CNO Neutrino Grand Prix: The race to solve the solar metallicity problem

and discover dark matter!

Based on:

D. G. Cerdeño, J. H. Davis, M. Fairbairn and A. C. Vincent, arXiv:1712.06522
J. H. Davis, Phys.Rev.Lett. 119 (2017) 211302, arXiv:1708.01484

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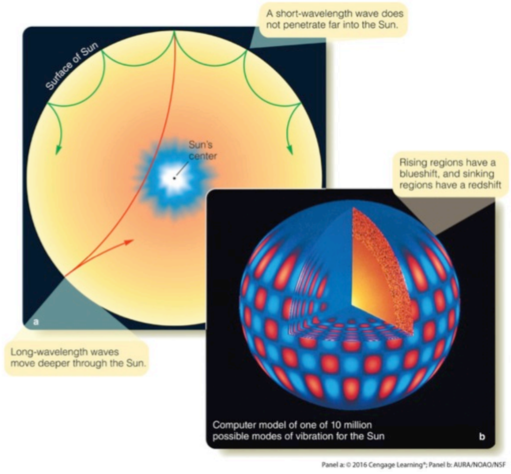
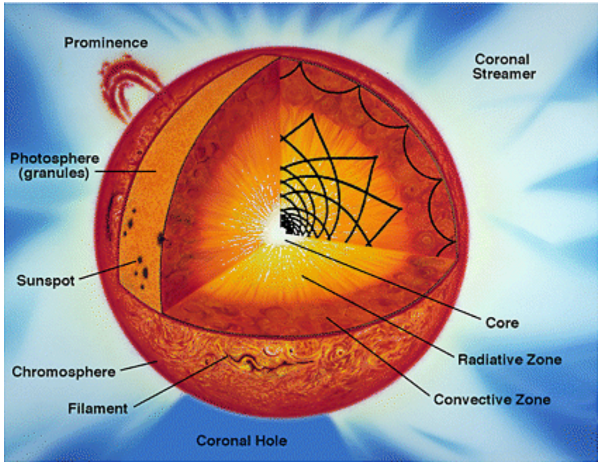
UCL Seminar – 26th January 2018

The solar metallicity problem

- Our knowledge of the Sun's composition comes from comparing simulations to information from probes such as **helioseismology** and electromagnetic **emission from the photosphere**.
- Helioseismology depends on the **whole Sun**.
- **The photospheric abundances depend on the solar surface** and are inferred by comparing absorption line measurements to models of the solar atmosphere.





Helioseismology and the photosphere disagree

- Metallicity measurements from the photosphere are consistent with the low-metallicity model.
- But, in order to fit to helioseismic data the surface metallicity needs to be larger i.e. the high-metallicity models.
- So models can fit either the photosphere metal abundances or helioseismic data but not both.
- We need more data.

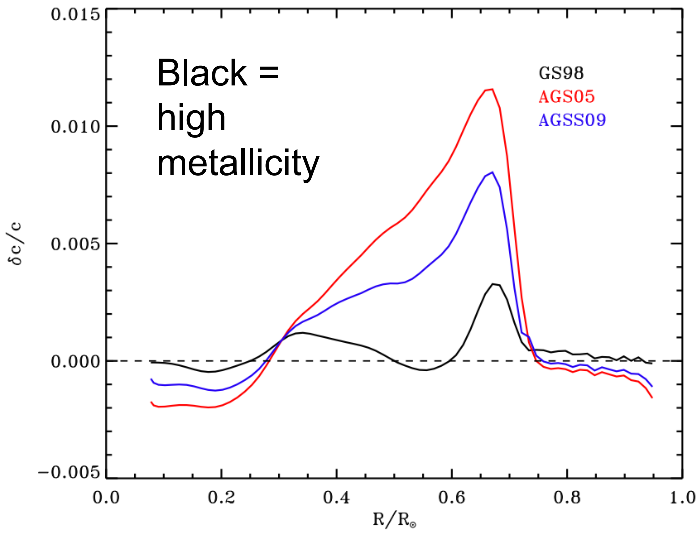
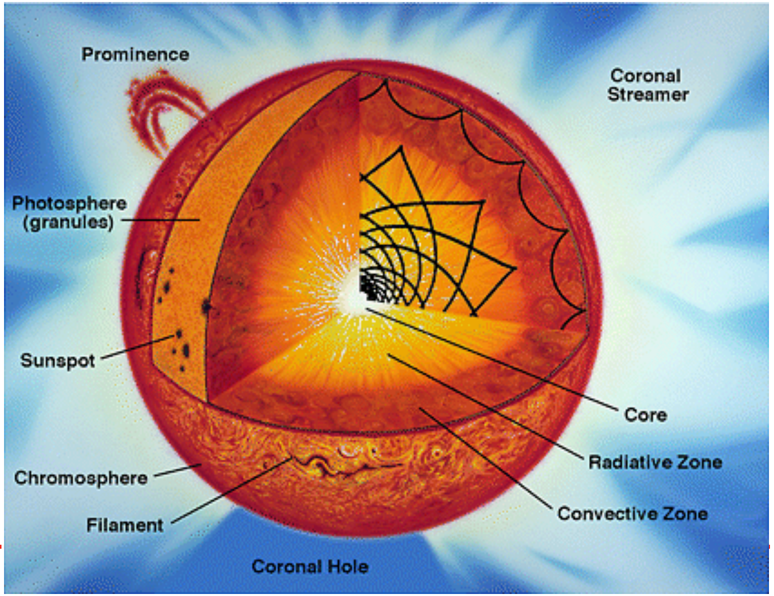


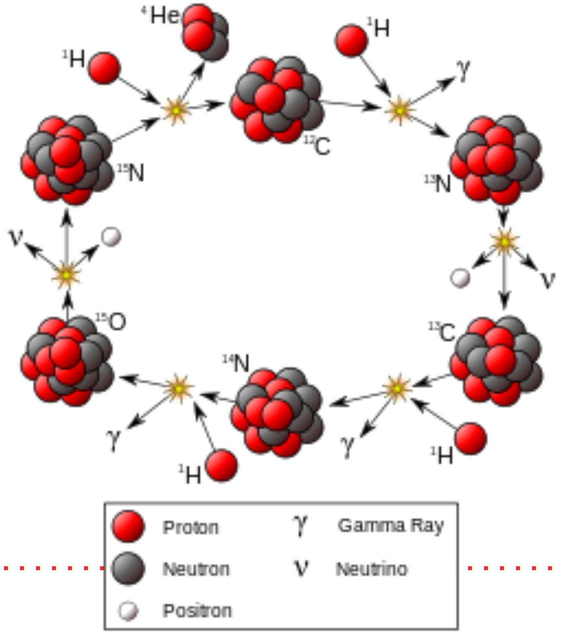
Figure 8: The differences between the helioseismic and predicted sound speeds as a function of depth (Serenelli et al. 2009). The standard solar models shown here only differ in the assumed chemical compositions: Grevesse & Sauval (1998) (black line, here denoted GS98), Asplund, Grevesse & Sauval (2005) (red line, AGS05) and the present work (blue line, AGSS09). Each model has independently been calibrated to achieve the correct solar luminosity, temperature and age. The base of the convection zone is at $R = 0.71\,R_\odot$, which is also where the discrepancy starts in earnest in all three cases.

Asplund et al., Ann.Rev.Astron.Astrophys. 47 (2009) 481-522

Solutions and CNO Neutrinos

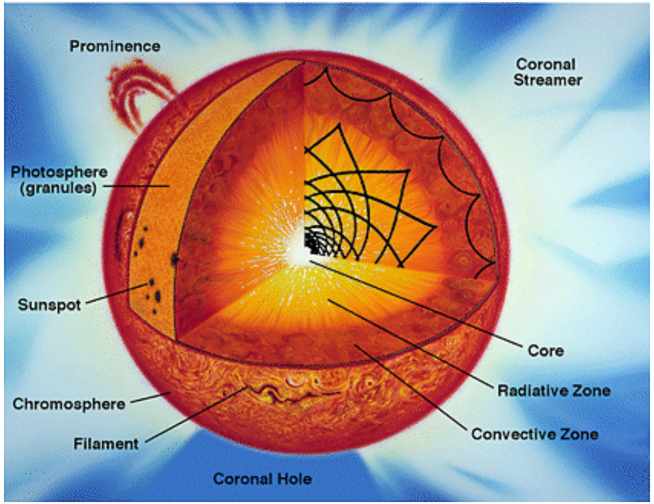
- A crucial extra measurement would be the metallicity in the solar core. One potential solution to the metallicity problem is that we do not understand conductivity and diffusion in the Sun. Changing this would lead to a different metal content in the core.
- The CNO neutrino flux depends sensitively on the metallicity of the solar core.

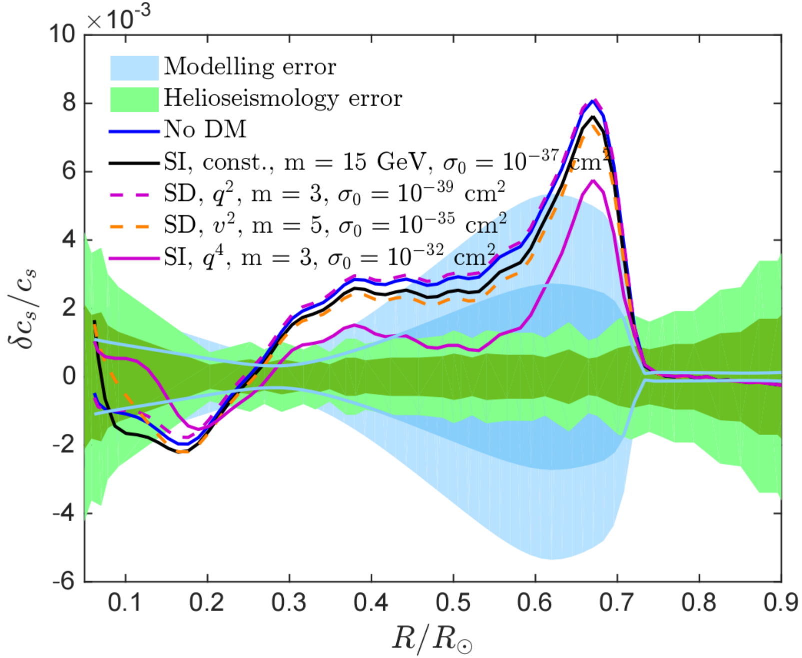




CNO neutrinos and new physics?

Measuring the CNO flux will tell us if the diffusion model is wrong, or whether something else is causing the discrepancy, potentially even New Physics (e.g. Frandsen and Sarkar, arXiv:1003.4505 or Vincent, Scott, and Serenelli, arXiv:1411.6626).

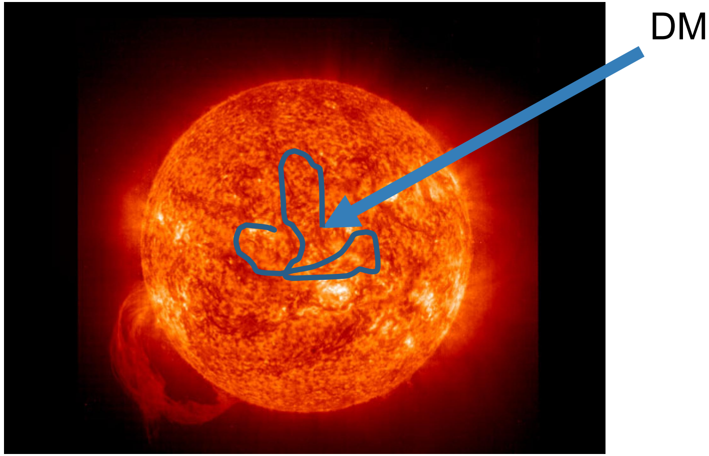


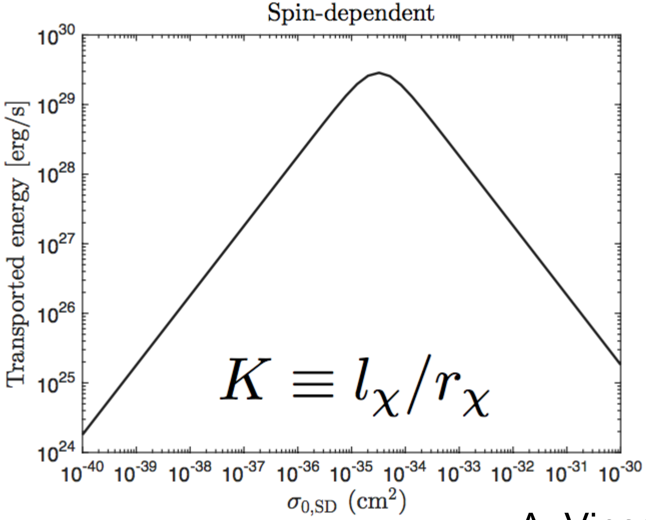


1605.06502

CNO neutrinos and new physics?

- Dark matter scatters in the Sun, where it loses energy and becomes bound.
- If it has just the right cross section its mean free path is long enough to transport energy through most of the Sun, but short enough not to escape the Sun entirely without scattering.

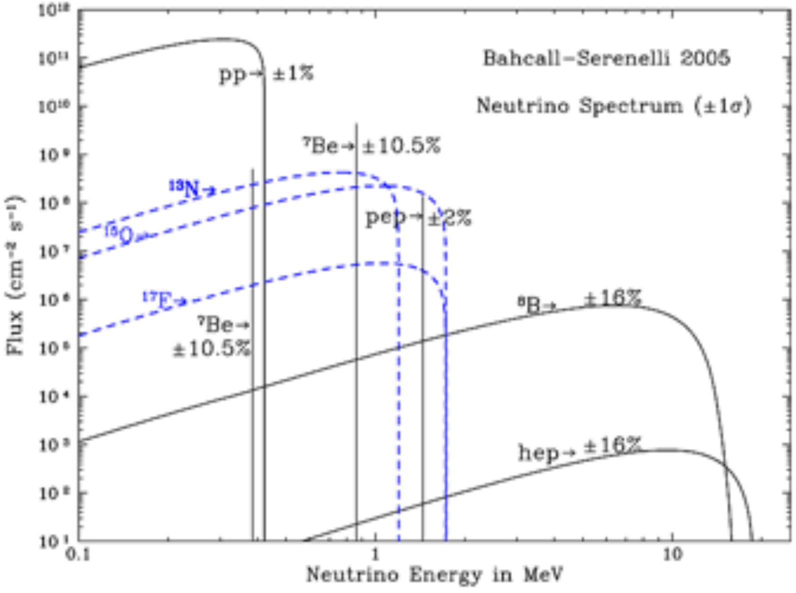


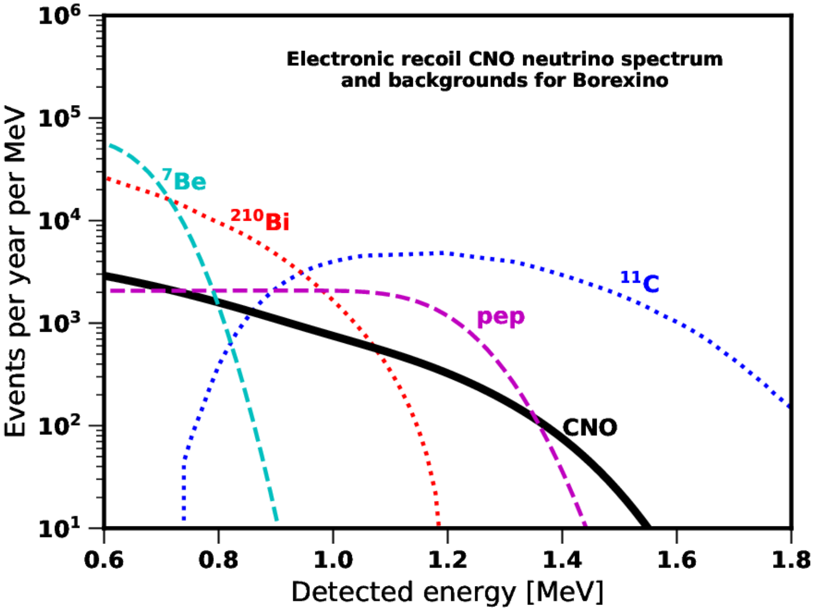


A. Vincent

Detecting CNO Neutrinos

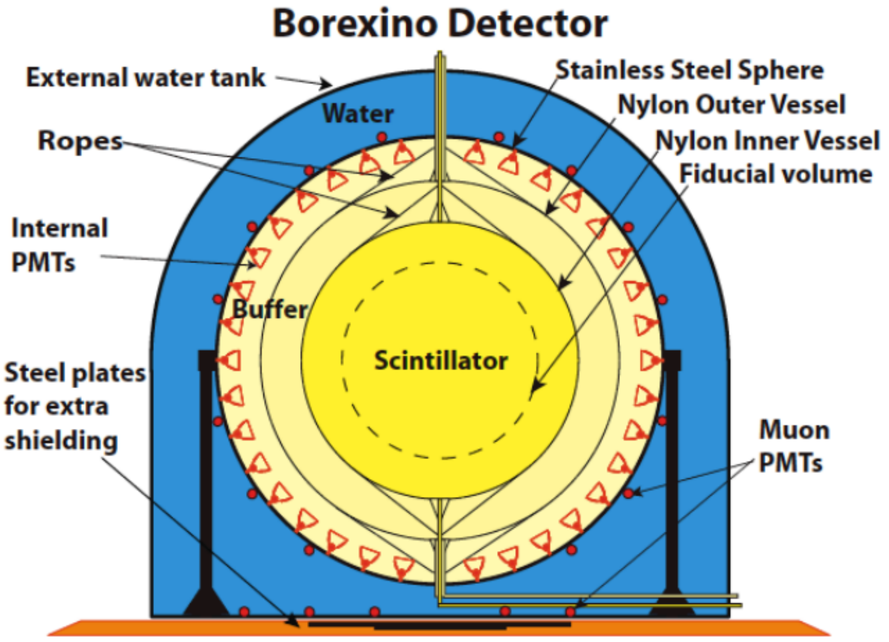
- Measuring the CNO flux is extremely difficult as their spectrum is sub-dominant compared to the other solar neutrino sources e.g. berylium-7 or pep.
- Will experiments ever be able to accurately measure the CNO neutrino flux?
- We have made projections for future experiments using a Markov Chain analysis.





Borexino

- A liquid scintillator with around 300 ton inner vessel.
- Has previously set constraints on the CNO neutrino flux in its Phase 1 and Phase 2 runs.
- Current upper limit is 7.9×10^8 per cm^2 per second at 95% confidence. About twice the flux we expect from models.



1707.09279

Borexino

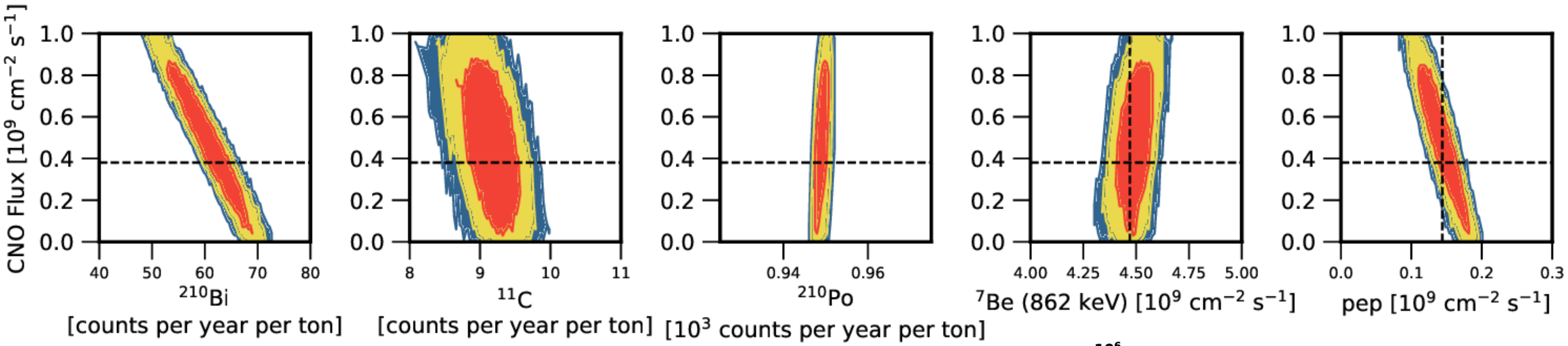
- Here I'm interested in the next phase (number 3 and beyond) of Borexino.
- Thermal insulation means that some key backgrounds can be measured.
- Focus is on being able to infer Bi-210 levels from Po-210 alpha decay rate.

Before Insulation

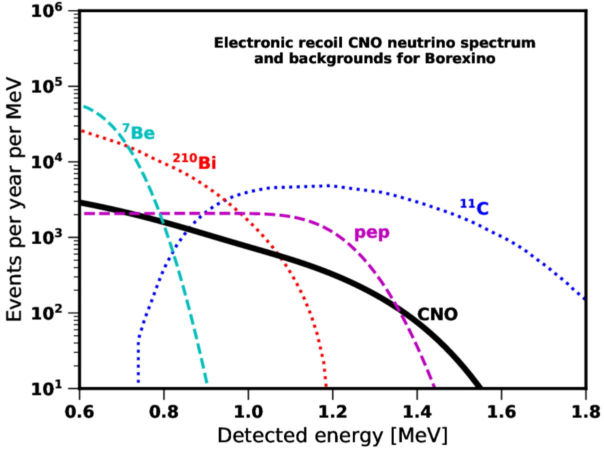
During Insulation

Frank Calaprice, Backgrounds in Borexino: A Long Quest for Solar Neutrinos with Low Background," (2017), Recent Developments in Neutrino Physics and Astrophysics Conference.

CNO Neutrinos in Borexino

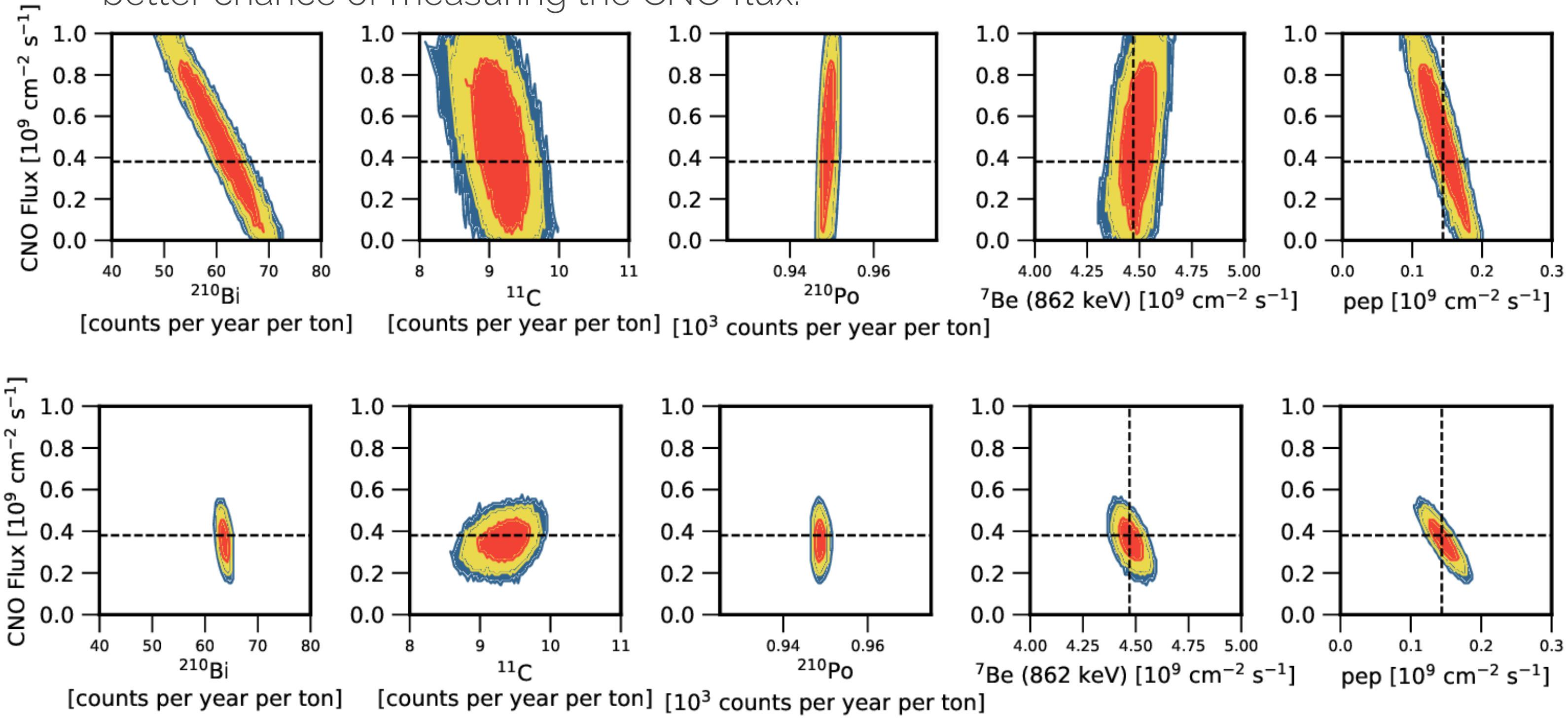


- The Bi-210 background is particularly troublesome, due to the similarity between its spectrum and the CNO one.
- If we do not know the Bi-210 rate, then there is a strong degeneracy between it and the CNO flux.



CNO Neutrinos in Borexino

If the Bi-210 background is known to 1% accuracy, then Borexino has a much better chance of measuring the CNO flux.

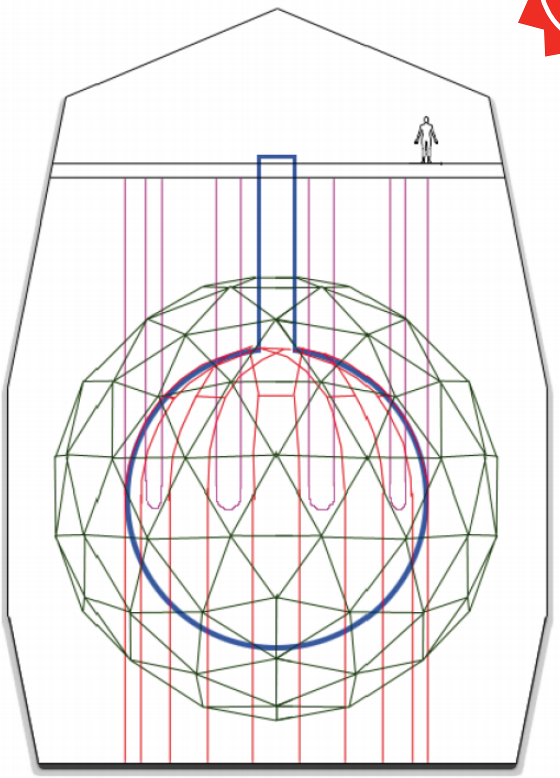


Pessimistic (Bi-210 rate known to 10%)

Optimistic (Bi-210 rate known to 1%)

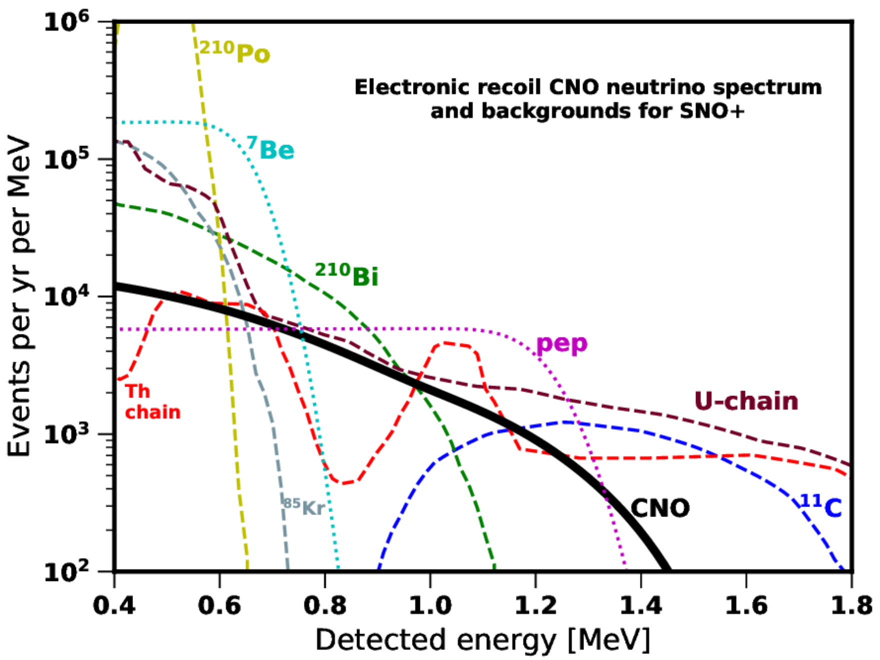
SNO+

- A liquid scintillator like Borexino, but with a larger target mass.
- Will be situated in SNO-lab, where the cosmogenic backgrounds will be lower than in Gran Sasso.
- It's main aim will be to look for neutrino-less double-beta decay through doping with Te-130.
- It is not clear how much time will be dedicated to solar neutrinos.



CNO neutrinos in SNO+

- The Bi-210 background is present as with Borexino, though the one from C-11 is smaller.
- Good energy resolution means the pep cut-off is shaper than for Borexino.



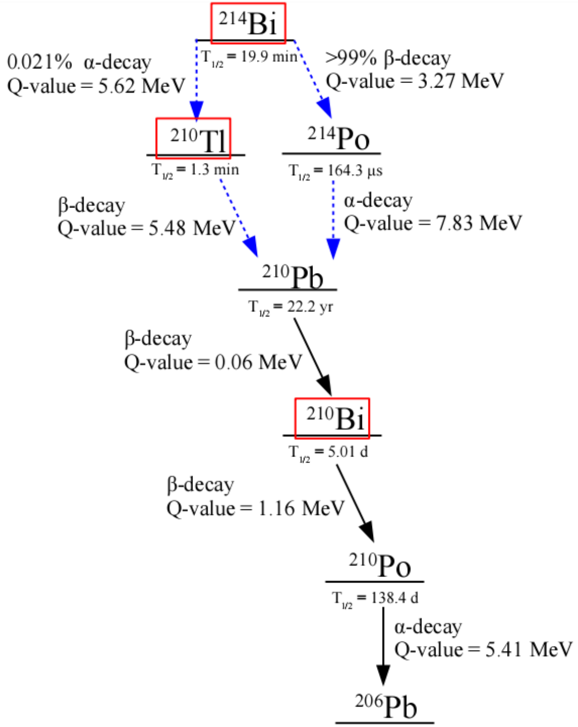
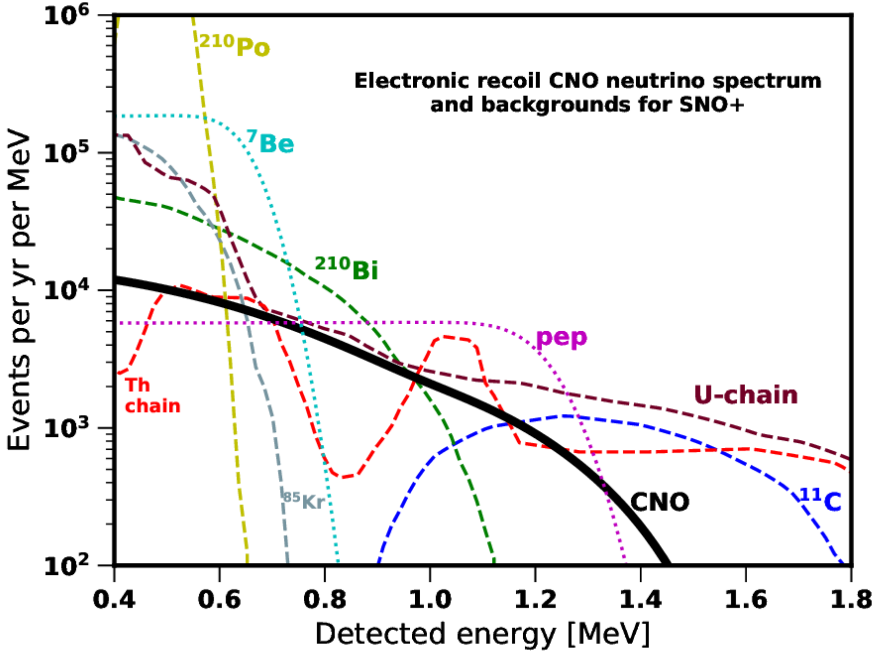
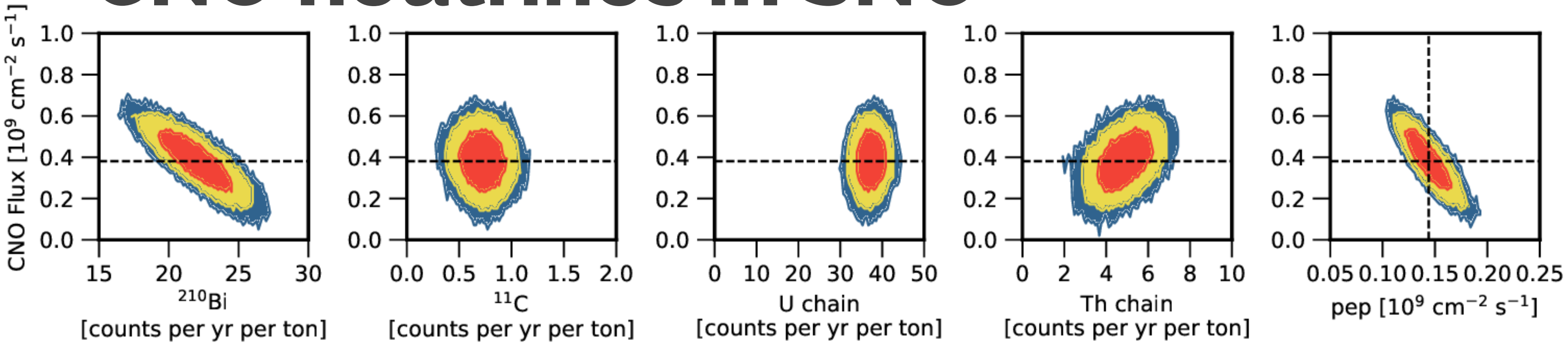


FIGURE 3: Part of ^{238}U-decay chain relevant for SNO+ with Q-values (total kinetic energy released in the ground state - ground state transition), half-life and decay modes [24]. The red squares highlight the nuclides of most concern: ^{214}Bi, ^{210}Tl, and ^{210}Bi. The decays used for α-β and β-α coincidence techniques are shown with a blue arrow (dash-dotted line).

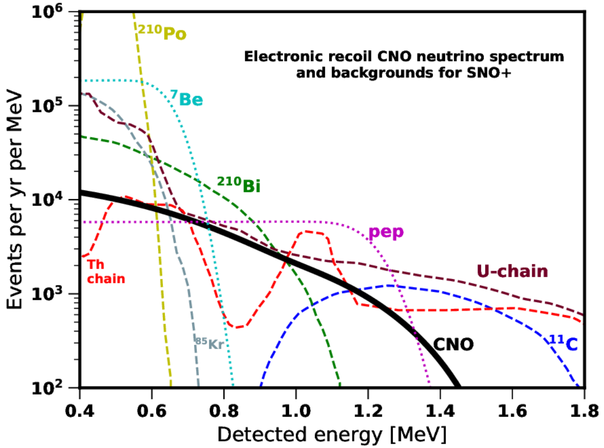
The Bi-210 rate could be inferred from Po-210 alpha decay, as for Borexino.



CNO neutrinos in SNO+

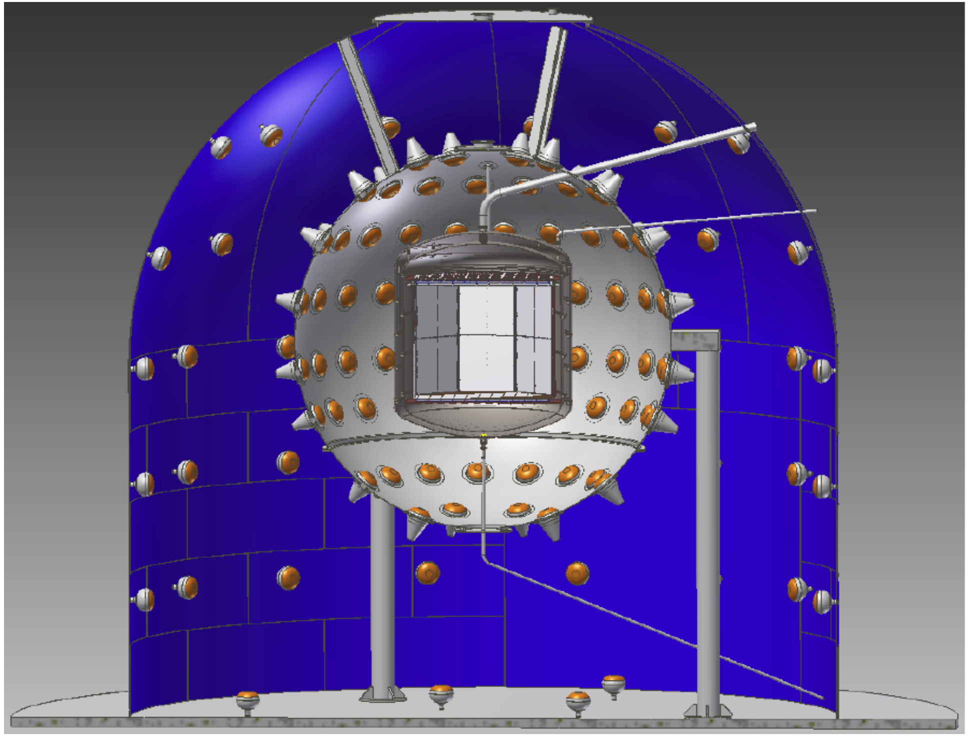


The Bi-210 rate is degenerate with the CNO flux, contributing to large systematic uncertainties.



Liquid-argon experiments

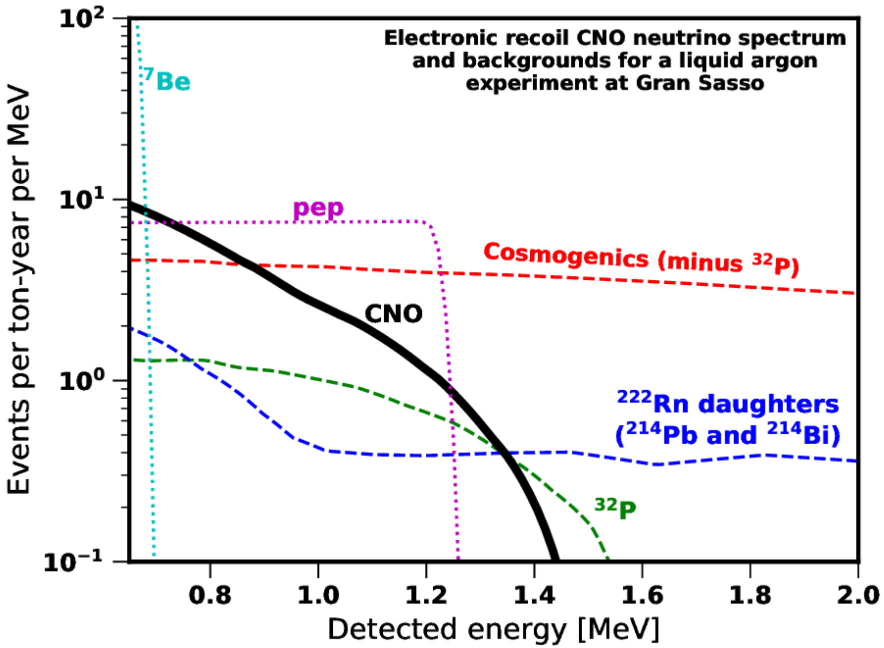
- Traditionally used for nuclear-recoil dark matter searches, but can also be used for electron-recoil solar neutrino scattering.
- I consider future experiments such as DarkSide-20k (with a 20 tonne mass) and Argo (with a 100 tonne fiducial mass).
- DarkSide-20k will be in Gran Sasso but Argo could be anywhere.



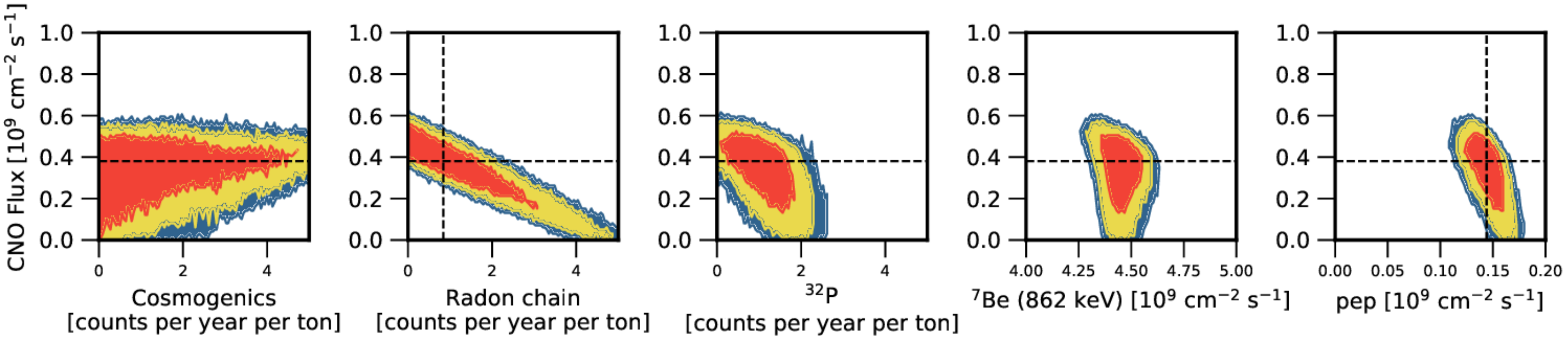
CNO neutrinos in Argo

- The background from beta-decay of the daughters of radon-222 resembles the CNO spectrum.
- The cosmogenic backgrounds would be around 100 times lower in SNO-lab or Jinping.

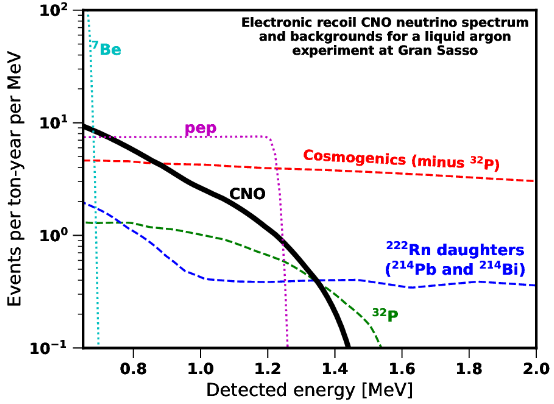
Backgrounds from simulations done in: D. Franco et al., “Solar neutrino detection in a large volume double-phase liquid argon experiment," JCAP 1608, 017 (2016),arXiv:1510.04196



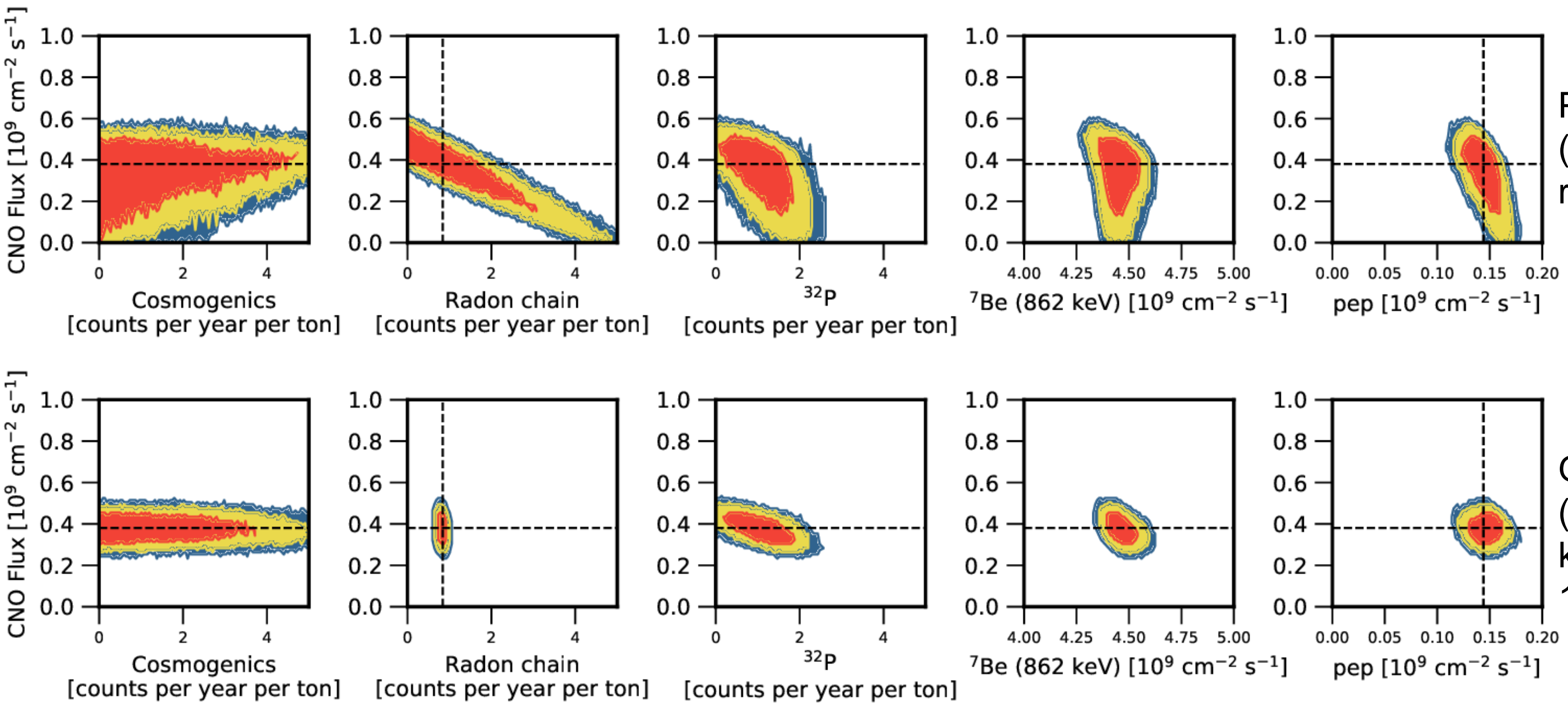
CNO neutrinos in Argo



- The radon chain background is degenerate partially with the CNO flux, leading to large systematic uncertainties.
- Fortunately the magnitude of the radon background can be measured through observations of the delayed coincidence between Bi-214 beta-decay and Po-214 alpha-decay.



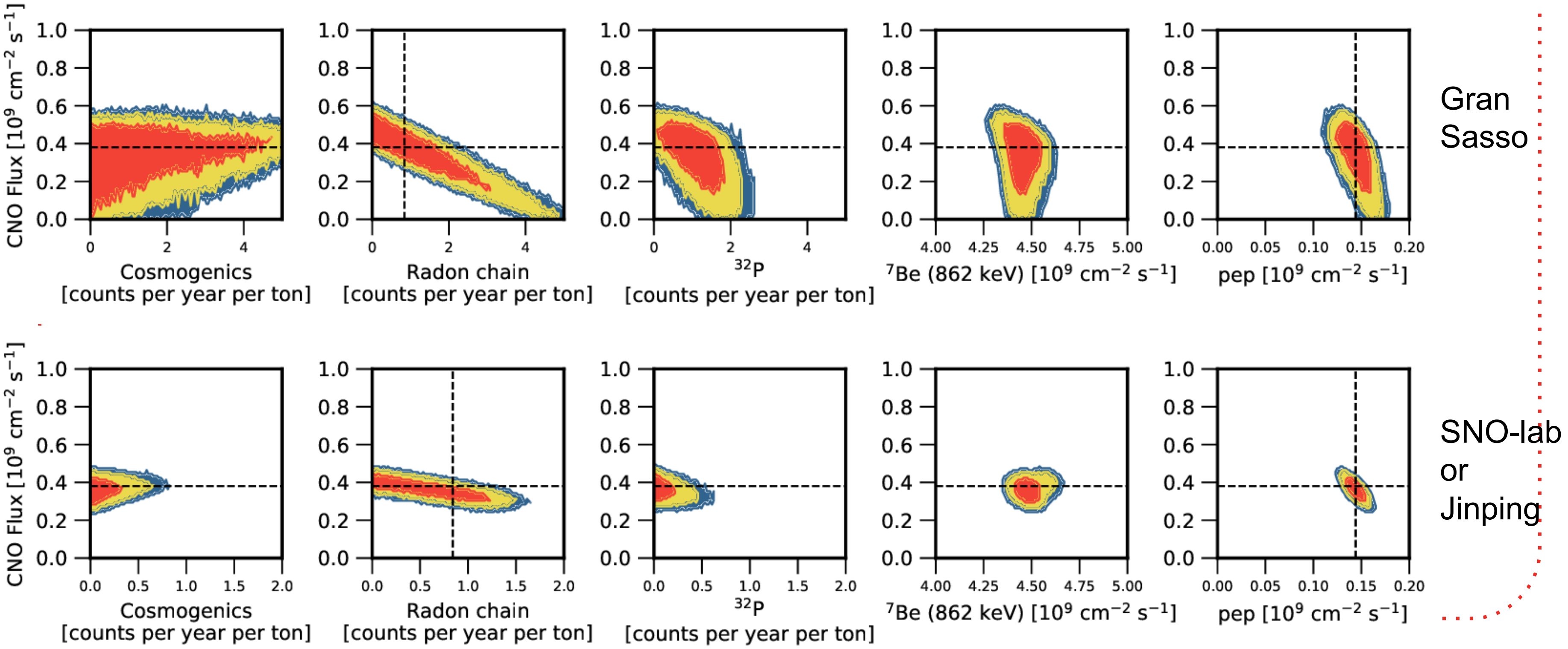
CNO neutrinos in Argo



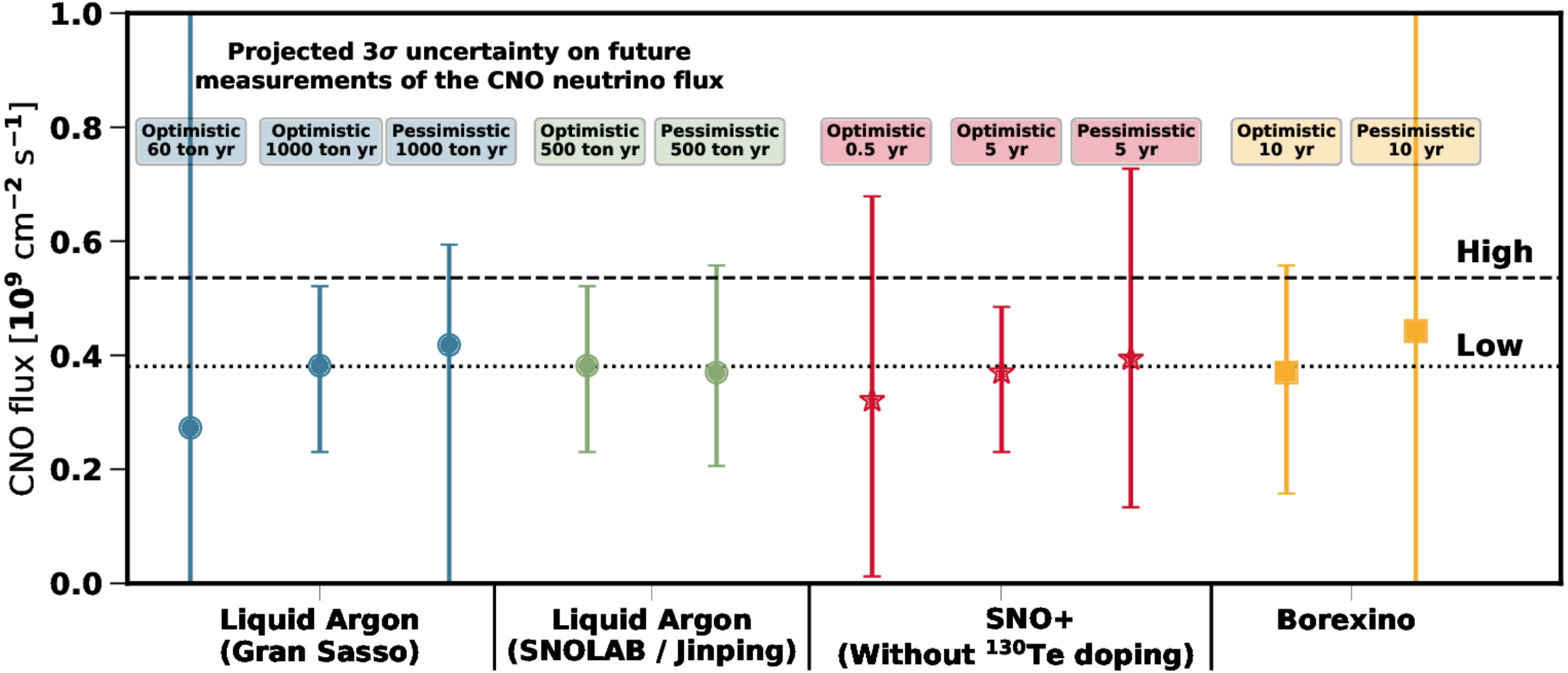
Pessimistic (unknown radon)

Optimistic (radon known to 10%)

Argo in different labs

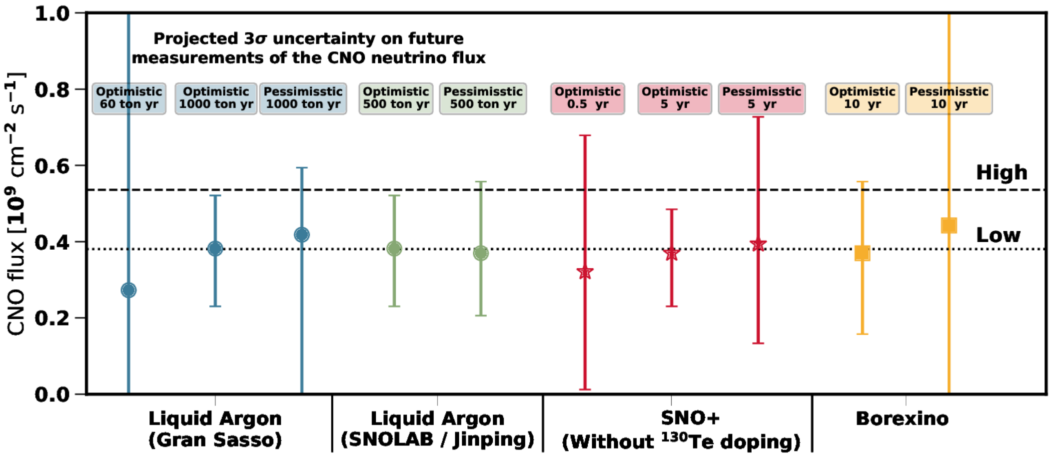


Comparing SNO+, Borexino and Argo



Comparing SNO+, Borexino and Argo

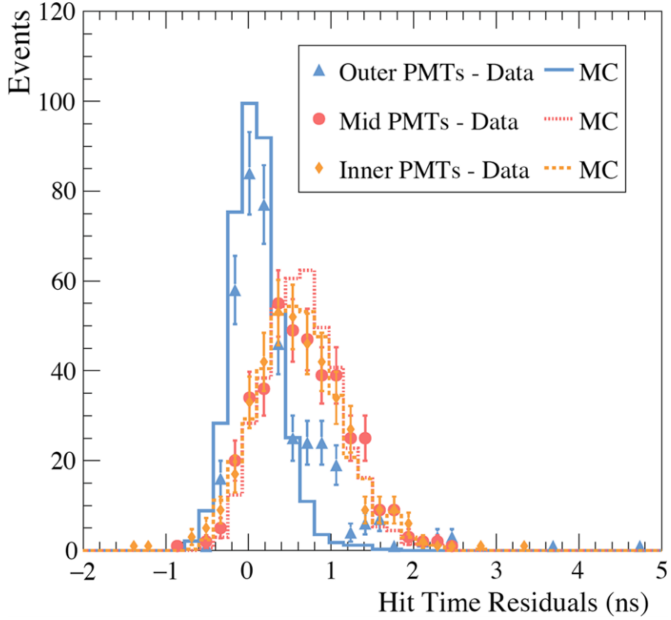
- Which experiment gets there first depends on background-control and on the time dedicated to a CNO search.
- SNO+ can not look for CNO neutrinos while it is in its neutrinoless double-beta decay mode.
- Argo would be potentially ideal if it were built in SNO-lab or Jinping, but this is likely to be many years away.



Does this time-frame leave room for alternative technologies? ……

Seeing both Cherenkov and scintillation light

- For a water-based liquid scintillator, there are two signals from a neutrino scattering with an electron: Cherenkov light and scintillation light.
- The scintillation light gives the energy of the event to high precision, while the Cherenkov light gives directionality.
- This would break the degeneracy between CNO and backgrounds like Bi-210, reducing systematics.
- Need very good time resolution to separate the two signals. Cherenkov comes first followed by scintillation.
- The CHESS experiment has demonstrated sub-nanosecond time resolution (Eur.Phys.J. C77 (2017) no.12, 811). See also THEIA (1504.08284).

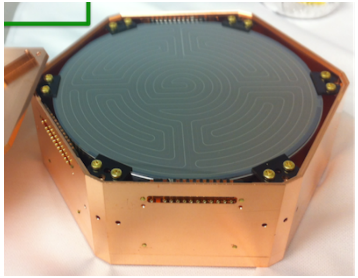


Outer = Cherenkov + scintillation
Inner = scintillation only

Nuclear-recoil experiments

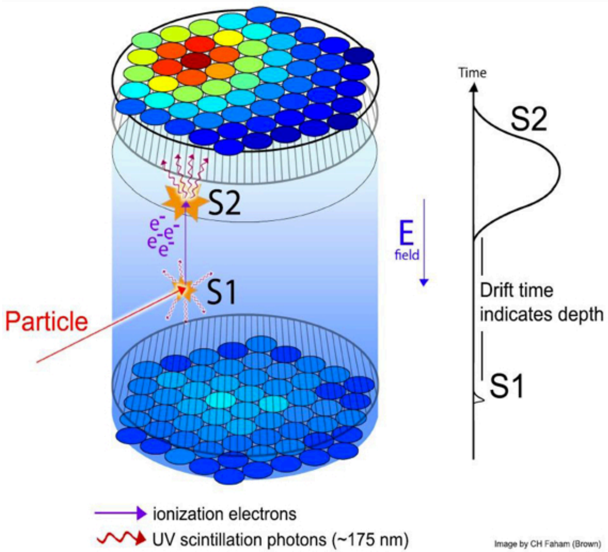
Cryogenic Detectors

SuperCDMS
Looking for
ionization
and phonons



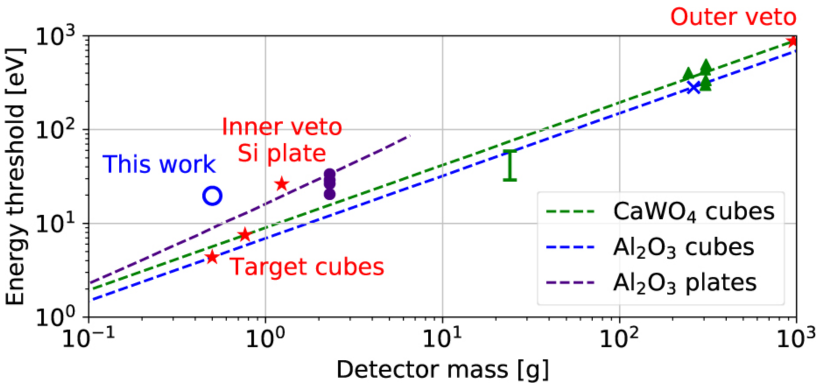
CRESST
Looking for
tiny temperature
changes

Liquid Noble Detectors



Gram-scale cryogenic experiments

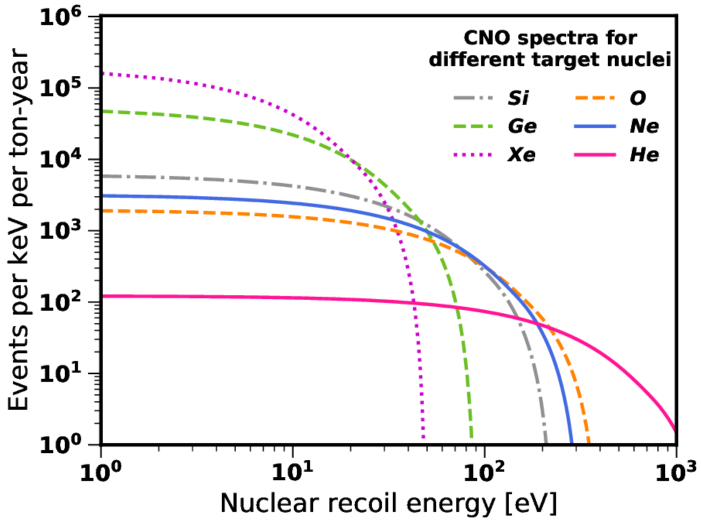
Gram-scale crystals mean that the experiment has an extremely low energy threshold, but at the expense of a smaller exposure.

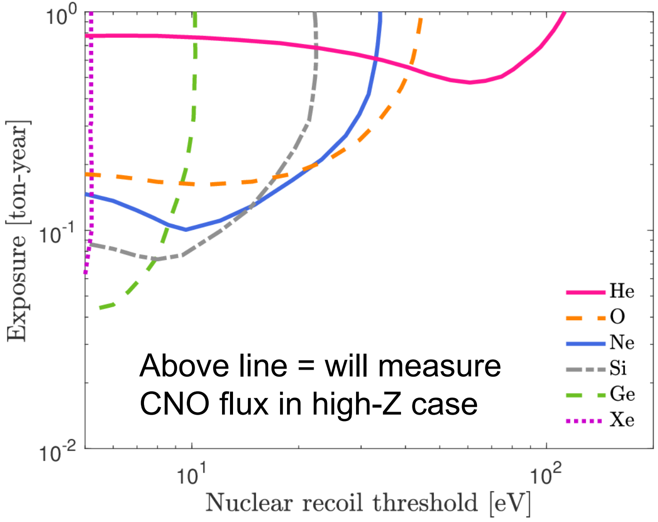


R. Strauss, **Eur.Phys.J. C77 (2017) 506**, arXiv:1704.04320

Measuring the CNO flux with nuclear-recoil experiments

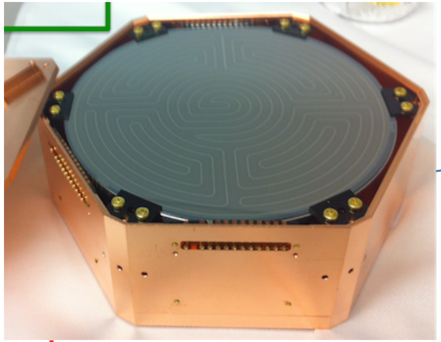
Looking for nuclear-recoils could be a viable alternative, but experiments will need both a low threshold and a large exposure.

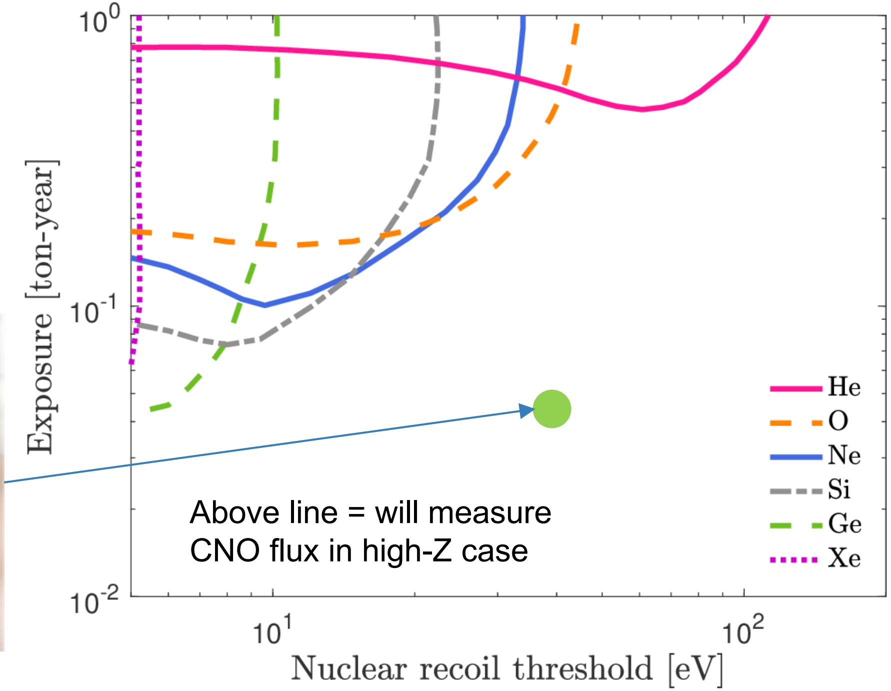




Prospects for CNO-NR observation

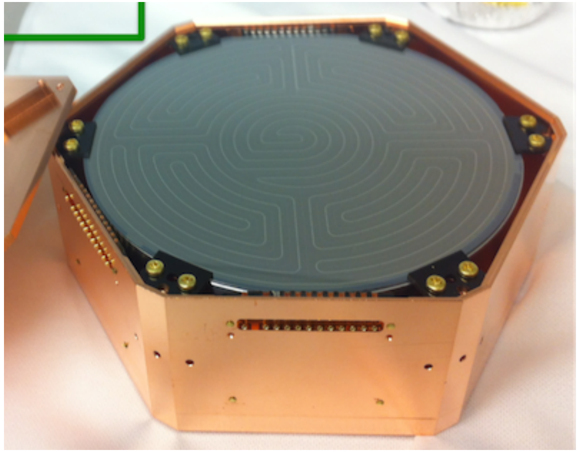
SuperCDMS in SNOLAB looks to be the best hope with germanium.





CRESST with its 0.5g sapphire crystal can get the required threshold with oxygen, but the exposure is far too small.

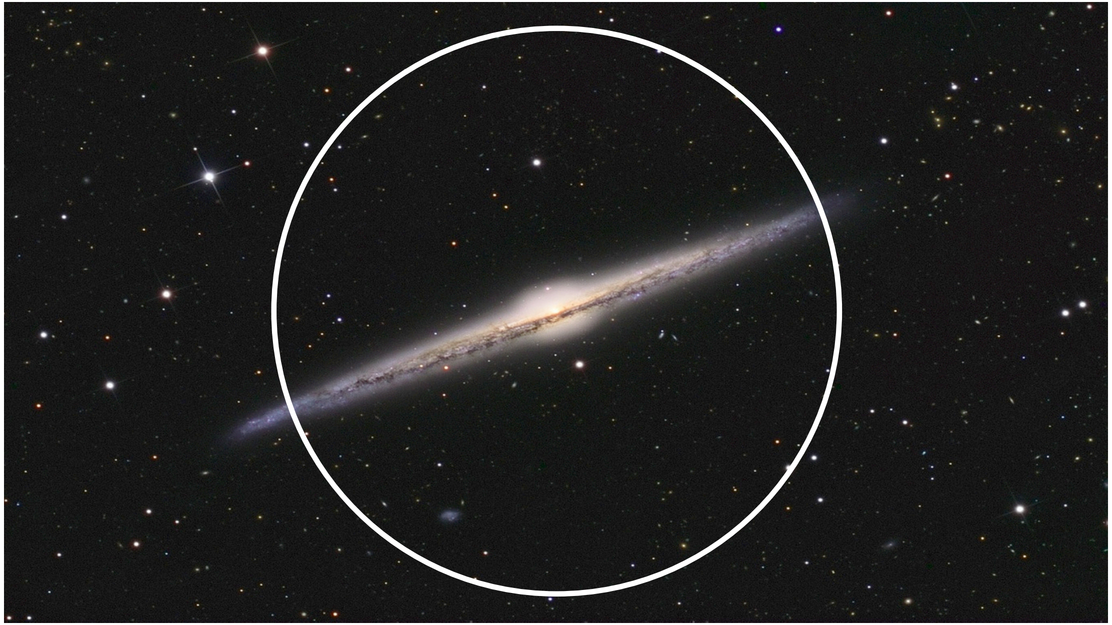
These detectors are also ideal for the detection of sub-GeV mass dark matter



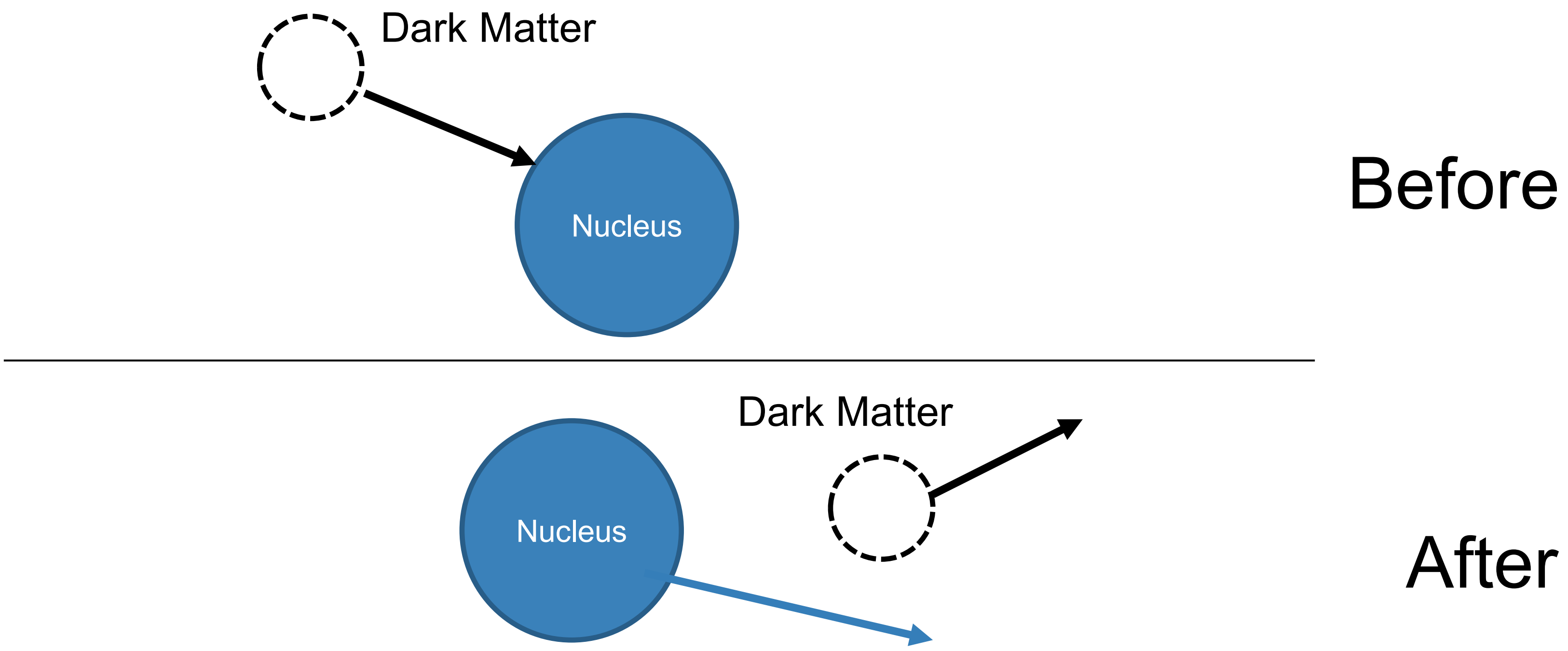
Dark matter

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

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

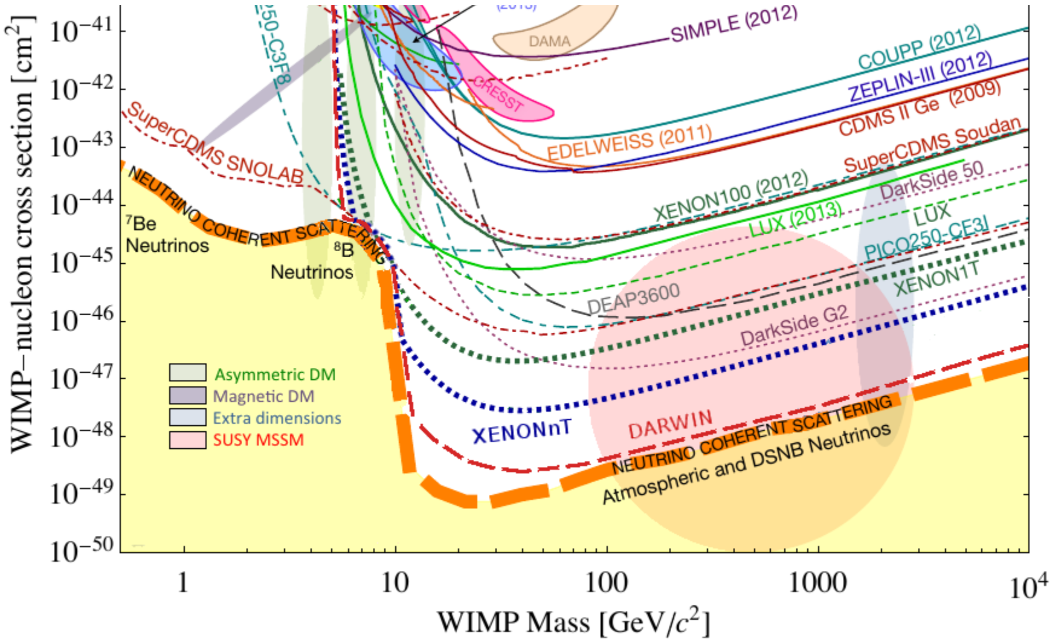


Direct detection



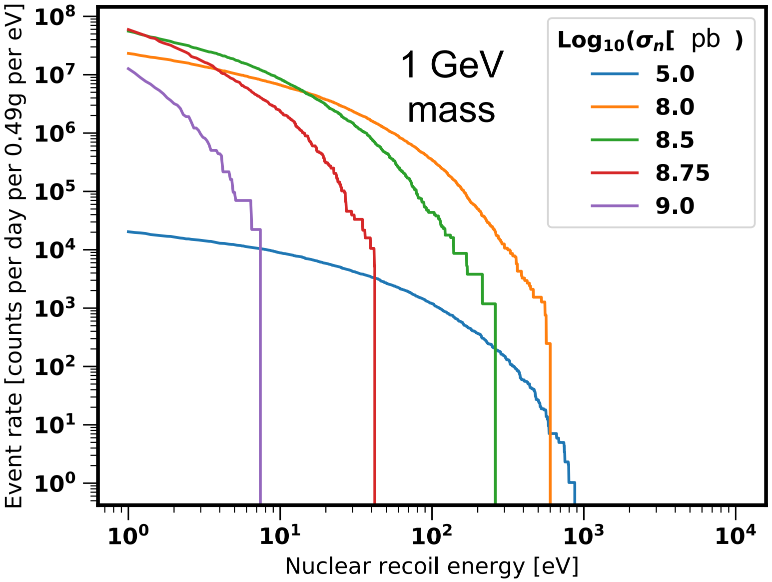
Status of direct detection

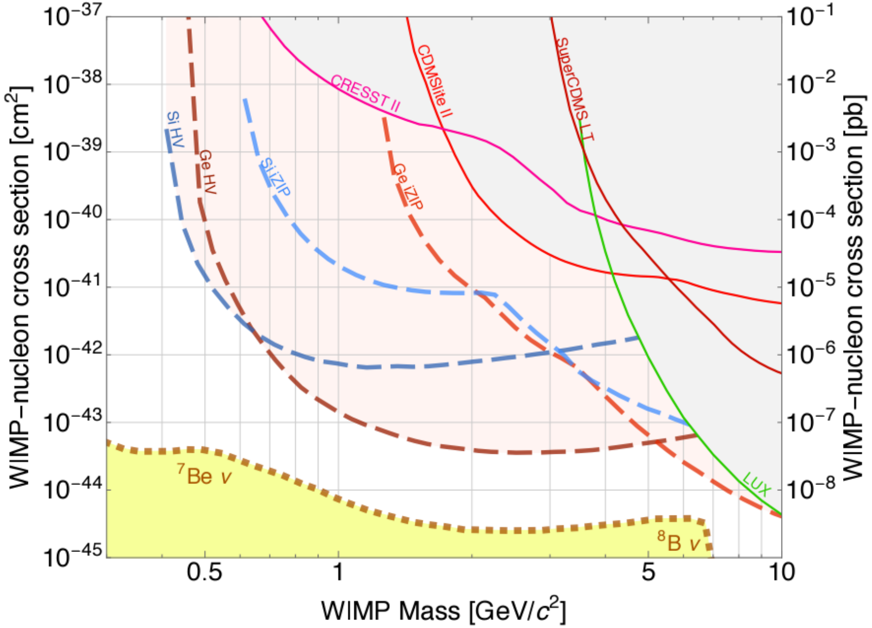
The sensitivity to dark matter scattering with nucleons is steadily improving, with new technologies allowing us to reach into the sub-GeV range of masses.



Dark matter with low-threshold detectors

Detectors which are sensitive to energies below a keV can detect sub-GeV mass dark matter, and more exotic models too.

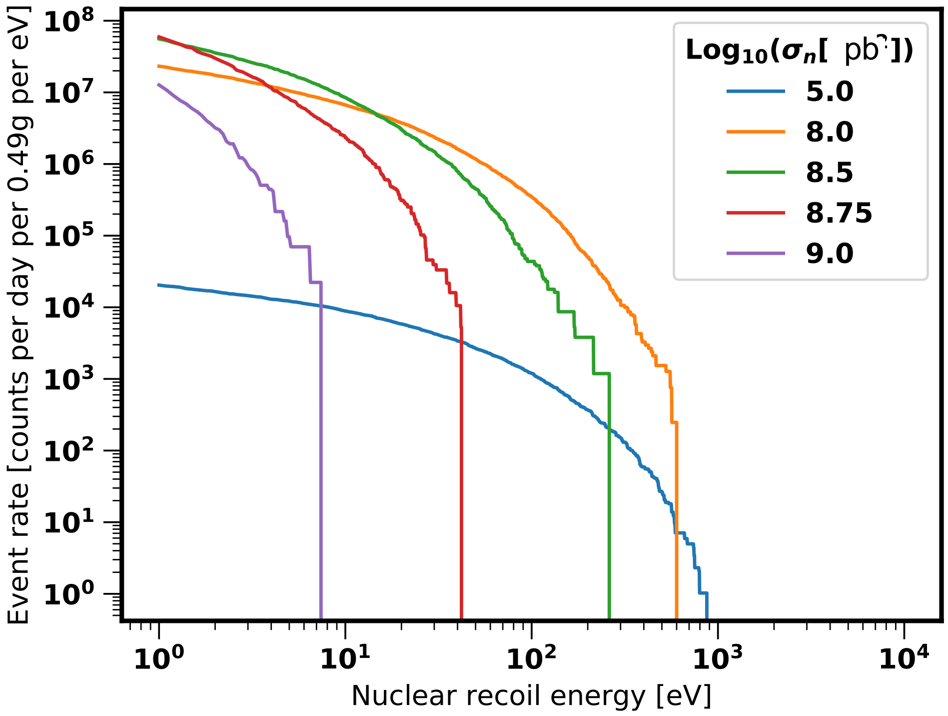




SuperCDMS-SNOLAB, arXiv:1610.00006

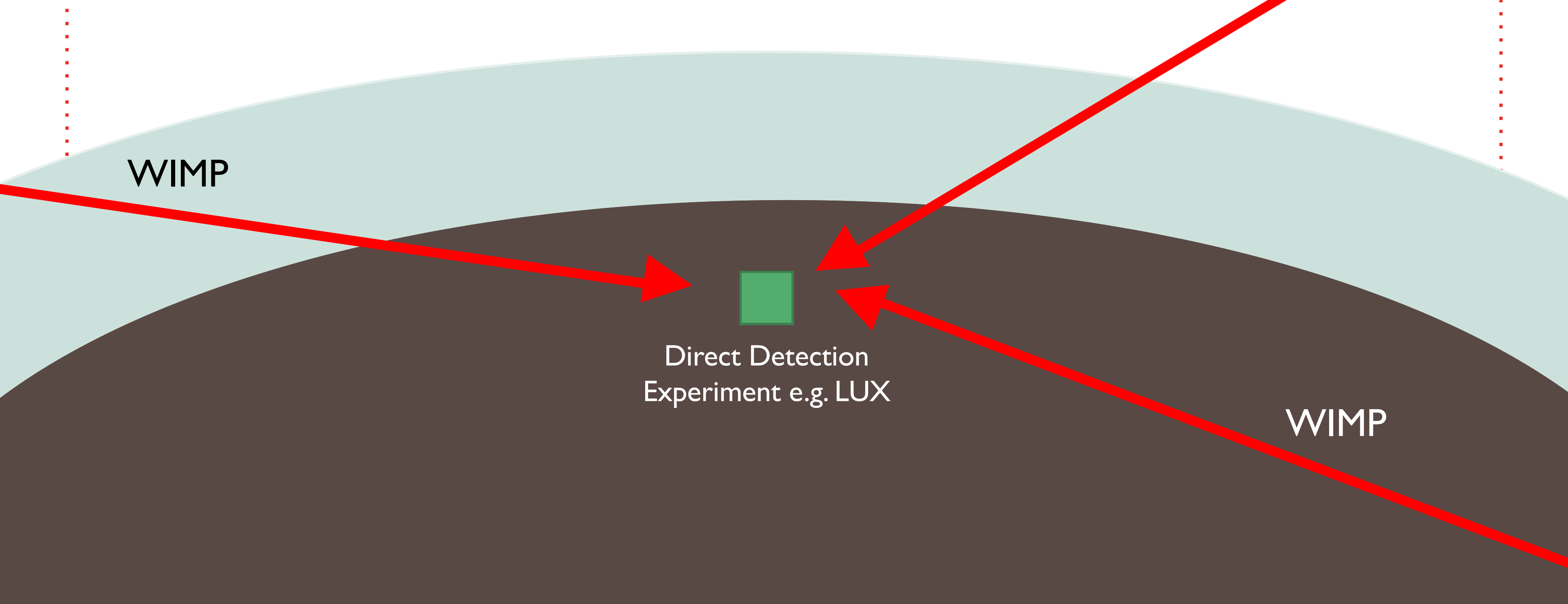
Strongly-interacting dark matter

- Increasing the DM-nucleon cross section leads to a larger expected recoil rate, until the cross section enters the SIMP-regime.
- Beyond this point the SIMPs lose energy due to interactions in the Earth or atmosphere, leading to lower-energy recoils in the detector.



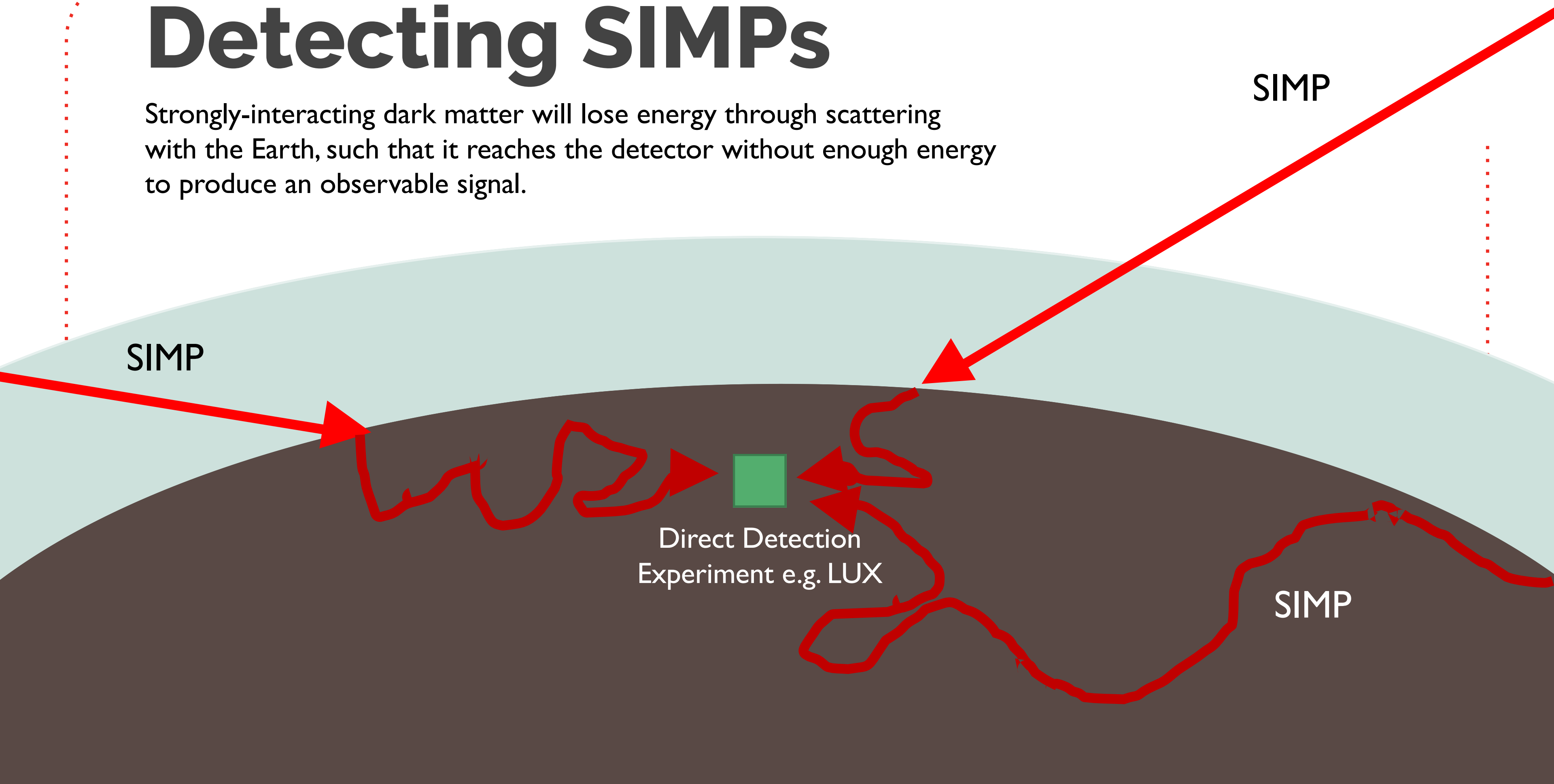
Detecting WIMPs

Weakly-inteacting dark matter should pass unimpeded through the Earth and atmosphere on its way to the underground detector.



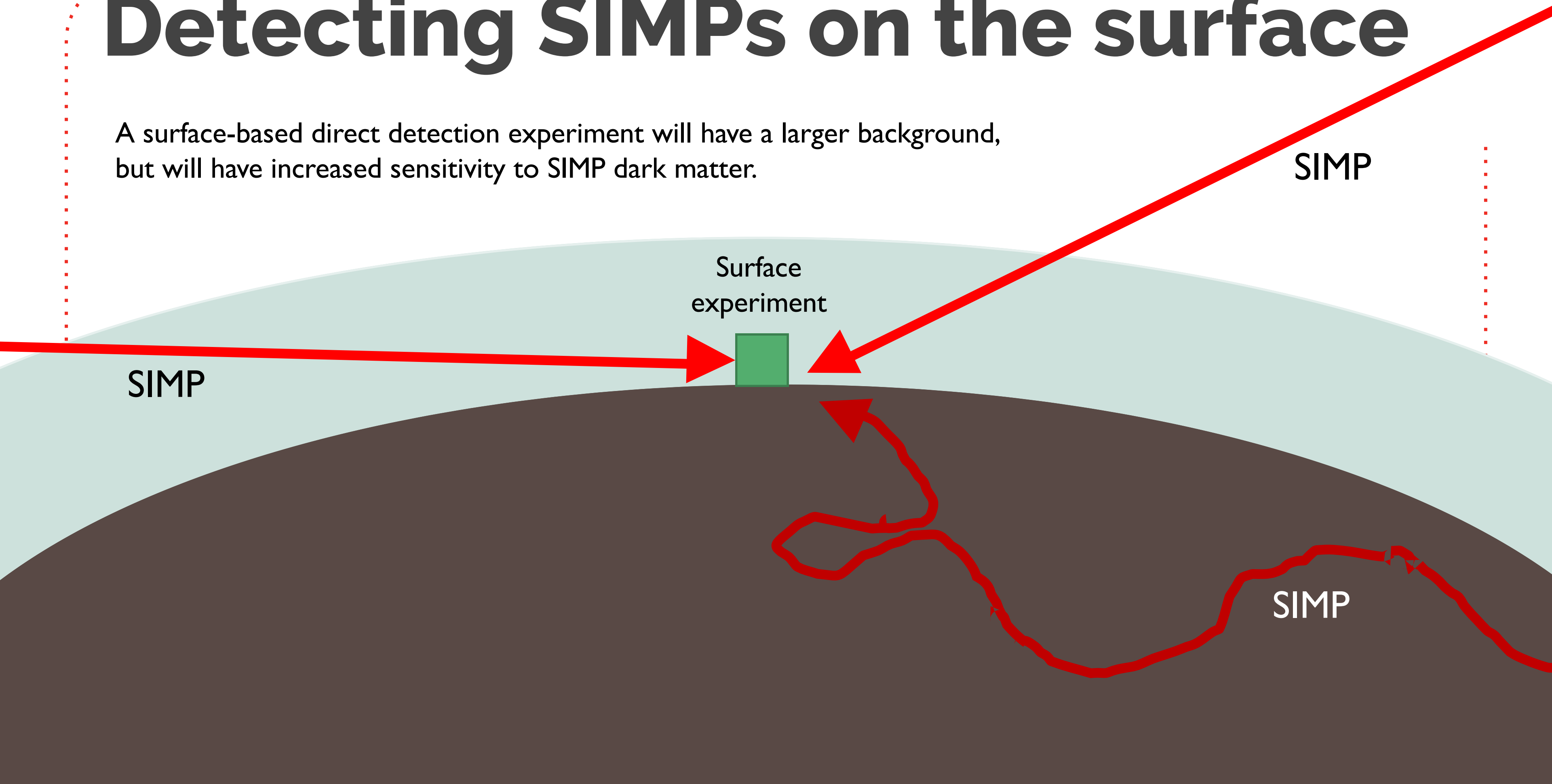
Detecting SIMPs

Strongly-interacting dark matter will lose energy through scattering with the Earth, such that it reaches the detector without enough energy to produce an observable signal.



Detecting SIMPs on the surface

A surface-based direct detection experiment will have a larger background, but will have increased sensitivity to SIMP dark matter.

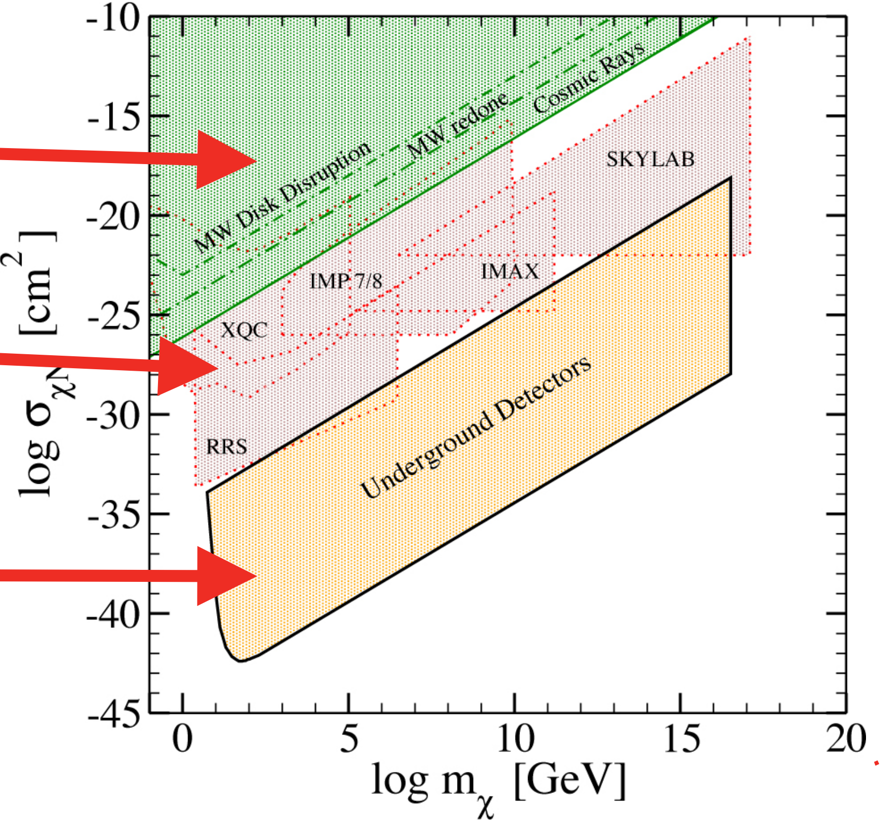


SIMP direct detection

Even larger cross sections are ruled out by astrophysical constraints.

At larger cross sections constraints come from balloon and rocket-borne experiments.

Direct detection experiments are not sensitive to larger DM-nucleon cross sections, in the so-called SIMP region.



New results from a surface-based cryogenic detector

The CRESST collaboration ran a short surface-run at the Max-Planck institute in Munich, where the only significant shielding was from the 30cm of concrete in the roof of the building and the atmosphere.

Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground

G. Angloher[1], P. Bauer[1], A. Bento[1,8], C. Bucci[2], L. Canonica[2,9], X. Defay[3], A. Erb[3,10], F. v. Feilitzsch[3], N. Ferreiro Iachellini[1], P. Gorla[2], A. Gütlein[4,5], D. Hauff[1], J. Jochum[6], M. Kiefer[1], H. Kluck[4,5], H. Kraus[7], J.-C. Lanfranchi[3], A. Langenkämper[3], J. Loebell[6], M. Mancuso[1], E. Mondragon[3], A. Münster[3], L. Oberauer[3,a], C. Pagliarone[2], F. Petricca[1], W. Potzel[3], F. Pröbst[1], R. Puig[4,5], F. Reindl[1,b], J. Rothe[1], K. Schäffner[2,11], J. Schieck[4,5], S. Schönert[3], W. Seidel[1,c], M. Stahlberg[4,5], L. Stodolsky[1], C. Strandhagen[6], R. Strauss[1,d], A. Tanzke[1], H.H. Trinh Thi[3], C. Türkoğlu[4,5], M. Uffinger[6], A. Ulrich[3], I. Usherov[6], S. Wawoczny[3], M. Willers[3], M. Wüstrich[1], and A. Zöller[3]

(The CRESST Collaboration)

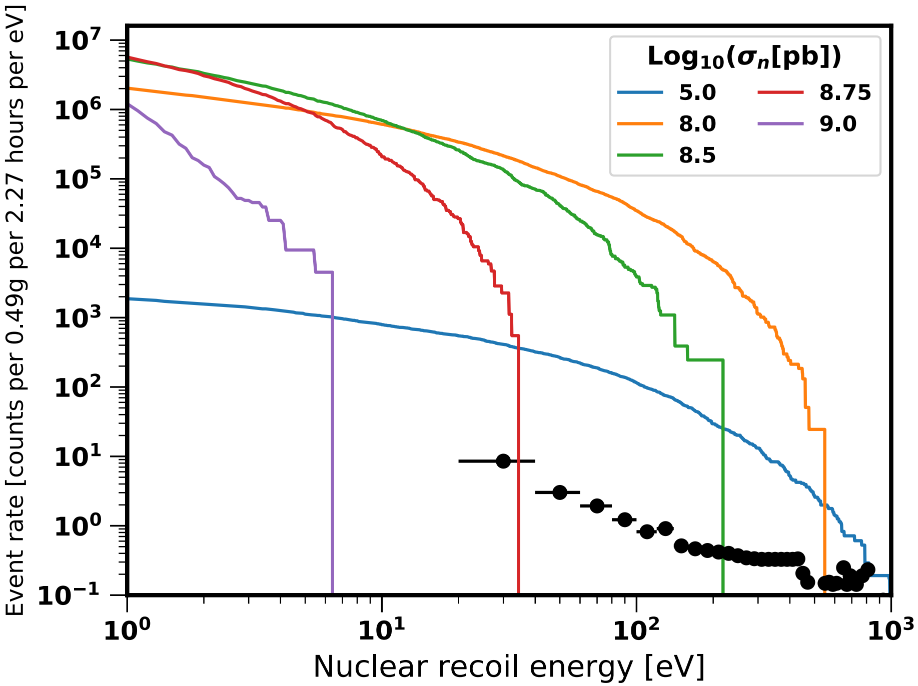
Eur.Phys.J. C77 (2017) no.9, 637 - arXiv:1707.0674

SIMPs in a surface-based cryogenic experiment

- The rate of events expected from SIMPs is far larger than the observed rate.

- Sensitivity to SIMPs is lost when the spectrum drops below the 20eV threshold due to SIMPs scattering in the shielding and atmosphere.

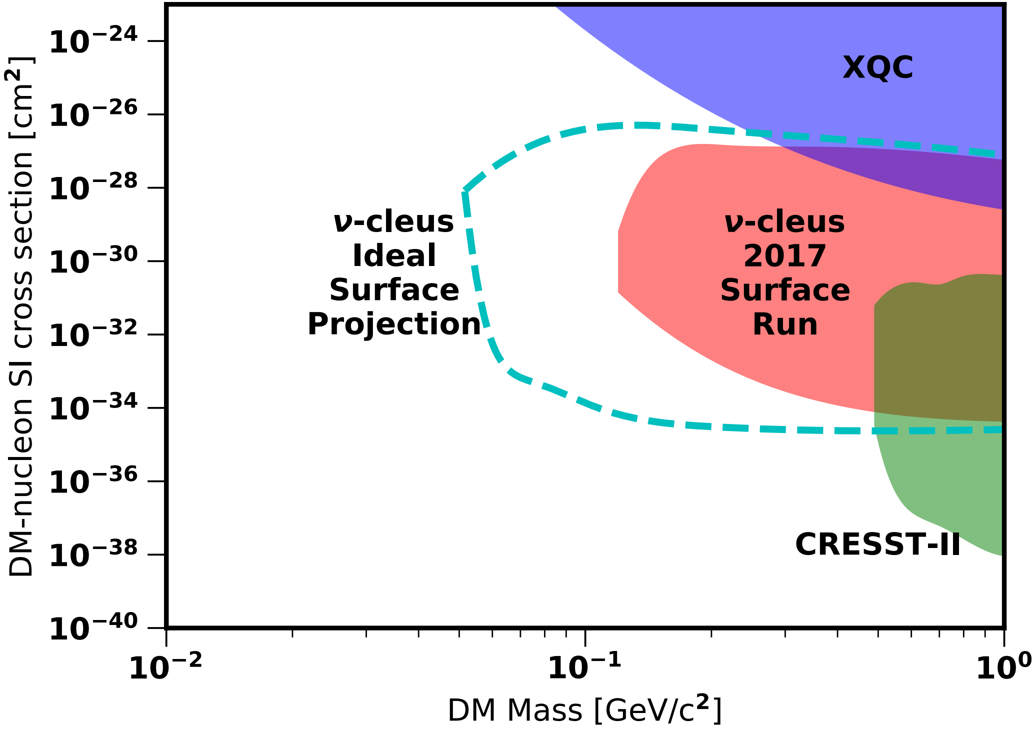
Data from: Results on MeV-scale dark matter from a gram-scale cryogenic calorimeter operated above ground, Eur.Phys.J. C77 (2017) no.9, 637 , arXiv:1707.067



New constraints on SIMP dark matter

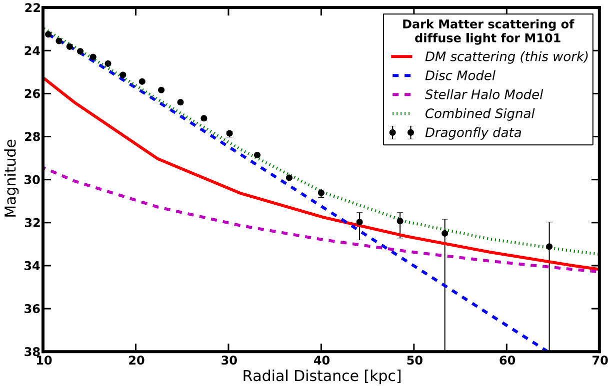
- The red region shows SIMP cross sections and masses which can be ruled out with the data from this surface run.

- The blue dashed line shows projections for a surface-based detector with a 4eV threshold.



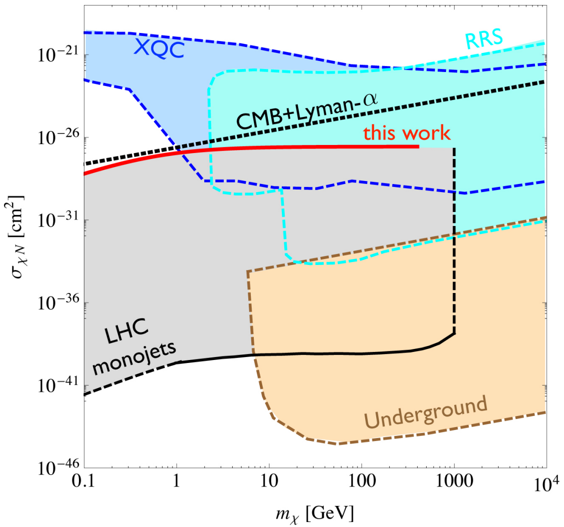
More constraints on SIMPs

Faint scattered light around galaxies



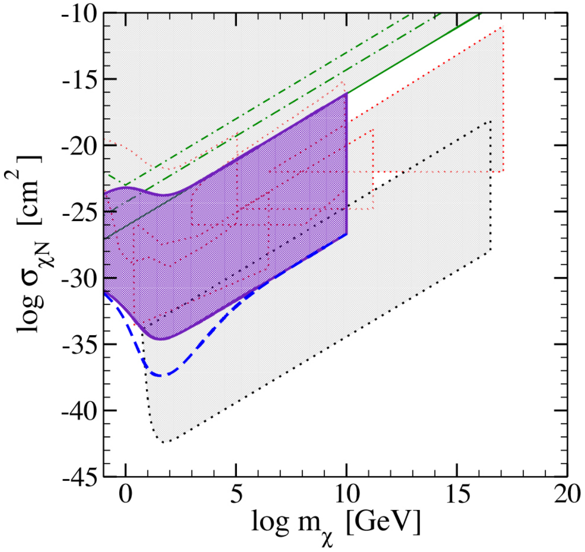
Glow in the Dark Matter: Observing galactic halos with scattered light
J.H.Davis and J.Silk,
PRL 114 (2015) 051303

Collider constraints



Simplified SIMPs at the LHC
Daci et al.
JHEP 1511 (2015) 108

Earth heating



Mack, Beacom and Bertone
Phys.Rev. D76 (2007) 043523

Constraining DM solutions to the solar metallicity problem

These low-threshold experiments can also constrain the new physics solutions to the solar metallicity problem, as well as measuring the CNO flux.

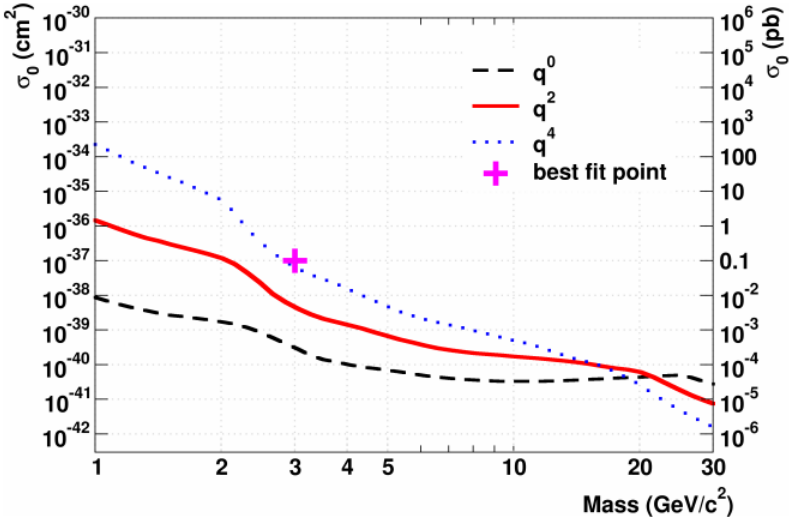
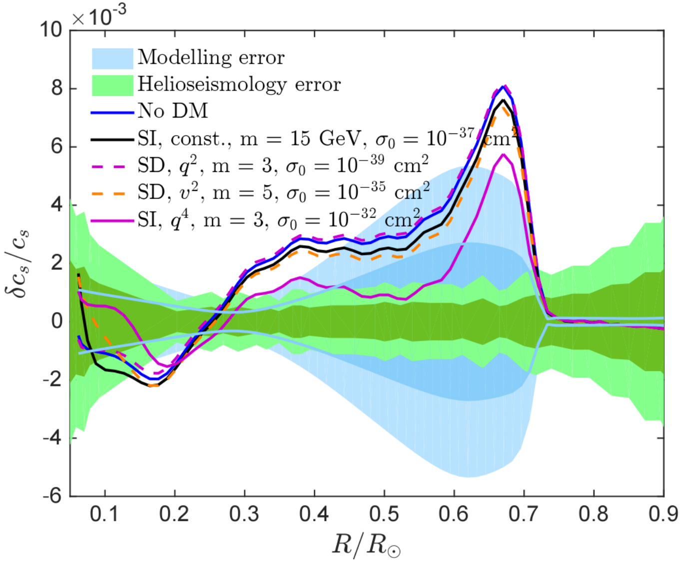


FIG. 4. 90 % C.L. upper limits on σ_0 for different for different powers of q. The limit for q^2-dependent scattering is drawn in solid red ruling out the best fit point from [3] (magenta cross). For comparison also the limit for q^4-dependent scattering (dotted blue) and scalar interaction (dashed black) are shown.

Limits on momentum-dependent asymmetric dark matter with CRESST-II, Phys.Rev.Lett. 117 (2016) 021303, arXiv:1601.04447

Constraining DM solutions to the solar metallicity problem

But there is still a region of parameter space where the fit to helioseismology is improved.



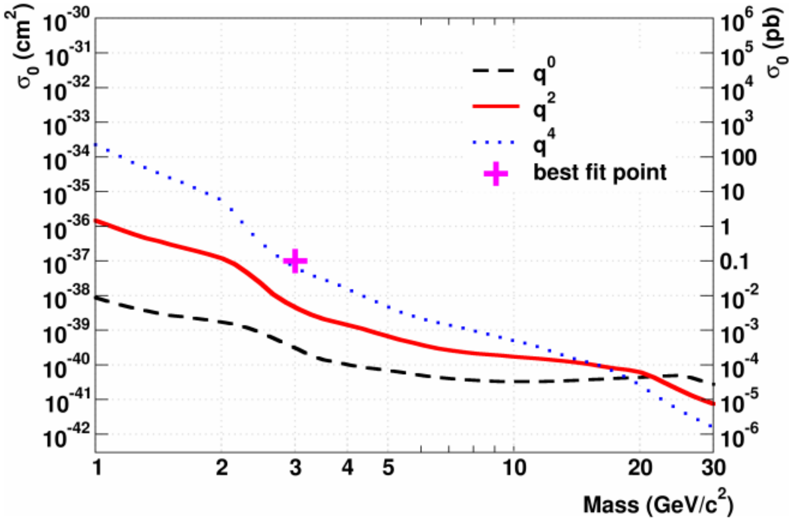


FIG. 4. 90 % C.L. upper limits on σ_0 for different for different powers of q. The limit for q^2-dependent scattering is drawn in solid red ruling out the best fit point from [3] (magenta cross). For comparison also the limit for q^4-dependent scattering (dotted blue) and scalar interaction (dashed black) are shown.

Conclusion

- Solar models can only fit to helioseismic data if the metallicity is set to be higher than the measured values from the photosphere i.e. the solar metallicity problem.
- It's solution may involve the capture of dark matter.
- By measuring the flux of CNO neutrinos, next-generation experiments will provide a crucial new piece of data to solve this problem.
- Some of this detector technology can also be used to look for sub-GeV mass dark matter, which may be strongly-interacting.

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