The search for dark matter particles with mass below the GeV scale

Elías López Asamar

Café com Física, Universidade de Coimbra, 20th of March 2019

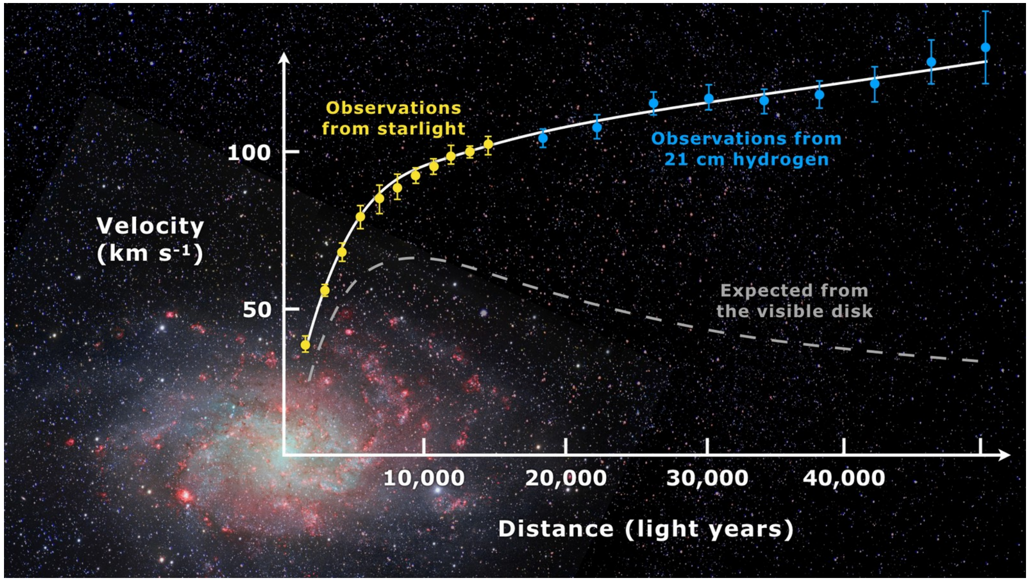
OVERVIEW

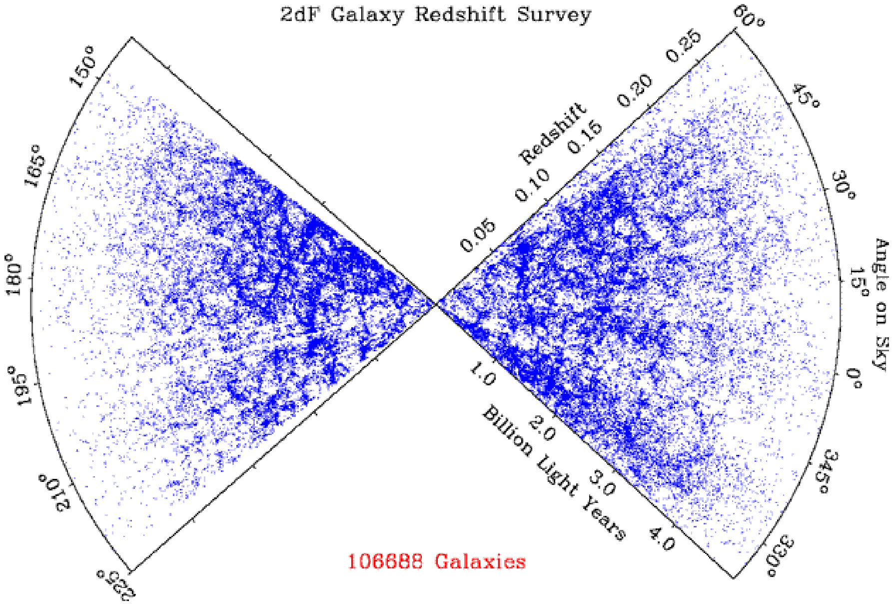
- **Introduction: Dark matter problem**
- **Direct dark matter detection, interest in sub-GeV regime**
- **Semiconductor detectors: SuperCDMS**
- **New detection approaches**

THE DARK MATTER PROBLEM

From <u>gravitational effects</u> observed over a <u>wide range of astronomical scales</u> we infer that ~85% of the mass content of the universe does not interact with electromagnetic radiation ⇒ Dark matter (DM)

- **Galaxy rotation, motion of galaxies in clusters, Bullet Cluster**
- **Large-scale structure of universe, anisotropies in CMB**





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But:

Standard Model (SM) particles cannot account for DM ⇒ New elementary particles?

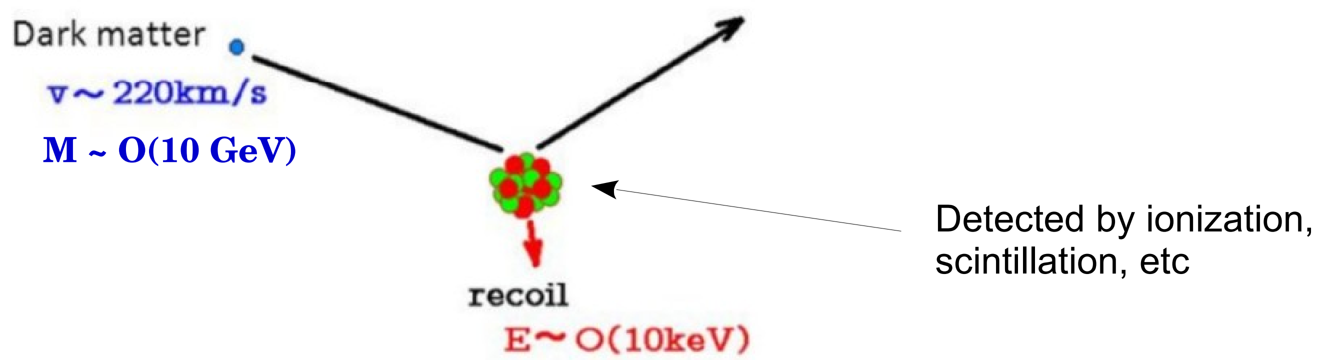
Traditional candidates: "WIMPs", with mass ~ O(10 GeV) – O(100 GeV)

DIRECT SEARCH FOR DARK MATTER

DM is expected to be distributed all over our galaxy, including the vicinity of Earth

Then, if DM has some coupling to SM particles, we expect it to interact with matter on Earth

Direct search for DM: Signal is a recoiling nucleus/electron, produced after the interaction with a DM particle



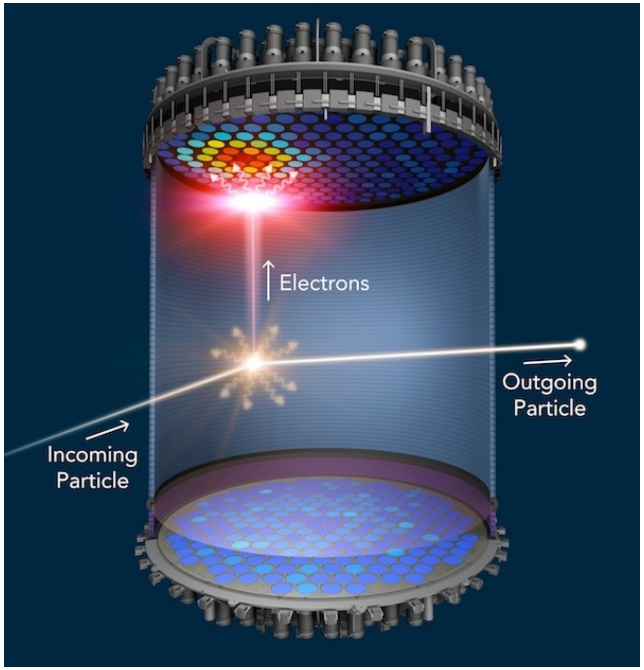
This talk will focus on the <u>recoiling nuclei</u> case: In many DM models the interaction with electrons is suppressed w. r. t. that with nucleons

DIRECT SEARCH FOR DARK MATTER

Direct detection (DD) experiments consist of a specific target material that has the ability to detect the recoiling nuclei produced within it

Frequently, experiments combine signals to properly identify recoiling nuclei:

- **Ionization+scintillation: LZ, XENON (Xe), DarkSide (Ar)**
- **Phonons+ionization: SuperCDMS (Ge, Si), EDELWEISS (Ge)**
- **Phonons+scintillation: CRESST ($CaWO_4$)**



Example: Xe detector (LZ)

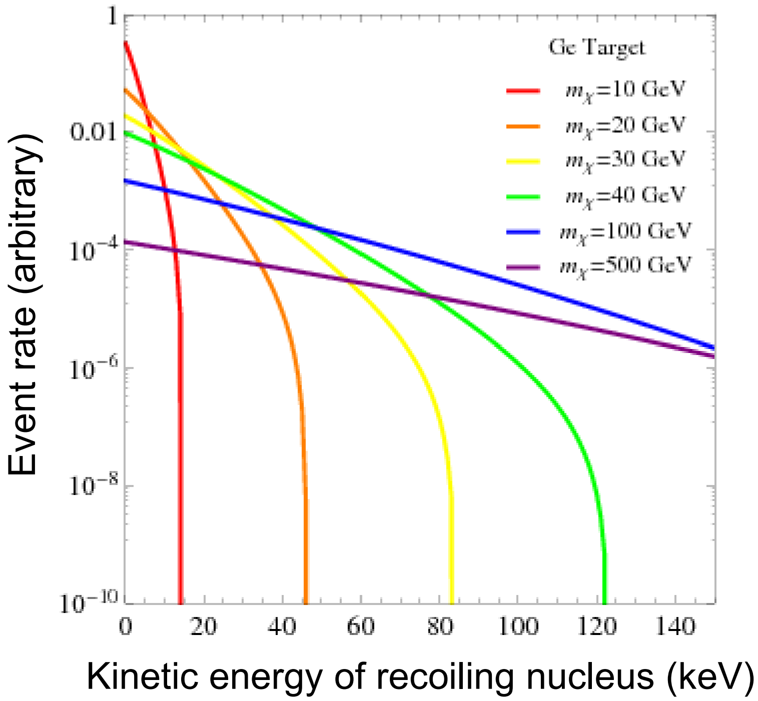
Solid-state detectors will be considered in more detail later

DIRECT SEARCH FOR DARK MATTER

The energy spectrum of the recoiling nuclei depends on the properties of DM:

- **Spectrum shape determined by <u>mass of DM particle(s)</u> (m_χ)**
- **Spectrum normalization determined by <u>strength of DM-nucleon coupling</u> ($\sigma_{\chi N}$)**

(The density and velocity distribution of DM particles are assumed to be known)



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(The density and velocity distribution of DM particles are assumed to be known)

Therefore, the energy spectrum measured by a DD experiment provides information about the existence of DM particles with specific values of m_χ and $\sigma_{\chi N}$

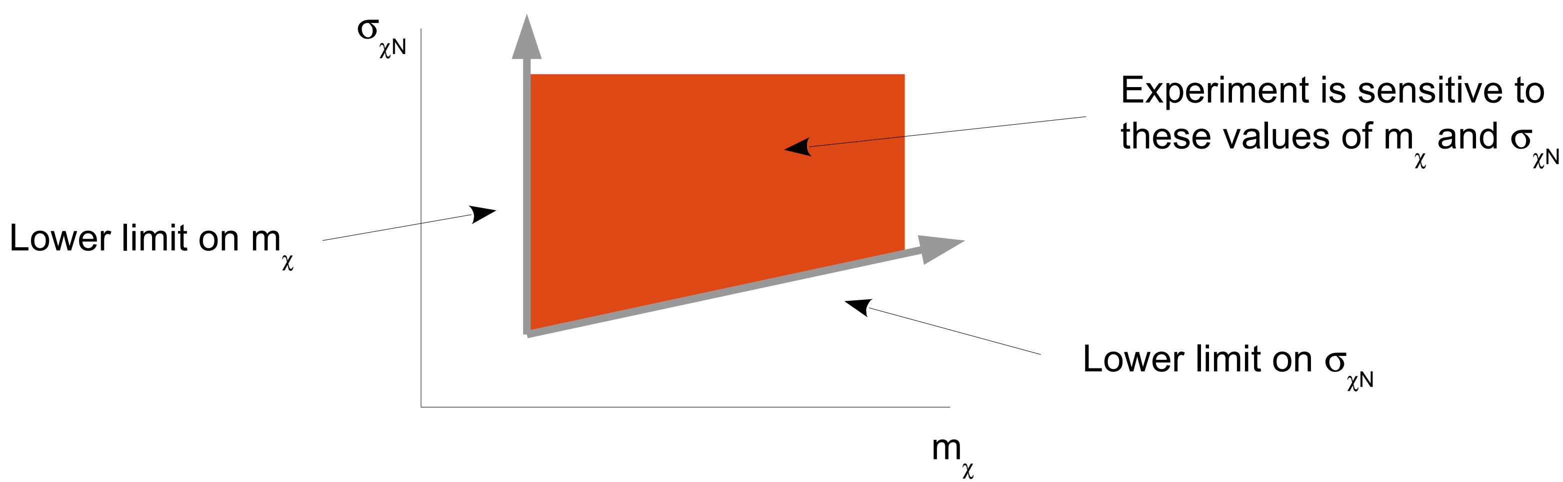
DIRECT SEARCH FOR DARK MATTER

For a given experiment, the minimum value of m_χ that can be attained depends on:

- **The mass of the target nucleus (lighter nuclei receive larger recoil energy)**
- **The threshold on the measurement of the recoil energy**

Whereas the minimum value of $\sigma_{\chi N}$ that can be attained depends on:

- **The number of target nuclei (i. e. the amount of target material)**
- **The exposure time**
- **The occurrence of events other than recoiling nuclei caused by DM: <u>Background</u>**

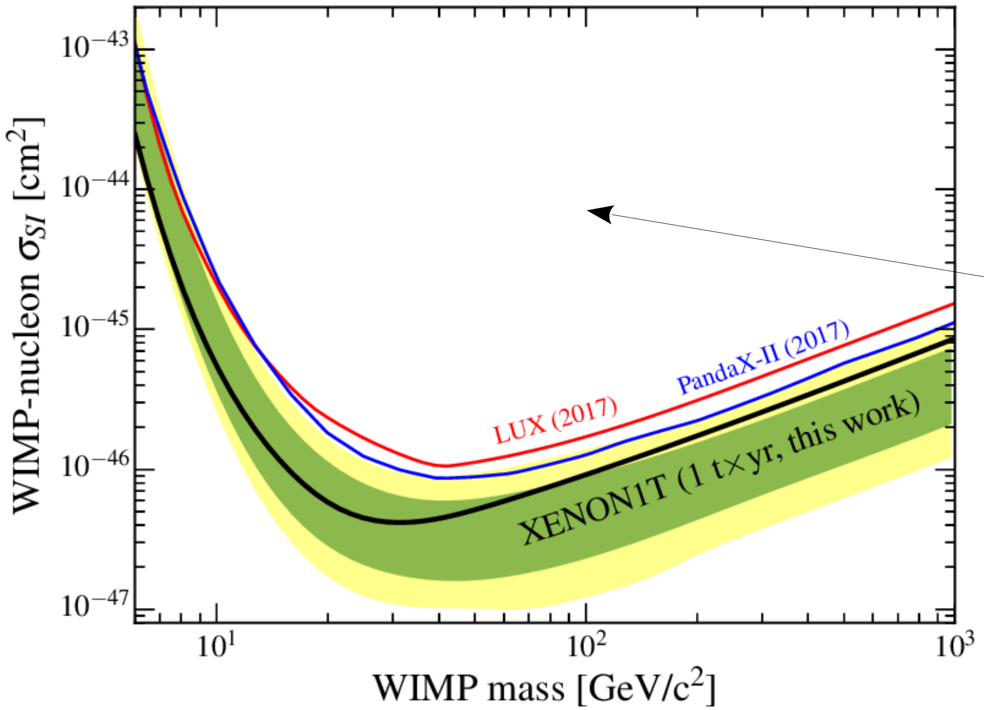


DIRECT SEARCH FOR DARK MATTER

Traditionally, DD experiments have searched for ~ O(10 GeV) – O(100 GeV) DM particles ("WIMPs")

But: So far, these experiments have not yet found a conclusive DM signal

The null results obtained so far constrain the value of m_χ and $\sigma_{\chi N}$



Exclusion limits for m_χ > 10 GeV

Excluded values of m_χ and $\sigma_{\chi N}$

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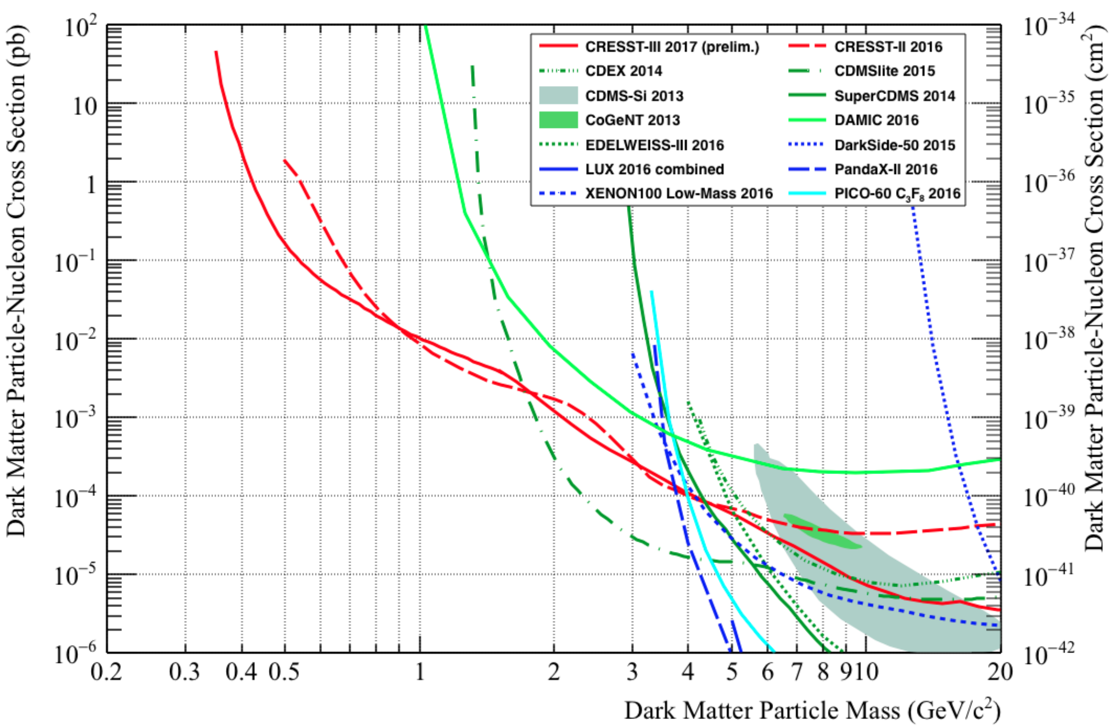


Exclusion limits for m_χ < 10 GeV

Again, excluded values of m_χ and $\sigma_{\chi N}$ are those above the curves

DarkSide-50 results (2018) not included

G2 PROGRAM AND BEYOND

The null results obtained so far have motivated the development of more sensitive DD experiments

Two main directions:

- **Increase sensitivity to lower values of $\sigma_{\chi N}$: Larger targets+lower backgrounds**
- **Increase sensitivity to lower values of m_χ: FOCUS OF THIS TALK**

G2 ("Generation 2") program: Experiments funded by US DoE and NSF:

- **LZ: Increased sensitivity to lower values of $\sigma_{\chi N}$**
- **SuperCDMS SNOLAB: Increased sensitivity to lower values of m_χ**
- **ADMX G2: Dedicated to search for axion DM**

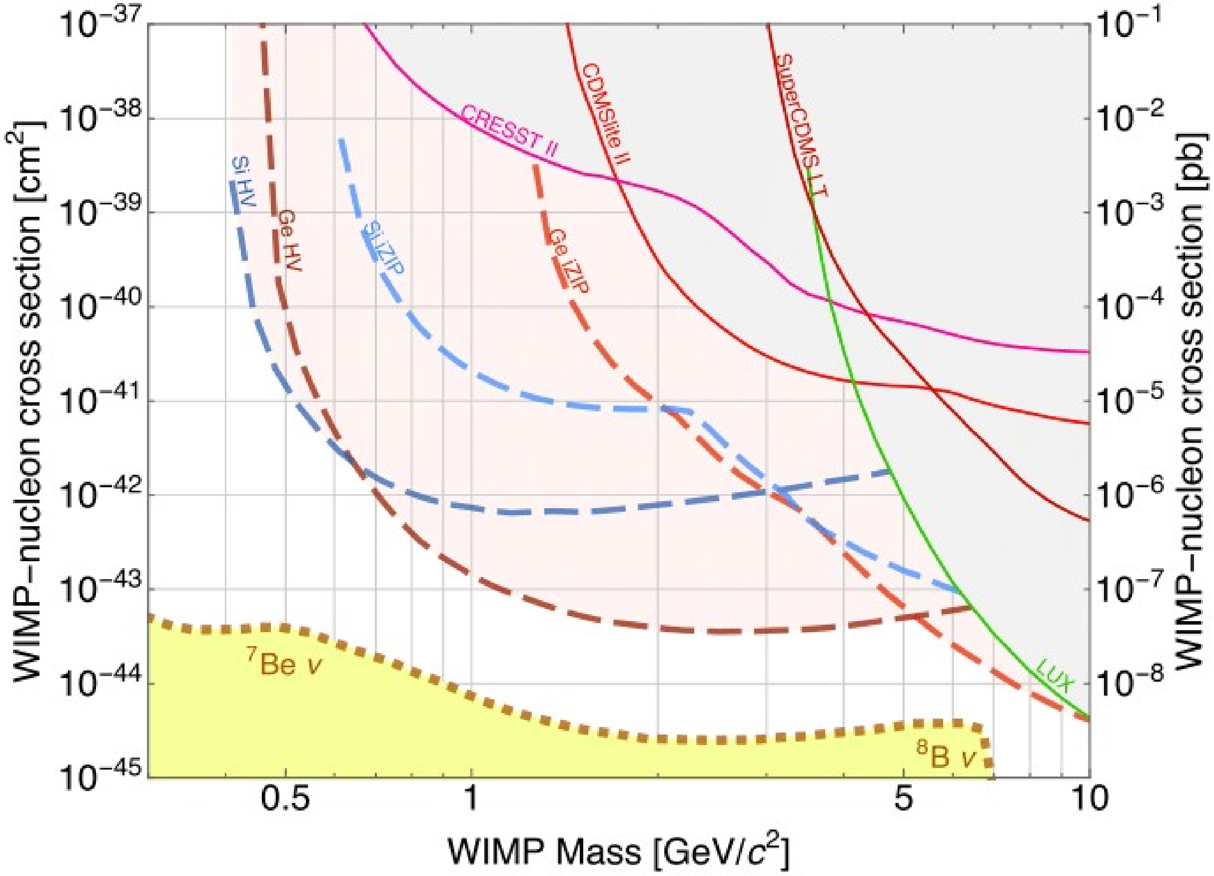
Currently under construction, expected to start operating around ~ 2020

However: Other experiments exist: XENONnT, CRESST III, etc

G2 PROGRAM AND BEYOND

In the near future, SuperCDMS is expected to lead the sensitivity to DM particles with mass below ~ 1 GeV

arXiv:1610.00006



G2 PROGRAM AND BEYOND

In addition to G2 experiments, the DM community considers appropriate to start developing ideas to further extend the exploration of the sub-GeV regime

B. Summary of Science Case for New Small-Scale Direct-Detection Experiments

Direct-detection experiments play a unique and essential role in our quest to identity the DM. Several proposals and ideas exist for new experiments that present a low-cost opportunity — well within the "small-project" scale — to **probe DM with masses between the meV to GeV scale**, many orders of magnitude in mass below the planned searches by the G2 experiments LZ and SuperCDMS (see Fig. 4 for a schematic overview). In fact, the working group recognizes that recent advances in theory and experiment means that *now* is the right time for targeted investments to bring to fruition several recent new ideas and proposals and develop them into real experiments.

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Community Report of workshop "US Cosmic Visions: New Ideas in Dark Matter" (2017), pg. 32
arXiv:1707.04591

Also interesting: "Summary of the High Energy Physics Workshop on Basic Research Needs for Dark Matter Small Projects New Initiatives" (2018)
HEP Community Resources, US DoE Office of Science

G2 PROGRAM AND BEYOND

Based on the previous discussions, the rest of this talk will cover:

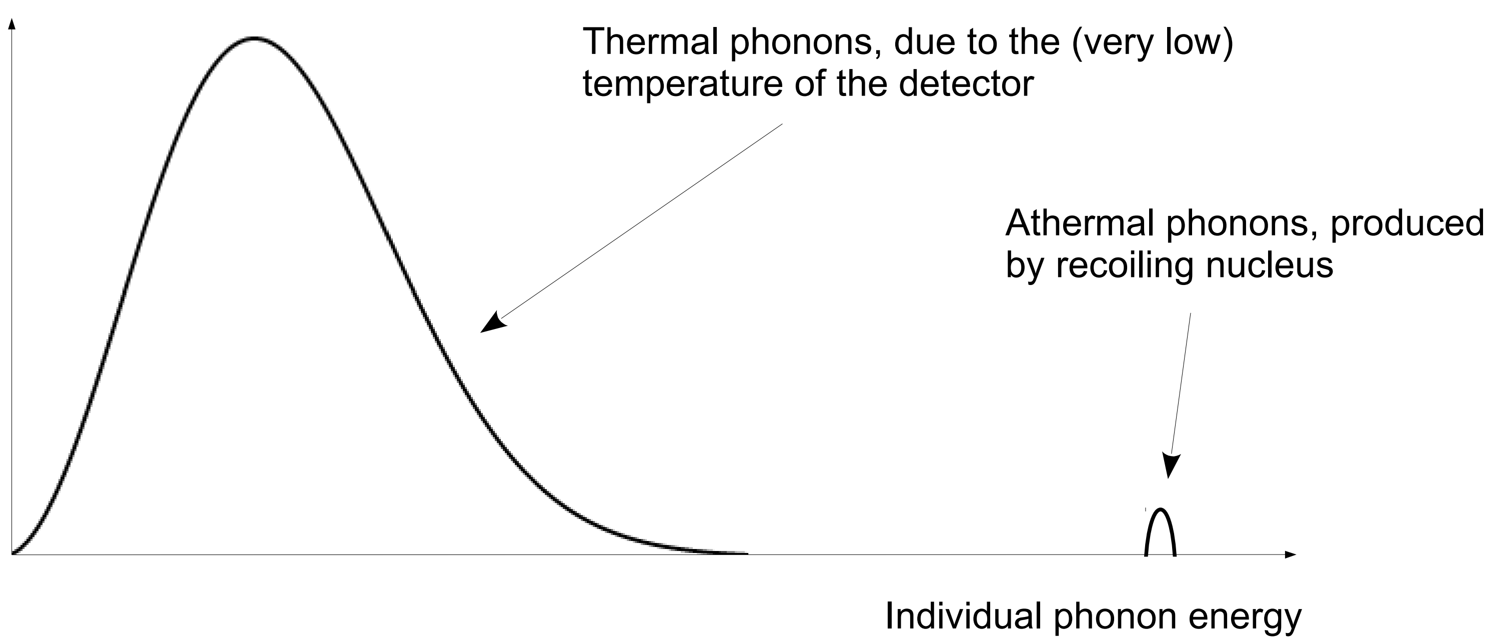
- **A detailed description of the SuperCDMS detectors**
- **Brief review of new direct detection approaches**

THE SUPERCDMS DETECTORS

THE SUPERCDMS CONCEPT

Single Ge or Si crystals, instrumented to measure signals from recoiling nuclei:

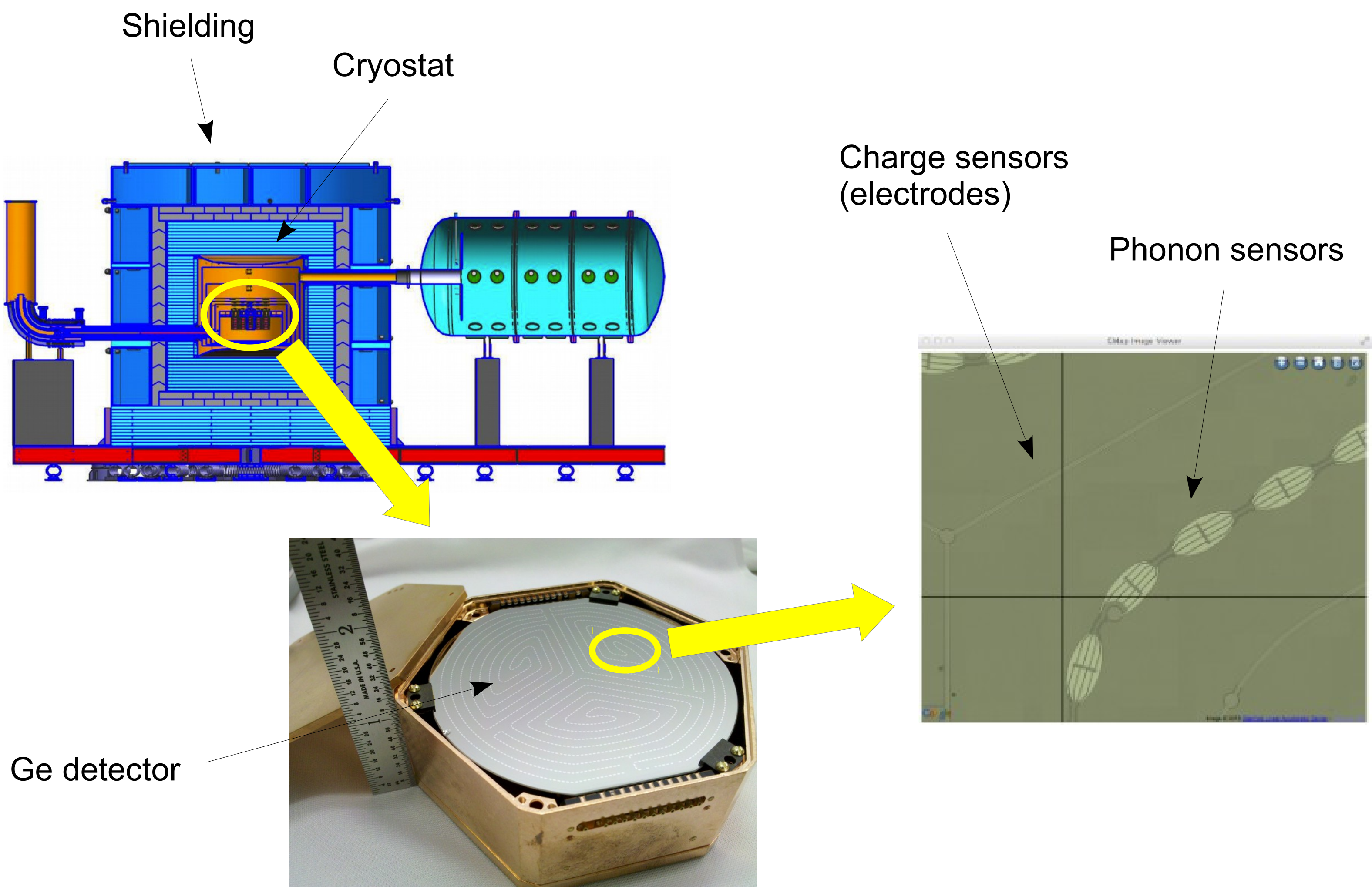
- **Number of charge carriers created (electron, holes) (N_Q)**
- **Energy carried by athermal phonons (quanta of lattice vibrations) (E_P)**



Require cryogenic operation (~ 50 mK)

THE SUPERCDMS CONCEPT

Cylindrical detectors, instrumented on both sides, with electric field applied



THE CHARGE SIGNAL

Ionization yield (Y): Fraction of recoil energy that is used to create charge carriers

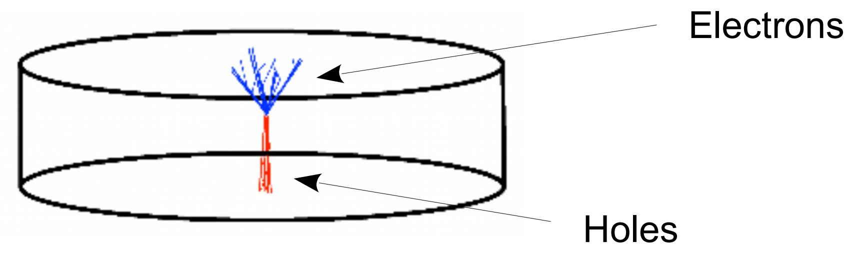
Y depends on recoiling particle: ~ 0.3 for nuclei, ~ 1 for electrons

Propagation of charge carriers that drift in an electric field:

- Electrons propagation is oblique w. r. t. the electric field
- Luke scattering: Charge carriers can interact with lattice, transferring some kinetic energy as additional phonons

Luke scattering limits the drift velocity

MC simulation of charge carrier propagation



MEASUREMENT OF THE CHARGE SIGNAL

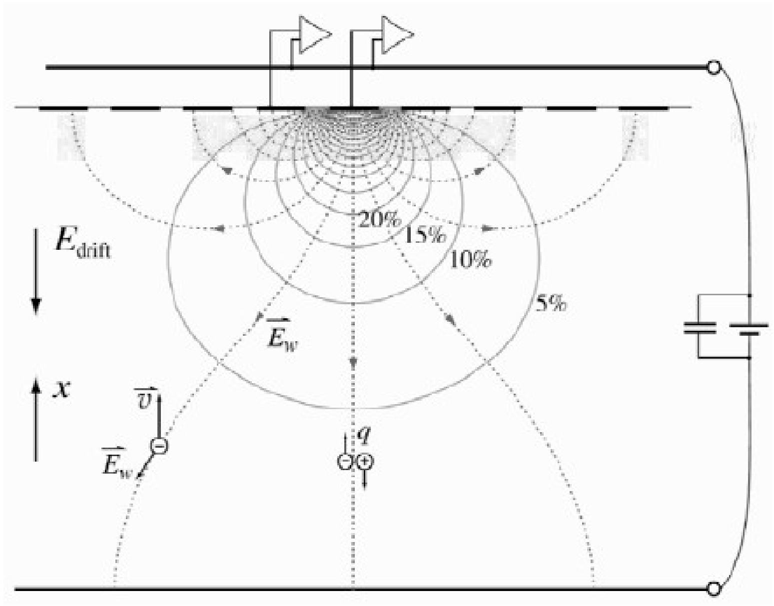
Drifting charge carriers are measured by current induced in the electrodes

Based on Shockley-Ramo theorem

$$I = e\,\mathbf{E}_w(\mathbf{x}) \cdot \mathbf{v}$$ (instantaneous)

$$Q_{induced} = -e\phi_w(\mathbf{x})$$ (integrated over time)

$E_w(x)$ and $\phi_w(x)$ quantify the electrode sensitivity at x
(they are not related to the applied electric field)

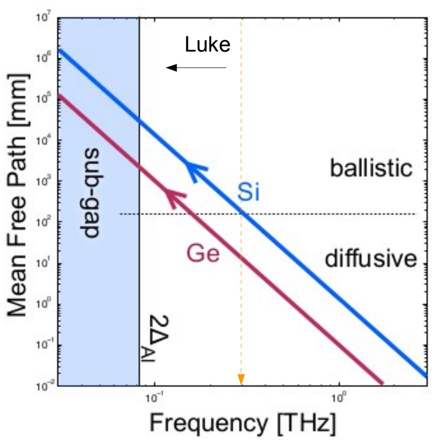


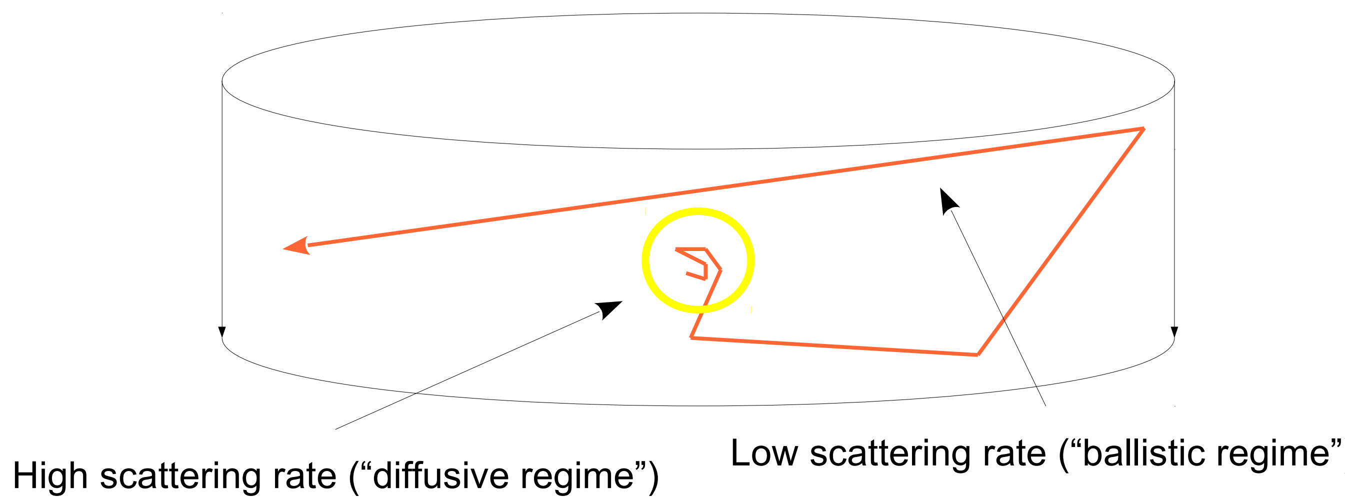
THE PHONON SIGNAL

Individial phonons lose energy by:

- **Isotopic scattering (rate ~ ν^4): Ge and Si isotopes break lattice periodicity**
- **Anharmonic decay (rate ~ ν^5): Due to non-harmonic terms in phonon hamiltonian**

Given the dependence on ν, initial phonons scatter much more frequently than late phonons





Phonons directly created by recoiling particles (“prompt phonons”) are diffusive, phonons created by Luke scattering are almost ballistic

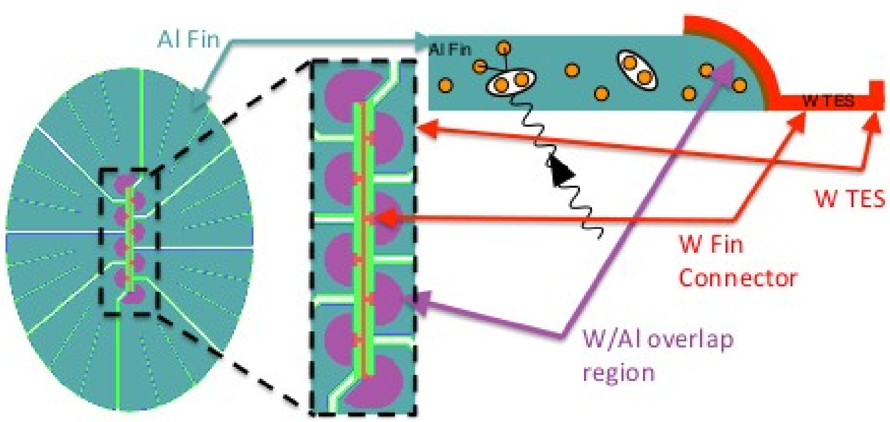
MEASUREMENT OF THE PHONON SIGNAL

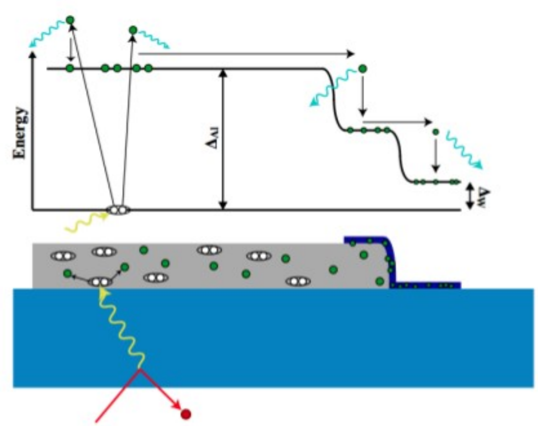
Phonon measurement require detectors with very small heat capacity ⇒ Need to concentrate phonon energy in very small volumes

Phonon energy is concentrated with superconducting <u>Al-W quasiparticle (QP) traps</u>

QP: Excited state in a superconductor ("broken Cooper pairs"), electron-hole superposition (⇒ neutral)

The Al-W overlap creates a gradient in the excitation energy of the superconductor that traps QPs as they diffuse from Al to W





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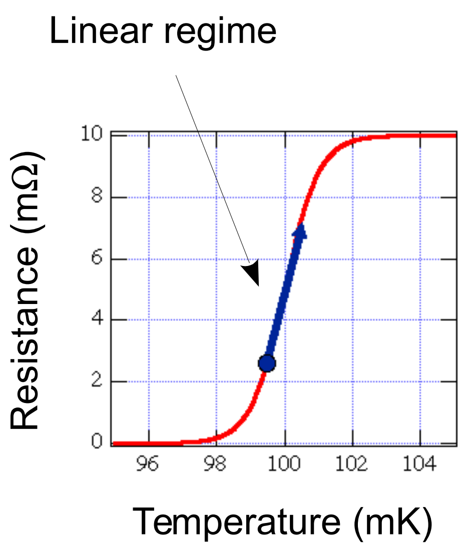
Only phonons above a given threshold can produce QPs in the Al-W traps: This requirement blocks the income of thermal phonons from the Ge volume

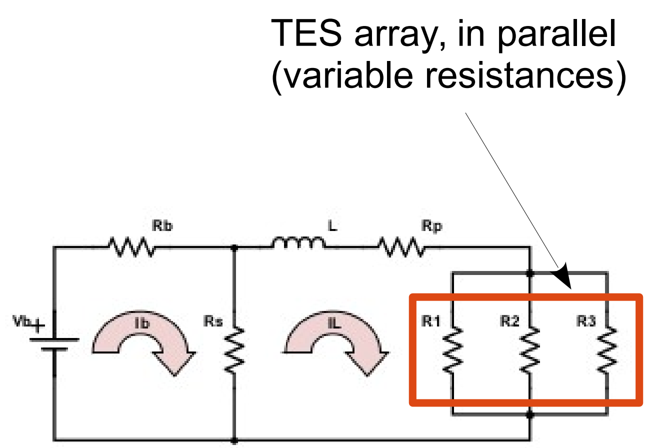
MEASUREMENT OF THE PHONON SIGNAL

Al-W QP traps concentrate the phonon energy in W transition-edge sensors (TES)

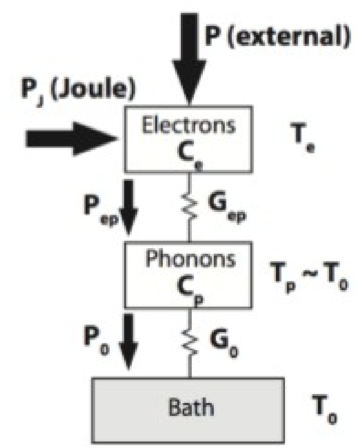
TES: Device kept at its superconducting transition temperature, so that a small heat input leads to a substantial decrease in its conductivity

<u>Stable system</u>: returns to equilibrium by electrothermal feedback (decreased conductivity lowers the current, and therefore the Joule heating)





Electrical model

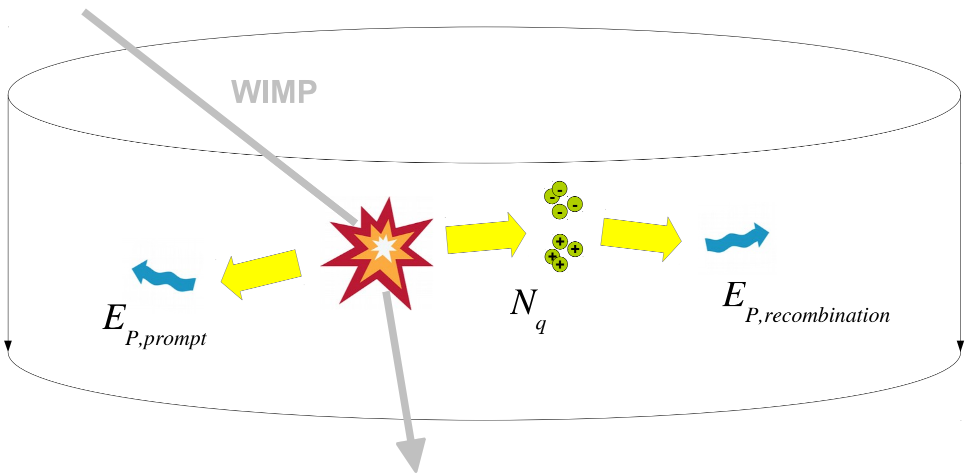


Thermal model

RECONSTRUCTION OF RECOIL PROPERTIES

N_Q (charge signal) and E_P (phonon signal) allow to determine:

- **<u>Recoil energy</u> (E_R) (kinetic energy of recoiling nucleus)**
- **<u>Ionization yield</u> (Y) (quantifies the suppression of the ionization signal, related to the type of recoiling particle)**



Detector, assuming no electric voltage applied

$$\boxed{N_q} = \boxed{Y}\frac{\boxed{E_R}}{\epsilon}, \qquad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$\boxed{E_P} = E_{P,prompt} + E_{P,recombination} = \boxed{E_R}$$

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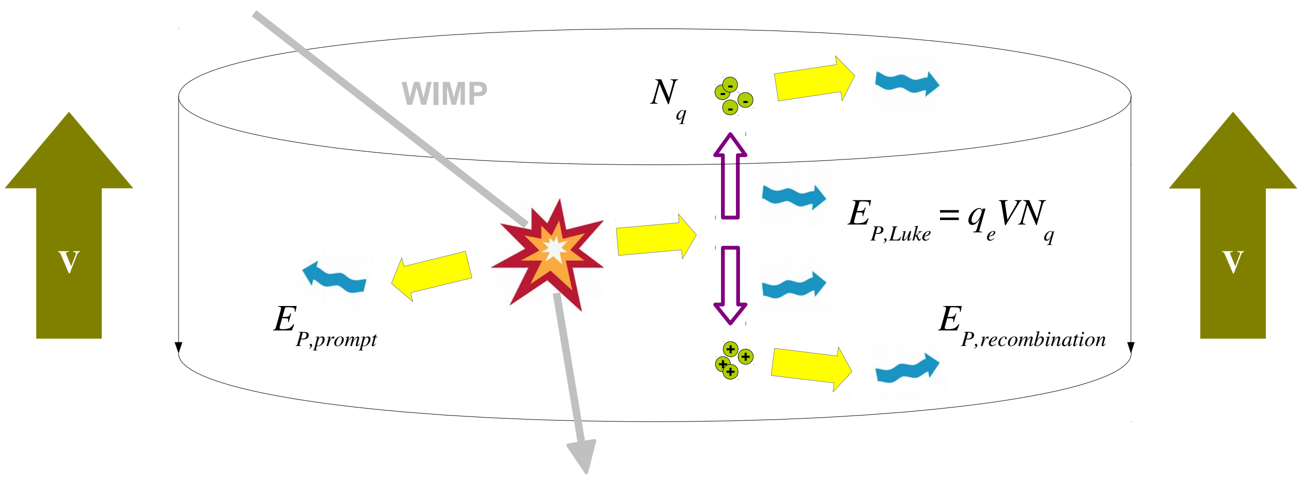


Detector, with electric voltage applied (V)

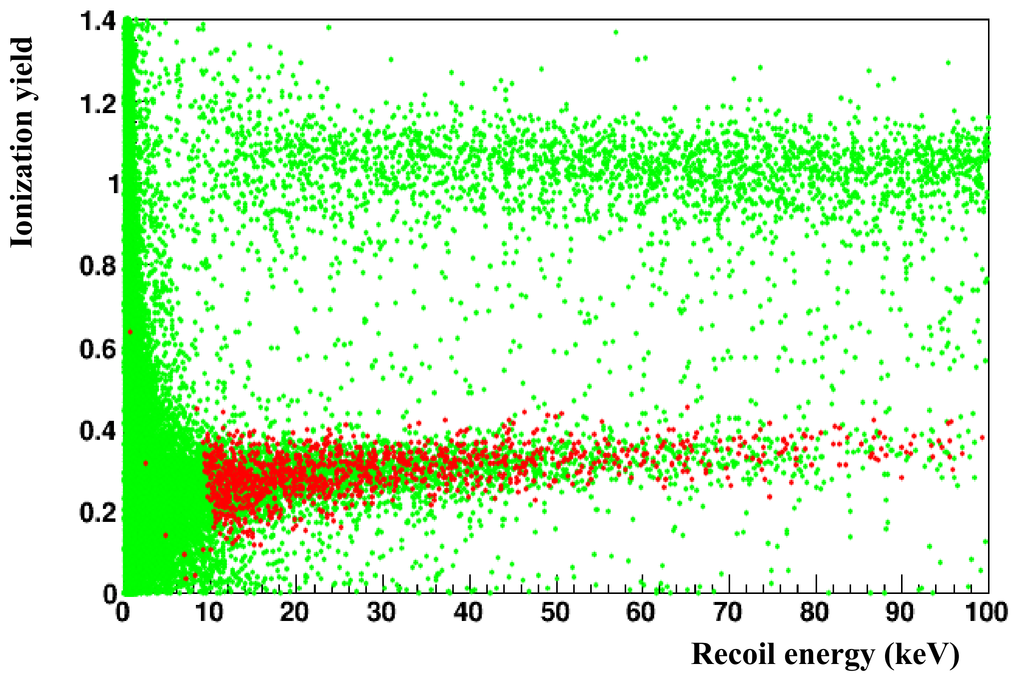
Additional phonons from charge carriers

$$\boxed{N_q} = \boxed{Y}\frac{\boxed{E_R}}{\epsilon}, \qquad \epsilon(\mathrm{Ge}) = 3.0\ eV$$

$$\boxed{E_P} = E_R + q_e V N_q = \boxed{E_R}\left(1 + \boxed{Y}\frac{q_e V}{\epsilon}\right)$$

BACKGROUND REJECTION

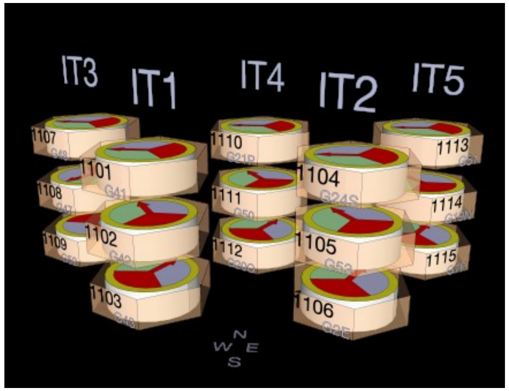
Y (ionization yield) depends on recoiling particle ⇒ Used to <u>reject recoiling electrons</u>



^{52}Cf calibration data (neutrons+gammas)

Recoiling electrons (from gammas)

Recoiling Ge nuclei (from neutrons)

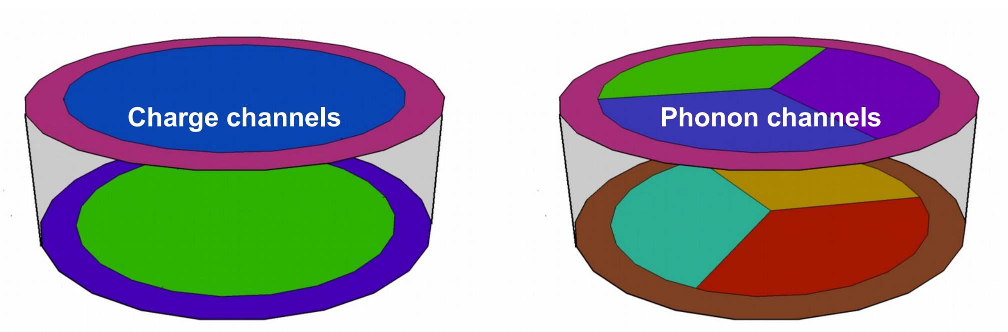


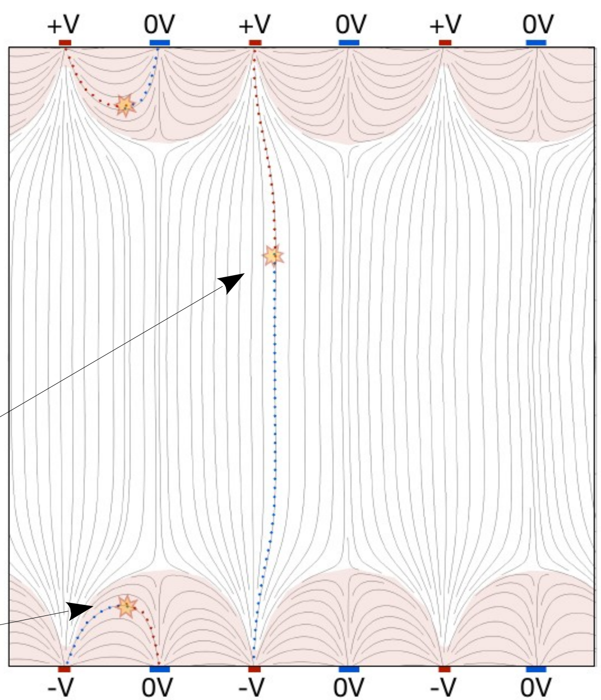
In addition, array of detectors enable multiple-scattering cut

BACKGROUND REJECTION

<u>**Full fiducialization**</u> **achieved by:**

- **Segmented readout**
- **Applied electric voltage (4 V)**
- **Phonon sensors (0 V) interleaved with charge sensors (±2 V)**





Bulk event: charge collected on both sides

Surface event: charge collected on one side only

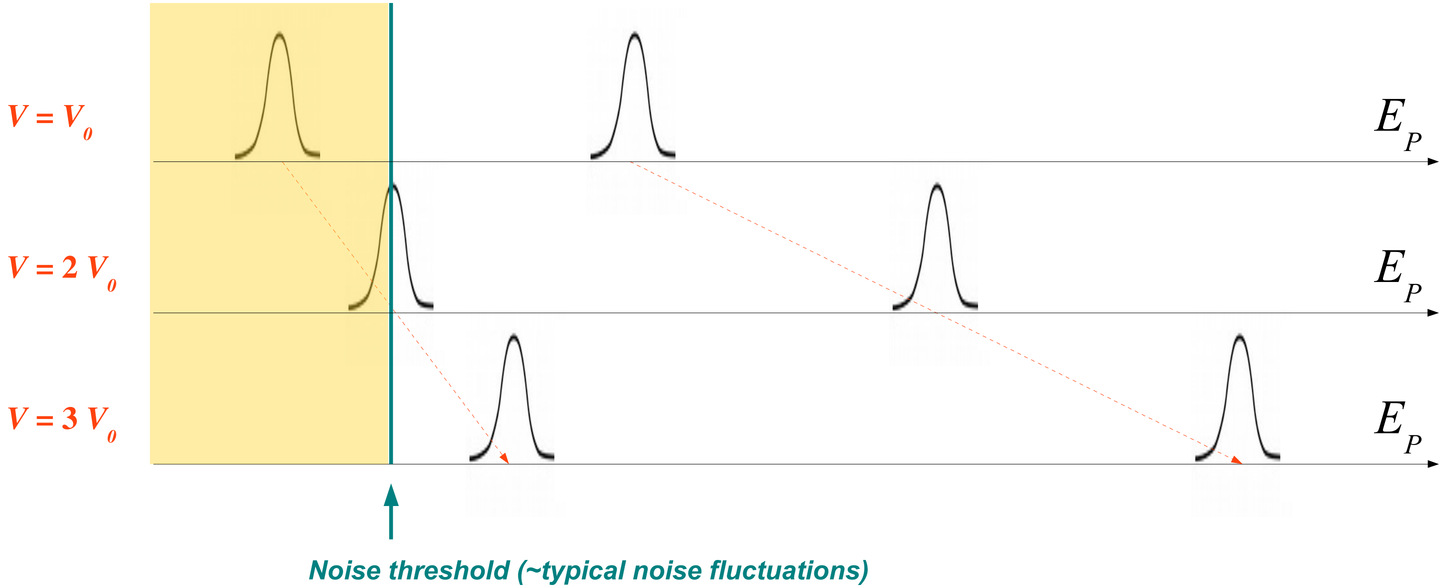
HIGH-VOLTAGE OPERATION

Increased applied voltage (V) allows to effectively decrease the phonon threshold

$$E_P = E_R + q_e V N_q = E_R(1 + Y\frac{q_e V}{\epsilon}) = \boxed{g(V)} E_R$$

$g(V) > 1$

Additional phonons from charge carriers



<u>However charge signal remains below threshold</u>

SUPERCDMS SNOLAB

Project proposal:

- **Nominal detectors (full background rejection capabilities): 14 kg Ge, 1.2 kg Si**
- **HV detectors (lowered energy threshold): 10 kg Ge, 2.4 kg Si**

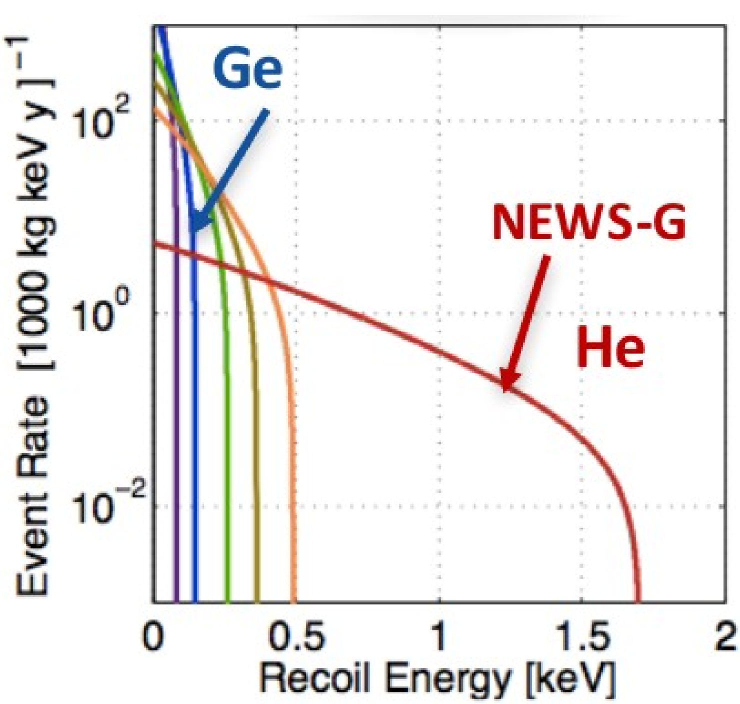
Currently under construction, plan is to start operations around ~ 2020, with ~ 5 years of data taking

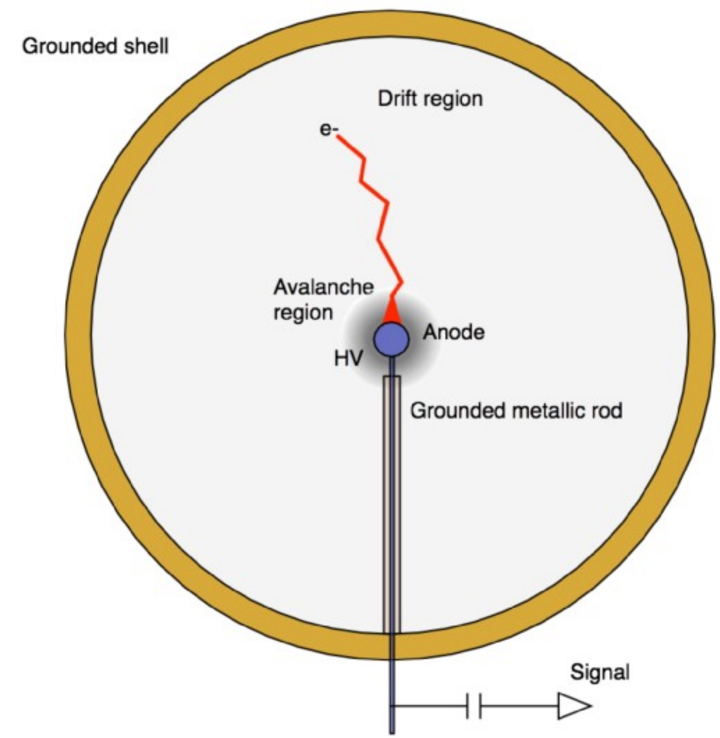
NEW DETECTION APPROACHES

GASEOUS PROPORTIONAL CHAMBER

Concept: Amplify ionization signal produced by a light recoiling nucleus (Ne, He, H)

Currently developed by the NEWS-G Collaboration





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Pros:

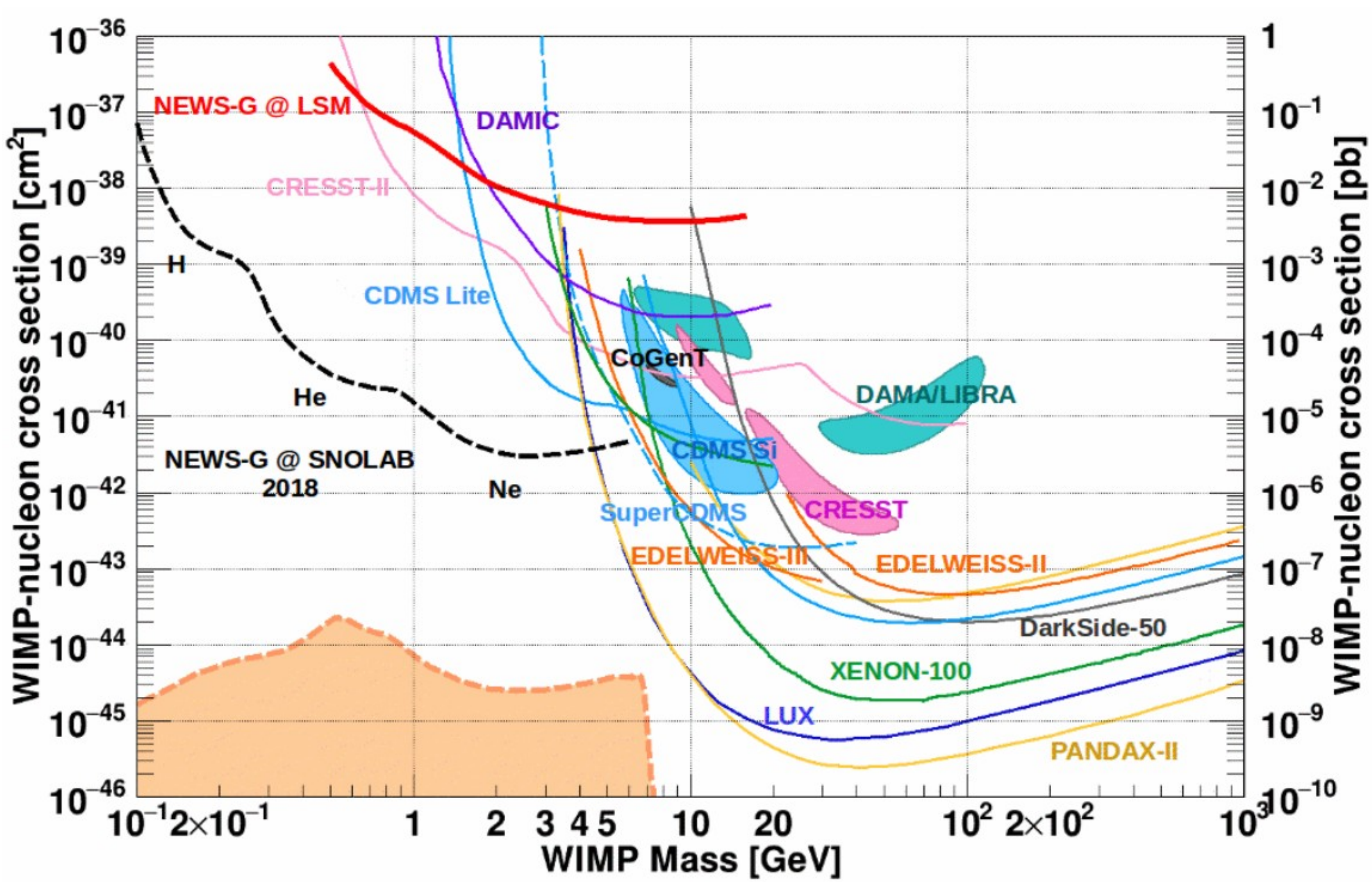
- **Good kinematical match between DM particle and target nucleus**
- **Single-electron resolution**

Cons:

- **Require high pressures to have a relevant target mass**
- **Mass threshold is limited by ionization threshold**

GASEOUS PROPORTIONAL CHAMBER

Sensitivity calculated for 100 kg day exposure (@ 10 bar), assuming single-electron resolution



GASEOUS PROPORTIONAL CHAMBER

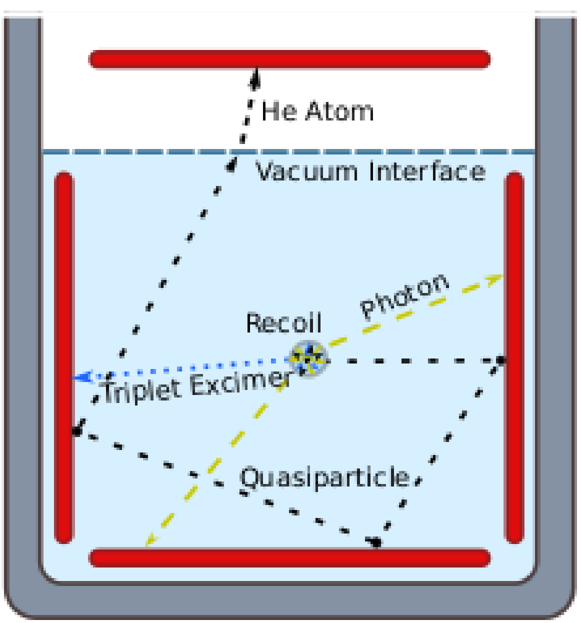
Further information:

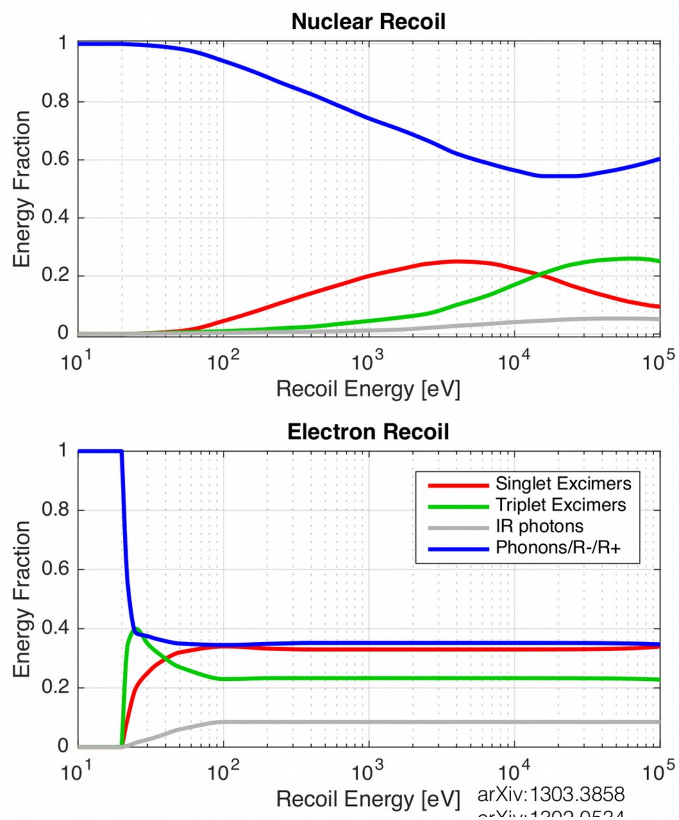
- Talk at "Unraveling the Dark Matter Mystery" (2018)

SUPERFLUID HELIUM DETECTOR

Concept: Dual signal detector based on ^{4}He, measured by TES:

- **^{4}He atoms evaporated by (quantized) excitations of the superfluid (1 excitation quanta evaporates 1 ^{4}He atom): Top calorimeter only**
- **Scintillation light (analogous to other noble gases): All other calorimeters**





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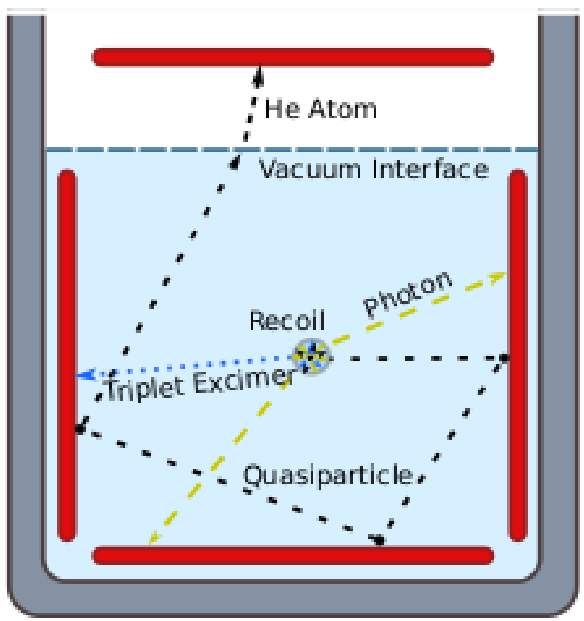

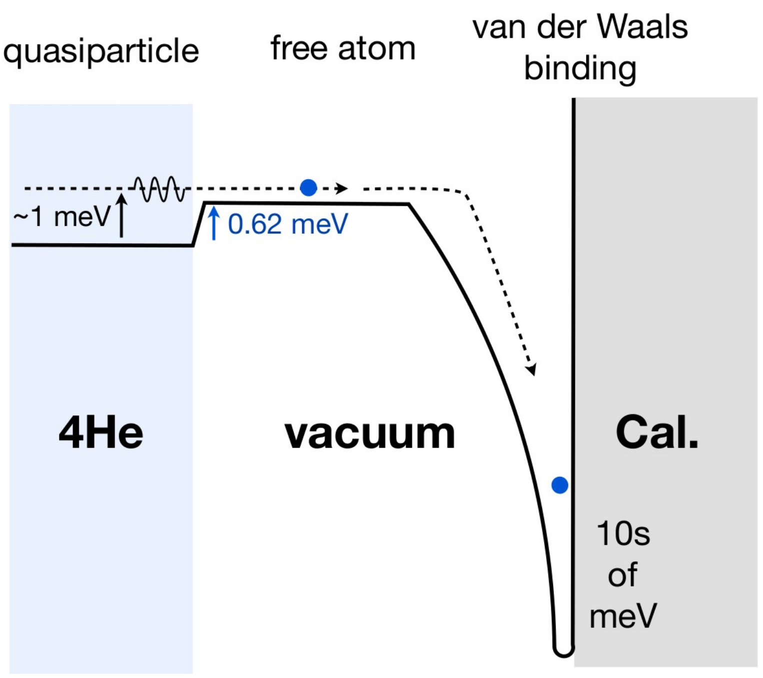

Detection of 4He atoms by adhesion to top calorimeter surface

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Pros:

- **Good kinematical match between DM particle and target nucleus**
- **Very low mass threshold**
- **No dark counts**
- **Allow to reject recoiling electrons down to $E_R \sim 20$ eV**

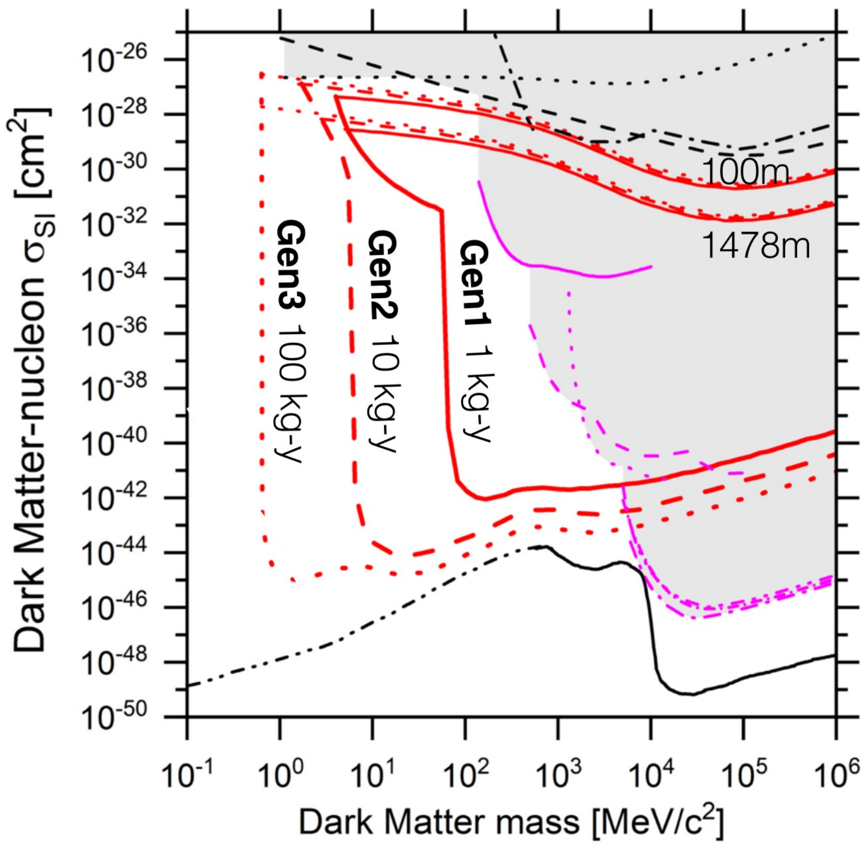
Cons:

- **Require TES microcalorimetry over large areas**

SUPERFLUID HELIUM DETECTOR

Sensitivity calculated for three cases (exposures in Fig. below):

- **Gen1: 5 eV calorimeter threshold (10 eV recoil energy threshold)**
- **Gen2: 1 eV (0.1 eV)**
- **Gen3: 20 meV (1 meV)**



SUPERFLUID HELIUM DETECTOR

Further information:

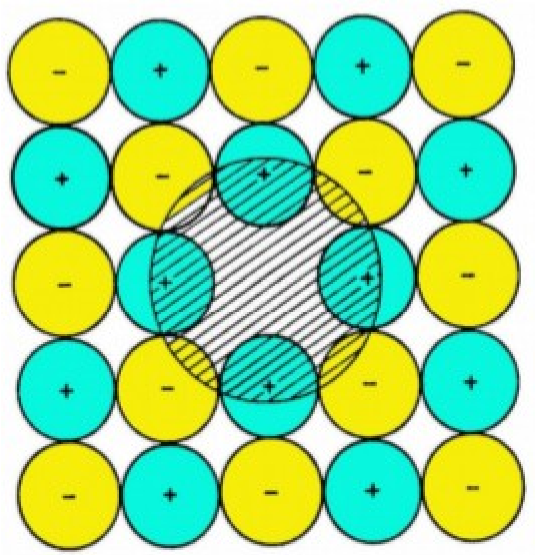
- arXiv:1810.06283
- Talk at IDM 2018

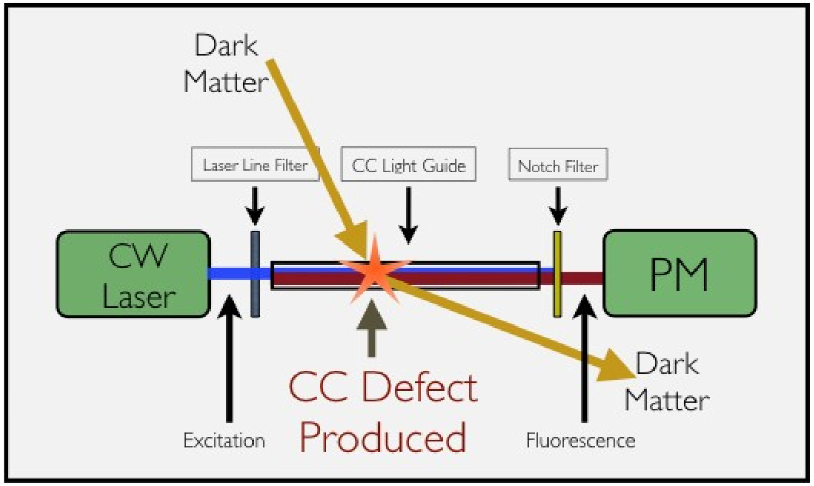
COLOR CENTERS IN CRYSTALS

Concept: Measure the fluorescence induced by a laser on crystal defects caused by the interaction of DM particles

Radiation can produce crystal defects with thresholds as low as ~ O(10 eV)

Natural defects from crystal formation represent a background





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Pros:

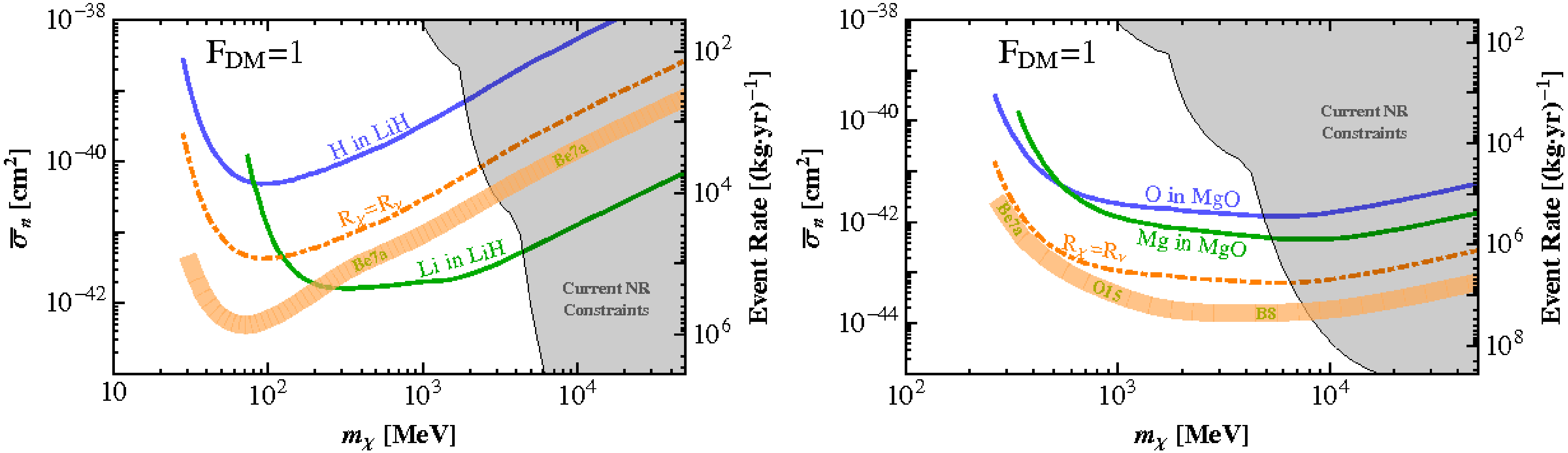
- **Good kinematical match between DM particle and target nucleus**
- **Low mass threshold**
- **Might allow background rejection based on identification of defects**
- **Might provide directionality**

Cons:

- **To have a significant observation of new defects against the background of crystal formation defects, it is necessary to 1) use intense laser beams, and 2) measure fluorescence over ~ O(min) times**

COLOR CENTERS IN CRYSTALS

Sensitivity calculated for 1 kg year exposure



COLOR CENTERS IN CRYSTALS

Further information:

- Talk at “Dark Sectors Workshop” (2016)
- Talk at “US Cosmic Visions: New Ideas in Dark Matter” (2017)
- arXiv:1705.03016

MOLECULAR EXCITATIONS

Concept: Measure de-excitation radiation (infrared) of molecules that vibrate after interacting with a DM particle

Pros:

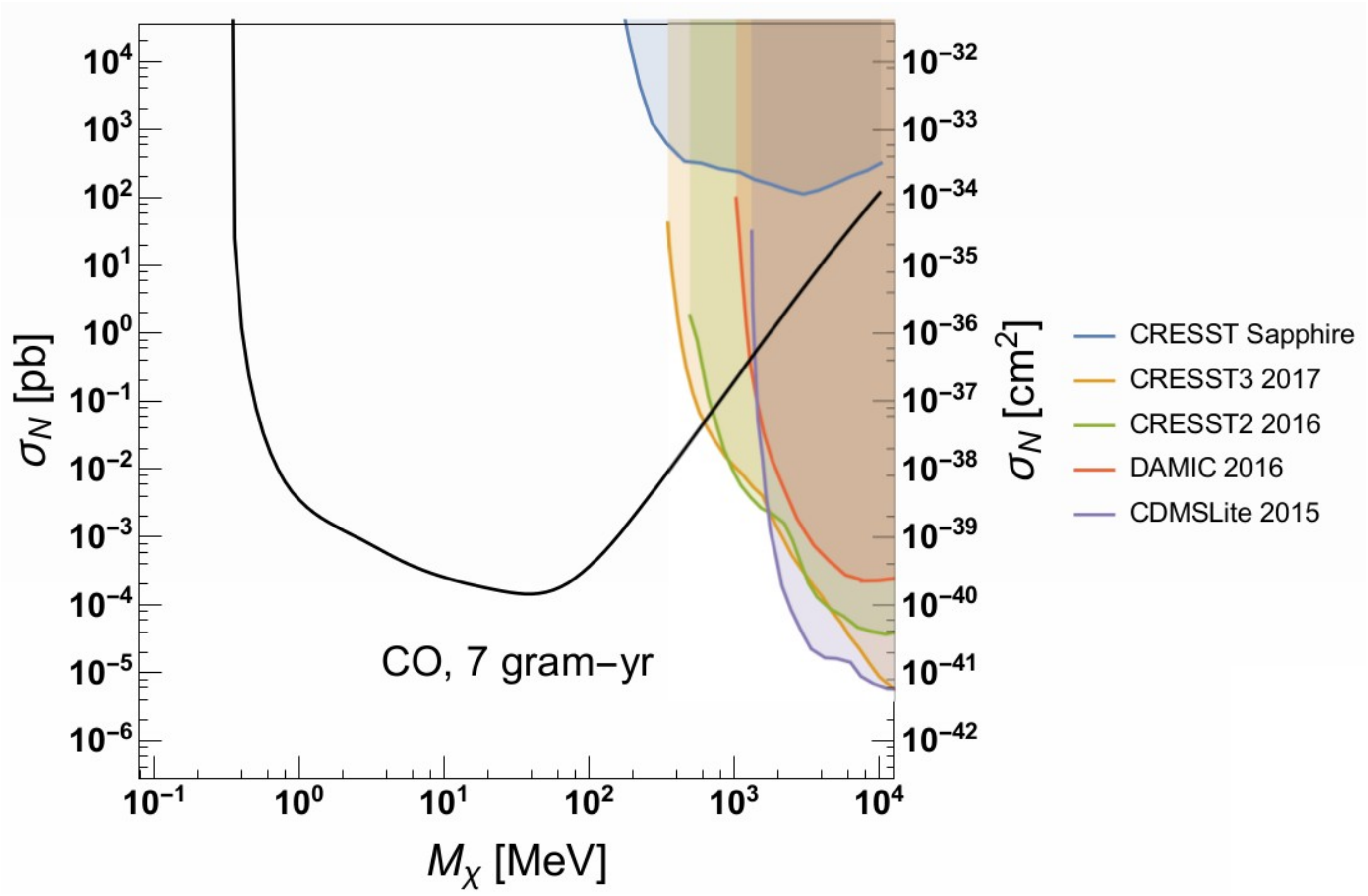
- **Very low mass threshold**

Cons:

- **Require (infrared) microcalorimetry over large areas**
- **Need large volumes because of the low density requirements**

MOLECULAR EXCITATIONS

Sensitivity calculated for 7 gram year (2 m^3 volume) of CO



MOLECULAR EXCITATIONS

Further information:

- Talk at "New Probes for Physics Beyond the Standard Model" (2018)

CONCLUSIONS

- **Determining the fundamental components of DM is one of the most pressing objectives of modern science**
- **So far DM searches have provided null results, but there are experiments under construction that will provide improved sensitivity in the near future**
- **In particular, SuperCDMS SNOLAB is expected to dominate the search for sub-GeV DM during the next years**
- **In addition, the DM community considers that it is important to start developing new approaches to provide further improved sensitivity in the mid- and long-term**
- **These approaches include concepts such as superfluid ^{4}He detectors, or measurement of color centers in crystals**

THANK YOU FOR YOUR ATTENTION...