Sub-eV threshold qubit-based sensors for Dark Matter

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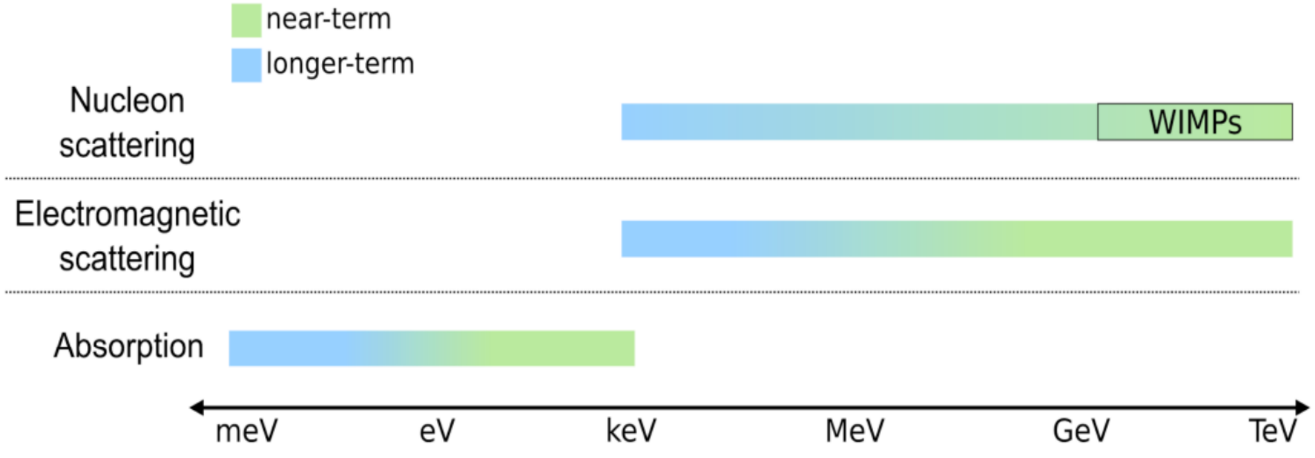
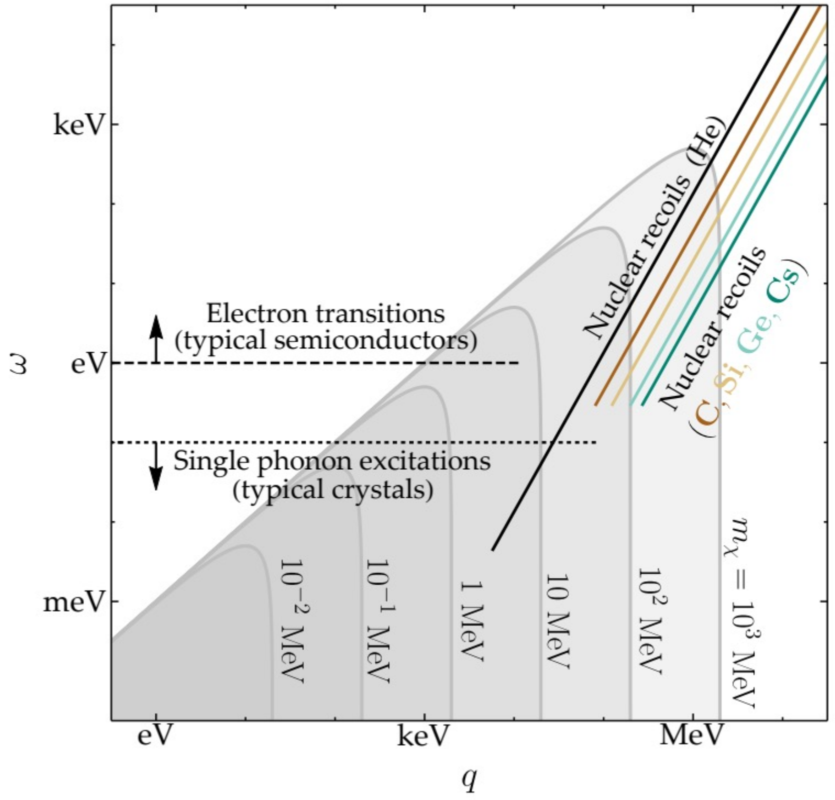
Motivation





Energy deposited by DM $\boldsymbol{\omega}$ vs. DM momentum transfer q.

- How do we look for sub-MeV (scattering) and sub-eV (absorption) Dark Matter?
- What mechanisms in materials will be able to produce < 1 eV energy excitations?
  -- phonons (collective excitations of ions) are effective since deBroglie wavelength of sub-MeV Dark Matter > than interatomic spacing

DM mass	DM energy or momentum	CM scale
50 MeV	$p_\chi \sim 50$ keV	zero-point ion momentum in lattice
20 MeV	$E_\chi \sim 10$ eV	atomic ionization energy
2 MeV	$E_\chi \sim 1$ eV	semiconductor band gap
100 keV	$E_\chi \sim 50$ meV	optical phonon energy

Basic Research Needs for Dark Matter small projects new Initiatives

Trickle, T., Zhang, Z., Zurek, K.M. *et al.* Multi-channel direct detection of light dark matter: theoretical framework. *J. High Energ. Phys.* **2020**, 36 (2020).

Sapphire target
Single phonon sensor

-- Polar crystals -- Sapphire

-- single phonon excitation modes ~ 100 to 10s of meV

-- directional detection of Dark Matter possible due to crystal anisotropy (DM momentum direction makes different angle with the primary crystal axis throughout the day)

-- Radiopure, bulk target necessary, which Sapphire crystal provides

-- TESSARACT experiment conceptually proposed with an external phonon sensor attached to the Sapphire target.

-- TES based phonon sensor demonstrated to have sensitivity of ~ 45 meV or so but its unclear what its sensitivity is going to be when coupled to a Sapphire target

-- CRESST experiment explored higher mass DM using Sapphire

-- No actual running experiment that explores low mass DM search using Sapphire

-- **Explore DM scattering off of optical phonon modes (oscillating electric dipole) through dark photon exchange**.

-- **Explore dark photon DM absorption by the optical phonon modes.**

Sapphire Phonon modes

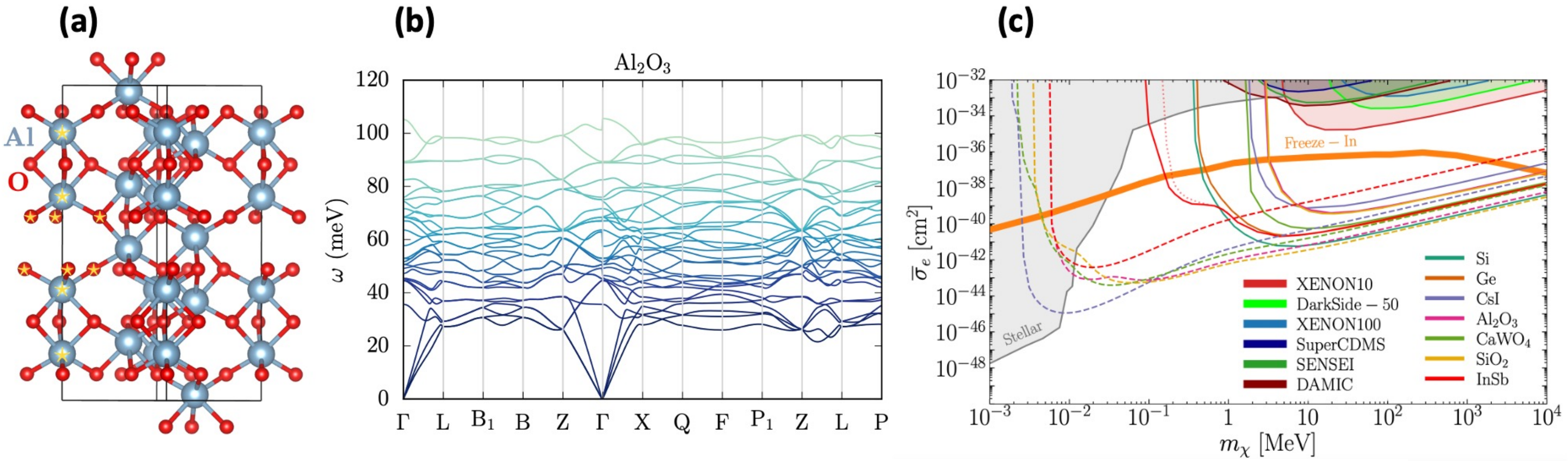


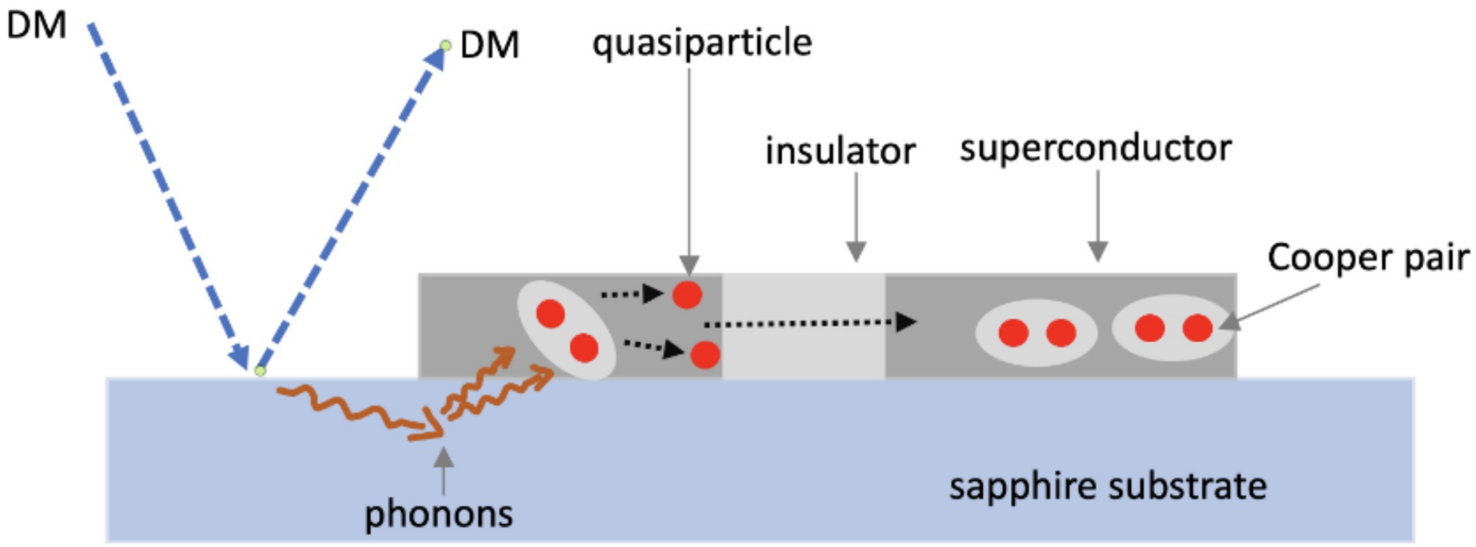
Figure 2: (a) Sapphire (Al_2O_3) unit cell representation. The primitive atom belonging to the single primitive cell are denoted by *. The in plane axes are different than the out of plane vertical axes causing the anisotropy in the crystal. (b) Optical and acoustic phonon bands of sapphire along withe their energies and different Brillouin zones with Γ corresponding to q = (0, 0, 0) [47] (c) A comparison of the **projected** reach of various target materials to DM scattering mediated by a dark photon, assuming either single-phonon excitations (dashed) or electron transitions (solid) [48]. For the phonon calculations, a 1 meV detector threshold is used. For electron excitations, all energy depositions greater than the band gap energies are used. Direct detection projections with electron transitions for current prominent experiments are also indicated.

Sinead Griffin, Simon Knapen, Tongyan Lin, and Kathryn M. Zurek, Phys. Rev. D **98**, 115034 – Published 27 December 2018

Sapphire substrate qubits-based detector?

- Qubits: great potential for low energy radiation/excitation detection
- Sapphire substrate qubits, common technology: easy to fab. gm scale Sapphire
- Can produce broken Cooper pairs of electrons in Al when $E > 2\ \Delta_{Al} \sim 0.6$ meV
- Demonstrated sensitivity to a few Δ_{Al} energies already (voltage pulse injection)

- Map out: Energy deposited -> phonon excitations and down-conversion -> quasiparticles produced in Al -> qubit readout 'signal' ?



Potential qubit based Dark Matter detector

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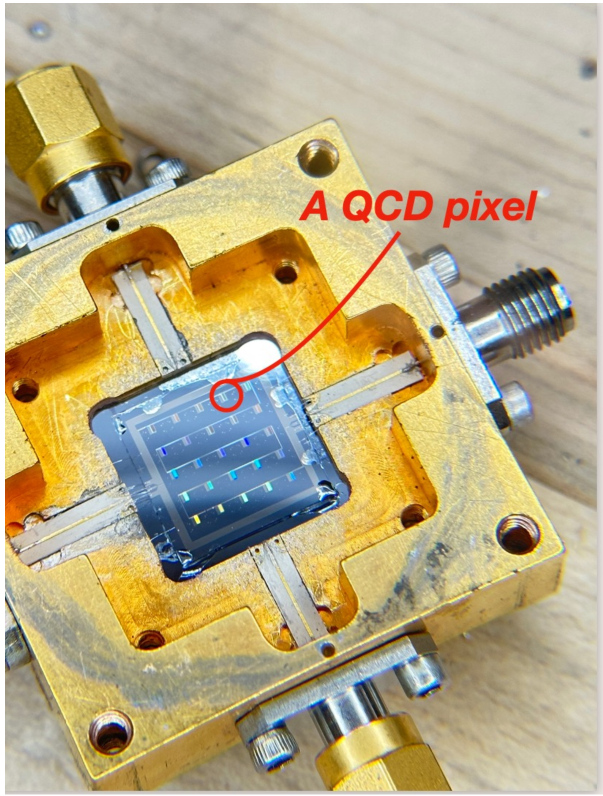
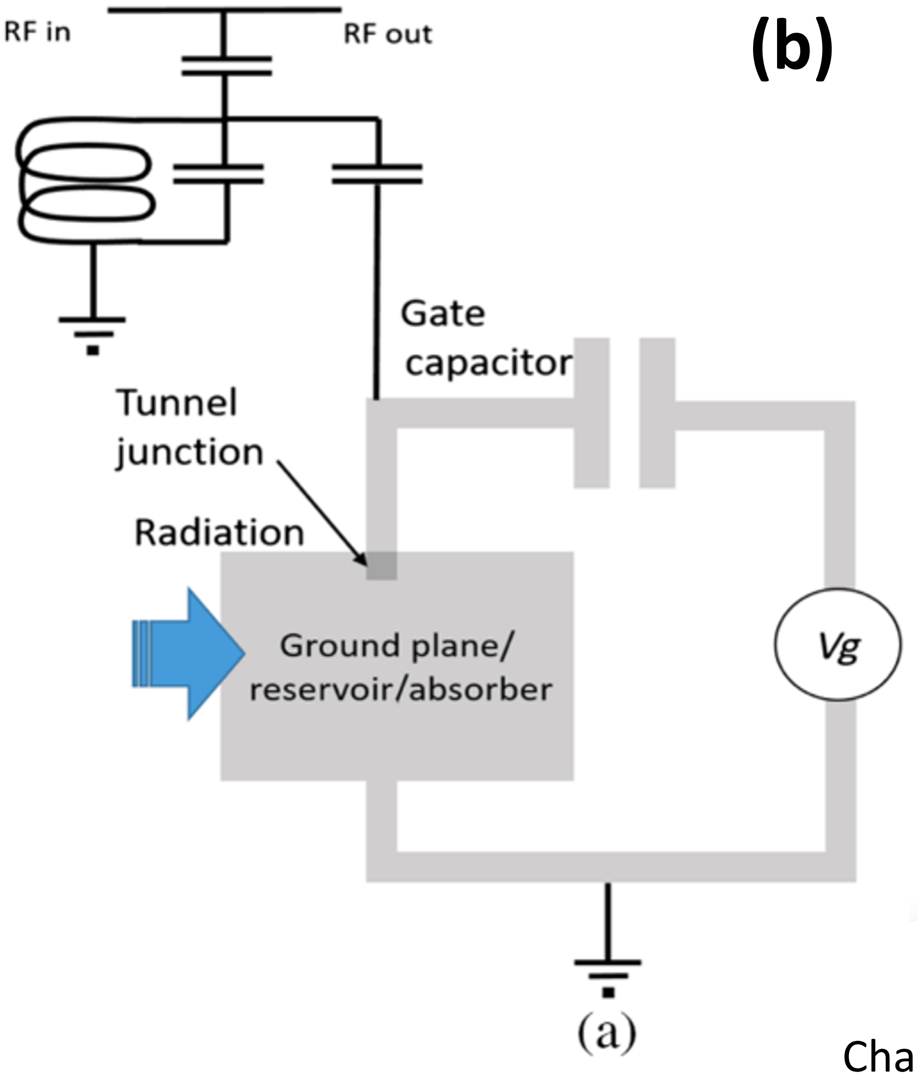
Single photon sensors using qubits

Quantum Capacitance Detectors (QCD)

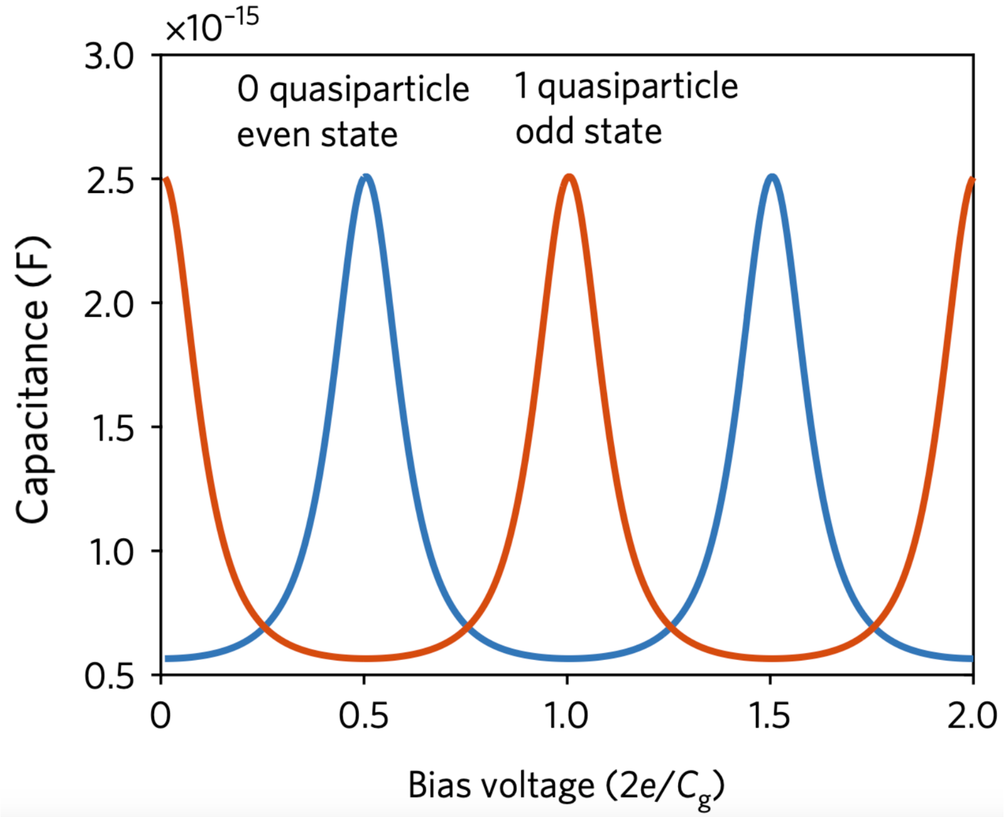
(a)



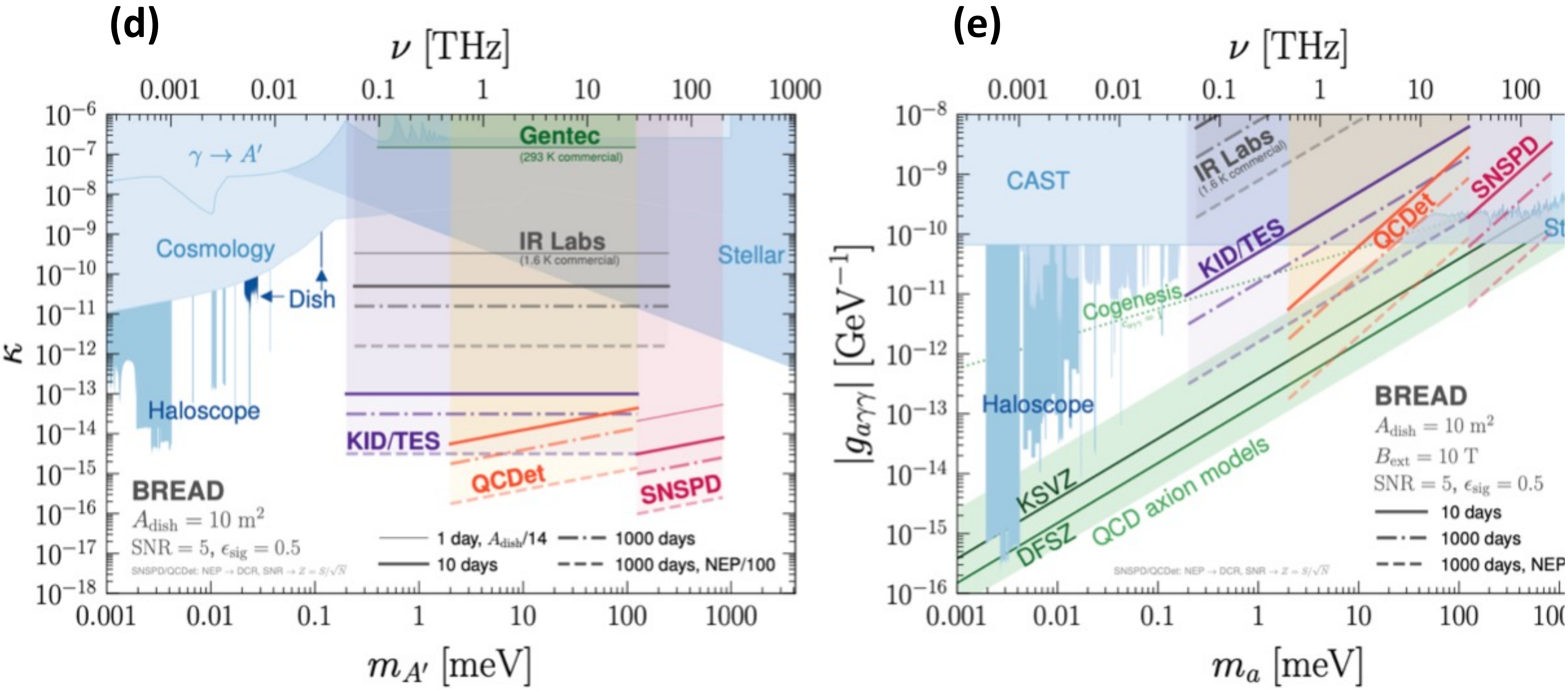
(b)



(c)



Charge parity readout



Projected BREAD sensitivity by sensor technology in the dark photon A'(left) and axion a (right) coupling vs. mass plane