Coherent Elastic Neutrino-Nucleus Scattering

Marie Vidal on behalf of the NEWS-G collaboration

Queen's University

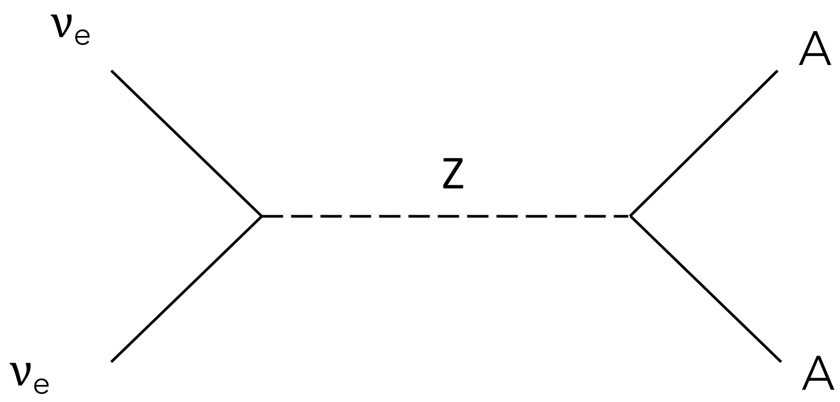
June 8th 2021

Outline

- Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)
    - What is CEνNS?
    - Applications
    - State of the art

- CEνNS and the NEWS-G detectors
    - NEWS-G collaboration
    - Spherical proportional counters (SPCs)
    - CEνNS program

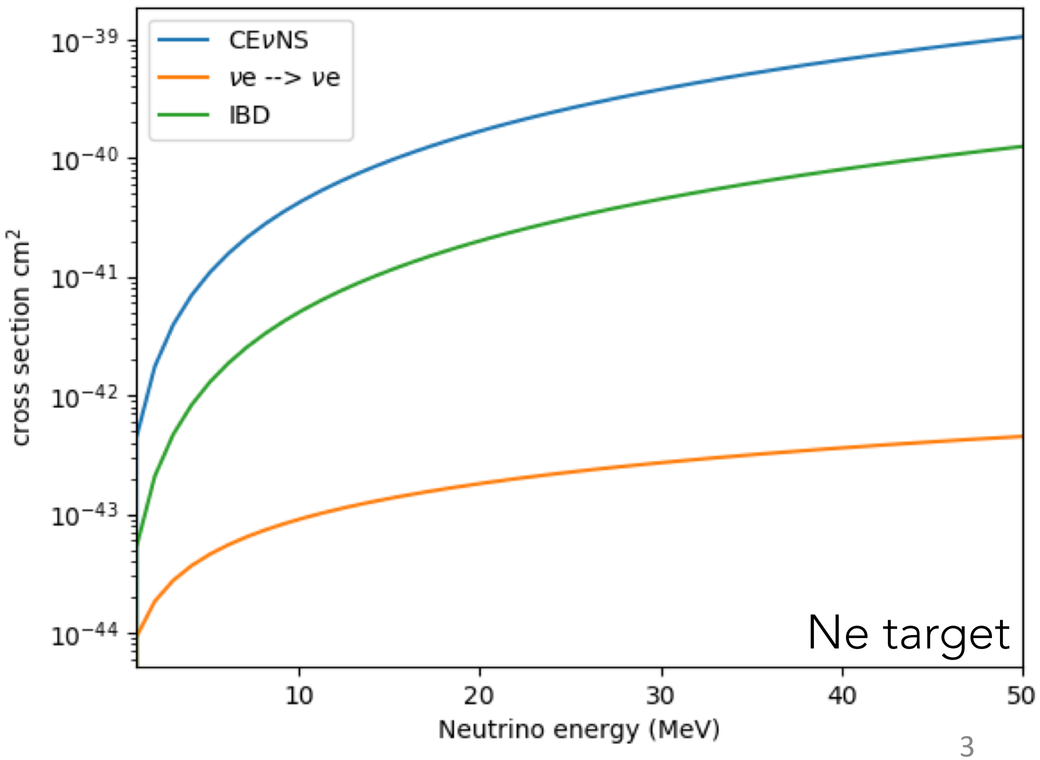
What is CEνNS?



- Predicted by Freedman in 1974 [1]
- Coherent elastic neutrino-nucleus scattering: neutral current
- Coherence = nucleons recoil in phase

  → low momentum transfer qR ≤ ~ 1 (q depends on target mass)
  - $E_\nu \leq \sim 50$ MeV for medium A nuclei (Cs, Ar)
  - Low energy nuclear recoils → challenging to detect

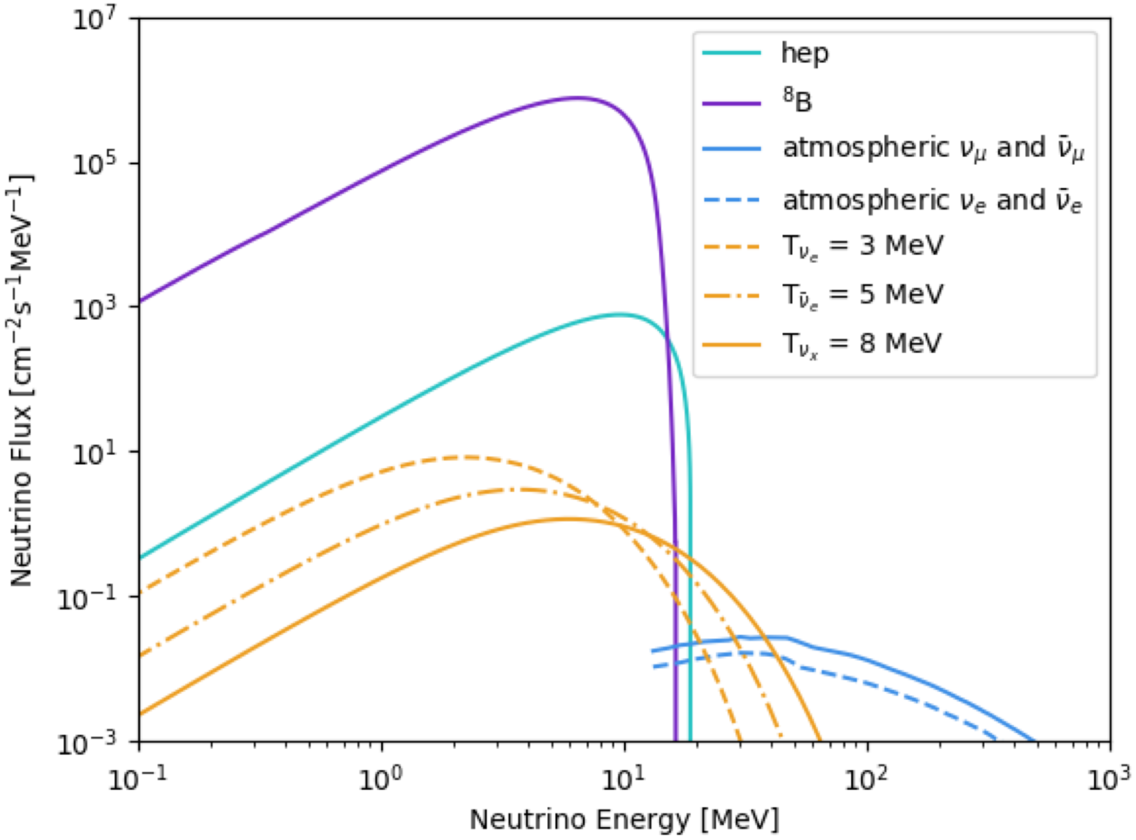
- Large cross-section [2]: $\propto N^2$
- First detection by COHERENT in 2017 [3]



[1] *D. Z. Freedman, Phys. Rev. D 9, 1389– 1392 (1974)*
[2] *A. Drukier, L. Stodolsky, Phys. Rev. D 30, 2295–2309 (1984)*
[3] *D. Akimov et al. (COHERENT), Science 357, 1123 (2017)*

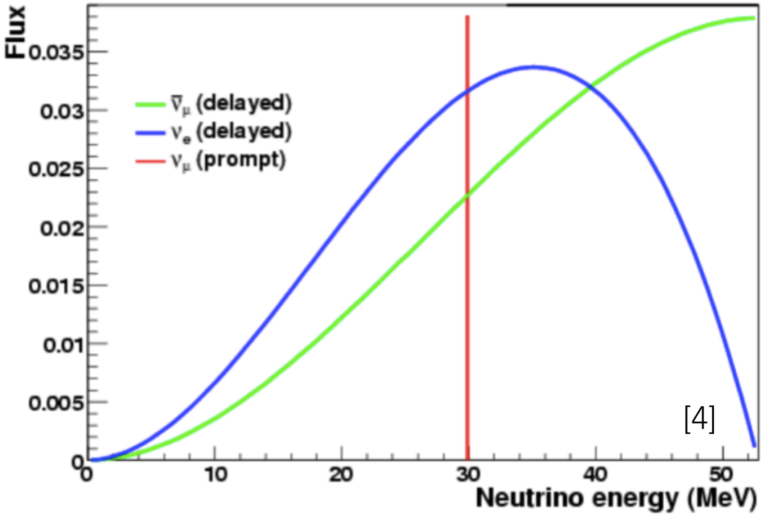
Detectable natural sources

- Solar neutrinos from pp-chain
  - ^{8}B and hep neutrinos: ~10^6 and 10^3 cm^{-2} s^{-1}
  - Maximum E_ν ~ 20 MeV
  - Exp. signal: ~ 700 /t/year (^{8}B, >100 eV$_{nr}$) in Xe
- Atmospheric neutrinos
  - ~ 10^0 cm^{-2} s^{-1}
  - E_ν < 50 MeV: a source of CEνNS
  - Exp. signal: < 10^{-2} /t/year (>100 eV$_{nr}$) in Xe
- Supernovae neutrinos
  - Remnant of SN explosion: ~ 10^1 cm^{-2} s^{-1}
  - Exp. signal: ~ 10^{-3} /t/year (>100 eV$_{nr}$) in Xe
- BG for WIMP searches



Detectable artificial sources

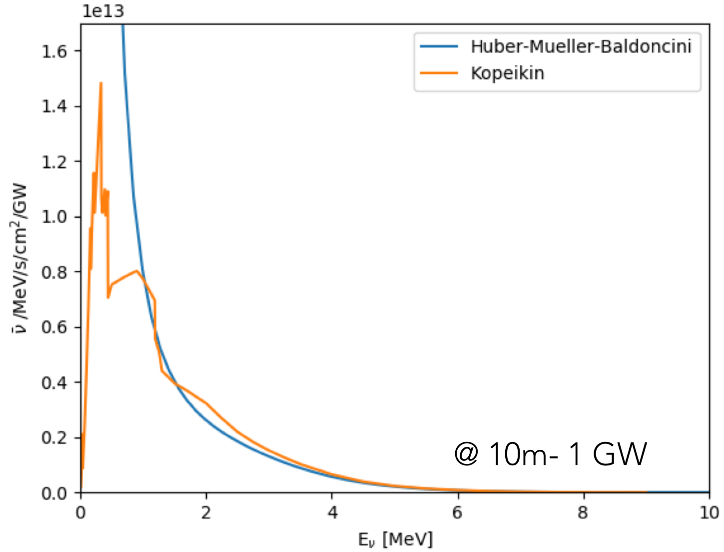
Accelerator



[4]

- multiple flavors of neutrinos
- pulsed source → background rejection
- **ν flux: ~ 10^{15} s^{-1}**
- $E_\nu \in [0, 50]$ MeV (not fully coherent)
- $E_{nr} > 1$ keV_{nr}

Nuclear reactor



@ 10m- 1 GW

- single flavor: ν_e
- continuous source: need to understand cycle for BG rejection
- **ν flux: ~ 10^{20} GW^{-1} s^{-1}**
- $E_\nu \in [0, 12]$ MeV
- $E_{nr} < \sim 1$ keV_{nr}

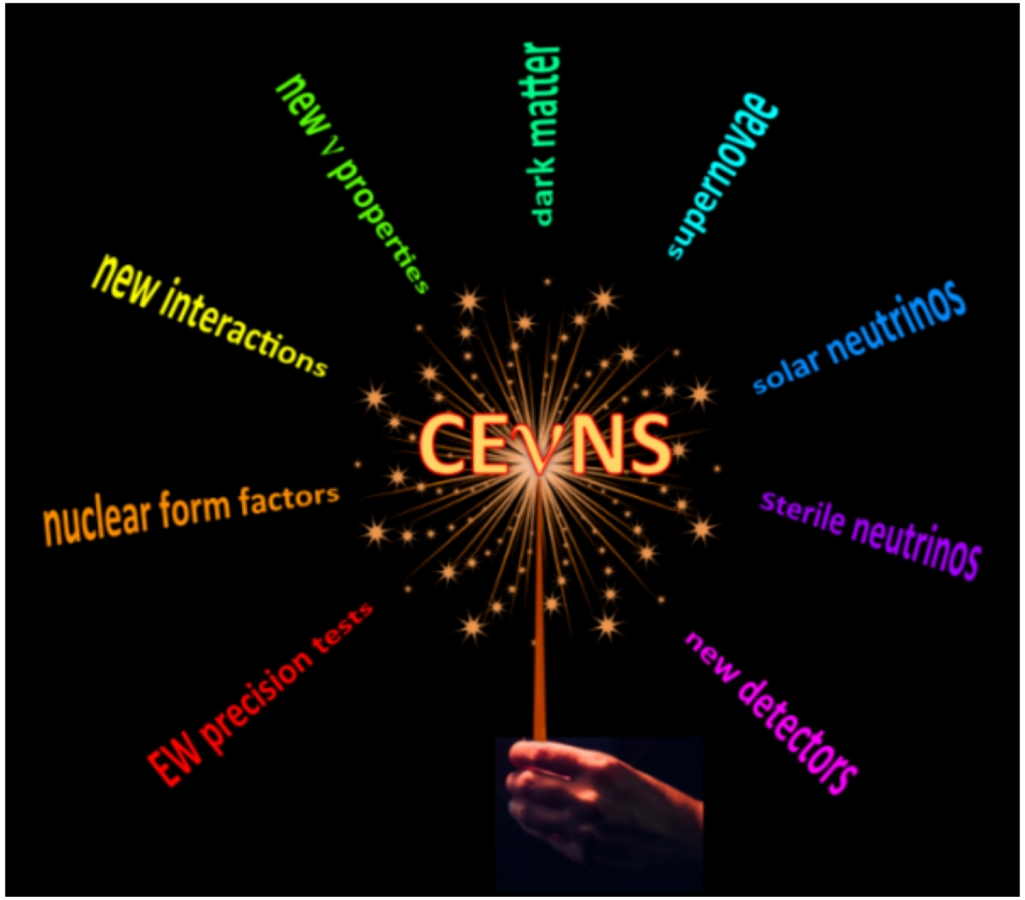
[4] K. Scholberg: COFI Seminar 2017

[5] M. Baldoncini et al., Phys. Rev. D 91, 065002 (2015)
[6] T. A. Mueller et al., Phys. Rev. C 83, 054615 (May 2011)

[7] P. Huber and T. Schwetz, Phys. Rev. D70, 053011 (2004)
[8] V. I. Kopeikin, Phys. Atomic Nucl., 2012, Vol.75, No. 2

Applications of CEνNS

- Study of the neutrino flux from nuclear reactor
  - Application in monitoring reactor neutrino flux for nuclear non-proliferation [9]
  - Sterile neutrino search [10]
- Non-Standard Neutrino interactions [11]
  - Deviation from SM prediction
- Nuclear form factor measurements [12]
- Weak mixing angle precision measurements [13]
- Supernovae neutrinos search [1][14][15]
- Neutrino magnetic moment searches [16]
- …

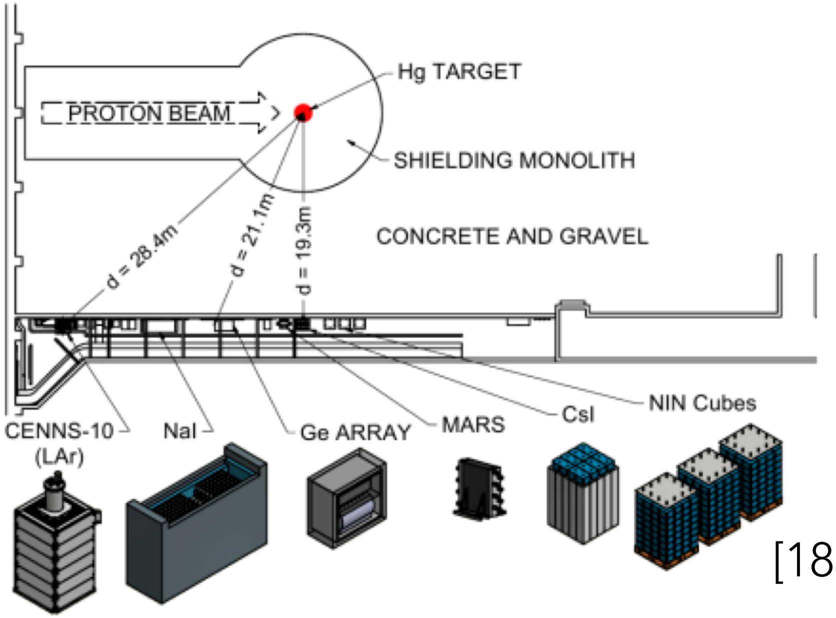


E. Lisi: Neutrino 2018

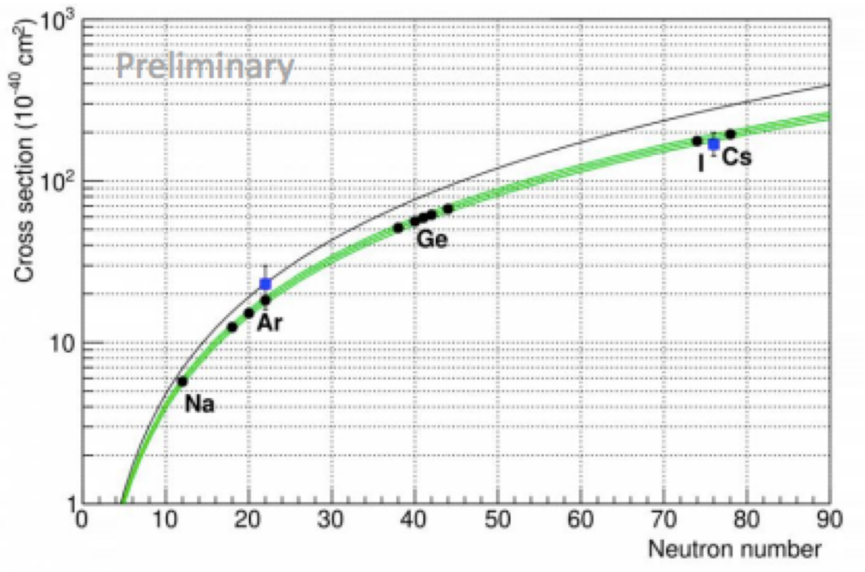
[9] Y. Kim, Nucl. Eng. Tech. 48, 285 (2016)
[10] B. Dutta, Y. Gao, A. Kubik, R. Mahapatra, N. Mirabolfathi, L.E. Strigari, and J.W. Walker, Phys. Rev. D 94.9 (2016)
[11] K. Scholberg, Phys. Rev. D., 73033005, (2006)
[12] P.S. Amanik and G.C. McLaughlin, J. Phys. G Nucl. Partic. 36.1 (2008)
[13] C.J. Horowitz, S.J. Pollock, P.A. Souder, and R. Michaels, Phys. Rev. C 63.2 (2001)
[14] D. Z. Freedman, Annu. Rev. Nucl. Sci. 27.1 (1977)
[15] C.J. Horowitz, K.J. Coakley, and D.N. McKinsey, Phys. Rev. D 68.2 (2003)
[16] J. Papavassiliou, J. Bernabéu, and M. Passera, Proceedings of the International Europhysics Conference on High Energy Physics, (July 21–27, 2005)

State of the art
COHERENT

- Source: Spallation neutron source (SNS) @ Oak Ridge NL
- Multiple detector deployment: various technologies and targets (4)
- CsI[Na] scintillation detector
  - 1^{st} detection of CEνNS in 2017 with 6.7σ C.L. [3]
  - Uncertainties dominated by quenching factor (25%) and ν flux (10%)
  - New analysis with more stat + precision measurement of QF (3.6%)
  - New C.L. of 11.6 σ (not published yet: communicated by the COHERENT collaboration)
- LAr scintillation detector
  - Detection with 3.5 σ C.L. [17]



[18]



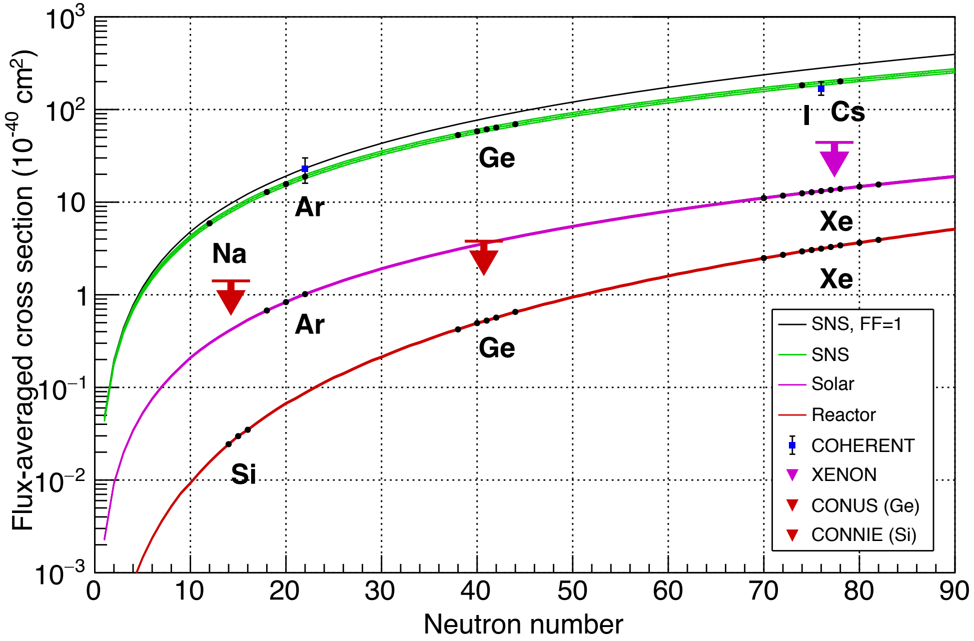
K. Scholberg for the COHERENT Coll.

[17] *Phys. Rev. Lett. 126, 012002 (2021)*
[18] *https://sites.duke.edu/coherent/detectors/*

State of the art

Sources	Target	Technology	Distance	E_{th}	QF	Status
Reactor						
COνUS	Ge	HPGe	17m	300$\mathrm{eV}_{\mathrm{ee}}$	Yes	1st limits [19] 2019-2020 data-taking
CONNIE	Si	CCD arrays	30m	40 $\mathrm{eV}_{\mathrm{ee}}$	Yes	1st limits [20] Upgrade: 7$\mathrm{eV}_{\mathrm{ee}}$ E_{th}
Miner	Si & Ge	Cryogenic	2-10m	100$\mathrm{eV}_{\mathrm{nr}}$	Yes	Commissioning 2022
NU-CLEUS	$CaWO_4$	Cryogenic	72-100m	20eV	No	Physics run by 2022
Ricochet	Zn & Ge	Semi-conductor	8m	50eV	No	Physics run by 2023
Accelerator						
COHERENT	Ge	HPGe	~ 20m	1 $\mathrm{keV}_{\mathrm{nr}}$	Yes	Commissioning 2021
	LAr	Scintillation		20 $\mathrm{keV}_{\mathrm{nr}}$	Yes	Upgrade: 750 kg in 2022
	NaI	Scintillation		13 $\mathrm{keV}_{\mathrm{nr}}$		Commissioning 2021
CCM	LAr	Scintillation	~ 20m	20 $\mathrm{keV}_{\mathrm{nr}}$	Yes	Physics run 2021-2022
Solar						
XENON1T	LXe	TPC		0.5 $\mathrm{keV}_{\mathrm{nr}}$	Yes	1st limits [21]

and many other experiments!



K. Scholberg COHERENT Coll.

[19] Phys. Rev. Lett. 126, 041804 (2021)

[20] Phys. Rev. D 100, 092005 (2019)

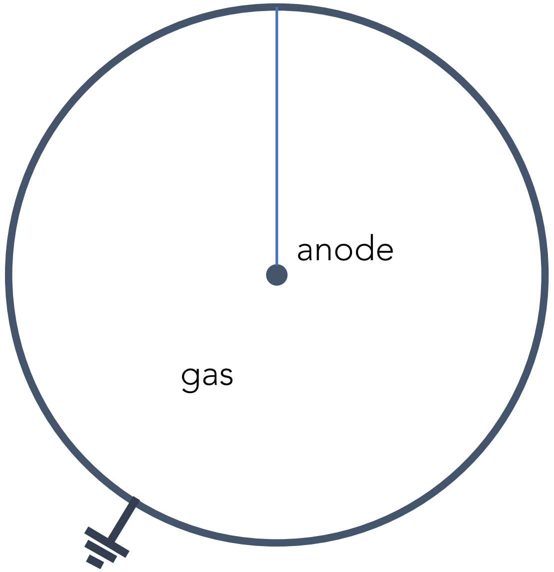
[21] E. Aprile et al. (XENON Collaboration) Phys. Rev. Lett. 126, 091301

NEWS-G

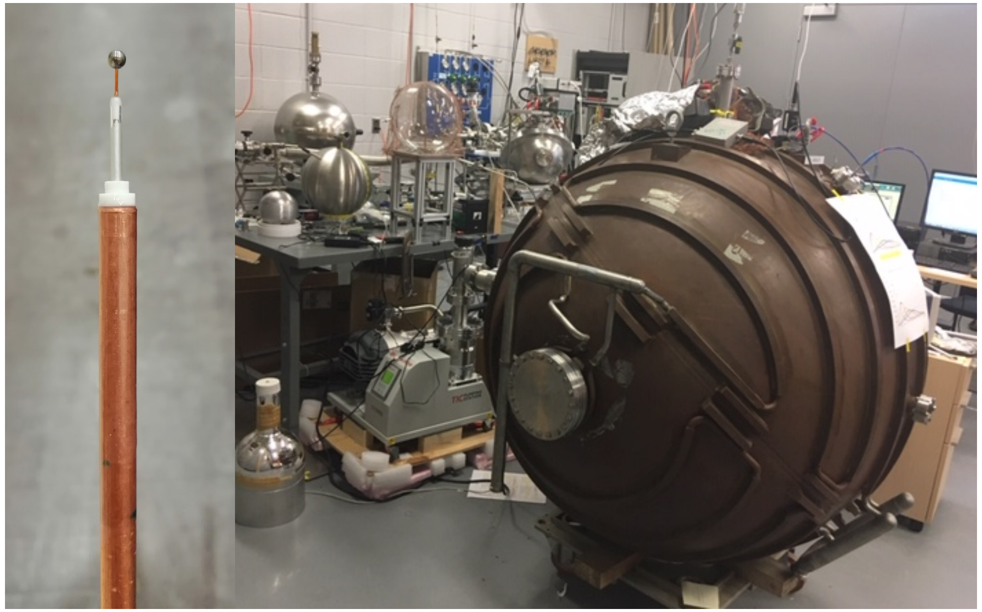
- Groups scientists from 10 different institutions.
- Main goal: search for low-mass dark matter (WIMPs)
  - direct detection: nuclear recoils
- Other applications:
  - **Coherent elastic neutrino-nucleus scattering detection**
  - Axions
  - Neutrinoless double beta decay
- Detector technology: spherical proportional counters

NEWS-G Collaboration Meeting 14-18 December 2020

Spherical proportional counters



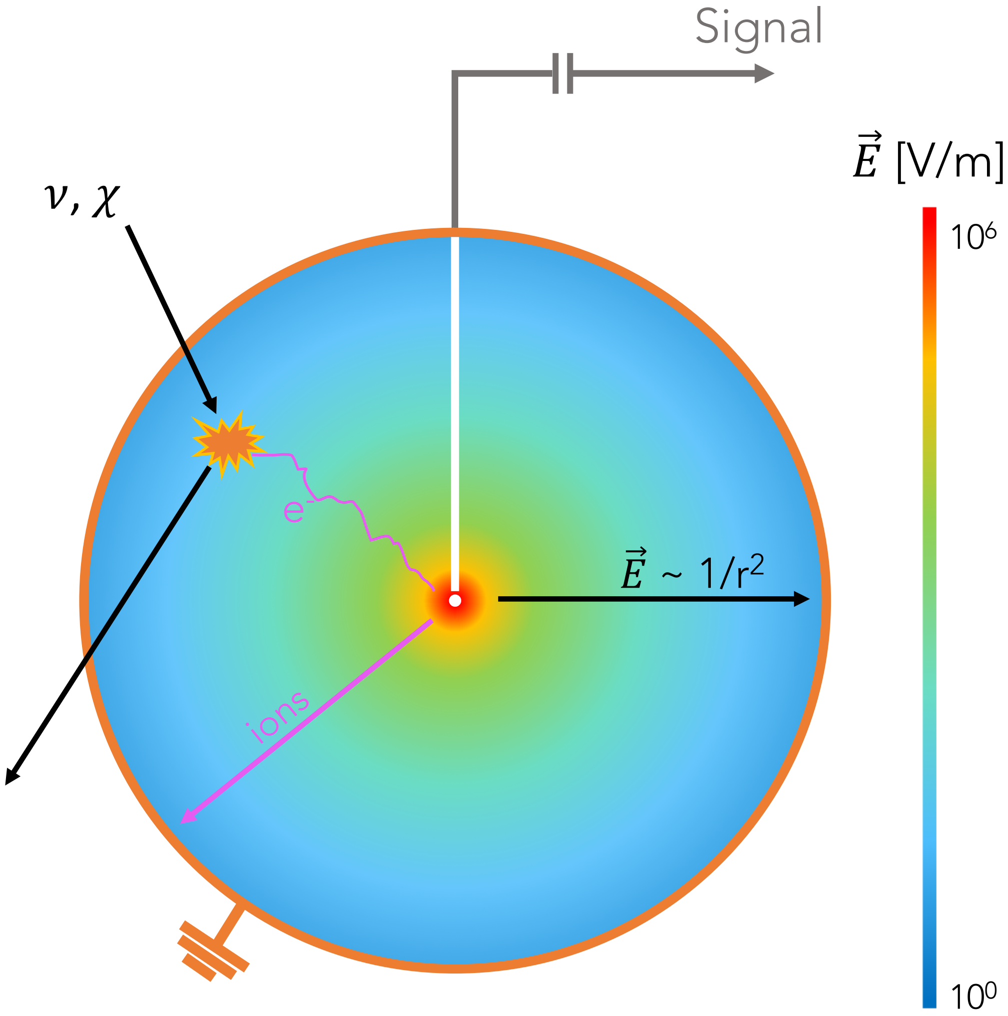
- Spherical metallic vessel filled with gas target + HV on central anode.
- SPC diameter: flexible
- SPC shell: stainless steel, copper, aluminum
- Gas: Neon, Argon, Helium, CH_4
- Large gain
- Low energy threshold, independent of the SPC size: single electron
- Discrimination surface/volume events



Queen’s University lab

SPC: principle

1. Primary ionization
   Mean energy necessary to generate 1 e^-/ion pair
2. Drift of primary e^- (pe) towards sensor
   Typical drift times: ~ 100 μs for 30cm Ø
3. Avalanche in the vicinity of the anode
   Generation of thousands of secondary e^-/ion pairs
4. Signal formation
   Current induced by ions → sphere surface
5. Signal readout
   Induced current integrated by a preamplifier

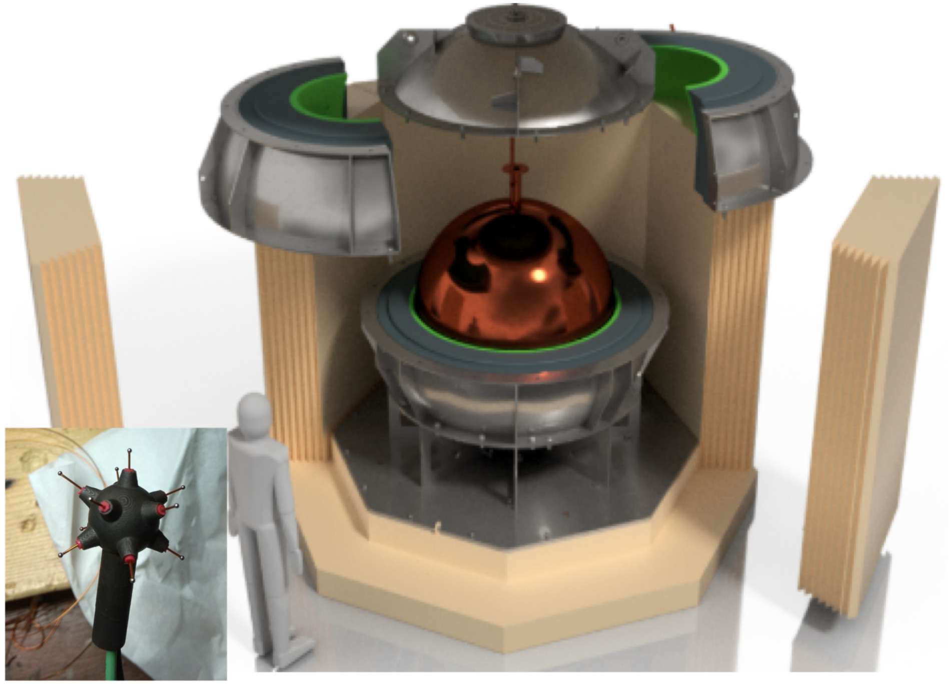


Cartoon: arbitrary scale

NEWS-G and DM searches

- 1^{st} DM data at the LSM
  - 60 cm Ø copper sphere (SEDINE)
  - Filled with 3.1 bar of neon (+0.7% CH_4)
  - Shielding: 30 cm PE, 15 cm Pb, 8 cm Cu
  - 9.6 kg days of exposure
  - Set leading low mass WIMP limit in the sub-GeV mass region (2018) [22]

- Next phase: NEWS-G at SNOLAB
  - New detector: 140 cm Ø low activity copper sphere (C10100) + electroplating of inner surface with 500 μm of pure copper [23] + new sensor
  - New shielding: with layer of archeological lead



NEWS-G @ SNOLAB

See G. Savvidis' poster
2021-06-09

See C. Garrah's talk
2021-06-10

[22] Q. Arnaud et al. (NEWS-G), Astropart. Phys. 97, 54 (2018)
[23] P. Knights et al.: arXiv:2008.03153

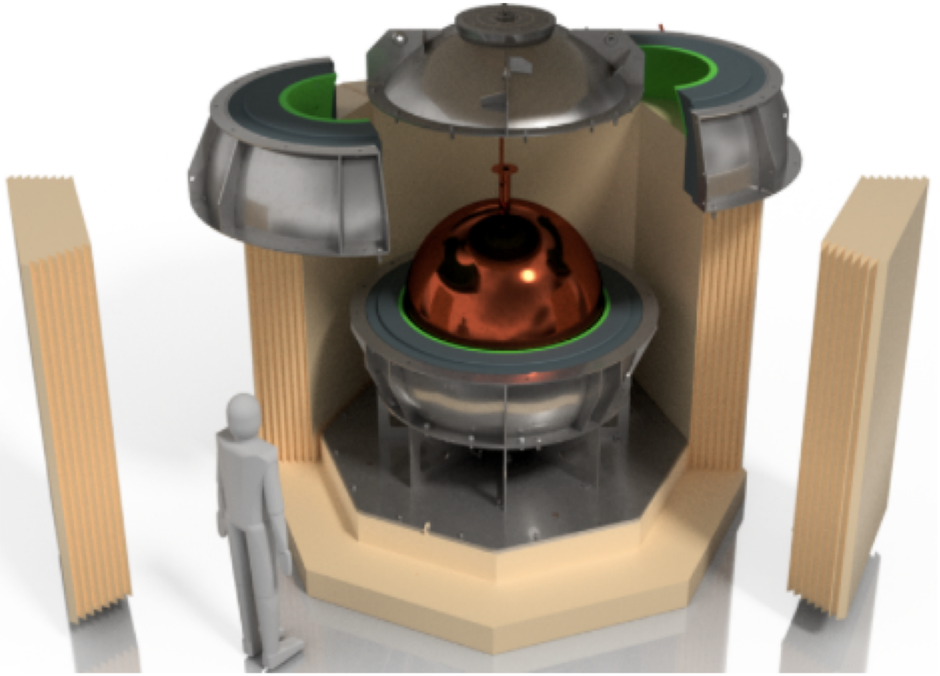
NEWS-G and DM searches: SNOLAB

- Commissioning of the detector at the LSM in Summer 2019:
  - physics run with pure CH_4 gas mixture
  - analysis on-going: results to be published soon.

- Installation of the detector at SNOLAB in 2020.
- First physics run at SNOLAB Summer 2021!

See J-M. Coquillat's poster
2021-06-09

See A. Brossard's talk
2021-06-07



NEWS-G @ SNOLAB

- Other talks:

See Y. Deng's talk
2021-06-10

See P. O'Brien's talk
2021-06-10

See F. Andres Vazquez de Sola's talk
2021-06-07

CEνNS & NEWS-G

- Interested in detecting CEνNS at nuclear reactor
  - High neutrino flux
- Reactor neutrinos up to ~12 MeV → E_{nr} <~1keV$_{nr}$

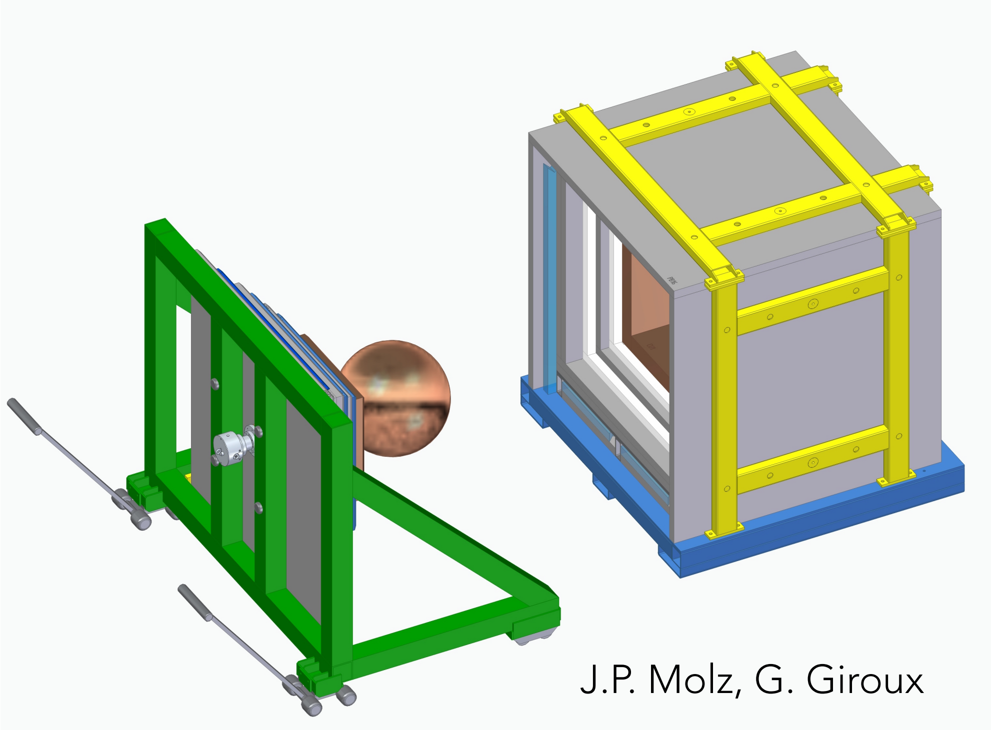
- When we include the QF the detectable nuclear recoil energies are quenched.
- Need low energy threshold
  - SPCs are sensitive to single electron response

- Can try different targets with the same detector

- Status: study of the feasibility of detecting CEνNS at a nuclear reactor using a SPC on-going.

Background

- NEWS-G is mainly a dark matter experiment → underground
- Need to understand surface background: 1st step NEWS-G3 shield @Queen's
  - cosmogenic activation + cosmic muon
  - compact shielding: Cu, Pb, PE
  - muon veto
  - commissioning planned for 2021 using a 60 cm Ø SPC
- Other background:
  - from material purity: study on going (Geant4 simulation)
  - from reactor: gamma and neutron


J.P. Molz, G. Giroux

NEWS-G3 shield

Expected CEνNS signal

- Event rate: differential rate as a function of E_{nr}

$$\frac{dR}{dE_{nr}} = \mathcal{N} \int_{E_\nu^{min}} \frac{d\phi}{dE_\nu} \times \frac{d\sigma(E_\nu, E_{nr})}{dE_{nr}} dE_\nu$$

- The neutrino flux: Huber-Mueller-Baldoncini's flux [5],[6],[7]

- We consider 1GW thermal power
- The detector is 10m from the source
- We consider 1kg of target material

- Expected signal in detector:
  - Response of the detector: primary and secondary ionization statistical fluctuations.
  - Quenching factor: Lindhard model [24]

- 4 candidates: xenon, argon, neon and helium
- Considering a 60 cm Ø SPC:

	Pressure (bar)			
Temperature	Xenon	Argon	Neon	Helium
273 K	1.5	5	9.9	50
293 K	1.6	5.3	10.6	53

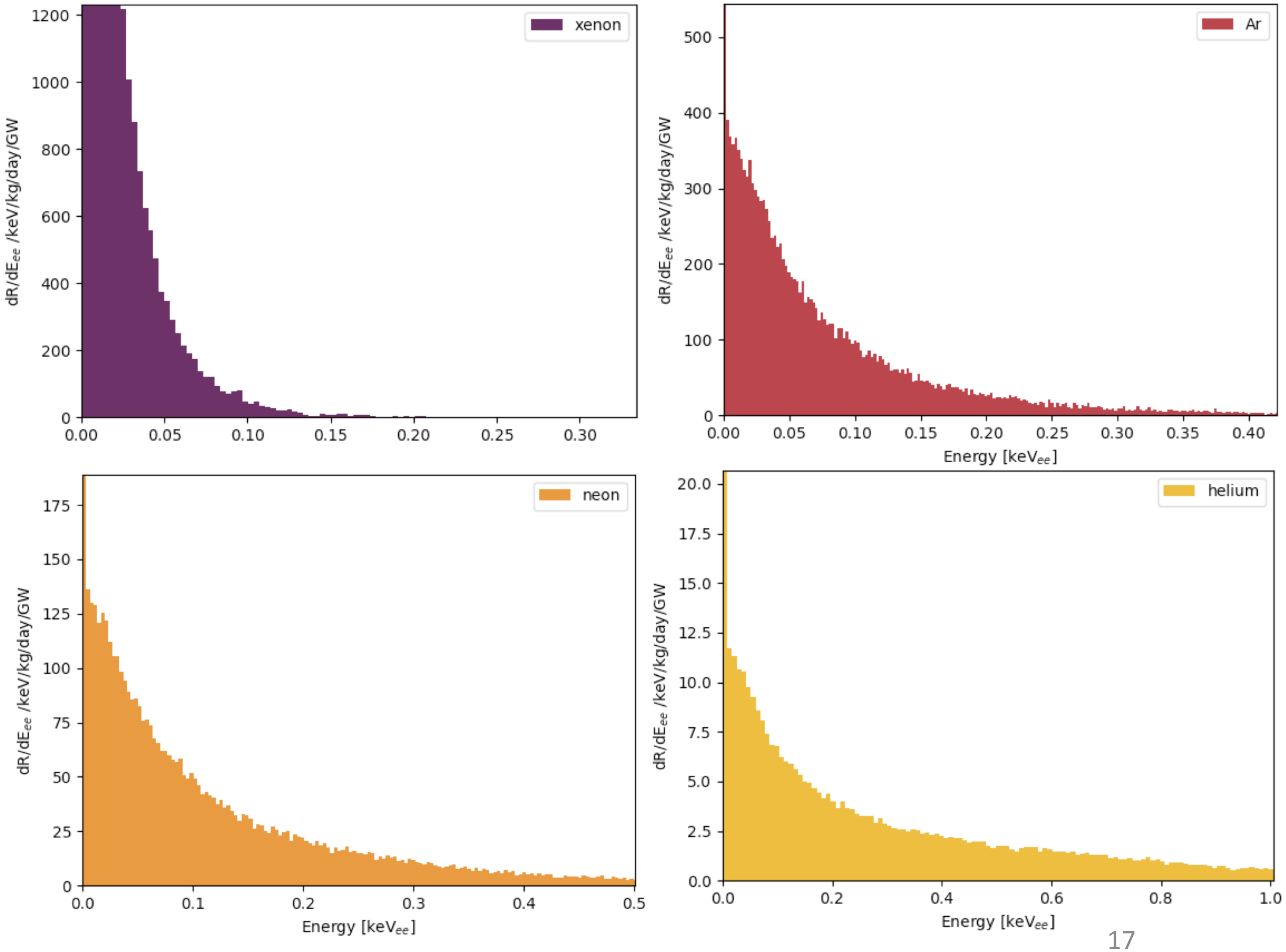
[24] J. Lindhard, V. Nielsen, M. Scharff and P.V. Thomsen, Mat. Fys. Medd. Dan. Vid. Selsk. 33 10 (1963)

Expected CEνNS signal

- Considering $E_{th} = 50\ \mathrm{eV}_{ee}$
- Pressurized Water Reactors and Pressurized Heavy Water Reactors

Event rate: /kg/day/GW	PWR	PHWR (CANDU)
Xenon	13	17
Argon	16	20
Neon	11	13
Helium	4	4

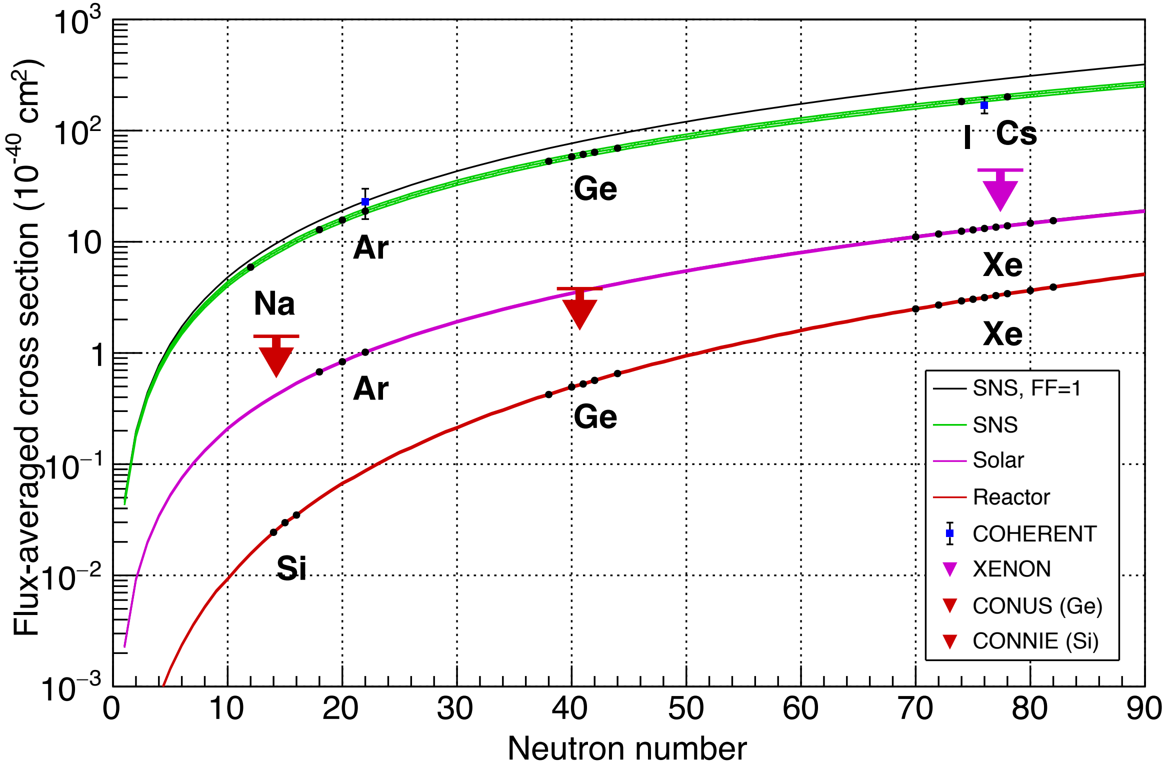
- The knowledge of the QF is of the most importance in CEνNS experiments.
  - 1st measurement of QF of neon gas (will be published soon) @TUNL



Conclusion

- First detections of CEνNS by the COHERENT experiment with CsI and LAr detectors.
- International efforts to detect and use CEνNS as a tool for rich physics program.
  - Collaborative CEνNS community: Magnificent CEνNS workshop every year
  - Benefit greatly from the work done in the dark matter field
  - Constrains set on CEνNS by 2 reactor experiments CONNIE and COνUS
  - 1st constrain on solar ν: XENON1T

- NEWS-G and CEνNS
  - Study of the feasibility of an experiment using a SPC at a nuclear reactor is on-going.
  - Argon is the best candidate for a CEνNS experiment.
  - CANDU reactors provide a higher event rate than PWR reactors.
  - Study of surface background: NEWS-G3 experiment commissioning planned for 2021.



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[19], [20], [21]

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

NSERC
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Canada Excellence
Research Chairs

Chaires d’excellence
en recherche du Canada

Thank you

Questions?

SAPIENTIA ET DOCTRINA STABILITAS
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VewS

Backup slides

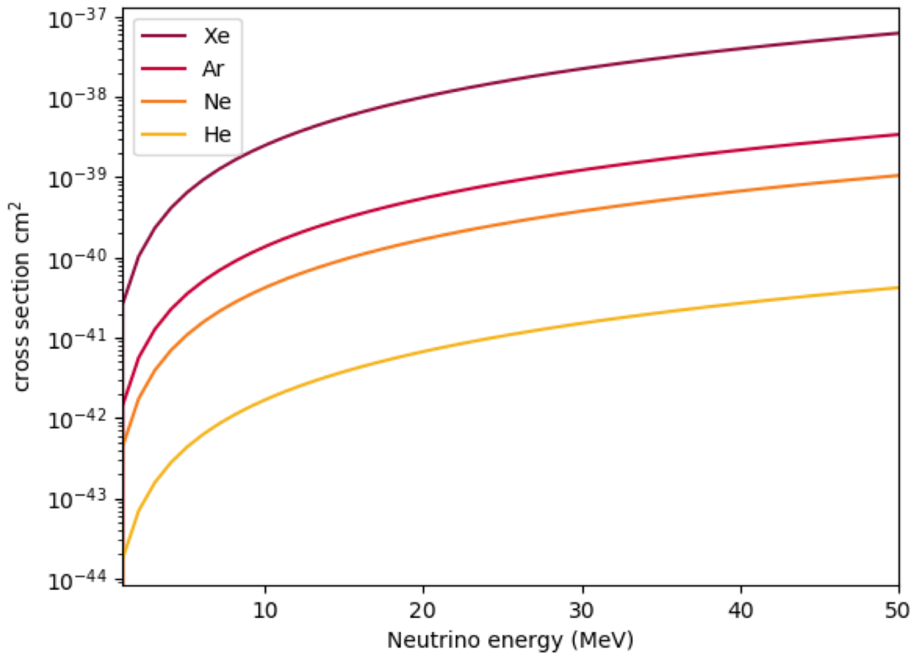
Preliminary calculation

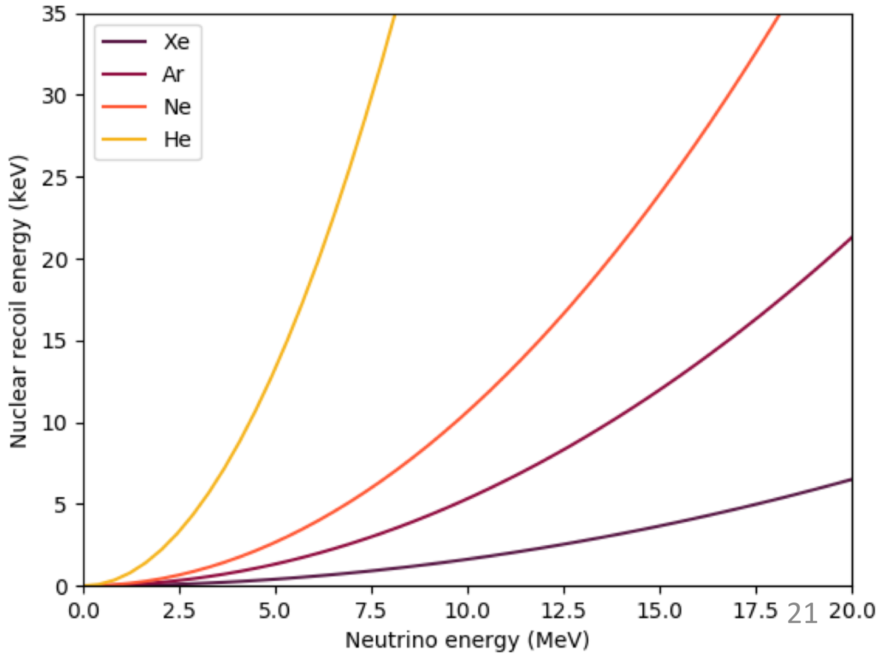
- From the cross sections comparison:
    - He: difficult

- Maximum nuclear recoil energy: $E_{max} = \frac{2E_\nu^2}{M}$

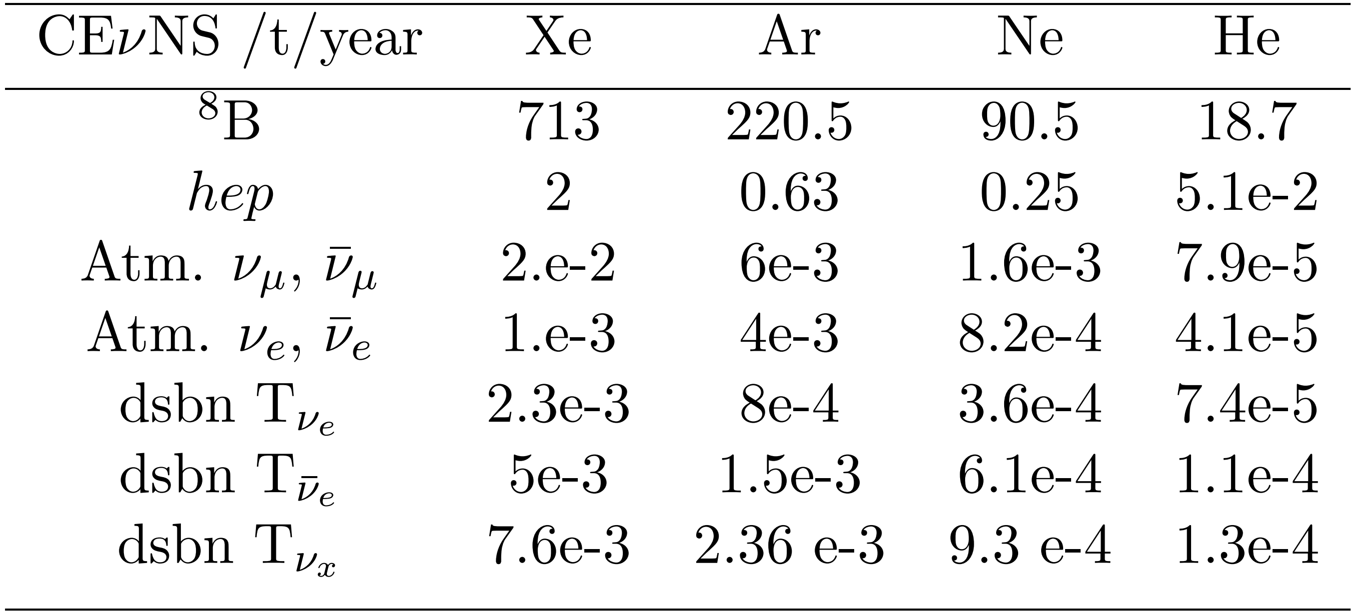
- Considering a E_ν = 6 MeV
    - Xe: $E_{nr,max}$ = 0.5 keV_{nr} → difficult
    - Ar: $E_{nr,max}$ = 2 keV_{nr}
    - Ne: $E_{nr, max}$ = 3 keV_{nr}
    - He: $E_{nr,max}$ = 15 keV_{nr}

- Need to include QF





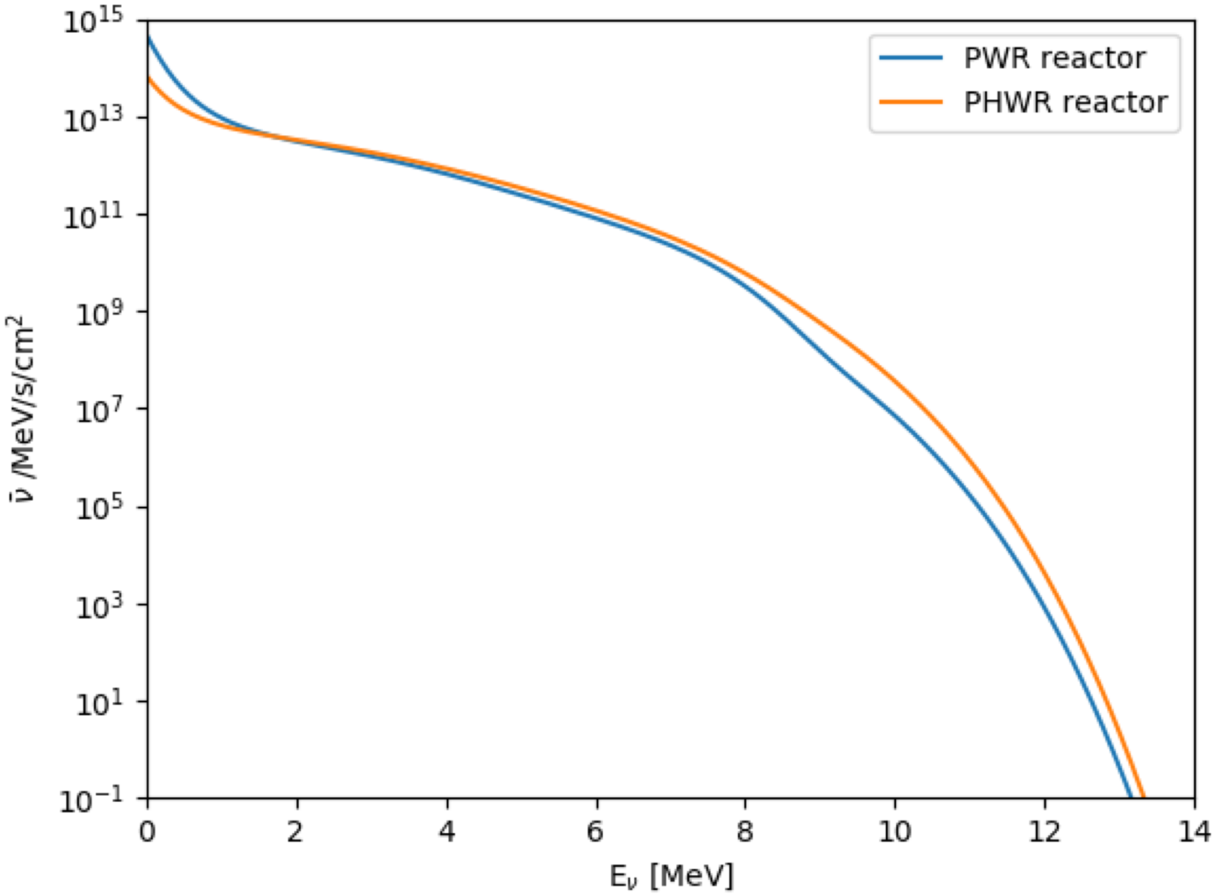
Event rates for natural sources



CEνNS /t/year	Xe	Ar	Ne	He
^{8}B	713	220.5	90.5	18.7
hep	2	0.63	0.25	5.1e-2
Atm. ν_μ, $\bar{\nu}_\mu$	2.e-2	6e-3	1.6e-3	7.9e-5
Atm. ν_e, $\bar{\nu}_e$	1.e-3	4e-3	8.2e-4	4.1e-5
dsbn T_{ν_e}	2.3e-3	8e-4	3.6e-4	7.4e-5
dsbn $T_{\bar{\nu}_e}$	5e-3	1.5e-3	6.1e-4	1.1e-4
dsbn T_{ν_x}	7.6e-3	2.36 e-3	9.3 e-4	1.3e-4

Considering arbitrary energy threshold of 100 $\mathrm{eV_{nr}}$.

Neutrino energy spectra comparison



$$S(E_{\bar{\nu}}) = P_{th} L F \sum_{i=1}^{4} \frac{p_i}{Q_i} \lambda(E_{\bar{\nu}})$$

$$\lambda(E_{\bar{\nu}}) = exp\Big(\sum_{p=1}^{6} a_p^i E_{\bar{\nu}}^{p-1}\Big)$$

	^{235}U	^{238}U	^{239}Pu	^{241}Pu
Q$_i$, E (MeV)/fission	202.36 ± 0.26	205.99 ± 0.52	211.12± 0.34	214.26 ± 0.33
$\bar{E}_{\bar{\nu}_e}$ (MeV)	1.46	1.56	1.32	1.44
$\bar{\nu}_e$ / fission	5.58	6.69	5.09	5.89
p$_i$ PWR	0.560	0.080	0.300	0.060
p$_i$ PHWR	0.543	0.411	0.022	0.024

Expected background from material radioactivity

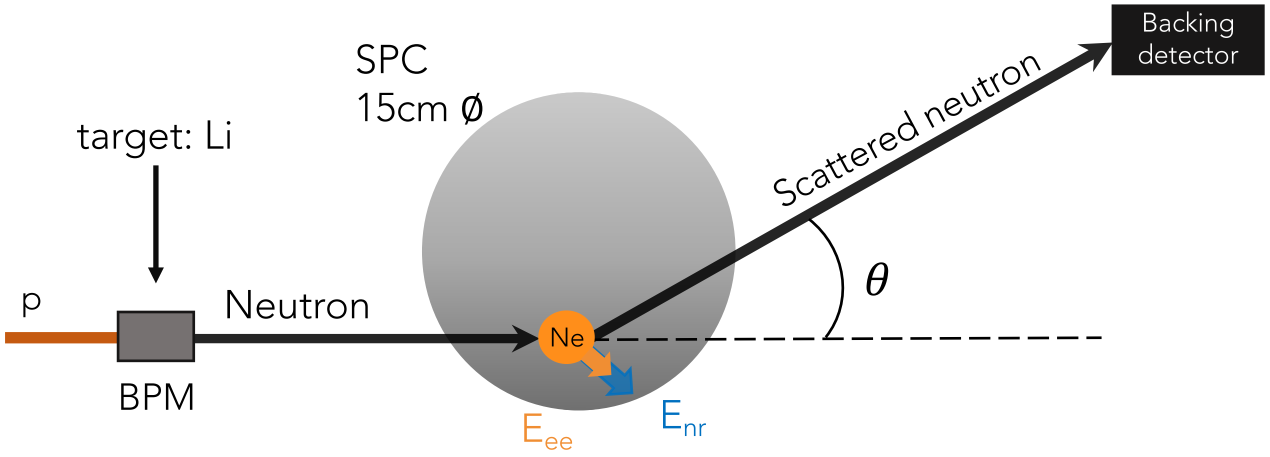
Cu SPC	dru $\gamma < 1$ keV / [Bq/kg]
Co60	4.48e2
Co57	7.35e2
Co58	4.53e2
Co56	8.16e2
Mn54	2.96e2
Pb 210 chain	4.1e1
U238 chain	1.08e3
Th232 chain	1.35e3

Cu shield	dru $\gamma < 1$ keV / [Bq/kg]
U238	8.29e3
Th232	3.32e3
Bi210	1.18e1
Co60	2.41e3
Co57	94.4
Co58	1.65e3
Co56	3.16e3
Mn54	3.16e3

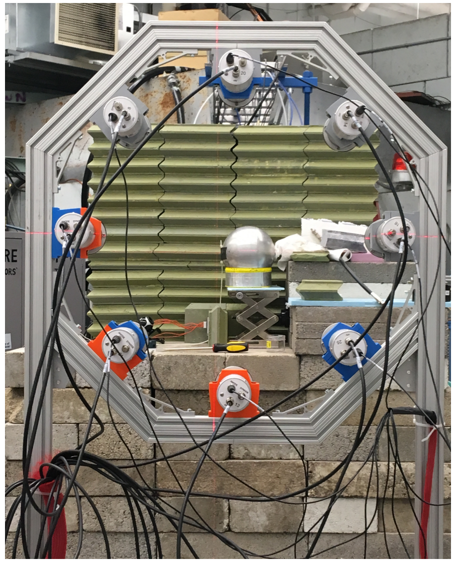
Pb shield	dru $\gamma < 1$ keV / [Bq/kg]
U238	1.05e1
Th232	7.9e1
Bi210	e-3

Preliminary estimations

QF measurement @TUNL



Run	E_{nr} [keV_{nr}]	θ [^{o}]
8	6.8	29.02
7	2.93	18.84
14	2.02	15.63
9	1.7	14.33
10	1.3	12.48
14	1.03	11.13
11	0.74	9.4
14	0.34	6.33



Method

- From kinematics: can calculate E_{nr} as a function of the scattering angle (θ_s) and the neutron energy (E_n).
- θ_s provided by backing detectors (BDs) configuration
- Calculate: $QF(E_{nr}) = E_{ee}/E_{nr}$

Experiment

- 15 cm SPC
- Gas: Neon + CH_4 (97:3) @ 2 bar
- Pulsed beam: $E_n = 545 \pm 20$ keV
- 8 energy points: 0.34 to 6.8 keV_{nr} (see table)

- DAQ triggered on BDs
- Beam Pick-off Monitor (BPM): TOF neutrons
- Energy calibration: ^{55}Fe source