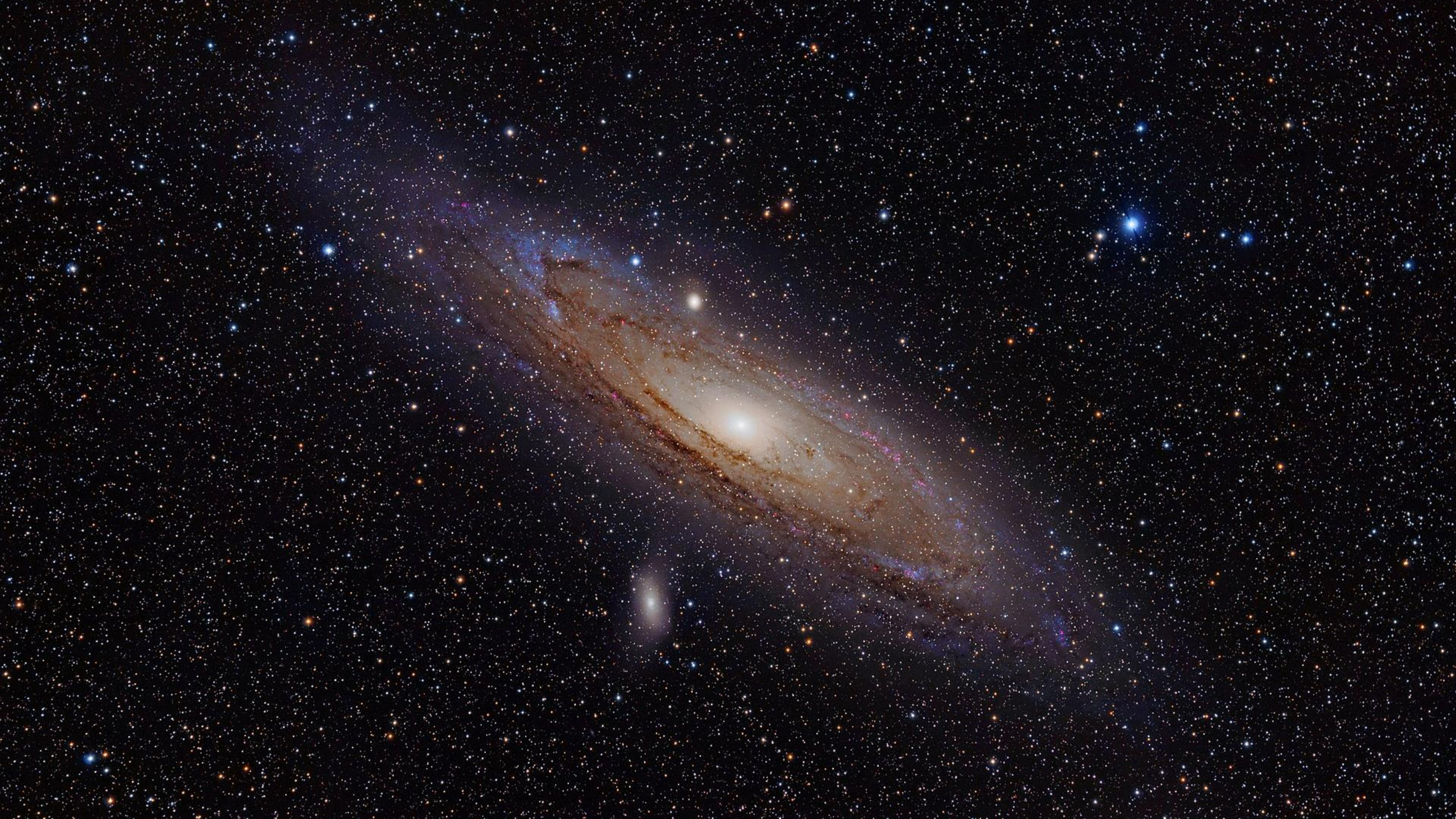
Precision searches for new physics using optically levitated sensors

Gadi Afek

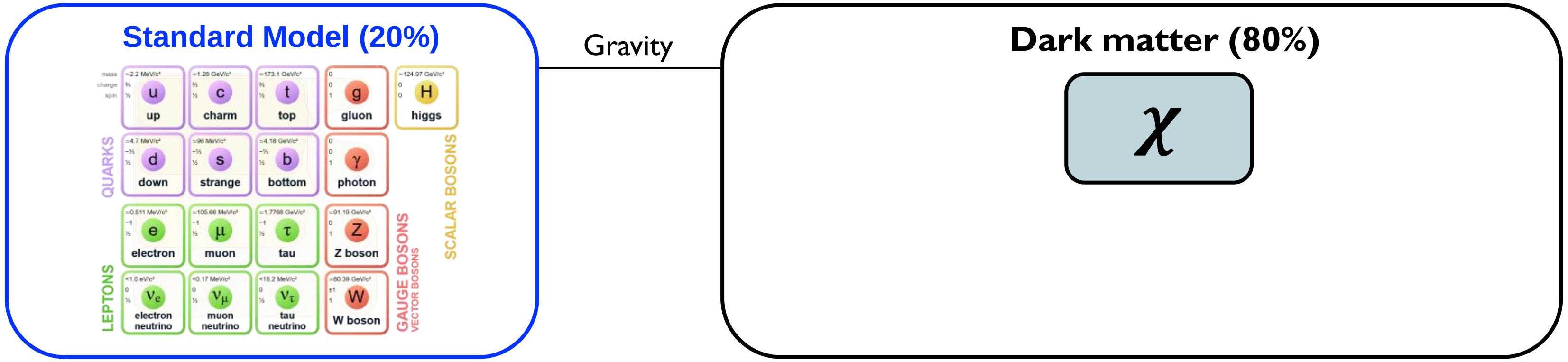
Yale University

Quantum Science Seminar
hot topics session, July 2021

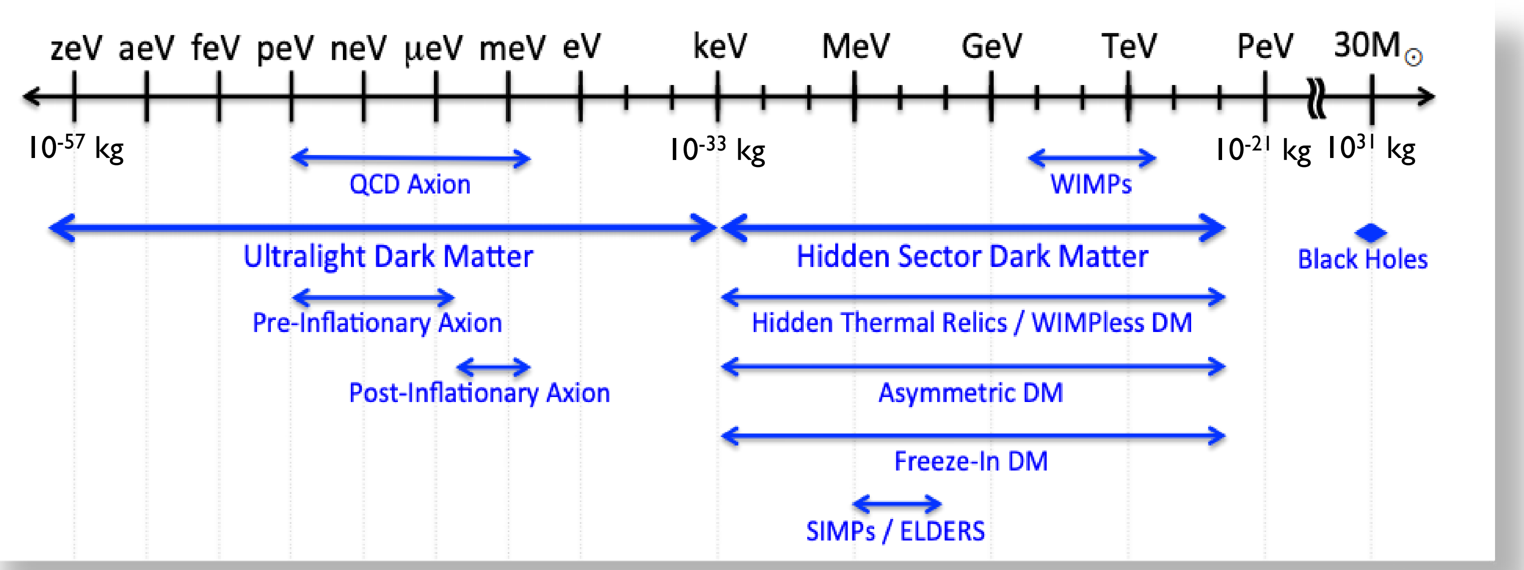
Wright Laboratory



WHAT DO WE KNOW SO FAR?



- Vast majority of terrestrial searches focus on **WIMPs** and **axions**
  - **Compelling + solve other problems**
  - **Ton-scale WIMP searches haven't seen anything yet..**
  - **Axion parameter space getting bigger (quantum!)**

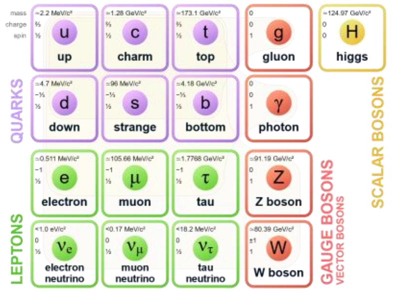


- **Many other models allowed**

US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report, arXiv:1707.04591, K. Backes *et al.*, Nature **590**, 7845 (2021)

MODEL-INDEPENDENT SEARCHES?

Standard Model (20%)



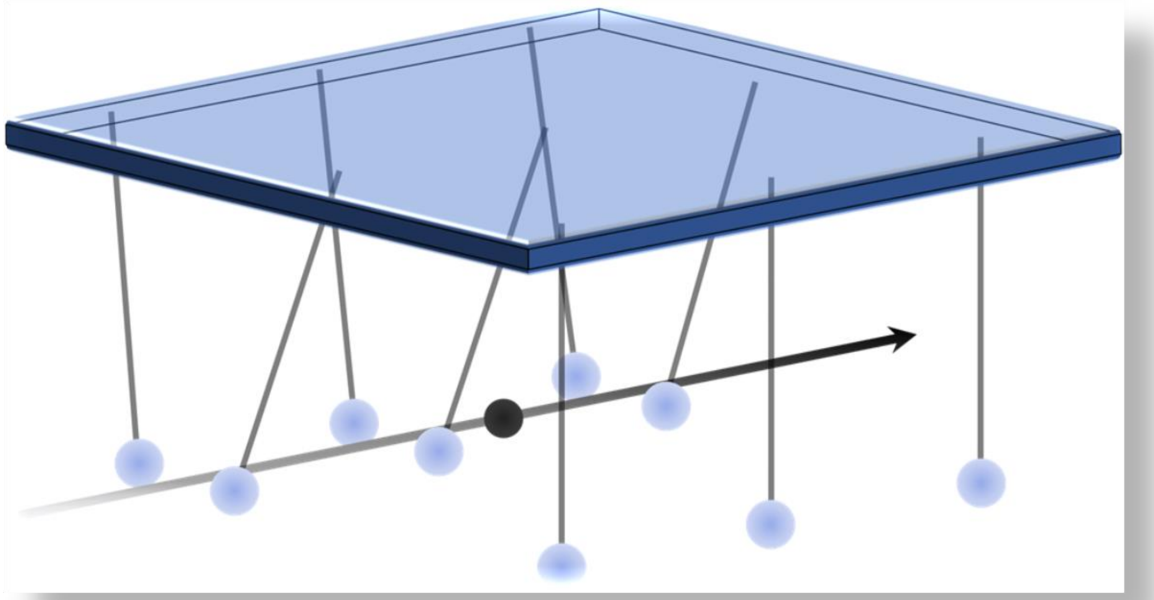
Gravity

Dark matter (80%)

χ

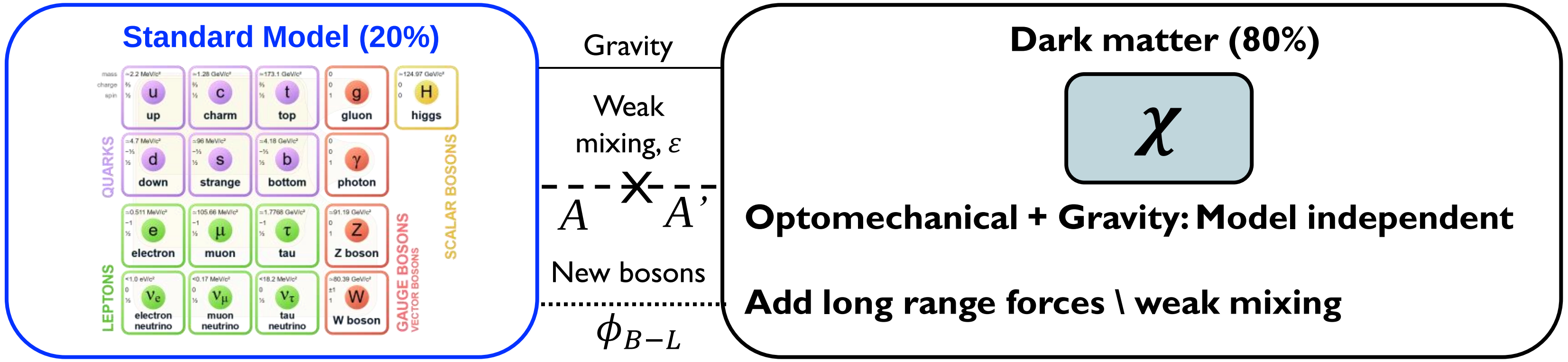
Optomechanical + Gravity: Model independent

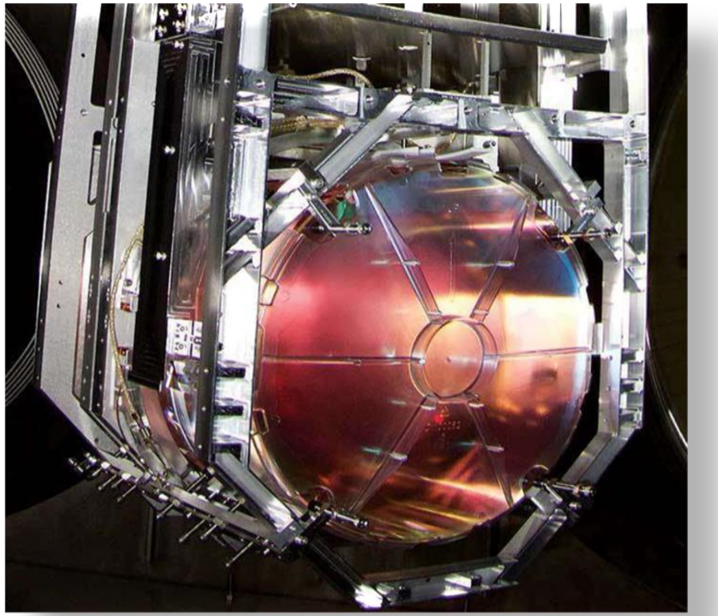
- What would a **model-independent** search look like?
- Search for **gravitationally induced** kicks from a passing dark matter particle in an **array of test masses**
- For DM masses > m_{Pl} might be possible but **very ambitious** (**30dB beyond SQL**, **cryogenic** environment, **10^9 sensors**…)



D. Carney *et al*, *PRD* **102**, 072003 (2020)

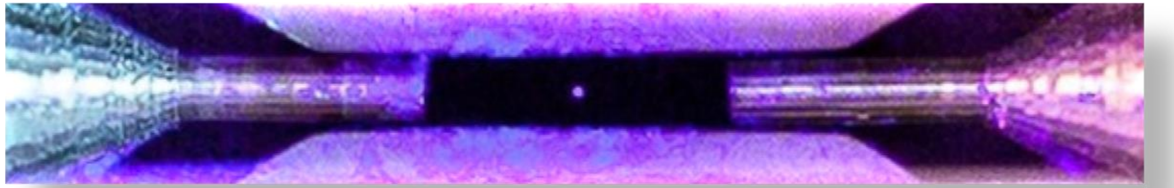
OPTOMECHANICAL SENSORS





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

- Opto-mechanical systems are **VERY precise force sensors**
- Control and measurement of **large range of test masses** (from 10^{-21} gr to 10^{3} gr)
- We use ~10^{-8} gr microspheres with **~100 ng/Hz$^{1/2}$ acceleration sensitivity (technically limited)**

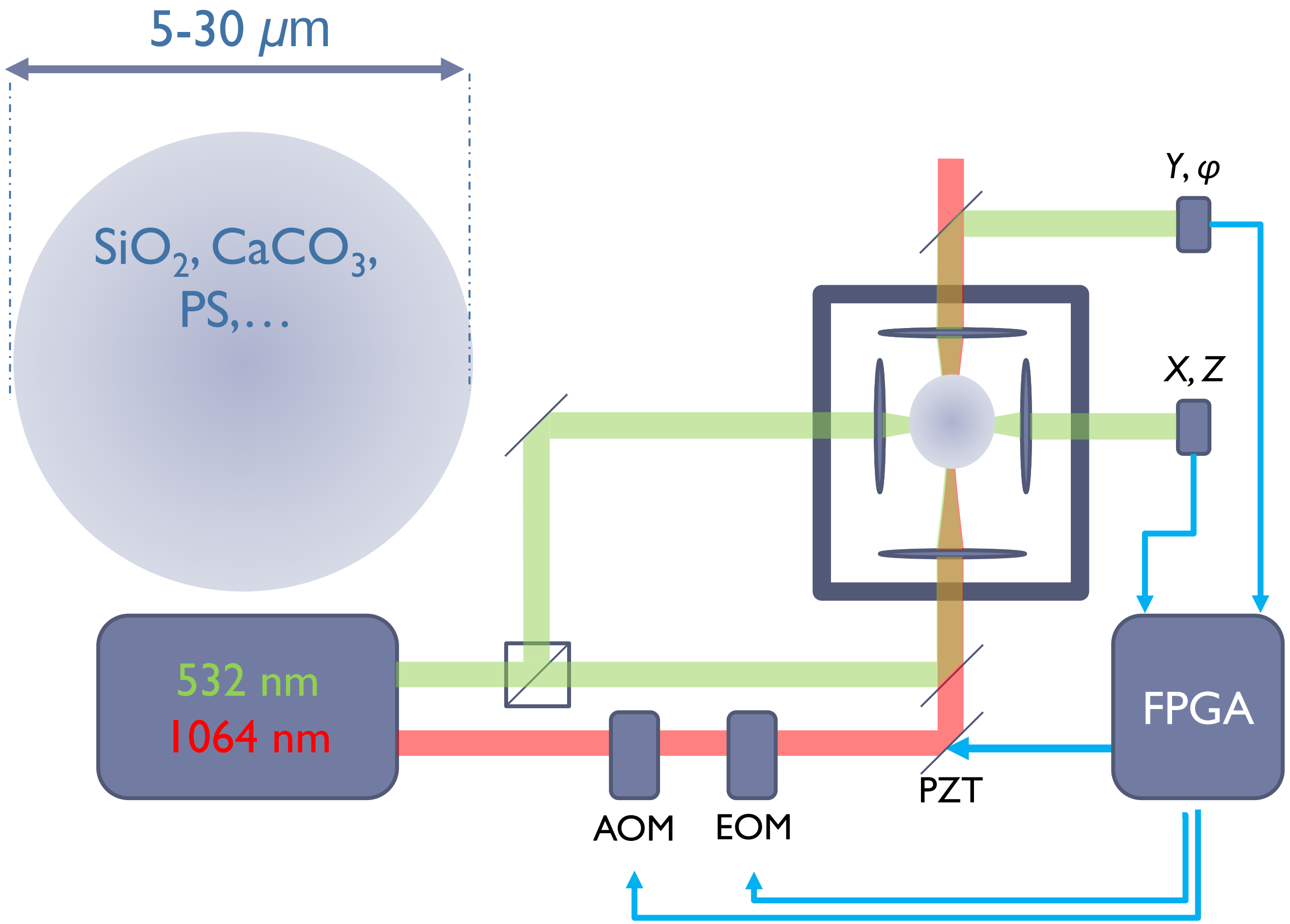


Single Sr ion in a "blade" trap (David Nadlinger, Lucas\Steane group, Oxford)

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

THE SYSTEM

- **Variety of materials and sizes, isolated electrically and thermally**
- Large spheres → better **acceleration sensitivity, DM searches couple to # constituents** in sensor
- Low NA gravito-optical configuration **→ ~μm probing distances**
- **Trap > 1 month → LONG integration times**
- Nanospheres already at SQL. **μspheres still ~100 above** (technically limited)



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)

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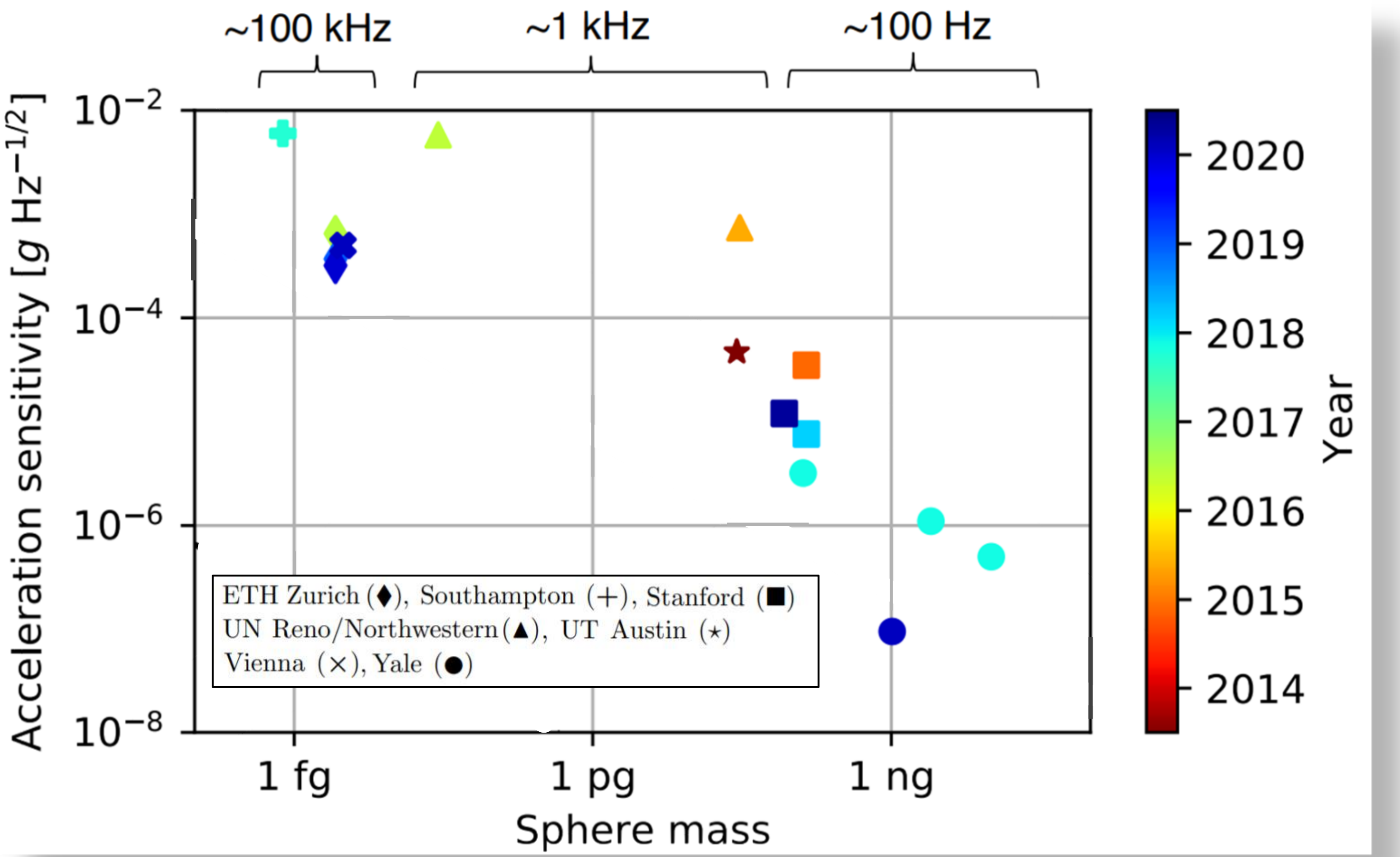

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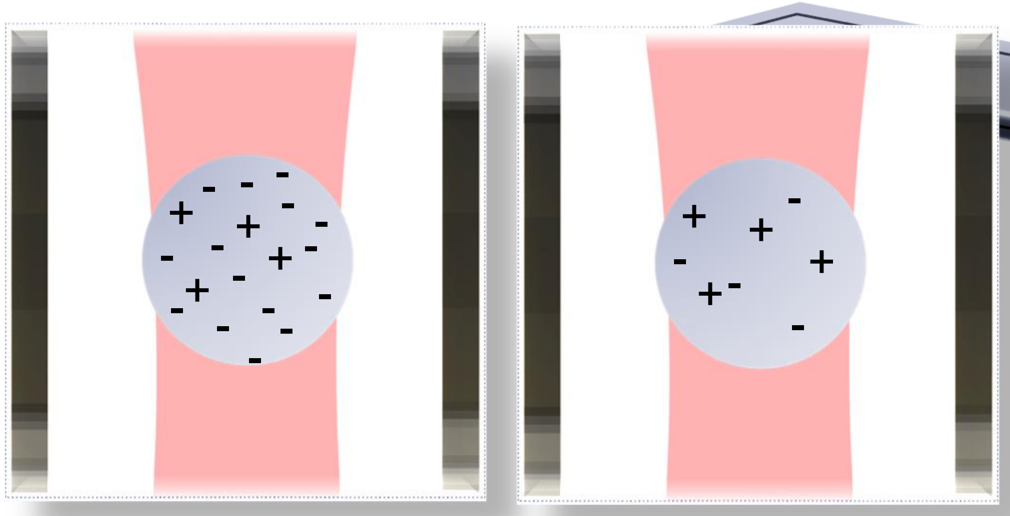
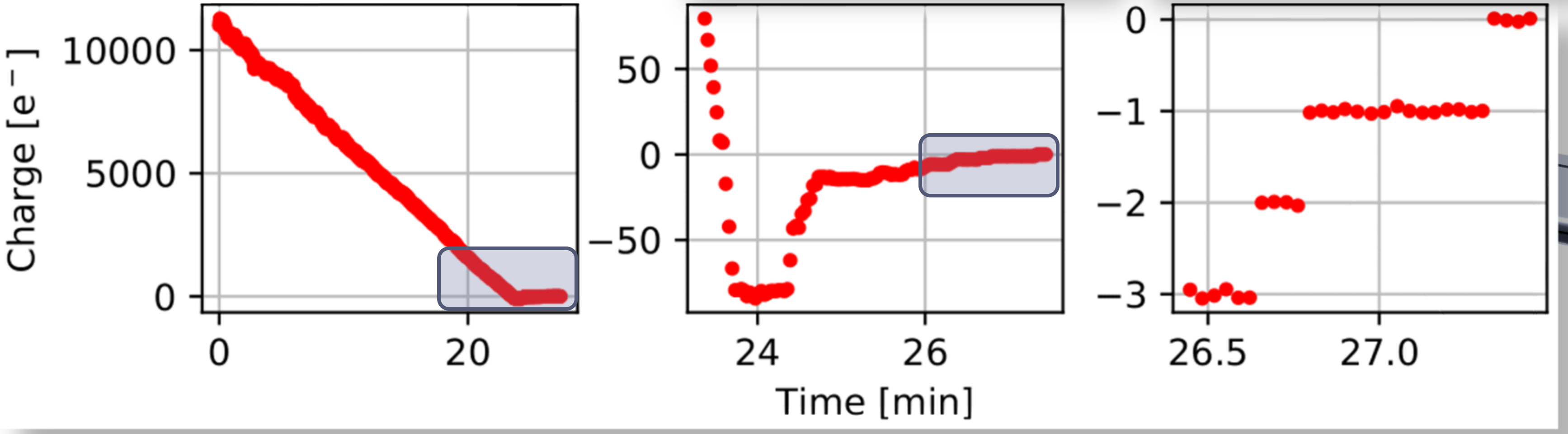
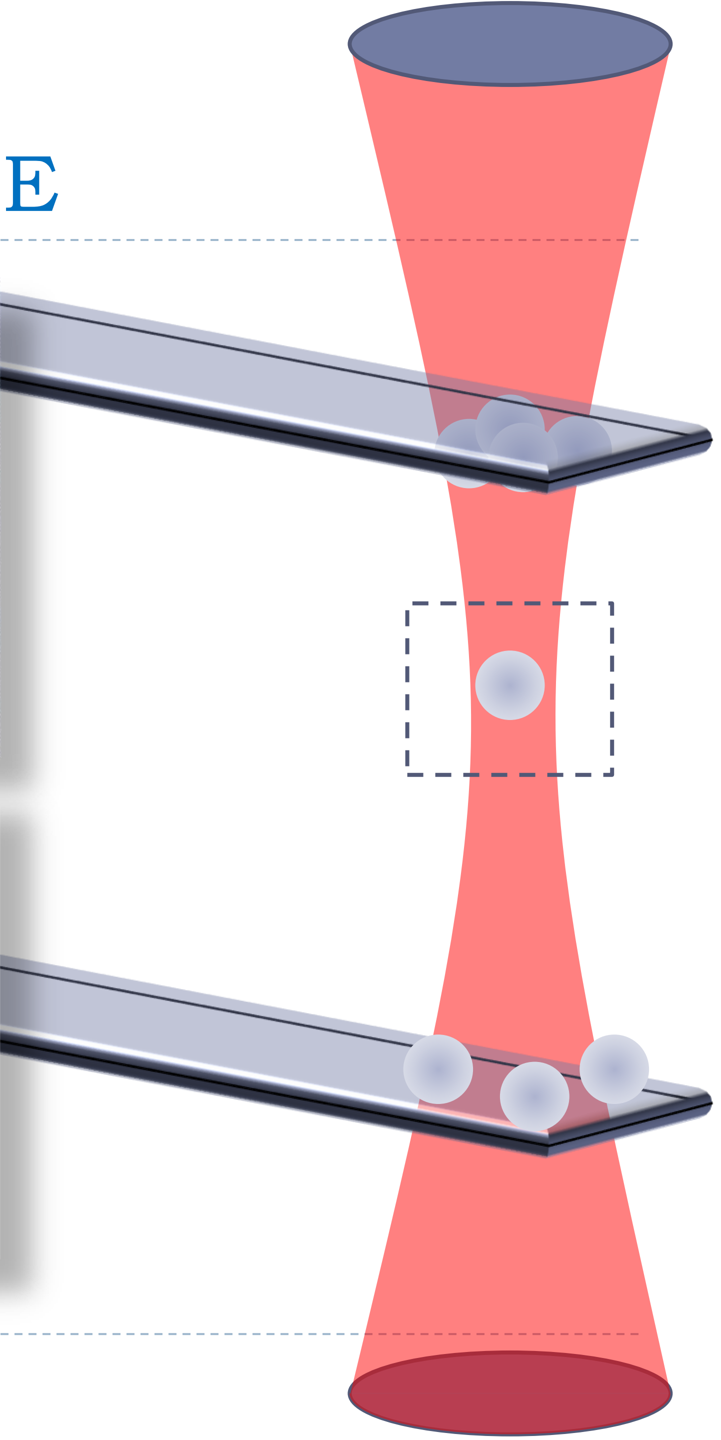
EXPERIMENTAL SEQUENCE

- Trap at high pressure
- pump down to ~10^{-7} torr
- Discharge with **single e precision** (Charging rates **< 1 e/week ~ 1 yA**)





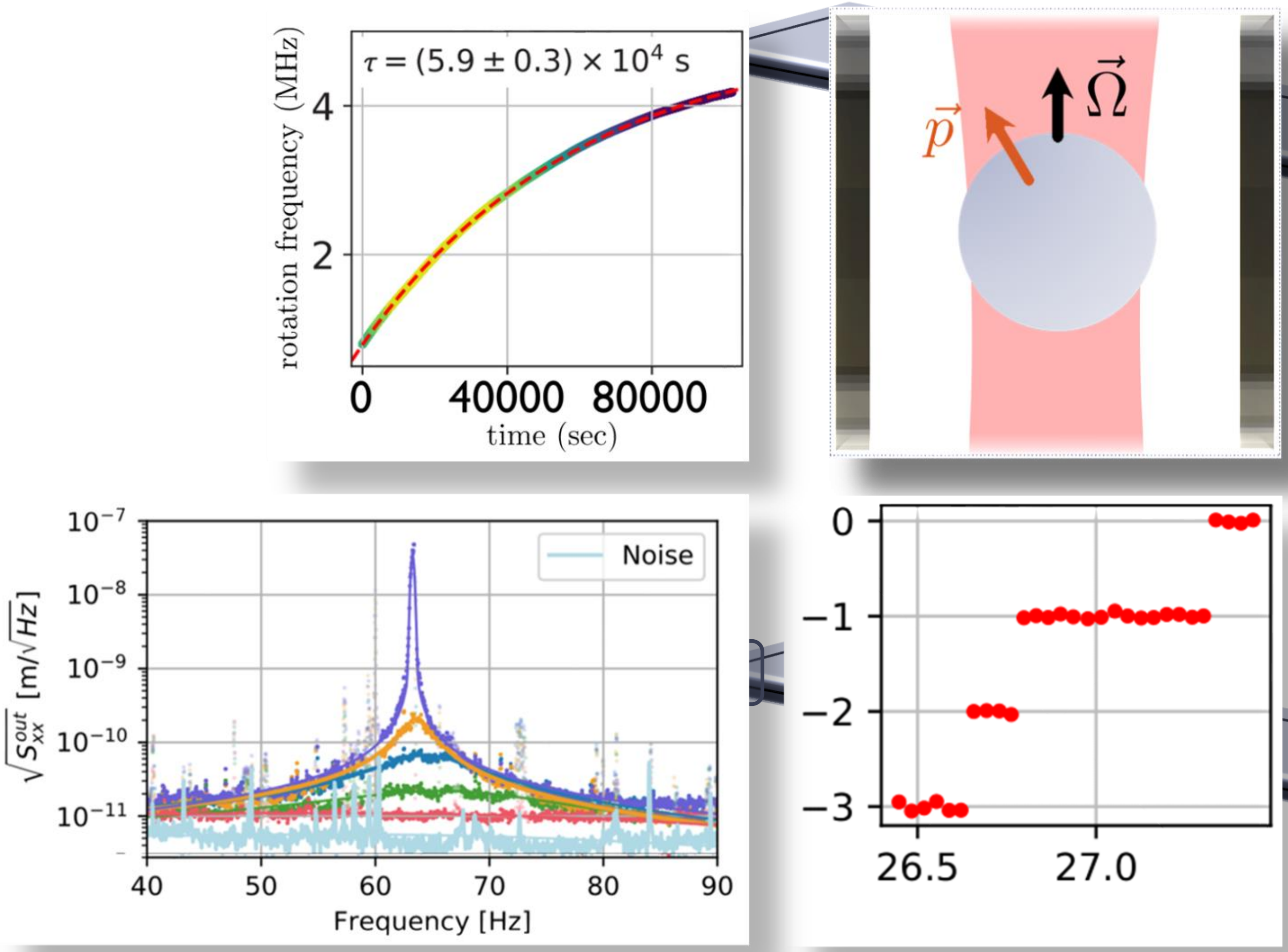


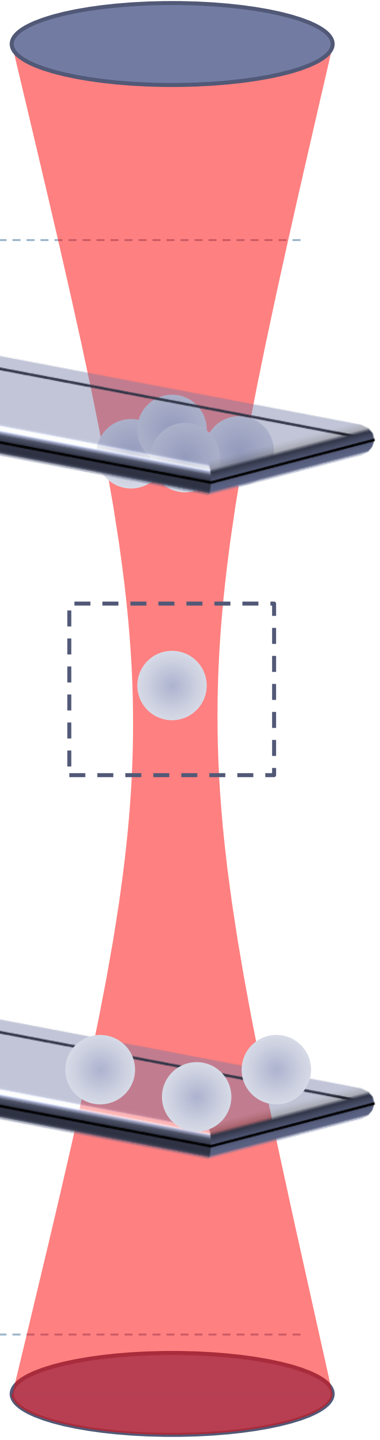
T. Li, S. Kheifets, D. Medellin, M. G. Raizen, *Science* **328** 5986 (2010), F. Monteiro *et al.*, *PRA* **97**, 051802(R) (2018)

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

EXPERIMENTAL SEQUENCE

- Trap at high pressure
- pump down to ~10^{-7} torr
- Discharge with **single e precision** (Charging rates **< 1 e/week ~ 1 yA**)
- Spin up **to ~ 10 MHz**
- **Cool** COM to **~50 μK**





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DM-INDUCED RECOILS

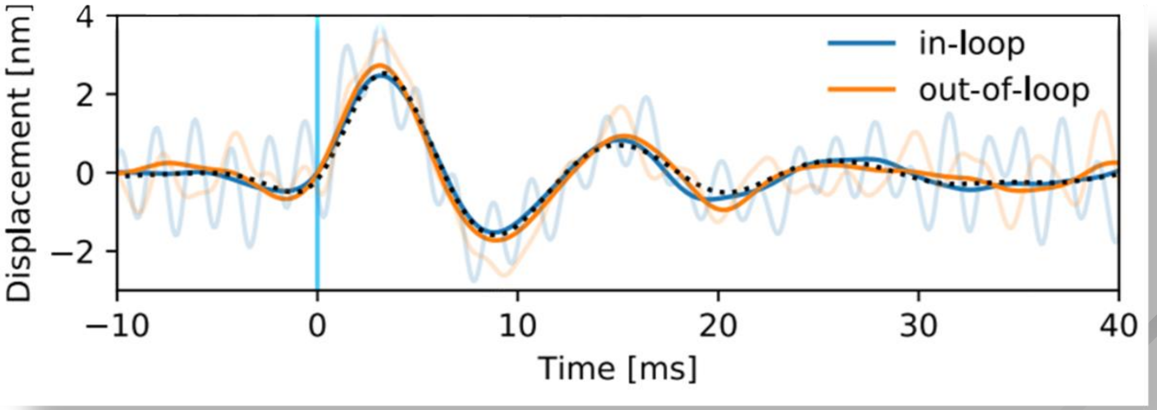
- Consider heavy **DM** particles
- Interaction mediated by a **long-range** force carrier $m_\phi \lesssim \mathrm{eV}$
- **Coherent enhancement!**
- **Low momentum threshold**

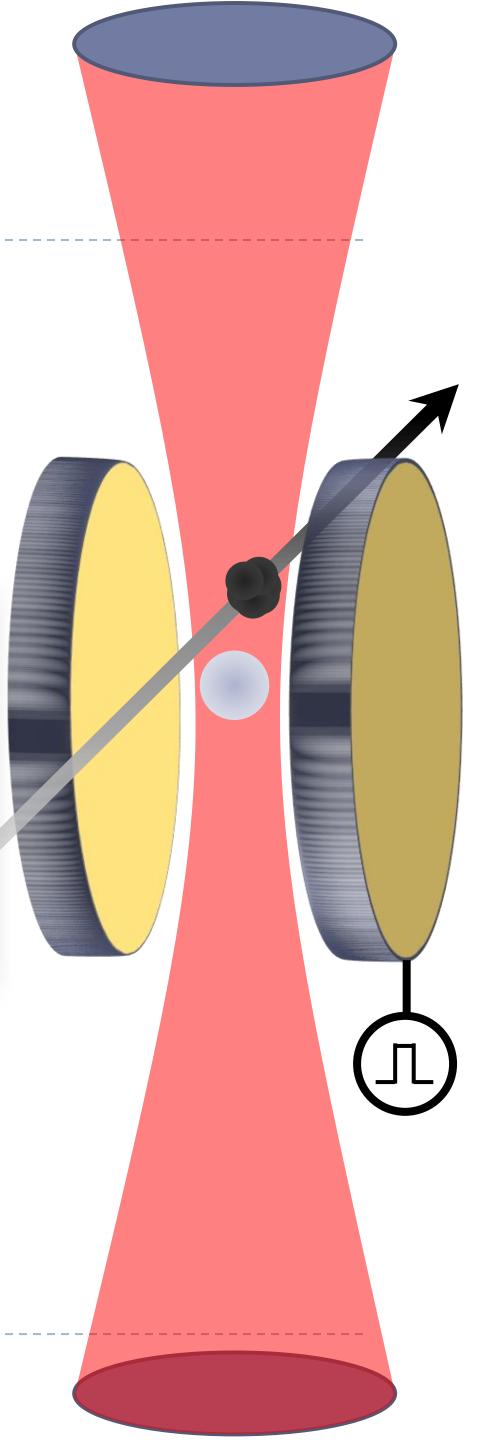
$$\sim 200\ \mathrm{MeV/c} \sim 0.1\ \mathrm{aN\ sec}$$

- Total exposure: **5 (10^{-9} gr X day)**

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

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





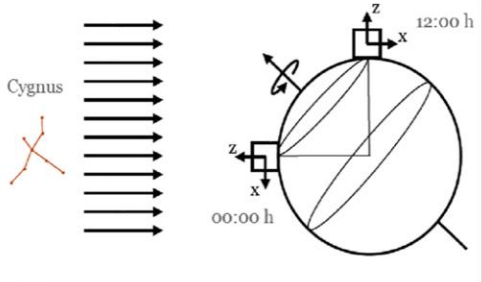
F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020)

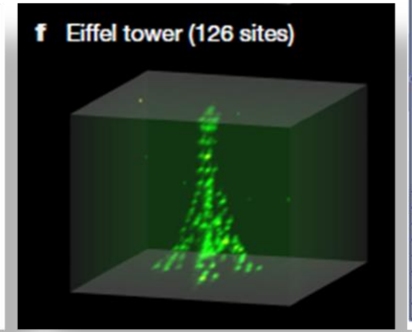
G. Krnjaic, and K. Sigurdson, *PLB* (2015), Coskuner *et al*, *PRD* **100** 035025 (2019)

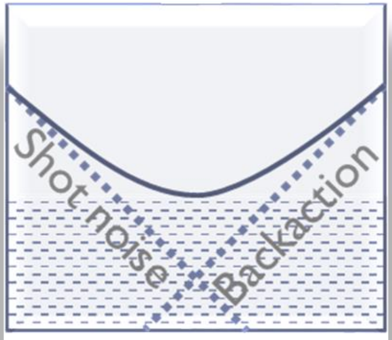
MODEL-INDEPENDENT LIMITS

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

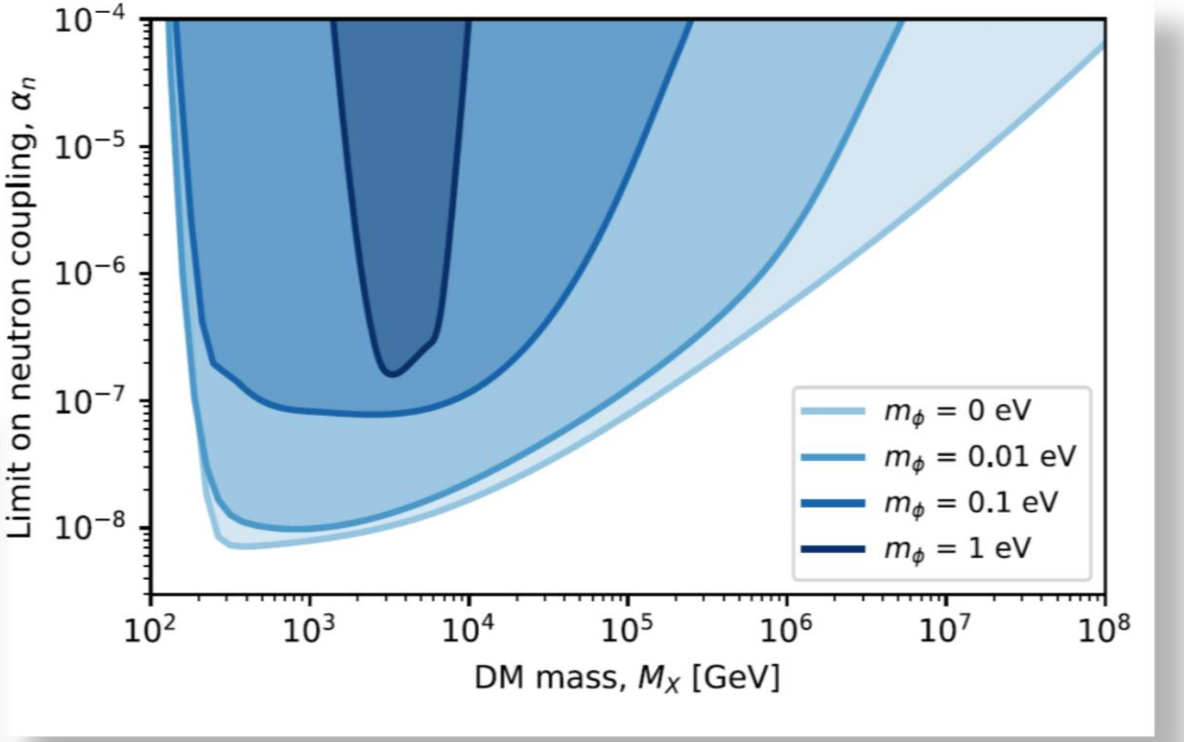
- Assuming specific composite dark matter model, can **compare to WIMP detectors**
- For sufficiently light mediators and large composite particles, **many orders-of-magnitude more sensitive**
- Only **first proof-of-principle. What's next?**







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



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Barredo *et al. Nature* **561** (2018)

D. Moore and A. Geraci, *Quantum Sci. Technol.* ***6*** *014008 (2021)*

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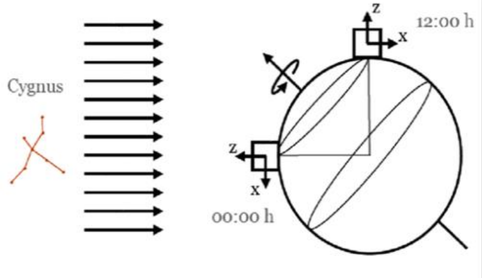

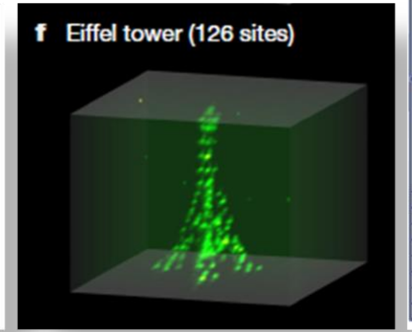

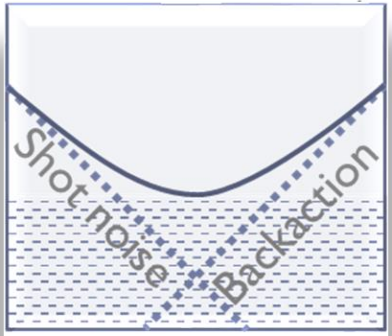

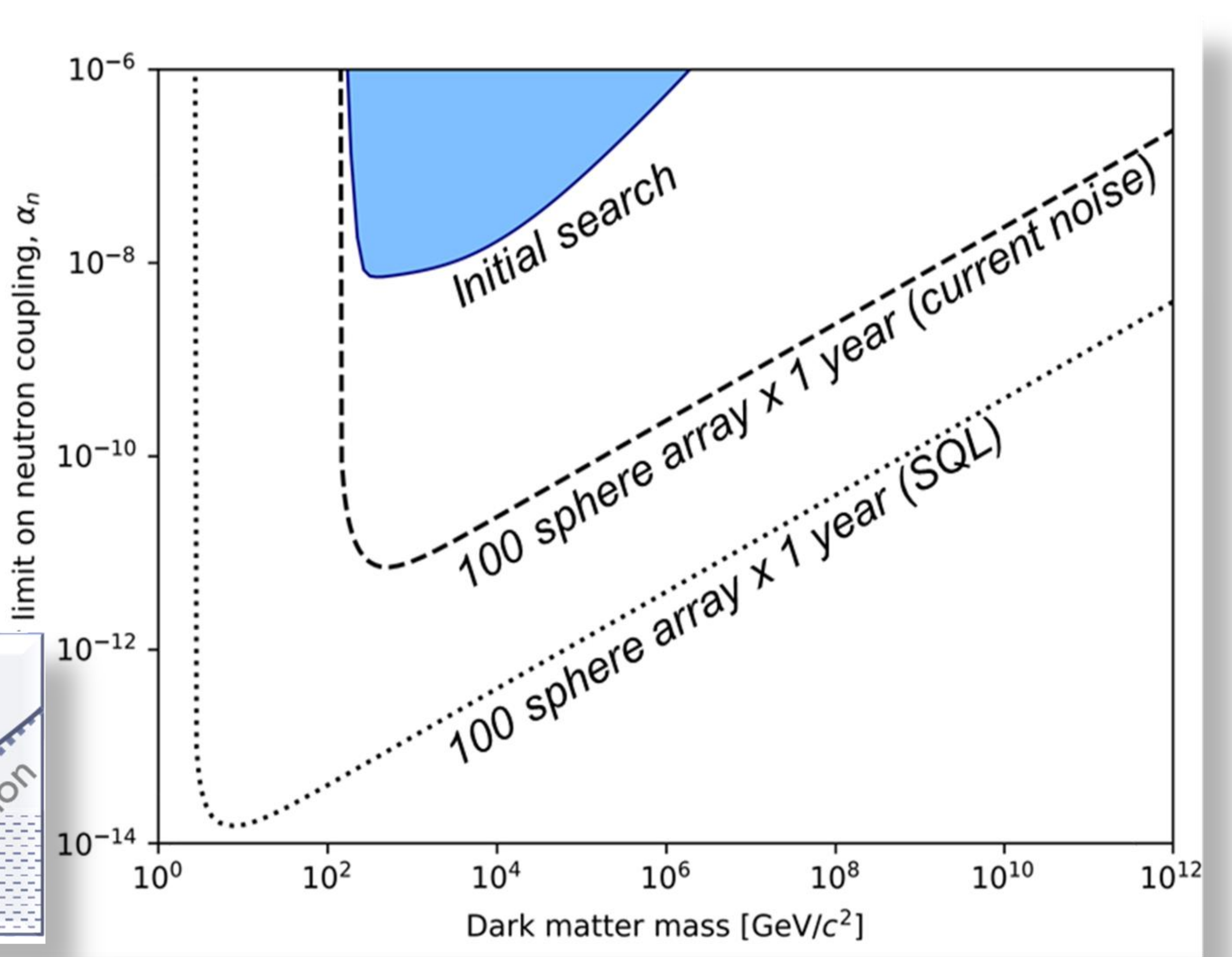

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WHAT IF DM COUPLES TO ELECTROMAGNETISM?

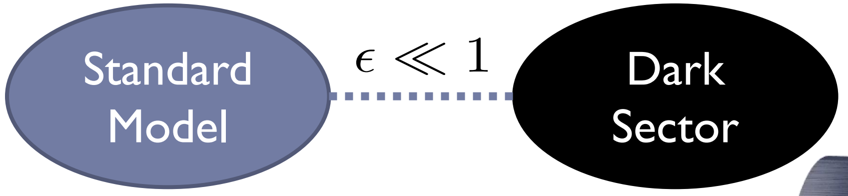
- **Particles with unity charge** under new dark force **can have fractional charge under electromagnetism**

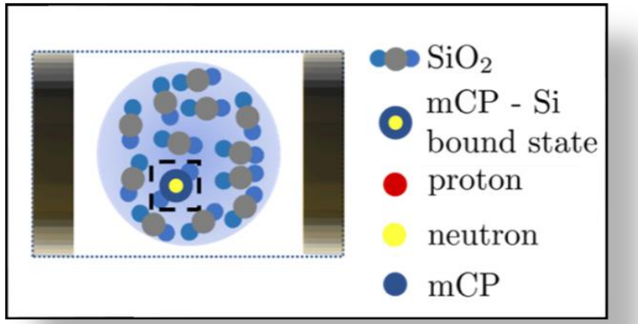
- **Charge/mass ratio ~ 10^9 worse** than, e.g., single Sr^{+2} ion or **~ 10^{14} worse** than a single *e*

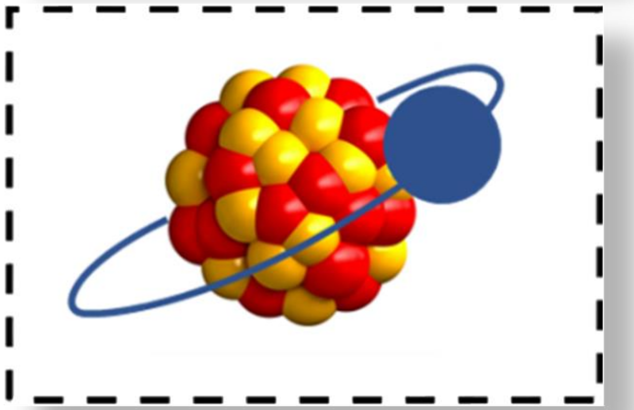
- Protons and electrons **form bound states**

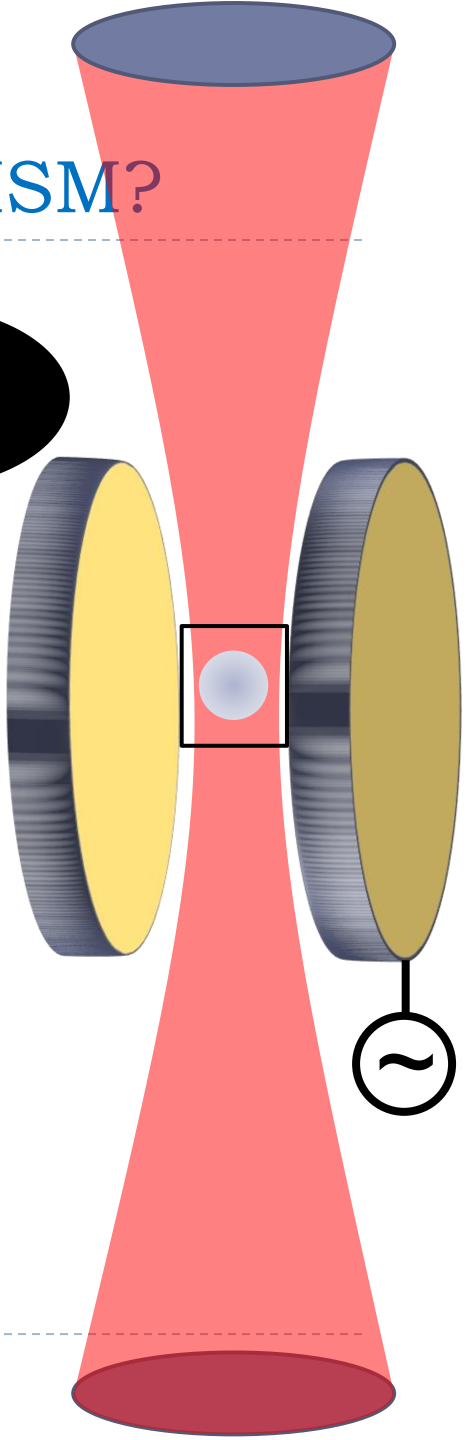
- The experiment: **Calibrate** response function to known charge, **discharge, spin up** apply **high voltage, measure correlation**

- **Neutrality of matter**



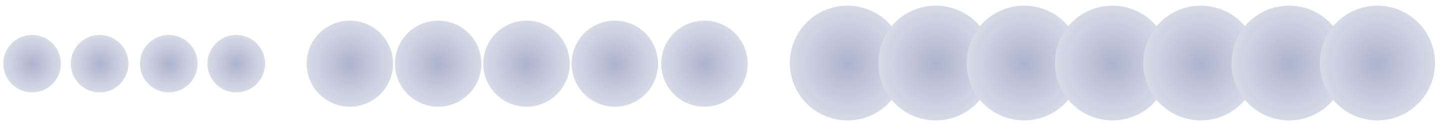




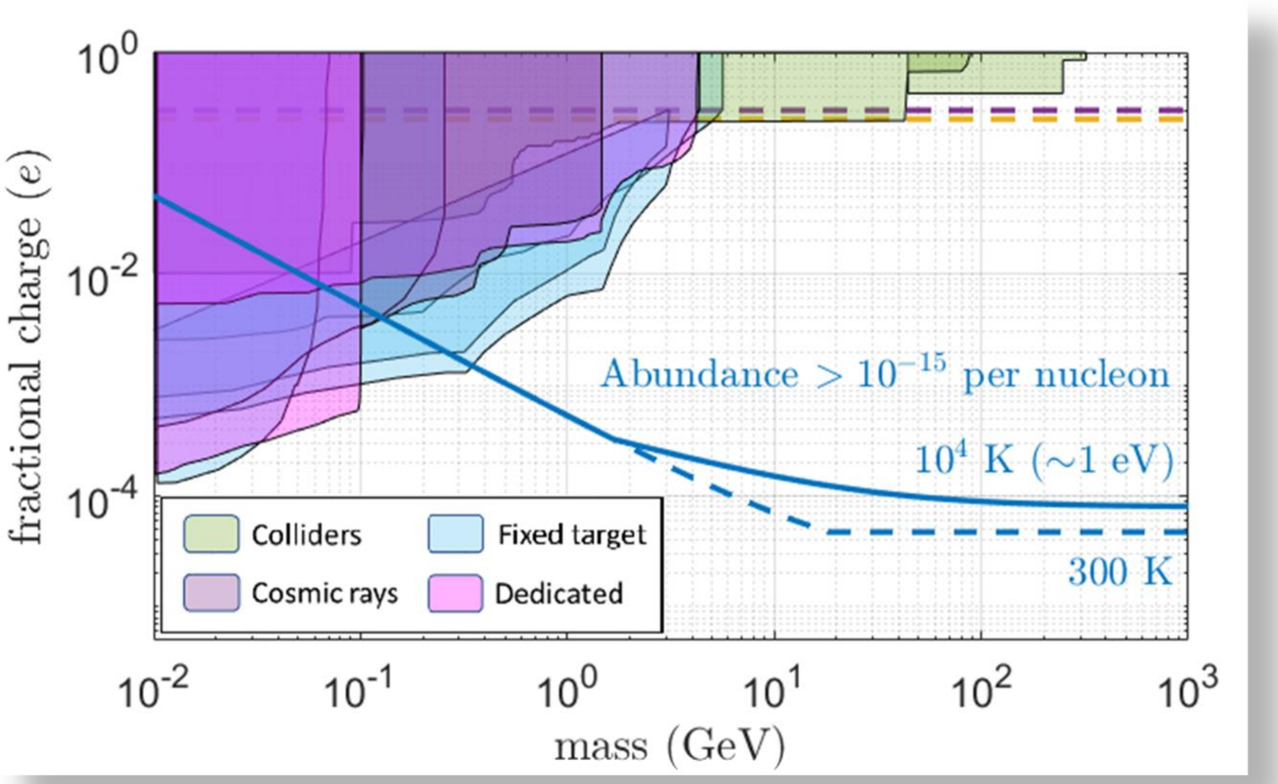


D. Carney, H. Haffner, D. Moore and J. Taylor *arXiv*:2104.05737 (2021) J. Baumann *et al.*, *PRD* **37**, 3107 (1988)
GA, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore, *PRD* **104**, 012004 (2021) G. Bressi *et al.*, *PRA* **83**, 052101 (2011)

LIMITS ON MILLICHARGED PARTICLES BOUND TO NORMAL MATTER



- Total mass **~ 76 X 10^{-9} gr**
- Probe **deep into 10^{-17} / nucleon,** <<< abundance of naturally occurring stable elements (10 parts in a quintillion…)
- Holds even in **comparison** with ambitious **future experiment projections**
- **10^{-19} *e* / nucleon limit < 10^{-21} *e* best**



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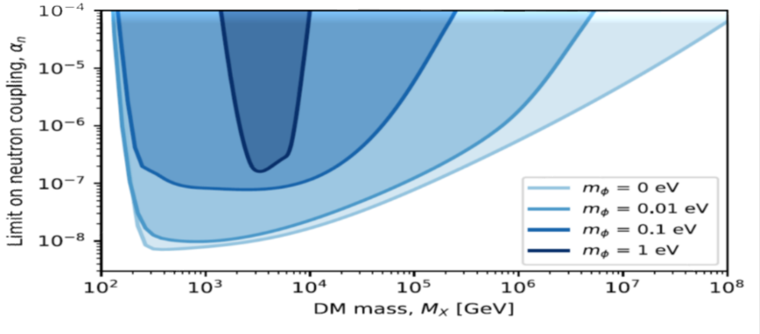
M. Marinelli *et al.*, *PhysRep* **85** 161 (1982), P.C. Kim *et al*, *PRL* **99** 161804 (2007), D. C. Moore *et al.*, *PRL* **113**, 251801 (2014), M. Pospelov *et al.*, arXiv:2012.03957 (2020)

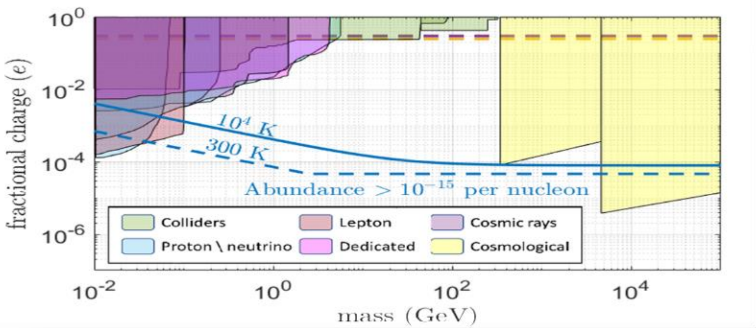
WHAT'S NEXT, THEN?

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



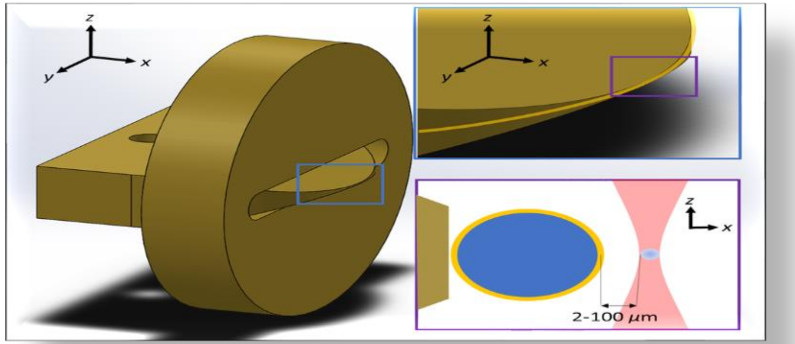
F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020)

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

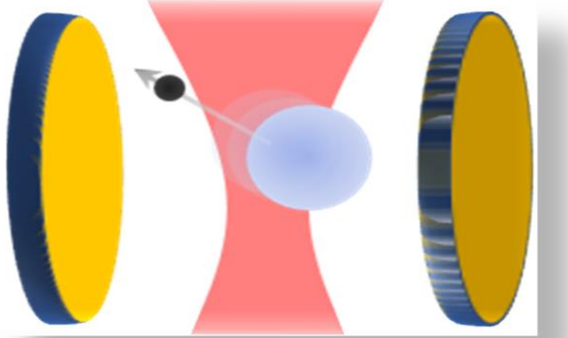


GA, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore., *PRD* 104, 012004 (2021)

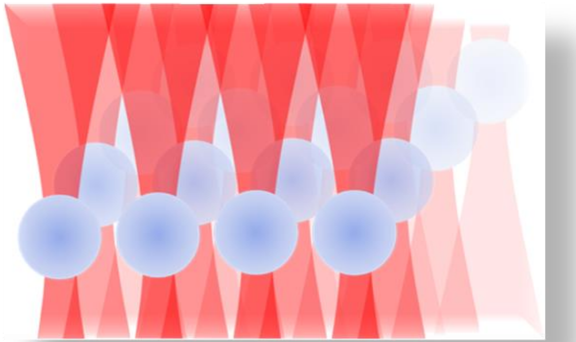
Testing **Newton's law** at ~ *um* distances



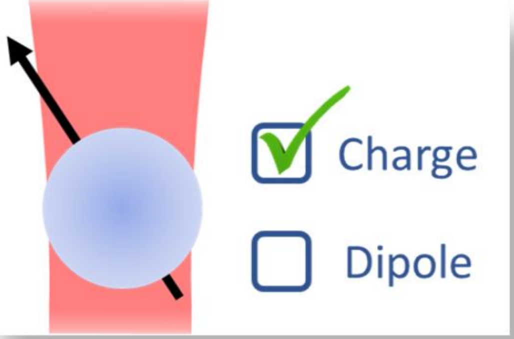
Nuclear forensics from α/β decays



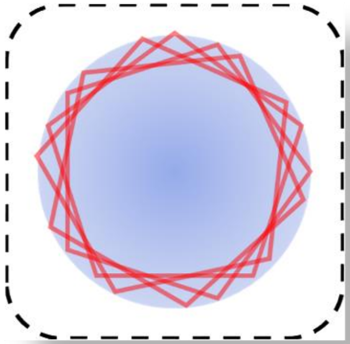
Arrays of ng masses



Controlling **dipole backgrounds**



WGM spectroscopy



THANK YOU!

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