Astrophysical and terrestrial applications of coherent neutrino scattering

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PRIMSA Colloquium
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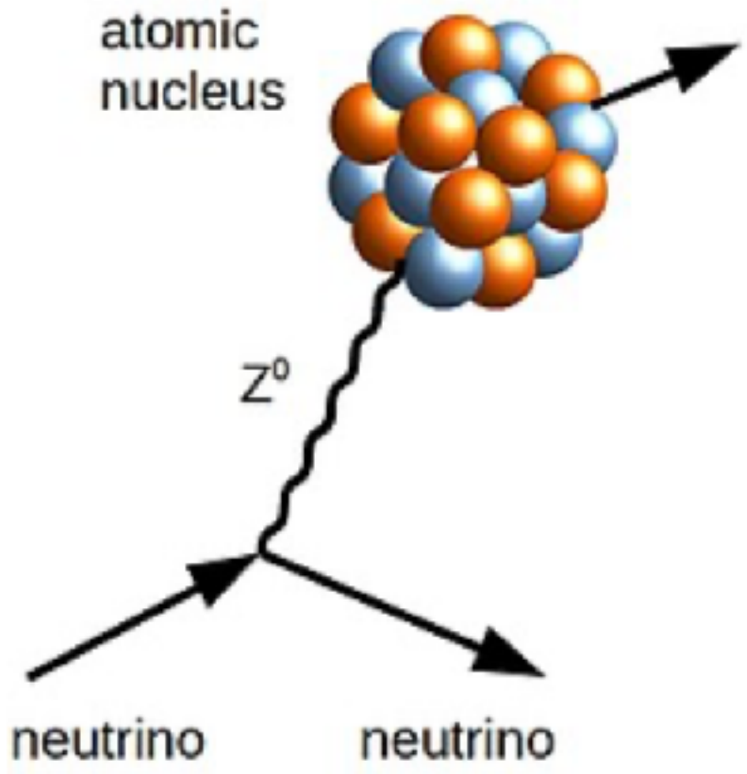
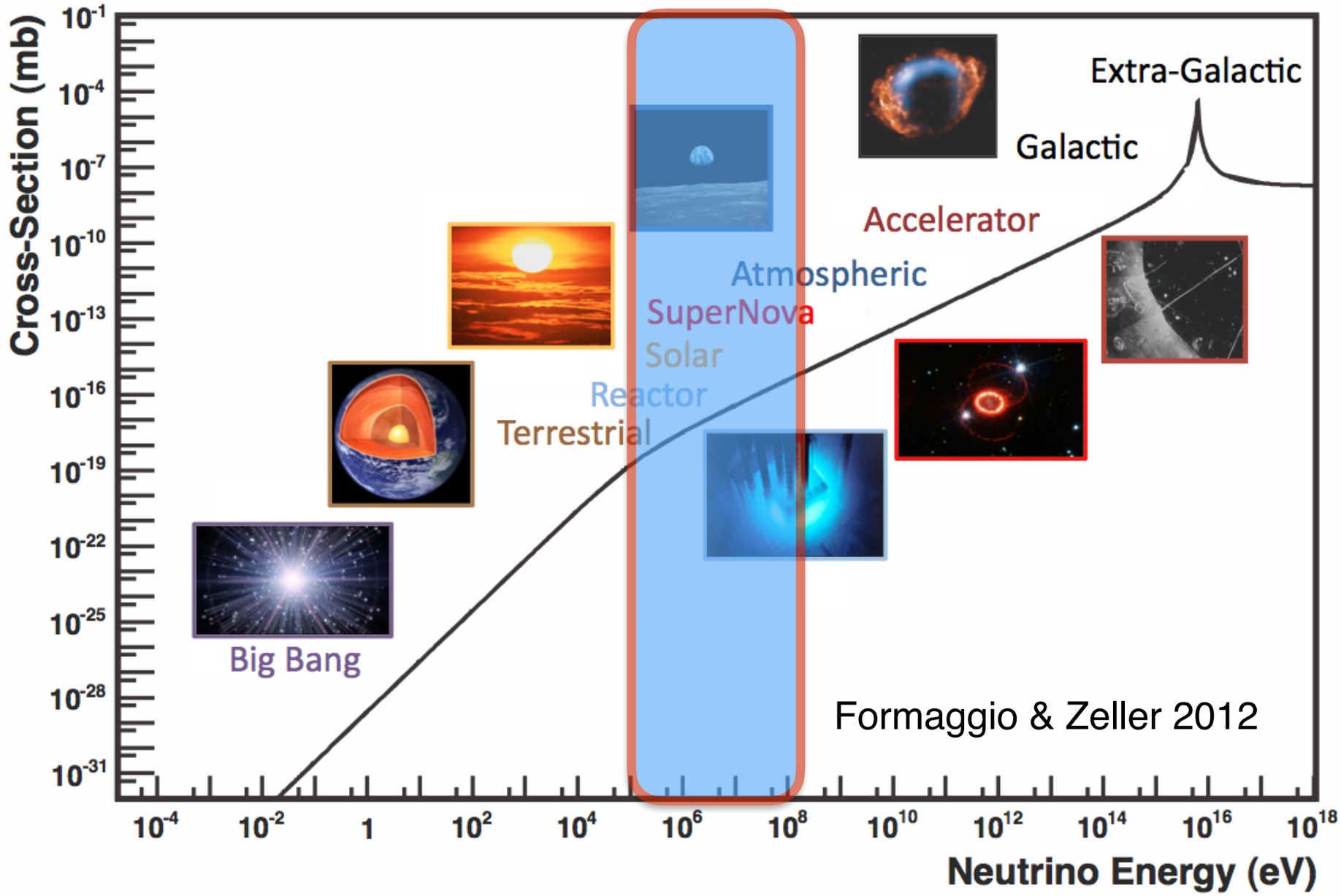
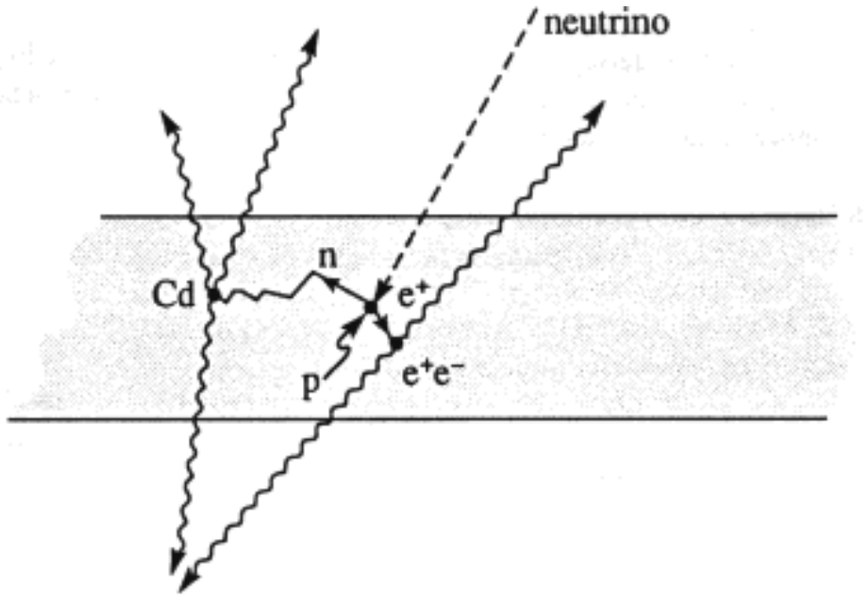
Artwork by Sandbox Studio, Chicago with Ana Kova



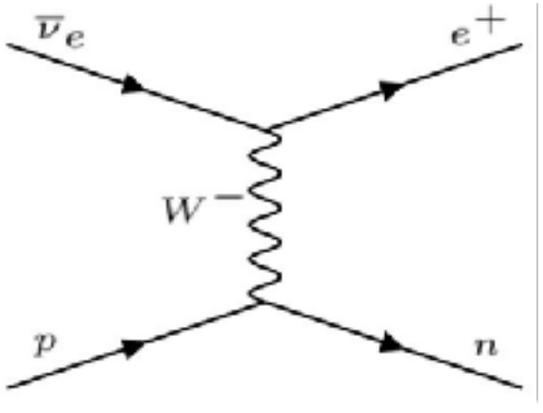
Neutrino cross sections across all scales

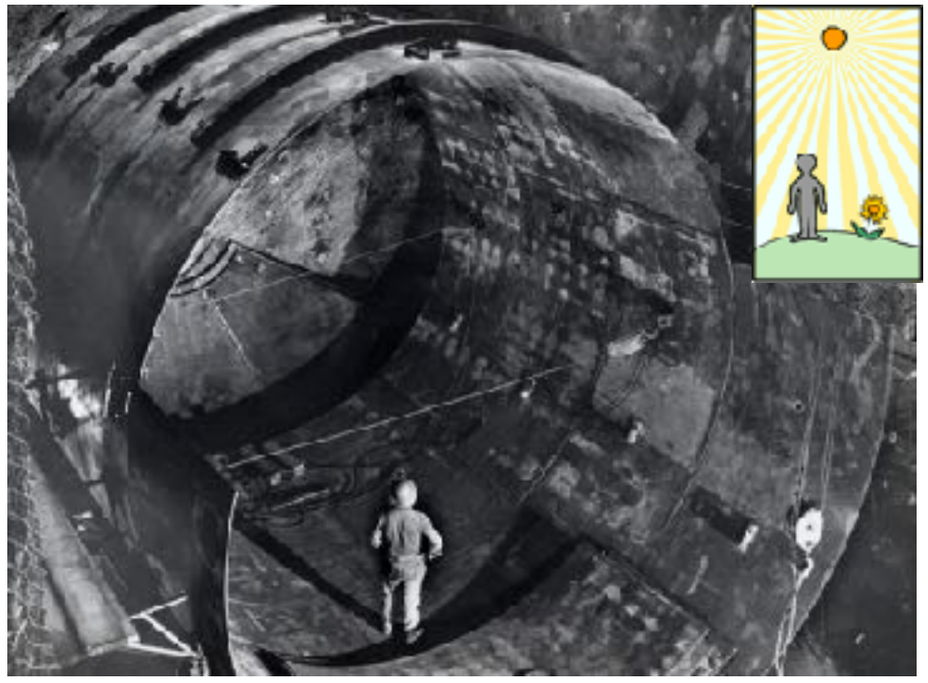


Low energy neutrino interactions



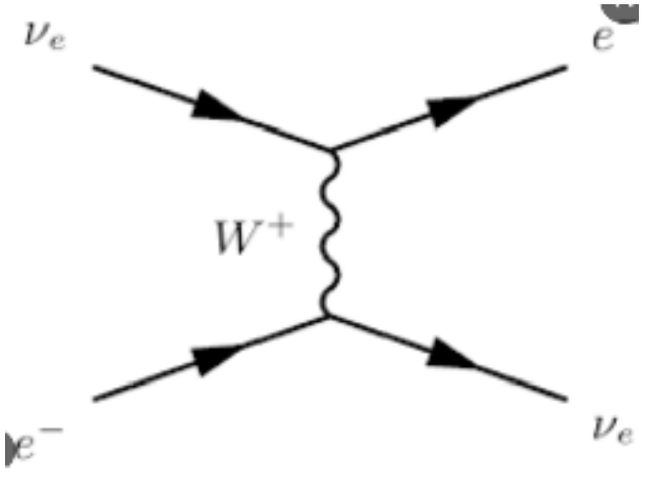
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



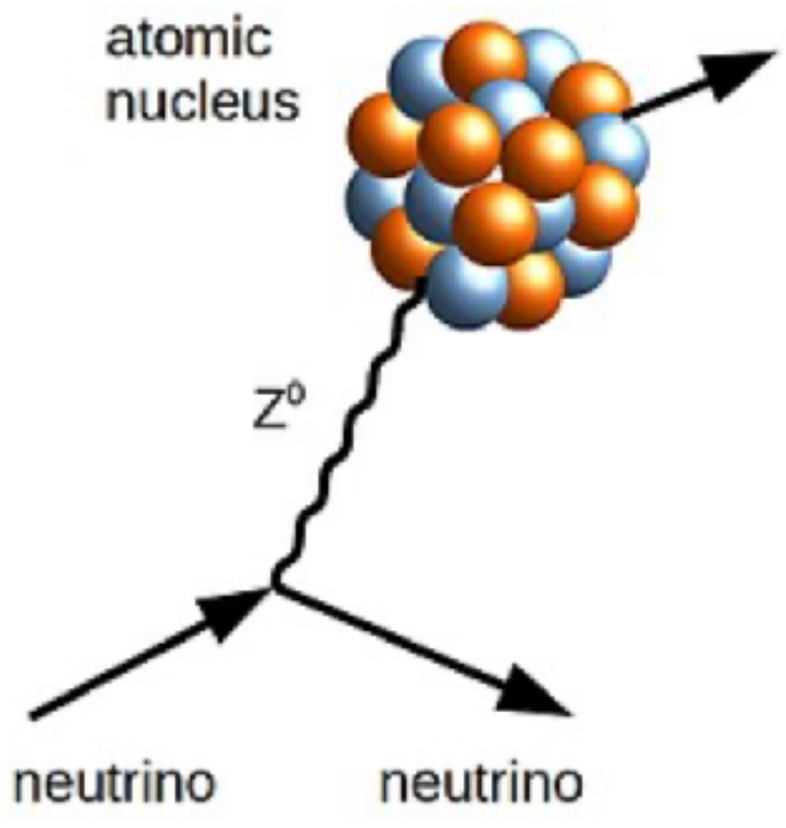


$$\nu_e + (A, Z) \rightarrow (A, Z+1) + e^-$$

$$\nu + e \rightarrow \nu + e$$



Coherent elastic neutrino-nucleus scattering (CEvNS)



Coherent effects of a weak neutral current

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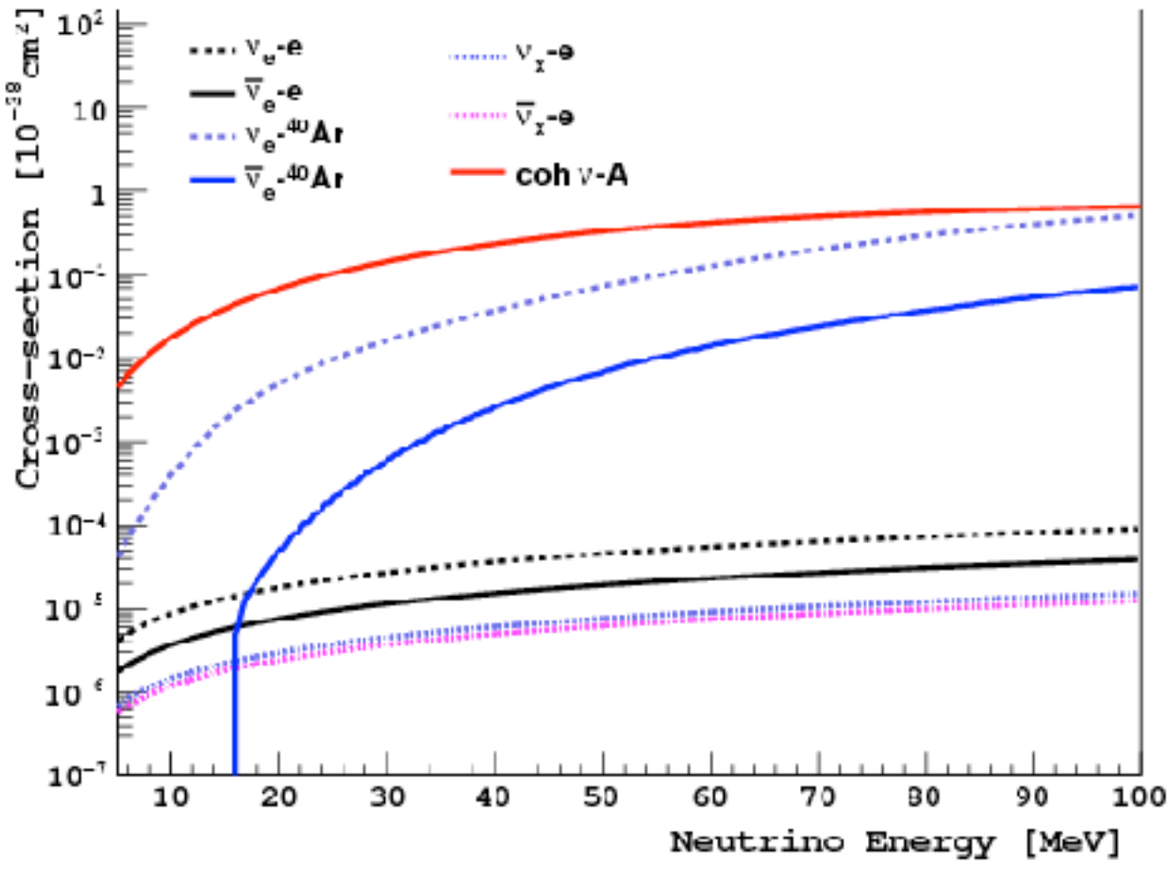
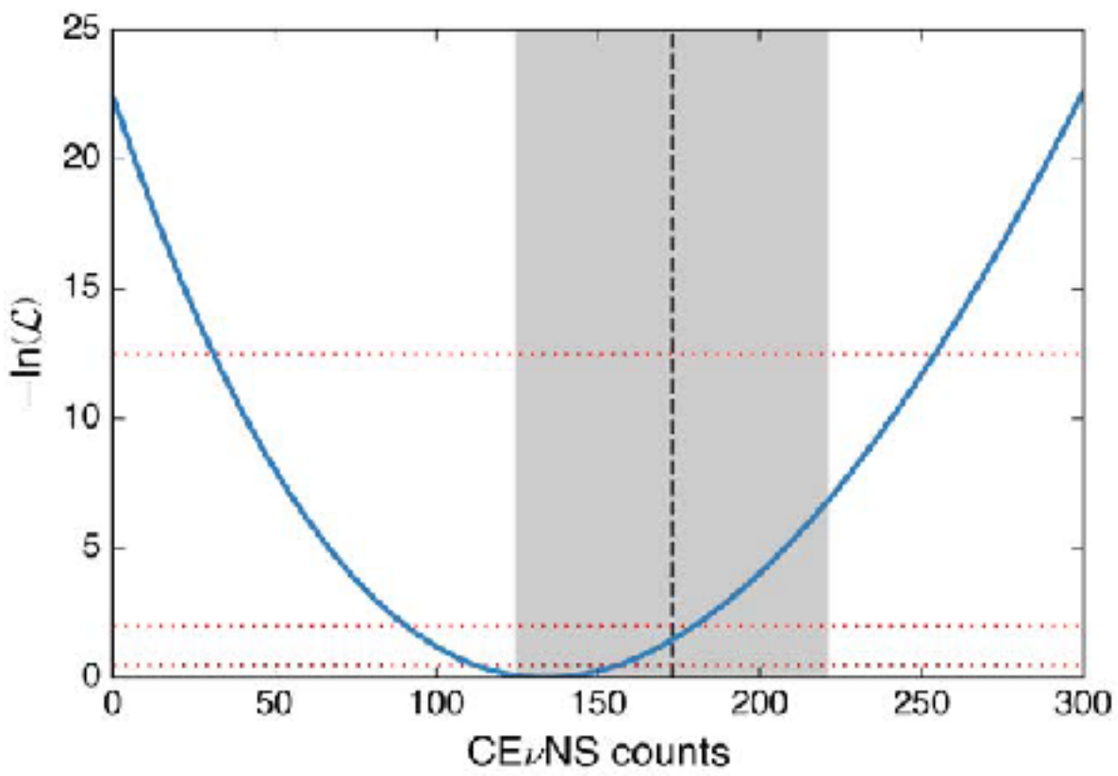
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)



Brice et al, 1311.5958

Detection 40+ years in making!



First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon

D. Akimov,[1,2] J.B. Albert,[3] P. An,[4,5] C. Awe,[4,5] P.S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] M.A. Blackston,[7] L. Blokland,[6] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] N. Chen,[9] D. Chernyak,[10] E. Conley,[4] R.L. Cooper,[11,12] J. Daughhetee,[6] M. del Valle Coello,[3] J.A. Detwiler,[9] M.R. Durand,[9] Y. Efremenko,[6,7] S.R. Elliott,[12] L. Fabris,[7] M. Febbraro,[7] W. Fox,[3] A. Galindo-Uribarri,[6,7] M.P. Green,[5,7,13] K.S. Hansen,[9] M.R. Heath,[7] S. Hedges,[4,5] M. Hughes,[3] T. Johnson,[4,5] M. Kaemingk,[11] L.J. Kaufman,[3,*] A. Khromov,[2] A. Konovalov,[1,2] E. Kozlova,[1,2] A. Kumpan,[2] L. Li,[4,5] J.T. Librande,[9] J.M. Link,[14] J. Liu,[10] K. Mann,[5,7] D.M. Markoff,[5,15] O. McGoldrick,[9] H. Moreno,[11] P.E. Mueller,[7] J. Newby,[7] D.S. Parno,[16] S. Penttila,[7] D. Pershey,[4] D. Radford,[7] R. Rapp,[16] H. Ray,[17] J. Raybern,[4] O. Razuvaeva,[1,2] D. Reyna,[8] G.C. Rich,[18] D. Rudik,[1,2] J. Runge,[4,5] D.J. Salvat,[3] K. Scholberg,[4] A. Shakirov,[2] G. Simakov,[1,2,19] G. Sinev,[4] W.M. Snow,[3] V. Sosnovtsev,[2] B. Suh,[3] R. Tayloe,[3] K. Tellez-Giron-Flores,[14] R.T. Thornton,[3,12] I. Tolstukhin,[3,†] J. Vanderwerp,[3] R.L. Varner,[7] C.J. Virtue,[20] G. Visser,[3] C. Wiseman,[9] T. Wongjirad,[21] J. Yang,[21] Y.-R. Yen,[16] J. Yoo,[22,23] C.-H. Yu,[7] and J. Zettlemoyer[3]
(COHERENT collaboration)

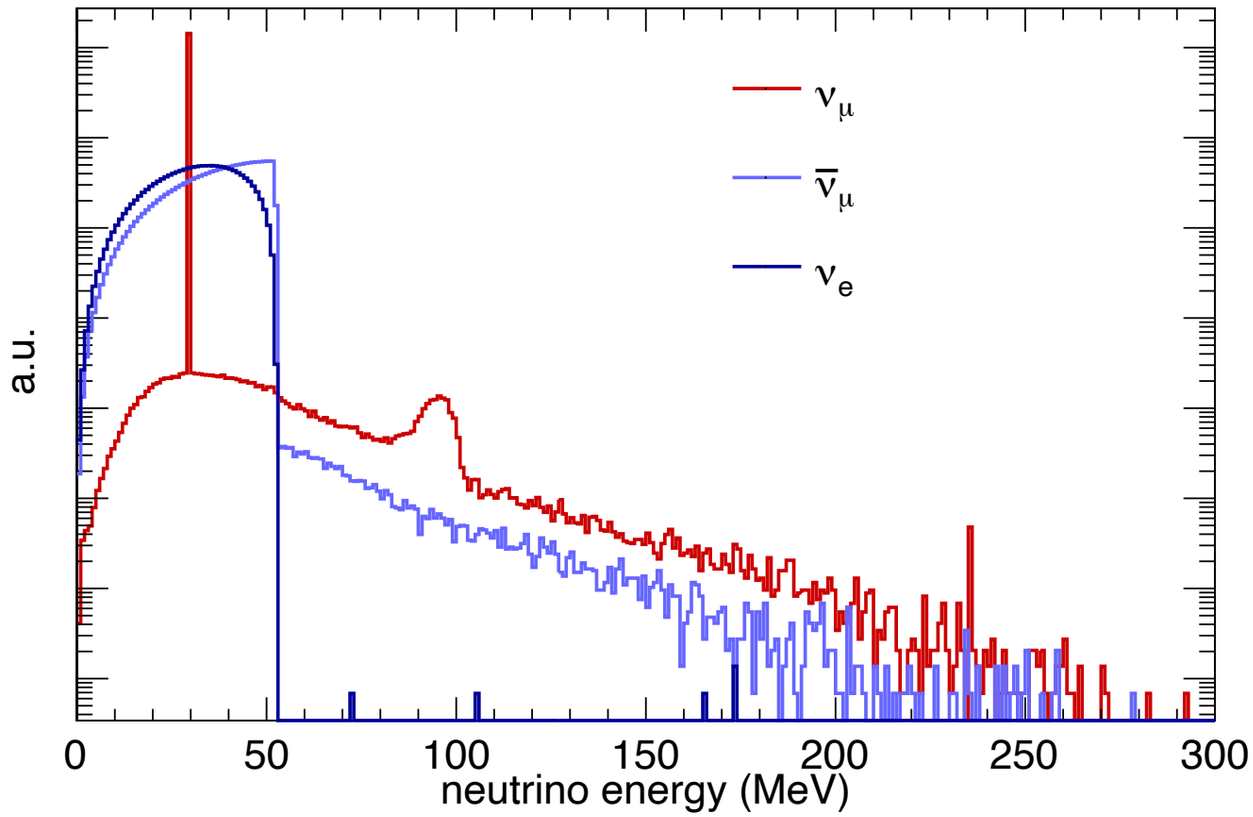
Observation of coherent elastic neutrino-nucleus scattering

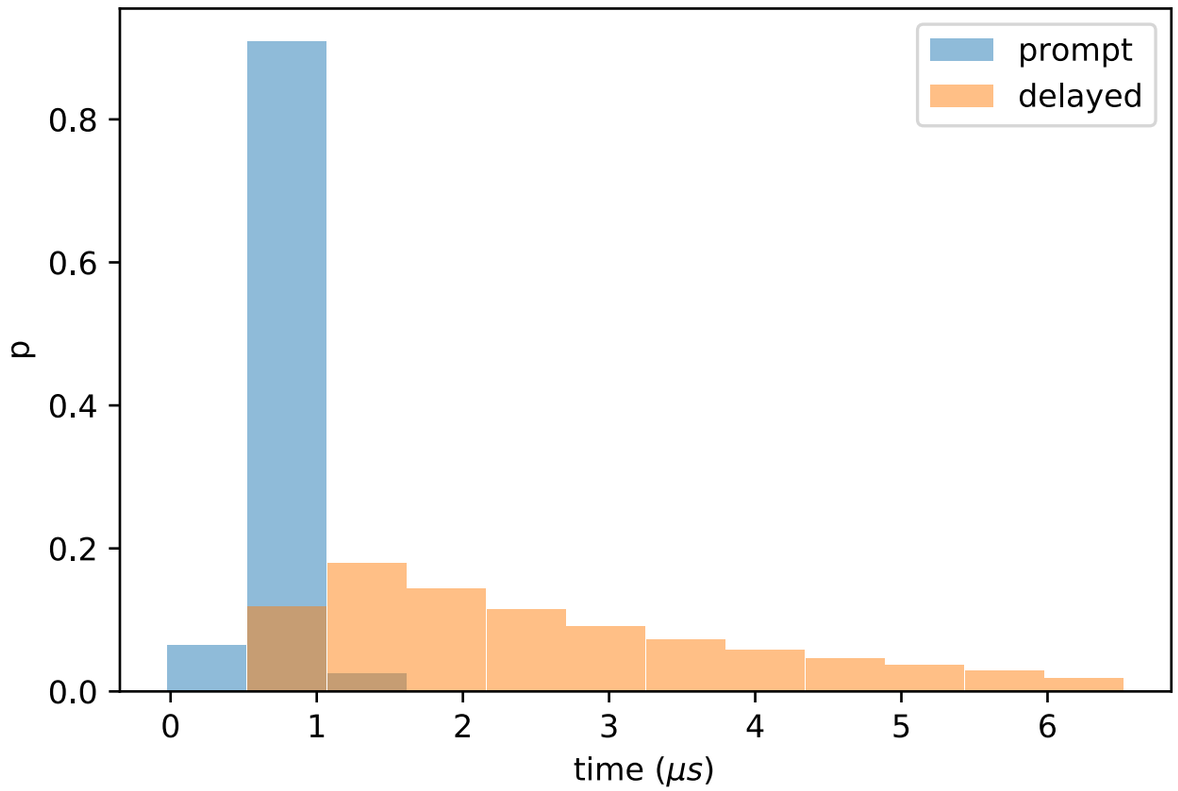
D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, A. Brown,
A. Bolozdynya, B. Cabrera-Palmer, M. Cervantes, J. I. Collar,* R. J. Cooper,
R. L. Cooper, C. Cuesta, D. J. Dean, J. A. Detwiler, A. Eberhardt, Y. Efremenko,
S. R. Elliott, E. M. Erkela, L. Fabris, M. Febbraro, N. E. Fields, W. Fox, Z. Fu,
A. Galindo-Uribarri, M. P. Green, M. Hai, M. R. Heath, S. Hedges, D. Hornback,
T. W. Hossbach, E. B. Iverson, L. J. Kaufman, S. Ki, S. R. Klein, A. Khromov,
A. Konovalov, M. Kremer, A. Kumpan, C. Leadbetter, L. Li, W. Lu, K. Mann,
D. M. Markoff, K. Miller, H. Moreno, P. E. Mueller, J. Newby, J. L. Orrell,
C. T. Overman, D. S. Parno, S. Penttila, G. Perumpilly, H. Ray, J. Raybern, D. Reyna,
G. C. Rich, D. Rimal, D. Rudik, K. Scholberg, B. J. Scholz, G. Sinev, W. M. Snow,
V. Sosnovtsev, A. Shakirov, S. Suchyta, B. Suh, R. Tayloe, R. T. Thornton, I. Tolstukhin,
J. Vanderwerp, R. L. Varner, C. J. Virtue, Z. Wan, J. Yoo, C.-H. Yu, A. Zawada,
J. Zettlemoyer, A. M. Zderic, COHERENT Collaboration

First detection of coherent elastic neutrino-nucleus scattering on germanium

S. Adamski,[1] M. Ahn,[2] P.S. Barbeau,[3,4] V. Belov,[5,6] I. Bernardi,[7] C. Bock,[5] A. Bolozdynya,[5] R. Bouabid,[3,4] J. Browning,[9] B. Cabrera-Palmer,[10] N. Cedarblade-Jones,[3,4] J. Colón Rivera,[3,4] E. Conley,[3] V. da Silva,[11] J. Daughhetee,[12] J. Detwiler,[13] K. Ding,[8] M.R. Durand,[13] Y. Efremenko,[7,12] S.R. Elliott,[14] A. Erlandson,[15] L. Fabris,[12] A. Galindo-Uribarri,[12,7] M.P. Green,[5,12,9] J. Hakenmüller,[3,*] M.R. Heath,[12] S. Hedges,[3,4,†] H. Jeong,[2] B.A. Johnson,[16] T. Johnson,[3,4] H. Jones,[5] A. Khromov,[5] A. Konovalov,[5,6] E. Kozlova,[5] A. Kumpan,[5] O. Kyzylova,[17] Y. Lee,[2] G. Li,[18] L. Li,[3,4] J.M. Link,[17] J. Liu,[8] M. Luxnat,[15] A. Major,[3] K. Mann,[9] D.M. Markoff,[19,4] J. Mattingly,[20] J. Moye,[18] P.E. Mueller,[12] J. Newby,[12] N. Opoi,[19,4] J. O'Reilly,[3] D.S. Parno,[18] D. Pérez Loureiro,[13] D. Pershey,[21] C.G. Prior,[3,4] J. Queen,[3] R. Rapp,[1] H. Ray,[22] O. Razuvaeva,[5,6] D. Reyna,[10] G.C. Rich,[4] D. Rudik,[5,6] J. Runge,[3,4] D.J. Salvat,[16] J. Sander,[5] K. Scholberg,[3] A. Shakirov,[5] G. Simakov,[5,6] W.M. Snow,[16] V. Sosnovtsev,[5] M. Stringer,[15] T. Subedi,[23] B. Suh,[16] B. Sur,[15] R. Tayloe,[16] K. Tellez-Giron-Flores,[17] Y.-T. Tsai,[24] E.E. van Nieuwenhuizen,[3,4] C.J. Virtue,[25] G. Visser,[15] K. Walkup,[17] E.M. Ward,[7] T. Wongjirad,[11] Y. Yang,[8] J. Yoo,[2] C.-H. Yu,[12] and A. Zaalishvili[3,4]

Neutrino signals at COHERENT

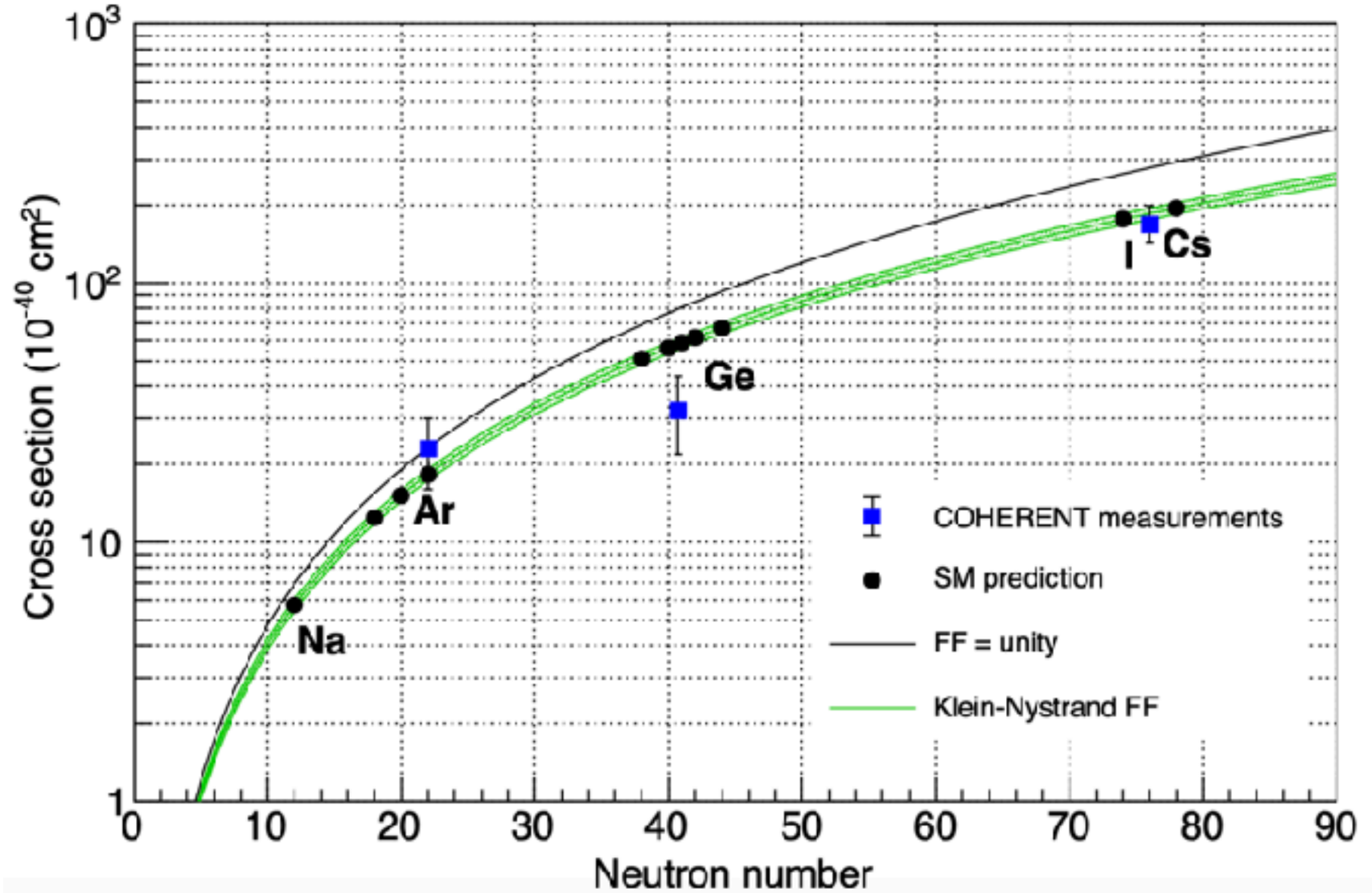




Prompt: $\pi^+ \to \mu^+ + \nu_\mu$ $3 \times 10^{-8}\,\mathrm{sec}$

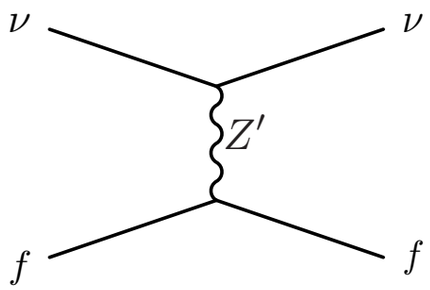
Delayed: $\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$ $2 \times 10^{-6}\,\mathrm{sec}$

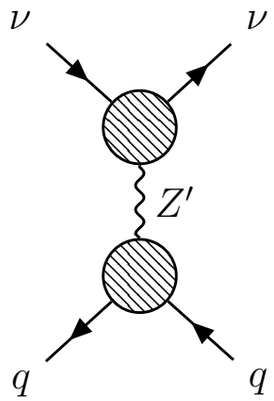
CEvNS cross section measurements



Impact of COHERENT results

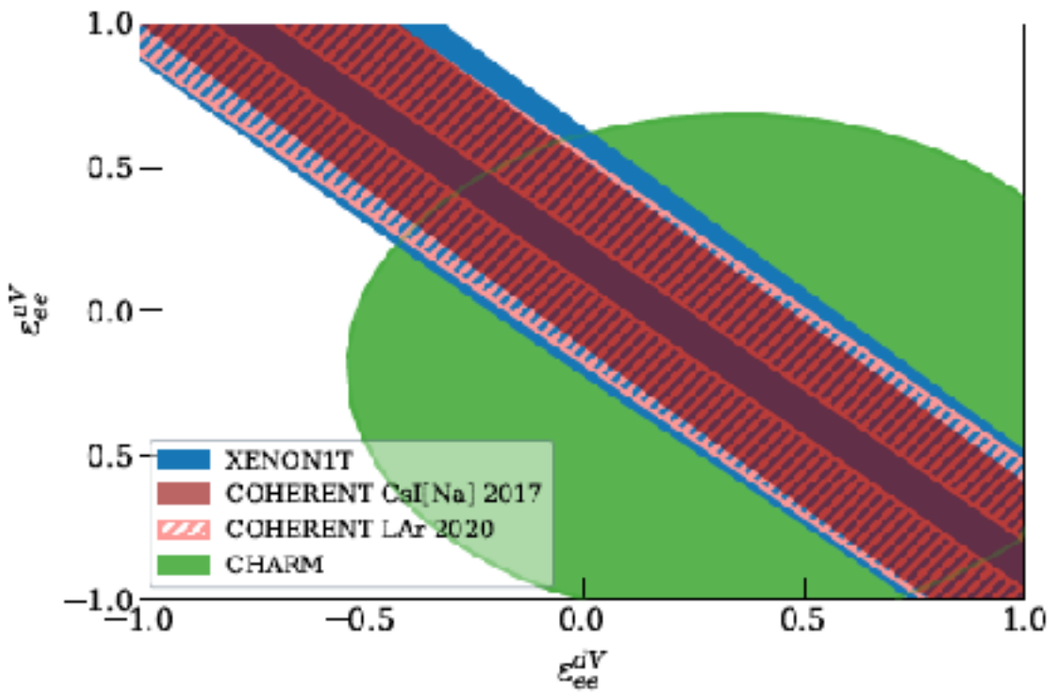
Non-standard interactions (NSI)



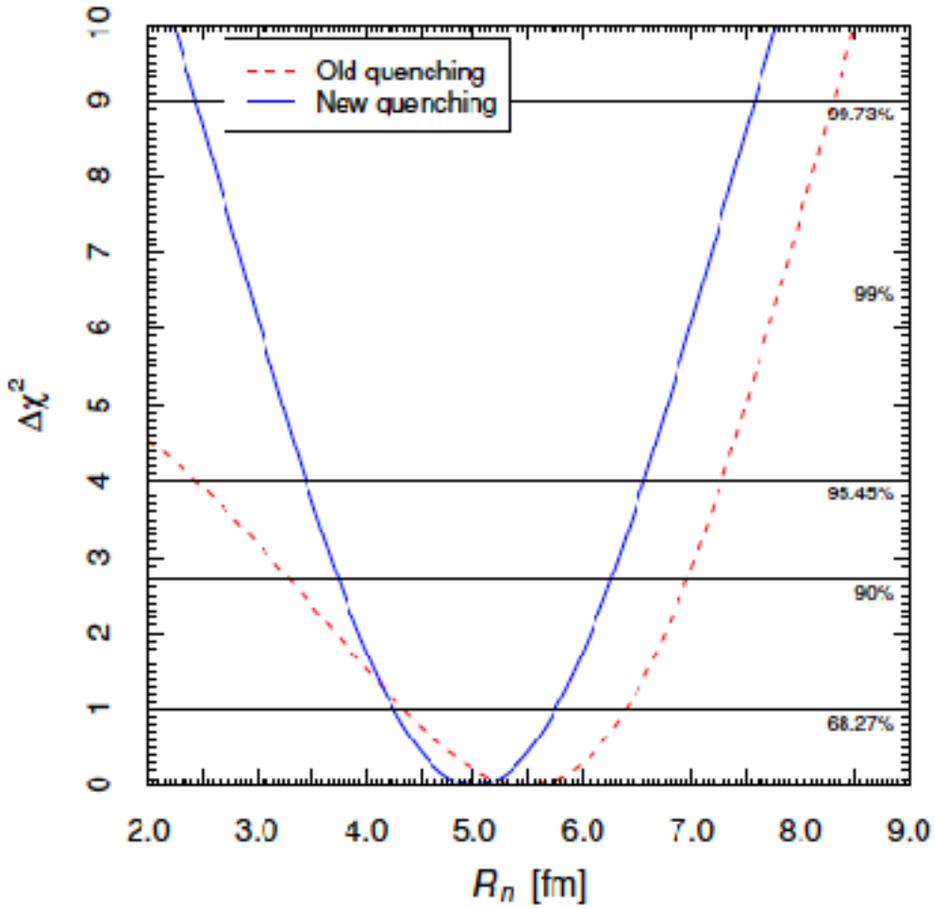


Independent constraints from oscillation experiments
Heavy mediators parameterized with EFT
Dark hypercharge gauge boson; Dark Z boson; Hidden Sector Fermions

Barranco et al. 2005, Scholberg 2005; Liao & Marfatia 2017; Lindner et al. 2017; Farzan et al. 2018; Abdullah et al. 2018, Brdar et al. 2018, Datta et al. 2019



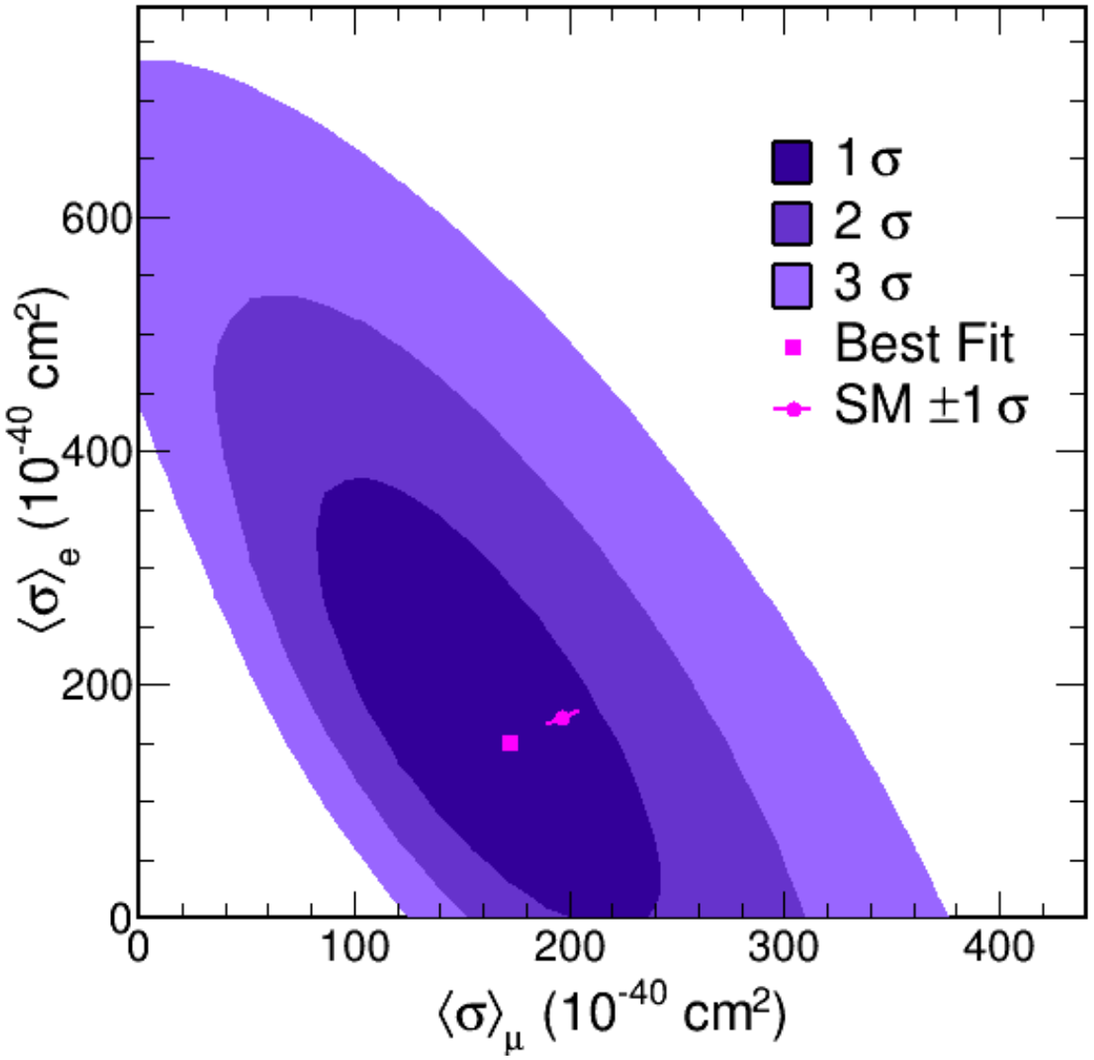
XENON collaboration, PRL 126 (2021) 091301: 2012.02846 [hep-ex]



Nuclear structure

Measurement of the neutron distribution in the nucleus [Cadeddu, Dordei, Giunti, Li, Zhang, 2019; Aristizibal-Sierra, Liao, Marfatia, 2019; Hoferichter, Menendez, Schwenk 2020]

Flavor separation of CEvNS



COHERENT collaboration 2021

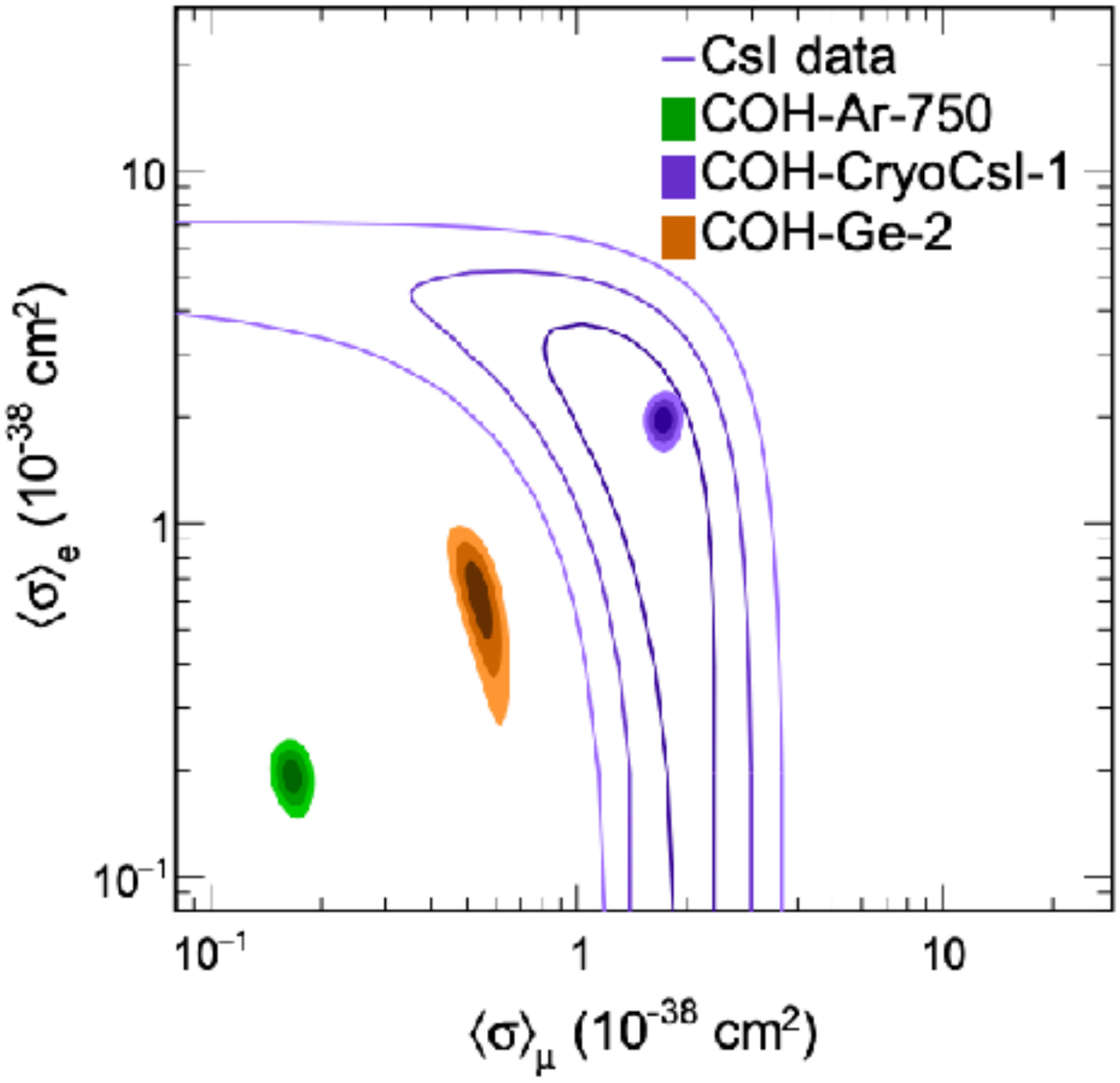
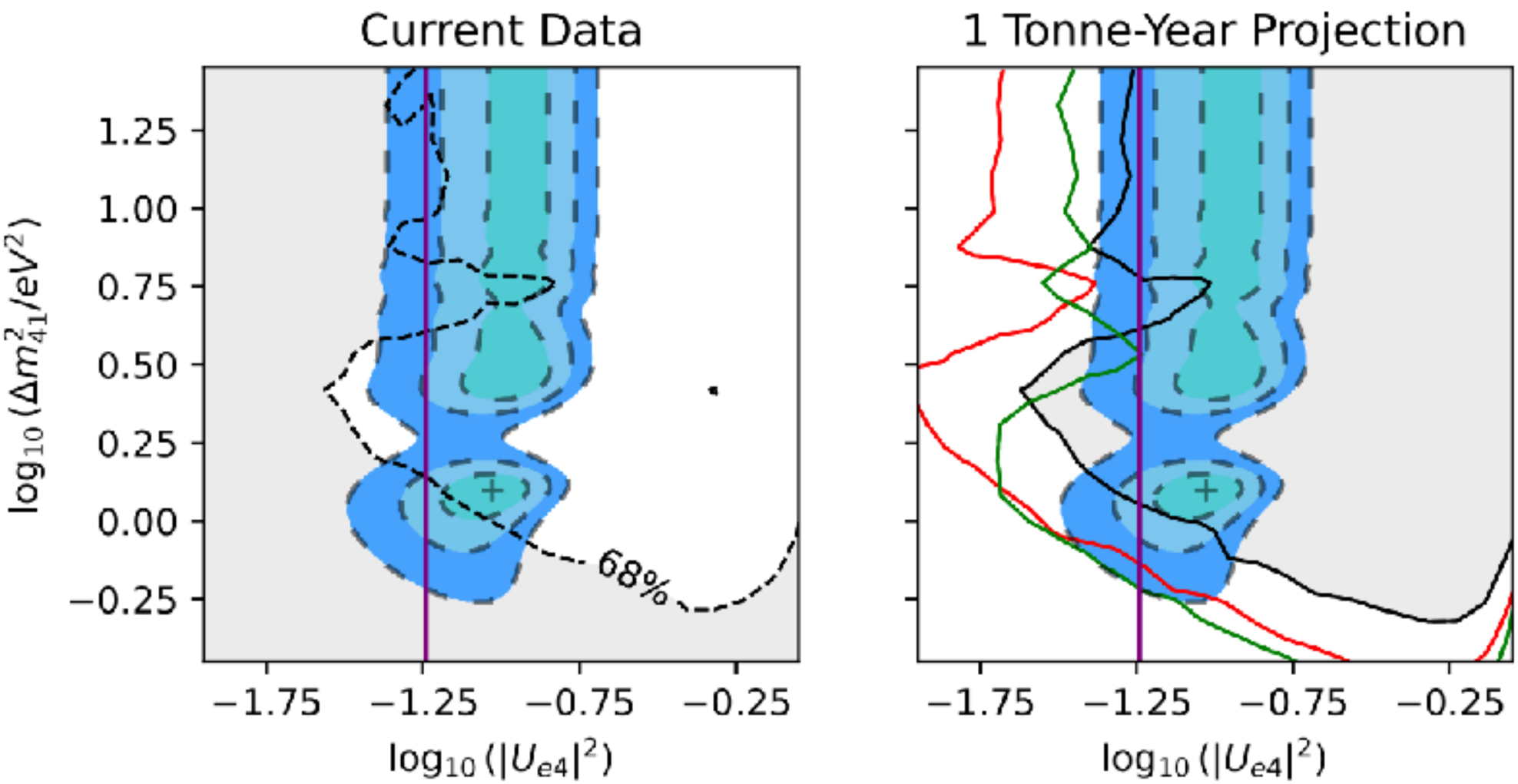


Figure: Dan Pershey

Sterile neutrinos and CEvNS

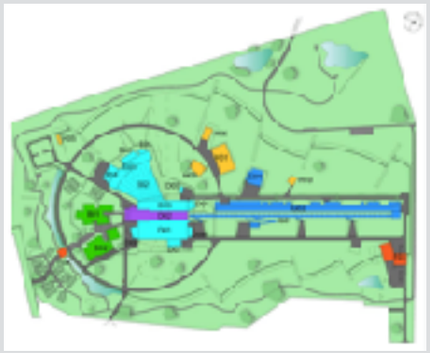


Sterile neutrinos: Anderson et al. 2012; Dutta et al. 2016; Blanco, Machado, Hooper 2019; Miranda et al. 2020, Prospect collaboration, 2024

Bisset, Dutta, Huang, LS, arXiv: 2310.13194

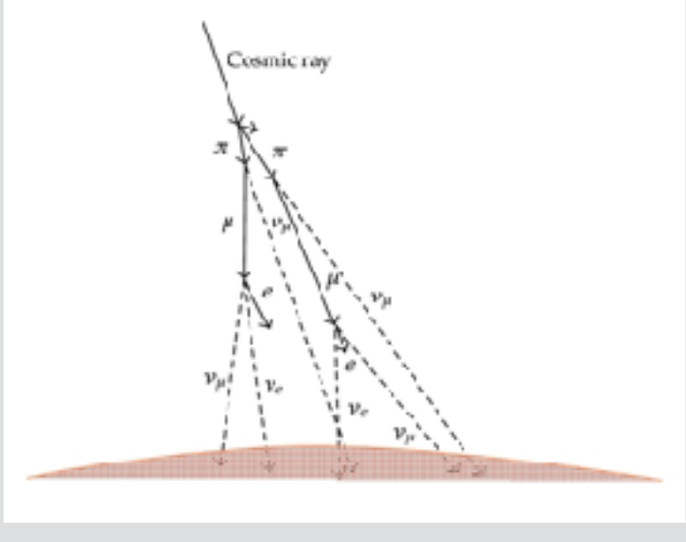
Complementarity in CEvNS

Spallation sources

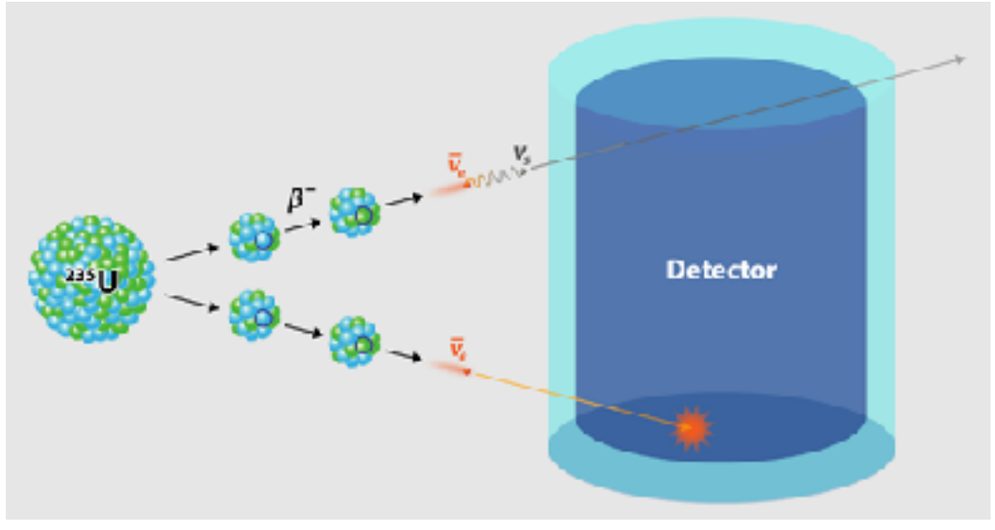


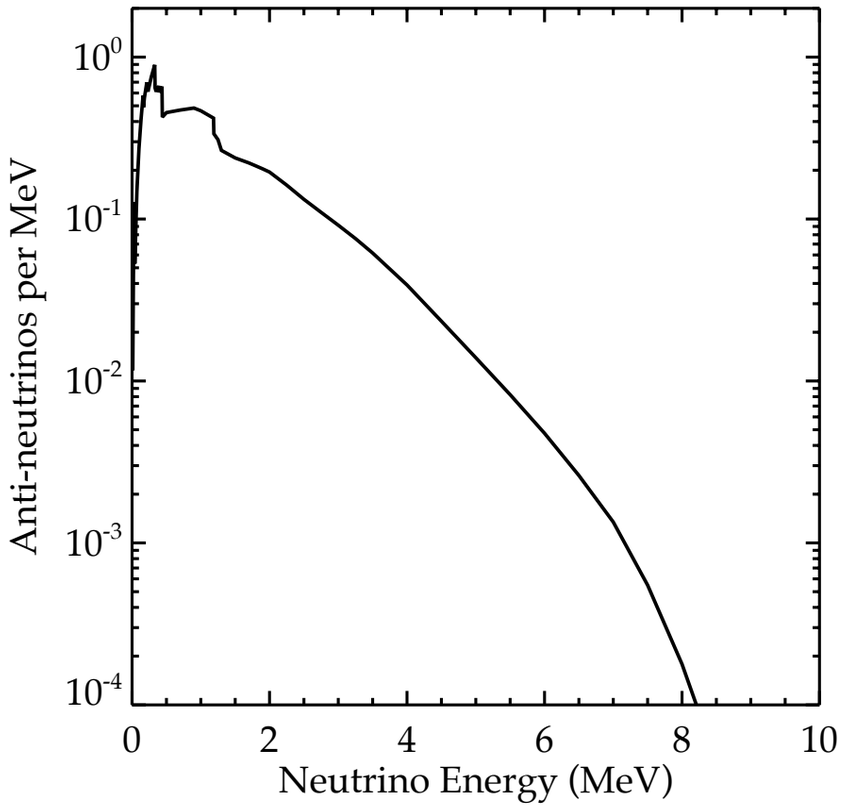
Reactors

Astrophysical sources



CEvNS at nuclear reactors





The CONNIE experiment

A. Aguilar-Arevalo[1], X. Bertou[2], C. Bonifazi[3], M. Butner[4], G. Cancelo[4], A. Castaneda Vazquez[1], B. Cervantes Vergara[1], C.R. Chavez[5], H. Da Motta[6], J.C. D'Olivo[1], J. Dos Anjos[6], J. Estrada[4], G. Fernandez Moroni[7,8], R. Ford[4], A. Foguel[3,6], K.P. Hernandez Torres[1], F. Izraelevitch[4], A. Kavner[9], B. Kilminster[10], K. Kuk[4], H.P. Lima Jr.[6], M. Makler[6], J. Molina[5], G. Moreno-Granados[1], J.M. Moro[11], E.E. Paolini[7,12], M. Sofo Haro[2], J. Tiffenberg[4], F. Trillaud[1], and S. Wagner[6,13]

Coherent Neutrino Scattering with Low Temperature Bolometers at Chooz Reactor Complex

J. Billard[1], R. Carr[2], J. Dawson[3], E. Figueroa-Feliciano[4], J. A. Formaggio[2], J. Gascon[1], M. De Jesus[1], J. Johnston[2], T. Lasserre[5,6], A. Leder[2], K. J. Palladino[7], S. H. Trowbridge[2], M. Vivier[5], and L. Winslow[2]

Research program towards observation of neutrino-nucleus coherent scattering

H T Wong[1,*], H B Li[1], S K Lin[1], S T Lin[1], D He[2], J Li[2], X Li[2], Q Yue[2], Z Y Zhou[3] and S K Kim[4]

[1] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan.
[2] Department of Engineering Physics, Tsing Hua University, Beijing 100084, China.
[3] Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China.
[4] Department of Physics, Seoul National University, Seoul 151-742, Korea.

Background Studies for the MINER Coherent Neutrino Scattering Reactor Experiment

G. Agnolet[a], W. Baker[a], D. Barker[b], R. Beck[a], T.J. Carroll[c], J. Cesar[c], P. Cushman[b], J.B. Dent[d], S. De Rijck[c], B. Dutta[a], W. Flanagan[c], M. Fritts[b], Y. Gao[a,e], H.R. Harris[a], C.C. Hays[a], V. Iyer[f], A. Jastram[a], F. Kadribasic[a], A. Kennedy[b], A. Kubik[a], I. Ogawa[g], K. Lang[c], R. Mahapatra[a], V. Mandic[b], R.D. Martin[h], N. Mast[b], S. McDeavitt[i], N. Mirabolfathi[a], B. Mohanty[f], K. Nakajima[g], J. Newhouse[i], J.L. Newstead[j], D. Phan[c], M. Proga[c], A. Roberts[k], G. Rogachev[l], R. Salazar[c], J. Sander[k], K. Senapati[f], M. Shimada[g], L. Strigari[a], Y. Tamagawa[g], W. Teizer[a], J.I.C. Vermaak[i], A.N. Villano[b], J. Walker[m], B. Webb[a], Z. Wetzel[a], S.A. Yadavalli[c]

Full background decomposition of the CONUS experiment

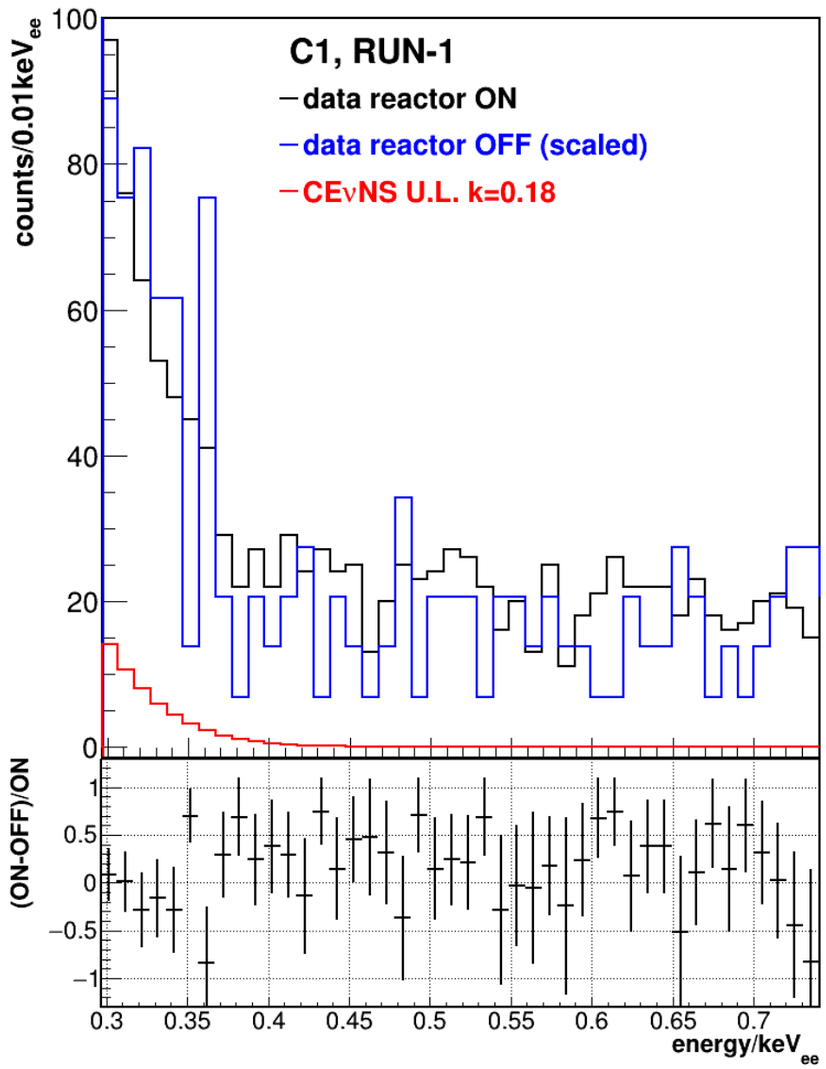
H. Bonet (1), A. Bonhomme (3), C. Buck (1), K. Fülber (2), J. Hakenmüller (1), J. Hempfling (3), G. Heusser (1), T. Hugle (3), M. Lindner (1), W. Maneschg (1), T. Rink (1), H. Strecker (1), R. Wink (2) ((1) Max-Planck-Institut für Kernphysik, Heidelberg, Germany, (2) Preussen Elektra GmbH, Osterende, Brokdorf, Germany)

CEvNS upper limits at reactors

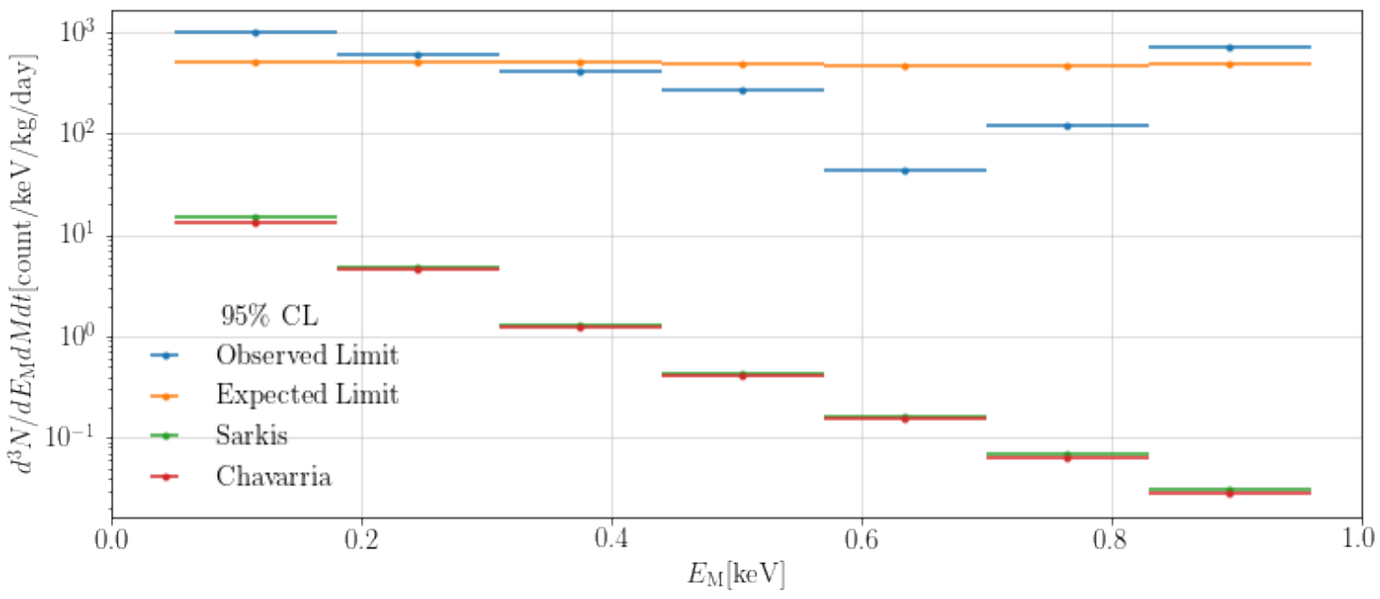
Constraints on elastic neutrino nucleus scattering in the fully coherent regime from the CONUS experiment

H. Bonet[1], A. Bonhomme[1], C. Buck[1], K. Fülber[2], J. Hakenmüller[1], G. Heusser[1], T. Hugle[1], M. Lindner[1], W. Maneschg[1], T. Rink[1], H. Strecker[1], R. Wink[2]

CONUS Collaboration



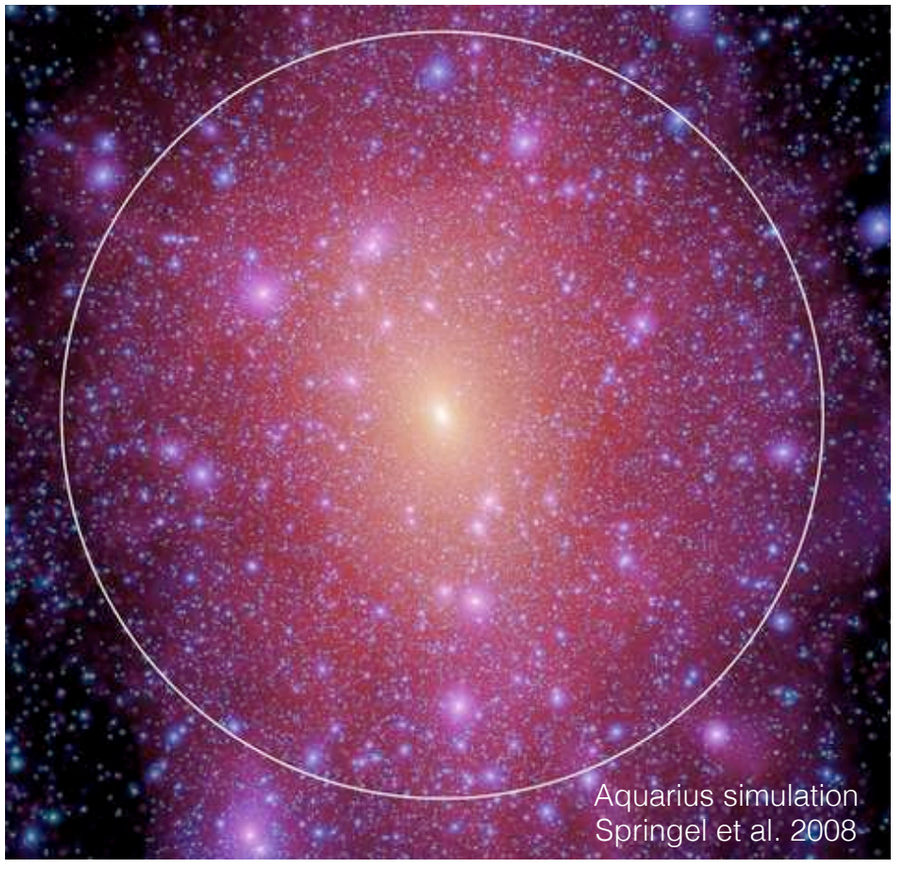
Search for coherent elastic neutrino-nucleus scattering at a nuclear reactor with CONNIE 2019 data

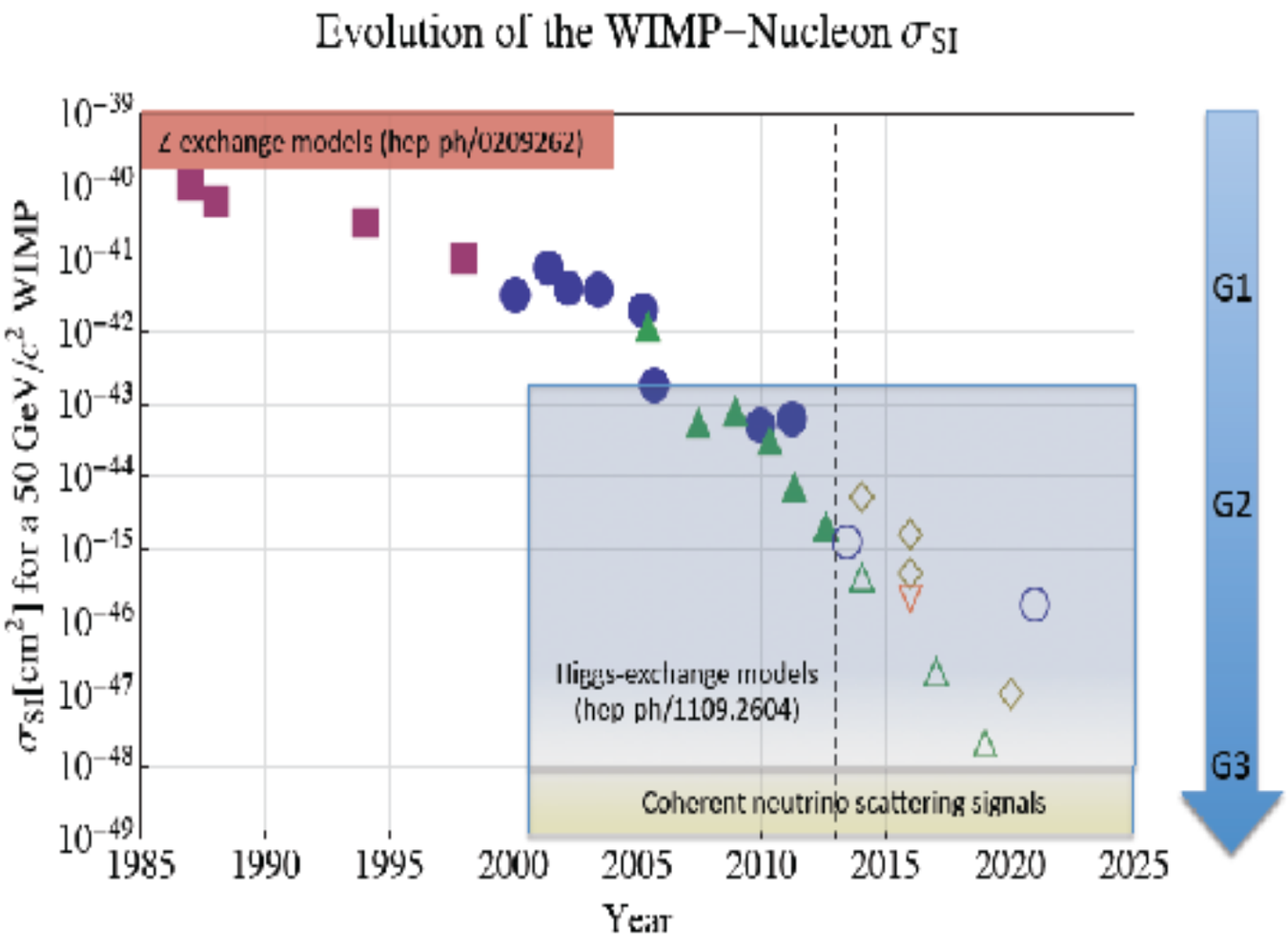


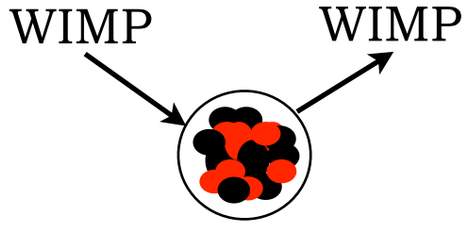
Sterile neutrinos: Anderson et al. 2012; Dutta et al. 2016; Blanco, Machado, Hooper 2019; Miranda et al. 2020

Weak mixing angle: Fernandez-Moroni et al. 2021

Detection of neutrinos and dark matter

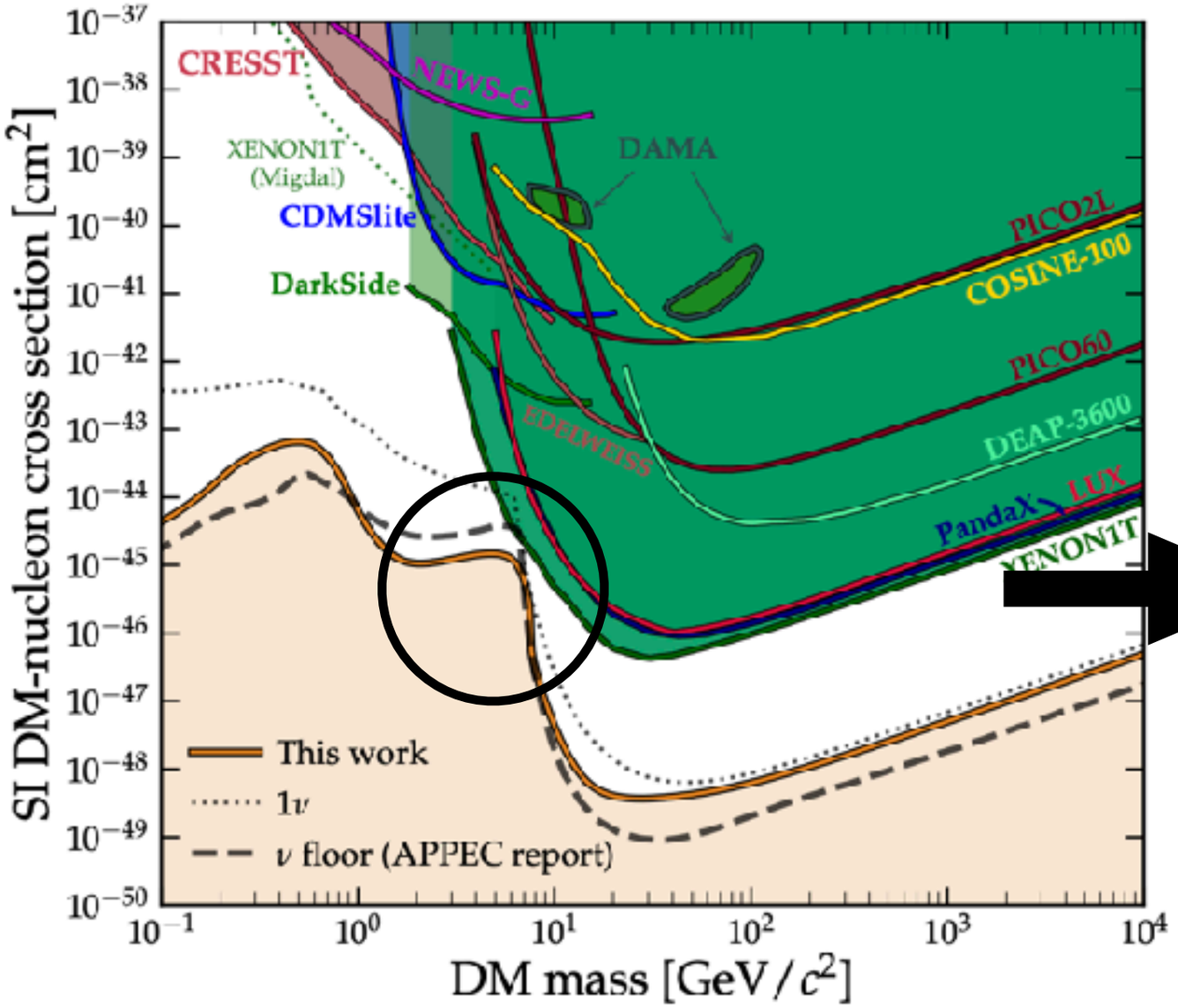


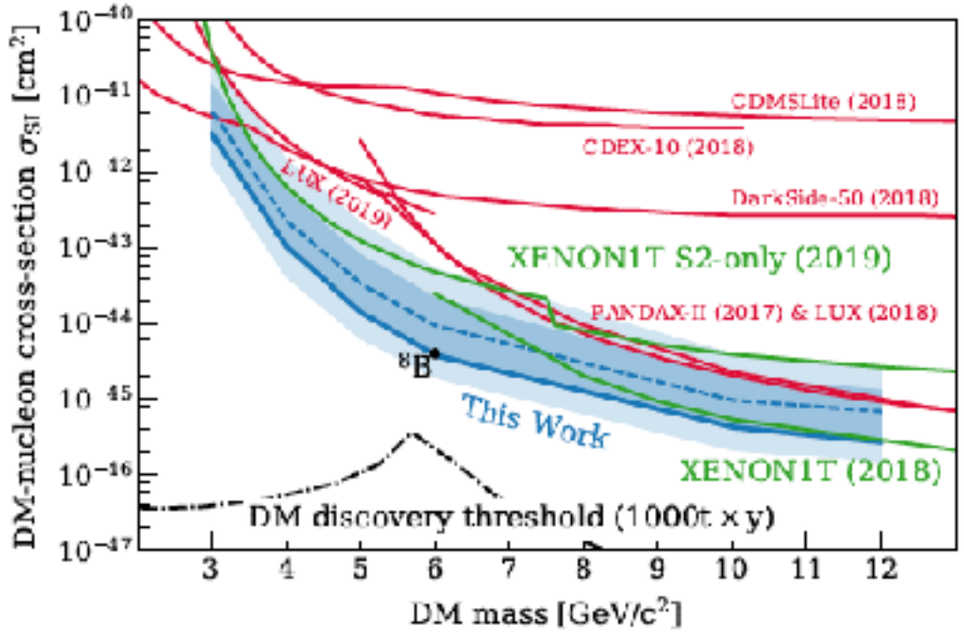




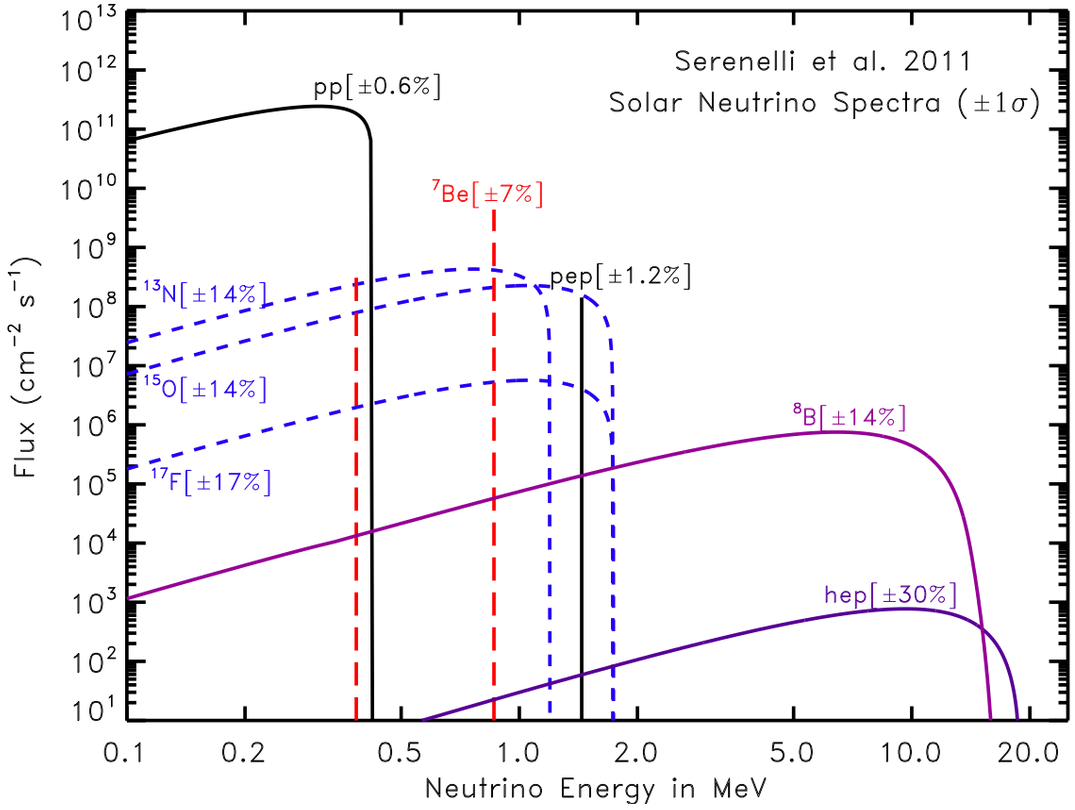
Search for Coherent Elastic Scattering of Solar ^{8}B Neutrinos in the XENON1T Dark Matter Experiment

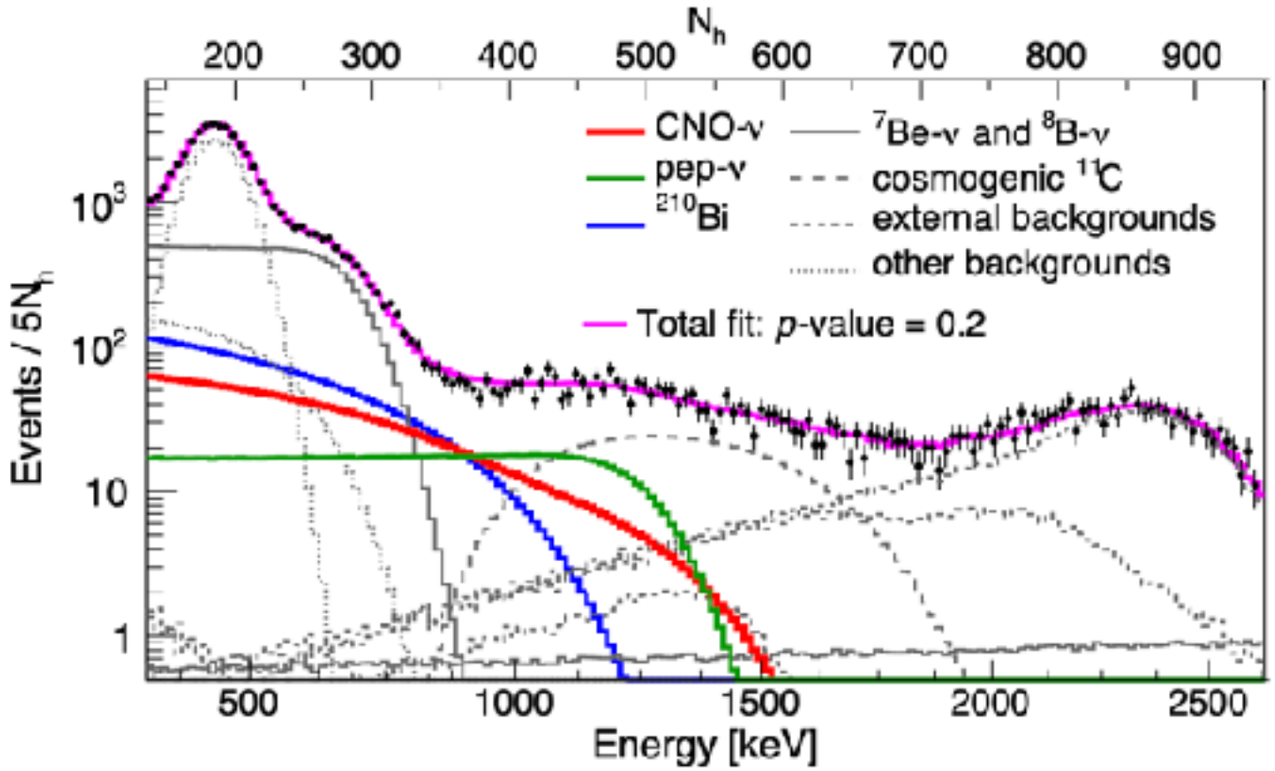
XENON collaboration, PRL 126 (2021) 091301: 2012.02846 [hep-ex]





Solar neutrinos



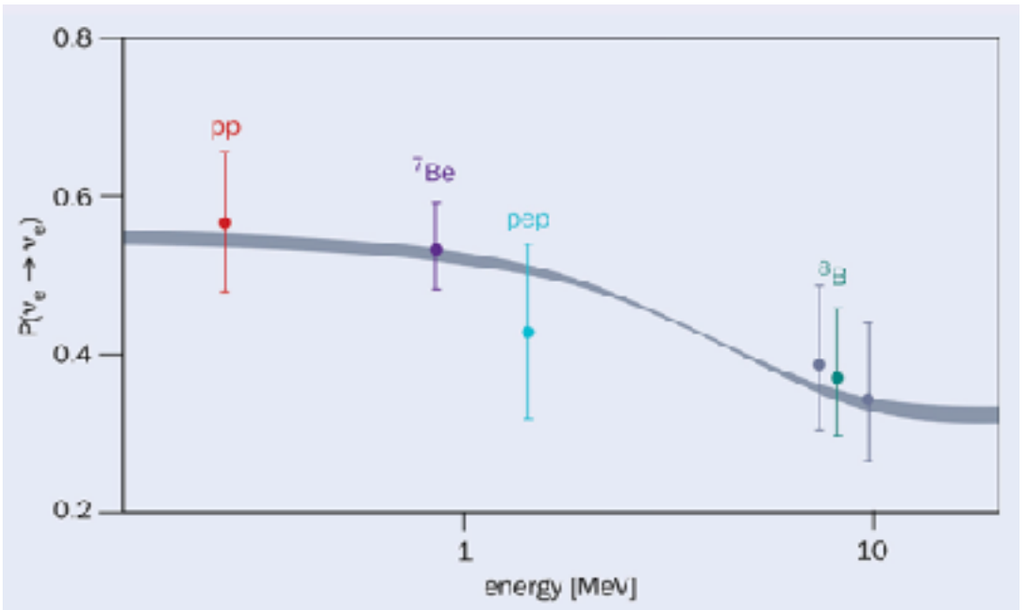


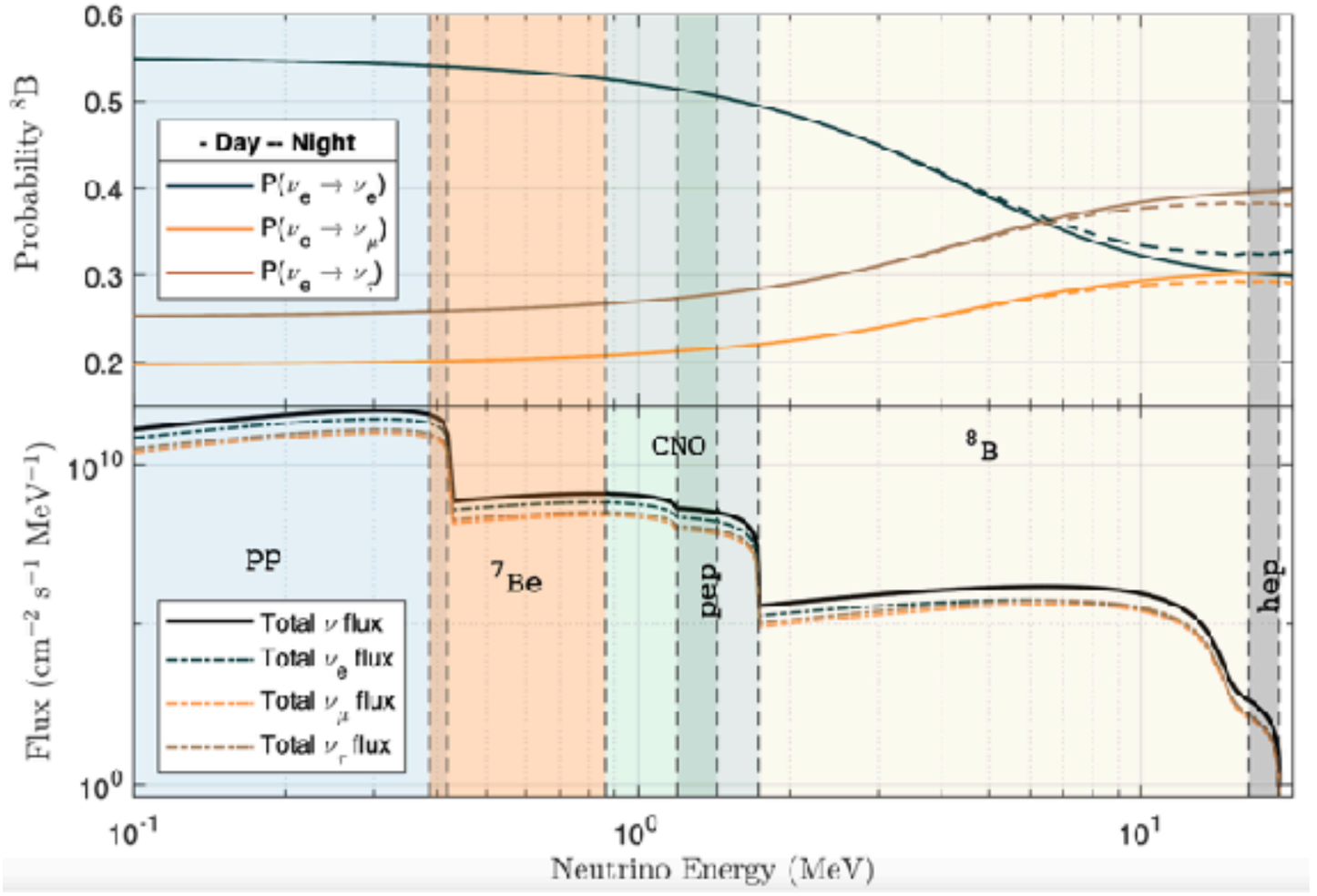
Borexino collaboration 2205.15975

Measurement of neutral current component of the 8B spectrum with CEvNS in a DM detector would directly measure the Solar metallicity

New bound on NSI [Dutta, Liao, Strigari, Walker 2017] and Sterile neutrinos [Billard, LS, Figueroa-Feliciano 2014]

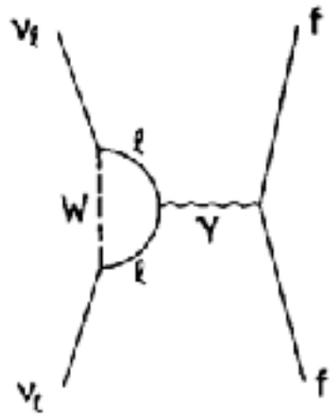
Flavor composition of solar neutrinos

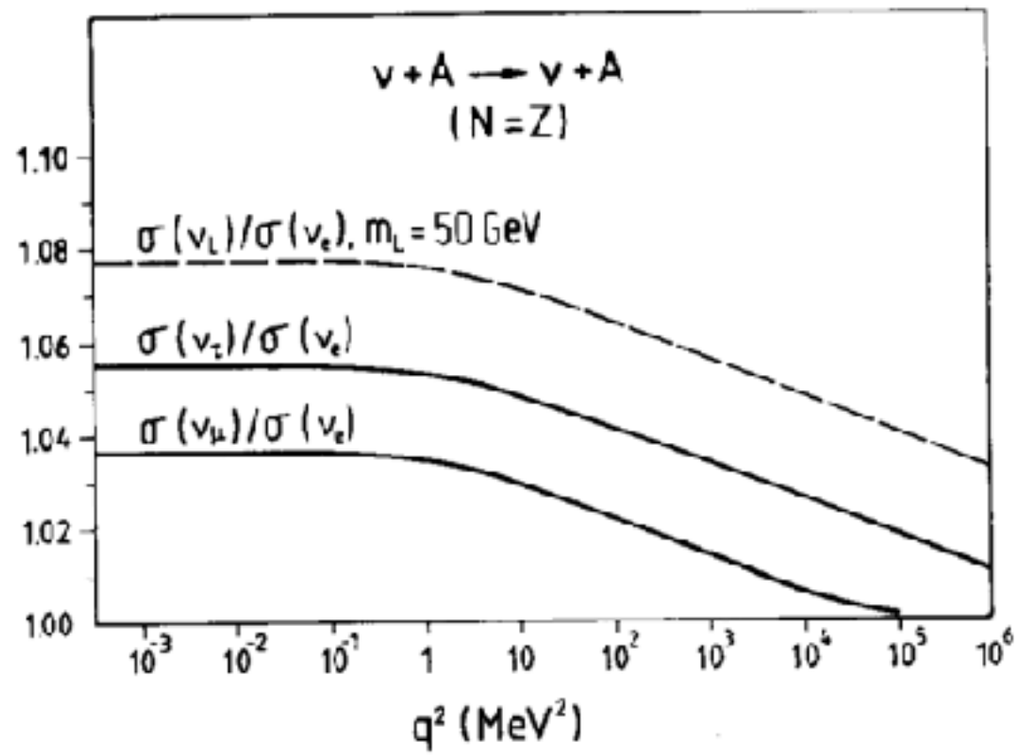


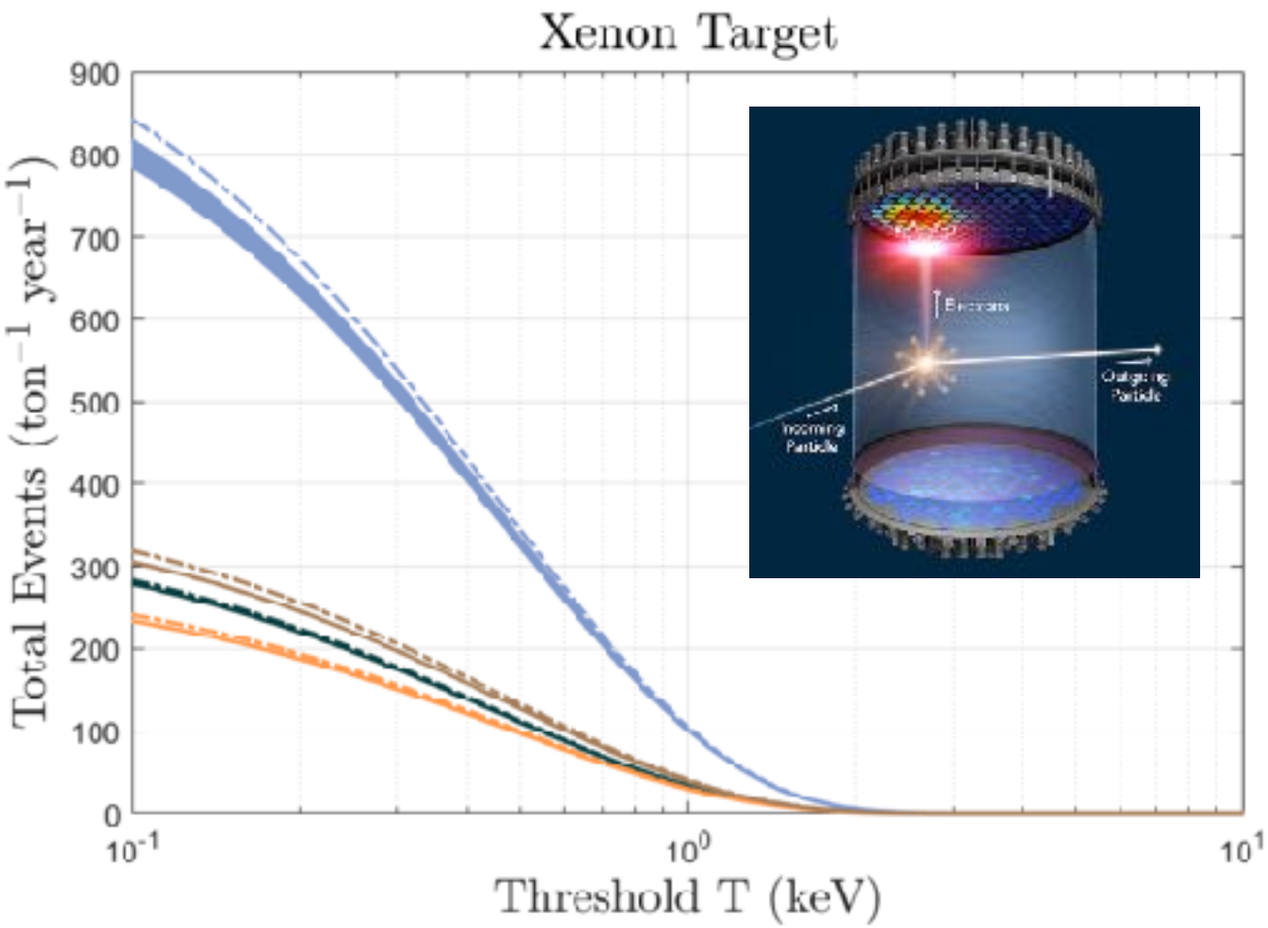


Nityasa Mishra & L. Strigari PRD 2023

Beyond tree level: ^{8}B solar neutrinos



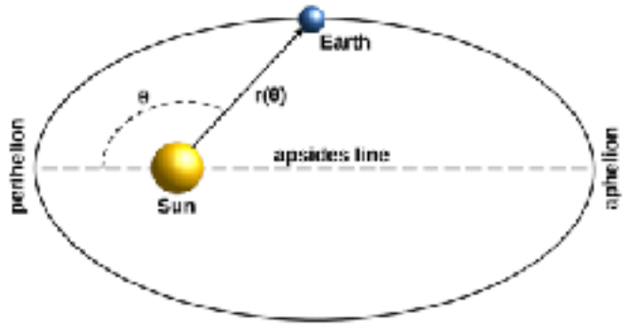


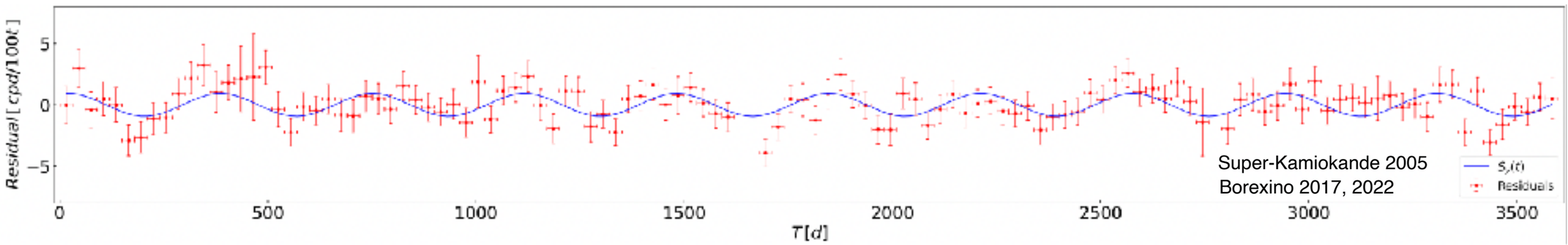


Radiative corrections to the CEvNS cross section induce small flavor dependences [Marciano & Sirlin 1980; Sehgal 1985; Tomalak et al. 2021] ; Charge radius contribution in CEvNS [Cadeddu et al. 2018; de Romeri et al. 2023]

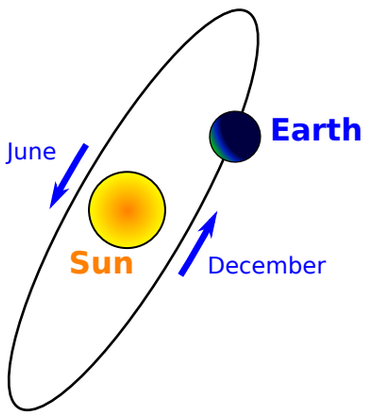
Flavor-dependent corrections introduce a small day/night asymmetry in solar neutrino rate [Nityasa Mishra & L. Strigari PRD 2023]

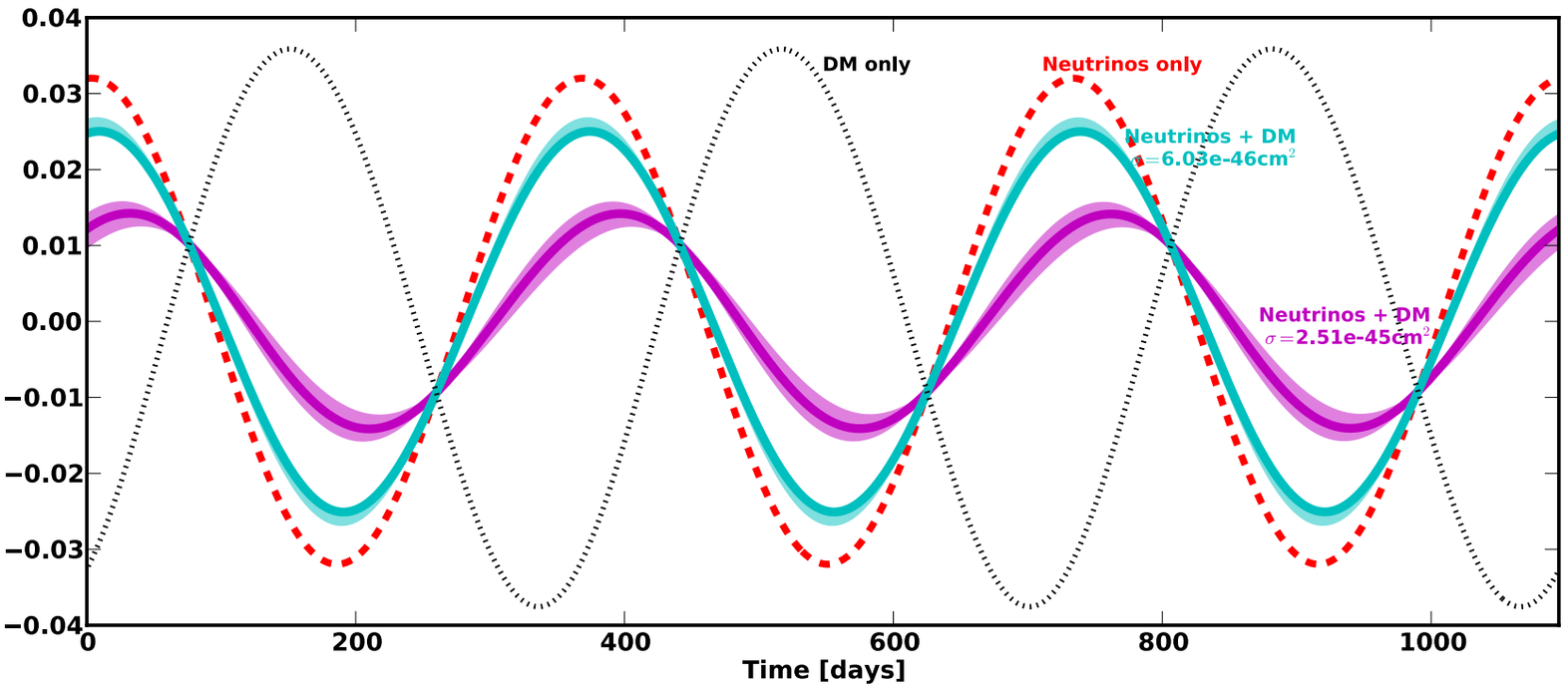
Time variation of solar neutrino flux





WIMP wind

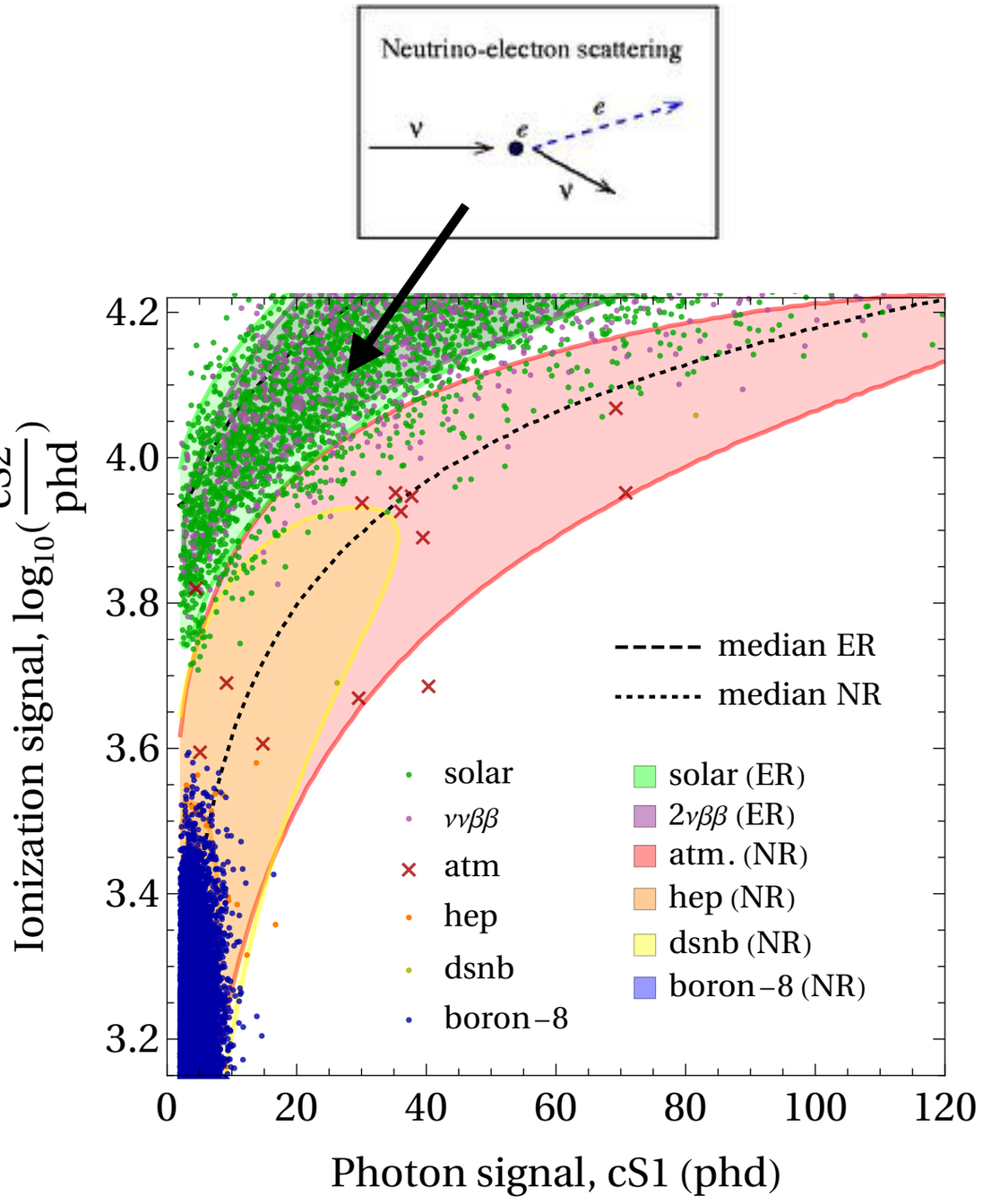


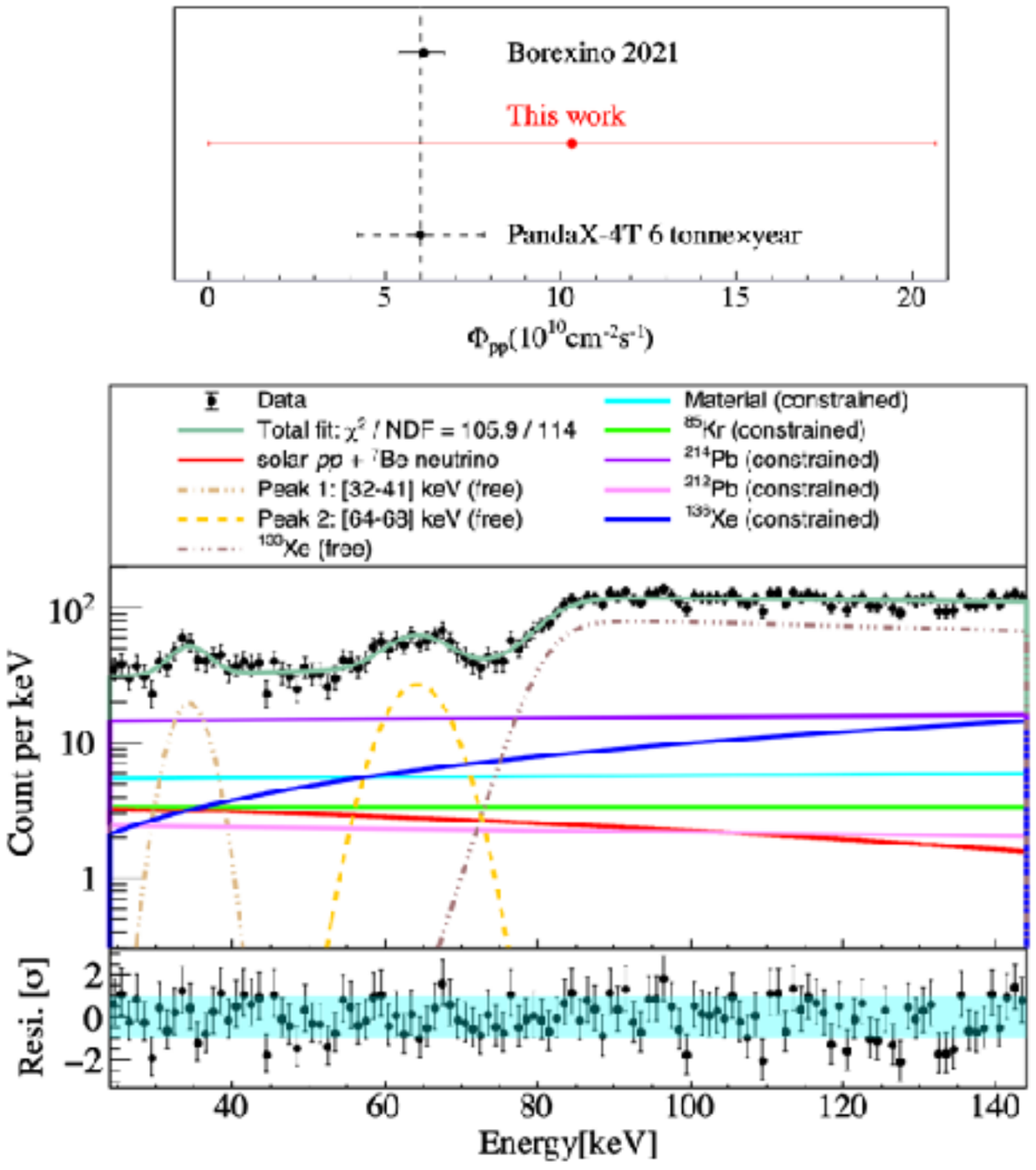


Dark matter modulation should be out of phase with solar neutrino modulation [Davis 2014]

Time variability should be observable in G3 Xenon detector for electron and nuclear recoils [Zhuang, Strigari, Jin, Sinha, 2023, 2024]

A Measurement of Solar *pp* Neutrino Flux using PandaX-4T Electron Recoil Data

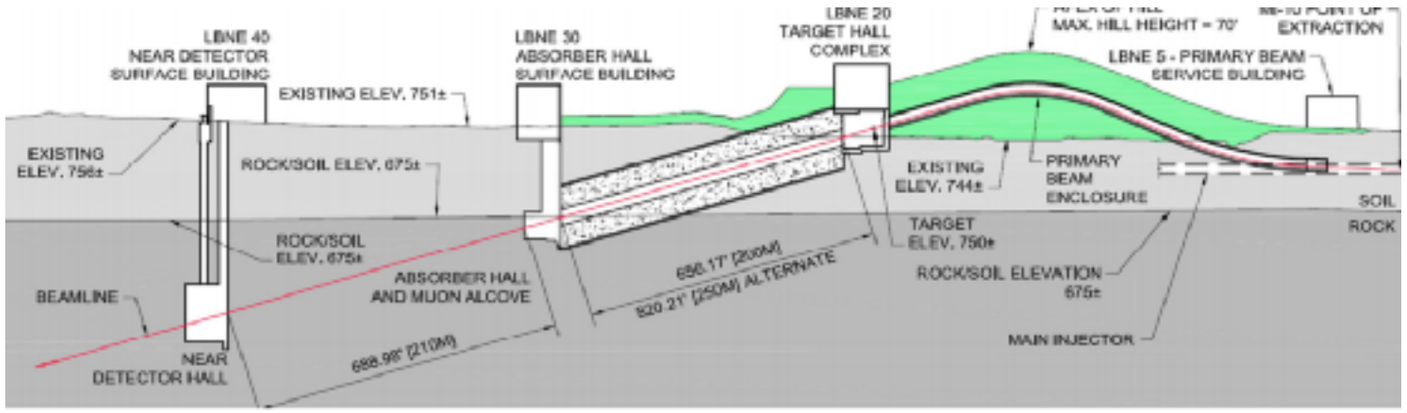




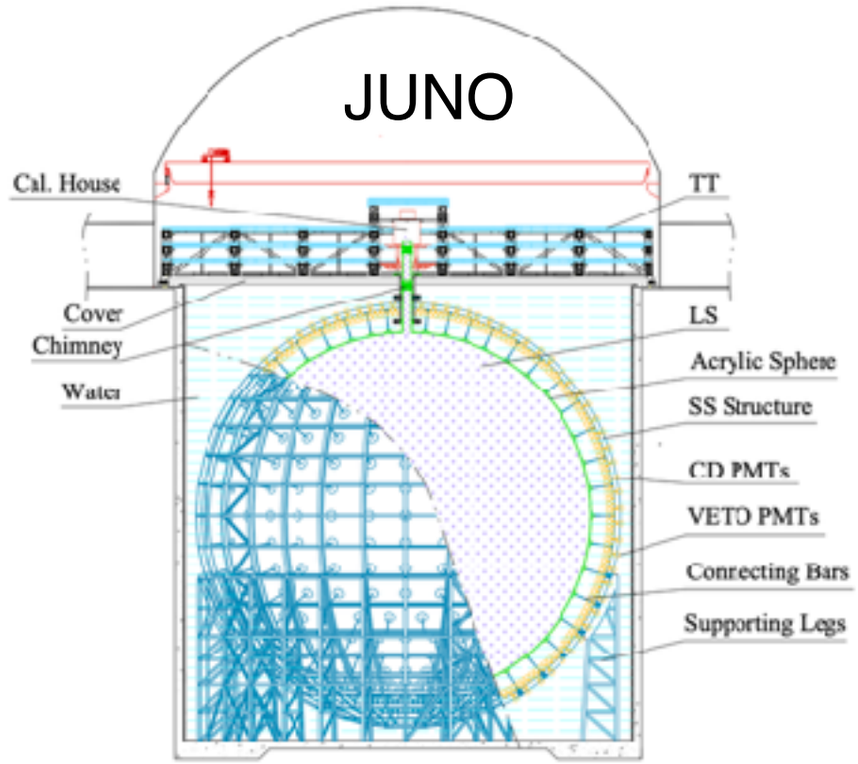
Pandax collaboration, 2401.07045

Next generation neutrino detection

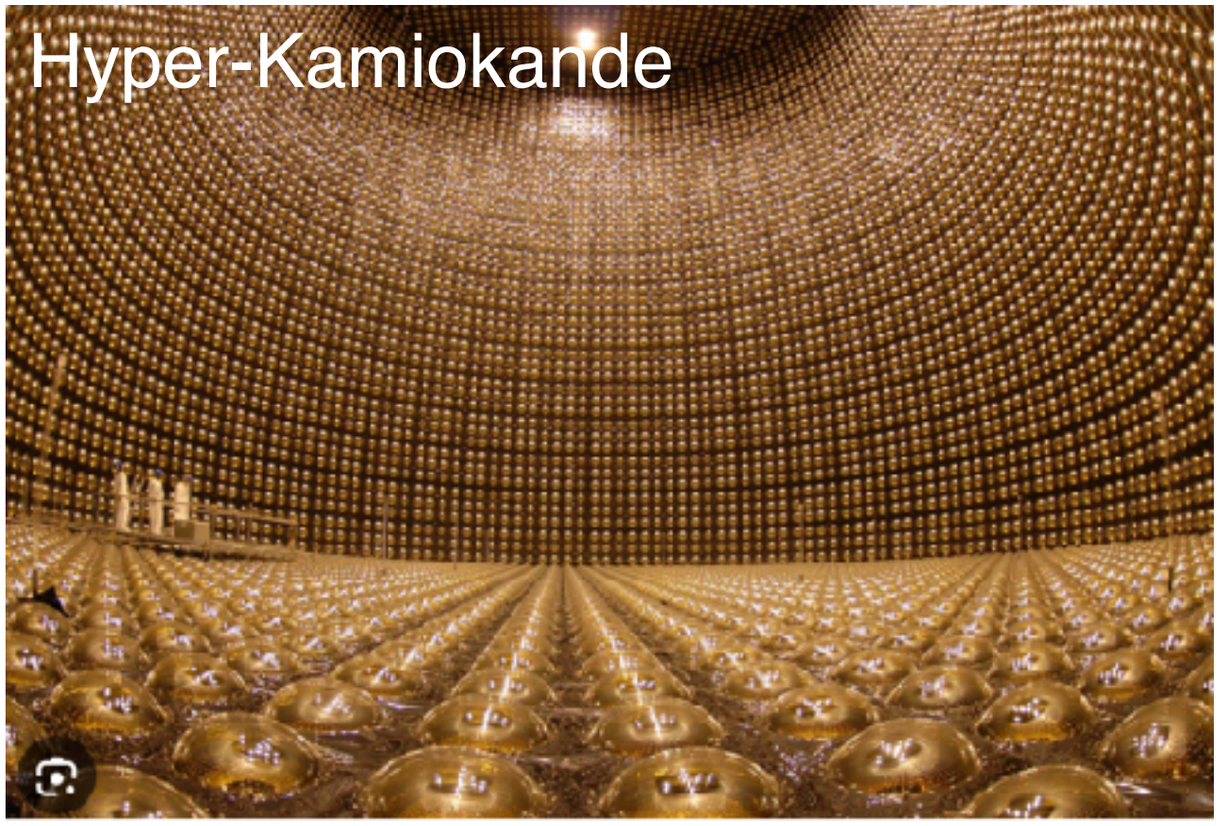
DUNE



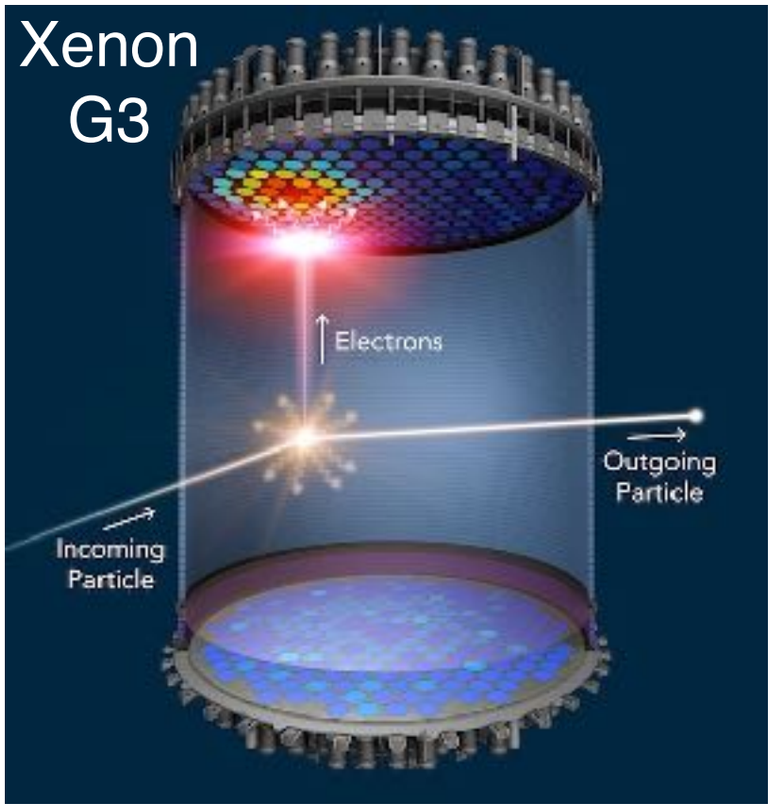
JUNO



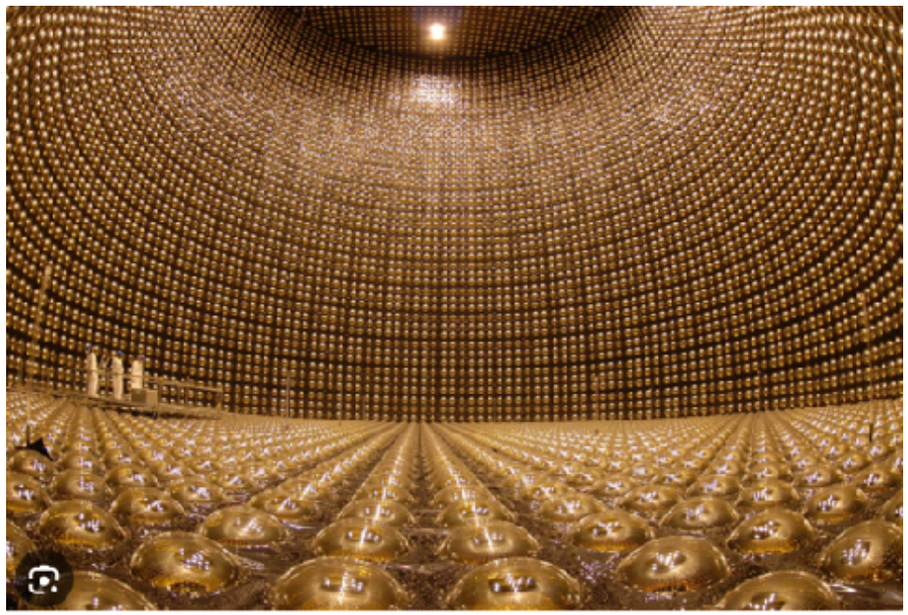
Hyper-Kamiokande

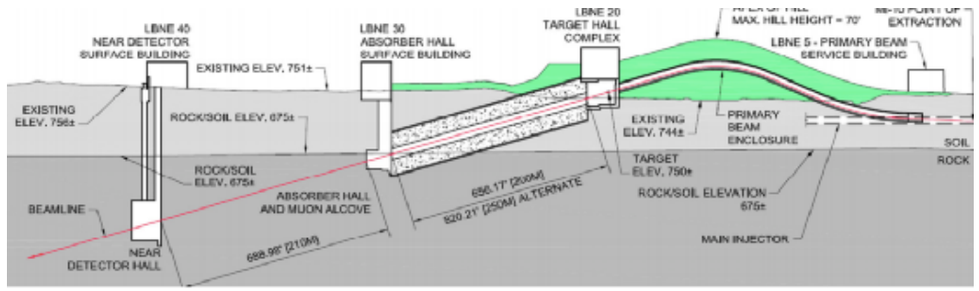


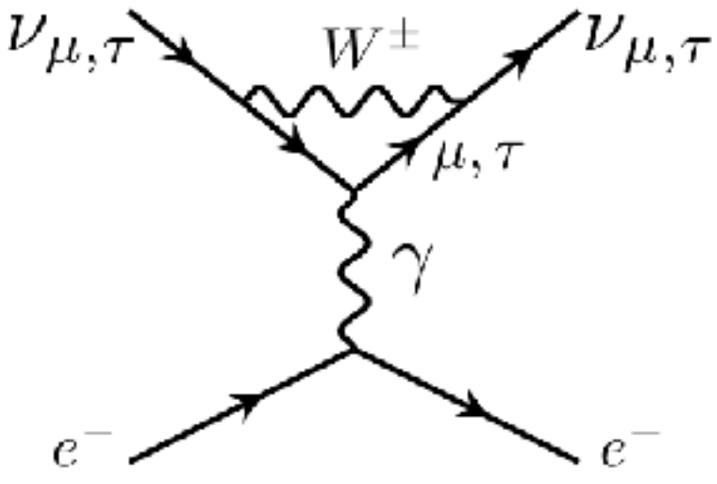
Xenon G3

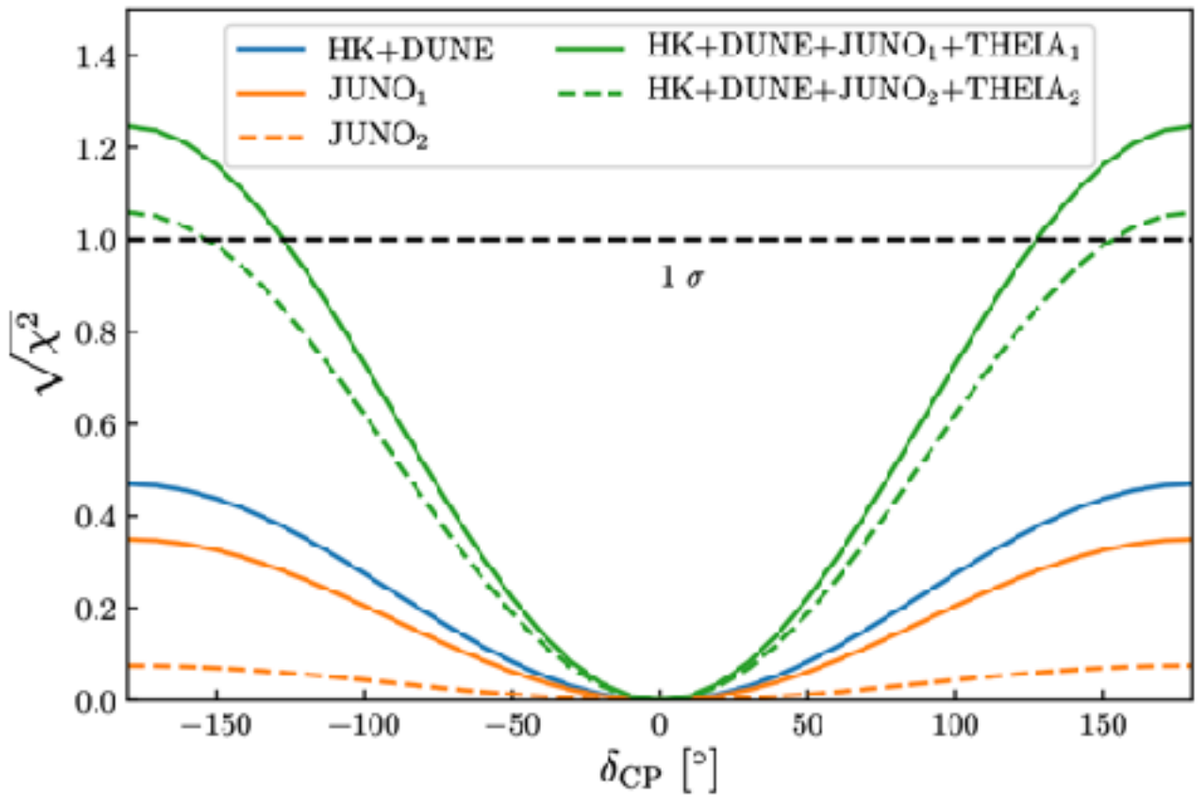


Beyond tree level: ^{8}B solar neutrinos



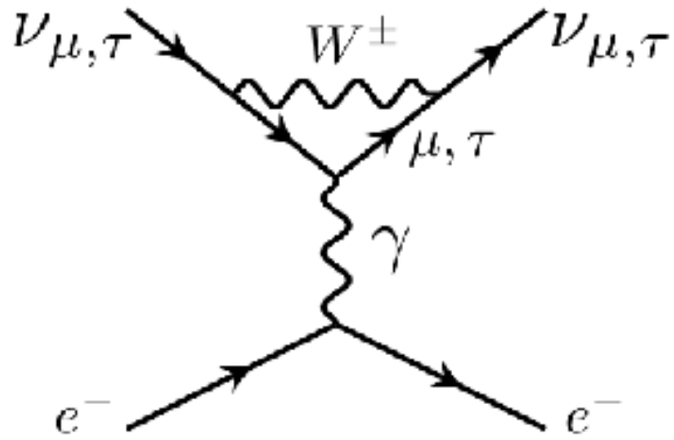


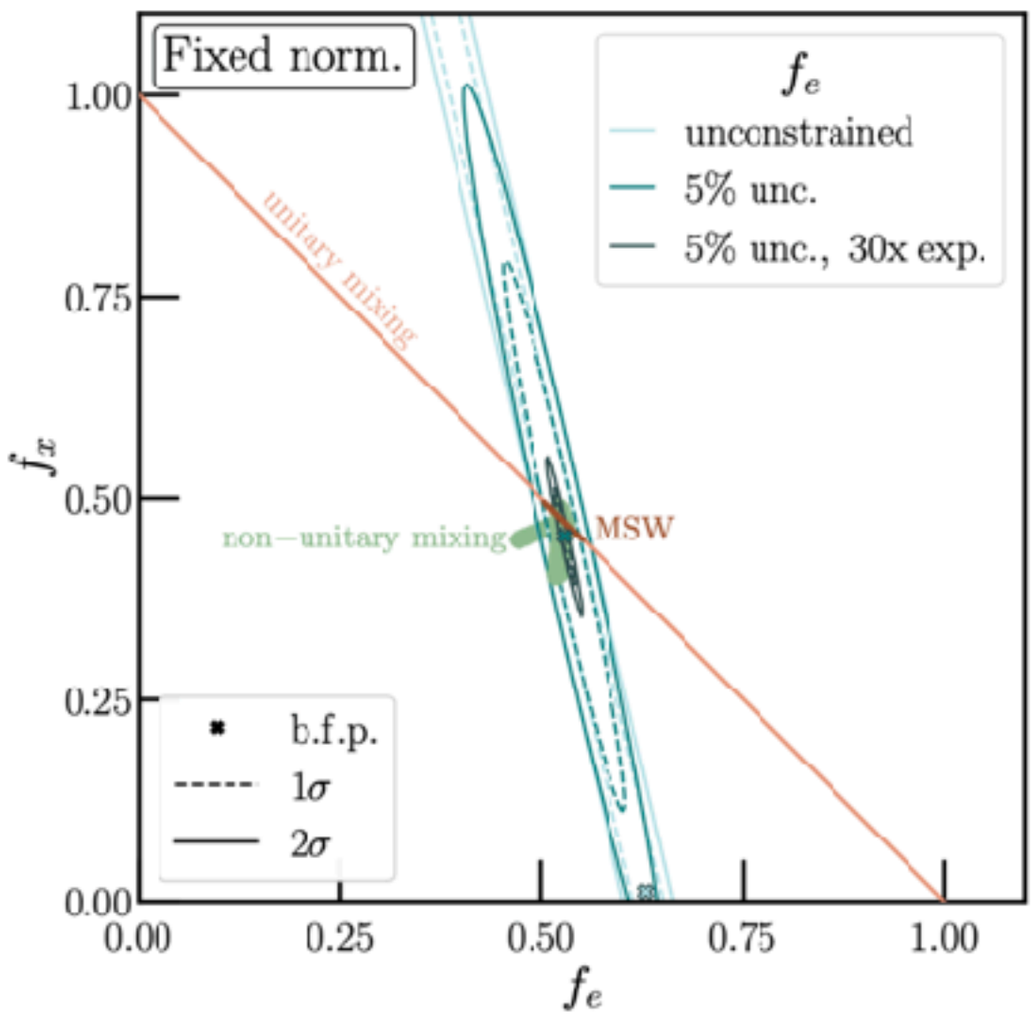


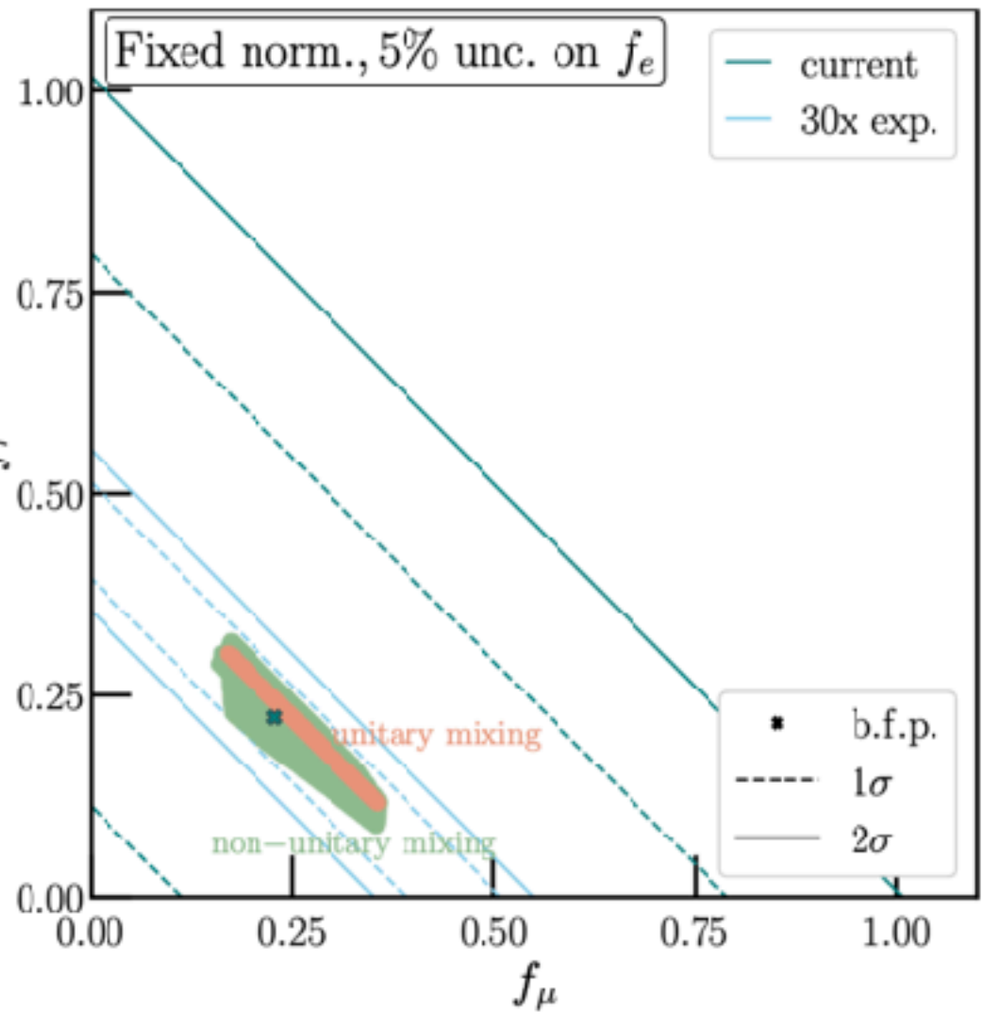


Brdar & Xu PLB 2024

Beyond tree level: ^{7}Be solar neutrinos

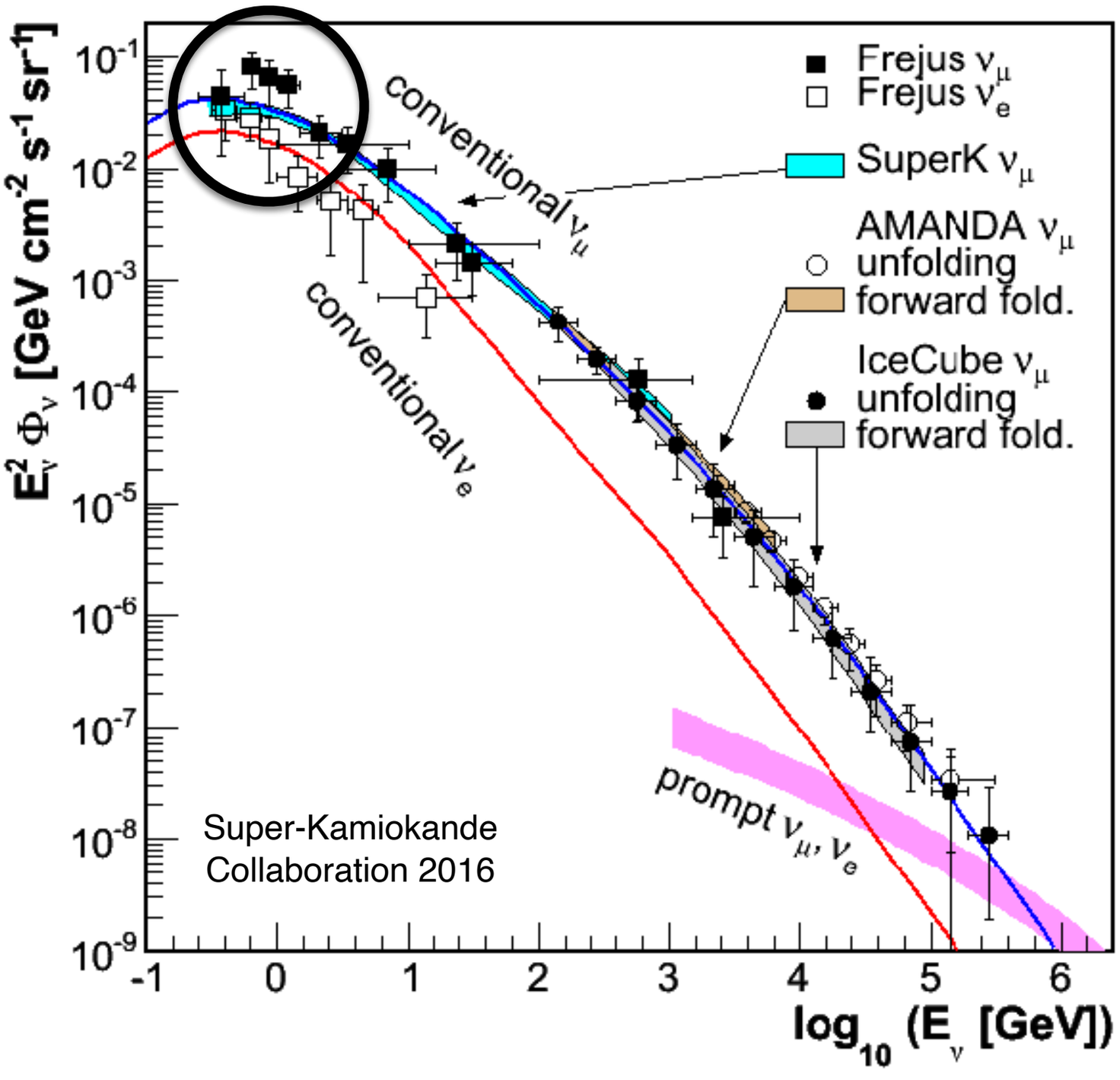




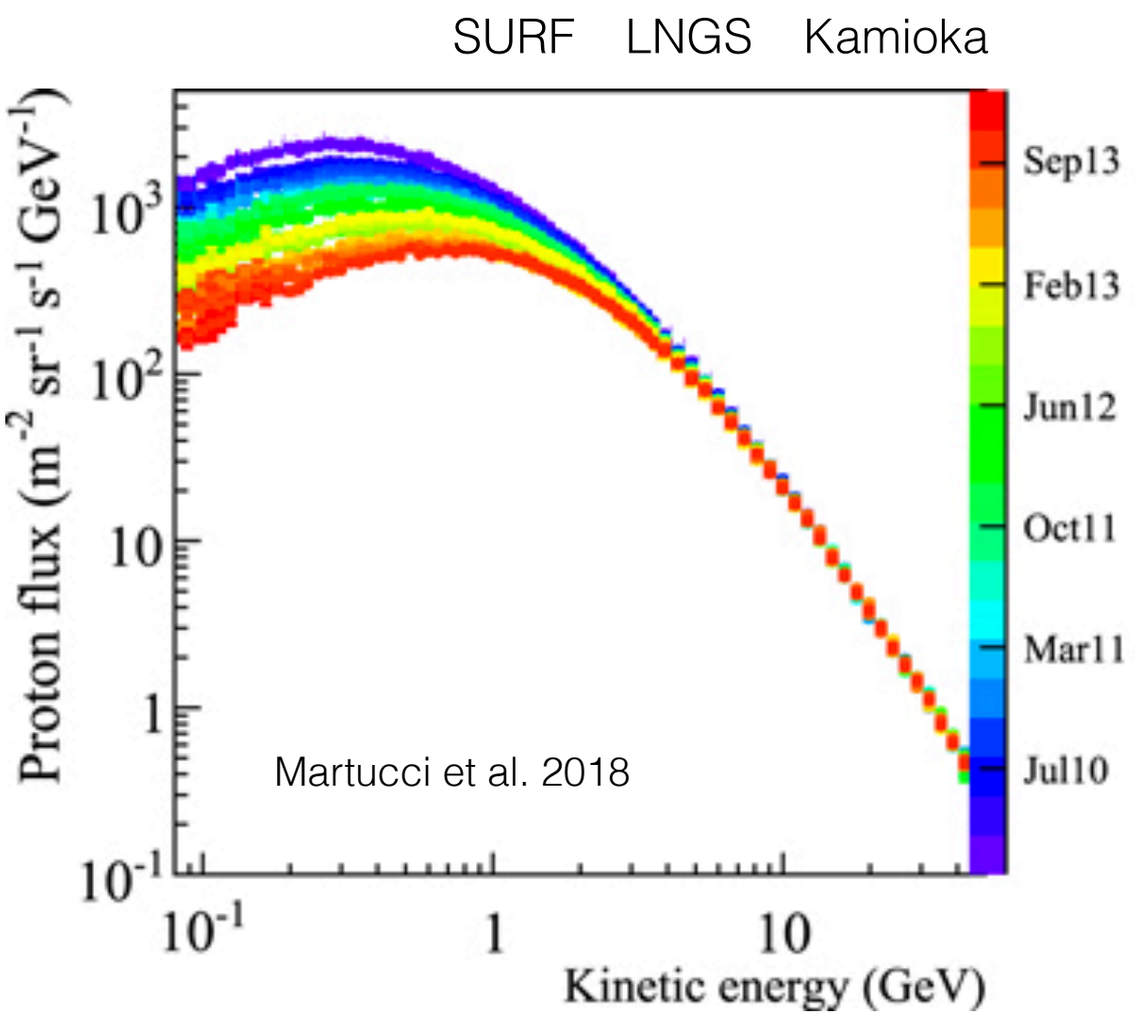


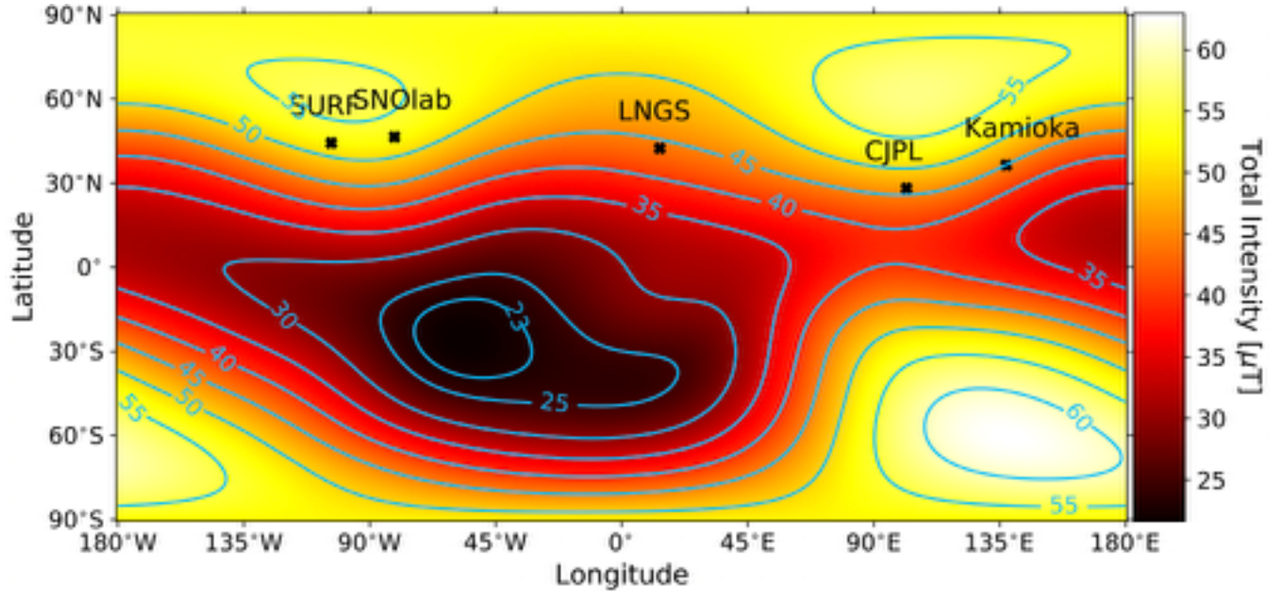
Larger scale experiment similar to Borexino, e.g. JUNO, may be sensitive to non-unitarity in 3-flavor oscillations
[K. Kelly, N. Mishra, M. Rai, LS 2024]

Low-energy atmospheric neutrinos



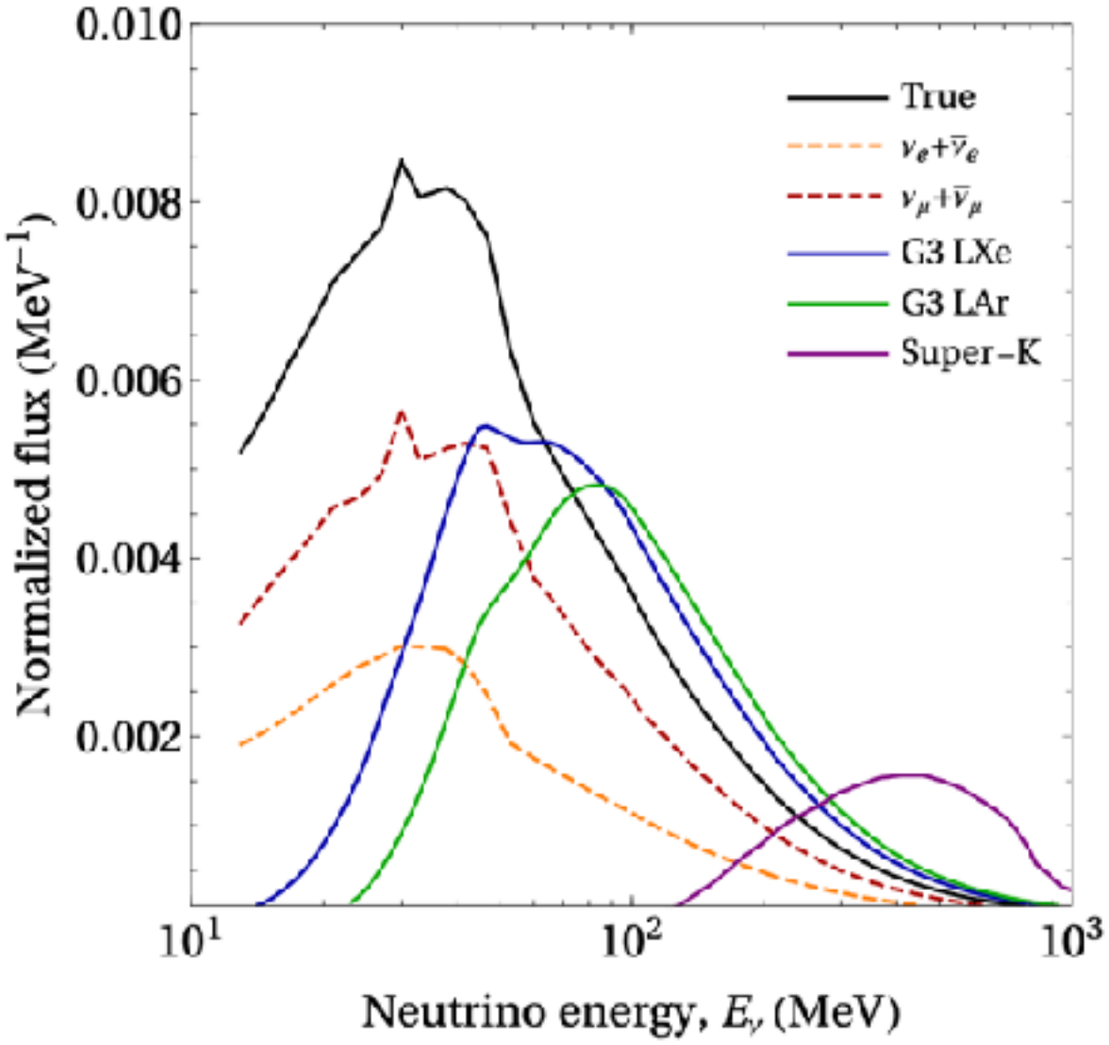
Solar and geomagnetic effects



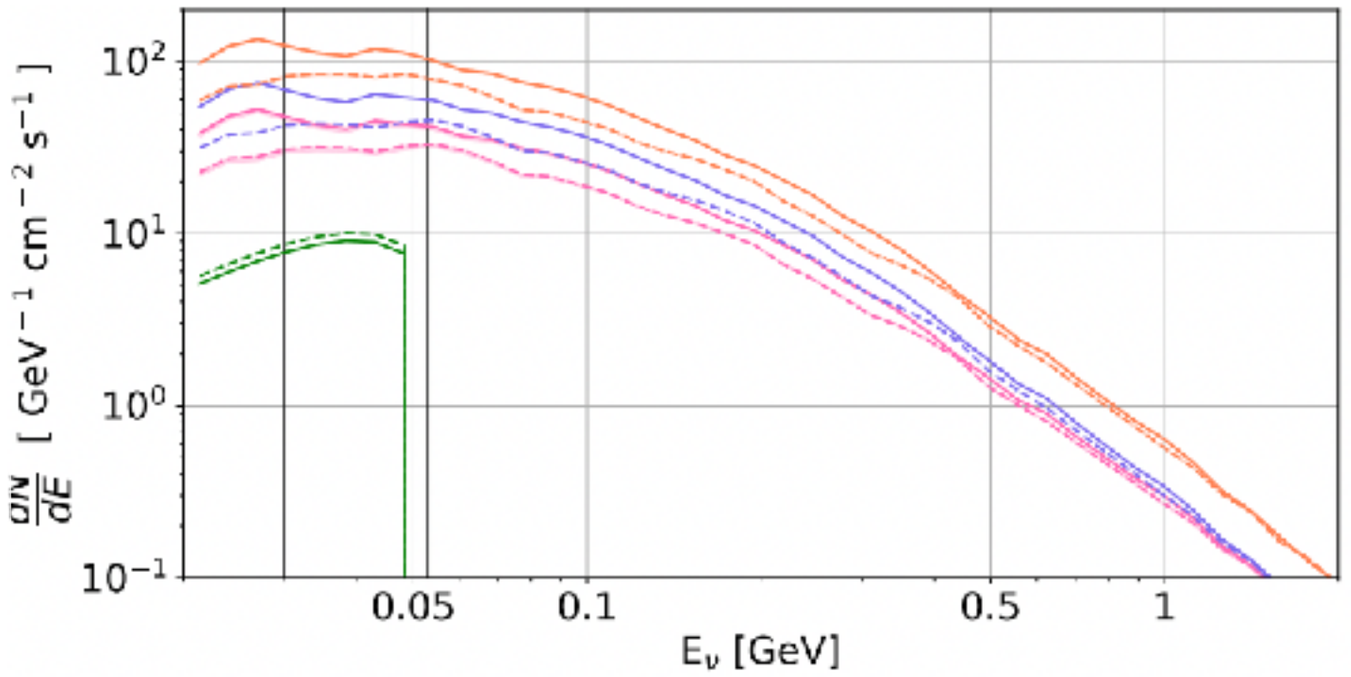


Time variation and geomagnetic effects depend on detector location [Zhuang, Strigari, Lang PRD 2021]

Low energy atmospheric neutrino fluxes

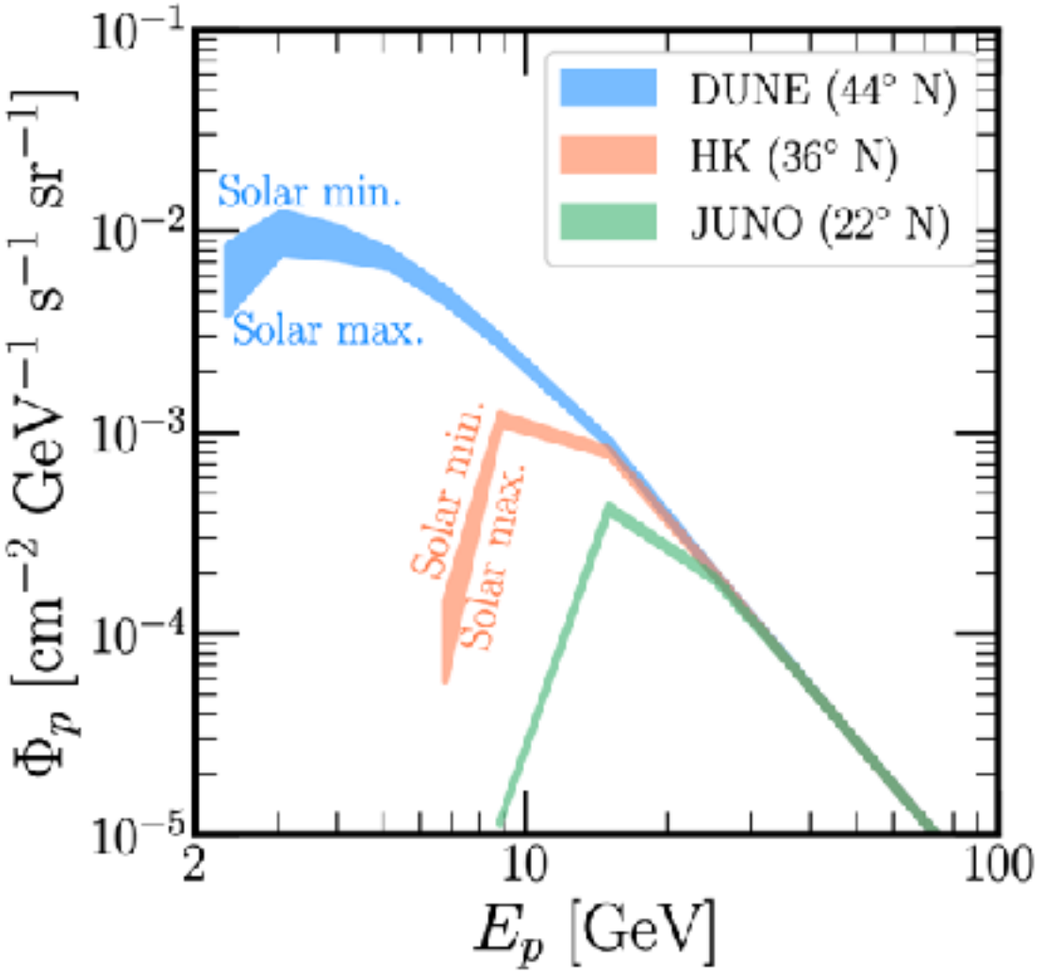


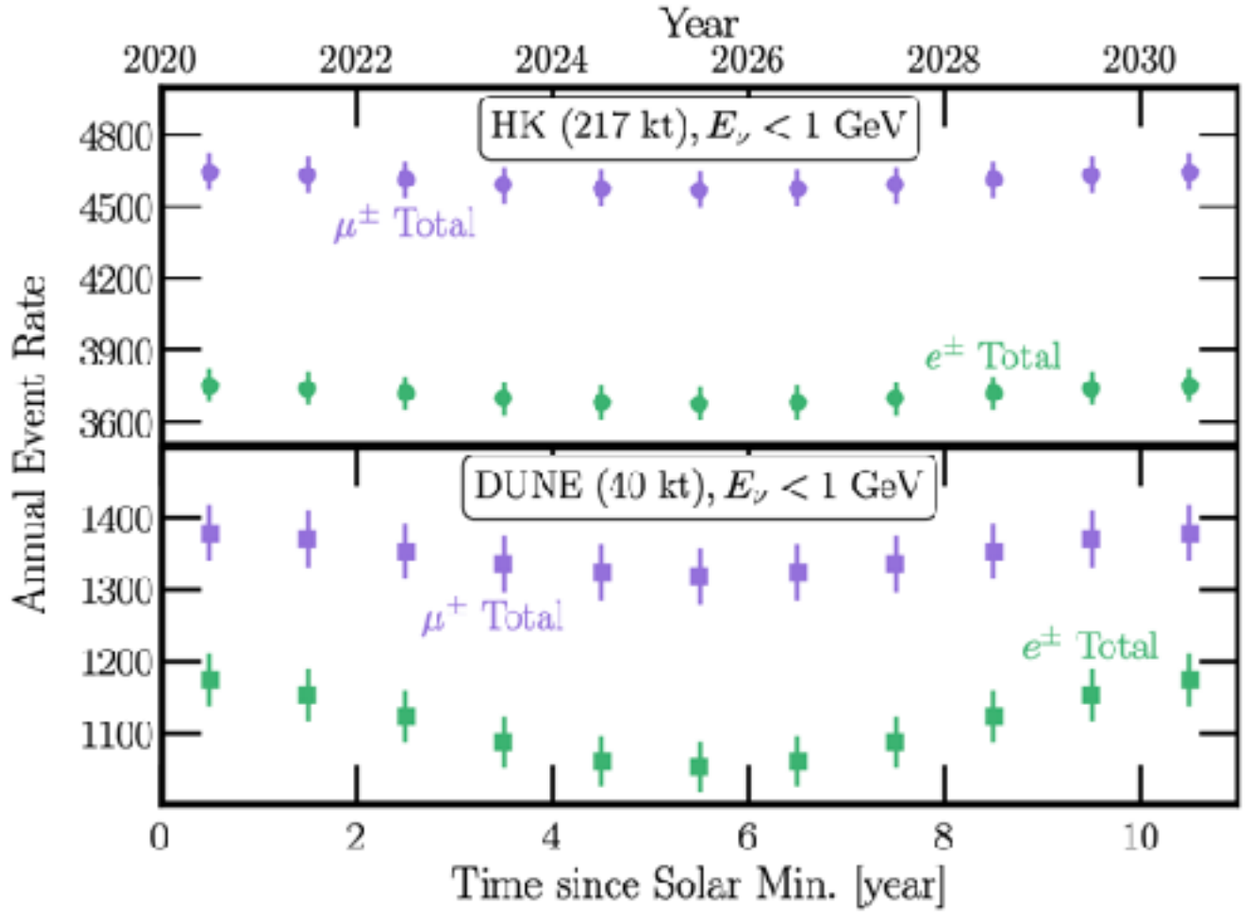
Newstead, Lang, LS PRD 2020



Honda et al. 2015, Zhuang, LS, Lang PRD 2021

Solar and geomagnetic effects at DUNE and Hyper-Kamiokande

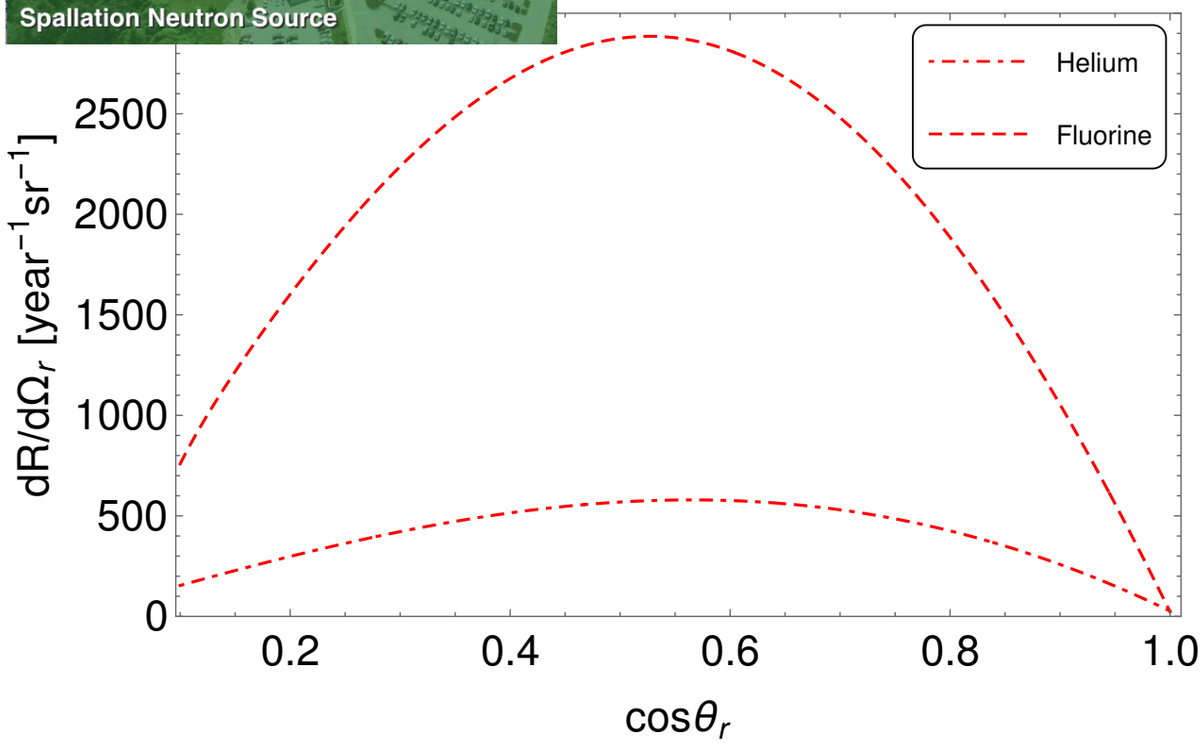


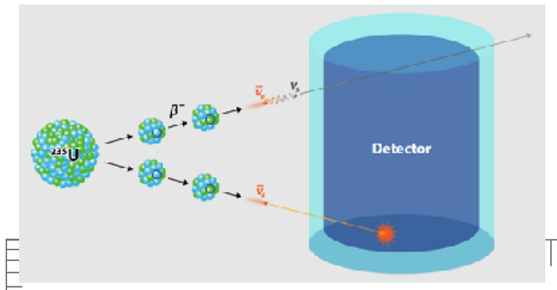


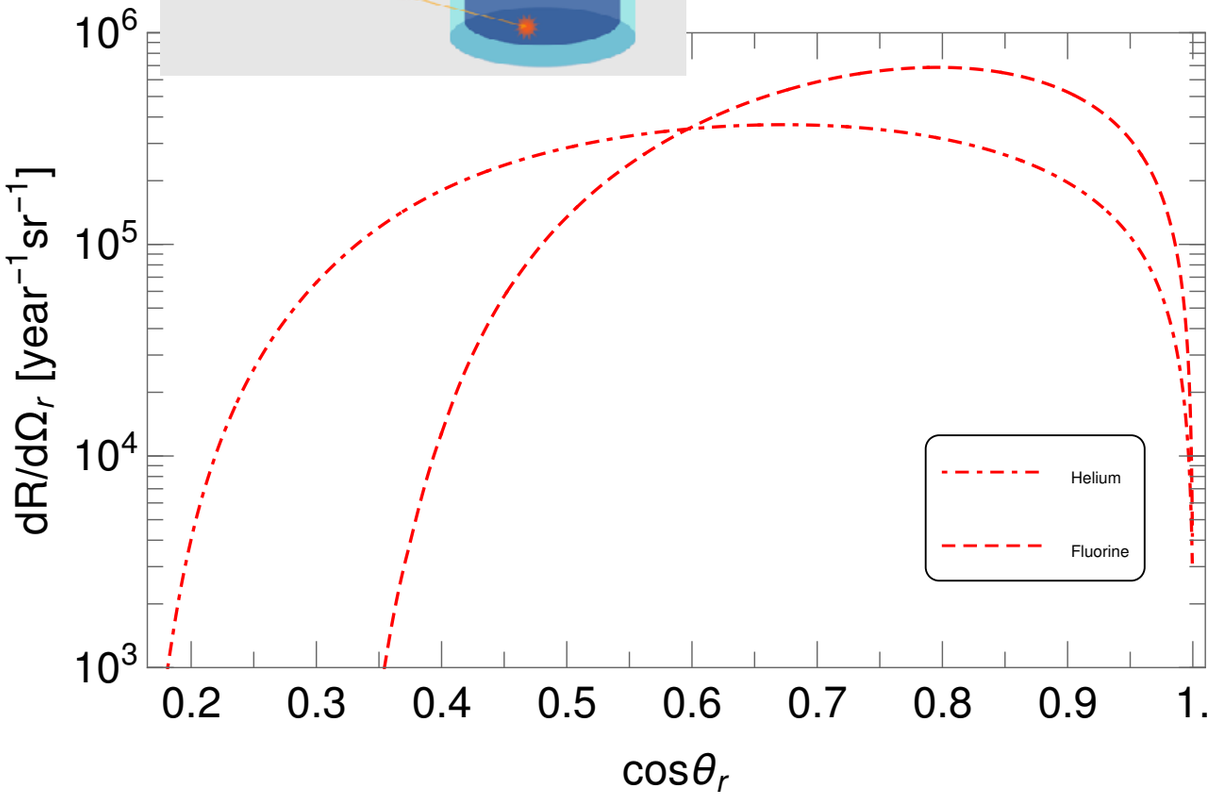
- Over 11-year solar cycle, statistical significance for observing time modulation of atmospheric neutrinos is 4.8σ for DUNE and 2.0σ for HK.
- Flux measurements at both DUNE and HK important for understanding systematics and oscillations in low-energy atmospheric neutrinos.

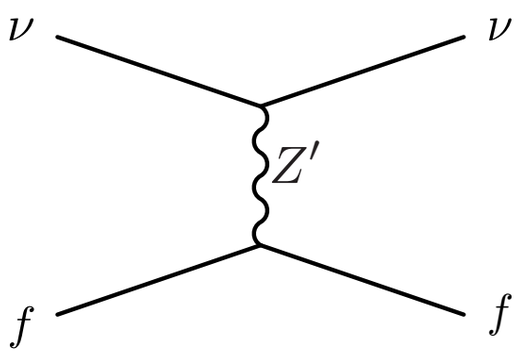
Kelly, Machado, Mishra, LS, Zhuang PRD2023

CEvNS with directional detectors





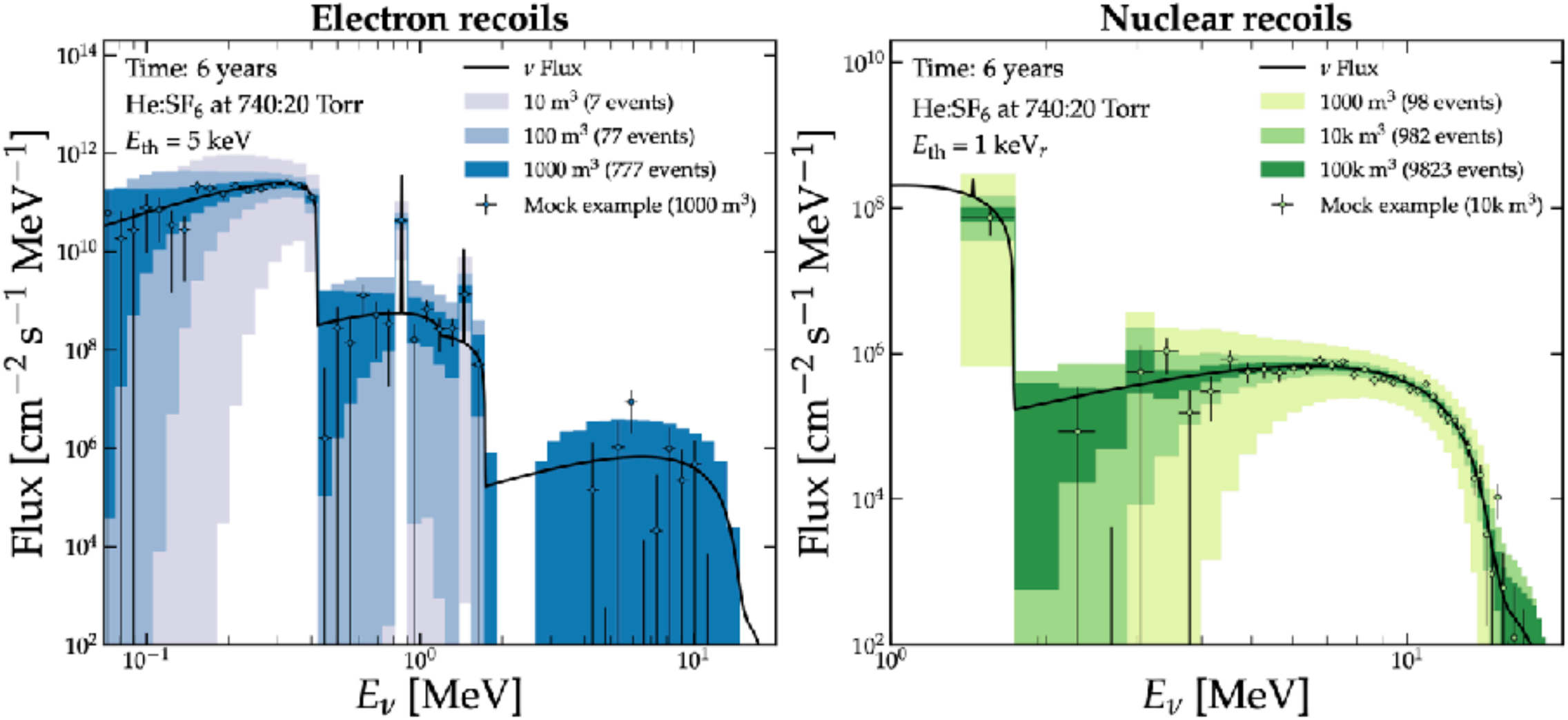




Light mediators alter the shape of angular distribution

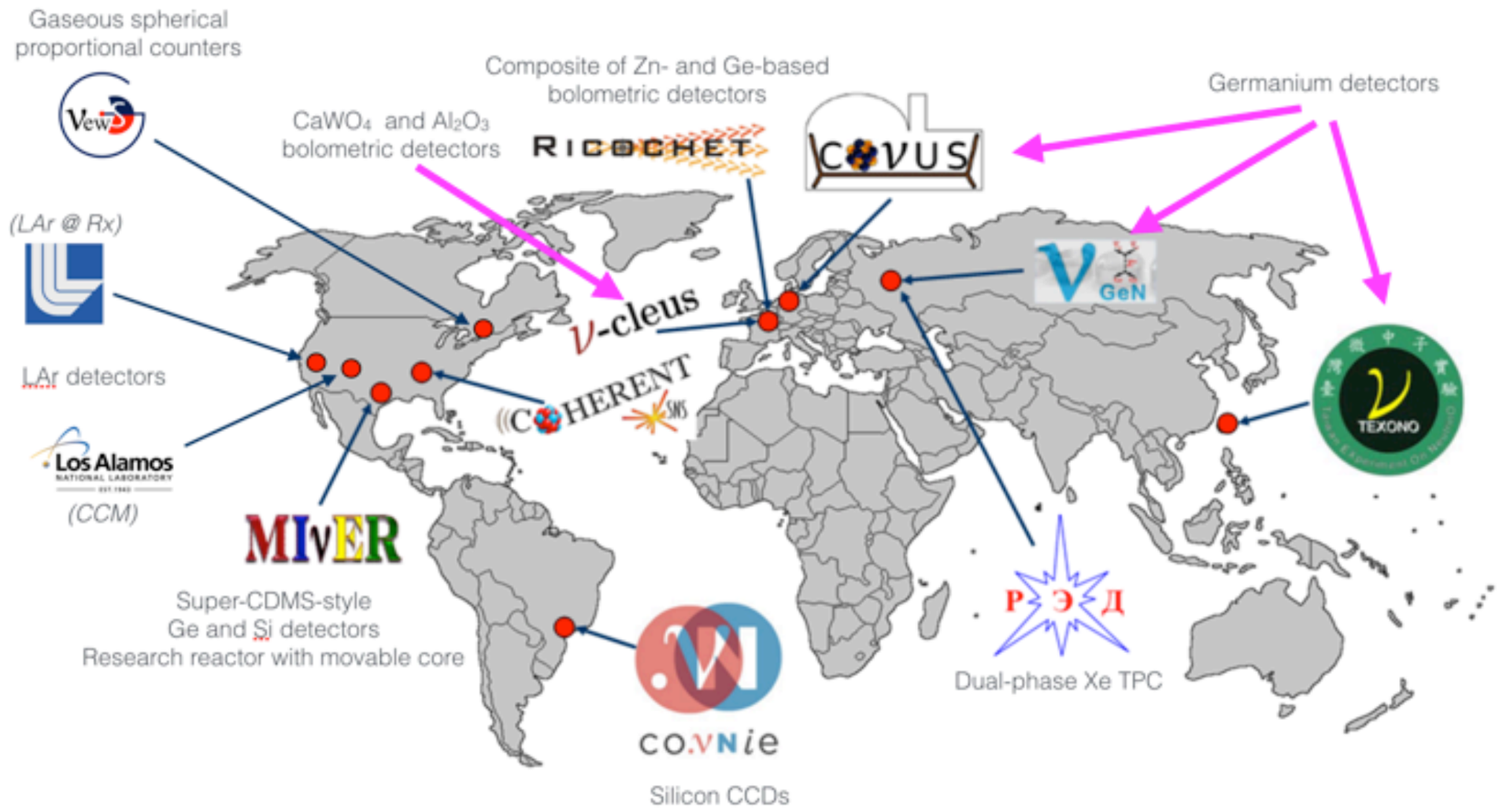
Abdullah, Aristizabal-Sierra, Dutta, Strigari
Phys.Rev.D 102 (2020) 1, 015009 2003.11510

Neutrino energy reconstruction



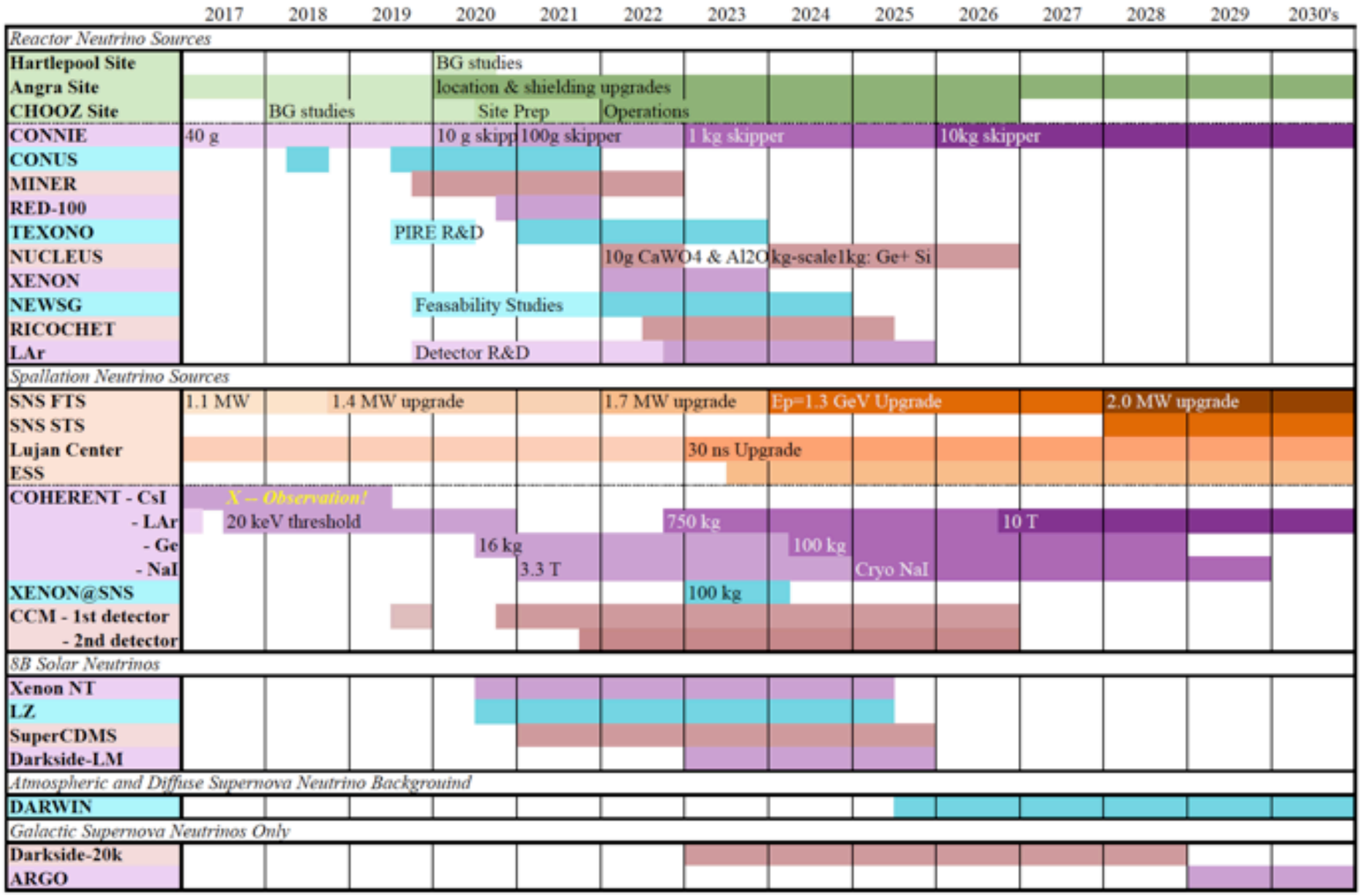
Lisotti et al, 2404.03690

CEvNS in the coming decade



Phil Barbeau

CEvNS in the coming decade



Phil Barbeau

Neutrino physics opportunities with dark matter detectors

- 8B solar neutrinos likely to be the first astrophysical measurement of CEvNS
- Opportunities for atmospheric neutrinos at dark matter detectors
- Flavor dependencies in CEvNS, and future precision measurements
- Opportunities with CEvNS and terrestrial detectors
- CEvNS experiments using decay in-flight