Probing New Physics

with Slow and Trapped Molecules

Steven Hoekstra, University of Groningen and Nikhef, The Netherlands

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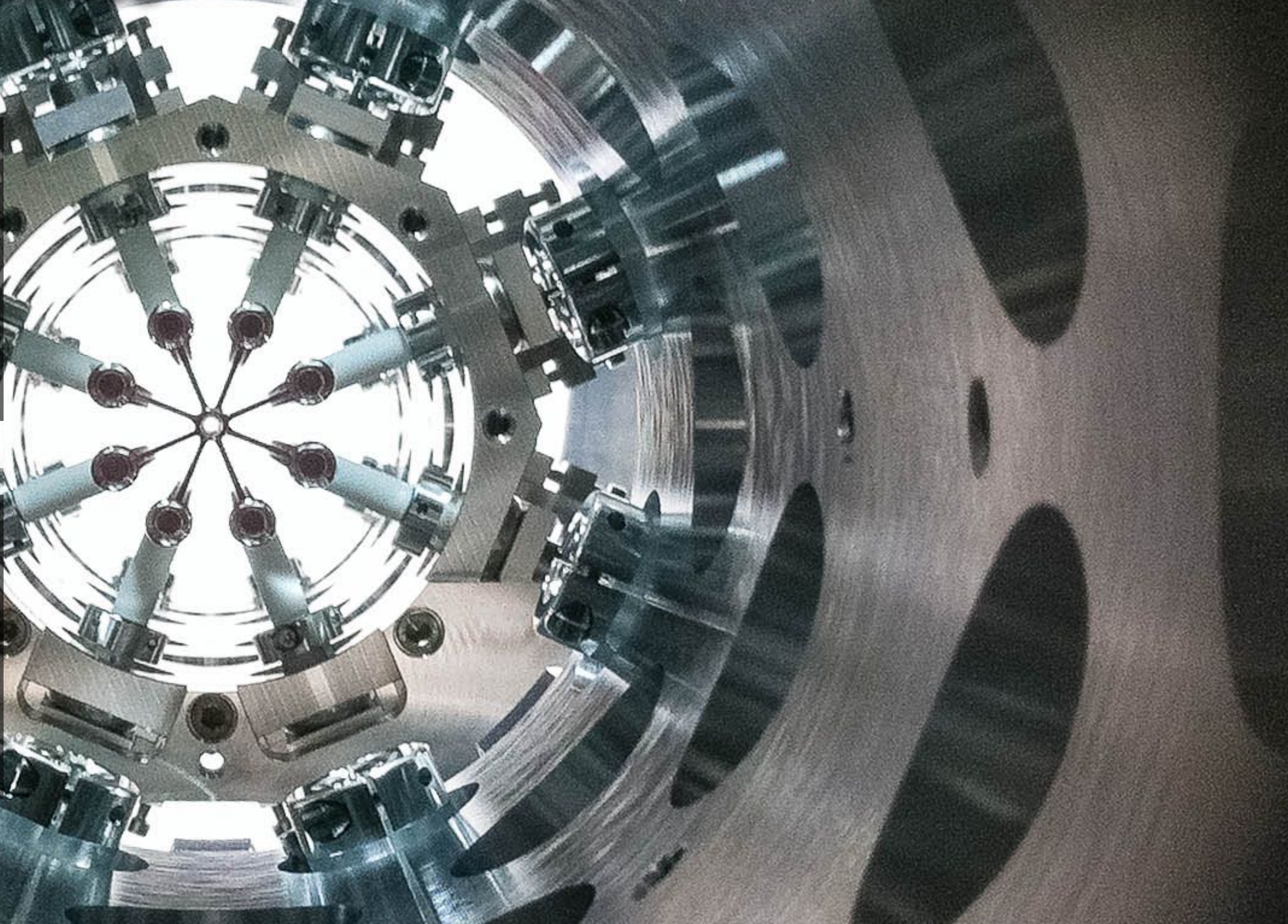
Part 1: Table-top particle physics

- 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



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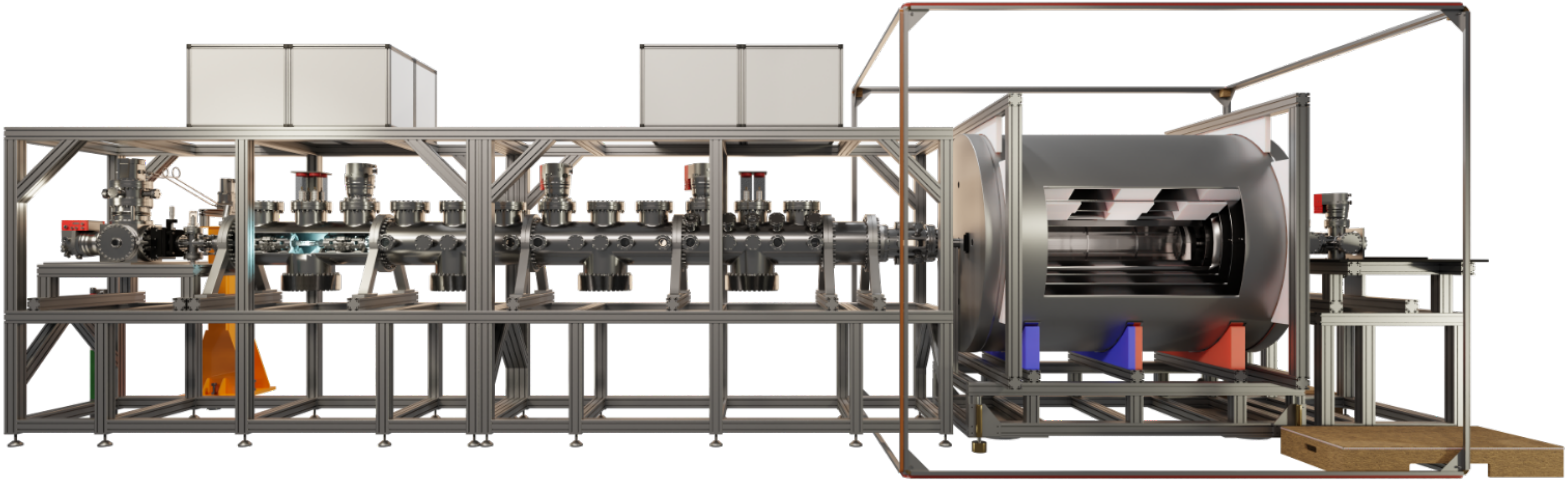

university of groningen
van swinderen institute for particle physics and gravity

Nikhef
Dutch National Institute for (astro)Particle Physics

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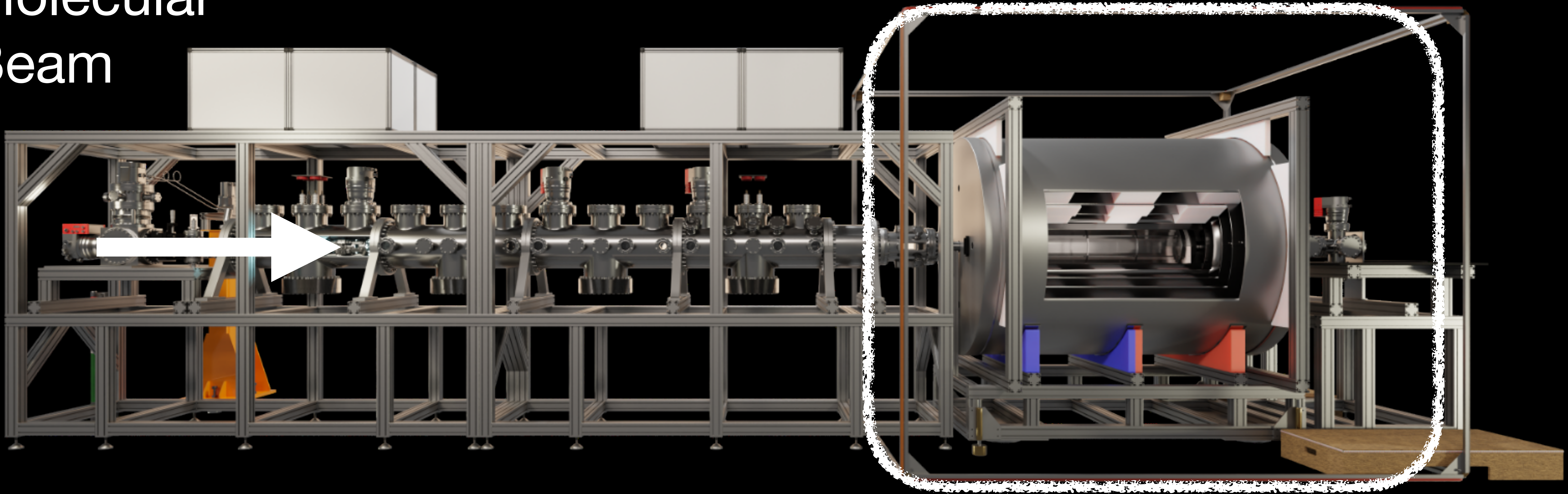
Table-top particle physics with slow and trapped molecules

Pulsed Molecular Beam

Probe physics beyond the Standard Model of particle physics



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Beyond the Standard Model of particle physics

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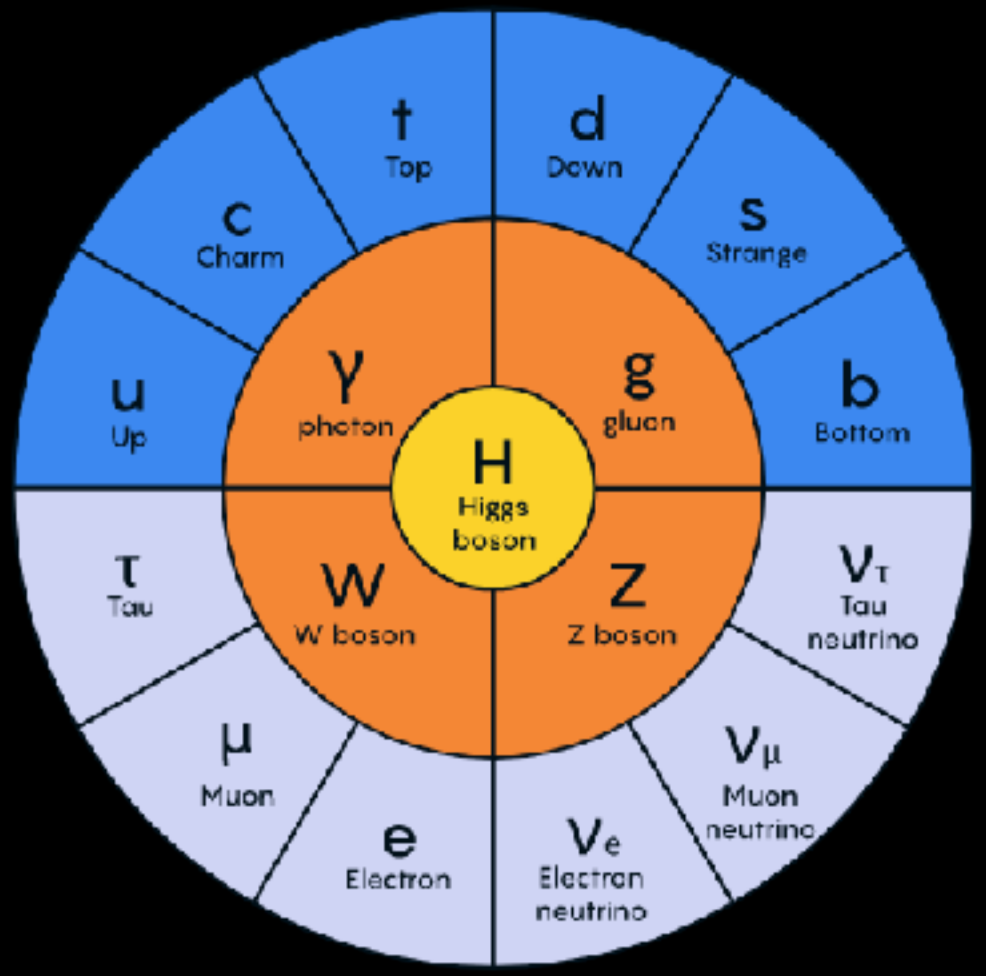

12 fundamental particles
and their interactions

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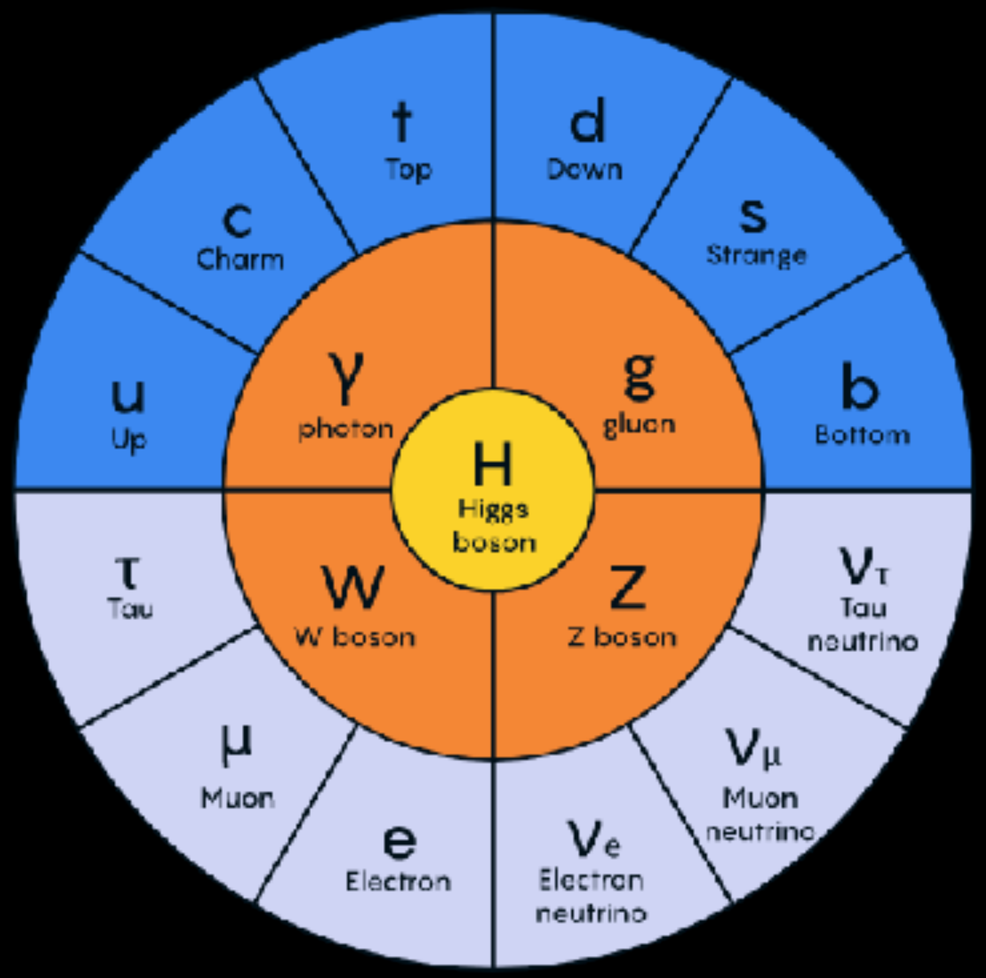

12 fundamental particles
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Why these particles?

What is Dark Matter?

How can we understand the matter-antimatter asymmetry?

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

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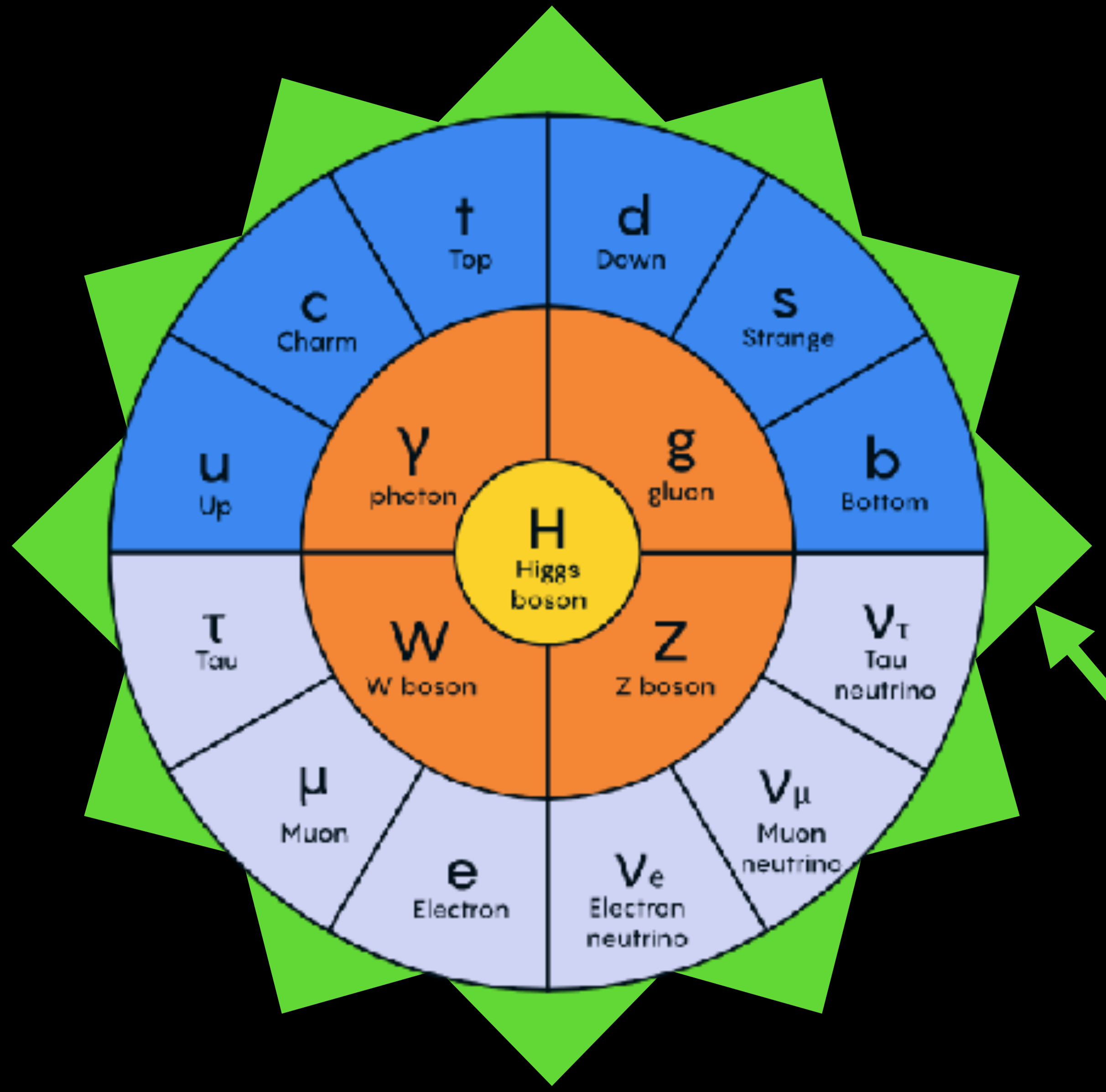

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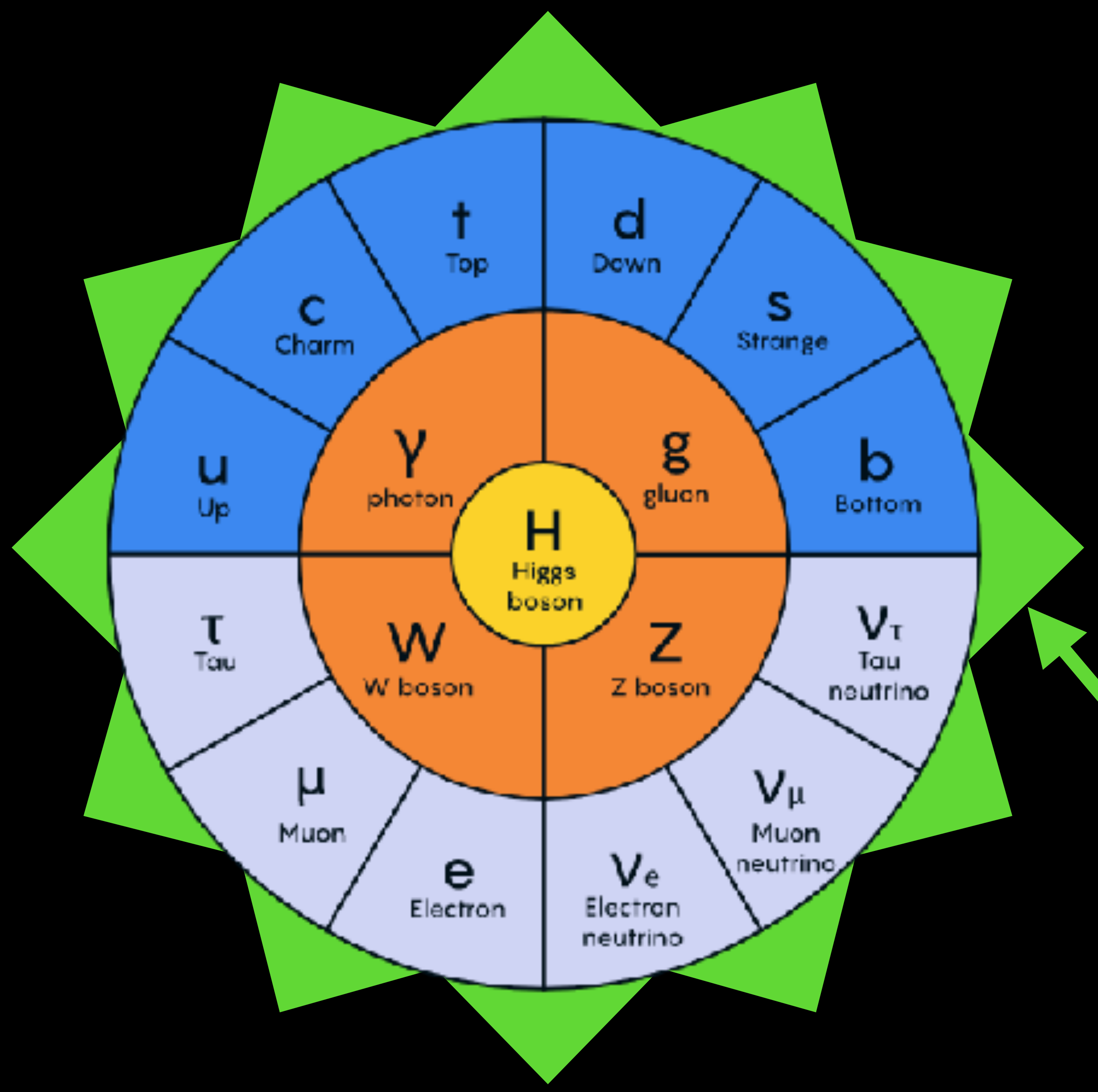

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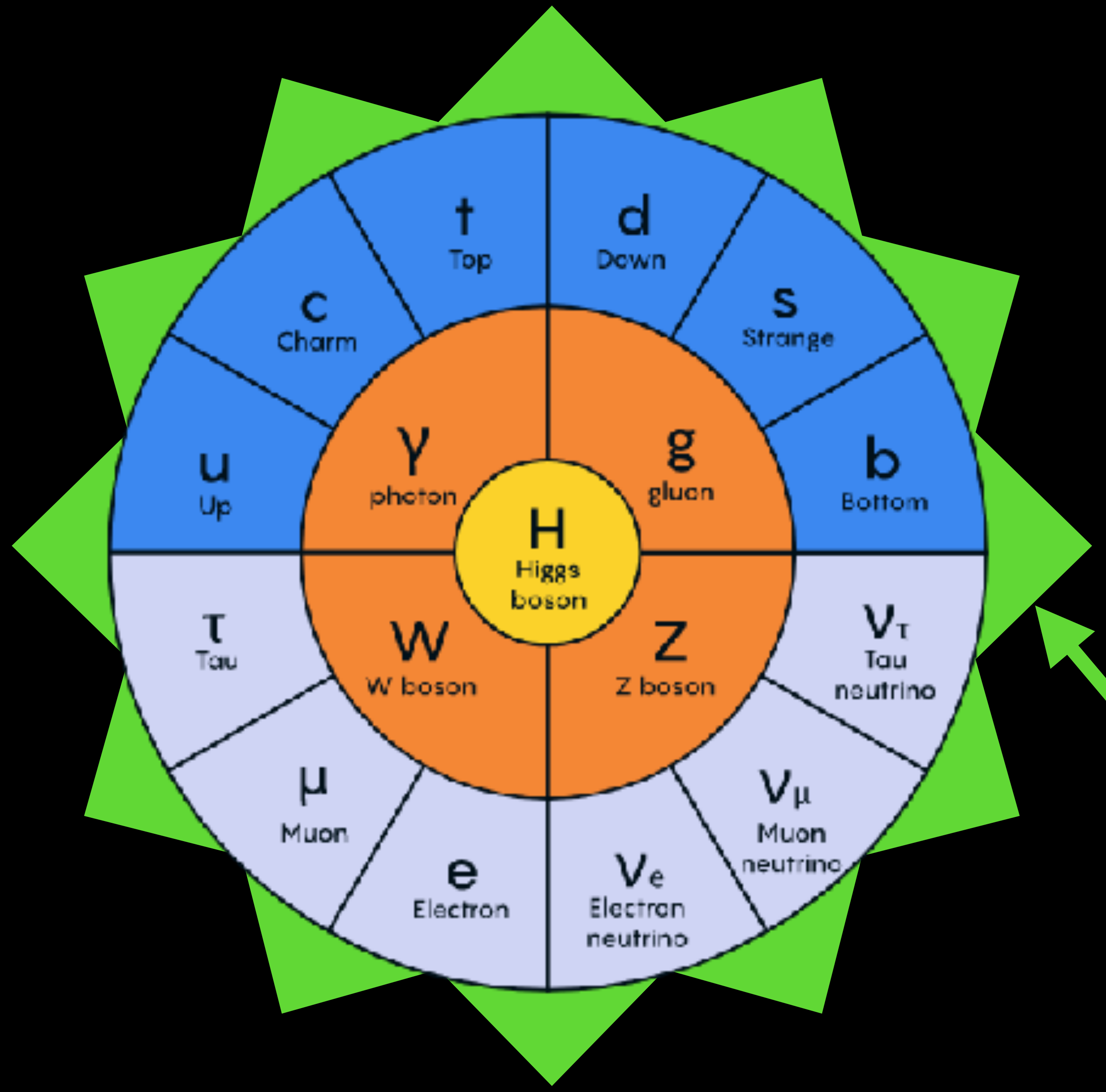

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Search for new physics in future experiments at even larger colliders, at even higher energies…

… 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.

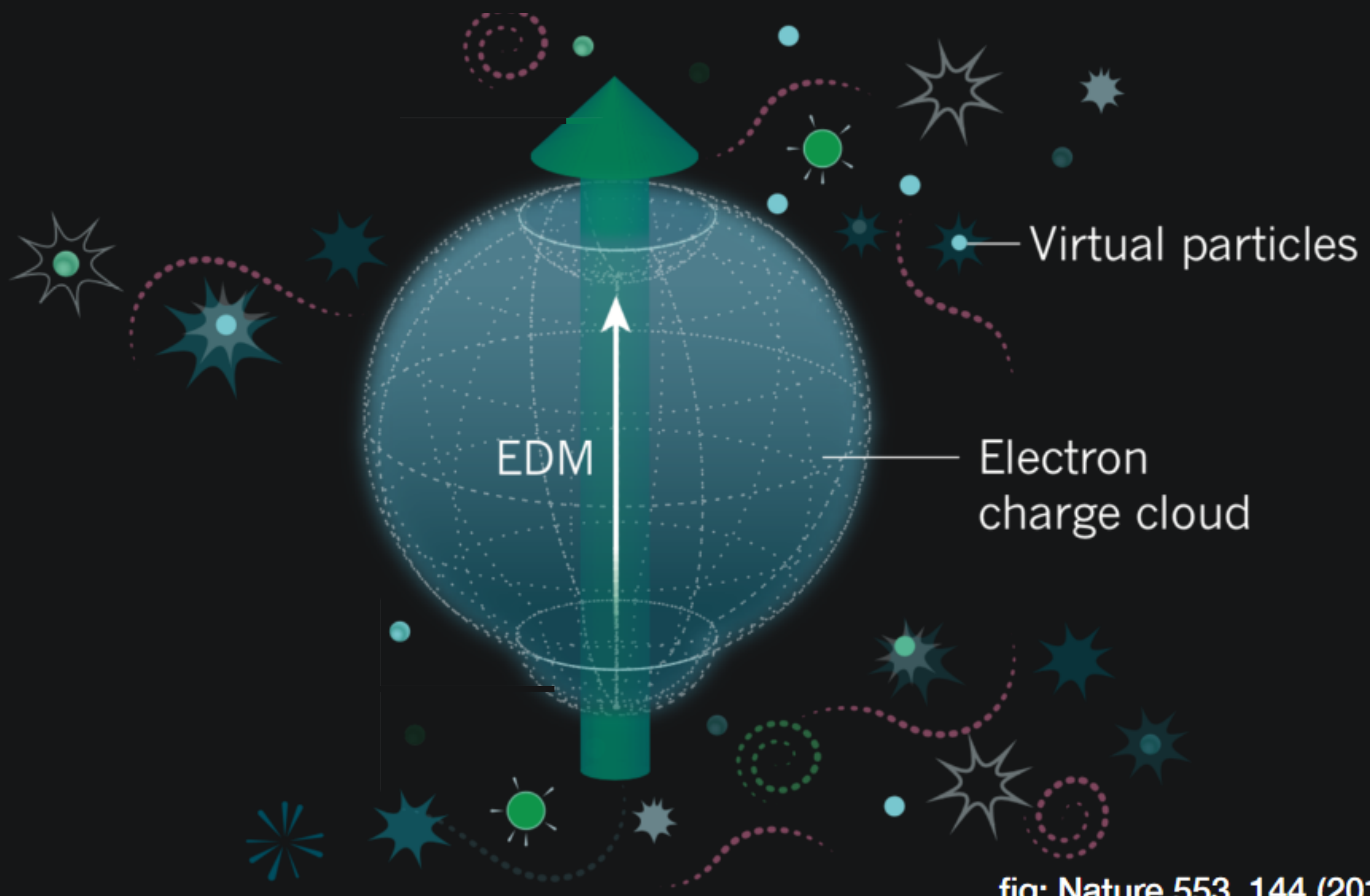

fig: Nature 553, 144 (2018)

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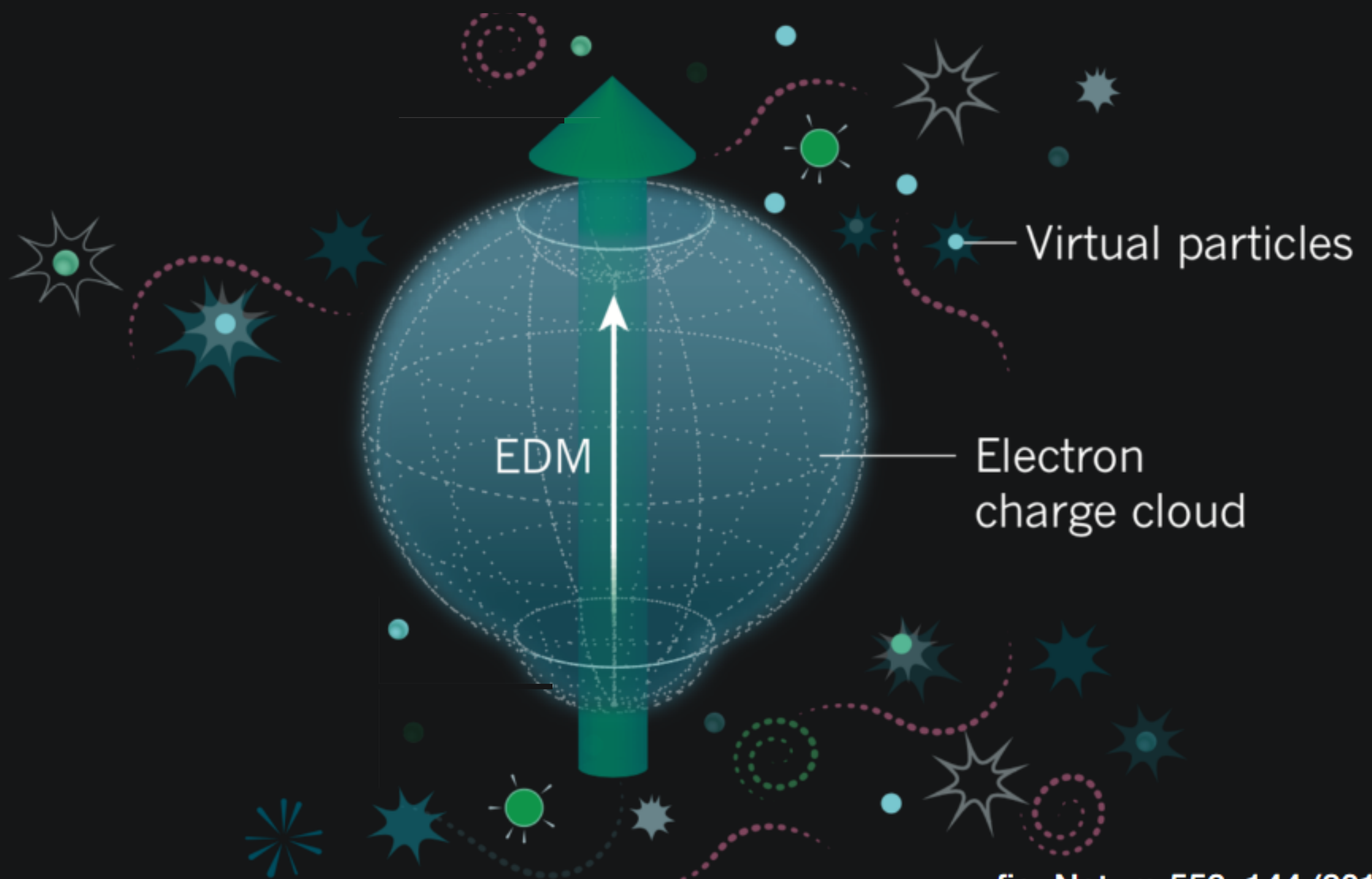

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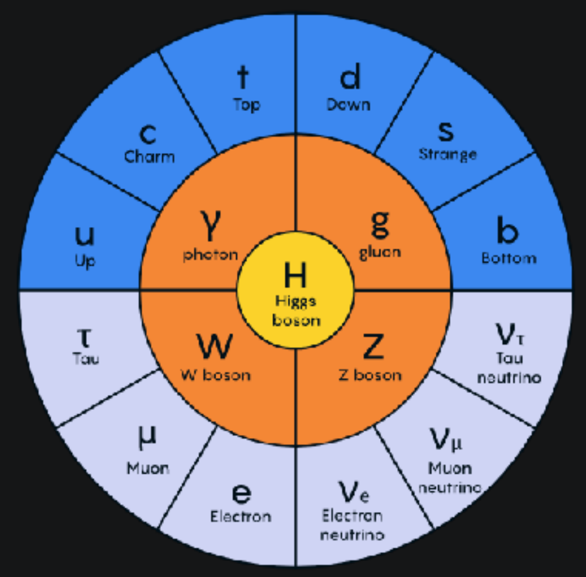
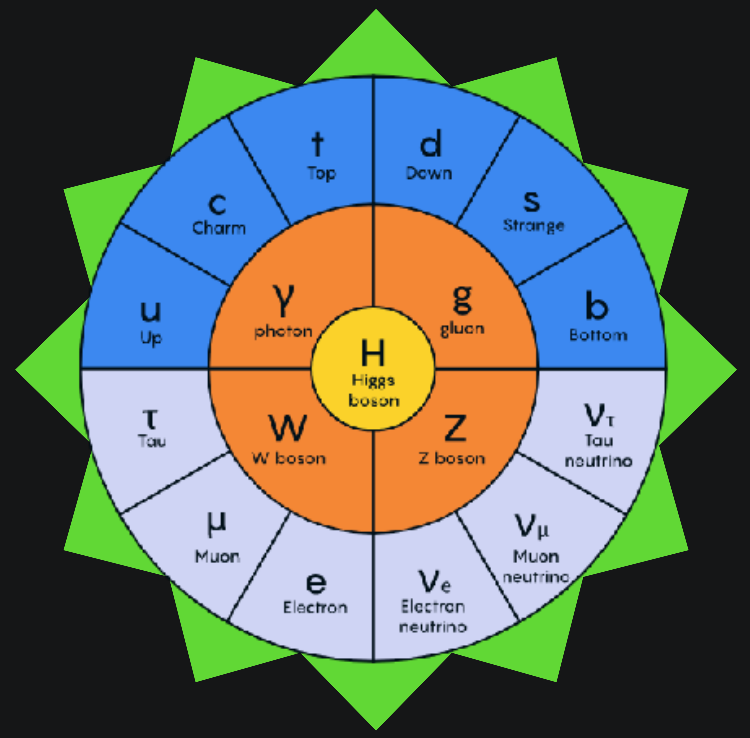


The Standard Model:
the eEDM is tiny, not measurable
(~10^{-40} e.cm)



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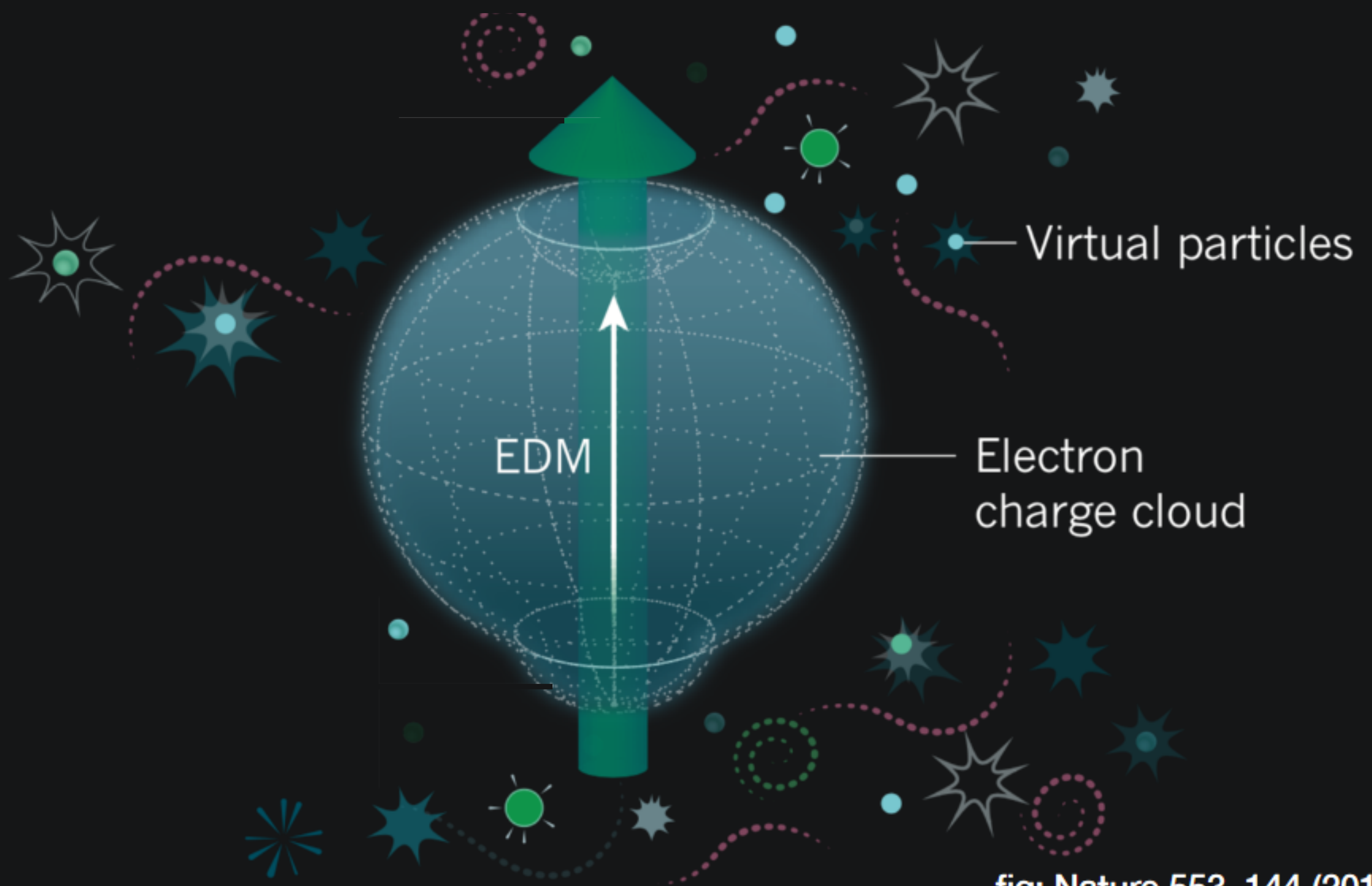

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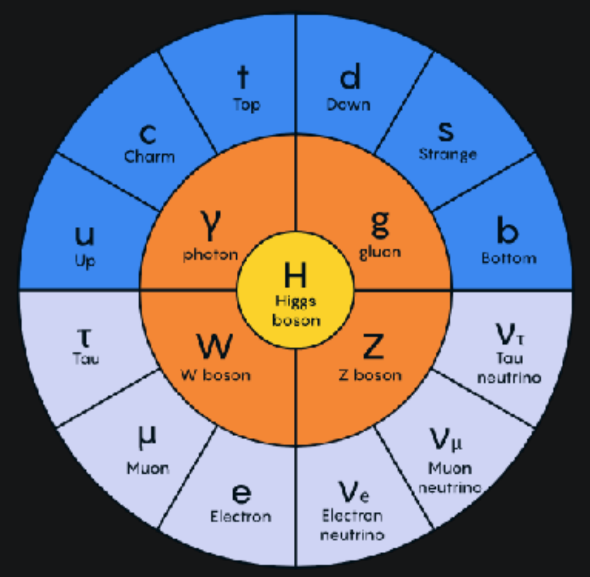

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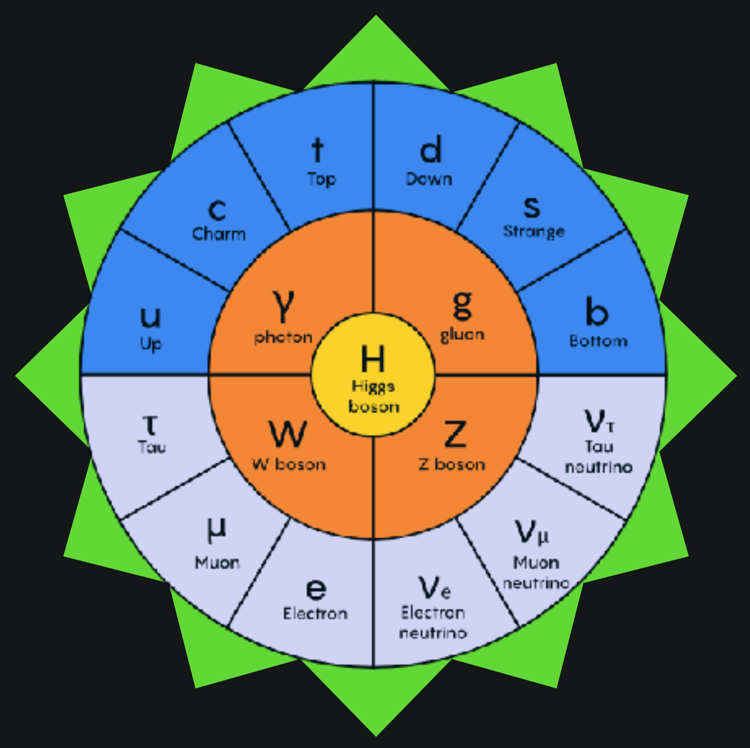

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10 orders of magnitude difference!

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

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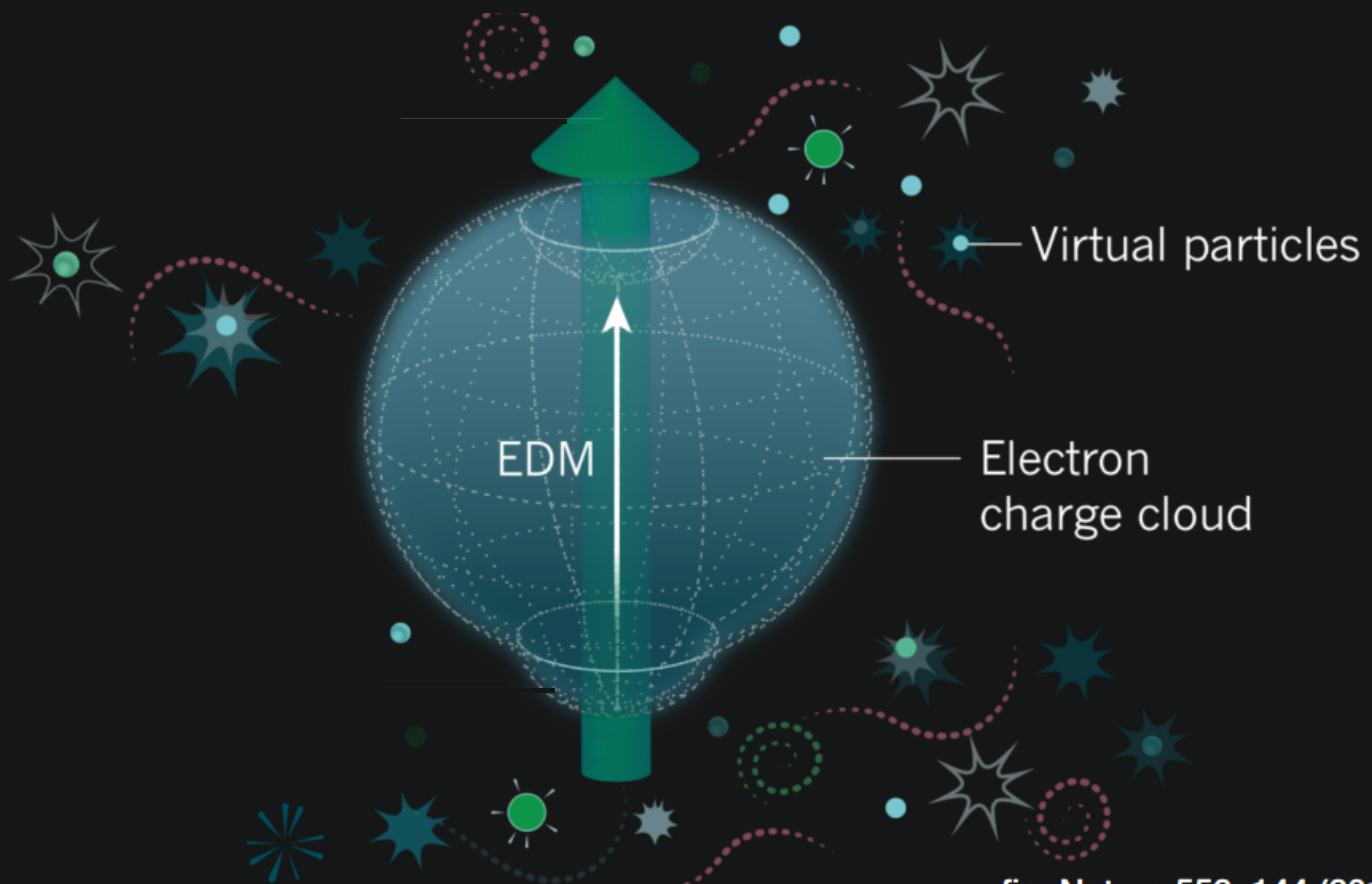

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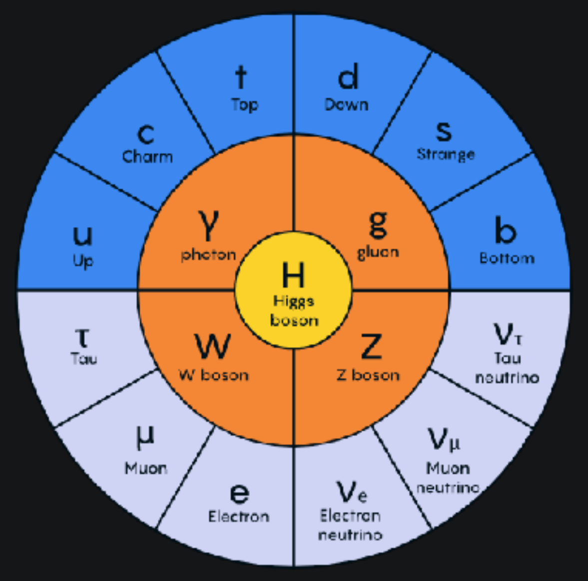

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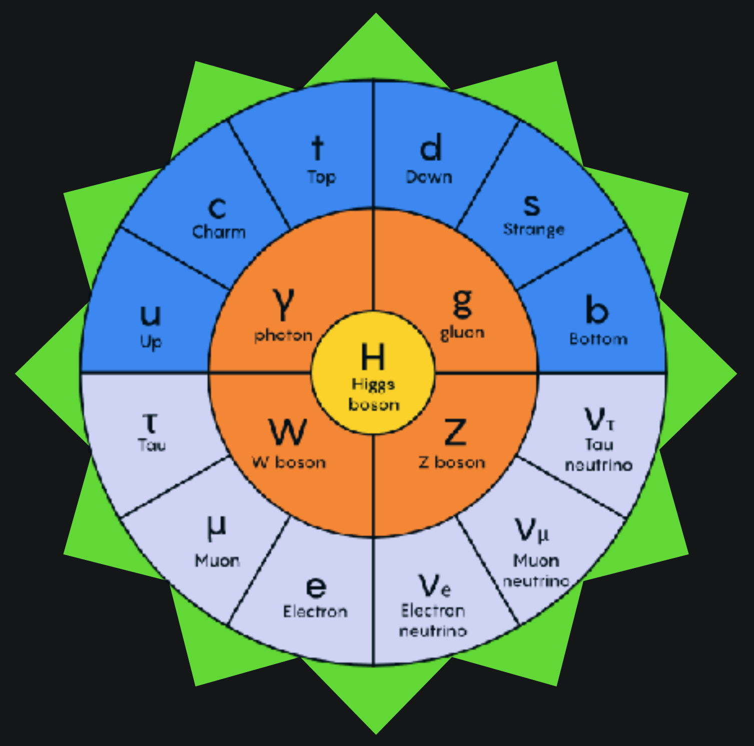

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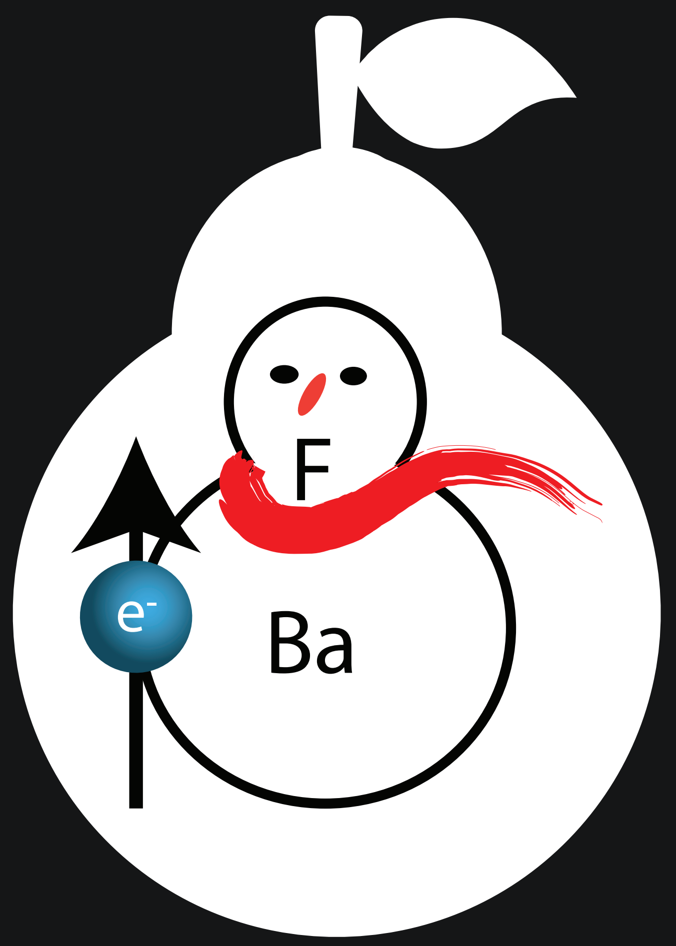
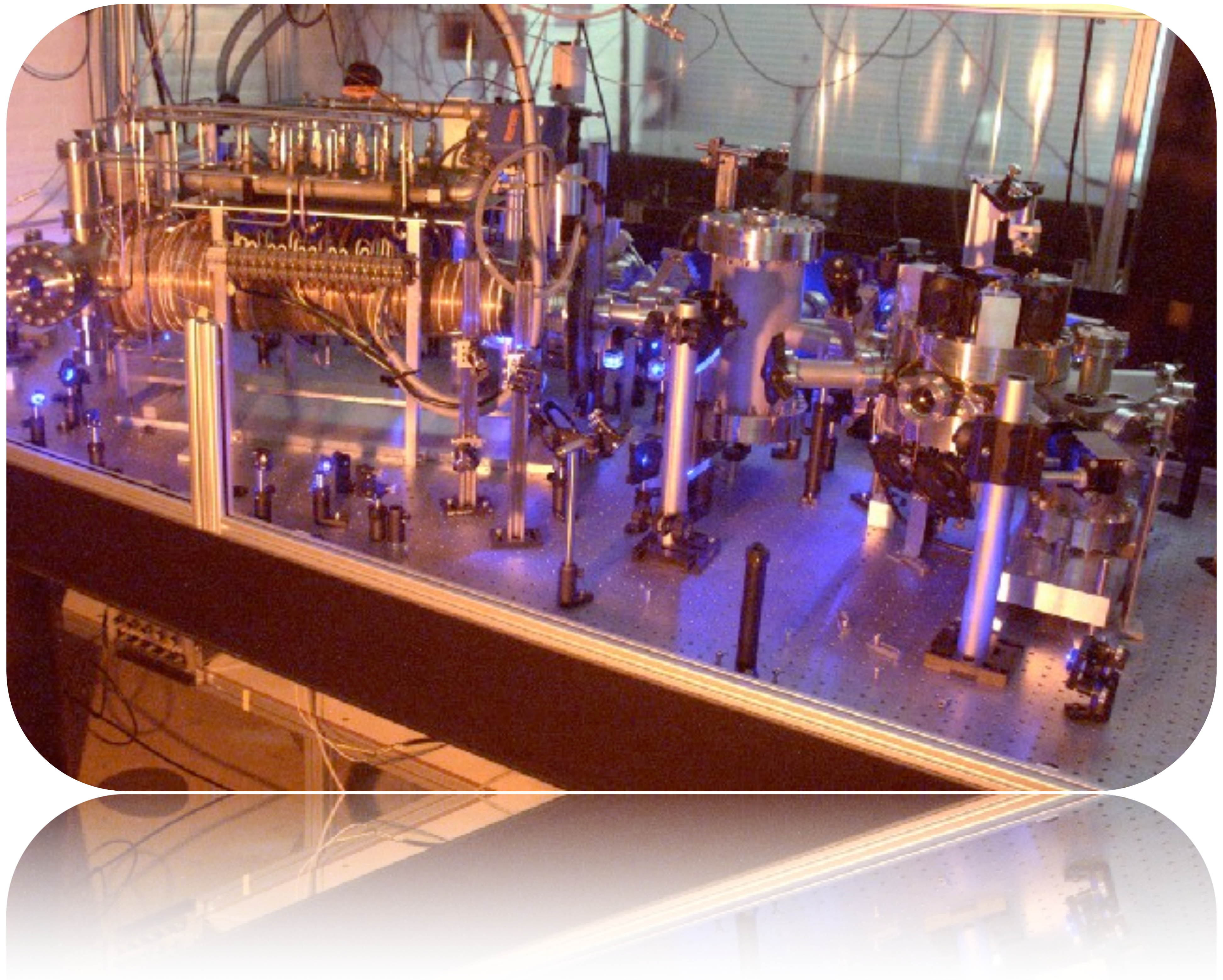
Observation of eEDM hugely enhanced in a molecule: Barium monofluoride (BaF)



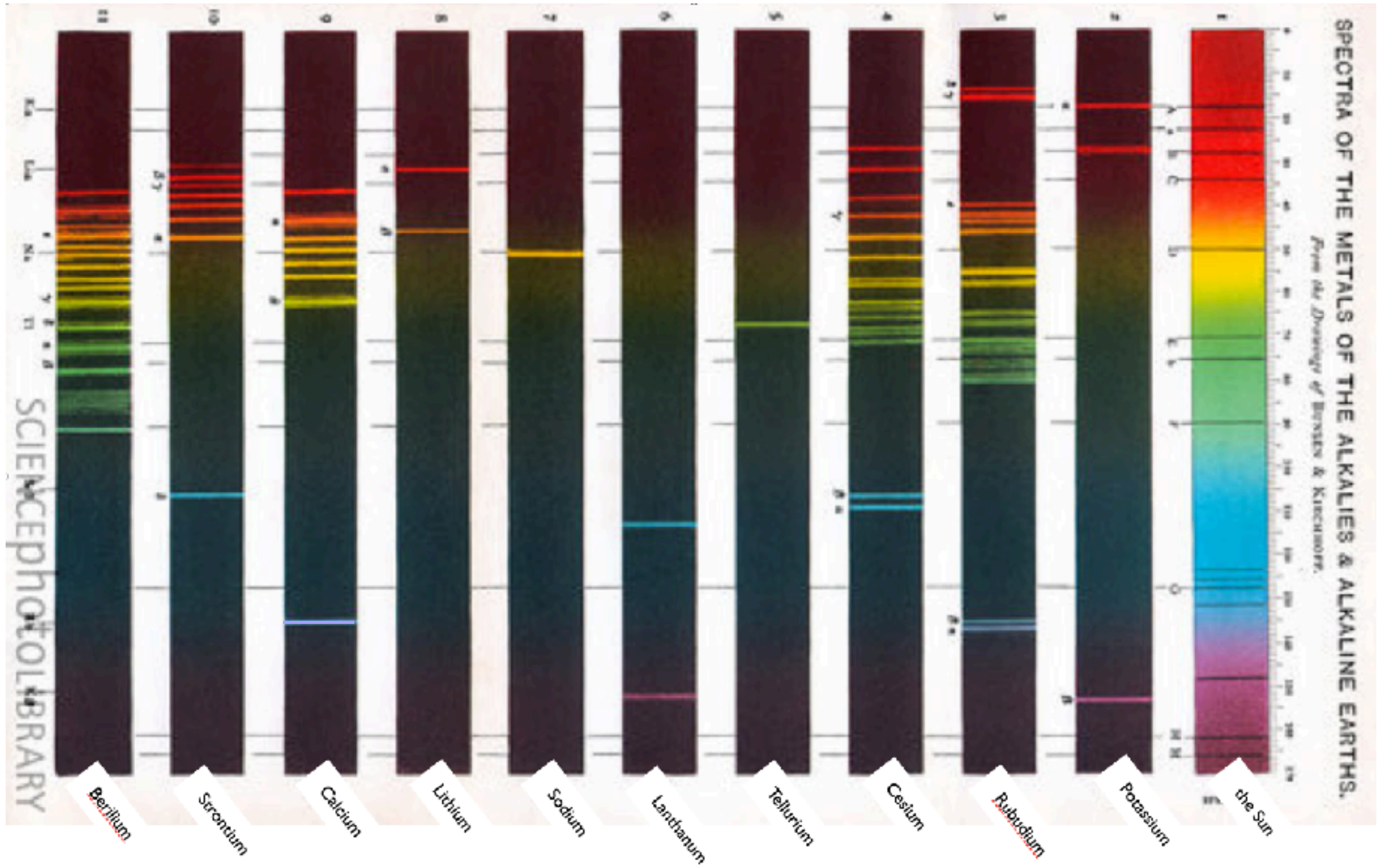
Think different!

Table-top particle physics

Complementary approach: precision measurements on atoms



Magneto-optical trapping of Calcium atoms, for isotope separation



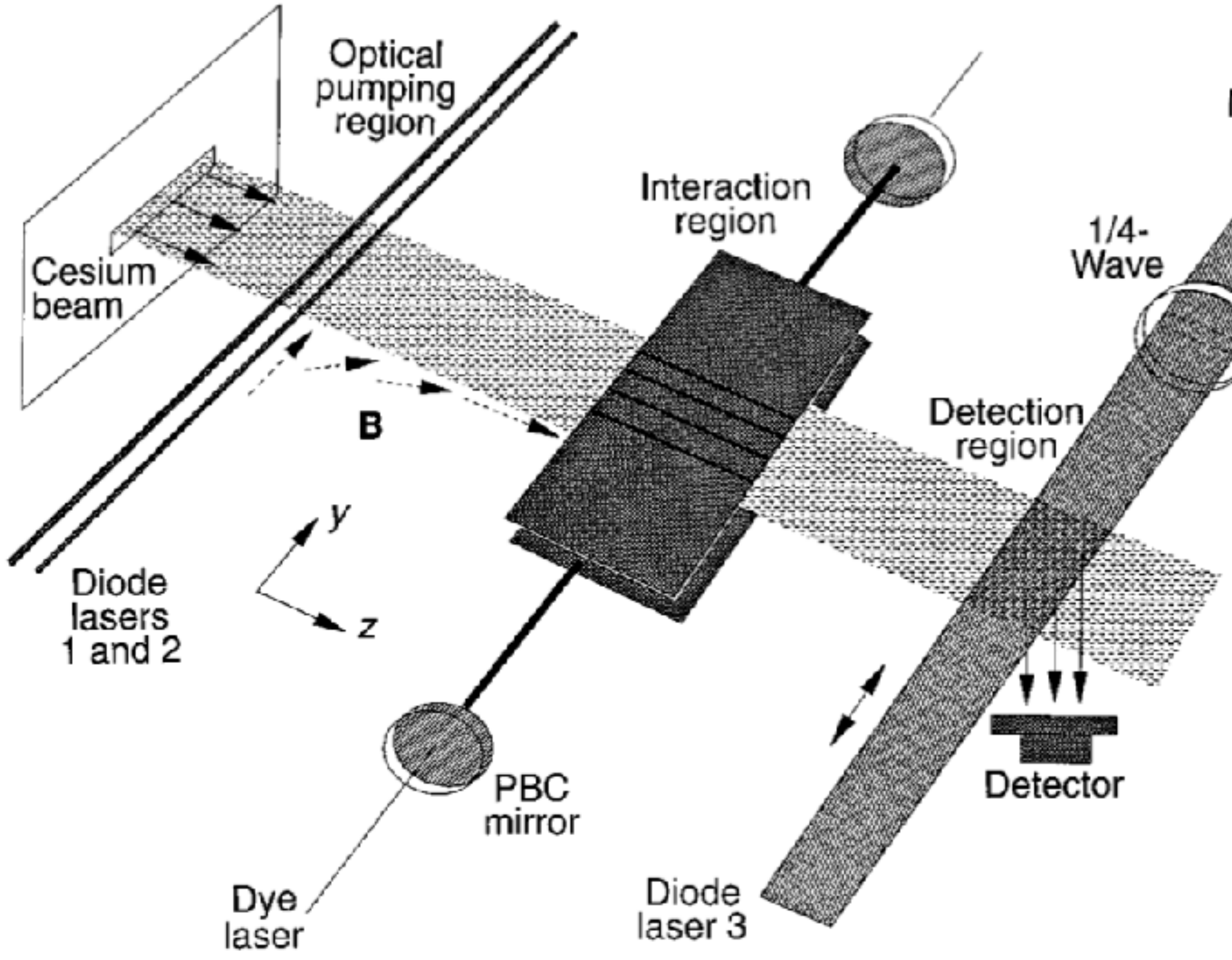
Simple idea: measure quantum structure and compare to theory

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)

Experiment: beam of Cs atoms

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

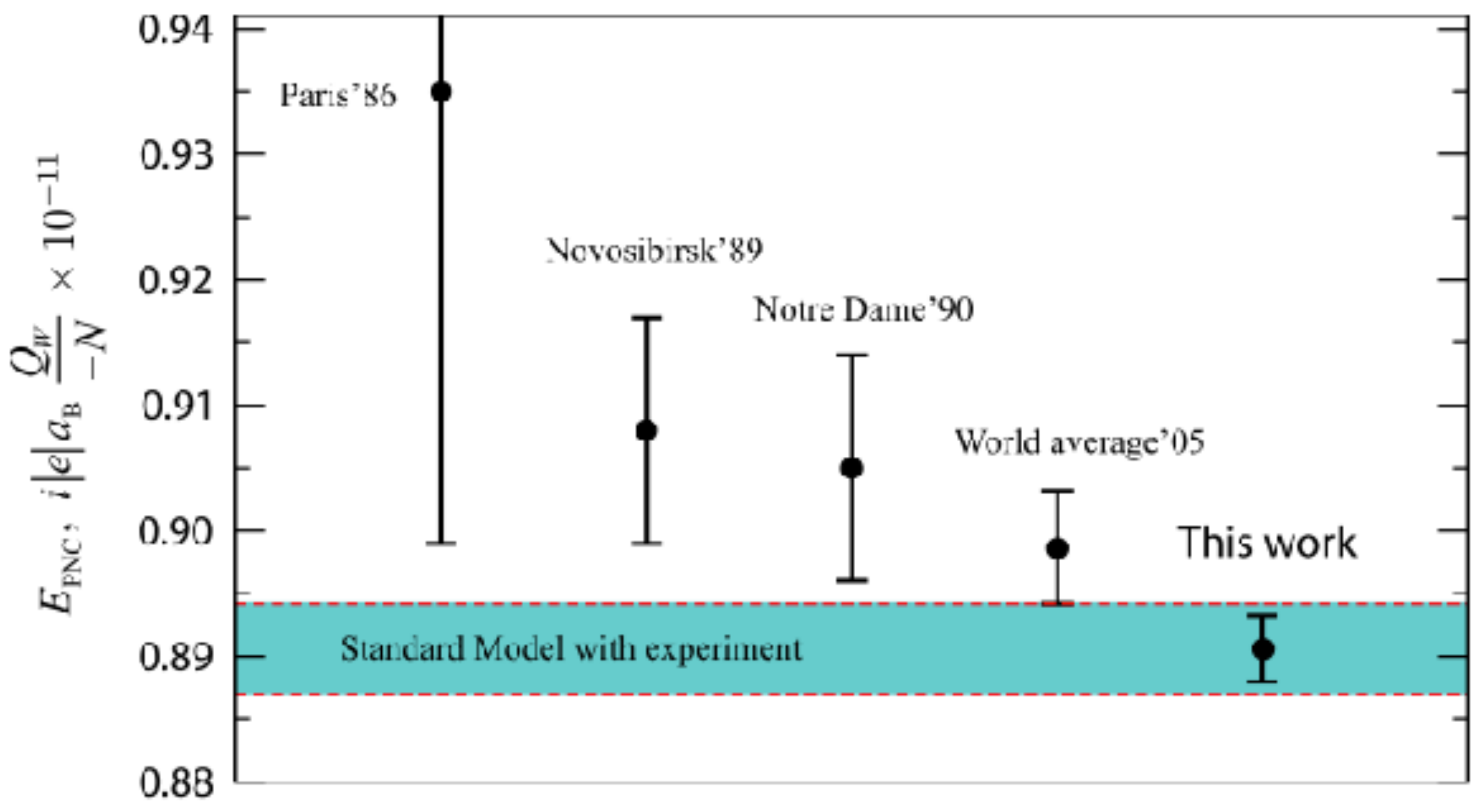


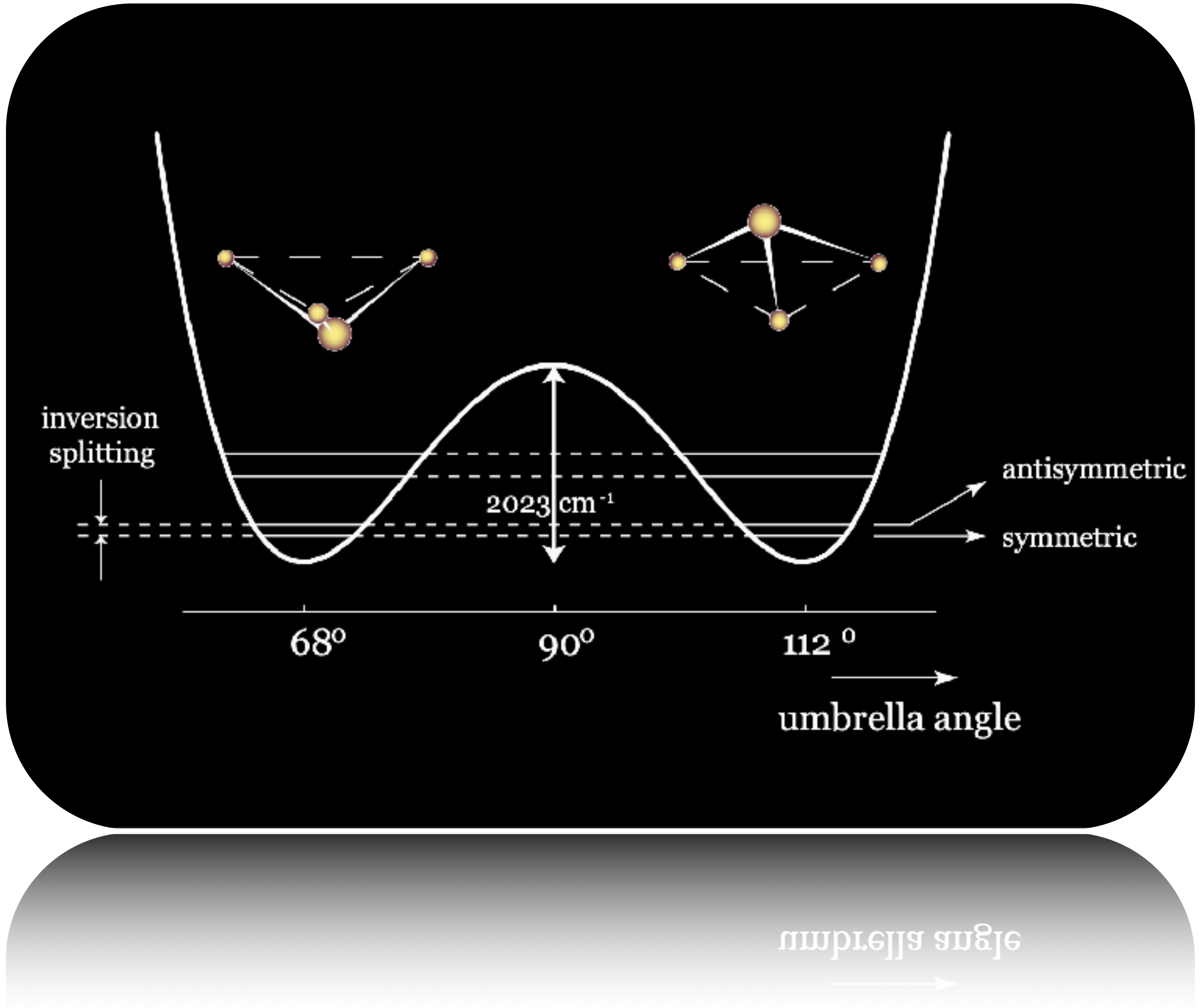
FIG. 1 (color online). Progress in evaluating the PNC amplitude. Points marked Paris '86, Novosibirsk '89, Notre Dame '90 correspond to Refs. [10,11,31]. Point marked World average '05 is due to efforts of several groups [12–16] on sub-1% Breit, QED, and neutron-skin corrections reviewed in Ref. [17]. 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 $E_{\rm PNC}$ 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, $-N$.

Theory

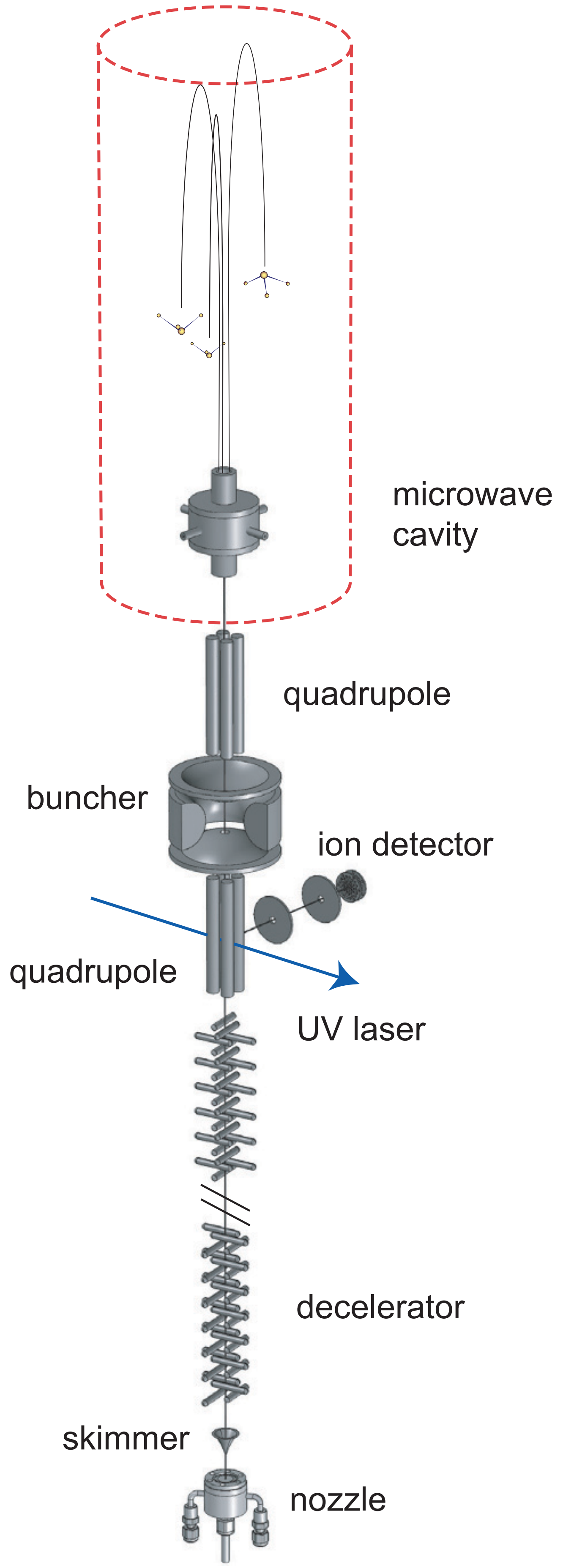
Precision measurements with molecules

Complex quantum systems with an advantage

Example 2: Variation of constants



Very sensitive to proton / electron mass ratio



proposed experiment

?

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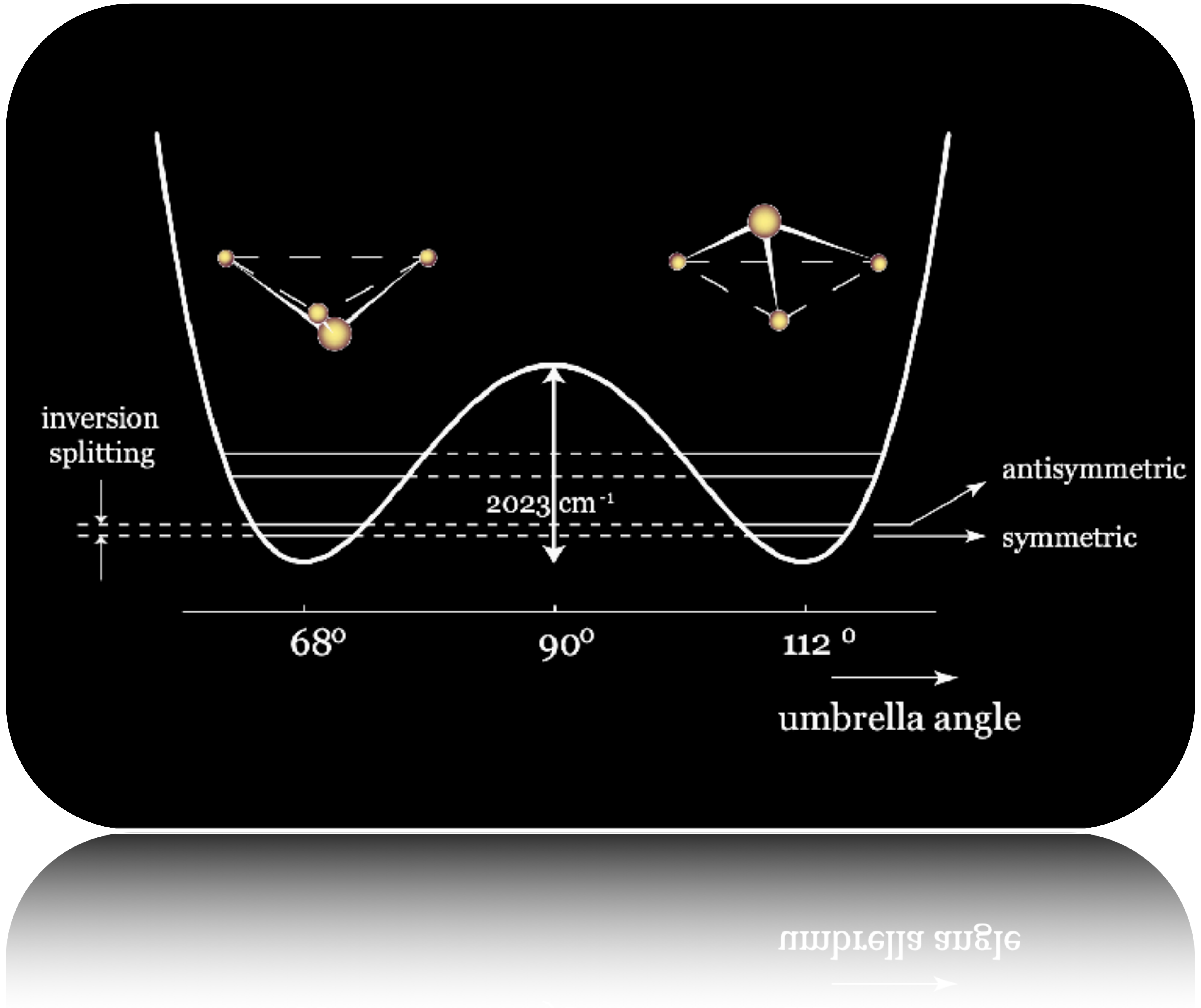

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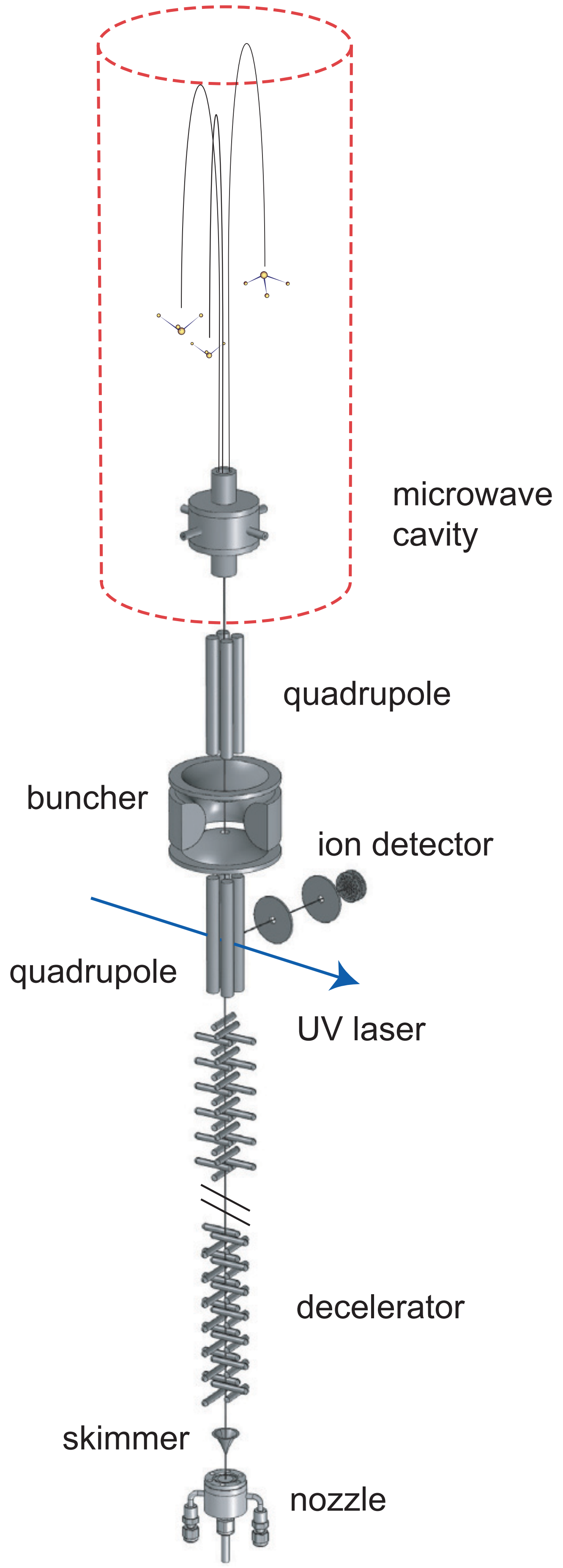


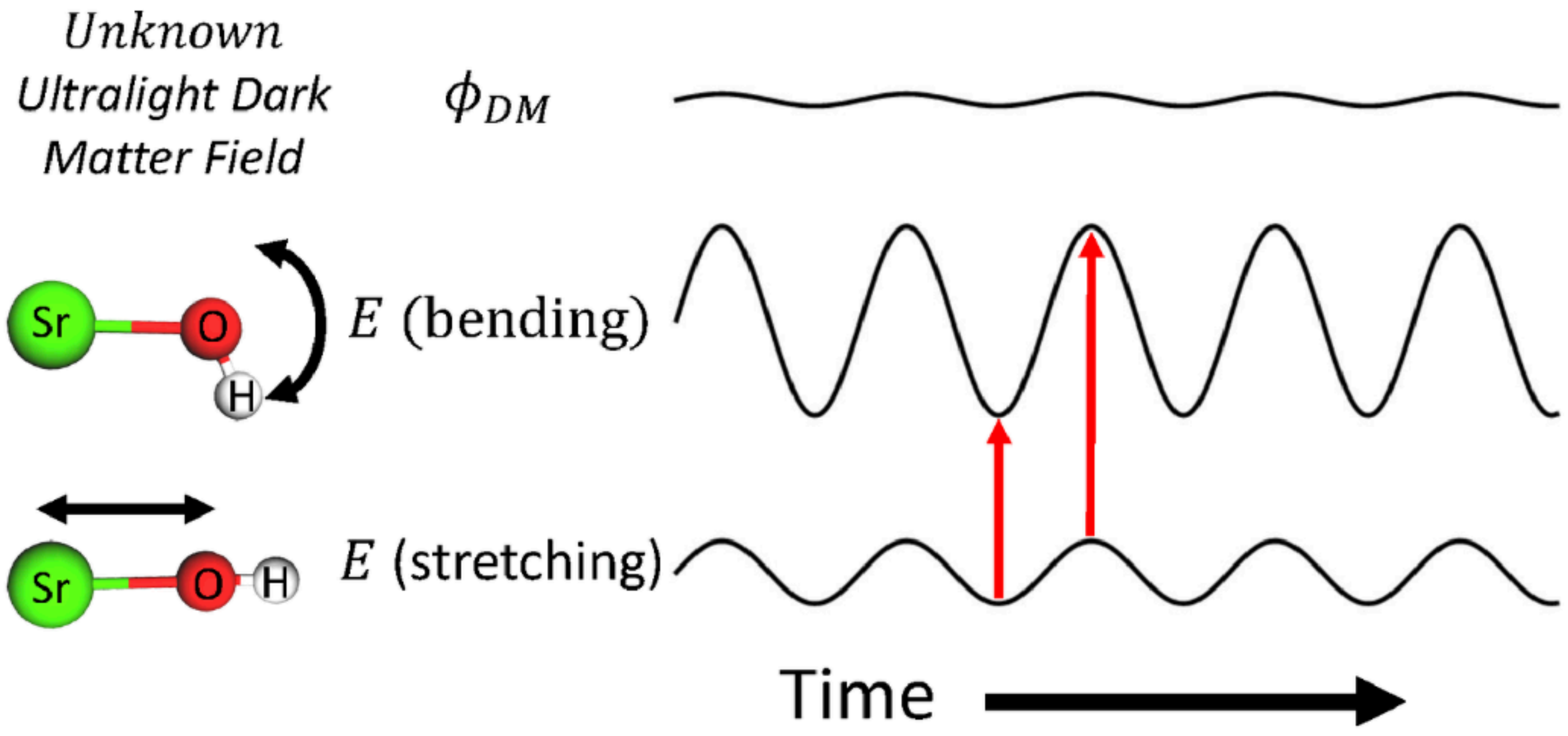
proposed experiment

Axions!

Theory

Dark matter coupling to molecules

SrOH as a recent example



Credit: website John Doyle @ Harvard, more details: Phys. Rev. A 103, 043313 (2021)

earlier work on nEDM to set axion limits: Abel et al., Phys. Rev. X 7, 041034 (2017)

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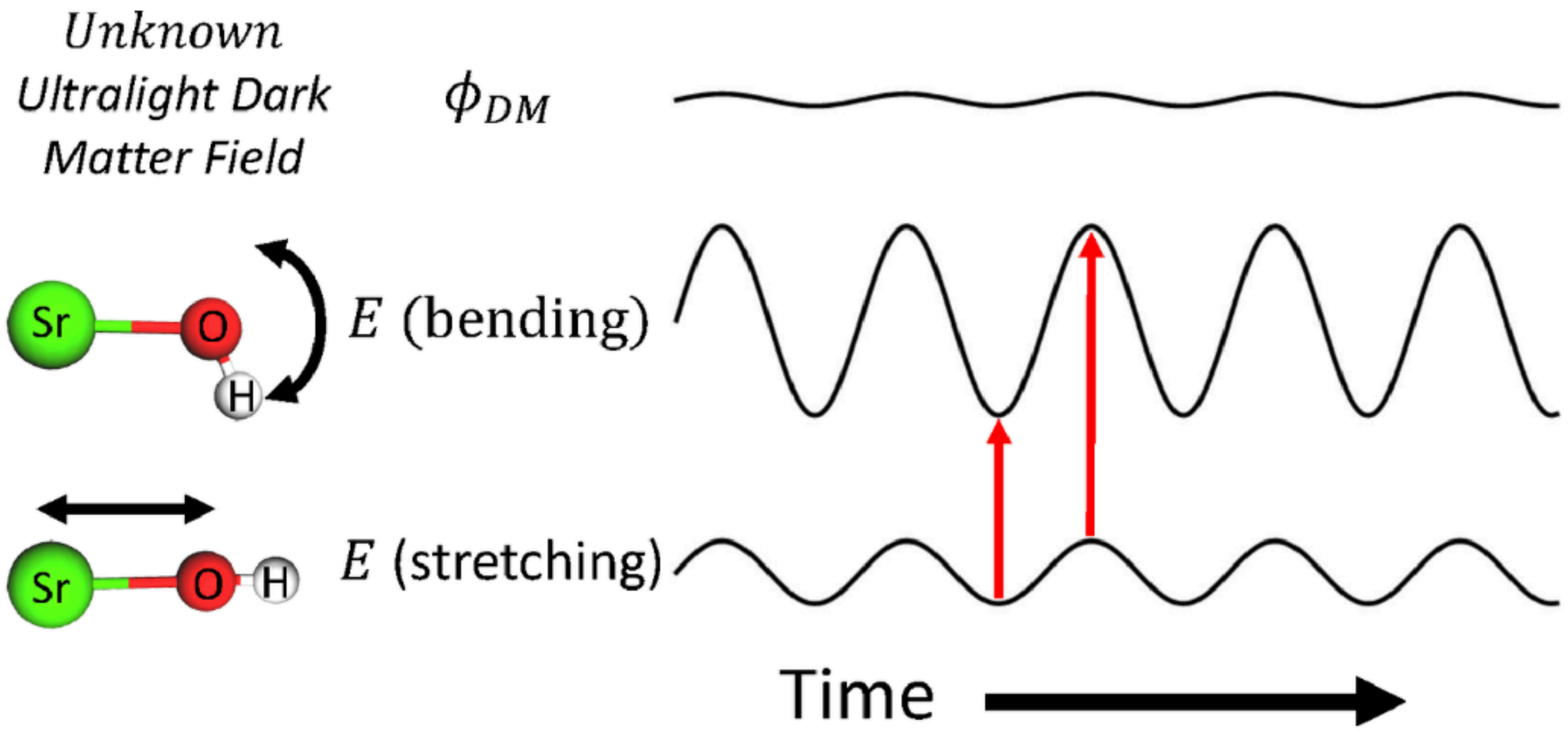

It turns out that the molecules and techniques needed to do a precise electron-EDM experiment are also those for a sensitive axion-detection experiment!

Credit: website John Doyle @ Harvard, more details: Phys. Rev. A 103, 043313 (2021)

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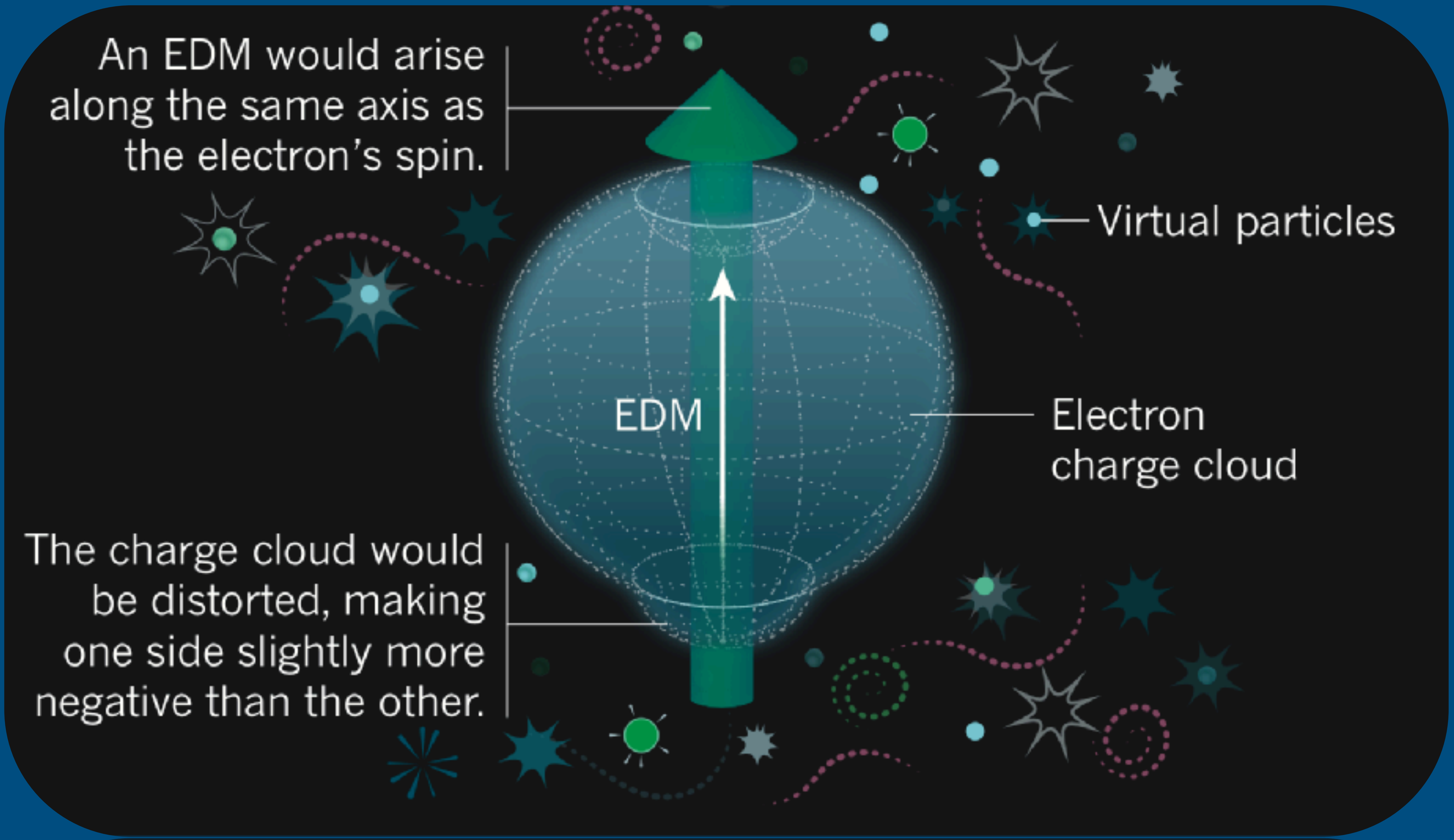
Precision measurements with molecules

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

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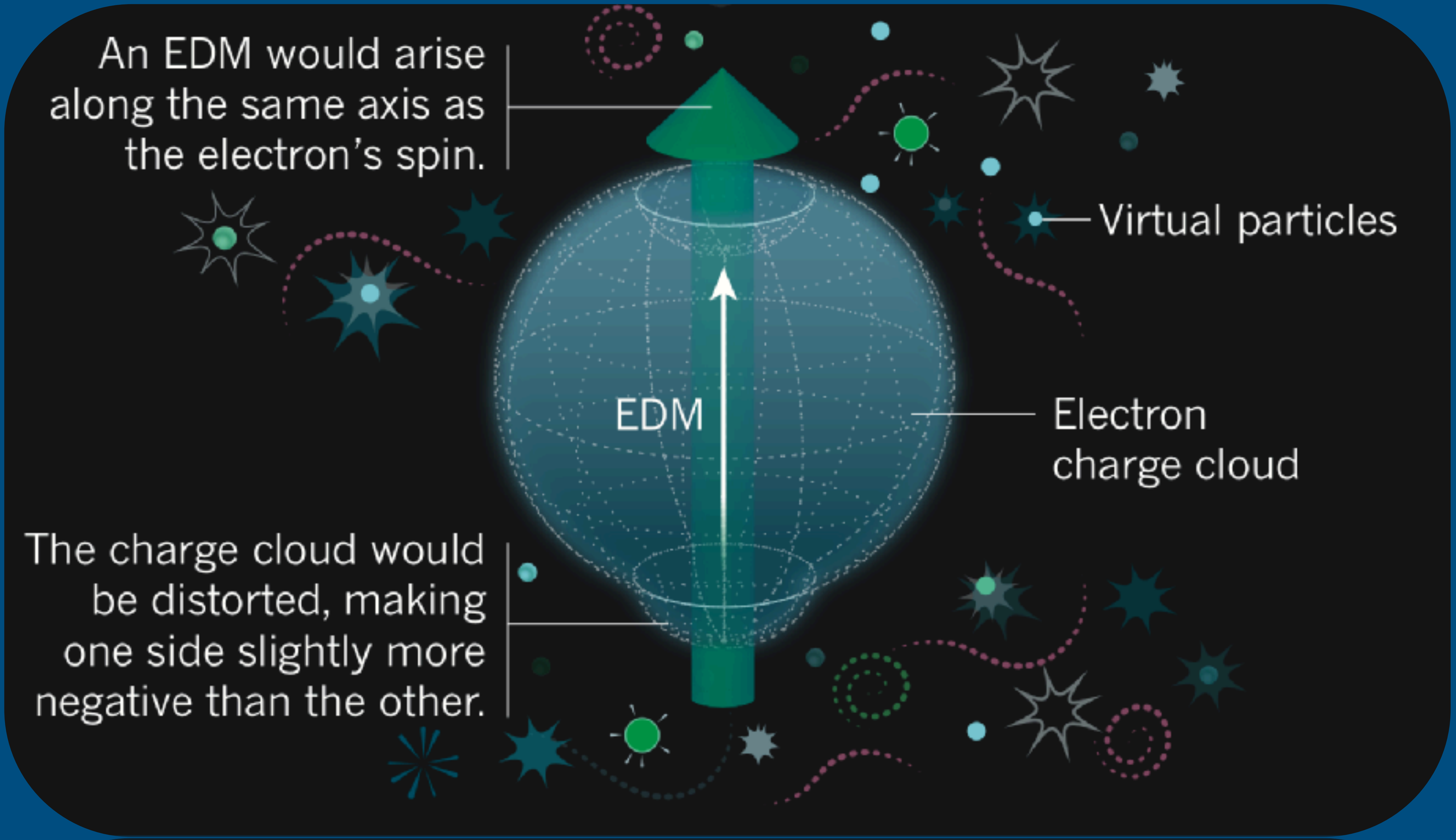

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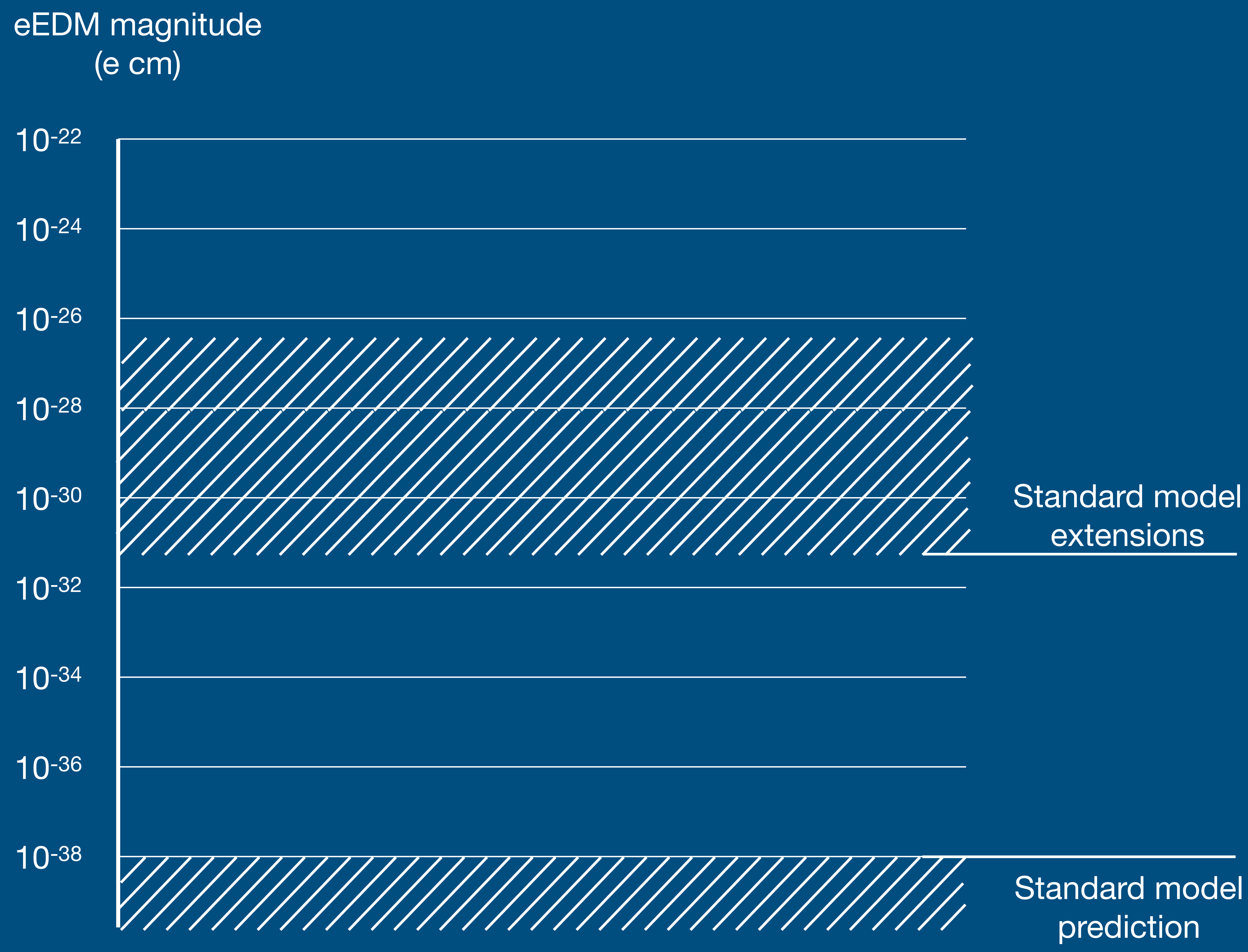

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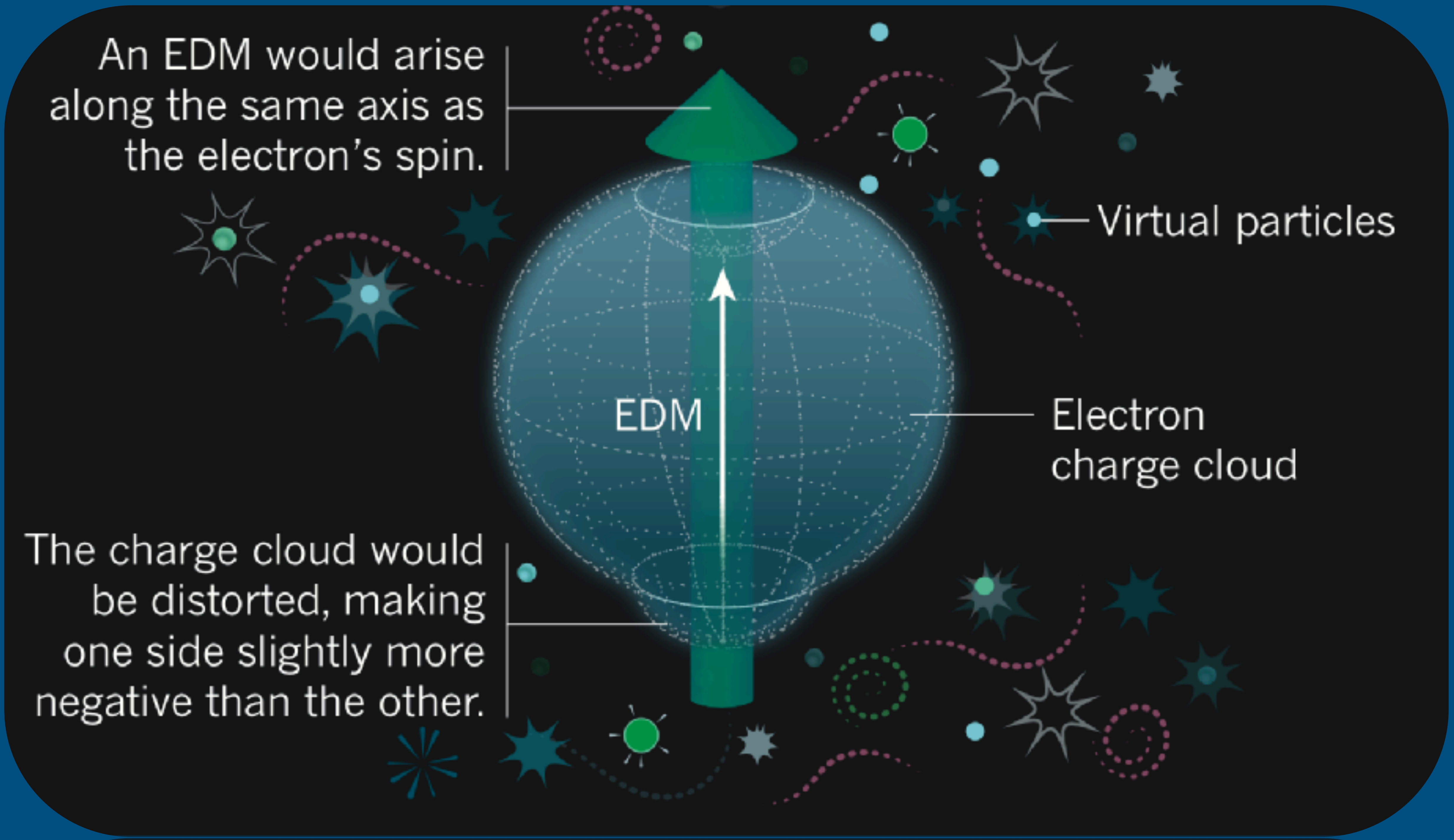

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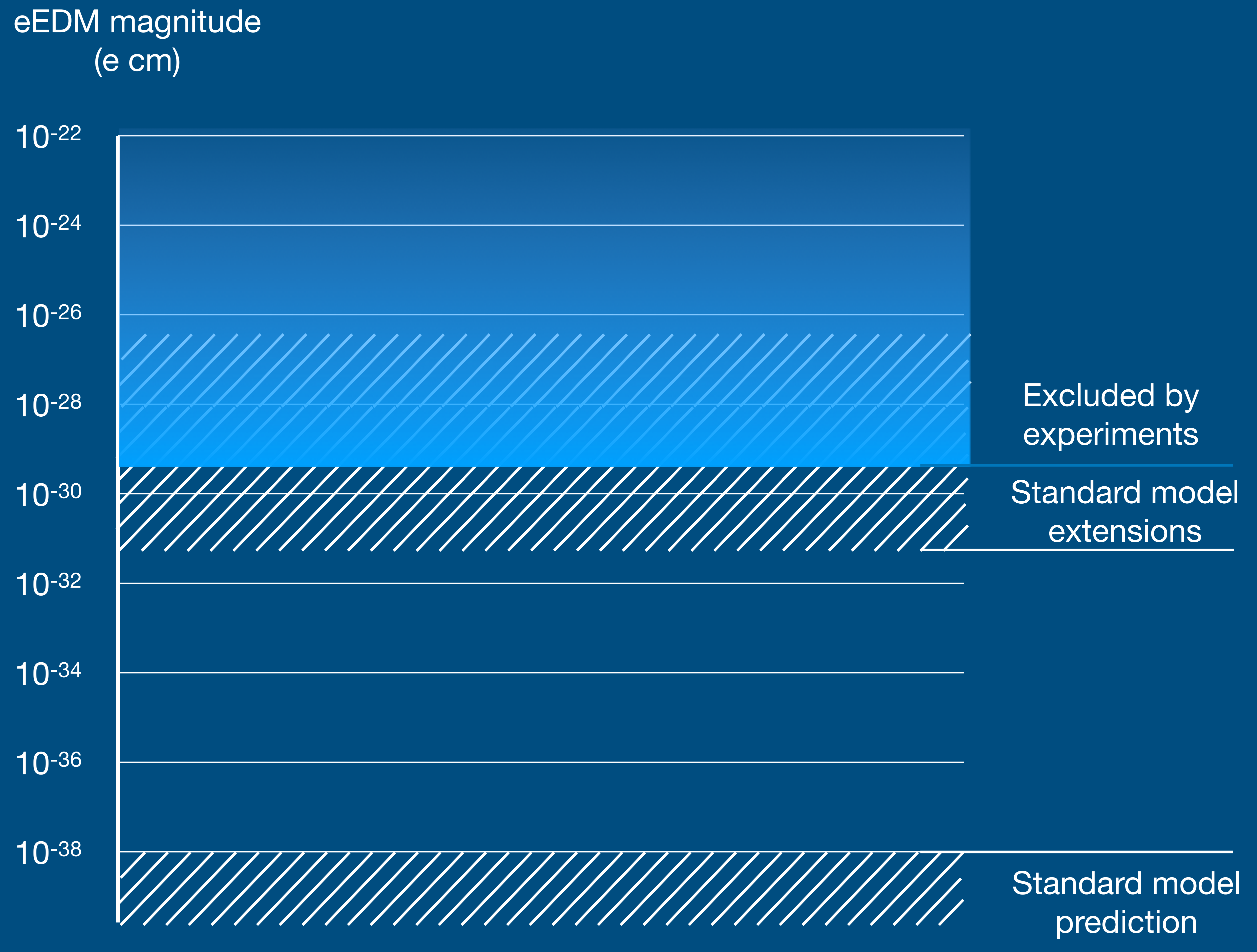

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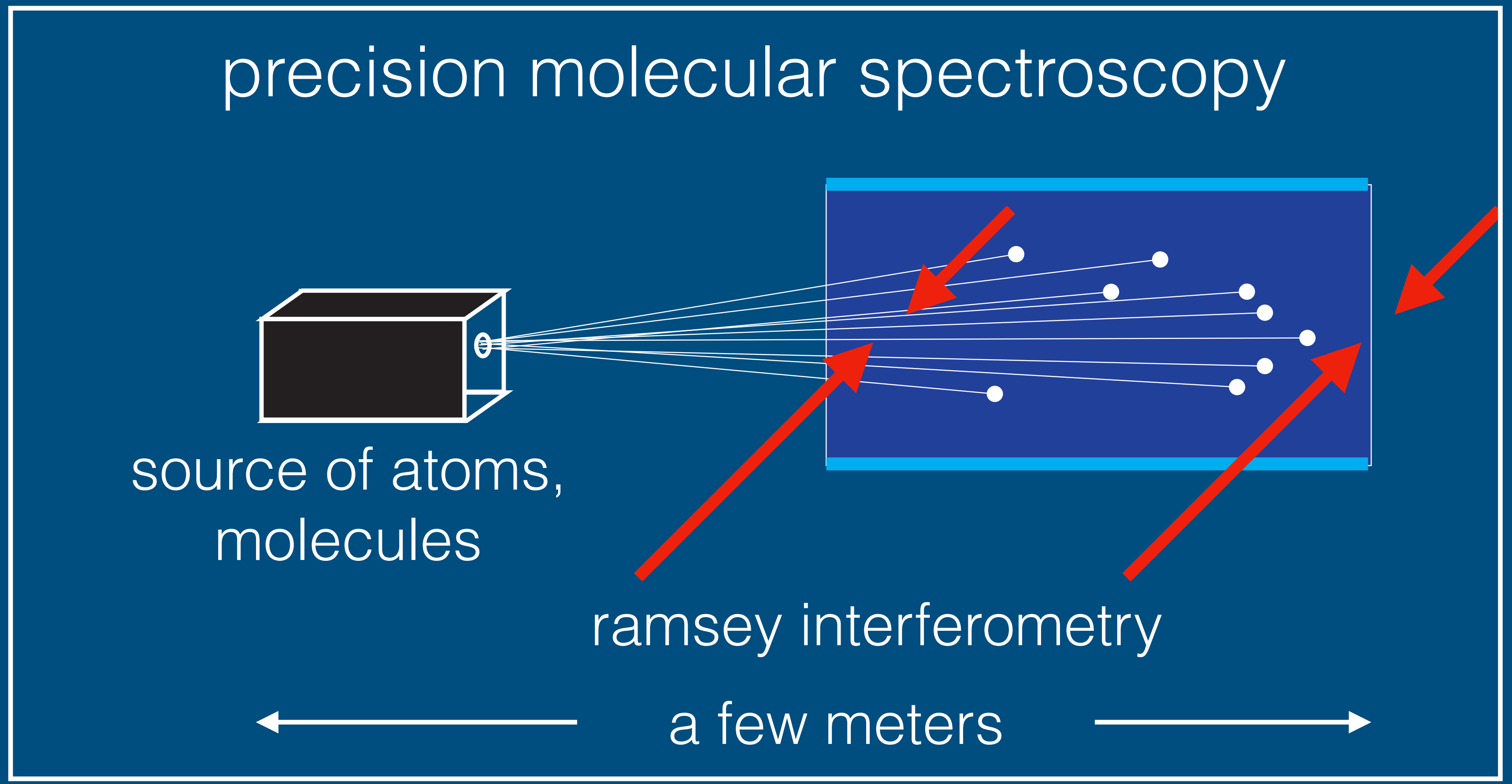

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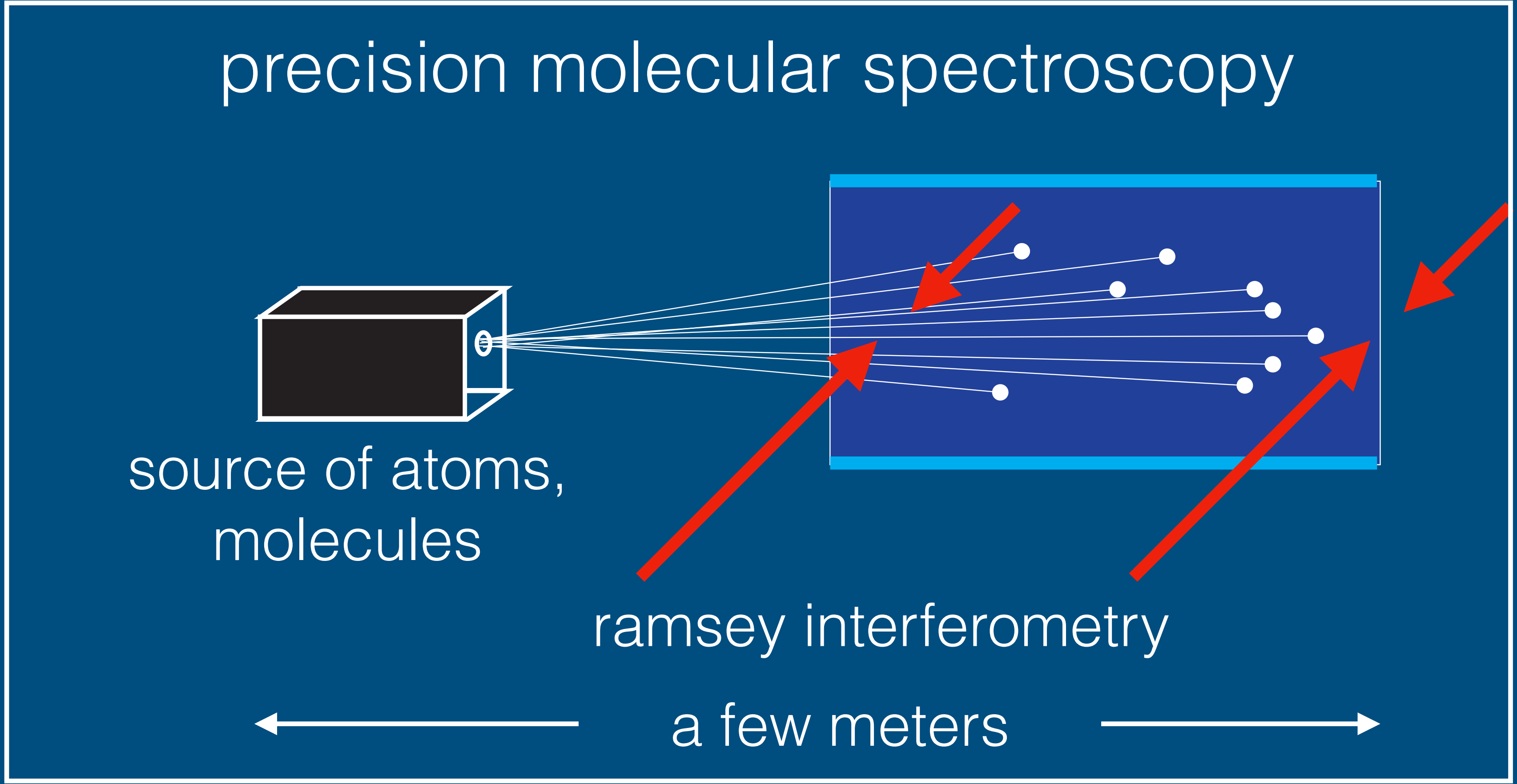

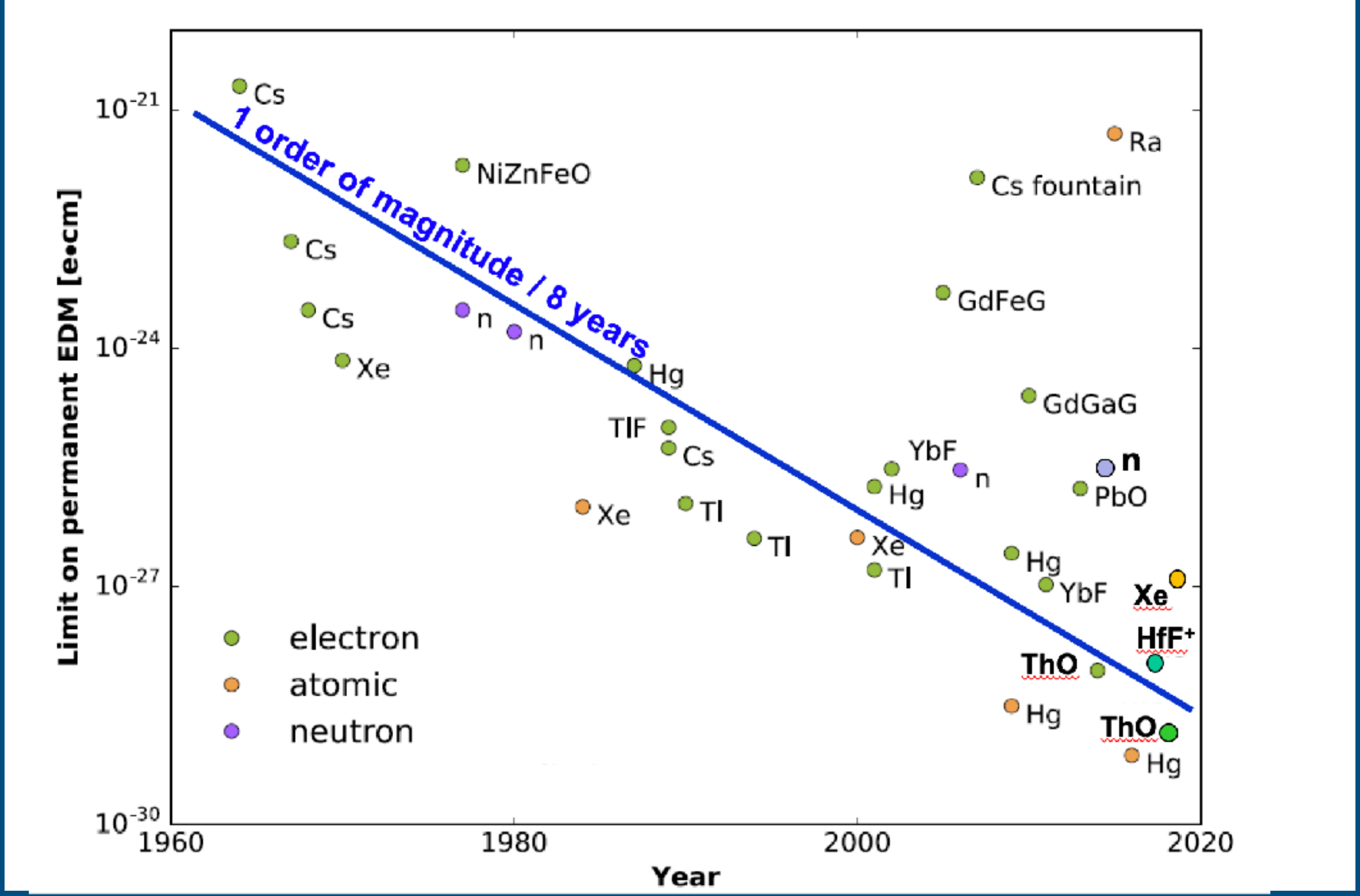

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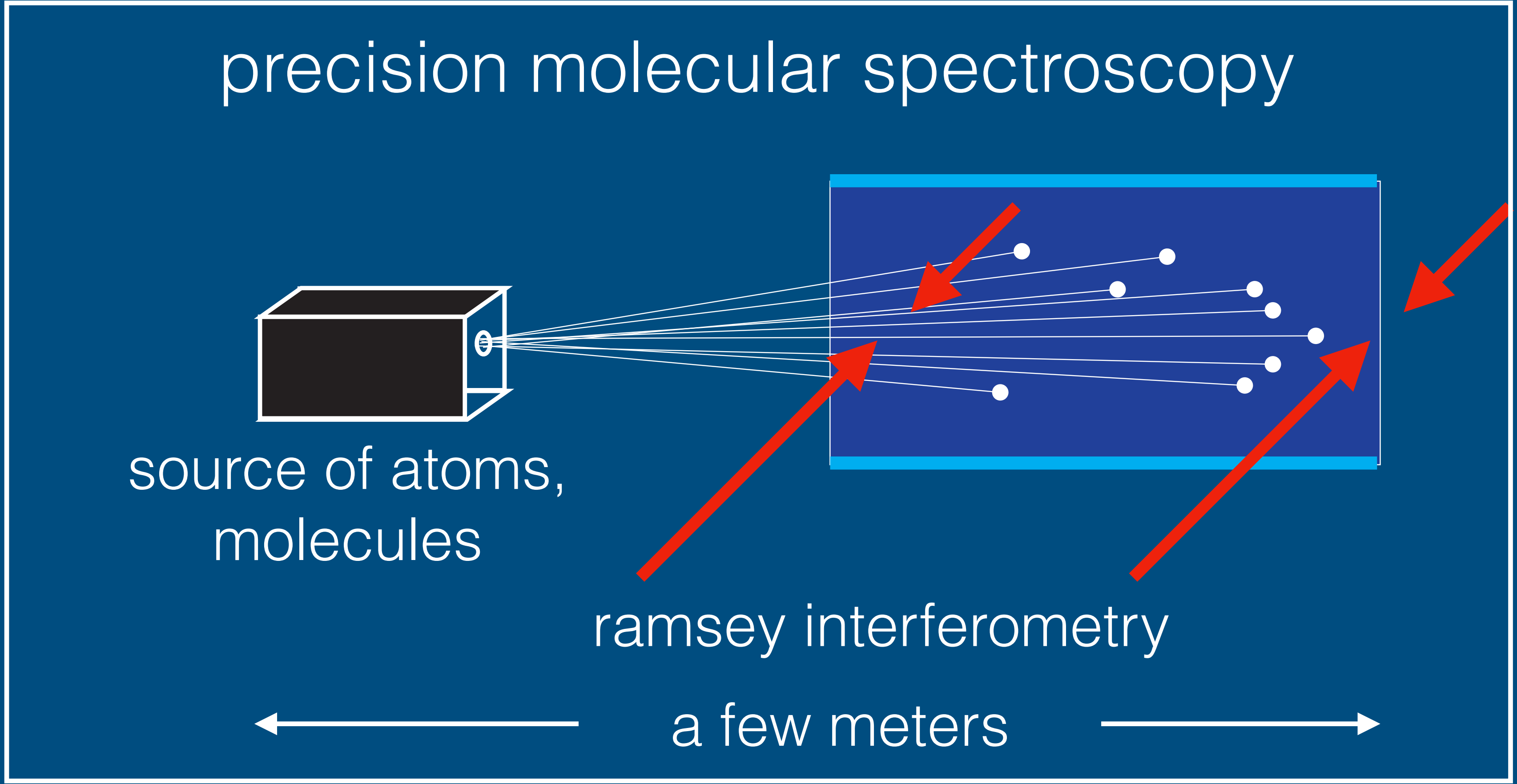
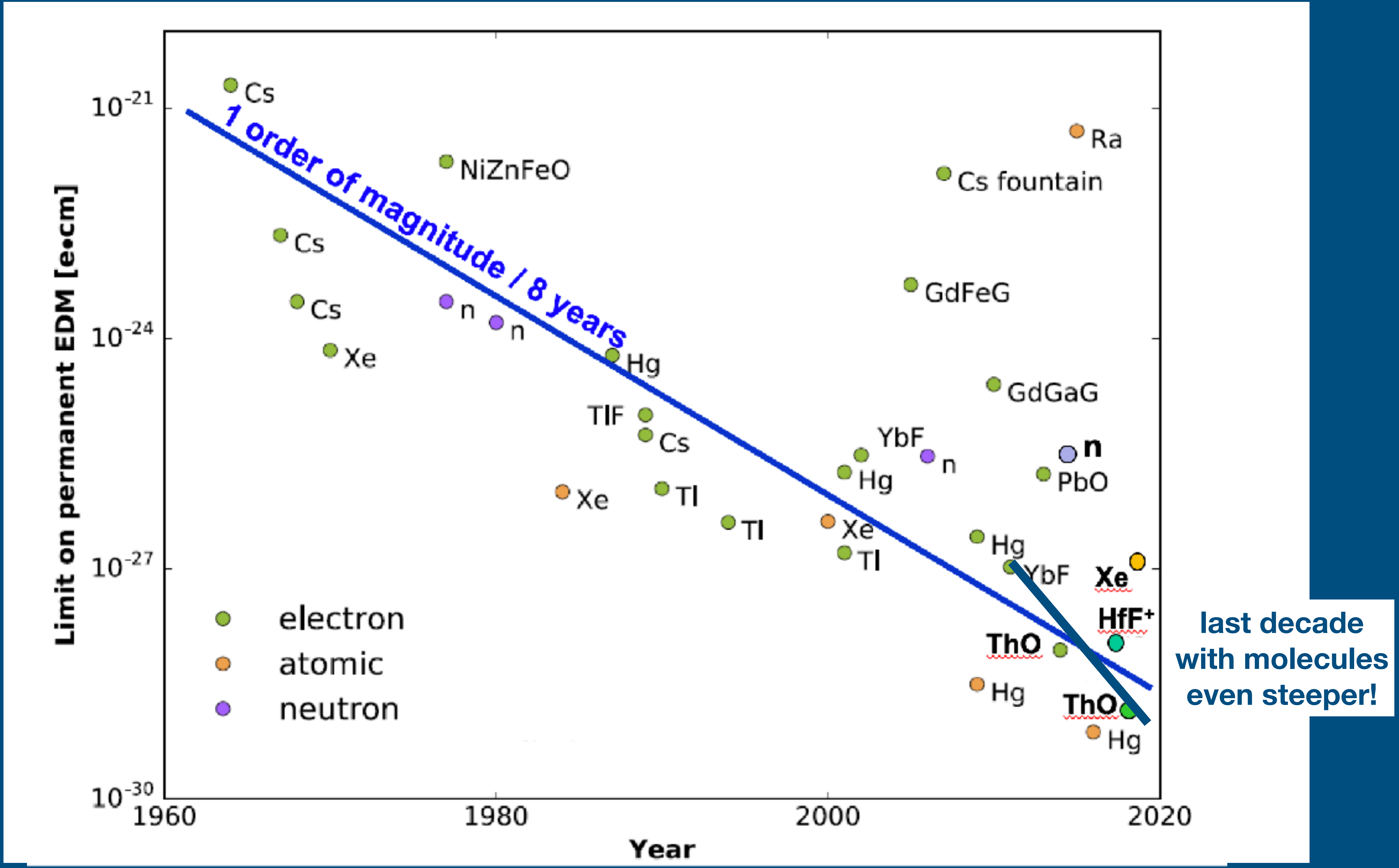


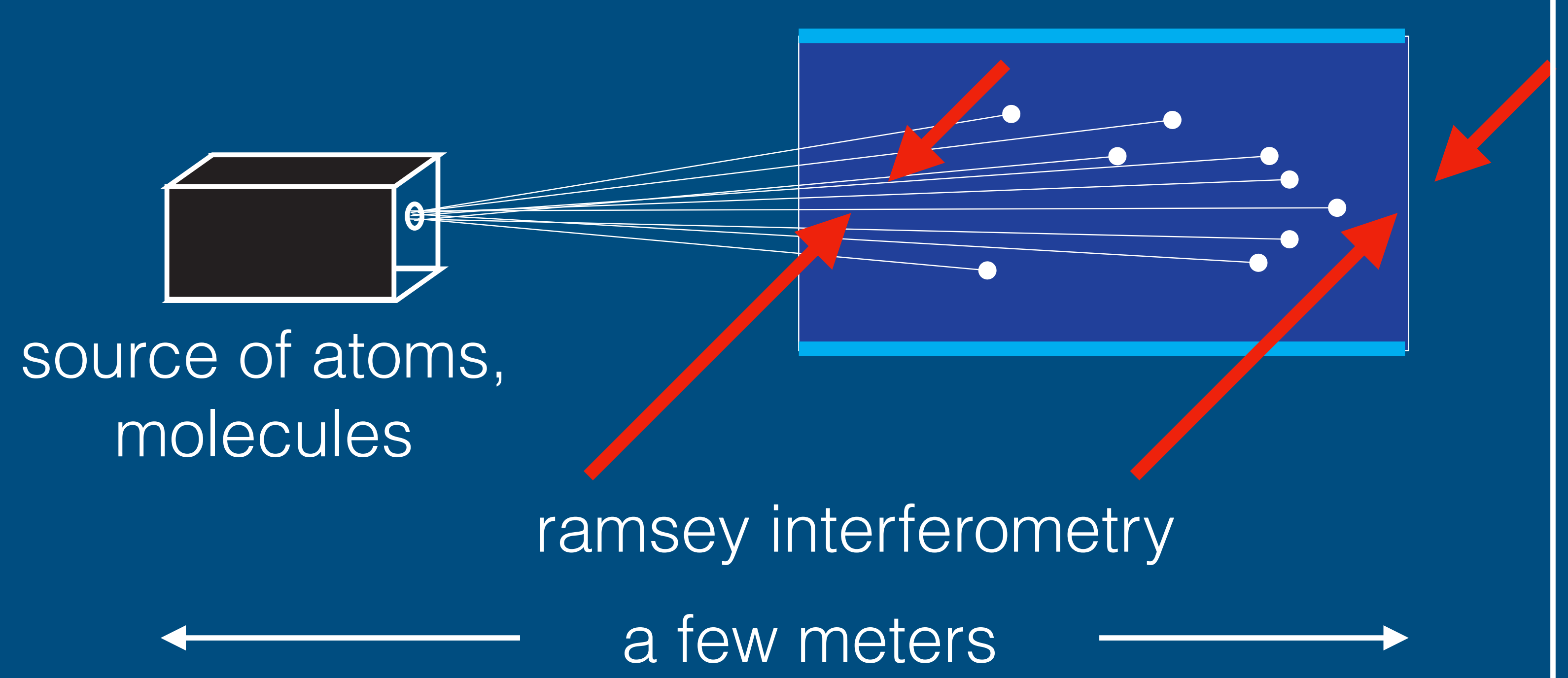


Precision measurements with molecules

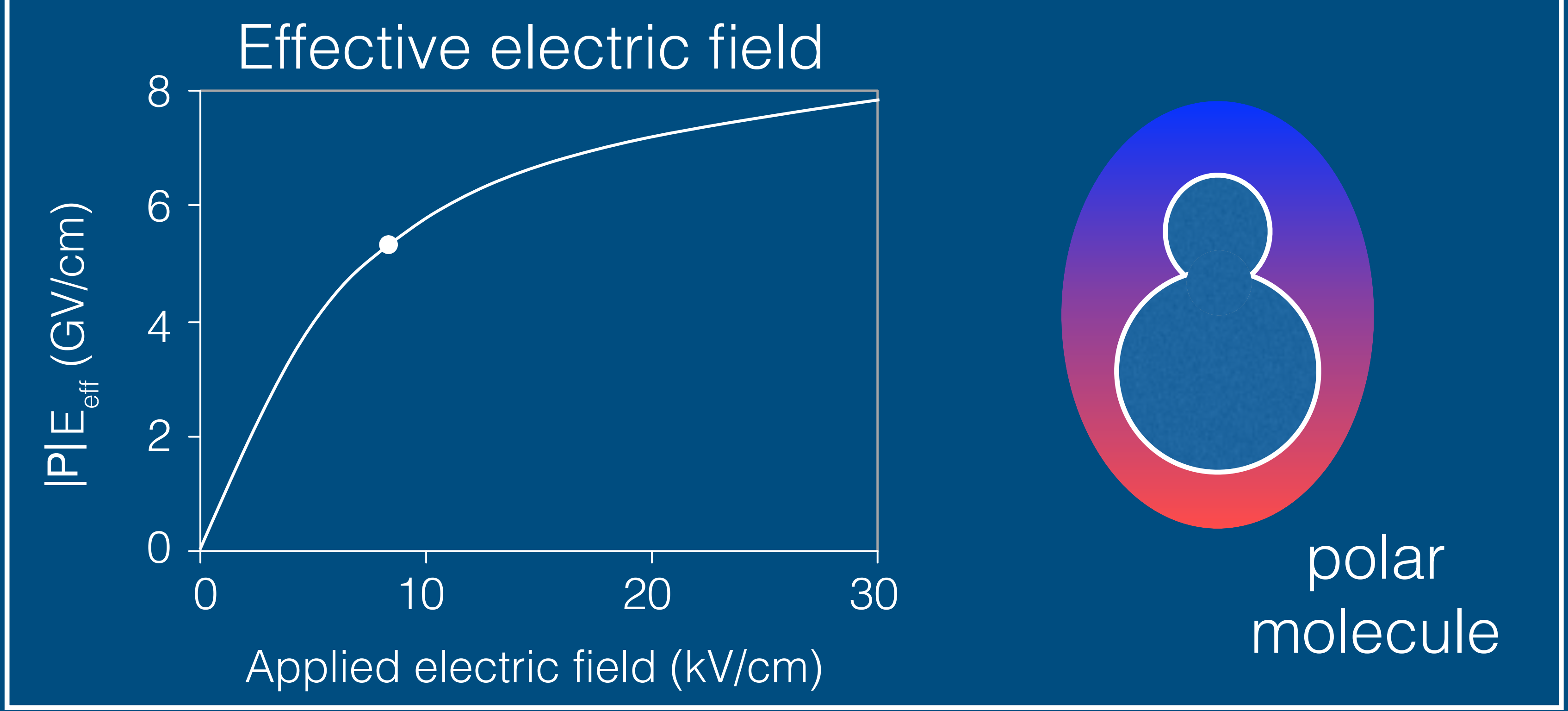
Complex quantum systems with an advantage

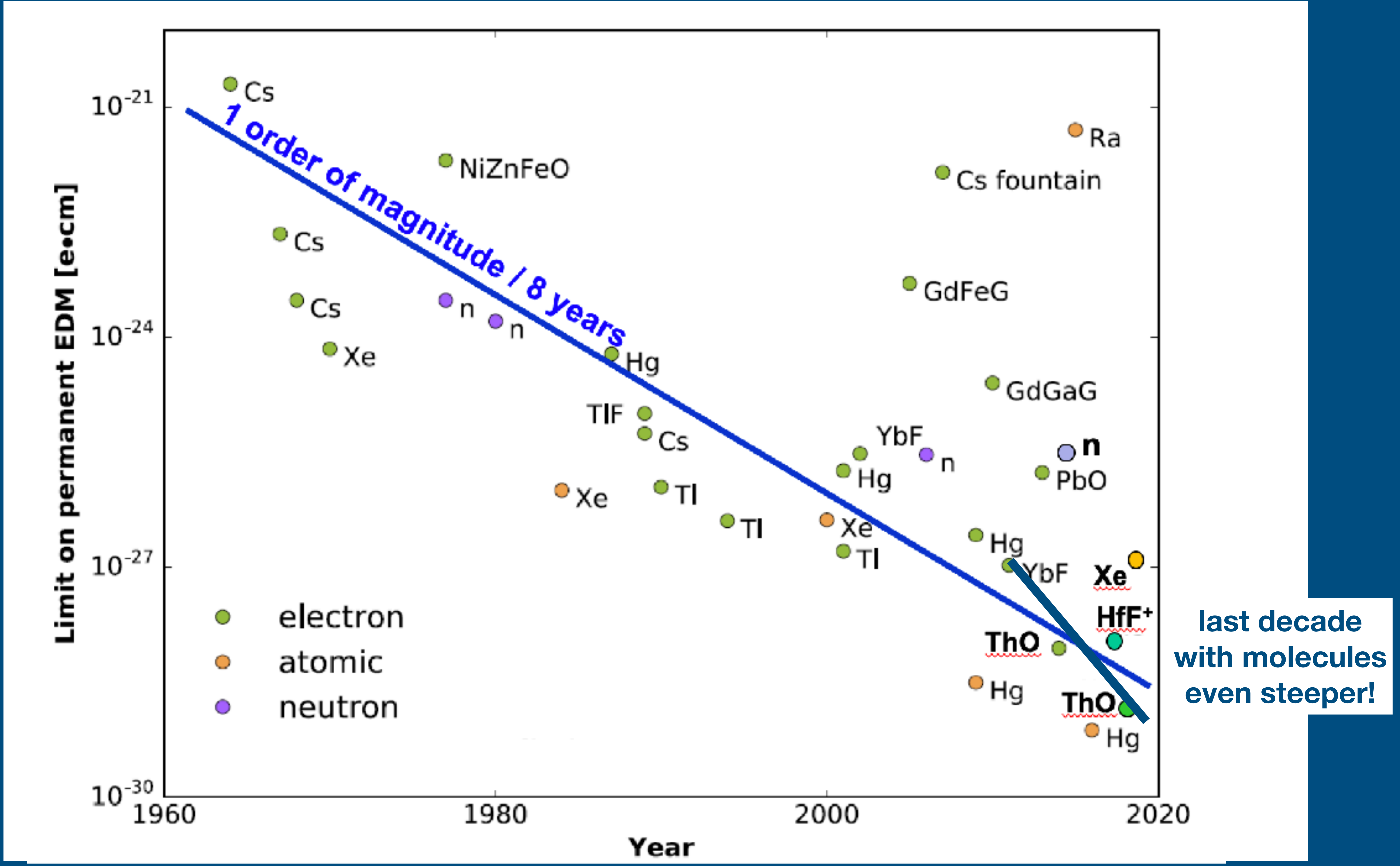
Example 3: The electric dipole moment of the electron

precision molecular spectroscopy

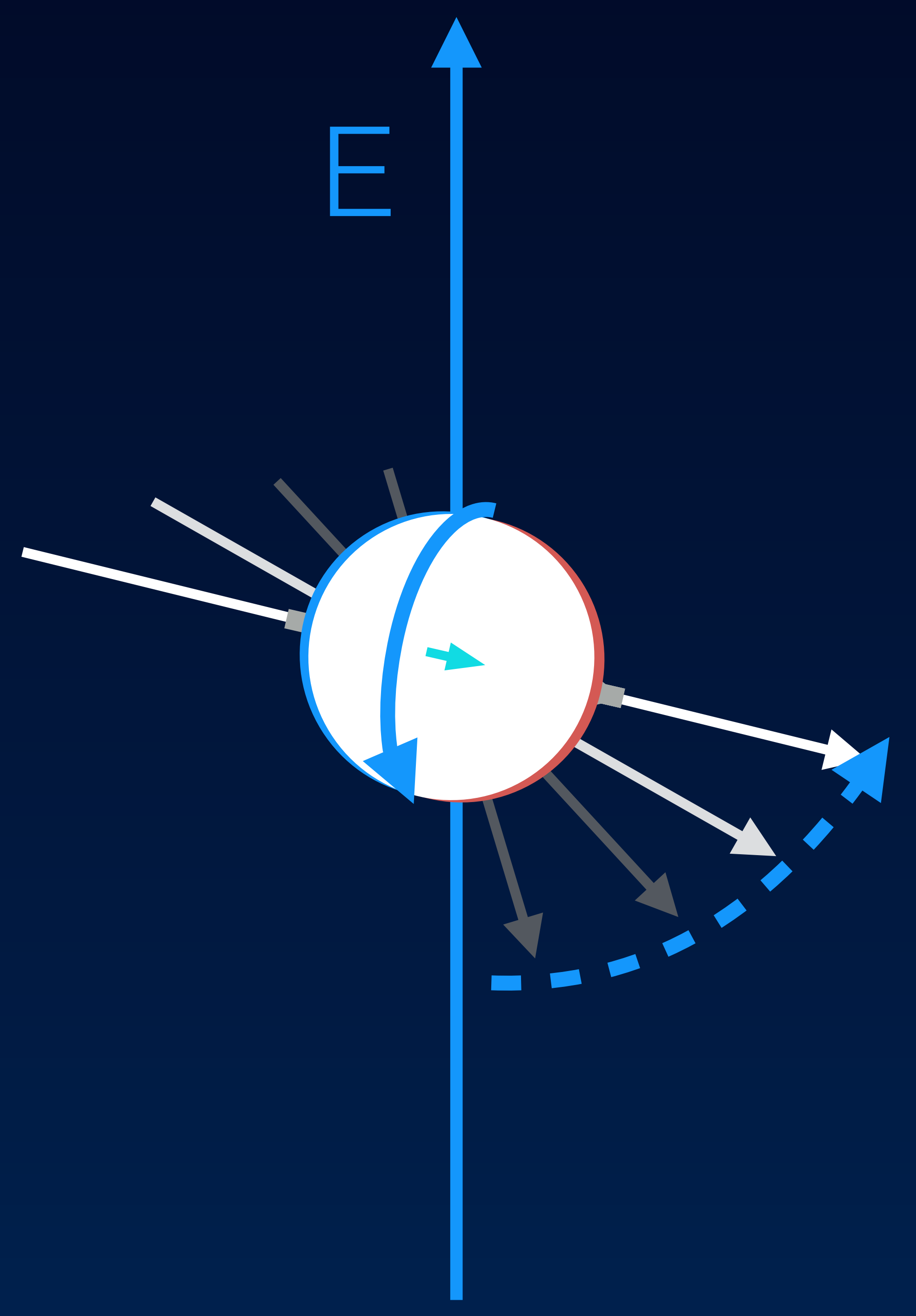


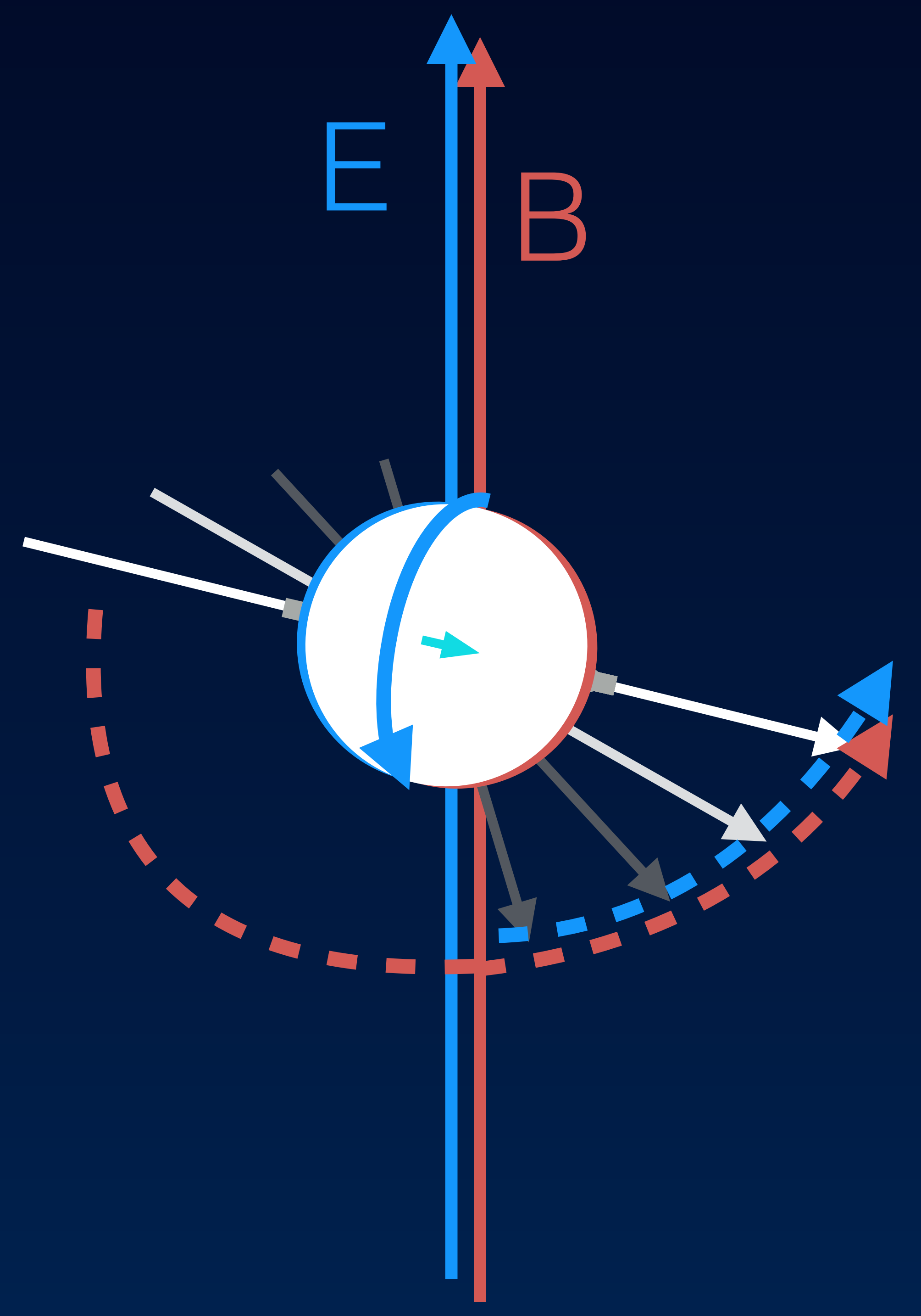
huge enhancement of E-field in molecule





How to measure a dipole moment?





precession!

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

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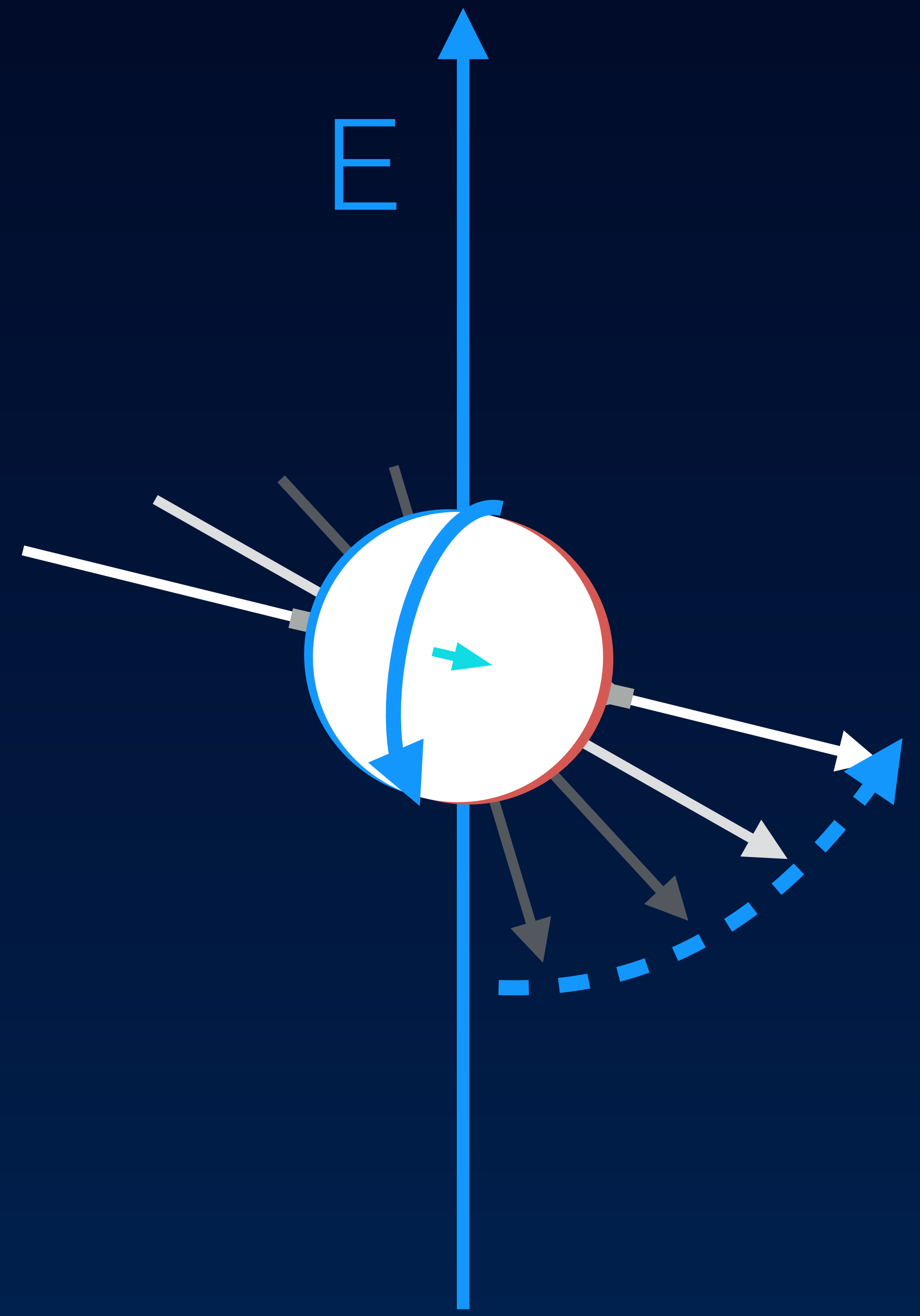

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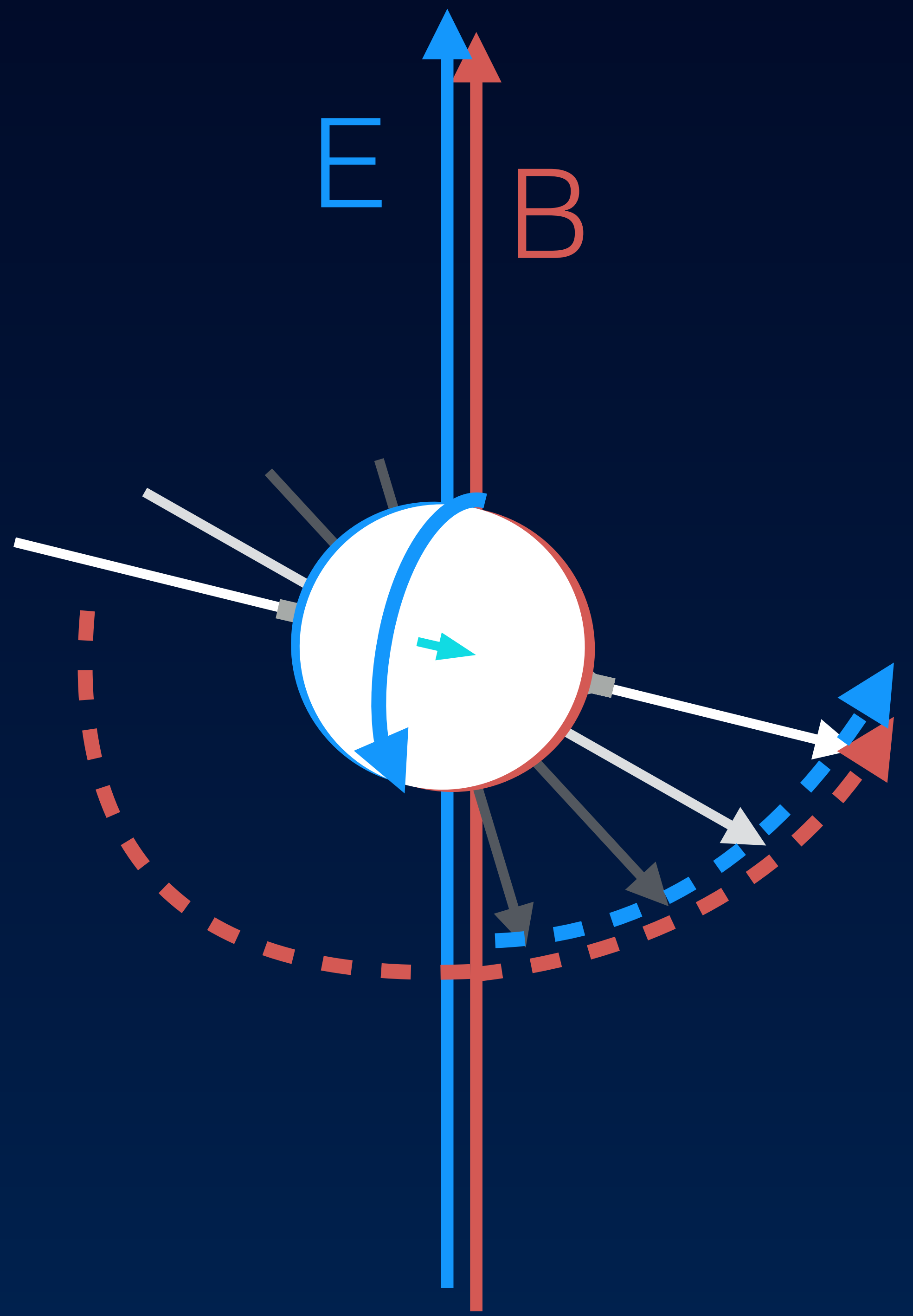

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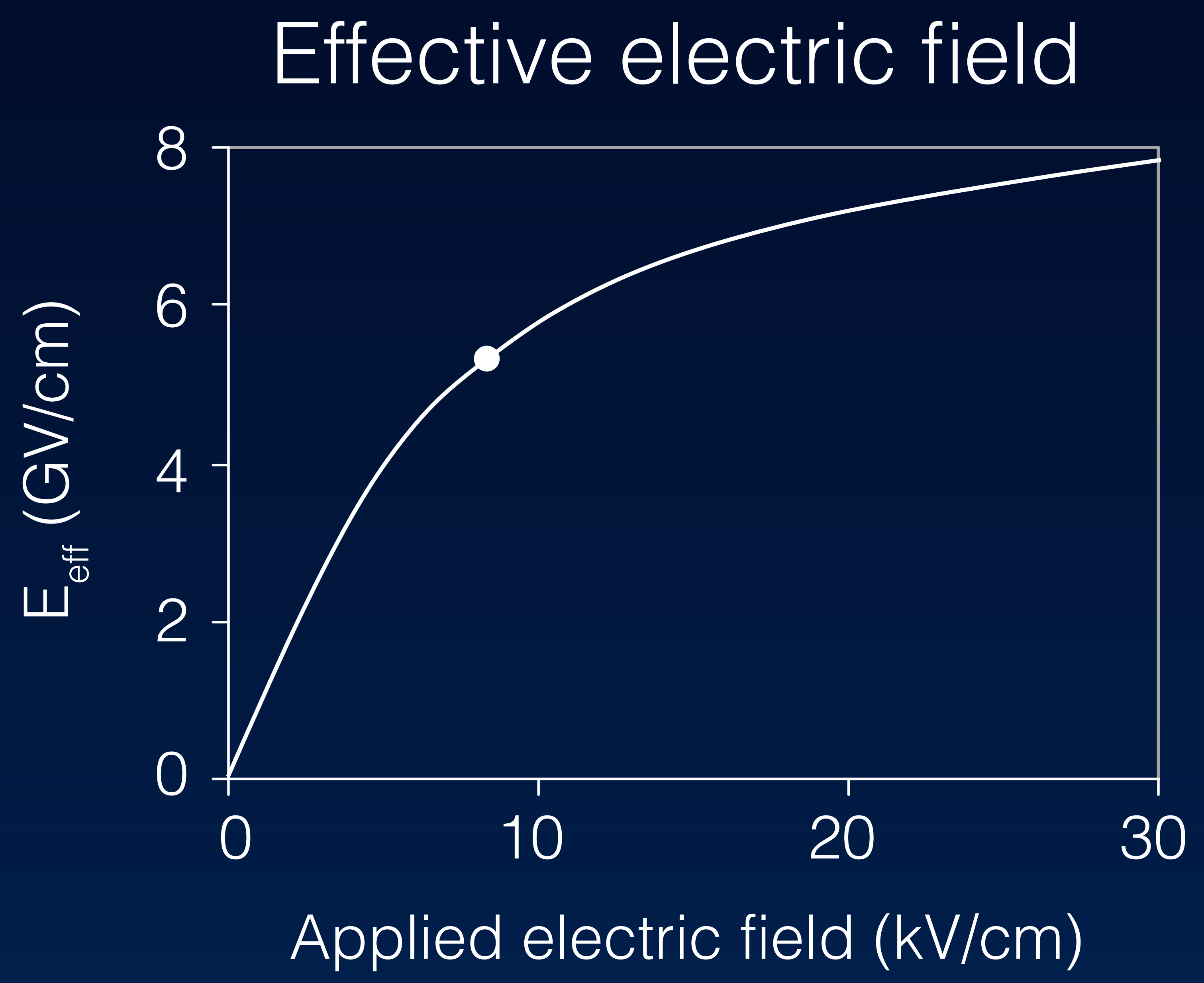
polar molecule



Solution:
use electron embedded in a polar molecule!

Enhances E
Shields B

Statistical sensitivity for eEDM

$$\sigma = \frac{\hbar}{2|\langle\Omega\rangle|W_{\mathrm{d}}\tau\sqrt{N_{\mathrm{p}}}},$$

statistical error

Choice of molecule

state sensitivity

molecular sensitivity (effective E-field)

Experimental approach

total # detected particles

coherent interaction time of spin precession

In addition to this, control of systematic effects is crucial!

Coherent interaction time

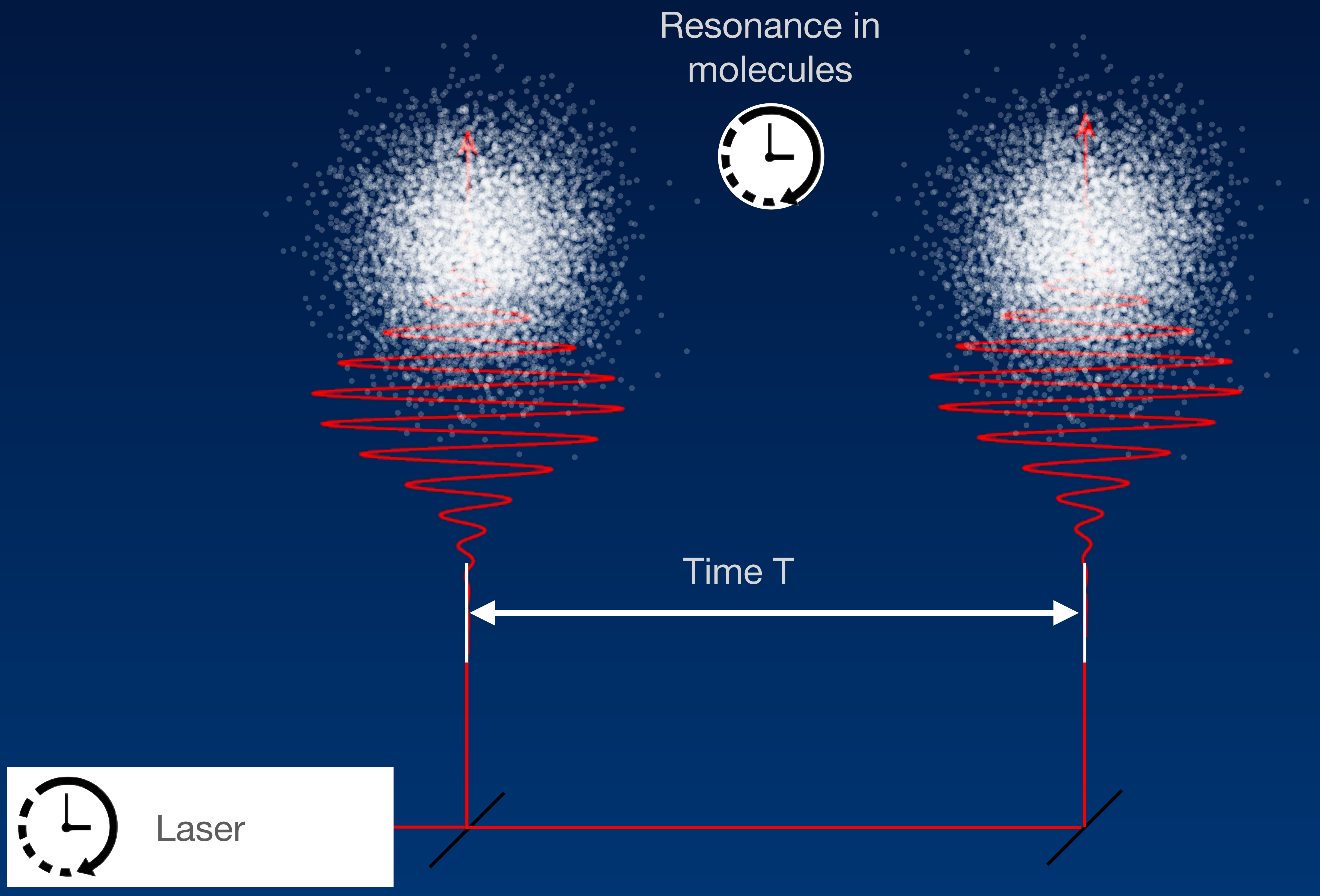
Key technique: Ramsey spin interferometer

laser pulse 1:

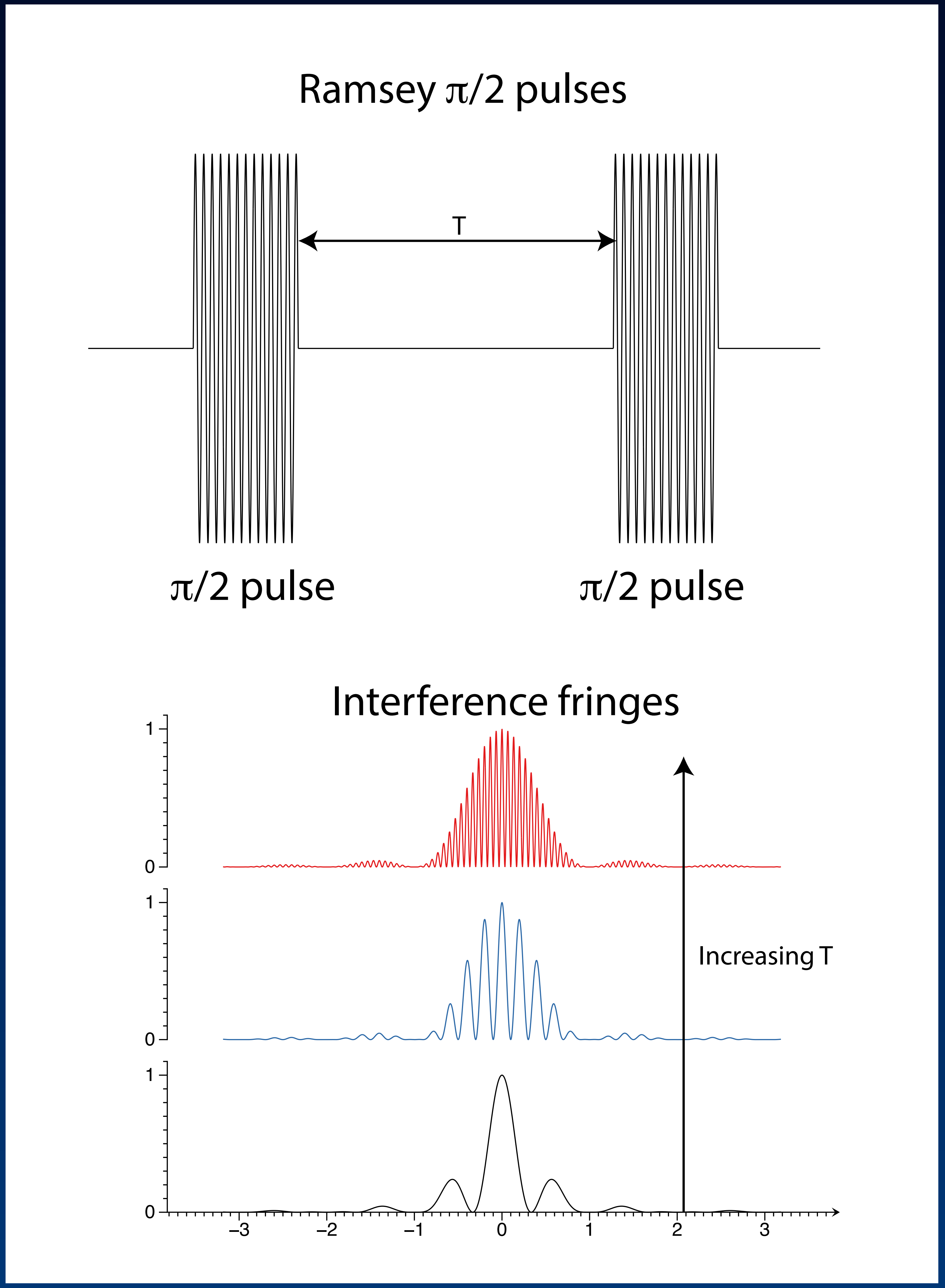
Creates a quantum superposition, creating coherent excitation of all molecules

laser pulse 2:

Measures state of the molecules through interference



Frequency set by external reference, tuned to molecular resonance



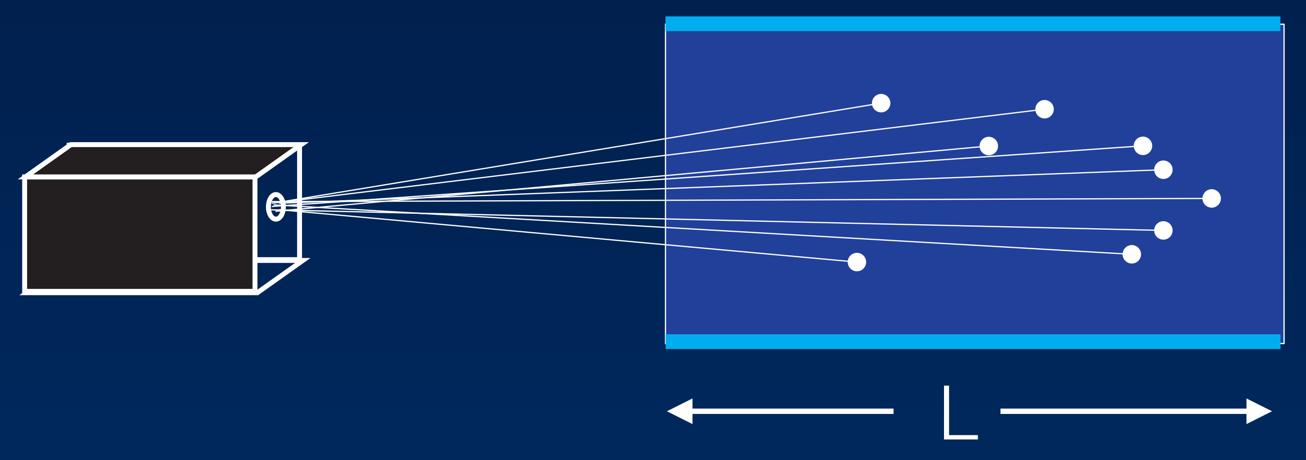
Towards longer coherent interaction times

fast beam

τ ~ 1-2 ms

L ~ 0.5 m

v ~ 250-500 m/s



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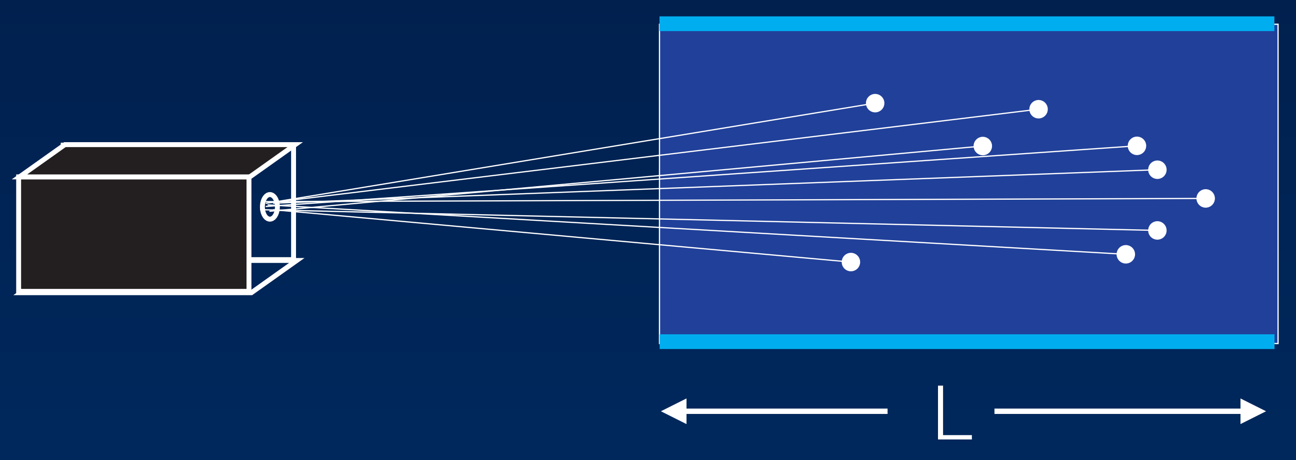
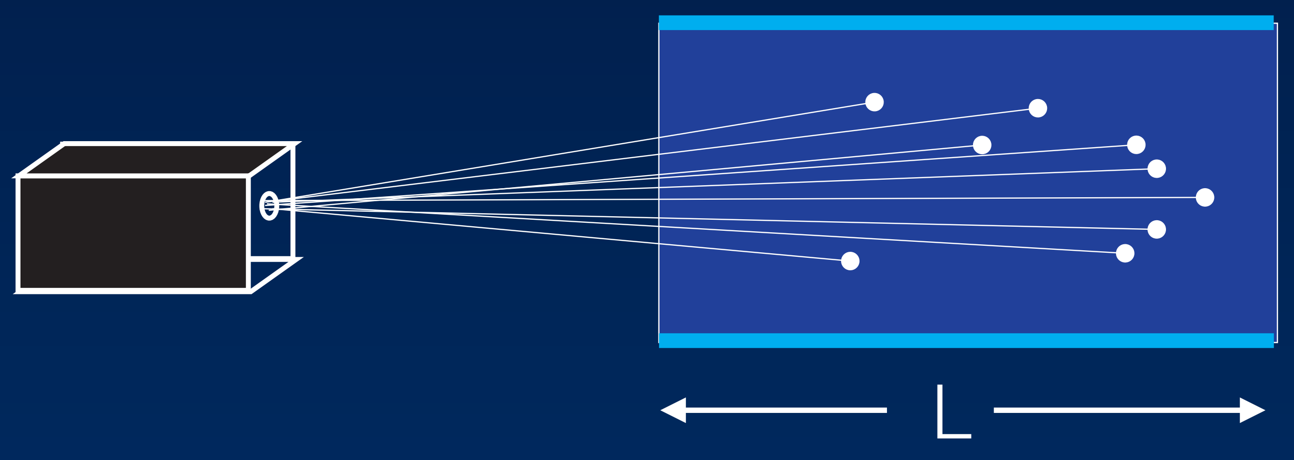


slow beam

τ ~ 15 ms

L ~ 0.5 m

v ~ 30 m/s



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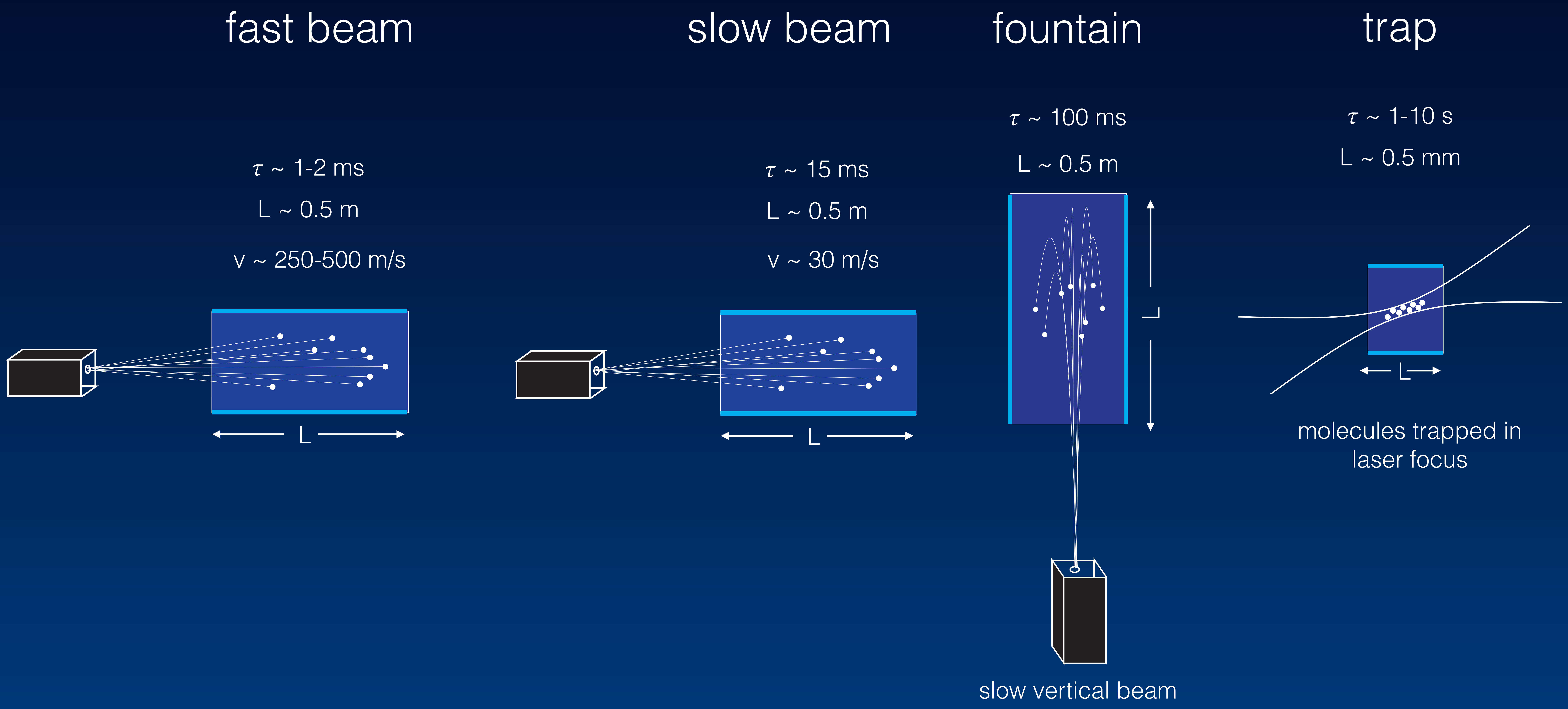

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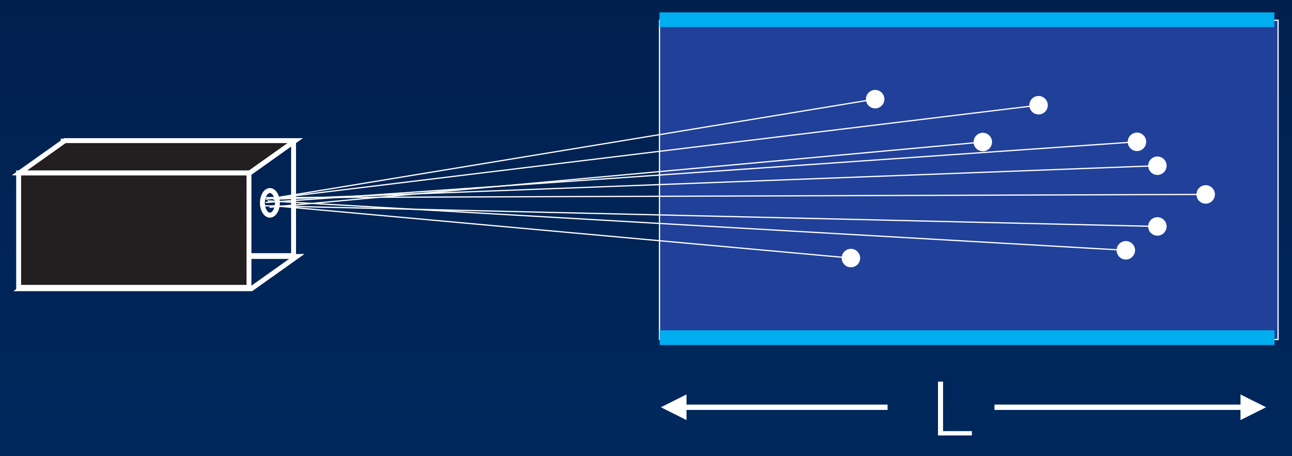
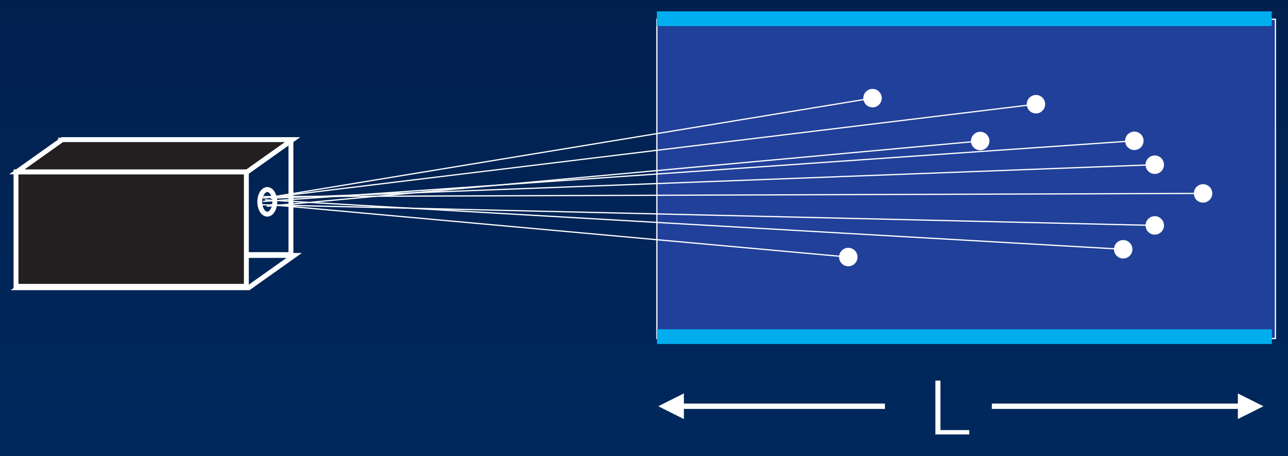


slow beam

τ ~ 15 ms

L ~ 0.5 m

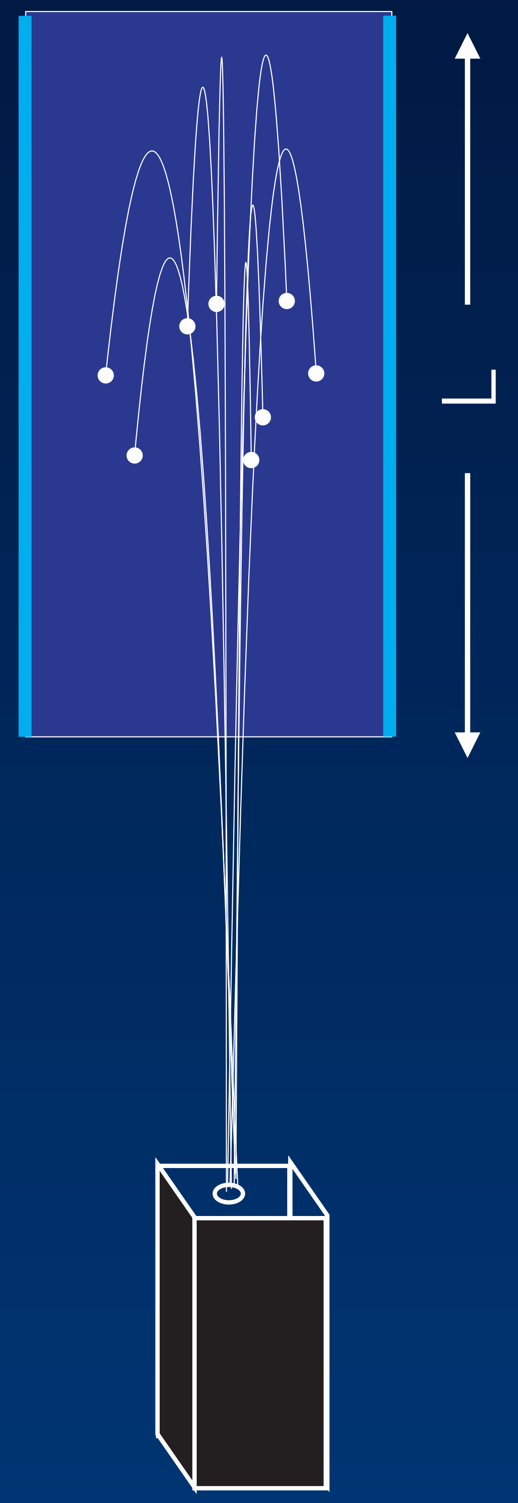
v ~ 30 m/s



fountain

τ ~ 100 ms

L ~ 0.5 m

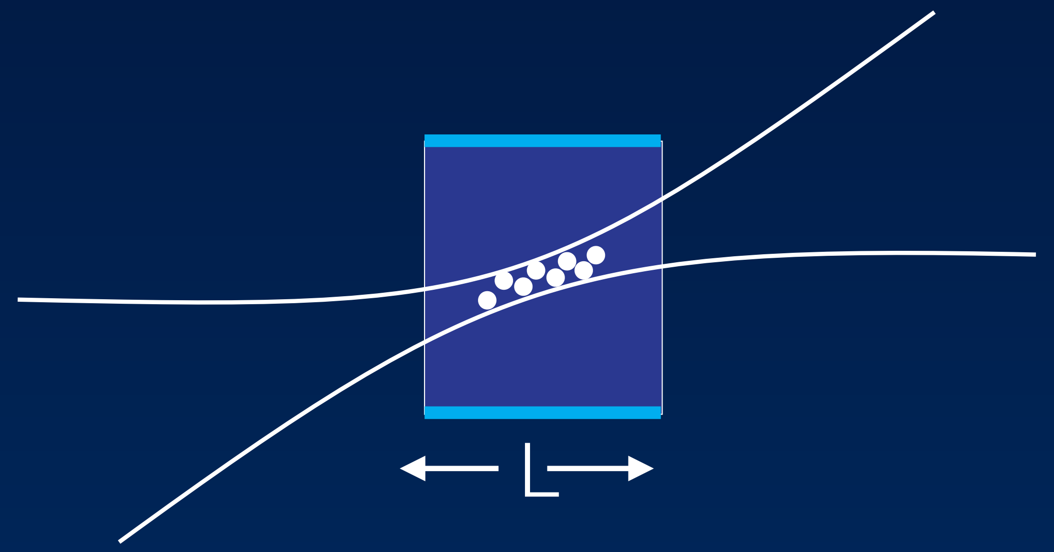


slow vertical beam

trap

τ ~ 1-10 s

L ~ 0.5 mm

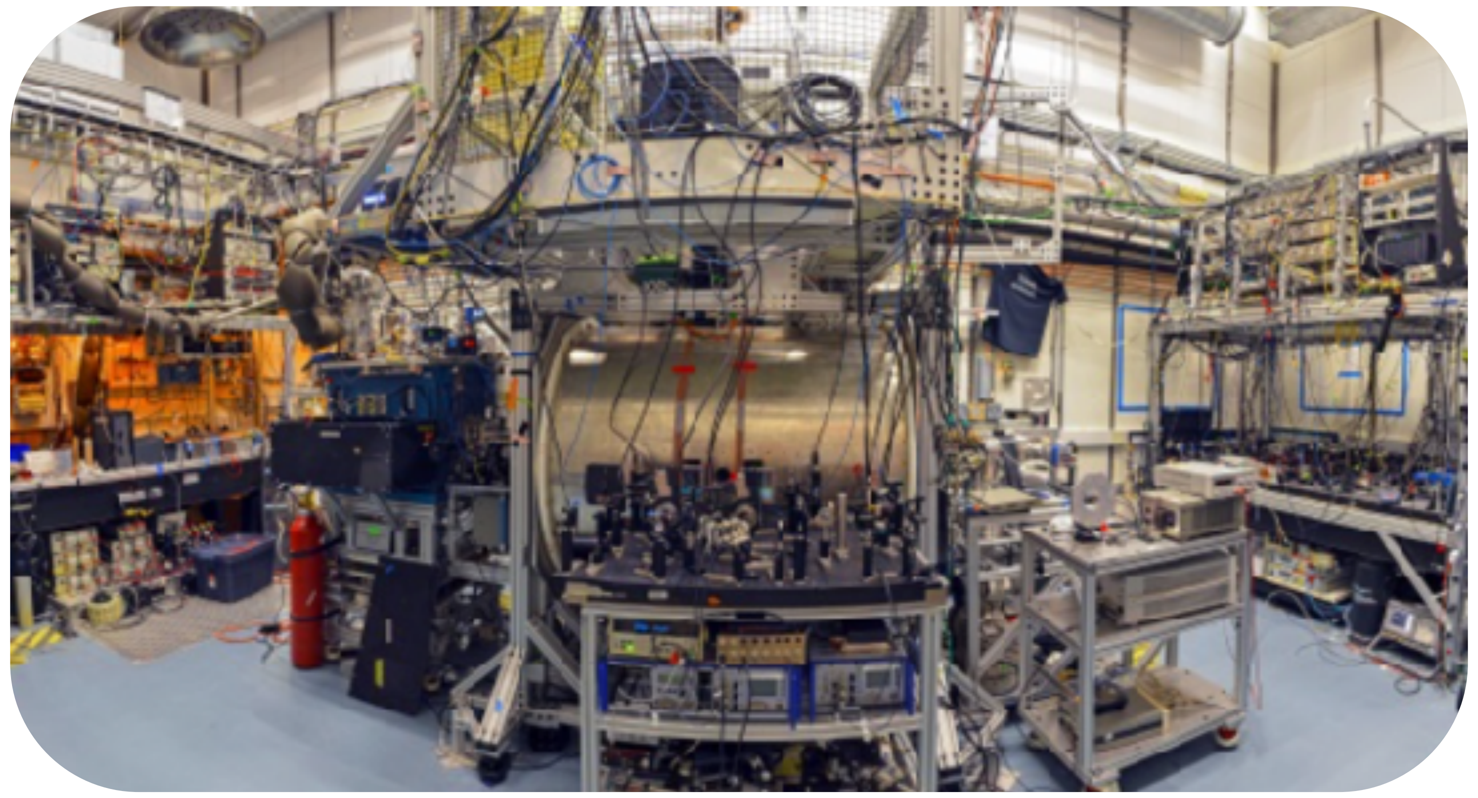


molecules trapped in laser focus

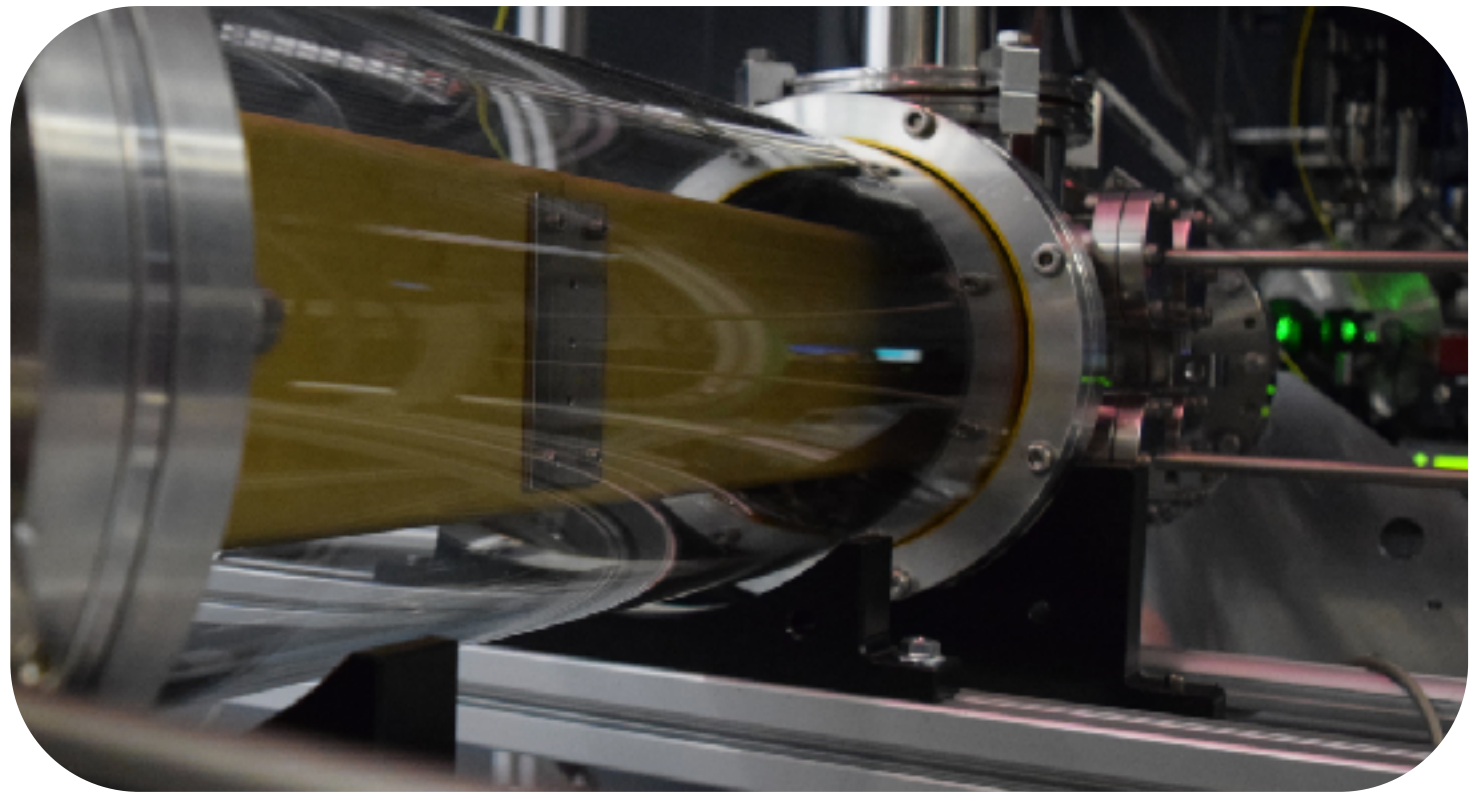
Main challenge:
how to maintain N while increasing t

Strongly connected to choice of molecule!

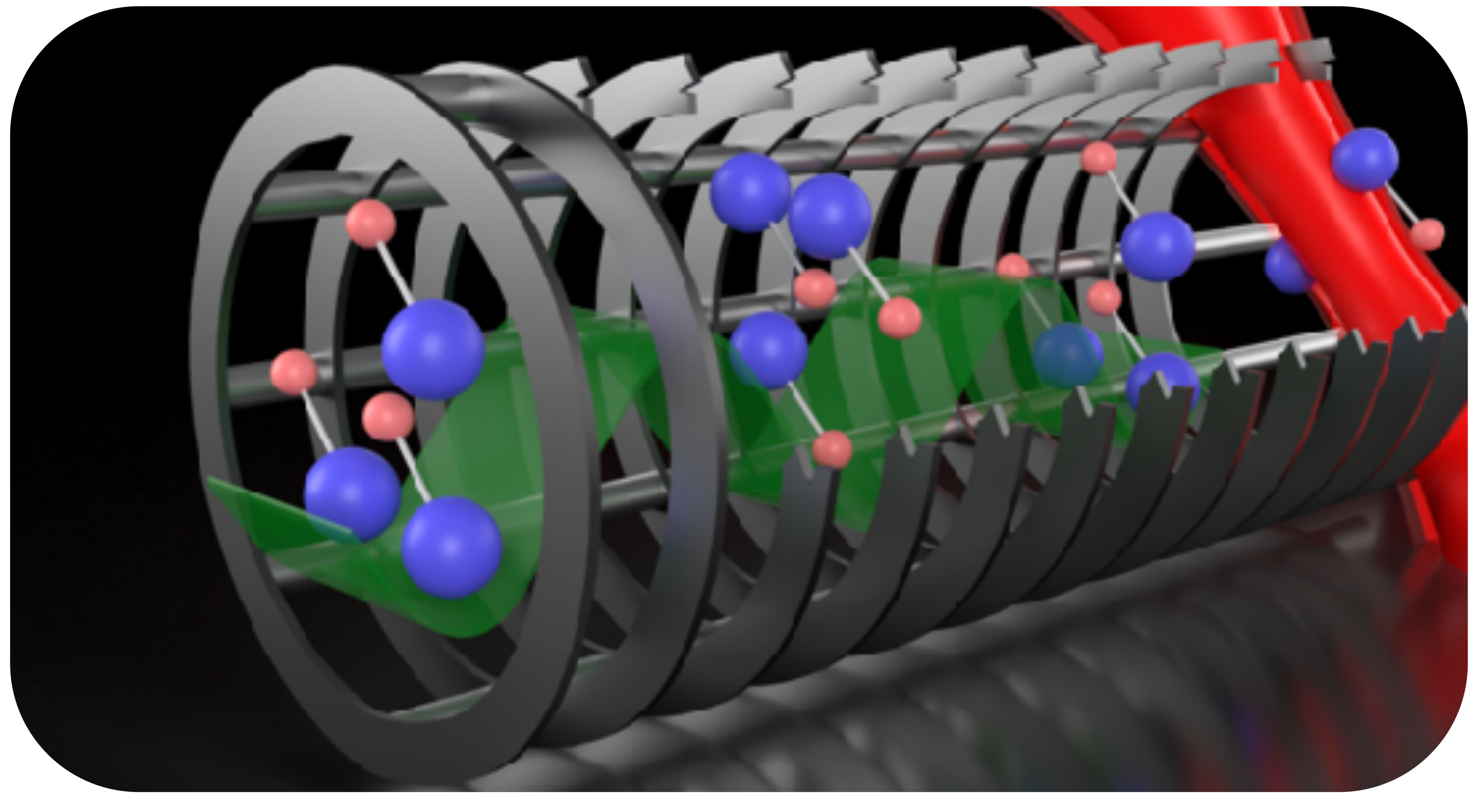
eEDM experiments using molecules



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

Statistical sensitivity for eEDM

$$\sigma = \frac{\hbar}{2|\langle\Omega\rangle|W_{\rm d}\tau\sqrt{N_{\rm p}}},$$

statistical error

state sensitivity

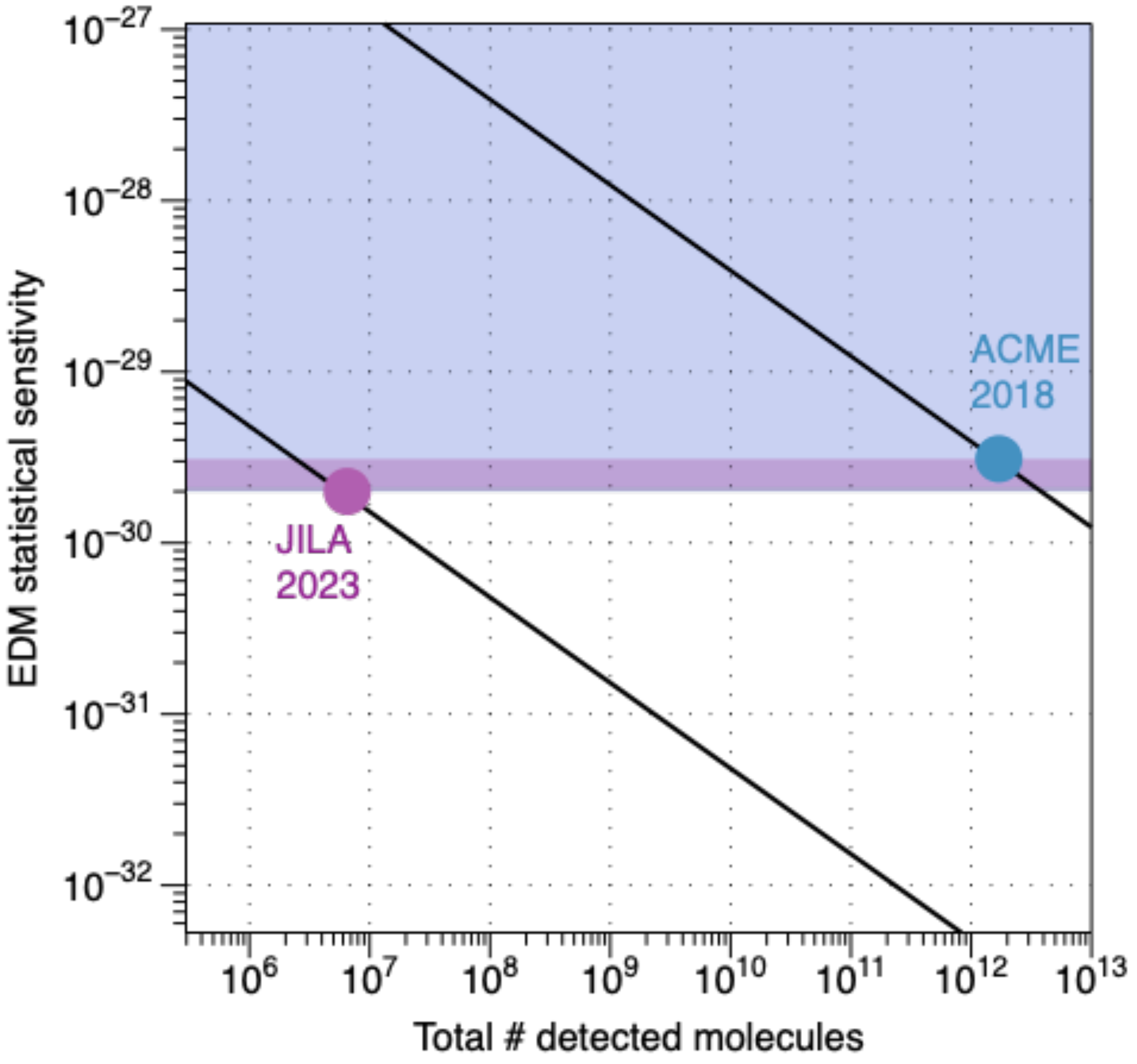
molecular sensitivity (effective E-field)

Choice of molecule

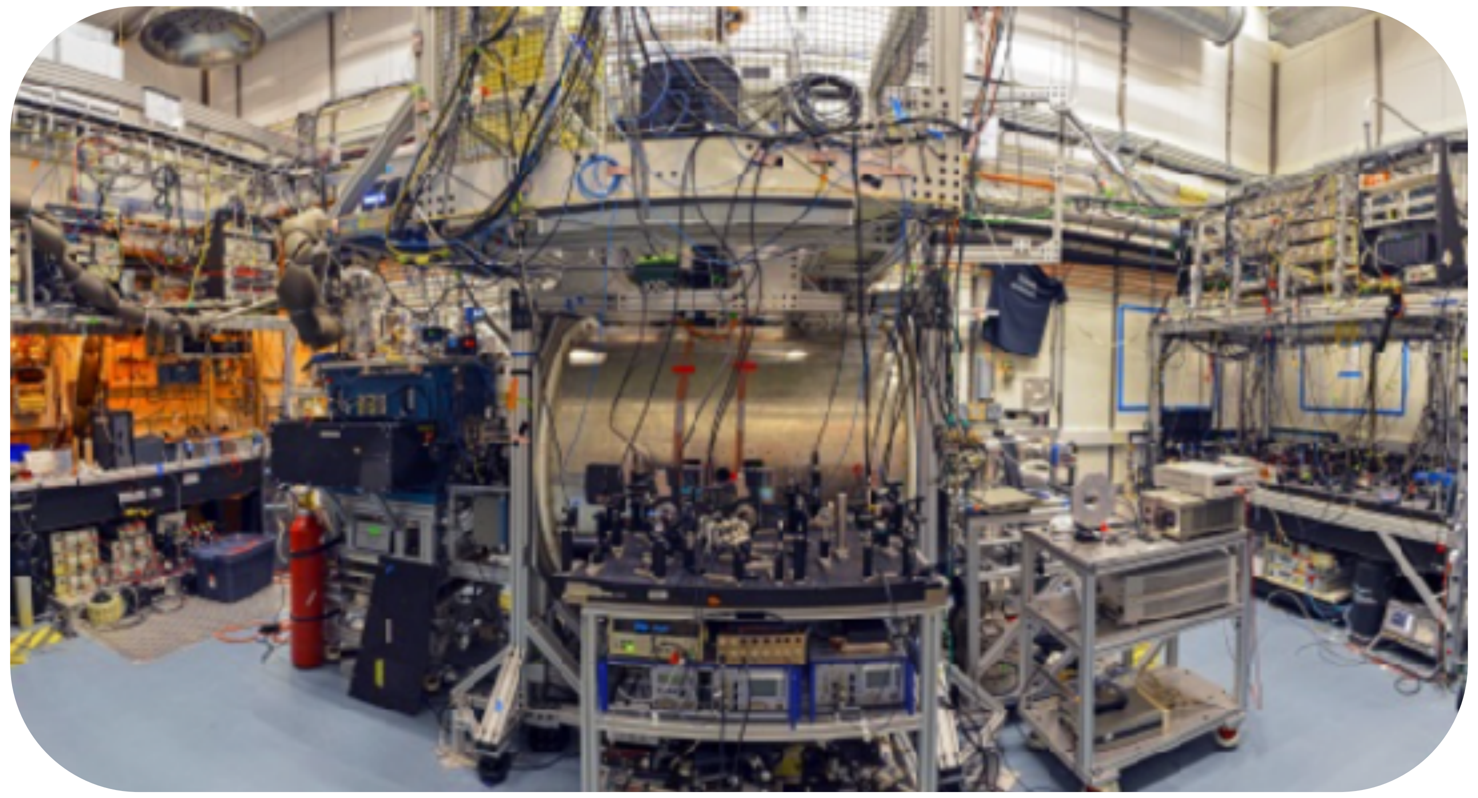
total # detected particles

coherent interaction time of spin precession

Experimental approach



eEDM experiments using molecules



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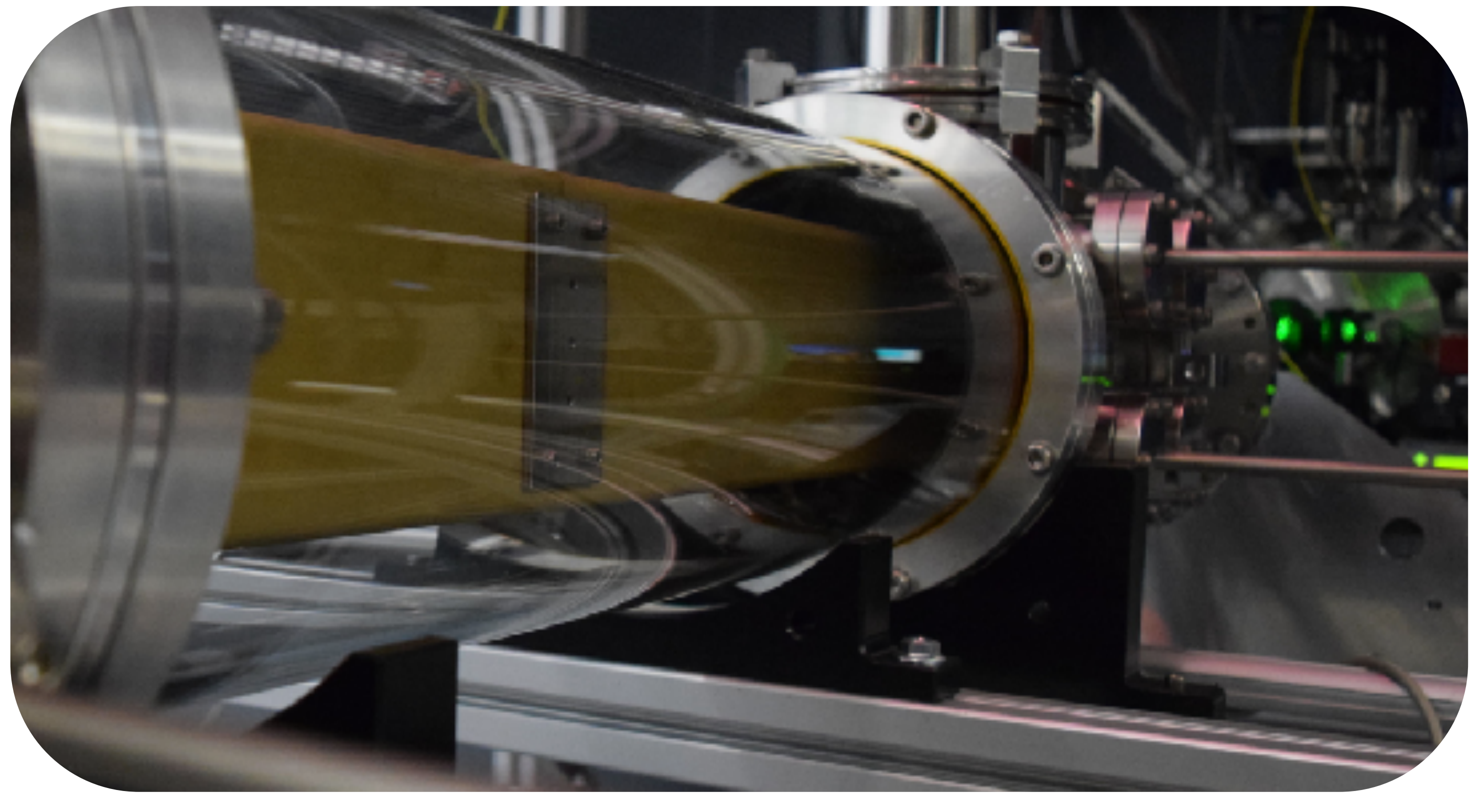

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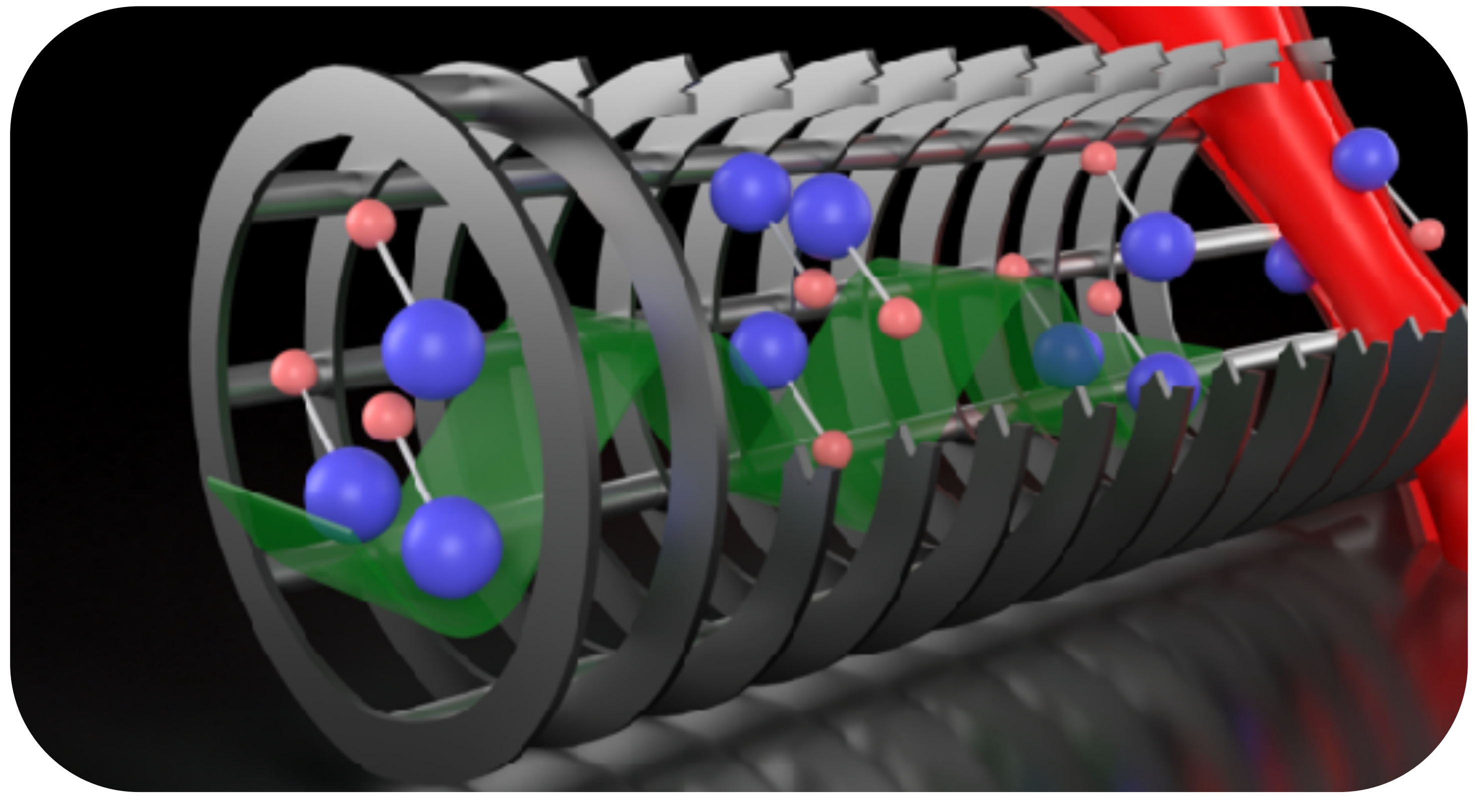
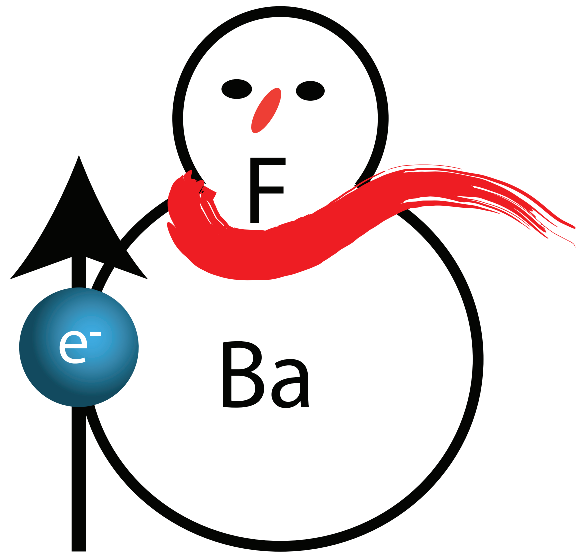


JILA - trapped HfF^+ ions
Eric Cornell, Jun Ye

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

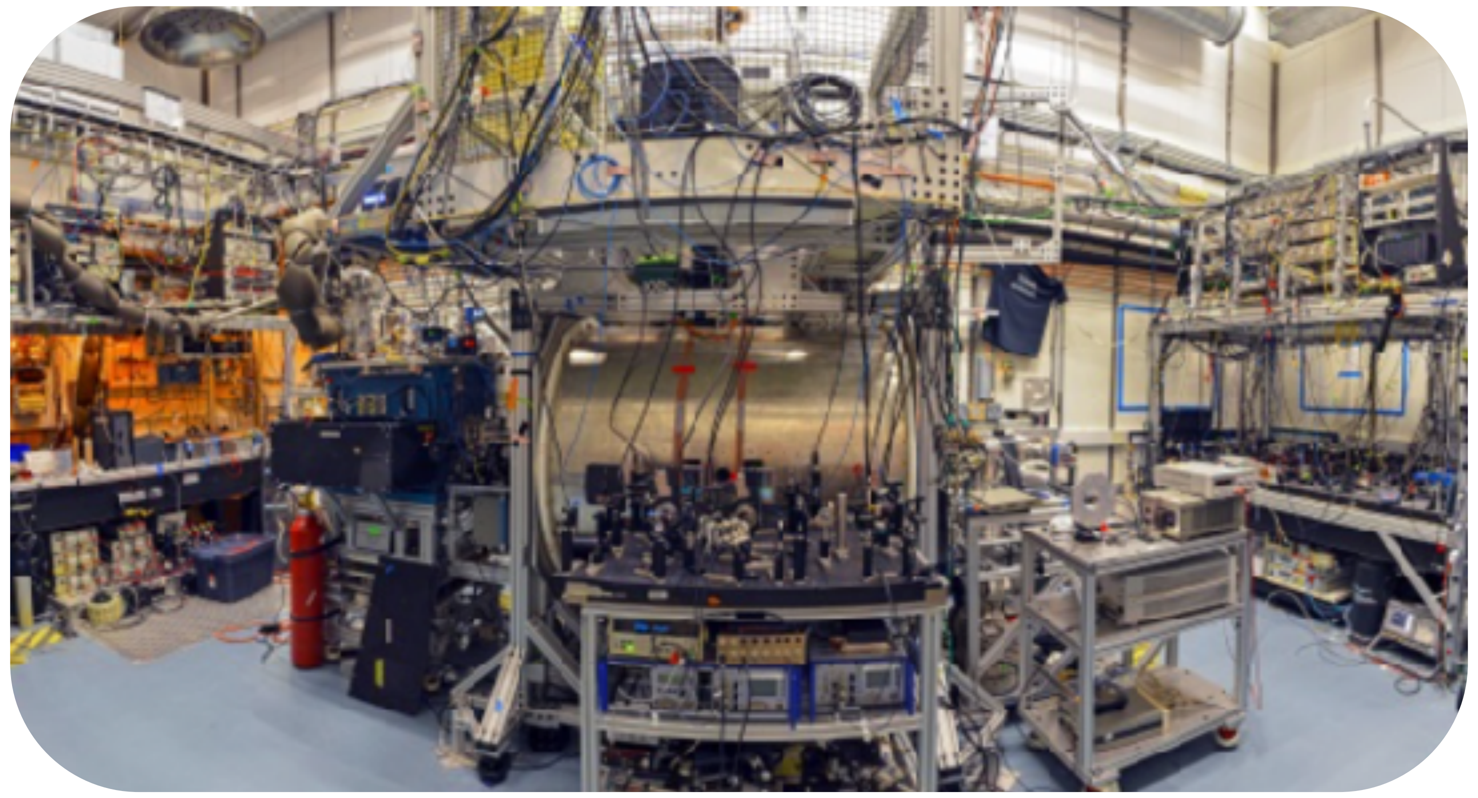
YORK UNIVERSITÉ UNIVERSITY

MICHIGAN STATE UNIVERSITY

UNIVERSITY OF TORONTO

EDM^3 Collaboration

eEDM experiments using molecules



ACME - beam of ThO molecules
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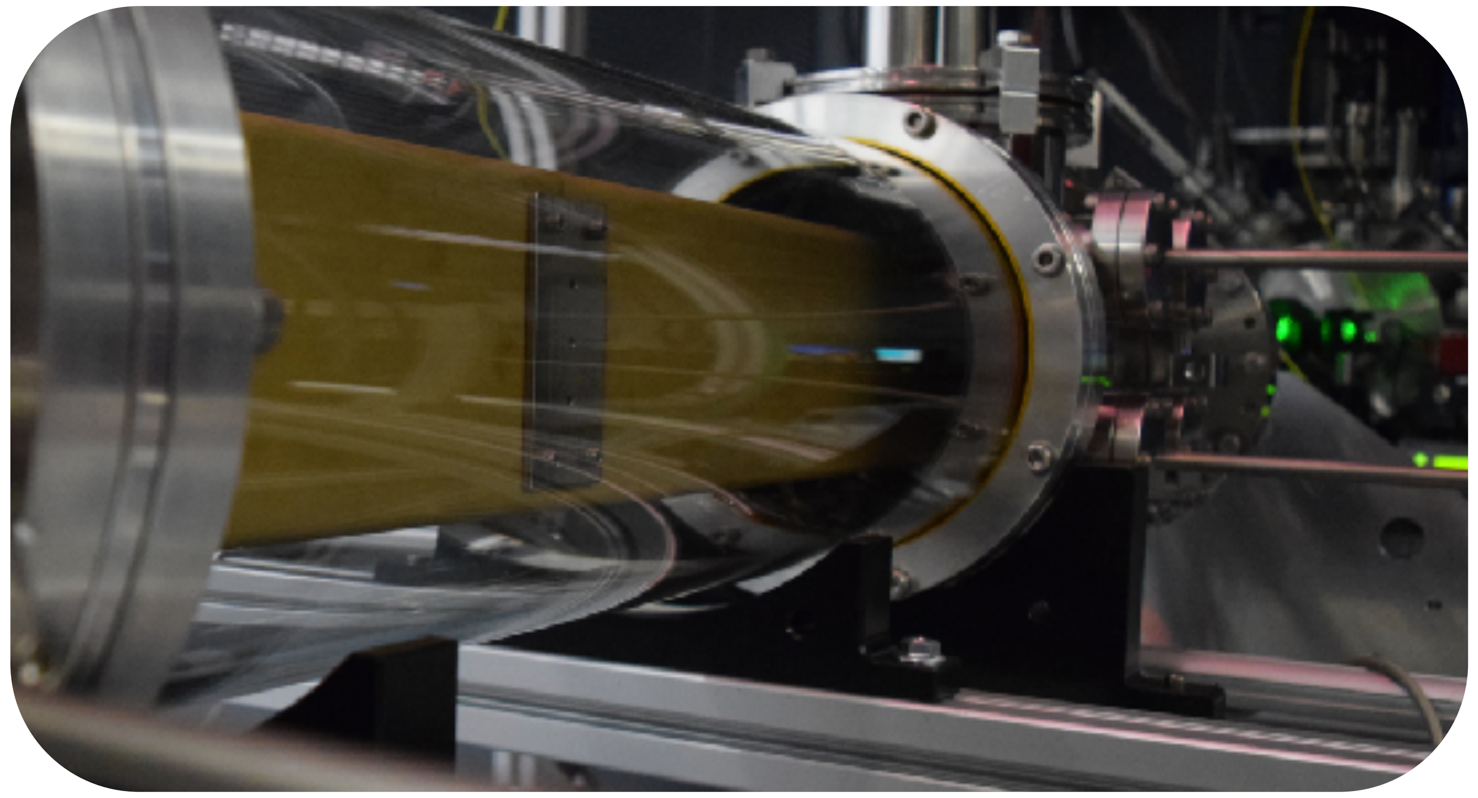
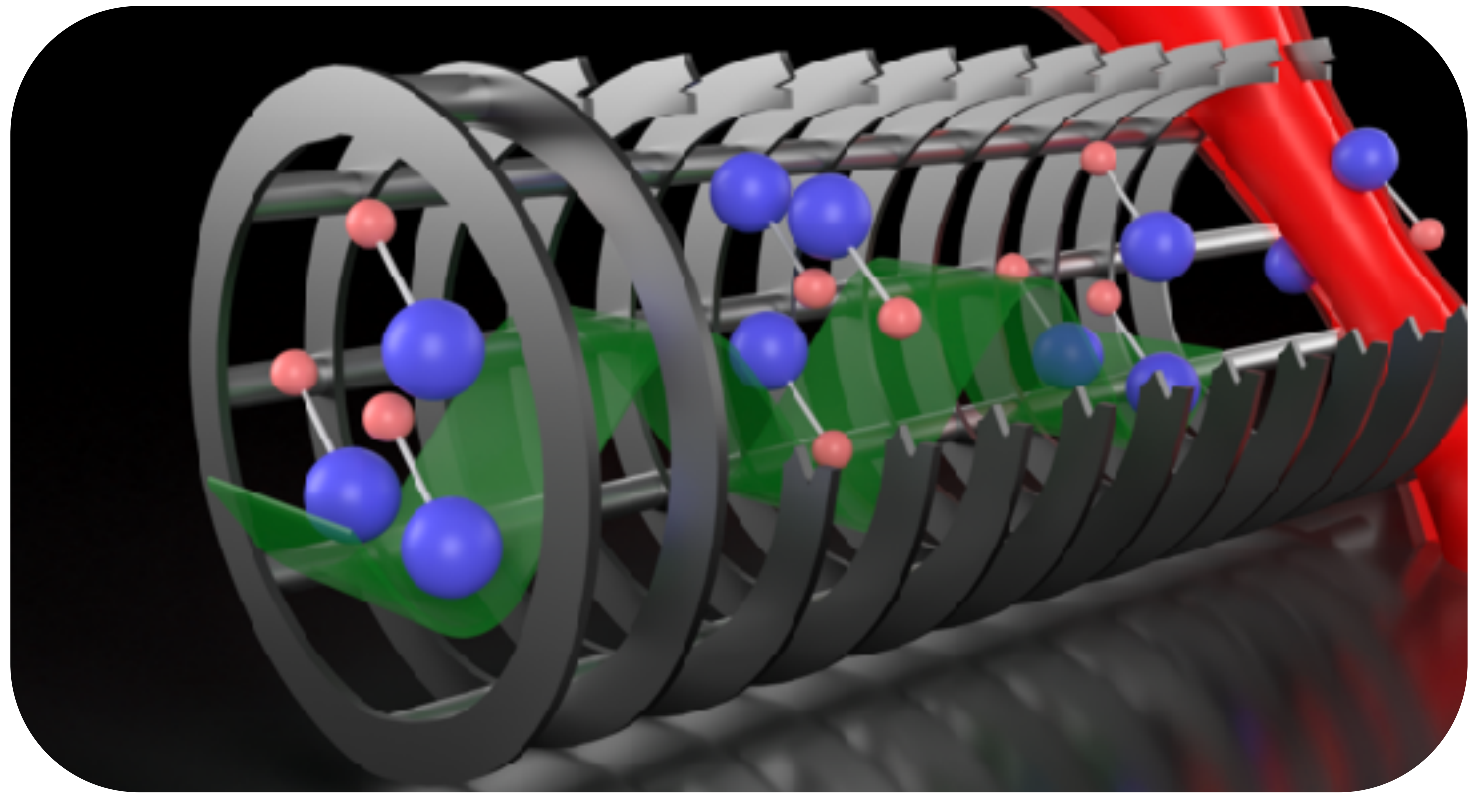
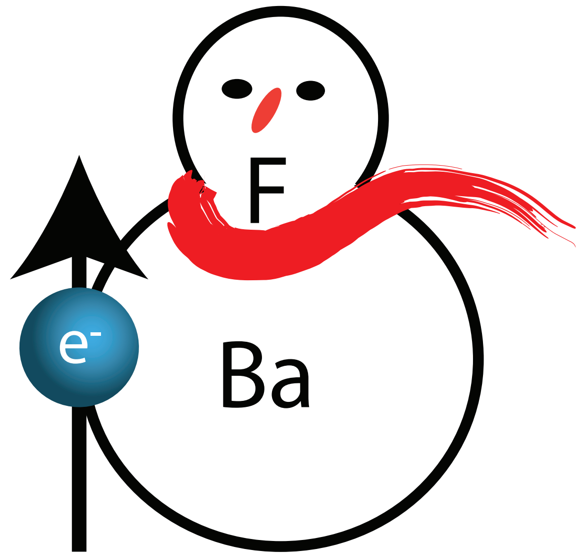


Imperial College London - beam of YbF molecules
Mike Tarbutt, Ben Sauer, Ed Hinds



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

Others are being set up:



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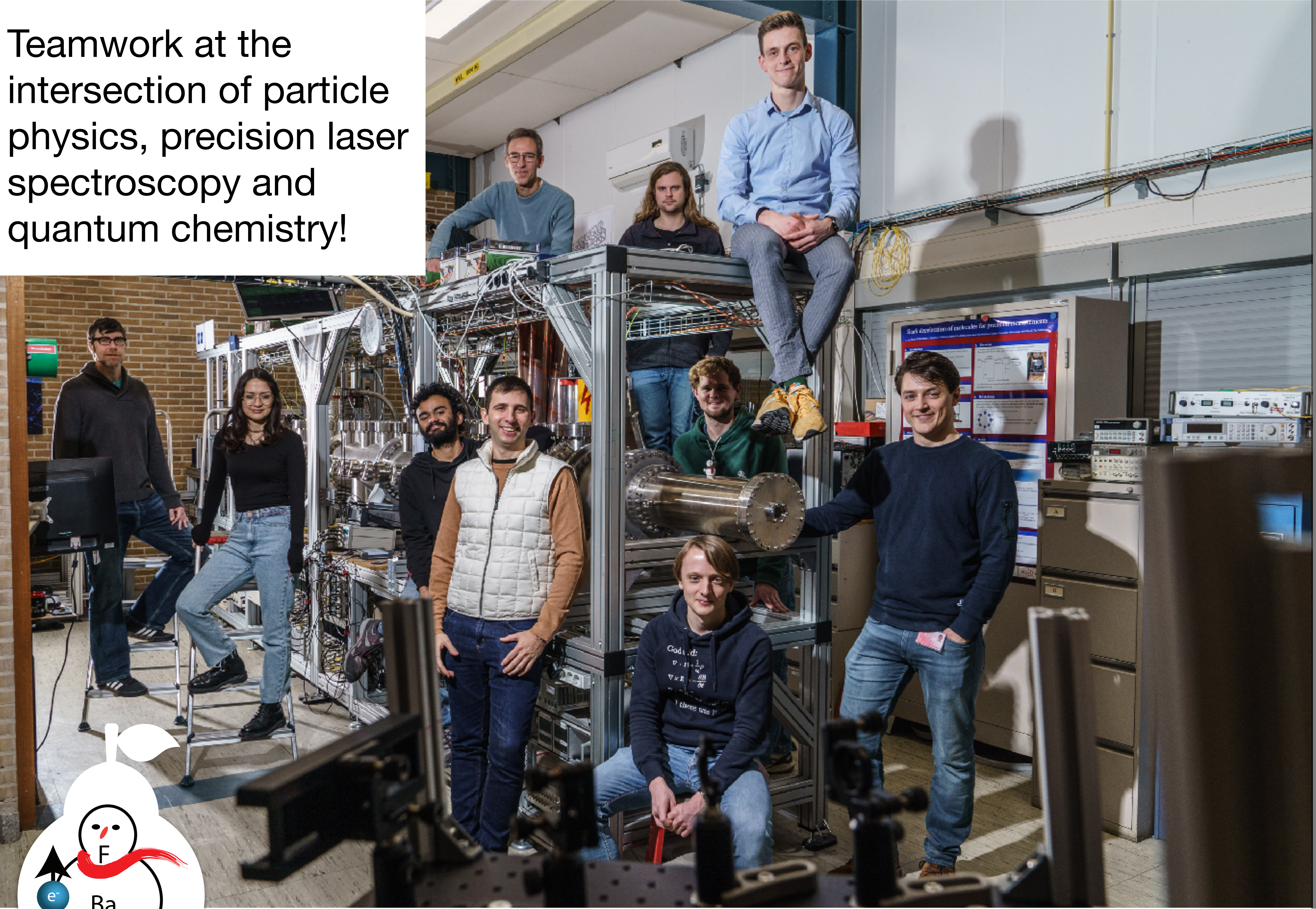
Para-Hydrogen and Diatomic for eEDM Study

Electric Dipole Measurements using Molecules within a Matrix

- York University
- Michigan State University
- University of Toronto

EDM^3 Collaboration

Teamwork at the intersection of particle physics, precision laser spectroscopy and quantum chemistry!



Current team:

Particle physics theory

- **Jordy de Vries**
- **Rob Timmermans**
- Heleen Mulder

Quantum chemistry

- **Anastasia Borschevsky**
- Lukas Pastecka
- Agustin Aucar
- Yuly Chamorro
- Eiffion Prinsen

Precision experiments

- **Steven Hoekstra (PI)**
- **Lorenz Willmann**
- **Rick Bethlem**
- **Steve Jones**
- **Wim Ubachs**
- Lucas van Sloten
- Jelmer Levenga
- Bastiaan Nijman
- Joost van Hofslot
- Bart Schellenberg
- Ties Fikkers
- Nithesh Balasubramanian
- Izabella Thompson
- Marianne Westerhof

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

Community input to the European Strategy on particle physics: Searches for Permanent Electric Dipole Moments

edited by:

M. Athanasakis-Kaklamanakis (*Imperial College London, United Kingdom*), M. Au (*CERN, Geneva, Switzerland*), R. Berger (*University of Marburg, Germany*), S. Degenkolb (*Heidelberg University, Germany*), J. De Vries (*University of Amsterdam, The Netherlands*) S. Hoekstra (*University of Groningen, The Netherlands*), A. Keshavarzi (*University of Manchester, United Kingdom*), N. Neri (*University of Milan and INFN Milan, Italy*), D. Ries (*Paul Scherrer Institute, Villigen, Switzerland*), P. Schmidt-Wellenburg (*Paul Scherrer Institute, Villigen, Switzerland*), and M. Tarbutt (*Imperial College London, United Kingdom*)

endorsed by the
European EDM projects and collaborations:

DOCET EDM experiment – G. Carugno (*INFN Padua, Italy*)
PanEDM collaboration – S. Degenkolb (*U. Heidelberg, Germany*) and P. Fierlinger (*Technical University of Munich, Germany*)
nEDMSF collaboration – W.C. Griffith (*U. Sussex, UK*) and M. Jentschel (*ILL, France*)
NL-eEDM collaboration – S. Hoekstra (*U. Groningen, The Netherlands*)
nEDM at PSI collaboration – B. Lauss (*Paul Scherrer Institute, Villigen, Switzerland*)
ALADDIN collaboration – N. Neri (*University of Milan and INFN Milan, Italy*) and F. Martinez-Vidal (*U. Valencia and IFIC, Spain*)
Beam EDM collaboration – F. Piegsa (*U. Bern, Switzerland*)
HeXe collaboration – U. Schmidt (*U. Heidelberg, Germany*)
pEDM collaboration – Y. K. Semertizidis (*KAIST, Daejeon, Korea*)
Imperial eEDM collaboration – M. R. Tarbutt (*Imperial College London, UK*)
muEDM collaboration – A. Papa (*INFN Pisa, Italy*)
quMercury experiment – S. Stellmer (U. Bonn, Germany)

individually endorsed by:

A. Borschevsky (*U. Groningen, The Netherlands*), V. Cirigliano (*U. Washington, USA*), J. Dobaczewski (*U. Warsaw, Poland*), K. Flanagan (*U. Manchester, UK*), T. Fleig (*U. Toulouse, France*), M. Kortelainen (*U. Jyväskylä, Finland*), L. Di Luzio (*INFN Padova, Italy*), G. Neyens (*KU Leuven, Belgium*), L. Nies (*CERN*), G. Onderwater (*U. Maastricht, The Netherlands*), U. van Kolck (*ECTStar, Trento, Italy*), V. Sanz (*U. Valencia, Spain*), P. Stoffer (*PSI, Switzerland*), O. Vives (*IFIC, Spain*)

Collaboration	Species	Method	Sensitivity (10^{-29} $e$cm)	Status	Duration (years)	Ref
PanEDM I	n	UCN	380	Commissioning	5	[43]
PanEDM II	n	UCN	79	Commissioning	8	[43]
Beam EDM	n	beam	500	proof-of-principle	?	[44]
n2EDM	n	UCN	110	Start data-taking	4	[45]
n2EDMagic	n	UCN	50	Construction	5	[45]
nEDMsf	n	UCN	20	Development	7	[42]
ACME III	ThO ($^3\Delta_1$)	Beam	0.1	Commissioning		[93]
JILA III	ThF^+ ($^3\Delta_1$)	Ion trap		Commissioning		[94]
Imperial II	YbF ($^2\Sigma$)	μK beam	0.1	Commissioning	3	[47]
Imperial III	YbF ($^2\Sigma$)	Lattice	0.01	Construction	6	[47]
NL-eEDM I	BaF ($^2\Sigma$)	Slow beam	0.5	Commissioning	3	[48]
NL-eEDM II	BaOH ($^2\Sigma$)	Lattice	0.1	Construction	6	[50]
PolyEDM	SrOH ($^2\Sigma$)	Lattice		Construction		[51]
EDM^3	BaF ($^2\Sigma$)	Matrix		Construction		[52]
DOCET	BaF ($^2\Sigma$)	Matrix		Construction	3	[53]
CeNTREX	^{205}TlF	Beam		Commissioning		[58]
HeXe	^{129}Xe	^{3}He-comagnetometer	10	Construction	4	[57]
quMercury	^{199}Hg	ultracold atoms	1	Construction	5	[61]
ALADDIN	Λ_c^+, Ξ_c^+	collider	1×10^{13}	Development	?+2	[64]
muEDM I	μ	frozen-spin	4×10^8	Commissioning	3	[67]
muEDM II	μ	frozen-spin	6×10^6	Conception	10	[67]
pEDM I	p	frozen-spin	1	Development	5	[69]
pEDM II	p	frozen-spin	0.01	Conception	5	[69]

TABLE II: Sensitivity goals of planned EDM measurements. All values are reported as transmitted in private communication or published in cited references.

Table-Top Particle Physics

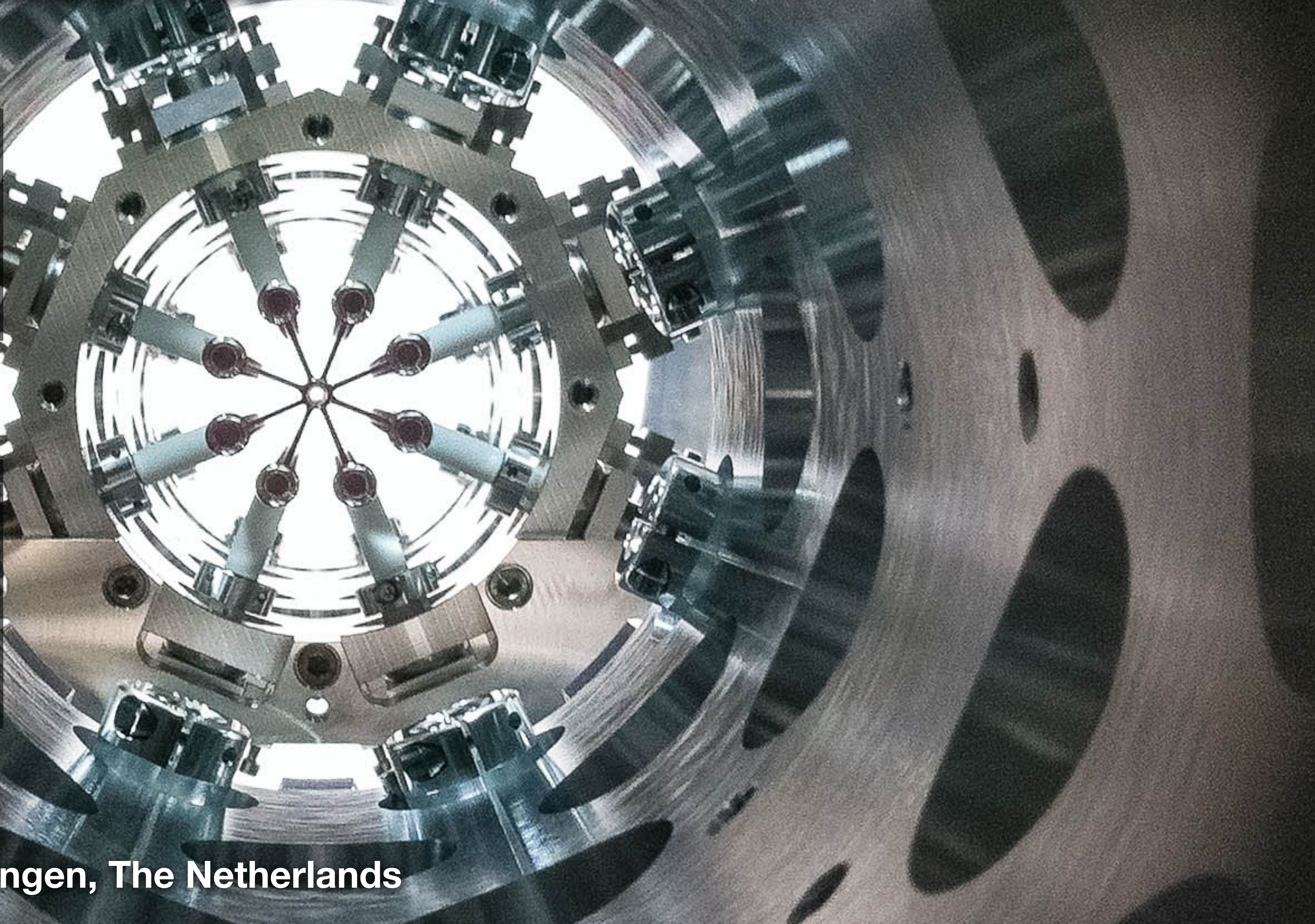
with Slow and Trapped Molecules

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
- Trapping
- Precision measurements



Steven Hoekstra, University of Groningen, The Netherlands

Key ingredients of our approach

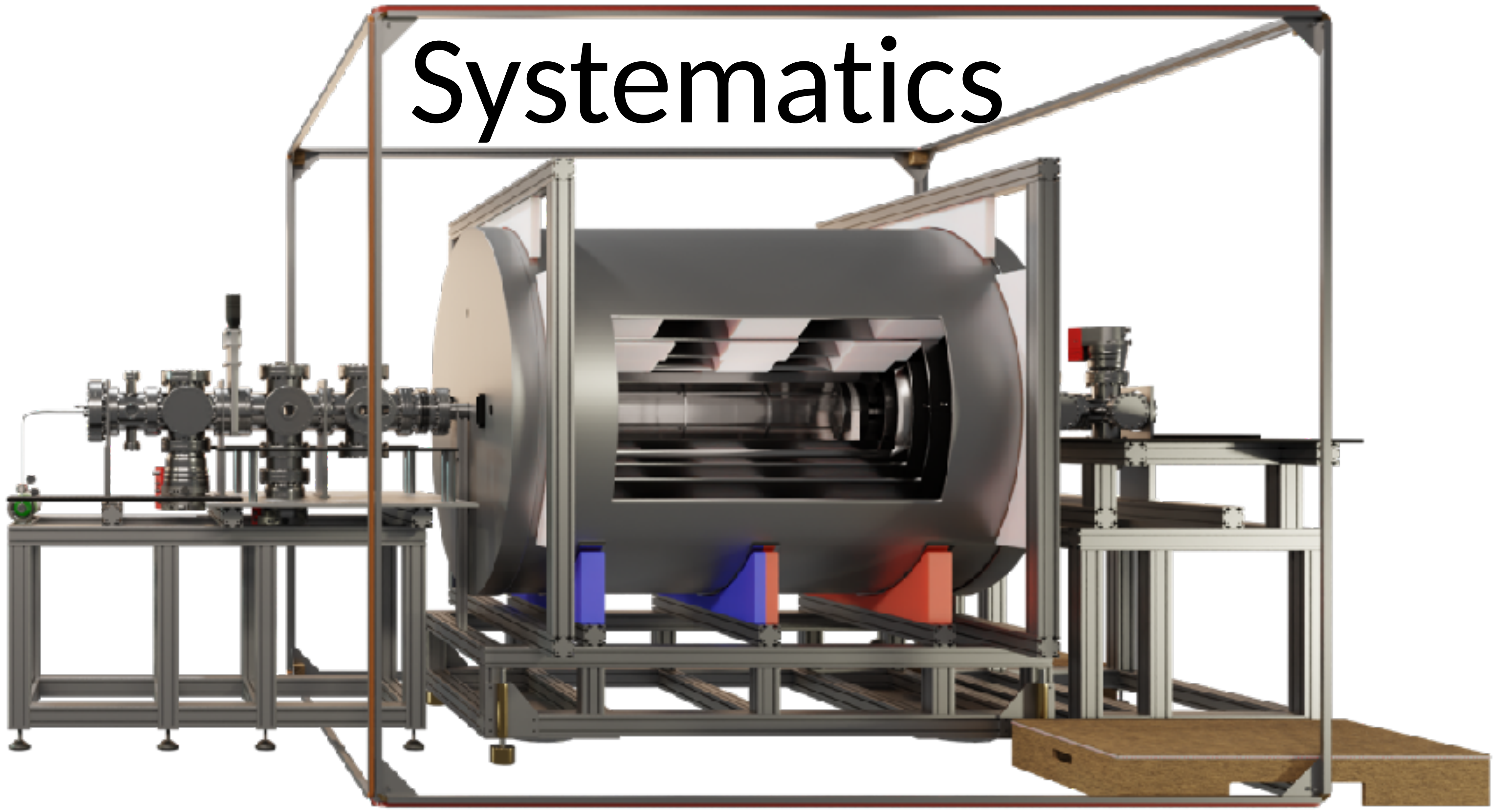
Fast beam

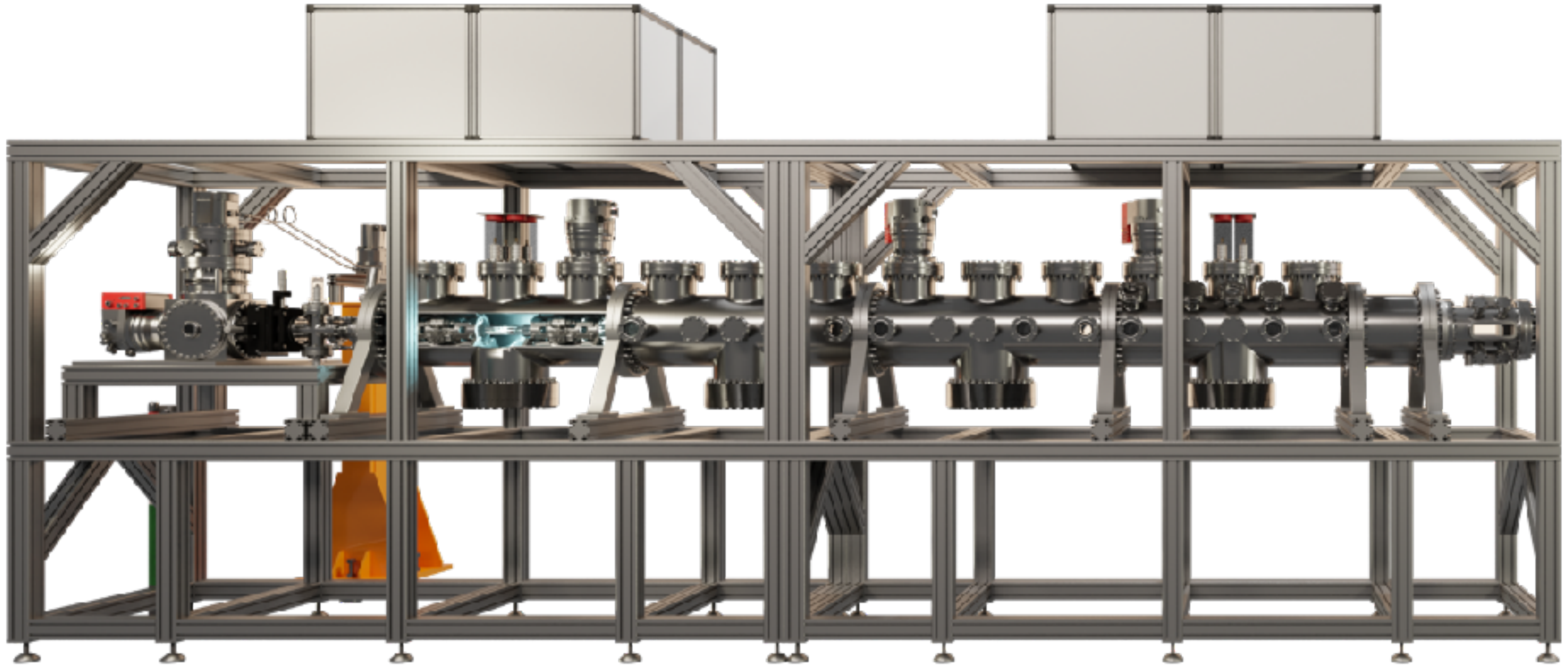
Supersonic beam (600 m/s)

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

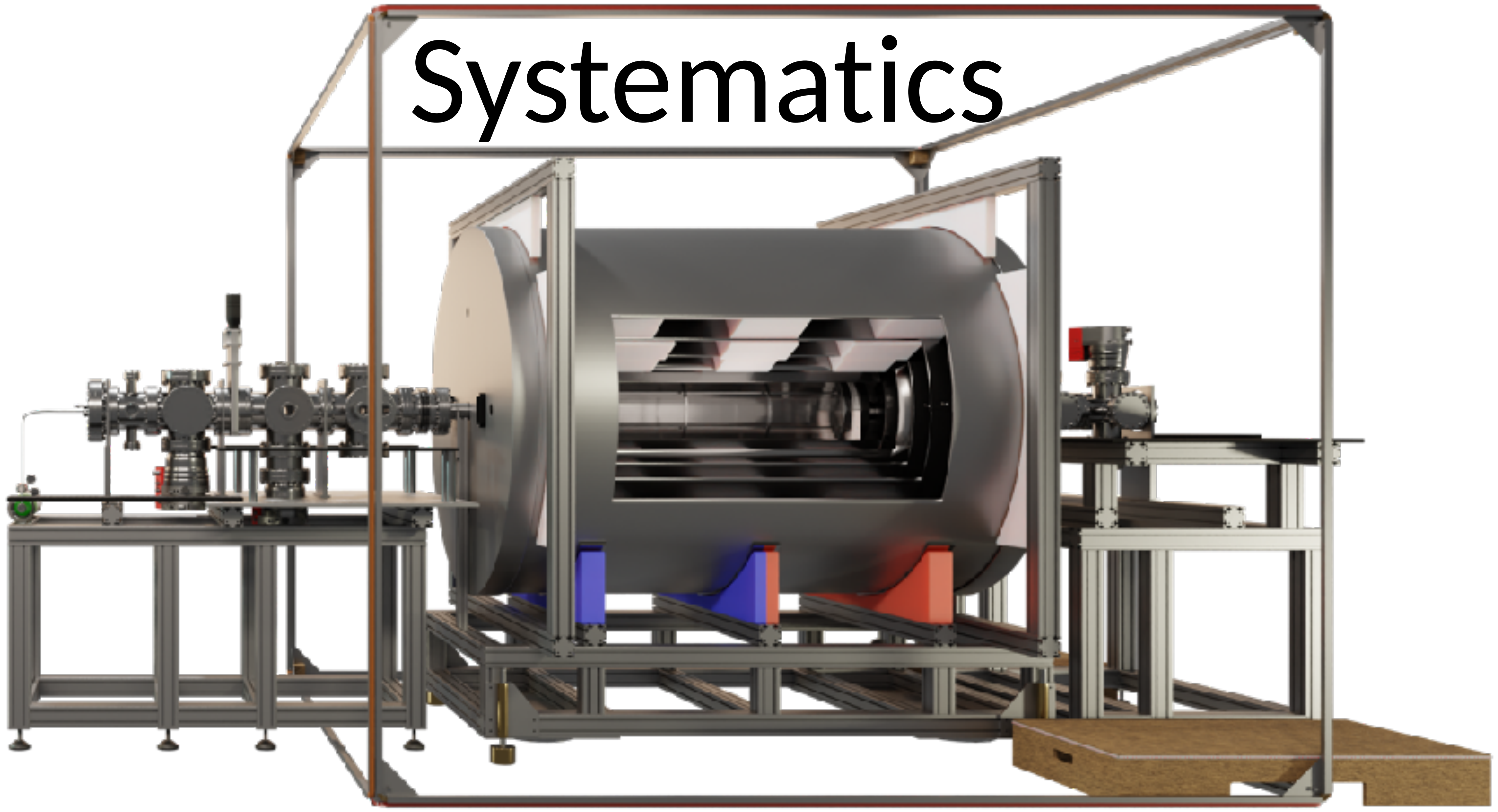
Fast beam

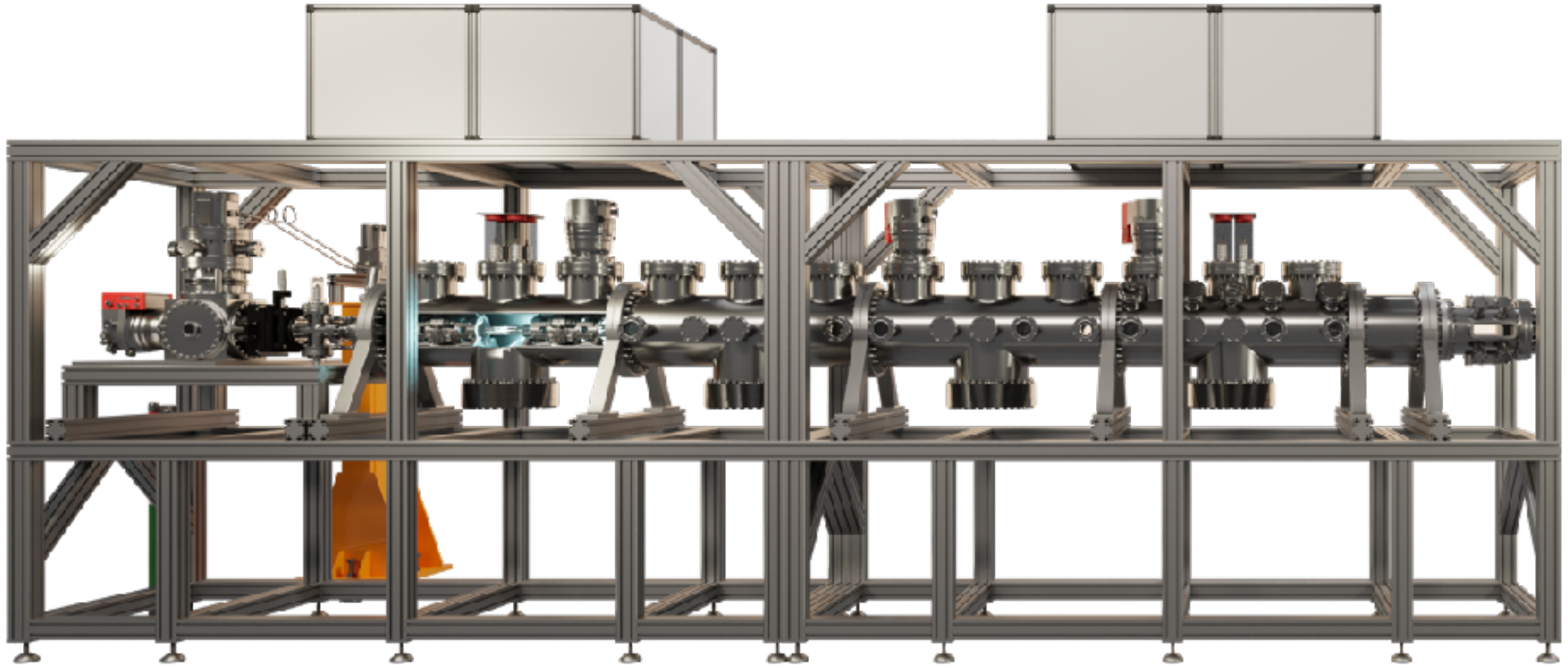
Supersonic beam (600 m/s)

Controlled field environment

Explored molecular structure

Spin interferometer measurement





Statistics

Slow beam

Cryogenic beam (200 m/s)

Stark decelerator (30 m/s)

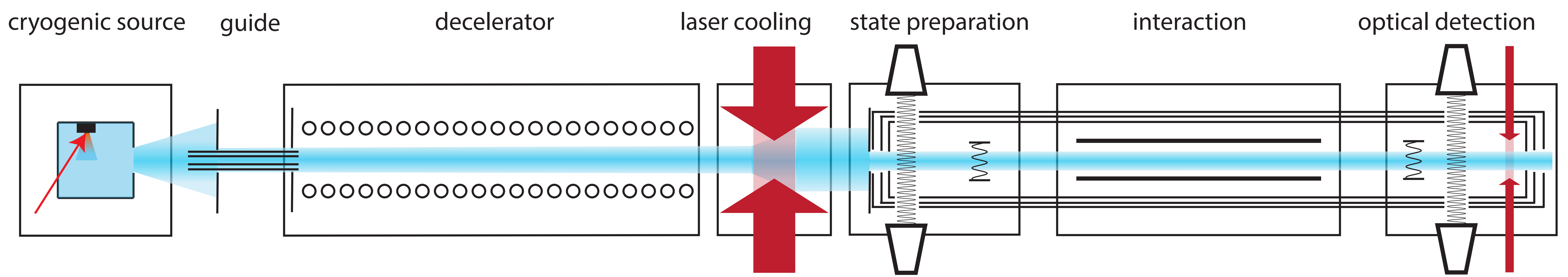
Cycling and lasercooling

An intense, slow and cold beam of molecules

Our approach

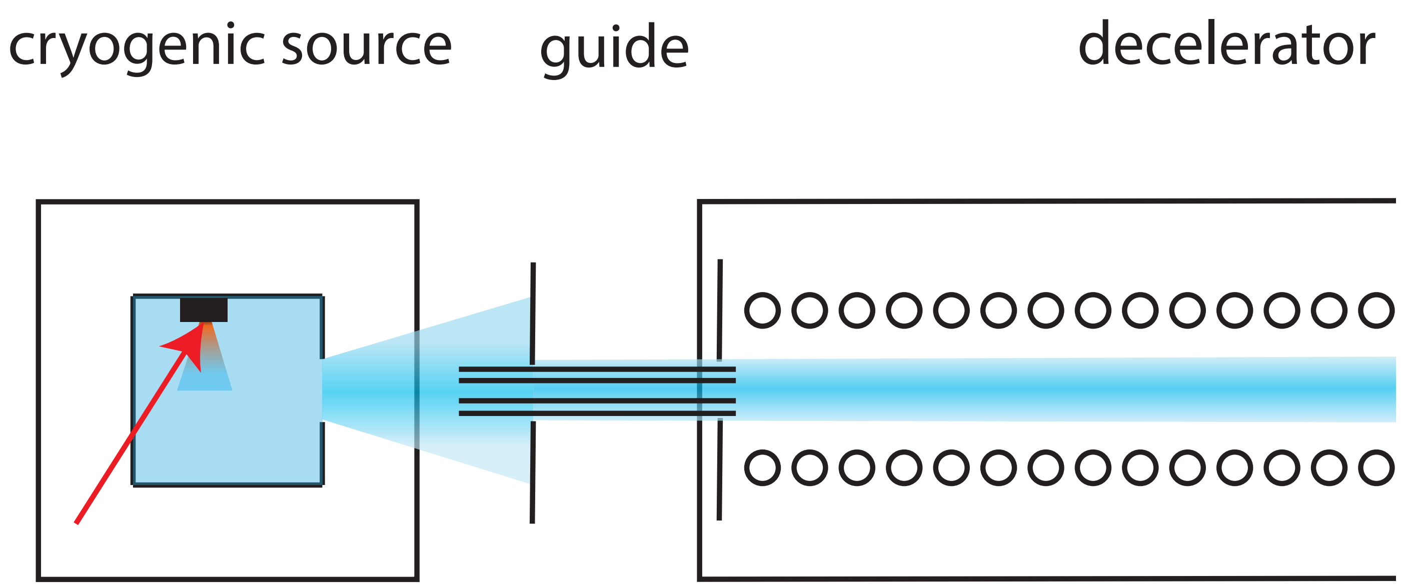
Combining three recent experimental breakthroughs

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

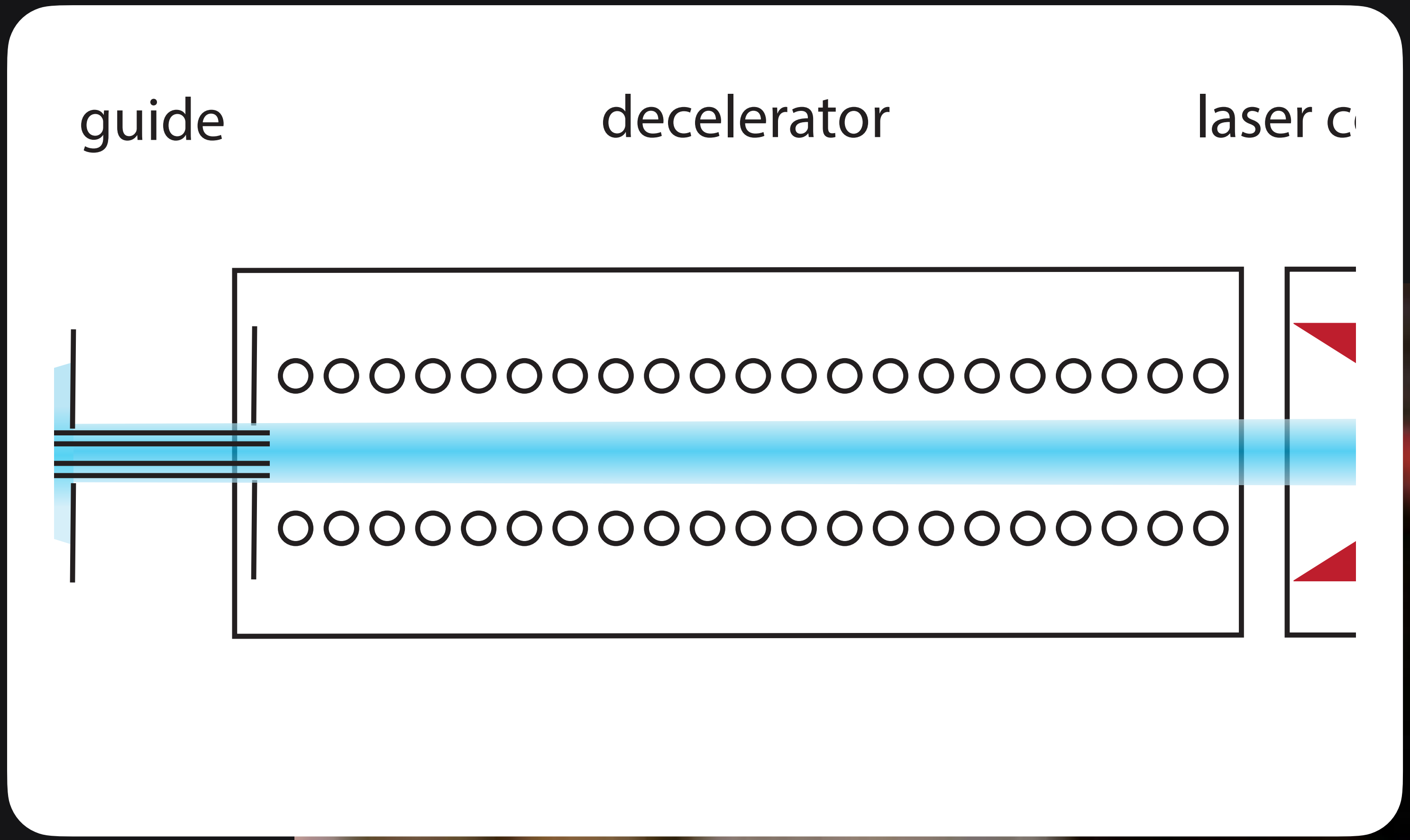
Aims:
- slow beam (~180 m/s)
- High N: $4x10^9$/shot in the desired state
- Use for eEDM measurement

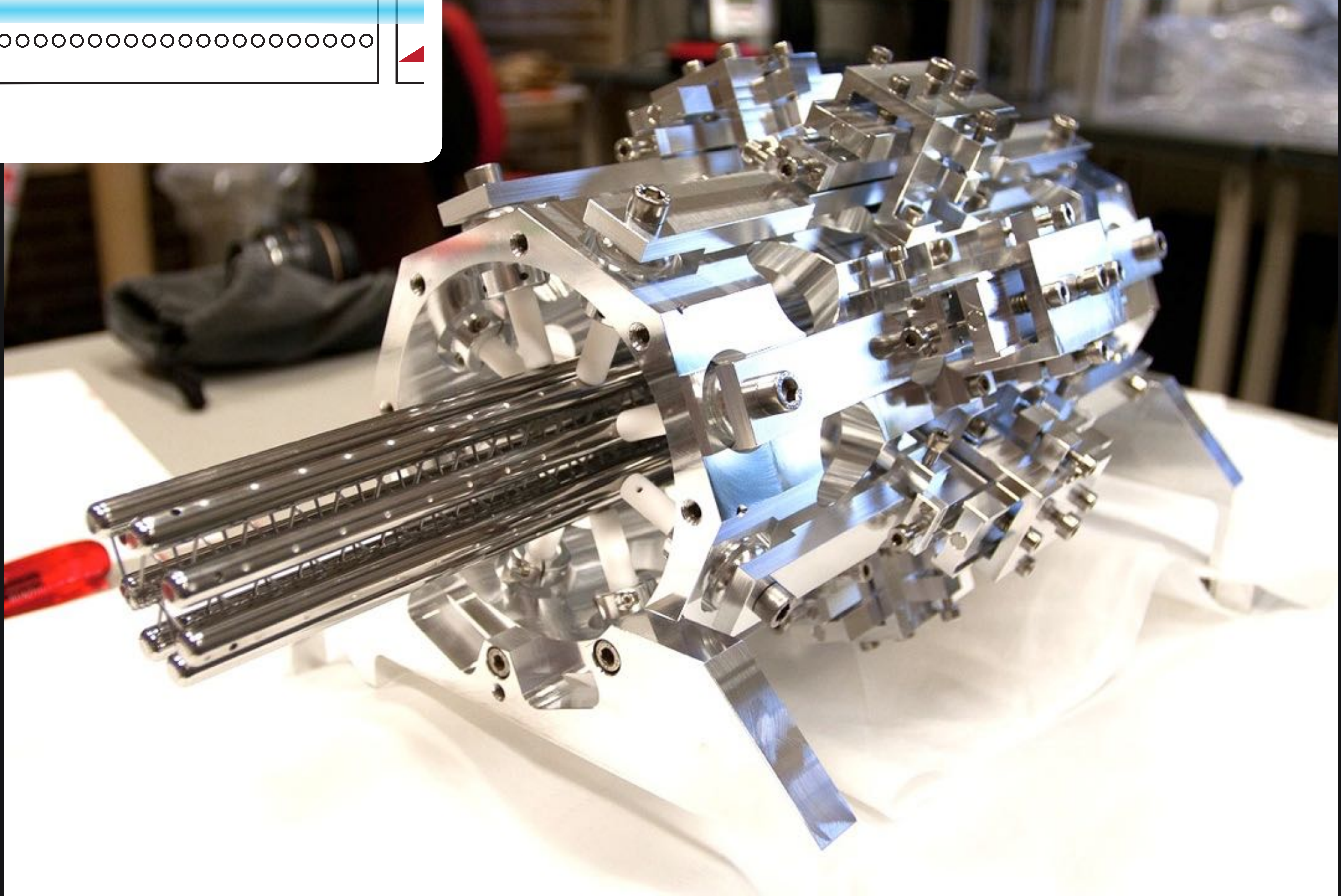
A slow beam of molecules

Molecule deceleration

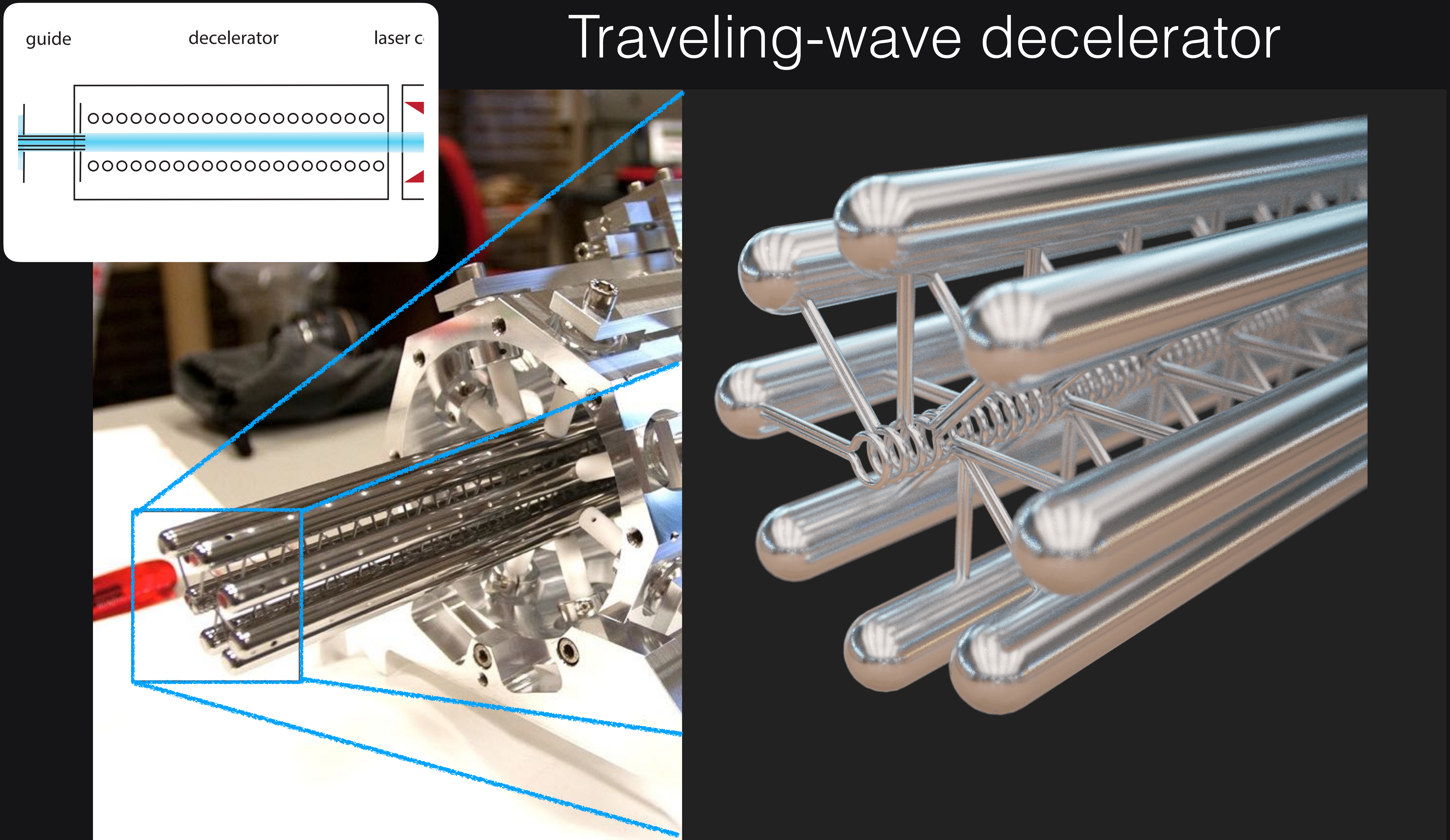
A traveling-wave with a tunable velocity

Traveling-wave decelerator

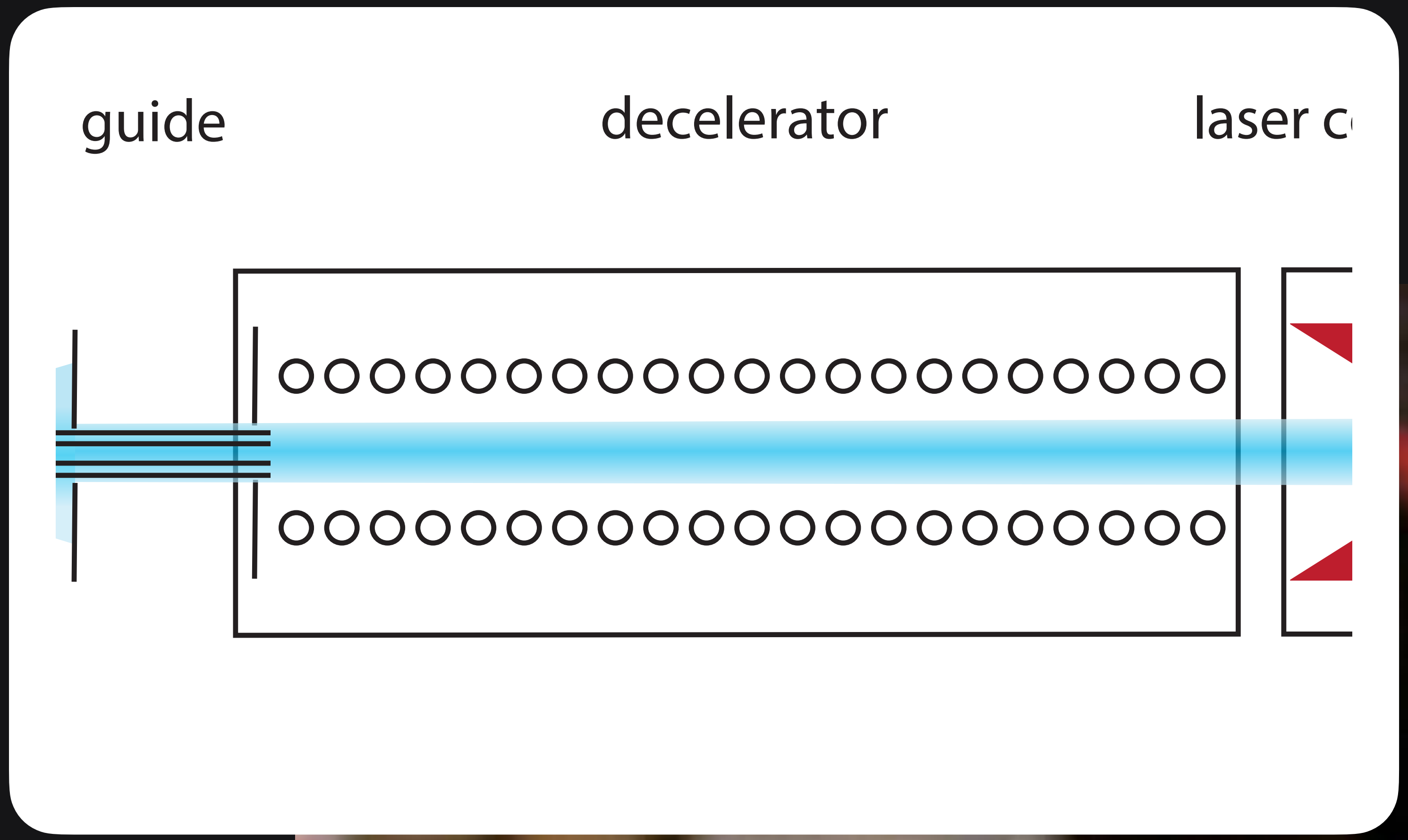


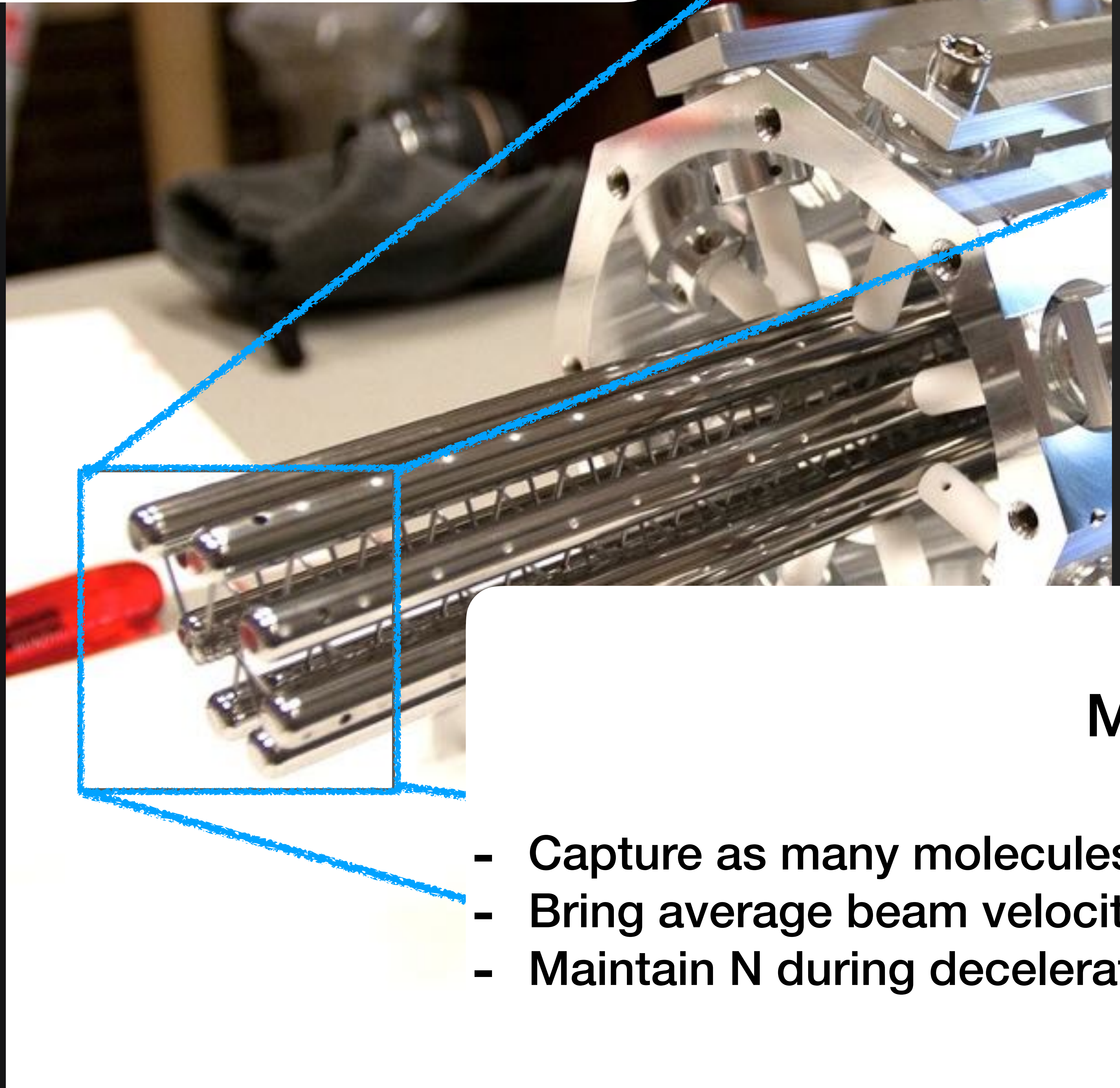


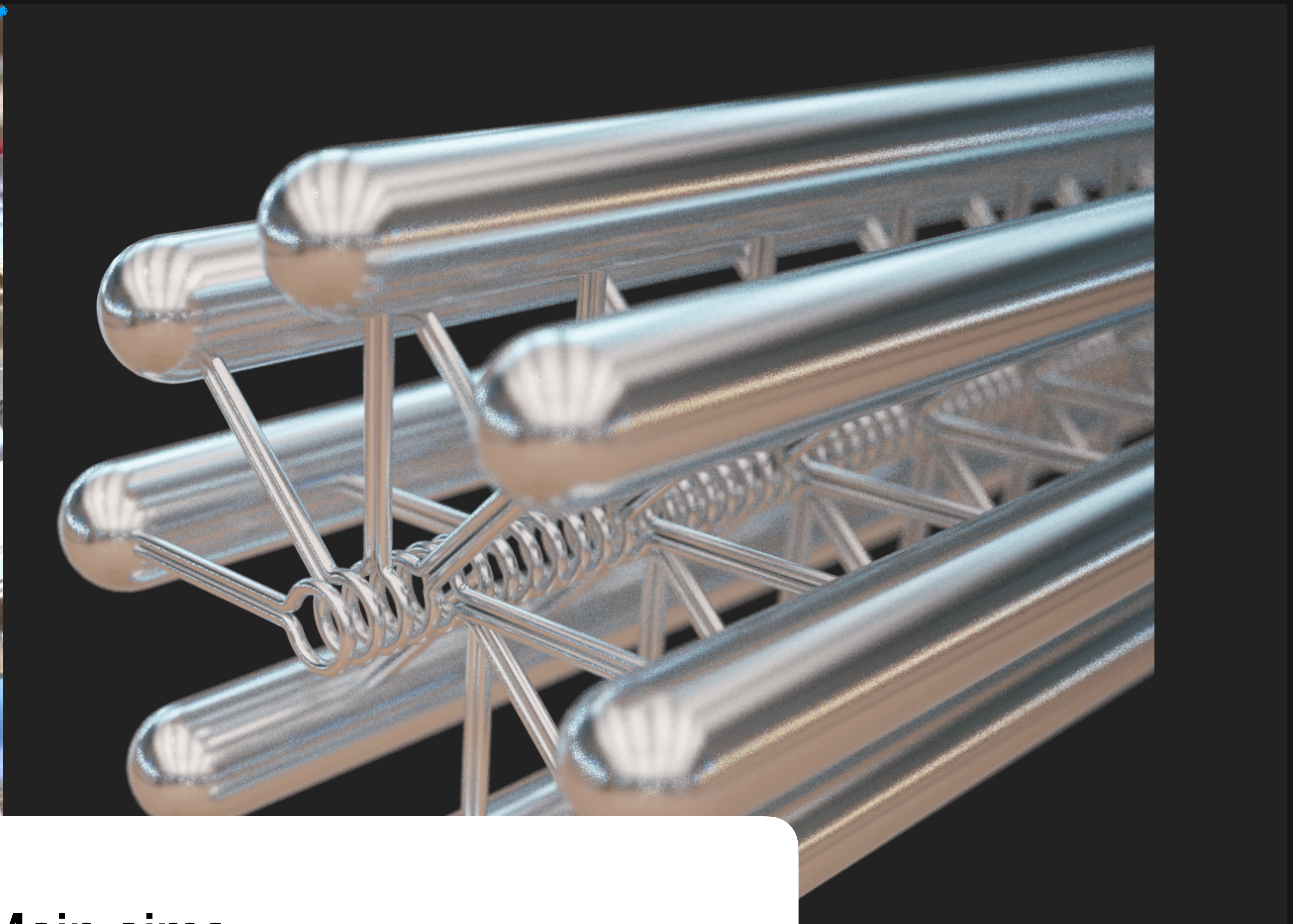
Traveling-wave decelerator



Traveling-wave decelerator



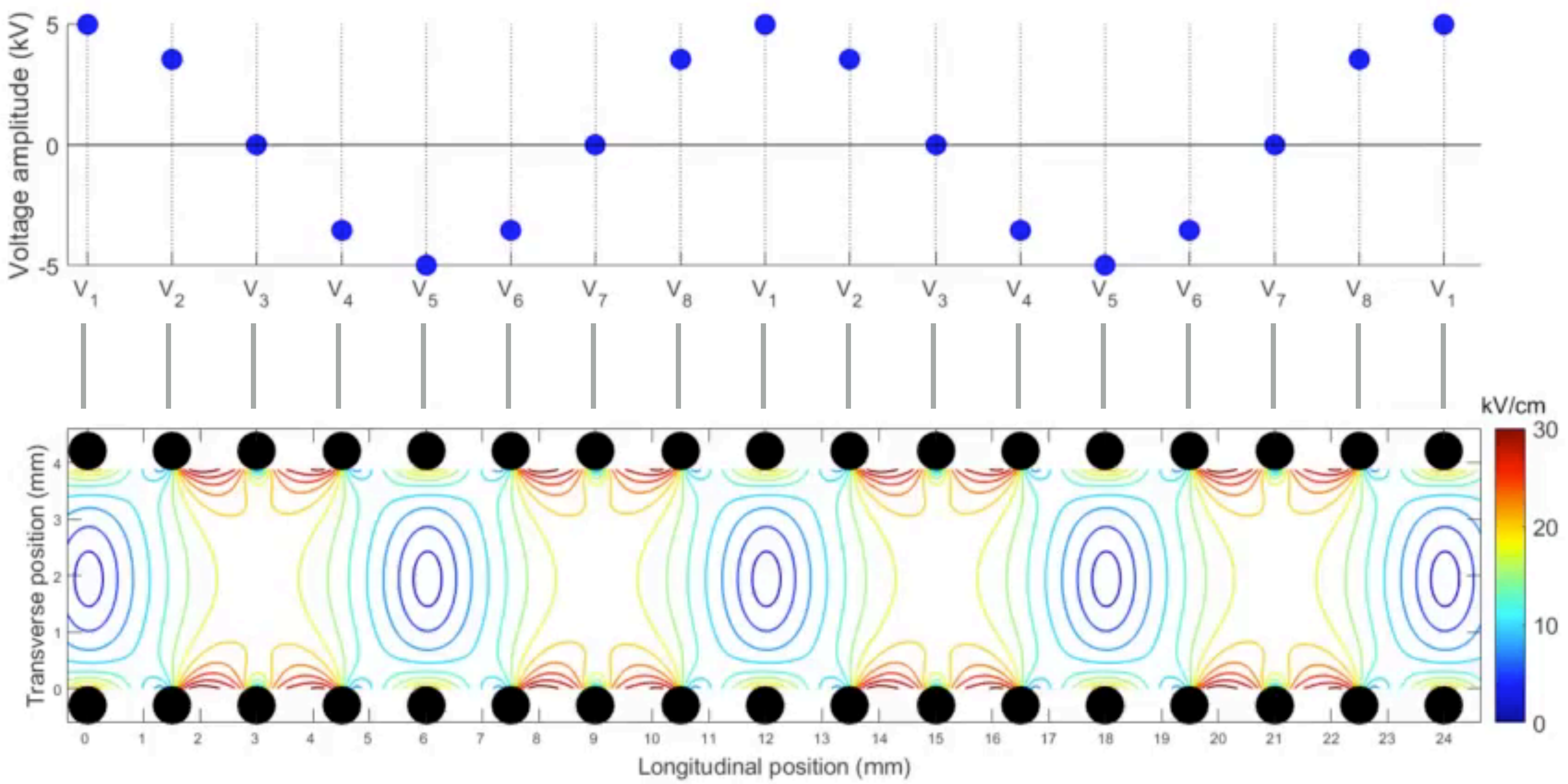




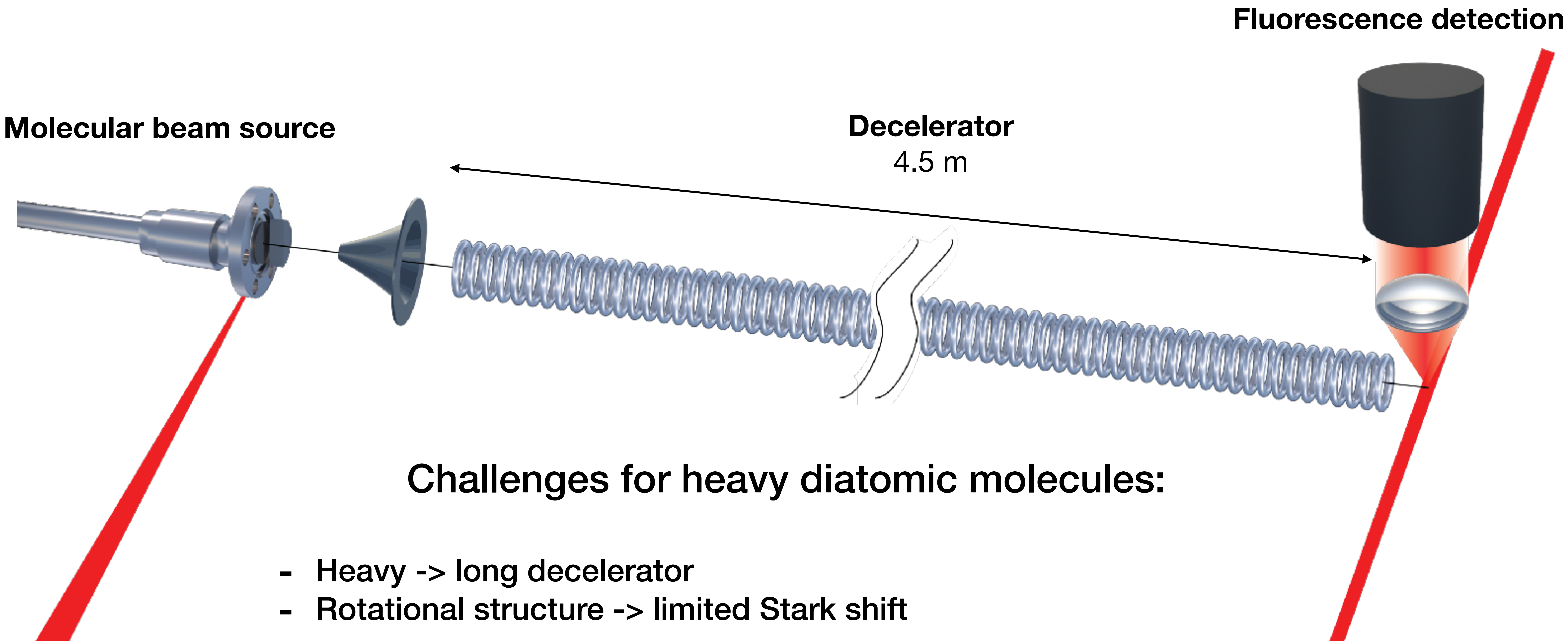
Main aims:

- 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



Traveling-wave decelerator



Challenges for heavy diatomic molecules:

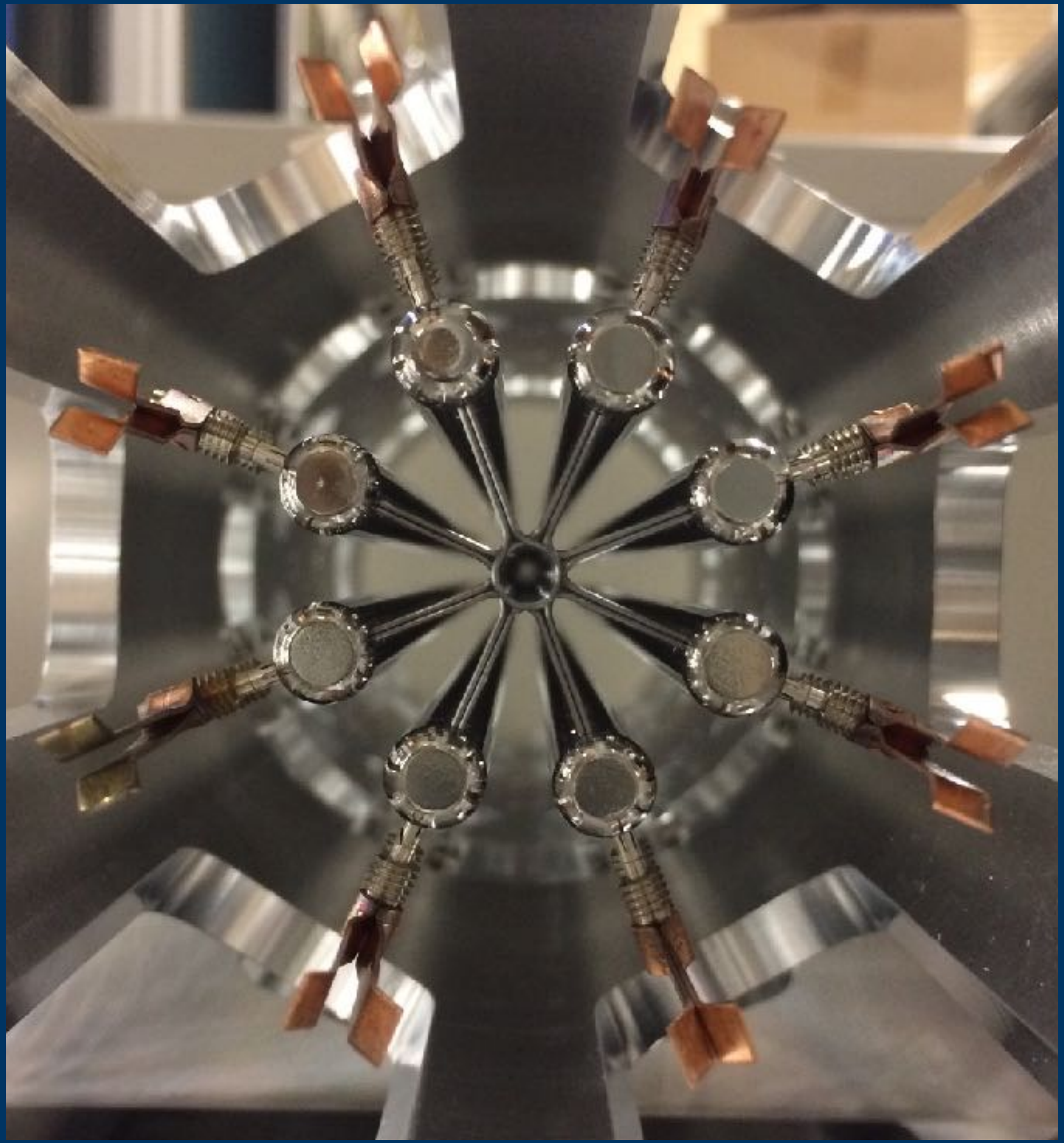
- Heavy -> long decelerator
- Rotational structure -> limited Stark shift

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)

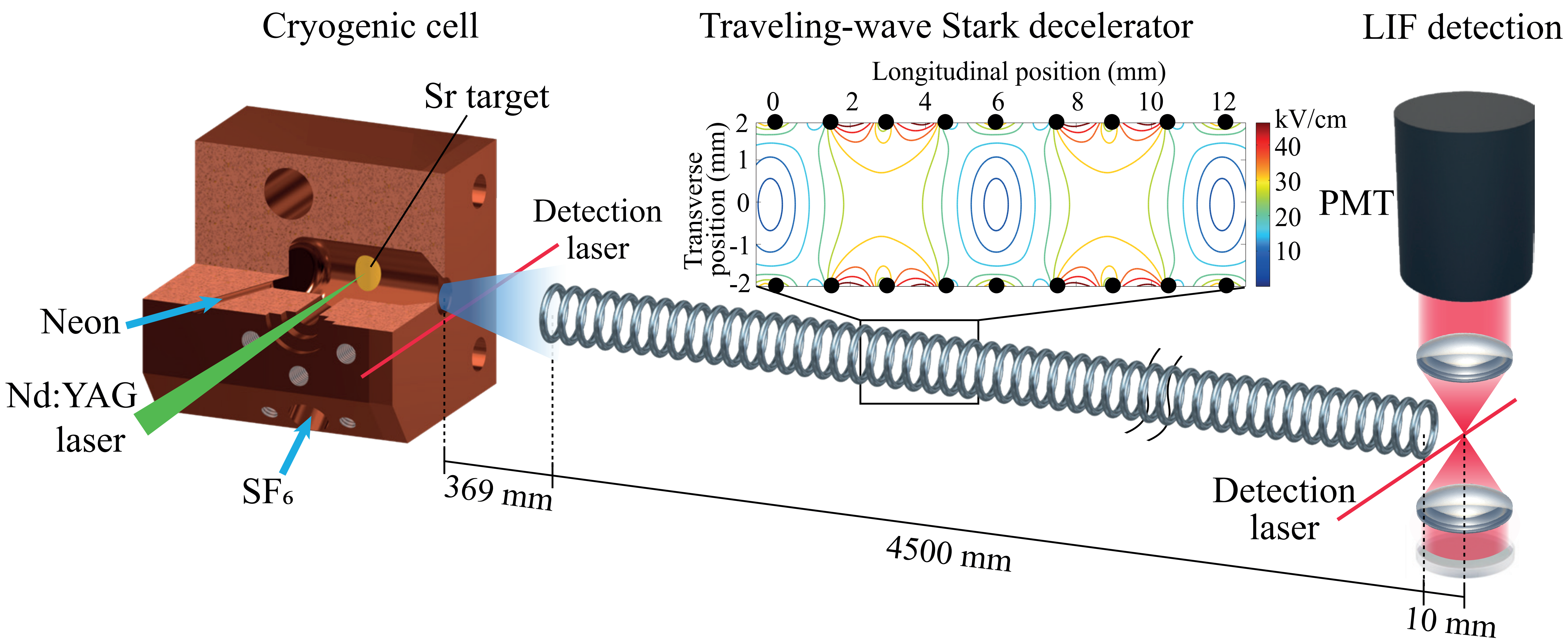
Modular traveling-wave decelerator

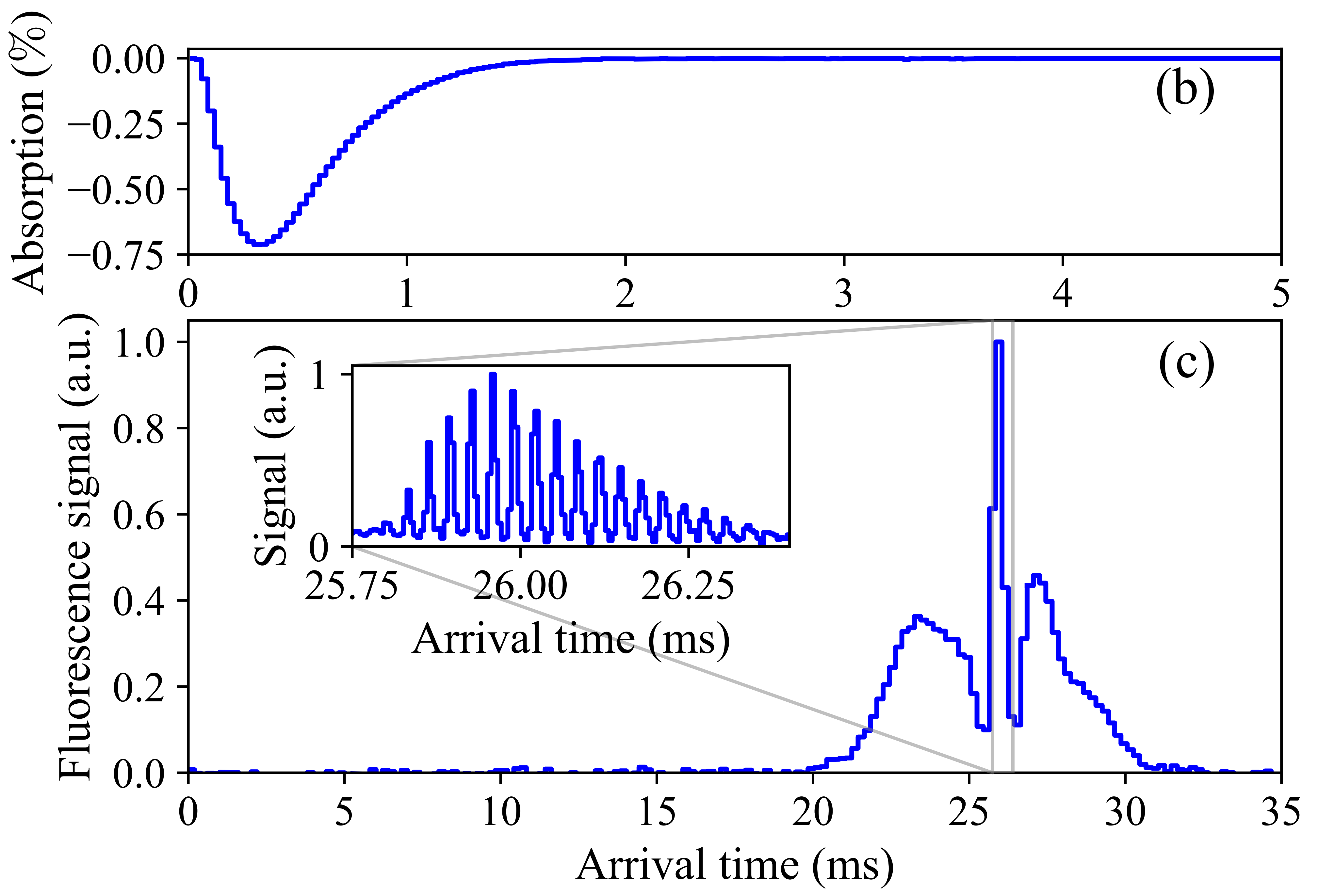


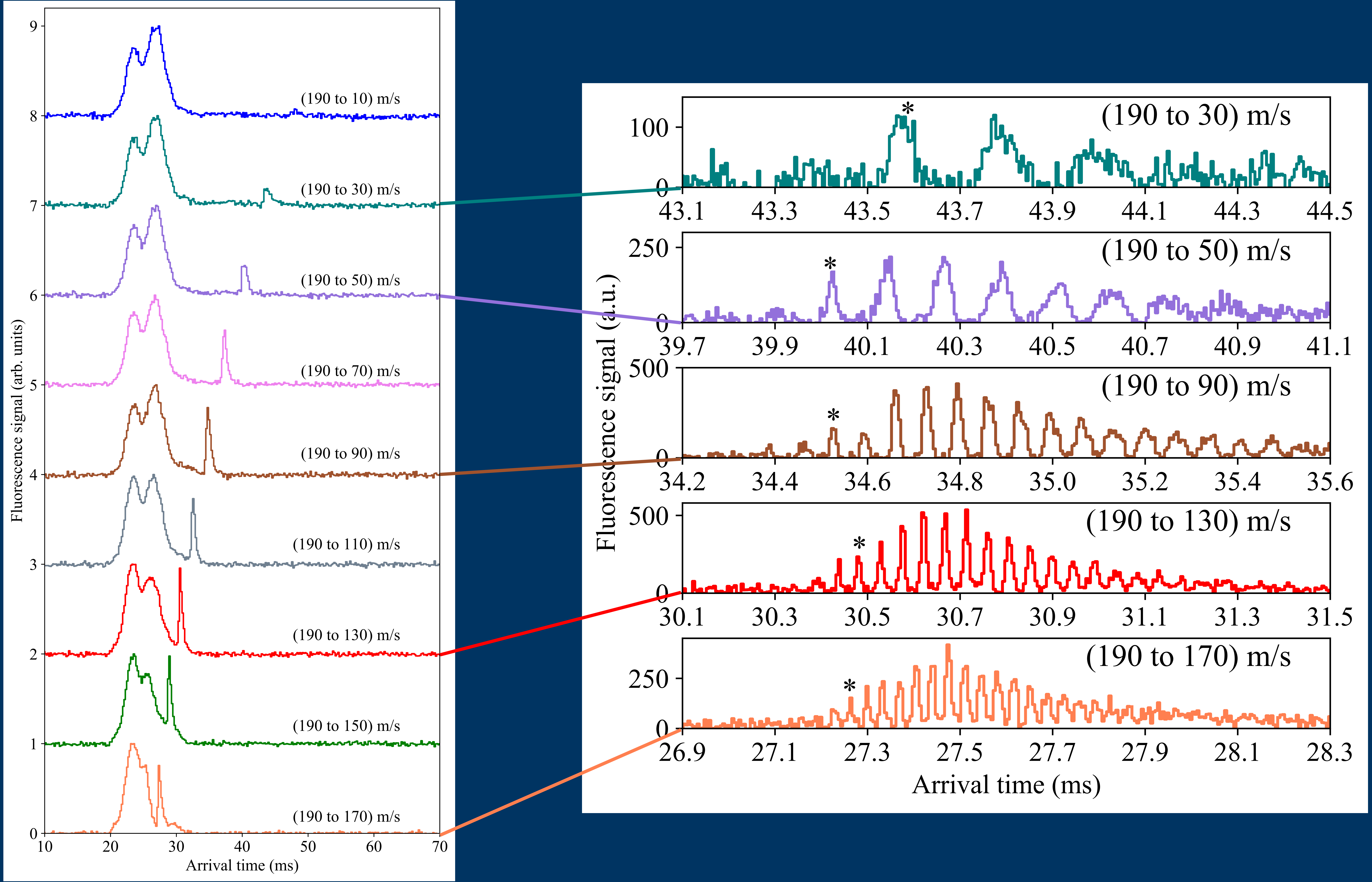
Traveling-wave decelerator

A slow beam of molecules

SrF: First combination of deceleration and cryogenic source





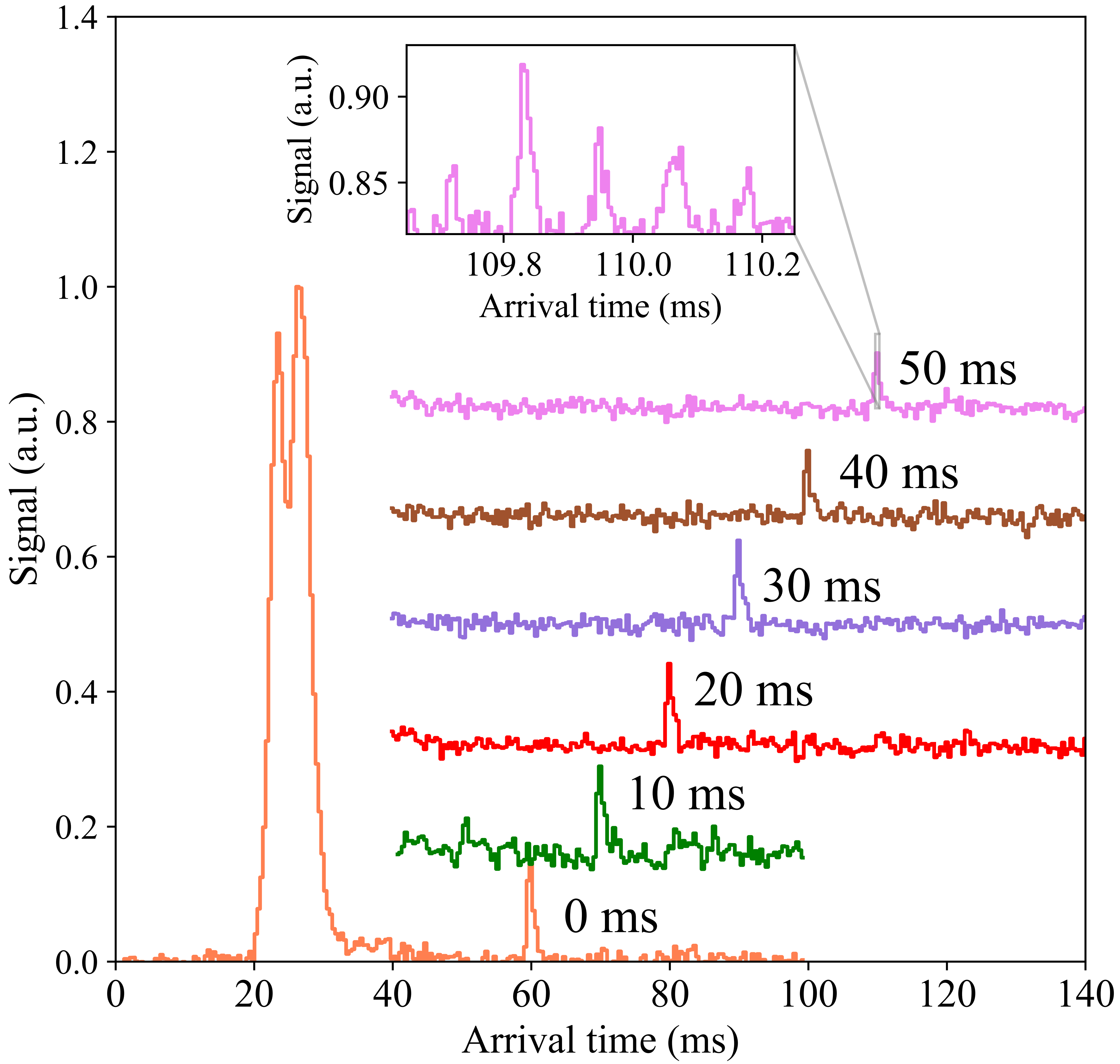


Fluorescence signal (arb. units)
Arrival time (ms)
(190 to 10) m/s
(190 to 30) m/s
(190 to 50) m/s
(190 to 70) m/s
(190 to 90) m/s
(190 to 110) m/s
(190 to 130) m/s
(190 to 150) m/s
(190 to 170) m/s
Fluorescence signal (a.u.)
(190 to 30) m/s
(190 to 50) m/s
(190 to 90) m/s
(190 to 130) m/s
(190 to 170)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

Great! Let’s do a supersensitive eEDM measurement!

Challenge 1: the electric fields needed to hold the molecules in the trap interfere with the eEDM measurement….

OK, let’s make a slow beam for now.

Challenge 2: if you decelerate molecules without cooling them, they spread out on their way to the eEDM measurement

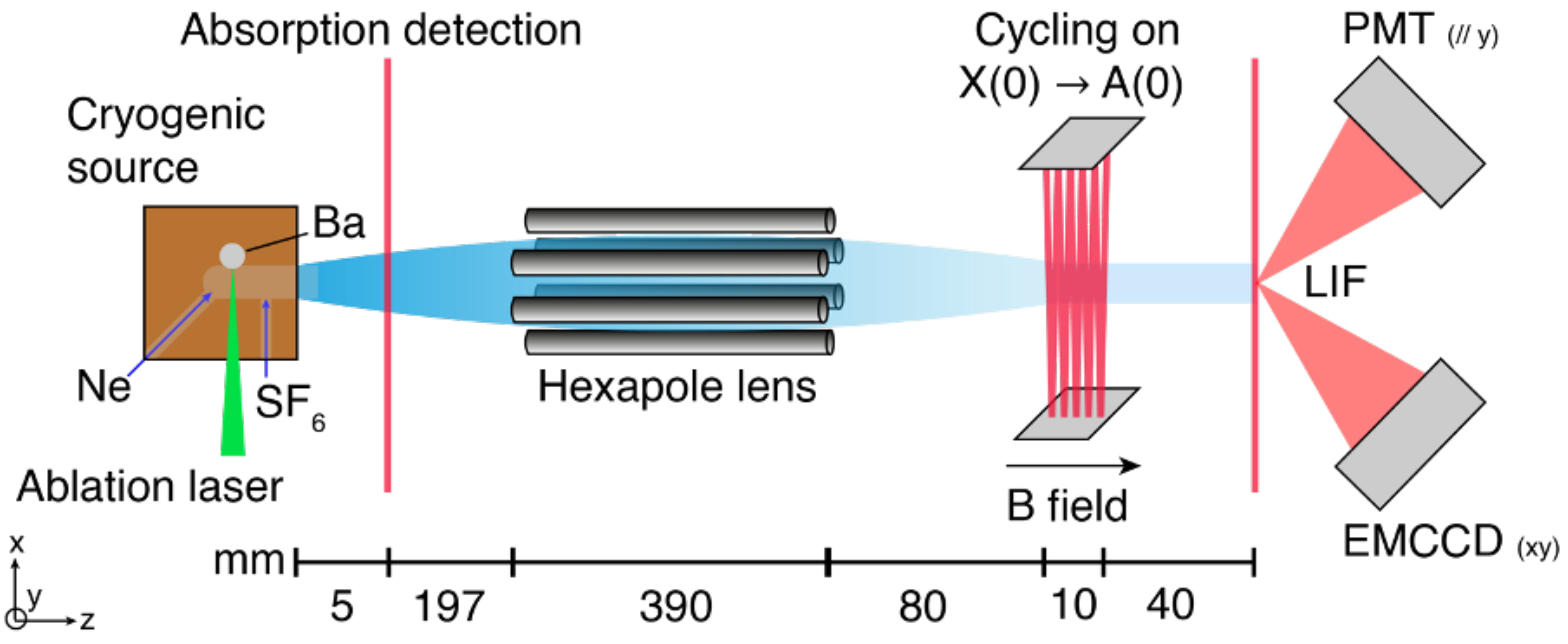
…

and you have not gained anything!

Hexapole focusing

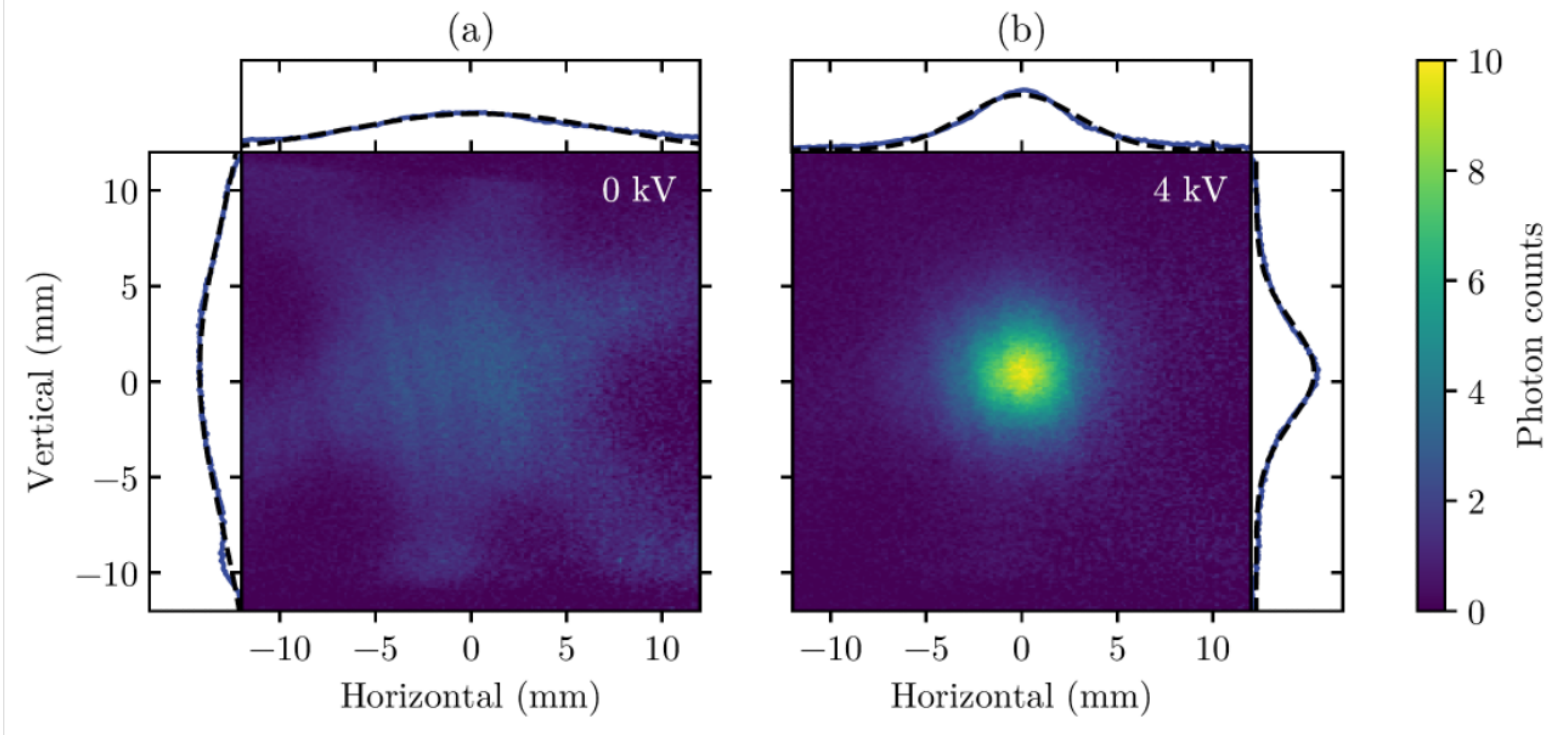
In combination with laser cooling

2D transverse laser cooling of a hexapole focused beam of cold BaF molecules, arXiv:2506.19069 (june 2025)



A hexapole electrostatic lens

CCD camera images the molecular beam



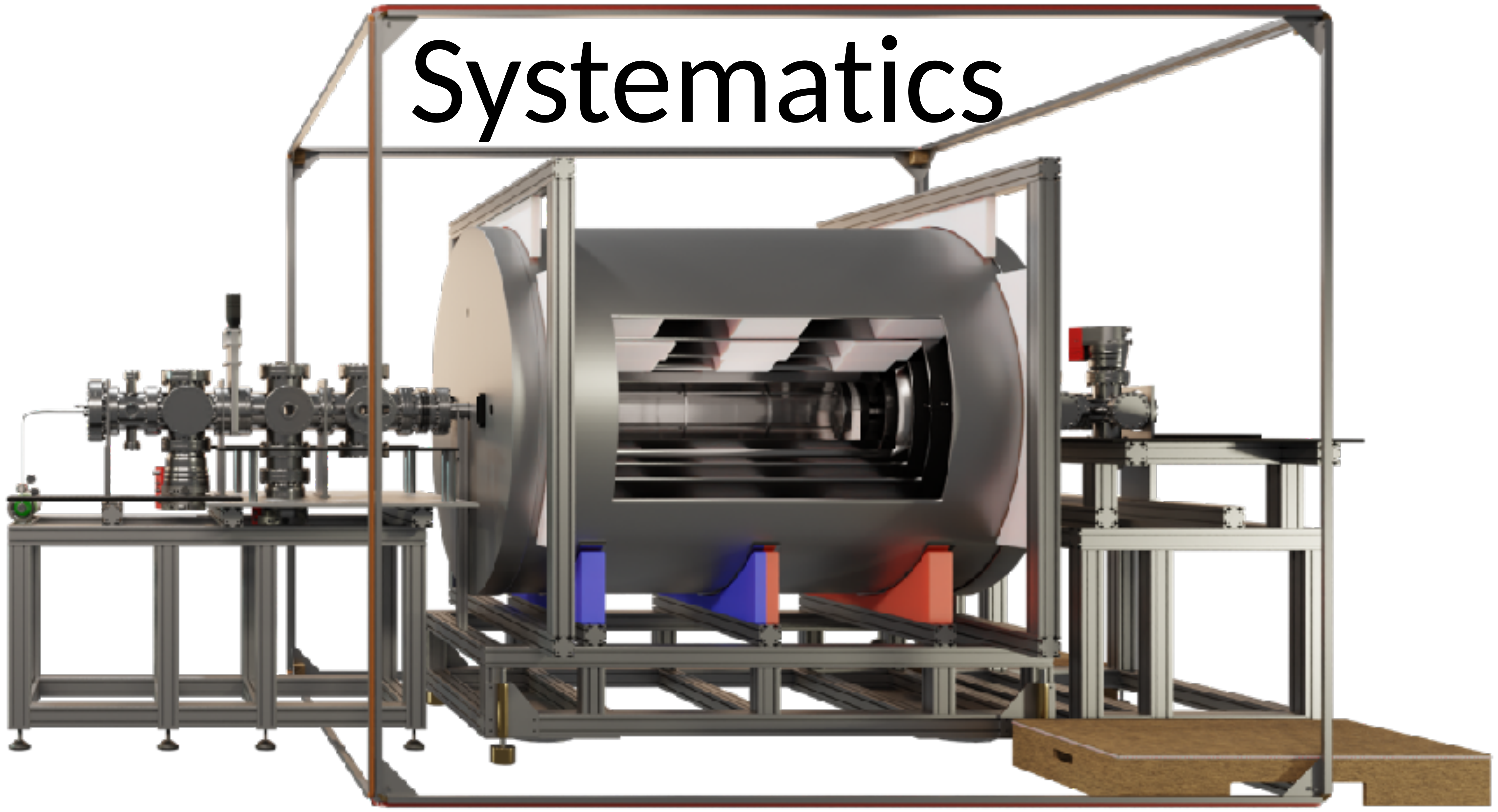
Fast beam

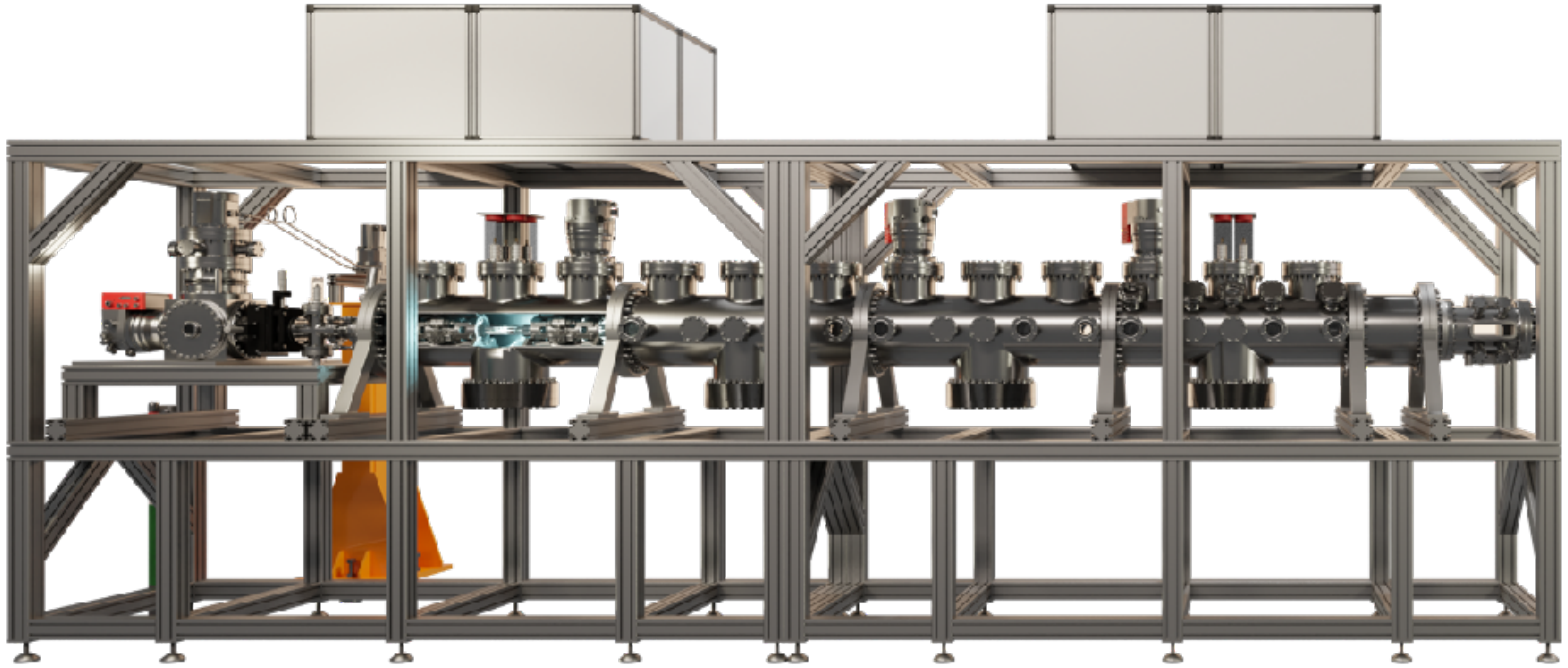
Supersonic beam (600 m/s)

Controlled field environment

Explored molecular structure

Spin interferometer measurement





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Slow beam

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Fast beam

Supersonic beam (600 m/s)

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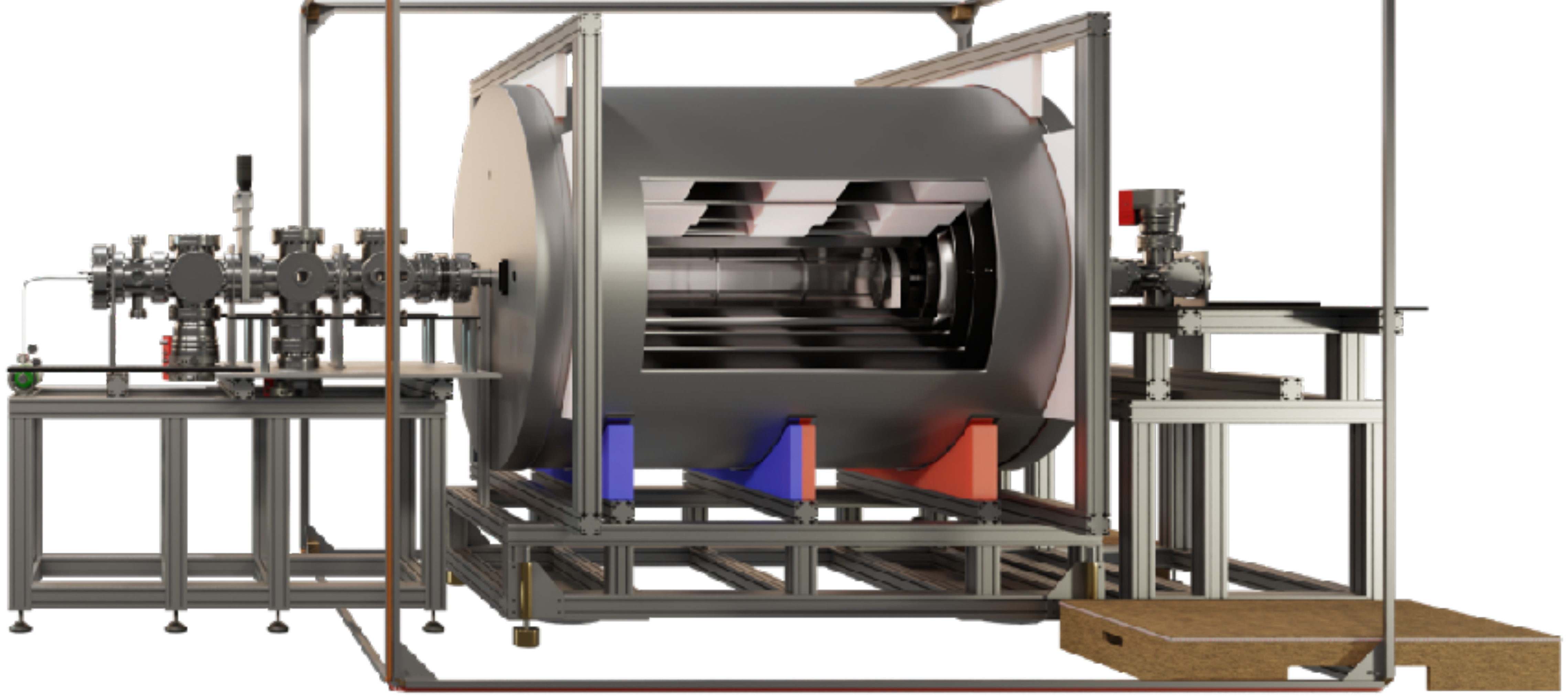
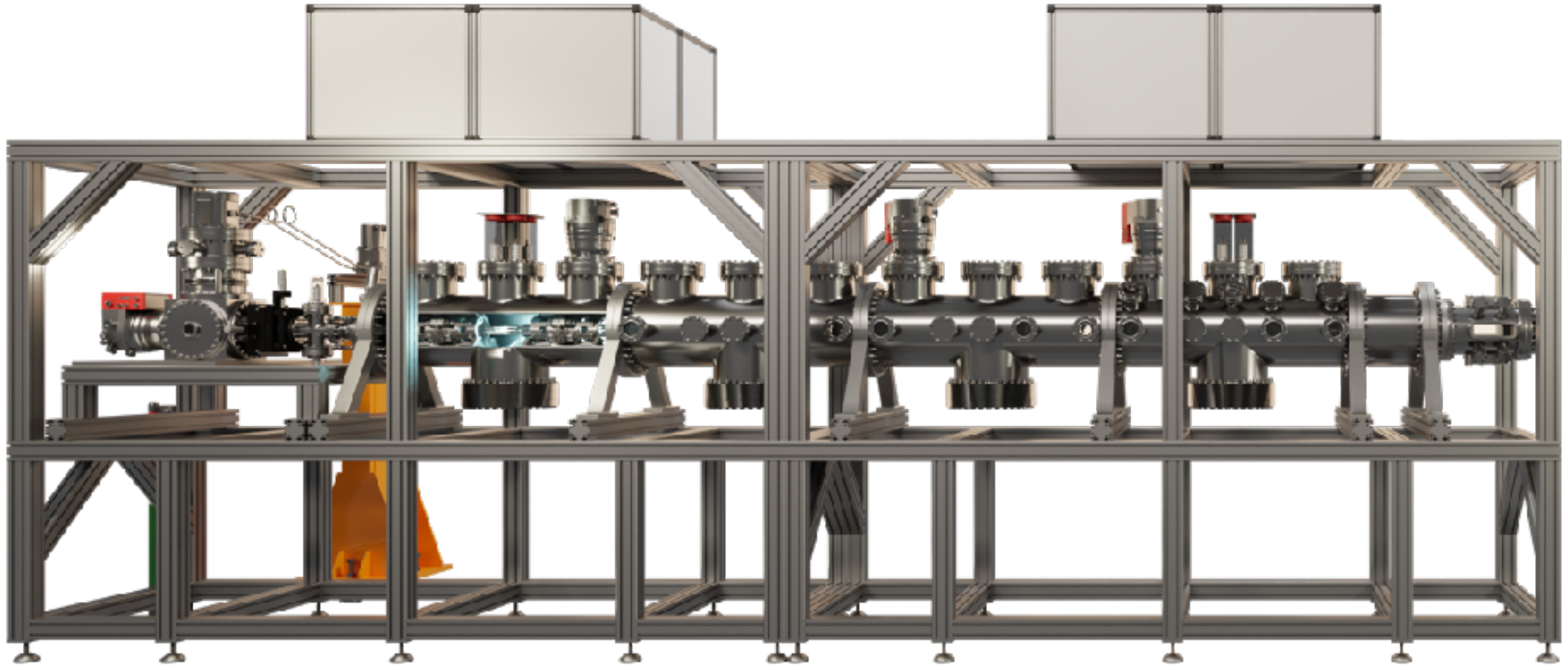
Spin interferometer measurement

Systematics





Statistics

Slow beam

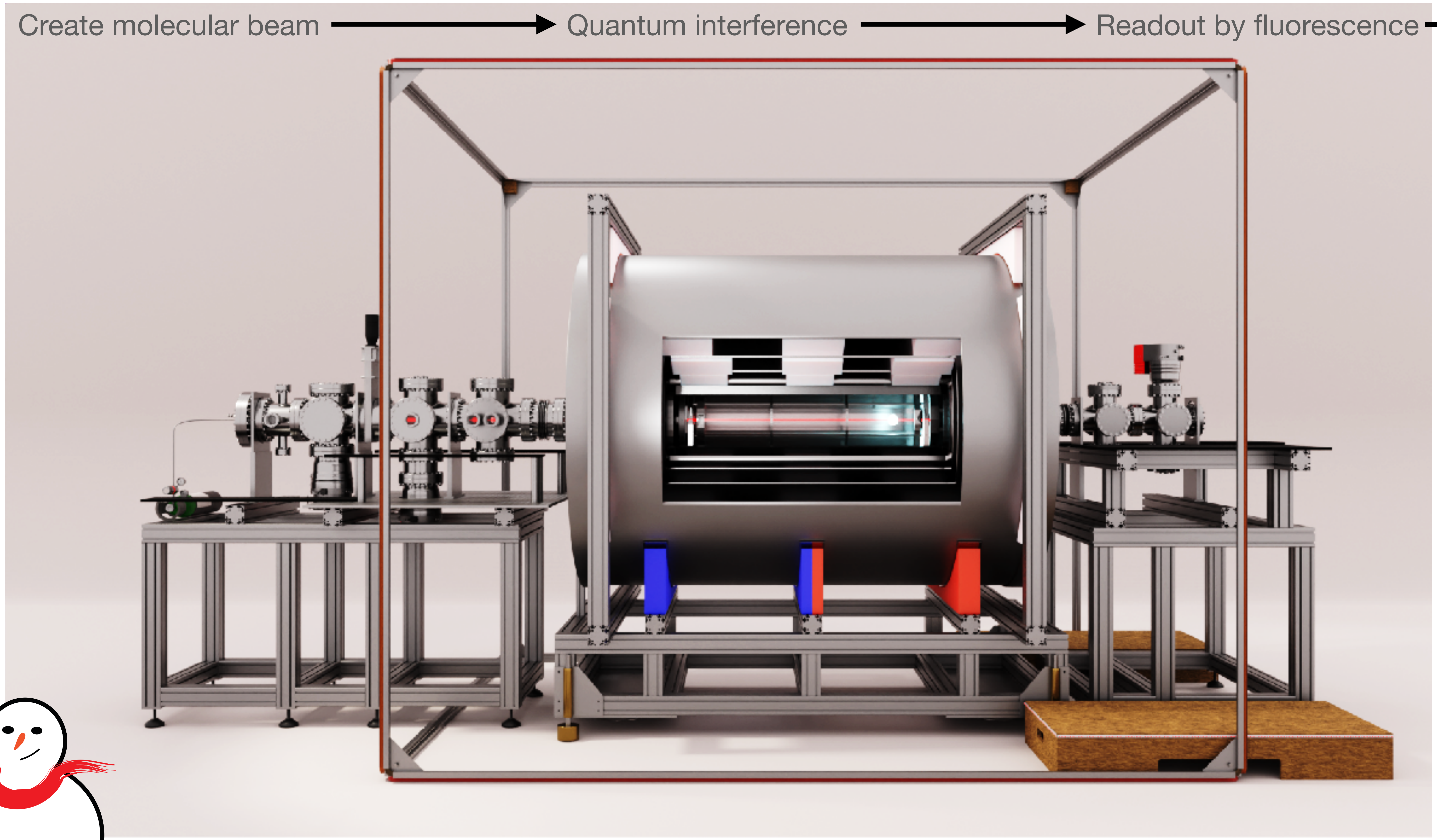
Cryogenic beam (200 m/s)

Stark decelerator (30 m/s)

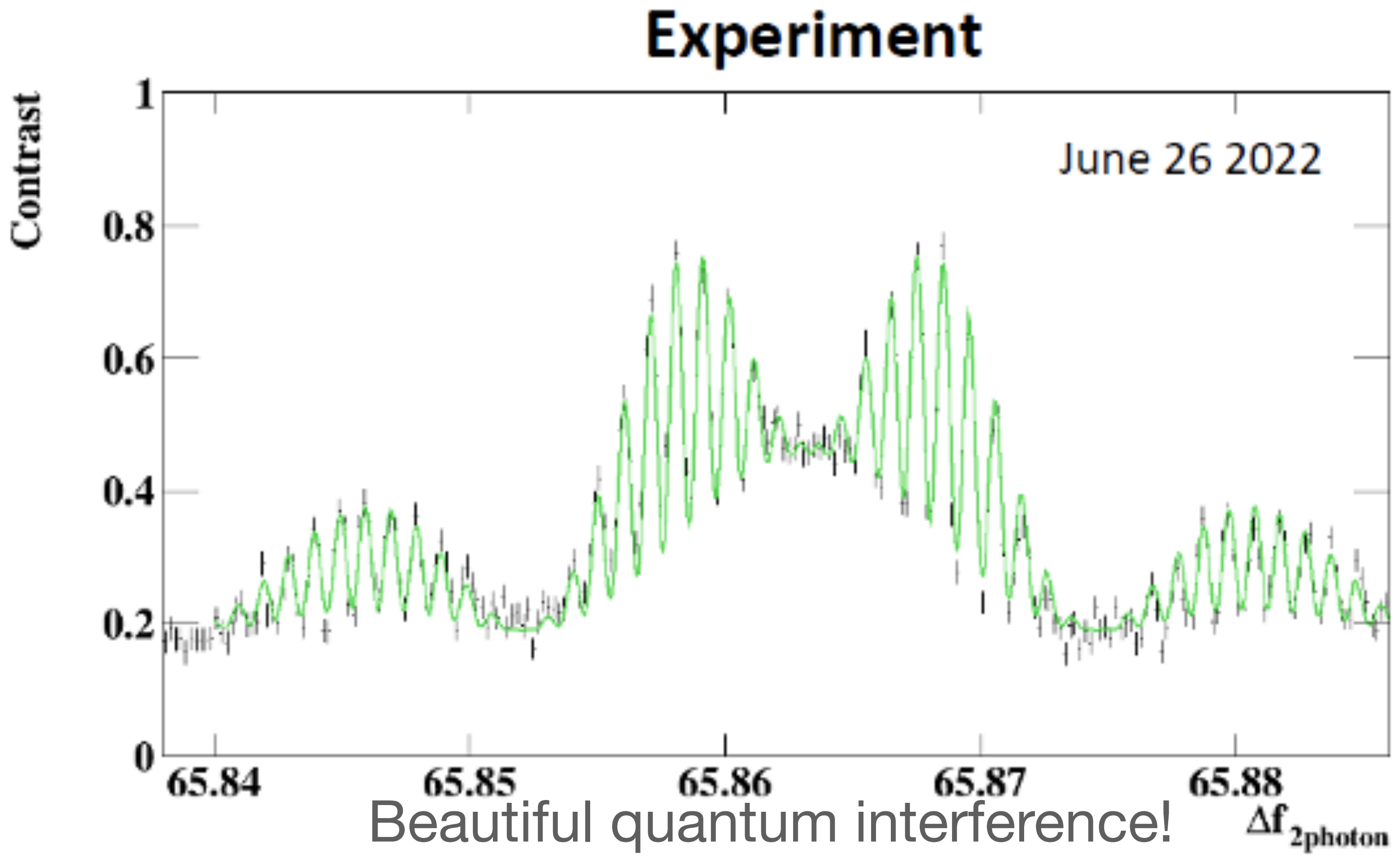
Cycling and lasercooling

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)

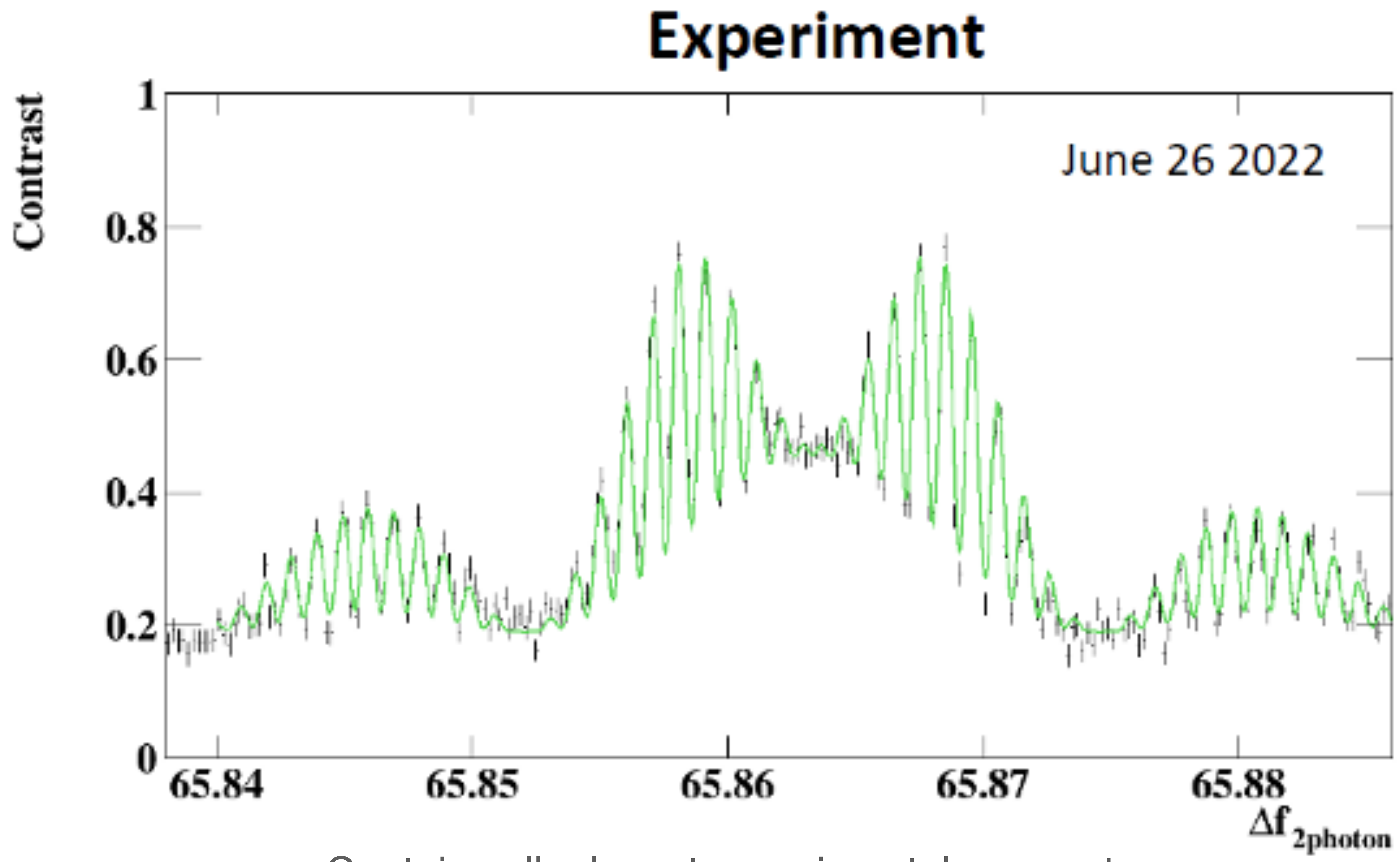


Beautiful quantum interference!

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

NL-eEDM

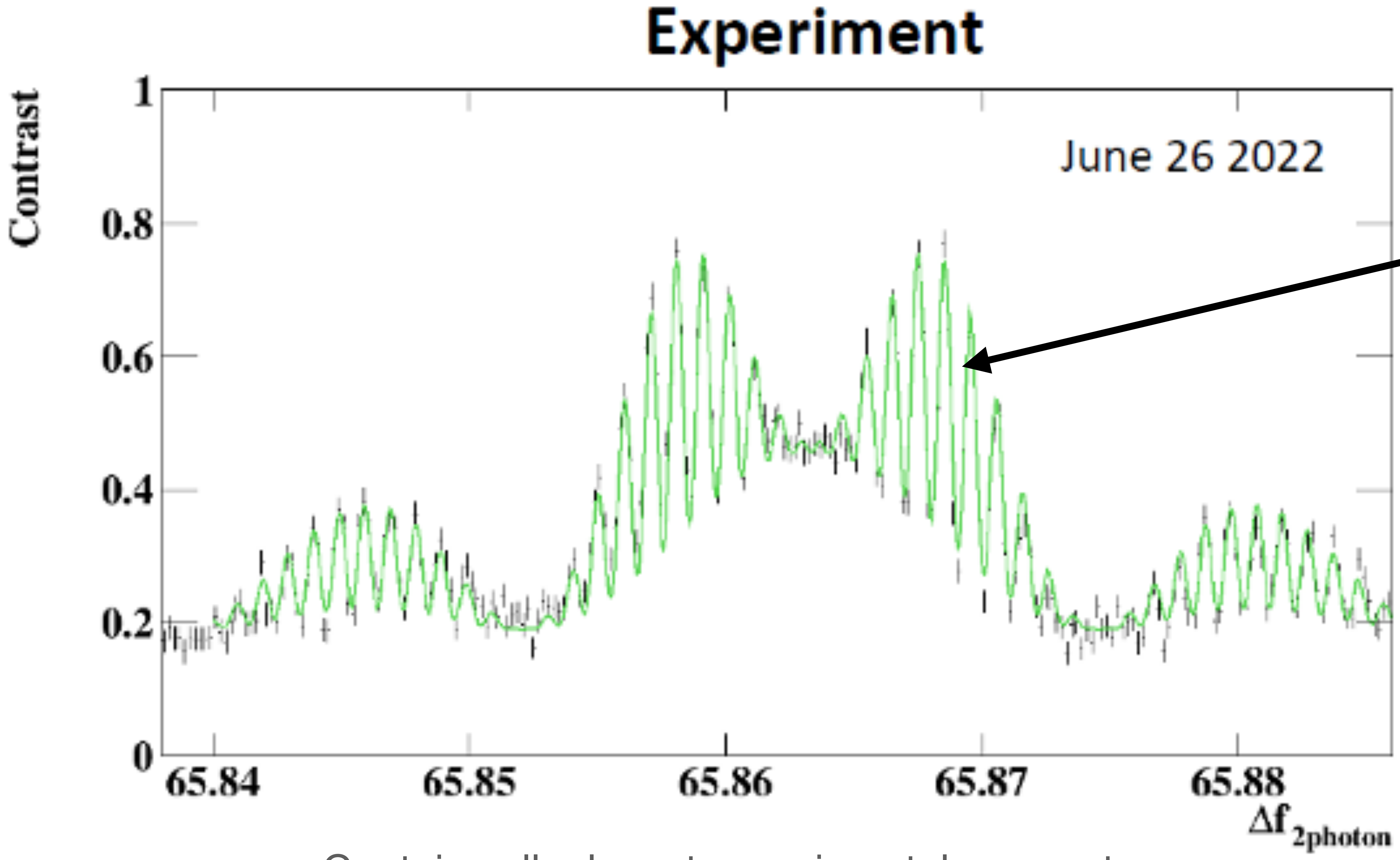
Measured interference pattern



Laser detuning (MHz)

Contains all relevant experimental parameters
Crucial for reduction of systematic effects

Measured interference pattern



Laser detuning (MHz)

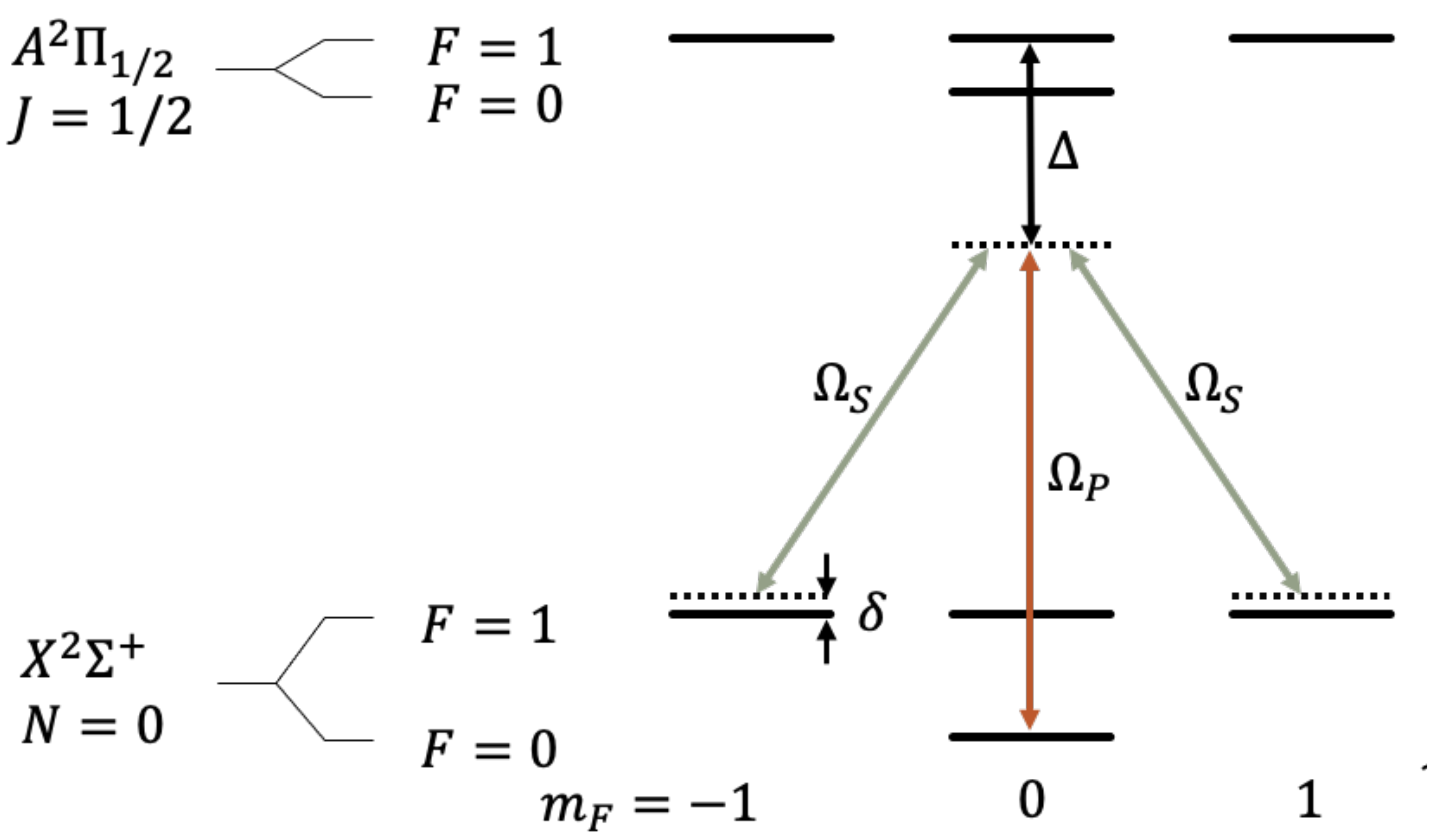
When flipping E-field direction, this pattern will change.

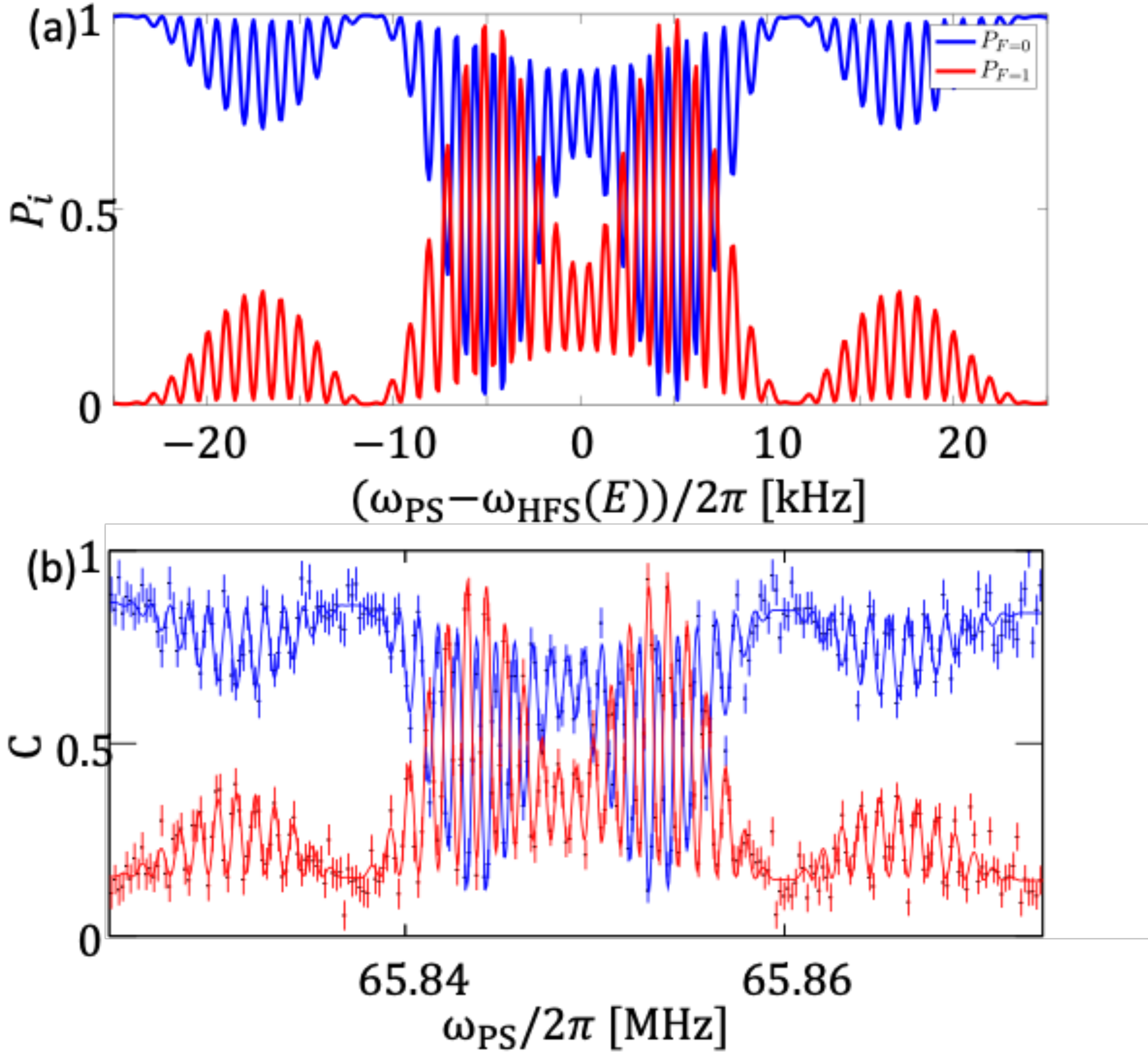
Slow beam, more molecules
->
higher eEDM sensitivity

Contains all relevant experimental parameters
Crucial for reduction of systematic effects

Experiment and theory

Optical Bloch equations

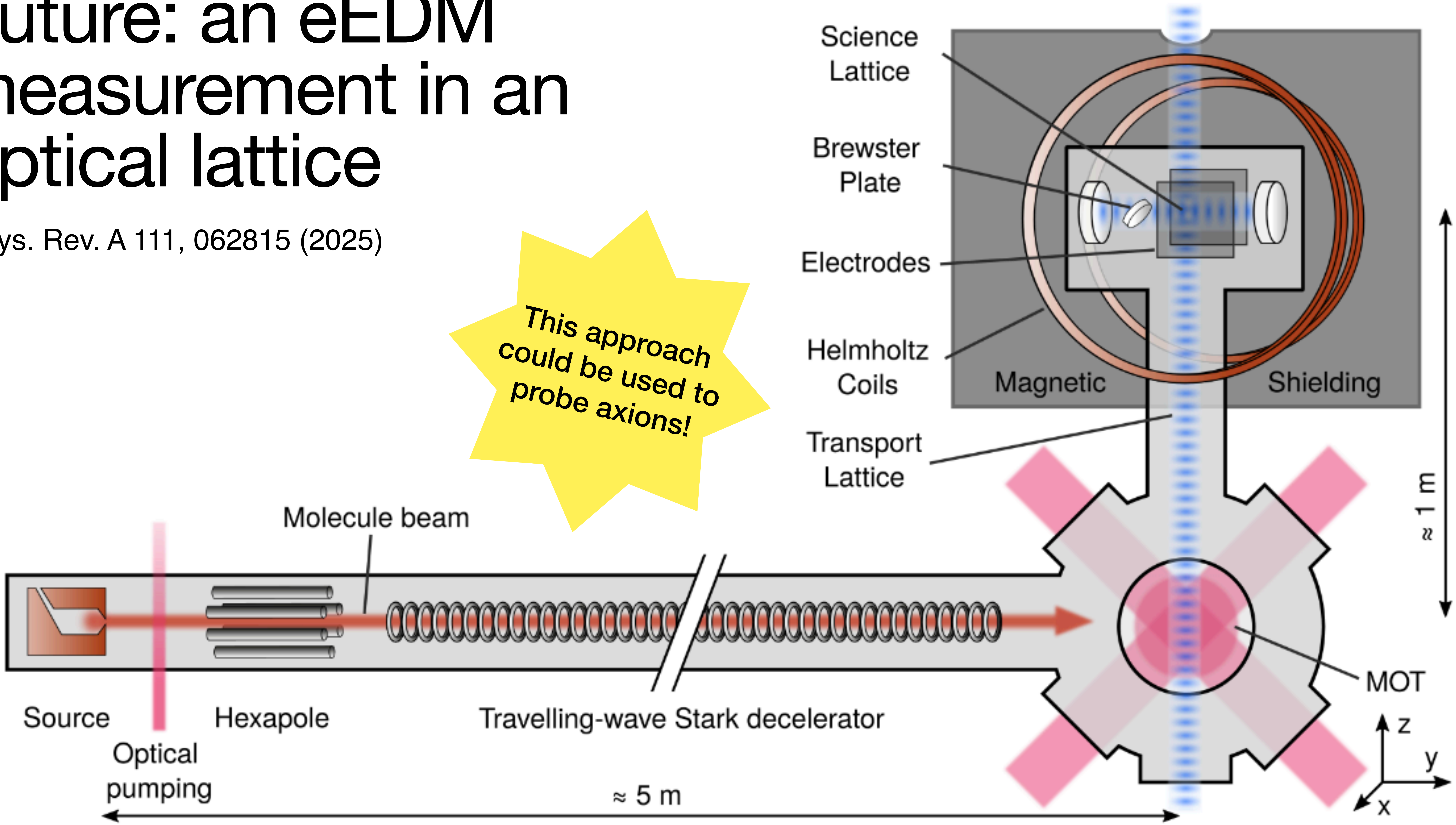




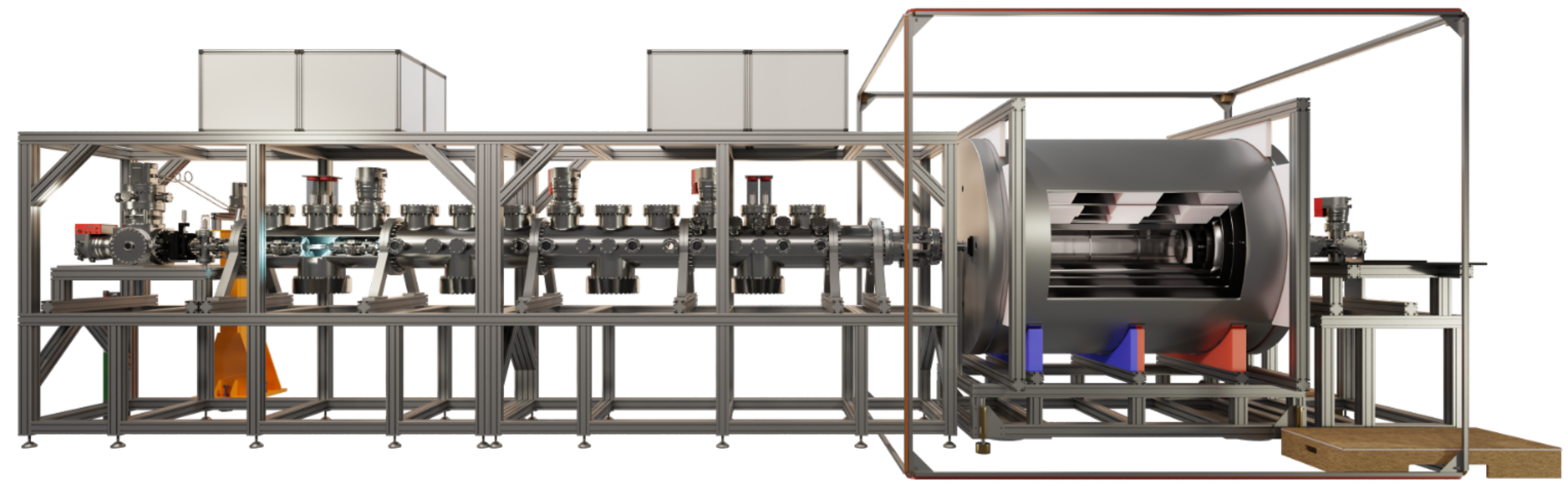
Future: an eEDM measurement in an optical lattice

Phys. Rev. A 111, 062815 (2025)

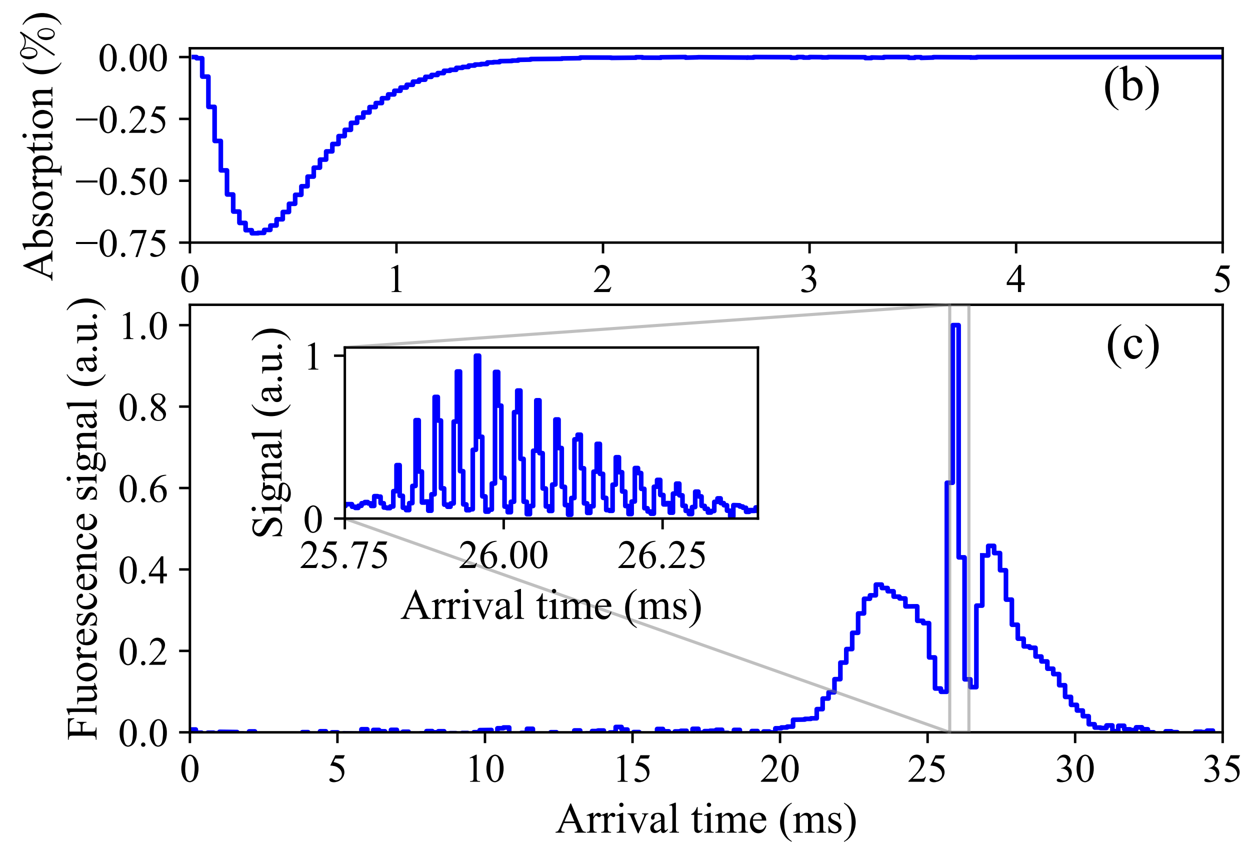
This approach could be used to probe axions!



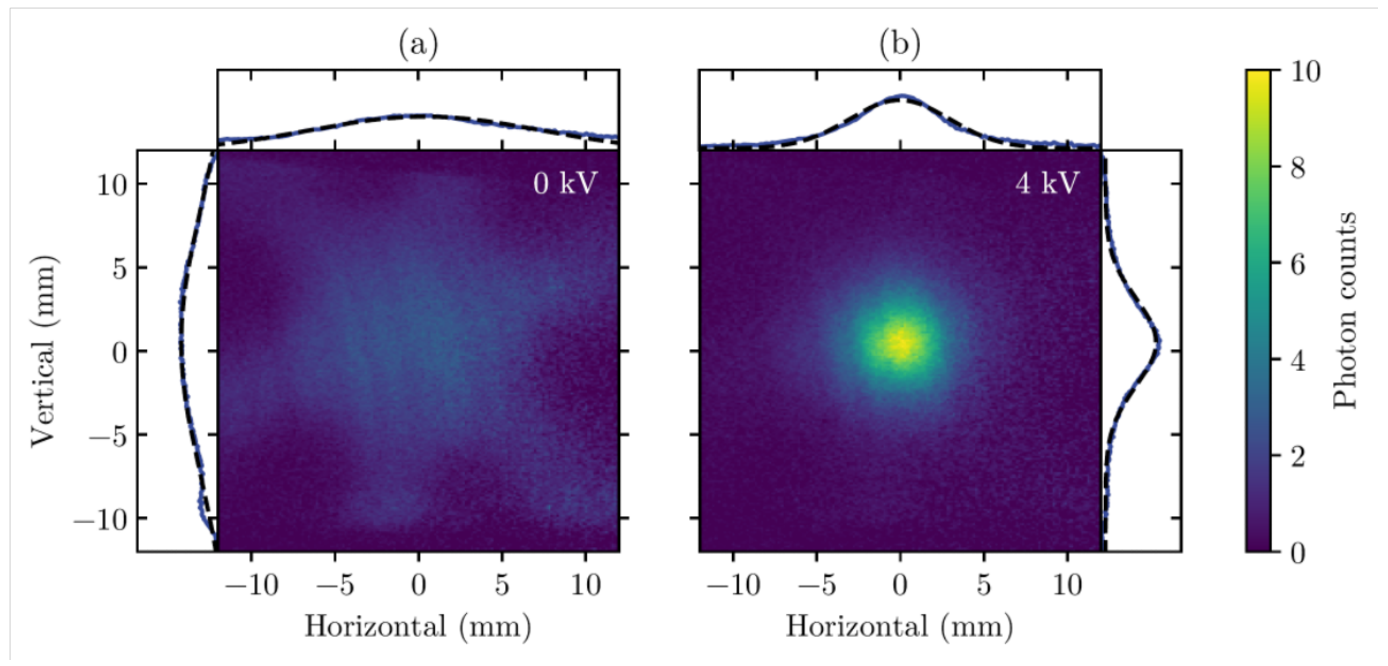
Summary



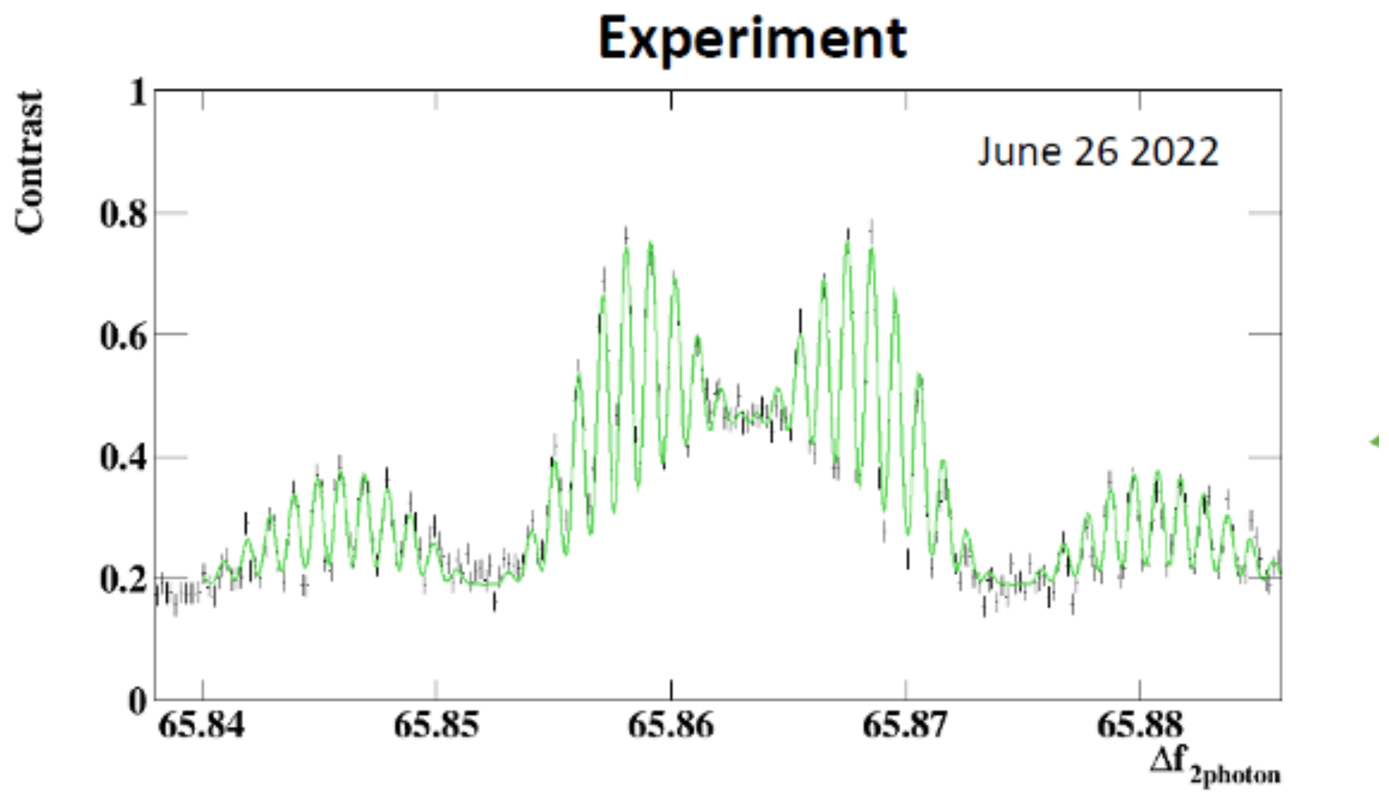
Testing the Standard Model in a table-top experiment



Deceleration demonstrated

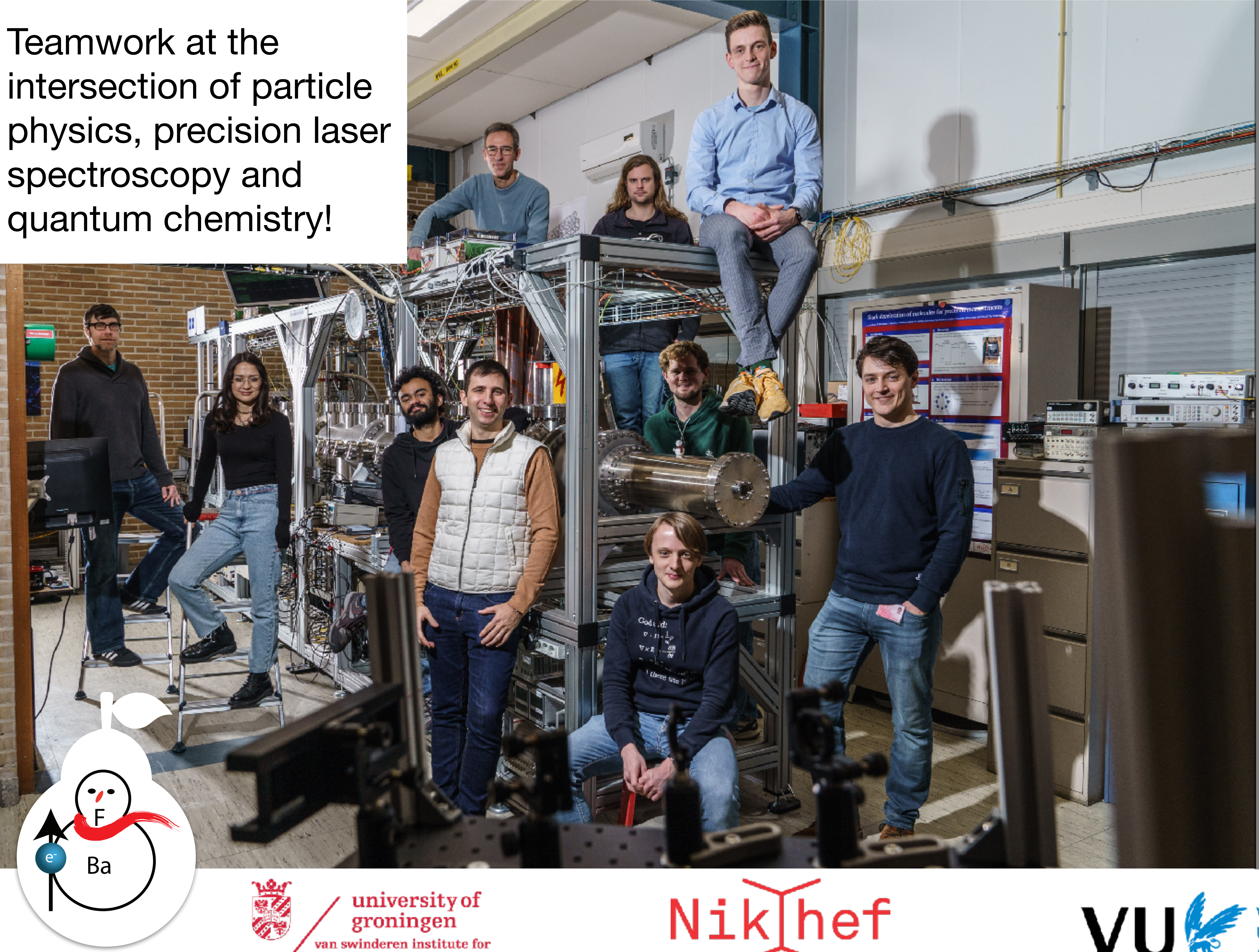


Focussing of molecular beam



Spin interference demonstrated and understood

Teamwork at the intersection of particle physics, precision laser spectroscopy and quantum chemistry!



Think different!

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