Low energy signals in xenon detectors *from supernova neutrinos to light dark matter*

Christopher M^cCabe

arXiv:1606.09243 (PRD) & arXiv:1702.04730

UCL - 5th May 2017

Outline

- Motivation: Dark matter
- Direct detection experiments & recent progress
- New low-energy signals in xenon detectors:
	- 1. Nuclear recoils: supernova neutrinos
	- 2. Electronic recoils: sub-GeV dark matter

Motivation: Dark matter

Dark Matter

Home *

Extended dark matter halo

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Evidence for dark matter

Matter in the Universe

Evidence from gravitational interactions over many distance scales

What would we like to know? assume the papers of the papers of the \sim

Here we limit \mathcal{H}^{H} is the mass values of 20 GeV, 100 GeV, and 100 GeV, 100 GeV, and 100 GeV, and 100 GeV, a

Limits for Spin-Independent Cross Section Limits for Spin-Independent Cross Section Dark Matter Particle (X^0) R_{R} and R_{R} and R_{R} and R_{R} and M_{R}

1. Luminosity 1. Luminosit

2 × 10−6 90 4 ANGLOHER 14 ANGLOHER 14
2 Magazina - Angloher 14 A

 \sim 10−6 \sim 10−6

. 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.08 × 1.0
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 114 coupling is assumed to extract the limits from those on \mathcal{L} BOORLET X^0 lifetime: $\tau = ?$ rake bad from the *emands of Products Property*
•• A Calveradial (Particle Data Gratics),
• Chin Phys C. 38, 000001 (2014) λ SCALLCHIIIS CHOSP-SCCLIUII UII HUCIC X^0 mass: $m = ?$ X^0 spin: $J = ?$ X^0 parity: $P = ?$ X^0 scattering cross-section on nucleons: ?

Eninese Physics C *X*⁰ production cross-section in hadron colliders: ? X^0 self-annihilation cross-section: ?

1. Accelerator physics of colliders 1

Interactions with matter are generic

Dark Matter

Home *

Extended dark matter halo

 $\rho_{\rm DM} \sim 0.3 \,\, \mathrm{GeV/cm^3}$ $\langle v_{\rm DM} \rangle \sim 300$ km/s $\phi_{\mathrm{thumb}} \sim 10^7$ $\left(\frac{m_{\text{proton}}}{m_{\text{DM}}}\right)$

particles*/*s

Direct detection experiments & Recent progress

Direct detection experiments

Aim: detect collisions of dark matter with an atom/nucleus

Goodman & Witten (1985)

Ultra-sensitive keV energy detectors Event rate: few events / year

Direct detection signals

Measurement/constraints on

- *1. Dark matter mass*
- *2. Scattering cross section with nucleons*

Direct detection limits

culated with the *LUX2015* photon emission model: the solid blue line represents the median value, Experiments with xenon (LUX & XENON) are the most sensitive median sensitivity, also calculated with the *LUX2015* model, is shown with the dashed blue line.

sion limits of other experiments: X other experiments: X and X \geq S , S \geq S , S \geq S $\$

Xenon dark matter detectors 1.2 Instrument Overview of the Company The core of the LZ experiment is a two-phase xenon (Xe) time projection chamber (TPC) containing 7

Xenon detectors: Recent progress 1

Xenon detectors have been getting (much) bigger

Recent progress 2: Much better calibration \mathbf{A} discussed in Section 7.3, and understanding of the threshold (requires-

B solar neutrino signals. By placing a deuterium-

LUX leads the way in sensitivity... and in calibrating their detector ϵ and ϵ and ϵ are used to 272 keV. These lower energy neutrons can be used to 272 keV. The used to 272 keV.

Nuclear recoil calibration to 0.7 keV calibrate in a new energy regime. Lower energy regime shows provide smaller uncertainty, because the angles of **EXAMPLE FAVOLUTE FAVORAGISHE. IN A GIGAL SPECIE SPECIFIED FOR FROM THE RECOIL SPECIFIED FROM 74 KEV**

ment $R_{\rm eff}$ is contributed by \sim 170005) is contributed by \sim 170005, and 80005, an

σ and σ and σ in σ is the LUX measured low-energy ionization σ Christopher 19 Cabe - King's College Lond Christopher M^cCabe - King's College London conduit. (Right) The configuration for 272 keV calibration. The generator head (red) is offset from the

Recent progress 2: Much better calibration energetic neutron beam with a minimum energy of 272 keV. These lower energy neutrons can be used to

LUX leads the way in sensitivity... and in calibrating their detector

Nuclear recoil calibration to 0.7 keV… and plans to go lower (150 eV?) would assist in the direct Ly calibration in the direct Ly calibration \mathbb{R}

LZ TDR arXiv:1703.09144 collimation with lower flux by using the smaller collimation with lower flux by using the smaller, 5.25 cm in 100 cm Figure 7.4.1: Approximate setup of the DD generator and neutron conduits. The y-shaped conjoined conduits. The y-shaped conjoined co

are more favorable. In addition, the recoil spectrum endpoint in Xe is reduced from 74 keVnr to 8.2 keVnr to 8
In addition, the recoil spectrum endpoint in Xe is reduced from 74 keVnr to 8.2 keVnr to 8.2 keVnr to 8.2 keVn

t
ch **1** Recent progress 2: Much better calibration

LUX leads the way in sensitivity... and in calibrating $\sqrt[0.4]{\frac{1}{2}}$

Electronic recoil calibration to 1.3 keV (tritium)

35

 0.8

Christopher M^cCabe - King's College London $\mathcal{O}(\log n)$ and 105 V/cm (blue squares) compared (bl case range consiguentem Christopher M^cCabe - King's College London

Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Electronic recoil calibration to 1.3 keV (tritium) 0.19 keV (127-Xe)

 $\mathcal{L}_{\mathcal{S}}$ vertex $\mathcal{L}_{\mathcal{S}}$ vertex $\mathcal{L}_{\mathcal{S}}$ is the of second vertex $\mathcal{L}_{\mathcal{S}}$

Recent progress 2: Much better calibration

LUX leads the way in sensitivity… and in calibrating their detector

Electronic recoil calibration to 1.3 keV (tritium) 0.19 keV (127-Xe) 0.27 keV (37-Ar)

Calibration: summary

$Pre-LUX: ~ 4 keV$ $Post-LUX: ~ 0.2 keV$

Xenon direct detection experiments:

- 1. Becoming much bigger (x10-100)
- 2. Better calibration: now at sub-keV energies

So what?

New low-energy signals in xenon detectors:

- 1. Nuclear recoils: supernova neutrinos
- 2. Electronic recoils: sub-GeV dark matter

New low energy signals: 1. Supernova neutrinos

Dual-phase xenon detectors

• Dual-phase xenon as *neutrino* detectors

From kinematics:
$$
E_R \sim 2.4 \text{ keV} \left(\frac{E_{\nu}}{12 \text{ MeV}}\right)^2
$$

(Neutrino signal similar to low-mass dark matter signal)

Supernova neutrinos

Supernovae: among the most energetic events in the Universe. Originate from the core-collapse of very massive stars

Energy: \sim 10⁵³ erg released ~99% is emitted by all neutrino flavours Neutrino energy \sim 15 MeV

Time:

Neutrino emission lasts ~10 s

When/where:

~1-3 SN/century in our galaxy distance ~10 kpc

detection: will shed light on the properties of neutrinos and the explosion

DM detectors as neutrino detectors

Principles and applications of a neutral-current detector Principles and applications of a neutral-current detector for neutrino physics and astronomy PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984 principles and applications of a neutral current detector furnio physics and astronom *experiences* of a households

A. Drukier and L. Stodolsky

A neutral-current detector: al-current detector[.] The very large value of the neutral-current cross section on nuclei and identification o $\overline{}$ the very discussion of the neutral-current cross section due to coherence individual cross section due to coherence individual cross section due to coherence individual cross section due to coherence individua $arctan \theta$ detector would be relatively light and suggests the possibility of a true "neutrino" observator $arctan \theta$

greatest interest is the nascent field of neutrino as the nascent field of neutrino as the neutrino astronometri

the question of neutrinos from stellar collapse is completely open. Second, many important questions of par-

pletely open. Second, many important questions of particle physics revolve around the question of σ around the question of σ around σ

1. responds to all types of neutrinos equally We study detection of MeU-range neutrinos through elastic scattering on nuclei and identification 1. responds to all types of neutrinos equally **cometa**onds to all types of neutrinos equally \mathbf{r} and the all two sea of noutrings agus ly ponds to all types of neutrinos equally

- 2. gains from a coherence factor: neutron-number² and the superconduction in the superconduct cates a detector would be relatively light and suggests the possibility of a true \sim 2. gains from a coherence factor: Z^0 the through extrapolation and extrapolation of currently known techniques. Such a detector could permit be result per through and extension and extrapolation of currently could permit \mathbf{c} determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations of α since it detects all neutrino types. Various applications and tests are discussed, including spallation-sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the sources, reactors, supernovas, and solar and solar and terrestrial neutrinos. A preliminary estimate of the ter through extrapolation and extrapolation of currently known techniques. Such a detector could permit α determined of the neutrino energy spectrum and should be insensitive to neutrino oscillations of the neutrino o since it detects all neutrino types. Various applications and tests are discussed, including spallationmost different backgrounds is a term of the set of the s
- 3. responds to neutrinos in a known way: can infer incoming neutrino spectrum \mathbf{v} \mathcal{S} . It deposites all neutrinos in a Known way. most different backgrounds is a terminal background in the set of th onds to neutrings One of the most fascinating and challenging problems Can inter incoming neutri of experimental physics at present is connected with the

In the superconducting colloid, metastable superconducting colloid, metastable supercon-

very small value of the specific heat at low temperature of the specific heat at low temperature of the specifi

can sufficiently the grain, as we show the grain, as we show below. As the grain, as we show below. As the gra
The grain, as we show below. As the grain, as we show the grain, as we show the grain, as well as the grain, a

DM detectors as SN neutrino detectors

"Elastic scattering detectors can have yields of a few or more neutrino events per tonne for a supernova at 10 kpc"

Horowitz et al 2003

Why is it timely to think about this?

Tonne scale experiments are here: running: $XENONIT$ (~ 2 t) in design/construction: $XENONnT & LZ$ (~ 7 t) R&D: DARWIN (~ 40 t)

What physics can we do with these detectors?

DM detectors as SN neutrino detectors

Supernova neutrino physics with xenon dark matter detectors: A timely perspective

Rafael F. Lang, Christopher McCabe, Shayne Reichard, Marco Selvi, and Irene Tamborra Phys. Rev. D 94, 103009 - Published 23 November 2016 arXiv[:1606.09243](http://arxiv.org/abs/arXiv:1606.09243)

1. Simulate the SN neutrino signal in a dual-phase xenon detector

Extracting physics from:

- *2. the number of events*
- *3. the shape of the spectrum*

(first pass at this problem: everything could be improved)

1. Simulating the supernova neutrino signal in a dual-phase xenon detector

Rate calculation: Ingredients

Use results from four ID simulations by the Garching group:

- Two progenitor masses $(11 & 27$ $M_{Sun})$
- Two equation of states (LS220 & Shen EoS)

27 M_{Sun} LS220; 27 M_{Sun} Shen; 11 M_{Sun} LS220; 11 M_{Sun} Shen

Use results from four ID simulations by the Garching group:

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27 M_{Sun} LS220; 27 M_{Sun} Shen; 11 M_{Sun} LS220; 11 M_{Sun} Shen

Detector response the charge signal produced by internal produced by interesting produced by interesting \mathbf{r}_i [14, 15]. The ratio of these two signals differs between ER

and $N_{\rm eff}$ events, allowing particle-type discrimination. Thus it proves discrimination. Thus it proves discrimination. Thus it proves

ionization yields not only for energy reconstruction, but to Ask me afterwards…

 $\mathcal{L}_{\mathcal{L}}$

Extracting physics from:

2. the number of events

Expected number of events

Past detection of supernova neutrinos

Neutrinos from SN1987A detected with

- Kamiokande-II (12 events)
- IMB (8 events)
- Baksan (5 events) (3 events)

 $\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1$ much present the present theorem in the present term in the study. In the set of the study of the study. In the study of the study

Christopher M^cCabe - King's College London event in the sample of each detector has, arbitrarily but not unelementary-particle physics which may be reached from

Current detectors for supernova neutrinos

Events from a supernova burst at 10 kpc arXiv:1310.5783

Discovery significance

XENONIT: discovery to 20 kpc XENONnT/LZ: discovery to Milky Way edge DARWIN: discovery to Large/Small Magellanic Cloud

$$
\text{XENON1T}: 35.2 \left(\frac{10 \text{ kpc}}{d}\right)^2 \text{events}
$$

$$
\text{XENONnT/LZ}: 123 \left(\frac{10 \text{ kpc}}{d}\right)^2 \text{events}
$$

$$
\text{DARWIN}: 704 \left(\frac{10 \text{ kpc}}{d}\right)^2 \text{events}
$$

Background estimate (0.1 event/tonne) from XENON10 & XENON100

Neutrino light curve

Distinguishing the phases of the (10 kpc) supernova neutrino emission

- Clear differentiation of phase with DARWIN \bullet
- Partial differential with XENONnT/LZ but none with XENONIT

Extracting physics from:

3. the shape of the spectrum (measured S2 value)

Energy released into neutrinos

- **Excellent reconstruction** with DARWIN
- **XENON1T also good** \bullet

SN neutrino flux

Flux parameterisation ansatz (motivated from simulations): \bullet Keil et al 0208035

 $A_T \, \xi_T \left(\frac{E_\nu}{\langle E_T \rangle}\right)^{\alpha_T} \exp\left(\frac{-(1+\alpha_T) E_\nu}{\langle E_T \rangle}\right)$ with $\alpha_T=2.3$, $\langle E_T \rangle$, A_T determined from fit

SN neutrino summary

A xenon direct detection experiment:

- 1. responds to all types of neutrinos equally
- 2. gains from a coherence factor (neutron-number²)
- 3. responds to neutrinos in a known way (can infer incoming neutrino spectrum)

For a SN at 10 kpc from Earth:

(SN at 2.2 kpc in $XENONIT = SN$ at 10 kpc in DARWIN)

New low energy signals: 2. Sub-GeV dark matter

Motivation

$\sum_{i=1}^{n}$ super limits on the spin-independent elastic WIMP-independent elastic WIMP-independent elastic WIMP-independent elastic WIMP-independent elastic WIMP-independent elastic WIMP-independent elastic WIMP-independe Christopher M^cCabe - King's College London

Motivation

Detecting dark matter is hard

Detecting sub-GeV dark matter is even harder

Normal signal

Normal signal

measure recoil energy of the xenon nucleus

 $E_{\rm R}^{\rm max} \approx 0.1 \text{ keV}$ $\times (131/A) (m_{\rm DM}/1 \text{ GeV})^2$

keV nuclear recoils in LUX

Not enough energy to produce a signal

Detecting dark matter is hard en and we dank matter is hard

Detecting sub-GeV dark matter is even harder

A new idea

Kouvaris & Pradler: 1607.01789, PRL

A new idea

Kouvaris & Pradler: 1607.01789, PRL

A new idea A new idea

DM

Kouvaris & Pradler: 1607.01789, PRL

A new idea: why is it interesting?

Kouvaris & Pradler: 1607.01789, PRL

Maximum photon energy:

$$
\omega^{\text{max}} \approx 3 \text{ keV} \cdot (m_{\text{DM}}/1 \text{ GeV})
$$

Maximum nuclear recoil energy: $E_{\rm R}^{\rm max}\approx 0.1 \,\, {\rm keV}$

 $\times (131/A) (m_{\rm DM}/1 \text{ GeV})^2$

keV photons in LUX \overline{k} photon in IIIX

What's the catch?

Can we overcome this suppression in the control of Christopher M^cCabe - King's College London

Energy spectrum

 $=$ importantly, we can determine the canonical listing \mathcal{L} atomic data listing \mathcal{L}

- 1. Calculate the number of expected events (the efficiency)
- 2. Calculate what they would observe in the S1-S2 plane

report our results and the calculated best-fit charge and light yields. These quantities are continuously are continuously are continuously are continuously are continuously of liquid and detectors in the energy regime in the energy regime in the energy regime in the energy regime in rare event searches such as the direct detection of dark matter low energy nuclear recoils constitute the expected signal ϵ Loumner of events L 1. Expected number of events (efficiency)

Liquid xenon interest in the detec-
Liquid xenon is current in the detection and measurement of ionizing \mathbb{R}^n under study in direct data research in direct data matter dark matter dark matter dark matter dark matter dark \mathbf{a} is to accurately predict scintillation and \mathbf{c} i response: Ask me afferw understand background rejection in such experiments as well. The such experiments as well. The such experiments as well. Detector response: Ask me afterwards…

phase time projection chambers (TPCs) by measuring both the

1. Expected number of events (ef photon emission in the form of bremsstrahlung from the form of bremsstrahlung from the form of bremsstrahlung f
In the form of bremsstrahlung from the form of bremsstrahlung from the form of bremsstrahlung from the form of env tion with a cut-o↵ at *v*esc = 544 km*/*s and most probable Expected number of events (emclency) 1. Expected number of events (efficiency)

What LUX measured:

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2. Calculate what they would observe in the S1-S2 plane

Reproduce ER and NR bands:

2. Calculate what they would observe in the S1-S2 plane

All together:

Constraints

Constraints

Constraints

The parameters of sub-GeV DM can be reconstructed!

Summary

Xenon detectors are getting bigger Our understanding of them is getting better

Opportunities to search for (discover !) new signals

- 1. Nuclear recoils: supernova neutrinos
- 2. Electronic recoils: sub-GeV dark matter

Are there others?

Thank you

Backup

Backup: sub-GeV DM

tron scattering

Other ideas: absorption

 α α 3γ decays, assuming that decays contribute 100% (thin line) or 10% (thin line) to the observed flux. The observed fl

 $Chrichable Winc'$ energy instalaring from Corresponding C elles dep Christopher M^cCabe - King's College London

S2 efficiency: order of magnitude higher

A new idea: assumptions

DM

emits a photon energies at low photon

where the double line represents the nucleus initial α

(final) atomic state of electrons *i* (*f*), with intermediate

Kouvaris & Pradler: 1607.01789, PRL

• Nucleus kick instantaneous (on time scale for electrons in orbit to adjust to the perturbation τ_{α})

with radius *|*r↵*|* = 1*/*(*Z*↵*me*) and velocity *v*↵ ⇠ *Z*↵, we $\tau_{\chi}/\tau_{\alpha} \simeq 10^{-4} A^{1/3} Z^2$. Hence our approximation is well justified for light elements; for heavier targets such as xenon, the ratio can become $O(1)$, but only for the innermost electrons. Going beyond the mentioned approximations requires a dedicated atomic physics calculation, which is certainly welcome but well beyond the scope of this paper.

XENONI0 & XENONI00: S2-only \blacksquare \blacksquare

/µ = 0.19

100

Kouvaris & Pradler set constraints with S2-only analyses

Very high event rates - XENON100 has ~13000 events S1 was found are shown as #. The number of electrons in the

S2 signal is indicated by the inset scale. (top) Distribution

 $\mathsf{Christoph}$ Christopher M^cCabe - King's College London

XENON10 & XENON100: S2-only

Kouvaris & Pradler set constraints with S2-only analyses

ende and the DM-nucleus scattering of the DM-nucleus scattering of the SM-nucleus Scattering of the SM-nucleus S
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Dual-ph

Easy to characterise: NR events lie in the NR band and ER events lie in the ER band

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 \sim

Dual-ph

Easy to characterise: NR events lie in the NR band and ER events lie in the ER band …

?

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The behaviour of low energy signals

Example: LXe WIMP Search, 85 live-days, 118 kg

•WIMP Event Monte Carlo

LUX Dark Matter Experiment / Sanford Lab Rick Gaitskell (Brown)

The behaviour of low energy signals **-0.8 -0.6** a distribution is created using large numbers of statistics

-1.2

 \overline{G} and distributions of expected contains of expected contains of expected contains of expected contains \overline{G} Christopher McCabe - King's College London

and is scaled to the calculated exposure. The systematic exposure $\mathcal{L}_{\mathcal{A}}$

no indication of a low-energy increase as reported by the

The behaviour of low energy signals

f_{max} of low constraint digital green f_{max} The behaviour of low energy signals

FIG. 2: Distribution in uniformity-corrected S1 and S2 for the Data from PandaX-I [arXiv:1505.00771](http://arxiv.org/abs/1505.00771)

The anti-diagonal lines are the anti-diagonal lines are the anti-correlation fit at the anti-correlation fit at the two \sim

The behaviour of low energy signals - well below 10-3 Tour of low chergy signals ha
I

Different charge yields

Backup: SN neutrinos

Different detectors will test *N2* dependence of the scattering rate

phe/10 ns

S2

S1 and S2 signal simulation in the absence of signal charge loss to in drifting, have a mean of *S2* detected S2 photons. Calibration relative to these reference points accounts for

in the absence of signal charge loss to impurities during drifting, have a mean of *S2* detected S2 photons. Calibration relative to these reference points accounts for S2-only analysis

100

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S2

S2-only analysis

- Advantage: higher event rate
- 'Disadvantage': no background discrimination…
	- …but not an issue for neutrino signal (is an issue for DM search):
	- Signal is short (<10 seconds)
	- Background rate is small compared to signal rate

Background estimates: XENON10: 2.3×10-2 events/tonne/s XENON100: 1.4×10-2 events/tonne/s

[arXiv:1104.3088](https://arxiv.org/abs/1104.3088) [arXiv:1605.06262](https://arxiv.org/abs/1605.06262)

signal: 1.0 - 2.5 events/tonne/s *(40-100 x background)*

tained by the technique of \mathcal{I}_1 using a set of monocneus of monocneus of monocneus \mathcal{I}_2

Signal simulation: more details in the absence of signal charge loss to impurities during drifting, have a mean of *S2* detected S2 photons. Cal- $\ddot{}$ ive to the set **p** and the economic to extract an elec-

 $\frac{1}{1}$ 10 $\frac{1}{100}$ Nuclear recoil energy (keV)

of an S2 (2 electrons emitted); green: detection of an S1

10

3 5 \overline{a}

3 $\mathsf{L}\xspace_{\mathsf{y}}$ (ph / keV)

0.01

0.1 ϵ V)

 Q_y (e $^-$ / keV)

 $Q_v (e^-/k$

the photon yield and the electron yield is observed to \mathbf{b} frame the \mathbf{c} *W* value as defined in [19]; however, the individual yields do vary, because charge recombination probability de-¹ ¹⁰ ¹⁰⁰ 0.001 $\frac{1}{2}$ tected the CO of Efficiency \blacksquare trom the \blacksquare' bilitule _{de} More events from the S2 channel: estimated using LUXSim with parameters tuned to D-D calculated to D-D calibration. In descending order of ecoe The symbol (\mathcal{N} indicates the most likely threshold values (see equation). is from the OZ criticisms in the state of the in a higher number of detected events.

detection eciency, and for time-dependent xenon pu-

Requiring an S1 reduces event rate by factor ~3-4 1 **Heyuin** \blacksquare event rate by lactor \sim 3-4 $\mathbf{1}$ reduce the background signal. Although the requirement signal $\mathbf{1}$

 $\mathbf{S1}$ \equiv

Differential Rate [count/tonne/PE]

⁵⁵⁴ IV. S2-ONLY ANALYSIS

 $\frac{1}{3}$ $\frac{1}{4}$ $\frac{1}{5}$ $\frac{1}{6}$

Differential Rate [count/tonne/100PE]

5

F100 PE]

<7.0 [s] pb 0<t , LS220 EoS Sun 27 M , Shen EoS Sun 27 M , LS220 EoS Sun 11 M 11 M_{Sun} , Shen EoS

 $\frac{3}{4}$ 51, S

2 spectra ⁵⁵⁷ and an S2 signal. This stipulation reduces the back-

 $\frac{1}{3}$ $\frac{1}{3}$ both S1 and S2 enables discrimination between the dom- inant electronic recoil backgrounds and the expected nu-clear recoil signal, based on the ratio S2/S1 at a given

⁵⁶⁵ and the PMT hit pattern. The latter means that events \mathbf{f} 666 can be selected from the central region of the detector, and the detector, and the detector, and the detector, and 567.567 where the background rate is lowest. In the background rate is lowest. In the second-⁵⁶⁸ ical dark matter searches, which utilize data collected

⁵⁶⁹ over *O*(100) days, the S1 threshold is typically 2 PE or

 $\frac{1}{\sqrt{2}}$ and $\frac{1}{\sqrt{2}}$ and

 $\left[\begin{array}{c} \begin{array}{c} \text{all} \ \text{all} \end{array} & \begin{array}{c} \text{all} \ \text{all} \$

Use an S2-only analysis $\frac{1}{\sqrt{2}}$ of reducing the background rate, it also significantly re-1 Use an S2-only analysis $\mathbf{1}$ such the nuclear recoil energy where $\mathbf{1}$

 5799 ± 90 is small 292 \mathbf{S} 1 any value of S1 (including no S1 signal), the number of S1 signal), the number of S1 signal), the number of \mathbf{S}

 \mathbf{S} 1 SN neutrino events for the 27 M SN progenitor with \mathbf{S} 582.20 the LS220 EoS is 17.6 events/tonne. However, when ad- \mathbf{S} ⁵⁸⁴ number of events drops to only 7.2 events/tonne. Requir- 585 ± 0.000 in gradient and an $S_{1/2}$ signal therefore signal therefore signal therefore signal therefore signal the \sim

 575 of detecting both an S1 and an S1 and an S2 signal has the e 2

SN neutrinos: Low energy uncertainty

TABLE III: The expected number of neutrino events per tonne for various S2 thresholds under different assumptions for *Qy*. We compare the Lindhard and Bezrukov models and assume that $Q_y = 0$ for energies below $Q_{y,\text{min}}$. The results are for the $27 M_{\odot}$ LS220 EoS progenitor at 10 kpc and integrated over the first 7 s. Similar results hold for other progenitor models. The signal uncertainty in each row is $(S2_{\text{max}} - S2_{\text{min}})/(S2_{\text{max}} + S2_{\text{min}})$. The Lindhard model with $Q_{y,\text{min}} = 0.7$ keV gives the smallest number of events per tonne and is the benchmark assumption that we have made in this paper.

by Bezrukov et. al. [106]. As can be seen in the in-

present uncertainty in *Qy*. Clearly, it would be most de-