Searching for new physics in liquid xenon time projection chambers

Brian Lenardo

Wright Lab Seminar @ Yale University (virtually)

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LELAND STANFORD JUNIOR UNIVERSITY

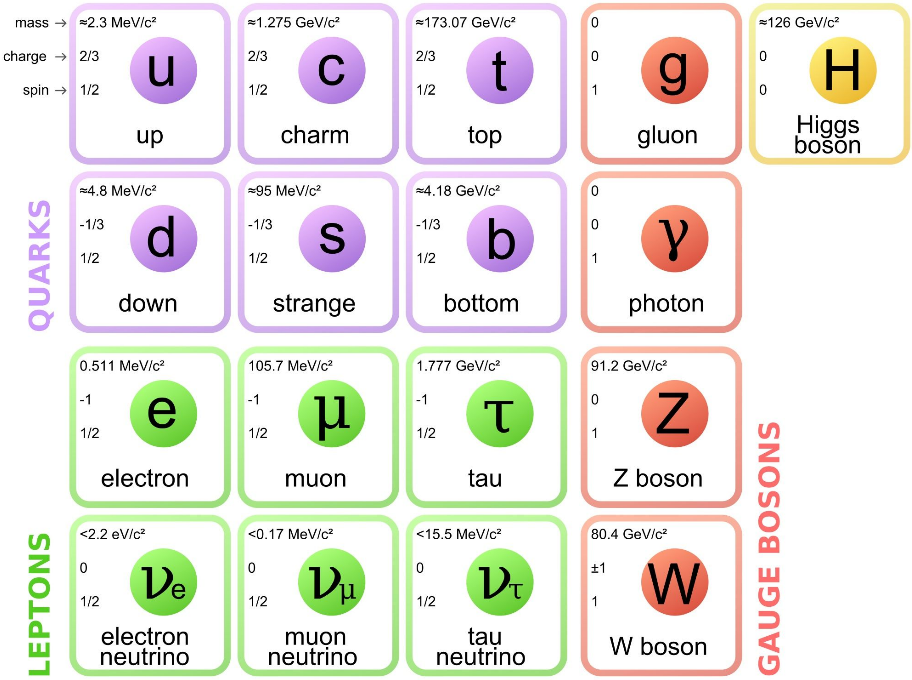
1891

Outline

1. **Why is the universe full of matter (i.e. not just radiation)?**
    - The Standard Model and lepton number violation
    - Searching for neutrinoless double beta decay
    - The nEXO experiment and discovery potential
    - Other science we can do with nEXO

2. **What is the nature of dark matter?**
    - The dark matter problem and WIMPs
    - Pushing to new parameter space with lower thresholds
    - Enhancing sensitivity via the Migdal effect

The Standard Model



The Standard Model (SM):

- Defines fundamental particles, their symmetries, and their interactions
- Remarkable predictive power:

Electron magnetic moment:

$$\begin{aligned} \textit{SM Prediction}: -\mu_{e-}/\mu_B &= 1.001\,159\,652\,181\,61\,(024) \quad [0.24\text{ ppt}], \\ \textit{Measured}: -\mu_{e-}/\mu_B &= 1.001\,159\,652\,180\,73\,(028) \quad [0.28\text{ ppt}], \end{aligned}$$

G. Gabrielse et al., *Atoms* (2019)

However, there are features of Nature which are not accounted for, including:

- Matter/antimatter asymmetry
- Dark matter
- Dark energy

What physics lies beyond the SM?

Matter/antimatter asymmetry

Why is there more matter than antimatter in the universe?

- Antigalaxies etc. ruled out by γ-ray astronomy
- Requires baryon/antibaryon asymmetry of ~10^{-9} in early universe

One possible solution: **leptogenesis**

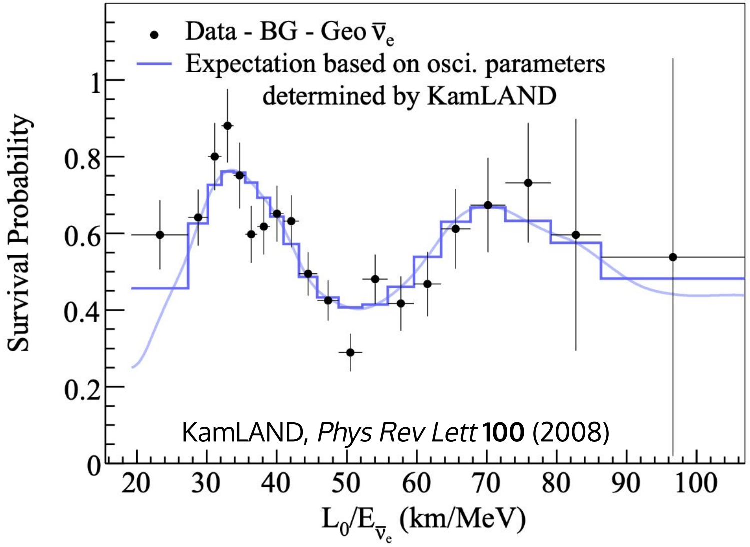
- Something generates more lepton than antileptons in the early universe
- Lepton asymmetry is then converted to baryon asymmetry via tunneling


Hubble Deep Field

Some interesting hints from the neutrinos

Several experimental observations that don't quite fit in the standard model:

- **Neutrinos oscillate between flavors**
- **Neutrino masses are non-zero**



KamLAND, *Phys Rev Lett* **100** (2008)

Some interesting hints from the neutrinos

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- **Neutrino masses are non-zero**
- **Neutrino masses are *much* smaller than those of other fermions**
- **We've only ever seen left-handed neutrinos**

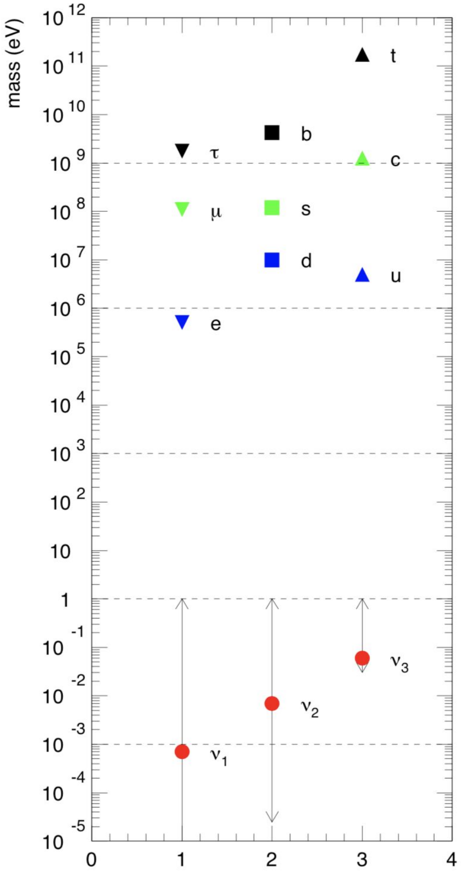

FIG. 3: Standard model fermion masses. For the neutrino masses, the normal mass hierarchy was assumed, and a loose upper bound $m_i < 1$ eV, for all $i = 1, 2, 3$ was imposed. From [1].

A. De Gouvea

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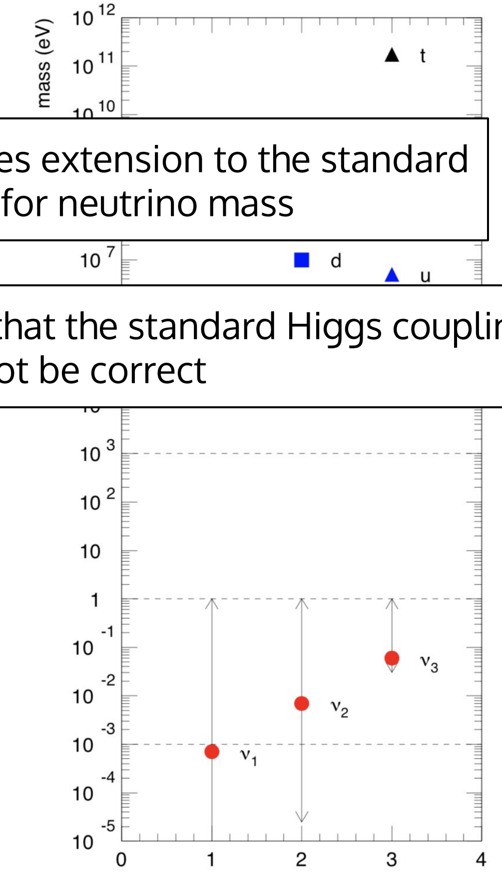
Requires extension to the standard model for neutrino mass

Hints that the standard Higgs coupling may not be correct



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A. De Gouvea

Majorana mass term

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- **Neutrino masses are non-zero**
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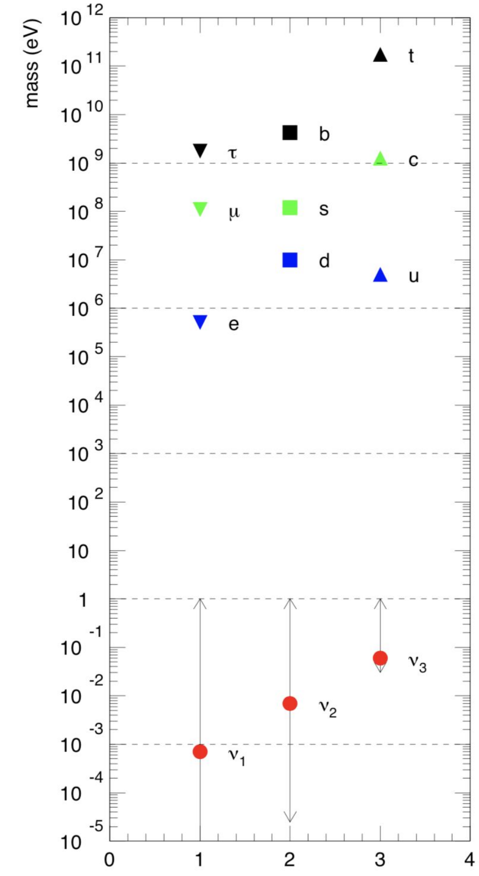
Majorana mass term for neutrinos can accomodate all of these observations, in an “economical” way, while also implying that:

$$\nu = \bar{\nu}$$



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A. De Gouvea

Lepton number symmetry

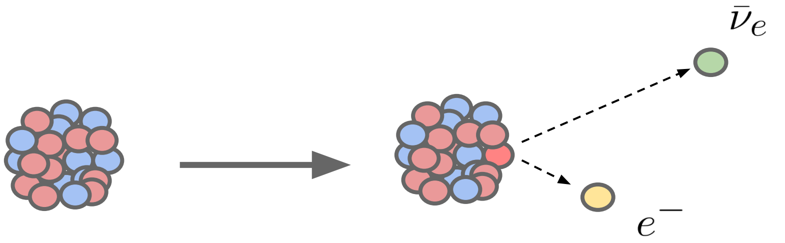
Lepton number is conserved in all known Standard model processes

- Example: nuclear beta decay

Majorana neutrinos inherently violate lepton number

$$\nu = \bar{\nu}$$

Nuclear β-decay:



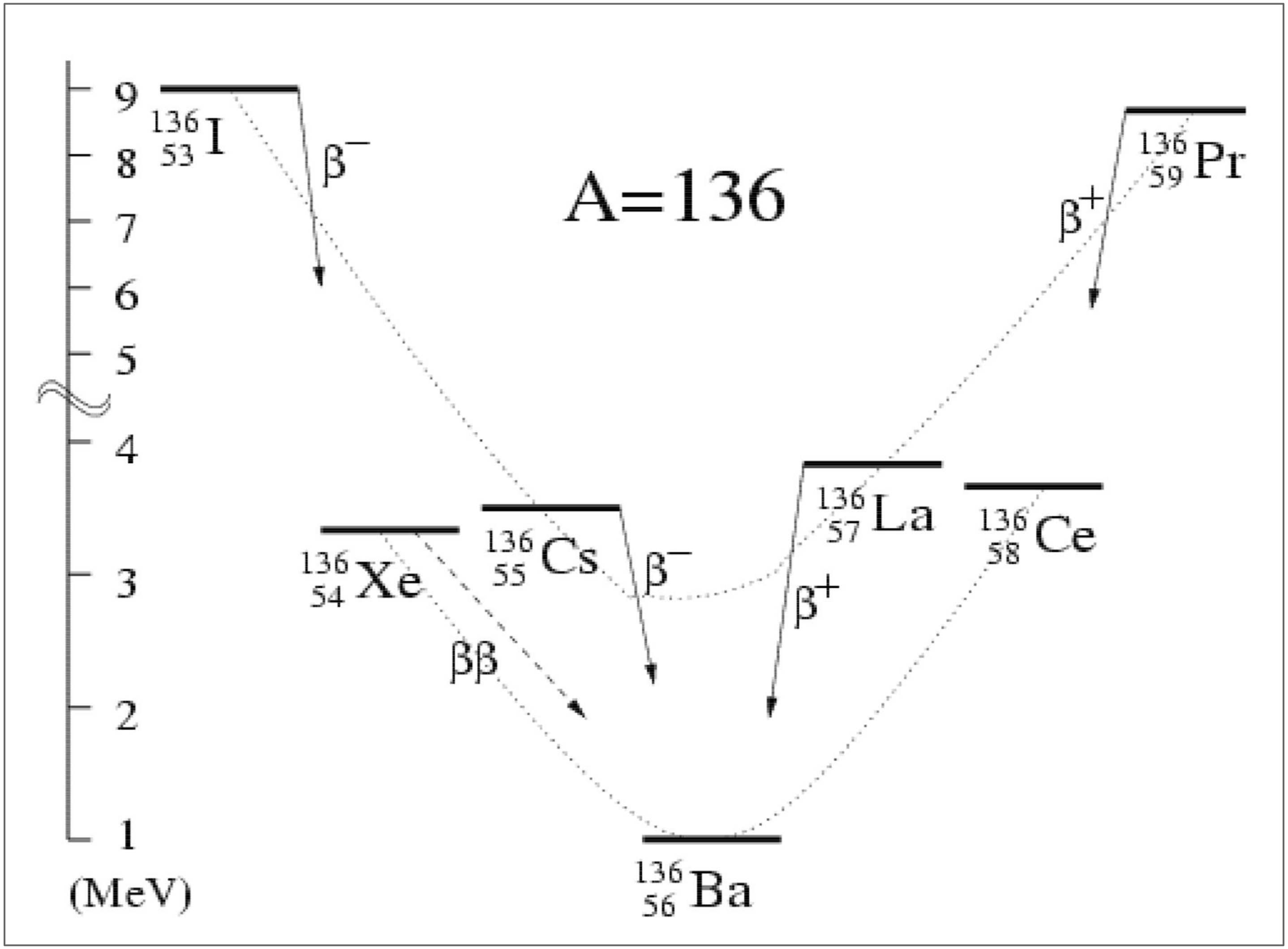
(A, Z) $\quad$ $(A, Z+1) + e^- + \bar{\nu}_e$

\# of leptons in initial state $=$ # of leptons in final state

→ **Lepton number violation gives us an experimental observable to search for new physics**

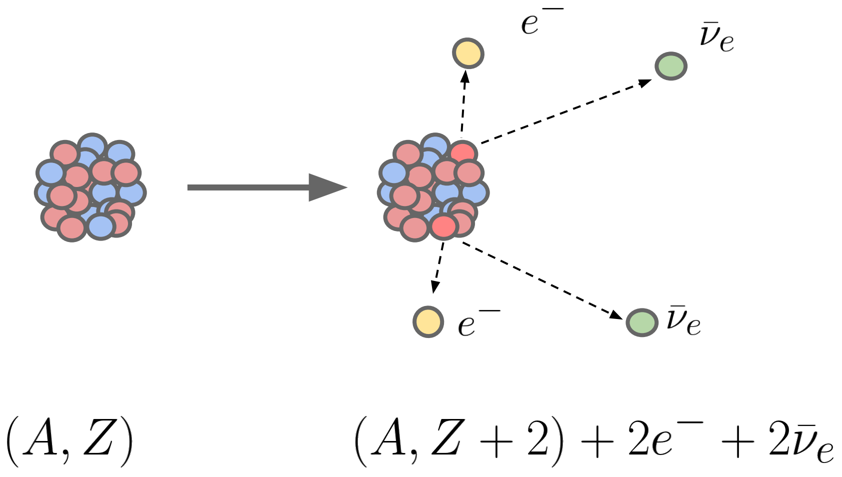
→ **Lepton number violation provides information on the symmetry structure of beyond-the-Standard-Model physics**

Double beta decay

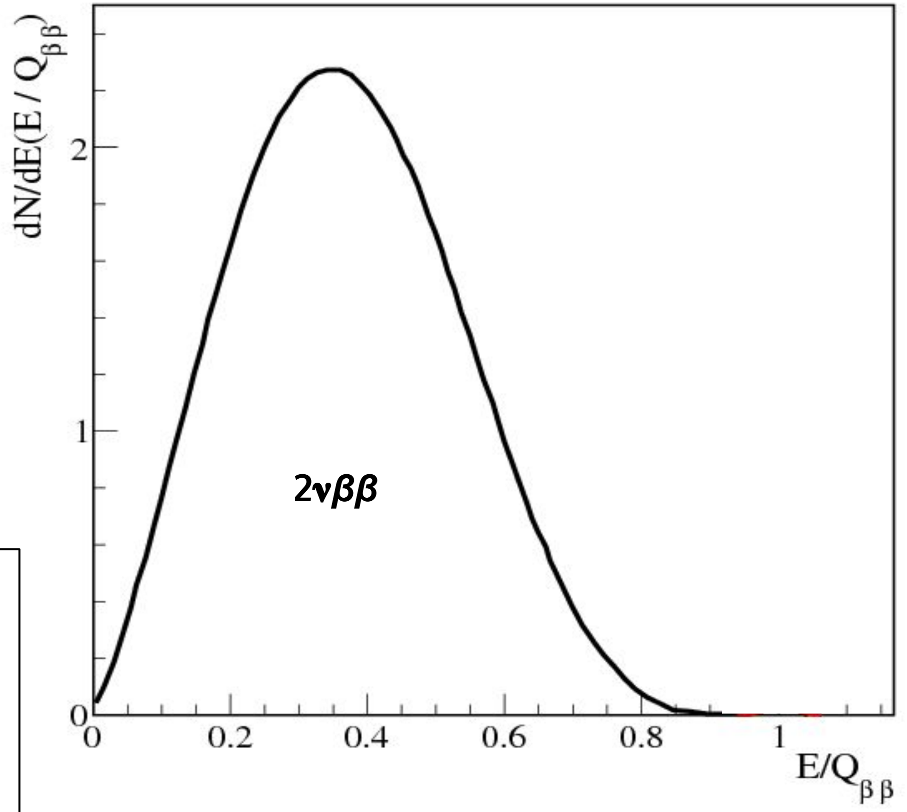


P. Vogel, *J. Phys. G* **39** (2012)

Standard double beta decay (2$\nu\beta\beta$)



(A, Z) $\quad$ $(A, Z+2) + 2e^- + 2\bar{\nu}_e$

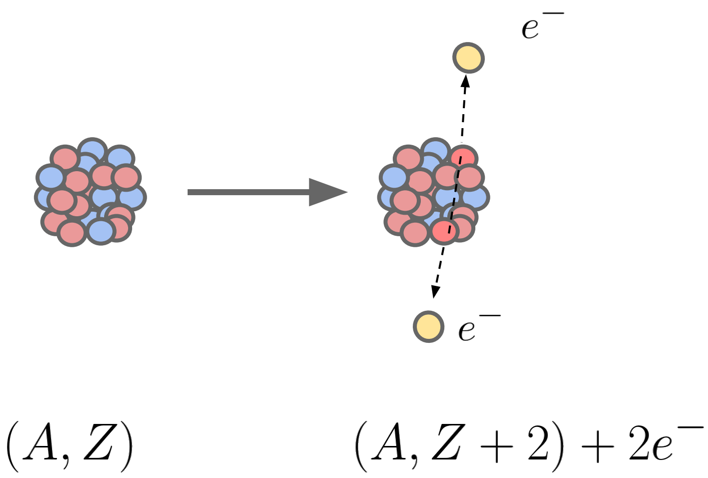


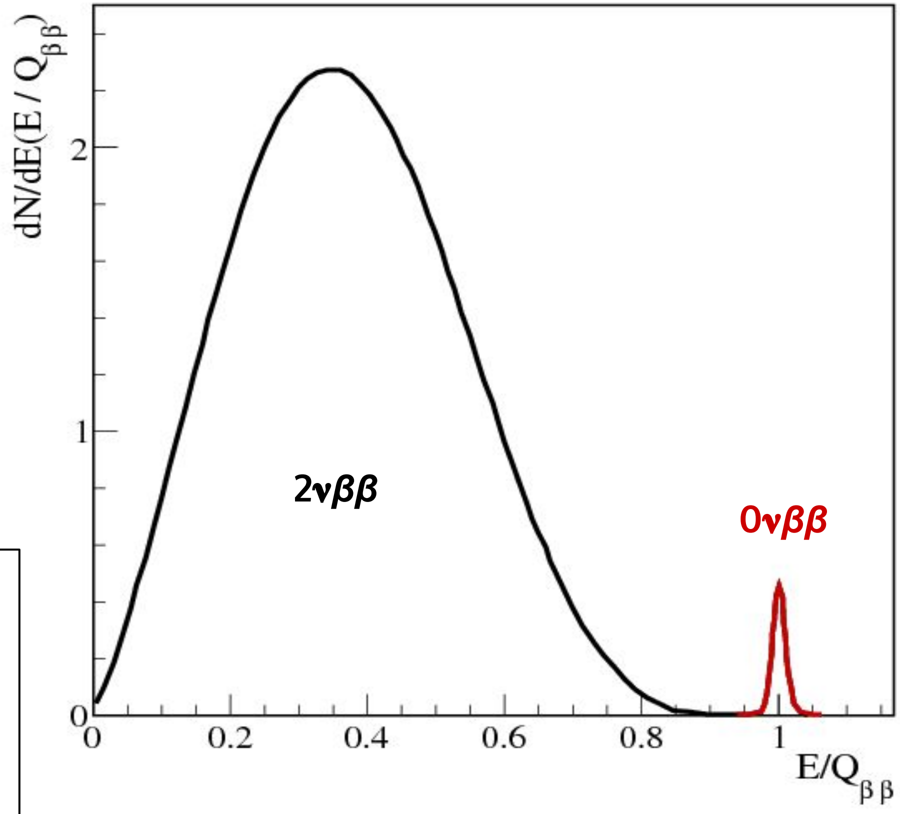
L. Winslow, *JINST* **7** 2012

Perfectly allowed within Standard Model

- Lepton-number-conserving
- Observed in 14 isotopes so far
- Halflives between 10^{18} -- 10^{21} years

Neutrinoless double beta decay ($0\nu\beta\beta$)





L. Winslow, *JINST* **7** 2012

Not allowed within the Standard Model

- Lepton-number-violating
- Immediately demonstrates Majorana nature of neutrinos*
- Current limits at $T_{1/2} > 10^{26}$ years

* Schecter/Valle "black box theorem": *PRD* **25** (1982)

Interpreting the results of 0νββ searches

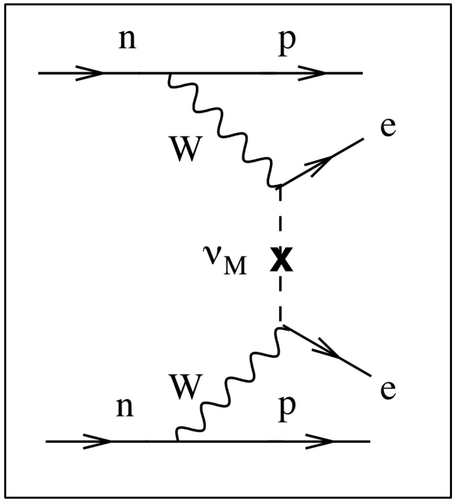
Simplest model -- light neutrino exchange:

$$\left[T^{0\nu}_{1/2}\right]^{-1} = \underbrace{\frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}}_{}\;\underbrace{G^{0\nu}}_{}\;\underbrace{\left|M_{GT} - \frac{g_A^2}{g_V^2}M_F\right|^2}_{}$$

“Effective Majorana mass”: Linear combination of mass states of light neutrinos mediating the decay

Phase space factor: defined by energy released in reaction (Q-value)

Matrix elements: Defined by nuclear structure



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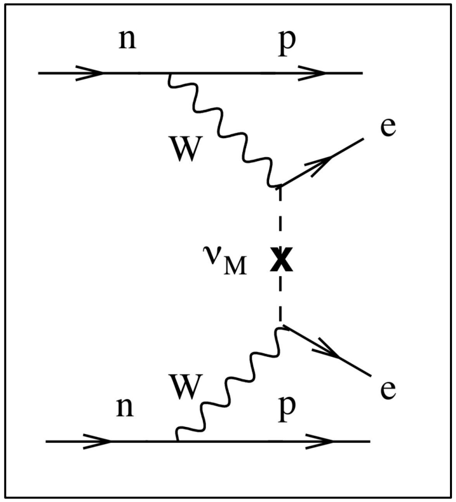
"Effective Majorana mass": Linear combination of mass states of light neutrinos mediating the decay

Phase space factor: defined by energy released in reaction (Q-value)

Matrix elements: Defined by nuclear structure

For a given nucleus, these can be calculated, e.g. with nuclear models



0νββ parameter space for light neutrino exchange

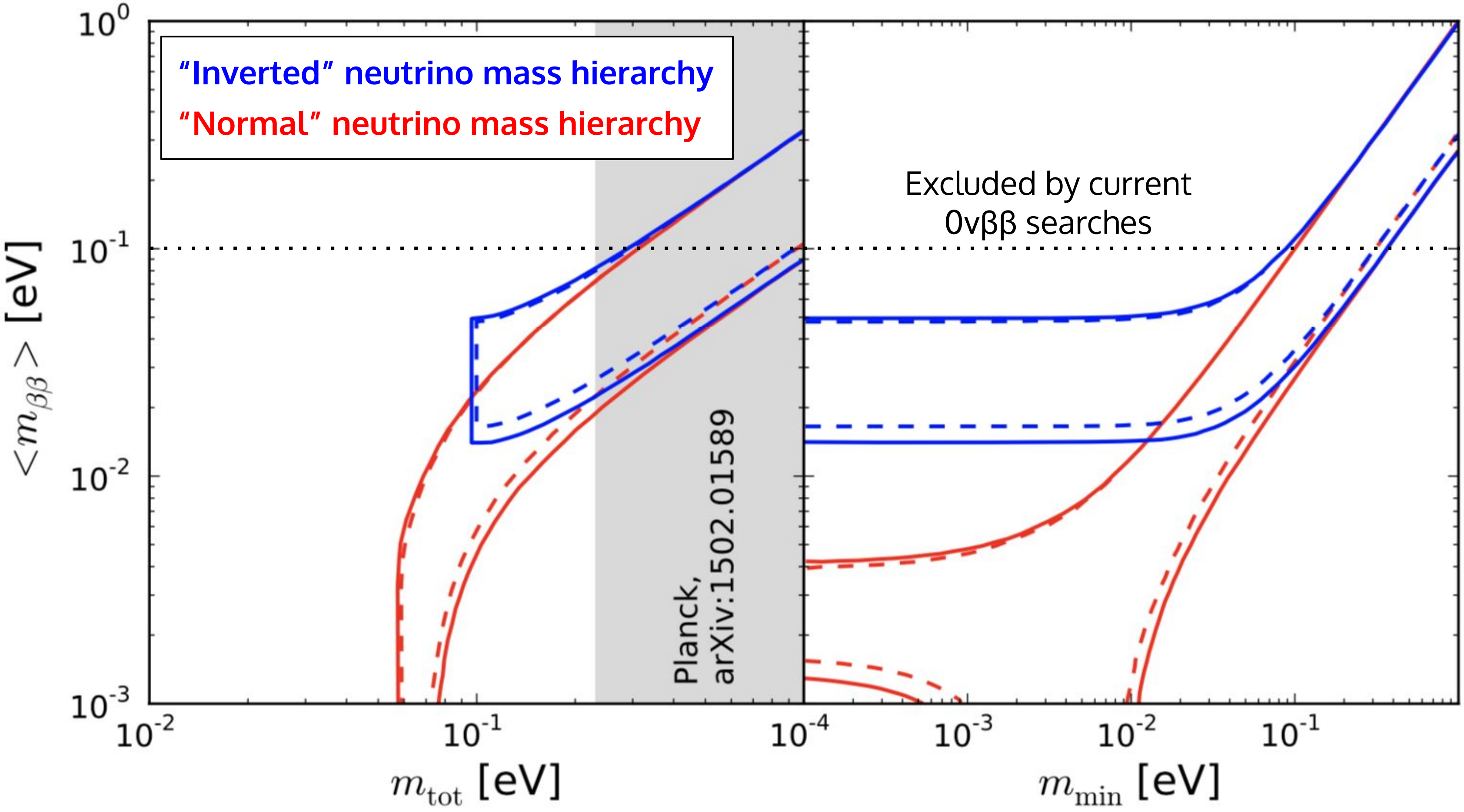
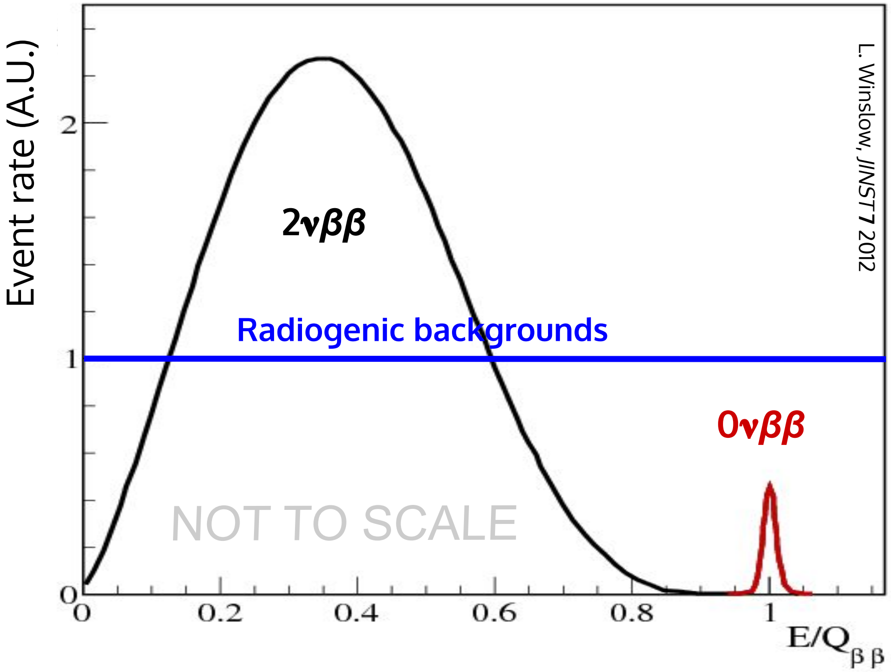


Fig. from M. Jewell

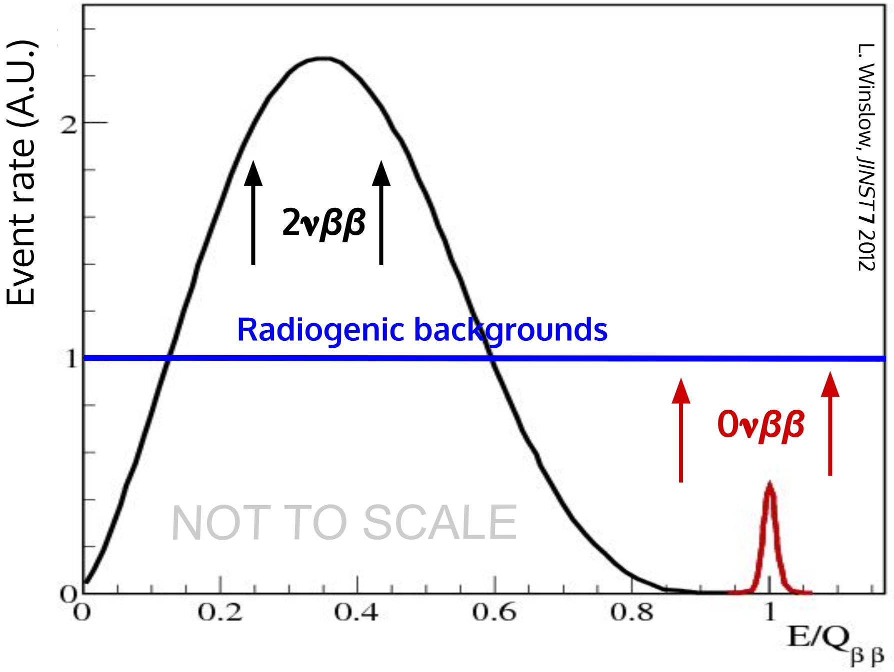
Optimizing a 0νββ search



L. Winslow, *JINST* **7** 2012

What drives the sensitivity of a 0νββ search experiment?

Optimizing a 0νββ search

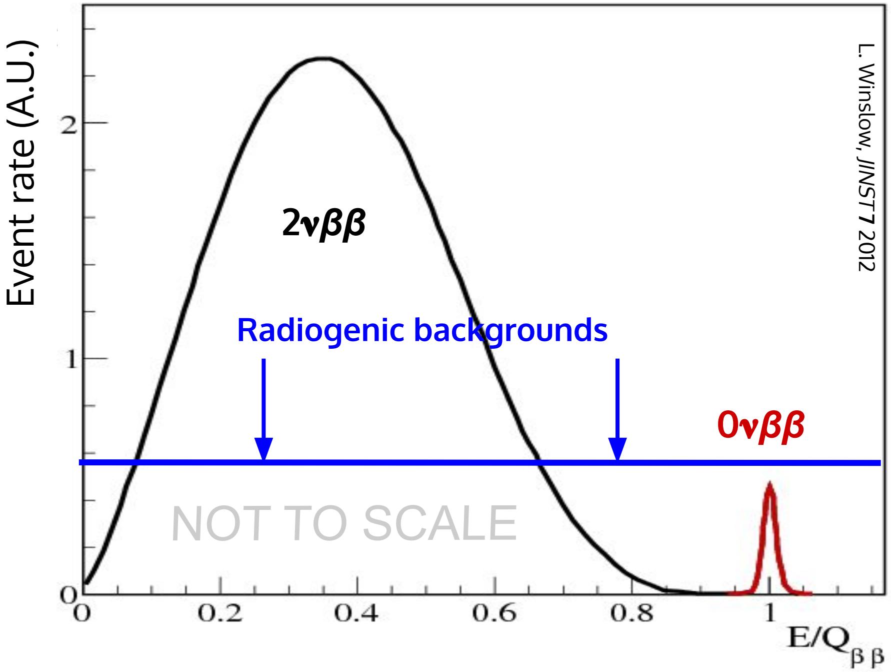


L. Winslow, *JINST* **7** 2012

What drives the sensitivity of a 0νββ search experiment?

1. A lot of the BB isotope

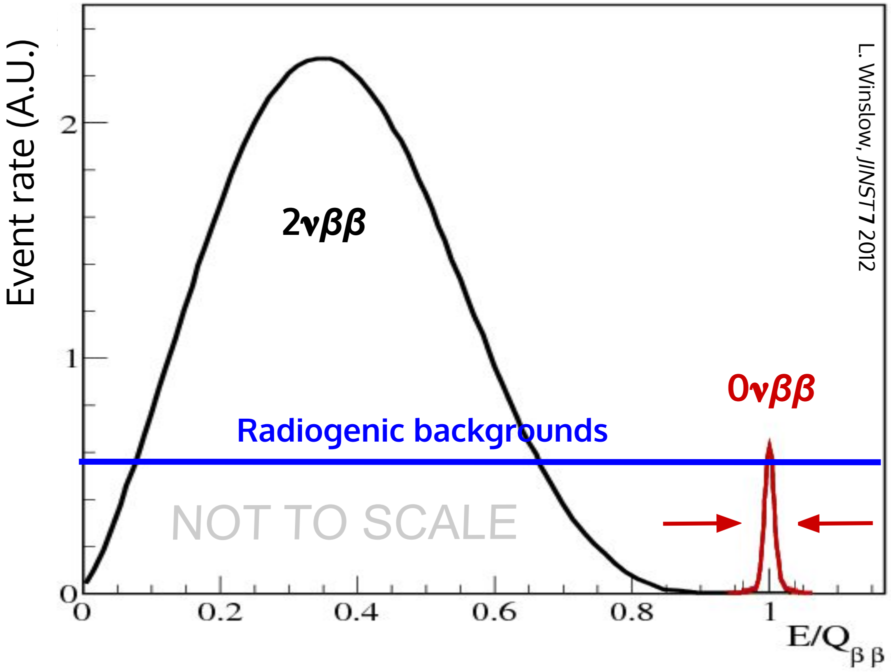
Optimizing a 0νββ search



What drives the sensitivity of a 0νββ search experiment?

1. A lot of the BB isotope
2. Ultra-low backgrounds

Optimizing a 0vββ search



L. Winslow, *JINST* 7 2012

What drives the sensitivity of a 0vββ search experiment?

1. A lot of the BB isotope
2. Ultra-low backgrounds
3. Good energy resolution

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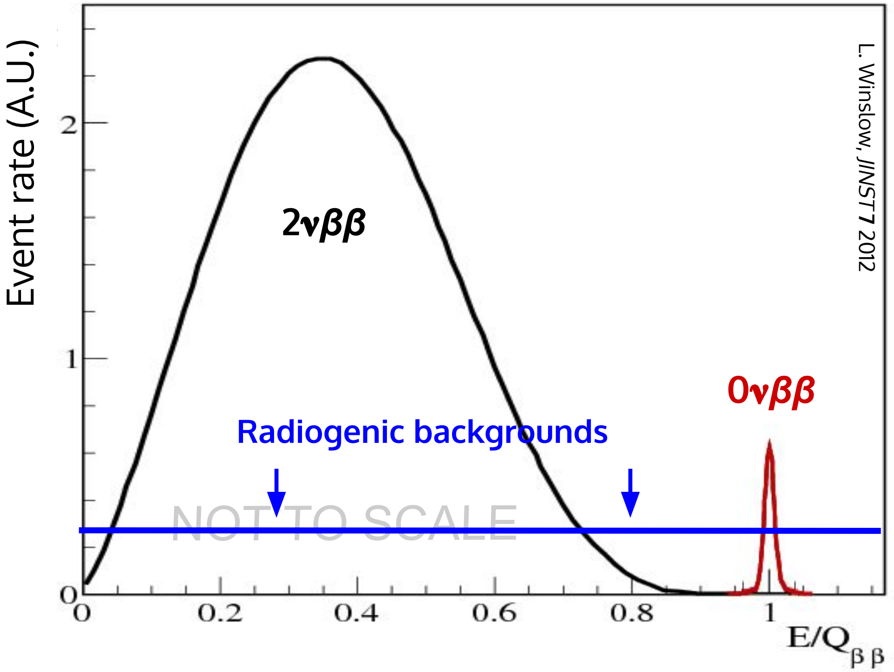
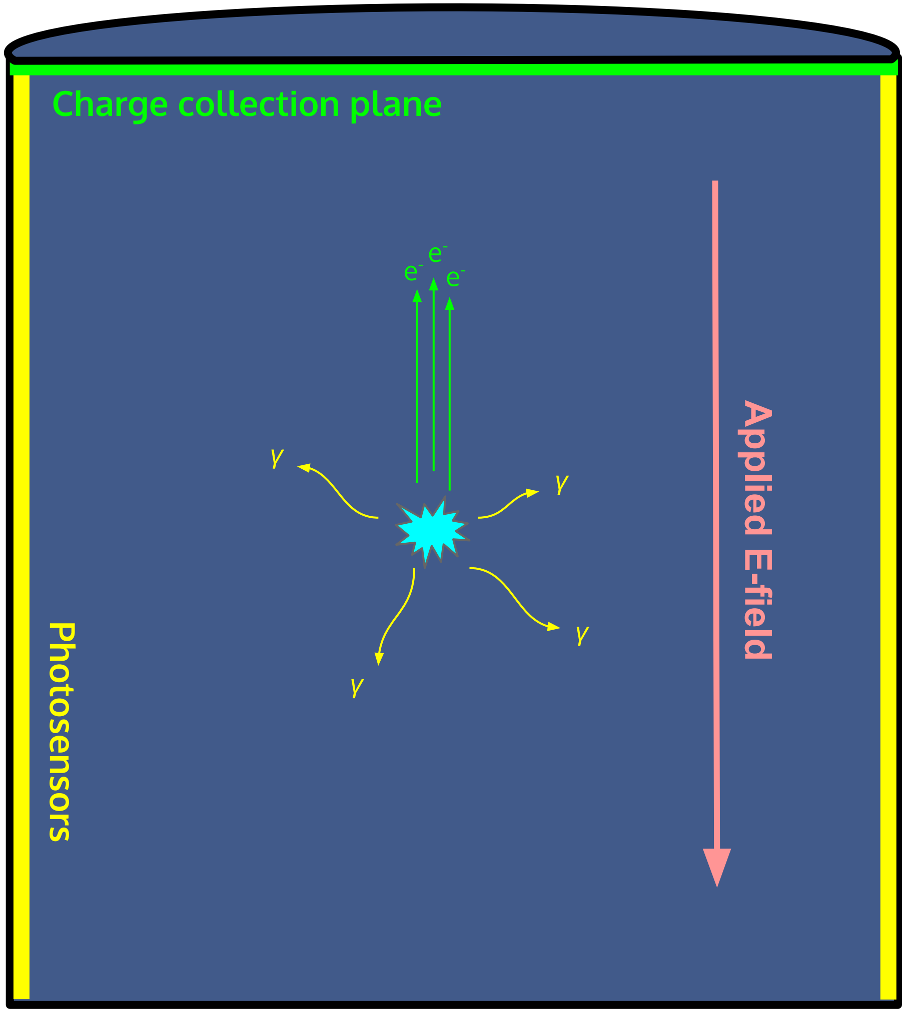


L. Winslow, *JINST* **7** 2012

What drives the sensitivity of a 0νββ search experiment?

1. A lot of the BB isotope
2. Ultra-low backgrounds
3. Good energy resolution
4. Signal/background discrimination capabilities

Liquid xenon time projection chambers (TPCs)

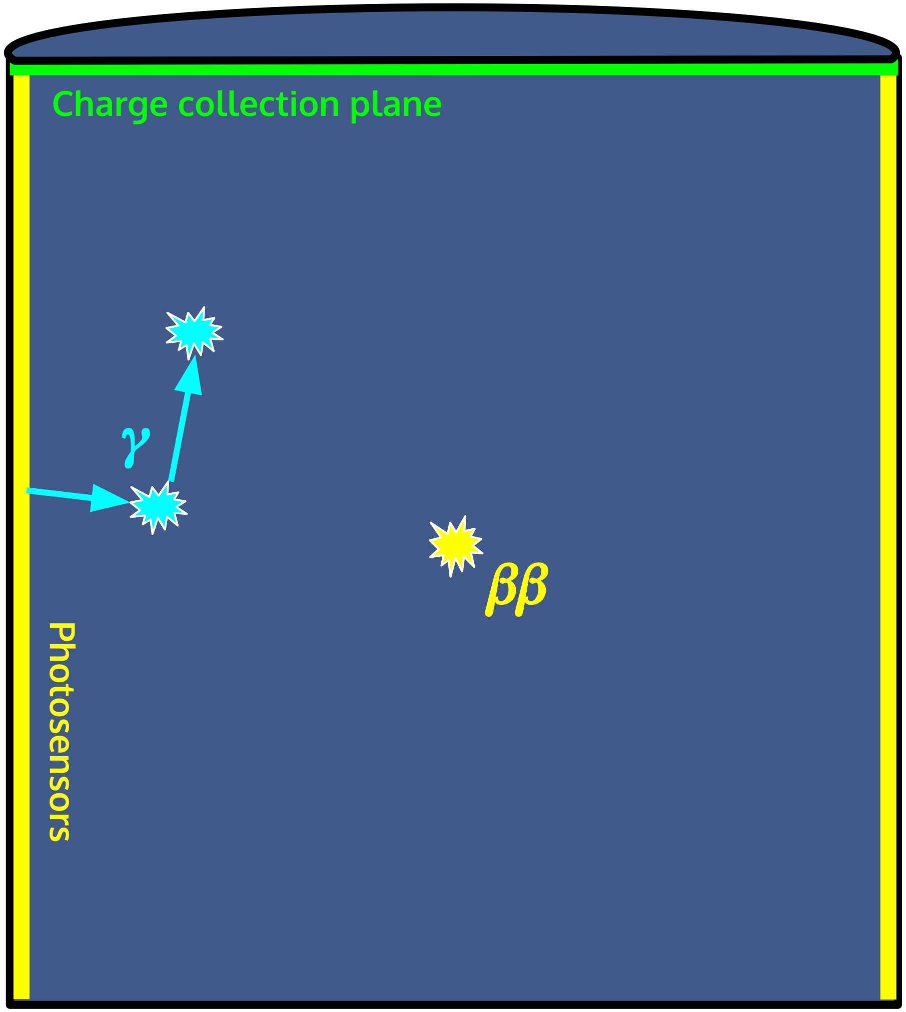


Dual-channel measurement
Scintillation light + ionized charge

3-D position reconstruction for each energy deposition

Can fill with ^{136}Xe, a $0\nu\beta\beta$ candidate
Detector medium = sample

Searching for 0νββ in a TPC



Addressing the challenges in 0νββ searches:

- **A LOT of the ββ isotope (^{136}Xe)**
  - Ton-scale LXe TPCs are already operating
  - Enrichment is straightforward
- **Low, well-characterized backgrounds in MeV range (low radioactivity)**
  - Very low intrinsic backgrounds
  - Excellent self-shielding reduces external radioactivity
- **Good energy resolution**
  - Combining charge and light can reach <1%
- **Signal/background discrimination**
  - Powerful position reconstruction and multi-site rejection to characterize and reject BG

nEXO: the next-gen Enriched Xenon Observatory

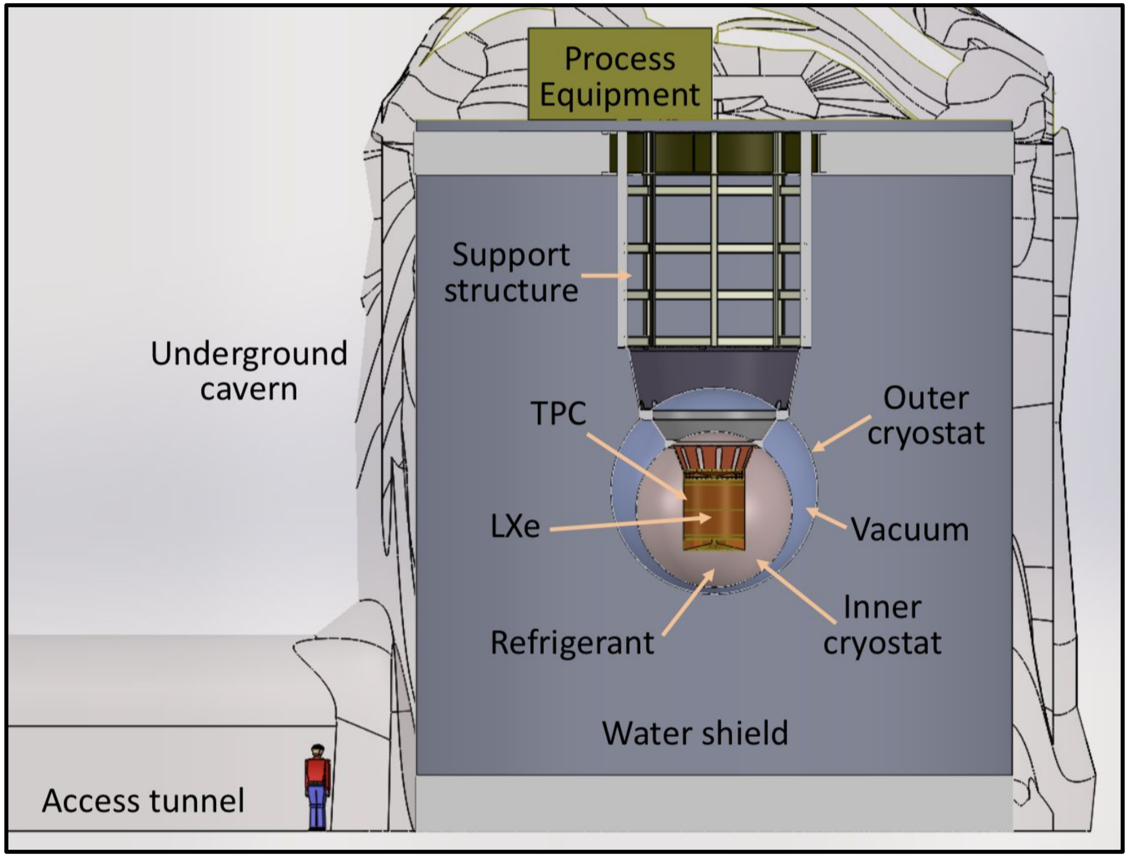
Search for 0νββ in a tonne-scale liquid xenon TPC

- Five tonnes (~10^{28} atoms)
- Enriched to 90% in ^{136}Xe
- $Q_{\beta\beta}$ = 2.457 MeV

Designed for ultra-low backgrounds:

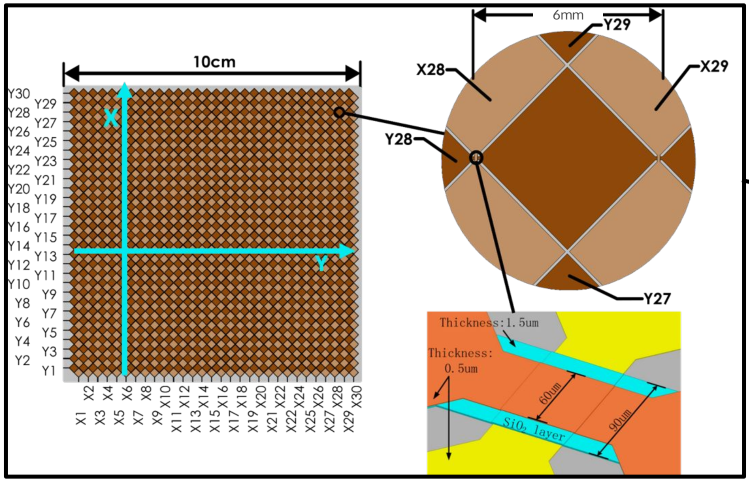
- Deep underground location
- Extensive shielding
- Meticulous materials screening

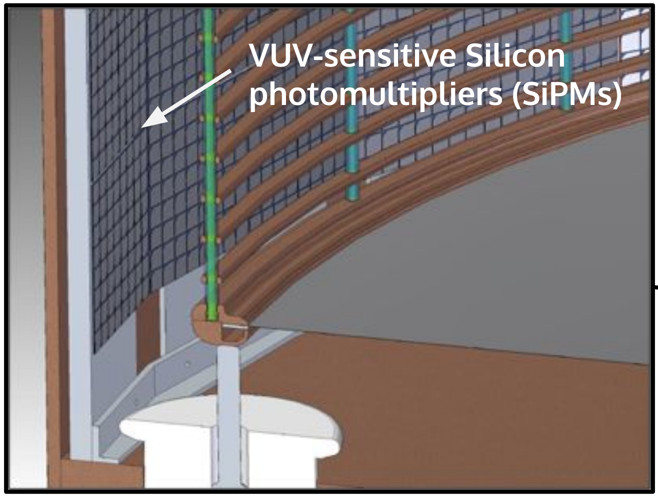
Goal: achieve a sensitivity to 0νββ that is two orders of magnitude beyond existing experiments (~10^{28} yr halflife)

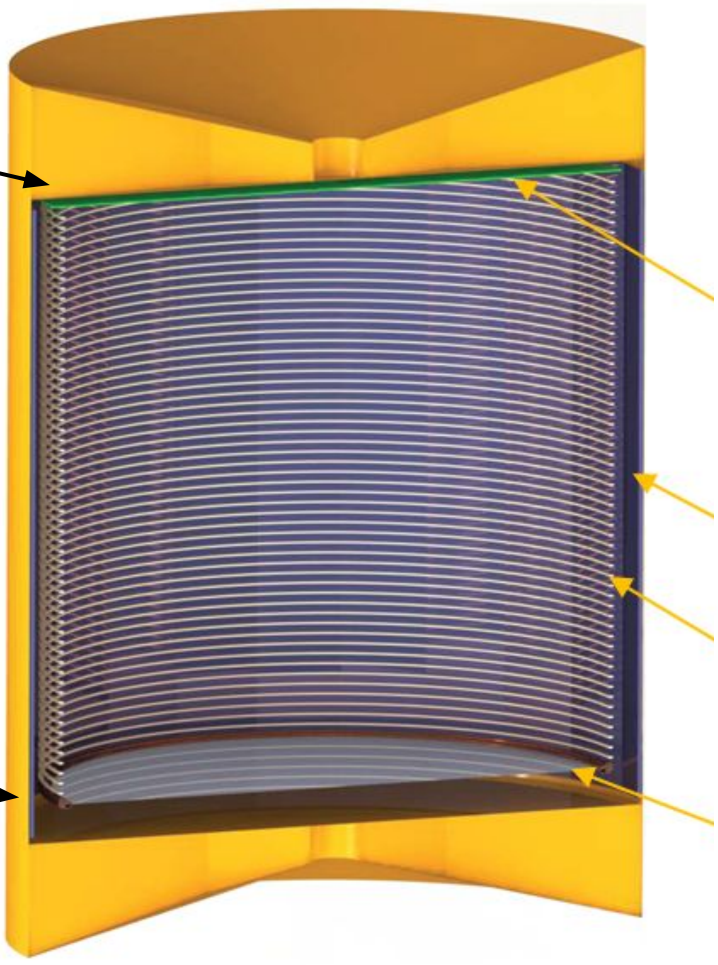


The nEXO collaboration

The nEXO TPC and signal readout







Charge collection tiles at anode

Photon detectors (SiPMs) on walls

High voltage field cage

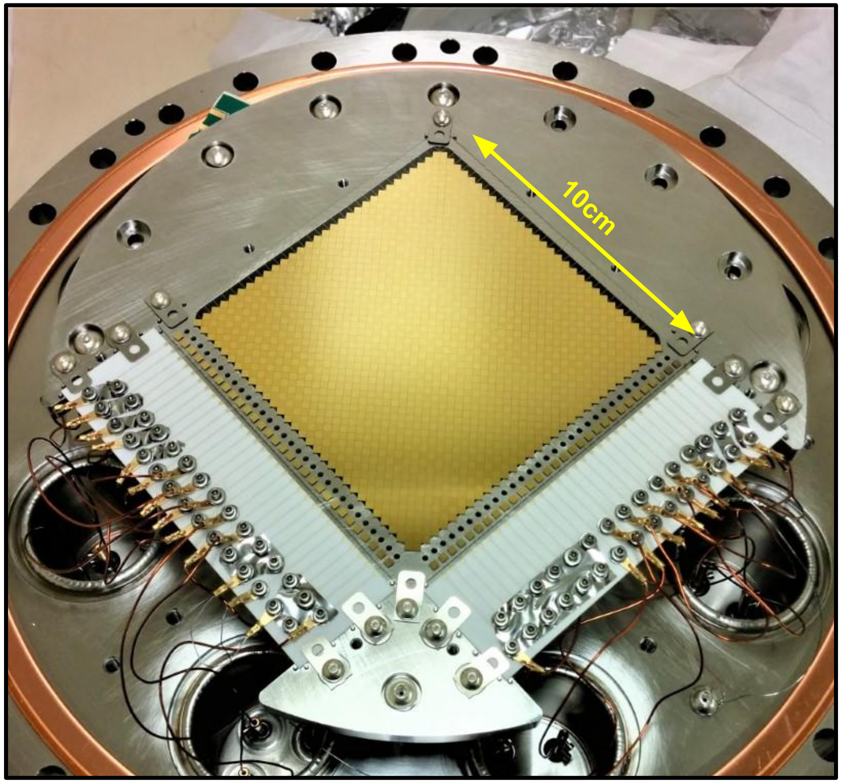
Cathode

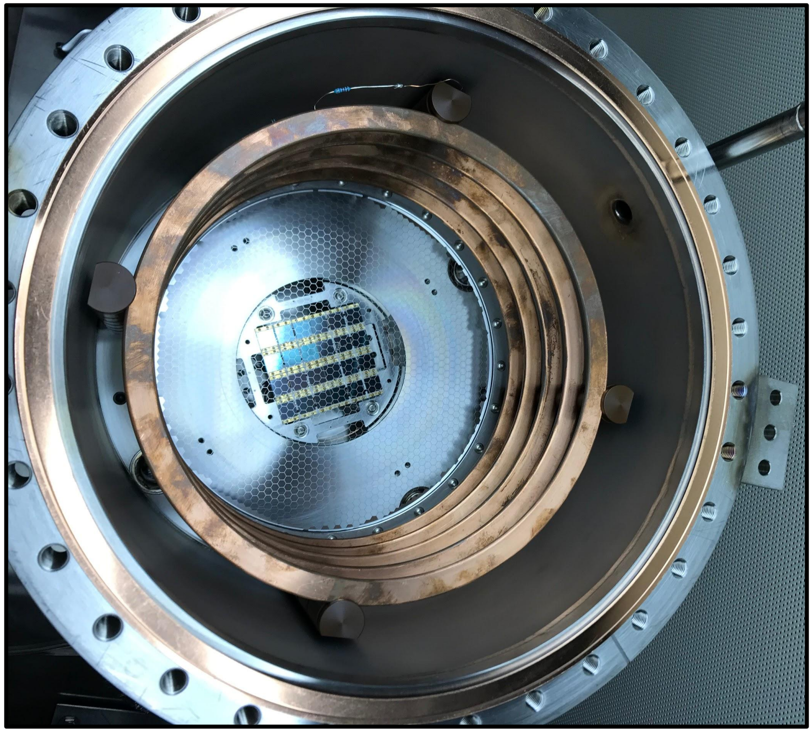
Prototyping and R&D

Bare strip charge readout tiles demonstrated using analog readout

Jewell et al. *JINST* **13** (2018)

Development of dedicated, cold ASIC electronics for nEXO ongoing





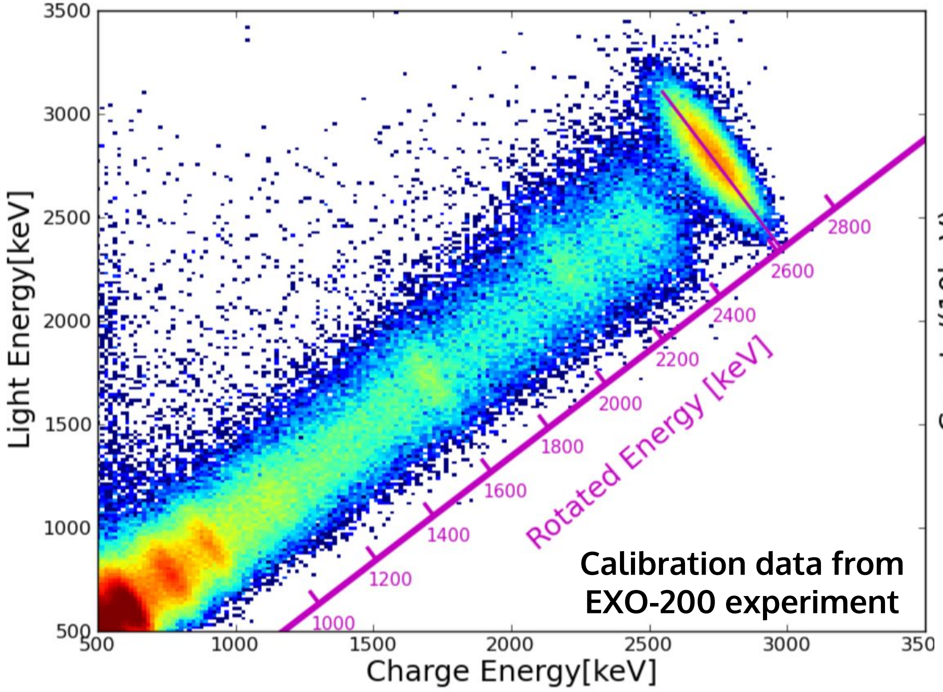
VUV-sensitive SiPMs are relatively new -- extensive R&D and characterization ongoing

- Photon detection efficiency, noise properties
  - Ostrovskiy et al., *IEEE TNS* **62** (2015) arXiv:1502.07837
  - Jamil et al., *IEEE TNS* **65** (2018) arXiv:1806.02220
  - Gallina et al., *NIM A* **940** (2019) arXiv:1903.03663

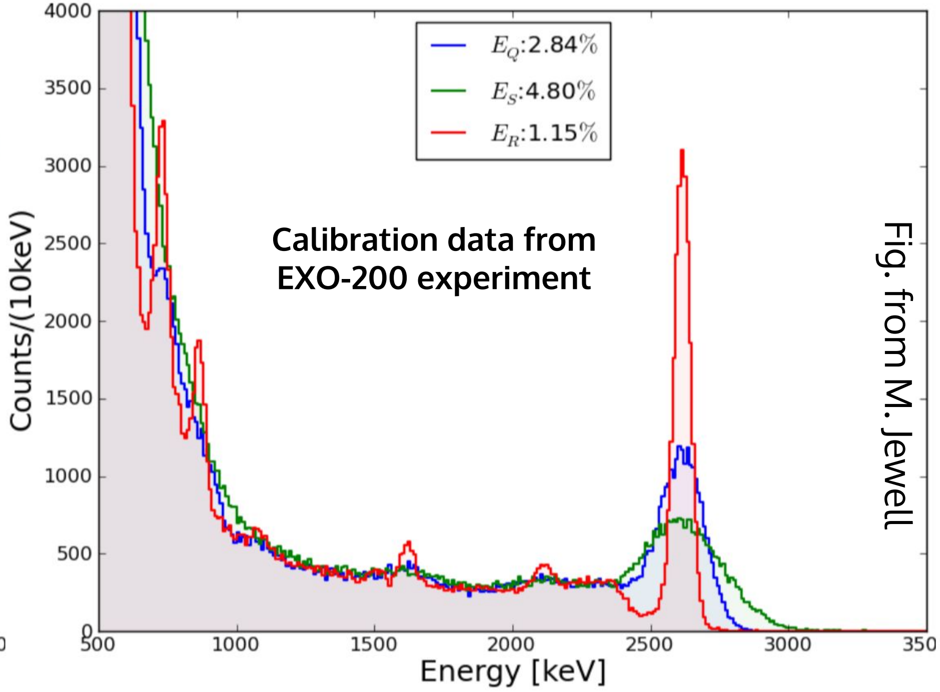
Testing of large-area readout underway @ Stanford

Energy resolution in liquid xenon

Require precise measurements of both scintillation and ionization signals:



Calibration data from EXO-200 experiment



Calibration data from EXO-200 experiment

Fig. from M. Jewell

nEXO readout designed to reduce noise in both channels, achieving <1% energy resolution at 0νββ Q-value

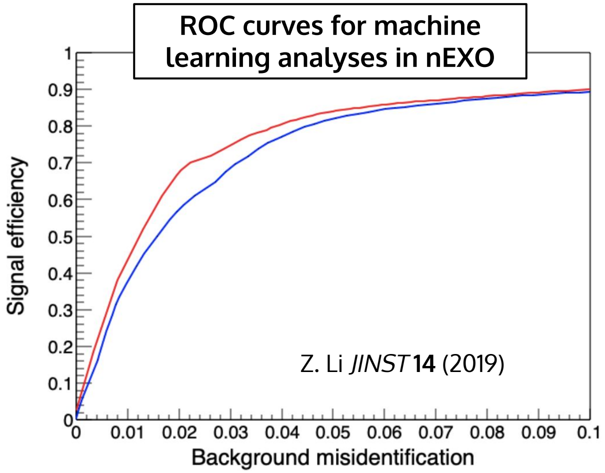
Particle-type discrimination in a TPC

Imaging capability of TPC can be used to separate signal from background

- ββ events are point-like in nEXO
- Background γ-rays will Compton scatter

Event classification in data analysis

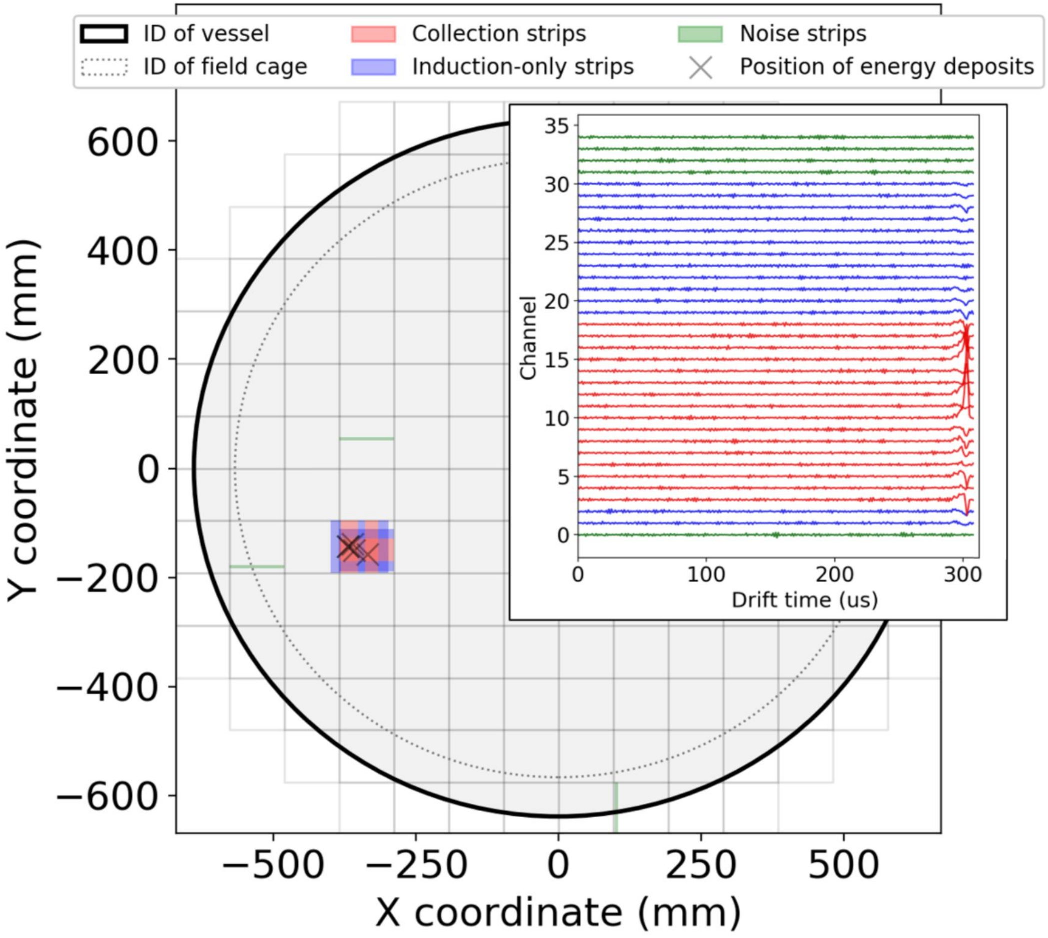
- Binary single-site/multi-site separation is well-established
- Deep-neural-network discrimination for nEXO developed in simulation



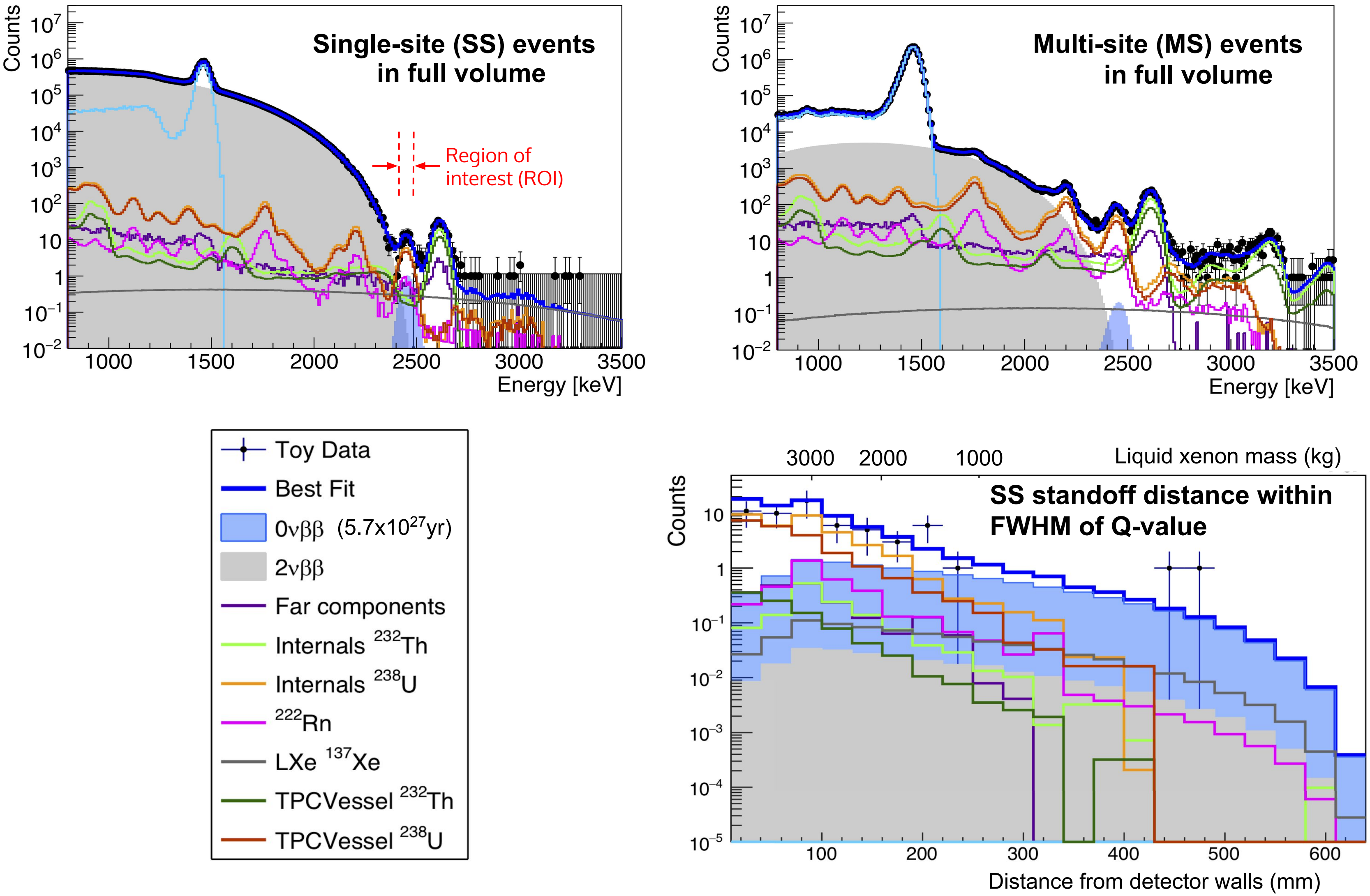
ROC curves for machine learning analyses in nEXO

Z. Li *JINST* **14** (2019)

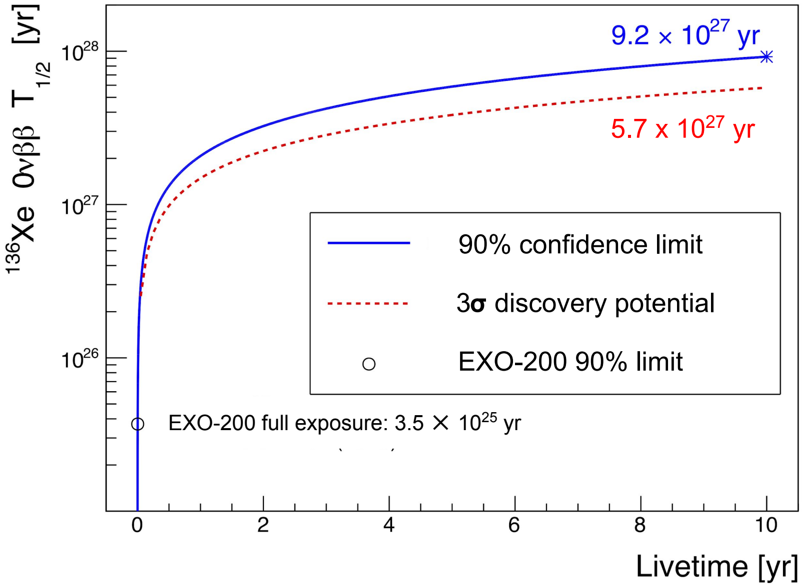
Example background event in nEXO

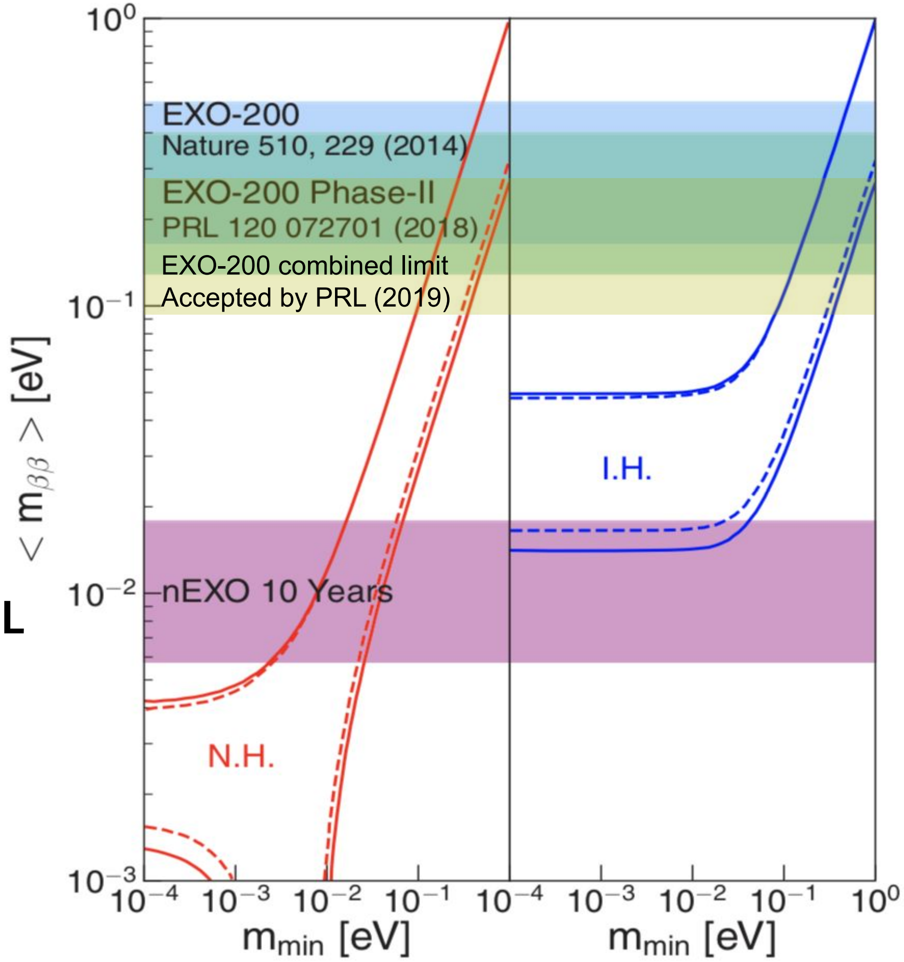


Projecting nEXO's performance in simulation



Projected physics reach ca. 2018





Projected sensitivity: $T_{1/2}$ > 9.2e27 yr @ 90% CL

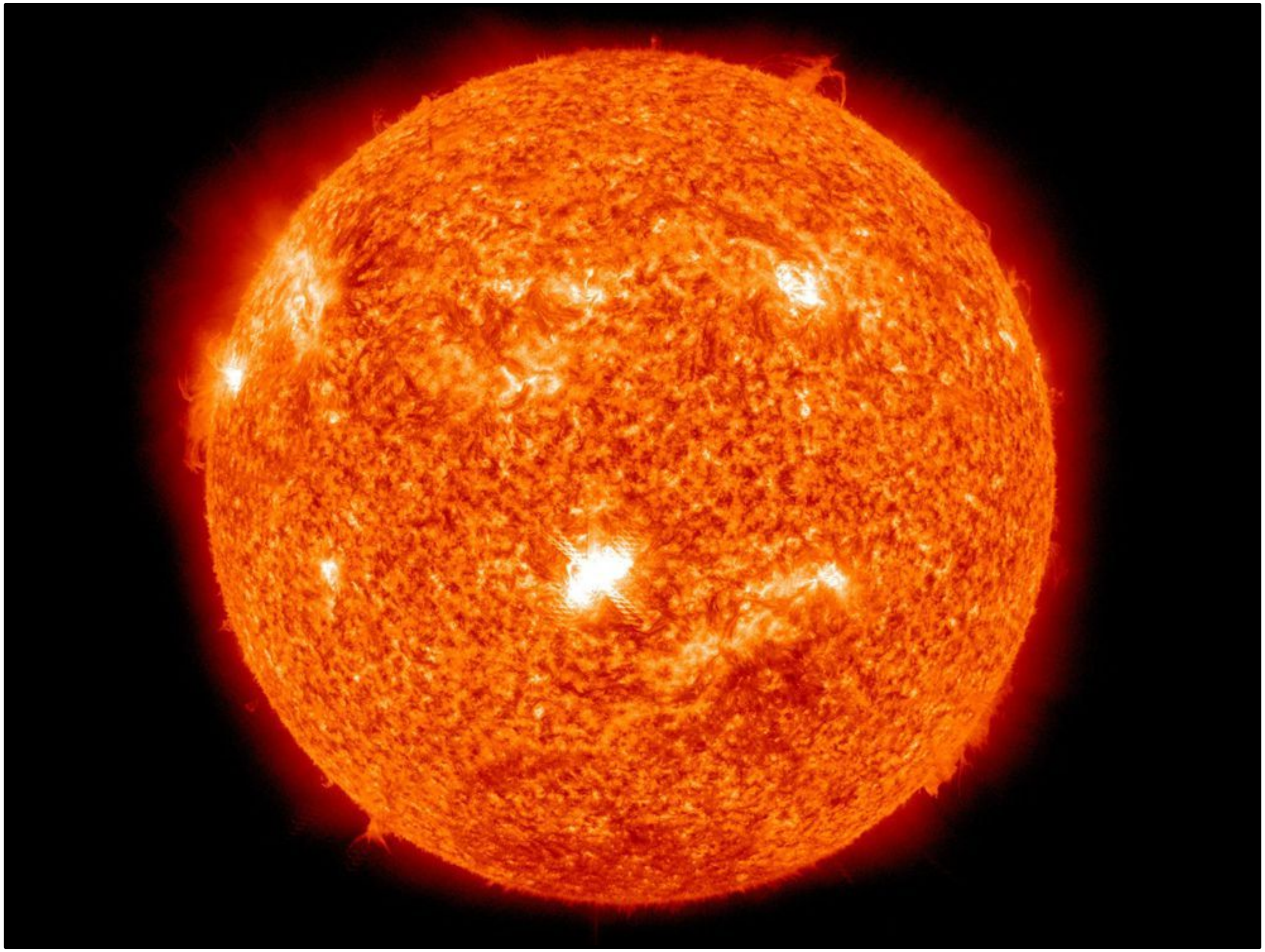
- J. Albert et al., *PRC* **97**, 2018

We are working hard to push this even further

- A projection reflecting new R&D is ongoing:
  - More aggressive assumptions regarding background sources and rejection
  - Neural-network-based signal/background discrimination

What else could we do with the nEXO detector?

Another possible signal: solar neutrinos



https://www.nationalgeographic.org/encyclopedia/sun/

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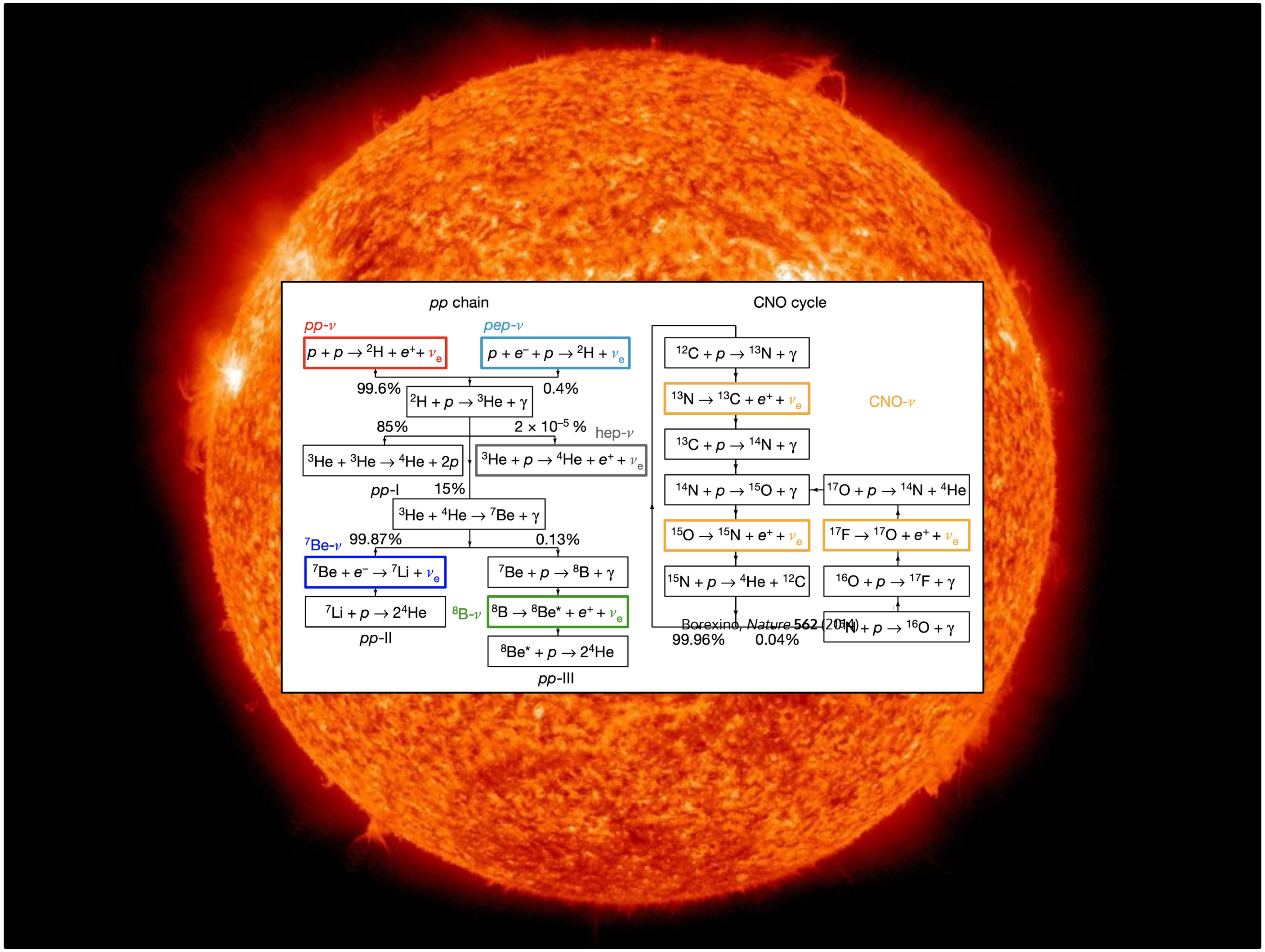


Borexino, *Nature* **562** (2018)

https://www.nationalgeographic.org/encyclopedia/sun/

Solar neutrinos and the metallicity problem

Solar composition of elements heavier than helium (a.k.a "metallicity") is not understood

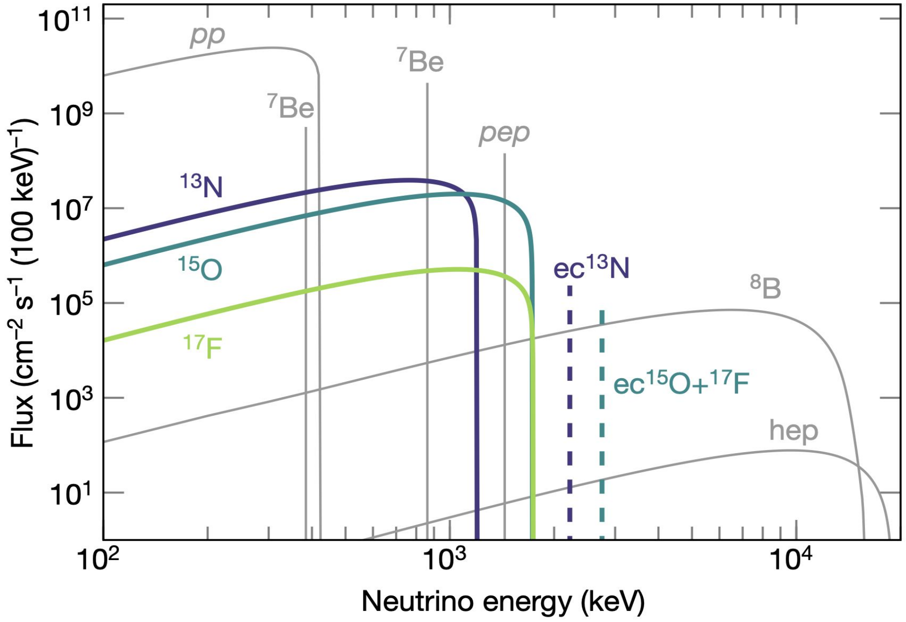
- Measurements of photosphere favor low-metallicity
- Helioseismology favors high-metallicity interior
- Tension at the 4σ level!

The sun provides a calibration for metallicity measurements of distant objects

- Calibrates temperature, age, etc. of stars and galaxies

CNO neutrino flux provides a direct measurement of heavy elements in the sun's core

Solar neutrino energy spectrum



Borexino, *Nature* **587** (2020)

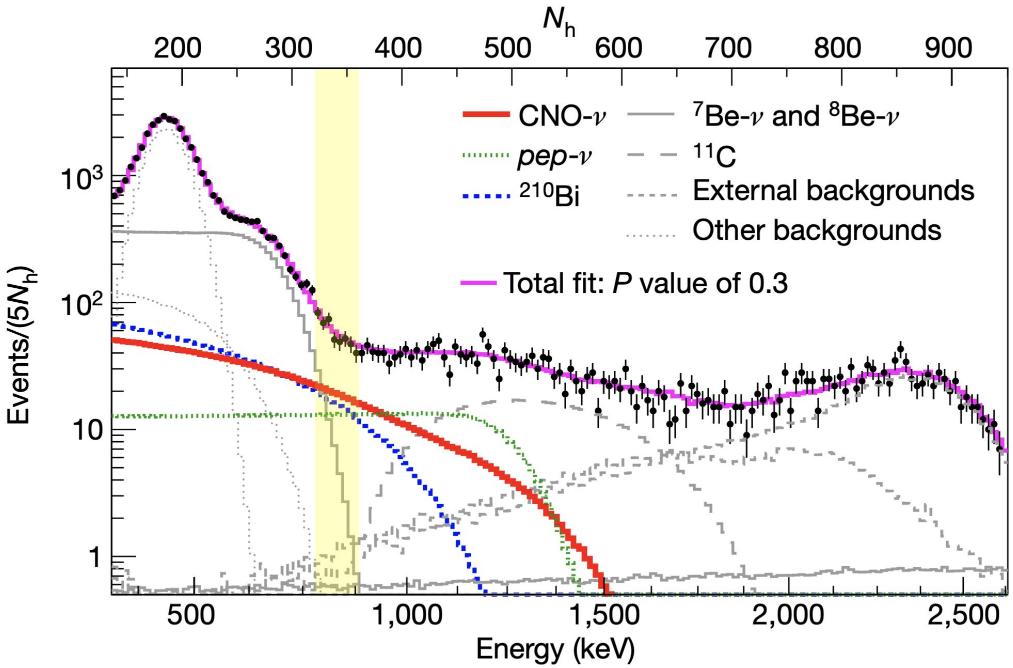
First measurement in Summer 2020!

Article

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

https://doi.org/10.1038/s41586-020-2934-0 The Borexino Collaboration*

Borexino, *Nature* **587** (2020)



Detection technique

- Neutrino-electron scattering in 1kTon of liquid scintillator
- Incredible effort to reduce convection to mitigate ^{210}Bi backgrounds

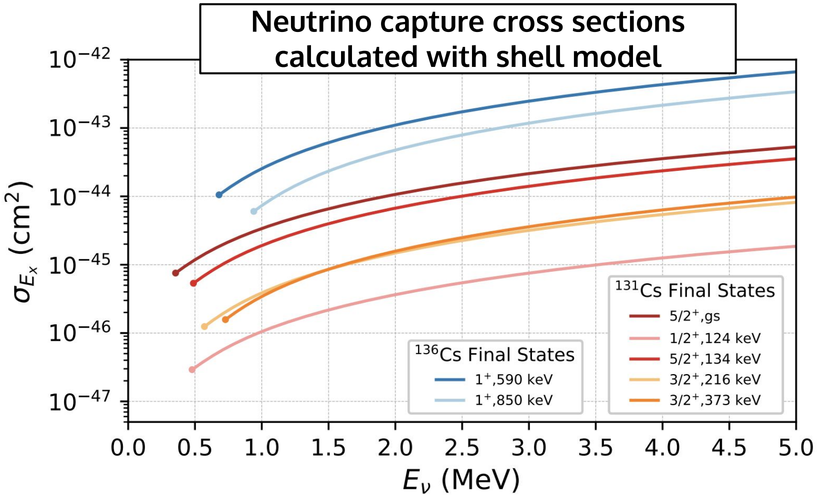
Uncertainties in rate too large to provide solution to metallicity problem

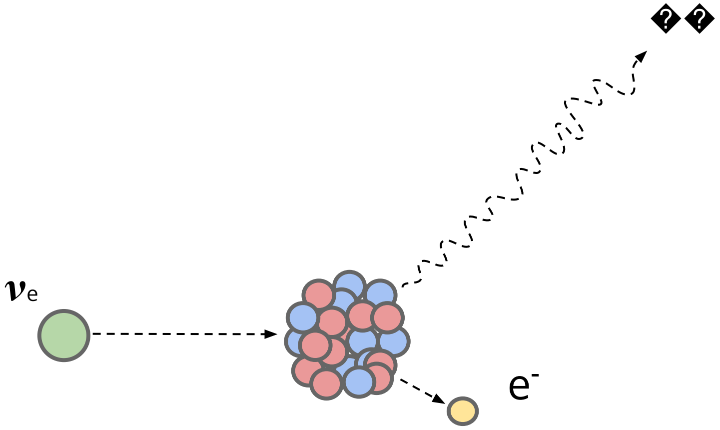
Solar neutrino capture in liquid xenon

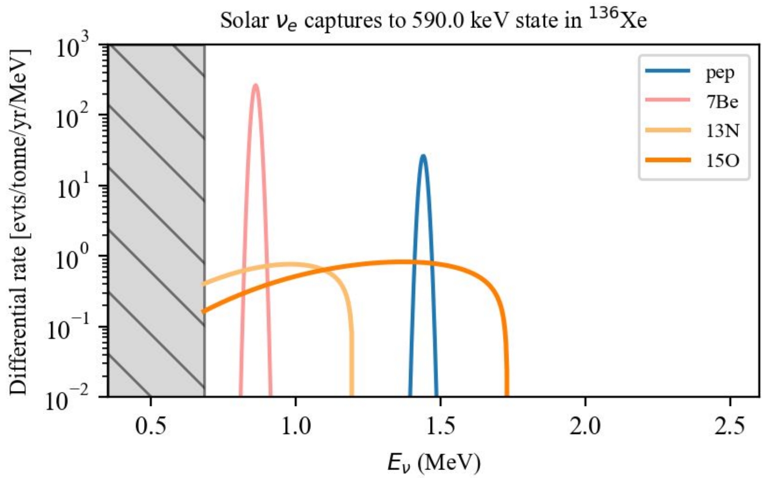
$$\nu_e + ^{136}\mathrm{Xe} \rightarrow ^{136}\mathrm{Cs} + e^-$$

Neutrino capture in xenon TPCs provides a new detection mechanism

- Provides direct neutrino energy measurement
- ^{136}Cs could be tagged via characteristic γ-rays

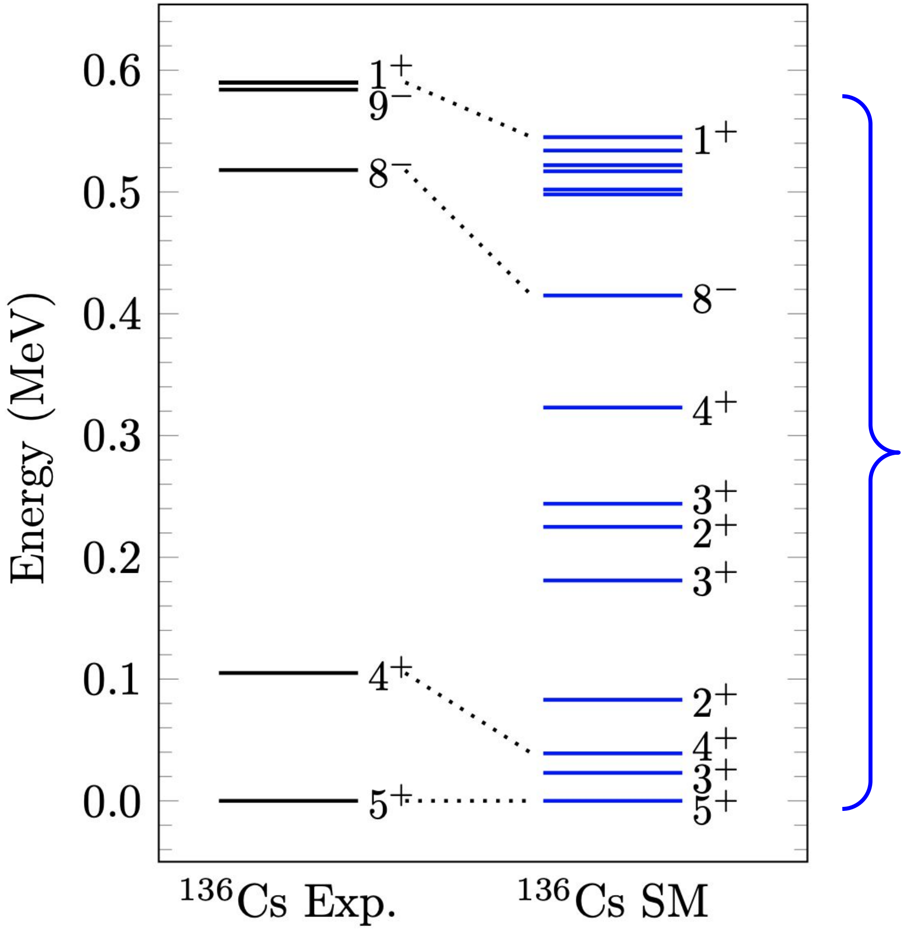

Neutrino capture cross sections calculated with shell model





S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

What will the gamma signals look like in NEXO?



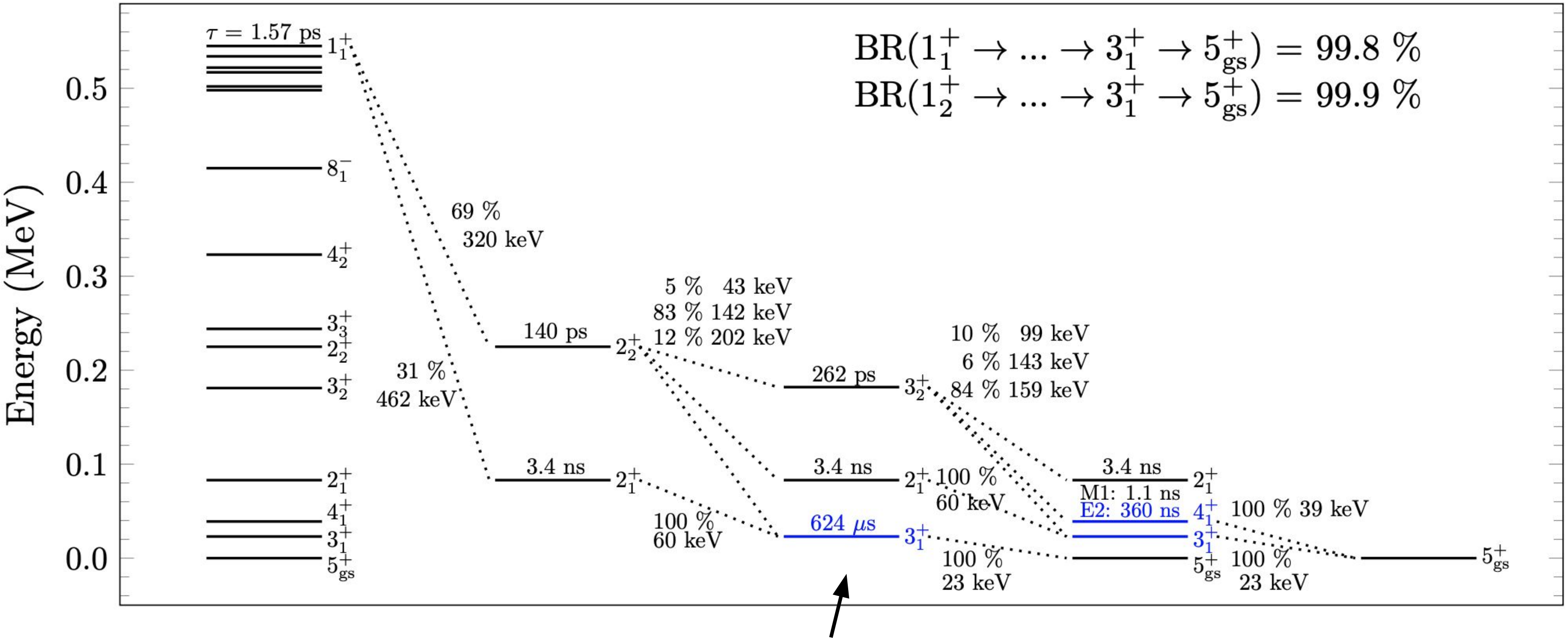
Nuclear data in ^{136}Cs is sparse

Used nuclear shell model calculations predict level scheme

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

Tagging ^{136}Cs via gamma cascade

Decay scheme of 1^+ state at 590 keV



Delayed signal from predicted 3^+ state could be easily resolved in time and position

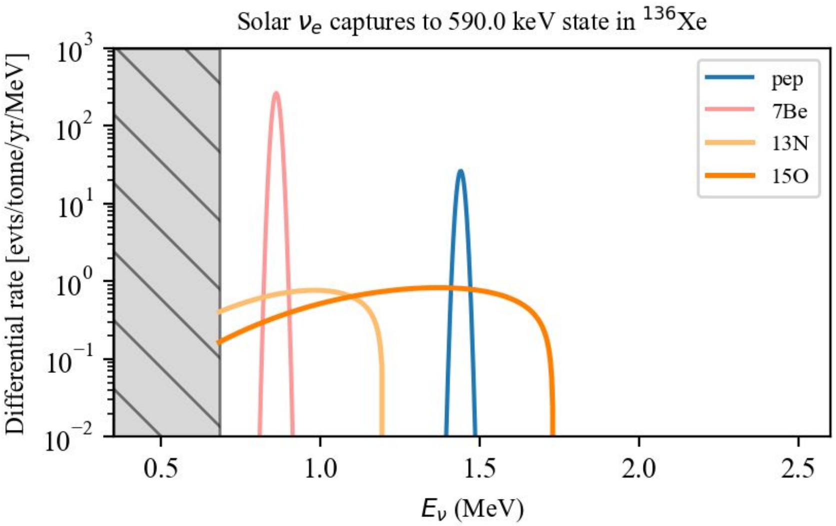
Estimated background suppression factor ~ 10^{-10}

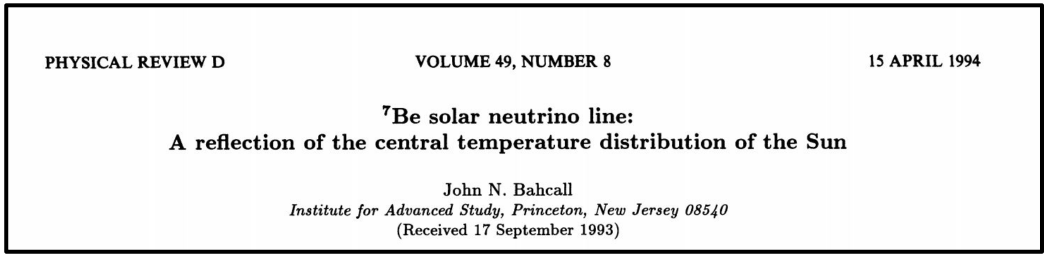
→ Estimated backgrounds <<1 ct in nEXO

S. Haselschwardt, **BL**, P. Pirinen, J. Suhonen, *Phys. Rev. D* **102** (2020)

What sort of impact can nEXO have?

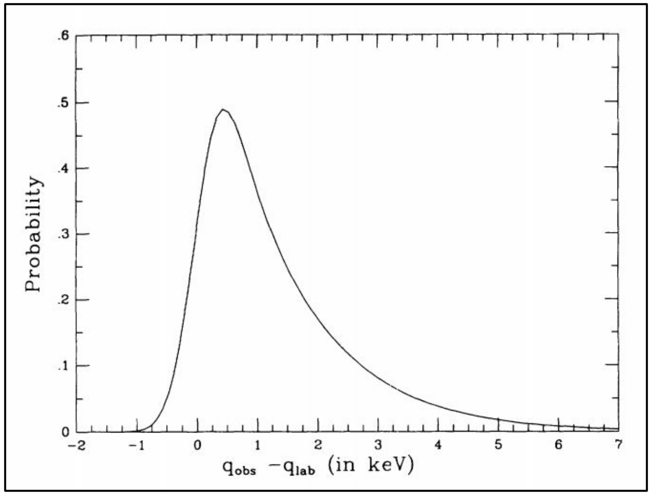
- **Predicted to observe ~35 CNO neutrino events, with essentially no background**
  - Statistical uncertainties 2x smaller than Borexino
  - Completely different systematics, provides independent verification
- **Beyond nEXO, liquid xenon TPCs could become a precision tool for solar neutrino physics**
  - New core temperature measurement via ^{7}Be neutrino line shift?



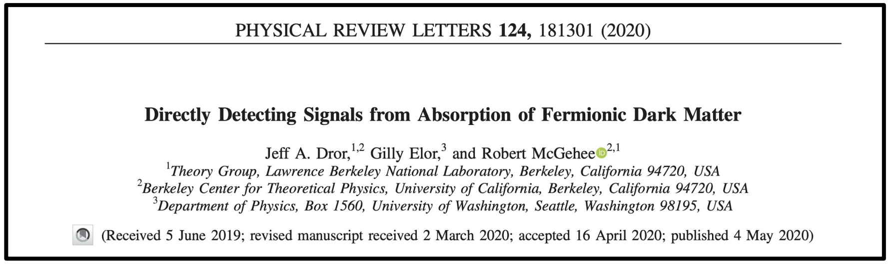

PHYSICAL REVIEW D VOLUME 49, NUMBER 8 15 APRIL 1994

^{7}Be solar neutrino line:
A reflection of the central temperature distribution of the Sun

John N. Bahcall
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 17 September 1993)



Fermionic dark matter CC interactions



PHYSICAL REVIEW LETTERS **124,** 181301 (2020)

Directly Detecting Signals from Absorption of Fermionic Dark Matter

Jeff A. Dror,[1,2] Gilly Elor,[3] and Robert McGehee[2,1]

[1]*Theory Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Berkeley Center for Theoretical Physics, University of California, Berkeley, California 94720, USA*
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(Received 5 June 2019; revised manuscript received 2 March 2020; accepted 16 April 2020; published 4 May 2020)

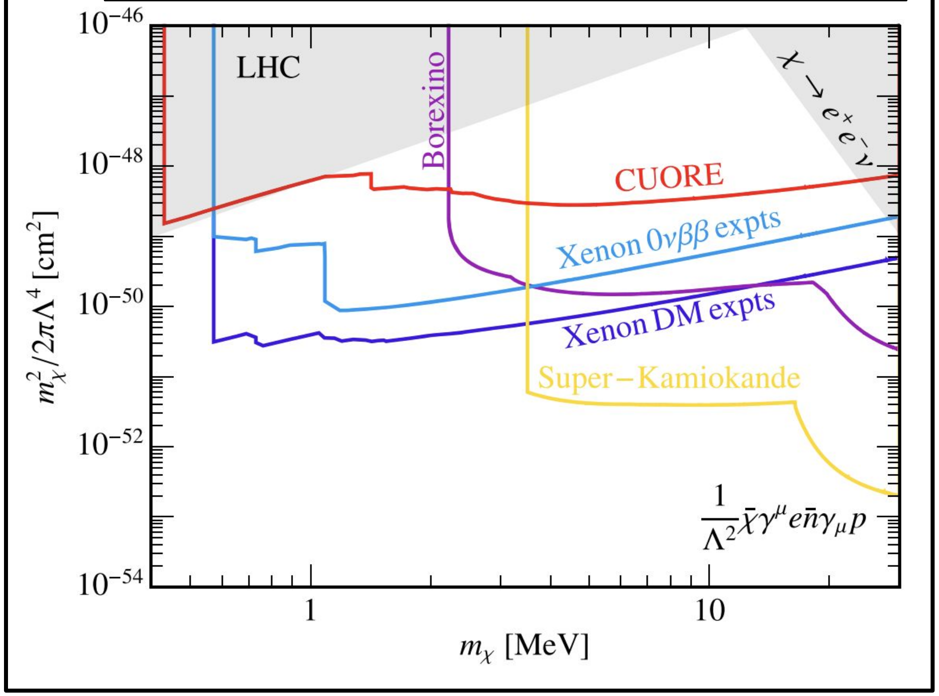
Fermionic dark matter can undergo absorption on nuclei via a new charged-current interaction with nuclei

$$\chi + {}^{136}\mathrm{Xe} \rightarrow {}^{136}\mathrm{Cs}^* + e^-$$

Projections indicate that next-generation 0νββ experiments have competitive sensitivity

- Delayed coincidence tagging could enable **leading sensitivity with nEXO**

(Very) rough projected constraints from current experiments



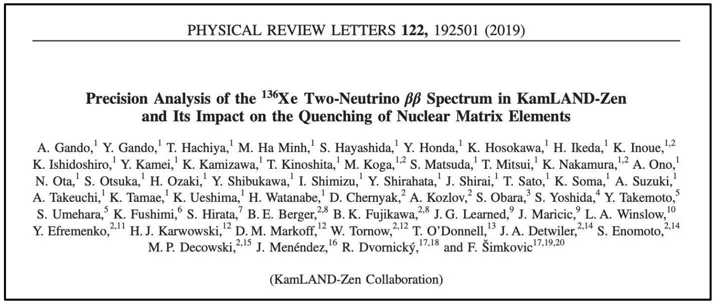
Precision measurements of 2$\nu\beta\beta$ decay

Second-order corrections to nuclear matrix elements to spectral shape of ^{136}Xe 2$\nu\beta\beta$ decay:

$$(T_{1/2}^{2\nu})^{-1} \simeq (g_A^{\rm eff})^4 |M_{GT}^{2\nu}|^2 G_0^{2\nu},$$

$$\downarrow$$

$$\begin{aligned}(T_{1/2}^{2\nu})^{-1} &\simeq (g_A^{\rm eff})^4 \left|(M_{GT}^{2\nu})^2 G_0^{2\nu} + M_{GT}^{2\nu} M_{GT-3}^{2\nu}\, G_2^{2\nu}\right| \\ &= (g_A^{\rm eff})^4 |M_{GT-3}^{2\nu}|^2 \frac{1}{|\xi_{31}^{2\nu}|^2} \left|G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right|, \quad (2)\end{aligned}$$

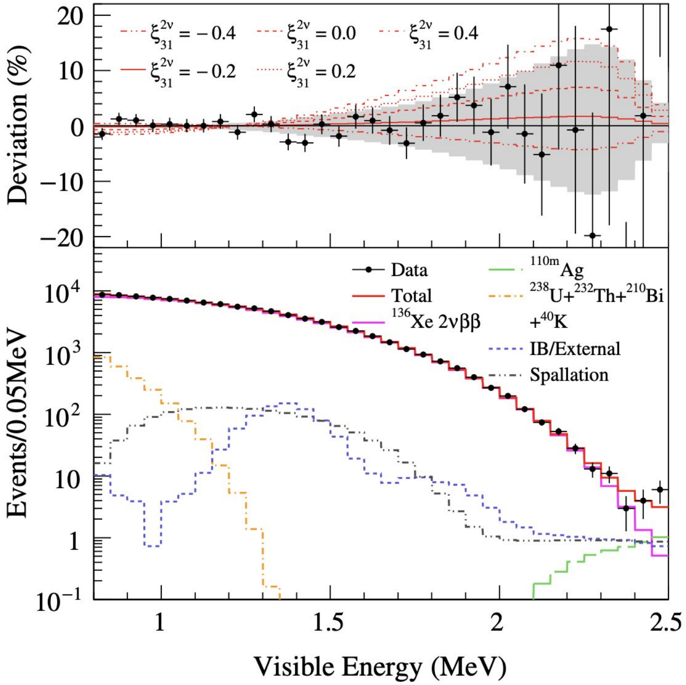


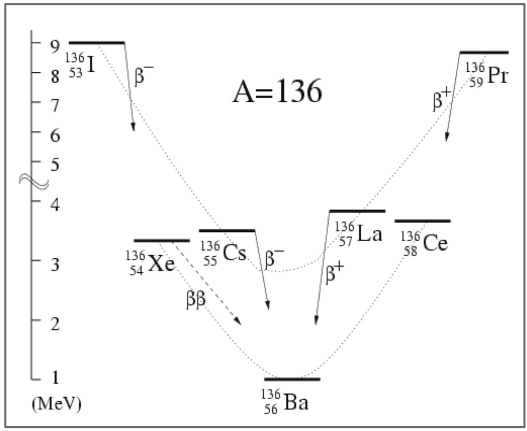
PHYSICAL REVIEW LETTERS **122,** 192501 (2019)

Precision Analysis of the ^{136}Xe Two-Neutrino $\beta\beta$ Spectrum in KamLAND-Zen and Its Impact on the Quenching of Nuclear Matrix Elements

A. Gando,[1] Y. Gando,[1] T. Hachiya,[1] M. Ha Minh,[1] S. Hayashida,[1] Y. Honda,[1] K. Hosokawa,[1] H. Ikeda,[1] K. Inoue,[1,2] K. Ishidoshiro,[1] Y. Kamei,[1] K. Kamizawa,[1] T. Kinoshita,[1] M. Koga,[1,2] S. Matsuda,[1] T. Mitsui,[1] K. Nakamura,[1,2] A. Ono,[1] N. Ota,[1] S. Otsuka,[1] H. Ozaki,[1] Y. Shibukawa,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] T. Sato,[1] K. Soma,[1] A. Suzuki,[1] A. Takeuchi,[1] K. Tamae,[1] K. Ueshima,[1] H. Watanabe,[1] D. Chernyak,[2] A. Kozlov,[2] S. Obara,[3] S. Yoshida,[4] Y. Takemoto,[5] S. Umehara,[5] K. Fushimi,[6] S. Hirata,[7] B. E. Berger,[2,8] B. K. Fujikawa,[2,8] J. G. Learned,[9] J. Maricic,[9] L. A. Winslow,[10] Y. Efremenko,[2,11] H. J. Karwowski,[12] D. M. Markoff,[12] W. Tornow,[2,12] T. O'Donnell,[13] J. A. Detwiler,[2,14] S. Enomoto,[2,14] M. P. Decowski,[2,15] J. Menéndez,[16] R. Dvornický,[17,18] and F. Šimkovic[17,19,20]

(KamLAND-Zen Collaboration)

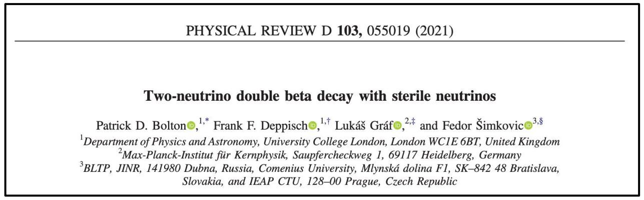




P. Vogel, *J. Phys. G* **39** (2012)

"While M_{GT} is sensitive to contributions from high-lying states in the intermediate odd-odd nucleus, for M_{GT-3} only the lowest-energy states are relevant due to rapid suppression in the energy denominator"

2𝜈ββ spectral shape is sensitive to new physics


PHYSICAL REVIEW D **103,** 055019 (2021)

Two-neutrino double beta decay with sterile neutrinos

Patrick D. Bolton,[1,*] Frank F. Deppisch,[1,†] Lukáš Gráf,[2,‡] and Fedor Šimkovic[3,§]
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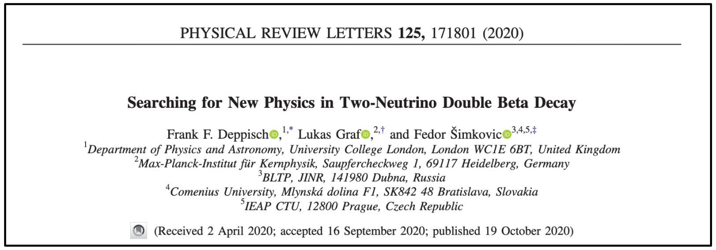
[3]*BLTP, JINR, 141980 Dubna, Russia, Comenius University, Mlynská dolina F1, SK–842 48 Bratislava, Slovakia, and IEAP CTU, 128–00 Prague, Czech Republic*

Sterile neutrino searches

Exotic right-handed vector lepton currents (e.g. left/right symmetric models)


PHYSICAL REVIEW LETTERS **125,** 171801 (2020)

Searching for New Physics in Two-Neutrino Double Beta Decay

Frank F. Deppisch,[1,*] Lukas Graf,[2,†] and Fedor Šimkovic[3,4,5,‡]
[1]*Department of Physics and Astronomy, University College London, London WC1E 6BT, United Kingdom*
[2]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
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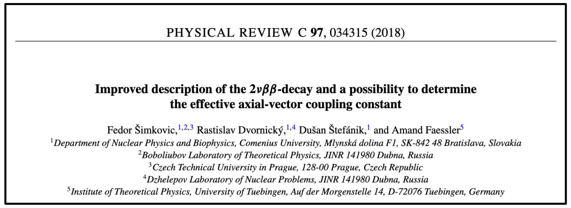
[5]*IEAP CTU, 12800 Prague, Czech Republic*

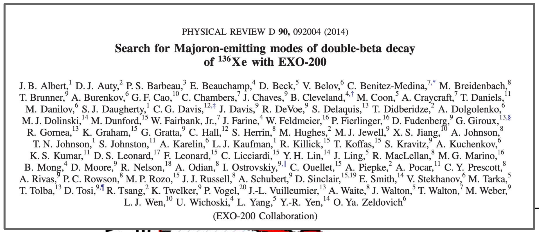
(Received 2 April 2020; accepted 16 September 2020; published 19 October 2020)

Modifications to the axial-vector coupling constant in heavy nuclei


PHYSICAL REVIEW C **97**, 034315 (2018)

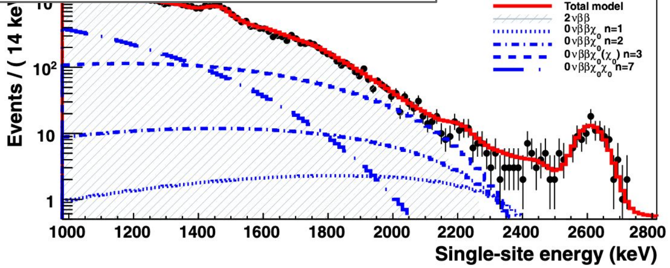
Improved description of the $2\nu\beta\beta$-decay and a possibility to determine the effective axial-vector coupling constant

Fedor Šimkovic,[1,2,3] Rastislav Dvornický,[1,4] Dušan Štefánik,[1] and Amand Faessler[5]
[1]*Department of Nuclear Physics and Biophysics, Comenius University, Mlynská dolina F1, SK-842 48 Bratislava, Slovakia*
[2]*Boboliubov Laboratory of Theoretical Physics, JINR 141980 Dubna, Russia*
[3]*Czech Technical University in Prague, 128-00 Prague, Czech Republic*
[4]*Dzhelepov Laboratory of Nuclear Problems, JINR 141980 Dubna, Russia*
[5]*Institute of Theoretical Physics, University of Tuebingen, Auf der Morgenstelle 14, D-72076 Tuebingen, Germany*

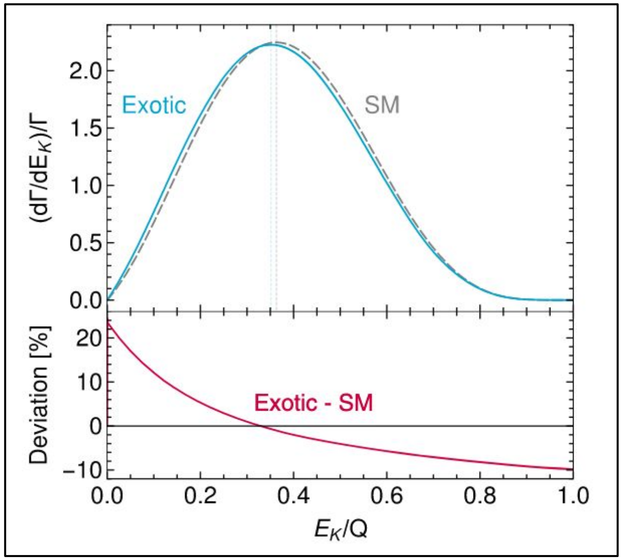

PHYSICAL REVIEW D **90,** 092004 (2014)

Search for Majoron-emitting modes of double-beta decay of ^{136}Xe with EXO-200

J. B. Albert,[1] D. J. Auty,[2] P. S. Barbeau,[3] E. Beauchamp,[4] D. Beck,[5] V. Belov,[6] C. Benitez-Medina,[7,*] M. Breidenbach,[8] T. Brunner,[9] A. Burenkov,[6] G. F. Cao,[10] C. Chambers,[7] J. Chaves,[9] B. Cleveland,[4,†] M. Coon,[5] A. Craycraft,[7] T. Daniels,[11] M. Danilov,[6] S. J. Daugherty,[1] C. G. Davis,[12,‡] J. Davis,[9] R. DeVoe,[9] S. Delaquis,[13] T. Didberidze,[2] A. Dolgolenko,[6] M. J. Dolinski,[14] M. Dunford,[15] W. Fairbank, Jr.,[7] J. Farine,[4] W. Feldmeier,[16] P. Fierlinger,[16] D. Fudenberg,[9] G. Giroux,[13,§] R. Gornea,[13] K. Graham,[15] G. Gratta,[9] C. Hall,[12] S. Herrin,[8] M. Hughes,[2] M. J. Jewell,[9] X. S. Jiang,[10] A. Johnson,[8] T. N. Johnson,[1] S. Johnston,[11] A. Karelin,[6] L. J. Kaufman,[1] R. Killick,[15] T. Koffas,[15] S. Kravitz,[9] A. Kuchenkov,[6] K. S. Kumar,[11] D. S. Leonard,[17] F. Leonard,[15] C. Licciardi,[15] Y. H. Lin,[14] J. Ling,[5] R. MacLellan,[8] M. G. Marino,[16] B. Mong,[4] D. Moore,[9] R. Nelson,[18] A. Odian,[8] I. Ostrovskiy,[9,‖] C. Ouellet,[15] A. Piepke,[2] A. Pocar,[11] C. Y. Prescott,[8] A. Rivas,[9] P. C. Rowson,[8] M. P. Rozo,[15] J. J. Russell,[8] A. Schubert,[9] D. Sinclair,[15,19] E. Smith,[14] V. Stekhanov,[6] M. Tarka,[5] T. Tolba,[13] D. Tosi,[9,¶] R. Tsang,[2] K. Twelker,[9] P. Vogel,[20] J.-L. Vuilleumier,[13] A. Waite,[8] J. Walton,[5] T. Walton,[7] M. Weber,[9] L. J. Wen,[10] U. Wichoski,[4] L. Yang,[5] Y.-R. Yen,[14] O. Ya. Zeldovich[6]
(EXO-200 Collaboration)



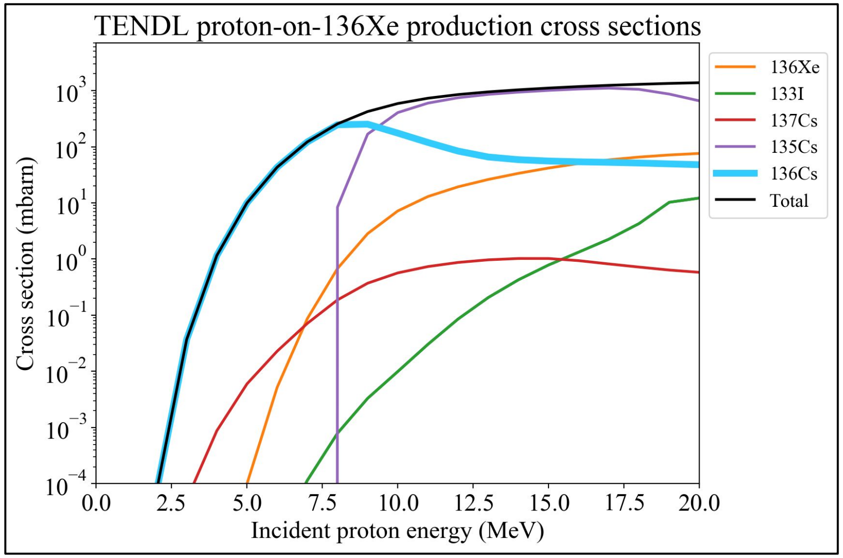
Exotic decay modes which emit new particles

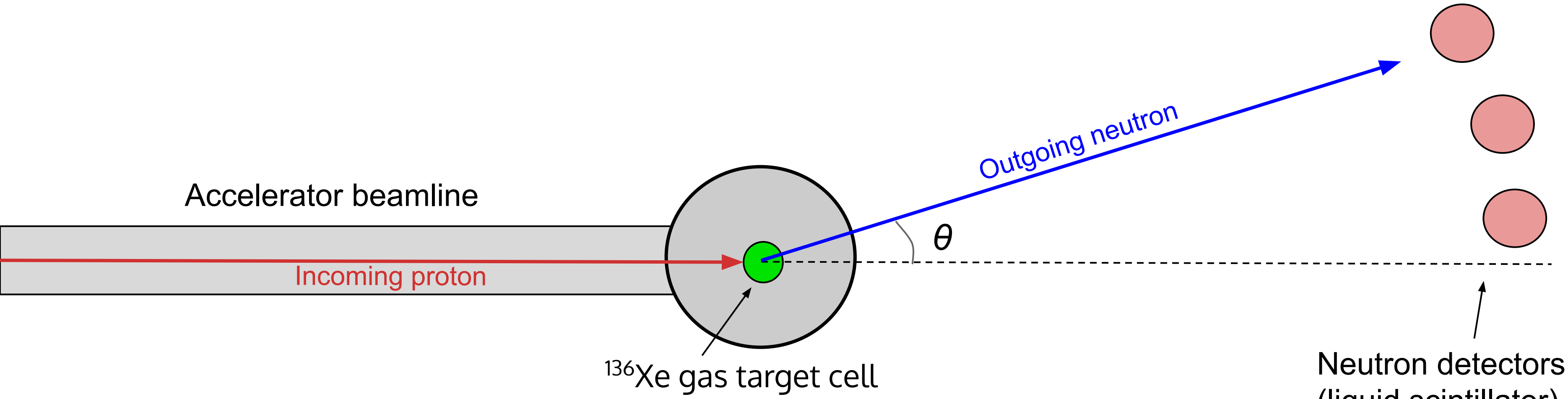


Proposed measurements

Low-energy (p,n) scattering on ^{136}Xe target

- 5-7 MeV protons create ^{136}Cs* with very little background
- Neutron TOF can select events which populate 1^+ state of interest
- Measure γ cascade with additional detectors




Accelerator beamline

Incoming proton

Outgoing neutron

θ

^{136}Xe gas target cell

Neutron detectors (liquid scintillator)

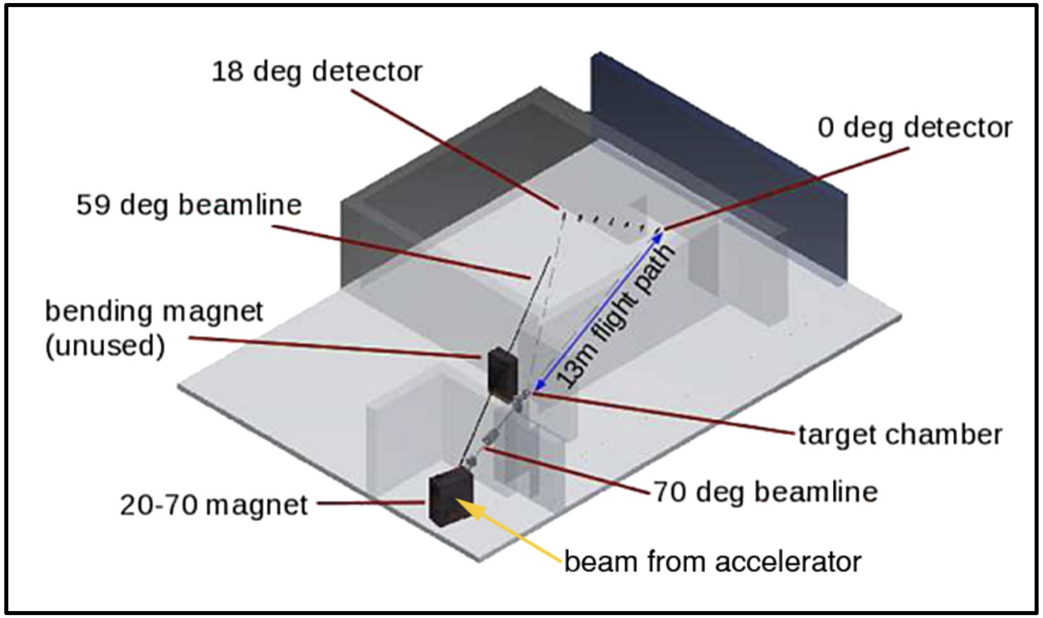
Prospects at TUNL

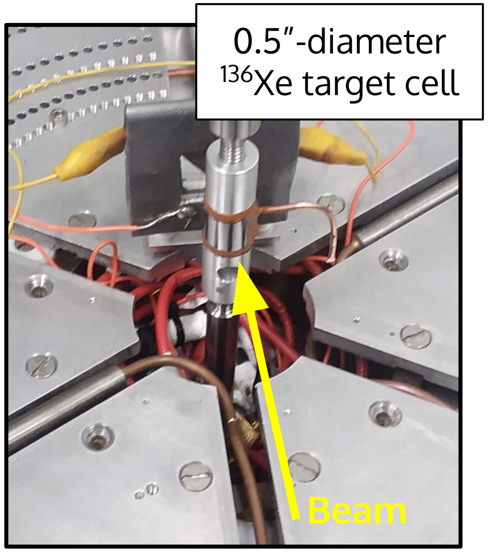
Triangle Universities Nuclear Lab (TUNL) has a neutron TOF beamline which is almost perfect!

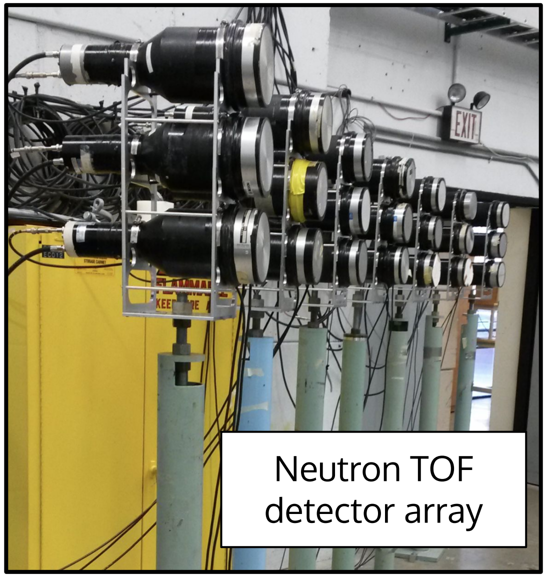
- Previously used for (^{3}He,n) experiments on ^{136}Xe
- Need to add γ-tagging to search for isomeric state

Measurements can start when COVID restrictions lifted

- Planning in progress with collaborators at LBL, UNC-Wilmington, Duke




0.5″-diameter ^{136}Xe target cell

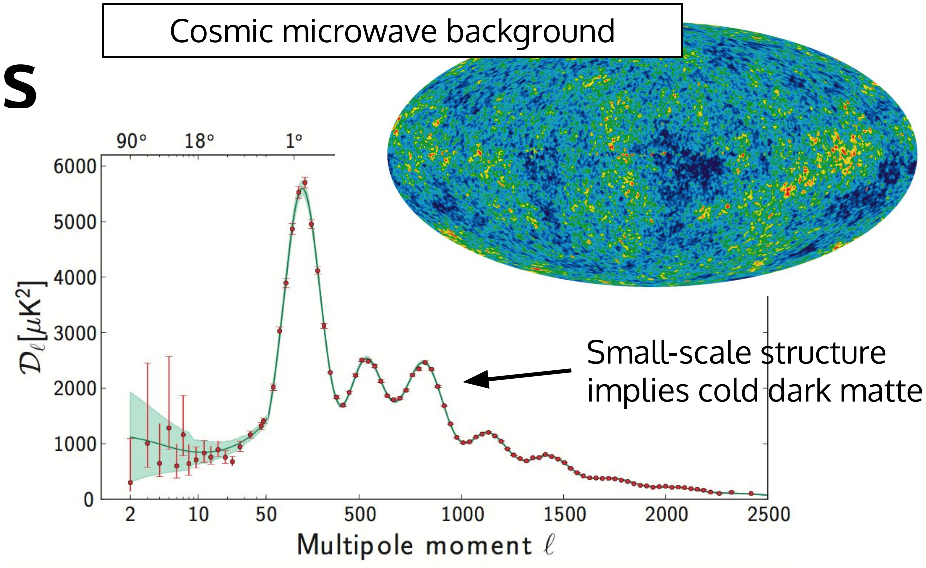

Neutron TOF detector array

Images from the thesis of D. Ticehurst (UNC)

Dark matter

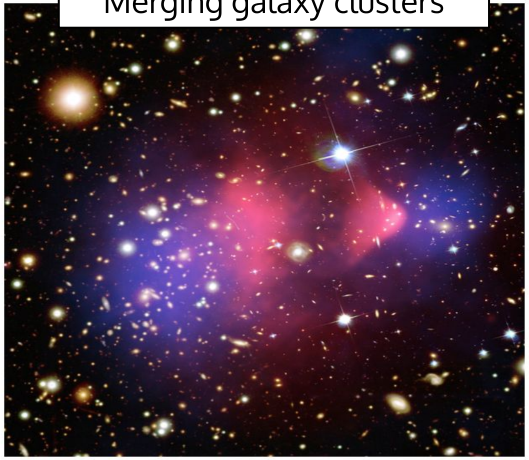
Evidence at many scales

Cosmic microwave background

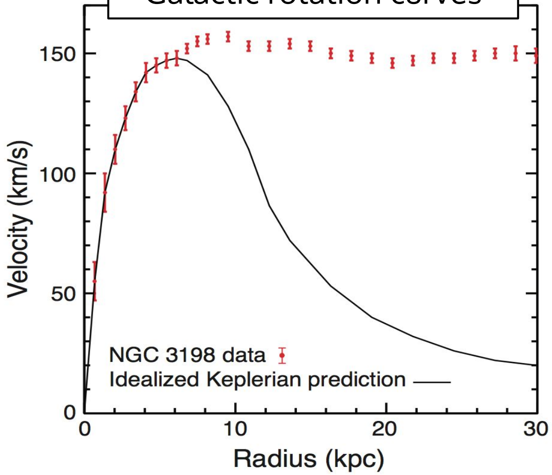


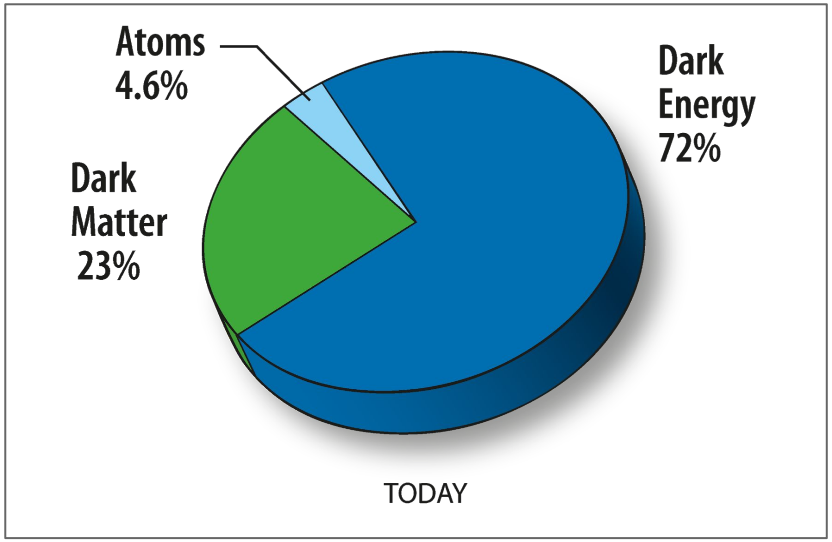
Small-scale structure implies cold dark matter

Merging galaxy clusters



Galactic rotation curves

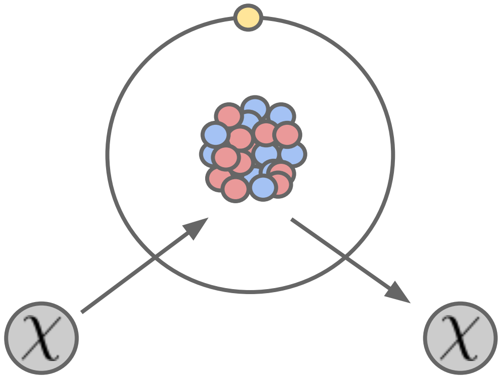


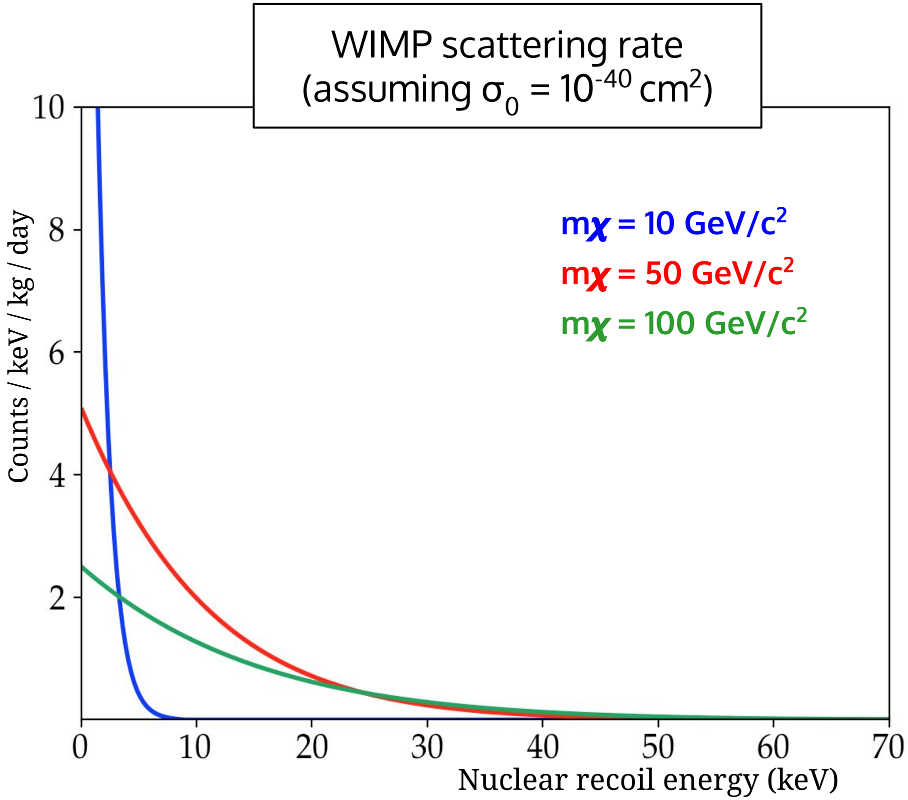


WIMP dark matter

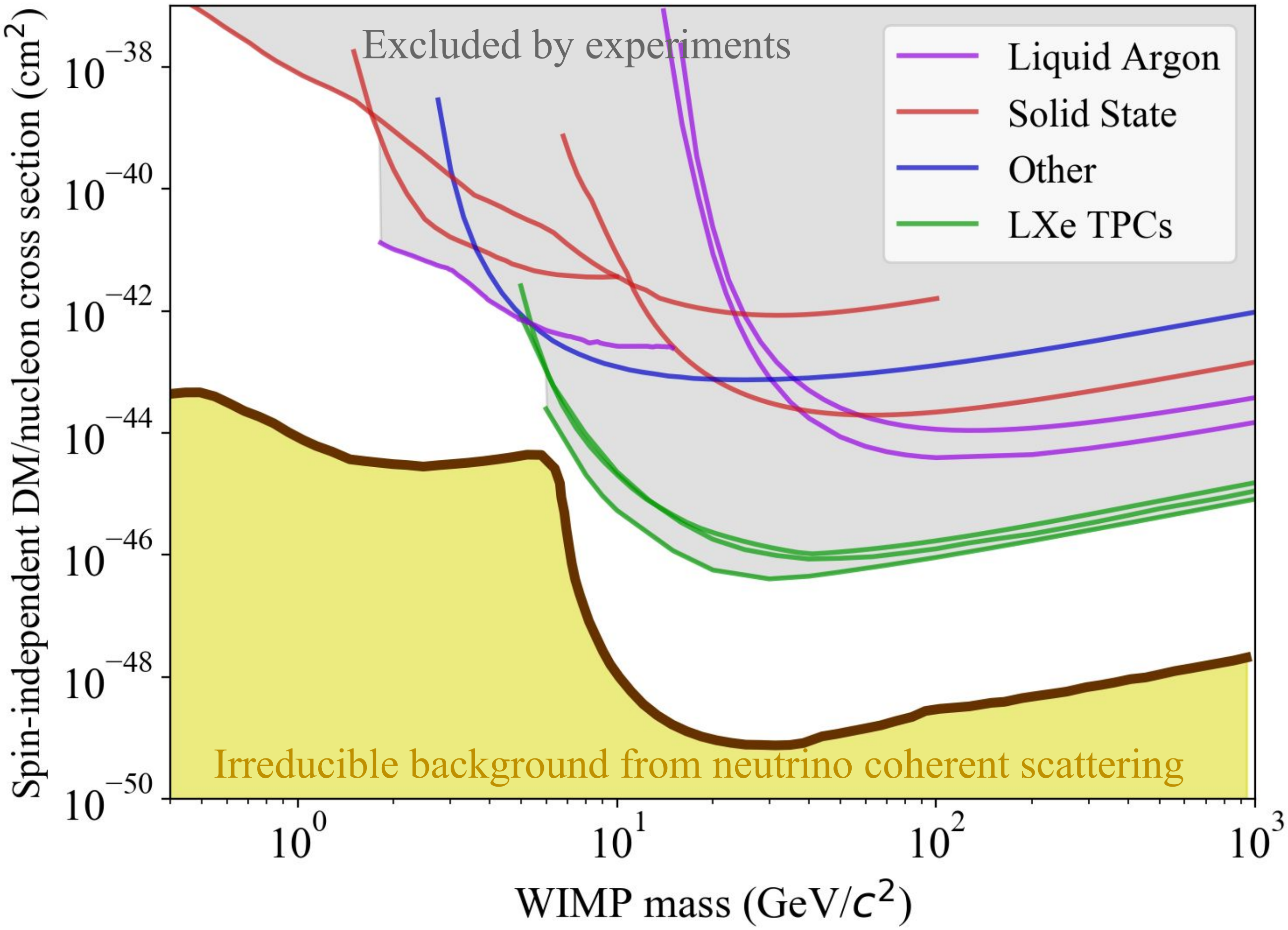
Weakly **I**nteracting **M**assive **P**articles

- **New neutral particle, beyond the standard model**
- **Weak-scale annihilation cross-section** gives us the right amount of dark matter
- **Expected mass ~1 GeV to 1 TeV,** but not well constrained
- Could be observed via **elastic scattering with nuclei** in a low-background detector




WIMP scattering rate (assuming $\sigma_0 = 10^{-40}$ cm^2)

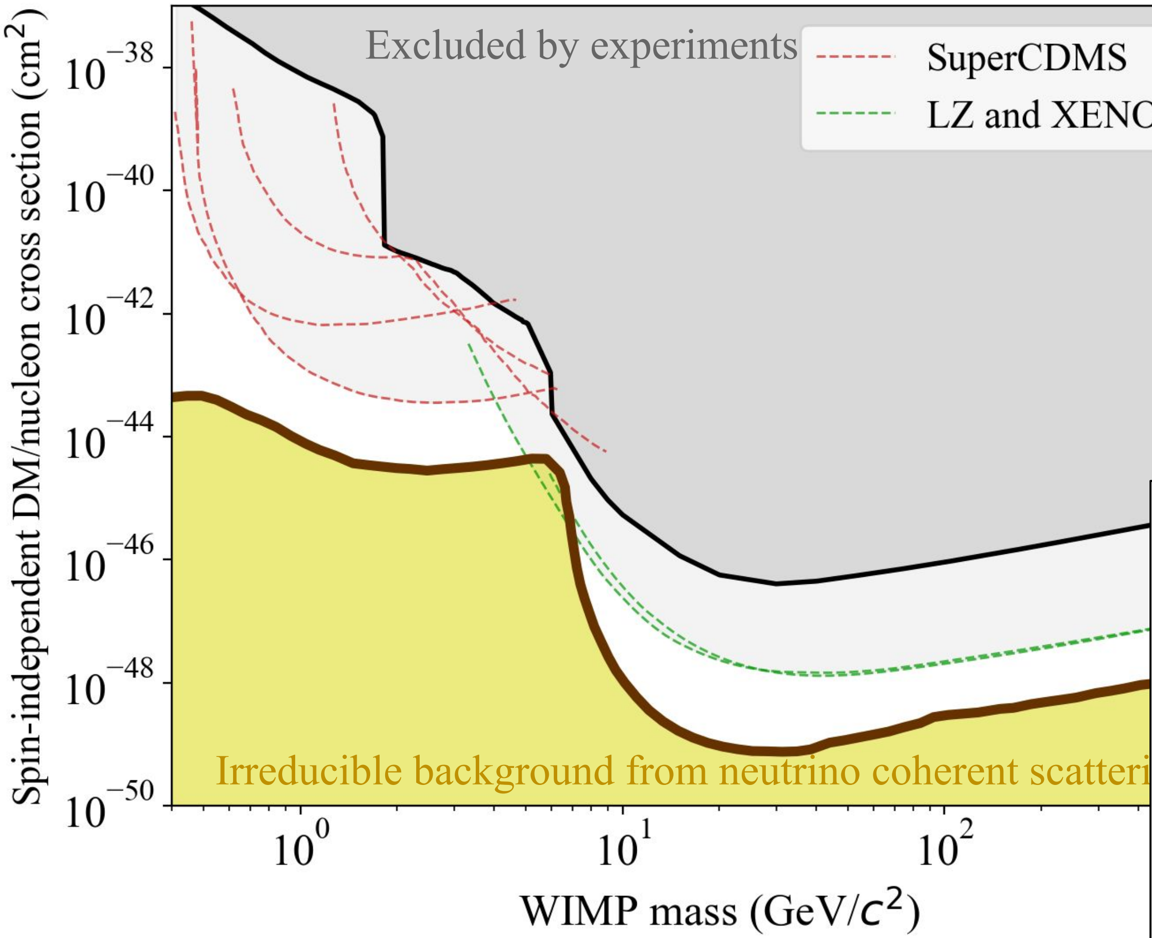
The hunt for WIMPs today



Large mass + low backgrounds are key

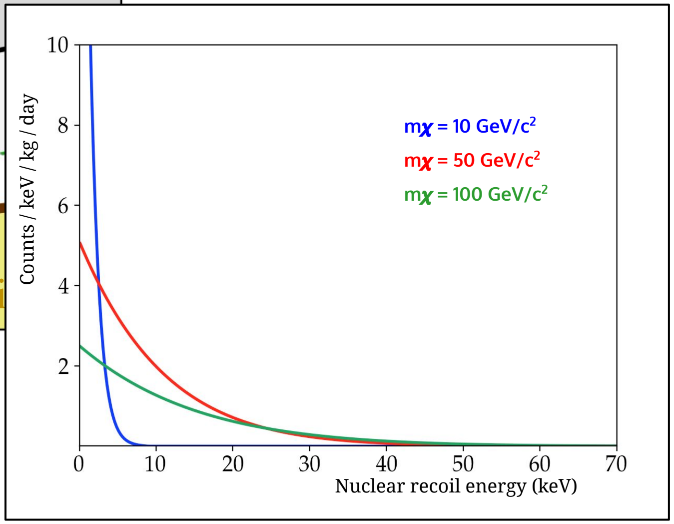
Liquid xenon TPCs are most sensitive experiments for WIMP masses >10 GeV

The hunt for WIMPs in the next decade



Liquid xenon TPCs will continue to lead searches for DM at high masses.

Other technologies are required to explore the low-mass parameter space.



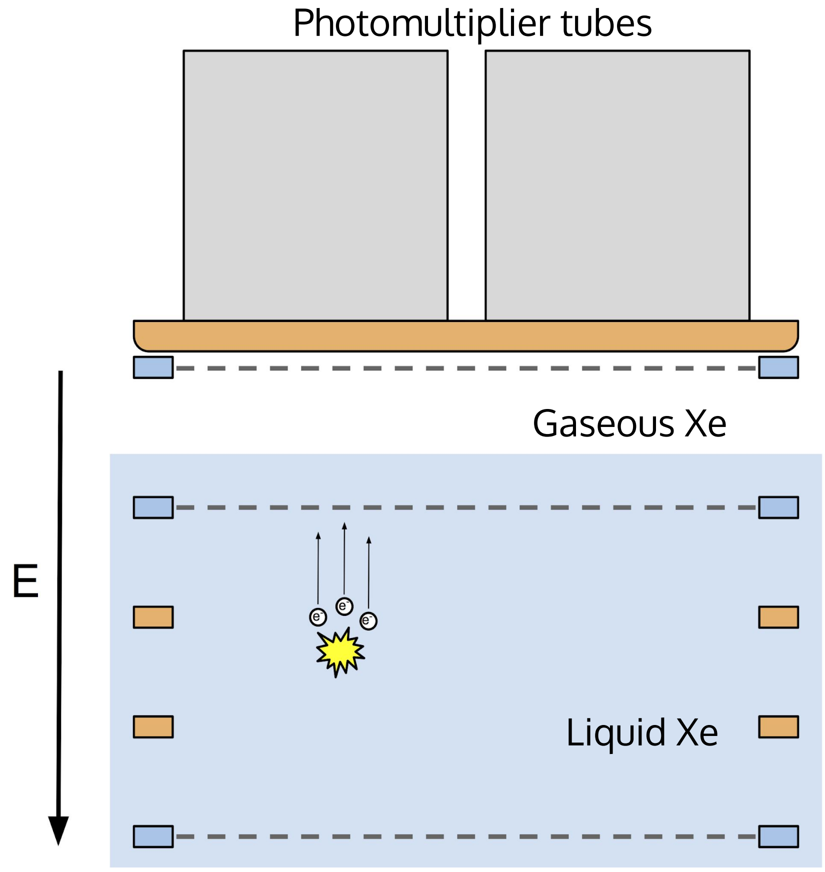
Lowering the threshold in liquid xenon detectors

Dual-phase xenon detectors

- Electroluminescence in gas enables detection of **single ionization electrons**

Need to understand signals at low energies to estimate dark matter sensitivity

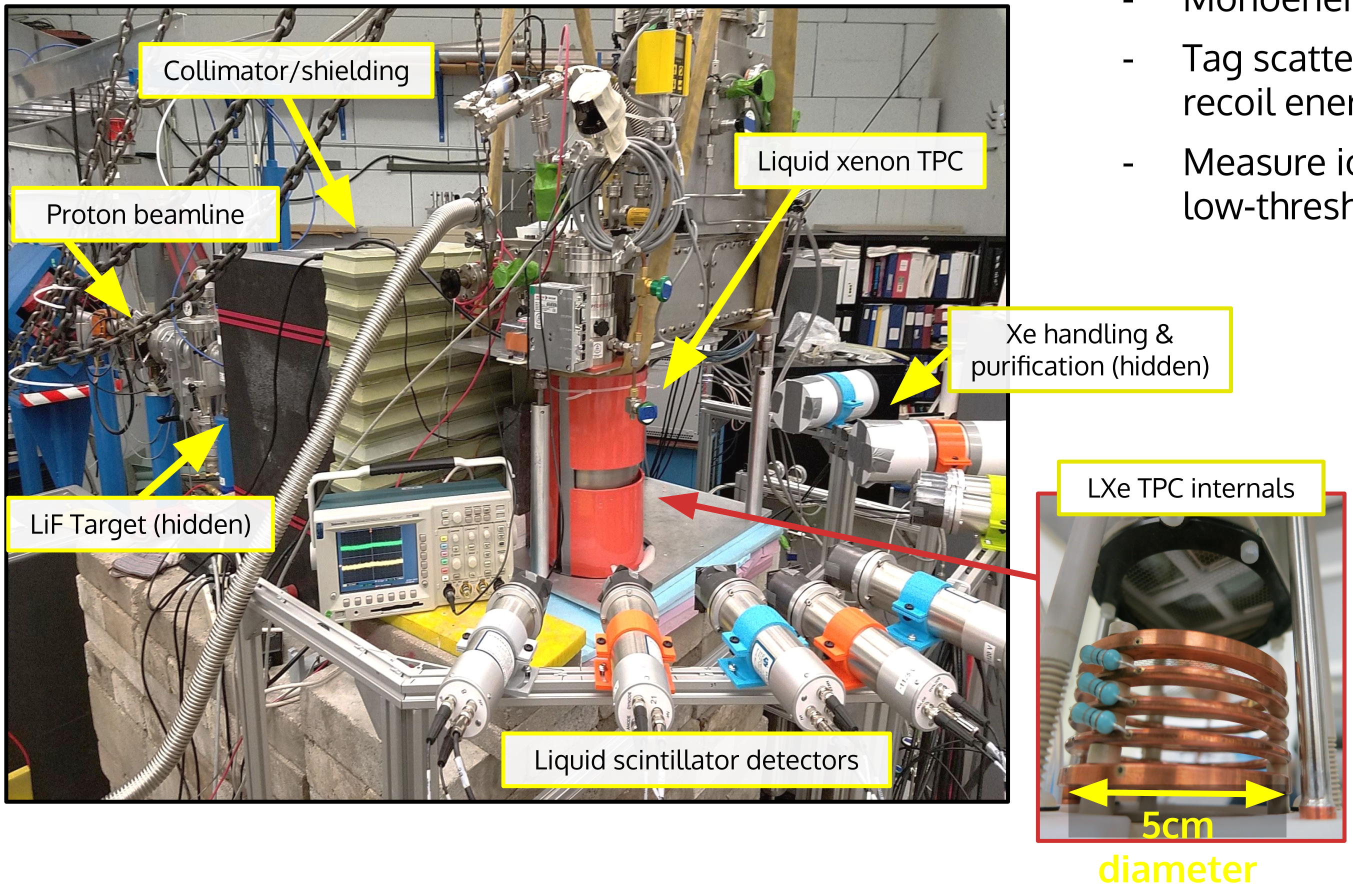
Ionization signal ⟷ ? **Nuclear recoil energy**



Ultra-low-energy nuclear recoil measurements

Create nuclear recoils in liquid xenon via elastic neutron scattering

- Monoenergetic neutrons (~600 keV)
- Tag scattering angle to determine recoil energy
- Measure ionization in custom-designed low-threshold xenon detector



The team

Lawrence Livermore National Lab:

- Jingke Xu
- Sergey Pereverzev
- Adam Bernstein
- Kareem Kazkaz
- Tomi Akindele

UC Davis:

- Daniel Naim
- Mani Tripathi

Duke/TUNL:

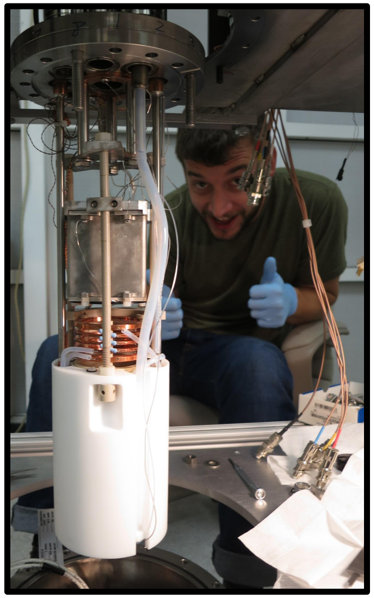
- Connor Awe
- Long Li
- Sam Hedges
- Jay Runge
- Peibo An
- Phil Barbeau

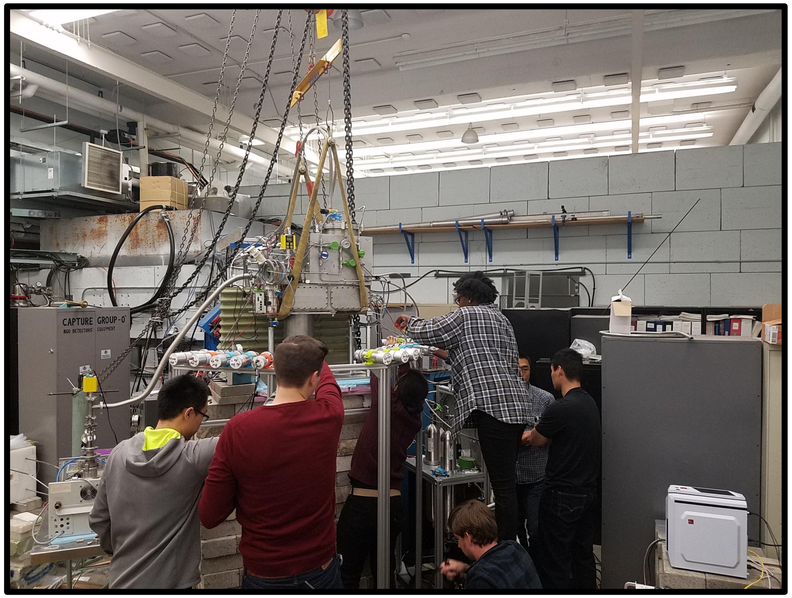
Stanford:

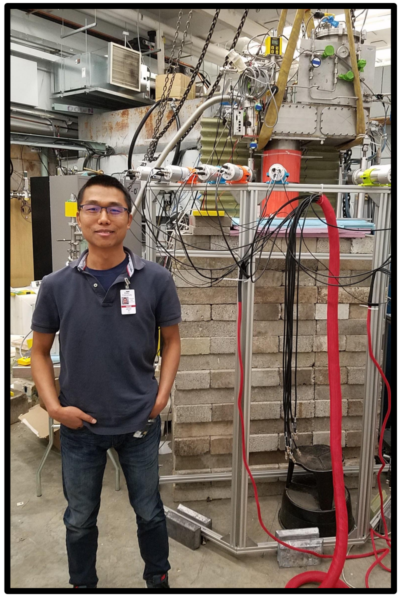
- Brian Lenardo

Now at UC Davis:

- Jimmy Kingston



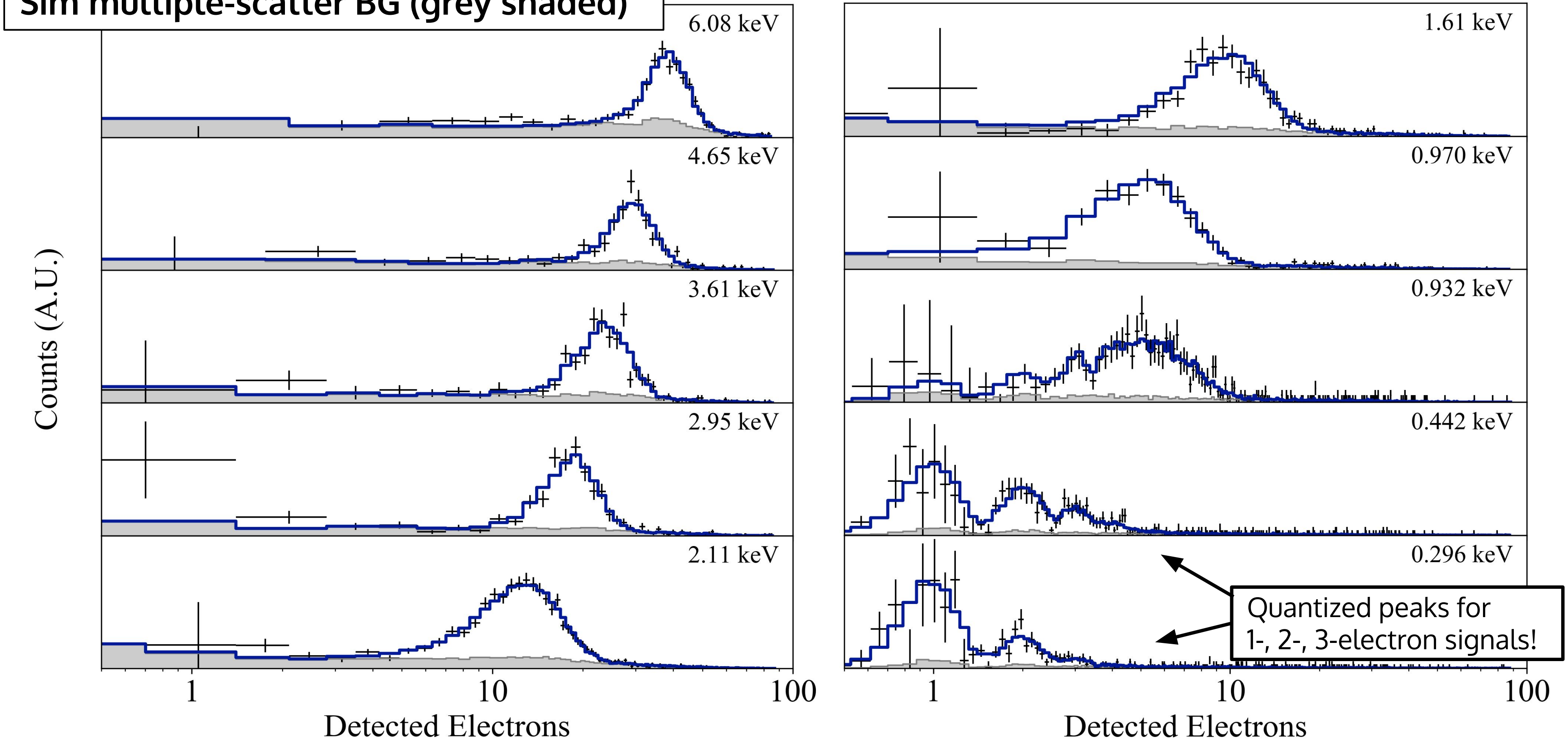




Nuclear recoil ionization measurements

Data (black points)
Full simulated distributions (blue lines)
Sim multiple-scatter BG (grey shaded)

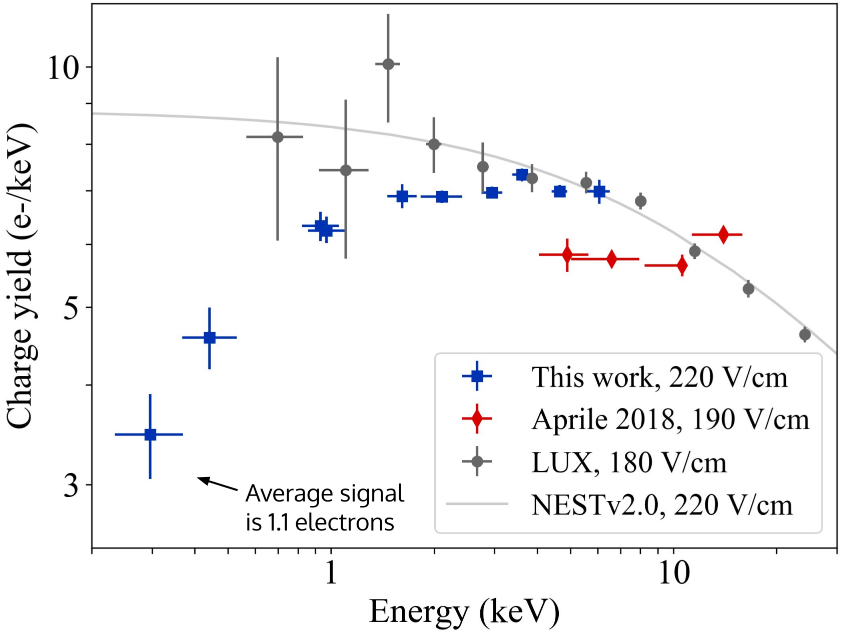
BL et al., *Phys. Rev. Lett.* **123** (2019)



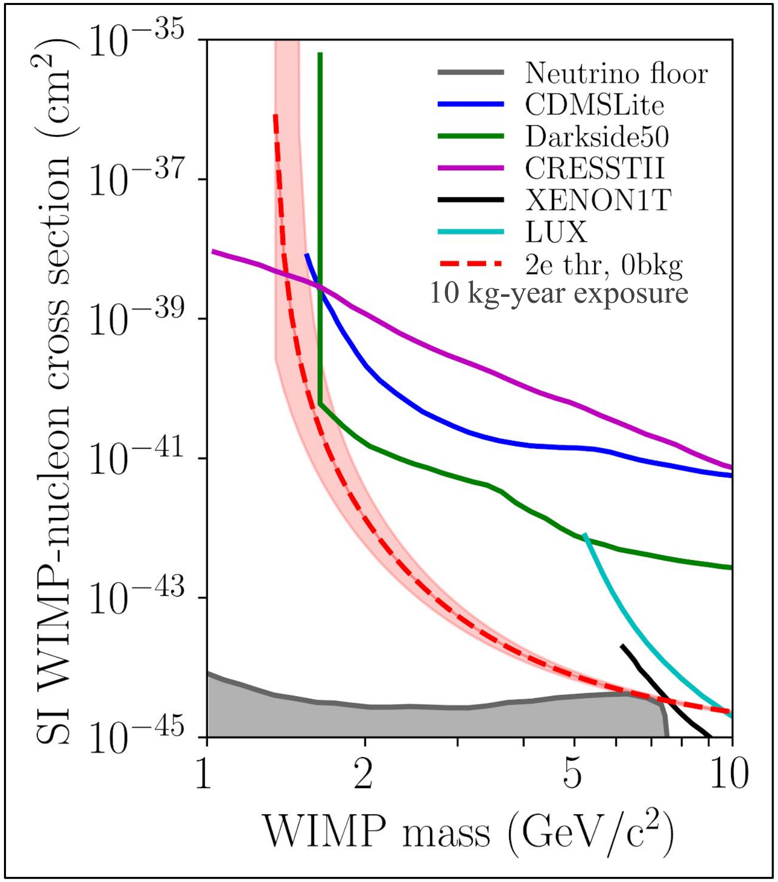
Quantized peaks for 1-, 2-, 3-electron signals!

How low can you go?

Nuclear recoil ionization yield in liquid xenon



Hypothetical LXe DM limits



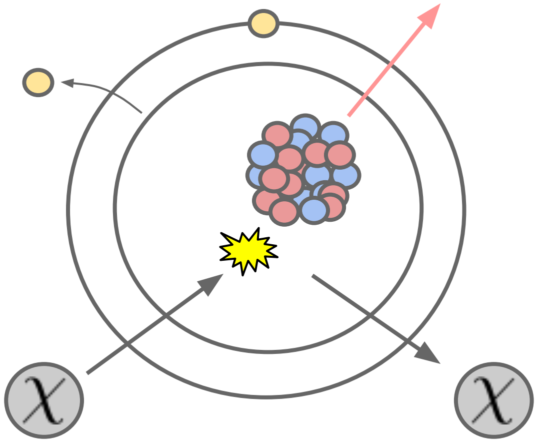
New measurements allow robust DM sensitivity projections down to lowest possible threshold.

This sets the *ultimate* possible sensitivity to low-mass WIMP dark matter using LXe detectors.

BL et al., *Phys. Rev. Lett.* **123** (2019)

…but can we lower the threshold further?

The Migdal effect

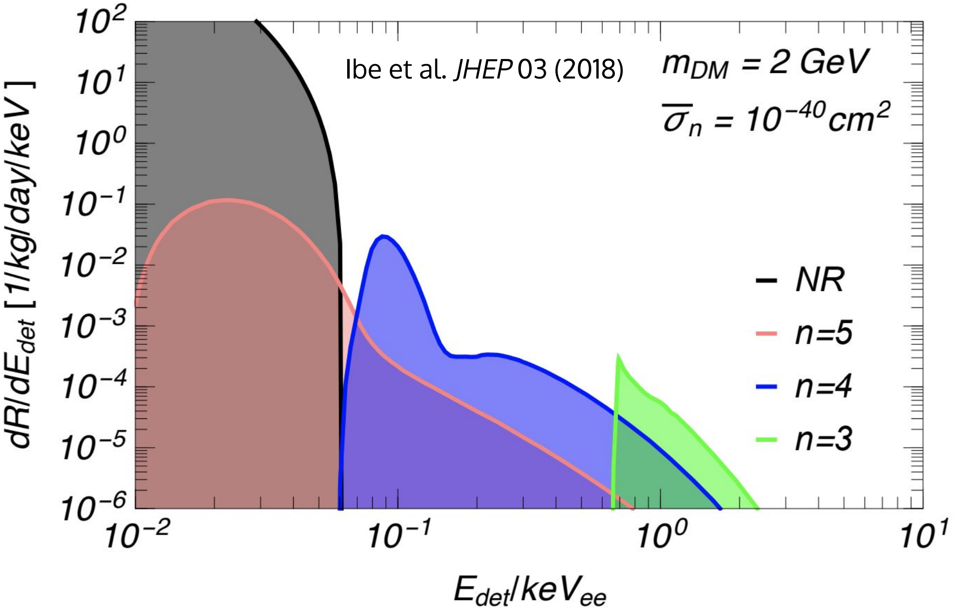


Nuclear recoils can redistribute energy to the atomic electrons, resulting in ionization with some low probability

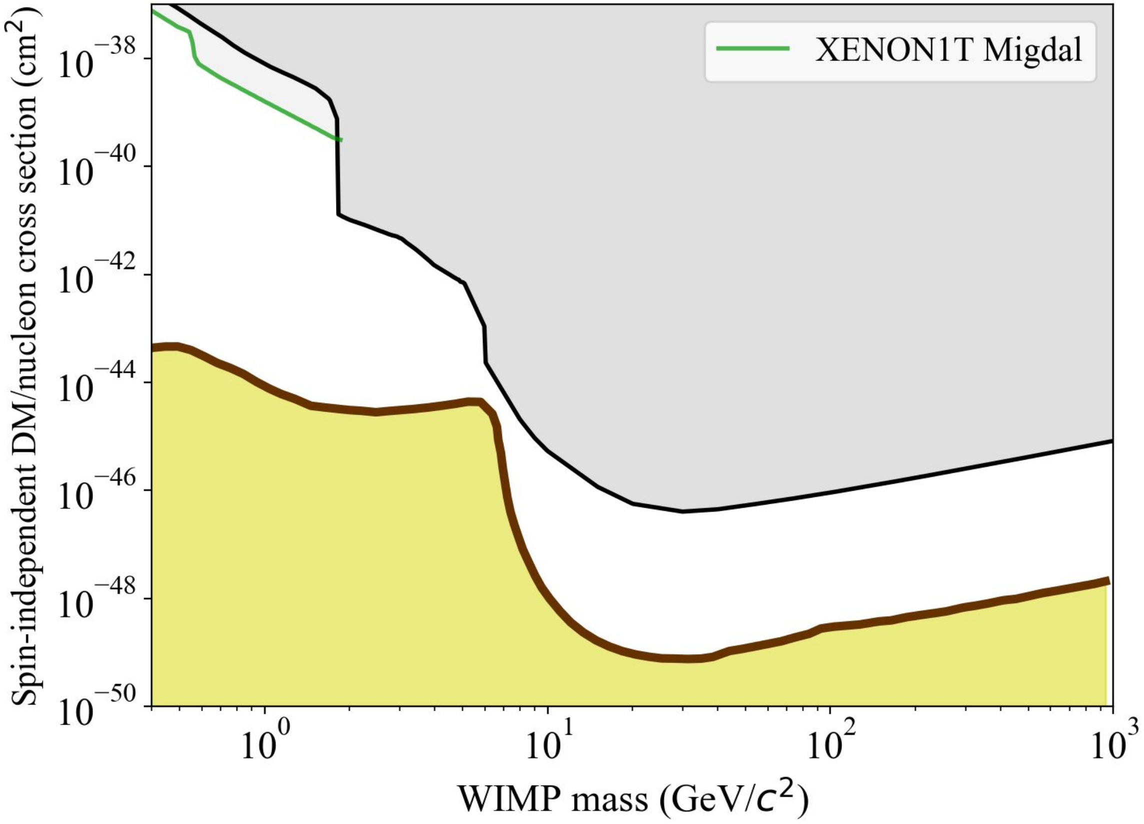
- Atomic relaxation will emit ~keV-scale X-rays

Trading rate for threshold

- Emission probability is small, but signals are visible above threshold



DM limits using Migdal effect in LXe



Migdal effect enables new low-mass sensitivity in liquid xenon dark matter experiments

However, it has never been observed experimentally!

Could we verify the Migdal effect?

Preliminary simulation work suggests that this may be possible with the LLNL prototype detector

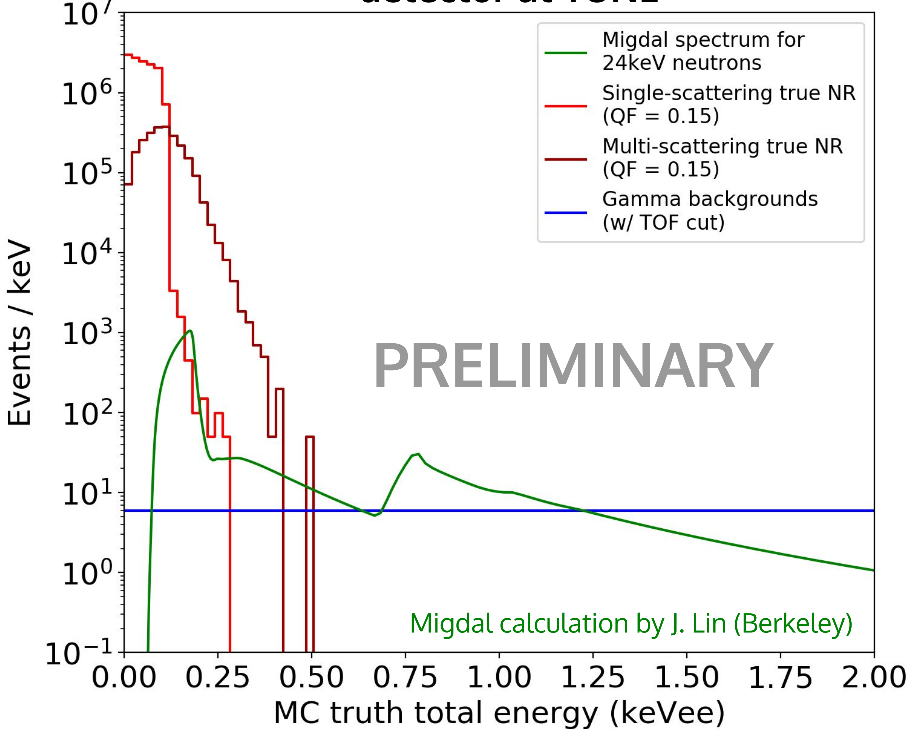
Assumptions:

- Same configuration as ionization yield measurements
- Pulsed beam of very low energy neutrons (24 keV)

Simulation results so far

- Primary backgrounds from neutron capture γ-rays
- Need additional work to characterize other backgrounds from e.g. activation

Simulation of 10^{10} neutrons with LLNL detector at TUNL



Migdal calculation by J. Lin (Berkeley)

Conclusions

Conclusions

- **The standard model of particle physics is a landmark theory, but is incomplete**
- **Liquid xenon detectors are a powerful tool in the hunt for new physics**
  - Low backgrounds and large masses enable extremely sensitive searches for 0νββ and WIMP dark matter
- **The search for 0νββ with NEXO will push 100x further than current experiments, with significant discovery potential**
  - May also provide new measurements of solar astrophysics and DM
- **Liquid xenon TPCs have great promise in the search for WIMPs, and new results may enable reaching new, low-mass parameter space**

Thank you!

Backup slides

Why double beta decay?

Effective field theory analysis for LNV operators up to dimension 9, for two processes:

0νβ⁻β⁻ decay

- $T_{1/2} > 1.06 \times 10^{26}$ years (KAMLAND-Zen)

μ⁻→ e⁺ conversion

- $R < 1.7 \times 10^{-12}$ (SINDRUM II)

Conclusion: 0νββ decay is generally the most sensitive probe of lepton number violation… *by far*

- Enhancement due to powers of energy transfer (Q) in the interaction
- Much larger “exposure” in 0νββ experiments compared to beam experiments

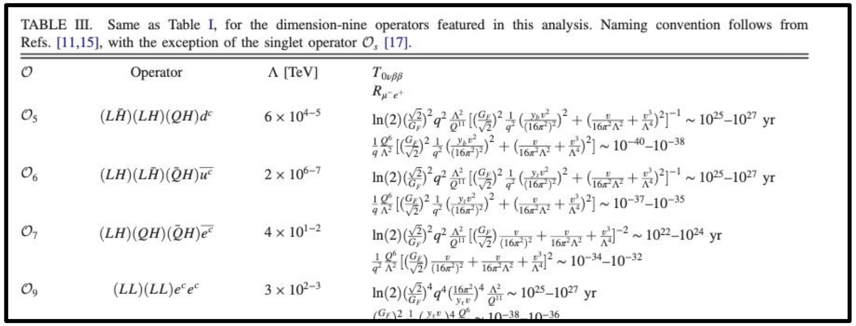
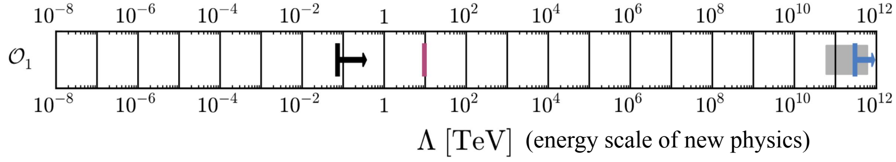


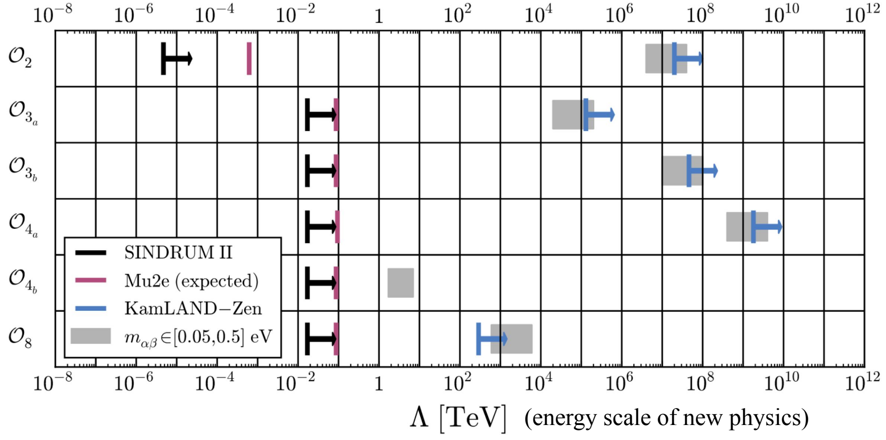
TABLE III. Same as Table I, for the dimension-nine operators featured in this analysis. Naming convention follows from Refs. [11,15], with the exception of the singlet operator $\mathcal{O}_s$ [17].

$\mathcal{O}$	Operator	Λ [TeV]	$T_{0\nu\beta\beta}$ $R_{\mu^- e^+}$
$\mathcal{O}_5$	$(L\bar{H})(LH)(QH)d^c$	$6 \times 10^{4-5}$	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^2 q^2 \frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2 \frac{1}{q^2}\left(\frac{y_b v^2}{(16\pi^2)^2}\right)^2 + \left(\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right)^2\right]^{-1} \sim 10^{25}\text{–}10^{27}$ yr $\frac{1}{q}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2 \frac{1}{q^2}\left(\frac{y_b v^2}{(16\pi^2)^2}\right)^2 + \left(\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right)^2\right] \sim 10^{-40}\text{–}10^{-38}$
$\mathcal{O}_6$	$(LH)(L\bar{H})(\bar{Q}H)\overline{u^c}$	$2 \times 10^{6-7}$	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^2 q^2 \frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2 \frac{1}{q^2}\left(\frac{y_t v^2}{(16\pi^2)^2}\right)^2 + \left(\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right)^2\right]^{-1} \sim 10^{25}\text{–}10^{27}$ yr $\frac{1}{q}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2 \frac{1}{q^2}\left(\frac{y_t v^2}{(16\pi^2)^2}\right)^2 + \left(\frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right)^2\right] \sim 10^{-37}\text{–}10^{-35}$
$\mathcal{O}_7$	$(LH)(QH)(\bar{Q}H)\overline{e^c}$	$4 \times 10^{1-2}$	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^2 q^2 \frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)\frac{v}{(16\pi^2)^2} + \frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right]^{-2} \sim 10^{22}\text{–}10^{24}$ yr $\frac{1}{q^2}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)\frac{v}{(16\pi^2)^2} + \frac{v}{16\pi^2\Lambda^2} + \frac{v^3}{\Lambda^4}\right]^2 \sim 10^{-34}\text{–}10^{-32}$
$\mathcal{O}_9$	$(LL)(LL)e^c e^c$	$3 \times 10^{2-3}$	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^4 q^4 \left(\frac{16\pi^2}{y_\tau v}\right)^4 \frac{\Lambda^2}{Q^{11}} \sim 10^{25}\text{–}10^{27}$ yr

Dimension 5 Weinberg operator



Dimension 7 operators



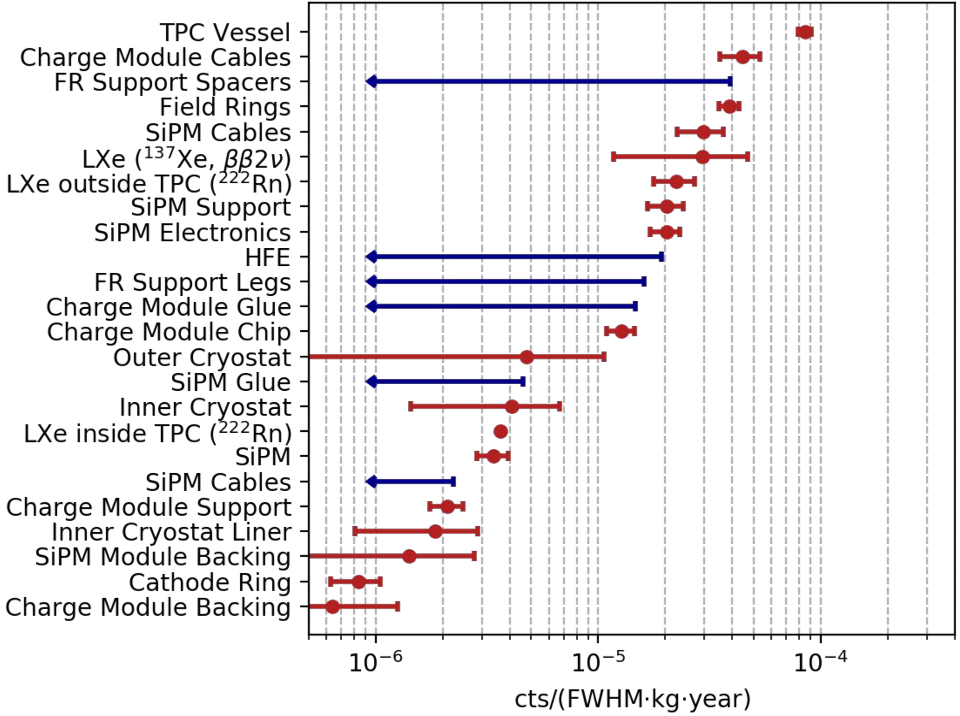
Berryman et al. *Phys Rev D* **95**, 115010 (2017)

Estimating background contributions for nEXO

Essentially every material in existing design has been screened for radiopurity

→ nEXO background model is conservative and data-driven

ROI background rate by detector component



ROI background contribution by source