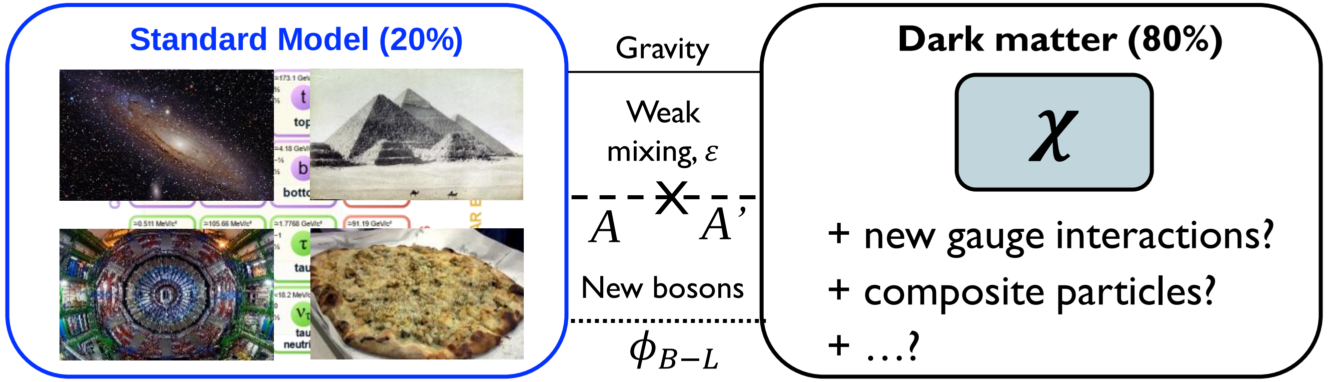
Searches for new physics using levitated optomechanics

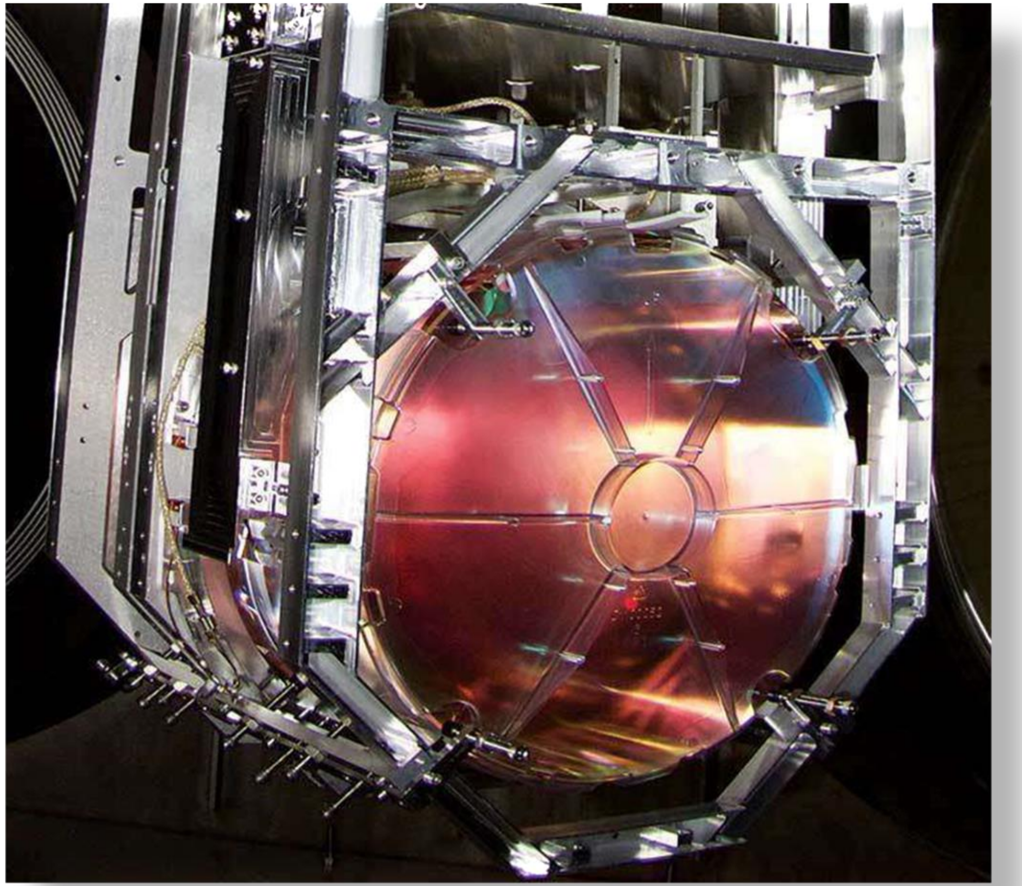
Gadi Afek

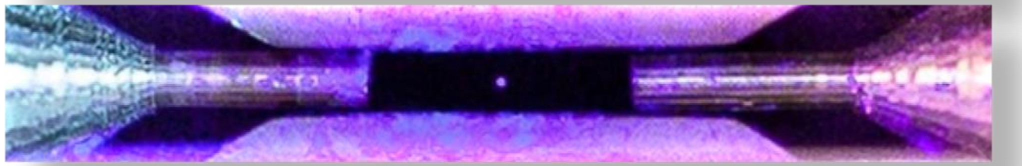
Yale University

Israel Joint Particle Physics Meetings, December 2020

OPTOMECHANICAL SENSORS







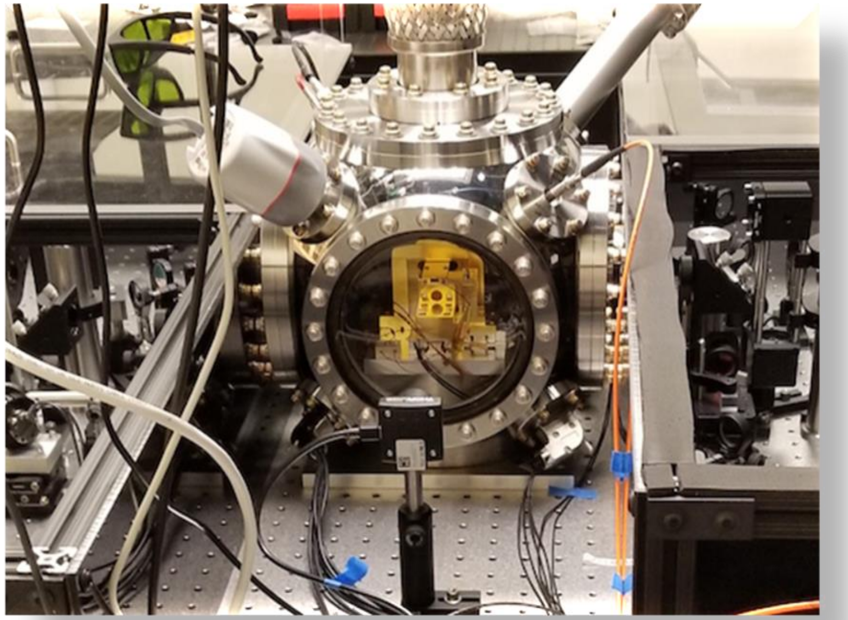
- “Opto-mechanical” systems are **VERY precise force sensors**
- Control and measurement of **large range of test masses** (from 10^{-21} g to 10^{3} g)
- We use ~10 ng microspheres with potentially **ng/Hz$^{1/2}$ acceleration sensitivity (SQL, 10^{-10} mbar)**

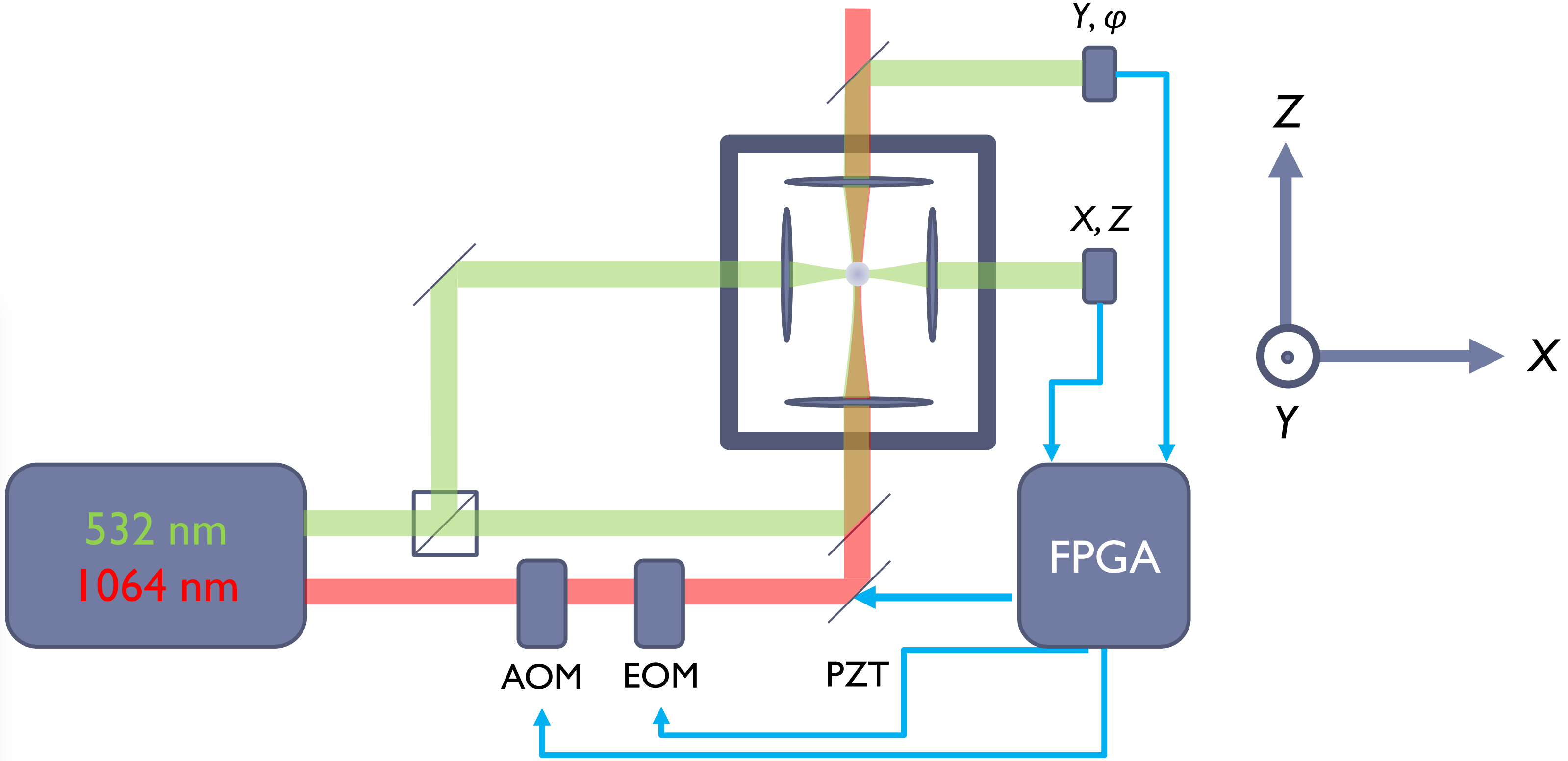
- https://www.newscientist.com/article/2084742-gravitational-wave-hunters-gear-up-to-detect-extreme-black-holes/

David Nadlinger (Lucas\Steane group, Oxford)

EXPERIMENTAL SETUP(S)

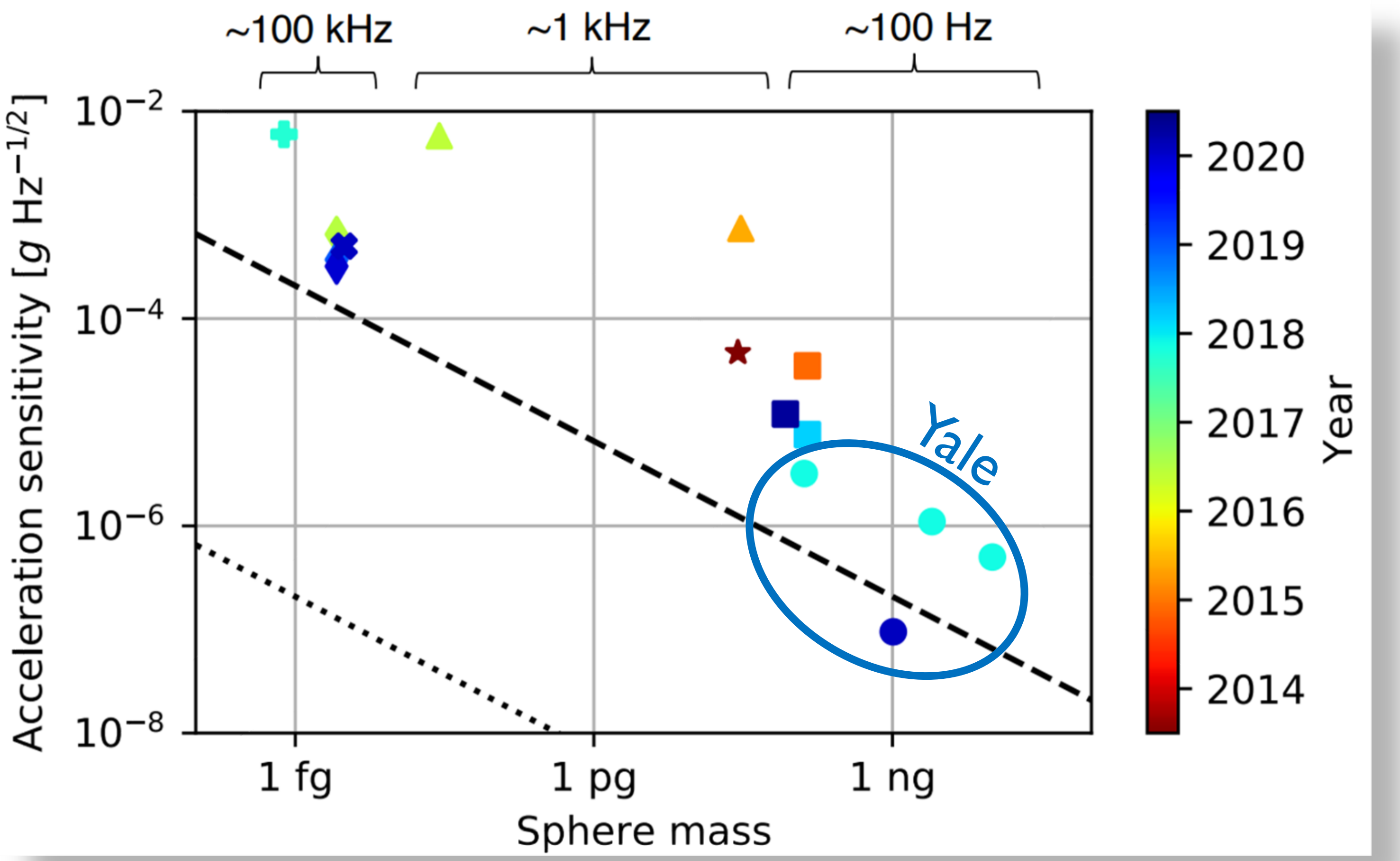
- **Variety of materials and sizes, isolated electrically and thermally**
- Low NA gravito-optical configuration → **~μm probing distances**





EXPERIMENTAL SETUP(S)

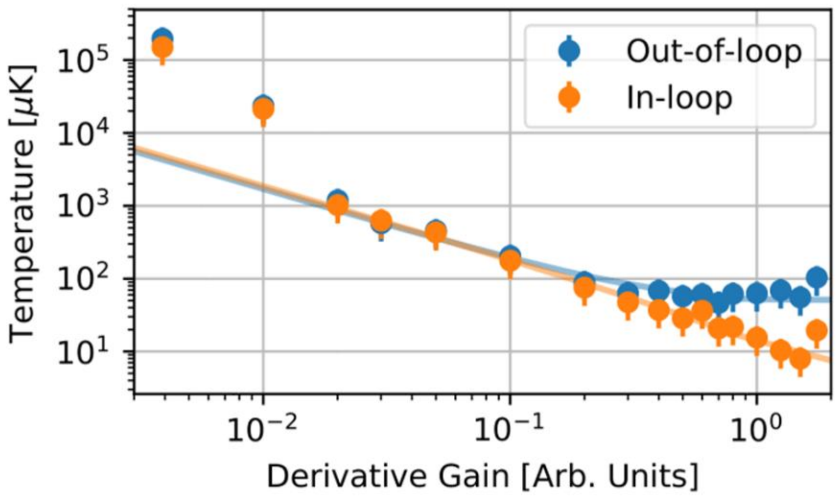
- **Variety of materials and sizes, isolated electrically and thermally**
- Low NA gravito-optical configuration → **~μm probing distances**
- Large spheres → better **acceleration sensitivity ~ 95 ng/Hz$^{1/2}$ ~ 1 aN/Hz$^{1/2}$**
- **DM searches couple to # constituents** in sensor
- **Trap > 1 month → LONG integration times**

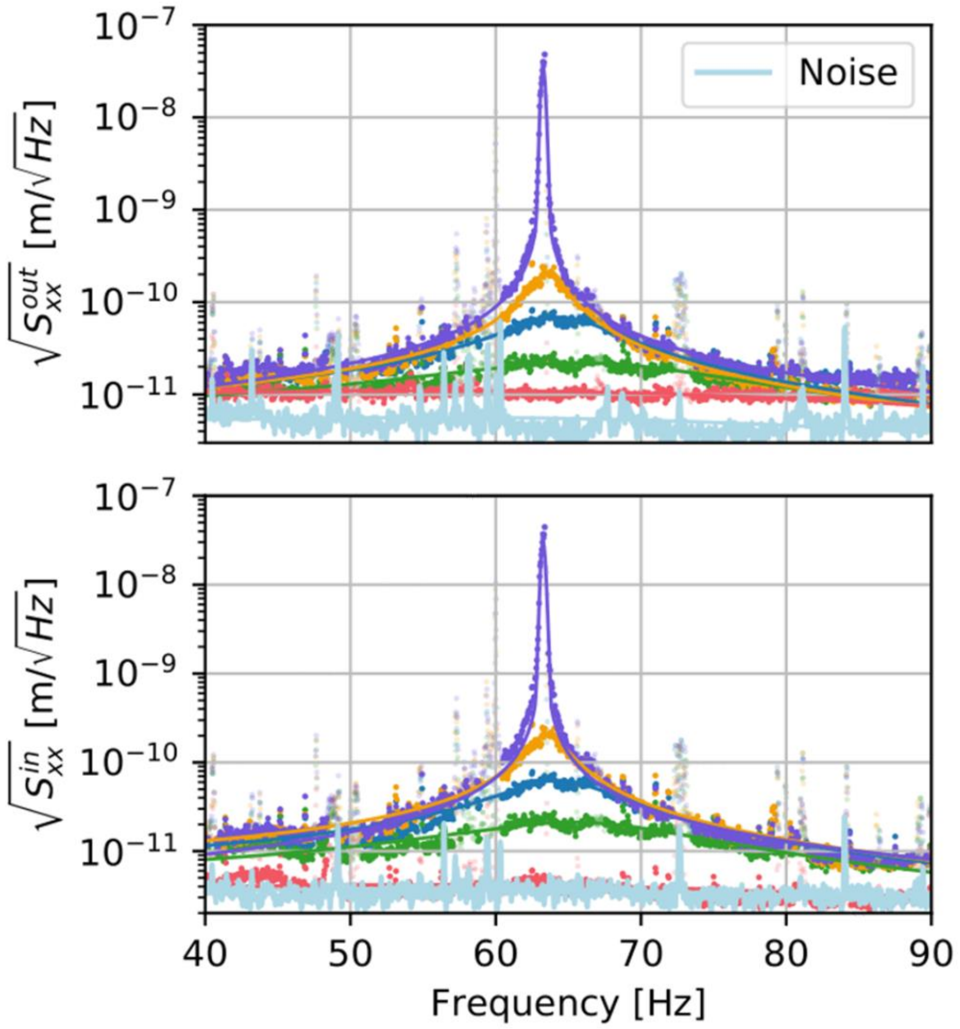


D. Moore and A. Geraci, *Quantum Science and Technology* (2020), F. Monteiro, W. Li, **GA**, C.L. Li, M. Mossman and D. Moore., *PRA* **101**, 053835 (2020)

μK TEMPERATURES

- Below ~1 mbar, active feedback cooling is needed for stable trapping
- Low pressure (~10^{-7} mbar), **Minimal damping** → High temperature (1K)
- **Increase damping** → Reduce temperature
- Center of mass ***T* = 50 ± 22 μK** (Imaging laser noise limited)
- Noise squashing averted with out-of-loop sensor

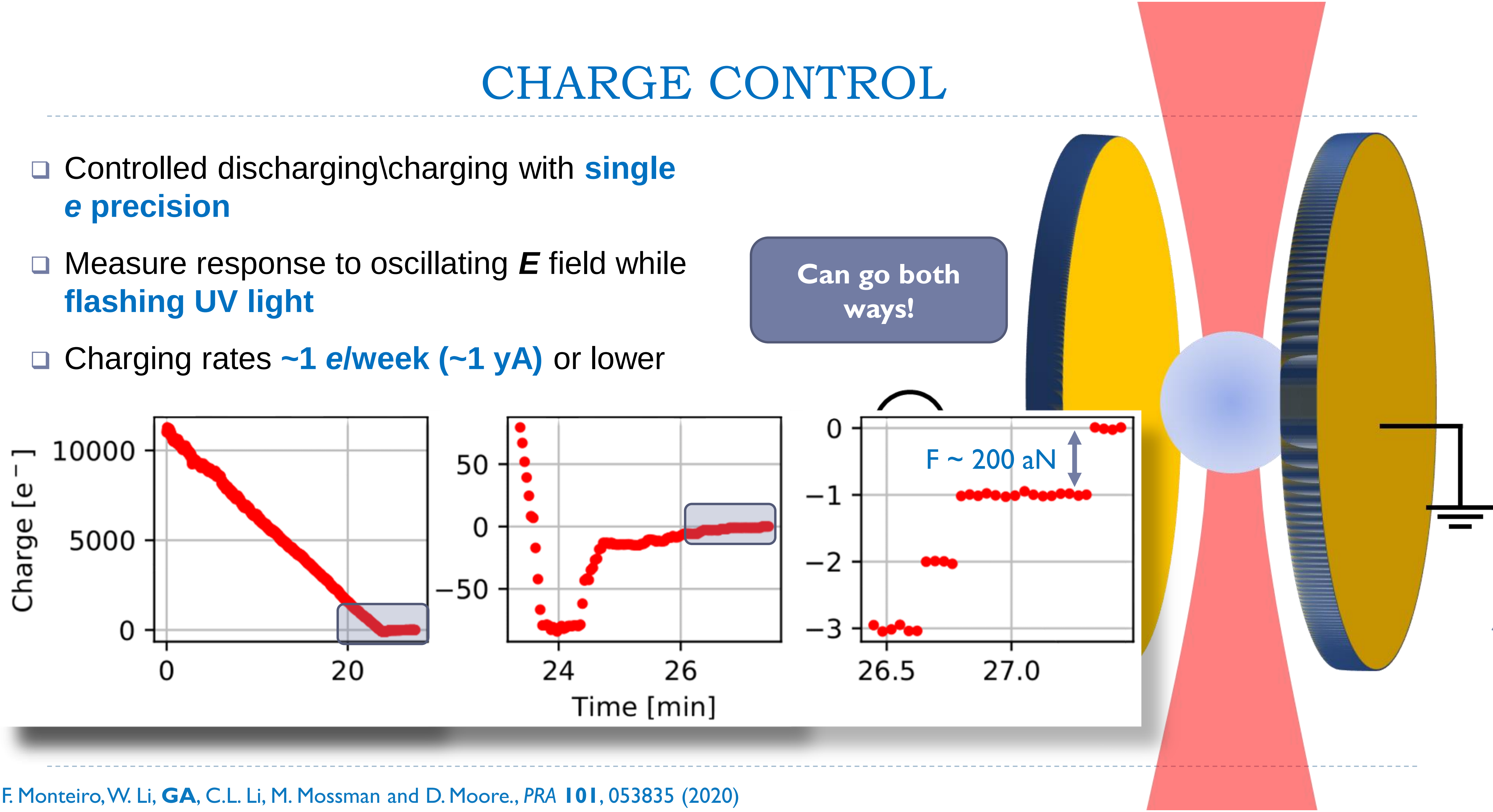




F. Monteiro, W. Li, **GA**, C.L. Li, M. Mossman and D. Moore., *PRA* **101**, 053835 (2020)

CHARGE CONTROL

- Controlled discharging\charging with **single e precision**
- Measure response to oscillating ***E*** field while **flashing UV light**
- Charging rates **~1 e/week (~1 yA)** or lower



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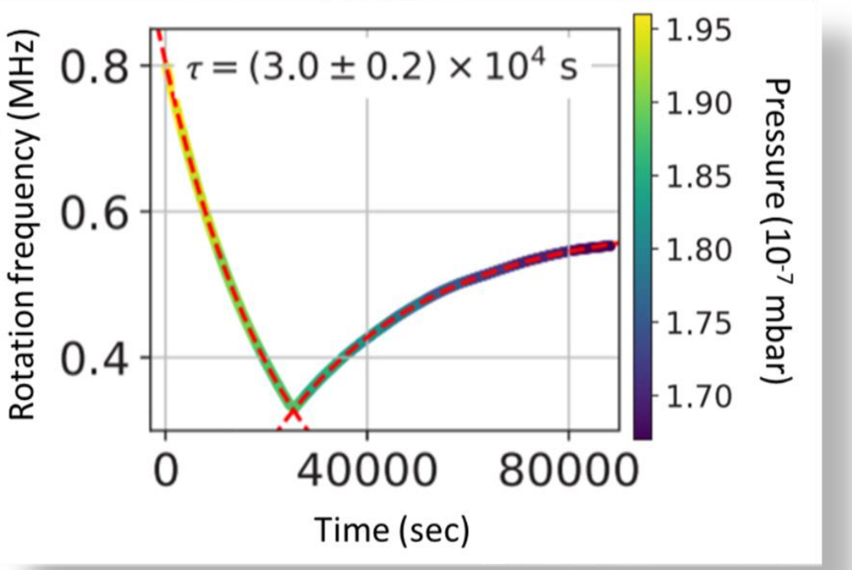
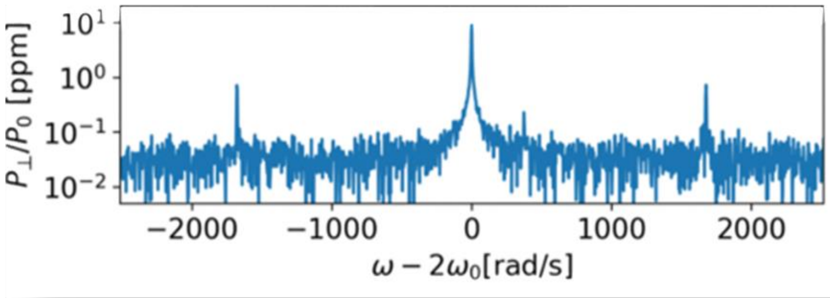
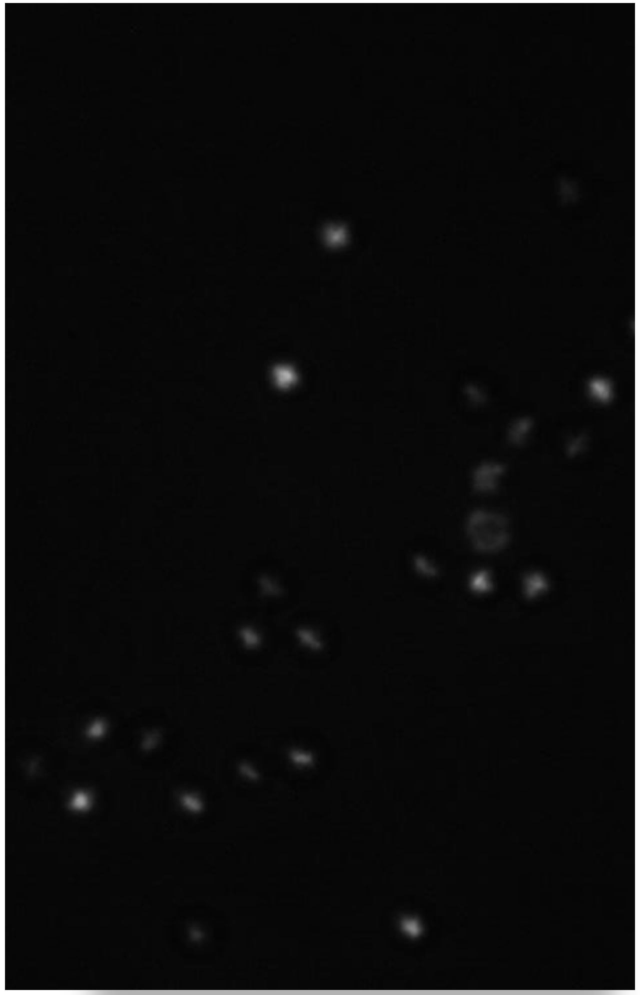
SPINNING SPHERES. *FAST.*

- Circularly polarized light → **torque on birefringent sphere**
- Damping time is **~1 day,** Sphere **rotates 10^{11} cycles in single damping time**
- Recently demonstrated rotation **up to 10 MHz** in high vacuum (> 1 Mach surface speed)
- **No dissipation** observed **above gas damping**
- **Librational mode** as **torque sensor?**







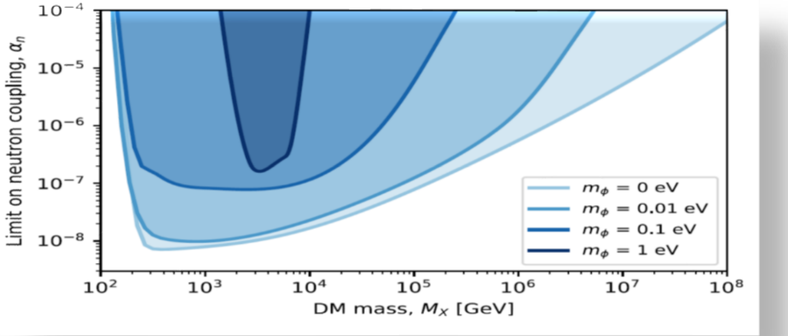
Friese *et al.*, *Nature* **394,** 348 (1998), Donato *et al.*, *Sci. Rep.* **6**, 31977 (2016), Monteiro *et al.*, *PRA* **97**, 051802(R) (2018) , Rider *et al.*, *PRA* **99**, 041802(R) (2019)

TESTING NEW PHYSICS

Testing **Newton's law** at ~ *um* distances

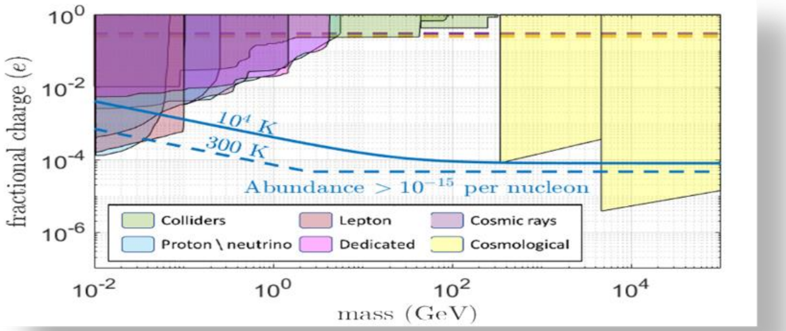
Searches for **"fifth forces"** and tests of **Coulomb's law**

Search for **recoils** from **composite DM**



F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020)

Testing **charge quantization** and search for **mCP**



GA, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore., *arXiv*:2012.08169 (2020)

Nuclear recoils from single α/β decays

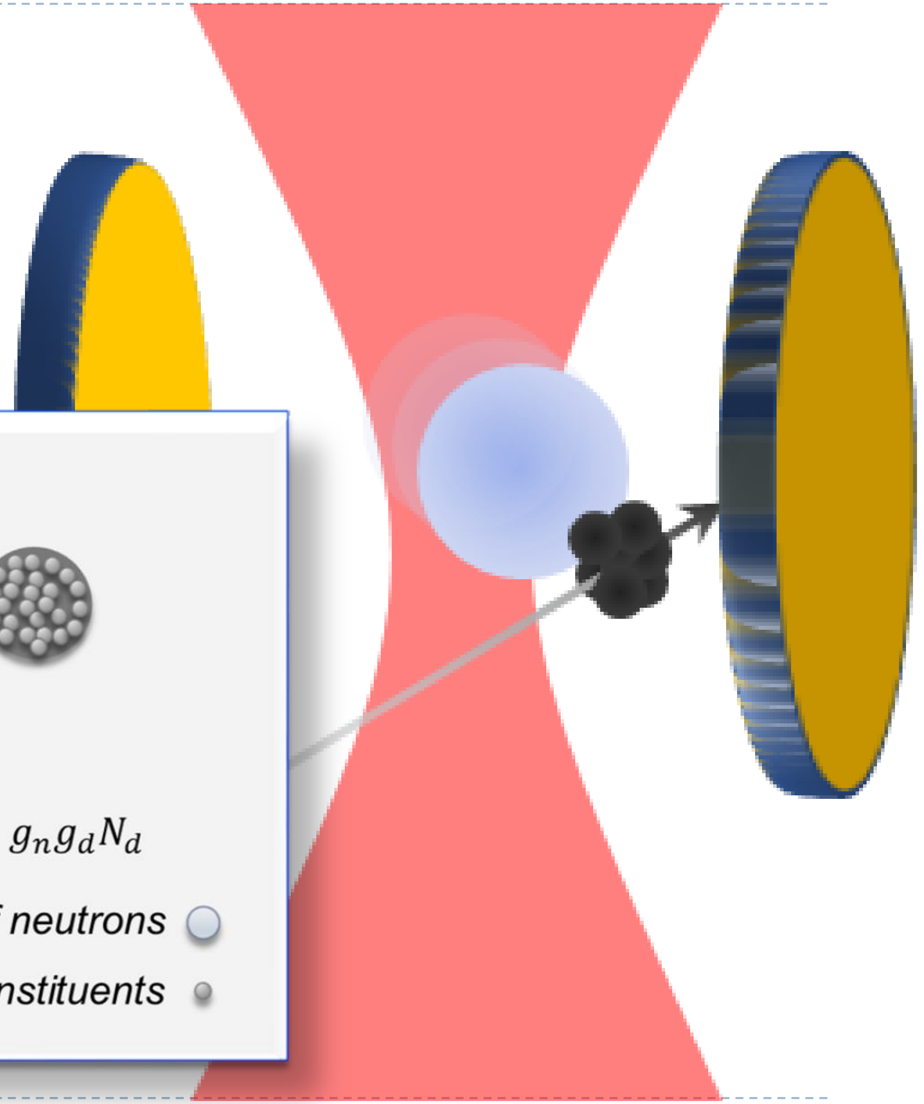
Large arrays (N X N?) of ng masses

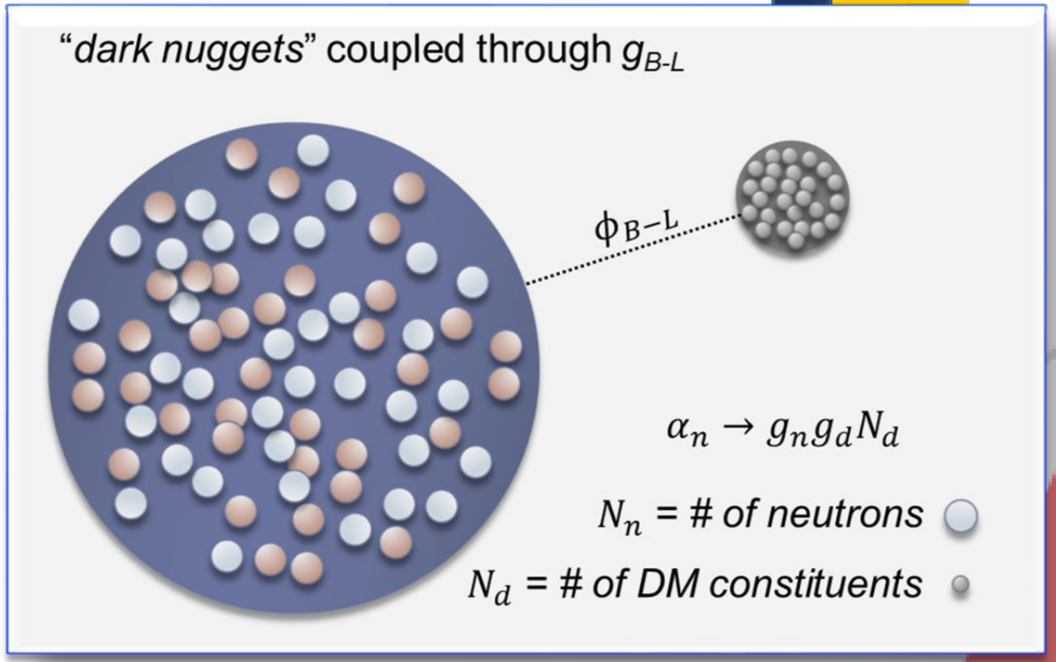
DM-INDUCED RECOILS

- Consider heavy **DM** particles
- Interaction mediated by a light force carrier $m_\phi \lesssim \mathrm{eV}$
- **Coherent enhancement!**
- Need to be cold
- **Low momentum threshold** $\sim 200\ \mathrm{MeV/c}$
- **Specific models exist**

$$V(r) = \alpha_n N_n \frac{e^{-m_\phi r}}{r}$$

$$\sigma \sim N_n^2 \sim 10^{29}$$





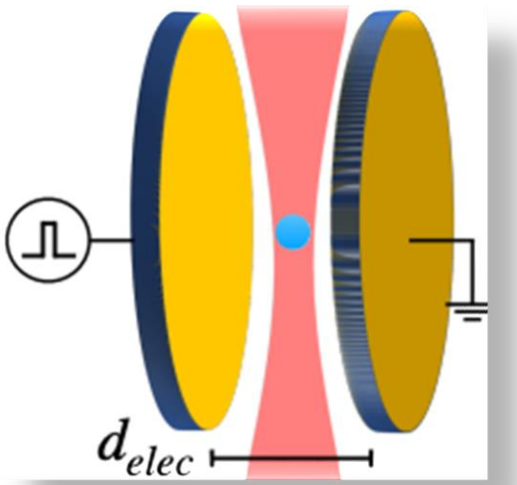
F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020), Krnjaic, G and Sigurdson, K, *PLB* (2015), Coskuner *et al*, *PRD* **100** 035025 (2019)

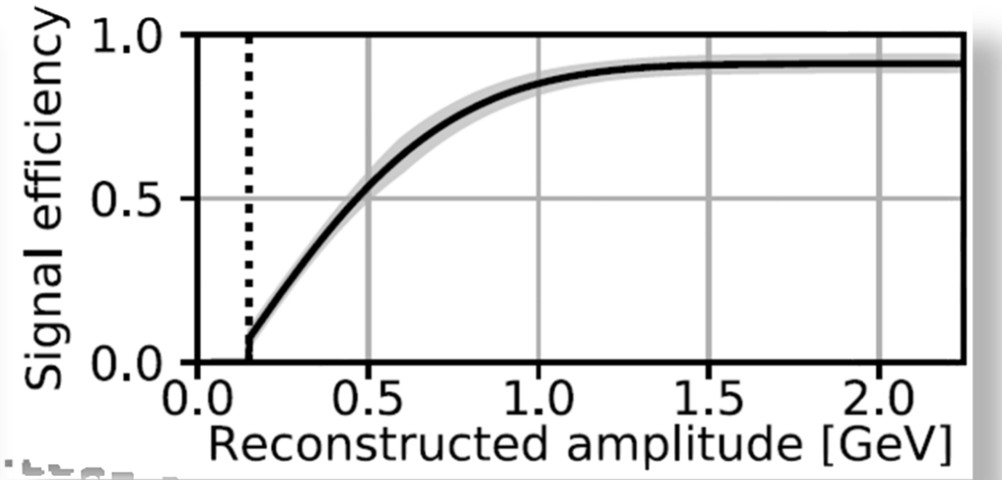
CALIBRATION using ELECTRIC IMPULSES

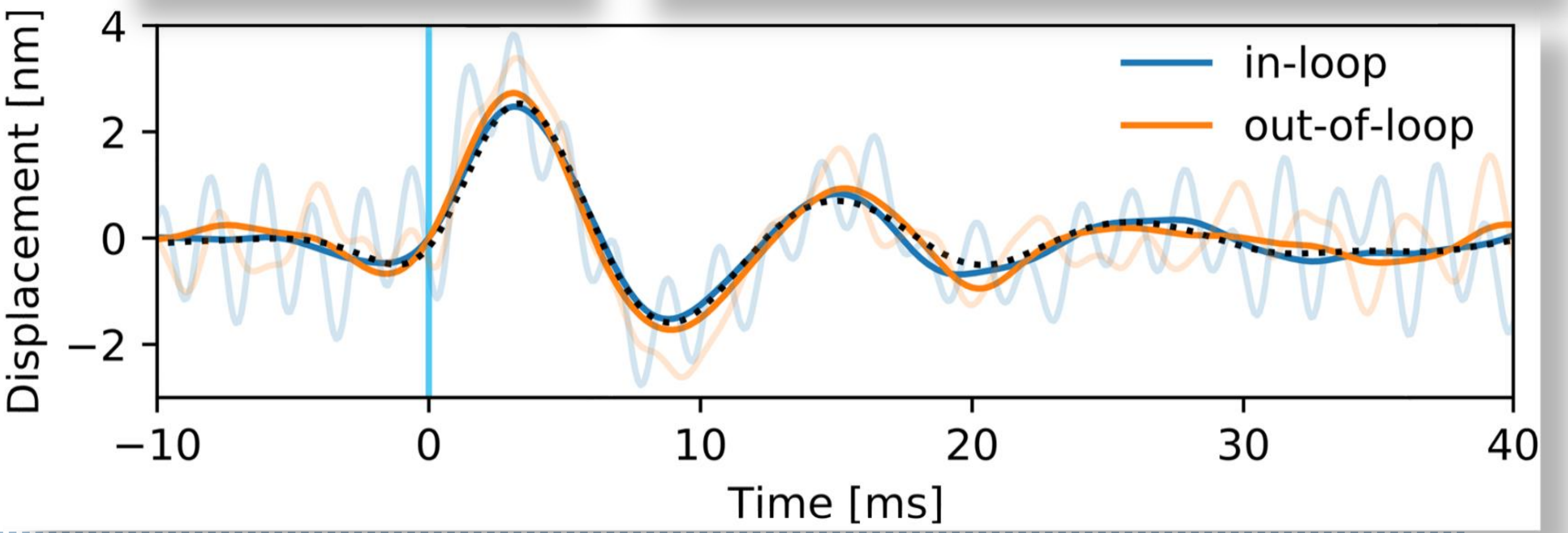
- Charge sphere up to precisely 1 *e*
- Apply a **train of short square pulses** with V = 20 V – 1.28 kV
- Analysis threshold set to 150 MeV
- Timescales:

$$\tau_{DM} \sim 5 \text{ ns} \ll$$
$$\tau_{Cal} \sim 100\ \mu\text{s} \ll$$
$$\tau_{sph} \sim 10 \text{ msec}$$

- **Directionality?!**







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DATA CUTS and RESULTS

Rate of all reconstructed impulses

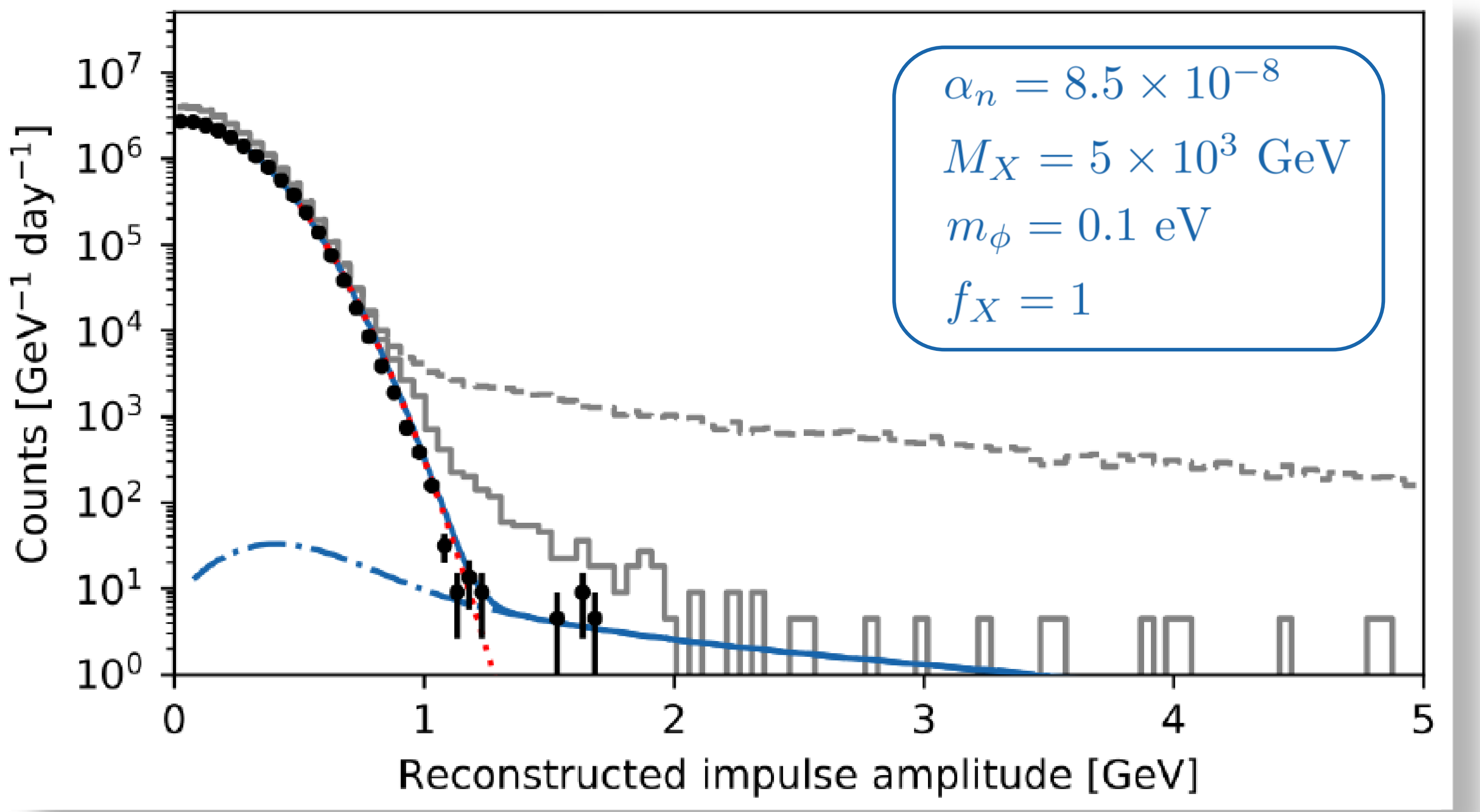
Live time selections only

All cuts applied

Gaussian BG

DM Signal

BG + DM Signal

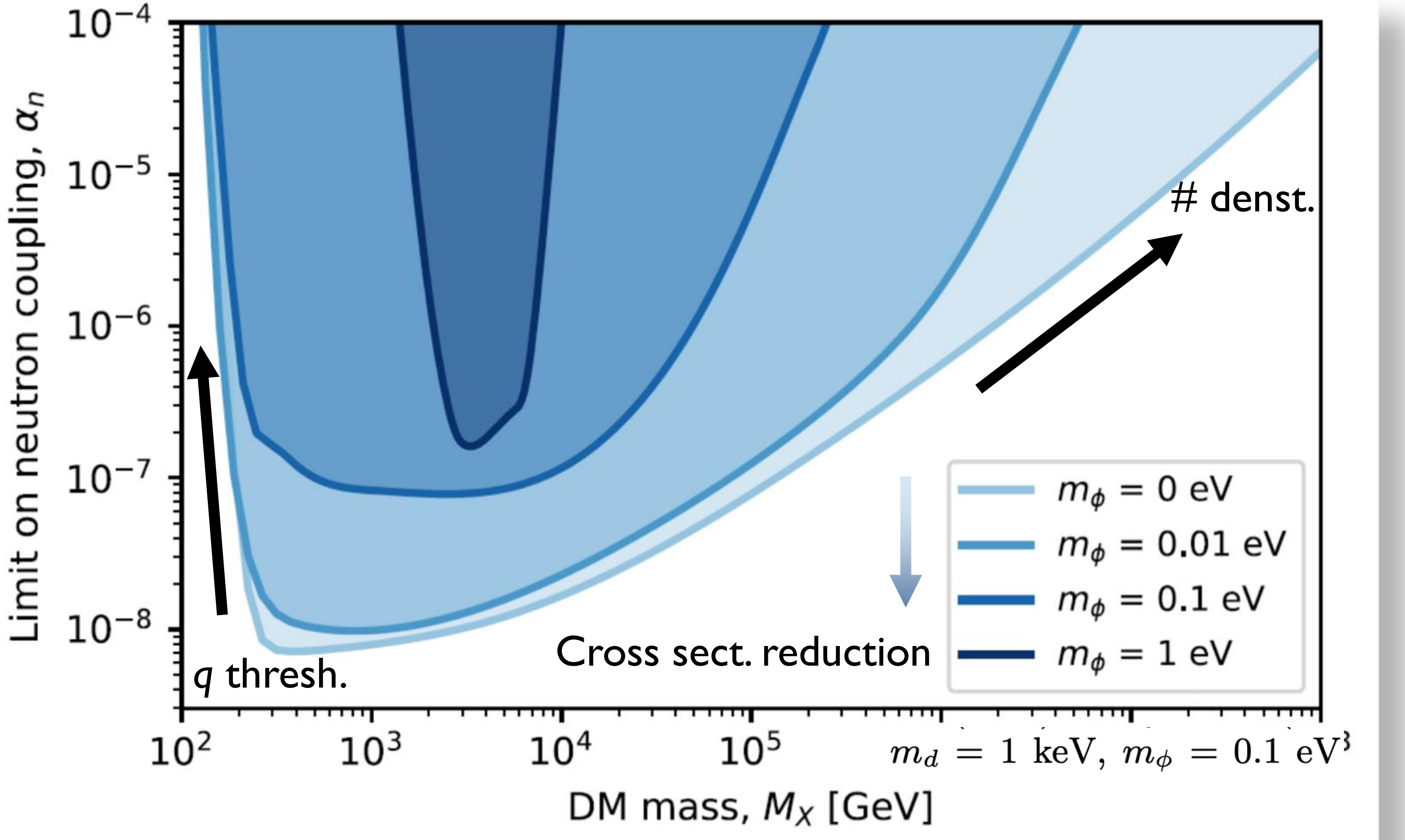


Livetime Cuts include a "lab entry" cut (14%), Accelerometer cut (2.6%), 1 sec, > 1 GeV anticoincidence cut (0.2%) → 4.97 days

Quality cuts include an in-loop\out of loop consistency (~95% efficient) and a χ^2 cut (95.9% efficient)

F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020)

LIMITS on NEUTRON COUPLING and COMPOSITE DM



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A. Coskuner *et al*, *PRD* **100** 035025 (2019), Fink *et al.*, *AIP Adv.* **10** 085221 (2020), S.A. Hertal *et al.*, *PRD* **100** 092007 (2019), Y. Hochberg *et al*, *PRL* **123** 151802 (2019)

LIMITS on NEUTRON COUPLING and COMPOSITE DM

- Assuming specific composite dark matter model, can **compare to WIMP detectors**
- For sufficiently light mediators and large composite particles, **many orders-of-magnitude more sensitive**

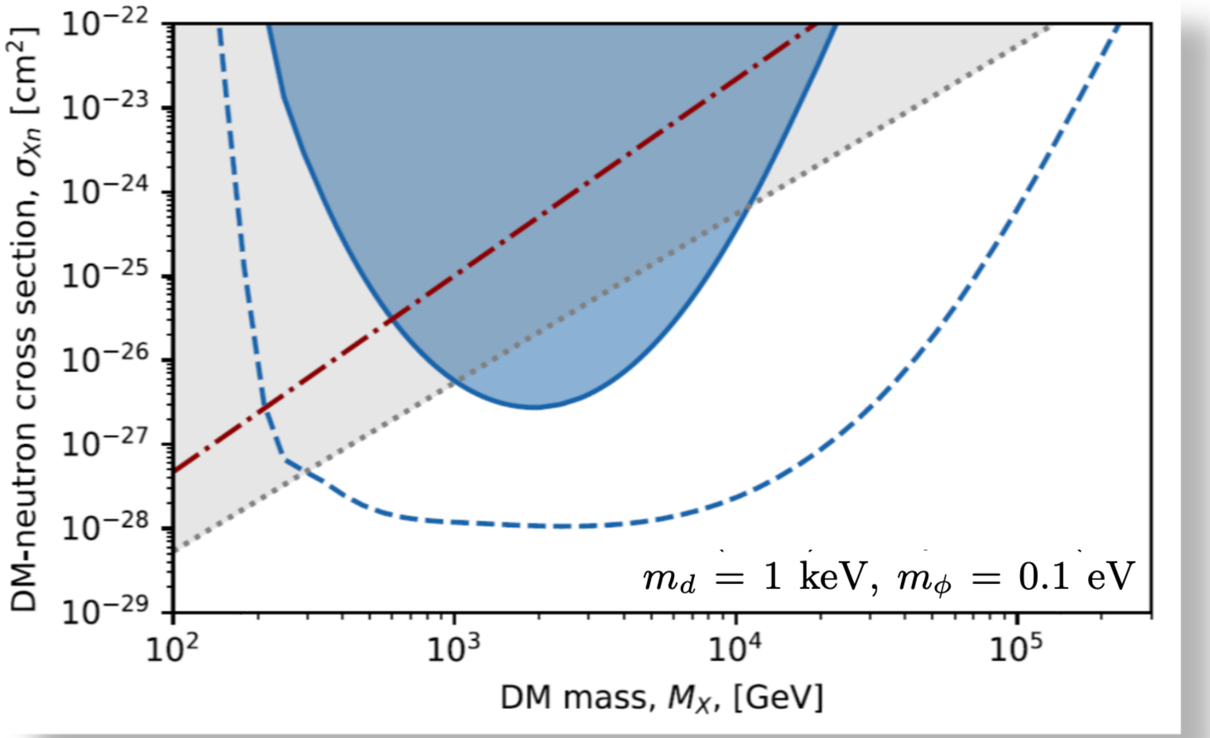
This work, (5ng day), 10% of DM

This work, (5ng day), 100% of DM

Model dependent (Eot-Wash, $g_d \sim 1$)

Future detector for low mass WIMPs, *e.g.* superfluid He (1 kg yr @ 1 meV)

XENON1T, LUX, SuperCDMS, … (> ton year)



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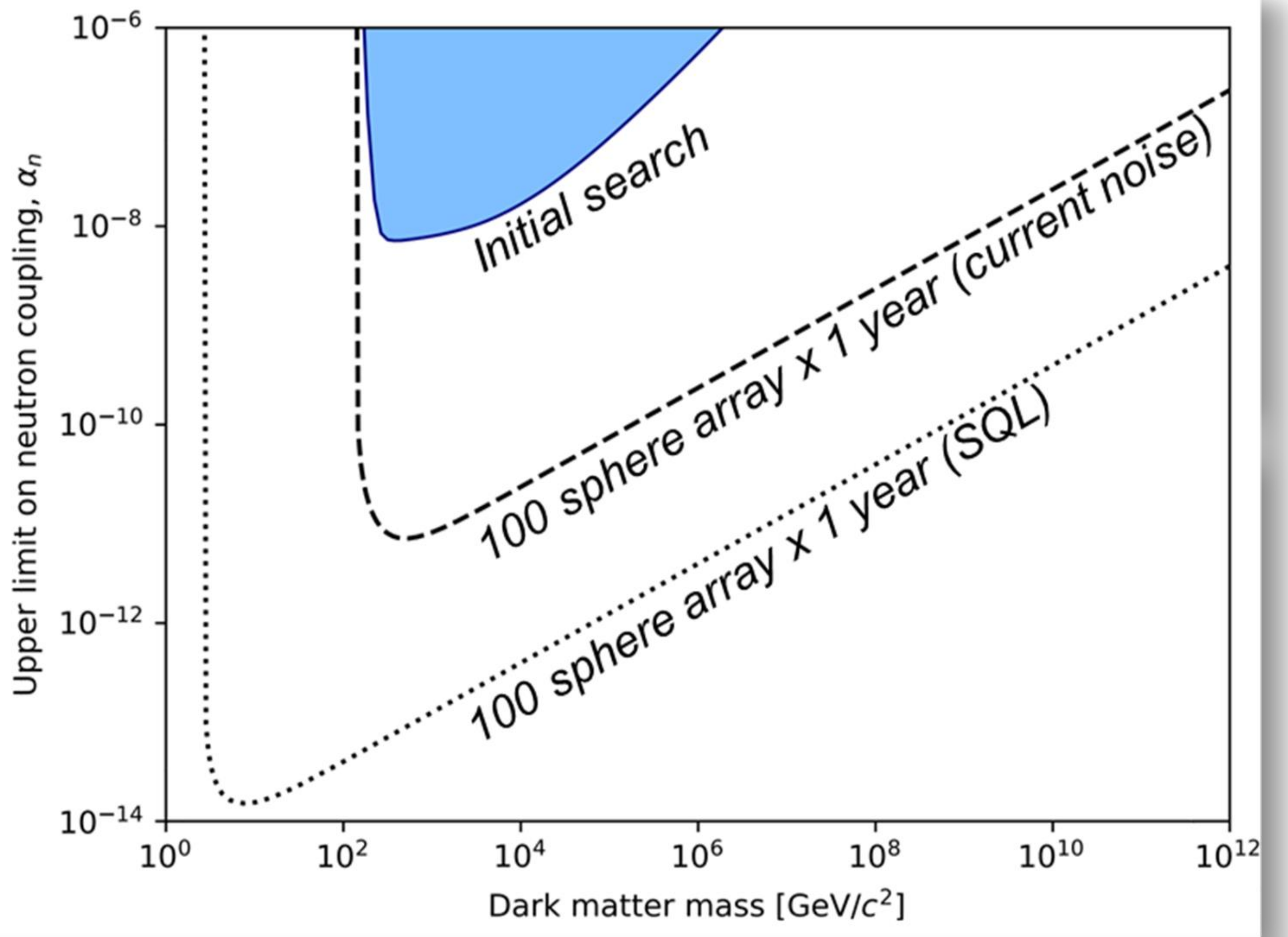
PLENTY of ROOM for IMPROVEMENT

- This **first proof-of-principle** already explores **well beyond existing searches** for certain classes of models

- **Next steps:**
  - Directionality
  - Large sensor arrays with longer exposure
  - Push to (beyond) SQL



D. Moore and A. Geraci, *arXiv*:**2008.13197** (2020)

Exp (atoms, spheres in fluid): Barredo *et al. Nature* **561** (2018), D. Grier and Y. Roichman, *Appl. Opt.* **45** (2006)
Dark matter search proposal: D. Carney et al., PRD 102 072003 (2020)

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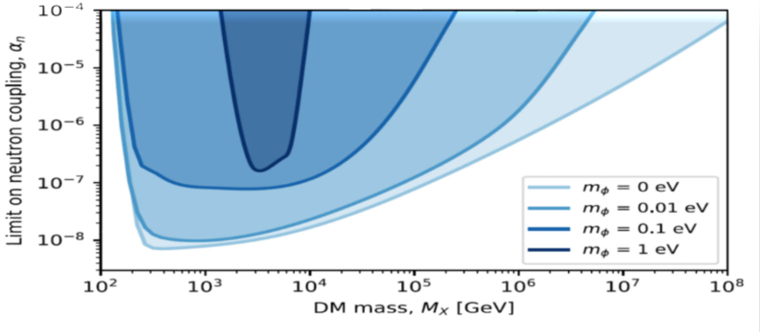

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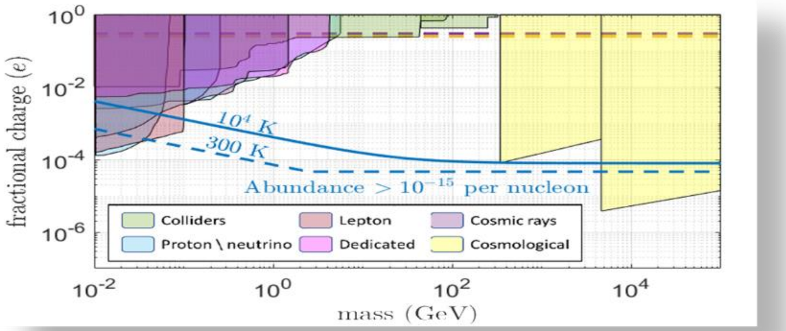

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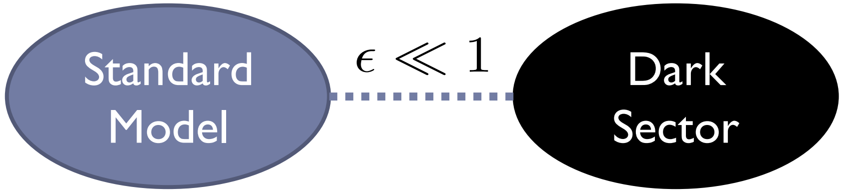
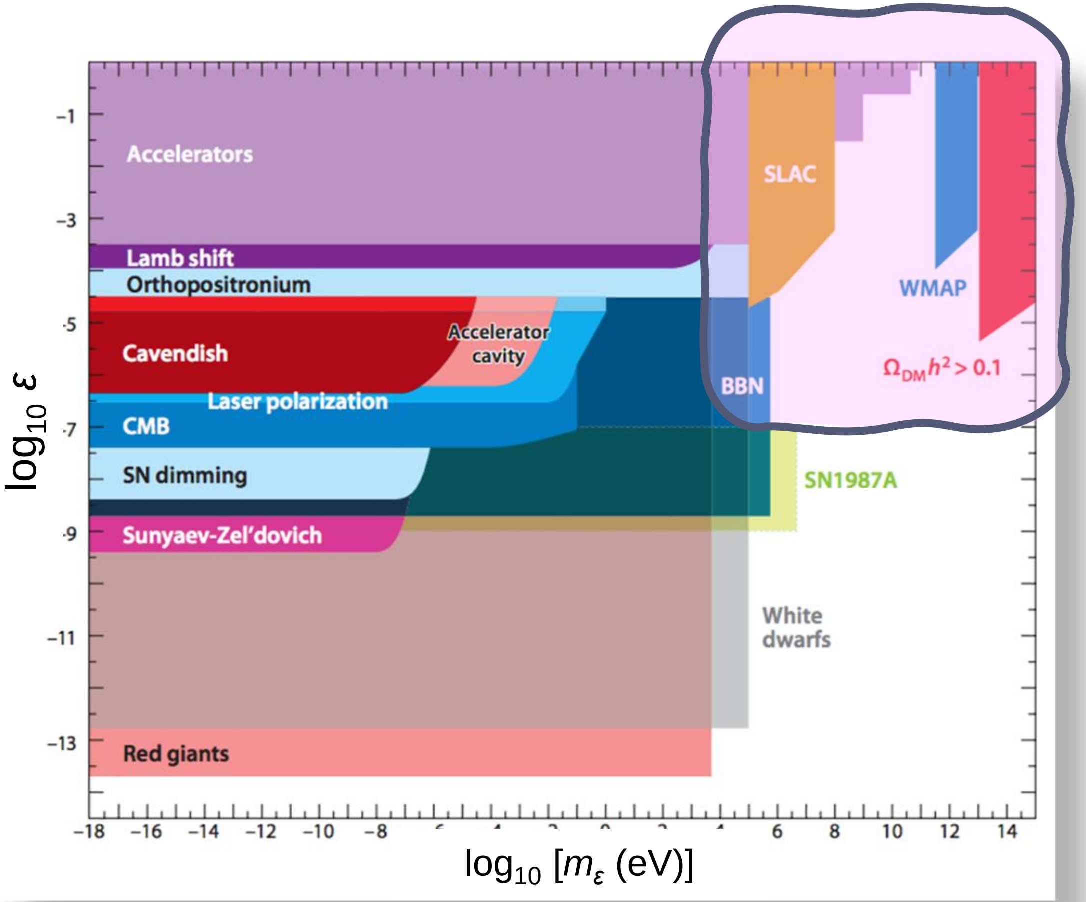
TESTS of CHARGE QUANTIZATION and the SEARCH for MILLICHARGED PARTICLES

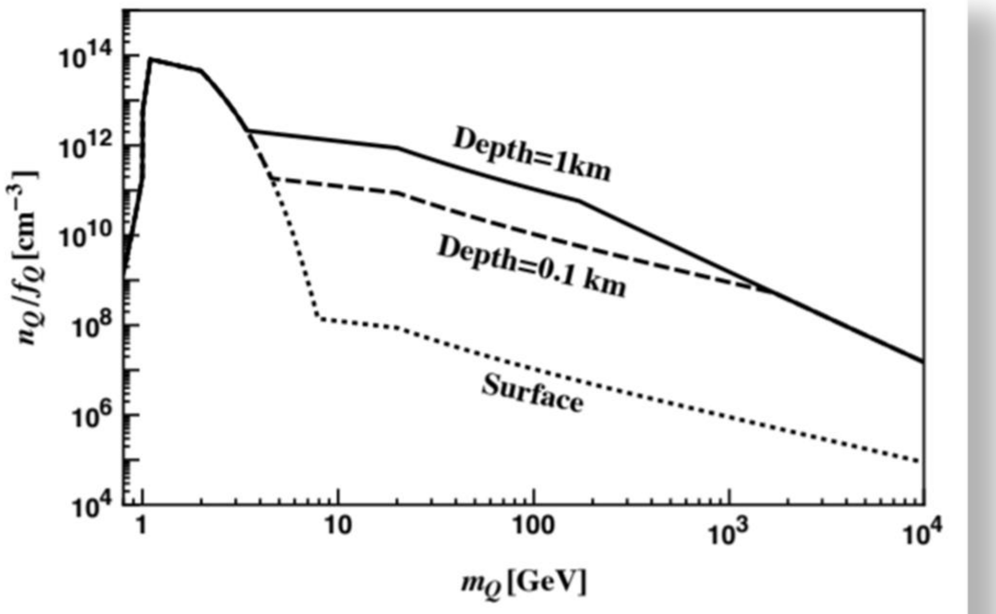
- Some dark matter models: single “dark matter particle”. Normal matter is more complicated → **Dark Sector**
- Possible that dark matter self-**interacts through “dark forces”, mediated by “dark photons”**
- **Particles with unity charge** under new dark force **can have fractional charge under electromagnetism**
- **Neutrality of matter:** $|q_e + q_p|, \quad |q_n| < 10^{-21}e$

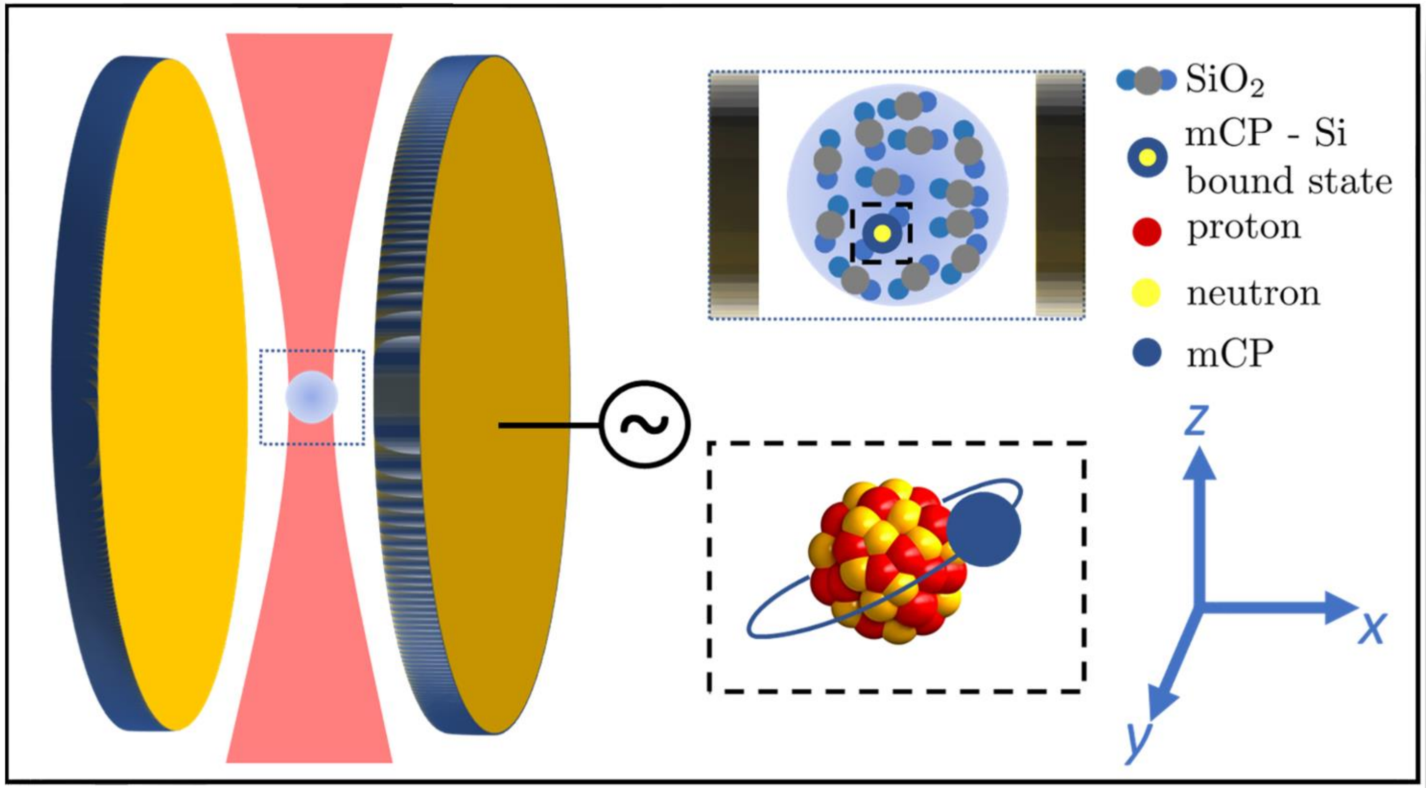




Jaeckel and Ringwald, *Ann. Rev. Nucl. Part. Sci.*, **60**, 405 (2010)
H. Dylla *et al.*, *PRA* **7**, 1224 (1973) , J. Baumann *et al.*, *PRD* **37**, 3107 (1988), G. Bressi *et al.*, *PRA* **83**, 052101 (2011)

RELIC mCPs BOUND to TERRESTRIAL MATTER

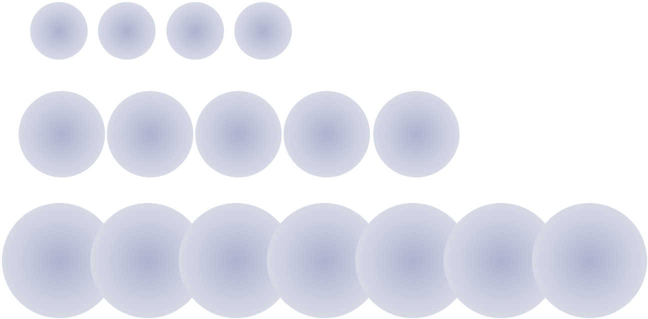


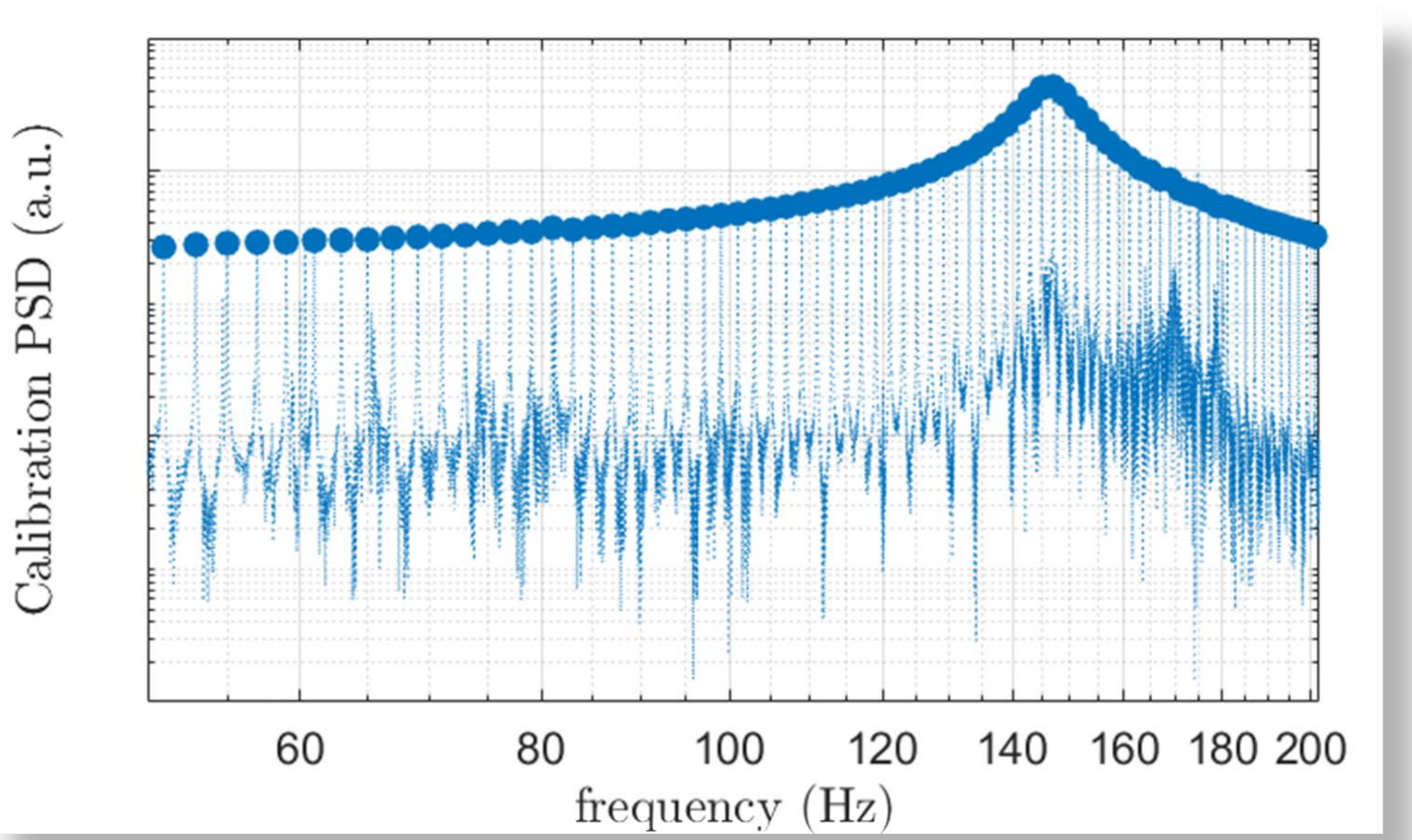


- M. Pospelov *et al.*, arXiv:2012.03957 (2020) , **GA**, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore, *arXiv*:2012.08169 (2020)

THE EXPERIMENT

- Trap sphere, **charge up** to (precisely) $N \times e$
- **Calibrate** response function
- **Discharge, Ramp up voltage (~ 5 kV/mm) and measure response**
- Total mass **~76 ng**





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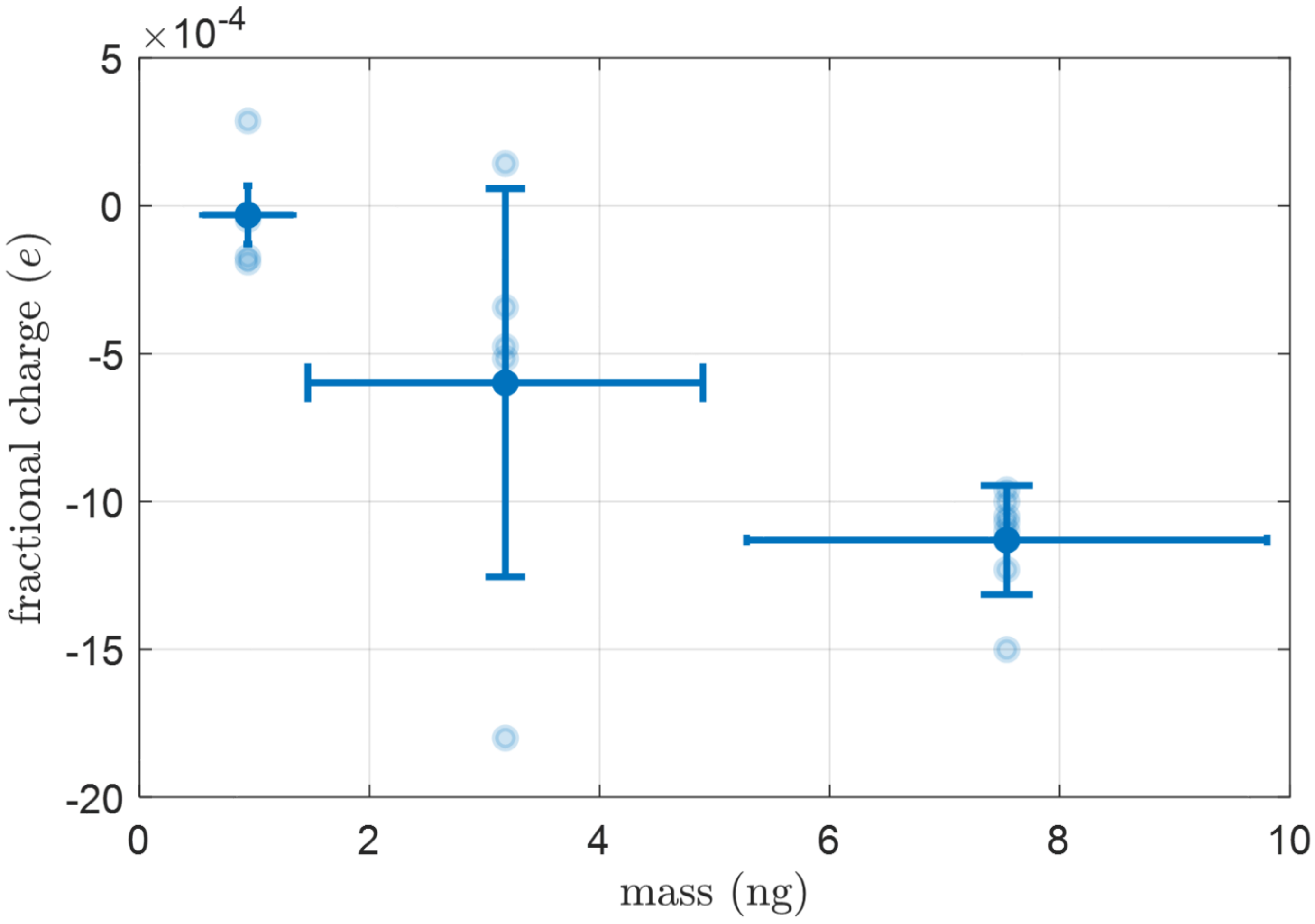
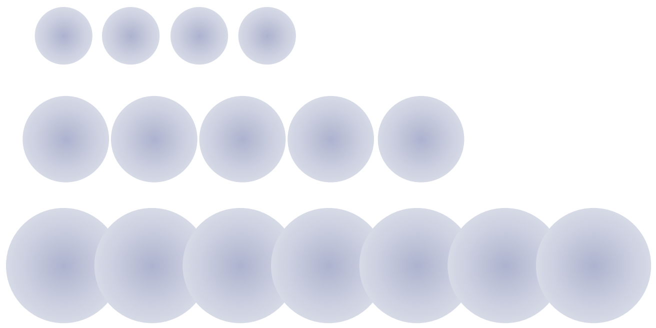
THERE'S A SIGNAL!





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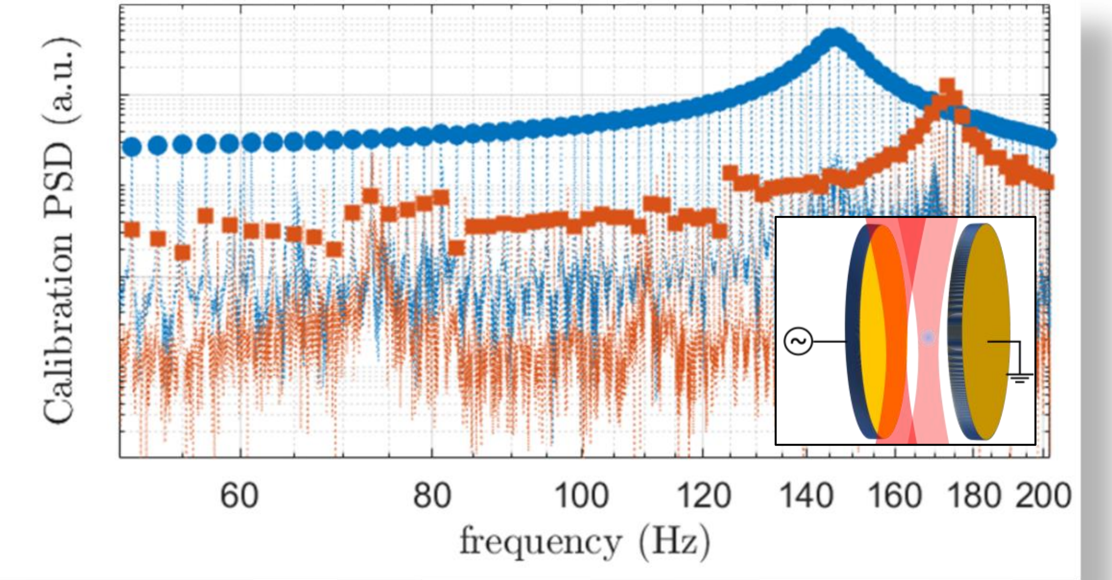
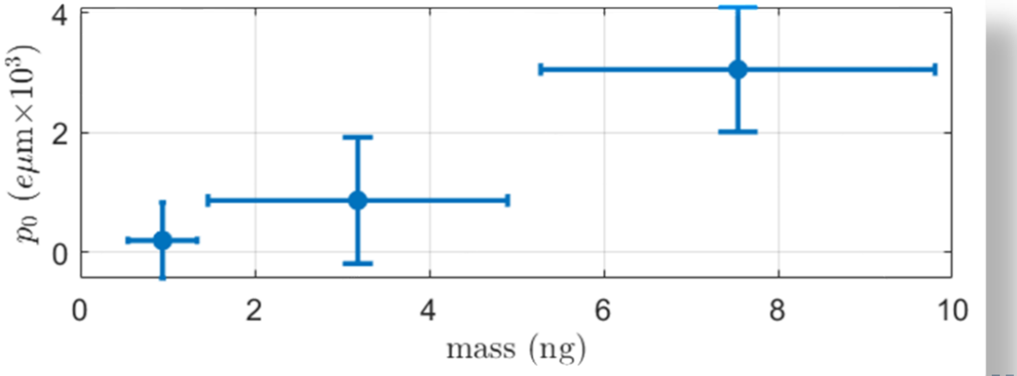
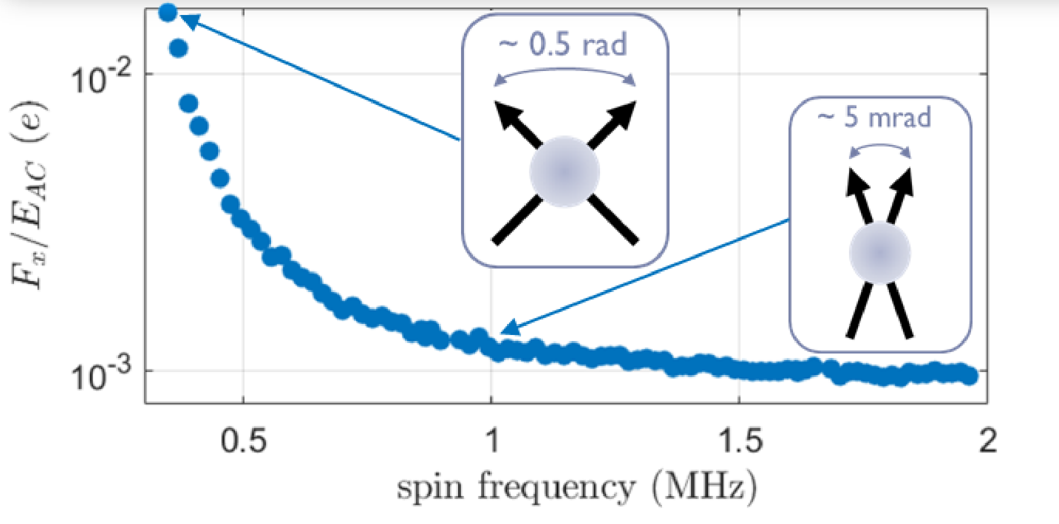
BACKGROUNDS

- Most BGs act at **"double" the drive frequency**. Of those that "leak":
- **Vibrations** → **use parallel beam to subtract** to within a factor of ~ 1-6
- **Torques** on the permanent dipole → **spin**
- **Force on permanent dipole** → estimate using Comsol + measured gradients, behaves like a signal!







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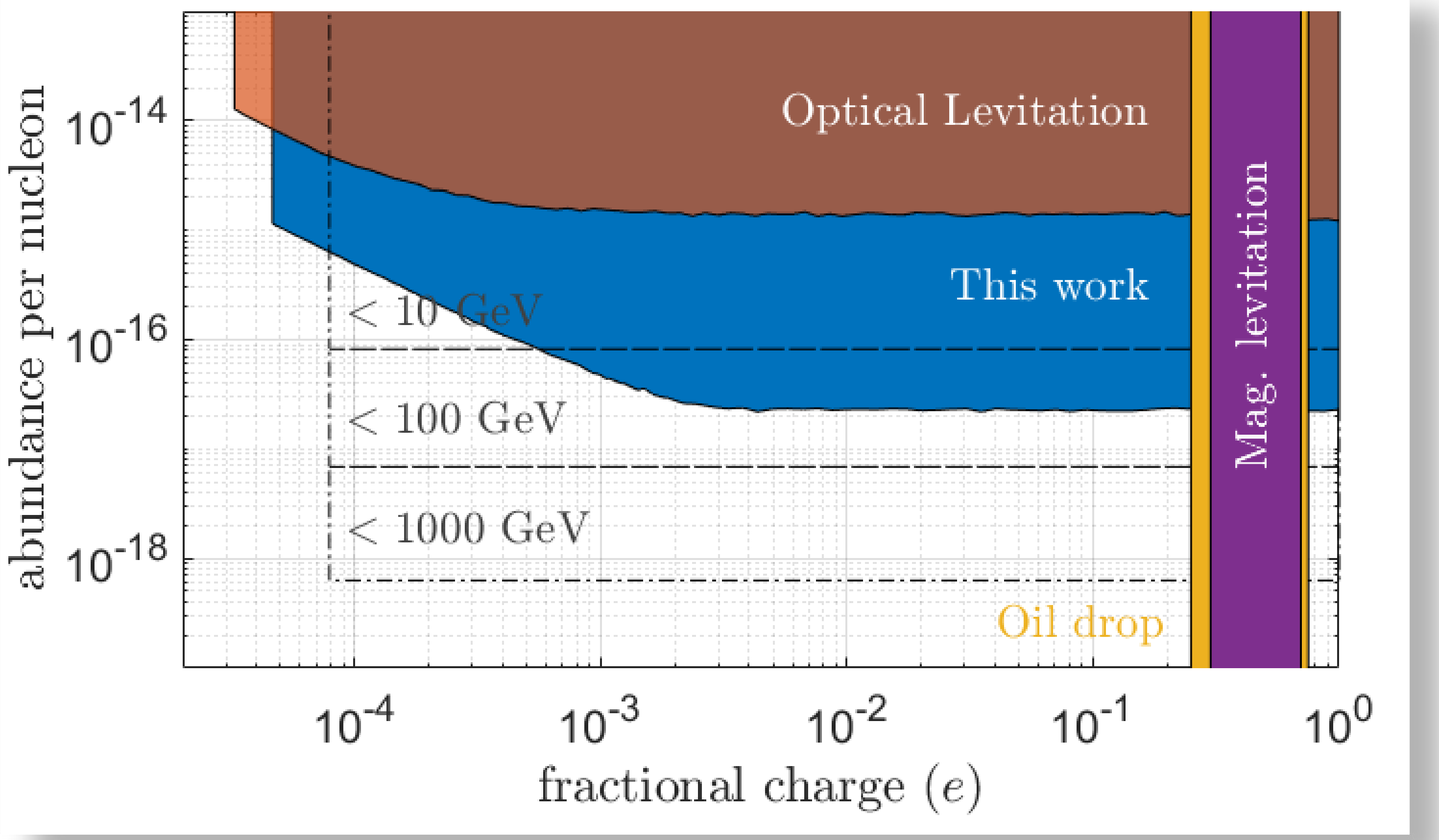
LIMITS on ABUNDANCE / NUCLEON

- Theorized relic abundance of DM mCPs, **accumulating in Earth** via interactions (assuming $E_B = 10^4$ K)
- **10^{-17}** is ~ 6 orders of magnitude less than natural abundance of other naturally occurring stable elements
- **Previous searches** limited to 1-10 GeV or low fractional charge
- We probe **deep into 10-100 GeV** and get a **10^{-19} e / nucleon limit** on the sum $|q_p + q_e + q_n|$



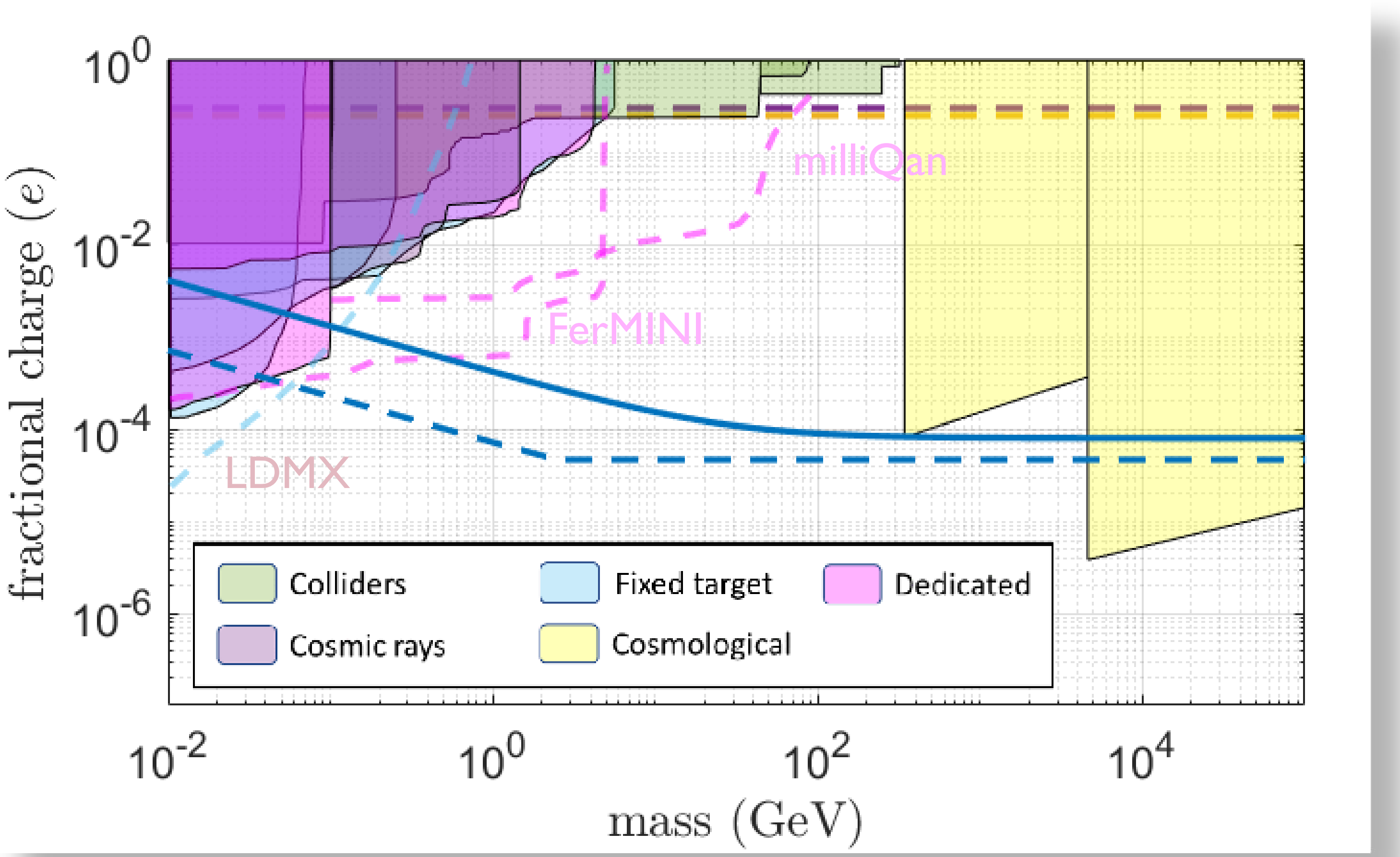
M. Pospelov *et al.*, arXiv:2012.03957 (2020)

M. Marinelli *et al.*, *PhysRep* **85** 161 (1982), P.C. Kim *et al*, *PRL* **99** 161804 (2007), D. C. Moore *et al.*, *PRL* **113**, 251801 (2014)

GA, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore, *arXiv*:2012.08169 (2020), J. Baumann *et al.*, *PRD* **37**, 3107 (1988), G. Bressi *et al.*, *PRA* **83**, 052101 (2011)

LIMITS on CHARGE vs. MASS

- Using a Bohr binding-energy argument, can **link charge to mass**
- **For an abundance > 10^{15}, bridge the gap** between terrestrial and cosmological
- Holds even in **comparison** with ambitious **future experiment projections**
- Looking at **relic abundance** benefits from **accumulation of mCPs on Earth**



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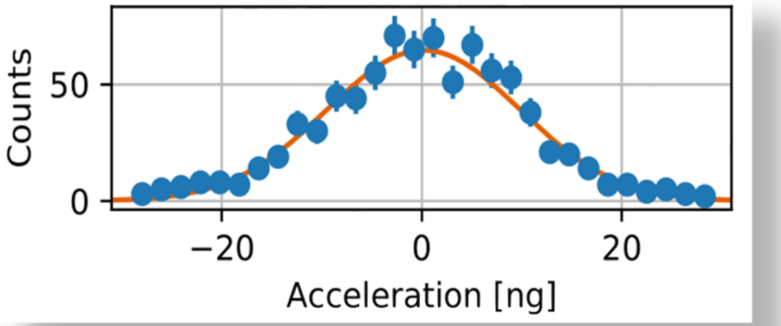
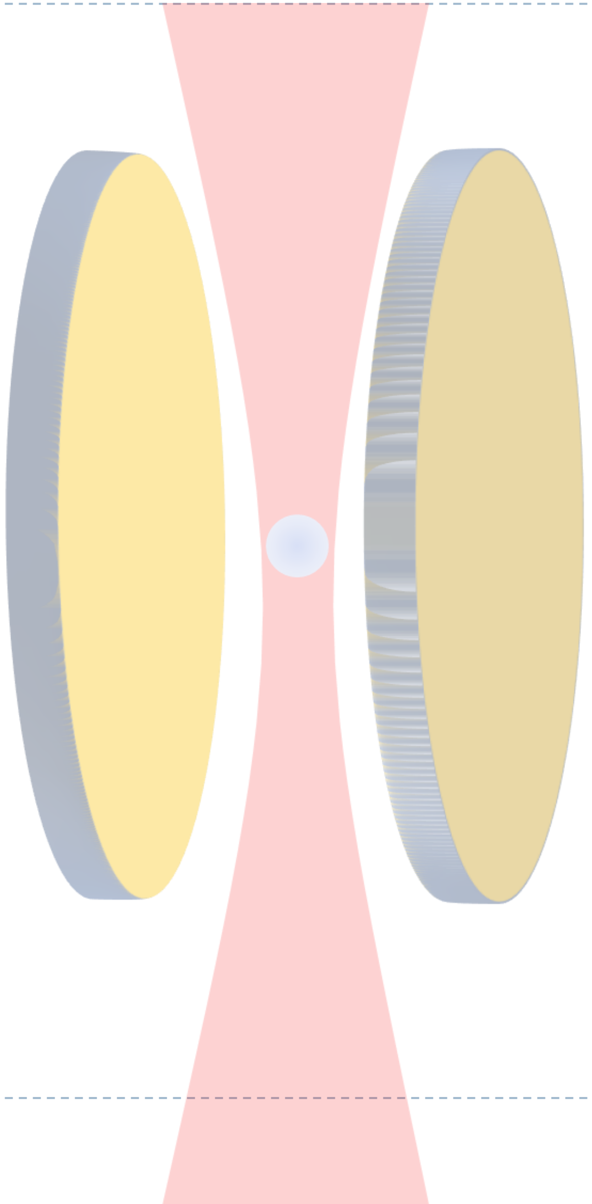
SUMMARY

A precise **acceleration, force, impulse** sensor, at ultra-low T





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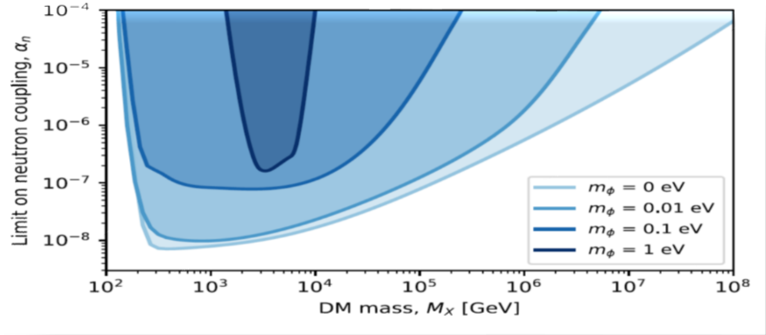

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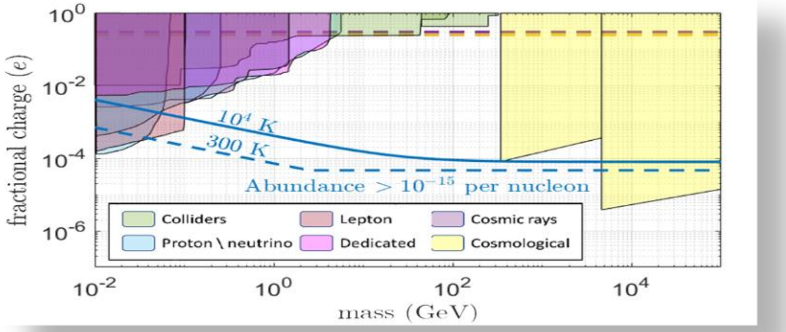

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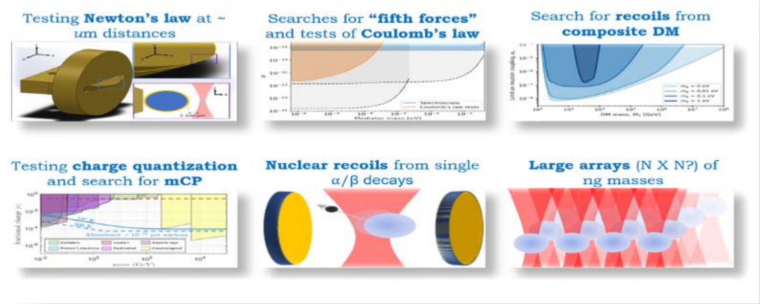
Exciting stuff lay ahead



THANK YOU!