The eEDM program

Table-Top Particle Physics

Hendrick Bethlem, Anastasia Borschevsky, Steven Hoekstra (PL), Steve Jones, Rob Timmermans, Wim Ubachs, Jordy de Vries, Lorenz Willmann

university of groningen
van swinderen institute for particle physics and gravity

Nikhef
Dutch National Institute for (astro)Particle Physics

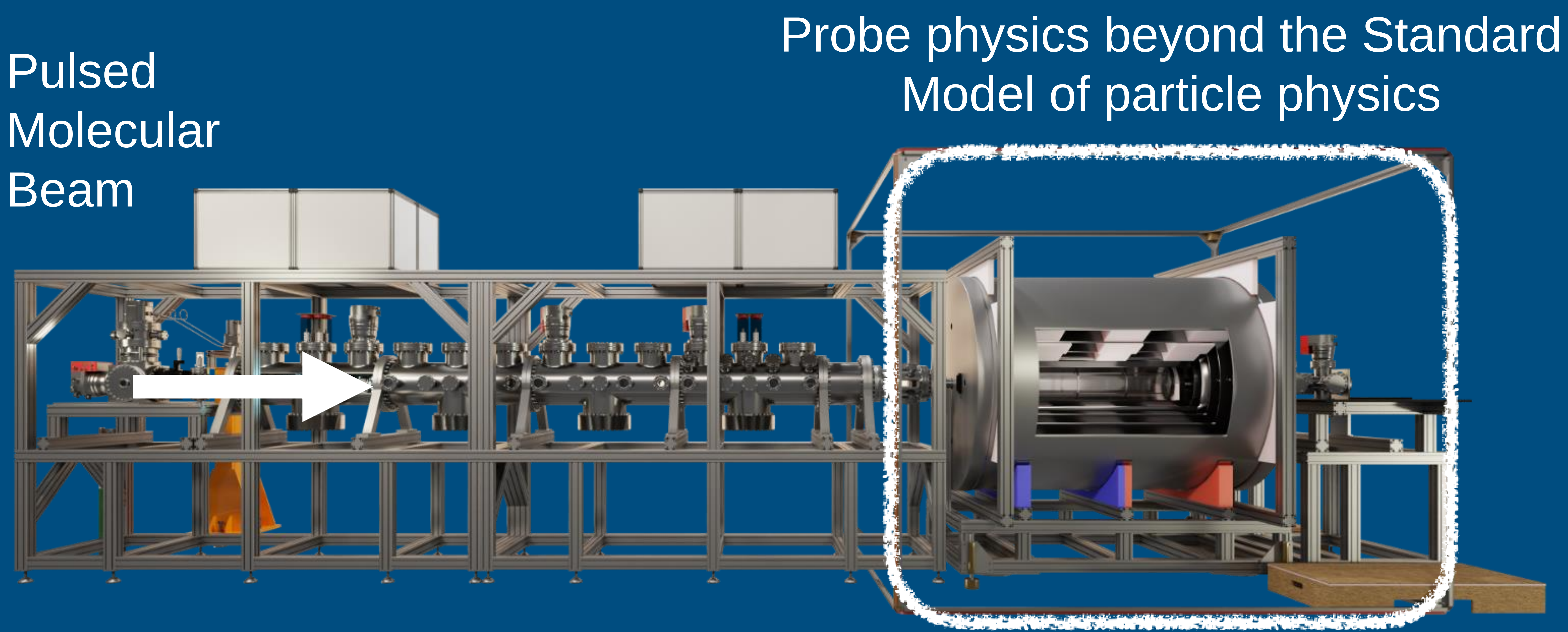
VU VRIJE UNIVERSITEIT AMSTERDAM

UvA

The eEDM program

Table-Top Particle Physics

- Use molecular enhancement to probe the electron's electric dipole moment
  - Symmetry-violating properties of fundamental particles may add minuscule but measurable shifts to the energies of molecular states



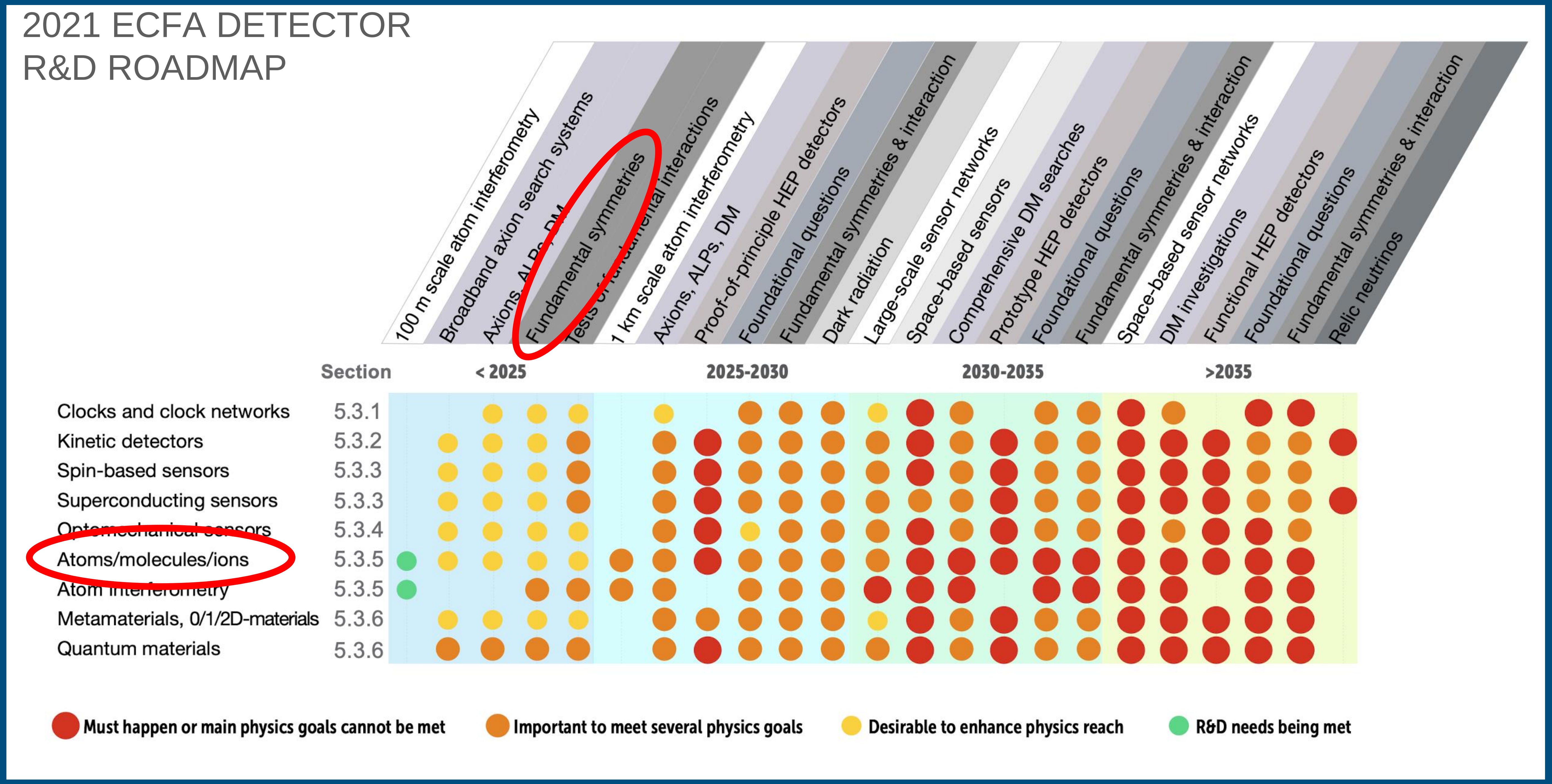
Context

ECFA detector R&D Roadmap - RDq: Quantum and Emerging Technologies

- Precision experiments using atoms, ions and molecules are part of larger framework of low-energy table-top particle physics

- Impact recognised, rapidly growing field, requires investments now

- Nikhef can play a significant role!



Status: people and funding

- Funding
  - First NWO program came to an end
  - Successful with ENW-XL (2.7 M€), M2 (700 k€) and VICI (1.5 M€) grants
  - Mostly for PhD students and postdocs, limited investment in equipment
- Staff changes
  - Jordy de Vries (UvA) joined: particle physics theory
  - Steve Jones (VSI Groningen) joined: antihydrogen precision table-top particle physics
  - Klaus Jungmann retired
- PhD students - transition to a next generation

  (3 finished, 4 will finish this year, 1 ongoing, 4 new hires, 6 open positions)

Status: the experiment

Two fronts

	• Spin-precession measurements	• Bright and slow beam
Last year	• All key elements in place • 600 m/s BaF molecular beam • First measurements successfully done, key publication submitted	• Intense cryogenic 200 m/s beam operational, meets all specifications • Some hardware setbacks: laser issues, high-voltage electronics. All resolved now - but shows crucial role of technical support for this in-house experiment
Next year	• Larger datasets -> first eEDM limit • Demonstrate control of systematics	• Combine with transverse laser cooling (all systems currently operational) • Quantify and optimise brightness of 200 m/s beam • Demonstrate 30 m/s BaF beam

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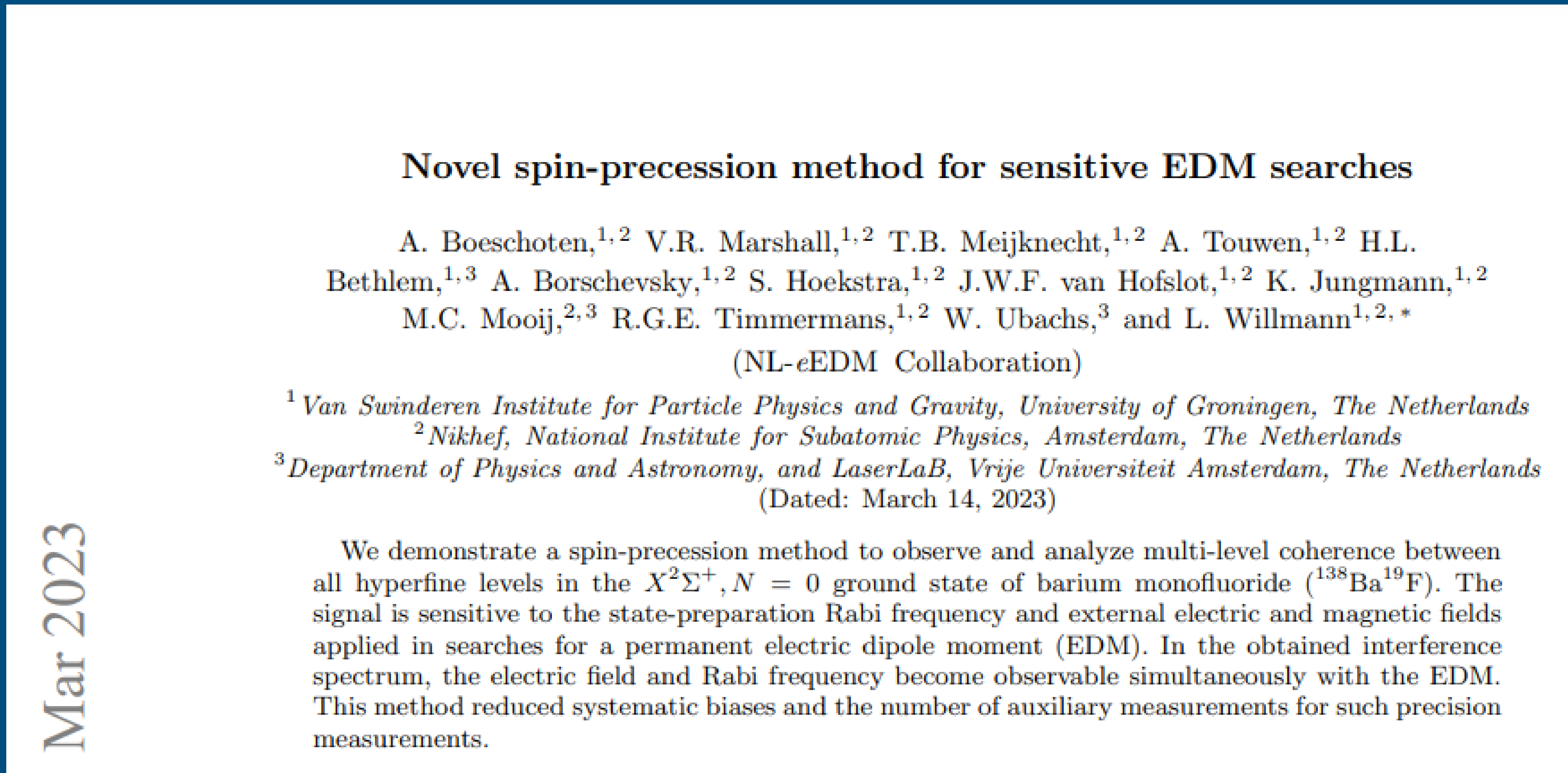


Novel spin-precession method for sensitive EDM searches

A. Boeschoten,[1,2] V.R. Marshall,[1,2] T.B. Meijknecht,[1,2] A. Touwen,[1,2] H.L. Bethlem,[1,3] A. Borschevsky,[1,2] S. Hoekstra,[1,2] J.W.F. van Hofslot,[1,2] K. Jungmann,[1,2] M.C. Mooij,[2,3] R.G.E. Timmermans,[1,2] W. Ubachs,[3] and L. Willmann[1,2,*]

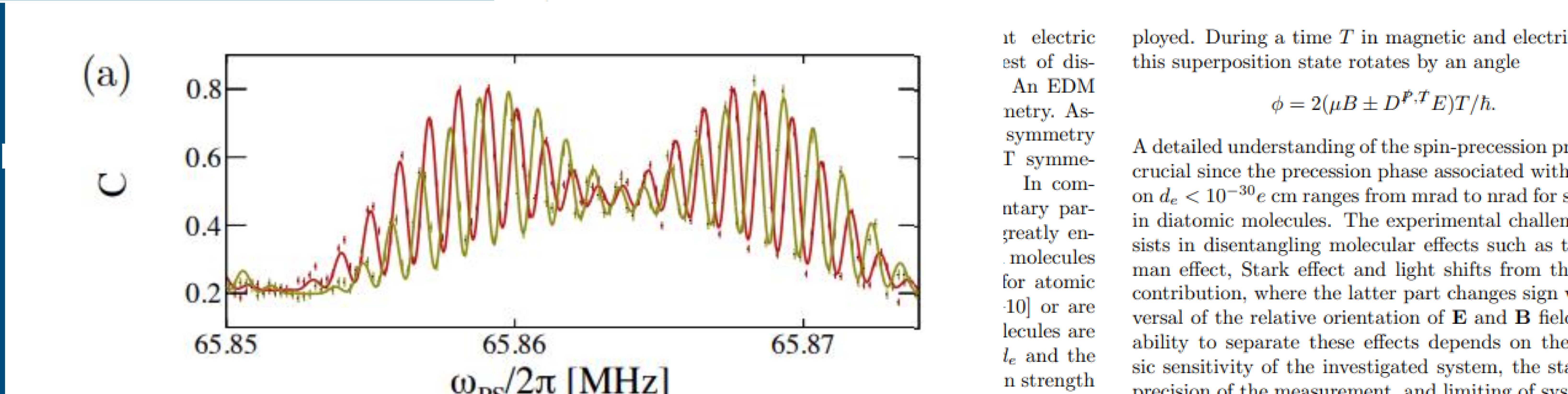
(NL-eEDM Collaboration)

[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*

(Dated: March 14, 2023)

We demonstrate a spin-precession method to observe and analyze multi-level coherence between all hyperfine levels in the $X^2\Sigma^+, N = 0$ ground state of barium monofluoride ($^{138}Ba^{19}F$). The signal is sensitive to the state-preparation Rabi frequency and external electric and magnetic fields applied in searches for a permanent electric dipole moment (EDM). In the obtained interference spectrum, the electric field and Rabi frequency become observable simultaneously with the EDM. This method reduced systematic biases and the number of auxiliary measurements for such precision measurements.

Mar 2023



$$\phi = 2(\mu B \pm D^{P,T} E)T/\hbar.$$

Status: the experiment

PHYSICAL REVIEW LETTERS 127, 173201 (2021)

Featured in Physics

Deceleration and Trapping of SrF Molecules

P. Aggarwal,[1,2,*] Y. Yin,[1,2,*] K. Esajas,[1,2] H. L. Bethlem,[1,3] A. Boeschoten,[1,2] A. Borschevsky,[1,2] S. Hoekstra,[1,2,†] K. Jungmann,[1,2] V. R. Marshall,[1,2] T. B. Meijknecht,[1,2] M. C. Mooij,[2,3] R. G. E. Timmermans,[1,2] A. Touwen,[1,2] W. Ubachs,[3] and L. Willmann[1,2]

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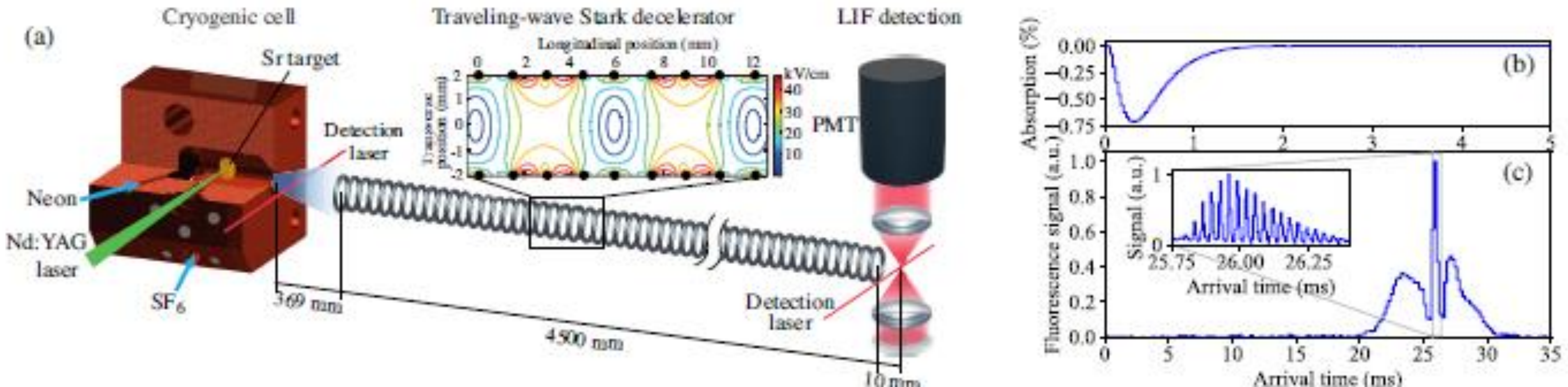
(Received 14 March 2021; accepted 7 September 2021; published 21 October 2021)

We report on the electrostatic trapping of neutral SrF molecules. The molecules are captured from a cryogenic buffer-gas beam source into the moving traps of a 4.5-m-long traveling-wave Stark decelerator. The SrF molecules in $X^2\Sigma^+ (v = 0, N = 1)$ state are brought to rest as the velocity of the moving traps is gradually reduced from 190 m/s to zero. The molecules are held for up to 50 ms in multiple electric traps of the decelerator. The trapped packets have a volume (FWHM) of 1 mm^3 and a velocity spread of 5(1) m/s, which corresponds to a temperature of 60(20) mK. Our result demonstrates a factor 3 increase in the molecular mass that has been Stark decelerated and trapped. Heavy molecules (mass > 100 amu) offer a highly increased sensitivity to probe physics beyond the standard model. This work significantly extends the species of neutral molecules of which slow beams can be created for collision studies, precision measurement, and trapping experiments.



- Bright and slow beam
  - Intense cryogenic 200 m/s beam operational, meets all specifications
  - Some hardware setbacks: laser issues, high-voltage electronics. All resolved now - but shows crucial role of technical support for this in-house experiment
  - Combine with transverse laser cooling (all systems currently operational)
  - Quantify and optimise brightness of 200 m/s beam
  - Demonstrate 30 m/s BaF beam

Status: the experiment

Two fronts

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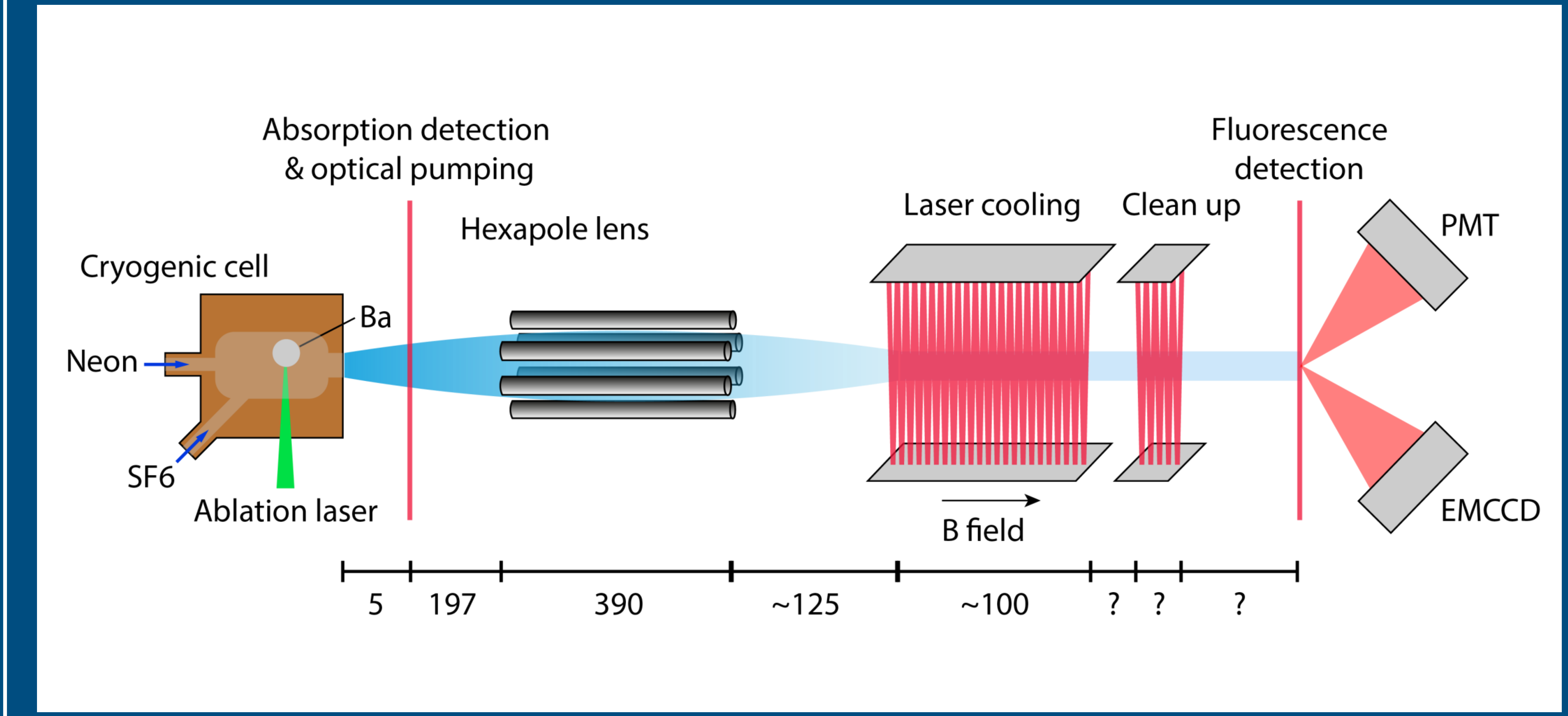
Status: the experiment

Two fronts

- Spin-precession measurements
- Bright and slow beam

Last year



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Status: preparing for a move

Merge the two fronts

- Move to new lab space

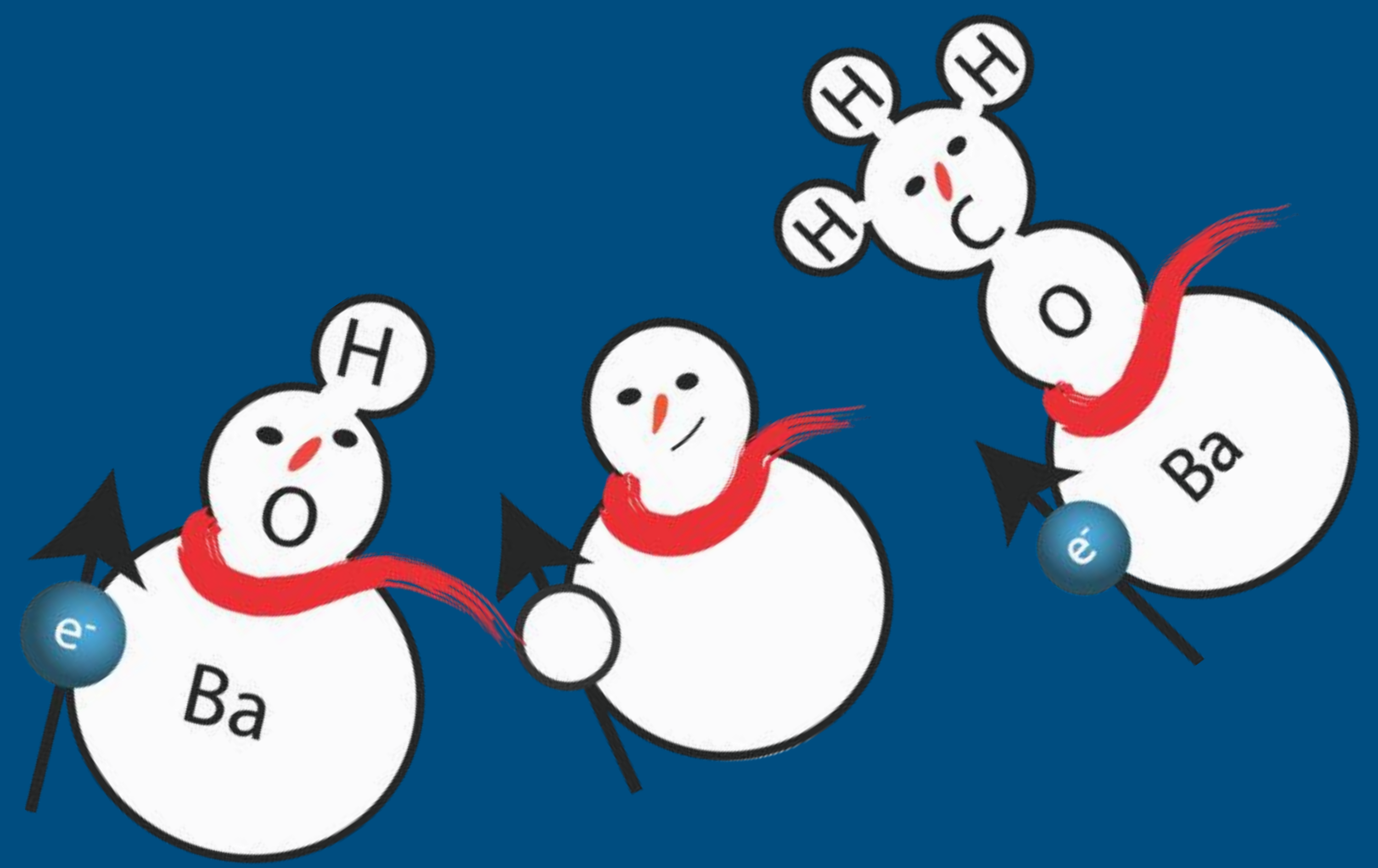
Q2 2024

- New building for faculty of science and engineering in Groningen
- Make use of this deadline: key moment to implement spin-precession measurement of 200 m/s BaF molecules
- Will take time and resources

Status: theory

Two fronts

- Effective field theories
  - Rob Timmermans, Jordy de Vries
  - Make more connections between eEDM and high-energy observables through effective field theories
- Ab-initio quantum structure
  - Anastasia Borschevsky
  - Enhancement factors, state lifetimes, behaviour in external fields, and discovery of even better molecules for future experiments



The VISTA for our program

Looking further ahead

Current best limit: 4×10^{-30}e. cm (Roussy et al. arXiv: 2212. 11841)

Minimize statistical uncertainty

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

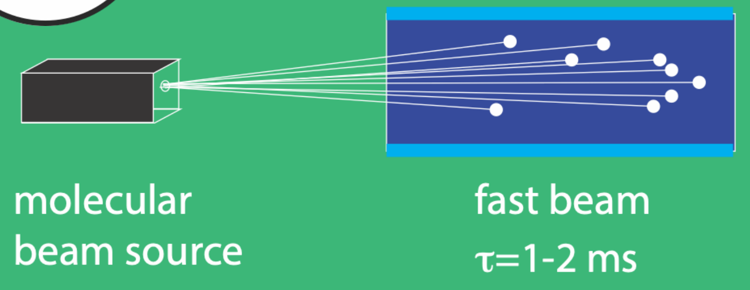
Heavy polar molecules give a high sensitivity to new physics

Slow and cold beams provide a long interaction time

Using entanglement enables linear scaling with the number of molecules

2017-2023
NWO program

3×10^{-28}e. cm

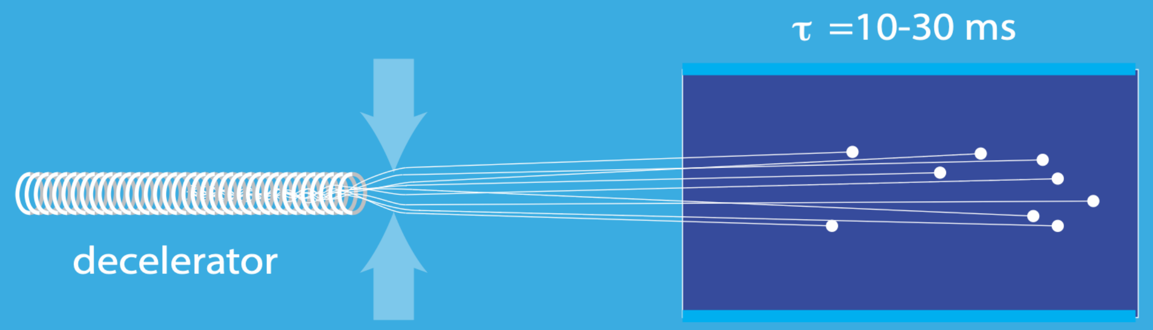


Phase 1
Fast beam of BaF molecules

2023-2028
ENW-XL

3×10^{-30}e. cm

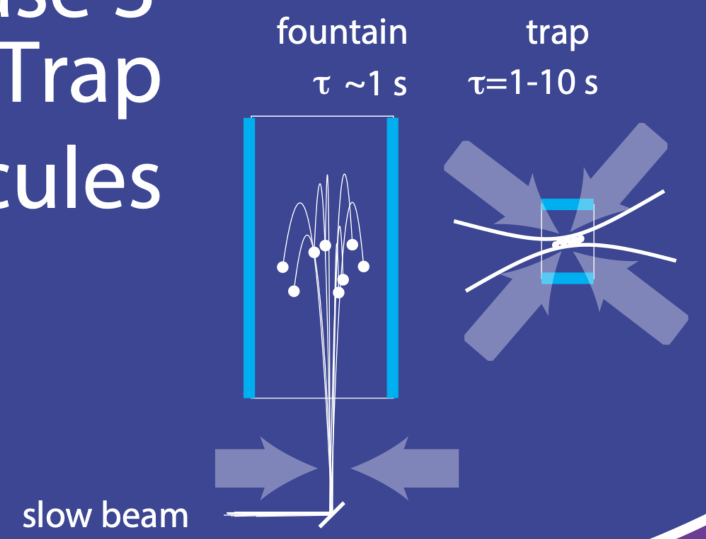
Phase 2
Slow and cold molecular beam



2023-2028
ENW-XL, M2 and VICI

1×10^{-31}e. cm

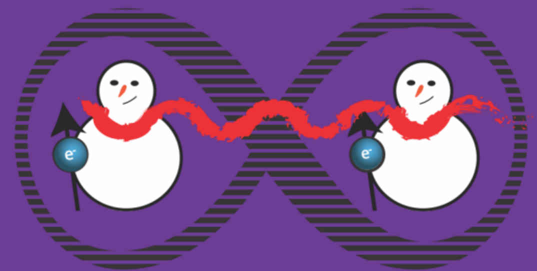
Phase 3
Fountain, Trap
Better molecules



2025-2035

1×10^{-32}e. cm

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

Key points

- eEDM: table-top particle-physics, within growing field
- Nikhef inhouse experiment
  - Unique experimental infrastructure combined with strong theory component
- Funding situation currently excellent
  - Mainly for junior scientists
  - Technical support of experiment remains crucial
- Clear future plans
  - Plan move to new lab well to minimise delays