Quantum Sensors (for dark matter)

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Snowmass Theory Frontier Conference, 2/24/22

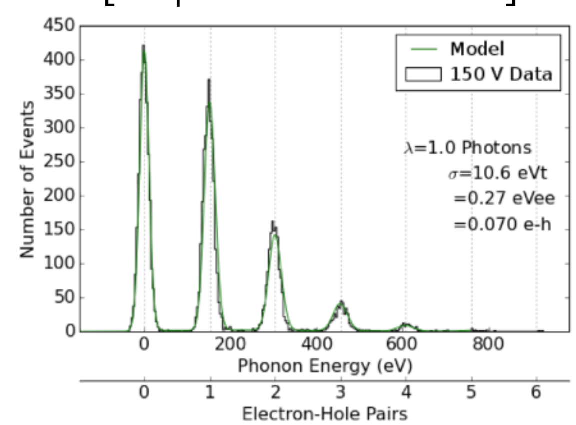
What is a quantum sensor?

No universally agreed-upon definition!

An attempt at a classification (boundaries are fluid):

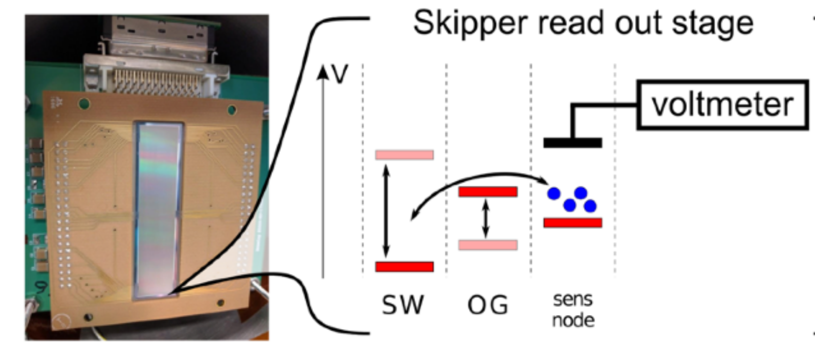
- Detecting a single quantum of something (classically)

[SuperCDMS 2018]



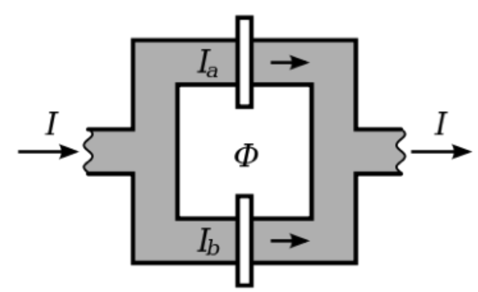
light

[SENSEI]



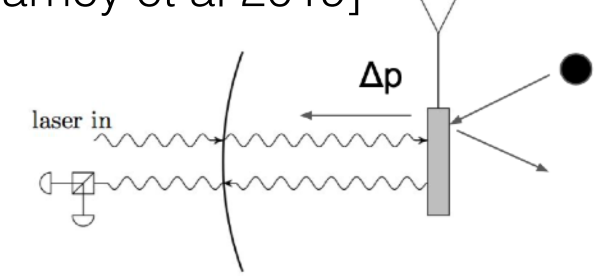
charge

- Using quantum mechanics to sense small (classical) things



magnetic fields

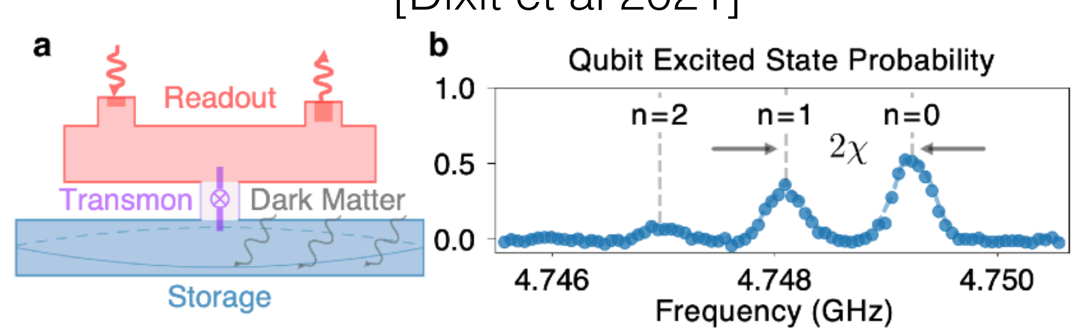
[Carney et al 2019]



impulse

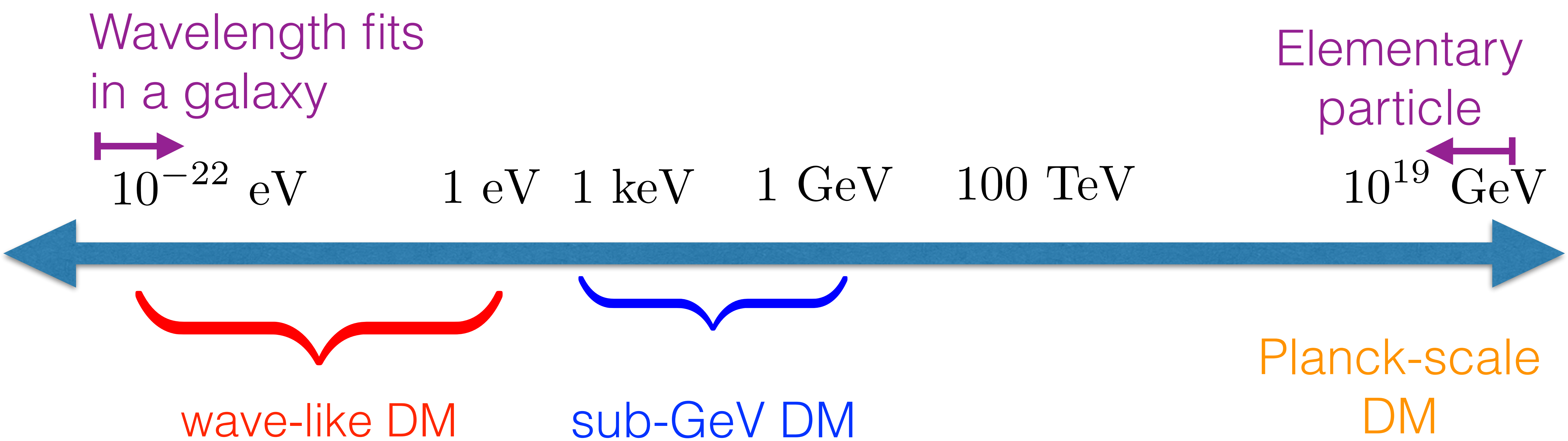
- Both at once (Quantum 2.0)

[Dixit et al 2021]



single-photon counting beyond the Standard Quantum Limit

Why should theorists care?



Broadband and Resonant Approaches to Axion Dark Matter Detection

Yonatan Kahn,[1,*] Benjamin R. Safdi,[2,†] and Jesse Thaler[2,‡]

[2016]

Direct Detection of sub-GeV Dark Matter with Semiconductor Targets

Rouven Essig,[a] Marivi Fernández-Serra,[b,c] Jeremy Mardon,[d] Adrián Soto,[b,c] Tomer Volansky,[e] Tien-Tien Yu[a]

[2015]

Gravitational Direct Detection of Dark Matter

Daniel Carney,[1,2,*] Sohitri Ghosh,[1] Gordan Krnjaic,[2] and Jacob M. Taylor[1,†]

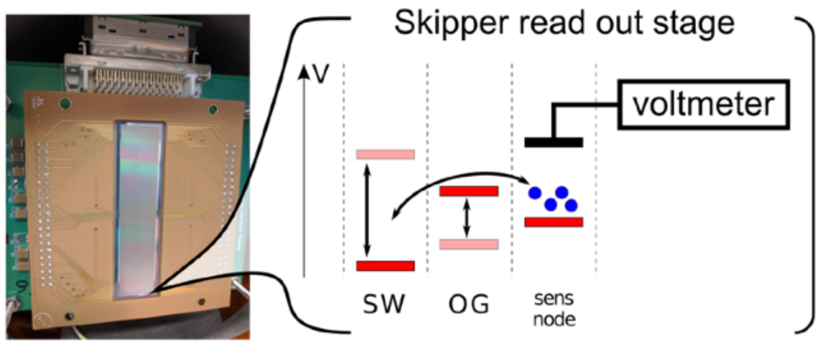
[2019]

New theory ideas exploiting these sensors let us cover 50 orders of magnitude in DM mass!

Single-quantum detectors

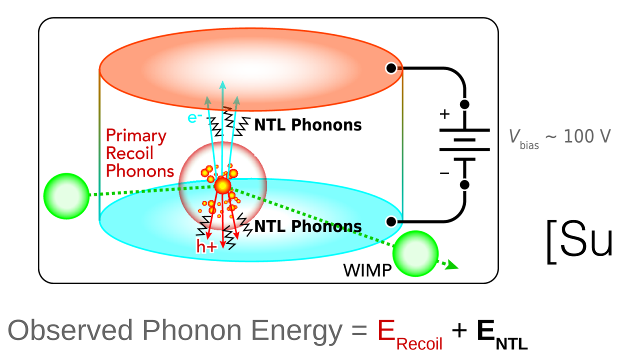
Have been around for a century (bubble chambers, LHC, …),
but recent advances are eV energy thresholds and ultra-low dark rates

Single-charge semiconductor detectors:



[SENSEI]

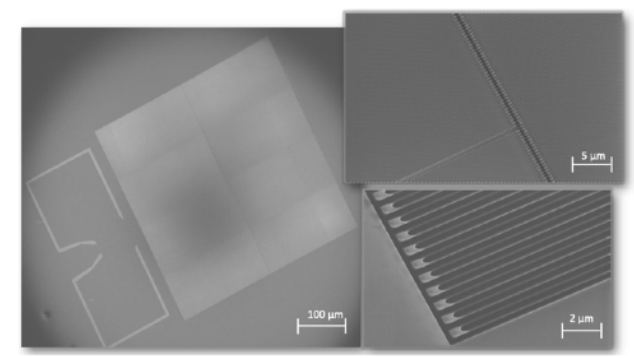
Skipper CCD: non-destructive charge measurements reduce noise



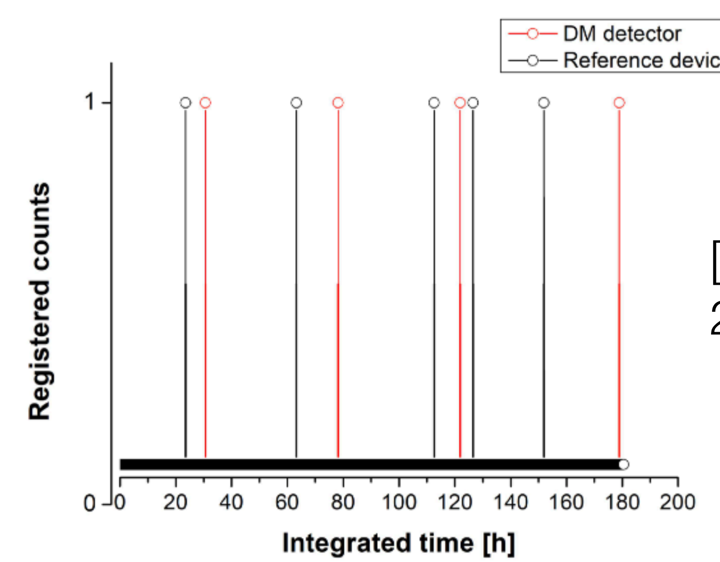
[SuperCDMS]

NTL effect: single charges give quantized phonon response

Superconducting nanowire photon detectors:



[Hochberg et al 2021]



[LAMPOST 2021]

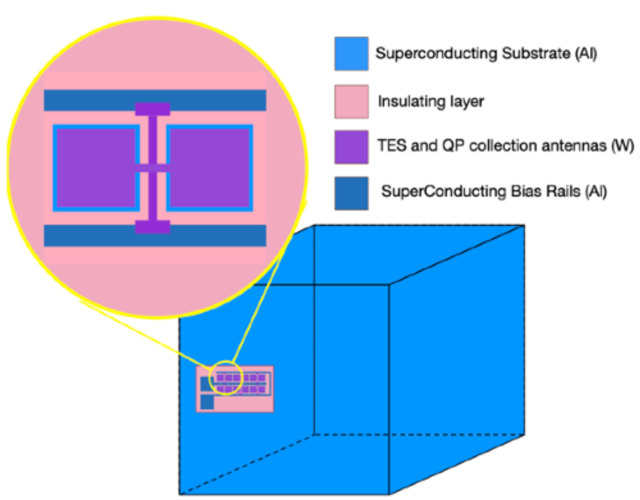
[see also Masha's talk]

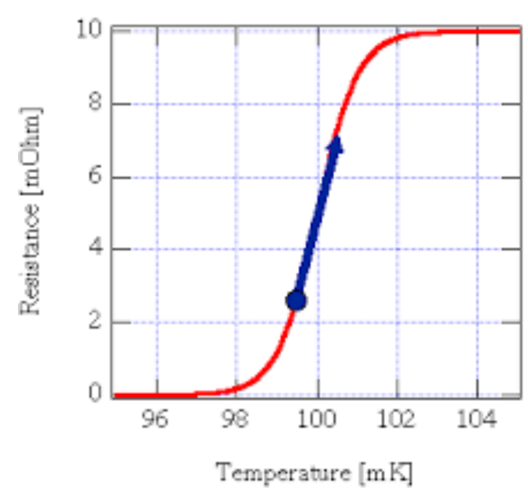
Single-quantum detectors

Towards the future:

Single-phonon detectors

[Hochberg et al 2015]

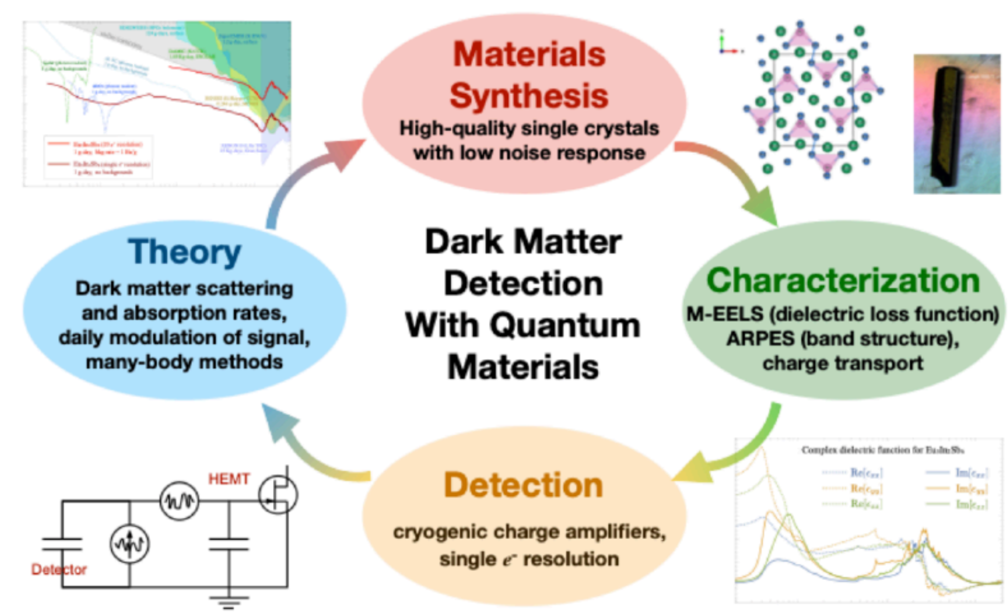




Transition-edge sensor:
with low enough threshold,
can see single optical phonons,
E ~ 50 meV

Charge and light at sub-eV scale

[SPLENDOR collab.]

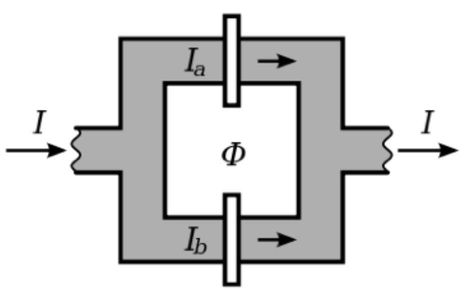


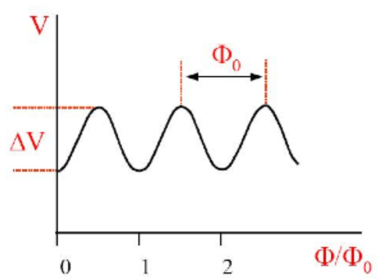
Exotic narrow-gap semiconductors
coupled to universal charge amplifier:
strong synergy w/condensed matter,
materials science

Measuring classical things quantum-ly

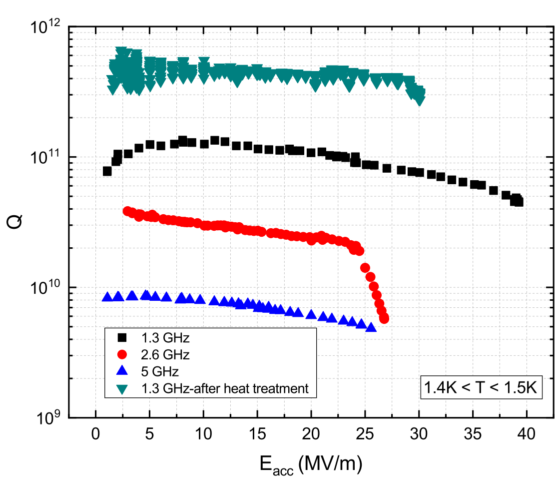
Two examples:

Superconductors for EM sensing





flux quantization: SQUID

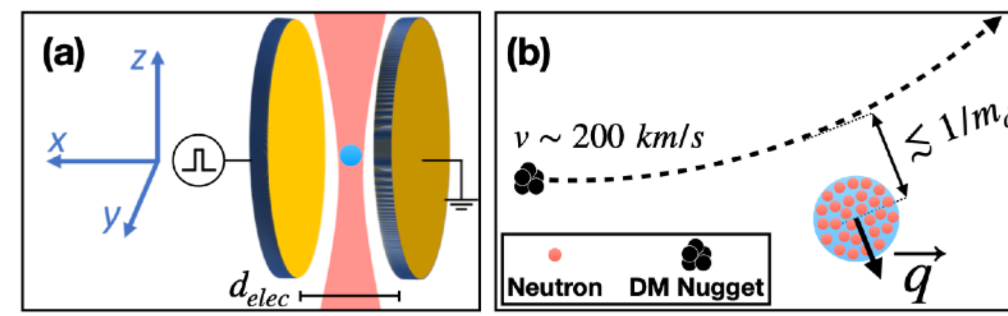


[Romanenko et al 2018; SQMS]

high-Q SRF cavities
(1 GHz photon lives 100 s!)

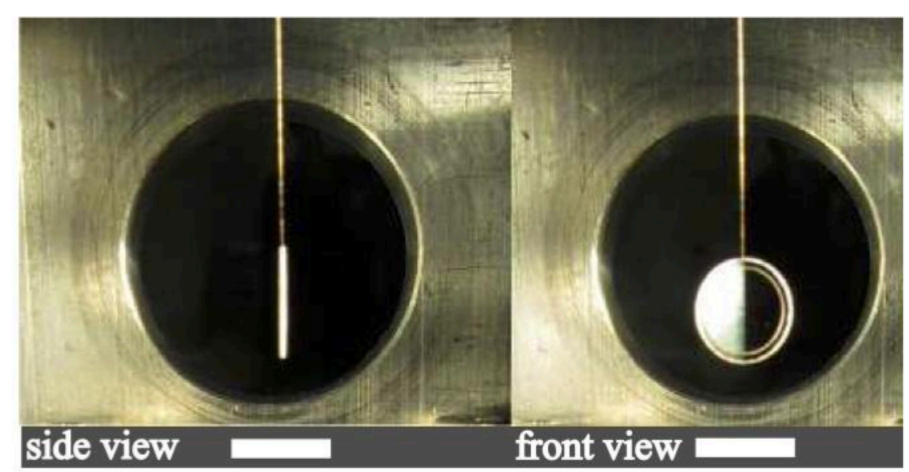
Optomechanical systems for force sensing

[Monteiro et al 2020]



optically-levitated microspheres

[Matsumoto et al 2019]

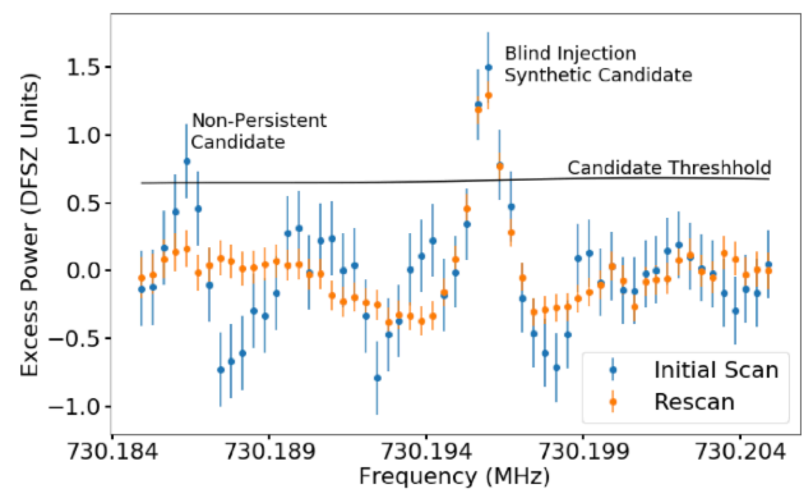


mirrors as pendulums

Quantum 2.0

To get beyond Standard Quantum Limit, need to measure or prepare an actual quantum state

Two examples from axion DM detection:

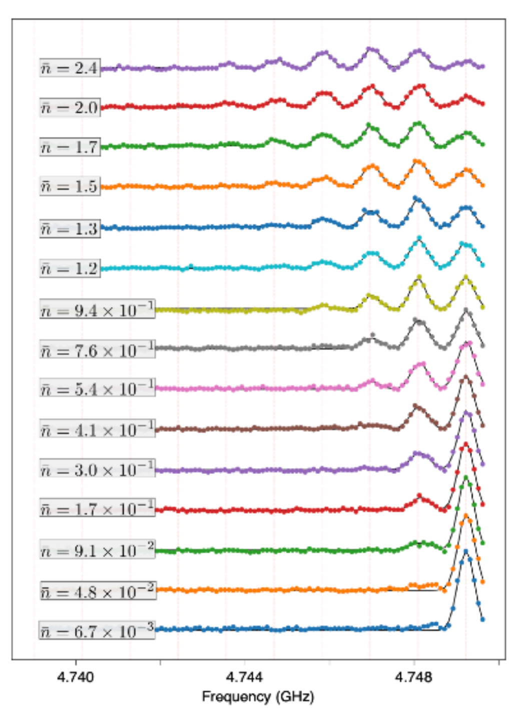


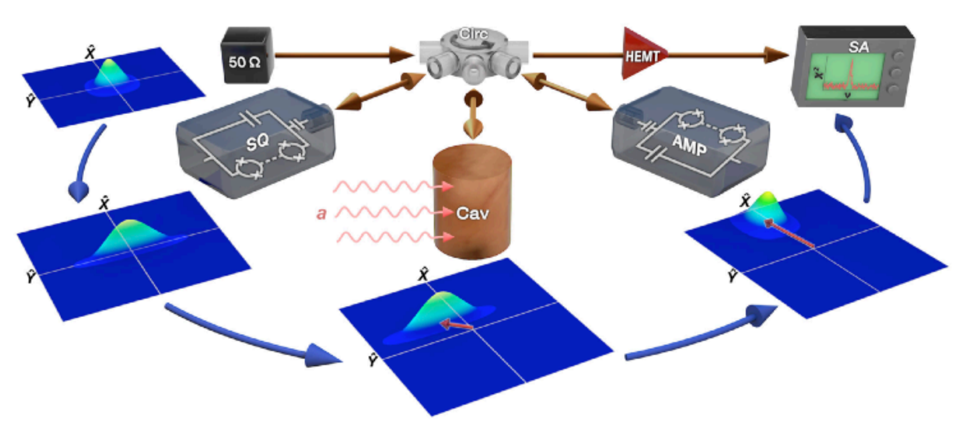
[ADMX 2020]

destructive (power) readout + thermal vacuum

non-destructive photon counting by coupling to qubit

[Dixit et al 2021]



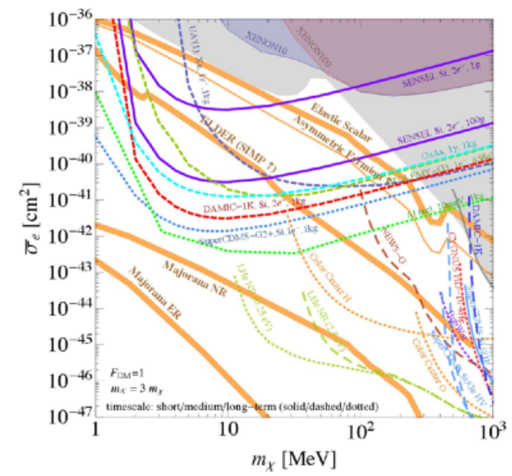


[Backes et al 2020]

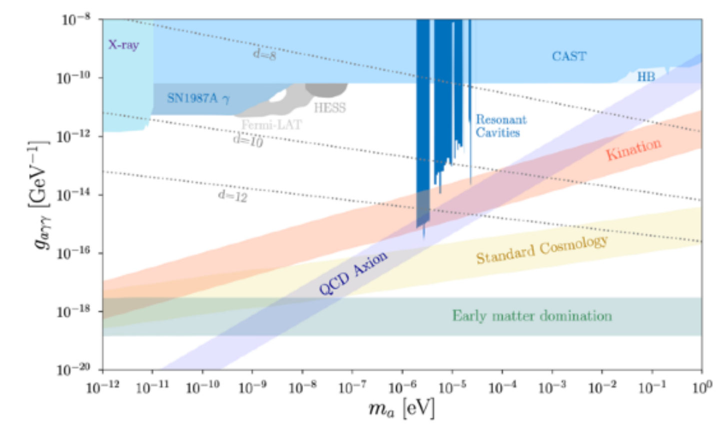
squeezed vacuum

Why are theorists crucial?

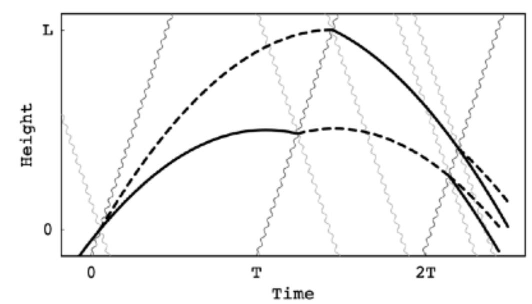
- Define theory targets
- Invent new uses for existing sensors
- Spur development of new sensors
- Help interpret new data (CM connections!)



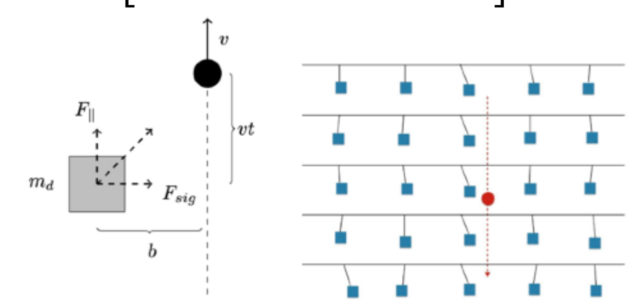
[Cosmic Visions 2018]



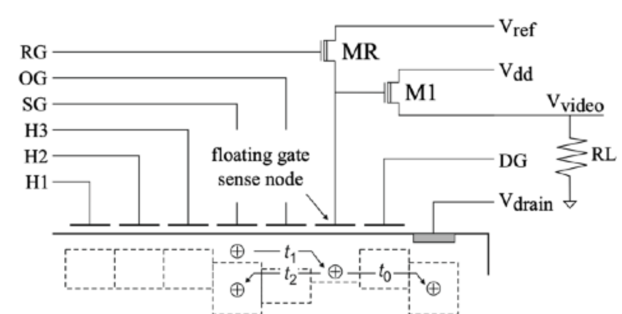
[Blinov et al 2019]



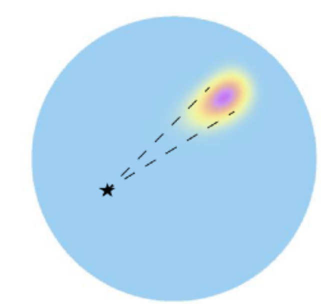
[Dimopoulos et al 2007]



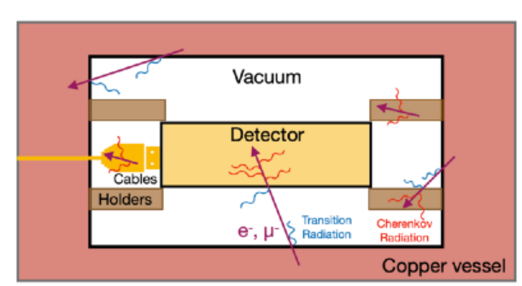
[Carney et al 2019]



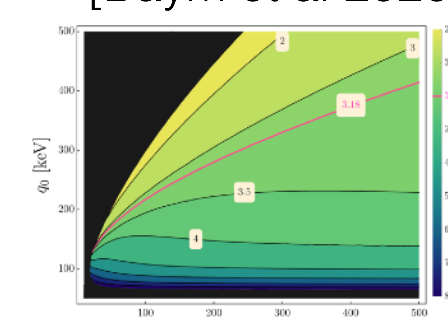
[Essig et al 2017]



[Baym et al 2020]

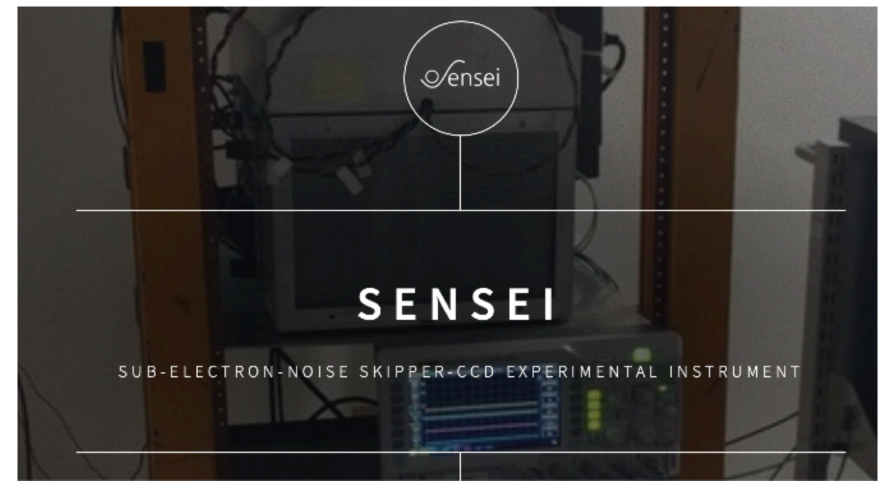


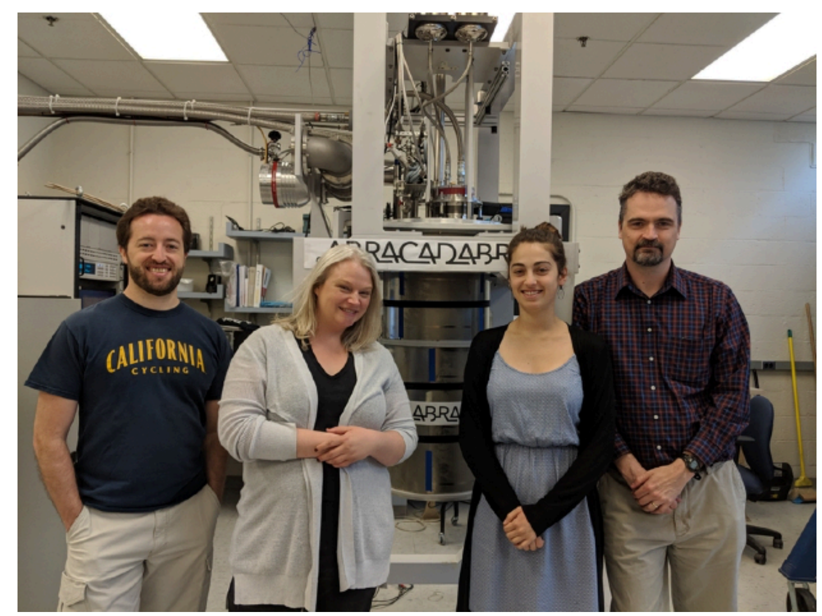
[Du et al 2021]



[Mandava et al 2022]

From theory to the lab





From theory paper to first data in **< 5 yrs:**

rapidly-advancing field and much more progress remains to be made!