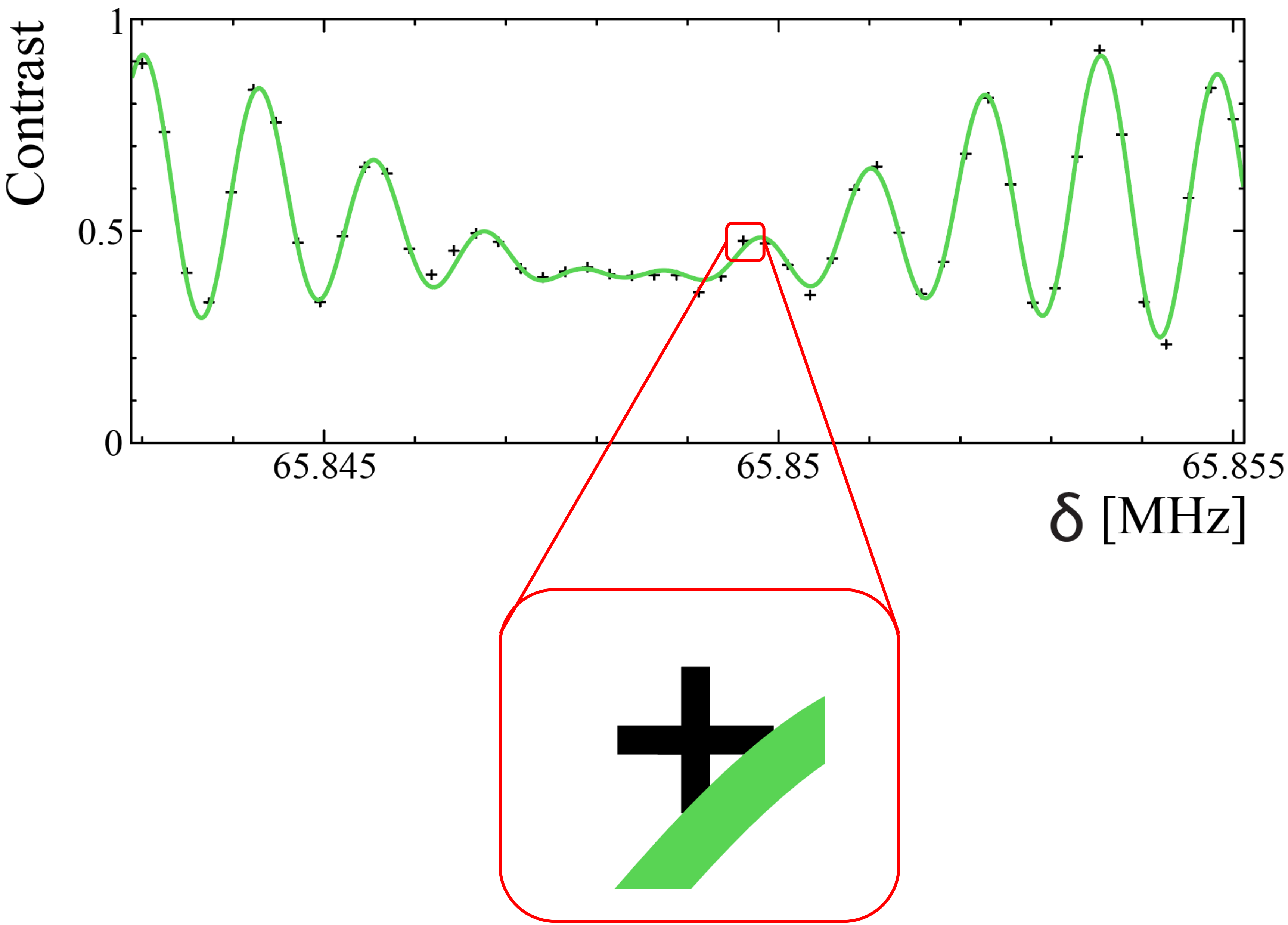
Background free detection of BaF for eEDM searches

Bastiaan Nijman

on behalf of the NL-eEDM collaboration

The goal



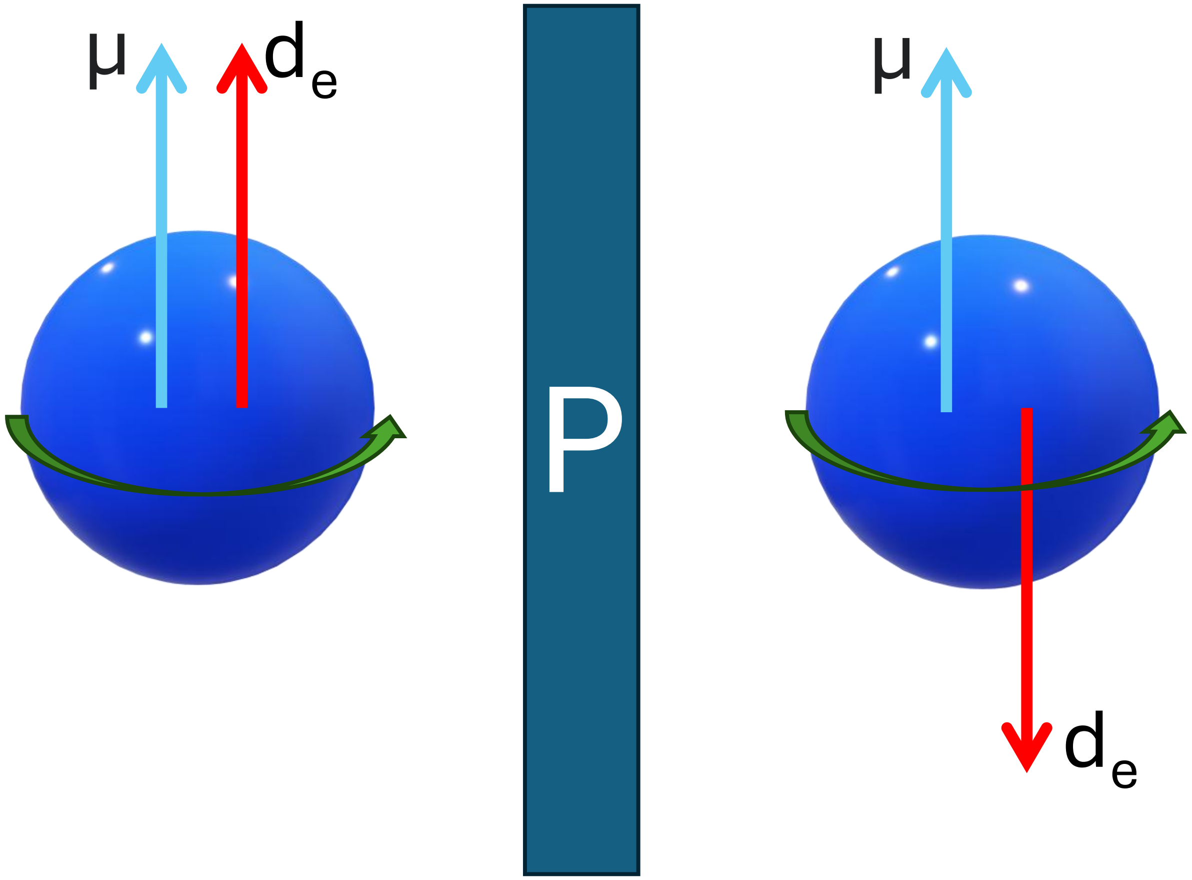
eEDM breaks P and T

- Direct probe of CP violation
- Standard model predicts:

  $d_e \sim O(10^{-38}) e\ cm$

- Beyond standard model theories predict

  $d_e \sim (10^{-26}$ - $10^{-35})\ e\ cm$

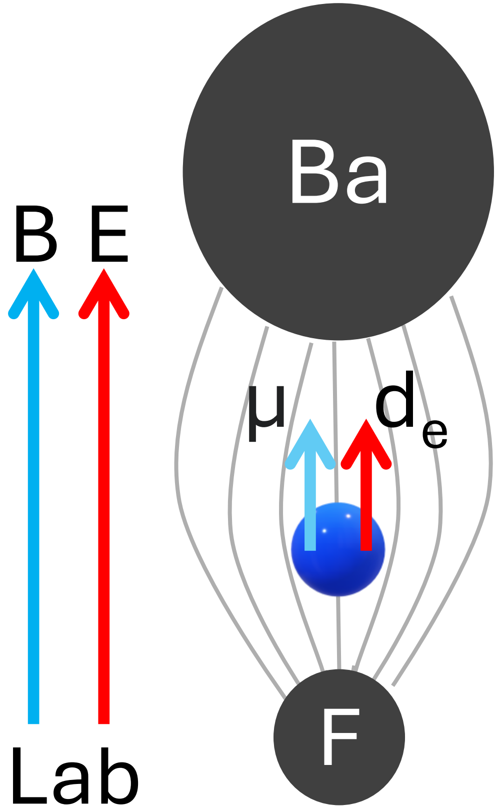


The NL-eEDM collaboration, *Measuring the electric dipole moment of the electron in BaF*, The European Physical Journal D, (2018)

eEDM in a molecule

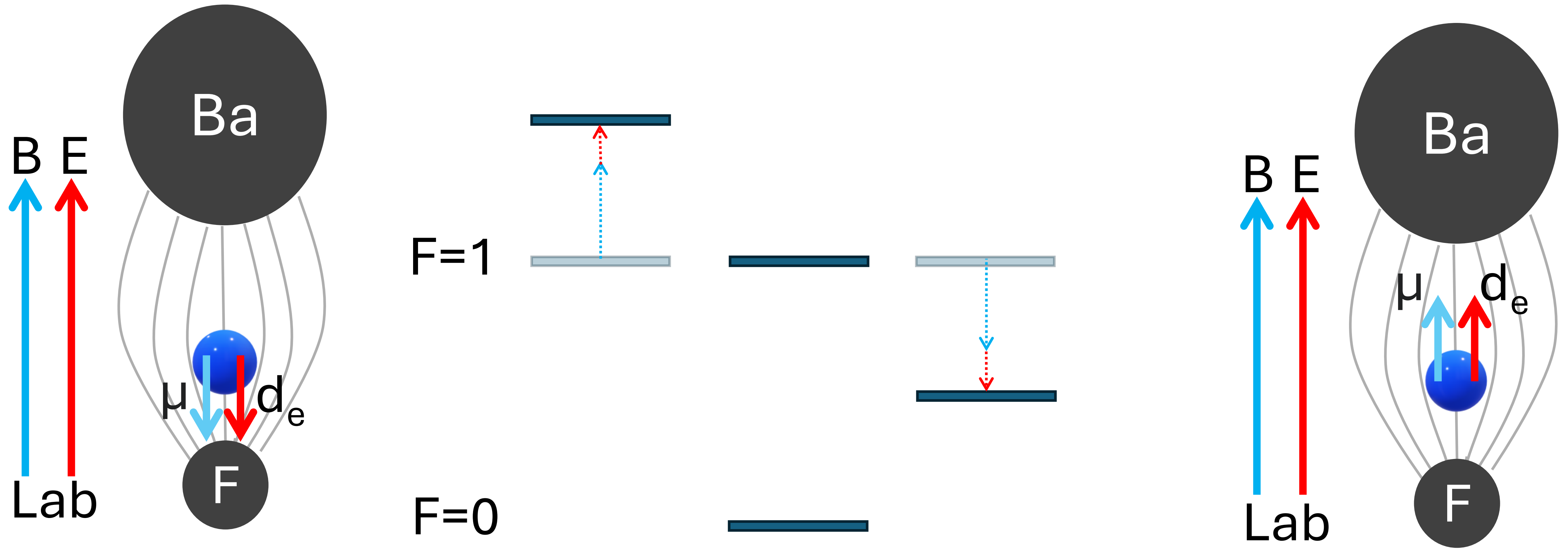
- Lab and intramolecular electric field align
- 10 kV/cm → 10 GV/cm
- Other experiments use YbF, ThO and more
- Best set limit HfF^+

$$|d_e| < 4.1 * 10^{-30} e\ cm$$

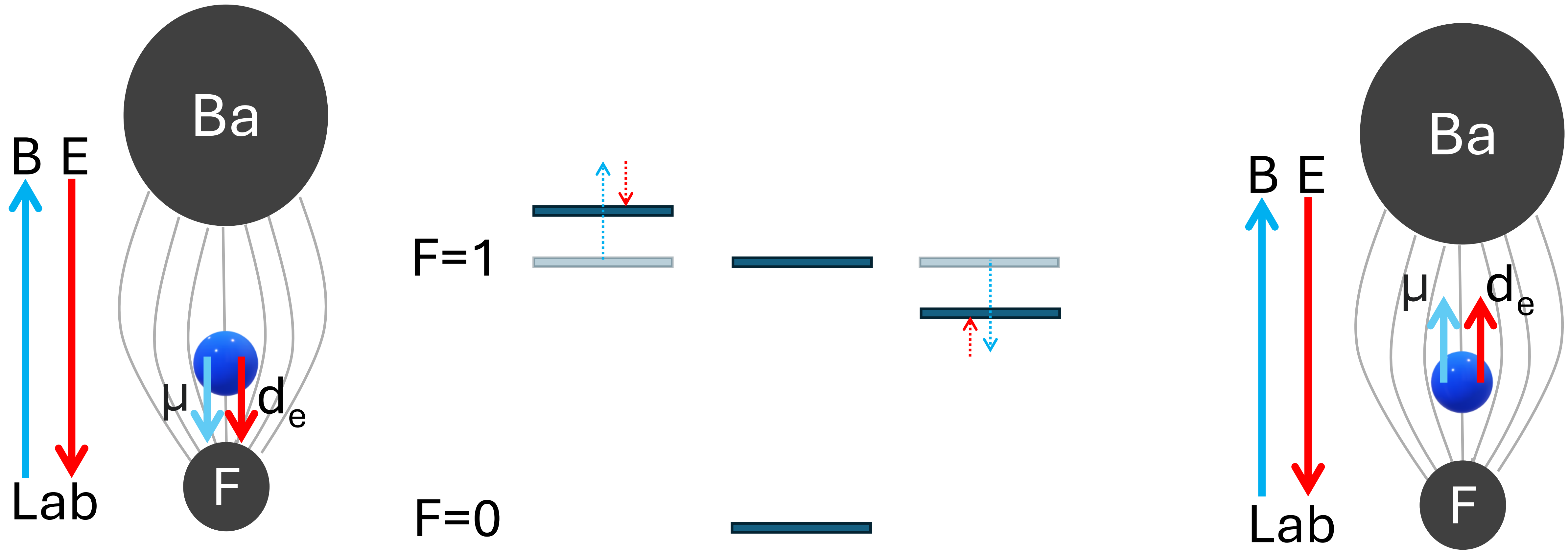


T. S. Roussy et al, *An improved bound on the electron's electric dipole moment*, Science, (2023)

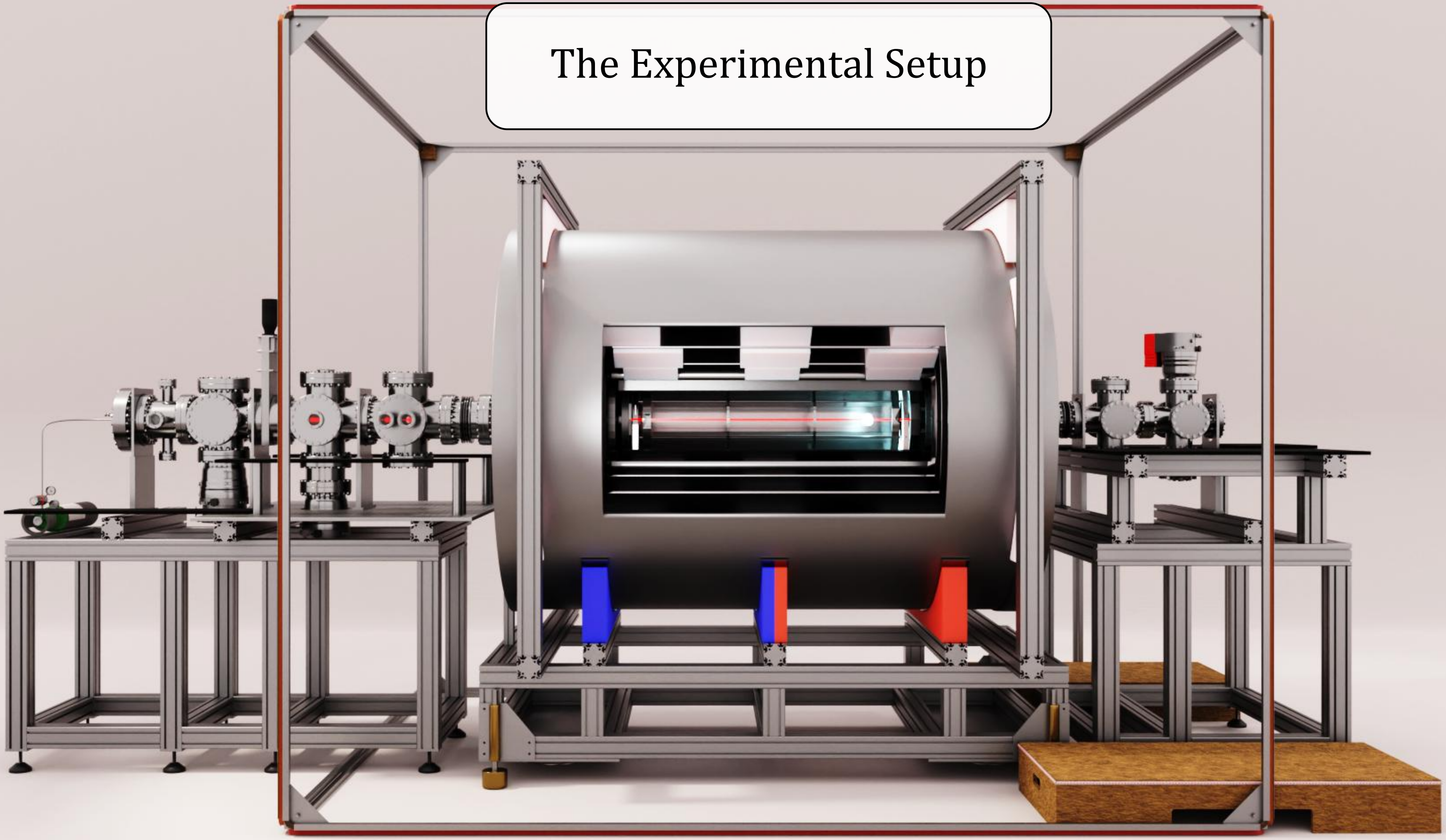
eEDM breaks P in molecule



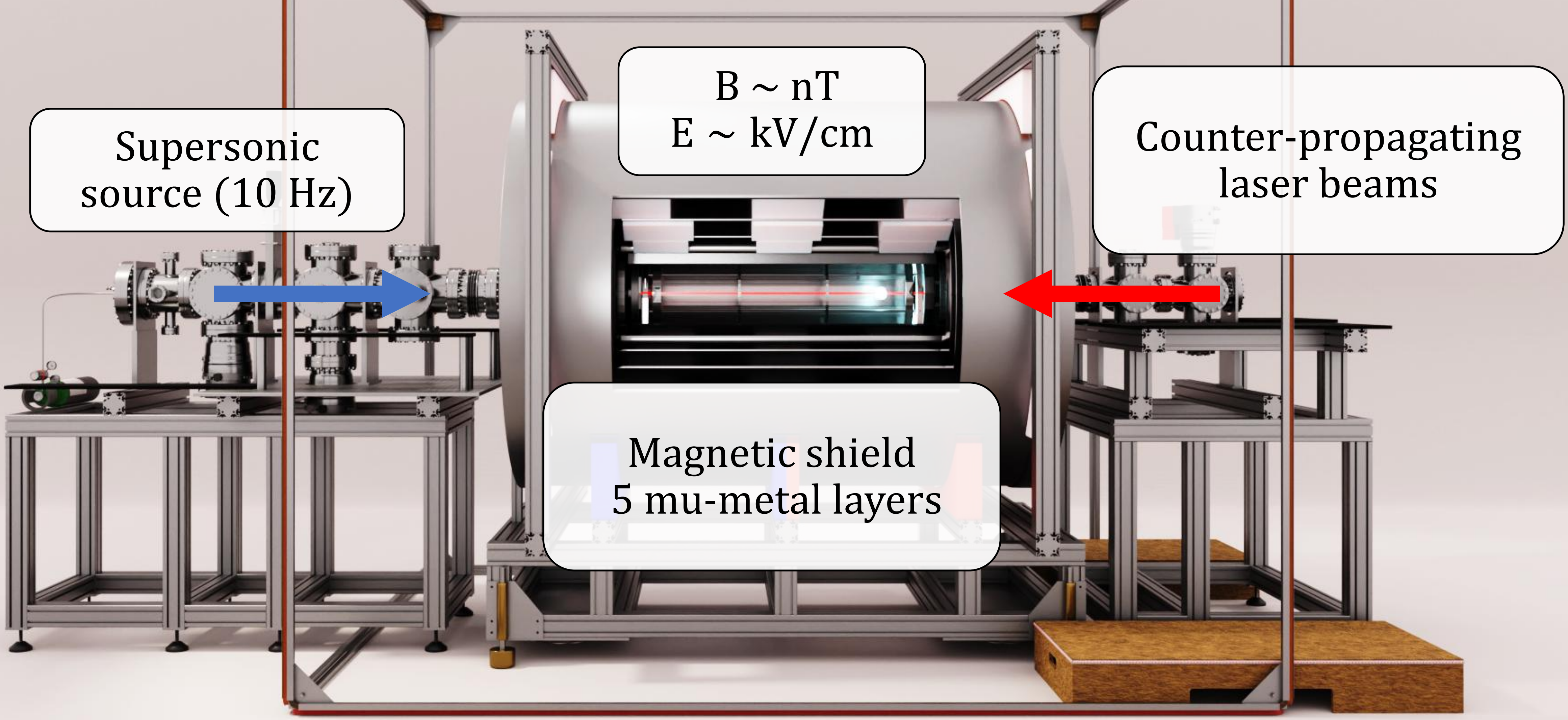
eEDM breaks P in molecule

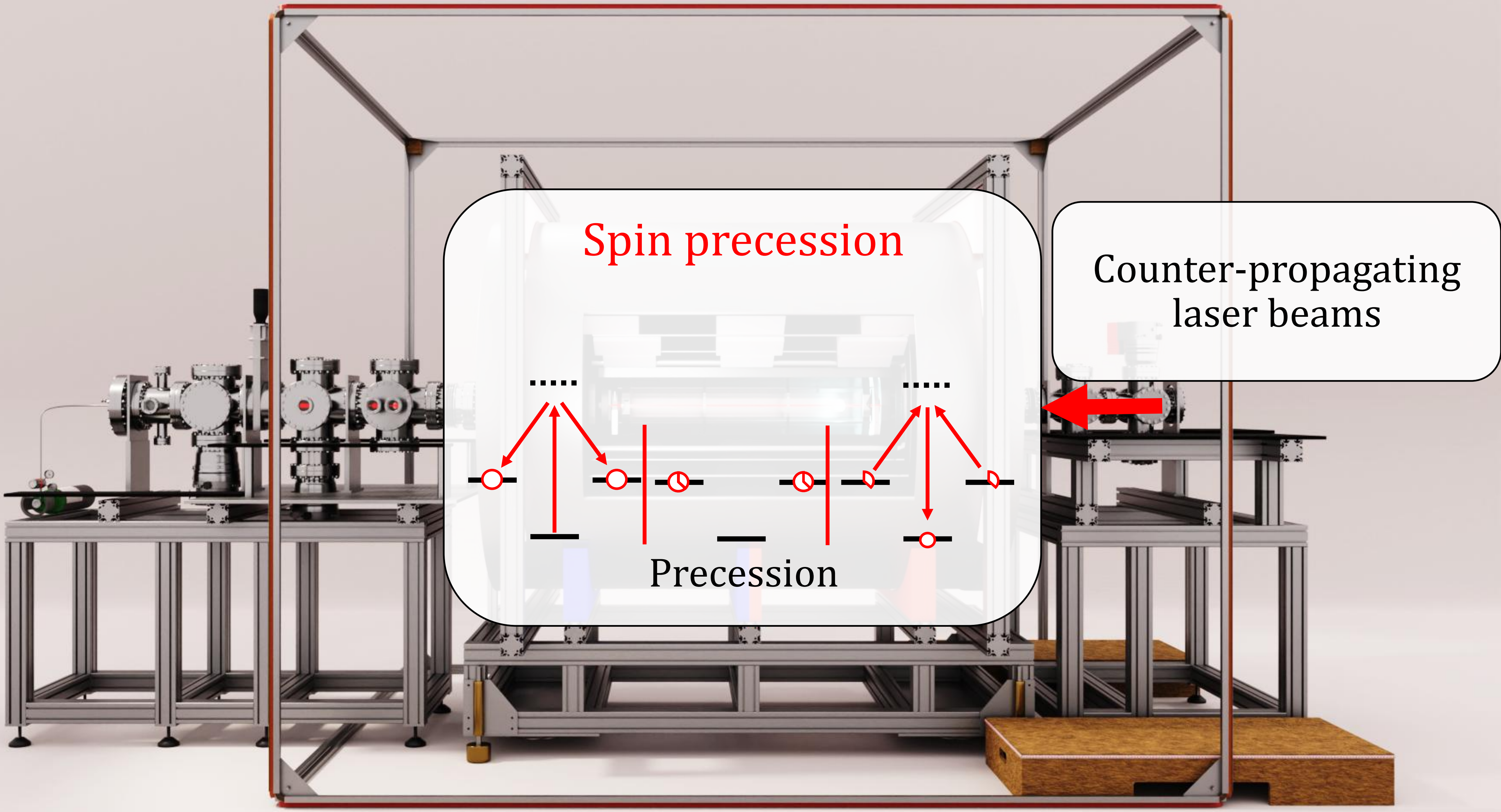


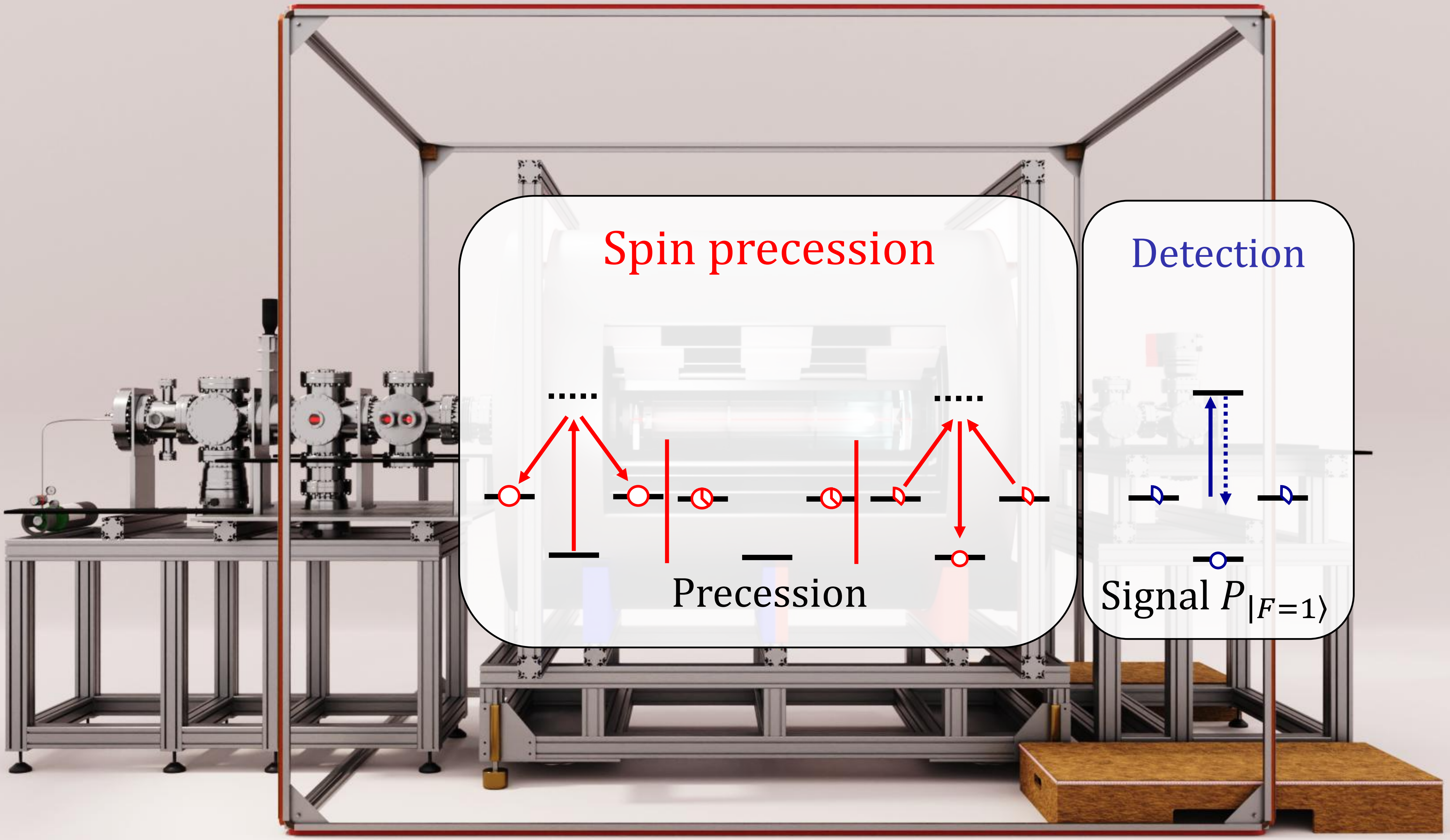
The Experimental Setup



The Experimental Setup




Spin precession
Precession
Counter-propagating
laser beams


Spin precession
Precession
Detection
Signal $P_{|F=1\rangle}$

Signal model from first principles

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

  δ, Δ Detunings

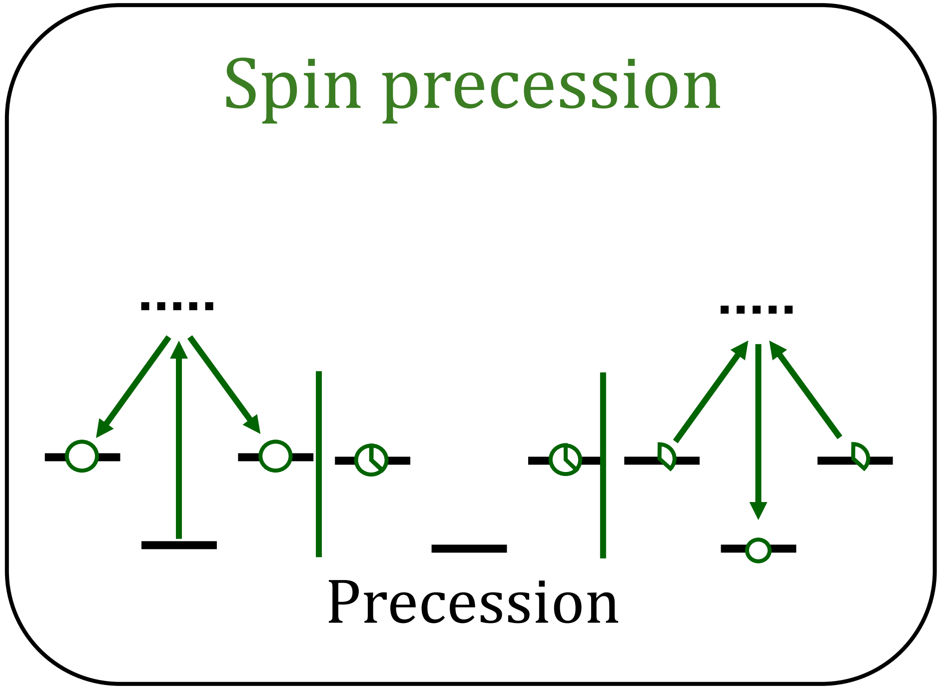
  t, T Timings

  $\Omega_{P,S}$ Laser Intensity

  $\hat{e}_{P,S}$ Light polarization

  $\Phi_{\mathrm{P,S}}$ Laser phase

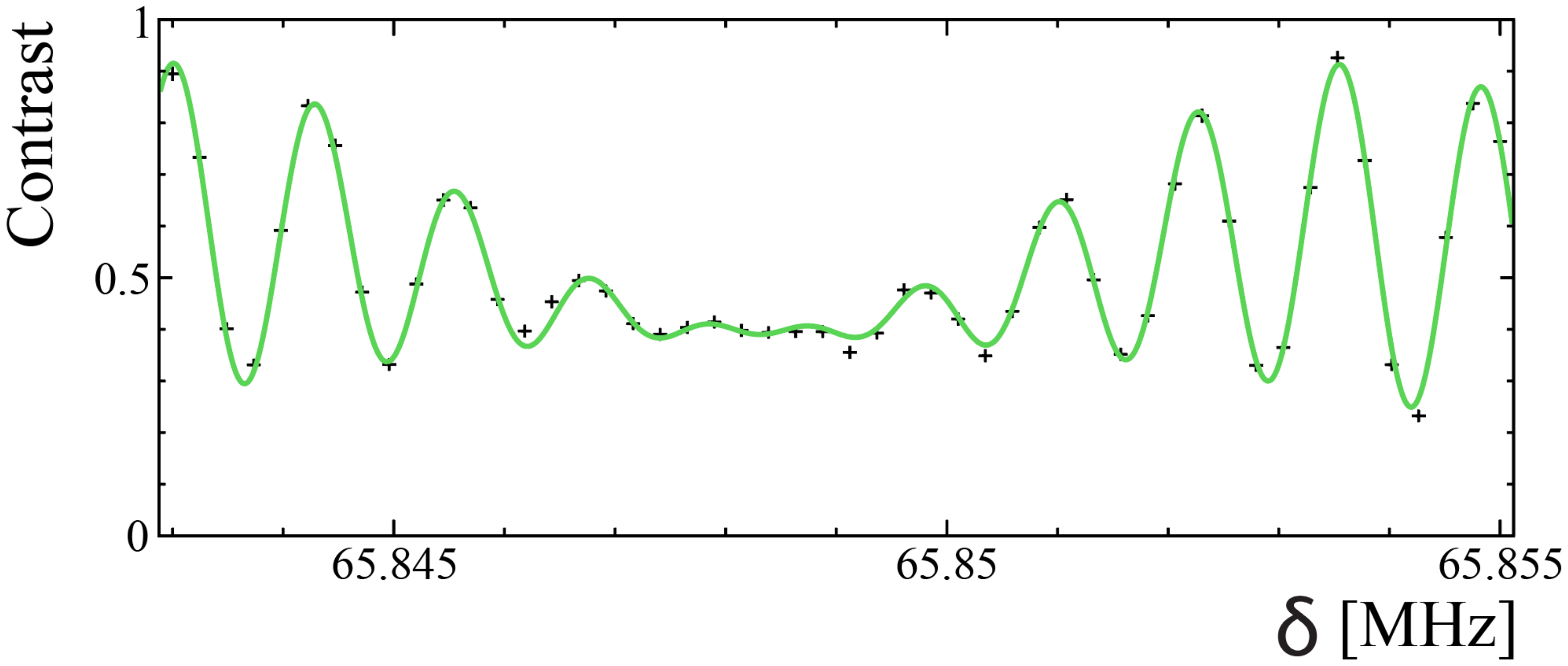
  E, B Electric and magnetic field



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

Signal model from first principles

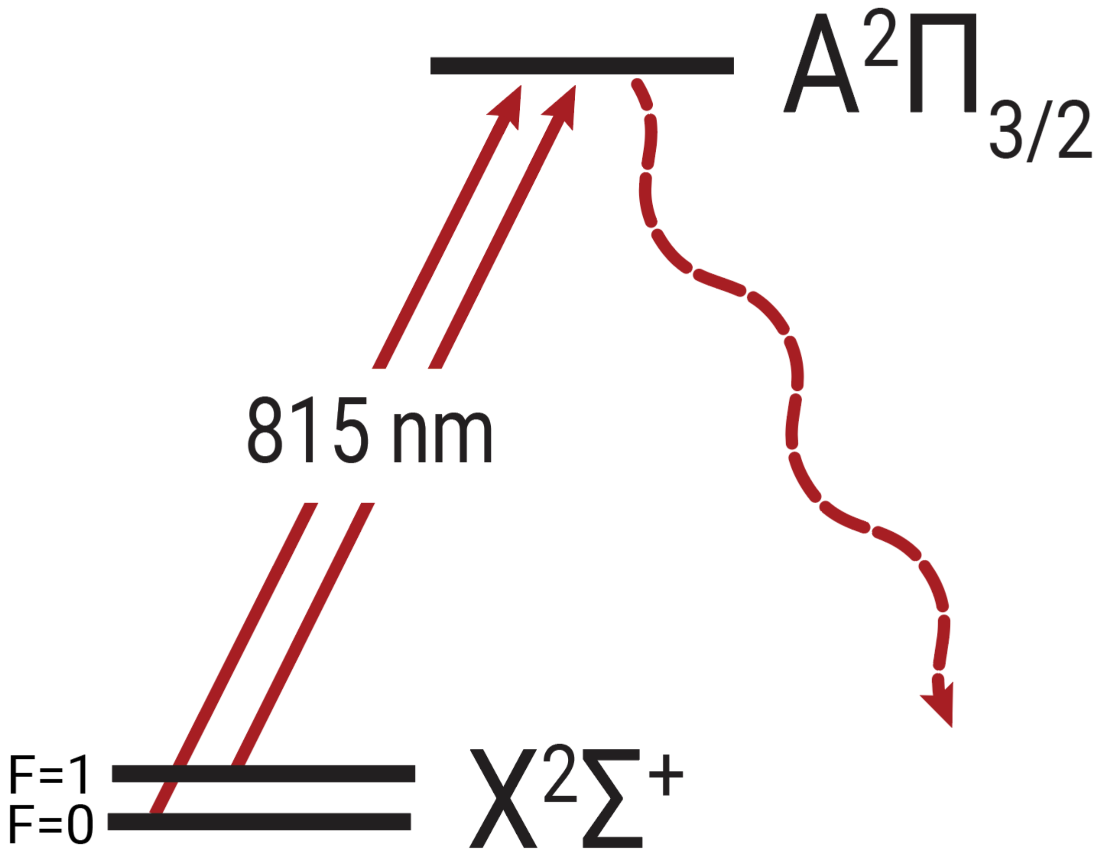
- $P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})$
- $Contrast = \dfrac{\varepsilon N_{F=1}}{\varepsilon N_{F=0} + \varepsilon N_{F=1}}$

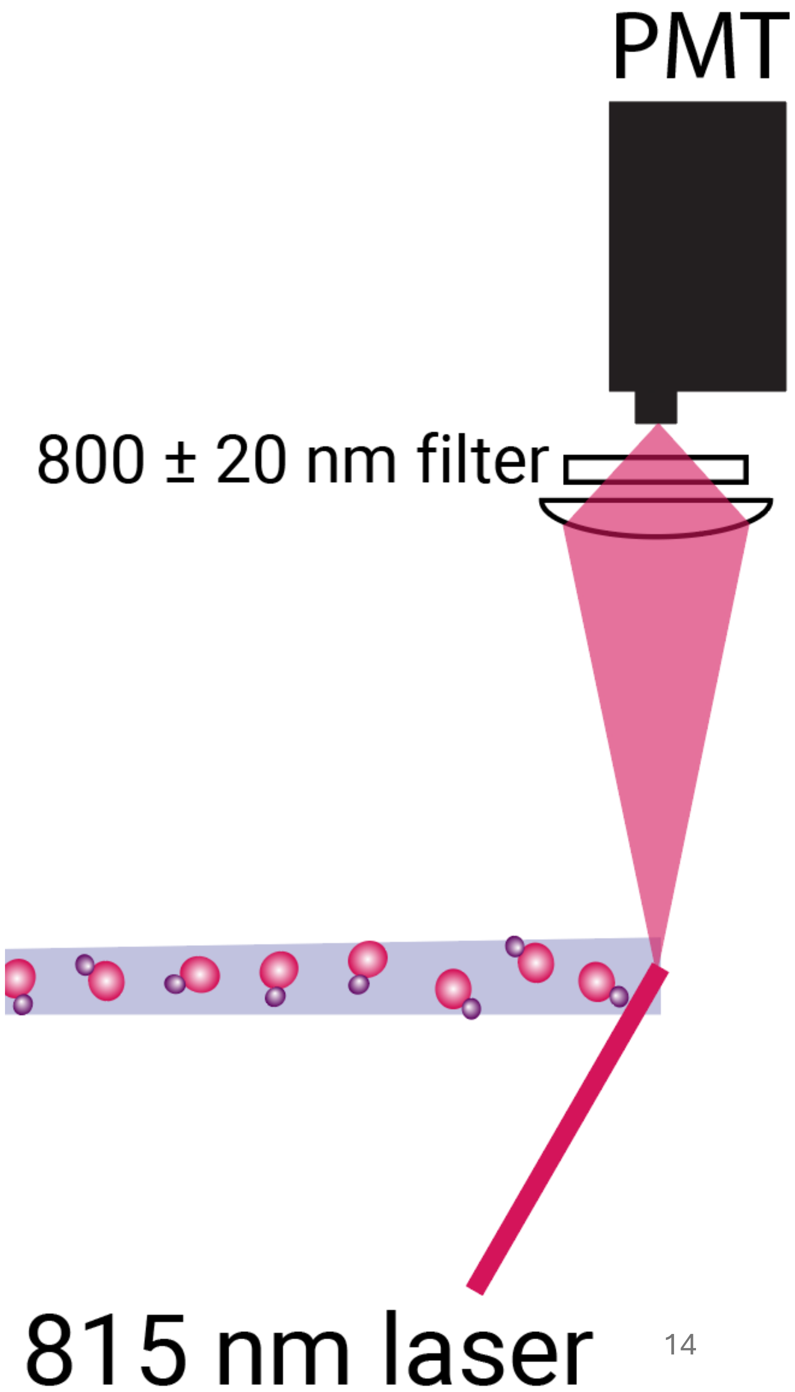


Boeschoten, A et al. Spin-precession method for sensitive electric dipole moment searches. *Physical Review A*, (2024)

Measuring population of molecules in a certain state

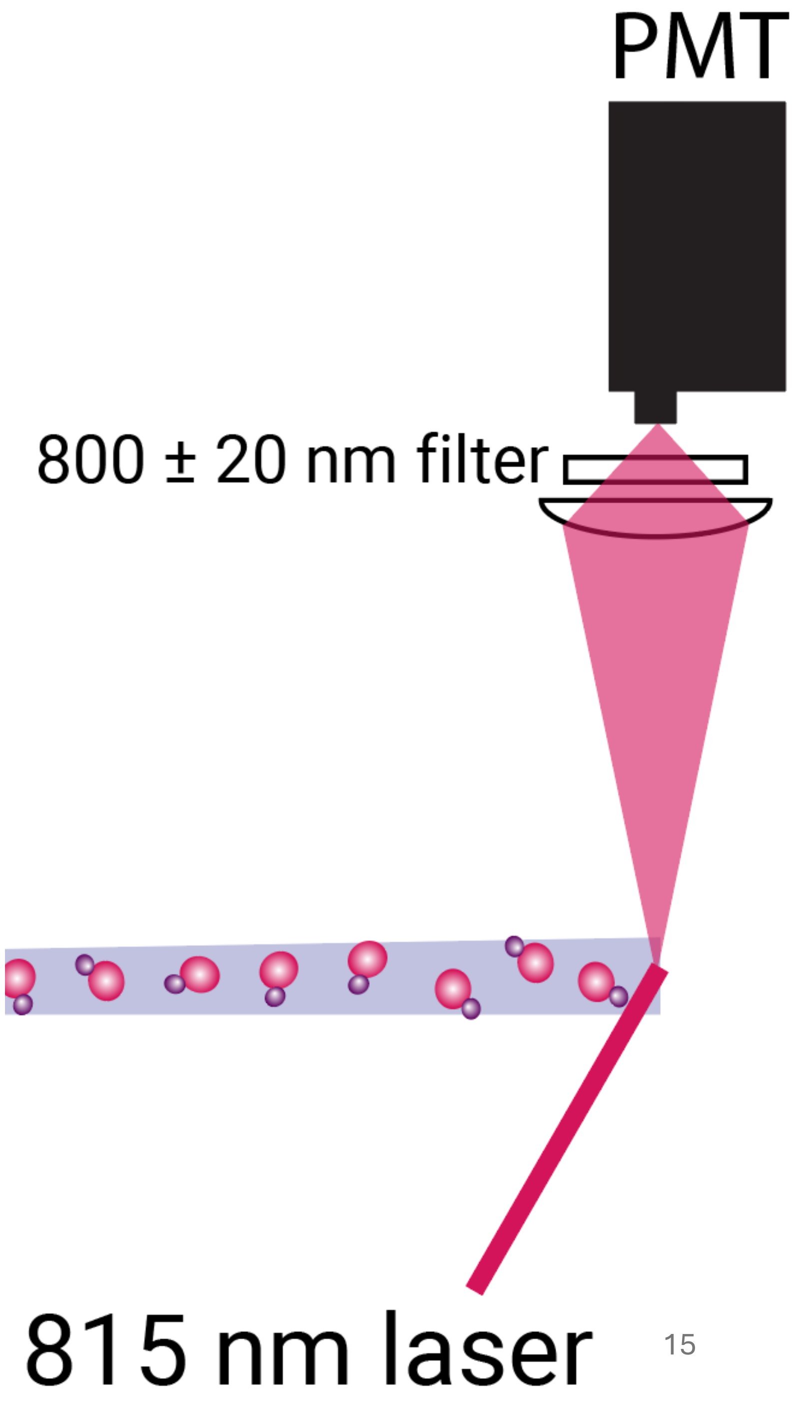
Detection scheme





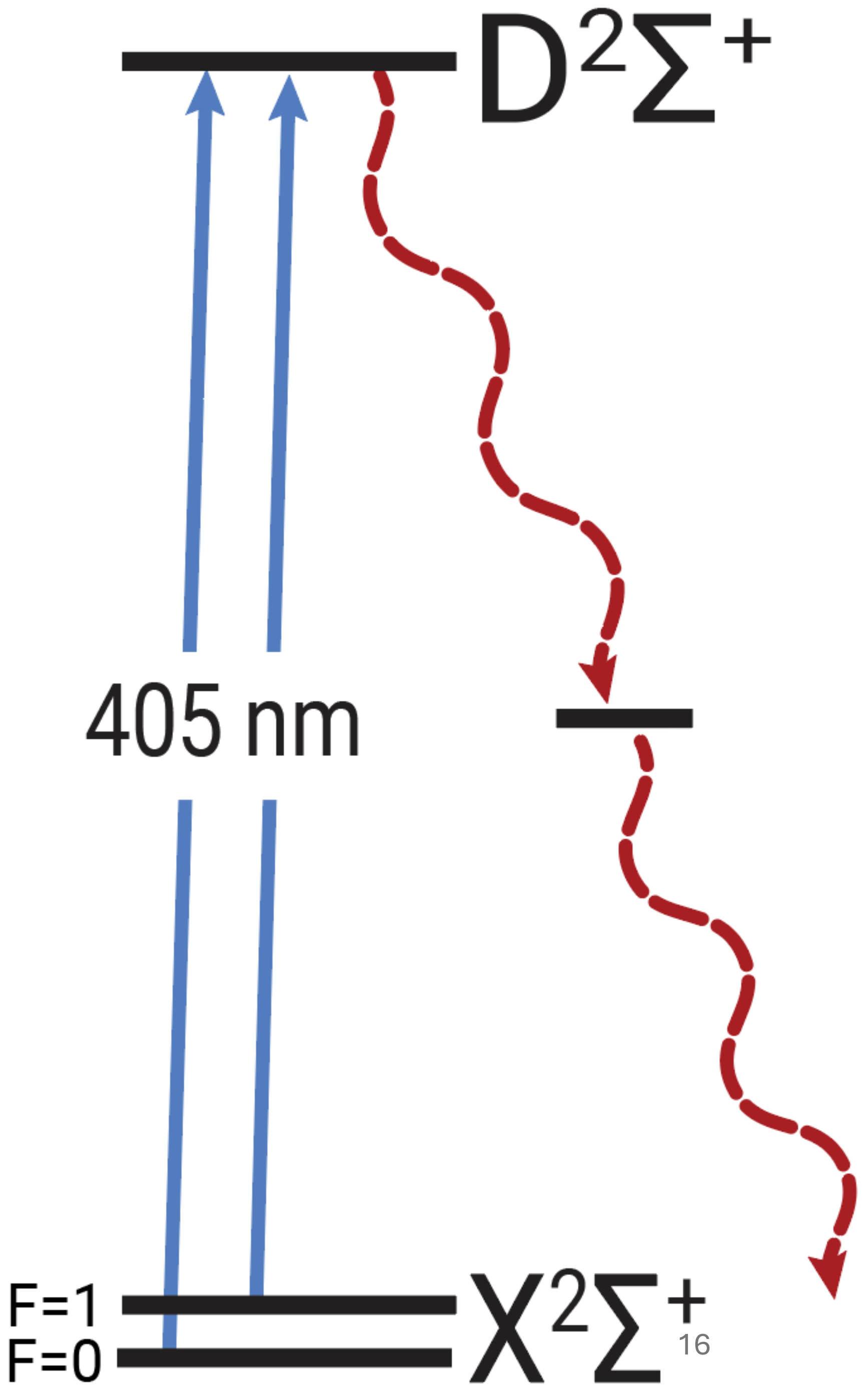
Detection scheme

- Limited by:
  - Light collection ≈ 2%
  - Quantum efficiency of detector ≈ 8%
  - 1 in 1000 photons is detected
- Signal
  - 40 photons per shot
- Background light
  - 30 photons per shot



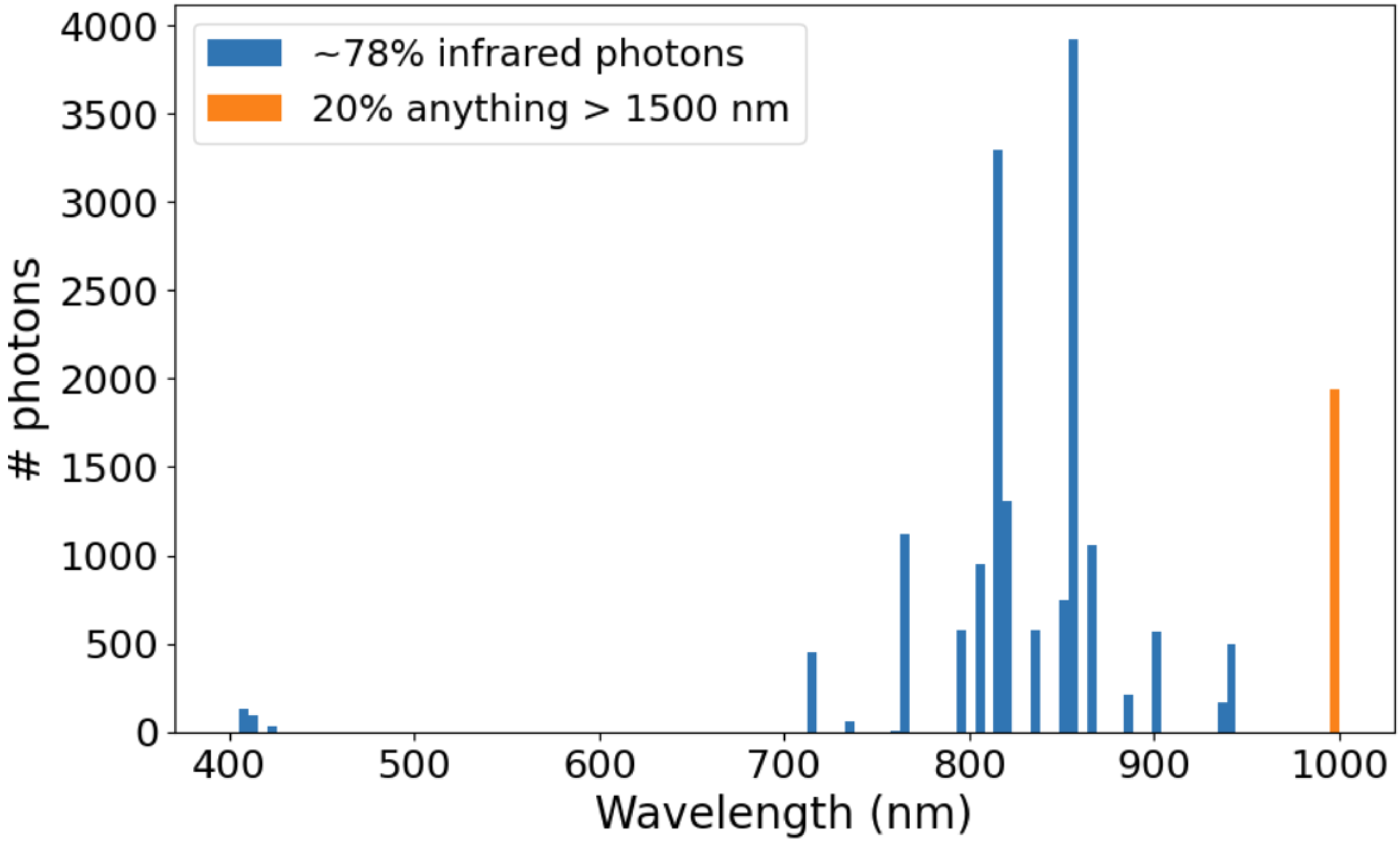
Updated detection scheme

- High excited state $D^2\Sigma^+$
- Known
  - Found in 1990 by Effantin et al
  - Approximate estimation of the energy
- Theory
  - Decays with 78% two infrared photons
- Unknown
  - Can we resolve F=0 and F=1?

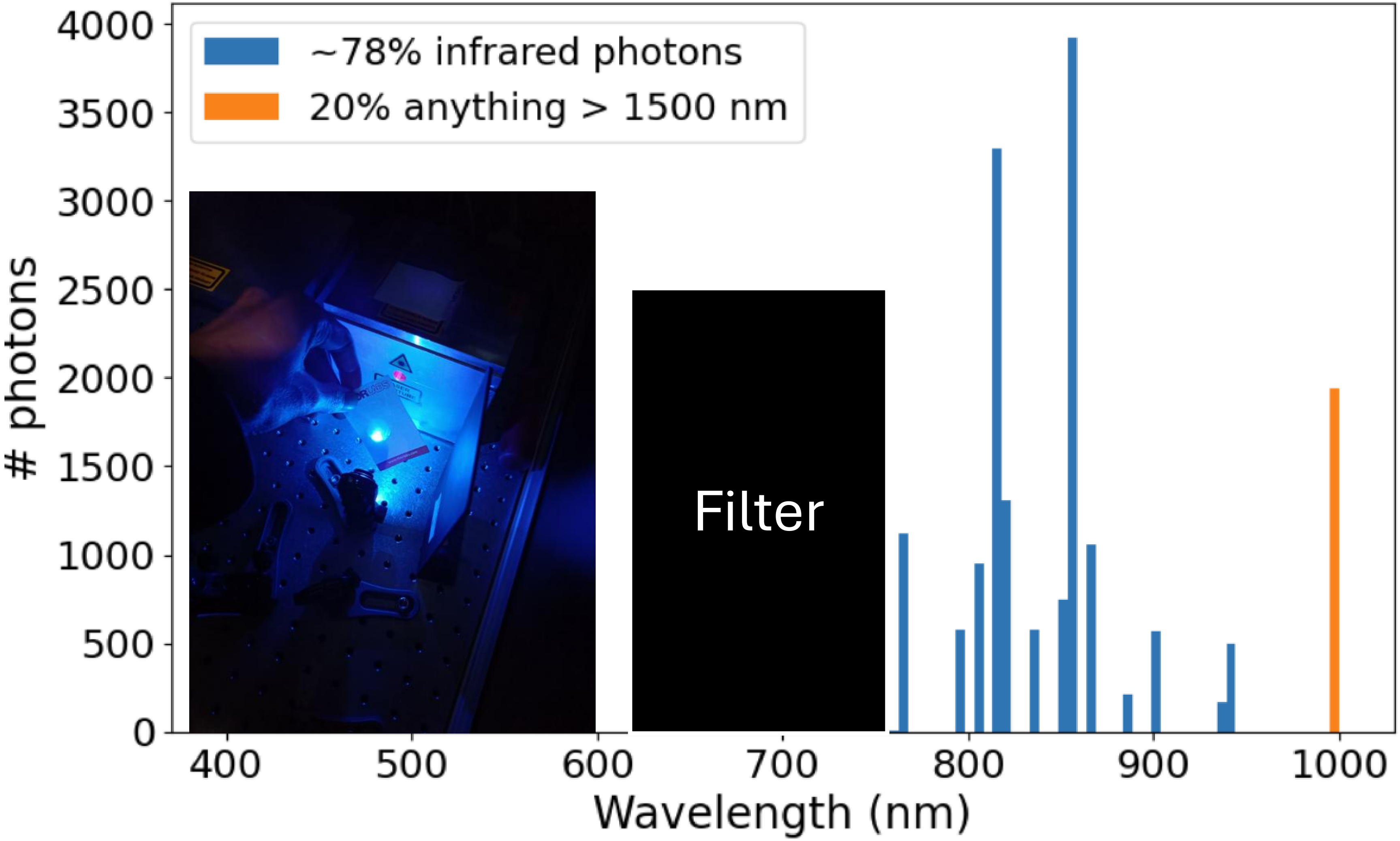


Effantin, C, *Studies of the electronic states of the BaF molecule*, Molecular Physics, *70*(5), 735–745, (1990)

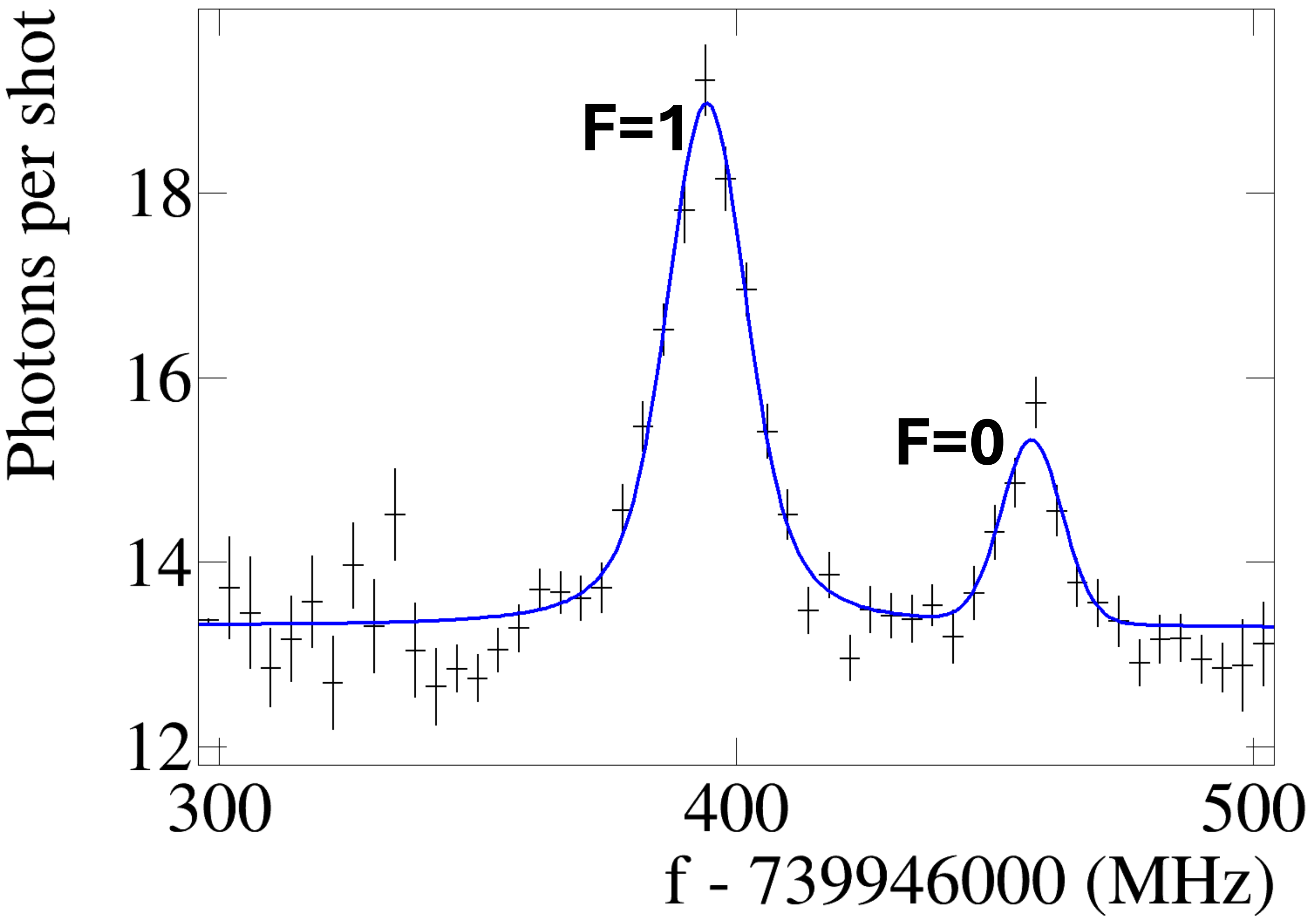
Spectrum of the $D^2\Sigma^+$ state

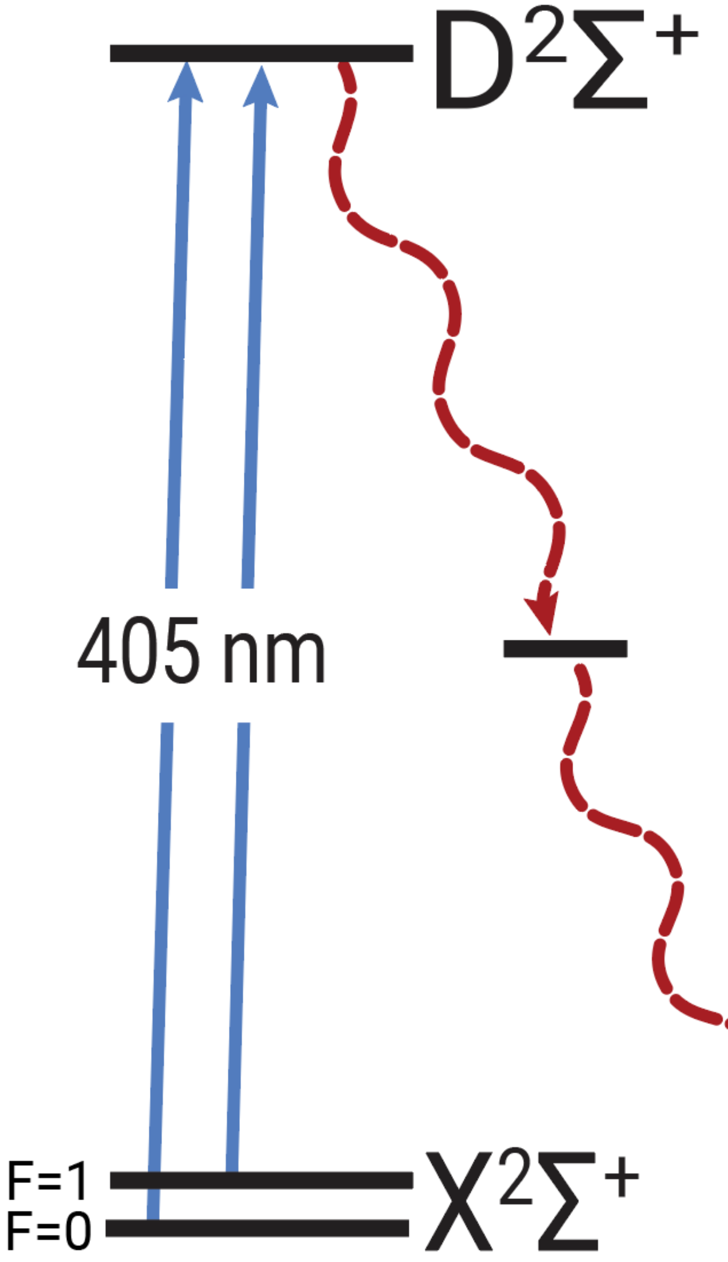


Spectrum of the $D^2\Sigma^+$ state

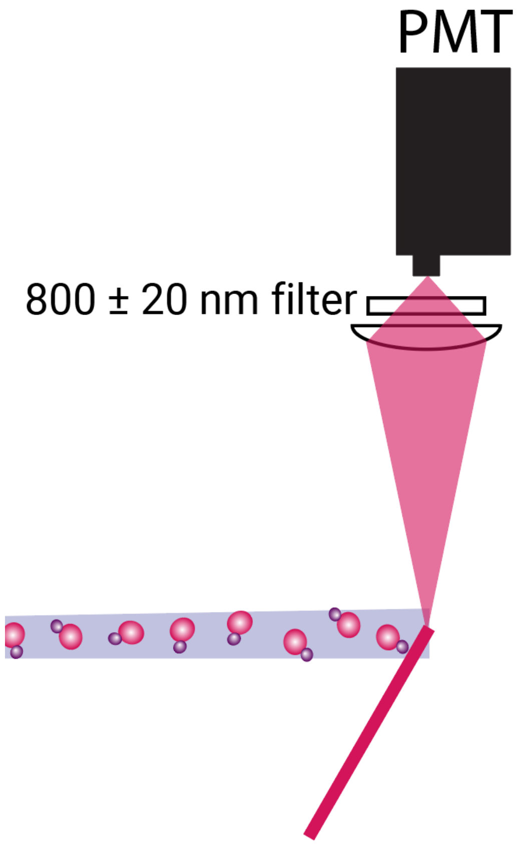


Spectroscopy of $D^2\Sigma^+$





Impact

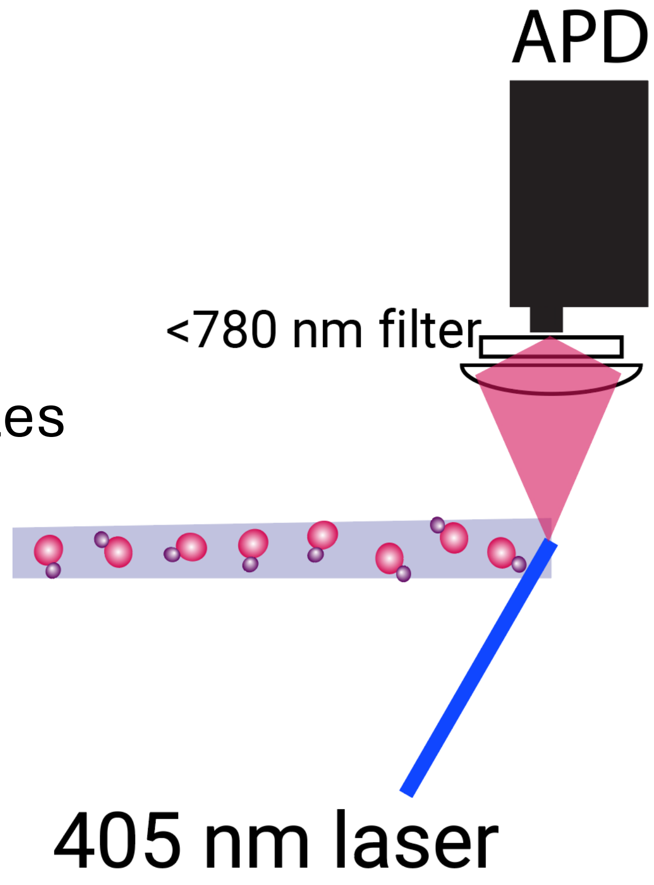


Background free	
No	Yes

Light collection	
2%	20%

+ 100x more molecules

Quantum efficiency	
8% (PMT)	80% (APD)



J. W. F. van Hofslot et al, 2d transverse laser cooling of a hexapole focused beam of cold BaF molecules, (2025)

Impact

Background free	
No	Yes

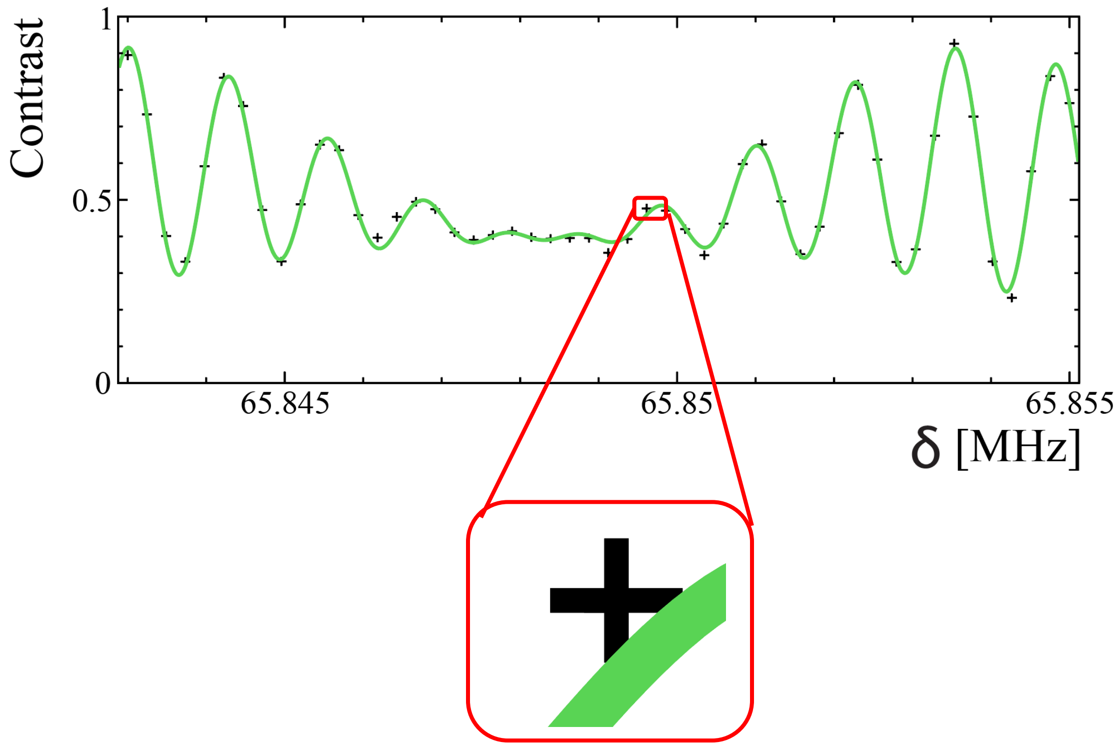
Light collection	
2%	20%

Quantum efficiency	
8% (PMT)	80% (APD)

Increases sensitivity to eEDM by factor of 10

Conclusion

- *e*EDM powerful probe of CP violation
- Background free detection technique
- Improved light collection and detector
- Increased sensitivity on *e*EDM by a factor of 10



The NL-eEDM team

Senior staff:

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Wim Ubachs
Jordy de Vries
Lorenz Willmann

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Ties Fikkers
Joost van Hofslot
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Heleen Mulder
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Former members:
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Klaus Jungmann
Virginia Marshall
Thomas Meijknecht
Maarten Mooij
Anno Touwen
Pi Haase
Parul Aggarwal
Kevin Esajas
Yanning Yin
Malika Denis
Roman Bause

Picture of the team with not every current member present

All parameters are linked to physical processes

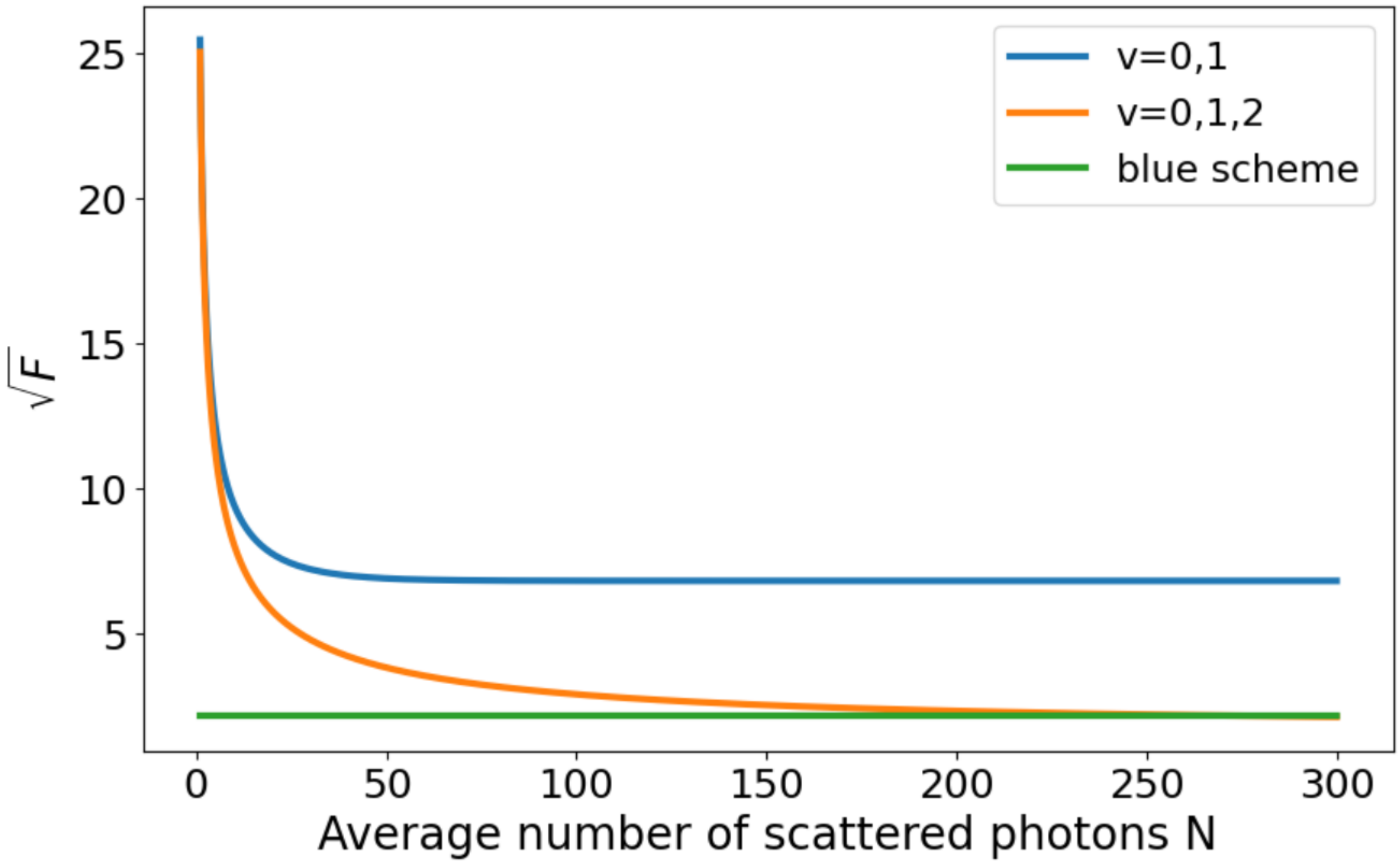
$$\boxed{P_{F=1}(\delta, \Delta, \mathrm{t}, T, \Omega_{P/S}\,, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{E}, \mathbf{B})}$$

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
Laser polarization $\hat{e}_{P/S}$,	Quality of superposition
Laser phase $\Phi_{P/S}$	Time scales, pulse timings
Electric field E	Hyperfine splitting from Stark shifts
Magnetic field B	Spin alignment, E field angle

$$\sigma_{d_e} = \frac{1}{W_d \mathcal{P}(E) T \sqrt{NM}} \sqrt{F}.$$

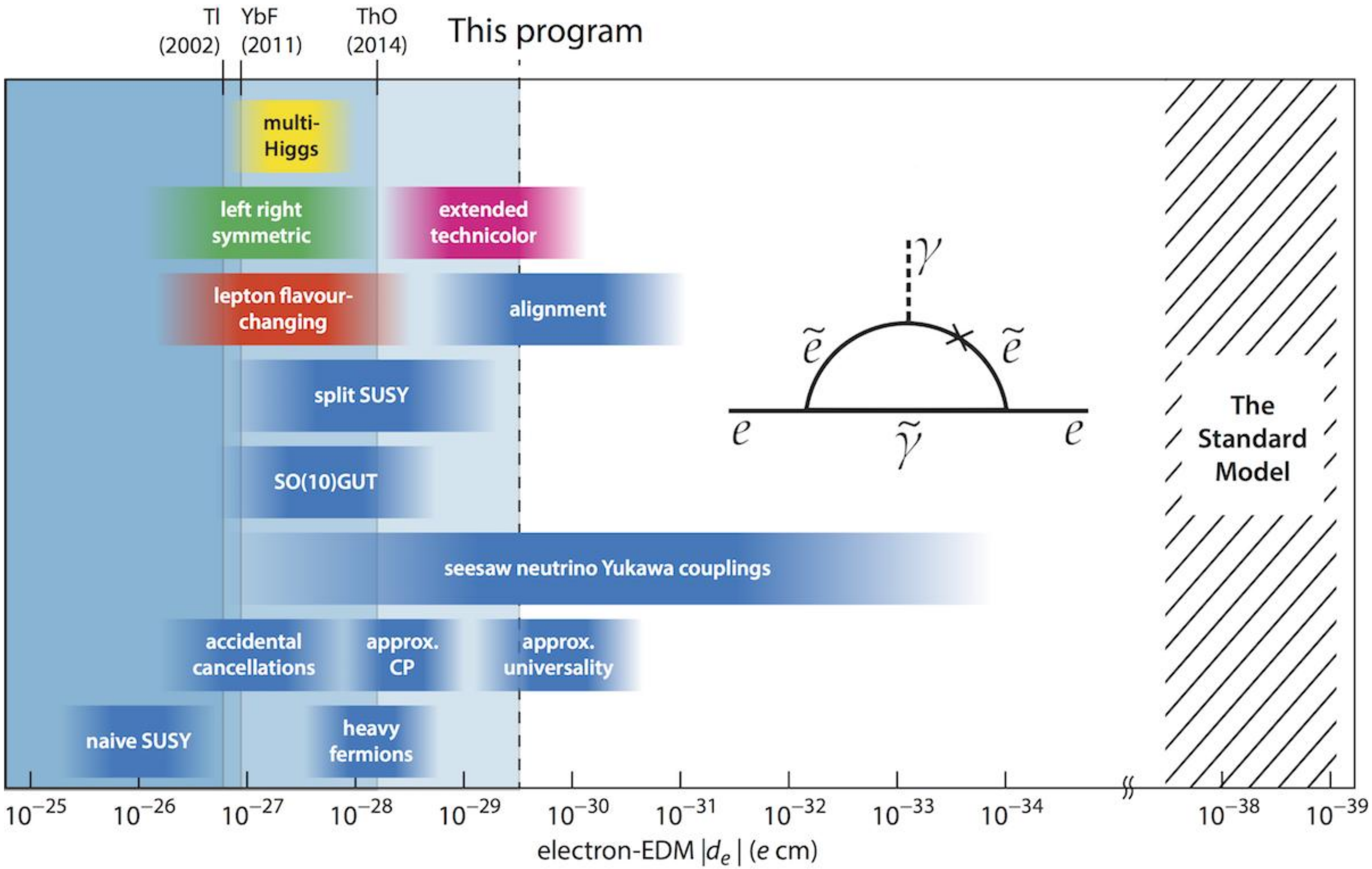
$$F = 1 + \frac{1}{\bar{n}} \left(\frac{1}{\epsilon} - 1 \right) + \frac{\sigma_n^2}{\bar{n}^2}.$$

[1] Boeschoten, A. (2023). Precision measurements in diatomic molecules: a route to a permanent electric dipole moment. [Thesis fully internal (DIV), University of Groningen]. University of Groningen. https://doi.org/10.33612/diss.674231809
[2] Lasner, Z., & DeMille, D. (2018). Statistical sensitivity of phase measurements via laser-induced fluorescence with optical cycling detection. *Physical Review. A/Physical Review, A*, *98*(5). https://doi.org/10.1103/physreva.98.053823



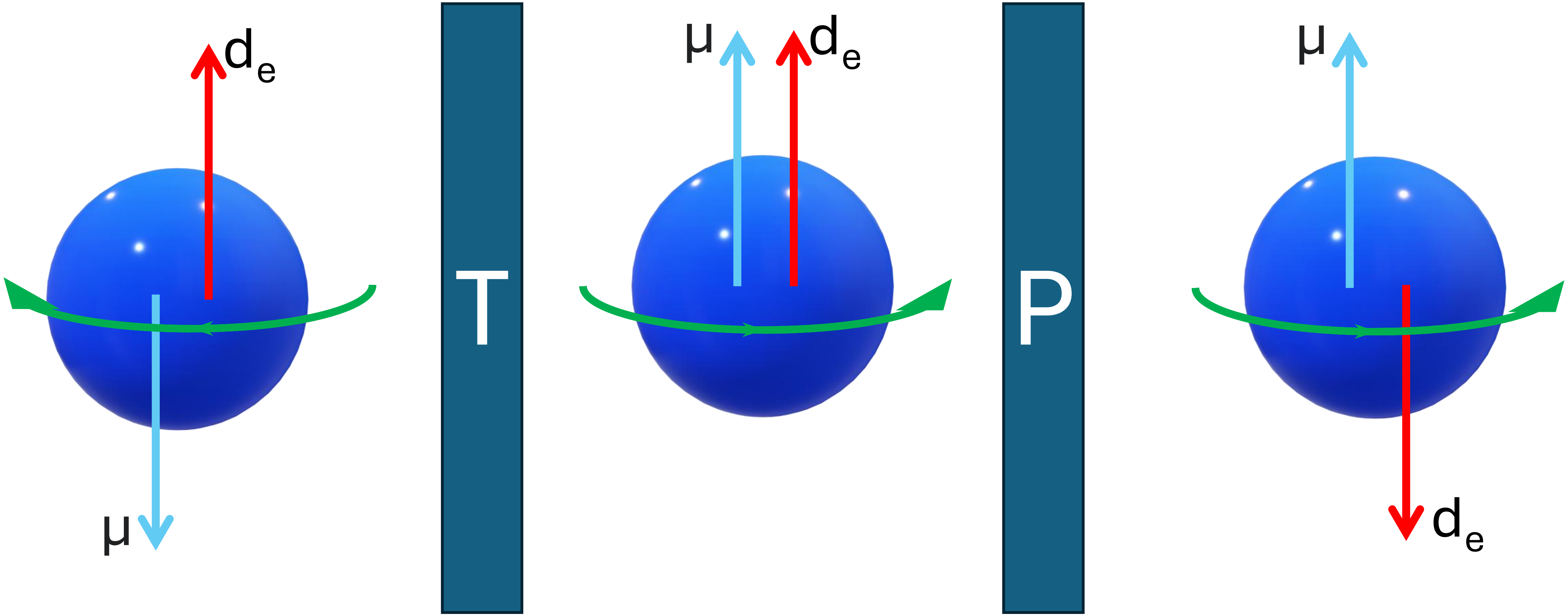
v=0,1
v=0,1,2
blue scheme
25
20
15
10
5
$\sqrt{F}$
0
50
100
150
200
250
300
Average number of scattered photons N

Beyond the standard model

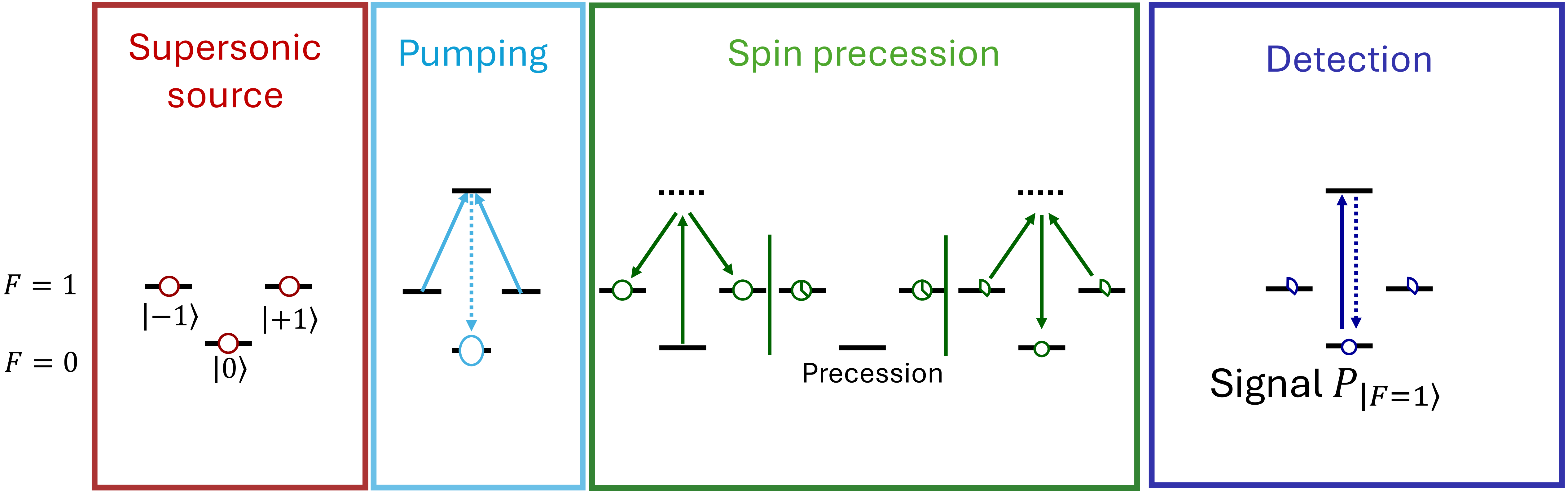


RUG Van Swinderen Instituut, accessed 06-11-2025 at https://www.rug.nl/research/vsi/newtopics/electron-edm?lang=en.

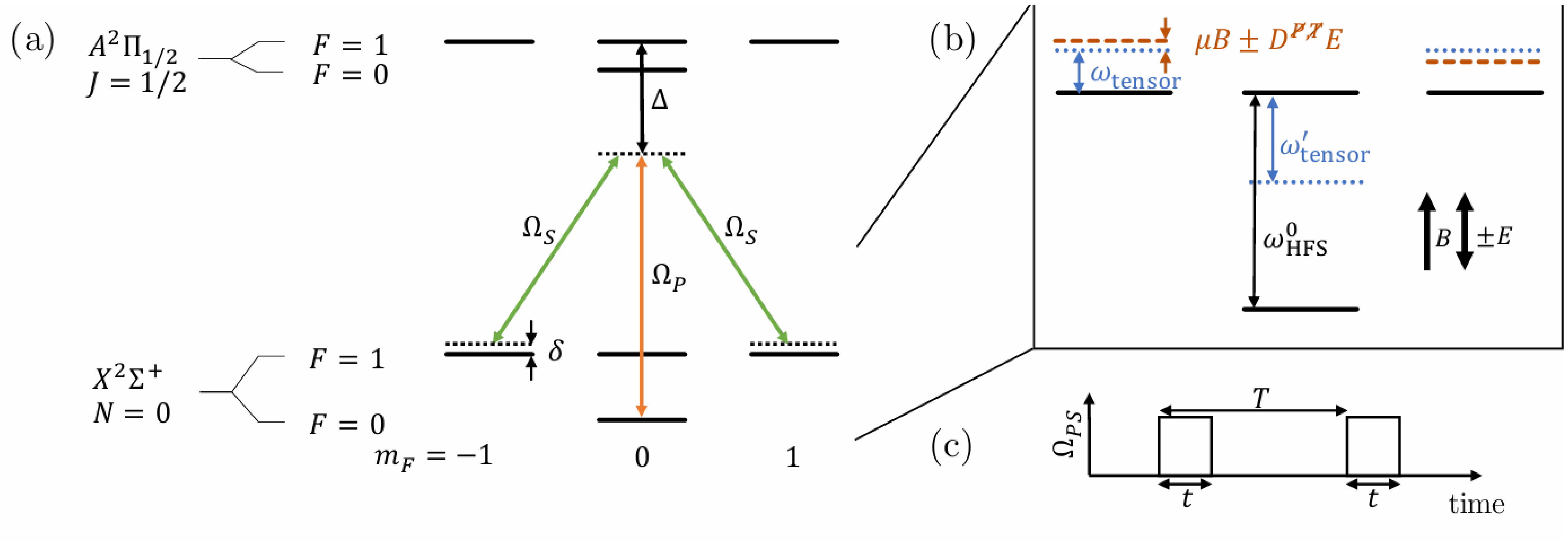
eEDM breaks P, T



Spin precession



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

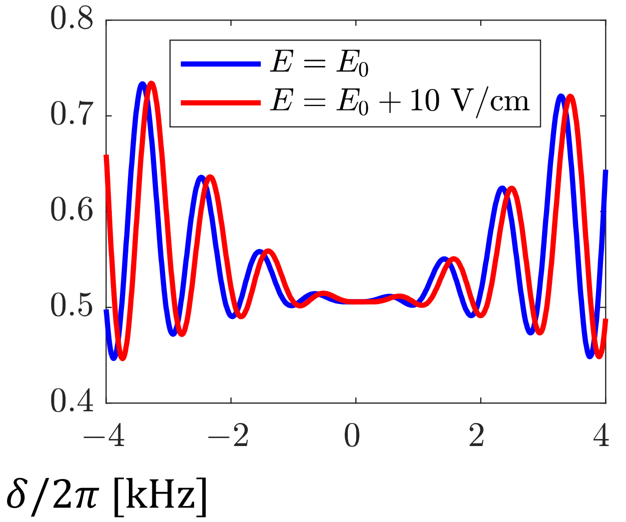


Example: information on E from detuning scan

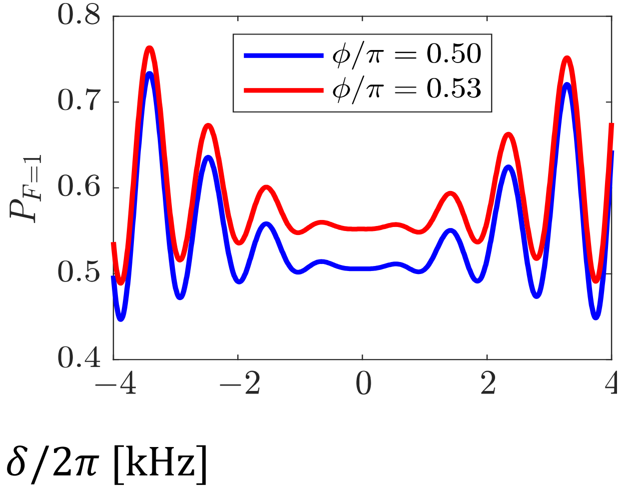
- $P_{F=1}(\delta, \Delta, t, T, \Omega_{P/S}, \hat{e}_{P/S}, \Phi_{P/S}, \mathbf{B}, \mathbf{E})$

- Each parameter has their own fingerprint in the signal

- They can be distinguished from a true EDM signal

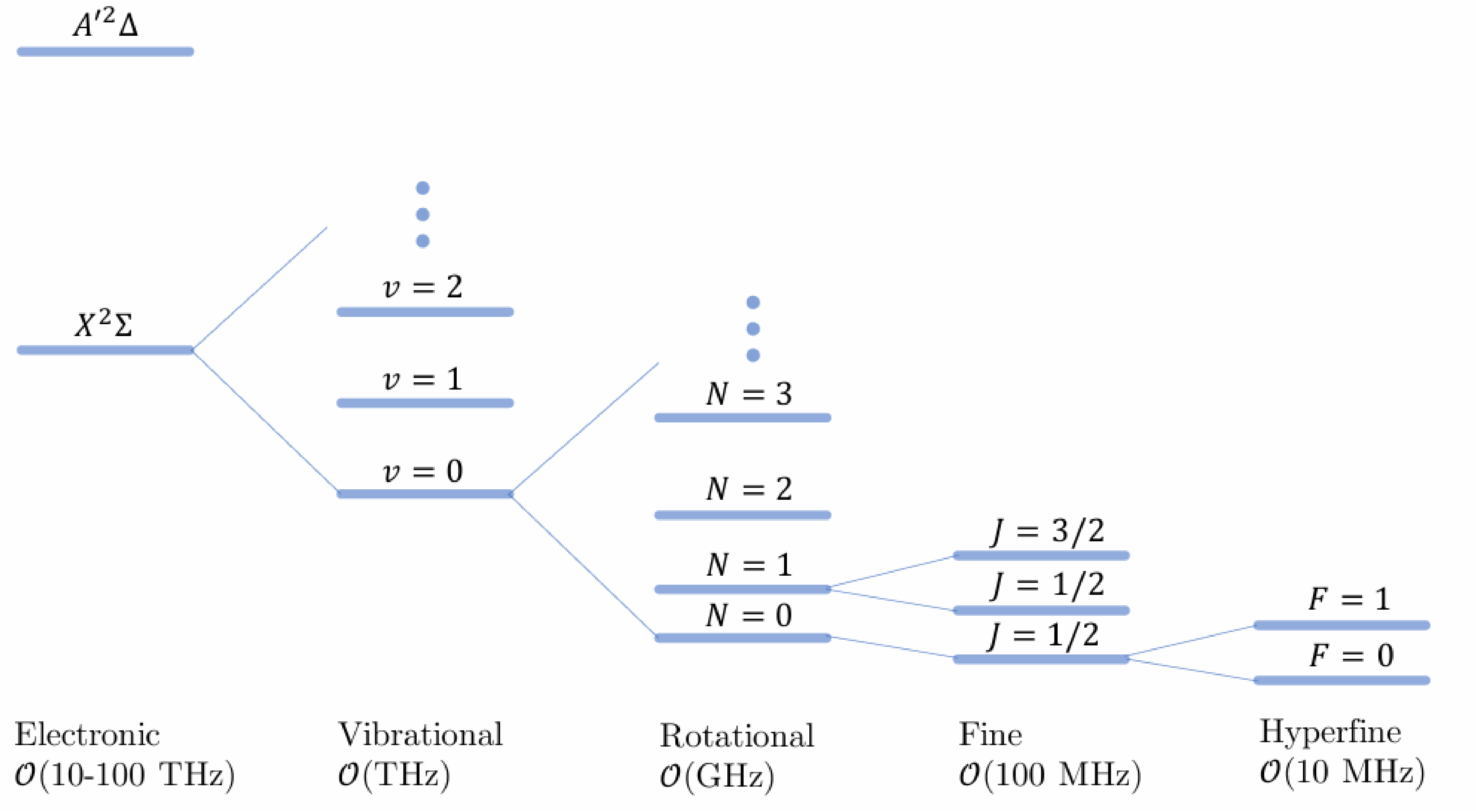


Changing E



EDM signal

Molecular structure



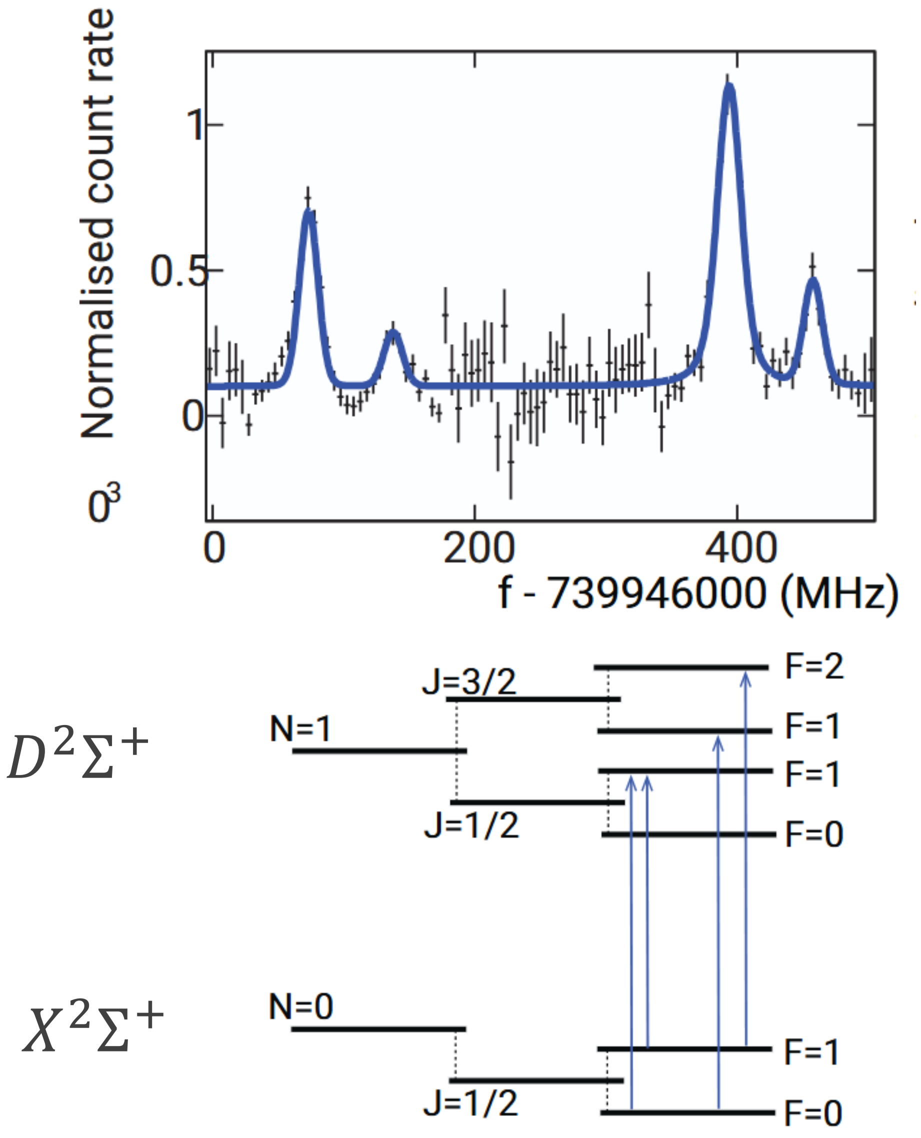
The permanent electron electric dipole moment (eEDM)

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

$$\begin{tikzcd} & H = \mu B + d_e E \arrow[dl, "T"'] \arrow[dr, "P"] & \\ H = -\mu B + d_e E & & H = \mu B - d_e E \end{tikzcd}$$

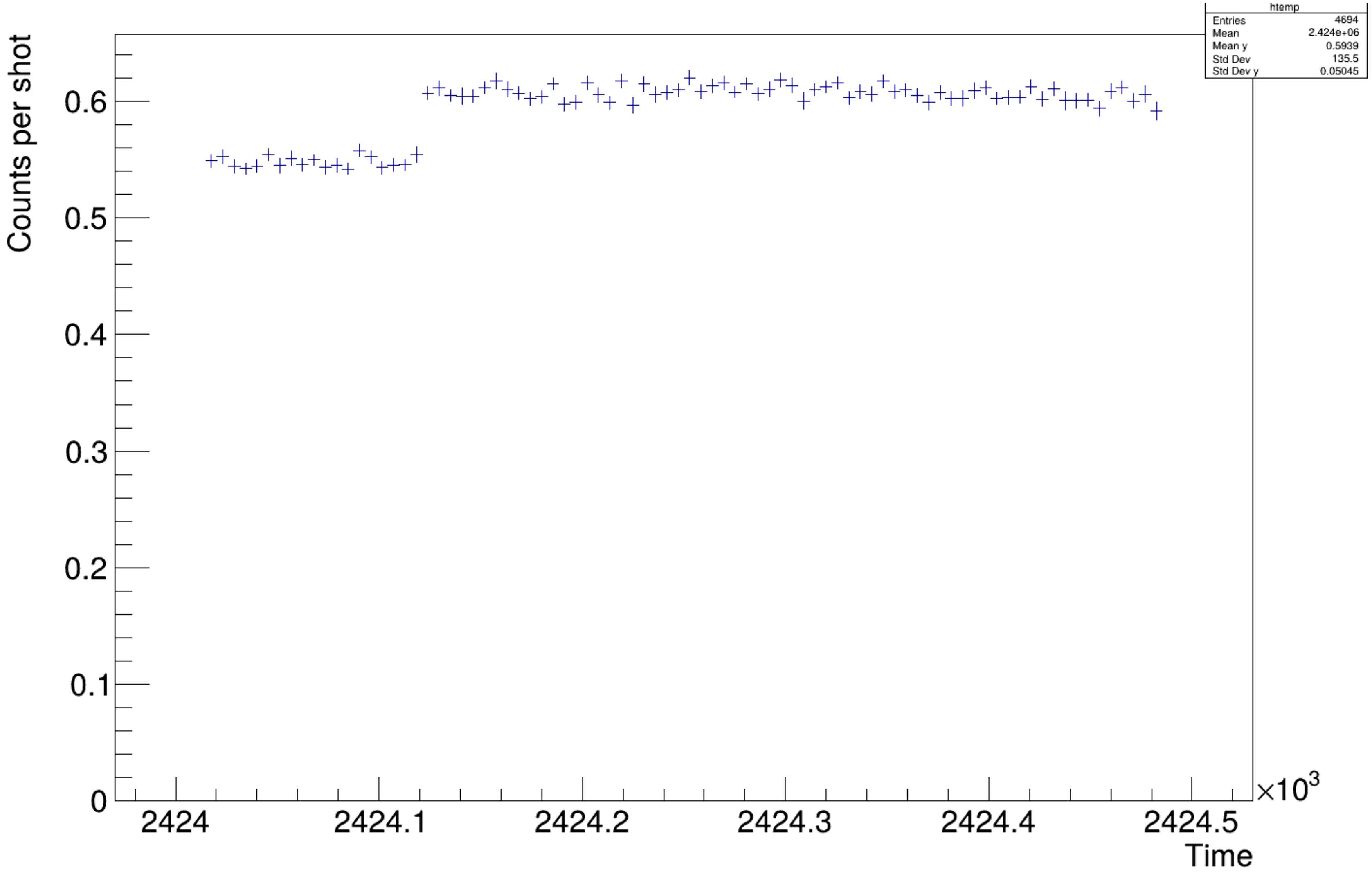
- Within molecules enhancement $d_e \rightarrow D^{\not P, \not T} > 10^6$ depending on molecule

The NL-eEDM collaboration. In: The European Physical Journal D, Vol. 72, No. 11, 197, 20.11.2018.



Normalised count rate
1
0.5
0
0
200
400
f - 739946000 (MHz)
$D^2\Sigma^+$
$X^2\Sigma^+$
N=1
J=3/2
J=1/2
F=2
F=1
F=1
F=0
N=0
J=1/2
F=1
F=0

Turning on infrared laser



Turning on blue laser