Using MKIDs for the Direct Detection of sub-GeV Dark Matter?

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MKIDs workshop @ Fermilab, Aug 27, 2013

with:
J. Mardon, T. Volansky (1108.5383, PRD)
A. Manalaysay, J. Mardon, P. Sorensen, T. Volansky (1206.2644, PRL)
+ several works in progress

The Search for Dark Matter

- Major efforts are underway to detect dark matter in the laboratory with "direct detection" experiments
- existing efforts usually focus on detecting elastic nuclear recoils from a 5-1000 GeV WIMP (e.g. neutralino)
- improvements expected from:
  - bigger detectors (to probe lower cross sections)
  - lower thresholds (to better probe 1-10 GeV WIMPs)

This program is clearly important and should be pursued

But are we looking everywhere we can and should?

The Search for Dark Matter

- The answer is no:

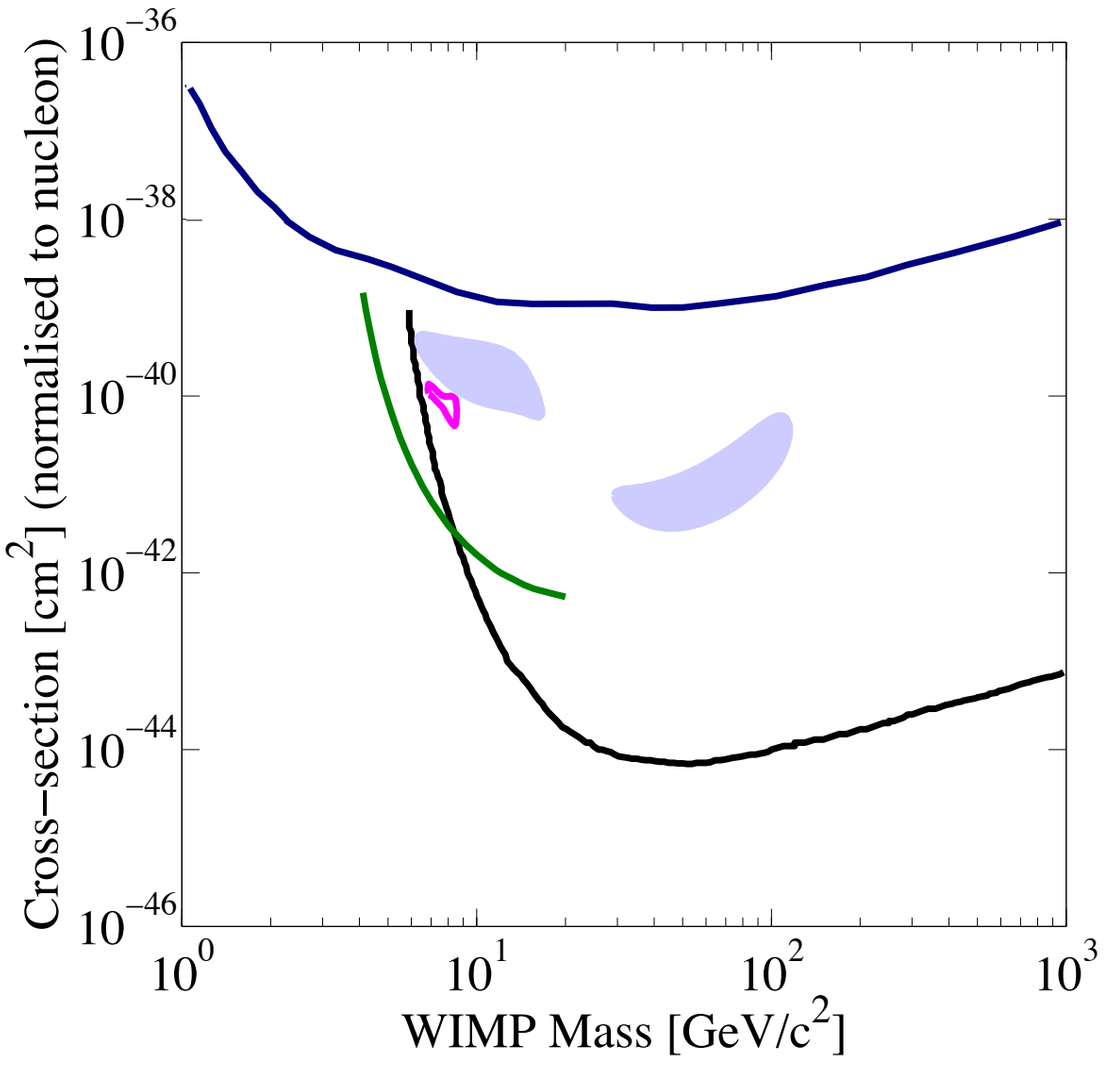
  DM does not have to be associated with Weak scale (with mass~5-1000 GeV)

- Many other excellent DM candidates exist

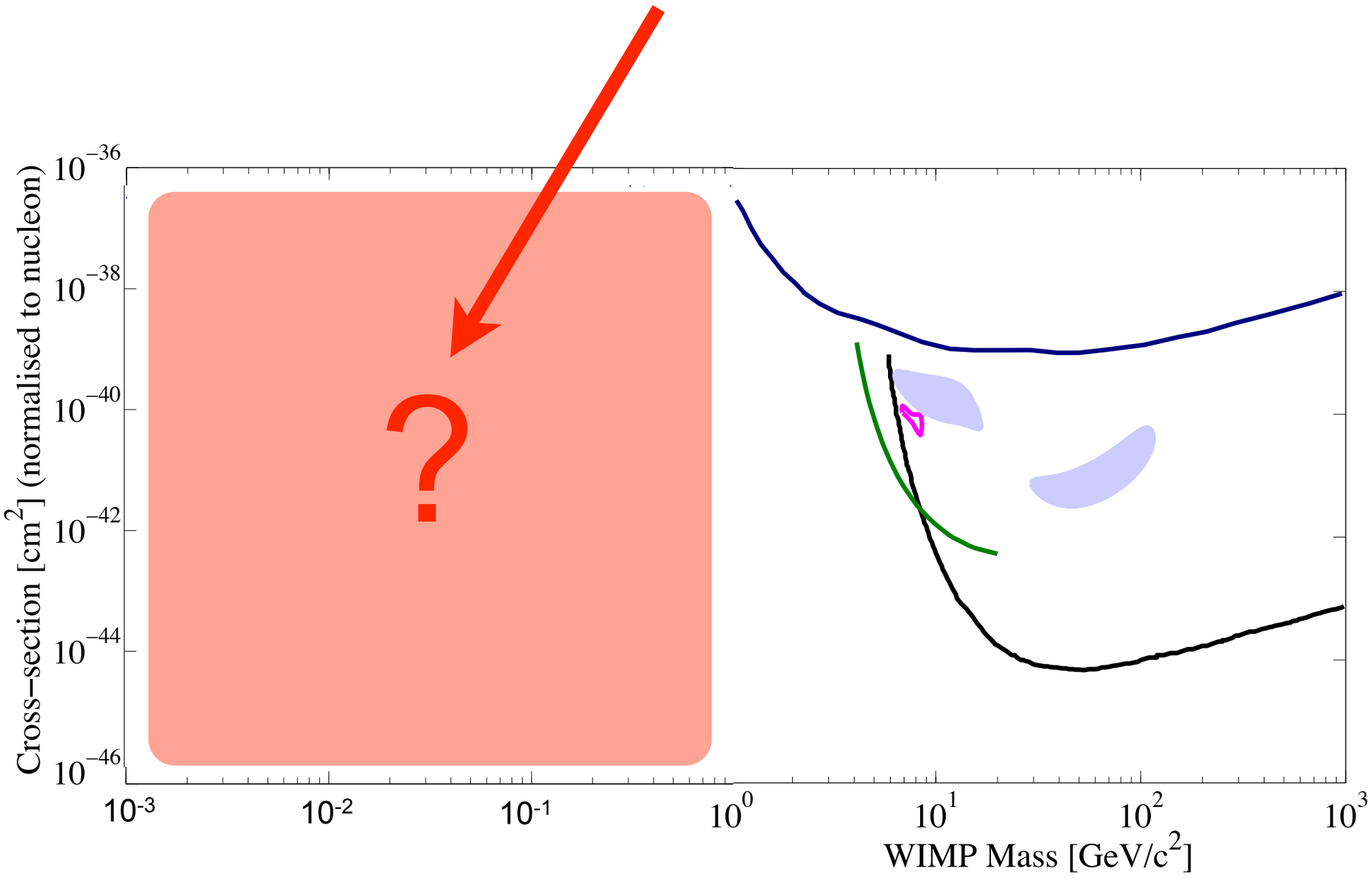
- In particular, many theoretical scenarios give rise to DM candidates with masses in the MeV-GeV range

Contrary to popular belief, sub-GeV DM is viable & can be probed with direct detection experiments!

So instead of considering only this…



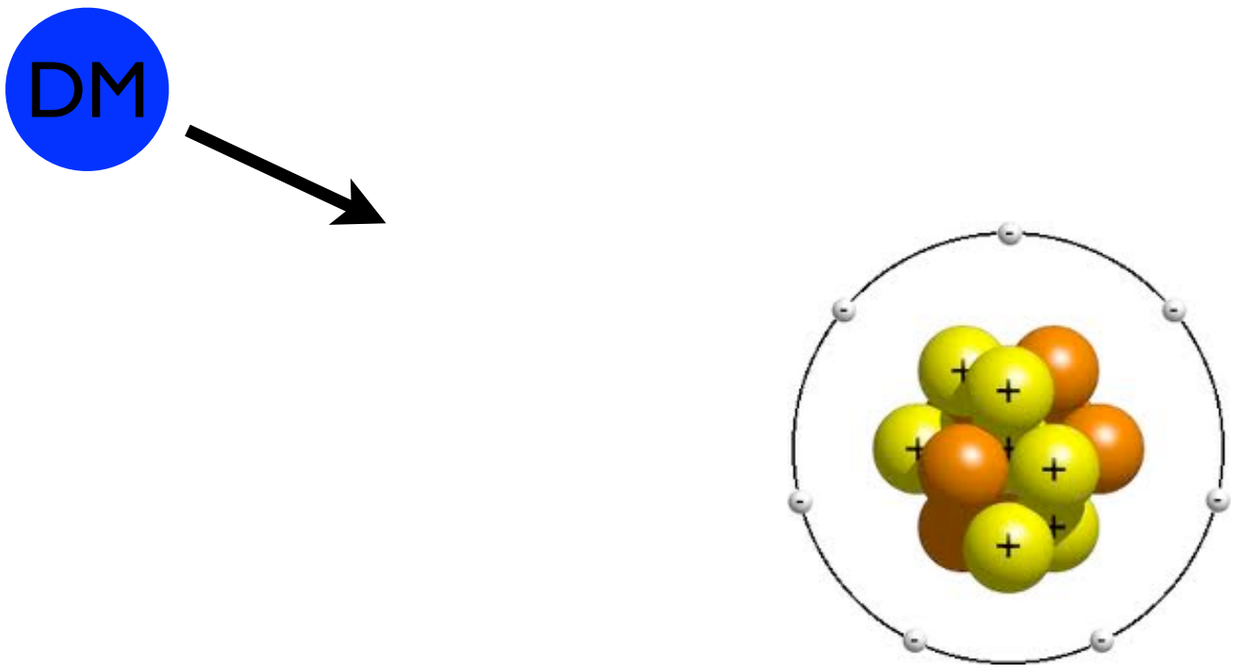
What if DM is here?



mass ~ MeV - GeV

Cannot use elastic nuclear recoils for detection

Recall: Heavy DM



Cannot use elastic nuclear recoils for detection

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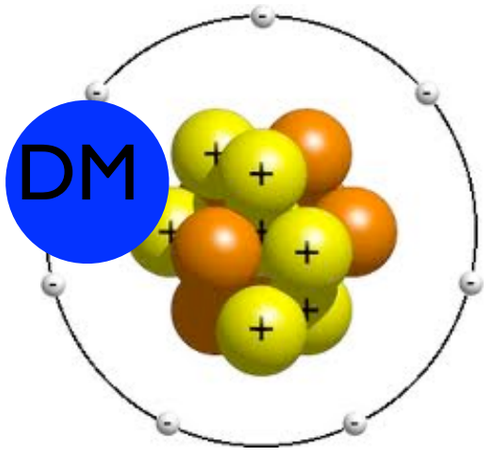

Cannot use elastic nuclear recoils for detection

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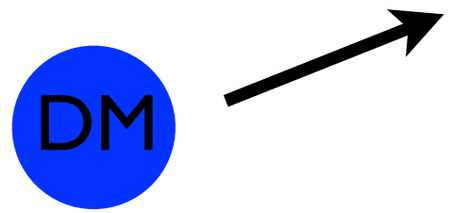
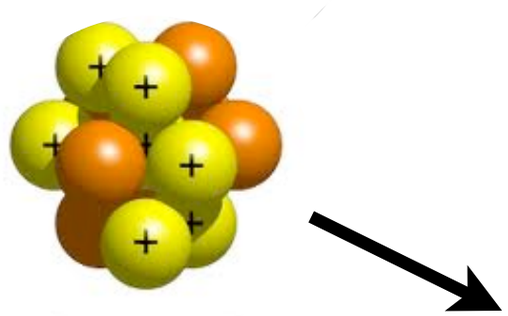
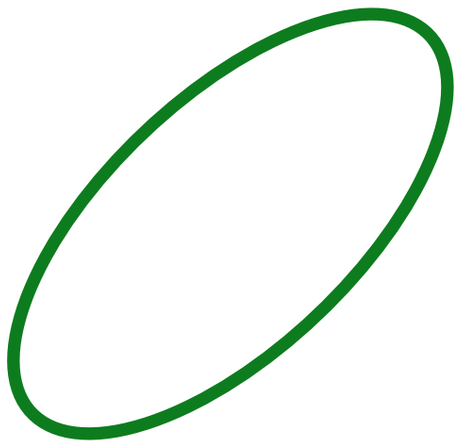




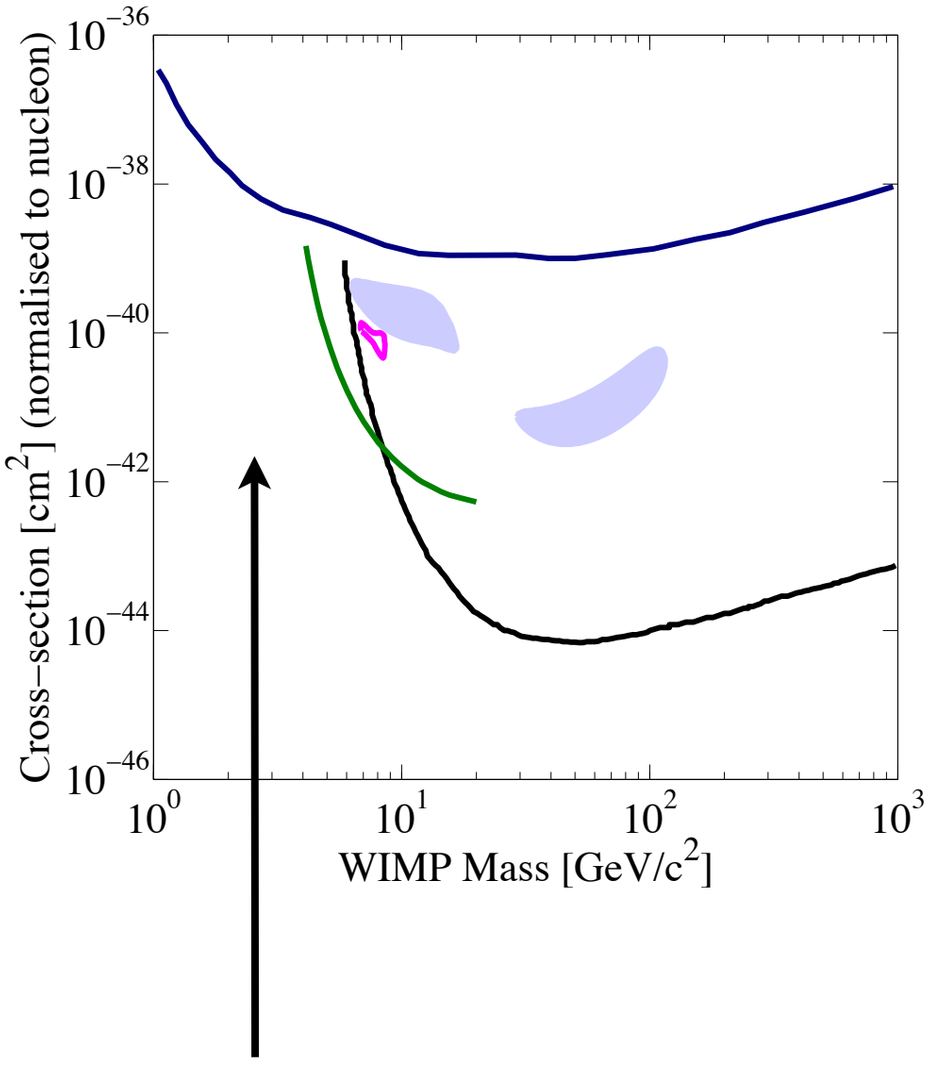
large recoil…
“no problem”

Cannot use elastic nuclear recoils for detection

nuclear recoil energy

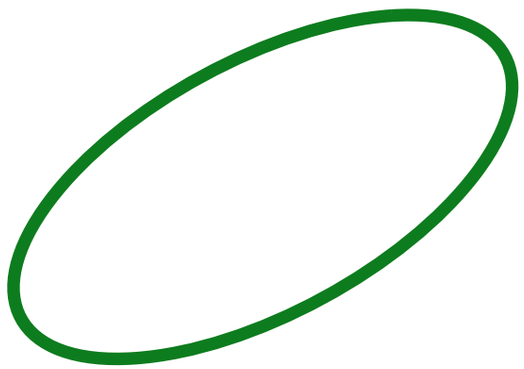


for sub-GeV DM, nuclear recoil energy is too small to produce visible scintillation, ionization, or phonon signal !



limits absent below ~few GeV

But, total energy available is much larger:



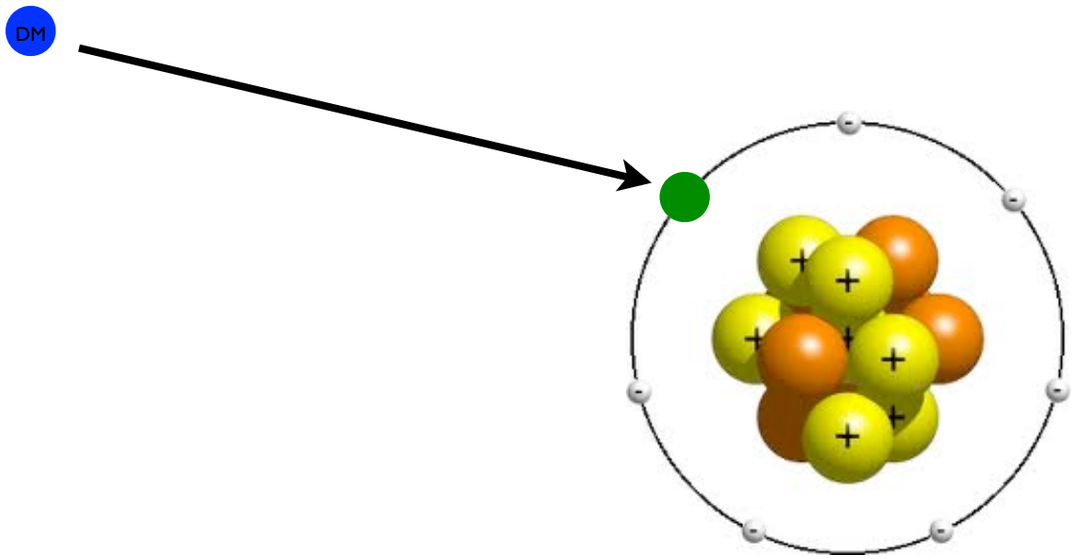
enough energy to excite or ionize an atom,
or dissociate molecules

(just not from nuclear recoils!)

How to detect sub-GeV DM

- ionization
- excitation
- molecular dissociation

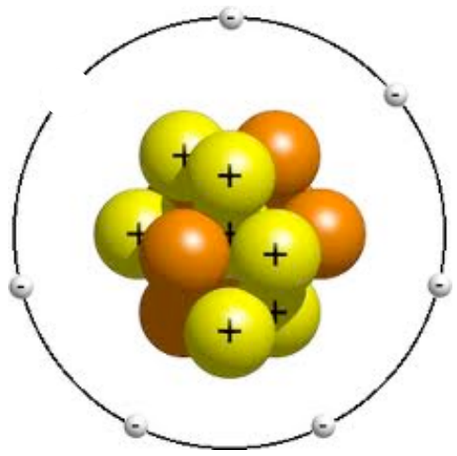
DM scattering off an electron: 1



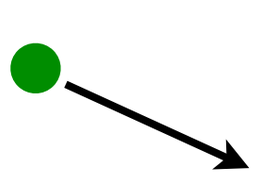
Atom

DM scattering off an electron: 1

We have a proof of principle that this works



Atom



threshold ~ 1-100 eV

Ionization

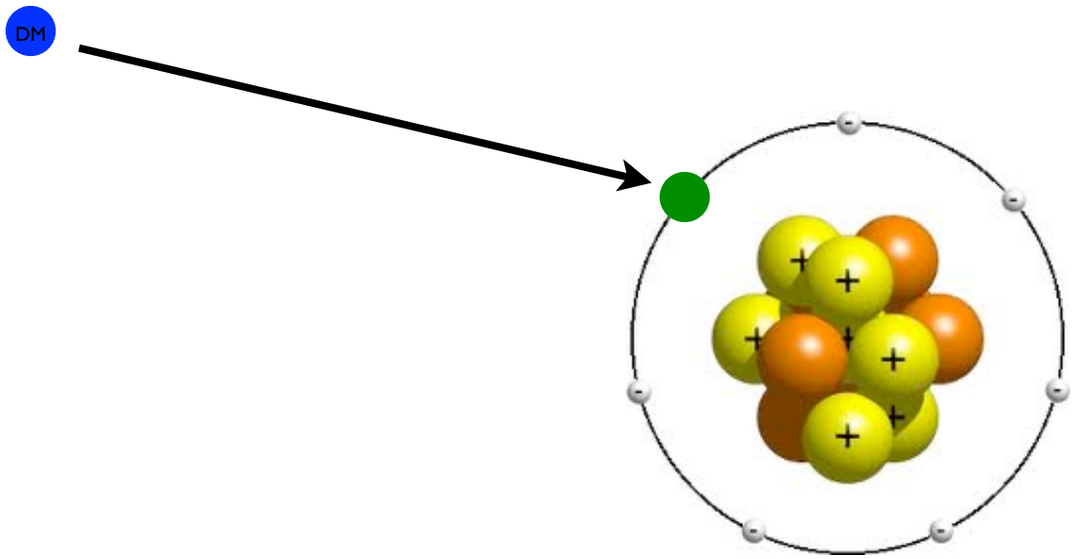
Signal: single (or few) electron events

existing technologies can measure ionization, even of a single electron !

How to detect sub-GeV DM

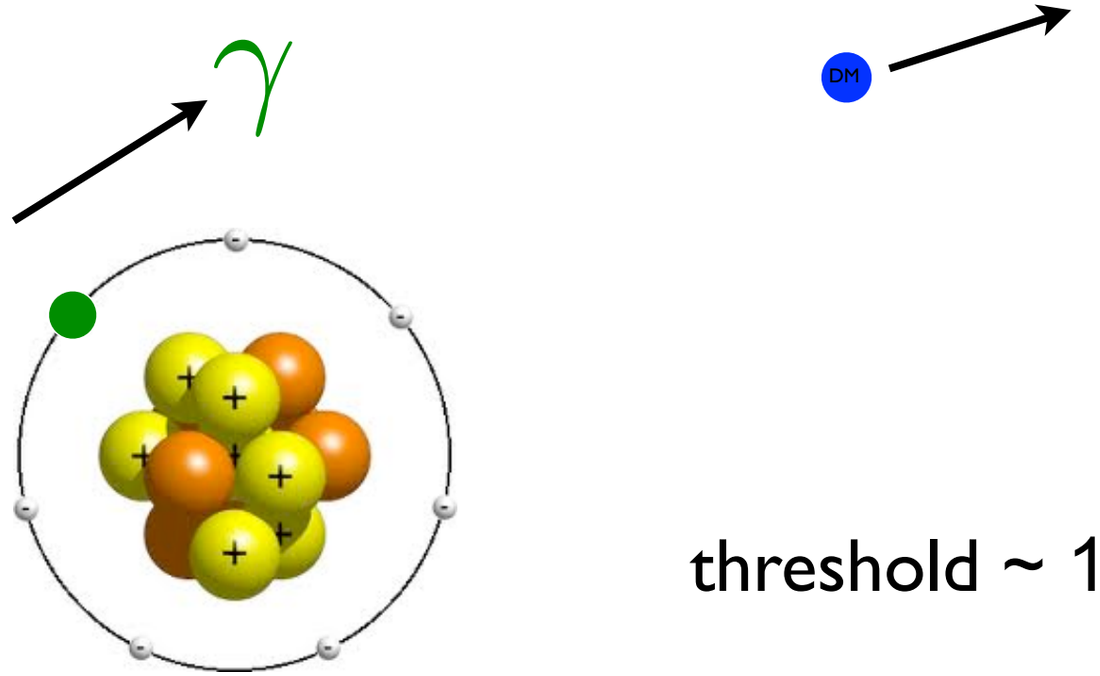
- ionization
- excitation
- molecular dissociation

DM scattering off an electron: 2



Atom

DM scattering off an electron: 2



threshold ~ 1-100 eV

Excitation

Atom

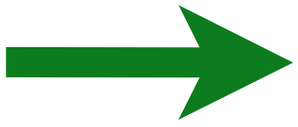
Excite atom…& look for de-excitation photon

Signal: photons

Use MKIDs to detect these photons?

How to detect sub-GeV DM

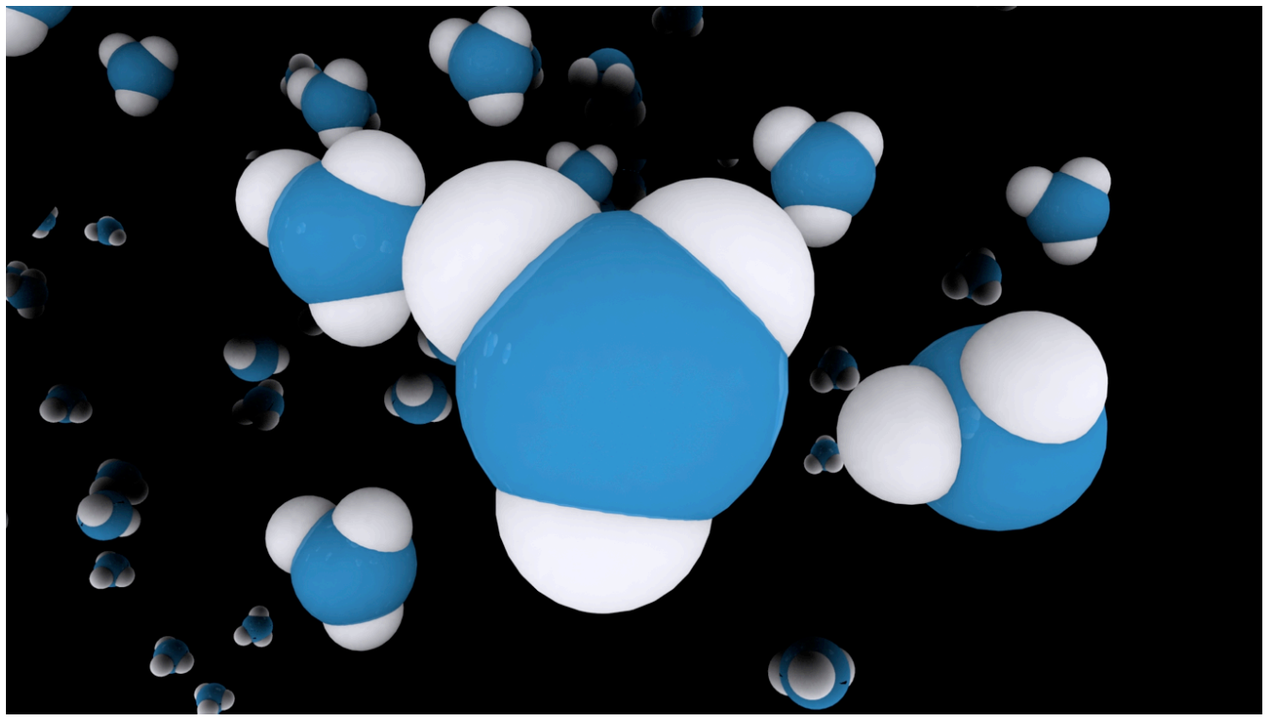
- ionization
- excitation



- molecular dissociation

DM (or ν) scattering off nuclei

Break apart molecules



threshold ~ few eV

Signal: various possibilities

We are calculating rates & talking w/ several experimentalists/chemists to investigate feasibility…

A Proof of Principle exists for Ionization Signal

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First Direct Detection Limits on Sub-GeV Dark Matter from XENON10

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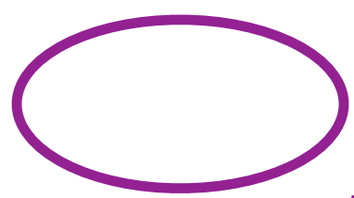
The first direct detection limits on dark matter in the MeV to GeV mass range are presented, using XENON10 data. Such light dark matter can scatter with electrons, causing ionization of atoms in a detector target material and leading to single- or few-electron events. We use 15 kg day of data acquired in 2006 to set limits on the dark-matter—electron scattering cross section. The strongest bound is obtained at 100 MeV where $\sigma_e < 3 \times 10^{-38}$ cm^2 at 90% C.L., while dark-matter masses between 20 MeV and 1 GeV are bounded by $\sigma_e < 10^{-37}$ cm^2 at 90% C.L. This analysis provides a first proof of principle that direct detection experiments can be sensitive to dark-matter candidates with masses well below the GeV scale.

arXiv:1206.2644

XENON10 was set-up to trigger on single e^- events (with S1 = 0) for *only 12.5 days* in 2006

Can use this data to set a limit (next page)

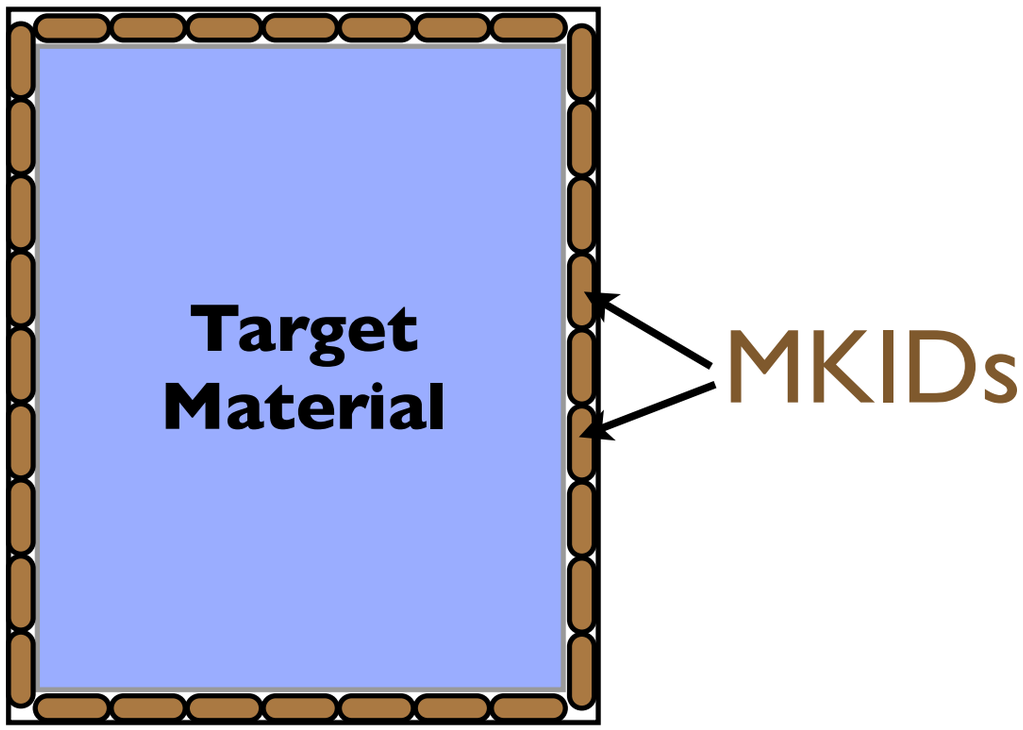
Limits on sub-GeV DM from XENON10



Note: MeV scale!

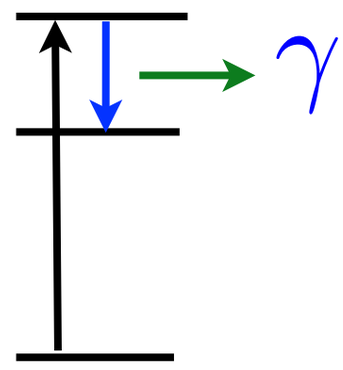
One possibility to use MKIDs?

- use MKIDs to detect γ from DM-induced atomic excitations
- e.g. instrument outer parts of target material with MKIDs



(could use mirrors/focusing to decrease number of MKIDs needed)

- material can be transparent if use photons from a double transition
  (easy to have forbidden transitions from symmetry)



Future?

- With ~20-30 yrs of research, direct detection w/ elastic nuclear recoils are almost "background free" experiments
  - use two handles to distinguish signal from background, e.g. ionization & scintillation in 2-phase TPC's for XENON100/LUX (background has larger ionization)
  - w/o 2 handles, can always use annual modulation (e.g. DAMA)
- need to start a similar program focused on sub-GeV DM
  - e.g. one idea: use MKIDs in combination with two-phase TPC to veto events *with* ionization?

Can we use MKIDs for direct detection of sub-GeV DM?

Backup

Elastic nuclear recoils don't work

nuclear recoil energy

$$E_{\rm nr} \sim \frac{(\mu v)^2}{2 m_N} \sim \frac{(m_{\rm DM}\, v)^2}{2\, m_N}$$

$$\sim 1 \text{ eV} \left(\frac{m_{\rm DM}}{100 \text{ MeV}}\right)^2 \left(\frac{10 \text{ GeV}}{m_N}\right) \left(\frac{v}{300 \text{ km/s}}\right)^2$$

too small to excite or ionize an atom or produce enough phonons !

nuclear recoil energy

$$E_{\rm nr} \sim 1 \text{ eV} \left(\frac{m_{\rm DM}}{100 \text{ MeV}}\right)^2 \left(\frac{10 \text{ GeV}}{m_N}\right) \left(\frac{v}{300 \text{ km/s}}\right)^2$$

But, total energy available is much larger!

$$E_{\rm tot} \sim \frac{1}{2} m_{\rm DM} v^2 \sim 50 \text{ eV} \left(\frac{m_{\rm DM}}{100 \text{ MeV}}\right) \left(\frac{v}{300 \text{ km/s}}\right)^2$$

much larger !

The XENON10 data

on average, a single electron produces
about 27 detected photo-electrons

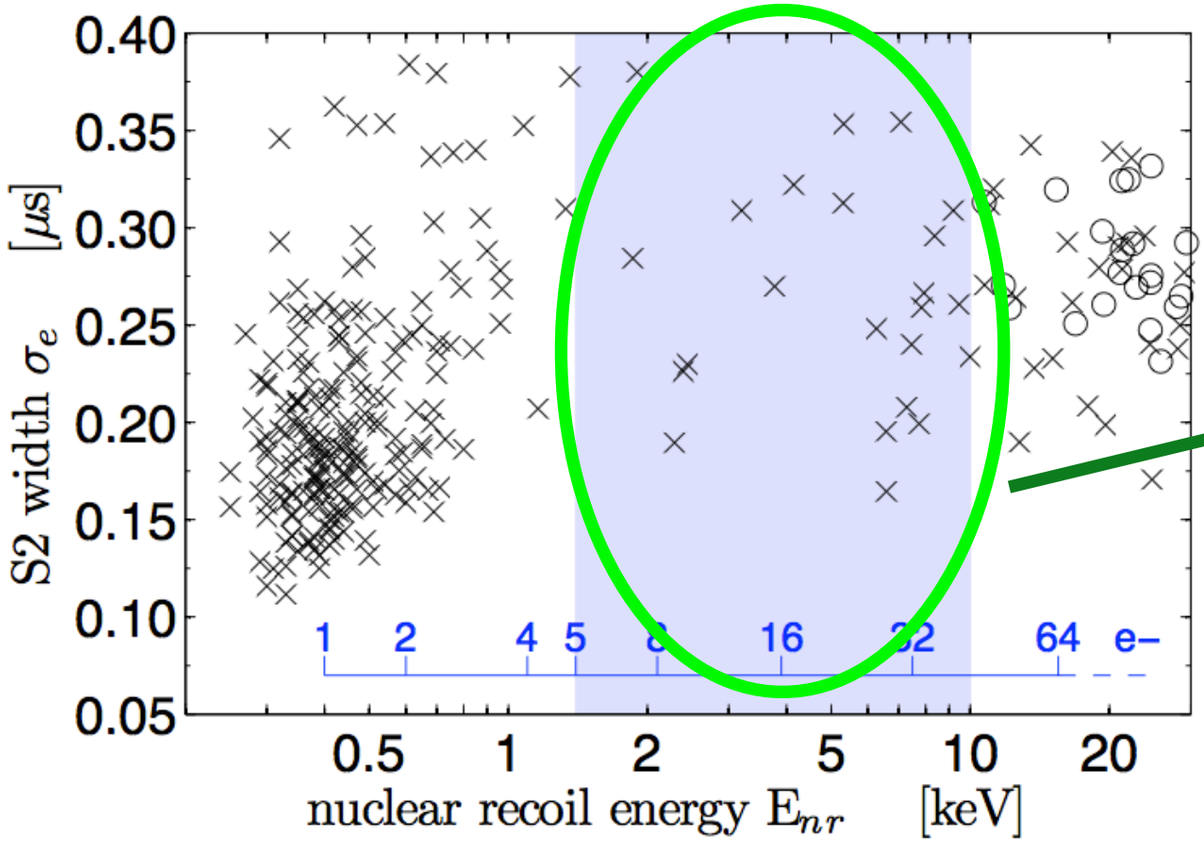
in principle, easy to detect in XENON10

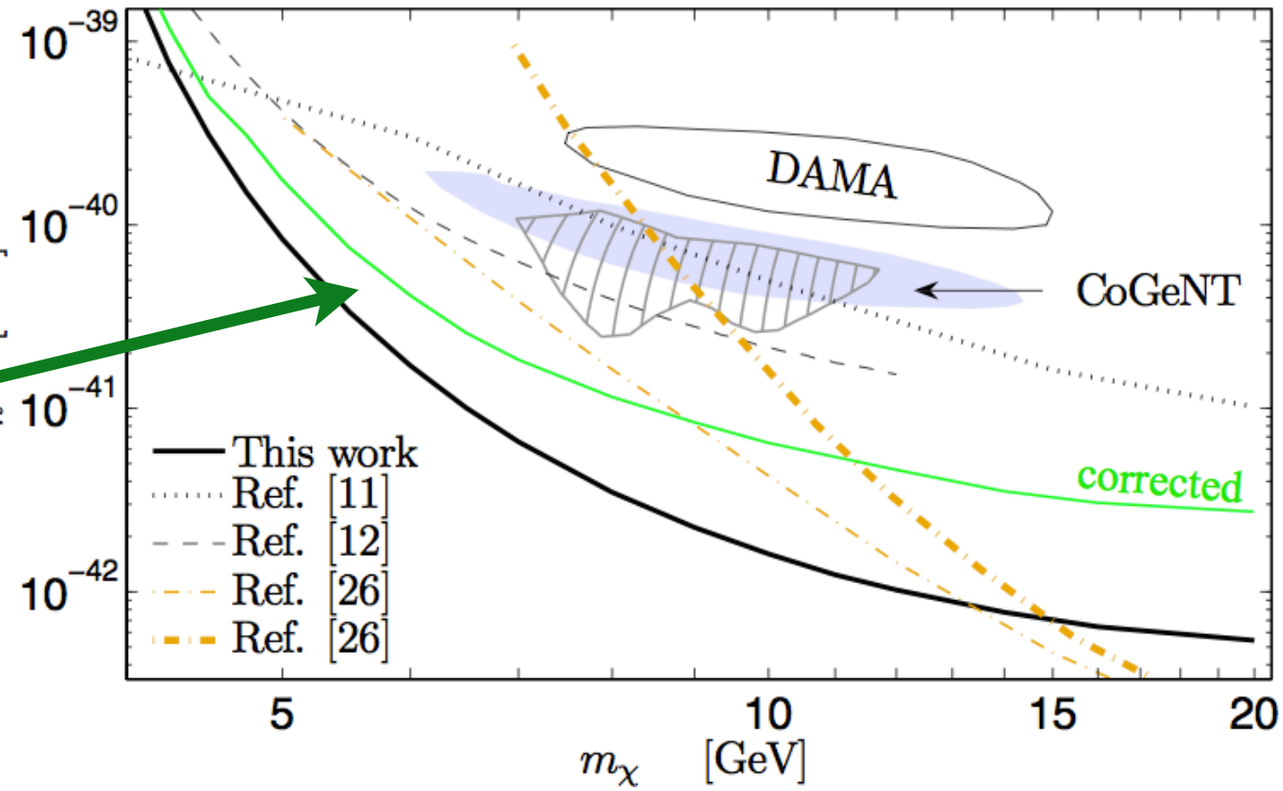
But XENON10 was set-up to trigger on single e^- events
(with S1 = 0) for *only 12.5 days* in 2006…

only 15 kg-days exposure

P. Sorensen (XENON10) used this data to set limits on ~10 GeV
DM from *nuclear recoils*, constraining DAMA/CoGeNT region

The XENON10 data

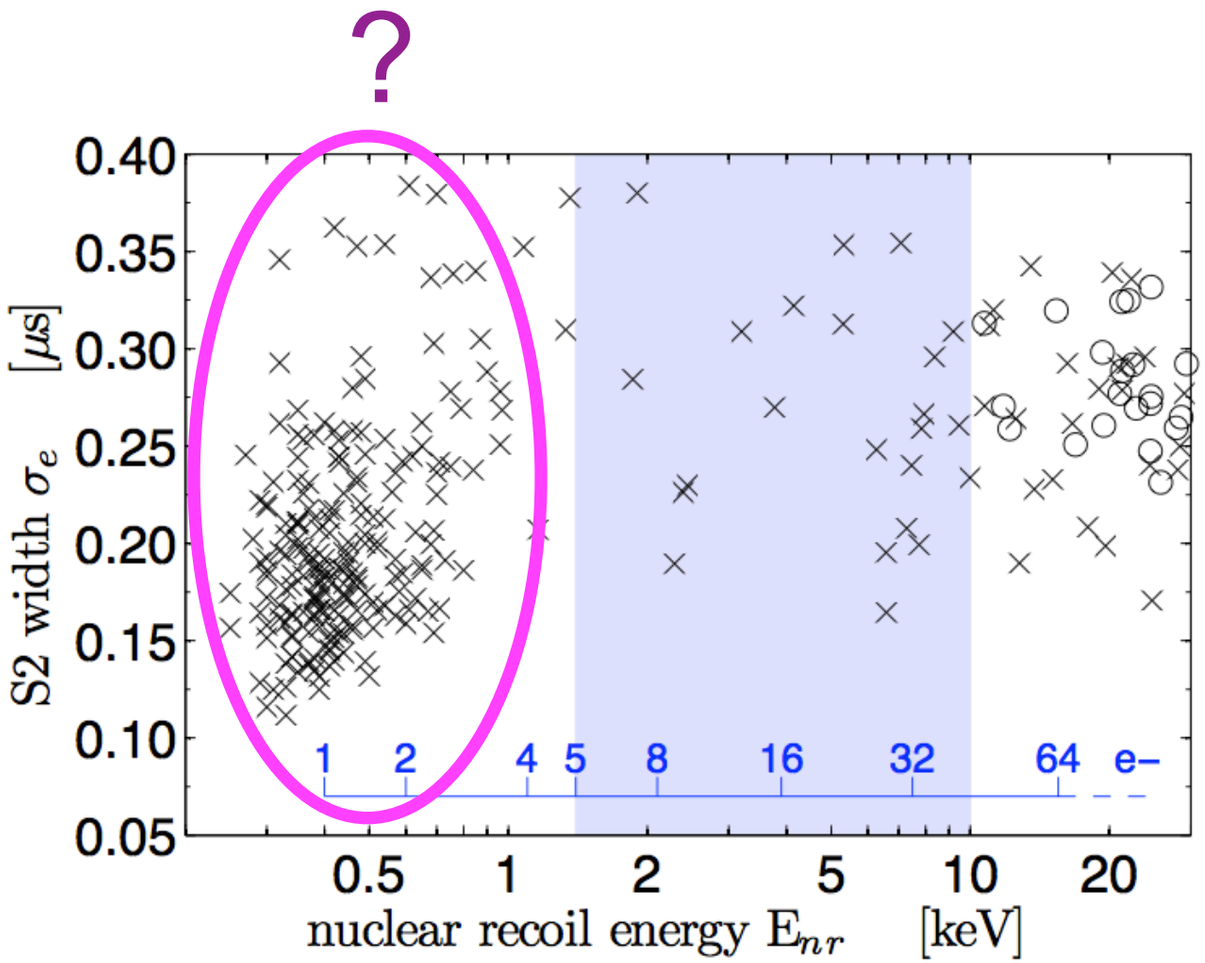


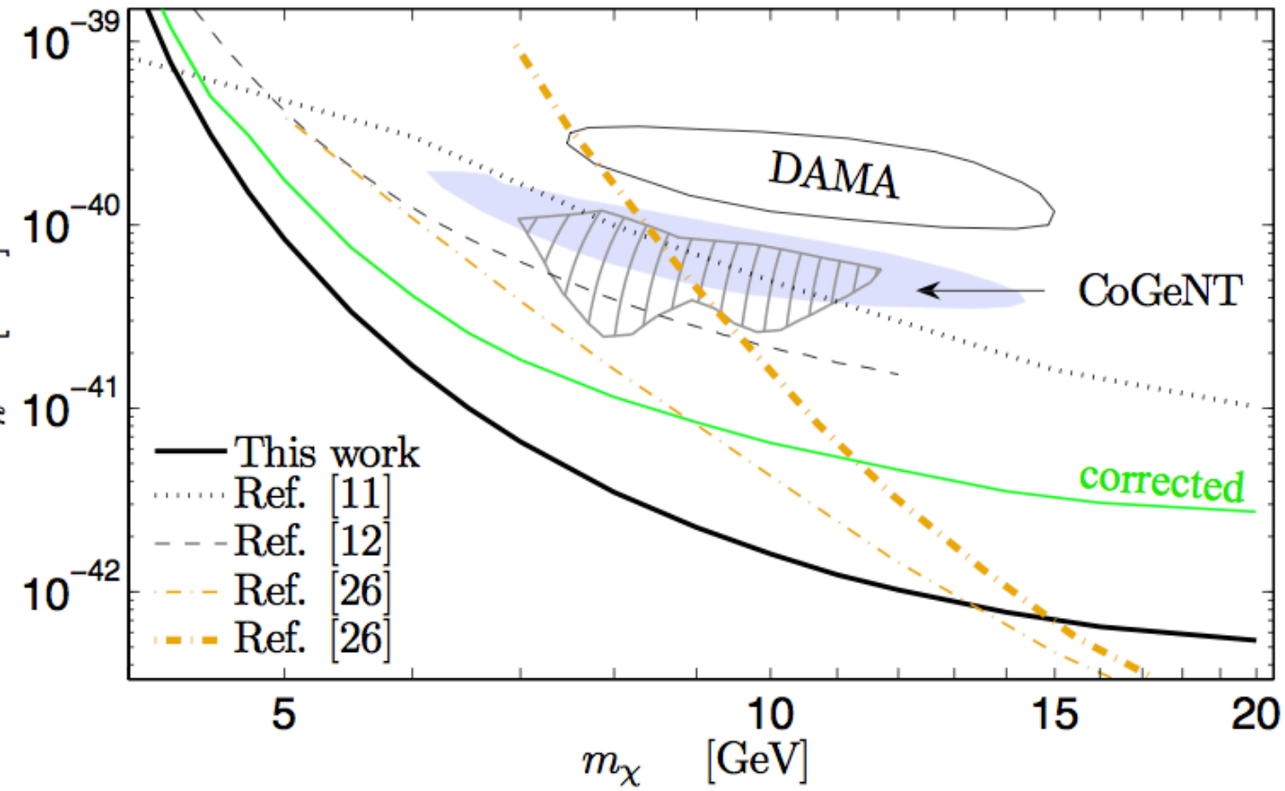


P. Sorensen (XENON10) used this data to set limits on ~10 GeV DM from *nuclear recoils*, constraining DAMA/CoGeNT region

(2011)

The XENON10 data





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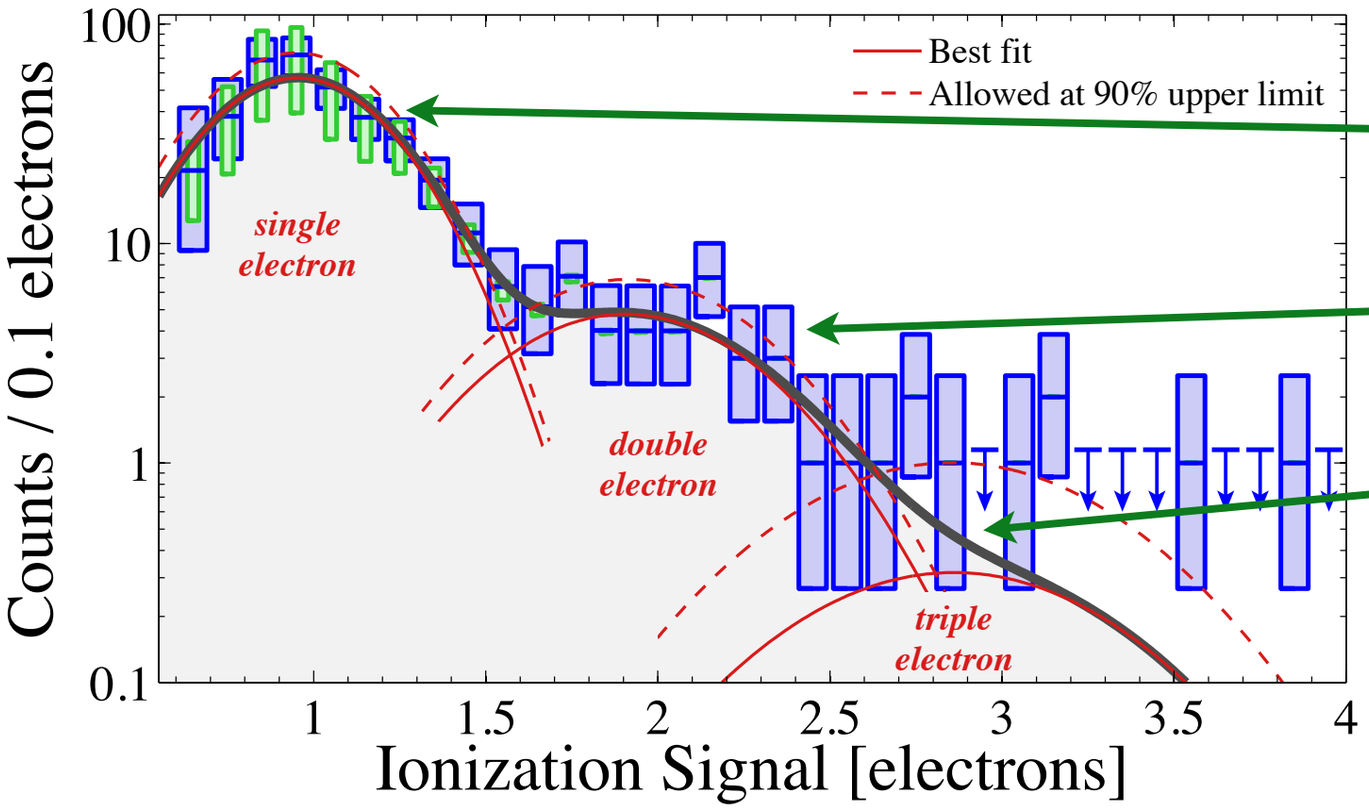
(2011)

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



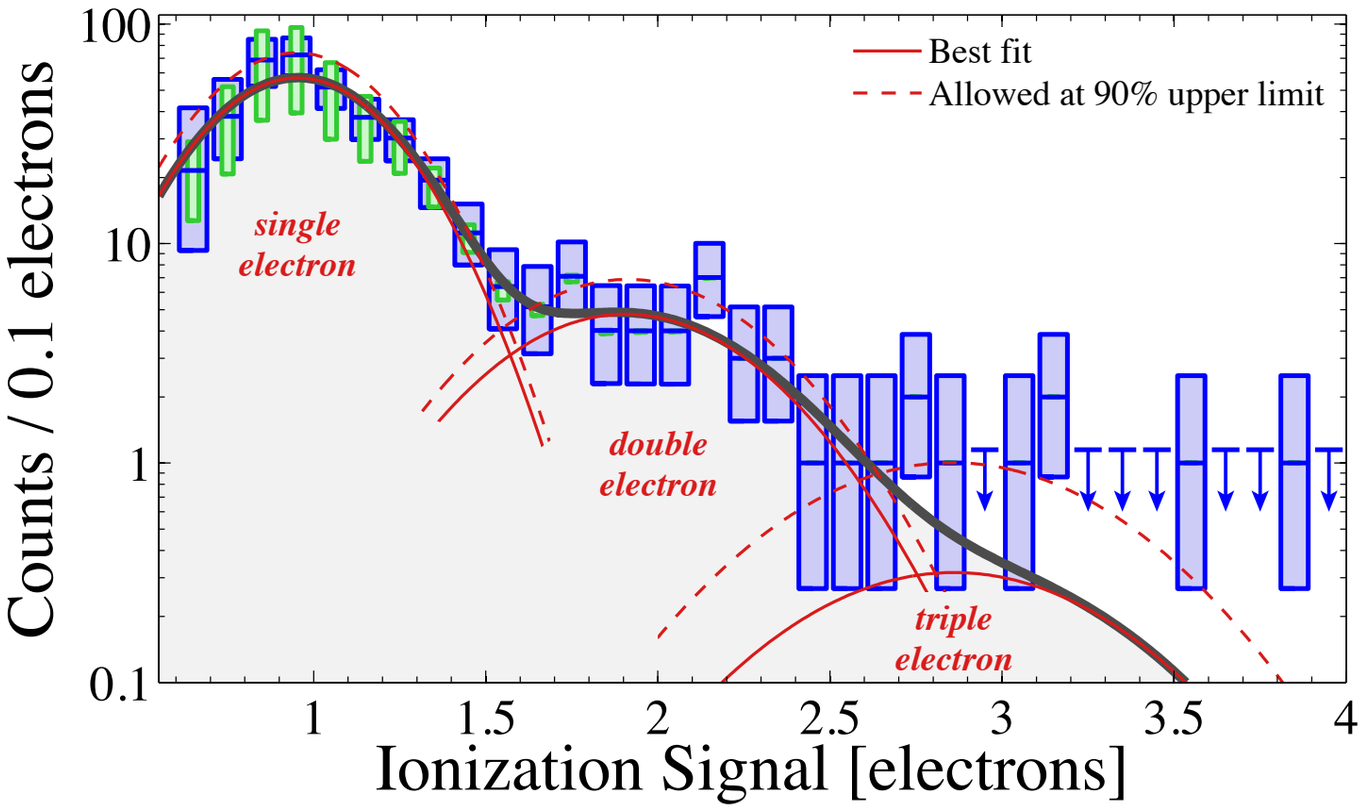
1-electron events

2-electron events

3-electron events

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



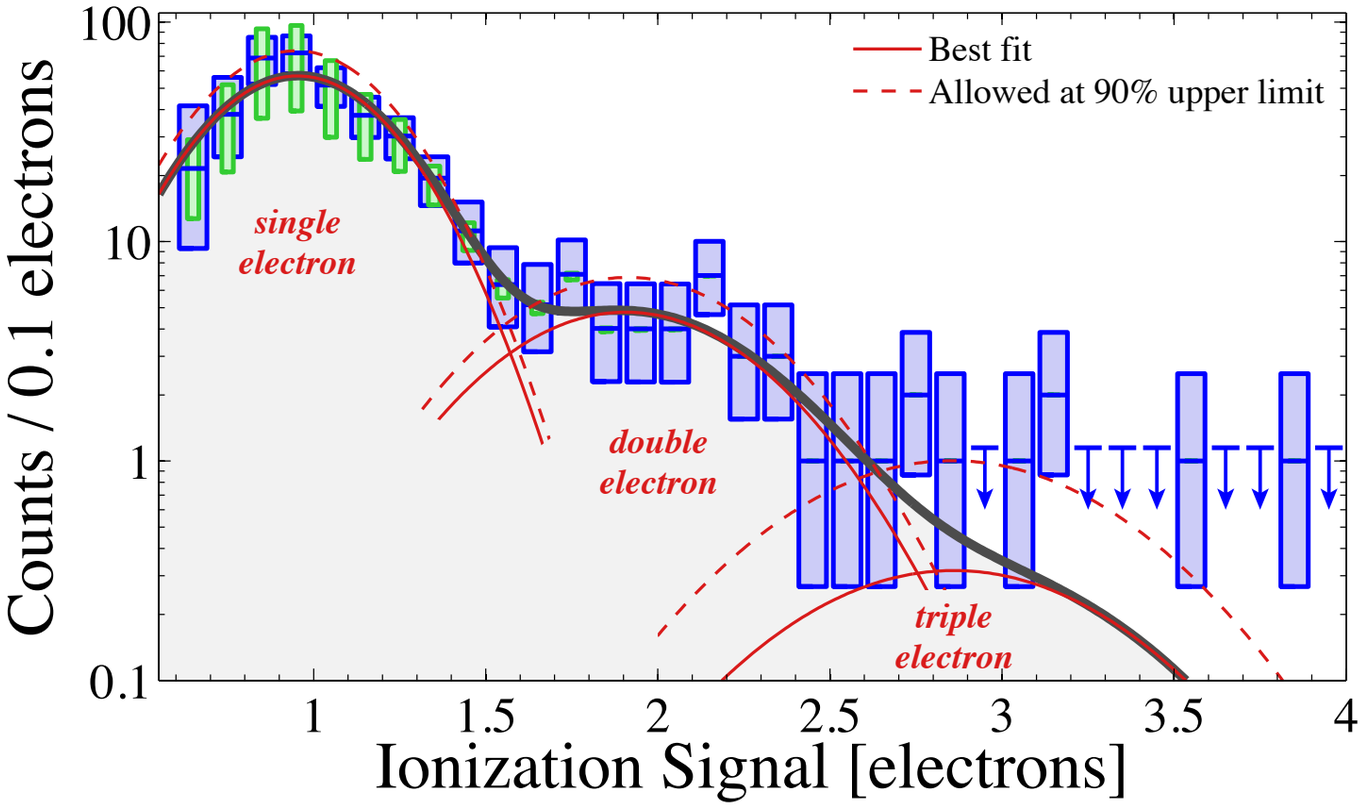
What *are* these events ??

Origin unclear! Some possibilities:

- Photo-dissociation of negatively charged impurities
- spontaneous emission of e^- trapped in potential barrier at liquid-gas interface
- field emission in region of cathode

The XENON10 data

~500 events w/ 1-, 2-, or 3-electrons are observed



90% c.l. upper bounds on rates:

1 e^-: 34.5 counts/kg/day

2 e^-: 4.5 counts/kg/day

3 e^-: 0.83 counts/kg/day

Note: DM *can* give rise to 2- and 3-electron events:

- outgoing e^- can ionize further e^-'s
- ionizing an inner-shell e^- gives a de-excitation photon that can ionize other e^-'s

Results

Summary for XENON10

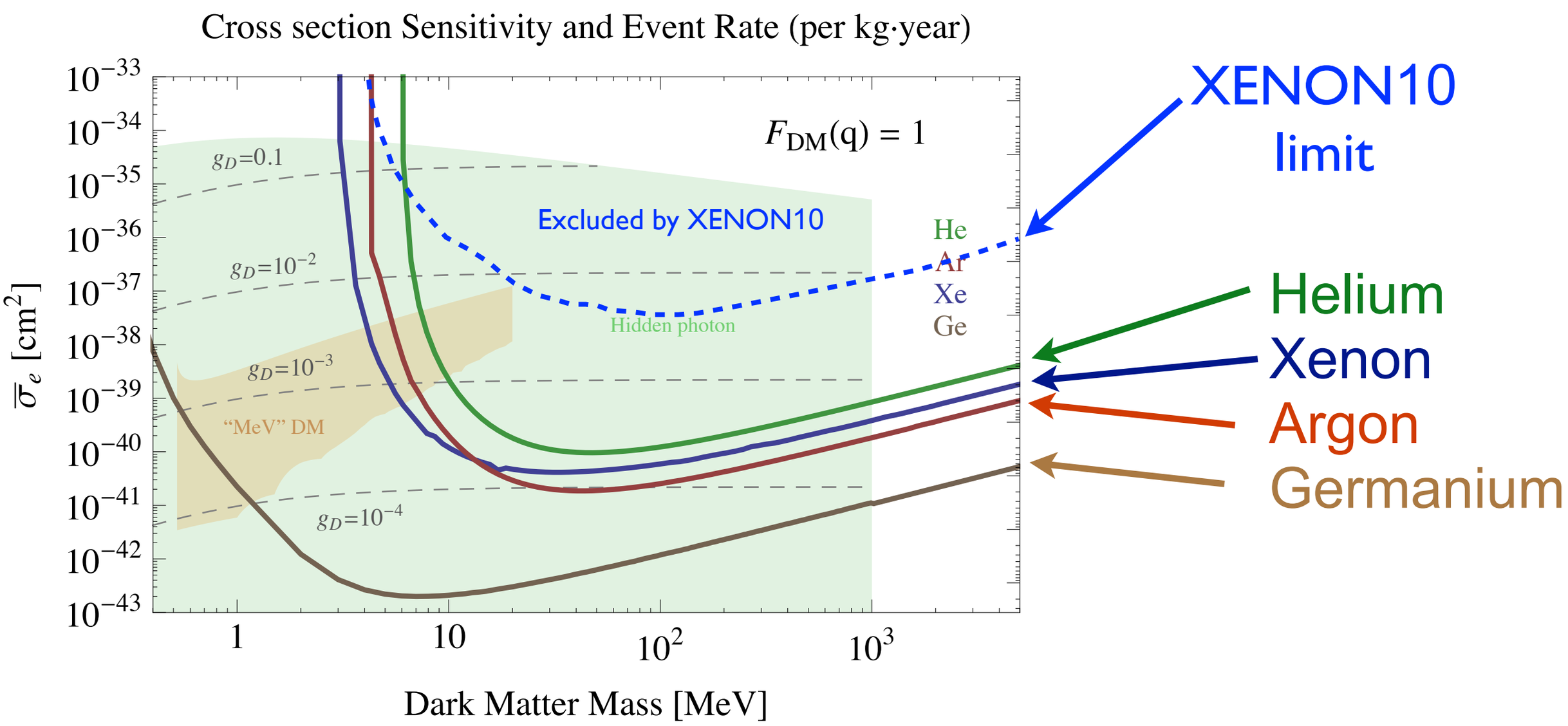
"accidentally" already sets meaningful limits on DM-electron recoils

But:

- only a measly 15 kg-days
- designed to study nuclear recoils

How well can an experiment do that purposefully looks for sub-GeV DM ?

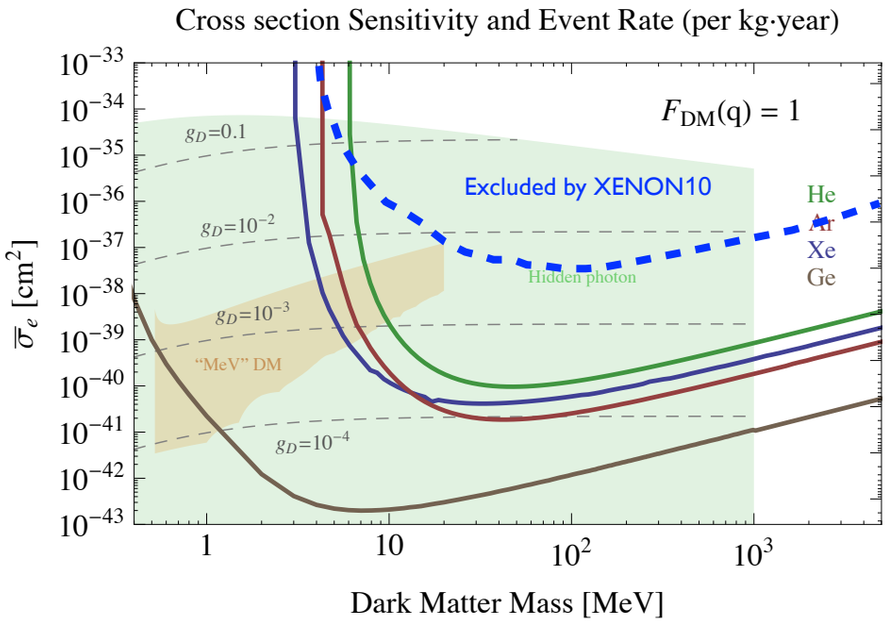
Projected reach for various elements



1 kg-year

NB: semi-conductors (e.g. Ge)

$\Longrightarrow$ reach to *very* low masses !



NB: semi-conductors (e.g. Ge)

$\Longrightarrow$ reach to *very* low masses !

see also Graham, Kaplan, Rajendran, Walters (2012)

- band-gap only ~ 1 eV (much lower than Xe!)
- current thresholds:
  - CDMS: ~300 e^-
  - "CDMS-light" (increase voltage) ~ O(few) electrons ?
  - DAMIC (Si, CCD's): current threshold ~40 eV (1105.5191)
    future: ~4 eV ?

- Currently investigating:
  - e^- excitation w/ photon signal
  - molecular dissociation
  - model building + other constraints

Our hope is to build
a dedicated experiment…