Experimental efforts on direct detection of cosmic dark matter

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Dark matter: the known and unknown

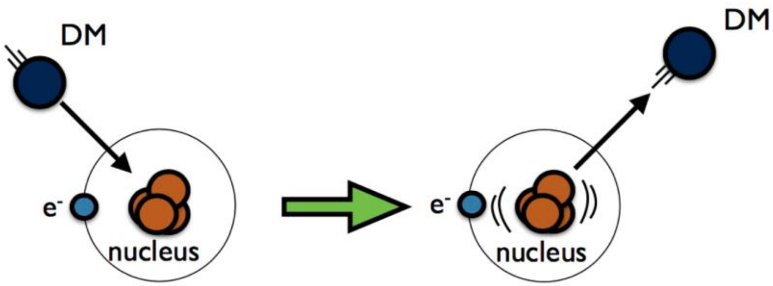
What we know:

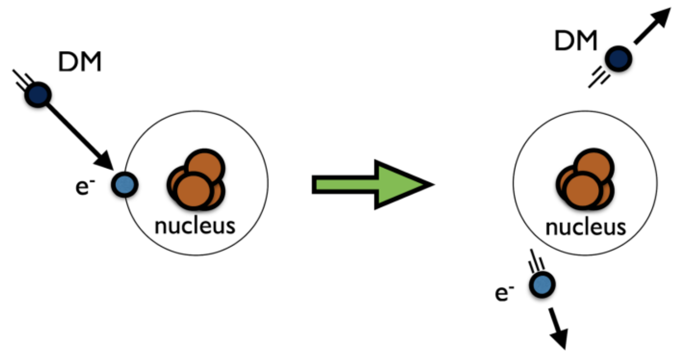
- It should exist
- ~5x more abundant than matter
- Likely no E&M interactions

What we don't know:

- What it is made of
- Its distribution at small scales
- How many species there are
- How it may self-interact or interact with other dark matter species
- How it may interact with matter
- …

(Possible) Dark matter interactions with atoms





Dark matter scatters with a nucleus

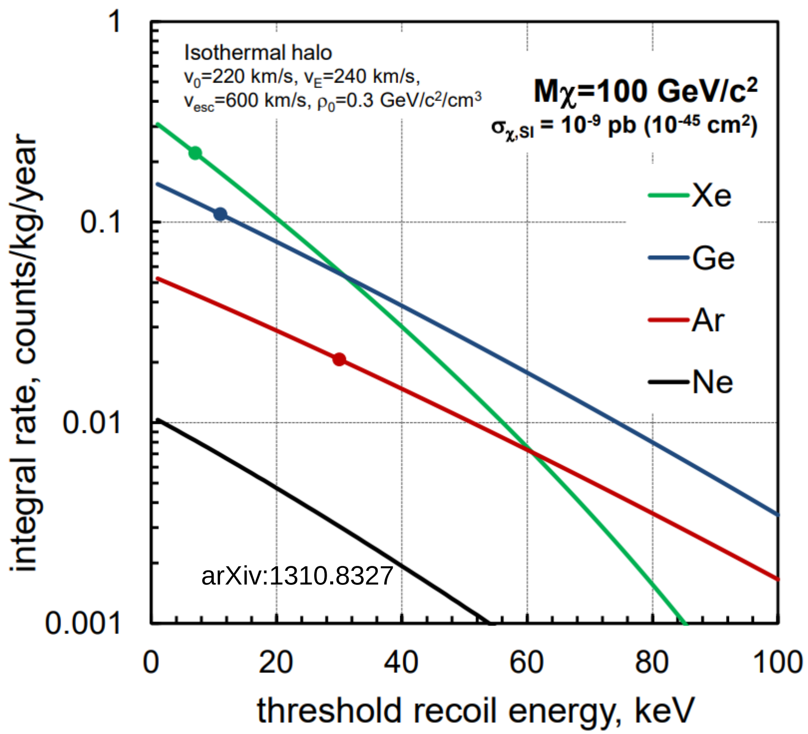
- Elastic process (mostly)
- Momentum transfer $k \sim M_T M_x v/(M_{T+} M_x)$
- Energy transfer $E \sim k^2/2M_T$
- Most relevant for $M_x \sim > M_T$
- Interaction could be enhanced by $\sim A^2$

Dark matter scatters with an electron

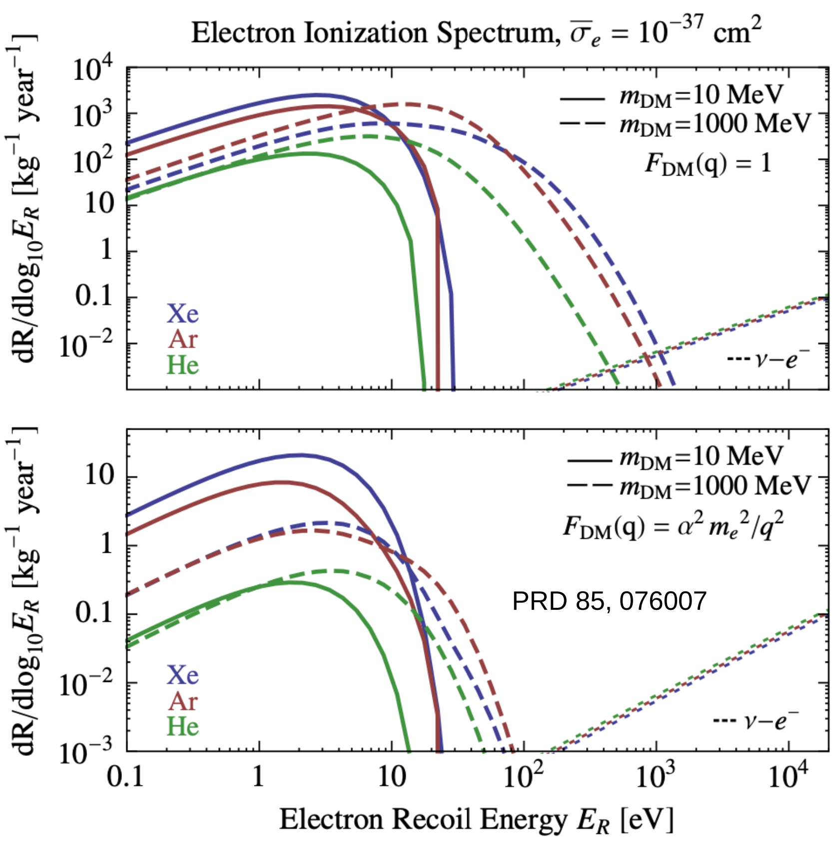
- Inelastic process
- Momentum transfer $k \sim \alpha m_e$
- Energy transfer $E \sim k \bullet v$
- Most relevant for $M_x << M_T$
- Interaction cross section suppressed

Expected direct detection signals

- Heavy dark matter scatters with nuclei
- E~1—100 keV

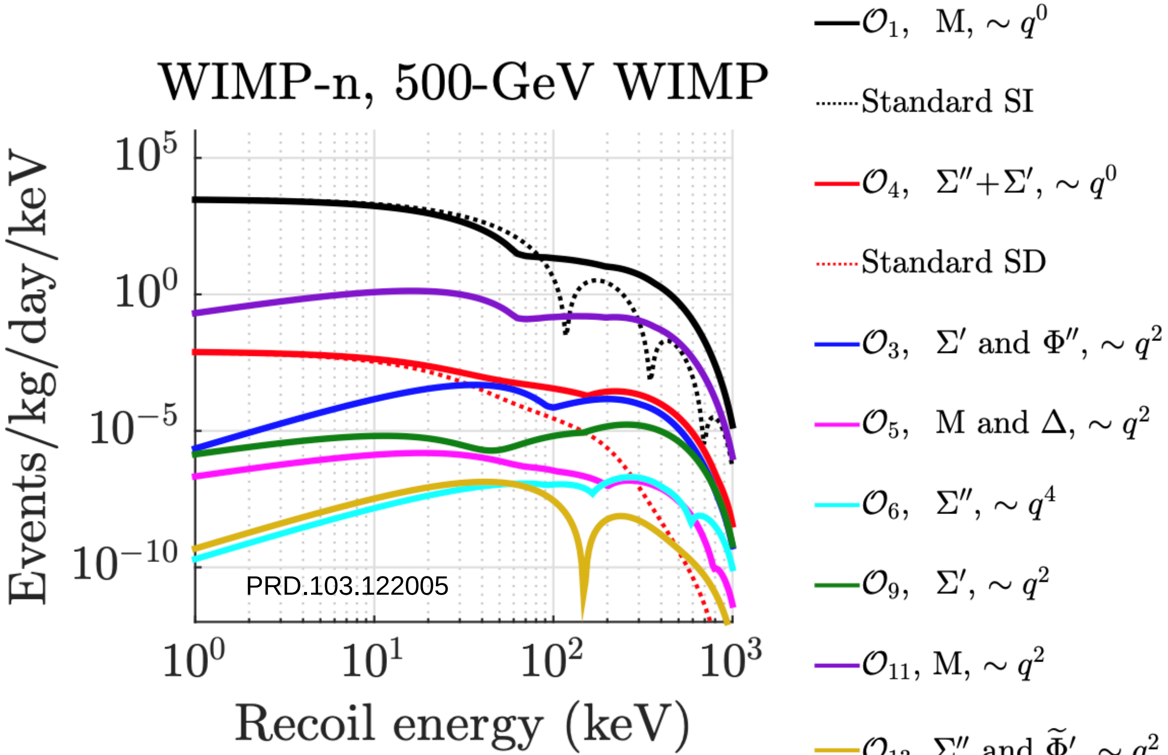


- Light dark matter scatters with electrons
- E~1—100 eV



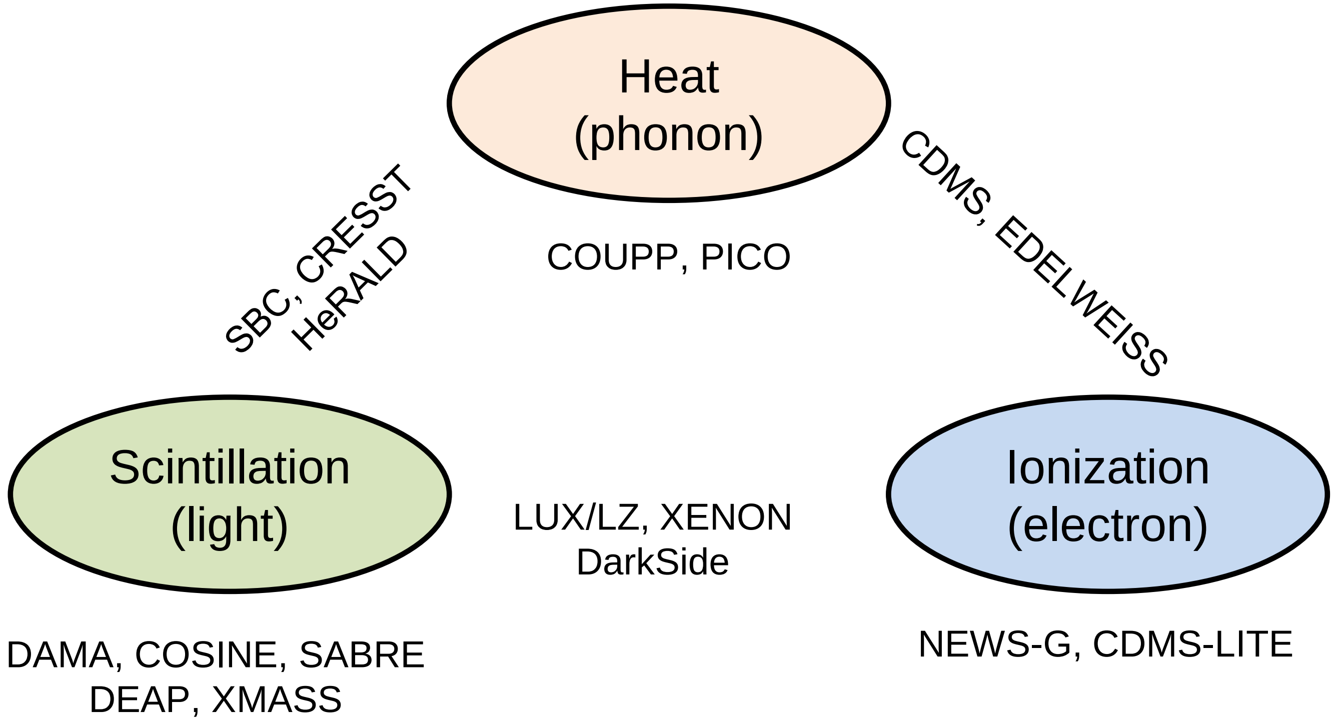
Expected direct detection signals

- Direct detection signal spectrum is model dependent
- Effective Field Theory WIMP interactions can lead to spectra suppressed at low energies
- Strong need to “Delve Deep and Search Wide”



Particle detection technologies

- Energy depositions in a detector medium can produce excitation, ionization and heat
- A rich class of detectors are exploiting one or more signal channels

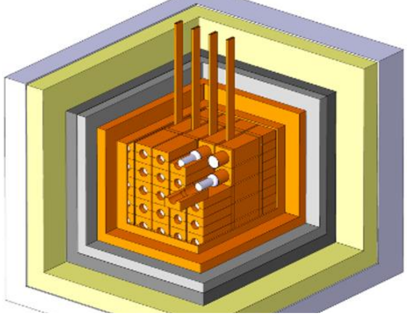


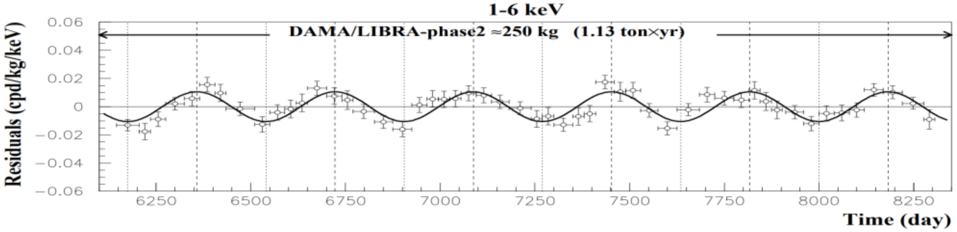
Scintillation-based experiments

Scintillation experiments use light as a measurement of energy

- Common scintillation materials: NaI(Tl), LAr/LXe
- Quanta energy: O(10)eV/photon
- Collection efficiency: ~10%
- Energy threshold ~1keV
- Size: ~10kg (crystals) – tons (LAr/LXe)
- DAMA/LIBRA observes a rate modulation, consistent with WIMP interactions and disputed by other experiments

DAMA/LIBRA

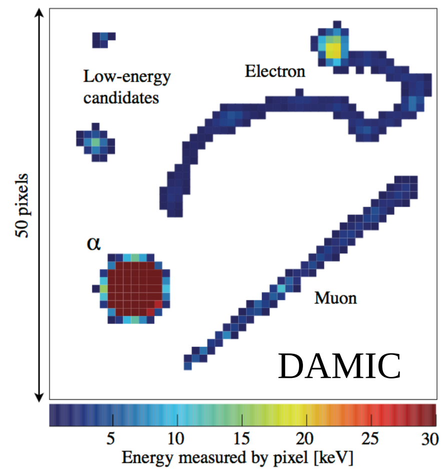




Ionization-based experiments

Semiconductor and noble element detectors can collect electrons

- Use internal or external amplification
- Quanta energy: O(1)eV/e-
- Collection efficiency: ~100%
- Energy threshold: keV or lower
  - ~1keV using external amplification
  - ~10-100 eV using internal amplification
- Size: O(1)g for CCDs, O(1)kg for crystal/gas detectors and up to ton scale for liquid nobles
- CoGeNT reported a rate modulation that might be explained by surface background



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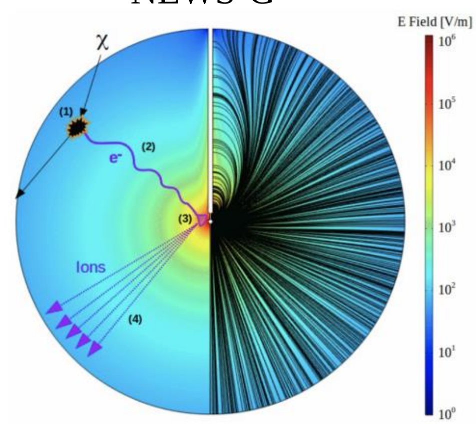
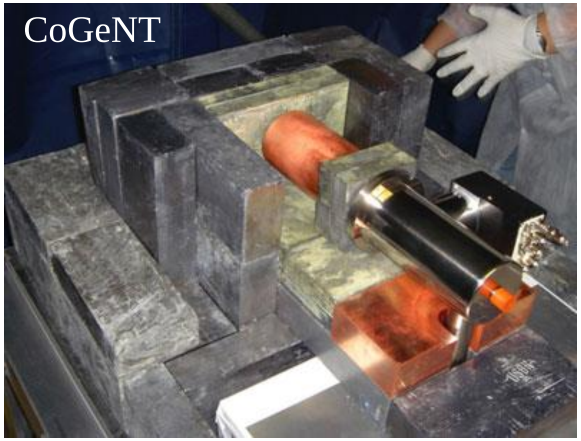
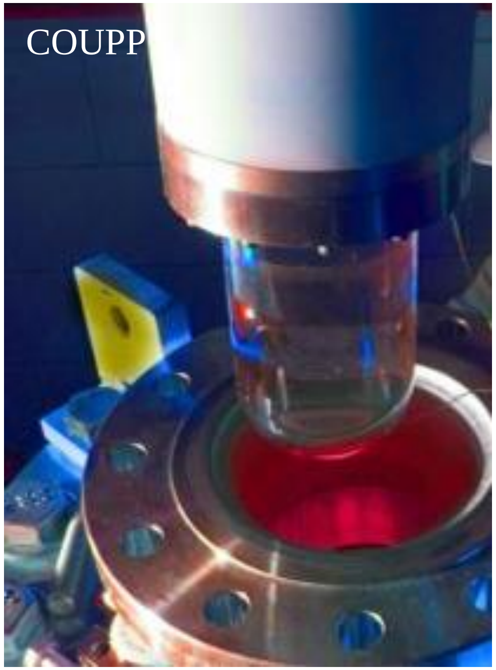


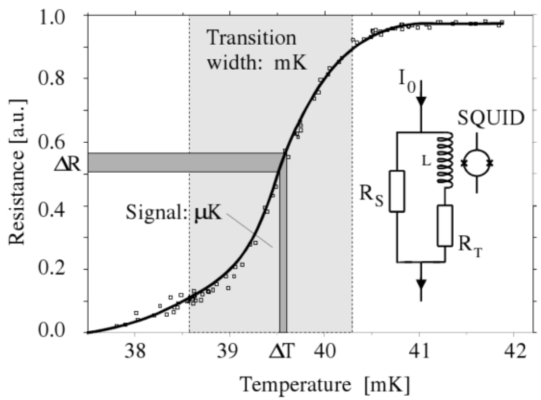


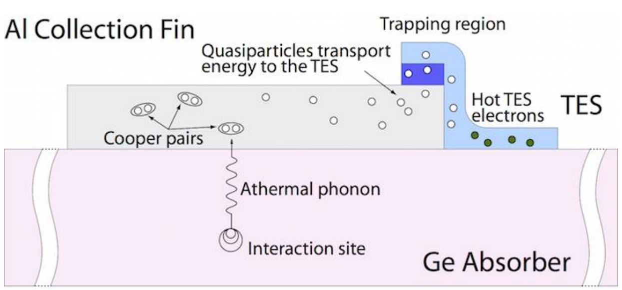
Heat-based experiments

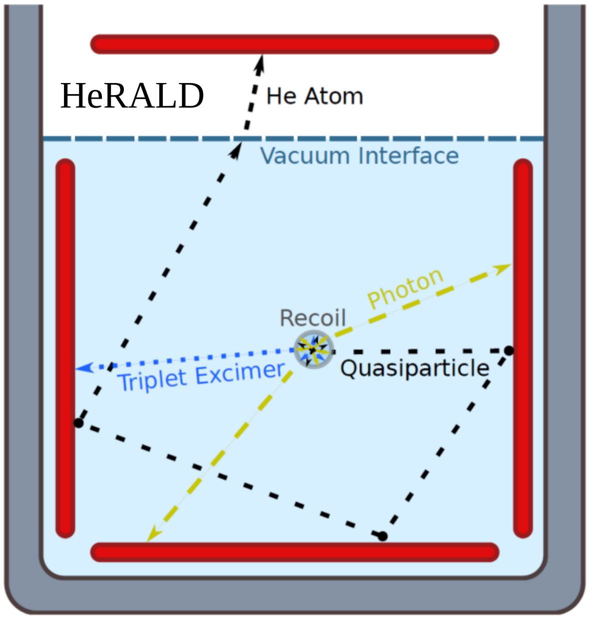
Nuclear recoils deposit most energy in heat

- Bubble chambers are well-developed technologies using super-heated liquid targets
  - Intrinsic nuclear/electron recoil discrimination capability
  - Snowball detector uses super-cooled liquid
- Cryogenic bolometers (~mK operation) can direct detect phonons and rotons





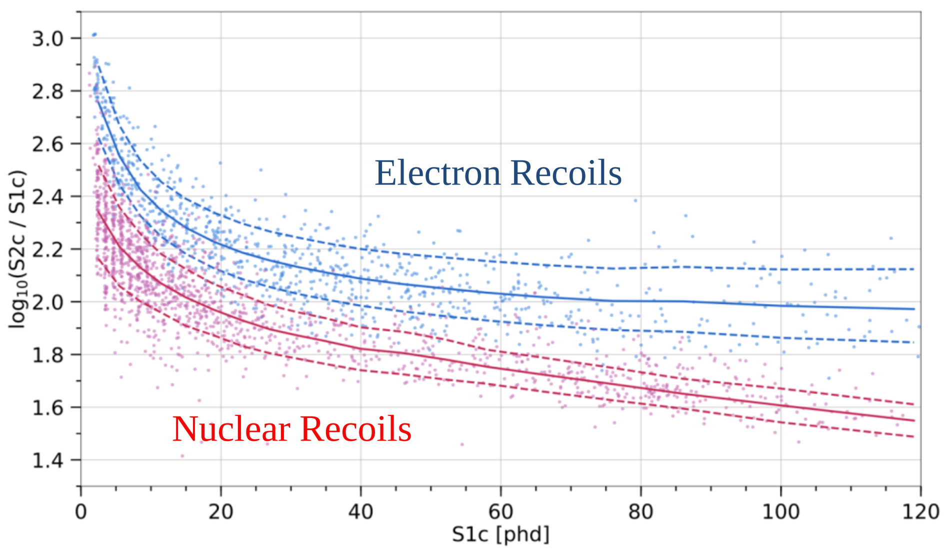


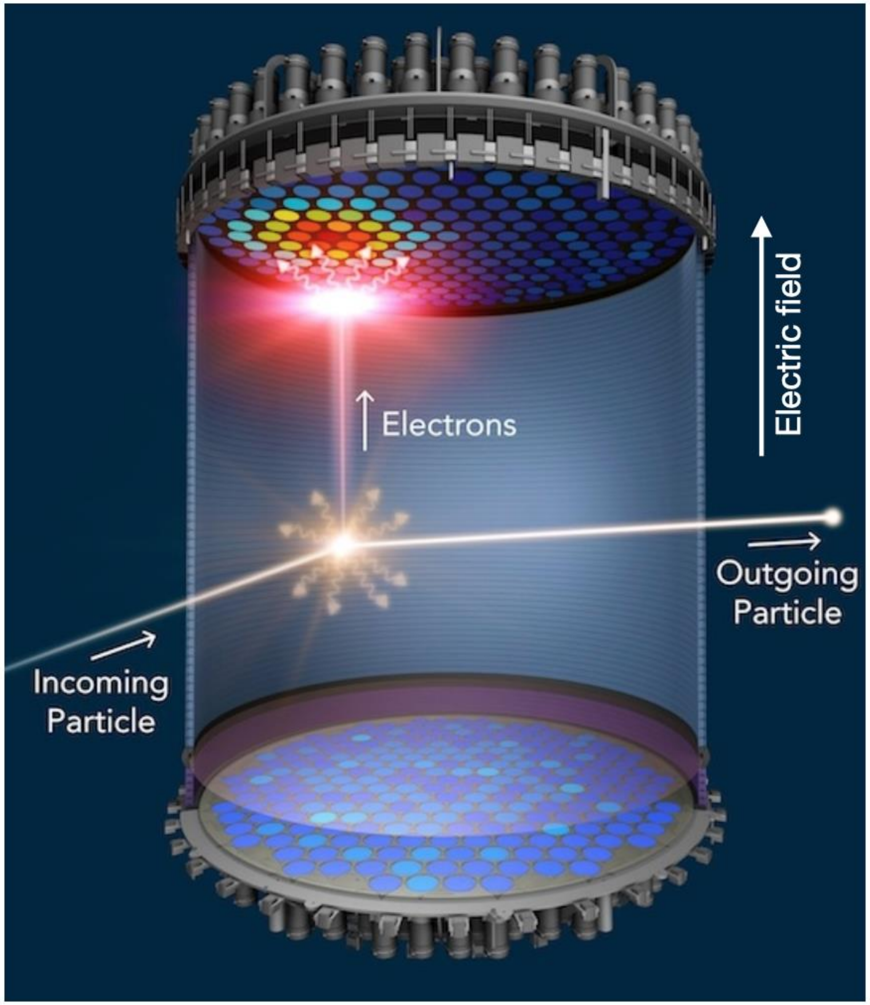


Scintillation-ionization experiments

Noble element TPC collect both scintillation and ionization

- Nuclear/electron recoil discrimination from energy partition between channels
- Improved energy and position reconstruction by combining both channels
- Electron gain: O(10)photon detected/e-

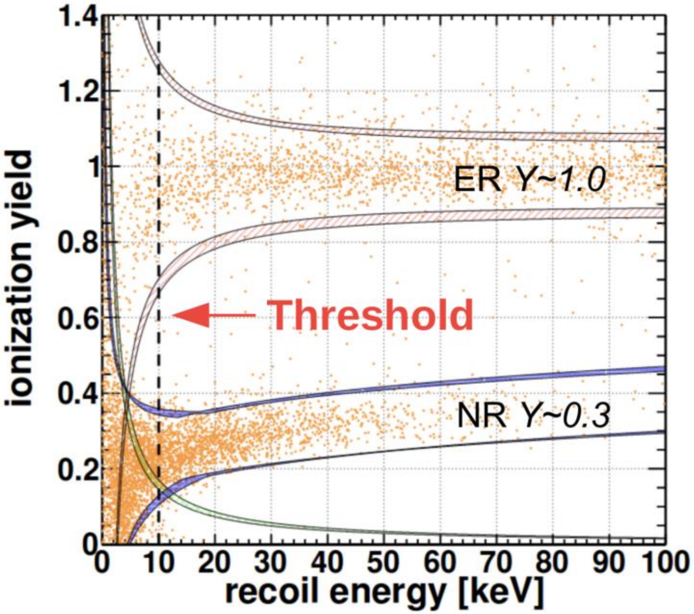




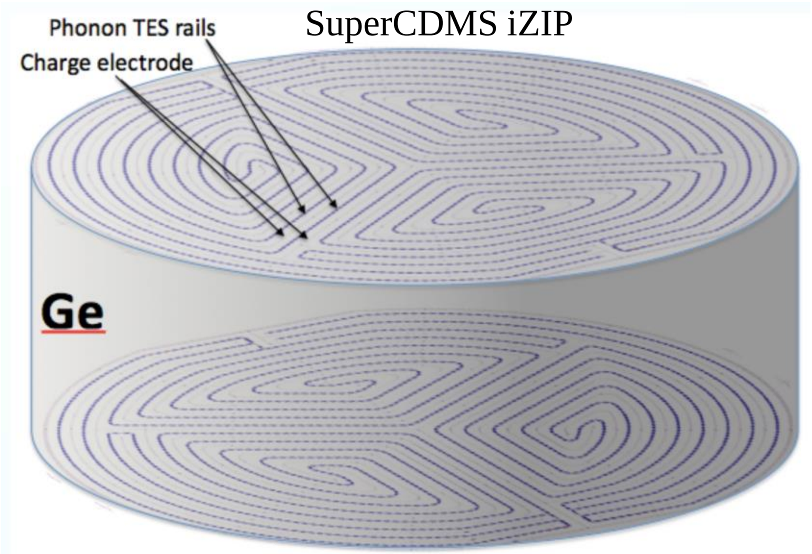
Ionization-heat experiments

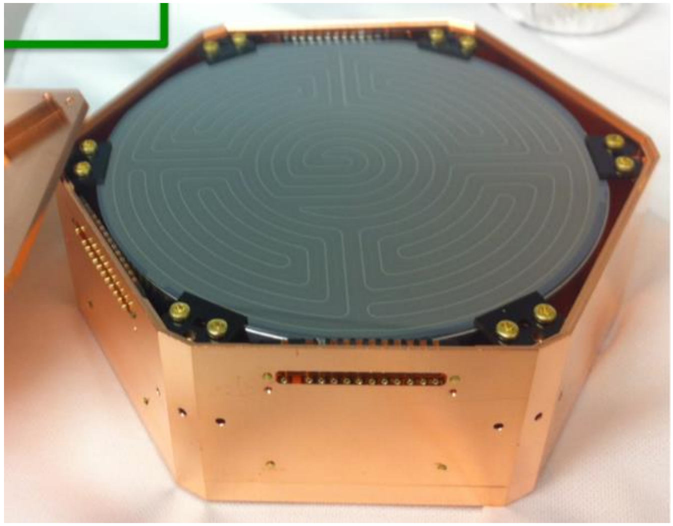
Semiconductor detectors can implement heat readouts

- Heat detection uses cryogenic devices including TES, NTD, MKIDs, etc
- Charge to heat ratio provides discrimination between nuclear and electron recoils
- SuperCDMS and EDELWEISS lead the development



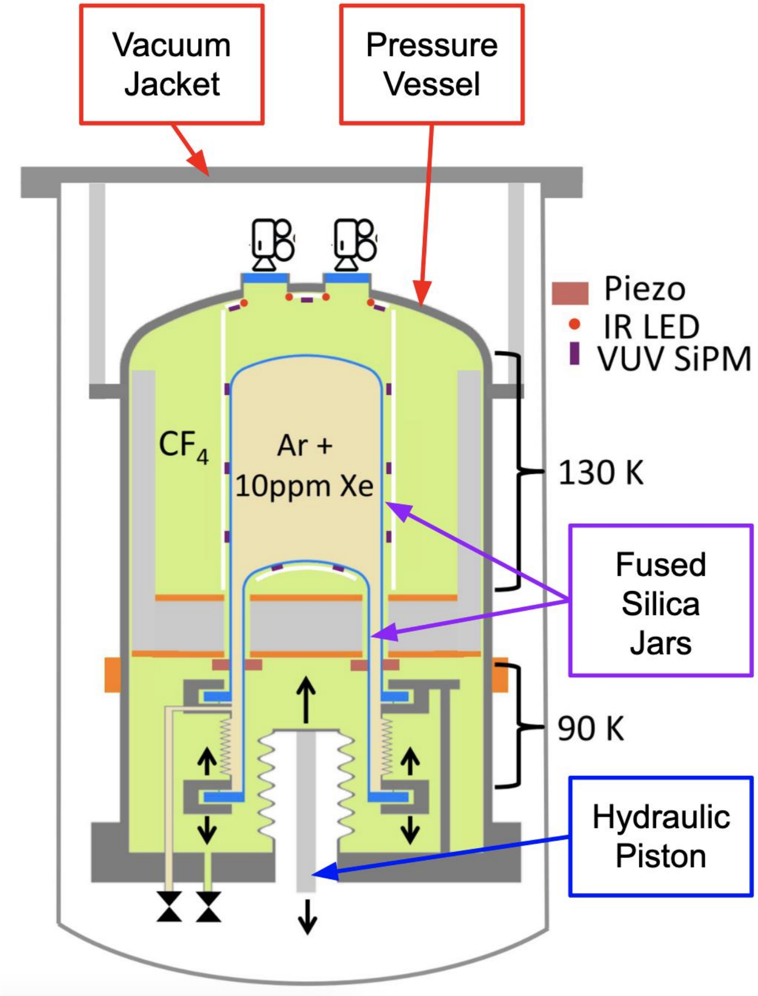
SuperCDMS iZIP





Scintillation-heat experiments

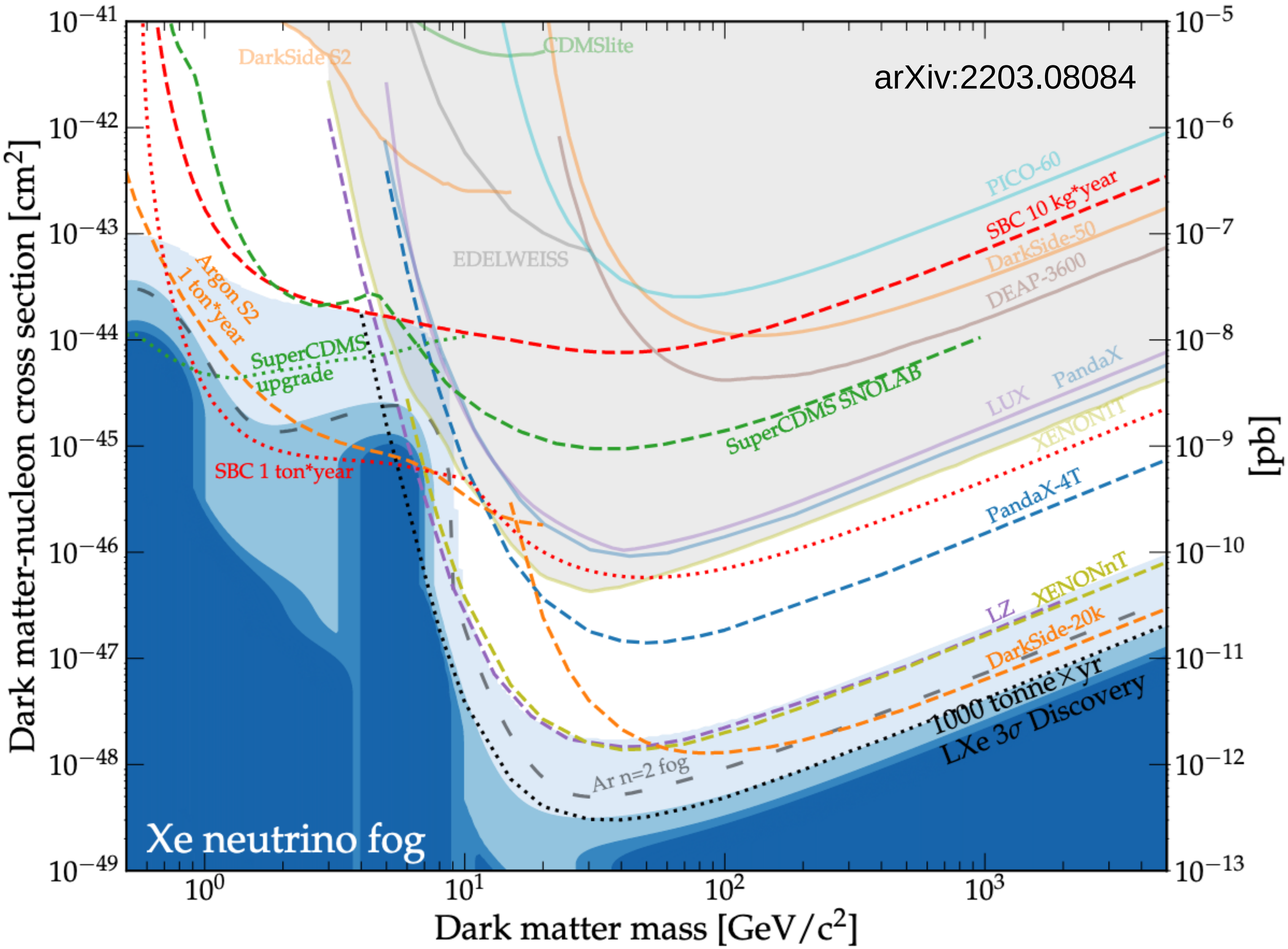
- Scintillation-to-heat ratio also provides electron/nuclear recoil discrimination
- Scintillation signal provides event-level energy information for bubble chambers
- HeRALD use TES to detect both He scintillation photons, athermal phonons, and evaporated He atoms



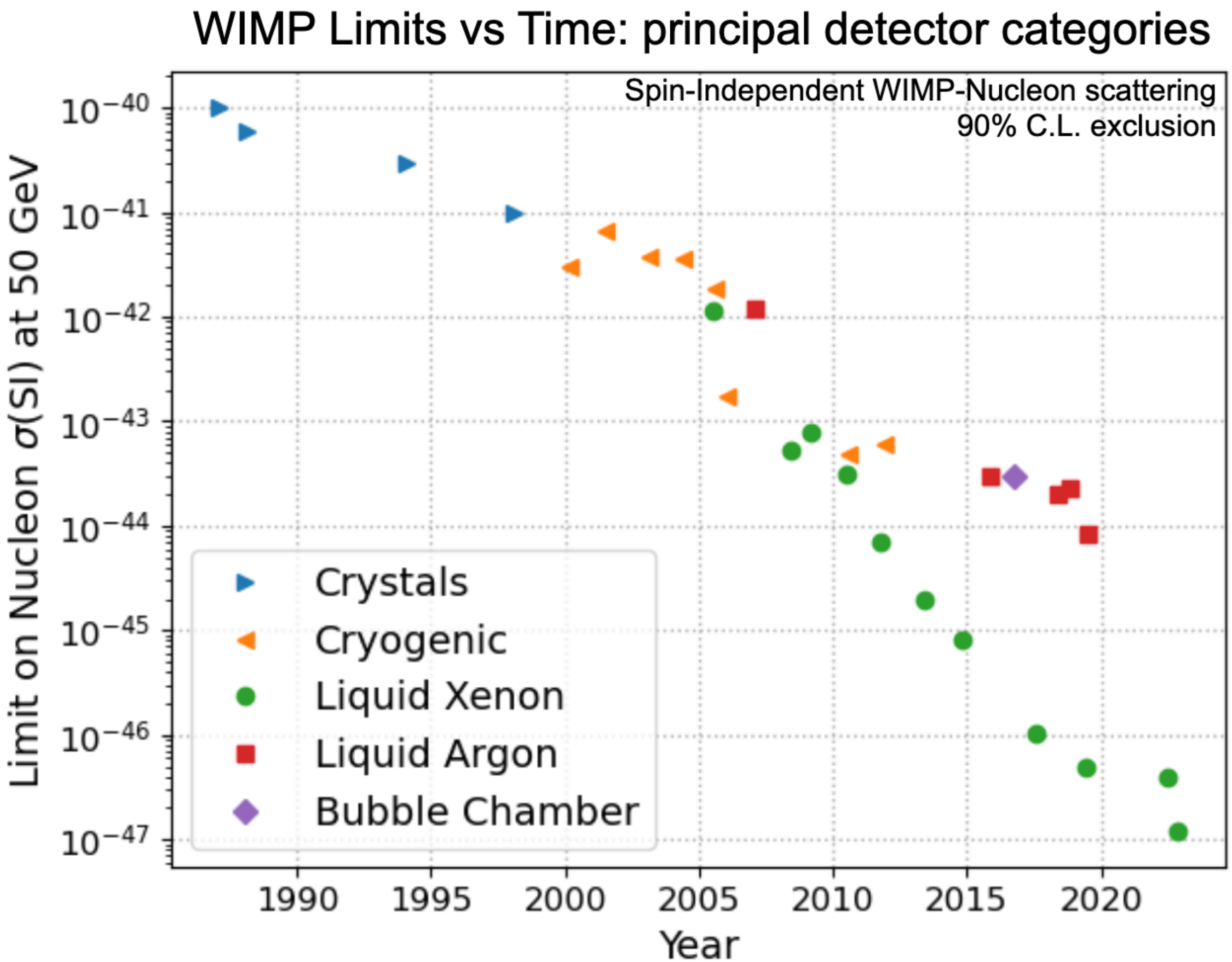
Scintillating Bubble Chamber illustration

Sensitivity improving fast, no definitive detection

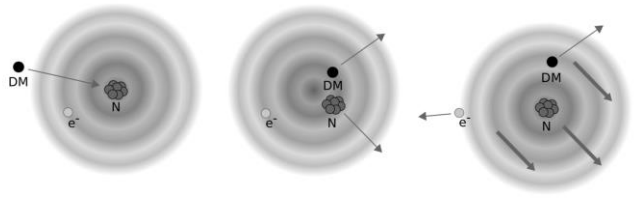
Vast parameter space explored, no definitive detection yet



Sensitivity improving fast, no definitive detection

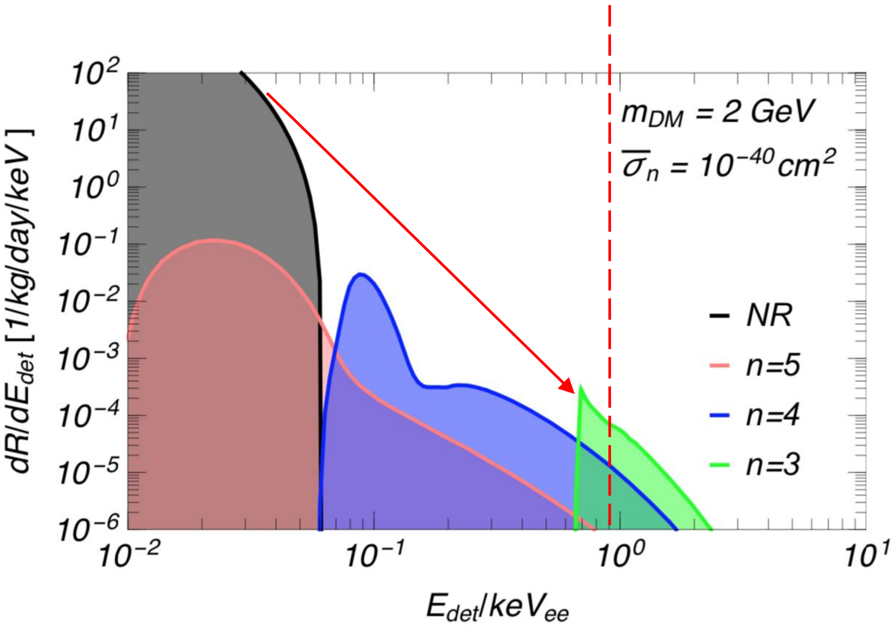


Toward low-mass dark matter detection

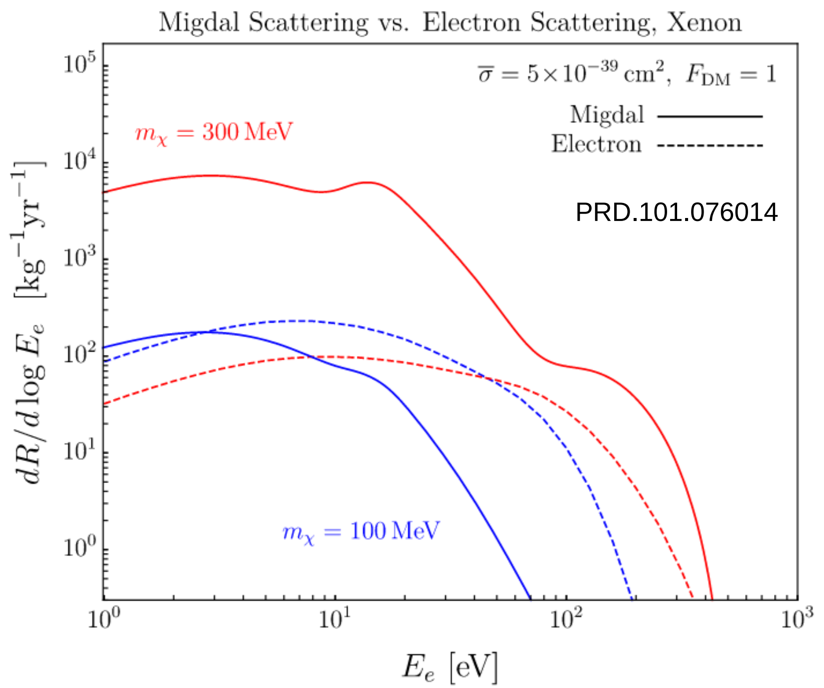


- Detection of dark matter-electron scatters requires eV—keV sensitivities
- Migdal effect also predicts electron signals to accompany nuclear recoils
- Migdal rate can dominate over DM-e interactions
- Migdal effect lowers energy thresholds of current detectors

Typical detector threshold

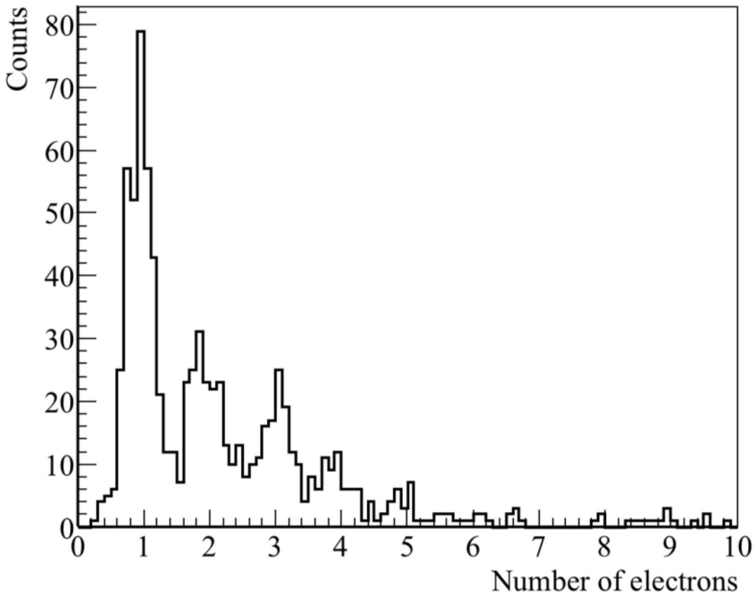


Predicted nuclear recoil and Migdal electron recoil energy distributions for 2 GeV WIMP interactions. *J HEP 03 (2018) 194*

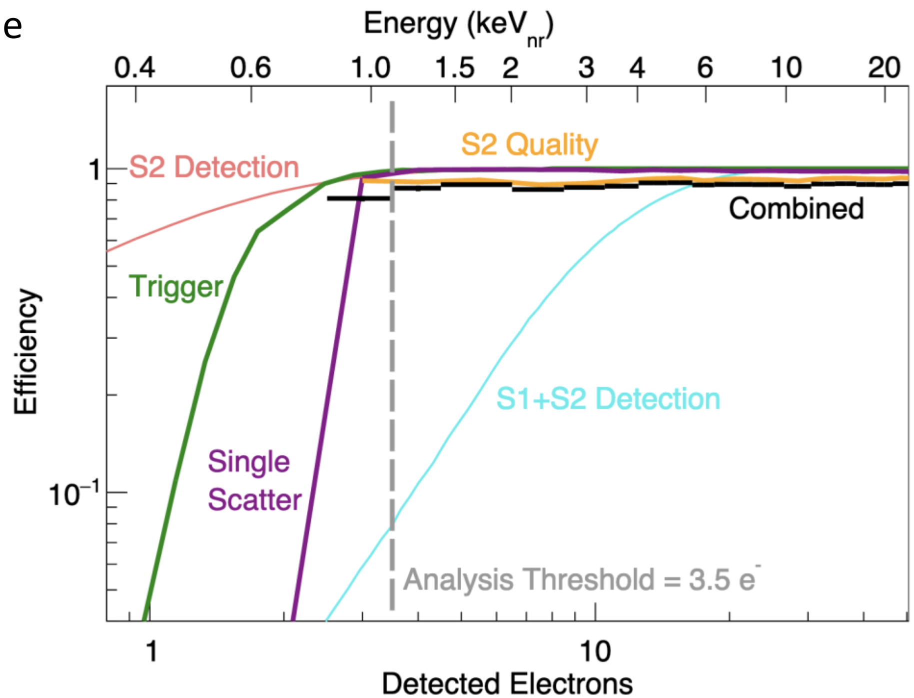


Noble liquid ionization-only searches

- LAr and LXe TPCs can detector single ionization electrons with high efficiency
- O(10)eV energy for electron recoil interactions to produce a single ionization electron
- O(100)eV energy for nuclear recoil interactions to produce a single ionization electron
- Migdal effect can provide an additional sensitivity boost
- Background rate usually increases in this mode



Measured electron spectrum for 0.4keV Xe recoils with the LLNL Xe TPC



Scintillation (S1) and ionization (S2) signal acceptance for the LUX dark matter detector PRD.104.012011

NTL photon amplification in Si/Ge

- Phonons produced by drifting electrons in Si/Ge can amplify faint ionization signals
- Single electron sensitivity has been demonstrated, with some loss of original heat signal
- Si/Ge has a lower band gap than Ar/Xe, so lower energy threshold

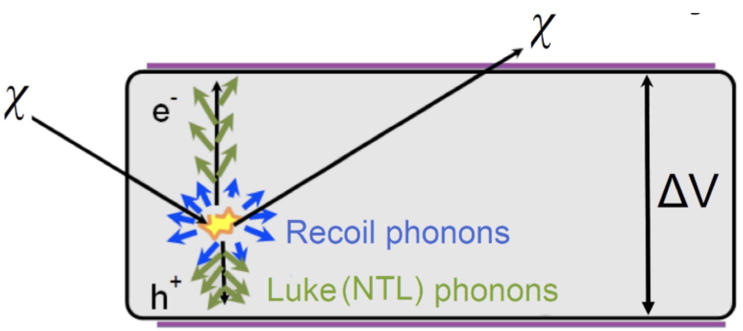
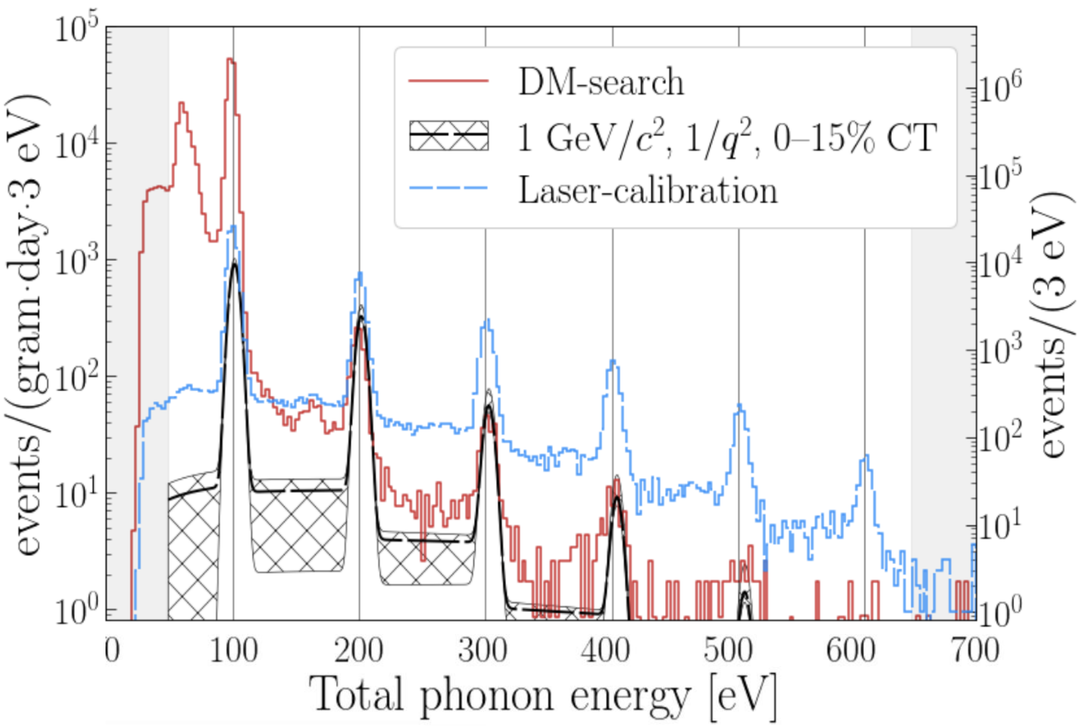


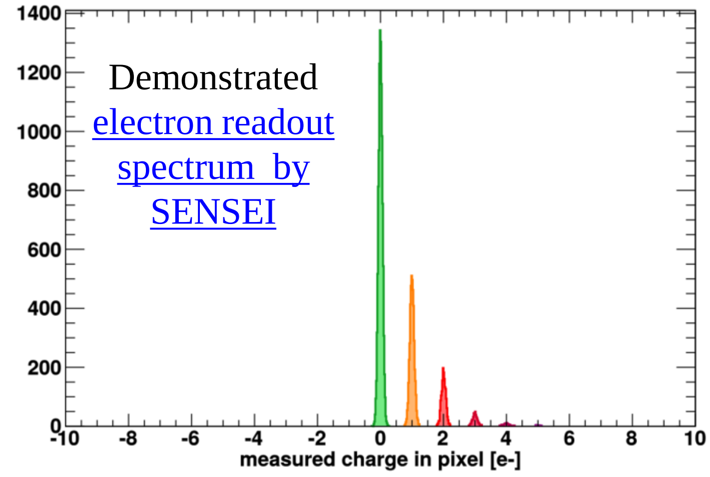
Illustration of the Neganov-Trofmov-Luke (NTL) phonon amplification of ionization signals

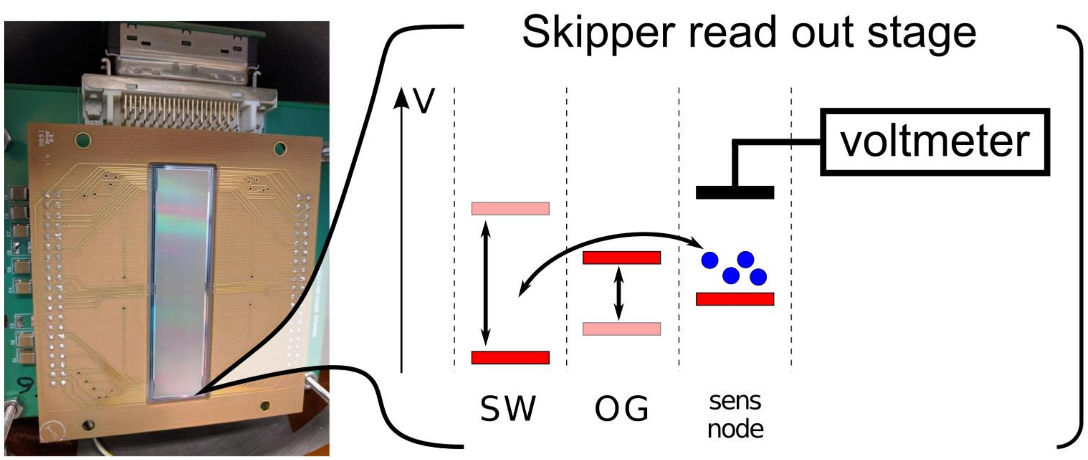


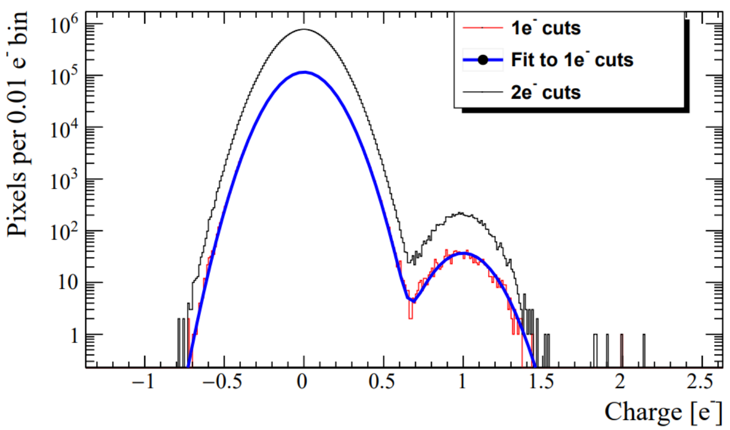
Measured background spectrum in a SuperCDMS HV detectors

Skipper CCDs

- Skipper CCDs get exceptional resolution through repeated non-destructive readout of stored charge
- Unprecedented low noise (<<1e-) demonstrated
- Low mass dark matter searches being carried out by SENSEI, DAMIC, OSCURA, etc

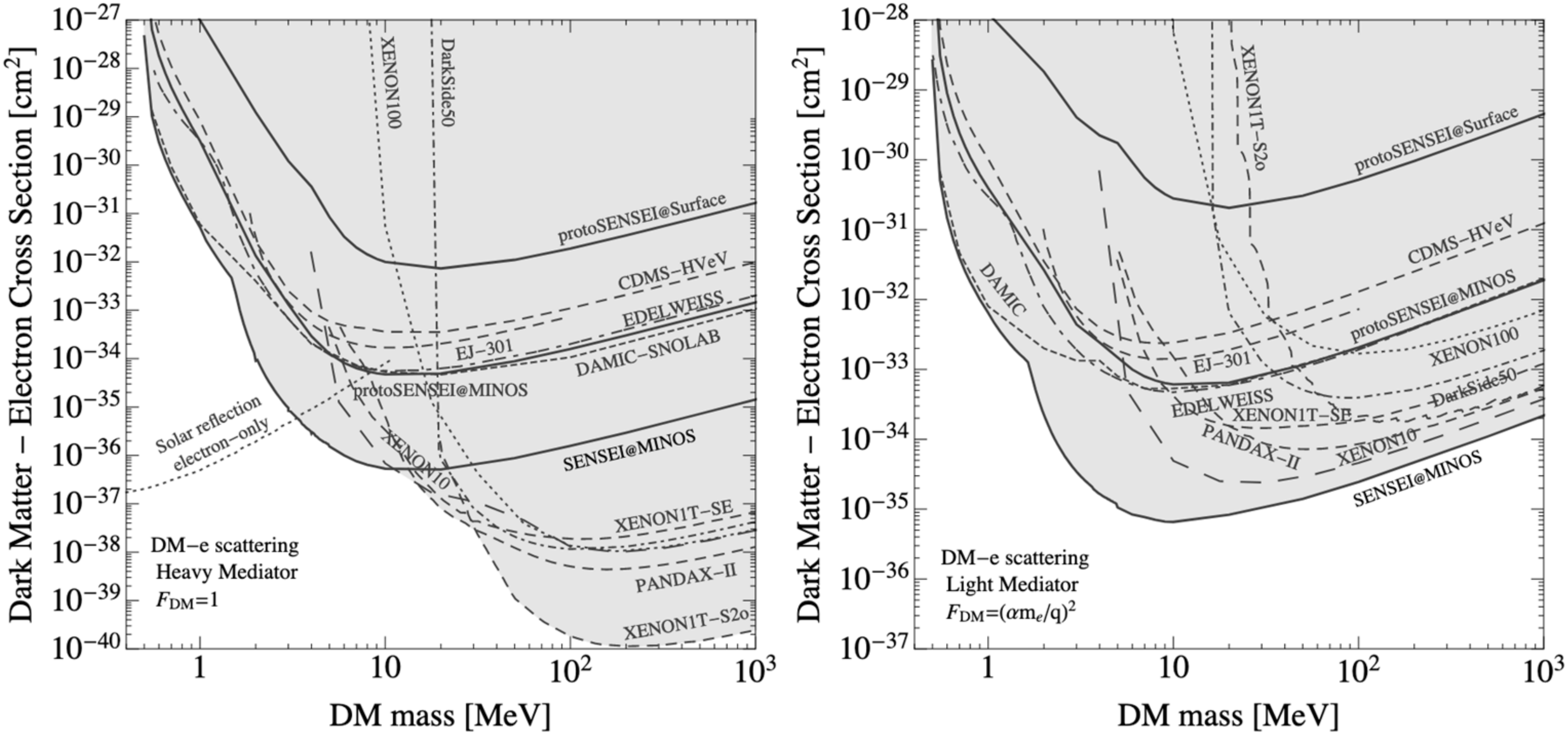






SENSI (2020), PRL 125, 171802

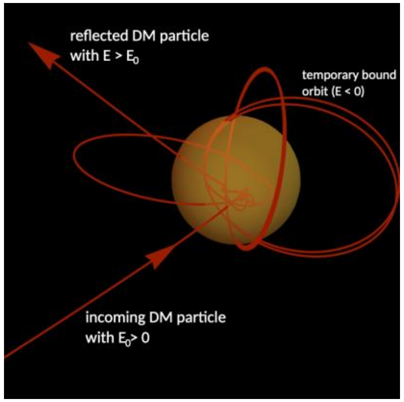
Current limits on low-mass dark matter interactions



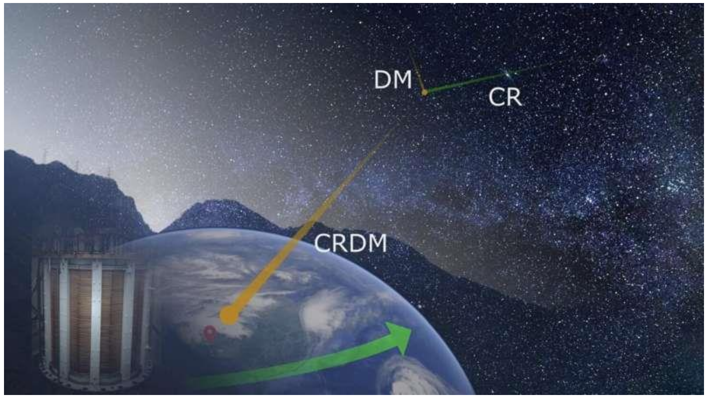
arXiv:2203.08297

Novel direct detection ideas

Sun reflected boosted dark matter

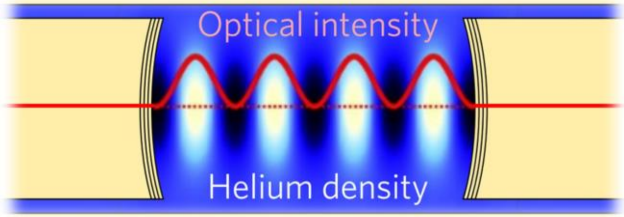


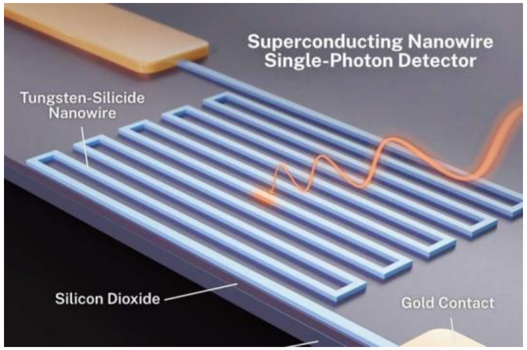
Cosmic ray boosted dark matter

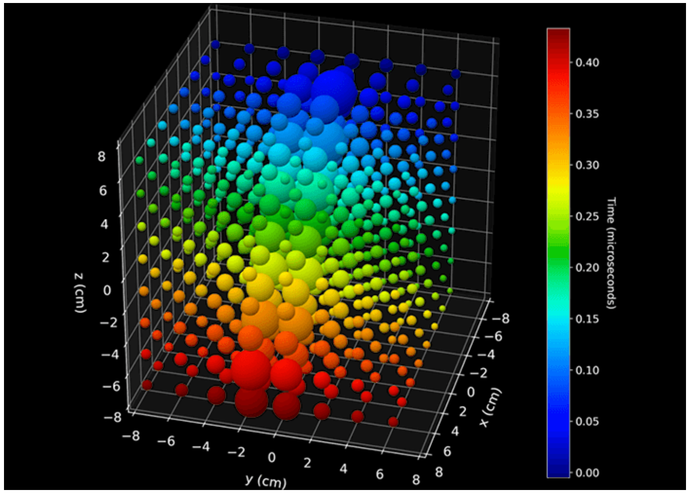


Dedicated Boosted Dark Matter (BDM) workshop is held after PPC2023

Single phonon and single photon detectors



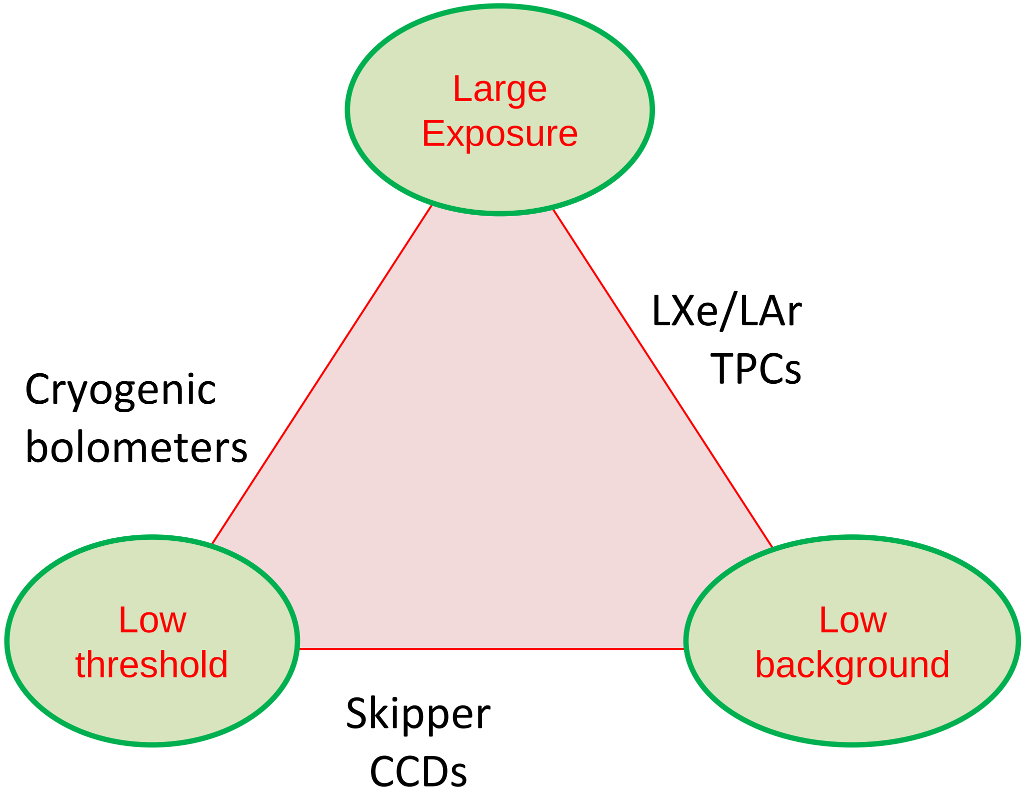




Direct detection of Planck-mass dark matter through gravity WINDCHIME

and more…

Continued challenges in direct detection



Summary

- Dark matter is a cornerstone in modern cosmology and a deep mystery in particle physics
- A rich class of dark matter theories predict dark matter-matter interactions
- The nature of dark matter could be revealed by direct detection experiments
- Direct detection experiments have scanned vast parameter space and improved sensitivities by over 10 orders of magnitude in 2 decades
- New detector technologies are being developed in pursue of new directions in dark matter searches
- A definitive detection of dark matter can revolutionize particle physics and complement cosmology

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