Developments and Prospects in the Direct Detection of Light Dark Matter

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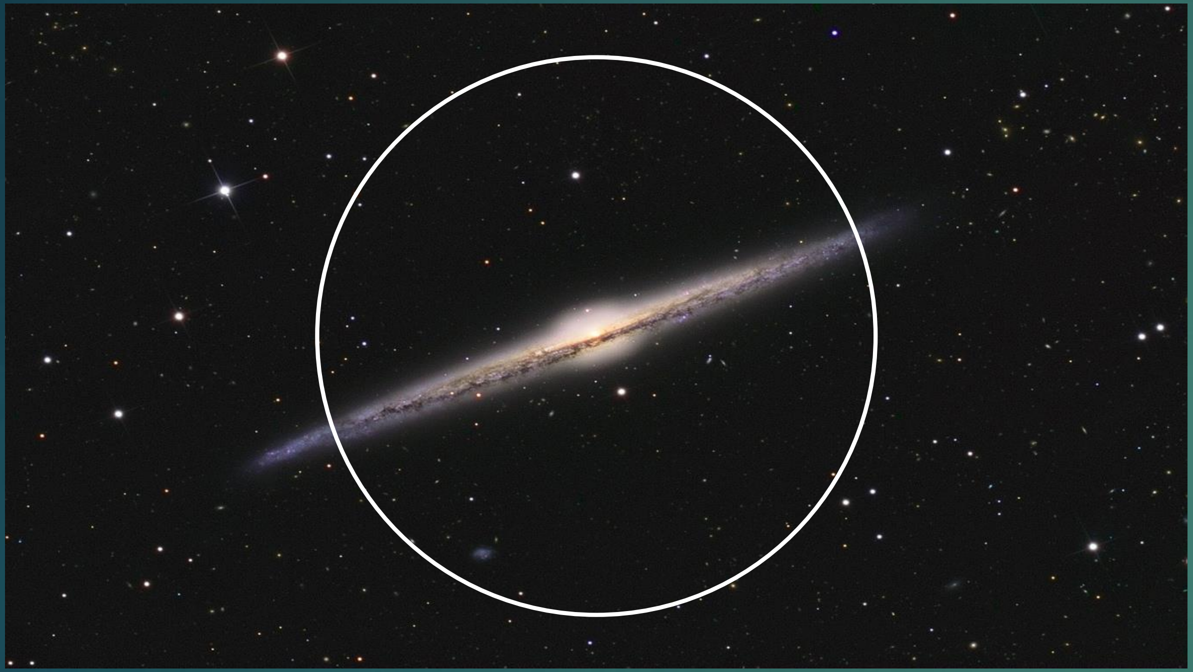
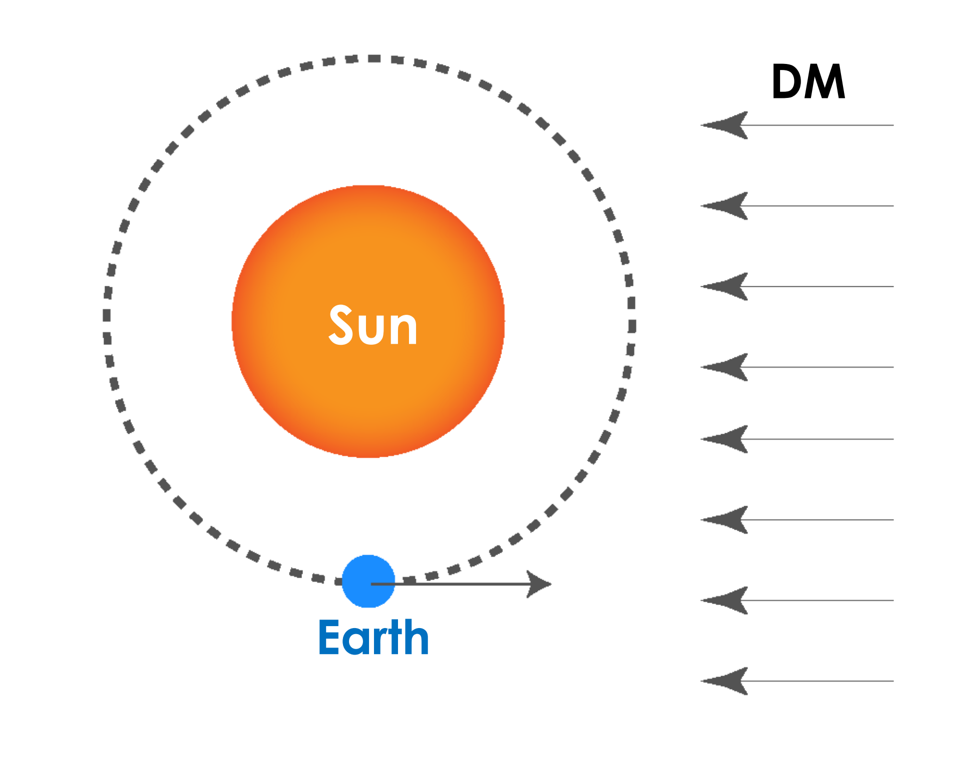
Direct Detection of Dark Matter



Dark Matter exists in a roughly spherical and non-rotating halo.

Luminous matter exists in a disc rotating at around 200 km/s.

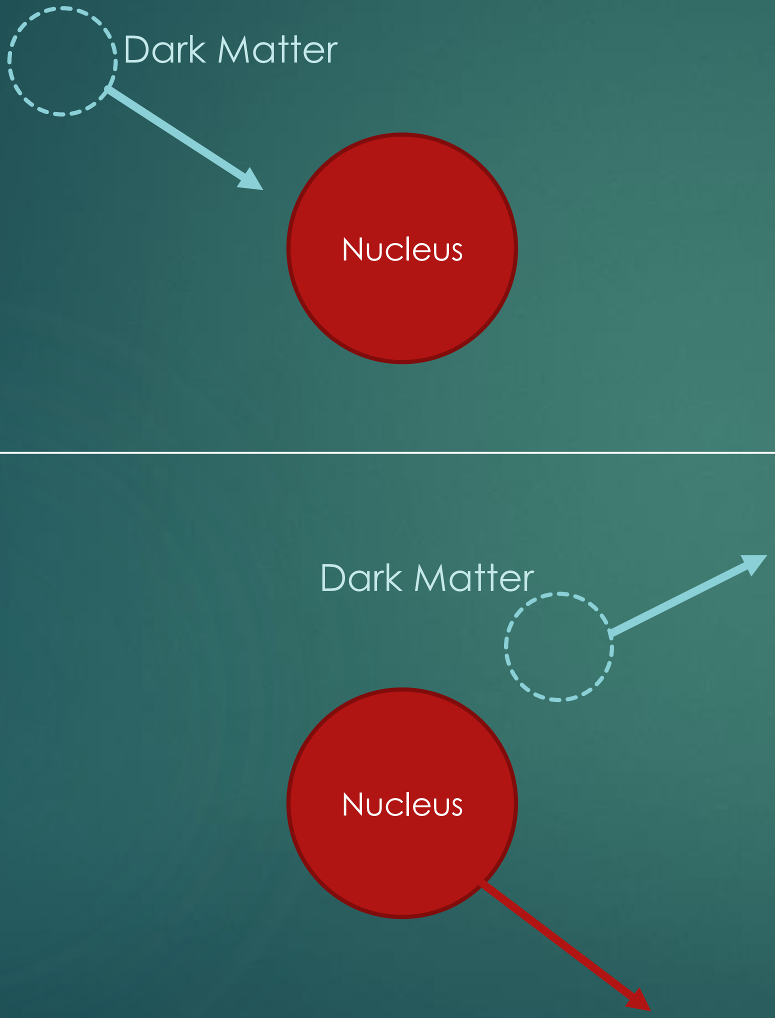
This relative rotation and the random motion of the DM particles results in a relative velocity between Earth and DM.

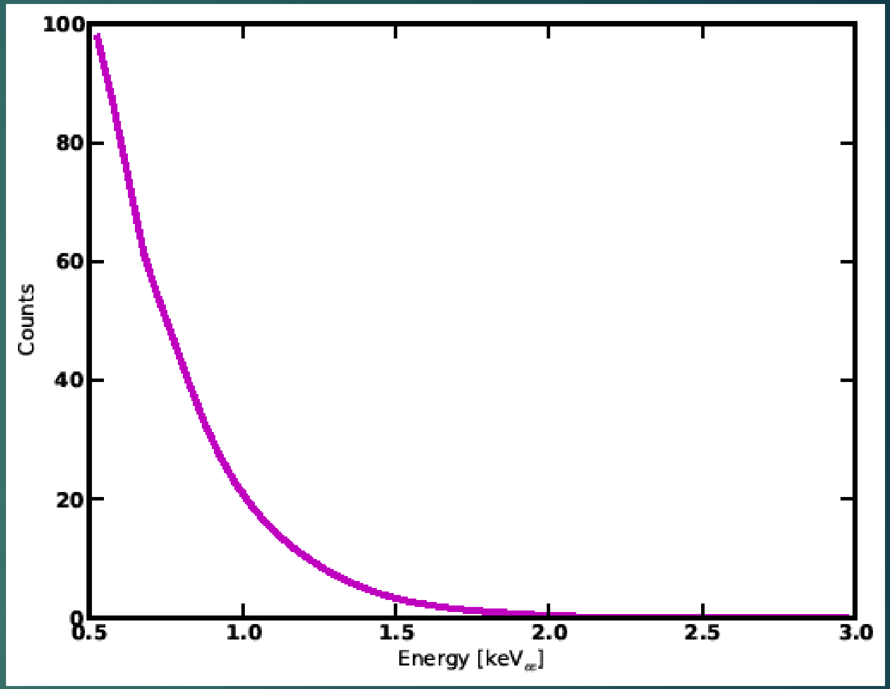


Direct Detection of Dark Matter

Before

After

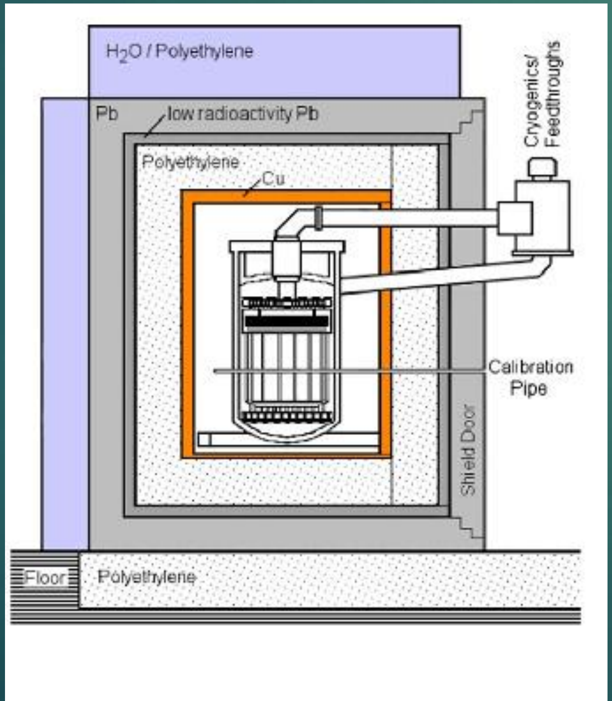


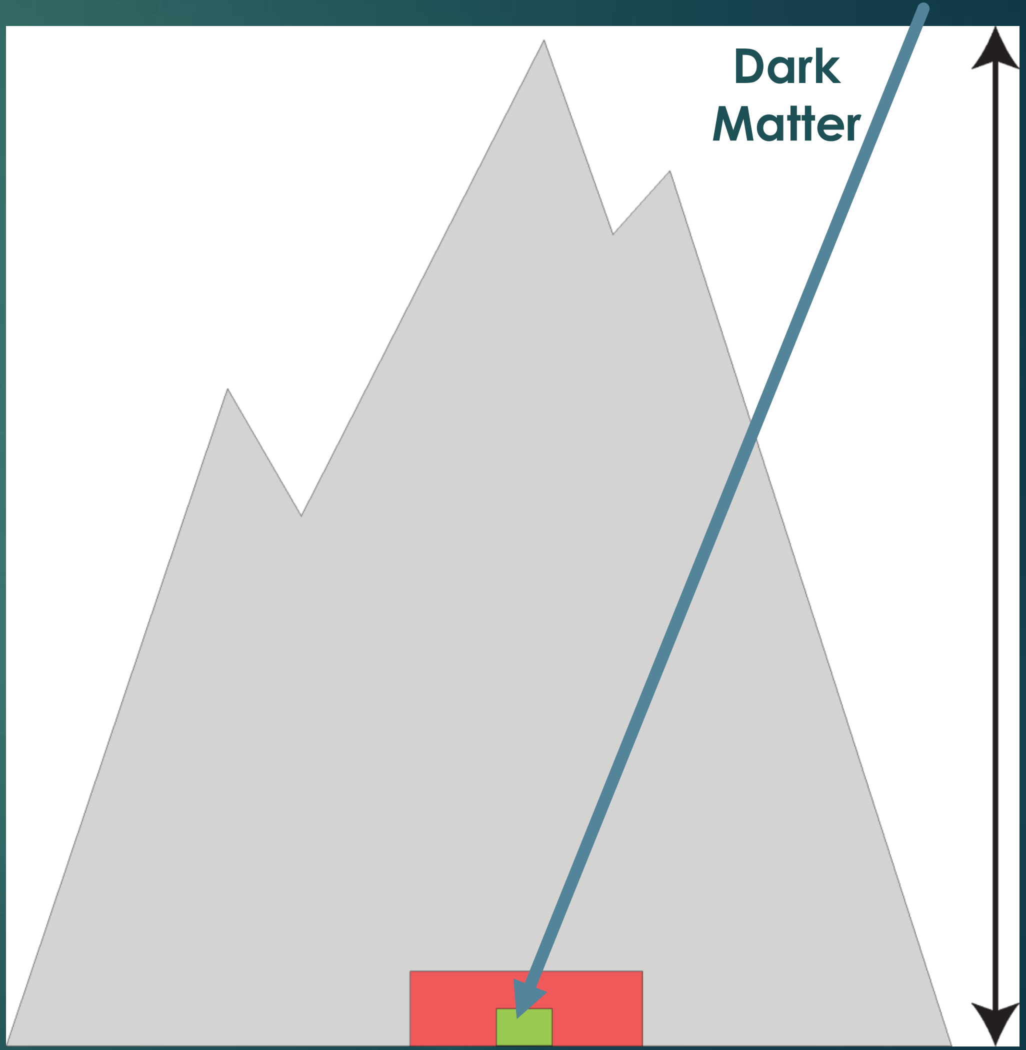


Look for keV-energy nuclear recoils.

Backgrounds to Direct Searches

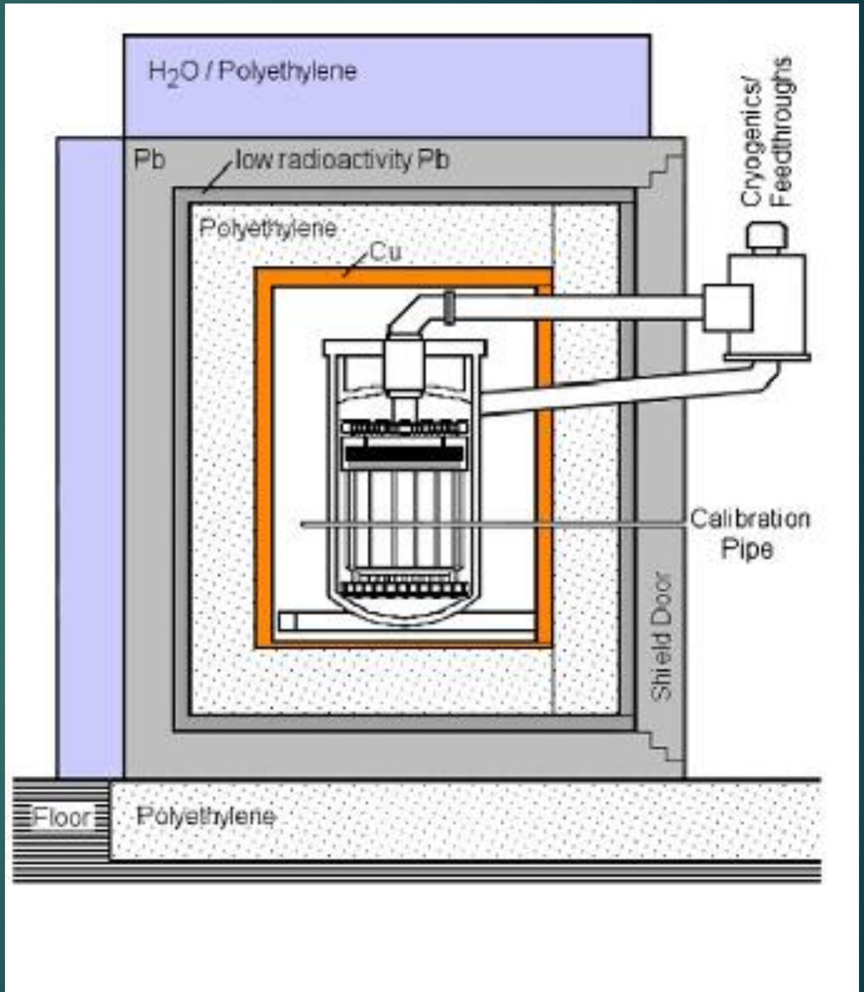
- The ability to look for these recoils is limited by backgrounds.
- One method to reduce backgrounds is through shielding.





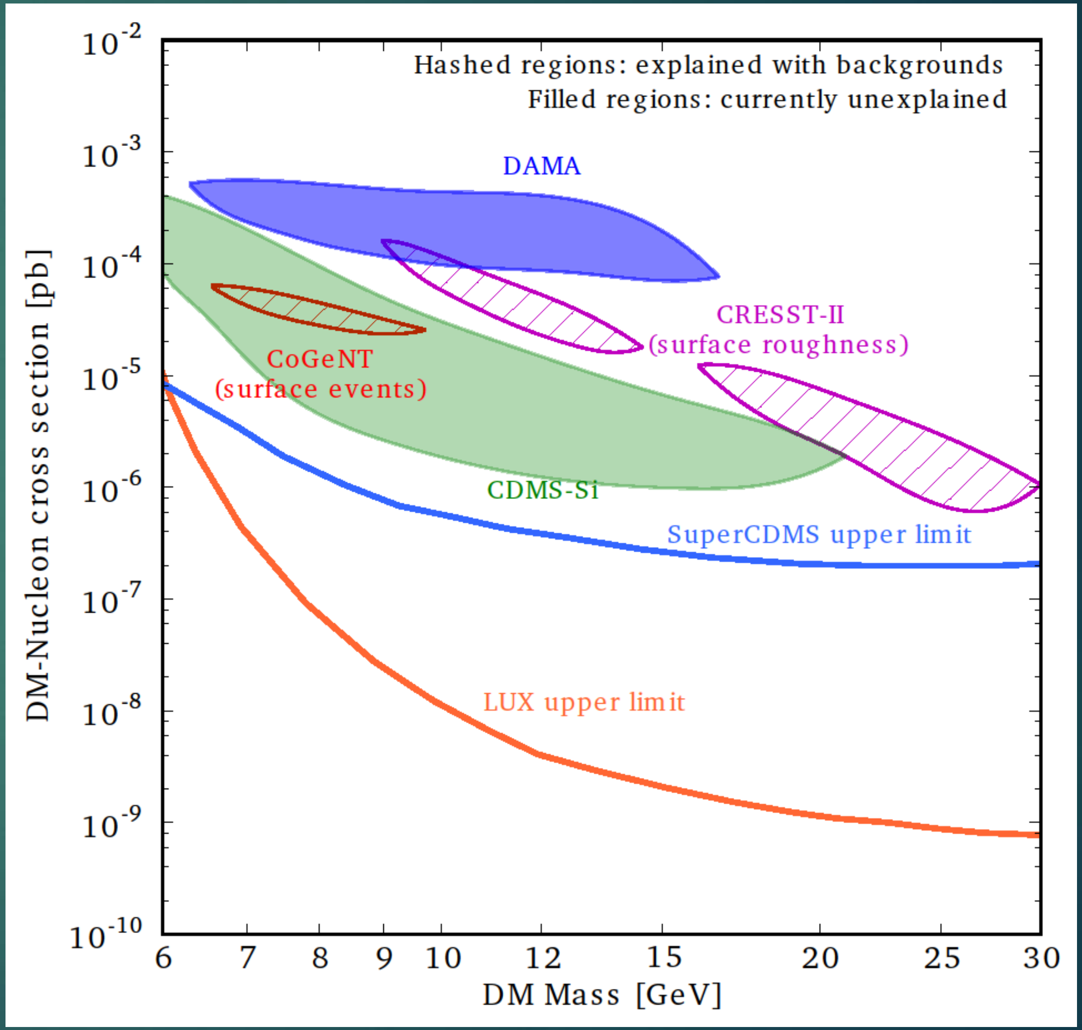
Backgrounds to Direct Searches

- However even the shielding can be a source of background through radioactivity.
- Improper understanding of these backgrounds can (and has) lead to false signals.
- Even so all of these backgrounds are reducible in that one can always add more shielding and use more pure materials.



Example: A false signal in CoGeNT

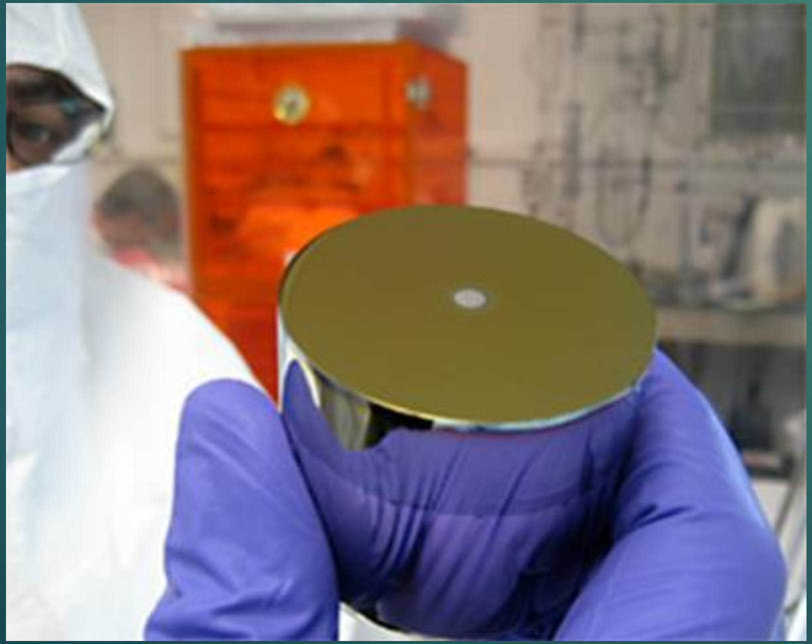
- Some experiments in the past few years have claimed to see signals of dark matter recoils.
- These are all excluded by LUX and SuperCDMS.
- Two of these: CoGeNT and CRESST-II have now both been explained as misidentified backgrounds.

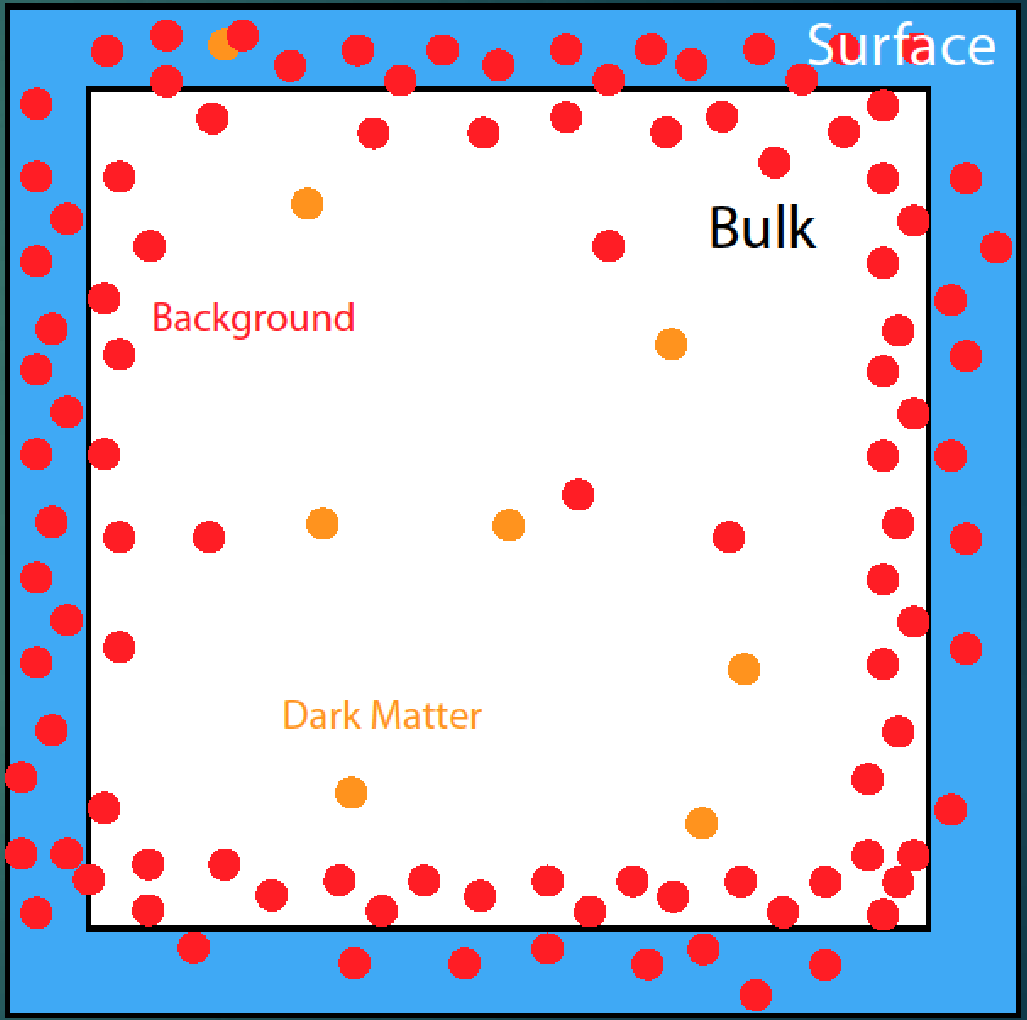


J.H.Davis, Int.J.Mod.Phys. A30 (2015) 15, 1530038, arXiv:1506.03924

Example: A false signal in CoGeNT

- CoGeNT detects keV-recoils through small changes in the voltage of its semiconductor-based modules.
- Dark Matter makes no distinction between the surface layer of these modules and their bulk.
- However many types of background scatter much more often on the surface. Hence all events on the surface are background.

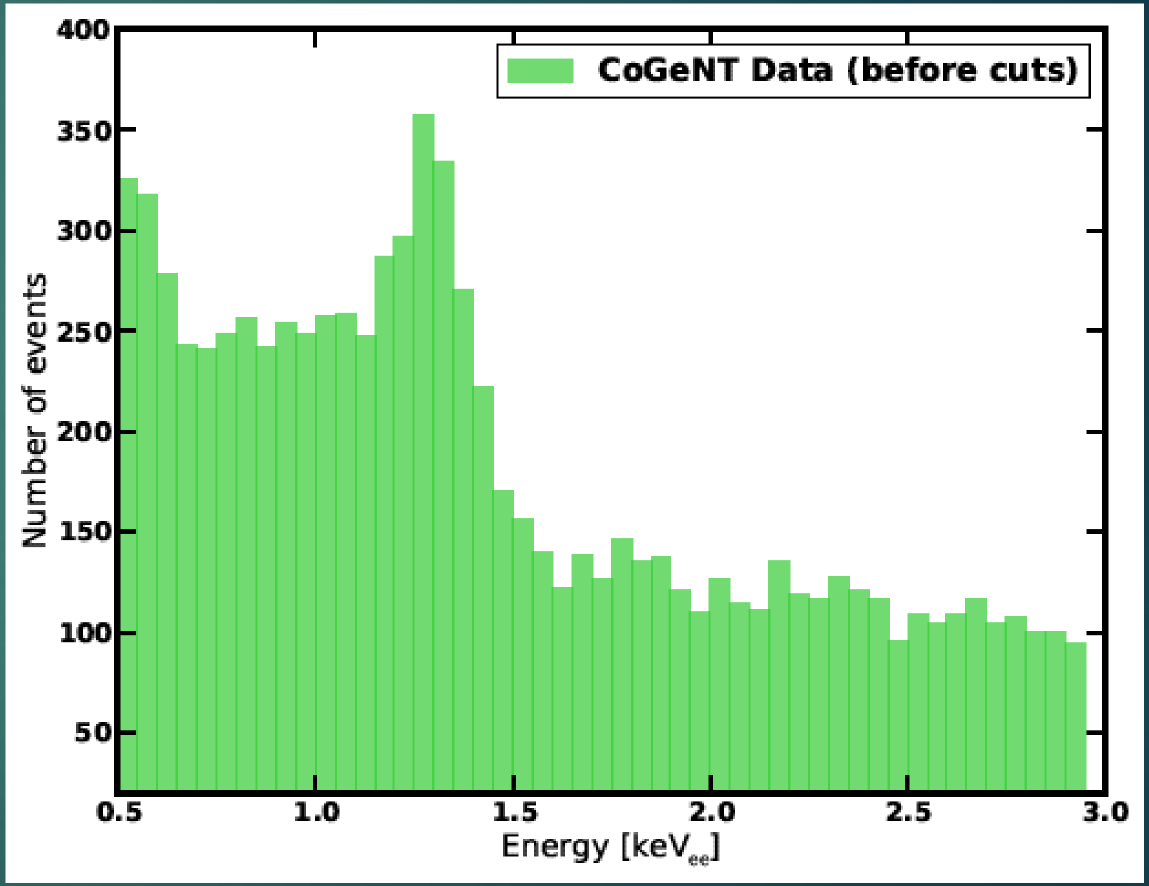




CoGeNT energy spectrum before cuts

Naively the low energy part of the signal looks like the rise expected from light dark matter. However we need to understand backgrounds before we can say more.

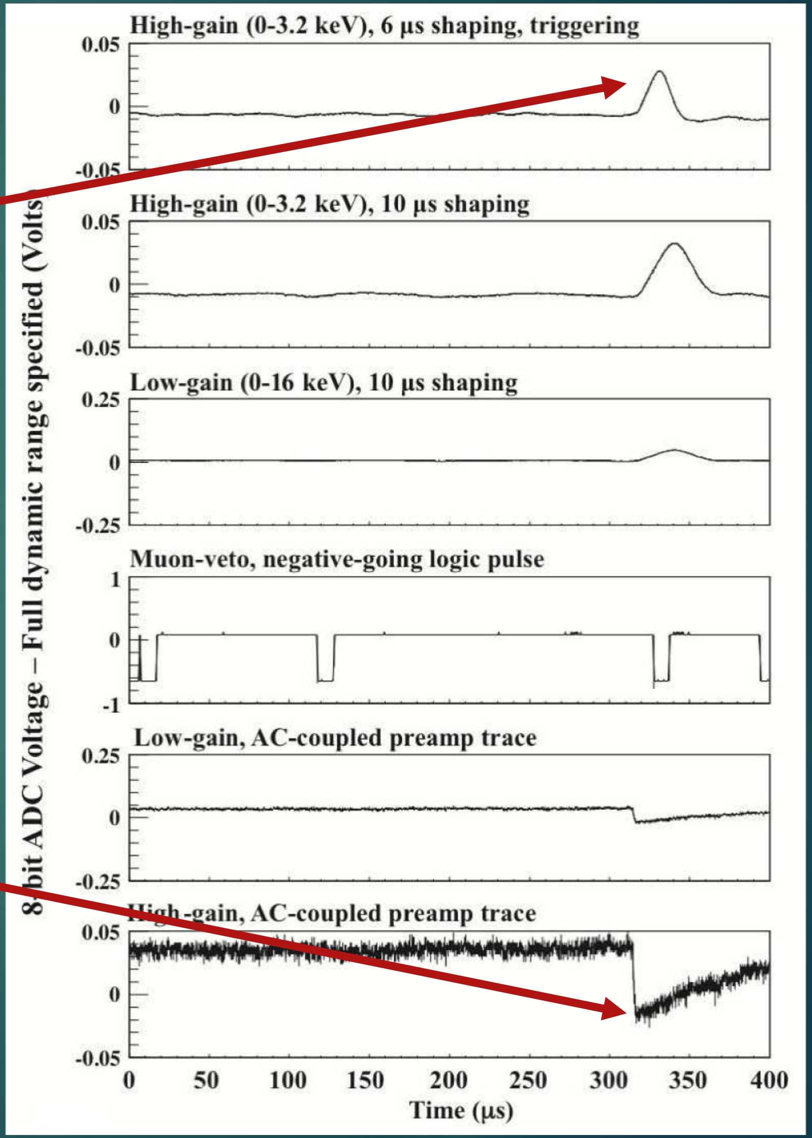
We need to take a closer look at an event in the detector.



An event in CoGeNT

An event is not instantaneous, but occurs over a finite time, called the rise-time.

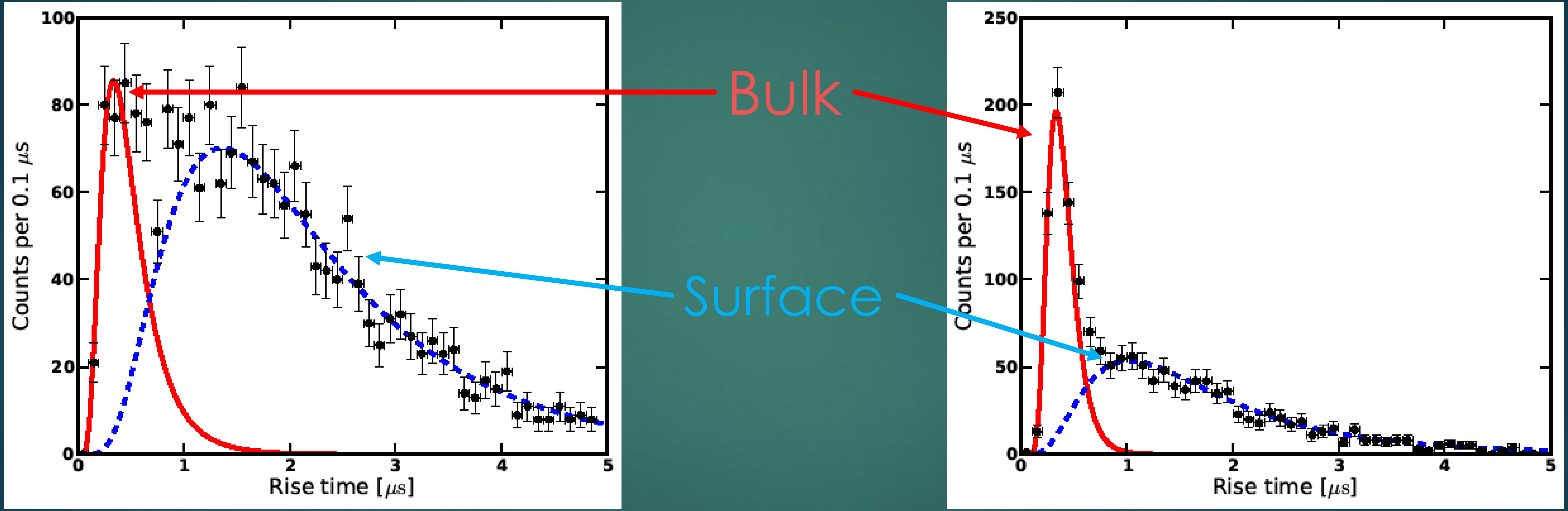
The voltage increase here implies an energy of about 2.5 keV.



Distribution of events in rise-time

0.5 – 0.9 keV

1.3 – 1.7 keV

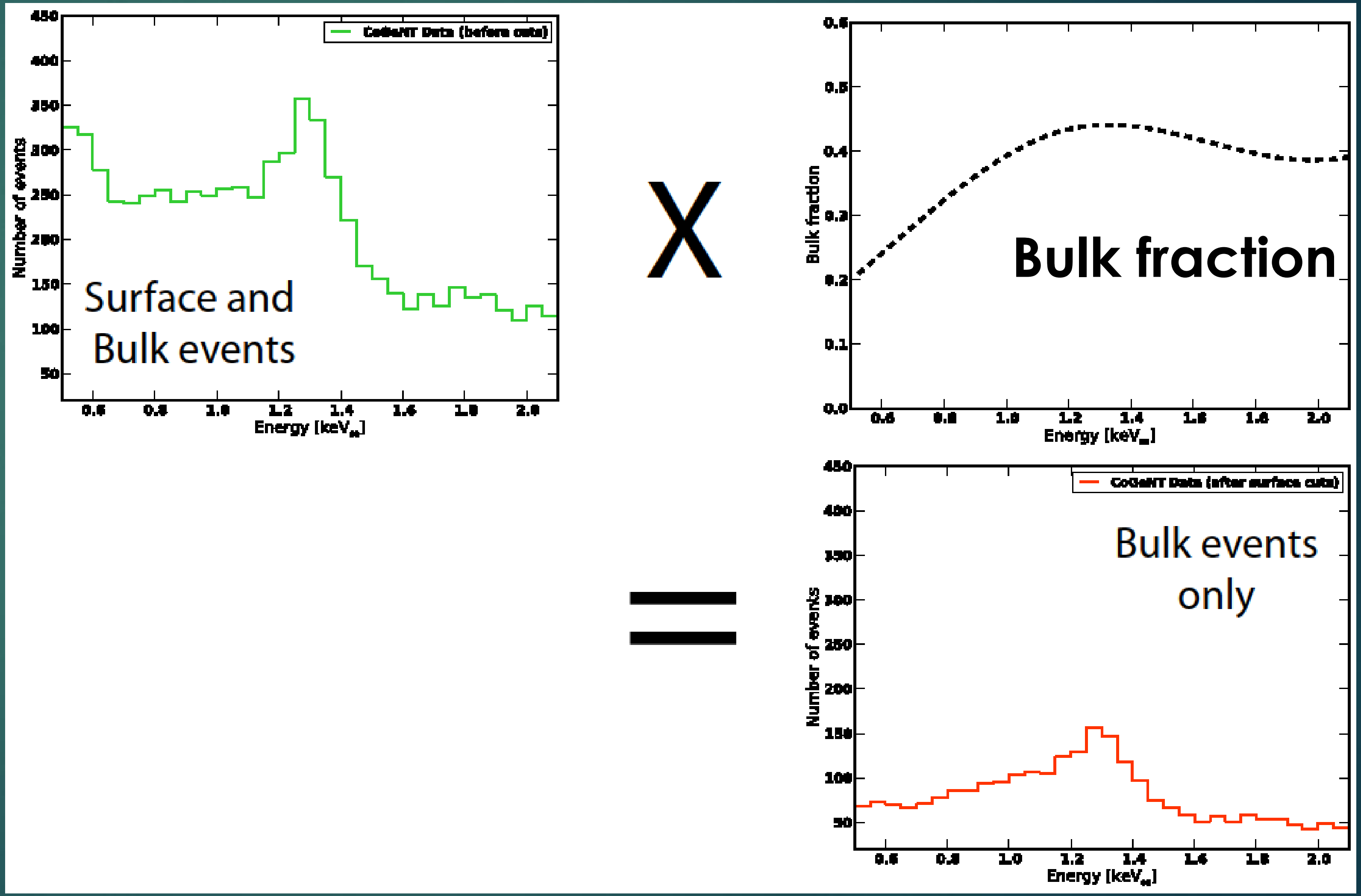


Davis, McCabe, Boehm, JCAP 1408 (2014) 014

Fit log-normal distributions. Surface events are slower and overlap significantly with bulk at low energy.

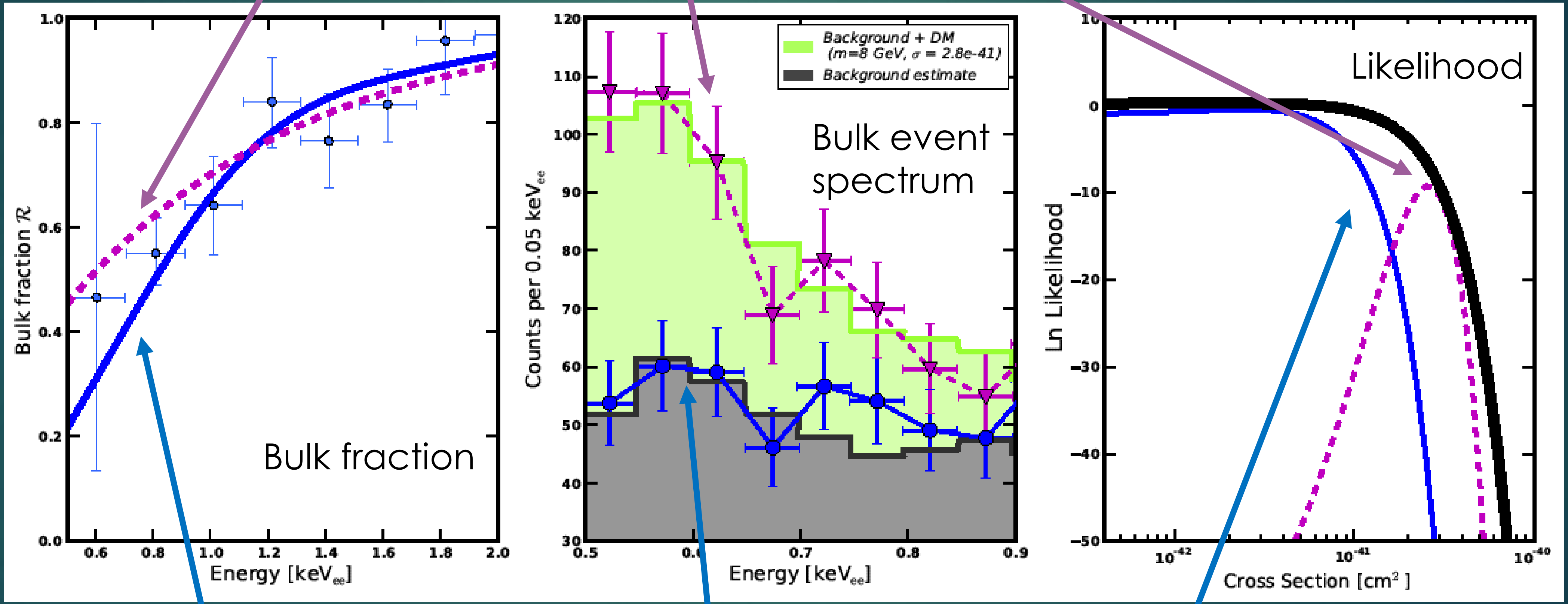
Using the rise-time discrimination

- Doing this separation for each bin gives us the bulk fraction as a function of energy.
- Multiplying the raw spectrum by the bulk fraction gives us what should be purely bulk events.



Uncertainties in the bulk fraction: fake signals

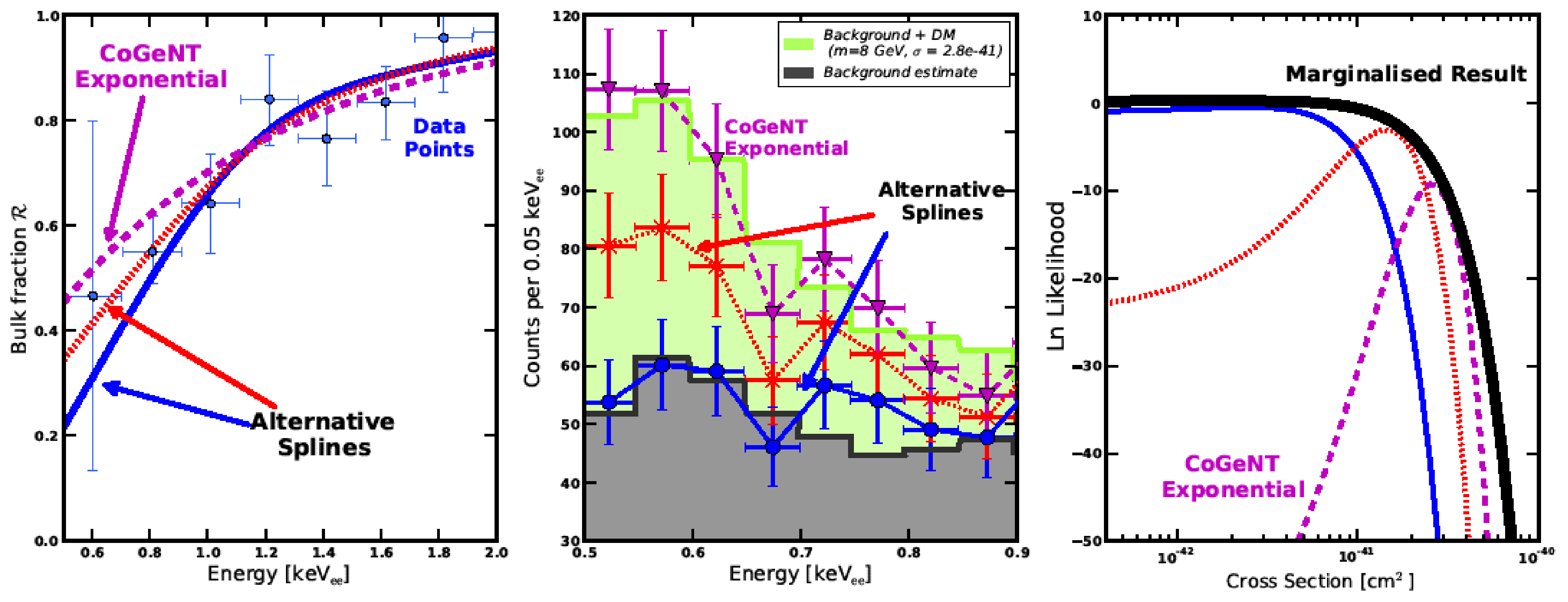
CoGeNT's exponential choice for surface event removal.



Blue spline is just as good a choice for the bulk fraction but gives no evidence for a DM signal.

Dangers of poorly understood backgrounds

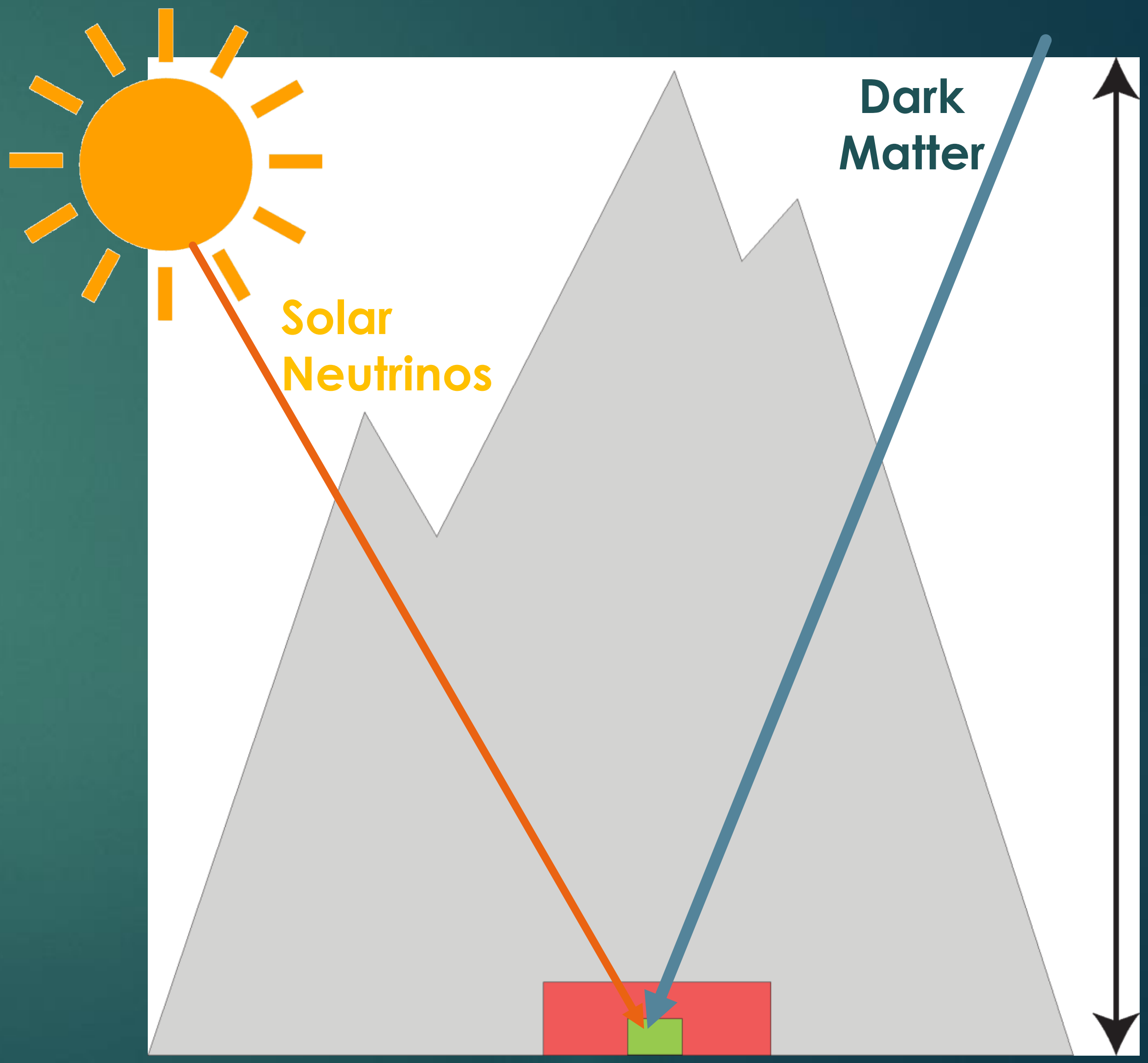
A background with a poorly-understood spectrum can easily mimic a dark matter signal.



Davis, McCabe, Boehm, JCAP 1408 (2014) 014

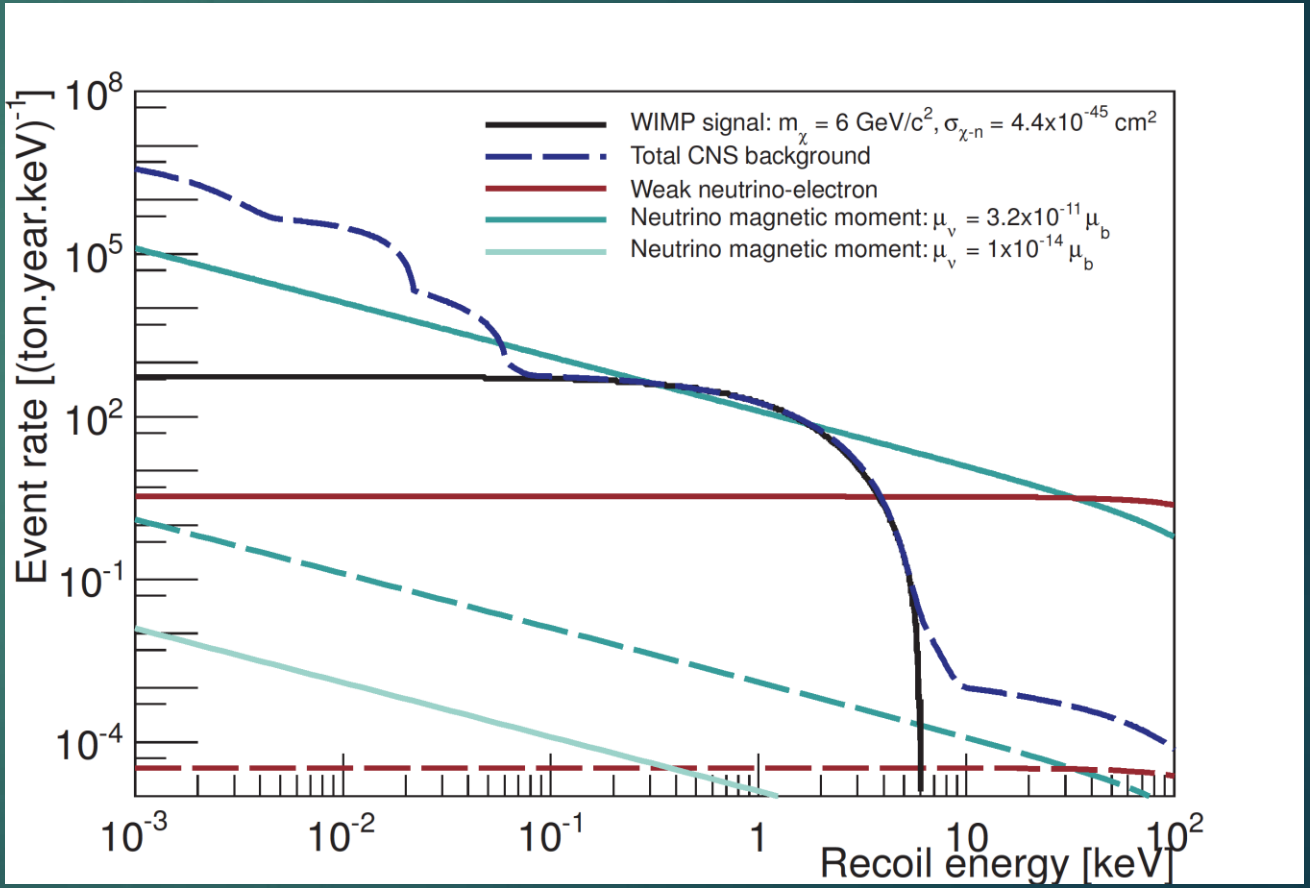
Backgrounds to future direct searches from solar neutrinos

- All current direct experiments are limited by reducible backgrounds such as radioactivity in the shielding materials.
- Future searches face an additional and irreducible background from neutrinos, particularly those from the Sun.



Backgrounds to future direct searches from solar neutrinos

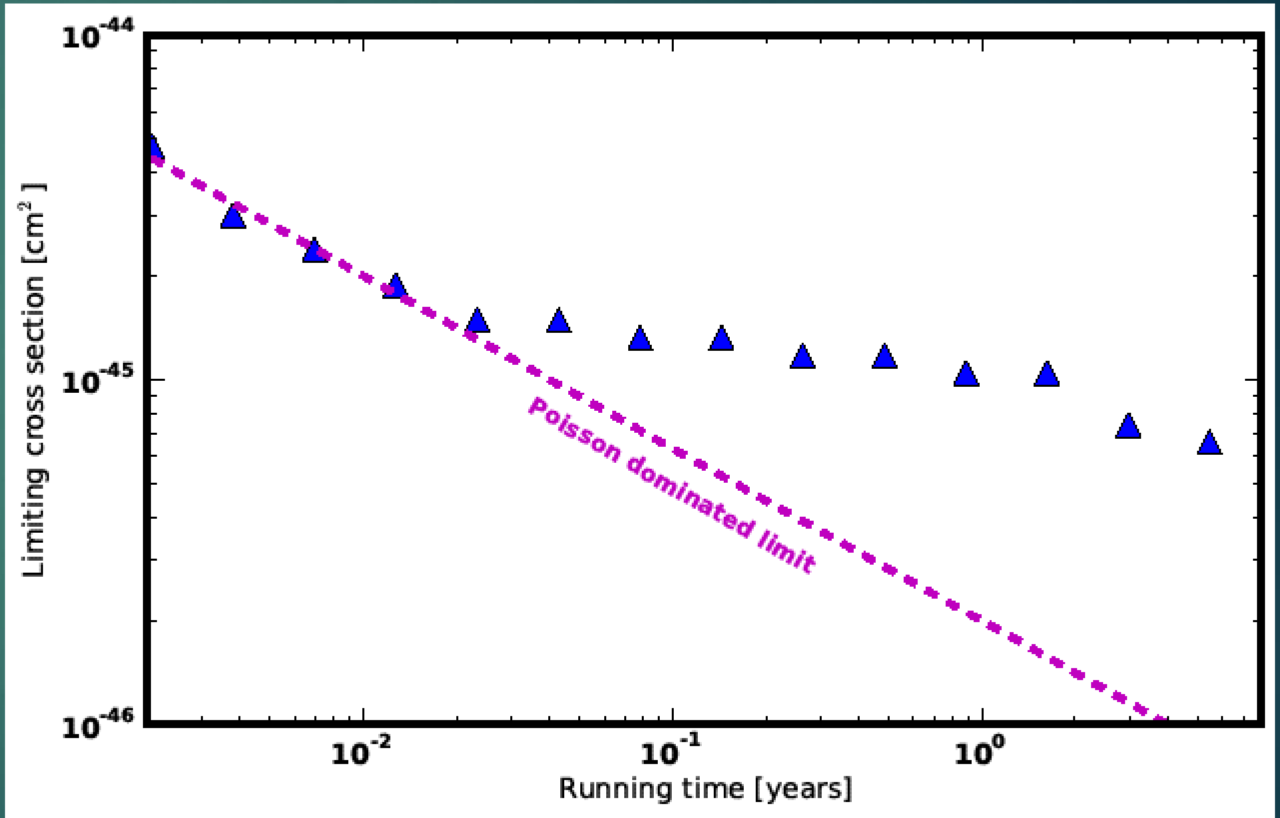
- Solar neutrinos will induce nuclear recoils with a spectrum similar to dark matter with a mass around 6 GeV.
- As we have seen already such a scenario is dangerous for direct detection experiments.



J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 89 (2014) 023524

Limits to future sensitivity due to solar neutrinos

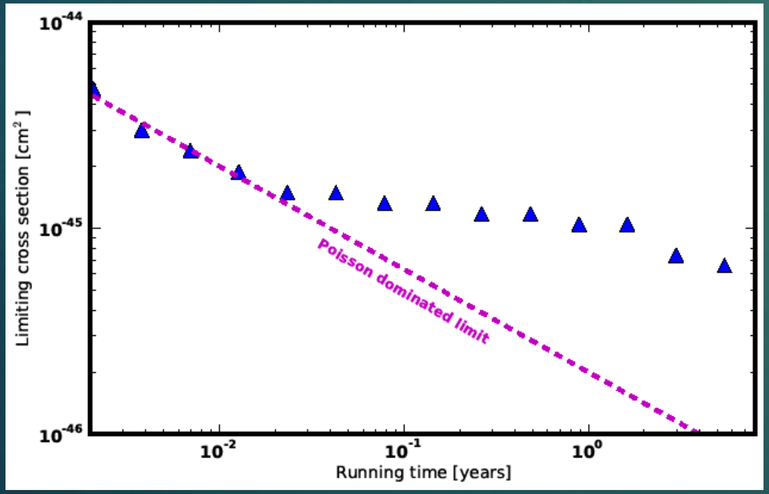
- For the same reason the sensitivity of future direct searches is limited by the systematic and statistical uncertainty on the neutrino background.
- We assume a 10 tonne xenon detector with a 0.1keV threshold.
- For 6 GeV dark matter the sensitivity hardly increases at all even as the experiment acquires more data.

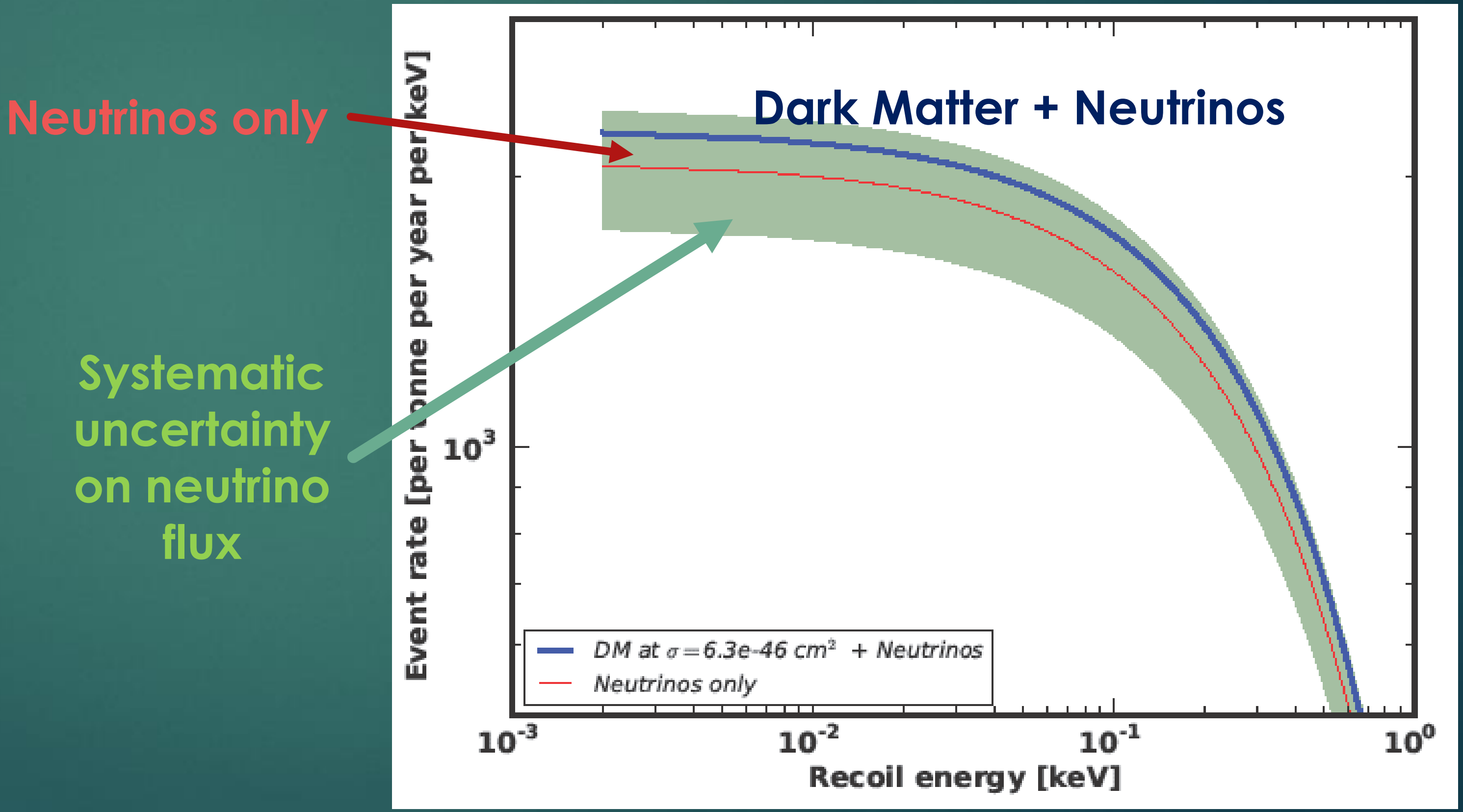


J. H. Davis, JCAP 1503 (2015) 012

The first effect: a ‘floor’ from systematic uncertainties

When the dark matter spectrum is indistinguishable from the neutrino spectrum within systematic uncertainties we see a ‘floor’ develop, where sensitivity can not improve.

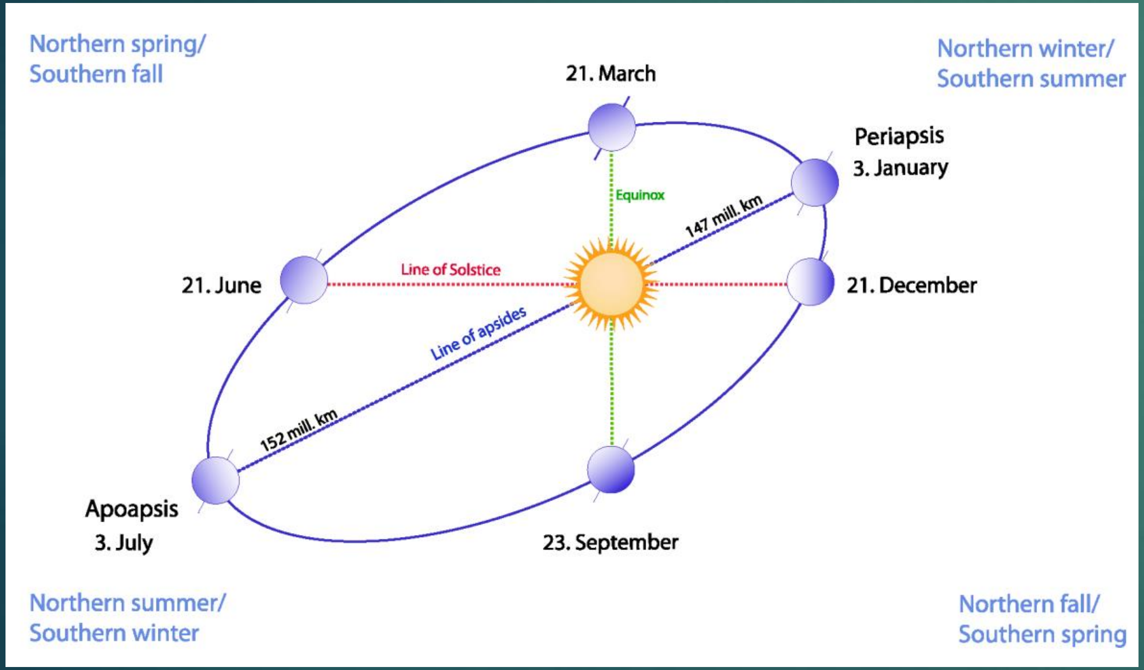




J. H. Davis, JCAP 1503 (2015) 012

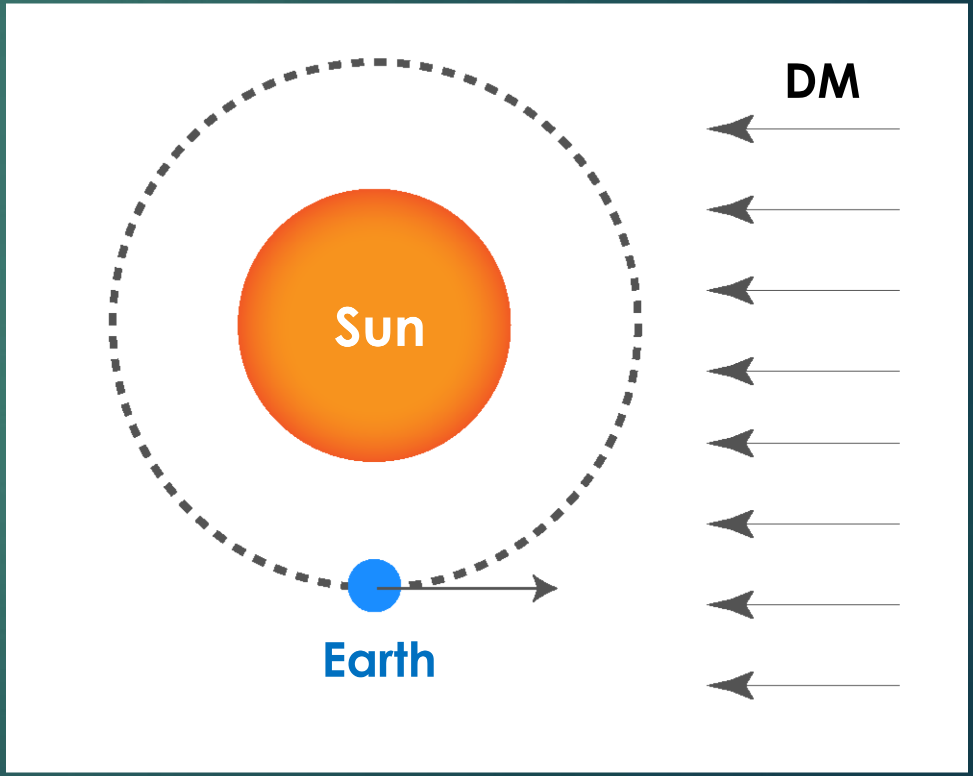
Time variation of dark matter and solar neutrinos

Solar neutrinos



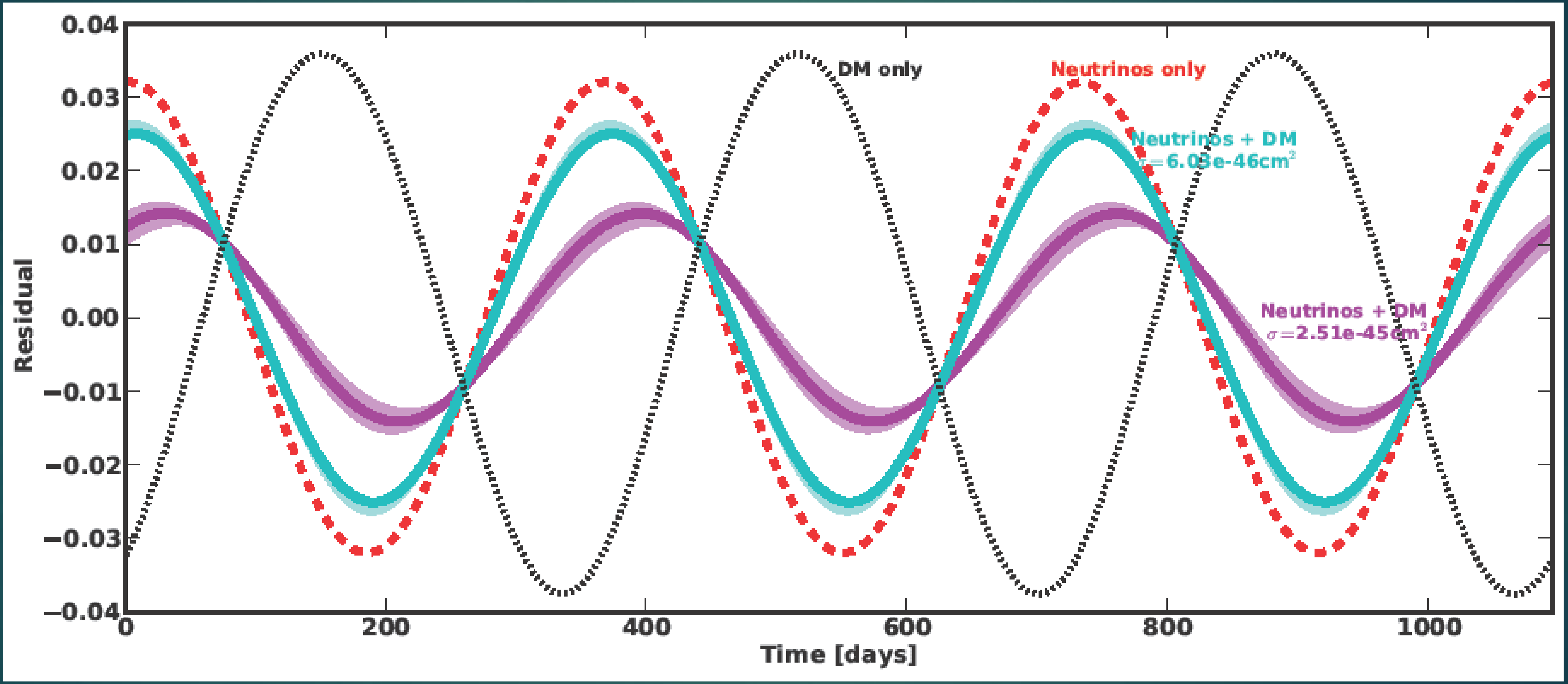
Varying Earth-Sun distance.

Dark matter



Varying Earth-DM relative velocity.

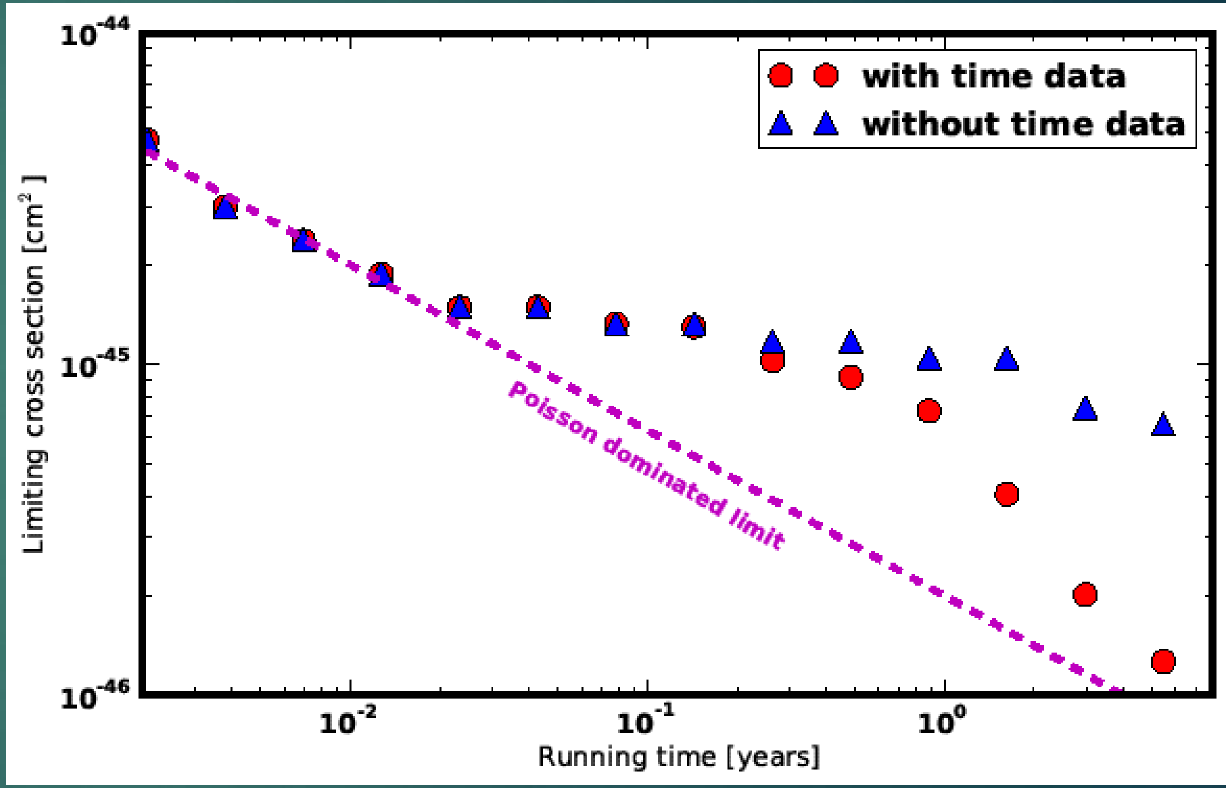
Time variation of dark matter and solar neutrinos



Temporal dependence gives us an additional discrimination parameter.

The effect of using timing information

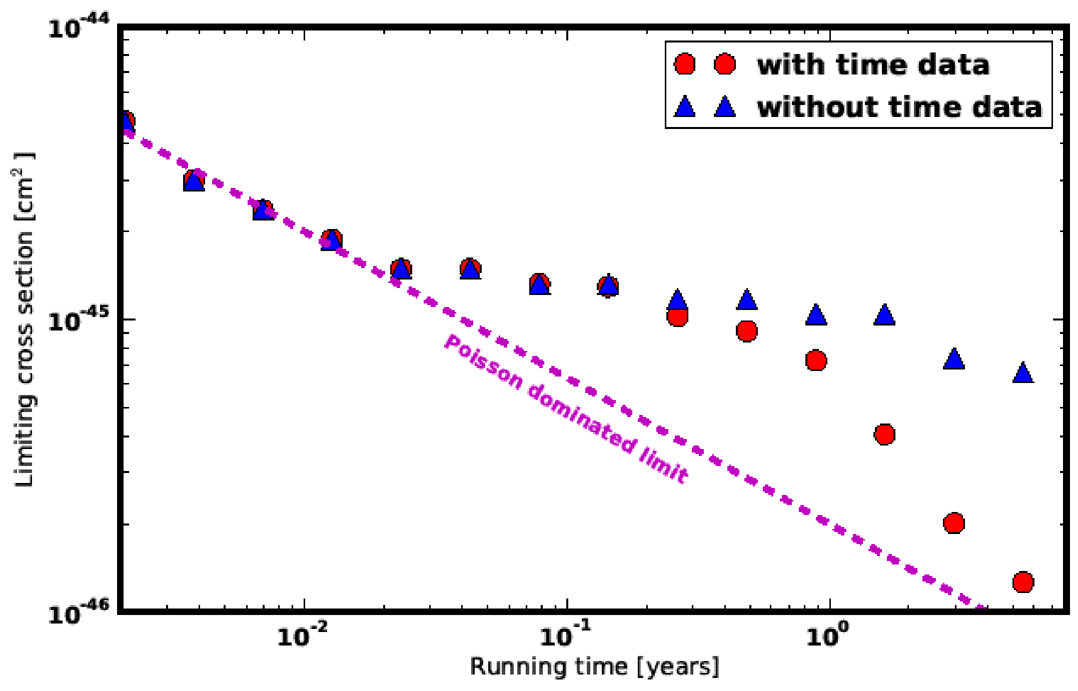
- Adding timing information means that the dark matter and neutrino events can be distinguished even if they have the same spectra.
- Hence the limiting power of the experiment returns to being restricted by Poisson statistics.



The second effect: limited sensitivity from statistical uncertainties

- We can essentially overcome the first effect of the neutrino background (i.e. the 'floor') using **any additional discrimination parameter** such as timing information, directionality (PRD 90 (2014) 5, 055018 and arXiv:1505.08061) or multiple experiments (PRD 90 (2014) 8, 083510).

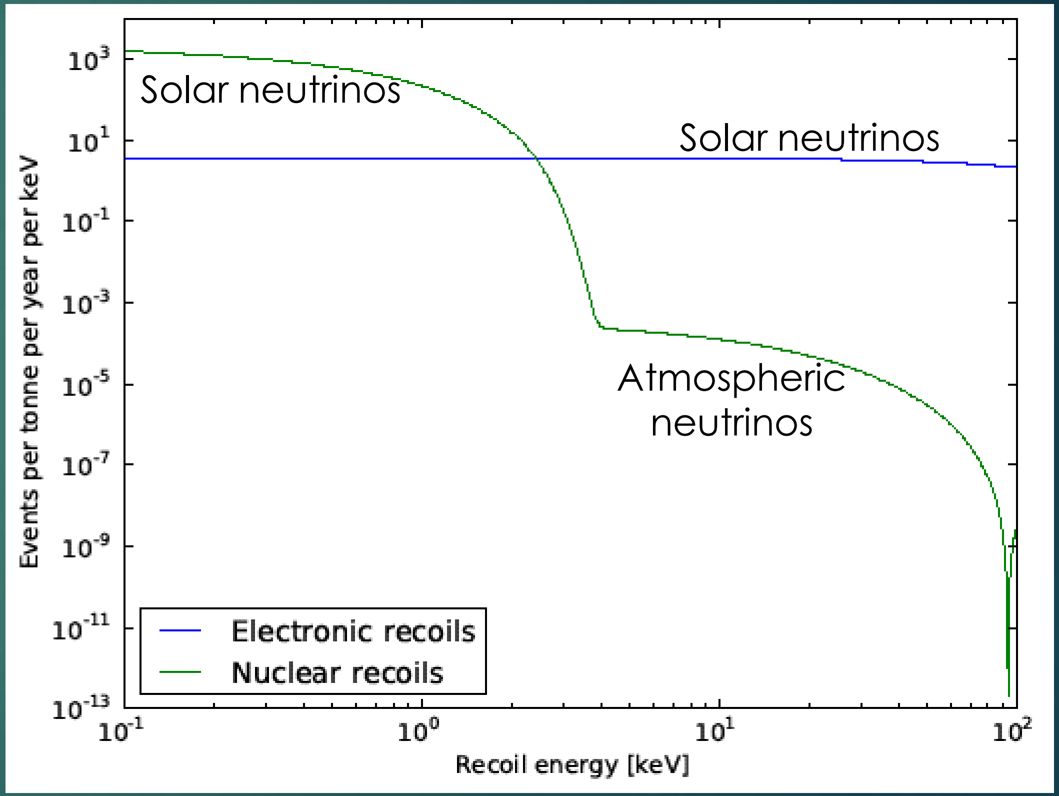
- However this separation is still done on a **statistical basis** and so we are limited to dark matter signals larger than the Poisson uncertainties on the neutrino background.



J. H. Davis, JCAP 1503 (2015) 012

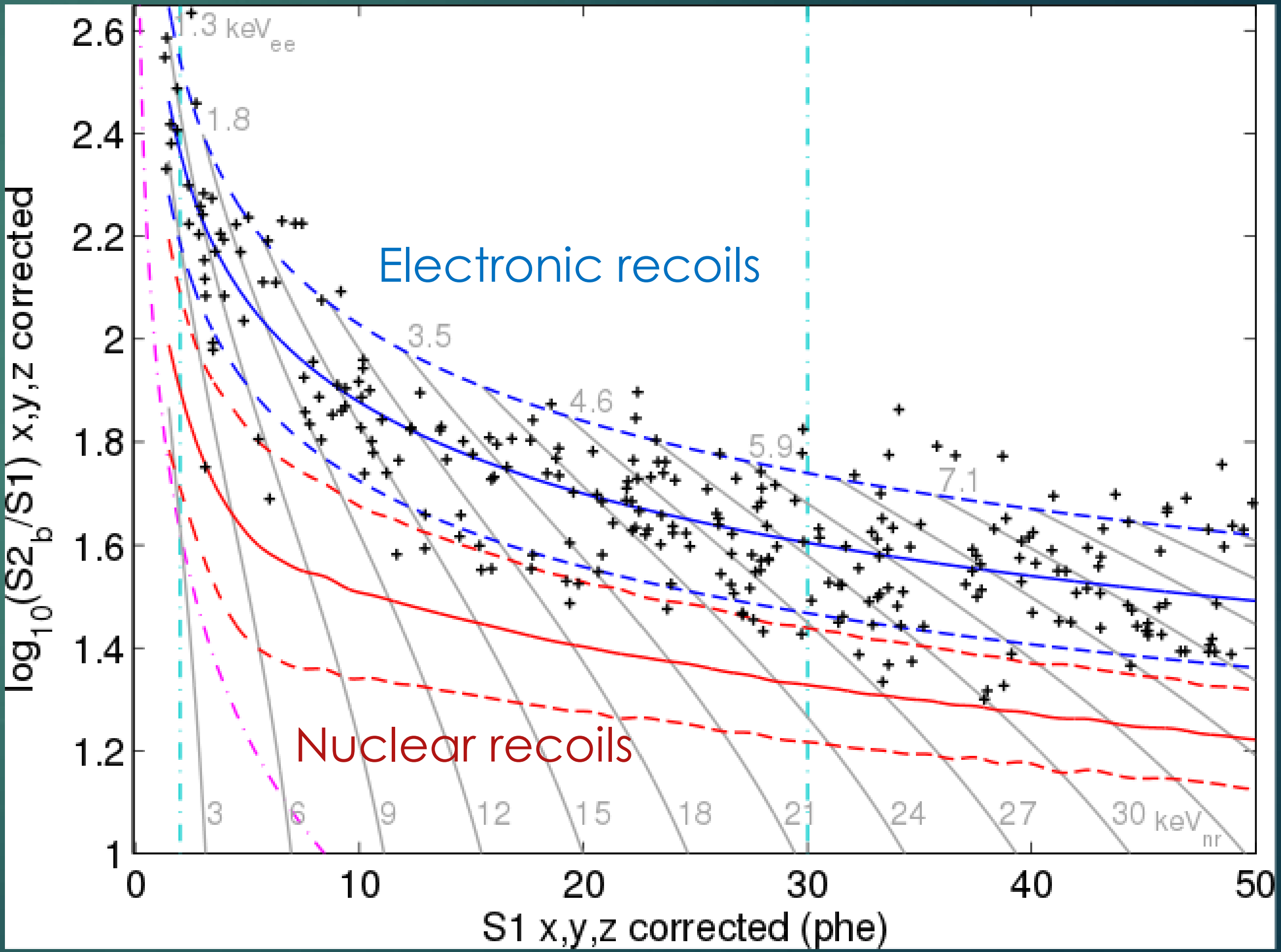
Statistical limitations due to solar neutrinos in future experiments

- Even without the neutrino 'floor' the potentially large neutrino background, particularly from the Sun, will still pose a problem.
- This is true for both nuclear and electronic recoils.
- At recoil energies above around 3 keV the neutrino background for nuclear recoils comes mainly from atmospheric neutrinos.
- Hence at larger energies there will be **far more electronic recoils from neutrinos than nuclear recoils**, since the former originate from the Sun.



Electronic recoil backgrounds for dark matter searches

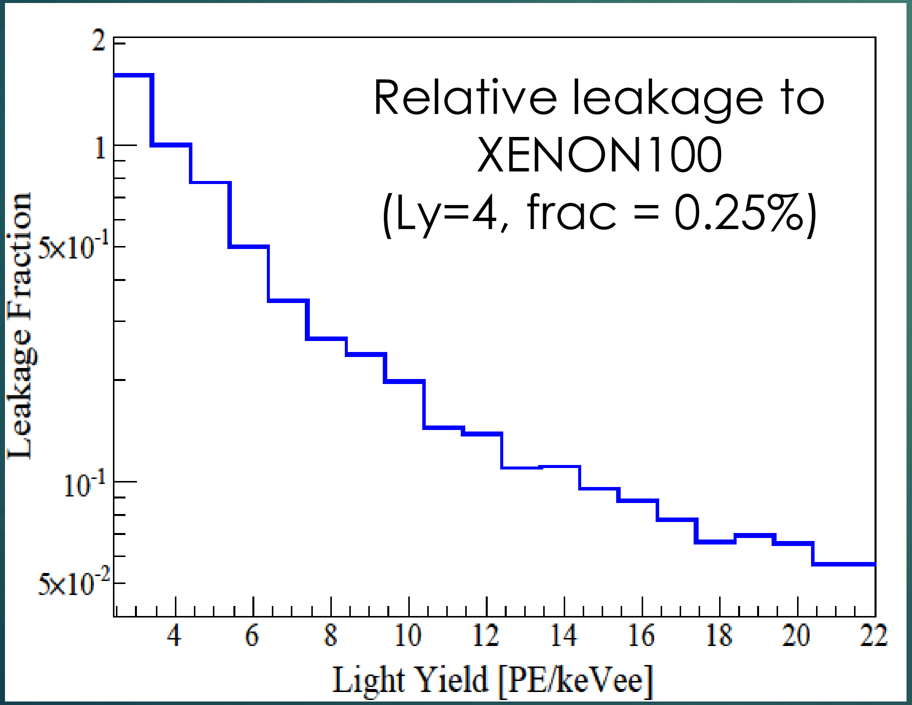
- Many direct detection experiments search only for nuclear recoils.
- This means they need to **distinguish nuclear recoils from electronic recoils**, for which the backgrounds are much larger.
- For example in LUX electronic recoils produce a larger ionisation signal (S2) for a given scintillation signal (S1).
- Hence the **effective electronic background can be reduced**, but only on a statistical basis.

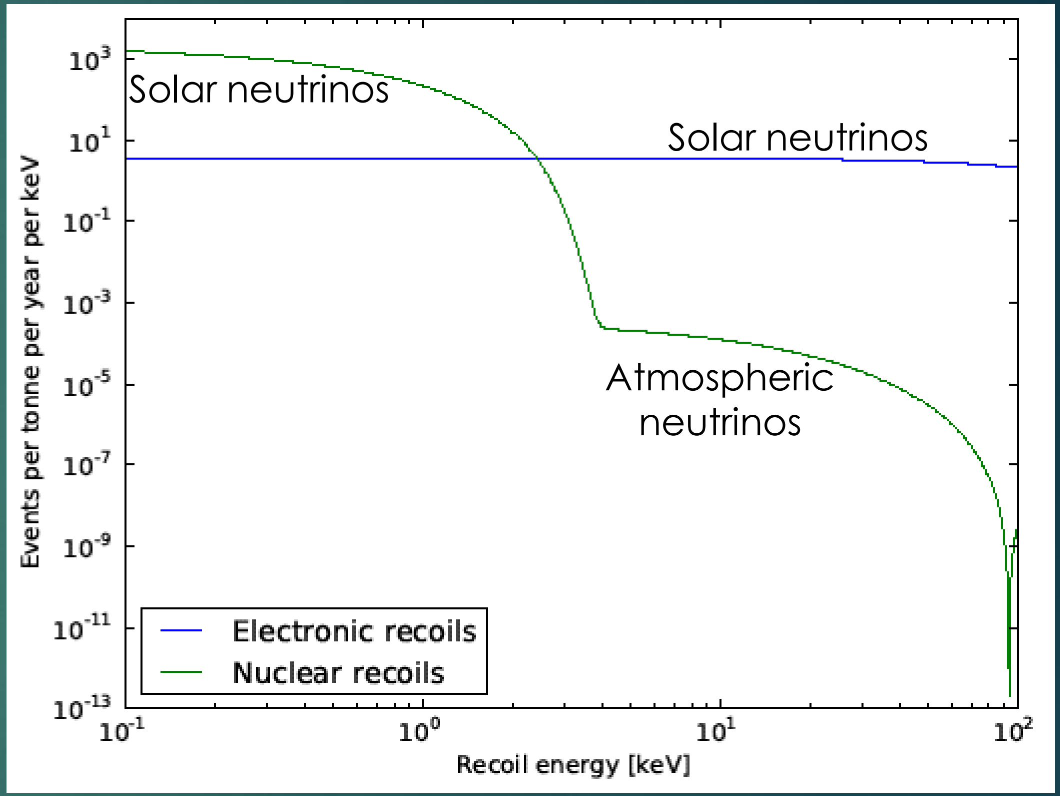


Electronic recoil backgrounds for dark matter searches

- Define the relative fraction of electronic recoils in the nuclear recoil region as the **leakage**.

arXiv:1506.08309

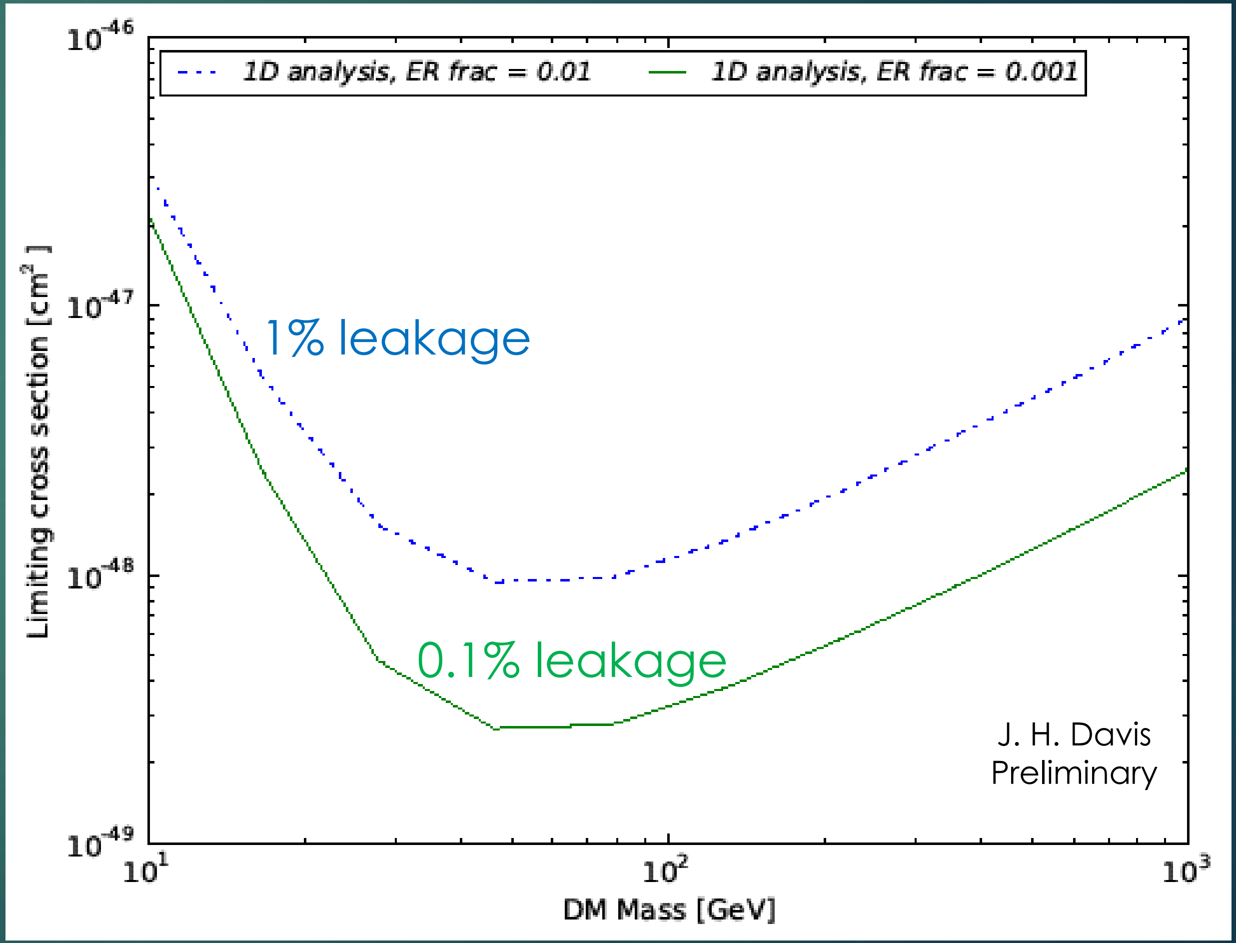




- Leakage for e.g. Darwin will depend on many parameters such as the light yield (Ly).

Uncertainties in the leakage fraction

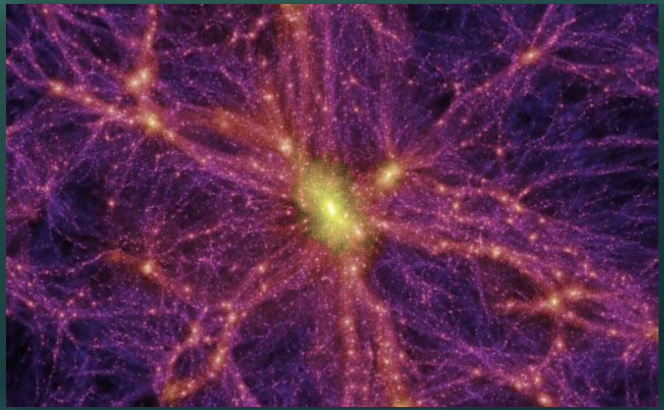
- Knowing the leakage fraction of electronic recoils is important if the dominant background is from neutrinos.
- E.g. a 100 tonne-year exposure for a LUX-like experiment.

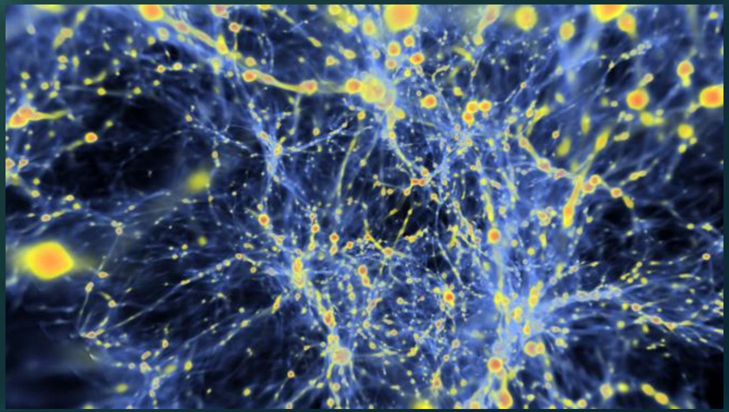


Conclusion

- Direct detection experiments look for dark matter scattering with nuclei.
- This is particularly difficult when the background has a similar spectrum to the potential dark matter signal.
- Future experiments face such a background from solar neutrinos.
- The systematic uncertainty from this background introduces a 'floor' for the projected sensitivity, but this can be overcome using timing information, directionality or multiple experiments.
- However statistical limitations remain from both nuclear and electronic recoil backgrounds, meaning limits improve only as (exposure)^(-1/2) instead of linearly.

See **arXiv:1506.03924** – "The Past and Future of Light Dark Matter Direct Detection" for more.





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