Detecting Solar Neutrinos with CYGNO

Elliott Reid

Supervised by David Cerdeño

Based on:

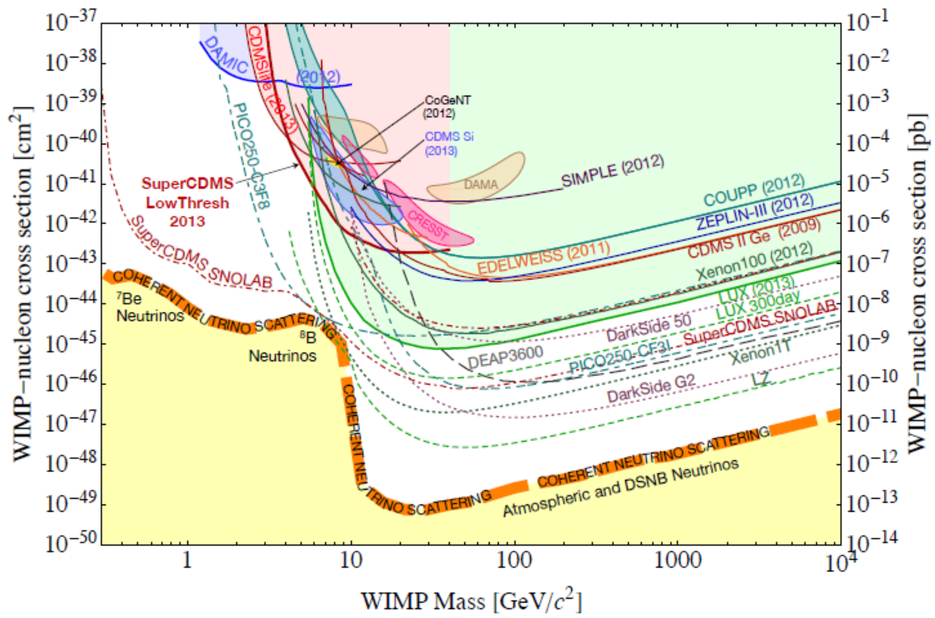
- Boehm, Cerdeño, Machado, Olivares-Del Campo and Reid; JCAP 01 (2019) 043 (1809.06385)
- Ongoing work with E. Baracchini, M. Benito, G. Cavoto, D. G. Cerdeño

Introduction: Dark Matter Direct Detection

- Dark matter direct detection experiments aim to detect the scattering of WIMPs with atomic nuclei

- As sensitivities improve, we approach the so-called neutrino floor

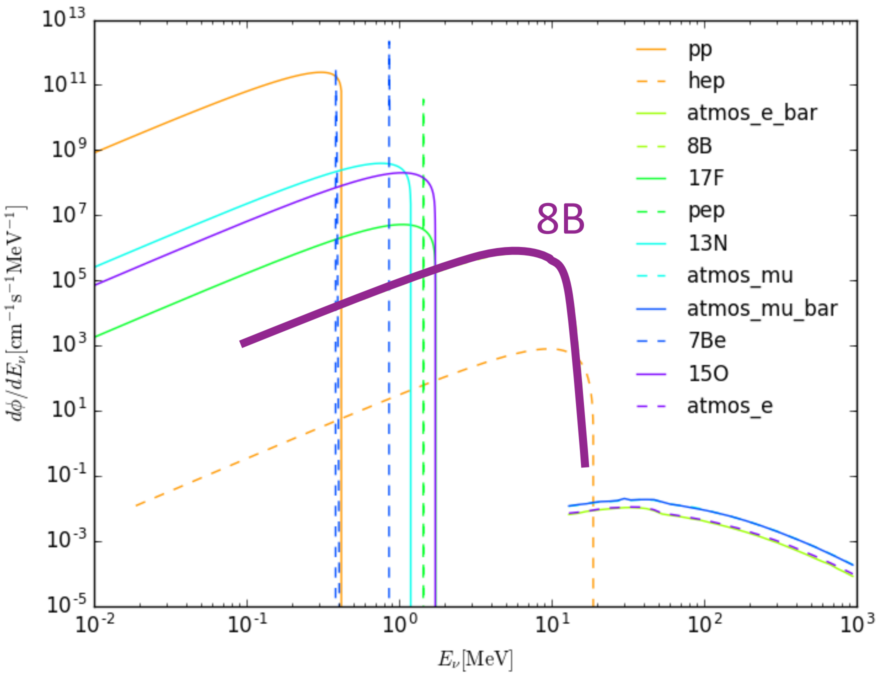
- Here, further WIMP discoveries are limited by an “irreducible” background due to CNS



Neutrino Scattering: Neutrino Fluxes

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

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

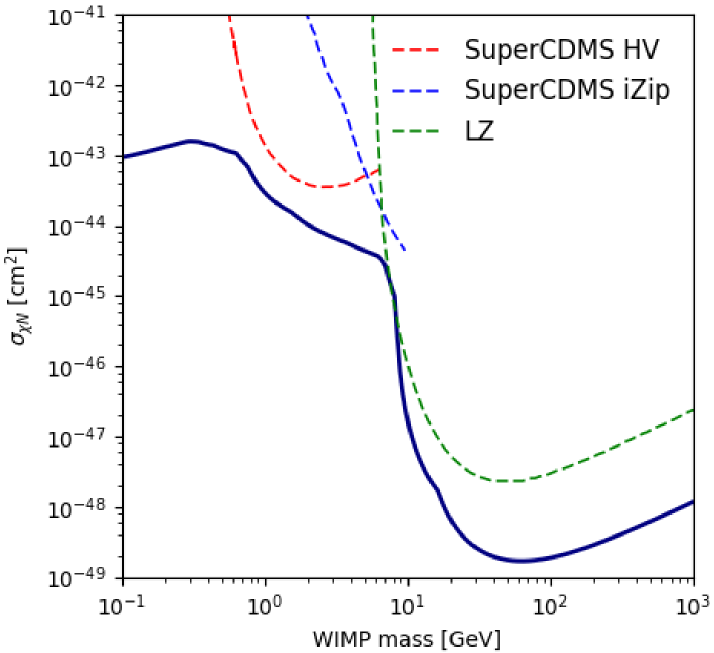


What Does the Neutrino Floor Represent?

- If the projected sensitivity curve for a DM experiment crosses this line, we expect to see >1 counts of CNS

- Some plots show a “discovery limit”

- This is the minimum WIMP cross section below which no further discovery could be made, given current uncertainties on the neutrino flux



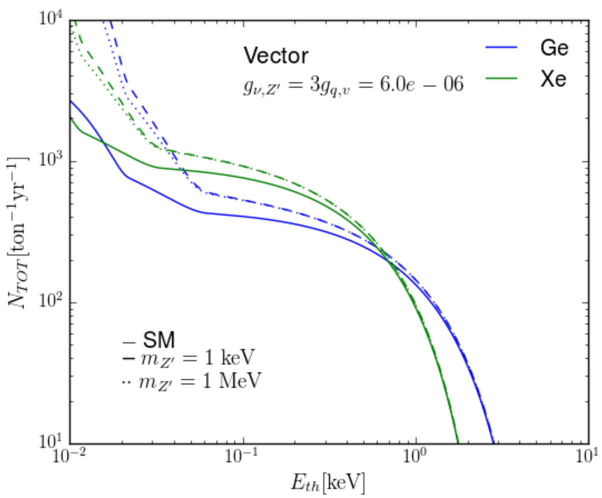
New Physics in the Neutrino Sector

- Until 2017, CNS had never been observed
- The COHERENT experiment utilised spallation neutrinos with energies around 15-50 MeV
- Although it is a SM process, new physics could affect the rate of coherent scattering
- We considered two models which introduce a new light mediator: one vector, one scalar

Vector Mediator: The B-L Model

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

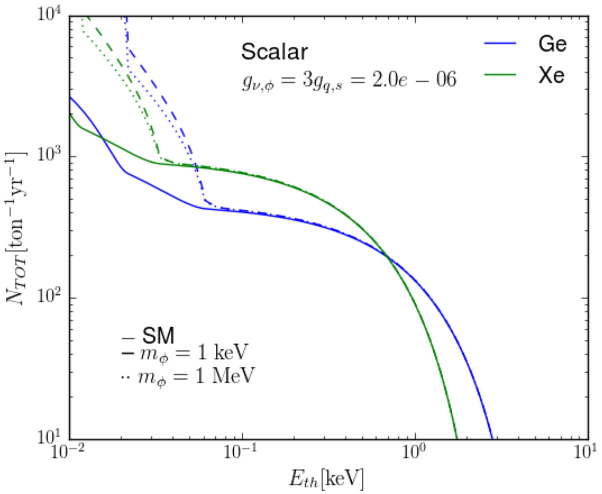
- We consider a model which introduces a new $U(1)_{B-L}$ symmetry
- This is spontaneously broken to give a new Z' mediator which couples to all Standard Model particles
- Leptons are charged under this new symmetry with $Q'_{l,\nu} = -1$; quarks have $Q'_q = \frac{1}{3}$
- Smaller mediator masses produce a greater enhancement to the spectrum at low energies



Scalar Mediator

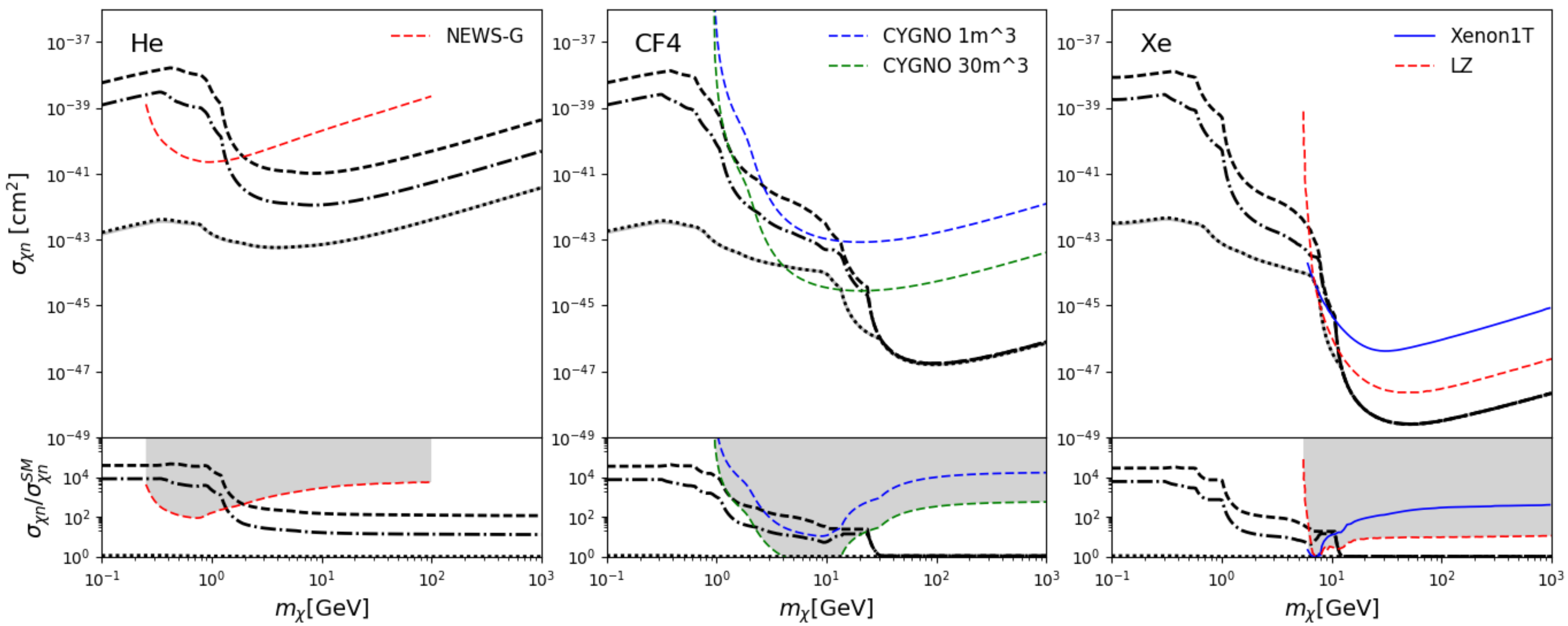
$$\mathcal{L} = -yQ'_\nu \bar{\nu}^c_L \phi \nu_L - yQ'_q \bar{q}\phi q - yQ'_\ell \bar{\ell}\phi\ell$$

- Similarly, we consider a model which introduces a new scalar, φ, which couples to SM fields
- All SM fermions have equal charge
- Again, the greatest enhancement to the cross section is at low energies
- This model is less well motivated than the B-L, but the parameter space is less constrained



Raising the Neutrino Floor

- By investigating models of new physics which introduce new light mediators we find that the neutrino floor can be raised by various OOM
- Any apparent WIMP signal in this region must be carefully examined



arXiv:1809.06385

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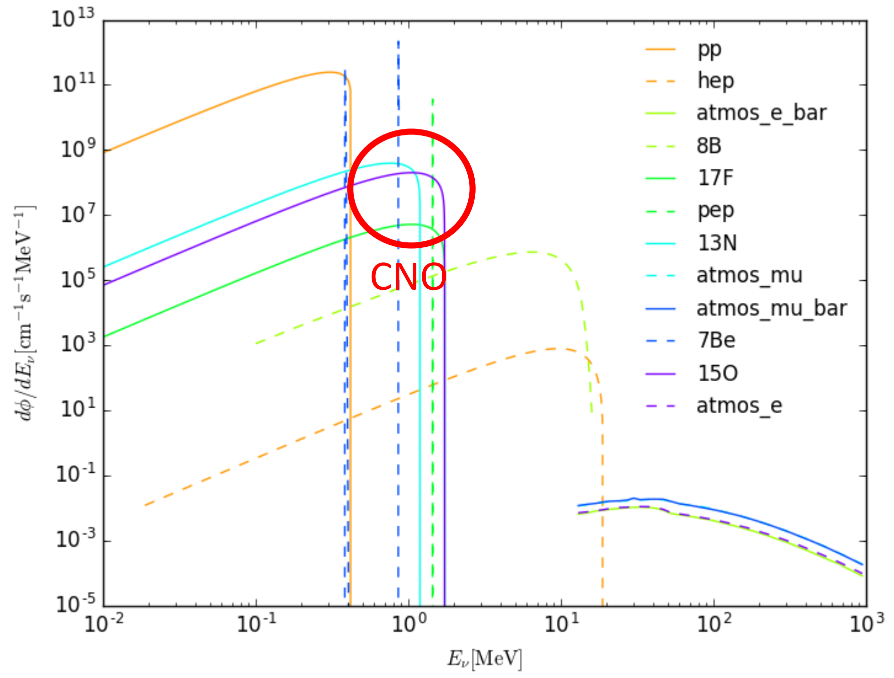
- Neutrinos produced in the CNO cycle are important for our understanding of the Sun
- Their position makes them troublesome to observe
- A future CYGNUS detector may be able to detect these elusive neutrinos



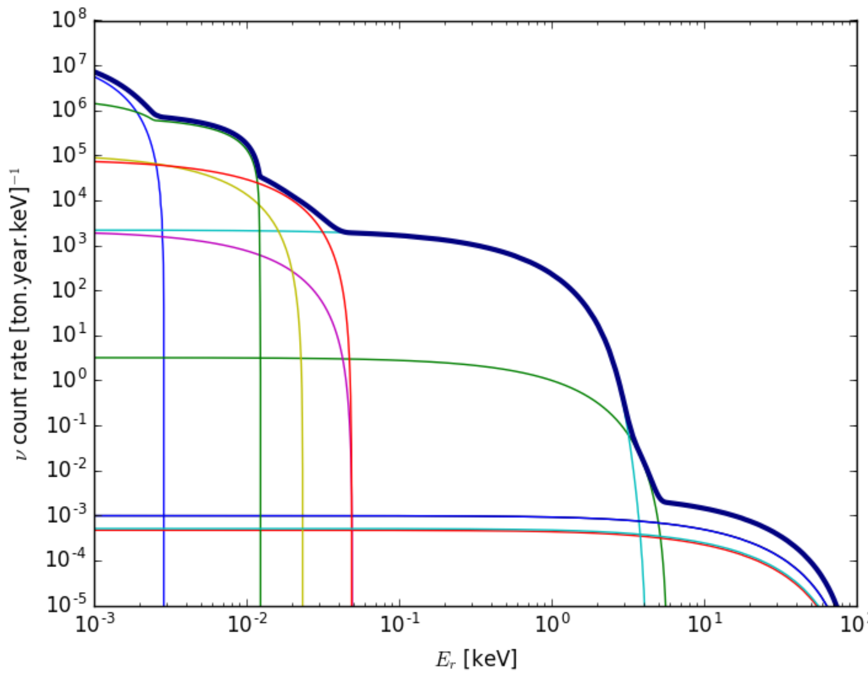
arXiv:1712.06522

CNO Neutrinos: Coherent Neutrino Scattering (CNS)

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

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

- CNO neutrinos cannot reach energies above 50 eV in $^{72}\mathrm{Ge}$
- pep neutrinos have a higher flux and form a background
- Even 8B neutrinos have not yet been observed via CNS



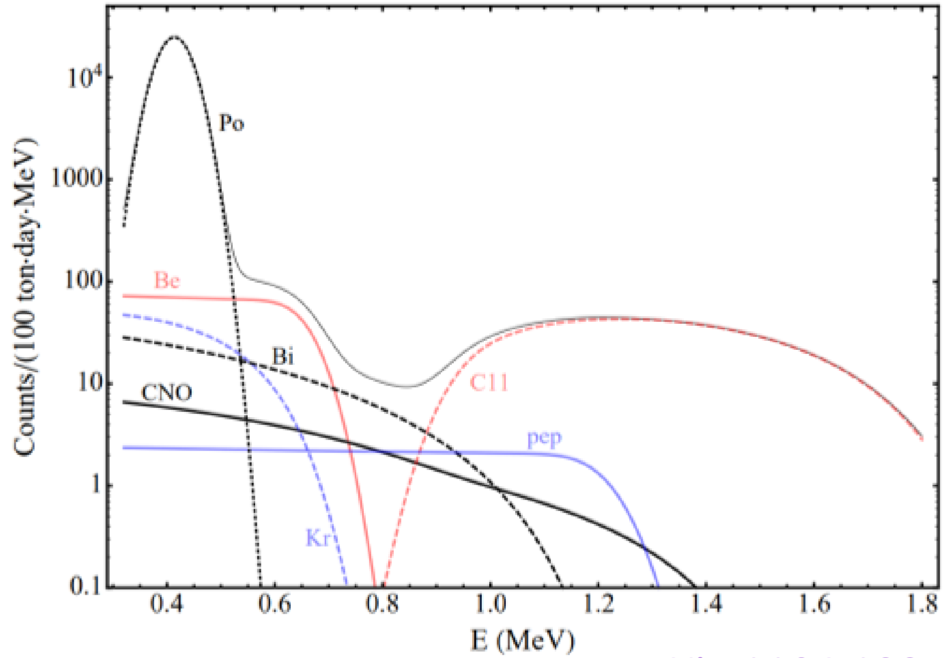
CNO Neutrinos: Limits from Borexino

- Our best measurements of most solar neutrino fluxes come from Borexino

- Borexino was able to measure interactions from pep neutrinos

- However, it could only put an upper limit on the CNO rate

- A background from $^{210}\mathrm{Bi}$ was particularly troublesome

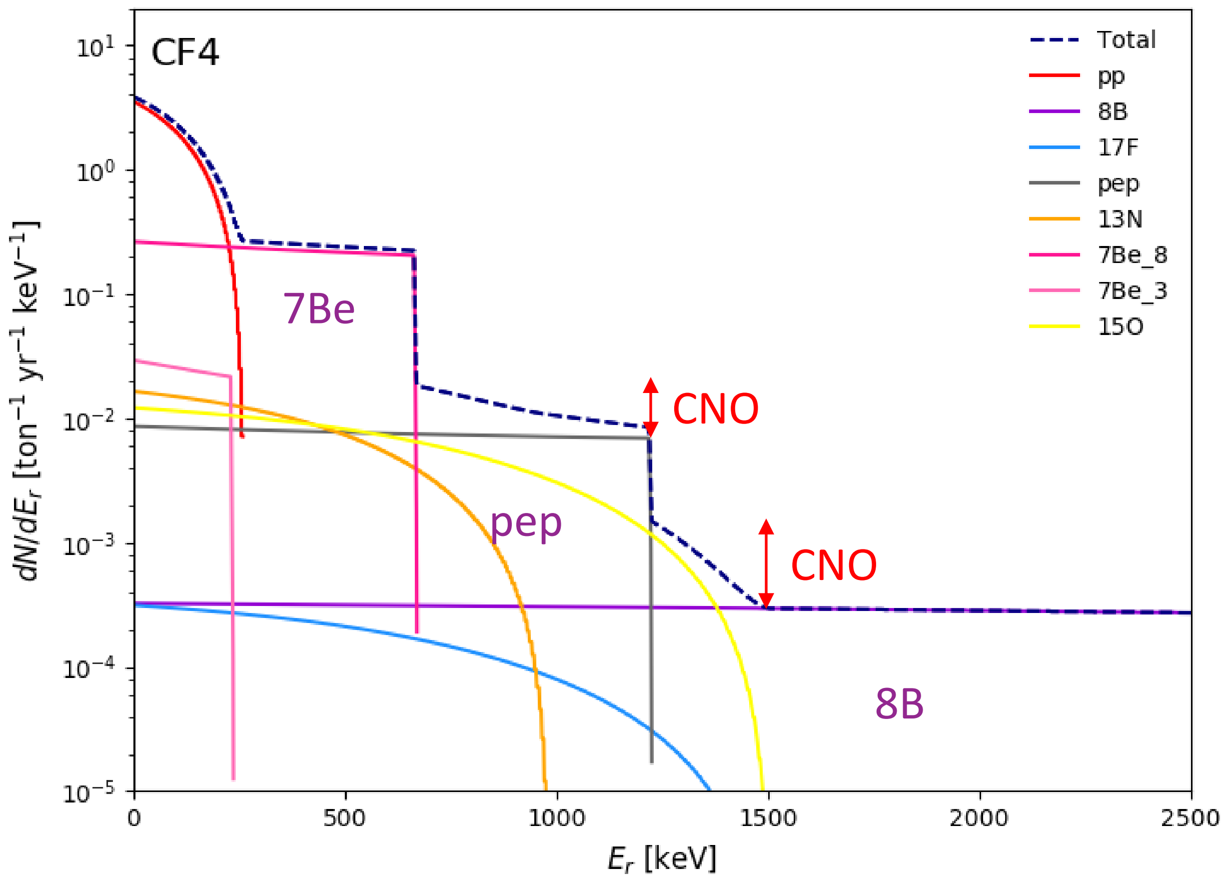


arXiv:1104.1335

CNO Neutrinos: Neutrino-electron Scattering

- Neutrinos can also interact with atomic electrons
- The different kinematics allows us to detect low energy solar neutrinos
- Conventional direct detection experiments are limited by large backgrounds
- Directional detection gives CYGNO a significant advantage

The Neutrino-electron Spectrum in CYGNO



CNO Neutrinos in CYGNO

- The optimal energy range for detecting CNO neutrinos is 700-1500 keV
- For such high energy recoils, we expect a good directional resolution
- However, it may be difficult to contain such high-energy tracks in a small detector
- A larger mass (ton scale) will be needed for sufficient statistics to distinguish CNO from pep neutrinos

CNO Neutrinos in CYGNO: Requirements

- Good discrimination between electron and nuclear recoils
- Large enough detector for containment of high energy (MeV) tracks
- Good directionality for background reduction
- High enough exposure: 1000m^3

Conclusions

- As direct detection experiments improve, they will soon reach the neutrino floor and be sensitive to coherent neutrino scattering

- Directional detection with CYGNO could allow us to distinguish a WIMP signal from neutrinos

- It could also reduce backgrounds allowing detection of neutrino-electron scattering

- Ultimately, a ton-scale directional detector could be used to measure CNO neutrinos for the first time, solving the solar metallicity problem

Extra Slides: The Coherent Neutrino Scattering Rate

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

$$\mathrm{Q}_w = N - (1 - 4\sin^2\theta_w)Z$$

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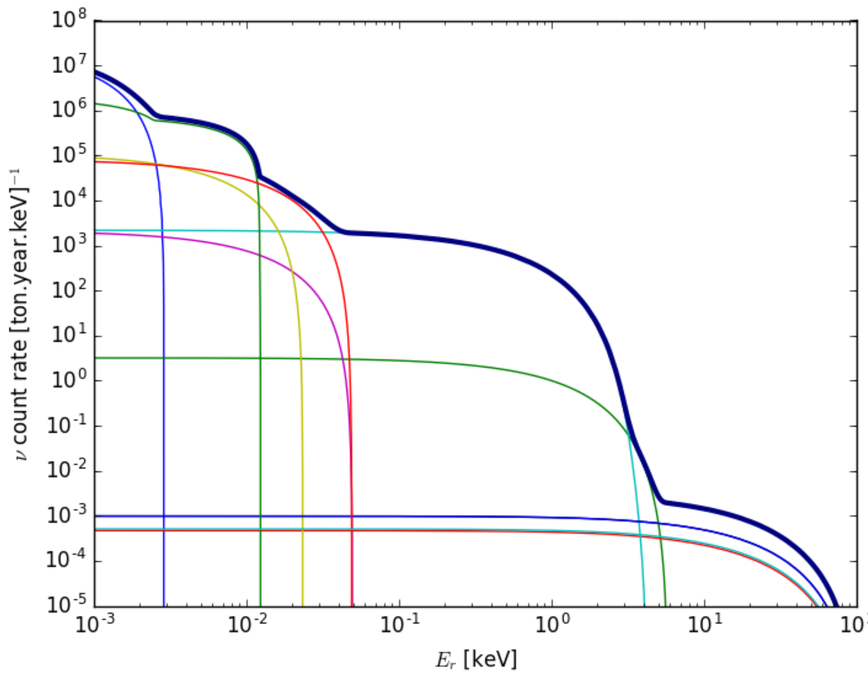
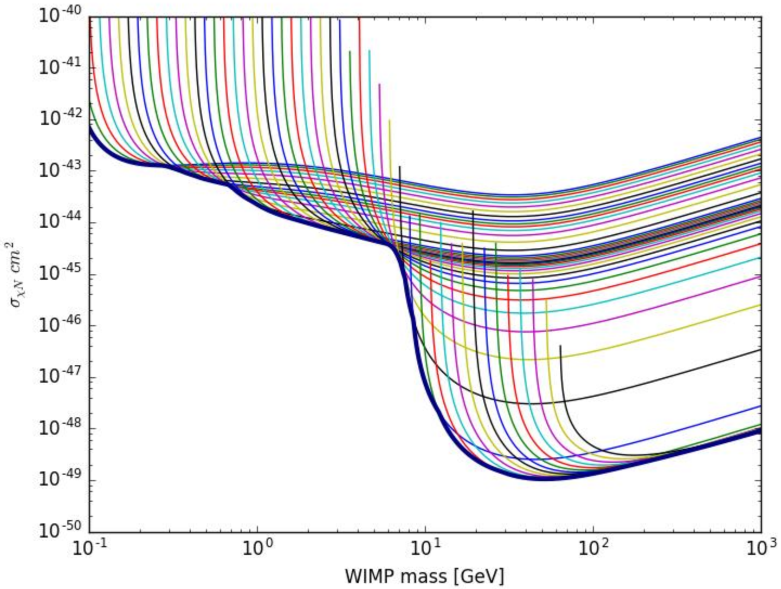
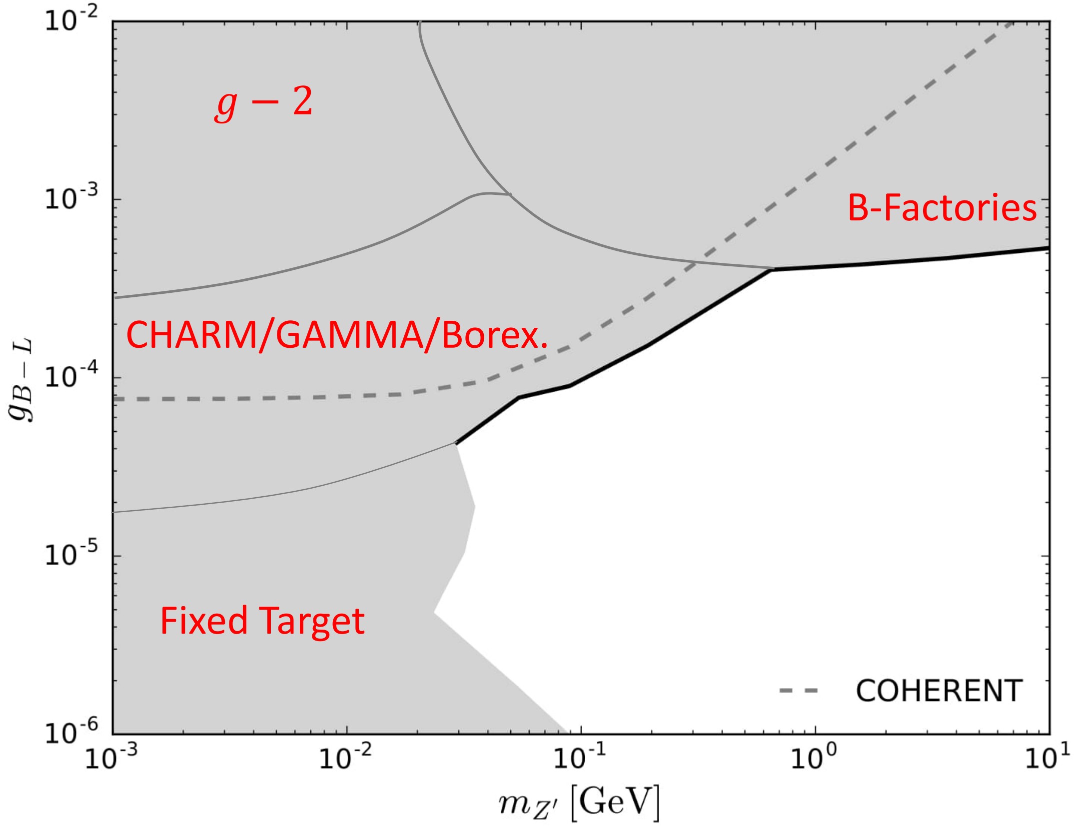


Extra Slides: Computing the Neutrino Floor

- Choose a threshold energy for the experiment and integrate the count rate above it
- Set the exposure to give 1 ν count
- For each WIMP mass, calculate the cross section at which a 90% CL could be drawn
- Now, vary the threshold and take a lower envelope

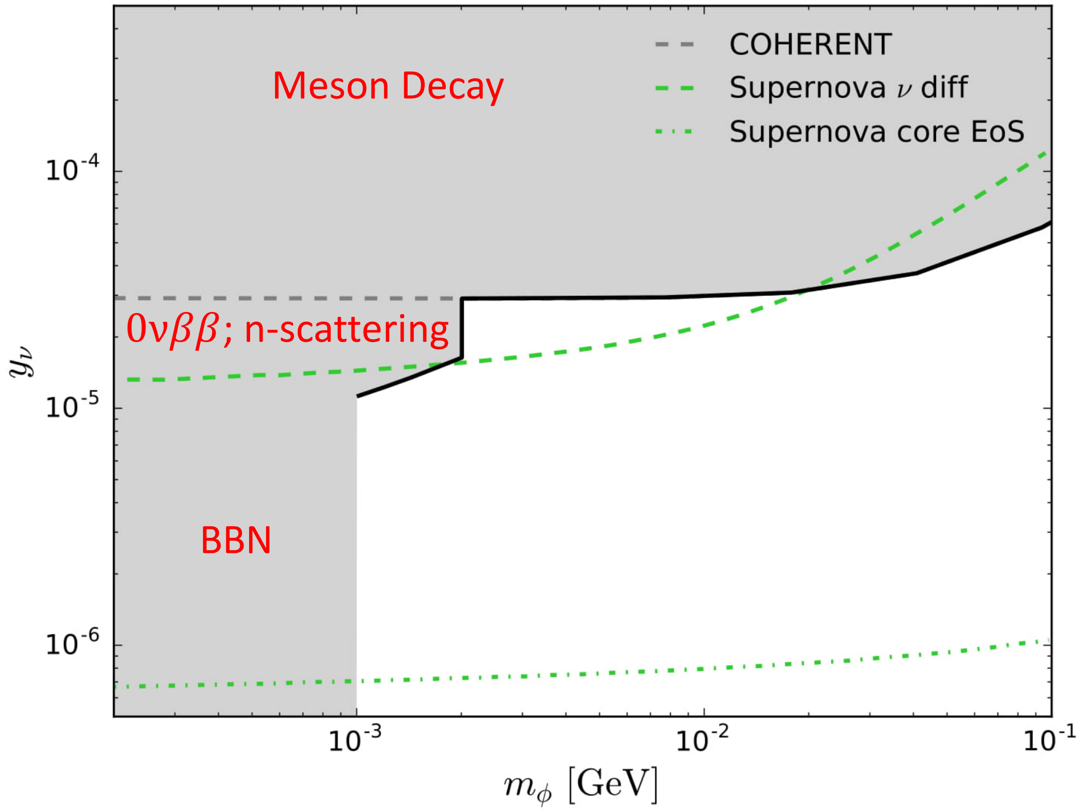


Extra Slides: Vector Mediator Constraints



arXiv:1604.01025

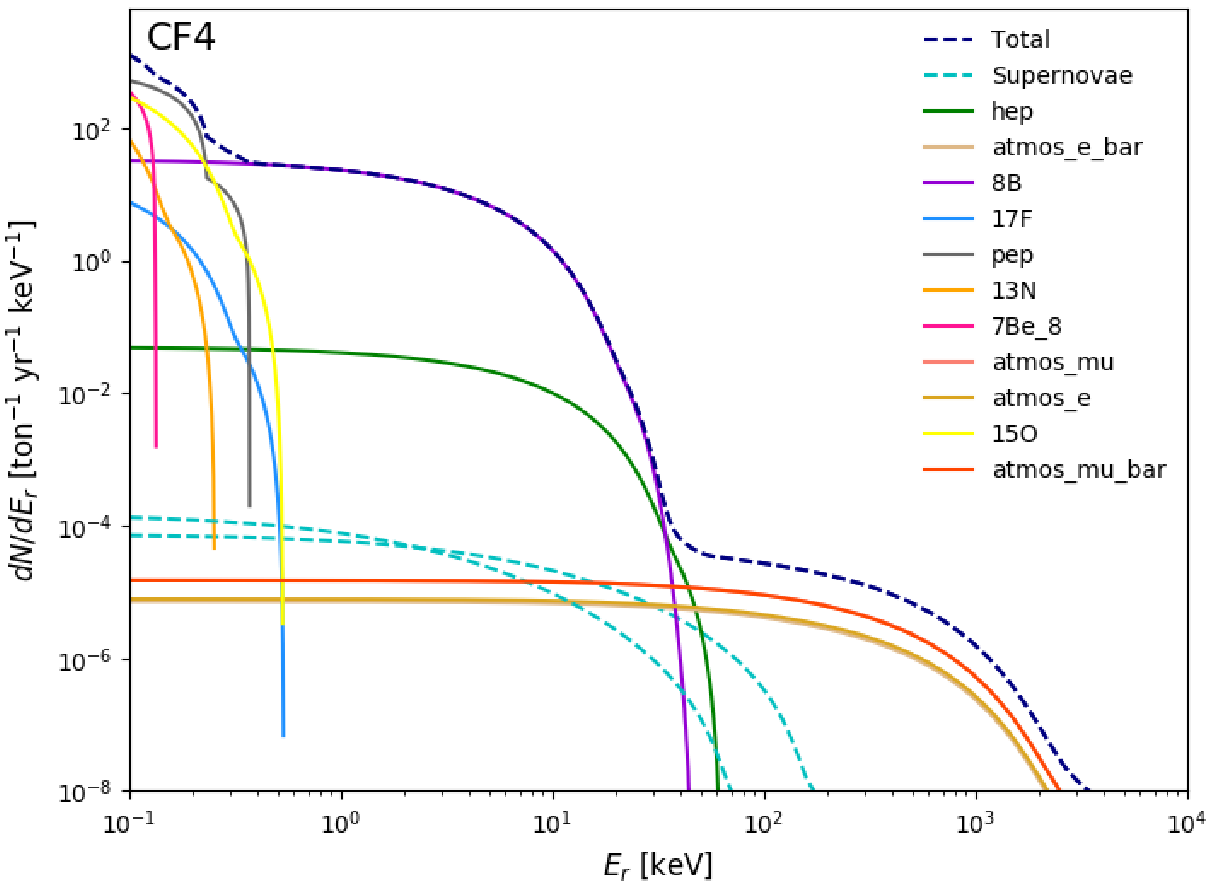
Extra Slides: Scalar Mediator Constraints



arXiv:1802.05171

D. G. Cerdeño, M. Cermeño Gavilán, M. Á. Pérez García, E. Reid (ongoing)

Extra Slides: The CNS Spectrum in CYGNO: CF4



Extra Slides: The CNS Spectrum in CYGNO: He