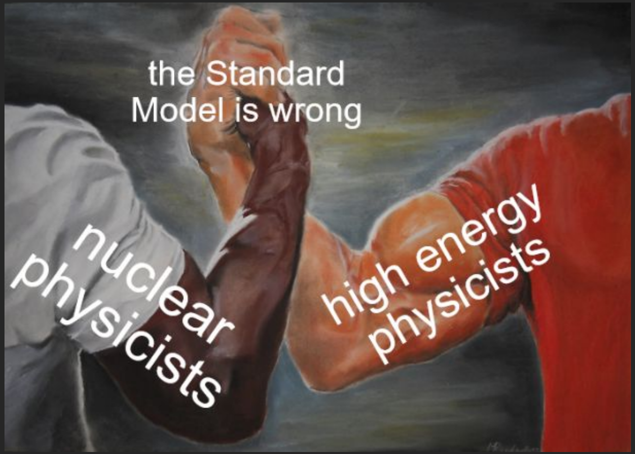
Daniel J Salvat

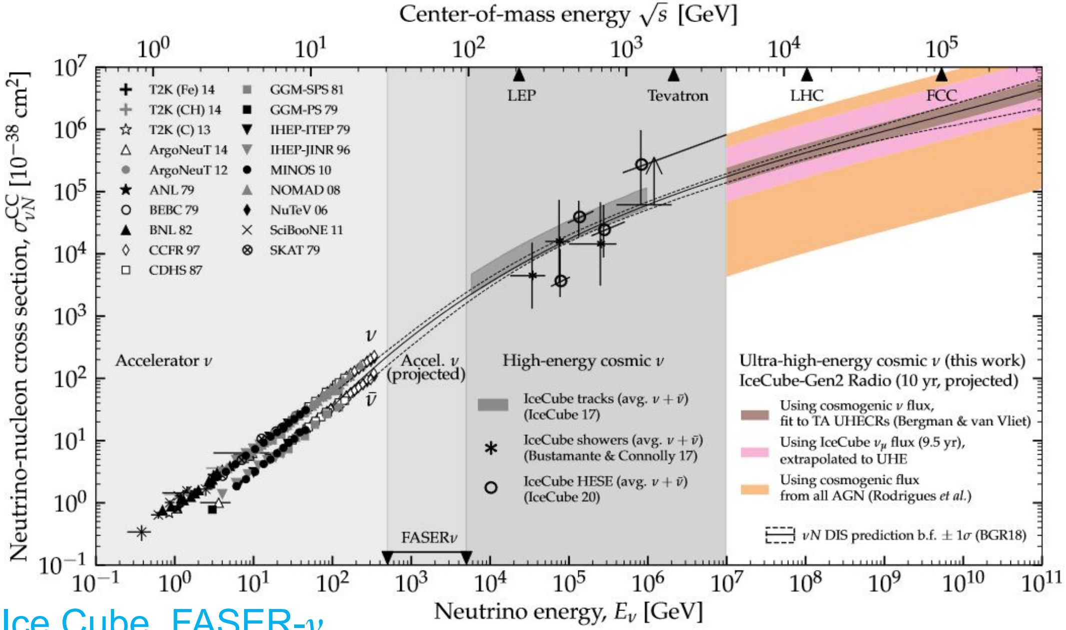
# Neutrino-nuclear cross sections, beyond-standard-model physics, and accelerator-produced dark matter




Daniel J Salvat

# Neutrino-nuclear cross sections, beyond-standard-model physics, and accelerator-produced dark matter

# Ultra-high energy, high energy




Ice Cube, FASER-ν, …

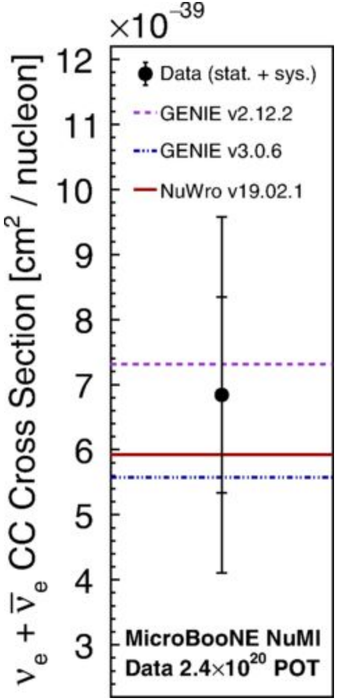
The ultra-high-energy neutrino-nucleon cross section: measurement forecasts for an era of cosmic EeV-neutrino discovery


Víctor B. Valera* and Mauricio Bustamante†
*Niels Bohr International Academy, Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark*

Christian Glaser‡
*Department of Physics and Astronomy, Uppsala University, Uppsala, SE-752 37, Sweden*


(Dated: December 9, 2022)

arXiv:2204.04237v3 [hep-ph]




MicroBooNE, ICARUS, …

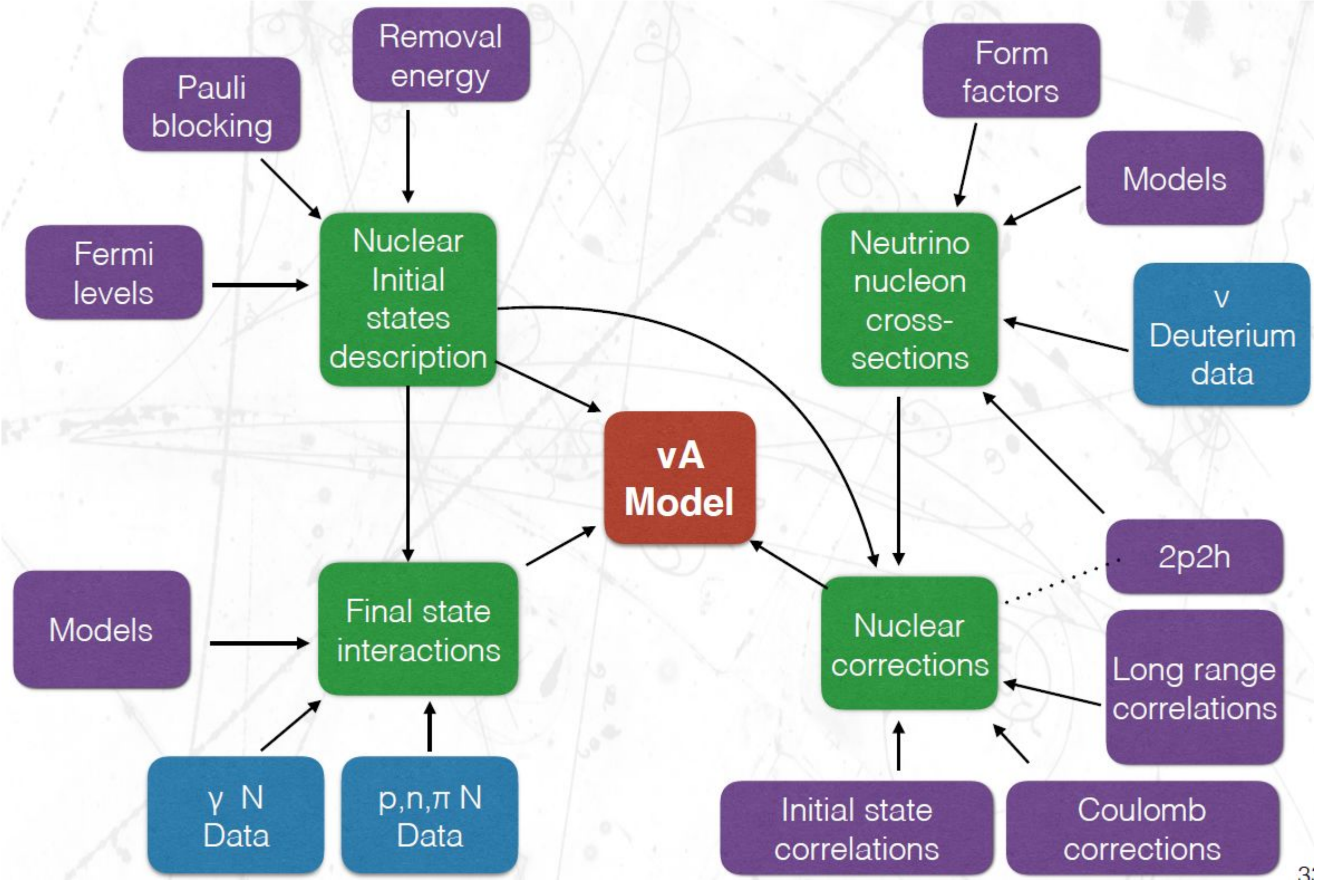
Measurement of the flux-averaged inclusive charged-current electron neutrino and antineutrino cross section on argon using the NuMI beam and the MicroBooNE detector

P. Abratenko *et al.* (MicroBooNE Collaboration)

Phys. Rev. D **104**, 052002 – Published 8 September 2021

From F. Sanchez (2019)

# Neutrino-nuclear interactions (high energy)



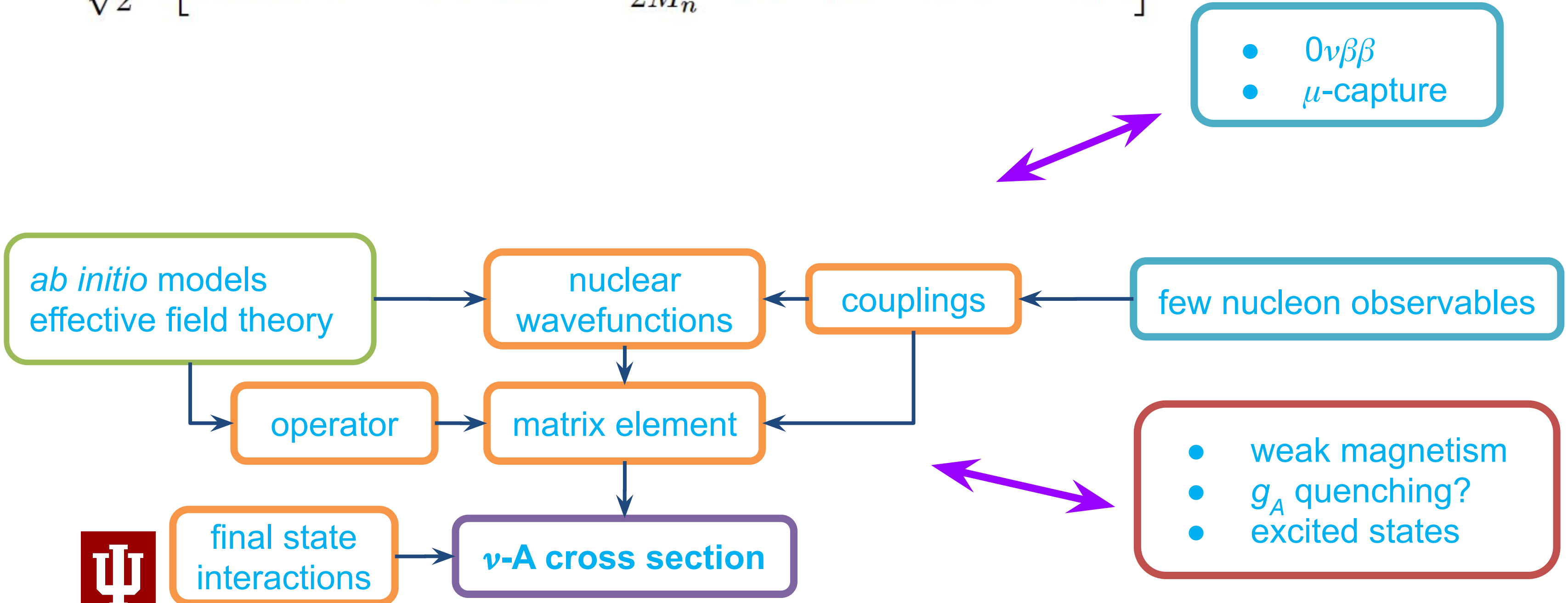
# Low energy A-$\nu$ cross sections

me (now)

# Neutrino-nuclear interactions (low energy)

$$\langle \Psi_f | \mathcal{O} | \Psi_i \rangle$$

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \left[ \langle \bar{n} | \left( \gamma_\mu f_V(0) - \gamma_\mu \gamma^5 f_A(0) - \frac{i f_P(0)}{2M_n} \sigma_{\mu\nu} q^\nu \right) | p \rangle \langle \bar{\nu}_e | \gamma^\mu (1 - \gamma^5) | e \rangle \right]$$



# Neutrino-nuclear interactions (low energy)

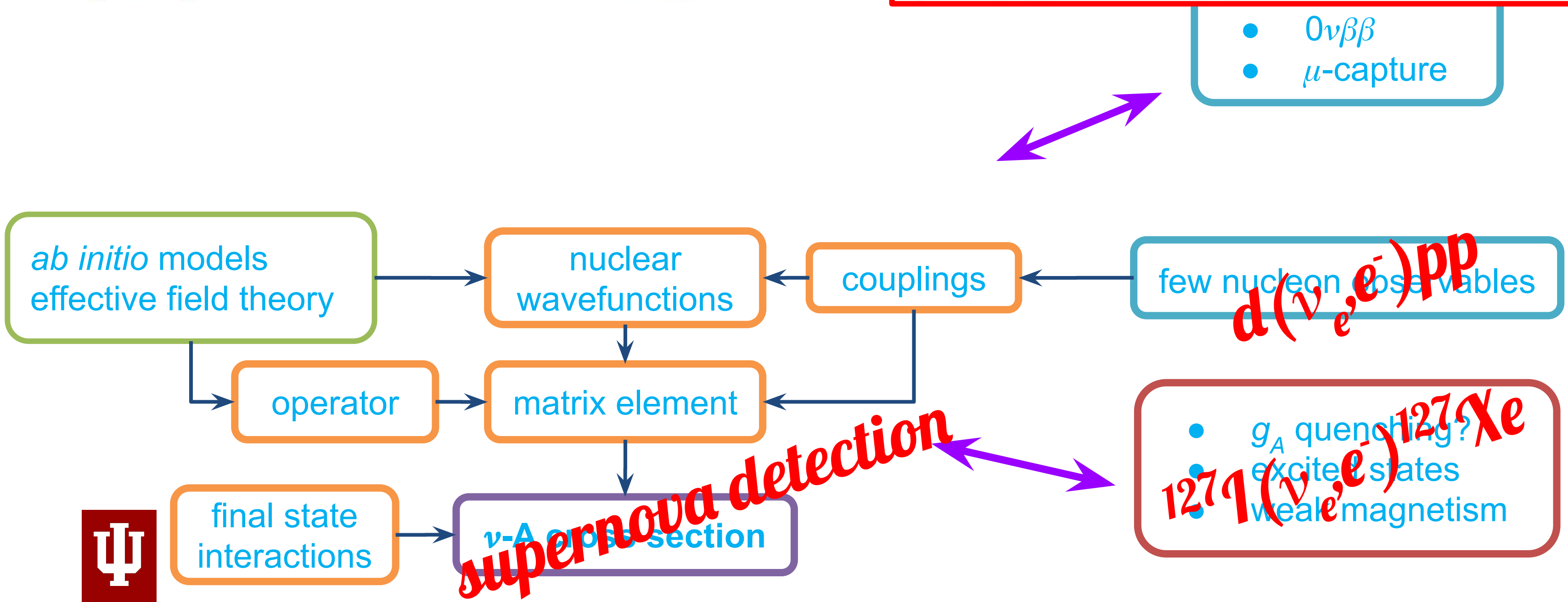
$$\langle \Psi_f | \mathcal{O} | \Psi_i \rangle$$

$$\mathcal{M} = \frac{G_F V_{ud}}{\sqrt{2}} \Big[ \langle \bar{n} | \left( \gamma_\mu f_V(0) - \gamma_\mu \gamma^5 f_A(0) - \frac{i f_P(0)}{2M_n} \sigma_{\mu\nu} q^\nu \right) | p \rangle \langle i$$

Muon-capture strength functions in intermediate nuclei of $0\nu\beta\beta$ decays

L. Jokiniemi and J. Suhonen

Phys. Rev. C **100**, 014619 – Published 31 July 2019



# Existing data

| Isotope | Reaction Channel | Source | Experiment | Measurement ($10^{-42}$ cm$^2$) | Theory ($10^{-42}$ cm$^2$) |
|---|---|---|---|---|---|
| $^2$H | $^2\mathrm{H}(\nu_e, e^-)\mathrm{pp}$ | Stopped $\pi/\mu$ | LAMPF | $52 \pm 18(\mathrm{tot})$ | 54 (IA) (Tatara *et al.*, 1990) |
| $^{12}$C | $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$ | Stopped $\pi/\mu$ | KARMEN | $9.1 \pm 0.5(\mathrm{stat}) \pm 0.8(\mathrm{sys})$ | 9.4 [Multipole](Donnelly and Peccei, 1979) |
| | | Stopped $\pi/\mu$ | E225 | $10.5 \pm 1.0(\mathrm{stat}) \pm 1.0(\mathrm{sys})$ | 9.2 [EPT] (Fukugita *et al.*, 1988). |
| | | Stopped $\pi/\mu$ | LSND | $8.9 \pm 0.3(\mathrm{stat}) \pm 0.9(\mathrm{sys})$ | 8.9 [CRPA] (Kolbe *et al.*, 1999b) |
| | $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$ | Stopped $\pi/\mu$ | KARMEN | $5.1 \pm 0.6(\mathrm{stat}) \pm 0.5(\mathrm{sys})$ | 5.4-5.6 [CRPA] (Kolbe *et al.*, 1999b) |
| | | Stopped $\pi/\mu$ | E225 | $3.6 \pm 2.0(\mathrm{tot})$ | 4.1 [Shell] (Hayes and S, 2000) |
| | | Stopped $\pi/\mu$ | LSND | $4.3 \pm 0.4(\mathrm{stat}) \pm 0.6(\mathrm{sys})$ | |
| | $^{12}\mathrm{C}(\nu_\mu, \nu_\mu)^{12}\mathrm{C}^*$ | Stopped $\pi/\mu$ | KARMEN | $3.2 \pm 0.5(\mathrm{stat}) \pm 0.4(\mathrm{sys})$ | 2.8 [CRPA] (Kolbe *et al.*, 1999b) |
| | $^{12}\mathrm{C}(\nu, \nu)^{12}\mathrm{C}^*$ | Stopped $\pi/\mu$ | KARMEN | $10.5 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{sys})$ | 10.5 [CRPA] (Kolbe *et al.*, 1999b) |
| | $^{12}\mathrm{C}(\nu_\mu, \mu^-)\mathrm{X}$ | Decay in Flight | LSND | $1060 \pm 30(\mathrm{stat}) \pm 180(\mathrm{sys})$ | 1750-1780 [CRPA] (Kolbe *et al.*, 1999b) |
| | | | | | 1380 [Shell] (Hayes and S, 2000) |
| | | | | | 1115 [Green's Function] (Meucci *et al.*, 2004) |
| | $^{12}\mathrm{C}(\nu_\mu, \mu^-)^{12}\mathrm{N}_{\mathrm{g.s.}}$ | Decay in Flight | LSND | $56 \pm 8(\mathrm{stat}) \pm 10(\mathrm{sys})$ | 68-73 [CRPA] (Kolbe *et al.*, 1999b) |
| | | | | | 56 [Shell] (Hayes and S, 2000) |
| $^{56}$Fe | $^{56}\mathrm{Fe}(\nu_e, e^-)^{56}\mathrm{Co}$ | Stopped $\pi/\mu$ | KARMEN | $256 \pm 108(\mathrm{stat}) \pm 43(\mathrm{sys})$ | 264 [Shell] (Kolbe *et al.*, 1999a) |
| $^{71}$Ga | $^{71}\mathrm{Ga}(\nu_e, e^-)^{71}\mathrm{Ge}$ | $^{51}$Cr source | GALLEX, ave. | $0.0054 \pm 0.0009(\mathrm{tot})$ | 0.0058 [Shell] (Haxton, 1998) |
| | | $^{51}$Cr | SAGE | $0.0055 \pm 0.0007(\mathrm{tot})$ | |
| | | $^{37}$Ar source | SAGE | $0.0055 \pm 0.0006(\mathrm{tot})$ | 0.0070 [Shell] (Bahcall, 1997) |
| $^{127}$I | $^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$ | Stopped $\pi/\mu$ | LSND | $284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$ | 210-310 [Quasi-particle] (Engel *et al.*, 1994) |

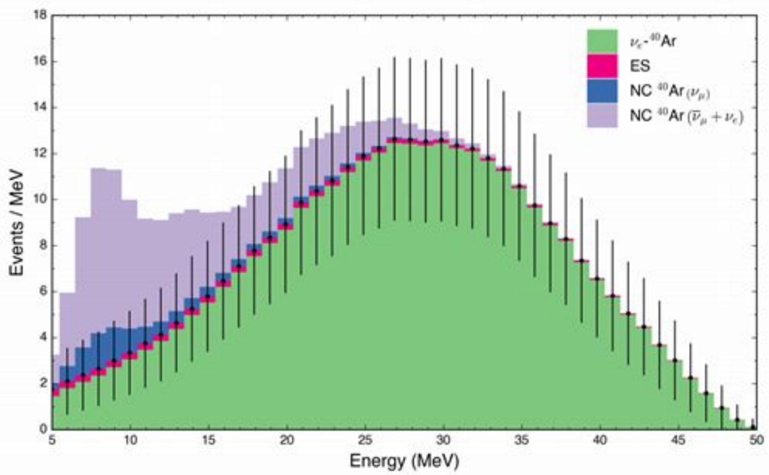
[J. A. Formaggio & G. P. Zeller, Rev. Mod. Phys **84** (2012)]

# All's loud on the theory front

Coherent elastic neutrino-nucleus scattering on $^{40}$Ar from first principles

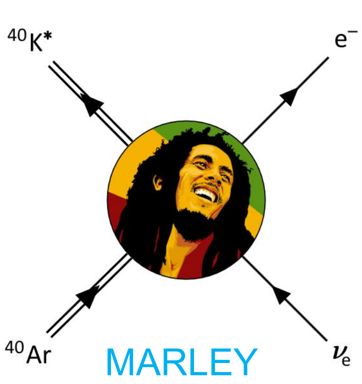
C. G. Payne,[1] S. Bacca,[1] G. Hagen,[2,3,*] W. Jiang,[3,2] and T. Papenbrock[3,2]
[1]*Institut für Kernphysik and PRISMA$^+$ Cluster of Excellence, Johannes Gutenberg-Universität, 55128 Mainz, Germany*
[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA*
[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*

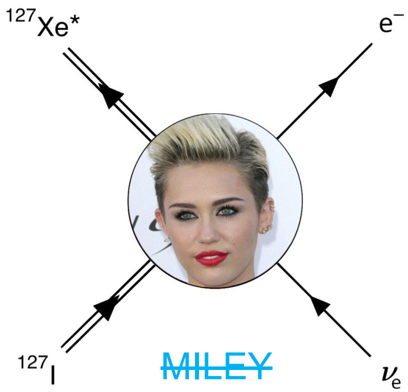
Coherent elastic neutrino scattering on the $^{40}$Ar nucleus is computed with coupled-cluster theory based on nuclear Hamiltonians inspired by effective field theories of quantum chromodynamics. Our approach is validated by calculating the charge form factor and comparing it to data from electron scattering. We make predictions for the weak form factor, the neutron radius, and the neutron skin, and estimate systematic uncertainties. The neutron-skin thickness of $^{40}$Ar is consistent with results from density functional theory. Precision measurements from coherent elastic neutrino-nucleus scattering could potentially be used to extract these observables and help to constrain nuclear models.



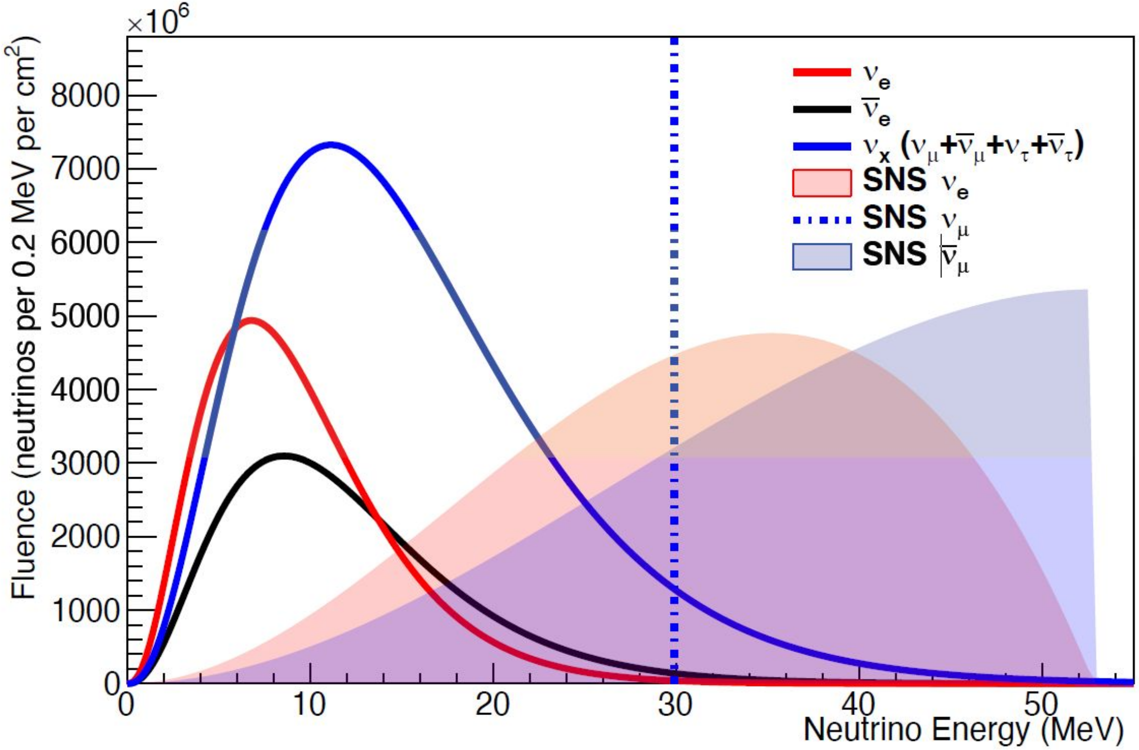
# Low energy event generators

- Higher energy neutrino efforts (Genie, NEUT, NuWro, GiBUU, …)
- Low energy generators often motivated by SN, nucleus-specific (sntools, SKSNSim, newton, *JUNO generator?* …)
- Model of Argon Reaction Low Energy Yields (MARLEY) adding more nuclei, benchmarking with new data…



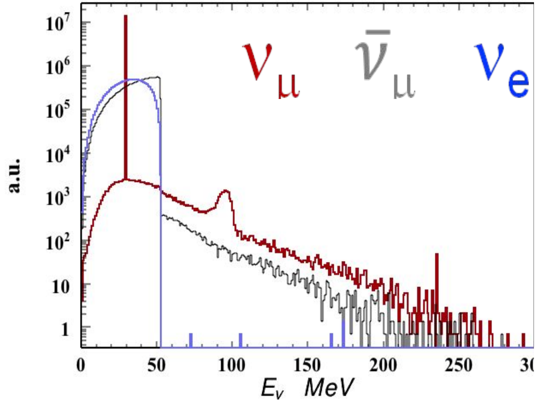



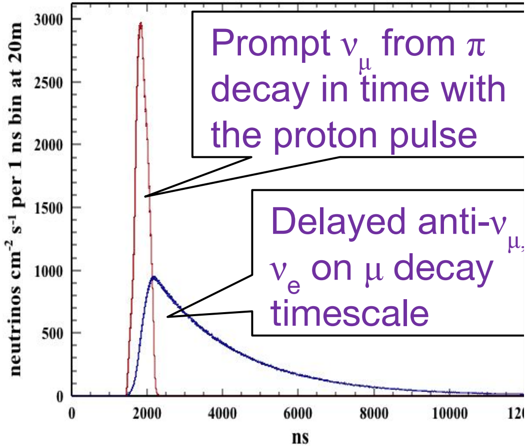

# Supernova neutrinos

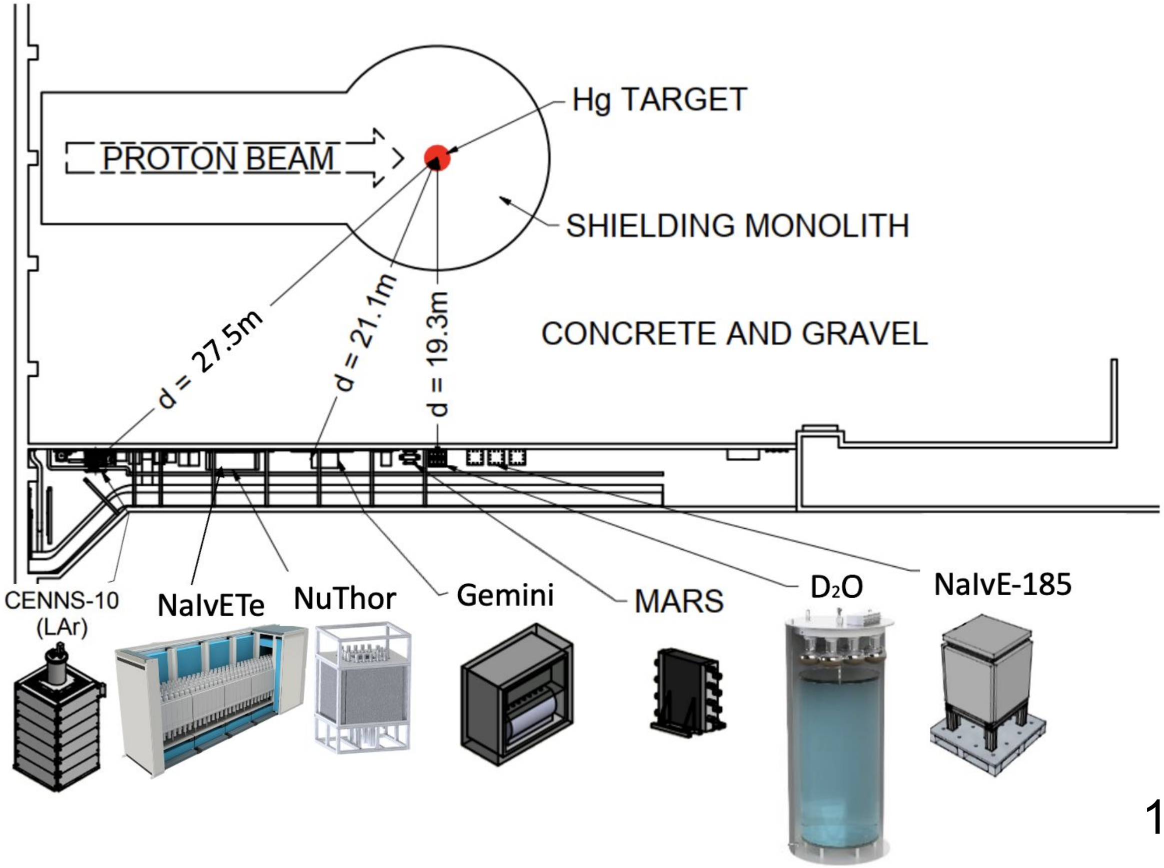



[image by K. Scholberg]

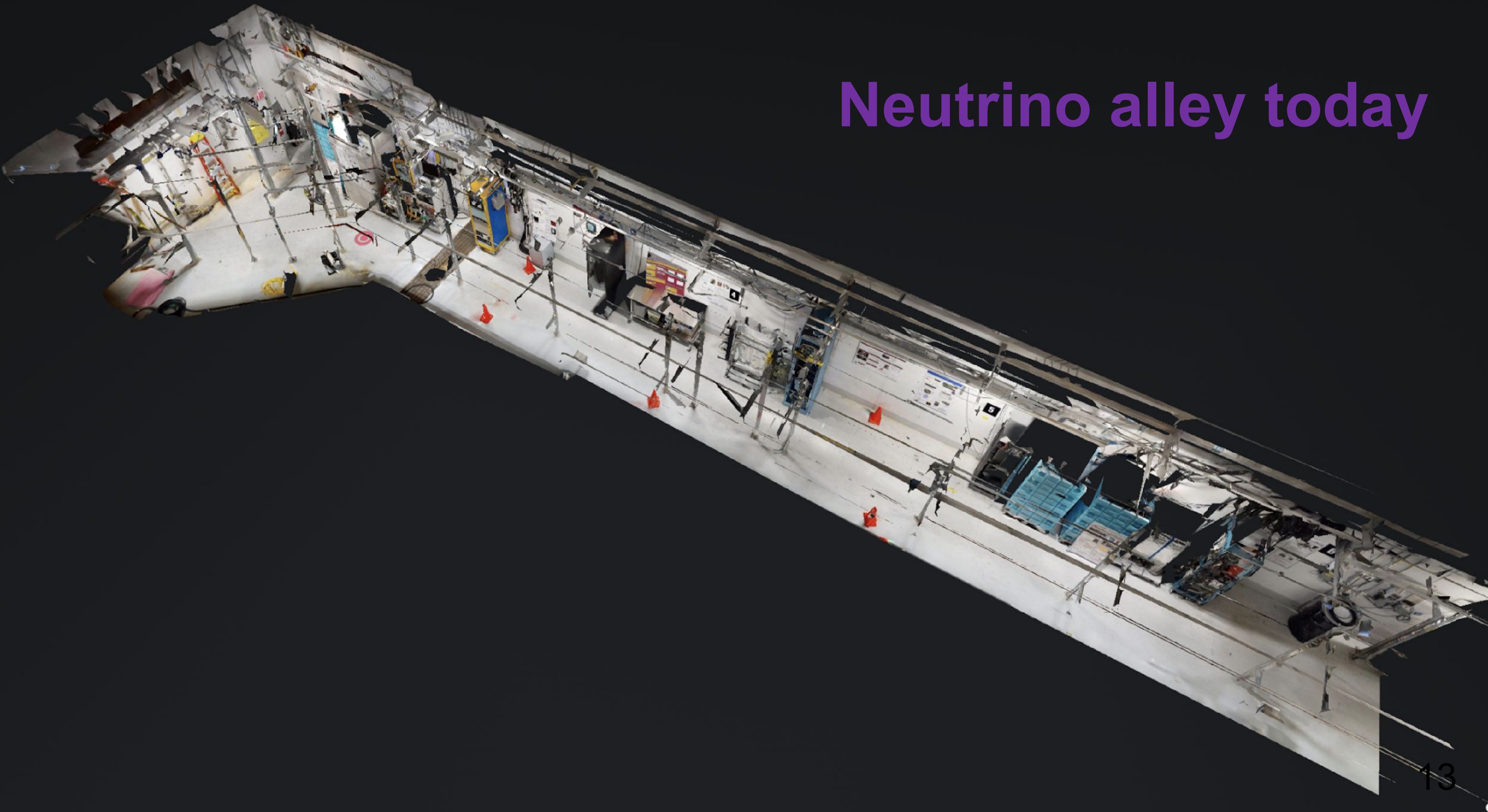
# COHERENT @ ORNL SNS



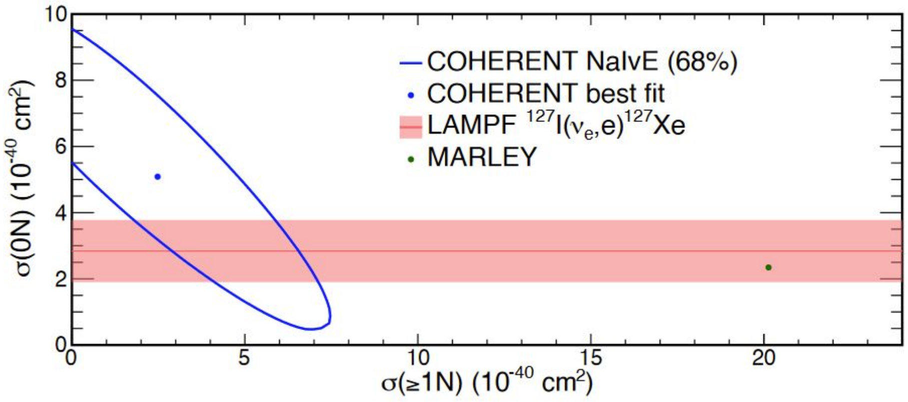
# Neutrino alley today



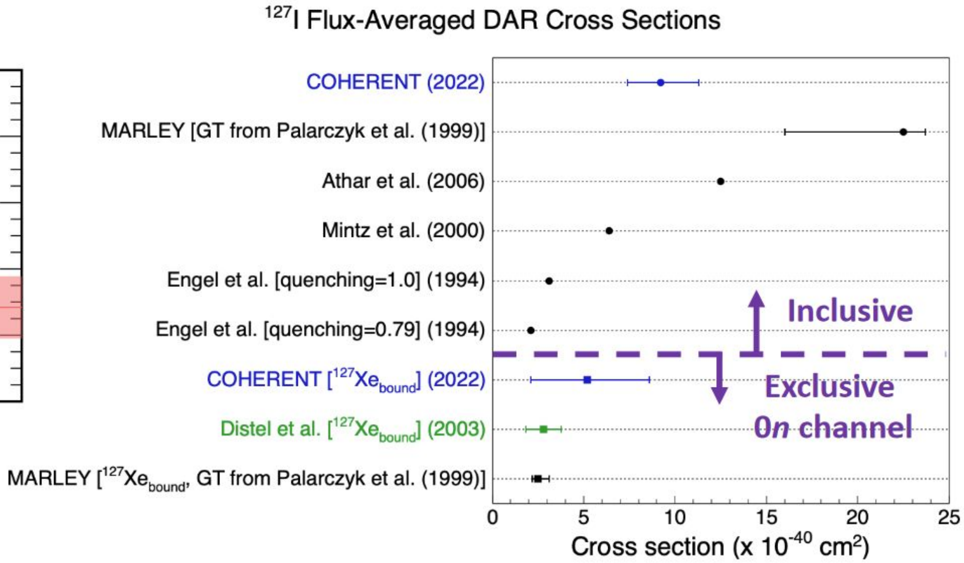
# NaIvE-185

- 7.7kg NaI[Tl] detectors
- 185 kg total mass
- CC interactions on Na, I

# NaIvE-185



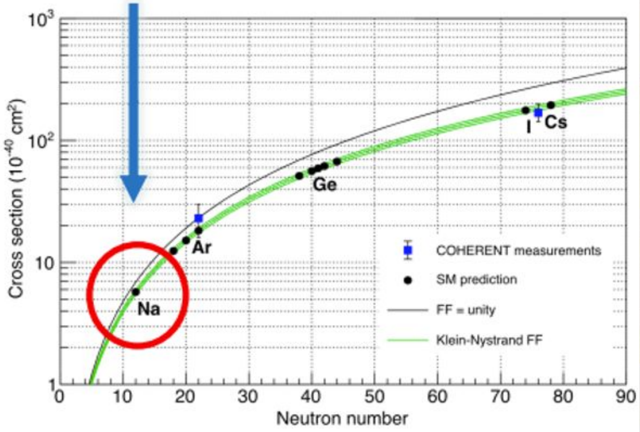
COHERENT NaIvE (68%)
COHERENT best fit
LAMPF $^{127}I(\nu_e,e)^{127}Xe$
MARLEY
$\sigma(0N)$ ($10^{-40}$ cm$^2$)
$\sigma(\geq 1N)$ ($10^{-40}$ cm$^2$)

$^{127}$I Flux-Averaged DAR Cross Sections
COHERENT (2022)
MARLEY [GT from Palarczyk et al. (1999)]
Athar et al. (2006)
Mintz et al. (2000)
Engel et al. [quenching=1.0] (1994)
Engel et al. [quenching=0.79] (1994)
COHERENT [$^{127}Xe_{bound}$] (2022)
Distel et al. [$^{127}Xe_{bound}$] (2003)
MARLEY [$^{127}Xe_{bound}$, GT from Palarczyk et al. (1999)]
Inclusive
Exclusive
0*n* channel
Cross section (x $10^{-40}$ cm$^2$)

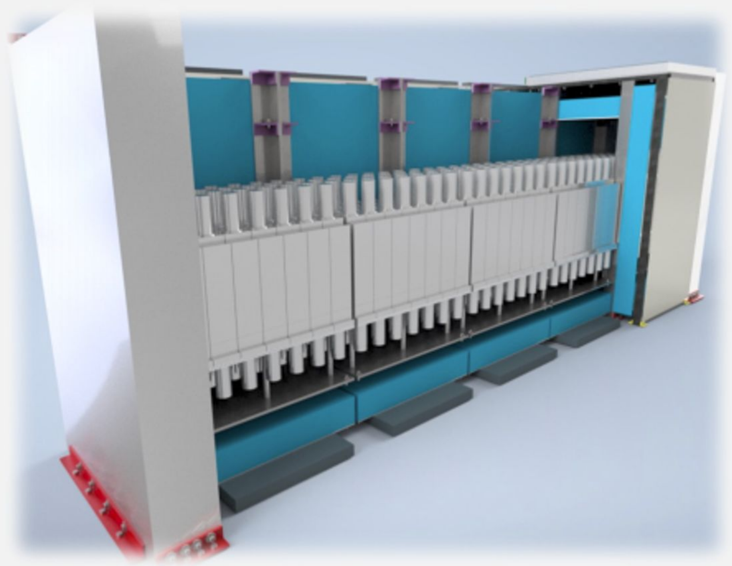
# NaIvETe $^{127}I(\nu_e,e^-)^{127}Xe$

- 7.7kg NaI[Tl] detectors
- 63 crystals per module
- 2.4 tons being deployed
- CEvNS on Na
- CC interactions on Na, I

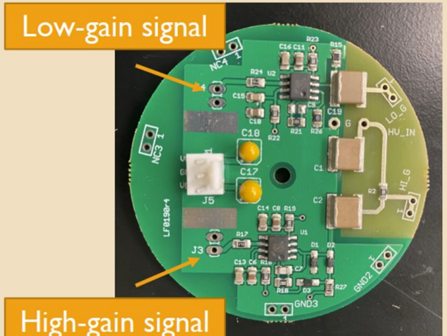




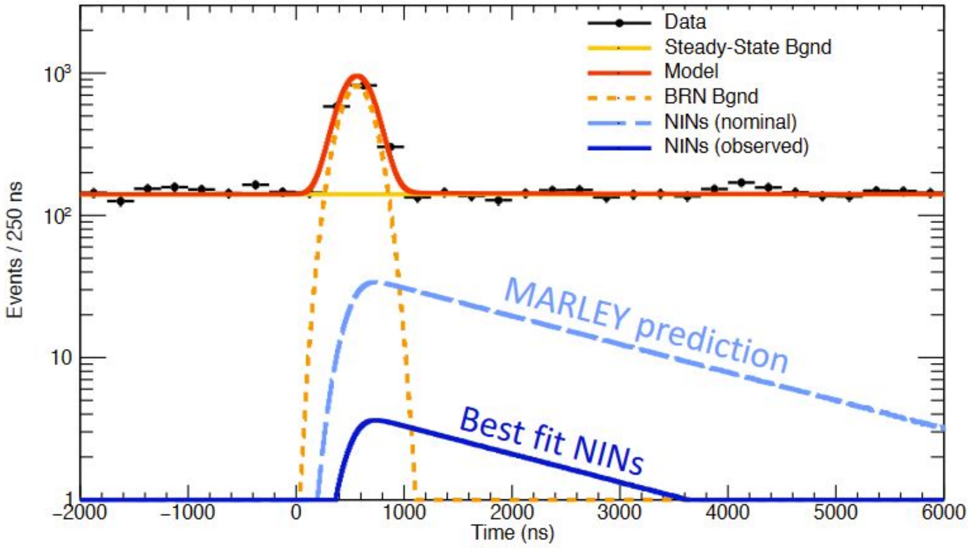
One module test assembly at Duke

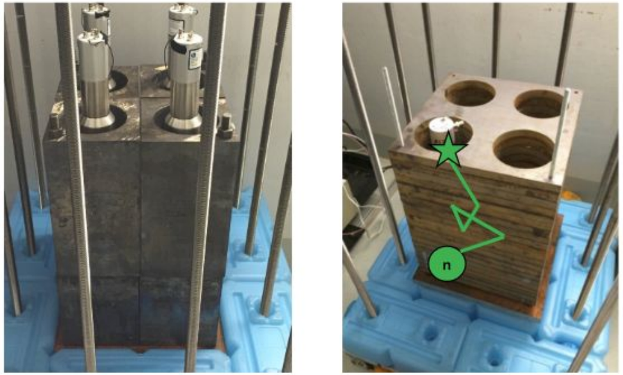


**Dual-gain base design** → low-energy CEvNS and high-energy CC signals can be read out from *same* crystal



# Neutrino induced neutrons

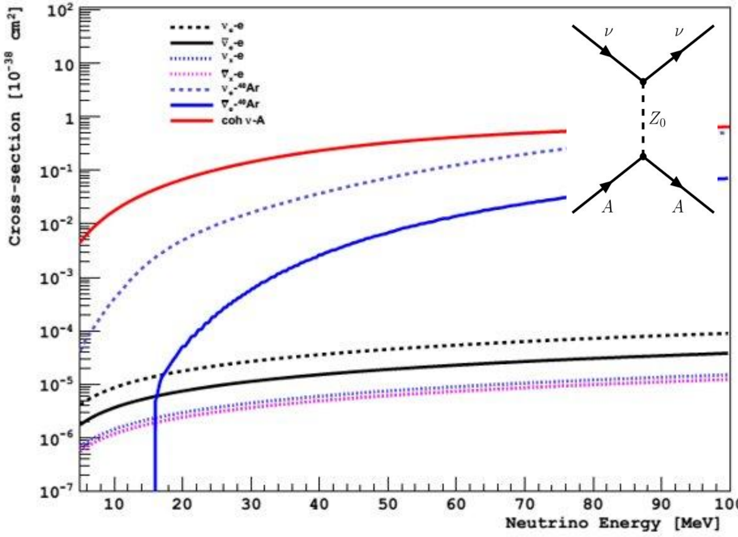



# CEvNS

# Coherent Elastic Neutrino-Nucleus Scattering

$$\lambda = \frac{\hbar}{p} = \frac{1200\ \mathrm{MeV\ fm}}{50\ \mathrm{MeV}} \sim 25\ \mathrm{fm}$$




$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} G_V^2 \left[1 + \left(1 - \frac{T}{E_\nu}\right)^2 - \frac{MT}{E_\nu^2}\right]$$

$$G_V = (g_V^p Z + g_V^n N) F_{\mathrm{nucl}}^V (Q^2)$$

small proton weak charge

$\sigma \sim N^2$

~few-% uncertainty

# CEvNS cross section ingredients

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} G_V^2 \left[1 + \left(1 - \frac{T}{E_\nu}\right)^2 - \frac{MT}{E_\nu^2}\right]$$

$$G_V = (g_V^p Z + g_V^n N) F_{\rm nucl}^V(Q^2)$$

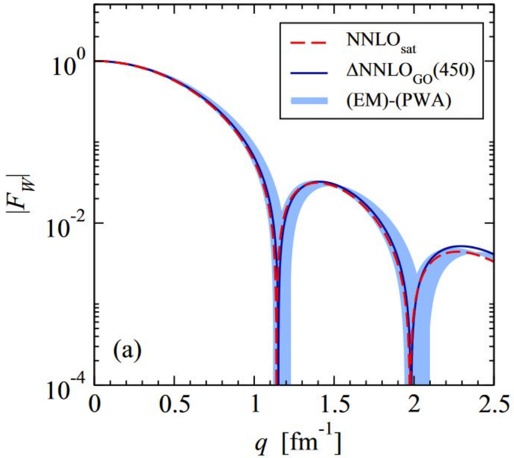
Neutrino-nucleus coherent scattering as a probe of neutron density distributions

Kelly Patton, Jonathan Engel, Gail C. McLaughlin, and Nicolas Schunck
Phys. Rev. C **86**, 024612 – Published 30 August 2012

**Nuclear Structure Physics in Coherent Elastic Neutrino-Nucleus Scattering**

N. Van Dessel,[1] V. Pandey,[2,*] H. Ray,[2] and N. Jachowicz[1,†]

[1] *Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium*
[2] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*




C. G. PAYNE *et al.* PHYSICAL REVIEW C **100**, 061304(R) (2019)

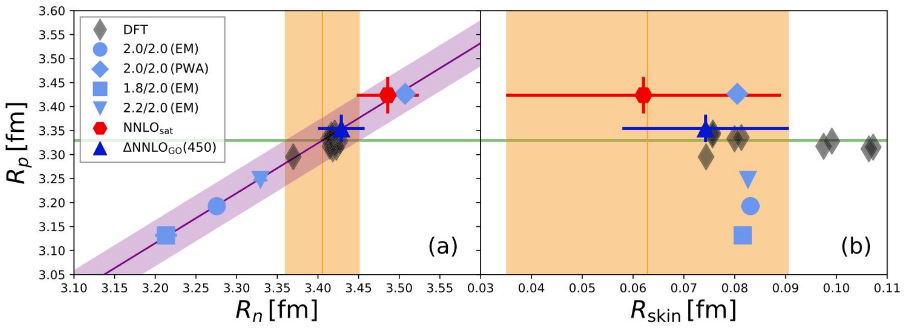
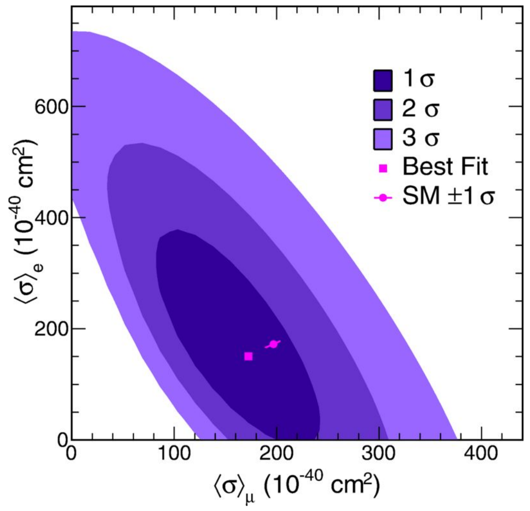
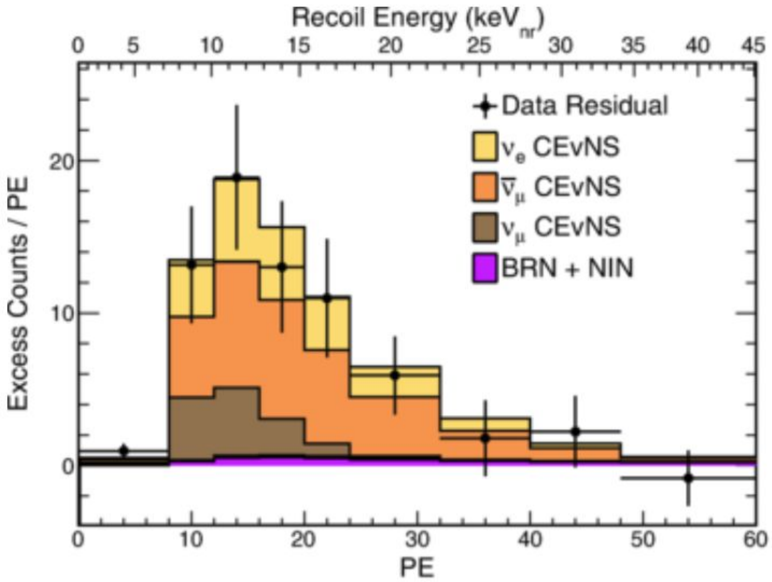


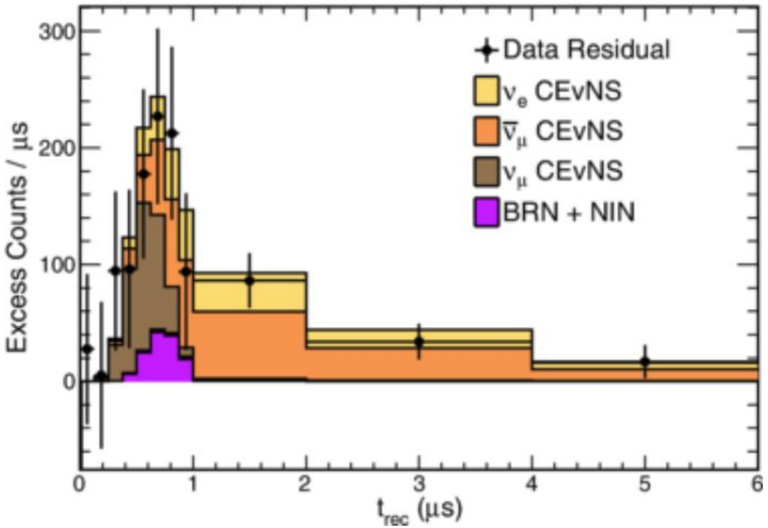

FIG. 3. Correlation (a) between $R_p$ and $R_n$ and (b) between $R_p$ and $R_{\rm skin}$ for various Hamiltonians. The experimental $R_p$ is also shown by the horizontal green line [48] as well as the DFT data [49] by the diamonds.

# CEvNS around the globe

# Separating neutrino flavors



# Neutrino flux

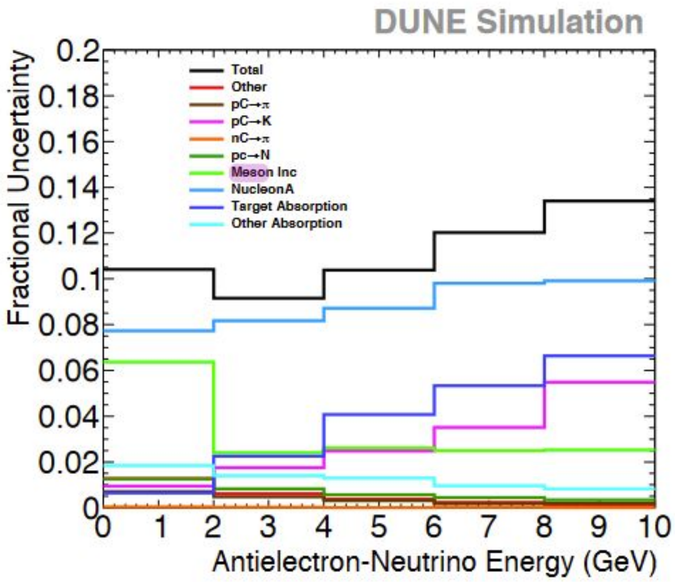
# Flux improvements

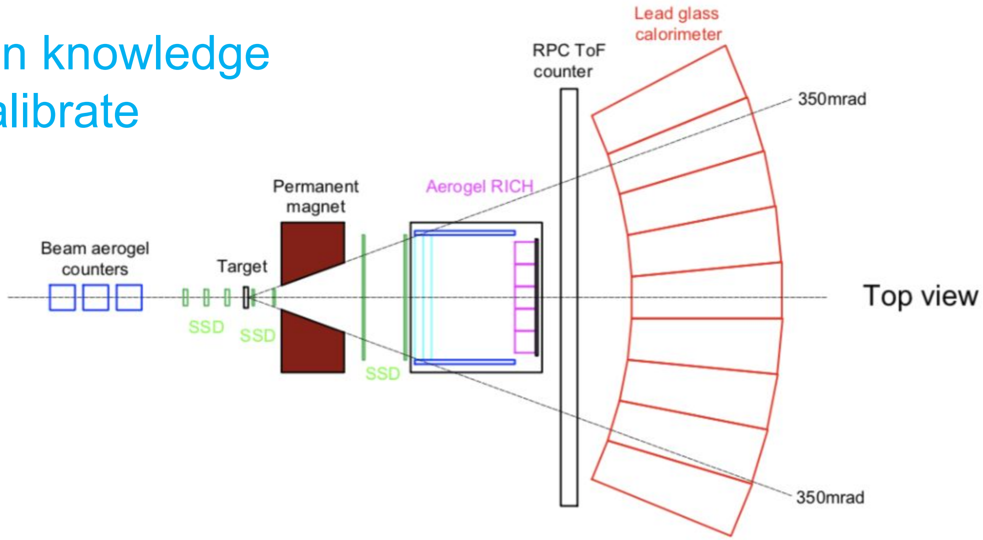
Session L12: Minisymposium: Low Energy Neutrinos V: Neutrino Mass & Reactor Neutrinos
9:00 AM–11:30 AM, Friday, December 1, 2023
Hilton Waikoloa Village Room: Kona 5

Chair: Alan Poon, Lawrence Berkeley National Laboratory

**Abstract: L12.00009 : Progress towards understanding the source of the Reactor Antineutrino Anomaly***
11:15 AM–11:30 AM

- reactor neutrino anomaly
- improve modeling, hadron production knowledge
- use theoretically clean channel to calibrate



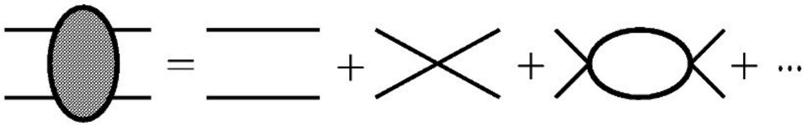

Measurement of proton-carbon forward scattering in a proof-of-principle test of the EMPHATIC spectrometer

M. Pavin *et al.* (EMPHATIC Collaboration)
Phys. Rev. D **106**, 112008 – Published 23 December 2022

# $\nu$-d scattering for flux calibration

$d(\nu_e, e^-)pp$

- Use *precisely predicted cross section* to determine neutrino flux
- Systematic treatment of neutrino-deuteron cross-section
- Leveraged for Sudbury Neutrino Observatory
- Modern pionless-EFT and chiral-PT calculations



$$\sigma\left(\nu(\bar{\nu})d \rightarrow \nu(\bar{\nu})np\right) = 0.999 \pm 0.026 + 0.013 L_{1,A} + 10^{-5}\Delta s(\pm 0.5 \pm 1.2\mu_s + 6.3\Delta s - 4.6 L_{2,A})$$

Weak interaction processes on deuterium: Muon capture and neutrino reactions

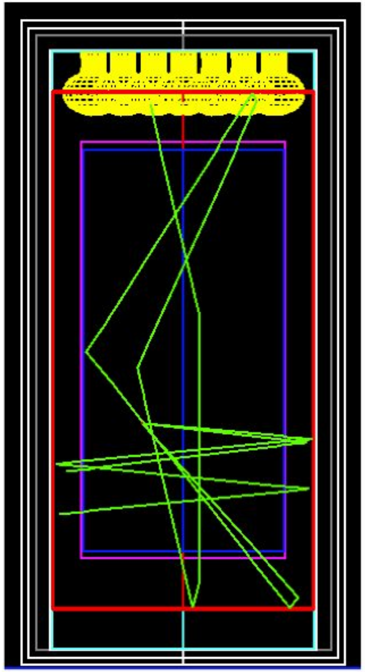
Naoko Tatara, Y. Kohyama, and K. Kubodera
Phys. Rev. C **42**, 1694 – Published 1 October 1990

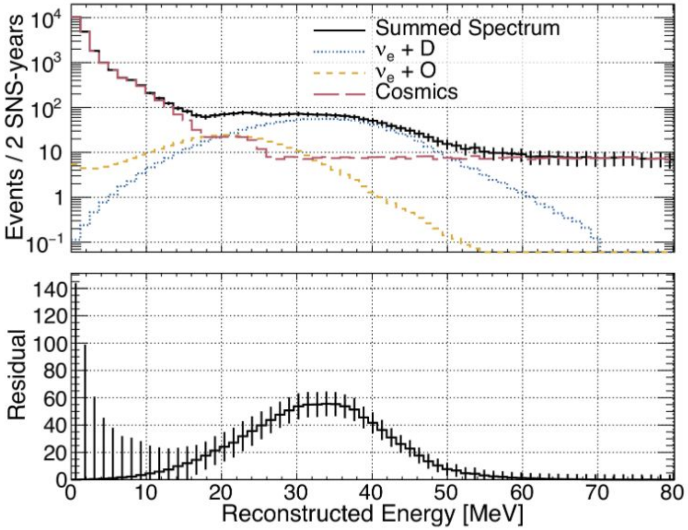
Elastic and inelastic neutrino–deuteron scattering in effective field theory

Malcolm Butler[a,1], Jiunn-Wei Chen[b,2]

# COHERENT $D_2O$ detector

- two 670-kg modules
- Can achieve ~few-% sensitivity after 3 years
- $D_2O$ available
- First module deployed, first light with $H_2O$







Journal of Instrumentation

PAPER

A $D_2O$ detector for flux normalization of a pion decay-at-rest neutrino source

COHERENT collaboration, D. Akimov[1], P. An[2,3], C. Awe[2,3], P.S. Barbeau[2,3], B. Becker[4], V. Belov[5,1], I. Bernardi[4], M.A. Blackston[6], A. Bolozdynya[1] + Show full author list

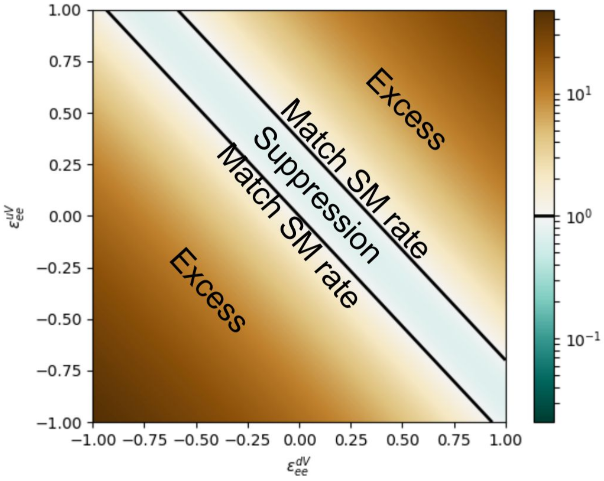
Published 16 August 2021 • © 2021 IOP Publishing Ltd and Sissa Medialab

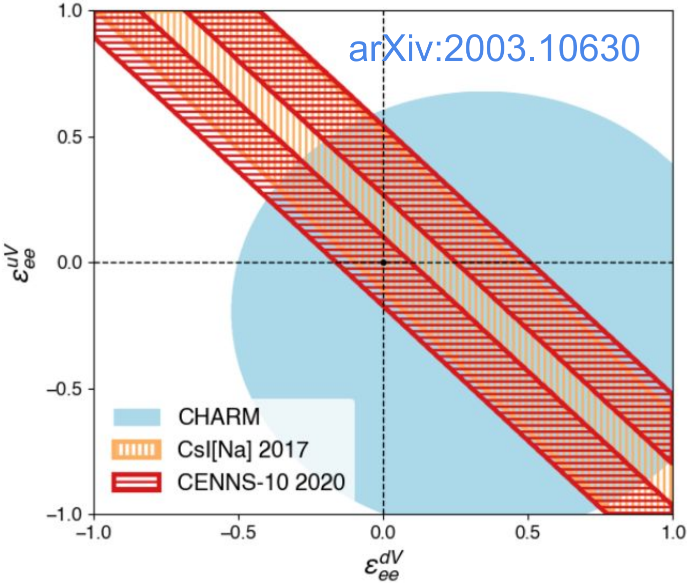
# New physics

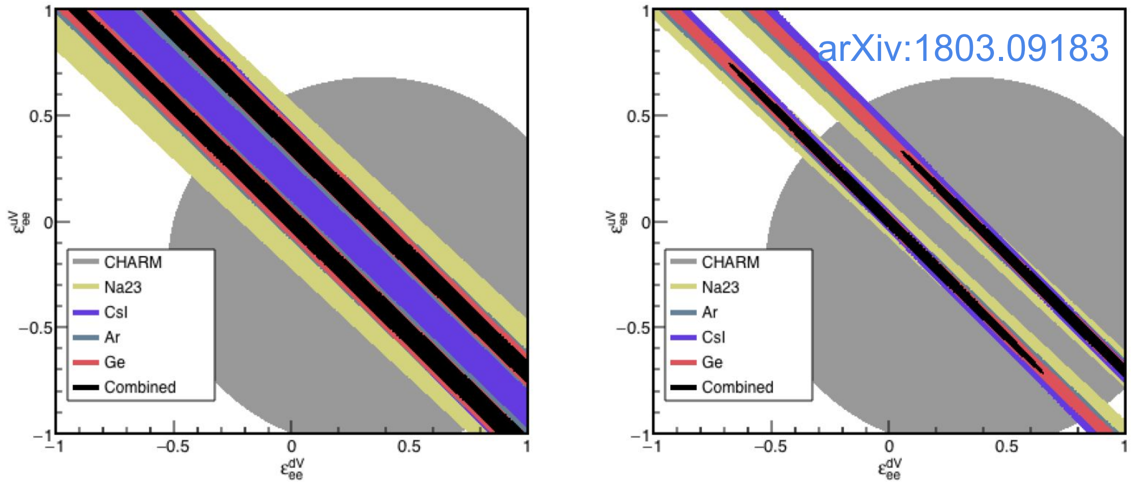
# Non-standard interactions

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$Q_W^2 \to Q_{\rm NSI}^2 = 4\left[N\left(-\frac{1}{2} + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}\right) + Z\left(\frac{1}{2} - 2\sin^2\theta_W + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}\right)\right]^2 + 4\left[N(\epsilon_{e\tau}^{uV} + 2\epsilon_{e\tau}^{dV}) + Z(2\epsilon_{e\tau}^{uV} + \epsilon_{e\tau}^{dV})\right]^2 .$$

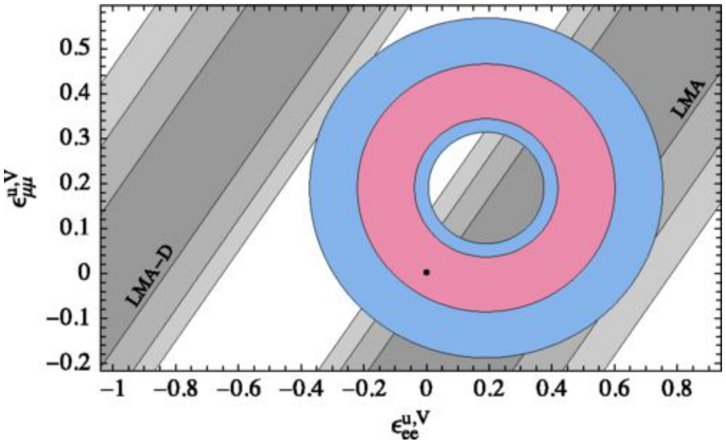


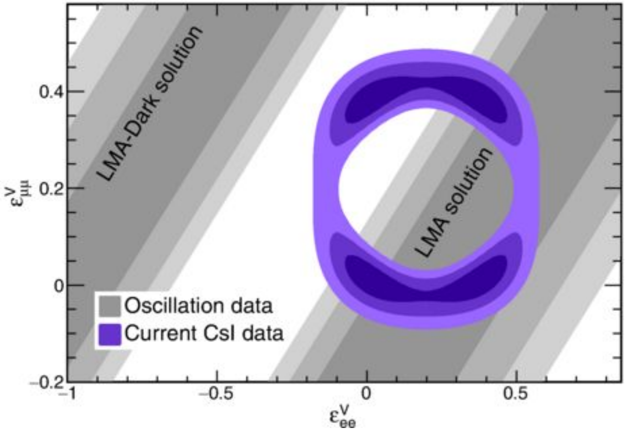




See also: O.G. Miranda, *et al.* arXiv:2003.12050v3 (2020)

# LMA-Dark solution




*CEvNS compliments oscillation data to break LMA-D degeneracy*




*Constraints from CsI result*

PHYSICAL REVIEW D **96**, 115007 (2017)

**COHERENT enlightenment of the neutrino dark side**

Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,[2,3,4,†] Michele Maltoni,[5,‡] and Thomas Schwetz[6,§]

# Scalar and tensor currents

$$\frac{d\sigma_a^\beta}{dE_r} = \frac{G_F^2}{4\pi} M_a N_a^2 [(\xi_S^\beta)^2 \frac{E_r}{E_{r,\max}} + (\xi_V^\beta)^2 (1 - \frac{E_r}{E_{r,\max}} - \frac{E_r}{E_\nu}) + (\xi_T^\beta)^2 (1 - \frac{E_r}{2E_{r,\max}} - \frac{E_r}{E_\nu})] F^2(q^2)$$

**Scalar and tensor neutrino interactions**

arXiv:2004.13869 [hep-ph] (2020)

**Tao Han,[a] Jiajun Liao,[b] Hongkai Liu,[a] Danny Marfatia[c]**

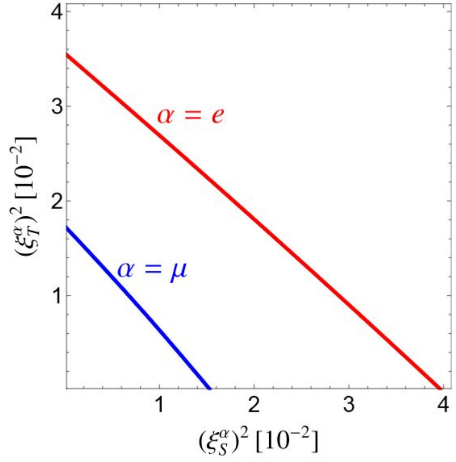



**Figure 4**: Projected 90% C.L. upper bounds from the future COHERENT experiment with a 610 kg fiducial mass of LAr.

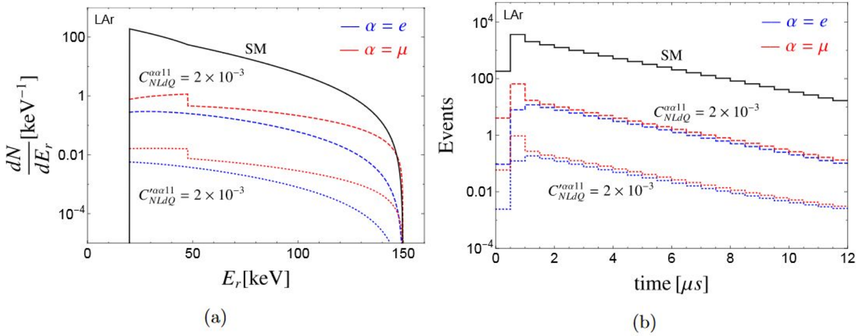
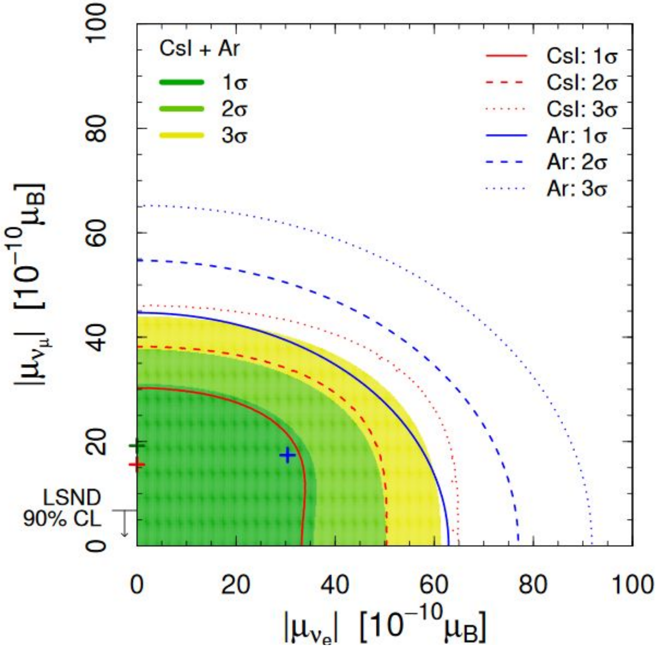



**Figure 3**: The recoil energy (left) and temporal (right) distributions in a future COHERENT LAr detector. Threshold effects are included. The black solid lines are the SM case including all flavors. The blue (red) curves correspond to the electron (muon+antimuon) flavor contributions. The dashed (dotted) curves correspond to the contributions from the scalar (tensor) interactions with $C_{NLdQ}$ ($C'_{NLdQ}$) $= 2 \times 10^{-3}$.

# $\nu$ magnetic moment

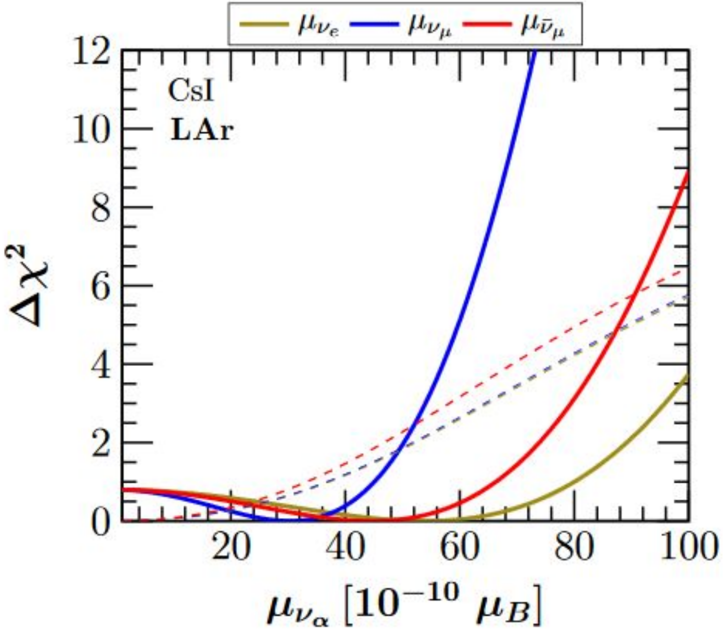
Physics results from the first COHERENT observation of CE$\nu$NS in argon and their combination with cesium-iodide data

M. Cadeddu,[1,*] F. Dordei,[1,†] C. Giunti,[2,‡] Y.F. Li,[3,4,§] E. Picciau,[5,6,¶] and Y.Y. Zhang[3,4,**]




Implications of the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) with Liquid Argon

O. G. Miranda,[1,*] D. K. Papoulias,[2,†] G. Sanchez Garcia,[1,‡] O. Sanders,[1,§] M. Tórtola,[3,¶] and J. W. F. Valle[3,**]




$$\frac{d\sigma^{ij}_{\nu\mathrm{MM}}}{dt} = \frac{e^2}{8\pi\lambda}\left|\frac{\mu_{ij}}{\mu_B}\right|^2 Z^2 F_Z^2(q^2)\left[\frac{1}{t}\left(2\lambda + 4M^2 m_i^2 + 2A\Delta + 2M^2\Delta + \Delta^2\right) + (2A+\Delta) + \frac{2M^2\Delta^2}{t^2}\right]$$

# Neutrino charge, charge radii

**Physics results from the first COHERENT observation of CE$\nu$NS in argon and their combination with cesium-iodide data**

M. Cadeddu,[1,*] F. Dordei,[1,†] C. Giunti,[2,‡] Y.F. Li,[3,4,§] E. Picciau,[5,6,¶] and Y.Y. Zhang[3,4,**]

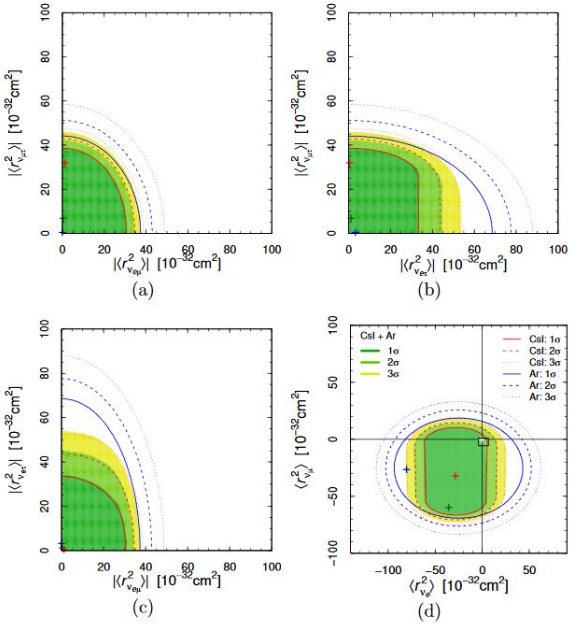



FIG. 5. Contours of the allowed regions in different planes of the neutrino charge radii parameter space obtained with fixed $R_n$ obtained from the analysis of COHERENT CsI data (red lines), from the analysis of COHERENT Ar data in this paper (blue lines), and from the combined fit (shaded green-yellow regions). The crosses with the corresponding colors indicate the best fit points. The white cross near the origin in panel (d) indicates the Standard Model values in Eqs. (40) and (41). The black rectangle near the origin shows the 90% bounds on $\langle r^2_{\nu_e} \rangle$ and $\langle r^2_{\nu_\mu} \rangle$ obtained, respectively in the TEXONO [65] and BNL-E734 [66] experiments.

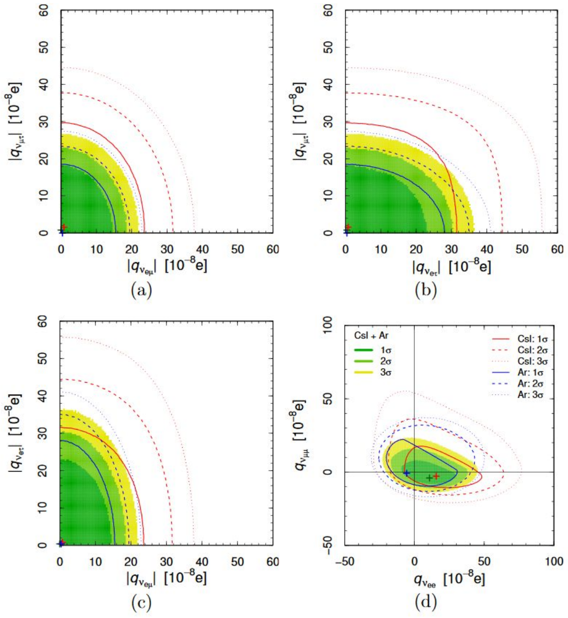



FIG. 8. Contours of the allowed regions in different planes of the neutrino electric charge parameter space obtained with fixed $R_n$ obtained from the analysis of COHERENT CsI data (red lines), from the analysis of COHERENT Ar data in this paper (blue lines), and from the combined fit (shaded green-yellow regions). The crosses with the corresponding colors indicate the best fit points.

# Light vector and scalar mediators

**Implications of the first detection of coherent elastic neutrino-nucleus scattering (CEvNS) with Liquid Argon**

O. G. Miranda,[1,*] D. K. Papoulias,[2,†] G. Sanchez Garcia,[1,‡]
O. Sanders,[1,§] M. Tórtola,[3,¶] and J. W. F. Valle[3,**]

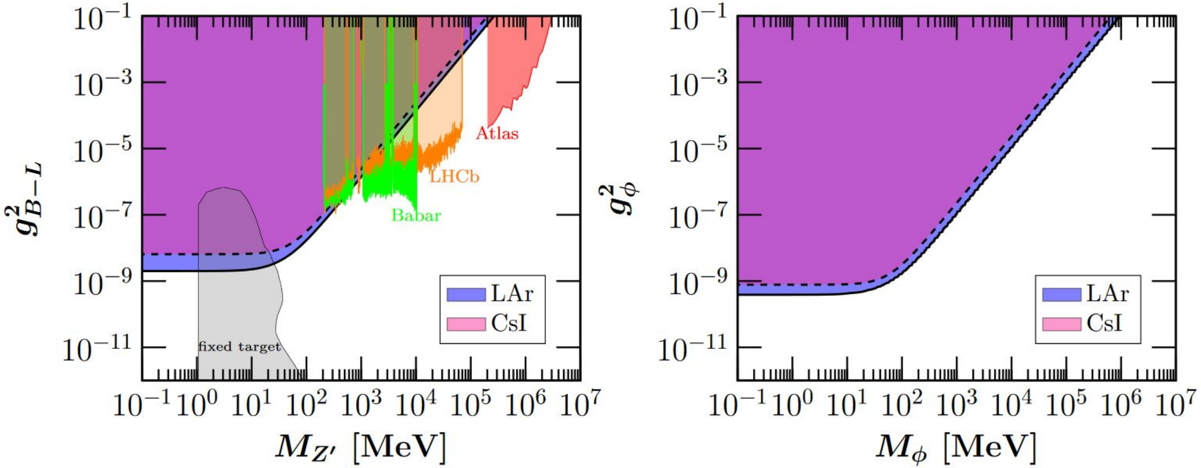
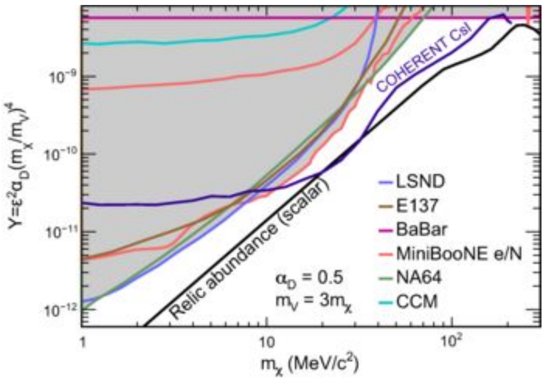
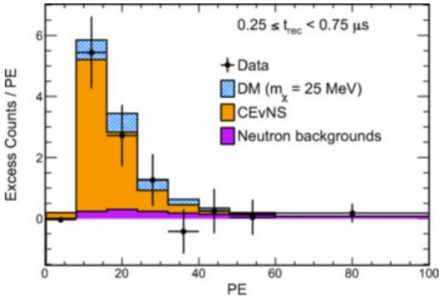


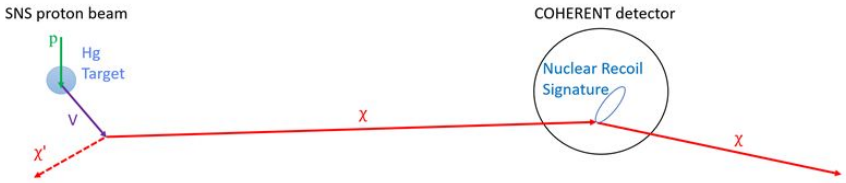

FIG. 7: Excluded region at 90% C.L in the parameter space $(M_{Z'}, g^2_{B-L})$ for the vector mediator scenario (left) and $(M_\Phi, g^2_\Phi)$ for the scalar mediator scenario (right), from the analysis of the recent LAr data. In both cases, a comparison is given with the CsI data.

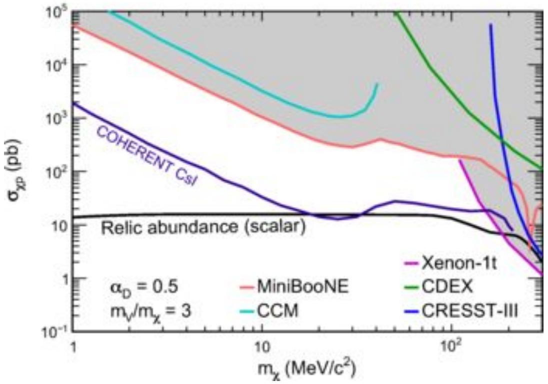
# Accelerator-produced DM

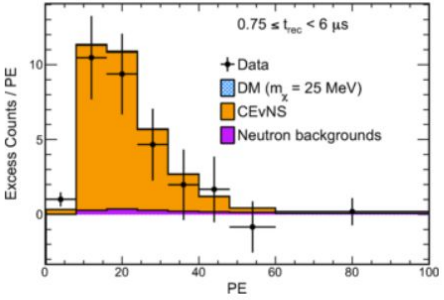
- Vector-portal dark matter from neutral mesons in target
- Prompt
- Recoil spectrum depends upon mediator mass
- Coherent nuclear enhancement




First Probe of Sub-GeV Dark Matter beyond the Cosmological Expectation with the COHERENT CsI Detector at the SNS

D. Akimov *et al.*
Phys. Rev. Lett. **130**, 051803 – Published 3 February 2023

Sensitivity of the COHERENT experiment to accelerator-produced dark matter

D. Akimov *et al.*
Phys. Rev. D **102**, 052007 – Published 29 September 2020

# Outlook

- Neutrino-nucleus cross section measurements (and improved flux assessments) facilitate an array of BSM searches, provide robust assessments of SN neutrino signals, and contribute to the rich interplay between nuclear physics and the physics of weak interactions
- CEvNS is a “clean” channel for a number of BSM searches and for vector-portal dark-matter searches
- Stopped pion sources provide a relatively well characterized source of neutrinos for cross section measurements
- High and ultra-high energy neutrino interaction measurements likewise benefit from both new experiments and refined theoretical evaluations