Exploring New Physics and Nuclear Structure through Coherent Elastic Neutrino-Nucleus Measurements

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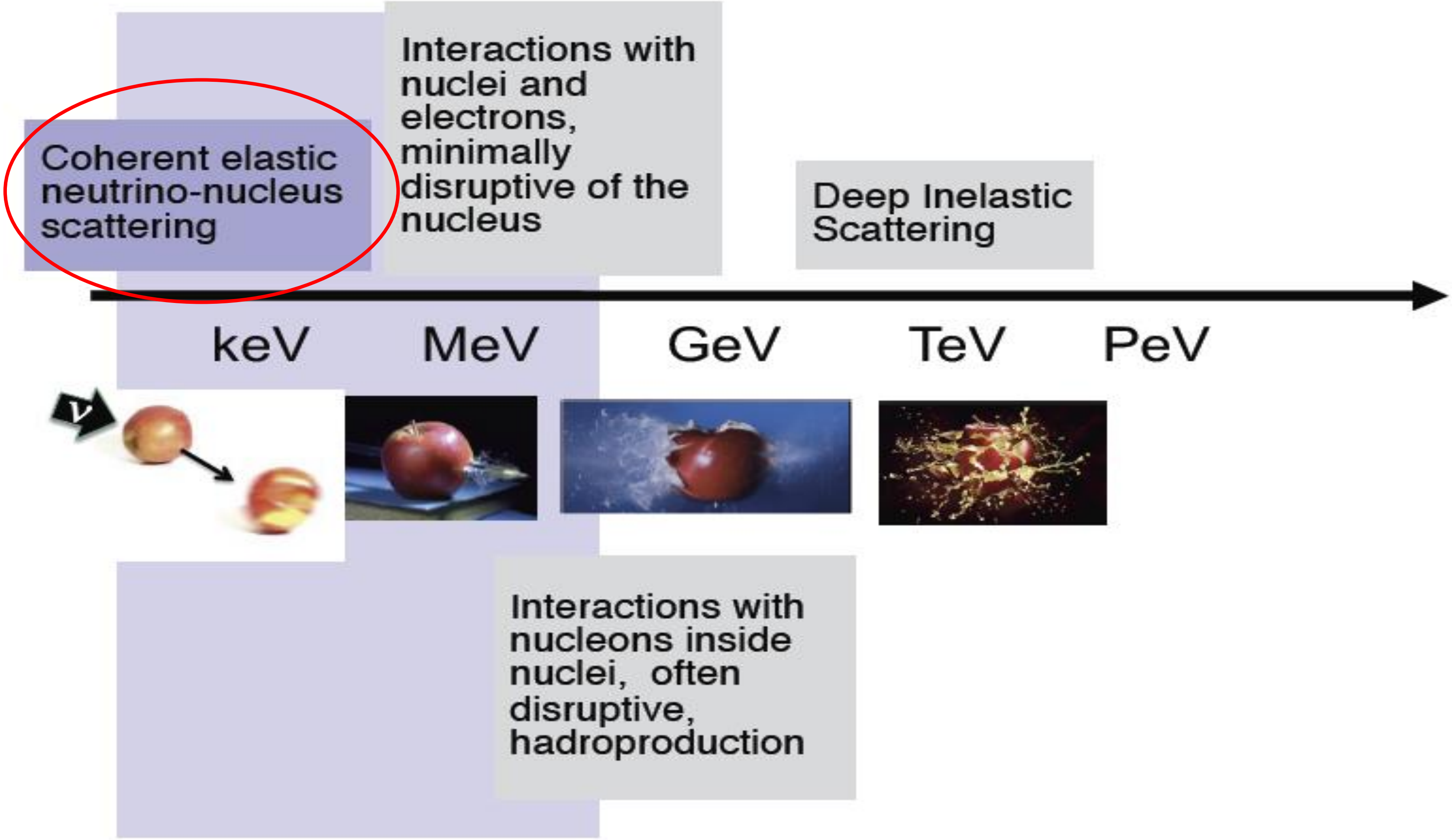
紫金山暗物质研讨会

@南京师范大学

31st Dec. 2023

Neutrino properties & neutrino as a probe

Neutrino interactions over a range of energies



Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

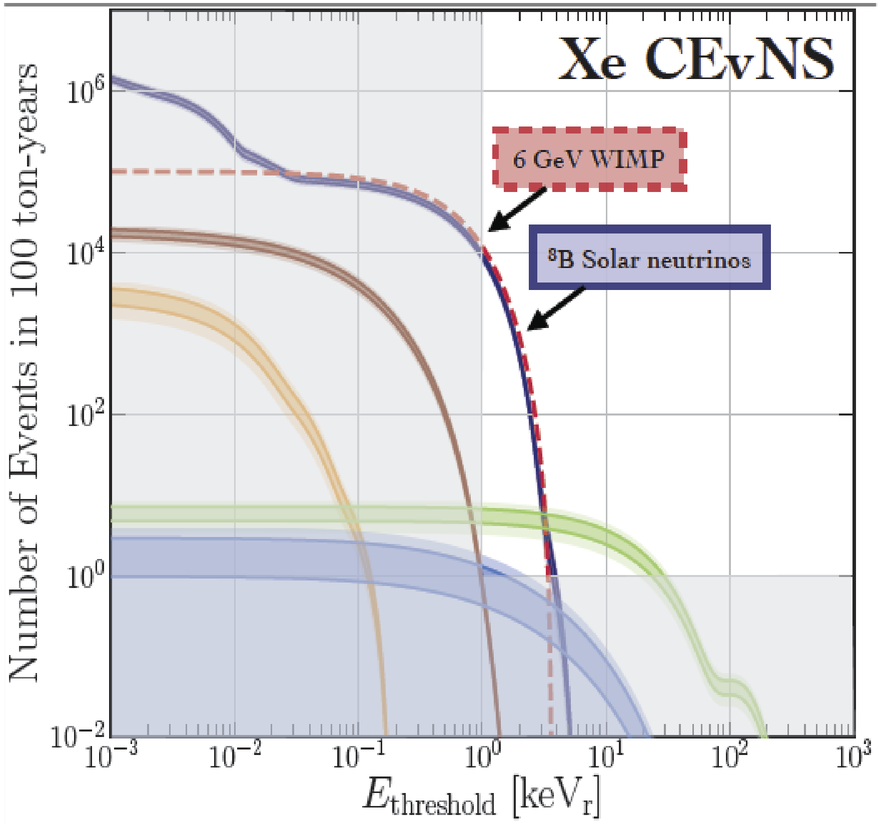
Deep Inelastic Scattering

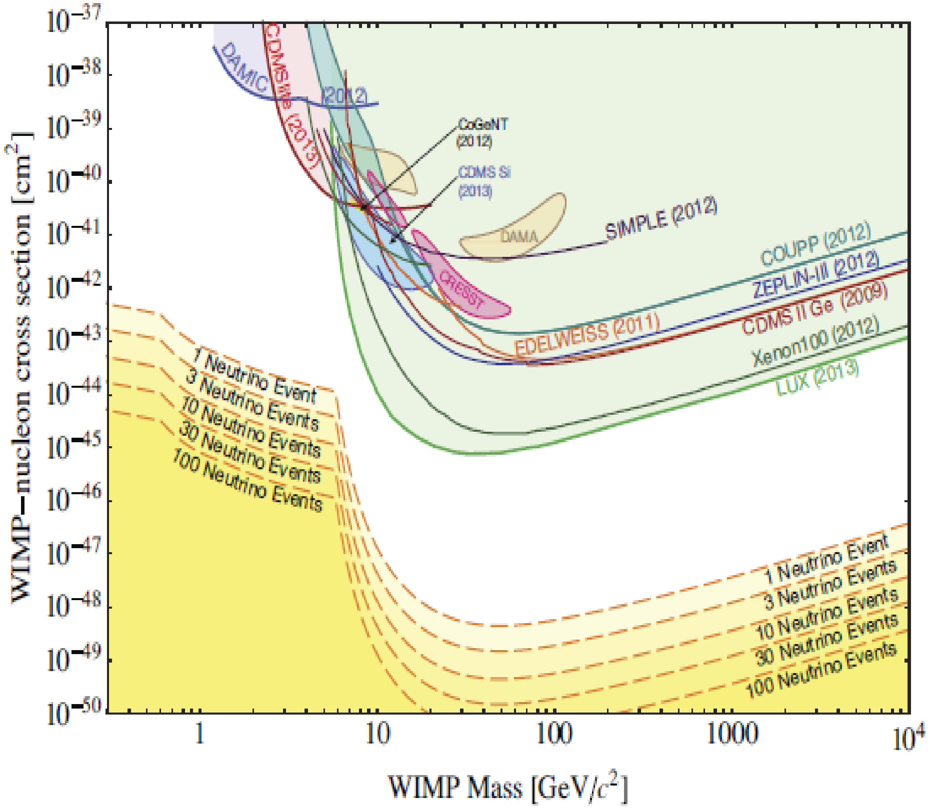
keV MeV GeV TeV PeV

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino floor as ultimate background

- **Natural Neutrino Sources are the ultimate background in the Dark Matter Direct Detection experiment**





- **However, it will become a future neutrino detector, very soon!**

Part A: Some History

Discovery of NC Interactions in 1973

- **Alternating neutral currents:**

- **Two neutrino experiments were running:**
  (A) Gargamelle at the CERN Proton Synchrotron
  (B) HPWF (Harvard, Pennsylvania, Wisconsin, Fermilab) counter at Fermi

- **To measure the NC & CC Interactions with muon neutrinos:**

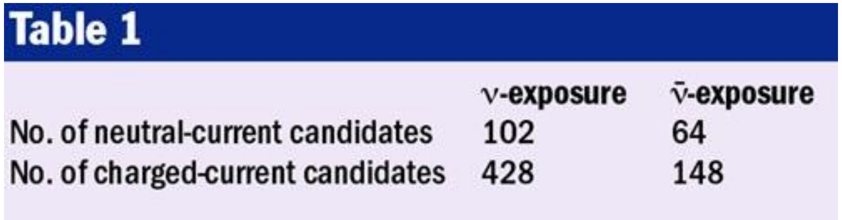


Table 1

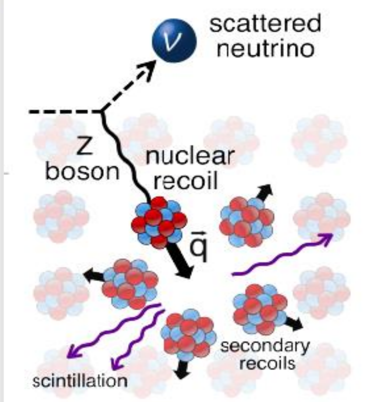
	ν-exposure	$\bar{\nu}$-exposure
No. of neutral-current candidates	102	64
No. of charged-current candidates	428	148

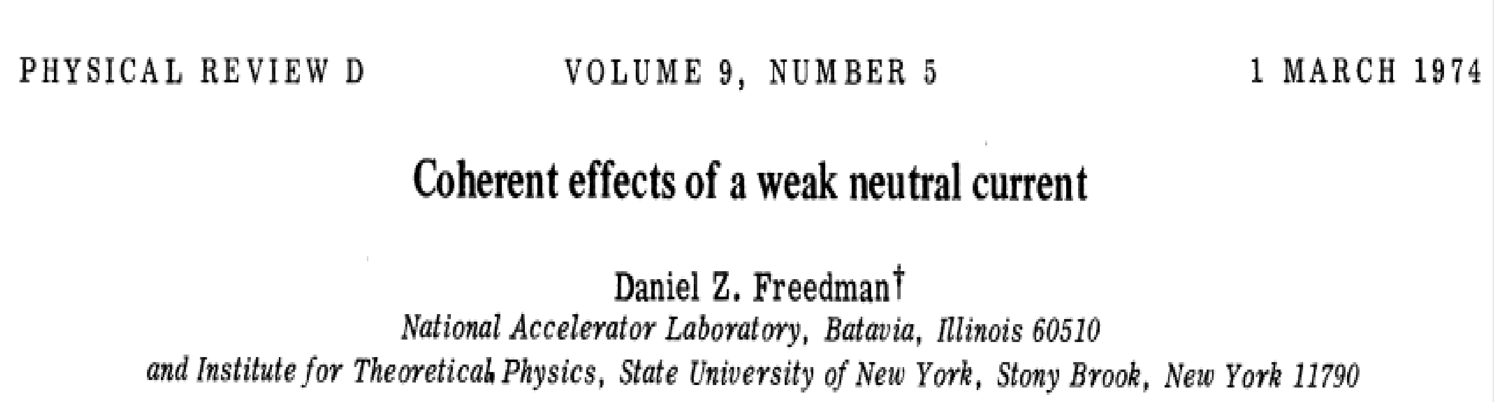
Fig. 1. The Gargamelle heavy-liquid bubble chamber, installed into the magnet coils, at CERN in 1970.

- **The result from Fermi lab was published in 1974.**

- **W&Z at CERN were discovered in 1983.**

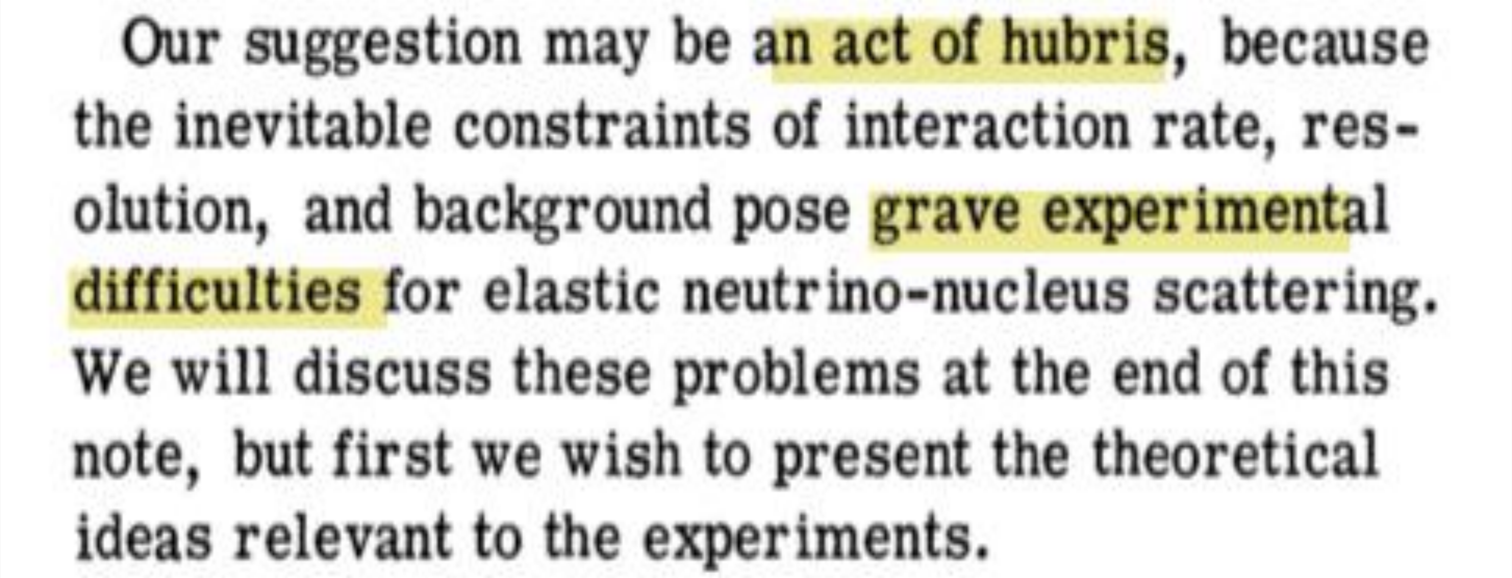
First Prediction in 1974




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

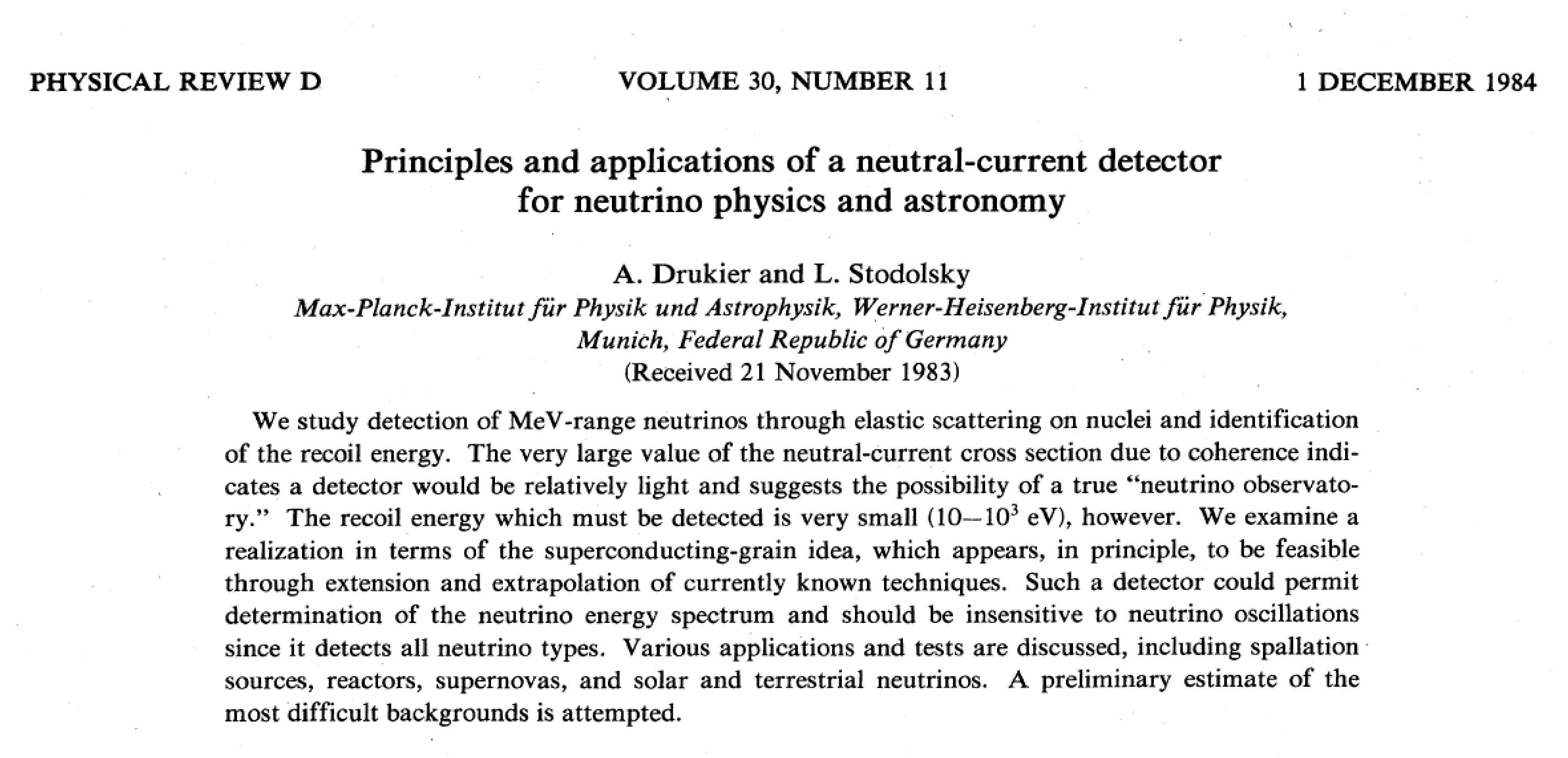

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical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

In analogy to the coherent behavior of electron-nucleus scattering

First idea on the detection?

First idea on how to detect the neutrino coherent scattering process:

Superconducting-grain detector for (10-1000 eV) recoiled energies



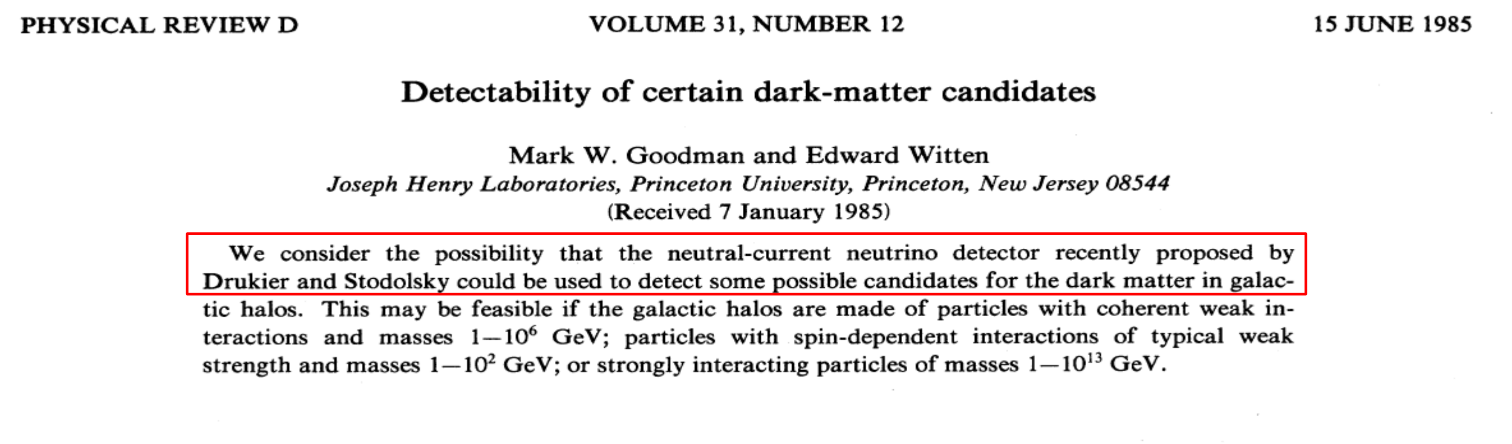
PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small (10–10^3 eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

Direct detection of dark matter

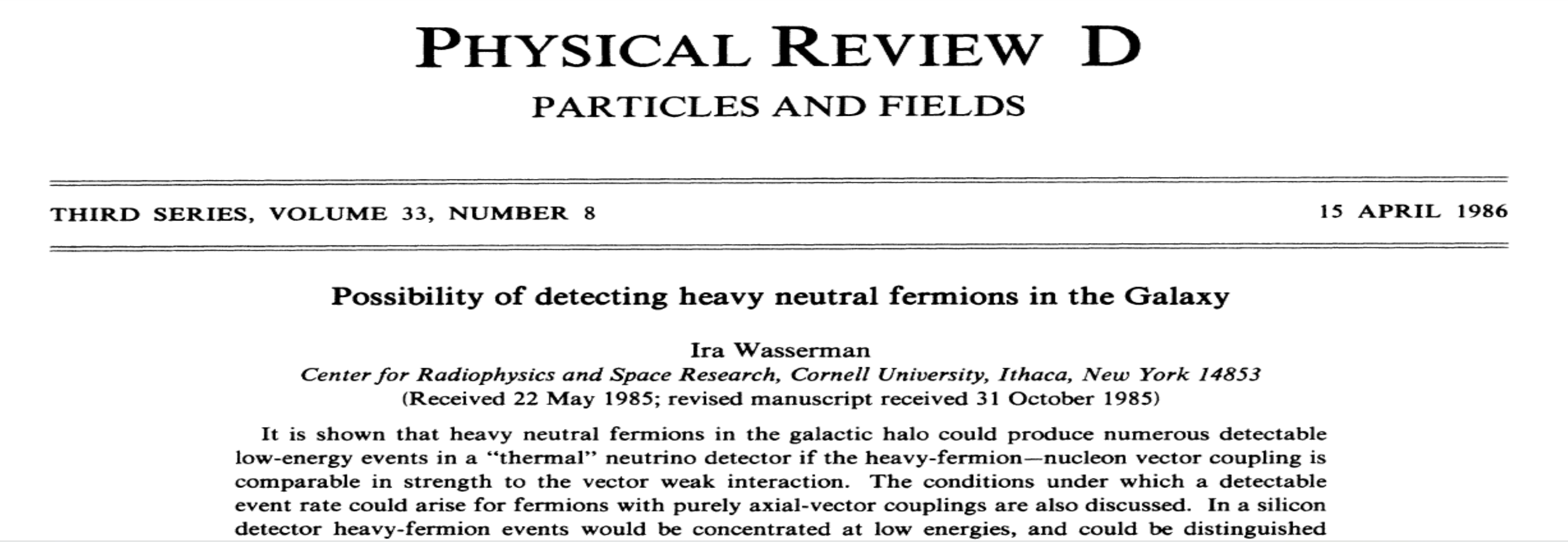


PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.



PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 33, NUMBER 8 15 APRIL 1986

Possibility of detecting heavy neutral fermions in the Galaxy

Ira Wasserman
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853
(Received 22 May 1985; revised manuscript received 31 October 1985)

It is shown that heavy neutral fermions in the galactic halo could produce numerous detectable low-energy events in a "thermal" neutrino detector if the heavy-fermion—nucleon vector coupling is comparable in strength to the vector weak interaction. The conditions under which a detectable event rate could arise for fermions with purely axial-vector couplings are also discussed. In a silicon detector heavy-fermion events would be concentrated at low energies, and could be distinguished

First direct detection in 2017

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

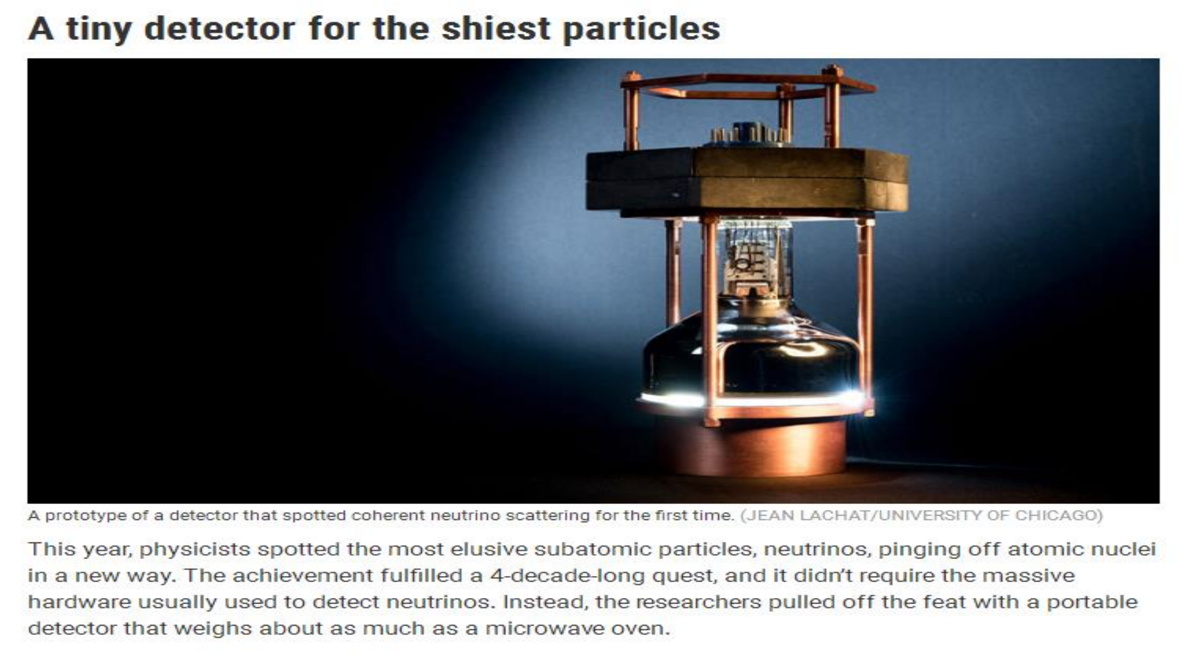
Science

2017 BREAKTHROUGH OF THE YEAR

Cosmic convergence

RUNNERS-UP

- Life at the atomic level
- A tiny detector for the shiest particles
- Deeper roots for *Homo sapiens*
- Pinpoint gene editing
- Biology preprints take off
- A cancer drug's broad swipe
- A new great ape species
- Earth's atmosphere 2.7 million years ago
- Gene therapy triumph



A tiny detector for the shiest particles

A prototype of a detector that spotted coherent neutrino scattering for the first time. (JEAN LACHAT/UNIVERSITY OF CHICAGO)

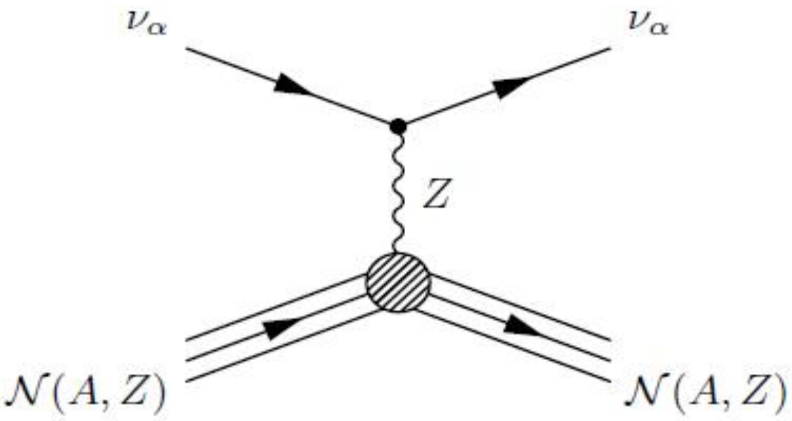
This year, physicists spotted the most elusive subatomic particles, neutrinos, pinging off atomic nuclei in a new way. The achievement fulfilled a 4-decade-long quest, and it didn't require the massive hardware usually used to detect neutrinos. Instead, the researchers pulled off the feat with a portable detector that weighs about as much as a microwave oven.

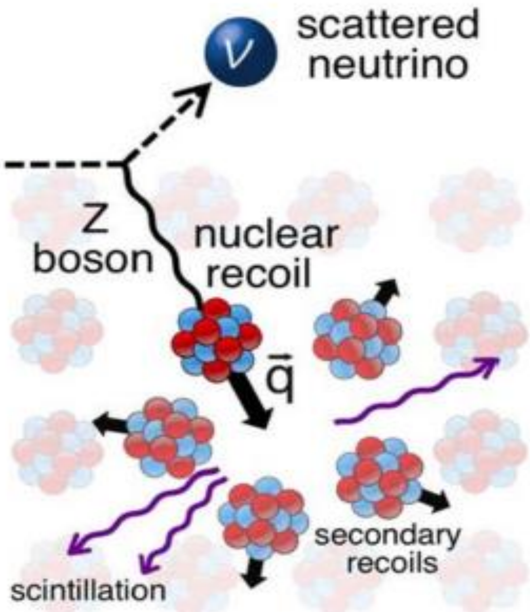
Part B: Brief Introduction

Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS: pronounced "sevens"
- Weak Neutral-Current (NC) interaction:

$$\boxed{\nu_\alpha + \mathcal{N}(A,Z) \rightarrow \nu_\alpha + \mathcal{N}(A,Z)}$$

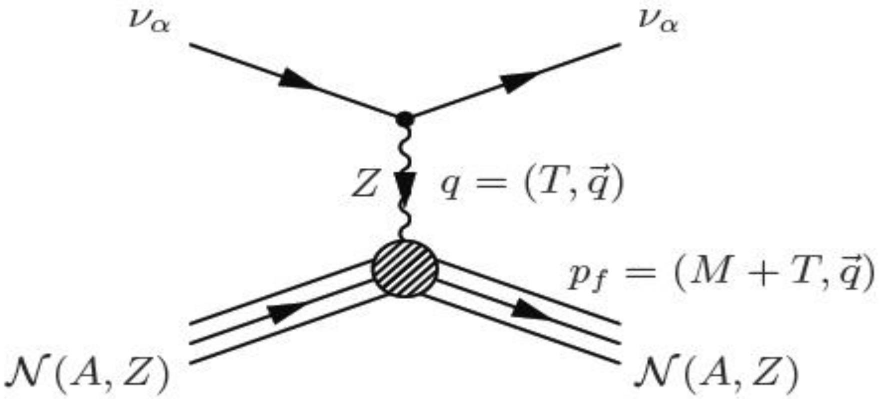




- The nucleus $\mathcal{N}(A,Z)$ recoils as a whole!
- So what?

The CEνNS kinematics

$$\boxed{|\vec{q}|\,R \lesssim 1}$$



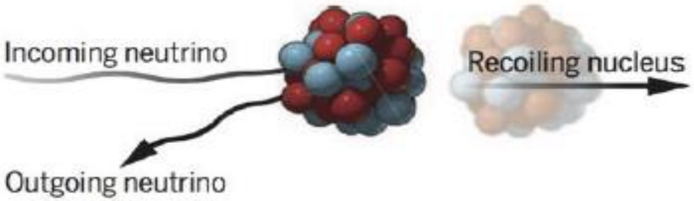
- Heavy target nucleus $\mathcal{N}(A, Z)$:

$$A \sim 100 \qquad M \sim 100\,\text{GeV}$$

$$R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm}$$

- CEνNS for $|\vec{q}| \lesssim 40\,\text{MeV}$
- Non-Relativistic nuclear recoil:

$$|\vec{q}| \simeq \sqrt{2\,M\,T} \qquad\qquad q^0 = T \quad \leftarrow \quad \text{Kinetic Energy}$$



- Observable nuclear recoil kinetic energy:

$$T \simeq \frac{|\vec{q}|^2}{2\,M} \lesssim 10\,\text{keV} \quad \leftarrow \quad \text{Very Small!}$$

The CEνNS Cross Section

Standard Model: $$\frac{d\sigma_{\text{CE}\nu\text{NS}}}{dT}(E_\nu, T) = \frac{G_{\text{F}}^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[Q_W(Q^2)\right]^2$$

- Weak charge of the nucleus $\mathcal{N}$: $\boxed{|\vec{q}| = \sqrt{2\,M\,T}}$

$$Q_W(Q^2) = g_V^n\, N\, F_N(|\vec{q}|) + g_V^p\, Z\, F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W(Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

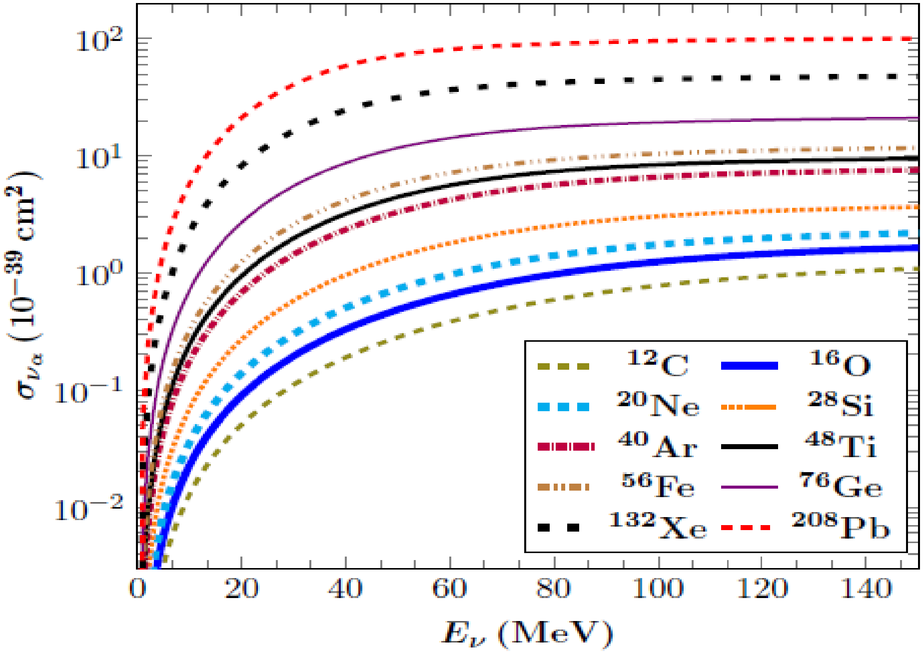
The neutron contribution is dominant! $\Longrightarrow$ $\dfrac{d\sigma_{\text{CE}\nu NS}}{dT} \propto N^2$

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

- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{\text{NC}}^{\text{incoherent}} \propto N \Longrightarrow \sigma_{\text{CE}\nu NS}/\sigma_{\text{NC}}^{\text{incoherent}} \propto N$
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

The CEνNS Cross Section

- Big cross section enhancement for heavy nuclei $\mathcal{N}(A, Z)$ with many nucleons N_i:
  - Incoherent scattering: $\sigma(\nu\mathcal{N}) \sim \sum_i |\mathcal{A}(\nu N_i)|^2 \propto A$
  - Coherent scattering: $\sigma(\nu\mathcal{N}) \sim \left|\sum_i \mathcal{A}(\nu N_i)\right|^2 \propto A^2$

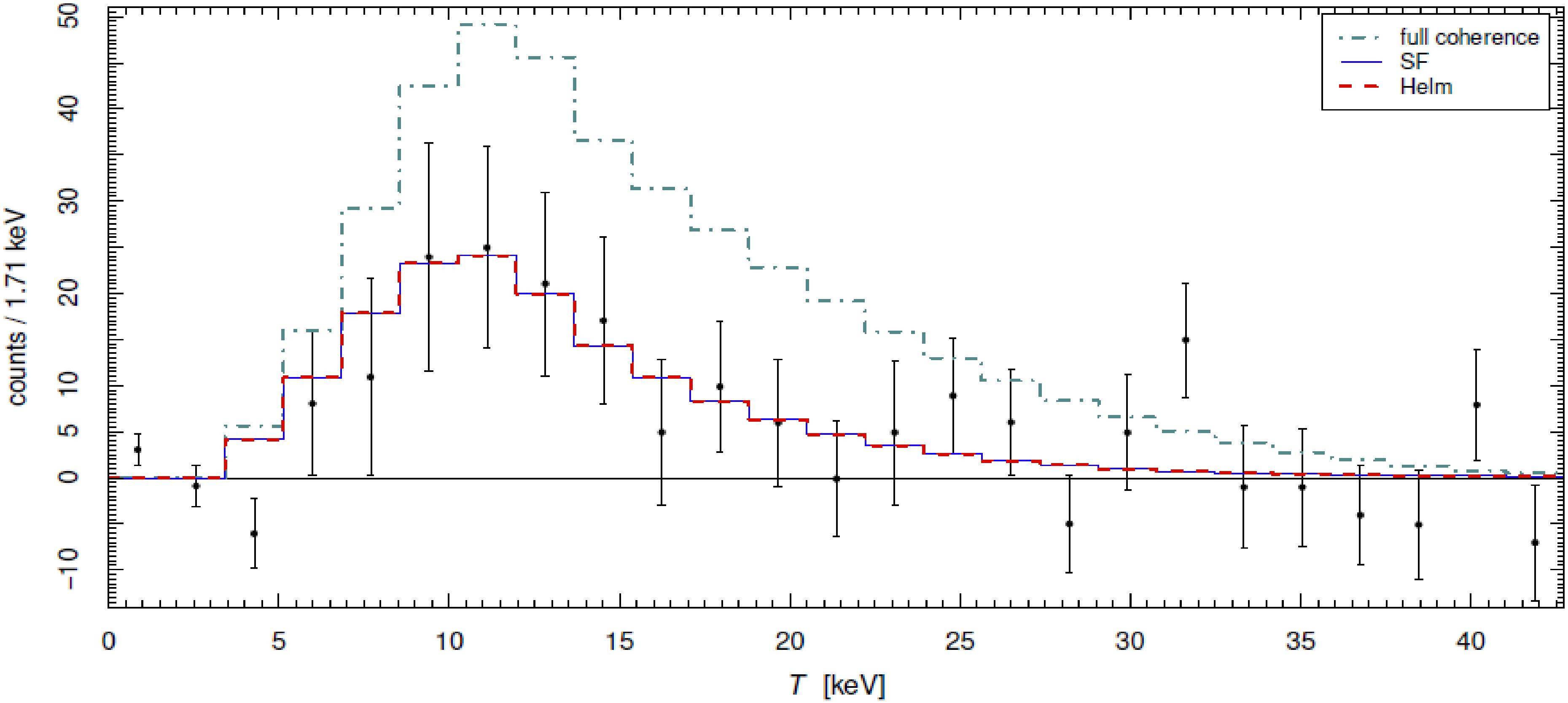


[Papoulias, Kosmas, Kuno, arXiv:1911.00916]

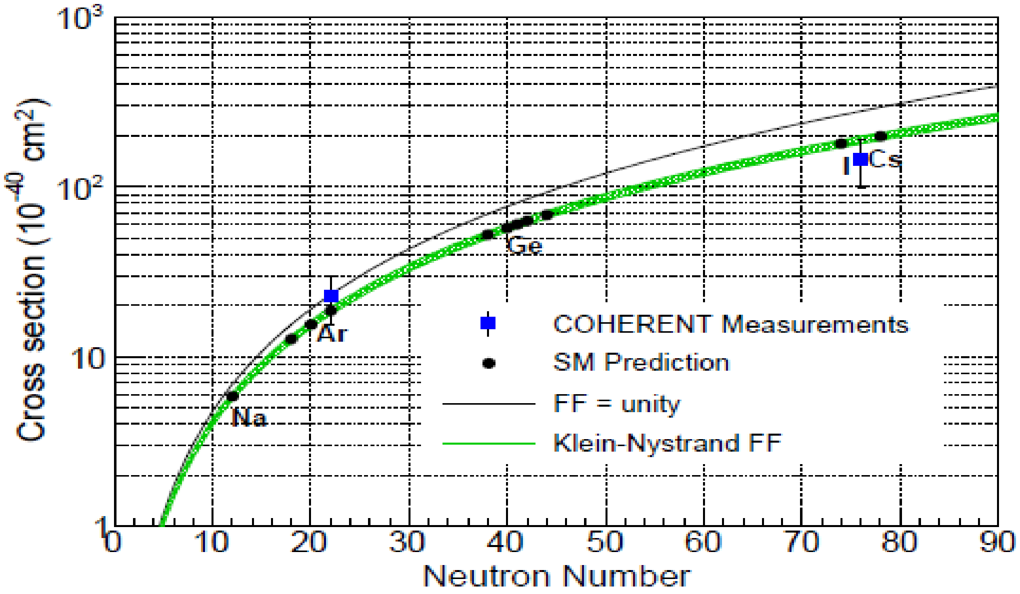
Partial Coherence

- In the COHERENT experiment the scattering is not completely coherent

$$\text{CsI:}\ \left\{\begin{array}{l} |\vec{q}| \sim 30 - 80\,\text{MeV} \sim 0.1 - 0.4\,\text{fm}^{-1} \\ R \approx 1.2\,A^{1/3}\,\text{fm} \approx 5\,\text{fm} \end{array}\right\} \Longrightarrow |\vec{q}|R \sim 0.5 - 2$$



Neutron Form Factor



[COHERENT, arXiv:2003.10630]

- Partial coherency is described by the nuclear neutron form factor $F_N(|\vec{q}|)$
- Fourier transform of the neutron distribution in the nucleus $\rho_N(r)$:

$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}}\, \rho_N(r)\, d^3r$$

- Measurable parameter: the radius R_n of the nuclear neutron distribution

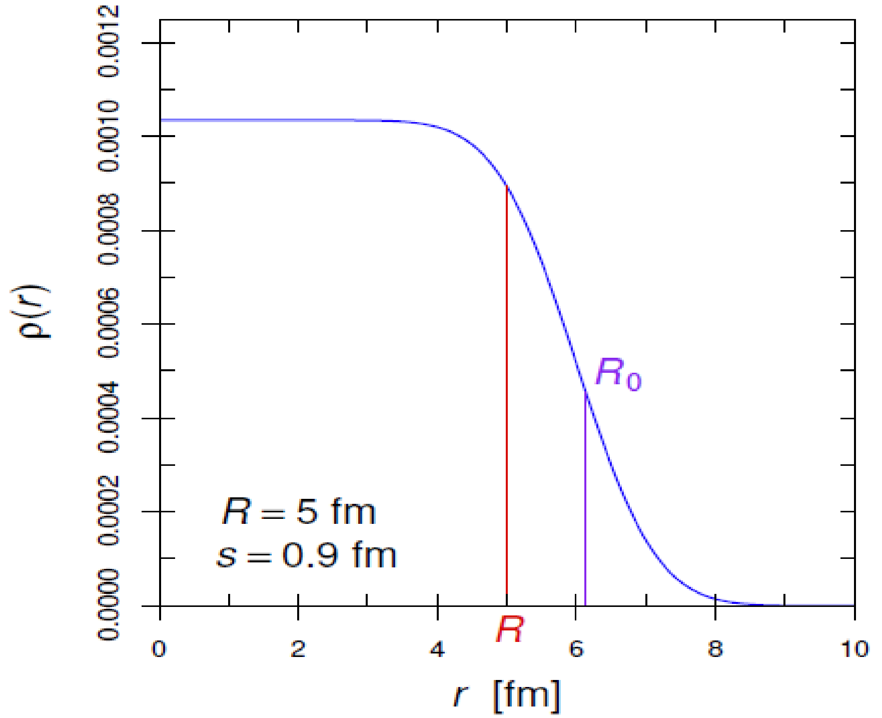
Neutron Form Factor

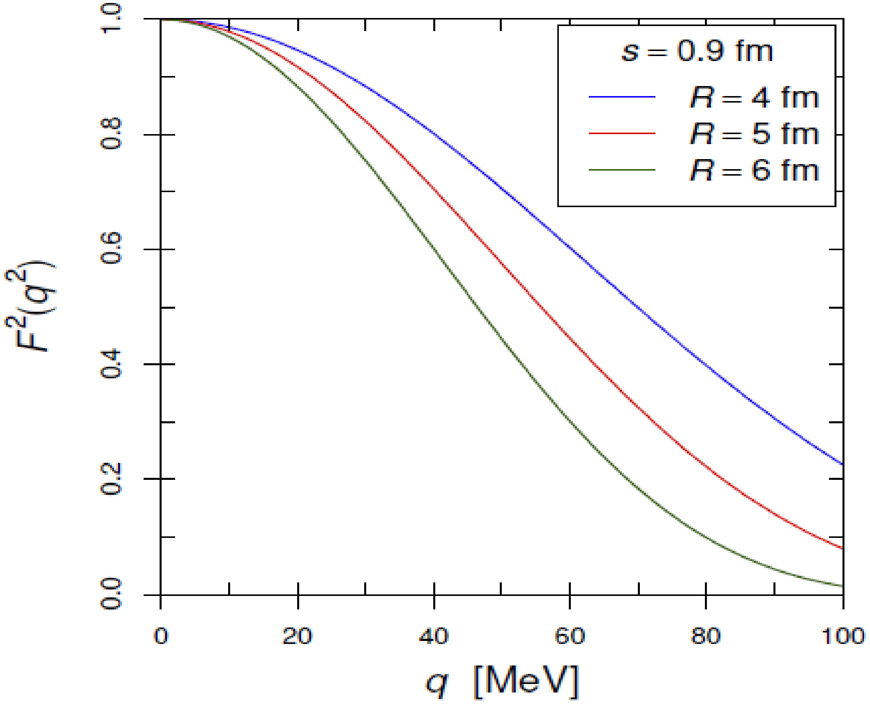
Helm form factor: $F_N^{\text{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

Obtained from the convolution of a sphere with constant density with radius R_0 and a gaussian density with standard deviation s

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5} R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\text{fm}$





Part C: Observation and Implications

The COHERENT experiment

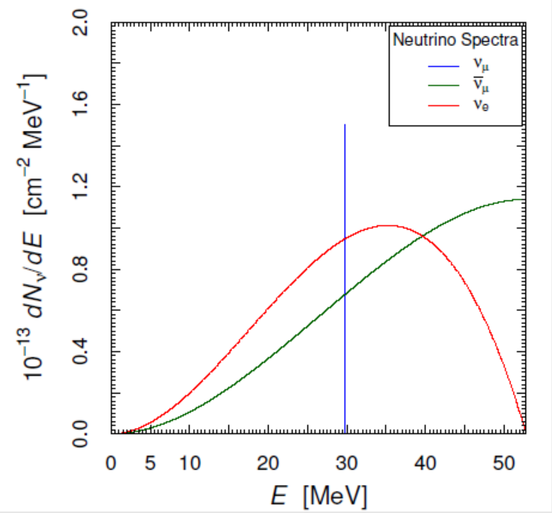
- **14.6 kg CsI scintillating crystal and 24 kg LAr detector.**
- **Prompt monochromatic ν_μ from stopped pion decays:**

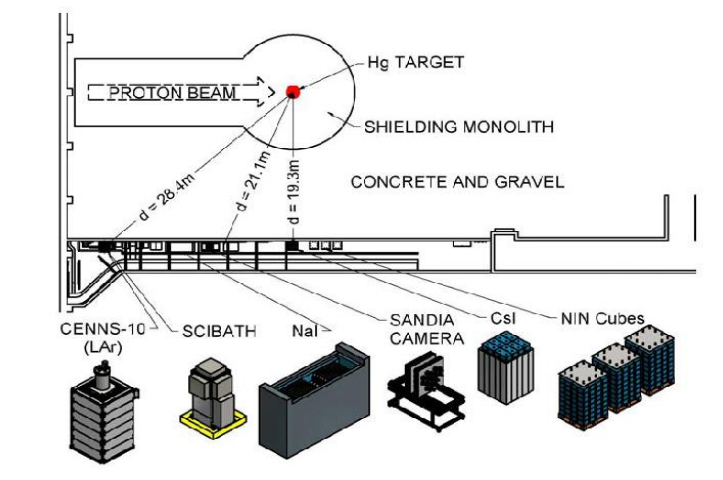
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- **Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:**

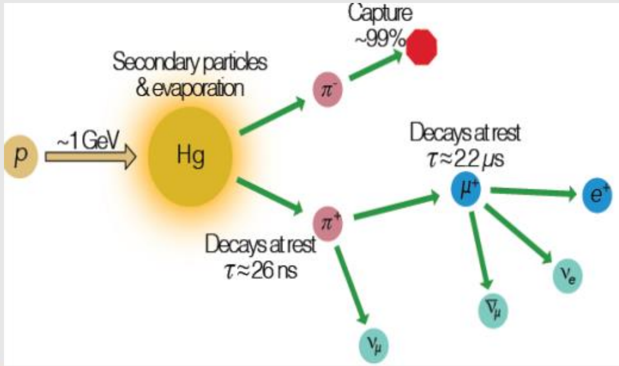
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

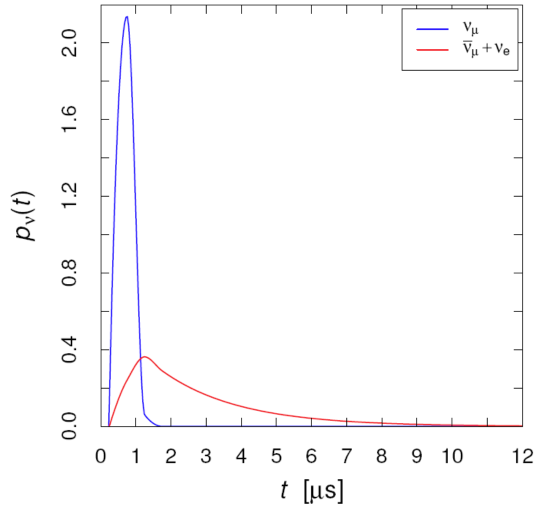
- **The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$**



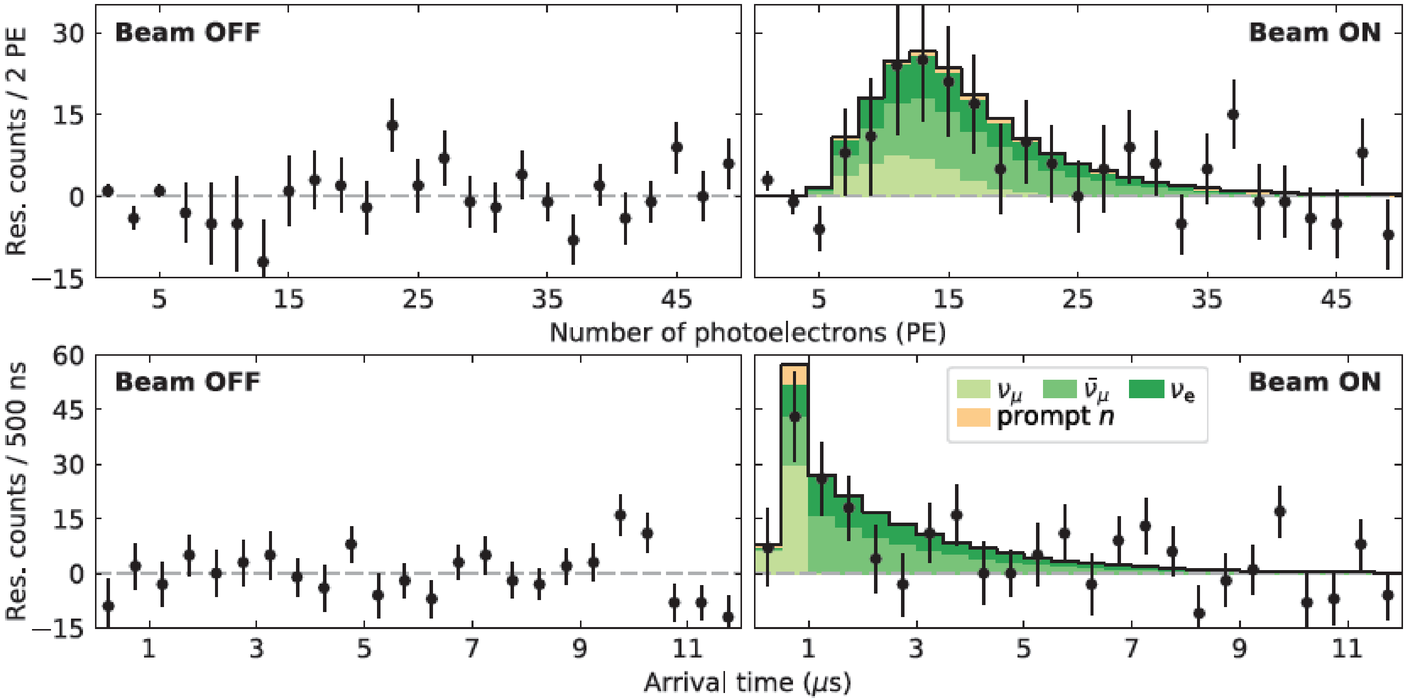


[COHERENT, arXiv:1803.09183]





First observation of CEvNS at CsI (2017)



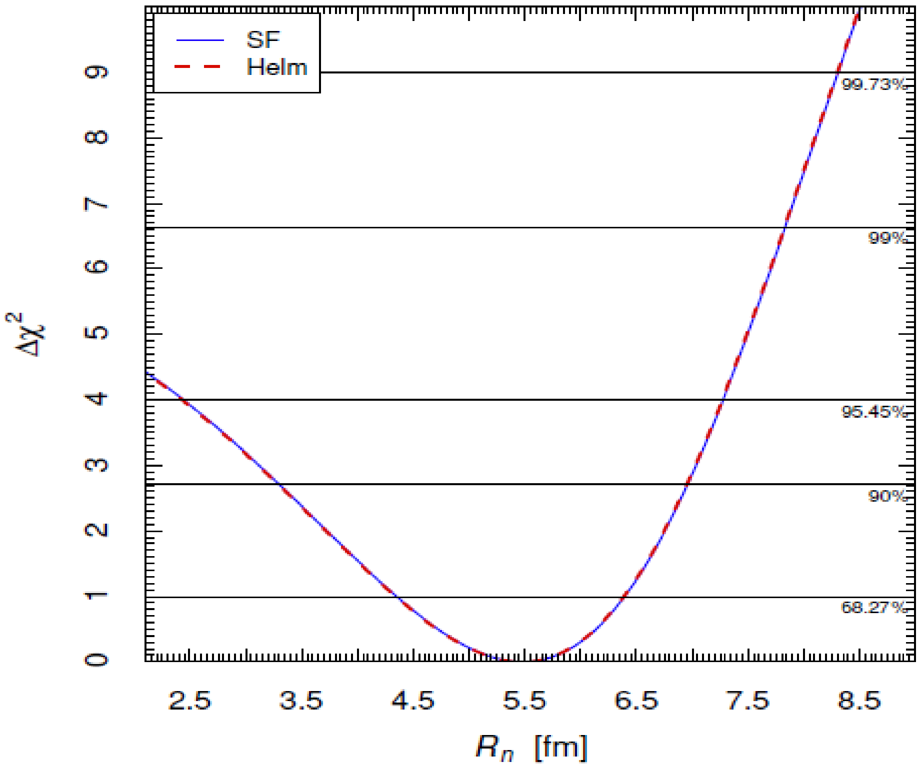
Akimov et al. *Science*
Vol 357, Issue 6356
15 September 2017

- Data are beam coincident and anti-coincident residuals during SNS operation, “On”, and during SNS shutdown periods, “Off”.
- Excess in light yield and timing distributions only for Beam on.

$^{133}_{55}\mathrm{Cs}_{78}$ and $^{127}_{53}\mathrm{I}_{74}$ ← Heavy nuclei well suited for CEνNS

Neutron Distributions of Cs & I

- Fit of the 2017 COHERENT CsI data to get $R_n(^{133}\mathrm{Cs}) \simeq R_n(^{127}\mathrm{I})$:



First determination of R_n with neutrino-nucleus scattering:

$$\boxed{R_n(\mathrm{CsI}) = 5.5^{+0.9}_{-1.1}\ \mathrm{fm}}$$

[Cadeddu, Giunti, Li, Zhang, arXiv:1710.02730]

- With new 2020 COHERENT CsI data:

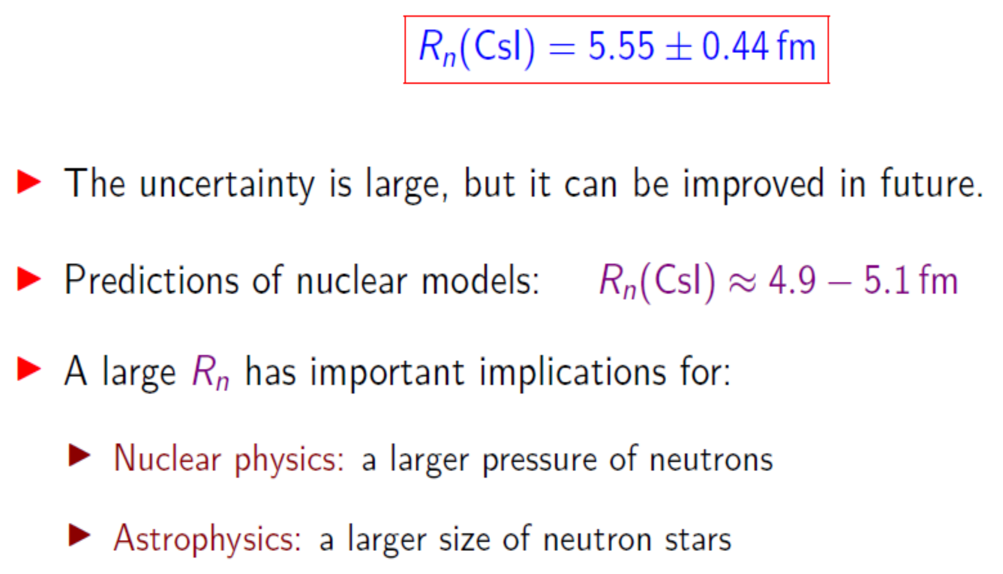
[Pershey @ Magnificent CEνNS 2020]

$$\boxed{R_n(\mathrm{CsI}) = 5.55 \pm 0.44\ \mathrm{fm}}$$

[Cadeddu et al, arXiv:2102.06153]

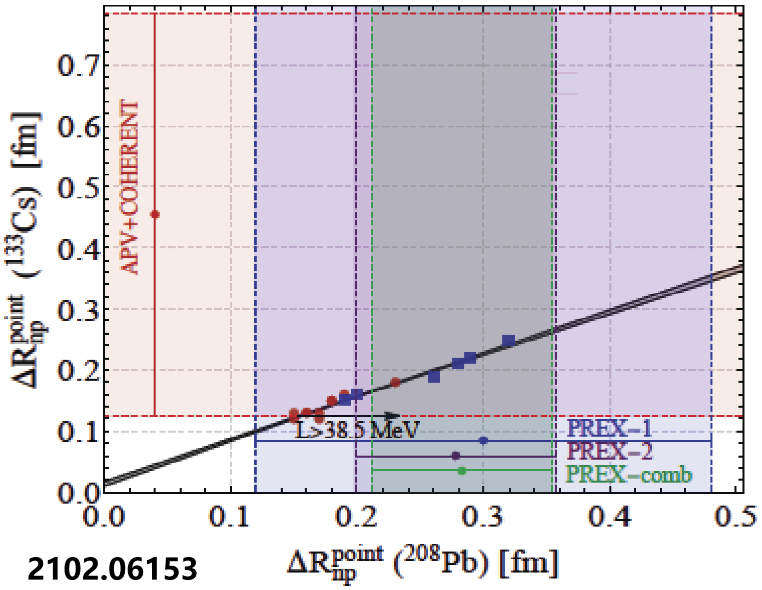
Neutron Distributions of Cs & I

- Neutron form factor is the Fourier transform of the neutron distribution
- **First measurement of neutron radius with neutrinos, pure weak NC measurement!**
- neutron skin → the nuclear Equation of State (EOS)→ neutron star radius



$$\boxed{R_n(\mathrm{CsI}) = 5.55 \pm 0.44\,\mathrm{fm}}$$

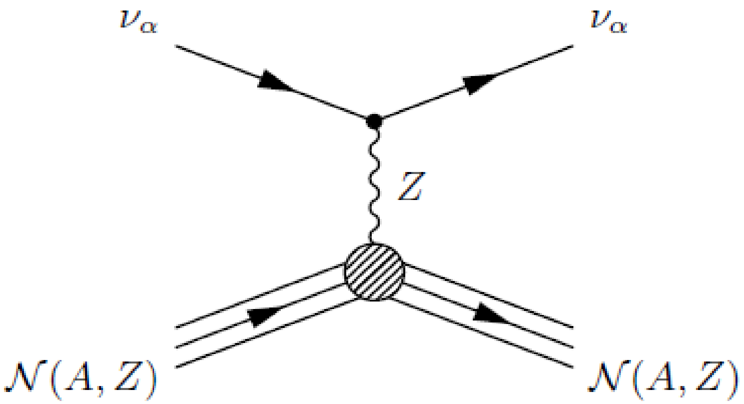
- The uncertainty is large, but it can be improved in future.
- Predictions of nuclear models: $R_n(\mathrm{CsI}) \approx 4.9 - 5.1\,\mathrm{fm}$
- A large R_n has important implications for:
  - Nuclear physics: a larger pressure of neutrons
  - Astrophysics: a larger size of neutron stars



2102.06153

BSM Neutrino Interactions in CEvNS

Standard Model NC



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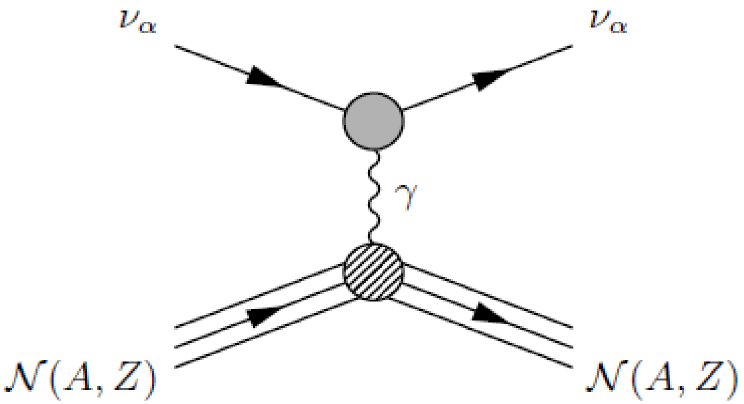
Electromagnetic Interactions



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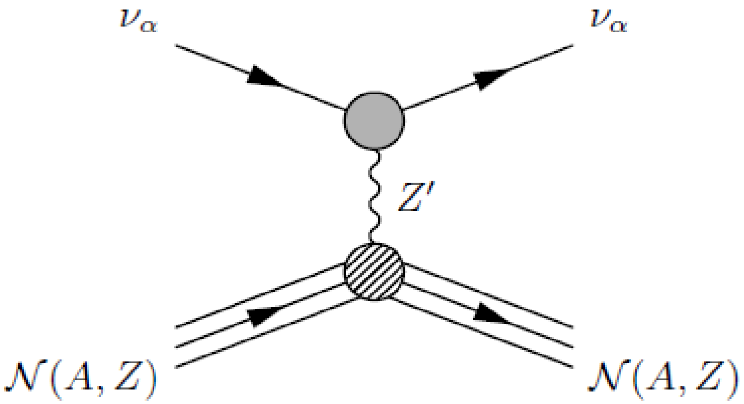
BSM Vector Mediator



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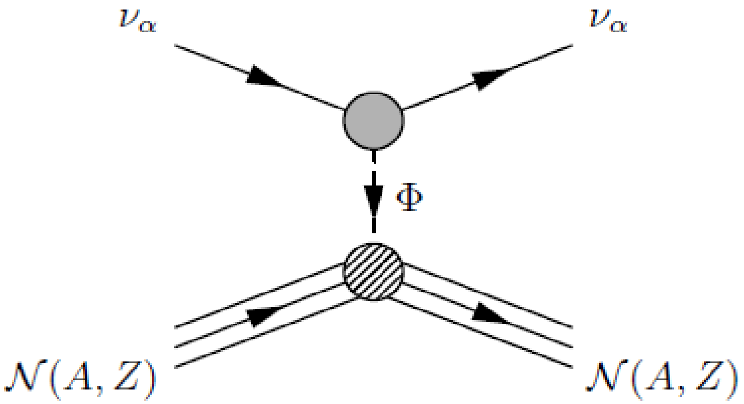
BSM Scalar Mediator

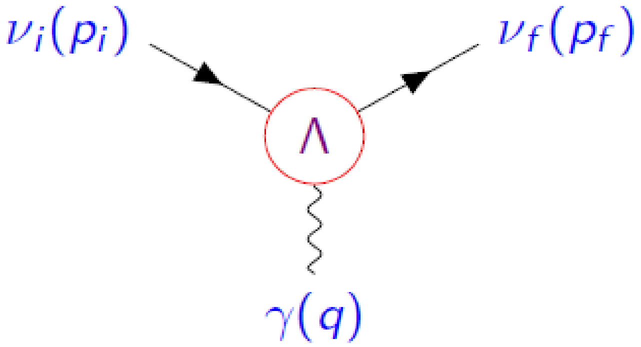


More details See 2202.11002, 2205.09484

Neutrino Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}^{(\nu)}_{\text{em}}(x) = j^{(\nu)}_{\mu}(x) A^{\mu}(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda^{kj}_{\mu} \nu_j(x) A^{\mu}(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j^{(\nu)}_{\mu}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda^{fi}_{\mu}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i \sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \quad \Longrightarrow$	q	a	μ	ε

helicity-conserving

helicity-flipping

Diagonal charge radii

Method	Experiment	Limit $[10^{-32}\ \text{cm}^2]$	C.L.	Year
Reactor $\bar{\nu}_e\, e^-$	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3$	90%	1992
	TEXONO	$-4.2 < \langle r^2_{\nu_e}\rangle < 6.6^a$	90%	2009
Accelerator $\nu_e\, e^-$	LAMPF	$-7.12 < \langle r^2_{\nu_e}\rangle < 10.88^a$	90%	1992
	LSND	$-5.94 < \langle r^2_{\nu_e}\rangle < 8.28^a$	90%	2001
Accelerator $\nu_\mu\, e^-$	BNL-E734	$-5.7 < \langle r^2_{\nu_\mu}\rangle < 1.1^{a,b}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2^a$	90%	1994
CEvNS [arXiv:2205.09484]	COHERENT + Dresden-II	$-7.1 < \langle r^2_{\nu_e}\rangle < 11.2$ $-8.1 < \langle r^2_{\nu_\mu}\rangle < 4.3$	90%	2022

a Corrected by a factor of two due to a different convention.
b Corrected in Hirsch, Nardi, Restrepo, hep-ph/0210137.

[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1810.05606, arXiv:1908.06045, arXiv:2005.01645]

Magnetic dipole moment

Method	Experiment	Limit $[\mu_B]$	CL	Year
Reactor ES $(\bar{\nu}_e\, e^-)$	Krasnoyarsk	$\lvert\mu_{\nu_e}\rvert < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\lvert\mu_{\nu_e}\rvert < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\lvert\mu_{\nu_e}\rvert < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\lvert\mu_{\nu_e}\rvert < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\lvert\mu_{\nu_e}\rvert < 2.9 \times 10^{-11}$	90%	2012
Reactor CEvNS+ES	Dresden-II [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$\lvert\mu_{\nu_e}\rvert < 3.3 \times 10^{-10}$	90%	2022
Accelerator ES $(\nu_\mu\, e^-)$	BNL-E734	$\lvert\mu_{\nu_\mu}\rvert < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\lvert\mu_{\nu_\mu}\rvert < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\lvert\mu_{\nu_\mu}\rvert < 6.8 \times 10^{-10}$	90%	2001
Accelerator CEvNS+ES	COHERENT [Coloma et al, arXiv:2202.10829] [Atzori Corona et al, arXiv:2205.09484]	$\lvert\mu_{\nu_\mu}\rvert < 2 \times 10^{-9}$	90%	2022

[See also: Liao et al, arXiv:2202.10622; Aristizabal Sierra et al, arXiv:2203.02414; Khan, arXiv:2203.08892]

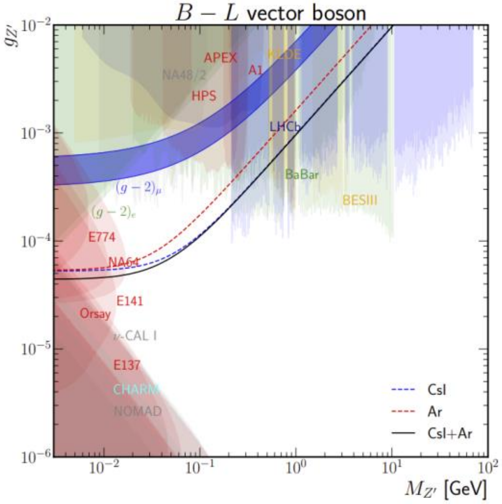
[Previous CEvNS results: Papoulias et al, arXiv:1711.09773, arXiv:1905.03750, arXiv:1907.11644, arXiv:2003.12050; Khan and Rodejohann, arXiv:1907.12444; Cadeddu et al, arXiv:1908.06045, arXiv:2005.01645; CONUS, arXiv:2201.12257]

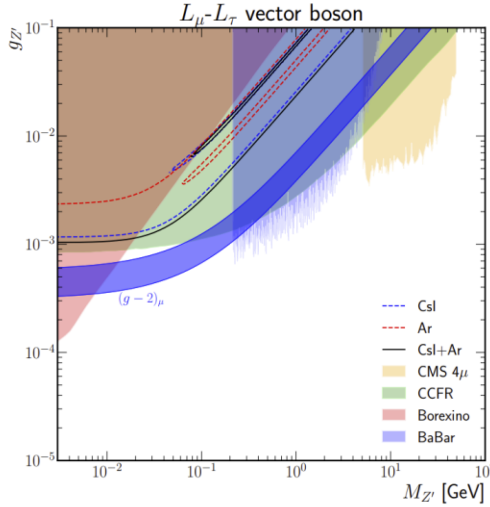
[Future prospects: Miranda et al, arXiv:1905.03750]

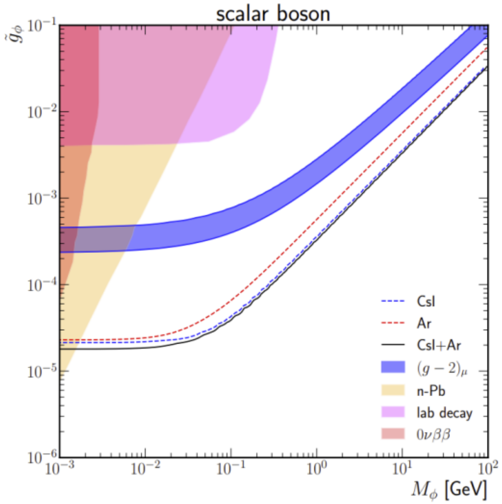
Light mediators

Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
universal	1	1	1	1	1
$B-L$	$1/3$	$1/3$	-1	-1	-1
$B-3L_e$	$1/3$	$1/3$	-3	0	0
$B-3L_\mu$	$1/3$	$1/3$	0	-3	0
$B-2L_e-L_\mu$	$1/3$	$1/3$	-2	-1	0
$B-L_e-2L_\mu$	$1/3$	$1/3$	-1	-2	0
$B_y+L_\mu+L_\tau$	$1/3$	$1/3$	0	1	1
L_e-L_μ	0	0	1	-1	0
L_e-L_τ	0	0	1	0	-1
$L_\mu-L_\tau$	0	0	0	1	-1

	Ar		CsI		CsI+Ar	
model	$g_{Z'}$(low $M_{Z'}$)	$\frac{g_{Z'}}{M_{Z'}}$(high $M_{Z'}$)	$g_{Z'}$(low $M_{Z'}$)	$\frac{g_{Z'}}{M_{Z'}}$(high $M_{Z'}$)	$g_{Z'}$(low $M_{Z'}$)	$\frac{g_{Z'}}{M_{Z'}}$(high $M_{Z'}$)
universal	3.91×10^{-5}	0.82×10^{-3}	2.36×10^{-5}	0.53×10^{-3}	2.07×10^{-5}	0.48×10^{-3}
$B-L$	5.35×10^{-5}	1.67×10^{-3}	5.27×10^{-5}	1.00×10^{-3}	4.42×10^{-5}	0.99×10^{-3}
$B_y+L_\mu+L_\tau$	10.4×10^{-5}	3.58×10^{-3}	4.97×10^{-5}	1.14×10^{-3}	4.47×10^{-5}	1.04×10^{-3}
$B-3L_e$	4.91×10^{-5}	1.55×10^{-3}	5.16×10^{-5}	0.96×10^{-3}	4.34×10^{-5}	0.95×10^{-3}
$B-3L_\mu$	3.45×10^{-5}	1.09×10^{-3}	3.21×10^{-5}	0.64×10^{-3}	2.76×10^{-5}	0.63×10^{-3}
$B-2L_e-L_\mu$	4.62×10^{-5}	1.48×10^{-3}	4.79×10^{-5}	0.89×10^{-3}	3.95×10^{-5}	0.88×10^{-3}
$B-L_e-2L_\mu$	3.97×10^{-5}	1.28×10^{-3}	3.86×10^{-5}	0.75×10^{-3}	3.26×10^{-5}	0.74×10^{-3}
L_e-L_μ	161×10^{-5}	54.2×10^{-3}	166×10^{-5}	36.1×10^{-3}	137×10^{-5}	34.9×10^{-3}
L_e-L_τ	204×10^{-5}	71.1×10^{-3}	140×10^{-5}	29.9×10^{-3}	125×10^{-5}	26.6×10^{-3}
$L_\mu-L_\tau$	234×10^{-5}	80.9×10^{-3}	116×10^{-5}	26.6×10^{-3}	103×10^{-5}	24.2×10^{-3}
	$\tilde{g}_\phi$(low M_ϕ)	$\frac{\tilde{g}_\phi}{M_\phi}$(high M_ϕ)	$\tilde{g}_\phi$(low M_ϕ)	$\frac{\tilde{g}_\phi}{M_\phi}$(high M_ϕ)	$\tilde{g}_\phi$(low M_ϕ)	$\frac{\tilde{g}_\phi}{M_\phi}$(high M_ϕ)
scalar	2.30×10^{-5}	0.58×10^{-3}	1.80×10^{-5}	0.31×10^{-3}	1.68×10^{-5}	0.30×10^{-3}

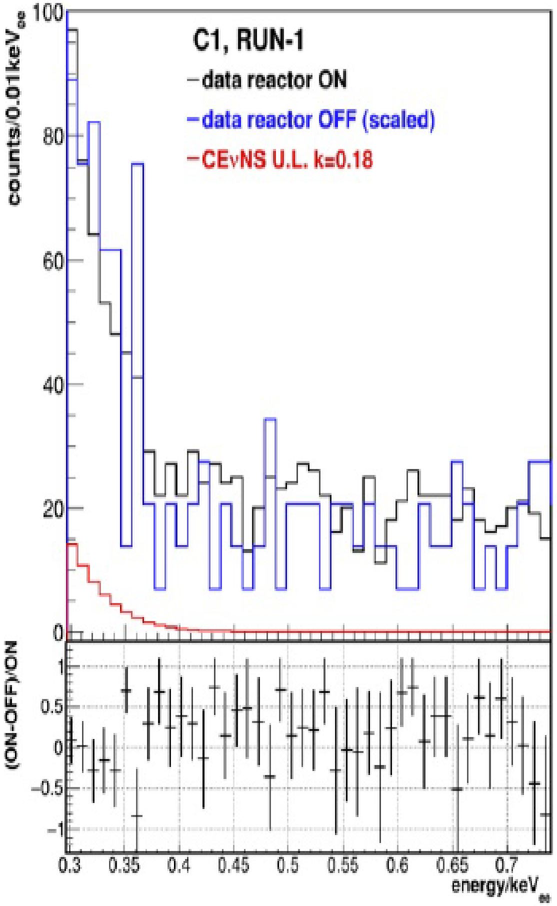






CONUS

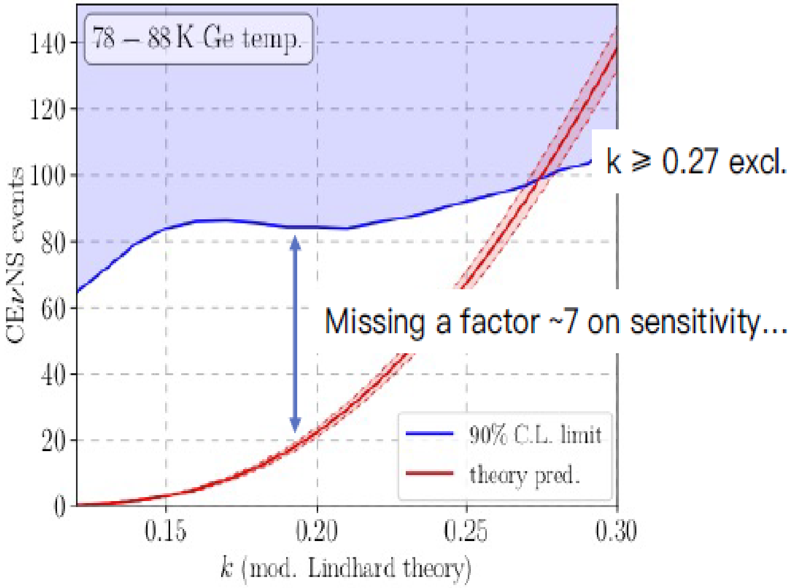
- Analysis of RUN–1 (2018) & RUN–2 (2019/2020) data → best UL on CEvNS with Ge !



X 4

250/60 kg.d
ON/OFF data

Quenching matters !



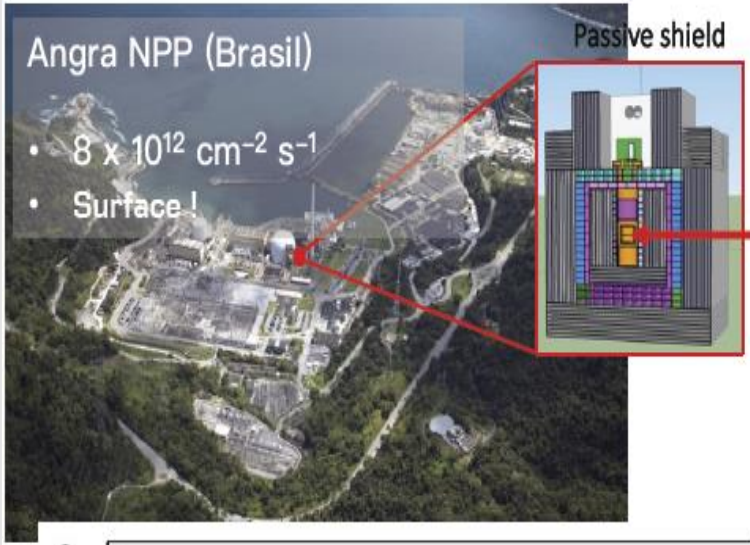
k ⩾ 0.27 excl.

Missing a factor ~7 on sensitivity…

Perspectives

- New data + shutdown of KBR > 2021 → stat. unc ↓
- Improved analysis techniques → bck ↓ + sensitivity ↑

CONNIE

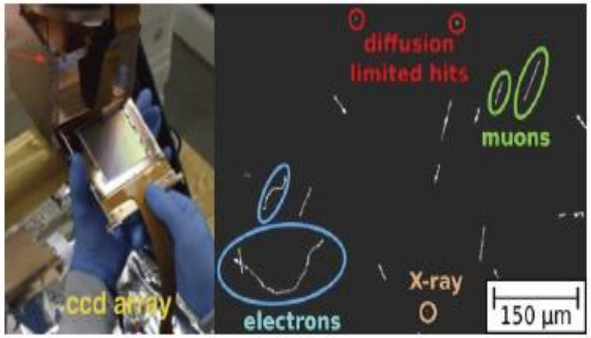


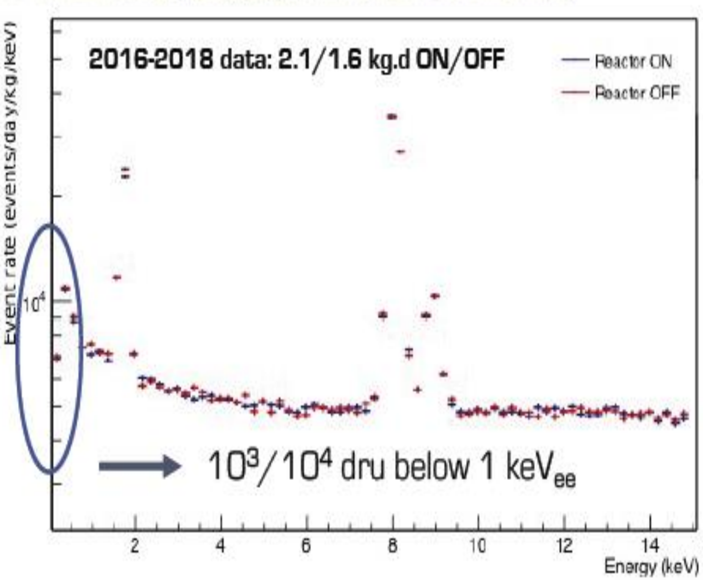
Angra NPP (Brasil)

- 8×10^{12} cm^{-2} s^{-1}
- Surface !

Mpixels Si CCD array

- Particle id.
- ~40 eV$_{ee}$ threshold
- Total mass ~ 70 g



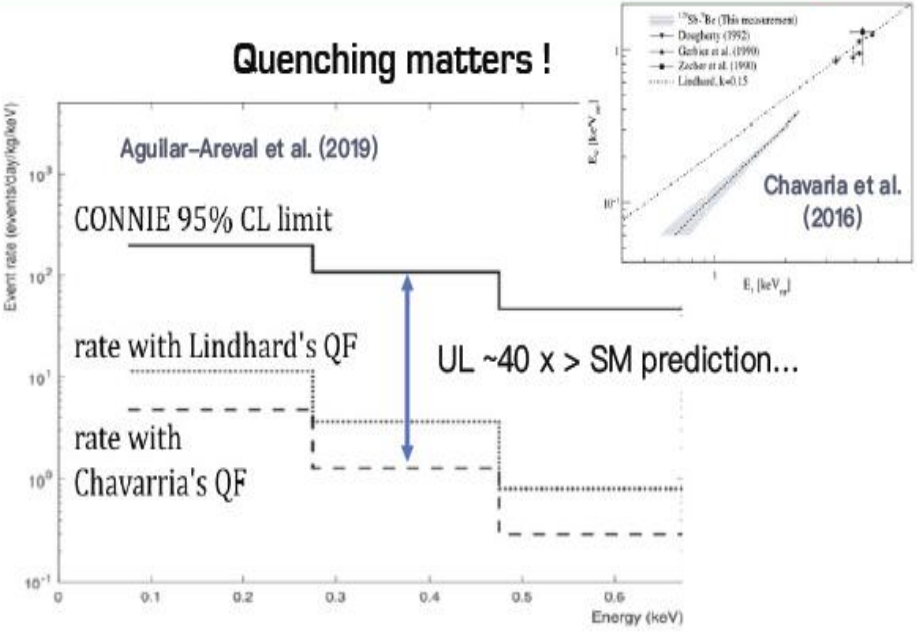


2016-2018 data: 2.1/1.6 kg.d ON/OFF

→ $10^3/10^4$ dru below 1 keV$_{ee}$

→

Quenching matters !



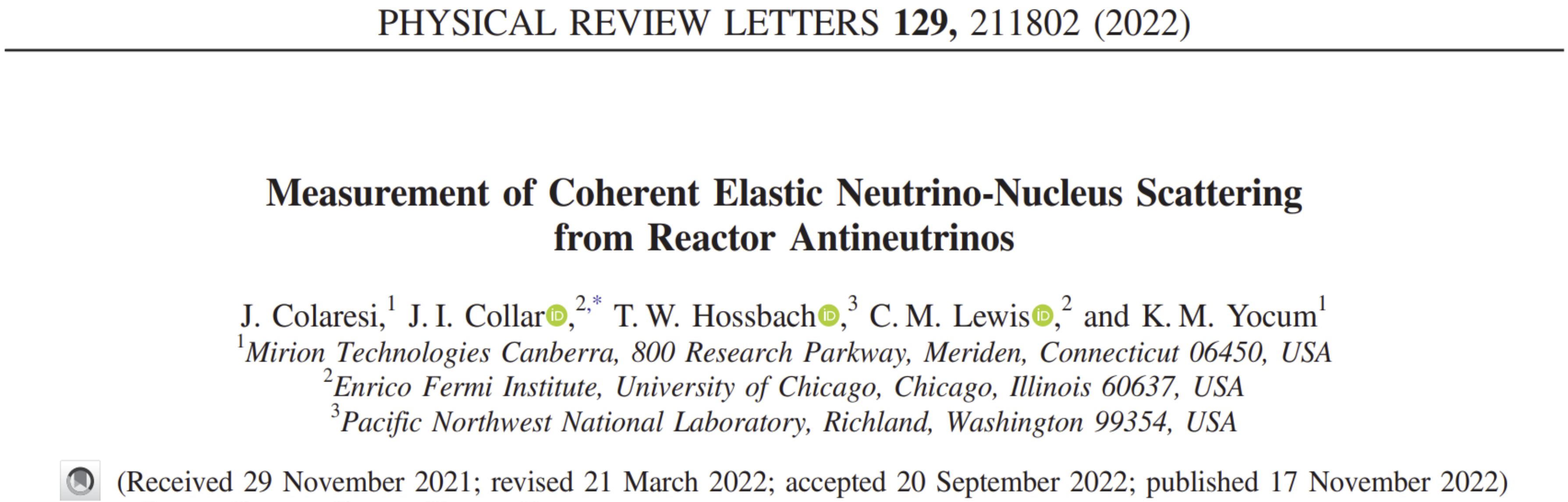
CONNIE 95% CL limit

rate with Lindhard's QF

rate with Chavarria's QF

UL ~40 x > SM prediction...

Dresden–II: Suggestive evidence



PHYSICAL REVIEW LETTERS **129,** 211802 (2022)

Measurement of Coherent Elastic Neutrino-Nucleus Scattering from Reactor Antineutrinos

J. Colaresi,[1] J. I. Collar,[2,*] T. W. Hossbach,[3] C. M. Lewis,[2] and K. M. Yocum[1]
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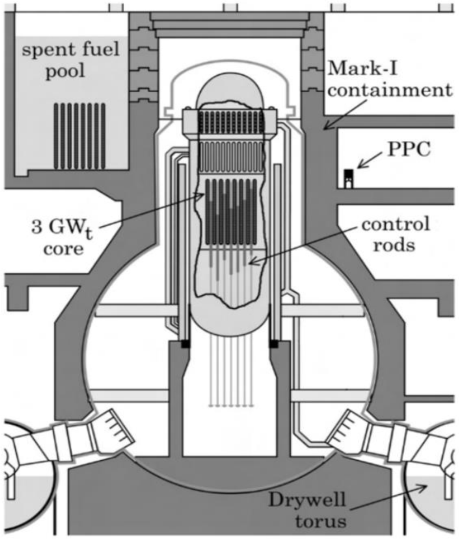
(Received 29 November 2021; revised 21 March 2022; accepted 20 September 2022; published 17 November 2022)

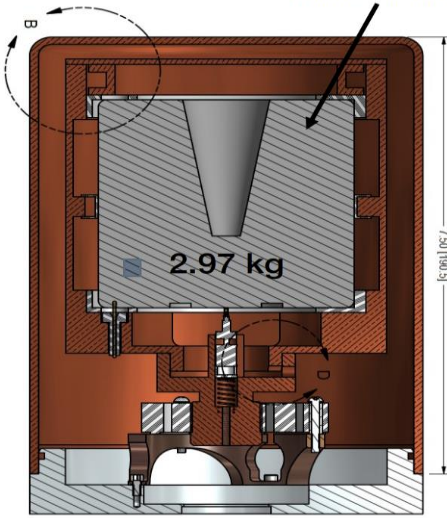
Fuel Elements 10.4 m away (7.5-13.3m)

4.8E13 ν/cm²s

60cm x 60cm footprint.

Assembled by 3 workers in one day.

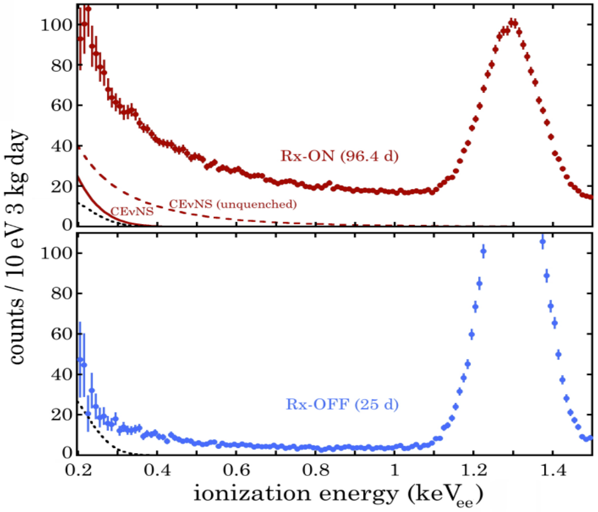




Inverted coax PPC
NIM A 665 (2011) 25

Design uses ultra-low background materials.

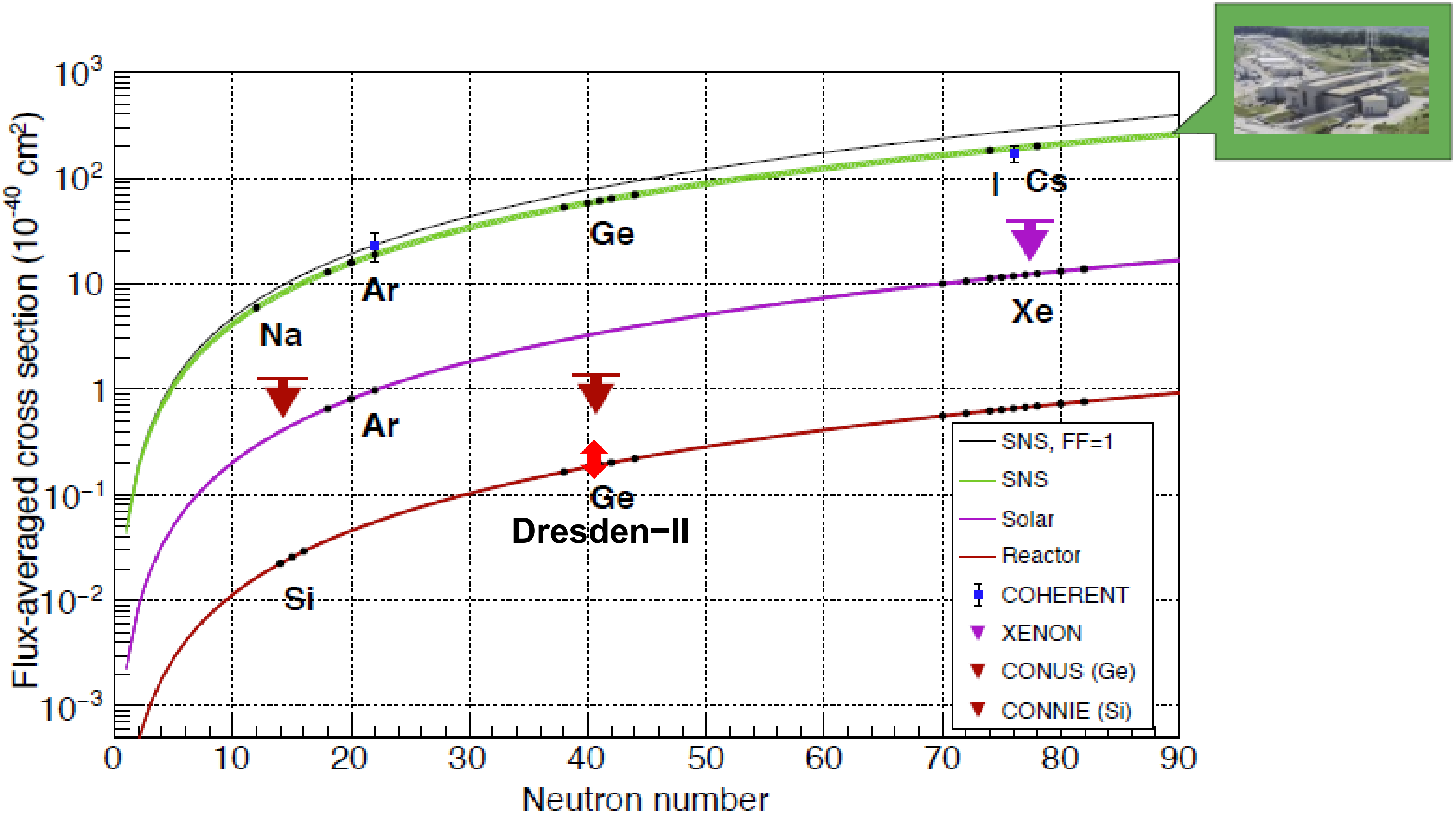
Modified cryostat reduces sensitivity to microphonics.



Part D: Concluding Remarks

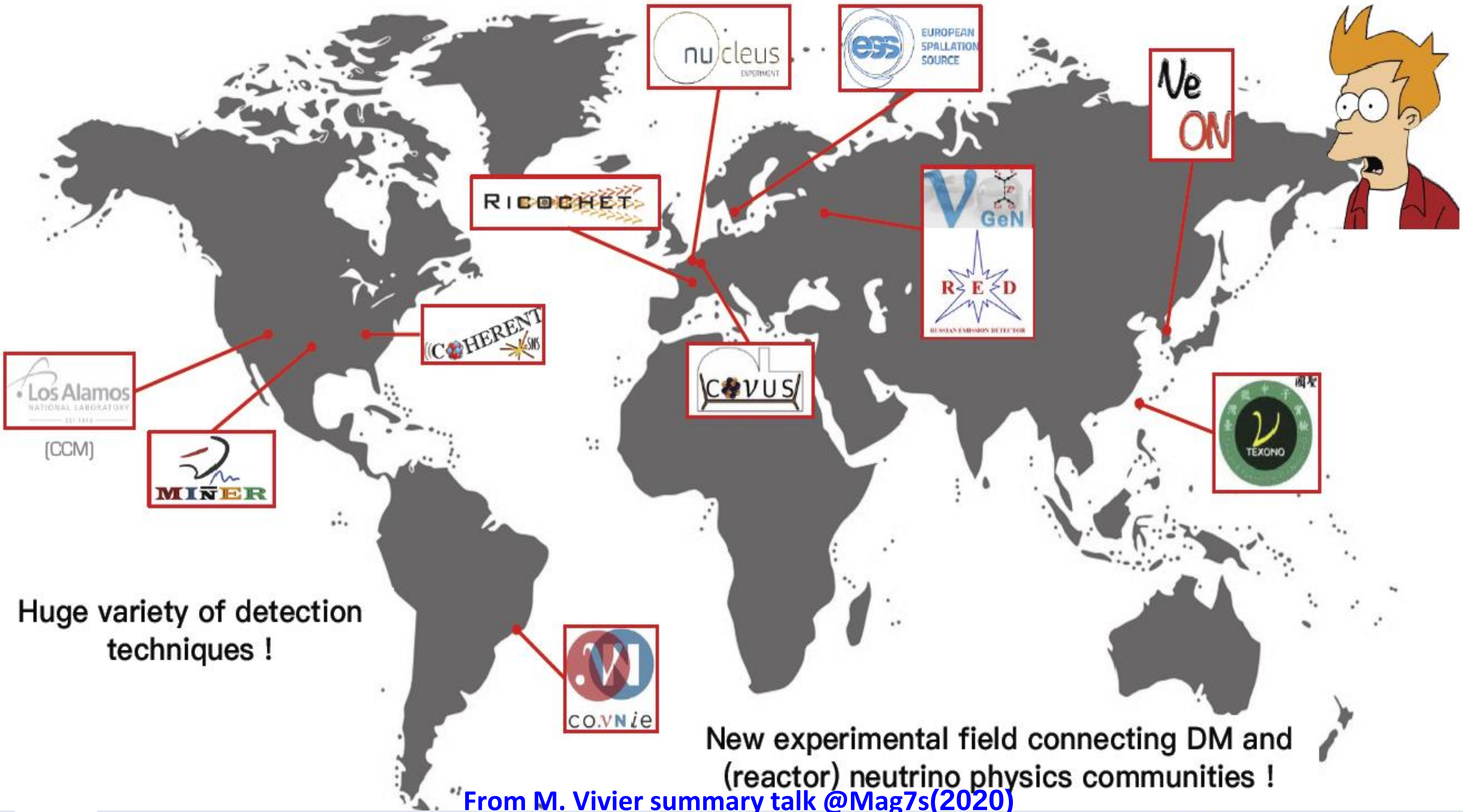
Summary of CEvNS experimental searches

Summary of CEvNS Results



Exp. Program worldwide

Proliferation of experimental efforts worldwide !

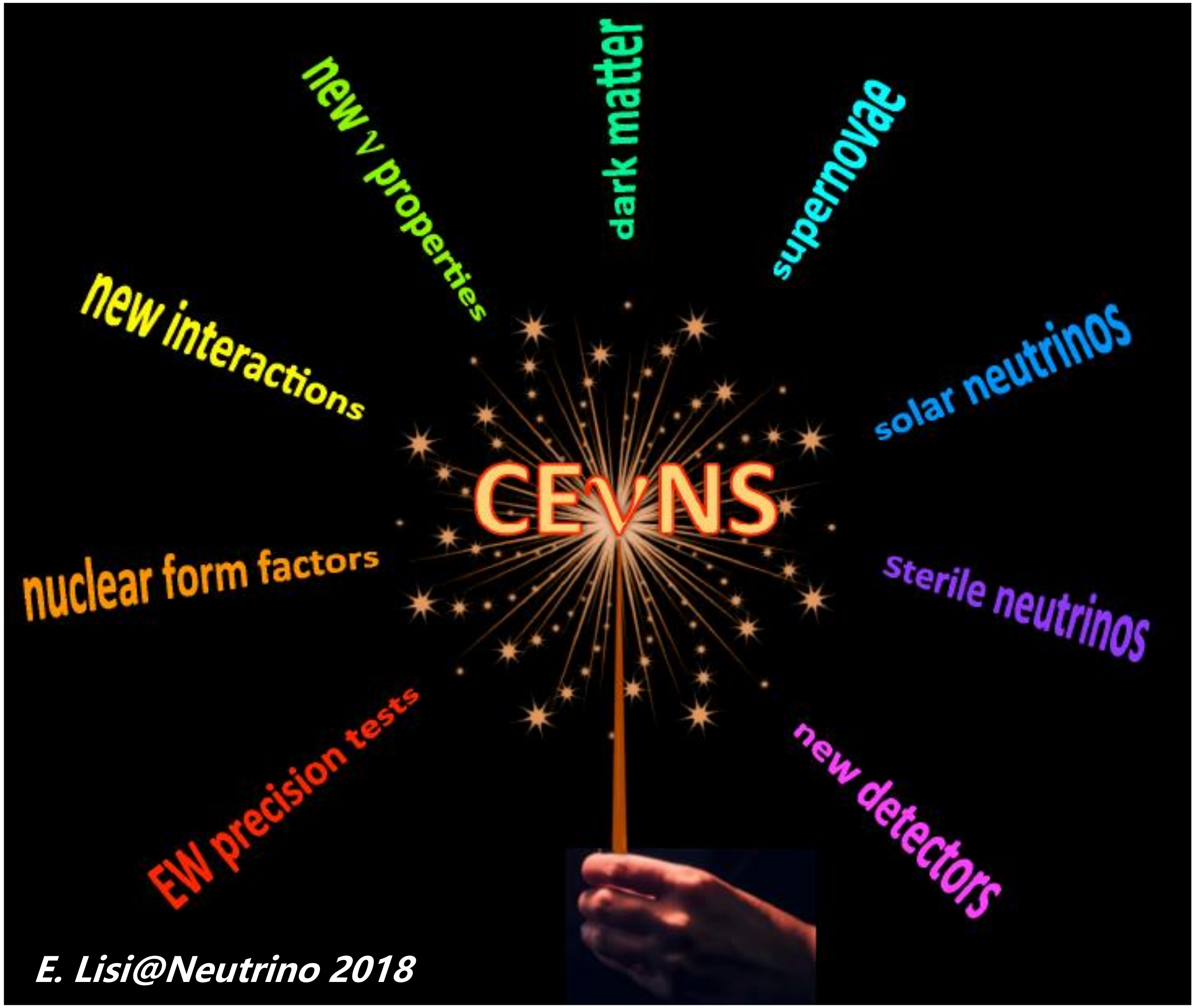


Huge variety of detection techniques !

New experimental field connecting DM and (reactor) neutrino physics communities !

From M. Vivier summary talk @Mag7s(2020)

Implications: What can we do with CEνNS ?

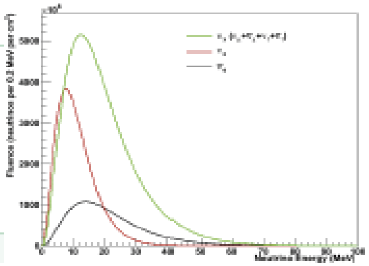


E. Lisi@Neutrino 2018

EXTRAS

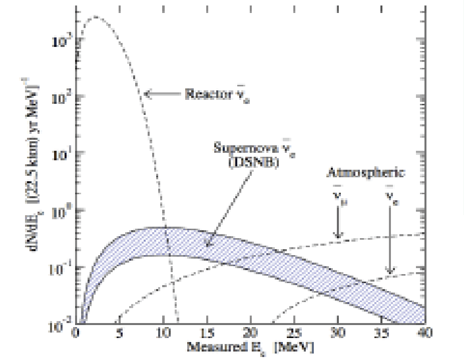
Natural sources of low-energy neutrinos

Supernova burst neutrinos



Every ~30 years in the Galaxy,~few 10’s of sec burst, all flavors

Supernova relic neutrinos

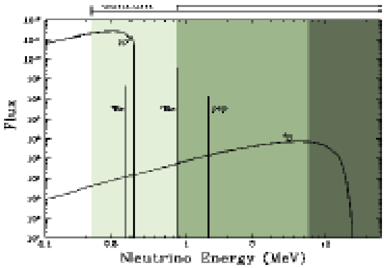


All flavors, low flux

Atmospheric neutrinos

Some component at low energy

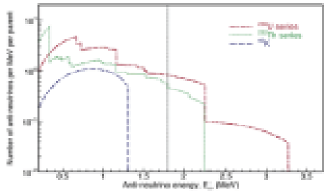
Solar neutrinos



Most flux below 1 MeV

CEvNS eventually seen in DM expts

Geoneutrinos

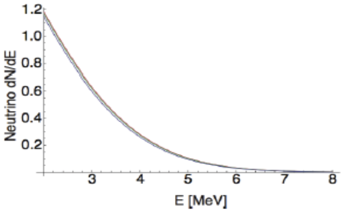


Very low energy

[Scholberg @ CNNP2017]

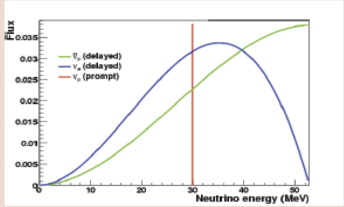
Artificial sources of low-energy neutrinos

Reactors



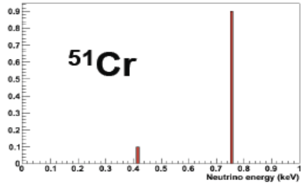
Low energy, but very high fluxes possible; ~continuous source, good bg rejection needed

Stopped pions
(decay at rest)



High energy, pulsed beam possible for good background rejection; possible neutron backgrounds

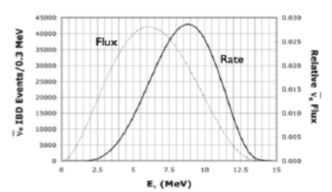
Radioactive sources
(electron capture)



Portable; can get very short baseline, monochromatic

Low energy challenging

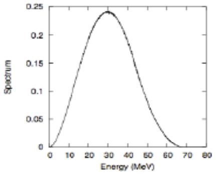
Beam-induced radioactive sources
(IsoDAR)



Relatively compact, higher energy than reactor; time structure not sharp

Does not exist yet

Low-energy beta beams



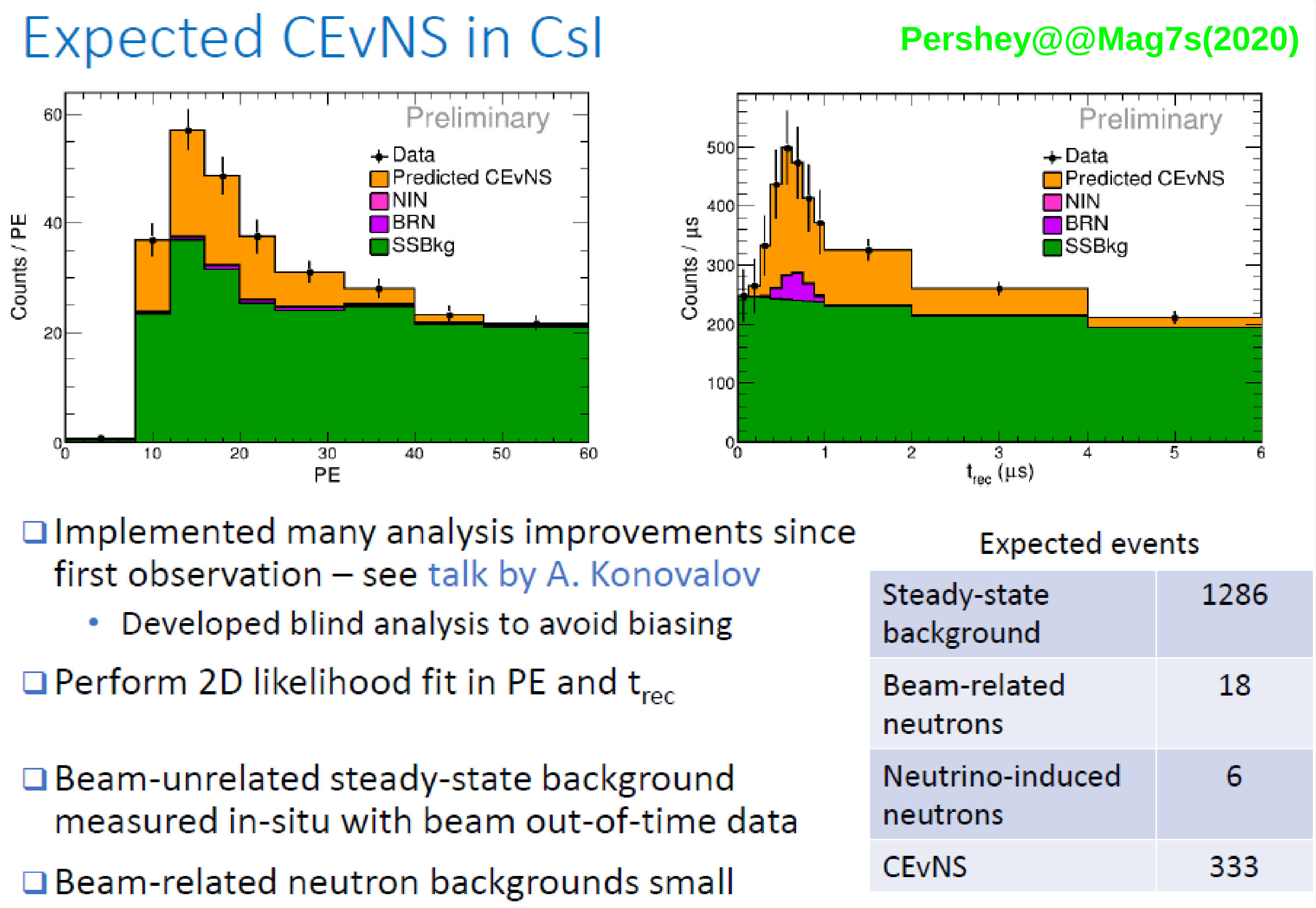
γ=10 boosted ^{18}Ne ν_e

Tunable energy, but not pulsed

Does not exist yet

[Scholberg @ CNNP2017]

New observation with CsI (2020)



Expected CEvNS in CsI

Pershey@@Mag7s(2020)

- ❑ Implemented many analysis improvements since first observation – see talk by A. Konovalov
  - Developed blind analysis to avoid biasing
- ❑ Perform 2D likelihood fit in PE and t_{rec}
- ❑ Beam-unrelated steady-state background measured in-situ with beam out-of-time data
- ❑ Beam-related neutron backgrounds small

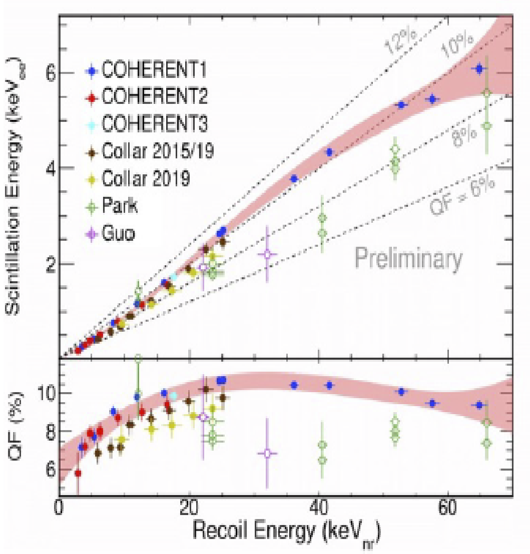
Expected events

Steady-state background	1286
Beam-related neutrons	18
Neutrino-induced neutrons	6
CEvNS	333

New observation with CsI (2020)

- Continued data collection up to June 2019 → increased statistics by a factor > 2
- Refinements in the SSB characterization and beam power determination

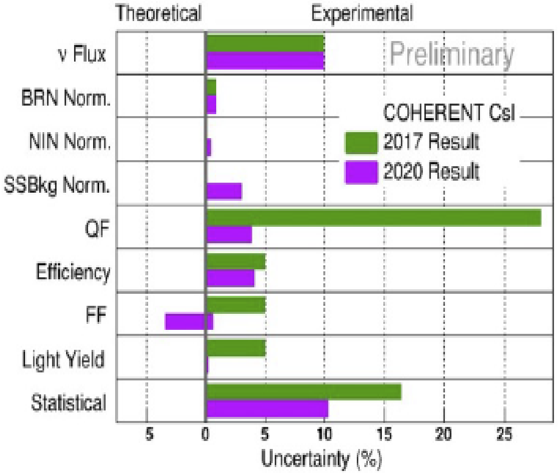
See A. Konovalov's talk



- Big work on re–measuring and understanding the QF

→ Unc. reduced to 3.6% in the new analysis !

- Updated measurement of CEvNS on CsI with new unc. budget !



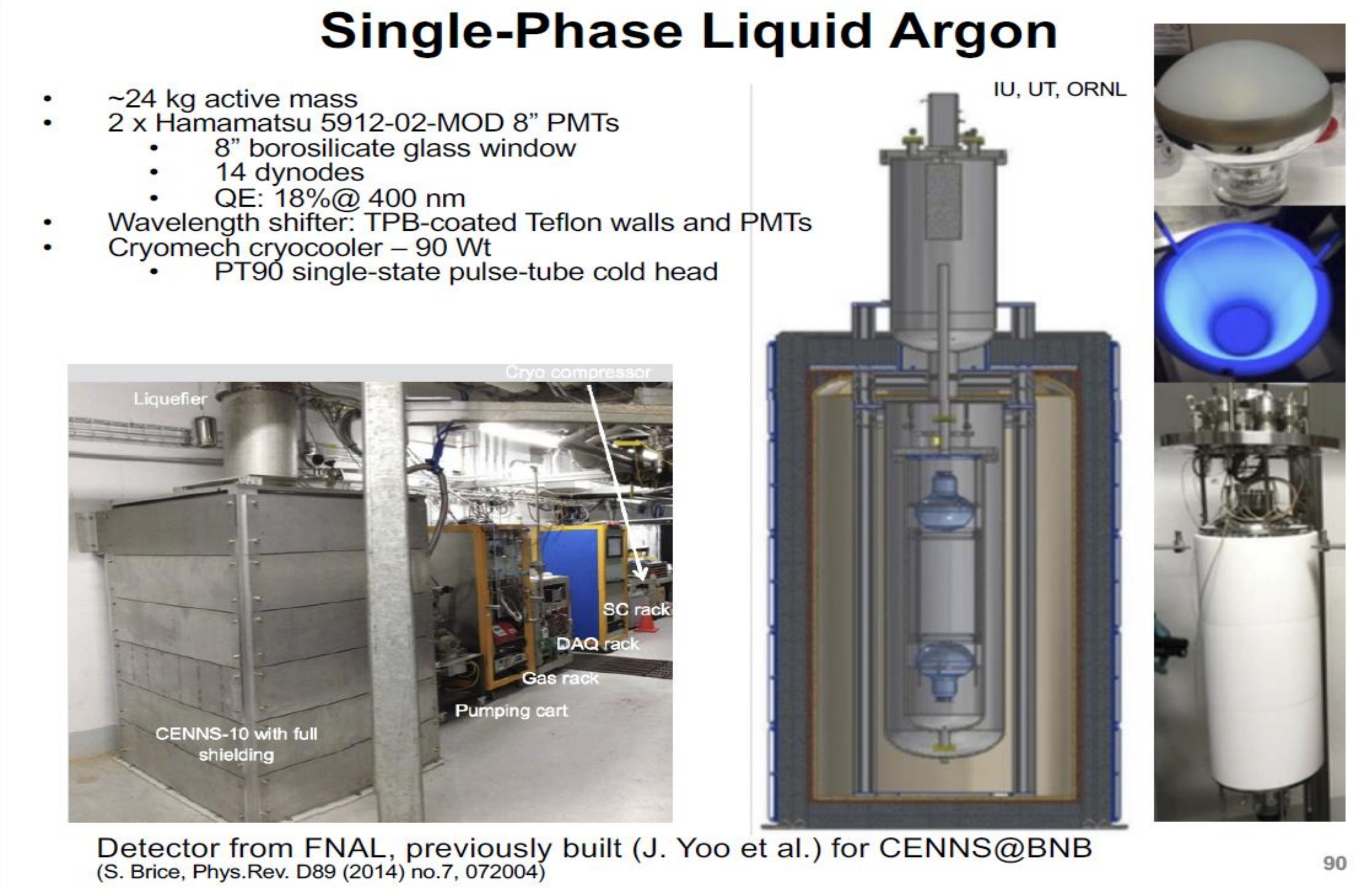
No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\mathrm{th}) \pm 42(\mathrm{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

+ various searches of BSM physics…

See D. Pershey's talk

From M. Vivier summary talk @Mag7s(2020)

Single-Phase Liquid Argon



Single-Phase Liquid Argon

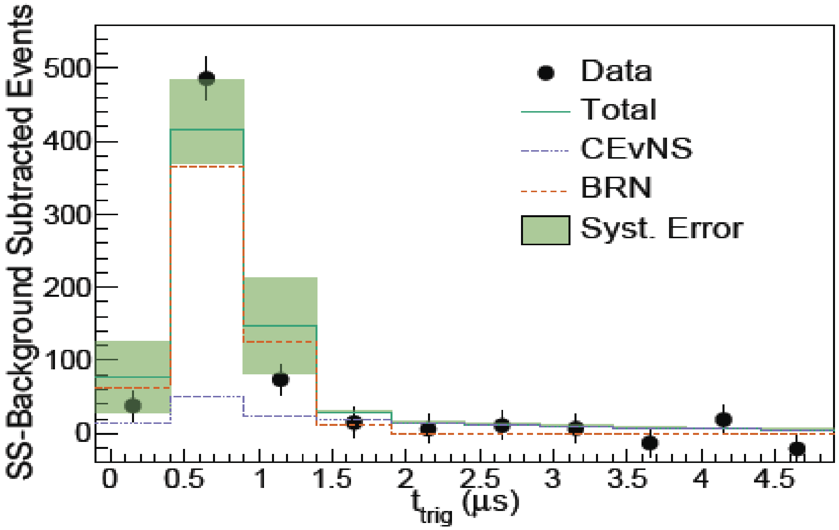
- ~24 kg active mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
  - 8” borosilicate glass window
  - 14 dynodes
  - QE: 18%@ 400 nm
- Wavelength shifter: TPB-coated Teflon walls and PMTs
- Cryomech cryocooler – 90 Wt
  - PT90 single-state pulse-tube cold head

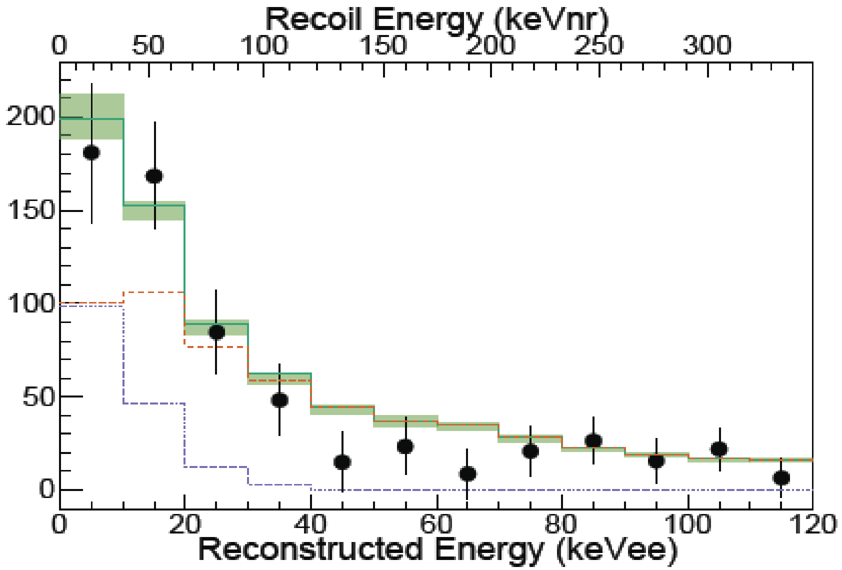
IU, UT, ORNL

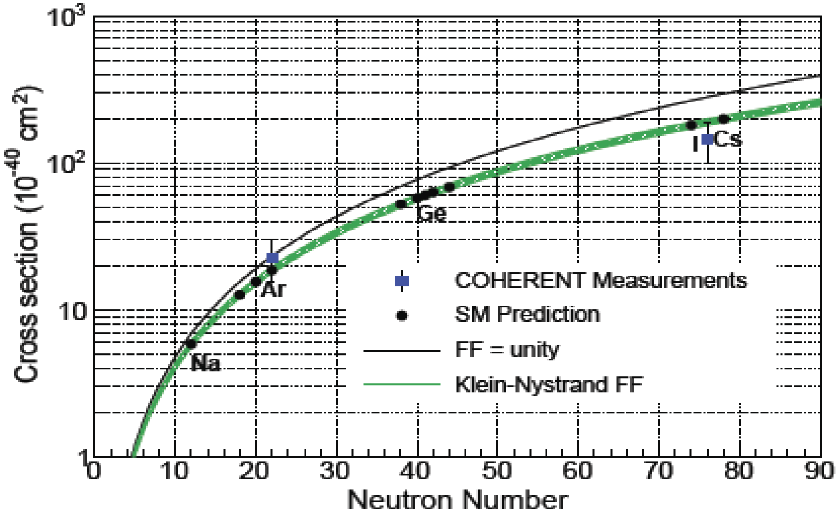
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

COHERENT 2020: Argon (Ar)

[arXiv:2003.10630]







$^{40}_{18}\mathrm{Ar}_{22}$ not so heavy

Verified theoretical $\boxed{\sigma \underset{\sim}{\propto} N^2}$

Electromagnetic Vertex Function

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[F_Q(q^2) + F_A(q^2)\,q^2\gamma_5\right] - i\sigma_{\mu\nu}q^\nu \left[F_M(q^2) + iF_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \Longrightarrow$ q, a, μ, ε

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

no diagonal charges and electric and magnetic moments in the mass basis

- For left-handed ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole are similar and the phenomenology of the magnetic and electric moments are similar.
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.