The Migdal effect and bremsstrahlung in effective field theories of dark matter scattering

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Sydney

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arXiv:1905.00046
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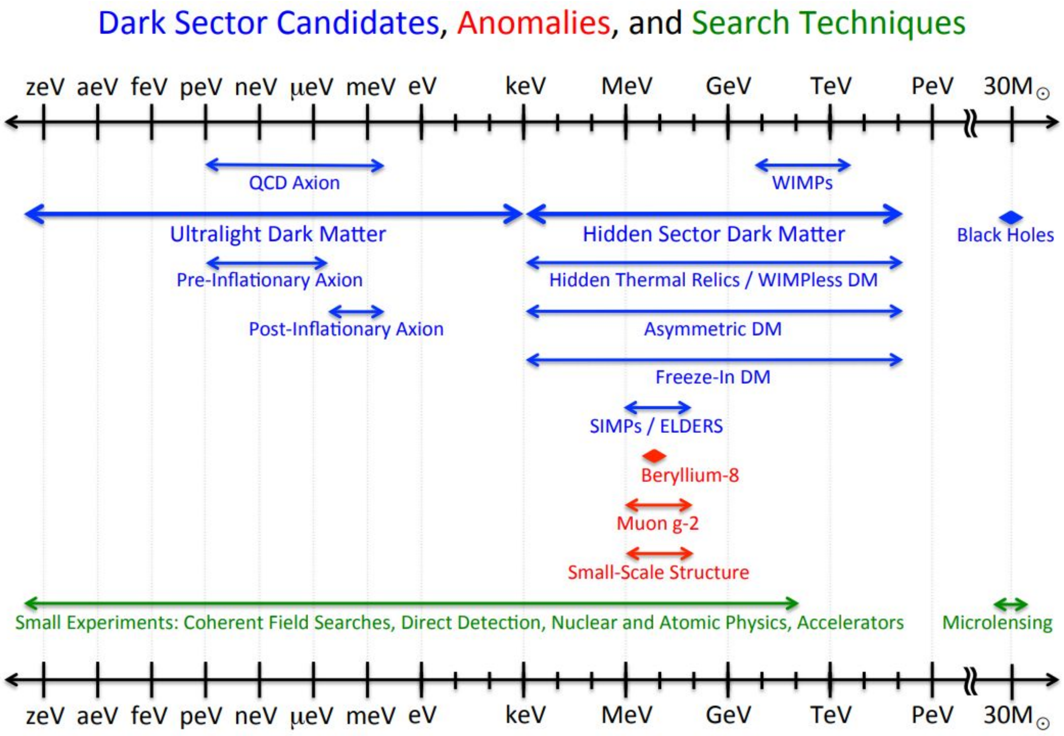
Overview

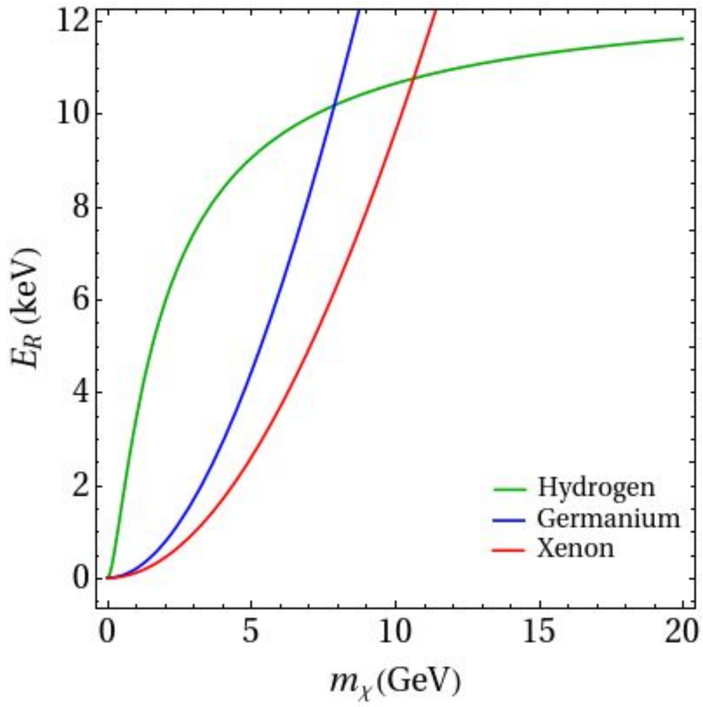
There has been a concerted effort to extend our WIMP horizons, notably in the direction of lighter masses.

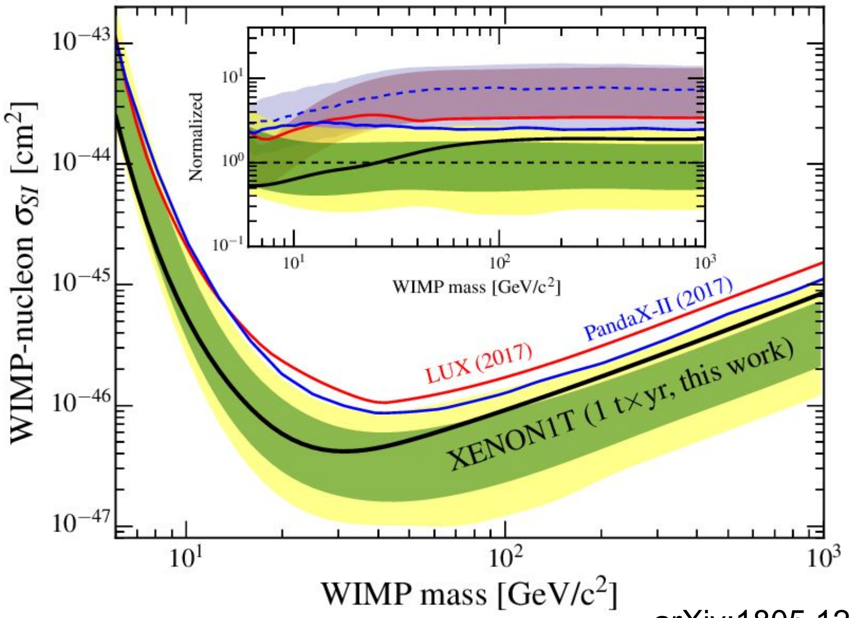


From US Cosmic Visions
arXiv:1707.04591

The kinematic problem

- Light dark matter does not pack much of a punch: $$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$





arXiv:1805.12562

Methods for probing lighter dark matter
(an incomplete list)

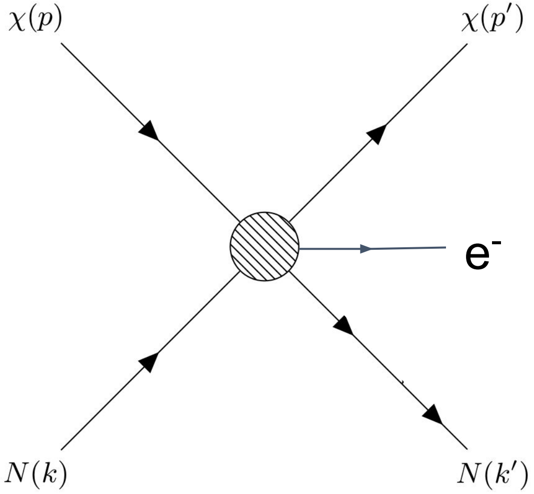
Existing direct detection:
- Cosmic ray dark matter (arXiv:1810.10543)
- The Migdal effect (arXiv:1707.07258)
- Bremsstrahlung (arXiv:1607.01789)
- Electron scattering (arXiv:1703.00910)

Cosmology/Astrophysics/other
- DM-proton CMB (arXiv:1712.07133)
- Reverse direct detection (arXiv:1810.07705)
- Neutron star heating (arXiv:1704.01577)
- Boosted dark matter (arXiv:1405.7370)
- Colliders (arXiv:1903.01400)

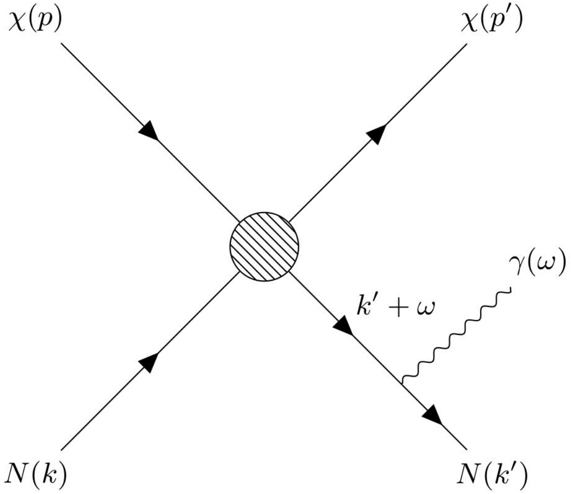
Improved (traditional) direct detection:
- Diamond detectors (arXiv:1901.07569)
- Single charge germanium (arXiv:1804.10697)
- Single charge xenon (e.g. ALBECA)
- Helium detectors (arXiv:1302.0534)

New Ideas
- Multi-exciton/rotons in LHe (arXiv:1611.06228)
- Absorption (arXiv:1608.01994)
- Chemical bond breaking (arXiv:1608.02940)
- Spin-flip avalanche (arXiv:1701.06566)

The Migdal effect and bremsstrahlung



The Migdal effect



Bremsstrahlung

Why are these detection modes useful?

1. Kinematic advantage: light particles carry away more energy per unit momentum

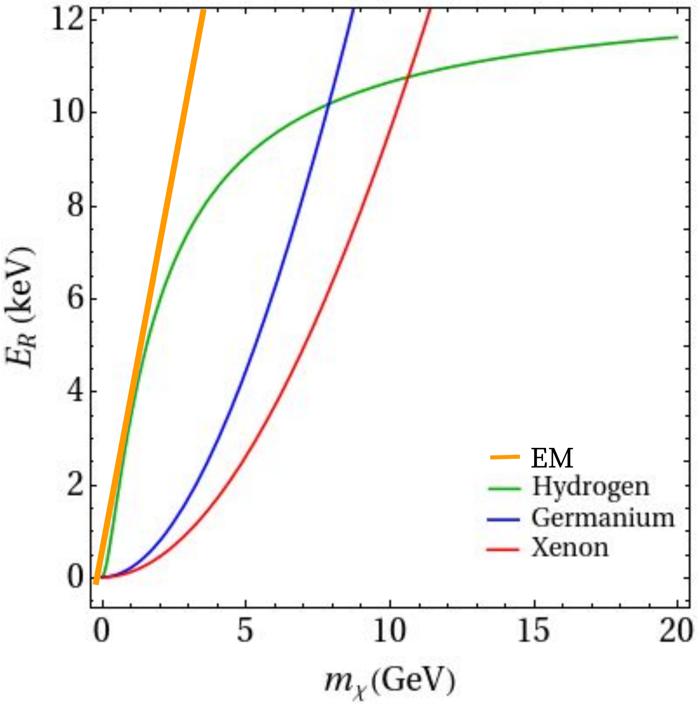
Nuclear:

$$E_{R_{\max}} = \frac{2\mu_T^2}{m_T} v_{\max}^2$$

Electronic (Migdal/Brem):

$$E_{EM_{\max}} = \frac{\mu_T}{2} v_{\max}^2$$

2. Electronic energy isn't quenched



A brief history of the Migdal effect

1941: A.B. Migdal, J. Phys. USSR 4 449

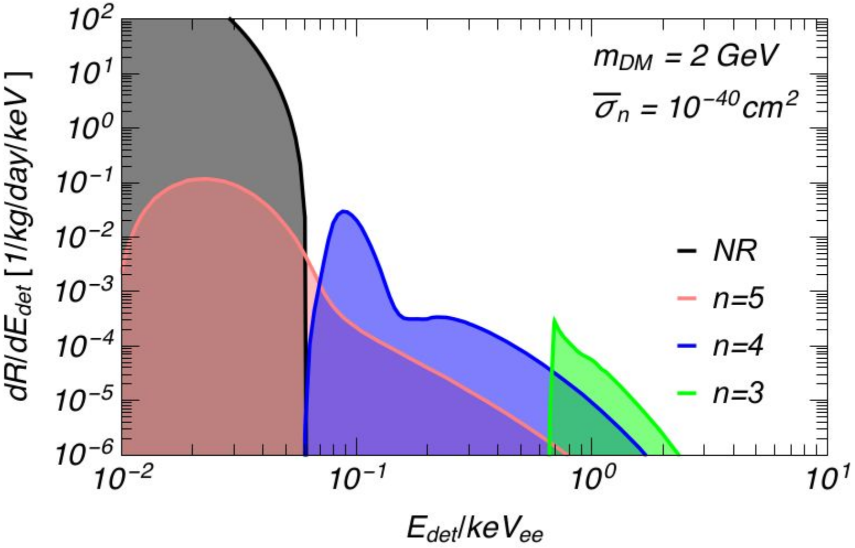
1958: Landau and Lifshitz Vol. 3: Quantum Mechanics, sec. 41:

> PROBLEM 2. The nucleus of an atom in the normal state receives an impulse which gives it a velocity v; the duration τ of the impulse is assumed short in comparison both with the electron periods and with a/v, where a is the dimension of the atom. Determine the probability of excitation of the atom under the influence of such a "jolt" (A. B. MIGDAL 1939).

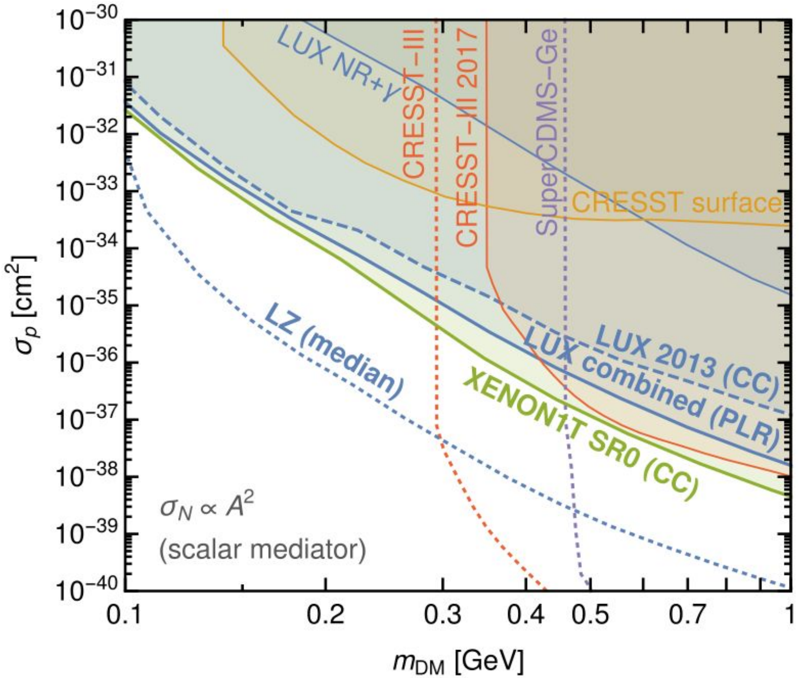
2005: J.D. Vergados and H. Ejiri, Phys. Lett. B 606, 313, [hep-ph/0401151]

2018: M. Ibe, W. Nakano, Y. Shoji and K. Suzuki, JHEP 1803 (2018) 194 [arXiv:1707.07258]

Bounds from the Migdal effect

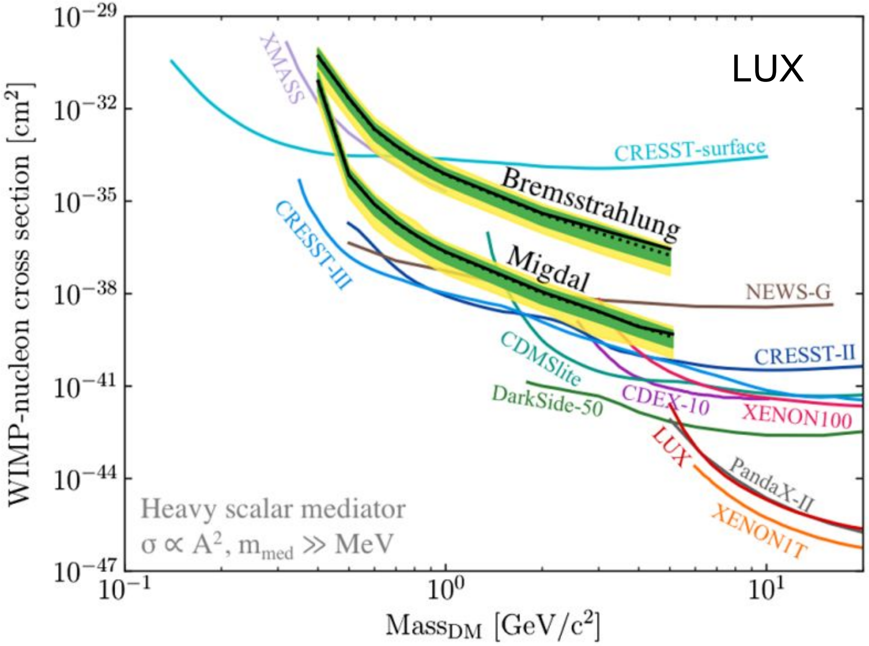


M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, arXiv:1707.07258

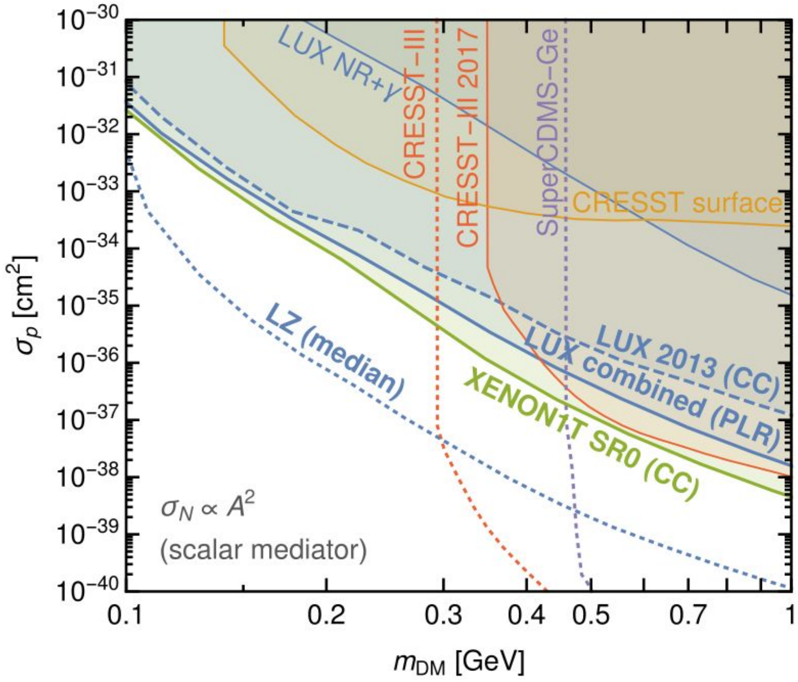


M. J. Dolan, F. Kahlhoefer, and C. McCabe, (PRL) arXiv:1711.09906

Bounds from the Migdal effect



Akerib et al. Phys. Rev. Lett. **122**, arXiv:1811.11241



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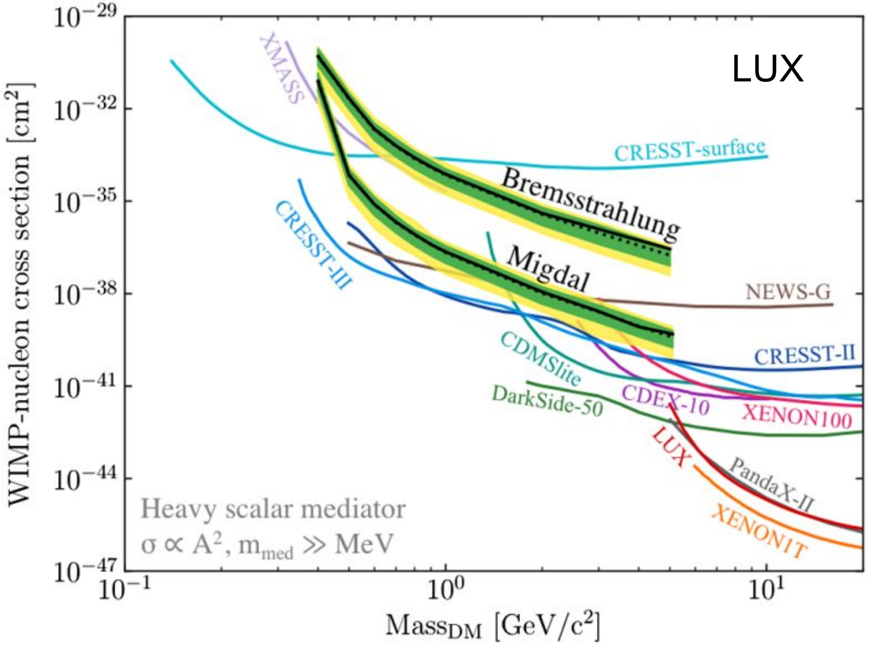
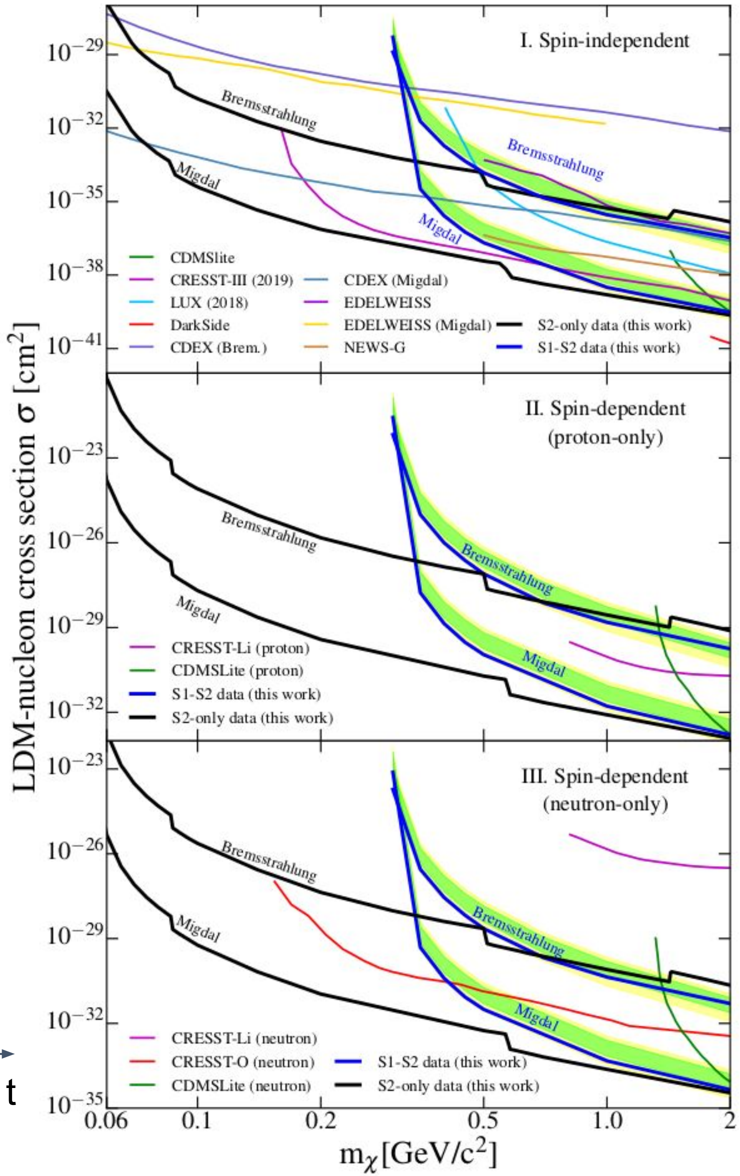


Akerib et al. Phys. Rev. Lett. **122**, arXiv:1811.11241

XENON1t



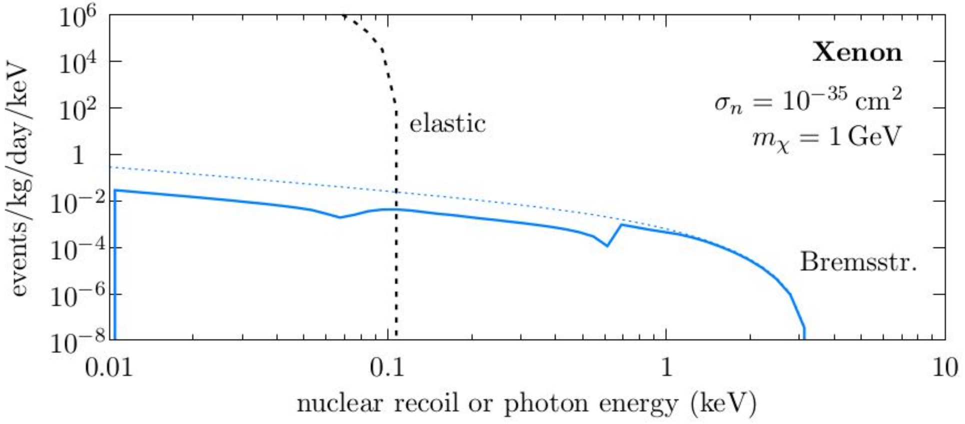
Bounds from bremsstrahlung

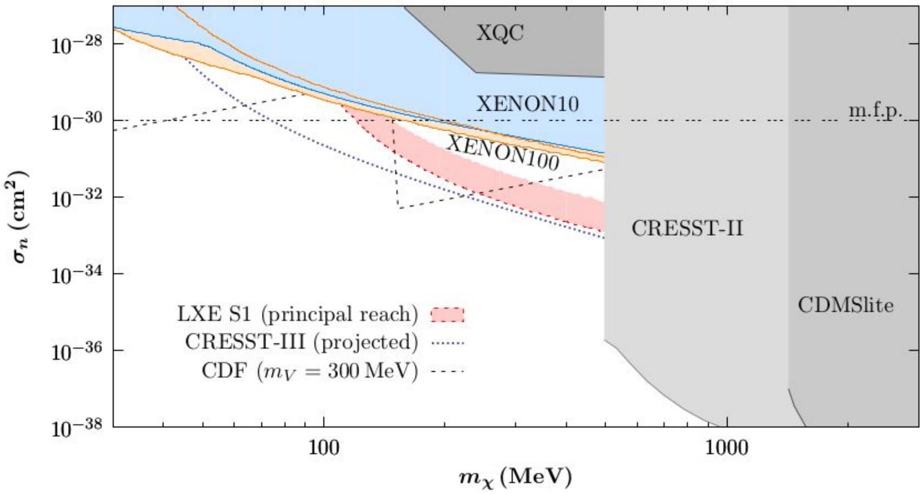
Kouvaris and Pradler calculate the rate of nuclear bremsstrahlung due to DM nuclear recoil from The factorized cross section:

arXiv:1607.01789

Phys. Rev. Lett. 118, 031803 (2017)

$$\left.\frac{d^2\sigma}{dE_R d\omega}\right|_{\text{naive}} = \frac{4Z^2\alpha}{3\pi}\frac{1}{\omega}\frac{E_R}{m_N} \times \frac{d\sigma}{dE_R}\Theta(\omega_{\max} - \omega)$$





Calculating Migdal and Brem. rates

Bremsstrahlung

$$\frac{d^3R}{dE_R d\omega dv} = \frac{d^2R_{\chi T}}{dE_R dv}\frac{4\alpha Z^2}{3\pi}\frac{E_R}{m_T\omega}$$

The Migdal effect

$$\frac{dR}{dE_R\, dE_e\, dv_{DM}} \simeq \frac{dR_0}{dE_R\, dv_{DM}} \times \frac{1}{2\pi}\sum_{n,\ell}\frac{d}{dE_e}p^c_{q_e}(n\ell \to E_e)$$

Calculating Migdal and Brem. rates

Bremsstrahlung

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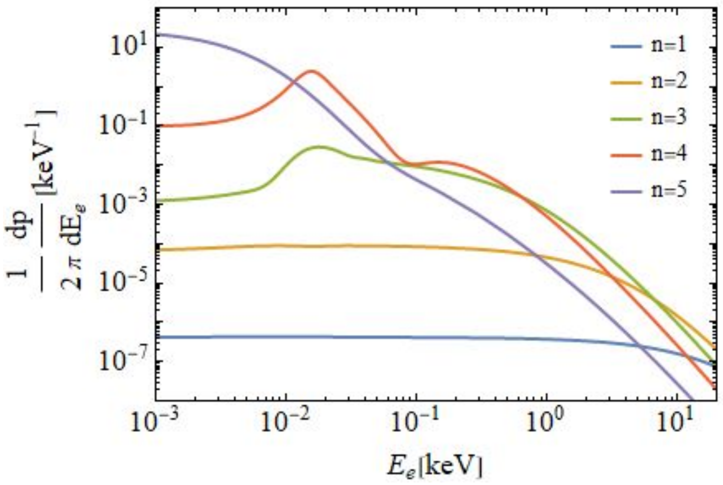


What does a Migdal event look like?

There are three components:

i. Nuclear recoil
ii. Electron energy
iii. Atomic de-excitation

De-excitation proceeds via radiative, Auger or Coster-Kronig transition, dependent on which shell the vacancy is in.

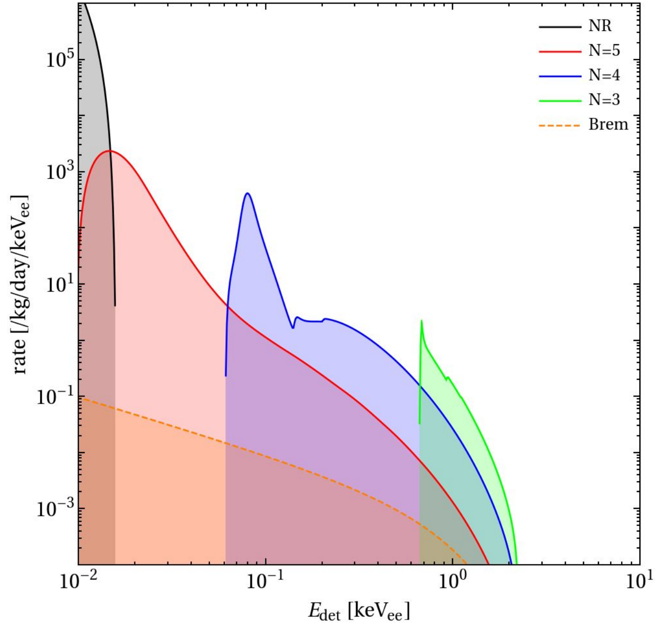
Total detected energy:

$$E_{det} = q_{nr} E_R + E_{EM}$$

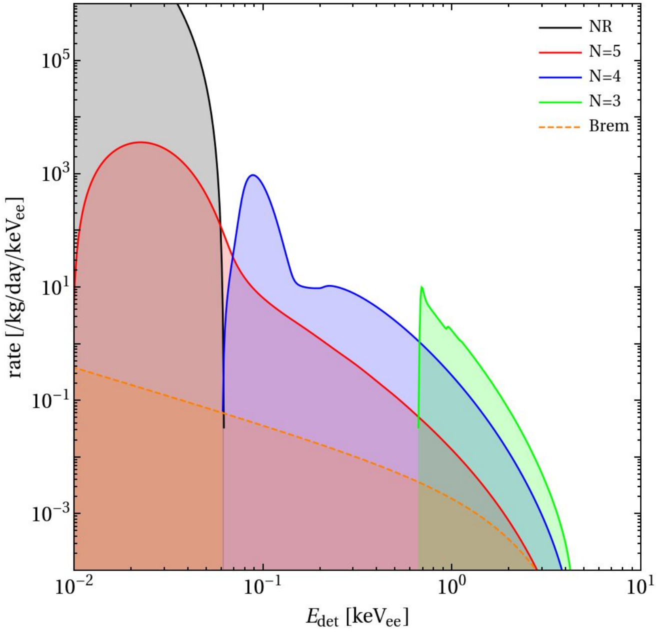
$$E_{EM} = E_e + E_{nl}$$

Migdal and Brem. rates for WIMPs

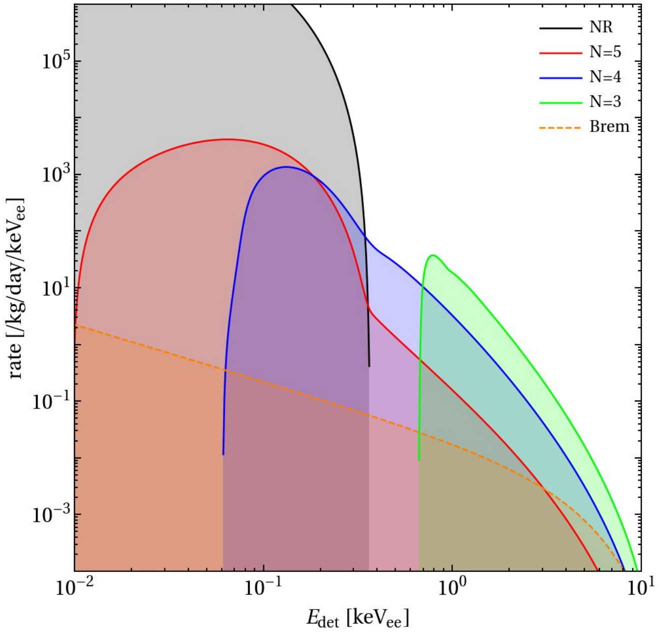
m_x = 1 GeV



m_x = 2 GeV

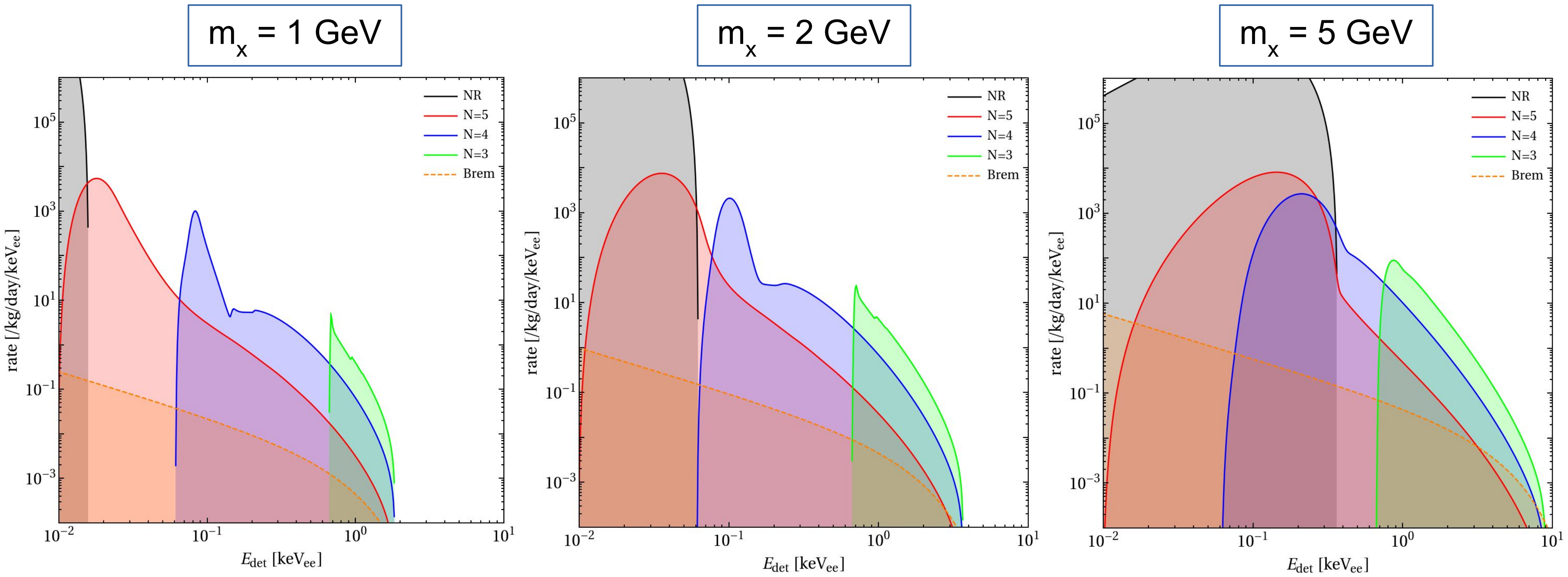


m_x = 5 GeV



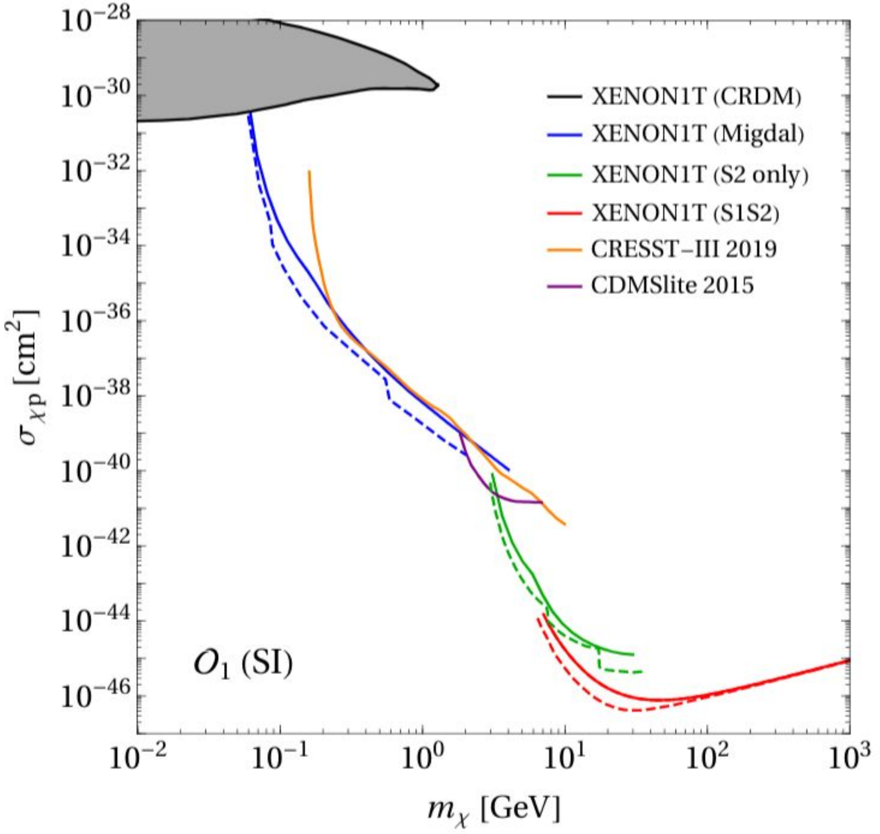
Spin-independent

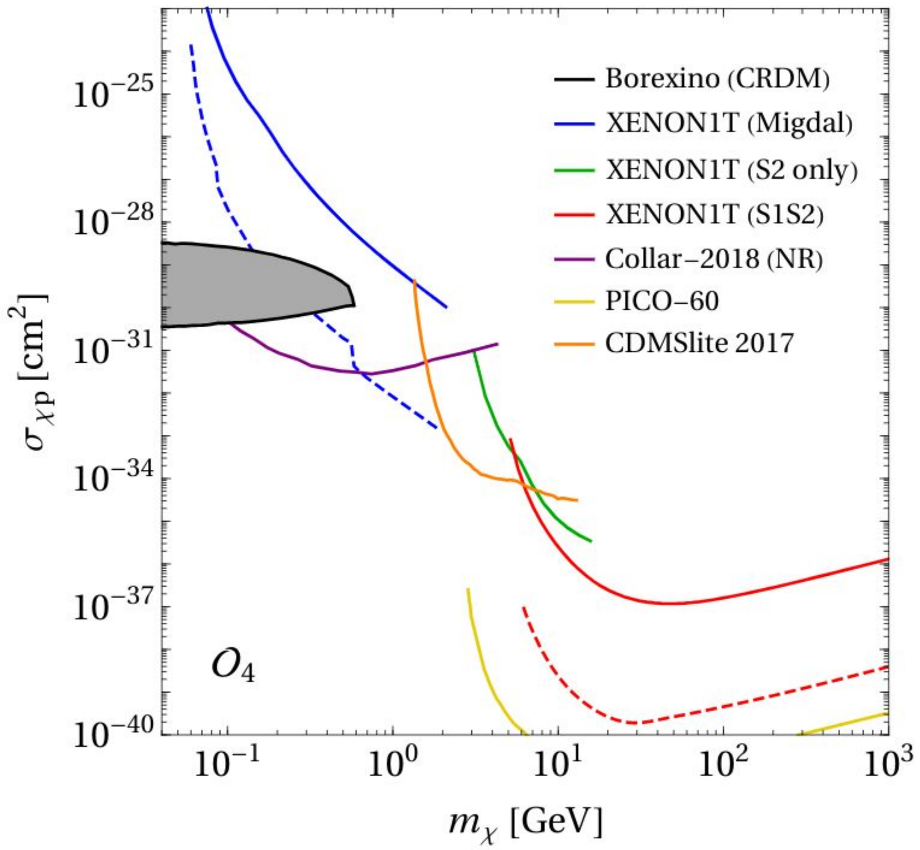
Migdal and Brem. rates for WIMPs



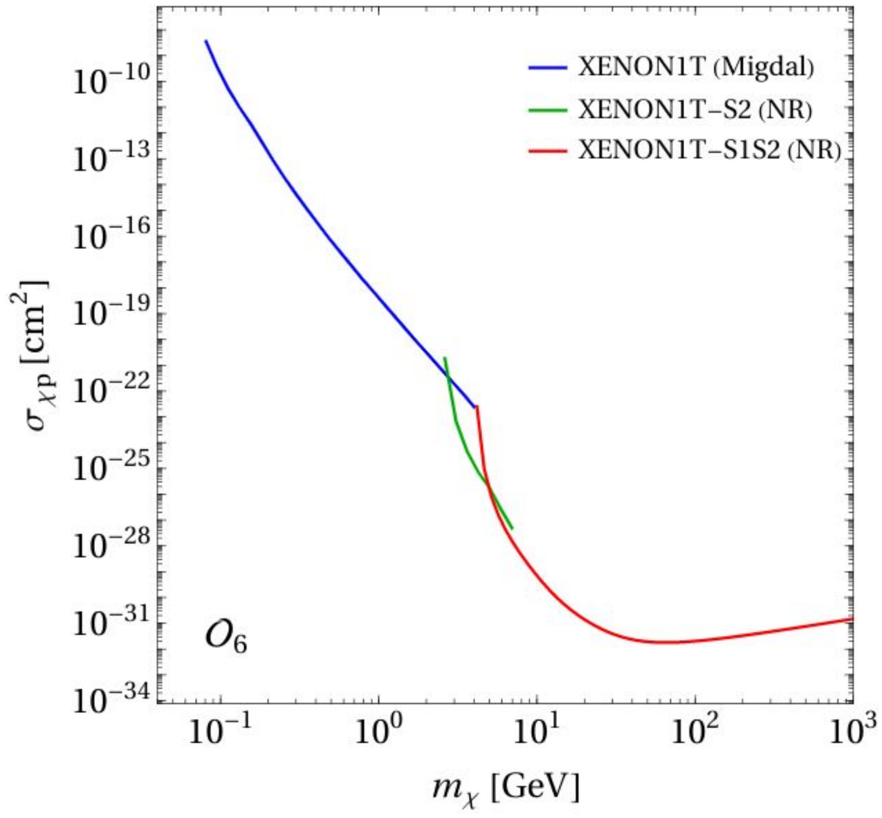
$O_6 = (S_x.q/m_N)(S_N.q/m_N)$
- spin and momentum dependent

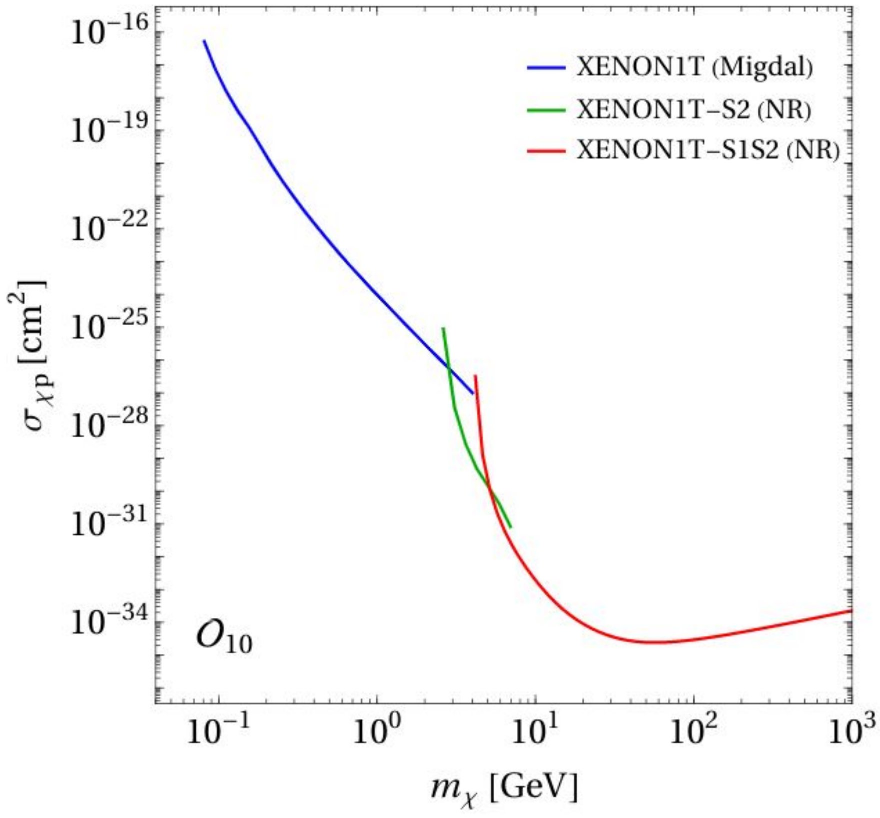
Our bounds from the Migdal effect



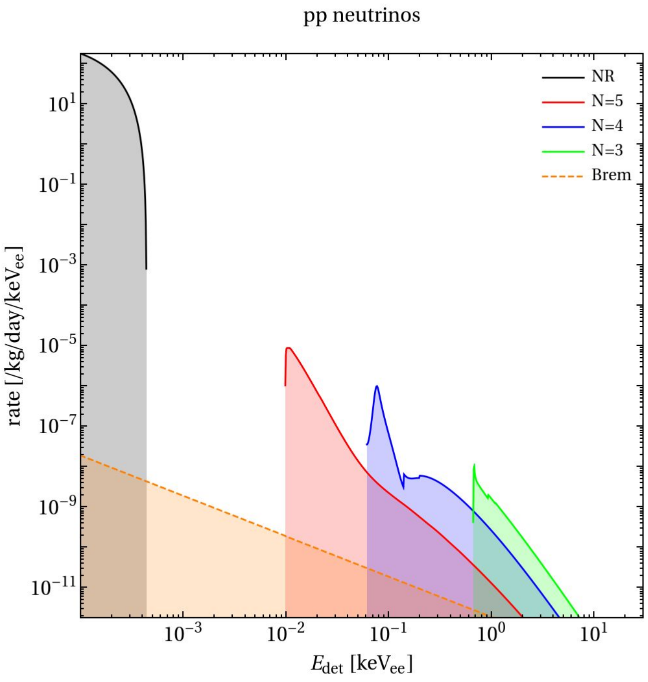


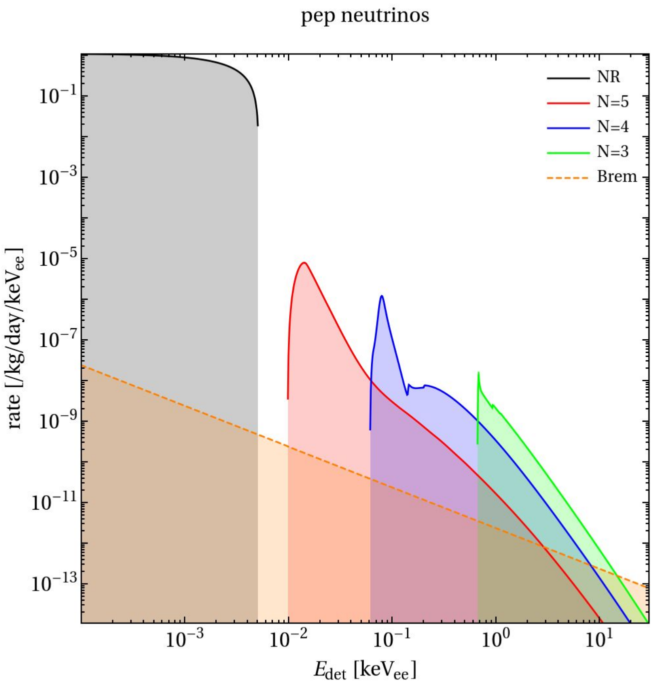
Our bounds from the Migdal effect

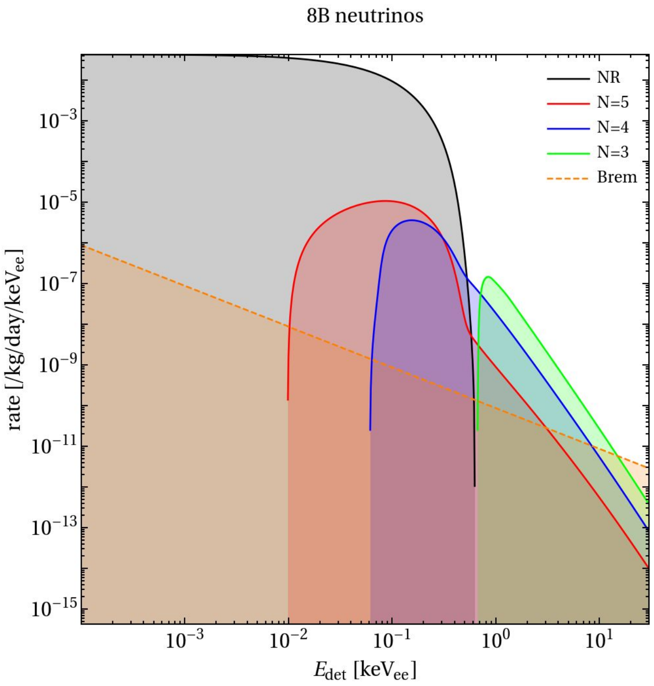




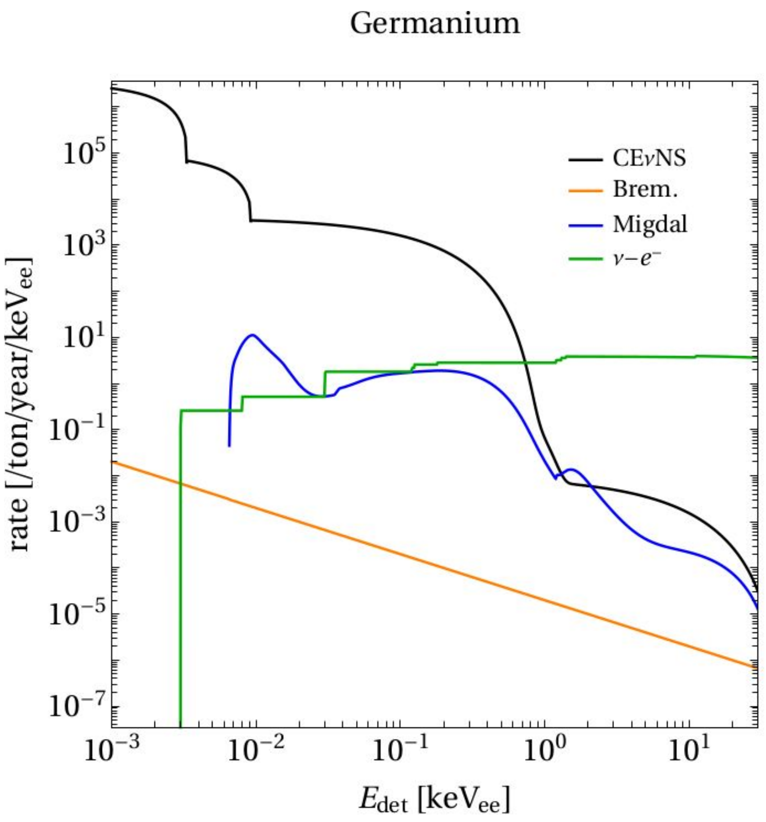
Migdal and Brem. rates for neutrinos

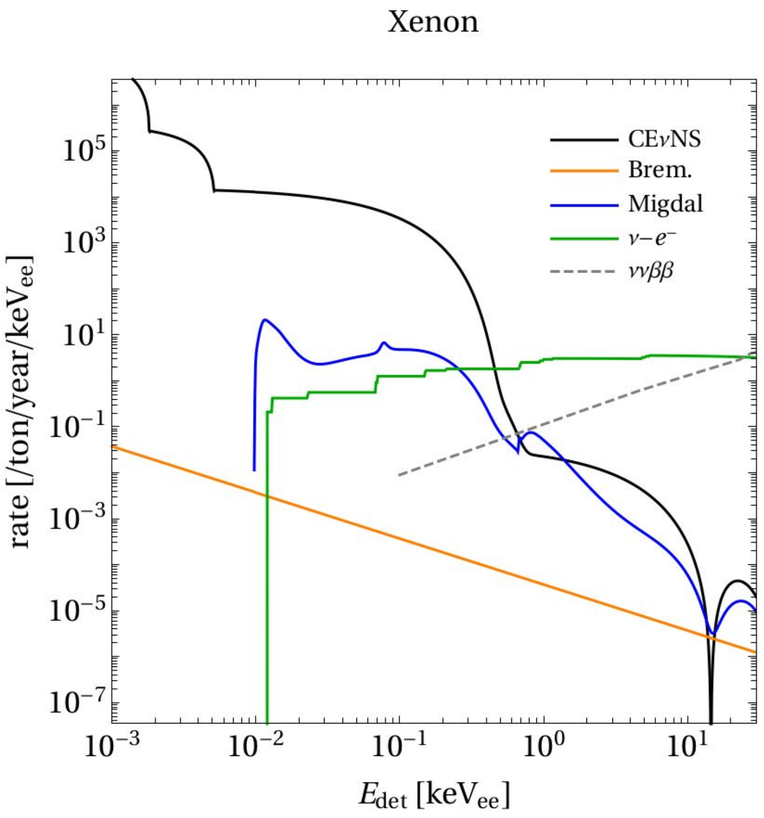






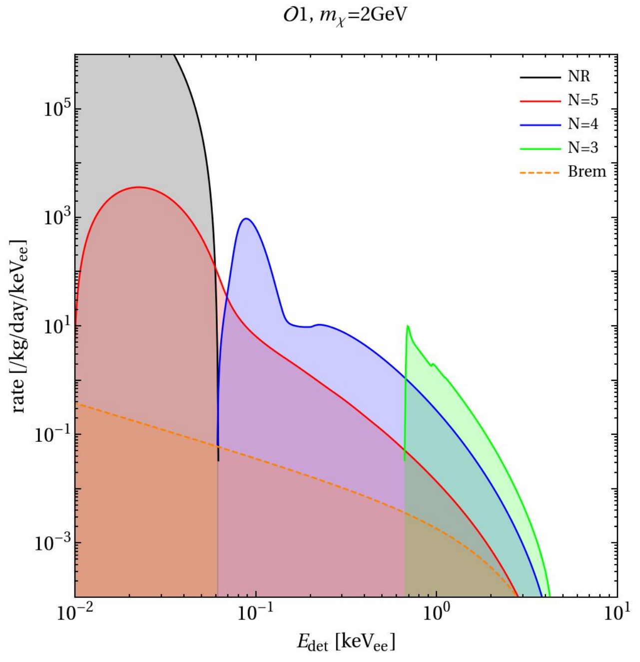
Relevance of the Migdal effect for neutrino rates

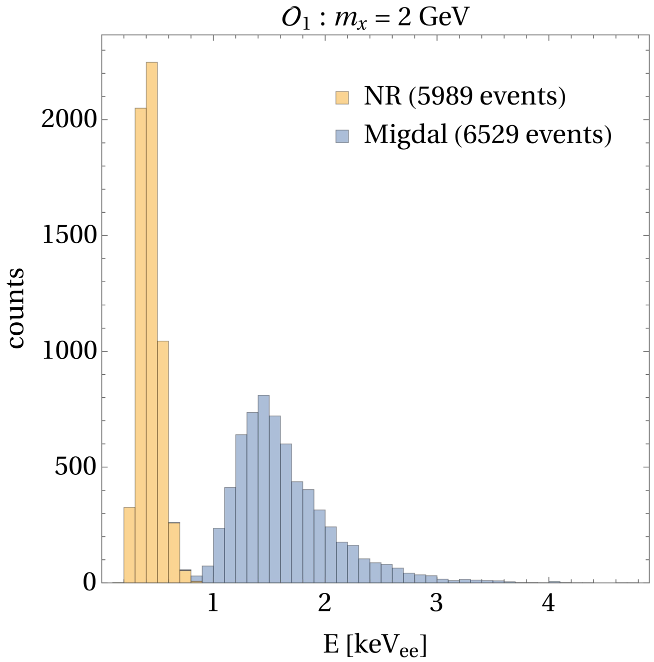




Using NEST to simulate Migdal events

1. Sample the NR and Migdal spectrum directly, treating all events individually





- Ignores that part of Migdal event's energy comes from NR

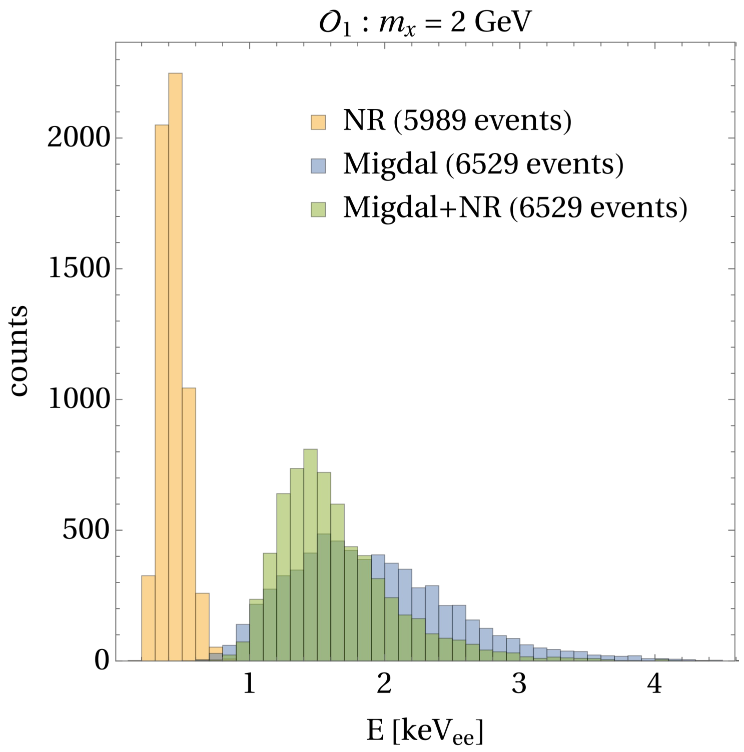
$$E_{det} = q_{nr} E_R + E_{EM}$$

- Only suitable if NR is *well* below threshold

Using NEST to simulate Migdal events

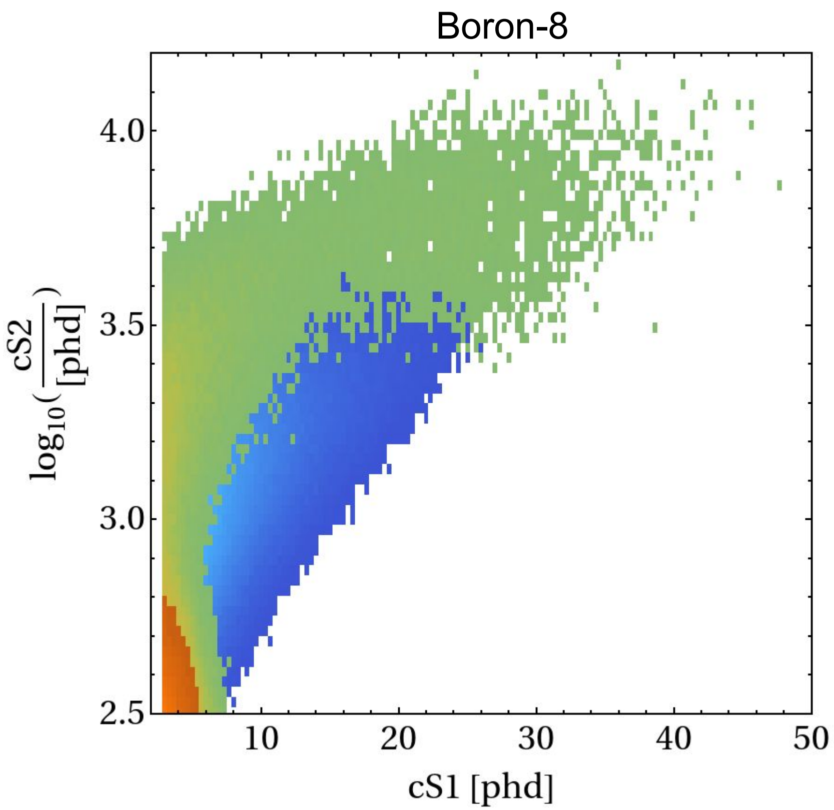
2. Event-by-event simulation: use NRs to produce Migdal events

i. MC sample E_{NR} and v
ii. Randomly select an electron (or none) with scaled probability
iii. MC sample E_e for selected electron shell
iv. De-excite atom, producing gamma or Auger electrons



Using NEST to simulate Migdal events

- In S1/S2 space we see that the Migdal events occupy a different region when simulated event-by-event



95% regions:

- NR
- NR+Migdal
- Migdal (as ER)

Three take-aways:

- The Migdal effect is a useful probe of light dark matter, and dominates over brem for all cases explored
- The Migdal effect from solar neutrinos has a rate comparable to the atmospheric rate
- Need to model the Migdal effect event-by-event with the NR, not as a separate signal channel in ER