



Search for composite dark matter with optically levitated sensors

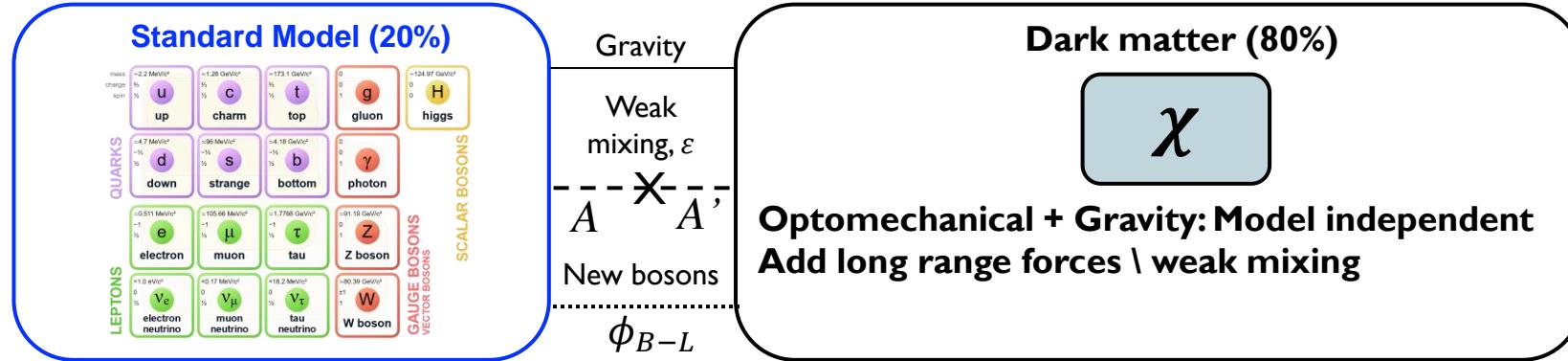
Gadi Afek
Yale University



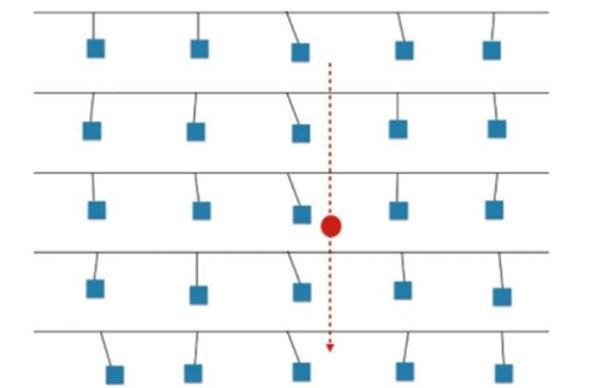
OPTO-DM 2 Workshop, April 2021



TOWARDS MODEL-INDEPENDENT SEARCHES?



- 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...)
- We use ~ 10 ng microspheres with ~ 100 **ng/Hz^{1/2} acceleration sensitivity**



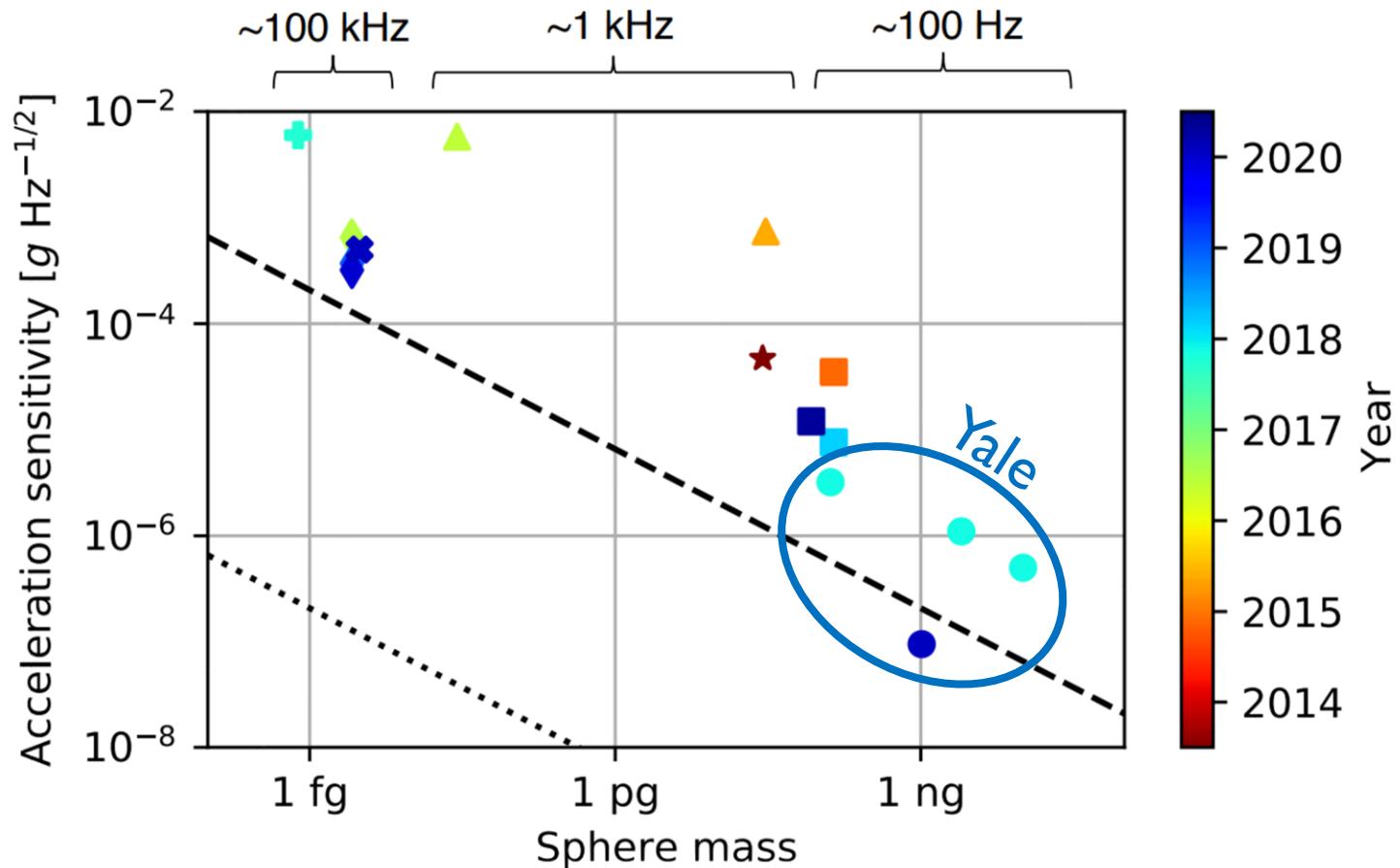
$$\text{SNR}^2 = \frac{4G_N^2 m_\chi^2 L}{v d^4 P A_d \sqrt{m_a k_B T}} \frac{m_s^2}{\approx 10^4 \times \left(\frac{m_\chi}{1 \text{ mg}}\right)^2 \left(\frac{m_s}{1 \text{ mg}}\right)^2 \left(\frac{1 \text{ mm}}{d}\right)^4}$$

Array of $N = L/d$ sensors with spacing d
Assumes $P = 10^{-10} \text{ Pa}$ and $T = 10 \text{ mK}$
 $L = 1 \text{ m}$, $d = 1 \text{ mm} \rightarrow 10^9$ sensors!

$$R = \frac{\rho_\chi v A_d}{m_\chi} \sim \frac{1}{\text{year}} \left(\frac{m_{Pl}}{m_\chi}\right) \left(\frac{A_d}{1 \text{ m}^2}\right) \quad m_{Pl} \sim 20 \mu\text{g}$$

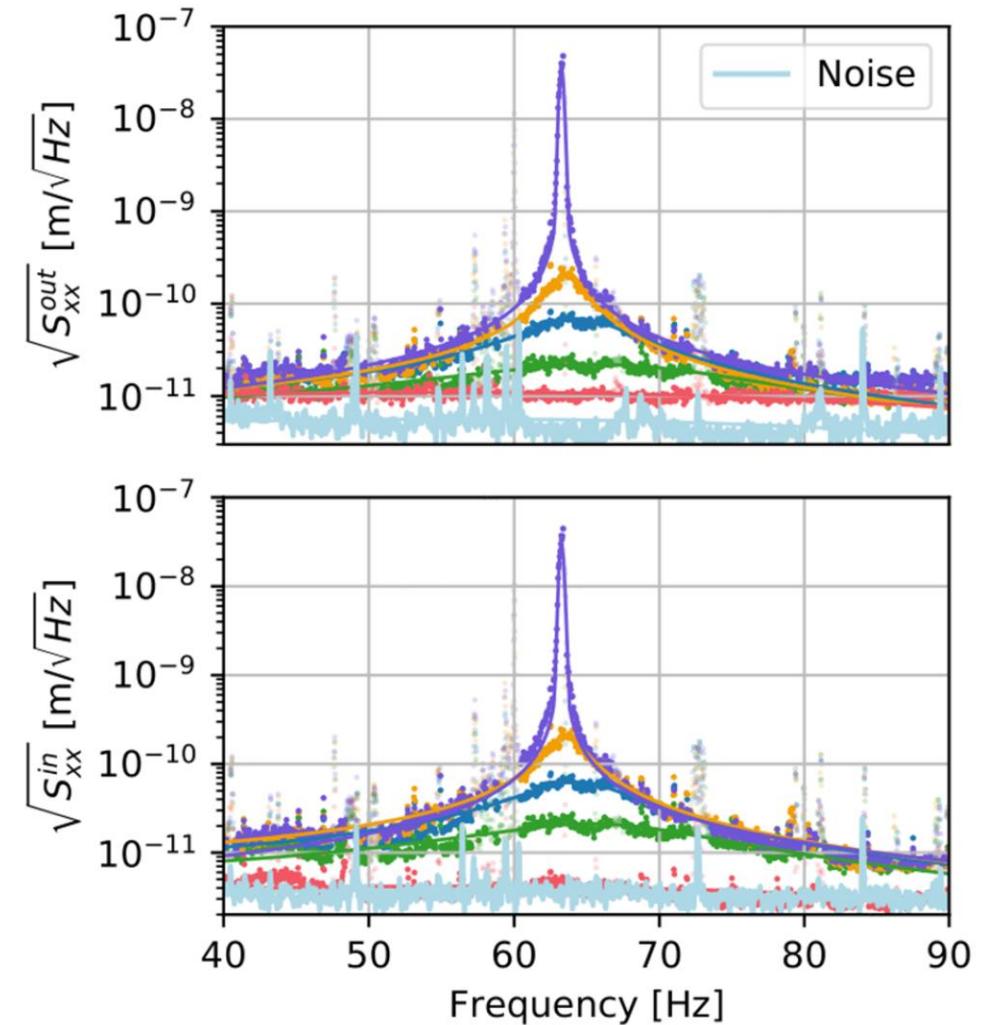
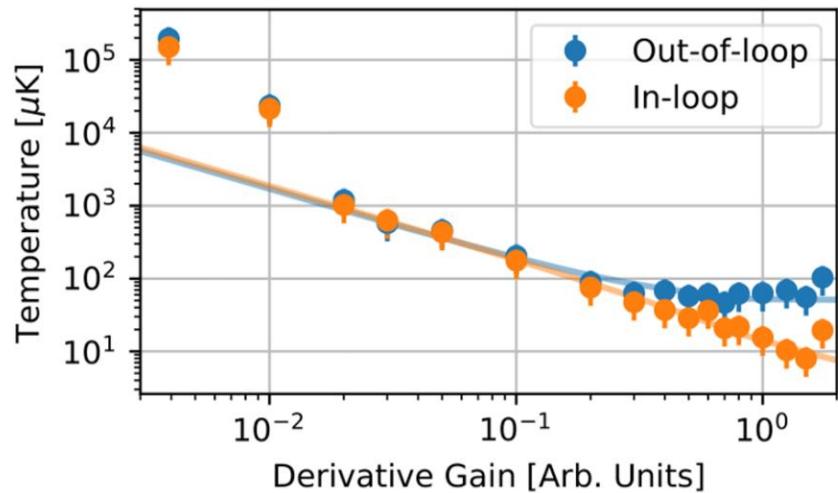
THE SYSTEM

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



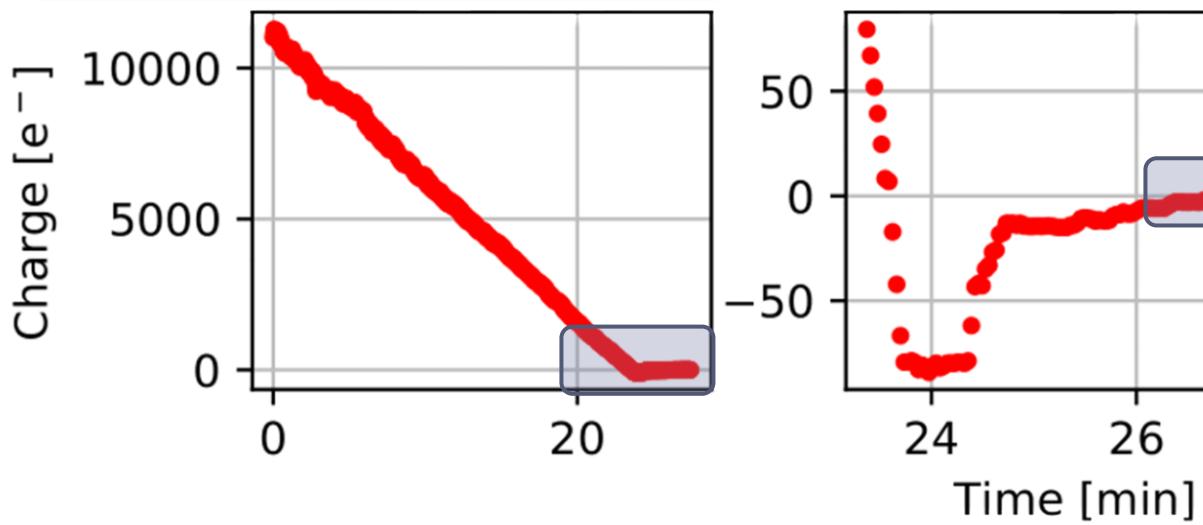
μK TEMPERATURES

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



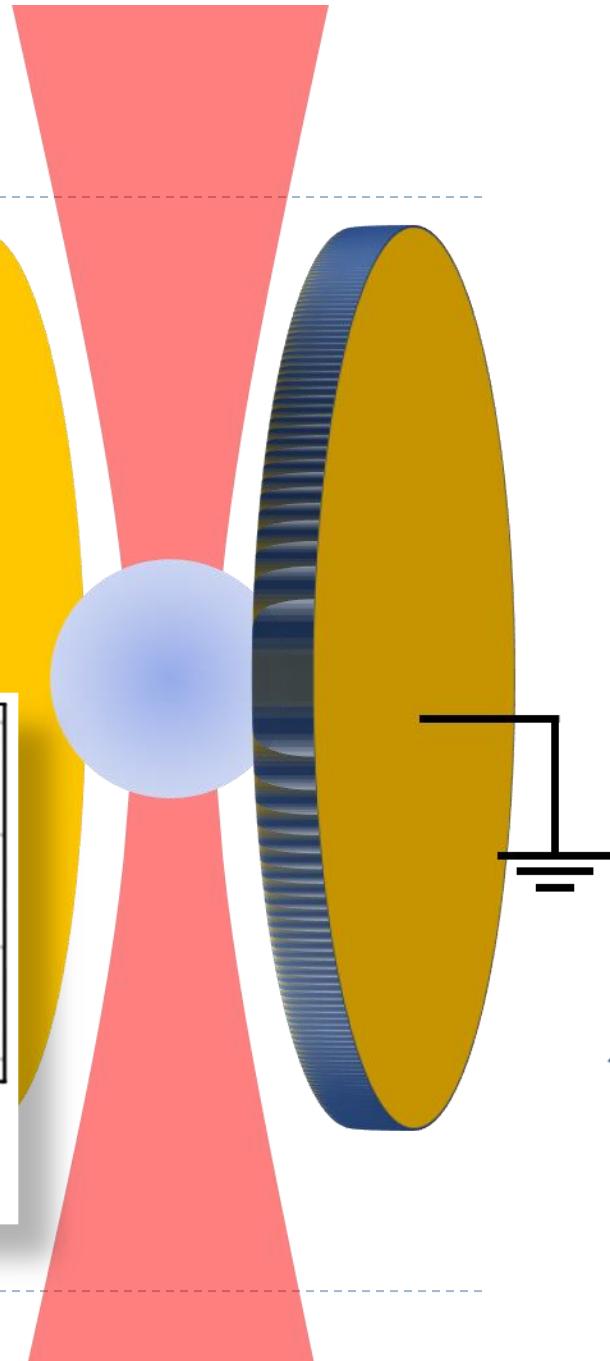
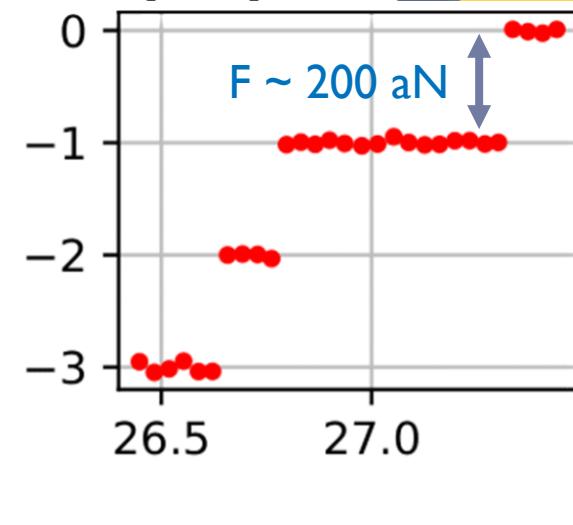
CHARGE CONTROL

- 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



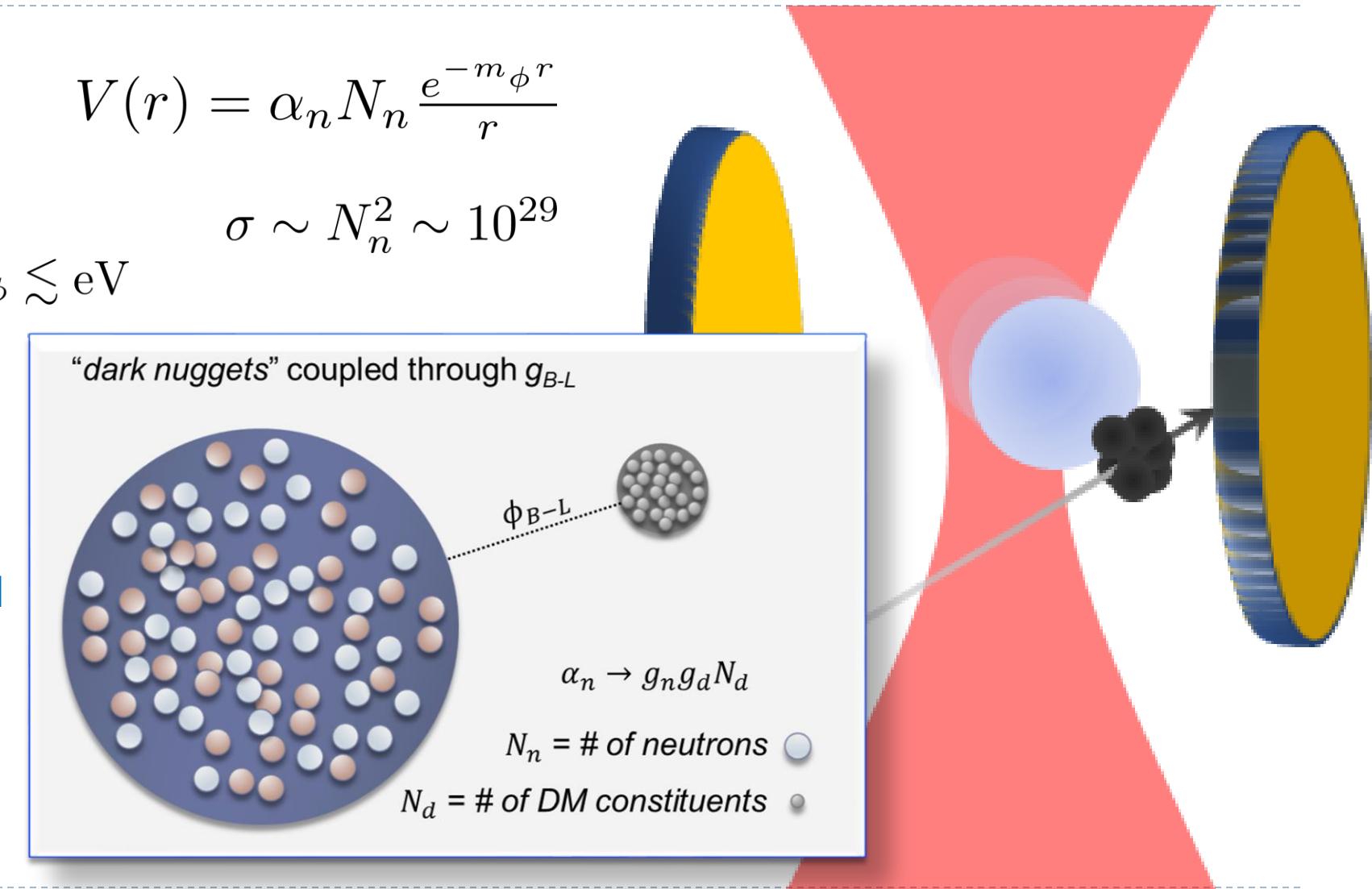
Can go both ways!

What about dipoles?

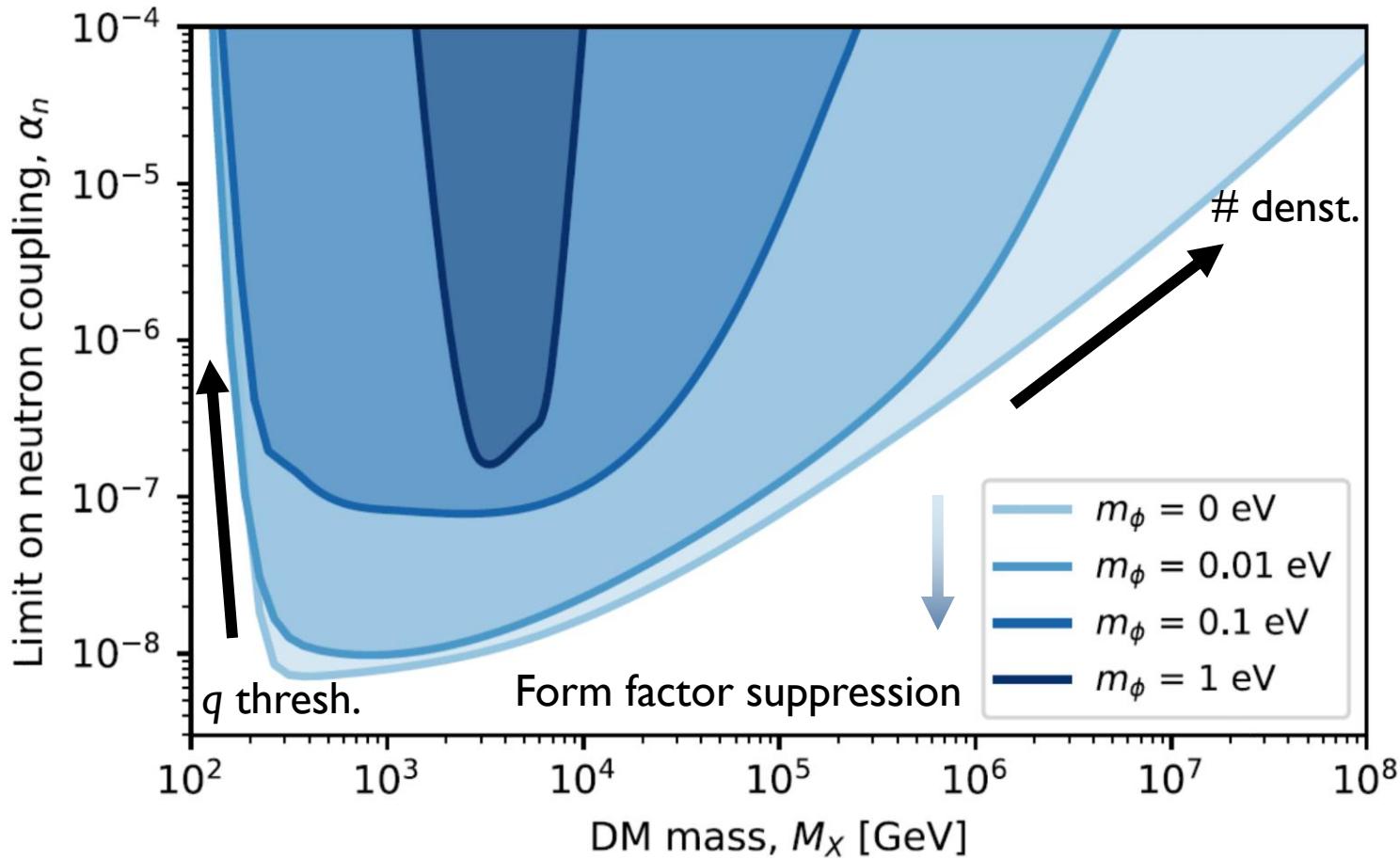


DM-INDUCED RECOILS

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



MODEL-INDEPENDENT LIMITS on NEUTRON COUPLING



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

LIMITS on 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**

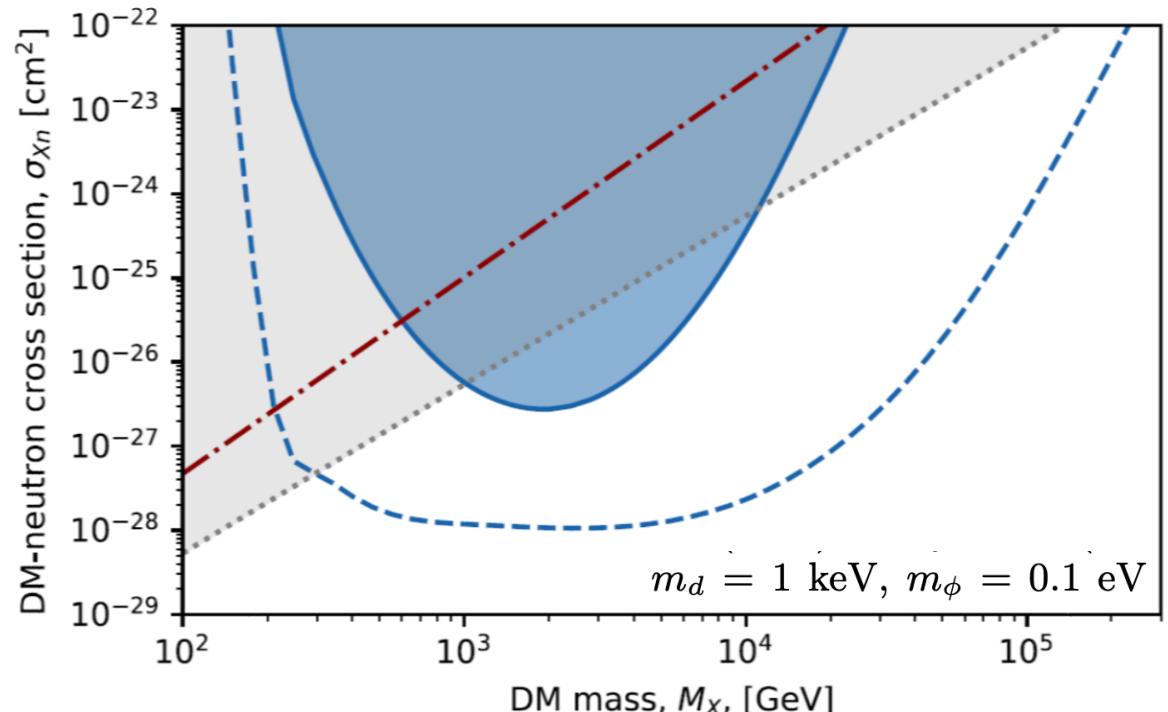
This work, (5ng day), 10% of DM

— — — 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 (1kg yr @ 1meV)

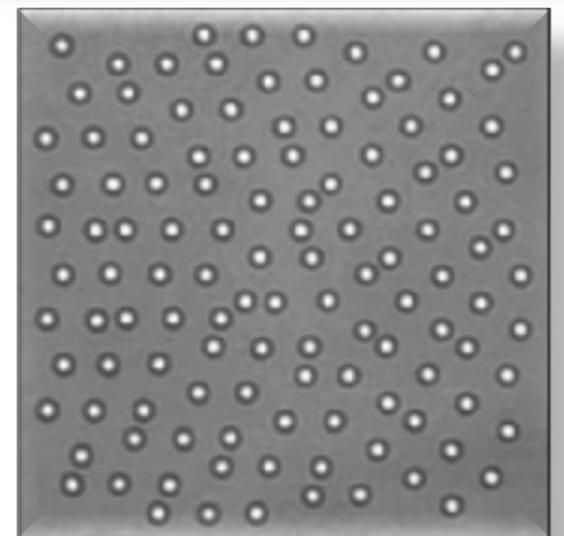
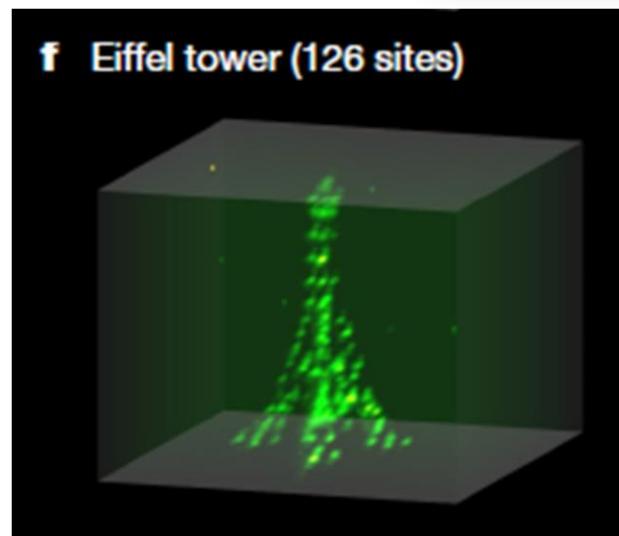
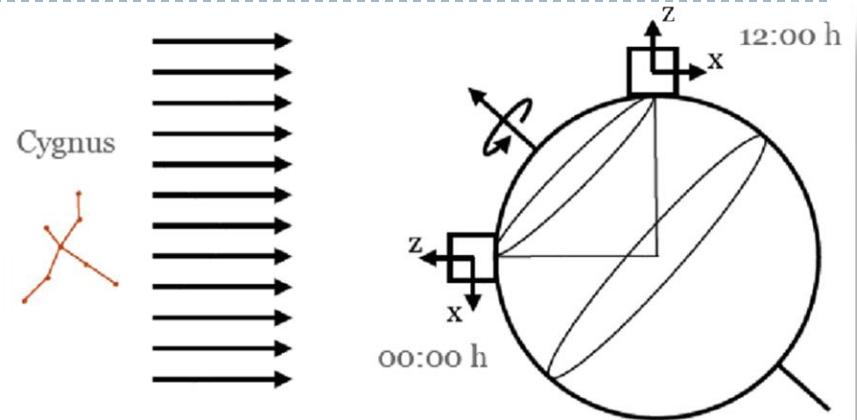
XENON1T, LUX, SuperCDMS, ... (> ton year)
Sharp DM nugget form-factor suppression



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

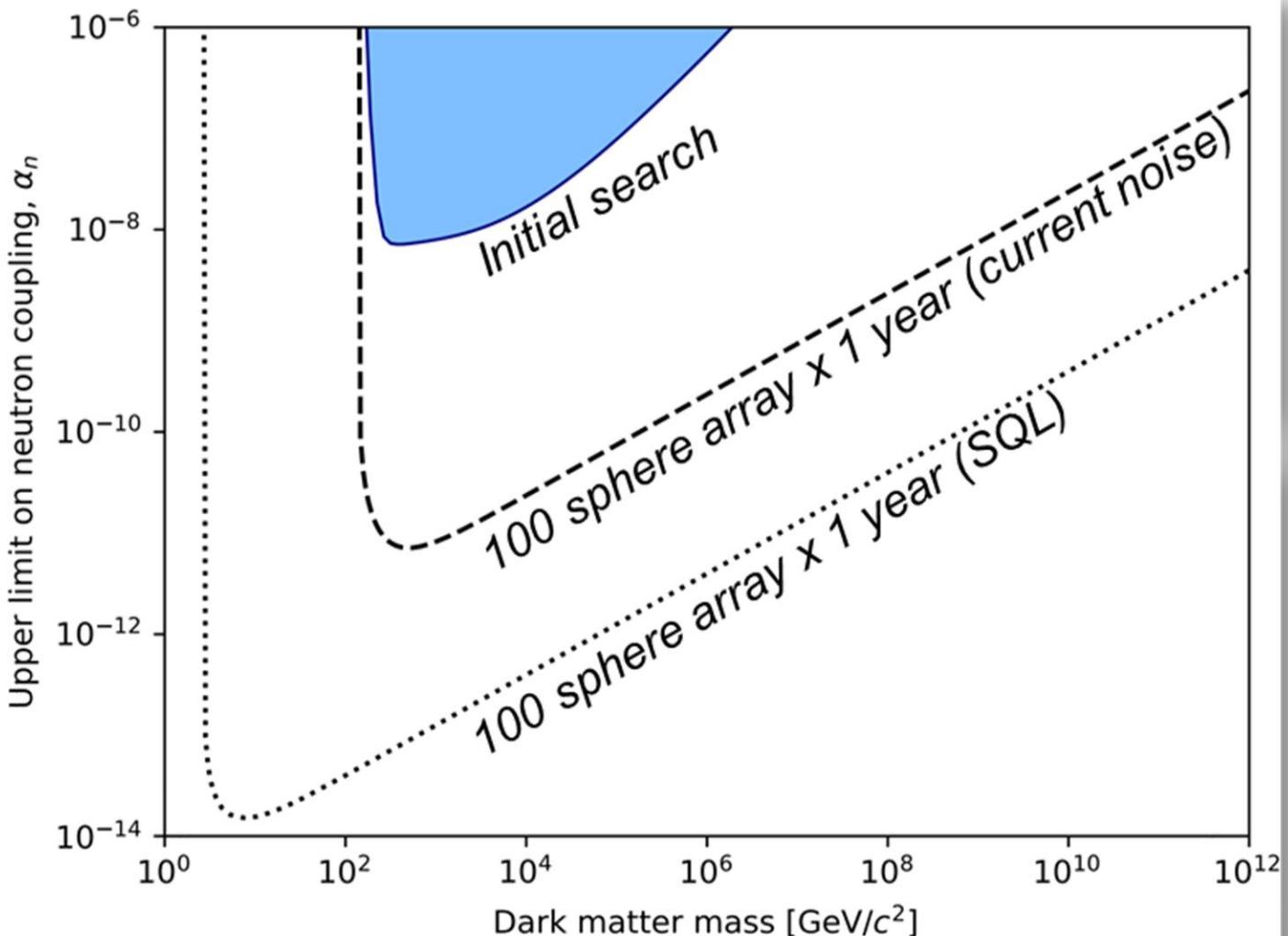


Exp (atoms, spheres in fluid): Barredo et al. *Nature* **561** (2018), D. Grier and Y. Roichman, *Appl. Opt.* **45** (2006)

Dark matter search proposal: D. Carney et al., PRD **102** 072003 (2020), D. Moore and A. Geraci, *Quantum Sci. Technol.* **6** 014008 (2021)

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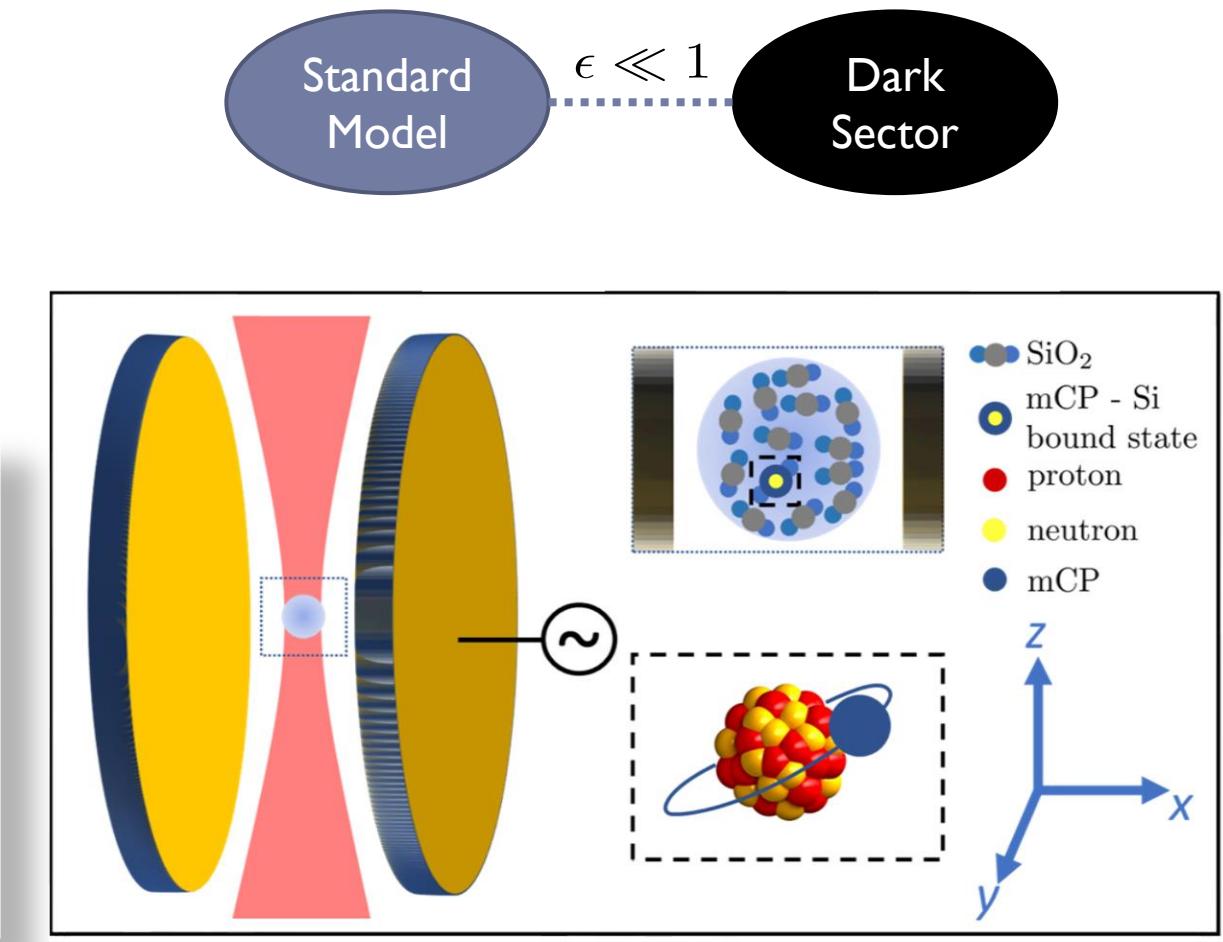
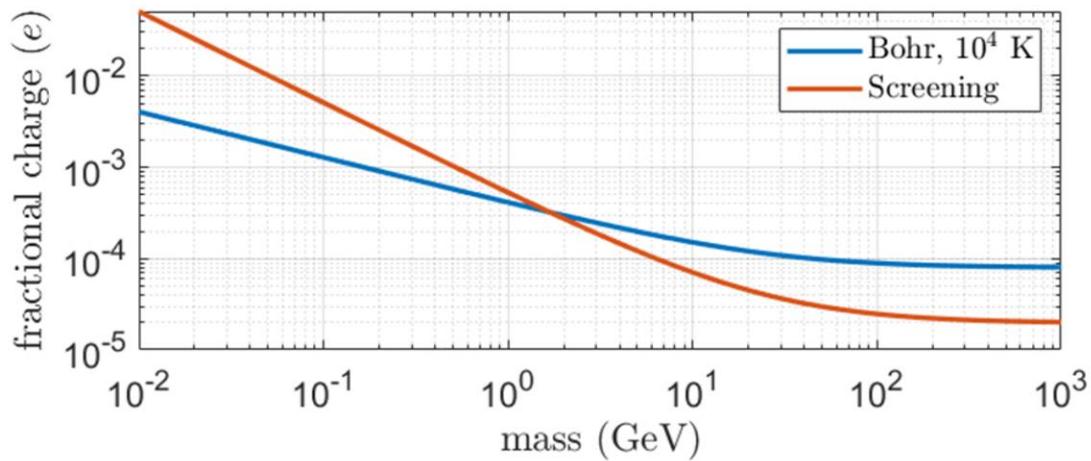


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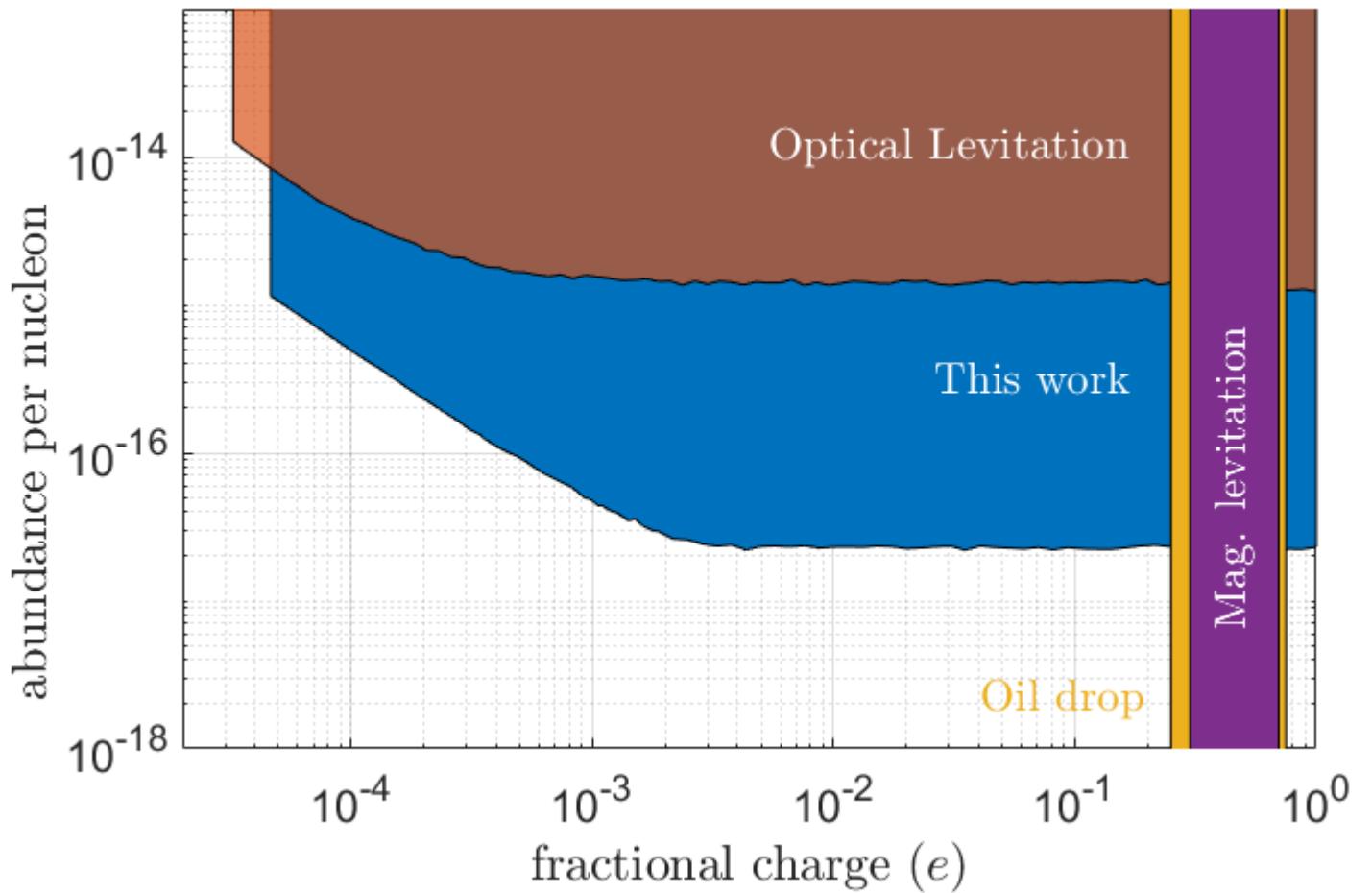
WHAT if DM COUPLES to N_p - N_e ?

- ❑ Particles with unity charge under new dark force can have fractional charge under electromagnetism
- ❑ Charge/mass ratio $\sim 10^9$ worse than, e.g., single Sr⁺² ion or $\sim 10^{14}$ worse than a single e
- ❑ Protons and electrons form bound states



LIMITS on ABUNDANCE / NUCLEON

- Theorized enhancement in relic abundance of DM mCPs, **accumulating in Earth**
- We probe **deep into 10^{-17} / nucleon**
- ~ 6 orders of magnitude under natural abundance of naturally occurring stable elements (10 parts in a quintillion...)
- We set a **10^{-19} e / nucleon limit** on the sum $|q_p + q_e + q_n|$



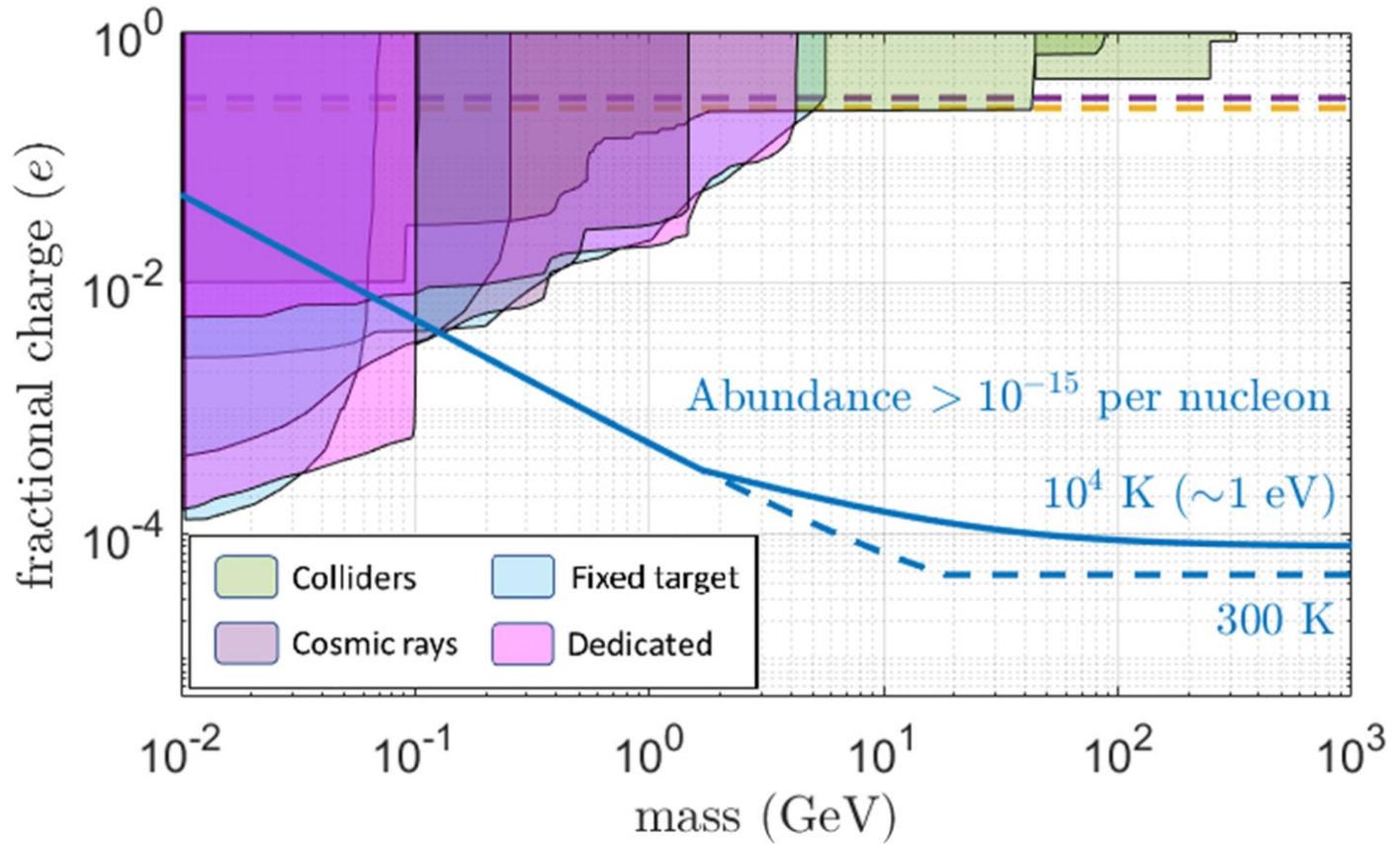
M. Pospelov et al., arXiv:2012.03957 (2020)

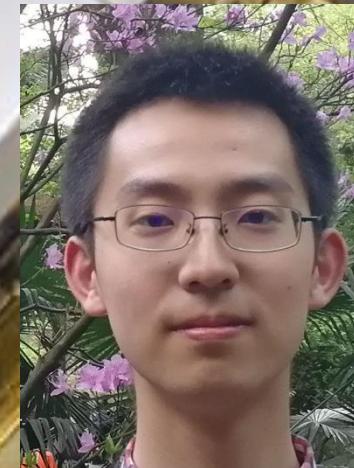
M. Marinelli et al., PhysRep 85 161 (1982), P.C. Kim et al, PRL 99 161804 (2007), D. C. Moore et al., PRL 113, 251801 (2014)

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 $> 10^{15}$, explore new parameter space**
- Holds even in **comparison** with ambitious **future experiment projections**
- Looking at **relic abundance** benefits from **accumulation of mCPs on Earth**

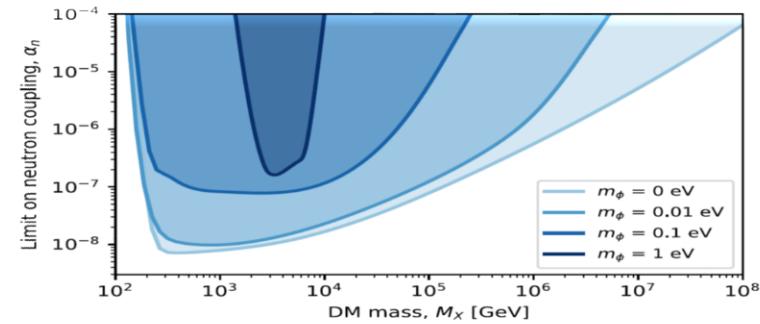




You?
? Postdoc
positions
available

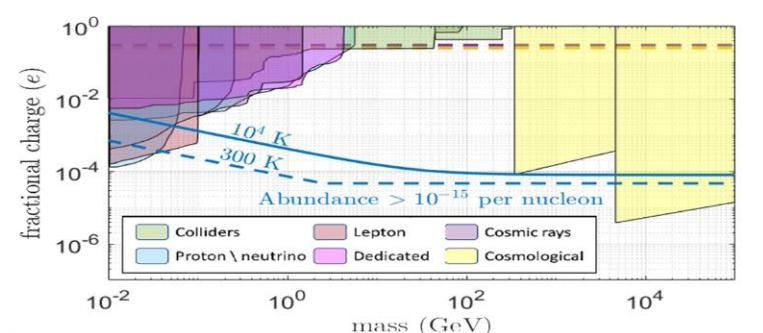
CURRENTLY IN THE LAB...

Search for **recoils** from composite DM



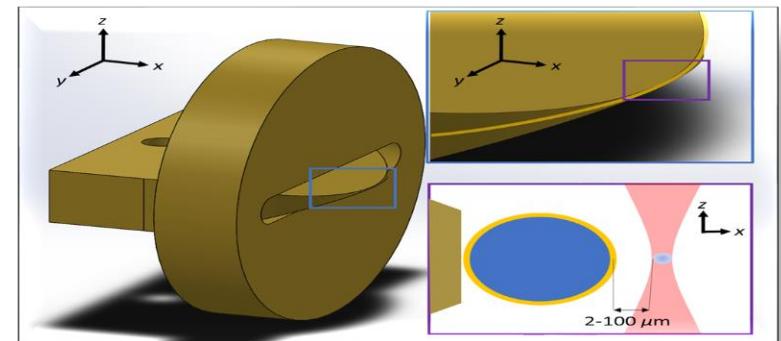
F. Monteiro, **GA**, D. Carney, G. Krnjaic, J. Wang and D. Moore., *PRL* **125**, 181102 (2020)

Testing **charge quantization** and search for mCP

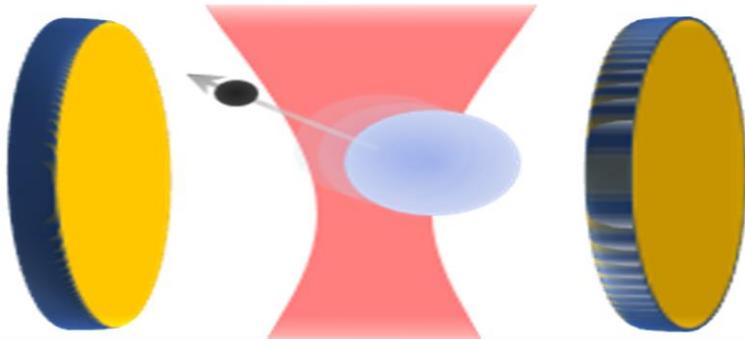


GA, F. Monteiro, J. Wang, B. Siegel, S. Ghosh and D. Moore., *arXiv:2012.08169* (2020)

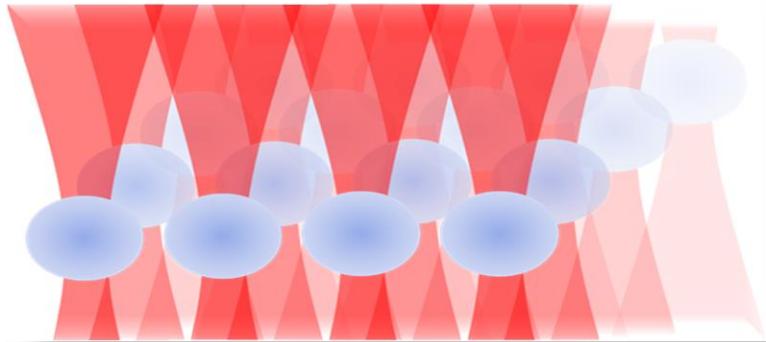
Testing **Newton's law** at $\sim \mu\text{m}$ distances



Nuclear recoils from single α/β decays



Large arrays of ng masses



Controlling **dipole** backgrounds

