Table-Top Particle Physics

with Slow and Trapped Molecules

Part 1: Table-top particle physics

- Issues in particle physics
- Table-top precision experiments
- Using molecules?
- The electron's electric dipole moment
- Opportunities and challenges

Part 2: Slow and trapped molecules

- Goals
- Techniques
- Sources
- Deceleration and trapping
- Precision measurements

Steven Hoekstra, University of Groningen and Nikhef, The Netherlands

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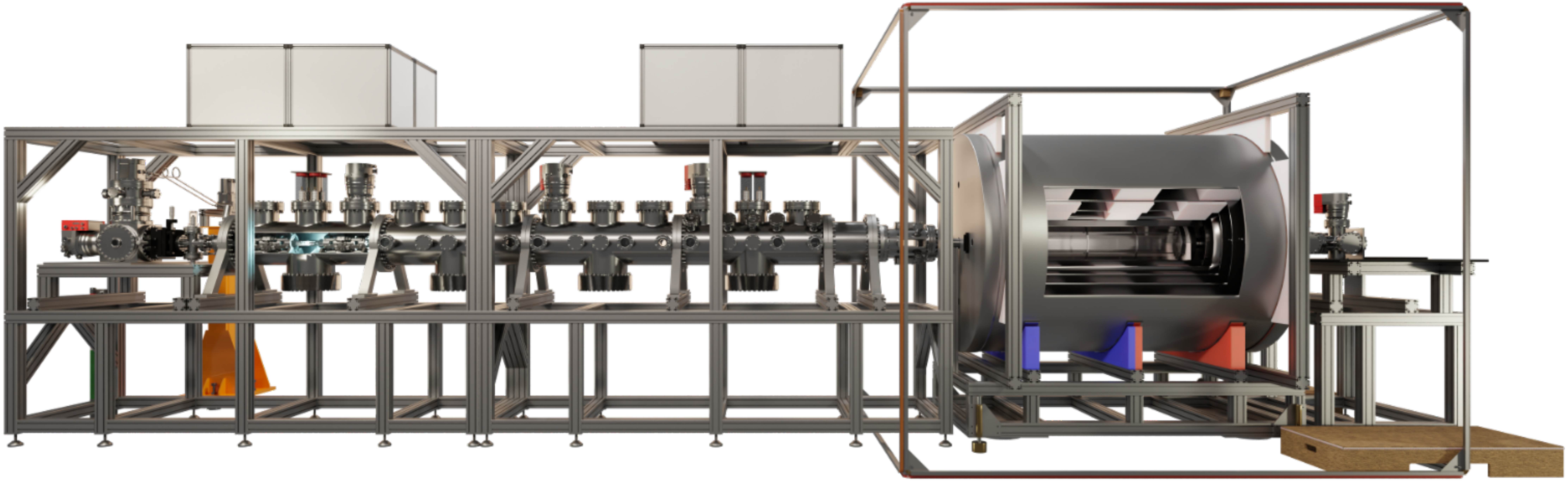
Dutch National Institute for (astro)Particle Physics

Table-top particle physics with slow and trapped molecules



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Ba
e⁻

university of groningen
van swinderen institute for particle physics and gravity

Nikhef
Dutch National Institute for (astro)Particle Physics

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UvA

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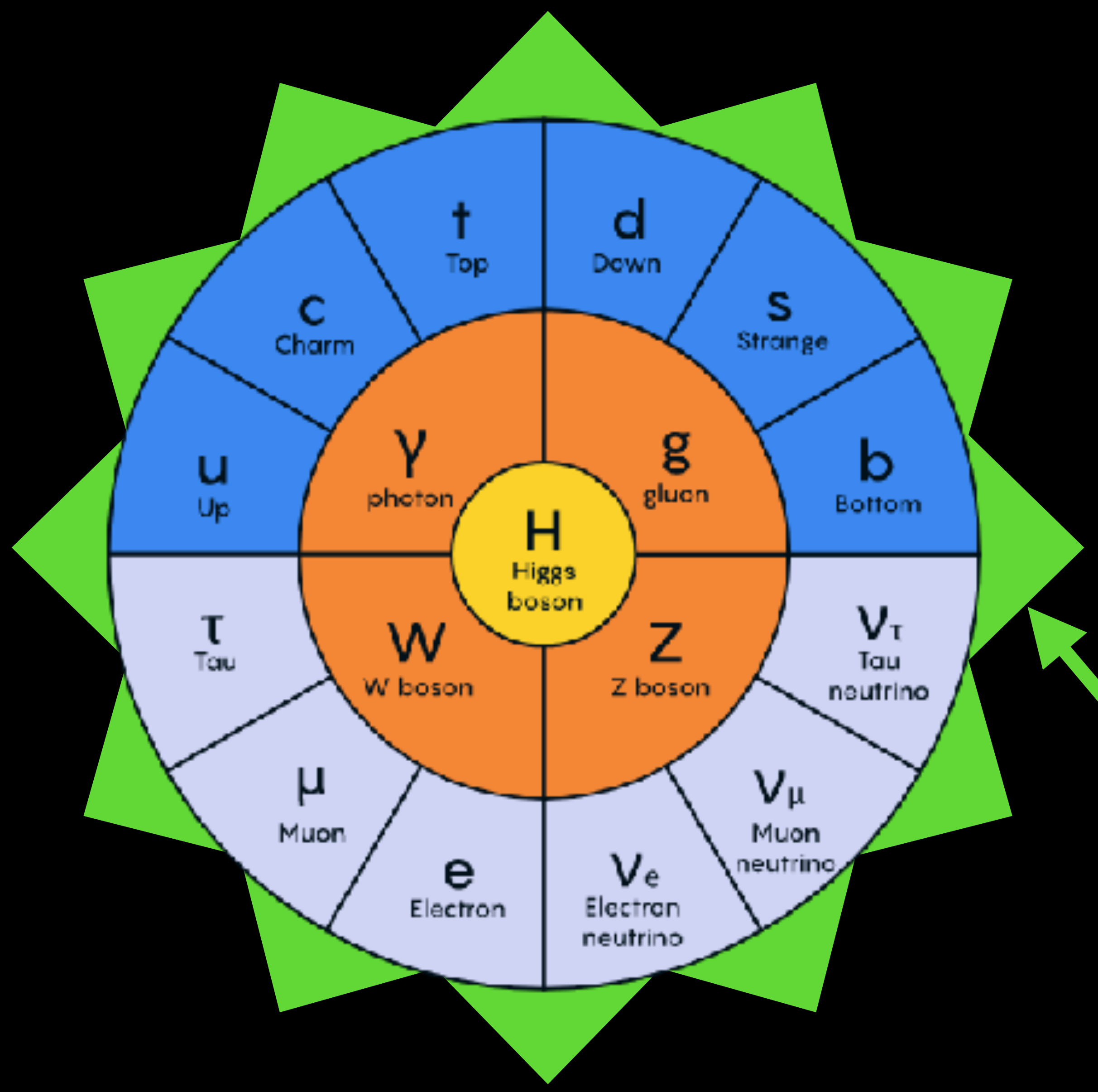
UvA

Beyond the Standard Model of particle physics

The Standard Model:



12 fundamental particles
and their interactions

Why these particles?

What is Dark Matter?

How can we understand the
matter-antimatter asymmetry?

?

So new theories are proposed, that
have to be tested in experiments.

Since Higgs discovery (2012),
some hints for new physics,
but no breakthrough

Search for new physics in future experiments at even larger colliders, at even higher energies…

… but also at low energy and small scale through a precision measurement of the electron!

The electron’s electric dipole moment (eEDM)

Besides the magnetic dipole moment (spin), the electron could have an *electric dipole moment (eEDM).*

This violates time-reversal violation.

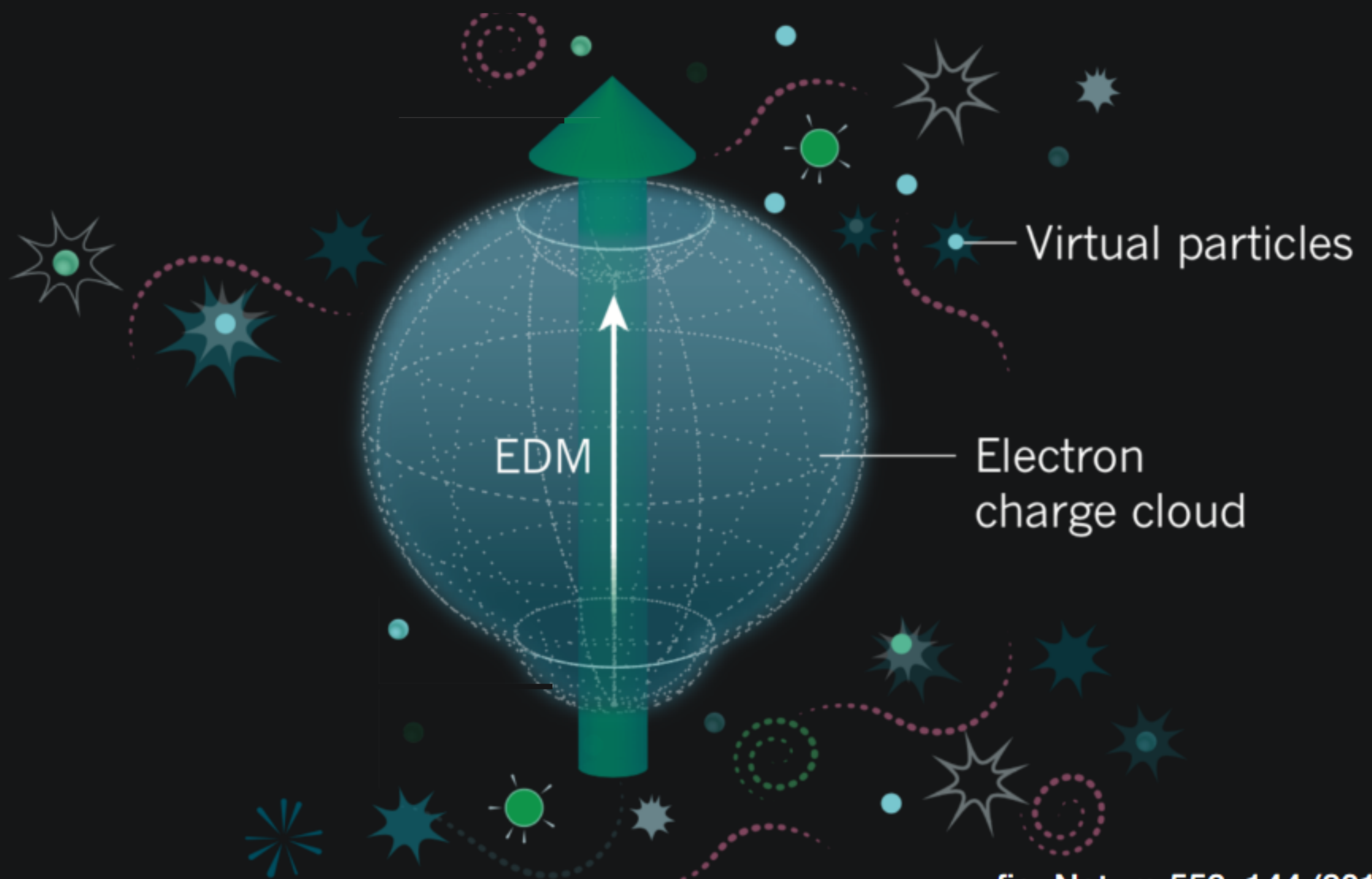
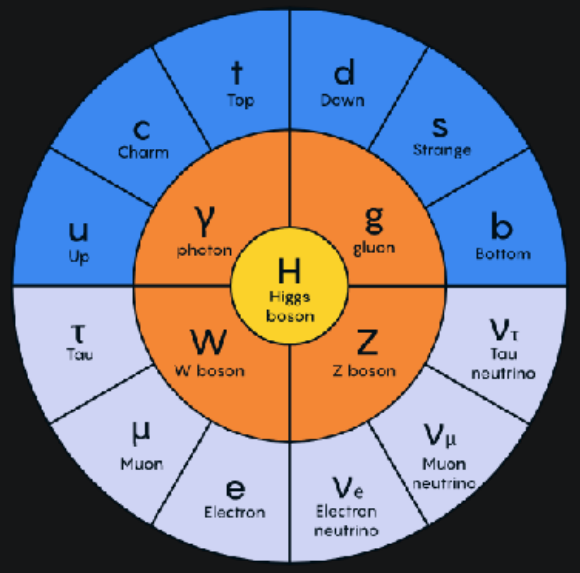
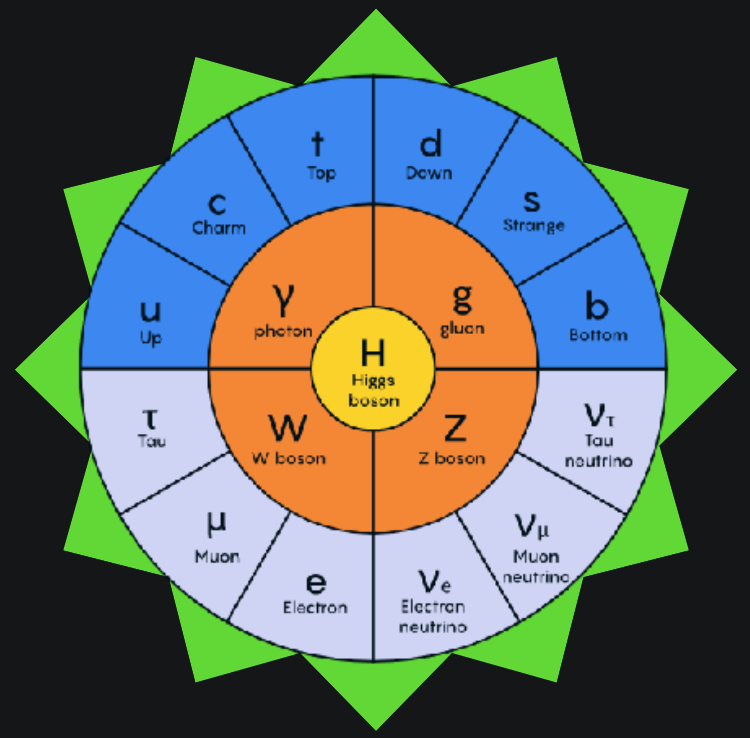


fig: Nature 553, 144 (2018)



The Standard Model:
the eEDM is tiny, not measurable
($\sim 10^{-40}$ e.cm)

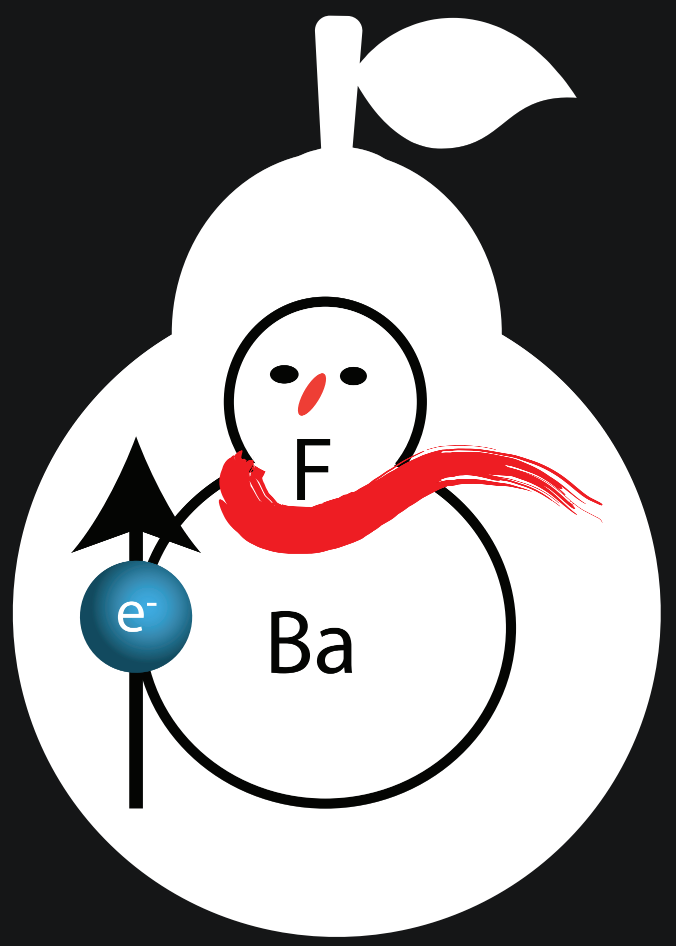


New theories:
the eEDM is small but measurable!
($\sim 10^{-30}$ e.cm)

10 orders of magnitude difference!

We test time-reversal violation and probe physics beyond the Standard Model through a precision measurement of the electron’s EDM.

Observation of eEDM hugely enhanced in a molecule: Barium monofluoride (BaF)



Think different!

Particle physics

Traditional approach: CERN

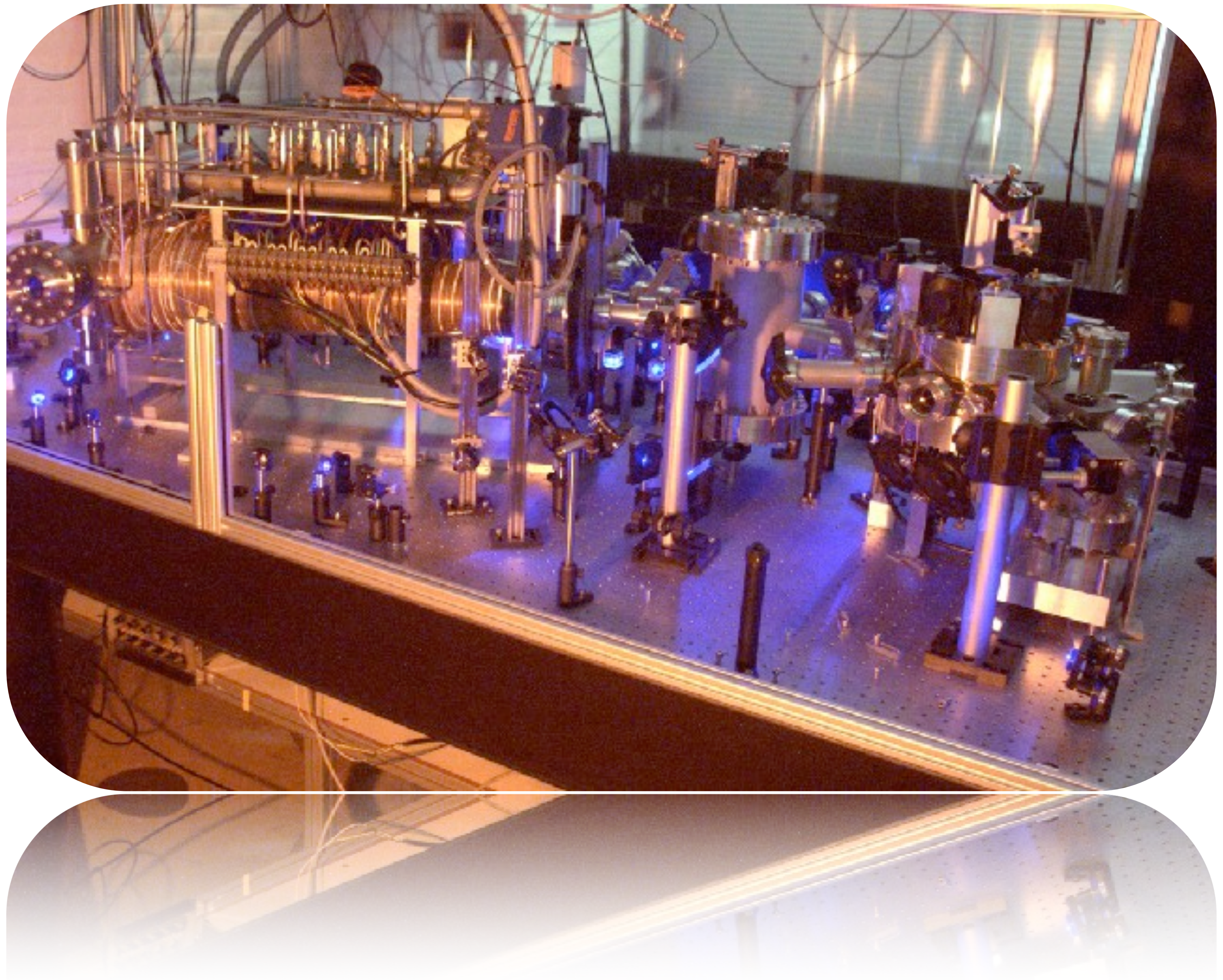
Colliding protons at high energies, studying fragments

Particle physics
Traditional approach

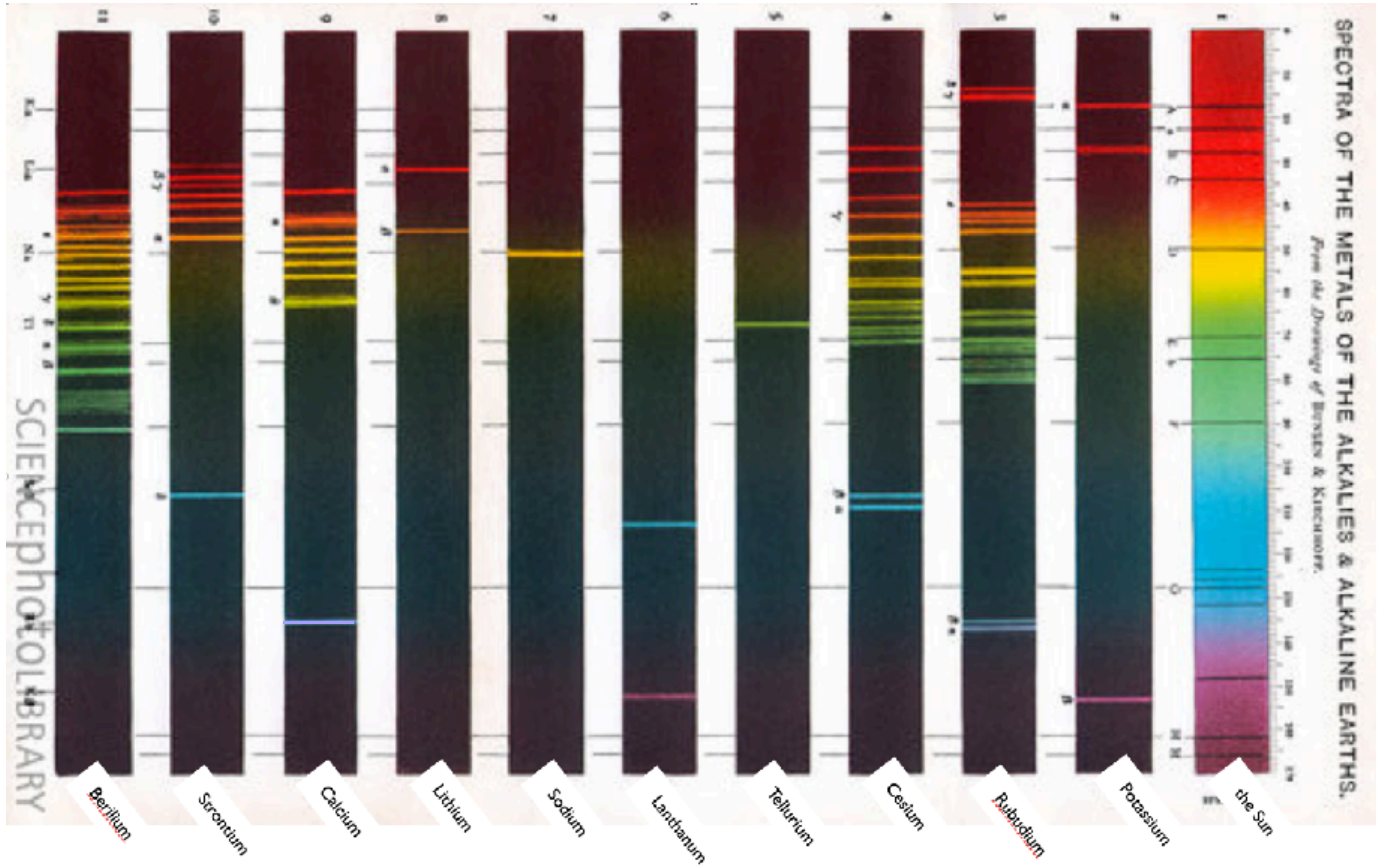
big questions, big machines and big collaborations

Table-top particle physics

Complementary approach: precision measurements on atoms



Magneto-optical trapping of Calcium atoms, for isotope separation



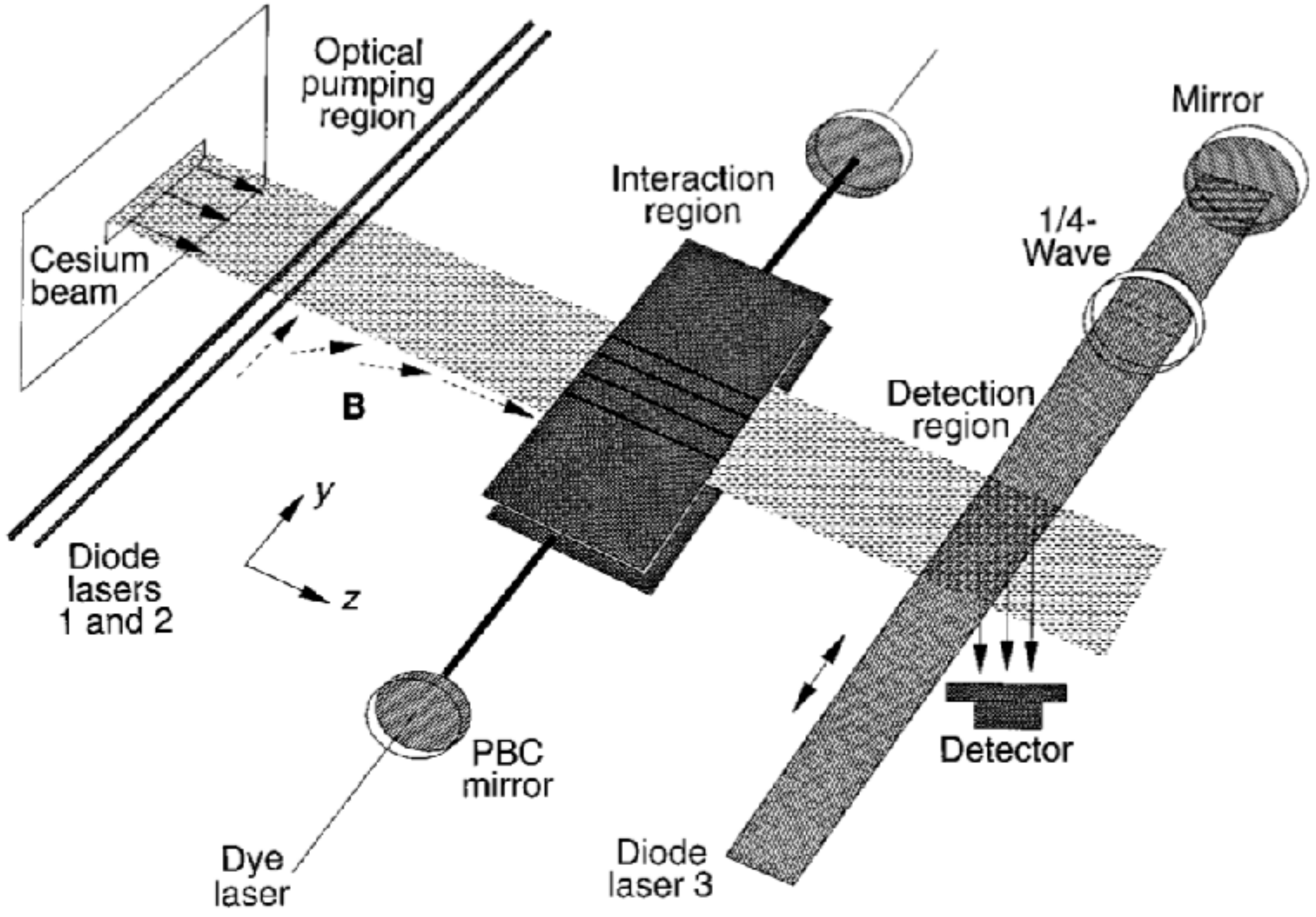
Simple idea: measure quantum structure and compare to theory

Using advances of laser technology, and control over atoms and molecules

Precision measurements with atoms

Quantum systems with an advantage

Example 1: Parity non-conservation



Measurement of Parity Nonconservation and an Anapole Moment in Cesium
C Wood, S Bennett, D Cho, B Masterson, J Roberts, C Tanner, and C Wieman.
Science, **275,** 1759 (1997)

PRL **102,** 181601 (2009) PHYSICAL RE

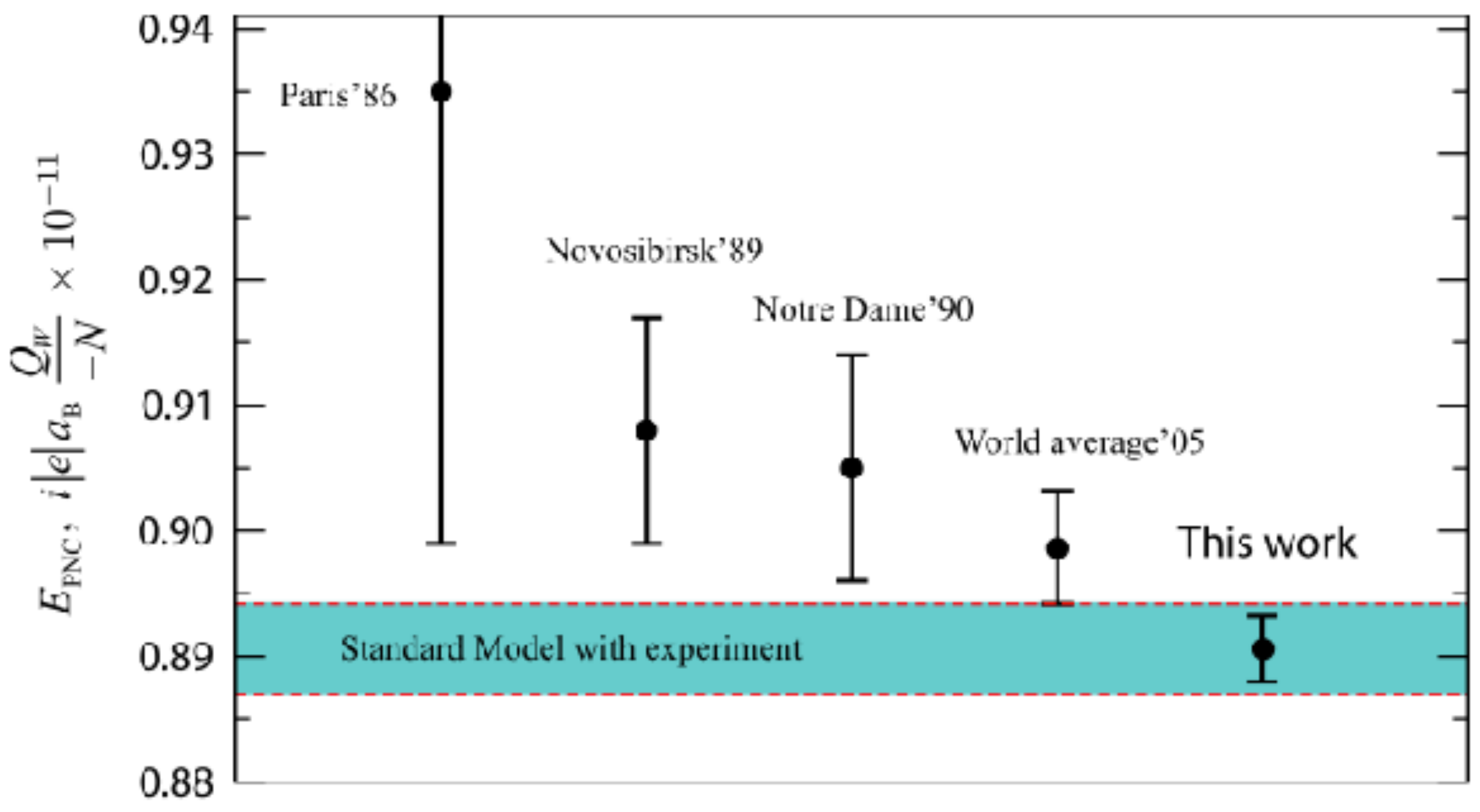


FIG. 1 (color online). Progress in evaluating the PNC amplitude. Points marked Paris '86, Novosibirsk '89, Notre Dame '90 correspond to Refs. [10,11,31]. Point marked World average '05 is due to efforts of several groups [12–16] on sub-1% Breit, QED, and neutron-skin corrections reviewed in Ref. [17]. The strip corresponds to a combination of the standard model Q_W with measurements [3,4]. The edges of the strip correspond to $\pm\sigma$ of the measurement. Here we express E_{PNC} in conventional units of $i|e|a_B(-Q_W/N) \times 10^{-11}$, where e is the elementary charge and a_B is the Bohr radius. These units factor out a ratio of Q_W to its approximate value, $-N$.

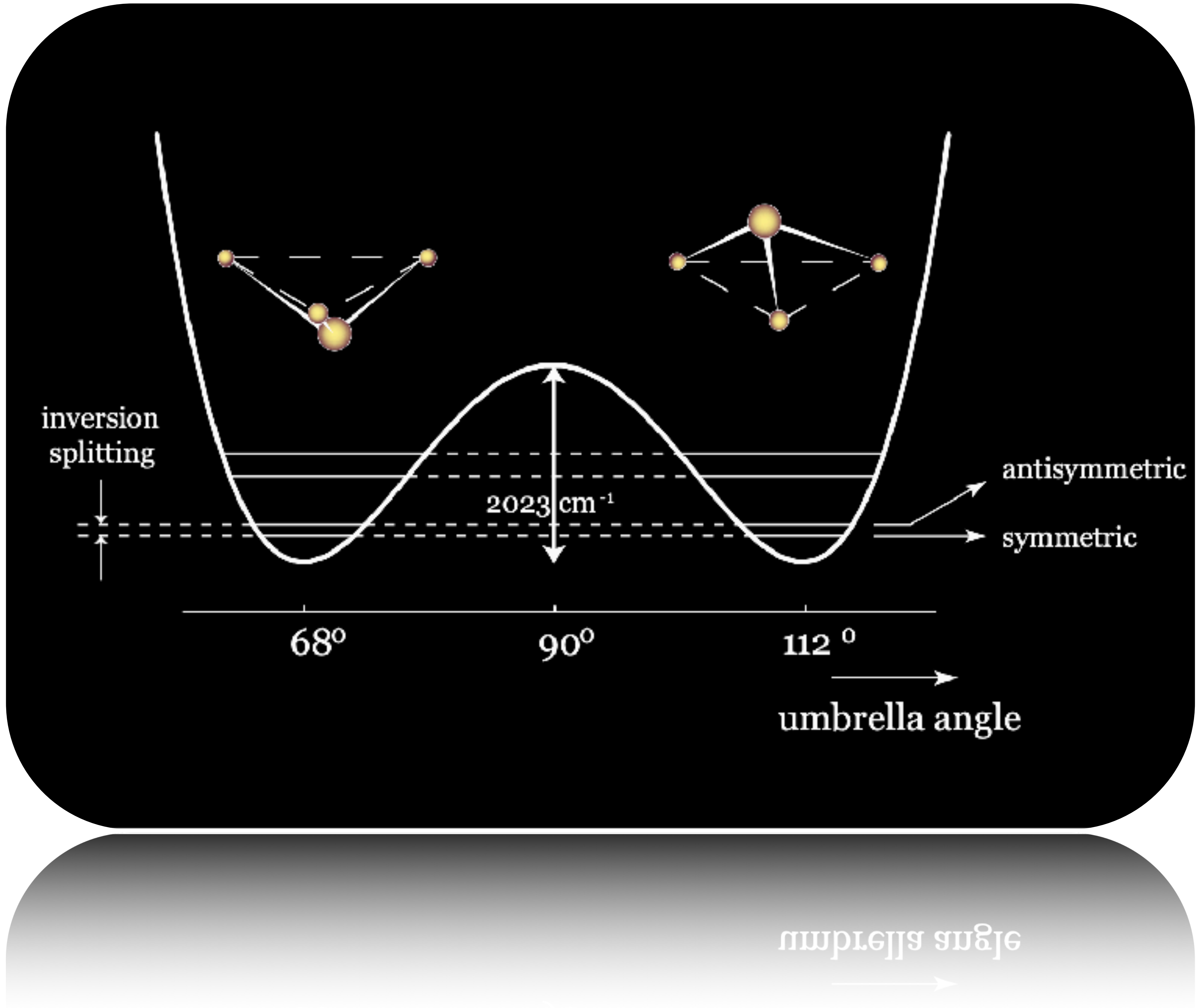
Experiment: beam of Cs atoms

Theory

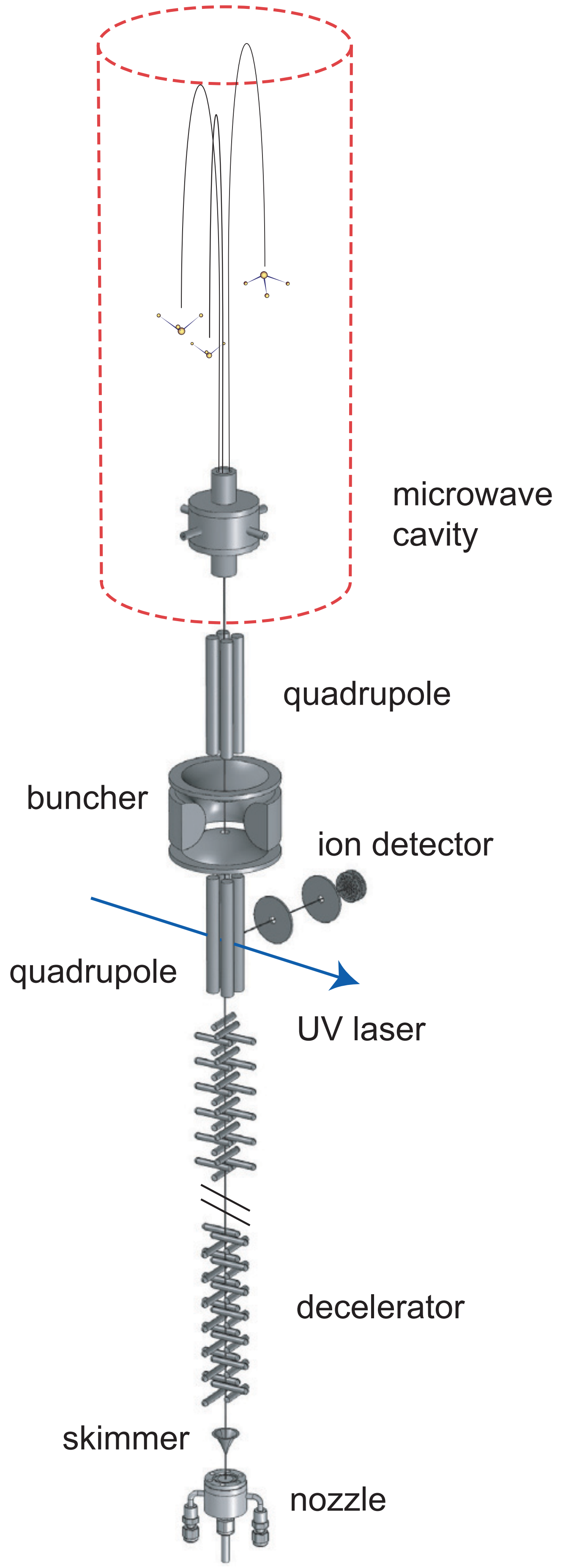
Precision measurements with molecules

Complex quantum systems with an advantage

Example 2: Variation of constants



Very sensitive to proton / electron mass ratio



proposed experiment

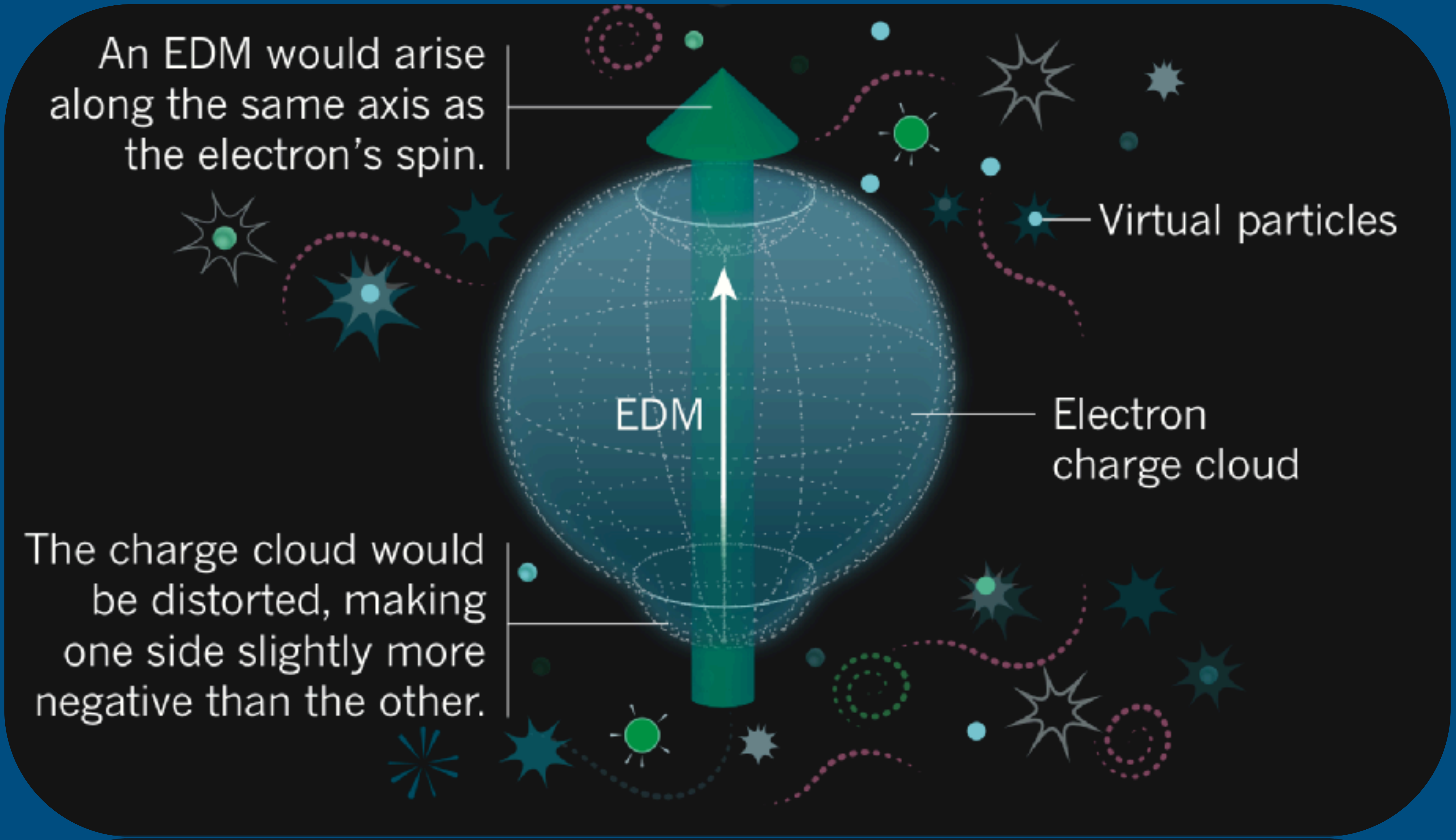
?

Theory

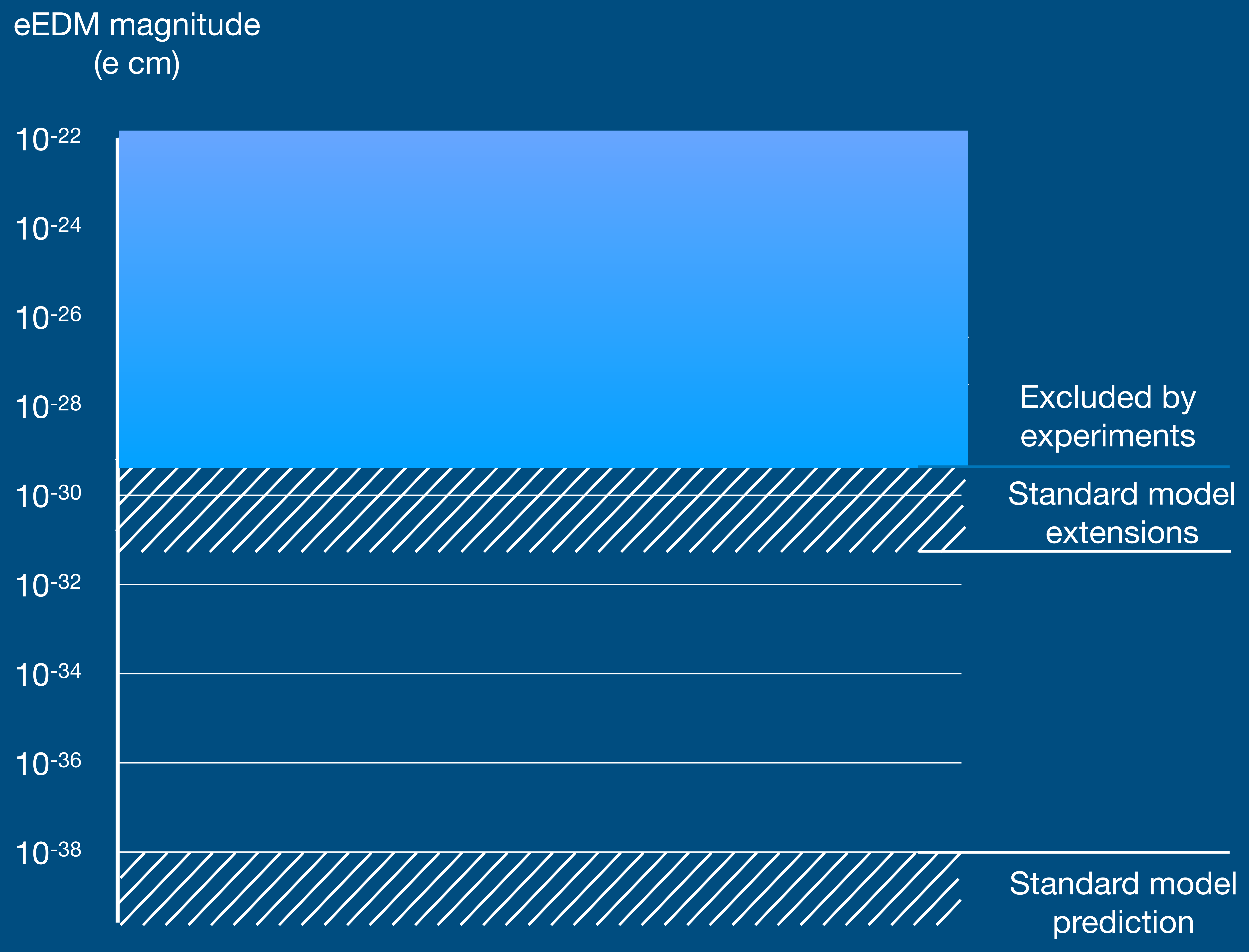
Precision measurements with molecules

Complex quantum systems with an advantage

Example 3: The electric dipole moment of the electron



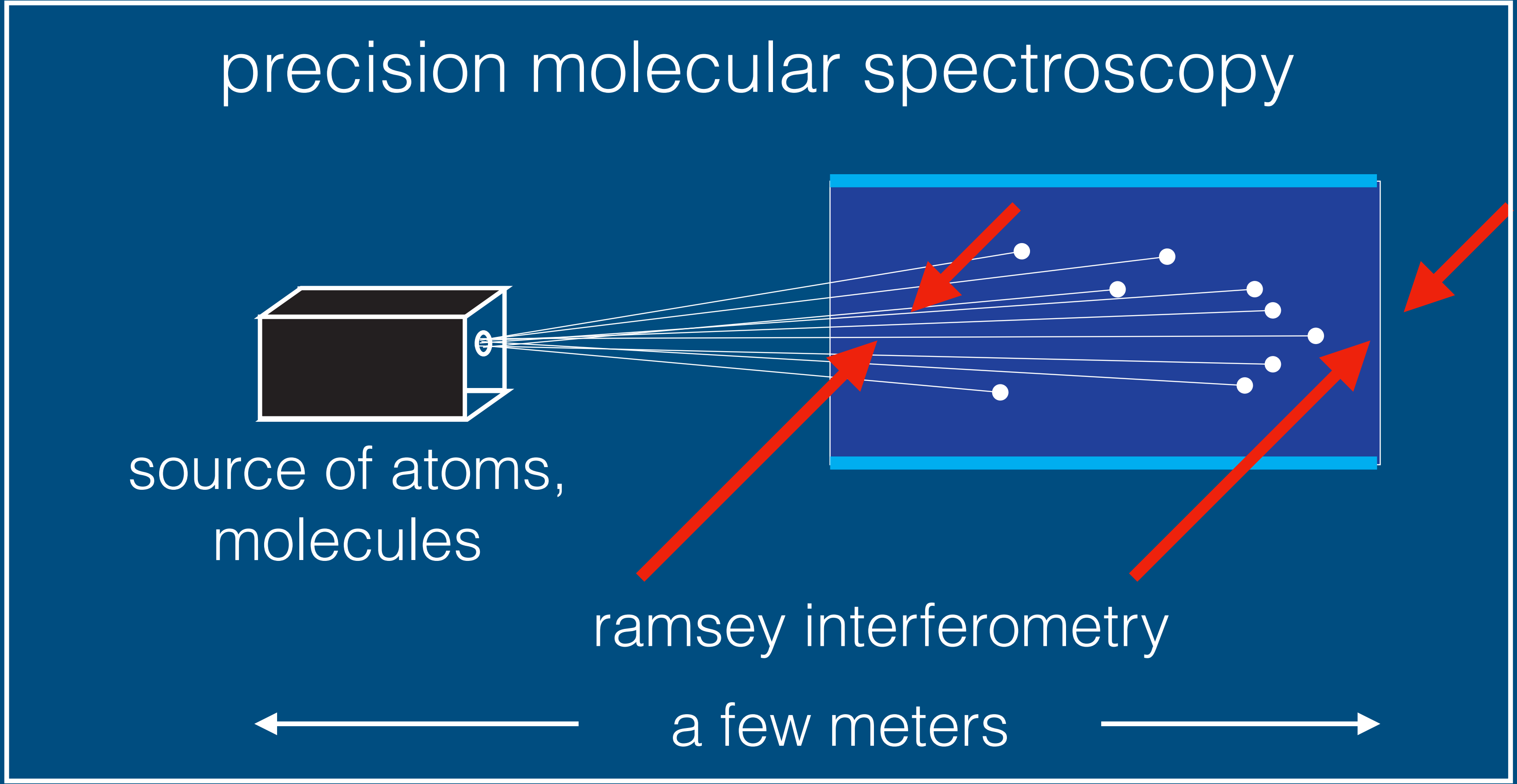
eEDM violates P, T and CP symmetry
(provided CPT holds)

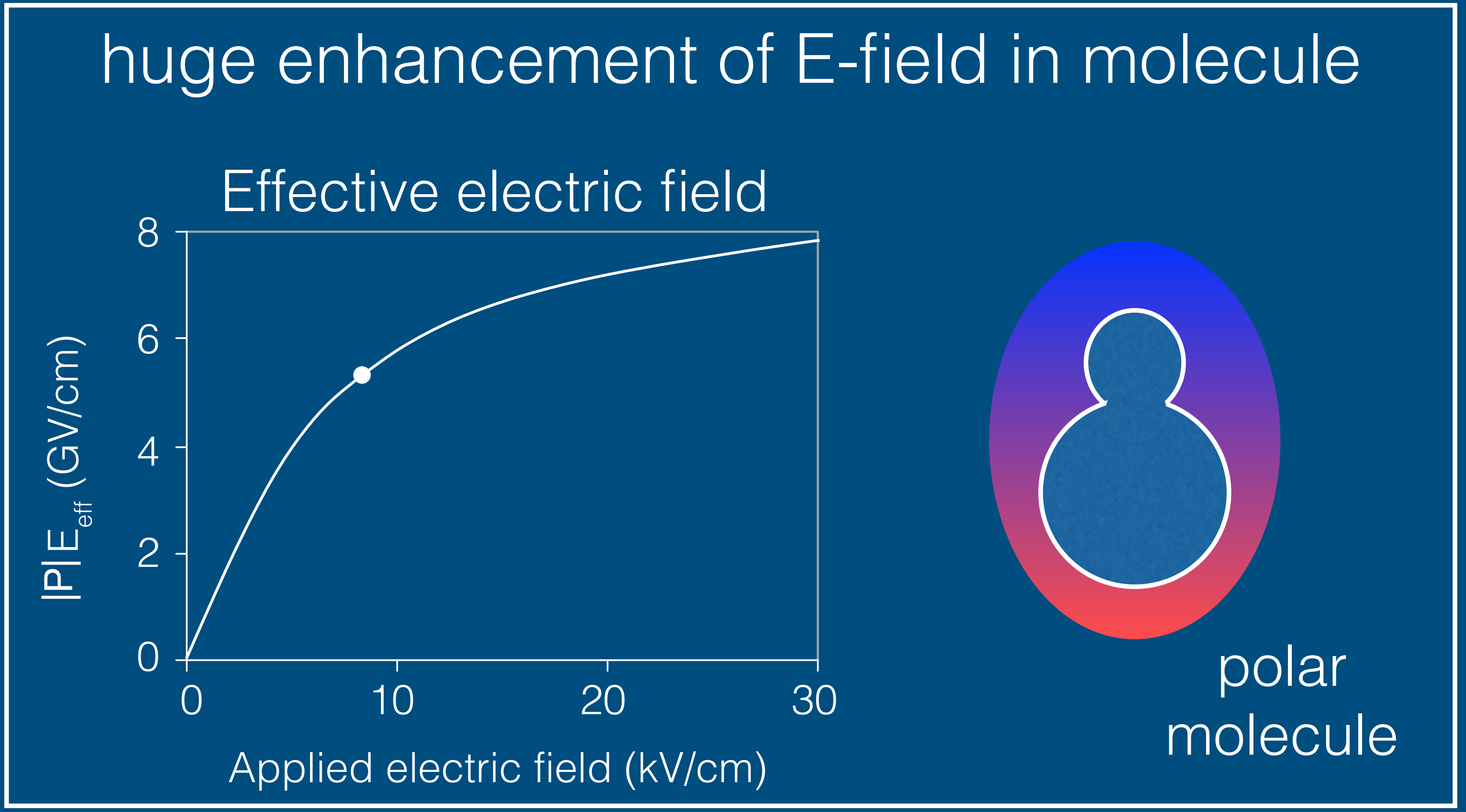


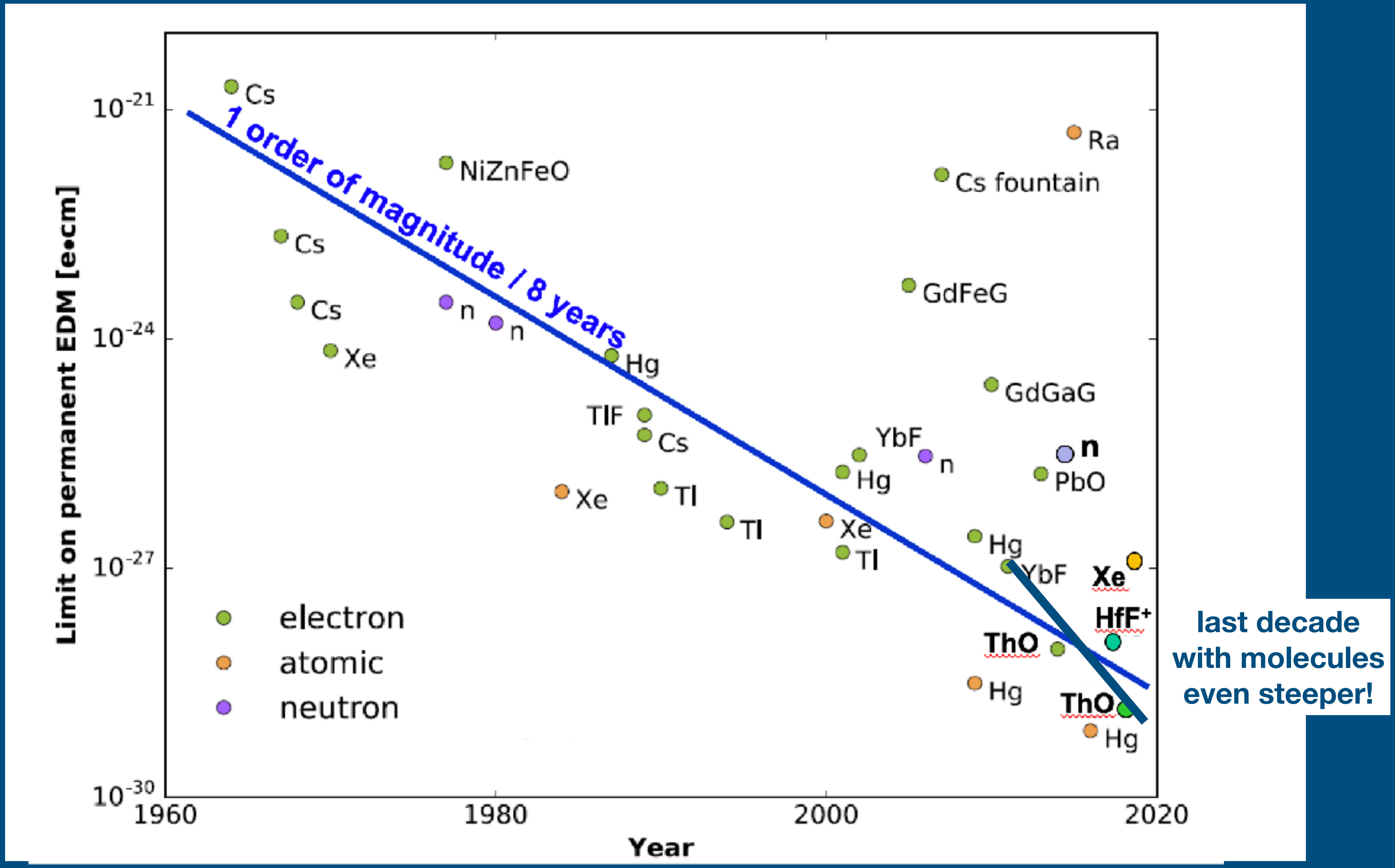
Precision measurements with molecules

Complex quantum systems with an advantage

Example 3: The electric dipole moment of the electron

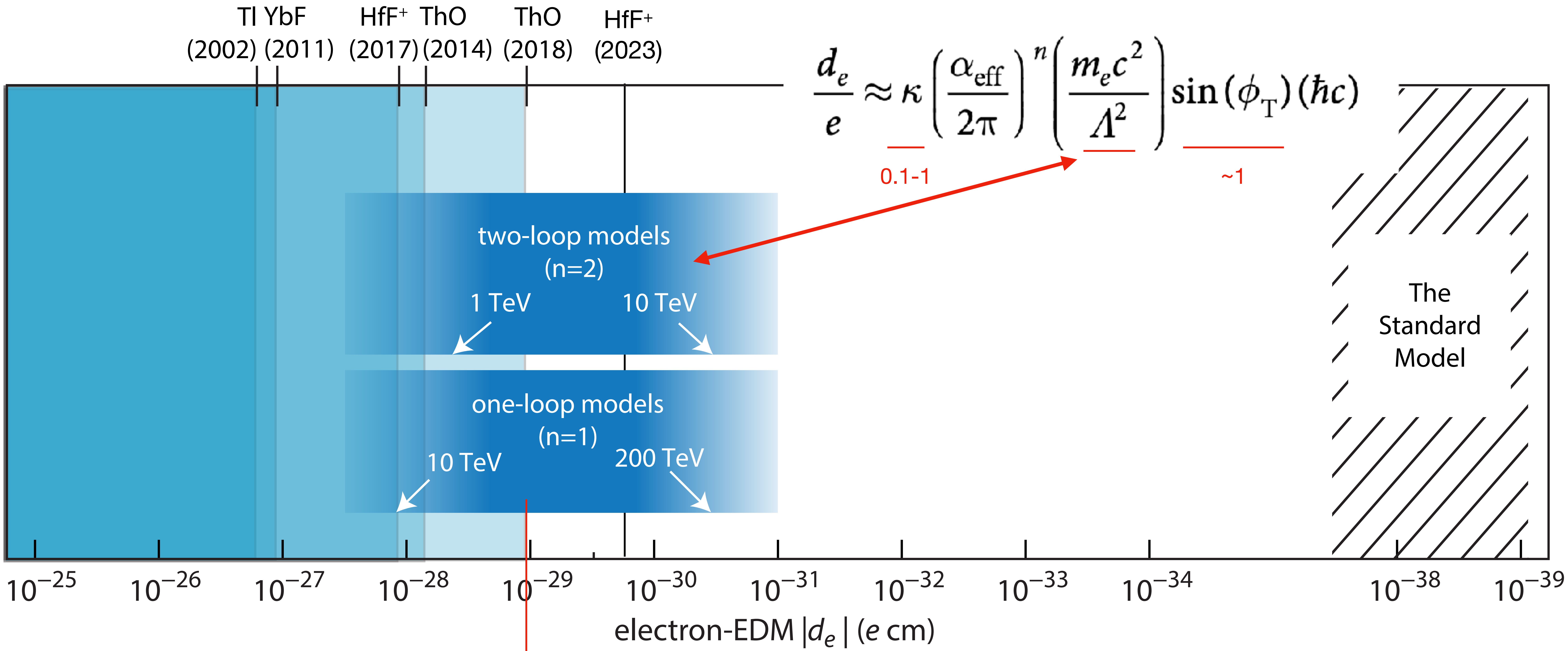






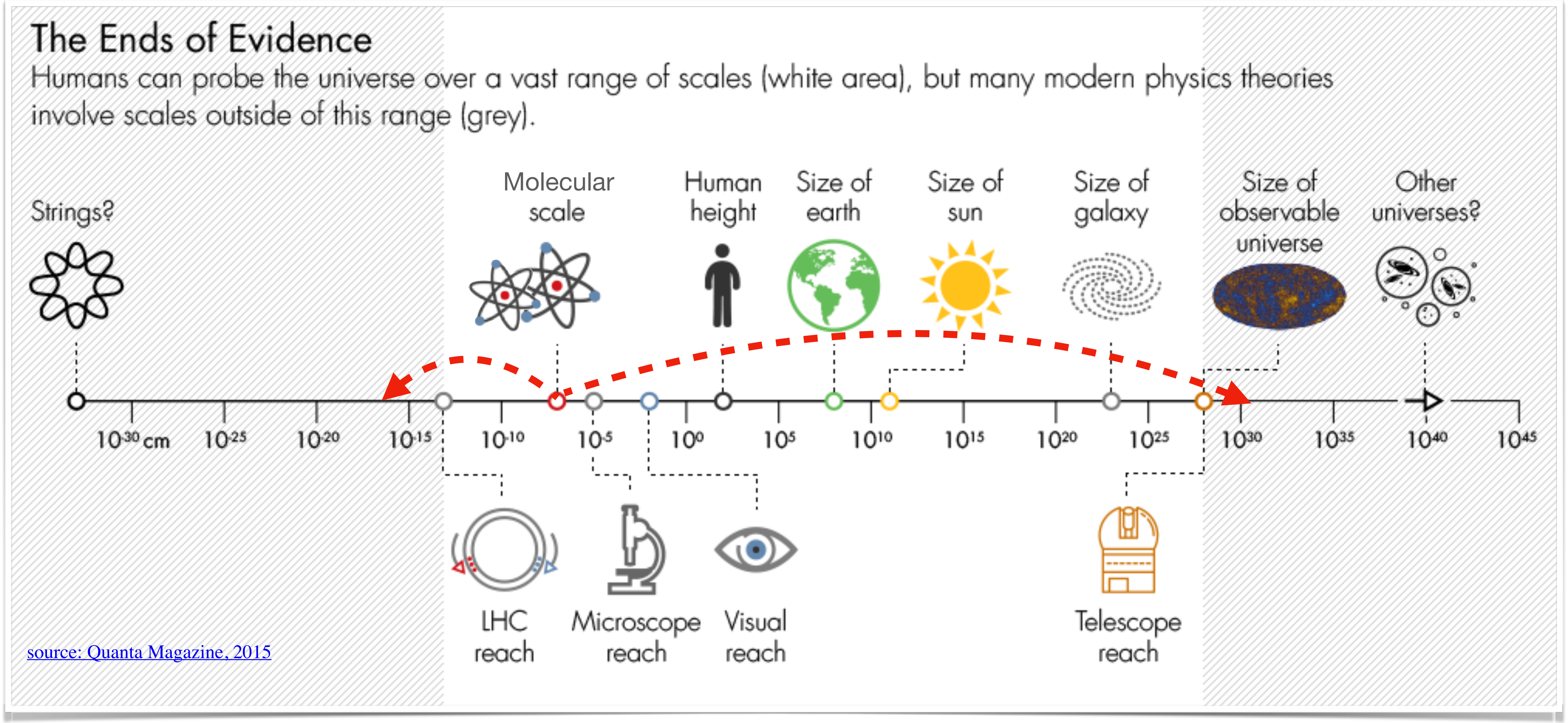
The electron's electric dipole moment (eEDM)

Effectively a background-free method to probe new physics



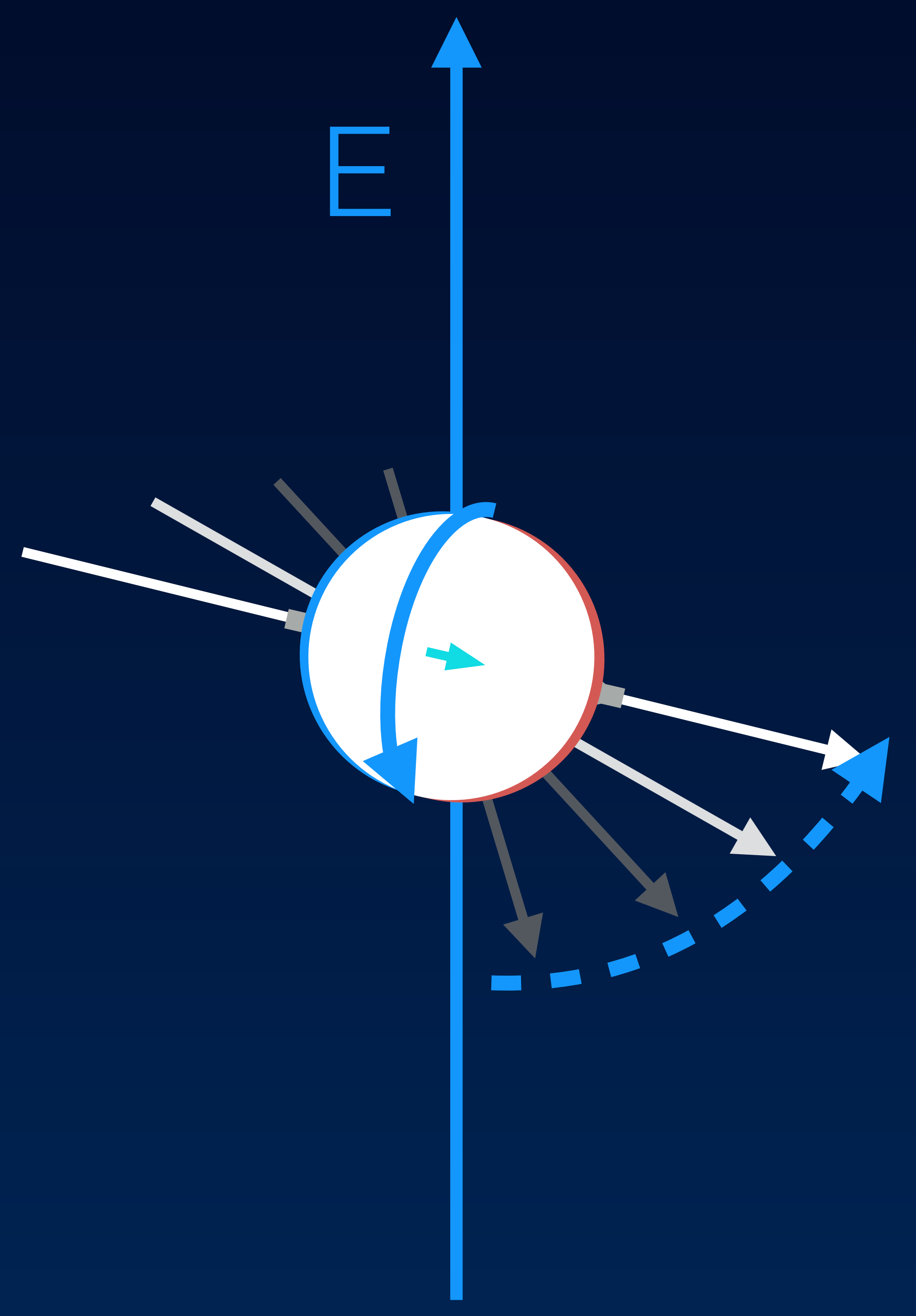
The ThO result limits time-reversal-symmetry-violating new physics to energy scales above Λ≈ 30 TeV or Λ≈ 3 TeV, for n=2 or 1, respectively

Motivation

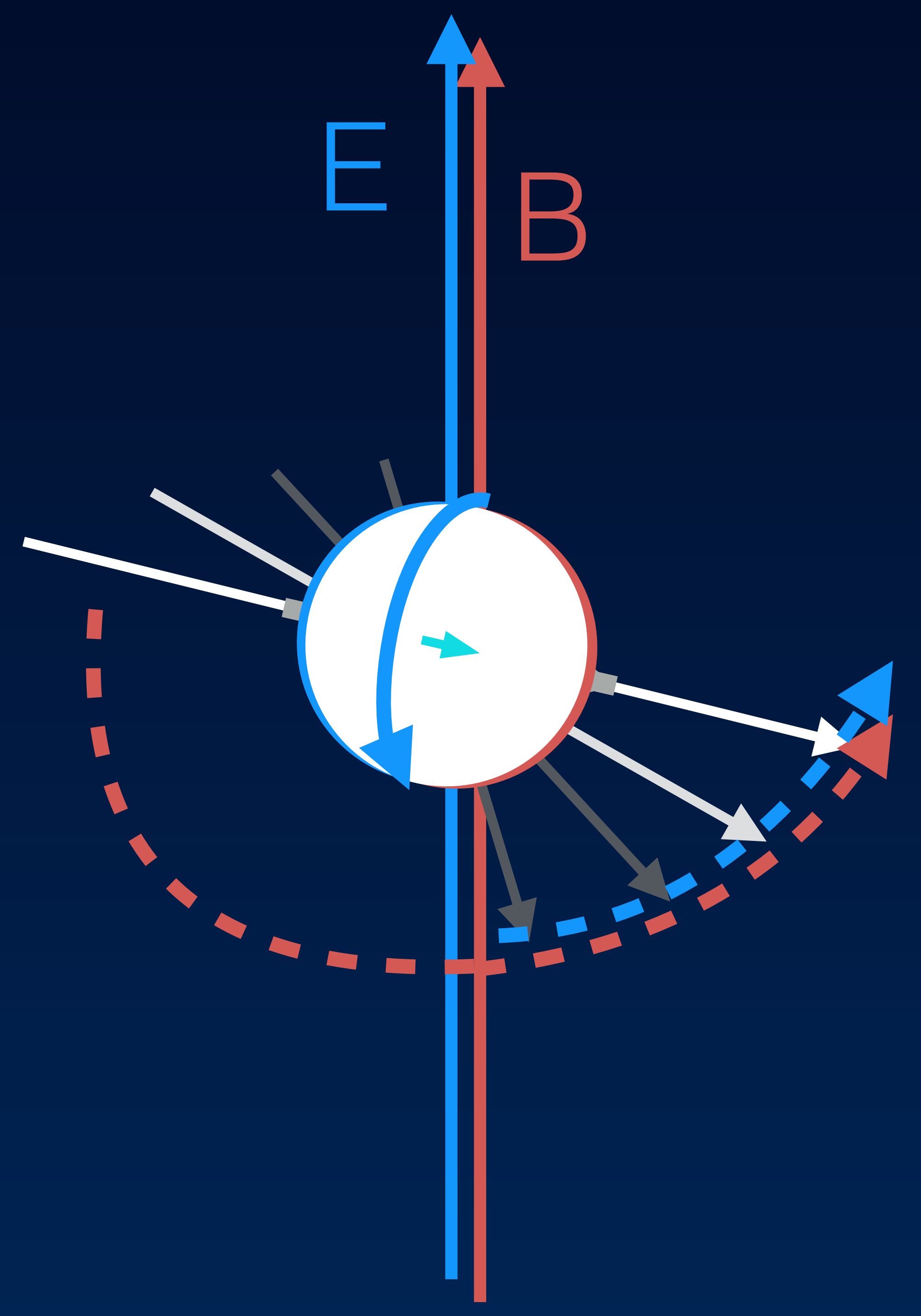


Molecules can be extremely sensitive quantum sensors for fundamental physics!

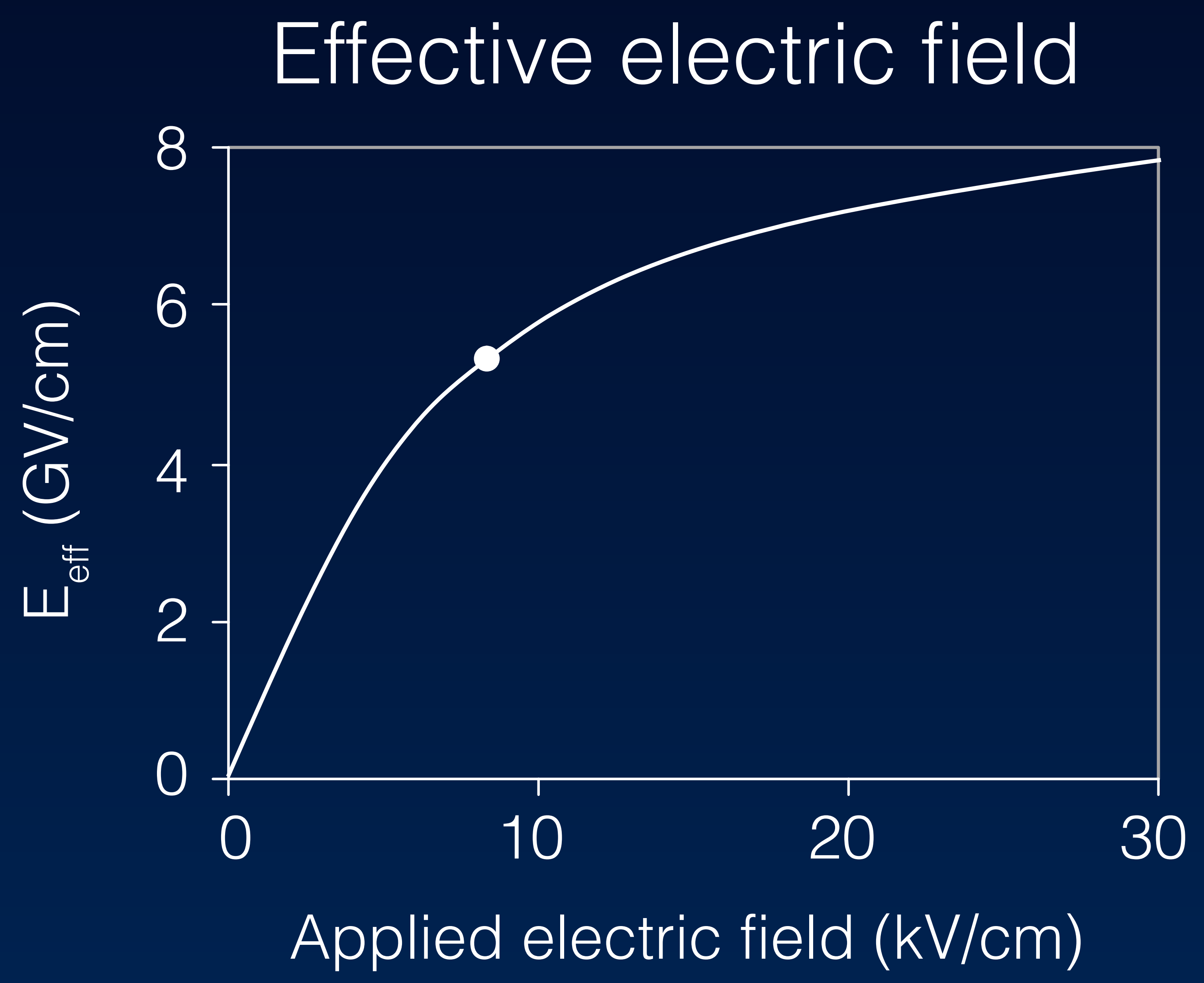
How to measure a dipole moment?



precession!



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



Solution:
use electron embedded in a polar molecule!

Enhances E
Shields B

Increasing the eEDM sensitivity

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

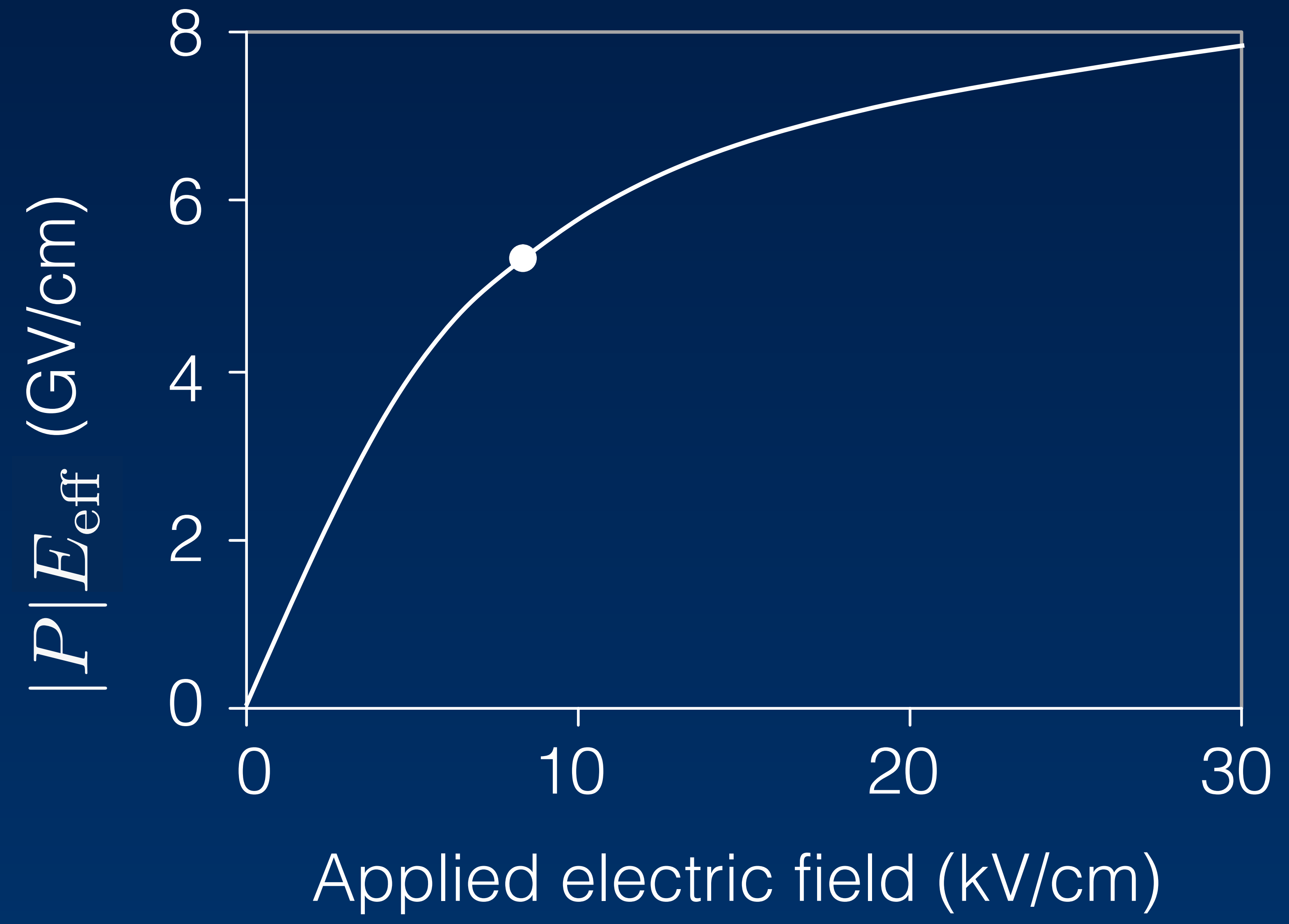
statistical error: $\sigma_d = \frac{\hbar}{e} \frac{1}{2|P|E_{\text{eff}}\tau\sqrt{\dot{N}T}}$

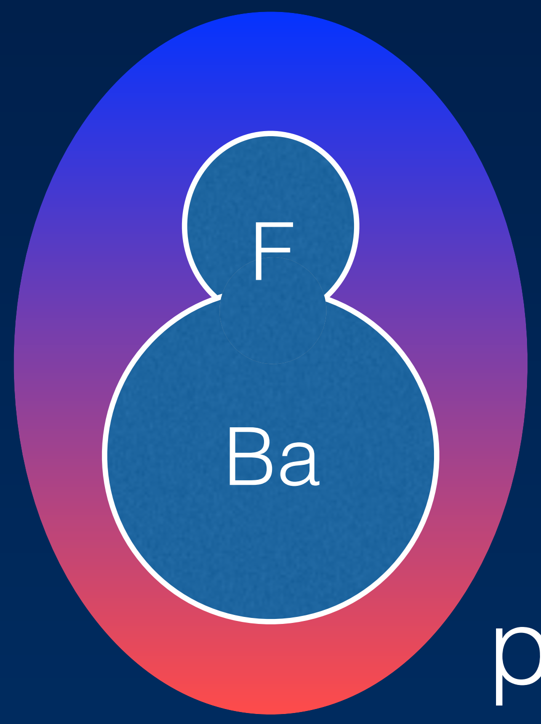
Cold Molecules

Number of detected molecules

Coherent interaction time

Effective electric field





polar molecule

Coherent interaction time

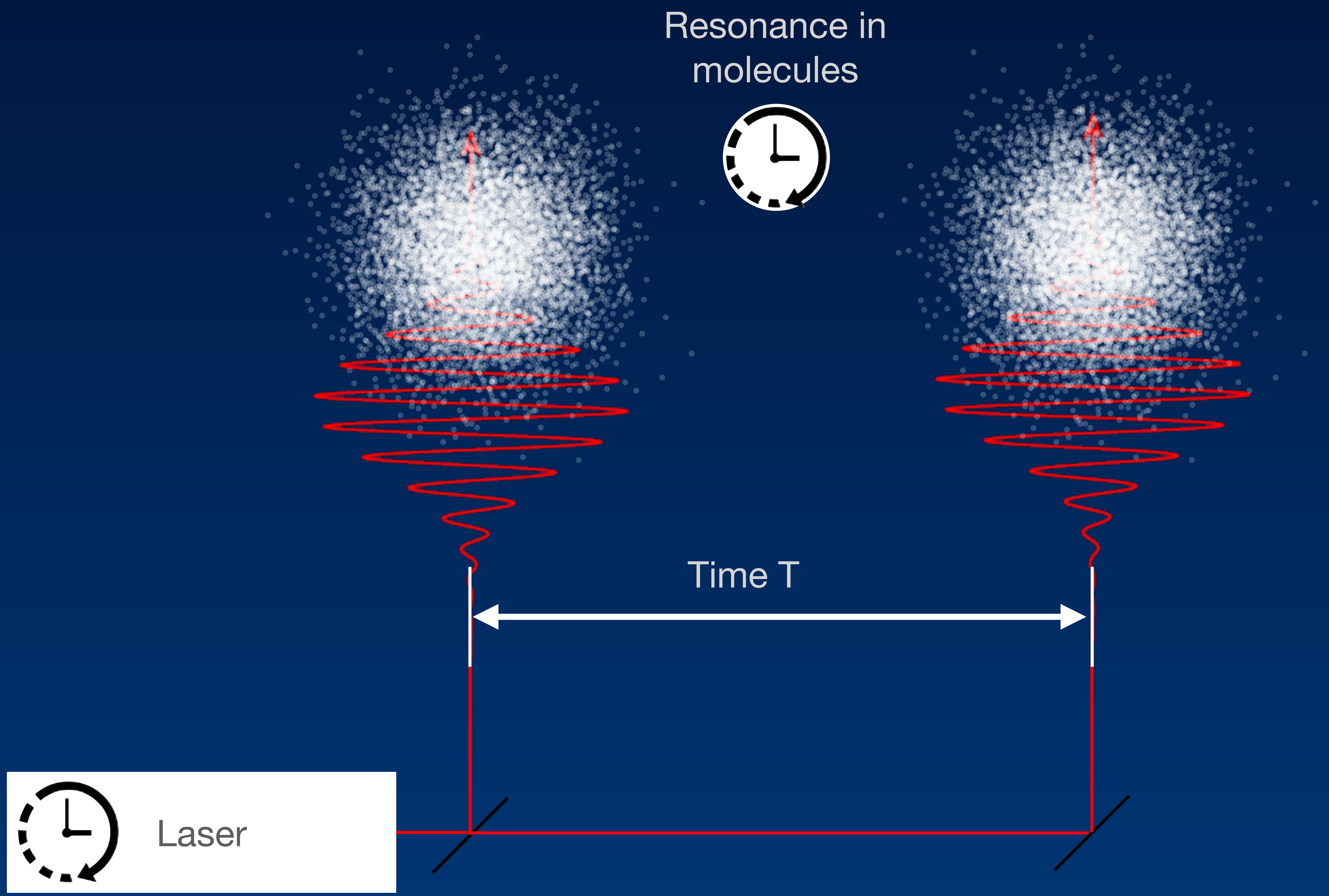
Key technique: Ramsey spin interferometer

laser pulse 1:

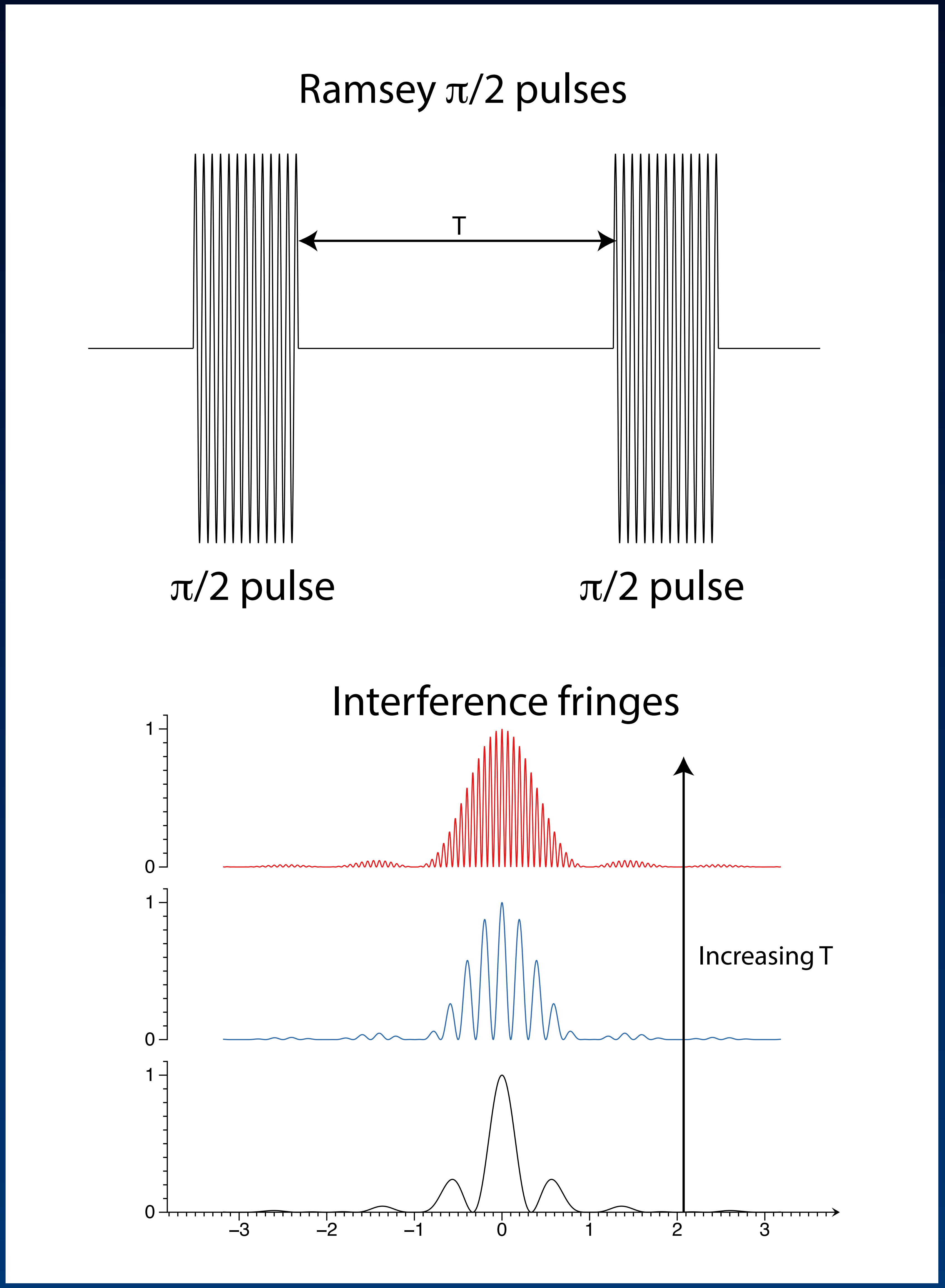
Creates a quantum superposition, creating coherent excitation of all molecules

laser pulse 2:

Measures state of the molecules through interference



Frequency set by external reference, tuned to molecular resonance



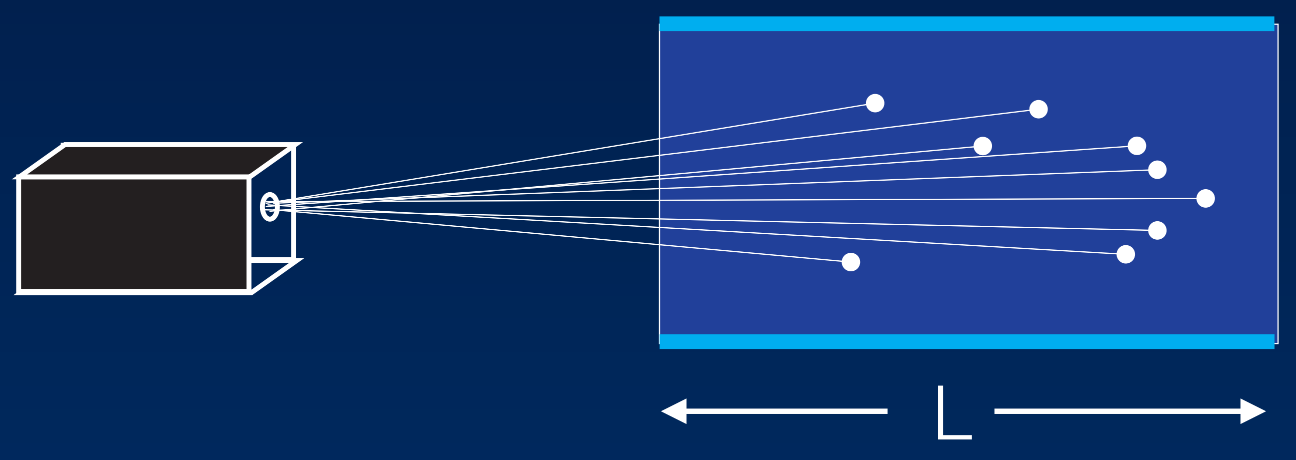
Towards longer coherent interaction times

fast beam

τ ~ 1-2 ms

L ~ 0.5 m

v ~ 250-500 m/s

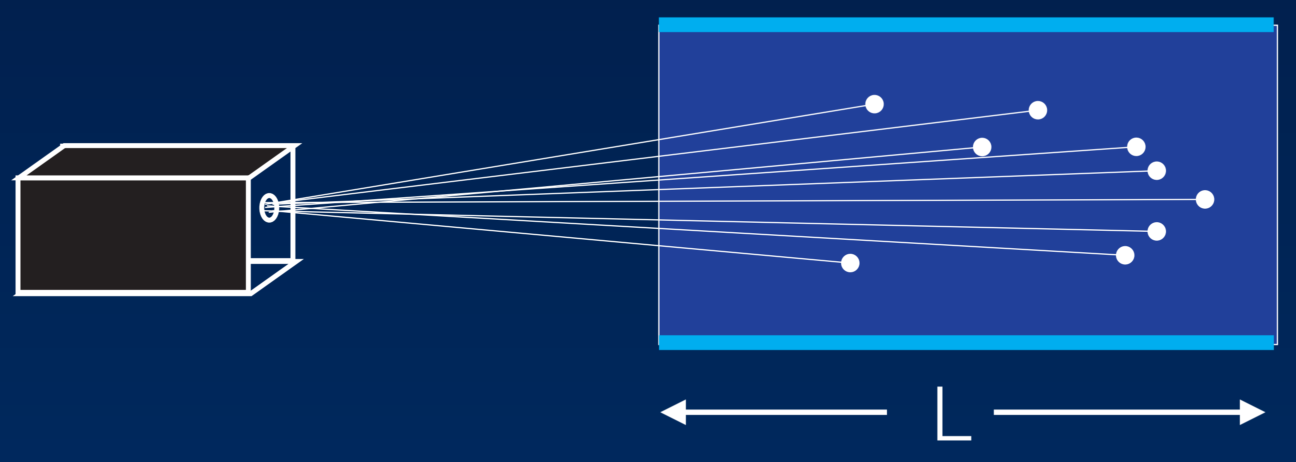


slow beam

τ ~ 15 ms

L ~ 0.5 m

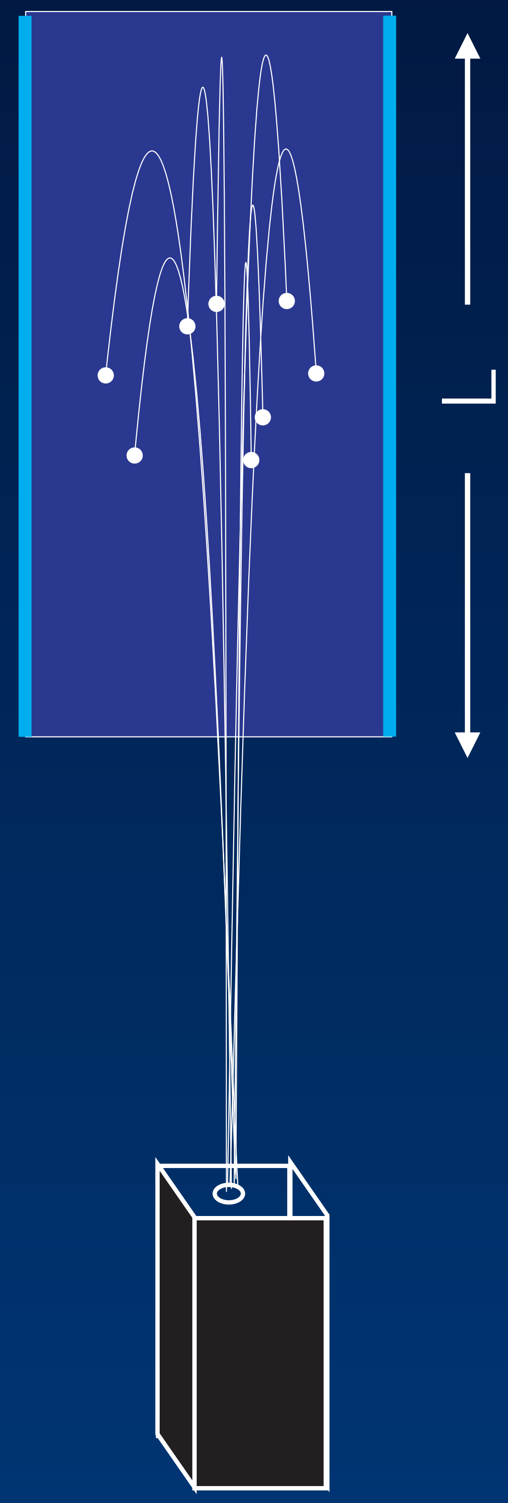
v ~ 30 m/s



fountain

τ ~ 100 ms

L ~ 0.5 m

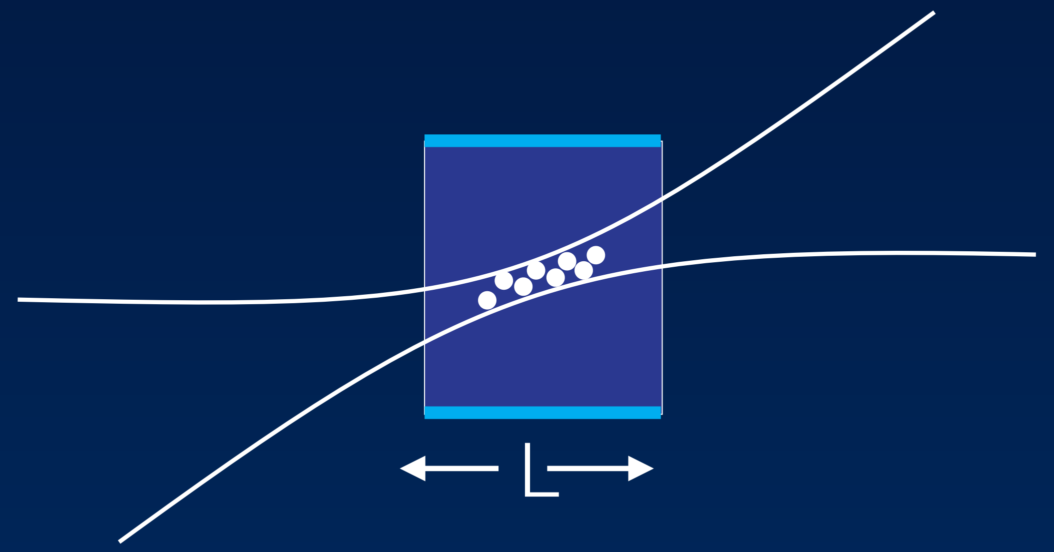


slow vertical beam

trap

τ ~ 1-10 s

L ~ 0.5 mm

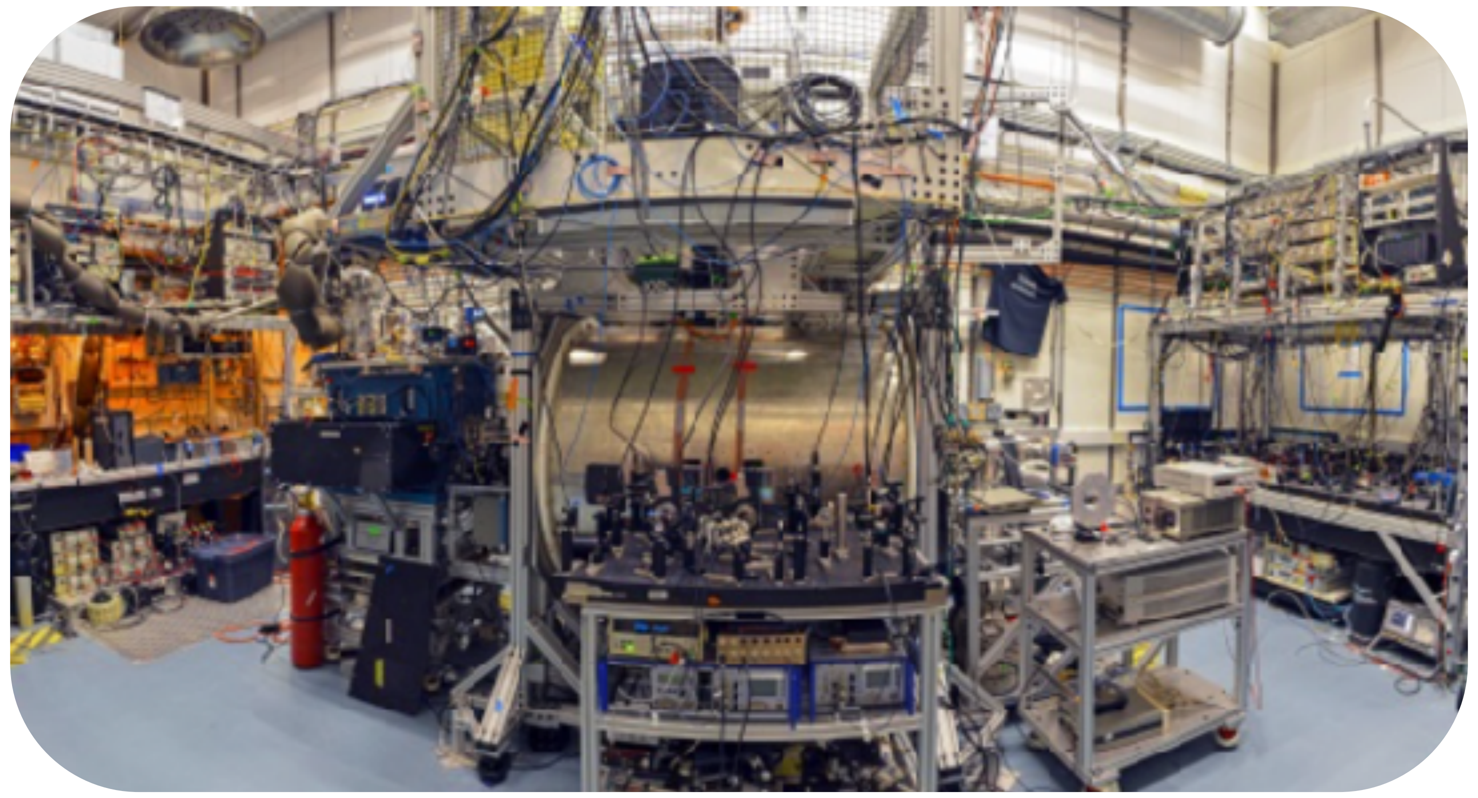


molecules trapped in laser focus

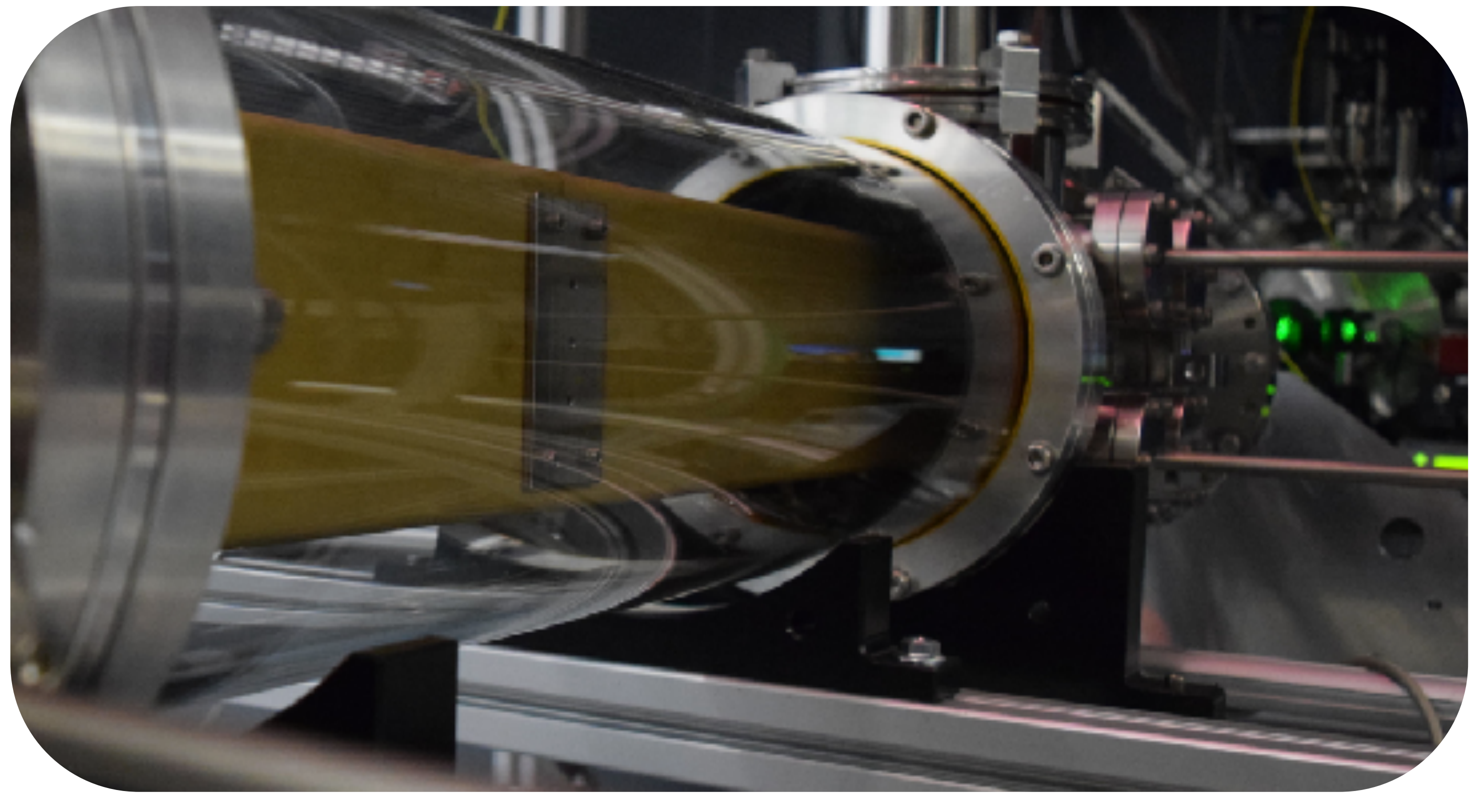
Main challenge:
how to maintain N while increasing t

Strongly connected to choice of molecule!

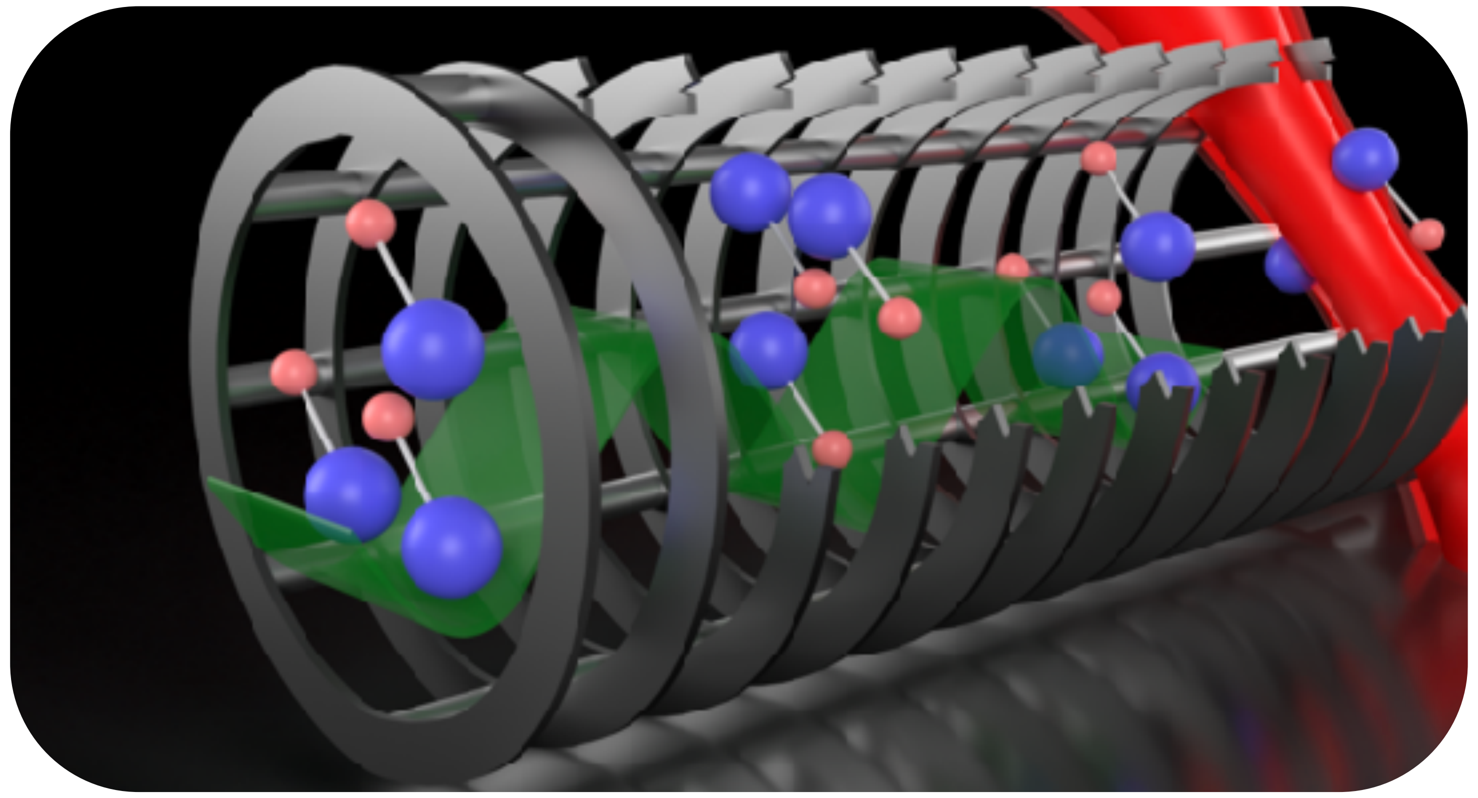
eEDM experiments using molecules



ACME - beam of ThO molecules
John Doyle, David DeMille,
Gerald Gabrielse

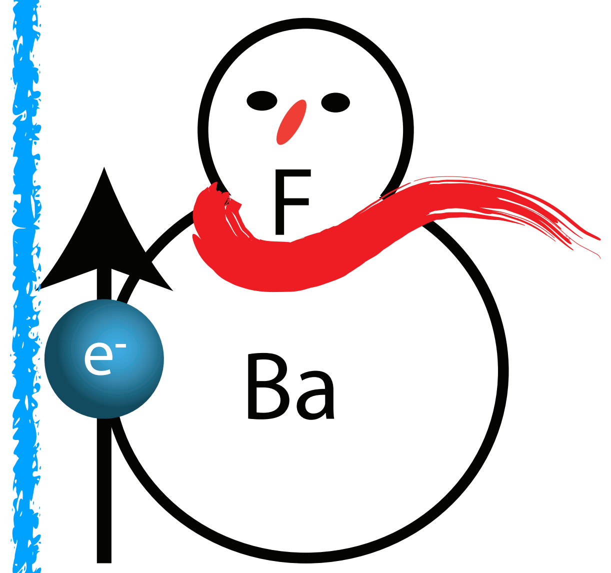


Imperial College London - beam of YbF molecules
Mike Tarbutt, Ben Sauer, Ed Hinds



JILA - trapped HfF^+ ions
Eric Cornell, Jun Ye

Others are being set up:



Decelerated BaF beam experiment in Groningen, The Netherlands since 2018 (NL-eEDM)

Search for eEDM in cryogenic crystals

PHYDES:
Para-Hydrogen and Diatomic for eEDM Study

Università degli Studi di Ferrara

INFN Istituto Nazionale di Fisica Nucleare

Electric Dipole Measurements using Molecules within a Matrix

- York University
- Michigan State University
- University of Toronto

YORK UNIVERSITÉ UNIVERSITY

MICHIGAN STATE UNIVERSITY

UNIVERSITY OF TORONTO

EDM³ Collaboration

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university of groningen

Key ingredients of our approach

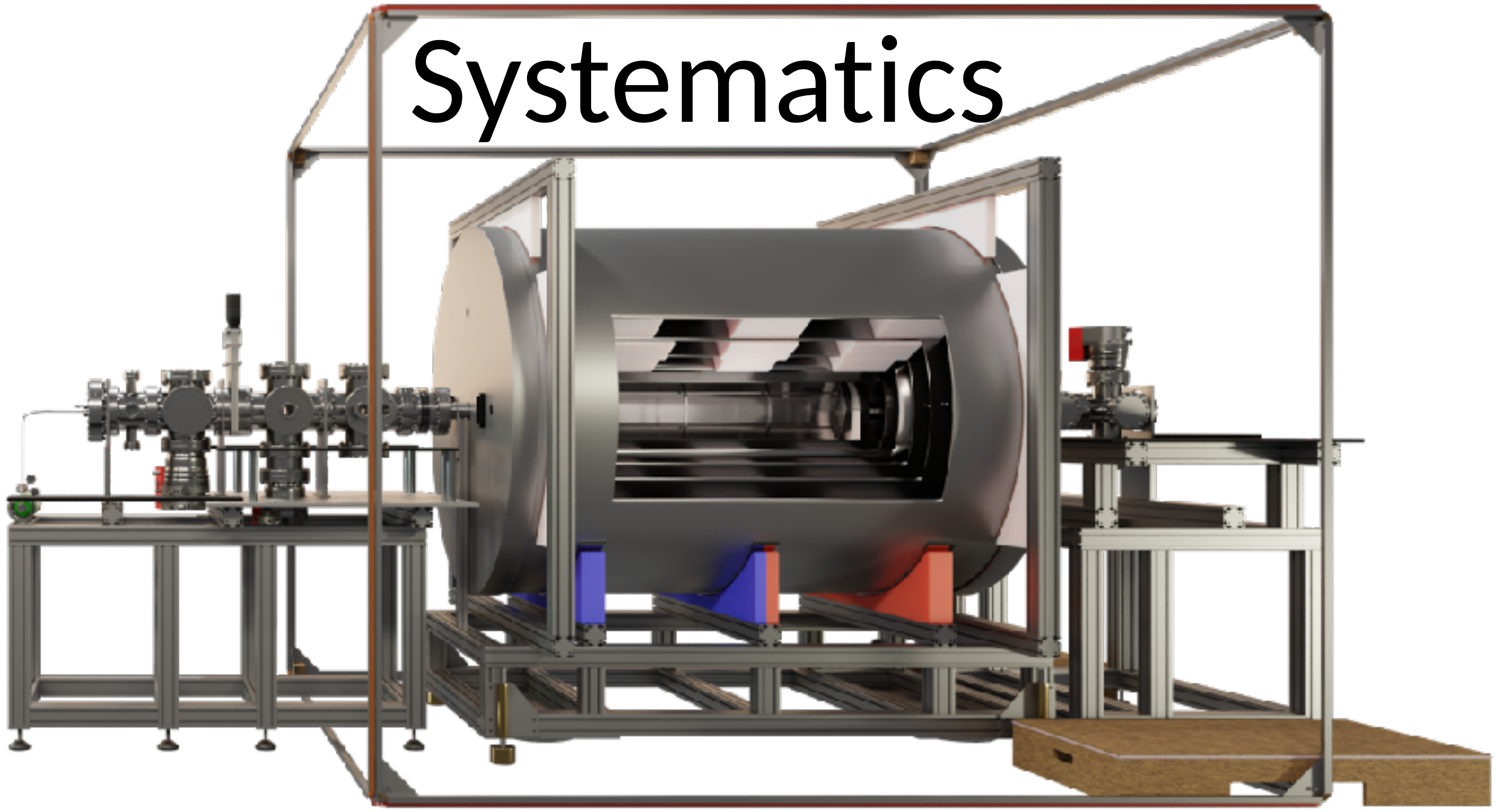
Fast beam

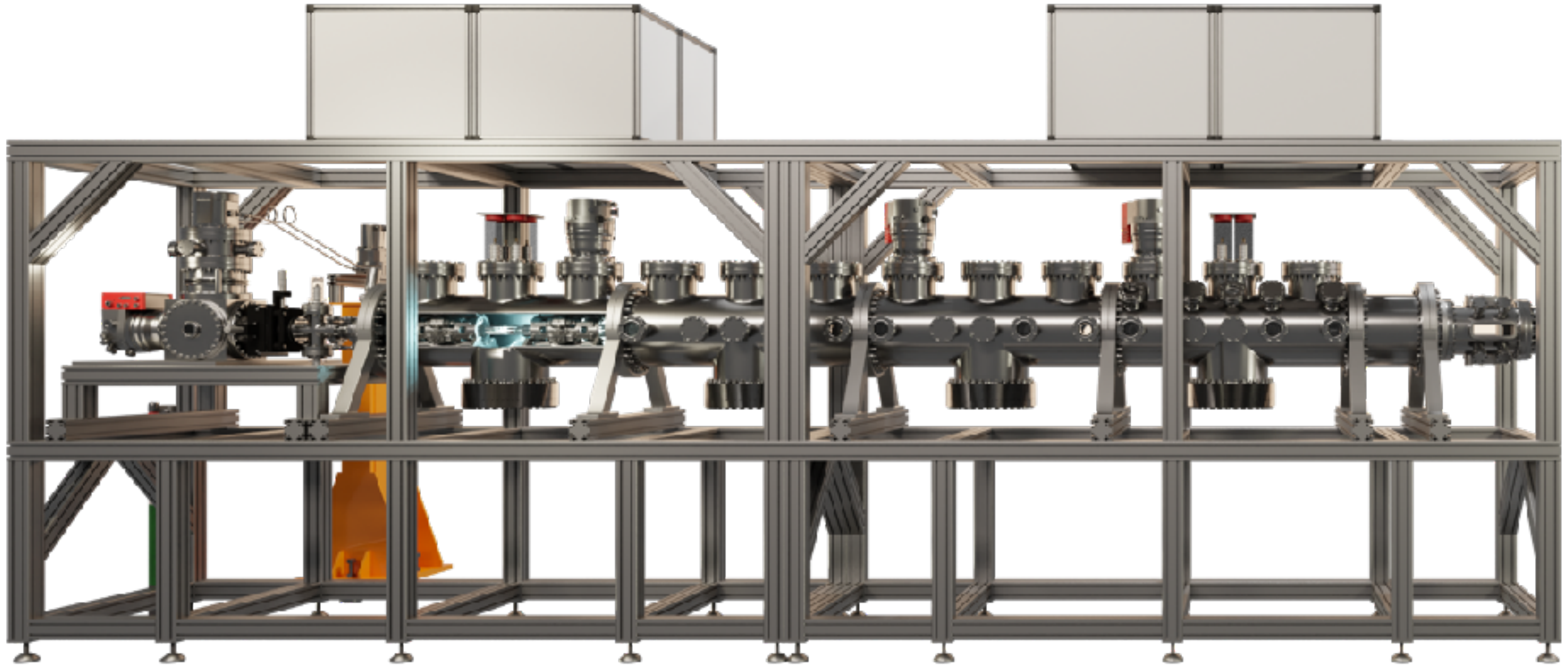
Supersonic beam (600 m/s)

Controlled field environment

Explored molecular structure

Spin interferometer measurement





Statistics

Slow beam

Cryogenic beam (200 m/s)

Stark decelerator (30 m/s)

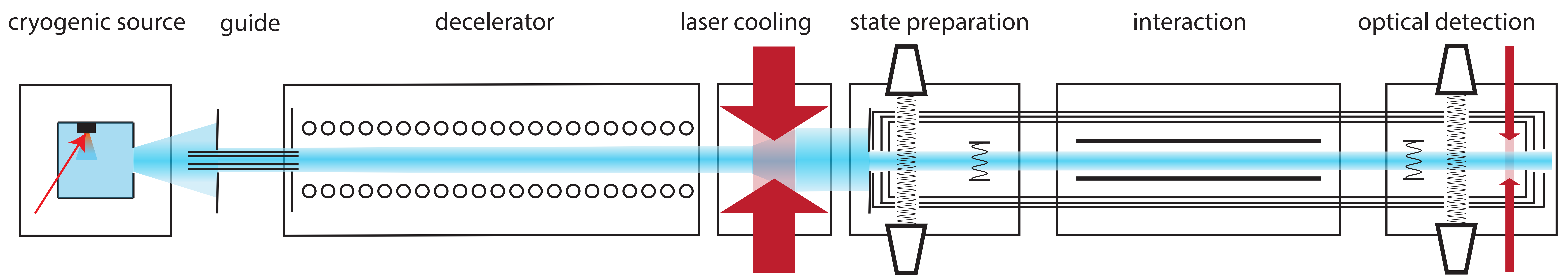
Cycling and lasercooling

An intense, slow and cold beam of molecules

Our approach

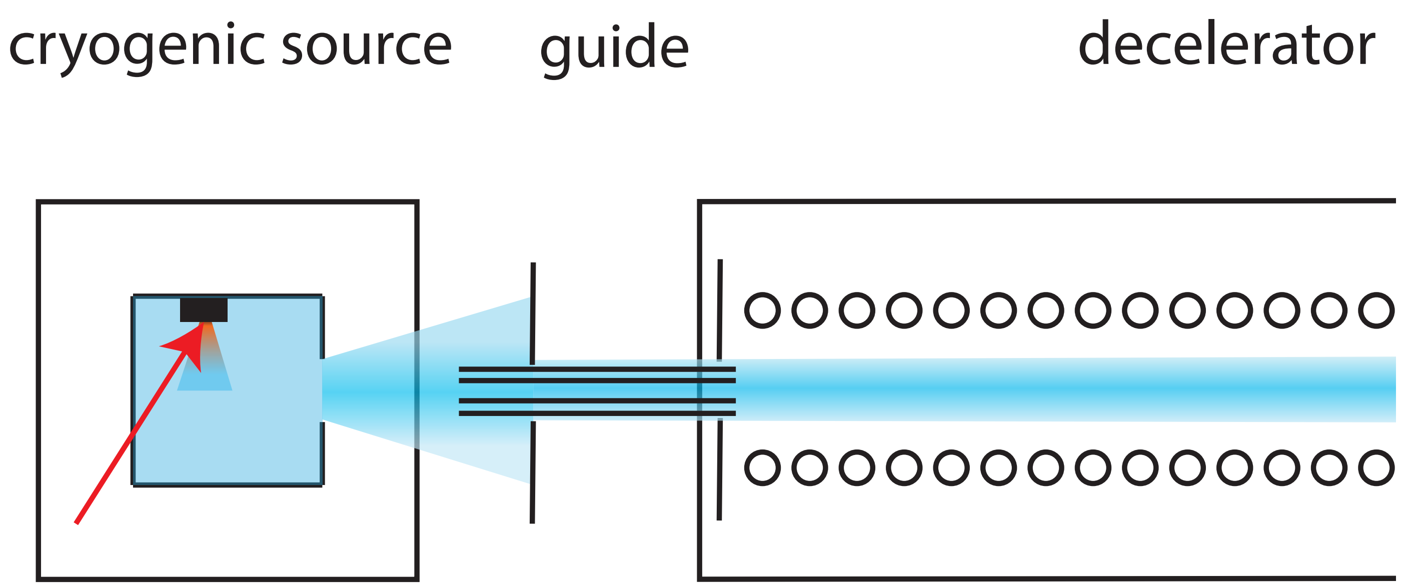
Combining three recent experimental breakthroughs

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



An intense beam of molecules

How-to: source



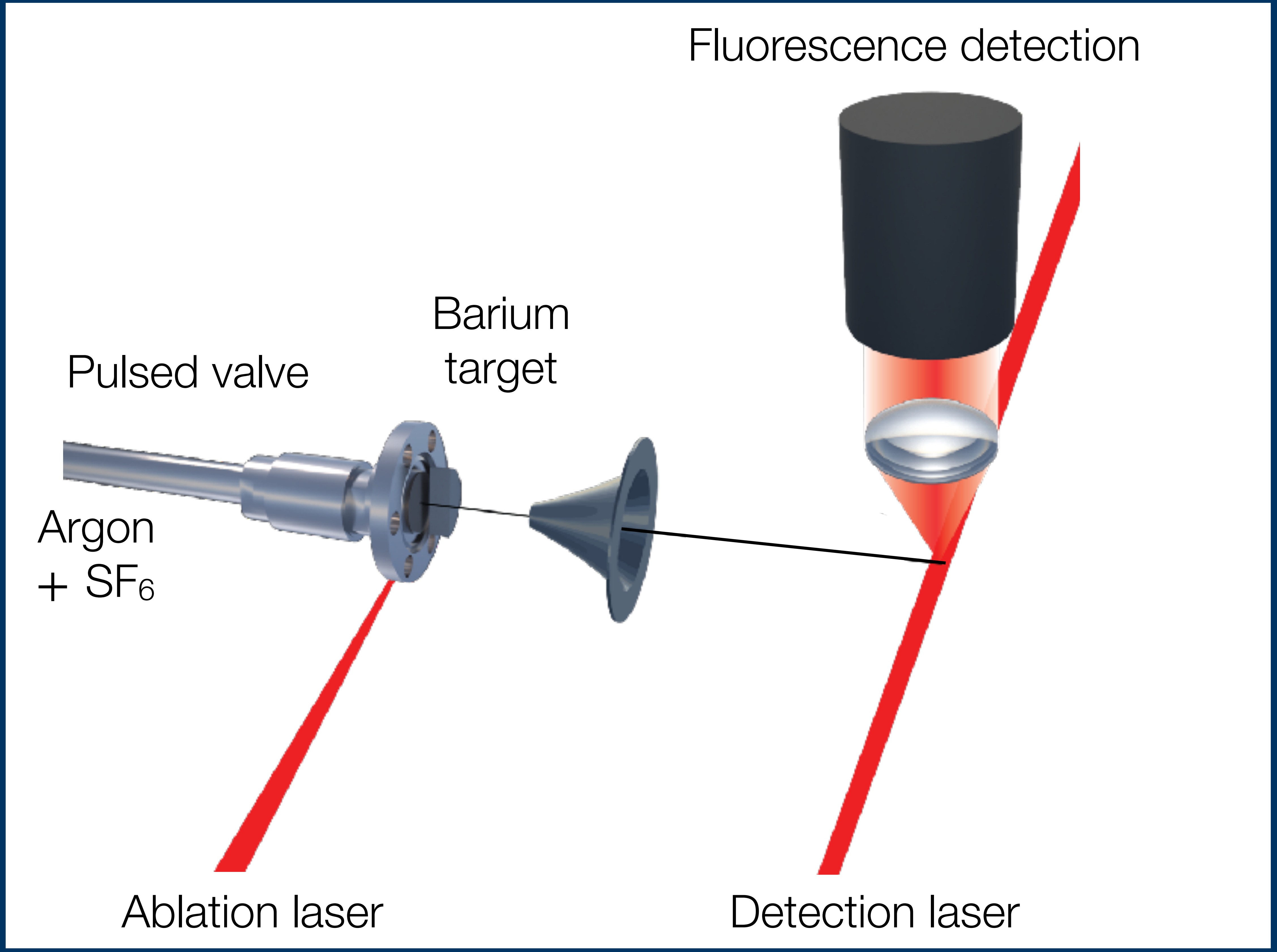
Supersonic

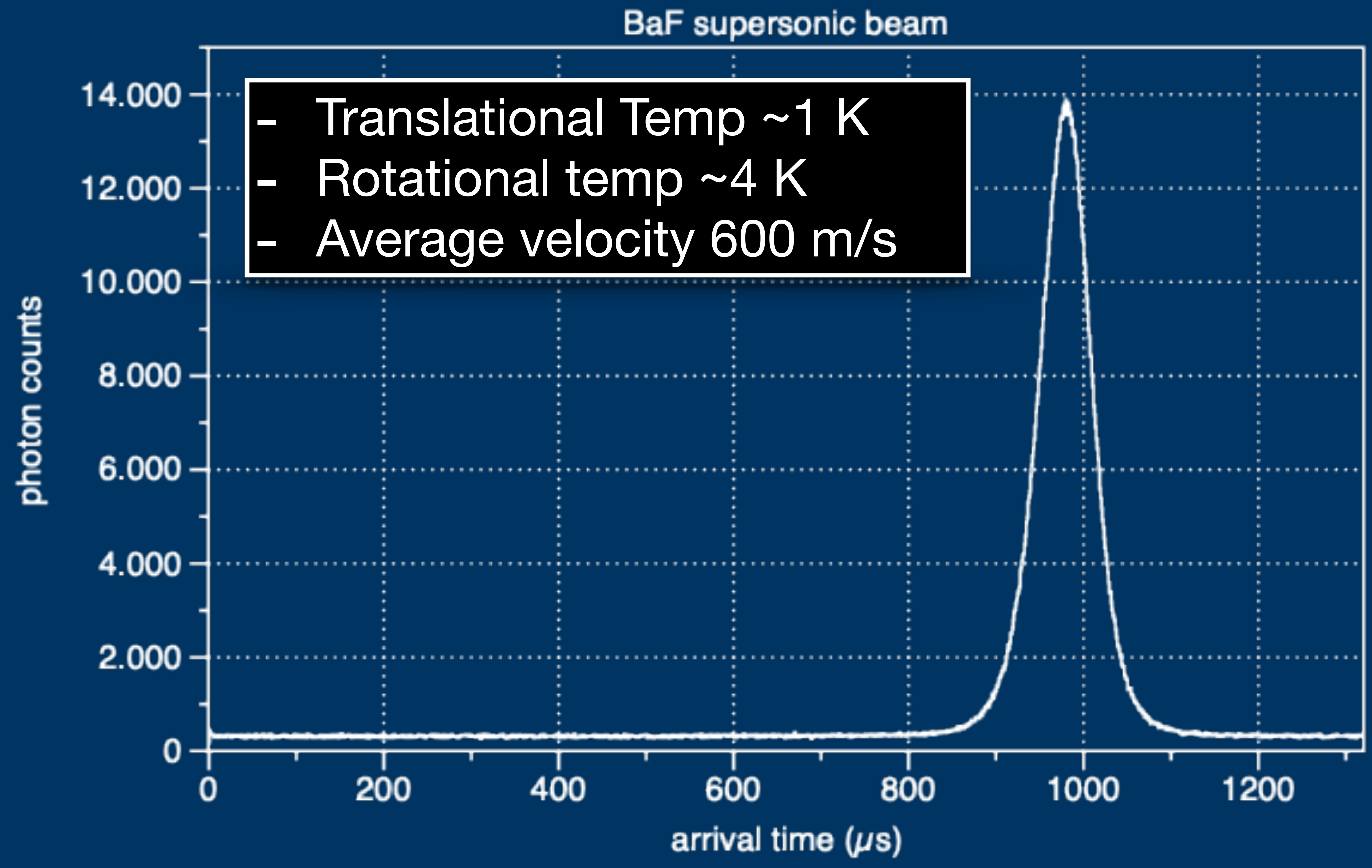
Aims:
- Intense, fast beam (600 m/s)
- Short pulse
- Test lasers systems, state manipulation and interaction zone

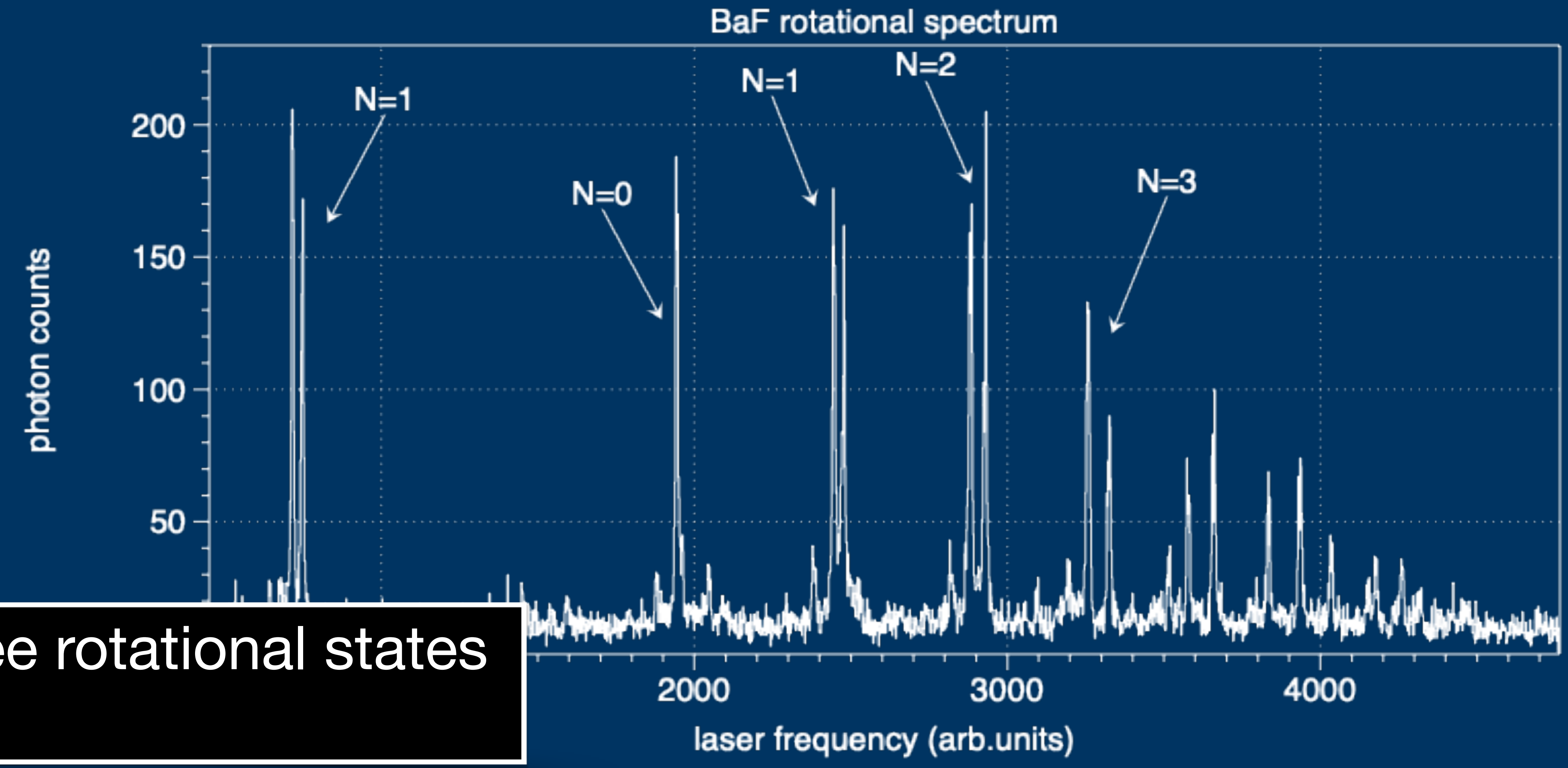
Cryogenic

Aims:
- slow beam (~180 m/s)
- High N: $4x10^9$/shot in the desired state
- Use for eEDM measurement

Supersonic beams of SrF and BaF molecules



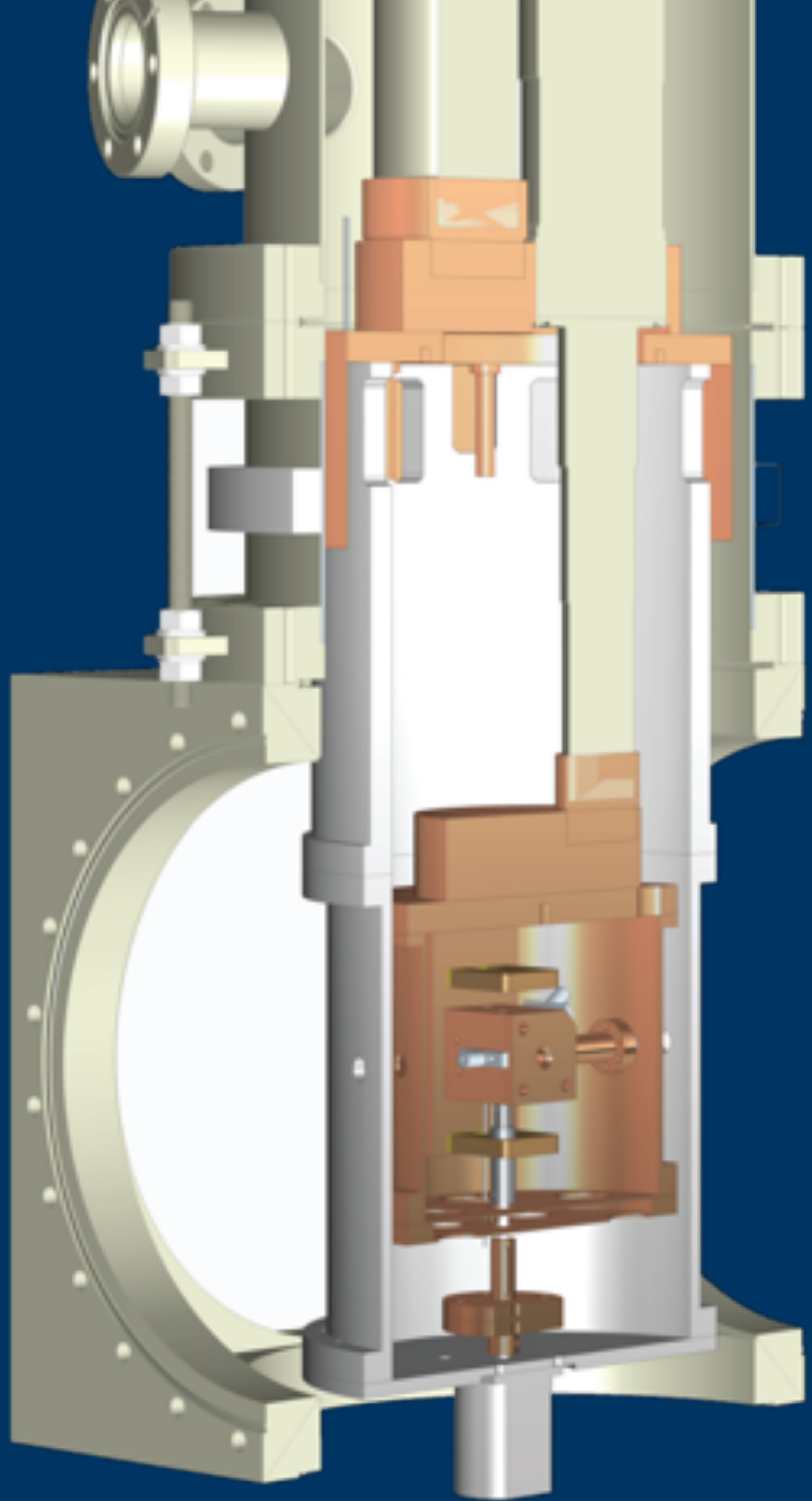




Lowest three rotational states populated

P. Aggarwal et al. A supersonic laser ablation beam source with narrow velocity spreads. Rev Sci Instrum 92, 033202 (2021).

P. Aggarwal et al. Lifetime measurements of the A $^2\Pi_{1/2}$ and A $^2\Pi_{3/2}$ states in BaF. Phys Rev A 100, 052503 (2019).



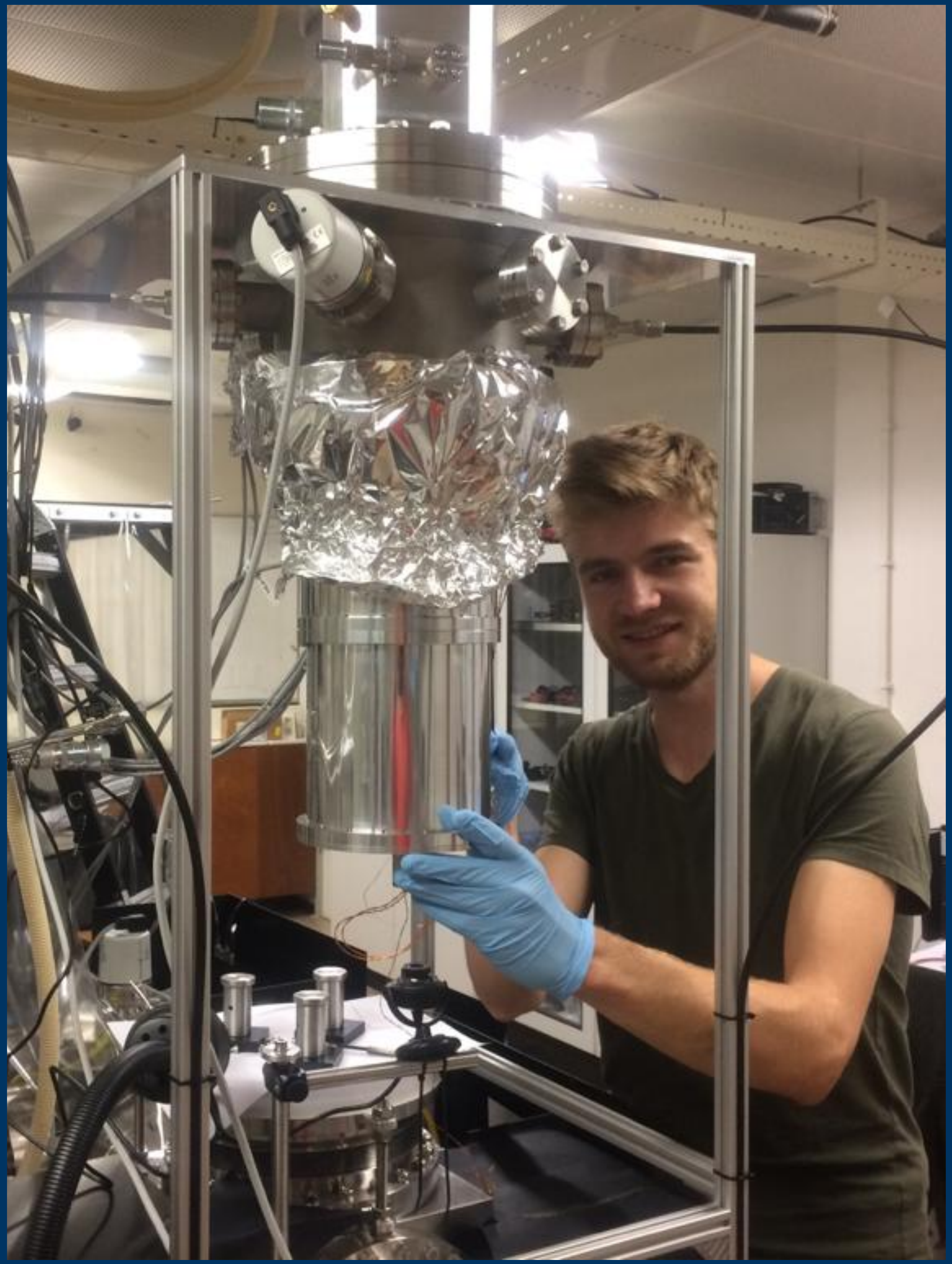
Cryogenic beam

- Evaporating Sr metal target
- Neon carrier gas + SF_6
- Absorption,1 cm from cell
- Fluorescence, 30 cm from cell
- Translational Temp ~10 K
- Velocity 150-200 m/s

Based on design from Stefan Truppe, Mike Tarbutt @ Imperial

Goal: make the most intense slow source of BaF molecules

1 in Groningen (BaF, production)
1 in A'dam (BaF, optimisation)
1 under construction in Groningen (polyatomic molecules)



Maarten Mooij, Rick Bethlem @ VU Amsterdam

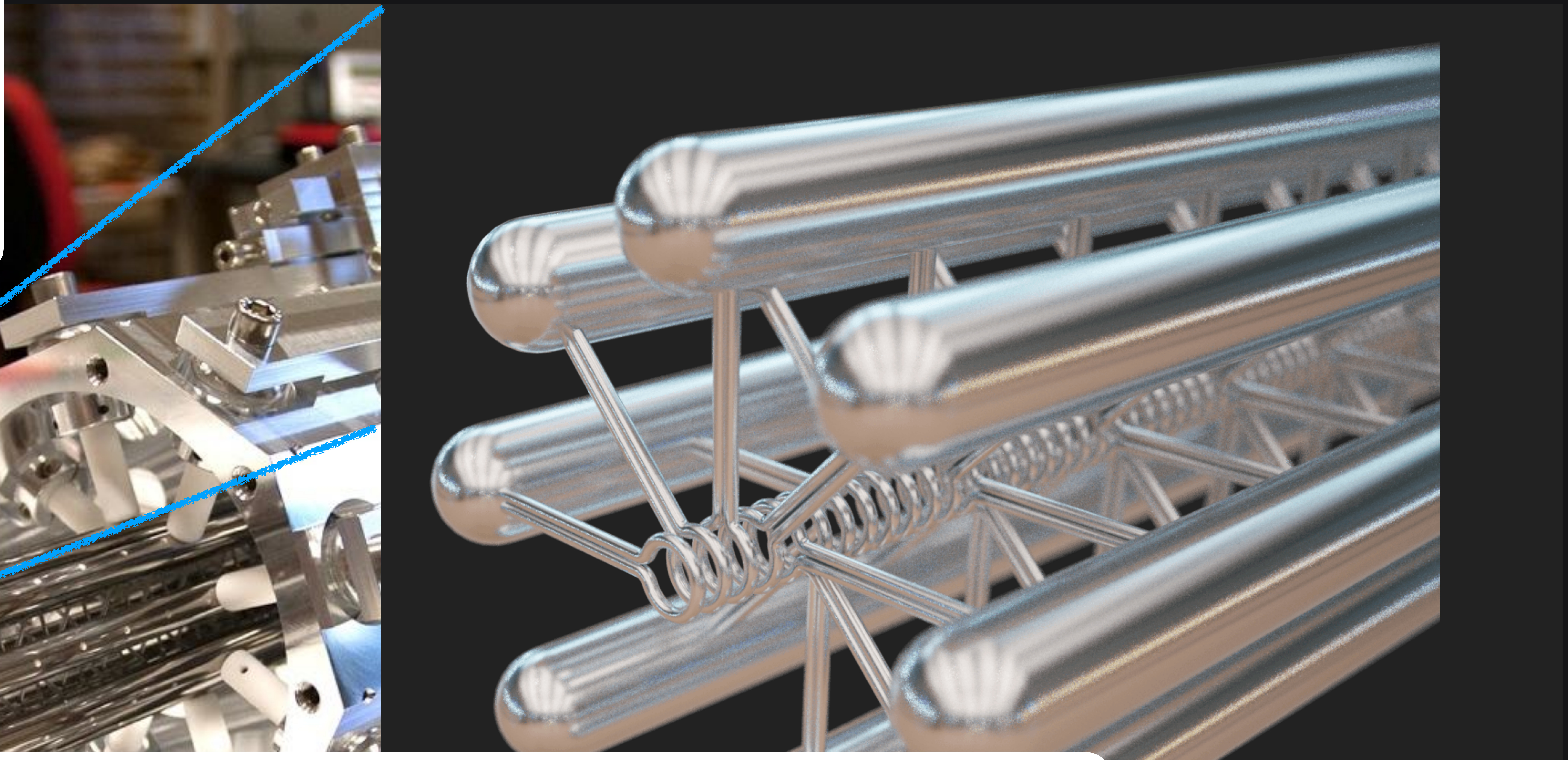
Truppe, S. et al. A buffer gas beam source for short, intense and slow molecular pulses. Journal Of Modern Optics 65, 246–254 (2018).

A slow beam of molecules

Molecule deceleration

A traveling-wave with a tunable velocity

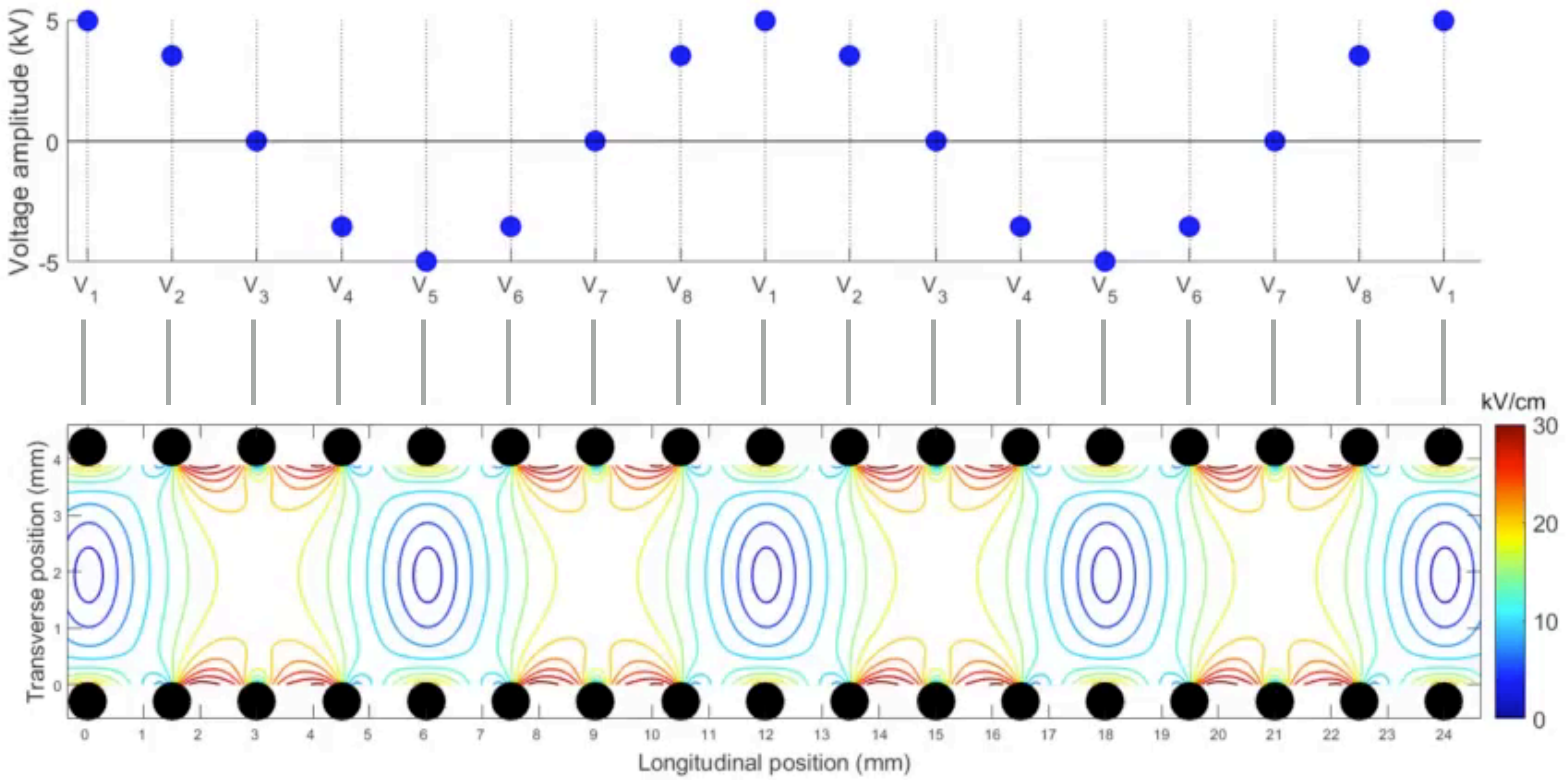
Traveling-wave decelerator



Main aims:

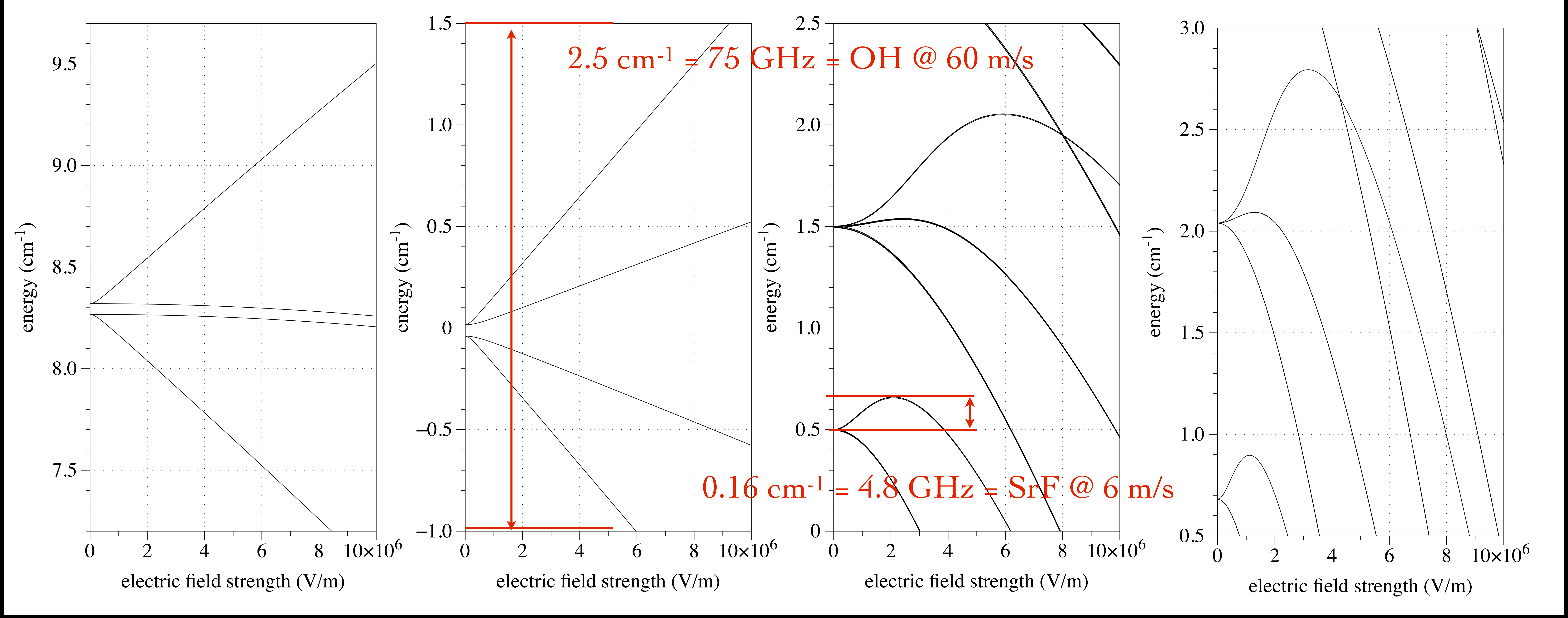
- Capture as many molecules as possible from molecular beam
- Bring average beam velocity from ~190 to ~30 m/s
- Maintain N during deceleration

Traveling-wave decelerator



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.

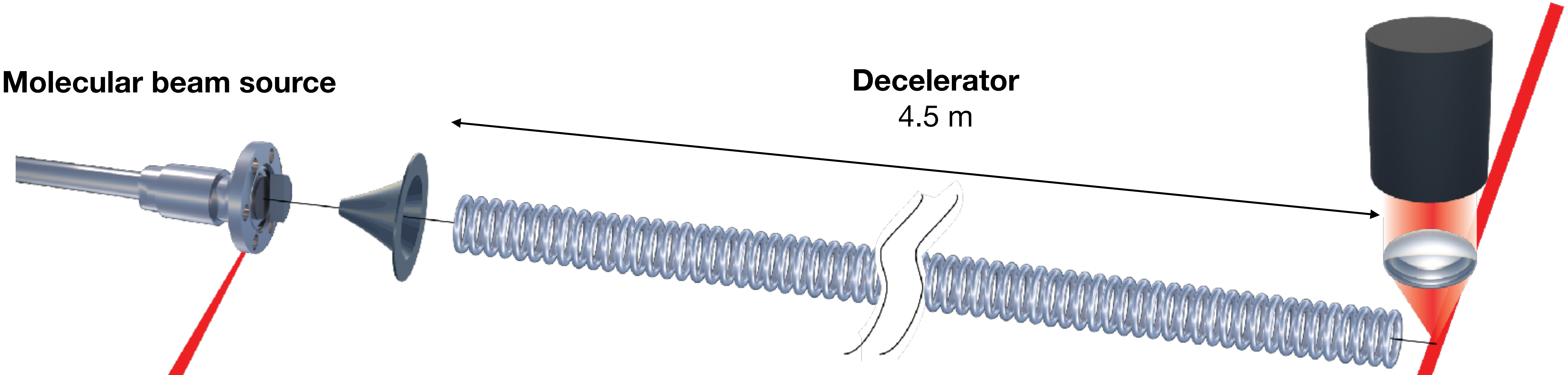


ND_3 | OH $^2\Pi_{3/2}$ | SrF $^2\Sigma$ | SrO $^1\Sigma$

3.5 Debye

Limited force: -> a long decelerator

Traveling-wave decelerator



Challenges for heavy diatomic molecules:

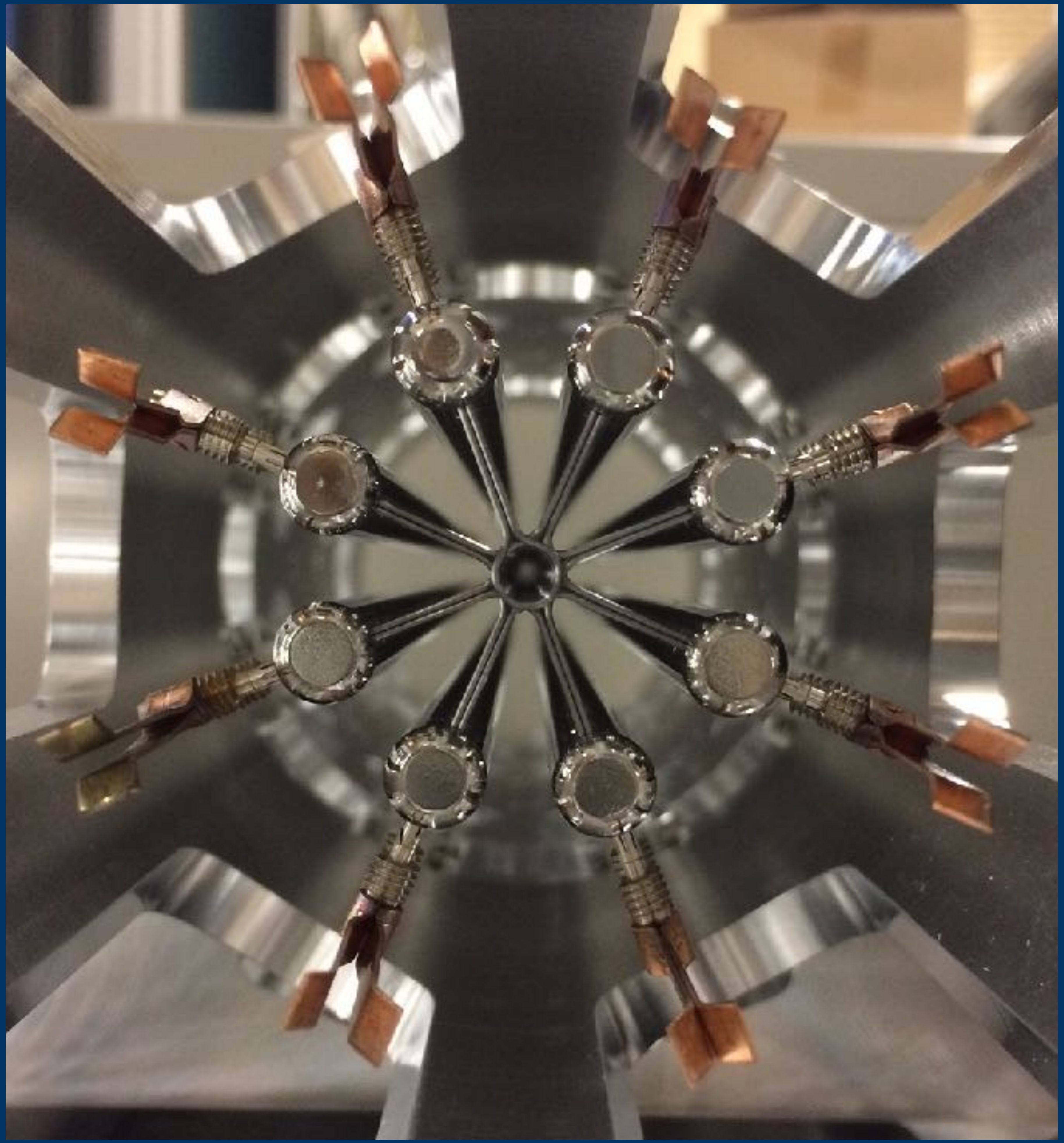
- Heavy -> long decelerator
- Rotational structure -> limited Stark shift

Deceleration, trapping, collision studies, lifetime measurements

Demonstrated for light molecules: OH, CO, NH_3, NH

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

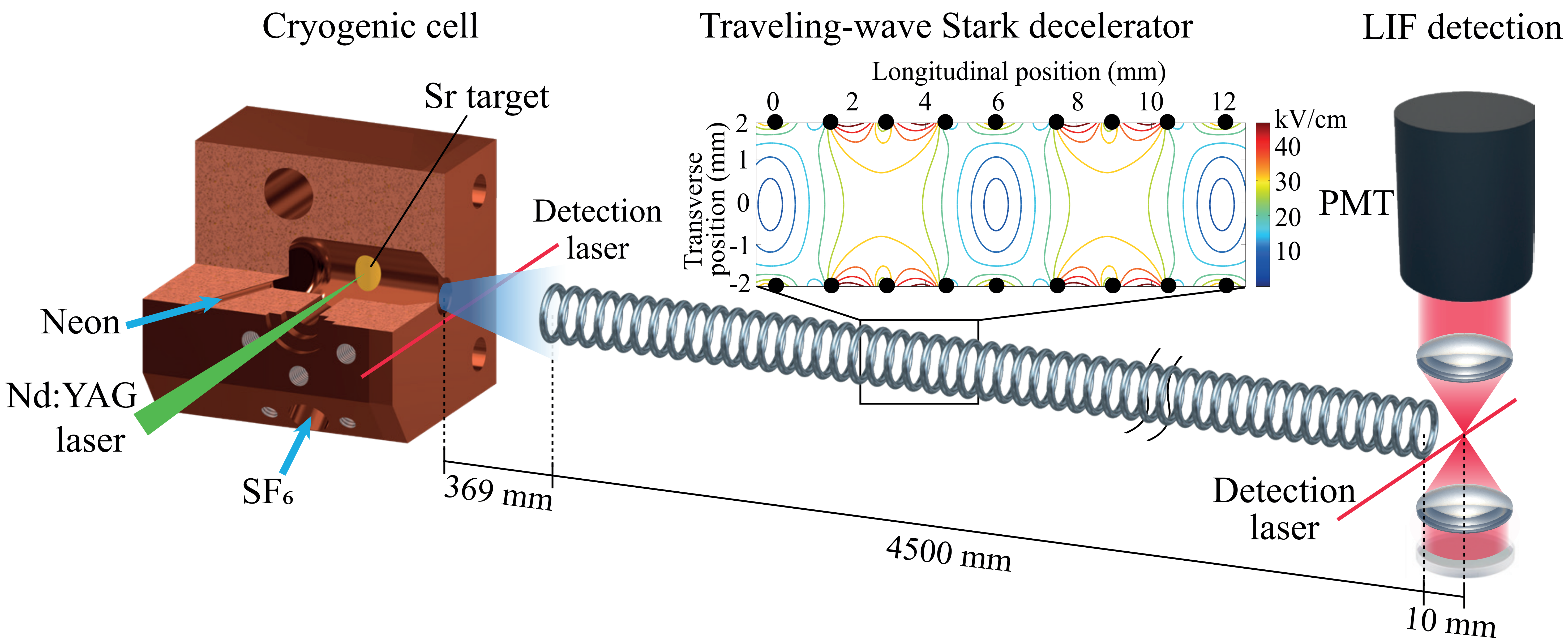
Modular traveling-wave decelerator

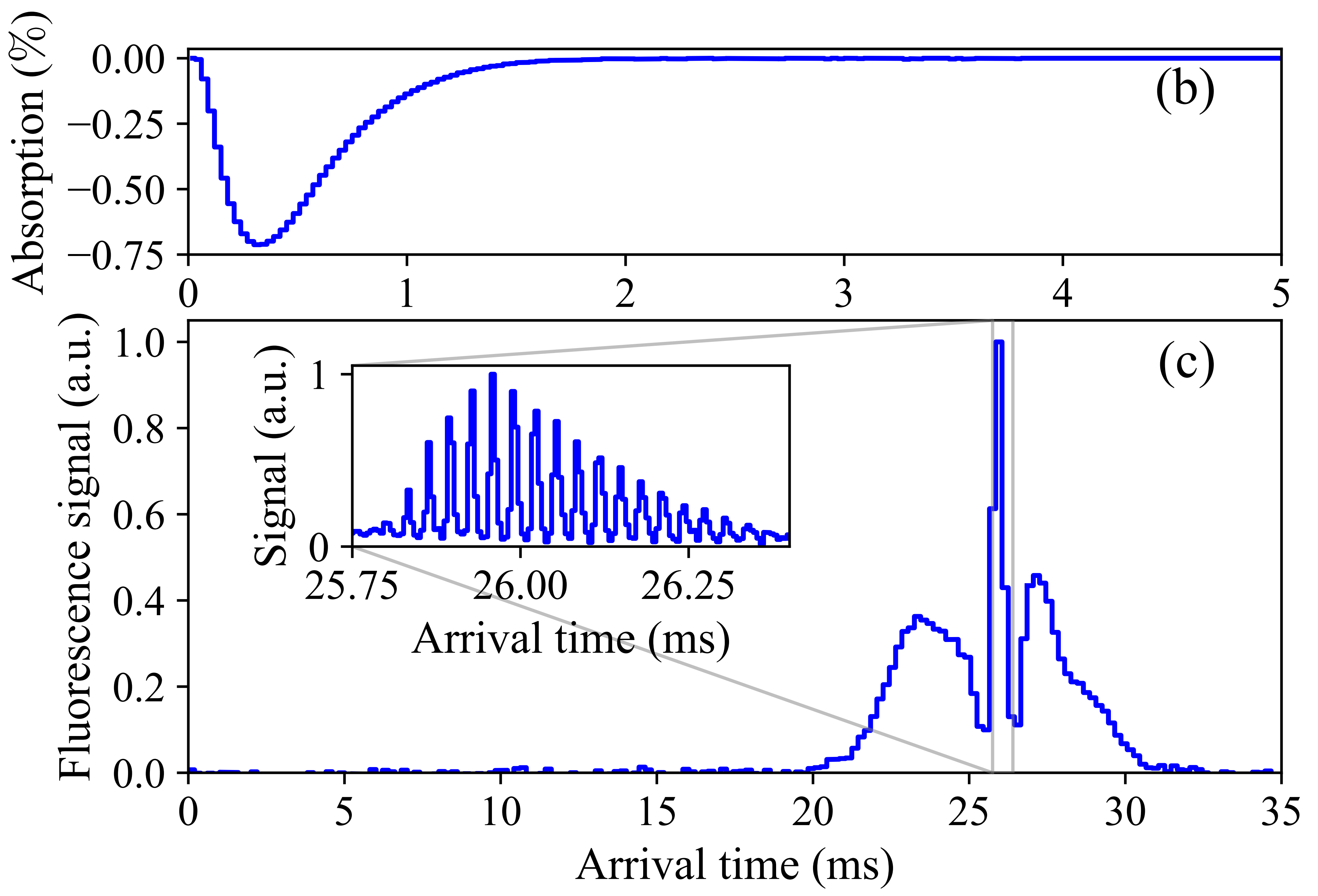


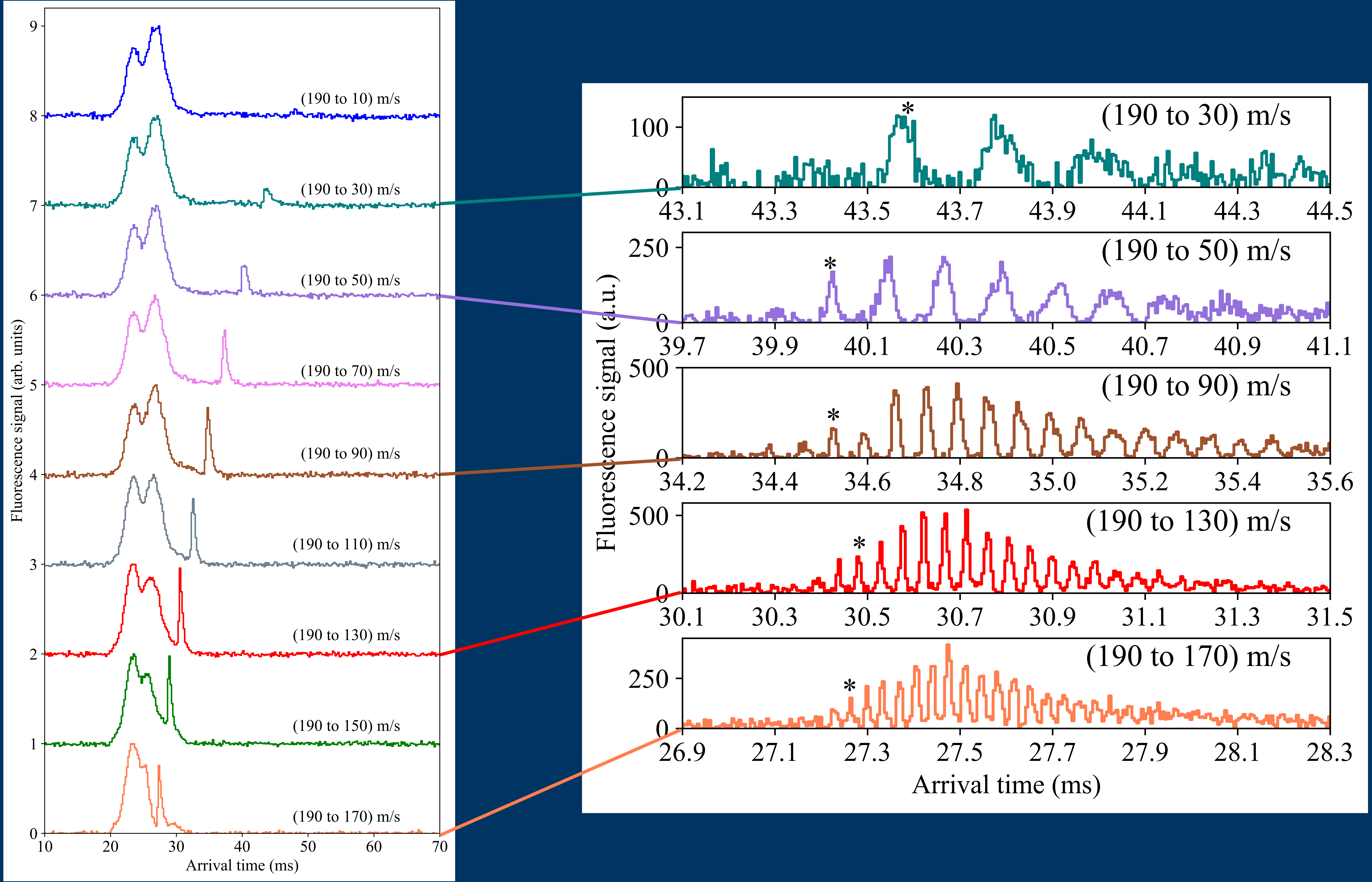
Traveling-wave decelerator

A slow beam of molecules

SrF: First combination of deceleration and cryogenic source



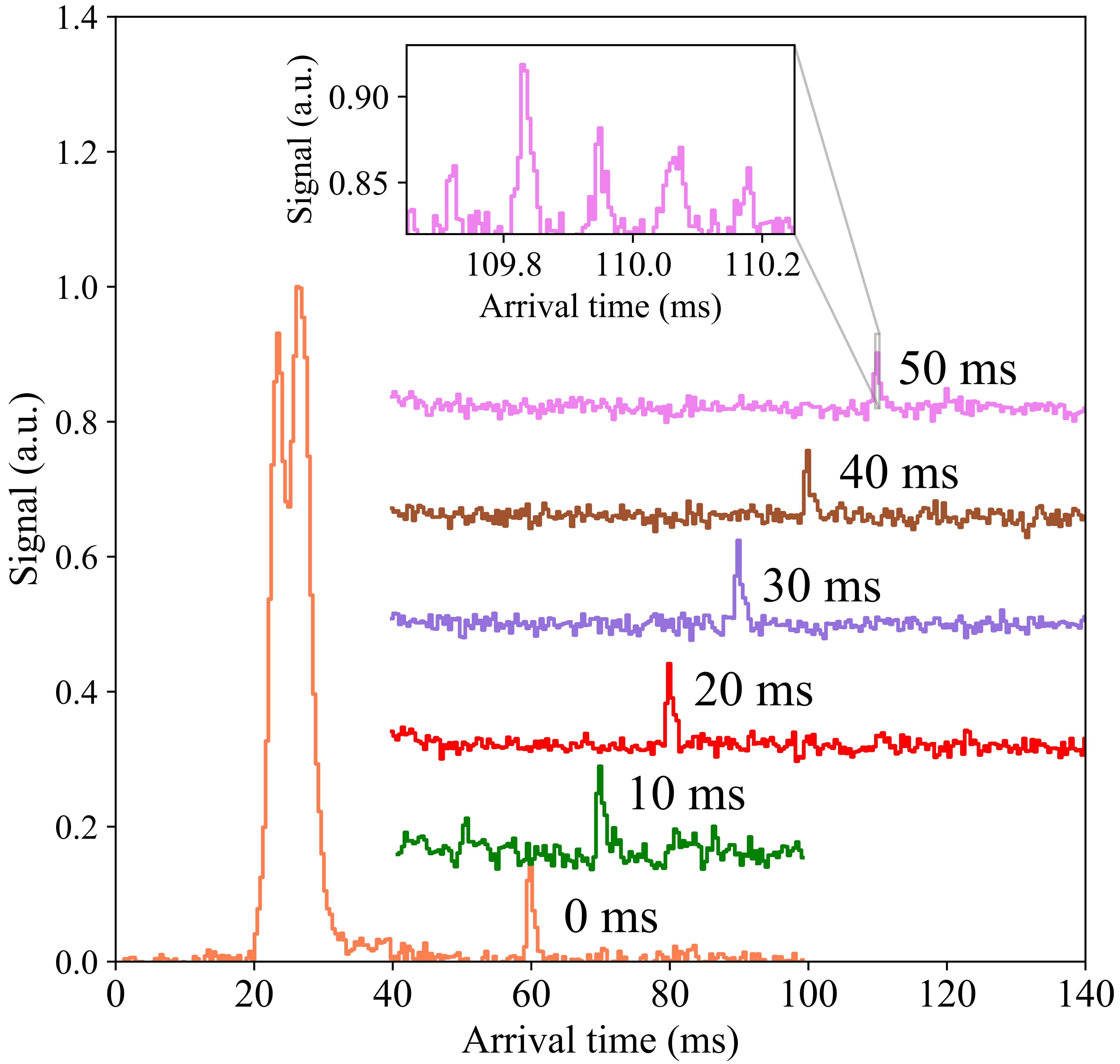



(190 to 10) m/s
(190 to 30) m/s
(190 to 50) m/s
(190 to 70) m/s
(190 to 90) m/s
(190 to 110) m/s
(190 to 130) m/s
(190 to 150) m/s
(190 to 170) m/s
Fluorescence signal (arb. units)
Arrival time (ms)
Fluorescence signal (a.u.)
Arrival time (ms)

A slow beam of molecules

Deceleration to standstill

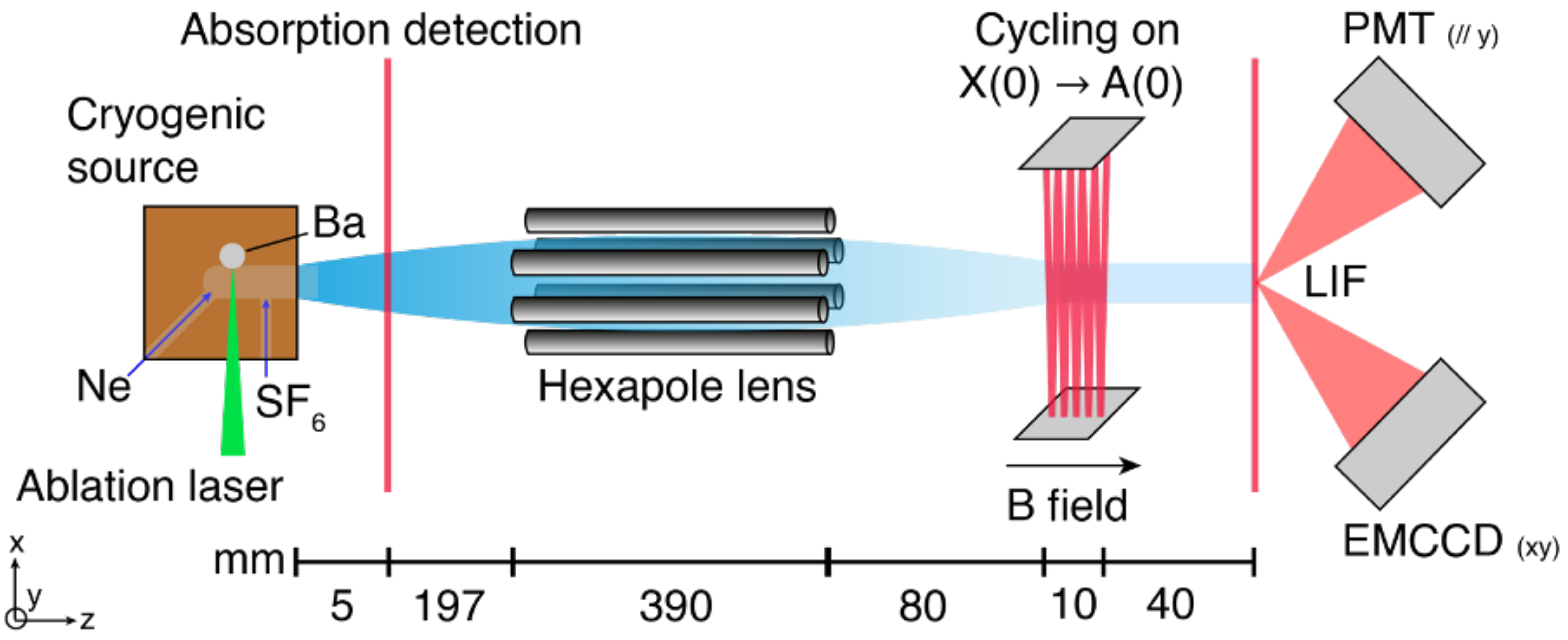
Deceleration to standstill in 4.2 m, hold there for some time, accelerate out again to 50 m/s to detect



Deceleration and trapping of SrF molecules
Parul Aggarwal, Yanning Yin et al (NL-eEDM),
PRL **127** 173201 (2021)

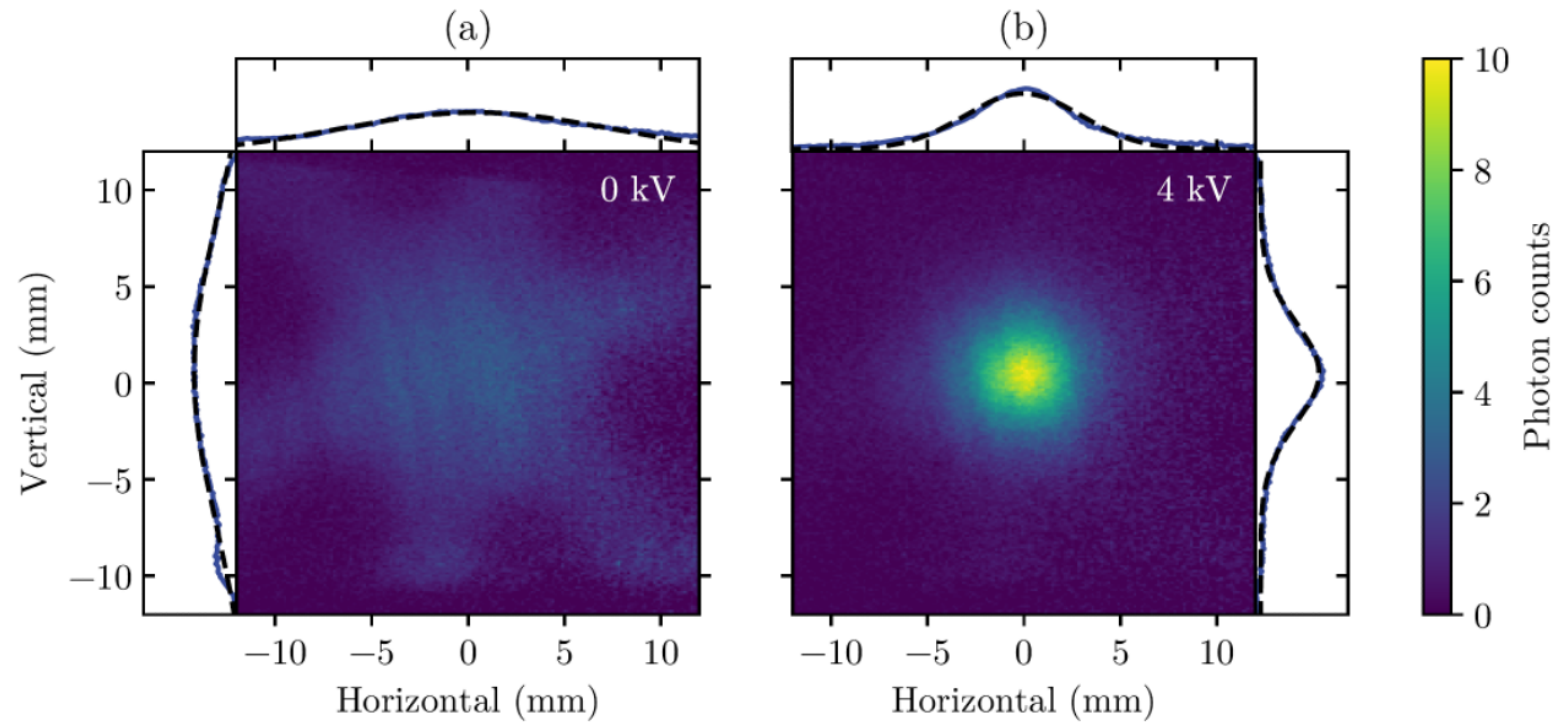
Hexapole focusing

Will be combined with laser cooling



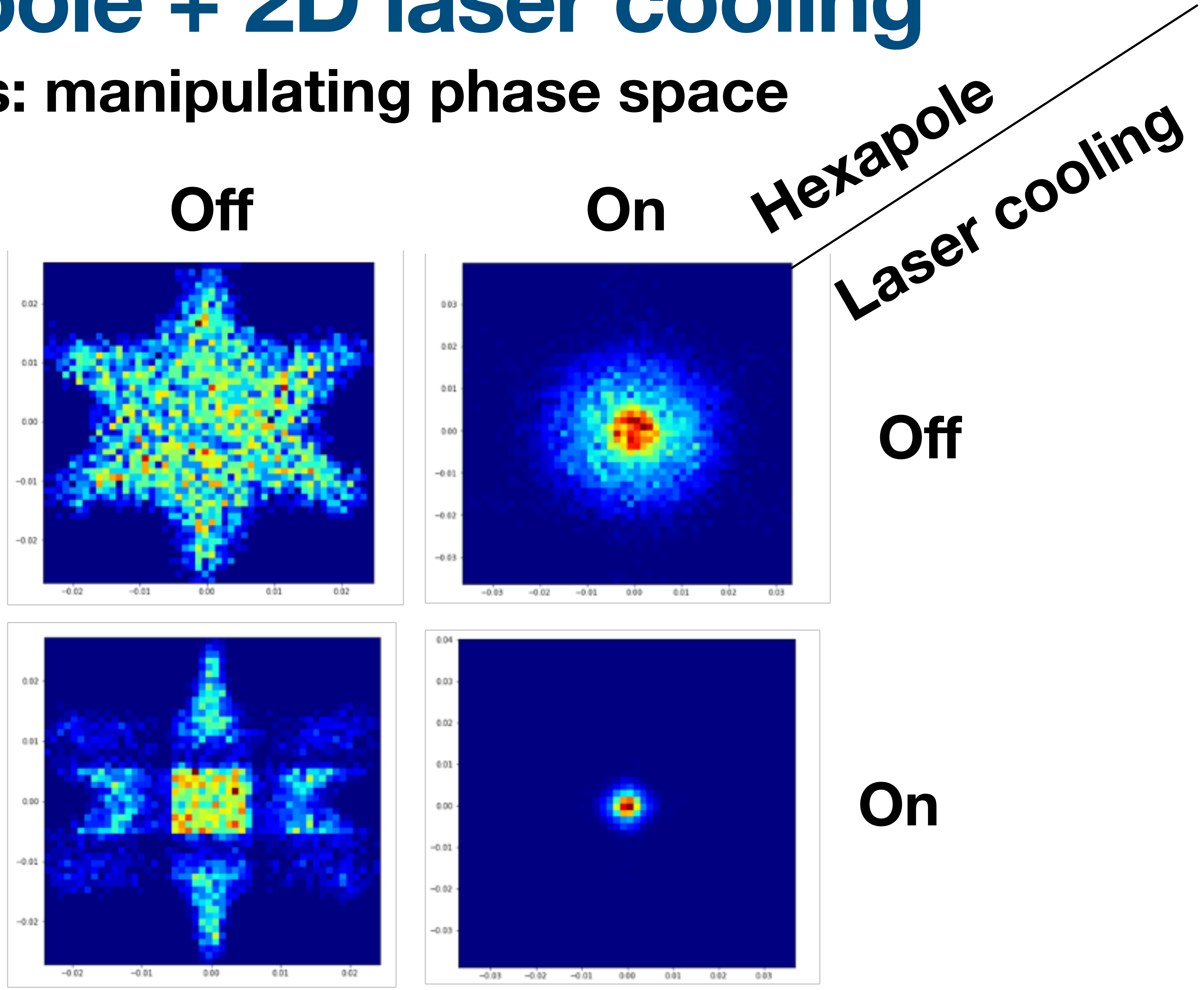
A hexapole electrostatic lens

CCD camera images the molecular beam



Next: Hexapole + 2D laser cooling

Simulation results: manipulating phase space



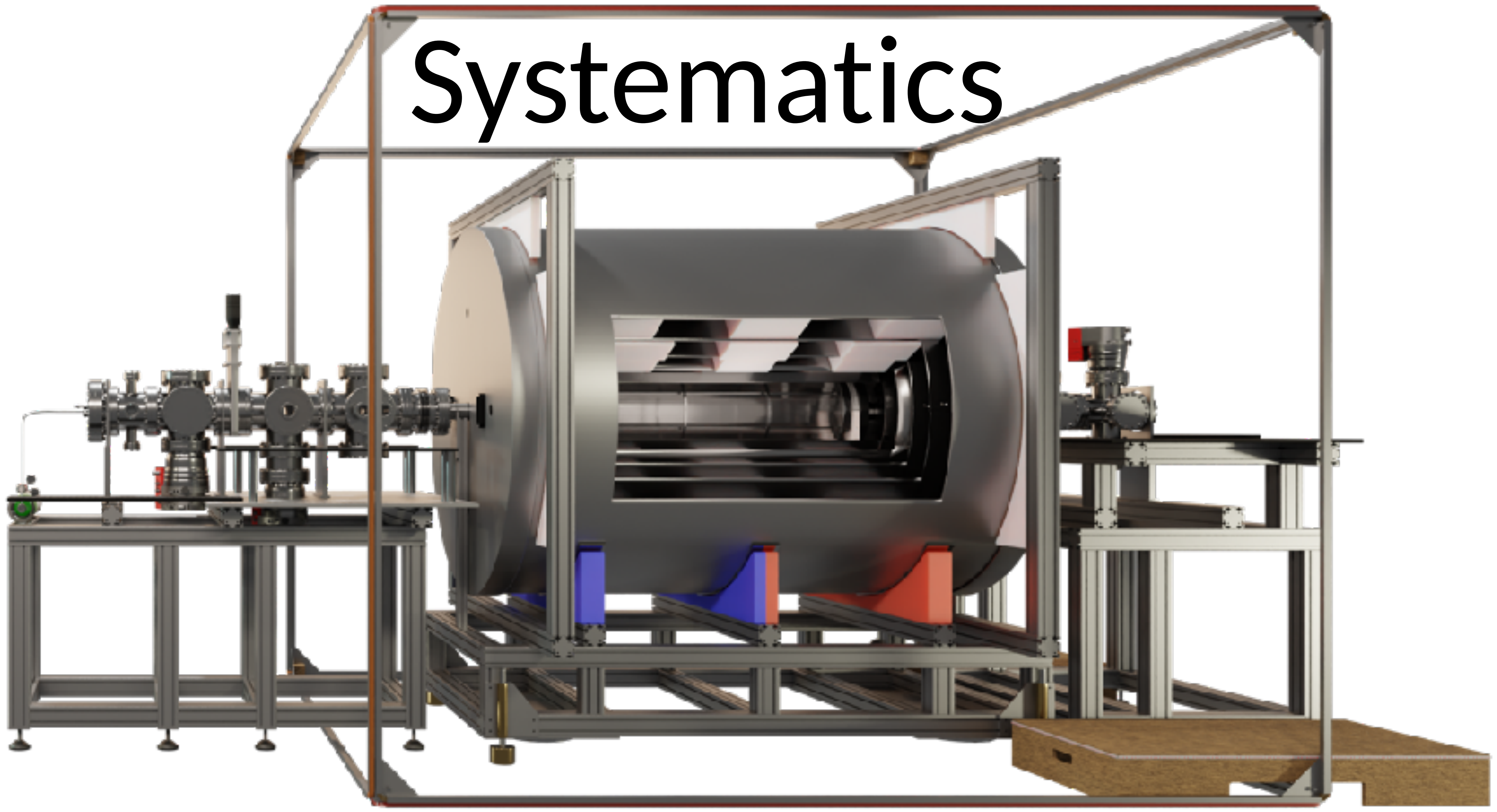
Fast beam

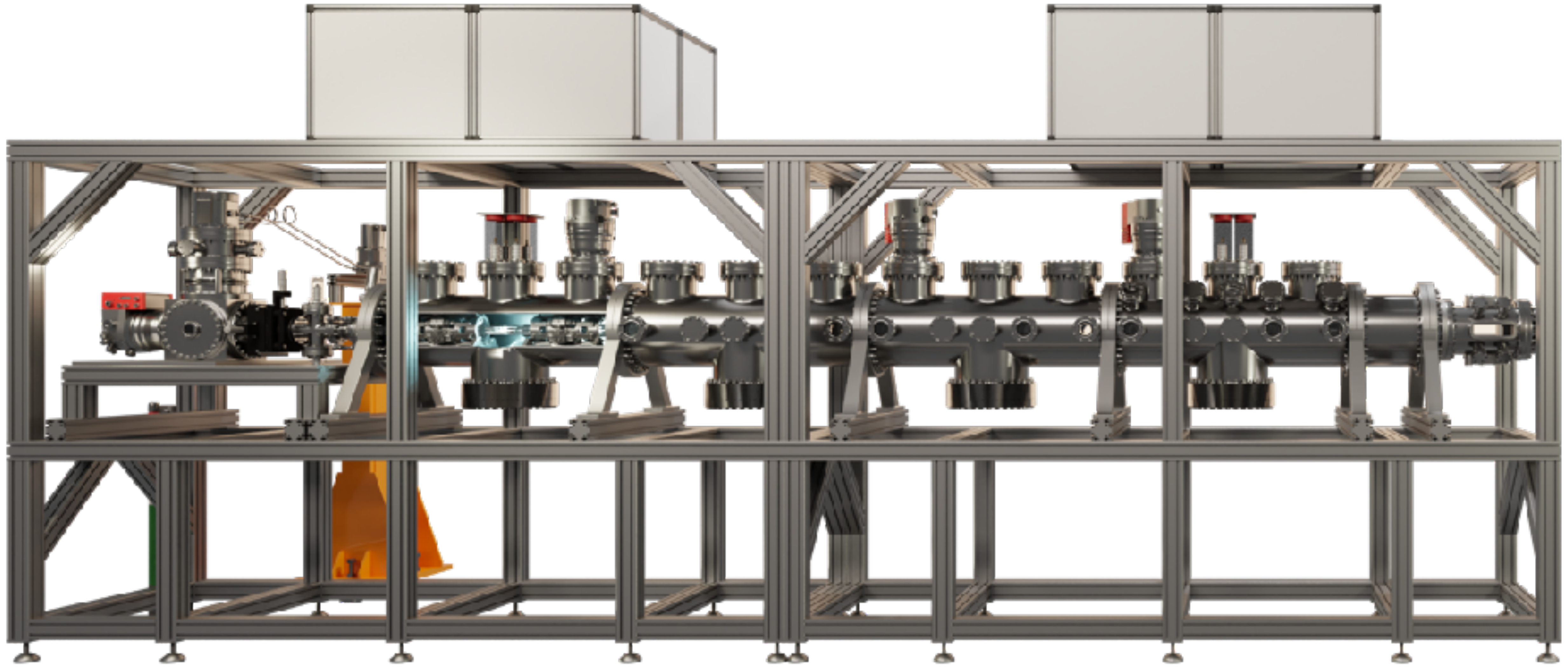
Supersonic beam (600 m/s)

Controlled field environment

Explored molecular structure

Spin interferometer measurement





Statistics

Slow beam

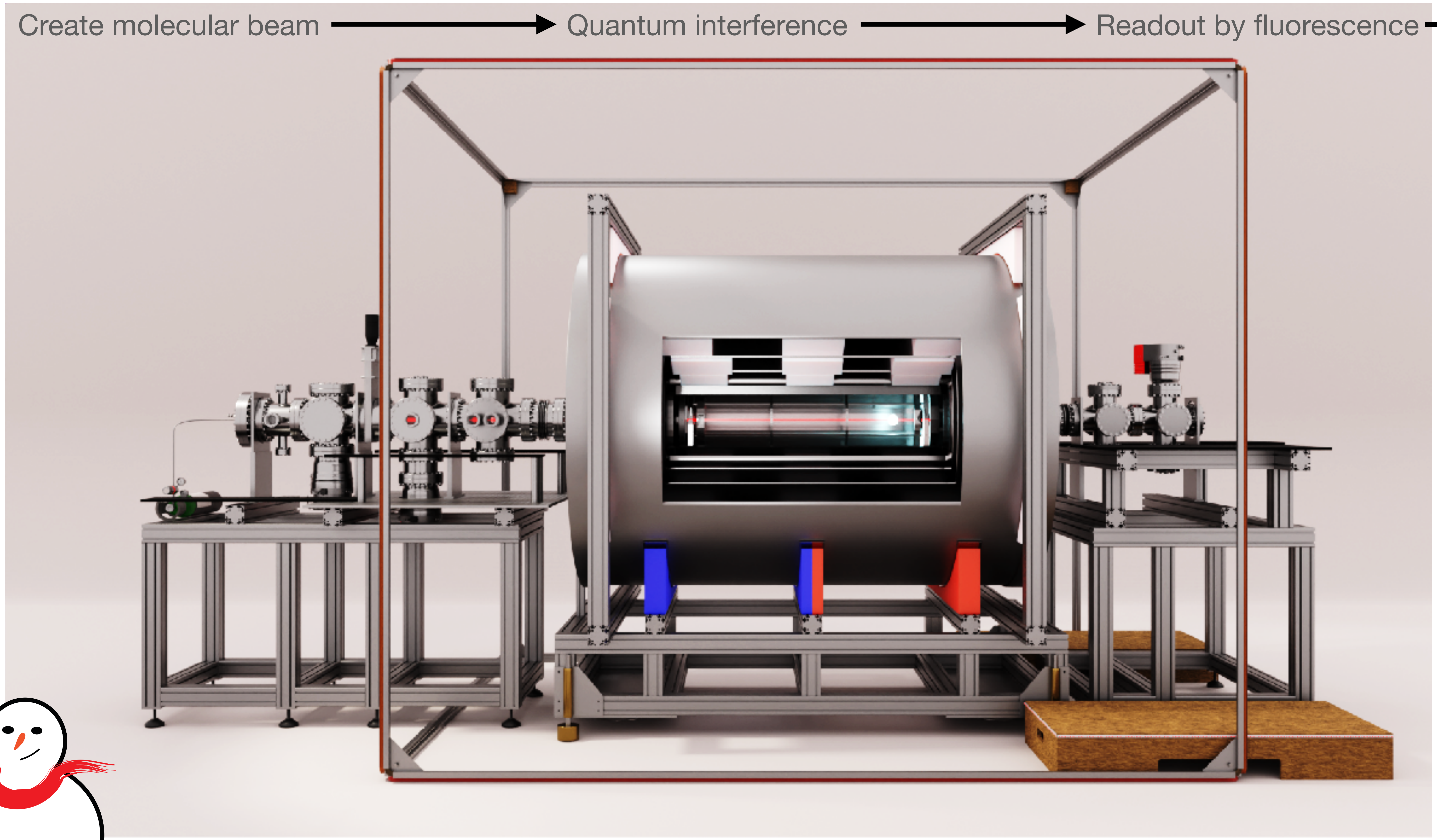
Cryogenic beam (200 m/s)

Stark decelerator (30 m/s)

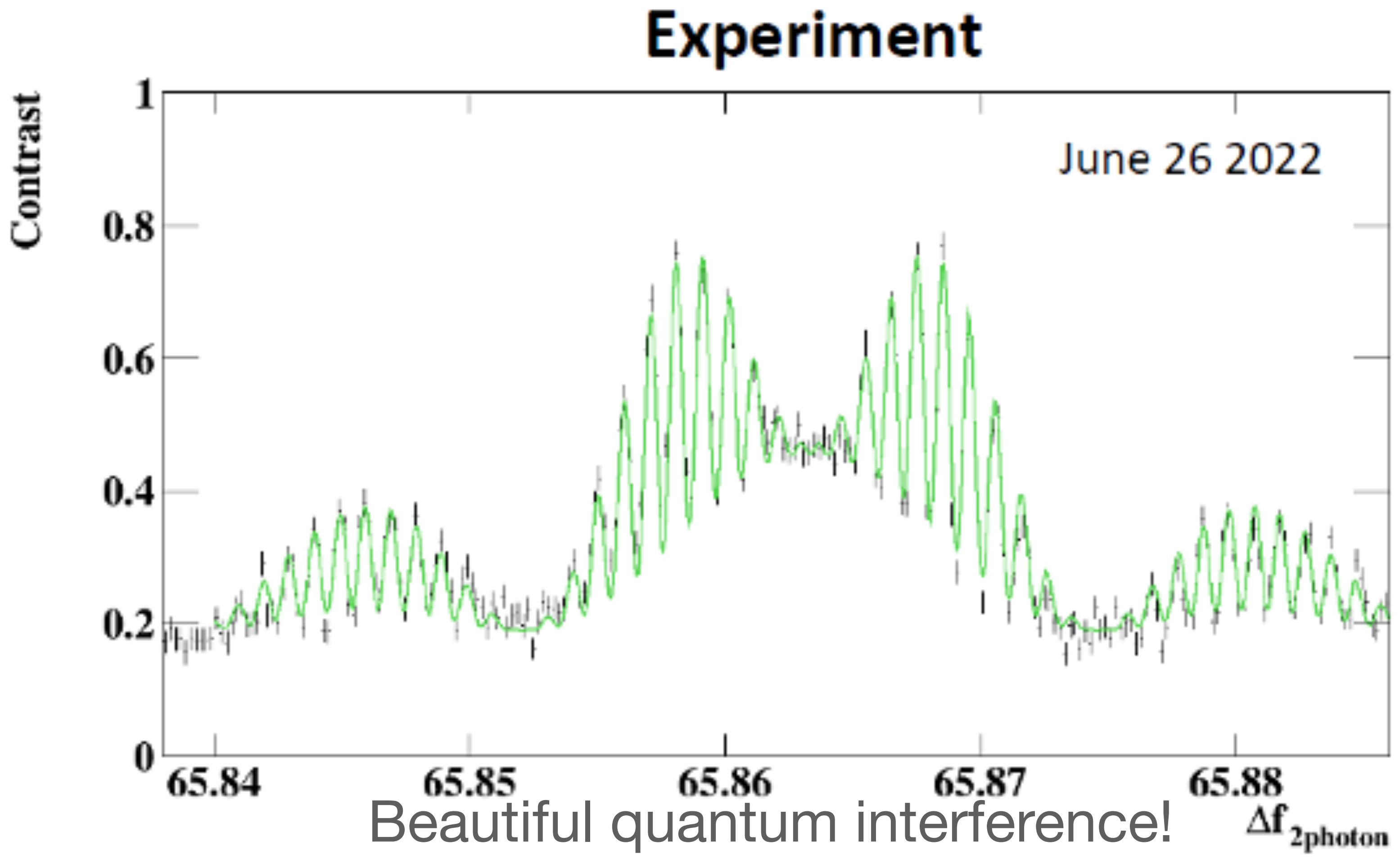
Cycling and lasercooling

Interference data using fast molecular beam

to demonstrate control over systematic effects



Compare to theory that includes the full interaction of the molecule with light, electric and magnetic fields (optical Bloch equations)

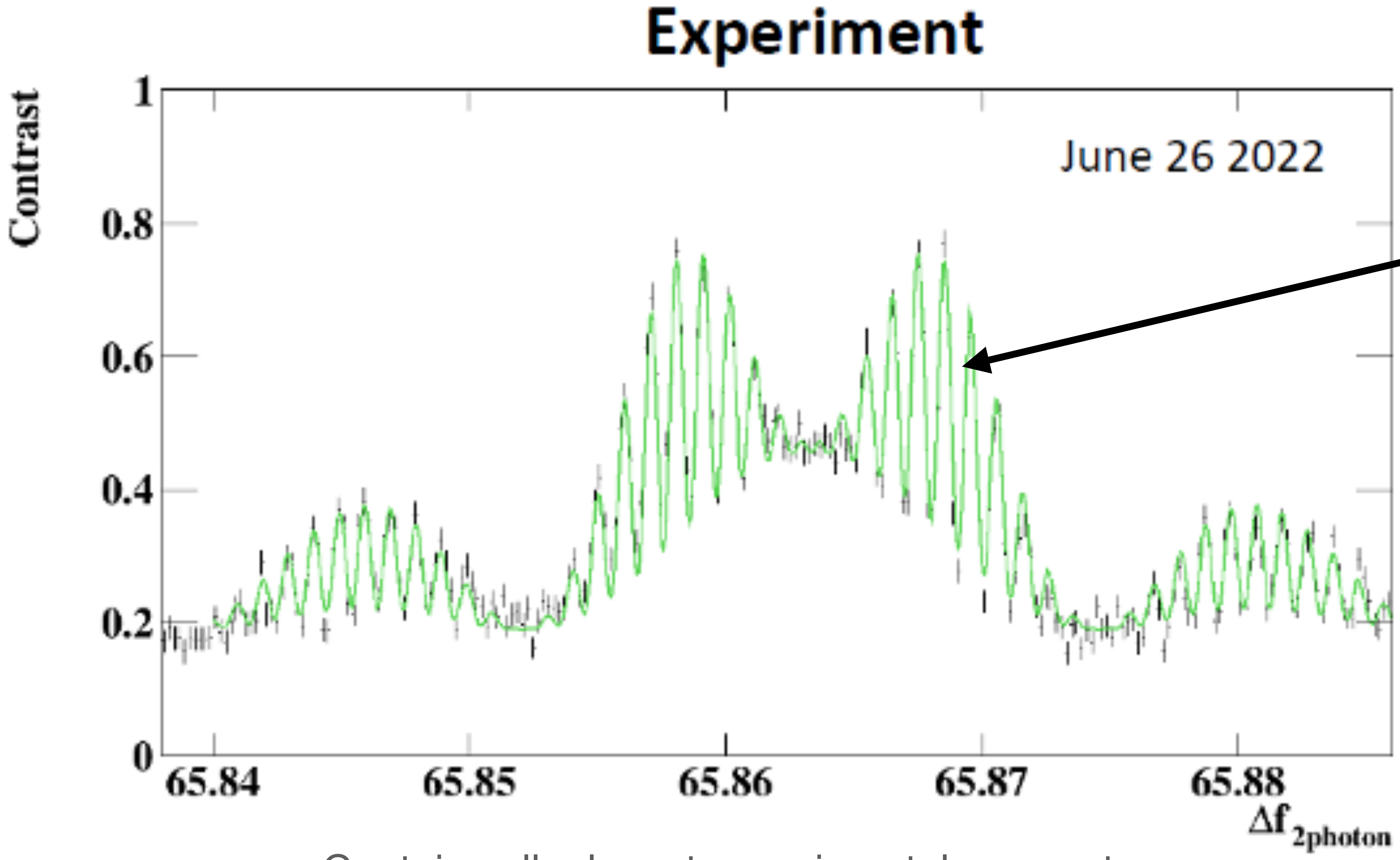


Beautiful quantum interference!

Contains all relevant experimental parameters
Crucial for reduction of systematic effects
(A.Boeschoten et al, NL-eEDM collaboration, arXiv:2303.06402v1)

NL-eEDM

Measured interference pattern



Laser detuning (MHz)

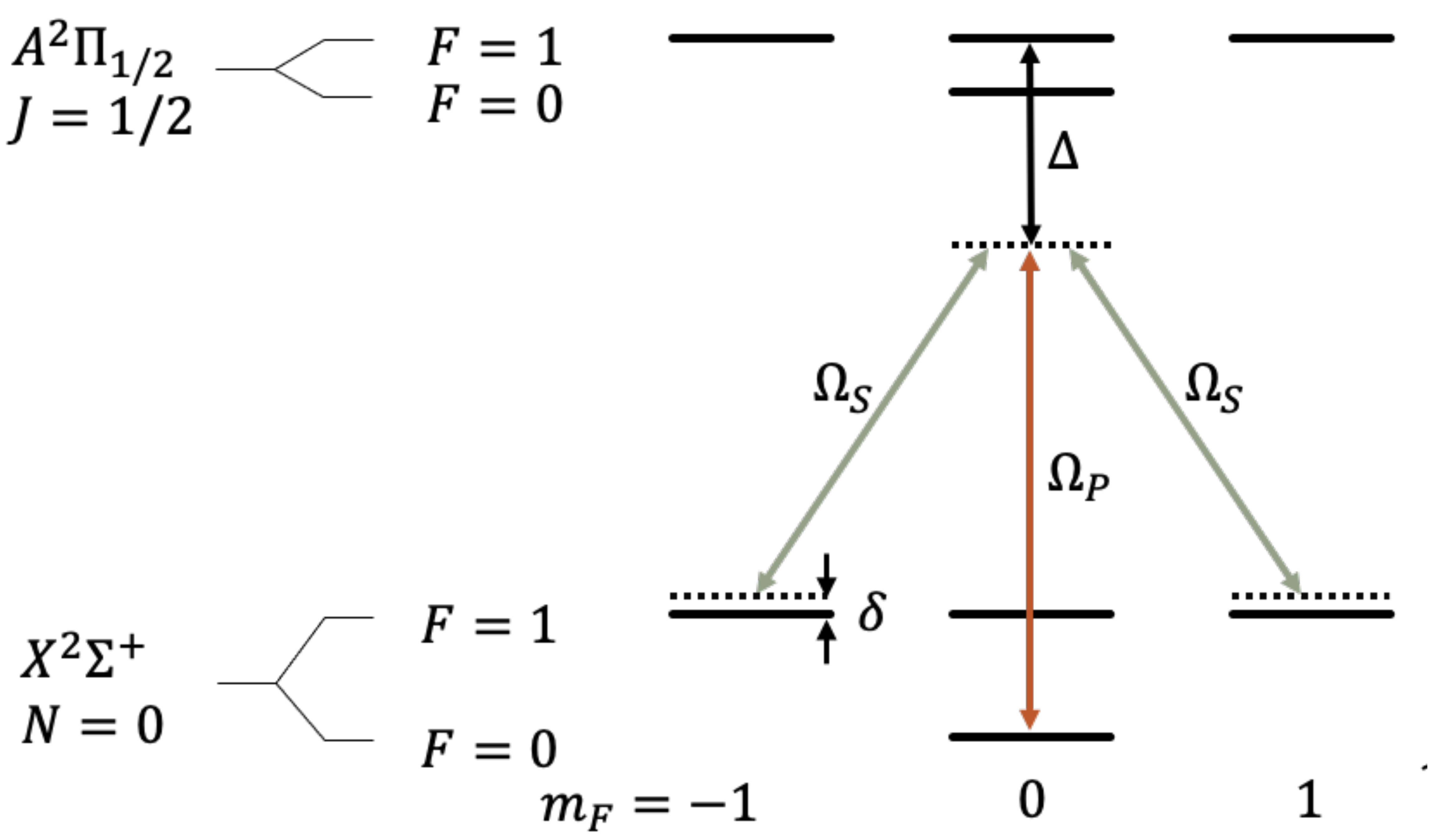
When flipping E-field direction, this pattern will change.

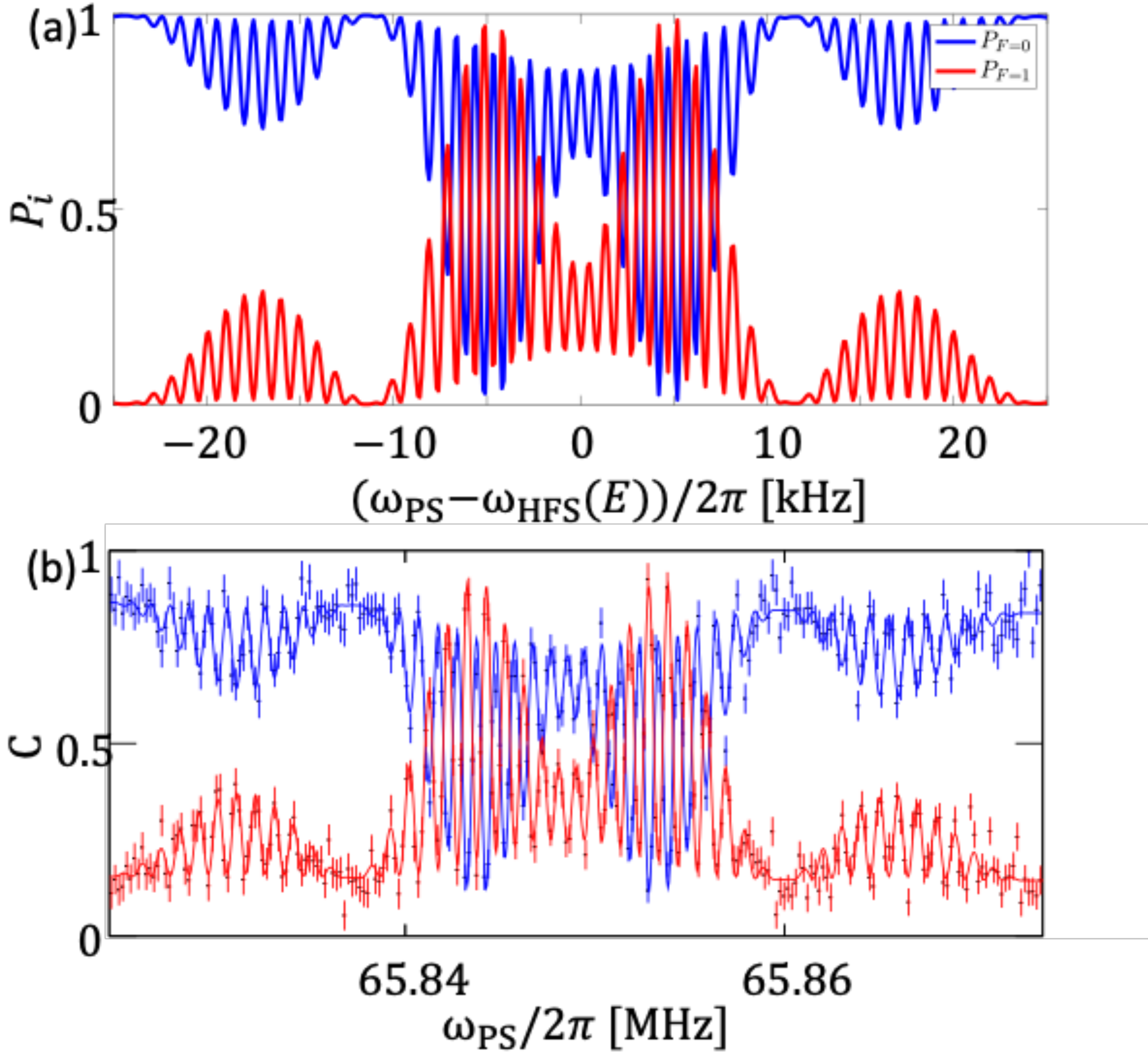
Slow beam, more molecules -> higher eEDM sensitivity

Contains all relevant experimental parameters
Crucial for reduction of systematic effects

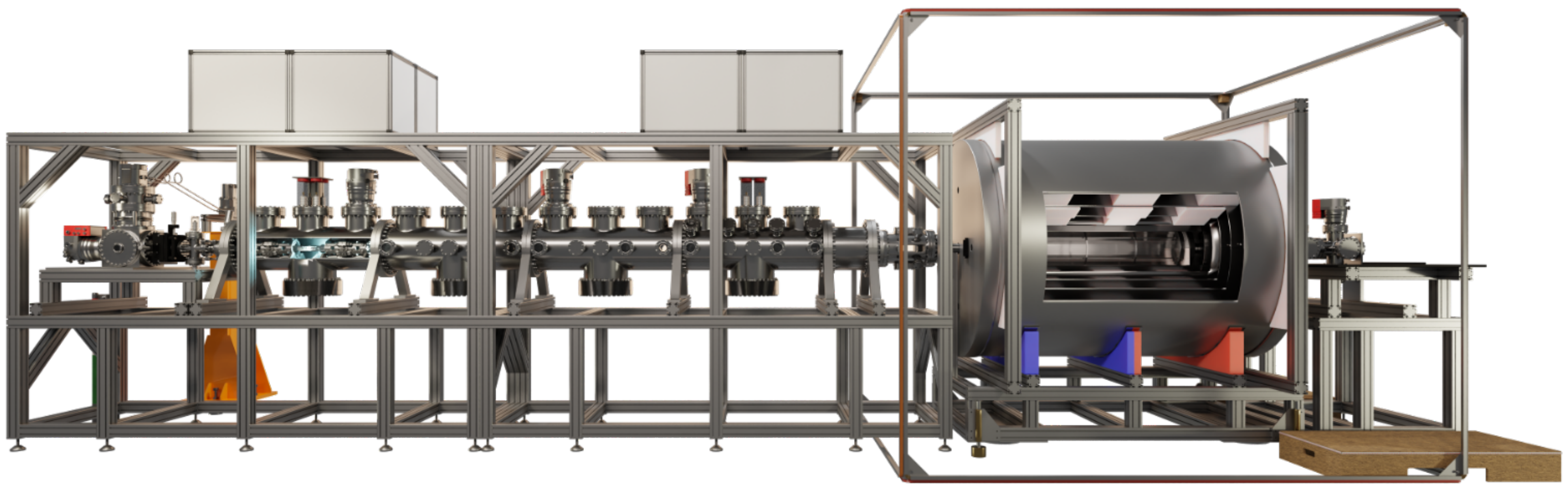
Experiment and theory

Optical Bloch equations

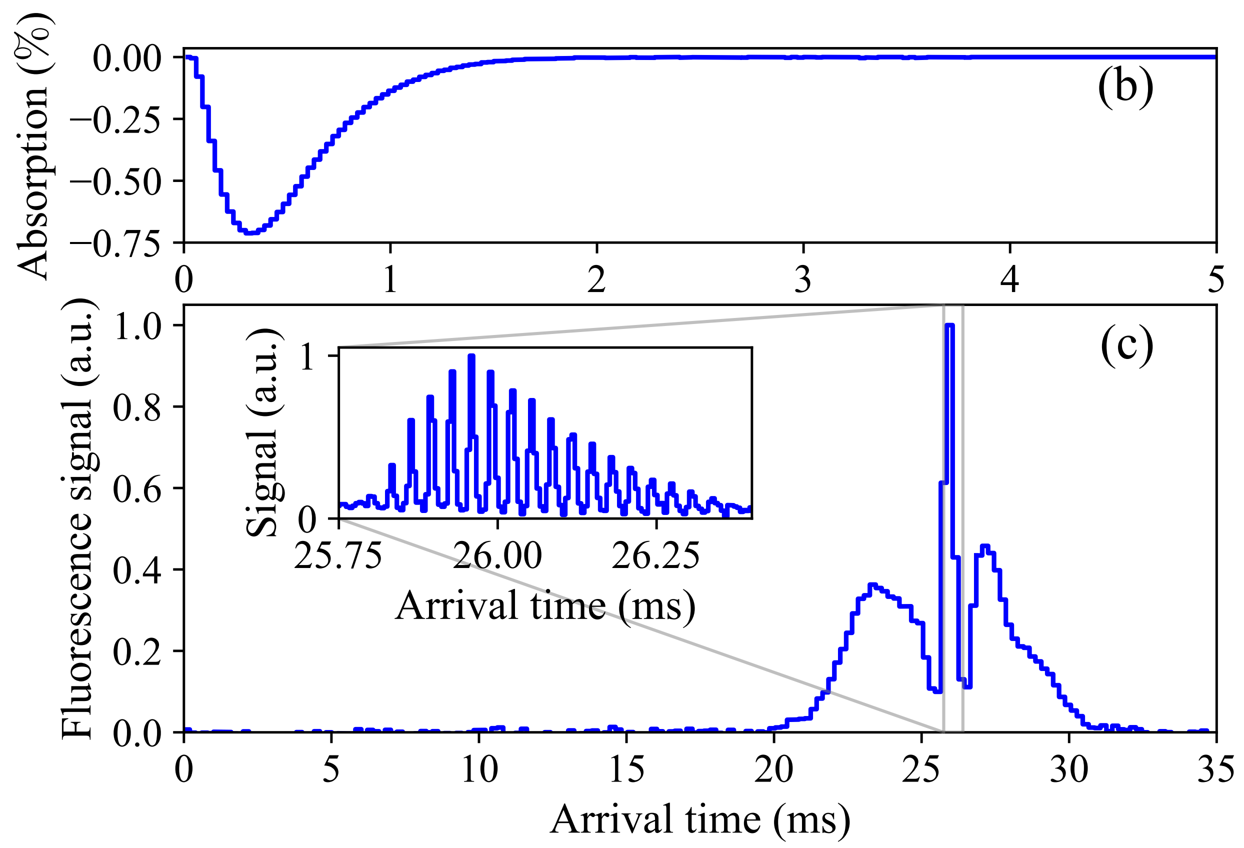




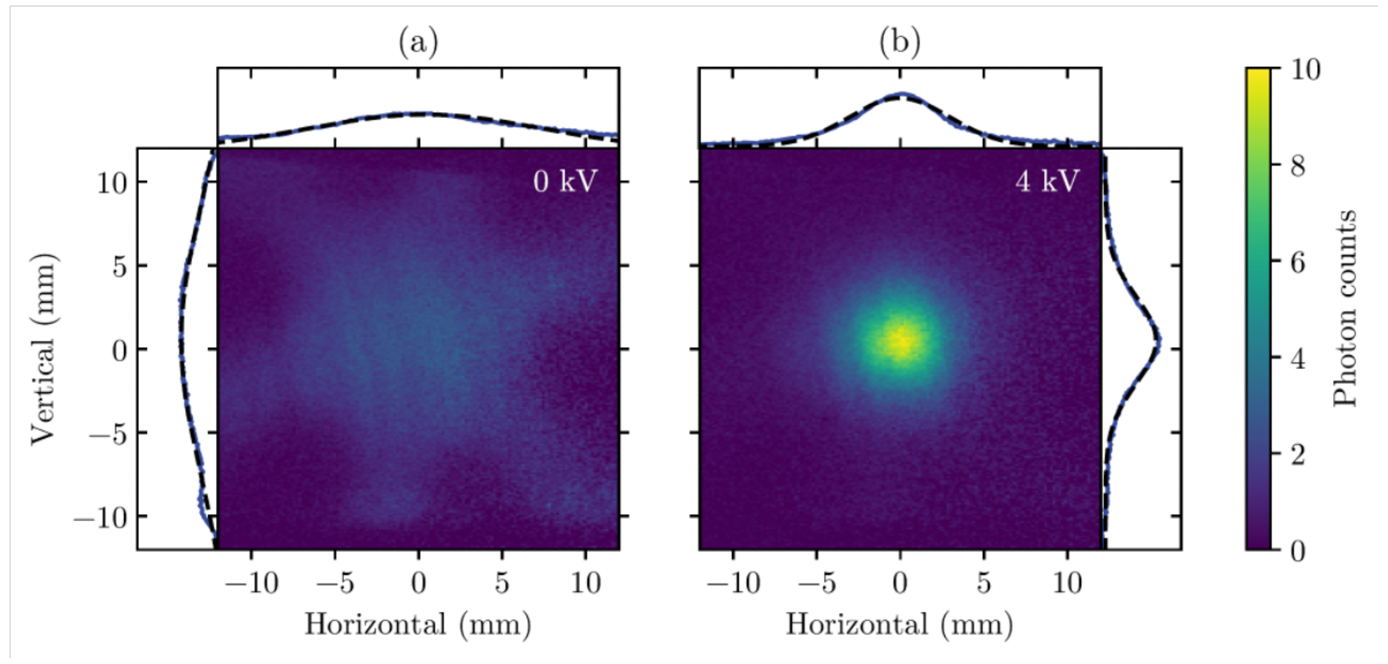
Summary



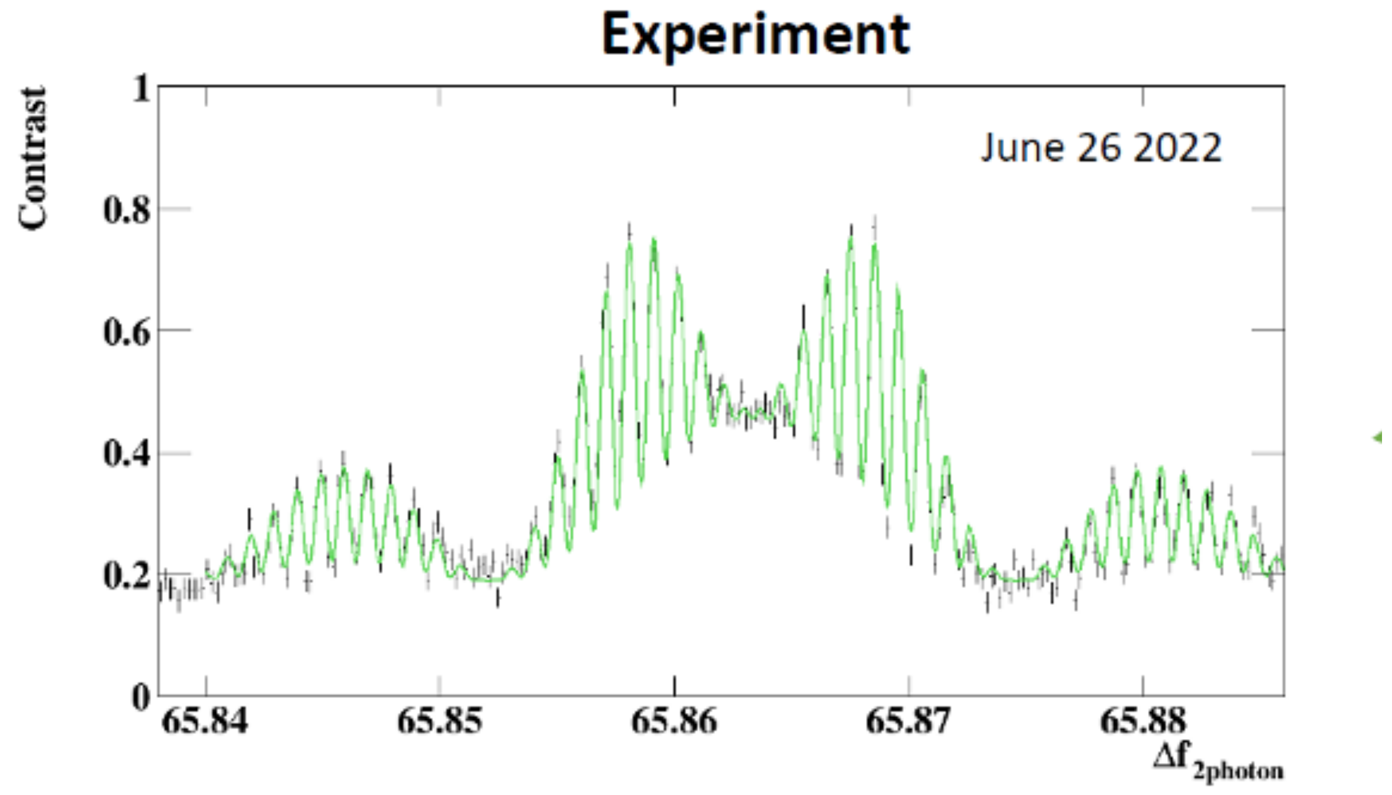
Testing the Standard Model in a table-top experiment



Deceleration demonstrated



Focussing of molecular beam



Spin interference demonstrated and understood

NL-*e*EDM: the team

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