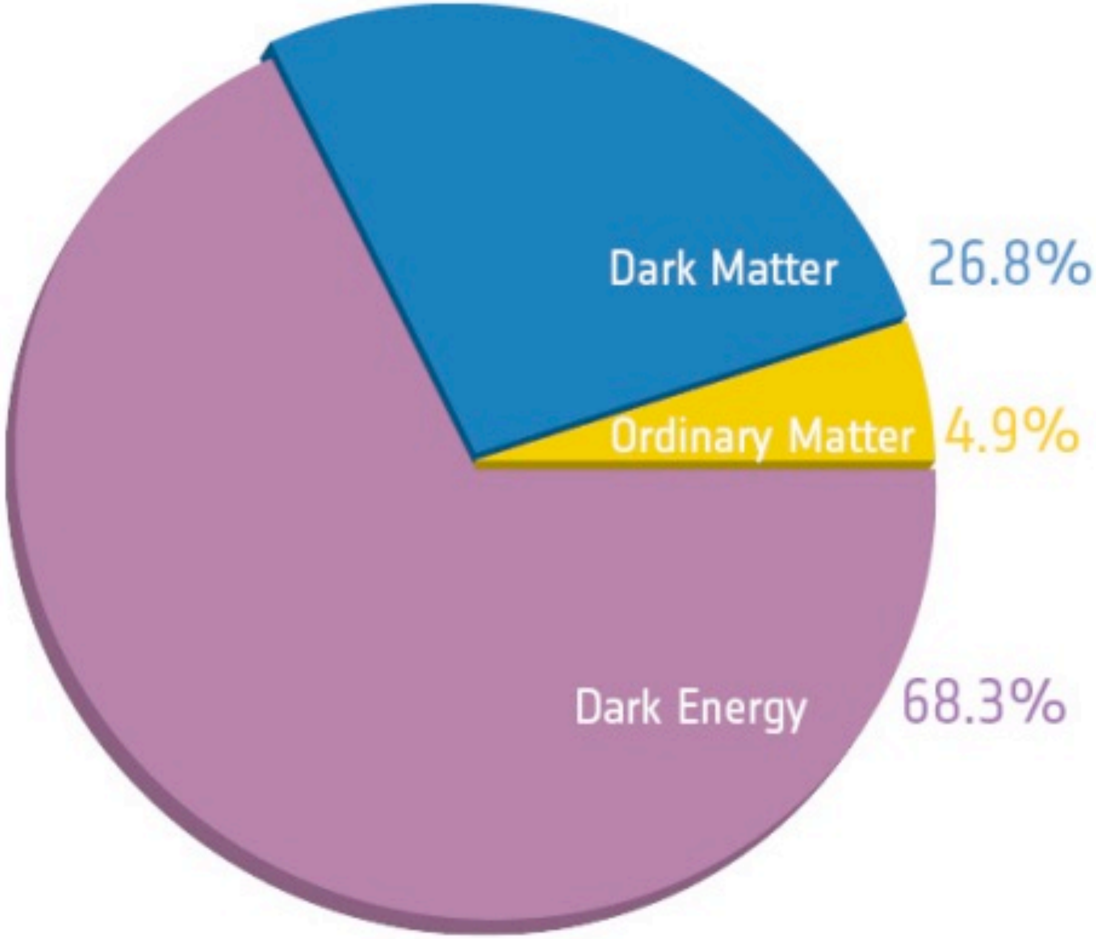
SEARCHING FOR MILLICHARGED PARTICLES USING OPTICALLY LEVITATED MICROSPHERES

Sumita Ghosh | Moore Group
Yale University Wright Lab

THE DARK SECTOR

Dark matter + dark energy

More complicated model:
Hidden sector



HTTP://PLANCK.CF.AC.UK/RESULTS/COSMIC-MICROWAVE-BACKGROUND

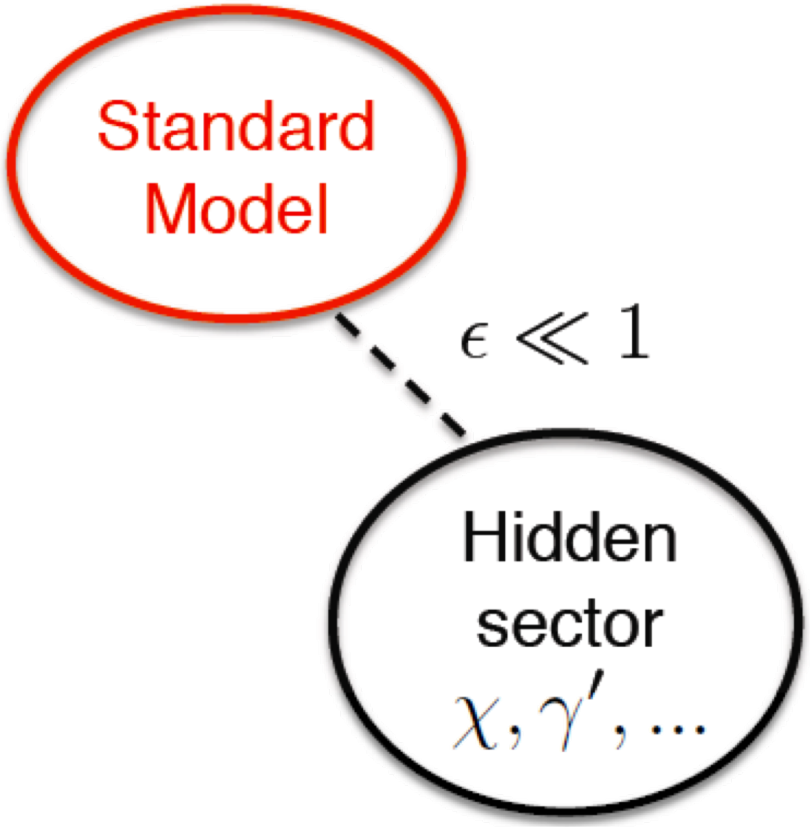
THE HIDDEN SECTOR

Complementary way: Search for new forces

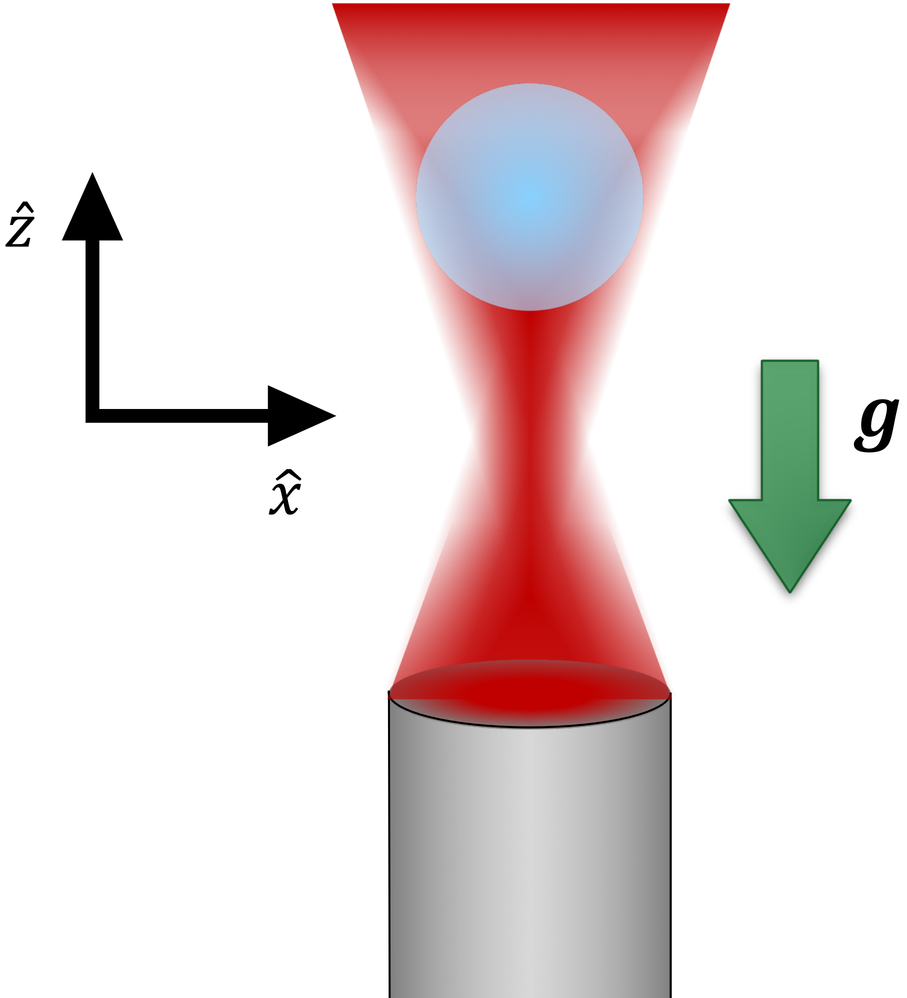
Canonical example: “Dark electromagnetic force” mediated by a “dark photon”

There may be weak interactions between Standard Model photons and dark photons

How do you make a precision force sensor?



OPTICAL LEVITATION FOR PRECISION FORCE SENSING



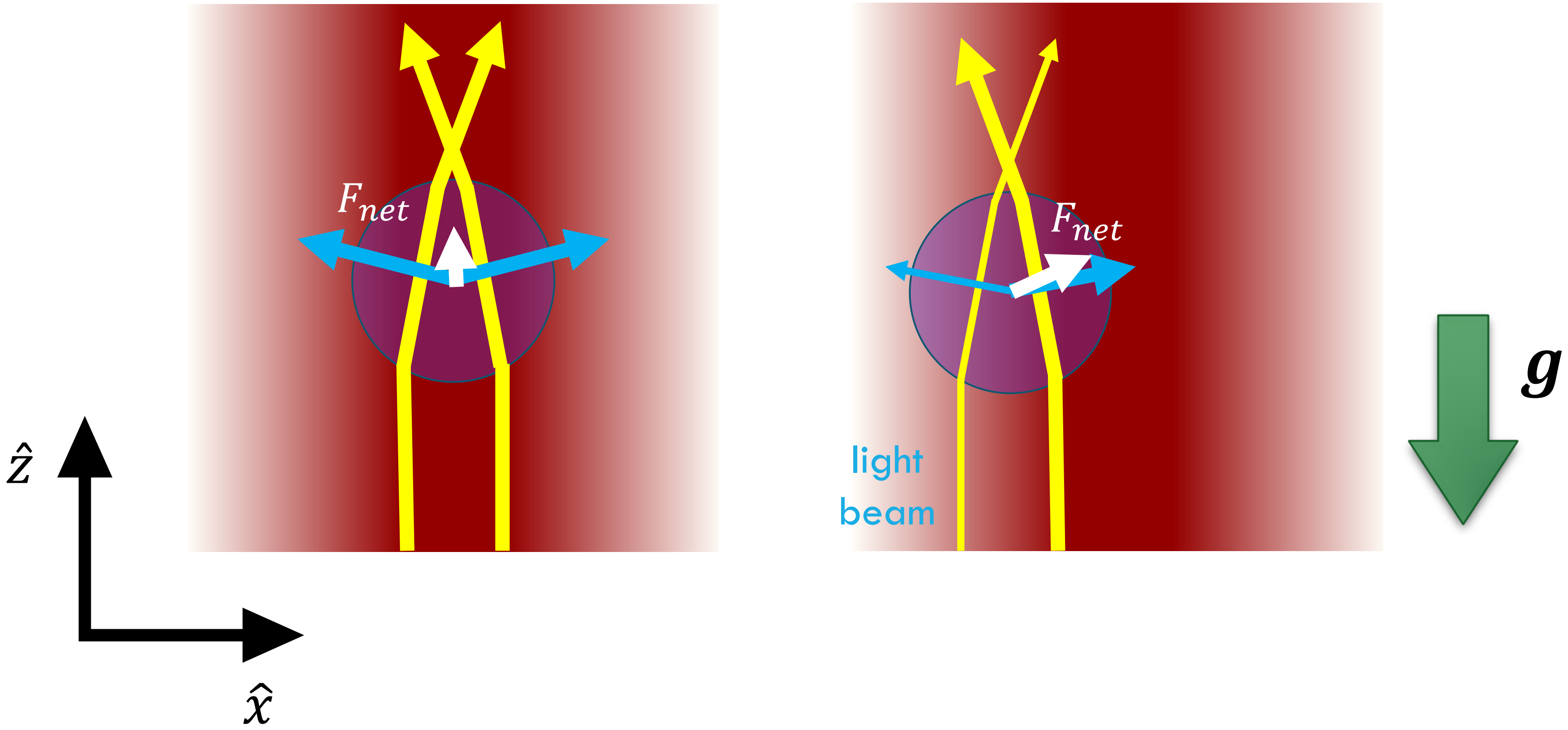
Object levitated on a laser beam in vacuum

Mass is thermally and electrically isolated

Control position, rotation, and charge

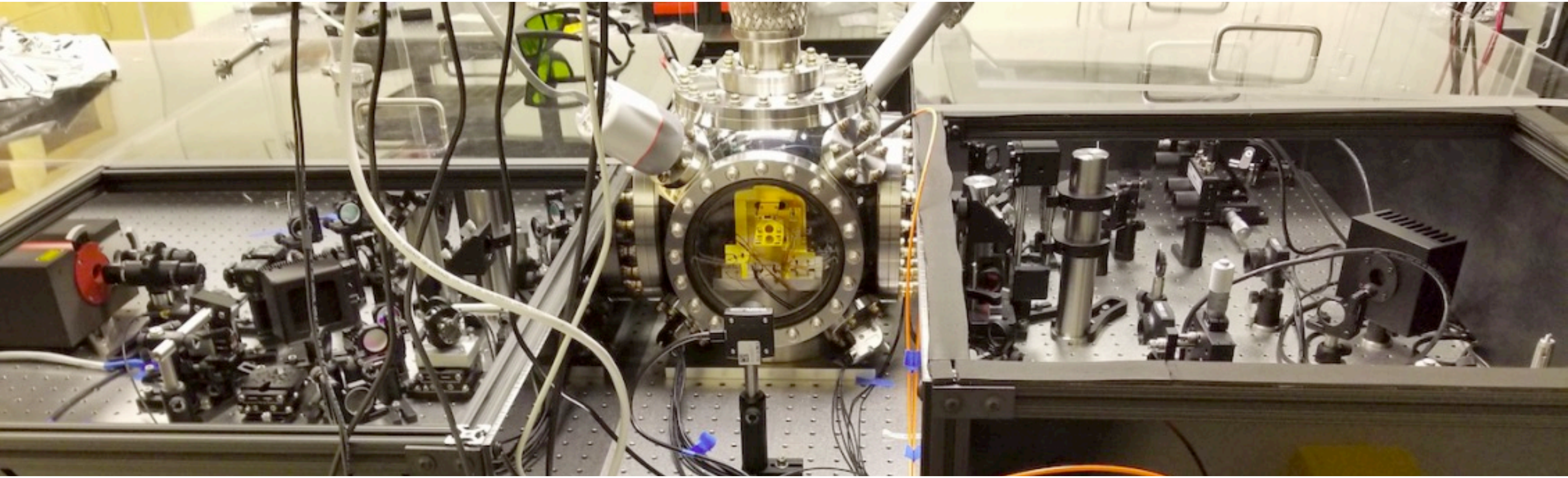
ASHKIN AND DZIEDZIC. APPLIED PHYSICS LETTERS 19.8 (1971)

THE OPTICAL TRAP AS A PRECISION FORCE SENSOR

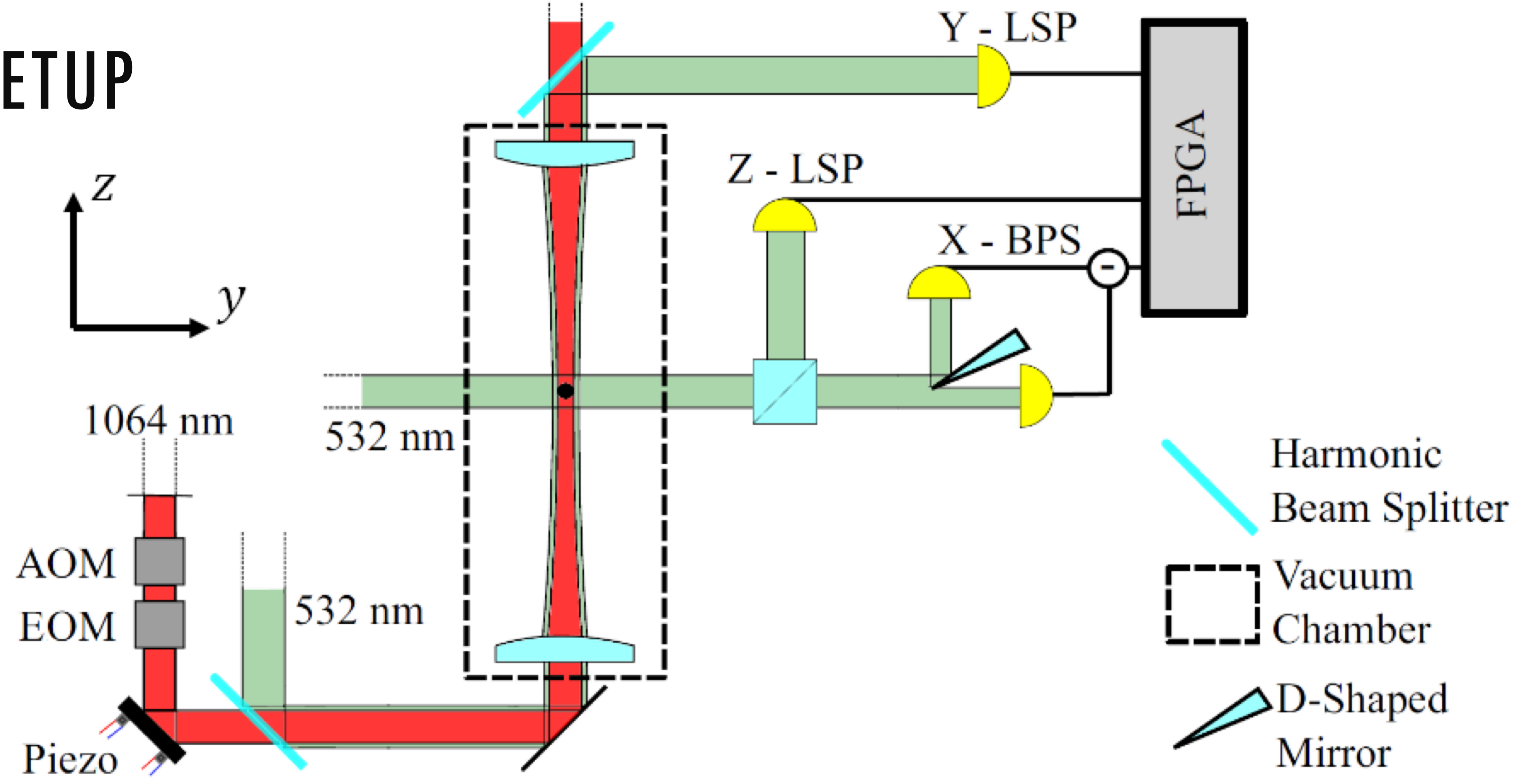


Stable equilibrium above focus of the laser

SETUP



SETUP



UPDATE FROM PRA 96, 063841 (2017)

THE FEEDBACK SYSTEM

Lower pressure to minimize noise

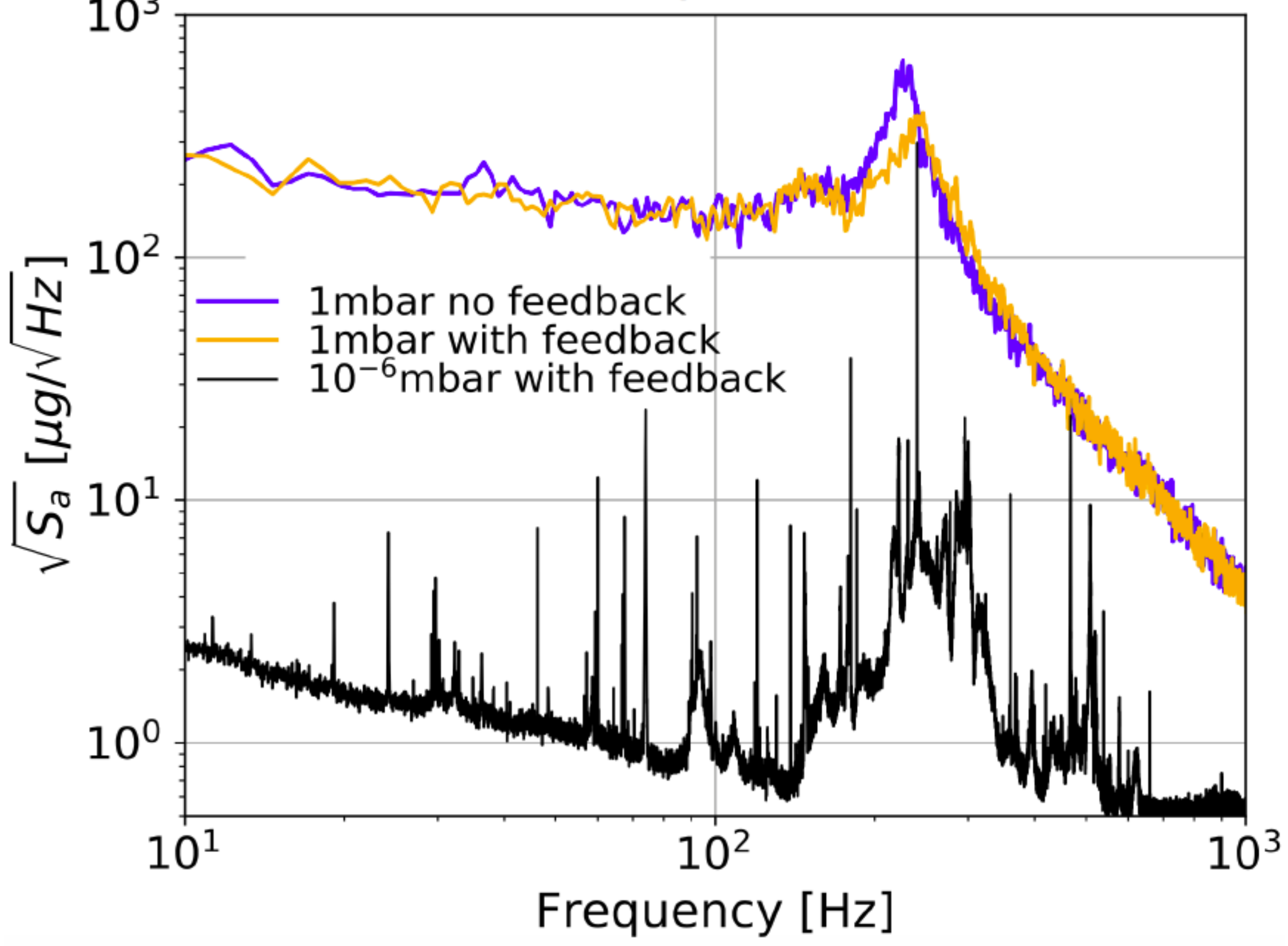
No damping at low pressure

Use PID feedback to damp motion

Sphere stays in trap at 1E-7 mbar for over a month

Longer measurement times give higher SNR measurements

$$1\mu g = 9.8 \times 10^{-6} m/s^2$$



THE FEEDBACK SYSTEM

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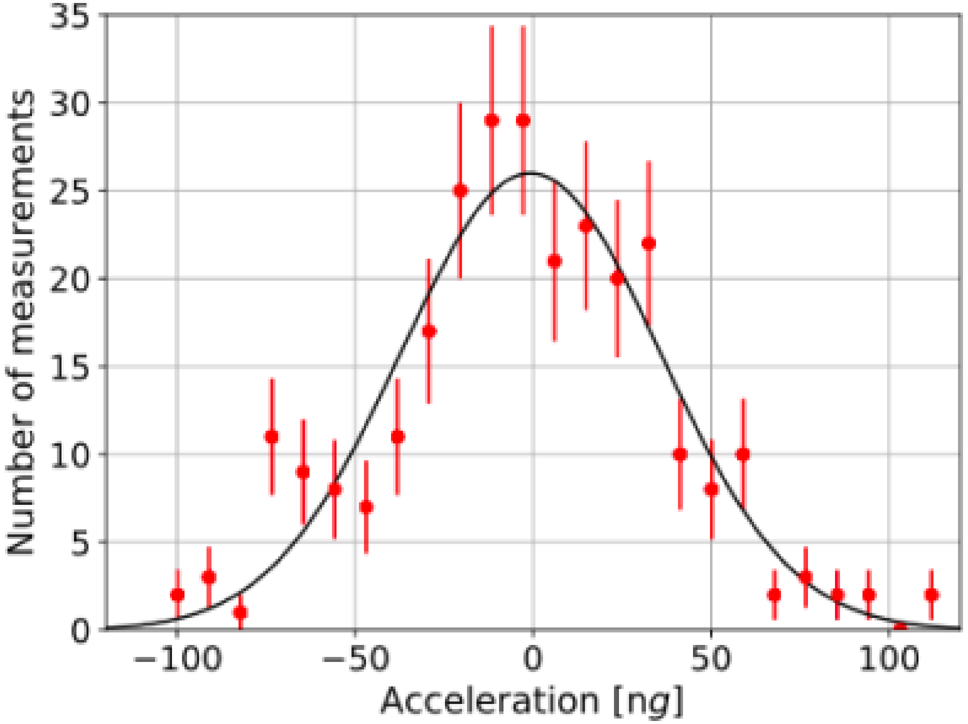
Sphere stays in trap at 1E-7 mbar for over a month

Longer measurement times give higher SNR measurements

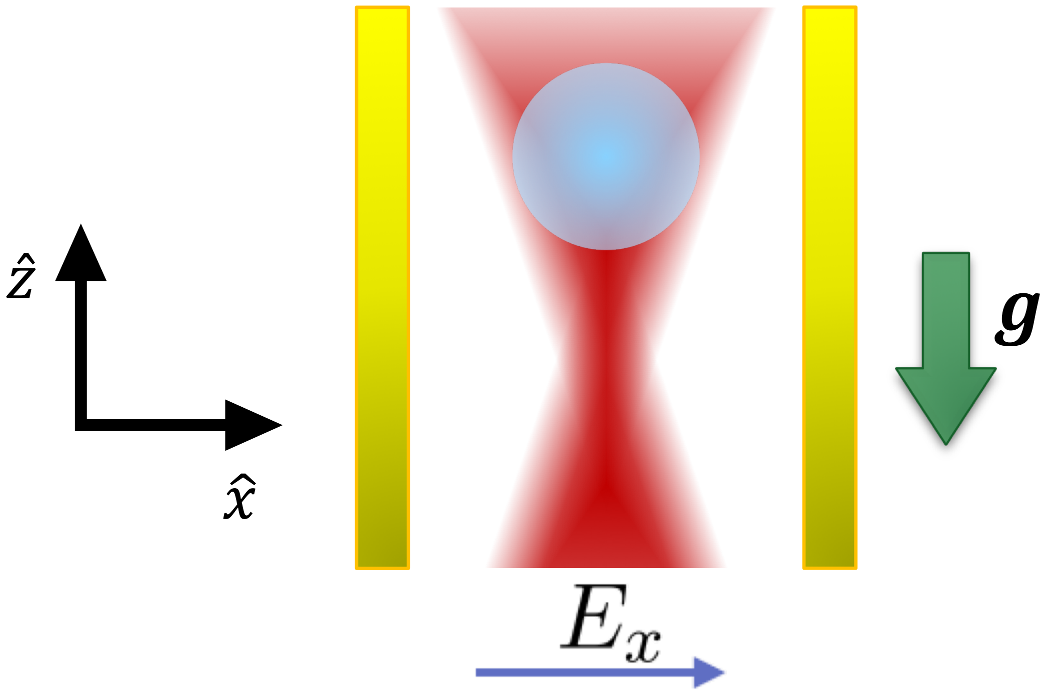
(-0.7 ± 2.4 [stat] $\pm$ 0.2 [syst]) ng in a total integration time of 1.4×10^4 s

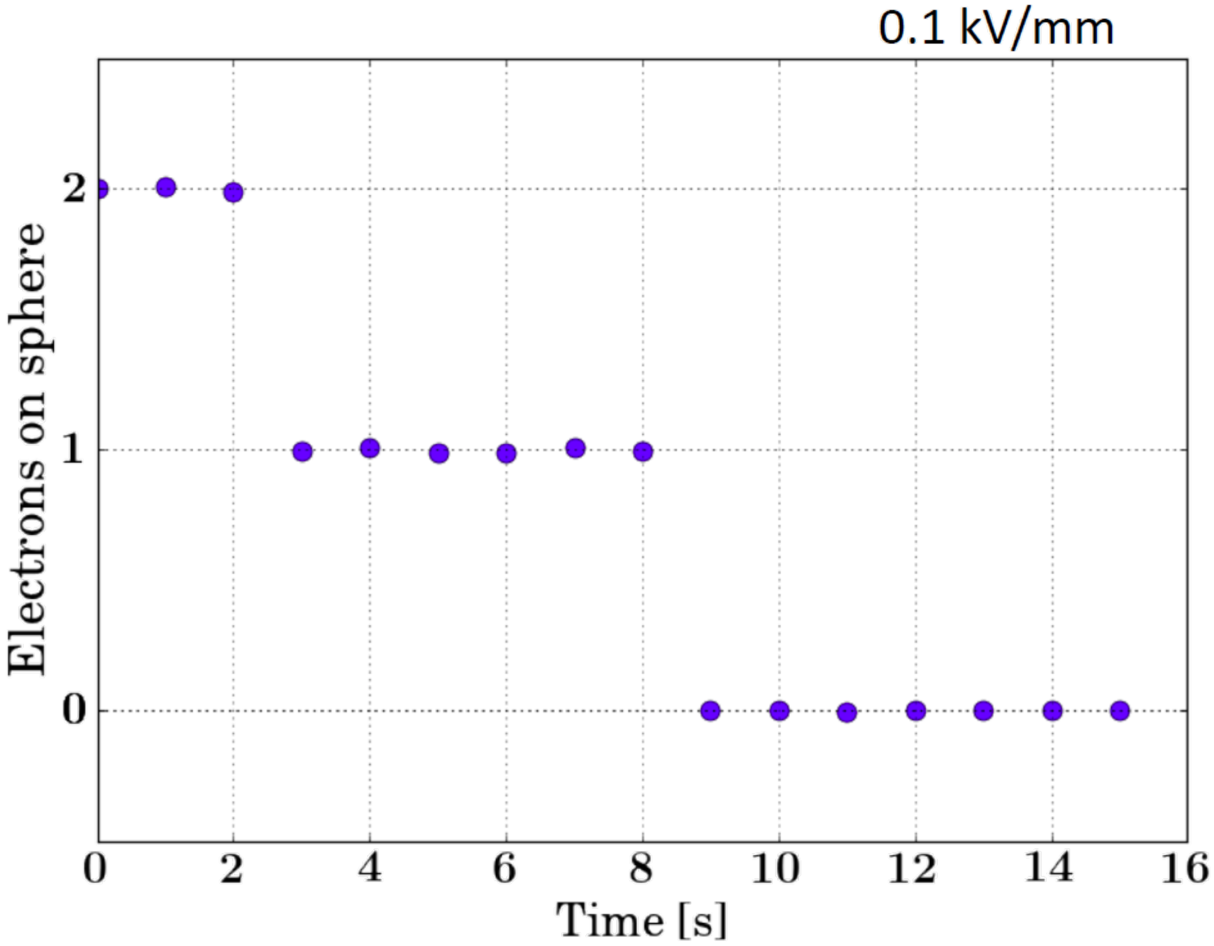


CHARGING AND DISCHARGING THE SPHERE

UV flashes add/subtract electrons

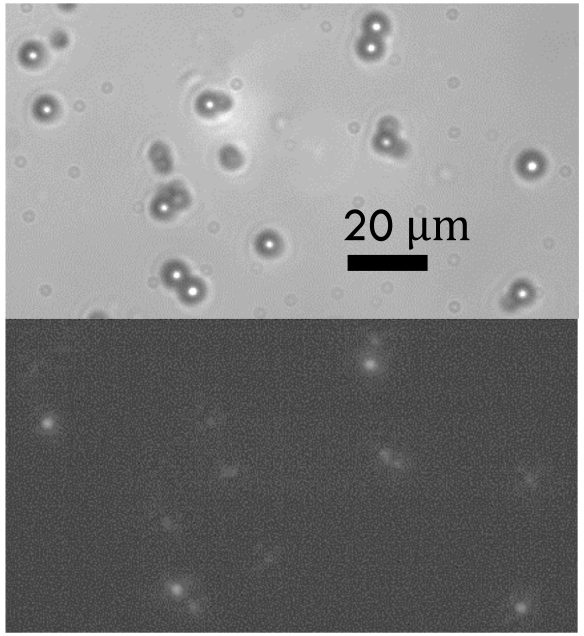
Correlate motion with electric field

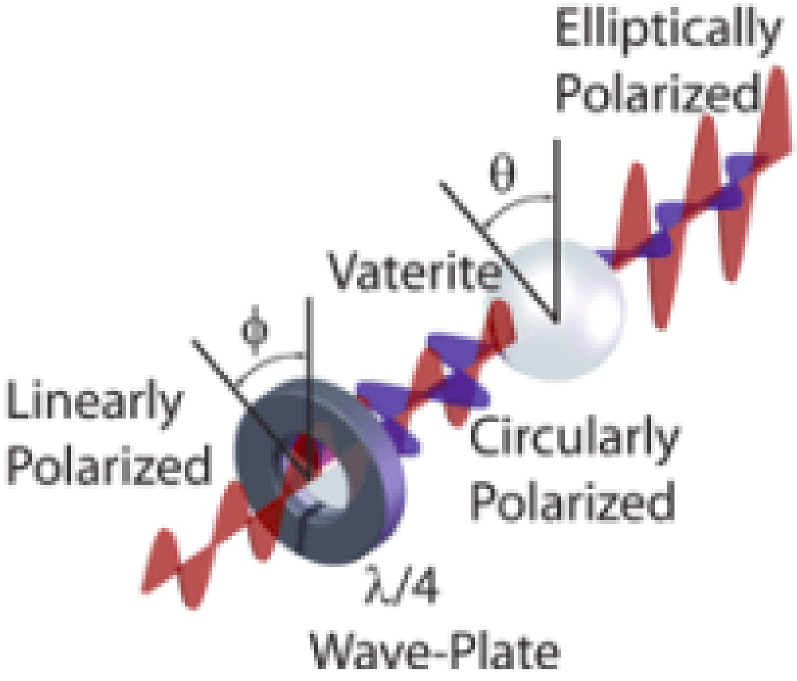


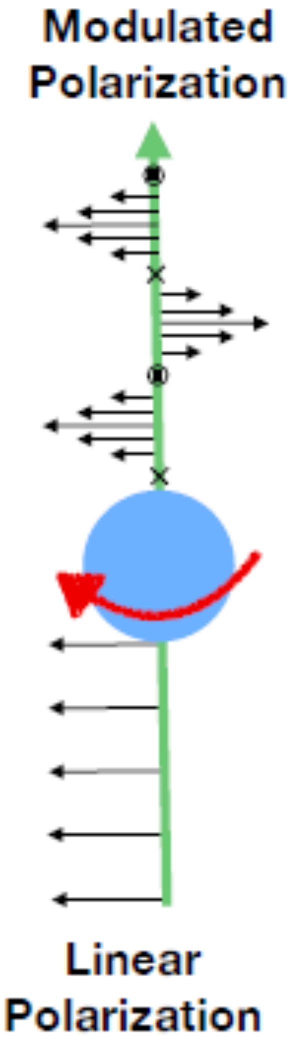


ROTATION DUE TO BIREFRINGENCE

Vaterite $CaCO_3$







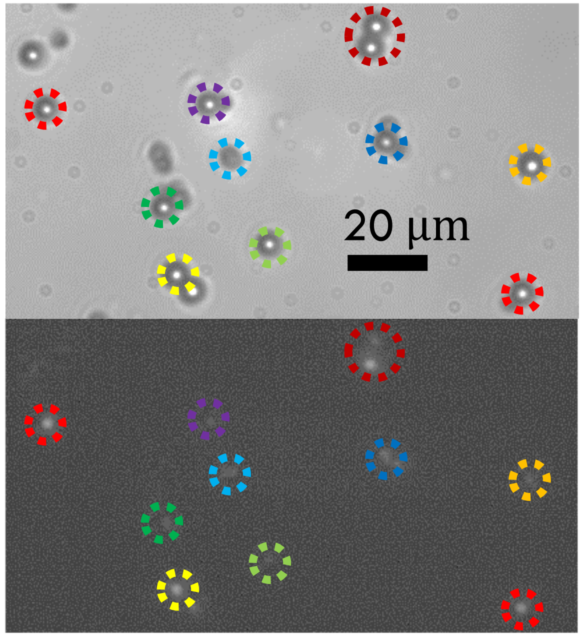
Friese et al., Nature 394, 348 (1998)

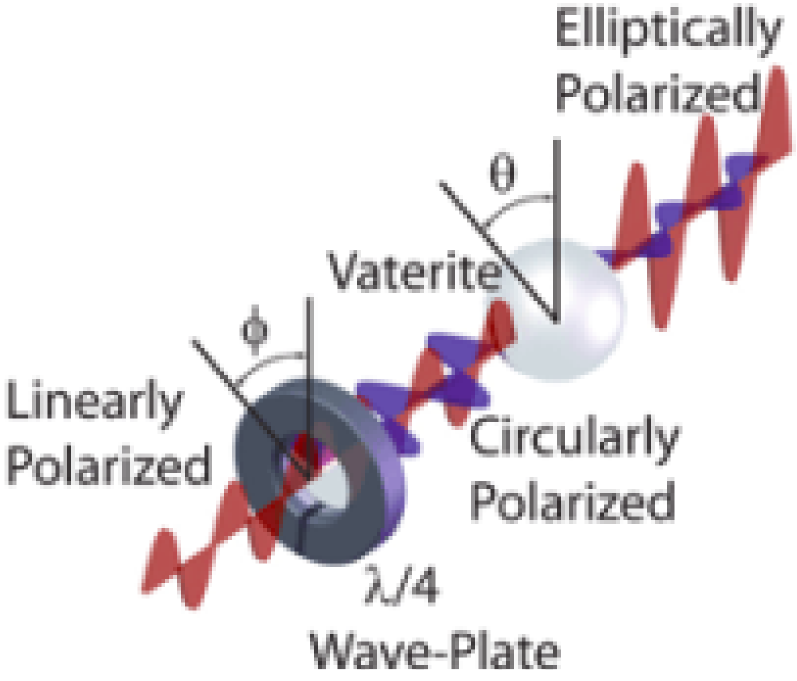
Donato et al., Sci. Rep. 6, 31977 (2016)

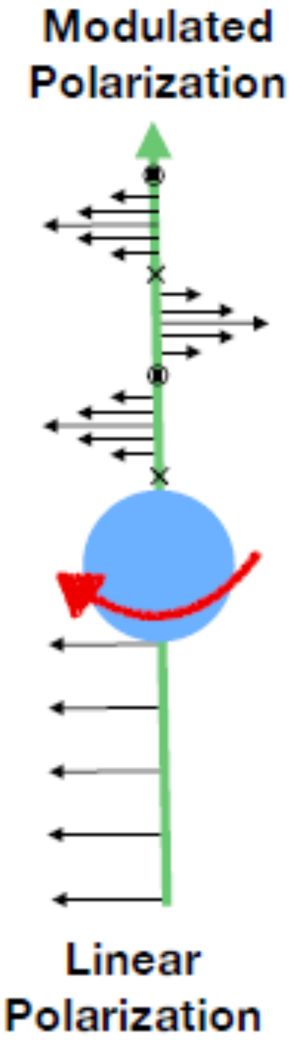
ROTATION DUE TO BIREFRINGENCE

Birefringent spheres

Vaterite $CaCO_3$

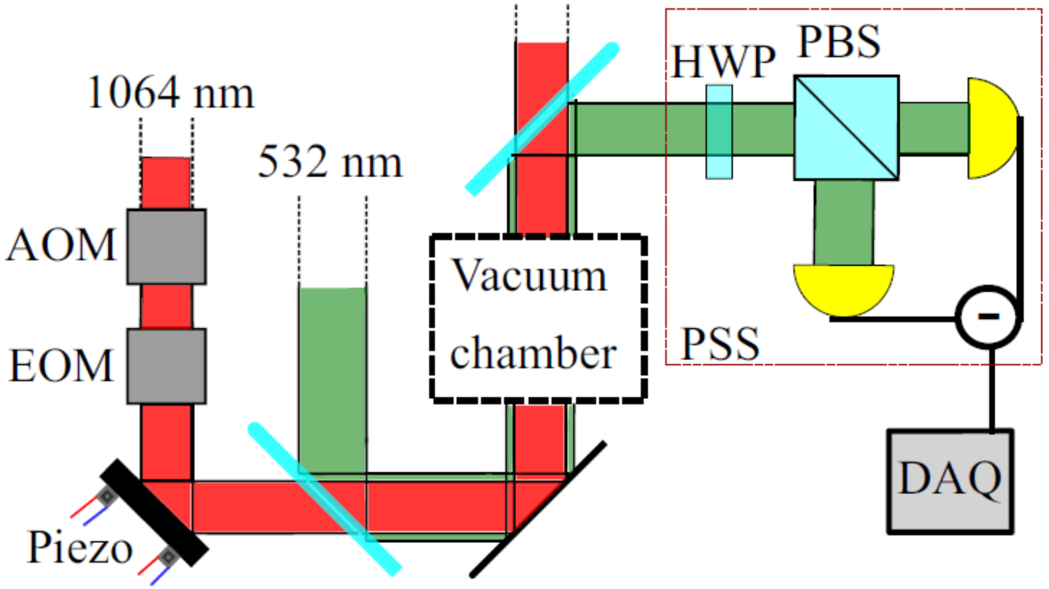


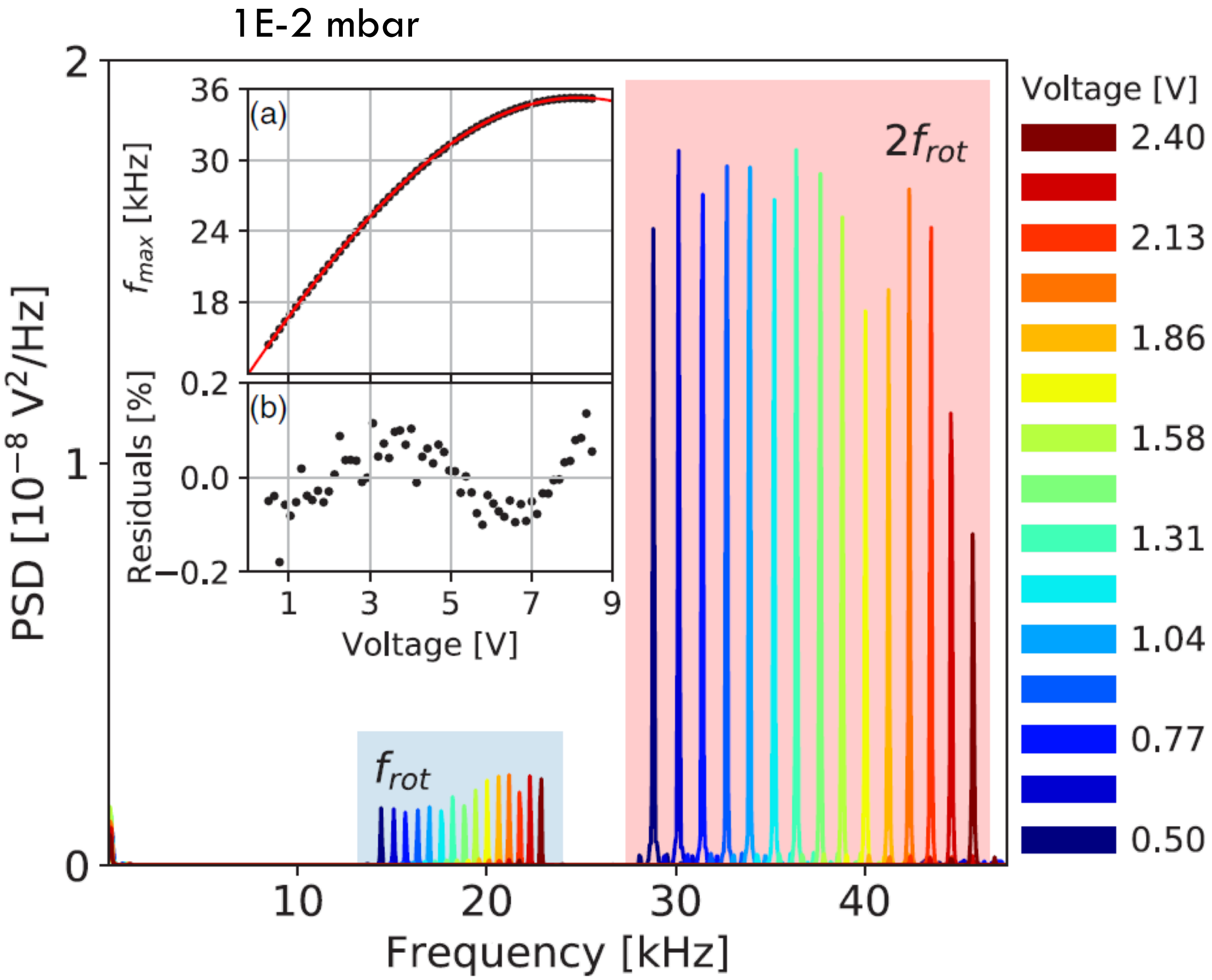




Friese et al., Nature 394, 348 (1998)
Donato et al., Sci. Rep. 6, 31977 (2016)

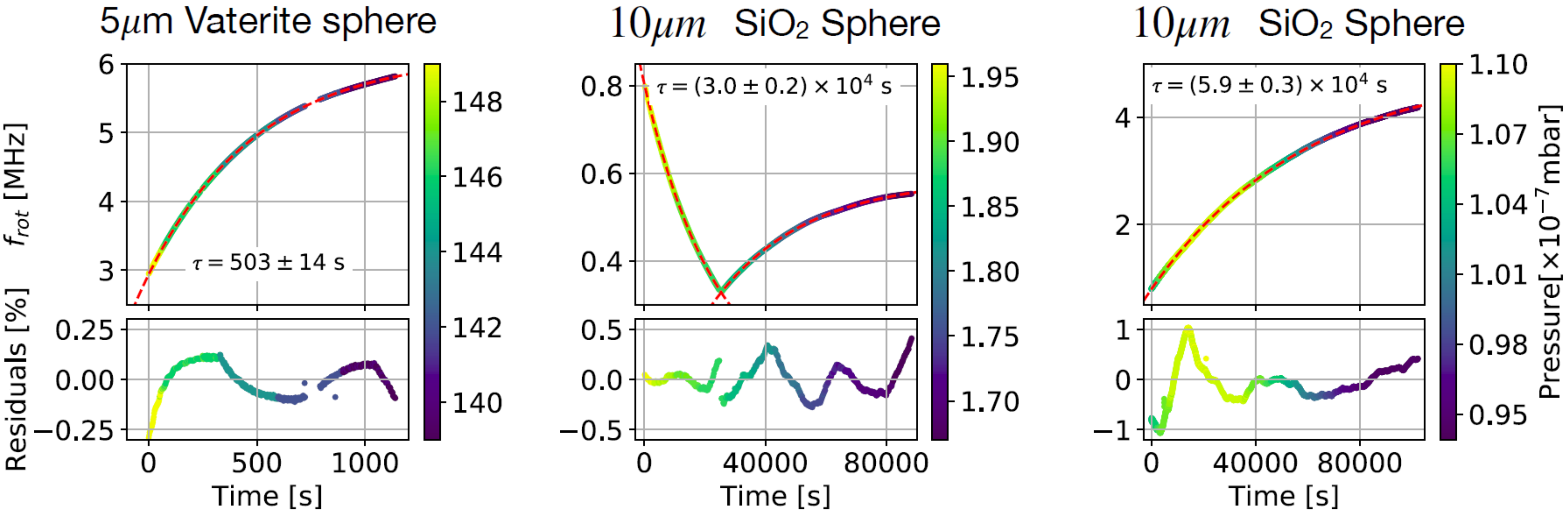
ROTATION





PRA 97, 051802(R) (2018)

DAMPING TIME



PRA 97, 051802(R) (2018)

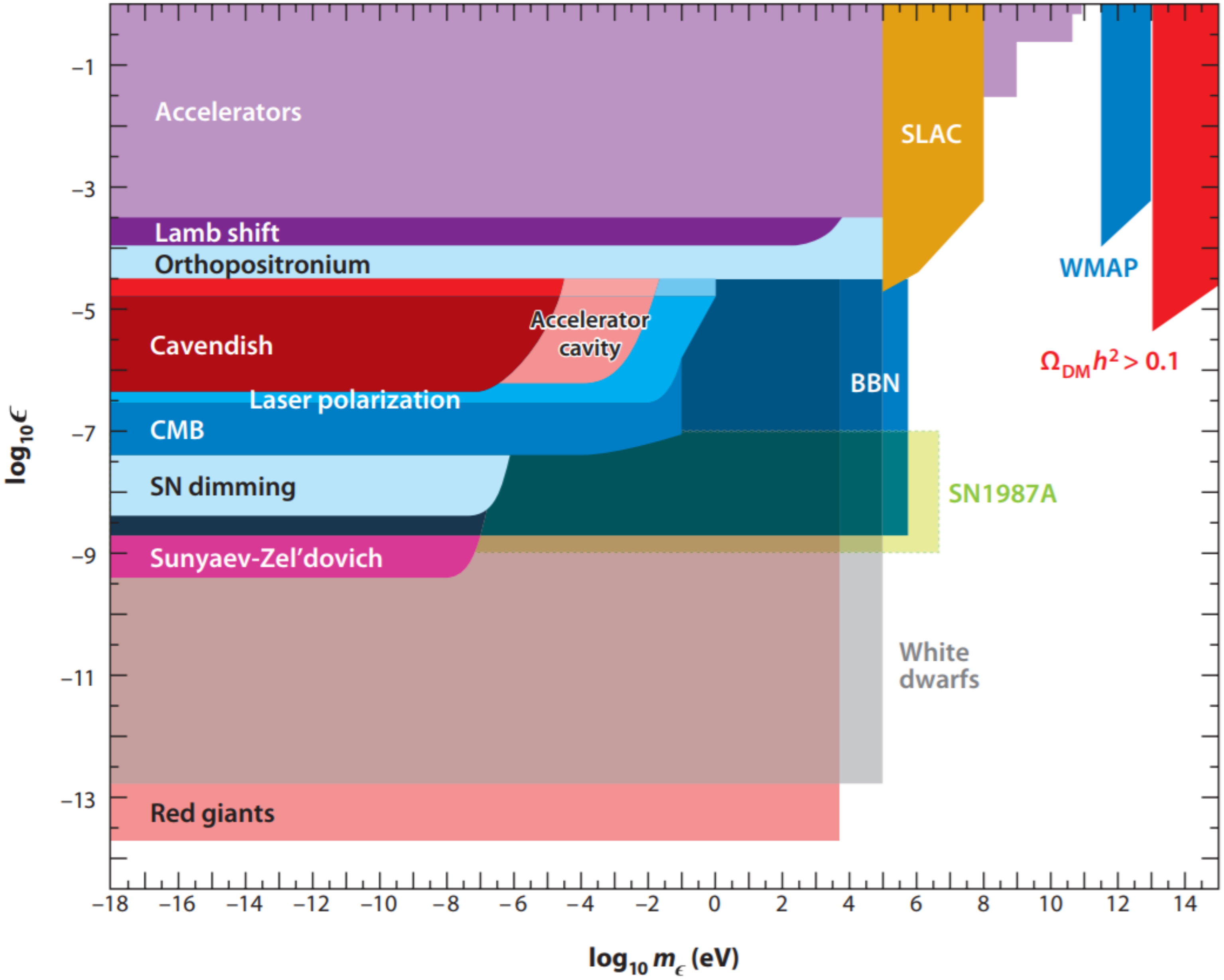
MILLICHARGED PARTICLES

Hidden sector DM: pick up tiny charges from interactions with SM ptcles

PARAMETER SPACE

Dark matter particles may pick up small charges through kinetic mixing

Complementary technique: search for fractional charges in matter



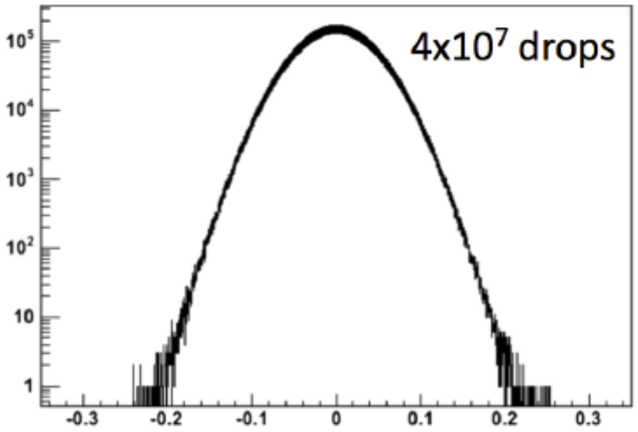
JAECKEL AND RINGWALD, ANN. REV. NUCL. PART. SCI., 60, 405 (2010)

LOOKING FOR FRACTIONAL CHARGES IN MATTER

Fractional charges

Previous Searches:Free Quarks

Astrophysical, bulk matter, Accelerators..

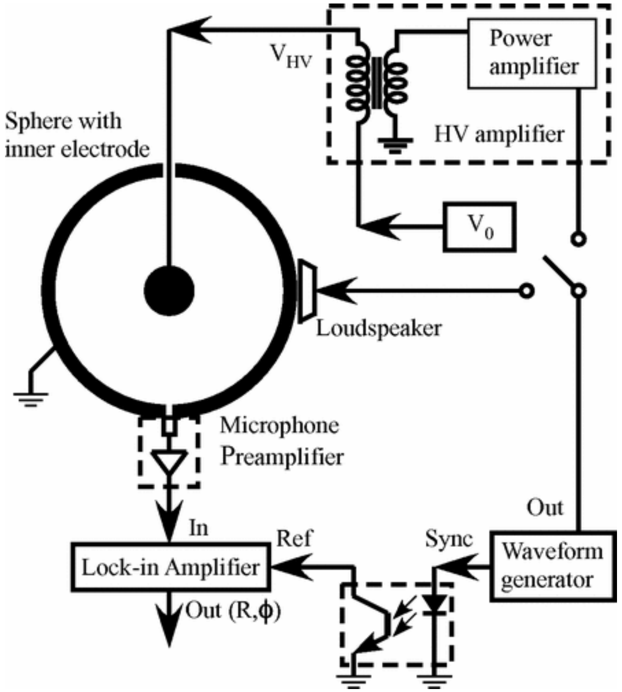


The q_c charge distribution in units of e

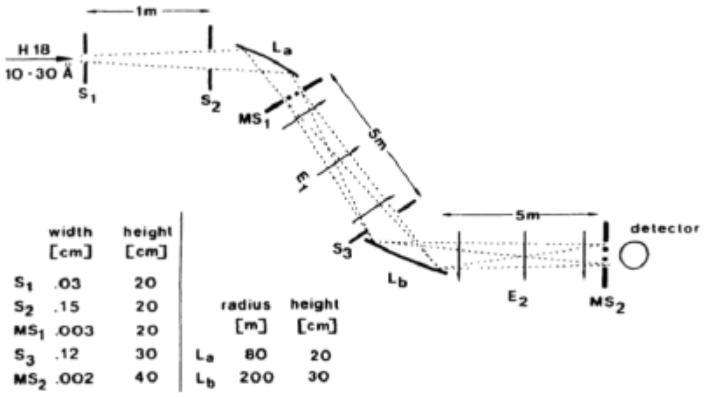
0.3g of matter were tested.
No evidence of millicharge was found.

P. Kim et al.,PRL **99**, 161804 (2007)

Neutrality of Matter



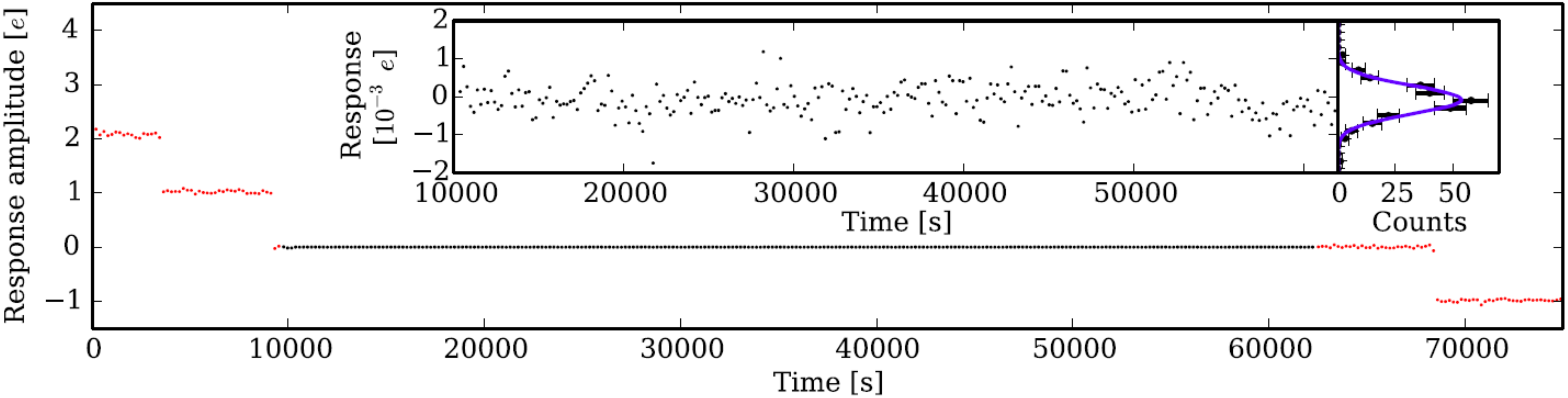
H. Dylla et al., PRA 7, 1224 (1973)
G. Bressi et al., PRA 83, 052101 (2011)



$|q_n| < 10^{-21} q_e$

J. Baumann et al., PRD 37, 3107 (1988)

PREVIOUS RESULT



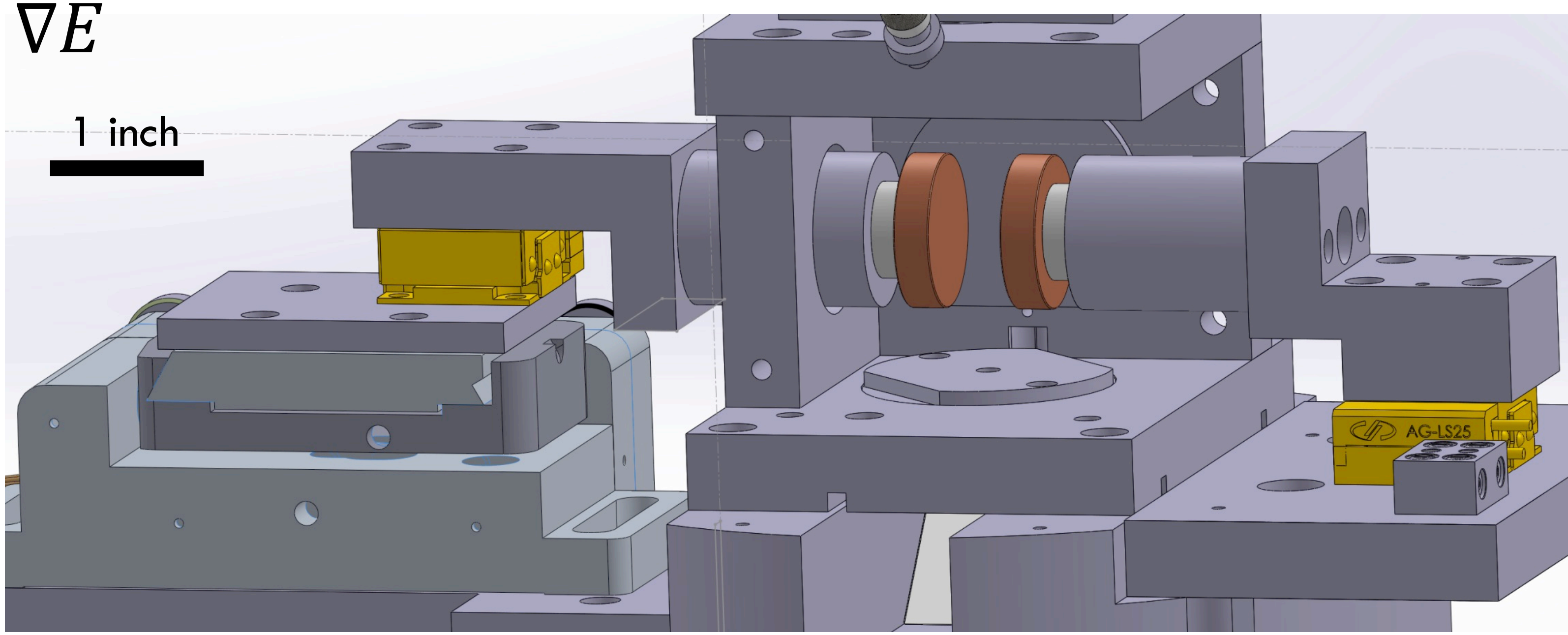
MOORE ET AL., PRL ***113*** *251801 (2014)*

DIPOLE BACKGROUND

Main background is due to dipole interactions

$\vec{F} = \vec{p} \cdot \vec{\nabla}\vec{E}$ → Minimize $\vec{\nabla} E$

- bigger plates
- gold coated
- ability to align the plates



DIPOLE BACKGROUND

$$\vec{E} \propto \sin \omega t \rightarrow E^2 \propto \sin 2\omega t$$

$$\vec{F} = (\vec{p} \cdot \vec{\nabla})\vec{E}$$

$$\vec{p} = \boxed{p_0 \hat{z}} + \boxed{\alpha_{ij} E_j \hat{\imath}}$$

Permanent dipole

Induced dipole

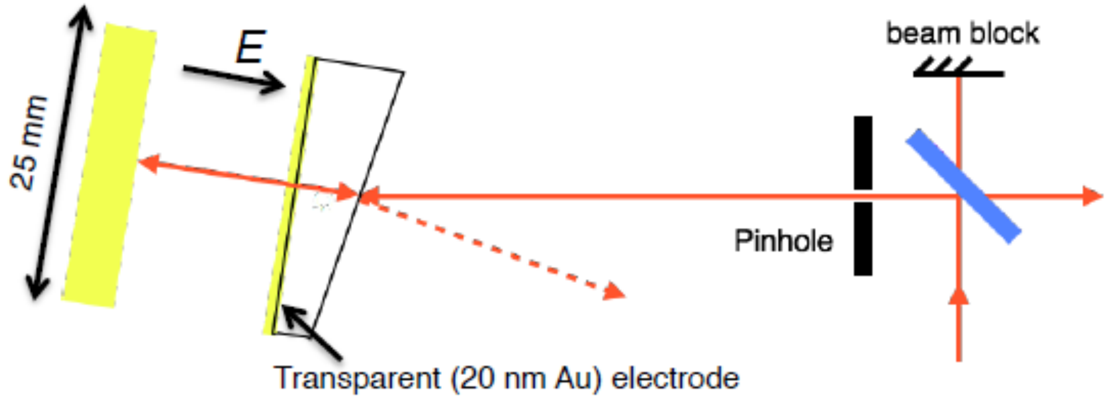
$$\rightarrow F_x = \boxed{p_0 \frac{\partial E_x}{\partial z}} + \boxed{\alpha_{ij} E_j \frac{\partial E_x}{\partial i}}$$

$\propto \sin \omega t$

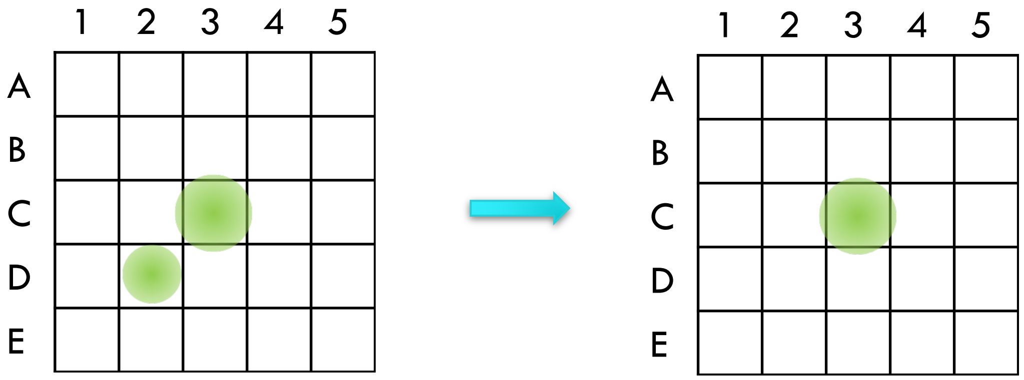
Like signal

$\propto \sin 2\omega t$

Like background



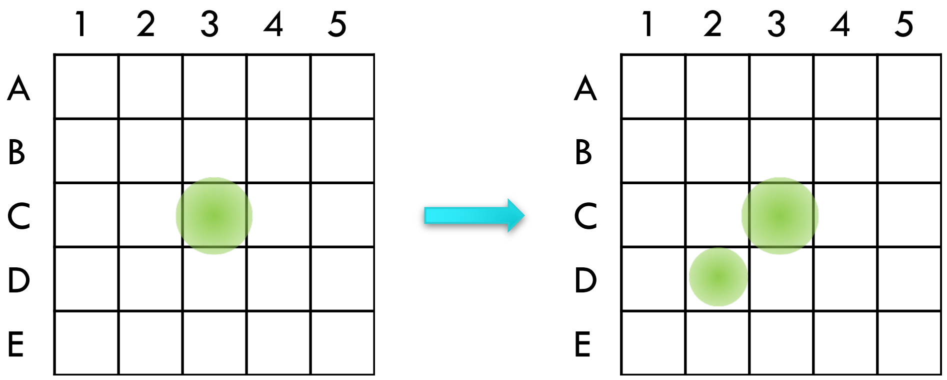
Plates can be aligned in situ to ~100 μrad

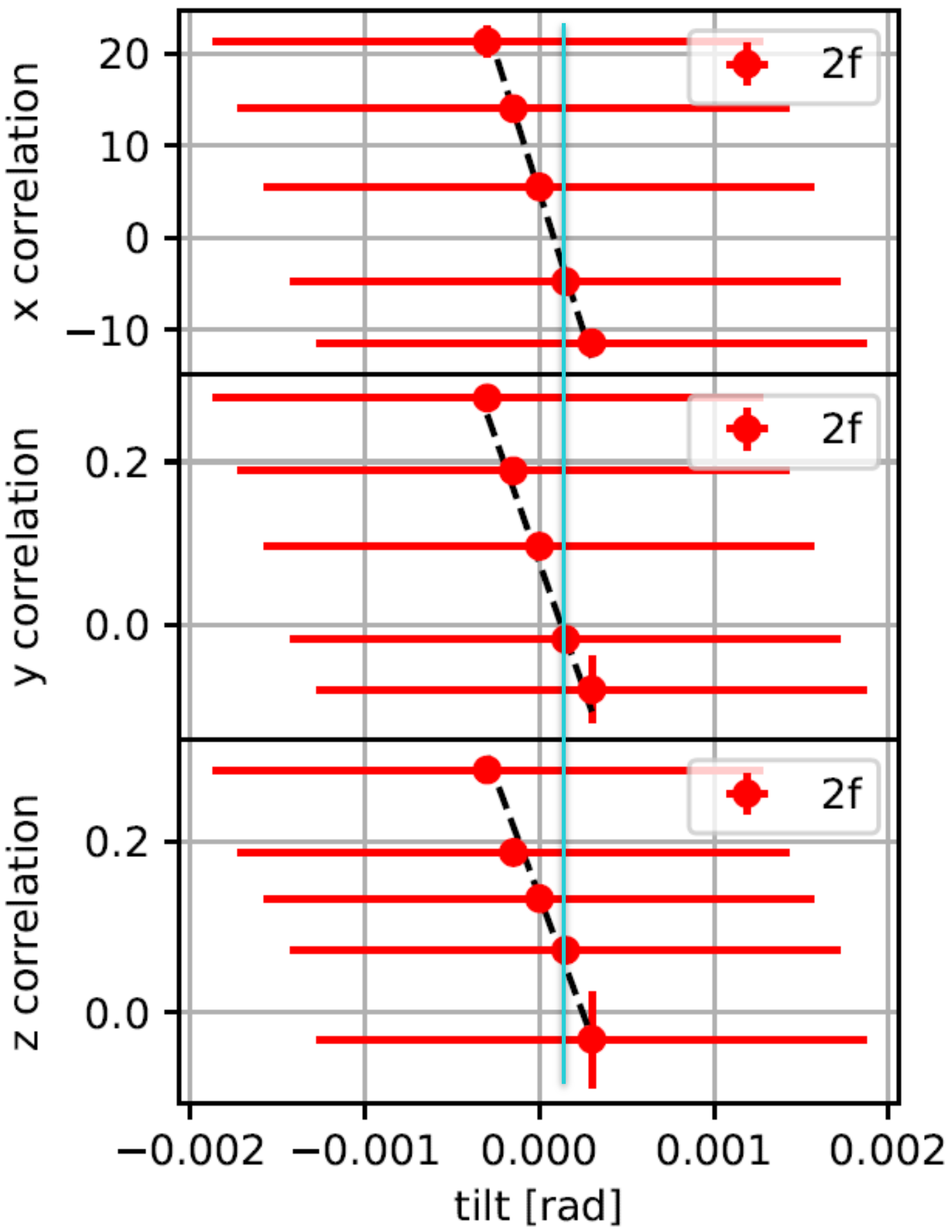


DIPOLE BACKGROUND

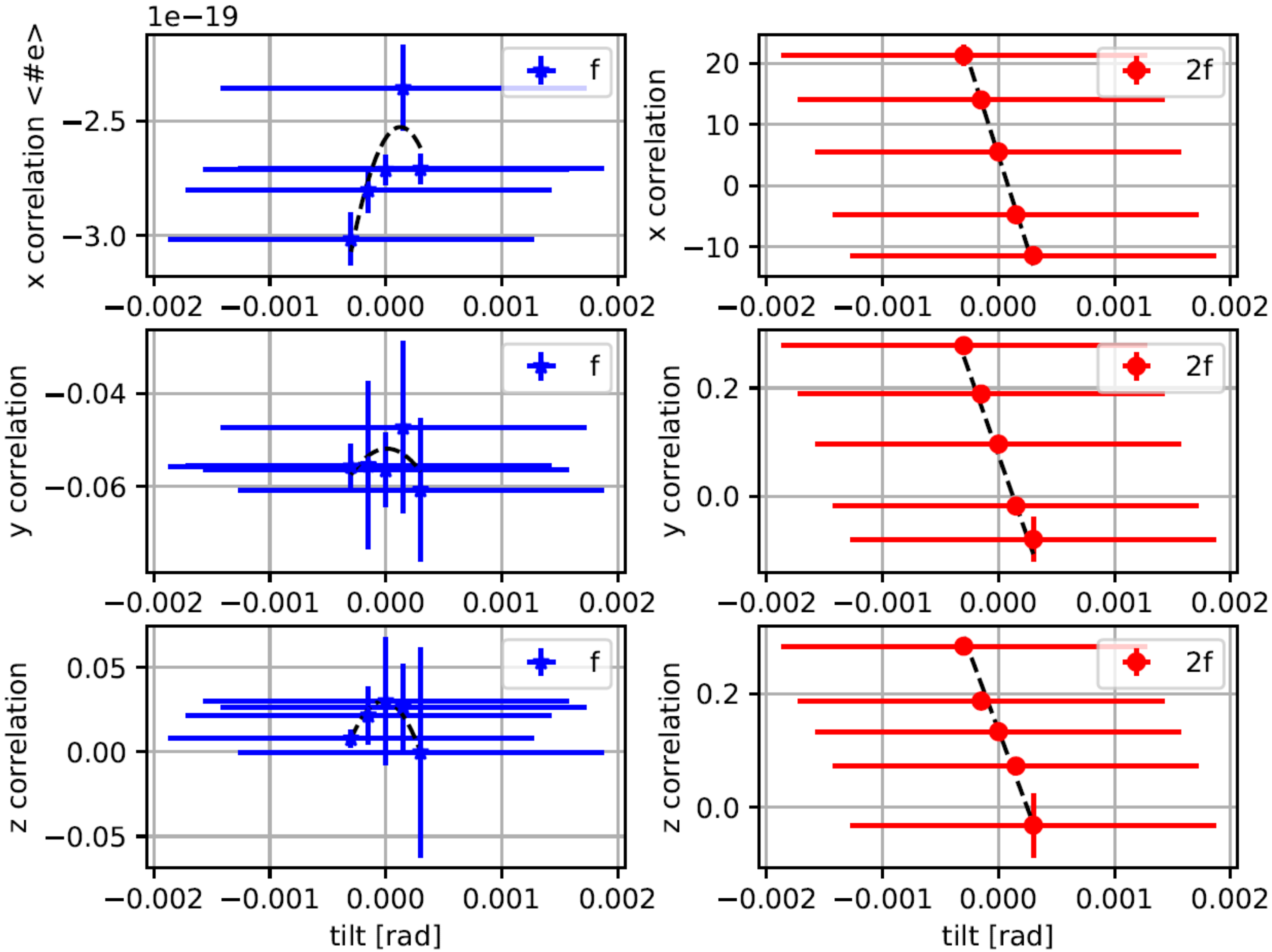
Make correlations at $2f$ while rasterizing tilt over grid

Move to minimum correlation at $2f$



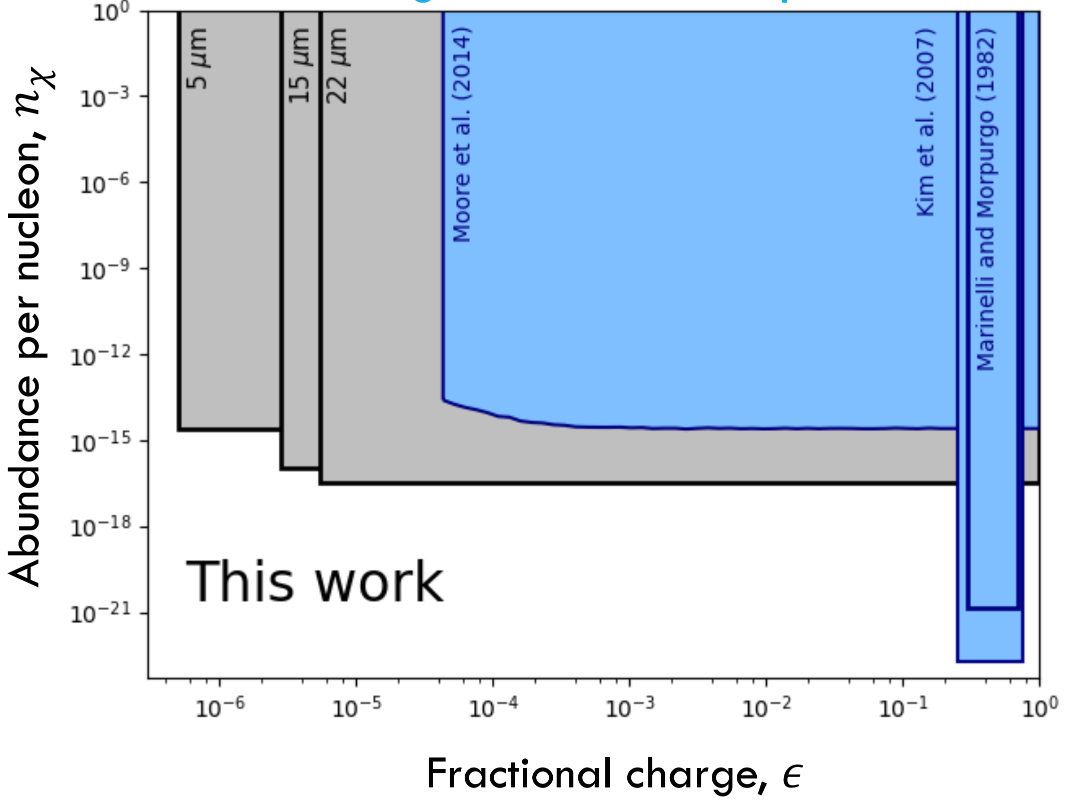


PICKUP BACKGROUND

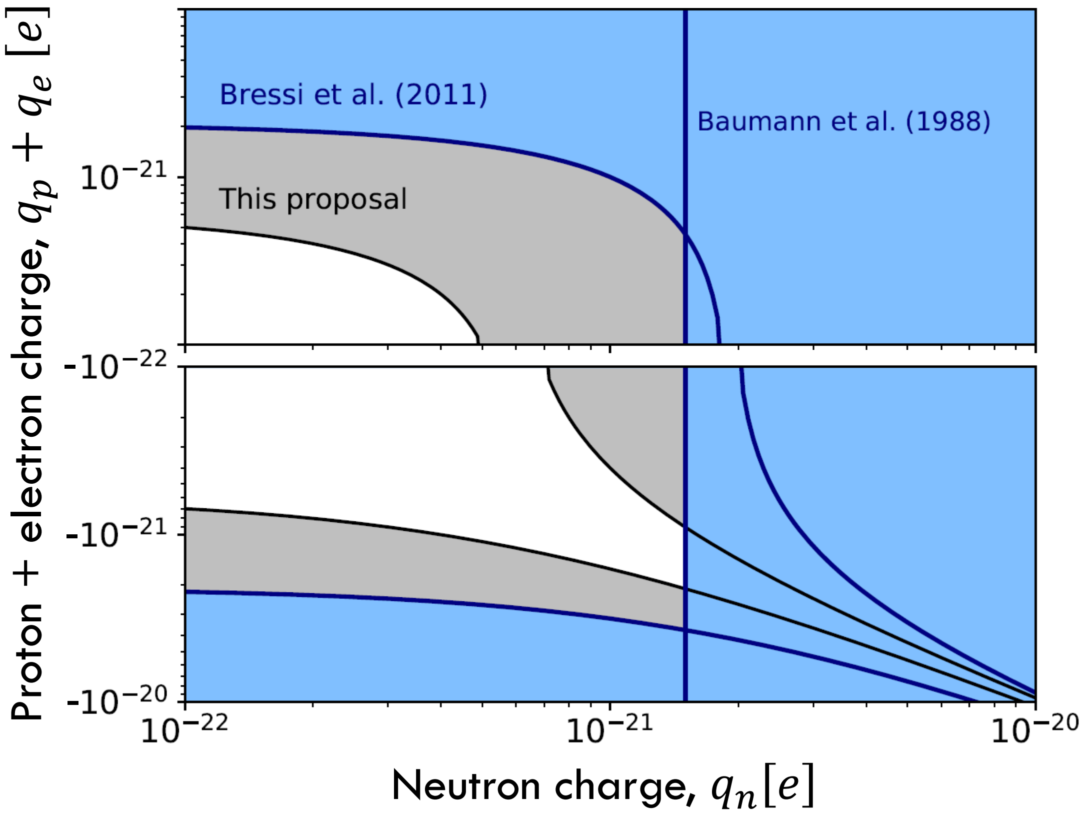


PROJECTED SENSITIVITY

Millicharged Particle experiment



Neutrality of Matter experiment



THANKS TO

Yale

Wright Laboratory

NSF

David C. Moore

Fernando Monteiro

Cady van Assendelft

Adam Fine

Alec Emser

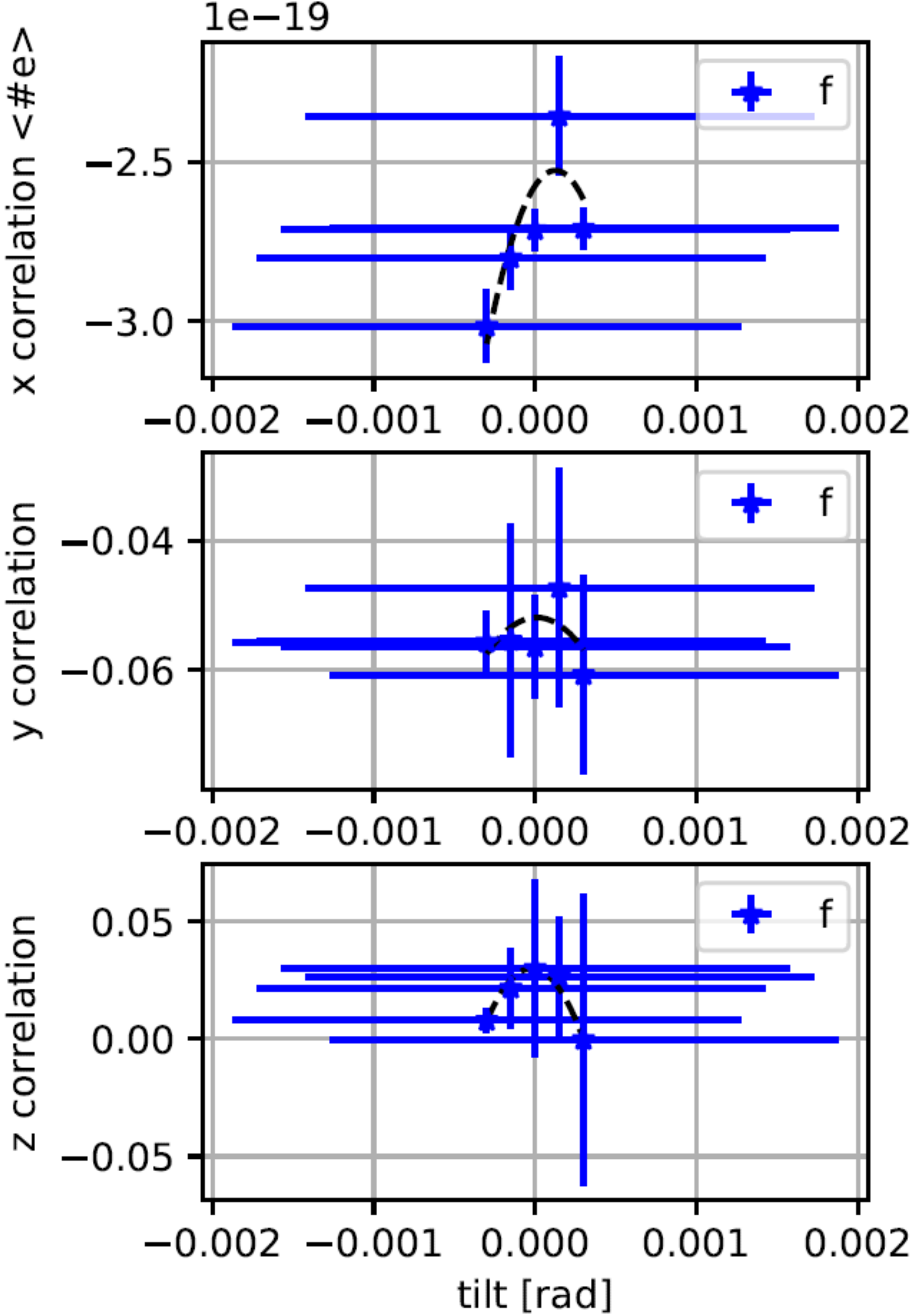
Andrew Kilby

Shoumik Chowdhury

Summary

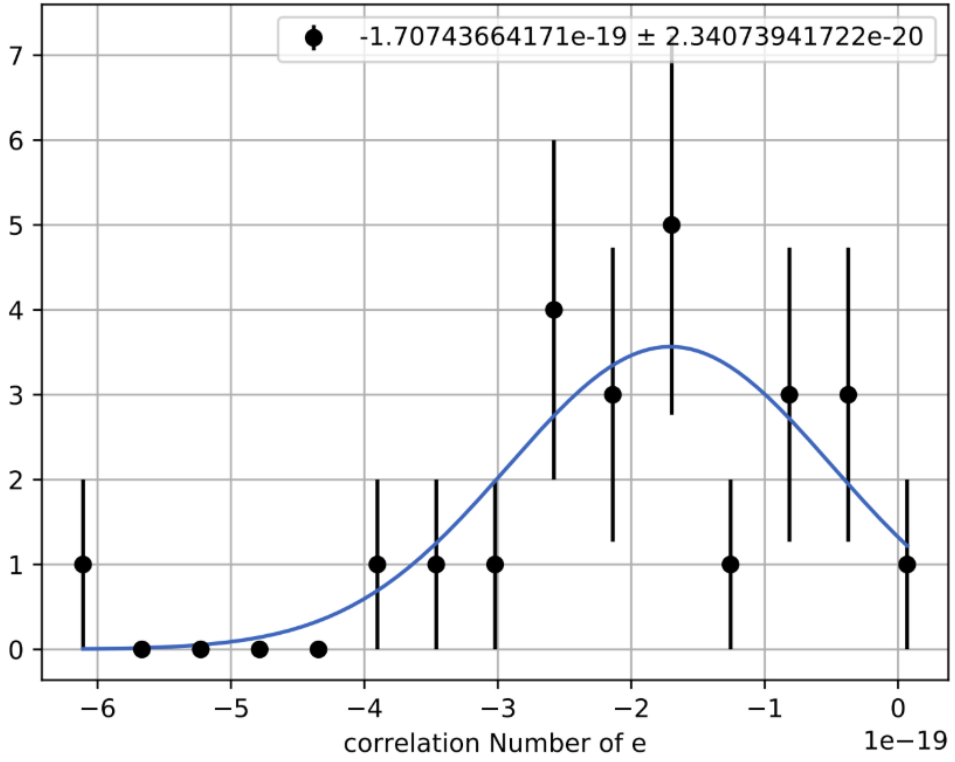
- Millicharged particles are dark matter candidates
- Levitated spheres in vacuum are electrically and thermally isolated
- Rotation, position, and charge are measurable and controllable
- Measuring the motion of a “neutral” sphere in a strong electric field allows for detection of tiny charges

EXTRA SLIDES

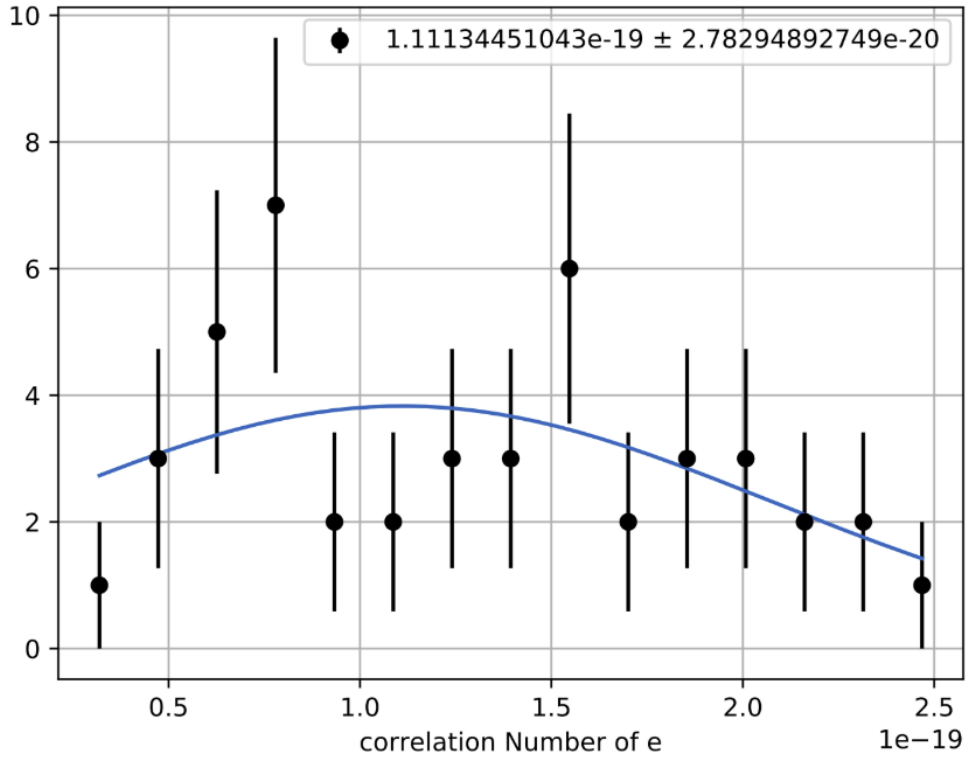

1e−19
x correlation <#e>
−2.5
−3.0
f
−0.002
−0.001
0.000
0.001
0.002
y correlation
−0.04
−0.06
f
z correlation
0.05
0.00
−0.05
f
tilt [rad]

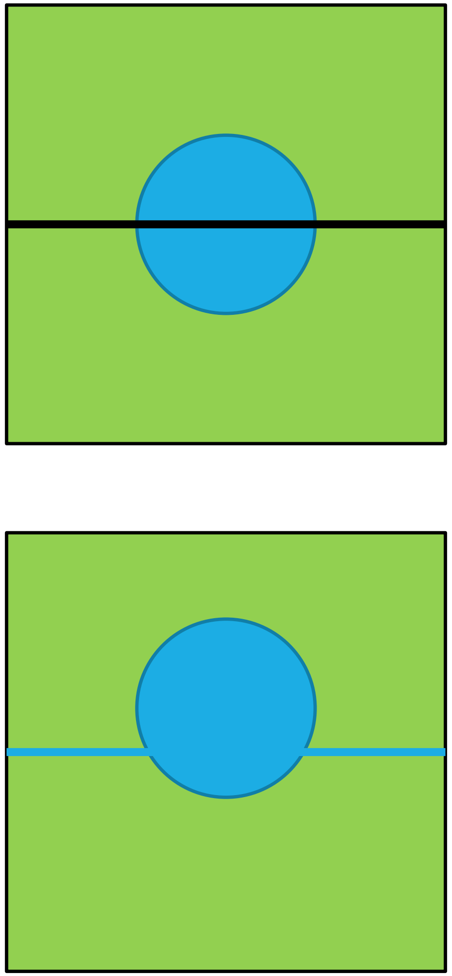
PICKUP BACKGROUND

With sphere: $1.7 \pm 0.2{\times}10^{-4}$e

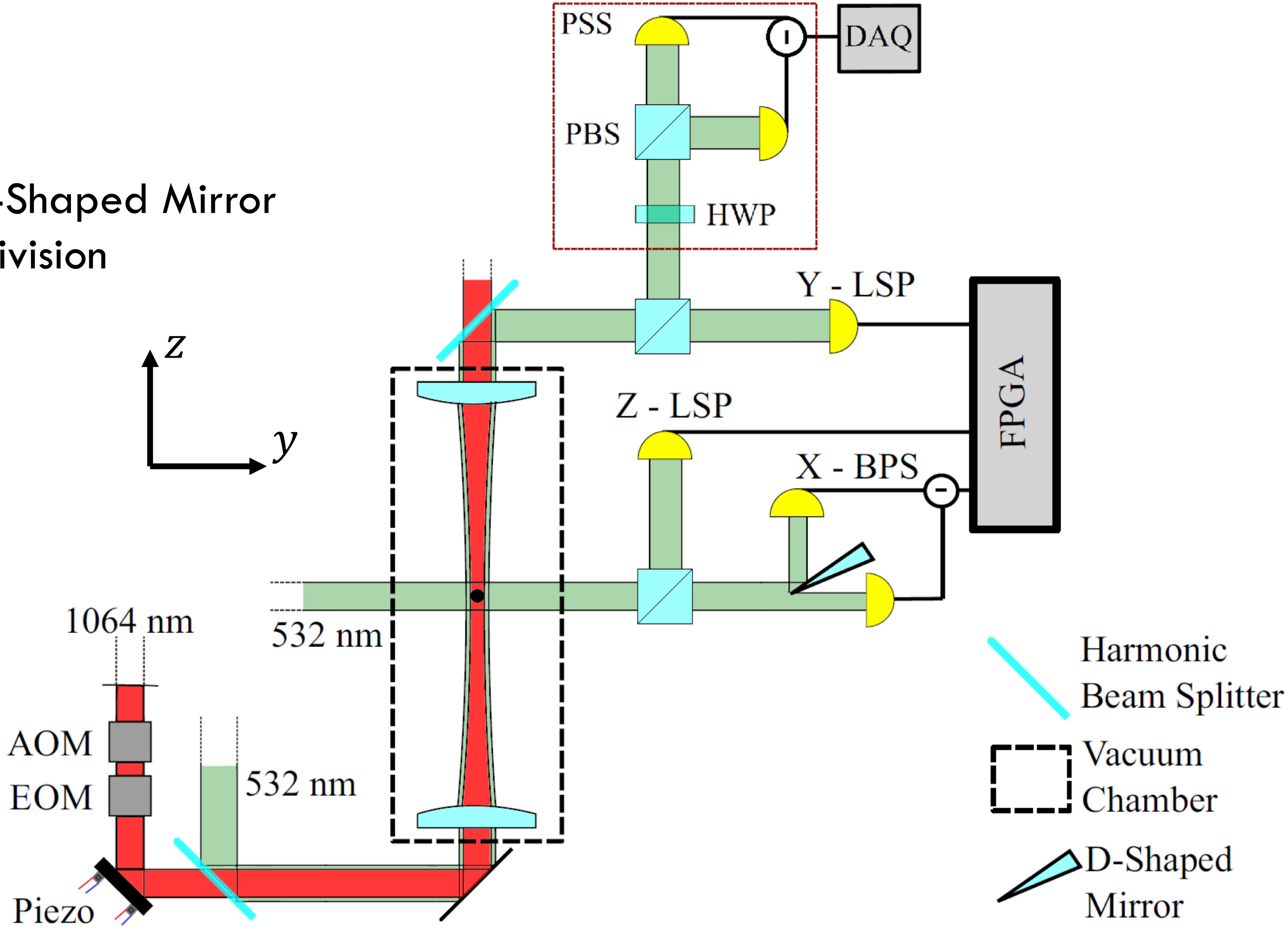


Just laser: $1.1 \pm 0.3{\times}10^{-4}$e





← D-Shaped Mirror division



ANALYSIS OF DATA

Correlation gives charge.

If charge is clearly nonzero and all sources of background have been ruled out:

Millicharged Particle Measurement

- Check this number over multiple spheres
- Make sure each measurement yields an integer times a constant number
- Check neutrality of matter

Neutrality of Matter Measurement

- Take overall charge and divide by number of nucleons
- Check that this number is the same over multiple spheres
- If it is, $e \neq p$
- If it isn't, we found a millicharge

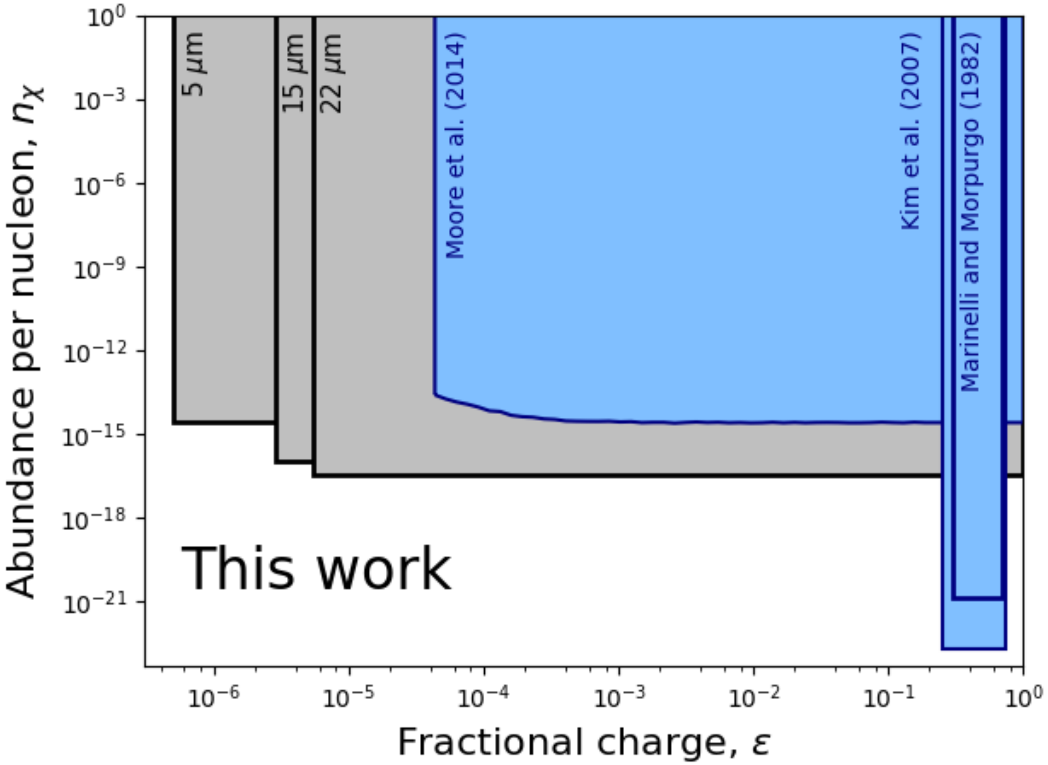
Otherwise report new lower bound

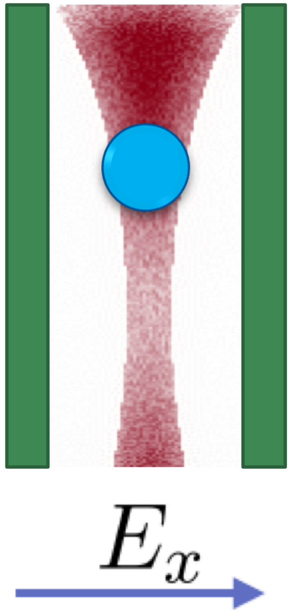
PROJECTED SENSITIVITY: MILLICHARGED PARTICLES

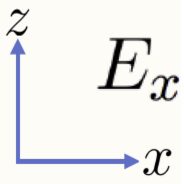
$$n_\chi = \frac{1}{\#\ \text{nucleons in sphere}}$$

ε = electron # sensitivity

This plot is over 10 spheres where each sphere is measured for 1 day.







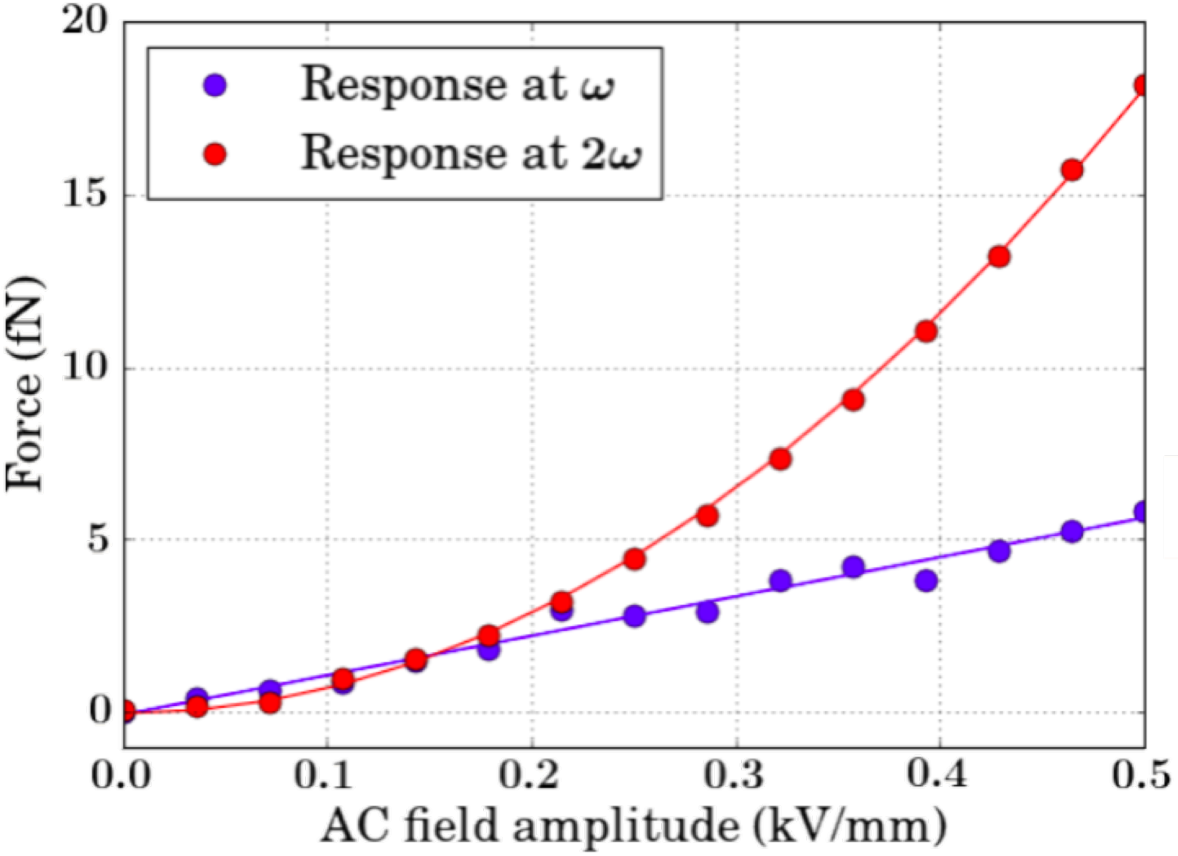
$$E_x \propto E_0 \sin(\omega t)$$

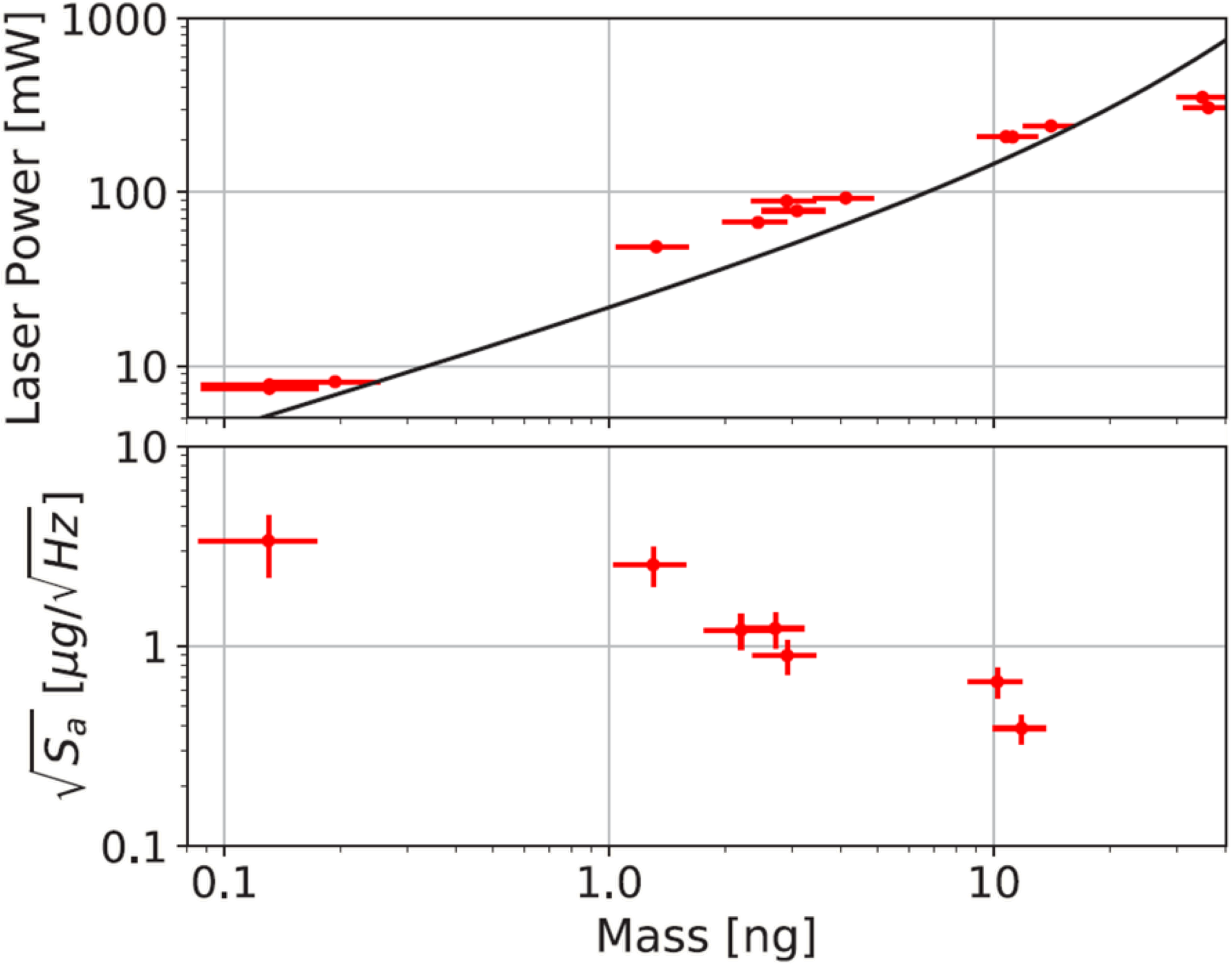
$$\vec{F} = (\vec{p}\cdot\vec{\nabla})\vec{E}$$

$$\vec{p} = \underbrace{\boxed{\vec{p}_0}}_{\text{Permanent dipole}} + \underbrace{\boxed{\alpha\vec{E}}}_{\text{Induced dipole}}$$

$$F_x = \boxed{\underbrace{\sum_{j}^{j=x,y,z} p_{0j}\frac{\partial E_x}{\partial j}}_{\substack{\propto E_0\sin(\omega t)\\ \text{Signal like}}}} + \boxed{\underbrace{\alpha E_x\frac{\partial E_x}{\partial x}}_{\substack{\propto E_0^2\cos(2\omega t)\\ \text{Background like}}}}$$

Permanent dipole $p_0 = 10^4$ eμm

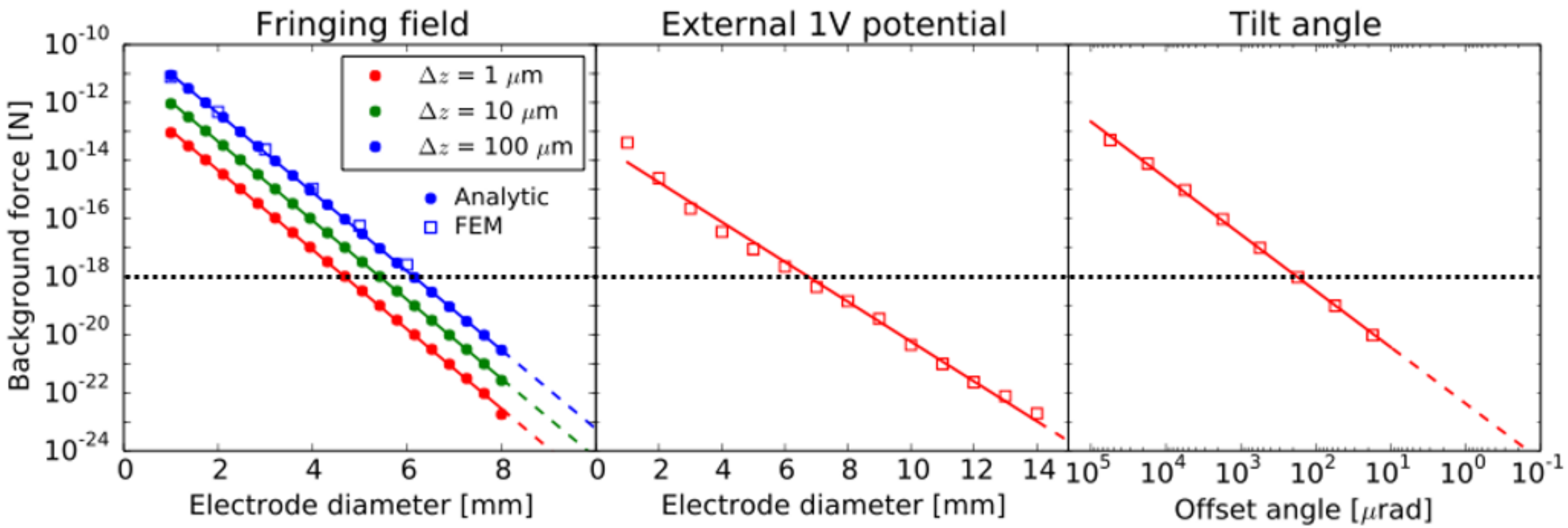




PRA 96, 063841 (2017)

Main Source of Field Gradient

$$1 \times 10^{-21}\,\mathrm{e} \Longleftrightarrow 1 \times 10^{-18}\,\mathrm{N}$$



Our electrodes have ≈ 25mm of diameter

Angle adjustable on the μrad level

INTERESTING PAPERS

https://arxiv.org/pdf/1408.4396

https://arxiv.org/pdf/1112.0493

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.99.161804

https://arxiv.org/pdf/1107.3131

https://arxiv.org/pdf/1507.00571

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.75.115001

https://journals.aps.org/prd/abstract/10.1103/PhysRevD.83.063509

https://www.annualreviews.org/doi/abs/10.1146/annurev.nucl.012809.104433

https://arxiv.org/abs/1311.0029

https://arxiv.org/pdf/1806.03310

https://arxiv.org/pdf/1803.03245

https://arxiv.org/abs/1802.10094

https://arxiv.org/abs/1803.02804