Détecter la matière noire sub-GeV

Gas Detectors for Direct and Directional Dark Matter Detection and Axion-Like Particle exploration

The direct search for Dark Matter in the keV/c² to GeV/c² range through its interaction with nucleons or electrons using solid-state cryogenic detectors

Direct detection of dark matter in the eV-to-GeV mass range

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pour A. Letessier-Selvon (LPNHE) et D. Santos (LPSC)
+ autres co-auteurs de ces trois contributions

Plan

- **Physics of direct DM searches in the eV-GeV range**
  - Physics arguments of the 3 contributions based on discussions already documented elsewhere
  - Present summary largely based on: *Dark Sectors 2016 Workshop: Community Report* (arXiv:1608.08632)

See also updates in « US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report » arXiv:1707.04591

3 contributions :

- Gas & directional detectors
- Skipper-CCD
- Cryogenic detectors

More details on detector technologies in GT08 contributions

Physics motivation

Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632):

- *"In recent years it has been shown that many production mechanisms that explain the observed DM relic abundance, point to light, sub-GeV DM, below the reach of standard direct detection techniques. It is thus crucial to develop direct-detection strategies for such low DM masses."*

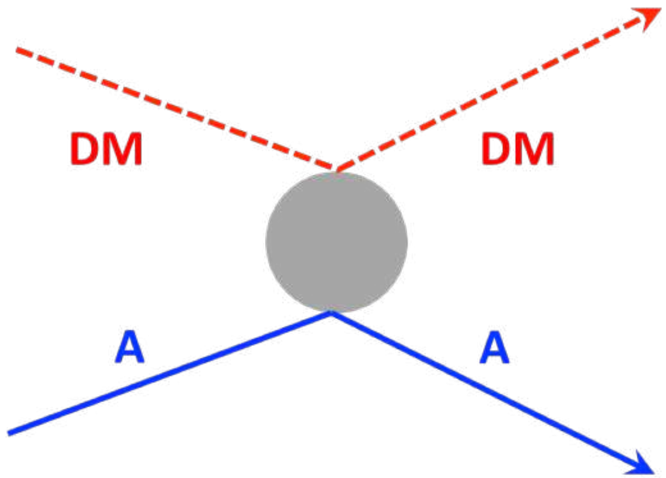
- $m_\chi >$ eV if fermion (Galactic DM halo = Fermi gas)
- $m_\chi >$ 3 keV if thermal equilibrium with SM particles (Ly-α forest)
- $E_{NR} \leq 2(\mu_{\chi,N} v_\chi)^2/m_N$, with $v_\chi \sim 10^{-3}$ c
- For a Si nucleus and $m_\chi \sim$100 MeV, $E_{NR} \sim$1 eV
- Scattering on electron favored as m_χ approaches m_e
- Complementarity with searches at beam dumps & colliders

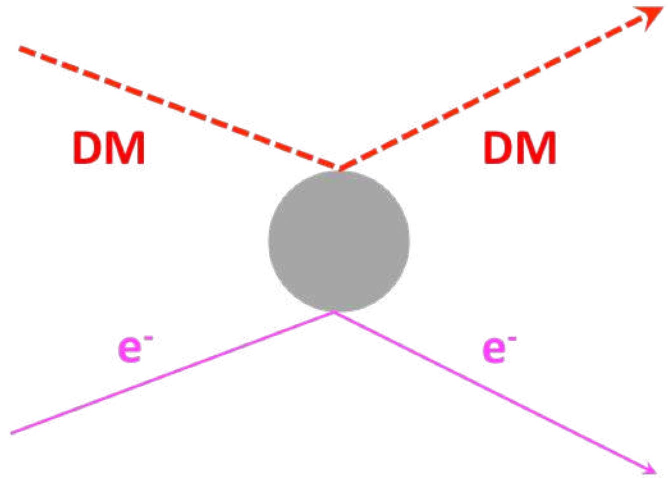
DM models in eV-GeV range

- **Freeze-out DM:** relic density obtained from thermal equilibrium of SM+SM->DM+DM, but via ***Dark Sector mediators*** instead of SM mediators. ***e.g. Dark Photon, with small couplings to standard*** γ
- **Asymmetric DM:** final relic abundance of DM from particle/antiparticle asymmetry in the DM sector. **Natural mass ~GeV**, but keV-GeV possible depending on DM sector
- **Freeze-in DM:** *no thermal equilibrium of DM with SM:* instead, SM particles slowly annihilate or decay into DM, via DS
- **SIMPs** (strongly interacting) thermally coupled to SM, relic abundance set by ($3 \rightarrow 2$ freeze-out): **natural sub-GeV mass + high DD rates**
- **Elastically Decoupling Relic** : DM relic abundance determined by its inelastic scattering with SM: MeV to <GeV and DD signal possible
- **Bosonic DM (can be <1 keV):** QCD axion, axion-like particles, and the dark photon itself. **DM entirely absorbed in detector in DD experiments. Axions produced in the sun** can also be detected.

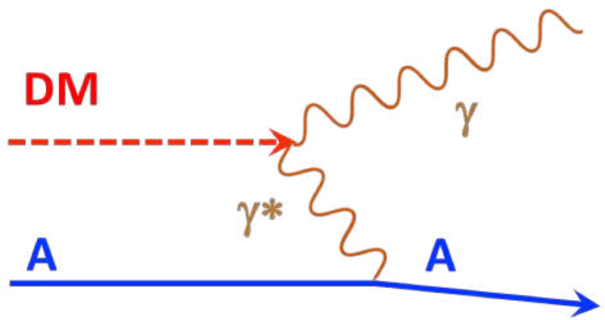
Detection signals

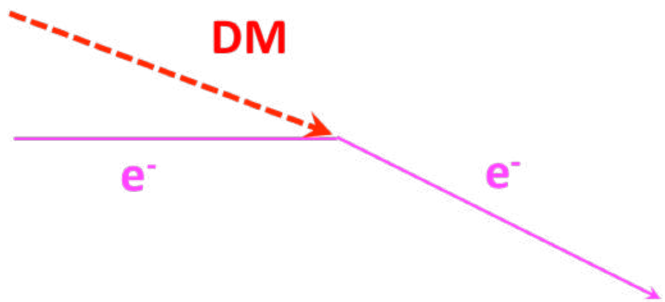
- Fermion: scattering off nuclei or electrons





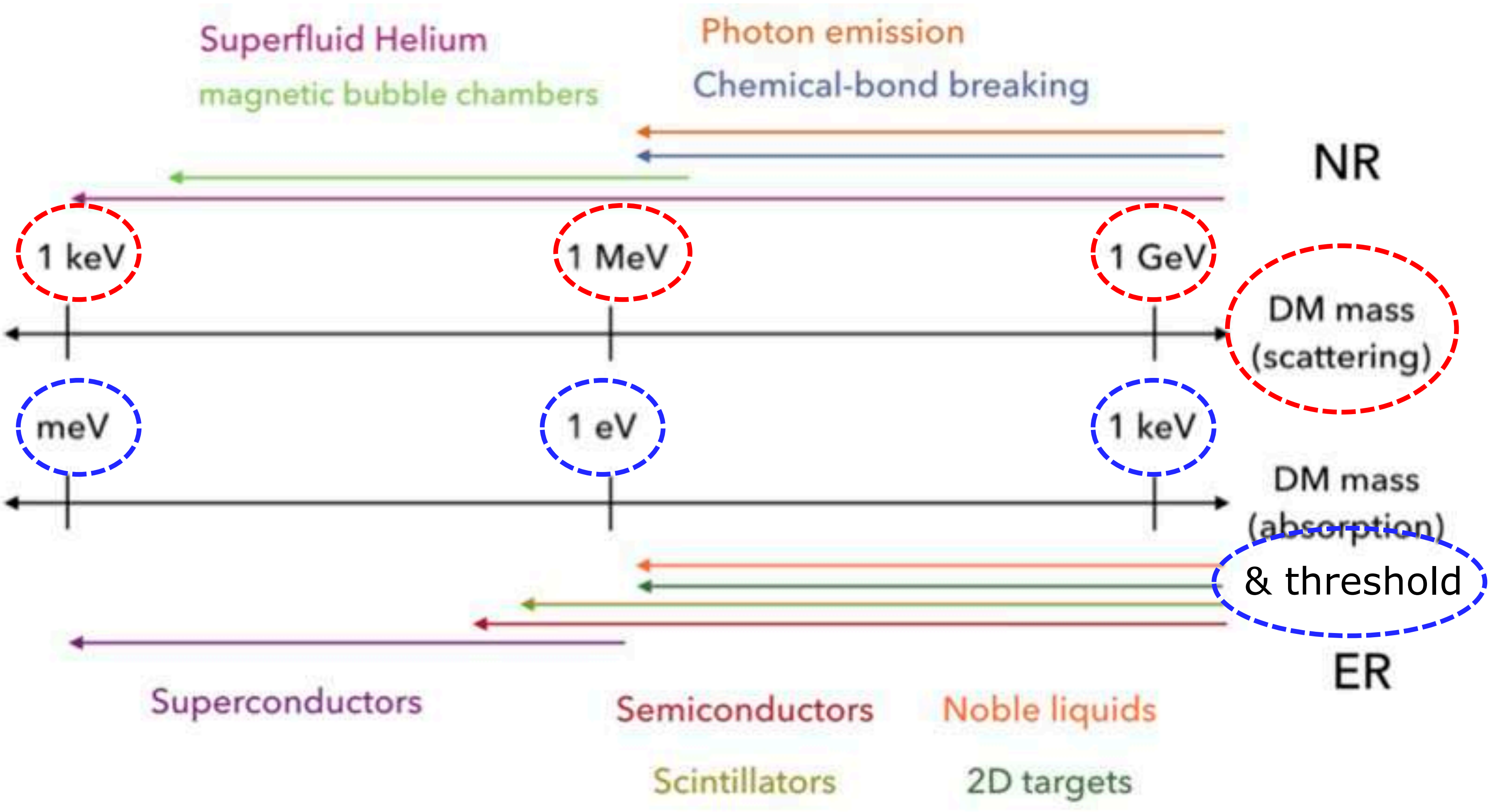
- Bosons: Primakoff effect (ALPs), photoabsorption (dark photons)





Scattering: materials vs mass & energy scale

US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report [arXiv:1707.04591]



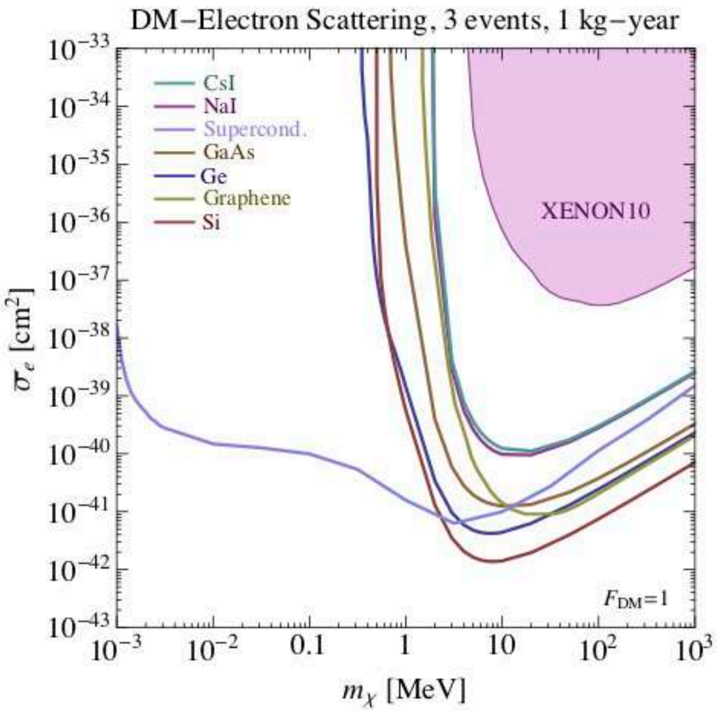
See also: K. Zurek, CERN-th colloquium 03.08.16

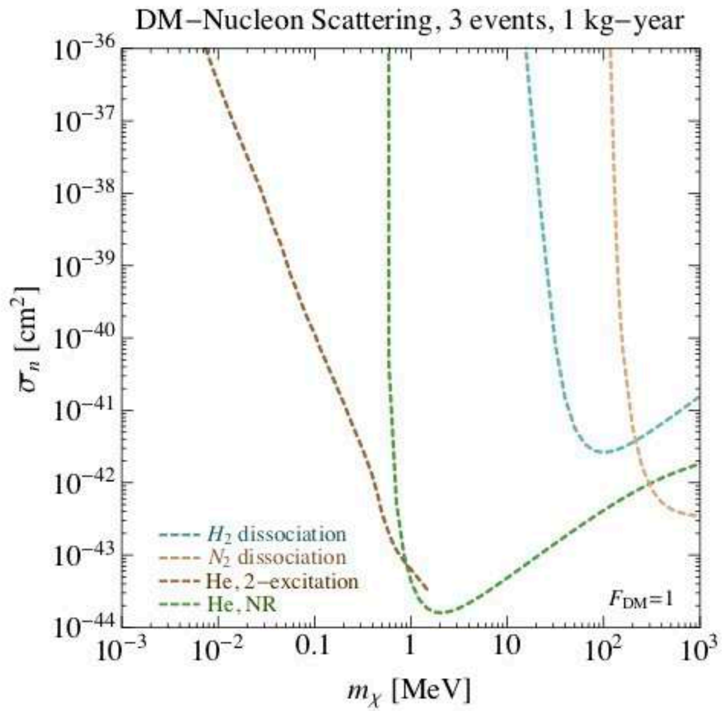
Electron vs nucleon scattering

Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632):

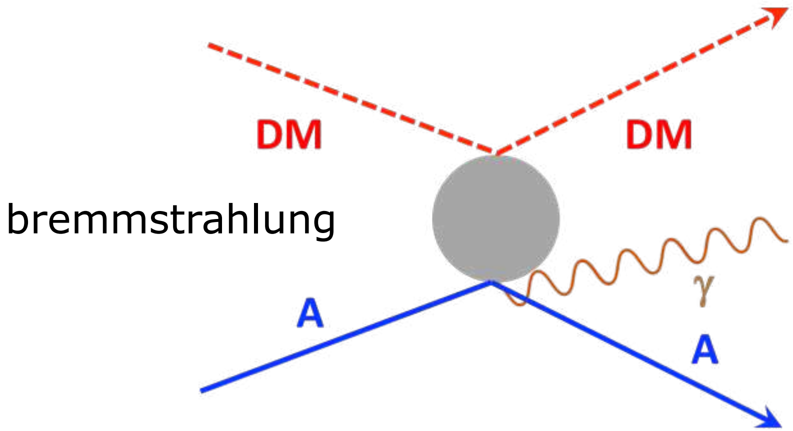
- ~eV to few eV thresholds possible in semiconductor/scintillators: sensitivity to MeV DM via electron scattering
- meV thresholds in (future) superconducting detectors -> keV DM
- Nucleon scattering adversely affected by *kinematics* and by *quenching*

arXiv:1608.08632

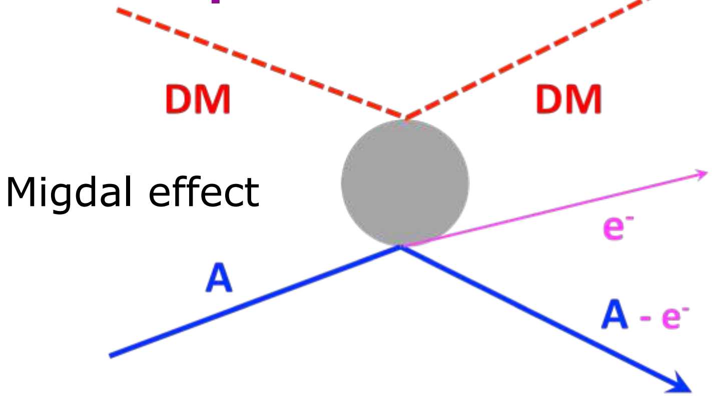




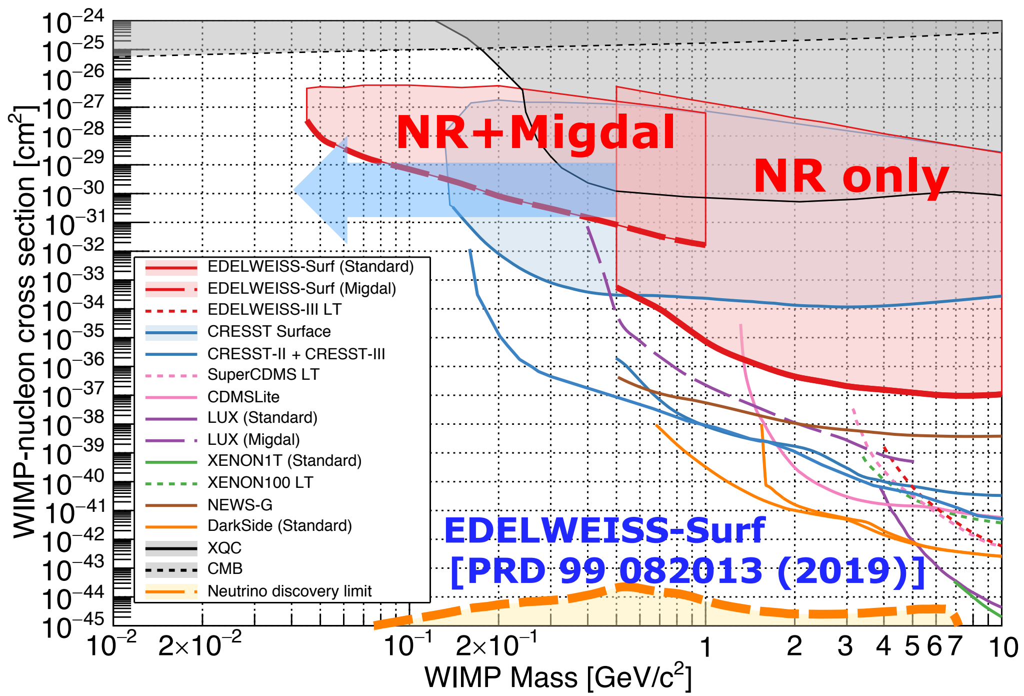
Inelastic scattering on atoms: Migdal effect



Update wrt 2016!

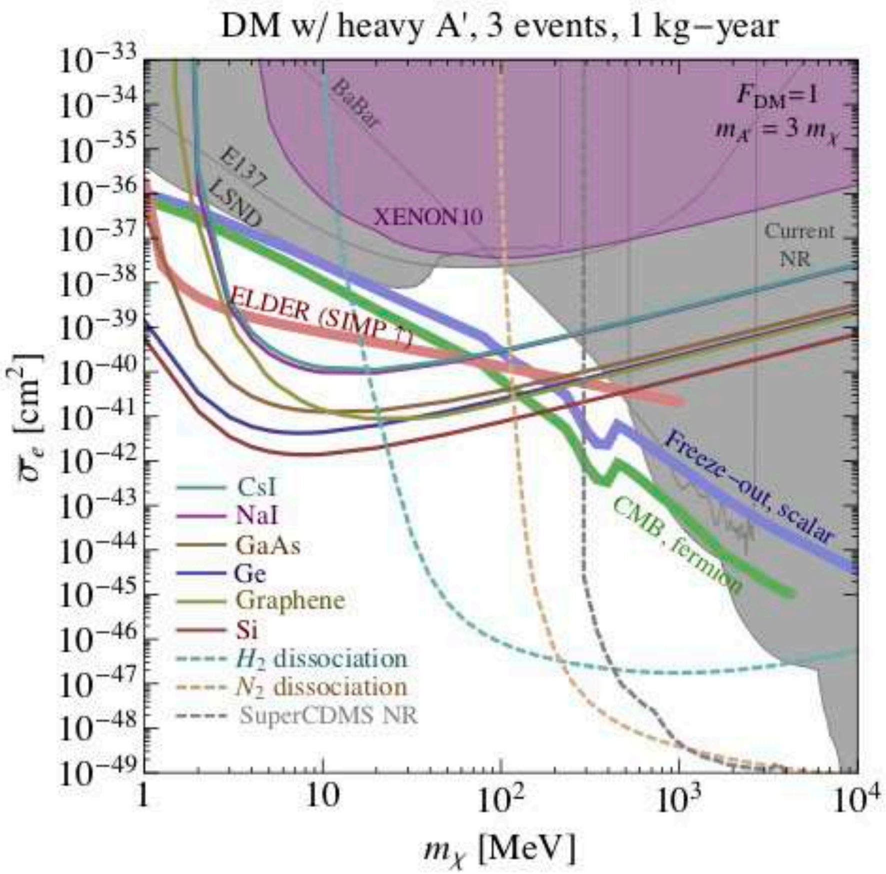


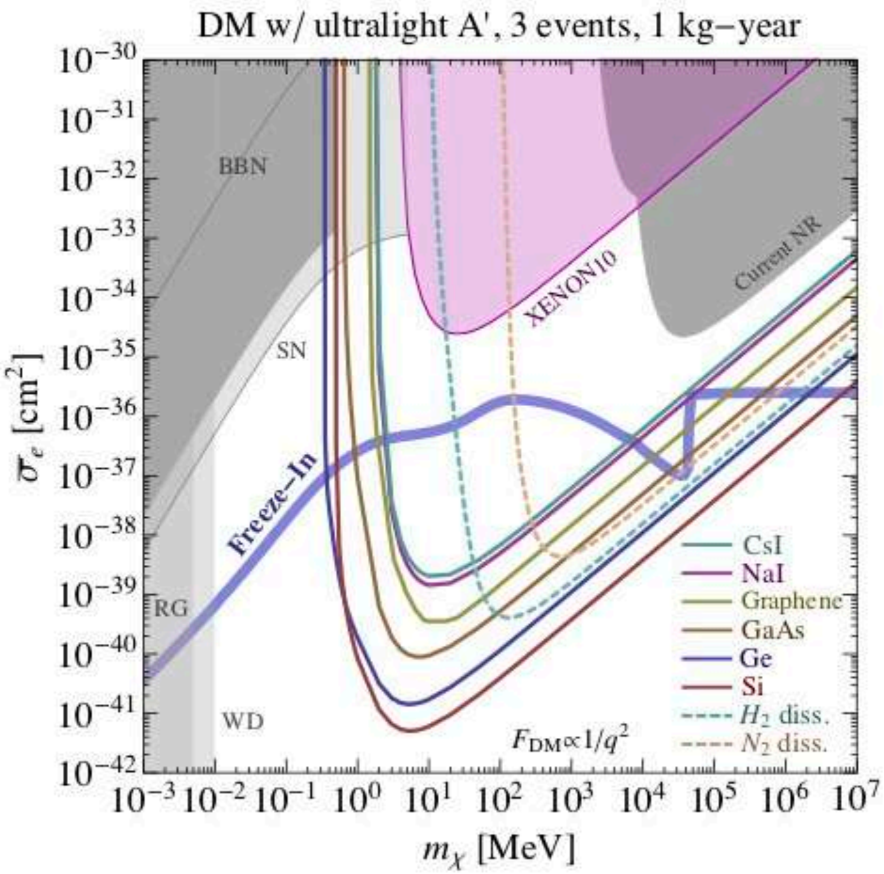
- Similar to bremmstrahlung effect
- Inelastic scattering on atom (nucleus+e⁻'s): transferred energy not limited by two-body kinematics
- Increases sensitivity to scattering of **Nuclear Recoils** (energy boost), but relatively rare process ($<10^{-3}$)
- **Electron signal** (no quenching)
- *Calculation only: an experimental confirmation would be welcomed*



Electron searches

- Two cases: Dark Photon heavier (left) or lighter (right) than DM particle
- Most interesting models (on or above green/orange/blue lines) can be probed using a 1 kg-y exposure of a detector with zero background + single-electron sensitivity
- If dark sector DM subdominant: need larger bkg-free exposure





Goals and Challenges

Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632):

- Low threshold
  - DM kinetic energy ~ (1 eV) *(M_{DM}/1 MeV)
- Backgrounds
  - Bkg usually associated to >1 GeV searches (γ / neutrons from internal+external radioactivity, cosmic rays, activation) are less important than detector-specific bkg (e.g. dark current)
- Scaling up exposure
  - Low threshold usually associated with small detectors
  - Internal/external radioactivity becomes an issue again
- Signal discrimination and background model
- Material

Gas Detectors for Direct and Directional Dark Matter Detection and Axion-Like Particle exploration:

NEWS-G and gas TPC

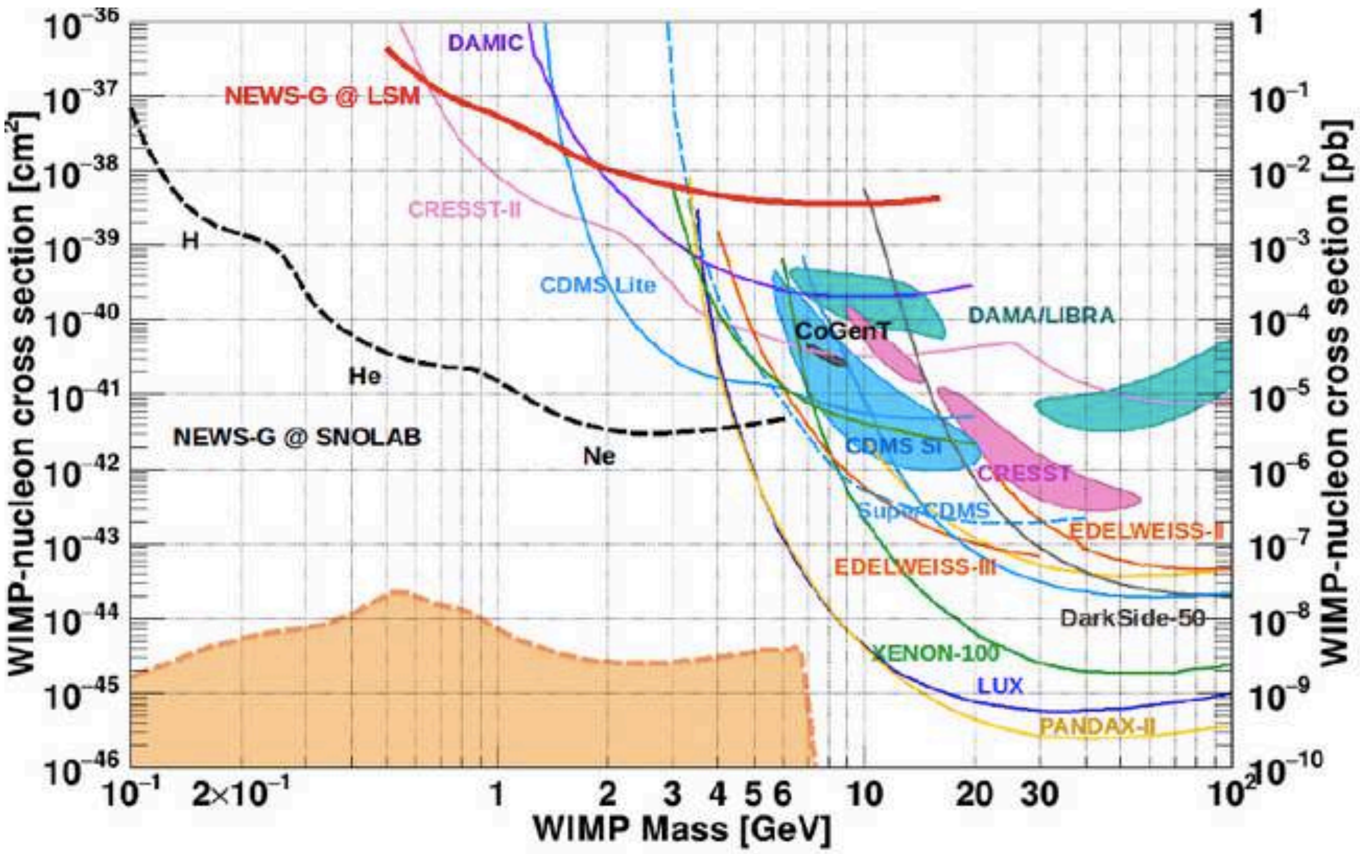
GAS DETECTORS

Gas detectors: NEWS-G

- NEWS-G (New Experiment for Wimps detection with a Sphere filled with Gas)
- Direct search for very-low mass WIMPs, from 0.1 to 10 GeV.
  - 1.4 diameter, single-channel readout
  - Sub-keV energy threshold
  - Fiducialisation via pulse shape
  - Background rejection by pulse shape analysis
  - Up to 10 bars: ten's of kg with various light gas targets: H, He, Ne.
- First tests at LSM: summer/autumn 2019.

NEWS-G@LSM physics reach

- Installation of NEWS-G at SNOLAB is scheduled November 2019
- Physics reach: sub-GeV with light gas targets



- + Quenching measurements @ LPSC

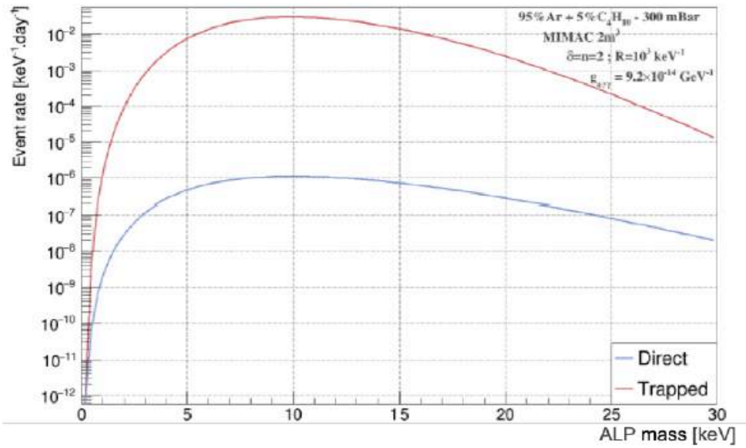
Gas detector: TPC for axion

- MIMAC: gaseous micro-TPC with pixelized Micromega readout, designed to test the directionality of an eventual DM signal

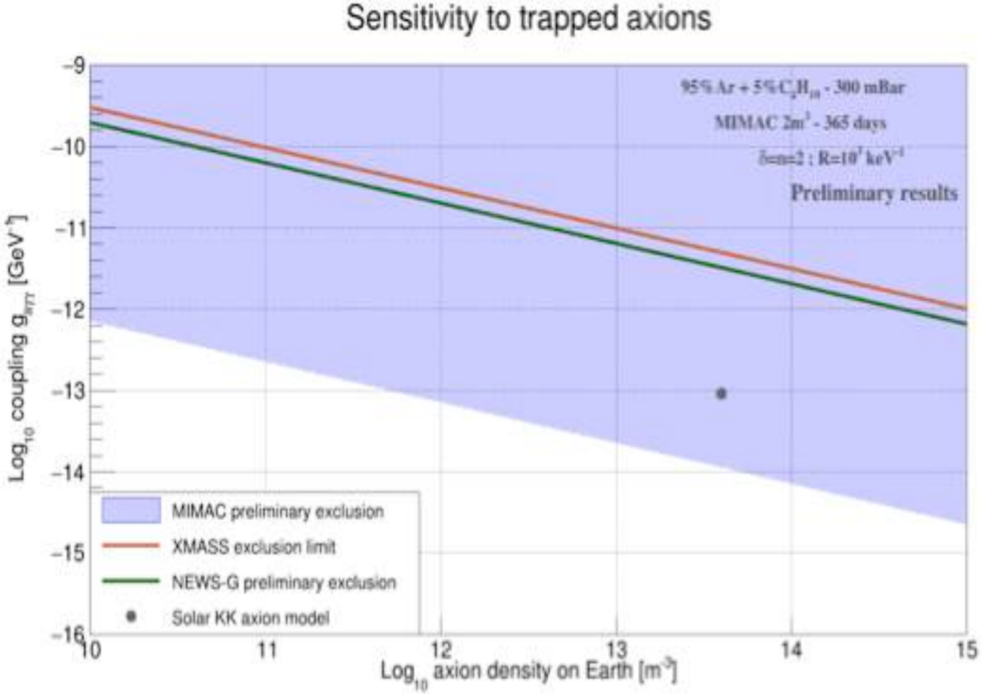
- Proposal for an application for ALP DM in the mass window from 100 eV up to 20 keV
- *Kaluza-Klein Axion-Like particles: long lifetimes, detection of its decays into two identical photons (no strong electric field needed).*
- New generation of micro-TPCs with 100 eV energy threshold and a high spatial 3D resolution in a large active volume.
- Background reduced by the many discrimination observables offered by this technique.
- Matrix of many individual bi-chamber modules (with low individual background rates) for a total of 2 m^3.

Physics reach of gas TPC for axions

- Rate of KK-axion decays detected MIMAC active volume (300 mbar, ^{40}Ar + 5% C_4H_{10}) as a function of ALP mass. Strongly increase when the flux from those trapped by the sun (red) is added to the direct flux from the Sun (blue).



- MIMAC 1-y exclusion region (blue) vs axion density on Earth compared with the XMASS exclusion (red) and NEWS-G exclusion (green). MIMAC should reach the Kaluza-Klein-axion model (*cf* dot: not yet excluded).



Direct detection of dark matter in the eV-to-GeV mass Range

SKIPPER-CCDS

Skipper CCDs

- Improved signal/noise from repeated measurement of the charge (wrt pedestal)

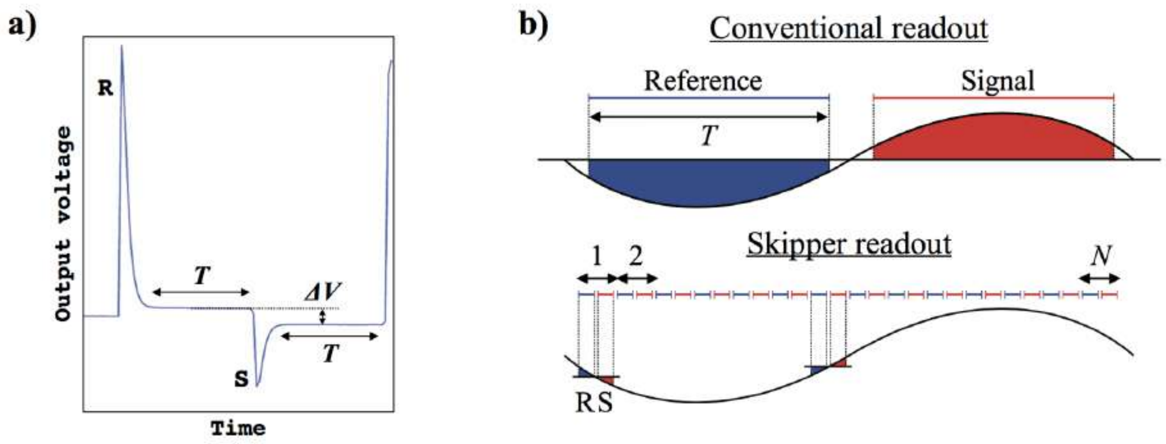


Figure 3 : a) CCD output signal for one pixel illustrating the principle of CDS (R: reset, S: charge transfer). b) Skipper vs. conventional readout: during the same time of a conventional readout, the pixel charge is measured N times in skipper mode. The effect of a low-frequency noise waveform is much smaller in skipper mode because the waveform changes very little during the short CDS sequence.

- 0.07 electron resolution already achieved

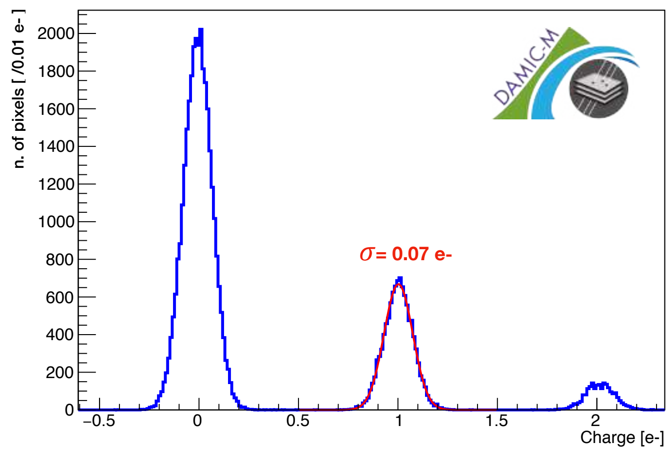
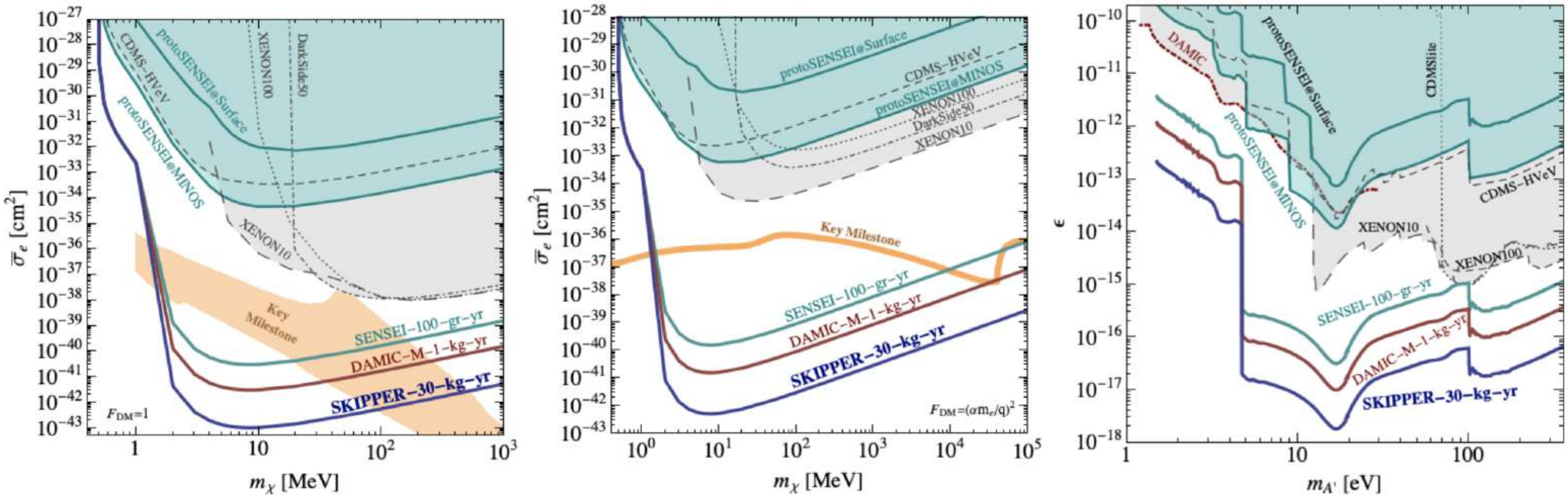


Figure 4: Pixel charge distribution of a DAMIC-M skipper CCD. Peaks corresponding to pixels with zero, one and two charges are clearly distinguished. A Gaussian fit to the charge distribution yields a resolution of 0.07 electrons [23].

Skipper-CCD

- Skipper-CCD's already produced world leading limits for sub-GeV DM (SENSEI and DAMIC@SNOLAB)
- Arrays of 100 g (SENSEI) and 1 kg (DAMIC-M @LSM) under construction.
- Future project: 10 kg experiment to probe sub-GeV DM even if it makes only a small fraction of the halo density

DM-electron limits (heavy/light Dark Mediator) + dark photon limits, based on 1 and 2 electron signal, assuming negligible background



Skipper-CCD

Advantages:

- **Very low leakage current**, < 10^{-21} A/cm^2 at 140 K
- Excellent **spatial resolution**
- Background identification and rejection, **3D reconstruction for surface events**, follow up of **radioactive decay** chains using **spatial correlation of events**.

GT08: Toward a 10-kg skipper-CCD sensor

- Must develop new fabrication method for the large number of skipper-CCDs required by the 10 kg experiment. New foundry needed for future fabrication: opportunity to migrate into the more modern CMOS technology.
- Low noise readout for 10 kg system: several thousand channels, comparable in size with that of the largest CCD cameras ever built for astronomy, but with more stringent noise requirements.
- Needed background more than an order of magnitude lower than planned for SuperCDMS at SNOLAB (goal of zero ionization events in the 2-10 e- signal range)

Skipper-CCD @ in2p3

- Involvement in DAMIC-M @LSM; low-radioactivity.
- LSST+DAMIC-M: expertise in read-out and CMOS technology that are required for development of future 10 kg array
- Simulation and data analysis
- Strong connexion with US partners (Fermilab, Chicago, Washington, PNNL): US project for 10 kg

The direct search for Dark Matter in the keV/c2 to GeV/c2 range through its interaction with nucleons or electrons using solid-state cryogenic detectors

CRYOGENIC DETECTORS

SubGeV program (2020-2025)

1 kg array of Ge heat-and-ionization detectors with

- Full event-by-event ER/NR discrimination above 50 eV when operated at low bias (<10 V) *– NR searches of 0.1-1 GeV DM*
- Single-electron thresholds when operated at high bias (100 V and more) *– ER searches 0.5-10^5 MeV DM*
- Statistical separation (and comprehensive study) of backgrounds from the comparison of the data recorded at HV/LV

30 g Ge units with

- σ=10 eV phonon resolution (18 eV already achieved)
- σ=20 eV_{ee} ionization resolution (via HEMT preamp)
- 100 V achieved on large 800 g Ge, 400V on 200g

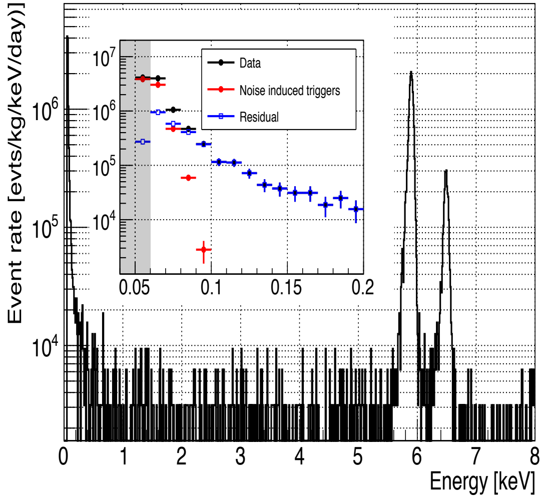
SubGeV program (2020-2025)

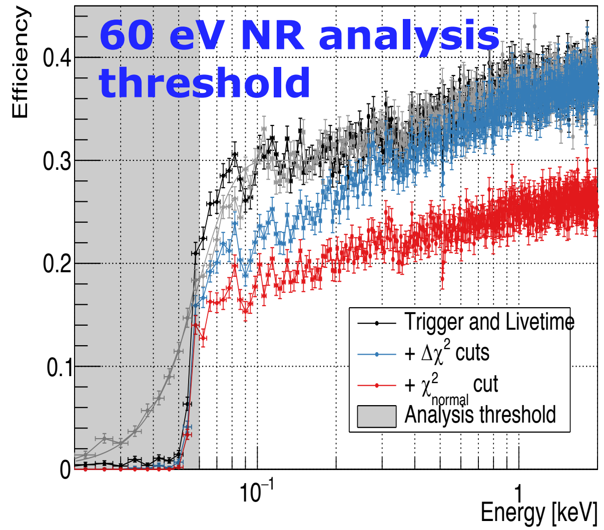
30 g Ge units with

- σ = 10 eV phonon resolution (18 eV already achieved)
- σ = 20 eV_{ee} ion. resolution (devel. of cold HEMT preamp)

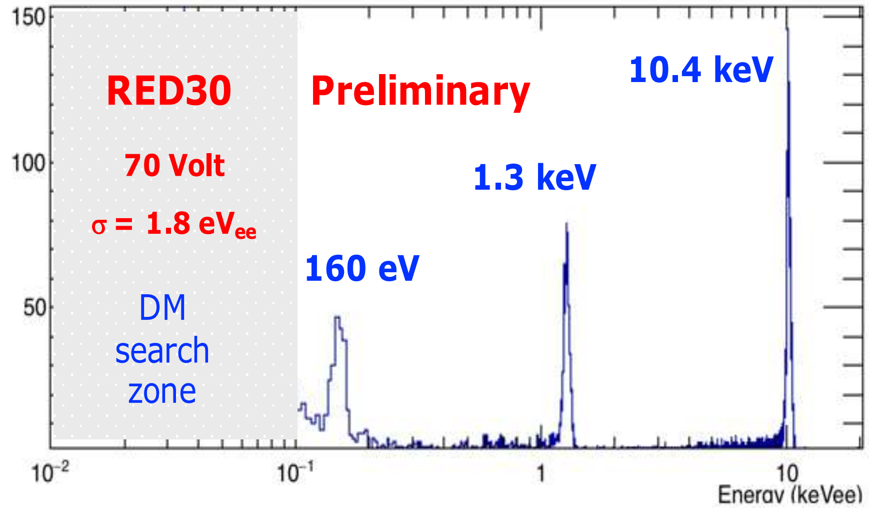
100 V achieved on large 800 g Ge; 400V on 200g

σ= 0.6 electron already achieved on 30 g @ 70V





- RED30 : 33 g Ge Al electrodes, NTD thermal sensor



Instrumentation challenges

Cf contributions to cryogenic detectors in GT08

- Dual (phonon+ionization) readout important for the study & control of instrumental backgrounds (heat-only, dark current due to trapping)

- R&D to combine high-resolution thermal readout with a tag on one charge (or more) using superconducting thin film sensors inspired by the Superconducting Single Photon Detectors (SSPD)

- Beyond 2025: extend cryogenic detector expertise to superconducting metal absorbers able to reach few meV energy thresholds and study their electromagnetic background suppression capabilities.

Solid-state cryogenics detectors @ in2p3

- Expertise in design, production and operation of solid-state cryogenic detectors: phonon sensor developments, low-noise charge readout, control of leakage currents.
- Very strong synergy with two other major projects using solid-state cryogenic detectors: Ricochet-CENNS and CUPID-Mo/CROSS double beta decay experiments
- Close relationship with the French company CryoConcept - best designer of ultra-low vibration dry dilution refrigerators
- Long standing experience and investment in a very-low background experiments at the LSM.
- Leadership position in EDELWEISS
- Collaboration with US and Canadian partners in SuperCDMS.

CONCLUSIONS

Conclusions

- Strong physics motivation & technological opportunity to explore eV-GeV range of DM mass with direct detection experiments
- Rapid advances in development of new detectors dedicated to that range – *Technological developments central issue*
  - Detector backgrounds, scalability
  - Contributions to GT08
- In France:
  - Gas detectors: NEW—G @SNOLAB, Mimac/ALPS
  - Skipper-CCD detectors with DAMIC-M @ LSM (1 kg) and future 10 kg
  - Cryogenic detectors @ LSM (heat+LN boost, single-electron tag)
- Note: LSM used in all 3 projects
  - Deepest lab in Europe, easy access: excellent platform for these detector developments, and <100 kg experiments.

BACKUPS

Scattering: materials vs mass & energy scale

Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632)

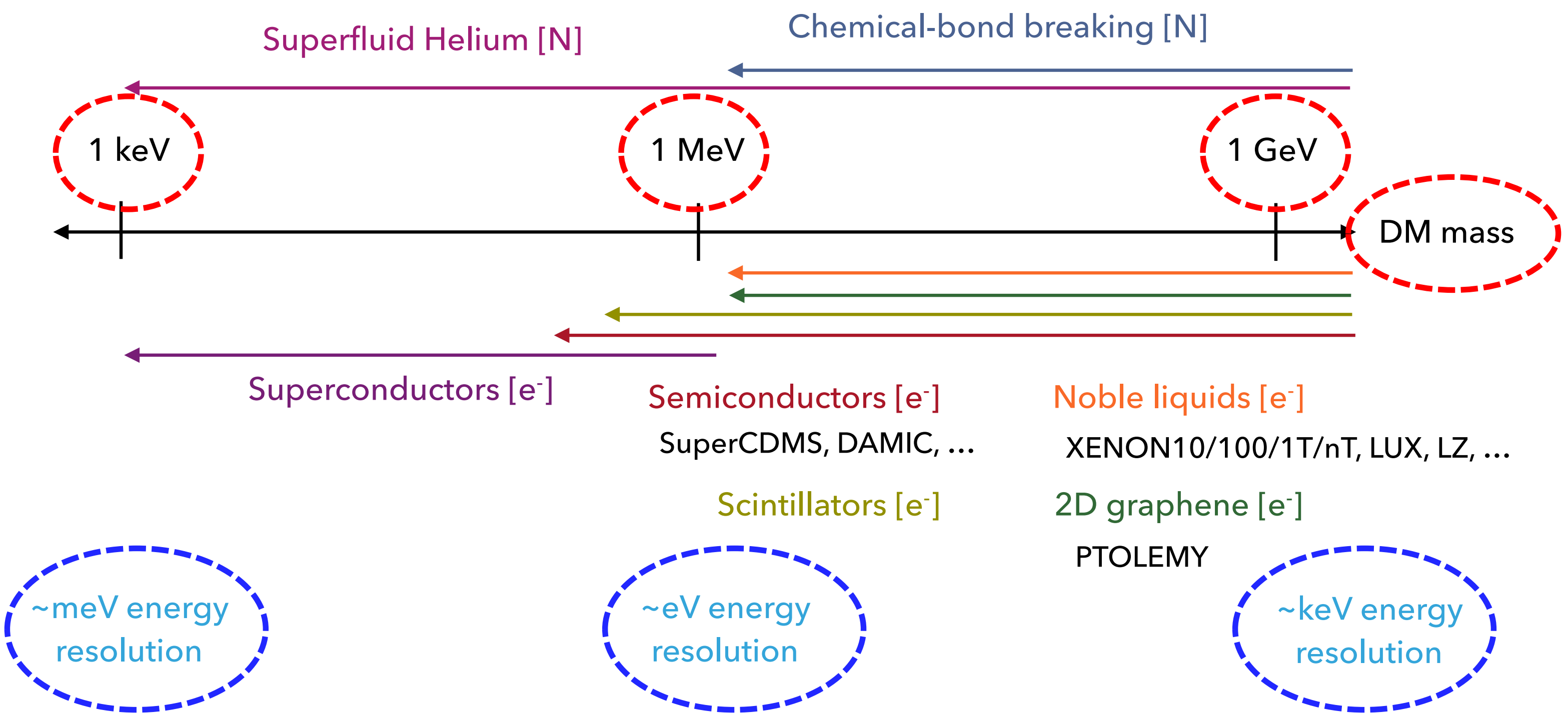


FIG. 11: Materials that could be used to probe sub-GeV DM, down to keV masses, by *scattering* off electrons [e^-] or nuclei [N]. Certain DM candidates, which can instead be *absorbed* by bound electrons in these materials, could be probed down to meV masses (not shown). Adapted from [173].

See also: K. Zurek, CERN-th colloquium 03.08.16

Technologies

Dark Sectors 2016 Workshop: Community Report (arXiv:1608.08632):

Material	$m_{\rm DM,th}$ (theoretical)	Technology	Challenges	(Optimistic) Timescale
Noble liquids (Xe, Ar)	few MeV	two-phase TPC	dark counts	existing
Semiconductors (Si, Ge)	$\sim 0.1 - 1$ MeV	CCDs & Calorimeter	dark counts (?)	$\sim 1 - 2$ years
Scintillators (GaAs, NaI, CsI)	$\sim 0.5 - 1$ MeV	Calorimeter: $\sigma_E \sim 0.2$ eV	sensitivity & afterglow (?)	$\lesssim 5$ years
Superconductors (Al)	~ 1 keV	Calorimeter: $\sigma_E \sim 1$ meV	sensitivity & unknown backgrounds	$\sim 10 - 15$ years
Superfluid He (NR)	~ 1 MeV	Calorimeter: $\sigma_E \sim 1$ eV	sensitivity & unknown backgrounds	$\lesssim 5$ years
Bond Breaking	$\sim$few MeV	color centers	sensitivity & unknown backgrounds	$\lesssim 5$ years
Superfluid He (2-excitation)	~ 1 keV	Calorimeter $\sigma_E \sim 10$ meV	sensitivity & unknown backgrounds	$\sim 5 - 10$ years
2D-targets (graphene)	few MeV	based on PTOLEMY	low exposure, unknown backgrounds	$\sim 5 - 10$ years

TABLE III: Material, theoretical mass threshold, required technology to achieve lowest mass threshold, potential or known challenges, and optimistic timescales. All materials and techniques, besides two-phase TPCs in noble liquids, still need to be demonstrated to have sensitivity to sub-GeV DM. Most timescales are thus only illustrative of the time needed to study their feasibility. Materials/techniques sensitive to DM-electron (DM-nucleus) interactions are at the top (bottom) of the table.