Fundamental Physics with Tabletop Experiments at the Quantum frontier

The PHYDES collaboration

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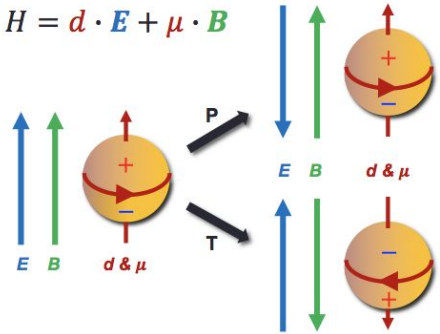
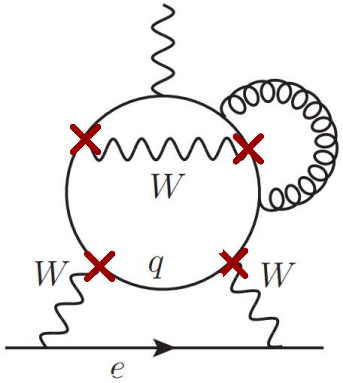
Madiha Masood *(PostDoc)*, and others…

The electron EDM

Electron Electric Dipole Moment (eEDM)

- [semi-classically] asymmetric charge distribution along the e^- spin
- [quantum field theory] high perturbative order loops CKM contributions





The eEDM is odd under both Parity and Time-reversal symmetries ⇒ **CP-violating**

In the ***Standard Model (SM)***, the eEDM is ***predicted*** to be tiny! **~10^{-38} ÷ 10^{-40} *ecm***

eEDM as a probe for New Physics

Why/how does this matter?

Because… **CP-violation (CPV) is required** to generate a cosmological **matter-antimatter asymmetry** (thus… us, here, today)

BUT… CPV **in the SM is many orders of magnitude below what is necessary**!

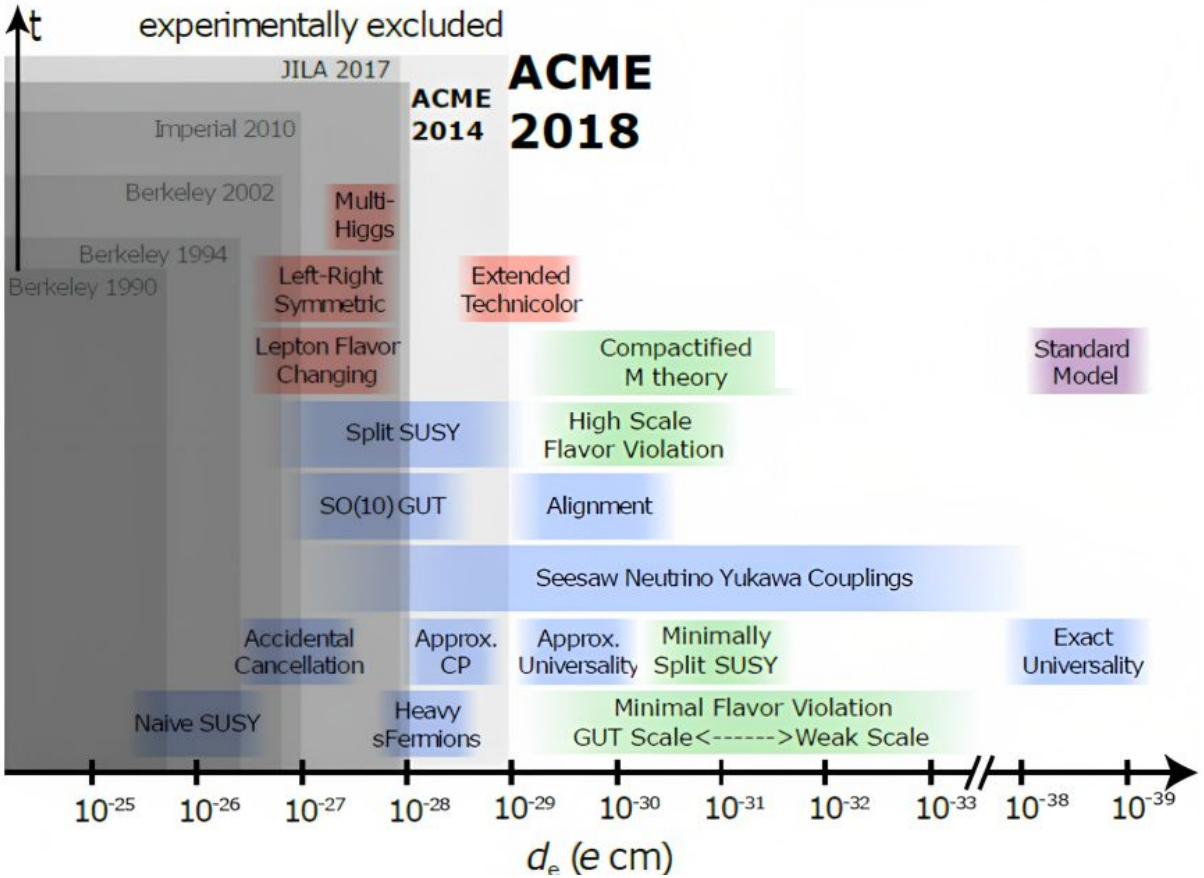
This (among other motivations) indicates that New (meaning… yet unknown) Physics phenomena may be lunging just outside our current grasp

A precise measurement of the eEDM can provide a model-independent probe of possible New Physics sources of CP violation in the universe

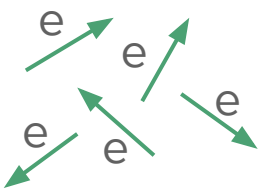
It can allow us to **probe scales up to PeV to EeV**, i.e. 1,000s to 1,000,000s times beyond the reach of particle colliders (even the 100 km future collider monsters)

This is the (rather ambitious) goal of the **PHYDES collaboration**

So far… a steamroller for exotic models



Measuring the eEDM



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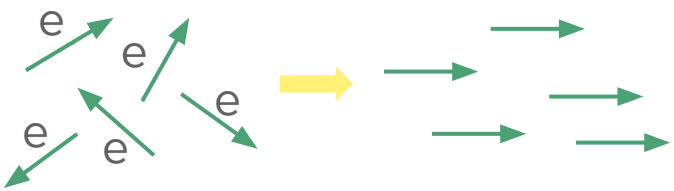
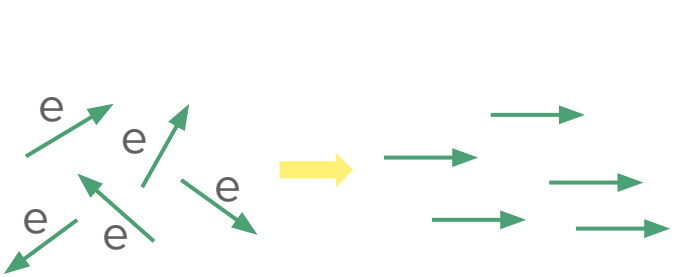
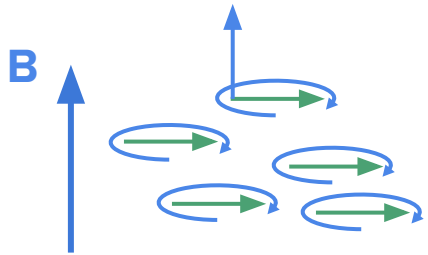
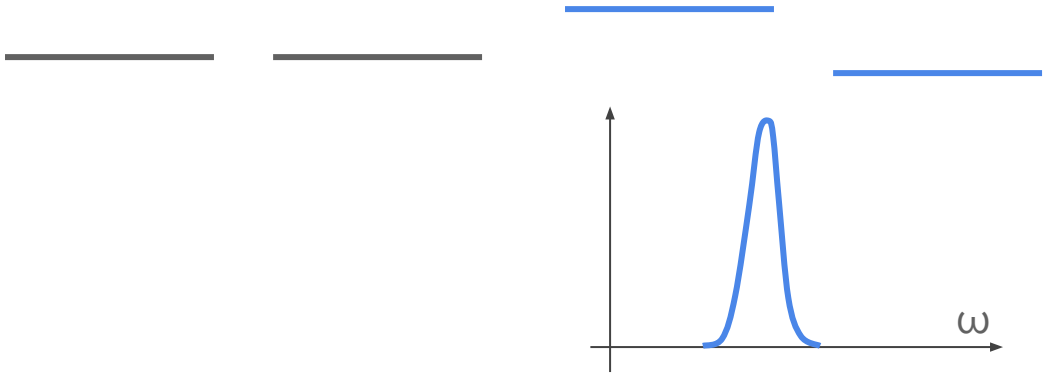


Measuring the eEDM

$\hbar\omega = 2\mu B$







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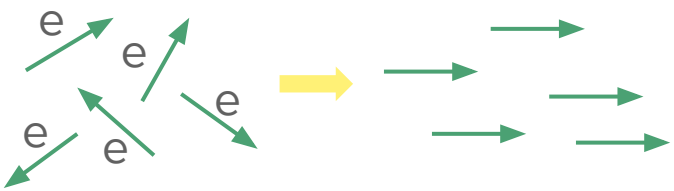

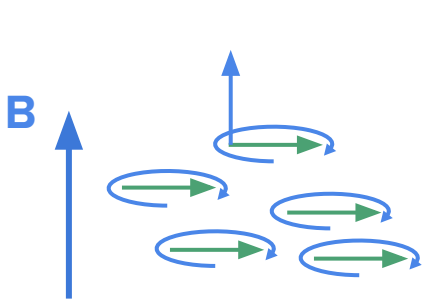

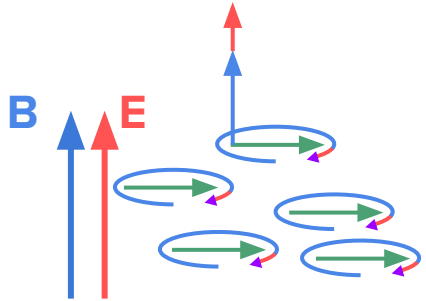

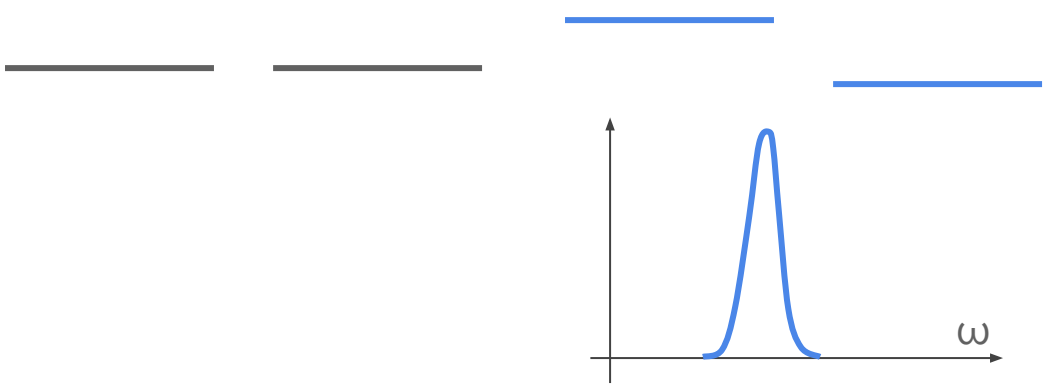

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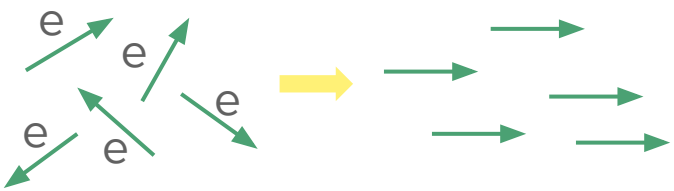
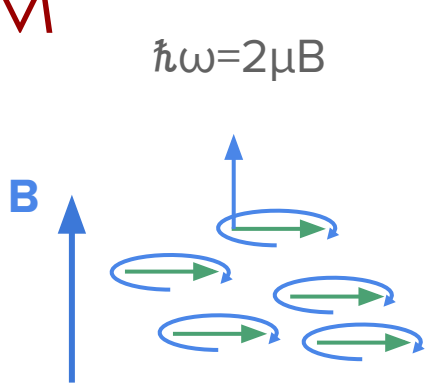
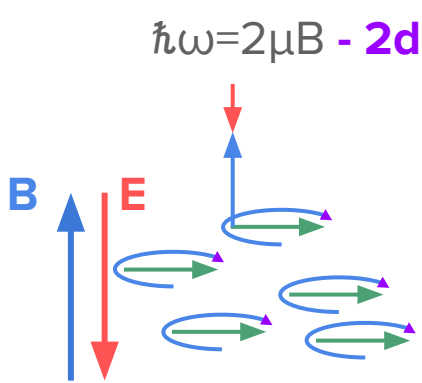
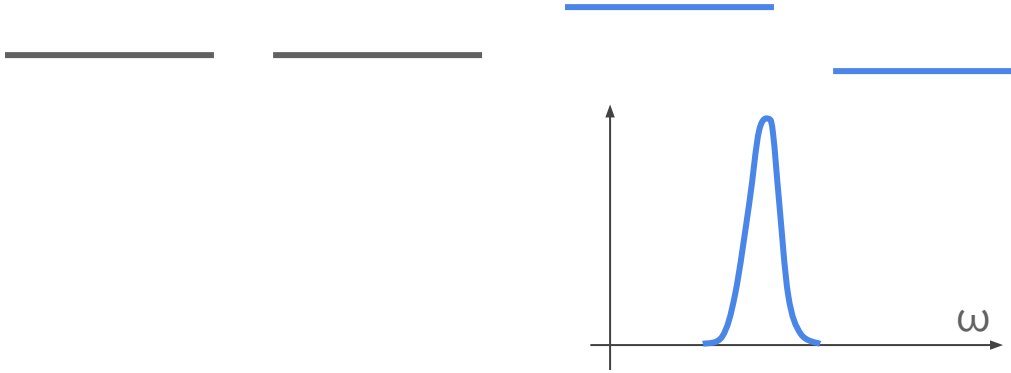




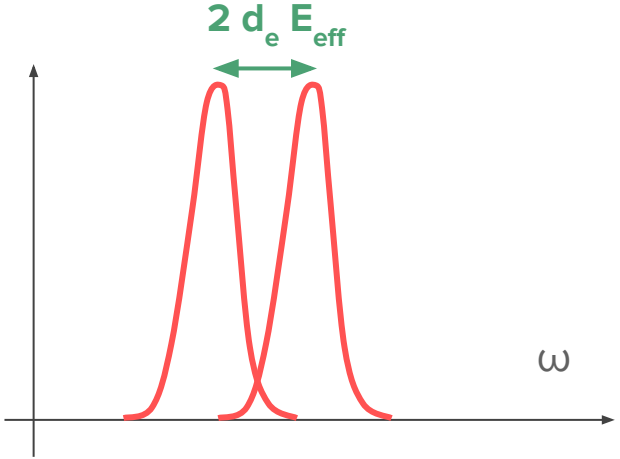




What to optimize

The figure of merit for the optimization of the measurement of the eEDM boils down to:

$$\delta d_e = \frac{1}{E_{eff}\ \tau\ \sqrt{N}}$$

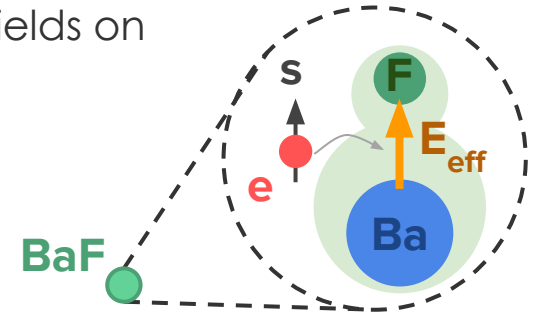


- E_{eff} → **Effective electric field**
- τ → **~ Coherence time**
- N → **Number of probed atoms/molecules**

Diatomic polar molecules

Barium Monofluoride (BaF) will be used

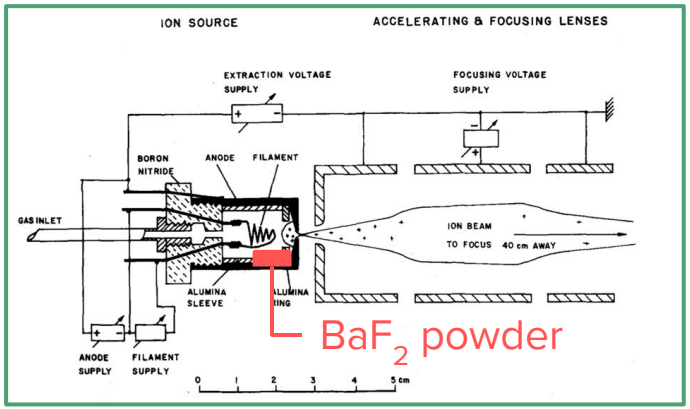
- BaF molecules are characterized by large effective electric fields on the **unpaired paramagnetic electron**
- E_{eff} ($\propto Z^3_{Ba}$) on the unpaired e^- of the order of **100 GV/cm**



We have to produce a large amount of BaF molecules (large **N**!)

- Produce BaF from BaF_2 powder
- Ionize it to BaF^+
- Accelerate it and filter it (cleanup from other species)
- Decelerate it

- **Beam simulations**
- **Monitoring/measurement of the beam of BaF^+ ion current**



Parahydrogen

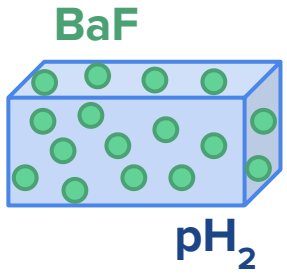
Neutral BaF will be embedded in a inert solid to suppress residual interactions

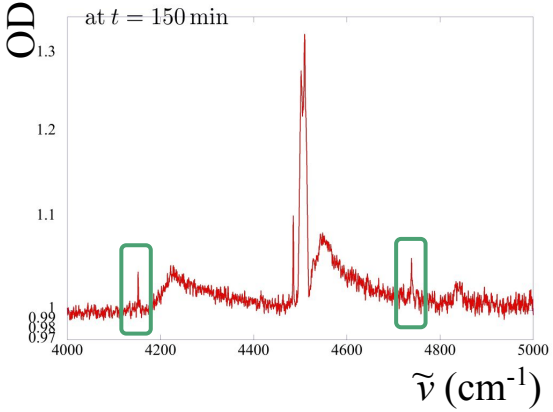
→ **Crystal of ParaHydrogen (nuclear spin J=0)**

BaF is free to rotate and be polarized in the **pH_2 lattice** (~a quantum solid!)

A continuous flow of pH_2 is sprayed onto a sapphire window kept at ~ 2.7 K in a vacuum

Infrared spectroscopy allows to monitor the growth rate of and measure para-vs-ortho H_2 fraction





- **Measurement of parahydrogen crystals**
- **Interferometry in the IR spectrum**
- **Cold (~ K) and vacuum technologies**

BaF neutralization

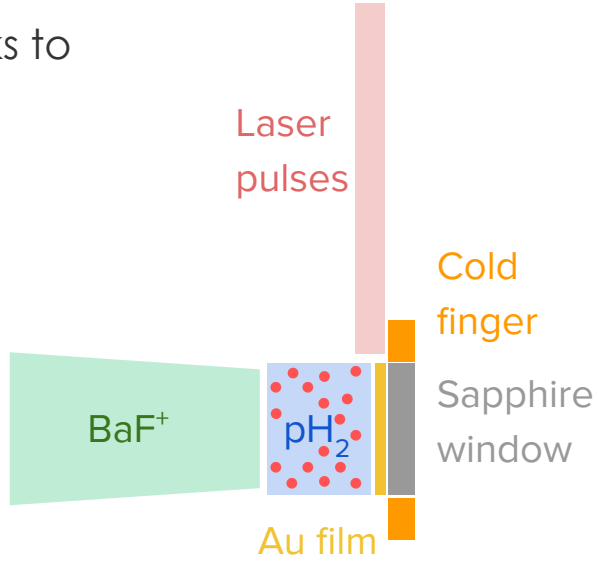
BaF from the beam is charged (**BaF+**) and it has **to be neutralized** to embed it in pH_2 and perform eEDM measurements

BaF^+ neutralization by photo-extraction of e^- from a Au film on the sapphire surface

Electrons drift through the solid pH_2 to bound with BaF^+ thanks to an external electric field

→ Study of the electron mobility through parahydrogen is paramount

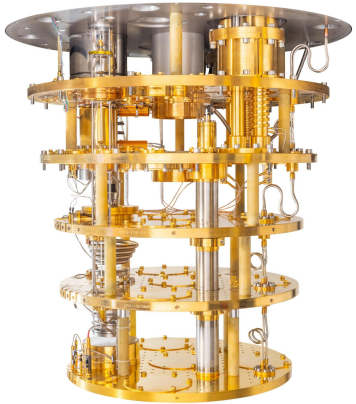
- **Electron mobility through solid (and liquid)**
- **Hydrogen/ParaHydrogen/Helium**
- **Lasers and electronics technologies**



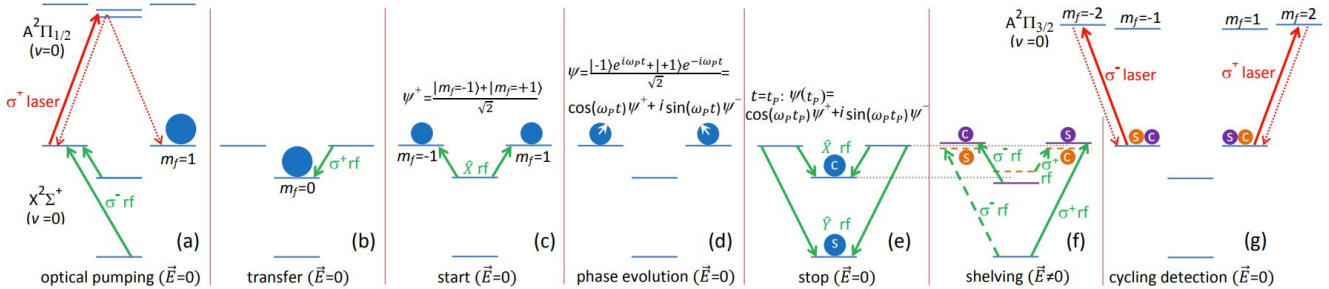
The eEDM measurement

Finally… we will want to probe the eEDM from the BaF molecules embedded in the pH_2 crystal

- The system must be maintained at **extremely cold temperature (~10s of mK)** to grant us the longest possible time of electron coherence (large τ)
- **Delicate preparation of the electron quantum states** through laser pumping
- Measurement of the **fluorescence emissions** from excited states



- **State preparation via laser excitation**
- **Measurement of fluorescence**
- **Lasers, electronics, vacuum, ultracold tech**



Wrap up

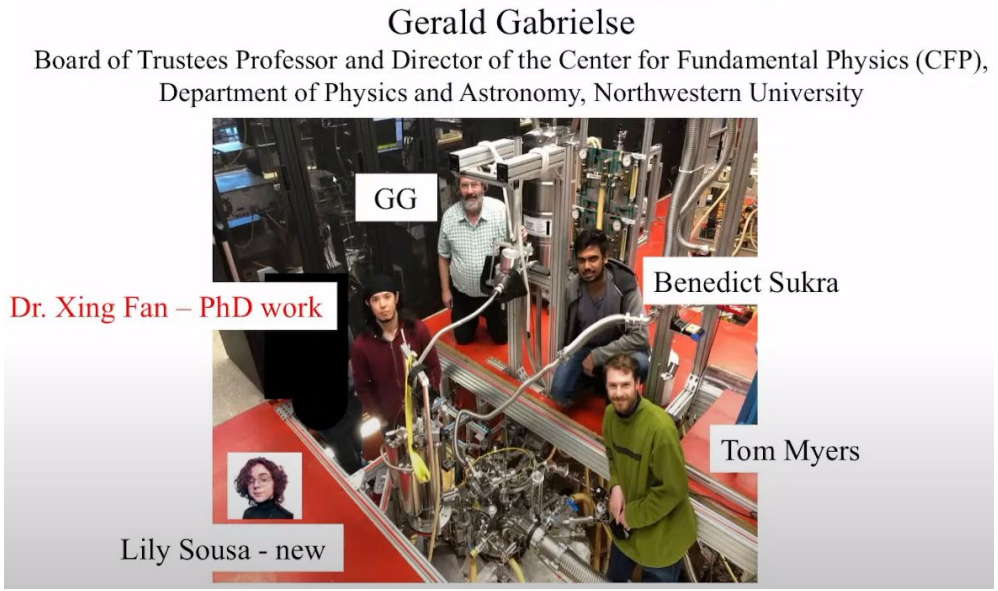
Precision physics beyond the frontier of what achievable in large collider

With a (almost) tabletop experiment

Students' involvements is paramount for success

Expertise to be gained on tools and techniques that are cornerstones for most quantum-physics related lab activities

Many different open activities: come and talk to us if you chime with any of these



From the seminar of Prof. Gabrielse on *the Electron Magnetic Moment measurement:* youtube recording

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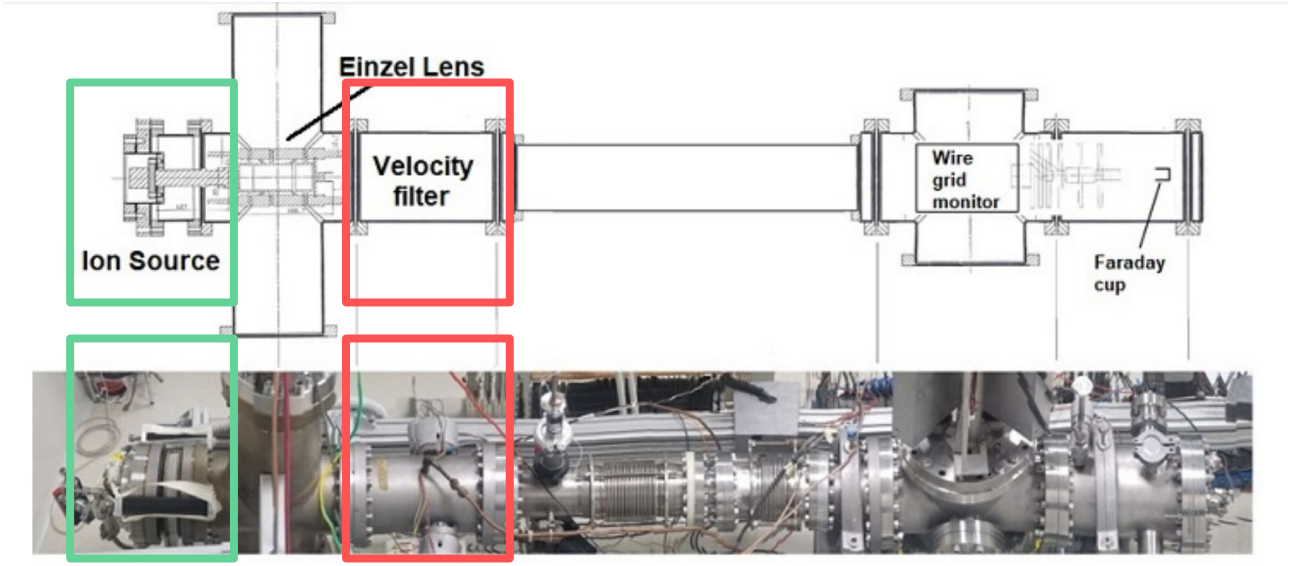
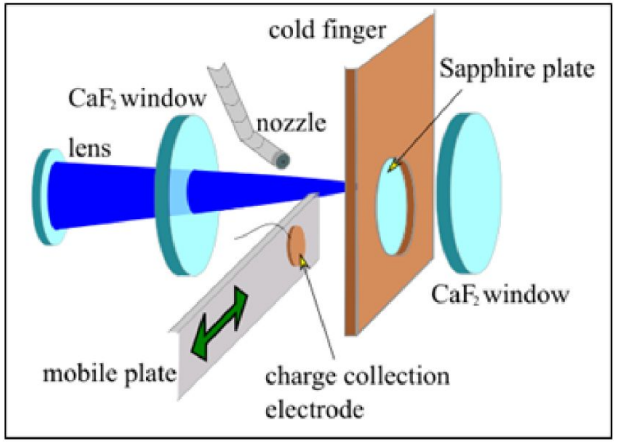
BaF beam preparation with isotopic separation:

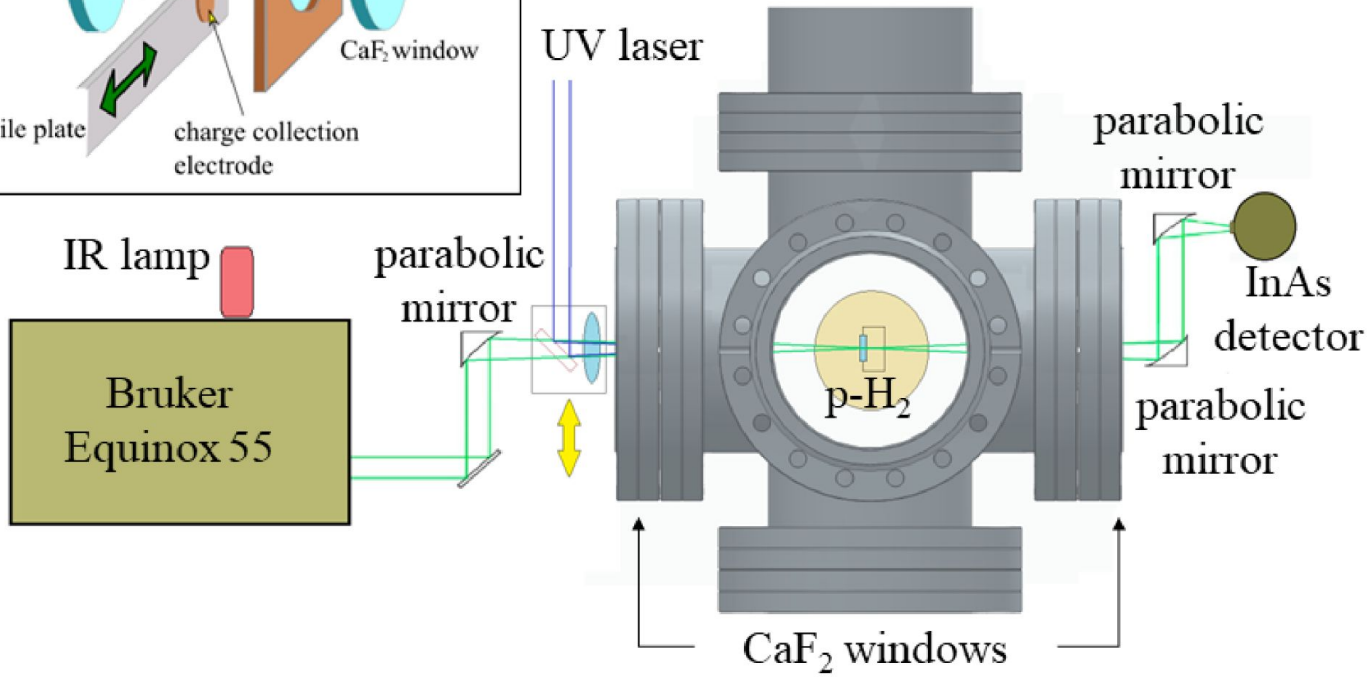
- BaF injection + ionization
- Wien filter (**B**x**E**) for mass selection

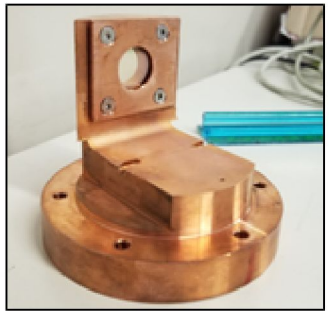
Preliminary tests with Xe^+ beam (mass similar to BaF):

- Beam current 100 nA
- Final Xe^+ energy = 5 eV
- Estimate of ~ 100 ppm for BaF^+ on pH_2 target




cold finger
Sapphire plate
CaF_2 window
nozzle
lens
CaF_2 window
mobile plate
charge collection electrode


UV laser
parabolic mirror
IR lamp
parabolic mirror
InAs detector
Bruker Equinox 55
$p\text{-}H_2$
parabolic mirror
CaF_2 windows



Sumitomo
cryocooler
top
pumping port
H_2 gas
valve
sapphire
substrate
flow meter
charge collection
electrode
vacuum
manipulator
Leybold-Heraeus
cryocooler
50K shield
turbomolecular
pump