

New constraint on neutrino magnetic moment and neutrino millicharge
from LUX-ZEPLIN dark matter search results

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The role of the elastic neutrino-electron scattering in constraining the neutrino magnetic moment and millicharge using the LUX-ZEPLIN data



Nicola Cargioli

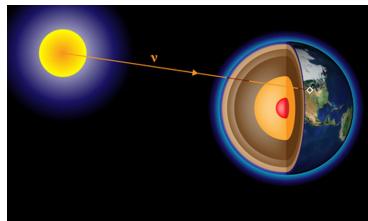
nicola.cargioli@ca.infn.it

Magnificent CEvNS Munich-23 March 2023

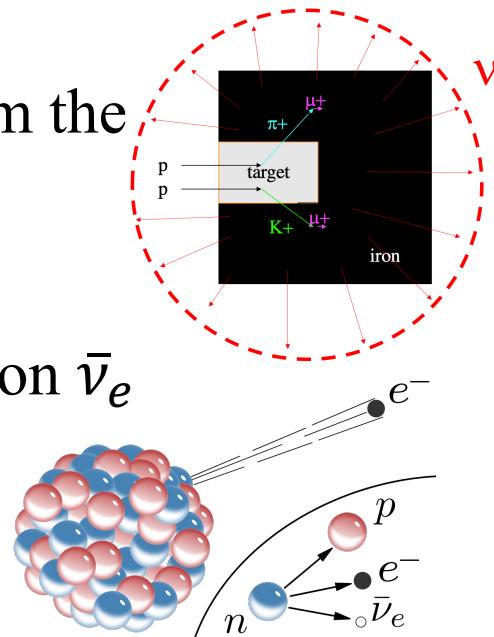
Neutrinos: Background For Dark Matter Searches

Low energy neutrino interactions are a powerful tool to test the SM and investigate BSM scenarios

Many different source that can be exploited

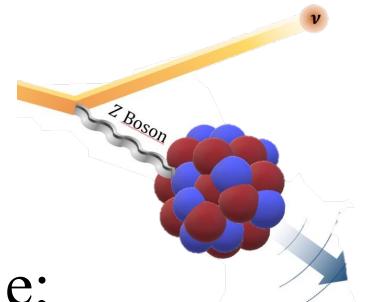
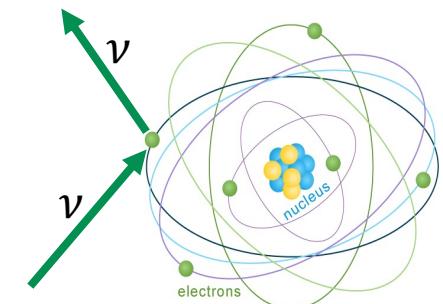


- **Solar Neutrinos:** huge flux of neutrinos coming from the Sun spanning on a wide range of energies up to 20 MeV
- **π/K -DAR:** neutrinos from the decay-at-rest of $\pi/\mu/K$ s (for example, @ SNS)
- **Reactor Neutrinos:** electron $\bar{\nu}_e$ produced by the β -decays during the fission chain



Mainly two processes that enter the game

- **ν ES:** elastic scattering off atomic electrons detectable recoil energy; elastic process with low momentum transfer
- **CE ν NS:** coherent interaction with atomic nuclei low momentum transfer and small nuclear recoil energy; the nucleus recoils as a whole; nuclear structure plays a role



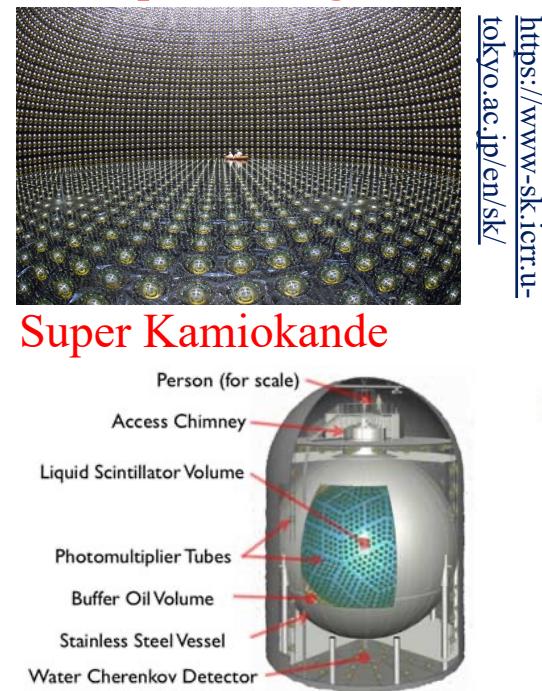
Neutrinos: Background For Dark Matter Searches

Solar Neutrinos: huge flux of neutrinos coming from the Sun

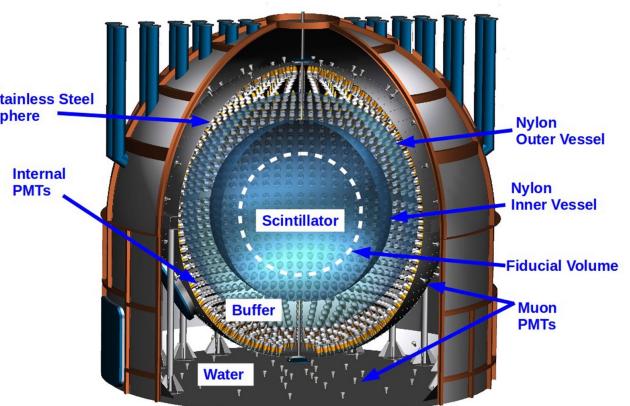
ν ES: elastic scattering off atomic electrons

Many experiments have been built for detecting solar neutrinos via ν ES and CE ν NS
But also, some other detectors could represent an **opportunity** for neutrino physics

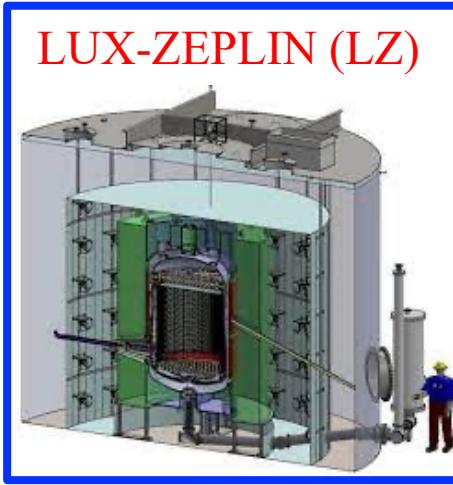
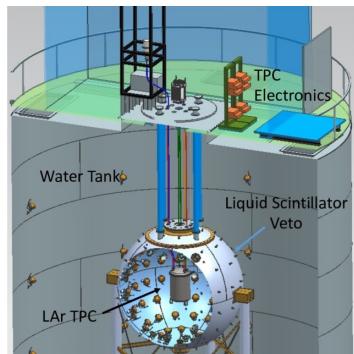
Examples of **Big Solar neutrino experiments:**



Interplay between Neutrino Experiments and Direct Dark Matter searches



Present and future looks bright with **Big Direct Dark Matter detectors:** designed for Dark Matter (WIMPs) searches: low thresholds, low background ...

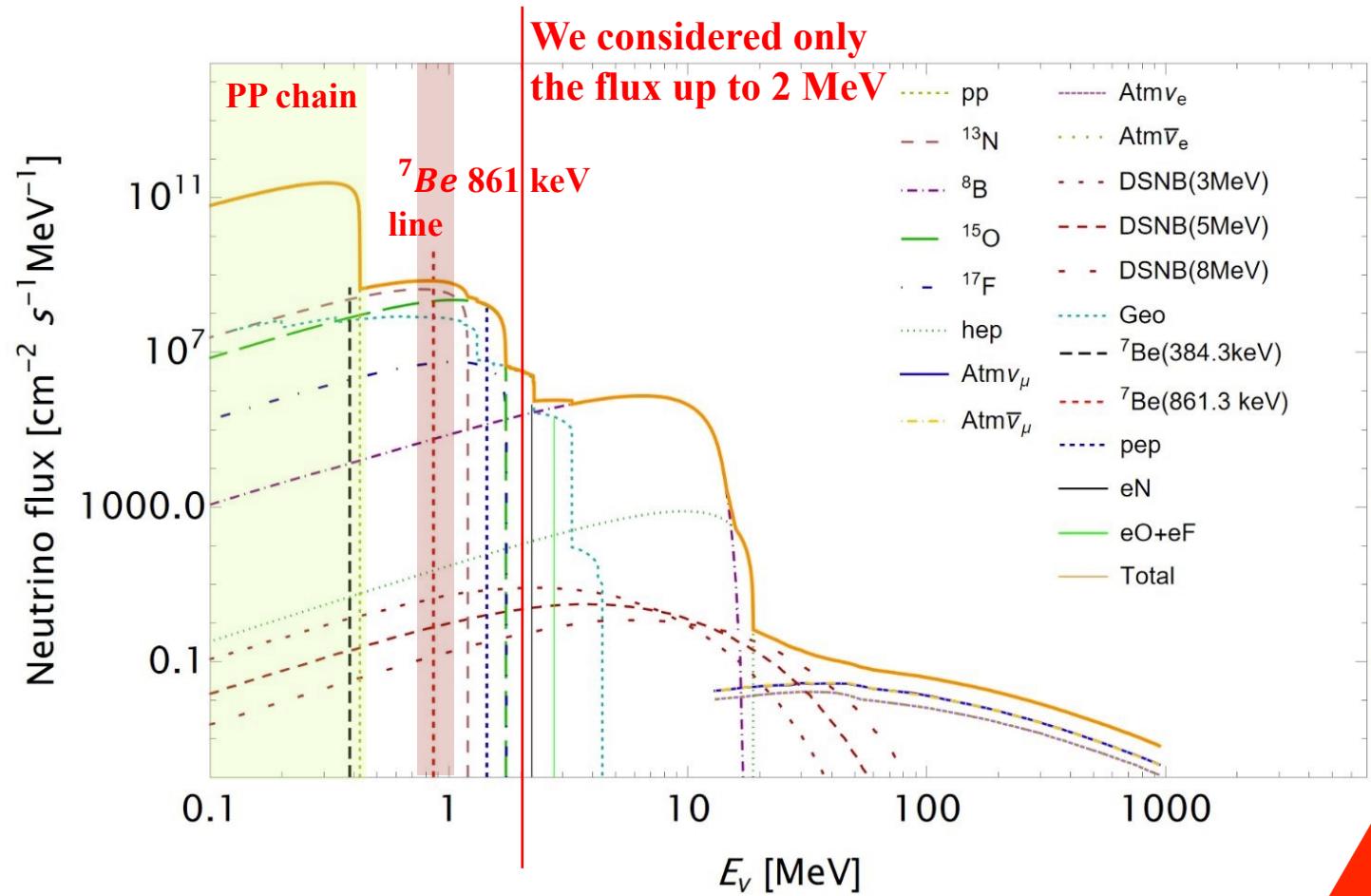


In this work we exploit LZ data

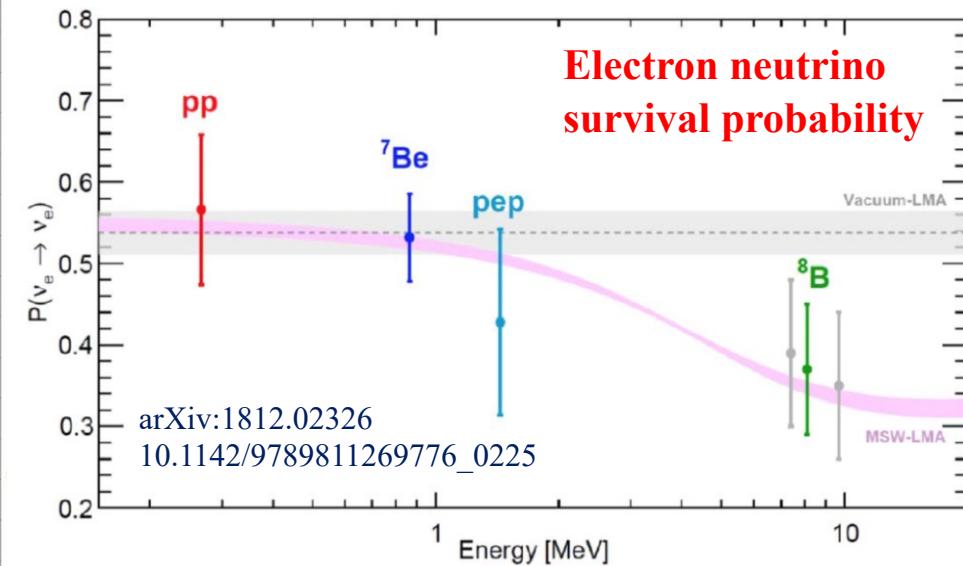
... and many more experiments

Solar Neutrinos Flux

Only a “narrow” part of the total flux contributes to the analysis: the low energy contributions



But interactions are **flavor dependent** in the SM → we need to identify the neutrino flavor for each flux component



Neutrino oscillations need to be accounted for when calculating the total cross section



$$\frac{d\sigma_\nu}{dT_e}(E, T_e) = P_{ee} \frac{d\sigma_{\nu_e}}{dT_e} + \sum_{f=\mu,\tau} P_{ef} \frac{d\sigma_{\nu_f}}{dT_e}$$

The total cross section is the sum of the different flavor contribution weighted by the probability of having a certain neutrino flavor

ν ES In Standard Model And Beyond

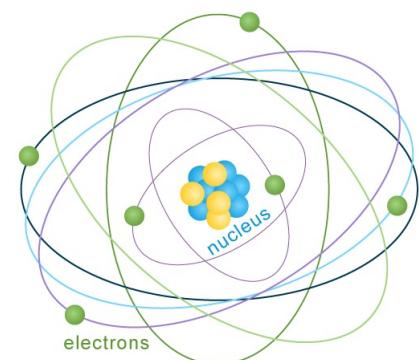
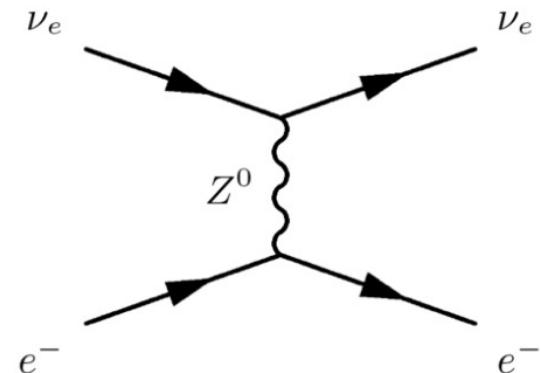
“Simple lepton-lepton” interaction

For electron neutrinos CC+NC, for muon and tau neutrinos only NC

The interactions is not with free electrons but atomic electrons

$$\frac{d\sigma_{\nu_e e}^{\text{free}}}{dT_e}(E, T_e) = \frac{G_F^2 m_e}{2\pi} \left[(g_V^{\nu_e} + g_A^{\nu_e})^2 + (g_V^{\nu_e} - g_A^{\nu_e})^2 \left(1 - \frac{T_e}{E}\right)^2 - (g_V^{\nu_e 2} - g_A^{\nu_e 2}) \frac{m_e T_e}{E^2} \right]$$

Neutrino-electron (free) cross section



The couplings can be calculated precisely in SM accounting for radiative corrections

For free electrons one would just define the free-electron cross section for the atomic number Z

For bound electrons the situation is more complicated, **we will discuss some possible descriptions**

The interaction is modified in presence of beyond the standard model neutrino properties

We consider the possibility for the so-called **neutrino Electromagnetic Properties**

Neutrino Magnetic Moment



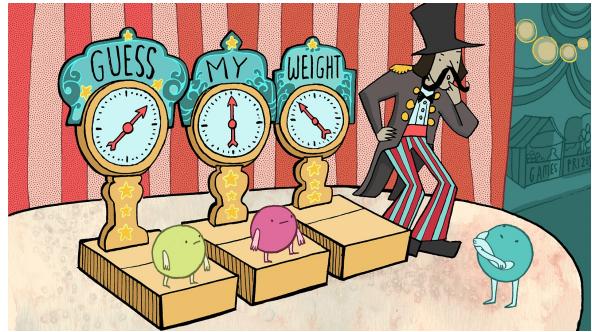
Neutrinos could have a “small” **magnetic moment**, also in relation with their small (but non-zero) masses

Neutrino Electric (milli-)Charge

Neutrinos could manifest an **electric charge**, even if significantly small

Neutrino Magnetic Moment

<https://neutrinos.fnal.gov/mysteries/mass/>



In the minimal extension of SM in which neutrinos acquire Dirac masses through the introduction of right-handed neutrinos, the **magnetic moment (MM)** is

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Rev.Mod.Phys. 87 (2015) 531

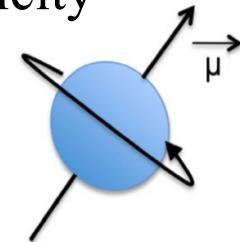
$$\mu_\nu = \frac{3 e G_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 * 10^{-19} \left(\frac{m_\nu}{eV} \right) \mu_B$$

The magnetic moment interaction adds **incoherently** to the weak interaction because it flips helicity

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$$\frac{d\sigma_{\nu_\ell}^{\text{MM, free}}}{dT_e}(E, T_e) = \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E} \right) \left| \frac{\mu_{\nu_\ell}}{\mu_B} \right|^2$$

MM cross section $\propto 1/T_e$



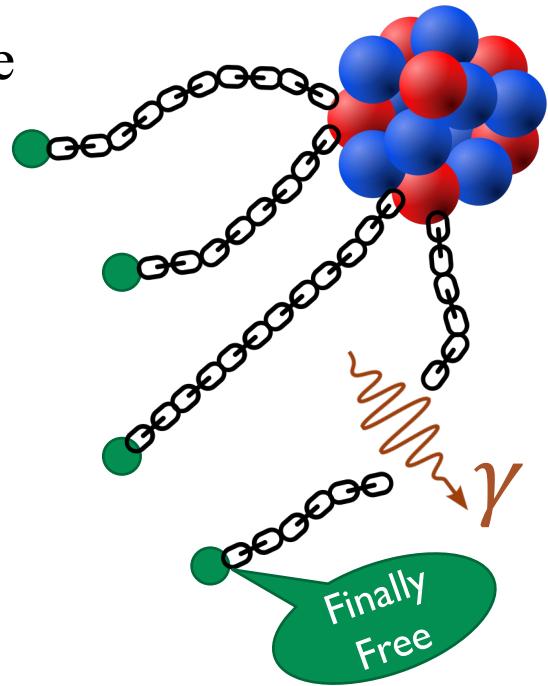
However, neutrinos are a **mixture** of mass eigenstates due to the phenomenon of oscillations; the measured MM from Solar ν ES is an **effective value** given by

$$\mu_\nu^{2, \text{ eff}} = \sum_j \left| \sum_k \mu_{jk} A_k(E, L) \right|^2$$

Where μ_{jk} is an element of the **neutrino electromagnetic moments matrix** and $A_k(E, L)$ is the amplitude of the k-mass state at the point of scattering

Neutrino Magnetic Moment

If atomic electrons were free, the cross section would just be multiplied by the atomic number Z . This is **not a good approximation**: electrons are **bound**!



FEA approximation: Free Electron Approximation modified via a stepping function

atomic number Z \longrightarrow effective $Z_{\text{eff}}(T_e)$

this accounts for the **effective number of electrons** that can be **ionized by a certain energy deposit T_e**

TABLE II. The effective electron charge of the target atom, $Z_{\text{eff}}^{\text{Xe}}(T_e)$.

| |
|--|
| $54, T_e > 34.561 \text{ keV}$ |
| $52, 34.561 \text{ keV} \geq T_e > 5.4528 \text{ keV}$ |
| $50, 5.4528 \text{ keV} \geq T_e > 5.1037 \text{ keV}$ |
| $48, 5.1037 \text{ keV} \geq T_e > 4.7822 \text{ keV}$ |
| $44, 4.7822 \text{ keV} \geq T_e > 1.1487 \text{ keV}$ |
| $42, 1.1487 \text{ keV} \geq T_e > 1.0021 \text{ keV}$ |
| $40, 1.0021 \text{ keV} \geq T_e > 0.9406 \text{ keV}$ |
| $36, 0.9406 \text{ keV} \geq T_e > 0.689 \text{ keV}$ |
| $32, 0.689 \text{ keV} \geq T_e > 0.6764 \text{ keV}$ |
| $26, 0.6764 \text{ keV} \geq T_e > 0.2132 \text{ keV}$ |
| $24, 0.2132 \text{ keV} \geq T_e > 0.1467 \text{ keV}$ |
| $22, 0.1467 \text{ keV} \geq T_e > 0.1455 \text{ keV}$ |
| $18, 0.1455 \text{ keV} \geq T_e > 0.0695 \text{ keV}$ |
| $14, 0.0695 \text{ keV} \geq T_e > 0.0675 \text{ keV}$ |
| $10, 0.0675 \text{ keV} \geq T_e > 0.0233 \text{ keV}$ |
| $4, 0.0233 \text{ keV} \geq T_e > 0.0134 \text{ keV}$ |
| $2, 0.0134 \text{ keV} \geq T_e > 0.0121 \text{ keV}$ |
| $0, T_e \leq 0.0121 \text{ keV}$ |

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$Z_{\text{eff}}(T_e)$ is specific for every atom

Important for Xenon (binding energies are not negligible)

It has been obtained using edge energies from photo-absorption data

$$\frac{d\sigma_{\nu_\ell e}^{\text{FEA}}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e) \frac{d\sigma_{\nu_\ell e}^{\text{free}}}{dT_e}(E, T_e) + Z_{\text{eff}}(T_e) \frac{d\sigma_{\nu_\ell e}^{\text{MM, free}}}{dT_e}(E, T_e)$$

Neutrino Electric Charge

In some BSM scenarios, neutrinos can have an **electric charge** EC (and thus a coupling to the photon)

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In the **FEA approximation**, the contribution of the EC to the cross section is not incoherent, and it is obtained by substituting the SM vector coupling with

$$g_V^{\nu_\ell} \rightarrow \tilde{g}_V^{\nu_\ell} = g_V^{\nu_\ell} + \frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu_\ell}$$

Contribution
 $\propto 1/q^2 \approx 1/T_e$
Cross section $\propto 1/T_e^2$

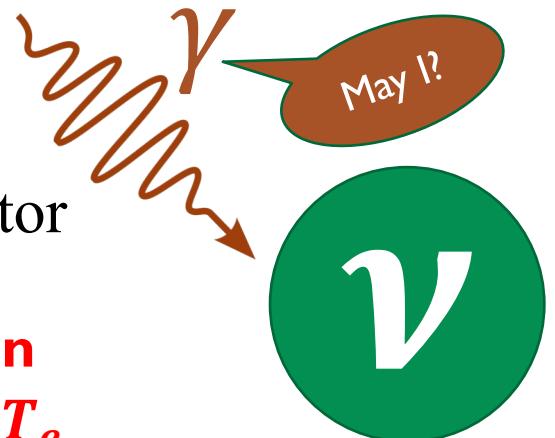
The **sign** of the electric charge **does matter!**



the contribution is enhanced at low recoil energies for both MM and EC

In the FEA approximation the cross section is

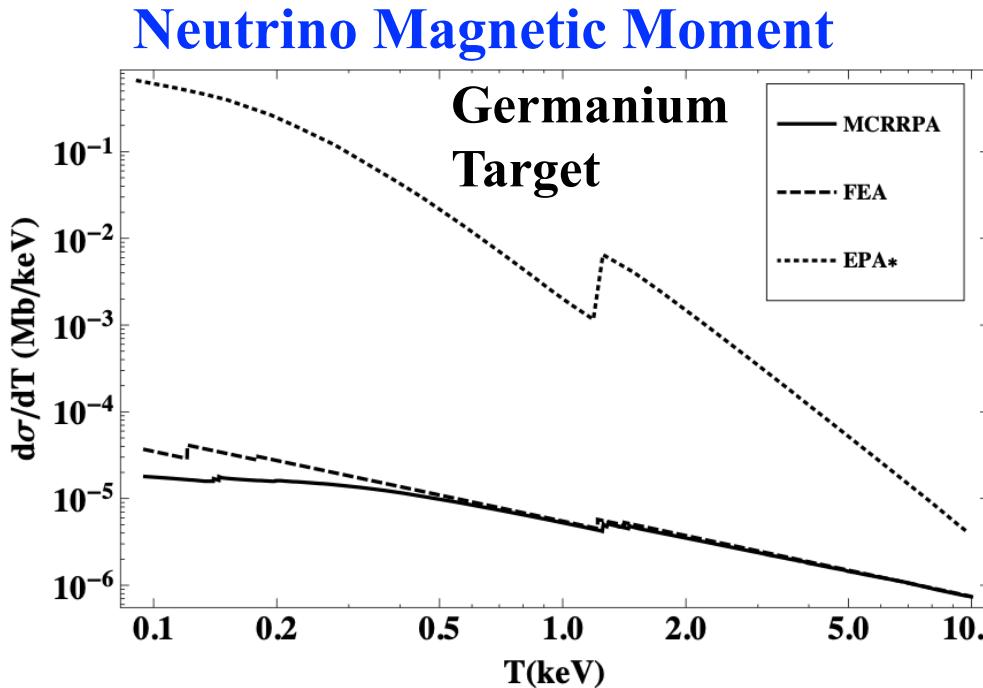
$$\frac{d\sigma_{\nu_\ell e}^{\text{FEA, EC}}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e) \frac{G_F^2 m_e}{2\pi} \left[\left(\tilde{g}_V^{\nu_\ell} + g_A^{\nu_\ell} \right)^2 + \left(\tilde{g}_V^{\nu_\ell} - g_A^{\nu_\ell} \right)^2 \left(1 - \frac{T_e}{E} \right)^2 - \left(\tilde{g}_V^{\nu_\ell \ 2} - g_A^{\nu_\ell \ 2} \right) \frac{m_e T_e}{E^2} \right]$$



FEA and EPA approximations

RRPA: Relativistic Random-Phase Approximation, ab-initio approach able to improve the description of the atomic many-body effects

EPA: Equivalent Photon Approximation, relates the ionization cross section to the photo-absorption one

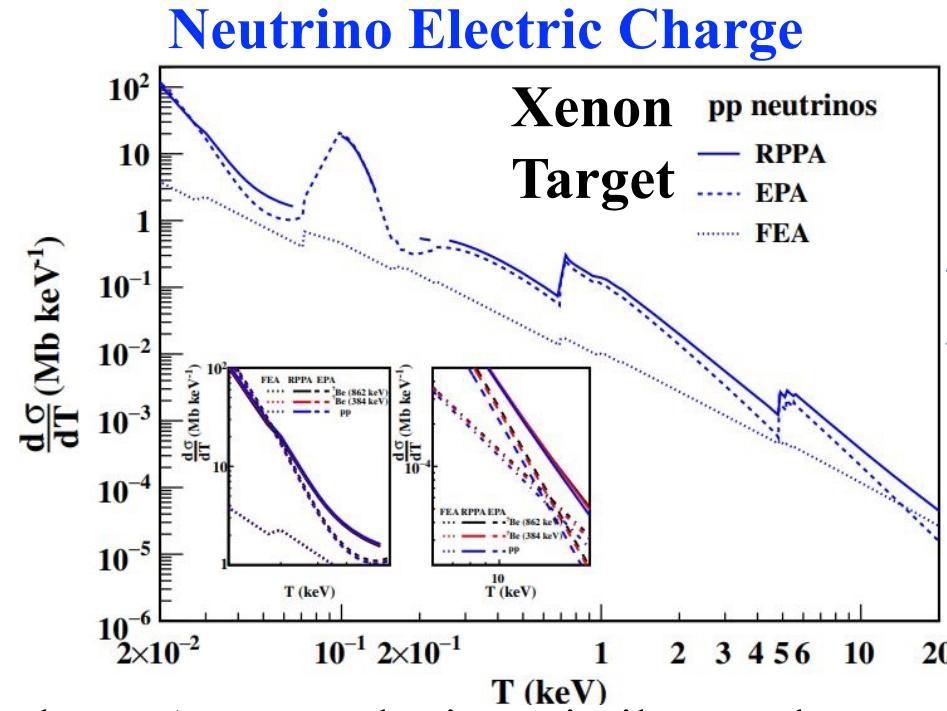


The FEA approach gives similar results to RRPA for the MM, while **EPA doesn't work well**

The EPA cross section depends on the neutrino mass ($m_\nu = 1 \text{ eV}$)
The sign doesn't matter

$$\frac{d\sigma_{\nu\ell e}^{\text{EPA, EC}}}{dT_e}(E, T_e) = \frac{2\alpha}{\pi} \frac{\sigma_\gamma(T_e)}{T_e} \log \left[\frac{E}{m_\nu} \right] q_{\nu\ell}^2$$

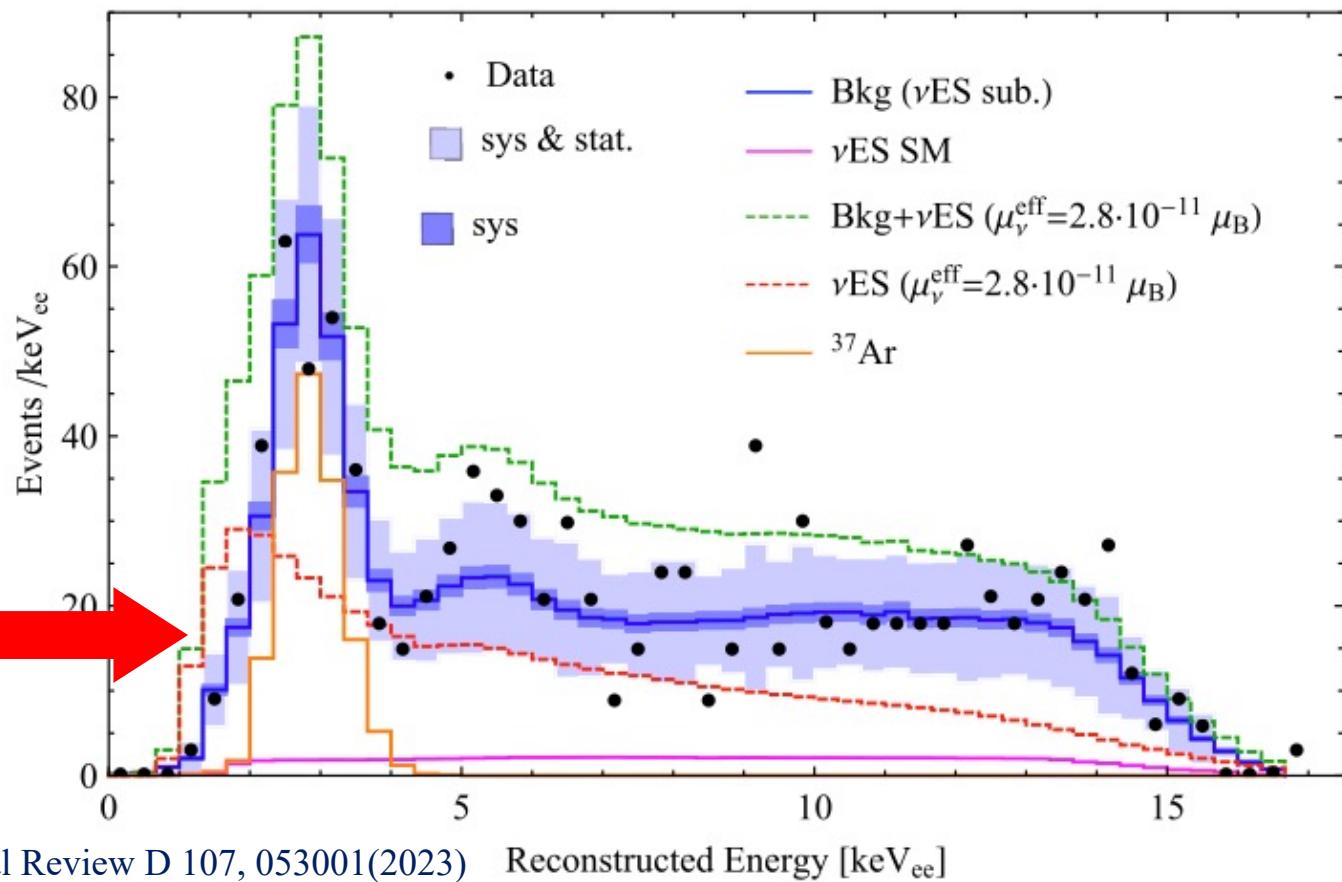
PHYSICAL REVIEW D
100, 073001 (2019)



The EPA approach gives similar results to RRPA for the EC, while **FEA doesn't work well**

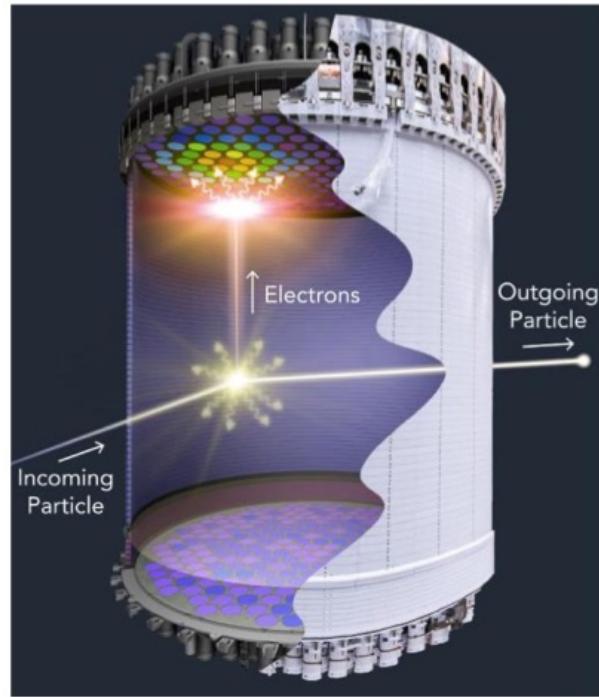
THE LZ Dark Matter Detector As A Probe Of Neutrinos

5.5 t fiducial LXe detector at Sanford Underground Research Facility in Lead, South Dakota
~5 keV_{nr} threshold (efficiency=50%)
60.3 live days
 333 ± 17 events of which 27.2 ± 1.6 events of νES



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Reconstructed Energy [keV_{ee}]



J. Aalbers et al., First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022), arXiv:2207.03764

What LZ Says About ν MM And ν EC

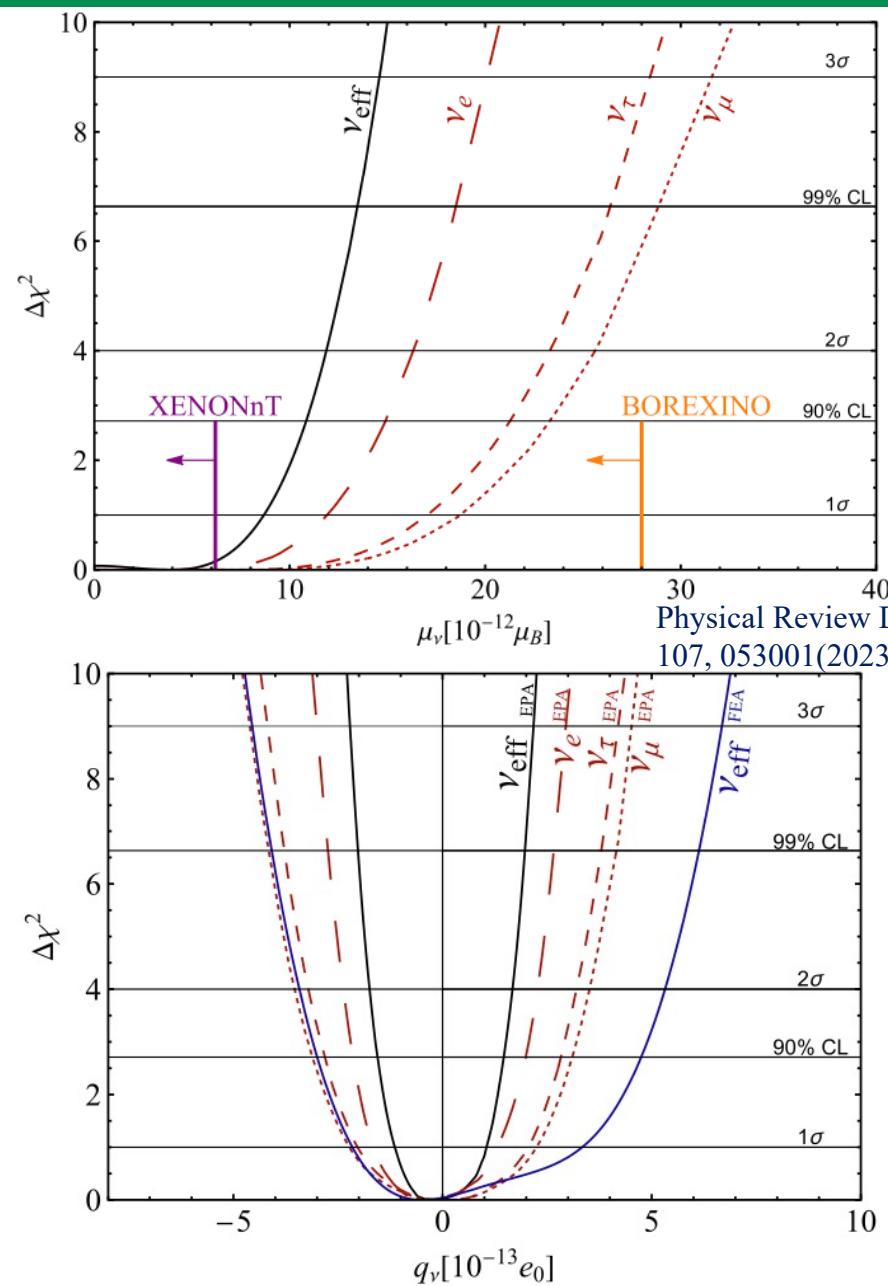
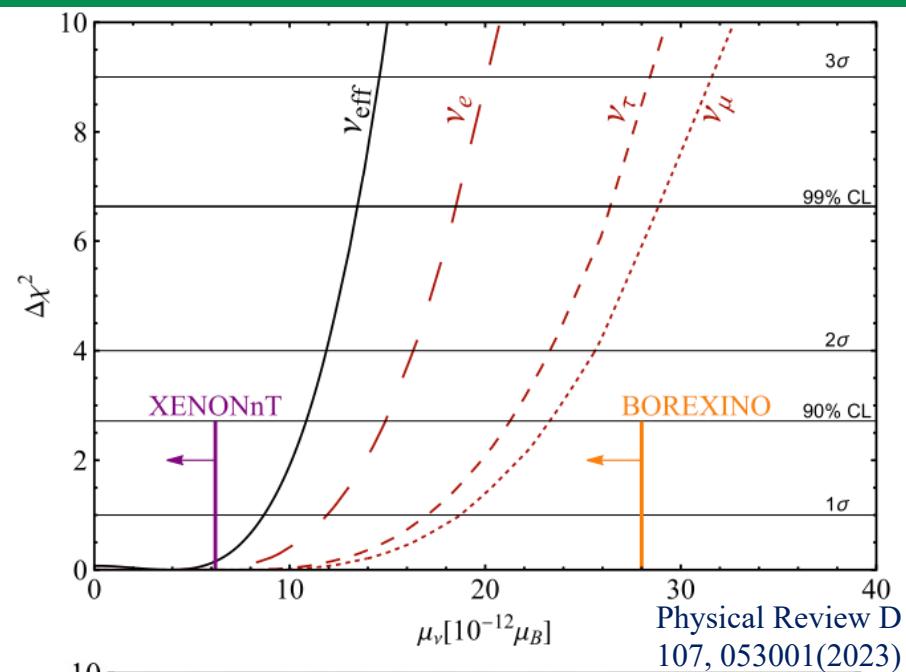
$$\chi^2 = 2 \sum_{i=1}^{51} \left[(1 + \alpha) N_i^{\text{bkg}} + (1 + \beta) N_i^{\nu\text{ES}} - N_i^{\text{exp}} \right. \\ \left. + N_i^{\text{exp}} \ln \left(\frac{N_i^{\text{exp}}}{(1 + \alpha) N_i^{\text{bkg}} + (1 + \beta) N_i^{\nu\text{ES}}} \right) \right] \\ + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2,$$

$\sigma_\alpha = 5.1\%$ neutrino background
 $\sigma_\beta = 7\%$ neutrino flux

TABLE I. Limits on the neutrino magnetic moment and neutrino millicharge at 90% C.L. obtained with a χ^2 analysis as defined in Eq. (10). For the neutrino millicharge, the limits are reported for both the FEA and the EPA formalism.

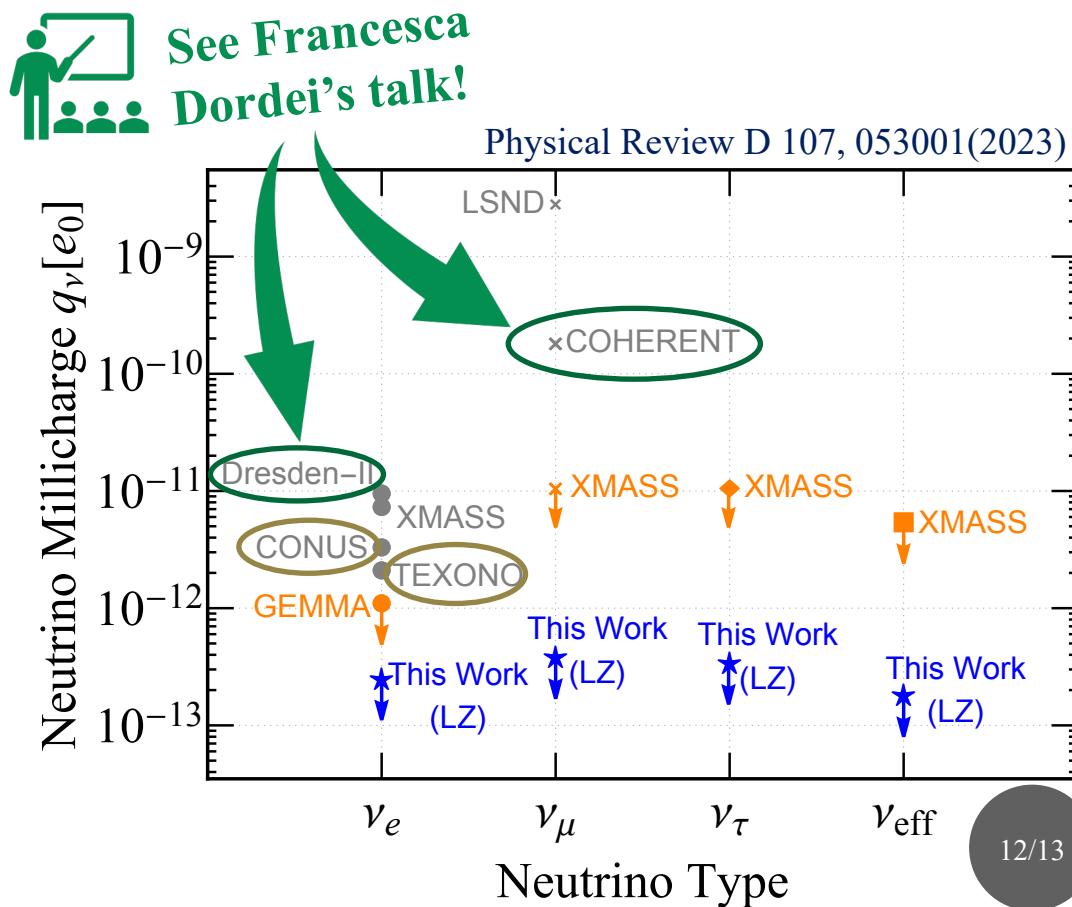
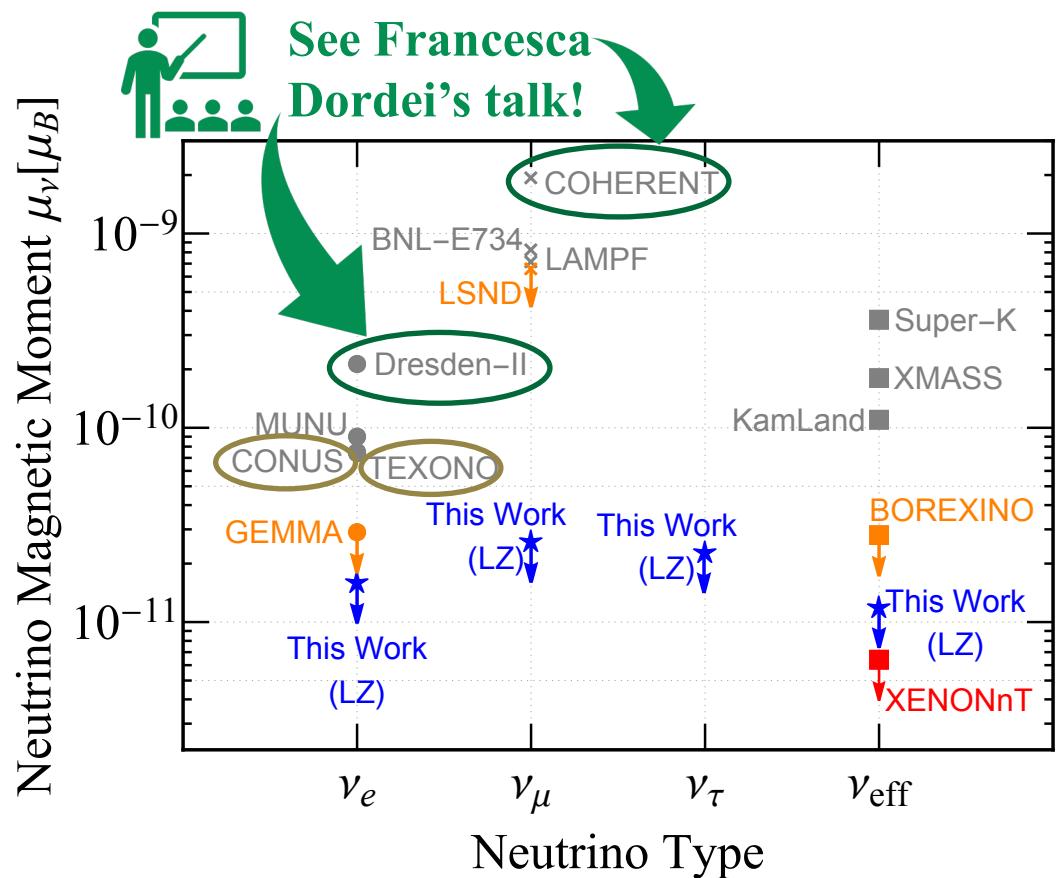
| | $q_\nu [\times 10^{-13} e_0]$ | FEA | EPA |
|--------------------|-------------------------------------|-------------|-------------|
| | $ \mu_\nu [\times 10^{-11} \mu_B]$ | | |
| ν_{eff} | <1.1 | [−3.0, 4.7] | [−1.5, 1.5] |
| ν_e | <1.5 | [−3.6, 6.5] | [−2.1, 2.0] |
| ν_μ | <2.3 | [−8.9, 8.8] | [−3.1, 3.1] |
| ν_τ | <2.1 | [−8.1, 8.1] | [−2.8, 2.8] |

$$\mu_v^{\text{eff}}(\text{XENONnT}) < 6.4 \times 10^{-12} \mu_B \quad \text{Phys. Rev. Lett. 129, 161805 (2022)}$$



World Wide Picture

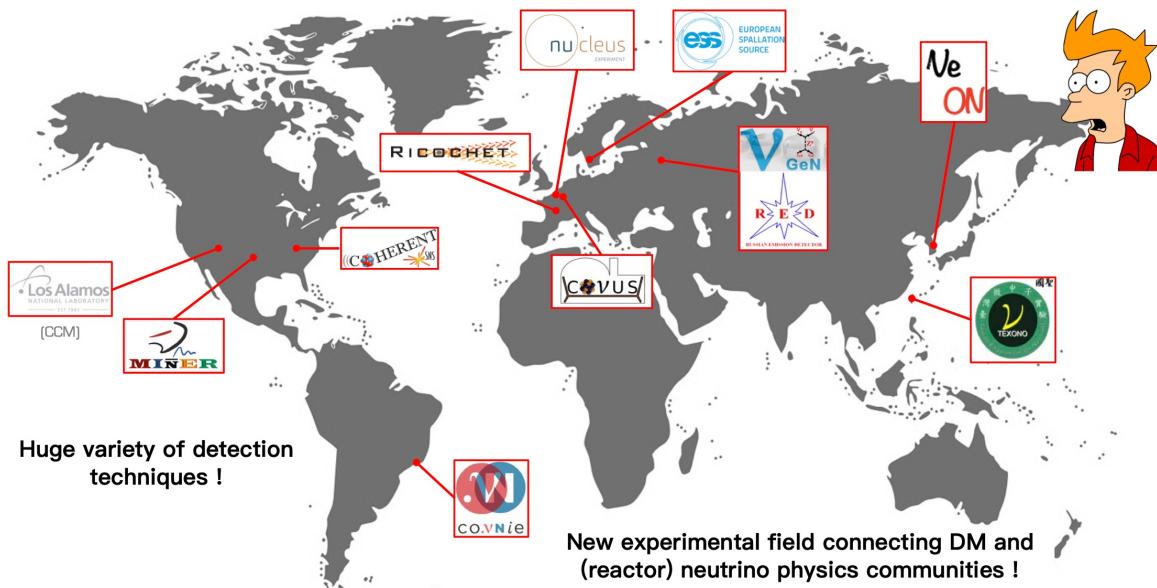
- LZ data allowed us to set the **second-best world limit on neutrino MM** from laboratory experiments, second to the recent XENONnT result
- And the **strongest constraint on neutrino EC** when the EPA approximation is adopted to describe the neutrino-electron interaction
- Great improvement with respect to previous bounds, and not far from indirect astrophysical constraints ($\mu_\nu^{\text{astro}} \sim 10^{-12} \mu_B$)



Outlook

- Dark Matter and CE ν NS Community are both putting a great effort to improve and enlarge the number of available experimental probes
- They will provide complementary information to **unveil neutrino properties**

Proliferation of experimental efforts worldwide !



Matthieu VIVIER@Magnificent CE ν NS workshop 2020



<https://ned.ipac.caltech.edu/level5/Sept17/Freese/Freese5.html>

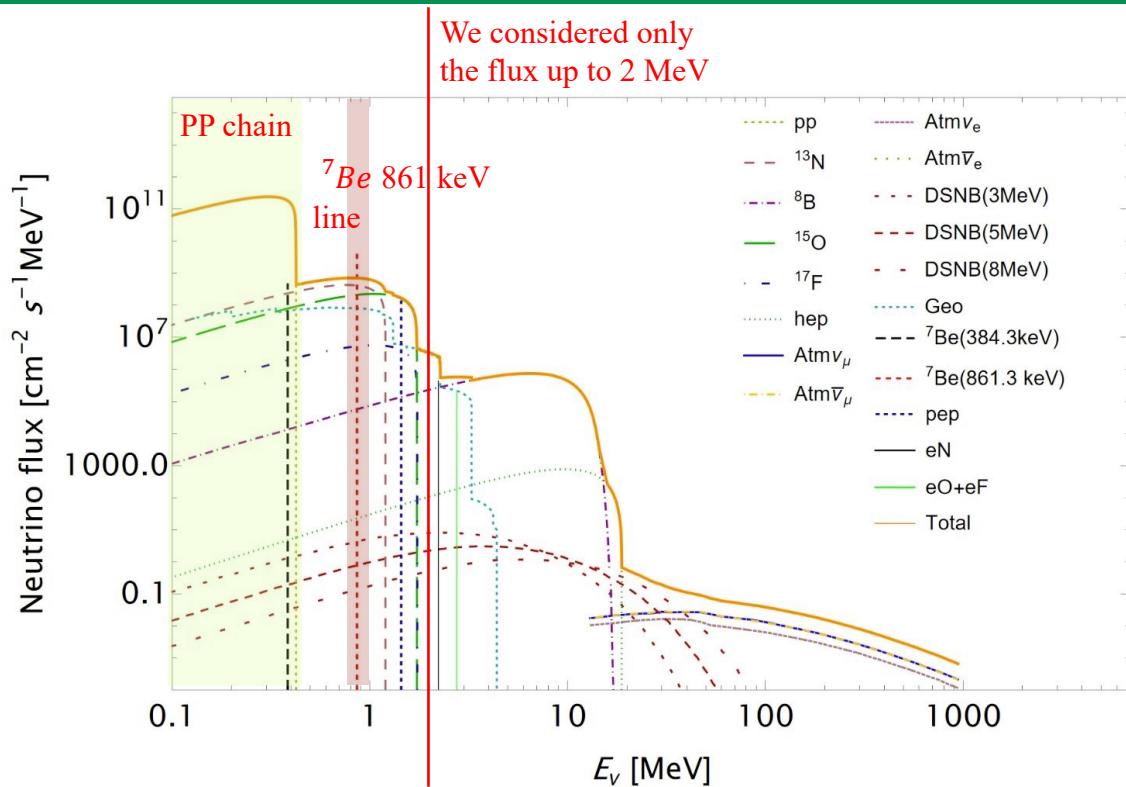
- An effort from the theoretical side is also needed, especially in defining a clear and **“user-friendly”** prescription for dealing with **neutrino scattering off atomic electrons**

THANK YOU FOR YOUR ATTENTION
QUESTIONS TIME



BACK UP SLIDES

Solar Neutrinos Flux



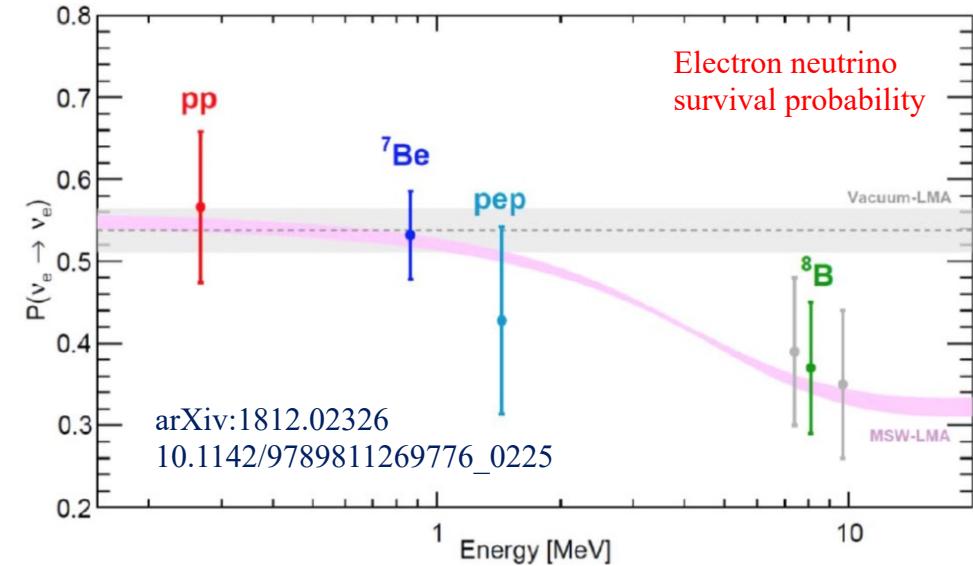
Neutrino oscillations need to be accounted for when calculating the total cross section

$P_{ee} = \sin^4 \theta_{13} + \cos^4 \theta_{13} P^{2\nu}$ is the average survival probability for solar neutrinos reaching the detector

We consider $P^{2\nu} = 0.55$, as the dominant components are pp and ${}^7\text{Be}$ fluxes (low energy spectrum)

$$P_{e\mu} = (1 - P_{ee}) \cos^2 \theta_{23} \quad \text{and} \quad P_{e\tau} = (1 - P_{ee}) \sin^2 \theta_{23}$$

But interactions are flavor dependent in the SM
We need to identify the neutrino flavor for each flux component



$$\frac{d\sigma_\nu}{dT_e}(E, T_e) = P_{ee} \frac{d\sigma_{\nu_e}}{dT_e} + \sum_{f=\mu,\tau} P_{ef} \frac{d\sigma_{\nu_f}}{dT_e}$$

ν ES In Standard Model And Beyond

$$\frac{d\sigma_{\nu_\ell e}^{\text{free}}}{dT_e}(E, T_e) = \frac{G_F^2 m_e}{2\pi} \left[(g_V^{\nu_\ell} + g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell} - g_A^{\nu_\ell})^2 \left(1 - \frac{T_e}{E}\right)^2 - (g_V^{\nu_\ell \ 2} - g_A^{\nu_\ell \ 2}) \frac{m_e T_e}{E^2} \right]$$

The couplings can be calculated precisely in SM accounting for radiative corrections

APPENDIX B: NEUTRINO-ELECTRON COUPLING DETERMINATION

In order to study the neutrino-electron scattering process, it is necessary to study in detail the calculation of the couplings, taking into account the radiative corrections. The latter are implemented following the formalism given in Ref. [64]. In particular, the ℓ flavor neutrino right and left couplings to fermions, with $f = e$, are given by

$$g_{LL}^{\nu_\ell f} = \rho \left[-\frac{1}{2} - Q_f \hat{s}_0^2 + \boxtimes_{ZZ}^{fL} \right] - Q_f \oslash_{\nu_\ell W} + \square_{WW}, \quad (\text{B1})$$

$$g_{LR}^{\nu_\ell f} = -\rho [Q_f \hat{s}_0^2 + \boxtimes_{ZZ}^{fR}] - Q_f \oslash_{\nu_\ell W}. \quad (\text{B2})$$

In these relations, $\rho = 1.00063$ represents a low-energy correction for neutral-current processes and Q_f is the

$$\oslash_{\nu_\ell W} = -\frac{\alpha}{6\pi} \left(\ln \frac{M_W^2}{m_e^2} + \frac{3}{2} \right), \quad (\text{B3})$$

$$\square_{WW} = -\frac{\hat{\alpha}_Z}{2\pi \hat{s}_Z^2} \left[1 - \frac{\hat{\alpha}_s(M_W)}{2\pi} \right], \quad (\text{B4})$$

$$\boxtimes_{ZZ}^{fX} = -\frac{3\hat{\alpha}_Z}{8\pi \hat{s}_Z^2 \hat{c}_Z^2} (g_{LX}^{\nu_\ell f})^2 \left[1 - \frac{\hat{\alpha}_s(M_Z)}{\pi} \right], \quad (\text{B5})$$

where $X \in \{L, R\}$ and $\hat{\alpha}_Z \equiv \alpha(M_Z)$. Note that in Eq. (B5) all the $(g_{LX}^{\nu_\ell f})^2$ are evaluated at lowest order but replacing \hat{s}_0^2 by \hat{s}_Z^2 and are given by $g_{LL}^{\nu_\ell e} = -\frac{1}{2} + \hat{s}_Z^2$ and $g_{LR}^{\nu_\ell e} = \hat{s}_Z^2$. For neutrino-electron scattering the couplings are given by

$$g_V^{\nu_\ell e} = \rho \left(-\frac{1}{2} + 2\hat{s}_0^2 \right) + \square_{WW} + 2\oslash_{\nu_\ell W} + \rho(\boxtimes_{ZZ}^{eL} - \boxtimes_{ZZ}^{eR}),$$

$$g_A^{\nu_\ell e} = \rho \left(-\frac{1}{2} + \boxtimes_{ZZ}^{eL} + \boxtimes_{ZZ}^{eR} \right) + \square_{WW},$$

$$\text{where } g_A^{\nu_\ell e} = g_{LL}^{\nu_\ell e} - g_{LR}^{\nu_\ell e}.$$

For the numerical SM evaluation we assume the values from Refs. [15,65], namely $\hat{s}_0^2 = 0.23857$, $\hat{s}_Z^2 = 0.23121$, $\alpha_s(M_W) = 0.123$, $\alpha_s(M_Z) = 0.1185$, and $\hat{\alpha}_Z^{-1} = 127.952$. We thus obtain the couplings $g_V^{\nu_e} = 0.9521$, $g_A^{\nu_e} = 0.4938$, $g_V^{\nu_\mu} = -0.0397$, $g_A^{\nu_\mu} = -0.5062$, and $g_V^{\nu_\tau} = -0.0353$ that take into account all radiative corrections. We note that, for the ν_e coupling, an unity factor has been added to the result in order to take into account the charge current contribution.

ν ES In Standard Model And Beyond

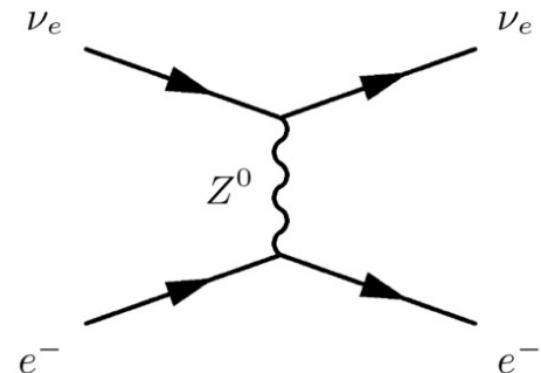
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Neutrino-electron (free) cross section



The couplings can be calculated precisely in SM accounting for radiative corrections, so that
 $g_V^{\nu_e} = 0.9521$, $g_A^{\nu_e} = 0.4938$, $g_V^{\nu_\mu} = -0.0397$, $g_V^{\nu_\tau} = -0.0353$, $g_A^{\nu_\mu, \nu_\tau} = -0.5062$

For free electrons one would just define the free-electron cross section for the atomic number Z



For bound electrons the situation is more complicated, **we will discuss some possible descriptions**

The interaction is modified in presence of beyond the standard model neutrino properties

We consider the possibility for the so-called neutrino Electromagnetic Properties

Neutrino Magnetic Moment

Neutrino Electric (milli-)Charge

Neutrinos could have a small magnetic moment, also in relation with their small (but non-zero) masses

Neutrinos could manifest an electric charge, even if significantly small

Neutrino Magnetic Moment

<https://neutrinos.fnal.gov/mysteries/mass/>



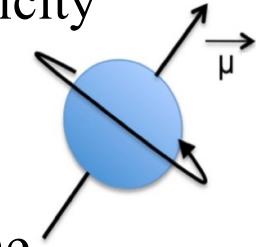
In the minimal extension of SM in which neutrinos acquire Dirac masses through the introduction of right-handed neutrinos, the magnetic moment (MM) is

$$\mu_\nu = \frac{3 e G_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 * 10^{-19} \left(\frac{m_\nu}{eV} \right) \mu_B$$

The magnetic moment interaction adds incoherently to the weak interaction because it flips helicity

$$\frac{d\sigma_{\nu_\ell}^{\text{MM, free}}}{dT_e}(E, T_e) = \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E} \right) \left| \frac{\mu_{\nu_\ell}}{\mu_B} \right|^2$$

MM cross section $\propto 1/T_e$



However, neutrinos are a mixture of mass eigenstates due to the phenomenon of oscillations; the measured MM from Solar ν ES is an effective value given by

$$\mu_\nu^{2, \text{ eff}} = \sum_j \left| \sum_k \mu_{jk} A_k(E, L) \right|^2$$

Where μ_{jk} is an element of the neutrino electromagnetic moments matrix and $A_k(E, L)$ is the amplitude of the k-mass state at the point of scattering

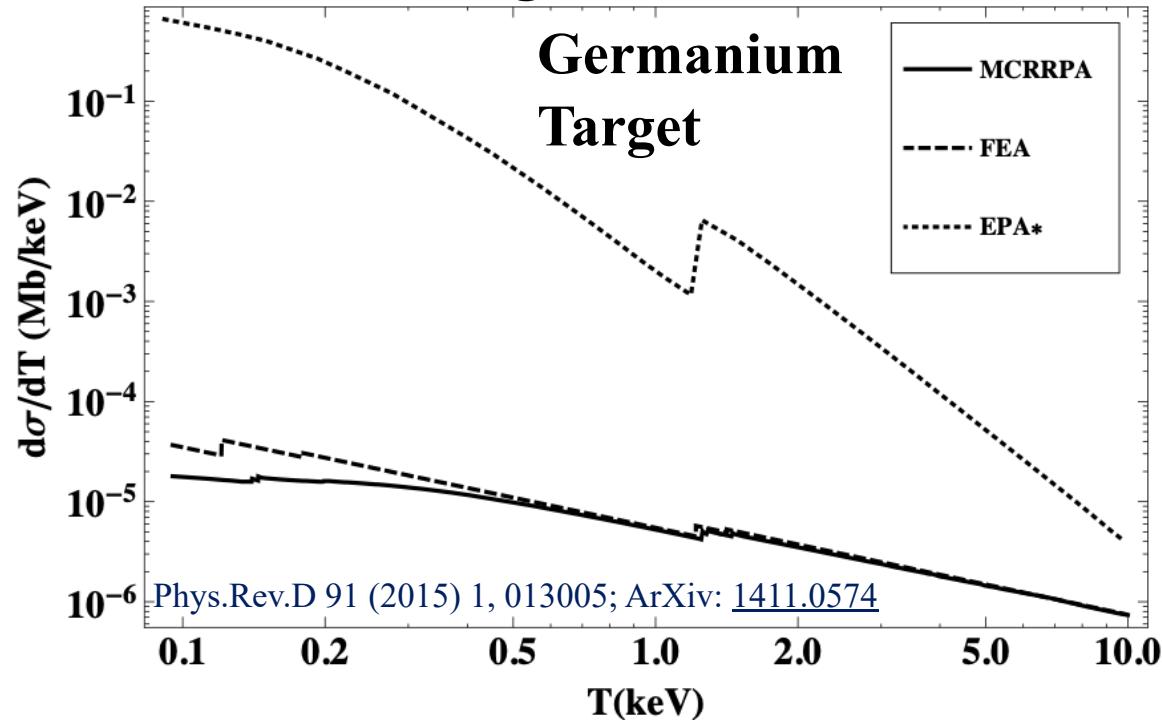
For the **Majorana neutrino**, only the transition moments are nonzero (diagonal set to zero due to CPT conservation)



For the **Dirac neutrino**, all elements are potentially nonzero

FEA and EPA approximations

Neutrino Magnetic Moment

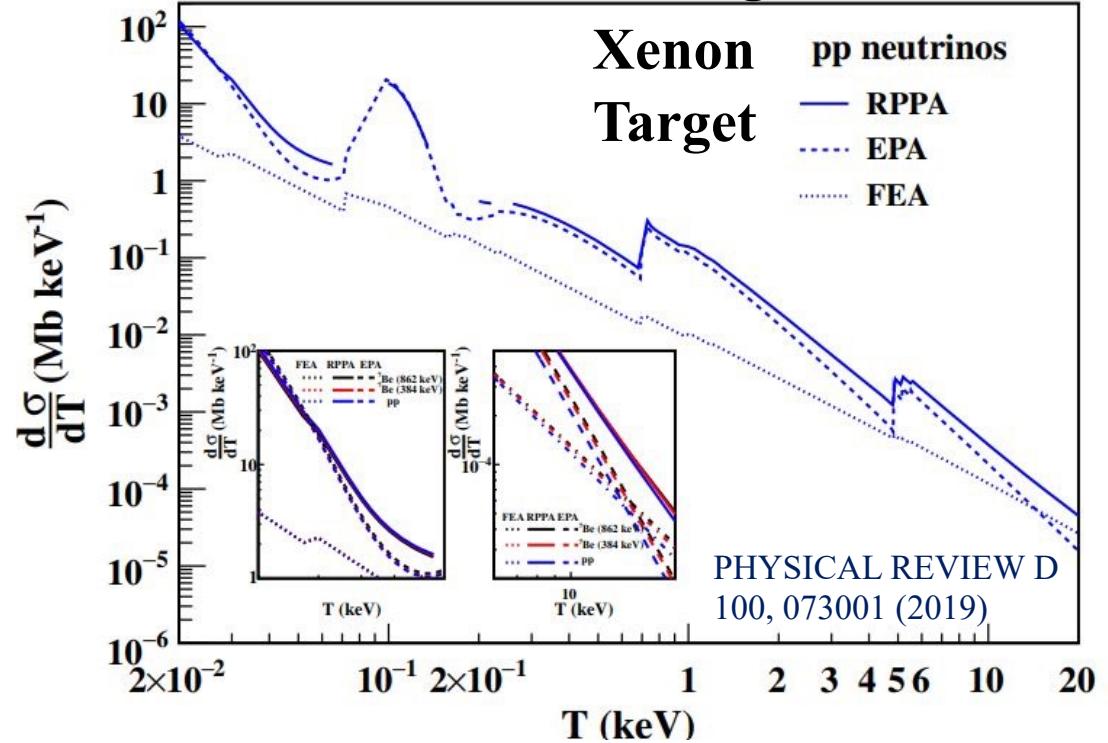


The FEA approach gives similar results to RRPA for the MM, while EPA doesn't work well

$$\frac{d\sigma_{\nu_\ell e}^{\text{EPA, EC}}}{dT_e}(E, T_e) = \frac{2\alpha}{\pi} \frac{\sigma_\gamma(T_e)}{T_e} \log \left[\frac{E}{m_\nu} \right] q_{\nu_\ell}^2$$

The cross section depends on the neutrino mass ($m_\nu = 1$ eV)
The sign doesn't matter

Neutrino Electric Charge



The FEA approach underestimates the cross section respect to RRPA for the EC, while EPA gives similar results

However, EPA works well only for recoils below few keVs, so when we use EPA, we actually take the larger cross section between EPA and FEA
Phys. Rev. D 99, 032009 (2019)

THE LZ Dark Matter Detector As A Probe Of Neutrinos

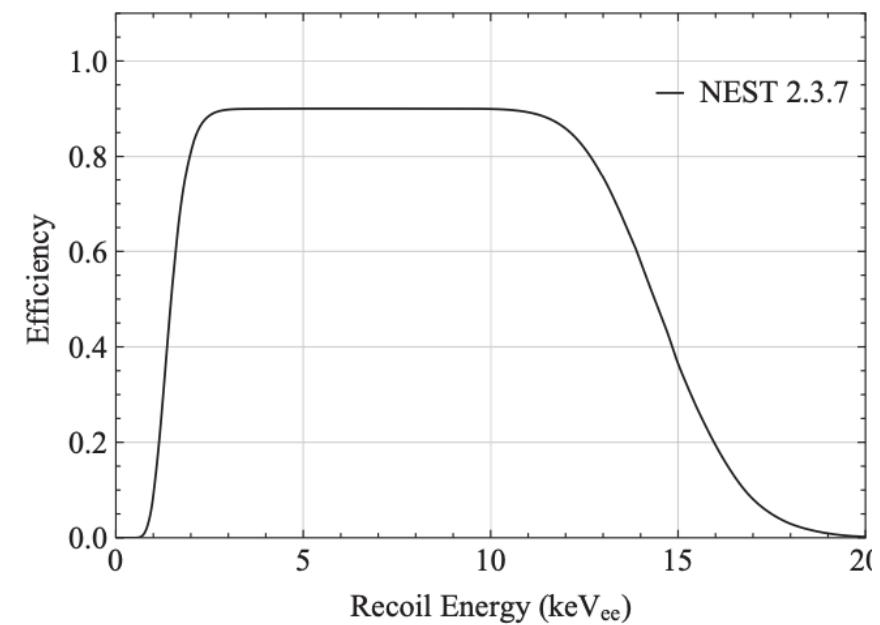
5.5 t fiducial LXe detector at Sanford Underground Research Facility in Lead, South Dakota

~5 keV_{nr} threshold

60.3 live days

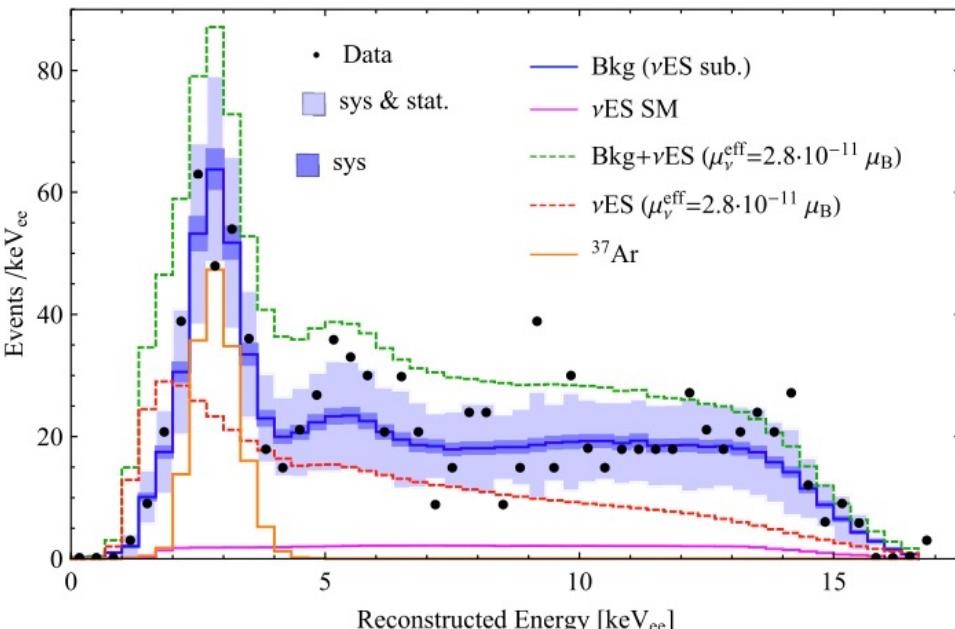
333±17 events of which 27.2 ± 1.6 events of ν ES

$$N_i^{\nu\text{ES}} = N(Xe) \int_{T_E^i}^{T_e^{i+1}} dT_e A(T_e) \int_{E_{\min}(T_e)}^{E_{\max}} dE \sum_j \frac{dN_{\nu, j}}{dE}(E) \frac{d\sigma_{\nu}}{dT_e}(E, T_e)$$



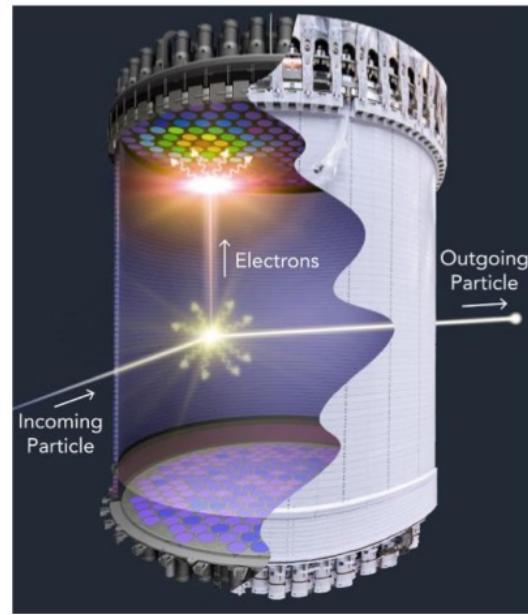
Physical Review D 107, 053001(2023)

NICOLA CARGIOLI



Physical Review D 107, 053001(2023)

23 MARCH 2023



J. Aalbers et al., First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022), arXiv:2207.03764

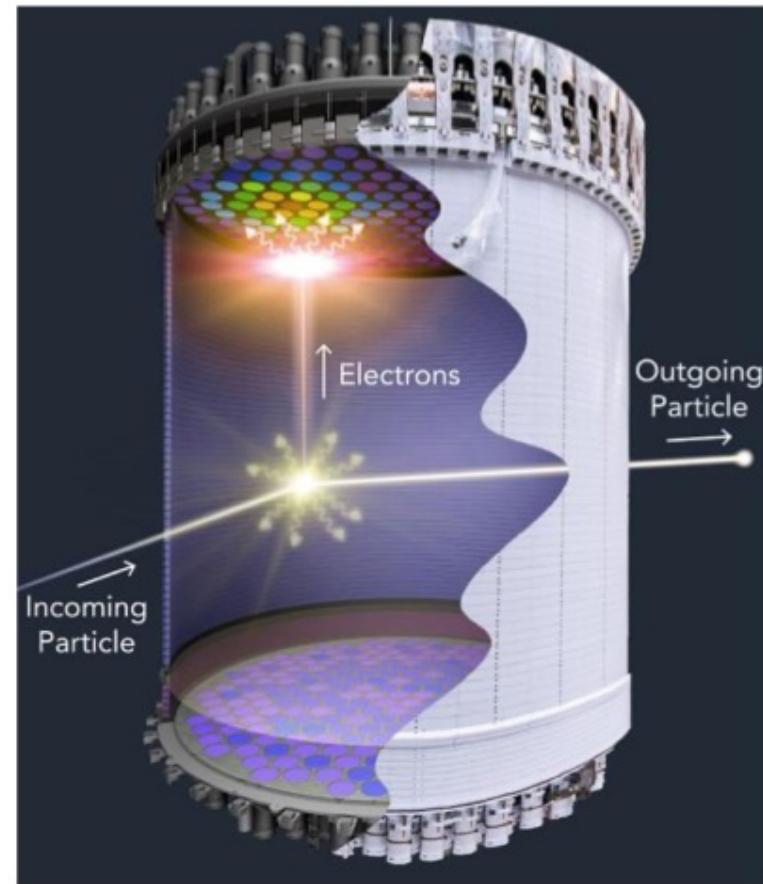
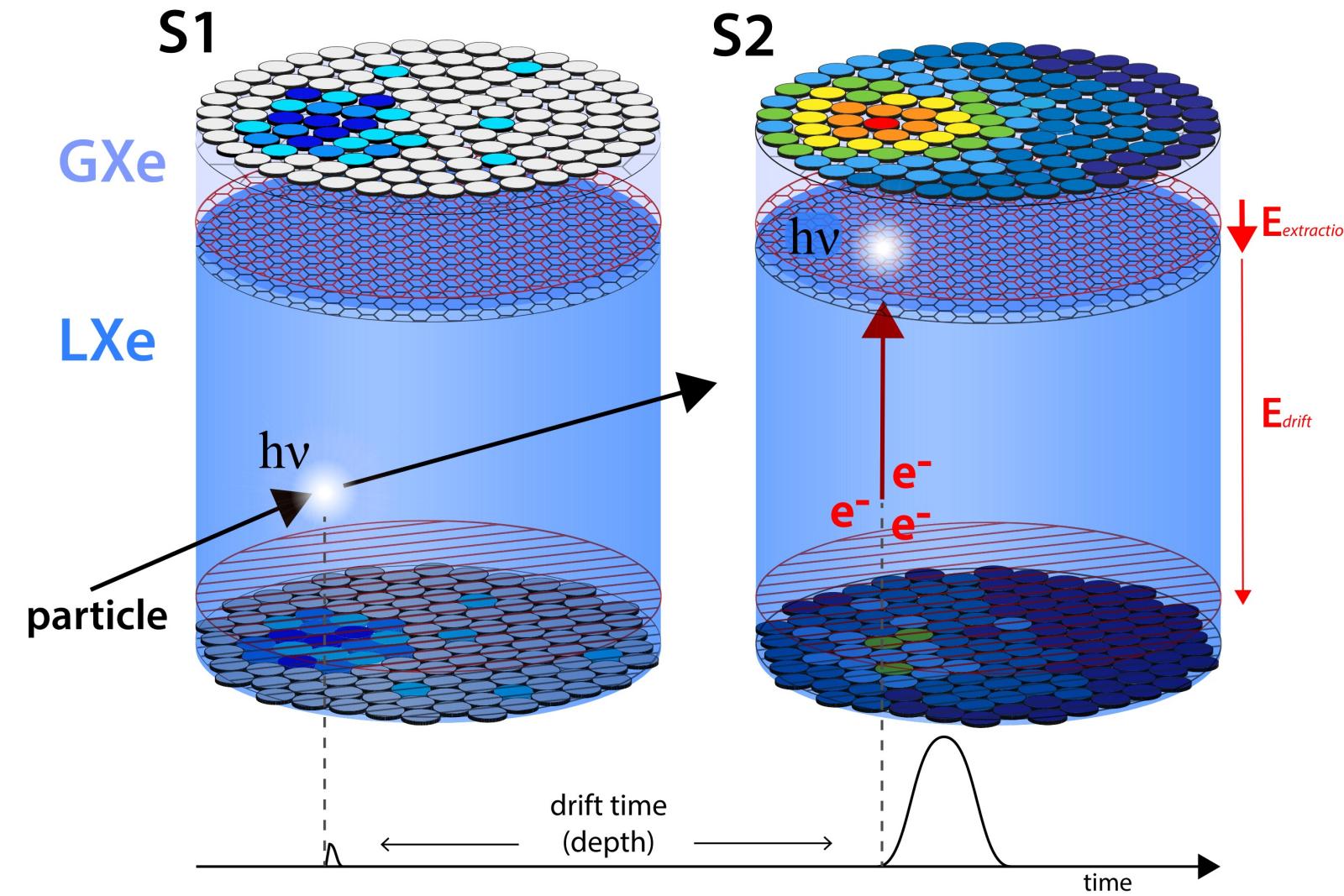


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Limits from LUX-Zeplin data

MAGNIFICENT CE ν NS

THE LZ Dark Matter Detector As A Probe Of Neutrinos



J. Aalbers et al., First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022), arXiv:2207.03764

<https://doi.org/10.3390/universe7080313>

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THE LZ Dark Matter Detector As A Probe Of Neutrinos

Physical Review D 107, 053001(2023)

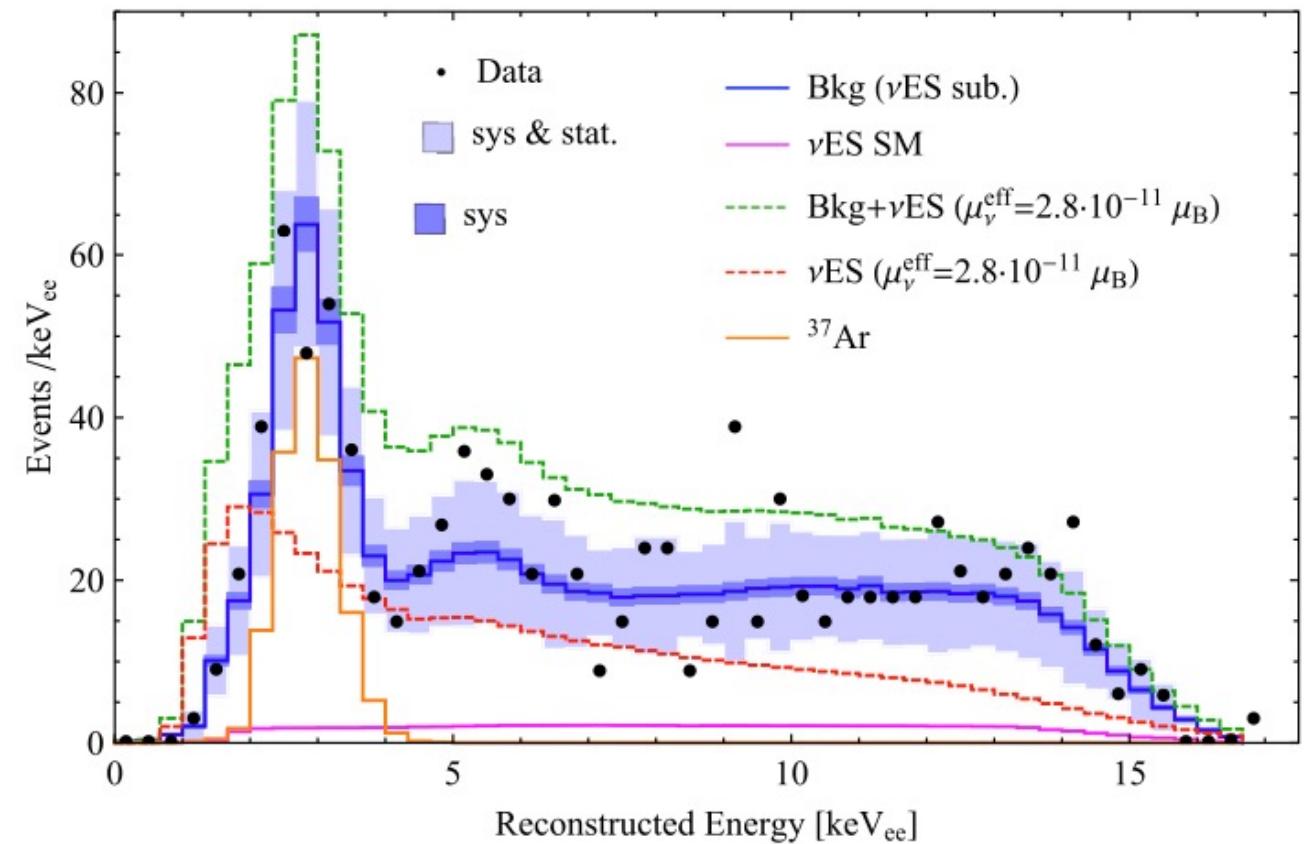
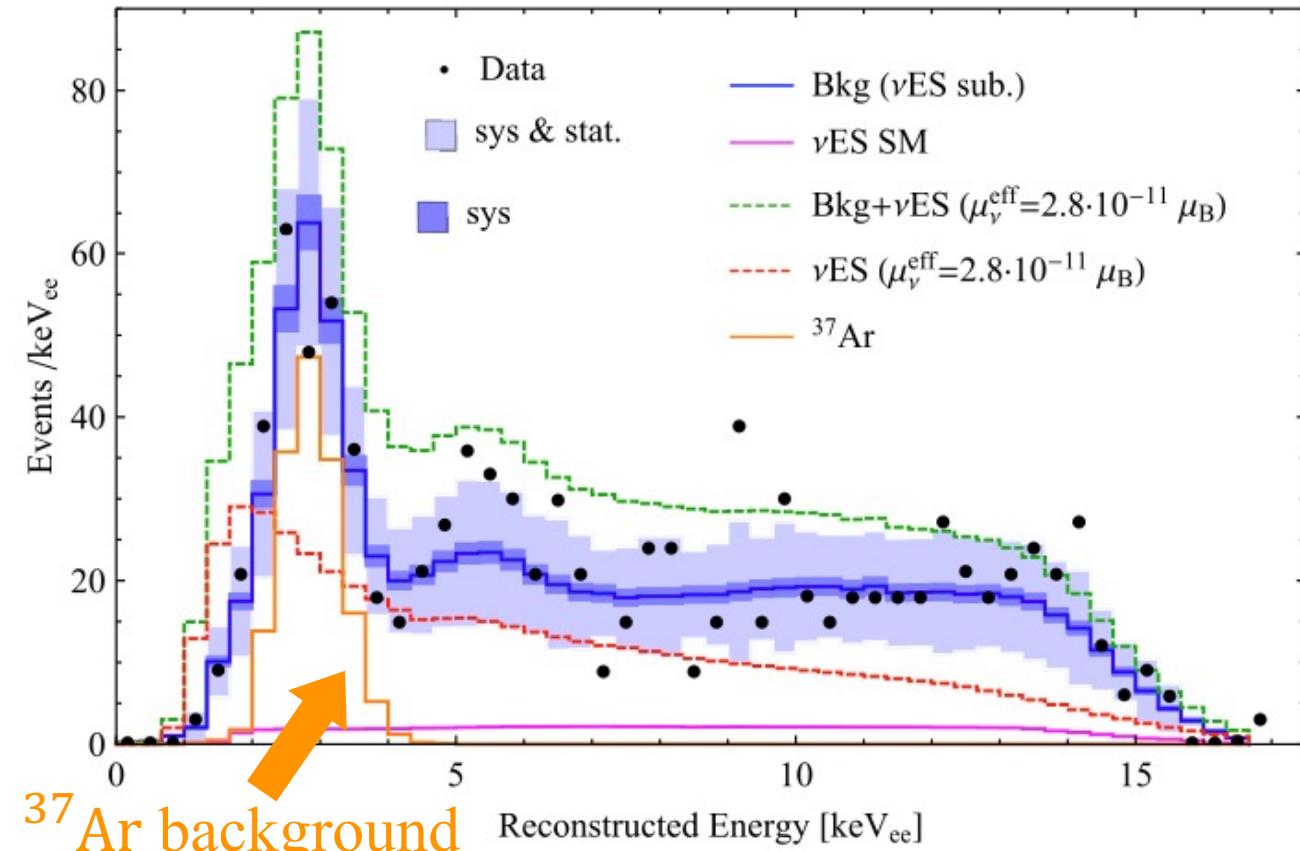


TABLE I. Number of events from various sources in the $60\text{ d} \times 5.5\text{ t}$ exposure. The middle column shows the predicted number of events with uncertainties as described in the text. The uncertainties are used as constraint terms in a combined fit of the background model plus a $30\text{ GeV}/c^2$ WIMP signal to the selected data, the result of which is shown in the right column. ^{37}Ar and detector neutrons have non-gaussian prior constraints and are totaled separately. Values at zero have no lower uncertainty due to the physical boundary.

| Source | Expected Events | Fit Result |
|-----------------------------|-----------------|----------------------|
| β decays + Det. ER | 215 ± 36 | 222 ± 16 |
| ν ER | 27.1 ± 1.6 | 27.2 ± 1.6 |
| ^{127}Xe | 9.2 ± 0.8 | 9.3 ± 0.8 |
| ^{124}Xe | 5.0 ± 1.4 | 5.2 ± 1.4 |
| ^{136}Xe | 15.1 ± 2.4 | 15.2 ± 2.4 |
| $^8\text{B CE}\nu\text{NS}$ | 0.14 ± 0.01 | 0.15 ± 0.01 |
| Accidentals | 1.2 ± 0.3 | 1.2 ± 0.3 |
| Subtotal | 273 ± 36 | 280 ± 16 |
| ^{37}Ar | $[0, 288]$ | $52.5^{+9.6}_{-8.9}$ |
| Detector neutrons | $0.0^{+0.2}$ | $0.0^{+0.2}$ |
| $30\text{ GeV}/c^2$ WIMP | — | $0.0^{+0.6}$ |
| Total | — | 333 ± 17 |

J. Aalbers et al., First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment (2022), arXiv:2207.03764

Argon-37 Analysis of the LZ data



$$\begin{aligned} {}^{37}\text{Ar} \text{ fixed } & \left\{ \begin{array}{l} \mu_\nu = 1.1 \times 10^{-11} \mu_B \\ \text{FEA: } -3.0 < q_\nu^{\text{eff}}[10^{-13} e_0] < 4.7, \\ \text{EPA: } -1.5 < q_\nu^{\text{eff}}[10^{-13} e_0] < 1.5, \end{array} \right. \end{aligned} \quad (14) \quad (15)$$

$$\begin{aligned} \chi^2_{{}^{37}\text{Ar}} = 2 \sum_{i=1}^{51} & \left[\alpha N_i^{\text{bkg}} + \beta N_i^{\nu\text{ES}} + \delta N_i^{{}^{37}\text{Ar}} - N_i^{\exp} \right. \\ & \left. + N_i^{\exp} \ln \left(\frac{N_i^{\exp}}{\alpha N_i^{\text{bkg}} + \beta N_i^{\nu\text{ES}} + \delta N_i^{{}^{37}\text{Ar}}} \right) \right] \\ & + \left(\frac{\alpha - 1}{\sigma_\alpha} \right)^2 + \left(\frac{\beta - 1}{\sigma_\beta} \right)^2 + \left(\frac{\delta - 1}{\sigma_\delta} \right)^2, \end{aligned}$$

$\sigma_\alpha = 13\%$ neutrino background

$\sigma_\beta = 7\%$ neutrino flux

$\sigma_\delta = 100\%$ ³⁷Ar normalization

More conservative analysis

$$\begin{aligned} {}^{37}\text{Ar} \text{ free } & \left\{ \begin{array}{l} \mu_\nu[{}^{37}\text{Ar}] = 1.2 \times 10^{-11} \mu_B \\ \text{FEA: } -3.3 < q_\nu^{\text{eff}}({}^{37}\text{Ar})[10^{-13} e_0] < 5.0, \\ \text{EPA: } -1.6 < q_\nu^{\text{eff}}({}^{37}\text{Ar})[10^{-13} e_0] < 1.5, \end{array} \right. \end{aligned} \quad (16) \quad (17)$$