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Valentina De Romeri
(IFIC Valencia - UV/CSIC)

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

2nd EuCAPT Astroneutrino Theory Workshop
IEAP CTU in Prague
16-27 September 2024

A FEW USEFUL REFERENCES

- Papers/Reviews:
  - Coherent elastic neutrino-nucleus scattering: Terrestrial and astrophysical applications M. Abdullah et al.
  - A view of Coherent Elastic Neutrino-Nucleus Scattering, M. Cadeddu, F. Dordei, C. Giunti
  - Recent Probes of Standard and Non-standard Neutrino Physics With Nuclei, Papoulias, Kosmas, Kuno
  - Probing new physics with coherent neutrino scattering off nuclei, Barranco, Miranda, Rashba
  - Walecka and Donnelly https://doi.org/10.1016/0375-9474(76)90209-8

- Dark Matter Direct detection:
  - The Theory of Direct Dark Matter Detection
  - https://arxiv.org/pdf/1904.07915
  - https://arxiv.org/pdf/1002.1912

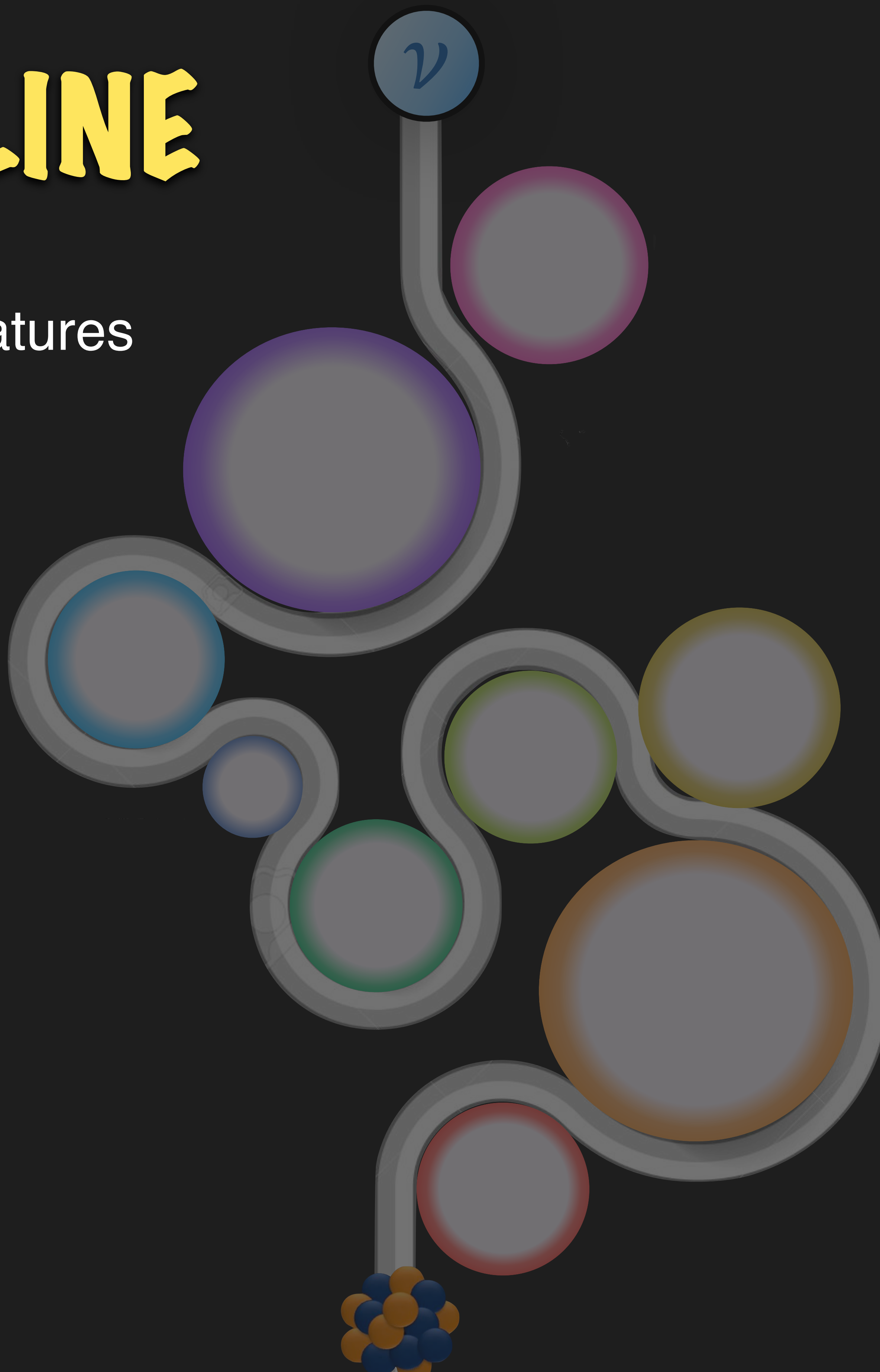
- Books:
  - Walecka Theoretical Nuclear and Subnuclear Physics, Oxford Stud.Nucl.Phys. 16 (1995) 1-610
  - Giunti & Kim: https://oxford.universitypressscholarship.com/view/10.1093/acprof:oso/9780198508717.001.0001/acprof-9780198508717

- Webpage:
  - http://www.nu.to.infn.it/Neutrino_Lectures

- Magnificent CEvNS workshop talks

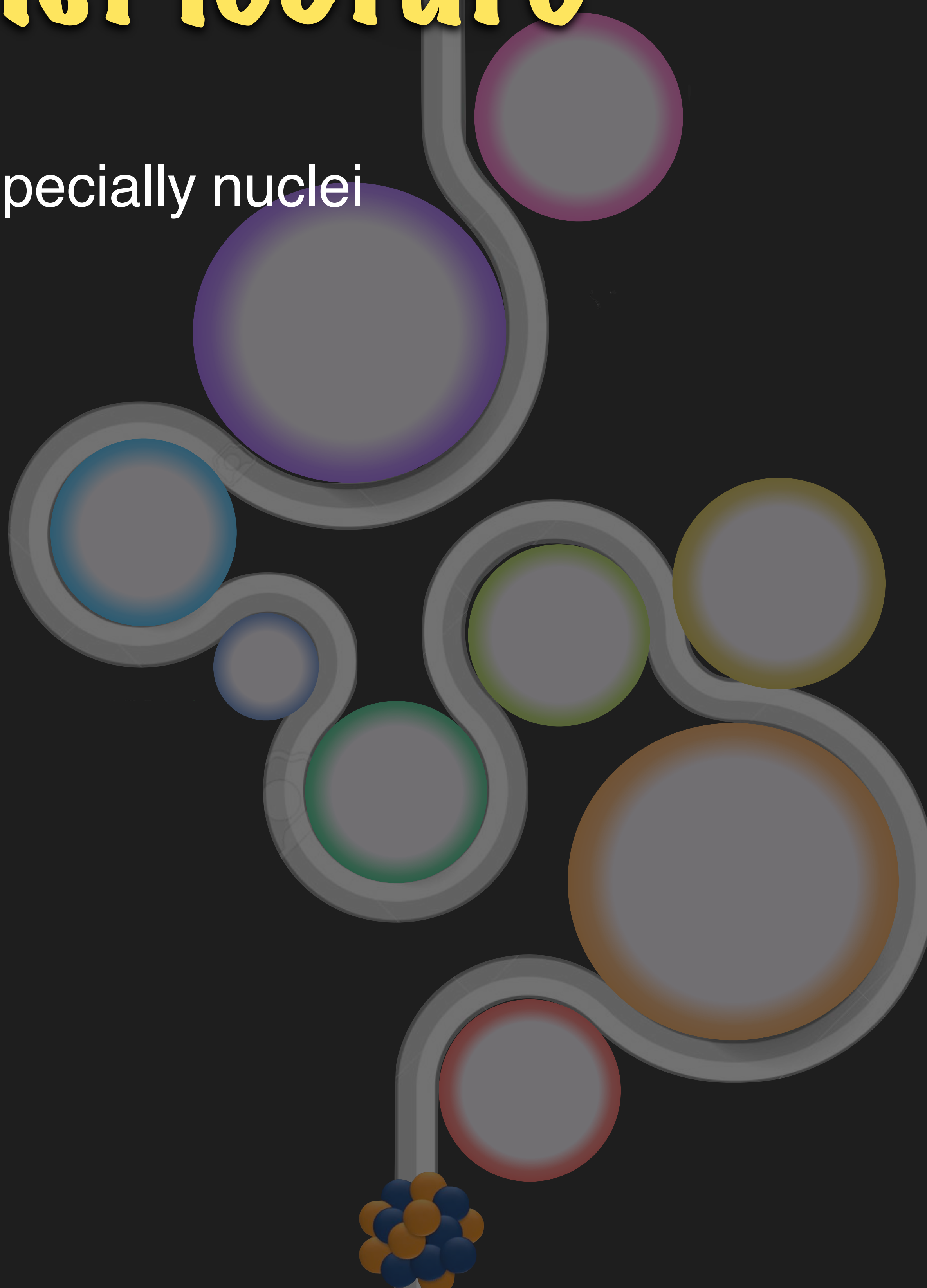
OUTLINE

1. Introduction to CEνNS and main features
2. CEνNS physics implications: SM
3. CEνNS physics implications: BSM



OUTLINE - 1st lecture

- Neutrino interactions with matter, especially nuclei
- CEvNS: introduction and features
- CEvNS: neutrino sources
- CEvNS: experiments and detection
- CEvNS: observations
- CEvNS cross section in the SM

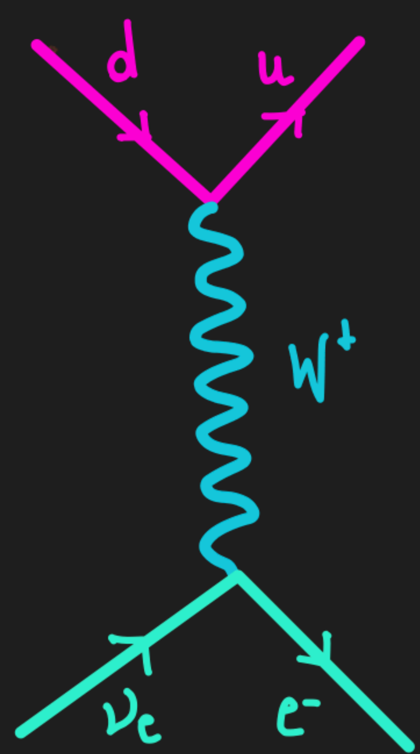


NEUTRINO INTERACTIONS WITH MATTER

Neutrinos are elusive particles but not completely unfriendly

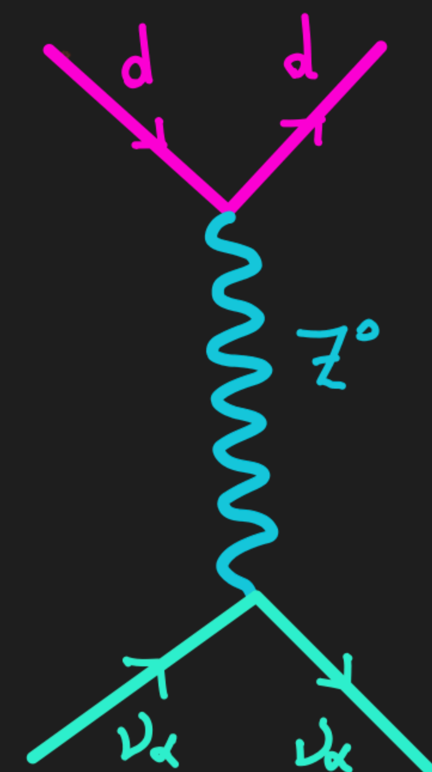
$$\mathcal{L}_{\rm SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L}\gamma^{\mu}\ell_{\alpha L}W_{\mu} - \frac{g}{2\cos\theta_{\rm W}} \sum_{\alpha=e,\mu,\tau} \bar{\nu}_{\alpha L}\gamma^{\mu}\ell_{\alpha L}Z_{\mu} + h.c.$$

Charged Current (CC)



Produces lepton with flavor corresponding to the neutrino flavor

Neutral Current (NC)

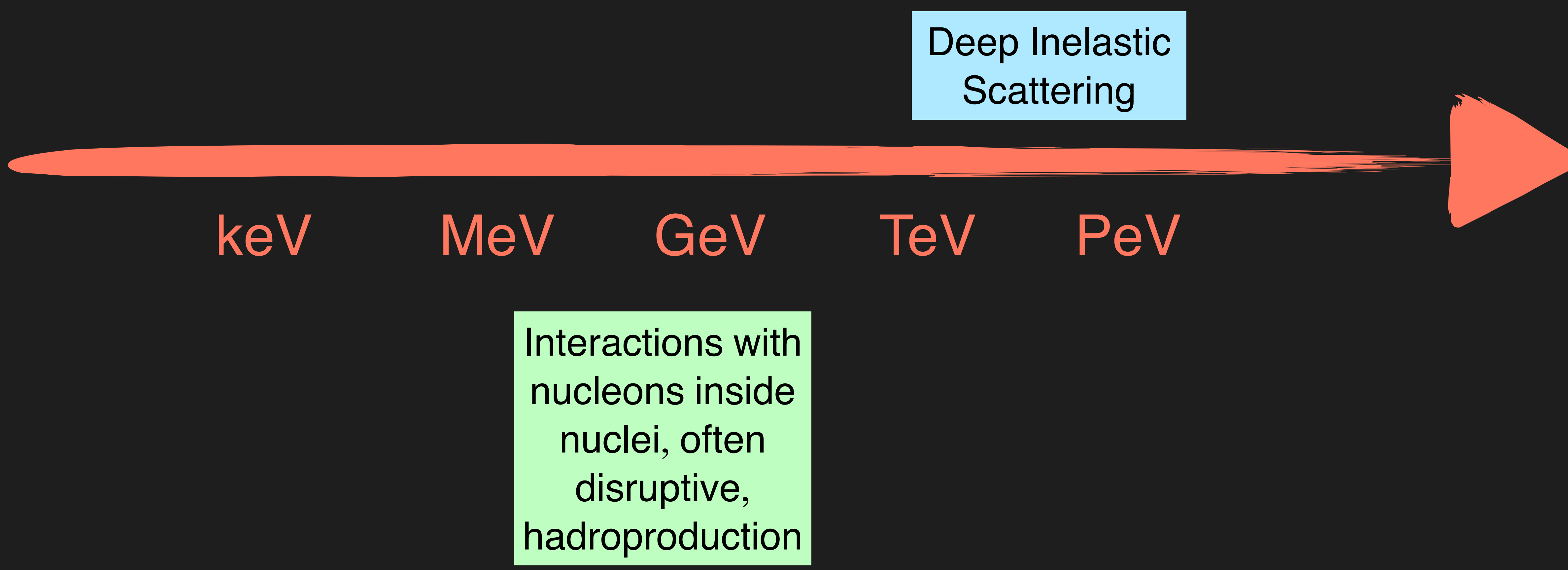


Flavor blind

NEUTRINO INTERACTIONS WITH NUCLEI

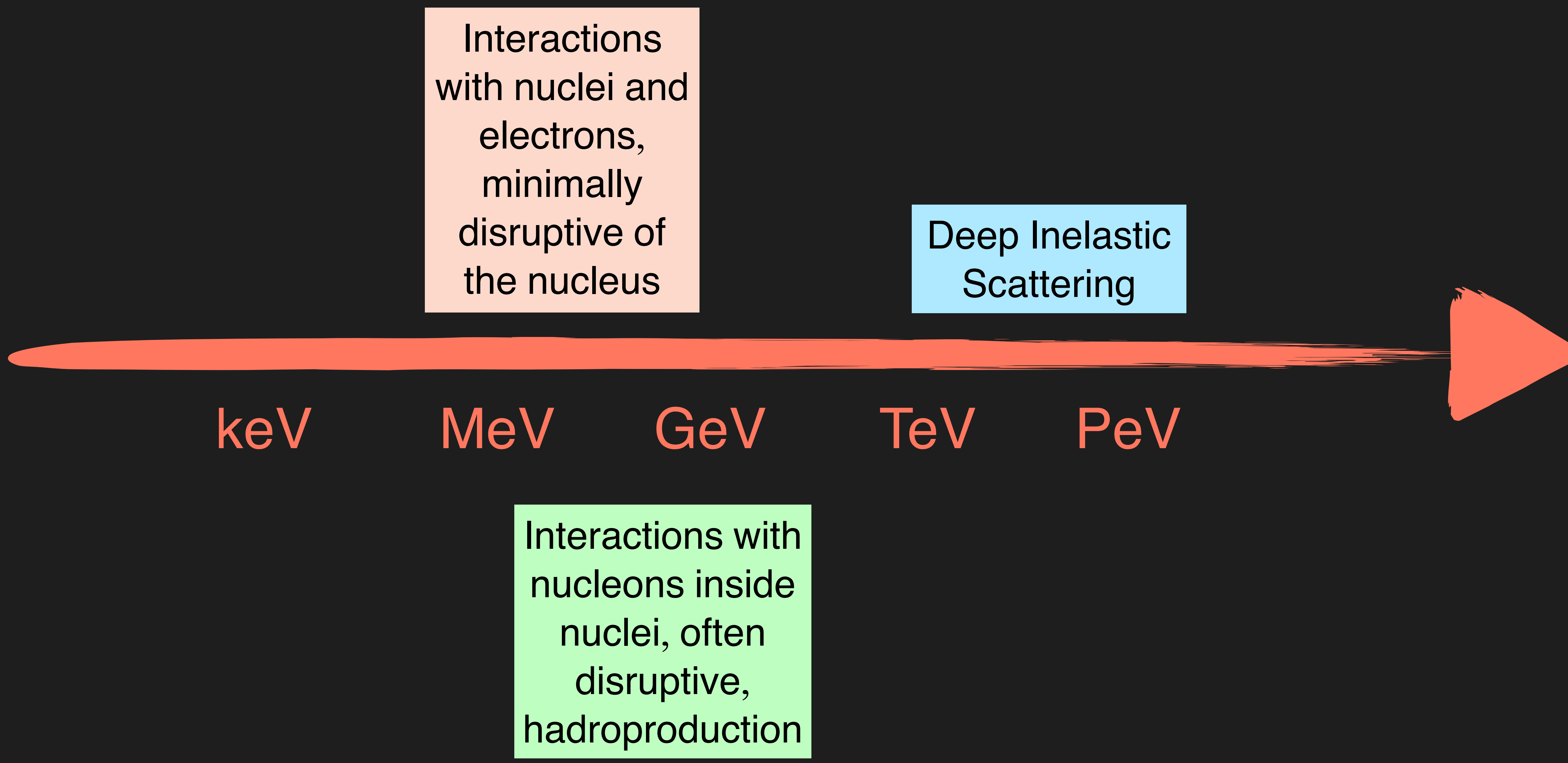
Adapted from Kate Scholberg

NEUTRINO INTERACTIONS WITH NUCLEI



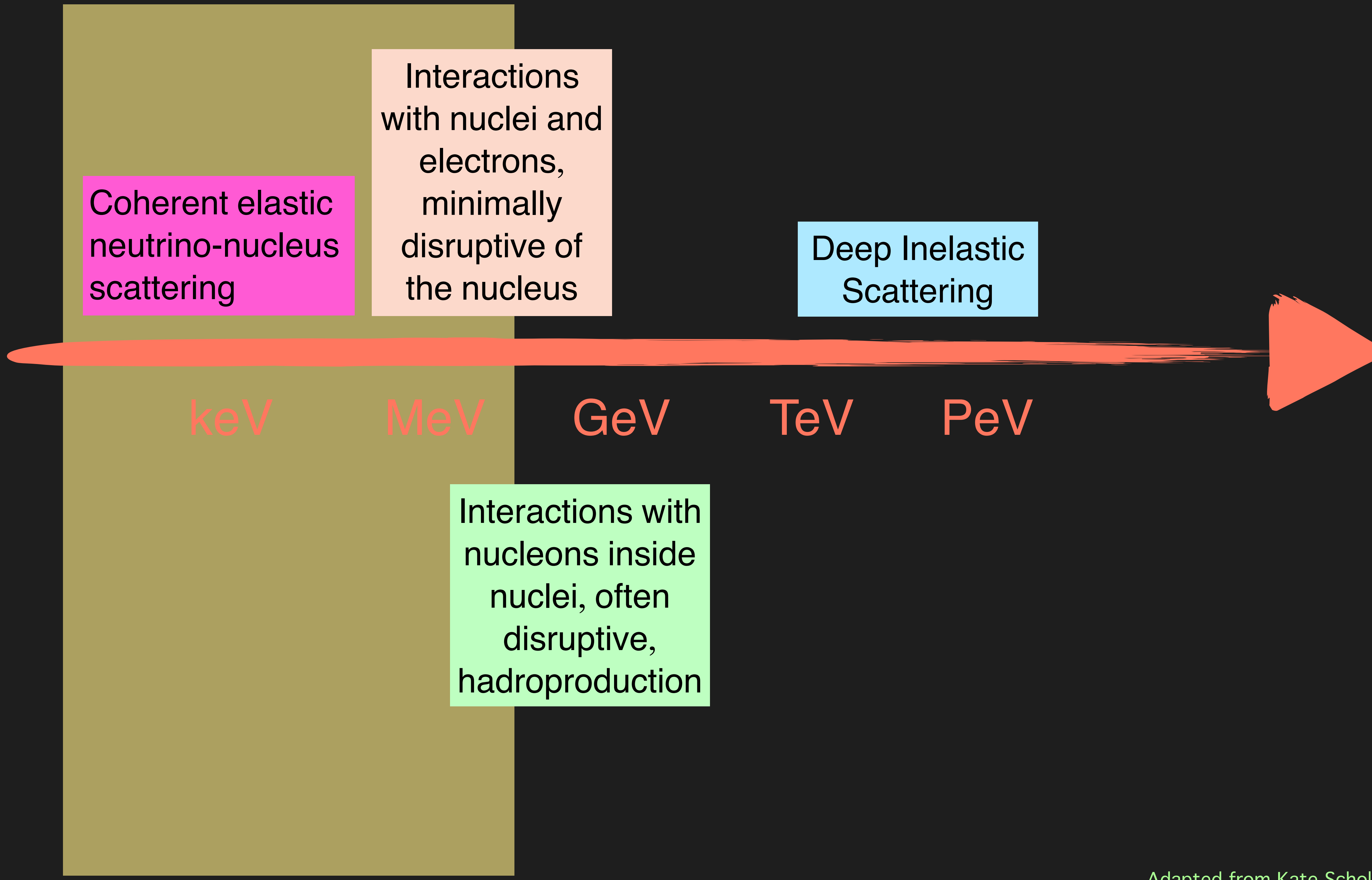
Adapted from Kate Scholberg

NEUTRINO INTERACTIONS WITH NUCLEI



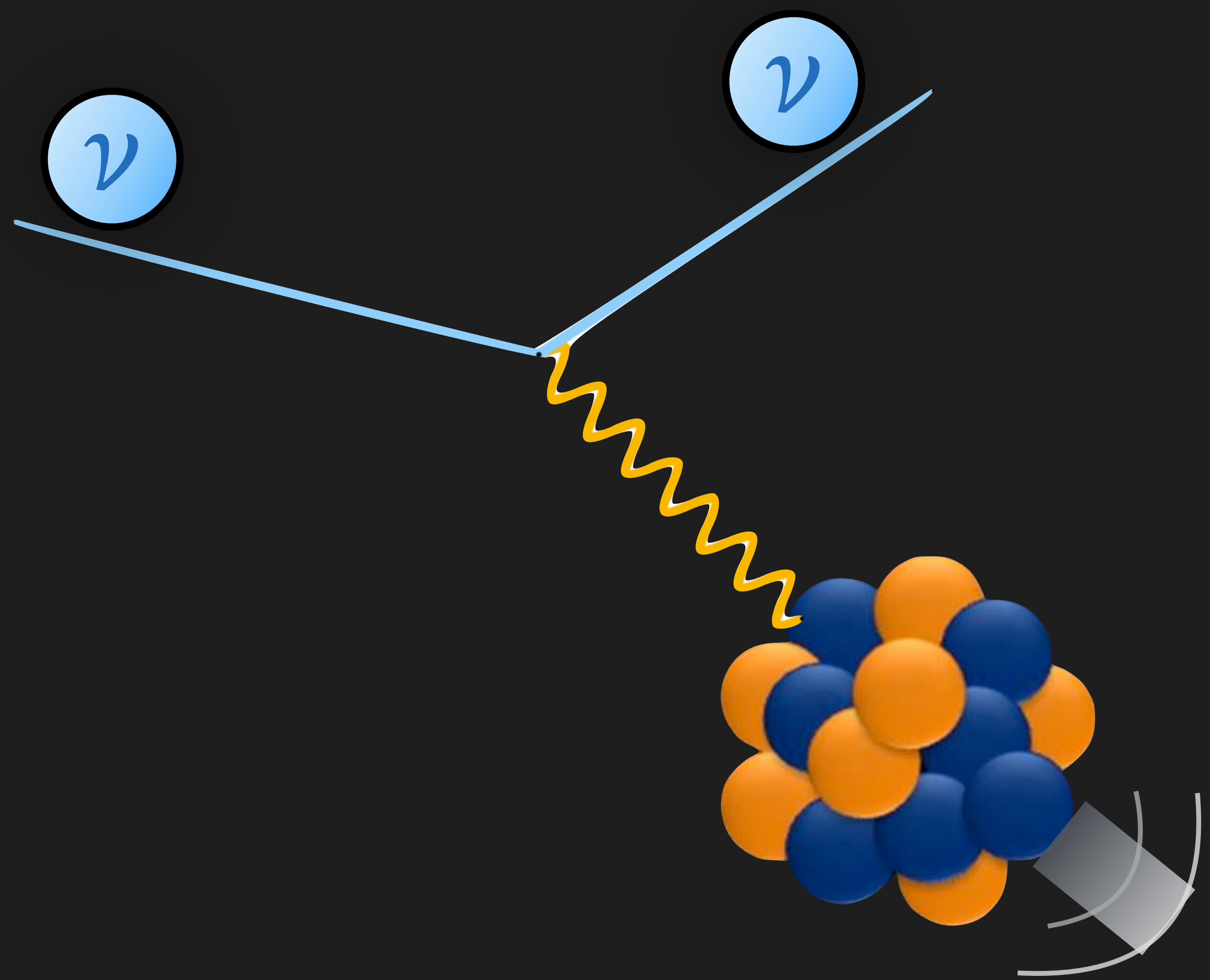
Adapted from Kate Scholberg

NEUTRINO INTERACTIONS WITH NUCLEI



Adapted from Kate Scholberg

CEνNS: INTRODUCTION AND FEATURES

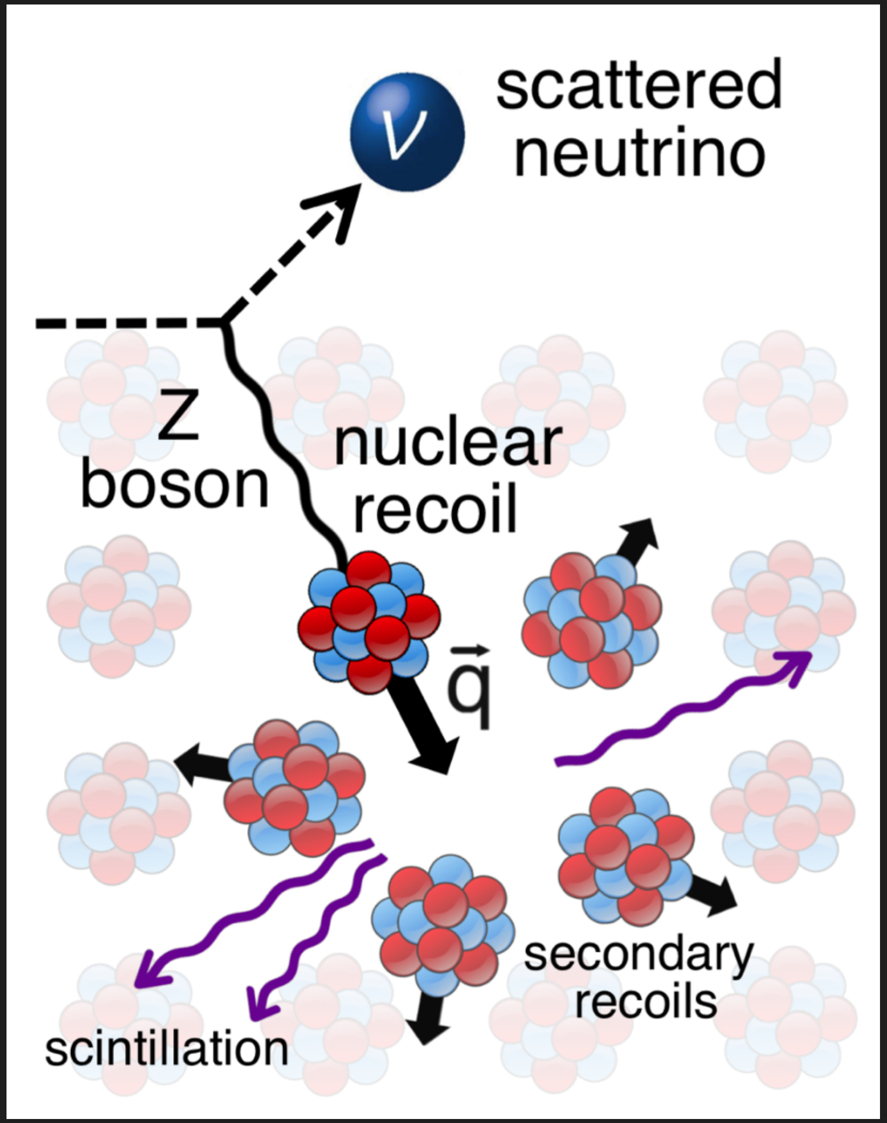


COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CEνNS)

- Neutral-current process: ν + N(A,Z) ⟶ ν + N(A,Z)
- Coherent: target nucleon wave functions remain in phase with each other before and after the collision. Amplitudes of scattering on individual nucleons add
- Elastic: no new particles are created and nuclear target remains in the same energy state
- The neutrino sees the nucleus as a whole:
  => cross section enhancement $\sigma \sim$ (#scatter targets)^2
  => upper limit on neutrino energy (up to $E_\nu \sim 100$ MeV)
- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be ~2 orders of magnitude larger than inverse beta decay process used first to observe neutrinos.



D. Akimov et al, Science 357 (2017)

INCOHERENT/INELASTIC SCATTERING

Incoherent scattering: $\sigma_{\rm NC}(\nu\mathcal{N}) \propto \sum_i |\mathscr{A}(\nu n_i)|^2 \propto N$ (Probabilities of scattering on individual nucleons add)

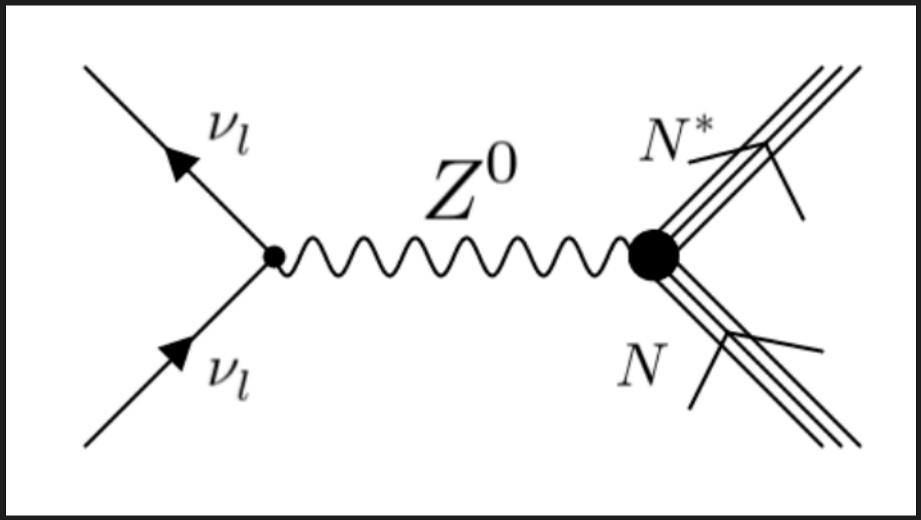
Coherent scattering: $\sigma_{\rm NC}(\nu\mathcal{N}) \propto \left|\sum_i \mathscr{A}(\nu n_i)\right|^2 \propto N^2$ (Amplitudes of scattering on individual nucleons add)

$$\mathscr{A}(\vec{q}) = \sum_{j=1}^{A} a_j(\vec{q})\exp^{i\vec{q}x_j}$$

When the momentum transfer times the dimension of the nuclear target is very small, qR $\ll 1$, the phase factors are negligible: the amplitude is given by the single constituent amplitude multiplied by the constituents number A.

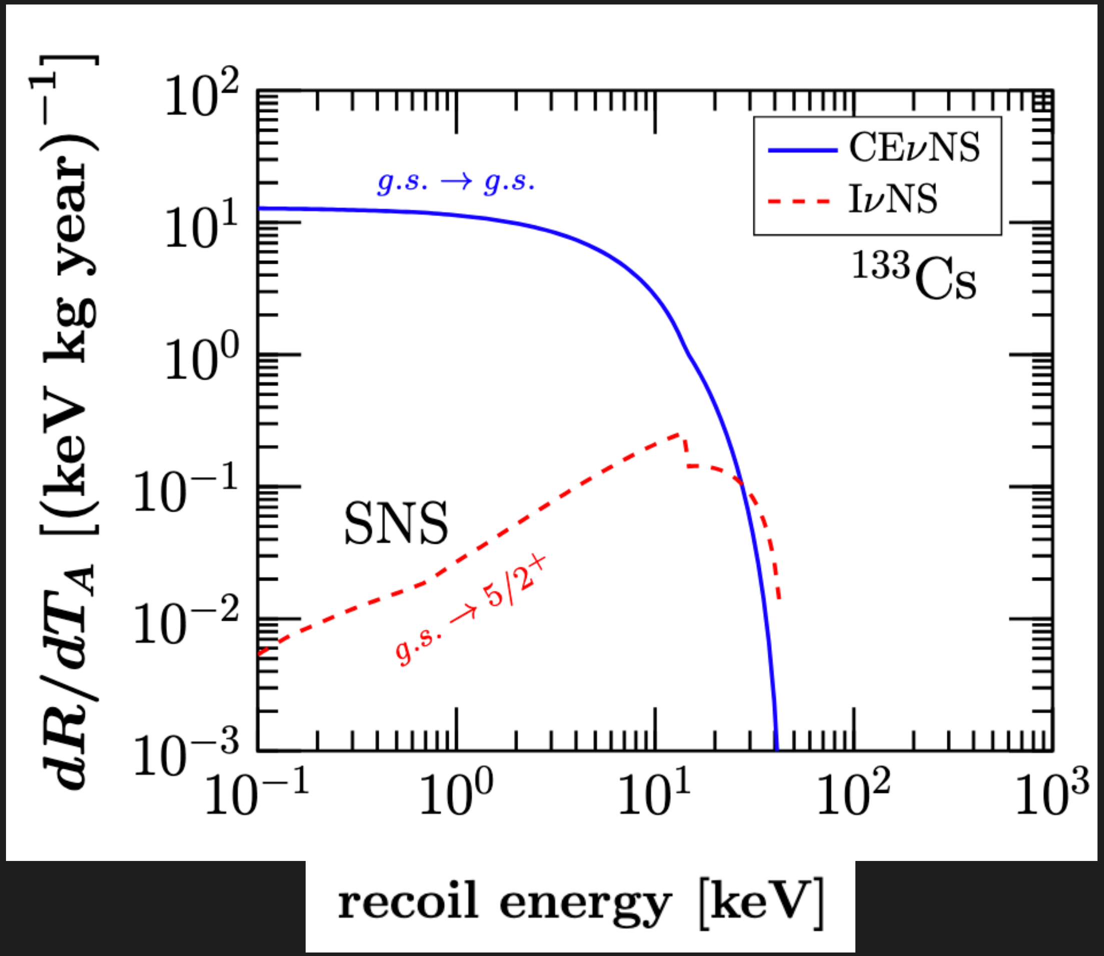
Bednyakov and Naumov Phys. Rev. D 98 no. 5, (2018) 053004
Pirinen+ Adv. High Energy Phys. 2018 (2018) 9163586,
Bednyakov and Naumov Phys. Part. Nucl. Lett. 16 no. 6, (2019) 638-646

INCOHERENT/INELASTIC SCATTERING



Neutrinos with energies of tens of MeV can excite many states in the target nuclei used for CEvNS experiments.

This cross-section has a linear dependence on the number of nucleons.



Going to higher neutrino energies, an approximation hints towards a smooth transition between the coherent and incoherent neutrino-nucleus scattering regime.

A correct treatment of both channels requires an accurate evaluation of the transition matrix elements describing the various interaction channels between the initial and final nuclear states.

Sahu+ Phys. Rev. C. 102 035501
Bednyakov+ Phys. Rev. D 98 (2018) 053004
Dutta+ Phys. Rev. D 106, 113006 (2022)
...

Sahu+ Phys. Rev. C. 102 035501

AN ACT OF HUBRIS

First theoretically predicted in 1974

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, JETP Lett. 19 4 236 (1974)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
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)

If there is a weak neutral current, then the elastic scattering process $\nu + A \rightarrow \nu + A$ should have a sharp coherent forward peak just as $e + A \rightarrow e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \rightarrow \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

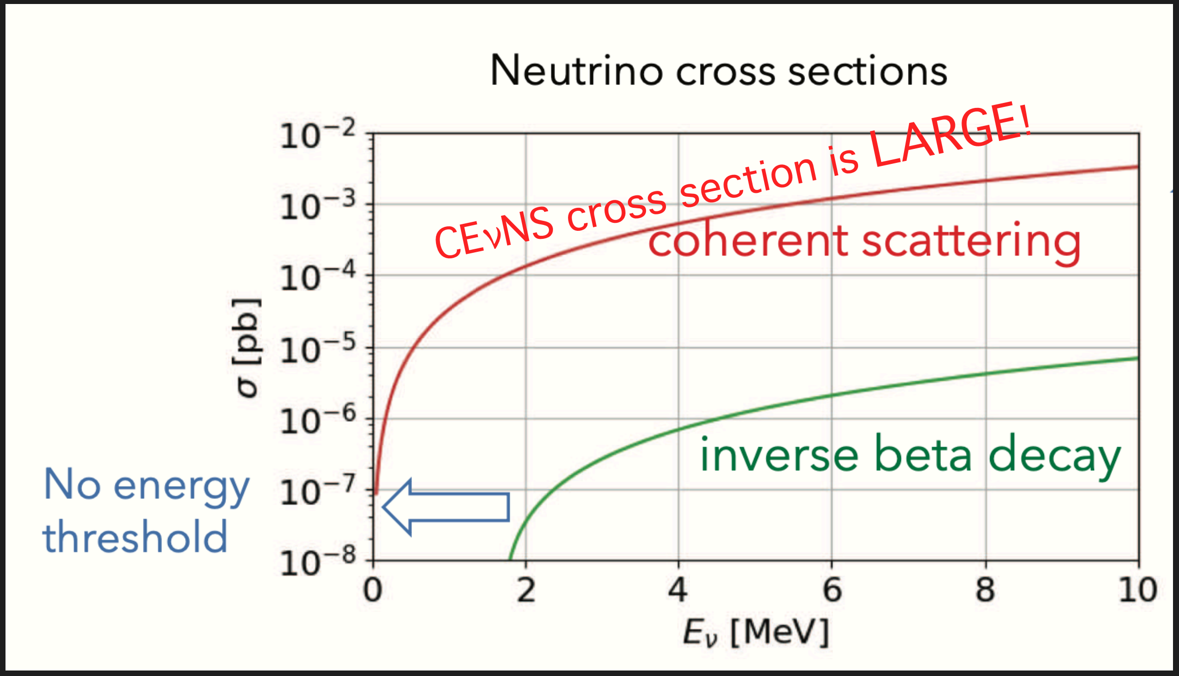
Experimentally the most conspicuous and most difficult feature of our process is that the only detectable reaction product is a recoil nucleus of low momentum. Ideally the apparatus should have sufficient resolution to identify and determine the momentum of the recoil nucleus and sufficient mass to achieve a reasonable interaction rate. Neutron background is a serious problem

CEνNS was observed for the first time ~40 years later,
in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source.

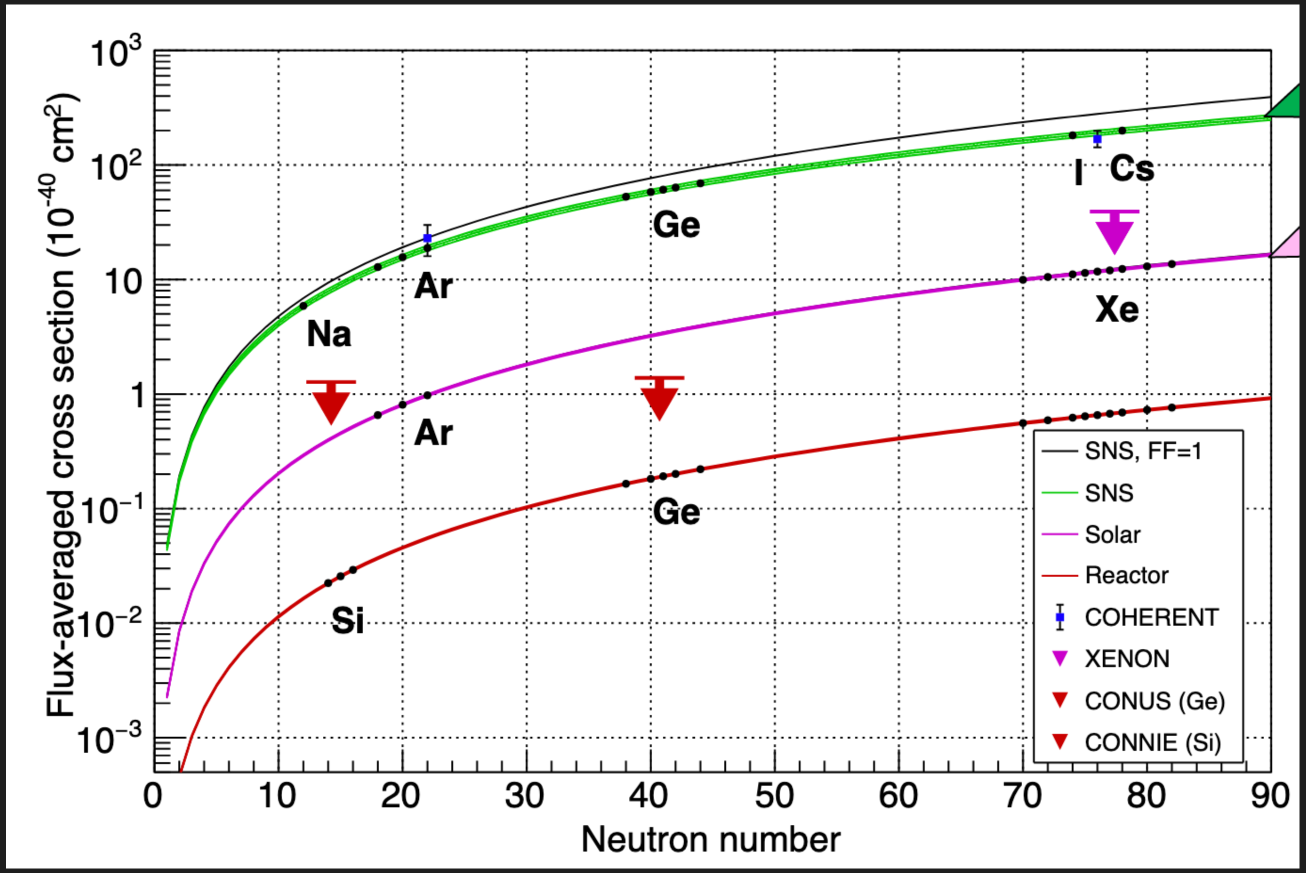
COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

CEνNS is an exceptionally challenging process to observe

Despite its large cross section, not observed for years due to tiny nuclear recoil energies

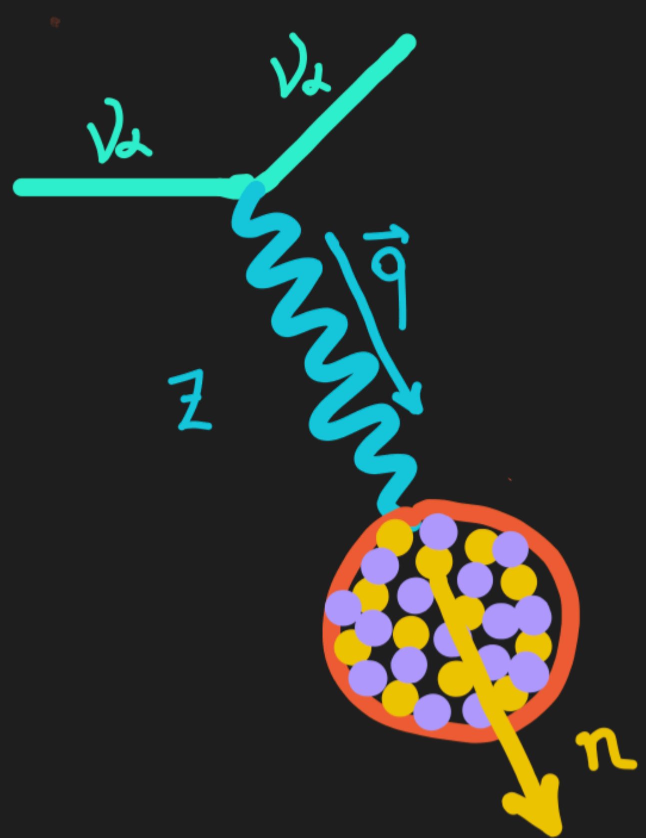


Credit: R. Strauss @ Magnificent CEvNS

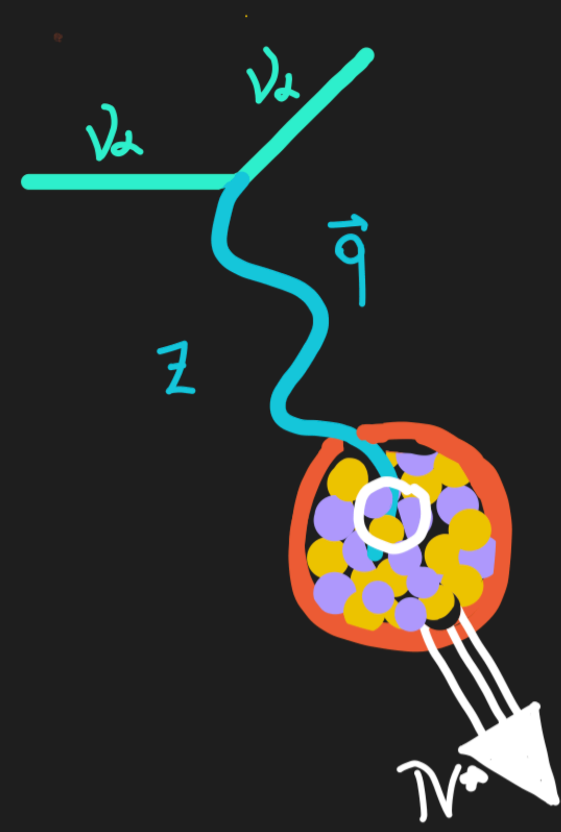


Credit to K. Scholberg @ISAPP 2021

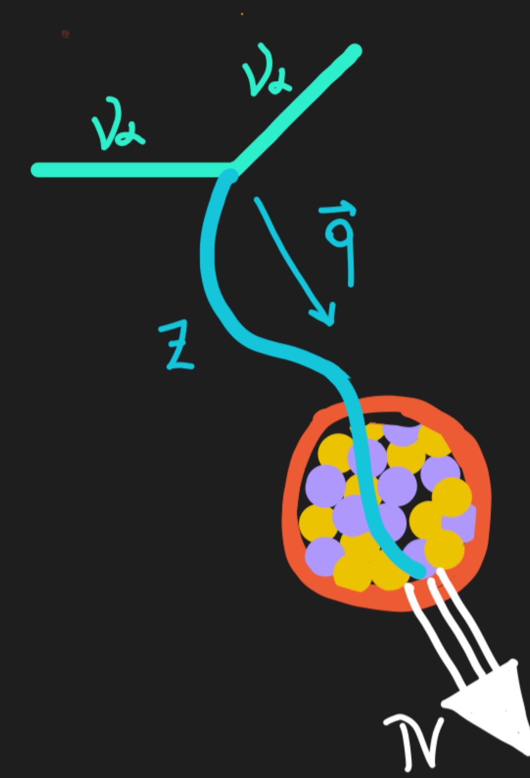
NEUTRINO-NUCLEUS SCATTERING



Inelastic incoherent
$\lambda_Z \ll 2R$



Elastic incoherent
$\lambda_Z \lesssim 2R$



Elastic coherent
$\lambda_Z \gtrsim 2R$

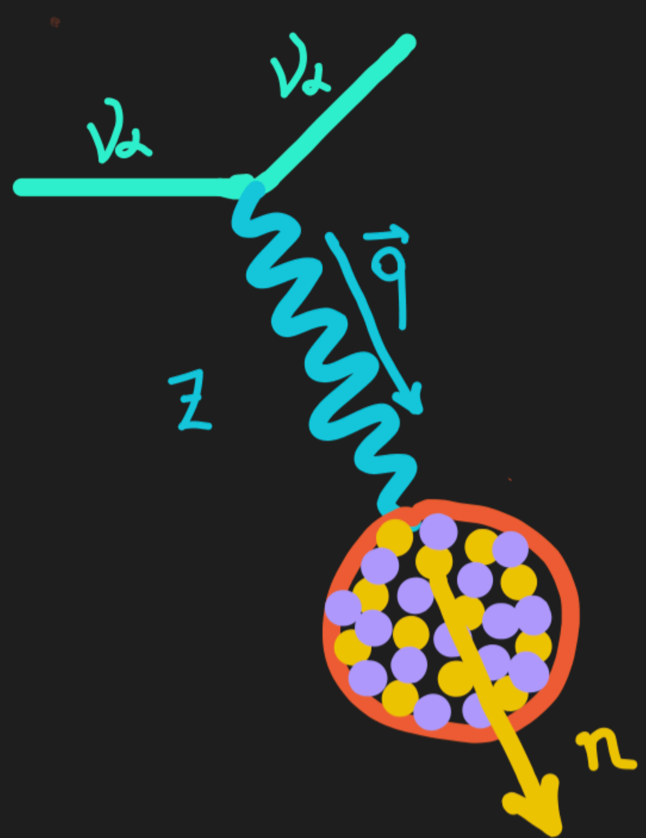
(Natural units!)

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}\,|}$$

Different types of interactions of a neutrino ν_α with a nucleus, depending on the wavelength of the mediator.

Adapted from Carlo Giunti

NEUTRINO-NUCLEUS SCATTERING

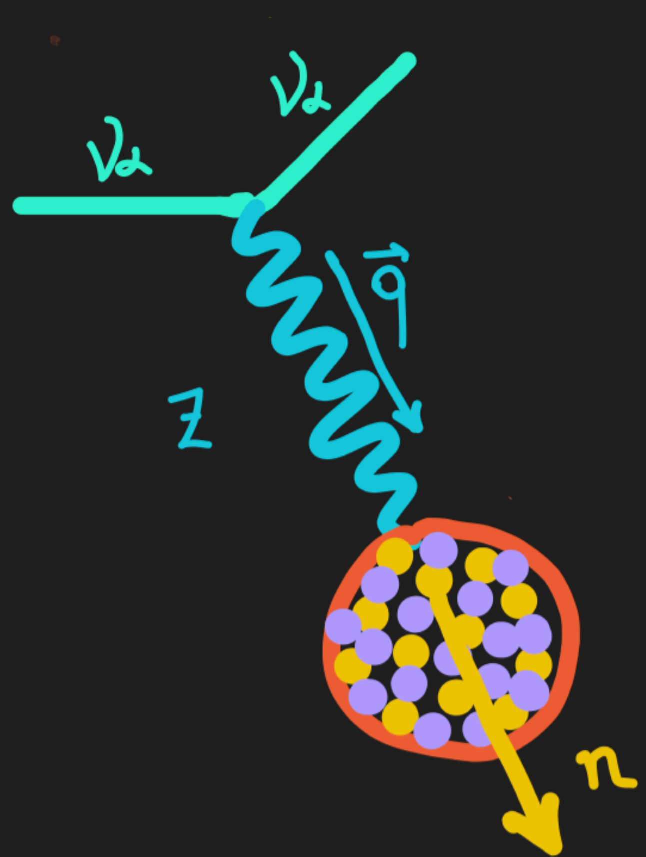


Inelastic incoherent
$\lambda_Z \ll 2R$

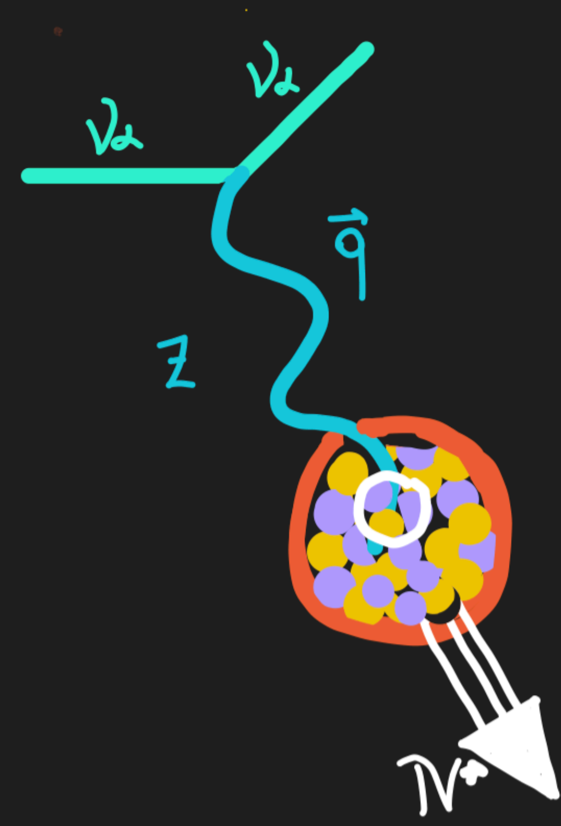
When $\lambda_Z \ll 2R$ the Z boson has a high probability of interacting with a single nucleon in the nucleus, ejecting it.

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}|}$$

NEUTRINO-NUCLEUS SCATTERING



Inelastic incoherent
$\lambda_Z \ll 2R$

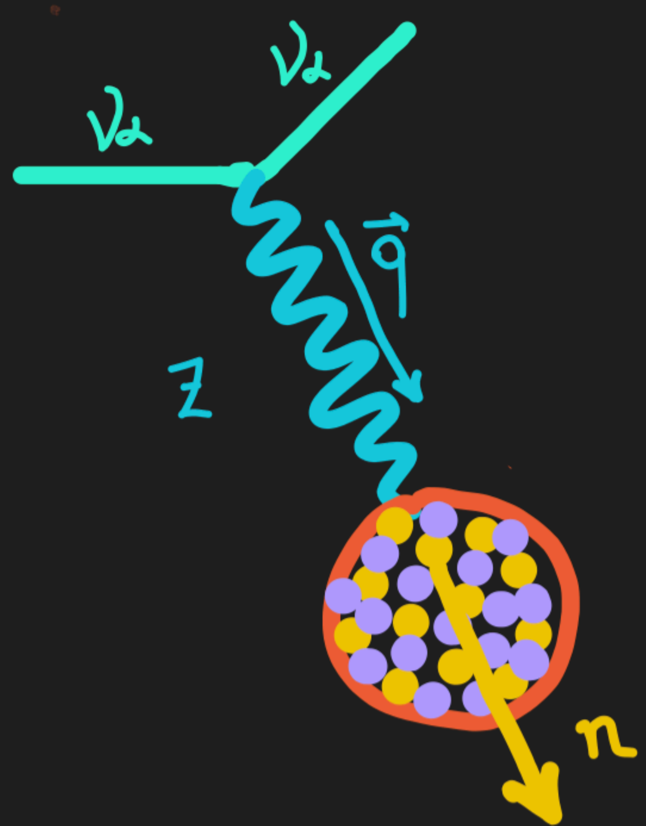


Elastic incoherent
$\lambda_Z \lesssim 2R$

When $\lambda_Z \lesssim 2R$ the Z boson has a high probability of interacting with a group of nucleons inside the nucleus, exciting the latter to the state N*.

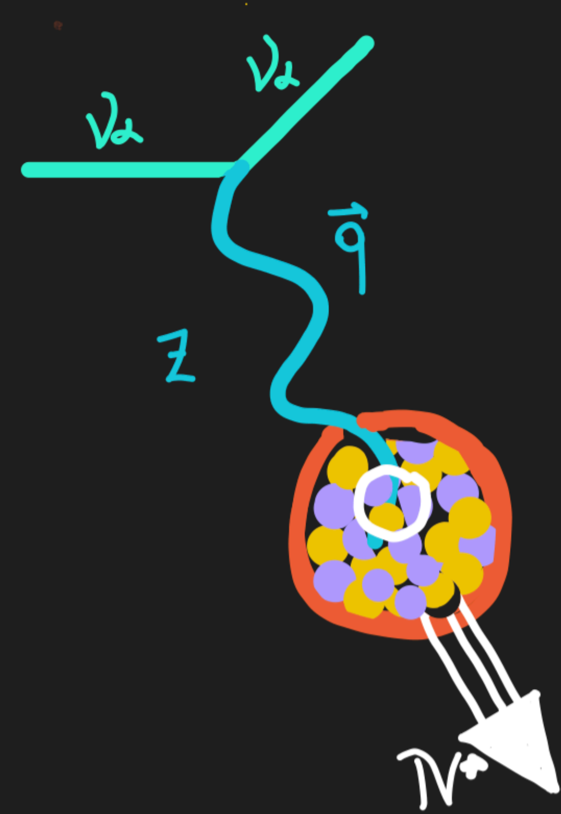
$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}\,|}$$

NEUTRINO-NUCLEUS SCATTERING



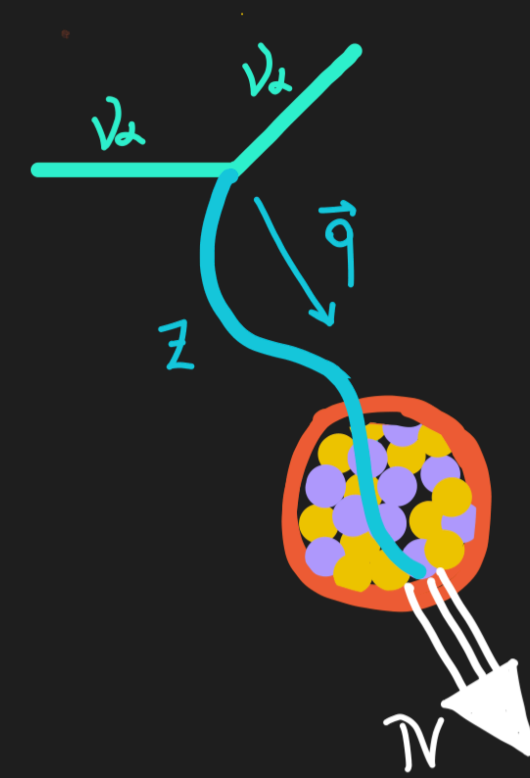
Inelastic incoherent

$\lambda_Z \ll 2R$



Elastic incoherent

$\lambda_Z \lesssim 2R$



Elastic coherent

$\lambda_Z \gtrsim 2R$

$$\lambda_Z = 2\pi \frac{\hbar}{|\vec{q}\,|}$$

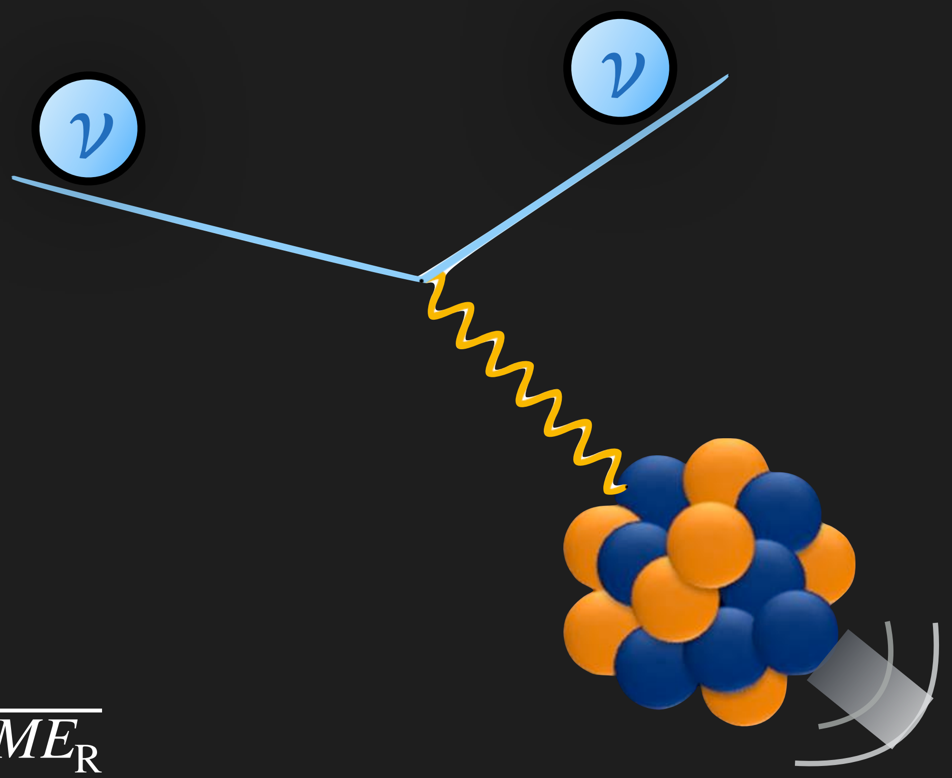
CEνNS occurs when the neutrino energy E_ν is such that amplitudes sum up coherently: $|\vec{q}| \leq 1/R_{\text{nucleus}}$ (Natural units!)

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

Heavy target nucleus:

A = 133, M ~ 133 GeV
R = 1.2 $A^{1/3}$ ~ 6 fm

CEνNS occurs for $|\vec{q}| \lesssim 35$ MeV



Non-relativistic nuclear recoil: $|\vec{q}| \sim \sqrt{2ME_R}$

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

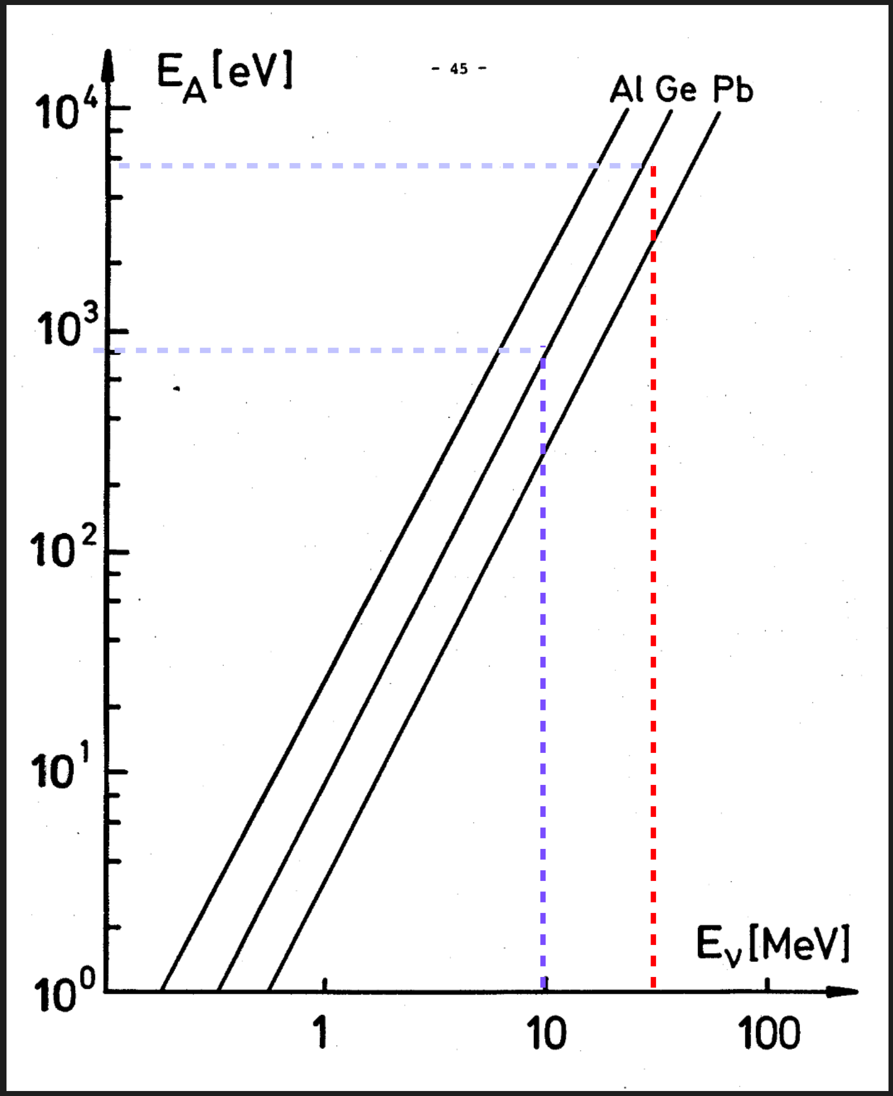
Maximum nuclear recoil is $E_R^{\max} = \frac{2E_\nu^2}{m_N}$

Accelerator neutrinos: $E_\nu \lesssim 50\ \mathrm{MeV}$ $E_R \lesssim \mathcal{O}(10)\ \mathrm{keV}$

Close to decoherence

Reactor neutrinos: $E_\nu \lesssim 10\ \mathrm{MeV}$ $E_R \lesssim \mathcal{O}(100)\ \mathrm{eV}$

Full coherence



Drukier, Stodolsky, PRD 30 (1984) 2295

- No threshold
- Heavier nuclei: higher cross section but lower recoil
- Both cross-section and maximum recoil energy increase with neutrino energy

BONUS SLIDE.
WHAT HAPPENS AT EVEN LOWER E_R?

The de Broglie wavelength of particles scales inversely with their momentum: $\lambda_{\rm DB} \sim \frac{1}{p}$.

Particles scattering with lower momentum see a larger target and scatter with larger cross sections.

BONUS SLIDE. WHAT HAPPENS AT EVEN LOWER E_R?

If $|\vec{q}| \leq 1/R_{atom}$ the reaction occurs with the whole atom.
Coherence would be visible for $|\vec{q}| \sim \mathbf{2\ keV}/R_{atom}$ with a corresponding recoil energy

$$E_R \approx 2\text{meV}/(AR^2_{\text{atom}}[\text{Å}])$$

For Helium, $R_{\text{atom}} = 0.5\text{Å}$ and $E_R \sim 2$ meV.

Sehgal+ Phys.Lett.B 171 (1986) 107-112
Cadeddu+ Phys. Rev. D 100, 073014 (2019)
Donchenko+ FIELDS, PARTICLES, AND NUCLEI 117 (2023)

Electrons “screen" the nuclear weak charge as seen by an electron neutrino (destructive interference).

Observation requires:
- Sensitivity to tiny recoil energies
- neutrinos with energy of few keV

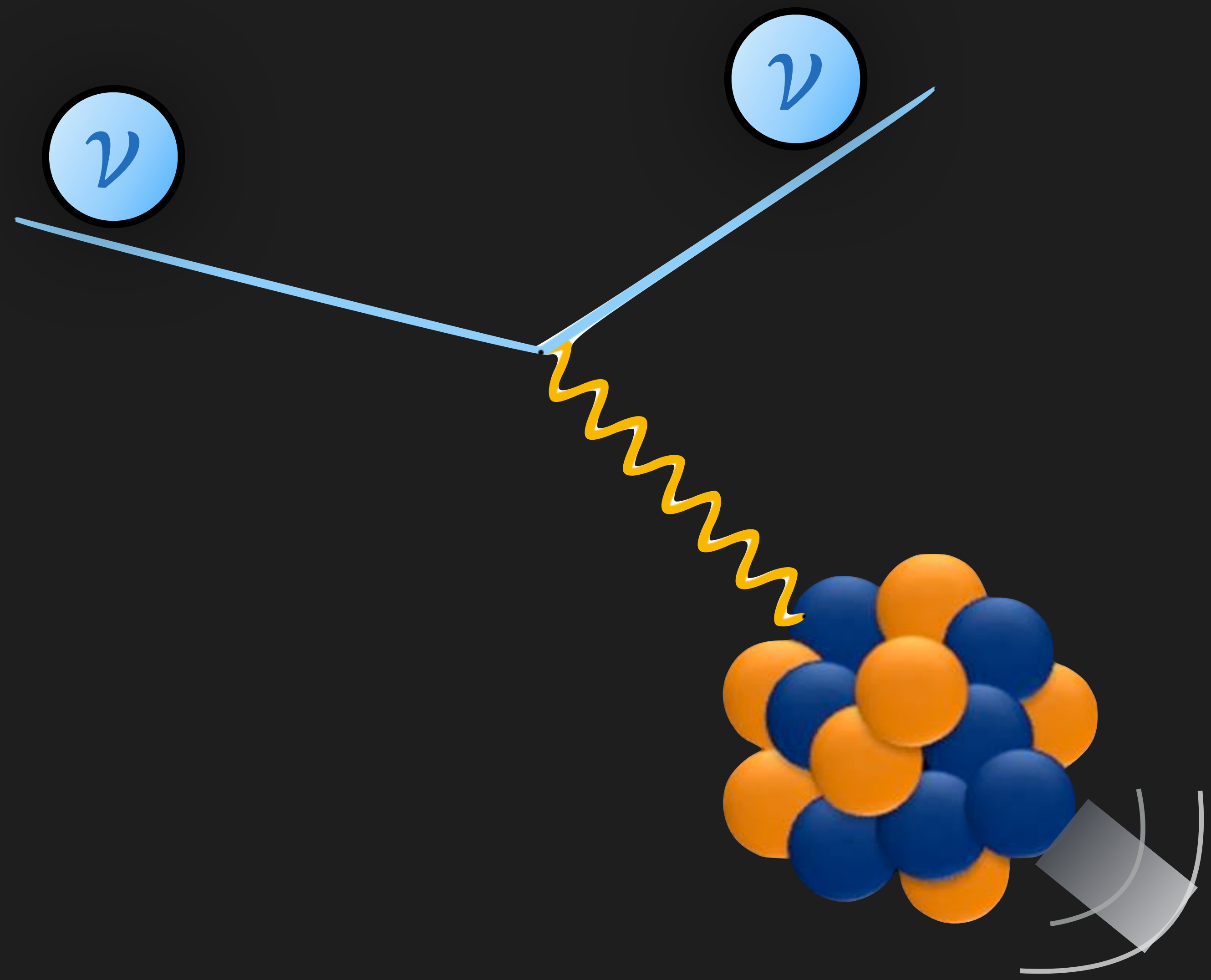
BONUS SLIDE. WHAT HAPPENS AT EVEN LOWER E_R?

Observing relic neutrinos?

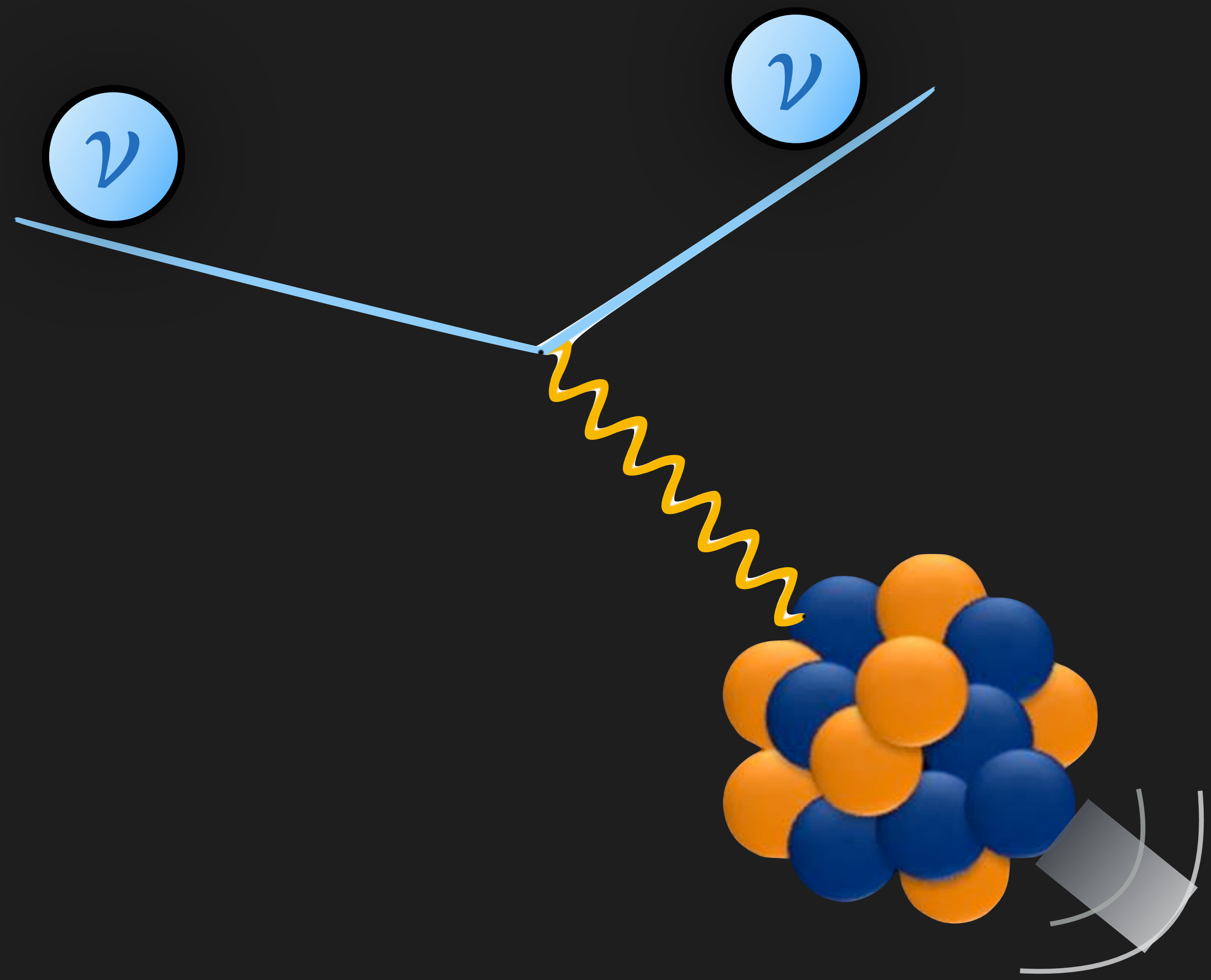
Relic neutrinos have momenta p ~ 0.5 meV, corresponding to macroscopic wavelengths $\lambda \sim$ mm and an enhancement factor of order the Avogadro number.

Opher, Astron. Astrophys. 37 (1974) no.1, 135-137
Lewis, PRD 21 (1980), 663
Shvartsman+, JETP Lett. 36 (1982), 277-279
Smith and Lewin, PLB 127 (1983), 185-190
Duda+ PRD 64 (2001), 122001
Domcke and Spinrath, JCAP 06 (2017), 055
Shergold JCAP 11 (2021), 052
...

CEνNS EXPERIMENTS AND DETECTION



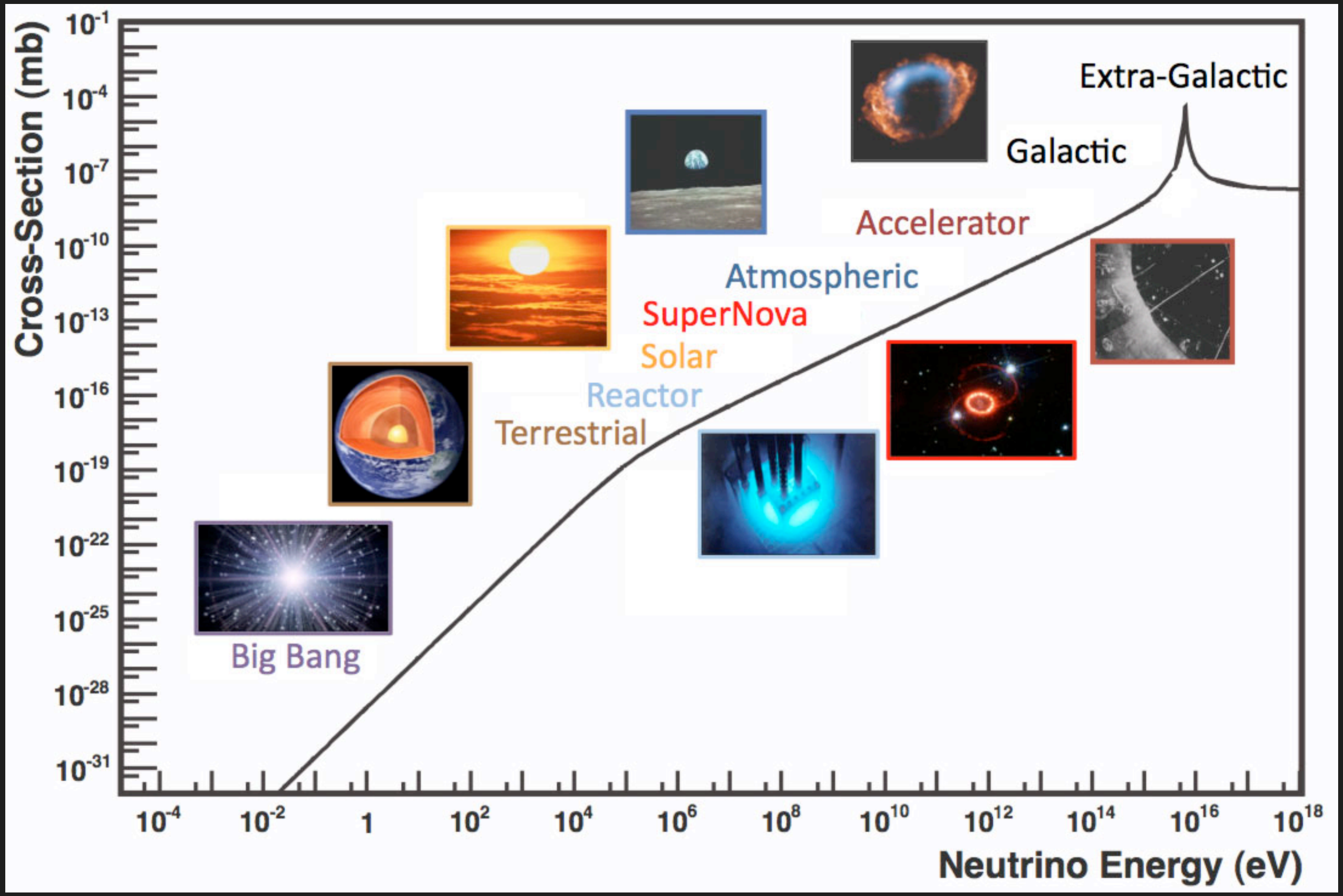
NEUTRINO SOURCES



NEUTRINO SOURCES

Preferable requisites:

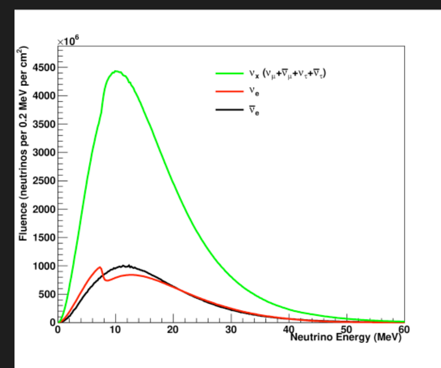
- High flux
- Well understood spectrum
- Multiple flavours
- Possibility of locating the detector close to the source
- Background rejection



Rev.Mod.Phys. 84 (2012) 1307-1341

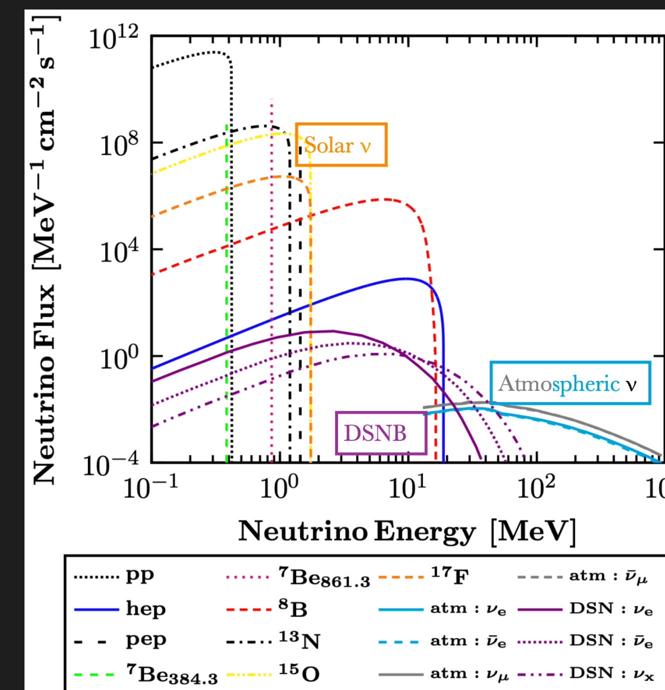
LOW-ENERGY NEUTRINOS FROM NATURAL SOURCES

Supernova bursts neutrinos



arXiv:1205.6003 [astro-ph.IM]

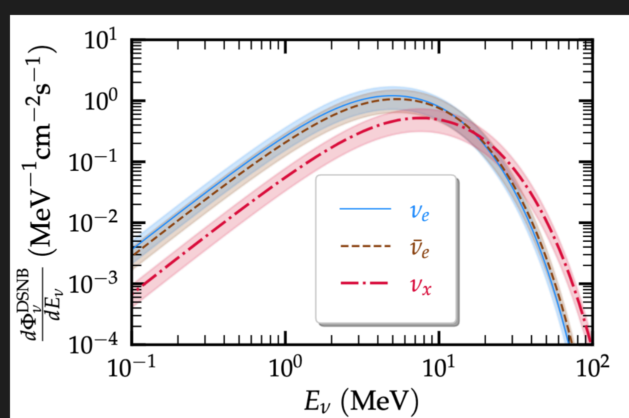
Atmospheric neutrinos



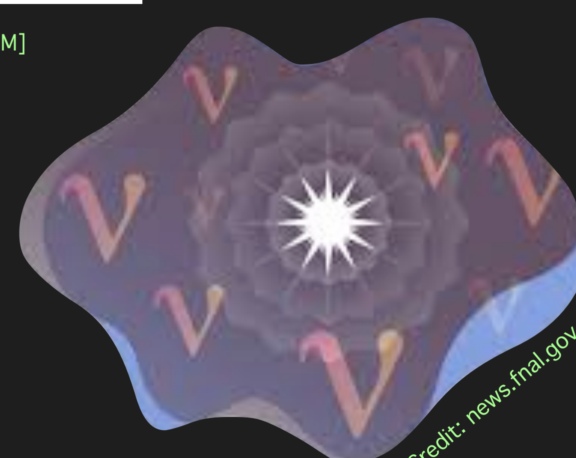
Aristizabal, VDR, Flores, Papoulias JCAP 01 (2022) 01, 055

Solar neutrinos

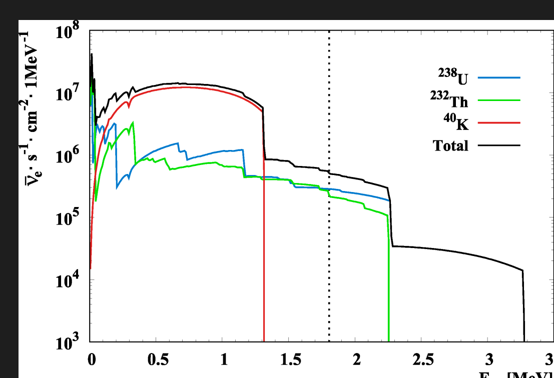
DSNB



VDR, Majumdar+ 2309.04117 [hep-ph]



Credit: news.fnal.gov

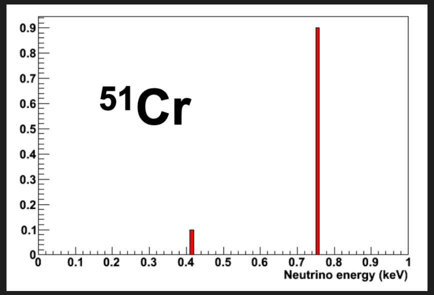


Phys. Rev. D 101, 012009

Geoneutrinos

LOW-ENERGY NEUTRINOS FROM ARTIFICAL SOURCES

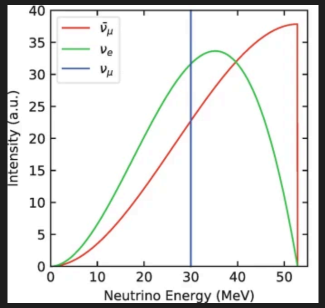
Radioactive source ^{51}Cr



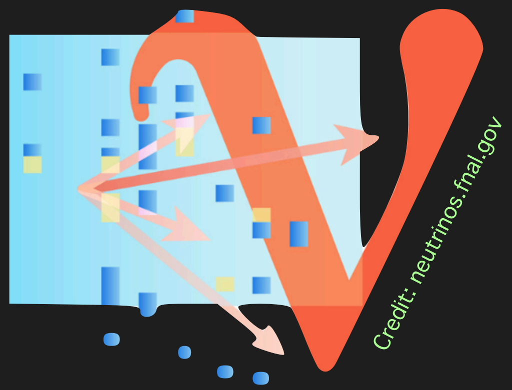
Electron-capture decaying isotope
4 monochromatic lines
very short baseline
low energy challenging

Stopped pions (Decay at rest)

High energy, pulsed beam



Scolz, https://doi.org/10.1007/978-3-319-99747-6_3



Beam induced radioactive sources (IsoDAR)

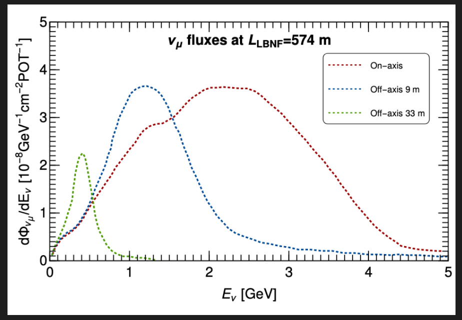
Higher energy than reactors
Does not exist yet

Reactors

Low energy, but high fluxes possible

Next-generation neutrino beams

Low-energy tail of the neutrino spectrum of LBNF



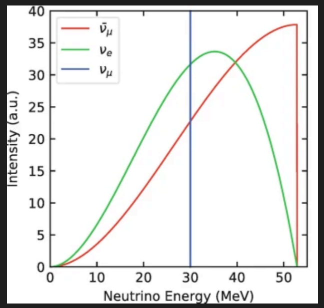
Aristizabal+ PRD 104, 033004 (2021)

Adapted from K. Scholberg @ CNNP2017 and Snowmass 2021 2203.07361

LOW-ENERGY NEUTRINOS FROM ARTIFICAL SOURCES

Stopped pions (Decay at rest)

High energy, pulsed beam

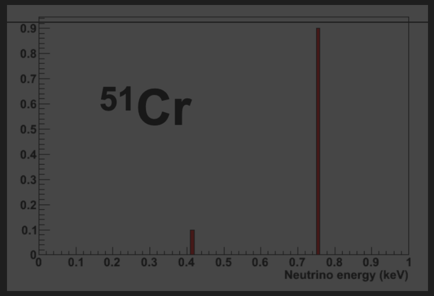


Scolz, https://doi.org/10.1007/978-3-319-99747-6_3

Reactors

Low energy, but high fluxes possible

Radioactive source ^{51}Cr



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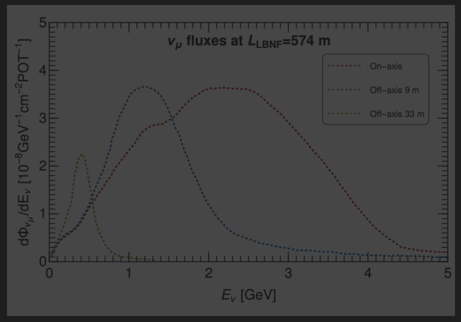
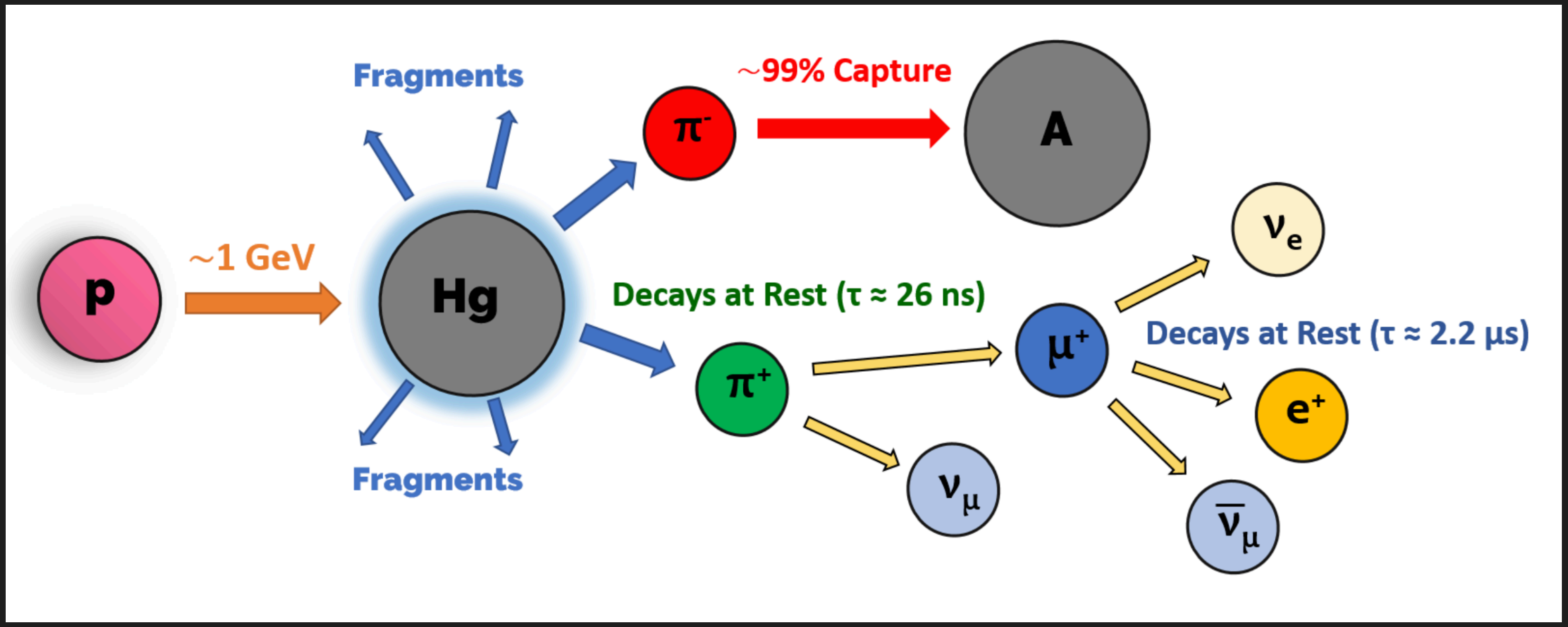


Aristizabal+ PRD 104, 033004 (2021)

Adapted from K. Scholberg @ CNNP2017 and Snowmass 2021 2203.07361

STOPPED-PION (π-DAR) NEUTRINOS



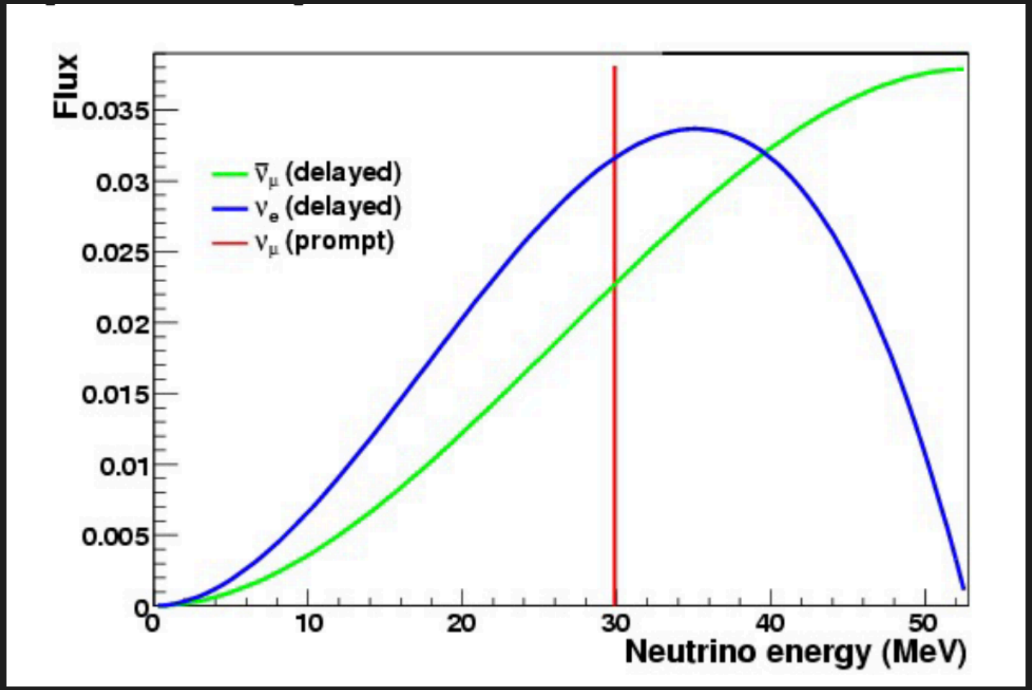
Credit: M. Green @ Magnificent CEvNS 2019

$$\pi^+ \to \mu^+ + \nu_\mu$$

Prompt monochromatic ν_μ from stopped pion decays

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

Delayed

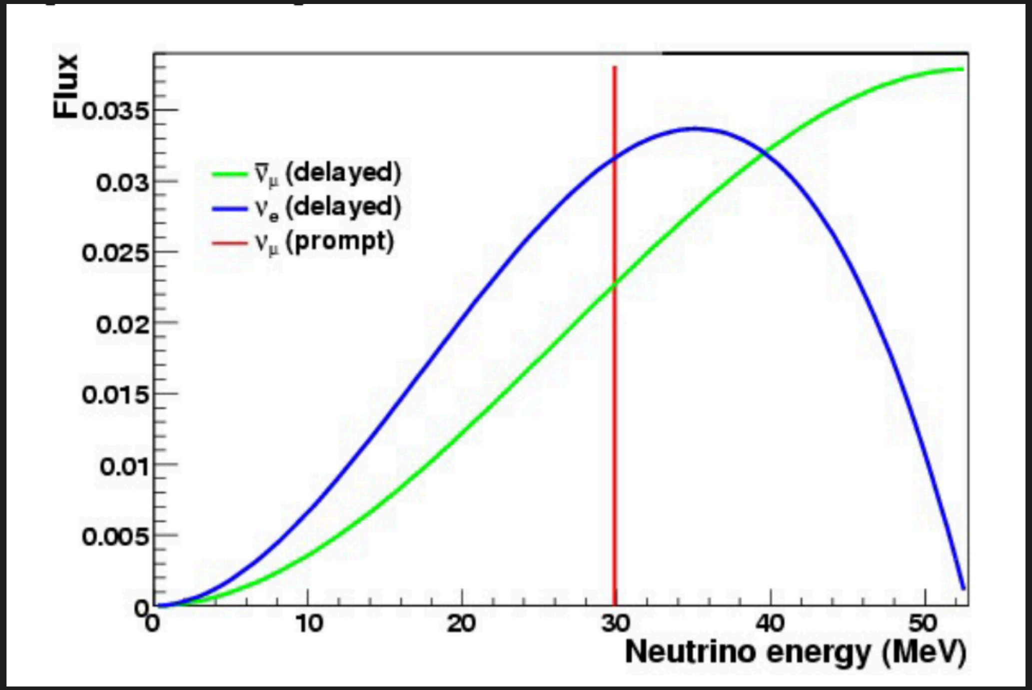


D. Akimov et al. (COHERENT). 2110.07730

STOPPED-PION (π-DAR) NEUTRINOS

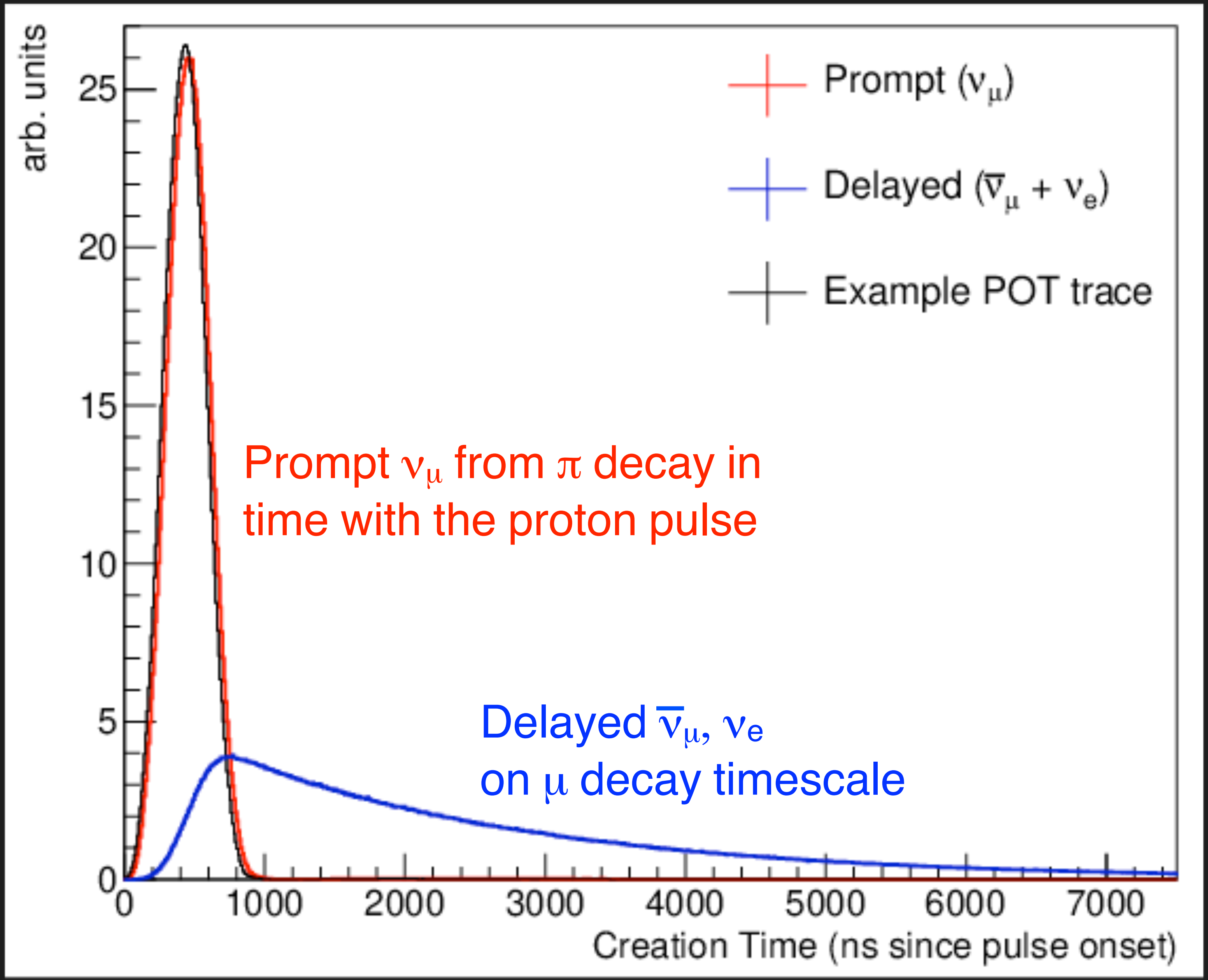
- Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (USA).
- Lujan center at Los Alamos Neutron Science Center LANSCE (USA).
- China Spallation Neutron Source CSNS (China).
- European Spallation Source (ESS) under construction (Sweden)

- High energy
- Pulsed beam → good background rejection
- Neutron backgrounds



D. Akimov et al. (COHERENT). 2110.07730

TIME DISTRIBUTION OF A π-DAR NEUTRINO SOURCE (SNS)



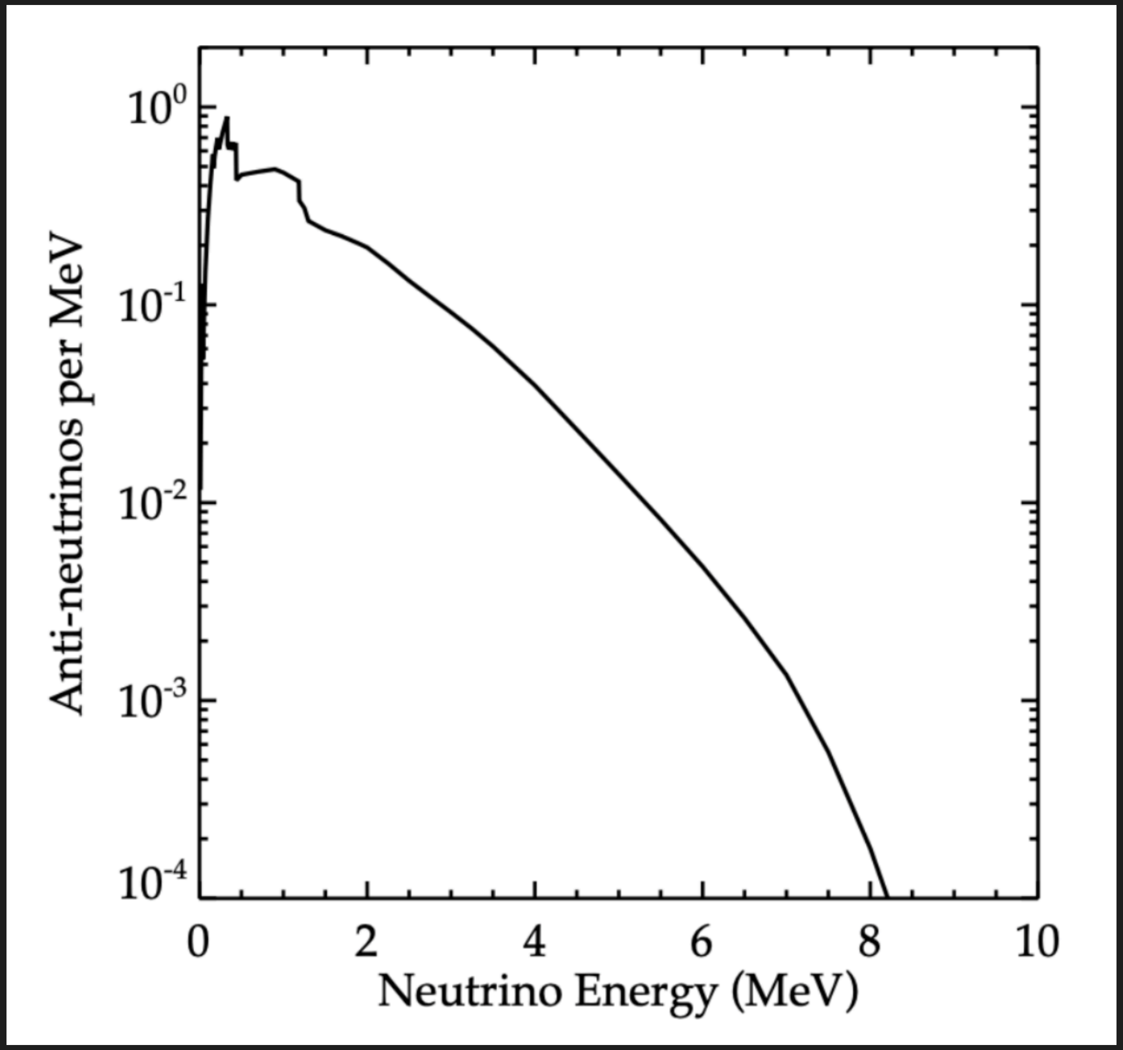
Snowmass 2021 2203.07361

NEUTRINOS FROM NUCLEAR REACTORS

PROs:
- Copious sources of electron antineutrinos
- Low energy (≲ 10 MeV): coherence condition for the recoil is largely preserved

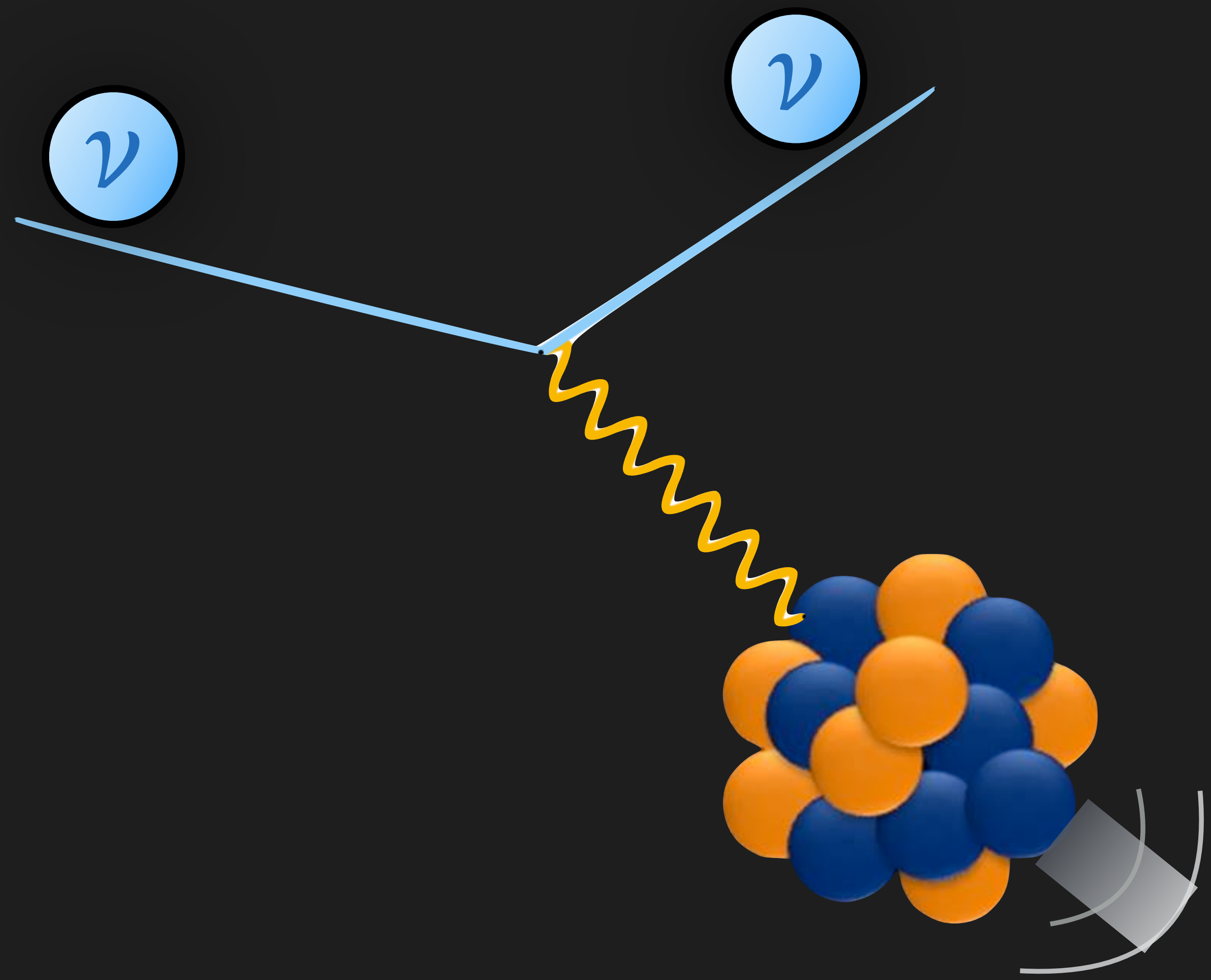
CONs:
- Even smaller recoil energies
- Large backgrounds (although reactor-off allows to measure bckg)
- Only one flavor accessible


Credit: constellationenergy.com

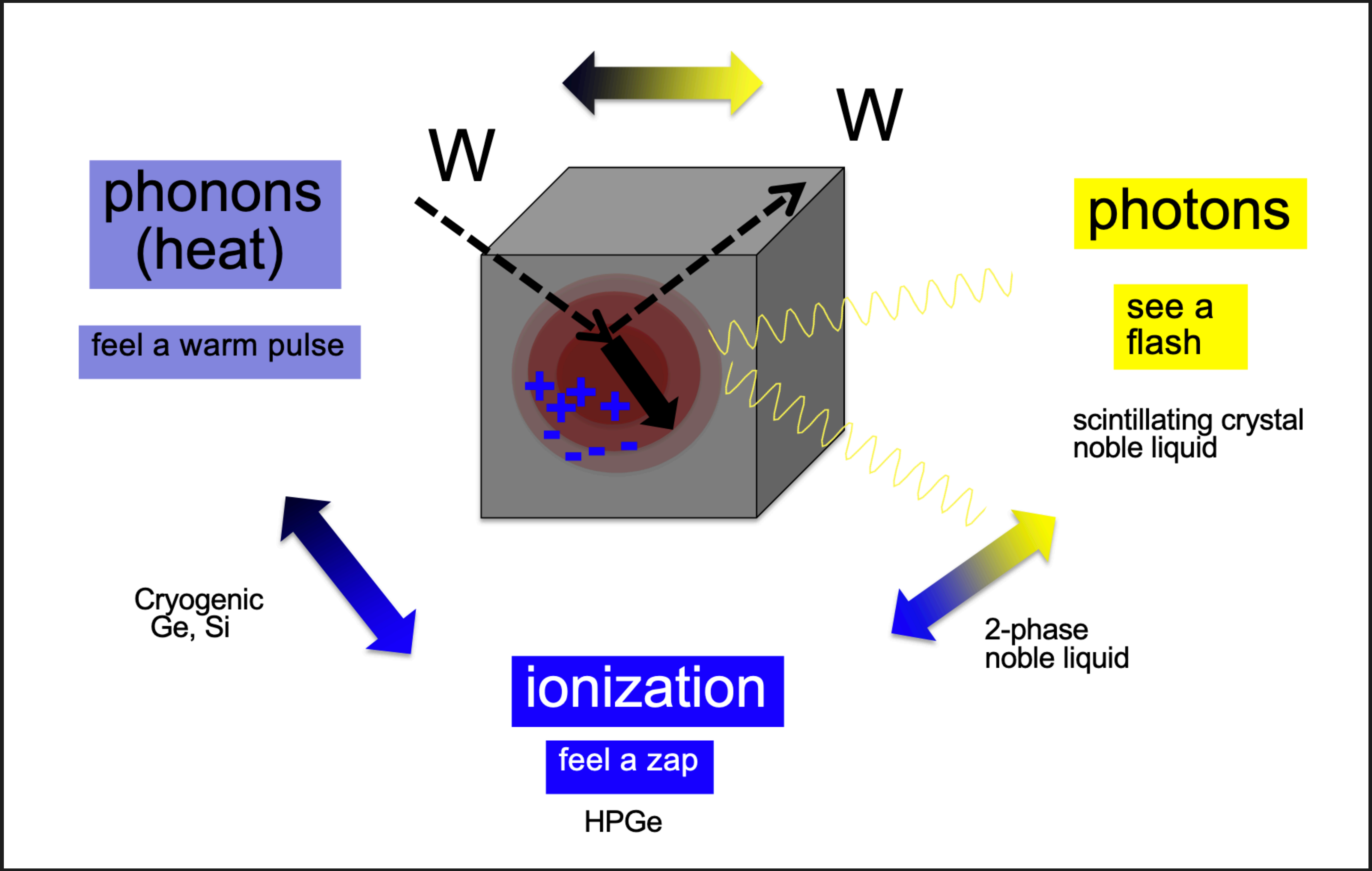


Snowmass 2021 2203.07361

EXPERIMENTS AND DETECTION

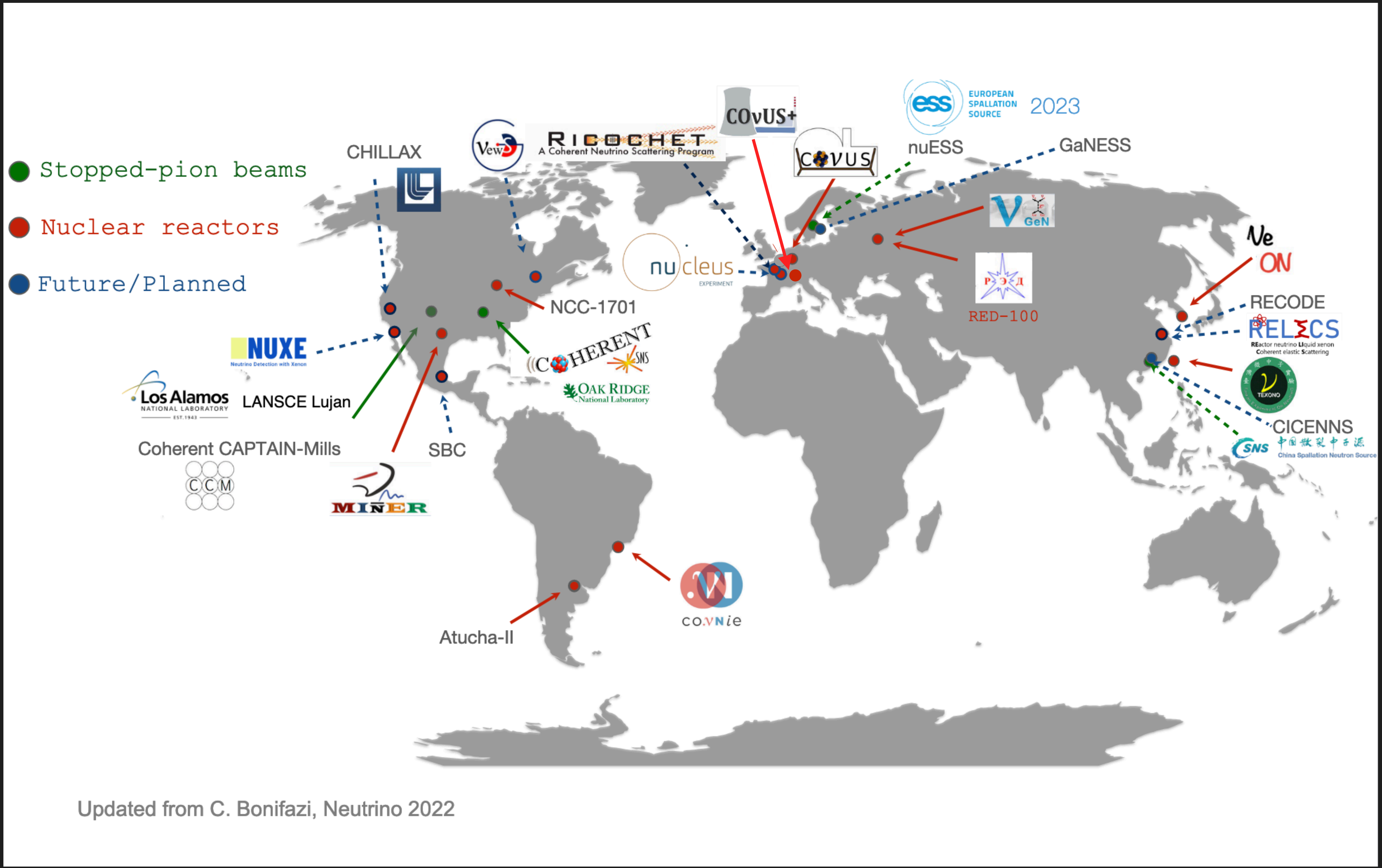


LOW-ENERGY NUCLEAR RECOIL DETECTION STRATEGIES



Credit to K. Scholberg @INSS 2021 and
http://dmrc.snu.ac.kr/english/intro/intro1.html

CEνNS EXPERIMENTS WORLDWIDE

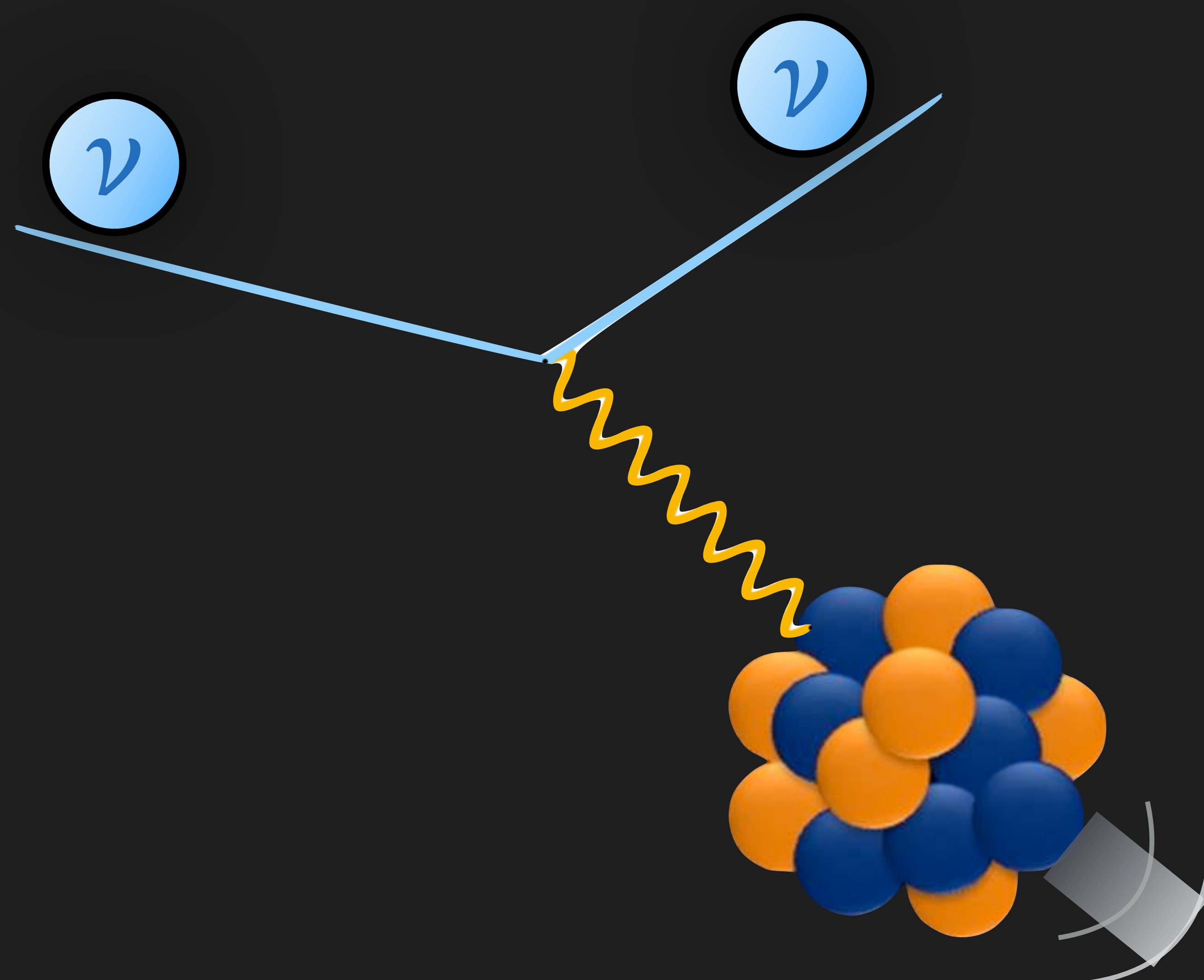


Credit to I. Nasteva @NEUTRINO 2024

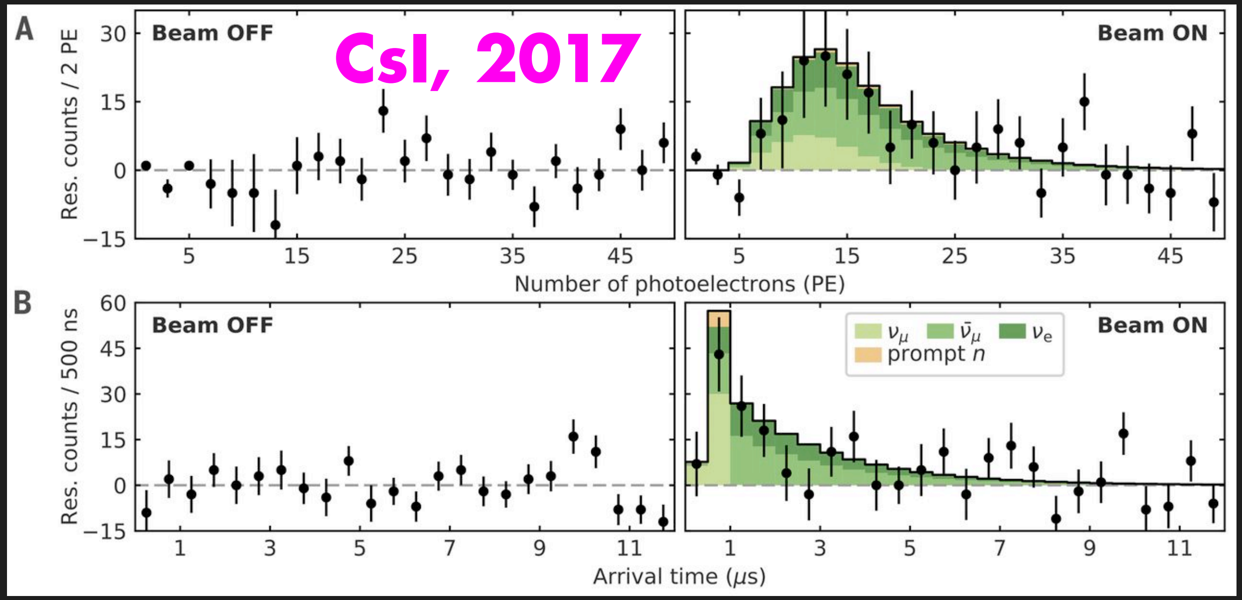
(INCOMPLETE! LIST OF) CEνNS EXPERIMENTS

Experiment	T_{th}	Baseline (m)	Target	Mass (kg)	Technology	Source	Neutrino flux ($\nu/cm^2/s$)
COHERENT	6.5 keV_{nr}	19.3	CsI[Na]	14.57	Scintillating crystal	π-DAR SNS	4.3×10^7
	1.5 keV_{ee}	22	Ge	10.66	HPGe PPC		
	20 keV_{nr}	29	LAr	2×10^3	Single phase		
	13 keV_{nr}	28	NaI[Tl]	185*/3388	Scintillating crystal		
CCM	10-20 keV	20-40	LAr	10^4	Scintillation	π-DAR Lujan	
ESS*			CsI, Ge, Xe, Ar			π-DAR	
CICENNS*	2 keV_{nr}	10.5	CsI(Na)	300	Scintillation	π-DAR	2×10^7
NCC-1701 (DRESDEN-II)	200 eV_{ee}	8	Ge	3	HPGe	NPP 2.9 GW	8.1×10^{13}
CONUS	210 eV_{ee}	17	Ge	4	HPGe	NPP 3.9 GW	2×10^{13}
CONUS+	150 eV_{ee}	20.7	Ge	4	HPGe	NPP 3.6 GW	1.45×10^{13}
MINER	100 eV_{nr}	1	Ge/Si/Al_2O_3	2-10	cryogenic	NPP 1 MW	1×10^{12}
CONNIE	15 eV_{ee}	30	Si	0.5×10^{-3}	Si CCDs	NPP 3.9 GW	7.8×10^{12}
Ricochet	300 eV_{nr}	8.8	Ge,Zn,Al, Sn	0.68	cryogenic	NPP 58 MW	1.6×10^{12}
NUCLEUS	200 eV_{ee}	77, 102	$CaWO_4$ Al_2O_3	10^{-2}	Cryogenic $CaWO_4$ Al_2O_3 calorimeter array	NPP 8.54 GW	1.7×10^{12}
RED100	500 eV	19	Xe	200	LXe dual phase	NPP 3.1 GW	1.35×10^{13}
vGEN	200 eV_{ee}	11-12	Ge	1.4	HPGe	NPP 3.1 GW	5.4×10^{13}
TEXONO	200 eV_{ee}	28	Ge	1.43	p-PCGe	NPP 2 × 2.9 GW	6.4×10^{12}
NEON	200 eV_{ee}	23.7	Na(Tl)	16.7	scintillator	NPP 2 × 2.8 GW	$\sim \times 10^{13}$
SBC*	100 eV_{ee}		Ar	10		NPP 2 × 2.9 GW	

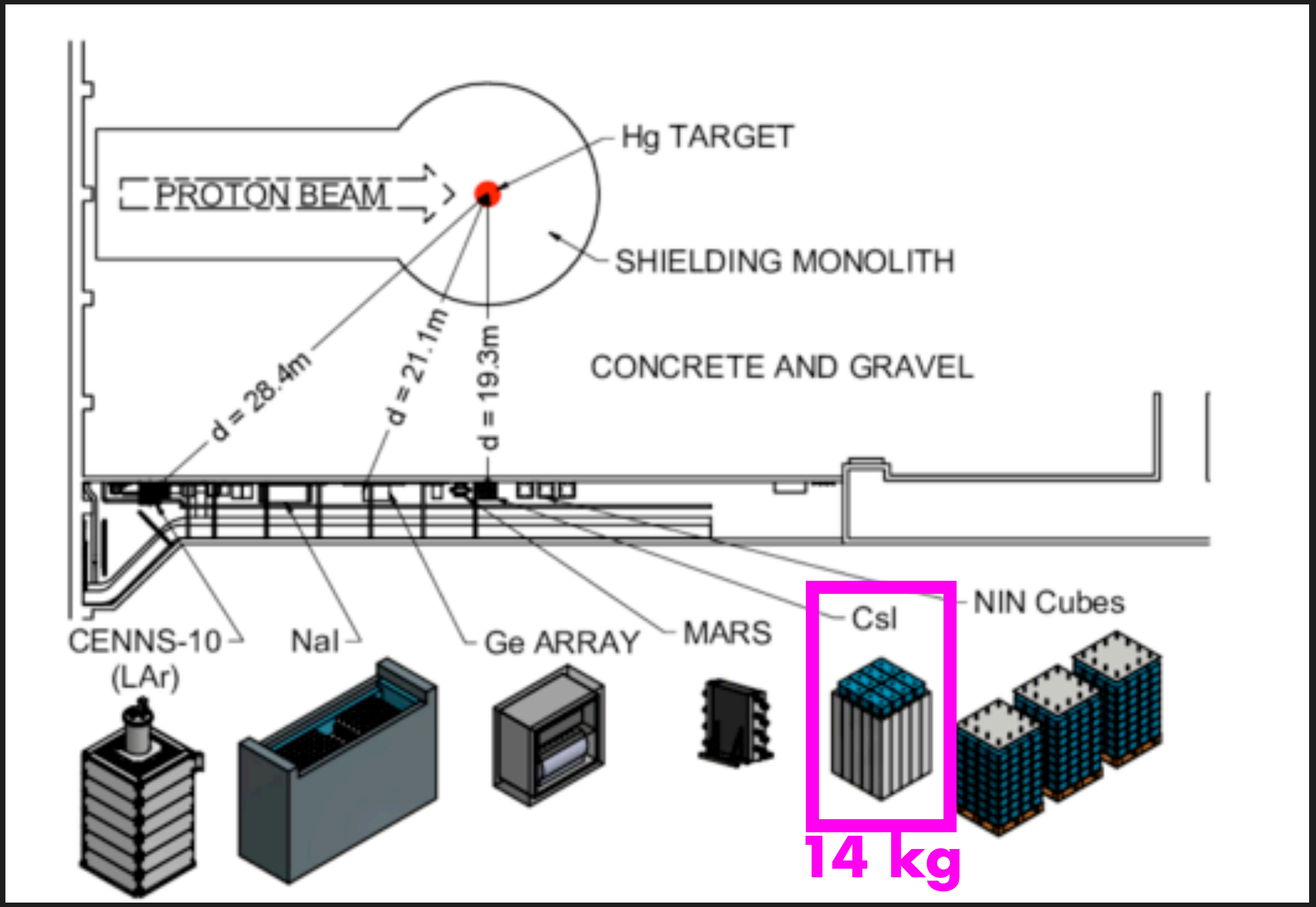
WHICH EXPERIMENTS HAVE OBSERVED CEνNS?



1st OBSERVATION OF CEvNS BY COHERENT



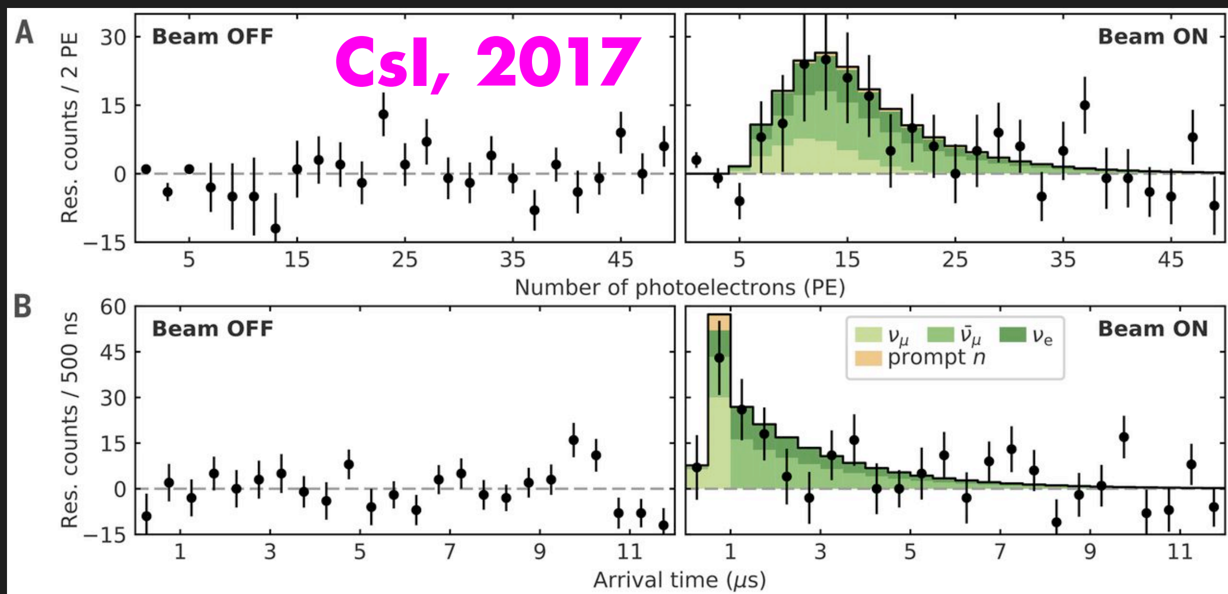
Observation at 6.7σ confidence level
~ 130 events observed

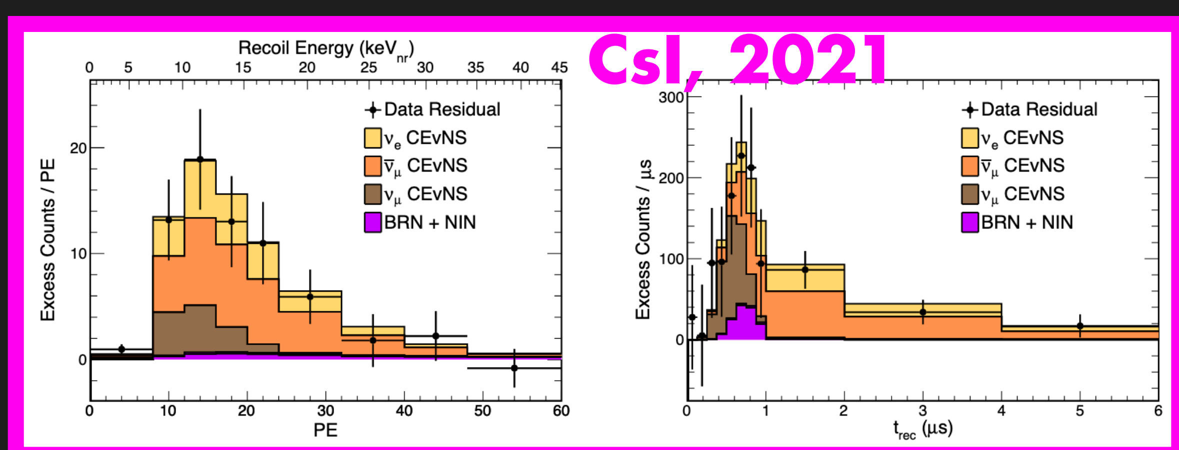


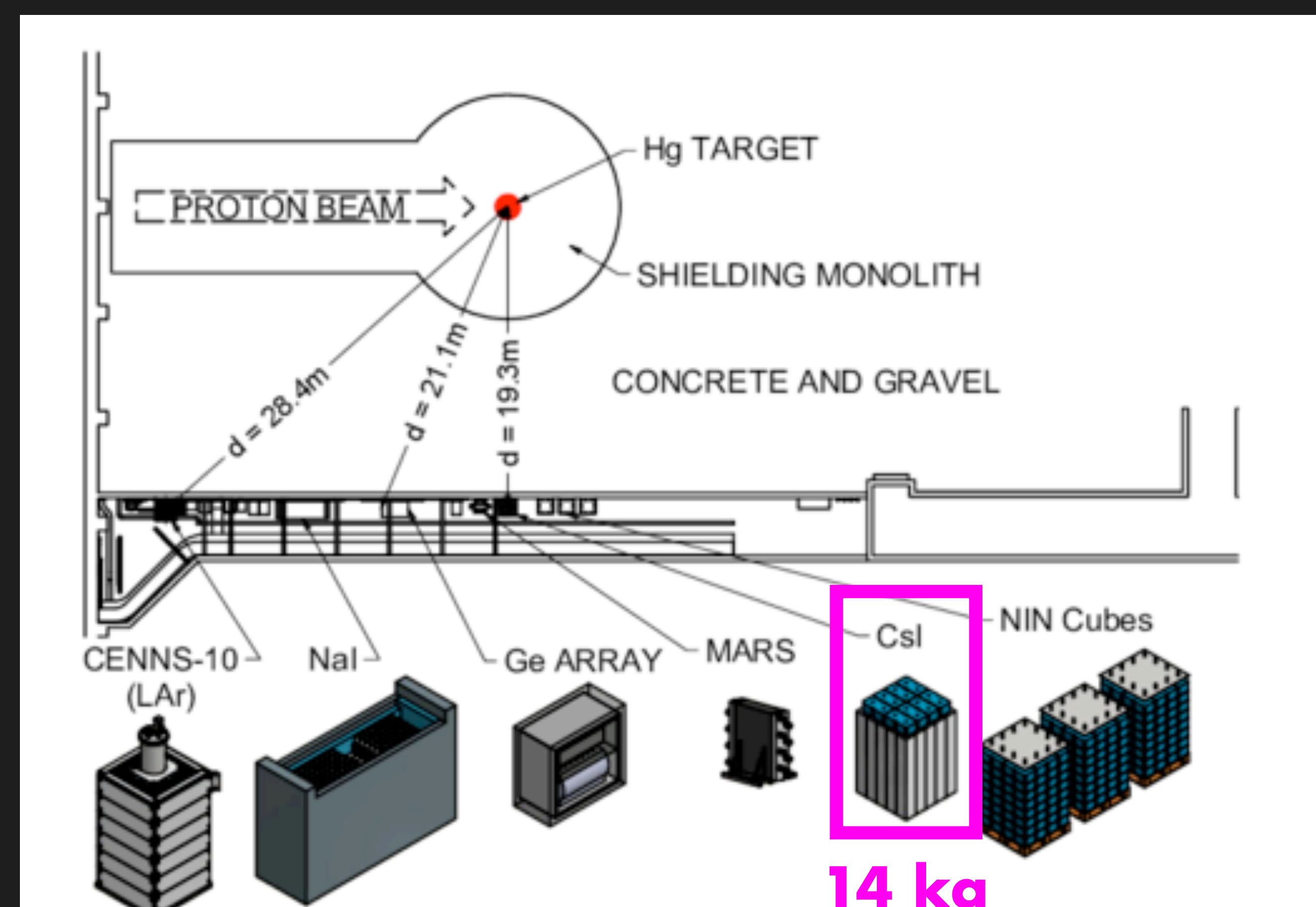
COHERENT-CsI[Na] was the world's smallest working neutrino detector!

D. Akimov et al. (COHERENT) Science 357, 1123–1126 (2017)

COHERENT CsI MEASUREMENT





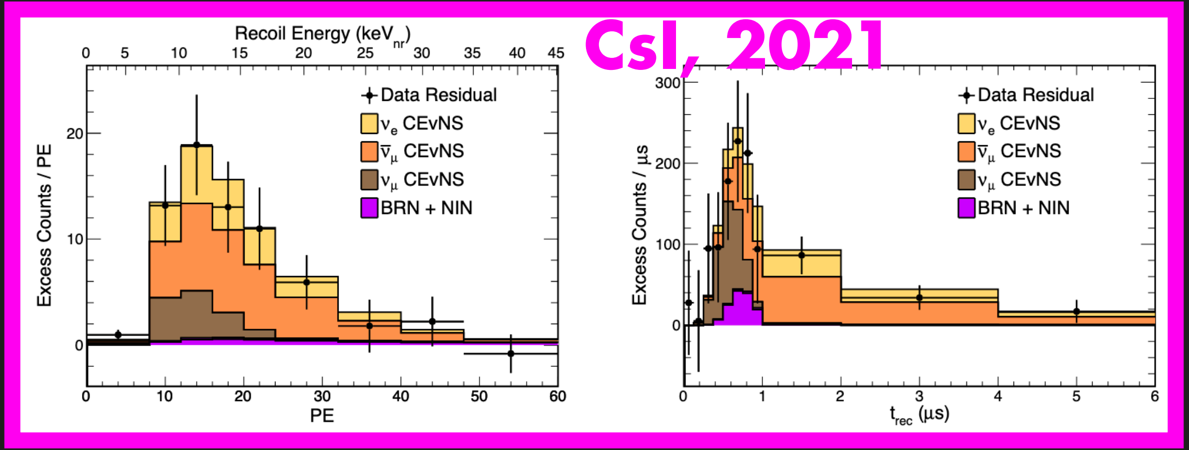


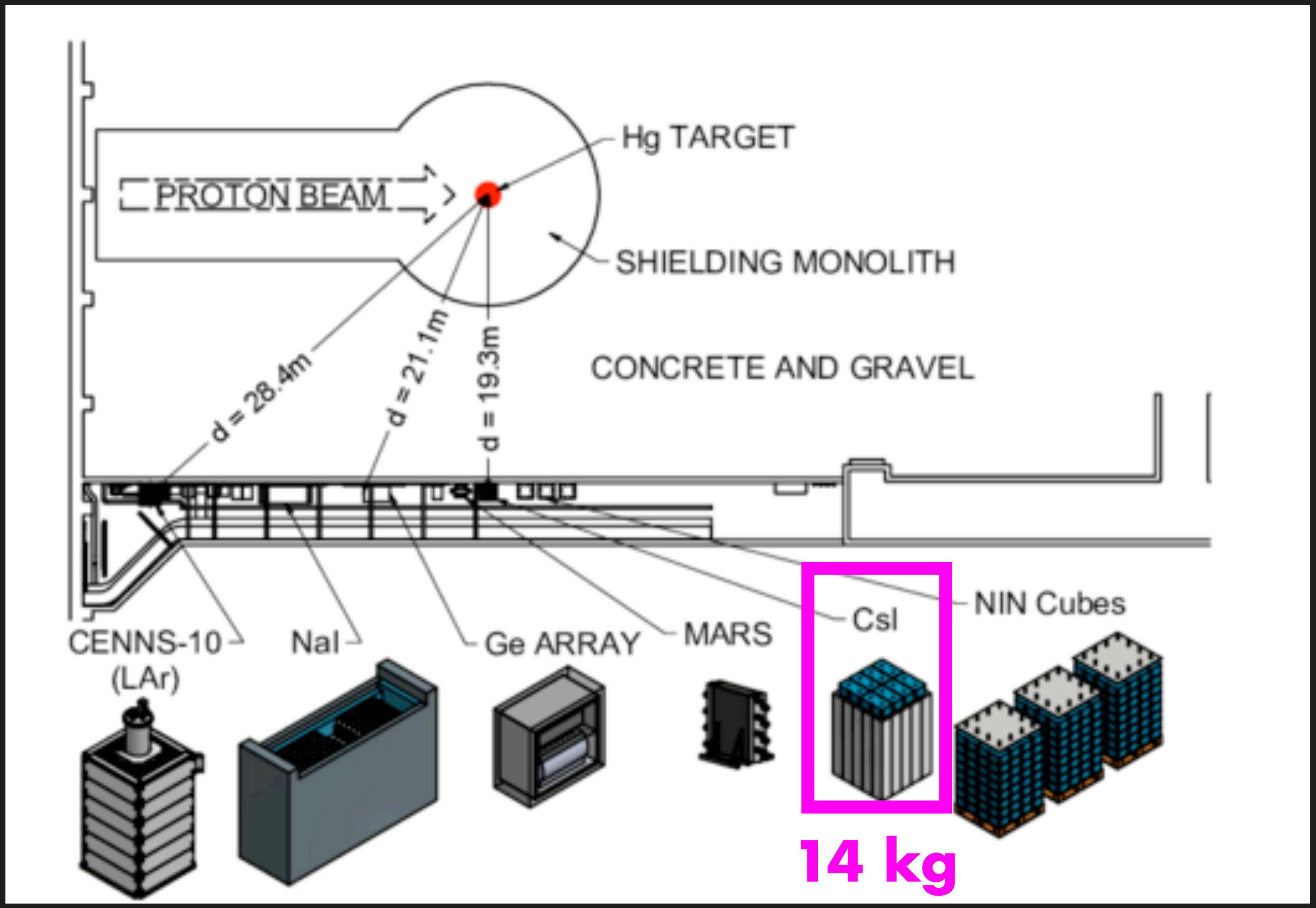
D. Akimov et al. (COHERENT) Science 357, 1123–1126 (2017)
D. Akimov et al. (COHERENT) Phys. Rev. Lett. 129, 081801

COHERENT CsI MEASUREMENT

Full CsI[Na] dataset 2.2 times bigger, before decommissioning in 2019.
Updated scintillator response model, improved systematic uncertainties

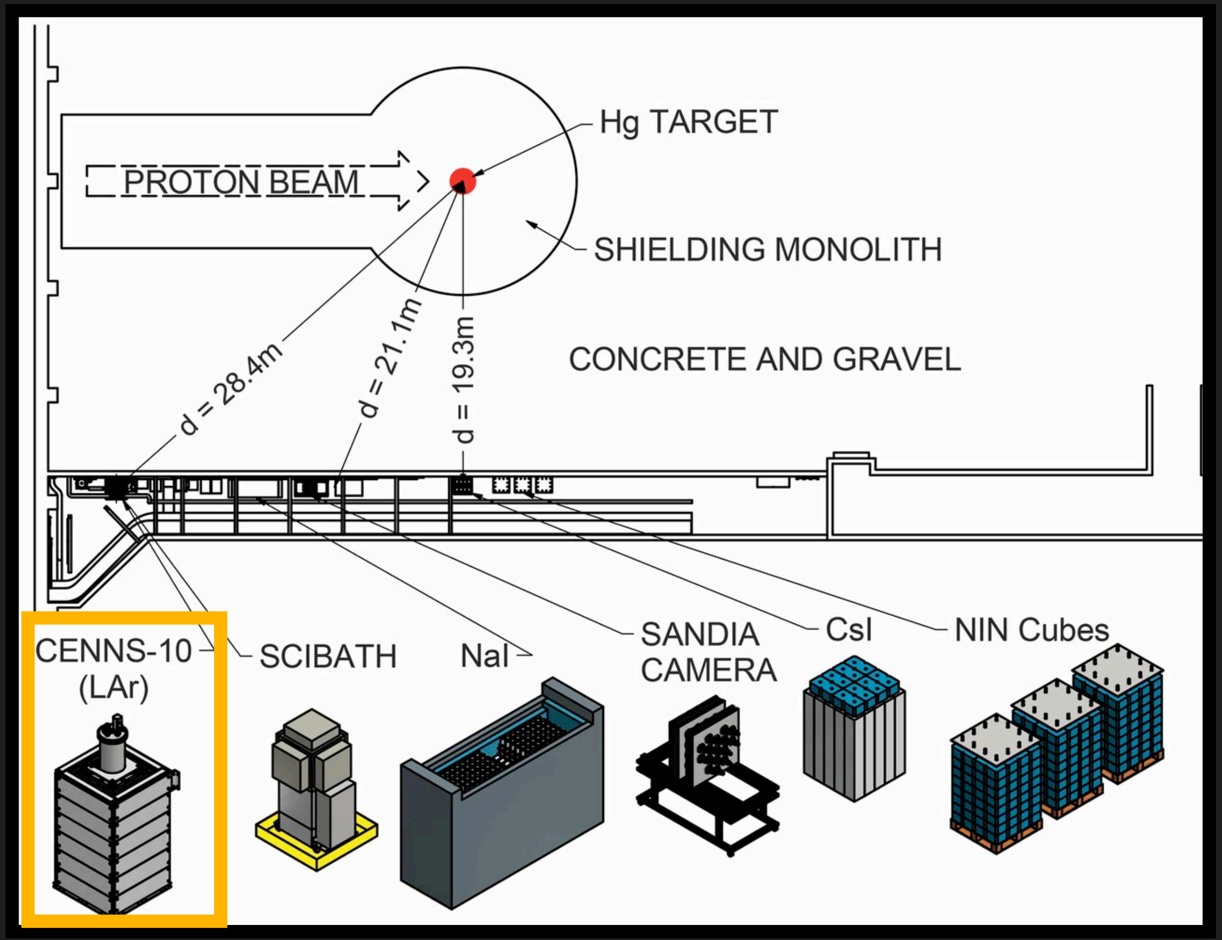
Reject the no-CEvNS hypothesis at $11.6\,\sigma$ level
~300 events observed



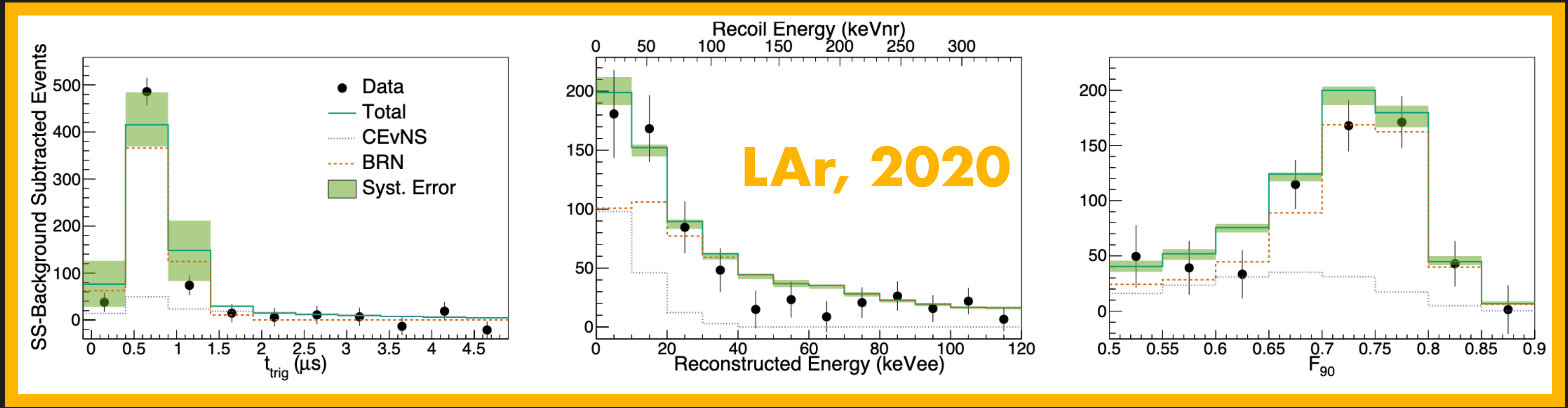


D. Akimov et al. (COHERENT) Science 357, 1123–1126 (2017)
D. Akimov et al. (COHERENT) Phys. Rev. Lett. 129, 081801

COHERENT LAr MEASUREMENT



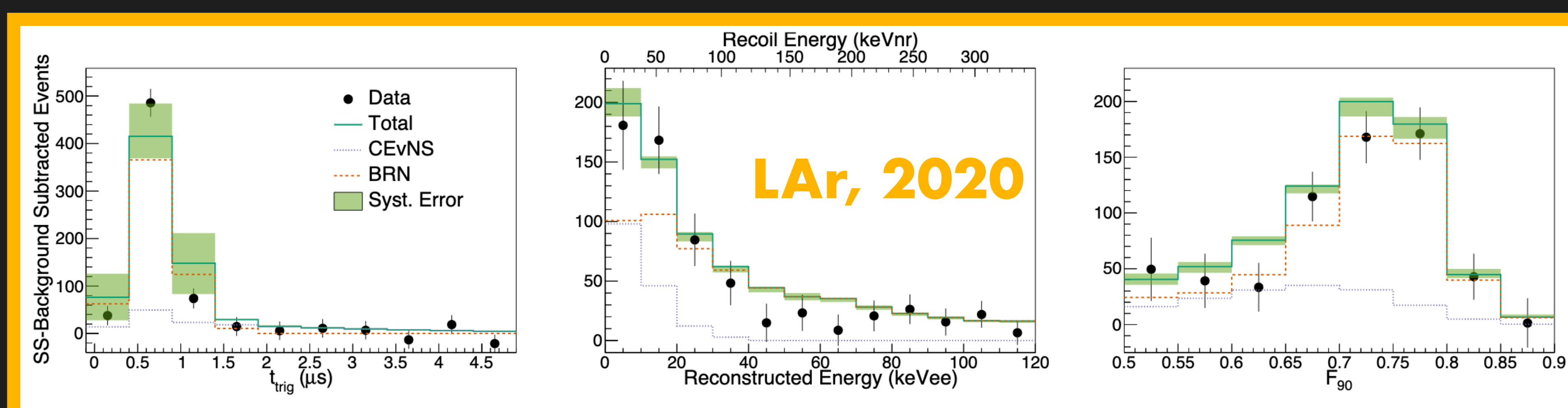
24 kg



D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)

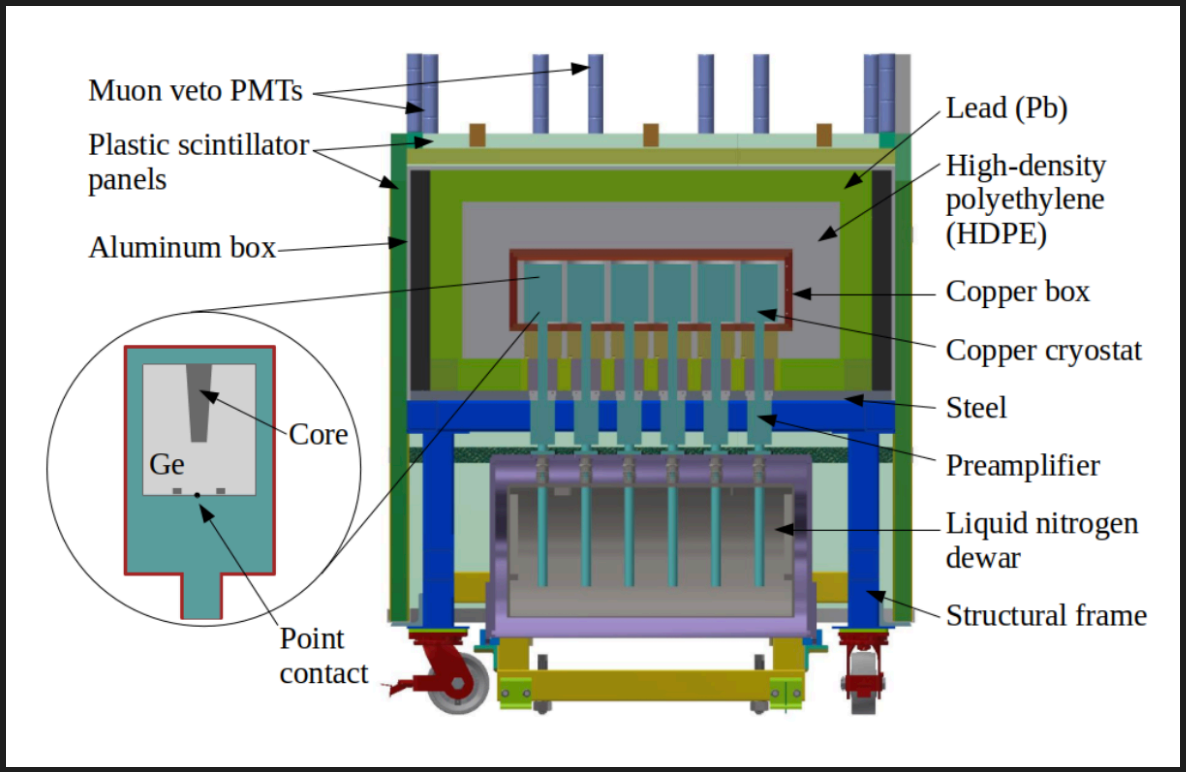
COHERENT LAr MEASUREMENT

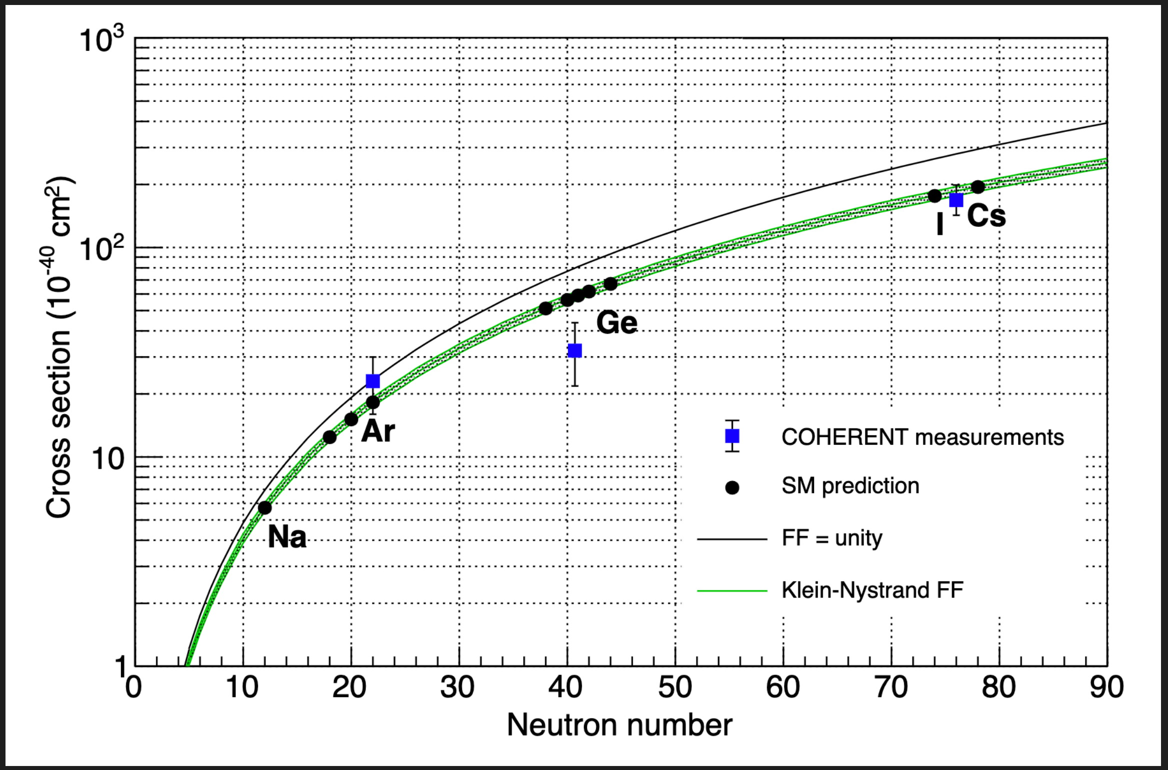
CENNS-10 Lar single-case (scintillation) detector.
Reject the no-CEvNS hypothesis at 3.9 σ level
~150 events observed
First confirmation of its N^2 dependence



D. Akimov et al. (COHERENT). Phys. Rev. Lett. 126, 012002 (2021)

COHERENT-Ge MEASUREMENT

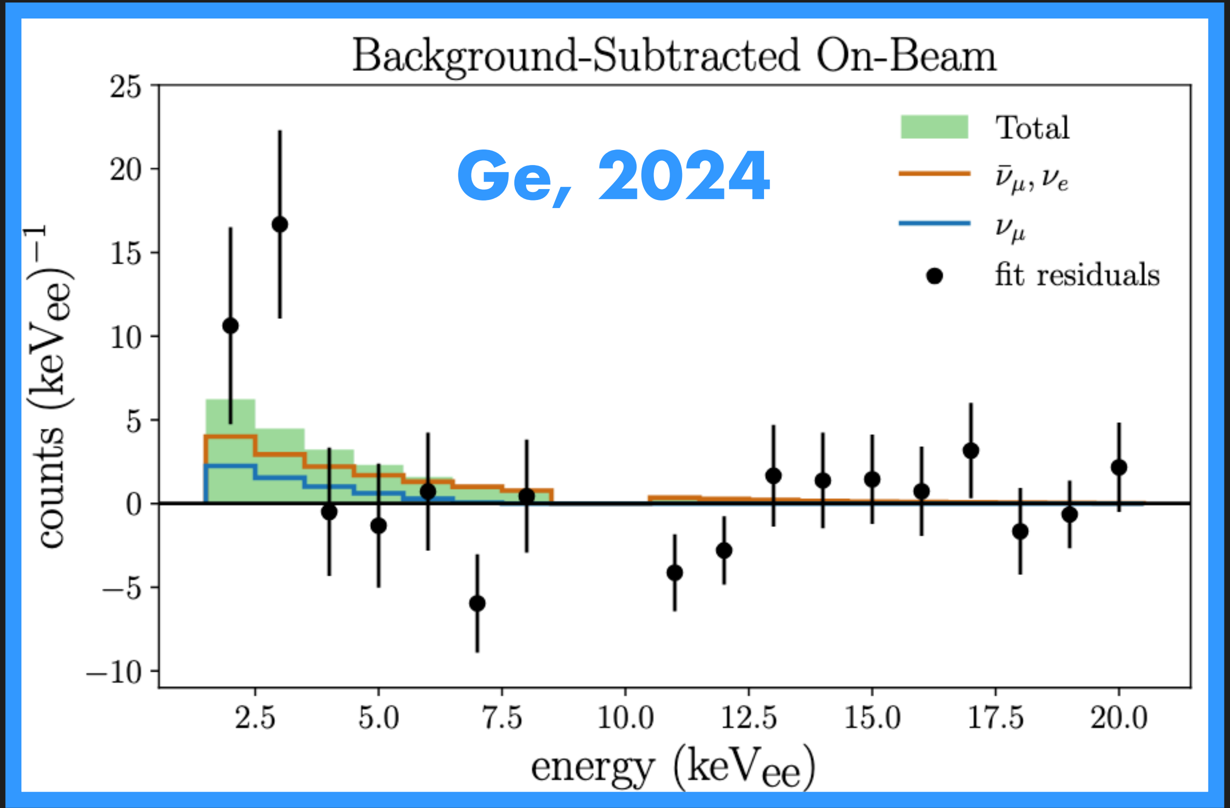




R. Bouabid @Magnificent CEvNS 2024

Ge-Mini detector system
~10 kg

Reject the no-CEvNS hypothesis at 3.9 σ level
~20 events observed



S. Adamski et al. (COHERENT) arXiV: 2406.13806

EVIDENCE OF CEvNS ?
AT NCC-1701 (DRESDEN-II REACTOR)

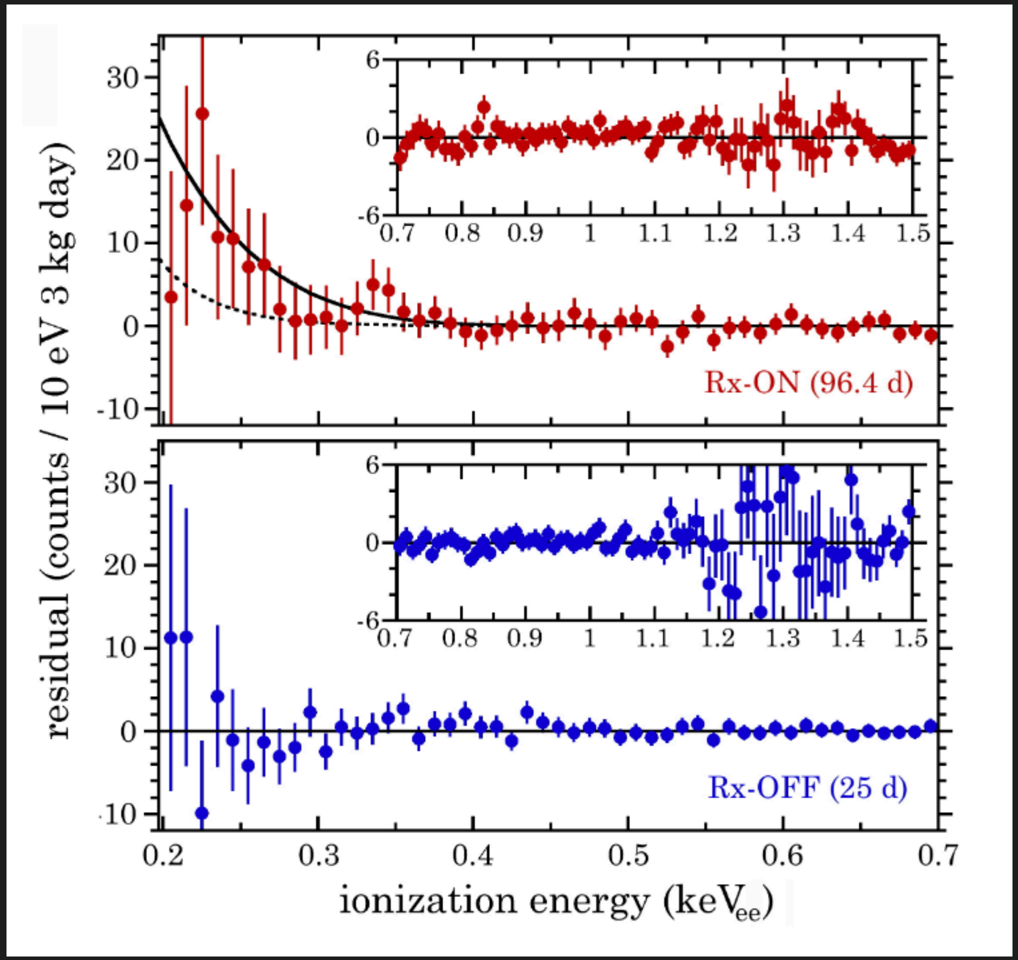
Neutrino source: Dresden-II boiling water reactor (USA) 2.96GW → 4.8×10^{13} neutrinos/sec/cm^2

Detector: NCC-1701, a 2.924 kg ultra-low noise p-type point contact (PPC) Germanium detector

- low energy threshold (0.2 keV_{ee})
- distance to core: 10.39m
- 96.4-day exposure

CEνNS results: suggestive evidence of CEνNS is reported with strong preference (with respect to the background-only hypothesis)

- strongly dependent on quenching factor model

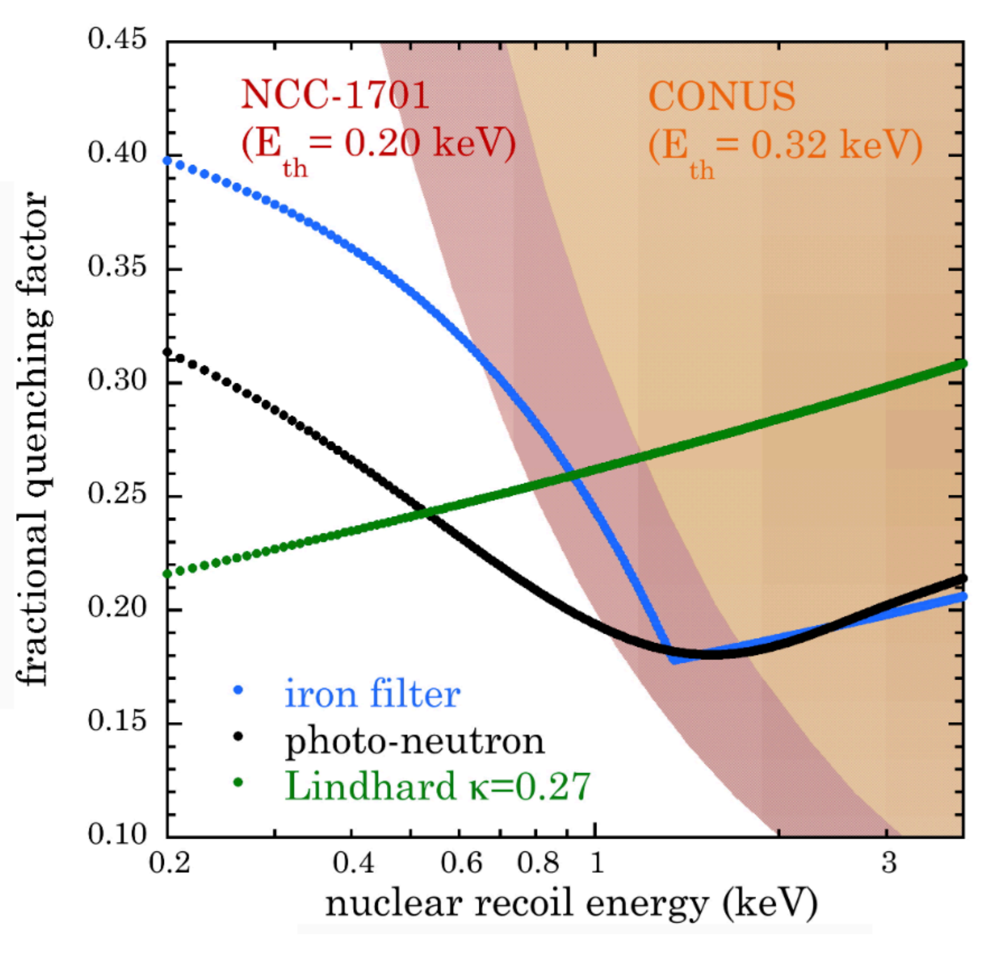


Colaresi, Collar et al. Phys. Rev. Lett. 129 (2022) 211802

EVIDENCE OF CEνNS ? AT NCC-1701 (DRESDEN-II REACTOR)

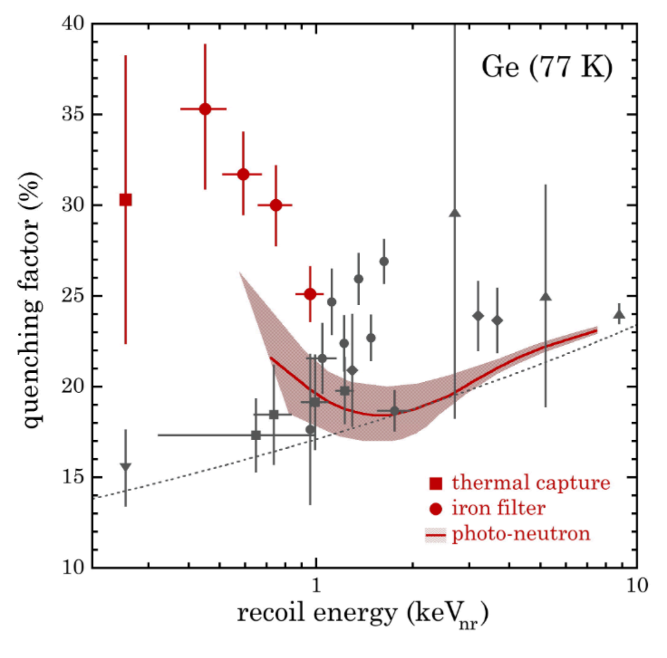
The quenching factor (QF) describes the observed reduction in ionization yield produced by a nuclear recoil when compared to an electron recoil of same energy

- often not (yet) well known at low recoil energies for CEνNS
- major uncertainty!



Colaresi et al., Phys. Rev. D 104, 072003 (2021)
Colaresi et al., 2202.09672 [hep-ex]

$$QF = E_{meas}/E_{nuclear\ recoil}$$

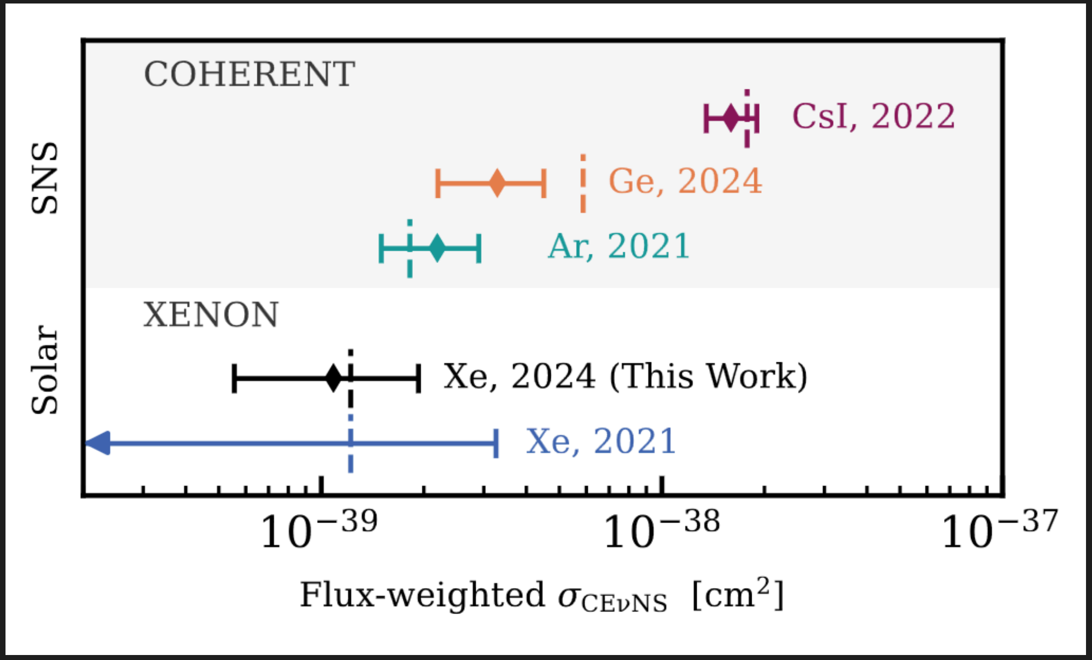


J.I. Collar et al, Phys. Rev. D 103, 122003

CONUS: Direct measurement of ionization quenching factor: k=0.162+-0.004 (compatible with Lindhard)

CONUS Phys. Rev. Lett. 126, 041804

XENONnT

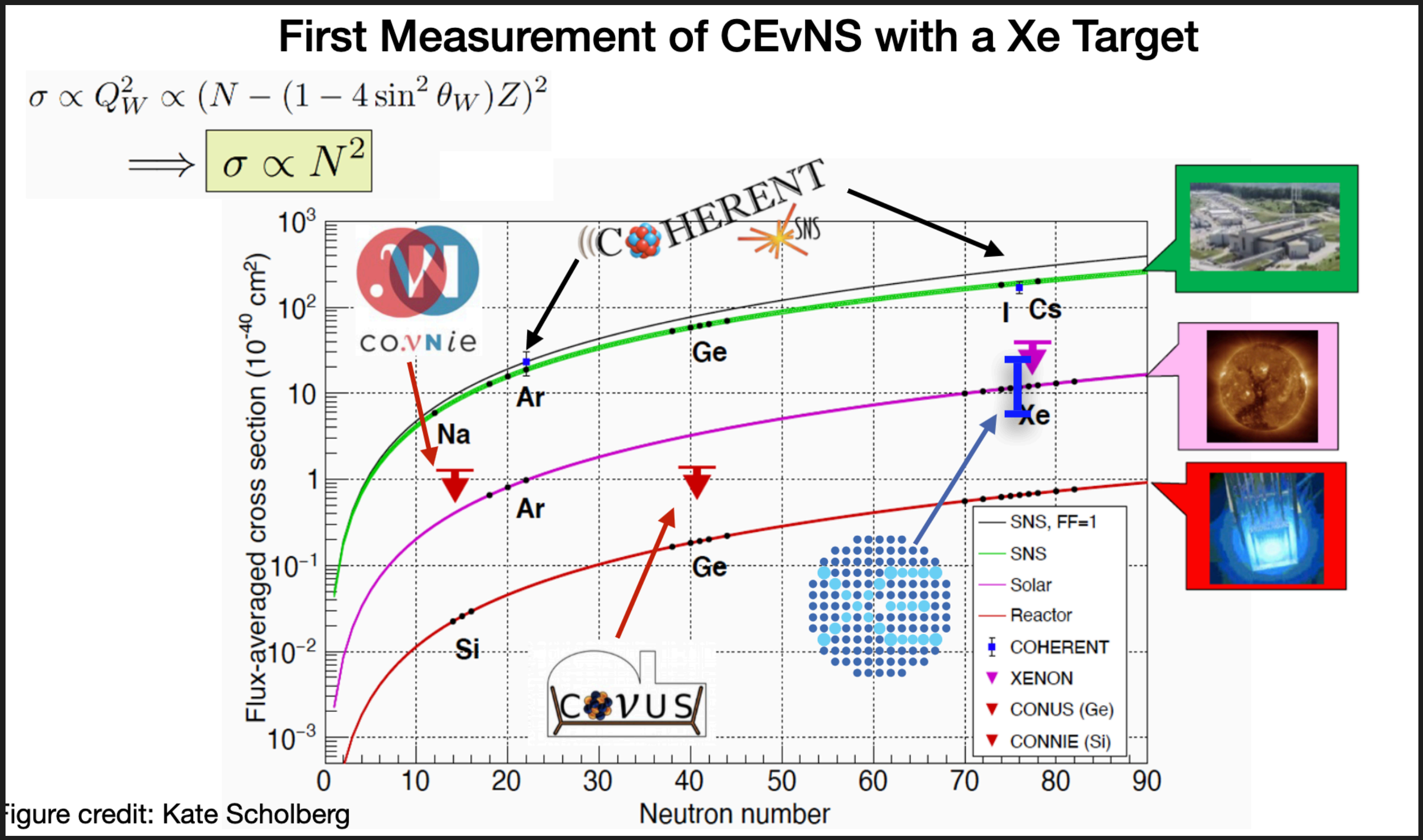


Aprile et al. arXiv:2408.02877v1

XENONnT "measures" the CEvNS signal in Xe from solar 8B neutrinos for the first time.

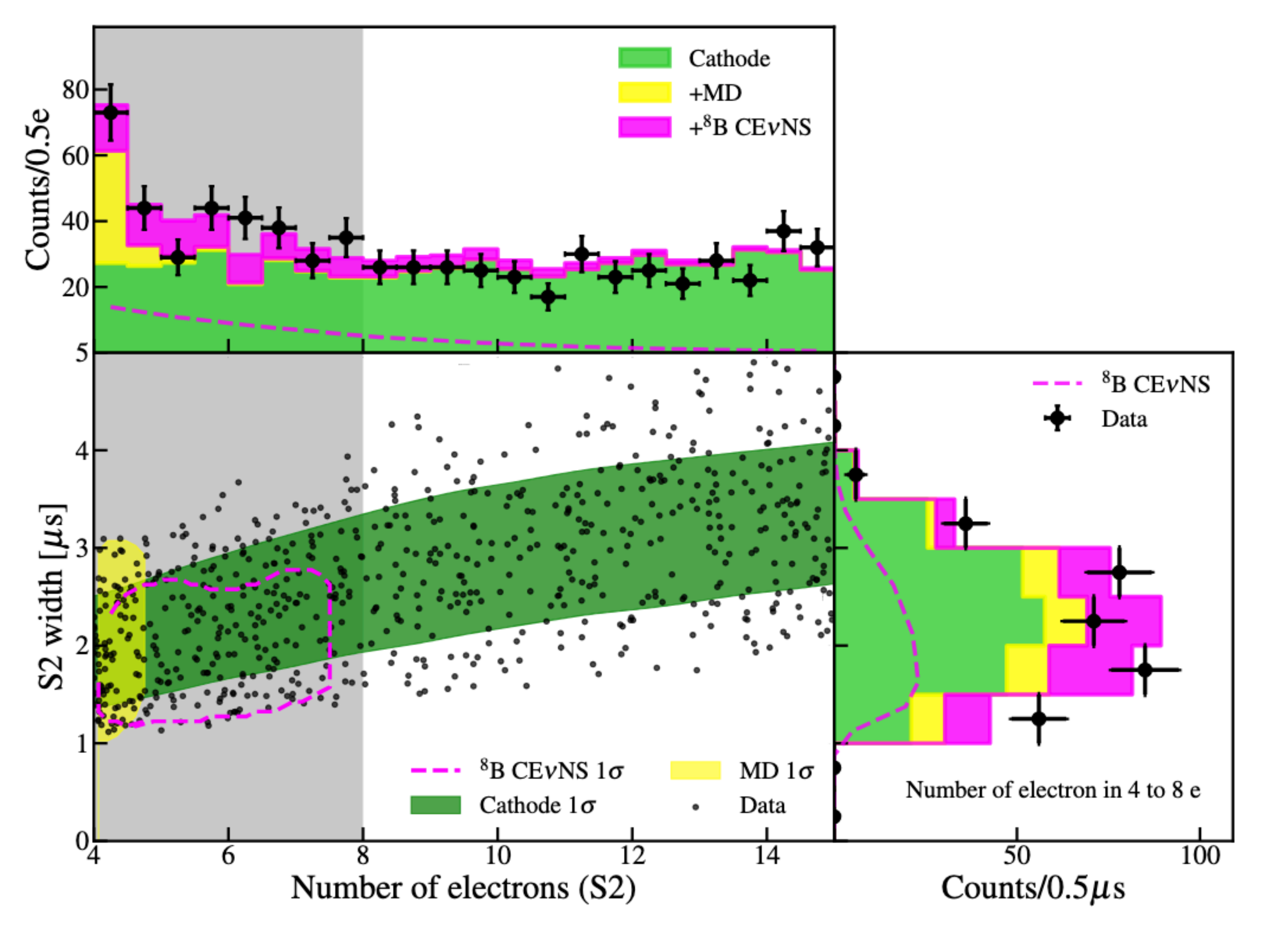
The background-only hypothesis is disfavored at 2.73σ

From Fei Gao's talk @ IDM 2024



PandaX-4T

A combined analysis yields a best-fit ^{8}B neutrino signal of $3.5\ (75)$ events from the scintillation and ionization (ionization-only) data sample.



Z. Bo et al. (PandaX collaboration) arXiv:2407.10892

The background-only hypothesis is disfavored at $2.64\ \sigma$ significance

LIST OF EXPERIMENTAL PAPERS

1. Coherent Elastic Neutrino-Nucleus Scattering Search in the νGeN Experiment, Phys.Part.Nucl.Lett. 21 (2024) 4, 680-682
2. First Measurement of SolarB Neutrino Flux through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T, Zihao Bo et al. (PandaX), arXiv:2407.10892
3. First detection of coherent elastic neutrino-nucleus scattering on germanium, S. Adamski et al. (COHERENT), arXiv:2406.13806
4. Final CONUS results on coherent elastic neutrino-nucleus scattering at the Brokdorf reactor, N. Ackermann et al. (CONUS), arXiv:2401.07684
5. First results of the nuGeN experiment on coherent elastic neutrino-nucleus scattering, I. Alekseev et al. (nuGeN), Phys.Rev.D 106 (2022) L051101, arXiv:2205.04305.
6. Suggestive evidence for Coherent Elastic Neutrino-Nucleus Scattering from reactor antineutrinos, J. Colaresi, J.I. Collar, T.W. Hossbach, C.M. Lewis, K.M. Yocum, Phys.Rev.Lett. 129 (2022) 211802, arXiv:2202.09672
7. Search for coherent elastic neutrino-nucleus scattering at a nuclear reactor with CONNIE 2019 data, Alexis Aguilar-Arevalo et al. (CONNIE), JHEP 22 (2020) 017, arXiv:2110.13033
8. Measurement of the Coherent Elastic Neutrino-Nucleus Scattering Cross Section on CsI by COHERENT, D. Akimov et al. (COHERENT), Phys.Rev.Lett. 129 (2022) 081801, arXiv:2110.07730
9. First results from a search for coherent elastic neutrino-nucleus scattering (CEvNS) at a reactor site, J. Colaresi, J. I. Collar, T. W. Hossbach, A. R. L. Kavner, C. M. Lewis, A. E. Robinson, K. M. Yocum, Phys.Rev.D 104 (2021) 072003, arXiv:2108.02880
10. Search for coherent elastic scattering of solar 8B neutrinos in the XENON1T dark matter experiment, E. Aprile et al. (XENON), Phys.Rev.Lett. 126 (2021) 091301, arXiv:2012.02846
11. COHERENT Collaboration data release from the first detection of coherent elastic neutrino-nucleus scattering on argon, D. Akimov et al. (COHERENT), arXiv:2006.12659
12. First Detection of Coherent Elastic Neutrino-Nucleus Scattering on Argon, D. Akimov et al. (COHERENT), Phys.Rev.Lett. 126 (2021) 012002, arXiv:2003.10630
13. First Constraint on Coherent Elastic Neutrino-Nucleus Scattering in Argon, D. Akimov et al. (COHERENT), Phys.Rev. D100 (2019) 115020, arXiv:1909.05913
14. COHERENT Collaboration data release from the first observation of coherent elastic neutrino-nucleus scattering, D. Akimov et al. (COHERENT), arXiv:1804.09459
15. Observation of Coherent Elastic Neutrino-Nucleus Scattering, D. Akimov et al. (COHERENT), Science 357 (2017) 1123-1126, arXiv:1708.01294

CEνNS CROSS SECTION: STANDARD MODEL

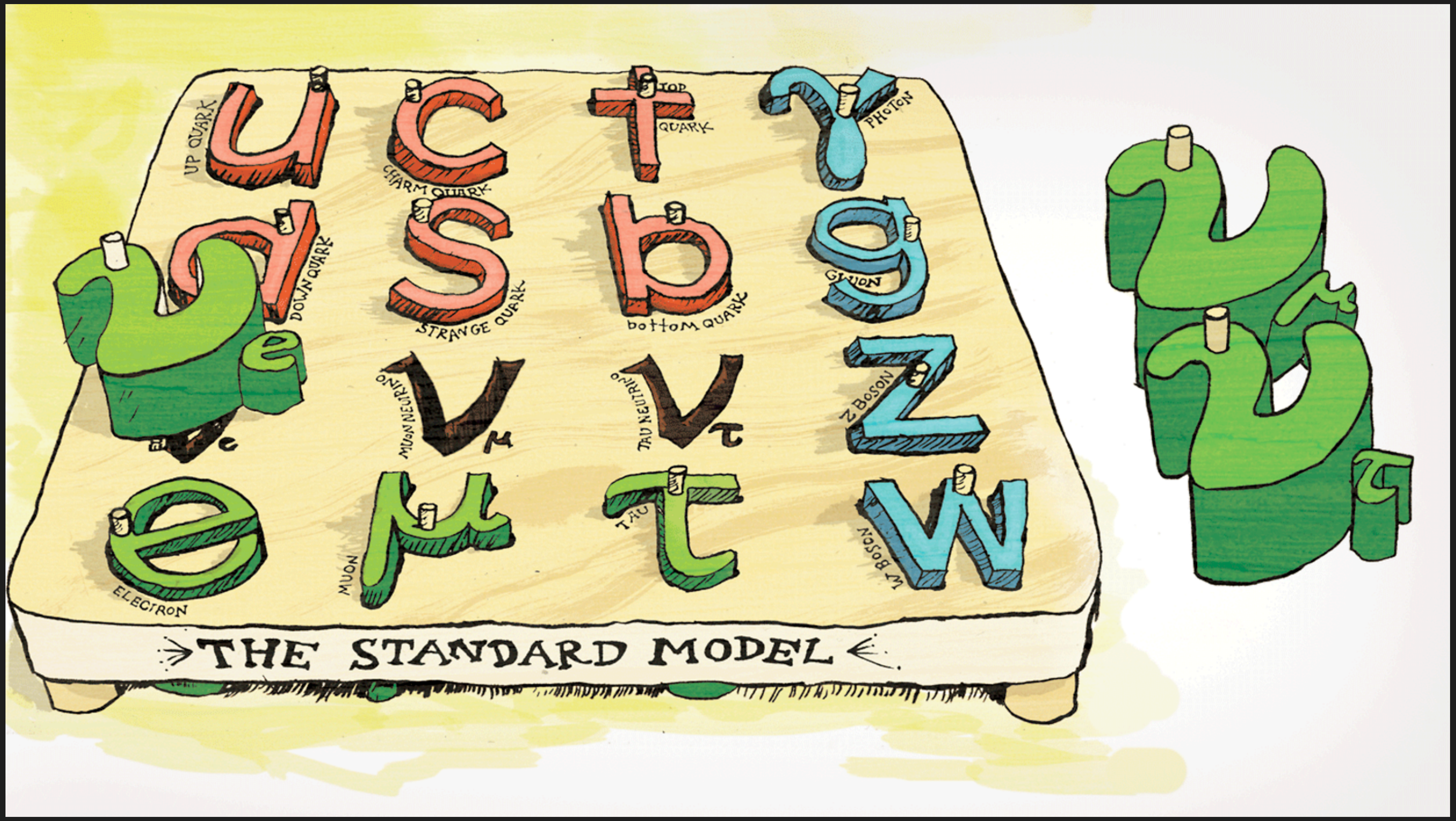


Illustration by Sandbox Studio, Chicago

CEνNS CROSS SECTION IN THE SM

Interplay of particle, hadronic and nuclear physics

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm SM} \propto \left|\sum_i c_i \,{\rm kin}_i\, \mathscr{F}_i\right|^2$$

Kin_i : kinematics terms
C_i: particle physics coefficients (coupling neutrino-quarks)
$\mathscr{F}_i$: nuclear structure physics

In the Donnelly-Walecka approach any semi-leptonic nuclear process at low and intermediate energies can be described by an effective interaction Hamiltonian, written in terms of the leptonic and hadronic currents

$$\langle \mathrm{final} \,|\, \mathscr{L} \,|\, \mathrm{initial} \rangle = \langle \mathrm{final} \,|\int d^3\mathbf{x}\; \hat{j}^{\rm lept}_{\mu}(\mathbf{x})\; \hat{J}^{\mu}(\mathbf{x})\,|\, \mathrm{initial}\rangle$$

The accurate evaluation of the required transition matrix elements is obtained on the basis of reliable nuclear wave functions.

CEνNS CROSS SECTION IN THE SM

We follow a multi-step process:

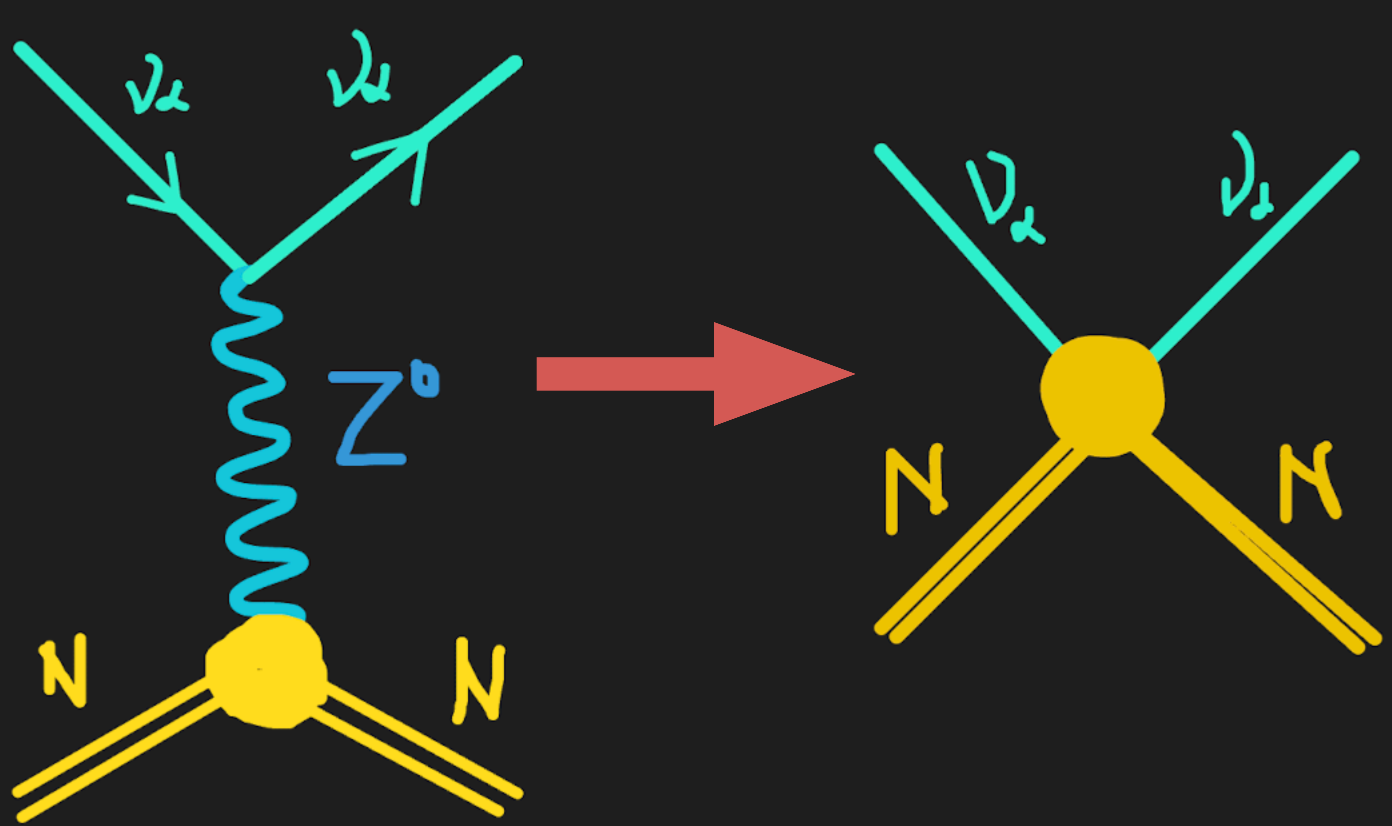
1. First, we define the effective neutrino-quark interaction in the non-relativistic limit (small momentum transfer) — same as going from the electroweak theory to the Fermi four-fermion theory
2. Second, we need to account for the quark content of the nucleons: we need to take the quark field operators and express them in terms of nucleon ones
3. Finally, we need to promote the operators at the nucleon level to the nuclear one. We need a nuclear model.

Freedman Phys. Rev. D 9, 1389-1392 (1974)
Drukier, Stodolsky, PRD 30 (1984) 2295
Amanik+ Astropart.Phys. 24 (2005) 160-182
J. Barranco+ JHEP 0512 (2005) 021
Papoulias+ Advances in High Energy Physics, vol. 2015, 763648
Lindner+ JHEP03(2017)097
Hoferichter+ Physical Review D 102, 074018 (2020)
Tomalak+ JHEP 2102, 097 (2021) (Radiative corrections)
Pandey Prog.Part.Nucl.Phys. (2023)
Khaleq+ arXiv:2405.20060

CEνNS CROSS SECTION IN THE SM

We want to compute the cross-section for the process $\nu_\ell \mathcal{N} \to \nu_\ell \mathcal{N}$.
Elastic process: final state nucleus remains unvaried.

The momentum transfer is much smaller than the mass of the mediator, so we can define an effective Lagrangian for the process.



CEνNS CROSS SECTION IN THE SM

$$\mathscr{L}_{\text{eff}}^{\text{NC}} = \frac{\text{G}_\text{F}}{\sqrt{2}} \sum_q \left[\bar{\nu}\gamma^\mu(g_V^\nu - g_A^\nu\gamma^5)\nu\right] \left[\bar{q}\gamma_\mu(g_V^q - g_A^q\gamma^5)q\right]$$

The Lagrangian is defined as a sum of the interactions at the quark level.
The vector and axial couplings at the tree level are:

$$g_V^\nu = 1/2$$

$$g_A^\nu = 1/2$$

$$g_V^q = \boxed{T_3^q} - 2Q^q \sin^2\theta_\text{w} = \begin{cases} 1/2 - 1/3\sin^2\theta_\text{w} & \text{q = u,c,t} \\ -1/2 + 2/3\sin^2\theta_\text{w} & \text{q = d,s,b} \end{cases}$$

3rd component
Weak Isospin

The term $\bar{q}\gamma^\mu\gamma^5 q$ is the spin-dependent one. It is suppressed compared to the vector current. Only relevant for light nuclei with non-zero spin. Nuclei with even number of protons and neutrons have zero spin, so that axial terms vanish.

CEνNS CROSS SECTION IN THE SM

Promote the quark operators to the nucleon level.
Project the quark current on the initial and final nucleon states:

$$\langle \eta(p_f) | \mathcal{O}_q | \eta(p_i) \rangle = \langle \eta(p_f) | \bar{q}\gamma^\mu q | \eta(p_i) \rangle$$

$$= \bar{u}_N \left(F_1^{q,\eta}(\mathbf{q}^2)\gamma^\mu + F_2^{q,\eta}(\mathbf{q}^2) \frac{i\sigma^{\mu\nu}q_\nu}{2m_\eta}\gamma^\mu \right) u_N$$

The nucleon matrix element can be parametrized by means of its transformation properties under the Lorentz symmetry, spatial parity and time reversal. F_2 is suppressed (involves spin and goes as q/m_η). At zero momentum transfer, vector currents 'count' the valence quarks in the nucleon.

$$\sum_{\eta=n,p} \sum_q \langle g_V^q \eta(p_f) | \bar{q}\gamma^\mu q | \eta(p_i) \rangle$$

$$= (g_V^u + 2g_V^d)\bar{n}\gamma^\mu n + (2g_V^u + g_V^d)\bar{p}\gamma^\mu p$$

g_V^p g_V^n

CEvNS CROSS SECTION IN THE SM

Final step: we need to go from interaction with nucleons to interaction with the nucleus.
At non-zero momentum transfer there will be a form-factor suppression given by the specific nuclear wave.
Construct the nuclear operator:

$$\langle \mathcal{N}(k_f) \,|\, \bar{\eta}\gamma^\mu\eta \,|\, \mathcal{N}(k_i)\rangle = \boxed{N_\eta}\, \bar{\mathcal{N}}\gamma^\mu\mathcal{N} F_{\rm v}^\eta(\mathbf{q}^2)$$

Counts nucleons inside nuclei

$$= \left[Z g_{\rm v}^p F_{\rm v}^p(\mathbf{q}^2) + N g_{\rm v}^n F_{\rm v}^n(\mathbf{q}^2)\right] \bar{\mathcal{N}}\gamma^\mu\mathcal{N}$$

The weak form factor is defined as

$$\tilde{F}_{\rm w}(\mathbf{q}^2) = \left[Z g_{\rm v}^p F_{\rm v}^p(\mathbf{q}^2) + N g_{\rm v}^n F_{\rm v}^n(\mathbf{q}^2)\right]$$

And then normalized to one through (valid at q $\to 0$)

$$Q_{\rm W} = (Z g_{\rm v}^p + N g_{\rm v}^n) = -N/2 + (1/2 - 2\sin^2\theta_{\rm w})Z \qquad F_{\rm w}(\mathbf{q}^2) = \frac{\tilde{F}_{\rm w}(\mathbf{q}^2)}{Q_{\rm W}}$$

CEνNS CROSS SECTION IN THE SM

$$\mathscr{L}_{\rm eff}^{\rm NC} = \frac{\rm G_F}{\sqrt{2}} \sum_q \left[\bar{\nu}\gamma^\mu P_L \nu\right] \left[Q_{\rm w} F_{\rm w}(\mathbf{q}^2) \bar{\mathcal{N}} \gamma_\mu \mathcal{N}\right]$$

Assume the nucleus is in a fermionic ground state, we can compute the amplitude squared of the process, starting from the matrix element

$$\mathscr{M}^{ss'rr'} = \frac{\rm G_F}{\sqrt{2}} Q_{\rm w} F_{\rm w}(\mathbf{q}^2) \left[\bar{u}^{s'}(p')\gamma^\mu P_L u^s(p)\right] \left[\bar{u}^{r'}(k')\gamma_\mu u^r(k)\right]$$

$$|\mathscr{M}|^2 = \frac{\rm G_F^2}{4} Q_{\rm w}^2 F_{\rm w}^2(\mathbf{q}^2) L^{\mu\nu} W_{\mu\nu}$$

Lepton tensor ($L^{\mu\nu}$) — Hadron tensor ($W_{\mu\nu}$)

CEνNS CROSS SECTION IN THE SM

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\bigg|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{128\pi}\frac{Q_{\rm w}^2 F_{\rm w}^2(\mathbf{q}^2)}{E_\nu^2 m_N} L^{\mu\nu}W_{\mu\nu}$$

Performing all traces calculations one obtains

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\bigg|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2(\mathbf{q}^2) Q_{\rm w}^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu} + \frac{E_{\rm nr}^2}{2E_\nu^2}\right)$$

$$Q_{\rm W} = -N/2 + (1/2 - 2\sin^2\theta_{\rm w})Z$$

$\sin^2\theta_w = 0.23$ → protons unimportant

Neutron contribution dominates

FORM FACTORS

The form factor corrects for scattering that is not completely coherent at higher energies. It encodes information about the nuclear densities through a Fourier transform of the nuclear charge density distribution

$$F_{n,p}(q^2) = \frac{1}{Q_a} \int \rho_{p,n}(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}$$

Q_a is the charge of the entire distribution.
Assuming a spherically symmetrical distribution:

$$F_{n,p}(q^2) = \frac{4\pi}{Q_a q} \int \rho_{p,n}(r) \sin(q \cdot r) r dr$$

Patton et al, arXiv:1207.0693
Bednyakov, Naumov, arXiv:1806.08768
Papoulias et al, Phys.Lett. B800 (2020) 135133
Ciuffoli et al, arXiv:1801.02166
Canas et al, arXiv:1911.09831
Van Dessel et al, arXiv:2007.03658
Aristizabal-Sierra JHEP 1906:141 (2019)
Coloma+ JHEP 08 (2020) 08, 030
Aristizabal-Sierra Phys.Lett.B 845 (2023) 138140

FORM FACTORS

We can expand the form factor in terms of q:

$$F_{n,p}(q^2) \approx \int \rho_{p,n}(r)\left(1 - \frac{q^2}{3!}r^2 + \frac{q^4}{5!}r^4 - \frac{q^6}{7!}r^6 + \ldots\right) r^2 dr$$

$$\approx 1 - \frac{q^2}{3!}\langle R^2_{p,n}\rangle + \frac{q^4}{5!}\langle R^4_{p,n}\rangle - \frac{q^6}{7!}\langle R^6_{p,n}\rangle + \ldots$$

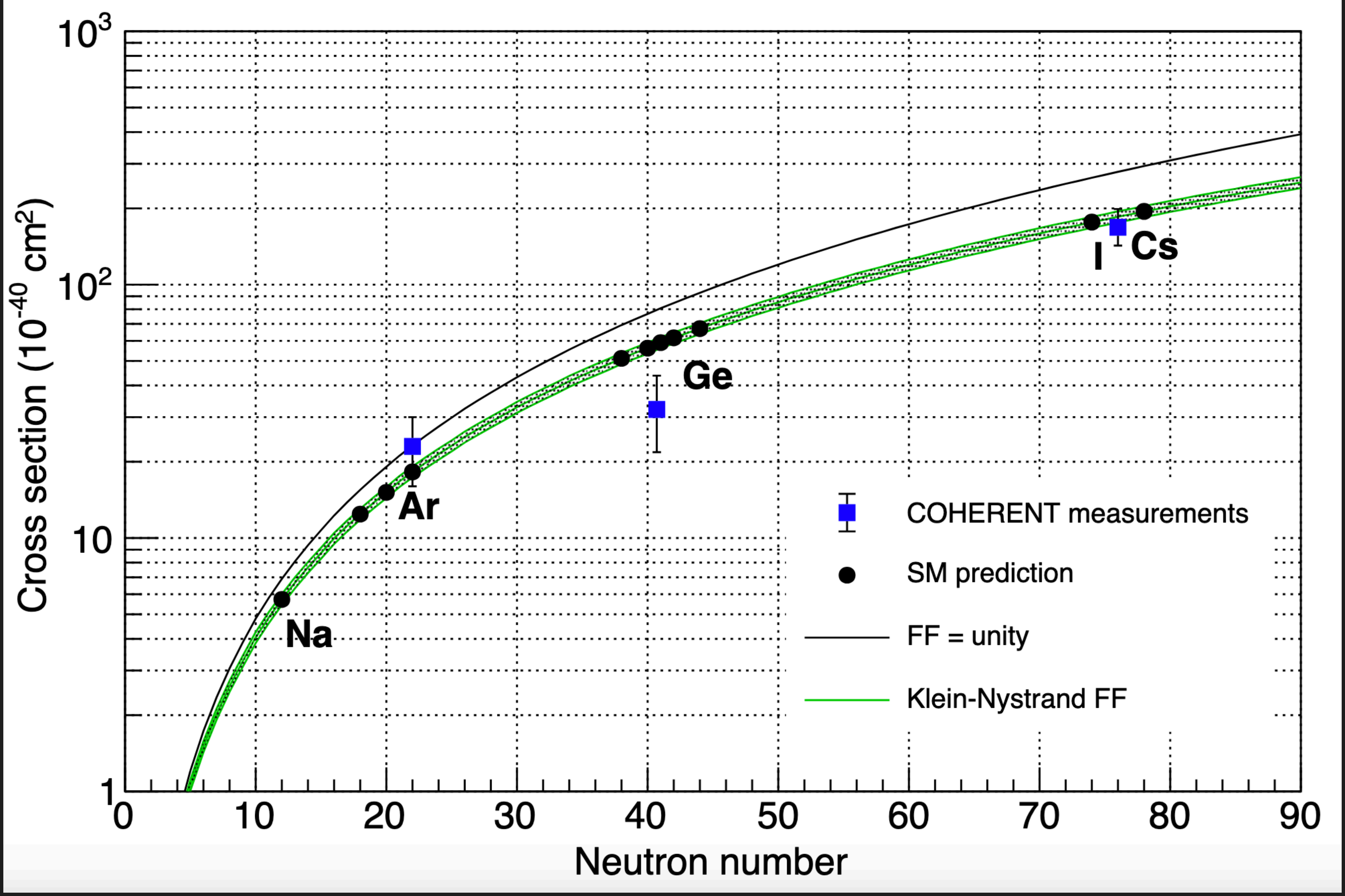
with the k-th radial moment defined as

Patton et al, arXiv:1207.0693
Papoulias et al, Phys.Lett. B800 (2020) 135133

$$\langle R^k_{p,n}\rangle = \frac{\int \rho_{p,n}(\vec{r}) r^k d^3\vec{r}}{\int \rho_{p,n}(\vec{r}) d^3\vec{r}}$$

In this way the form factor is a sum of the even moments of the neutron density distribution, that represent physically relevant and measurable quantities.

FORM FACTORS



From Ryan Bouabid's talk @Magnificent CEvNS2024

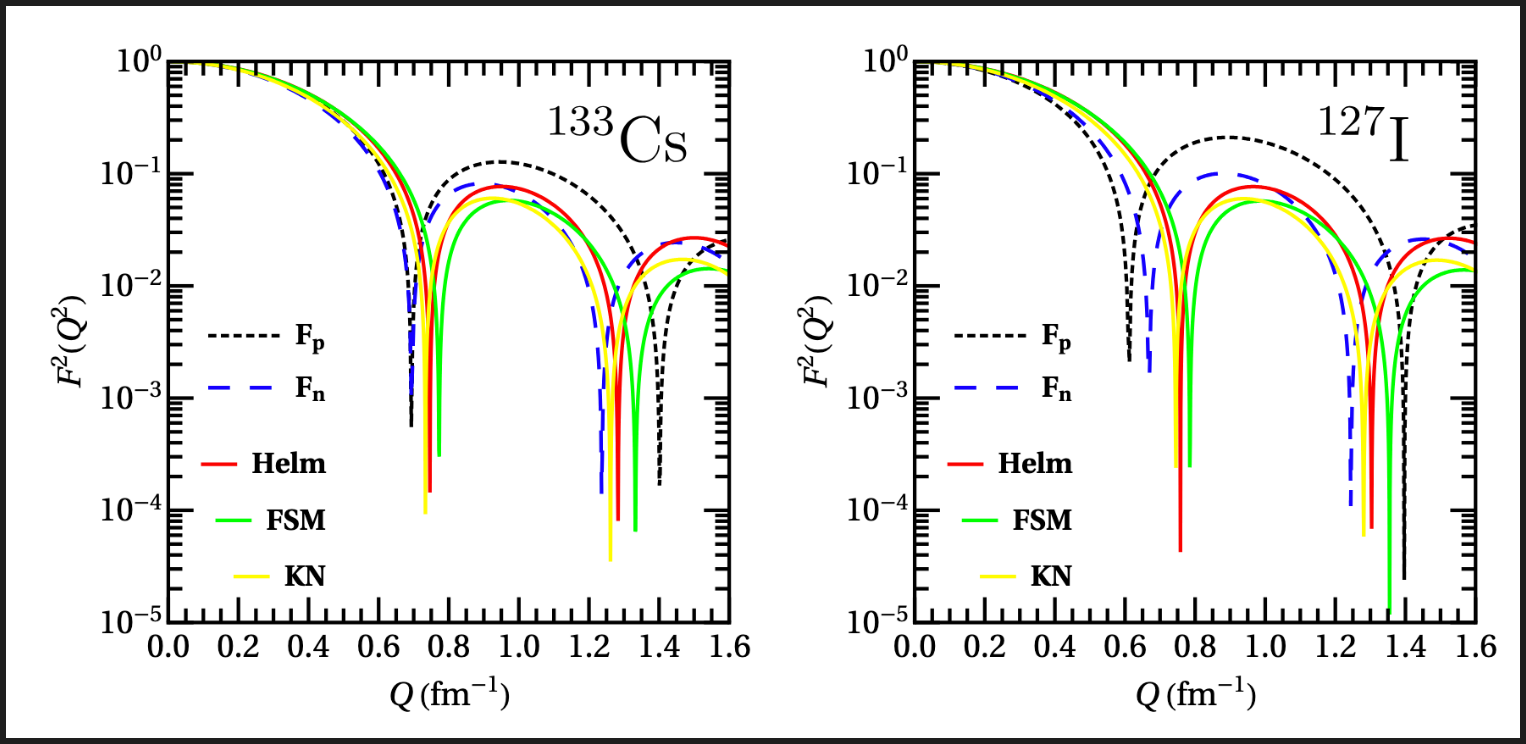
FORM FACTORS

How to obtain the nuclear form factors:

- Nuclear structure calculations; S. Kosmas+ Nucl. Phys. A 570 (1994) 637
  Papoulias+ Phys.Lett. B800 (2020) 135133

- Use of available experimental data: the proton nuclear form factors are computed by means of a model-independent analysis (using a Fourier-Bessel expansion model or others) of the electron scattering data for the proton charge density; De Vries+ Data and Nucl. Data Tables 36 (1987) 495536

- Use of analytical approximations for the nuclear form factors.



Papoulias+ Phys.Lett. B800 (2020) 135133

FORM FACTORS: PARAMETRIZATIONS

The basic properties of nucleonic distributions can be described by different parametrizations.

J. Engel, Phys.Lett. B 264 (1991) 114

In the Helm model, the nuclear form factor is given by the convolution of two nucleonic densities: a uniform-density one with a cut-off radius R_0 and a second one with a Gaussian profile, in terms of the surface thickness s.

$$F_{\mathrm{Helm}}(q^2) = 3\frac{j_1(qR_0)}{qR_0}e^{(-qs)^2/2}$$

Helm Phys. Rev. 104 (1956) 1466–1475

$j_1(x)$ denotes the 1st-order spherical Bessel function.

The root-mean-square (rms) radius $\langle R_n^2 \rangle = \frac{3}{5}R_0^2 + 3s^2$

s = 0.9 from muon spectroscopy data Fricke Nucl.Data Tabl. 60 (1995) 177–285

FORM FACTORS: PARAMETRIZATIONS

The Klein-Nystrand form factor follows from the convolution of short-range Yukawa potential with $a_k = 0.7$ fm, over a distribution approximated as a hard sphere with radius R_a.

$$F_{\mathrm{KN}}(q^2) = 3\frac{j_1(qR_A)}{qR_A}\left[1 + (qa_k)^2\right]^{-1}$$

Klein, Nystrand Phys. Rev. C60 (1999) 014903

$j_1(x)$ denotes the 1st-order spherical Bessel function.

The root-mean-square (rms) radius $\langle R_n^2 \rangle = \frac{3}{5}R_A^2 + 6a_k^2$

semi-empirical formula

$$R_A \approx 1.2 \times A^{1/3}\mathrm{fm}$$

NUCLEAR RMS RADIUS

The form factor parametrizations depend on two parameters that measure different nuclear properties and that are constrained by means of the rms radius of the distribution:

$$\langle R^2_{p,n} \rangle = \frac{\int \rho_{p,n}(\vec{r}) r^2 d^3\vec{r}}{\int \rho_{p,n}(\vec{r}) d^3\vec{r}}$$

The rms radii of the proton density distributions are determined from different experimental sources: optical and X-ray isotope shifts, muonic spectra, and electronic scattering experiments.

Angeli+ Atom. Data Nucl. Data Tabl. 99, 69 (2013)

Neutron rms radii: their experimental values follow from hadronic experiments which are subject to large uncertainties.

CEνNS CROSS SECTION: RECAP

CEνNS has a well-calculable cross-section in the SM:
(probability of kicking a nucleus with nuclear recoil energy T)

Fermi constant (SM parameter)

Kinematics

Nuclear Form Factor: F=1 full coherence

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right)Q_w^2\left[F_w(q^2)\right]^2 + \frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right)F_A(q^2)$$

Weak nuclear charge

$$Q_W = [Z(1 - 4\sin^2\theta_W) - N]$$

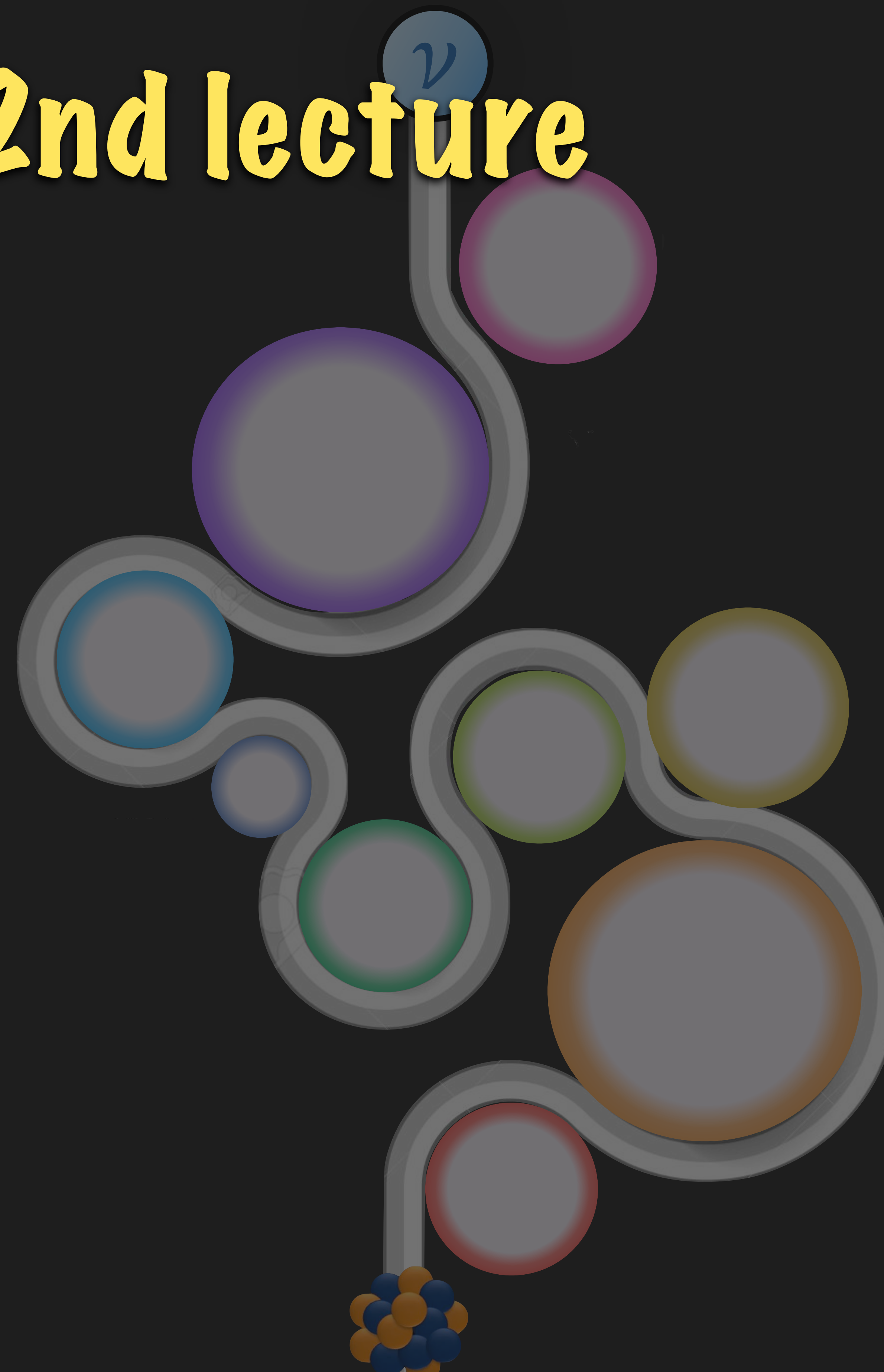
$s_W^2 = 0.23 \rightarrow$ protons unimportant
Neutron contribution dominates

- E_ν: is the incident neutrino energy
- M : the nuclear mass of the detector material
- 3-momentum transfer $|\vec{q}|^2 = 2MT$
- (Q_A included in F_A)

Axial contribution is small for most nuclei, spin-dependent.
It vanishes for nuclei with even number of protons and neutrons

Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299

OUTLINE - 2nd lecture



- CEvNS physics potential in the SM:
  - Weak mixing angle
  - Neutron rms radii
- CEvNS physics potential BSM:
  - Electromagnetic properties
  - NSI
  - NGI
  - Light mediators

IMPLICATIONS OF CEvNS: STANDARD MODEL

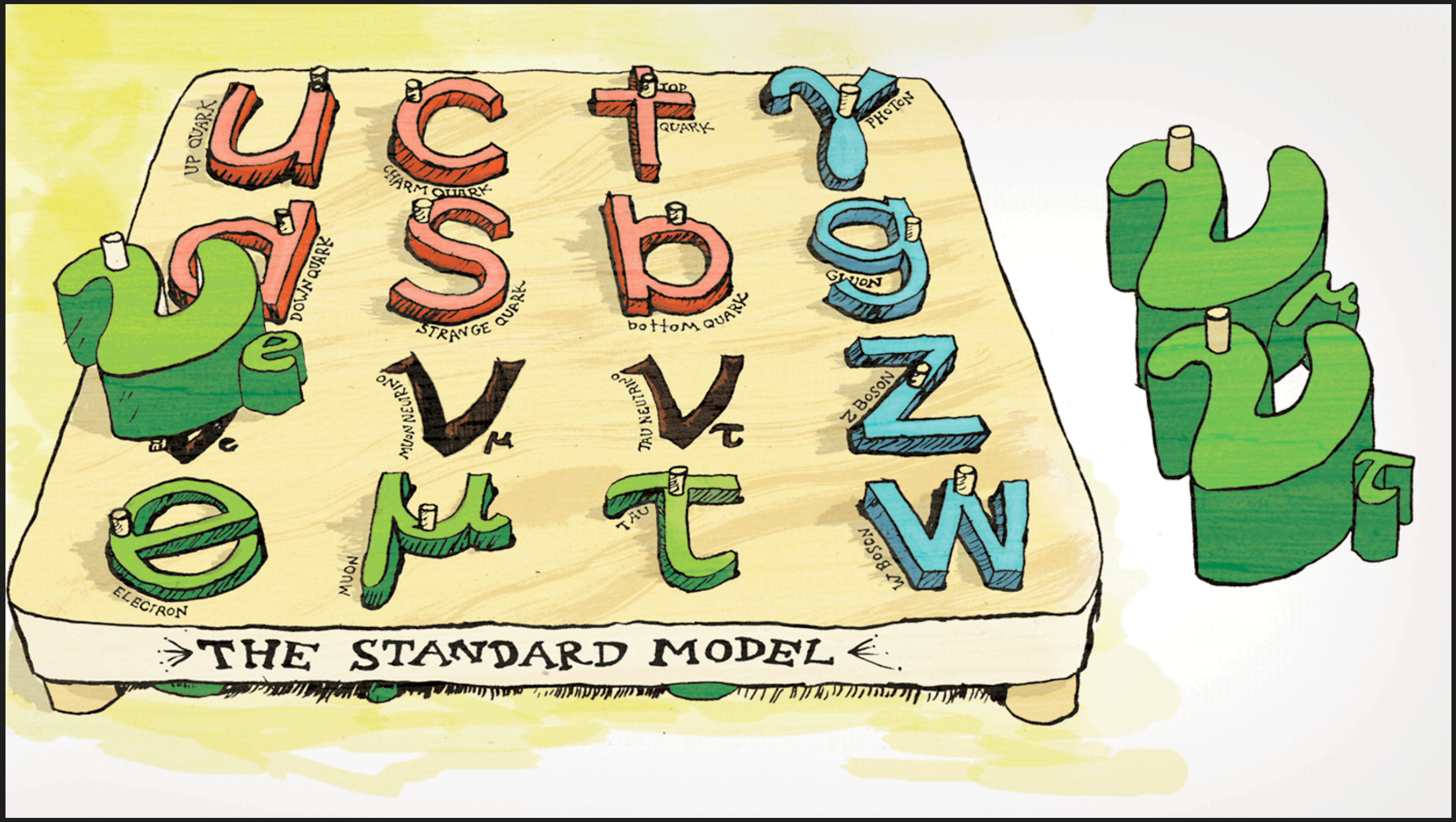
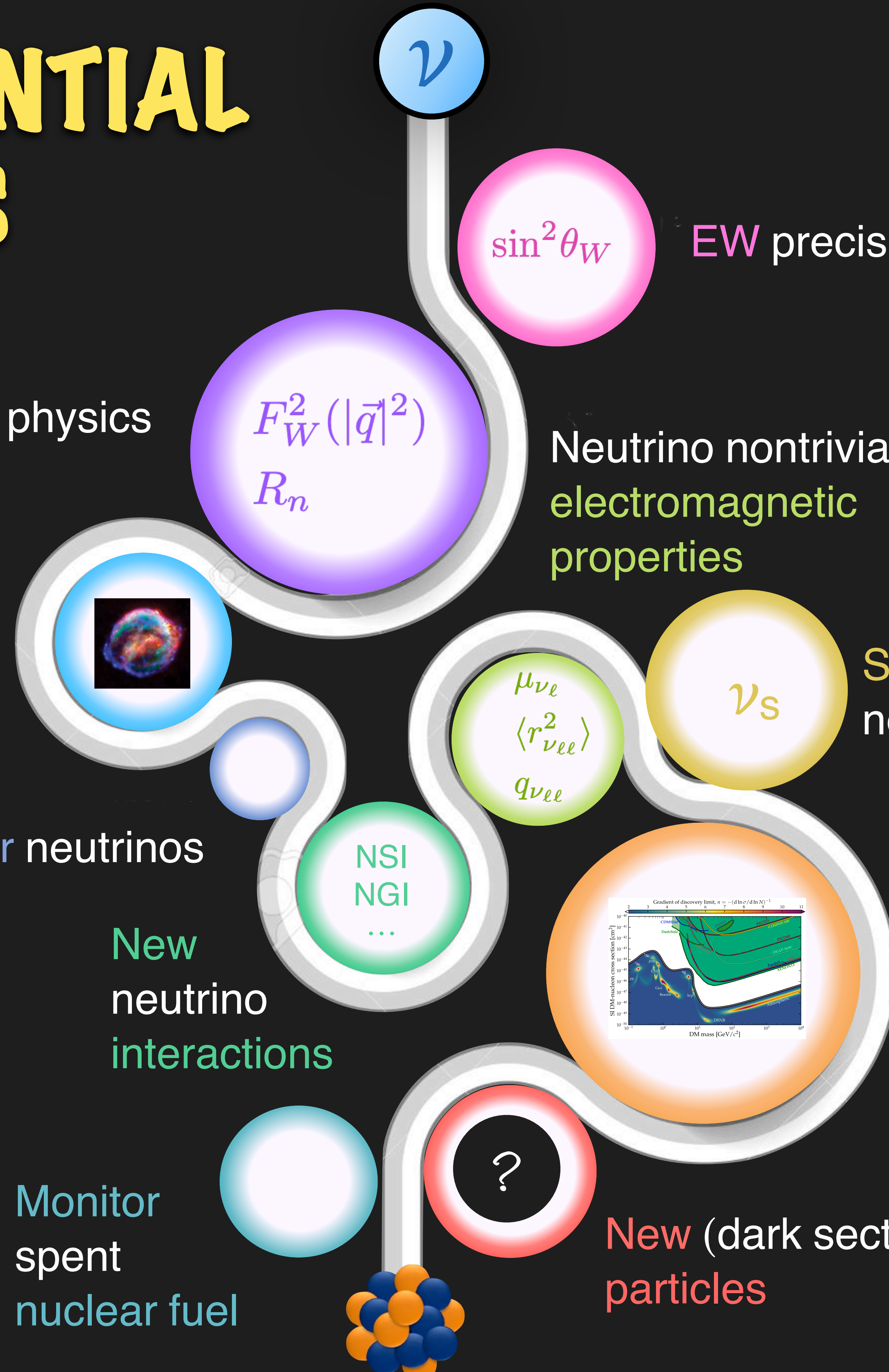


Illustration by Sandbox Studio, Chicago

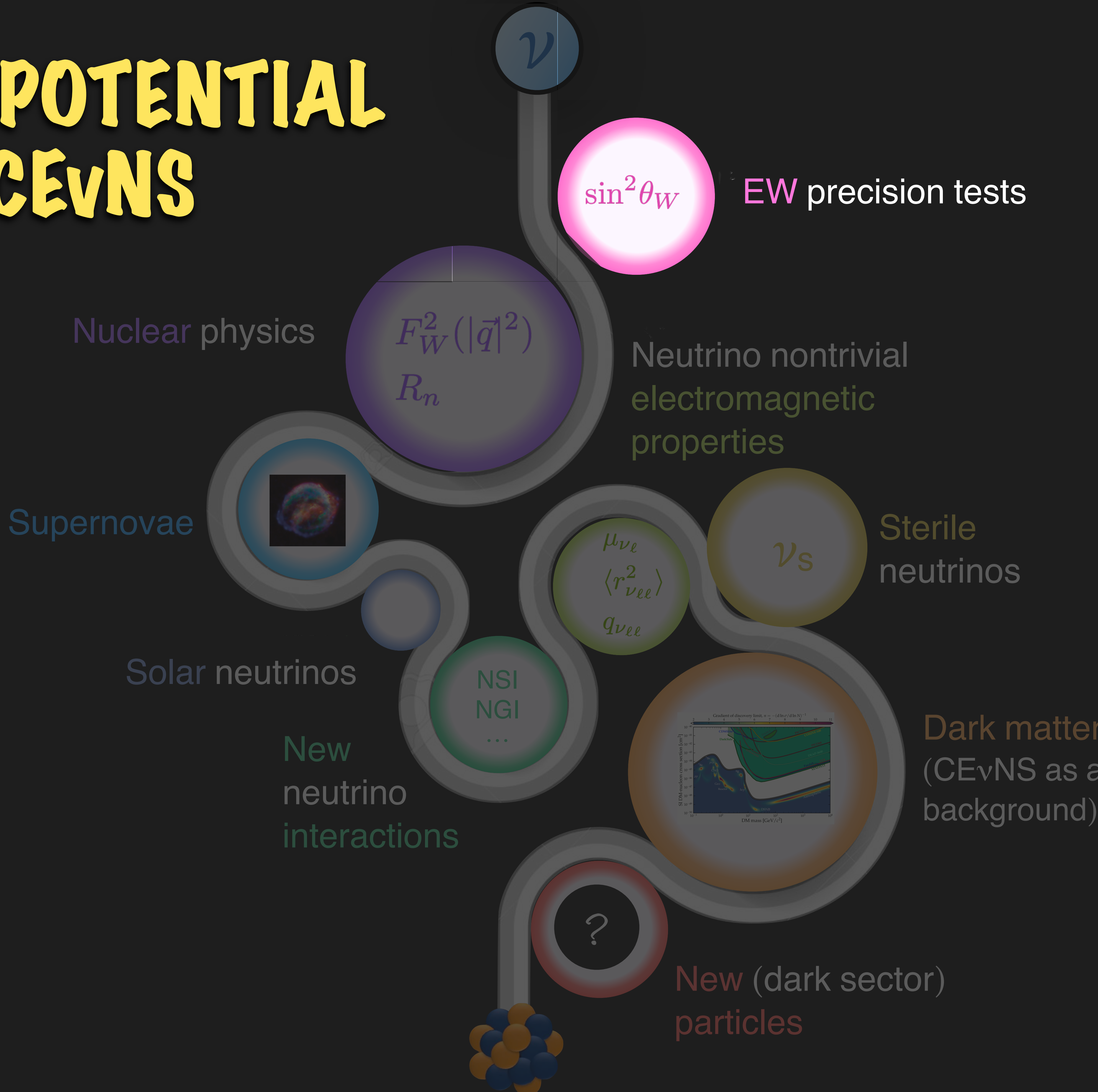
PHYSICS POTENTIAL OF CEvNS



Brdar and Rodejohann, 1810.03626; Chang and Liao, 2002.10275; Li et al, 2005.01543; CONUS, 2110.02174; Cadeddu et al, 1710.02730, 2005.01645, 1908.06045; Aristizabal Sierra et al, 1902.07398; Huang and Chen, 1902.07625; Papoulias et al, 1903.03722, 1907.11644; Miranda et al, 2003.12050; Papoulias et al, 1711.09773, 1907.11644; Cadeddu et al, 1808.10202, 2005.01645, 1908.06045, 2205.09484; Huang and Chen, 1902.07625; Miranda et al, 1902.09036, 2003.12050; Khan and Rodejohann, 1907.12444; COHERENT, 2110.07730; Papoulias and Kosmas, 1711.09773; Blanco et al, 1901.08094; Miranda et al, 1902.09036

Cerdeño et al, 1604.01025; Farzan et al, 1802.05171; Aristizabal Sierra et al, 1806.07424; Khan and Rodejohann, 1907.12444; Aristizabal Sierra et al, 1910.12437; Miranda et al, 2003.12050; Aristizabal Sierra et al, JHEP 09 (2019) 069; Suliga and Tamborra, 2010.14545; CONUS, 2110.02174; Li and Xia, 2201.05015; Atzori Corona et al, 2202.11002; Liao et al, 2202.10622; Coloma et al, 2202.10829; Lindner et al, 1612.04150; Aristizabal Sierra et al, 1806.07424; Aristizabal Sierra et al, JCAP 01 (2022) 01, 055, Atzori-Corona+ Eur.Phys.J.C 83 (2023) 7, 683, Behera+ 2304.00912, Cadeddu+ EPL 143 (2023) 3, 34001, Atzori-Corona+ 2307.12911, Von Raesfeld Phys.Rev.D 105 (2022) 5, 056002, Bresó-Pla JHEP05(2023)074
....

PHYSICS POTENTIAL OF CEνNS



STANDARD MODEL PHYSICS

$$\left.\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\right|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} F_W^2(\mathbf{q}^2)\, \boxed{Q_{\rm w}^2} \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu} + \frac{E_{\rm nr}^2}{2E_\nu^2}\right)$$

$$Q_{\rm W} = -N/2 + (1/2 - 2\sin^2\theta_{\rm w})Z$$

$s_W^2 = 0.23$ → protons unimportant

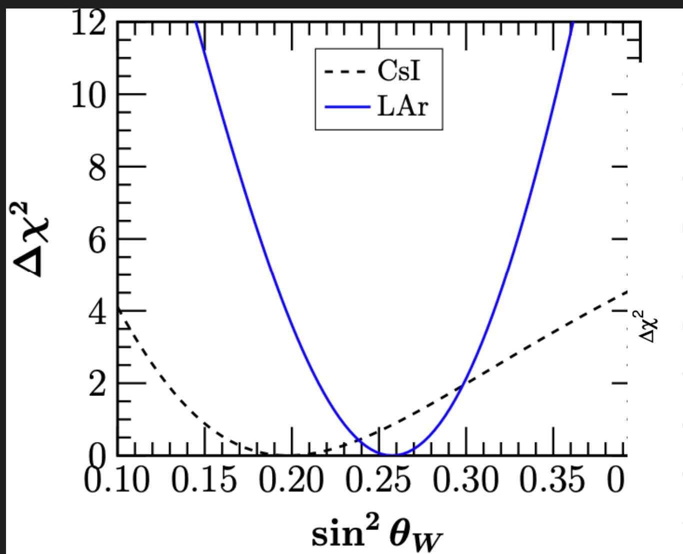
Neutron contribution dominates

Information on the value of the neutrino neutral-current interaction at low energy:

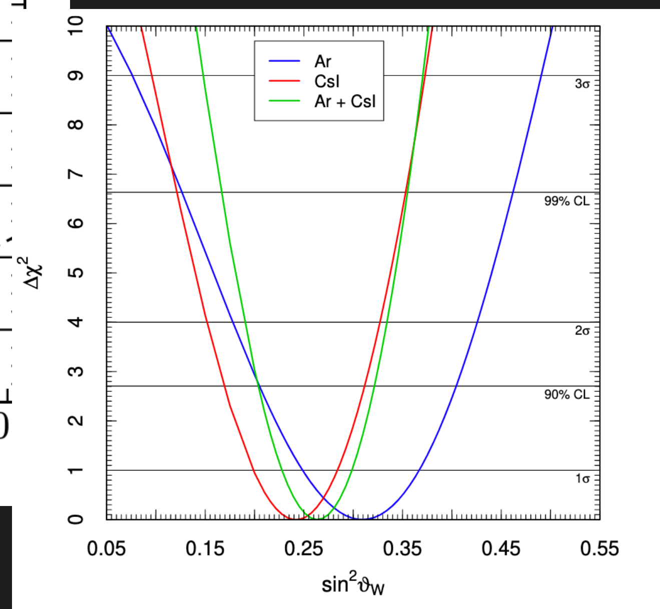
- Observable: $\sin^2\theta_w$
- poorly measured at low energies
- Affects the normalization of CEvNS spectra

EW PRECISION TESTS: WEAK MIXING ANGLE

COHERENT CsI (2017) + LAr

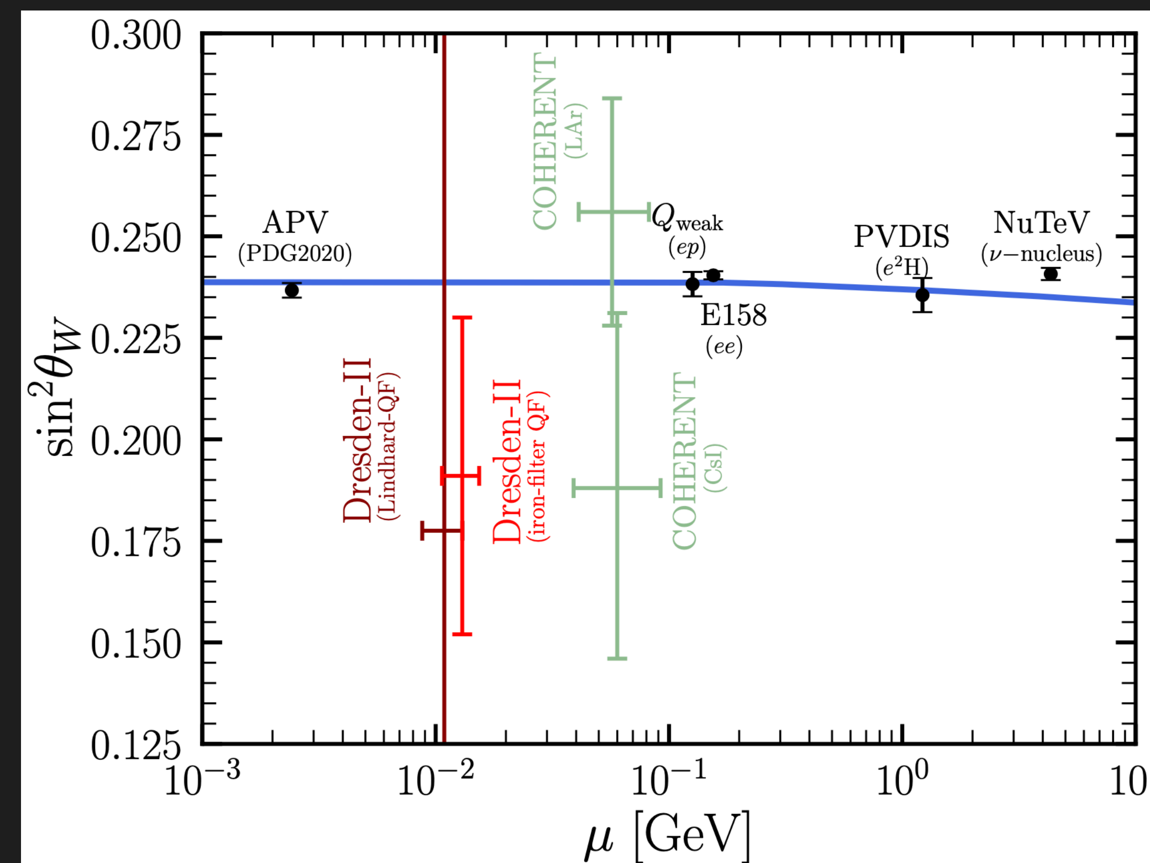


Miranda et al. JHEP 05 (2020) 130

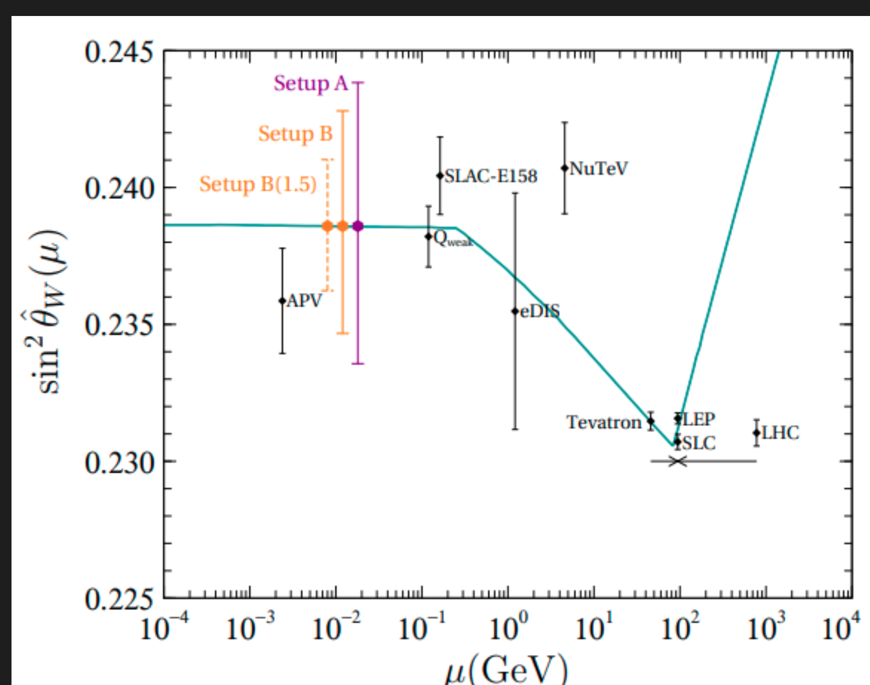


Cadeddu et al. Phys. Rev. D 102, 015030 (2020)

Dresden-II Ge



Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

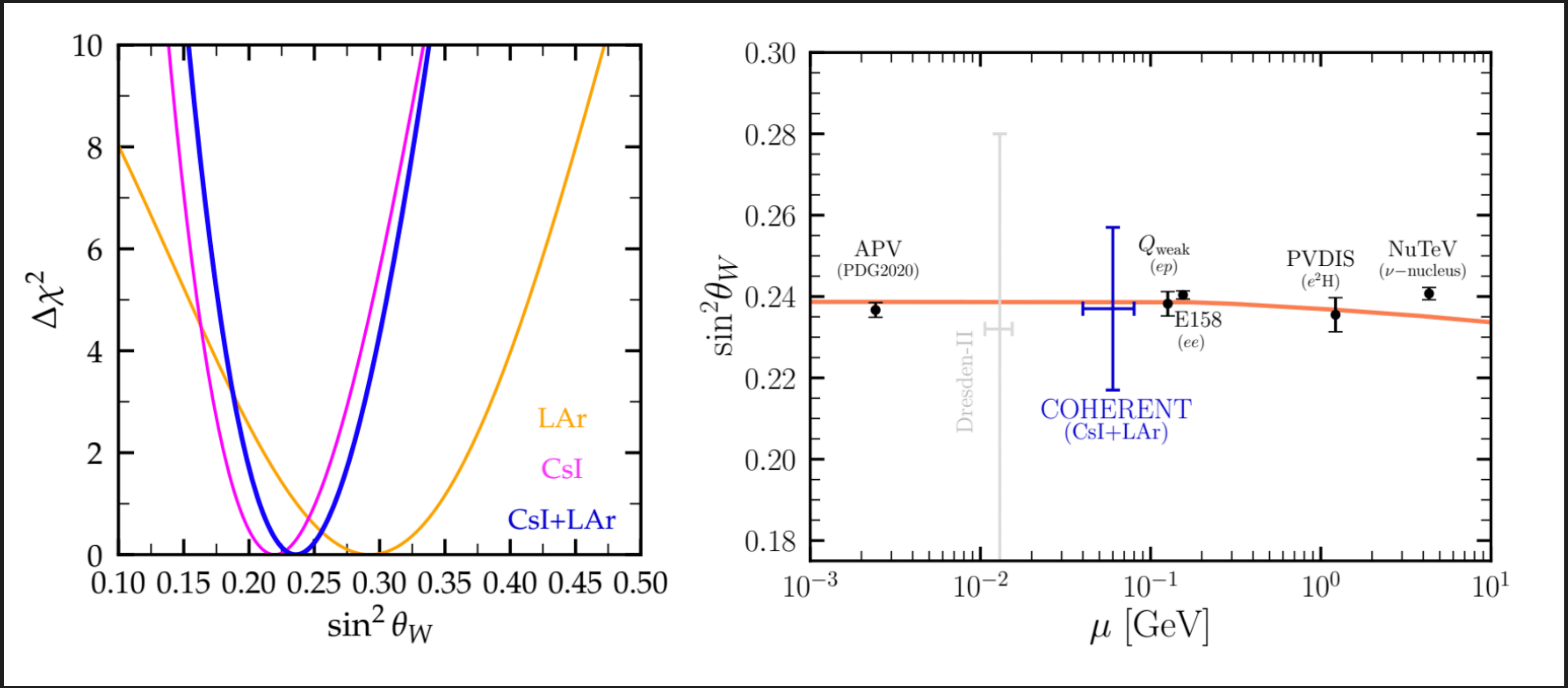


SBC LAr

[SBC Collaboration] L. J. Flores et al. Phys.Rev.D 103 (2021) 9, L091301

EW PRECISION TESTS: WEAK MIXING ANGLE

COHERENT CsI (2021) + LAr

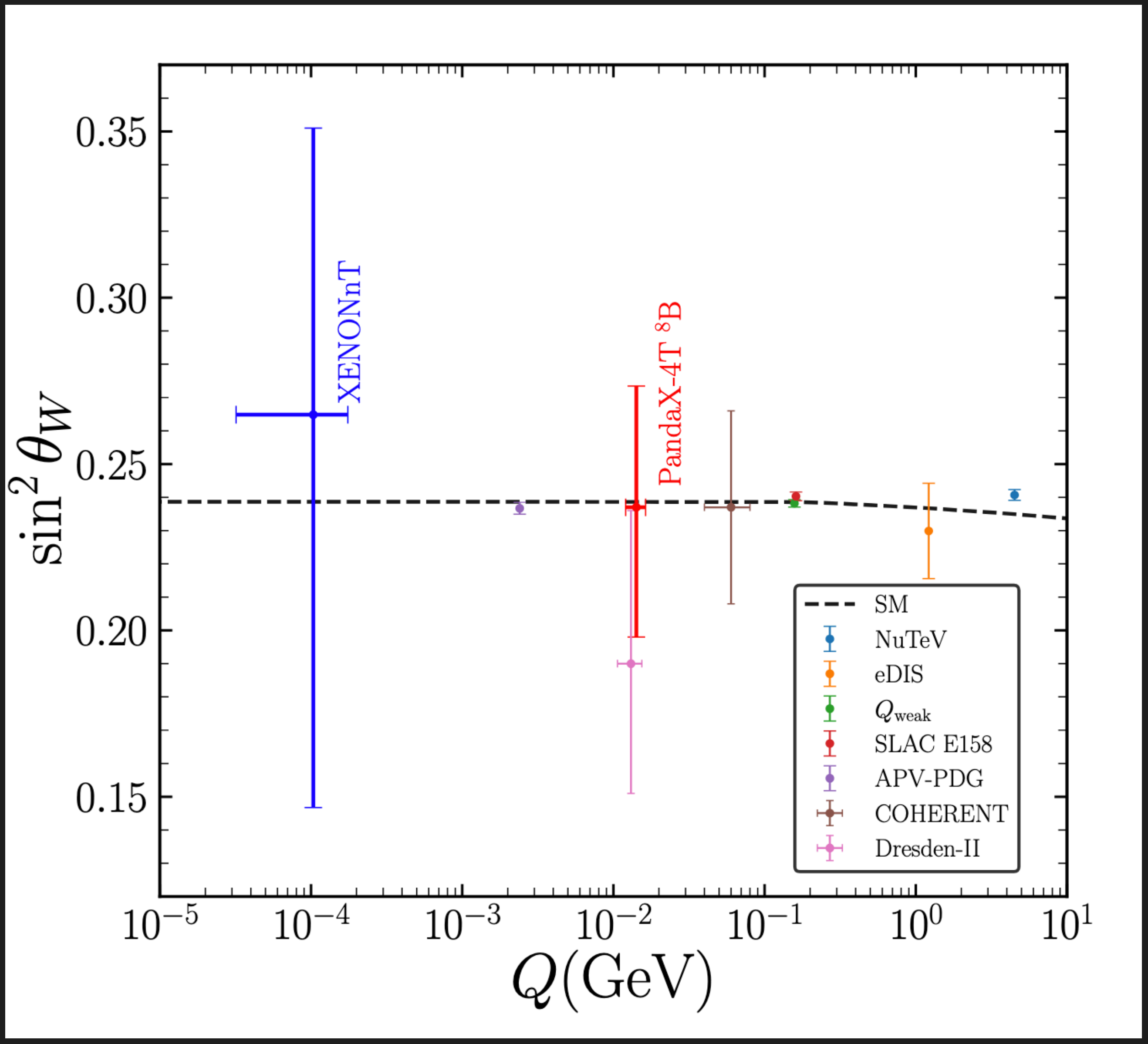


VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035
Majumdar, Papoulias, Srivastava and Valle, Phys.Rev.D 106 (2022) 9, 093010

$$\sin^2\theta_{\rm W} = 0.237 \pm 0.029 \quad (1\sigma)$$

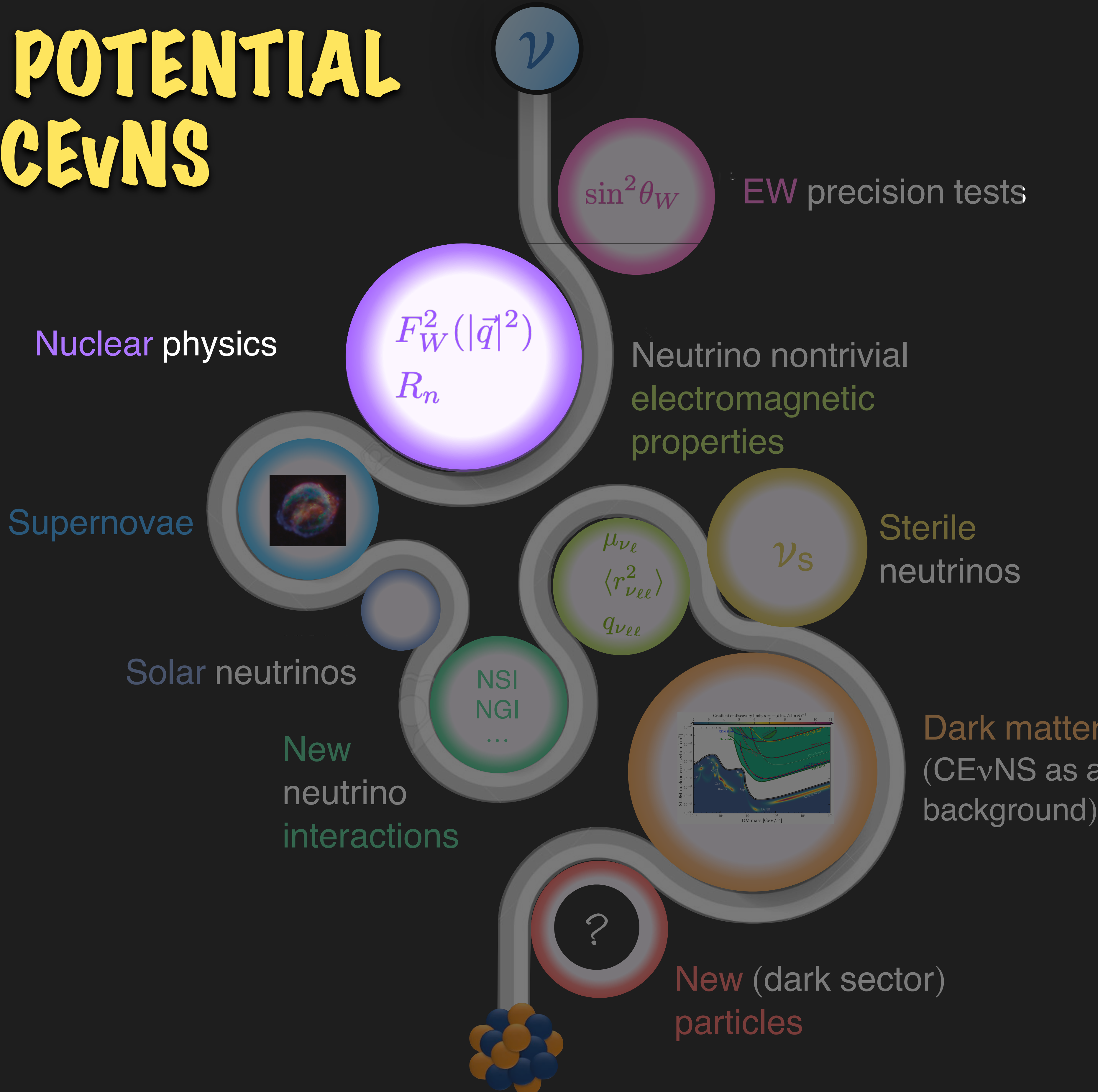
See also: Atzori-Corona+ JHEP 09 (2022) 164, Atzori-Corona+ Eur.Phys.J.C 83 (2023) 7, 683

EW PRECISION TESTS: WEAK MIXING ANGLE



Maity, Boehm 2409.04385

PHYSICS POTENTIAL OF CEvNS



NUCLEAR PHYSICS

$$\frac{d\sigma_{\nu\mathcal{N}}}{dE_{\rm nr}}\Bigg|^{\rm SM}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{\pi} \boxed{F_W^2(\mathbf{q}^2)} Q_{\rm w}^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu} + \frac{E_{\rm nr}^2}{2E_\nu^2}\right)$$

Nuclear form factor $$F_W^2(|\vec{q}|^2) = \int e^{-i\vec{q}\cdot\vec{r}} \rho(r) d^3 r$$

ρ(r) is the charge density distribution

is the Fourier transform of the neutron distribution in the nucleus

- Observable: nuclear rms radius
- Largest theoretical uncertainty
- Affects the shape of CEvNS spectra

Partial coherency gives information on the nuclear neutron form factor.

PROTON AND NEUTRON DENSITY DISTRIBUTIONS

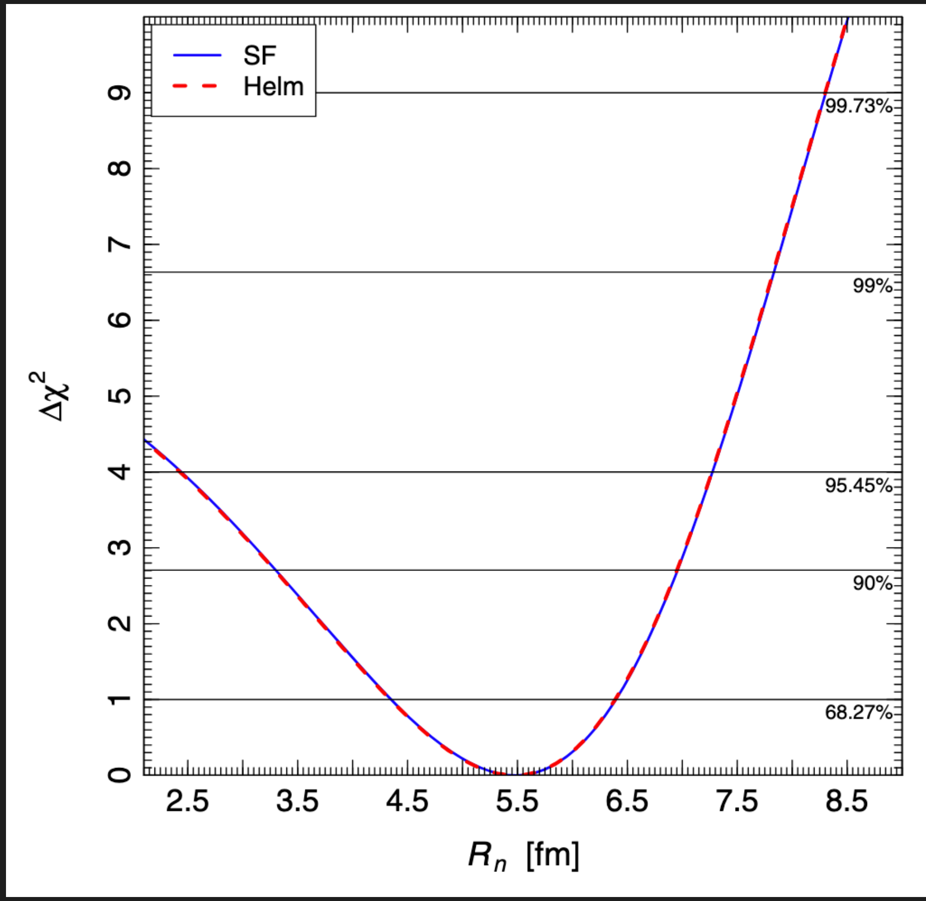
The nuclear proton distribution is probed with electromagnetic interactions.

What about neutron distributions? Hadron scattering experiments can give information, but their interpretation depends on the model used to describe non-perturbative strong interactions. Neutral-current weak interaction measurements are more reliable.

Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering (PREX).

The CEvNS process can be used to provide a model-independent measurement of the root-mean-square (rms) neutron distribution radius, Rn.

Determine for the first time the average neutron rms radius of ^{133}Cs and ^{127}I.



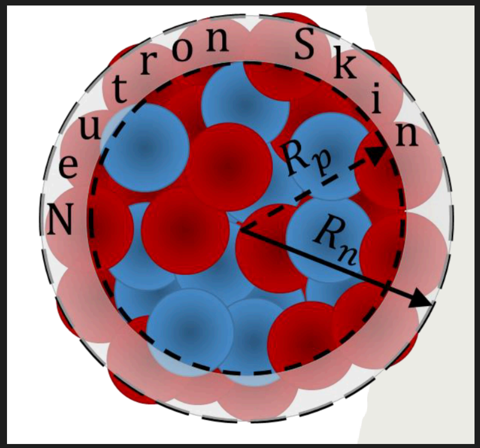
Cadeddu+ PRL 120, 072501 (2018)

NEUTRON DENSITY DISTRIBUTION

The CEvNS process can be used to provide a model-independent measurement of the root-mean-square (rms) neutron distribution radius, R_n.

$$F_W(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2 a_k^2}\right)$$

Klein-Nystrand parametrization

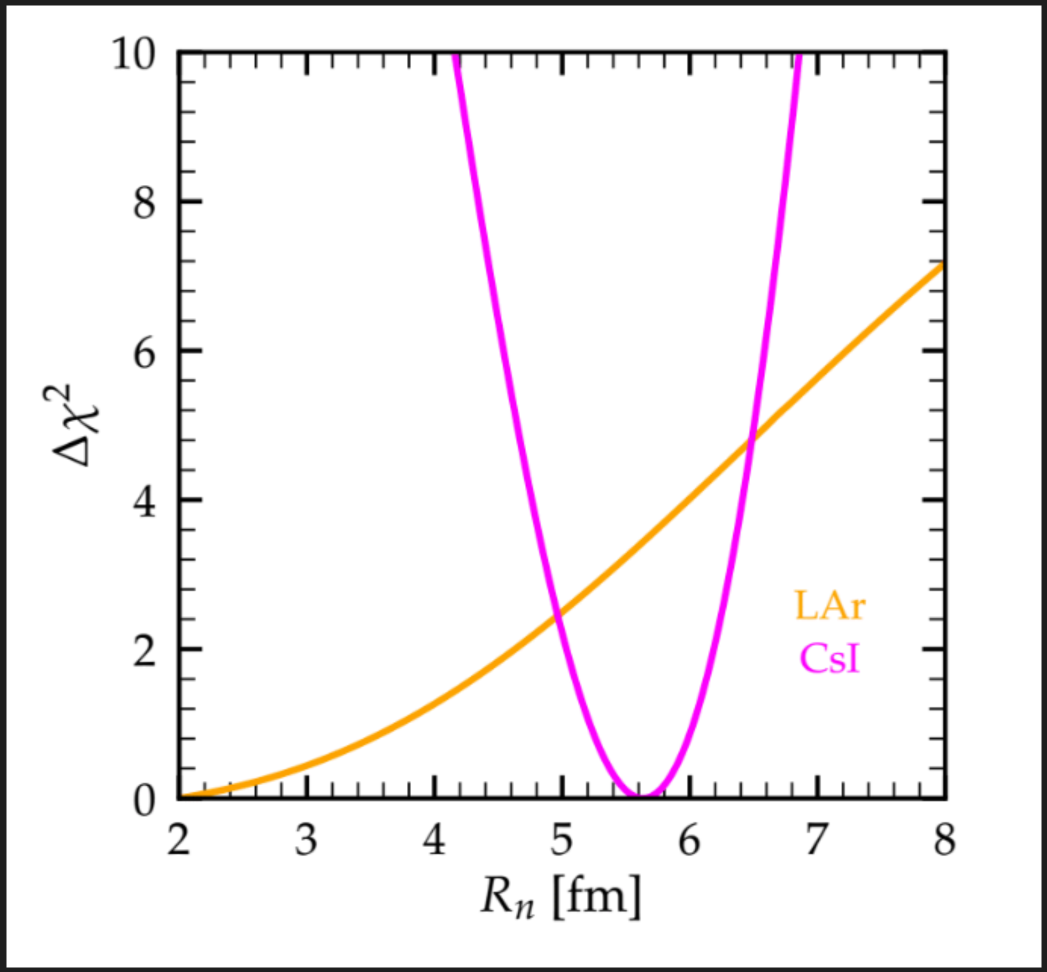


Credit: M. Cadeddu

Proton rms radii are fixed
$R_p(I) = 4.766$ fm
$R_p(Cs) = 4.824$ fm
$R_p(Ar) = 3.448$ fm

$$R_n = 1.23A^{1/3}(1+\alpha_4)$$

COHERENT CsI (2021) + LAr



See also: Aristizabal 2301.13249, Cadeddu+ Phys. Rev. D 101, 033004 (2020), Cadeddu+ Phys. Rev. D 102, 015030 (2020), Cadeddu-Dordei Phys. Rev. D 99, 033010 (2019), Cadeddu+ Phys. Rev. C 104, 065502 (2021), Atzori-Corona, Cadeddu, Cargioli, Giunti+, Cañas+ Phys. Lett. B 784, 159…

VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

NEUTRON DENSITY DISTRIBUTION

The CEvNS process can be used to provide a model-independent measurement of the root-mean-square (rms) neutron distribution radius, R_n.

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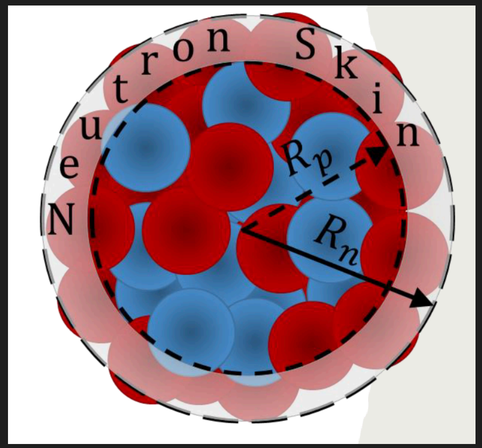
Klein-Nystrand parametrization



Credit: M. Cadeddu

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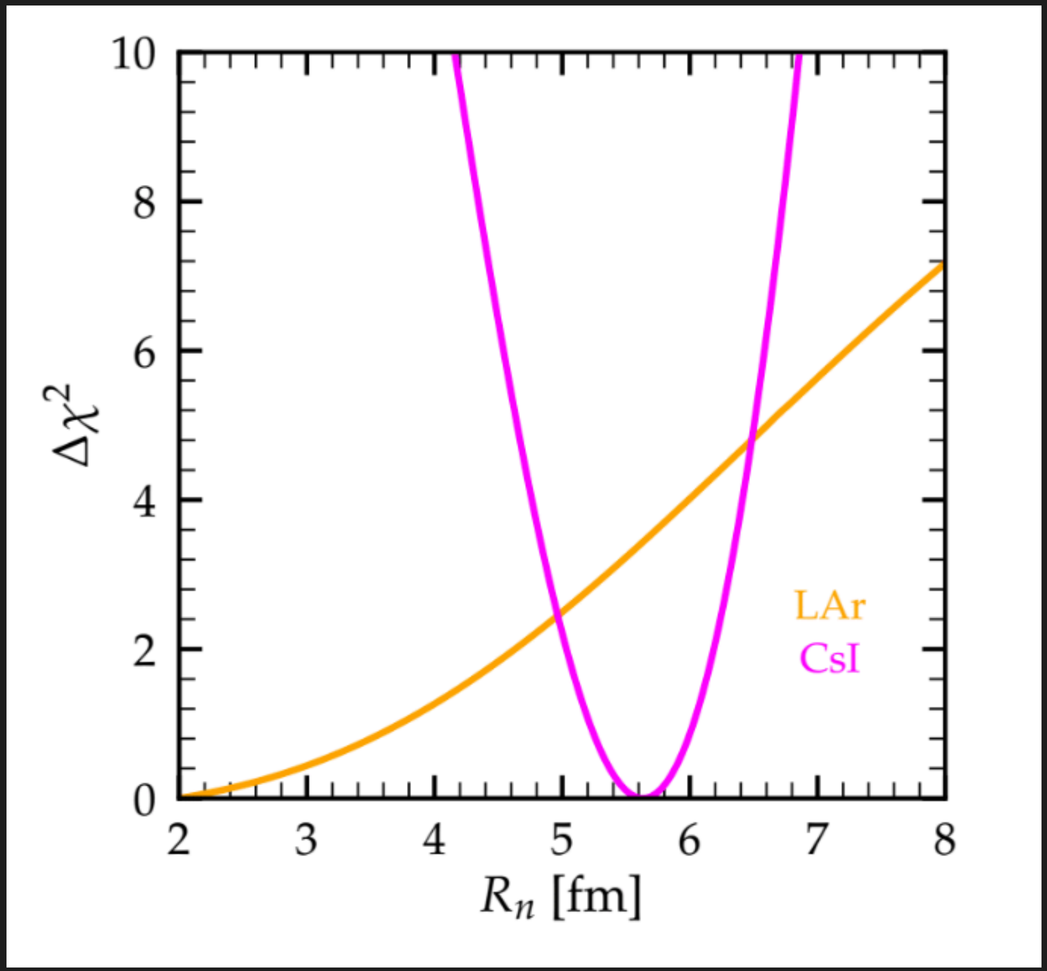


VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

$$R_n = 1.23 A^{1/3}(1+\alpha_4)$$

$$R_n(\mathrm{Ar}) \in [0.00, 3.72]\ \mathrm{fm}\,, \quad (1\sigma)$$
$$R_n(\mathrm{CsI}) \in [5.22, 6.03]\ \mathrm{fm}$$

See also: Aristizabal 2301.13249, Cadeddu+ Phys. Rev. D 101, 033004 (2020), Cadeddu+ Phys. Rev. D 102, 015030 (2020), Cadeddu-Dordei Phys. Rev. D 99, 033010 (2019), Cadeddu+ Phys. Rev. C 104, 065502 (2021), Atzori-Corona, Cadeddu, Cargioli, Dordei, Giunti+ Eur.Phys.J.C 83 (2023) 7, 683, Cañas+ Phys. Lett. B 784, 159...

NEUTRON DENSITY DISTRIBUTION

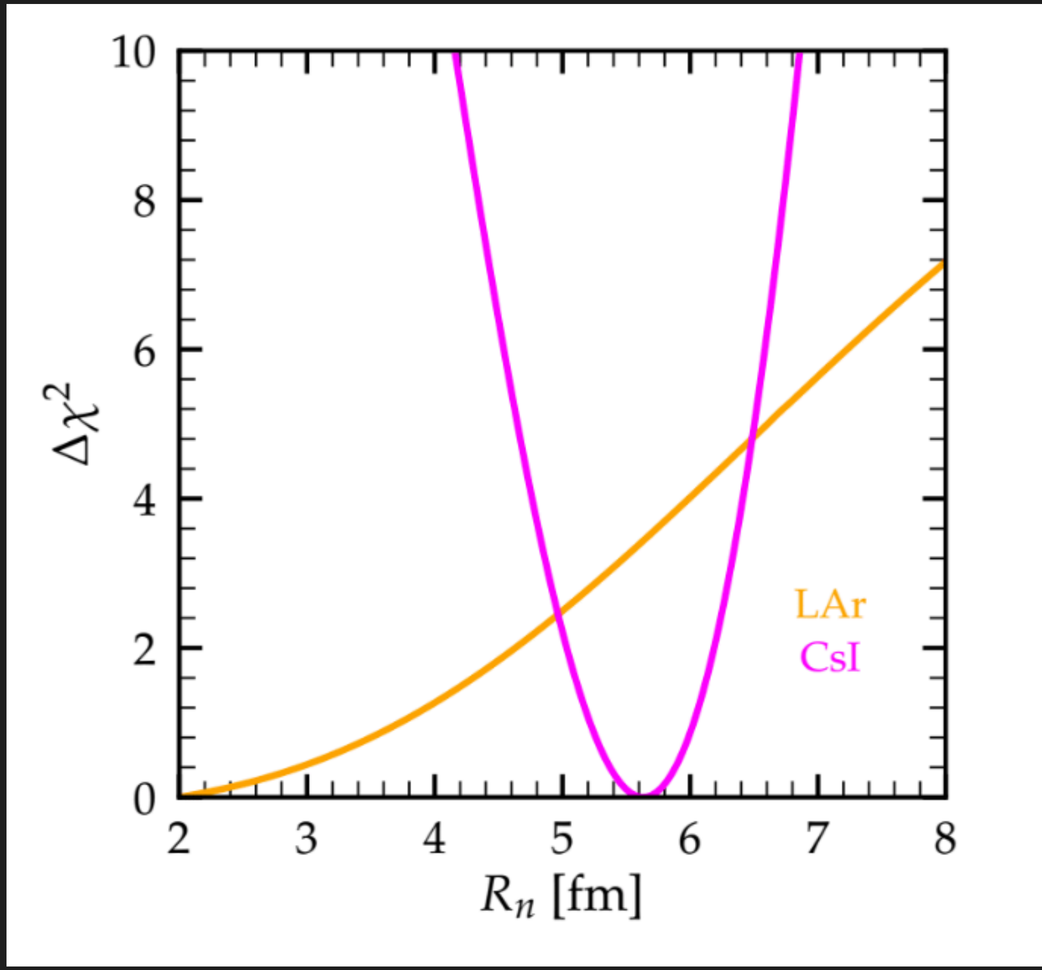
A large R_n has implications for:

- Nuclear physics → a larger pressure of neutrons, stability of nuclei
- Astrophysics → a larger size of neutron stars

$$R_n = 1.23 A^{1/3}(1+\alpha_4)$$

$$R_n(\mathrm{Ar}) \in [0.00, 3.72]\ \mathrm{fm}\,, \quad (1\sigma)$$
$$R_n(\mathrm{CsI}) \in [5.22, 6.03]\ \mathrm{fm}$$

COHERENT CsI (2021) + LAr

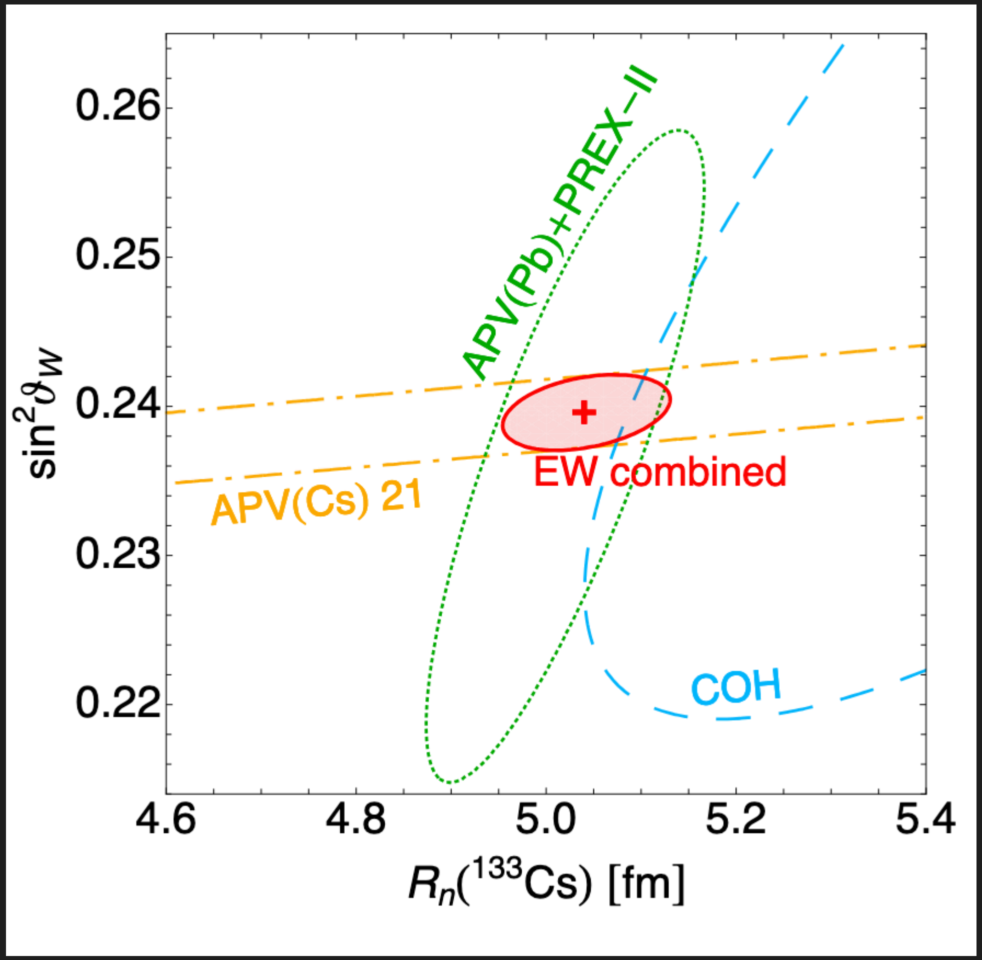


VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

COMBINING $\sin^2\theta_W$ AND THE AVERAGE CsI NEUTRON RADIUS

Attempt to exploit correlations among different probes available in order to maximize the reliability and significance on $\sin^2\theta_W$.

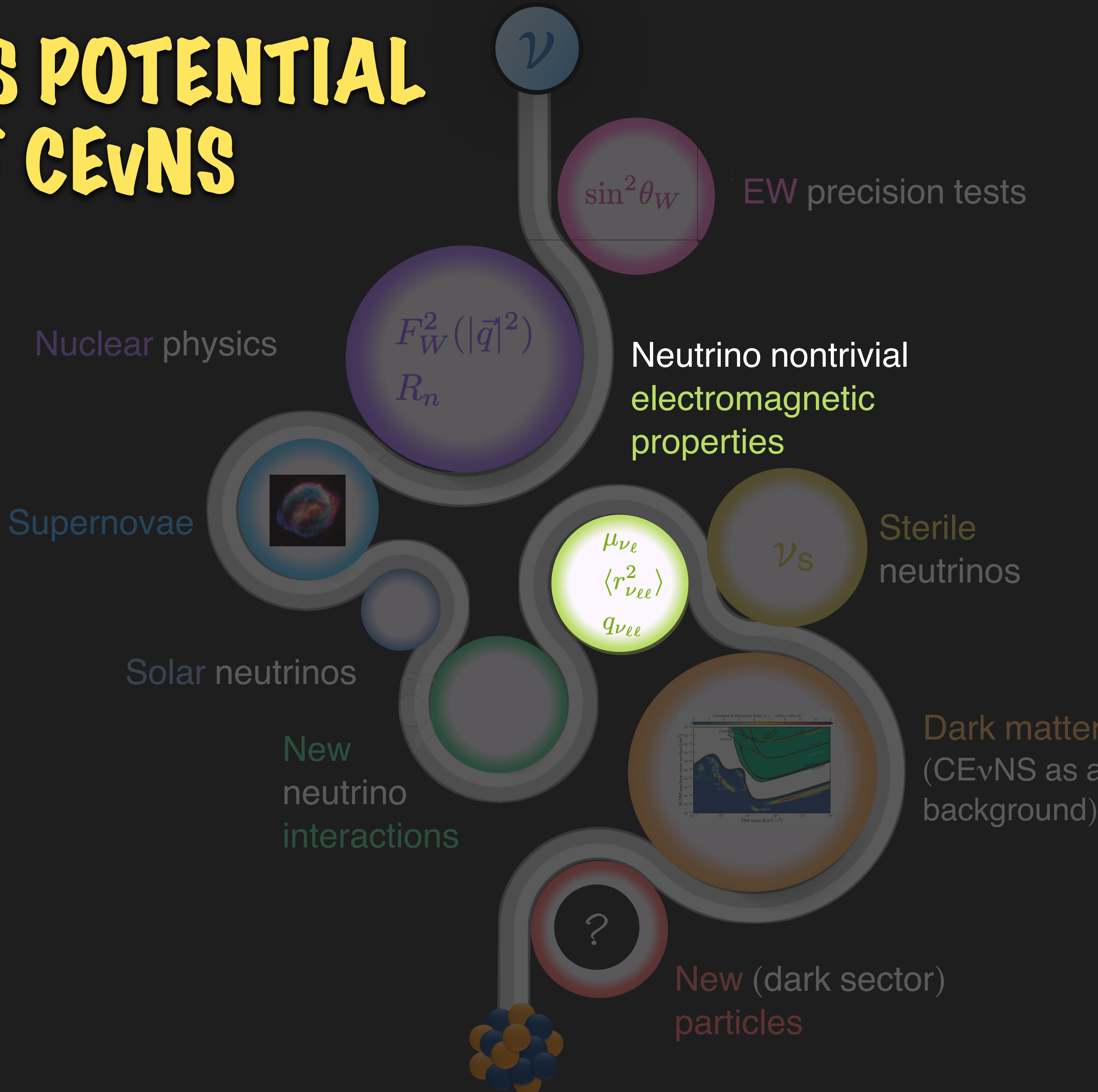
“Global fit” from atomic parity violation, coherent elastic neutrino-nucleus scattering and parity-violating electron scattering on different nuclei.



Atzori-Corona+ Eur.Phys.J.C 83 (2023) 7, 683
Atzori-Corona+ 2405.09416 [

IMPLICATIONS OF CEvNS: NEW PHYSICS

PHYSICS POTENTIAL OF CEνNS



NEUTRINO ELECTROMAGNETIC INTERACTIONS

Neutrino electromagnetic properties are important as they are connected to the fundamentals of particle physics.
They can be used to distinguish Dirac vs Majorana nature or to probe physics BSM.

The interaction of a fermionic field f(x) with the electromagnetic field A(x) is given by

$$\mathscr{H}^{f}_{\text{em}}(x) = j^{f}_{\mu}(x)A^{\mu}(x) = \mathbf{q_f}\bar{f}(x)\gamma_{\mu}f(x)A^{\mu}(x)$$

Charge of the fermion f

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

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Charge of the fermion f

The electric charge of neutrinos in the SM is zero and there are no electromagnetic interactions at tree level.

Such interactions can arise from loop diagrams at higher order of the perturbative expansion of the interaction.

4x4 matrix in spinor space, can contain space/time derivatives

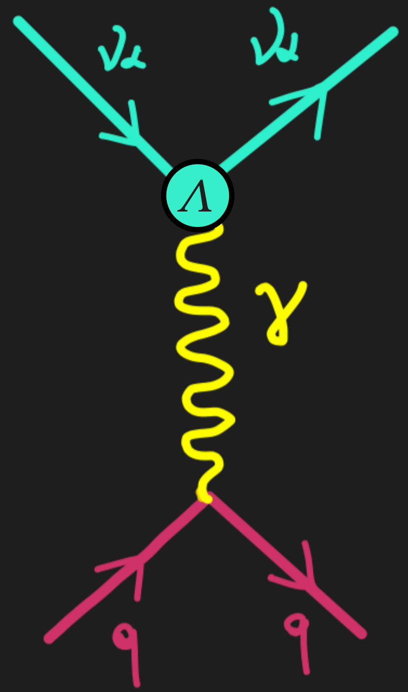
$$\mathscr{H}^{\nu}_{\rm em}(x) = j^{\nu}_{\mu}(x)A^{\mu}(x) = \bar{\nu}(x)\Lambda_{\mu}\nu(x)A^{\mu}(x)$$

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

Effective electromagnetic vertex:

$$\langle \nu_f(p_f)|j_\mu^{(\nu)}(0)|\nu_i(p_i)\rangle = \bar{u}_f(p_f)\Lambda_\mu^{fi}(p)u_i(p_i)$$

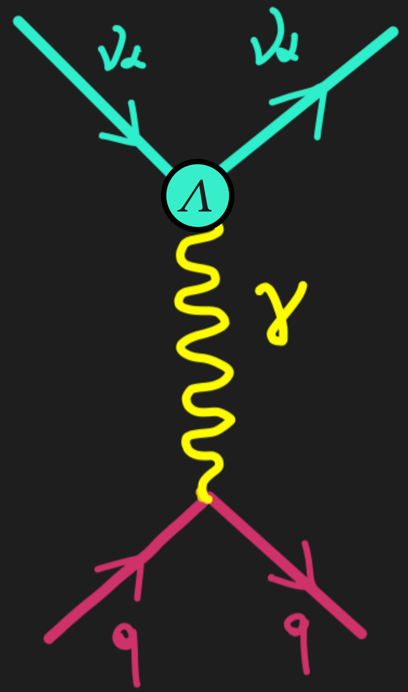


Neutrinos are assumed to be free particles described by Dirac fields.

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

Effective electromagnetic vertex:



$$\langle \nu_f(p_f)|j_\mu^{(\nu)}(0)|\nu_i(p_i)\rangle = \bar{u}_f(p_f)\Lambda_\mu^{fi}(p)u_i(p_i)$$

Neutrinos are assumed to be free particles described by Dirac fields.

Lorentz and electromagnetic gauge invariance imply that the most general composition of the vertex function, in terms of linearly independent products of Dirac γ matrices and the available kinematical four-vector, is

$$\Lambda_\mu(p_f,p_i) = \mathbb{F}_1(q^2)q_\mu + \mathbb{F}_2(q^2)q_\mu\gamma_5 + \mathbb{F}_3(q^2)\gamma_\mu + \mathbb{F}_4(q^2)\gamma_\mu\gamma_5 + \mathbb{F}_5(q^2)\sigma_{\mu\nu}q^\nu + \mathbb{F}_6\epsilon_{\mu\nu\rho\gamma}(q^2)q^\nu\sigma^{\rho\gamma}$$

$\mathbb{F}_i$ are Lorentz-invariant form factors and q is the four-momentum of the photon.

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

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$\mathbb{F}_i$ are Lorentz-invariant form factors and q is the four-momentum of the photon.

$\mathbb{F}_i$ depend only on q^2 which is the only available Lorentz-invariant quantity.

Using the properties of Dirac matrices, one can find that

$\mathbb{F}_2, \mathbb{F}_3, \mathbb{F}_4$ are real
$\mathbb{F}_1, \mathbb{F}_5, \mathbb{F}_6$ are imaginary

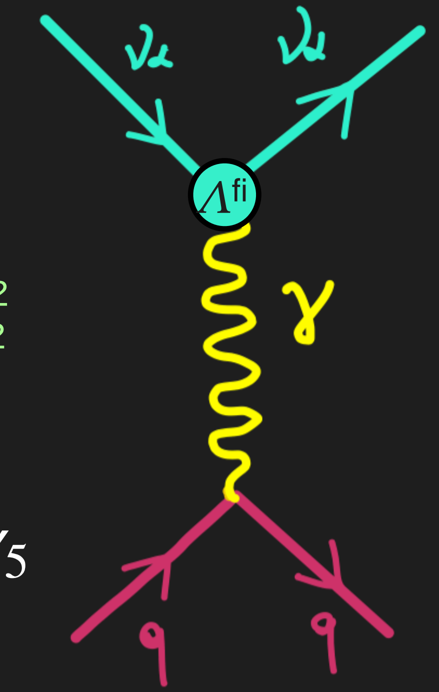
The number of independent form factors is further reduced by imposing current conservation

$$\partial^\mu j_\mu^\nu(x) = 0.$$

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

Lorentz and electromagnetic gauge invariance imply that the vertex functions is defined in terms of four form factors:



Kayser, Phys.Rev. D26 (1982) 1662
Nieves, Phys.Rev. D26 (1982) 3152

$$\Lambda_\mu(p_f, p_i) = \mathbb{F}_Q(q^2)\gamma_\mu - \mathbb{F}_M(q^2) i\sigma_{\mu\nu}q^\nu + \mathbb{F}_E\sigma_{\mu\nu}q^\nu\gamma_5 + \mathbb{F}_A(q^2)(q^2\gamma_\mu - q_\mu \not{q})\gamma_5$$

Where $\mathbb{F}_Q = \mathbb{F}_3, \mathbb{F}_M = i\mathbb{F}_5, \mathbb{F}_E = -2i\mathbb{F}_6$, and $\mathbb{F}_A = -\mathbb{F}_2/2m$.

We can then generalise to the case of N massive neutrino fields, with masses m_k and take into account possible transitions among different massive neutrinos.

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

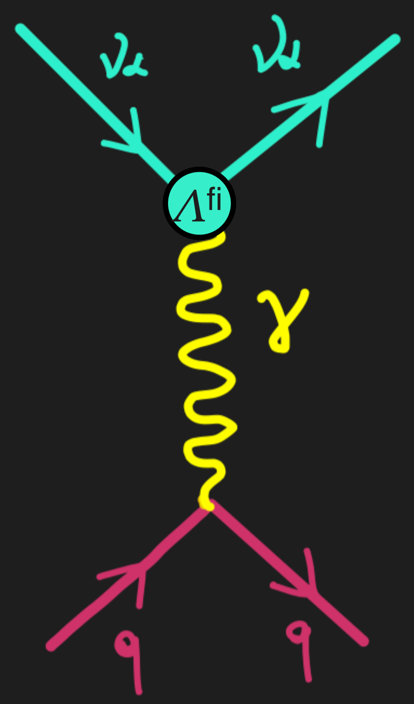
$\Lambda^{fi}_{\mu}(q)$ is a NxN matrix in the space of massive neutrinos expressed in terms of four Hermitian NxN form factors.

$$\Lambda^{fi}_{\mu}(q) = \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right)\left[\mathbb{F}^{fi}_{Q}(q^2) + \mathbb{F}^{fi}_{A}(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu}q^\nu \left[\mathbb{F}^{fi}_{M}(q^2) + i\mathbb{F}^{fi}_{E}(q^2)\gamma_5\right]$$

Lorentz-invariant form factors
($q^2 = 0$, coupling with a real photon)

Charge (q) Anapole (a) Magnetic (μ) Electric (ε)

Helicity conserving Helicity flipping



The form factors with f = i are called diagonal, if f ≠ I, are called transition form factors.

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO ELECTROMAGNETIC INTERACTIONS

$\Lambda^{fi}_{\mu}(q)$ is a NxN matrix in the space of massive neutrinos expressed in terms of four Hermitian NxN form factors.

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Lorentz-invariant form factors
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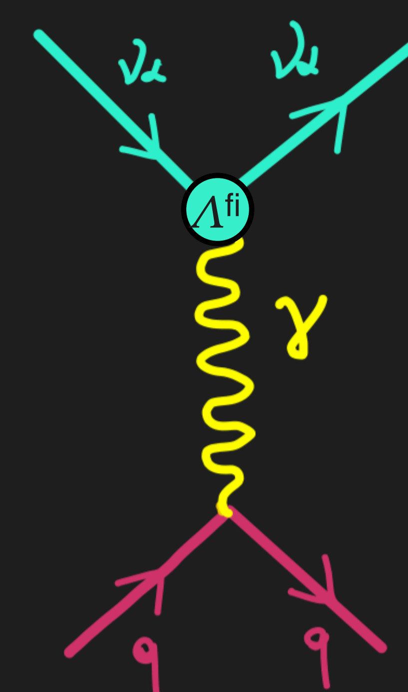
Charge (q) | Anapole (a) | Magnetic (μ) | Electric (ε)

Helicity conserving | Helicity flipping



For Majorana neutrinos the charge, magnetic and electric form factors are antisymmetric matrices and the anapole one is symmetric.

Since $\mathbb{F}^{M}_{Q}, \mathbb{F}^{M}_{E}$ and $\mathbb{F}^{M}_{M}$ are antisymmetric, Majorana neutrinos cannot have diagonal charge and dipole magnetic and electric form factors.

Nieves Phys. Rev. D 26, 3152
Kayser Phys. Rev. D 26, 1662

C. Giunti, A. Studenikin, Rev Mod Phys, 87, 531 (2015)

NEUTRINO MAGNETIC MOMENT

The most studied neutrino electromagnetic moments are the dipole magnetic and electric moments:

$$\mu_{ij} = \mathbb{F}_M(0)_{ij}, \epsilon_{ij} = \mathbb{F}_E(0)_{ij}$$

The diagonal magnetic and electric moments of a Dirac neutrino in the minimally-extended SM with right-handed neutrinos are strongly suppressed:

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \sim 3.2 \times 10^{-19} \left(\frac{m_i}{1eV}\right) \mu_B \qquad \epsilon_{ii}^D = 0$$

$$\mu_{ij}^D, i\epsilon_{ij}^D \sim -3.9 \times 10^{-23} \left(\frac{m_i \pm m_j}{1eV}\right) \mu_B \sum_{\ell=e,\mu,\tau} U_{\ell i}^* U_{\ell j} \left(\frac{m_\ell}{m_\tau}\right)^2$$

Transition moments are GIM-suppressed

Fujikawa, Shrock, PRL 45 (1980) 963;
Pal, Wolfenstein, PRD 25 (1982) 766;
Shrock, NPB 206 (1982) 359;
Dvornikov, Studenikin, PRD 69 (2004) 073001, JETP 99 (2004) 254

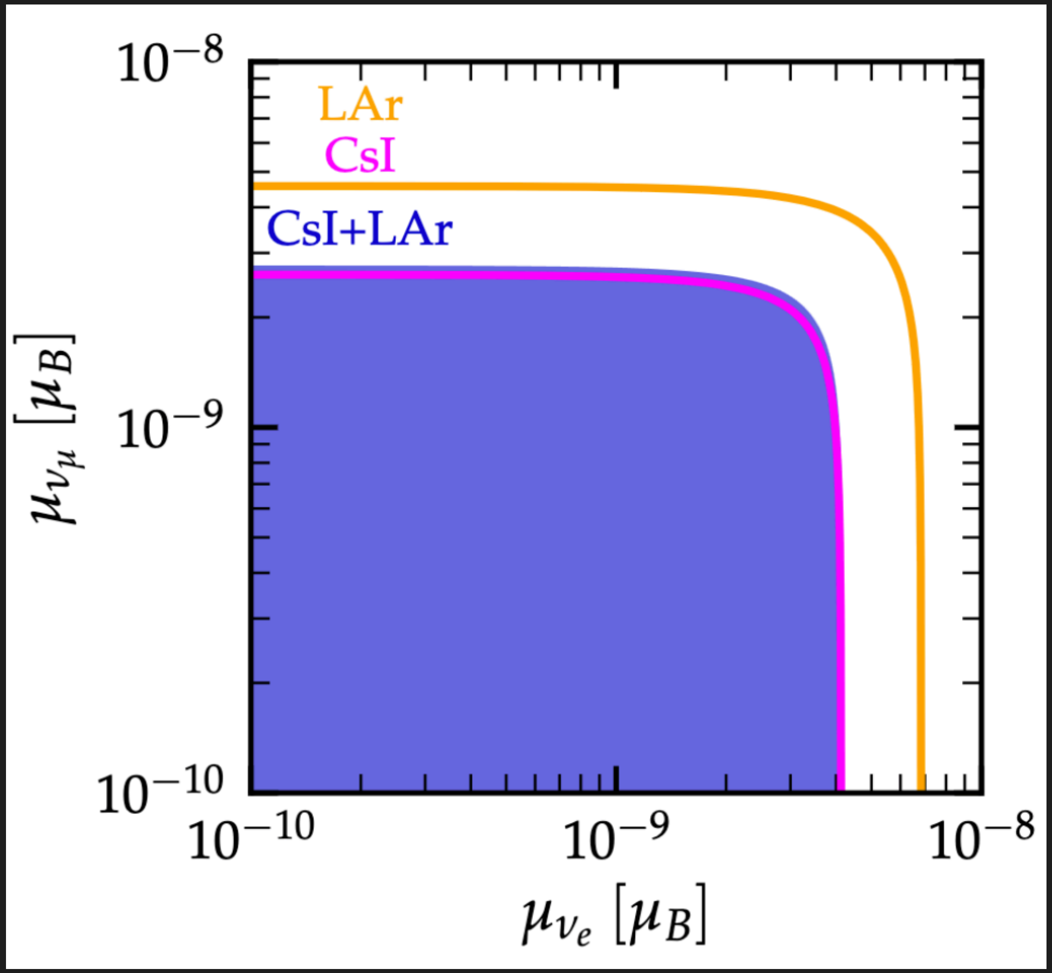
NEUTRINO MAGNETIC MOMENT

Neutrino magnetic moment interactions flip chirality and do not interfere with the SM terms. The differential cross section is incoherently added to the SM one:

$$\left.\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\mathrm{nr}}}\right|^{\mathrm{MM}}_{\mathrm{CE}\nu\mathrm{NS}} = \frac{\pi \alpha^2_{\mathrm{EM}}}{m_e^2}\left(\frac{1}{E_{\mathrm{nr}}} - \frac{1}{E_\nu}\right) Z^2 F_W^2(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right|^2$$

Vogel, Engel. PRD 39 [1989] 3378

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

μ_ν^2 is an effective neutrino magnetic moment dependent on a given neutrino beam (reactor, SNS, etc.)

Transition magnetic moments

Schechter Valle, PhysRevD.24.1883
Canas+ Phys.Lett. B753 (2016) 191–198
Miranda+ JHEP 1907 (2019) 103,
Aristizabal-Sierra+ Phys.Rev.D 105 (2022) 035027

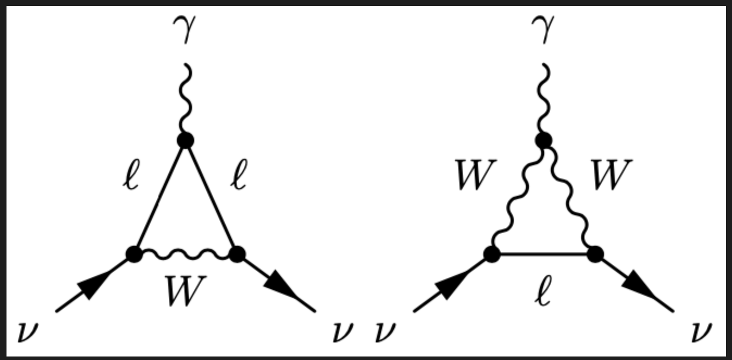
- can be dominant for sub-keV threshold experiments
- may lead to detectable distortions of the recoil spectrum

NEUTRINO CHARGE RADIUS

The neutrino charge radius is the only EM neutrino parameter different from zero within the SM framework.
A neutral particle can be characterized by a superposition of two charge distributions of opposite signs, so the particle form factor $\mathbb{F}_Q(q^2)$ can be nonzero for $q^2 \neq 0$.

Flavor-diagonal CR are generated via radiative corrections from the γ – Z boson mixing and box diagrams involving W and Z boson.

The mean charge radius of an electrically neutral neutrino is given by the second term in the power-series expansion of the neutrino charge form factor $\langle r_\nu^2 \rangle = 6 \frac{d\mathbb{F}_Q(q^2)}{dq^2}\Big|_{q^2=0}$



The SM values are $\left(\left\langle r^2_{\nu_{ee}}\right\rangle, \left\langle r^2_{\nu_{\mu\mu}}\right\rangle, \left\langle r^2_{\nu_{\tau\tau}}\right\rangle\right) = (-0.83, -0.48, -0.30) \times 10^{-32}\ \mathrm{cm}^2.$

Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450
Giunti, Studenikin, Rev Mod Phys, 87, 531 (2015)
Kouzakov and Studenikin, PRD 95 (2017) 055013

NEUTRINO CHARGE RADIUS

The contribution to the CEνNS cross section due to flavor-diagonal charge radii is obtained through the substitution $g_V^p \to g_V^p - Q_{\ell\ell}^{\rm CR}$

$$\langle r^2_{\nu_{\ell\ell}} \rangle_{\rm SM} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\ln\frac{m_\ell^2}{M_W^2}\right] \qquad Q_{\ell\ell}^{\rm CR} = \frac{\sqrt{2}\pi\alpha_{\rm EM}}{3G_F}\left\langle r^2_{\nu_{\ell\ell}}\right\rangle$$

Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450

In the SM there are only diagonal charge radii because lepton numbers are conserved.

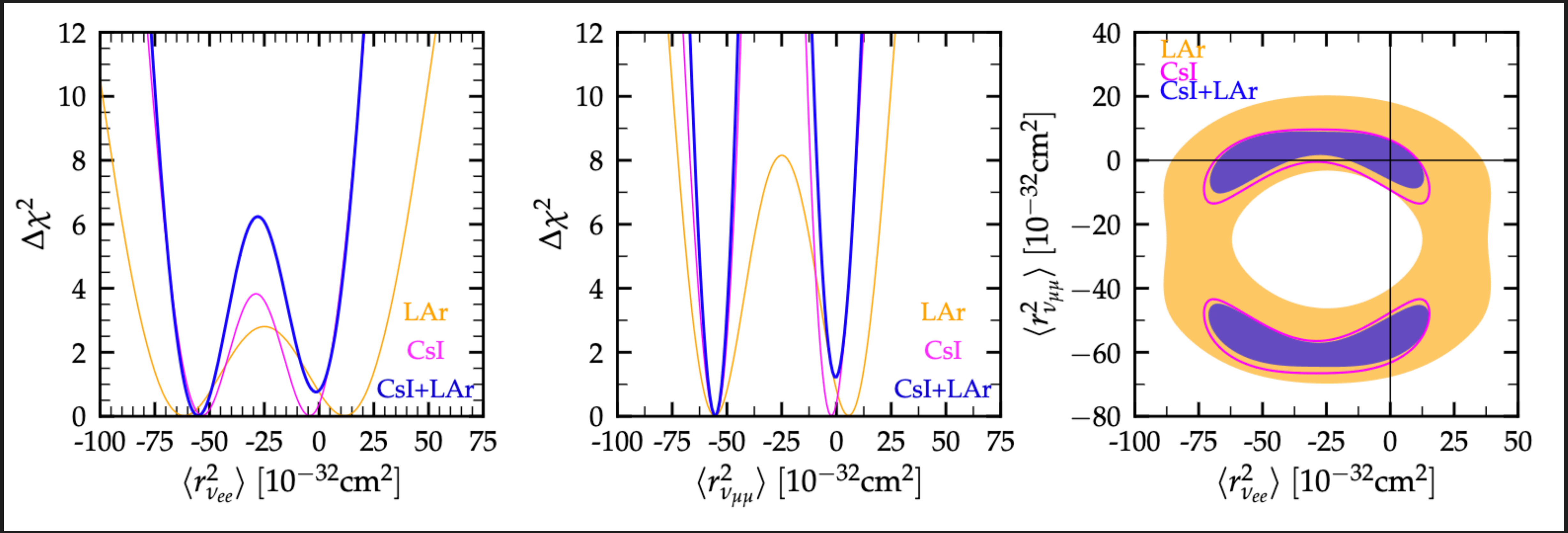
Transition charge radii can be generated via neutrino mixing and/or physics BSM and generate an incoherent contribution

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\rm nr}} = \frac{G_F^2 m_N}{\pi}\left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2}\right)\left[\left(g_V^n N F_N(\mathbf{q}^2) + g_V^p Z F_Z(\mathbf{q}^2)\right)^2 + 4/9 m_W^4 \sin^4\theta_w Z^2 F_Z^2(\mathbf{q}^2)\sum_{\ell'\neq\ell}|\langle r^2_{\nu_{\ell'\ell}}\rangle|^2\right]$$

Kouzakov and Studenikin, PRD 95 (2017) 055013
Cadeddu+ PRD98 (2018) 113010

NEUTRINO CHARGE RADIUS

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

Bounds on flavor-diagonal neutrino charge radii.
The analysis of CsI data includes only CEνNS interactions, since the EνES events contribution on CsI is negligible. CsI data result in a more constrained allowed area, with two separate regions.

TEXONO (reactor ν_e - e^-) and BNL-E734 (accelerator ν_μ - e^-) bounds more stringent.

See also Atzori-Corona+ JHEP 09 (2022) 164, JHEP 05 (2024) 271

NEUTRINO MILLICHARGE

In the SM the neutrality of neutrinos is a consequence of the quantization of electric charge.

Neutrinos can be millicharged particles in theories BSM that include right-handed neutrinos.

Babu and Mohapatra, PRL 63 (1989) 938

The contribution to the CEνNS cross section due to flavor-diagonal charge radii is obtained through the substitution $g_V^p \rightarrow g_V^p - Q_{\ell\ell}^{\mathrm{EC}}$

$$Q_{\ell\ell}^{\mathrm{EC}} = \frac{2\sqrt{2}\pi\alpha_{\mathrm{EM}}}{G_F q^2} q_{\nu_{\ell\ell}}$$

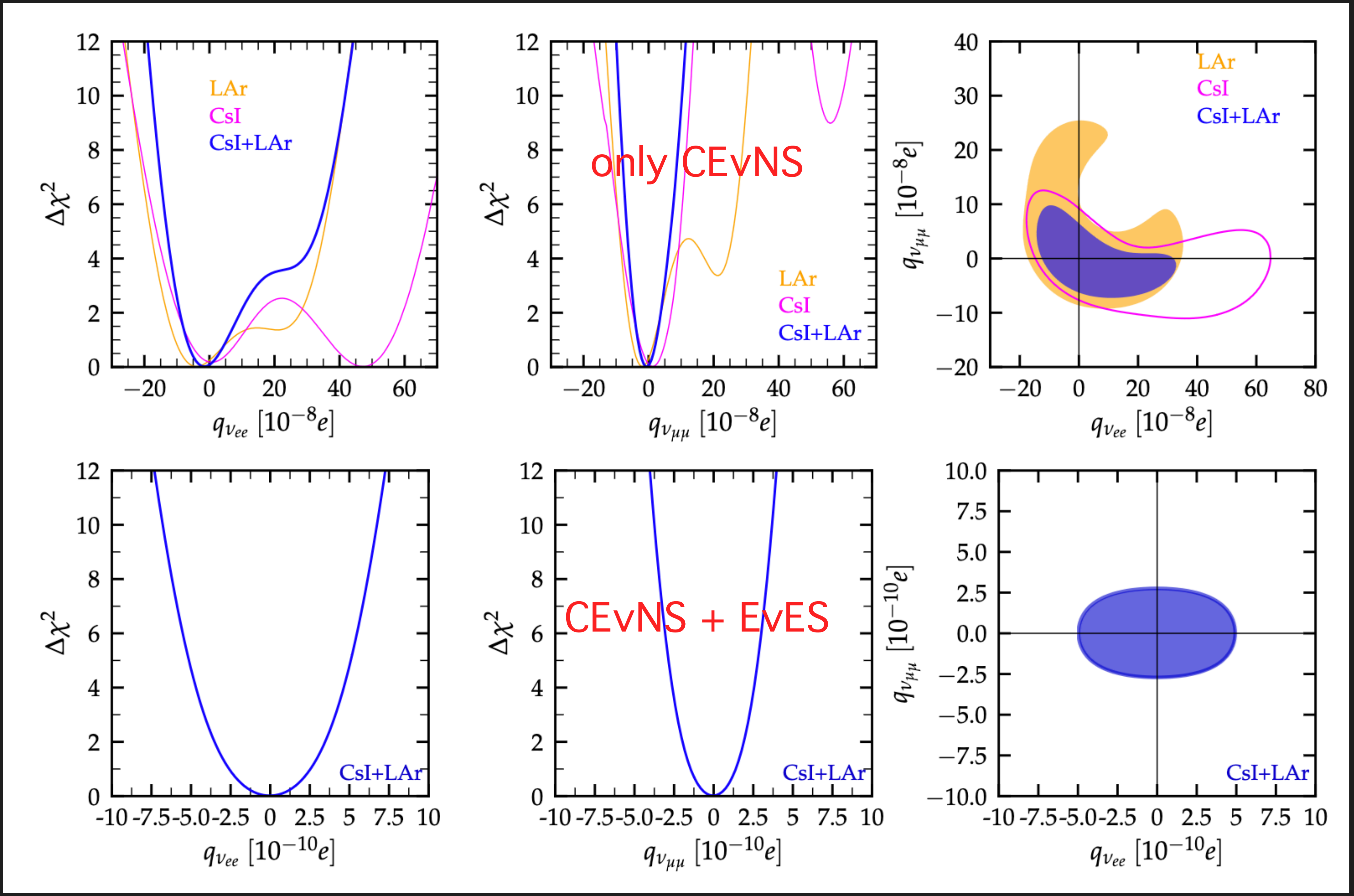
Atzori-Corona+ JHEP 09 (2022) 164

Being the four-momentum $q^2 = -2m_N E_{\mathrm{nr}}$

Interactions with flavor-nondiagonal EC are also possible.

Kouzakov and Studenikin, PRD 95 (2017) 055013

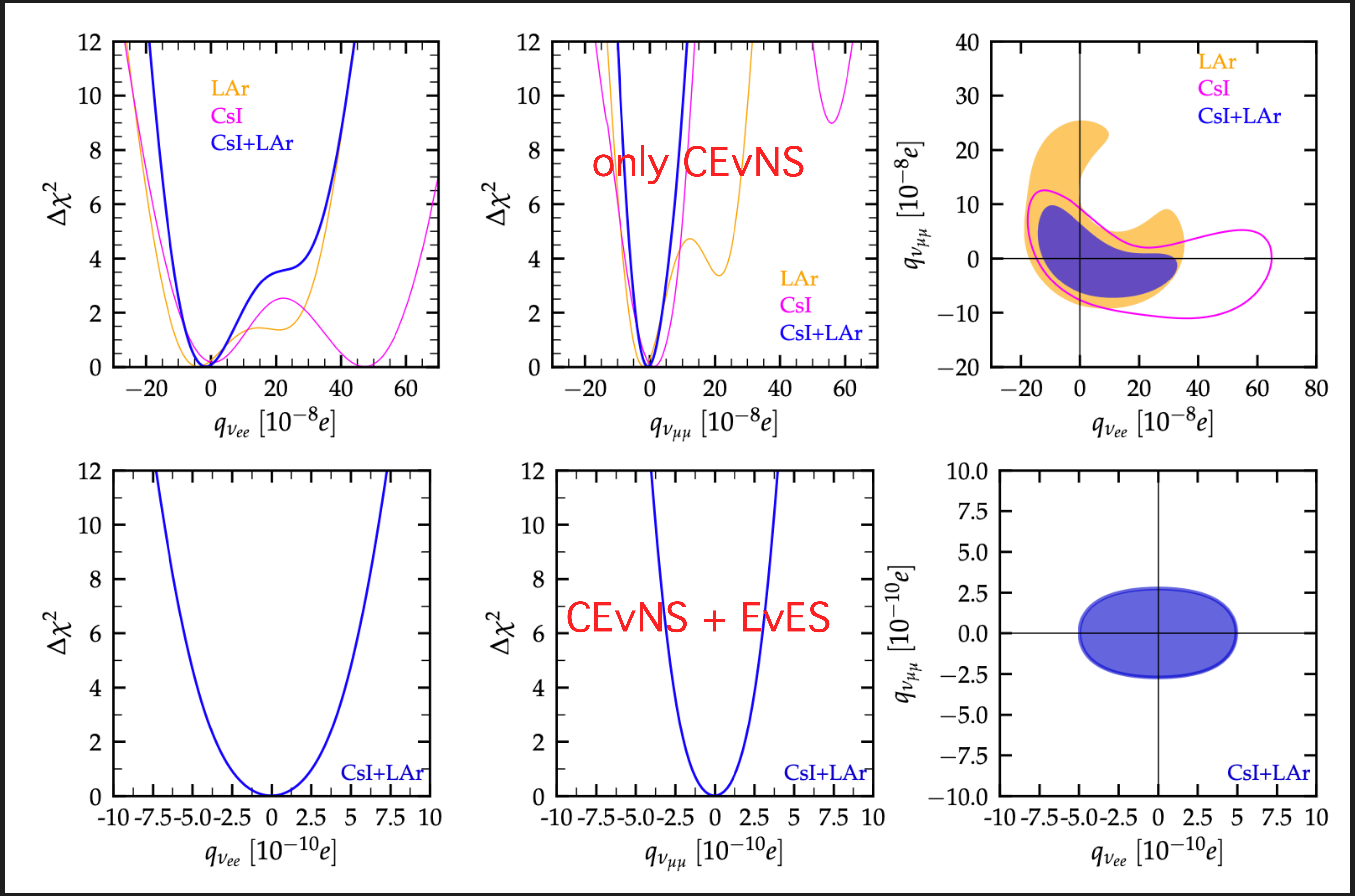
NEUTRINO MILLICHARGE



Including EvES events in the analysis strongly enhances the sensitivity of COHERENT data, because the momentum transferred is much smaller than in CEνNS interactions.

See also Atzori-Corona+ JHEP 05 (2024) 271, Khan Nucl.Phys.B 986 (2023) 116064

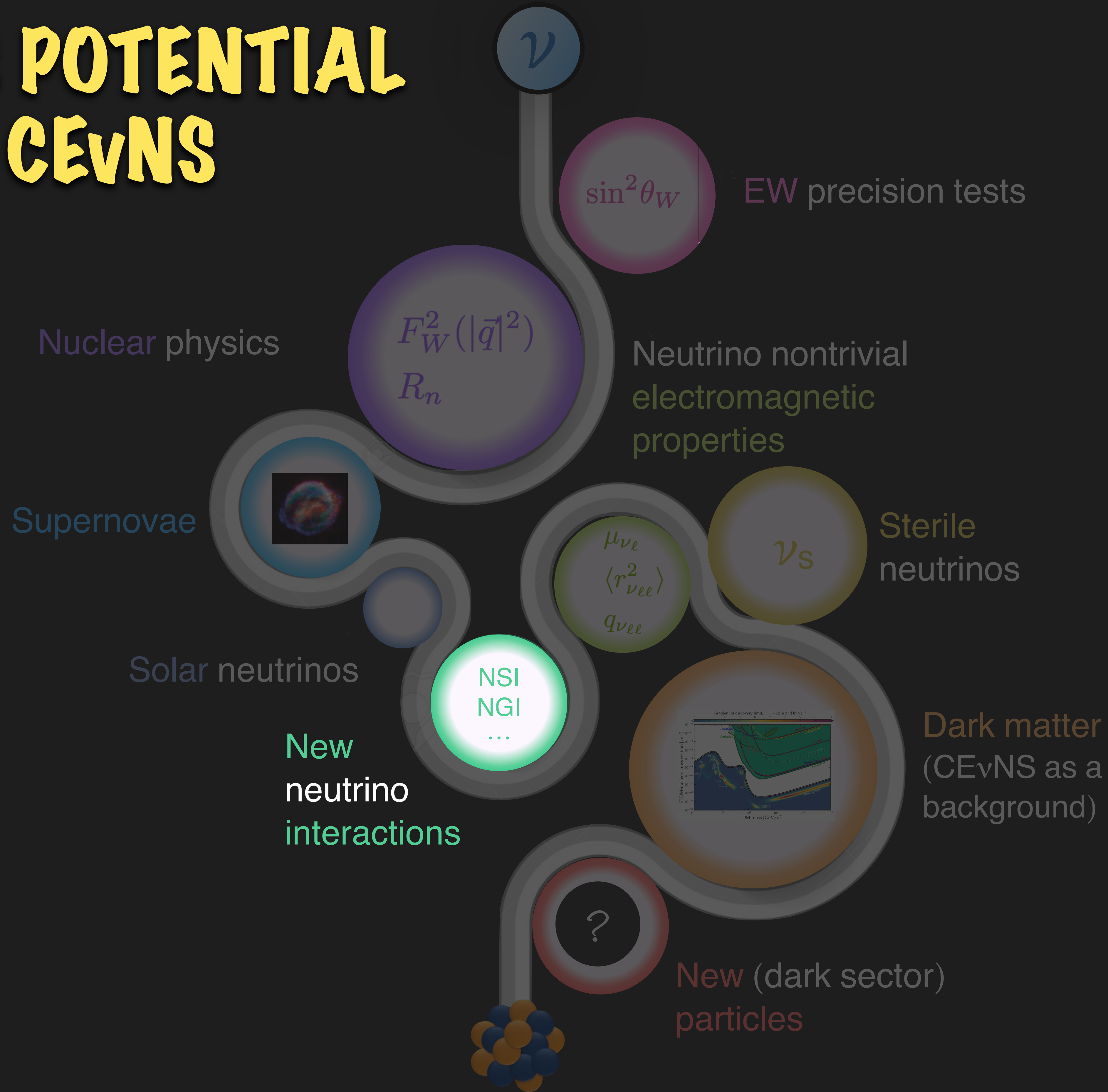
NEUTRINO MILLICHARGE



DM DD and accelerator bounds are stronger.

Gninenko+ Phys.Rev.D 75 (2007) 075014
Shivasankar+ Physics Letters B 839 (2023) 137742
Giunti and Ternes Phys.Rev.D 108 (2023) 9, 095044

PHYSICS POTENTIAL OF CEvNS



NEW NEUTRINO INTERACTIONS: NSI

New neutrino interactions BSM appear naturally in most neutrino mass models. Neutrino Non-Standard Interactions (NSI) may be of Charged-Current (CC) or of Neutral-Current (NC) type.

CC-NSI with the matter fields (e, u, d) affect in general the production and detection of neutrinos, while NC-NSI may affect the neutrino propagation in matter.

$$\mathscr{L}_{\rm NSI}^{\rm CC} \propto \epsilon_{\alpha\beta}^{ff'X} \left(\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta\right) \left(\bar{f}' \gamma_\mu P_X f\right)$$

$$\mathscr{L}_{\rm NSI}^{\rm NC} \propto \epsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X f\right)$$

These operators are expected to arise generically from the exchange of some mediator assumed to be heavier than the typical momentum transfer of the neutrino interaction.

T. Ohlsson, Rept. Prog. Phys. 76 (2013) 044201
O. Miranda and H. Nunokawa, New J.Phys. 17 (2015) 095002
Farzan and M. Tortola, Front.in Phys. 6 (2018) 10

NEW NEUTRINO INTERACTIONS: NSI

$$\mathscr{L}_{\rm NSI}^{\rm NC} \propto \epsilon_{\alpha\beta}^{fX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X f\right)$$

When embedded in a complete theory, electroweak gauge invariance generically implies that the NSI-NC parameters are expected to be subject to tight constraints from charged lepton observables.

Gavela+ Phys. Rev. D 79 (2009) 013007
Antusch+ Nucl. Phys. B810 (2009) 036

However, it is possible to build viable models for NSI by invoking an intermediate state of relatively light mass (~ 10 MeV) which has escaped detection so far because of its very small coupling.

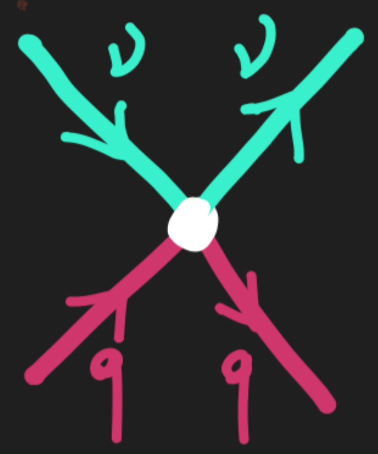
For light mediators bounds from high-energy neutrino scattering experiments such as CHARM and NuTeV do not apply.
NSI-NC generated by light mediators (~ 10 MeV) can only be constrained by their effect in oscillation data and by CEvNS.

Farzan Phys. Lett. B 748 (2015) 311
Farzan and Shoemaker, JHEP 07 (2016) 033
Babu+ JHEP 12 (2017) 096
Denton+ JHEP 07 (2018) 037
Farzan and M. Tortola, Front.in Phys. 6 (2018) 10
Esteban+ JHEP 08 (2018) 180

NEW NEUTRINO INTERACTIONS: NSI

Neutrino NSI can be formulated in terms of the effective (dimension-6) four-fermion Lagrangian:

$$\mathcal{L}_{\mathrm{NC}}^{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{q,\ell,\ell'} \boxed{\varepsilon_{\ell\ell'}^{qX}} (\bar{\nu}_\ell \gamma^\mu P_L \nu_{\ell'})(\bar{f}\gamma_\mu P_X f)$$



$$Q_V^{\mathrm{NSI}} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right] + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right]$$

The NSI couplings quantify the relative strength of the NSI in terms of G_F and can be either flavour preserving (non-universal) or flavor changing.

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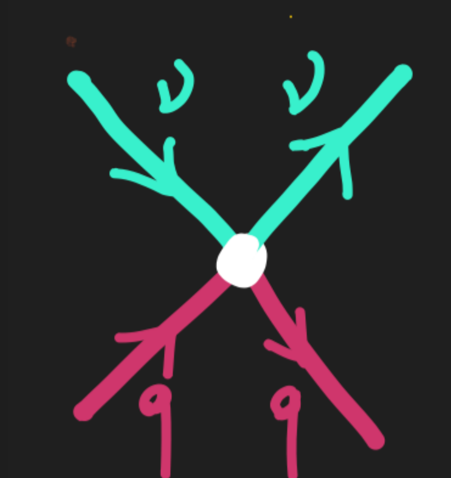

$$Q_V^{\rm NSI} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right] + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right]$$

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See also: S. Davidson et. al., JHEP 03 (2003) 011 J. Barranco, O.G. Miranda and T.I. Rashba, JHEP 0512 (2005) 021, K. Scholberg, PRD 73 (2006) 033005, Coloma+ Phys. Rev. D 96, 115007 (2017), JHEP 02, 023 (2020), JHEP 05 (2022) 037, Papoulias+ Phys. Rev. D 97, 033003 (2018), Giunti PRD 101, 035039 (2020), Denton+ JHEP 04, 266 (2021), Esteban+ JHEP 08, 180 (2018), COHERENT Colab. arXiv:2110.07730, Coloma+ JHEP 05 (2022) 037, Bresó-Pla+ JHEP 05 (2023) 074, Coloma+ JHEP 08 (2023) 03, Liao+ arXiv:2408.06255 ...

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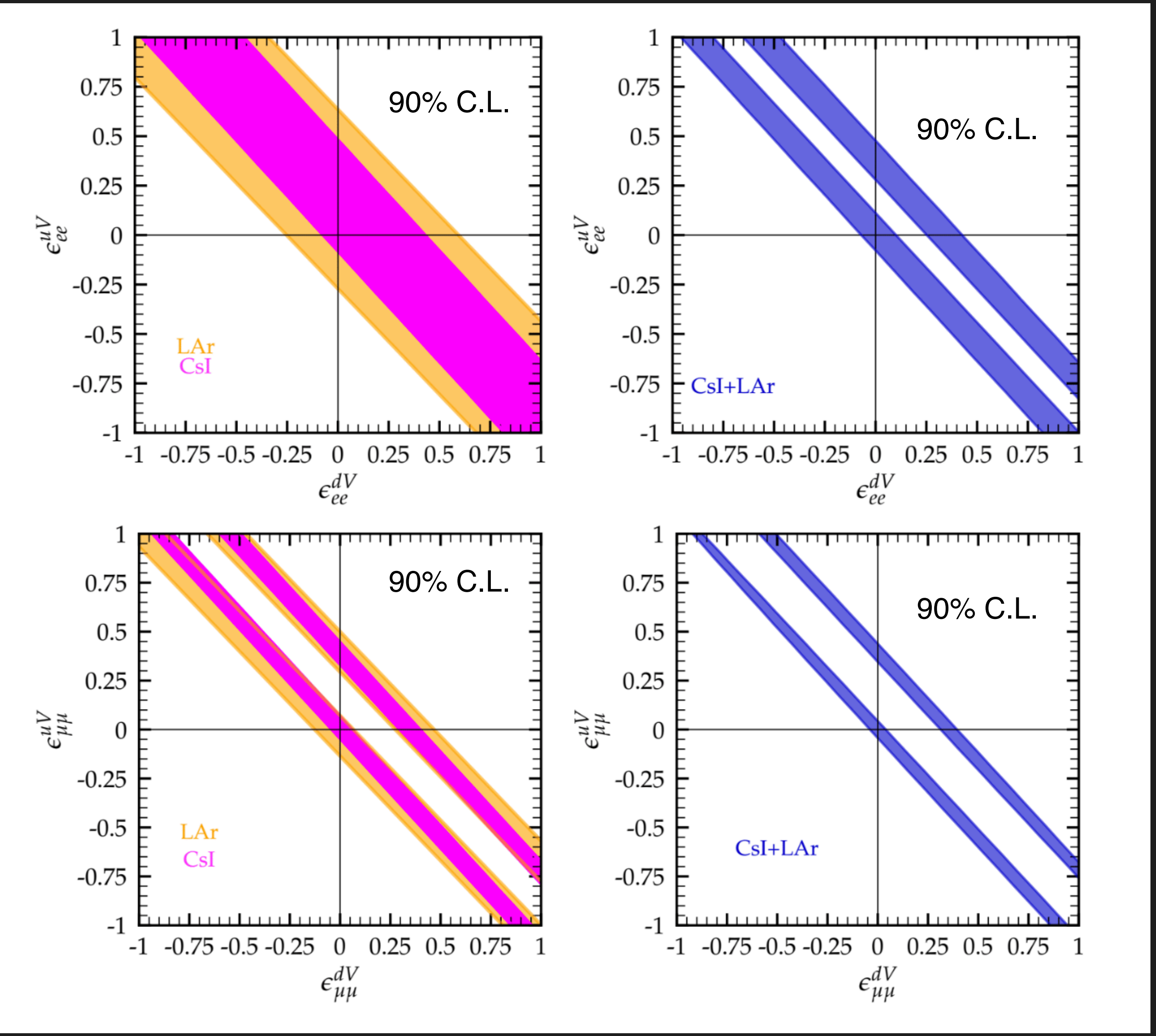
COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

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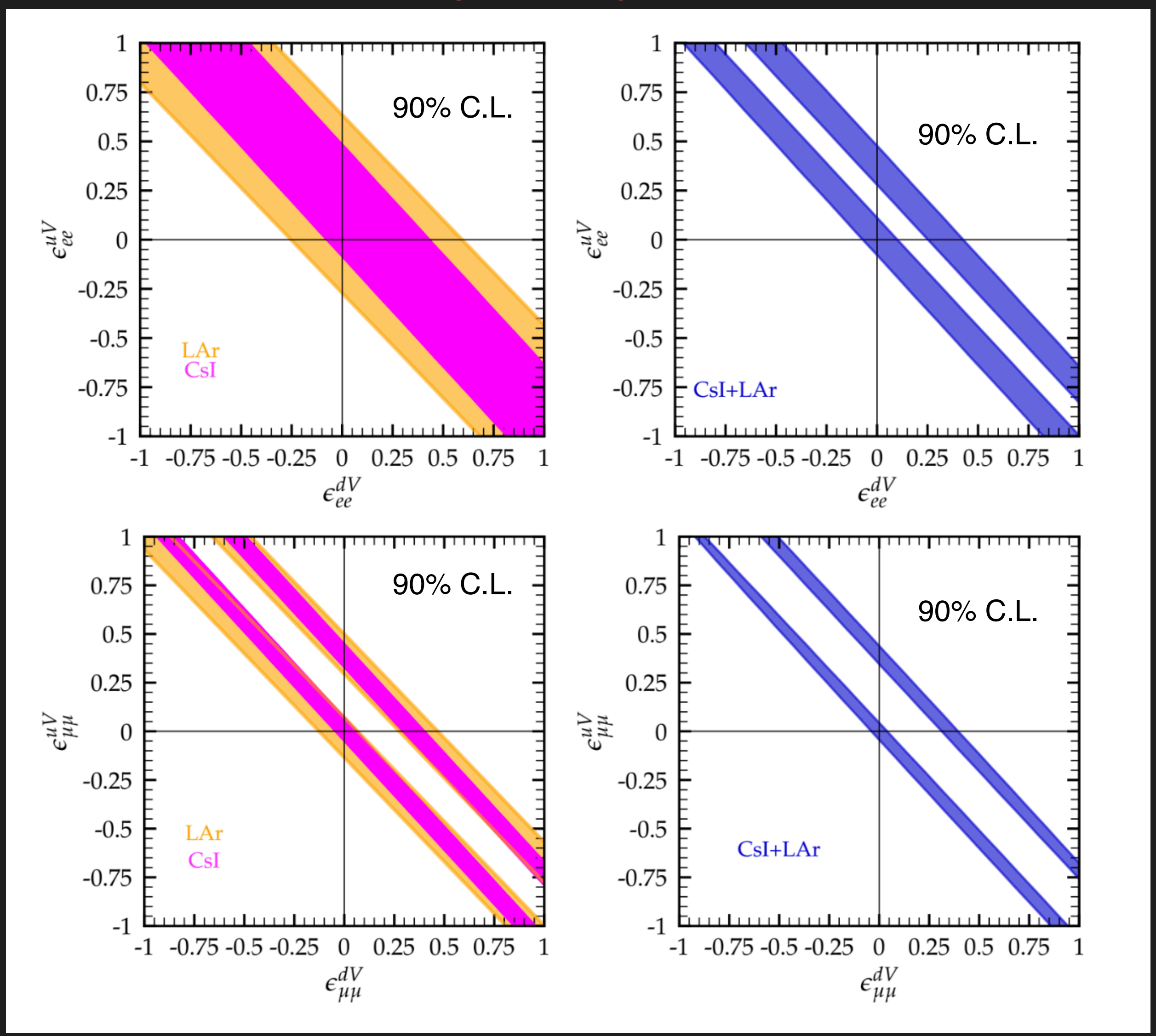
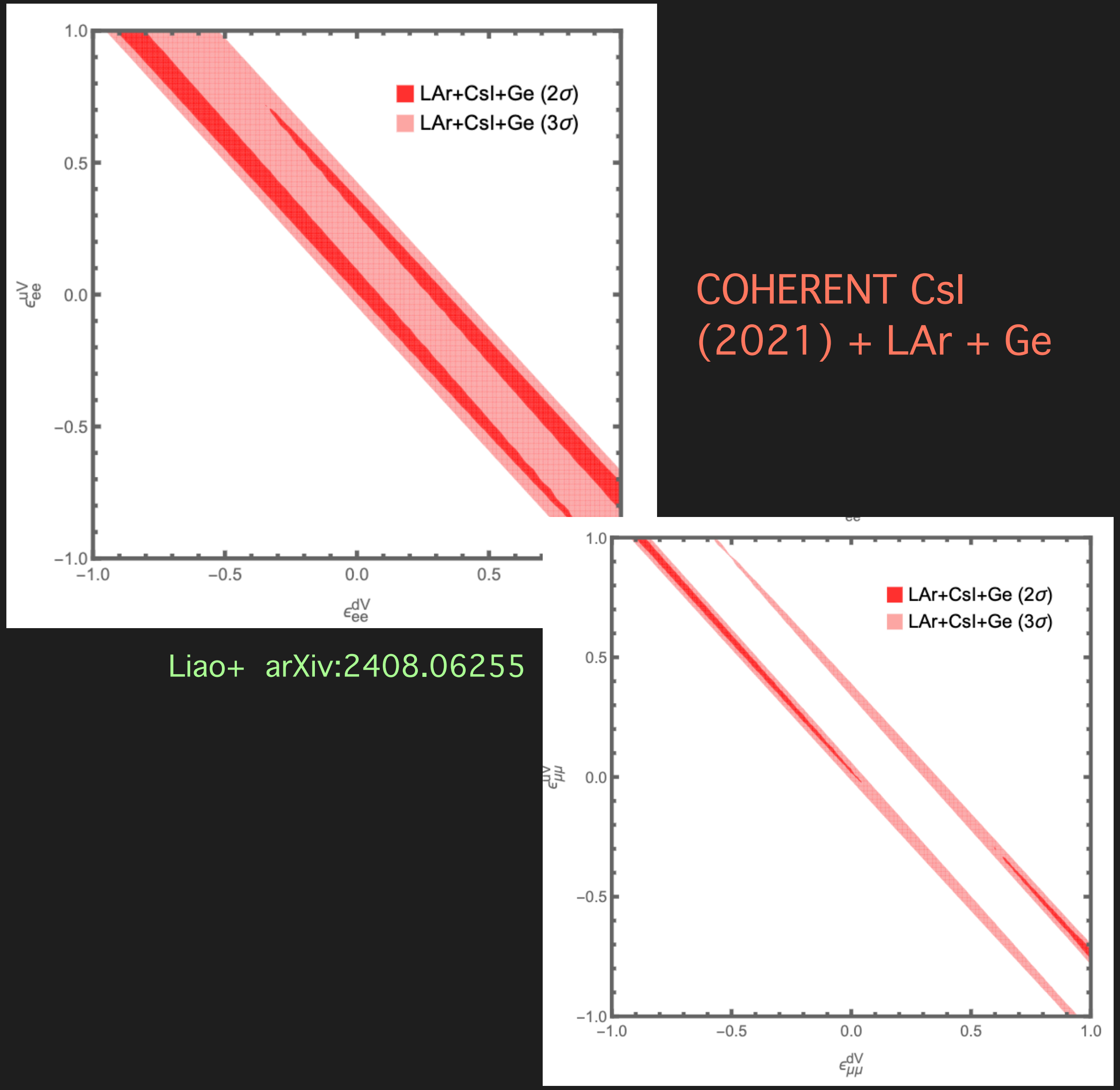
COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035



COHERENT CsI (2021) + LAr + Ge

Liao+ arXiv:2408.06255

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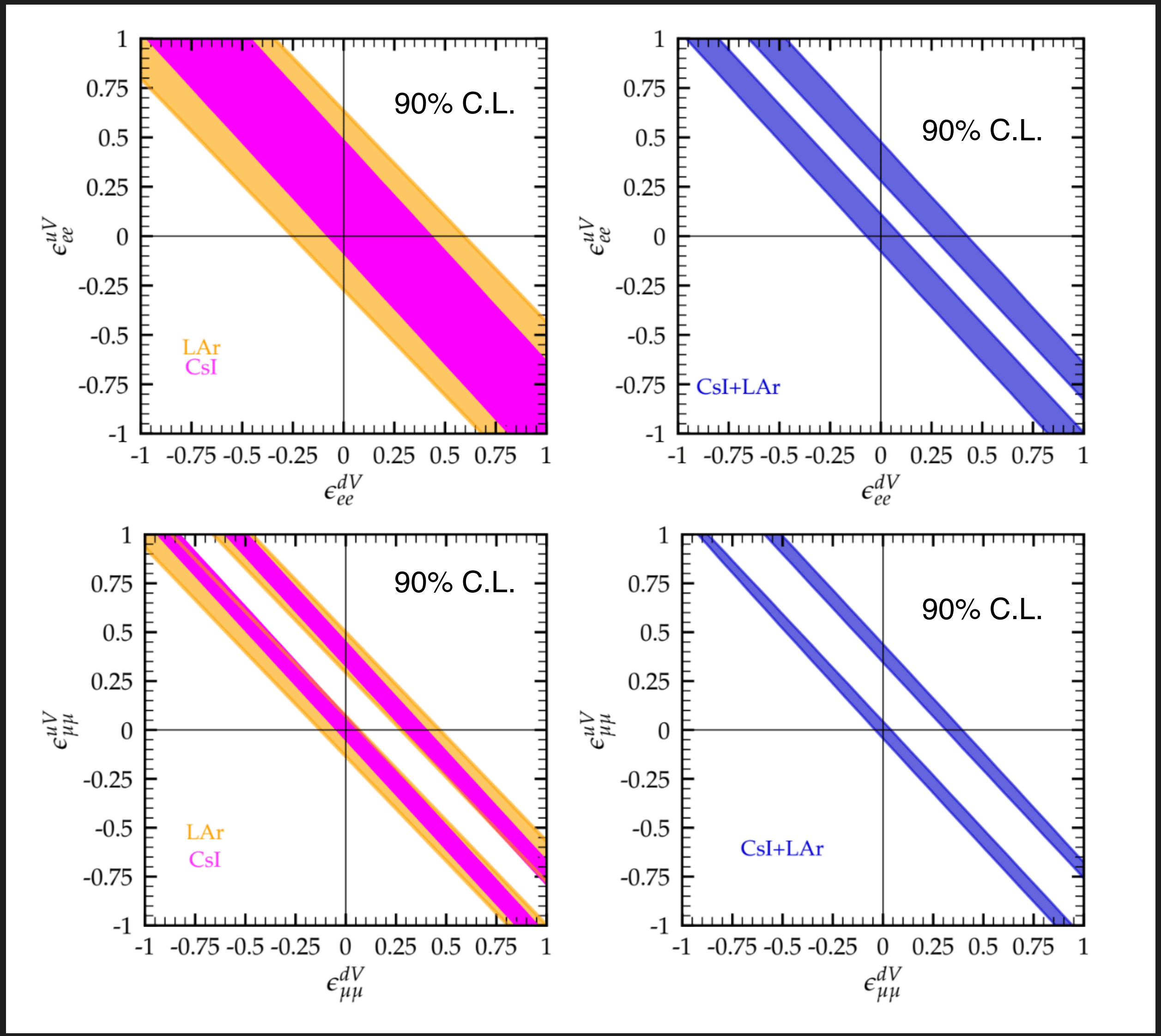
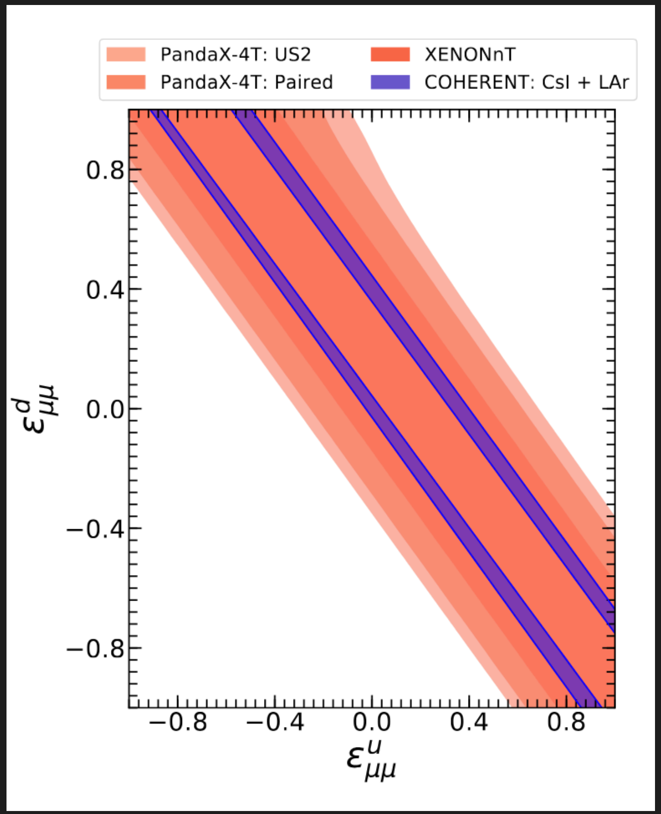
COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

COHERENT CsI (2021) + LAr + XENONnT + PANDAX-4T



Aristizabal+ arXiV: 2409.02003
See also Li+ 2409.04703

NEW NEUTRINO INTERACTIONS: NSI

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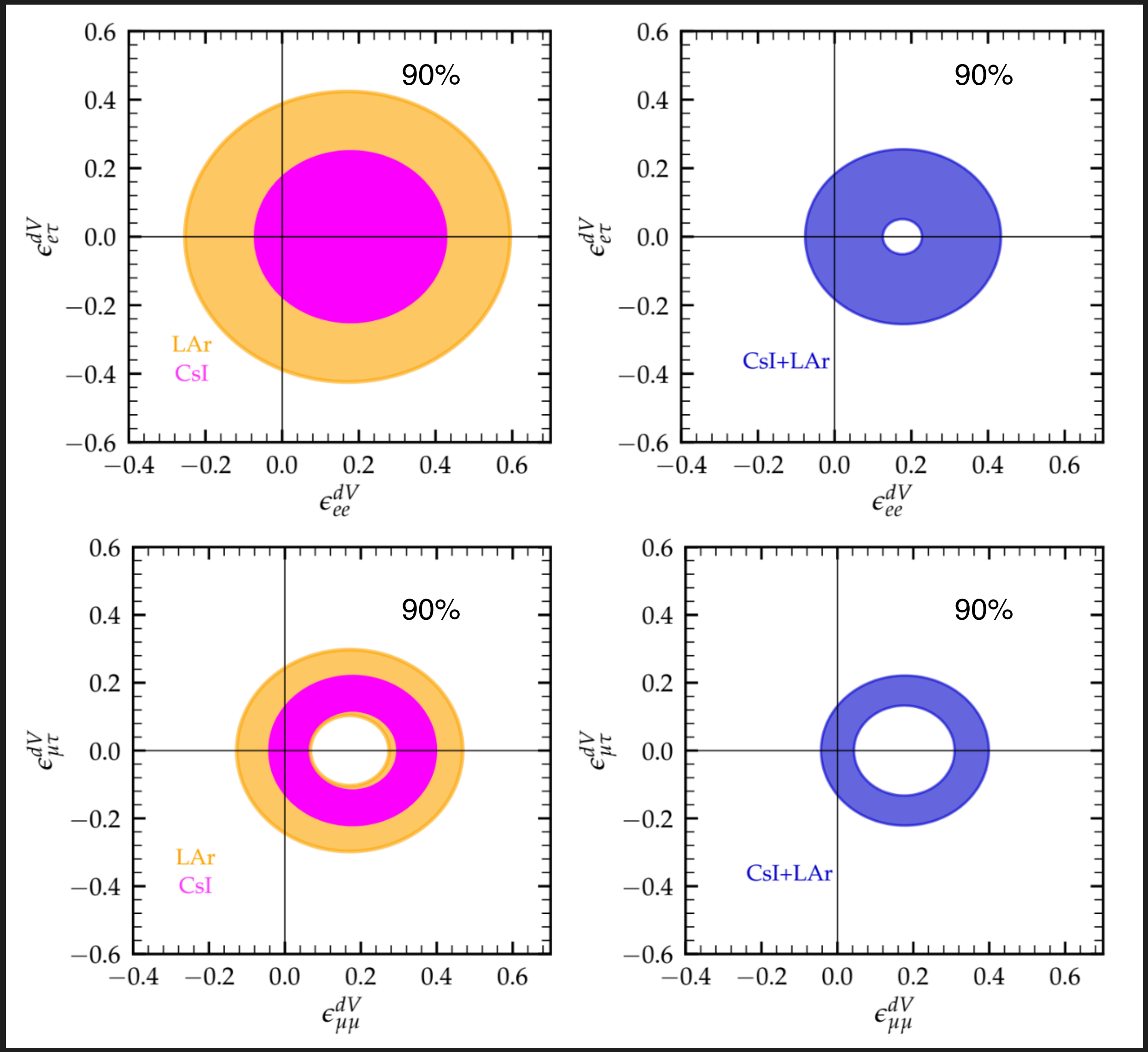
COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

NEW NEUTRINO INTERACTIONS: NGI

Beyond the typical NSI interactions that could arise in gauge extensions of the SM, a more general framework can be considered to accommodate all Lorentz invariant interactions

$$\mathscr{L}_{\rm NC}^{\rm NGI} \approx \sum_{\rm X=S,V,T} C_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}}\Gamma^X \mathcal{N} + \sum_{\rm (X,Y)=(P,S),(A,V)} D_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}} i\Gamma^Y \mathcal{N}$$

$$\Gamma^X = \{\mathbb{I}, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\} \qquad \sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$$

CX , DX denote the corresponding neutrino-nucleus couplings

Lee and Yang, Phys.Rev. 104 (1956) 254–258
Lindner+ JHEP 03 (2017) 097,
Aristizabal Sierra, VDR, Rojas, Phys.Rev.D 98 (2018) 075018
Flores et al. Phys. Rev. D 105 no. 5, (2022) 05501
...

NEW NEUTRINO INTERACTIONS: NGI

Beyond the typical NSI interactions that could arise in gauge extensions of the SM, a more general framework can be considered to accommodate all Lorentz invariant interactions

$$\mathscr{L}_{\rm NC}^{\rm NGI} \approx \sum_{\rm X=S,V,T} C_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}}\Gamma^X \mathcal{N} + \sum_{\rm (X,Y)=(P,S),(A,V)} D_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}} i\Gamma^Y \mathcal{N}$$

Interference new vector/SM

Interference scalar/tensor $R = 2C_S C_T$

$$\left.\frac{d\sigma}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm NGI} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\left\{ C_S^2 \frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2\,Q_V^{\rm SM}\right)^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) + 8\,C_T^2 \left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathscr{R}\frac{E_{\rm nr}}{E_\nu}\right\}$$

+: antineutrino

Weak charge associated to the new vector boson:

$$C_V = g_{\nu V}\left[\left(2 g_{uV} + g_{dV}\right) Z + \left(g_{uV} + 2 g_{dV}\right) N\right]$$

new mediator couplings with neutrinos and quarks

NEW NEUTRINO INTERACTIONS: NGI

Beyond the typical NSI interactions that could arise in gauge extensions of the SM, a more general framework can be considered to accommodate all Lorentz invariant interactions

$$\mathscr{L}_{\rm NC}^{\rm NGI} \approx \sum_{\rm X=S,V,T} C_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}}\Gamma^X \mathcal{N} + \sum_{\rm (X,Y)=(P,S),(A,V)} D_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}} i\Gamma^Y \mathcal{N}$$

Interference new vector/SM

Interference scalar/tensor R = 2Cs CT

$$\left.\frac{d\sigma}{dE_{\rm nr}}\right|_{\rm CE\nu NS}^{\rm NGI} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\left\{ C_S^2 \frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2\,Q_V^{\rm SM}\right)^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) + 8\,C_T^2\left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathscr{R}\frac{E_{\rm nr}}{E_\nu}\right\}$$

+: antineutrino

Weak charge associated to the new scalar boson:

$$C_S = g_{\nu S}\left(Z \sum_q g_{qS} \frac{m_p}{m_q} f_q^p + N \sum_q g_{qS} \frac{m_n}{m_q} f_q^n \right)$$

Cirelli+ JCAP 10 (2013) 019
Del Nobile arXiv:2104.12785
Belanger+ Comput. Phys. Commun. 185 (2014) 960–985
Anselmino+ Nucl. Phys. B Proc. Suppl. 191 (2009) 98–107
Candela+ 2404.12476

hadronic structure parameters (quark mass contributions to the nucleon)

NEW NEUTRINO INTERACTIONS: NGI

Beyond the typical NSI interactions that could arise in gauge extensions of the SM, a more general framework can be considered to accommodate all Lorentz invariant interactions

$$\mathscr{L}_{\rm NC}^{\rm NGI} \approx \sum_{\rm X=S,V,T} C_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}}\Gamma^X \mathcal{N} + \sum_{\rm (X,Y)=(P,S),(A,V)} D_X \bar{\nu}\Gamma_X \nu \bar{\mathcal{N}} i \Gamma^Y \mathcal{N}$$

Interference new vector/SM

Interference scalar/tensor $R = 2C_S C_T$

$$\frac{d\sigma}{dE_{\rm nr}}\Bigg|^{\rm NGI}_{\rm CE\nu NS} = \frac{G_F^2 m_N}{4\pi} F_W^2(|\vec{q}|^2)\left\{ C_S^2 \frac{m_N E_{\rm nr}}{2E_\nu^2} + \left(C_V + 2\,Q_V^{\rm SM}\right)^2 \left(1 - \frac{m_N E_{\rm nr}}{2E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) + 8\,C_T^2 \left(1 - \frac{m_N E_{\rm nr}}{4E_\nu^2} - \frac{E_{\rm nr}}{E_\nu}\right) \pm \mathscr{R} \frac{E_{\rm nr}}{E_\nu} \right\}$$

+: antineutrino

Weak charge associated to the tensor interaction:

$$C_T = g_{\nu T}\left(Z \sum_q g_{qT}\delta_q^p + N \sum_q g_{qT}\delta_q^n \right)$$

Cirelli+ JCAP 10 (2013) 019
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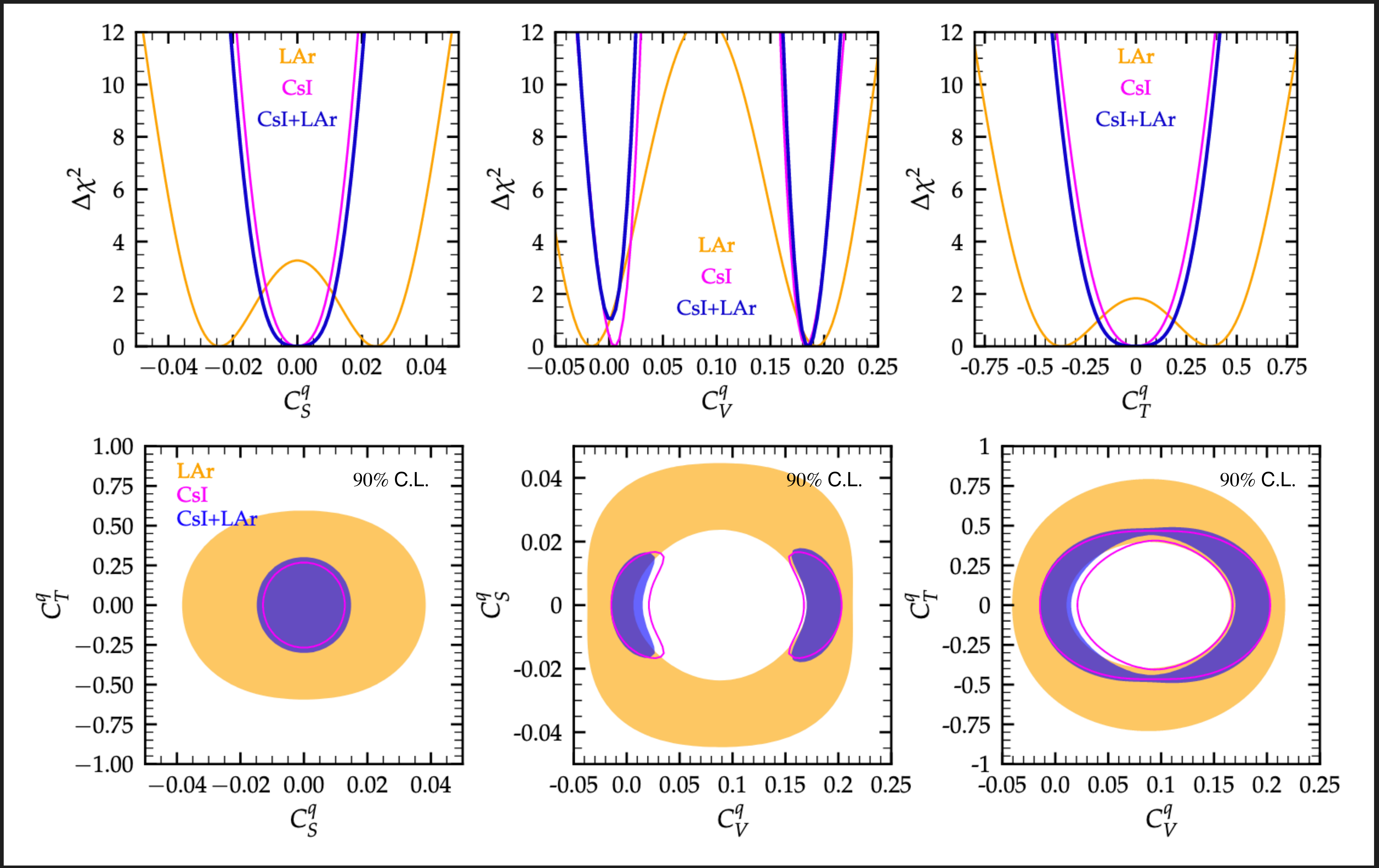
Belanger+ Comput. Phys. Commun. 185 (2014) 960–985
Anselmino+ Nucl. Phys. B Proc. Suppl. 191 (2009) 98–107
Candela+ 2404.12476

tensor charges (difference between the spin of quarks and anti-quarks inside the nucleon)

NEW NEUTRINO INTERACTIONS: NGI

COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García, Tórtola and Valle, JHEP 04 (2023) 035

NEW NEUTRINO INTERACTIONS: LIGHT MEDIATORS

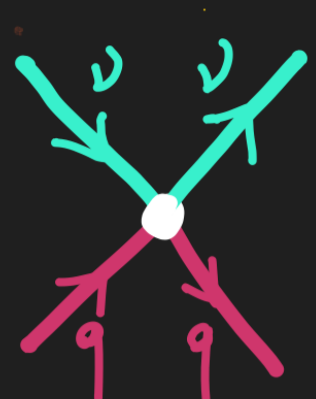
New BSM scenarios might be associated with different types of interactions and mediators. These mediators would contribute to CEνNS and EνES processes leading to detectable distortions of the event rates, especially at low-energy recoils.

Cerdeño+ JHEP 1605 (2016) 118
Bertuzzo+ JHEP 1704 (2017) 073
Farzan+ JHEP 1805 (2018) 066
Denton+ PRD 106 (2022) 015022

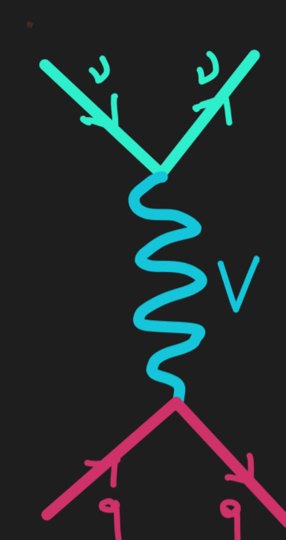
Low-energy neutrino experiments are sensitive to interactions involving light mediators, inducing spectral distortions at low recoil energies.

We may consider light mediators with a mass comparable to the typical momentum transfer

$$|\mathbf{q}| \approx \sqrt{2 m_{\mathcal{N}} E_{\rm nr}}$$



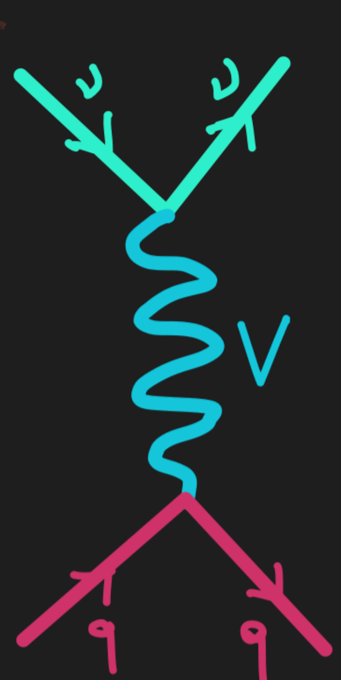
$$G_F^2 |\varepsilon_\ell^X|^2 \to \frac{2 g_X^4}{(m_X^2 + |\mathbf{q}|^2)^2}$$



NEW NEUTRINO INTERACTIONS: LV

$$\frac{d\sigma}{dE_{\rm nr}}\bigg|_{\rm CE\nu NS}^{\rm LV} = \left(1 + \kappa \frac{C_V}{\sqrt{2} G_F Q_W^{\rm SM} \left(2 m_N E_{\rm nr} + m_V^2\right)}\right)^2 \frac{d\sigma}{dE_{\rm nr}}\bigg|_{\rm CE\nu NS}^{\rm SM}$$

$$C_V = g_{\nu V}\left[\left(2 g_{uV} + g_{dV}\right) Z + \left(g_{uV} + 2 g_{dV}\right) N\right]$$



$\kappa = 1$ for universal couplings
$\kappa = -1/3$ in the B – L model

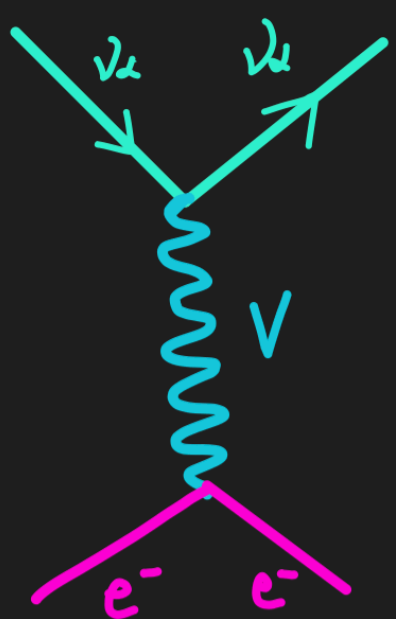
$$g_V = \sqrt{g_{\nu V} g_{qV}}$$

NEW NEUTRINO INTERACTIONS: LV

$$\frac{d\sigma_{\nu_\ell \mathscr{A}}}{dE_{\rm er}}\Bigg|^{\rm SM}_{{\rm E}\nu{\rm ES}} = Z^{\mathscr{A}}_{\rm eff}(E_{\rm er}) \frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\ell} + g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell} - g_A^{\nu_\ell})^2\left(1 - \frac{E_{\rm er}}{E_\nu}\right)^2 - \left((g_V^{\nu_\ell})^2 - (g_A^{\nu_\ell})^2\right)\frac{m_e E_{\rm er}}{E_\nu^2}\right]$$

effective number of protons seen by the neutrino for an energy deposition Eer

$$g_V^{\nu_\ell} = g_V^{\nu_\ell} + \kappa \frac{g_{\nu V} \cdot g_{eV}}{2\sqrt{2} G_F (2 m_e E_{\rm er} + m_V^2)}$$



$\kappa = 1$ for universal couplings
$\kappa = 1$ in the B – L model

$$g_V = \sqrt{g_{\nu V} g_{eV}}$$

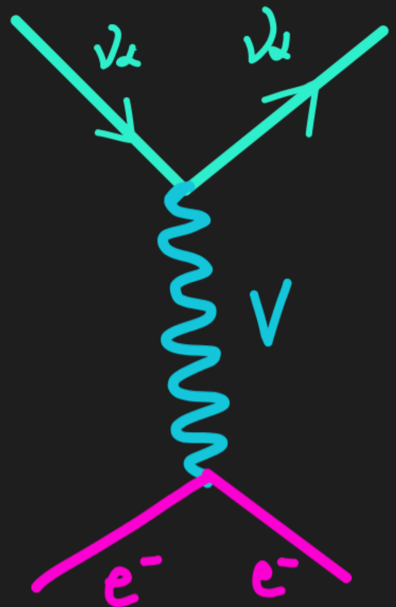
NEW NEUTRINO INTERACTIONS: LV

$$\left.\frac{d\sigma_{\nu_\ell \mathscr{A}}}{dE_{\text{er}}}\right|^{\text{SM}}_{\text{E}\nu\text{ES}} = Z^{\mathscr{A}}_{\text{eff}}(E_{\text{er}}) \frac{G_F^2 m_e}{2\pi}\left[(g_V^{\nu_\ell}+g_A^{\nu_\ell})^2 + (g_V^{\nu_\ell}-g_A^{\nu_\ell})^2\left(1-\frac{E_{\text{er}}}{E_\nu}\right)^2 - \left((g_V^{\nu_\ell})^2-(g_A^{\nu_\ell})^2\right)\frac{m_e E_{\text{er}}}{E_\nu^2}\right]$$

effective number of protons seen by the neutrino for an energy deposition Eer

$$g_V^{\nu_\ell} = g_V^{\nu_\ell} + \kappa \frac{g_{\nu V}\cdot g_{eV}}{2\sqrt{2}G_F(2m_e E_{\text{er}} + m_V^2)}$$

Only relevant for CsI data!
Flavor dependent



$\nu_e - e^-$ Scattering
NC and CC

$$g_V^{\nu_\ell} = 2\sin^2\theta_{\text{w}} + 1/2$$

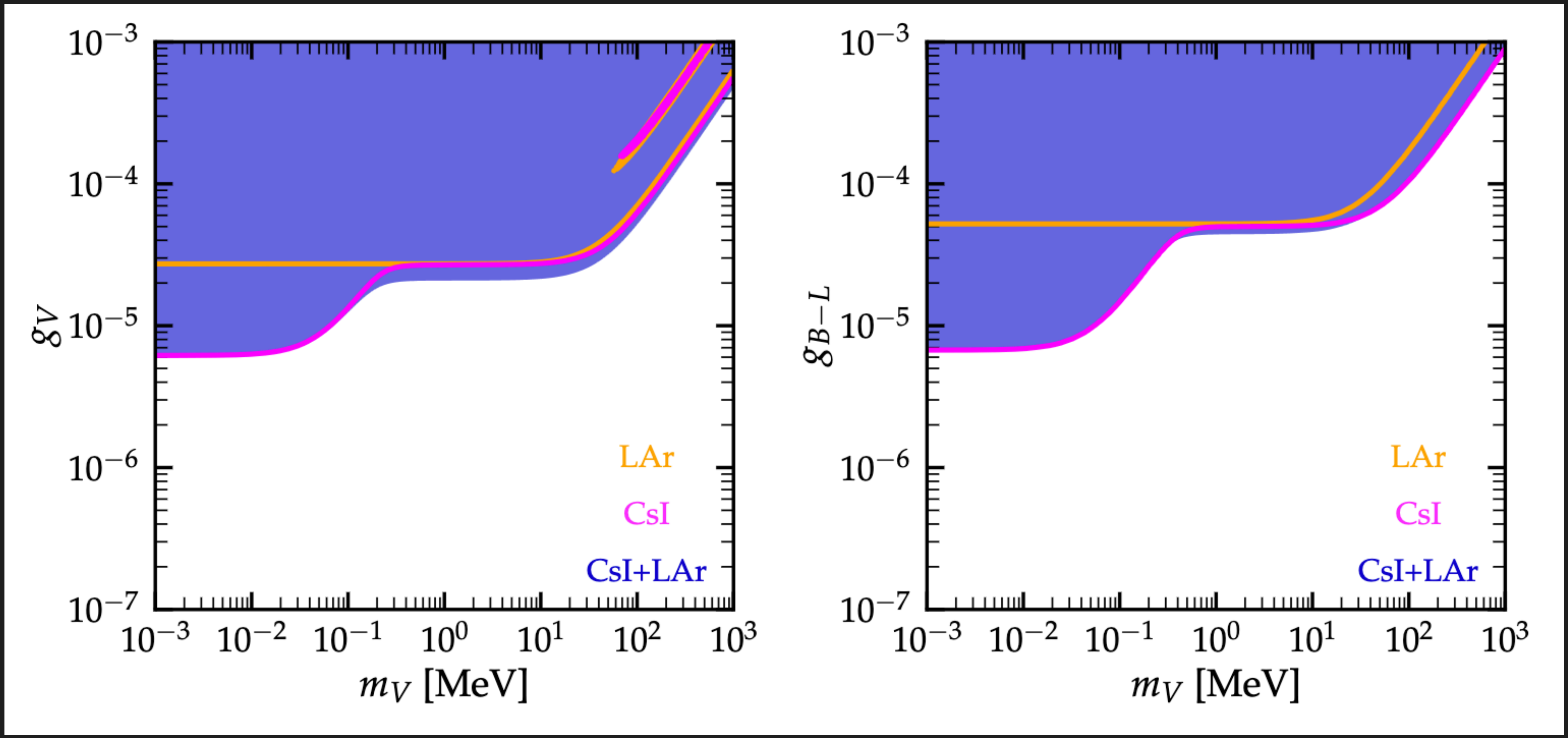
$$g_A^{\nu_\ell(\bar\nu_\ell)} = 1/2 \quad (-1/2)$$

$\nu_{\mu,\tau} - e^-$ Scattering
Only NC

$$g_V^{\nu_\ell} = 2\sin^2\theta_{\text{w}} - 1/2$$

$$g_A^{\nu_\ell(\bar\nu_\ell)} = -1/2 \quad (1/2)$$

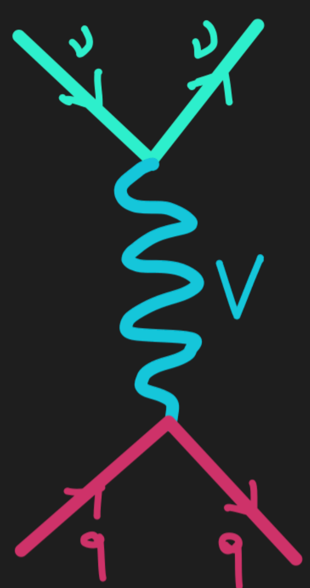
NEW NEUTRINO INTERACTIONS: LV



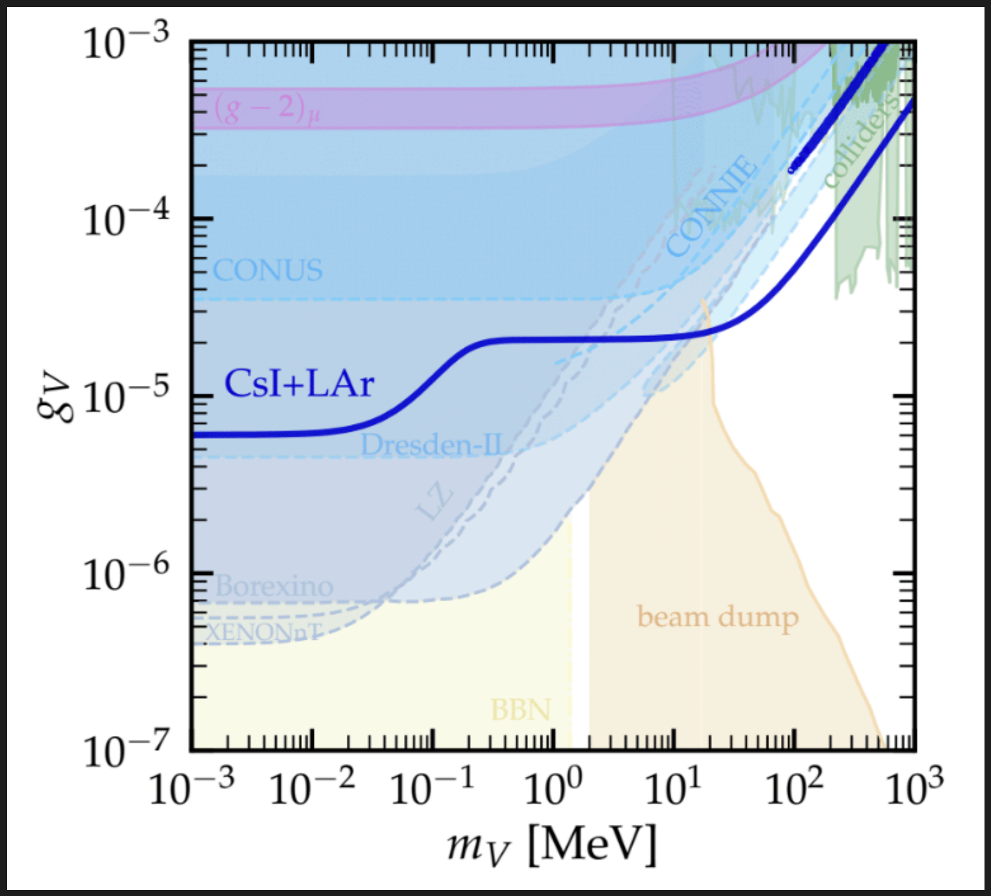
VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

- Complementary analyses in: J. Liao, H. Liu, and D. Marfatia, 2202.10622, Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484, A. Khan 2203.08892, Majumdar+ 2208.13262

NEW NEUTRINO INTERACTIONS: LV

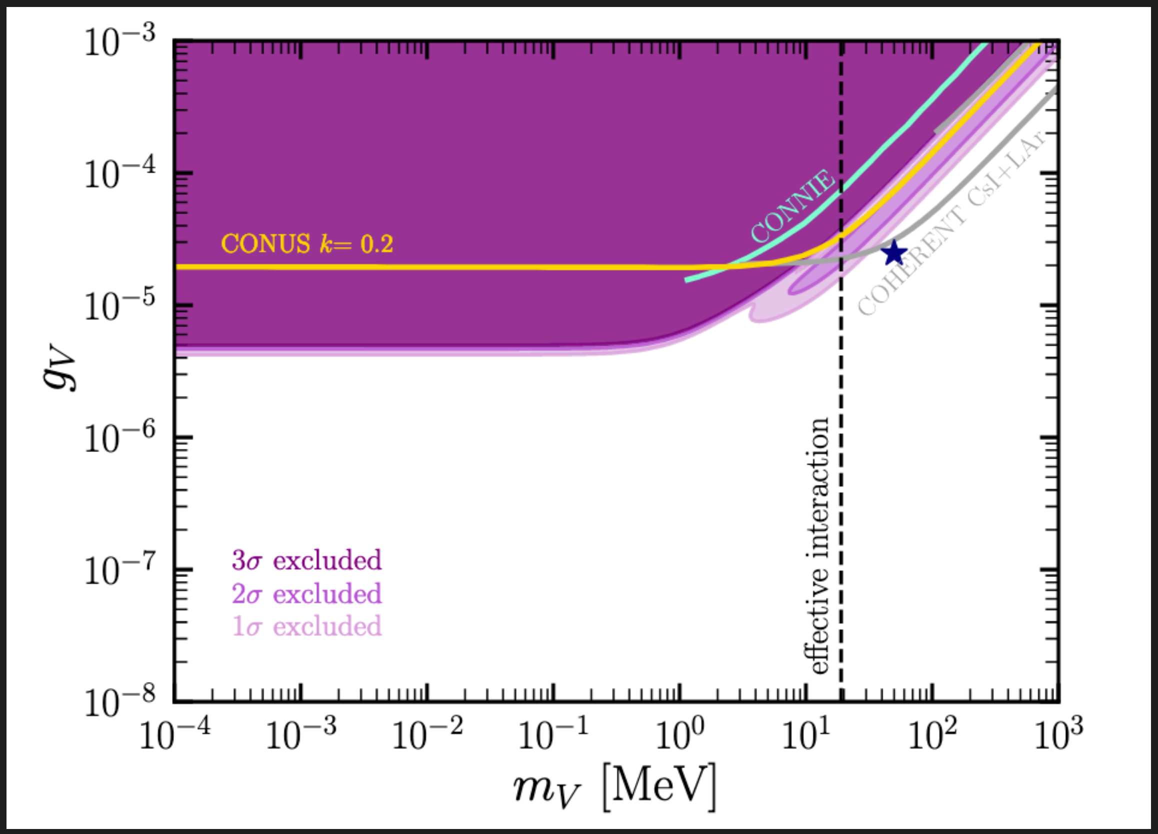


COHERENT CsI (2021) + LAr



VDR, Miranda, Papoulias, Sanchez-García,Tórtola and Valle, JHEP 04 (2023) 035

Dresden-II (Ge) - iron filter



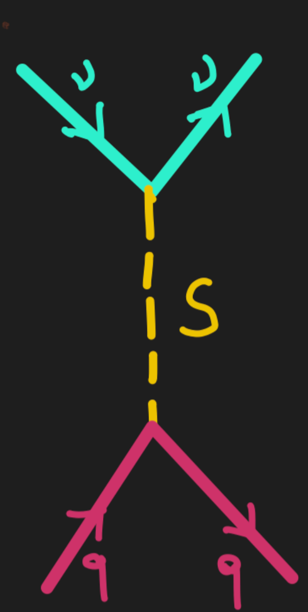
Aristizabal, VDR, Papoulias JHEP 09 (2022) 076

- Complementary analyses in: J. Liao, H. Liu, and D. Marfatia, 2202.10622, Coloma et al. 2202.10829, Atzori-Corona et al. 2205.09484, A. Khan 2203.08892, Majumdar+ 2208.13262

NEW NEUTRINO INTERACTIONS: LS

$$\frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE_{\text{nr}}}\Bigg|^{\text{LS}}_{\text{CE}\nu\text{NS}} = \frac{m_N^2 E_{\text{nr}}\, C_S^2}{4\pi E_\nu^2 \left(2m_N E_{\text{nr}} + m_S^2\right)^2} F_W^2(|\vec{q}\,|^2)$$

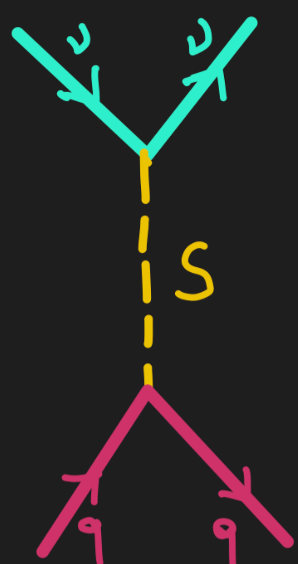
$$C_S = g_{\nu S}\left(Z\sum_q g_{qS}\frac{m_p}{m_q}f_q^p + N\sum_q g_{qS}\frac{m_n}{m_q}f_q^n\right)$$



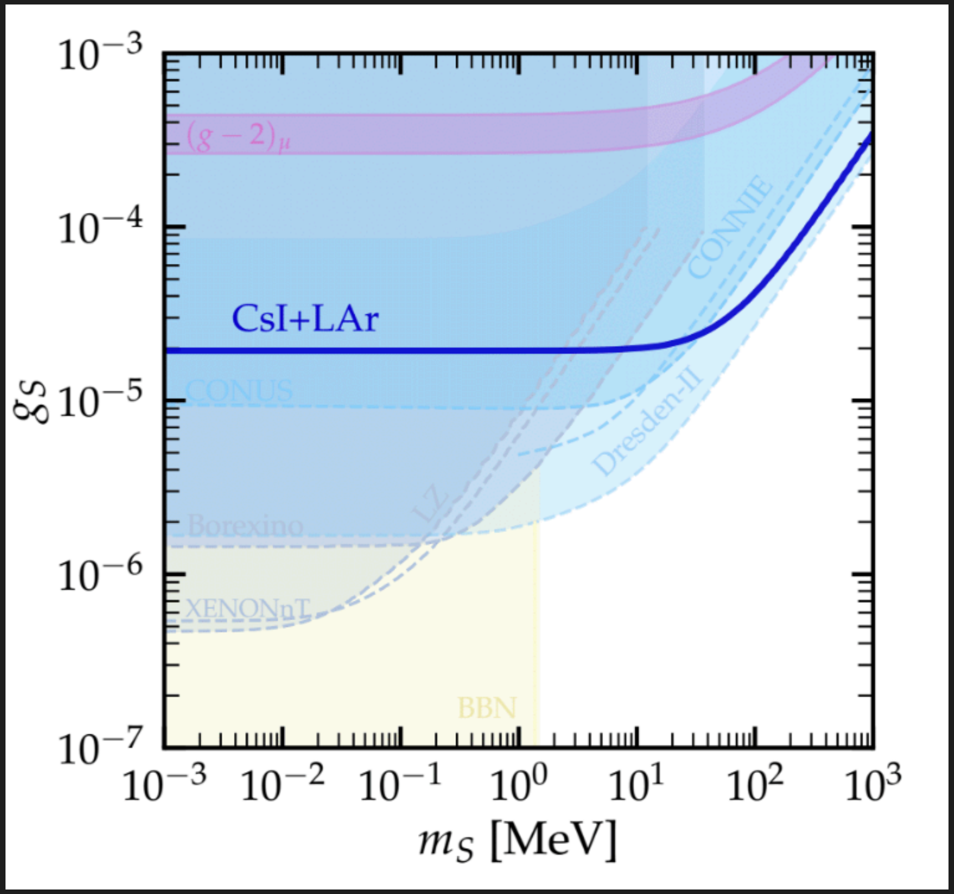
$$g_S = \sqrt{g_{\nu S}g_{qS}}$$

(Scalar-mediated EνES process has no substancial enhancement, the cross section is proportional to ~ $1/E_{er}$)

NEW NEUTRINO INTERACTIONS: LS



COHERENT CsI (2021) + LAr



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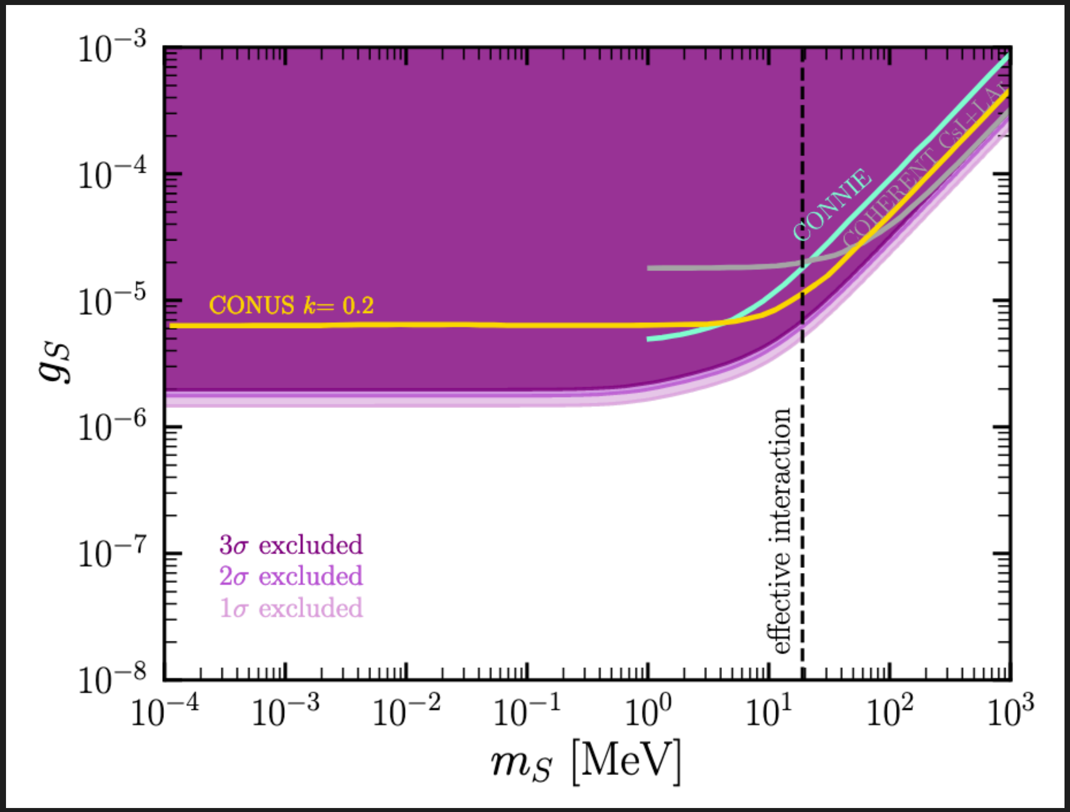

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