Solar neutrino physics at direct detection experiments

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Supervised by David Cerdeño

Based on:

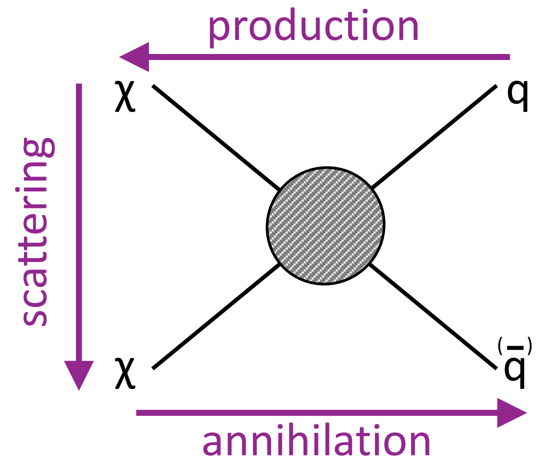
Boehm, Cerdeño, Machado, Olivares-Del Campo, Perdomo, and Reid; *JCAP* 01 (2019) 043 (1809.06385);

Amaral, Cerdeño, Foldenauer, and Reid; *JHEP* 12 (2020) 155 (2006.11225);

and ongoing works with the SuperCDMS collaboration and with M. Cermeño and M.Á. Pérez Garcia

What is a direct detection experiment?

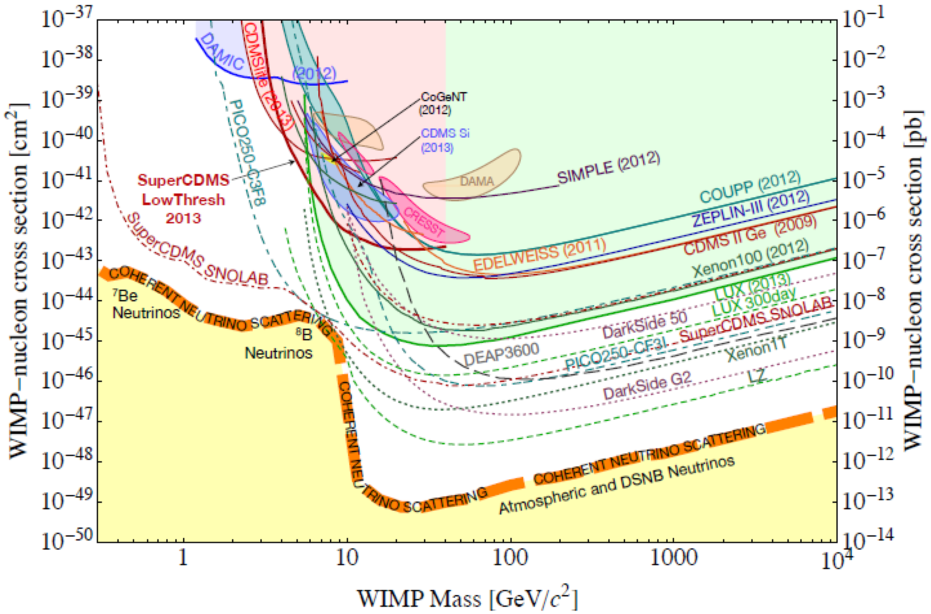
- Aim to detect the scattering of DM (WIMPs) with atoms (nuclei)
- Everything else is background
- Multiple signals are measured to aid background reduction



- The coherent neutrino scattering background cannot be reduced by normal means

What is a direct detection experiment?

- As sensitivity increases, we become sensitive to an “irreducible” neutrino background
- Further WIMP discovery is limited by CEvNS
- The neutrino floor is a useful tool for visualising this limit
- It represents some interesting physics



Coherent elastic neutrino-nucleus scattering (CEvNS)

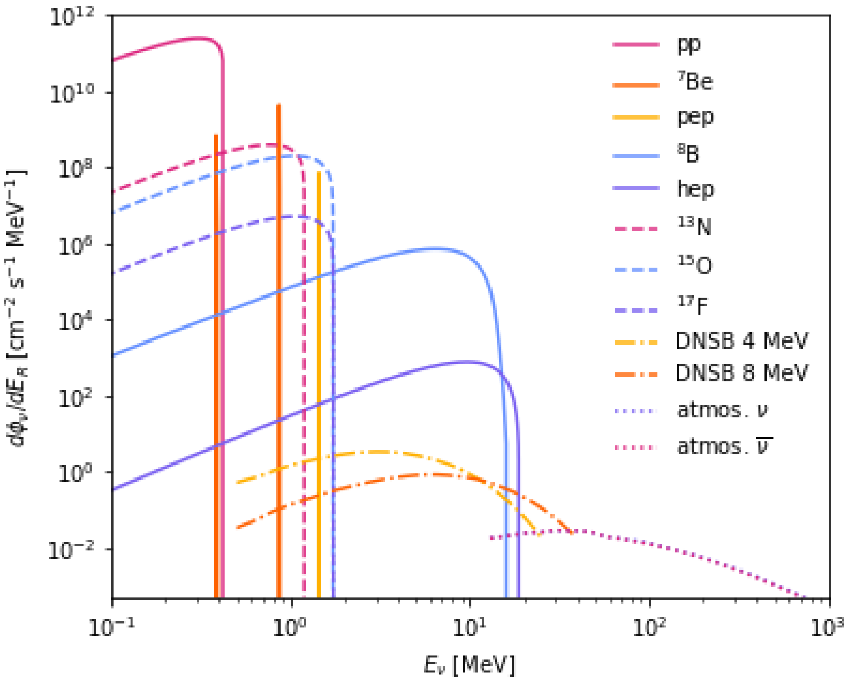
Detector physics

Nuclear/particle physics

$$N^k_{CE\nu NS} = \frac{\epsilon}{m_N}\int_{E_k}^{E_{k+1}} dE_R\, \varepsilon(E_R)\int_{E_\nu^{\min}} dE_\nu \frac{d\phi}{dE_\nu}\frac{d\sigma_{\nu N}}{dE_R}$$

Solar/neutrino physics

- Solar neutrinos dominate at low energies
- For CNS, Boron-8 neutrinos are important
- Atmospheric neutrinos reach higher energies, but with much lower flux



Coherent elastic neutrino-nucleus scattering (CEvNS)

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

$$Q_w = N - (1 - 4\sin^2\theta_w)Z$$

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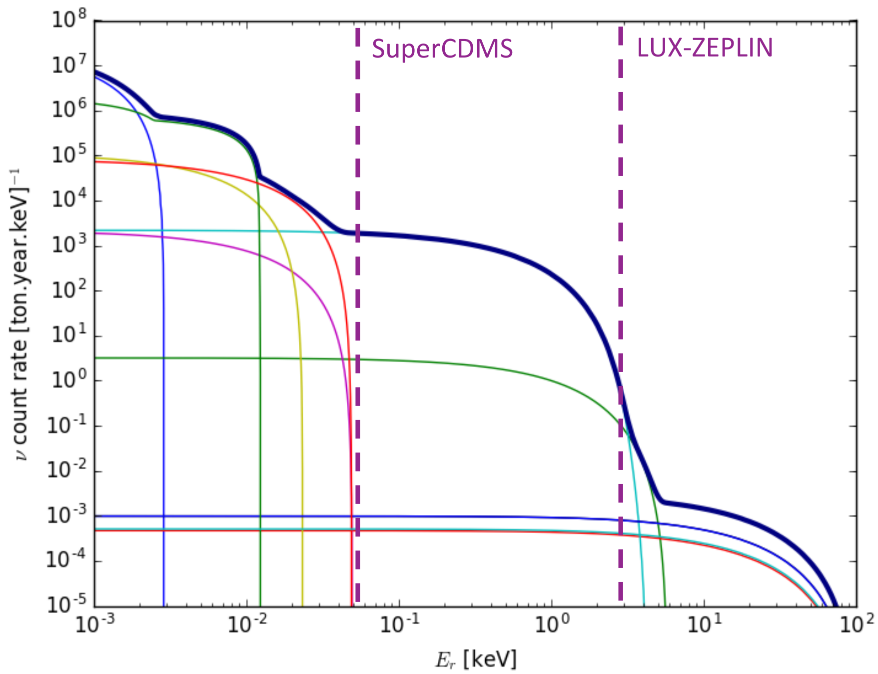
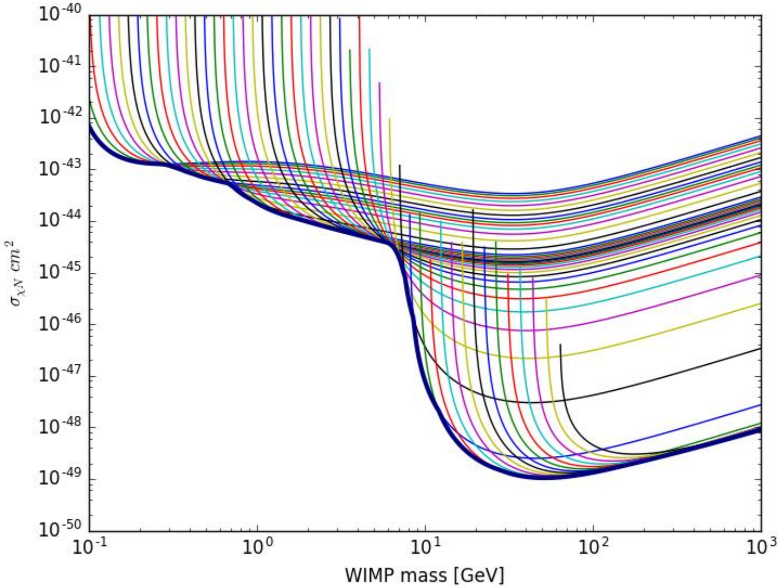


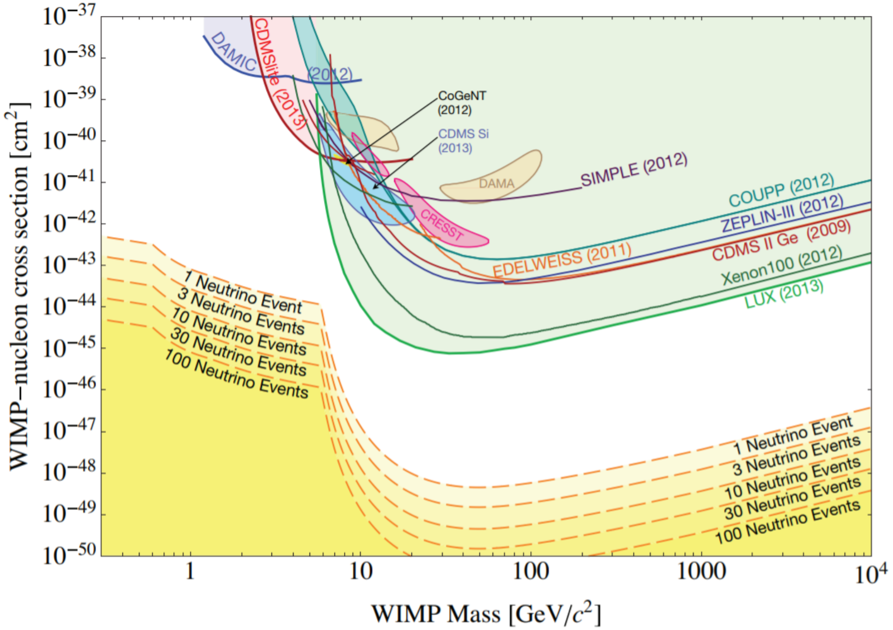
Computing the neutrino floor

- Choose a threshold energy for the experiment and integrate the count rate above it
- Set the exposure to give 1 neutrino count
- Now calculate the WIMP cross section that would give 1 DM count
- Along this contour, we expect equal numbers of DM and CEvNS events



Computing the neutrino floor

- This isovalue contour can be scaled to any ratio of neutrino to DM events
- Uncertainties on the neutrino flux eventually limit our reach
- The neutrino floor is a way of visualising this discovery limit
- But there are subtleties



arXiv:1307.5458

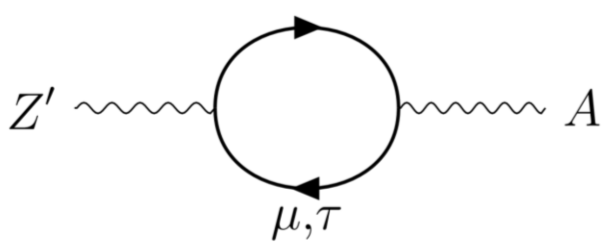
A neutrino floor for new physics?

- The WIMP discovery limit is really a SM object
- In the presence of new mediators, the CEvNS rate could increase
- What would this mean for DD experiments?
- Is there a way to visualise it, similar to the neutrino floor?

Vector Mediator: The gauged $U(1)_{L_\mu - L_\tau}$ model

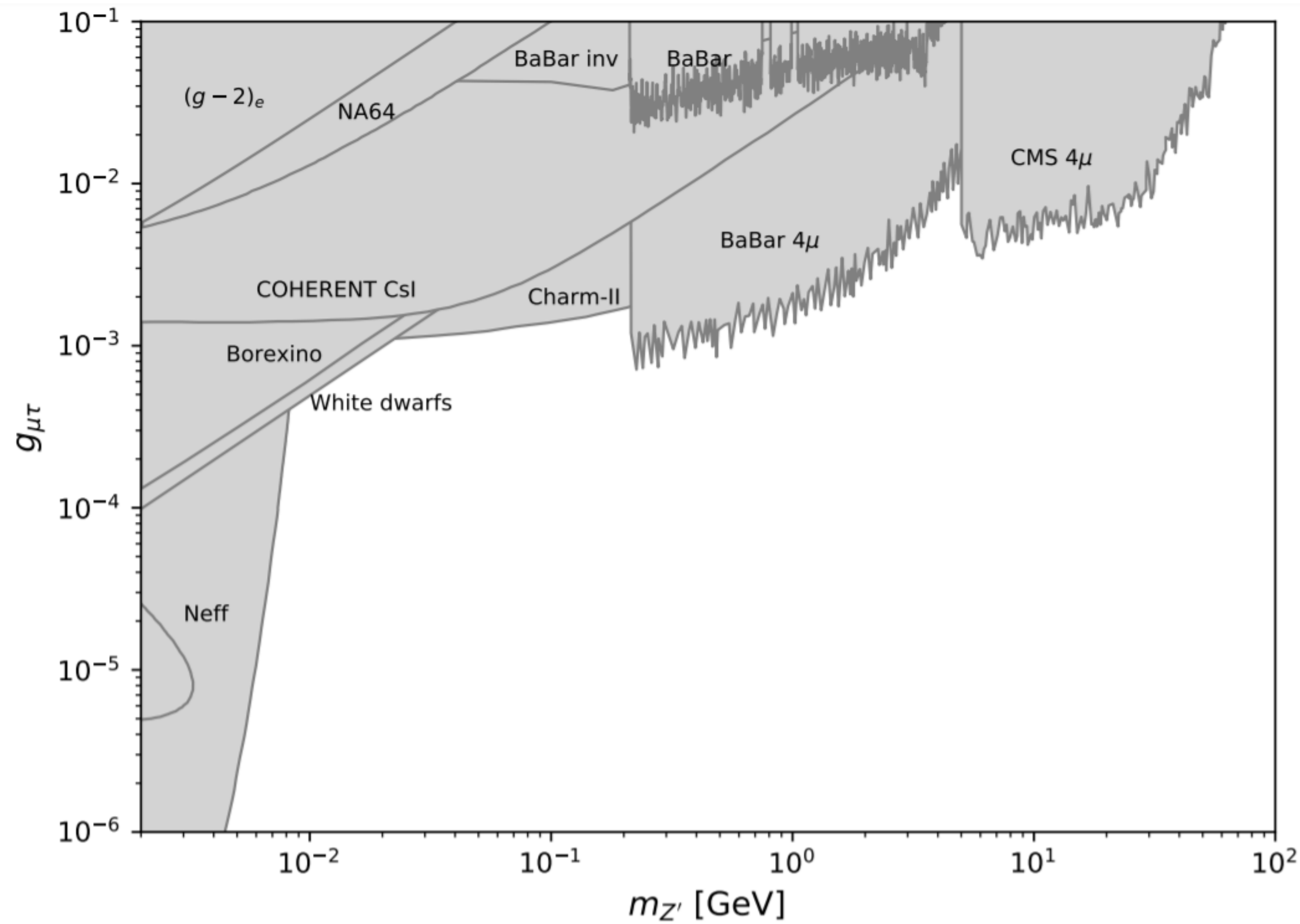
$$\mathcal{L} = -g'_v Q'_\nu \bar{\nu}_L Z' \gamma^\mu \nu_L - g'_v Q'_q \bar{q} Z' \gamma^\mu q - g'_v Q'_\ell \bar{\ell} Z' \gamma^\mu \ell$$

- We consider a model which introduces a gauged $U(1)_{L_\mu - L_\tau}$ symmetry
- This leads to a new Z' boson
- Only second generation leptons are charged: $Q'_{\mu,\nu_\mu} = +1$; $Q'_{\tau,\nu_\tau} = -1$
- Couplings to other SM fermions via loop-induced kinetic mixing



$$\approx \frac{e\, g_{\mu\tau}}{6\pi^2} \log\left(\frac{m_\mu}{m_\tau}\right) \sim -\frac{g_{\mu\tau}}{70}$$

Vector Mediator: The gauged $U(1)_{L_\mu - L_\tau}$ model



Vector Mediator: The gauged $U(1)_{L_\mu - L_\tau}$ model

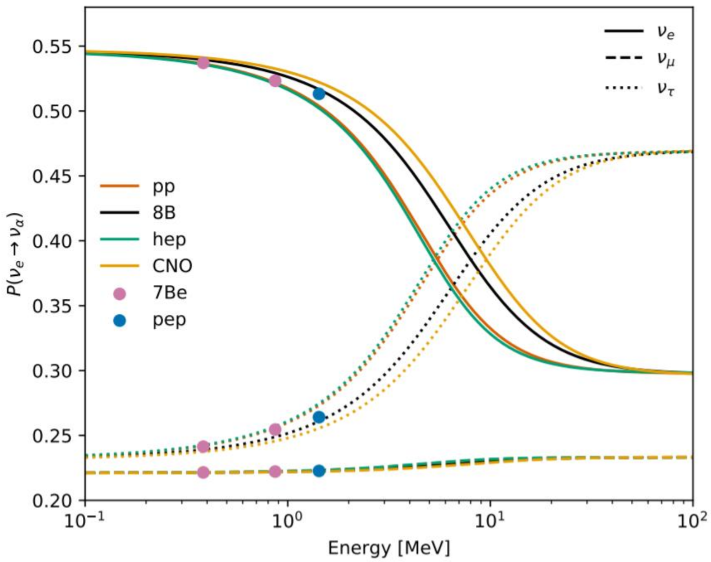
$$\frac{d\sigma^{\rm NP}_{\nu_\alpha A}}{dE_R} = \left(1 - \frac{m_A E_R}{2E_\nu^2}\right) \times \left[\frac{G_F\, e\, \epsilon_{\mu\tau}\, g_{\mu\tau} m_A\, Z\, Q'_{\nu_\alpha}\, Q_{\nu N}}{\sqrt{2}\pi(2m_A E_R + m_{Z'}^2)} + \frac{e^2\, \epsilon_{\mu\tau}^2\, g_{\mu\tau}^2\, m_A\, Z^2\, Q'^2_{\nu_\alpha}}{2\pi(2m_A E_R + m_{Z'}^2)^2}\right] F^2(E_R)$$

the important thing

- The sign of the interference term depends on the neutrino flavour

- ν_μ has destructive interference with the SM

- We need to know the solar neutrino oscillation probabilities ->



Scalar Mediator

- A scalar couples left-handed fields to right-handed fields
- What is the nature of the right-handed neutrino field?

Lepton number conserving (LNC)

$$\mathcal{L}_{\text{LNC}} \supset (y_\nu)_{\alpha\beta}\phi\overline{\nu}_{\alpha,R}\nu_{\beta,L}$$

- Requires a right-handed neutrino
- This ν_R appears in our final state, so its mass is important
- We assume a very light ν_R

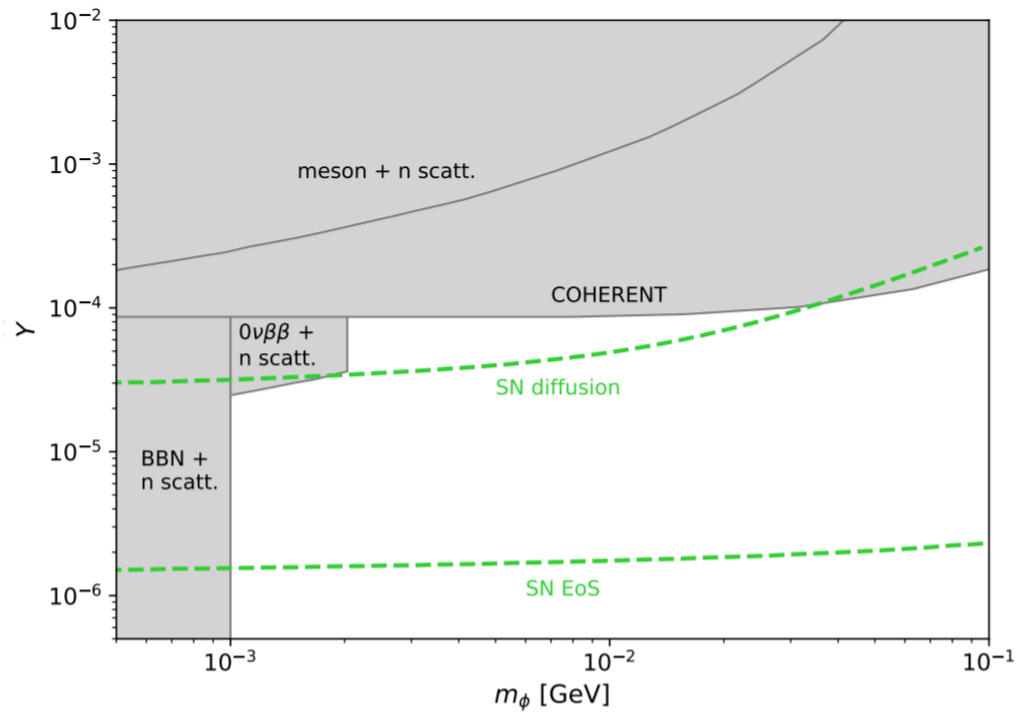
Lepton number violating (LNV)

$$\mathcal{L}_{\text{LNV}} \supset \frac{(y_\nu)_{\alpha\beta}}{2}\phi\overline{\nu}^c_{\alpha,L}\nu_{\beta,L}$$

- Requires Majorana neutrinos
- Converts neutrinos to antineutrinos
- Constraints from $0\nu\beta\beta$ searches

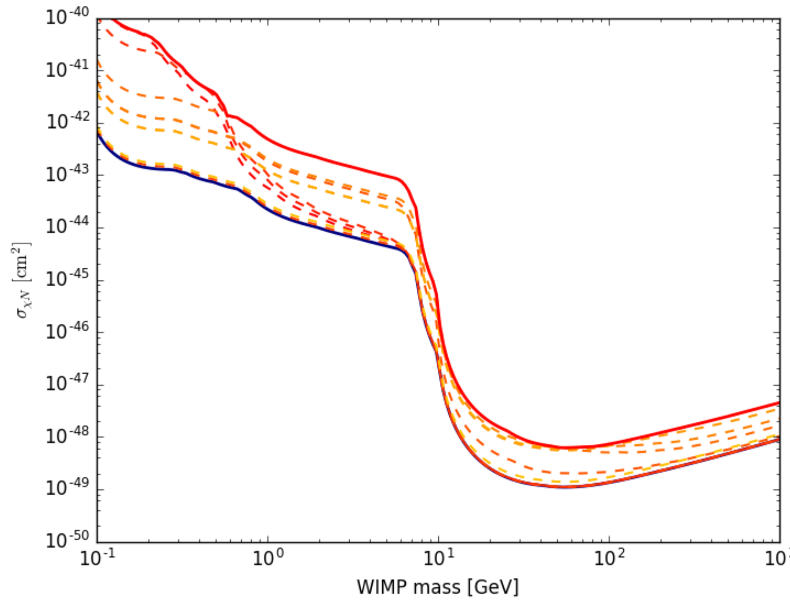
Lepton number violating scalar

- Unlike the vector model, SM particles don't have fixed couplings to φ
- We only consider limits on the combined coupling $Y = \sqrt{y_\nu Y_N}$



New physics at DD experiments

- The neutrino floor is a limit beyond which DM searches become very challenging
- However, we will argue that signals of new neutrino physics can present a challenge to DD experiments much sooner
- We can recompute our isovalue contours in the presence of new physics
- What is the maximum level of the isovalue contour allowed by current constraints?

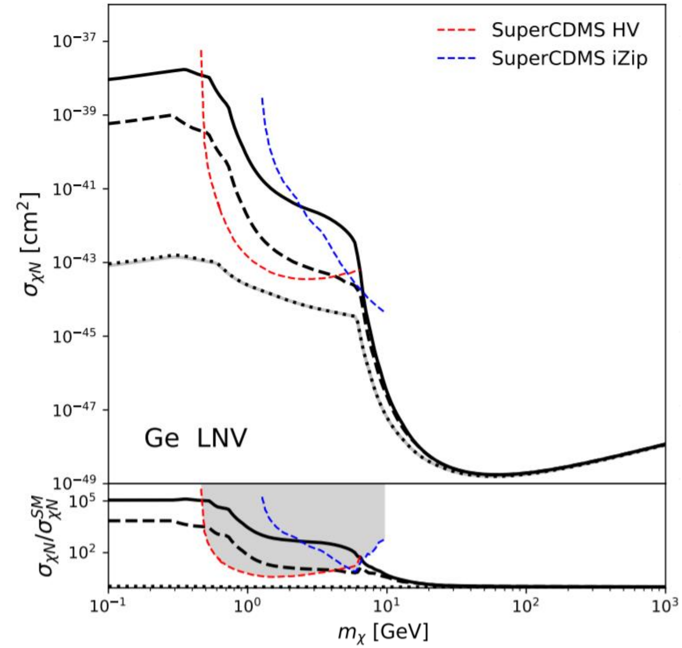


The neutrino ceiling…?

- The neutrino "ceiling" is the maximum value of the 1:1 DM/CEvNS isovalue contour

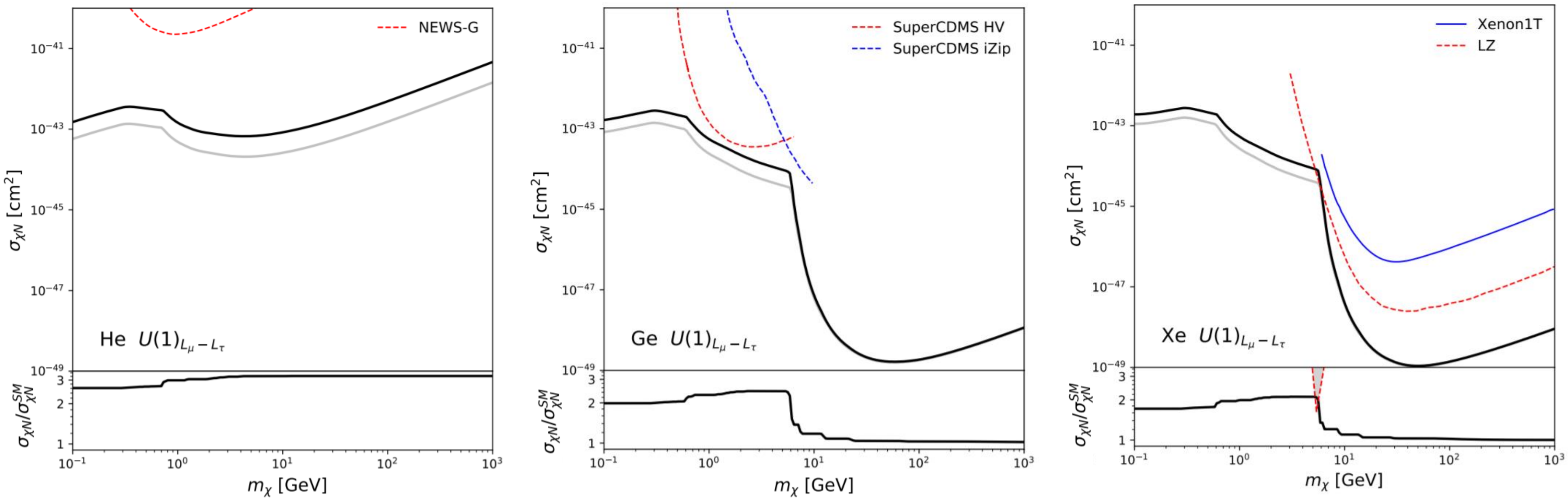
- An apparent signal of DM below the neutrino ceiling could be caused by coherent neutrino scattering

- But a DD experiment that is sensitive to DM below the neutrino ceiling, is likely to be sensitive to new neutrino physics



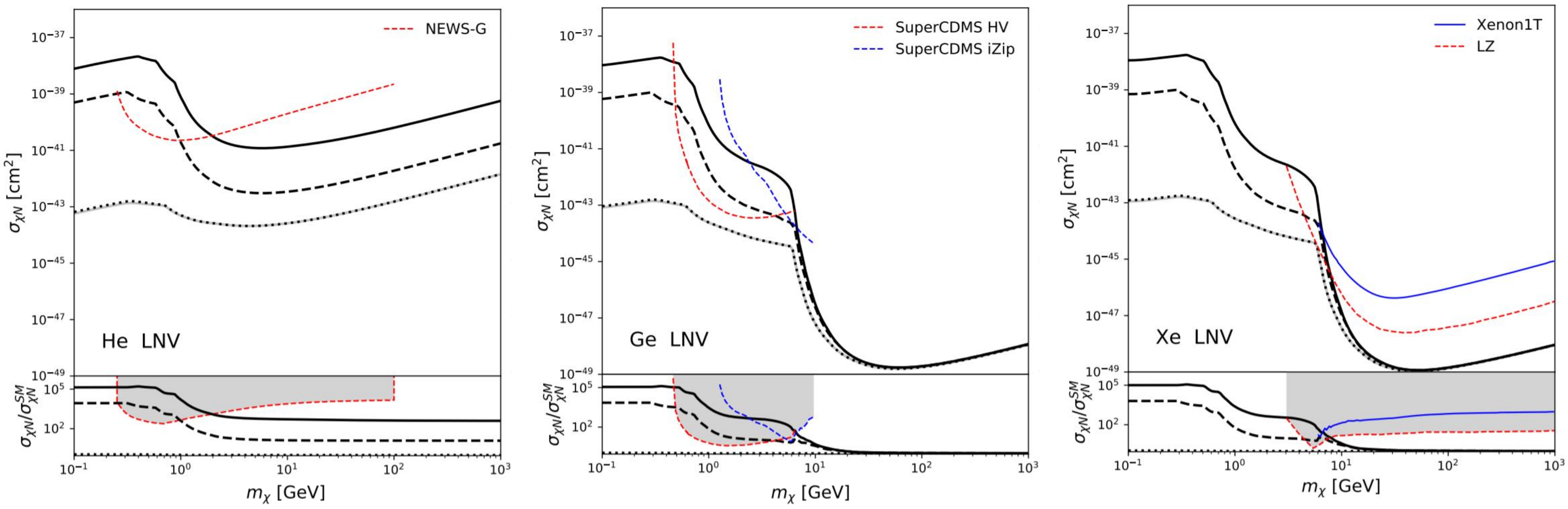
The neutrino ceiling: $L_\mu - L_\tau$

- The $L_\mu - L_\tau$ model can lead to a > factor 2 increase in the CEvNS rate
- The neutrino ceiling (and floor) is specific to each target nucleus
- Of our future DD experiments, only LZ has sensitivity below the ceiling



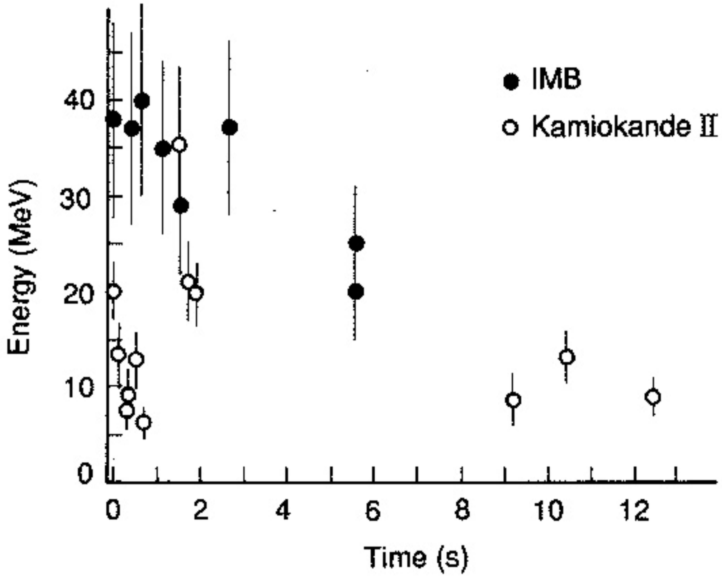
The neutrino ceiling: LNV scalar

- When supernova constraints are relaxed we can get a large increase
- Future DD experiments could put competitive constraints on new physics
- SN constraints are important!



Supernova constraints on an LNV scalar

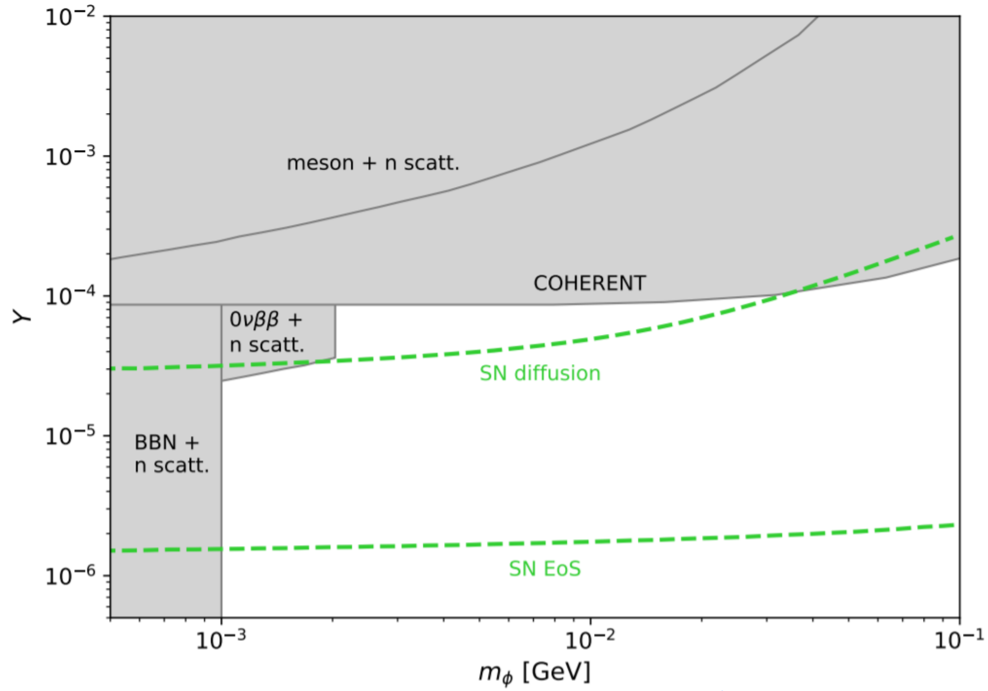
- Neutrinos play a crucial role in supernova dynamics
- We only have one observation of SN neutrinos, from SN1987A
- We can constrain new physics that changes the neutrino diffusion time
- Or that prevents supernovae from exploding properly



arXiv:1109.5368

Supernova constraints on an LNV scalar

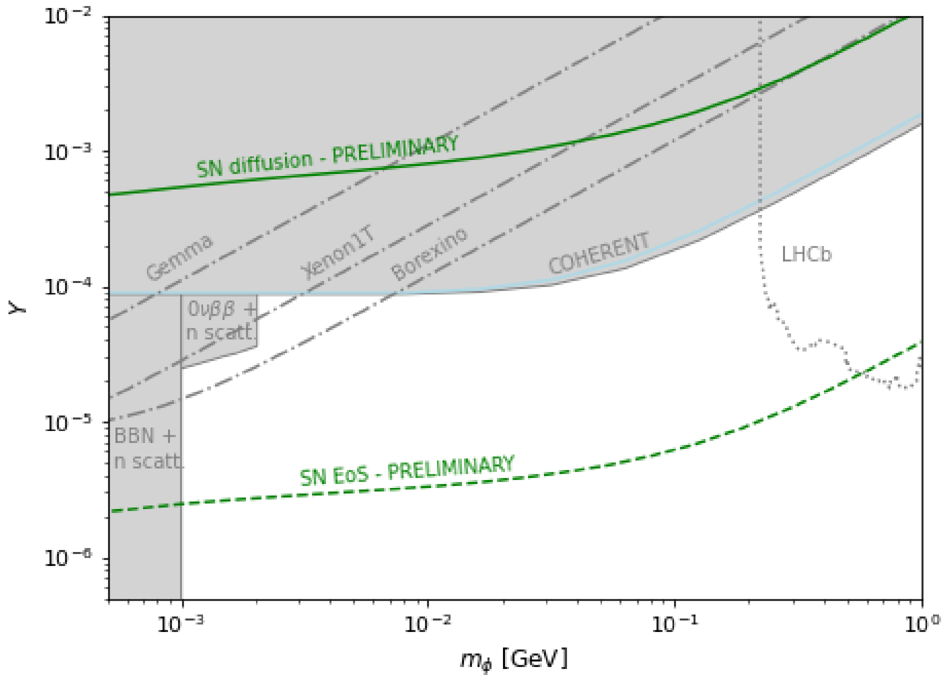
- The earlier constraints we found were computed imprecisely
- The "SN diffusion" line is defined where $\sigma^{\mathrm{NP}} = \sigma^{\mathrm{SM}}$
- The EoS line is where $\nu \leftrightarrow \bar{\nu}$ transitions become significant
- Both make many simplifying assumptions



arXiv:1802.05171

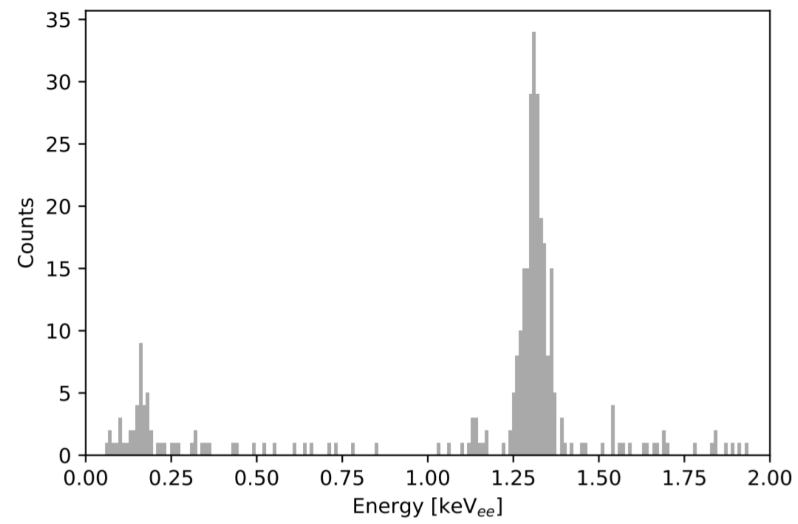
Supernova constraints on an LNV scalar

- The inclusion of matter effects in the cross section significantly lowers the neutrino-scattering cross section
- The EoS line should not be considered a constraint, but represents a significant physical transition



Constraining new physics with CDMSlite

- SuperCDMS uses germanium semiconductor crystals as a target
- Its CDMSlite mode cannot distinguish NR from ER
- This leads to higher backgrounds, but a lower energy threshold



- Can neutrino-electron scattering improve our sensitivity to new physics?

Neutrino-electron scattering

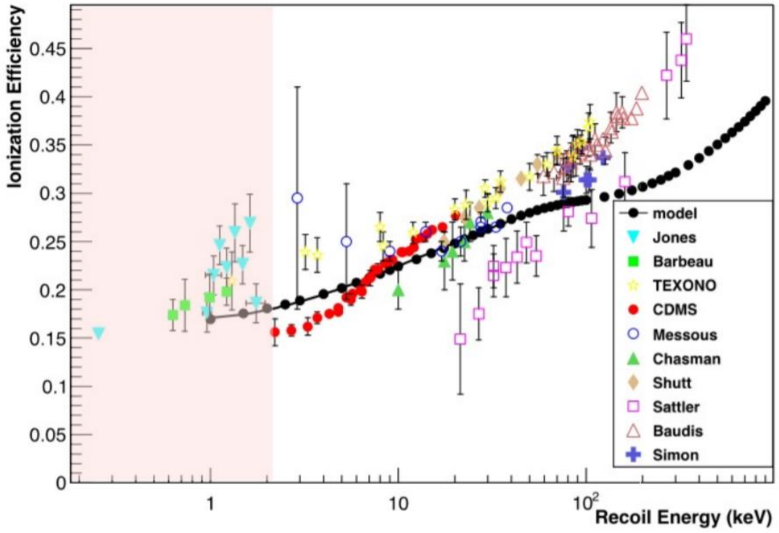
$$\frac{dR_{\nu e}}{dE_{ee}} = \frac{N_e}{m_A} \int_{E_\nu^{\min}} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_{\nu e}}{dE_{ee}}$$

- The inclusion of electron scattering introduces new challenges
- Nuclear and electron recoils of the same energy lead to different signals
- What is N_e, the number of electrons available to scatter per atom?

The Lindhard Model

$$E_{ee} = E_{nr}\left(\frac{1+Y\left(E_{nr}\right)eV_b/\epsilon_\gamma}{1+eV_b/\epsilon_\gamma}\right)$$

$$Y\left(E_{nr}\right) = \frac{k\cdot g(\varepsilon)}{1+k\cdot g(\varepsilon)}$$



[Ziqing Hong, 2019]

- We reconstruct all events assuming they are electron recoils

- We must then convert our predicted NR spectra to E_{ee}

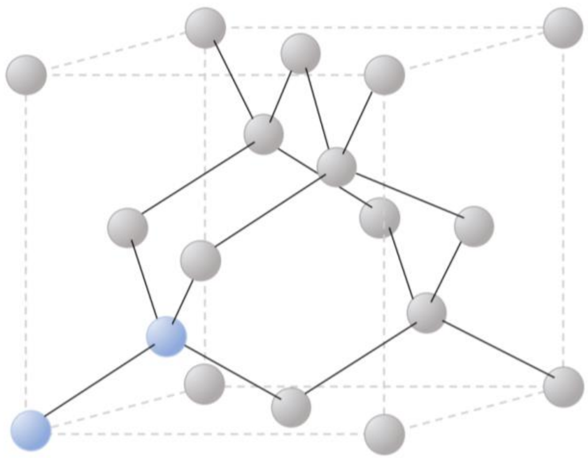
- The Lindhard model requires further testing at low energy

Scattering with electrons in a semiconductor

$$\frac{dR_{\nu e}}{dE_{ee}} = \frac{N_e}{m_A} \int_{E_\nu^{\min}} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_{\nu e}}{dE_{ee}}$$

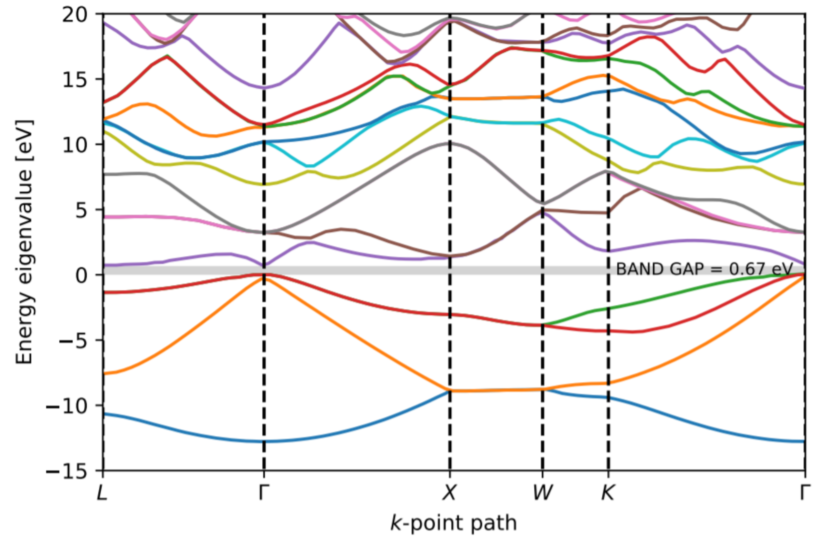
- Very naïve: $N_e = Z$
- Slightly less naïve: $N_e(E_{ee}) = \sum_{i=1}^{Z} \Theta(E_{ee} - B_i)$ (The Z_{eff} model)
- But electrons in a semiconductor are not free particles…

Scattering with electrons in a semiconductor



$$\frac{dR_{\nu e}}{dE_{ee}} = \frac{N_e}{m_A} \int_{E_\nu^{\min}} dE_\nu \frac{d\phi_\nu}{dE_\nu} \frac{d\sigma_{\nu e}}{dE_{ee}}$$

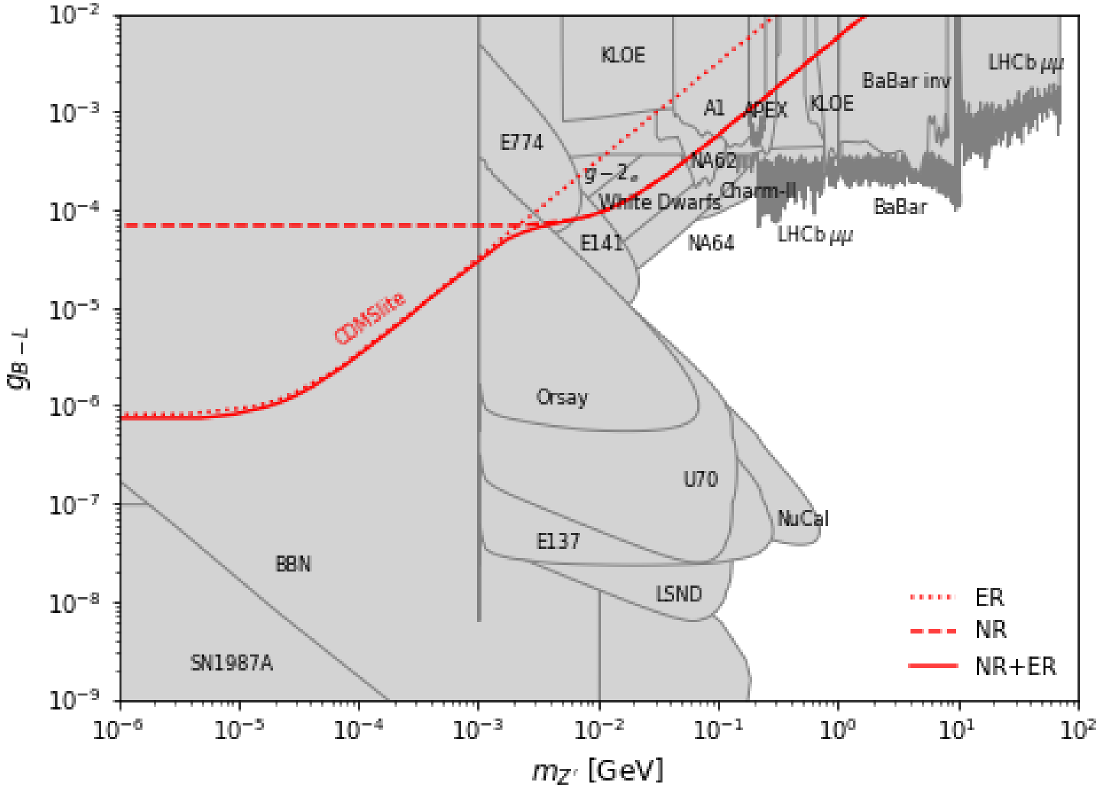
$$\psi_{j,\vec{k}}(\vec{x}) = \sum_{\vec{G}} c_{j,\vec{k}+\vec{G}}\, e^{-i(\vec{k}+\vec{G})\cdot\vec{x}}$$



- Electrons have a complex band structure
- Wavefunctions can be decomposed into plane waves, but computationally challenging

New physics constraints from CDMSlite

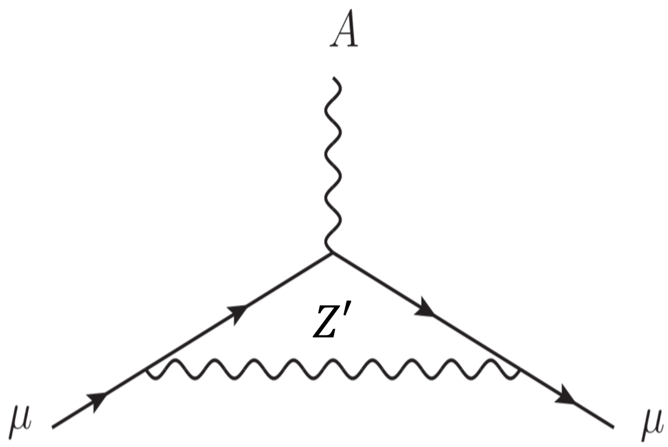
- The ER channel doesn't improve sensitivity our preferred mass range

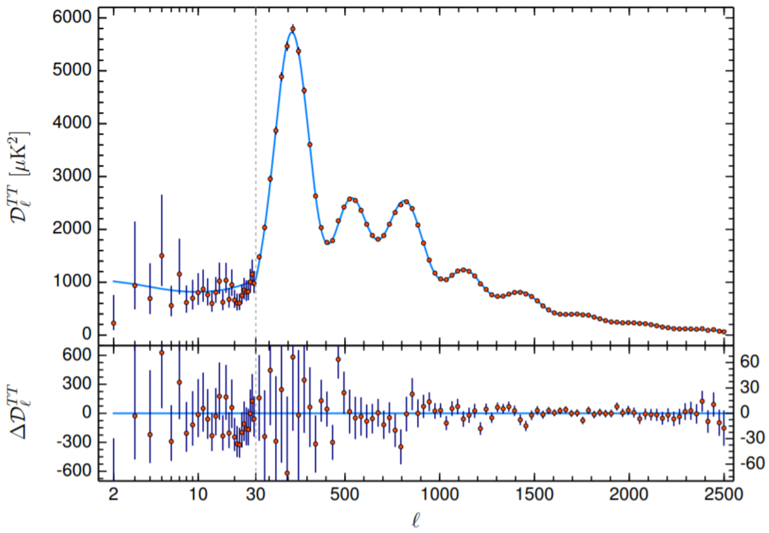


The $L_\mu - L_\tau$ can explain two physics anomalies

- With the result from Muon g-2 there is a 4.2σ tension with the SM

- A $U(1)_{L_\mu - L_\tau}$ gauge boson can resolve the tension, without spoiling other fits





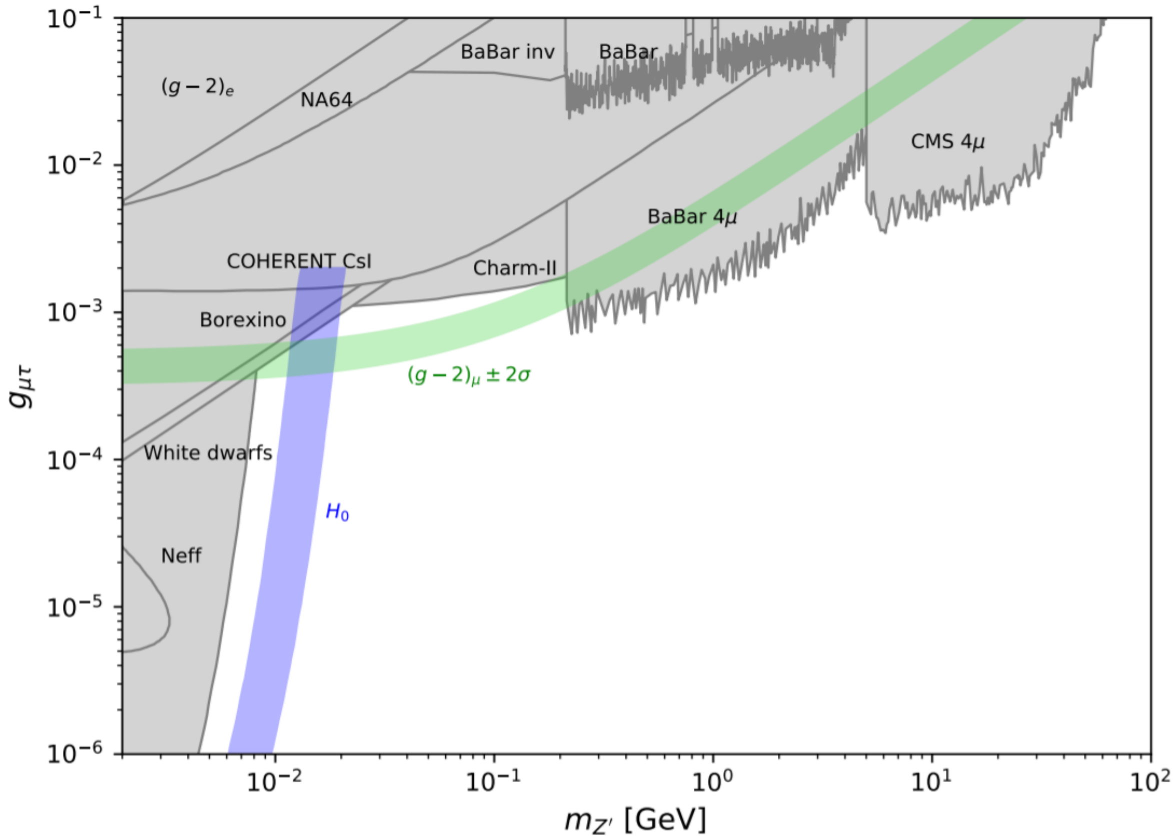
- Meanwhile, there is a tension in H_0

- Early- and late-time measurements disagree at >3σ

- The decay of a Z' can change N_{eff} and resolve the discrepancy

$L_\mu - L_\tau$ explanations for anomalies

- $L_\mu - L_\tau$ explanations are allowed by current constraints, including a simultaneous explanation of both anomalies



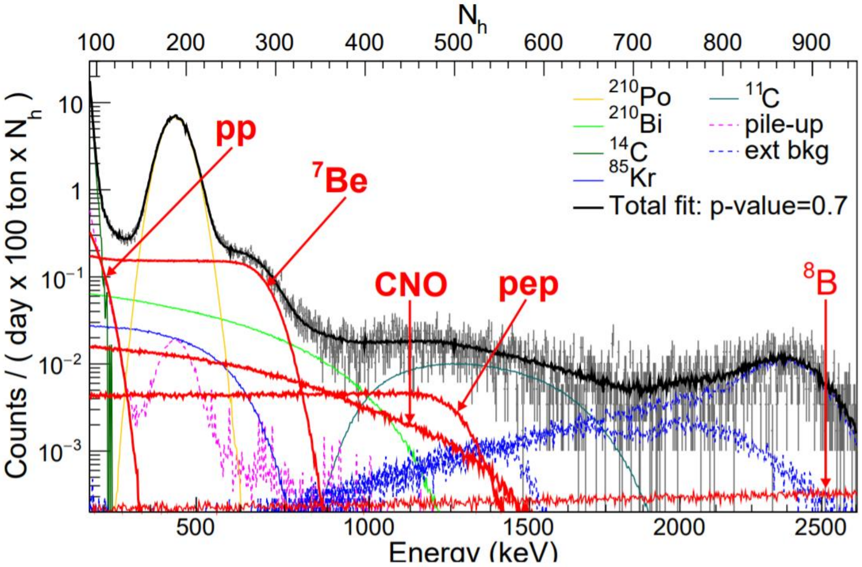
Constraints from Borexino

- Borexino: 272 ton years of proprietary scintillating liquid™

- The lowest energy measurements of neutrino-electron scattering to-date (?)

- Measured the rate of many solar neutrino populations

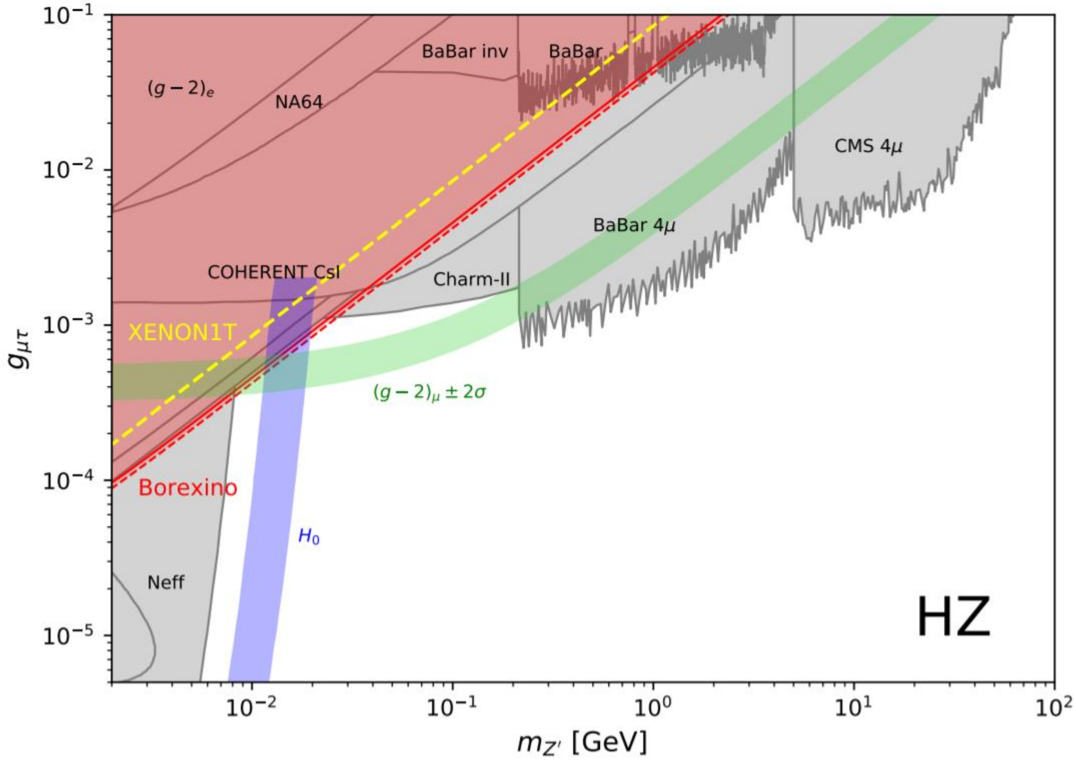
- $^{7}\mathrm{Be}$ flux measured with 2.7% precision



arXiv:1707.09279

Recomputed constraints from Borexino

- Previous constraints from Borexino used several approximations
- Results from Borexino Phase-I actually give us stronger constraints



Sensitivity of future DD experiments

SuperCDMS SNOLAB

- G2 germanium crystals
- Low threshold
- ~0.1 ton year exposure

LUX-ZEPLIN

- G2 liquid xenon
- Higher threshold
- 15 ton year exposure

DarkSide-20k

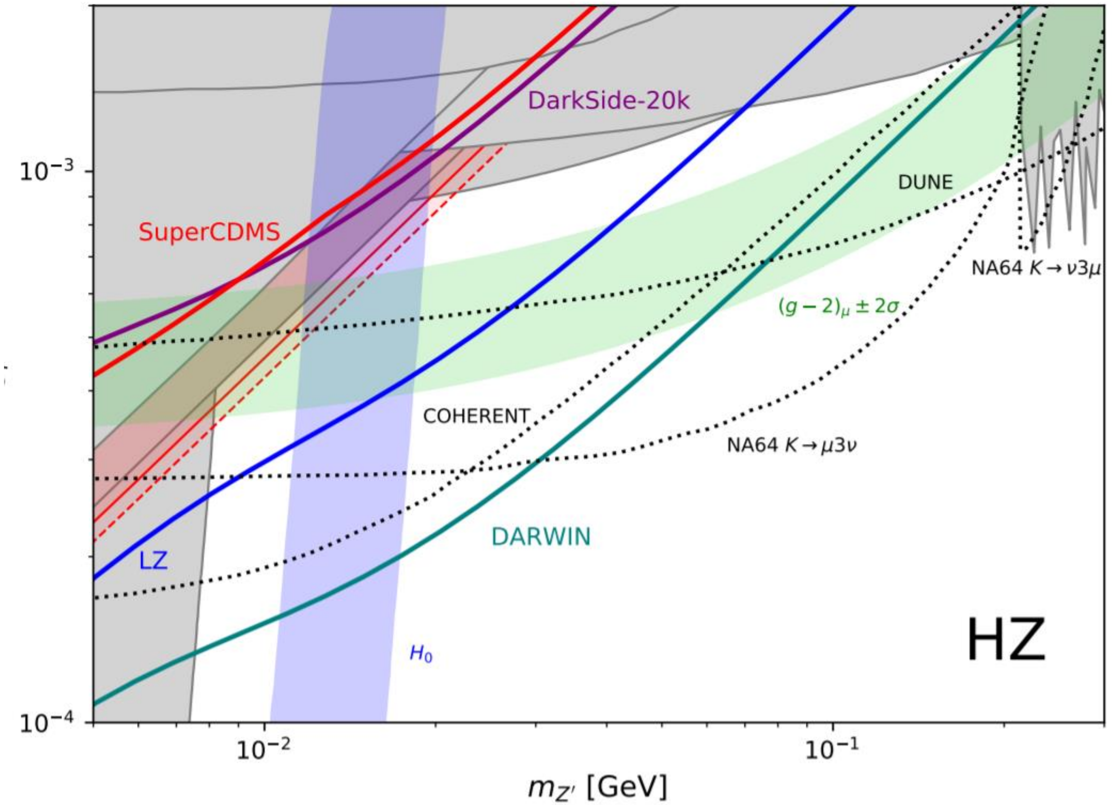
- G3 liquid argon
- High threshold, or no NR/ER discrimination
- 100 ton year exposure

DARWIN

- G3 liquid xenon
- Similar to LZ
- 200 ton year exposure

Sensitivity of future DD experiments

- Bad news: SuperCDMS isn't going to be competitive
- Good news: the neutrino ceiling seems to do its job



Conclusions

- Signals of coherent elastic neutrino-nucleus scattering may appear in direct detection experiments sooner than expected
- A “neutrino ceiling” can be constructed to show when new neutrino physics could appear, with positive and negative consequences
- Supernova constraints can be important for models introducing new light scalars, but are weaker than previously thought
- Neutrinos will also scatter with electrons, but CEvNS is more important for mediators with MeV-scale masses
- The $U(1)_{L_\mu - L_\tau}$ model offers an explanation to two ongoing mysteries in physics. Future DD experiments may be able to test these explanations