Electric **D**ipole moment **M**easurements using **M**olecules in a **M**atrix (EDM^3)

Eric Hessels

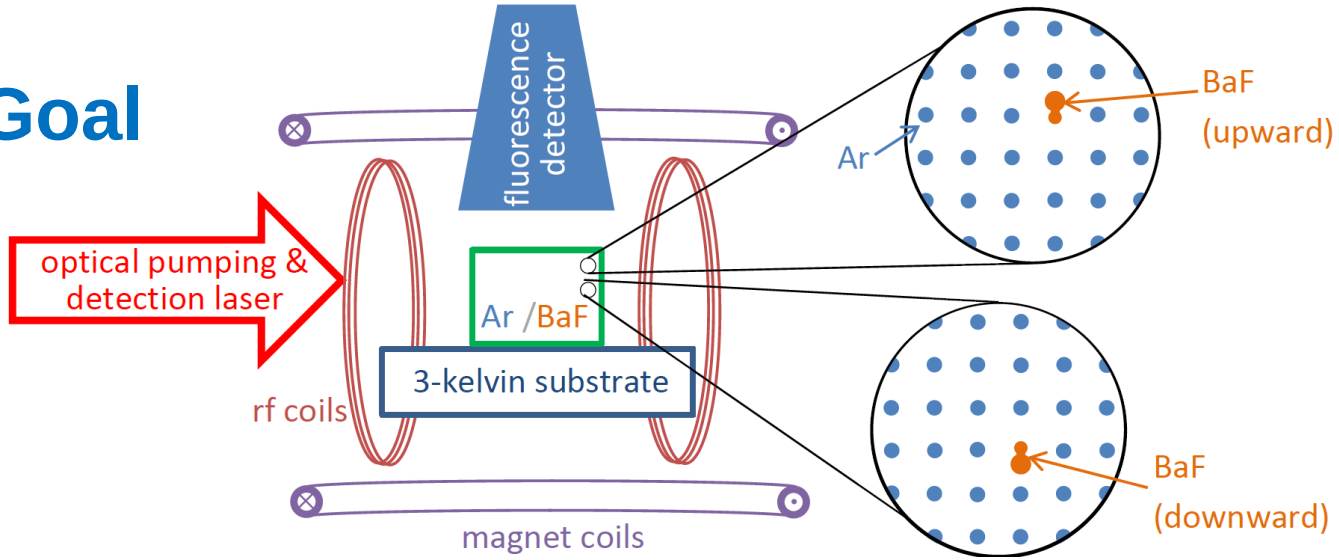
Supported by:

Canada Foundation for Innovation
Ontario Research Fund } (2022-2025) $6.7M equipment funding

Gordon and Betty Moore Foundation
Alfred P. Sloan Foundation
Templeton Foundation
York University } (2018-2023) $2.6M seed funding

NSERC Subatomic Project Grants (2019-2027) $1.1M continuing funding

Our Goal



EDM^3 aims to make electron electric dipole moment (d_e) measurements using BaF molecules embedded in cryogenic solid argon

Use a large number of (~1ppb BaF:Ar, ~1mm^3, ~10^{11} BaF)

Molecular orientation fixed by matrix – no need for external E field

Systematic effects for d_e measurement are expected to be favorable:
small volume, cold, stationary

Has the potential to improve d_e limit by 3 orders of magnitude (or more)

Some Numbers

The statistically accuracy of d_e is limited to: $\delta d_e = \frac{\hbar}{2 E_{\text{eff}} \sqrt{N T}}$

A total (integrated) N electrons that precess for a time T

E_{eff} is the effective field in the polar molecule, <~100GV/cm for polar molecules of interest -- need large N and T

Current limit: JILA (HfF^+): $|d_e| < 4.1 \times 10^{-30}\, e$ cm $N \sim 10^8$; $T \sim 1$ s

We are using BaF: $E_{\text{eff}} = 6.5$ GV/cm

10^{11} BaF used 10^8 times (every 30 ms for 1 month): N of up to 10^{19}

Precession time of T=10 ms, could lead to $\delta d_e < 10^{-32}\, e$ cm

Potential for a very precise measurement

Even higher precision imaginable for larger numbers of molecules, a molecule with higher E_{eff} and more months of data collection

Can dream of limits as low as $10^{-35}\, e$ cm (SM prediction)

Motivation (why measure an electron EDM?)

Test physics beyond the Standard Model

Most extension to the SM predict a $d_e >> 10^{-35}\ e\,\text{cm}$ (due to CP violation needed to explain matter/antimatter asymmetry)

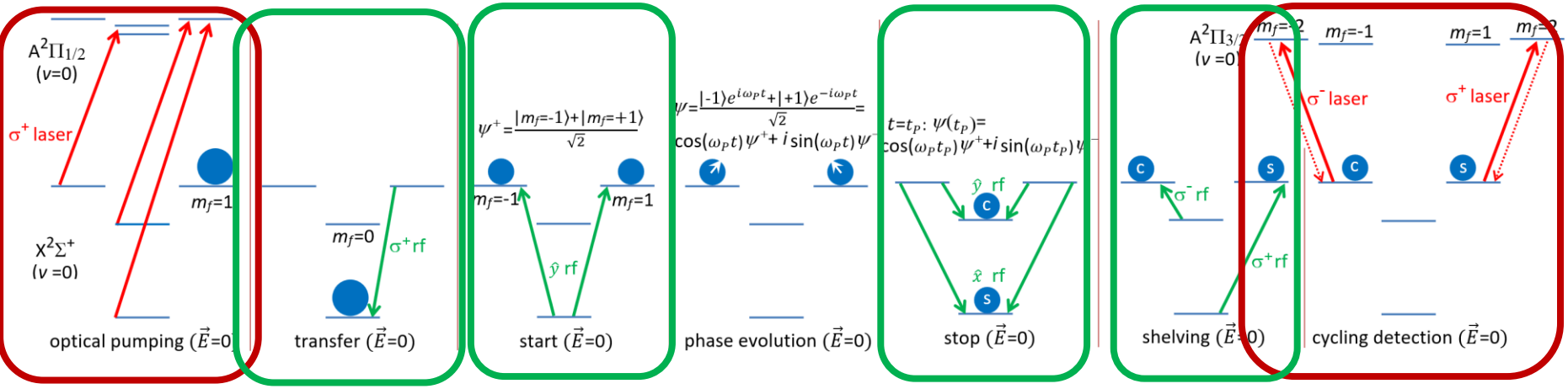
More precise measurement of d_e would guide SM extensions

Current limit on d_e already tests physics at >10-TeV level

A 10^3 improvement would test physics at 30 times higher energies – approaching PeV energies

Measurement Scheme

Similar to other d_e measurements – except with molecules frozen into an argon solid



Use lasers to optically pump molecules into one hyperfine state and to detect with laser-induced fluorescence

Use rf to transfer populations between hyperfine states

What Has Been Accomplished to Date?

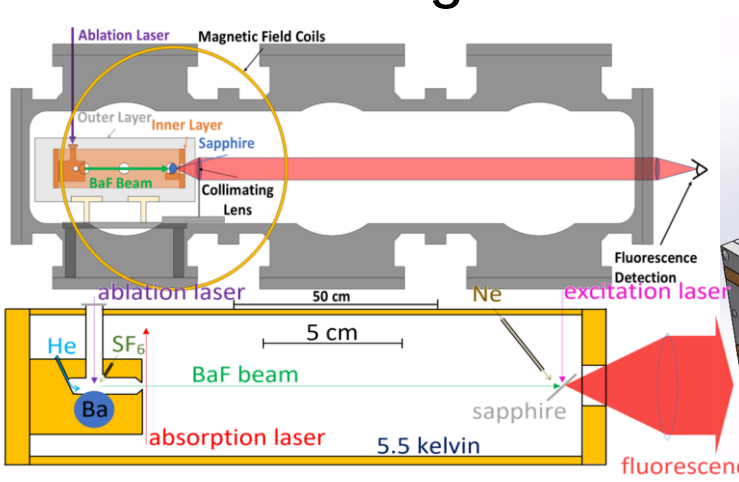
Assembled a team

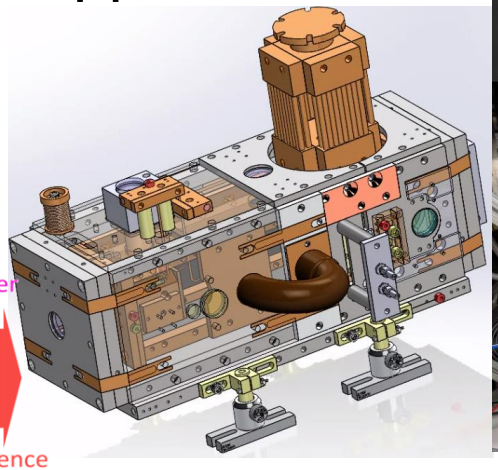
Physics/Chemistry

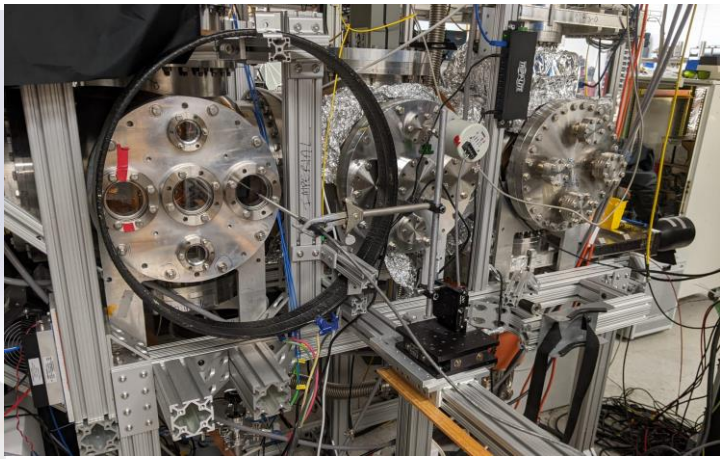
Expt/Theory

We are looking for graduate students and postdocs to join us

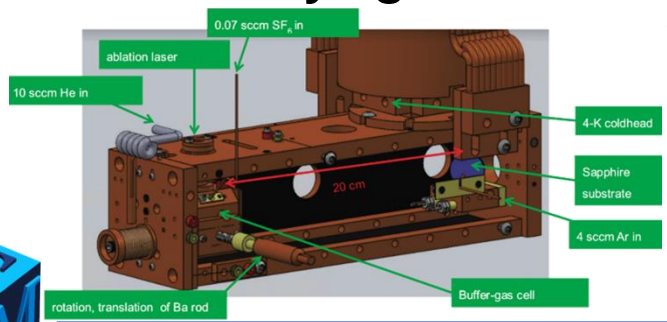
Assembled 1st generation apparatus

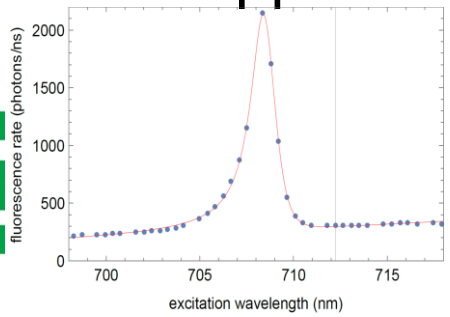


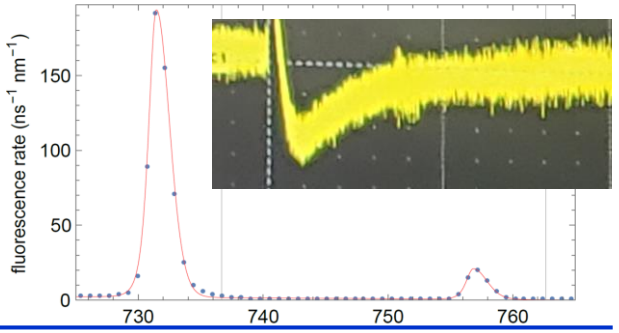




Assembled cryogenic solids with 1ppb BaF (and SrF)

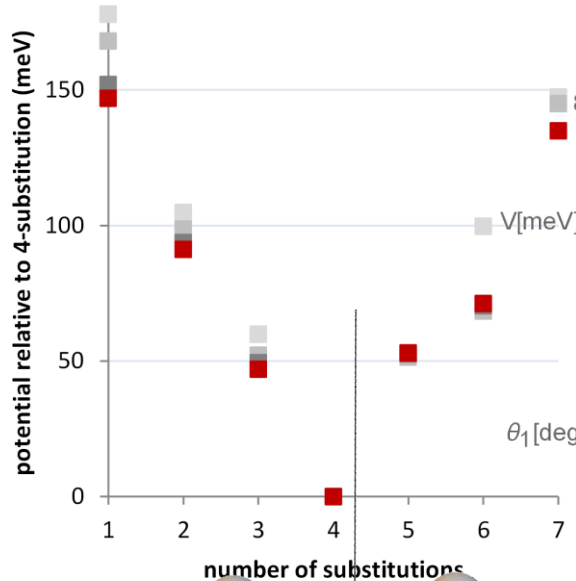


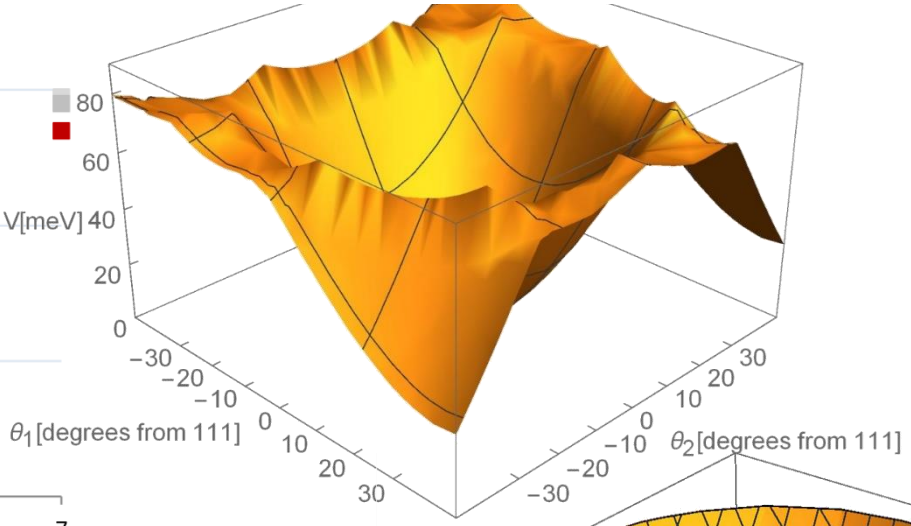


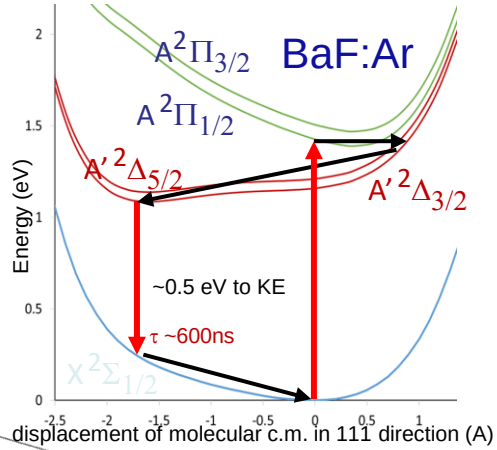


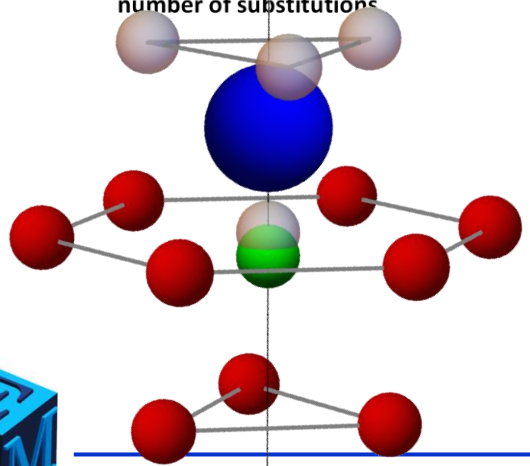
What Has Been Accomplished to Date?

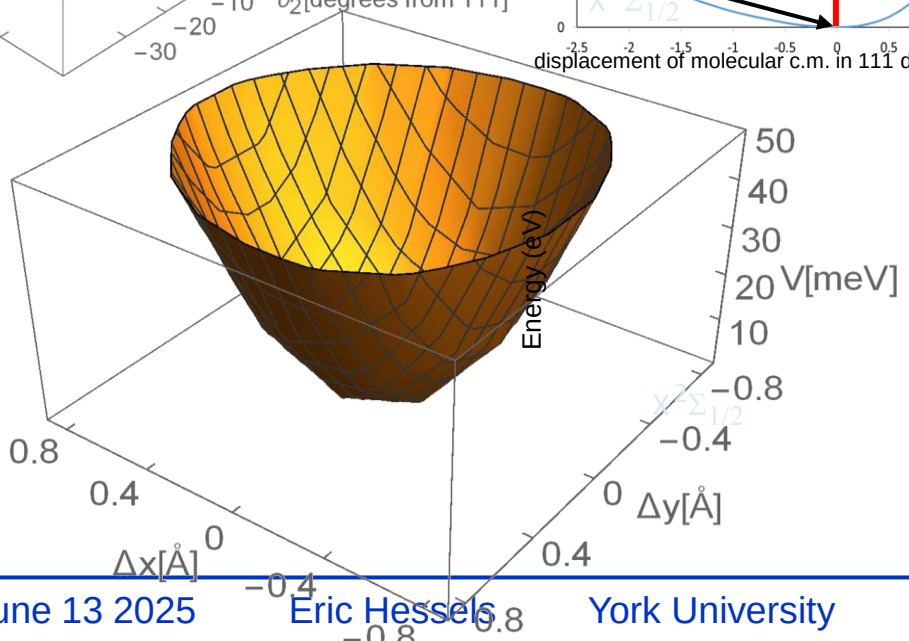
Large theoretical efforts: BaF substitutes for 4 Ar atoms, is oriented along the Ar crystal's 111 axis, is strongly restrained from rotating or migrating, and fluoresces further into the infrared



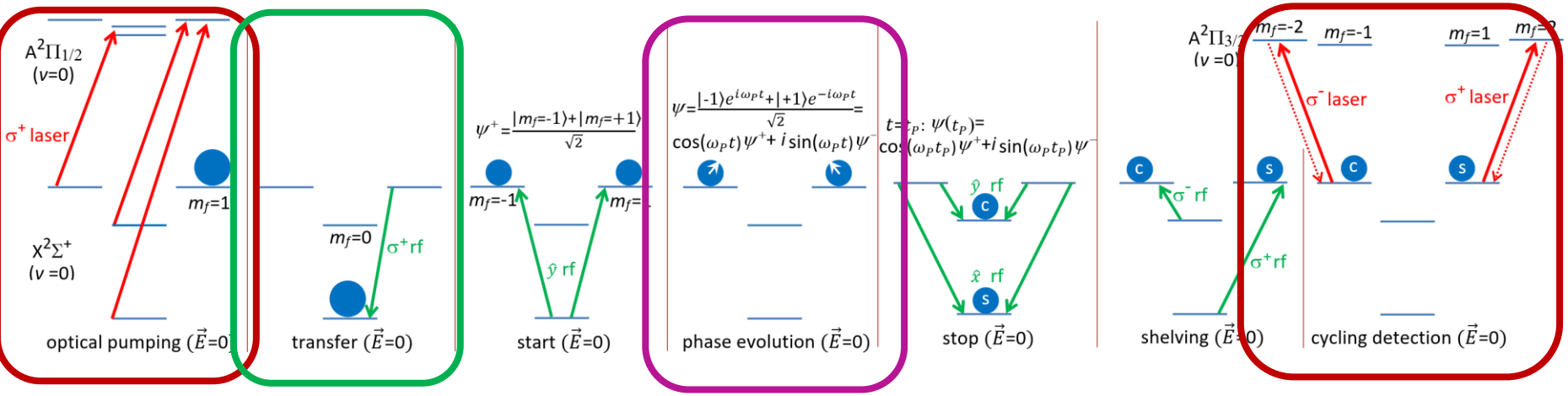








What Has Been Accomplished to Date?



Efficient optical pumping demonstrated. Unexpected bonus: depends on orientation of molecule -- useful for our measurement.

rf transitions demonstrated

Efficient detection using laser-induced fluorescence demonstrated

For the precession (phase evolution) step, the environment of the molecules has to be exquisitely controlled: colder, fewer impurities in solid and magnetic fields controlled at the μgauss level.

What Remains to be accomplished

Temperature:

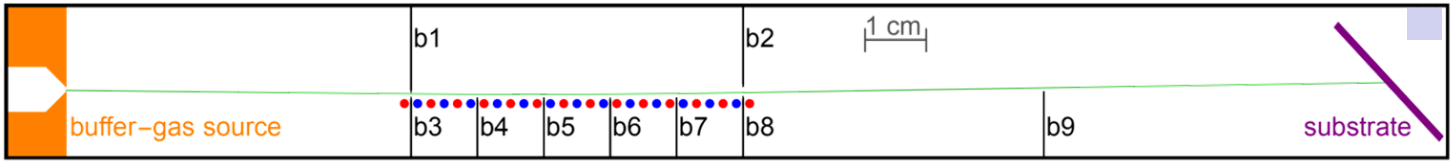
We have recently reduced temperature to 3K

Are designing a system that will get us to 1K.

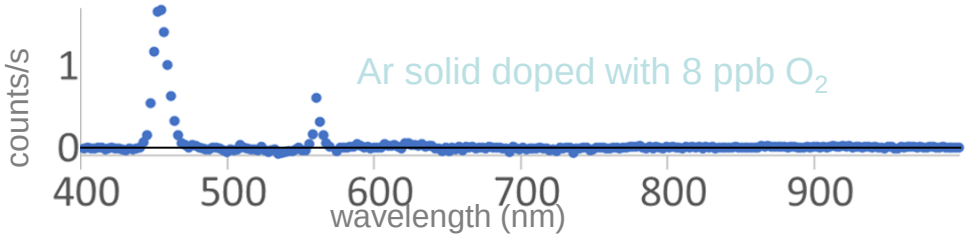
Purity:

We have a getter system for purifying our Ar

We have designed an electrostatic deflector to remove impurities from our molecular beam



We are using x-ray-induced fluorescence to measure purity



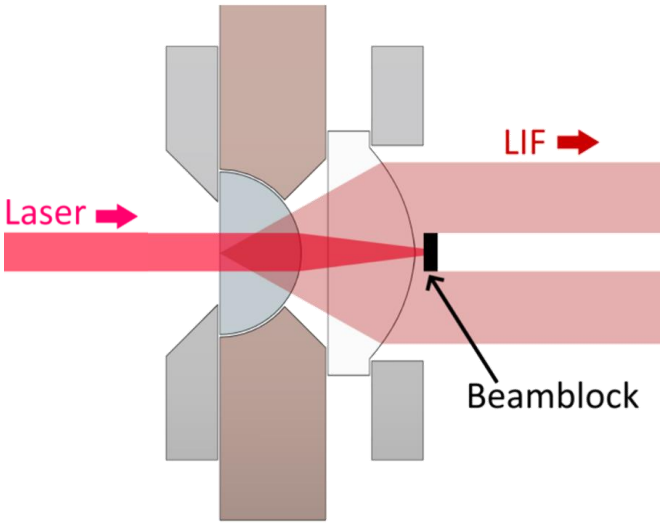
Magnetic field:

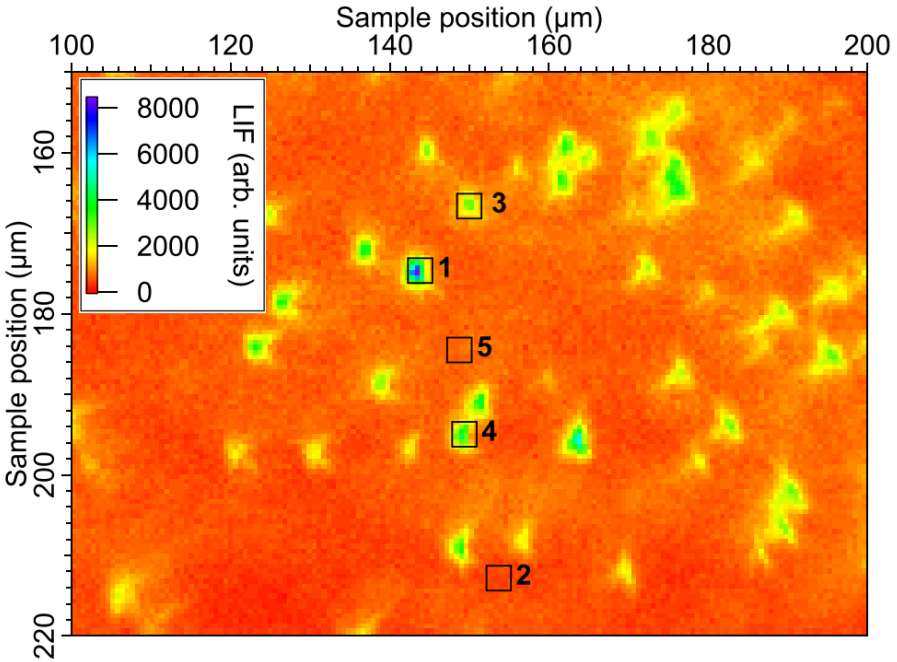
We are designing a superconducting magnetic shield

Next Step

Perform full experiment on individually imaged molecules (following the scheme used recently by Weinstein, et al)

LANCASTER, DARGYTE, AND WEINSTEIN PHYSICAL REVIEW RESEARCH **6**, L012048 (2024)





Allows for study of orientation and environment of each molecule

May already allow for a competitive d_e measurement

$$\delta d_e = 2 \times 10^{-30} e\,\mathrm{cm} \sqrt{\frac{2000}{N_{\mathrm{mol}}}} \sqrt{\frac{2.16\,\mathrm{GV/cm}}{E_{\mathrm{eff}}}} \sqrt{\frac{1\,\mathrm{s}}{T_{\mathrm{prec}}}} \sqrt{\frac{1\,\mathrm{month}}{T_{\mathrm{tot}}}}$$

Timeline

2 years: individual molecule imaging studies

5 years: full implementation of technique and d_e measurement

continuing: measurements of increasing precision

goal: measure CP violation responsible for matter/antimatter asymmetry in the universe

PRA 98 032513 (2018)
J Mol Spectr 391 111736 (2023)
Mol Phys 121 e2198044 (2023)
PRA 107 032811 (2023)
Mol Phys 121 e2232051 (2023)
PRA 108 012811 (2023)
arXiv:2410.04591 (2024)
arXiv:2410.04598 (2024)
arXiv:2410.04605 (2024)