Molecular systems for tests of fundamental physics

Steven Hoekstra, RUG & Nikhef

university of groningen
van swinderen institute for particle physics and gravity

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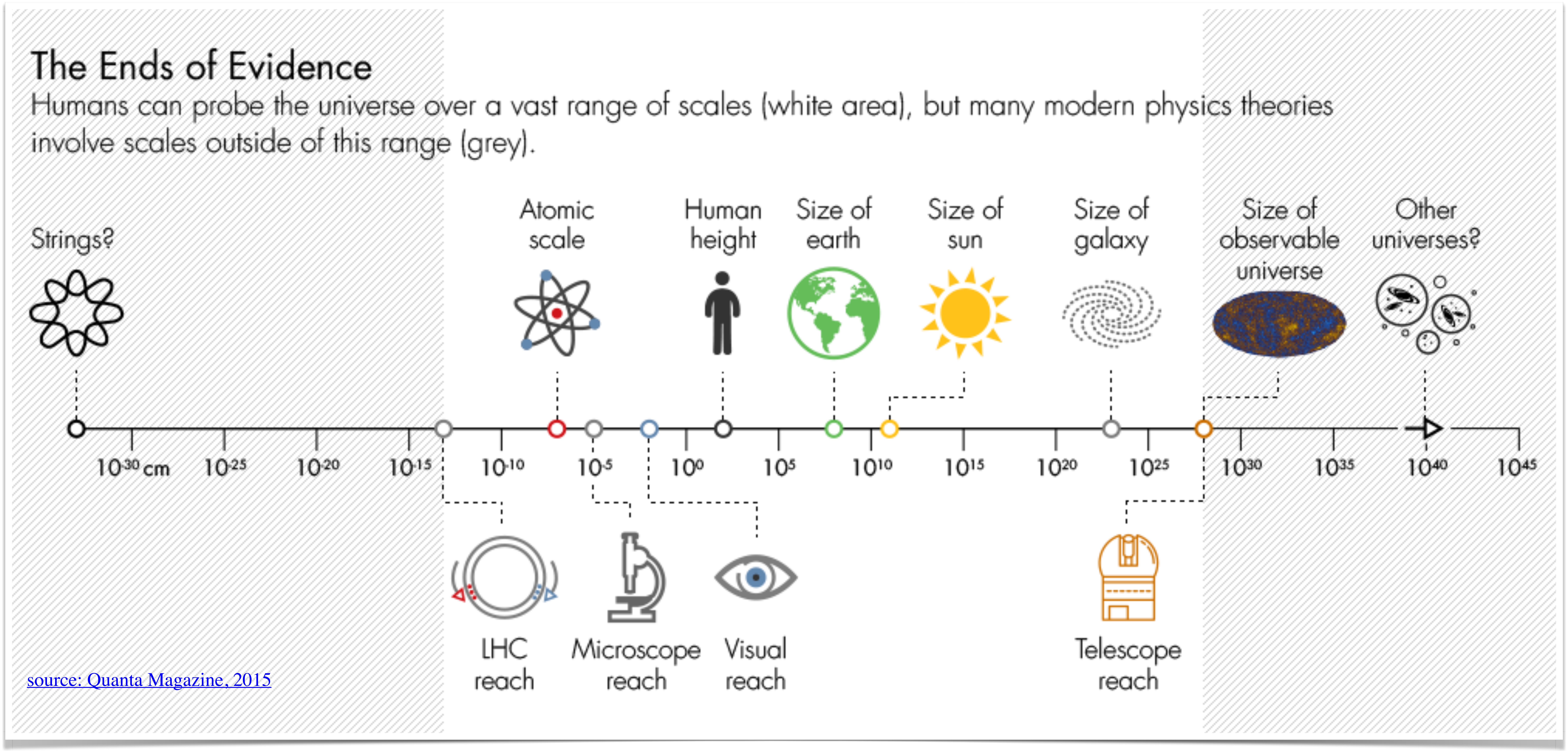
Dutch National Institute for (astro)Particle Physics

VU VRIJE UNIVERSITEIT AMSTERDAM

UvA

Motivation: reach beyond the current limits of observation



source: Quanta Magazine, 2015

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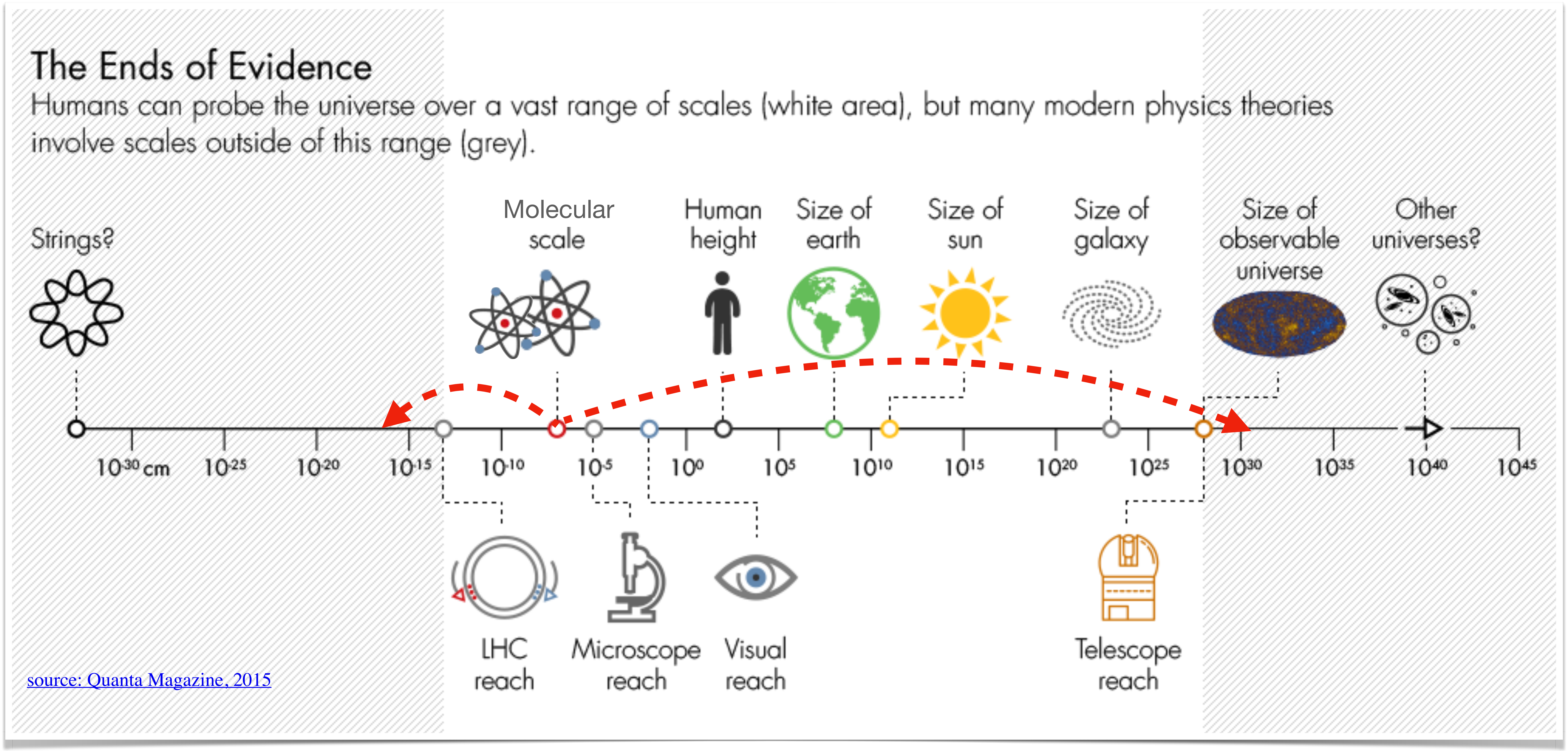

Molecules can be extremely sensitive quantum sensors for fundamental physics!

Molecules vs atoms

Extra complexity brings experimental challenges and new possibilities

Close-lying opposite parity levels: study parity violation
(also chirality)

Heavy polar molecules: hugely enhanced electron-EDM sensitivity

Tunneling in molecular motion: extremely sensitive to value of constants

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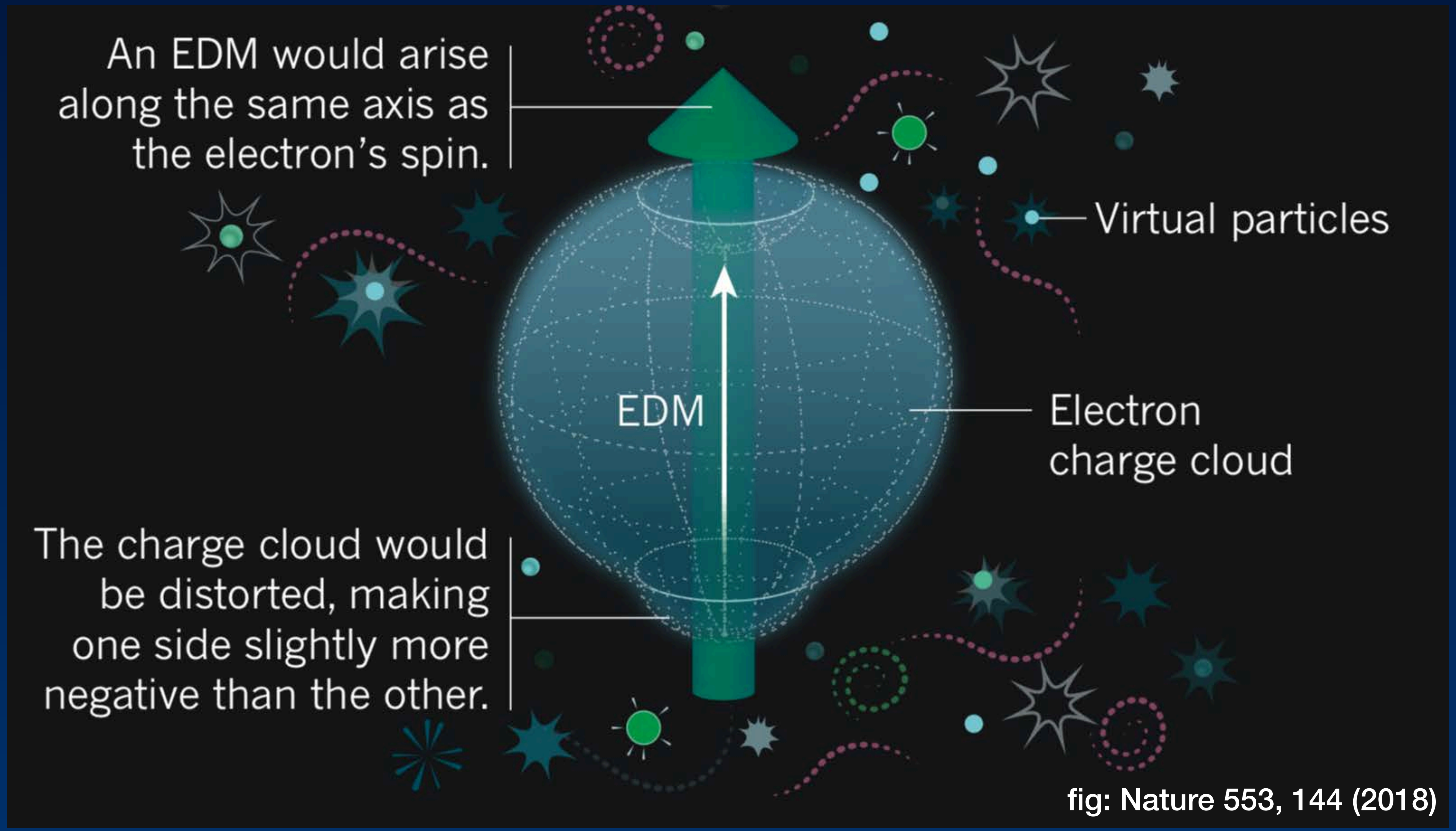
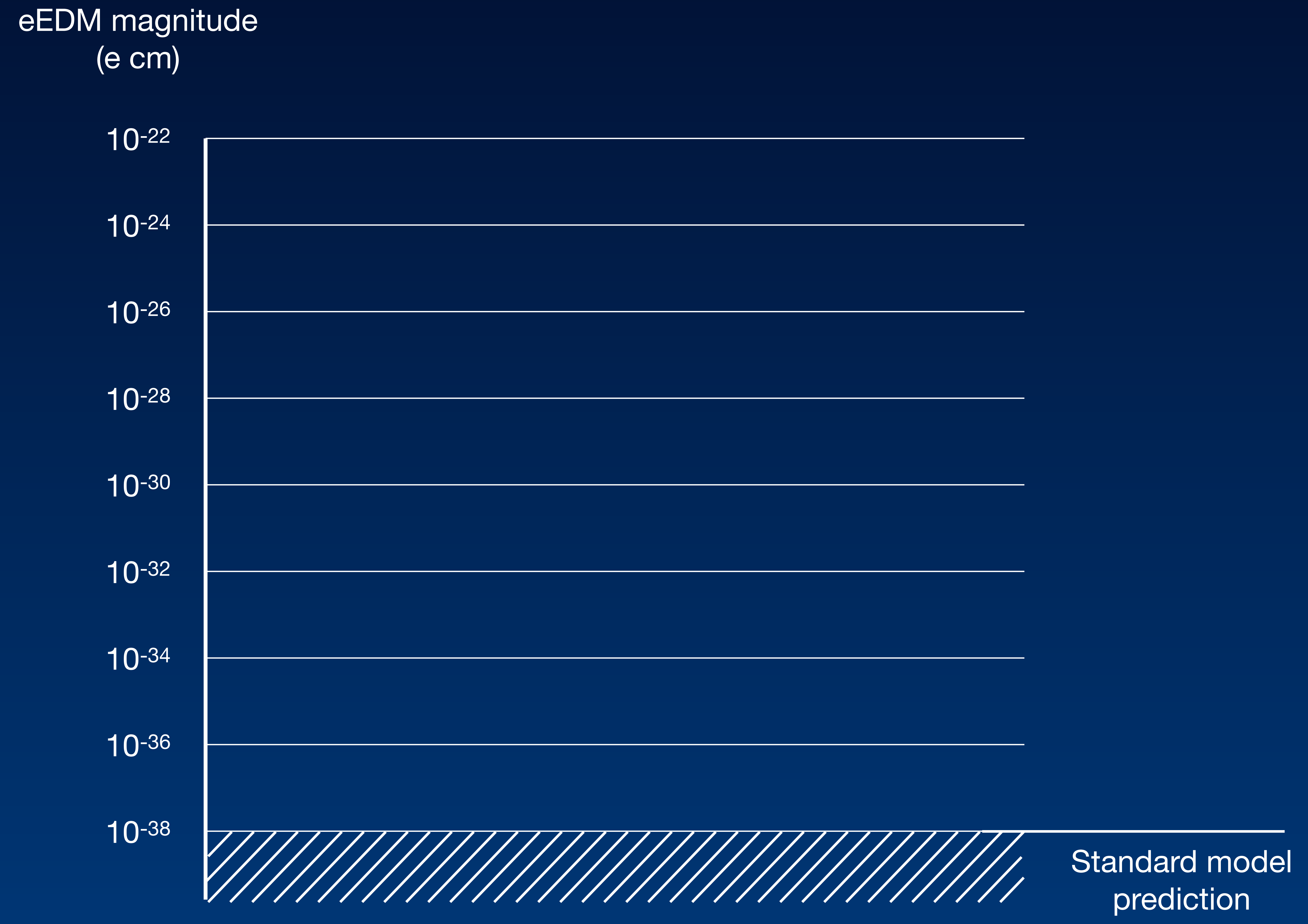
The electron's Electric Dipole Moment (eEDM)

probing CP violation beyond the standard model



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



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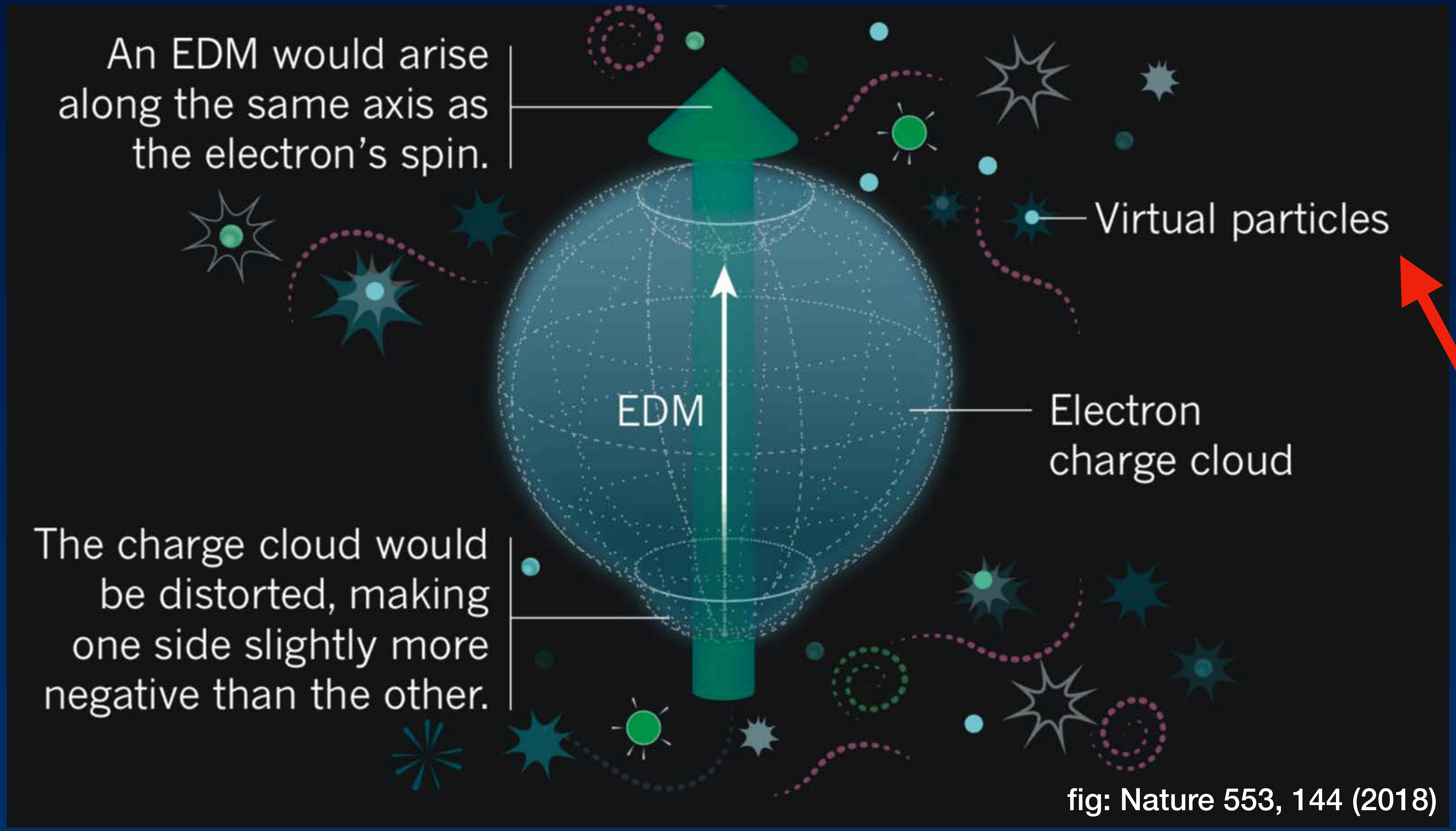

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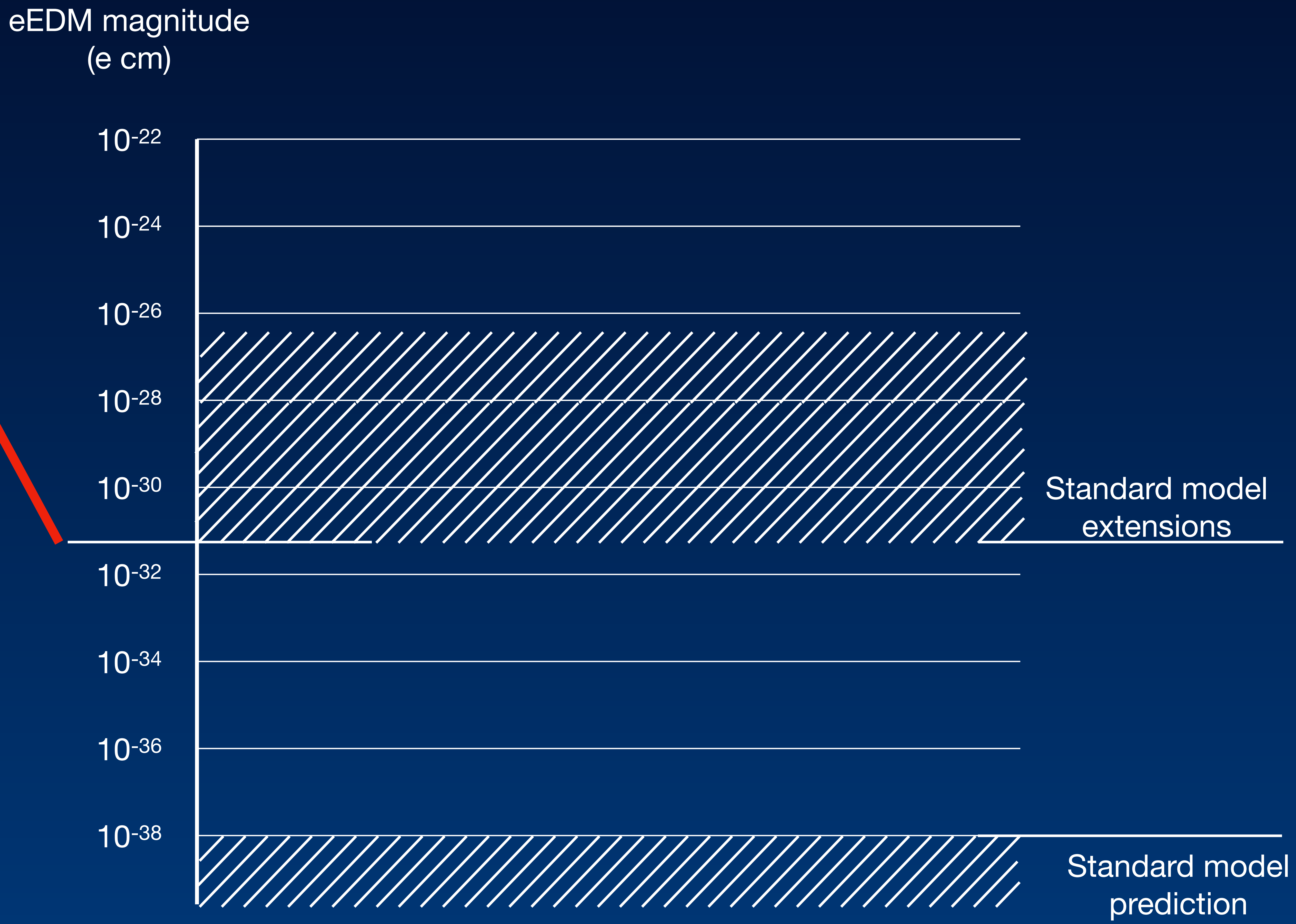

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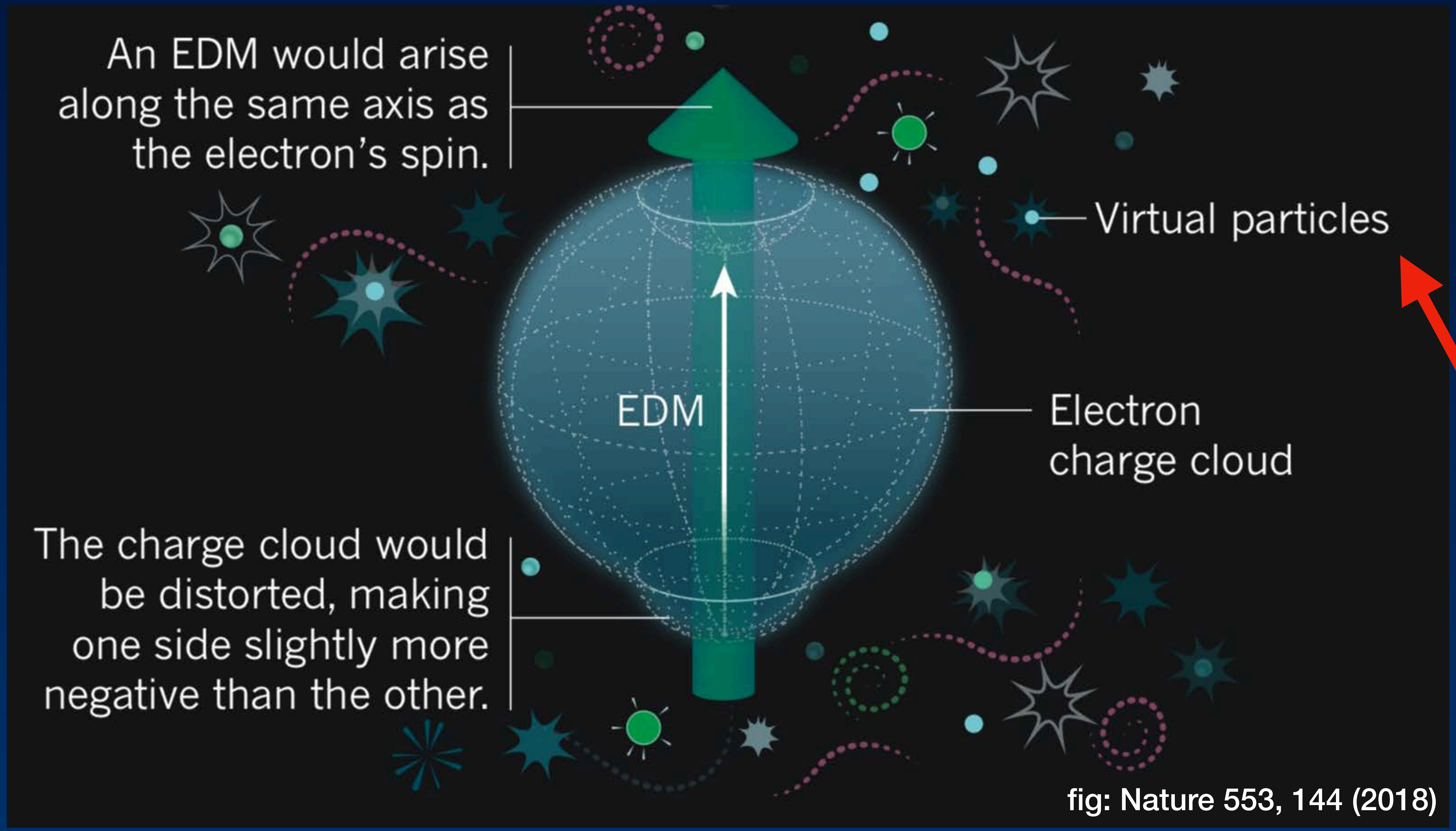

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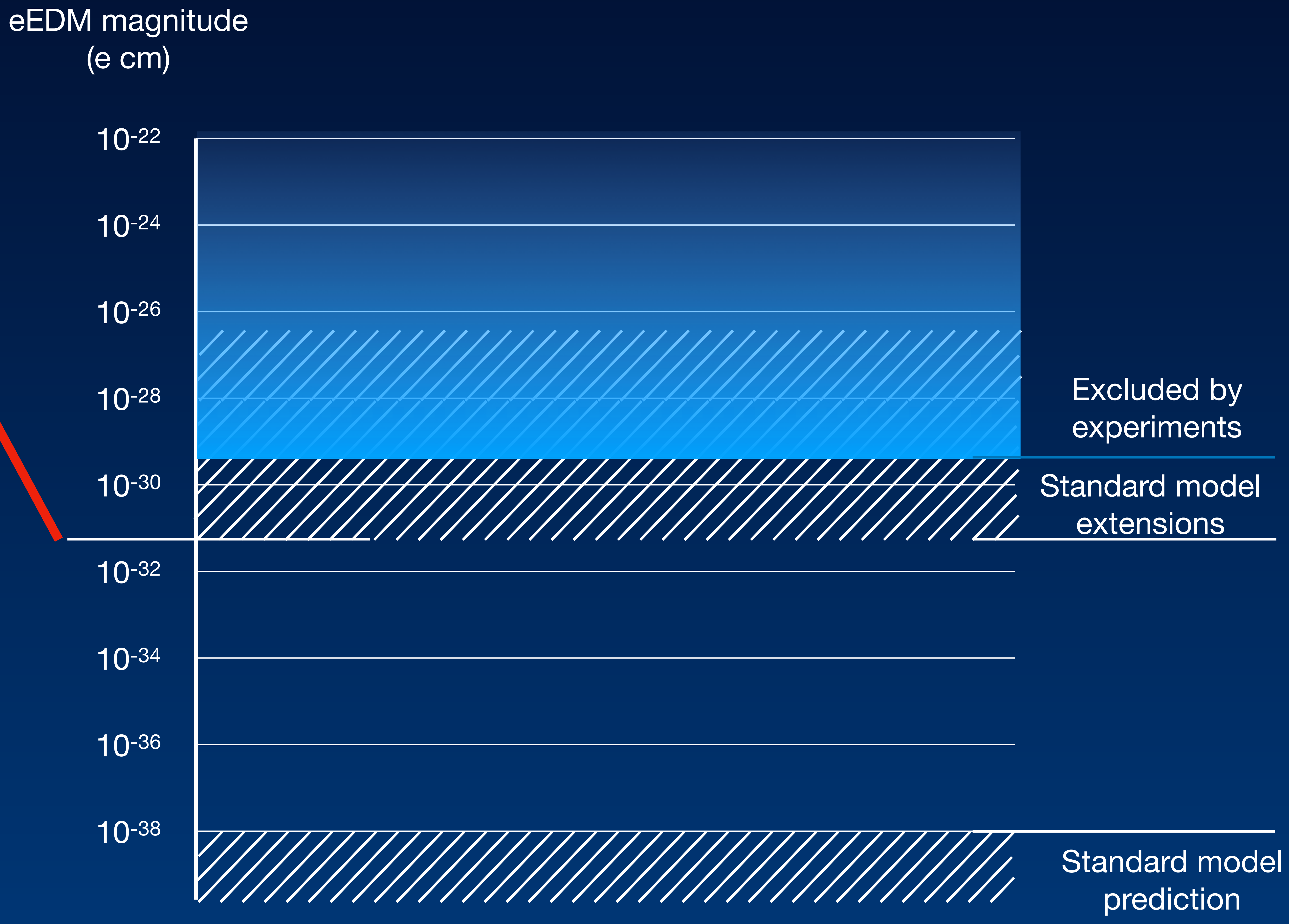
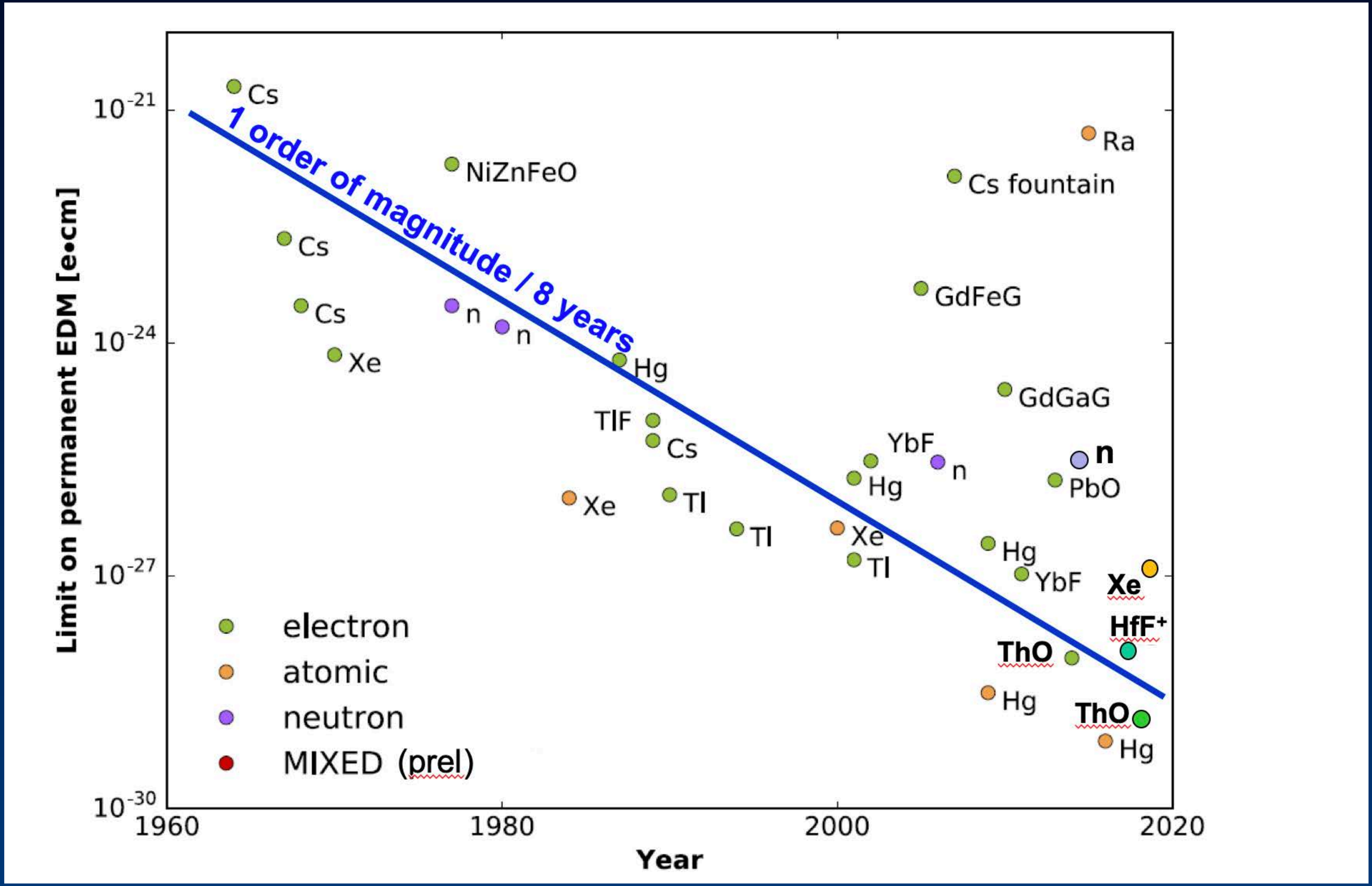


A history of measurements with steady progress



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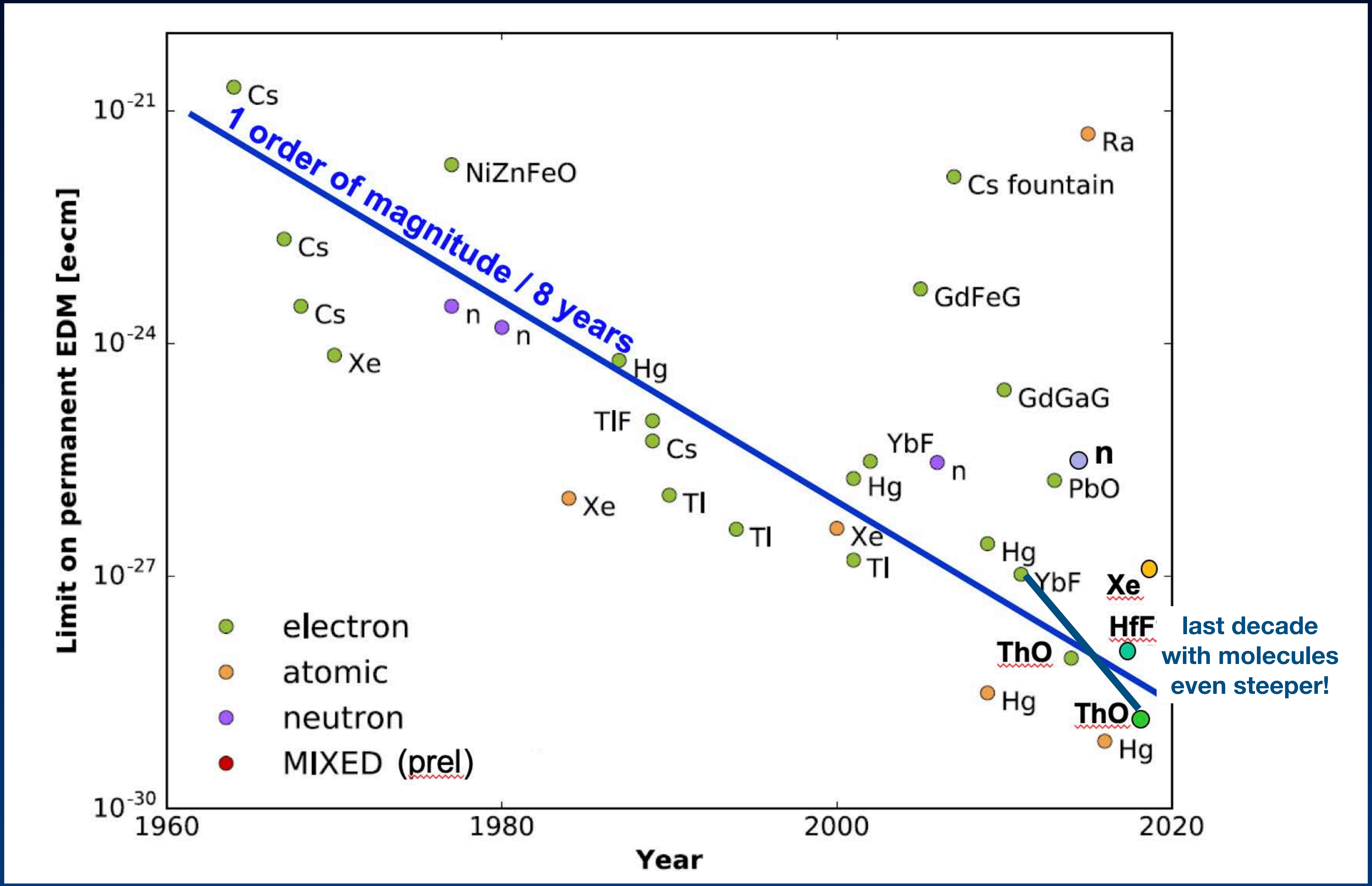
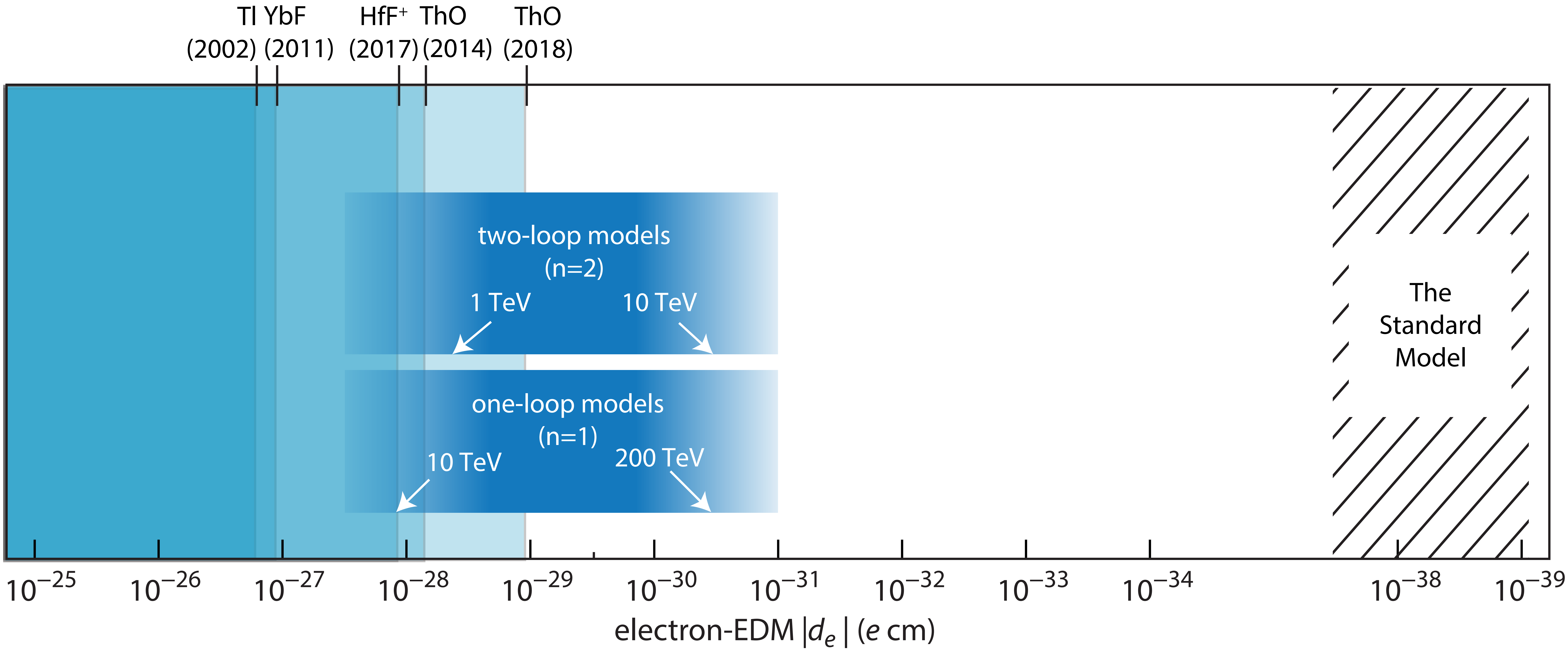


The electron's electric dipole moment (eEDM)

effectively a background-free method to probe new phyiscs



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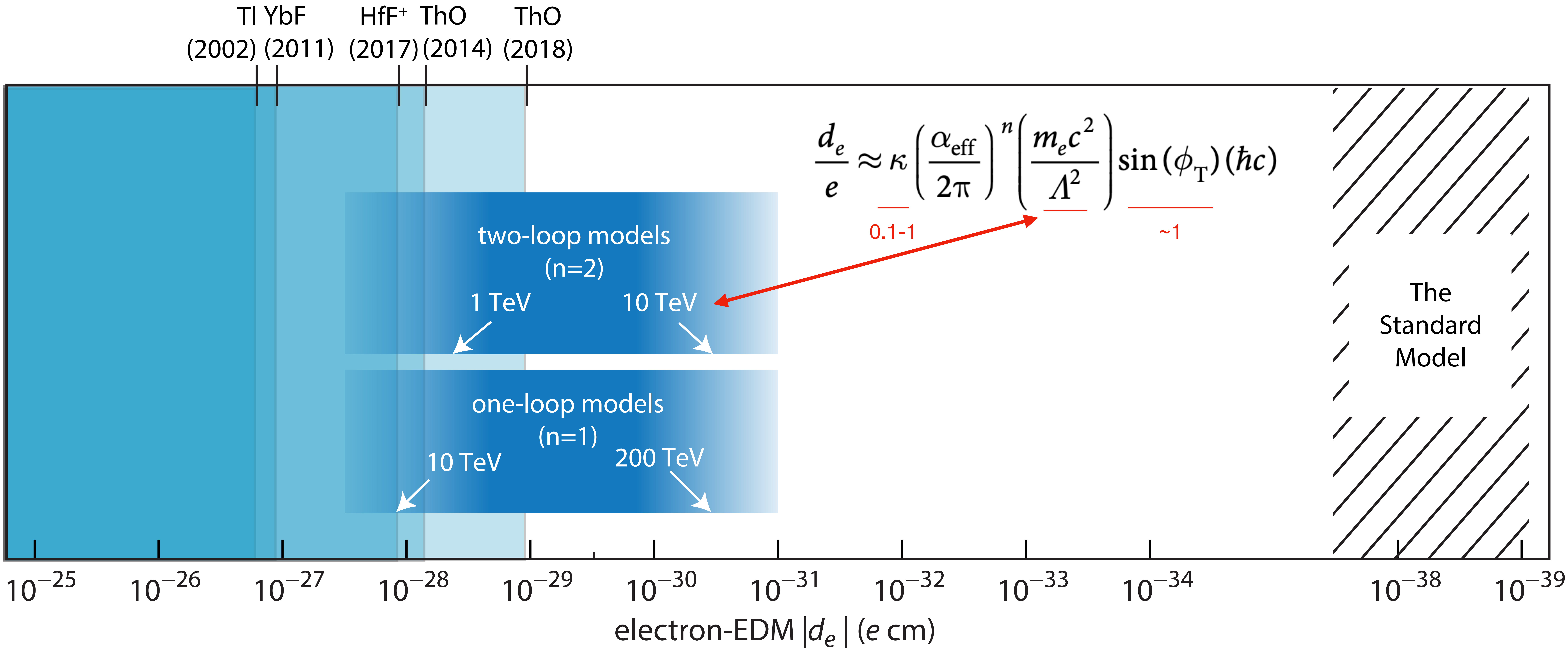

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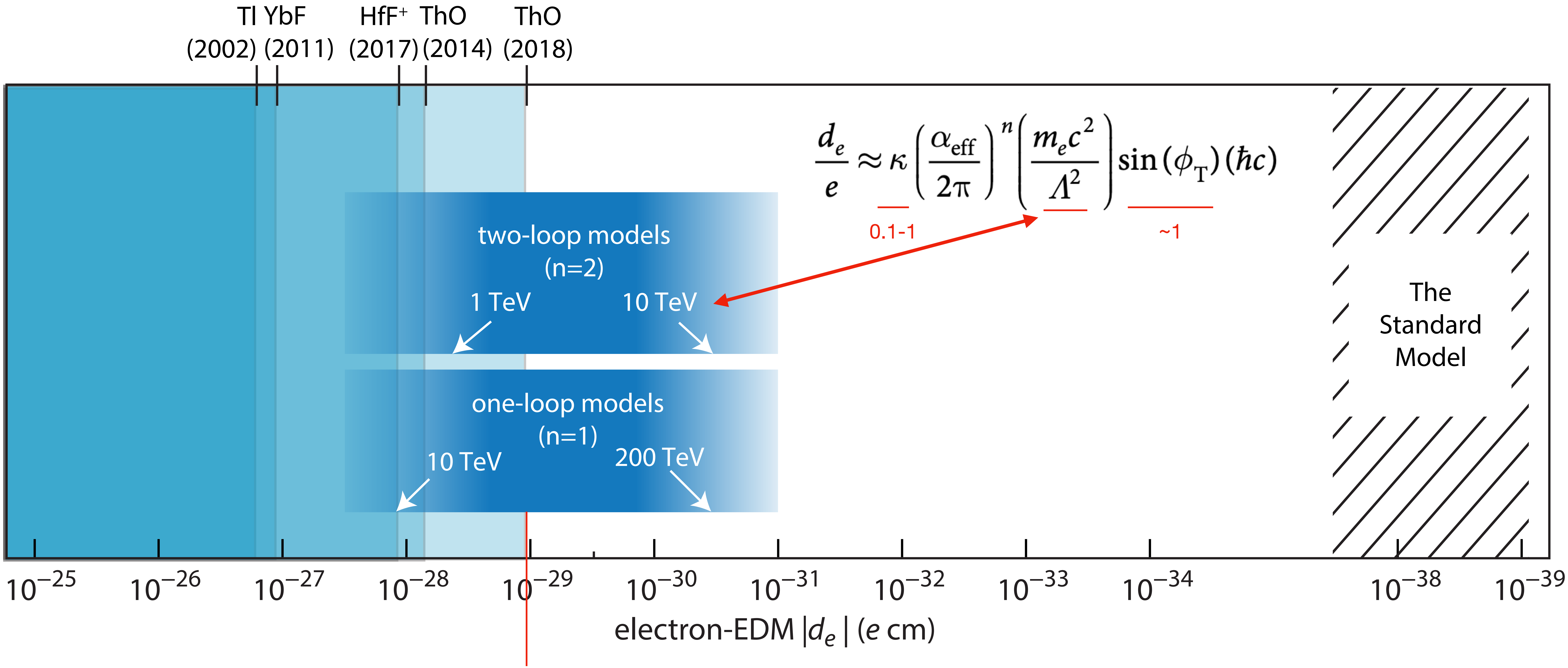
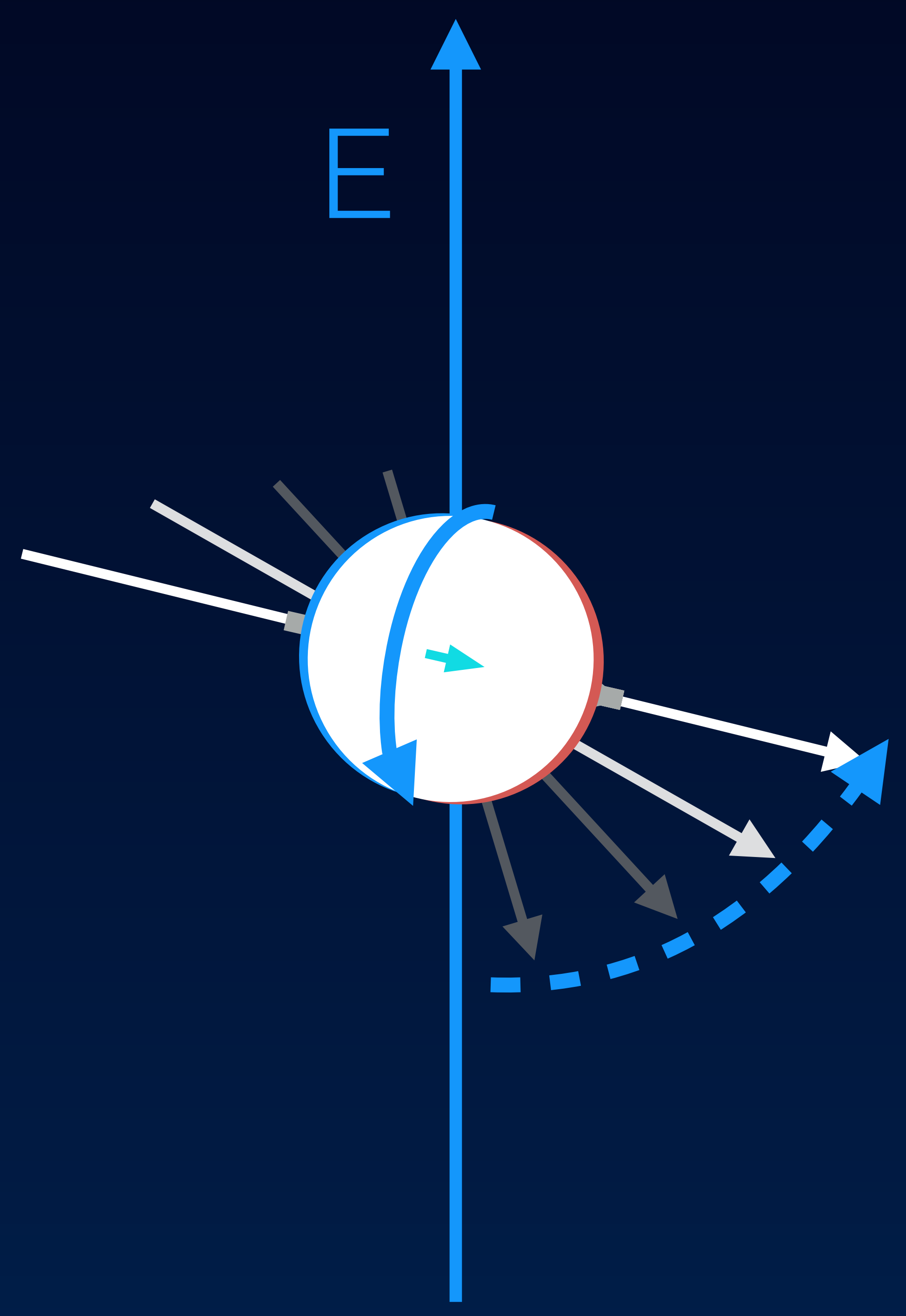
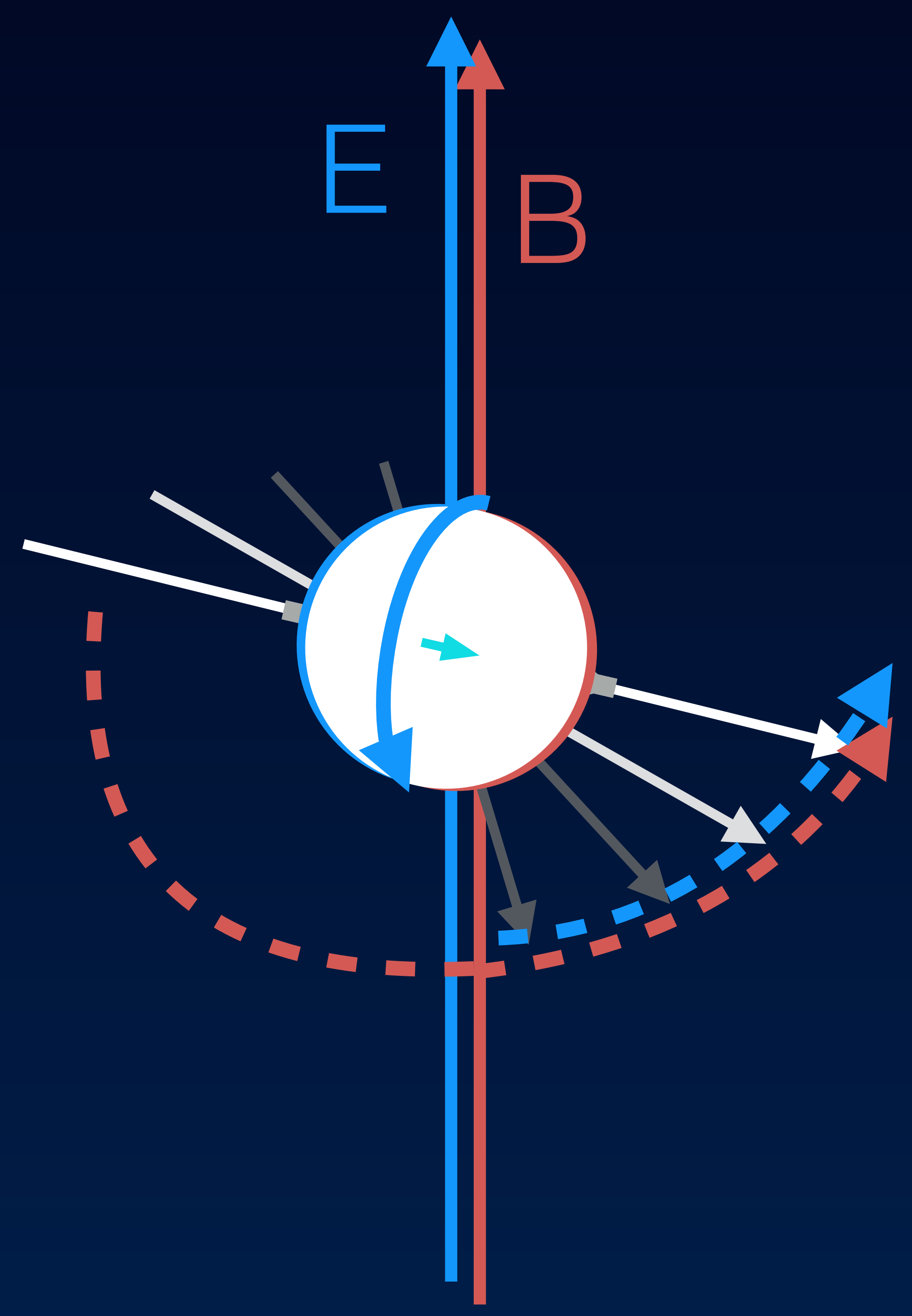


The ThO result limits time-reversal-symmetry-violating new physics to energy scales above $\Lambda \approx$ 30 TeV or $\Lambda \approx$ 3 TeV, for n=2 or 1, respectively

How to measure a dipole moment?





precession!

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

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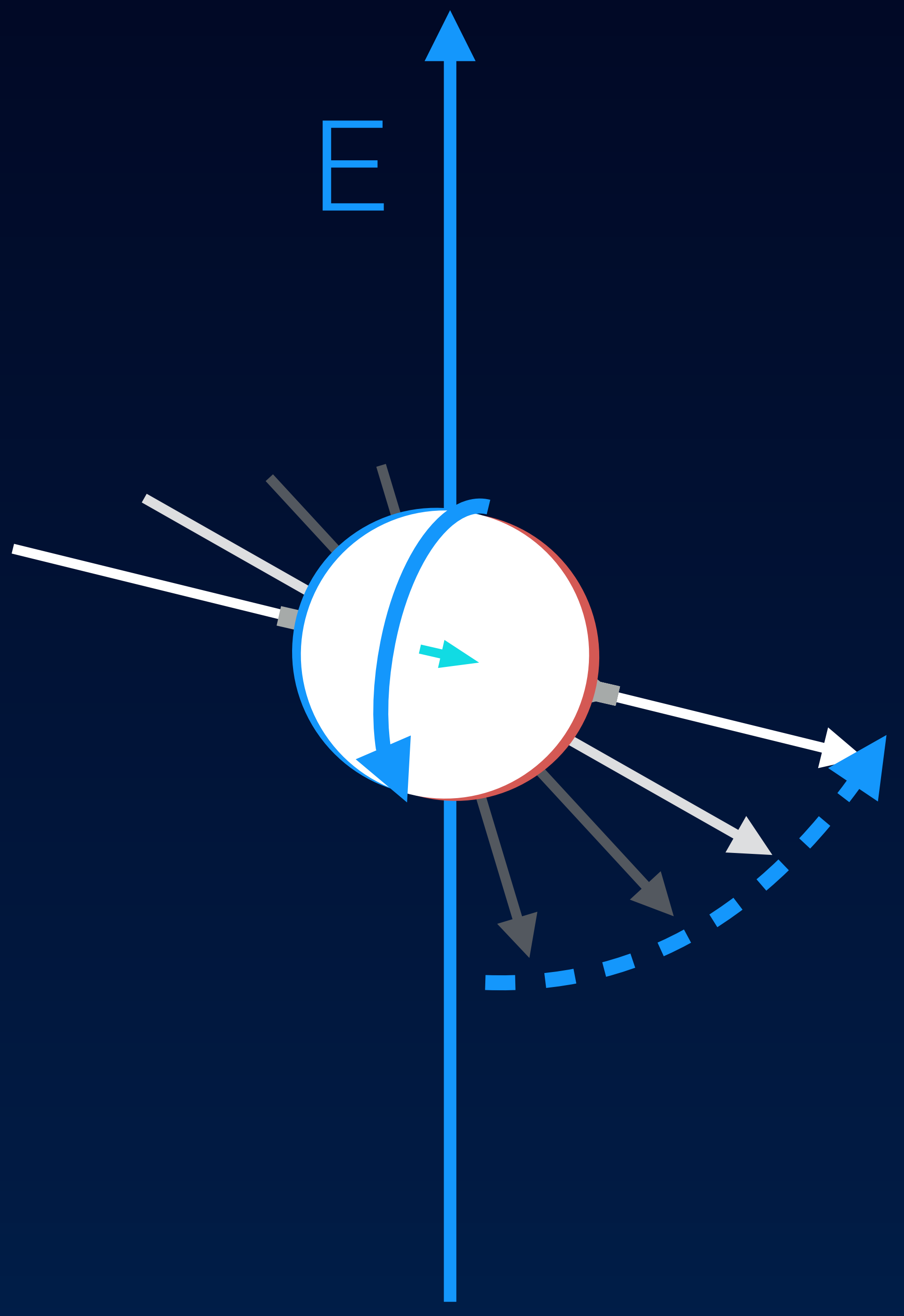

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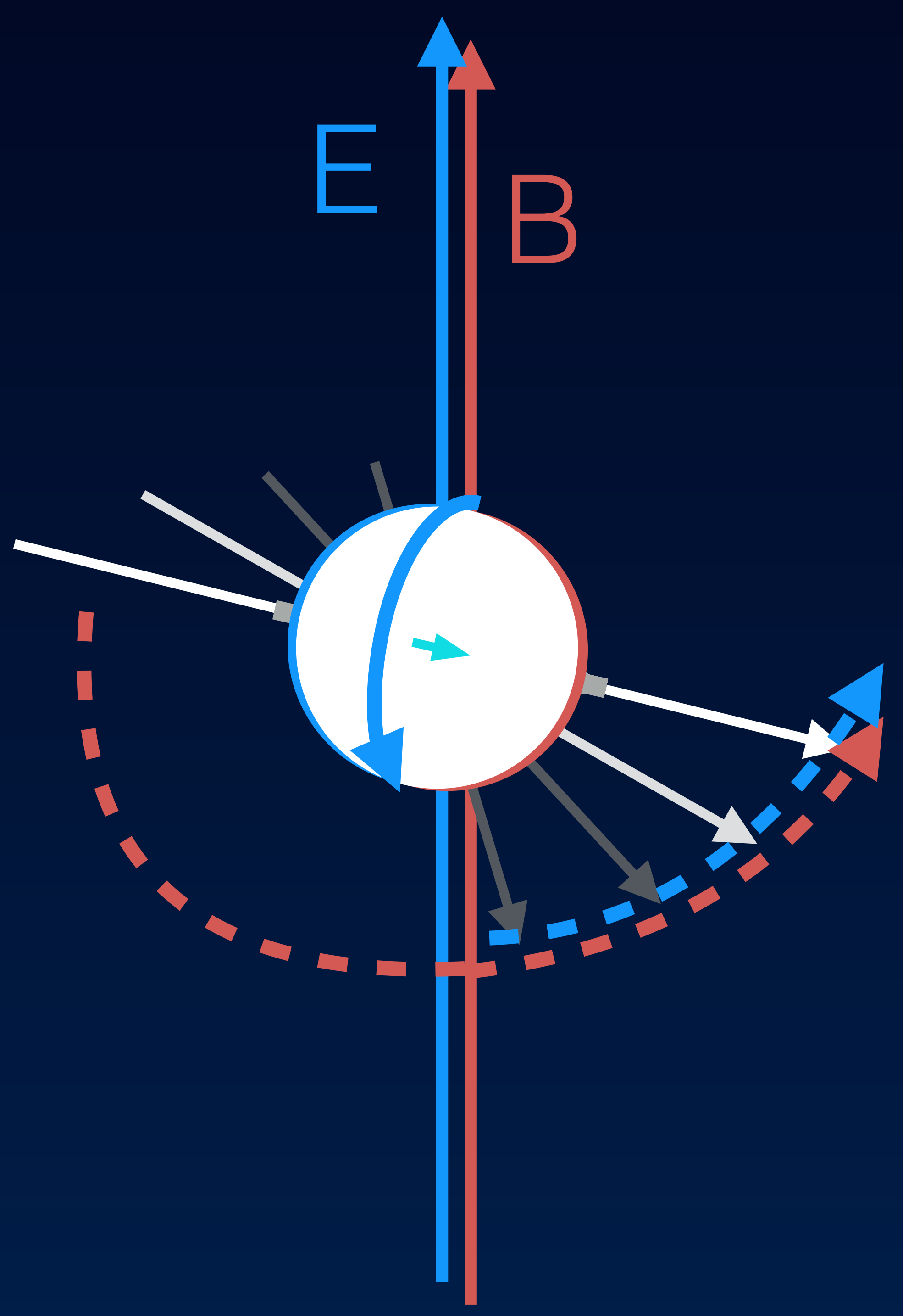

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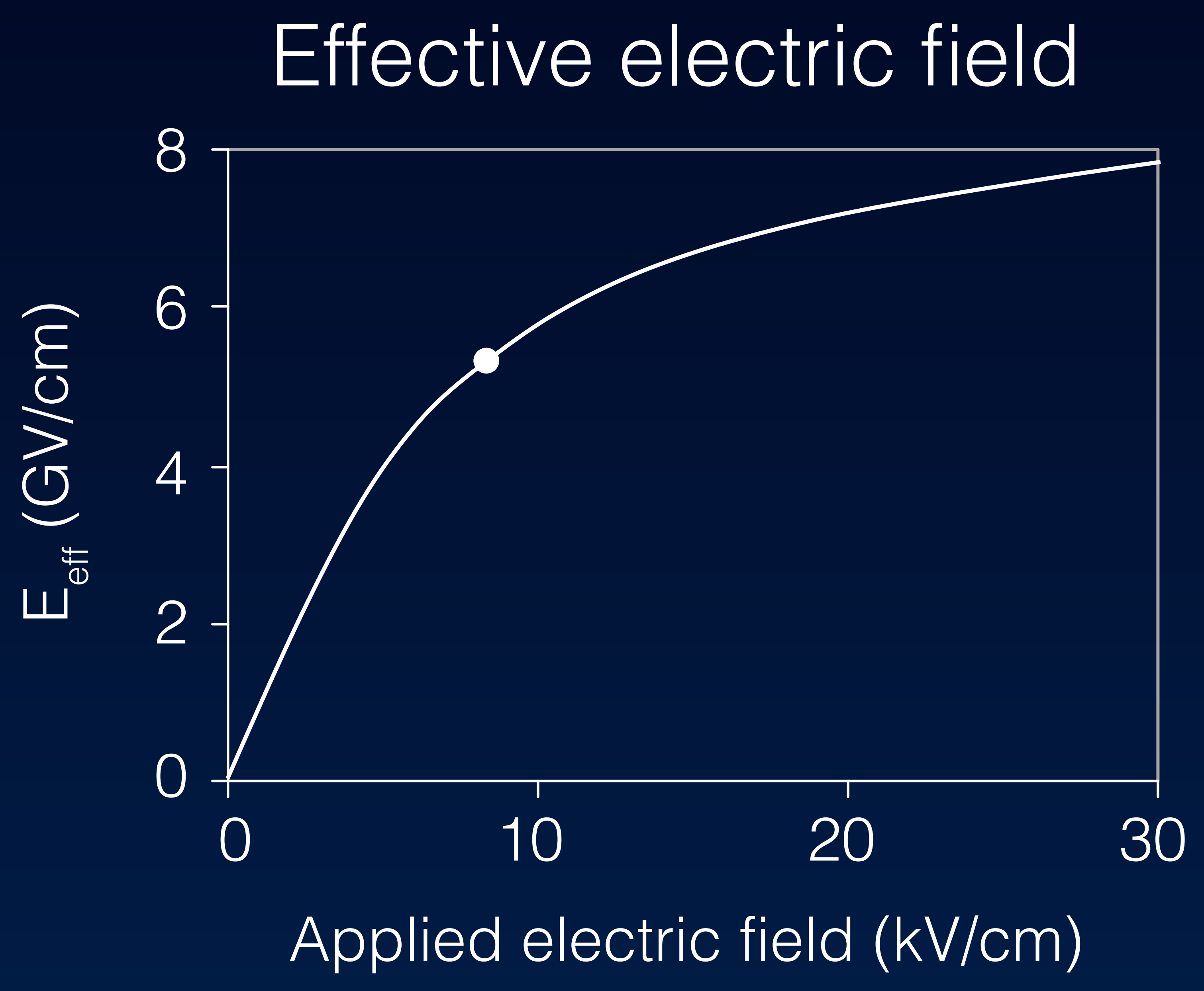
polar molecule

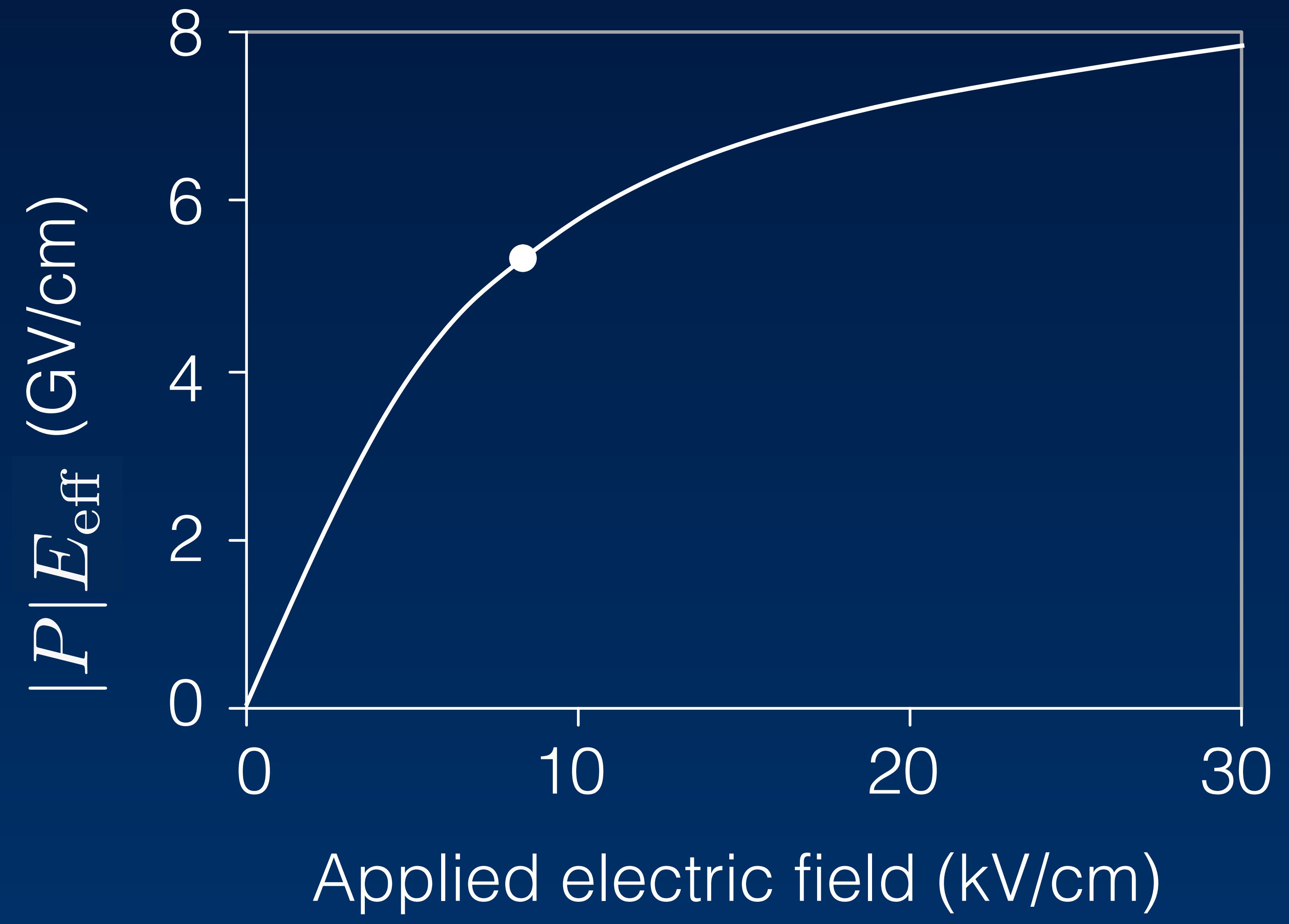


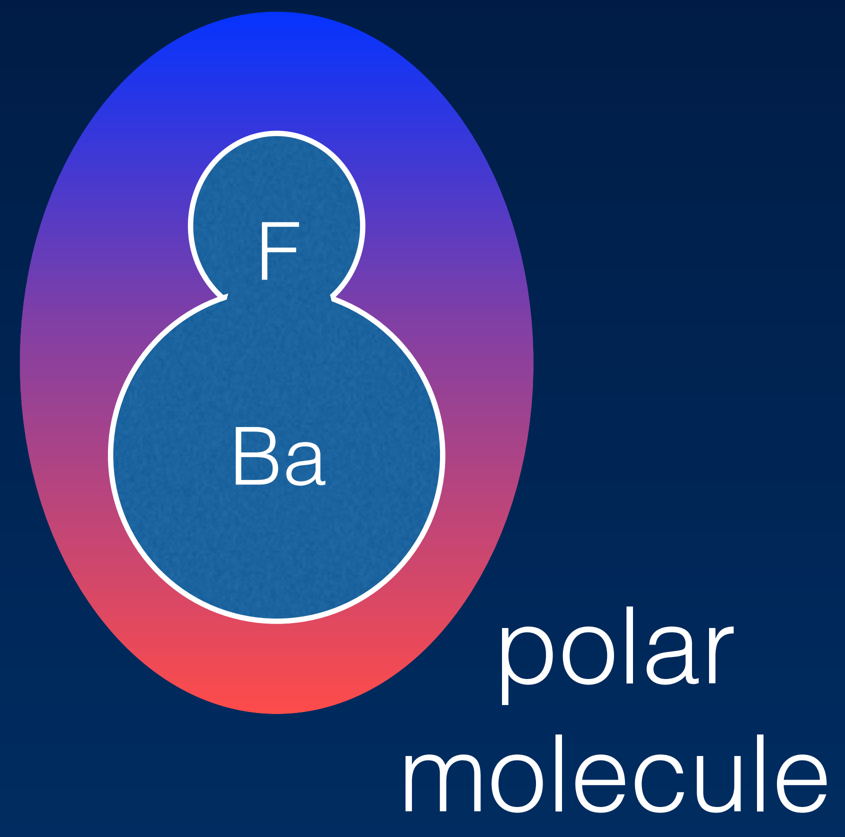
Solution:
use electron embedded in a polar molecule!

Enhances E
Shields B

Increasing the eEDM sensitivity

Effective electric field



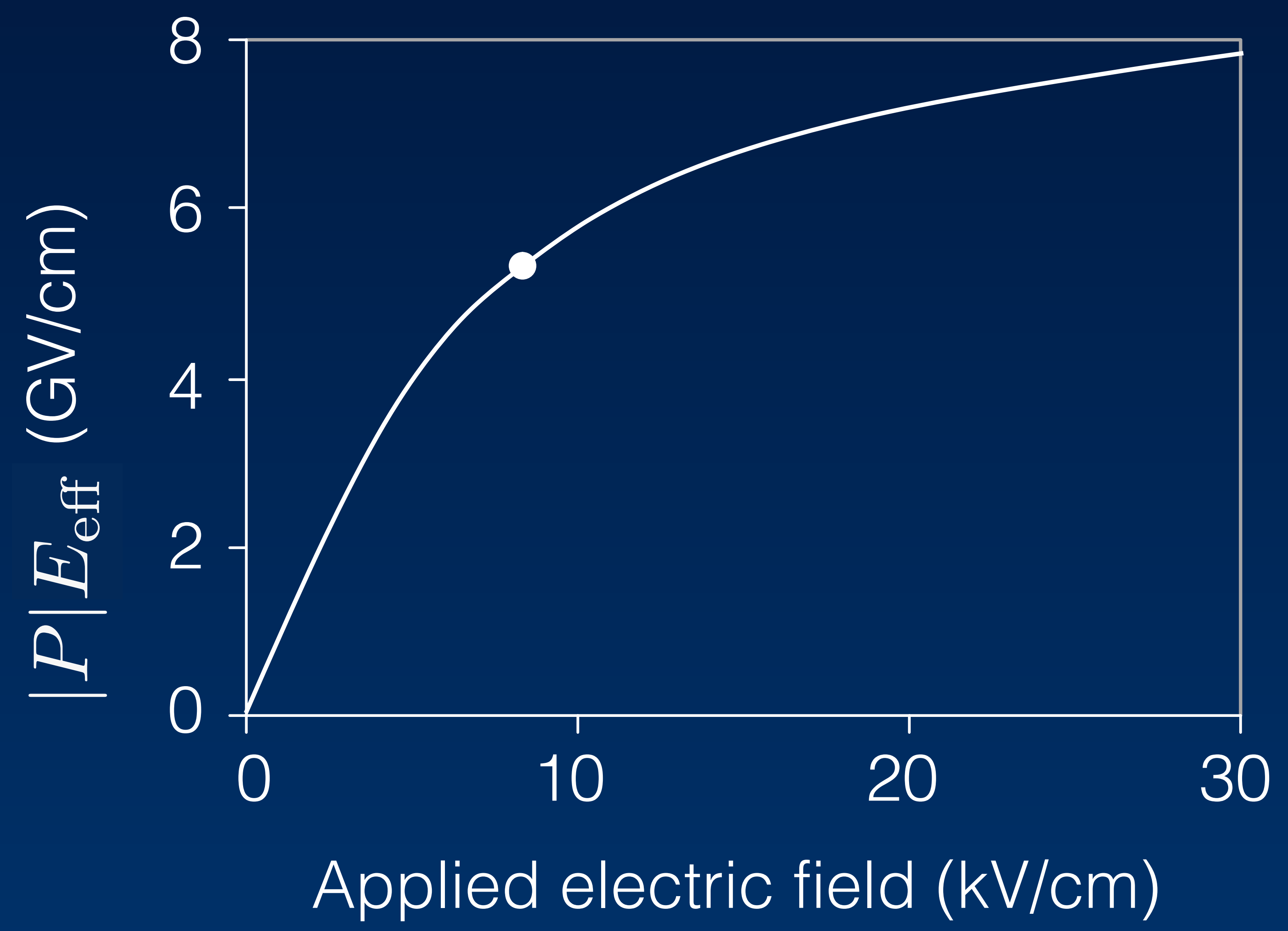


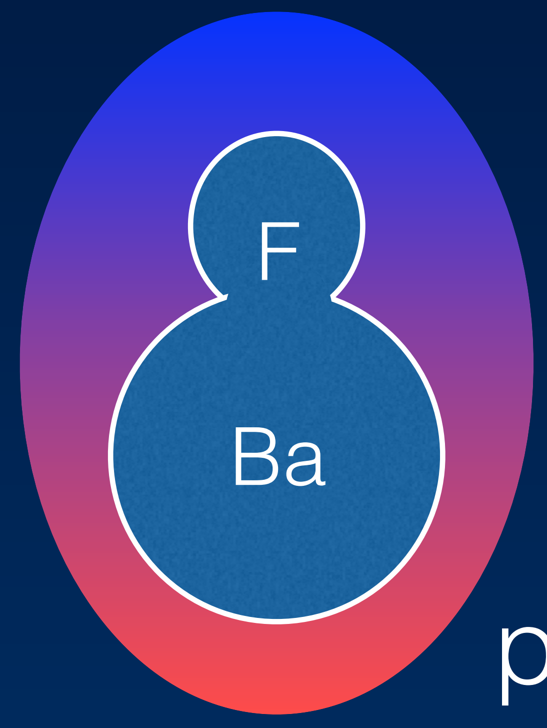
Increasing the eEDM sensitivity

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

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

Effective electric field





polar
molecule

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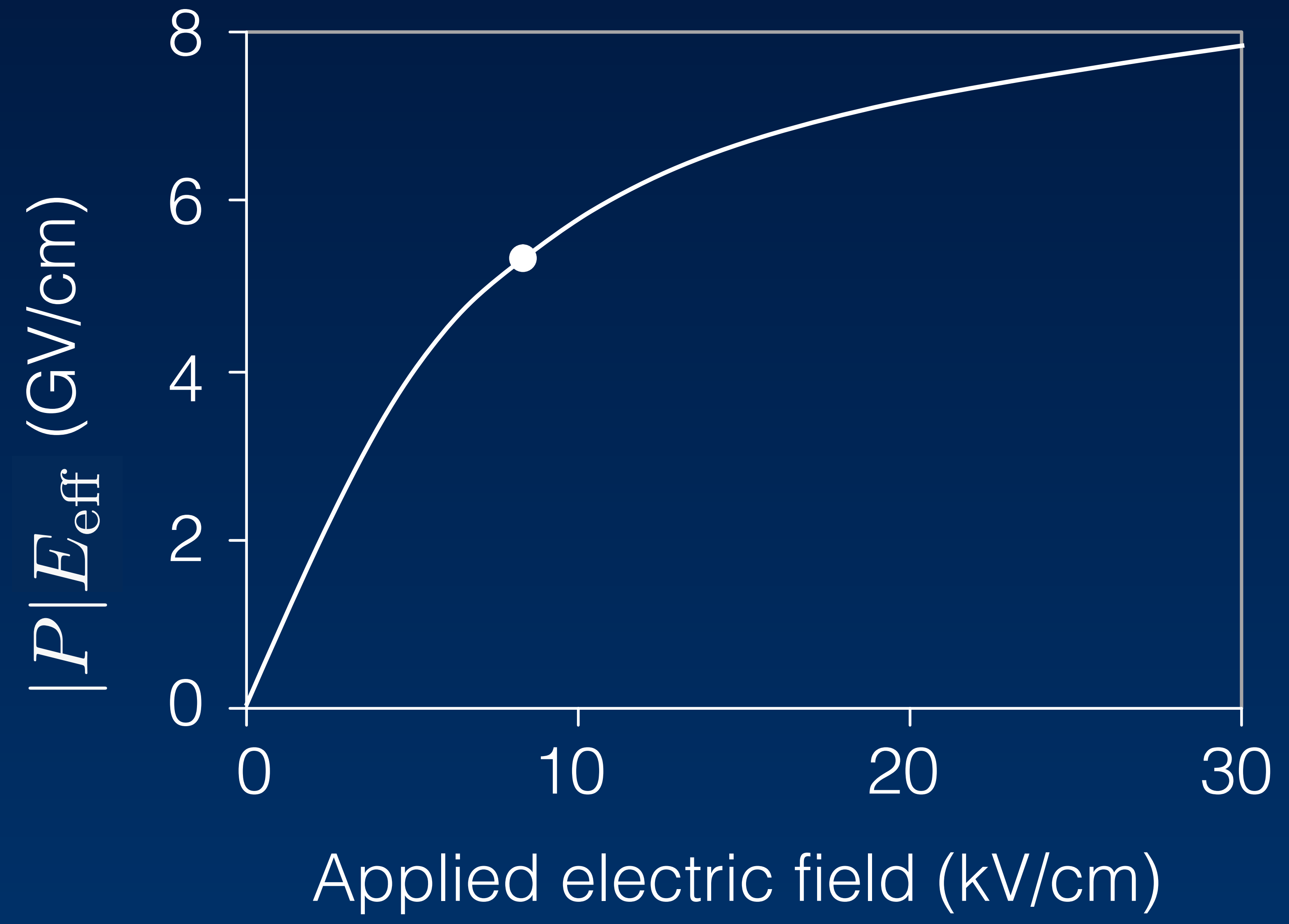
Effective electric field

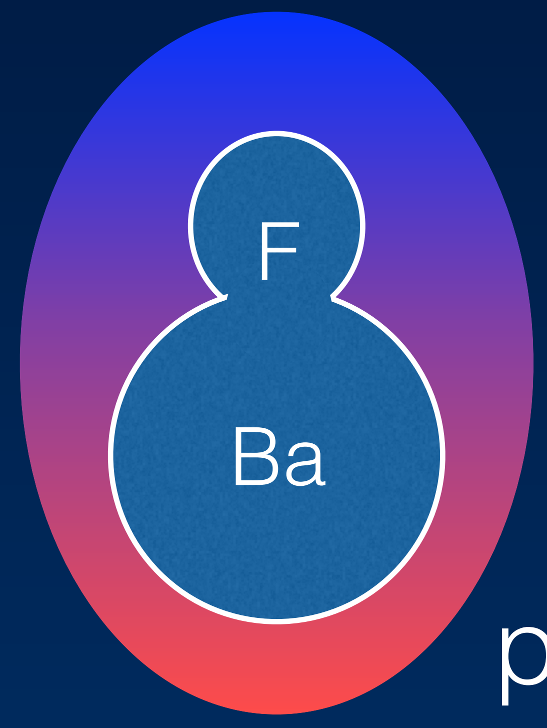
Coherent interaction time

Number of detected molecules

Quantum tricks

Cold Molecules





polar molecule

Coherent interaction time

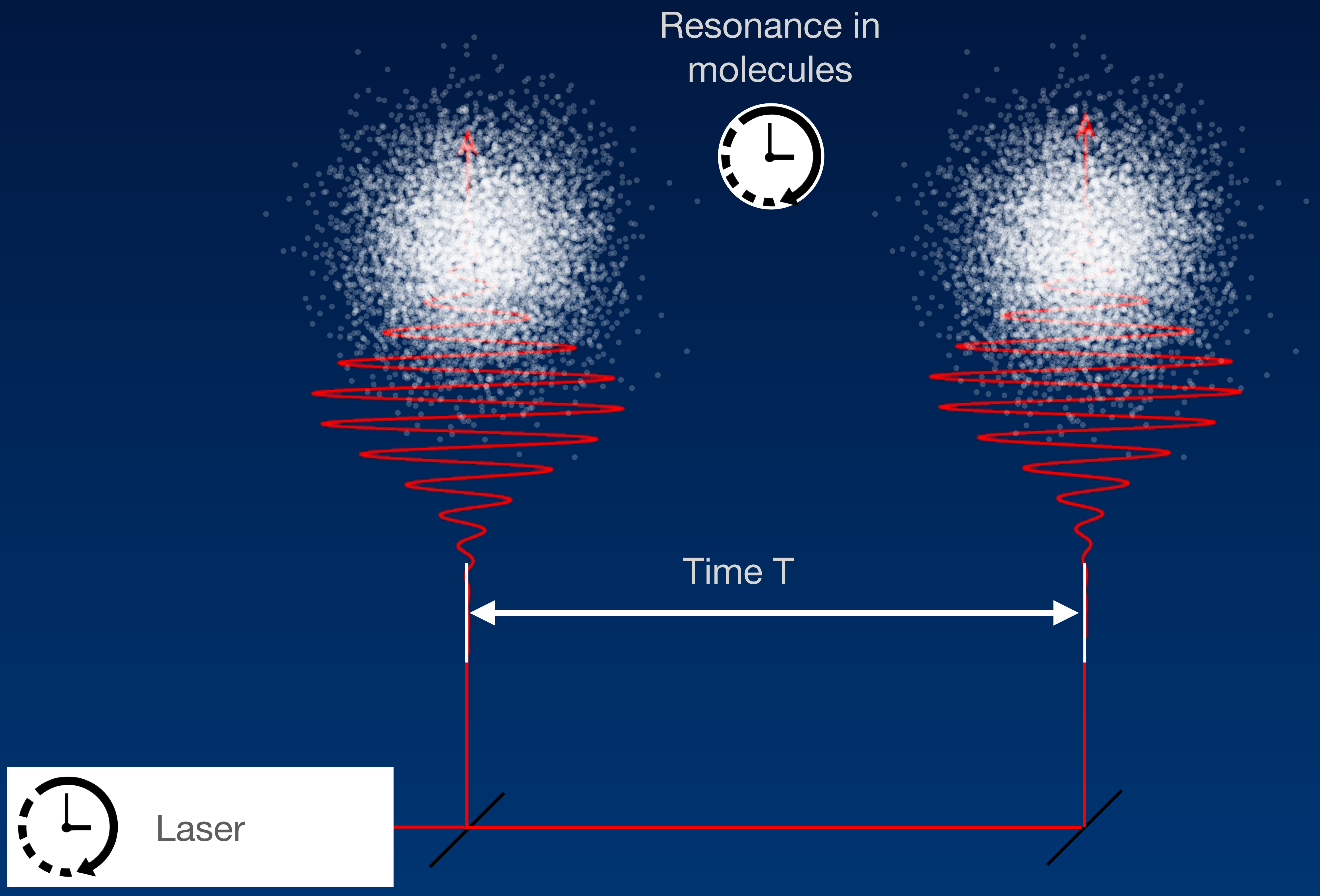
Key technique: Ramsey spin interferometer

laser pulse 1:

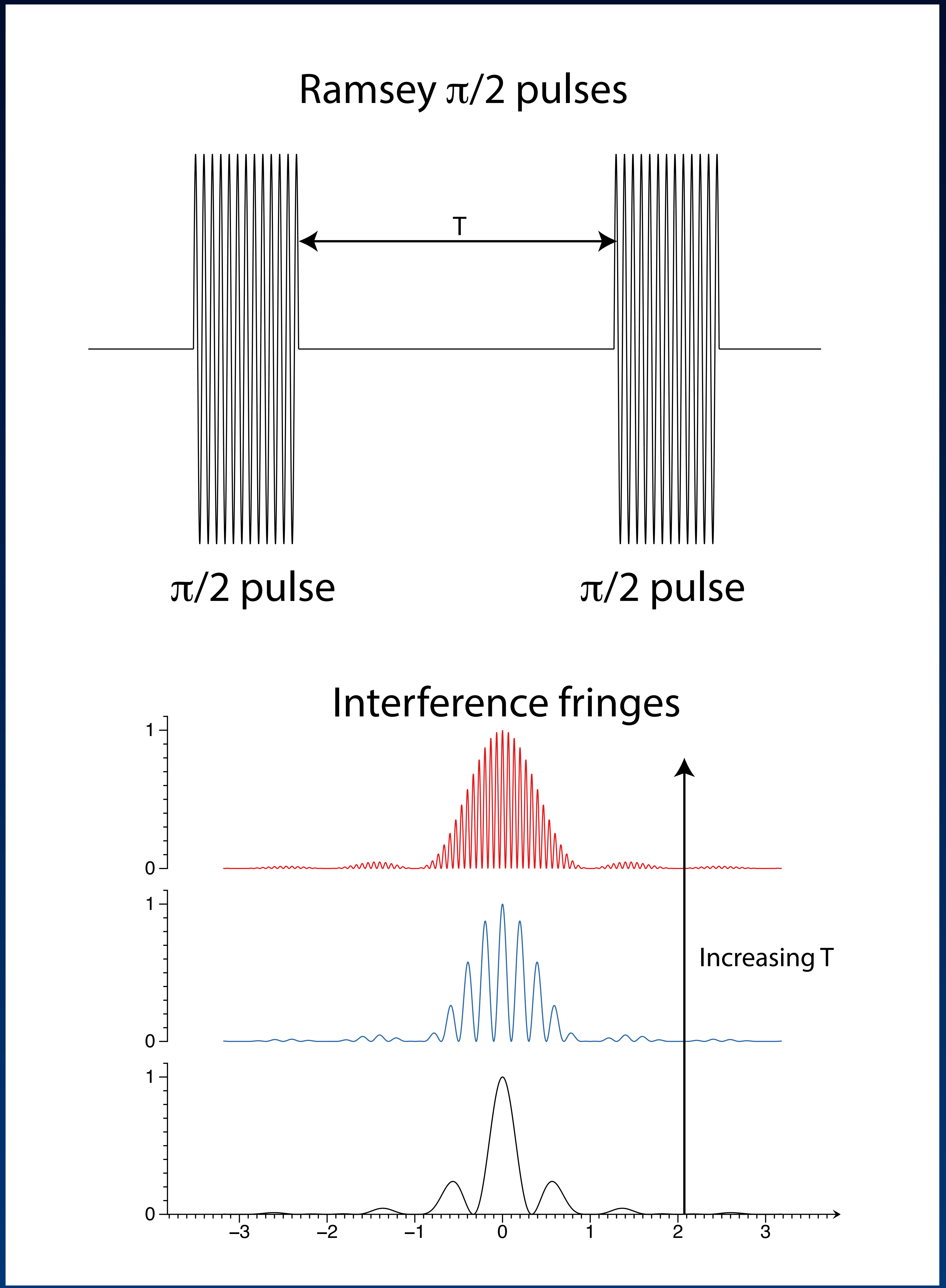
Creates a quantum superposition, creating coherent excitation of all molecules

laser pulse 2:

Measures state of the molecules through interference



Frequency set by external reference, tuned to molecular resonance



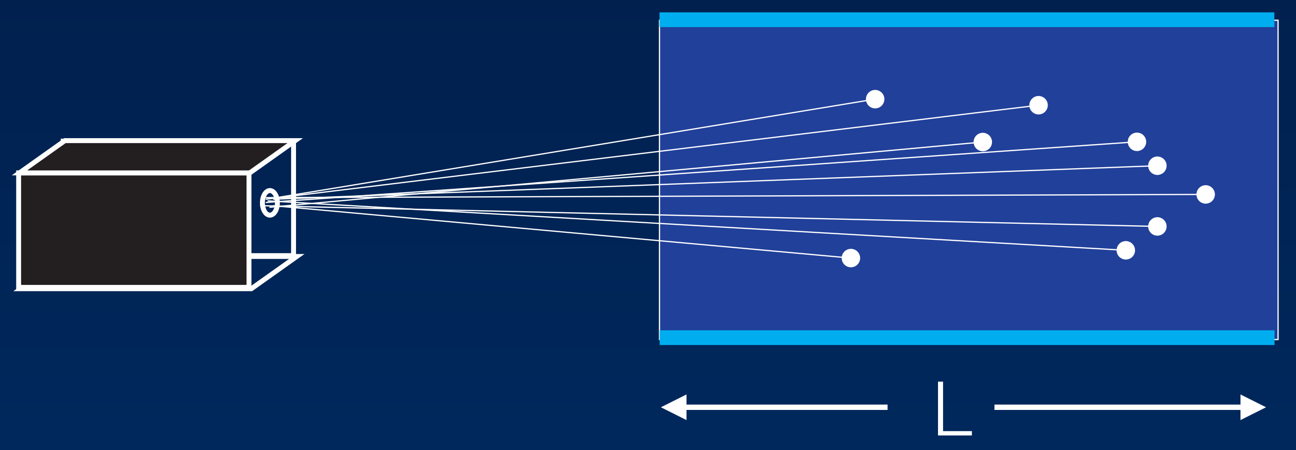
Cold molecules offer longer coherent interaction times

fast beam

τ ~ 1-2 ms

L ~ 0.5 m

v ~ 250-500 m/s



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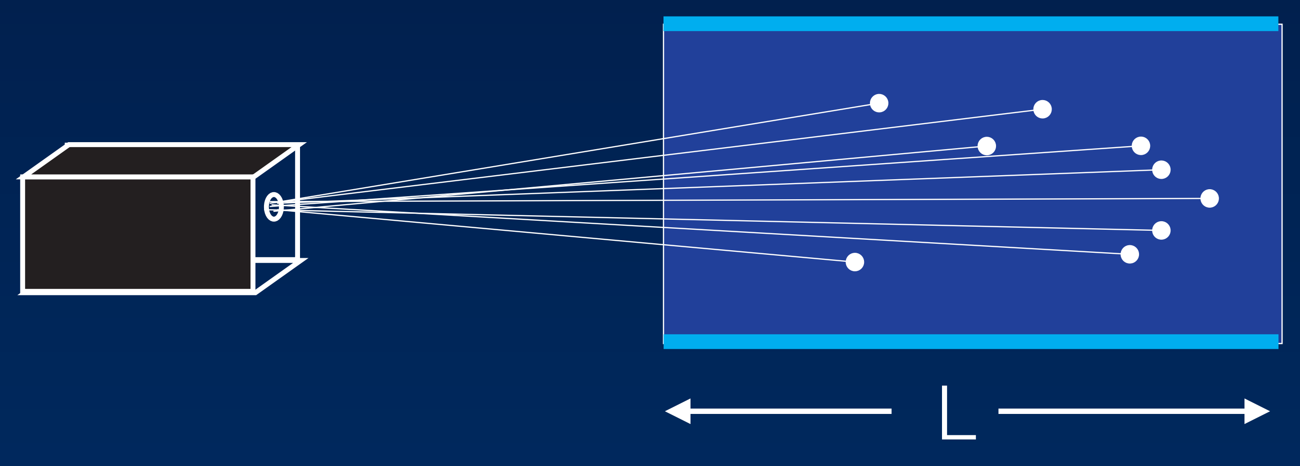

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$\tau \sim$ 15 ms

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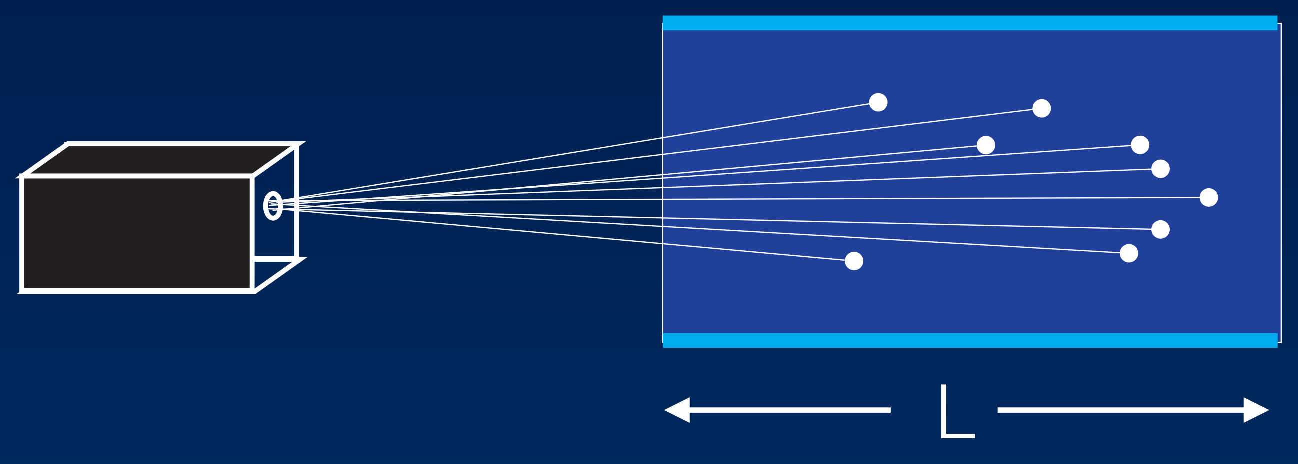

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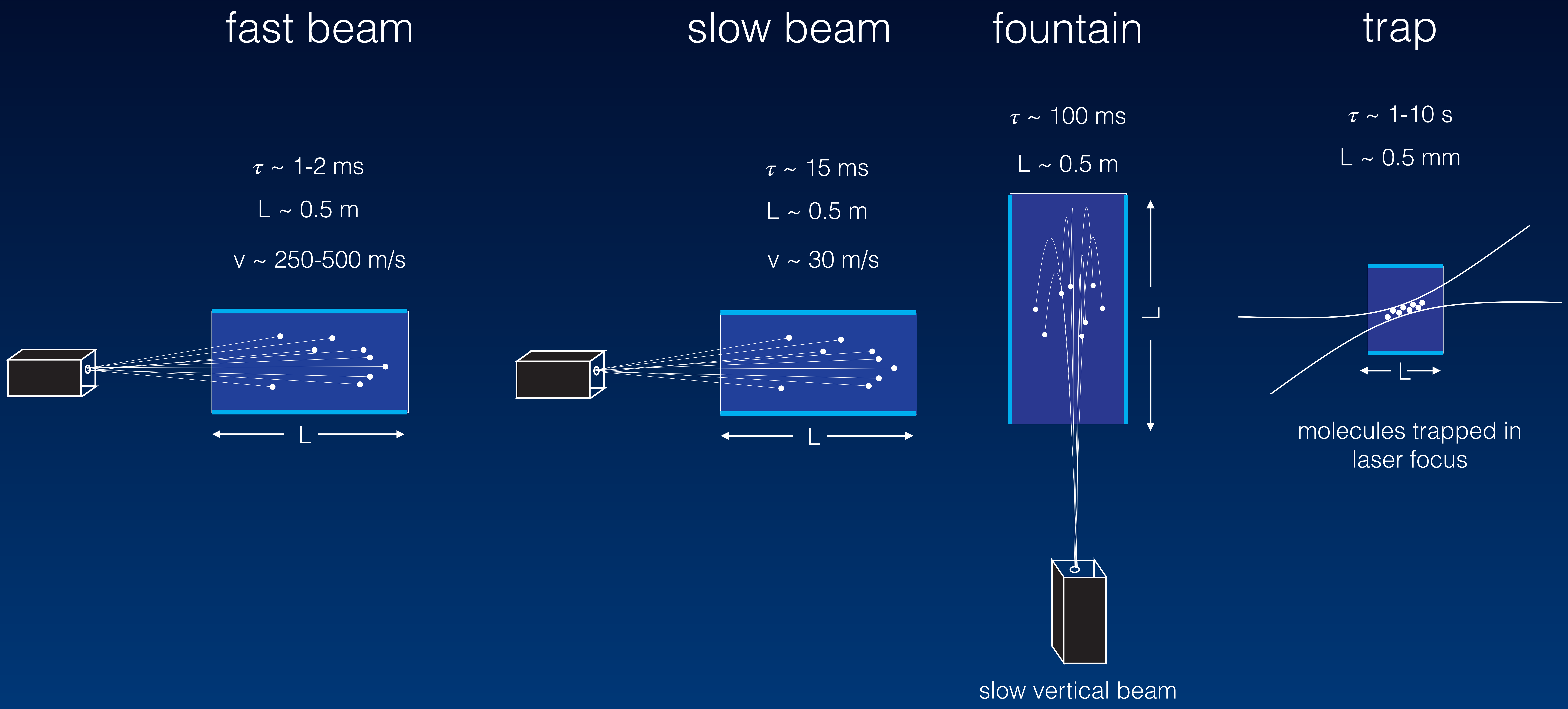

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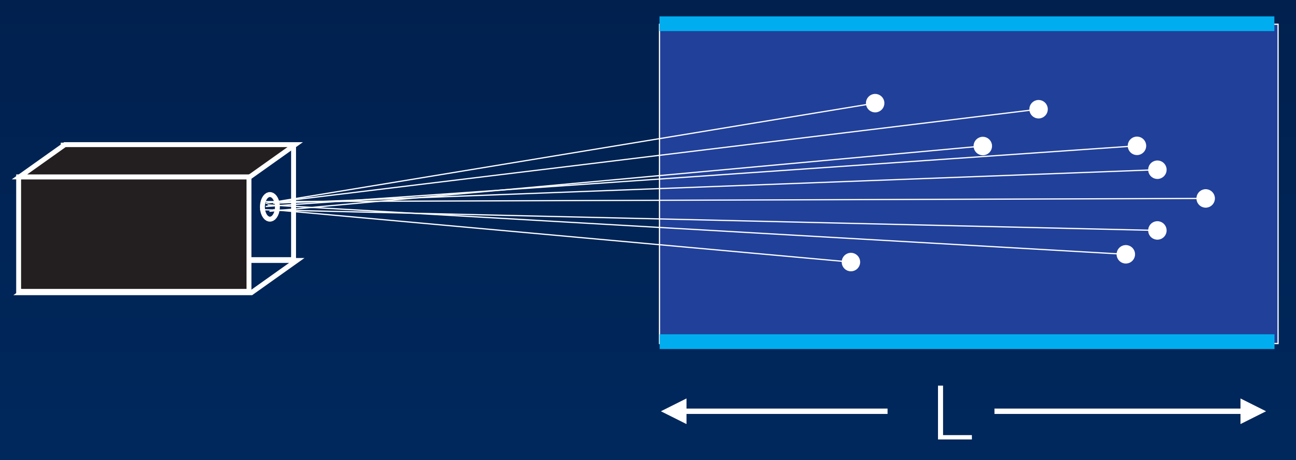

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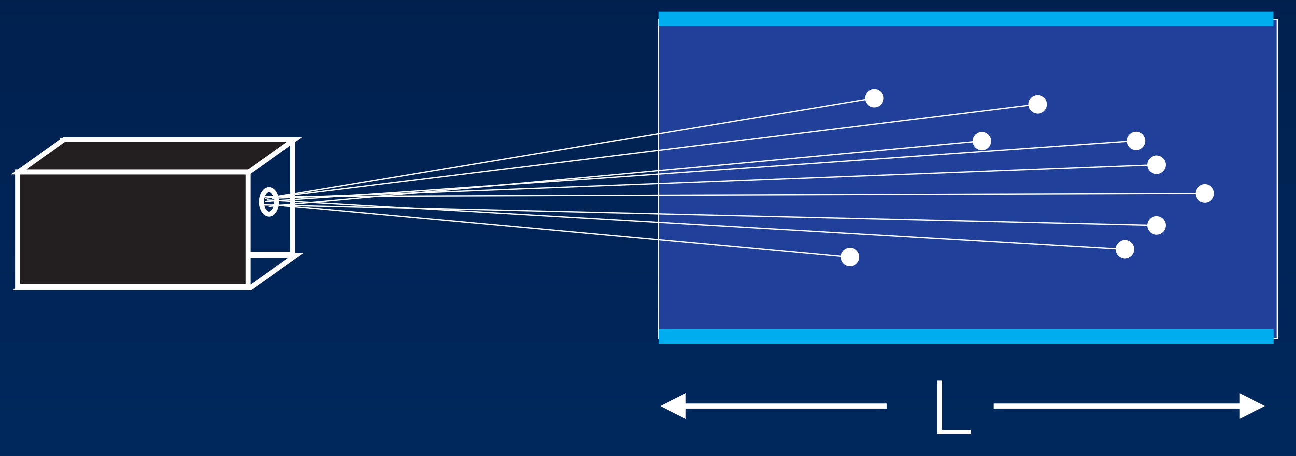
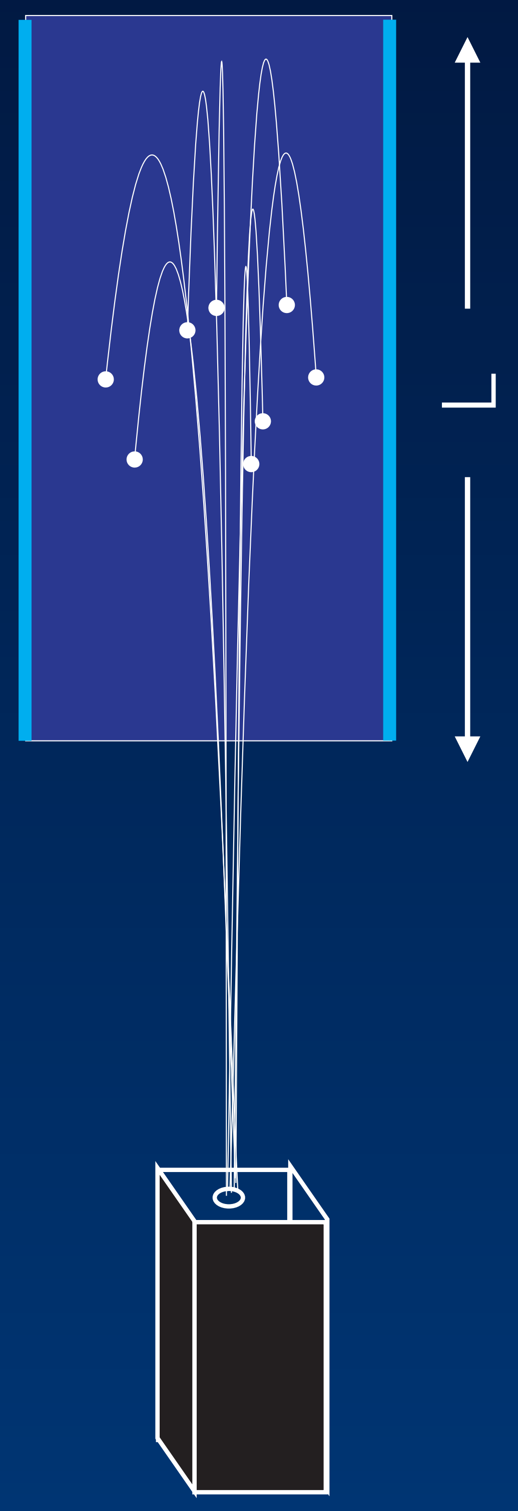


fountain

τ ~ 100 ms

L ~ 0.5 m

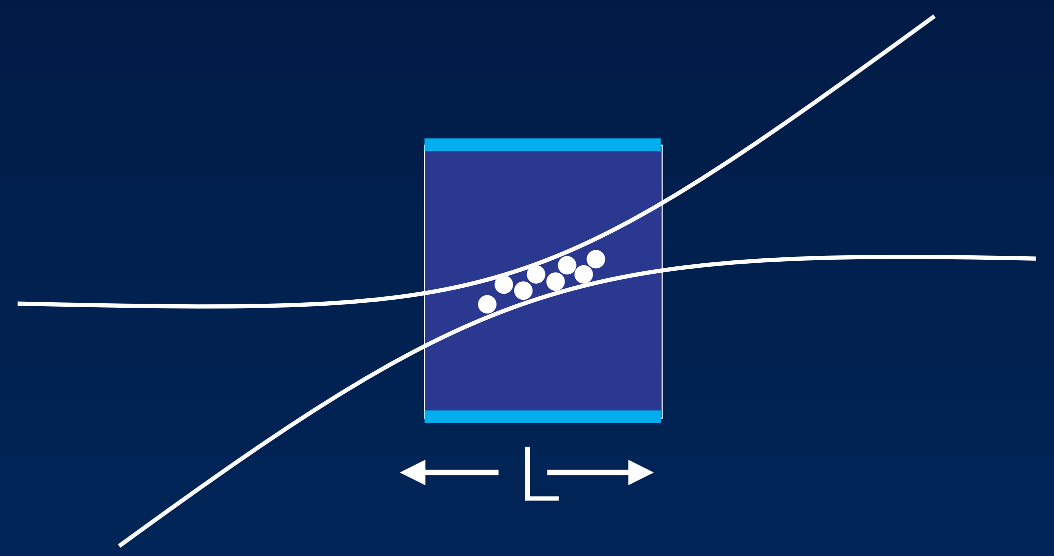


slow vertical beam

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!

Cold molecules offer longer coherent interaction times

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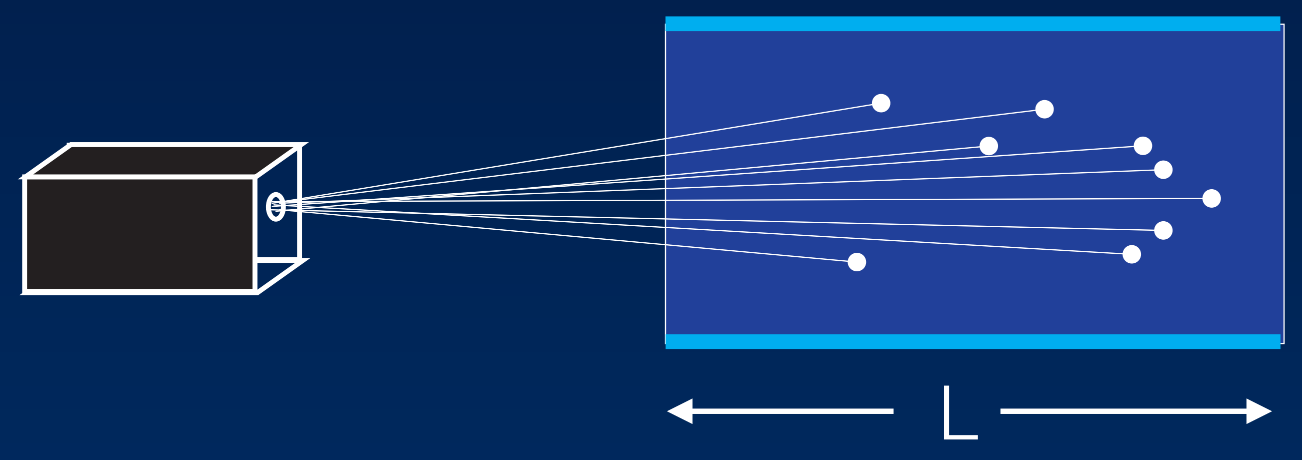

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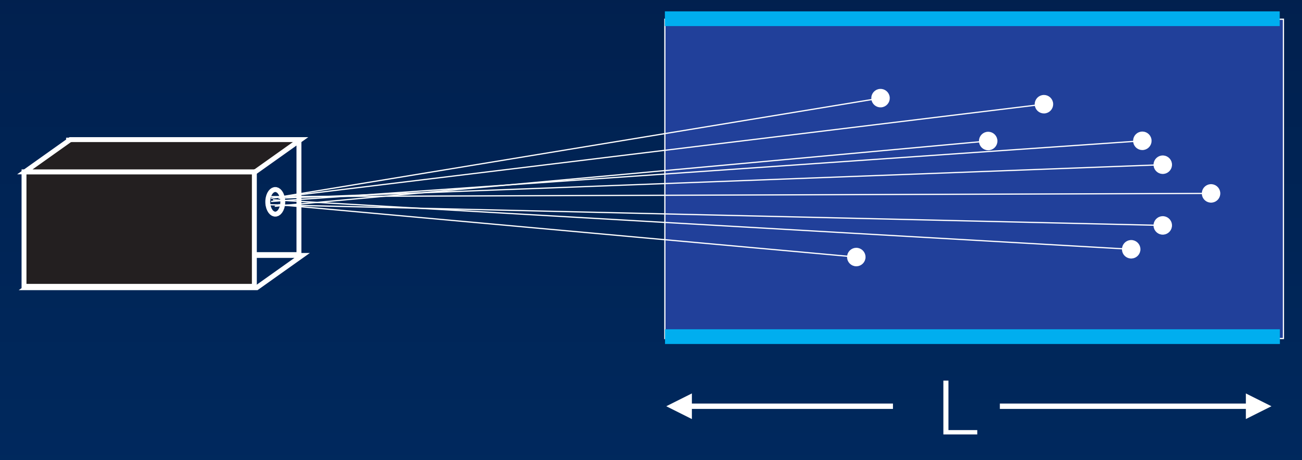

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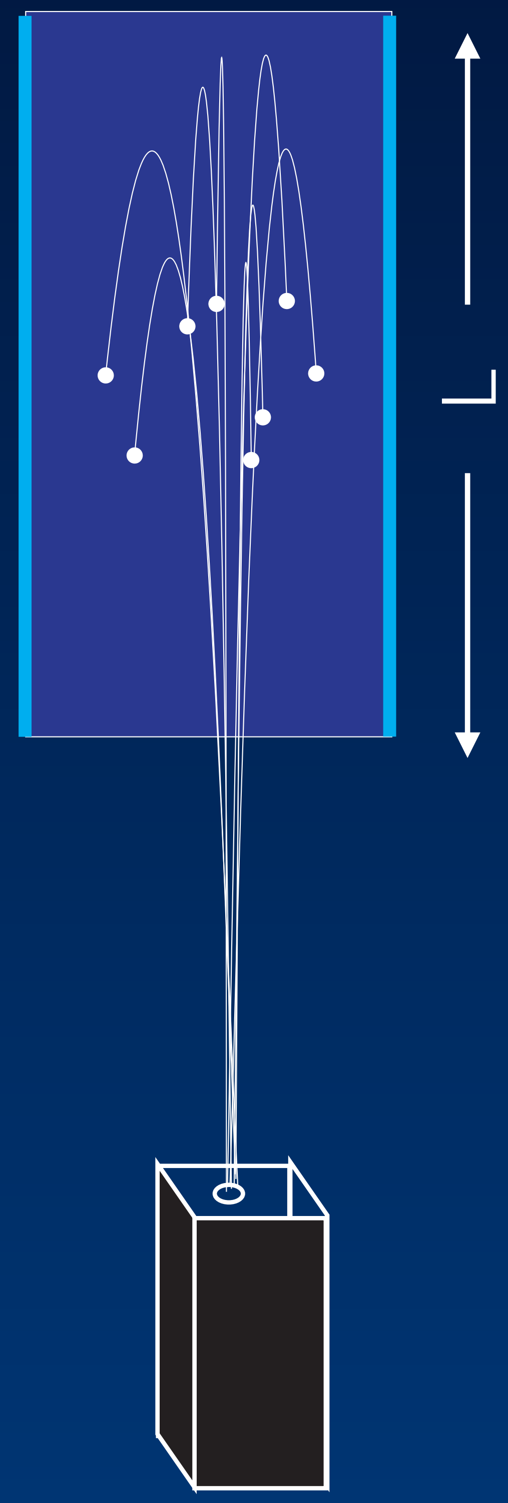
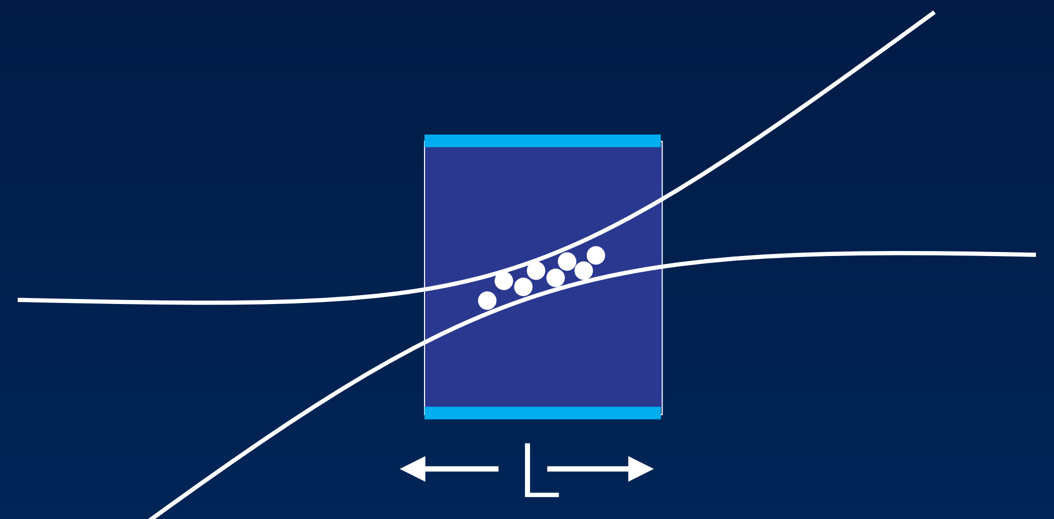


slow vertical beam

trap

τ ~ 1-10 s

L ~ 0.5 mm



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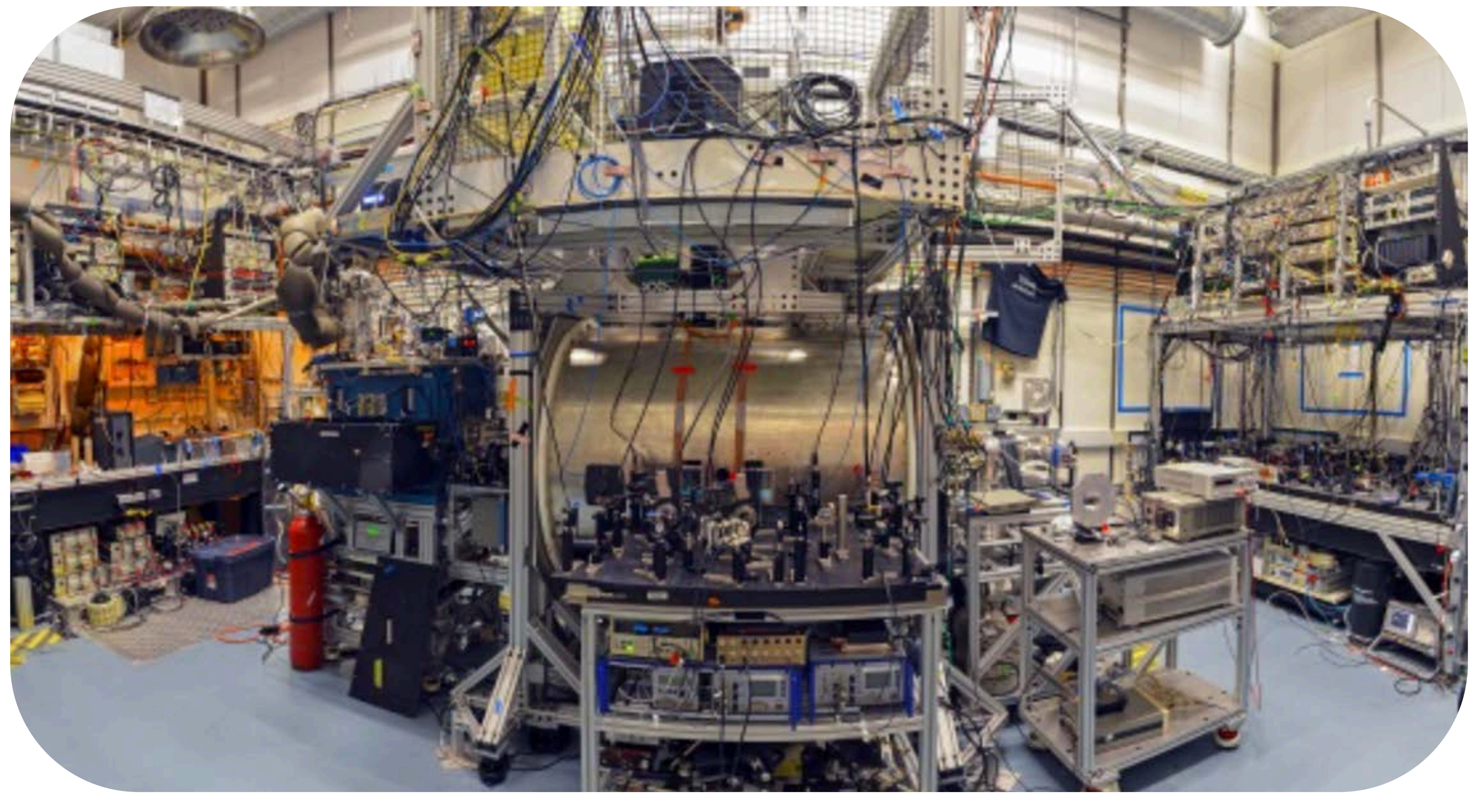
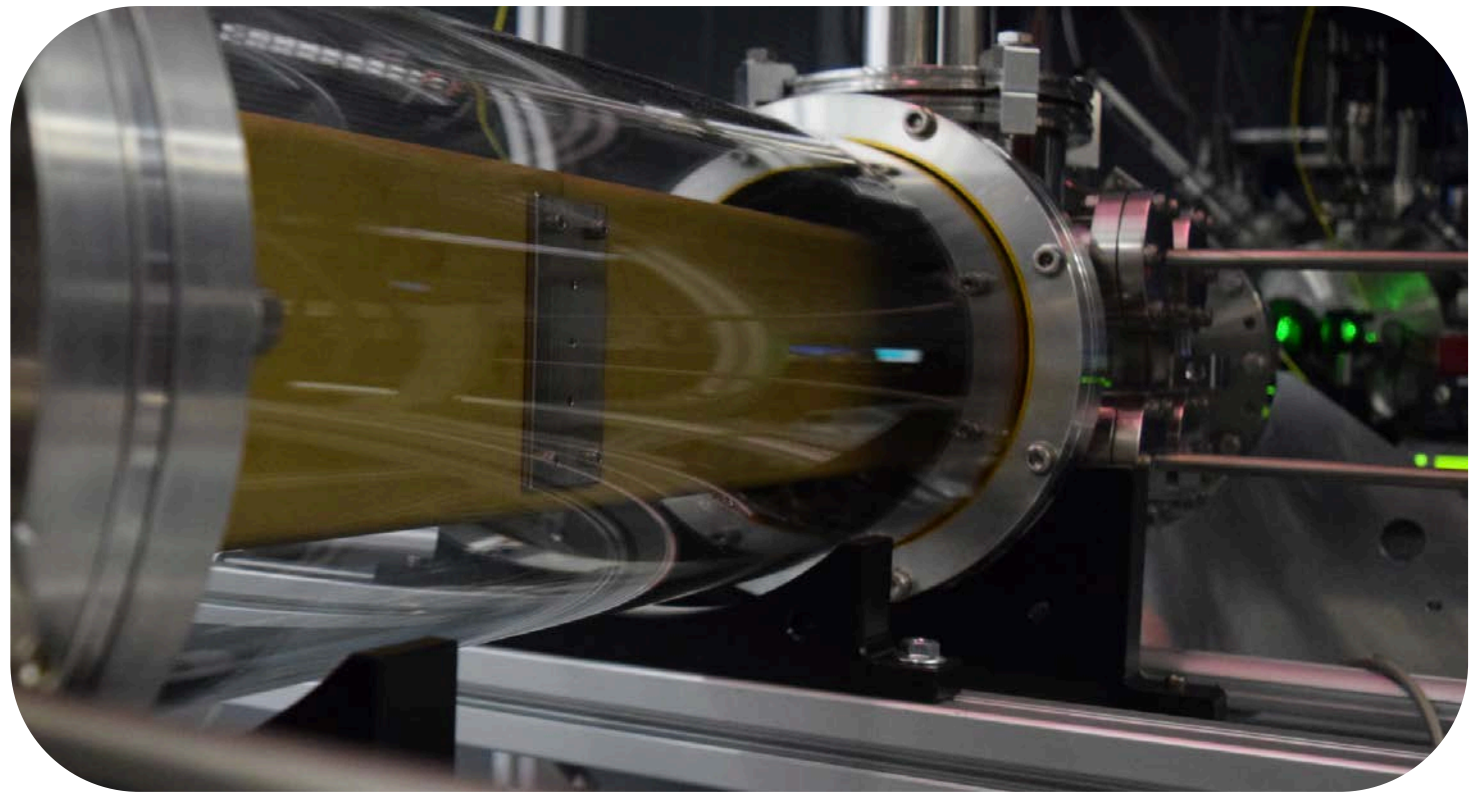
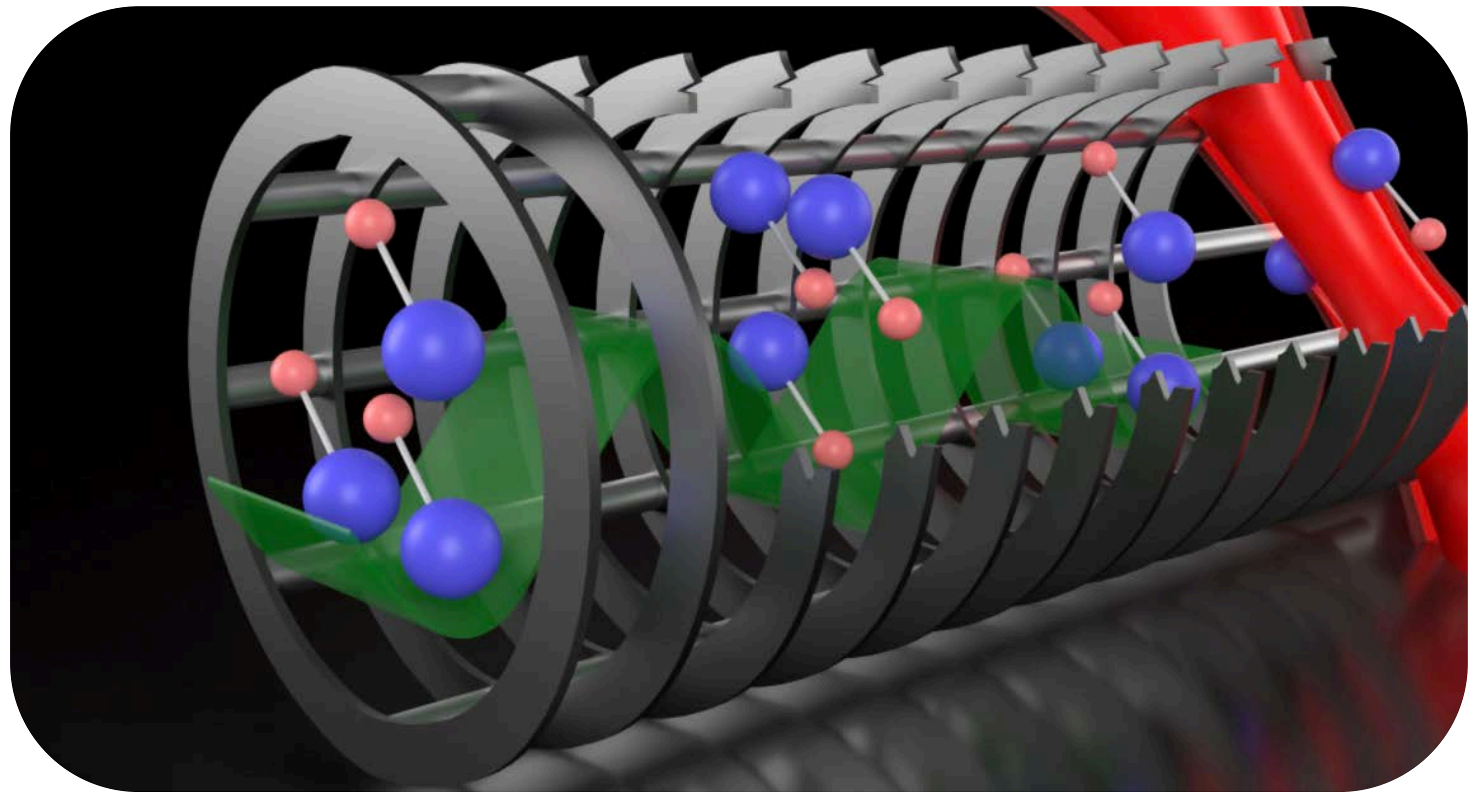
eEDM experiments using molecules



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

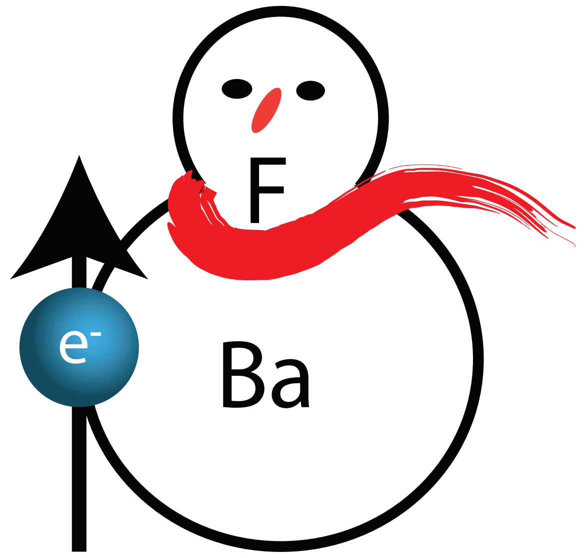


Imperial College London - beam of YbF molecules
Mike Tarbutt, Ben Sauer, Ed Hinds



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

Others are being set up:



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

Search for eEDM in cryogenic crystals

PHYDES:
Para-Hydrogen and Diatomic for eEDM Study

Università degli Studi di Ferrara

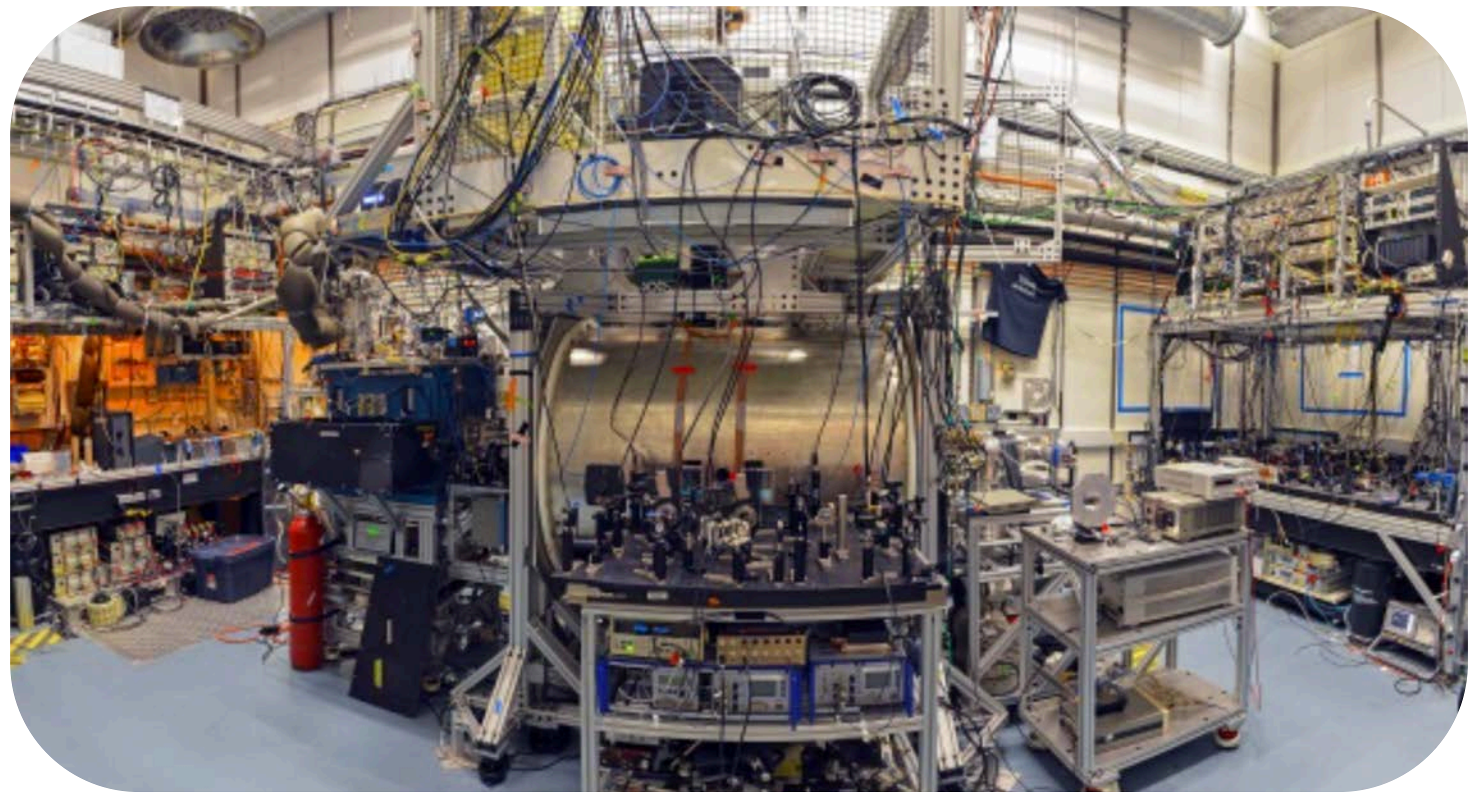
INFN Istituto Nazionale di Fisica Nucleare

Electric Dipole Measurements using Molecules within a Matrix

- York University
- Michigan State University
- University of Toronto

EDM^3 Collaboration

eEDM experiments using molecules



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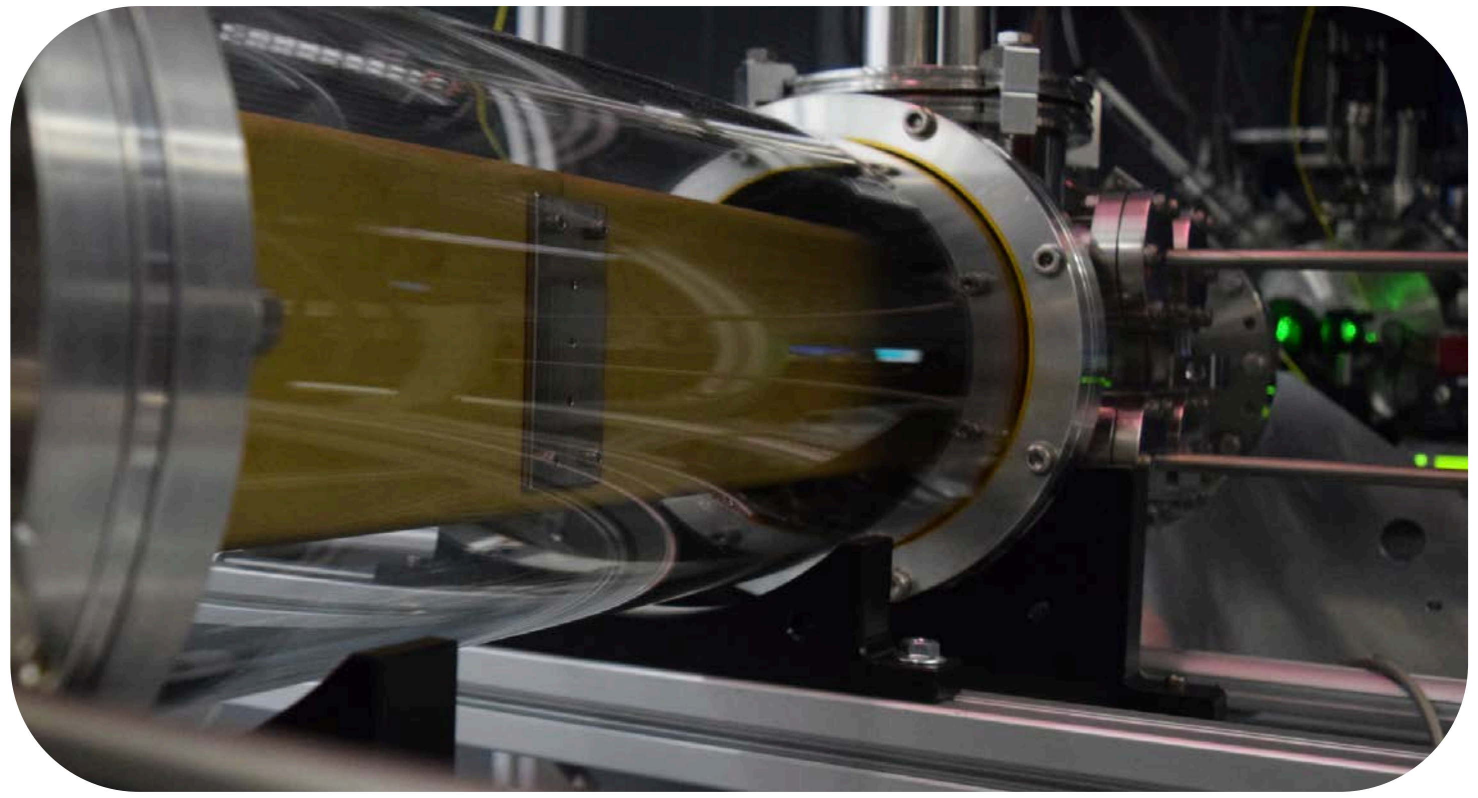

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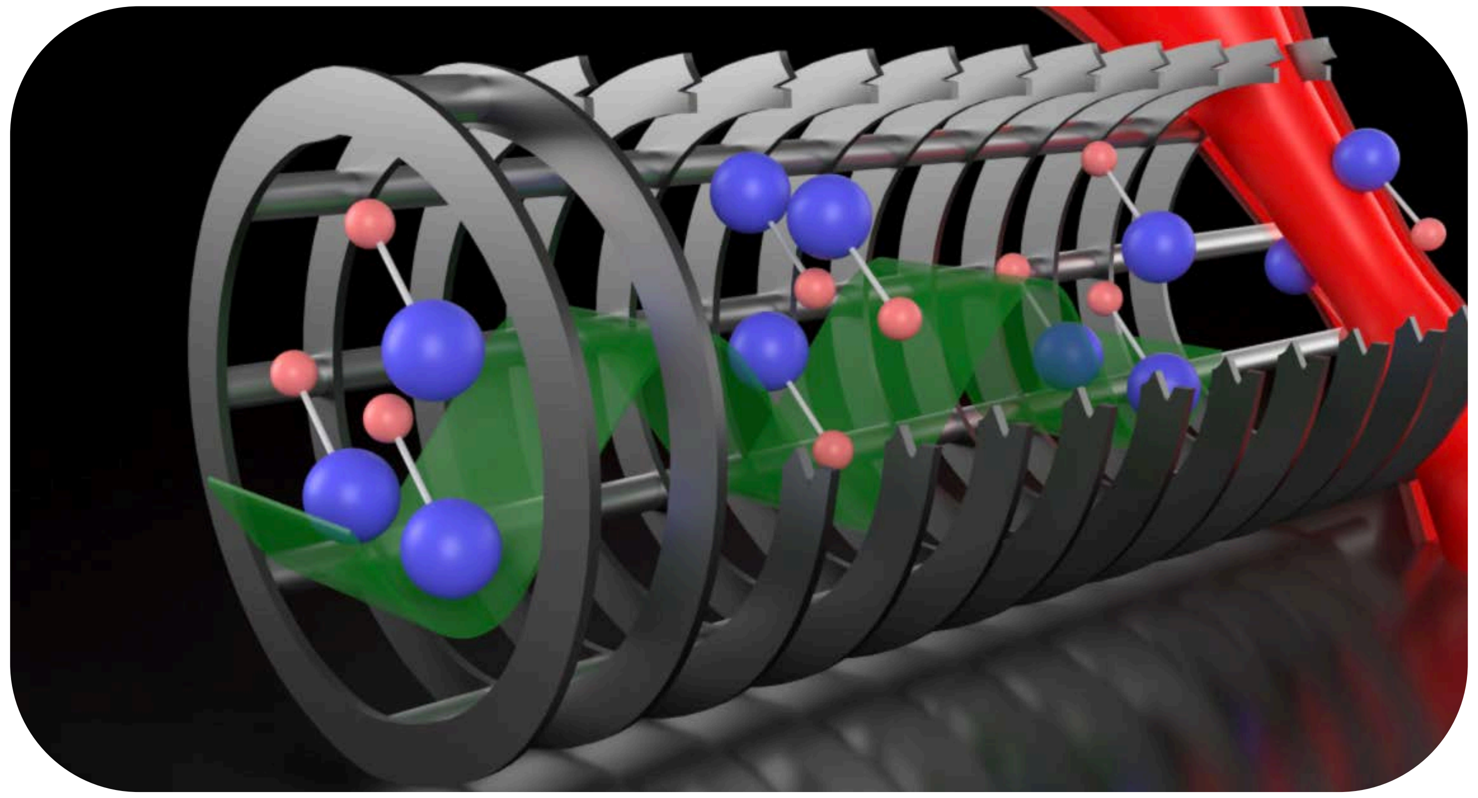

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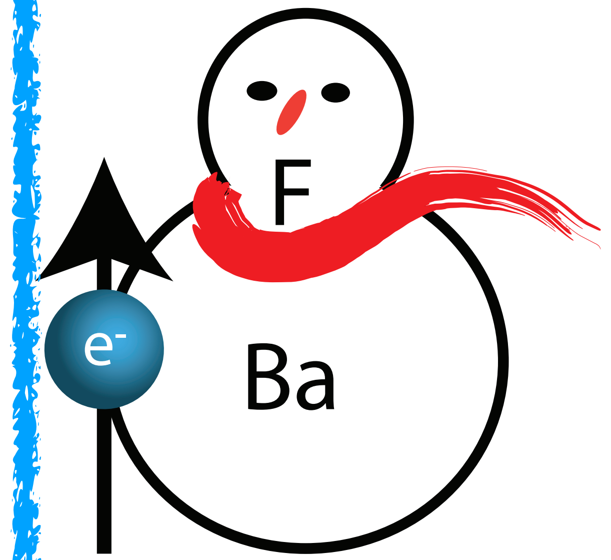

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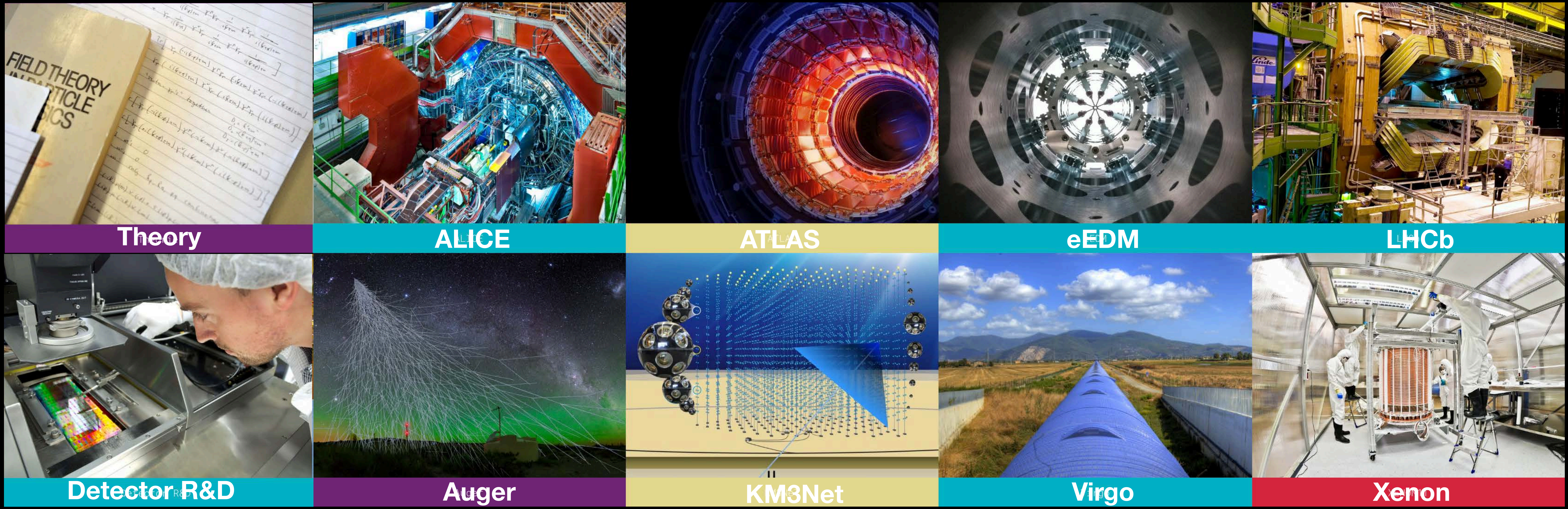
EDM^3 Collaboration

NL-eEDM: A Nikhef research programme started in 2017…

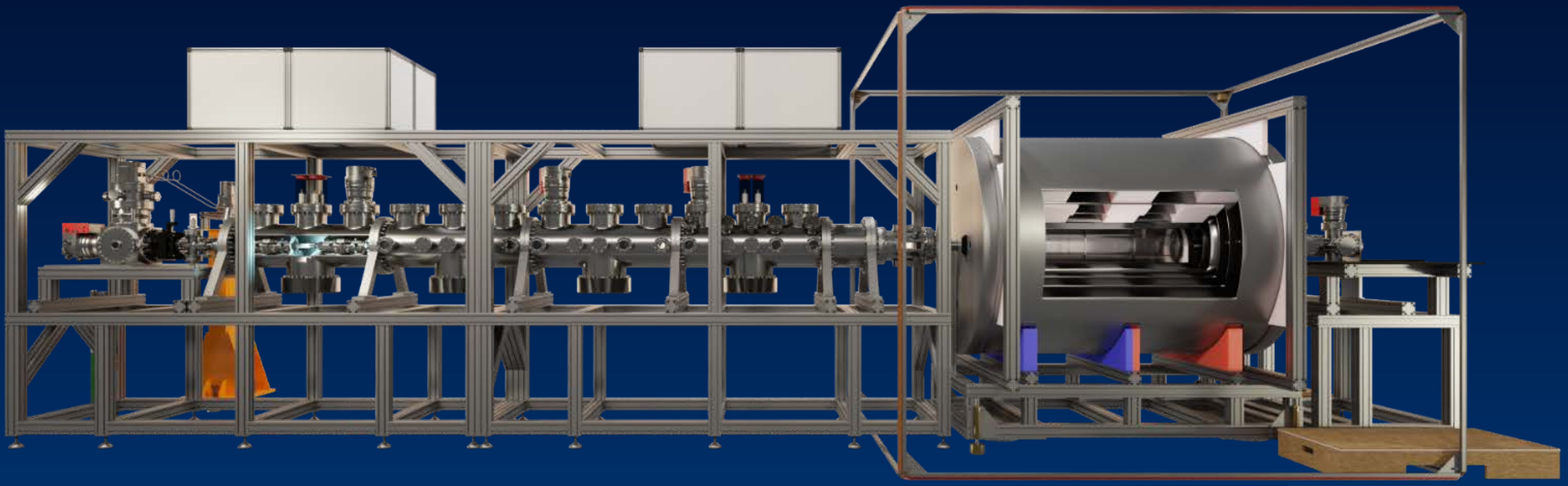


Nikhef

Dutch National Institute for (astro)Particle Physics

…using slow BaF molecules and lasers!

Cold molecules offer longer coherent interaction times



The NL-eEDM collaboration, Measuring the electric dipole moment of the electron in BaF, *European Phys J D* **72**, 197 (2018).

university of groningen
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Dutch National Institute for (astro)Particle Physics

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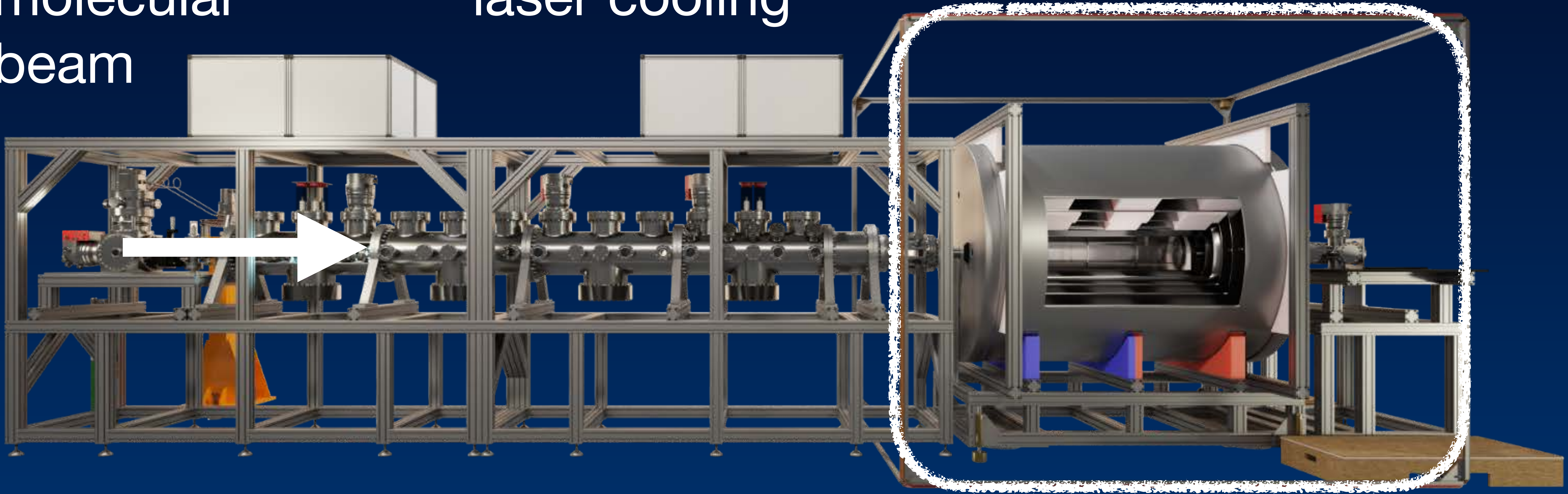
Cold molecules offer longer coherent interaction times

Pulsed molecular beam

deceleration & laser cooling

spin interferometer to probe eEDM



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Cold molecules offer longer coherent interaction times

F
e⁻
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van swinderen institute for particle physics and gravity
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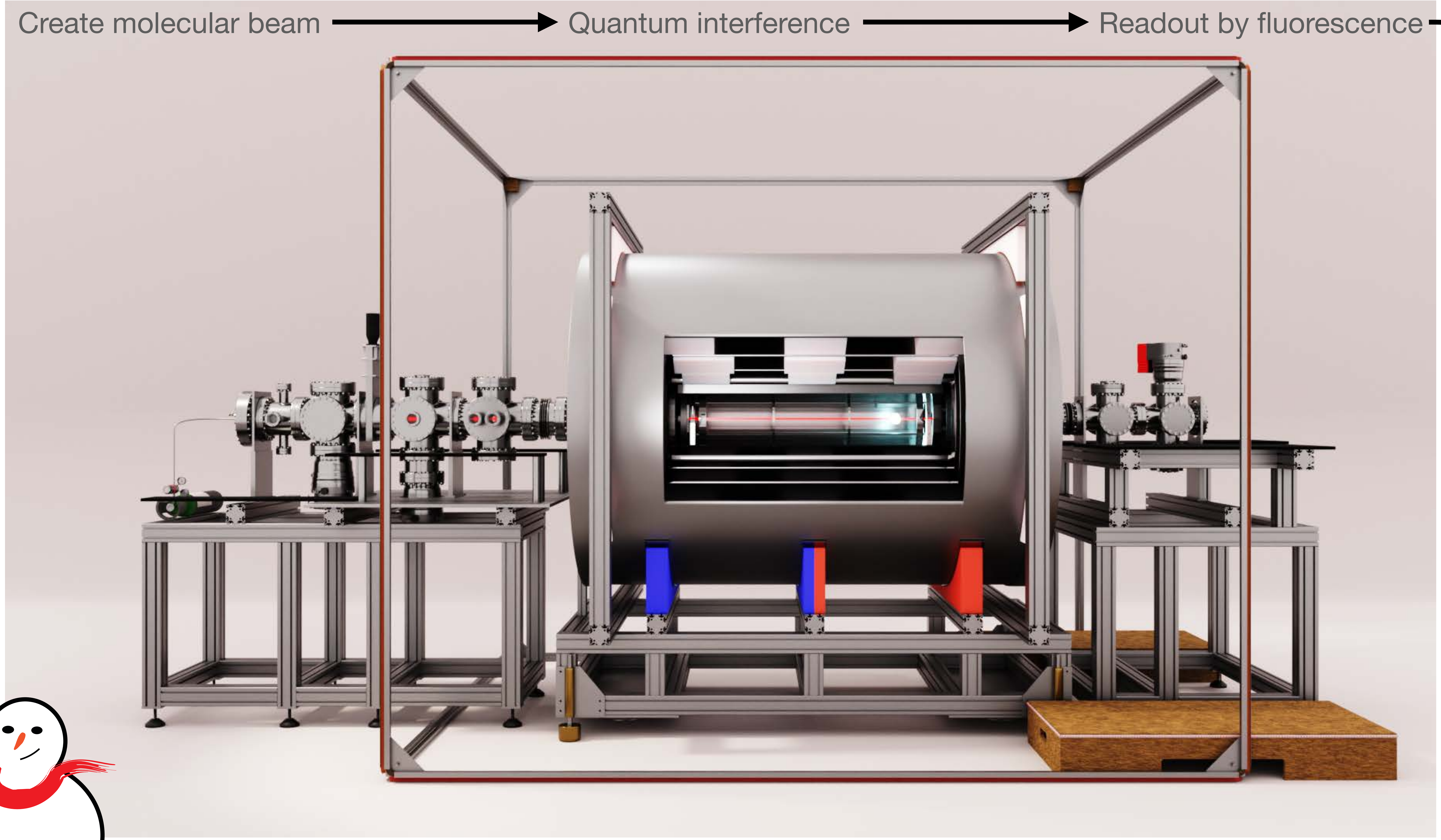
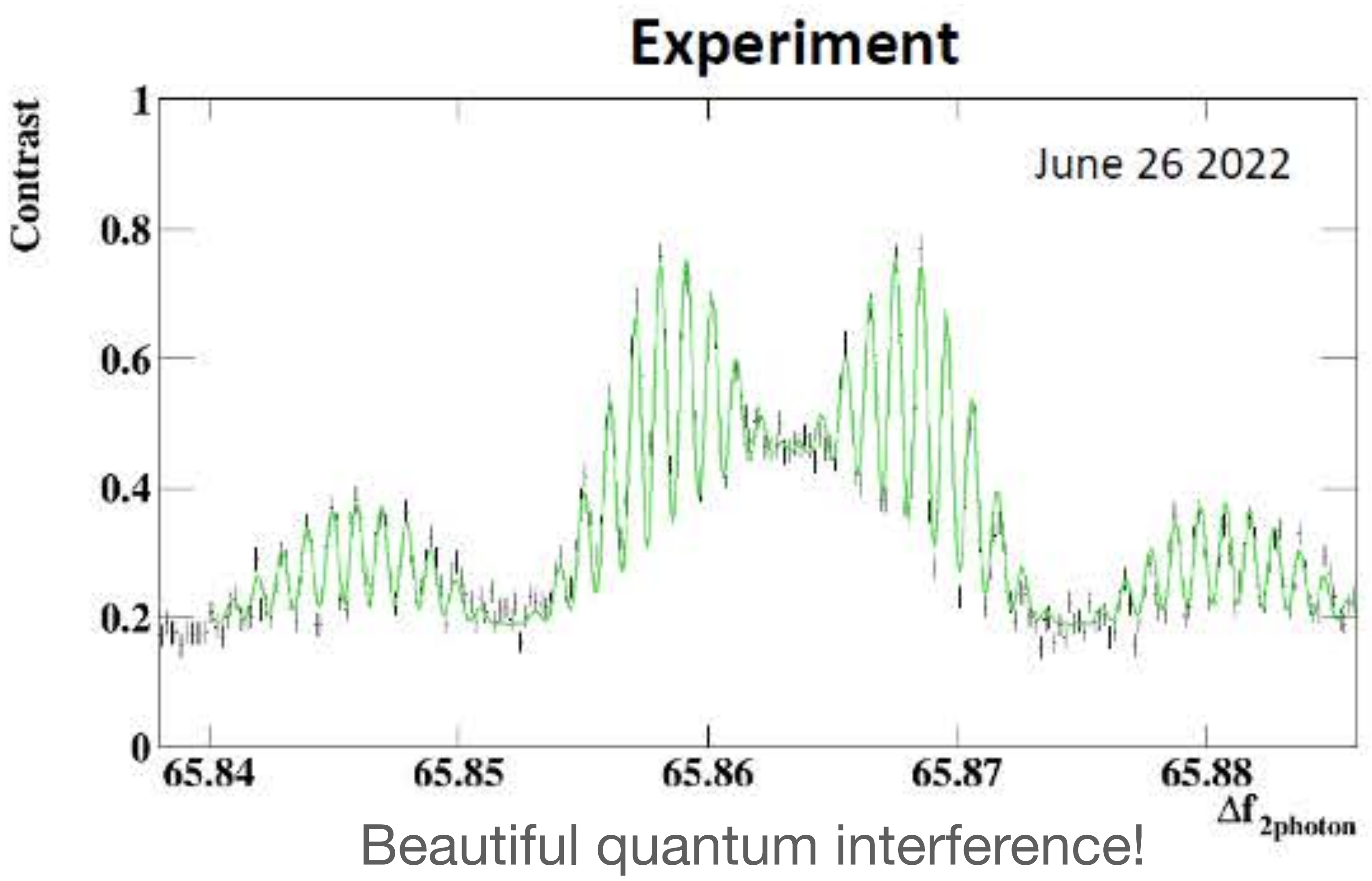
Interference data using fast molecular beam

to demonstrate control over systematic effects



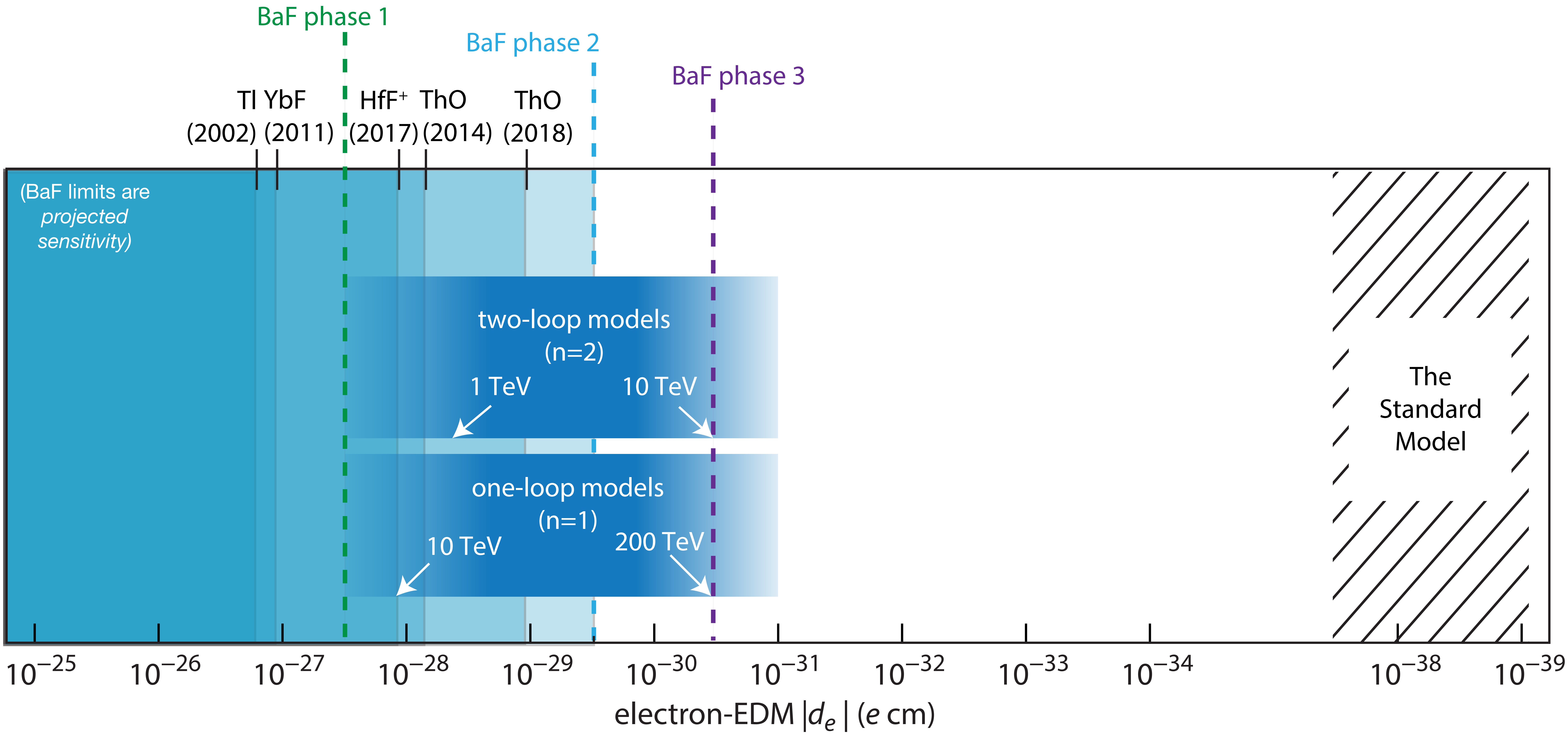
Compare to theory that includes the full interaction of the molecule with light, electric and magnetic fields (optical Bloch equations)



Beautiful quantum interference!

Contains all relevant experimental parameters
Crucial for reduction of systematic effects
(A.Boeschoten et al, NL-eEDM collaboration, in prep.)

… and a corresponding increase in eEDM sensitivity!



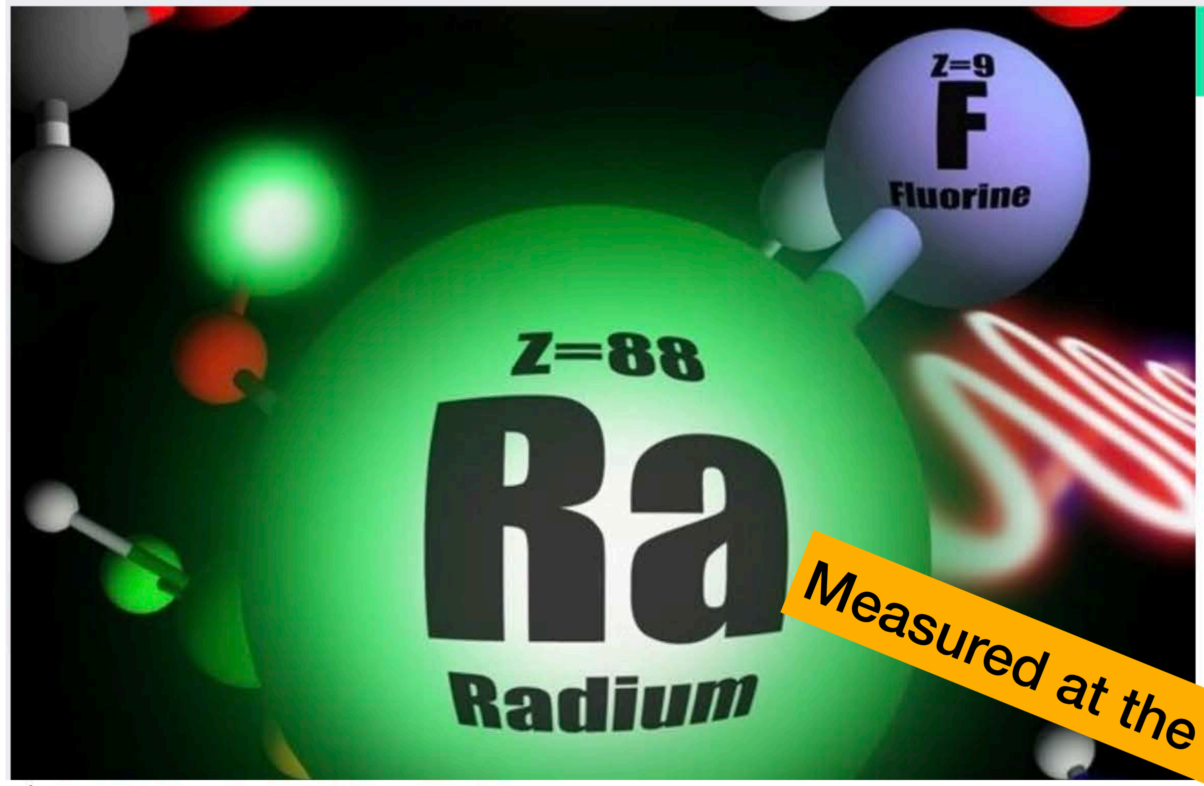
The choice of molecule

Exciting developments - some examples

Molecules containing radioactive elements

Proposal:

Isaev, T. A., Hoekstra, S. & Berger, R. Laser-cooled RaF as a promising candidate to measure molecular parity violation, Phys Rev A 82, 052521 (2010).



IN THE NEWS

Physicists measure a short-lived radioactive molecule for first time

Molecules containing heavy and deformed radioactive nuclei may help scientists to measure symmetry-violating phenomena and identify signs of dark matter.

Measured at the ISOLDE ion-beam facility at CERN!

Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

R. F. Garcia Ruiz, R. Berger, J. Billowes, C. L. Binnersley, M. L. Bissell, A. A. Breier, A. J. Brinson, K. Chrysalidis, T. E. Cocolios, B. S. Cooper, K. T. Flanagan, T. F. Giesen, R. P. de Groote, S. Franchoo, F. P. Gustafsson, T. A. Isaev, Á. Koszorús, G. Neyens, H. A. Perrett, C. M. Ricketts, S. Rothe, L. Schweikhard, A. R. Vernon, K. D. A. Wendt, F. Wienholtz, S. G. Wilkins & X. F. Yang — Show fewer authors

Nature **581**, 396–400 (2020) | Cite this article

Polyatomic molecules

Proposal:

Kozyryev, I. & Hutzler, N. R. Precision Measurement of Time-Reversal Symmetry Violation with Laser-Cooled Polyatomic Molecules, Physical Review Letters 119, 133002 (2017).

PolyEDM

Polyatomic Electron EDM Search

John M. Doyle

Harvard University

Nick Hutzler

Caltech

Tim Steimle

Arizona State University

Amar Vutha

University of Toronto

Advanced cooling techniques

Direct laser cooling - now extending to heavier and more complex species

Anderegg *et al.*, *Science* **365**, 1156–1158 (2019)

COLD MOLECULES

An optical tweezer array of ultracold molecules

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nature physics

LETTERS

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Molecules cooled below the Doppler limit

S. Truppe, H. J. Williams, M. Hambach, L. Caldwell, N. J. Fitch, E. A. Hinds, B. E. Sauer and M. R. Tarbutt*

Trapping of C_2^- in a digital ion trap

Alexander Hinterberger, Sebastian Gerber, Emanuel Oswald, Christan Zimmer, Julian Fesel and Michael Doser

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Journal of Physics B: Atomic, Molecular and Optical Physics, Volume 52, Number 22

Towards laser cooling of molecular anions - for antimatter physics

Advanced cooling techniques

Exciting developments - some examples

A molecular fountain

PRL **117,** 253201 (2016) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2016

Molecular Fountain

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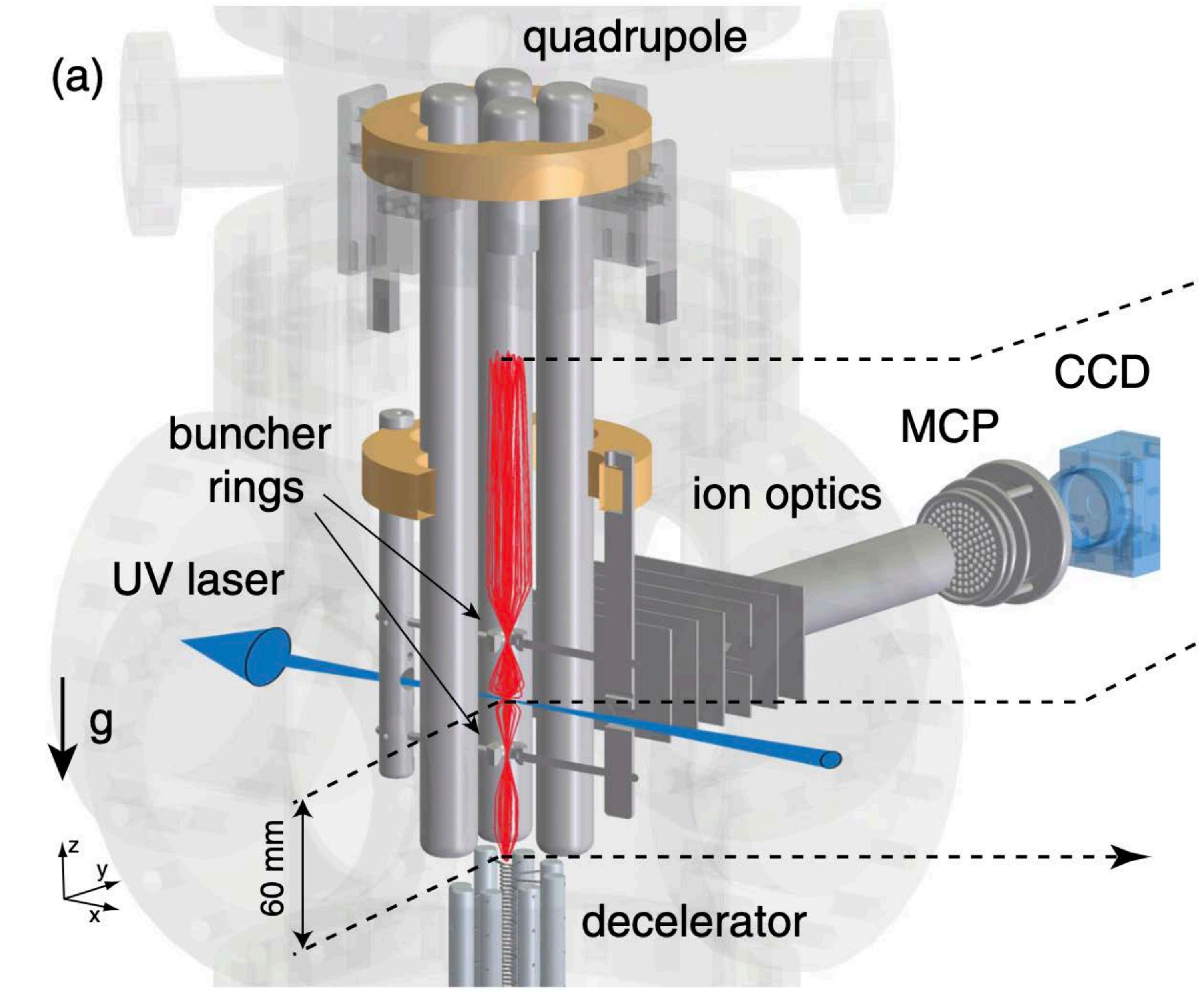

Deceleration and trapping of heavy diatomic molecules

PHYSICAL REVIEW LETTERS **127,** 173201 (2021)
Featured in Physics

Deceleration and Trapping of SrF Molecules

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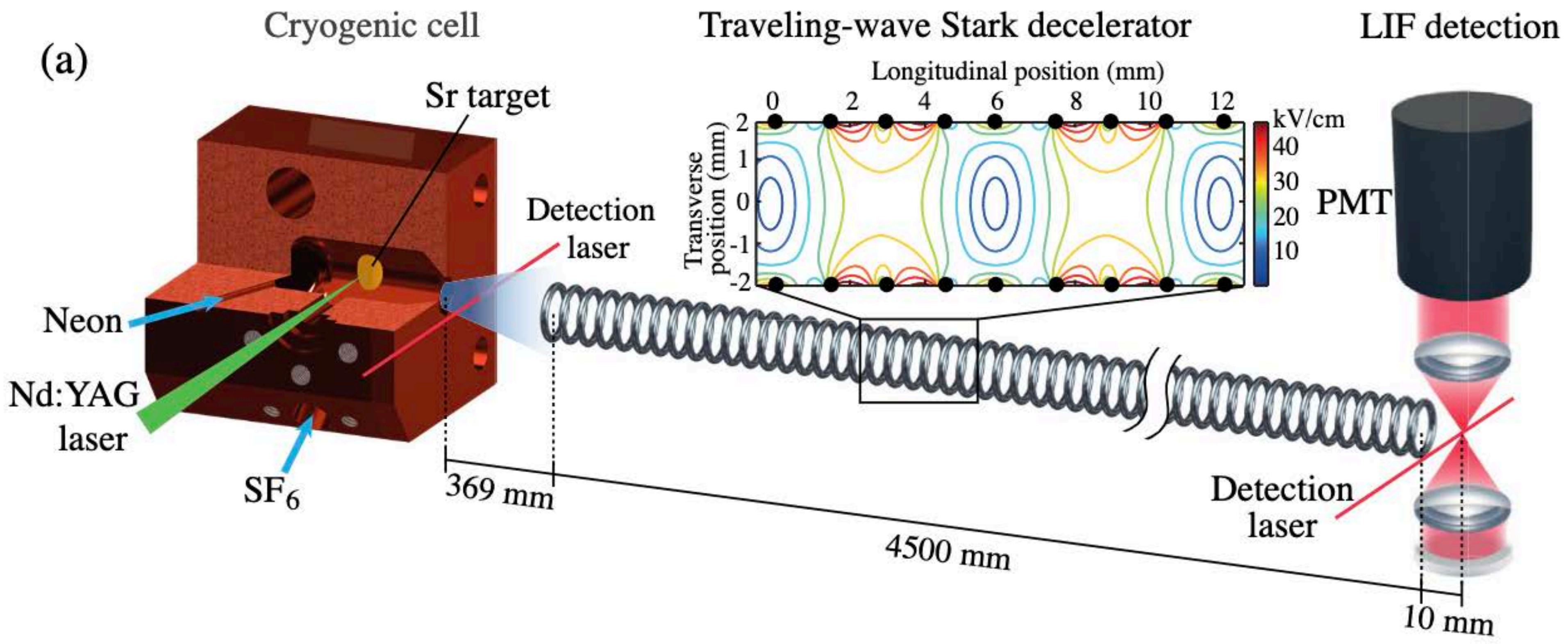
(NL-*e*EDM Collaboration)



Outlook: beyond Ramsey interferometry

Make use of entanglement and squeezing techniques

Science 352, 1552–1555 (2016)

REPORTS

QUANTUM PHYSICS

Quantum phase magnification

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Quantum metrology exploits entangled states of particles to improve sensing precision beyond the limit achievable with uncorrelated particles. All previous methods required detection noise levels below this standard quantum limit to realize the benefits of the intrinsic sensitivity provided by these states. We experimentally demonstrate a widely applicable method for entanglement-enhanced measurements without low-noise detection. The method involves an intermediate quantum phase magnification step that eases implementation complexity. We used it to perform squeezed-state metrology 8 decibels below the standard quantum limit with a detection system that has a noise floor 10 decibels above the standard quantum limit.

NL-eEDM: Teamwork!

university of groningen
van swinderen institute for particle physics and gravity

Nikhef
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