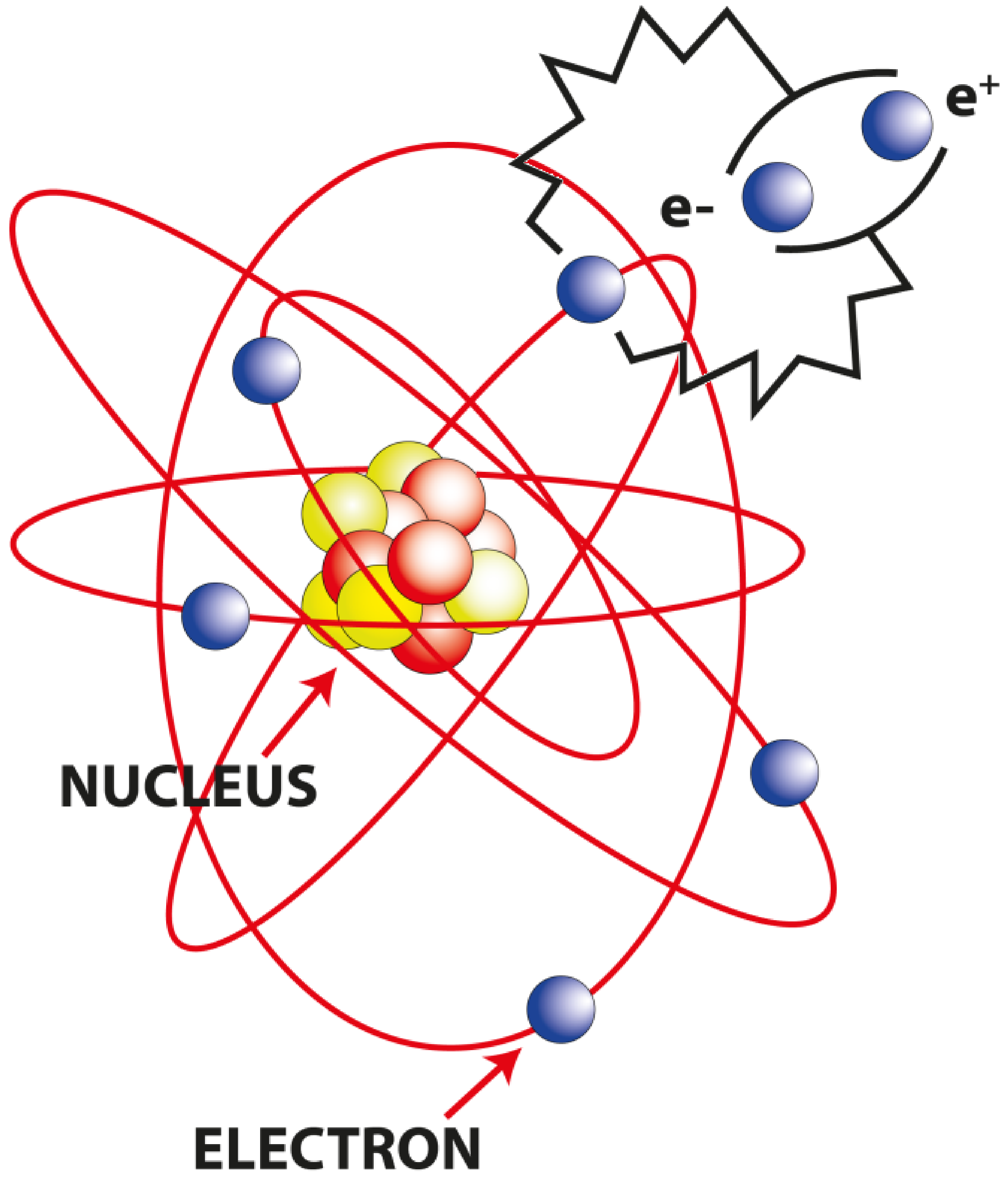
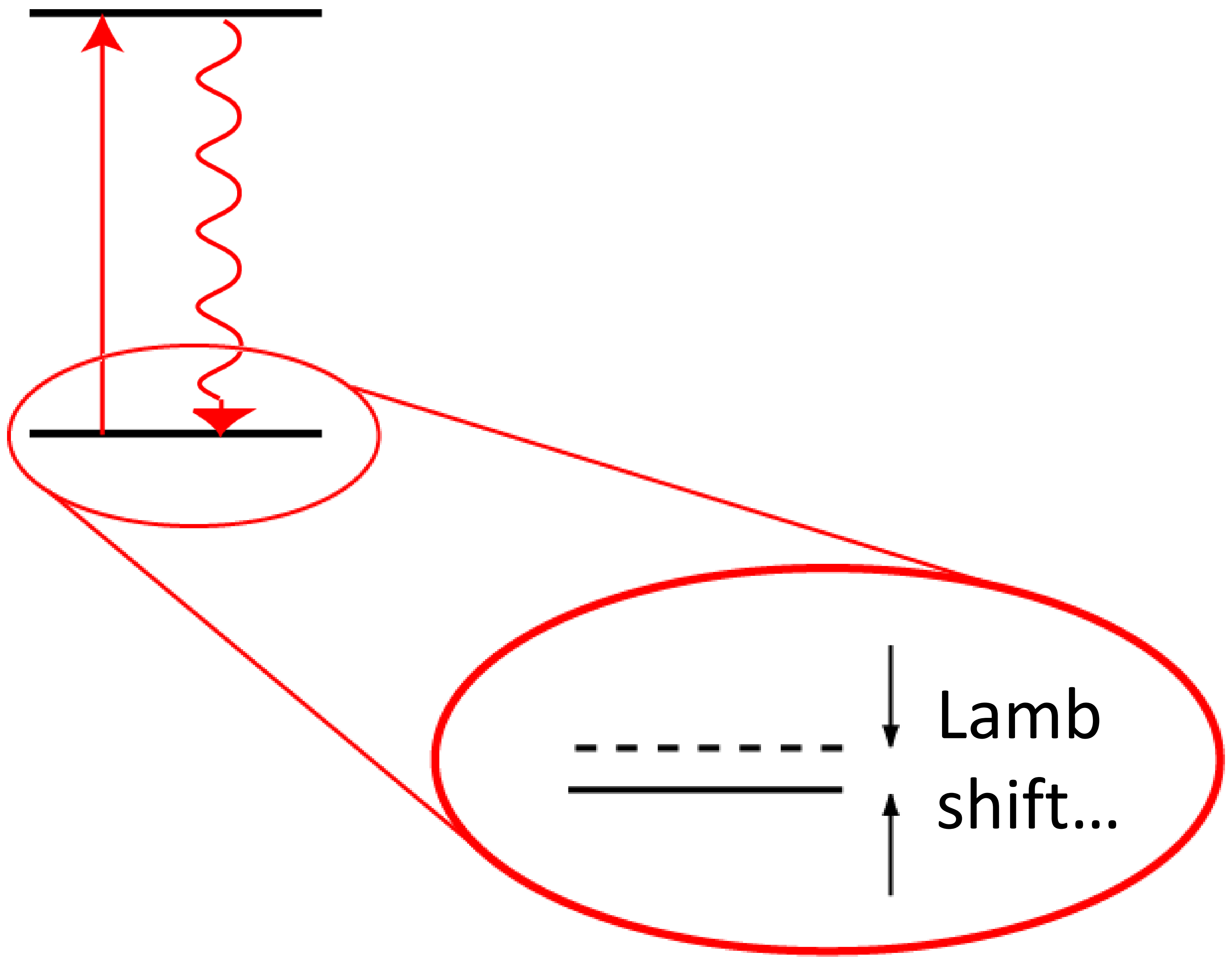
Testing Fundamental Physics using atomic physics techniques

There is a more to the atom than you might think…

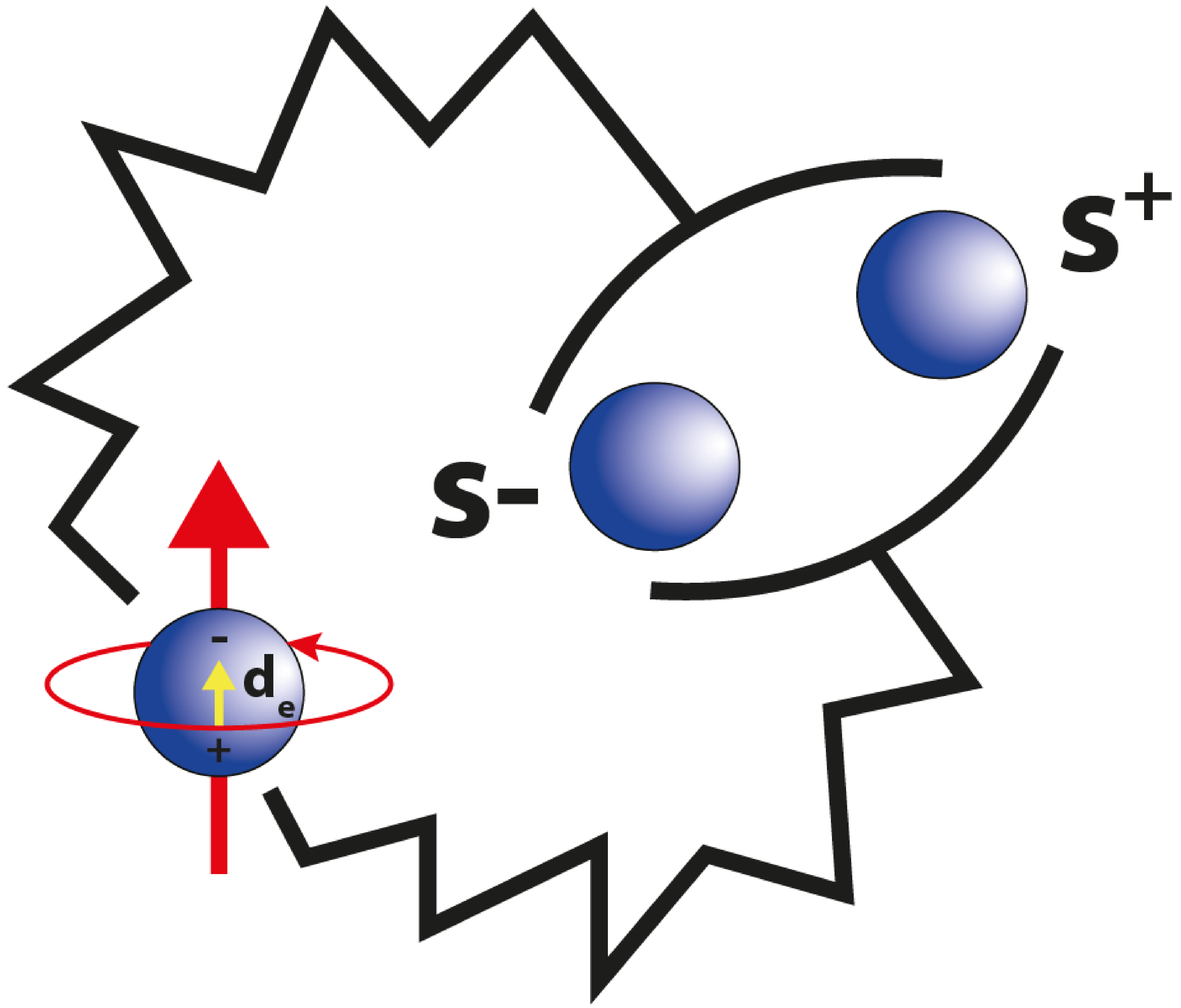
State-of-the-art atomic clocks reach fractional accuracies of 10^{-19} corresponding to absolute accuracies of < 1mHz.





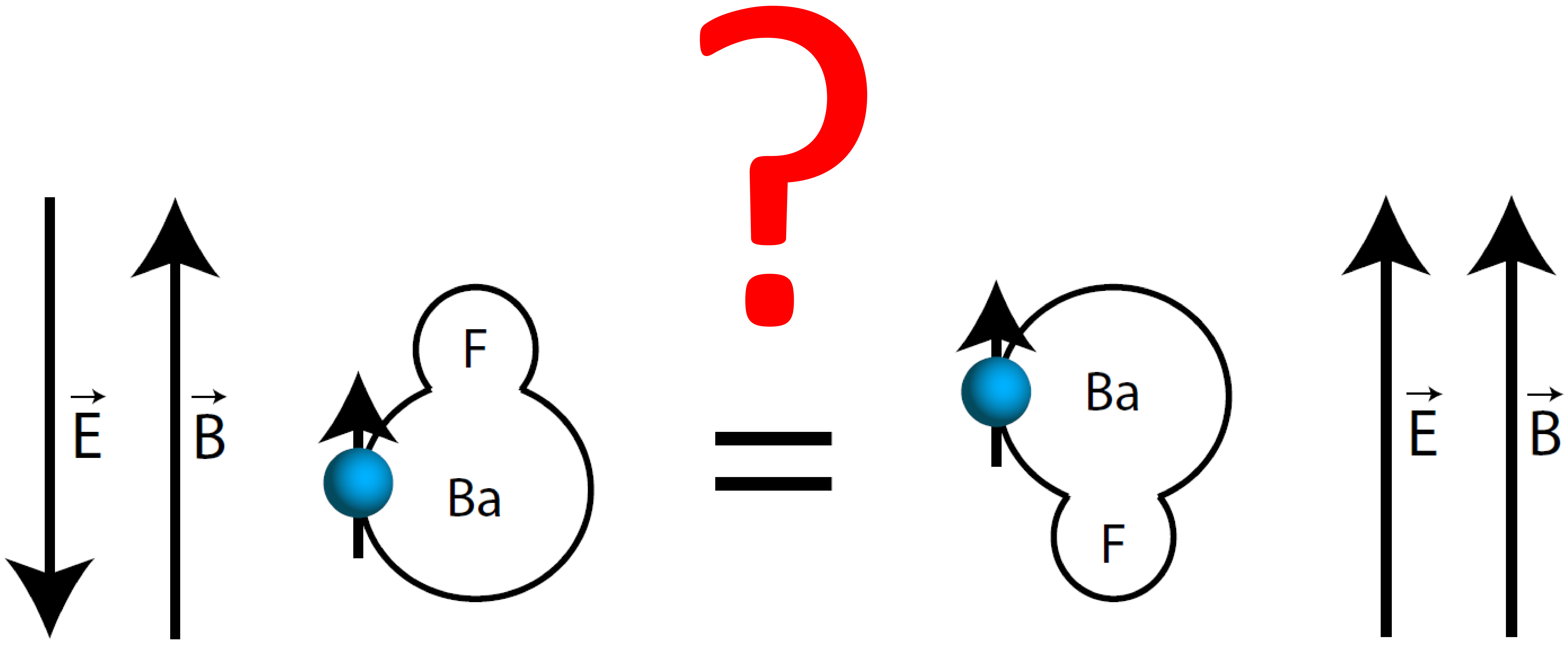
…with precision measurements we can test fundamental interactions and symmetries.

We are searching for CP-violating interactions that give the electron an asymmetric charge distribution



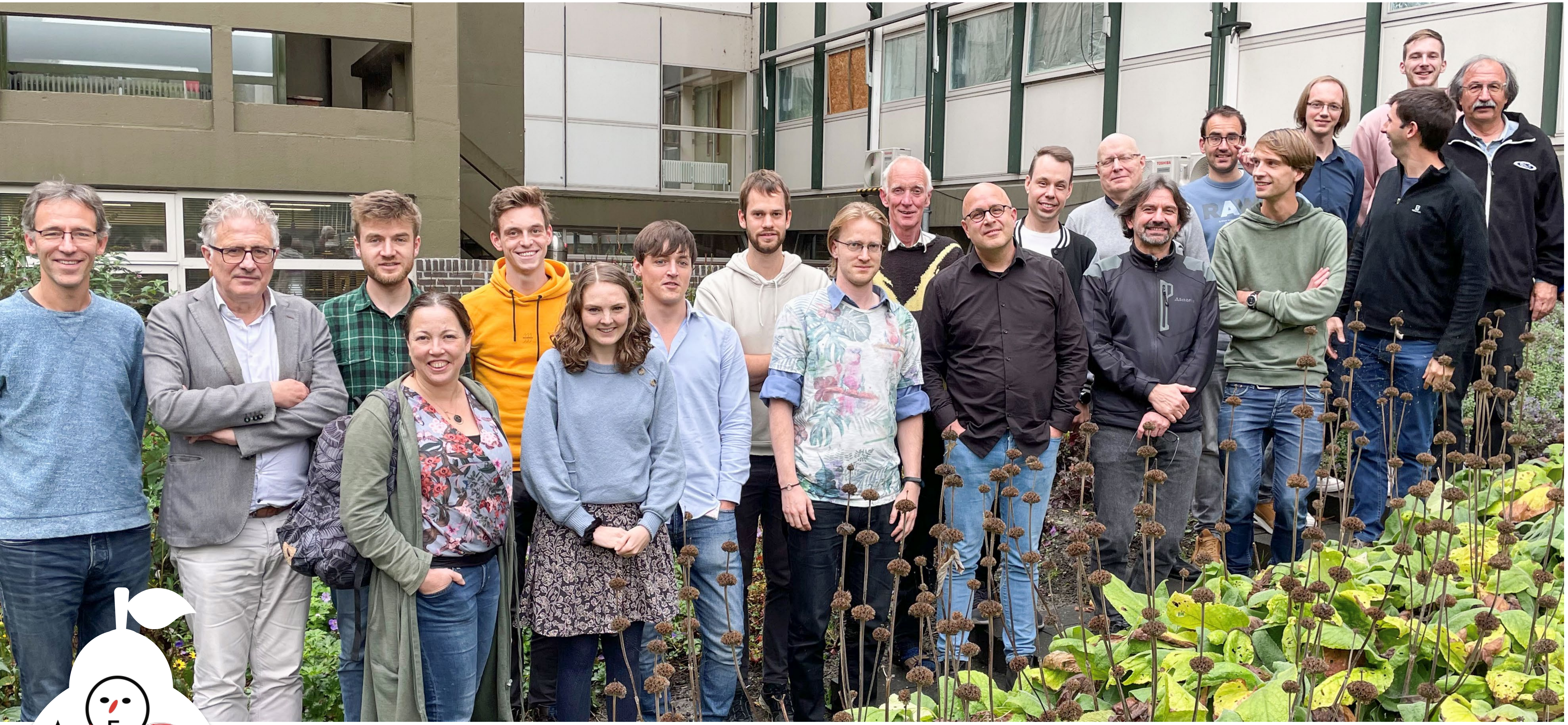
Current best limit in Hf^+:
$|d_e| < 4.1 \times 10^{-30}\ e.cm$
Roussy et al. Science **381**, 46 (2023)
Corresponding to an energy shift below of 50 μHz
SM-prediction: $10^{-38} - 10^{-40}\ e.cm$

How to measure an eEDM



Electromagnetic interactions depend only on absolute value of E-field
Anything that depends on the direction of E is new physics!

The team



Particle physics theory

Jordy de Vries
Rob Timmermans
Heleen Mulder
Lemonia Gialidi

Quantum chemistry

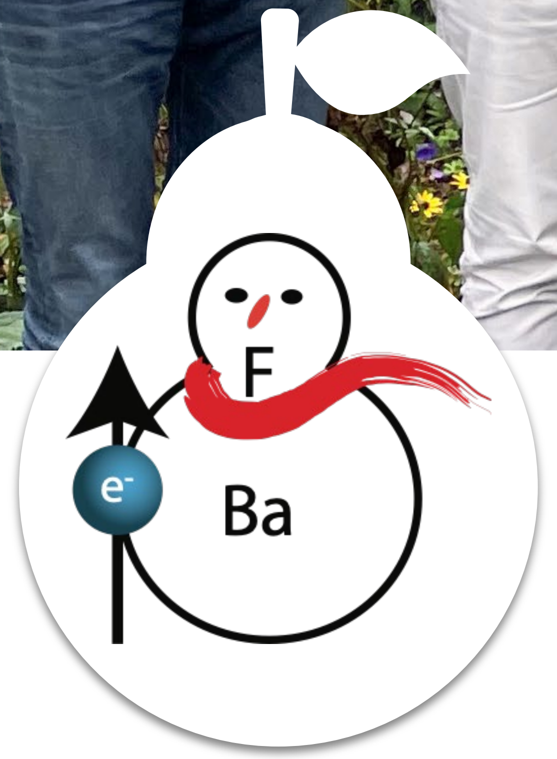
Anastasia Borschevsky
Lukas Pastecka
Agustin Aucar
Eifion Prinsen

Precision experiments

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

Technical staff

Leo Huisman
Oliver Böll
Robert Datema
Nikhef workshops



Think different!

university of groningen
van swinderen institute for particle physics and gravity

Nikhef
Dutch National Institute for (astro)Particle Physics

VU VRIJE UNIVERSITEIT AMSTERDAM

UvA

The experimental facilities

New Lab in Groningen (+ 2 Laserlabs) and @ VU

The eEDM program

Minimize statistical uncertainty

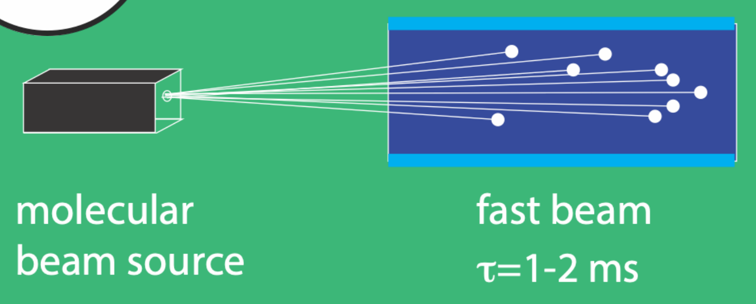
$$S \propto \frac{1}{E\tau\sqrt{N}}$$

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

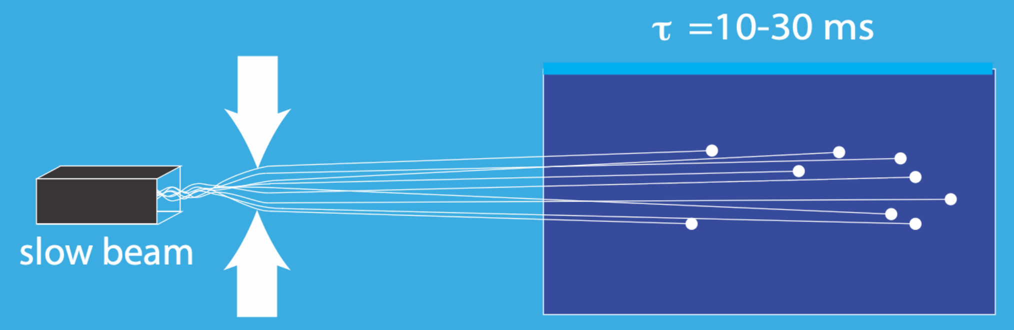
2017-2023
NWO program



Phase 1
Fast beam of BaF molecules

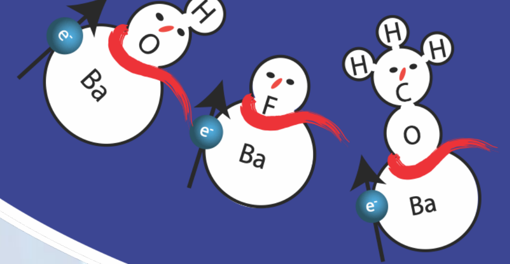
2023-2028
ENW-XL

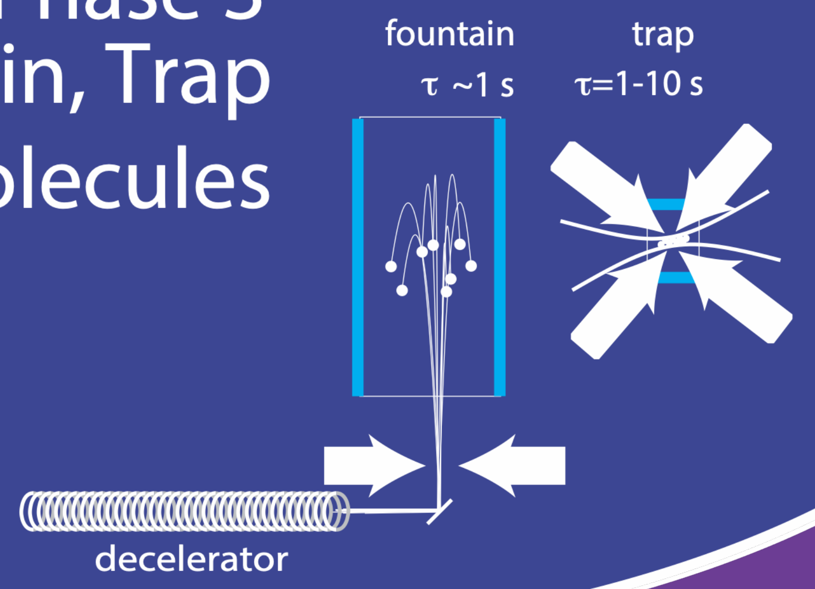
Phase 2
Slow and cold molecular beam



2023-2028
ENW-XL, M2 and VICI

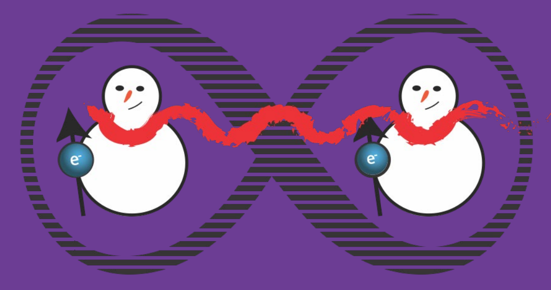
Phase 3
Fountain, Trap
Better molecules





2025-2035

Phase 4
Beyond the quantum limit



Demonstrate an all-optical superposition state creation

Slow beams push magnetic field senstivity to the limit

Polyatomic molecules provide co-magnetometer states

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

Control systematic effects

Phase 1

A complete eEDM experiment

Statistics and systematics of electron EDM searches with BaF

The NL-eEDM collaboration: A. Boeschoten[1,2], V.R. Marshall[1,2], T.B. Meijknecht[1,2], A.P. Touwen[1,2], P. Aggarwal[1,2], N. Balasubramanian[1,2], R. Bause[1,2], H. L. Bethlem[1,3], A. Borschevsky[1,2], T.H. Fikkers[1,2], P.A.B. Haase[1,2], Y. Hao[1], S. Hoekstra[1,2], J.W.F. van Hofslot[1,2], S.A. Jones[1,2], K. Jungmann[1], J.E.J. Levenga[1,2], M.C. Mooij[2,3], H. Mulder[1,2], B.A. Nijman[1,2], E.H. Prinsen[1,2], B.J. Schellenberg[1,2], I.E. Thompson[1,2], R.G.E. Timmermans[1,2], L. van Sloten[1,2], W. Ubachs[3], J. de Vries[2,4], L. Willmann[1,2], Y. Yin[1,2]

[1] Van Swinderen Institute for Particle Physics and Gravity (VSI), University of Groningen, Nijenborgh 3, 9747 AG Groningen, The Netherlands
[2] Nikhef, National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, The Netherlands
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January 30, 2026/ Received: date / Revised version: date

Abstract The NL-eEDM experiment searches for a non-zero electric dipole moment of the electron d_e (eEDM) in the ground state of barium monofluoride (BaF). A beam of BaF from a supersonic expansion source is probed with the spin precession method presented in [1]. This method permits the extraction of an eEDM value as well as values for parameters causing a possible systematic bias leading to a false eEDM. The currently achievable sensitivity is limited by statistics collected in a period of 34 hours and yields an d_e of $2(3) \times 10^{-25}$ e cm. Furthermore, from the same dataset sufficiently strong limits on parameters which can induce a false eEDM are extracted. These are mainly the electric field $\mathbf{E}$ and the intensity of the lasers fields in the fiducial volume of the experiment. We summarize the steps required to upgrade of the experiment to reach a competitive level on d_e, e.g. an intense laser-cooled beam from a cryogenic buffer gas source and the light collection efficiency of fluorescence.

PACS. XX.XX.XX No PACS code given

1 Introduction

Searches for permanent electric dipole moments (EDMs) with composite systems, such as atoms and molecules, benefit from their high sensitivity to new interactions between elementary particles that violate both time-reversal (T) and parity (P) symmetry. Since for local quantum field theories T violation is equivalent to the violation of CP – the combination of charge conjugation (C) and parity – a nonzero EDM implies P,T and equivalently CP violation [2, 3, 4].

The Standard Model (SM) of particle physics (with-

the experimental upper limits on EDMs of the neutron [9] and the ^{199}Hg atom [10]. It is a persistent puzzle why the $\bar{\theta}$ parameter is so small.

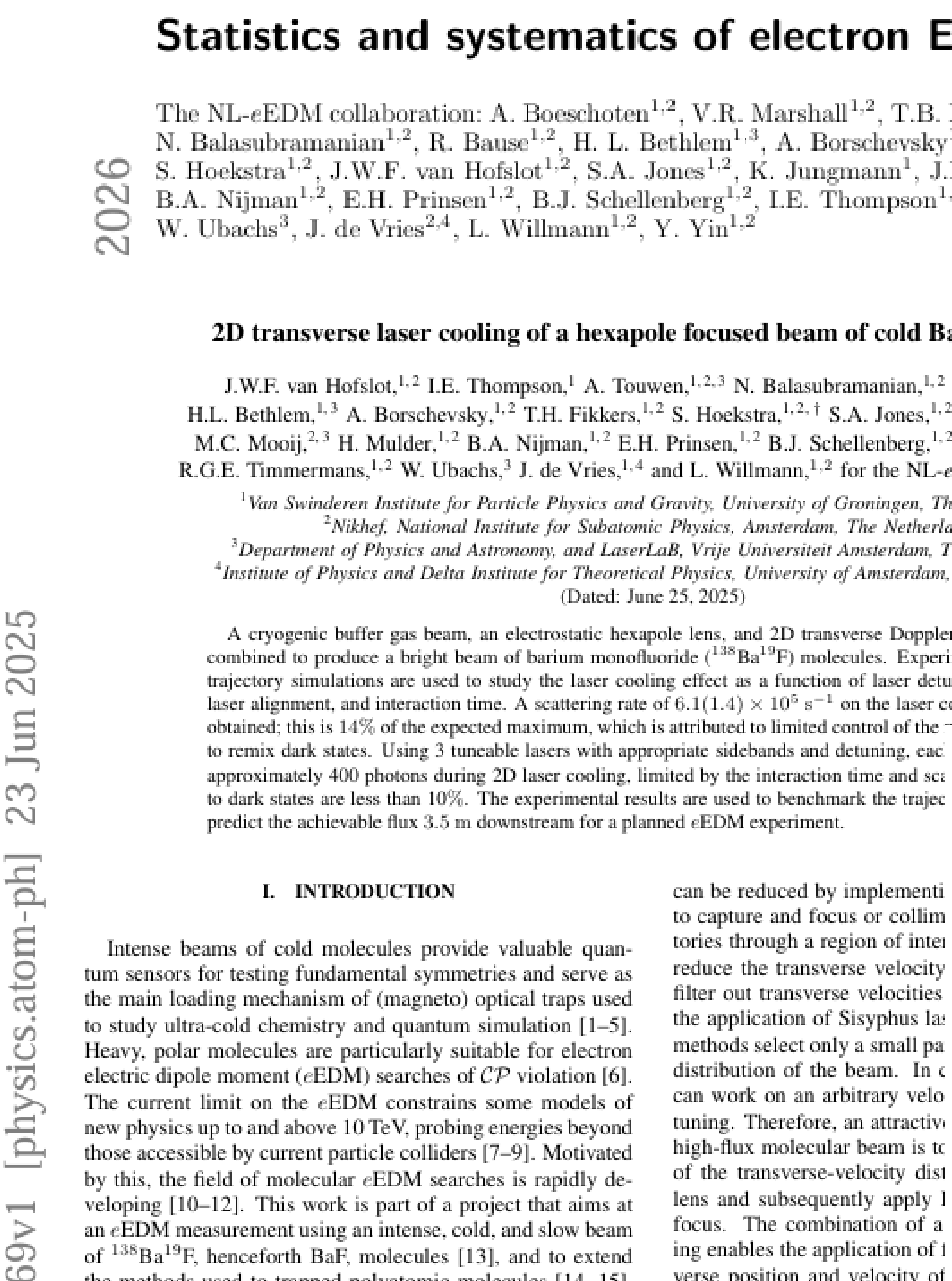
New sources of CP violation are expected in scenarios that embed the SM in a more complete theory of particle physics. Such theories generically predict EDM values that are measurable in the ongoing or upcoming EDM experiments. In addition, in order to generate a matter-antimatter asymmetry observed in the universe, CP violation beyond the SM is required [11] assuming CPT to be a good symmetry [12]. For example, in electroweak baryogenesis [13], this typically leads to EDMs larger than SM

Phase 1

A complete eEDM experiment

Phase 2

A slow and intense BaF molecular beam



2026

Statistics and systematics of electron EDM searches with BaF

The NL-eEDM collaboration: A. Boeschoten[1,2], V.R. Marshall[1,2], T.B. Meijknecht[1,2], A.P. Touwen[1,2], P. Aggarwal[1,2], N. Balasubramanian[1,2], R. Bause[1,2], H. L. Bethlem[1,3], A. Borschevsky[1,2], T.H. Fikkers[1,2], P.A.B. Haase[1,2], Y. Hao[1], S. Hoekstra[1,2], J.W.F. van Hofslot[1,2], S.A. Jones[1,2], K. Jungmann[1], J.E.J. Levenga[1,2], M.C. Mooij[2,3], H. Mulder[1,2], B.A. Nijman[1,2], E.H. Prinsen[1,2], B.J. Schellenberg[1,2], I.E. Thompson[1,2], R.G.E. Timmermans[1,2], L. van Sloten[1,2], W. Ubachs[3], J. de Vries[2,4], L. Willmann[1,2], Y. Yin[1,2]

G Groningen,

The Nether-

erlands

69v1 [physics.atom-ph] 23 Jun 2025

2D transverse laser cooling of a hexapole focused beam of cold BaF molecules

J.W.F. van Hofslot,[1,2] I.E. Thompson,[1] A. Touwen,[1,2,3] N. Balasubramanian,[1,2] R. Bause,[1,2,*] H.L. Bethlem,[1,3] A. Borschevsky,[1,2] T.H. Fikkers,[1,2] S. Hoekstra,[1,2,†] S.A. Jones,[1,2] J.E.J. Levenga,[1,2] M.C. Mooij,[2,3] H. Mulder,[1,2] B.A. Nijman,[1,2] E.H. Prinsen,[1,2] B.J. Schellenberg,[1,2] L. van Sloten,[1,2] R.G.E. Timmermans,[1,2] W. Ubachs,[3] J. de Vries,[1,4] and L. Willmann,[1,2] for the NL-eEDM collaboration

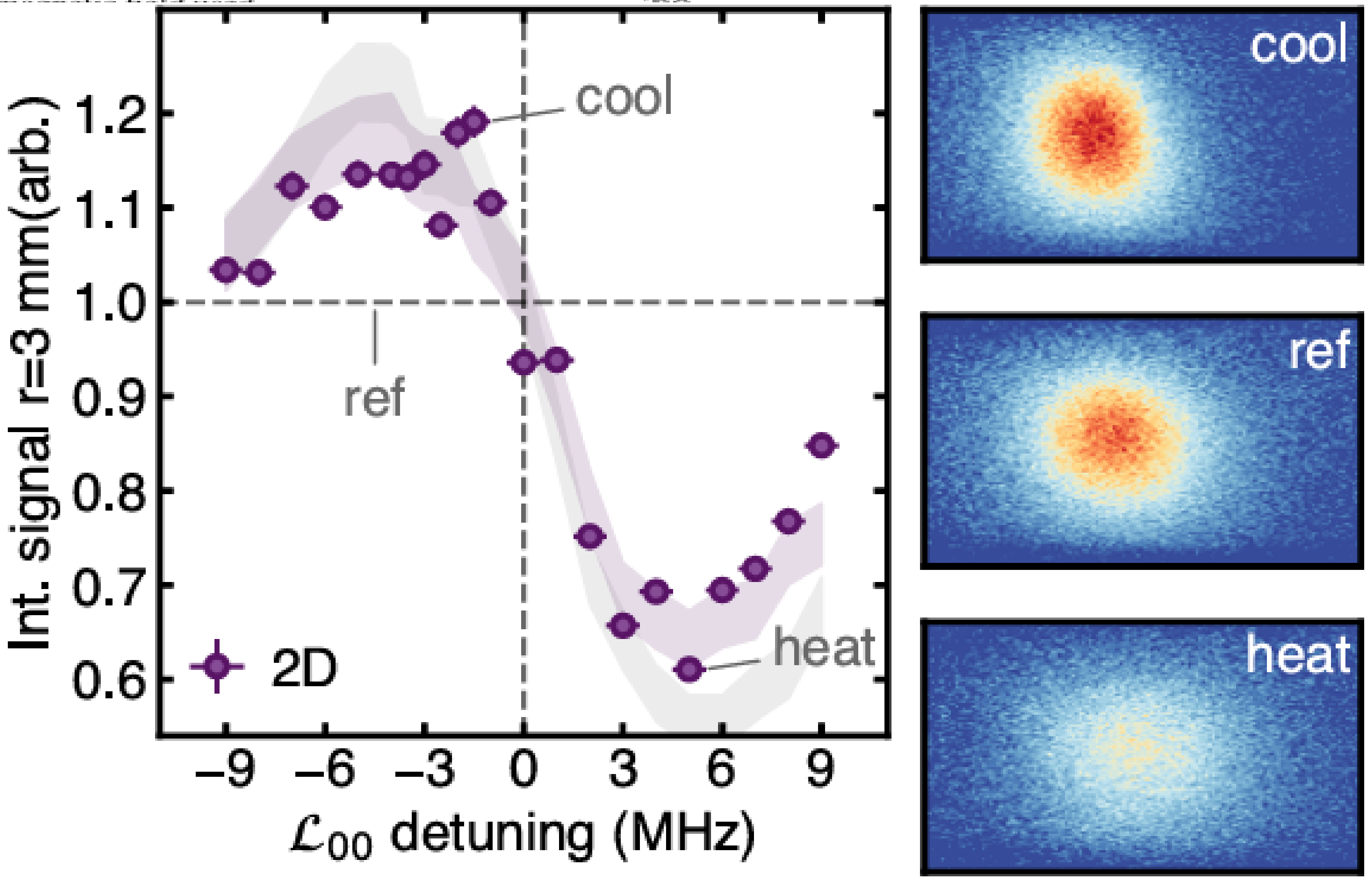
[1]*Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, The Netherlands*
[2]*Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands*
[3]*Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit Amsterdam, The Netherlands*
[4]*Institute of Physics and Delta Institute for Theoretical Physics, University of Amsterdam, The Netherlands*
(Dated: June 25, 2025)

A cryogenic buffer gas beam, an electrostatic hexapole lens, and 2D transverse Doppler laser cooling are combined to produce a bright beam of barium monofluoride ($^{138}Ba^{19}F$) molecules. Experimental results and trajectory simulations are used to study the laser cooling effect as a function of laser detuning, laser power, laser alignment, and interaction time. A scattering rate of $6.1(1.4) \times 10^5\ s^{-1}$ on the laser cooling transition is obtained; this is 14% of the expected maximum, which is attributed to limited control of the ... to remix dark states. Using 3 tuneable lasers with appropriate sidebands and detuning, eac... approximately 400 photons during 2D laser cooling, limited by the interaction time and sca... to dark states are less than 10%. The experimental results are used to benchmark the trajec... predict the achievable flux 3.5 m downstream for a planned eEDM experiment.

I. INTRODUCTION

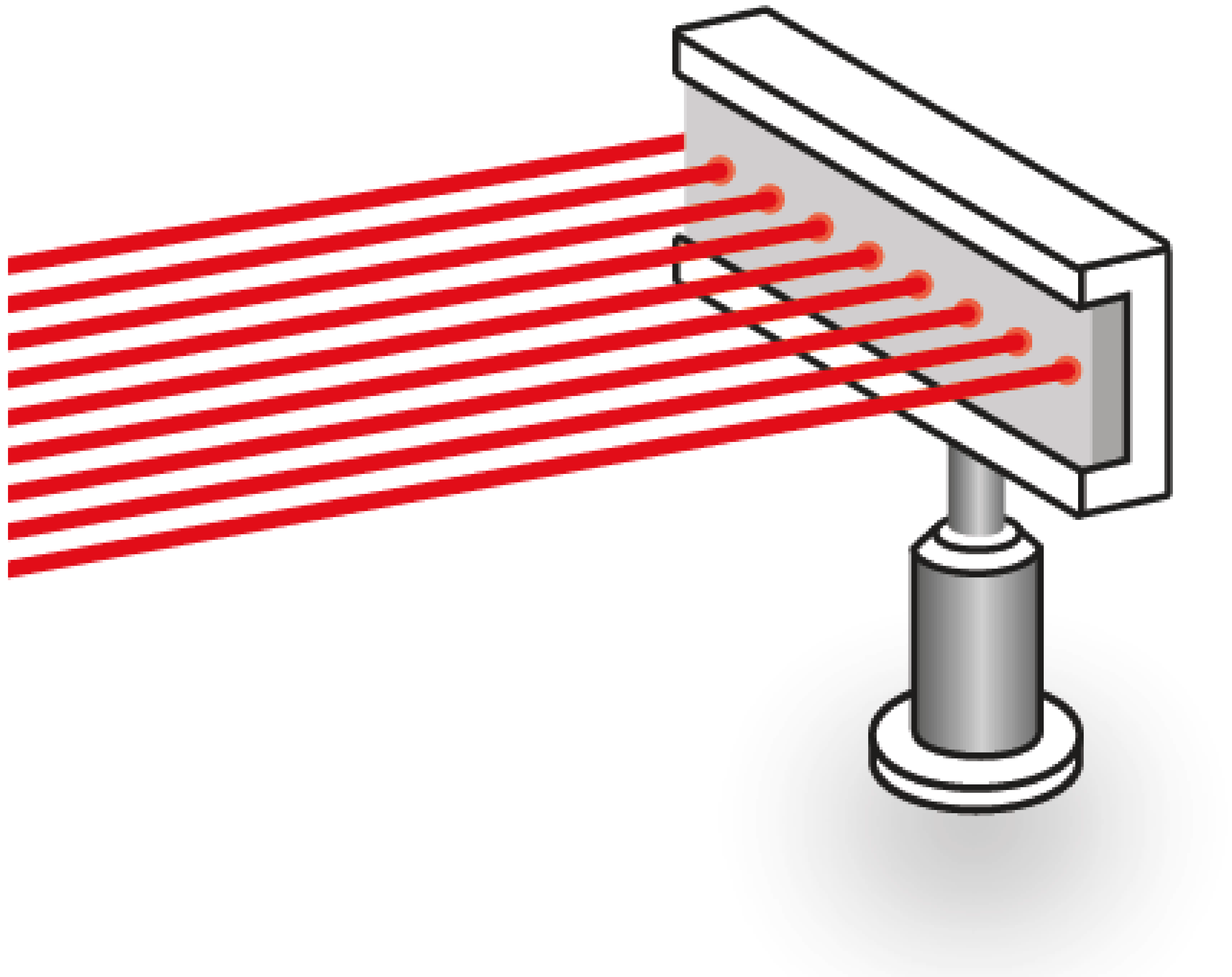
Intense beams of cold molecules provide valuable quantum sensors for testing fundamental symmetries and serve as the main loading mechanism of (magneto) optical traps used to study ultra-cold chemistry and quantum simulation [1–5]. Heavy, polar molecules are particularly suitable for electron electric dipole moment (eEDM) searches of $\mathcal{CP}$ violation [6]. The current limit on the eEDM constrains some models of new physics up to and above 10 TeV, probing energies beyond those accessible by current particle colliders [7–9]. Motivated by this, the field of molecular eEDM searches is rapidly developing [10–12]. This work is part of a project that aims at an eEDM measurement using an intense, cold, and slow beam of $^{138}Ba^{19}F$, henceforth BaF, molecules [13], and to extend ...

can be reduced by implementi... to capture and focus or collim... tories through a region of inter... reduce the transverse velocity... filter out transverse velocities... the application of Sisyphus las... methods select only a small pa... distribution of the beam. In c... can work on an arbitrary velo... tuning. Therefore, an attractive... high-flux molecular beam is to... of the transverse-velocity dist... lens and subsequently apply l... focus. The combination of a... ing enables the application of t... verse position and velocity of ...



A bright beam of laser cooled BaF molecules for precision experiments

Joost W.F. van Hofslot



Tuesday 12 May 2026 at 16.15
at the University of Groningen.

Phase 3

Creating and trapping polyatomic molecules

A cold beam of BaOH molecules using a water-vapour seeded neon gas

Ties H. Fikkers[1,2]

Nithesh Balasubramanian[1,2]

Joost W.F. van Hofslot[1,2]

Maarten C. Mooij[2,3]

Hendrick L. Bethlem[1,3]

Steven Hoekstra[1,2]

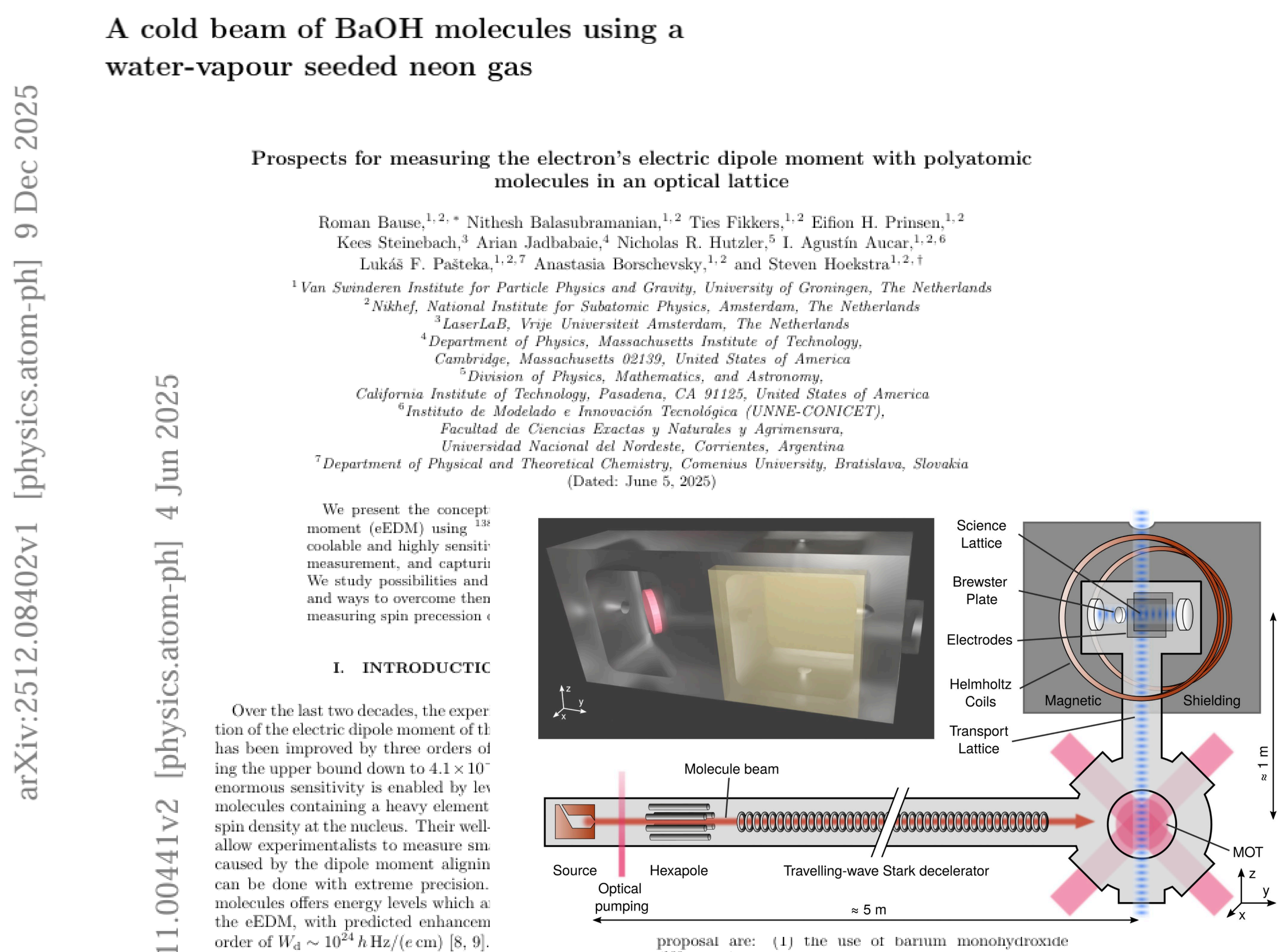
[1] Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, The Netherlands
[2] Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands
[3] Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit Amsterdam, The Netherlands

E-mail: s.hoekstra@rug.nl

Abstract. In this paper we report on the production and characterization of a cold beam of BaOH molecules using a cryogenic buffer-gas beam source. BaOH is a highly suitable molecule for studies of the violation of fundamental symmetries, such as the search for the electron's electric dipole moment. BaOH molecules are synthesised inside the cold source through laser ablation of a barium metal target while water vapor is seeded into the neon buffer gas. The BaOH flux is significantly enhanced (~11 times) when laser-exciting the barium atoms inside the buffer-gas cell on the $^1S_0 - ^3P_1$ transition. A similar enhancement has been reported for other alkaline-earth(-like) monohydroxides. For typical source conditions, the molecular beam has an average velocity of ≈ 180 m/s and an intensity of $\sim 10^9$ molecules s^{-1} in $N = 1$, which is comparable to that of cryogenic BaF beams.

Phase 3

Creating and trapping polyatomic molecules



arXiv:2512.08402v1 [physics.atom-ph] 9 Dec 2025

A cold beam of BaOH molecules using a water-vapour seeded neon gas

11.00441v2 [physics.atom-ph] 4 Jun 2025

Prospects for measuring the electron's electric dipole moment with polyatomic molecules in an optical lattice

Roman Bause,[1,2,*] Nithesh Balasubramanian,[1,2] Ties Fikkers,[1,2] Eifion H. Prinsen,[1,2] Kees Steinebach,[3] Arian Jadbabaie,[4] Nicholas R. Hutzler,[5] I. Agustín Aucar,[1,2,6] Lukáš F. Pašteka,[1,2,7] Anastasia Borschevsky,[1,2] and Steven Hoekstra[1,2,†]

[1] *Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, The Netherlands*
[2] *Nikhef, National Institute for Subatomic Physics, Amsterdam, The Netherlands*
[3] *LaserLaB, Vrije Universiteit Amsterdam, The Netherlands*
[4] *Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States of America*
[5] *Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, United States of America*
[6] *Instituto de Modelado e Innovación Tecnológica (UNNE-CONICET), Facultad de Ciencias Exactas y Naturales y Agrimensura, Universidad Nacional del Nordeste, Corrientes, Argentina*
[7] *Department of Physical and Theoretical Chemistry, Comenius University, Bratislava, Slovakia*

(Dated: June 5, 2025)

We present the concept
moment (eEDM) using [138]
coolable and highly sensiti
measurement, and capturi
We study possibilities and
and ways to overcome the
measuring spin precession

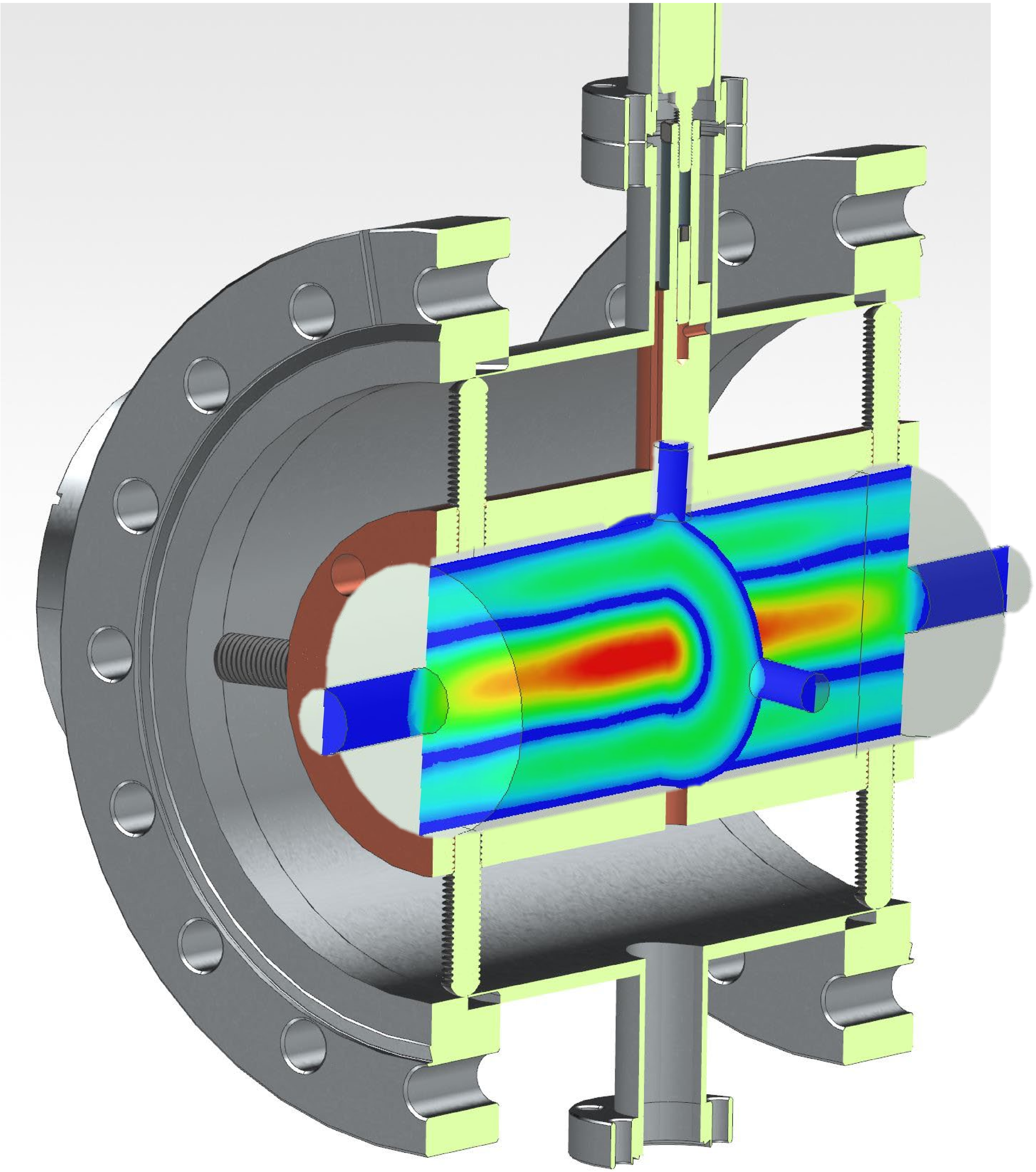
I. INTRODUCTIC

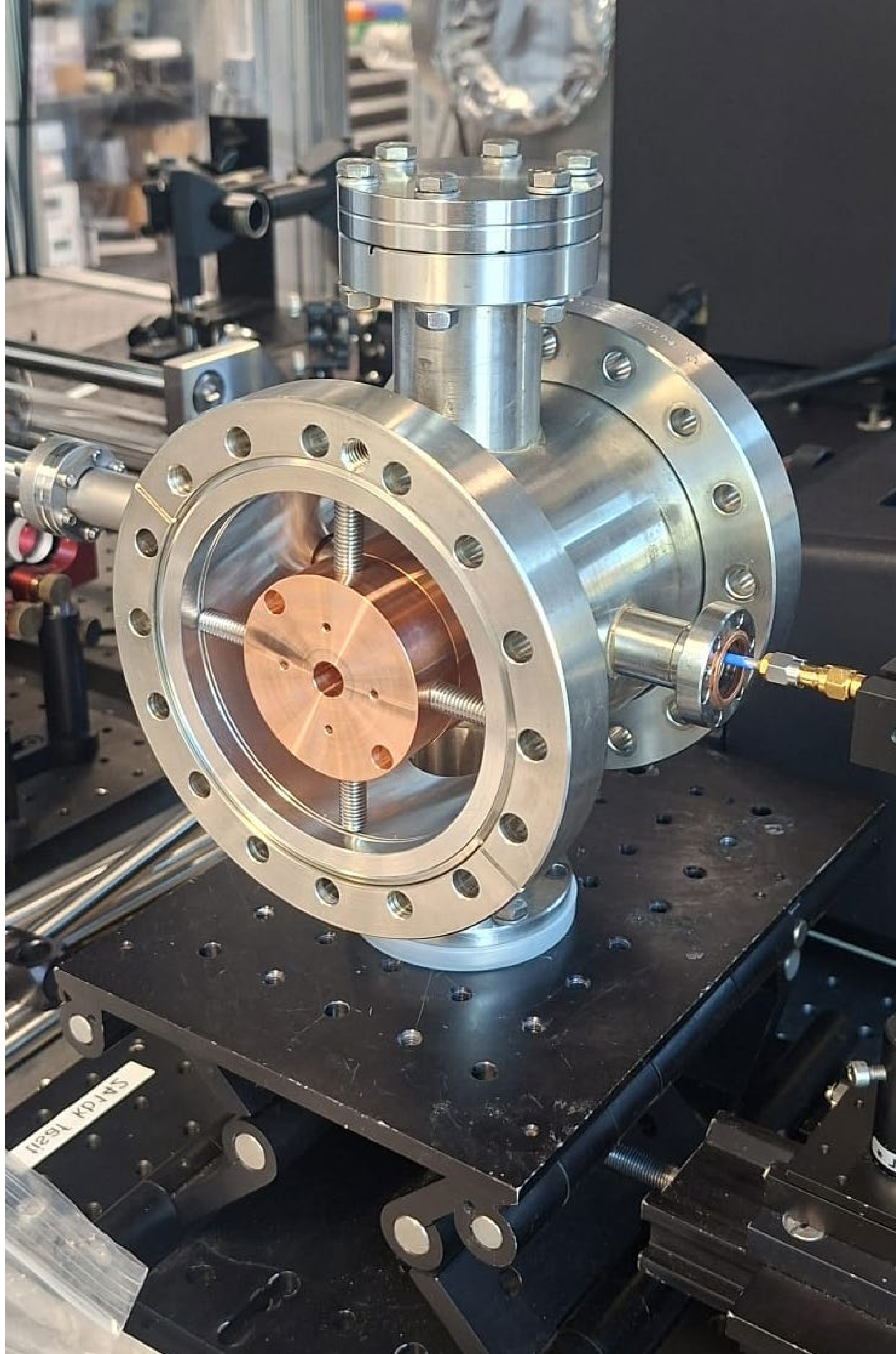
Over the last two decades, the exper
tion of the electric dipole moment of th
has been improved by three orders of
ing the upper bound down to $4.1 \times 10^{-}$
enormous sensitivity is enabled by le
molecules containing a heavy element
spin density at the nucleus. Their well-
allow experimentalists to measure sm
caused by the dipole moment alignin
can be done with extreme precision.
molecules offers energy levels which a
the eEDM, with predicted enhancem
order of $W_d \sim 10^{24}\, h\,\mathrm{Hz}/(e\,\mathrm{cm})$ [8, 9].

proposal are: (1) the use of barium monohydroxide

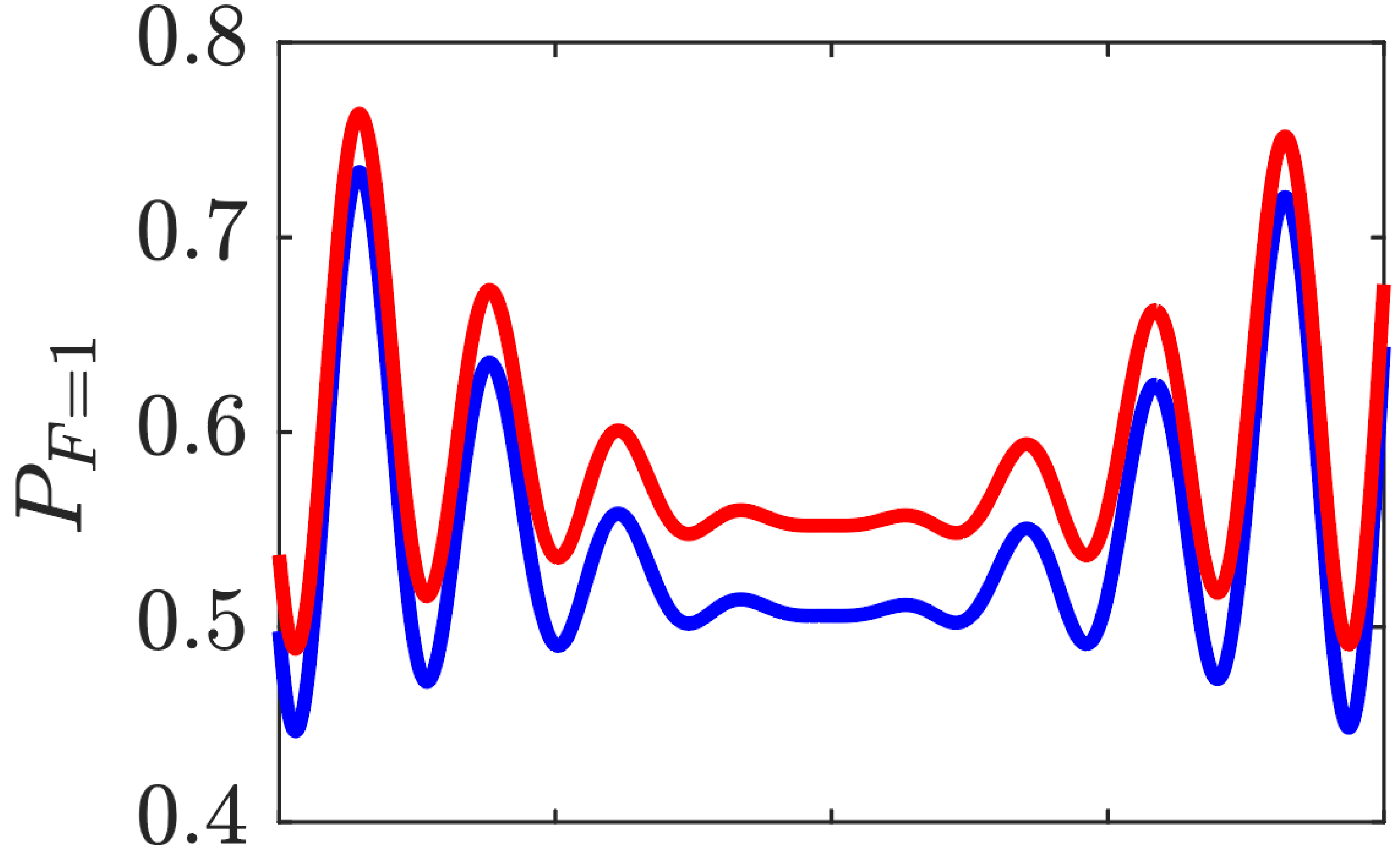
Phase 4

Increased sensitivity through entangled molecules



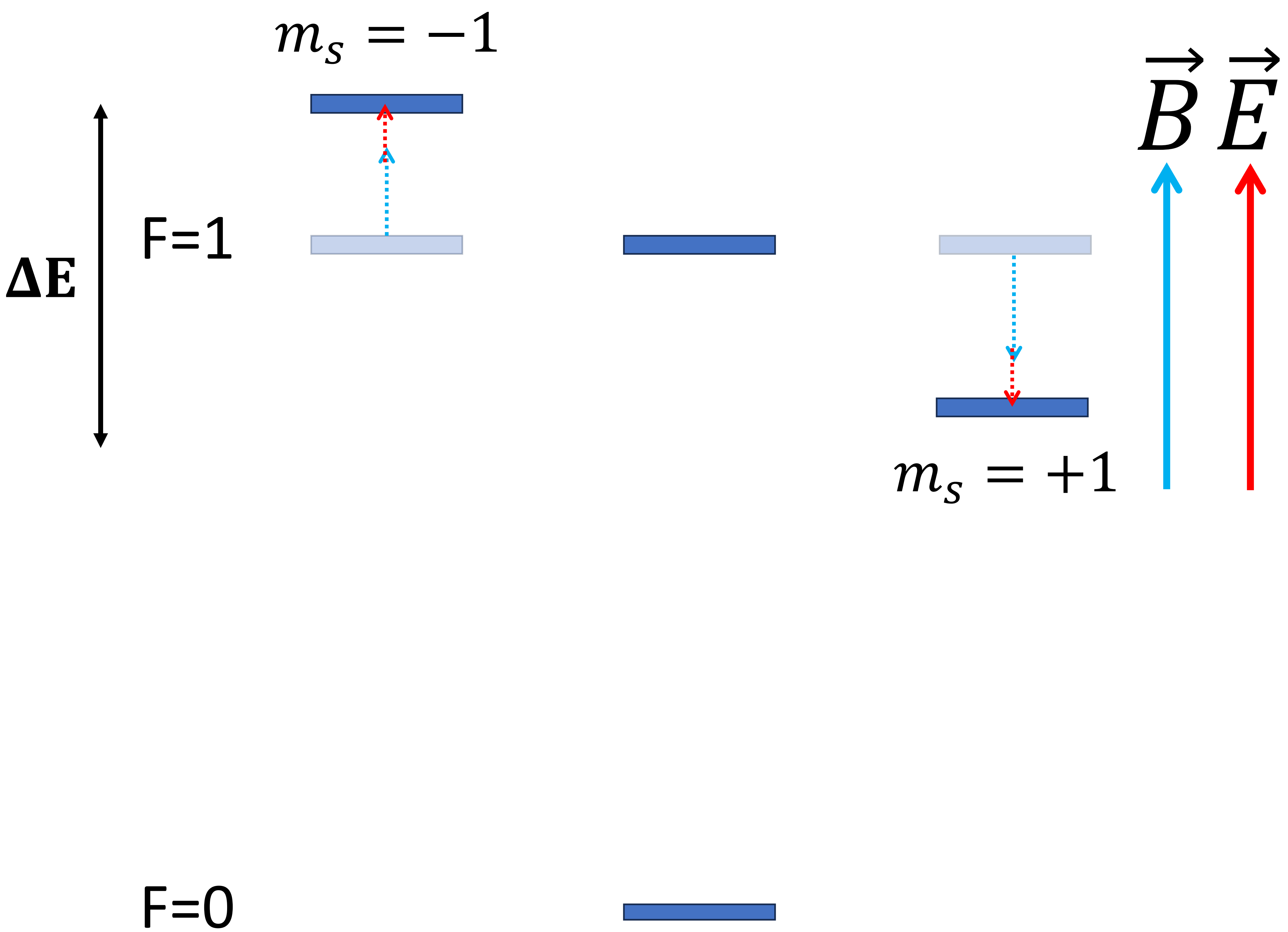


Statistics and Systematics of electron EDM searches with BaF



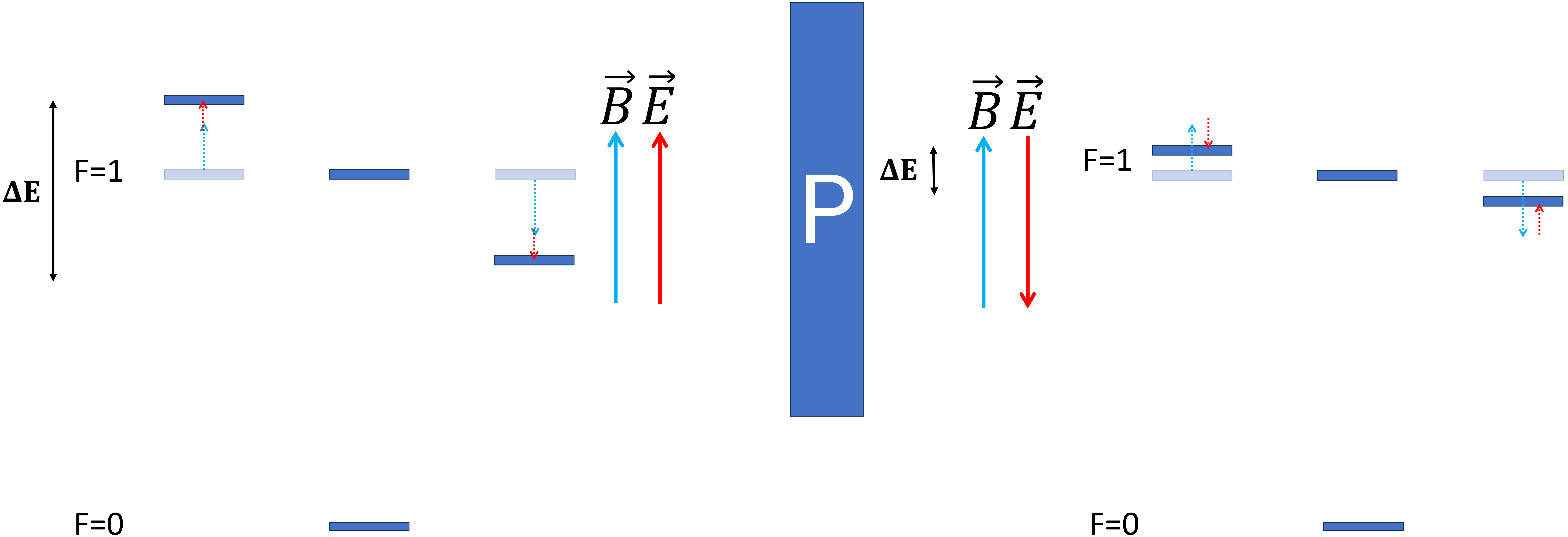
*e*EDM in a molecule

- Dipole moments → linear energy shifts with electric/magnetic fields

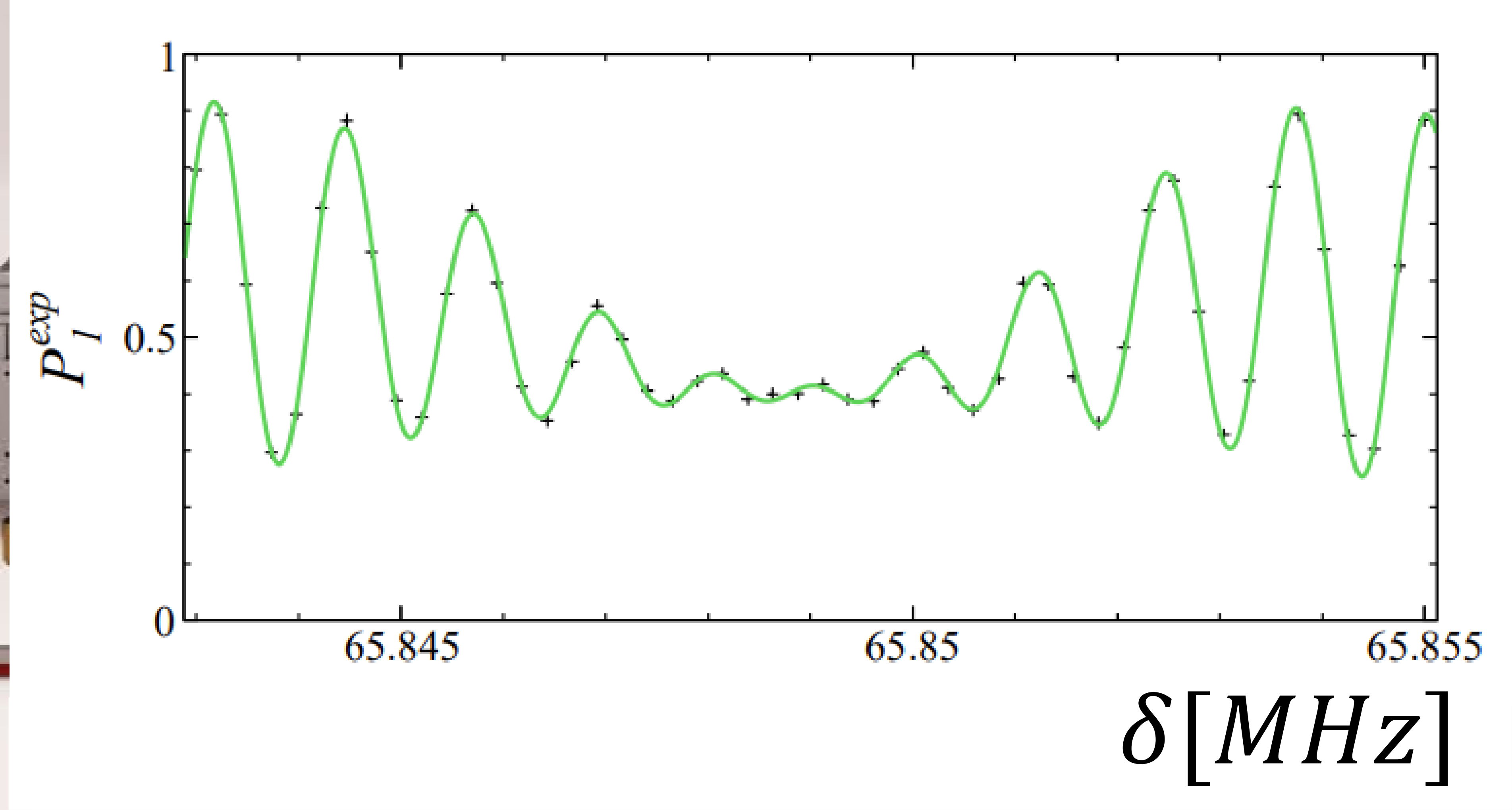


*e*EDM in a molecule

- ΔE is our EDM signature

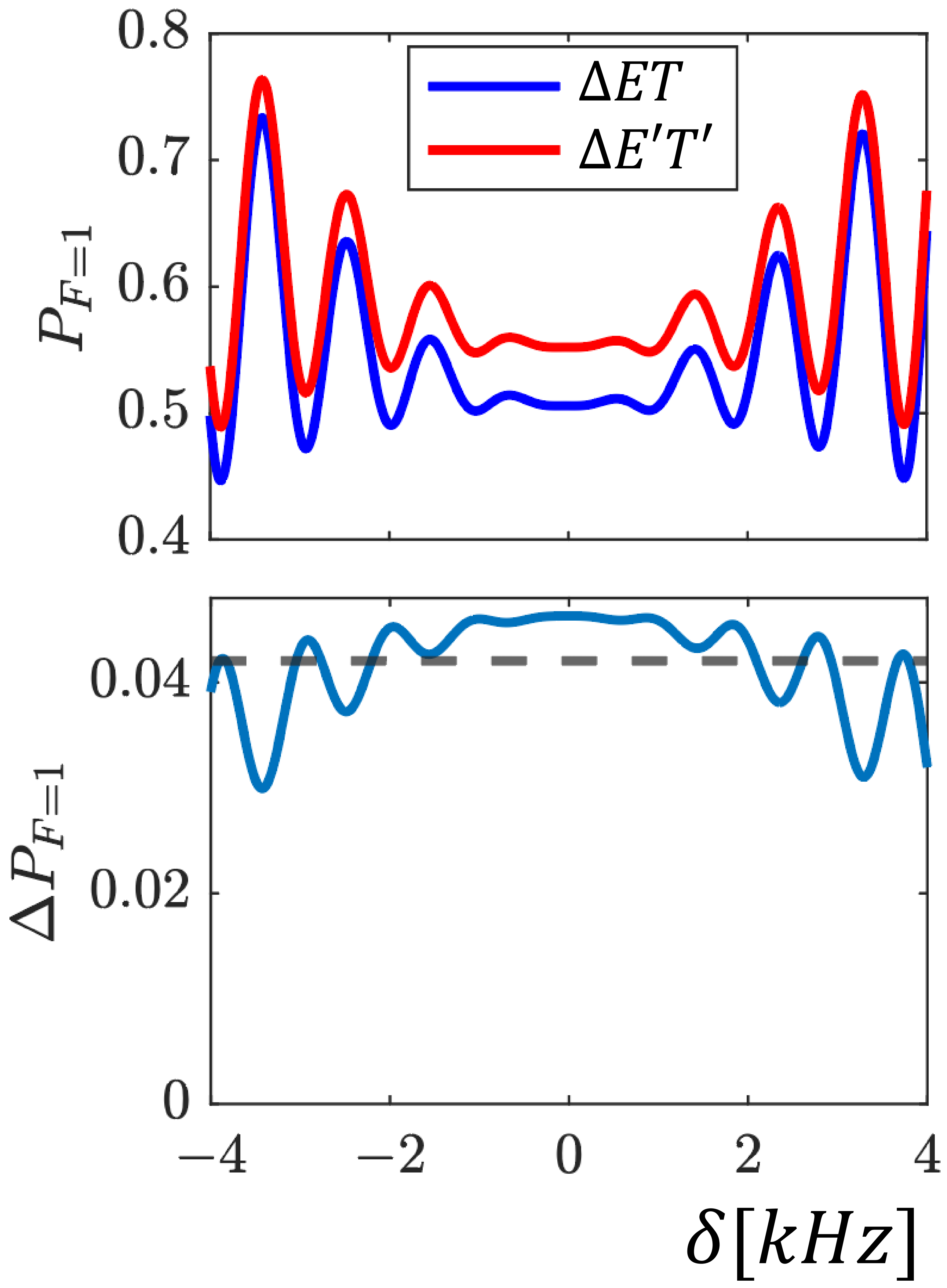


The Experimental Setup: Described by model from first principles



The eEDM effect

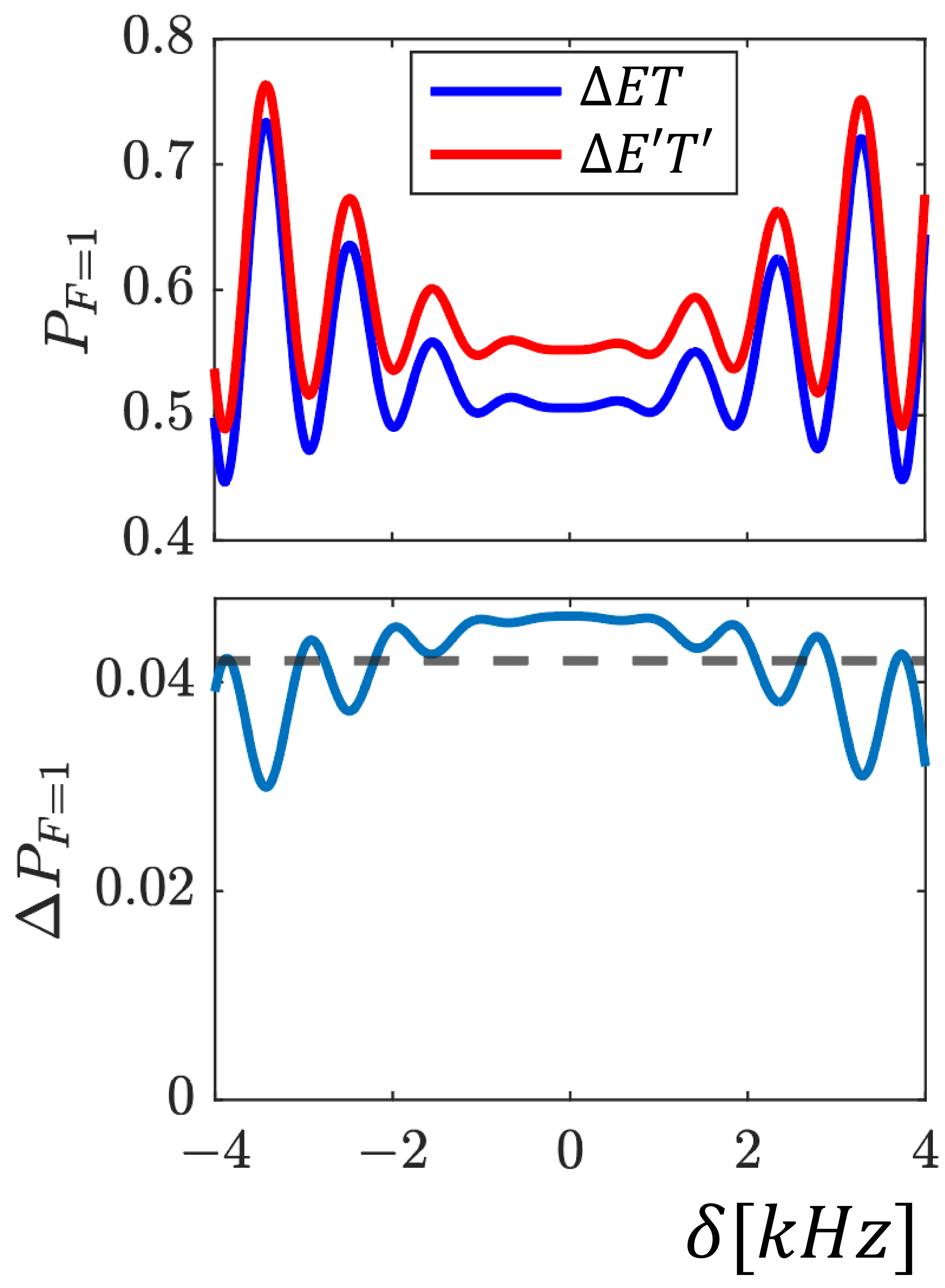
- Model includes
  - ΔE = Energy difference
  - T = Interaction time
  - + experimental parameters
- Effect of eEDM is a shift of the signal



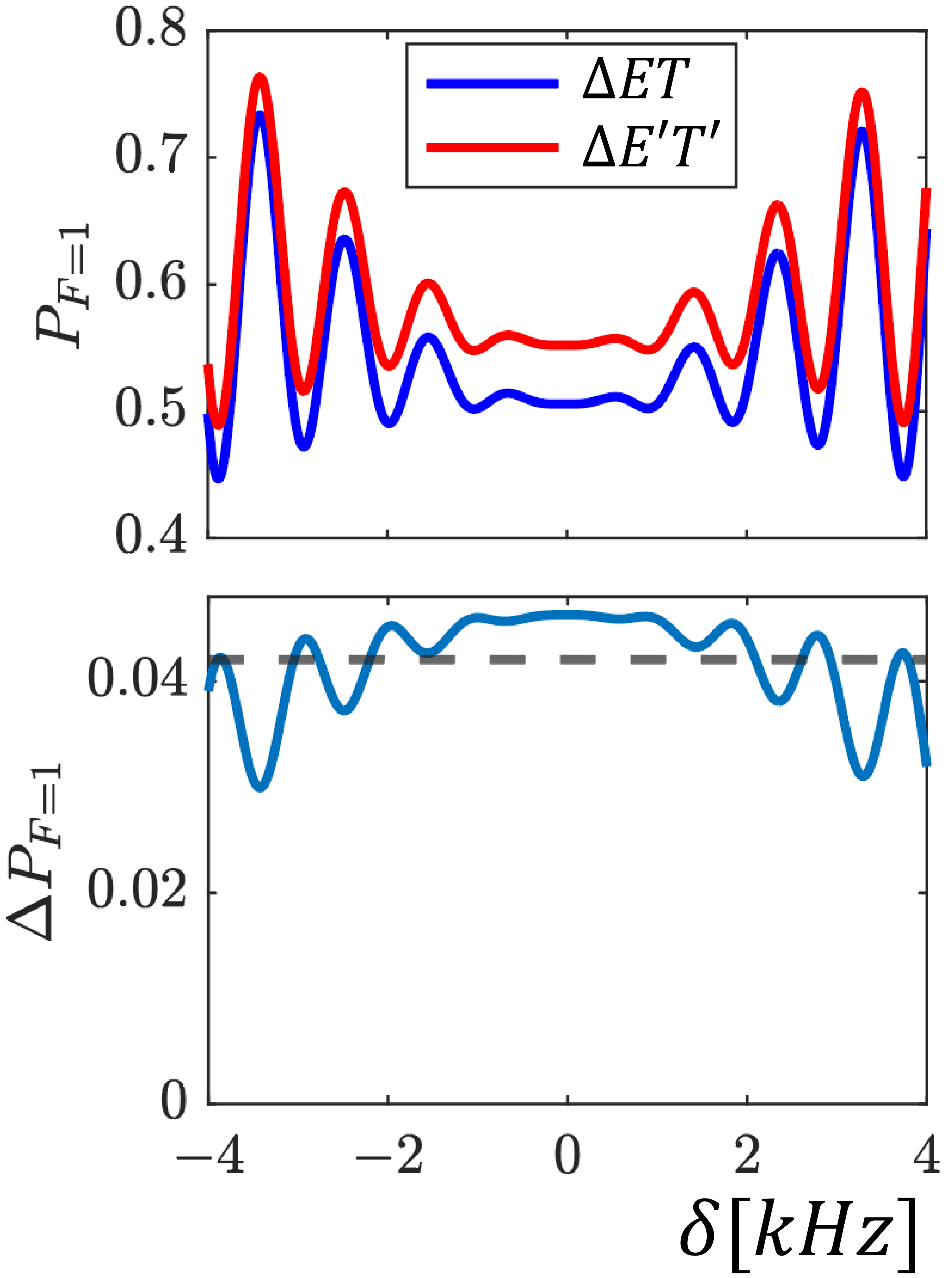
Boeschoten, A et al. Spin-precession method for sensitive electric dipole moment searches. *Physical Review A,* (2024).

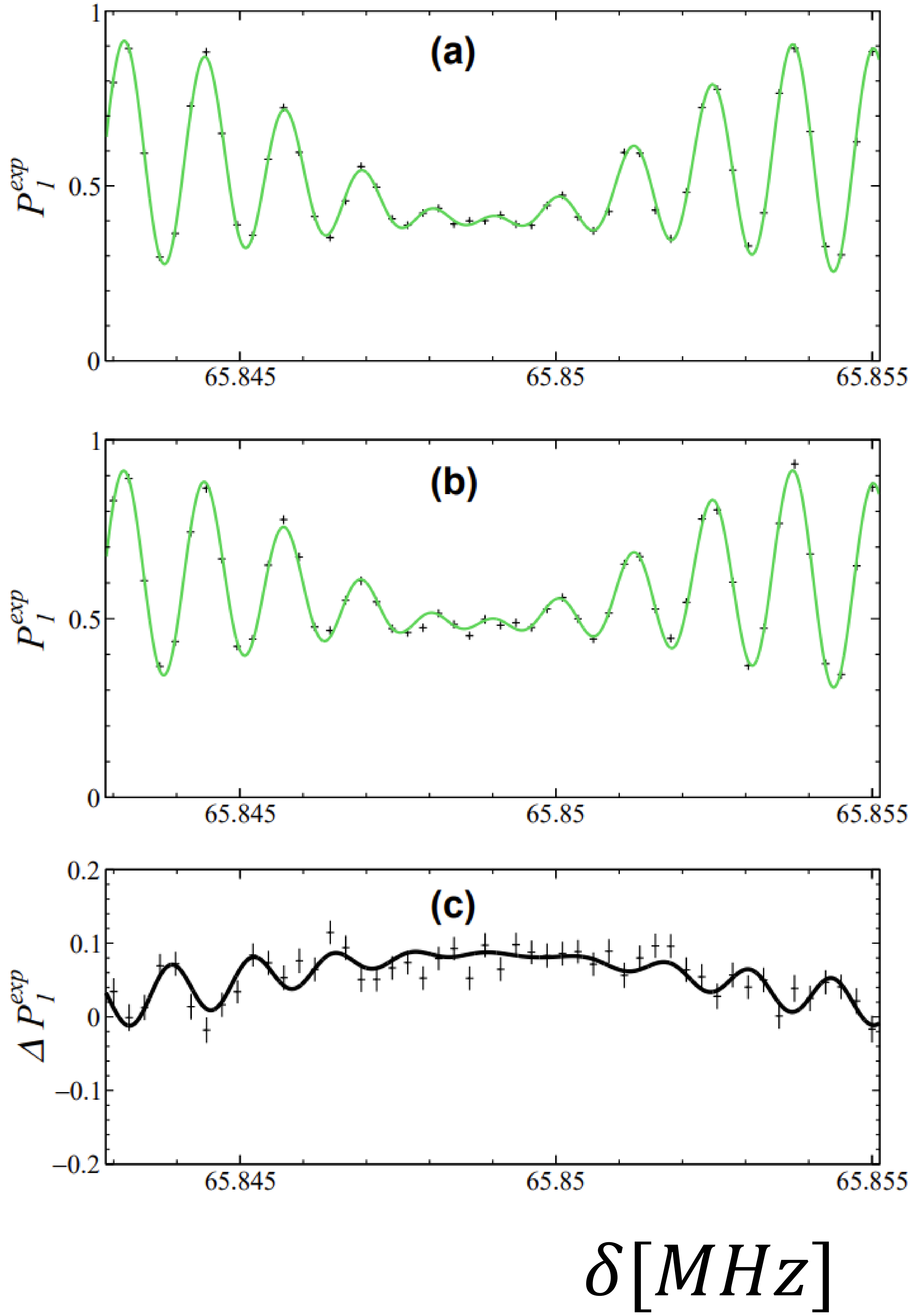
Proof of measurement technique

- $\Delta E = (\mu B \pm D^{\not{P},\not{T}} E)/\hbar$
- Changing B is the same as an eEDM measurement!
- Show that we can measure this shift



Proof of measurement technique



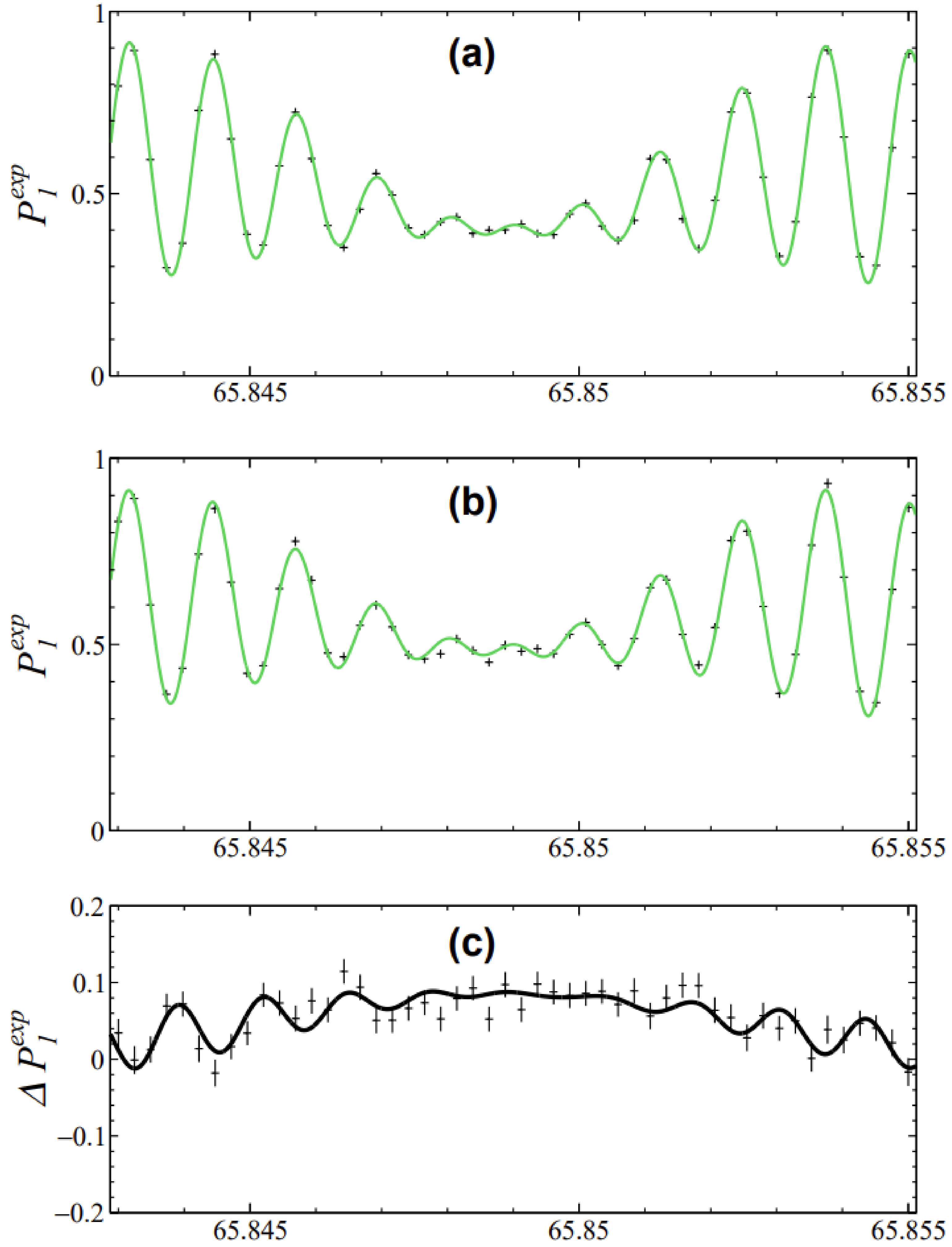


- A. Boeschoten, V. R. Marshall, T. B. Meijknecht, A. P.Touwen, Statistics and systematics of electron edm searches with BaF (2026)

Proof of measurement technique

- $\Delta B = 0.72(3)$ nT

$\delta d_e \sim 3 * 10^{-25}\ e\ cm$



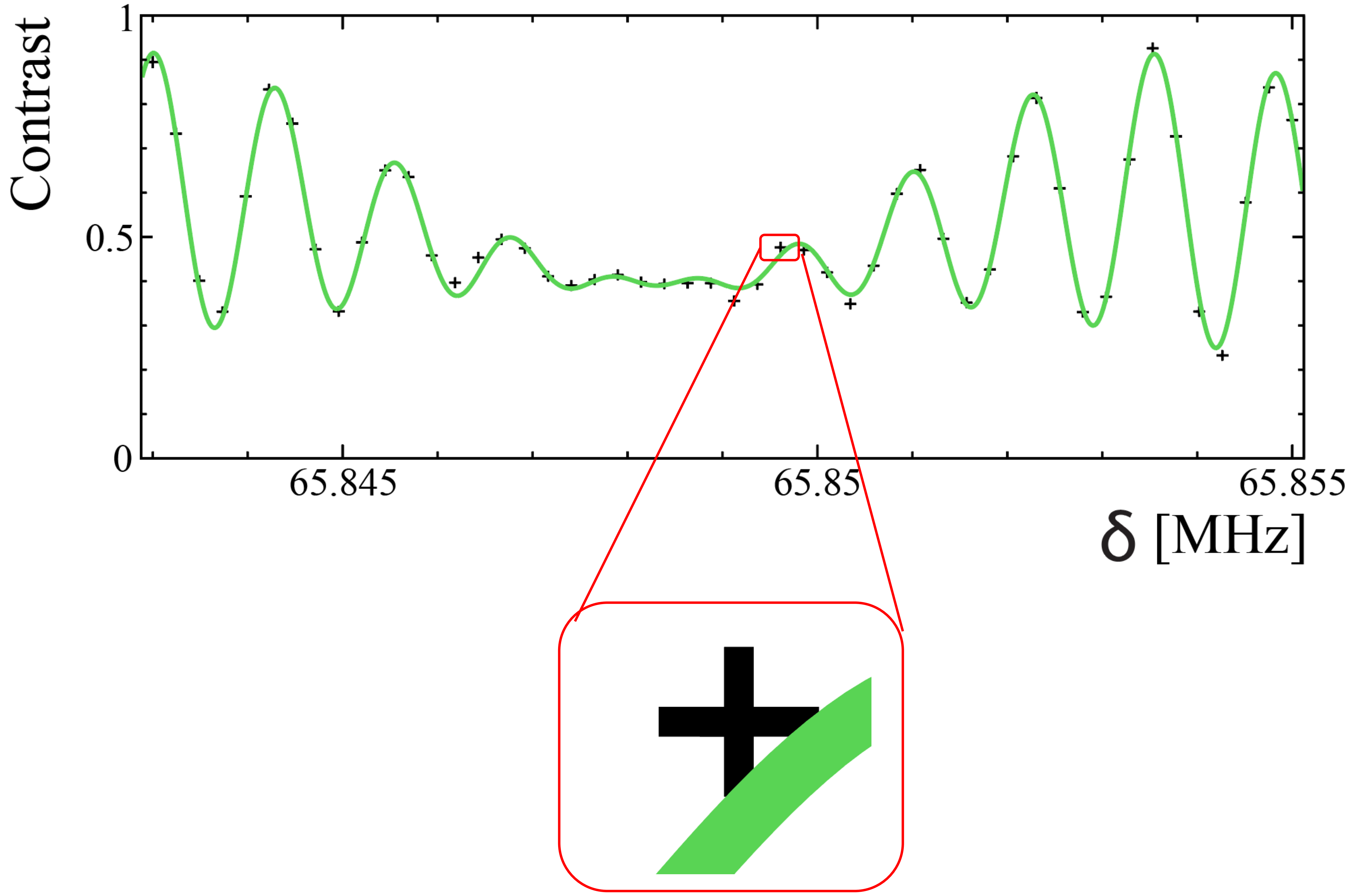
$\delta[MHz]$

- A. Boeschoten, V. R. Marshall, T. B. Meijknecht, A. P.Touwen, Statistics and systematics of electron edm searches with BaF (2026)

How to improve your eEDM sensitivity

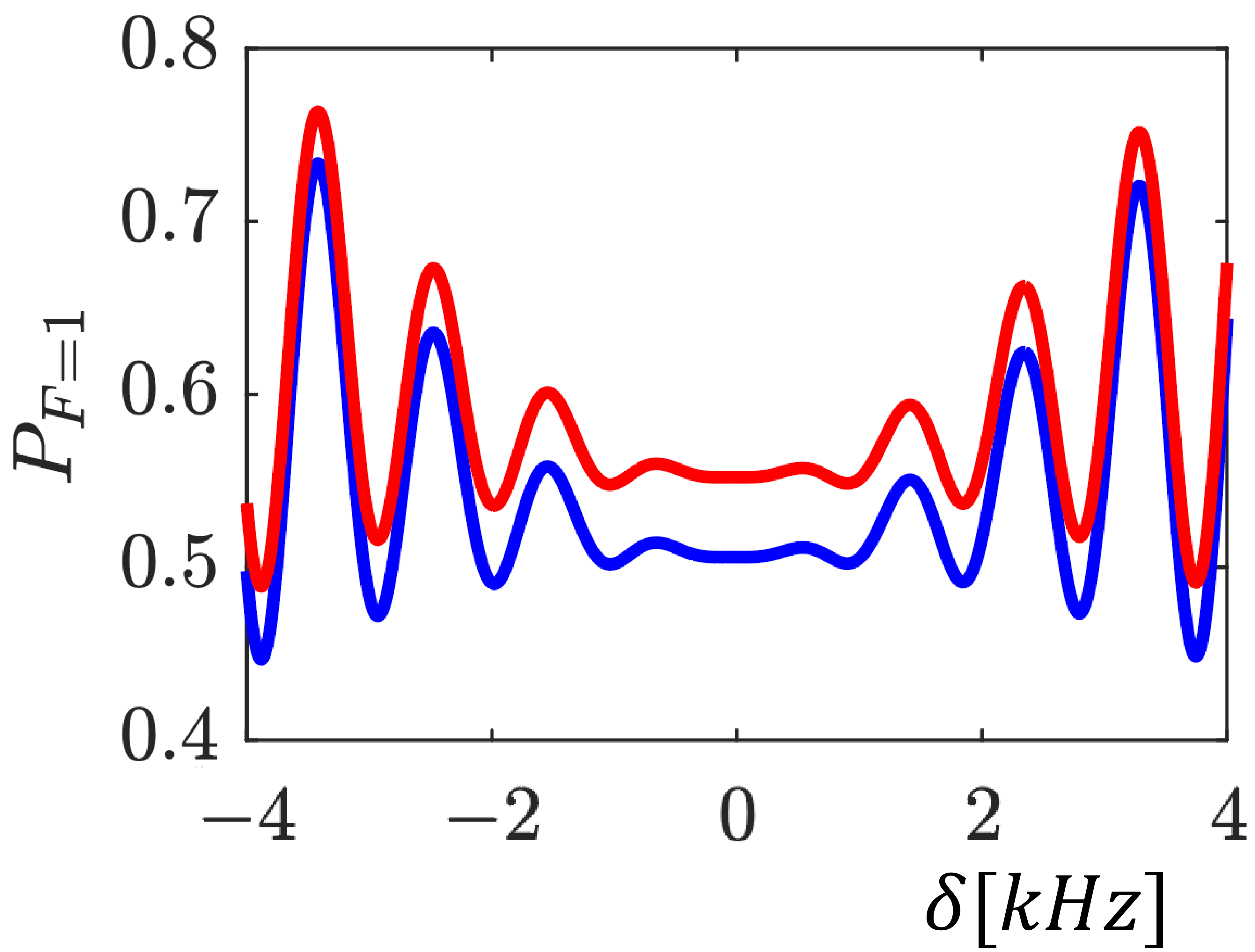
Increase the statistics

- More molecules
- Improve photon detection



Increase signal shift

- Slower molecules
- Larger electric field



New molecular source: Statistics

Cryogenic source

Hexapole lens

2D laser cooling

#Molecules

x200

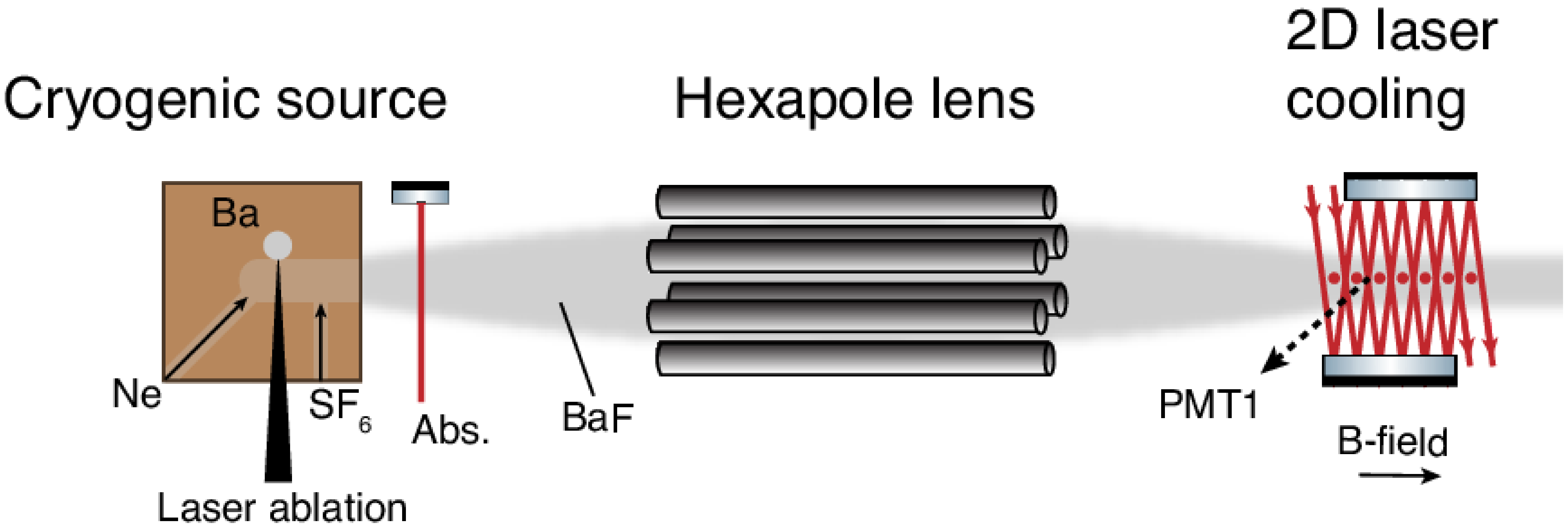
x2000

- Factor 630 in eEDM

Total sensitivity gained: x630

J. W. F. van Hofslot et al, 2d transverse laser cooling of a hexapole focused beam of cold BaF molecules, (2026)

New molecular source: Larger signal shift

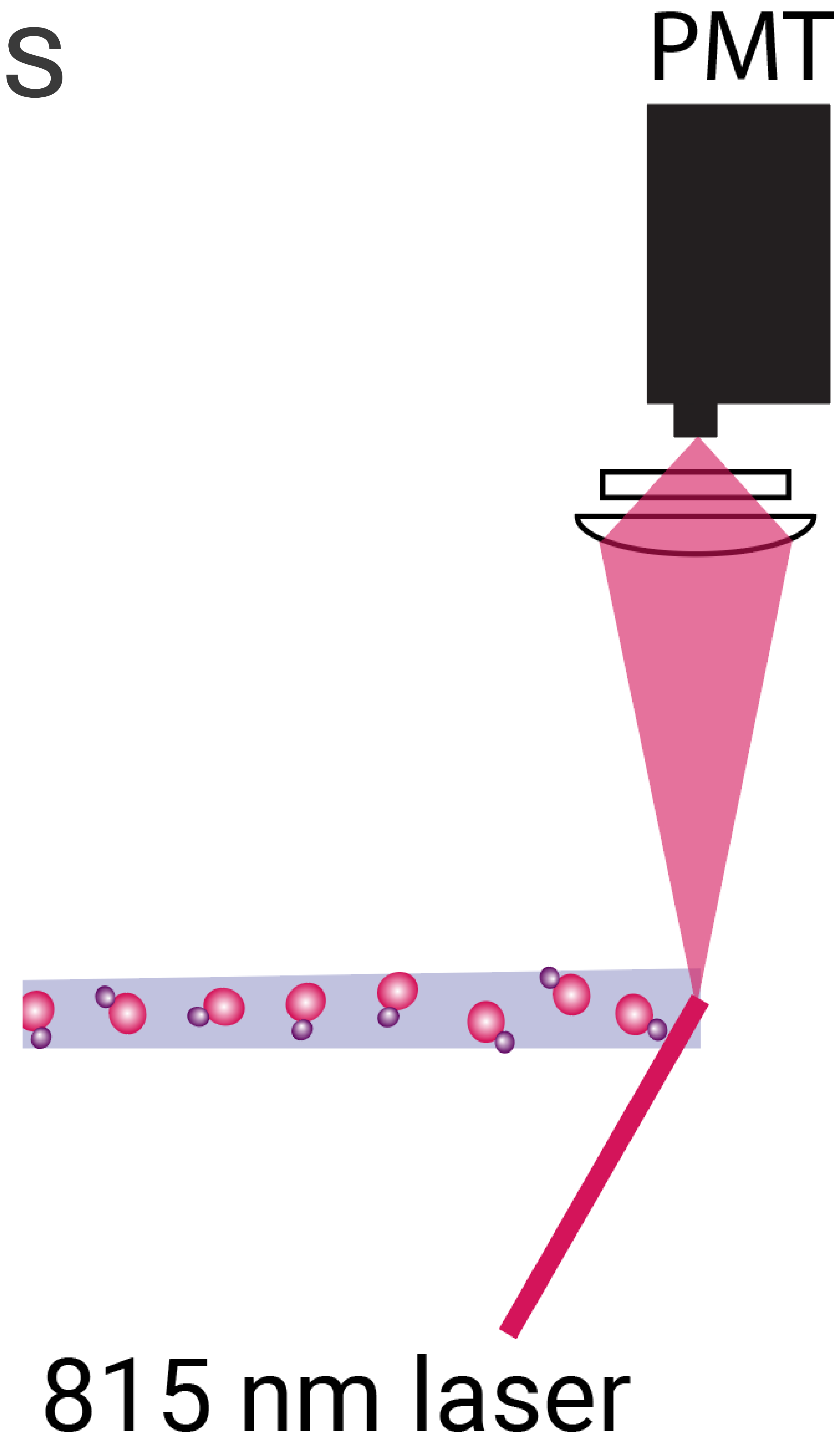


- 600 m/s → 200 m/s
- Factor 3 in eEDM

Total sensitivity gained:
x1890

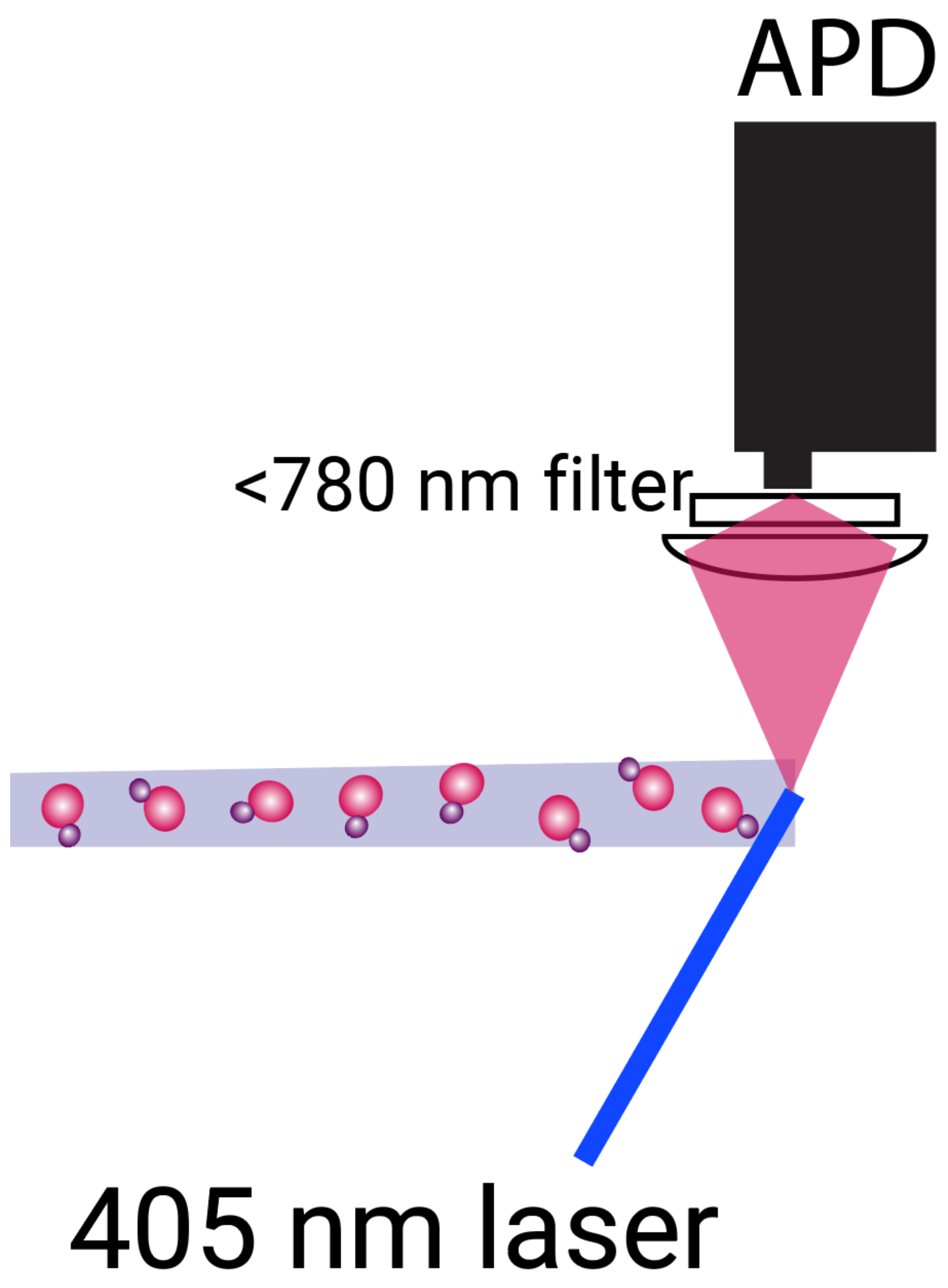
New detection method: Statistics

- Measurement of the molecules
  - Light collection ≈ 2%
  - Quantum efficiency of detector ≈ 8%
  - 1 in 1000 molecules is detected



New detection method: Statistics

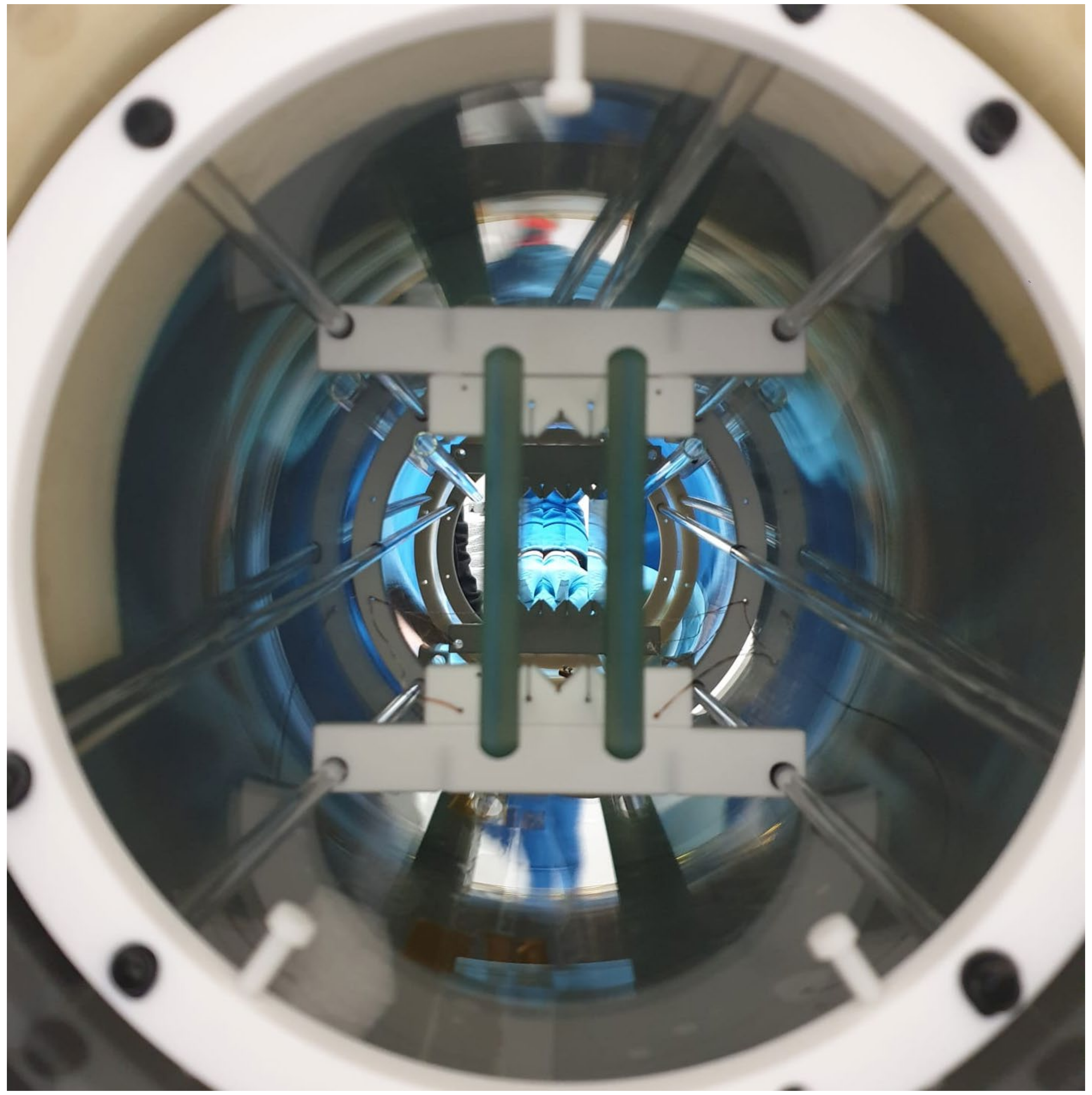
- New scheme
  - Light collection > 20%
  - Quantum efficiency of detector ≈ 80%
  - 1 in 10 molecules is detected
- Collaboration with ET department for low noise electronics
- Factor 10 in eEDM sensitivity



Total sensitivity gained: x18900

Larger electric field: Larger signal shift

- Higher electric field strength:10 kV/cm
- Factor 3 in eEDM sensitivity

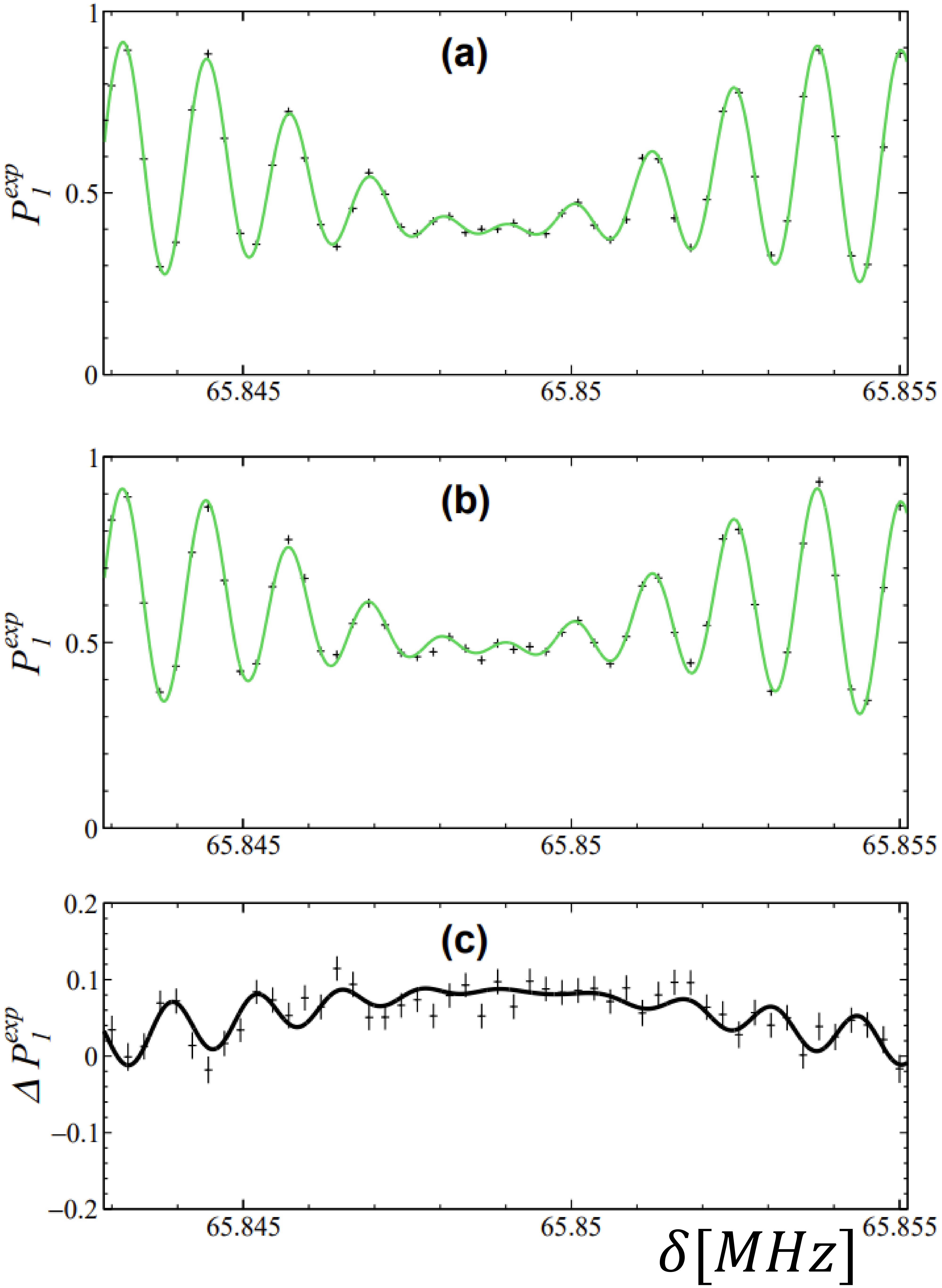


Total sensitivity gained: x56700

Outlook

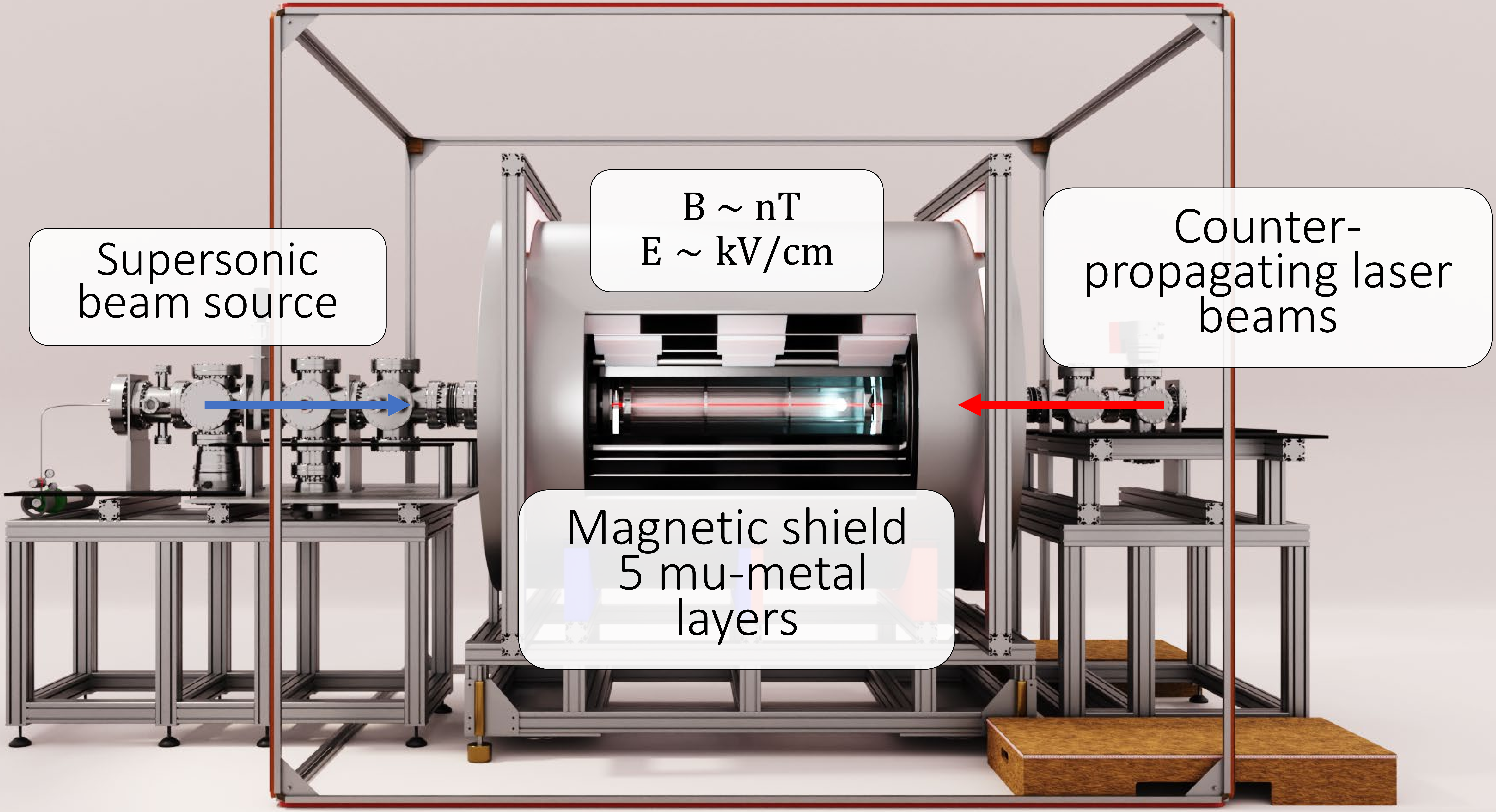
- Measure energy shift in molecule
- Proven concept of measurement
- Currently statistically limited
- All individual improvements are put together this year
- Next year aim to measure a projected:

$$\delta d_e < \ 2 * 10^{-29} e\ cm/\sqrt{day}$$



Thank you!

Spin precession

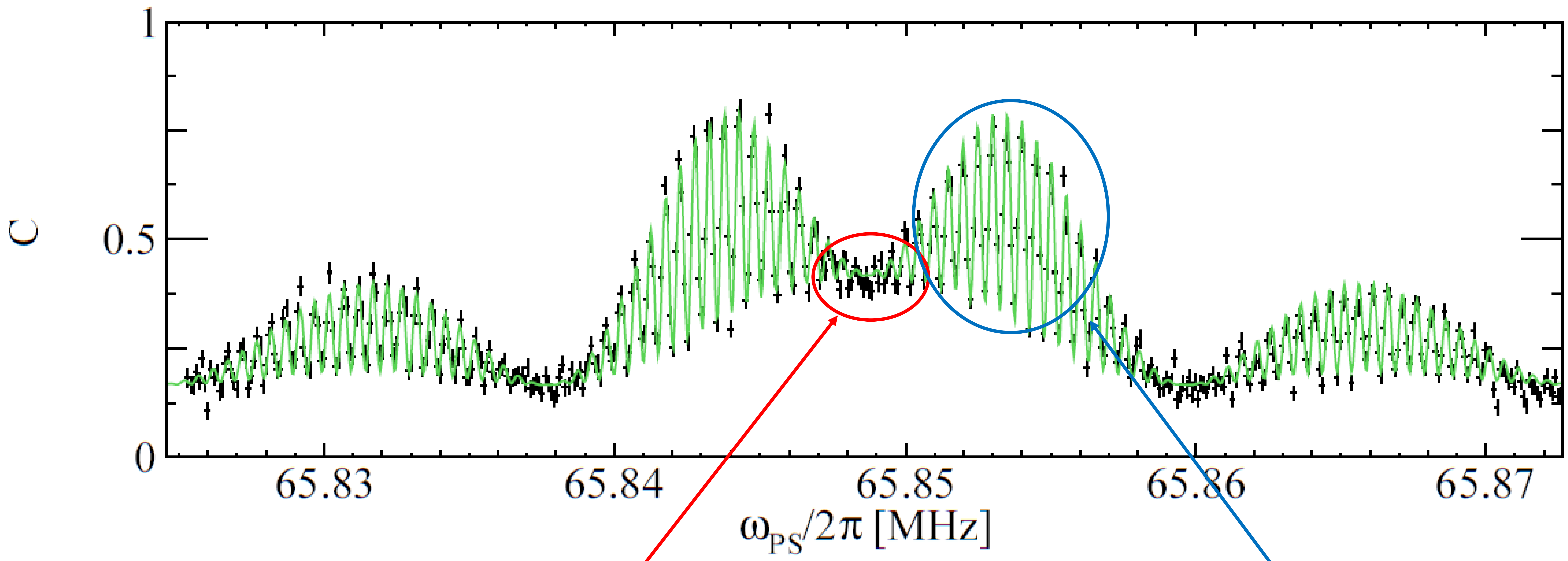

Supersonic beam source
B ~ nT
E ~ kV/cm
Counter-propagating laser beams
Magnetic shield
5 mu-metal layers

Model parameters

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

Parameter	Information
Hyperfine detuning δ	E-field strength, coherence
Two-photon detuning Δ	Light shift control
Pulse timings T,t	Laser phase
Rabi Frequencies, $\Omega_{P/S}$	Quality of superposition

Signal contains immense amounts of information



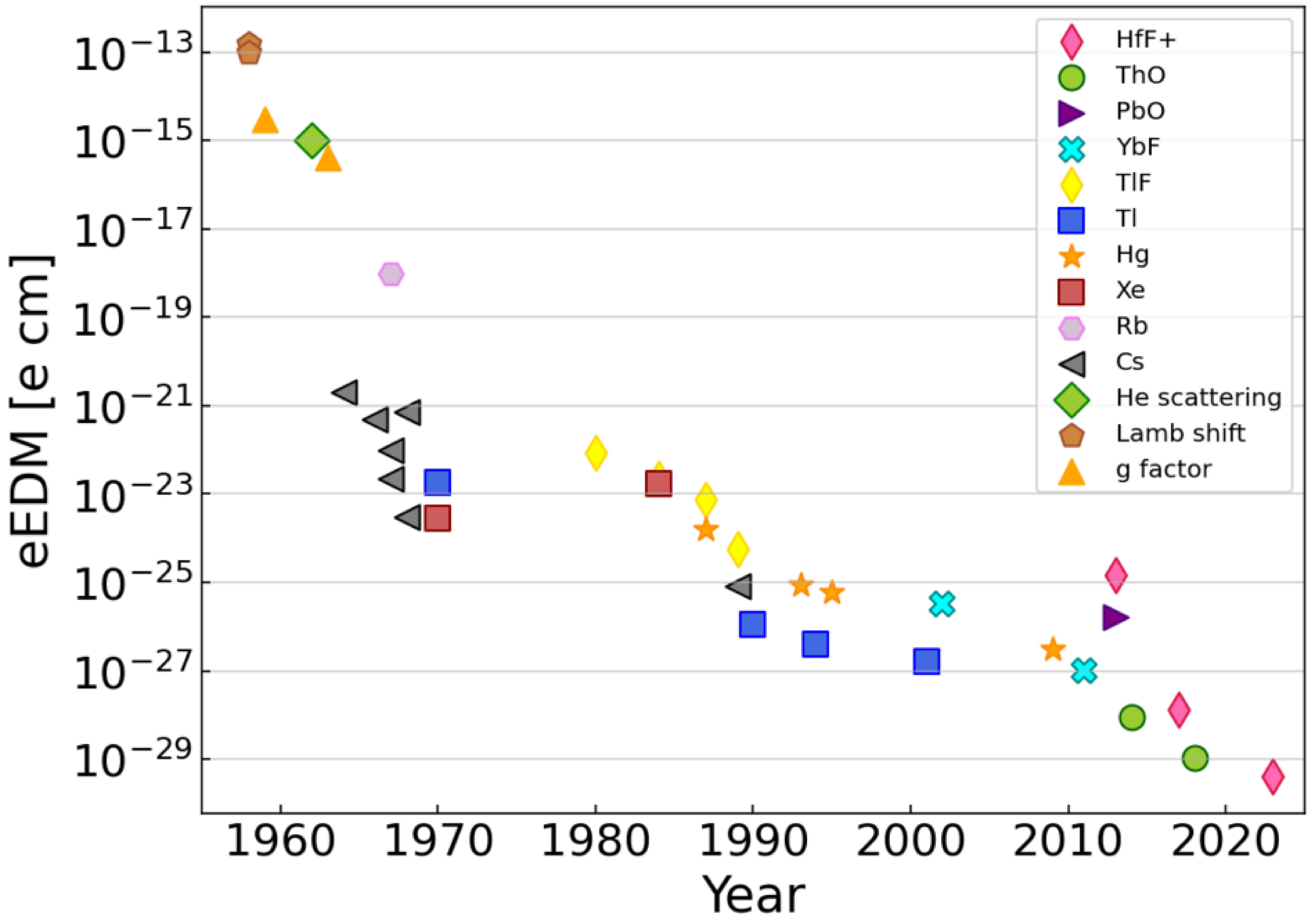
Most sensitive to EDM

Most sensitive to systematics

e.g. Peak spacing -> timings
Peak location -> E-field
Peak height -> B-field

Marshall, V. R. PhD thesis, University of Groningen, 2024

The competition



Probing the QCD $\bar{\theta}$ term with paramagnetic molecules

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October 24, 2025

Abstract

The experimental search for CP violation in paramagnetic atomic and molecular systems has made impressive progress in recent years. This has led to strong upper limits on the electron electric dipole moment. The same measurements can also be used to constrain hadronic sources of CP violation through CP-violating interactions between the electrons and the nucleus. We employ heavy-baryon chiral perturbation theory to compute such CP-violating semileptonic electron-nucleus interactions arising from the QCD theta term. We sharpen earlier results by determining the relevant short-distance effects and by an explicit two-loop calculation of meson-photon diagrams. We derive a bound of $|\bar{\theta}| < 1.5 \cdot 10^{-8}$ at 90% confidence, based on HfF^+ experiments at JILA. A further experimental improvement of one to two orders of magnitude would make paramagnetic molecular electric dipole moment experiments competitive with the neutron and diamagnetic atom program in constraining strong CP violation and higher-dimensional CP-odd quark-gluon operators.

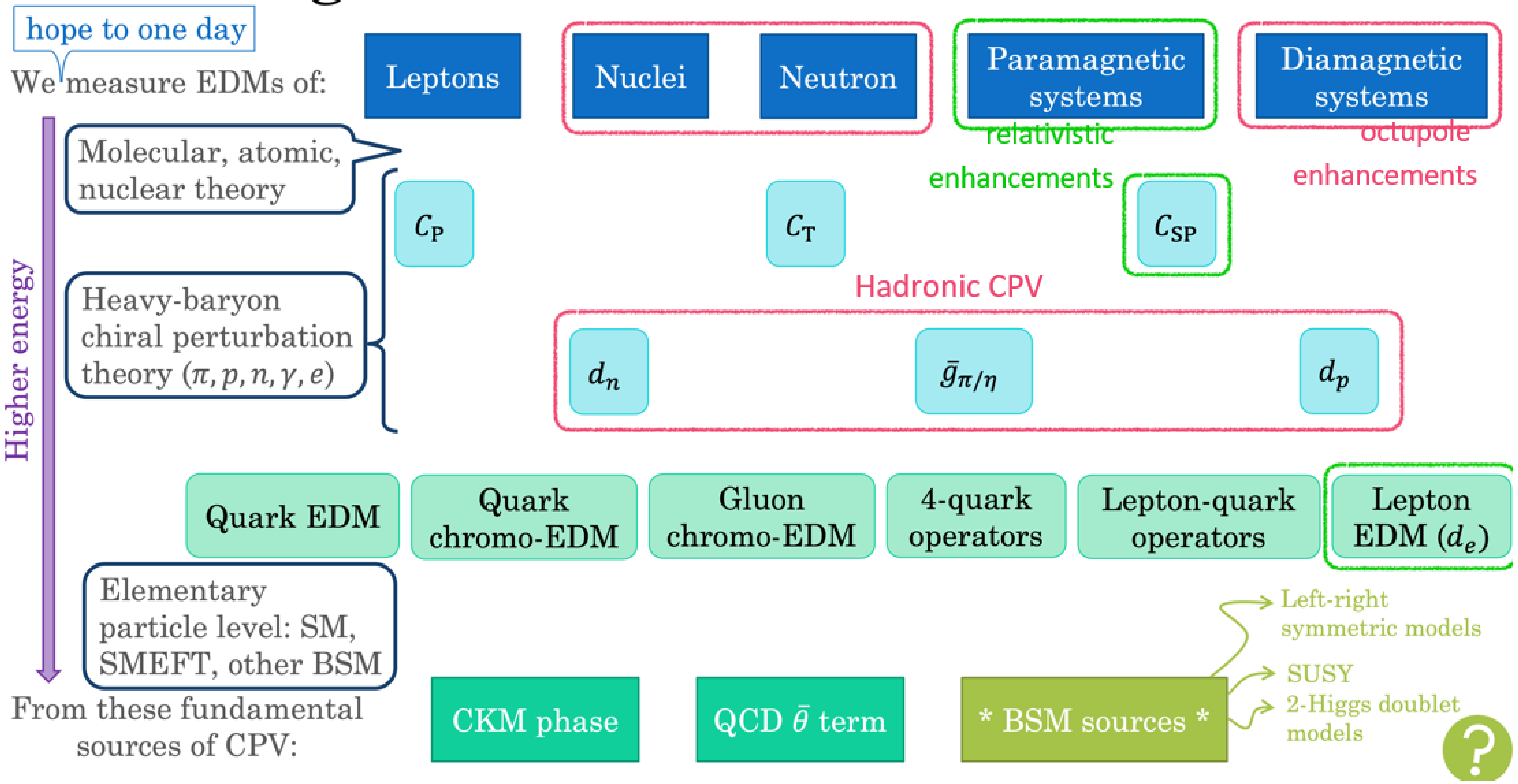
1 Introduction

Cosmological observations indicate an order 10^{10} asymmetry between the amount of baryons and antibaryons in our universe. As pointed out by Sakharov [1], a dynamical resolution of this asymmetry requires the violation of charge conjugation and parity (CP) or, equivalently, the violation of time-reversal symmetry[1]. The Standard Model (SM) of particle physics without neutrino masses contains two sources of CP violation. The first is the Cabibbo-Kobayashi-Maskawa

Pospelov & Ritz 0504231v2 (2005), Konstantin Gaul ECT* 4/3/24, Jordy de Vries SLAC 13/8/19

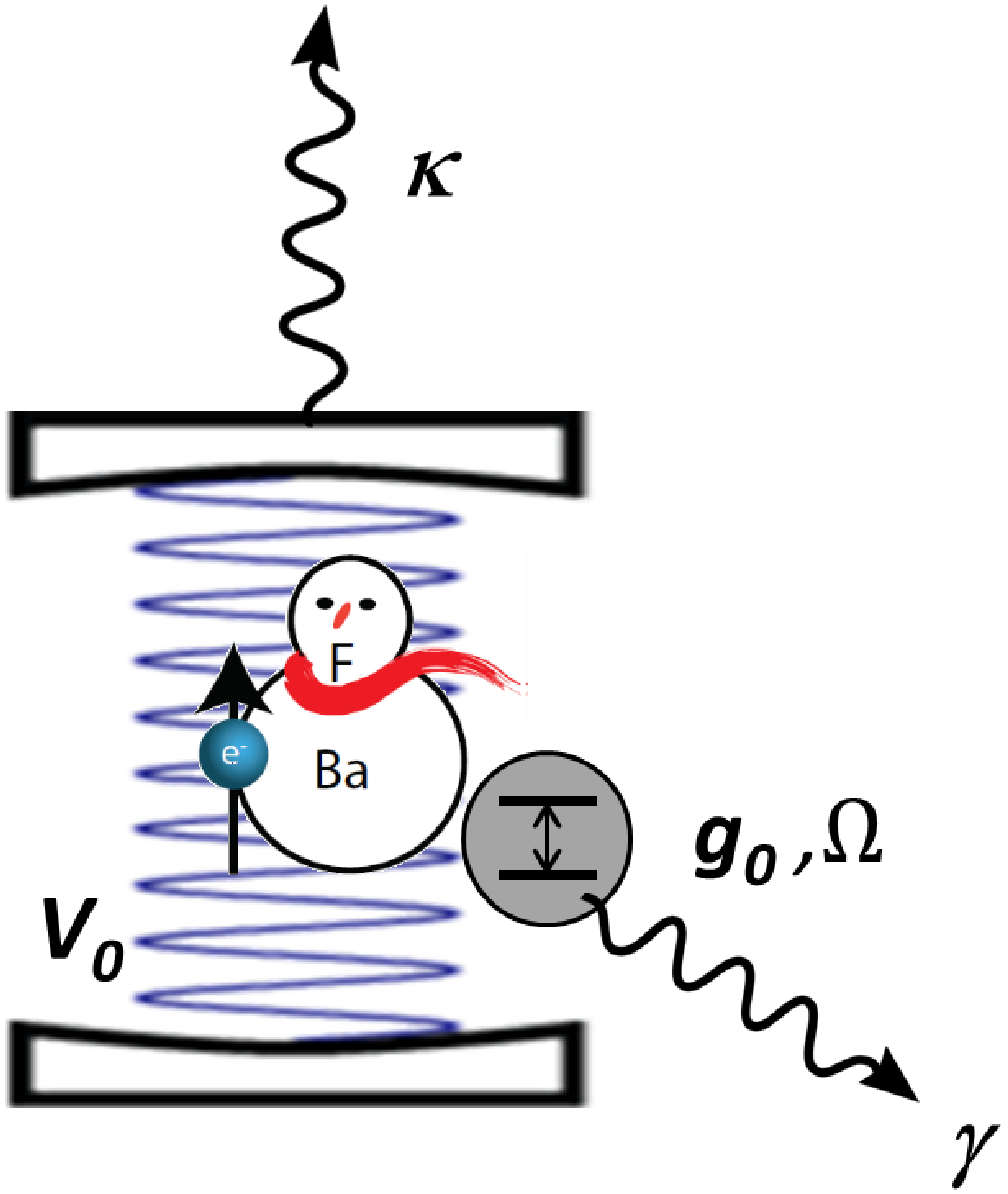
Tracing the CP violation

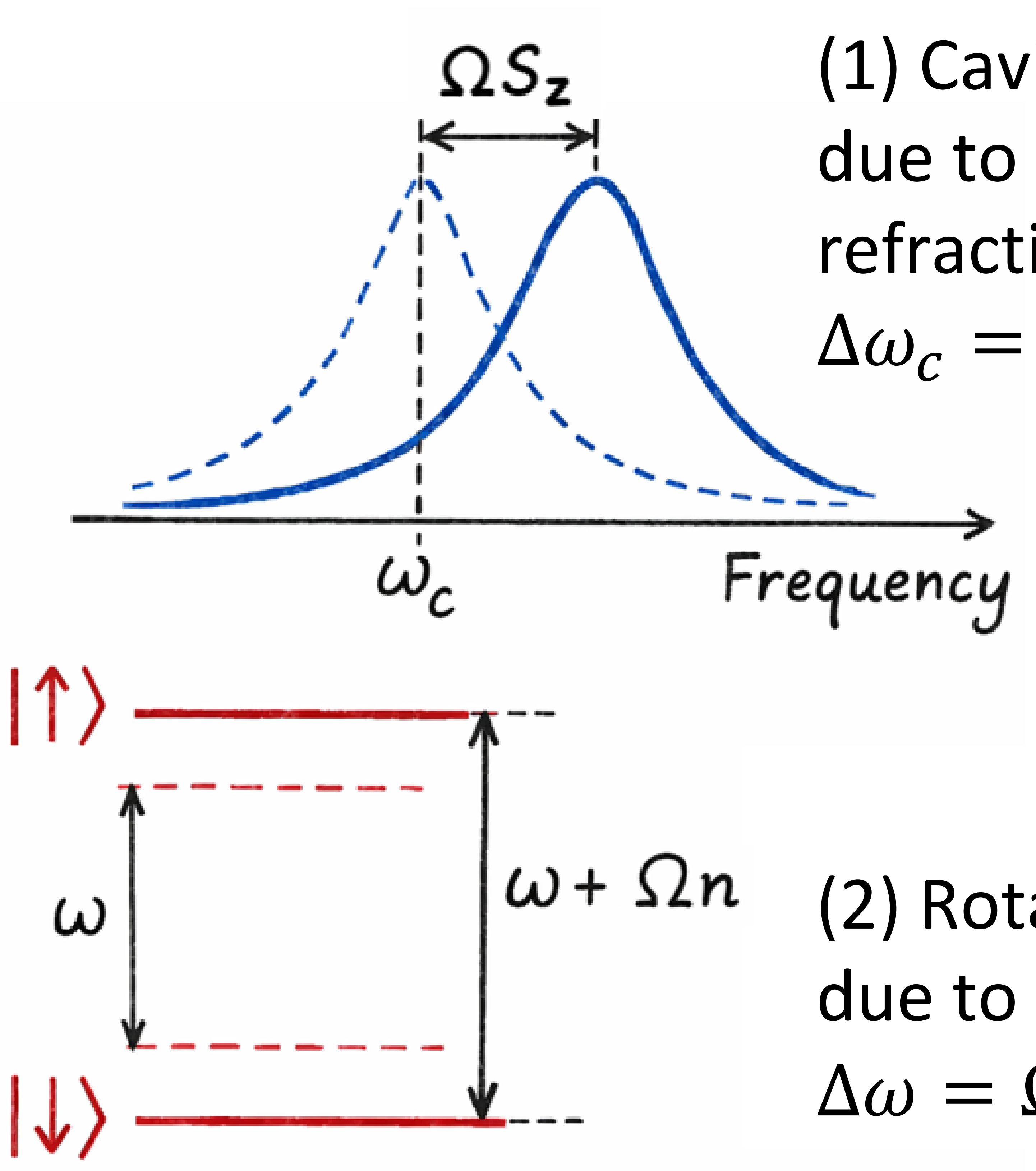
Paramagnetic: total electron spin non-zero
Diamagnetic: total electron spin = zero
Systems: atoms, molecules



Phase 4

Increased sensitivity through entangled molecules





(1) Cavity resonance shifts due to change of index of refraction:
$\Delta\omega_c = \Omega S_z = \Omega N(\rho_{22} - \rho_{11})$

(2) Rotational states shift due to AC-Stark effect:
$\Delta\omega = \Omega\hat{c}^{\dagger}\hat{c} = \Omega n$