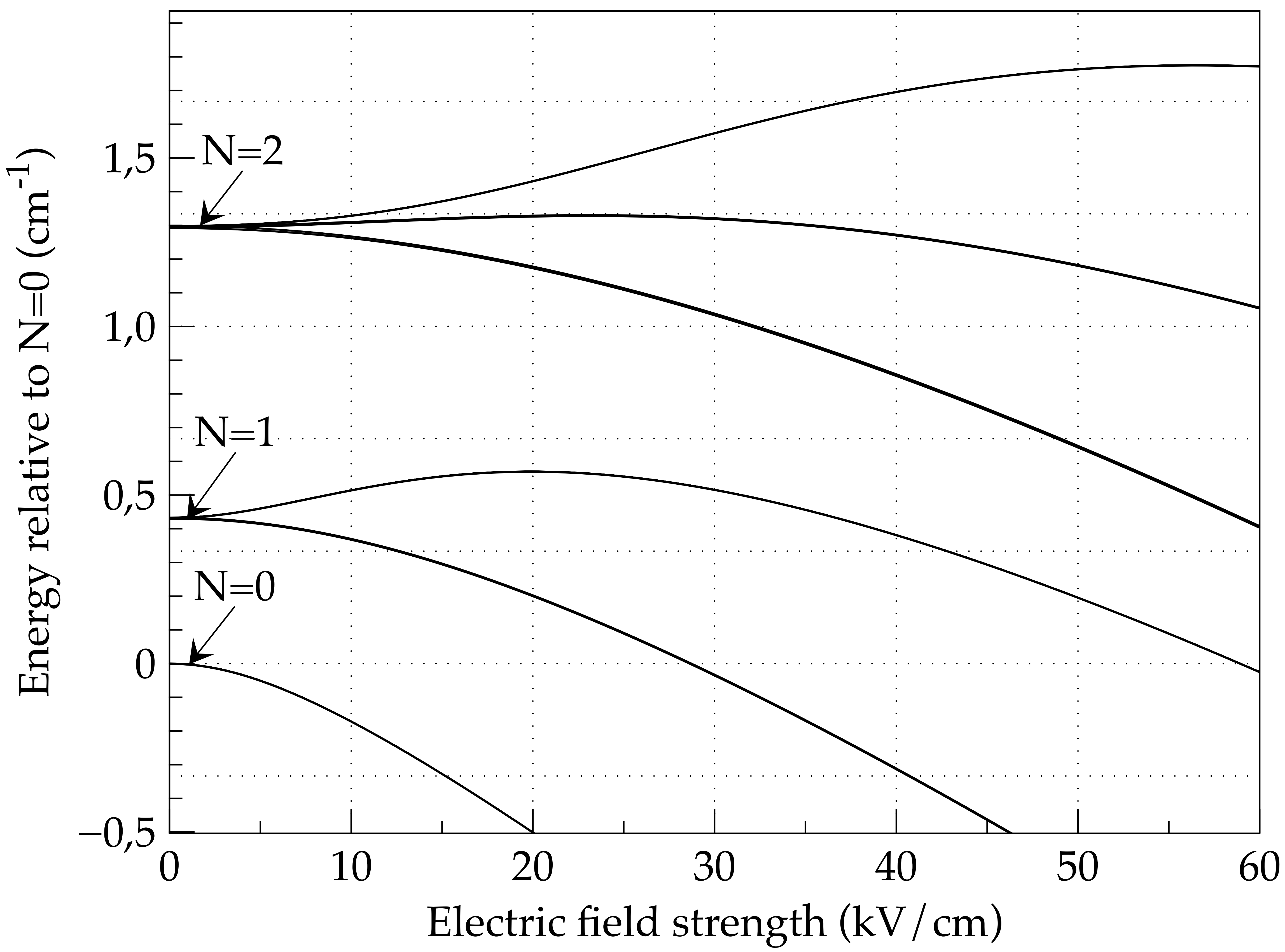
Deceleration

Mathavan et al, Chemphyschem. **17,** 3709 (2016)

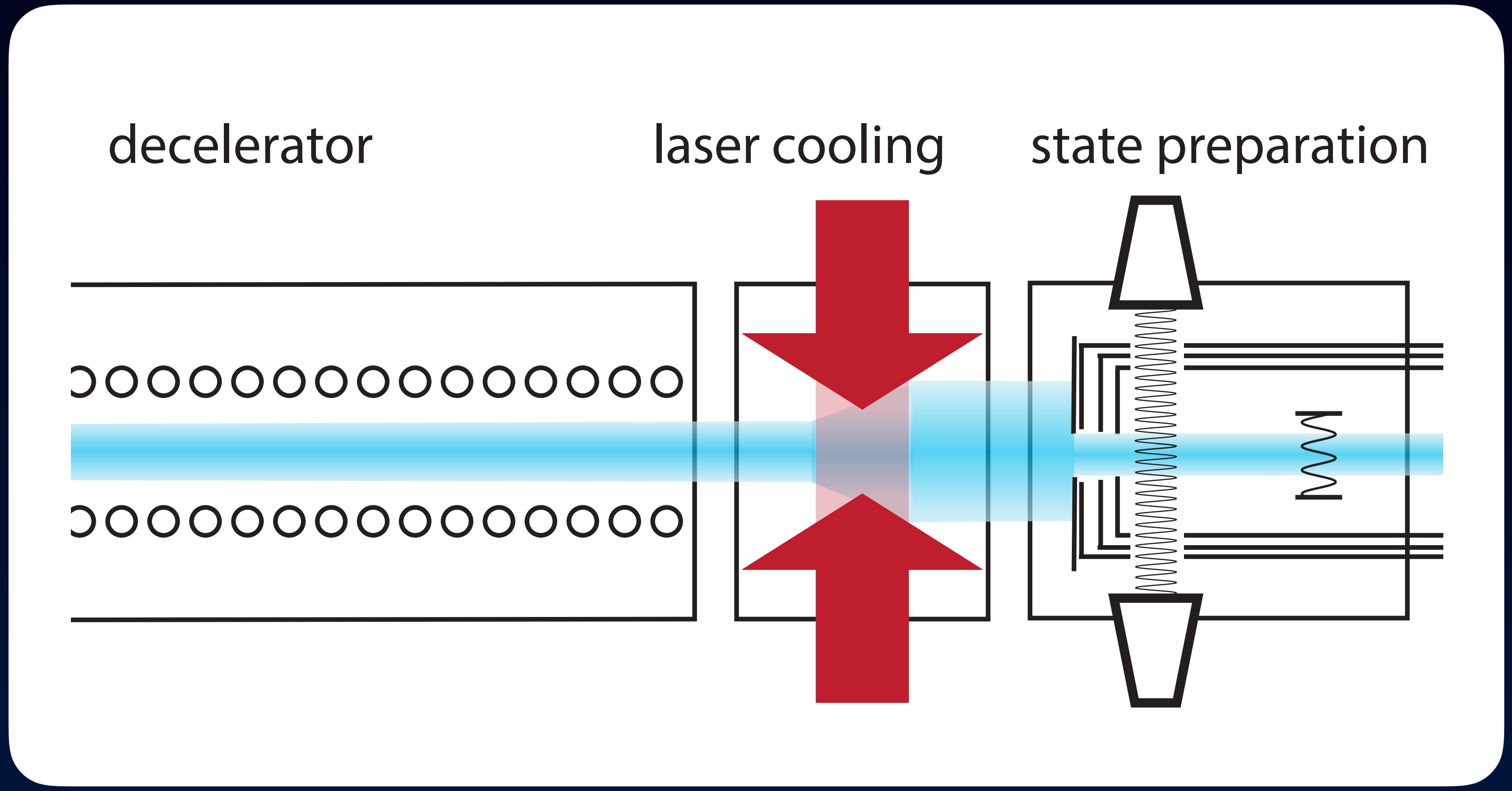
Stark deceleration from cryogenic source



Simulation: deceleration from cryogenic beam to 30 m/s



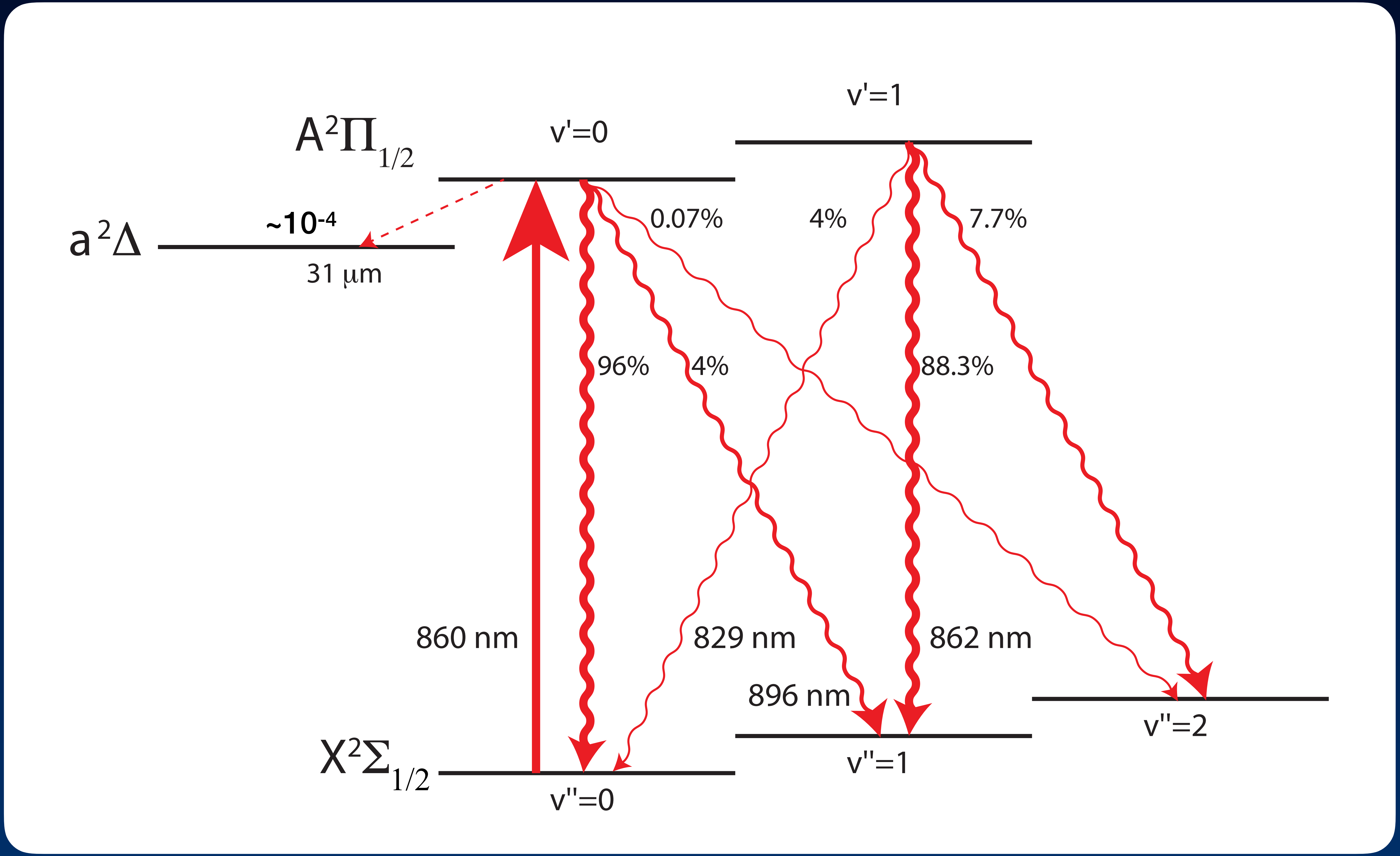
Aim: increase capture range by decelerating in N=2 state at 10 kV instead of N=1 at 5 kV



Laser cooling

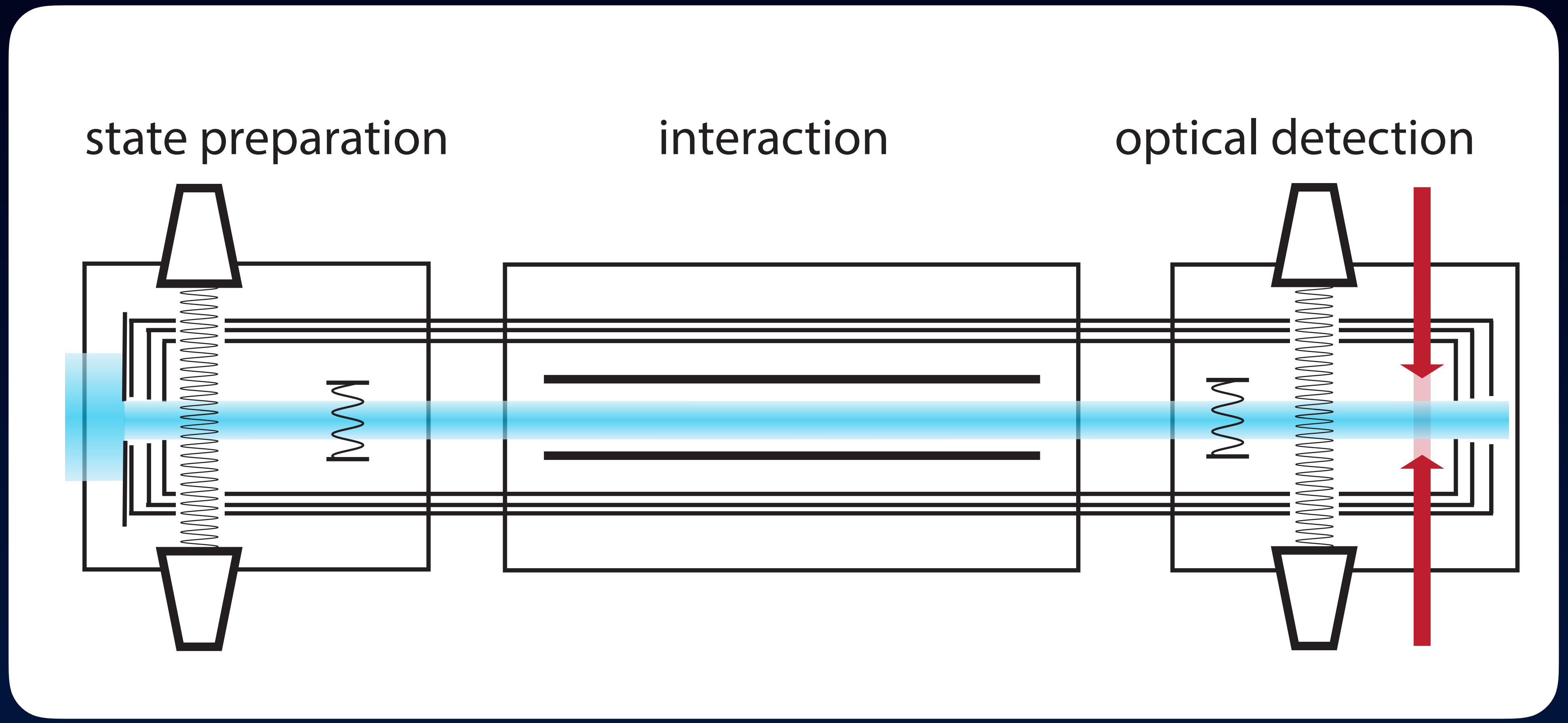
Aim:
- Stop the slow beam from transverse spreading
- Essential step to benefit from slow beam
- Transverse cooling takes ~ 2 ms

Status:
- Laser system has been set up
- Detailed investigation of BaF structure, to assess possible leak to Delta state
- Franck-Condon factors and transition dipole moments all seem favourable
- Laser cooling possibilities still very limited compared to Rb or similar atoms
- Planning first state manipulation experiments in BaF supersonic source



FC-factors sufficient for rapid (2 ms, 2000 photons) transverse laser cooling

Interaction zone

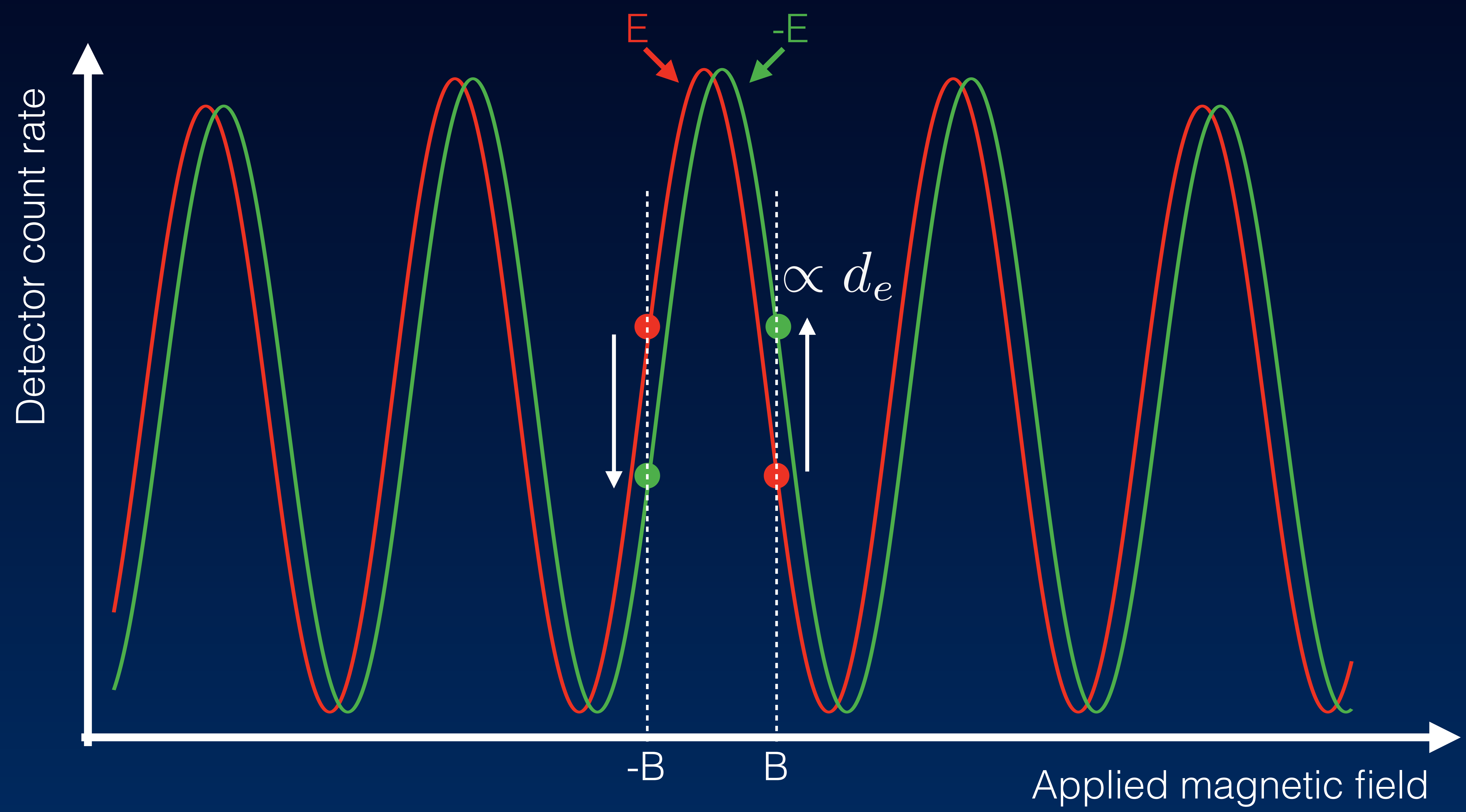


Aim:

- Polarise the molecules using an electric field, while providing a very stable and weak magnetic field

Status:

- Design finished, negotiating with manufacturers
- Longer interaction time result in more stringent requirements on the magnetic field (π/4 B-field is 600 pT = 6 microG)



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

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_{long}=(180 ± 50) m/s, v_{trans}=±30 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_{long}=(30 ± 6) m/s, v_{trans}=±5 m/s.
Laser cooling	0.8	Laser cooling efficiency	
	0.7	State transfer efficiency	9×10^{5}, v_{long}=(30±6) m/s, v_{trans}=±0.2 m/s.
Interaction zone	0.8	Transmission and state transfer efficiency	
	1.0	Detection efficiency	7×10^{5}

EPJD ***72****:197 (2018)*

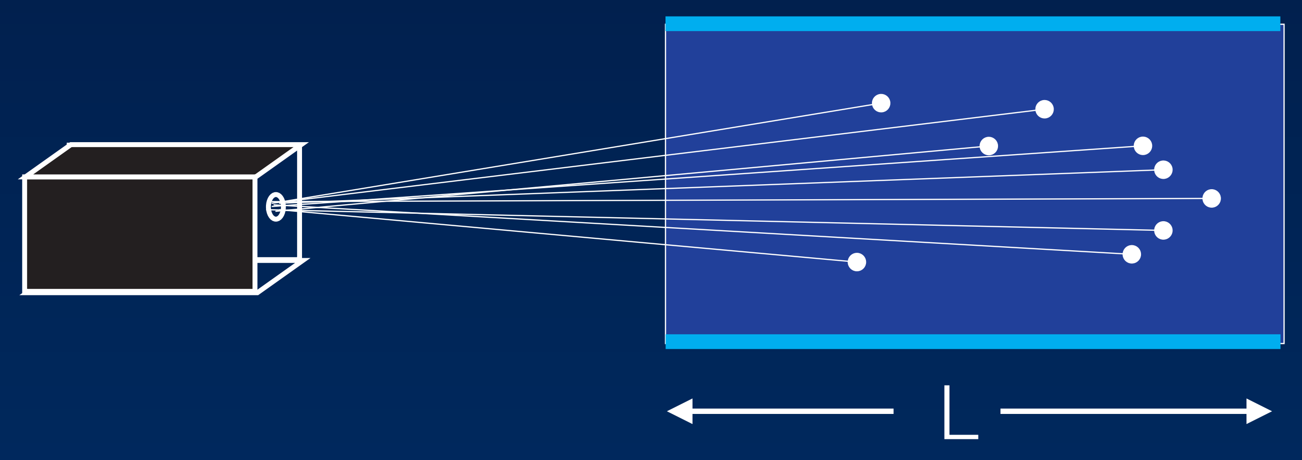
Towards longer coherent interaction times

fast beam

t ~ 1-2 ms

L ~ 0.5 m

v ~ 250-500 m/s

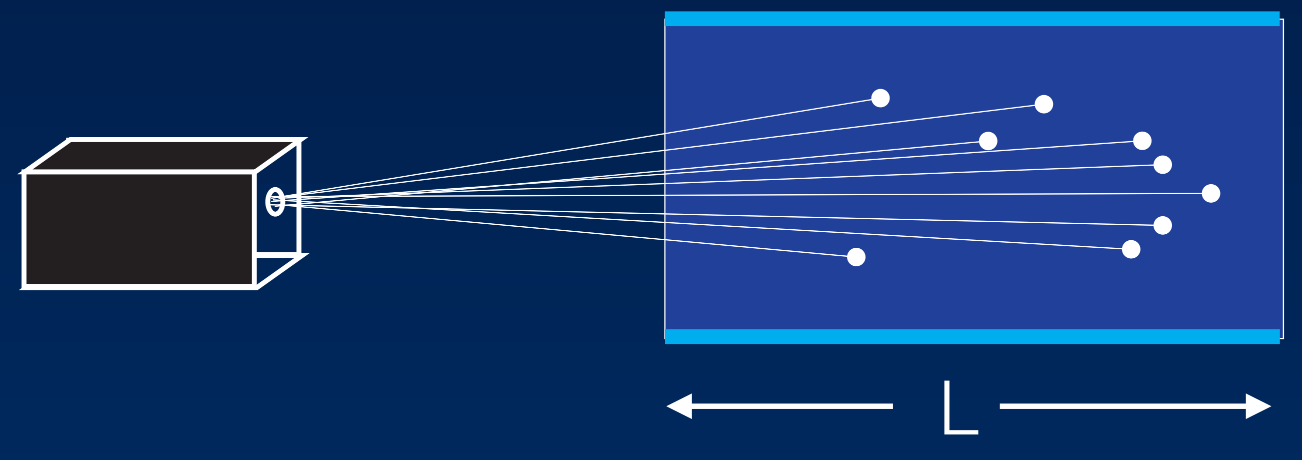


slow beam

t ~ 15 ms

L ~ 0.5 m

v ~ 30 m/s

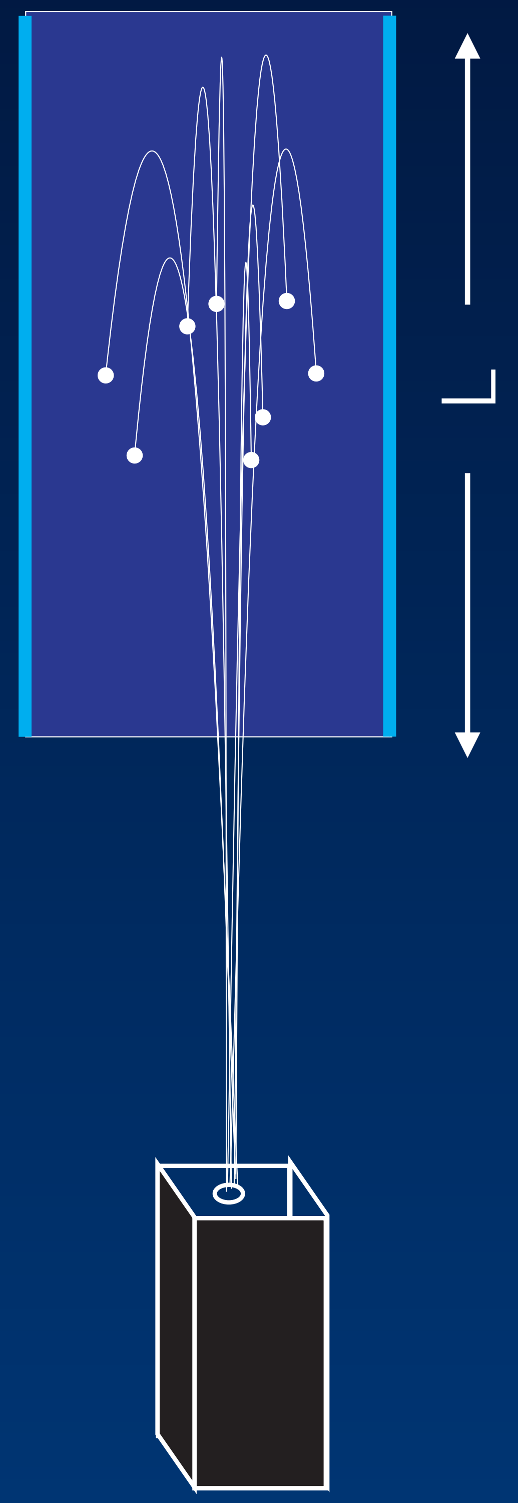


Future

fountain

t ~ 100 ms

L ~ 0.5 m

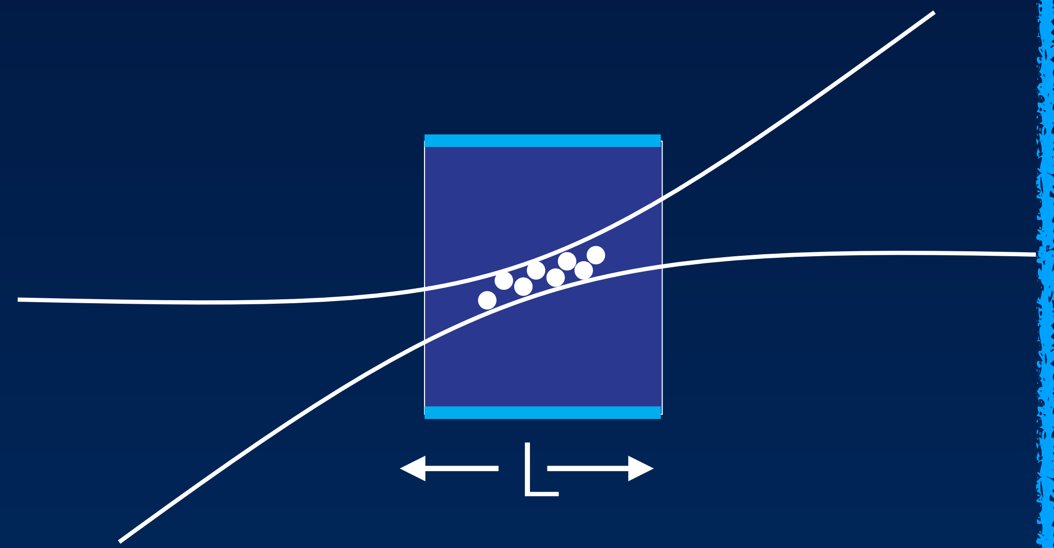


slow vertical beam

trap

t ~ 1-10 s

L ~ 0.5 mm



molecules trapped in laser focus

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Main challenge:
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The NL-eEDM team