# Lepton number violating Electron Recoils at XENON1T and PandaX in the $U(1)_{B-L}$ Model with Non-Standard neutrino Interactions

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# Outline

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- **Phenomenology Analysis (XENON1T and PandaX)**
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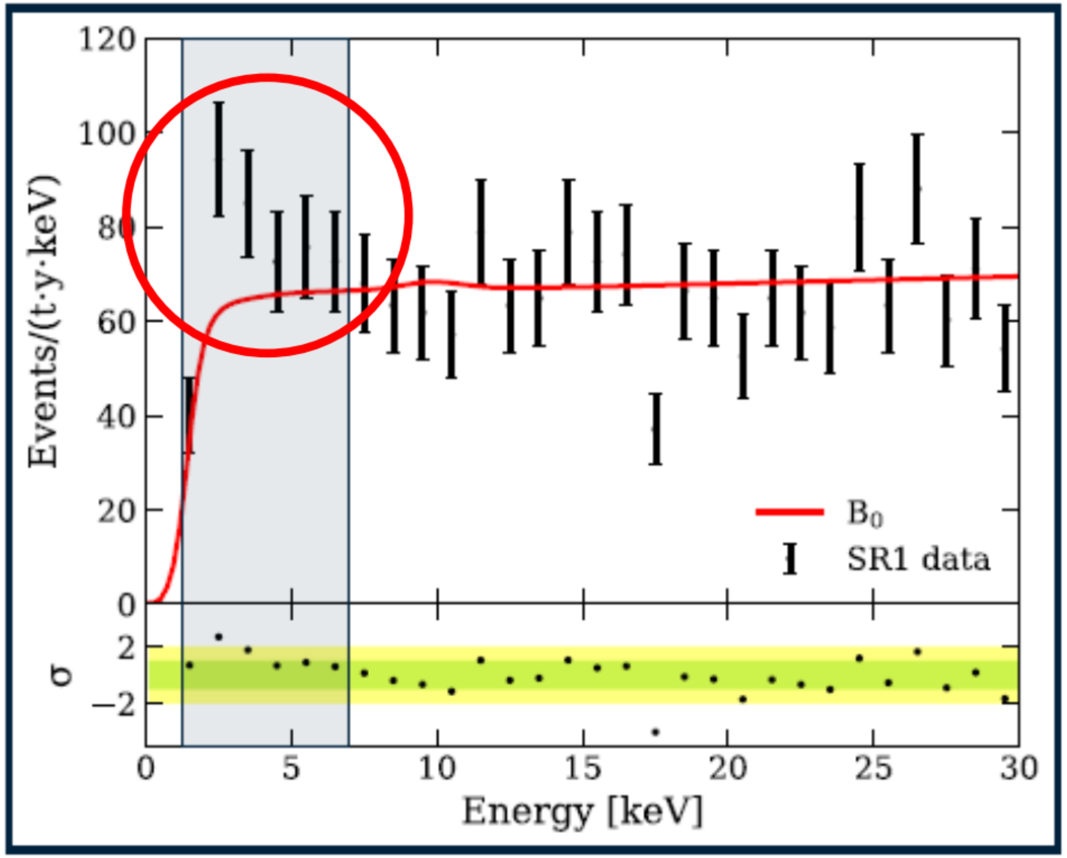
# Introduction

# XENON1T has excess around KeV



**Xenon1T's results on Electron Recoil**

Using the low-energy electronic recoil data with an exposure of 0.65 ton-years.

With 285 observed events over an expected background of 232±15 events, they observed an excess for the electron recoil energies below 7 keV, rising towards lower energies and prominent between 2 and 3 keV .

**These excess electron may come from $\beta$-decay due to a trace amount of tritium impurity in the detector**

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# Motivation and Model

- Following the XENON1T result, this excess has been extensively discussed. Including various dark matter model, axion and axion-like model, etc.

- The excess may be explained by model with prominent signal enhancement in the low energy region . We consider a model which can generate non-standard soft enhancement interaction between solar neutrino and electron with a new light mediator

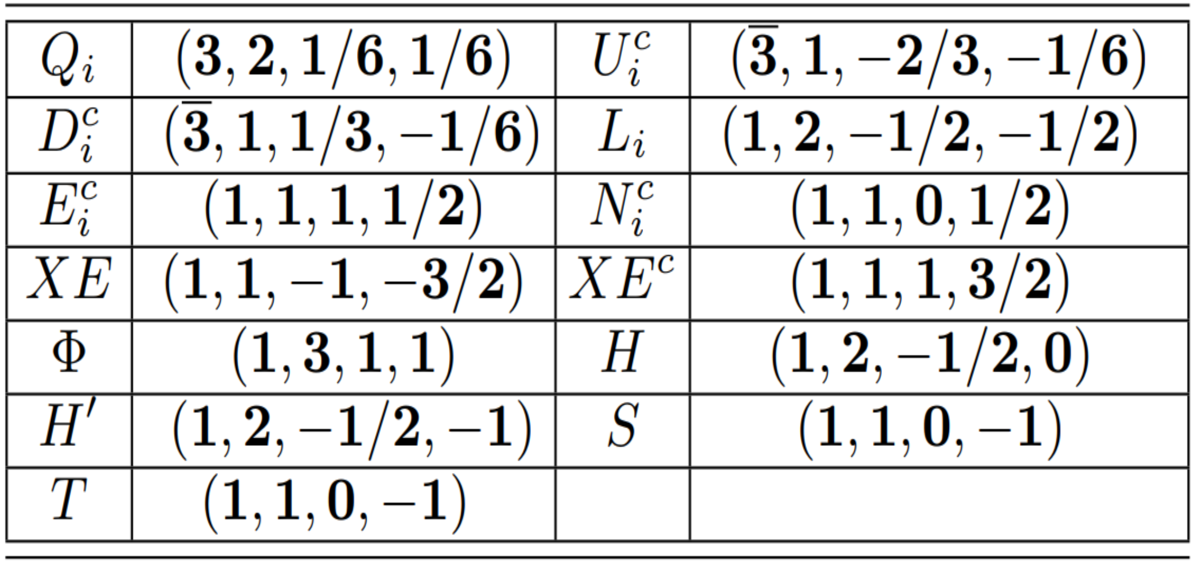
- The model is based on the $\boldsymbol{SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}}$ gauge group. I will show that the excess in electron recoil events at the XENON1T experiment can be explained via the solar neutrino due to these non-standard interactions.

# Model Setup

## $(SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L})$

Gauge group breaking pattern: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$
$\rightarrow SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

# particles in the model



| | | | |
|---|---|---|---|
| $Q_i$ | $(\mathbf{3}, \mathbf{2}, 1/6, 1/6)$ | $U_i^c$ | $(\overline{\mathbf{3}}, \mathbf{1}, -2/3, -1/6)$ |
| $D_i^c$ | $(\overline{\mathbf{3}}, \mathbf{1}, 1/3, -1/6)$ | $L_i$ | $(\mathbf{1}, \mathbf{2}, -1/2, -1/2)$ |
| $E_i^c$ | $(\mathbf{1}, \mathbf{1}, 1, 1/2)$ | $N_i^c$ | $(\mathbf{1}, \mathbf{1}, 0, 1/2)$ |
| $XE$ | $(\mathbf{1}, \mathbf{1}, -1, -3/2)$ | $XE^c$ | $(\mathbf{1}, \mathbf{1}, 1, 3/2)$ |
| $\Phi$ | $(\mathbf{1}, \mathbf{3}, 1, 1)$ | $H$ | $(\mathbf{1}, \mathbf{2}, -1/2, 0)$ |
| $H'$ | $(\mathbf{1}, \mathbf{2}, -1/2, -1)$ | $S$ | $(\mathbf{1}, \mathbf{1}, 0, -1)$ |
| $T$ | $(\mathbf{1}, \mathbf{1}, 0, -1)$ | | |

The particles and their quantum numbers under the $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ gauge group.

$T$ obtains a vacuum expectation value that breaks the $U(1)B\text{-}L$ gauge symmetry
$H$ is the SM Higgs doublet which breaks the electroweak gauge symmetry

We assume that $\Phi$, $H'$, and $S$ do not acquire vevs.

The effective Yukawa couplings between $H'$ and charged leptons can be generated if we introduce a pair of vector-like particles ($XE$,$XE^c$) as heavy mediators with masses above the $U(1)_{B-L}$ breaking scale, and $\Phi$ can couple to lepton doublets as well.

Gauge group breaking pattern: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \xrightarrow{\langle T\rangle} SU(3)_C \times SU(2)_L \times U(1)_Y$

$SU(2)_L \times U(1)_Y \xrightarrow{\langle H\rangle} U(1)_{EM}$

# Light mediator

- After $H$ and $T$ obtain vevs, the CP-even neutral components of $\Phi$, $H'$ and $S$ can mix with each other , and we assume the lightest CP-even mass eigenstate is s

$$s = \cos\alpha \ \mathrm{Re}S + \sin\alpha\cos\beta \ \mathrm{Re}\Phi^0 + \sin\alpha\sin\beta \ \mathrm{Re}H'^0 \qquad (1)$$

- $s$ can couple to the charged leptons as well as neutrinos which can be the light mediator between non-standard neutrino-electron interaction.

# Lagrangian

$$
\begin{aligned}
-\mathcal{L} = {} & y^U_{ij} Q_i U^c_j \overline{H} + y^D_{ij} Q_i D^c_j H + y^E_{ij} L_i E^c_j H + y^\nu_{ij} L_i N^c_j \overline{H} \\
& + y^N_{ij} T N^c_i N^c_j + y^\Phi_{ij} L_i \Phi L_j + y^{H'}_i H' L_i X E^c \\
& + y^T_i \overline{T} E^c_i X E + M_{XE} X E^c X E + \text{H.C.} \,, \qquad (2)
\end{aligned}
$$

integrating out the
vector-like particles (*XE; $XE^c$*)

$$-\mathcal{L} \supset -\frac{1}{M_{XE}} y^{H'}_i y^T_j H' \overline{T} L_i E^c_j + \text{H.C.} \,. \qquad (3)$$

After *U*(1)*B-L* gauge symmetry
breaking

$$-\mathcal{L} \supset -\frac{\langle \overline{T} \rangle}{M_{XE}} y^{H'}_i y^T_j H' L_i E^c_j + \text{H.C.} \,. \qquad (4)$$

We can get the $s\bar{e}e$ vertex

$$y_e \sin\alpha \sin\beta s\bar{e}e \qquad y_e = -\frac{\langle \overline{T} \rangle}{M_{XE}} y^{H'}_1 y^T_1$$

With the $y^\nu_{ij} L_i N^c_j \overline{H}$ and $y^N_{ij} T N^c_i N^c_j$ terms, we can generate the neutrino masses and mixings via Type I seesaw mechanism after *T* acquires a vev and breaks the *U*(1)*B-L* gauge symmetry .

From $y^\phi_{ij} L_i \phi L_j$ term, we can get the $s\bar{\nu}^c\nu$ vertex

$$-\mathcal{L} \supset \frac{y'^\Phi_{ij}}{2} \sin\alpha \cos\beta s \overline{\nu^c_i} \nu_j \ .(5)$$

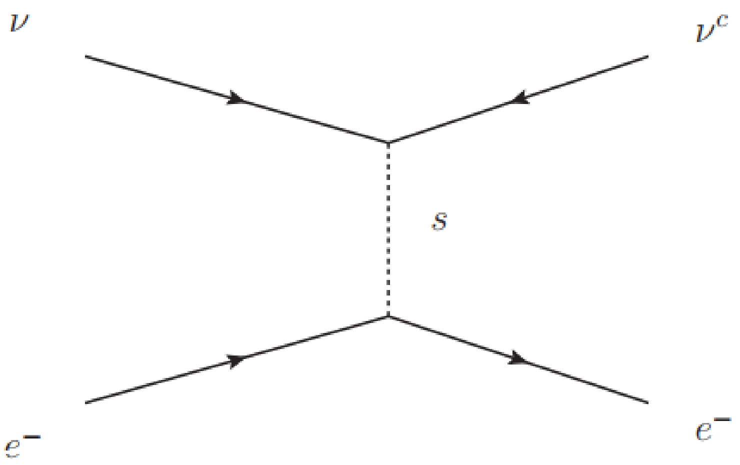
- **The $s\bar{\nu}^c\nu$ and $s\bar{e}e$ vertices allows *s* to mediate non-standard electron scattering process$\nu_i e^- \longrightarrow \nu^c_j e^-$**

(The heavy $M_{XE}$ mass above $\boldsymbol{U(1)_{B-L}}$ breaking scale will provide a small $y_e$ )

# Phenomenology Analysis

## (XENON1T and PandaX)

# The feature of NSI scattering



The $s\bar{\nu}^c\nu$ and $s\bar{e}e$ vertices in Eqs.4 and 5 allows $s$ to mediate non-standard electron scattering process $\nu_i e^- \longrightarrow \nu_j^c e^-$

$$|\mathcal{M}|^2 = -\frac{y_\nu'^2 y_e^2 (4M_e^2 - t)t}{(M_s^2 - t)^2},$$

$$\frac{\mathrm{d}\sigma^{\nu e}}{\mathrm{d}E_k} = \frac{y'^2 y_e^2 E_k M_e (E_k + 2M_e)}{8\pi E_\nu^2 (M_s^2 + 2M_e E_k)^2}.$$

$E_k$ is the electron's acquired kinetic energy after scattering, and $E_\nu$ is the incident neutrino energy

- At low $E_k$ range recoil (KeV) with an even lower $M_s$ , which features a kinematic region : $M_s \ll \sqrt{2M_e E_k} \ll M_e.$
- Low momentum transfer dominates the scattering as the cross-section behaves as $d\sigma/dE_k \propto E_k^{-1}$

# NSI event distribution

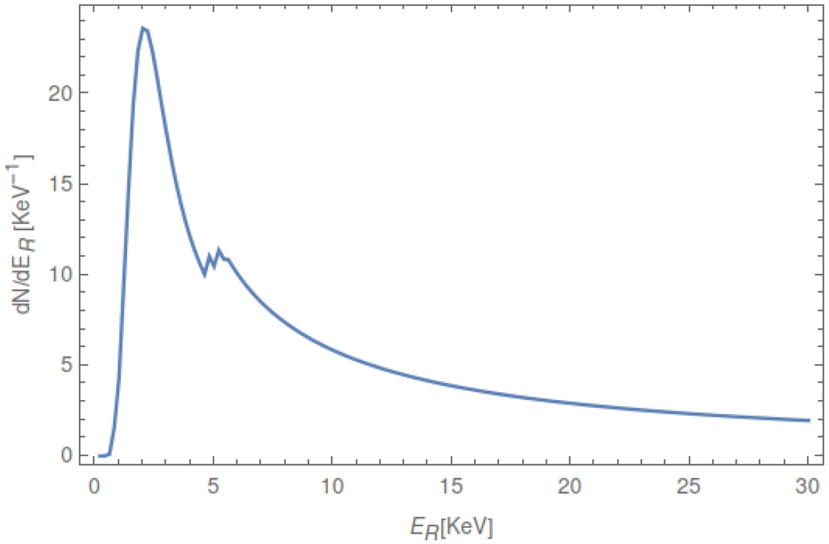
$\frac{d\sigma}{dE}$ is for a free electron, and the differential rate for recoil energy $E_R$ would be

$$\frac{dN}{dE_R} = N \cdot T \cdot \epsilon(E_R) \int \mathrm{d}E' \mathcal{G}(E', E_R) \int \mathrm{d}E_\nu \mathcal{F}(E') \frac{\mathrm{d}\phi_\nu}{\mathrm{d}E'} \frac{\mathrm{d}\sigma^{\nu e}}{\mathrm{d}E'}, \qquad \mathcal{F}(E) = \sum_i \theta(E - B_i)$$

- *N* and *T* are the number of targets and exposure time
- $\epsilon$ is the detector efficiency
- $\mathcal{G}$ is a Gaussian smearing on $E_R$ that accounts for detector resolution

$$\mathcal{G} = \frac{1}{\sqrt{\pi}\delta_E} \exp^{-\frac{(E_R - E')^2}{\delta_E^2}} \qquad \delta_E = \sqrt{0.31E} + 0.0037E$$

- $\phi_v$ is the Solar neutrino flux
- $\mathcal{F}(E)$ is a sum of step-functions with threshold at 54Xe atom's *i*th electron binding energy which represents corrections from atomic binding (arXiv:1610.04177)



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# Likelihood Fit with data

Make a likelihood fit to the 29 binned data below 30 KeV, by combining these NSI-induced events with XENON1T’s best-fit background modeling *B*0

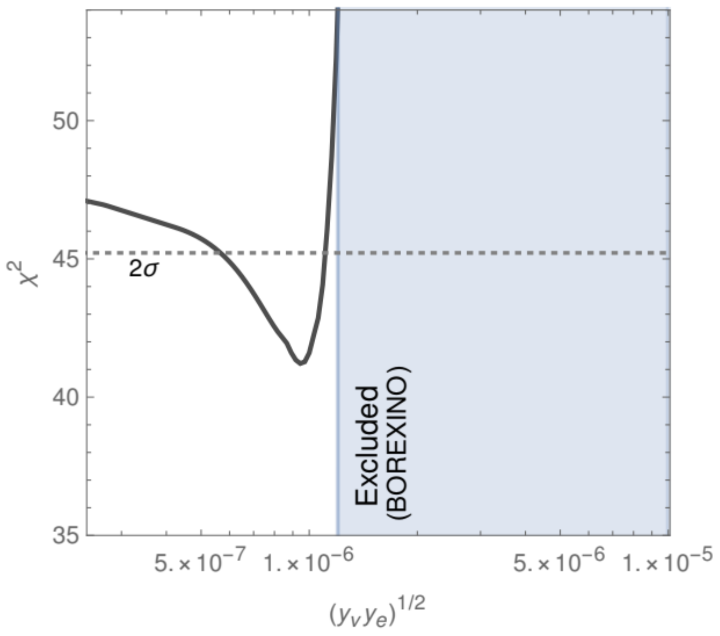
$$\chi^2 = \sum_i \frac{(\eta B0_i + N_i^{e\nu} - N_i^{\rm data})^2}{(\delta N_i)^2} + \frac{(1-\eta)^2}{(\delta\eta)^2}, \qquad \delta_\eta = 3\%.$$

The last term represents normalization uncertainty in the background model

In the low *ER* range, the detector background *B*0 is primarily the flat $^{214}\mathrm{Pb}$ component, which is a calibrated in the entire 1-210 KeV range and has a 2% statistic uncertainty. Detector efficiency modeling would contribute another 1% normalization uncertainty, so we take a combined $\delta\eta = 3\%$

# Fit to XENON1T

Minimal $\chi 2$ after marginalizing over $\eta$



**Best-fit point** at

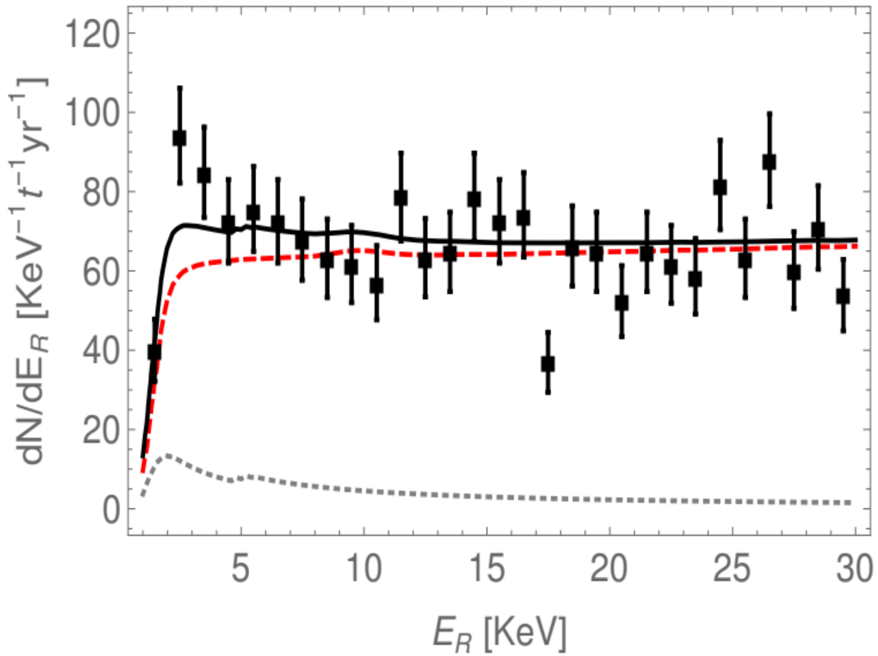
$\sqrt{y_\upsilon y_e}$= 0.96 $\times 10^{-6}$

Background $\eta$B0

with $\eta$ = 95.5%

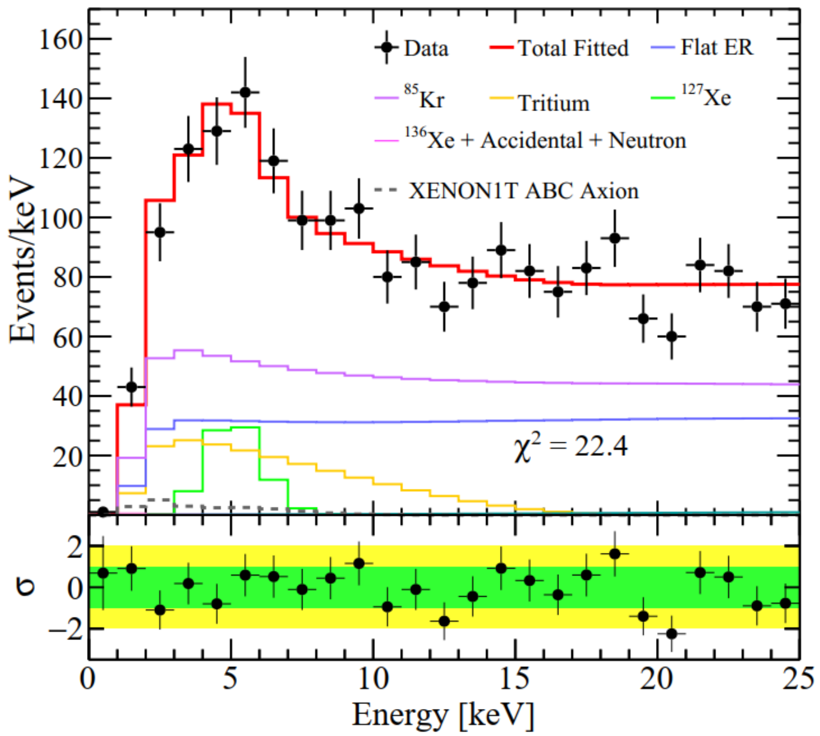
Best-fit solar neutrino NSI event distribution

The NSI signal assumes the low $M_s$ limit.



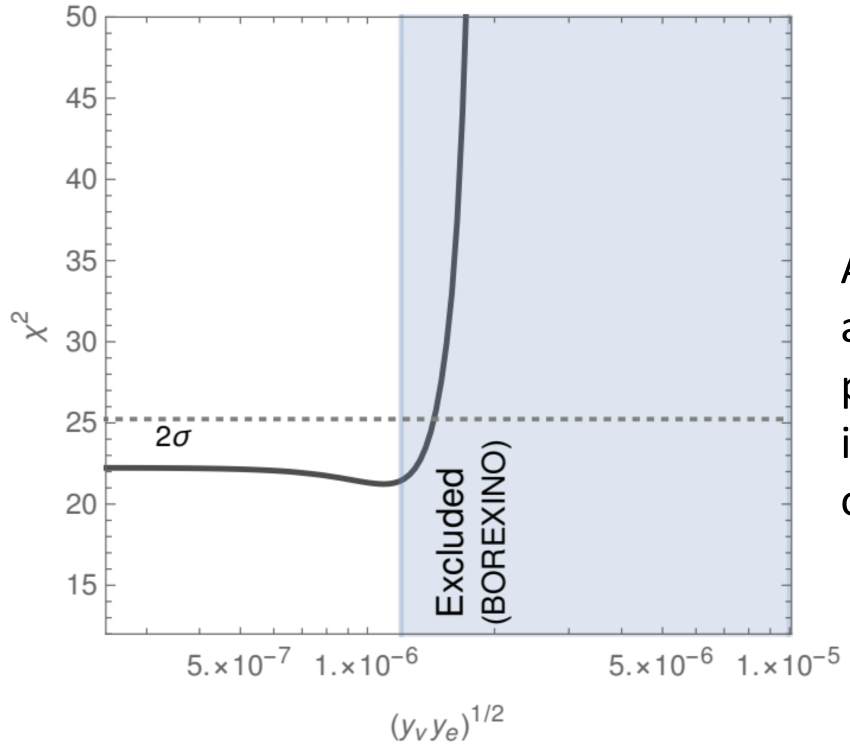
- $\sqrt{y_\upsilon y_e} \rightarrow 0$ direction approaches to the background-only fit , The shaded region is inferred from the BOREXINO bound.
- a minimal $\chi 2$ = 41 is obtained at $\sqrt{y_\upsilon y_e}$ = 0.96 $\times 10^{-6}$ with the background being slightly down-scaled at $\eta$ - 1 = -4.5%.
- The best fit point yields a $\Delta\chi 2$ = -6.7 improvement over fixed $B0$ fit ($\eta$ = 1).

# Fit to PandaX



**PandaX's results on Electron Recoil**

There is also a rise at 3-7KeV with 100.7 ton-day exposure



A minimal $\chi 2$ = 21.2 is obtained at $\sqrt{y_\upsilon y_e}$ = 1.1 $\times 10^{-6}$ and this point yields a $\Delta\chi 2$ = -1.6 improvement over background-only fitting results.

New physical contribution is consistent with background-only fit and we can constrain it as $\sqrt{y_\upsilon y_e} < 1.4 \times 10^{-6}$.

# Conclusion

- The $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model can generate s$\bar{\nu}^c\nu$ and $s\bar{e}e$ couplings via heavy fields above the $U(1)_{B-L}$ breaking scale. These couplings can lead to non-standard $\nu_i e^- \longrightarrow \nu_j^c e^-$scattering.

- Solar MeV neutrinos may scatter off detector's electron via NSI, and enhance low $E_R$ electron recoil event rate that explains the observed excess in XENON1T experiment.

- PandaX consider more background into experiment to explain the rise. But the new physical contribution is consistent with background-only fit and we can constrain it as $\sqrt{y_\upsilon y_e} < 1.4 \times 10^{-6}$.

# THANKS！