From Electrons to Phonons: Experimental Frontiers of Low-mass Dark Matter Searches

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Light Dark Matter, What and Why?

Conventional WIMP is motivated to be ***10 GeV ~ 10 TeV mass***, which naturally accounts for today's DM relic density.

Large LXe TPCs are already touching the ***neutrino fog***.

The community has been revisiting the theories and identified several scenarios in which ***sub-GeV dark matter arises naturally/are allowed***

- light dark matter or low-mass dark matter

How is Light Dark Matter Different?

lighter individual mass => less total kinetic energy available for (nuclear) recoil

- say DM moves with v ~ 10^{-3}, $E_r \sim 10^{-6} E_k$, ***GeV dark matter has O(keV) energy for recoil***

kinematic mismatch makes it even ***worse for nuclear recoil (but not for electron recoil)***

Fixed total density, lower individual mass gives ***larger flux***.

For DM mass around ~MeV, the de Broglie wavelength becomes comparable to the ***size of atoms***

For DM mass around ~keV, the de Broglie wavelength becomes comparable to ***interatomic spacing***

Technologies of Light DM Detection

Technology

Interaction	Ionization/Scintillation	Calorimetry
Nuclear	*light-element-based detector* *doping with light element* *Migdal effect*	cryogenic bolometer superfluid helium
Electronic	DM-electron scattering single photon excitation	mKIDs SNSPD TES graphene FETs etc.

DarkSide-50

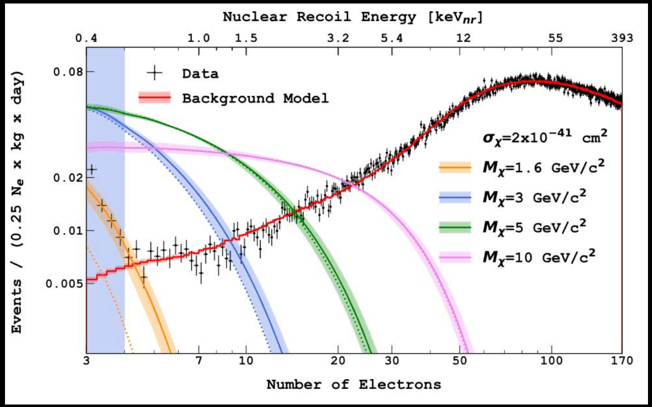
Argon produces ***more energetic recoils*** compared to Xe.

- lowest threshold achieved at ***S2-only*** (no PSD)

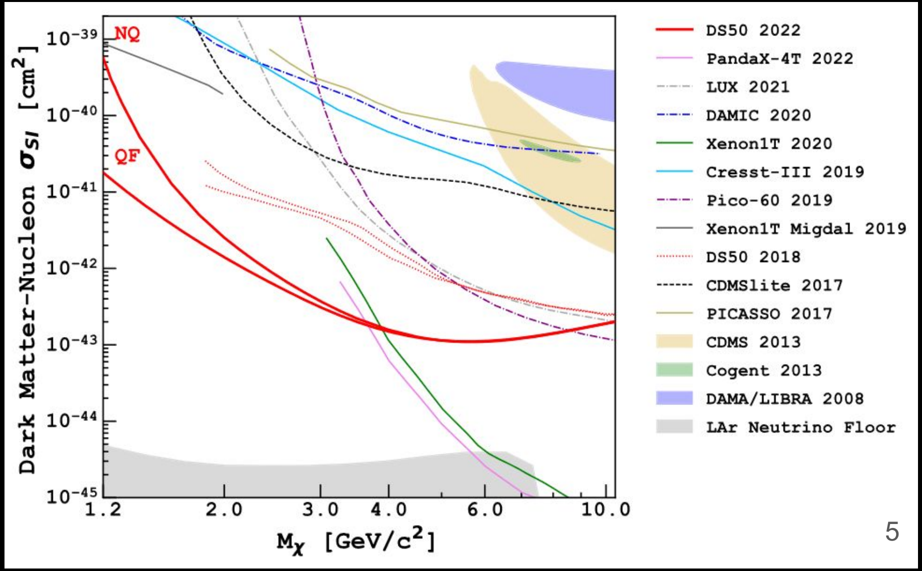
DarkSide-50: dual-phase LAr TPC with 46-kg active mass operated at LNGS, Italy

- 3” low-bg PMT readout
- ***0.06 keVer, down to 1.2 GeV***

DS-20k expected to reach sub-GeV sensitivity + dedicated low mass experiment



PRD 107, 063001 (2023)



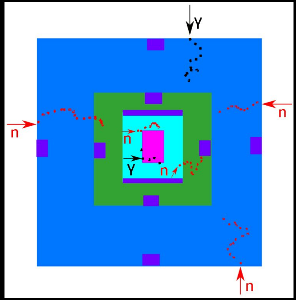
ALETHEIA - Liquid He TPC

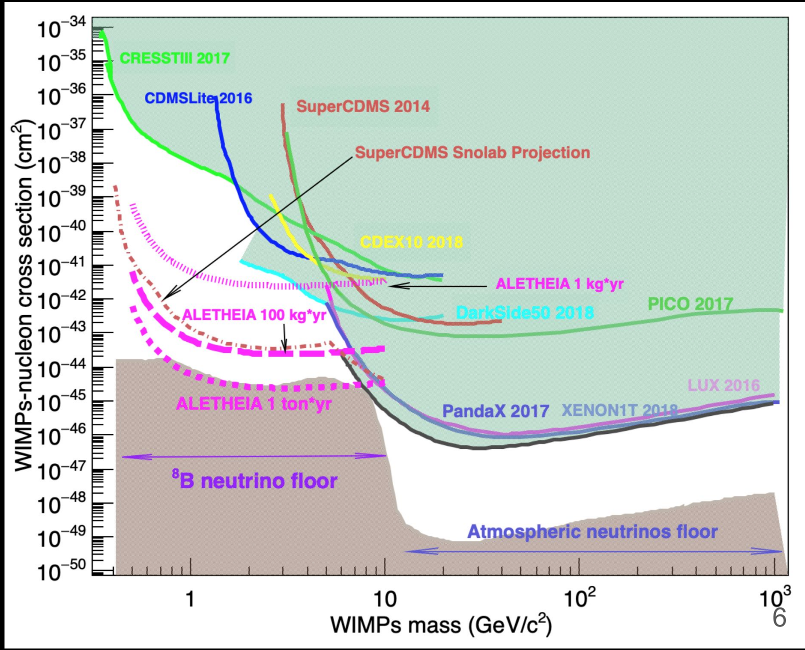
TPC has been shown to be very powerful in the search of WIMP

In extending the reach to lower mass, the most straightforward approach is to ***construct a TPC out of a light element - He***.

The ALETHEIA experiment:

- liquid helium TPC @ 4K
- aiming for 100 MeV ~ 10 GeV
- lower bkg, discrimination TPB + SiPM readout
- S1/S2 v.s. PSD
- large HV required



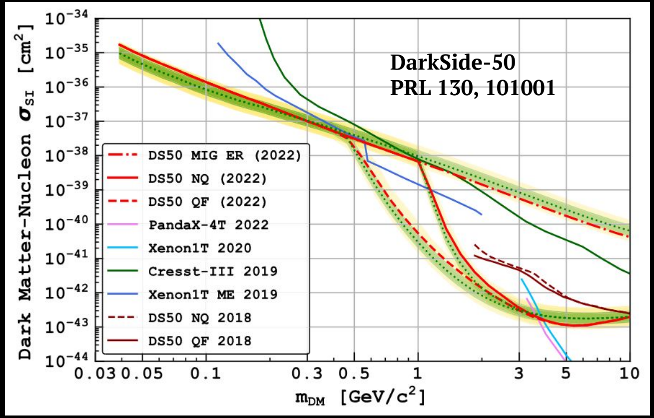


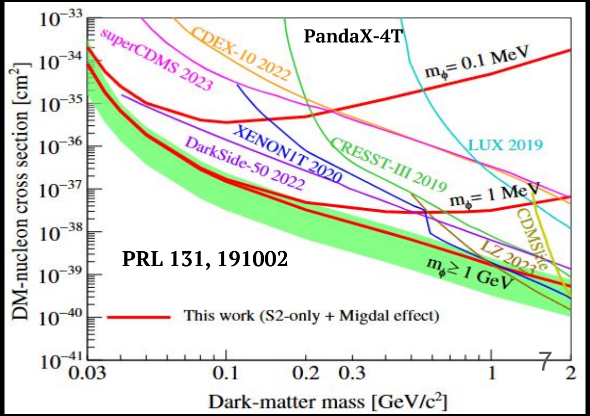
arXiv:2103.02161

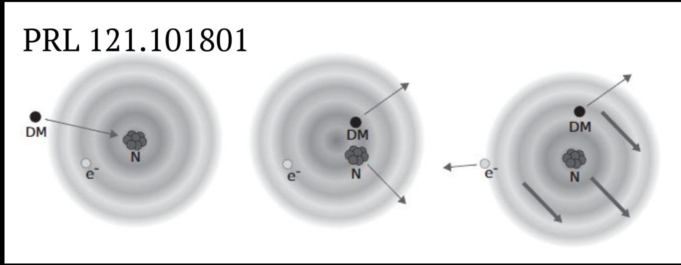
Migdal-Based S2-Only Analysis

Sudden acceleration of nucleus can “leave an electron behind” with **a small but non-zero and calculable probability**.

- First formulated by A. Migdal in 1940s
- “direct ionization” occurs when nuclear acceleration is fast compared to atomic orbital velocity
- Allows to create an **ionization signal with recoil energy much below threshold**
- Observed in nuclear decay process, currently searching in nuclear scattering experiments





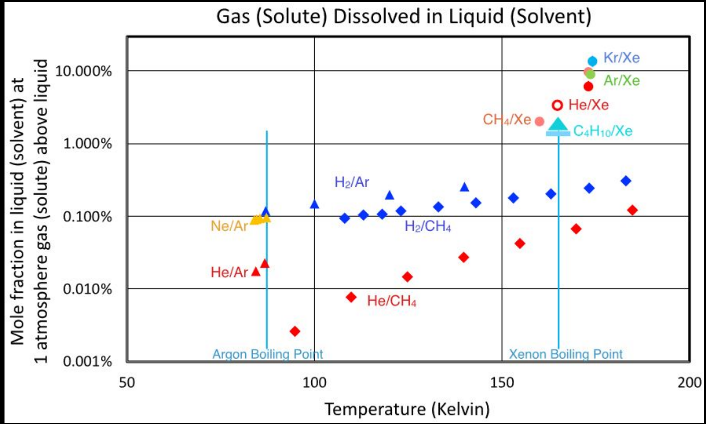


HydroX - Hydrogen-doped LXe TPC

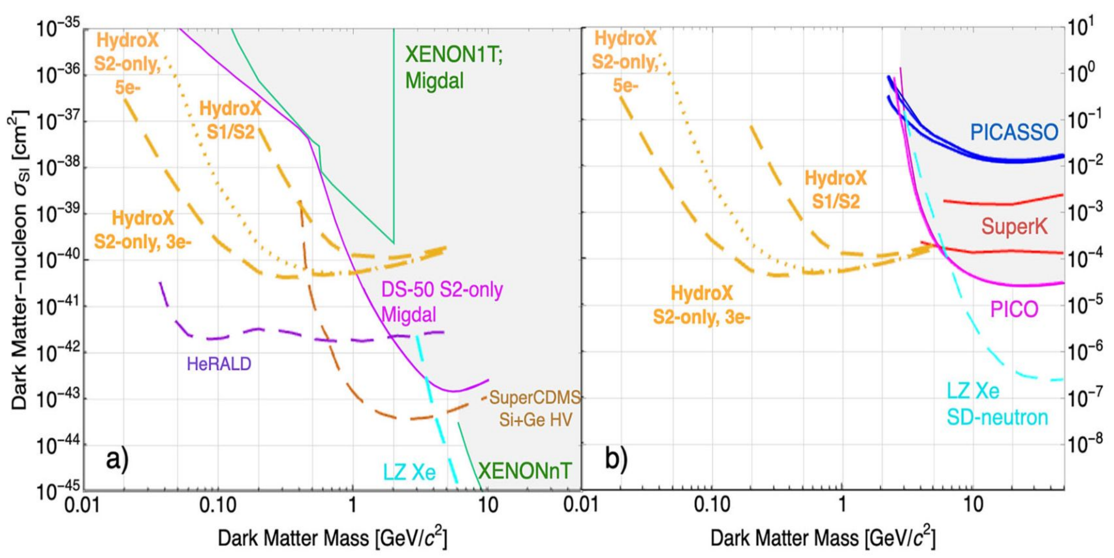
Due to the kinematic mismatch, Xe is not ideal for low-mass DM detection.

HydroX proposes to dope light element to LXe:

- no measurement of H2 in Xe but the solubility is likely high
- even with 1% loading,



Nature Communications Physics (2025)8:244

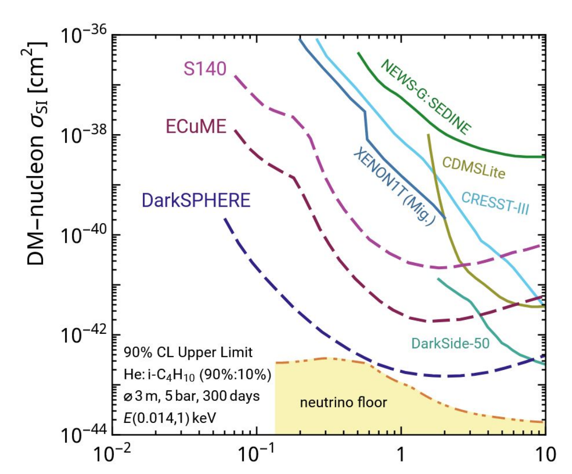


NEWS-G: a “hydrogen” proportional counter

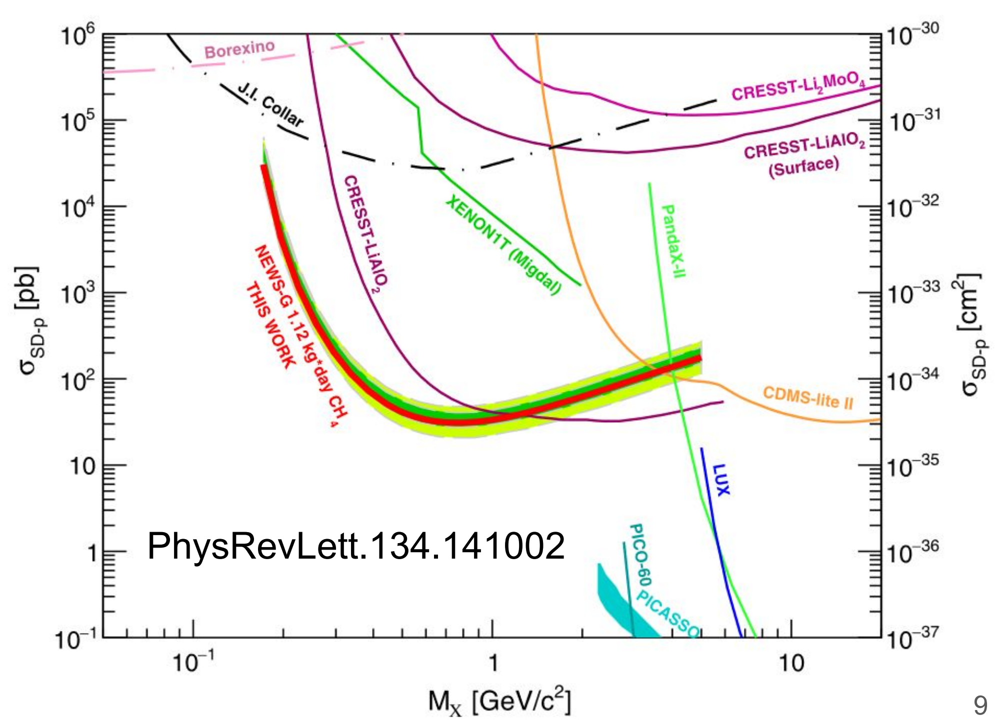
1.3m diameter sphere made of high-purity OFHC + inner e-formed surface; ~100 g methane

Multianode sensor “ACHINOS”

Leading SD result from 200 MeV to 1 GeV



arXiv:2301.05183



PhysRevLett.134.141002

Technologies of Light DM Detection

Interaction	Technology: Ionization/Scintillation	Technology: Calorimetry
Nuclear	light-element-based detector doping with light element Migdal effect	cryogenic bolometer superfluid helium
Electronic	***DM-electron scattering*** ***single photon excitation***	mKIDs SNSPD TES graphene FETs etc.

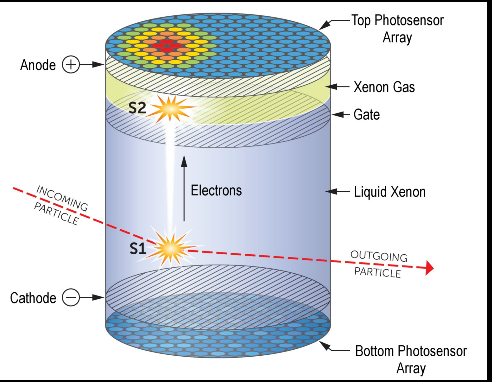
Dark Matter Search with Single Ionization/Excitation

For even lower mass below 1 MeV, ***ER is more effective in creating single ionization events***.

Large noble liquid TPC has a rather low efficiency/high background for measuring single photon, but due to electroluminescence ***it is very effective in detecting single ionization***.

- competitive results from XENONnT, PandaX, LZ, DarkSide

Another competitive technique is the ***Skipper CCD*** (DAMIC, SENSEI) - ***intrinsically e- counting device***



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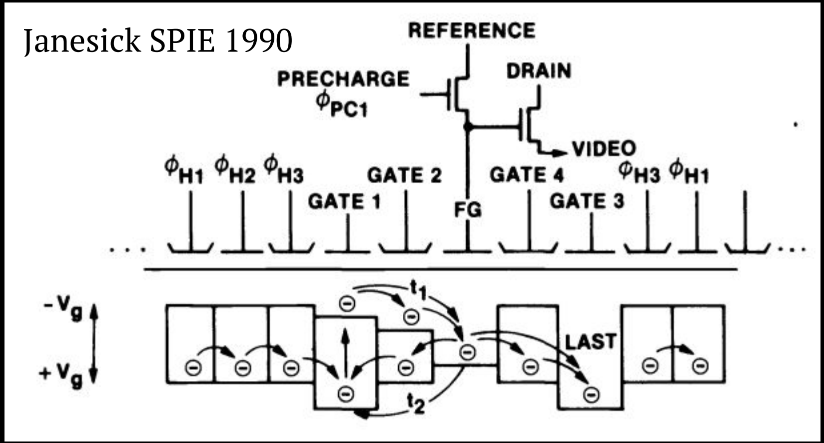
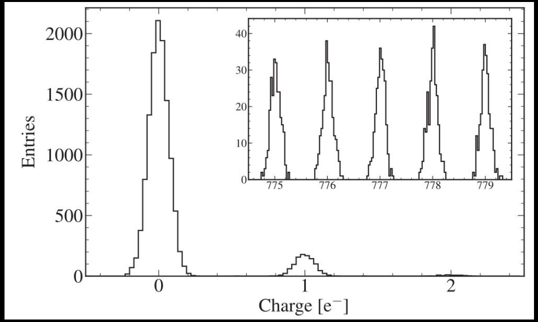




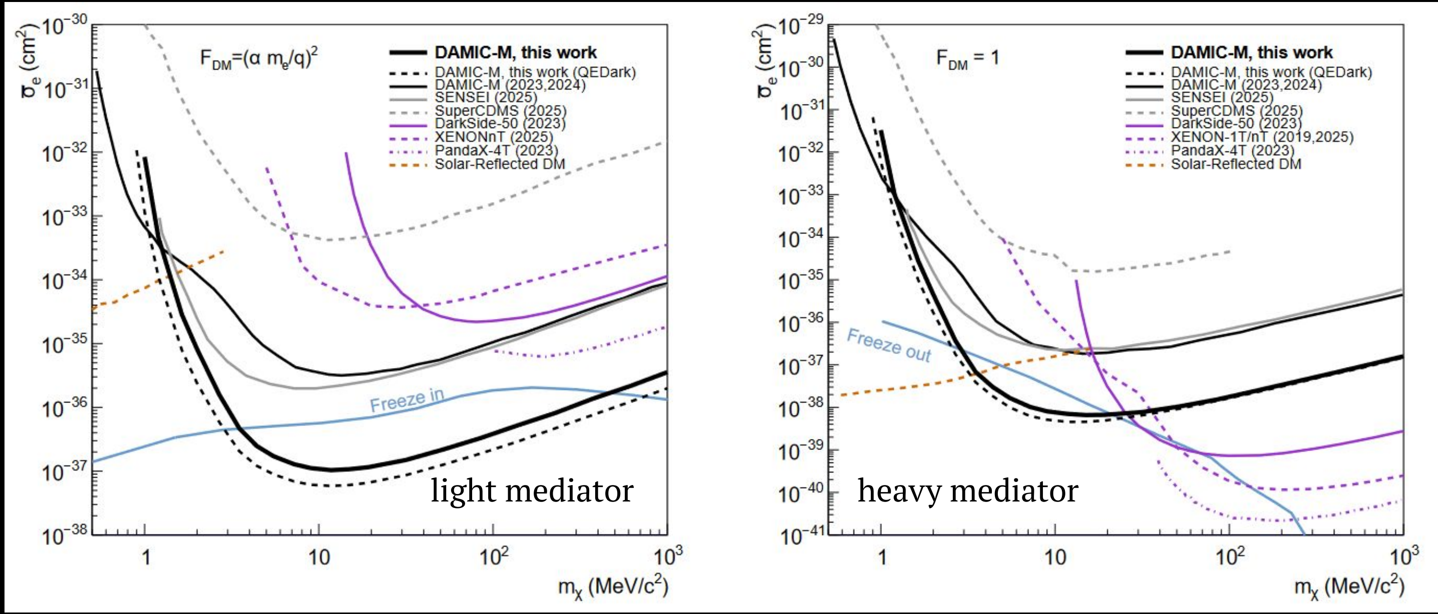
PRL 119, 131802

Dark Matter Search with Single Ionization/Excitation

Another competitive technique is the Skipper CCD (DAMIC, SENSEI)

- Sub-electron noise achieved by repetitive readout
- Already sensitive to some light dark matter models!

arXiv:2503.14617v1



Dark Matter Search with Single Ionization/Excitation

How about single photons?

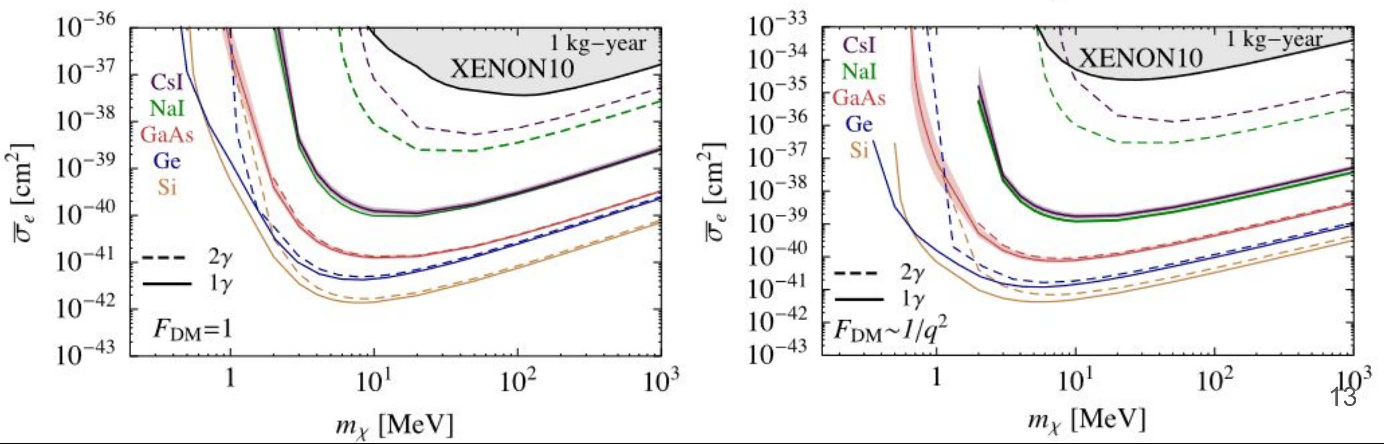
Single excitation by DM-electron scattering is plausible (PRD 85, 076007) but ***technically very challenging***

- conventional single photon detectors have ***too much single photon noise***
- novel cryogenic sensors are not available with large active areas
- afterglow not very understood at cryogenic temperatures

PRD 96, 016026

On the other hand:

- high-purity
- large exposure



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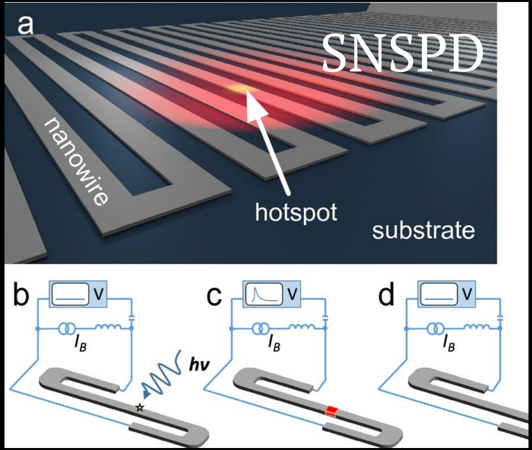
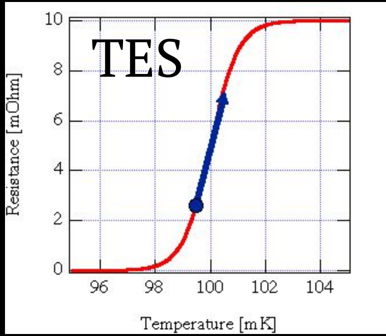
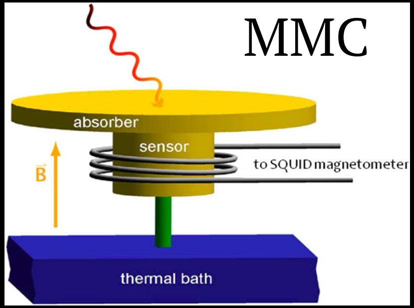
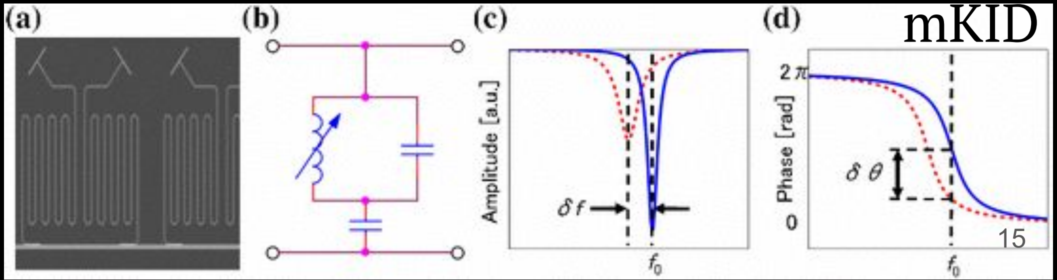
Cryogenic Calorimeter

- often requires ***Kelvin to sub Kelvin temperature*** to work
- often ***very small*** for improved sensitivity (O(1mm))
- ***sensitive to heat*** in one way or another
    - opens a new window in detector physics
- thermal/equilibrium or athermal/nonequilibrium
    - thermal detector: measures temperature-dependent properties
      higher resolution, no fano fluctuation
    - athermal detector: not (directly) dependent on temperature



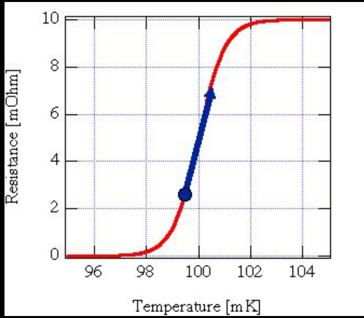


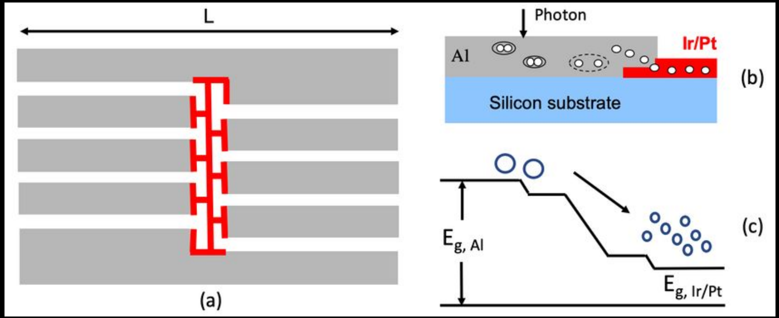


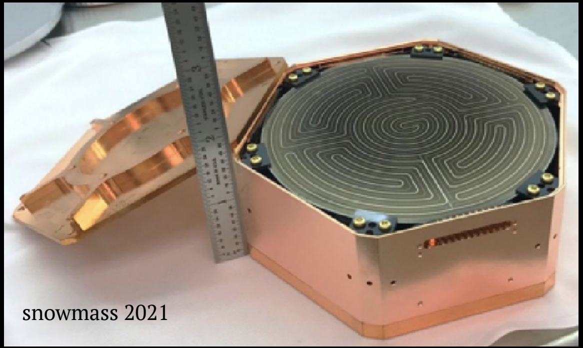


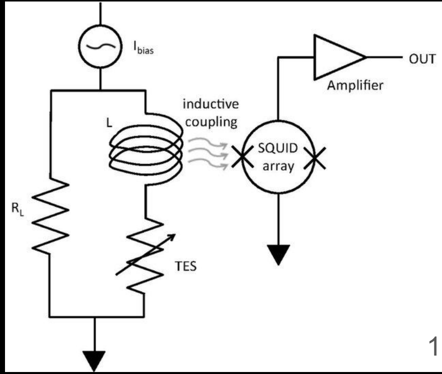
(Superconducting) Transition-Edge Sensors

- TES is one of the oldest cryogenic bolometric technology, made popularised by
    - SQUID (for low-impedance current measurement)
    - voltage-bias (current bias - thermal runaway)
- TES measures ***T-dependent resistivity*** during superconducting transition
- Conventional TES has a very small active mass - dark matter experiments need to increase the active mass
- SuperCDMS: ***quari-particle trap assisted transition edge sensor***
    - naturally sensitive to sub-GeV DM via NR
    - capable of single e- measurement with HV device





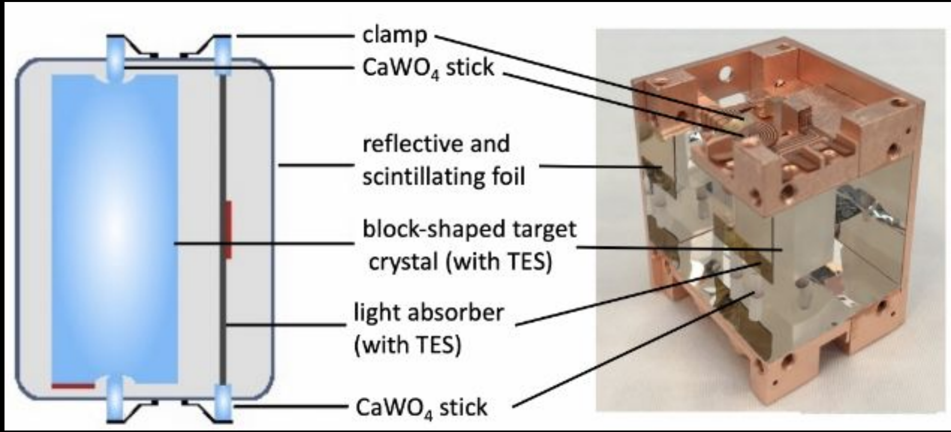


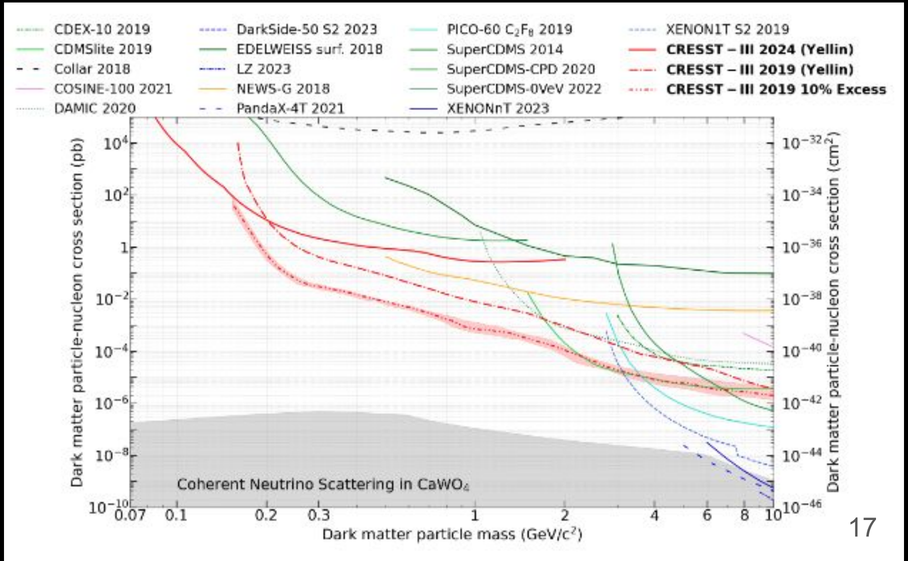


CRESST

- CRESST experiment uses TES on Si directly on crystal for measuring phonons
- Light-heat dual readout for background rejection.
- ***Sub-GeV sensitivity demonstrated; after upgrade - 50 MeV DM via NR***
- No DM-electron scattering (at the moment)
- Flexibility in target selection (Al_2O_3, $CaWO_4$, $LiAlO_2$)
- Easy to scale up

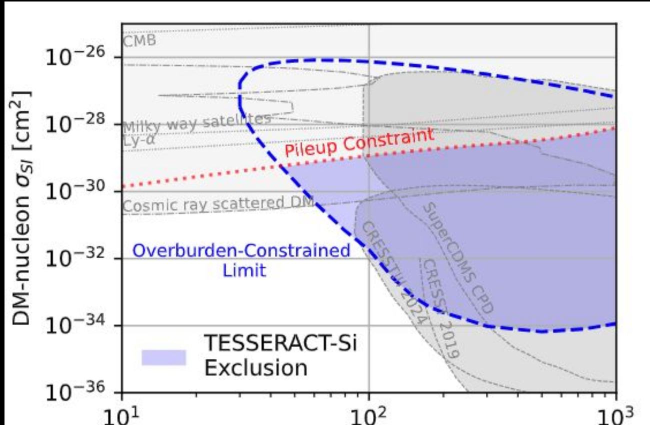
arXiv:2505.01183v1



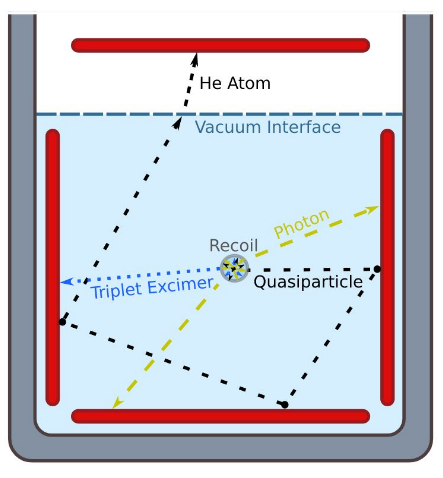


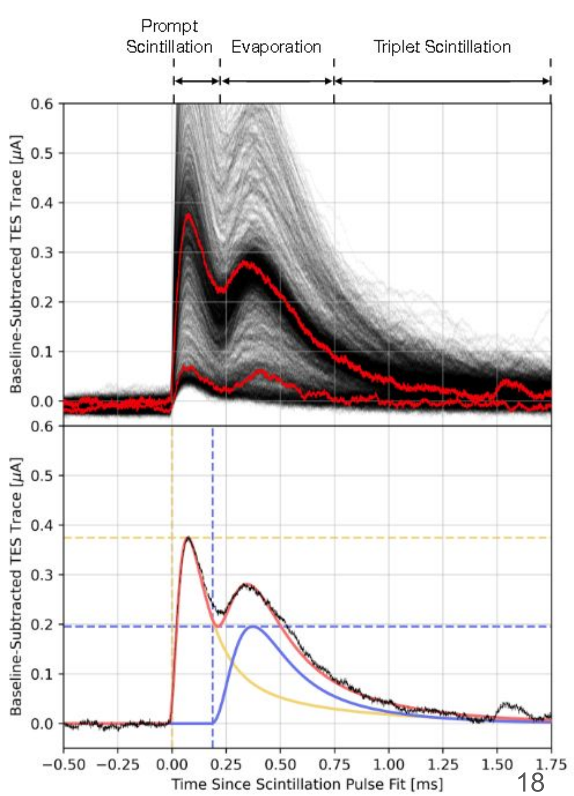
Liquid Helium with Calorimetric Readout

- TESSERACT project is a collection of experiments based on various targets and TES readout technology
- Recently TESSERACT demonstrated DM sensitivity on surface with gram-scale 1 cm2 detector
- HeRALD uses superfluid He as target and QET as readout
  - scintillation + quantum evaporation, discrimination/PSD
  - eventual goal to ~MeV DM near v floor



arXiv:2503.03683v2





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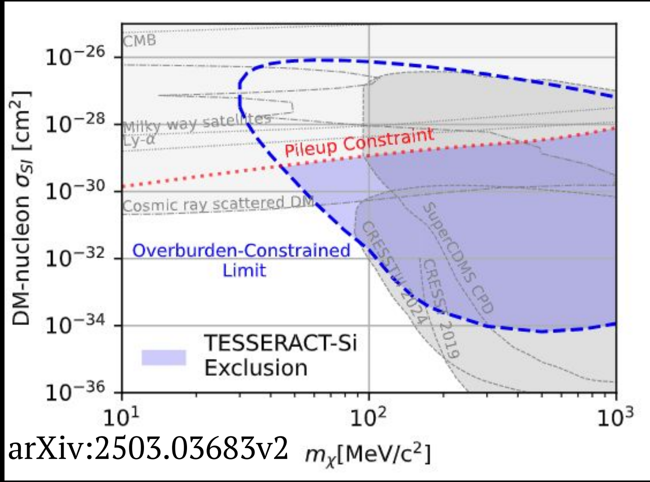

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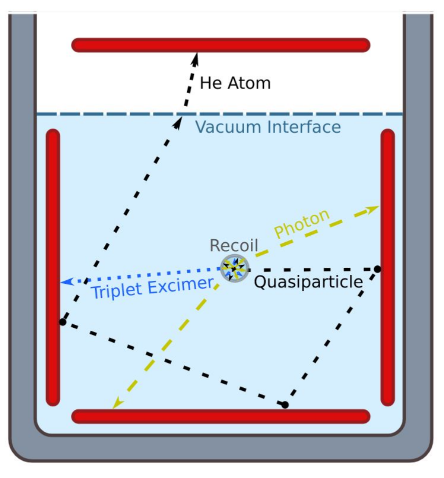
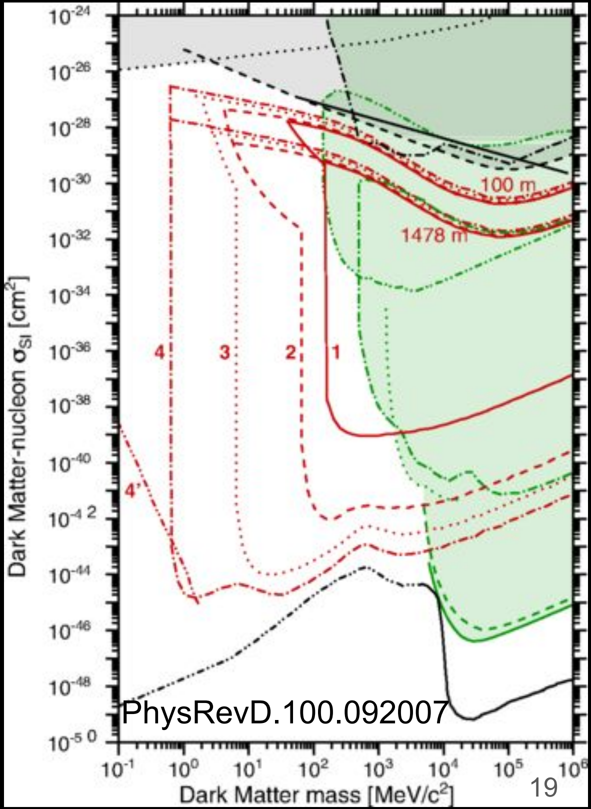
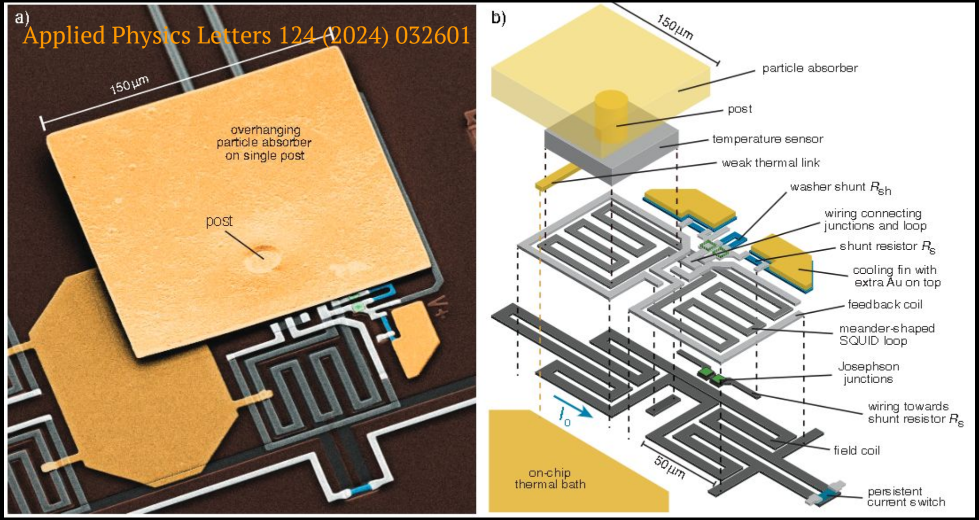




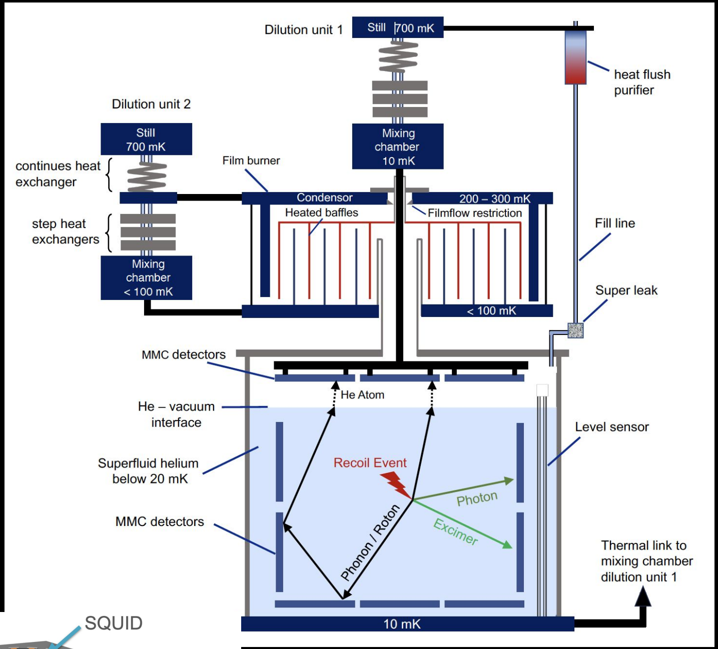
PhysRevD.100.092007

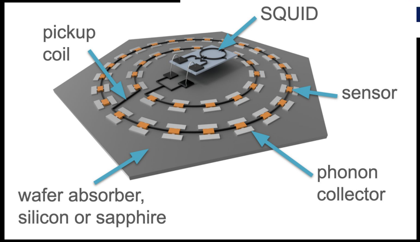
Liquid Helium with Calorimetric Readout

- DELight experiment:
  - uses MMC instead of athermal TES
  - T-dependent magnetization + SQUID readout
  - sensor itself: ***~1 eV resolution for 6-keV X-ray***
  - detector expects ***10~20 eV threshold*** w/ absorber



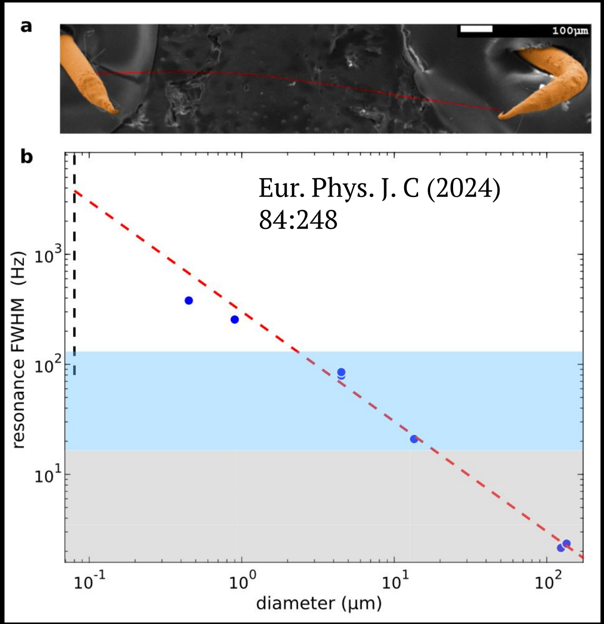
Applied Physics Letters 124 (2024) 032601

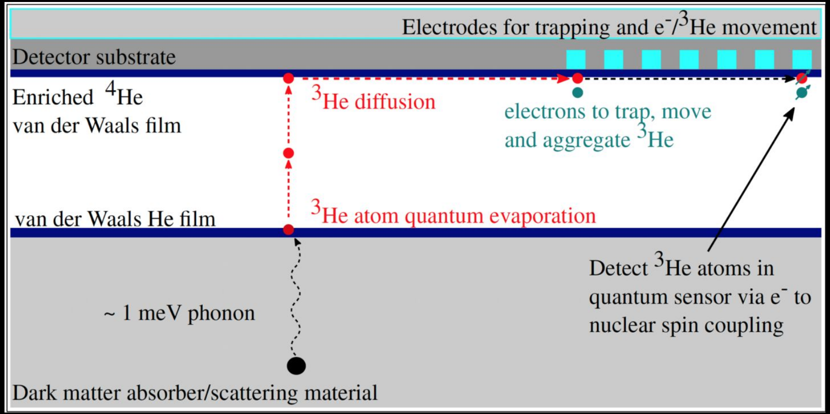




Liquid Helium with Calorimetric Readout

- QUEST-DMC
  - *superfluid He-3 for spin-dependent interaction*
  - 100 uK operating temperature (DR + demagnetization)
  - nanomechanical measurement of quasiparticle
    - heat => quasiparticle => drag to a nanowire => change in resonance frequency





PHYSICAL REVIEW D 109, 023010

Another group of scientists suggests using electron-nuclear spin coupling to detect single He3 atoms on a CCD-like quantum sensor

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Electronic	DM-electron scattering single photon excitation	***mKIDs*** ***SNSPD*** ***TES*** ***graphene FETs*** ***etc.***

Detecting e^- Scattering with Cryogenic Sensors

Cryogenic detectors have a unique strength of being able to detect very small amounts of energy deposits as quasiparticles (meV gap energy).

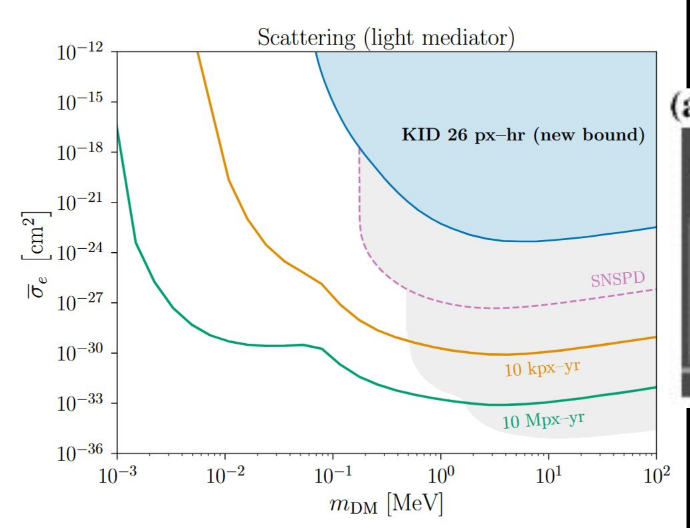
This renders a few detector techniques to put world-leading limits on DM-e interaction in the lowest mass range

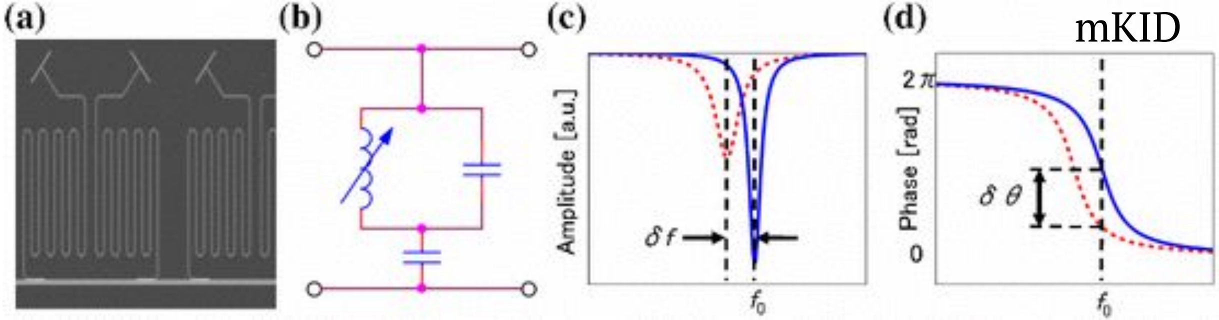
- with ***prototype devices and on the surface***
- ***mKIDs and SNSPDs*** are the strong players in this game
- QET-based TES proposed
- more efforts going into making more sensitive detectors & multiplexing rather than lower bkg

Detecting e$^-$ Scattering with Cryogenic Sensors

mKIDs work in frequency domain by nature - very easy to multiplex (O(1000) readily achievable)

- *IR sensitivity* demonstrated (0.2-eV threshold) (arXiv:2403.19739)
- relatively easy to fabricate, but complex signal processing
- also being used to search for DM-nuclear scattering and CEvNS (BULLKID)





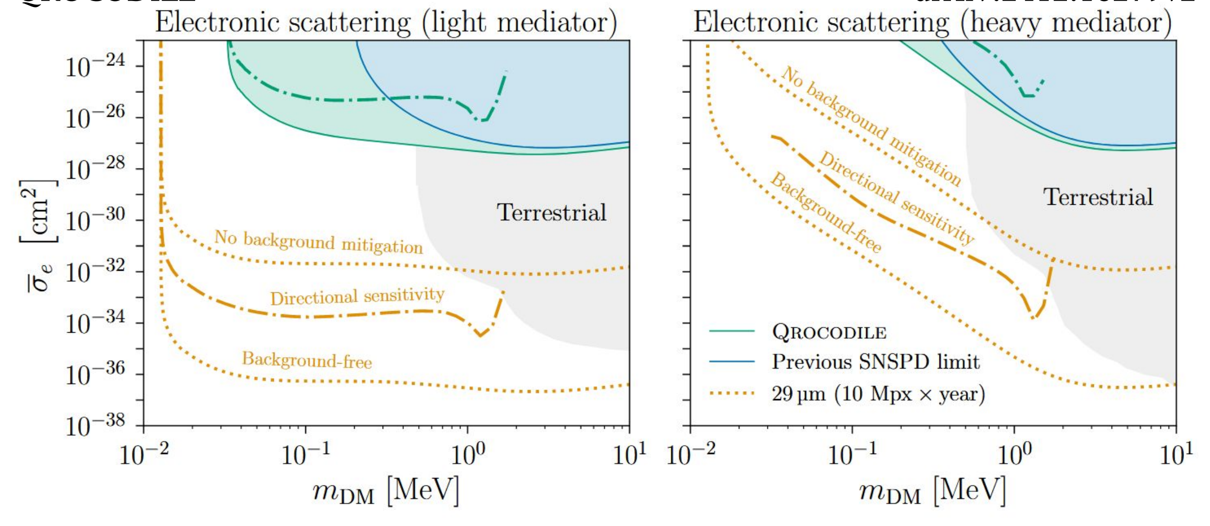
Detecting e^- Scattering with Cryogenic Sensors

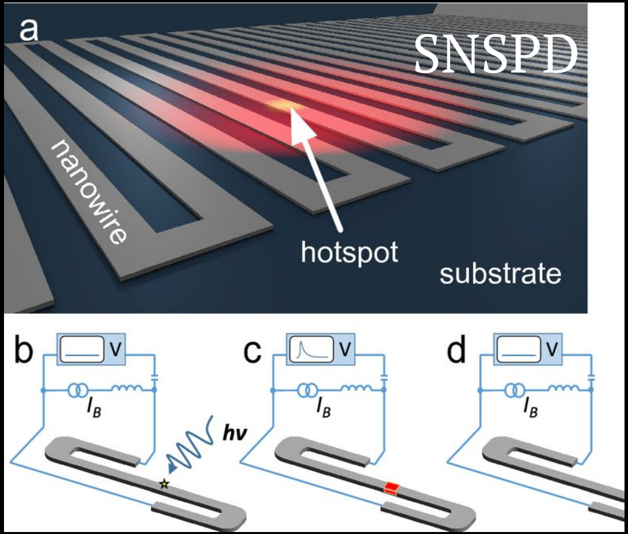
SNSPDs are ***photon counting devices*** working in “avalanche-mode”

- low-threshold of O(0.1 eV), high detection efficiency
- clean digital signal - no spectroscopy
- simple operation & readout

QROCODILE

arXiv:2412.16279v2





Summary

Given the null results after decades of efforts, starting to focus on light dark matter.

New technical challenges due to lower interaction energies.

- for NR, conventional detector ~ O(100 MeV) , then microcalorimeter seems to be the most popular choice.
- for ER, TPC (10MeV), CCD/semiconductor (1MeV), superconductor (sub-MeV)

New cryogenic detector evolving fast: in the next few years, they will be scaled up and moving underground for ***real science runs***.

Challenge on the theory side: is there a consensus about “best material model”?

Relevant Talks

Search for Light Dark Matter with ***XENONnT***

Sub-keV dark photon search with S2-only data in ***PandaX4T***

Search for new physics in low energy electron recoil signals in ***LZ*** WS2022+2024 combined dataset

Towards the deployment of ***DAMIC-M***: status and latest results

Searches for Light Dark Matter with DarkSide-20k and ***DarkSide-LowMass***

ALETHEIA: Hunting for low-mass dark matter with liquid helium-filled TPCs

The ***SuperCDMS*** SNOLAB experiment

Search for light dark matter with ***CRESST-III***

The Direct Search Experiment for Light Dark Matter (***DELight***): Overview and Perspectives

Search of light Dark Matter with ***TESSERACT*** experiment at LSM

The ***PICO-40L*** Dark Matter Search

BULLKID-DM: searching for light WIMP with monolithic arrays of detectors

Status of the ***Ptolemy*** project