# Probing the **neutrino floor** with direct DM detection experiments

**DAVID G. CERDEÑO**

Based on

| | |
|---|---|
| **Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm** | JHEP 1609 (2016) 048 |
| **Cerdeño, Davis, Fairbairn, Vincent** | JCAP 1804 (2018) 037 |
| **Boehm, Cerdeño, Machado, Olivares, Reid** | JCAP 1901 (2019) 043 |

IP3

# Outline

**Introduction/motivation**

direct DM detection and the neutrino floor

**Exploiting the neutrino floor**

The observation of the Standard Model neutrino floor can help understanding solar properties (e.g., metallicity)

CNO neutrinos

**Raising the neutrino floor**

New physics in the neutrino sector can raise the neutrino floor

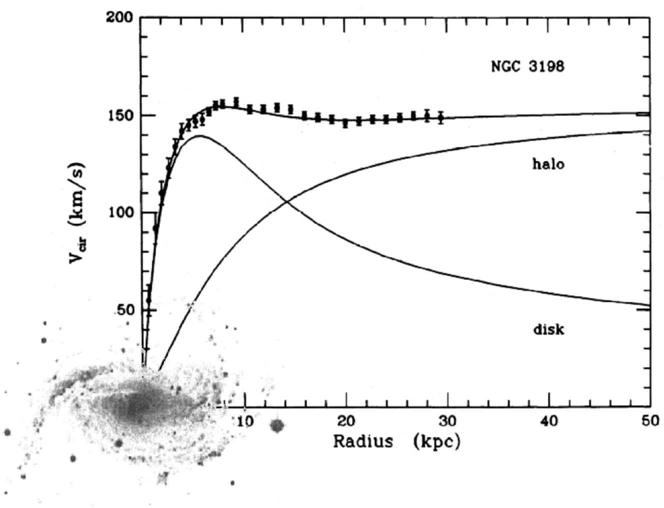
Measure new light mediators

# Dark Matter is a necessary (and abundant) ingredient in the Universe

It is one of the clearest hints of Physics Beyond the SM

## Galaxies

- Rotation curves of spiral galaxies
- Gas temperature in elliptical galaxies



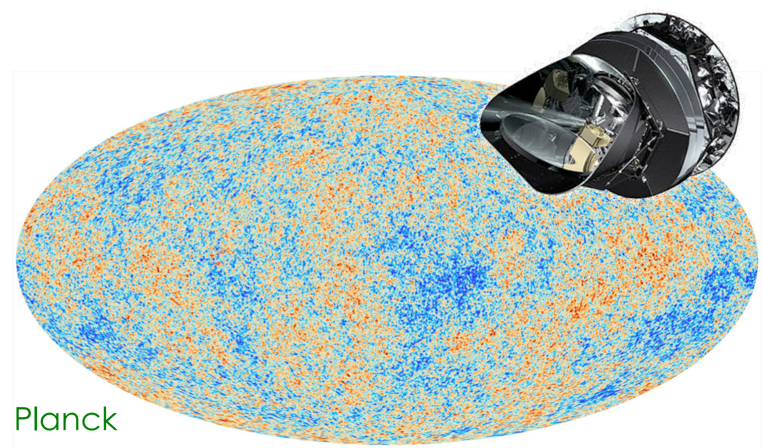

## Clusters of galaxies

- Peculiar velocities and gas temperature
- Weak lensing
- Dynamics of cluster collision
- Filaments between galaxy clusters

## Cosmological scales

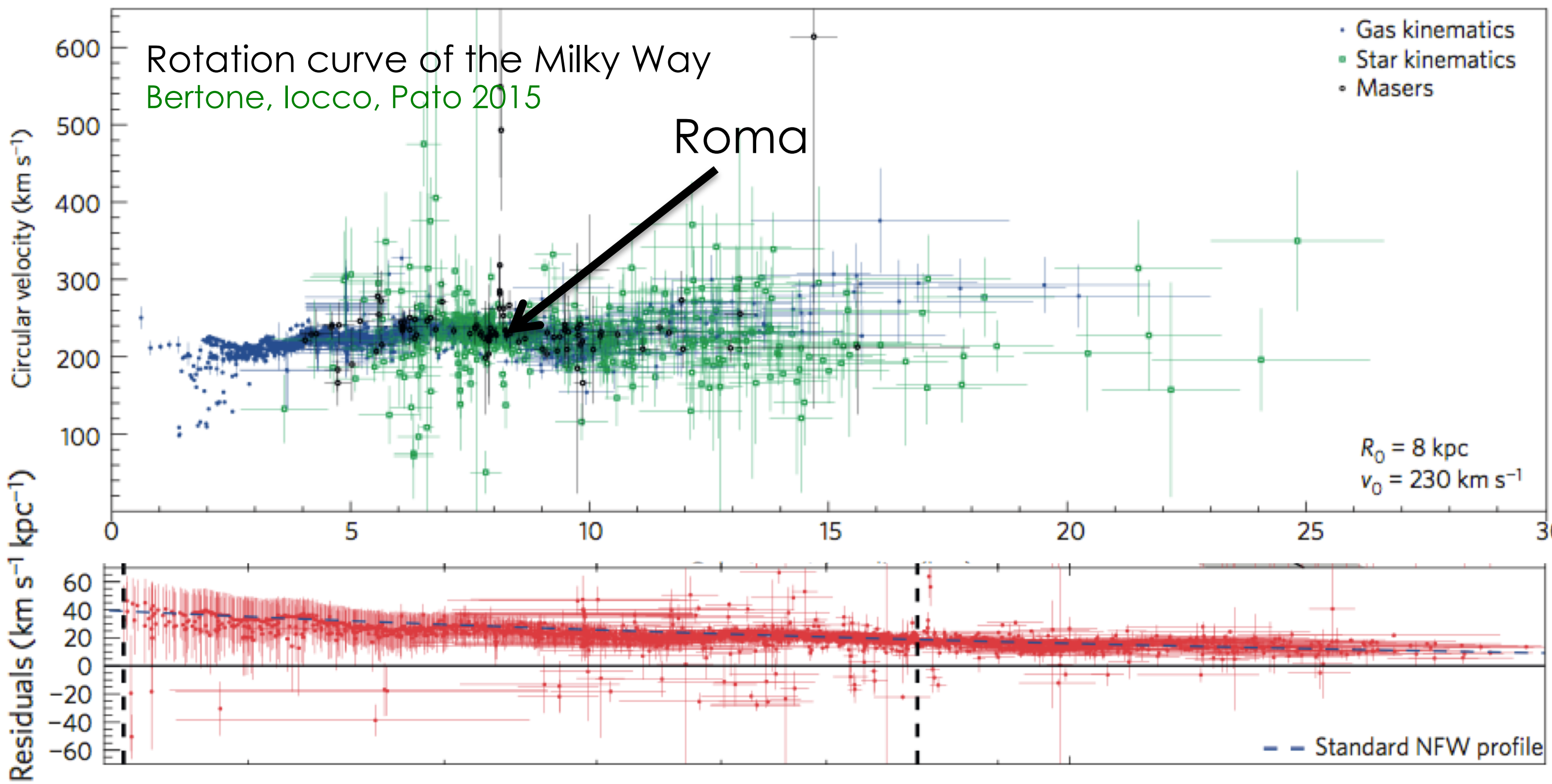
Anisotropies in the Cosmic Microwave Background

$$\Omega_{CDM}\, h^2 = 0.1196 \pm 0.003$$



## The effect of DM has also been observed in the Milky Way...

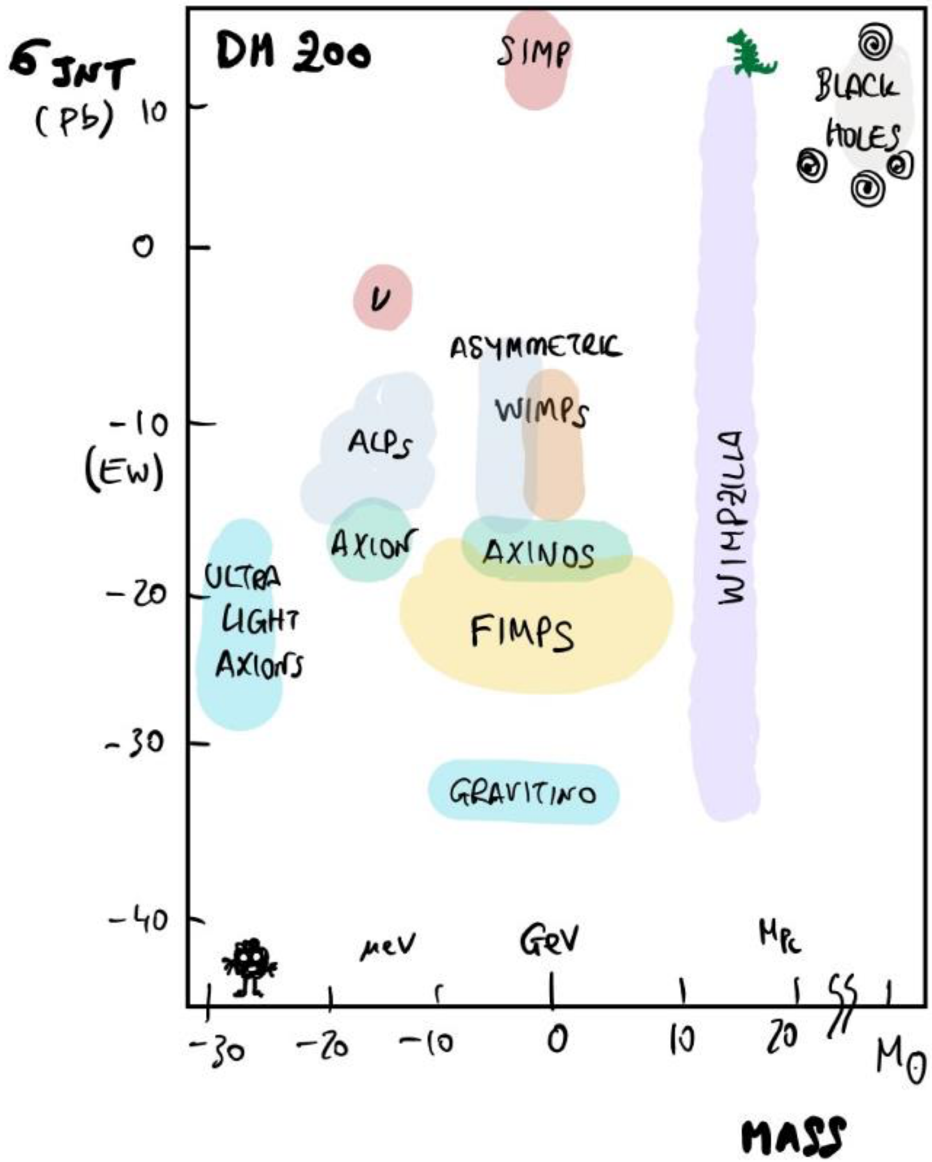
- There is DM in the centre of our Galaxy



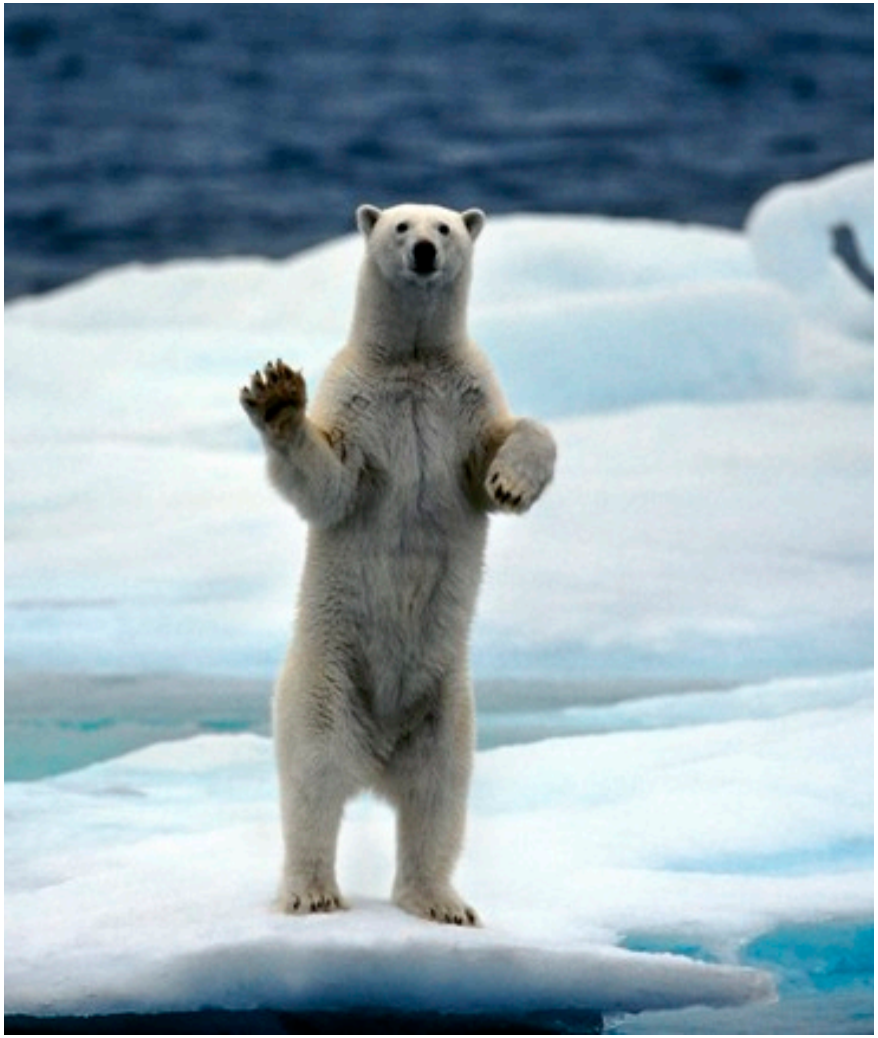

- Observations also show that there is need for DM in the solar neighbourhood

Bovy, Tremaine 2012

# A theorist's PARADISE…. an experimentalist's PURGATORY

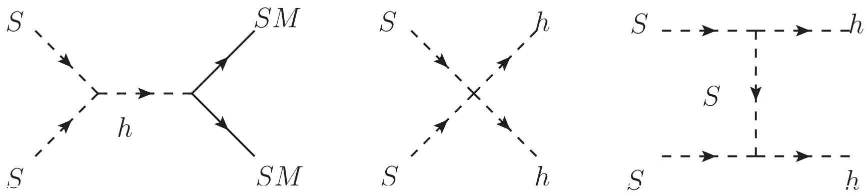


# DM ZOO



## "Lone DM"

- The DM particle is the only exotic addition to the Standard Model
- For example: **Higgs-portal DM**

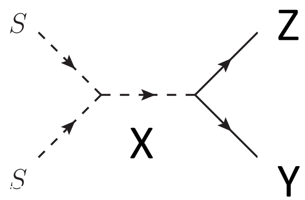



- Or **axions…**

# DM ZOO

**"Dark sector"**

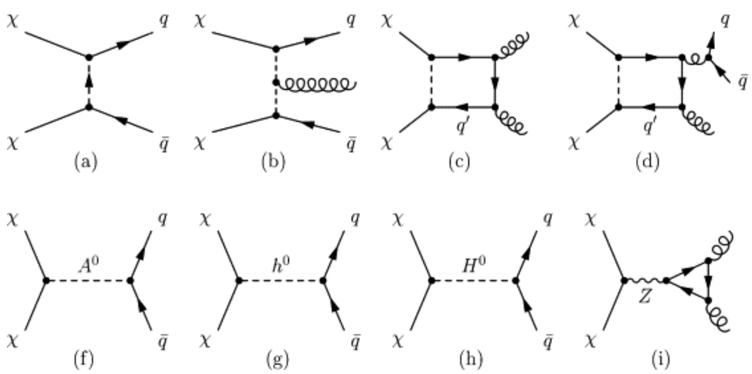
- The DM particle is accompanied by other **new exotics**.
- New **"mediators"** would connect the dark sector to the Standard Model.




# DM ZOO

**"Dark sector"**

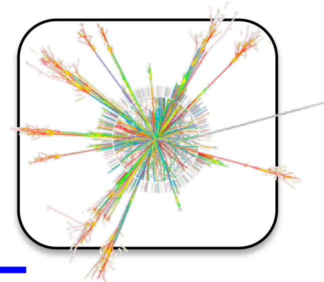
- The DM particle is accompanied by other **new exotics**.
- New **"mediators"** would connect the dark sector to the Standard Model.
- For example, **SUSY**



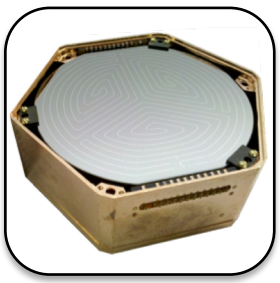

**Supersymmetric rave**

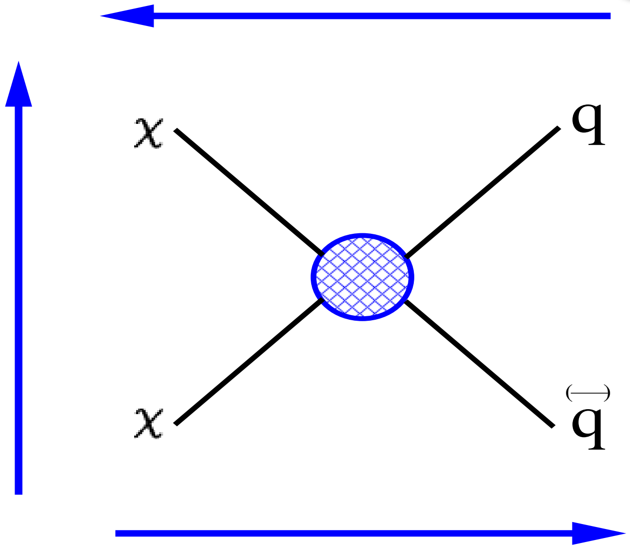
# Dark matter **MUST BE** searched for in different ways...

Accelerator Searches (production)



Direct Detection (scattering)

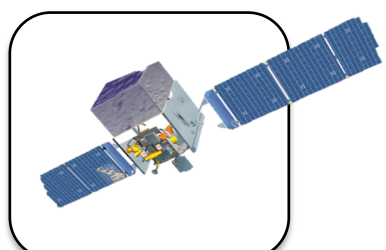




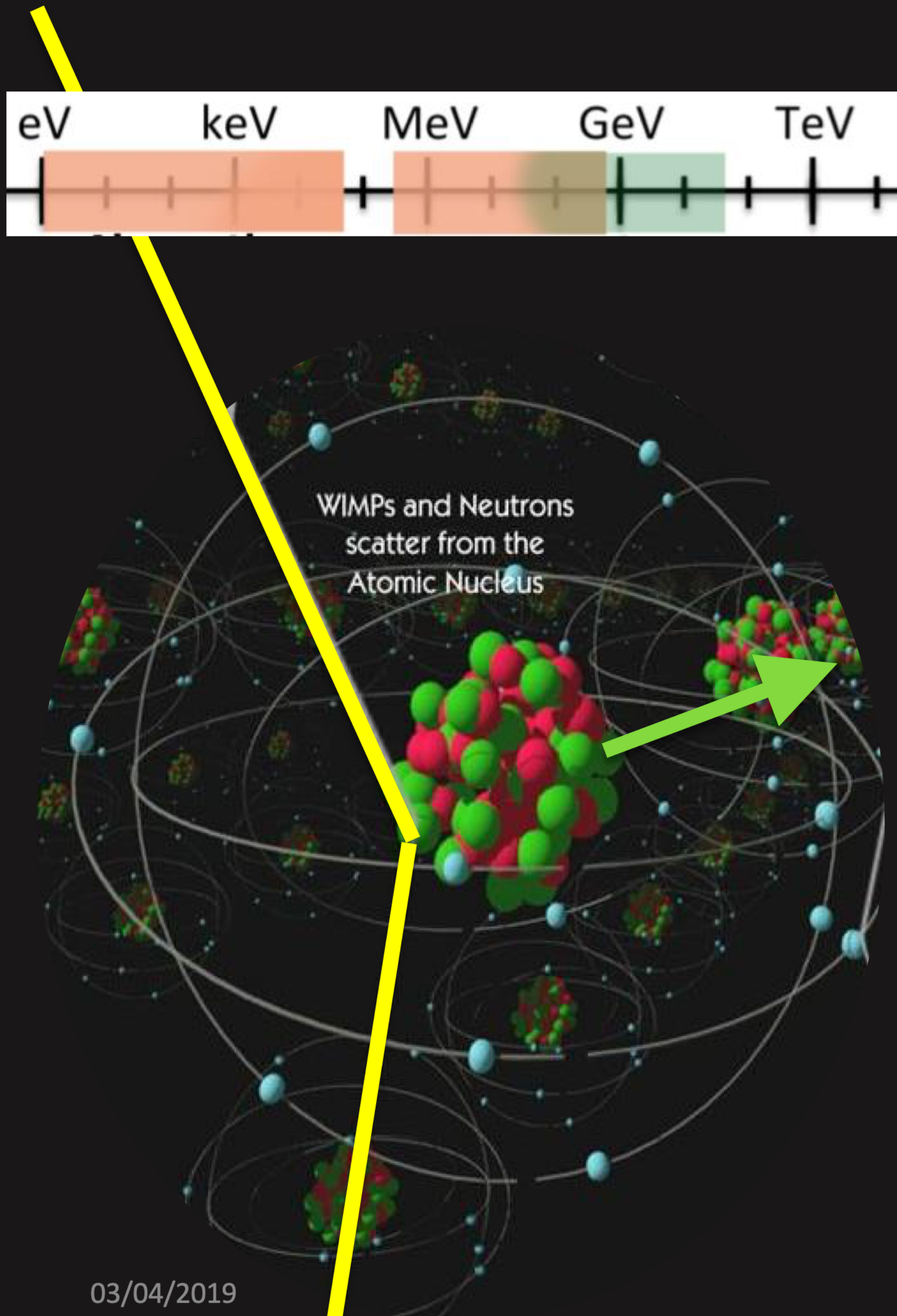

**Constraints** in one sector affect observations in the other two.

“**Redundant**” detection can be used to extract DM properties.

Indirect Detection (annihilation or decay)



# DIRECT DARK MATTER SEARCHES:
What can we measure?




**NUCLEAR SCATTERING**

- “Canonical” signature
- Elastic or Inelastic scattering
- Sensitive to m >1 GeV

**ELECTRON SCATTERING**

- Sensitive to light WIMPs

**ELECTRON ABSORBPTION**

- Very light (non-WIMP)

**EXOTIC SEARCHES**

- Axion-photon conversion in the atomic EM field
- Light Ionising Particles

# Conventional direct detection approach

$$N = \int_{E_T} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Experimental setup

Target material (sensitiveness to different couplings)

Detection threshold

Astrophysical parameters

Local DM density

Velocity distribution factor

Theoretical input

Differential cross section

(of WIMPs with quarks)

Nuclear uncertainties

$$\frac{d\sigma_{WN}}{dE_R} = \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SI} + \left(\frac{d\sigma_{WN}}{dE_R}\right)_{SD}$$

**Spin-independent** and **Spin-dependent** components, stemming from different microscopic interactions leading to different coherent factors

# Discriminating a DM signal: ENERGY SPECTRUM

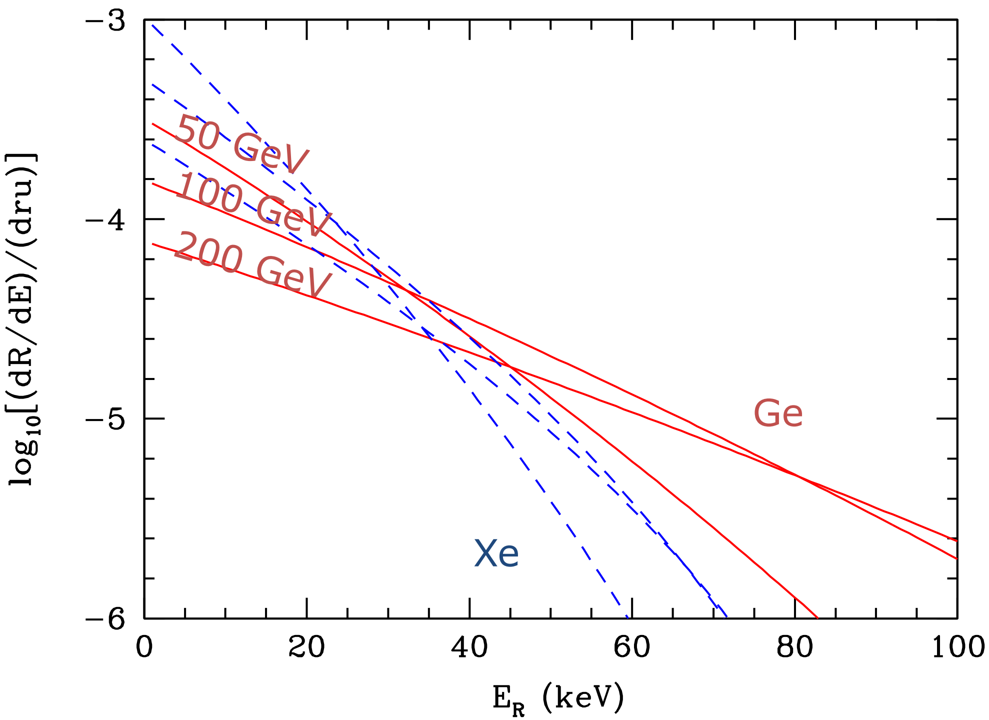
The nuclear recoil spectrum is expected to be approximately **exponential**

The slope is dependent on the DM mass and the target mass

Light WIMPs expected at very low recoil energies

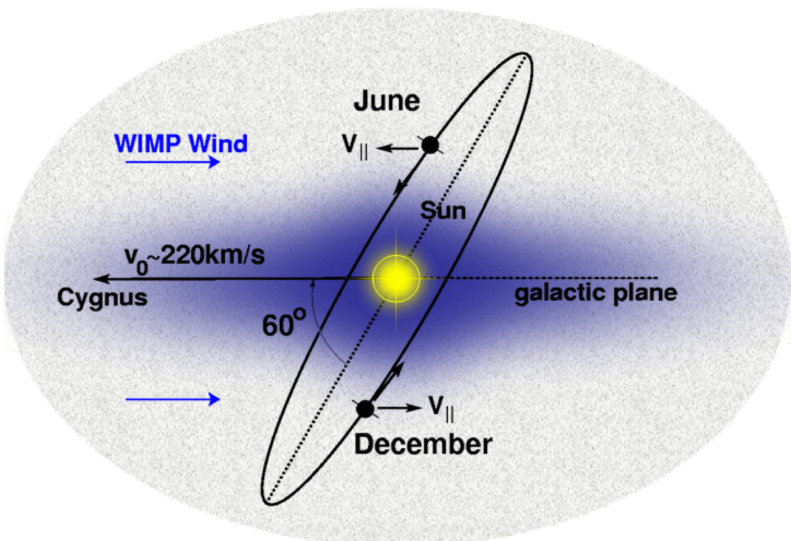
Favours light targets

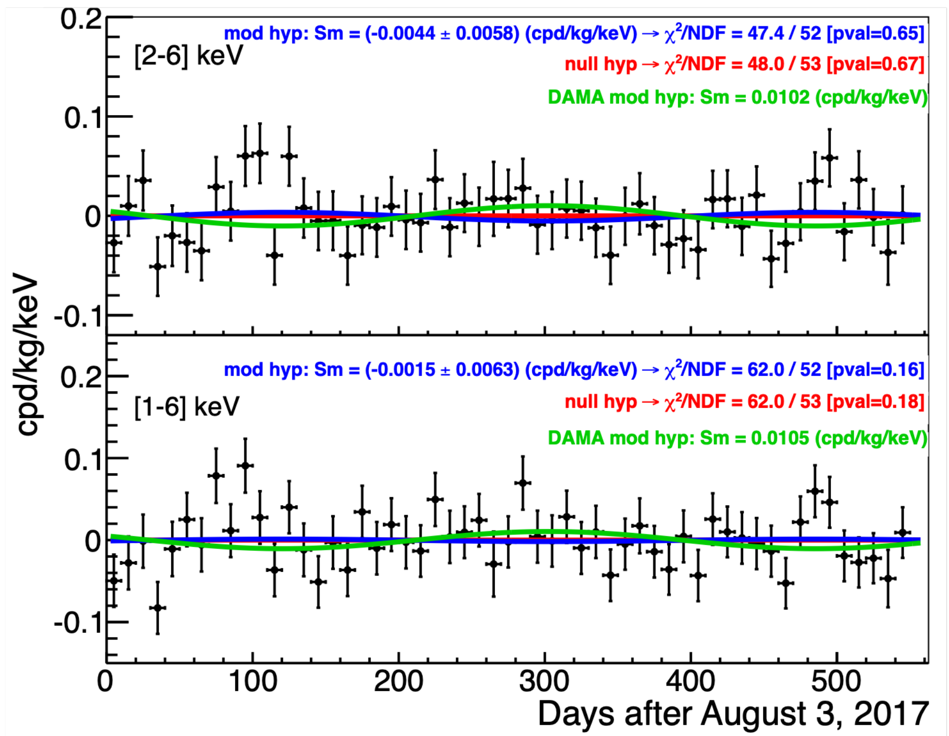
**Low-threshold searches**



# Discriminating a DM signal: ANNUAL MODULATION

An annual modulation is expected due to the seasonal variation of the Earth's velocity inside the DM halo.




DAMA has claimed a potential signature that is being currently probed by other detectors (e.g. ANAIS).

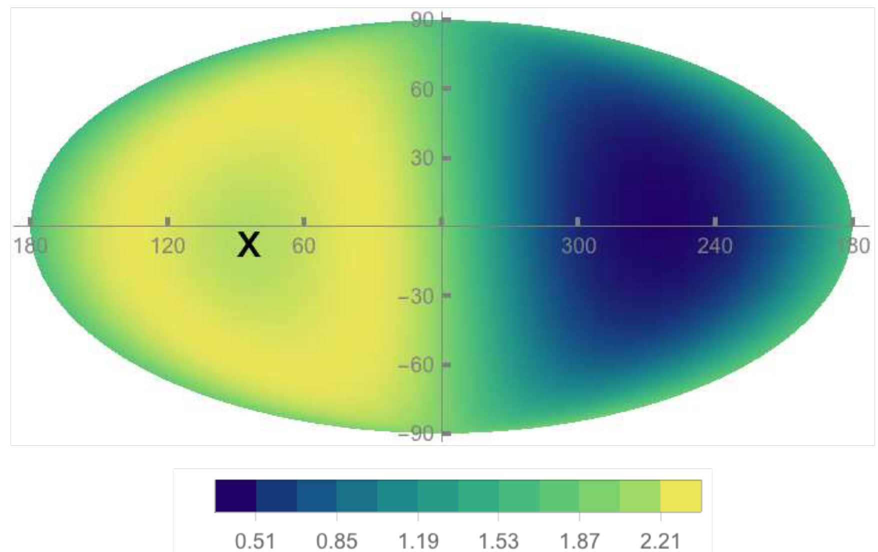
# Discriminating a DM signal: DIRECTIONALITY

The expected signal for WIMPs is expected to peak at the direction of motion of the Sun inside the Milky Way (Cygnus)

A dipole signal could be accompanied by ring-like features at low energies.

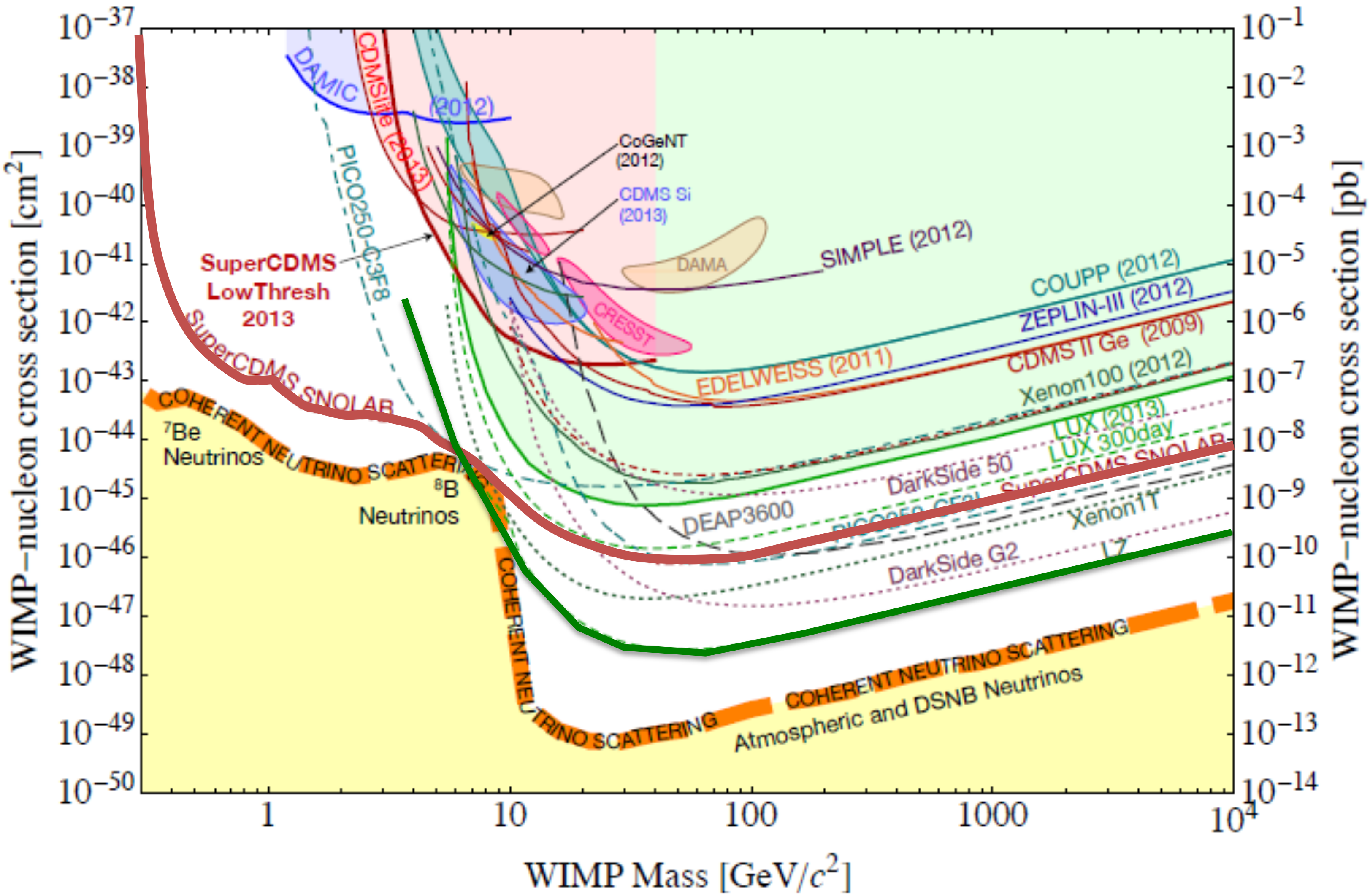
Requires measurement of both the direction and recoil energy

Very challenging but potentially ideal to remove all other sources of background




O'Hare 1602.03781
Bozorgnia, Gelmini, Gondolo 1111.6361

# Future prospects



# Coherent neutrino scattering

The de Broglie wavelength of neutrinos can exceed the radii of heavy nuclei for neutrino energies below ~100 MeV.

- Recently **observed SM phenomenon (COHERENT)**

  Extremely small cross section only within the reach of ultra-low background experiments.

- **Background** for DM experiments

  - The signature is similar to that expected for a WIMP

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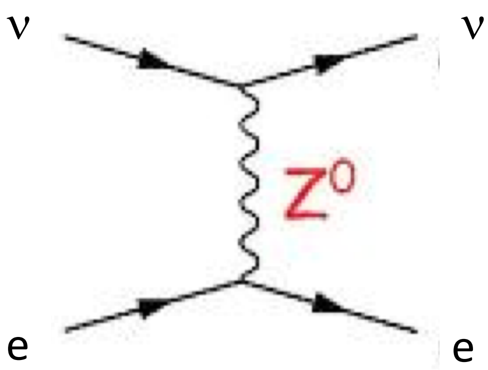
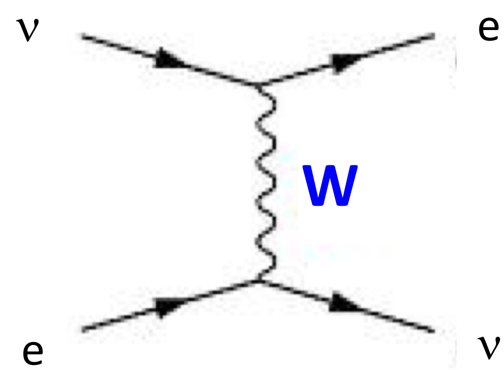
- It can give us access to **solar properties** (e.g., CNO neutrinos and solar metallicity)
- It can allow us to probe **new physics in the neutrino sector**

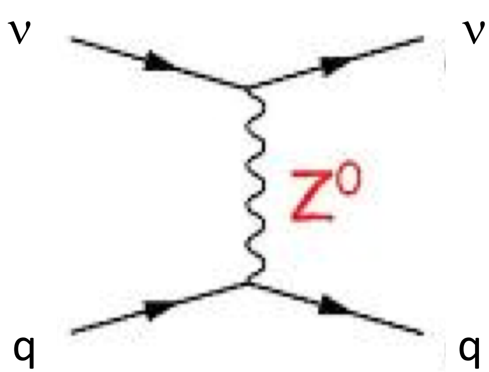
# Neutrino scattering in a DM experiment

Exchange of W and Z bosons with electrons




Exchange of a Z boson with the nucleus



# Neutrino scattering in a DM experiment

$$\frac{dR}{dE_R} = \frac{\epsilon}{m_T} \int dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_\nu}{dE_R}$$

## Neutrino-Electron scattering (ER)

$$\frac{d\sigma_{\nu e}}{dE_R} = \frac{G_F^2 m_e}{2\pi} \left[ (g_v + g_a)^2 + \quad (g_v - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2) \frac{m_e E_R}{E_\nu^2} \right]$$

for muon and tau only charged current $\quad g_{v;\mu,\tau} = 2\sin^2\theta_W - \frac{1}{2}; \;\; g_{a;\mu,\tau} = -\frac{1}{2}$

for electrons, charged and neutral currents $\quad g_{v;e} = 2\sin^2\theta_W + \frac{1}{2}; \;\; g_{a;e} = +\frac{1}{2}$

## Coherent Neutrino-Nucleus scattering (NR)

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2}{4\pi} Q_v^2 m_N \left(1 - \frac{m_N E_R}{2E_\nu^2}\right) F^2(E_R)$$

$$Q_v = N - (1 - 4\sin^2\theta_W) Z$$

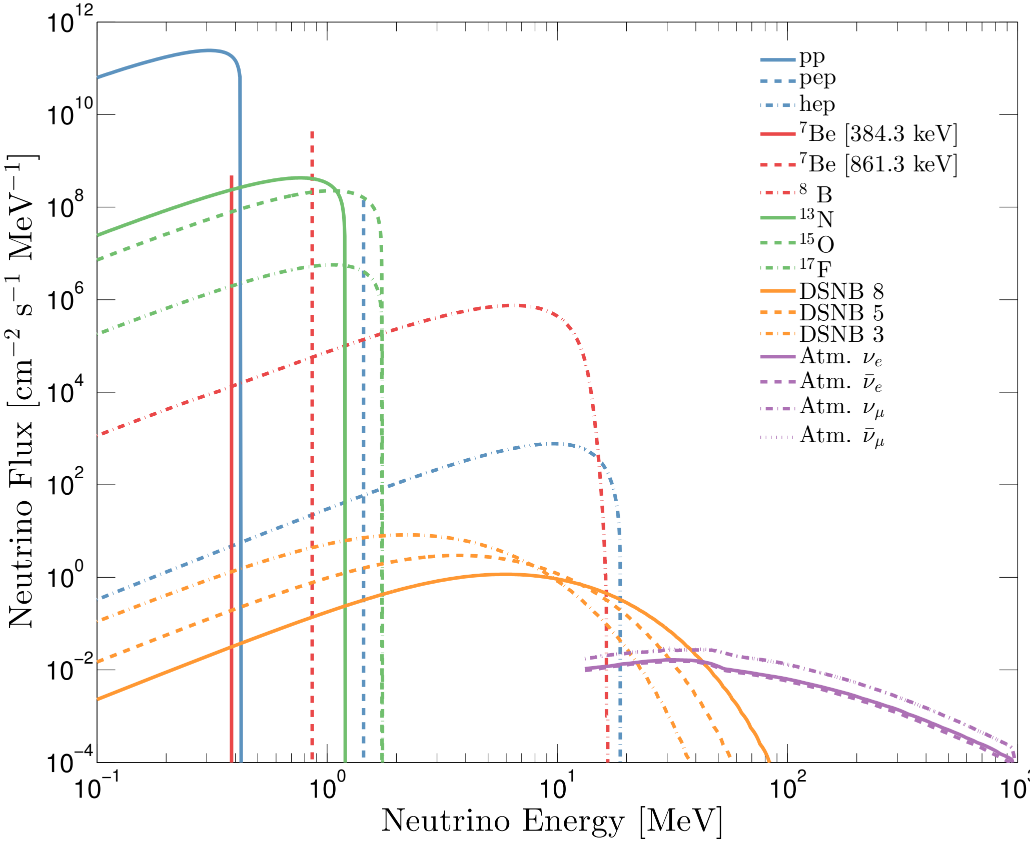
The form factor is the same as in WIMP-nucleus scattering.

The spectrum differs as it depends on neutrino flux.

# Neutrino fluxes

- Solar neutrinos dominate at low energy – the leading contribution is the pp chain below 1 MeV
- Atmospheric neutrinos contribute at higher energies but at a much smaller rate
- Diffuse Supernovae Background relevant around ~20-50 MeV

O'Hare, Green, Billard, Figueroa-Feliciano, Strigari 2015



# Experimental response to CNNS

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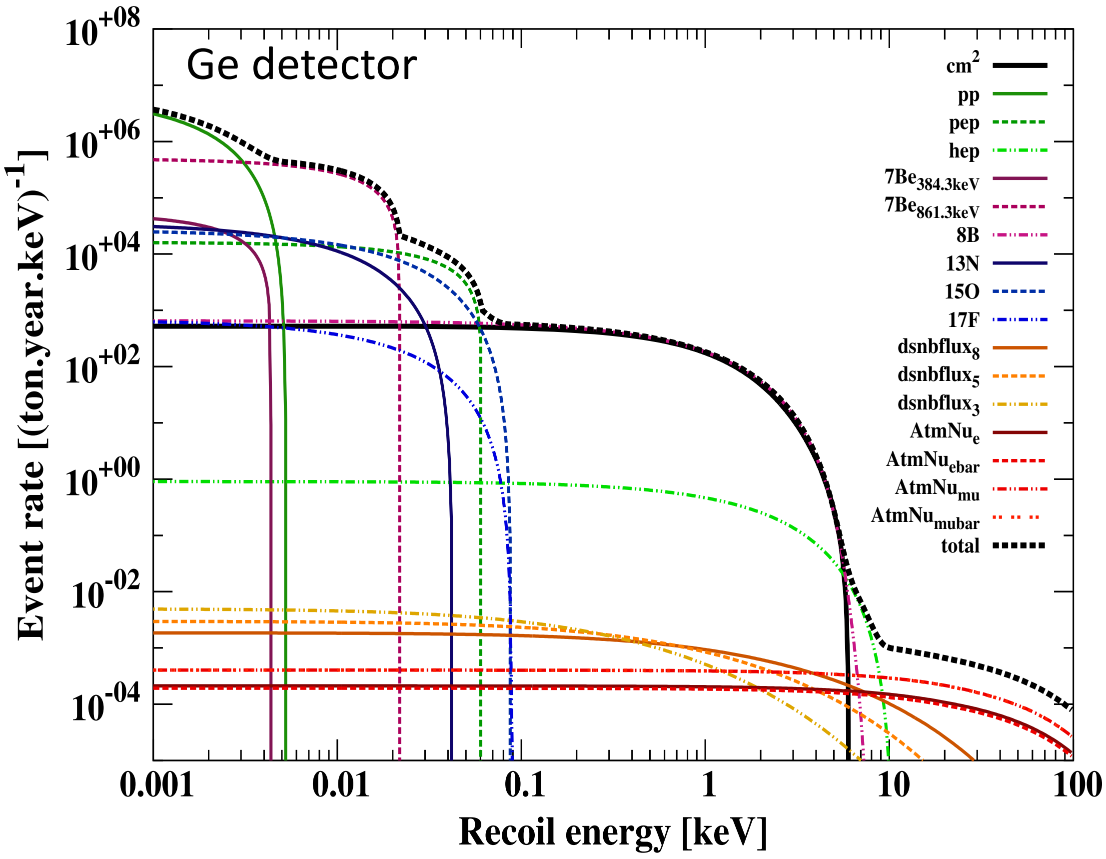

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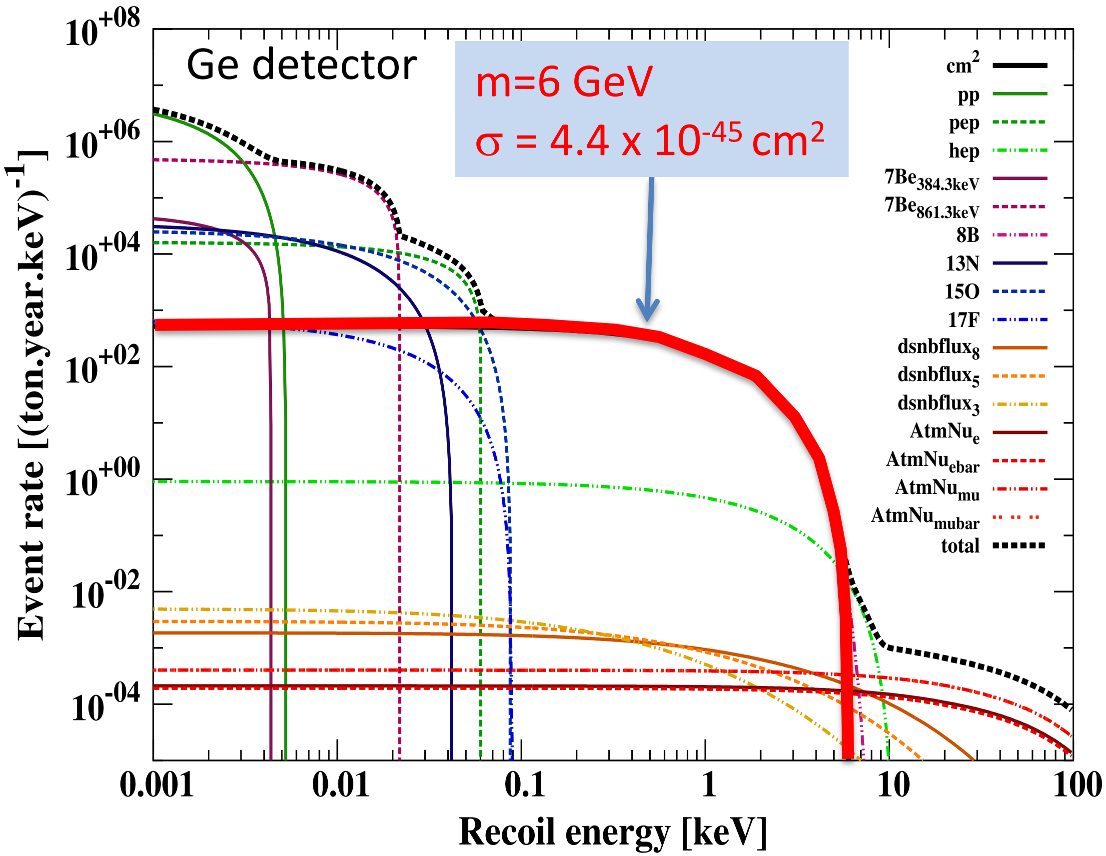

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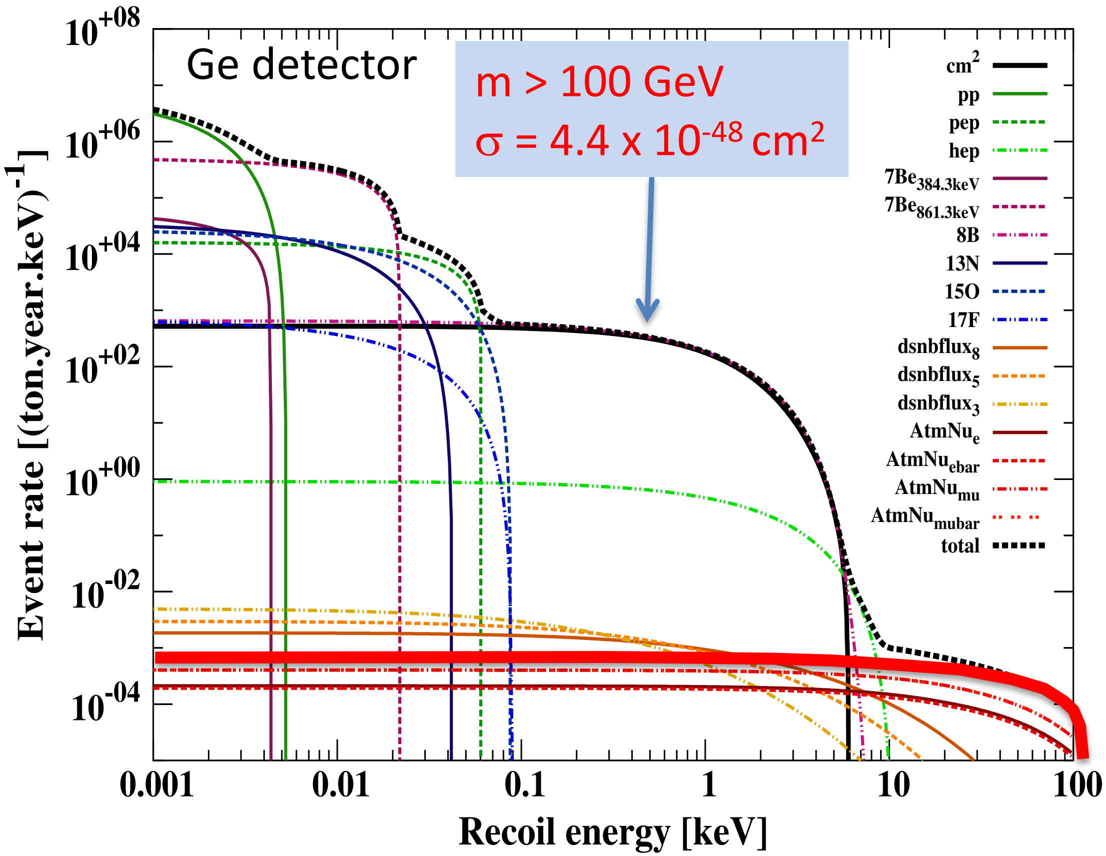


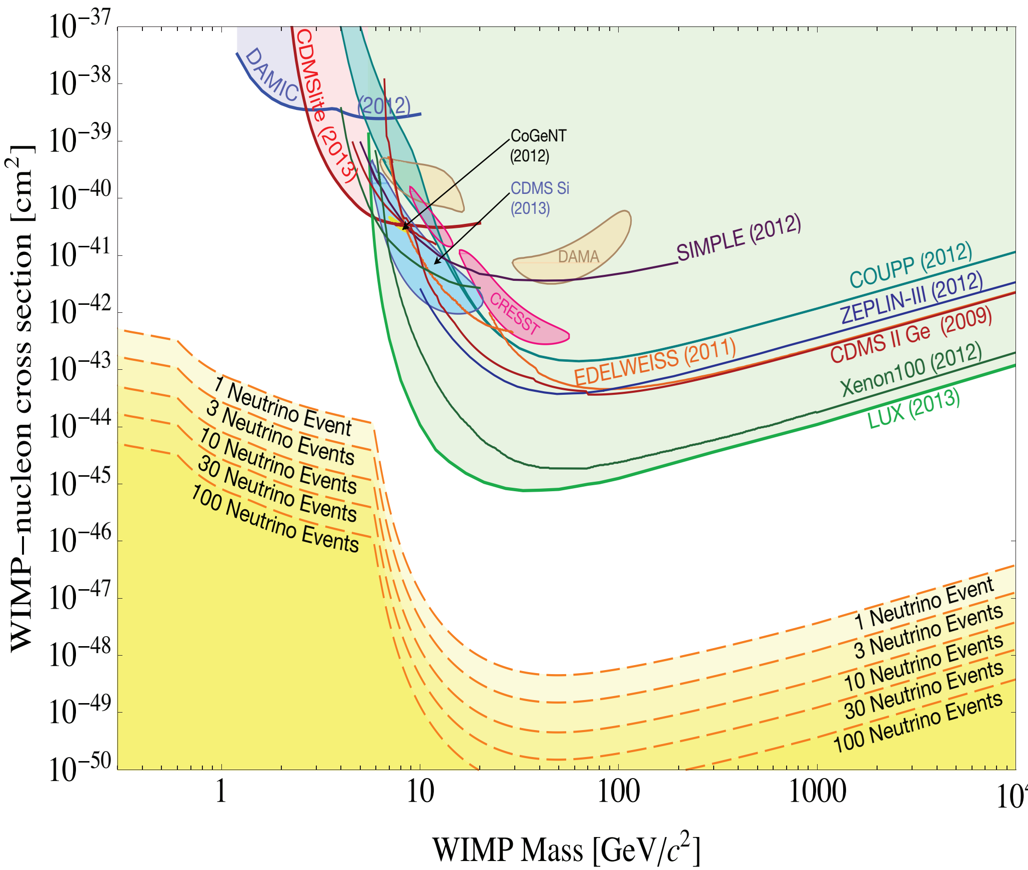
# Background for DM experiments

Future dark matter experiments will be sensitive to this SM process, limiting the reach for DM searches (Neutrino Floor)

Going beyond the neutrino floor:

- Spectral analysis
- Annual modulation
  Billard et al. 1307.5458
  Davis 1412.1475
- Combination of complementary targets
  Ruppin et al. 1408.3581
- Directional detection

  Grothaus et al. 1406.5047
  O'Hare et al. 1505.08061



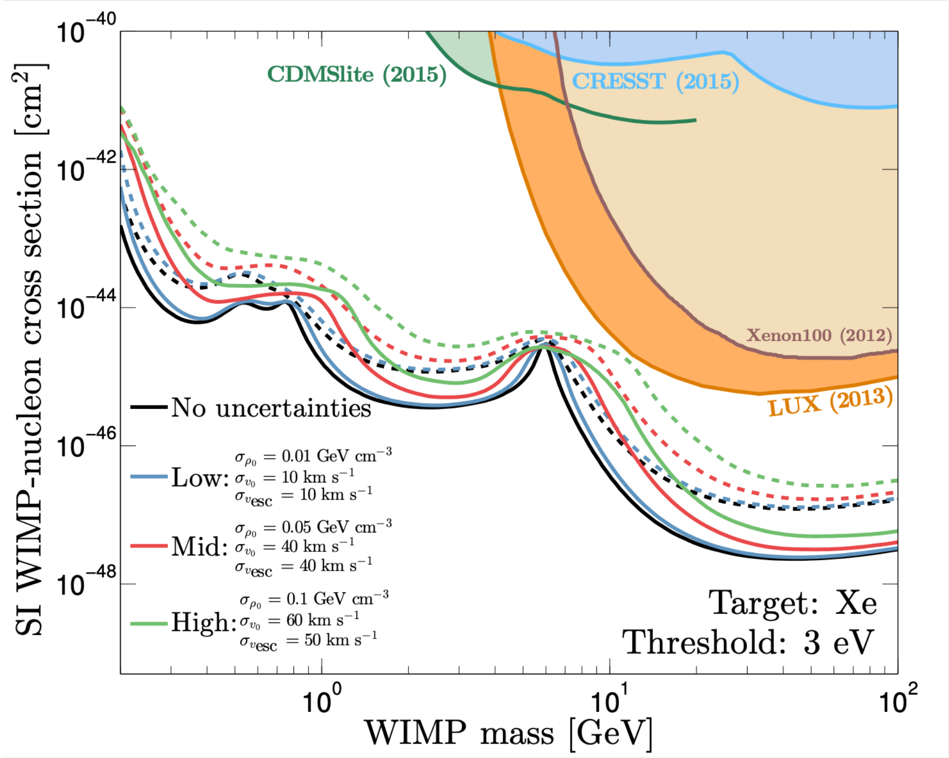
# Which neutrino floor?

One can also draw a “detection limit”, based on our capabilities of discriminating a DM and a neutrino signal from the observed spectrum

- Sensitive to astrophysical uncertainties in the DM halo

- 6 GeV WIMP is difficult to discriminate using only spectrum ($^8B$)

- Be and pep would resemble a lower mass WIMP




O’Hare 1604.03858

# Exploiting the neutrino floor

Measuring neutrinos from the Sun offers the possibility to test some properties of solar models, in particular the metallicity of the Sun.

We have considered the possibility of measuring both electron and nuclear recoils.

# Experimental setups considered

**Idealised** versions of current and future detectors using a nominal (n) and optimistic (o) value for the energy threshold

| Experiment | $\epsilon$ (ton-year) | $E_{th,n}$ (keV) | $E_{th,o}$ (keV) | $E_{max}$ (keV) | $R(pp)$ | $R(^8\mathrm{B})$ | $R(\mathrm{CNO})$ |
|---|---|---|---|---|---|---|---|
| G2-Ge | 0.25 | 0.35 | 0.05 | 50 | – | [62 – 85] | [0 – 3] |
| G2-Si | 0.025 | 0.35 | 0.05 | 50 | – | [3 – 3] | 0 |
| G2-Xe | 25 | 3.0 | 2.0 | 30 | [2104 – 2167] | [0 – 64] | 0 |
| Future-Xe | 200 | 2.0 | 1.0 | 30 | [17339 – 17846] | [520 – 10094] | 0 |
| Future-Ar | 150 | 2.0 | 1.0 | 30 | [14232 – 14649] | [6638 – 12354] | 0 |
| Future-Ne | 10 | 0.15 | 0.1 | 30 | [1141 – 1143] | [898 – 910] | [21 – 63] |

ER from pp chain
mostly independent on the threshold
sensitive to total size

Expected number of events:

CNS from $^8$B and CNS
Very sensitive to the threshold

# Neutrino scattering in a DM experiment

The recoil energy depends on the scattered particle

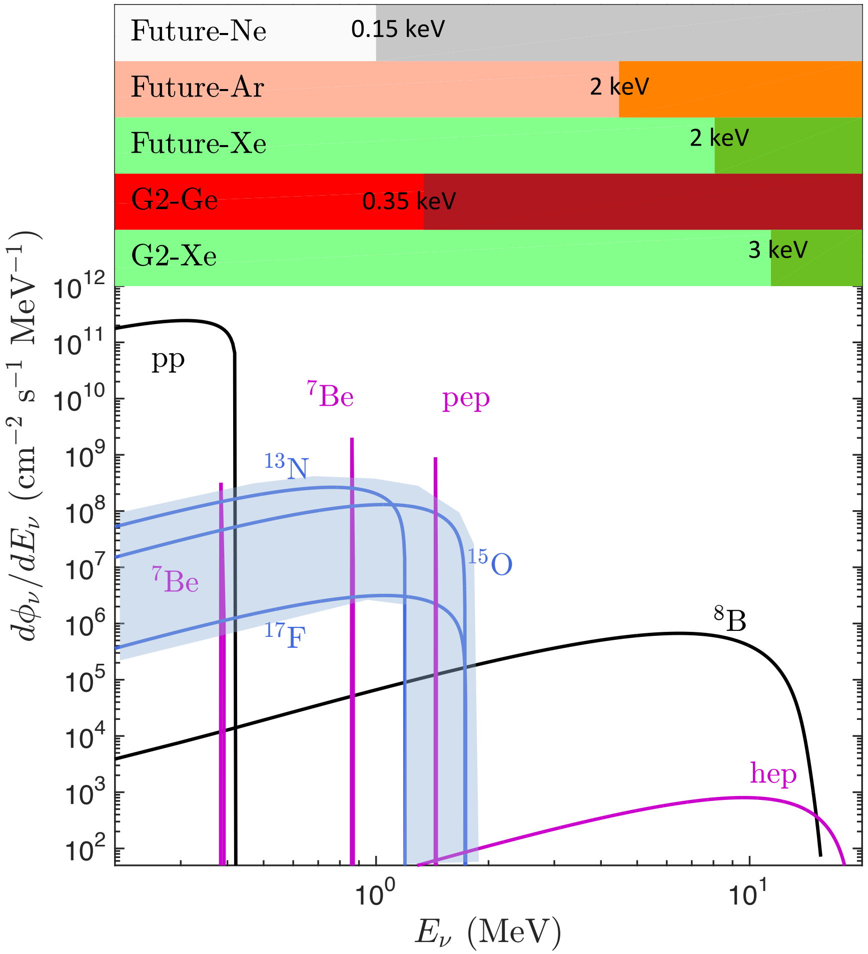
$$q = \sqrt{2E_R m_N}$$

ER can probe lower energies (thus only sensitive to pp neutrinos).

- Results are mainly independent on the threshold energy

NR more limited but sensitive to $^8$B and potentially also CNO neutrinos.

- Results very sensitive to the threshold energy



All the components of the proton-proton chain have all been measured

- Borexino (pp, pep, $^7$Be, $^8$B)
- SNO and SuperKamiokande ($^8$B)

The CNO neutrino flux has not yet been measured

| **Solar Metallicity** | **CNO Neutrino Flux [cm$^{-2}$ s$^{-1}$]** | | |
|---|---|---|---|
| | $^{13}$N [$10^8$] | $^{15}$O [$10^8$] | $^{17}$F [$10^6$] |
| High | $2.78 \pm 0.42$ | $2.05 \pm 0.35$ | $5.92 \pm 1.06$ |
| Low | $2.04 \pm 0.29$ | $1.44 \pm 0.23$ | $3.26 \pm 0.59$ |

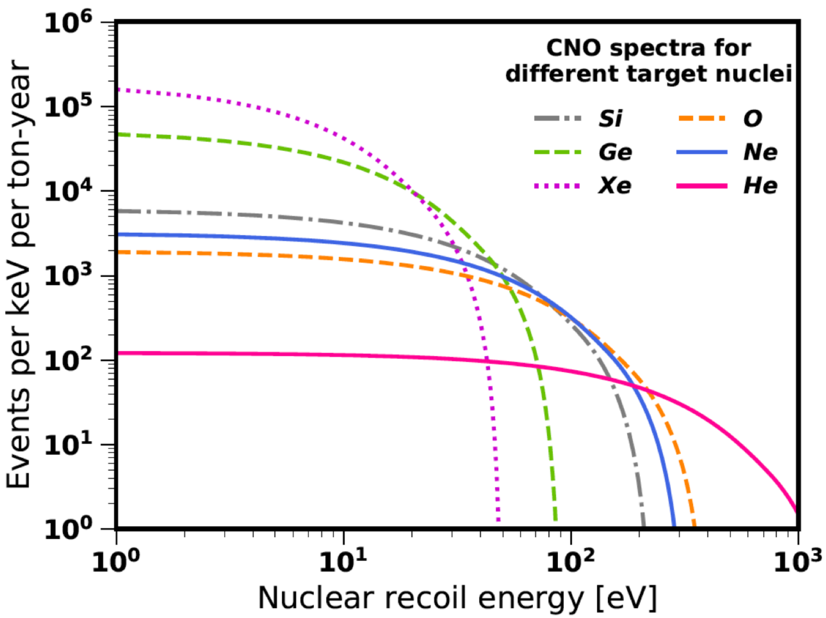
Predictions for CNO flux depend on solar models and are very sensitive to the Sun's metallicity (all elements heavier than $^4$He)

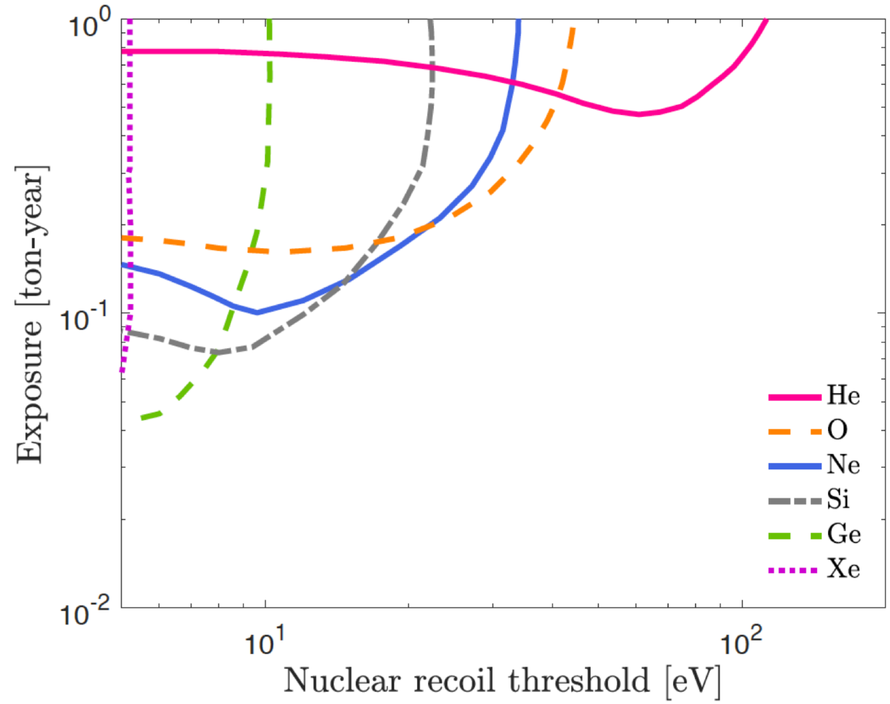
Recently proposed low-metallicity models are in disagreement with helioseismology data

# Direct DM detectors might observe CNO neutrinos

Extremely low energies are needed (below 100 eV – not within the reach of all technologies)

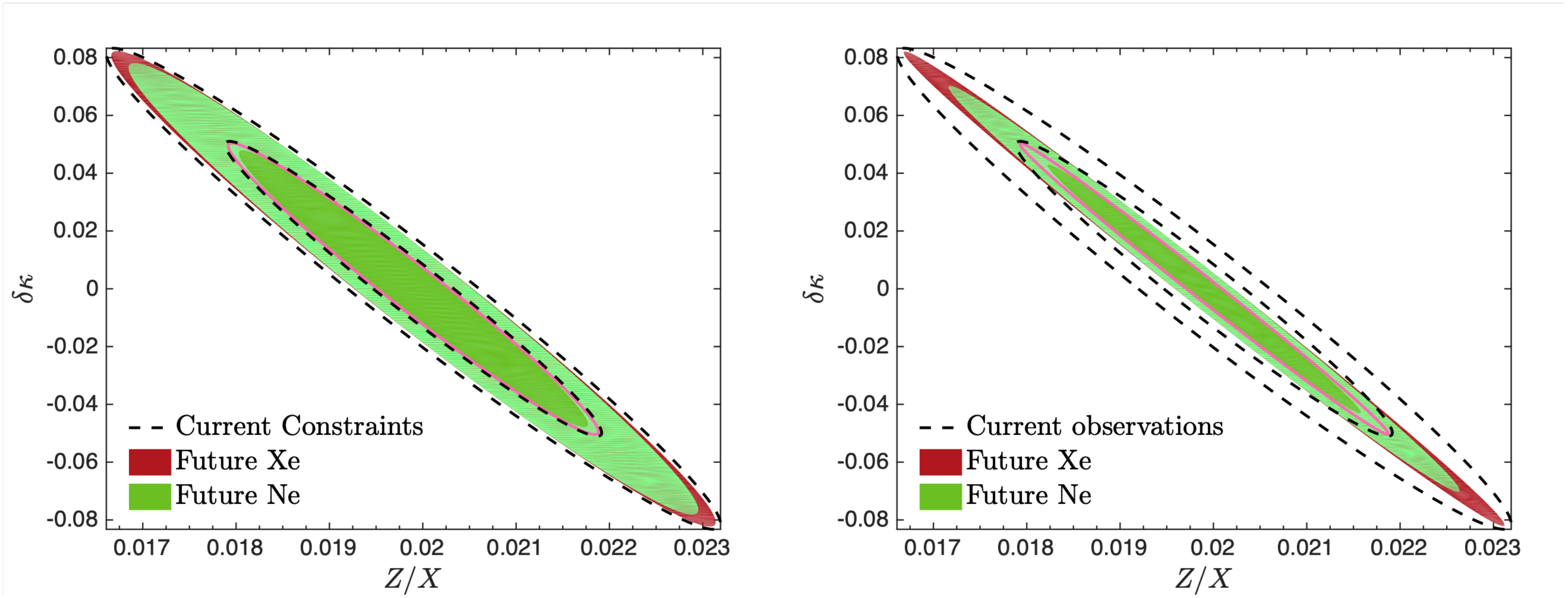
Cerdeño, Davis, Fairbairn, Vincent 2017




- LXe (and LAr) experiments would require an unrealistically low threshold
- Gaseous detectors would need to be really large (> 1 ton-yr)
- Solid state (Ge or Si) might be the best option (realistic threshold and exposure)

# Impact on solar parameters




Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

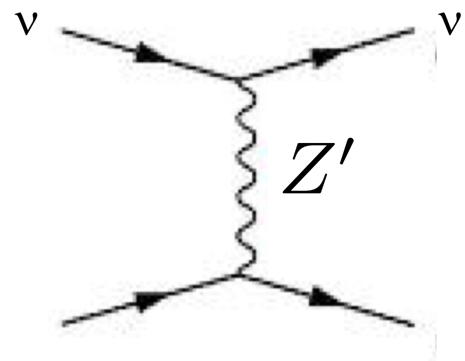
# Raising the neutrino floor

# Raising the neutrino floor

New physics in the neutrino sector can increase (or decrease) the predicted rates for electron and nuclear recoils.

# New Physics in the neutrino sector?

$$\mathcal{L} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{\ell} \gamma^\mu g_{\ell,v} \ell + Z'_\mu \bar{q} \gamma^\mu g_{q,v} q$$




Contributions from new physics to Electron and Nuclear recoils

$$d\sigma / dE_R - d\sigma^{\mathrm{SM}} / dE_R$$

ER:

$$\frac{\sqrt{2} G_F m_e g_v g_{\nu,Z'} g_{e,v}}{\pi\left(2E_R m_e + m_{Z'}^2\right)} + \frac{m_e g_{\nu,Z'}^2 g_{e,v}^2}{2\pi\left(2E_R m_e + m_{Z'}^2\right)^2}$$

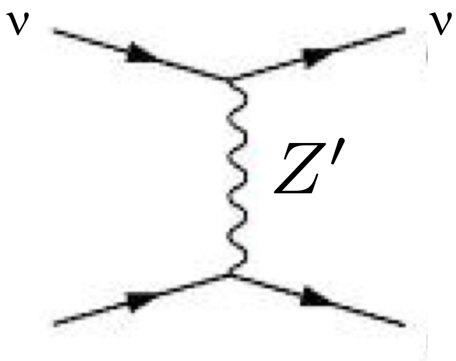
NR:

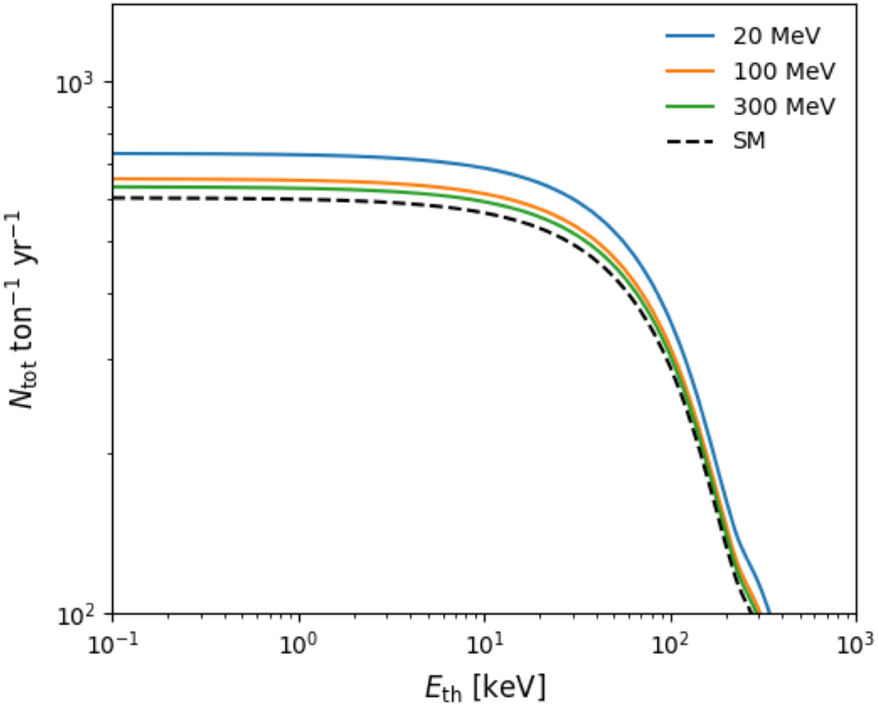
$$-\frac{G_F m_N Q_v Q'_v (2E_\nu^2 - E_R m_N)}{2\sqrt{2}\pi E_\nu^2 \left(2E_R m_N + m_{Z'}^2\right)} + \frac{Q'^2_v m_N (2E_\nu^2 - E_R m_N)}{4\pi E_\nu^2 \left(2E_R m_N + m_{Z'}^2\right)^2}$$

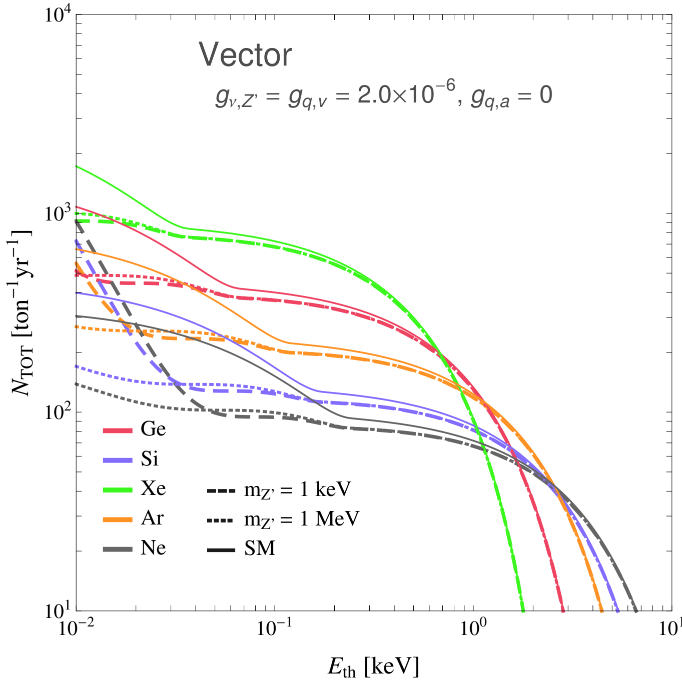
There are interference terms with the SM contribution for NR that can actually **suppress** the SM prediction for CNS.

# New VECTOR mediator

$$\mathcal{L} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{\ell}\gamma^\mu g_{\ell,v}\ell + Z'_\mu \bar{q}\gamma^\mu g_{q,v} q$$



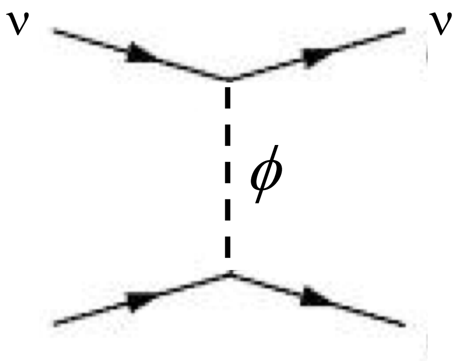



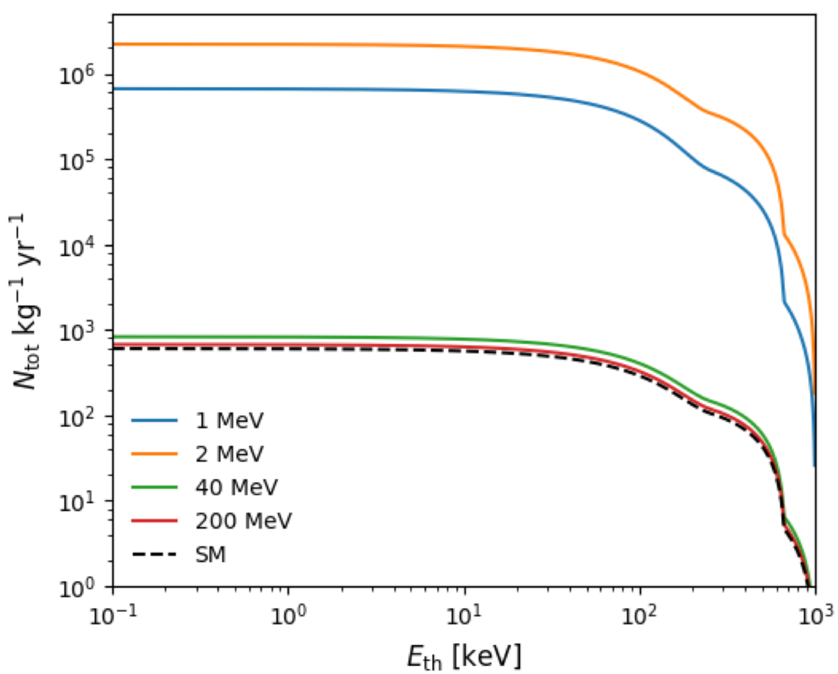



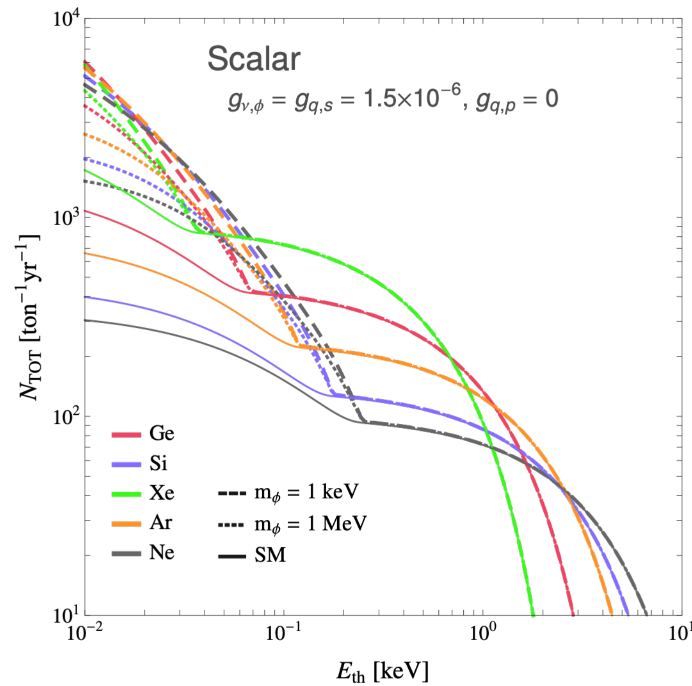

Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

# New SCALAR mediator

$$\mathcal{L} = (g_{\nu,\phi}\,\phi\bar{\nu}_R\nu_L + h.c.) + \phi\bar{\ell}g_{\ell,s}\ell + \phi\bar{q}g_{q,s}q$$




Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

- **Nuclear recoils**:

  - Mostly sensitive to $^{8}B$ neutrinos

  - The (low) threshold is crucial to increase the observed rate

  - Rate scales as $A^2$ (potentially benefiting heavy targets)

- **Electron recoils**:

  - Sensitive to pp neutrinos

  - Threshold unimportant – good background discrimination needed (directionality)

  - Scales as Z

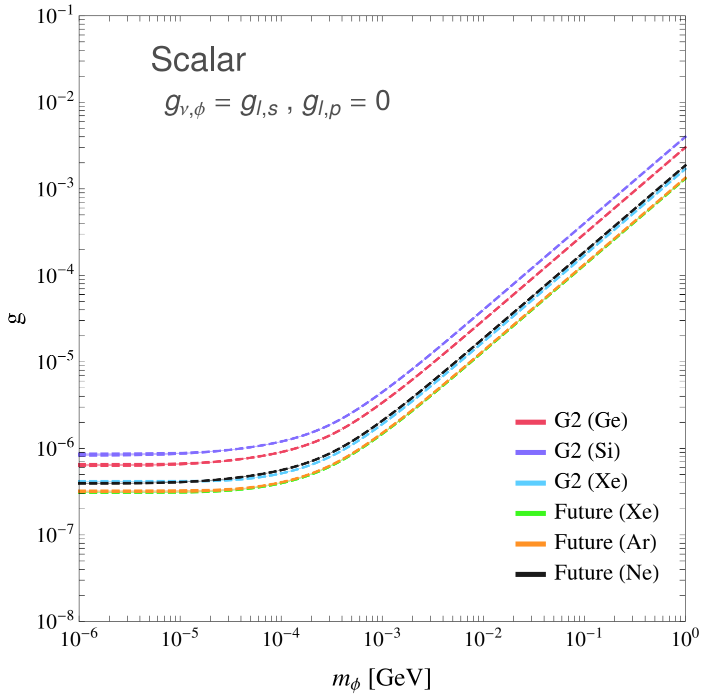
- The **morphology** of the signal depends on the nature of the mediator

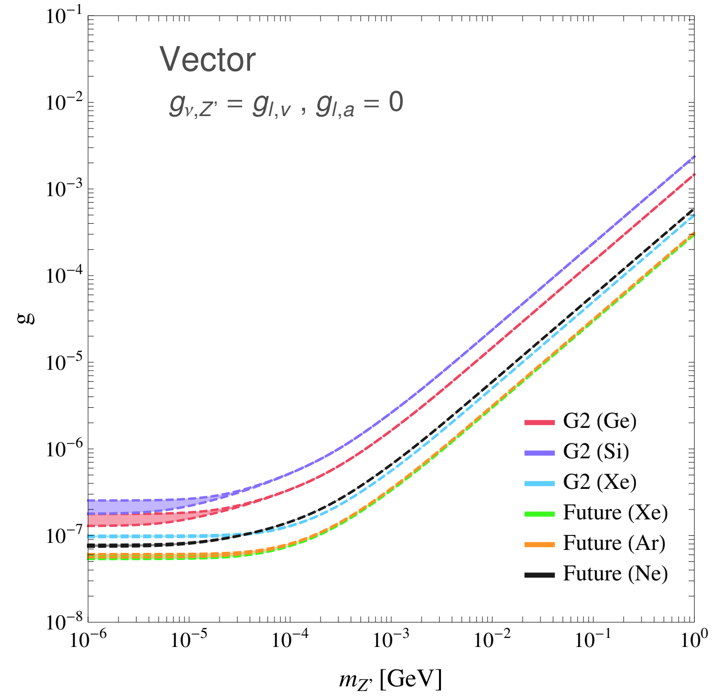
  - Features normally appear at low energies

  - Destructive interference for vector-mediators

# Bounds from electron recoils

- Bounds are mainly sensitive to the total exposure.
- **LUX, XENON, PANDA-X** are good for these searches if they can control their low-energy electron background.

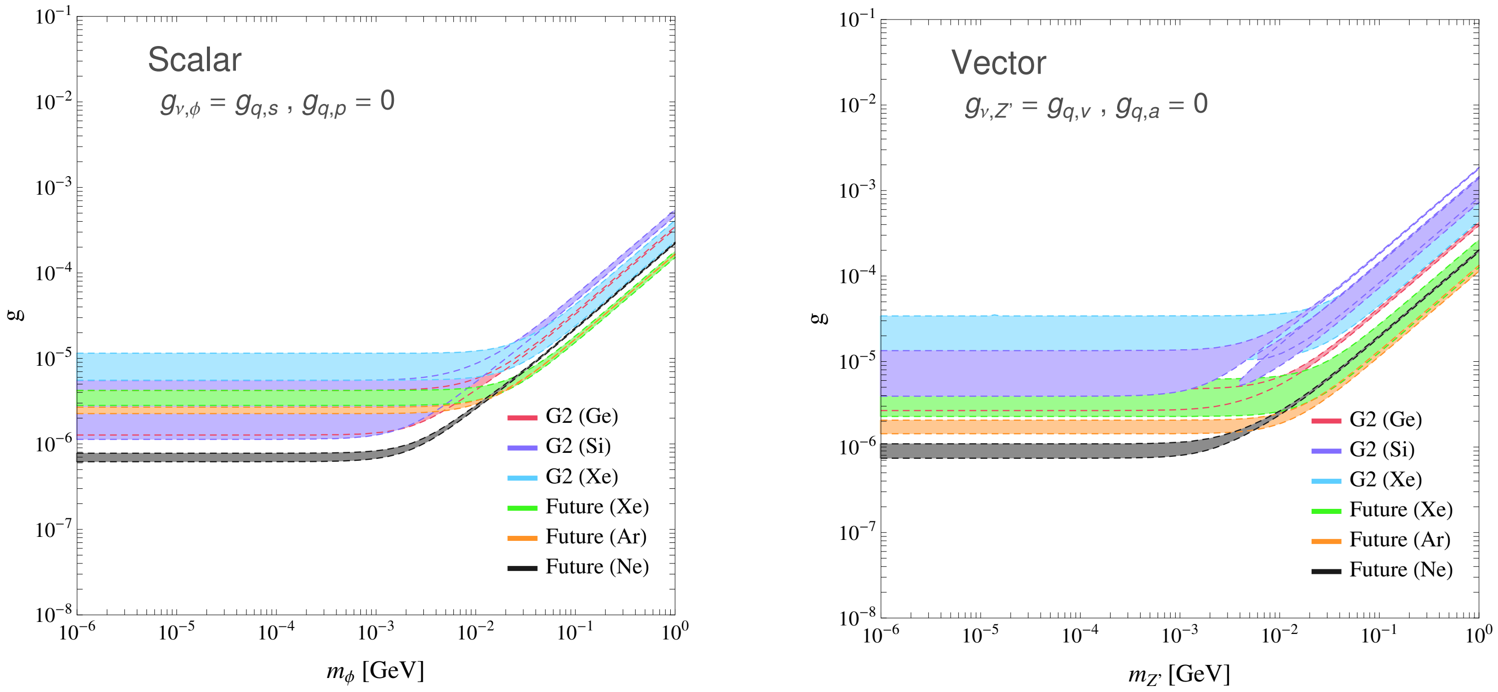


# Bounds from Nuclear Recoils

- The threshold is extremely important
  (notice the better performance of G2(Ge) versus G2(Xe)).

- **SuperCDMS** excels at these searches: using current Soudan data can probe similar areas than future Xe detectors.




Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

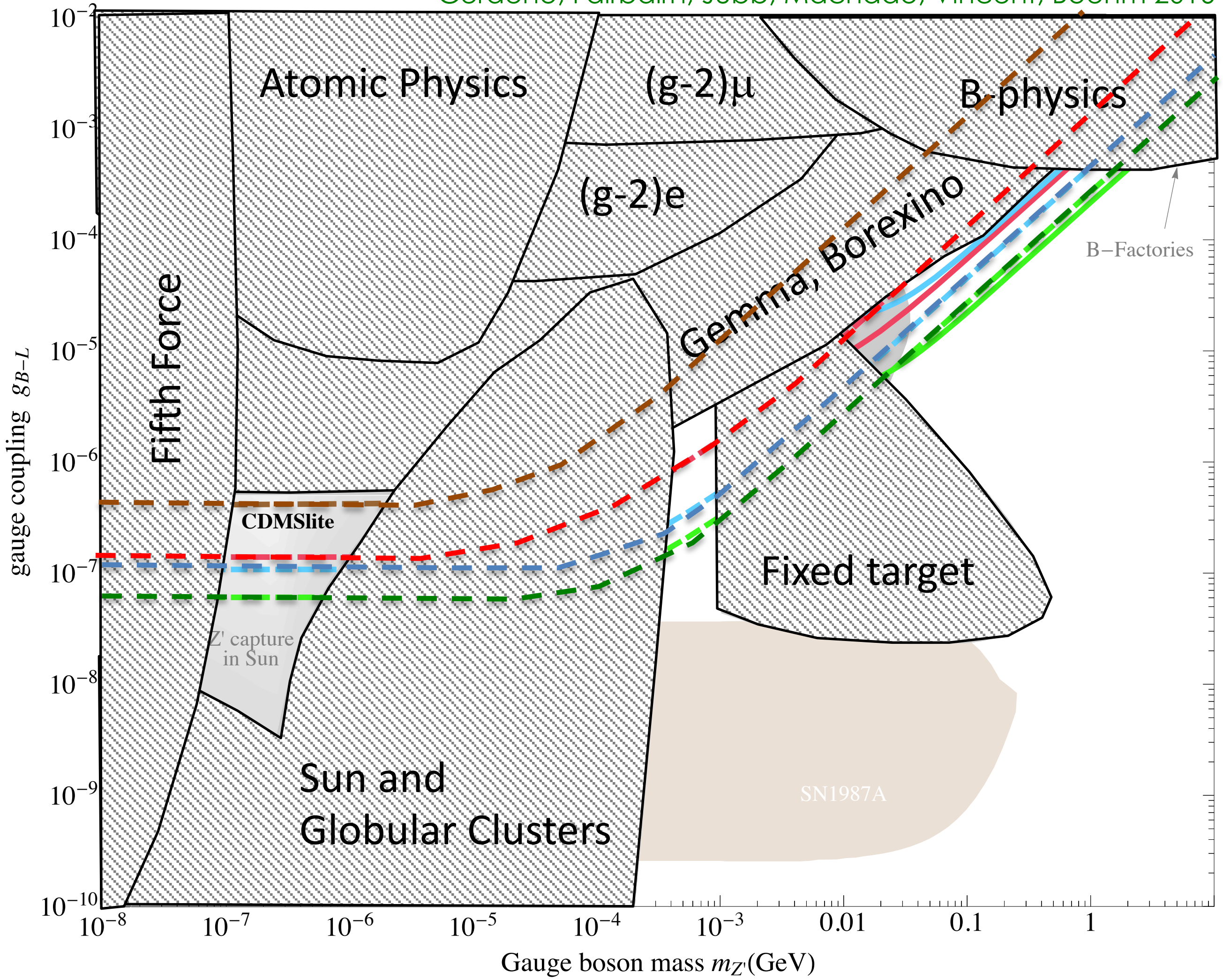
# Example: $U(1)_{B-L}$ model

Bounds from ER

New unexplored regions at large mediator masses

Ge, Xe, Ne

Cerdeño, Fairbairn, Jubb, Machado, Vincent, Boehm 2016

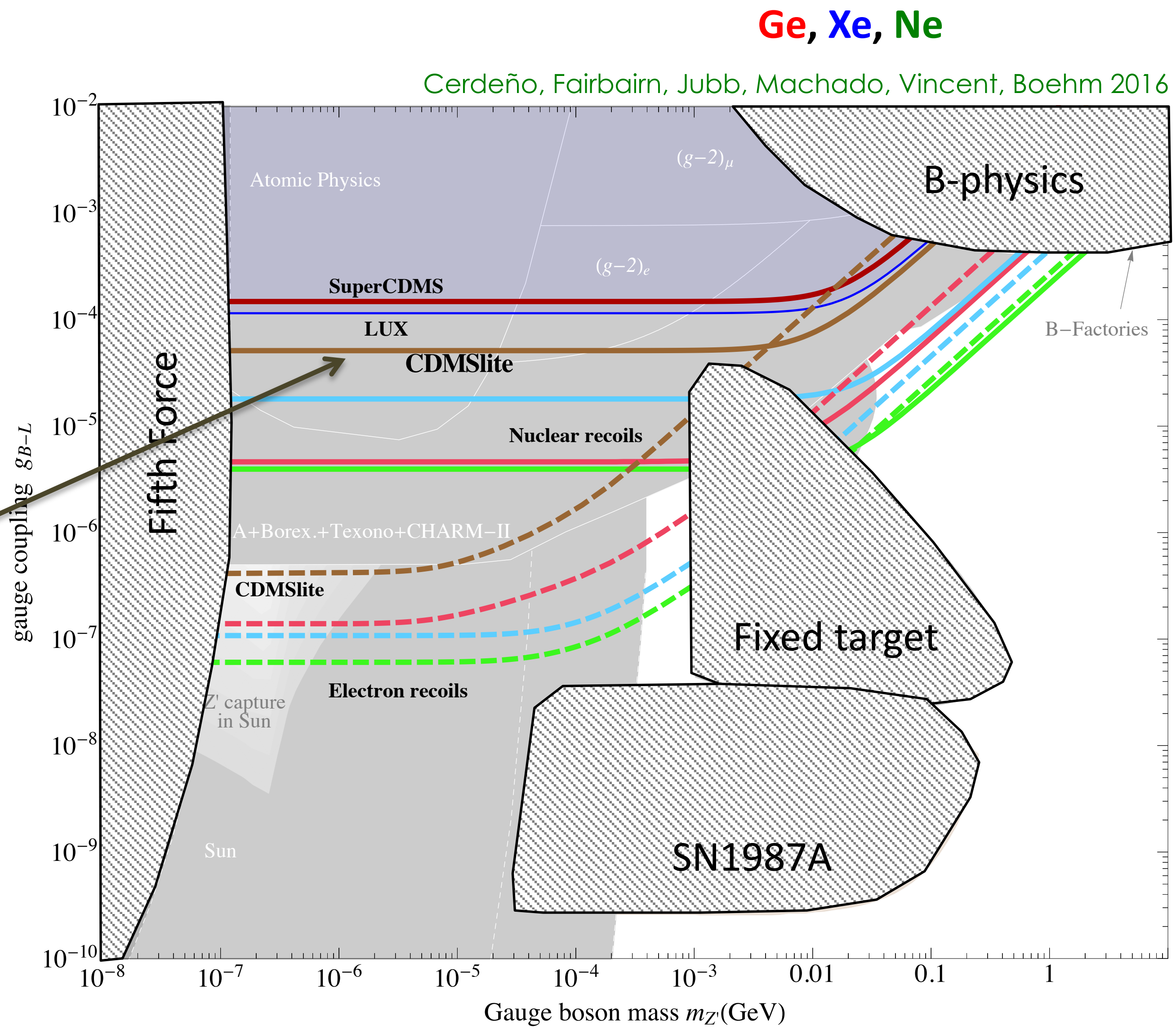


# Example: U(1)$_{B-L}$ model

Bounds from NR

Current bounds probe a new region (only tested previously by electron scattering)

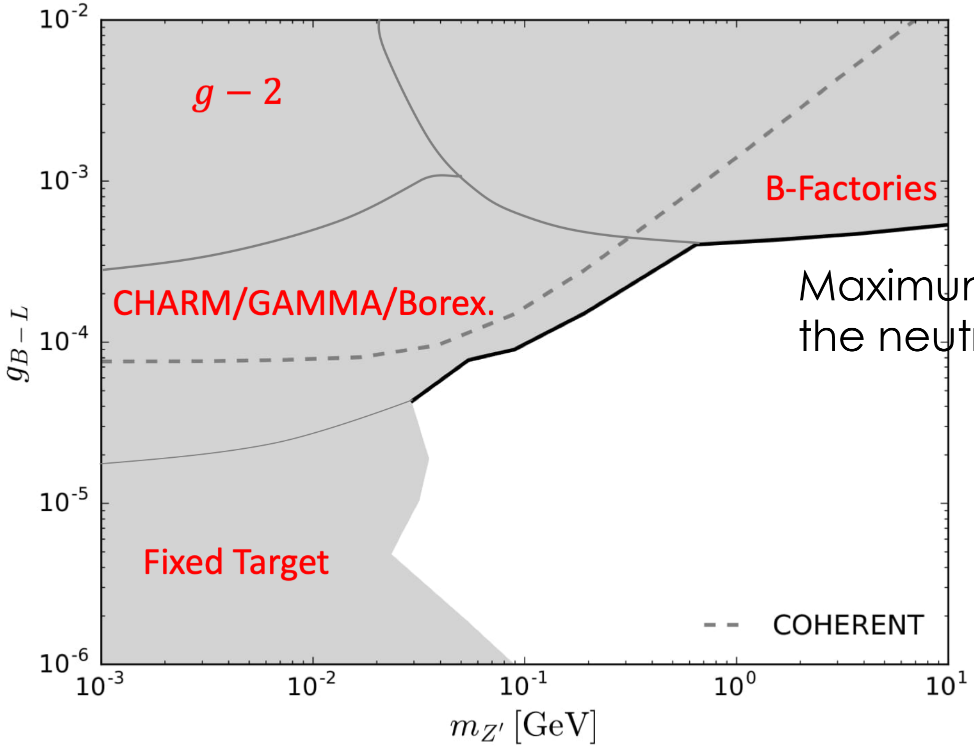
SuperCDMS at the same level as current LUX. CDMSLite is better.



# How high is the neutrino floor?

If we allow for new physics in the neutrino sector, the neutrino floor is actually ABOVE the SM one.

Vector-mediated models




Maximum contribution to the neutrino floor

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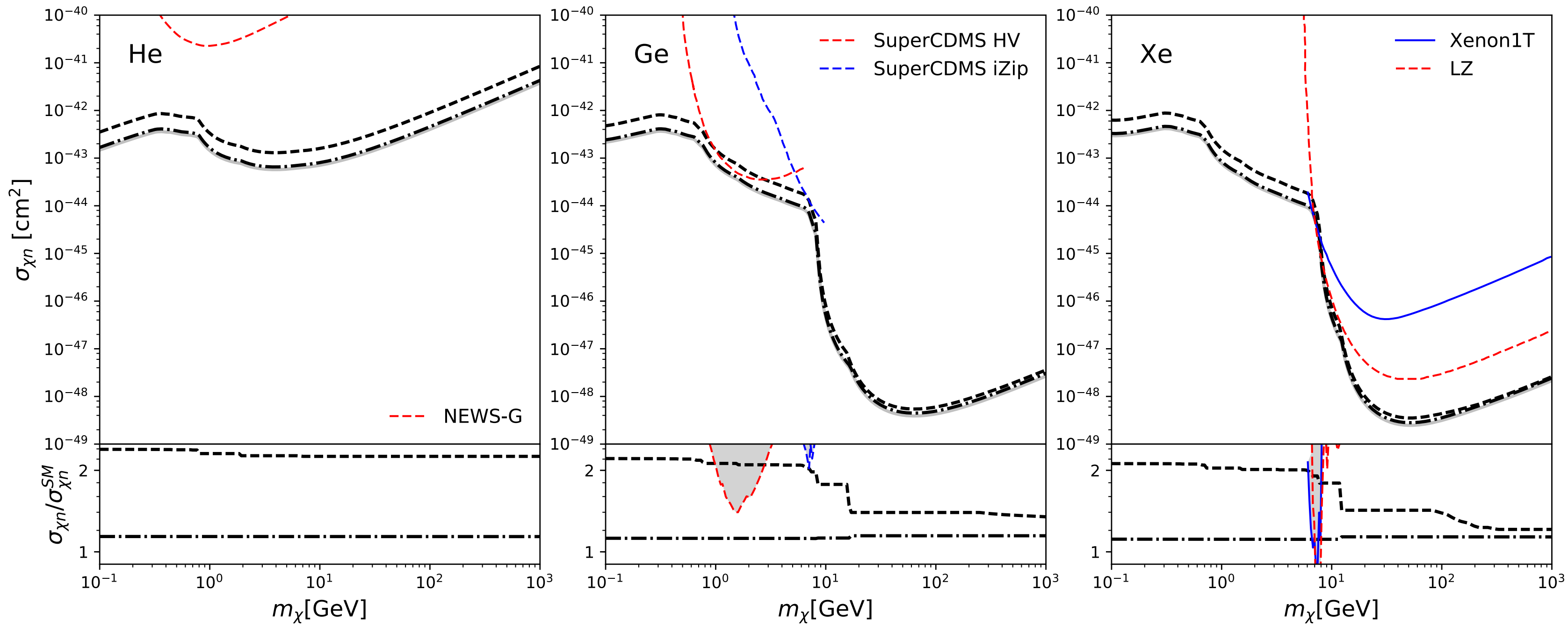
Vector-mediated models

Boehm, Cerdeño, Machado, Olivares, Reid 2018



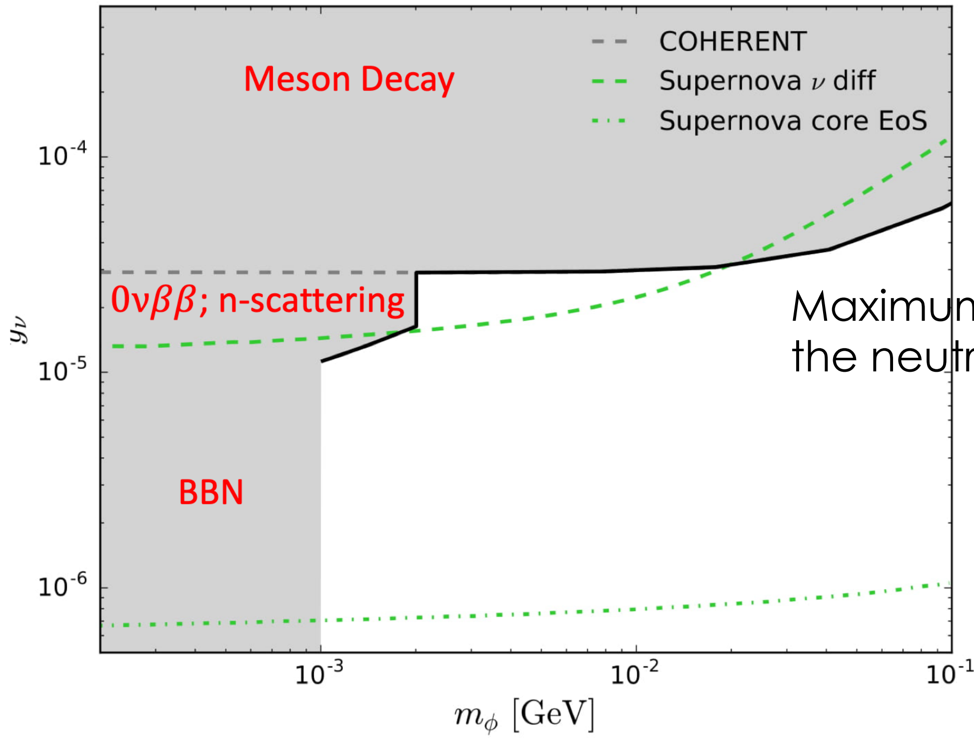

The neutrino floor can be approximately 2 times higher than in the SM

# How high is the neutrino floor?

If we allow for new physics in the neutrino sector, the neutrino floor is actually ABOVE the SM one.

Scalar-mediated models

$$\mathcal{L} = -y_\nu \bar{\nu}_L^c \phi \nu_L - \sum_{f\neq\nu} y_f \bar{f}\phi f - \sum_{f\neq\nu} y_f^5 \bar{f}\phi i\gamma_5 f + \text{h.c.} \ ,$$

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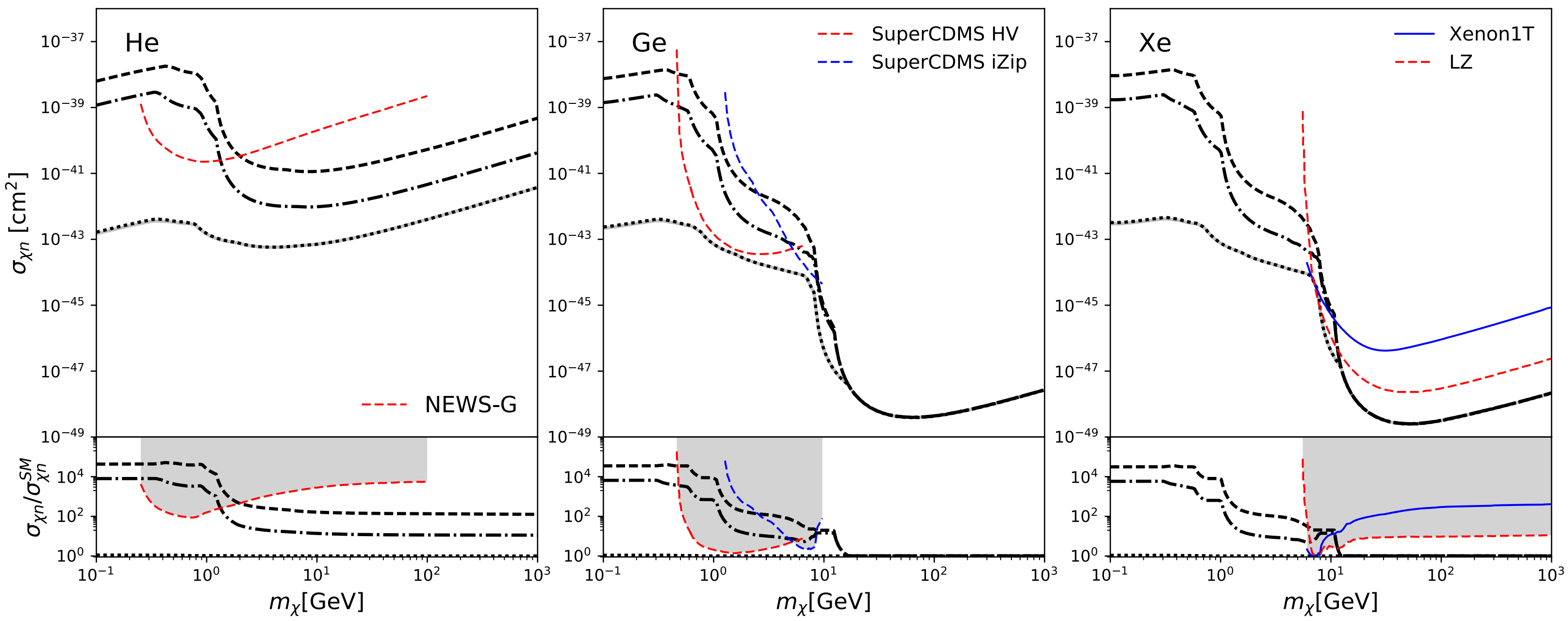


The neutrino floor can be orders of magnitude higher than in the SM

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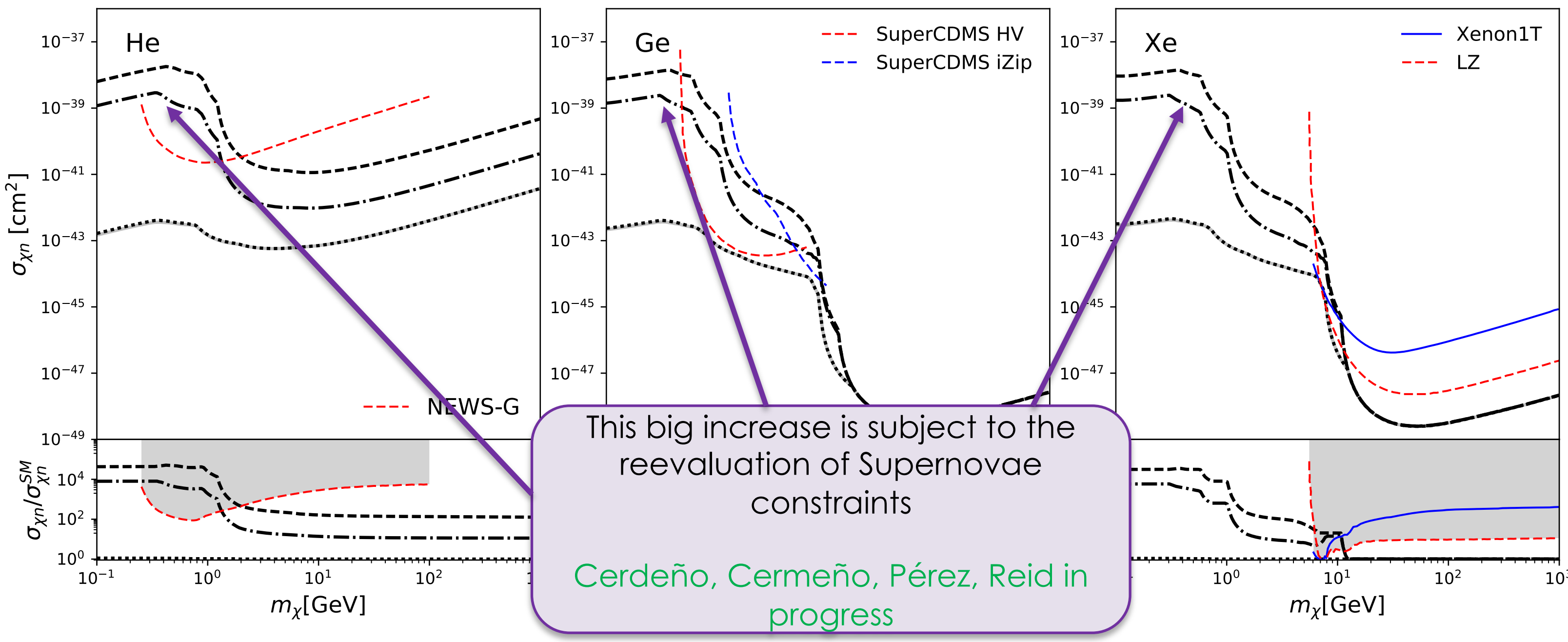
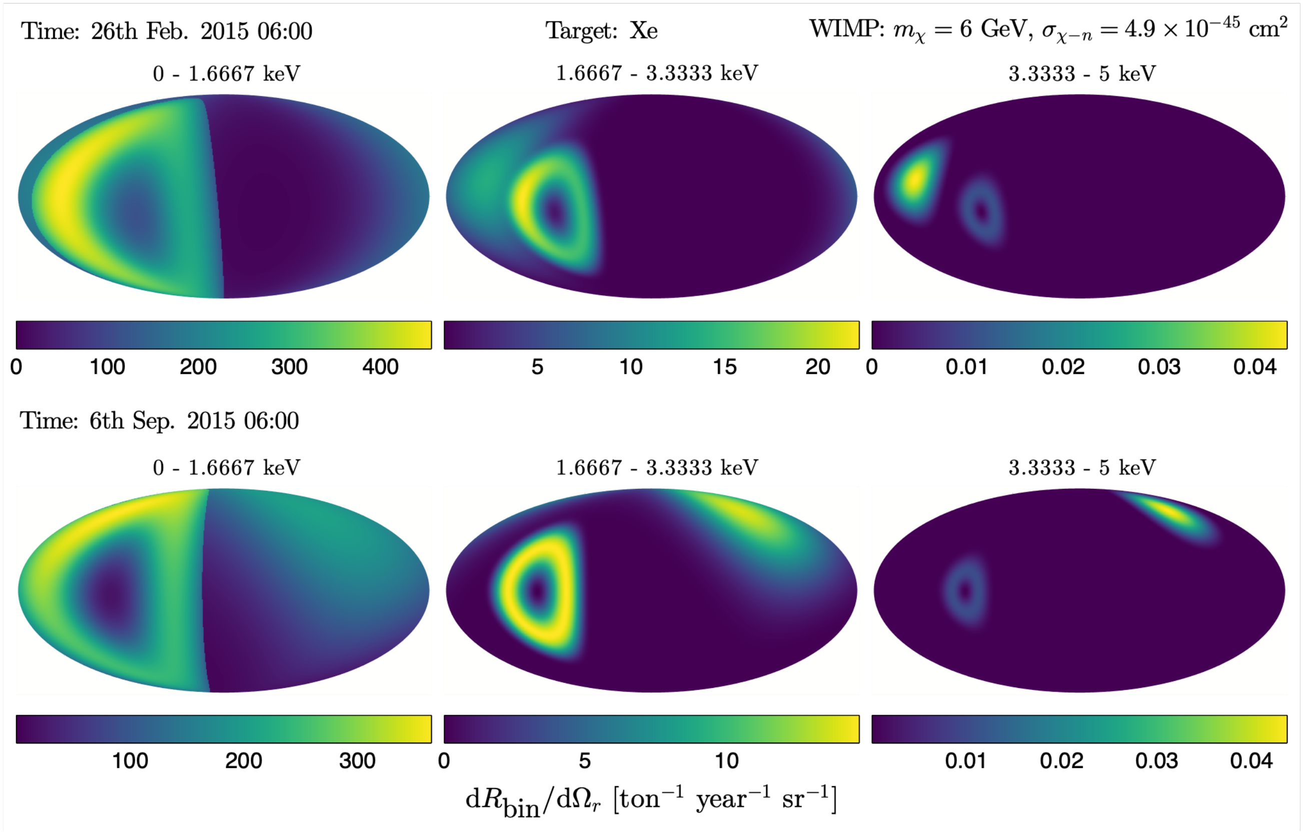



The neutrino floor can be orders of magnitude higher than in the SM

# Back to directional detection

Directional detection is an ideal way to disentangle both sources of background (since neutrinos come from the Sun and DM from Cygnus)




O'Hare 1602.03781

# Back to directional detection

Directional detection is an ideal way to disentangle both sources of background (since neutrinos come from the Sun and DM from Cygnus)

- Our results suggest that this discrimination is necessary **above the SM floor!** (i.e., in the next generation of experiments)

- Test new physics (**light mediators**) in the neutrino sector

- Simultaneous detection of electron recoils and nuclear recoils could be used to infer the nature of the mediator (scalar – pseudoscalar – vector)

Wishlist

- Low threshold and light target

- Directionality for electron recoils

- Good energy resolution at keV scale

# Conclusions

Direct detection experiments are going to be sensitive to coherent neutrino-nucleus scattering in the coming future

This can allow us to study solar properties. Observing **CNO** neutrinos is very challenging (and might favour solid state detectors)

The neutrino floor might not be where you think it is, and that is interesting

Be sensitive to **new physics in the neutrino sector** – light scalar or vector mediators

This might mean that the neutrino floor is **orders of magnitude larger** than the SM prediction (very interesting for gaseous targets)