Coherent Elastic Neutrino-Nucleus Scattering: an experimental review

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IRN neutrino meeting
June 10th-11th 2021, Cyberspace

Outline

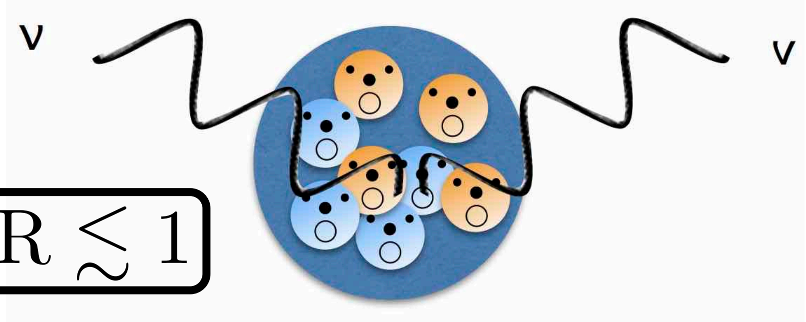
1. The process
2. Measurements at stopped-pion sources
3. Experimental efforts at reactors
4. The connection with DM observatories (if enough time)

The process in a nutshell

- Neutral current, independently predicted by Freedman and Kopeliovich & Frankfurt

1974

- Coherence condition:

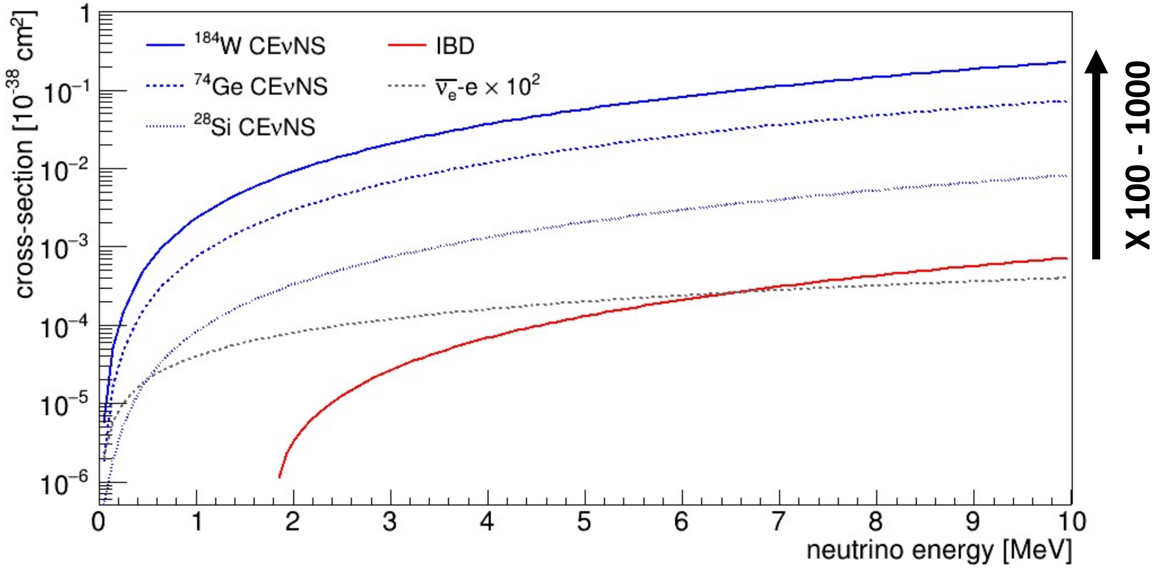


$qR \lesssim 1$

Typically happens for $E_\nu \lesssim$ 50–100 MeV

- Boost in cross–section with expected N^2 scaling

→ **Precision physics with ≲ ton–scale detectors !**



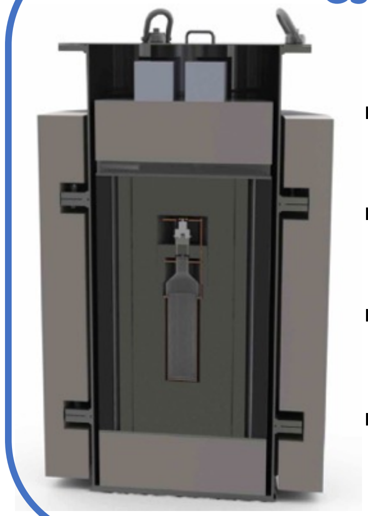
- Single nuclear recoil at very low energies (~ keV)

→ **Experimentally super challenging...**

First detection on CsI

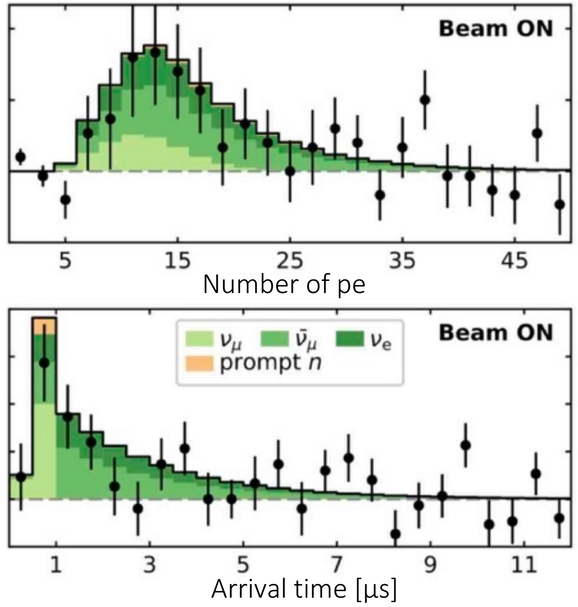
2017

CsI[Na] scintillation detector



- 14.6 kg @ 19.3 m from SNS source
- PE + lead passive shielding + μ veto
- Energy threshold ≈ 4 keV_{nr}
- Beam ON/OFF data: 308.1/153.5 live–days

2015-2017 data



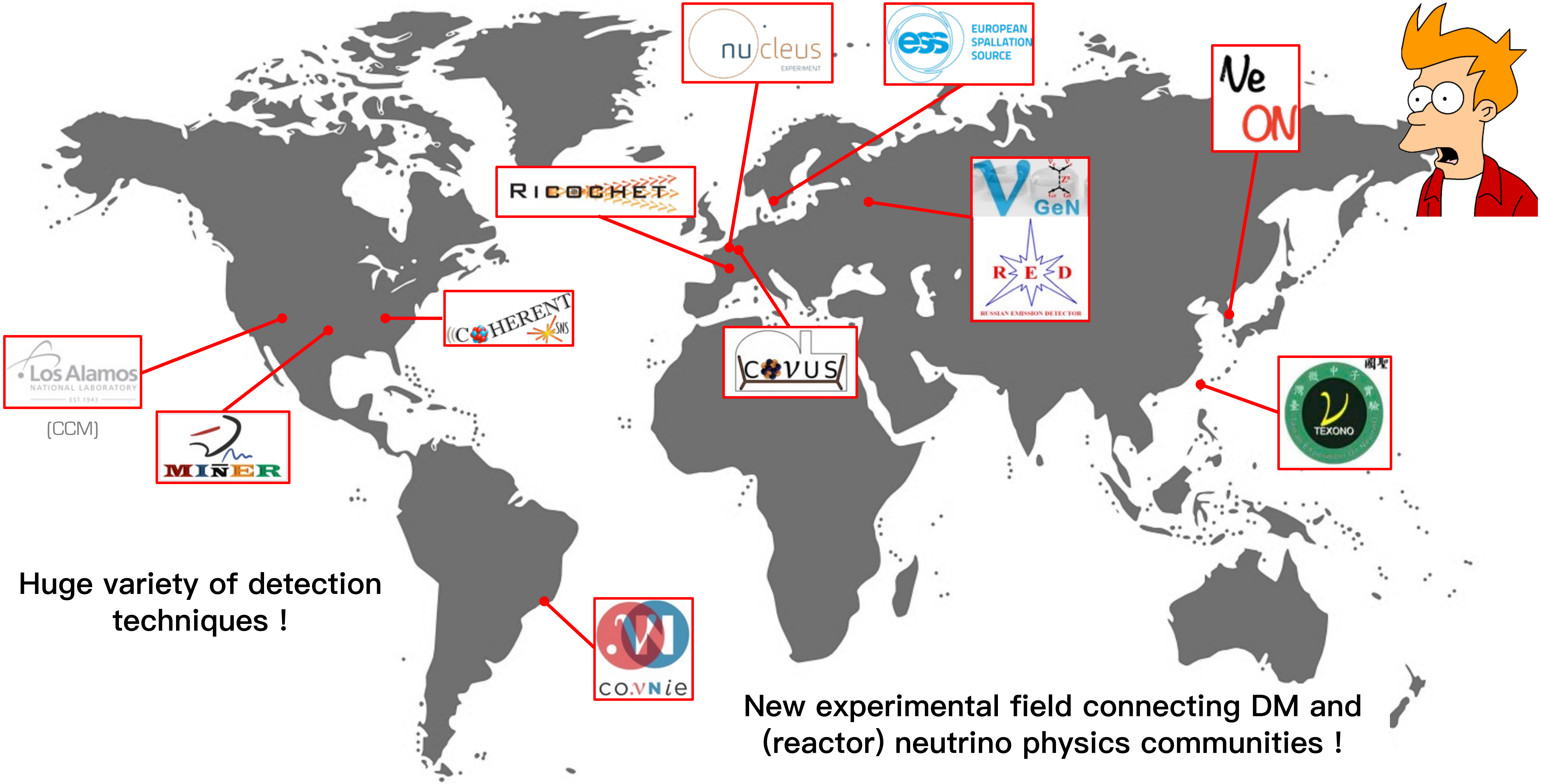
N_{CEvNS} = 134 ± 22
6.7σ significance

Breakdown of systematics

Source of systematic	Contribution
Form factor (in CEνNS cross-section)	5%
ν flux from SNS	10%
Quenching factor	25%
Det. efficiency	5%
Source-detector baseline	Negligible

D. Akimov et al., (2017)

Proliferation of experimental efforts worldwide…



Huge variety of detection techniques !

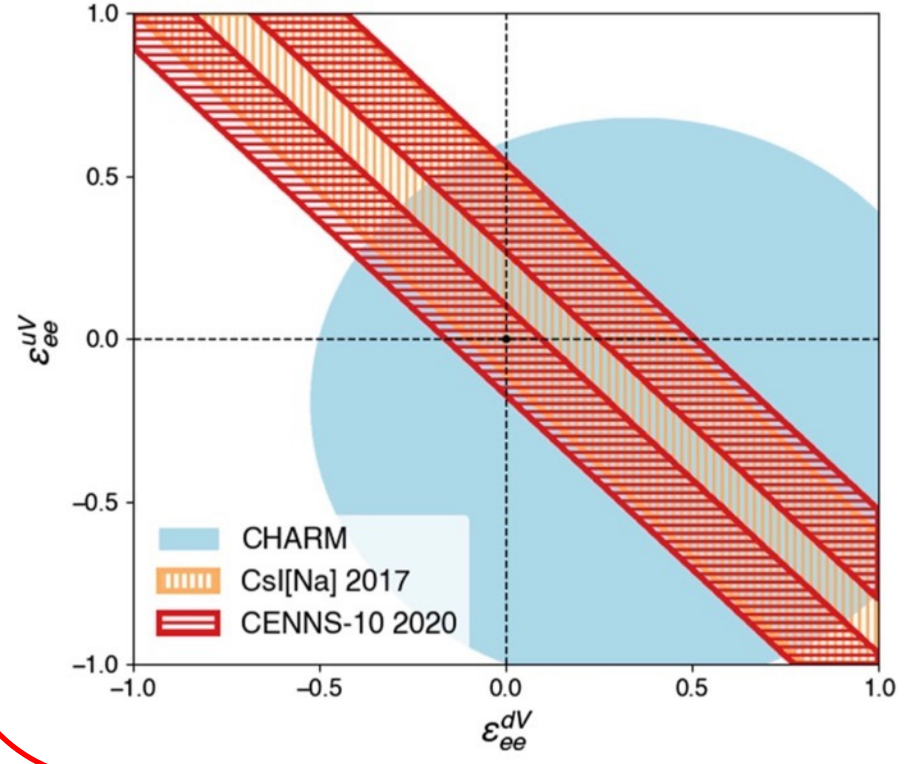
New experimental field connecting DM and (reactor) neutrino physics communities !

… and an expanding physics playground !

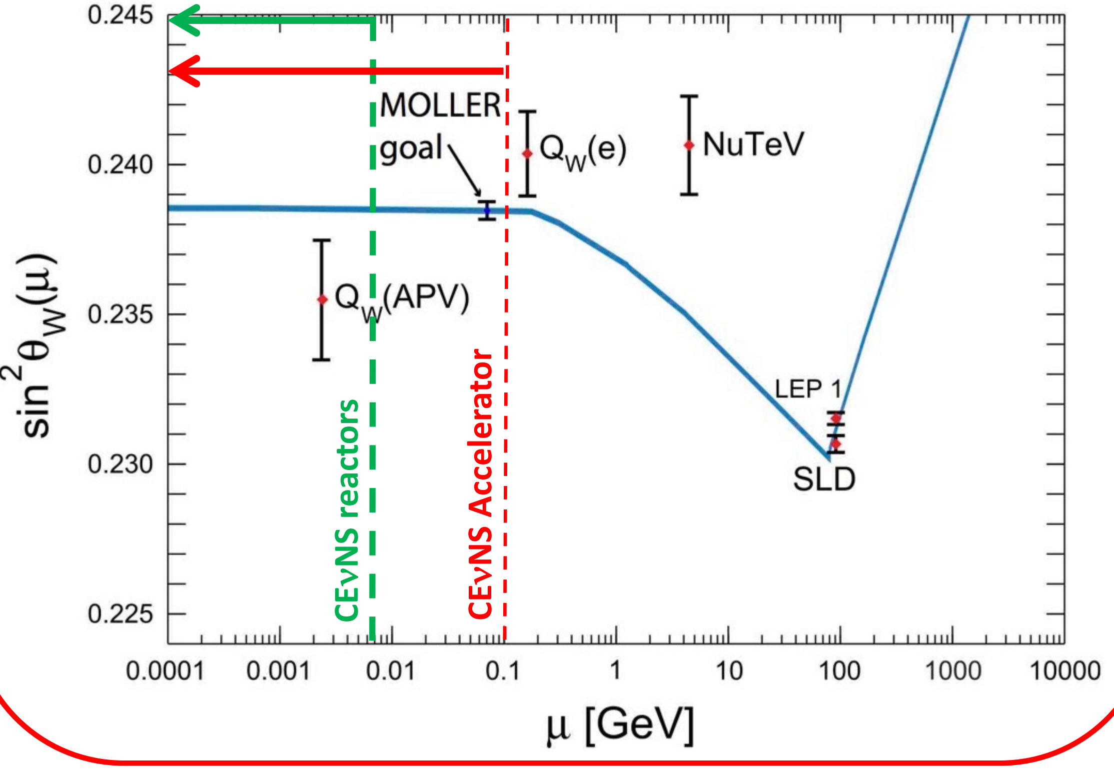
$$\frac{d\sigma}{dT} = \frac{M}{\pi} G_F^2 \mathcal{Q}^2(Z, N, \sin^2\theta_W) F^2(q^2) \left(1 - \frac{MT}{2E_\nu^2}\right)$$

Akimov et al. (2021)

New heavy mediators → neutrino NSI



EW sector at low E: weak mixing angle



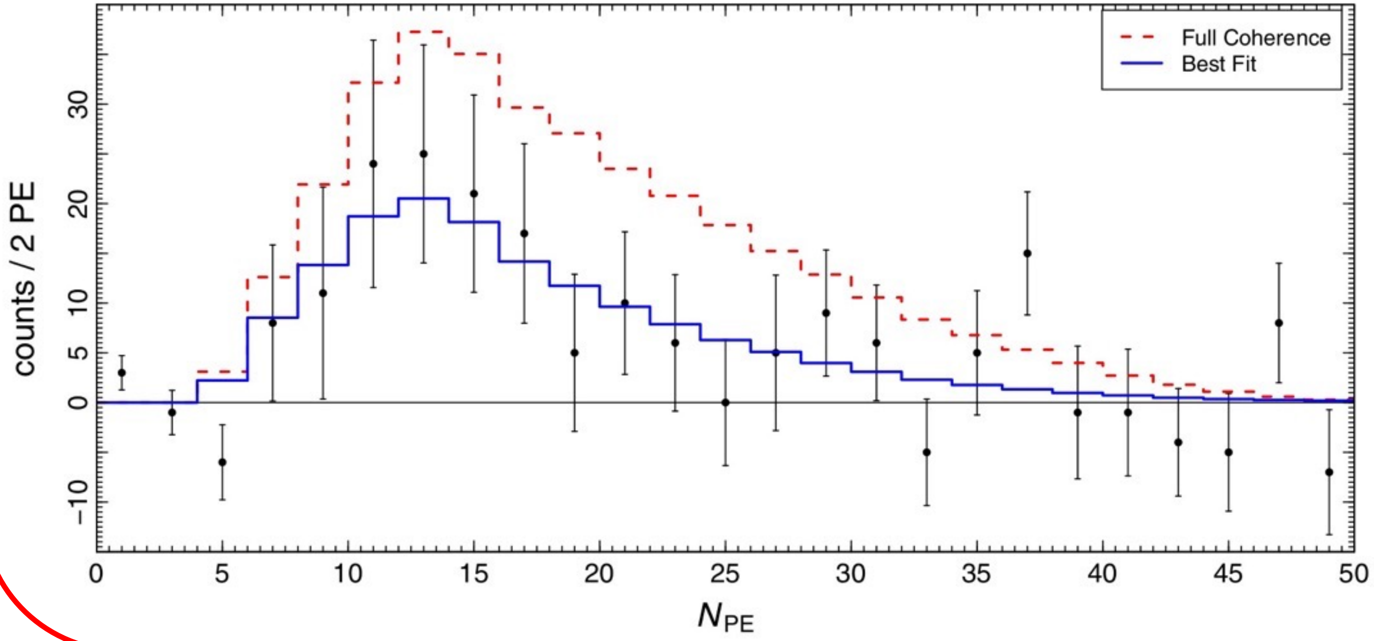
… and an expanding physics playground !

$$\frac{d\sigma}{dT} = \frac{M}{\pi} G_F^2 \mathcal{Q}^2(Z, N, \sin^2\theta_W) F^2(q^2) \left(1 - \frac{MT}{2E_\nu^2}\right)$$

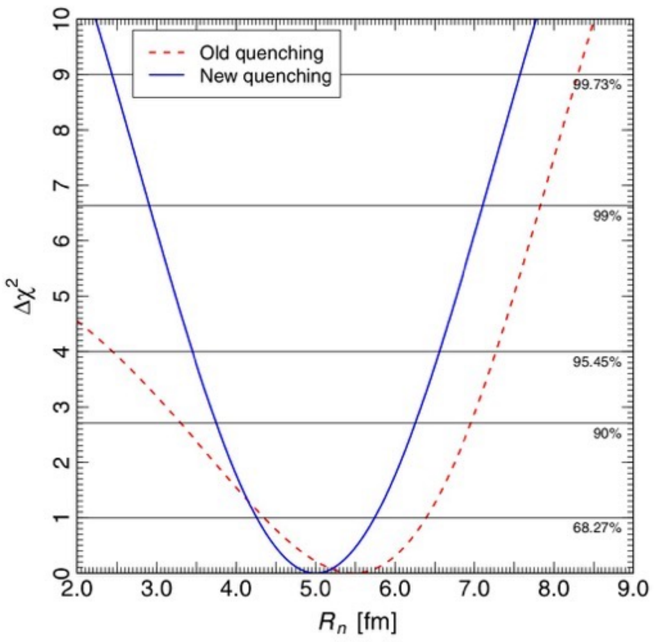
New insights into nuclear structure

Cadeddu et al., (2020)

Decoherence effect



Neutron rms radius

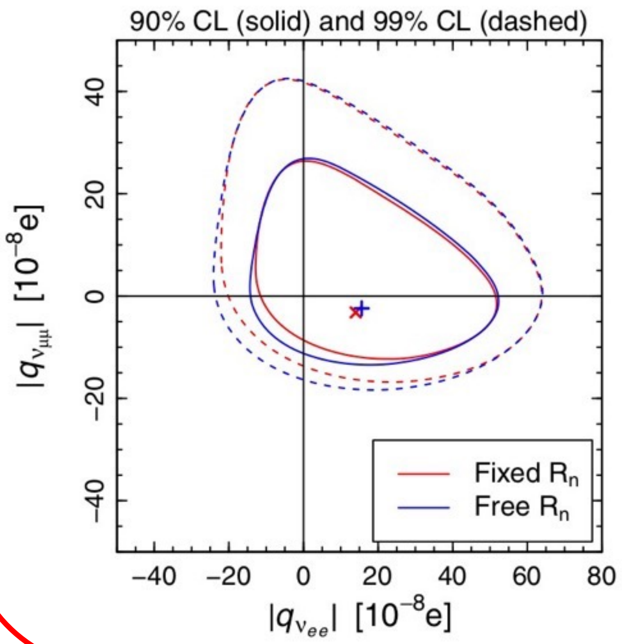


… and an expanding physics playground !

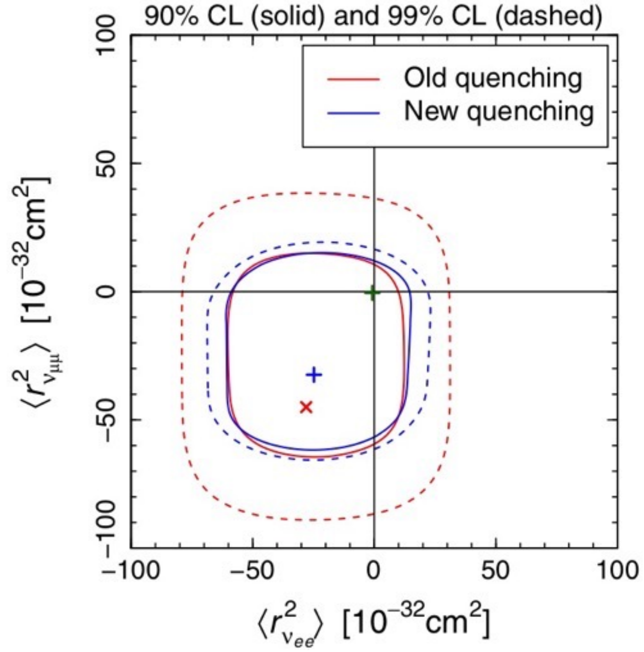
$$\frac{d\sigma}{dT} = \frac{M}{\pi} G_F^2 \mathcal{Q}^2(Z, N, \sin^2\theta_W) F^2(q^2)\left(1 - \frac{MT}{2E_\nu^2}\right) + \frac{\pi\alpha^2}{m_e^2}\left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 \left(\frac{\mu_{\nu_l}}{\mu_B}\right)^2$$

Neutrino electro–magnetic properties: portal to new physics

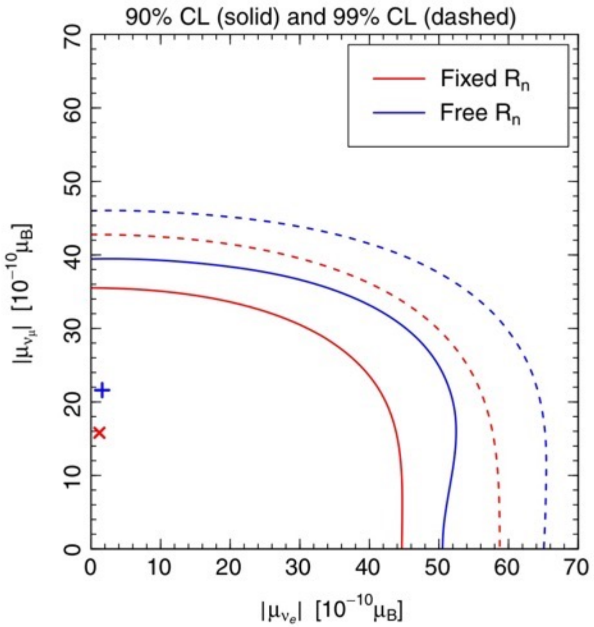
Charge



Charge radius



Dipole moment



Cadeddu et al., (2020)

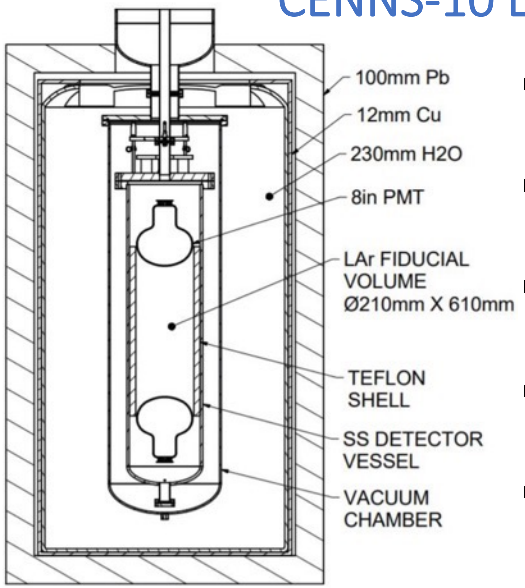
… and an expanding physics playground !

- Sterile neutrinos at the eV scale
- Light vector mediator Z' models, with connections to anomalous muon magnetic moment $(g-2)_\mu$
- Synergies with DM detection (neutrino floor)
- Miniaturization of setups applied to long range detection of neutrinos
  - Supernovae physics
  - New solar neutrinos programs
  - Reactor safeguarding, nuclear energy and non-proliferation
- …

COHERENT: present and future

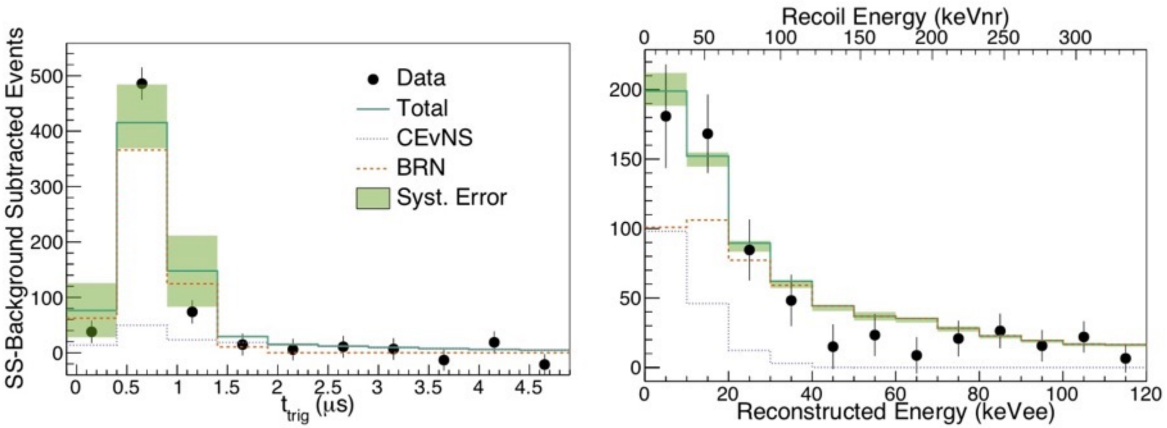
First detection on Ar

CENNS-10 LAr scintillation detector

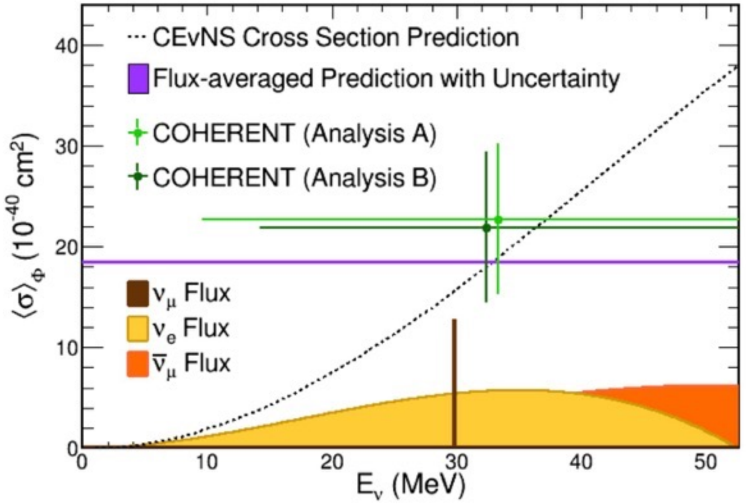


- 24 kg @ 27.5 m from SNS source
- H_2O + Cu + lead passive shield
- Data from 1st prod. run (2017–2018)
- Energy threshold ≈ 20 keV_{nr}
- Data taking continuing: 5σ detection expected soon

Akimov et al. (2021)



Within 1σ of SM pred.



$N_{CE\nu NS}$ = 159 ± 43 (stat.) ± 14 (syst.)

3.5σ significance

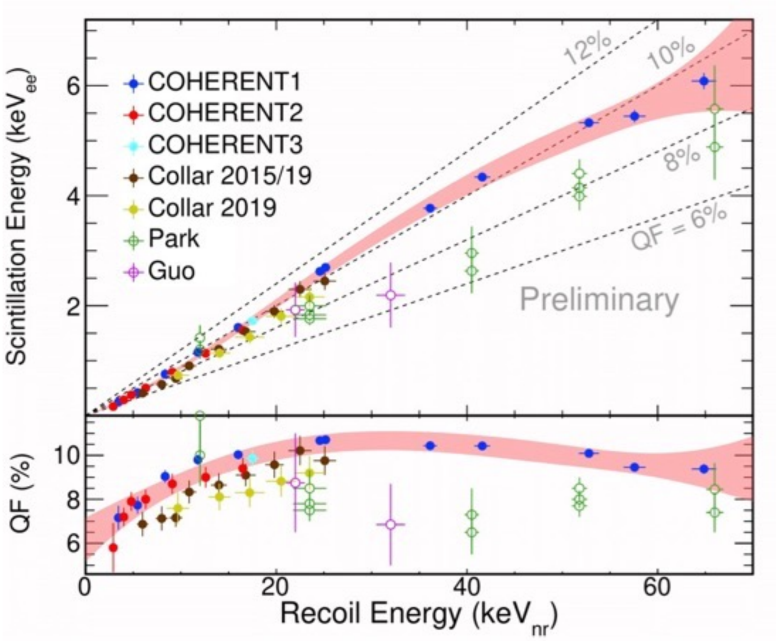
Breakdown of systematics

CEvNS Rate Measurement Systematic Errors	
Error Source	Total Event Uncertainty
Quenching Factor	1.0%
Energy Calibration	0.8%
Detector Model	2.2%
Prompt Light Fraction	7.8%
Fiducial Volume	2.5%
Event Acceptance	1.0%
Nuclear Form Factor	2.0%
SNS Predicted Neutrino Flux	10%
Total Error	13.4%

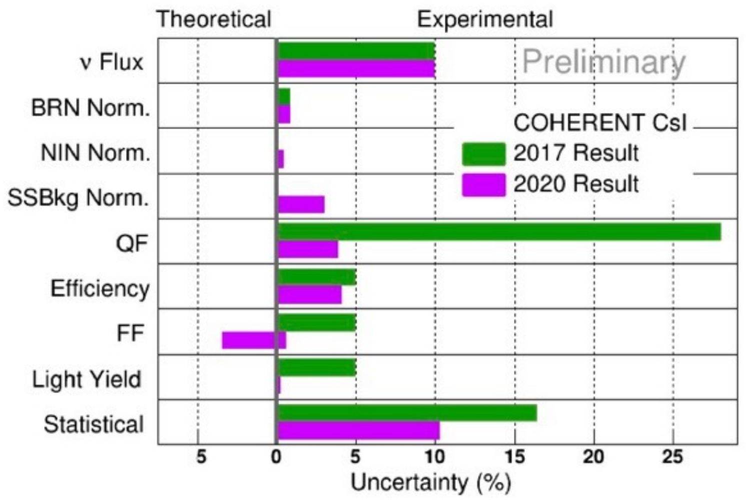
CsI[Na] setup: new results

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

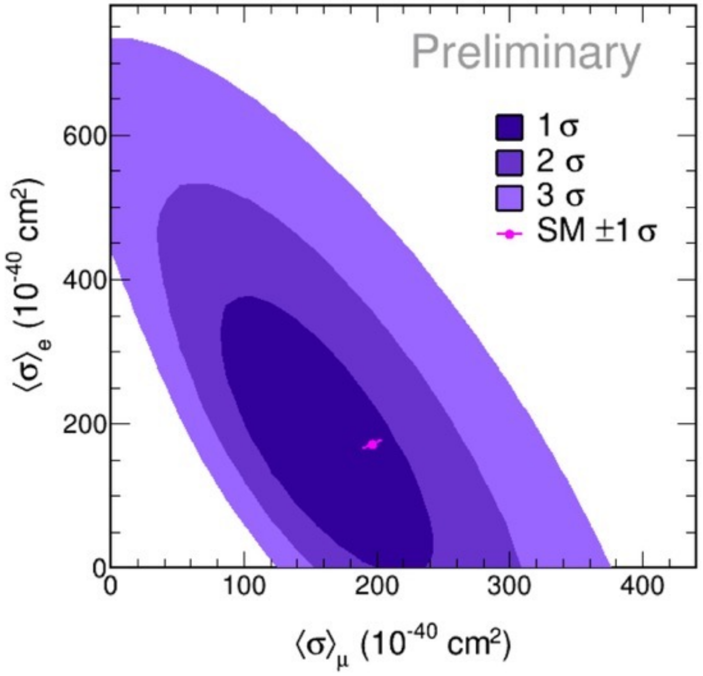


No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\text{th}) \pm 42(\text{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

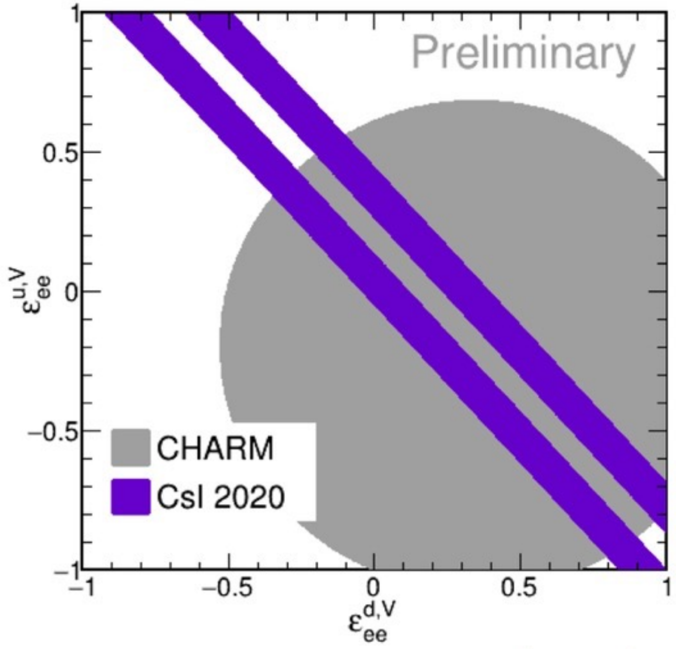
CsI[Na] setup: new constraints on NSIs

$$\mathcal{Q}^2(\mathrm{N},\mathrm{Z}) = \left[\mathrm{N} - (1 - 4\sin^2\theta_\mathrm{W})\right]^2 \rightarrow \mathcal{Q}^2_{\mathrm{NSI}} = 4\left[\mathrm{N}\,(-\frac{1}{2} + \epsilon^{\mathrm{uV}}_{\mathrm{ee}} + 2\epsilon^{\mathrm{dV}}_{\mathrm{ee}}) + \mathrm{Z}\,(\frac{1}{2} - 2\sin^2\theta_\mathrm{W} + 2\epsilon^{\mathrm{uV}}_{\mathrm{ee}} + \epsilon^{\mathrm{dV}}_{\mathrm{ee}})\right]^2$$

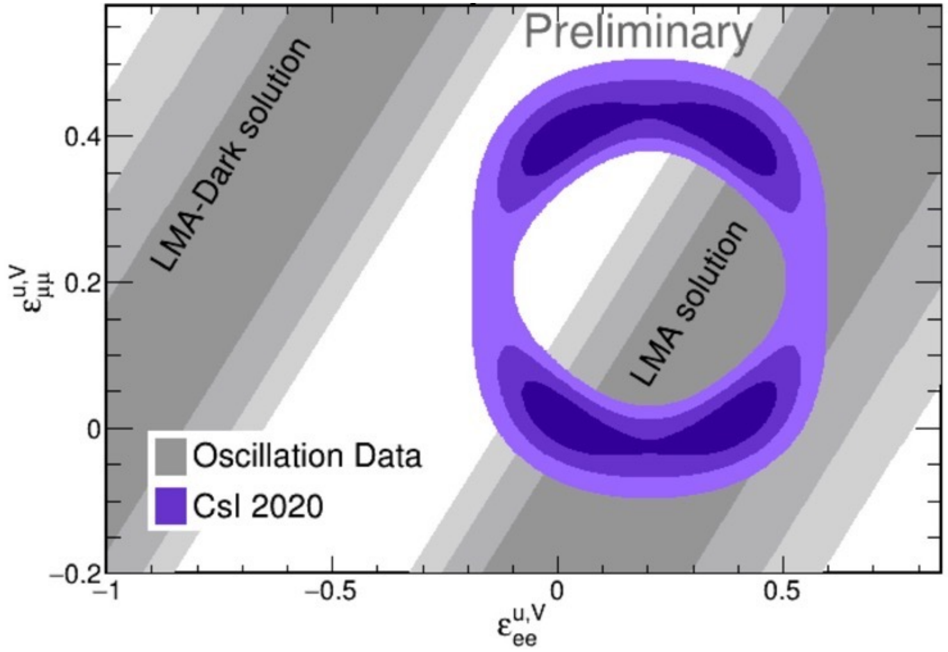
Flavored CEvNS?



NSI constrains

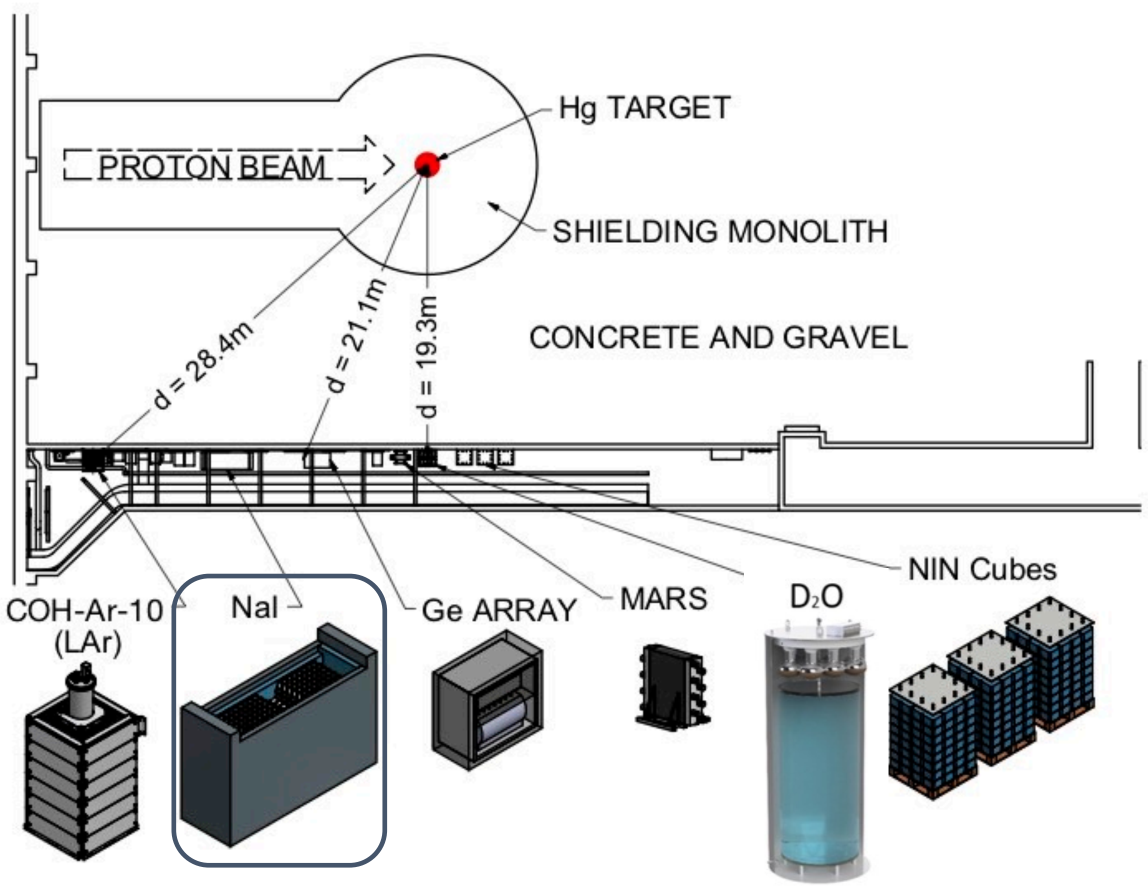


Tension with LMA-Dark solution

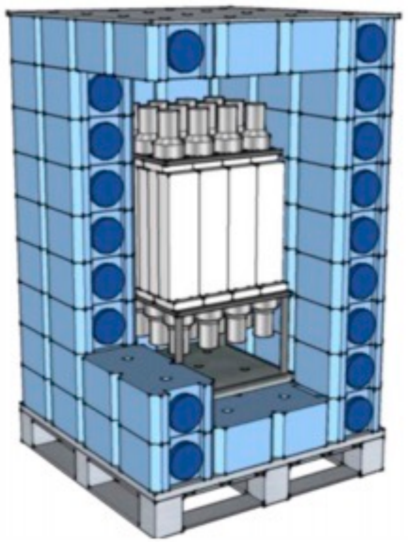


See also Caddedu et al. (2017)

New setup commissioning: COH-NaI-2

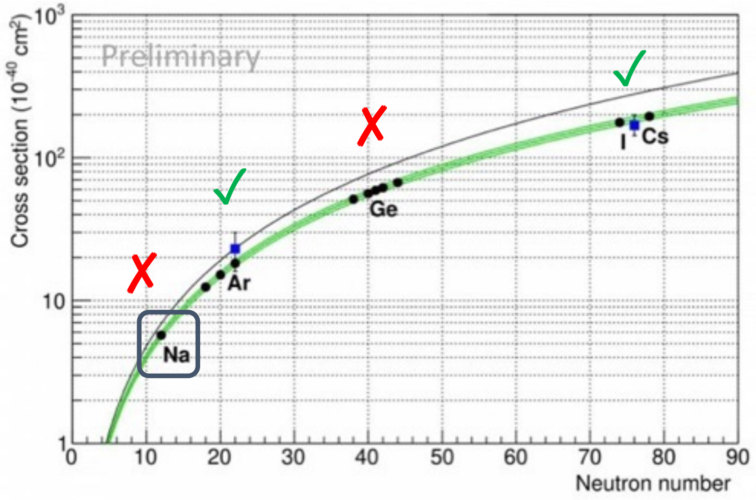


Multi–ton NaI[Tl] array

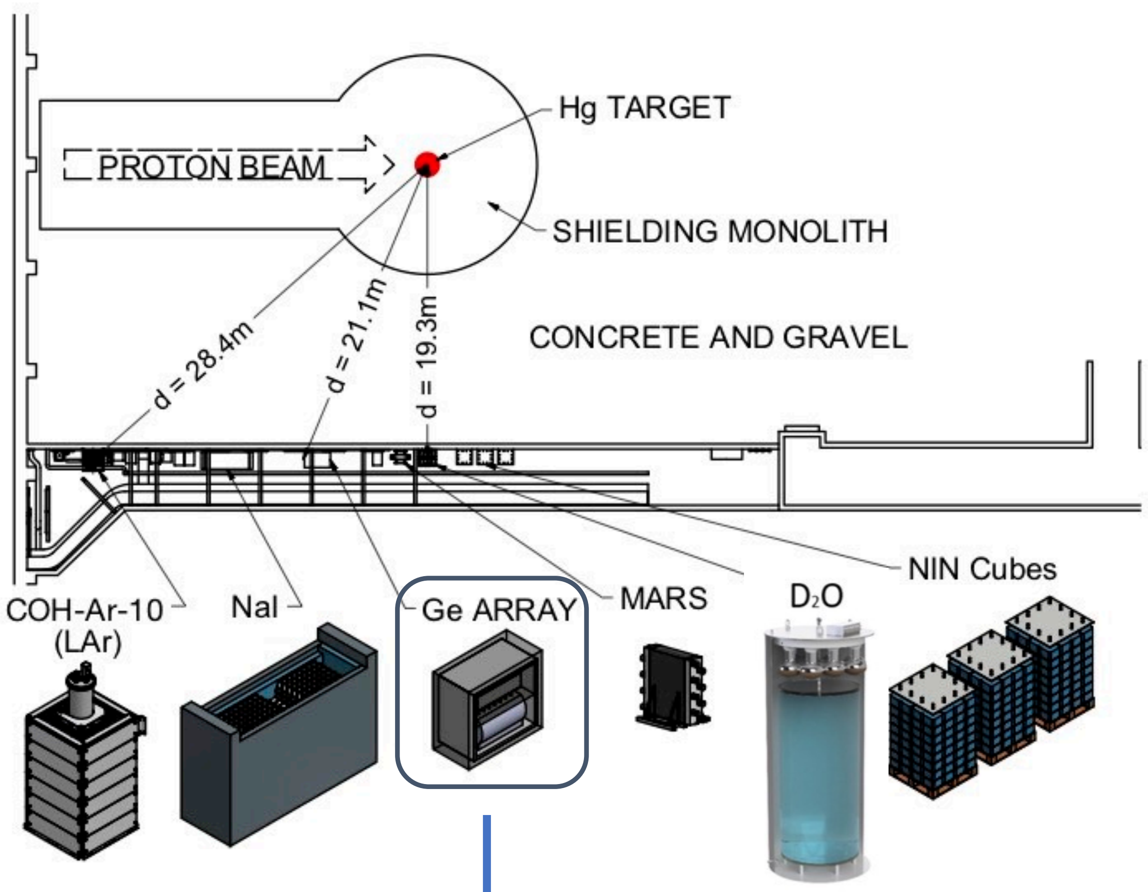


- 185–kg NaI scintillator setup running since end of 2017
- Primary goals of characterizing bck and measuring CC on ^{127}I
- R&D effort to upgrade for a ton–scale detector and conduct CEvNS program

Continuing physics run + R&D work for a future upgrade



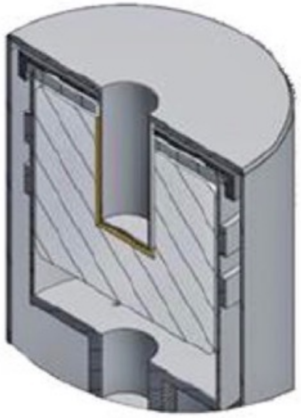
New setup commissioning: COH-Ge-1

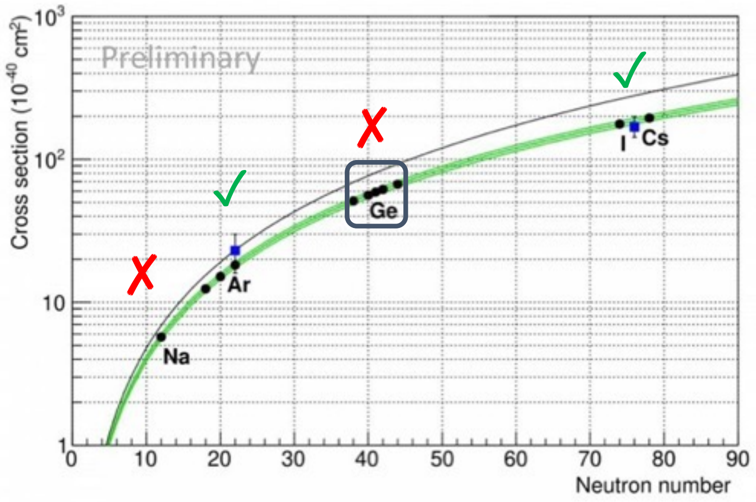


Commissioning early 2021

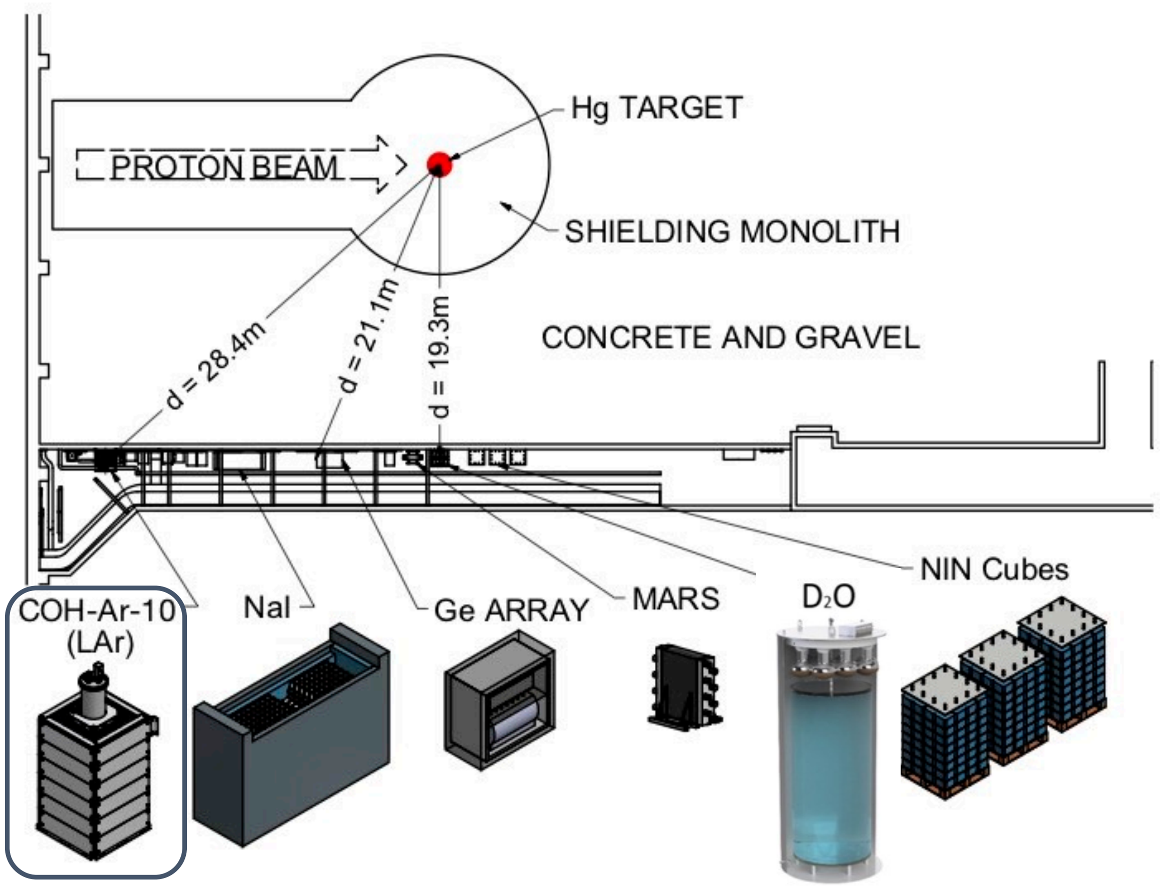
Detection on Ge

- Array of p–type point contact HPGe detectors
- 8 detectors > 2 kg each
- ~ 500 evt/y with E_{th} > 0.3 keV_{ee}





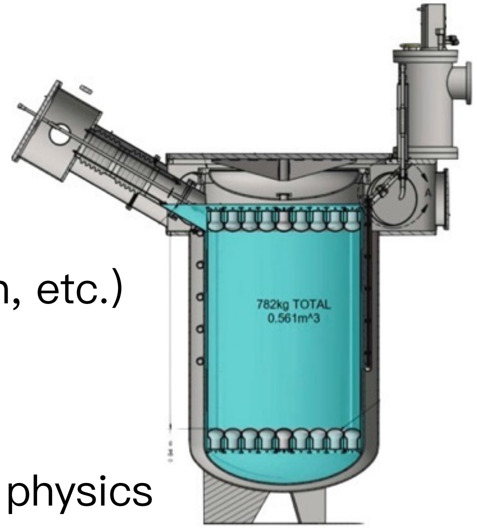
COHERENT future: liquid Ar program

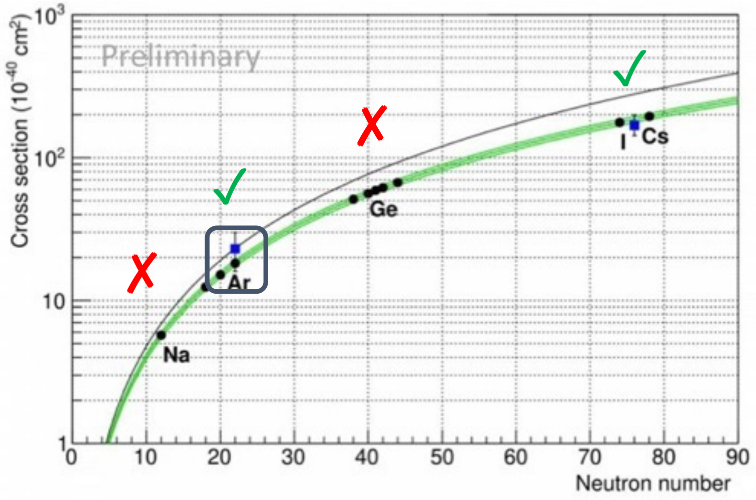


Further data to be analyzed + setup improvements + R&D work for COH–Ar–750 upgrade

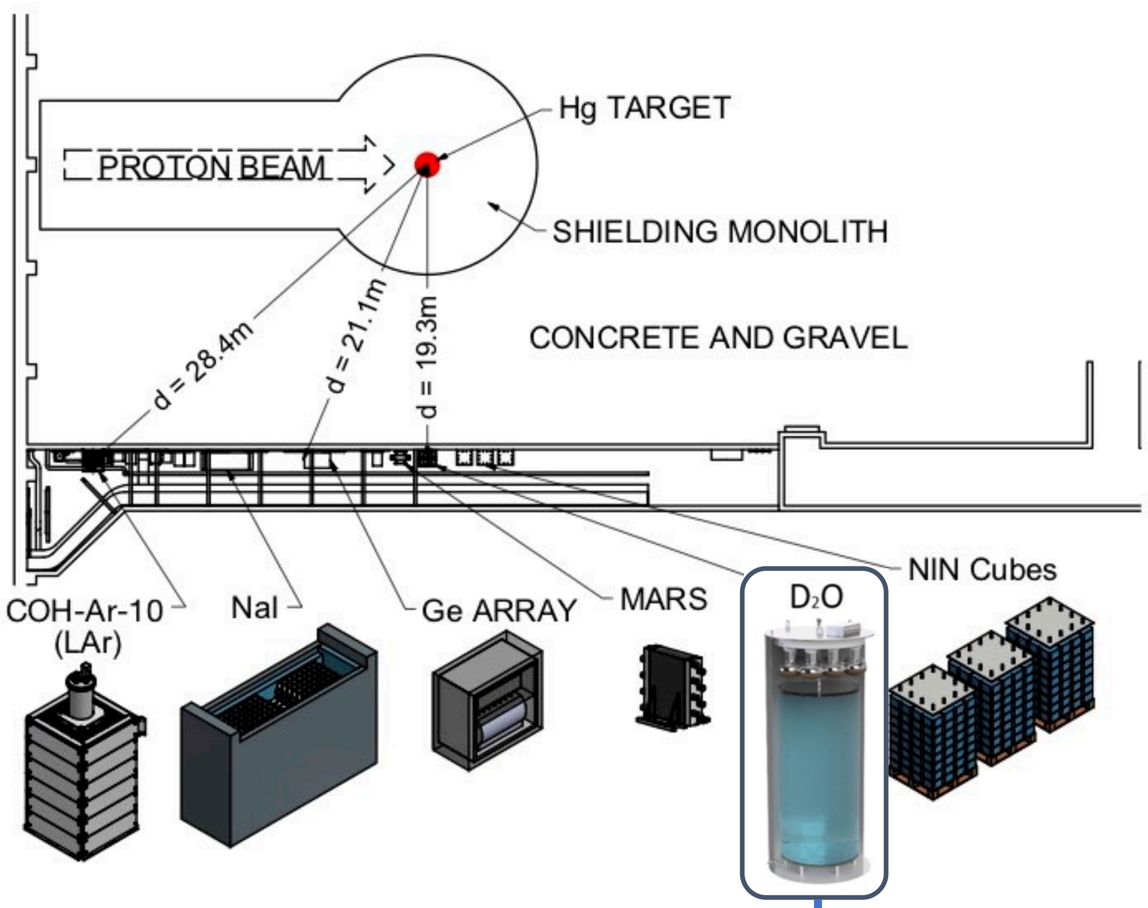
Detection on Ar: LAr–750 upgrade

- Builds on CENNS–10 expertise
- 750/610 kg total/fiducial mass
- R&D work on–going (light collection, etc.)
- ~ 3000 CEvNS/yr (~20 keV_{nr} thr.)
- Extended program of BSM and DM physics





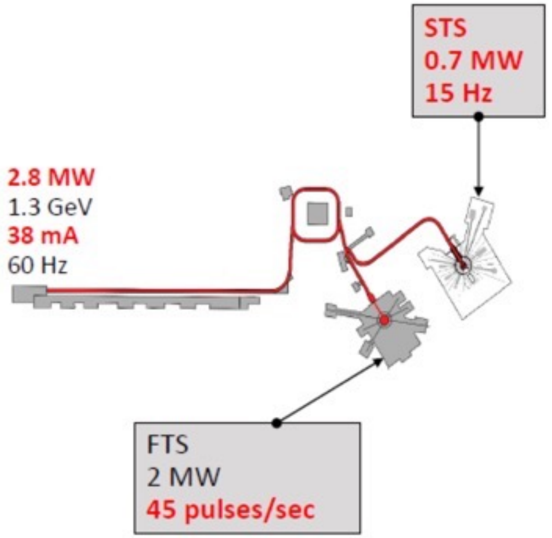
COHERENT future: beam upgrades



Rapp et al. (2019)

$$\nu_e + d \rightarrow p + p + e^-$$

- Beam power upgrade in 2024: 1.4 MW → 2 MW
- Second target station (2028) with a ~10 m baseline
  - ~ twice increase in ν luminosity
  - Space for larger setups



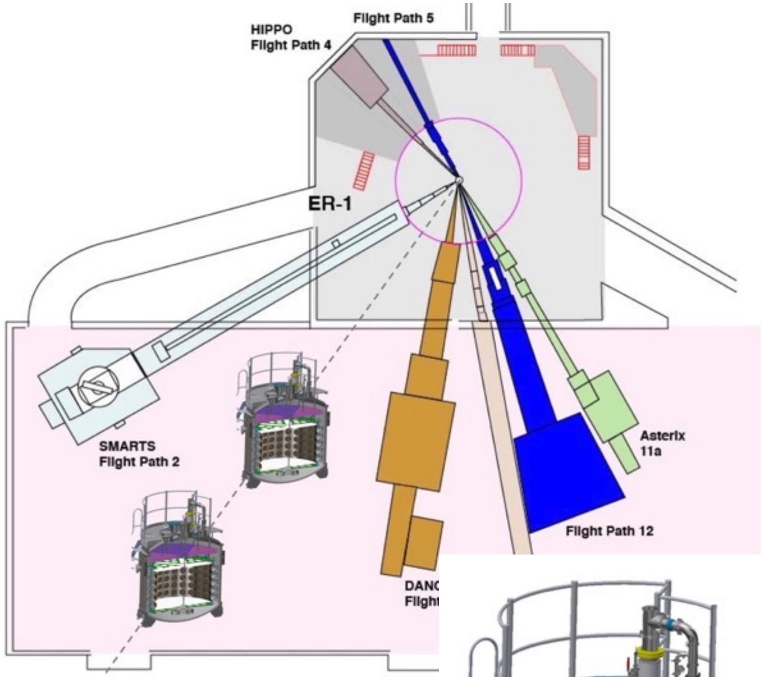
- Monitoring with D_2O detector planned (< 2024)

  → Target flux unc. at the few percent level

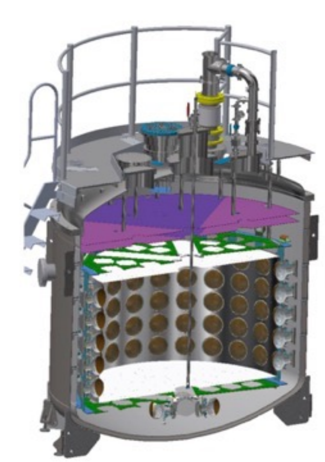
Other efforts at accelerator facilities

Coherent CAPTAIN-Mills at LANL

Los Alamos Neutron Science Center (LANSCE)



- 800 MeV p^+ on W target
- 20–Hz pulsed, 100 kW
- Flux: 5 x 10^5 ν cm^{-2} s^{-1} at 20 m



LAr scintillating detector

- DM detection + LSND anomaly test through CEvNS
- 7–t detector commissioned and successfully operated for a couple of months (CCM120)
- External and beam–related backgrounds (BRBs) studies + shielding optimization
- Upgrade phase
  - Improve PMT coverage and LAr LY (purification) → 10/20 keV_{NR} threshold
  - New shielding
  - Beam tuning: pulse width ↓ to clean RoI from BRBs

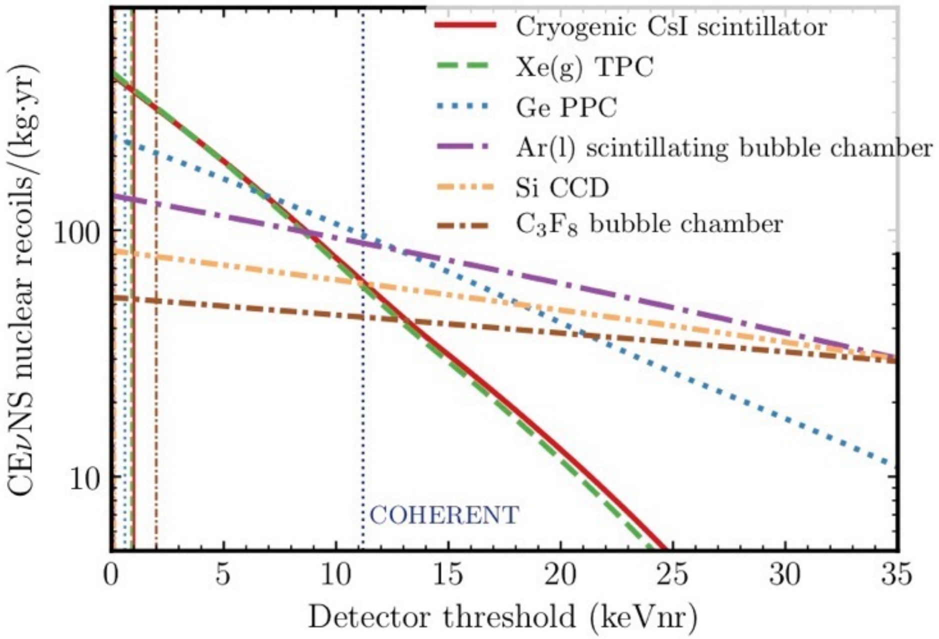
Aguilar–Arevalo et al., (2021)

Prospects for CEvNS at the ESS

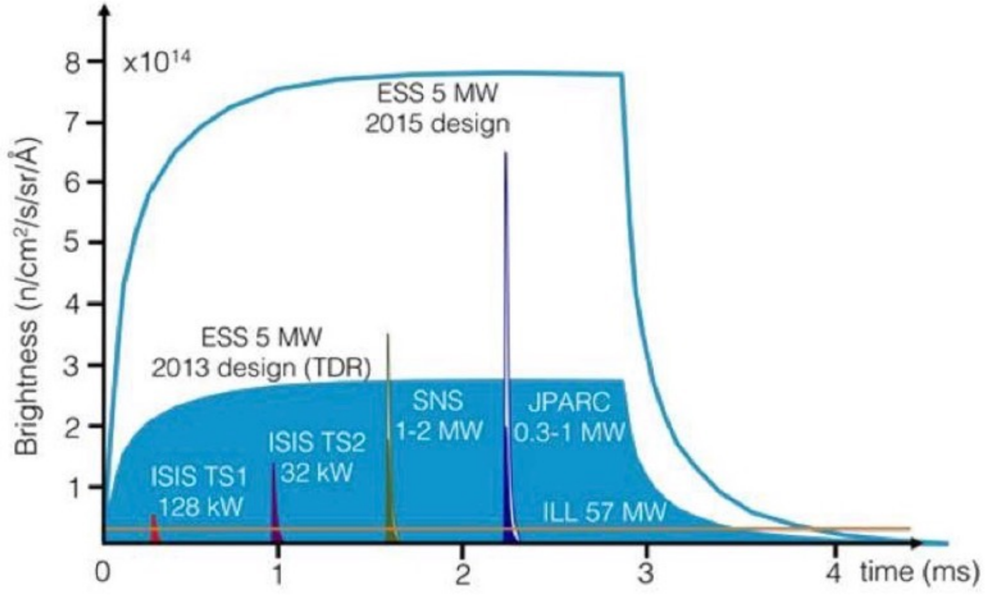
- COHERENT–like exp. strategy → multiple setups
- Overcome statistics limitation from SNS → ESS

Baxter et al. (2020)

Deploy low threshold, state-of-the-art detectors



Large neutrino flux (~ 1 order of magnitude > SNS)



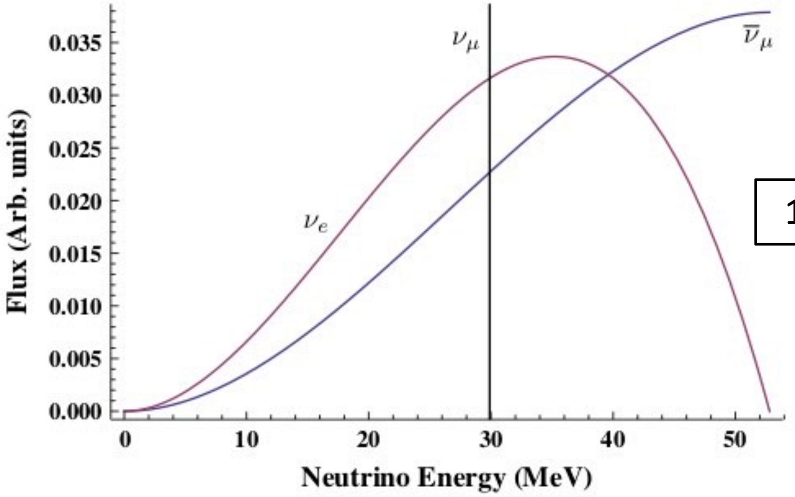
Online ~ 2023

- First discussions with ESS facility started.

Detection at reactors: the next challenge…

Stopped-pion vs reactor neutrino sources

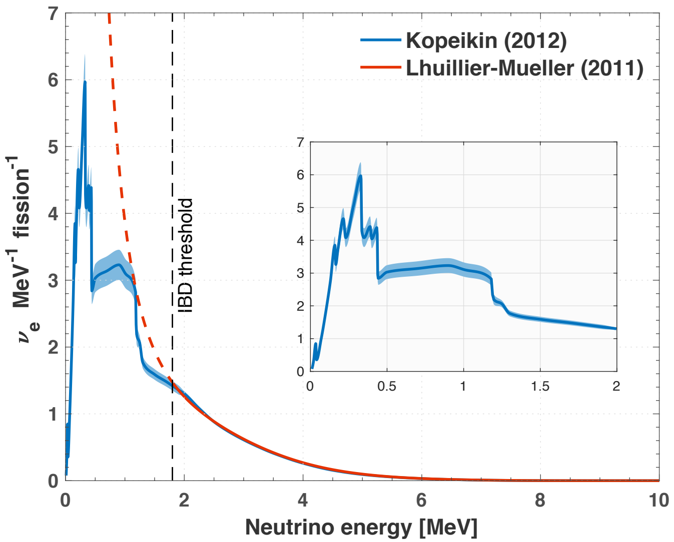
Low energy neutrinos from accelerators



10^7-10^8 cm^{-2} s^{-1}

- Pion–decay–at–rest (DAR) sources → multiple flavors
- Pulsed sources → high bck discrimination through timing
- Nuclear recoil energies ⩾ 1–10 keV + not fully coherent
- High cross–section

Reactor antineutrinos

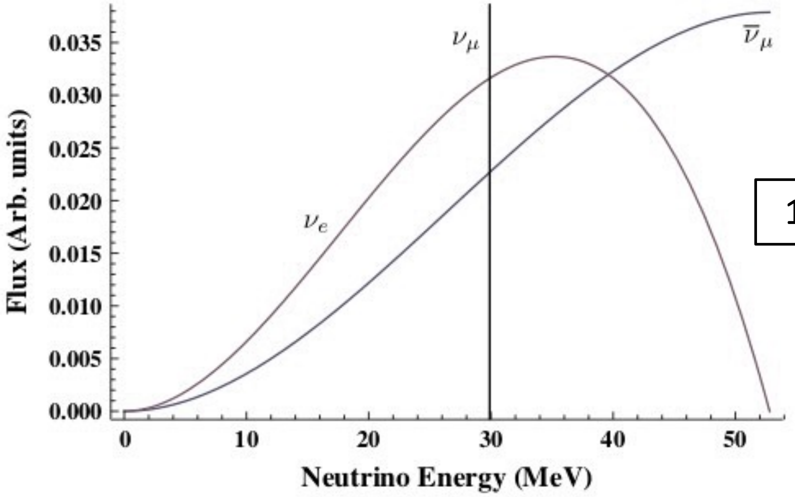


10^{12}-10^{13} cm^{-2} s^{-1}

- Nuclear fission → single (electronic) flavor
- Continuous source → duty cycle important for bck mitigation
- Nuclear recoil energies ⩽ 1 keV + fully coherent
- Lower cross–section, compensated by much higher flux though (depending on your threshold…)

Stopped-pion vs reactor neutrino sources

Low energy neutrinos from accelerators



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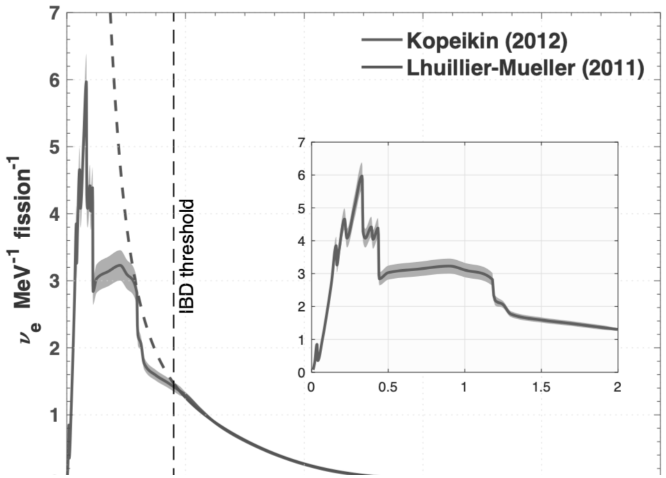


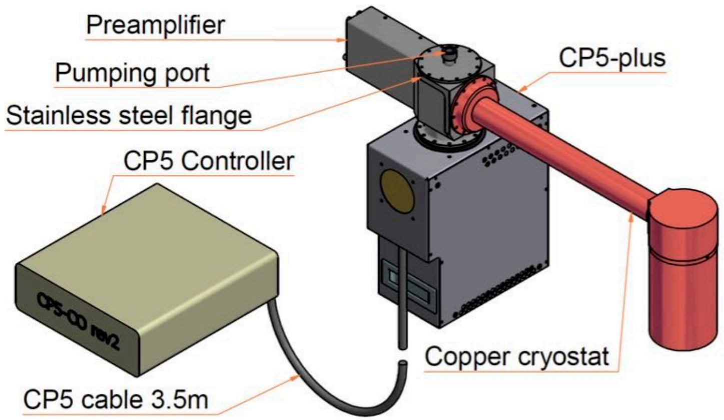
10^{12}-10^{13} cm^{-2} s^{-1}

→ **BIGGER CHALLENGES !**

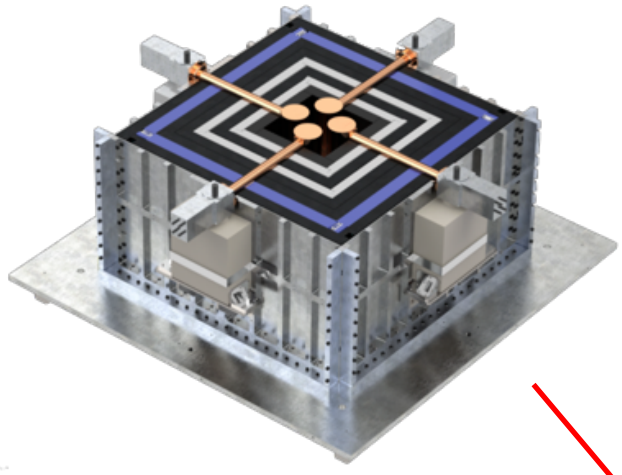
- Continuous source → duty cycle important for bck mitigation
- Nuclear recoil energies ⩽ 1 keV + fully coherent
- Lower cross–section, compensated by much higher flux though (depending on your threshold…)

Achievements from CONUS

4 x 1-kg p-type point contact HPGe (ionisation detectors)



Passive & active shields

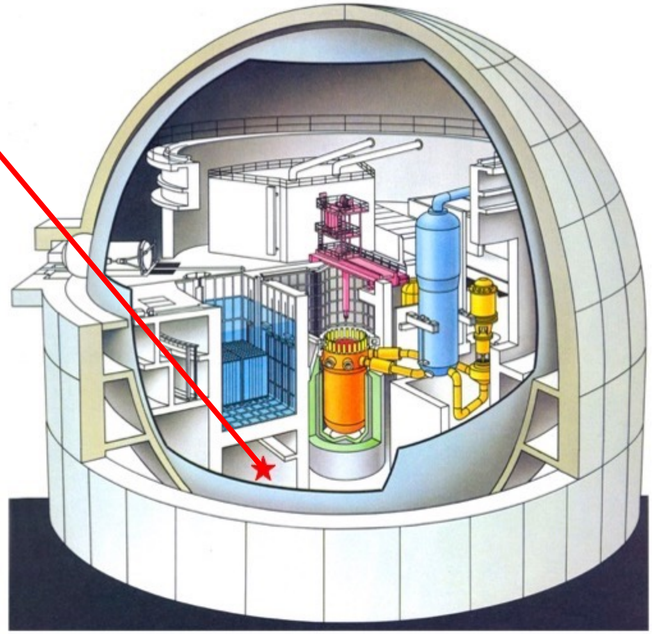


Brokdorf reactor (Germany)

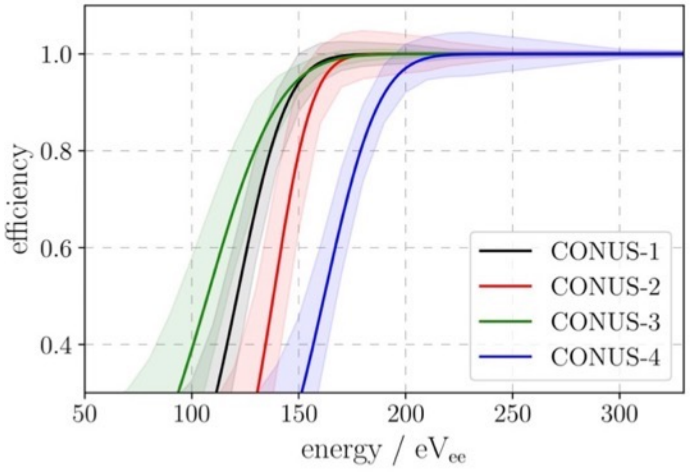
- D = 17 m
- P_{th} = 3.9 GW_{th}

} ~ 2 x 10^{13} cm^{-2} s^{-1}

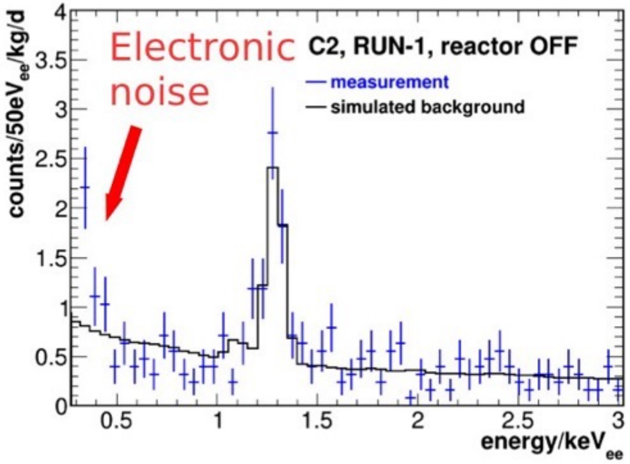
- Overburden = 10 → 45 m w.e



~ 200 eV_{ee} threshold

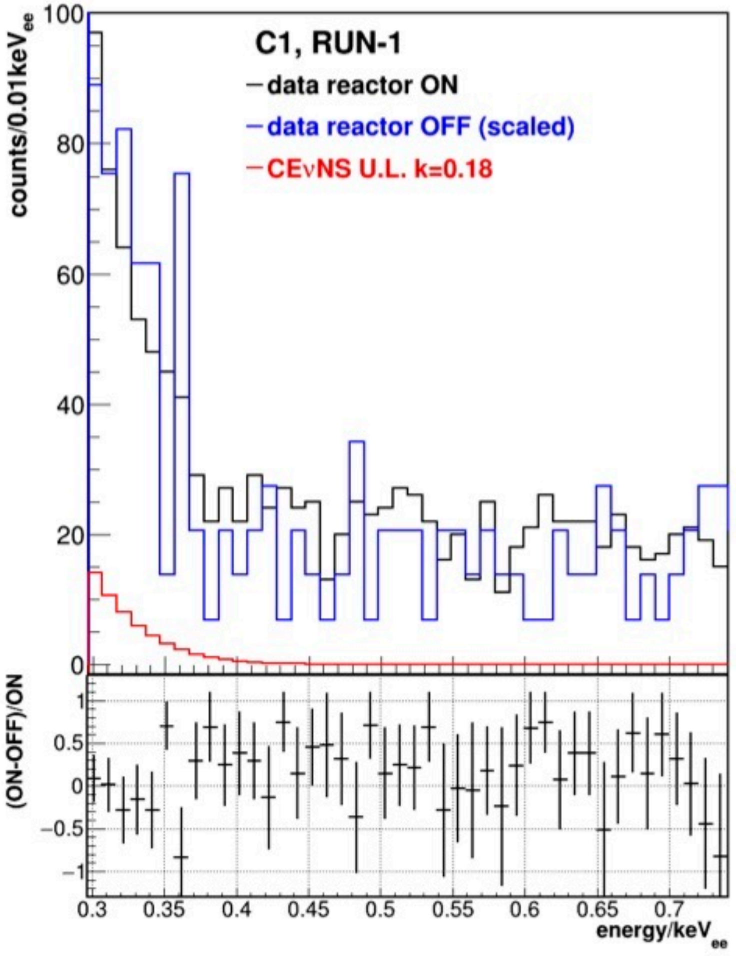


10^4 bck suppression → 10 dru @ 1 keV !



CONUS: latest results

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

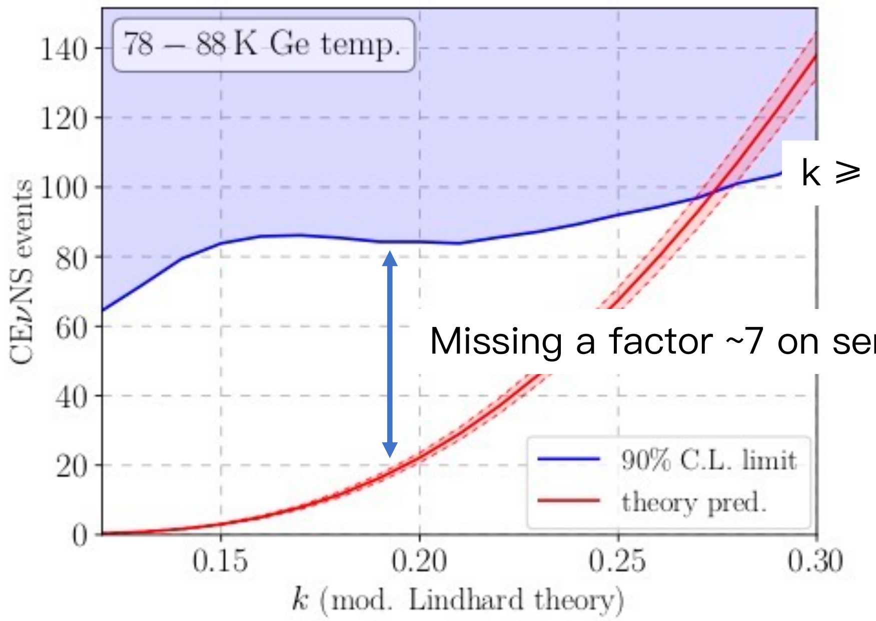


Bonet et al. (2021)

X 4

250/60 kg.d
ON/OFF data

Quenching matters !



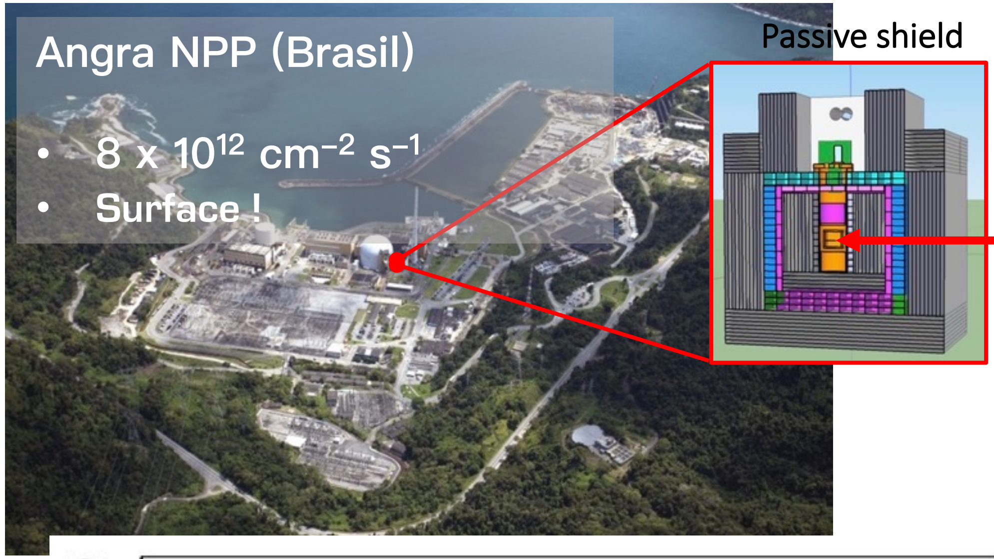
k ⩾ 0.27 excl.

Missing a factor ~7 on sensitivity…

Perspectives

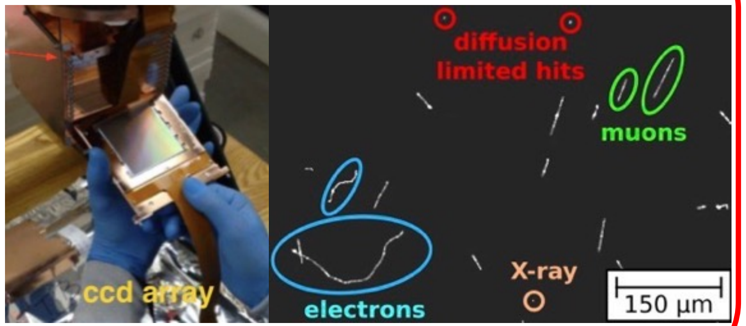
- New data + shutdown of KBR > 2021 → stat. unc ↓
- Improved analysis techniques → bck ↓ → sensitivity ↑

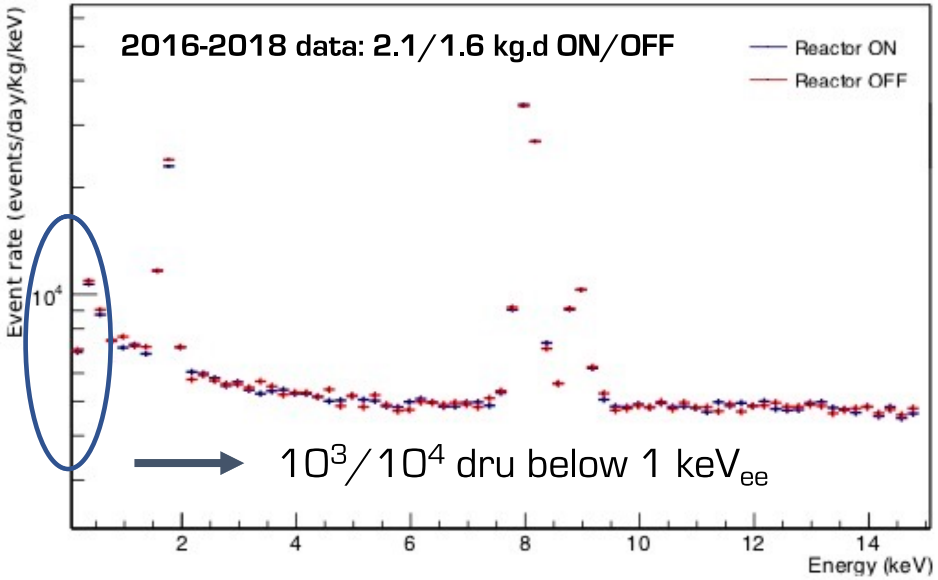
Achievements from CONNIE



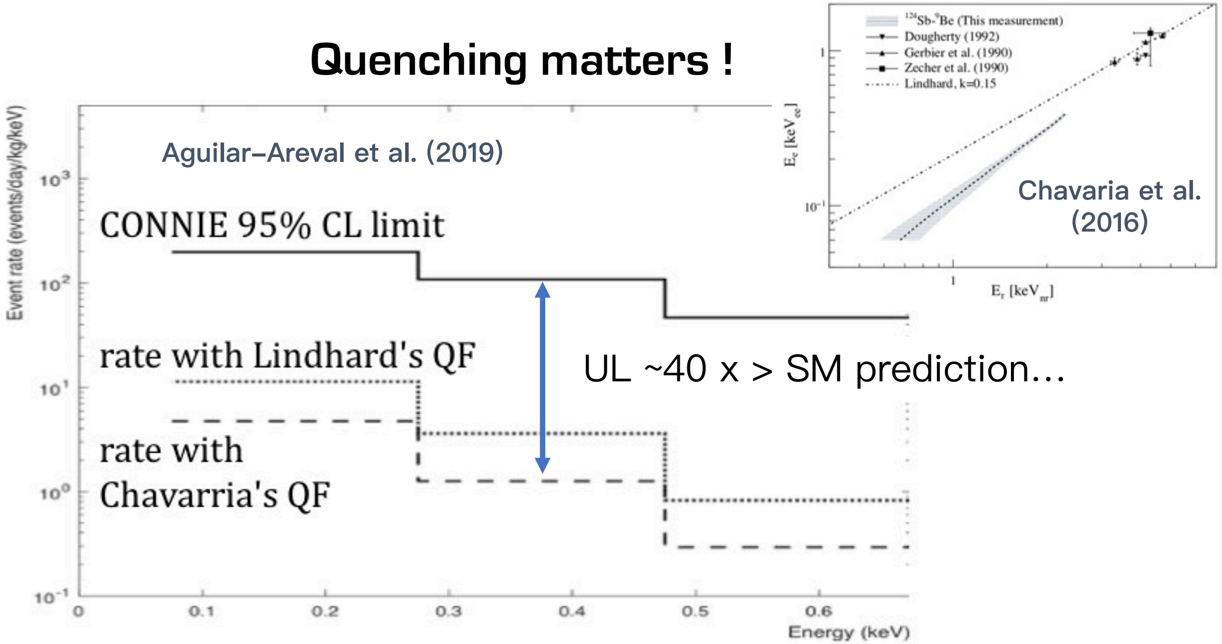
Mpixels Si CCD array

- Particle id.
- ~40 eV_{ee} threshold
- Total mass ~ 70 g
- Very slow det. (no μ veto !)





Quenching matters !



Future of CONNIE

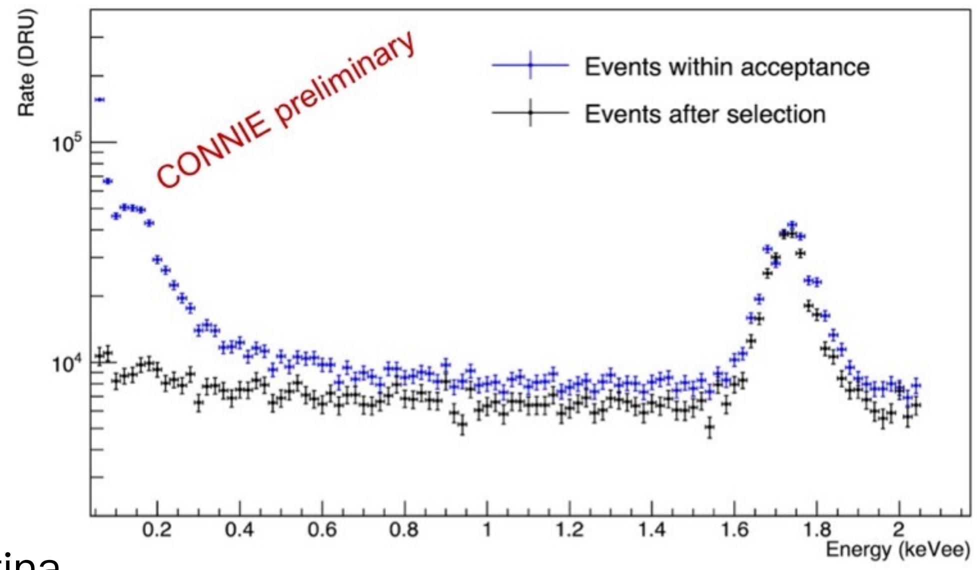
- New data (2019–2020) with many improvements in the analysis

  → Unblinding of the ON data (1.5 kg.d) soon

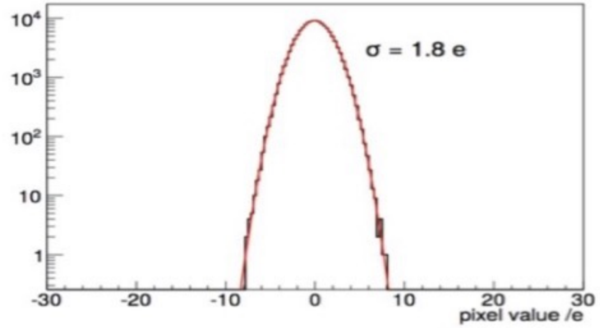
- Upgrade to a new readout system in 2021: **Skipper CCDs**
  - Multiple sampling of CCD pixels to reduce noise
  - Possibility to detect single e^-
  - **Reduce threshold down to 7 eV_{ee} !**

- νIOLETA → SBL CEvNS program with kg-scale Skipper CCDs in Argentina

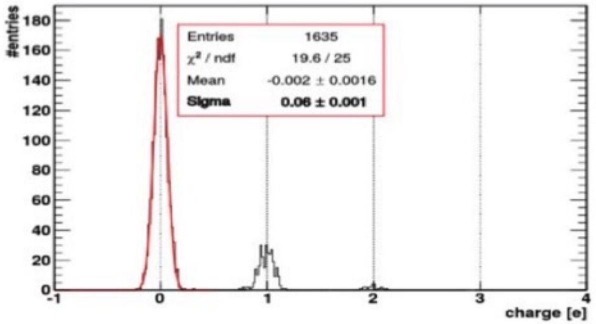
2019-2020 OFF data: 1.35 kg.d

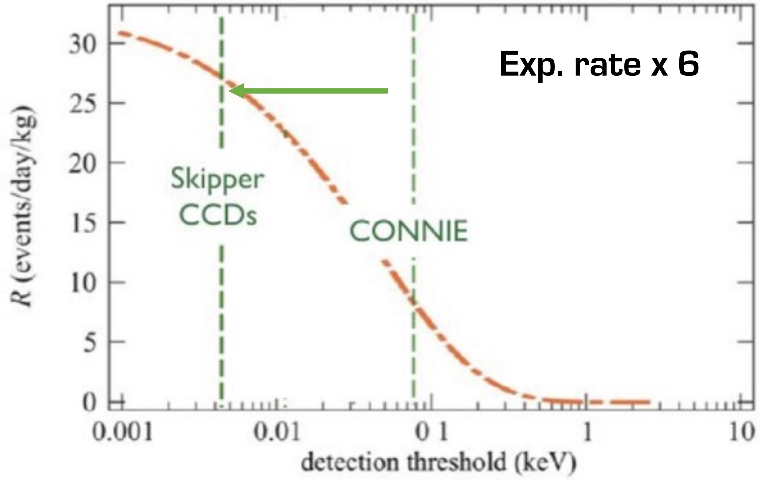


Standard

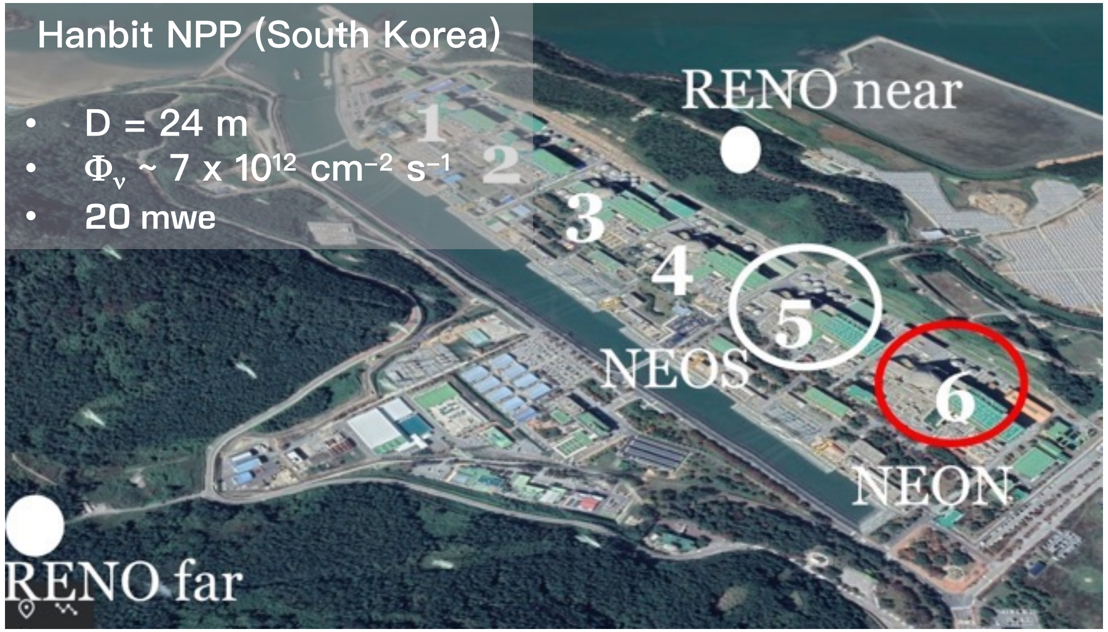


Skipper

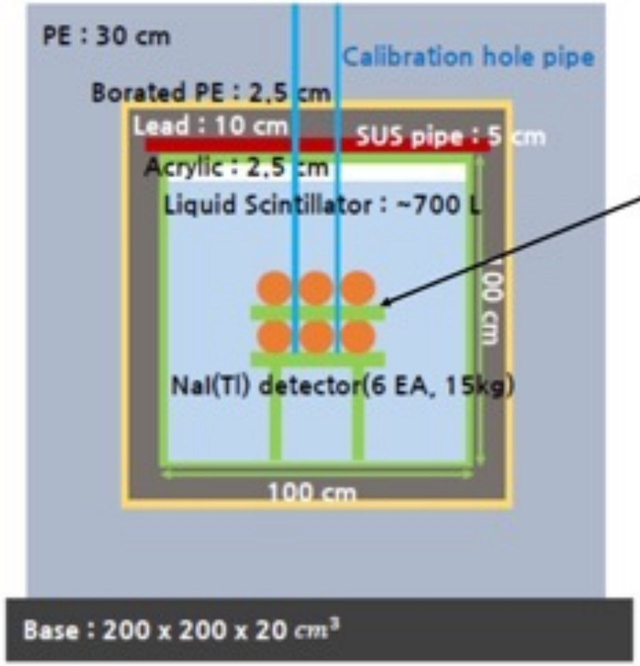




About to start physics run: NEON



NEON setup



- Ultra–pure **NaI scintillation crystals** (from COSINE DM exp.): 15 kg
- Optimized to reach low threshold → ~ 0.2–0.3 keV_{ee}
- QF needs to be characterized, prob. k ≲ 0.1–0.2 → E_{th} ~ 1–3 keV_{NR}
- Passive shield + active LS veto → ~ 10 dru ≲ a few keV
- Installation & commissioning at HNPP, data taking on–going (up to 2022) → expect 3σ/yr (assuming flat bck.)

J.J. Choi et al. (2020)

About to start physics run: RED-100

RUSSIAN EMISSION DETECTOR

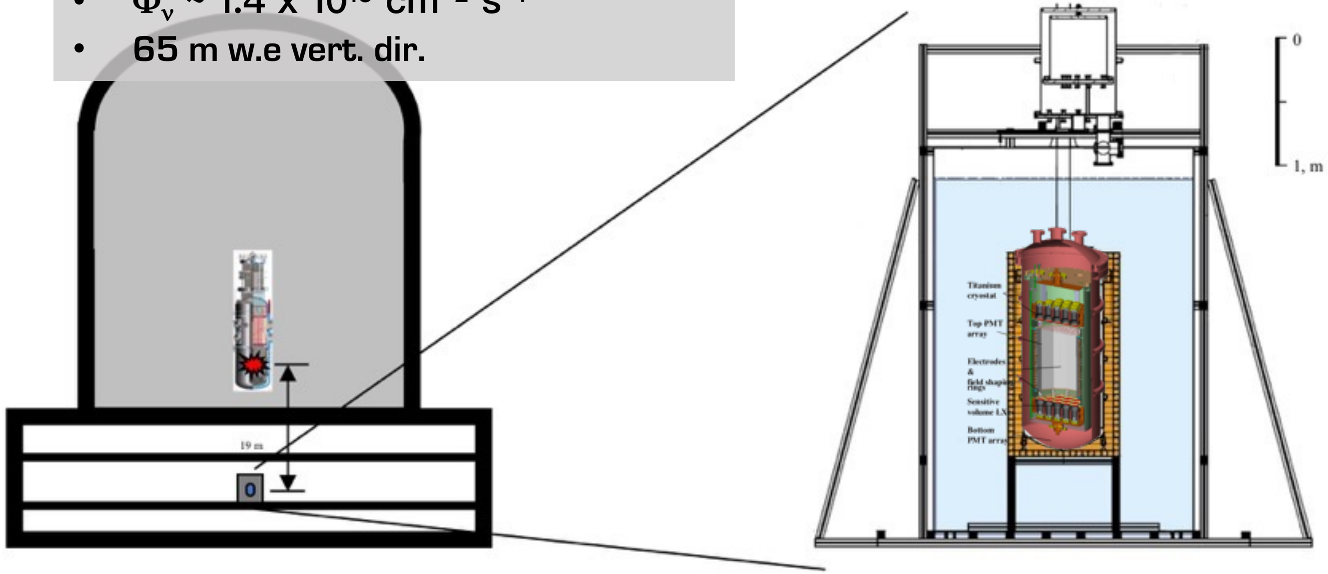
- **Dual-phase Xe TPC**, developed and tested at MEPHI: 200 kg (100 kg fiducial mass)
- Optimized to reach low threshold with single ionization e⁻ (SE) detection capabilities
- Bck. characterization at KNPP nearly finished → passive shield only (5–cm Cu + 60–cm H_2O)
- Spontaneous emission of SEs → main source of bck
- Installation & commissioning at KNPP should be done.
- Data taking should have started this Spring.

Akimov et al. (2021)

Kalinin NPP (Russia)

- D = 19 m
- $\Phi_\nu \sim 1.4 \times 10^{13}$ cm^{-2} s^{-1}
- 65 m w.e vert. dir.

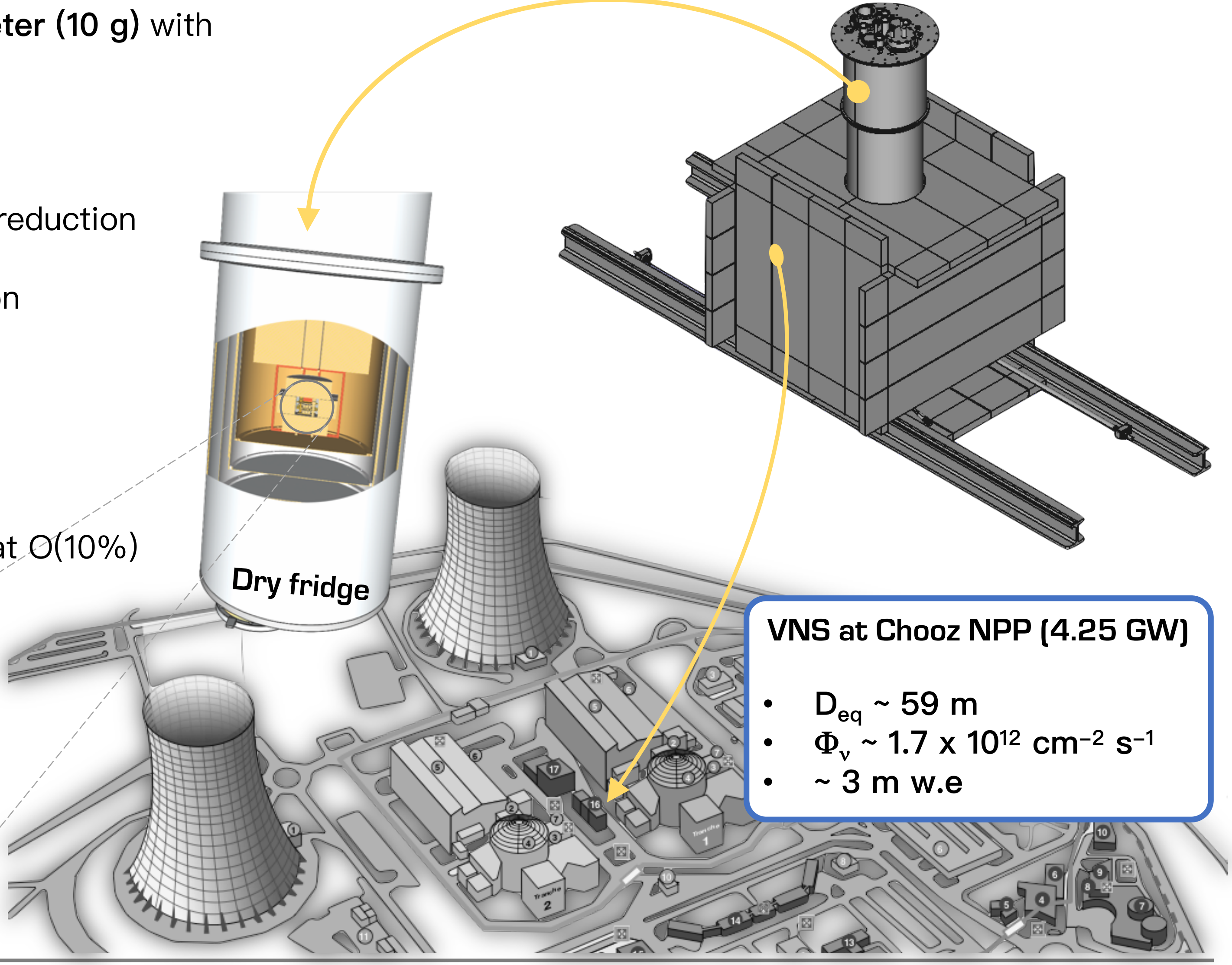
RED–100 setup



Bolometric detection: NUCLEUS

- Cryogenic detectors at commercial reactors (Chooz NPP):
  - ➢ Array of $CaWO_4/Al_2O_3$ **gram-scale cryogenic calorimeter (10 g)** with low threshold: **20 eV demonstrated !**
  - ➢ Phonon readout only → **no quenching !**
  - ➢ Cryogenic Si and Ge **vetoes** → internal + external bck reduction
  - ➢ Compact muon veto system → μ-induced bck reduction
- Staged approach:
  - ➢ End of 2021: commissioning at TUM – bck. run
  - ➢ End of 2022: Chooz NPP – 1st physics run → CEvNS at O(10%)
  - ➢ 2024: upgrade to kg-scale → CEvNS at ~% level

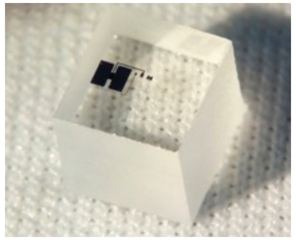
Angloher et al. (2019)

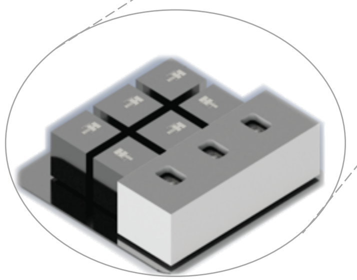


VNS at Chooz NPP (4.25 GW)

- D_{eq} ~ 59 m
- Φ_ν ~ 1.7 x 10^{12} cm^{-2} s^{-1}
- ~ 3 m w.e

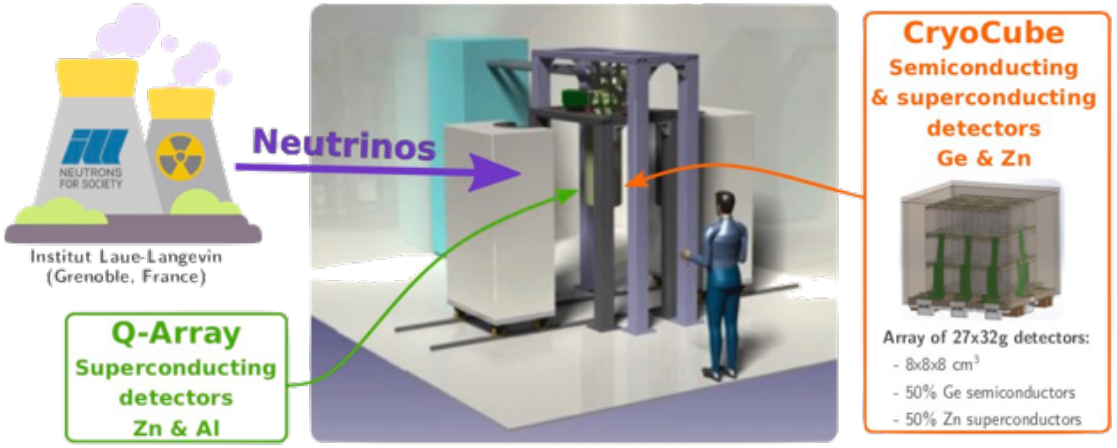
5 x 5 x 5 mm³

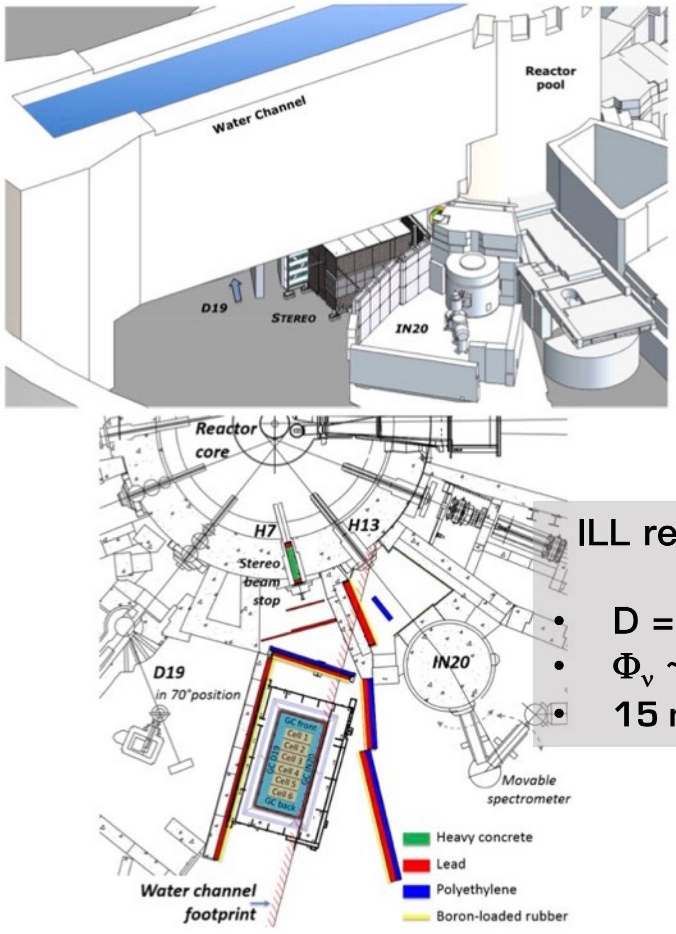




Strauss et al. (2017)

Bolometric detection: RICOCHET





Billard et al. (2017)

ILL research reactor (58 MW)

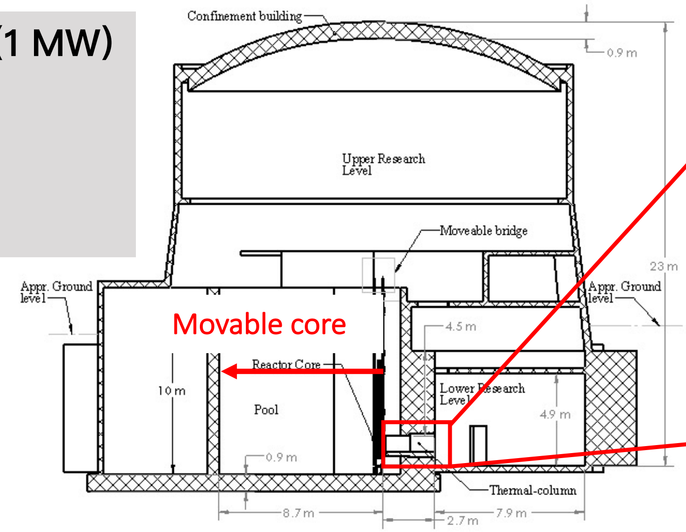
- D = 8 m
- Φ_ν ~ 1.6 x 10^{12} cm^{-2} s^{-1}
- 15 m w.e

- **EDELWEISS-style** 30-g Ge semiconductor:
  - ~60 eV thr. demonstrated with phonon-only (no quenching !)
  - LN electronics R&D to push ER/NR discr. down to 50 eV
- **New superconducting Zn & Al det.** with ER/NR discr.
- 1-kg payload → 20 cpd → 5σ detection in a couple of days
- Exp. site @ ILL characterized (STEREO) + shielding design on-going → **high level of reactor-correlated bck**
- Deployment and physics run by 2023

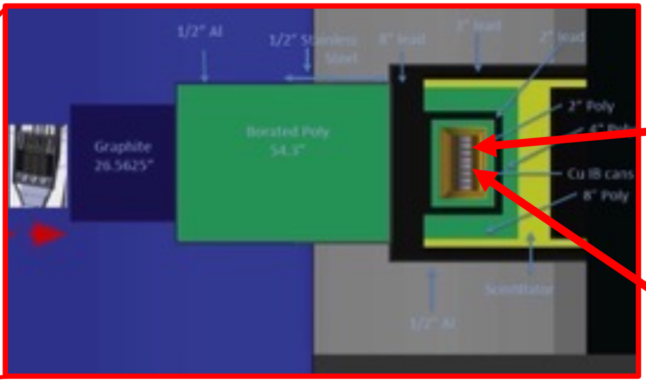
Bolometric detection: MINER

TAMU research reactor (1 MW)

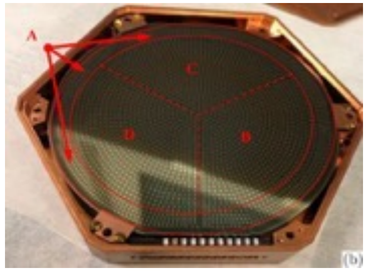
- D = 2–10 m
- Φ_ν ~ 5 x 10^{11} cm^{-2} s^{-1}
- 15 m w.e



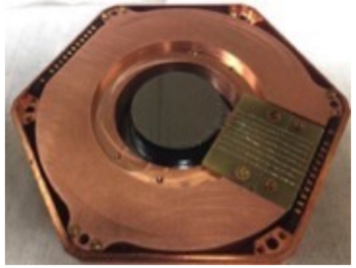
Experimental area + shielding setup



HV



Hybrid

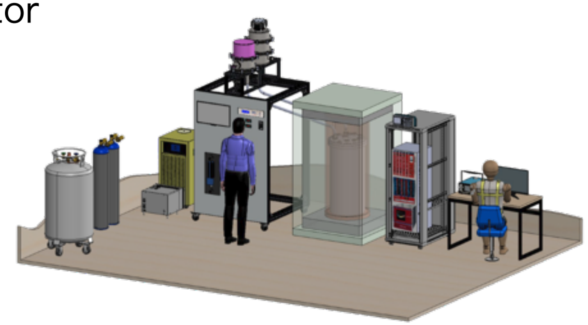


- **Si & Ge superCDMS-style** detectors:
  - ➢ 100-g HV → 0.1 keV$_{NR}$ threshold with TNL amplification
  - ➢ 100-g hybrid: separate collection of primary & TNL phonons → ER/NR disc. down to 0.1 keV$_{NR}$
- Background characterization done and shielding designed → reactor-correlated backgrounds?
- Staged approach:
  - ➢ Phase-1 (now): 2 x (3+1) HV/Hybrid Si. det
  - ➢ Phase-2 (2022): new hermetic shielding design (Icebox) + payload increase

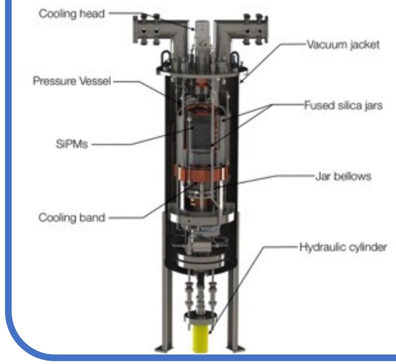
Agnolet et al. (2016)
Neog et al. (2020)
Iyer et al. (2021)

Other detection efforts…

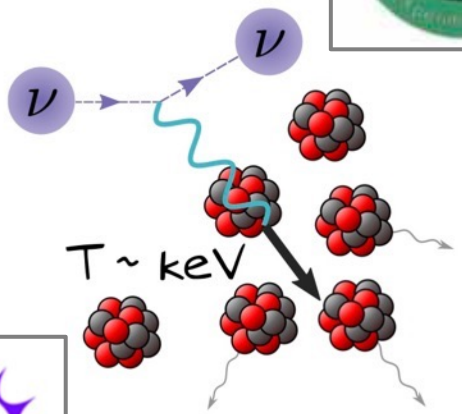
- **LXe det. operated in e⁻ counting mode**
- R&D program to build a low bck. 10–kg det. reaching 0.3 keV_{ee} thr.
- Aims at 5σ detection in ~40 days near a reactor



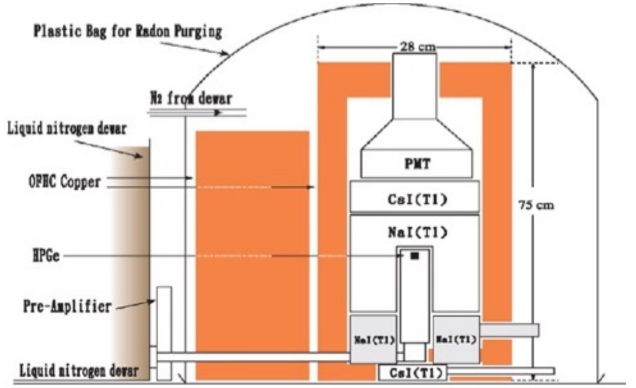
- **Scintillating LAr bubble chamber**
- ER blind with ~40 eV_{NR} achievable



- Commissioning at FermiLAB
- WIMP program at SNOLAB (> 2022)
- CEvNS program at a reactor: ININ TRIGA (Mexico)?



- Neutrino physics program started with ν_e–e⁻ scattering in CsI[TI], NaI[TI] and HPGe detectors
- Kuo–sheng HPP (Taiwan), end of operation by 2022/2023
- **Moving to Ge PPC** with 0.2–0.3 keV_{ee} thr. for CEvNS
- Data taking with an upgraded 1.5–kg det.

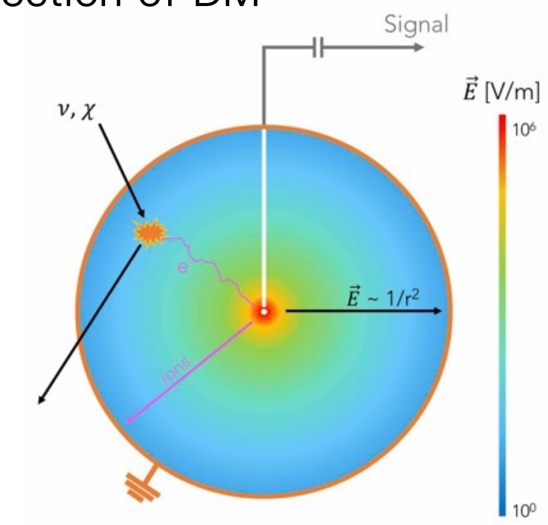


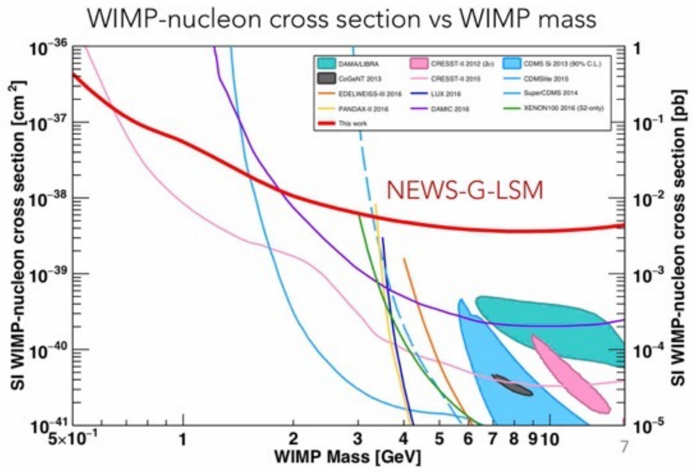
The connection with DM observatories

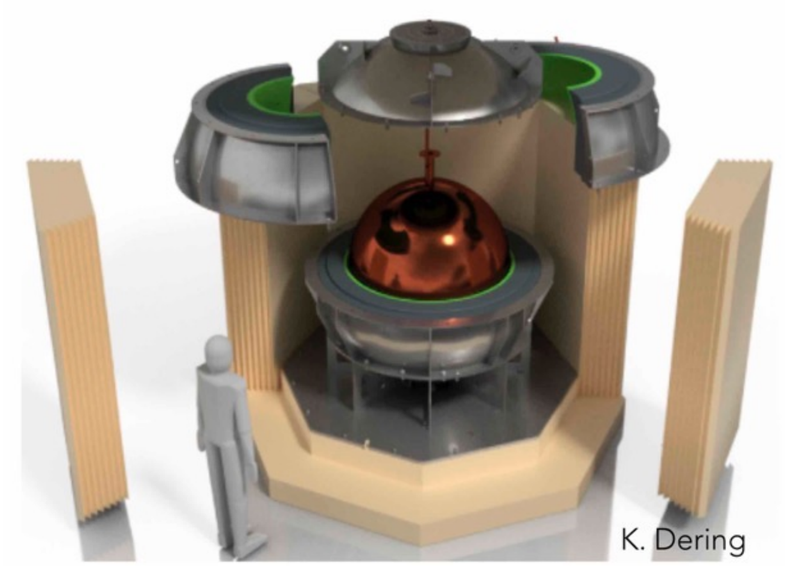
(very incomplete, not meant to be a review)

NEWS-G

- **Spherical proportional counter** technology for direct detection of DM
- SEDINE: 60–cm ∅ Cu sphere det. operated at LSM
  - ➢ Ne:CH4 run → DM limits
  - ➢ Pure CH_4 run → analysis on–going
- Installation of a 140–cm ∅ Cu sphere det. @ SNOLAB by early 2021





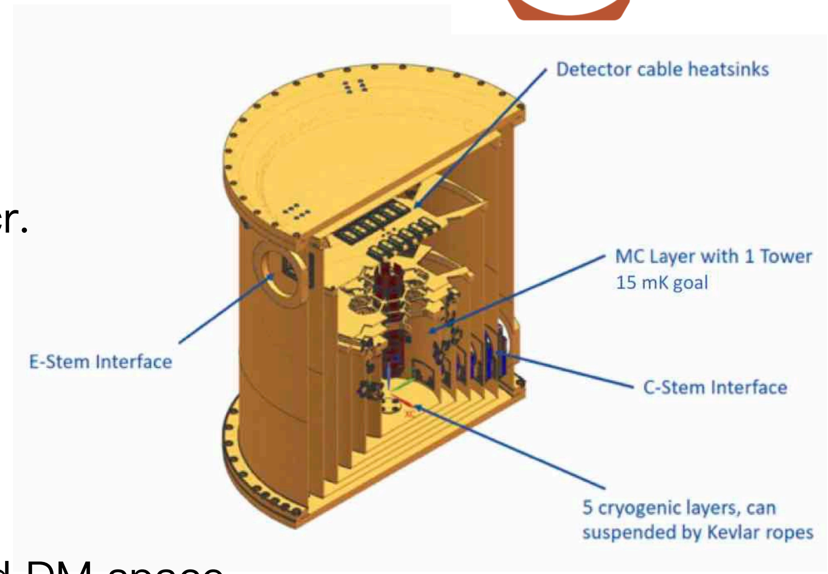


R&D effort under way for a reactor CEvNS program (G3)

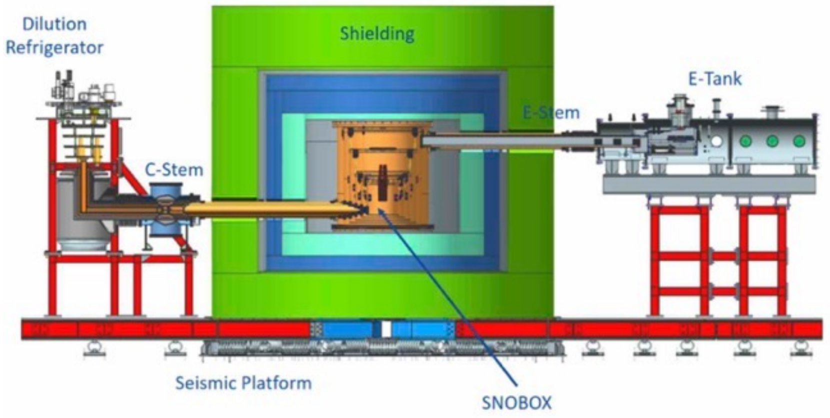
- ➢ Feasibility study on–going
- ➢ 60–cm ∅ SPC being constructed at Queen's lab
- ➢ Dedicated shields for surface bck. conditions
- ➢ Target 50 eV_{ee} threshold

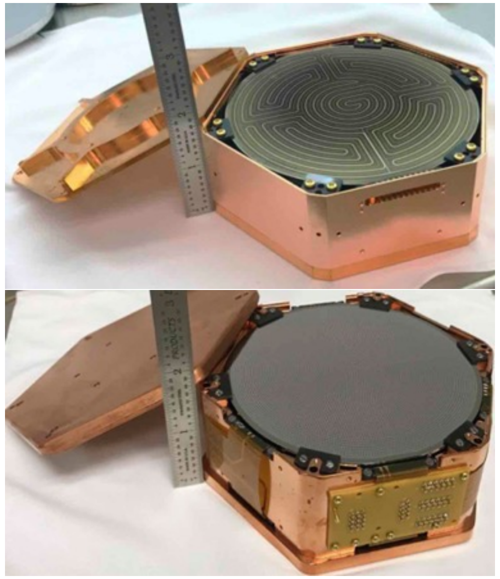
SuperCDMS program

- Building a next generation facility for rare event searches. Phased program:
  - ➢ Cryostat, shieldings, infrastructure
  - ➢ ~30–kg payload of **iZiP & HV det.** (Si & Ge) with low threshold + ER/NR discr.
  - ➢ Commissioning & physics run by 2022/2023
  - ➢ **CEvNS from solar ν should be reachable**



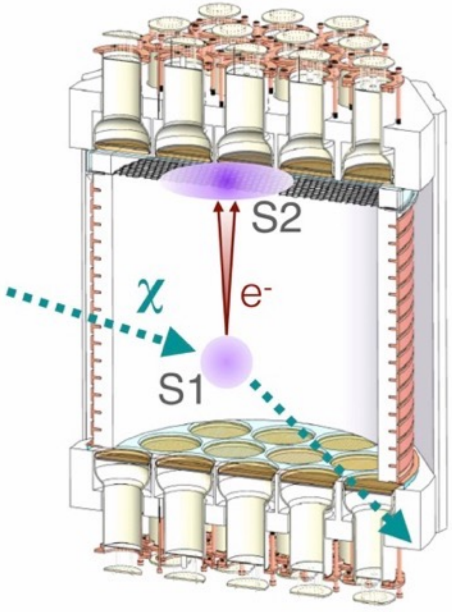
- Working on future upgrades to conduct solar ν physics program + reach extended DM space
  - ➢ Change det. size, material
  - ➢ Work on bck. reduction: enchance shield
  - ➢ Extend ER/NR discr. down to lower thr.

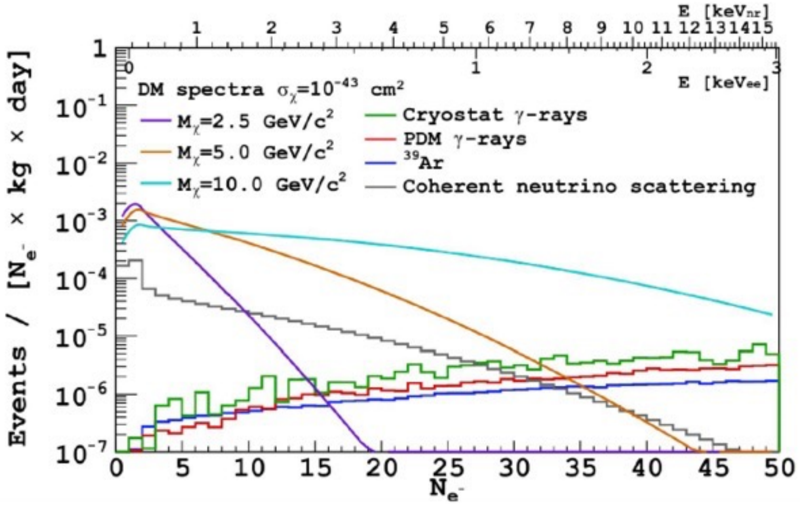


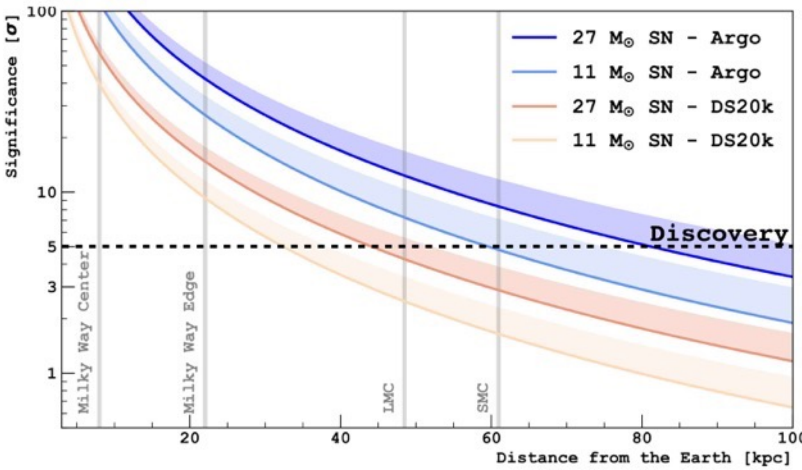


Global Argon DM collaboration (GADMC)

- Global effort to push and develop dual-phase Ar technique for an ambitious DM and neutrino physics program
  - ➢ DarkSide-20k (50 t)/Argo (300 t): WIMPs, SN ν, etc…
  - ➢ DarkSide-LM (1 t): low mass WIMPs
- Investigating sensitivity to SN burst with DS-20k & Argo through CEvNS
  - ➢ TPC operated in e^- counting mode → E_{th} ↓
  - ➢ 5σ sensitivity up to MW edge (DS-20k) & SMC (Argo)
- Solar neutrinos studies through CEvNS possible with DS-LM

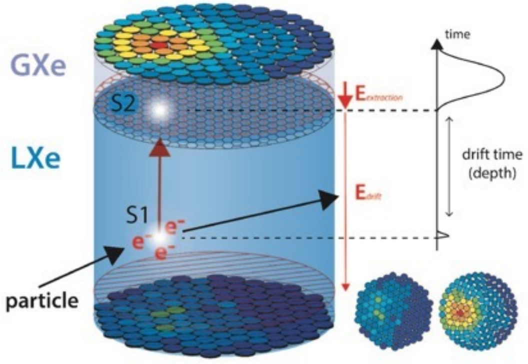






Dual-phase Xe detectors

- Many players in the field, all aiming at multi–ton scale setups + pushing ER/NR discr. down to lowest thresholds:

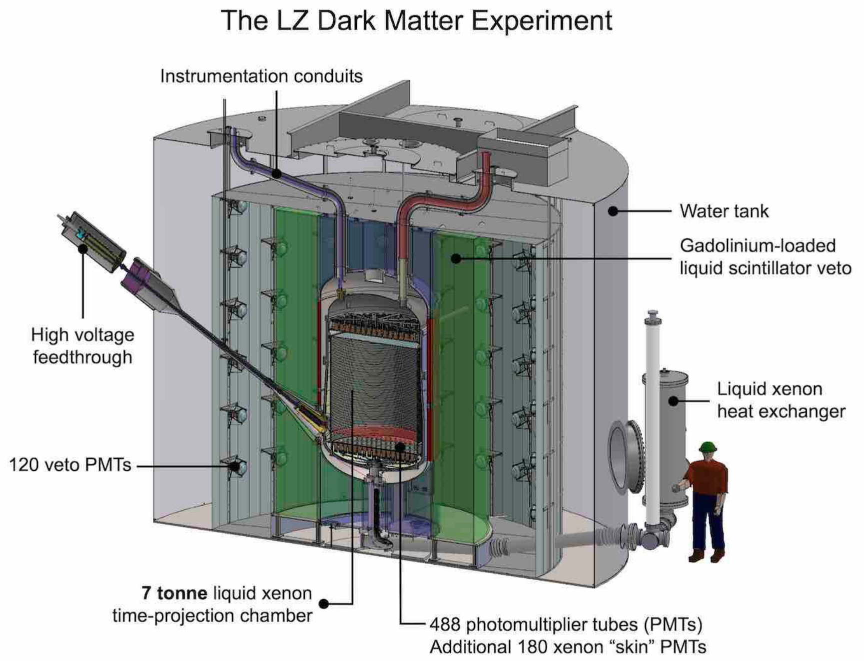


  - Lux–Zeppelin (LZ): 7 t
  - PandaX–4T: 4 t
  - Xenon–nT: 6 t

  } Time scale ~ now

  - Next gen. detectors: DARWIN (40 t) & PANDAX–30T (30 t)

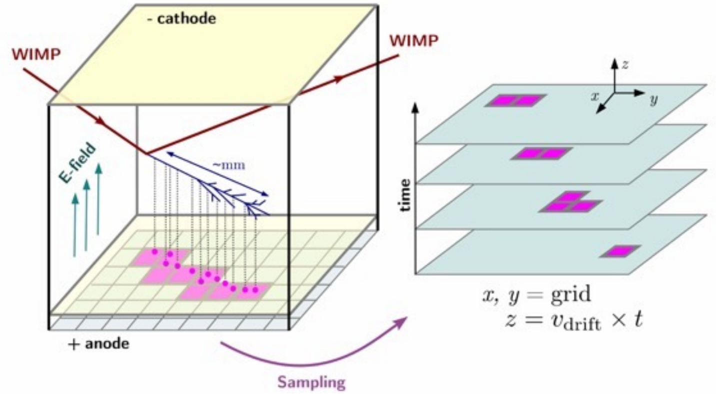
→ **should be sensitive to CEvNS from atmospheric ν**

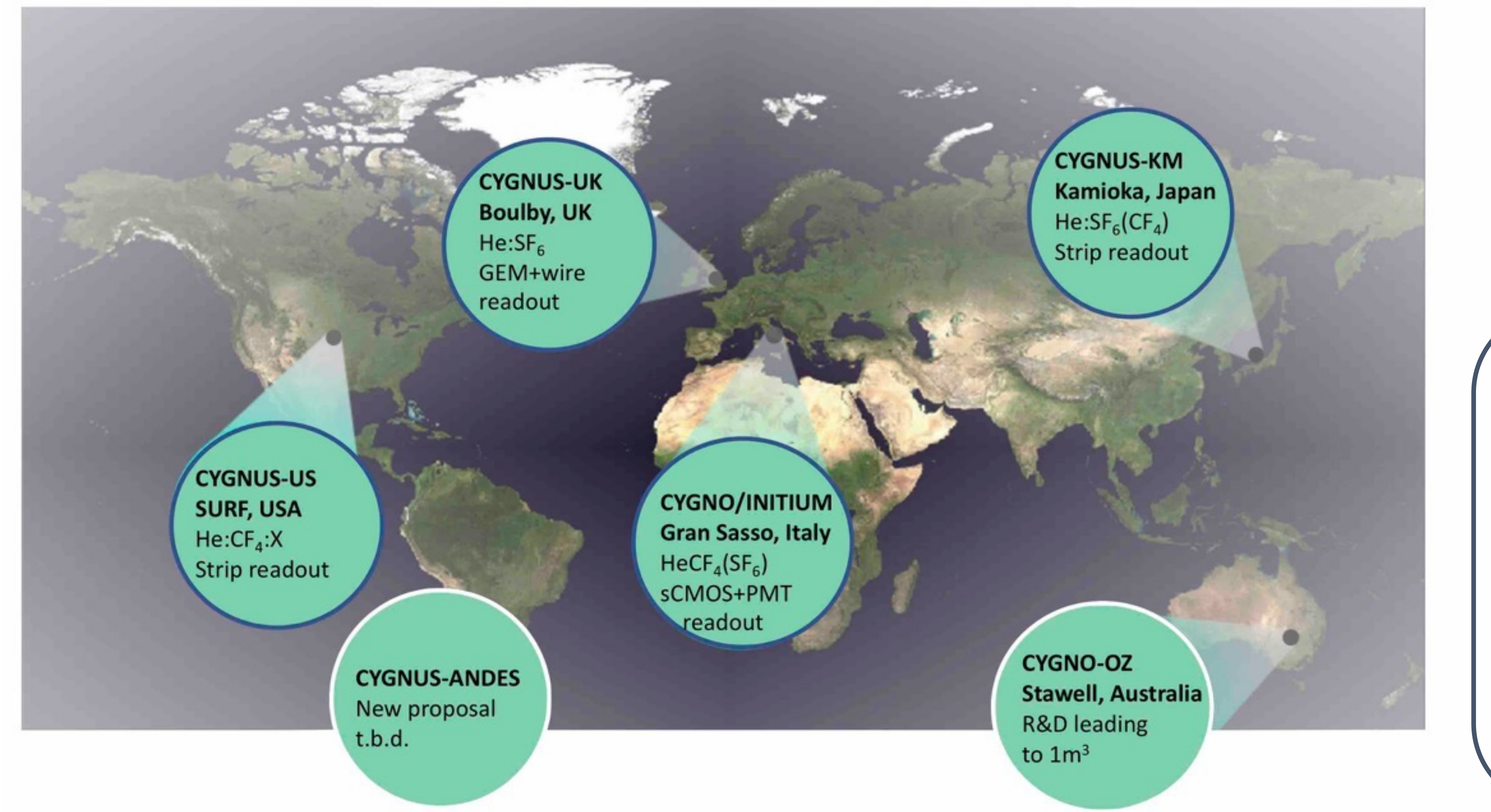


- Many R&D work on–going:
  - Xe ultra purification
  - Radon background removal (material purification, surface treatment, etc.)
  - Improvements in the detector design (large scale TPC electrodes, etc.)
  - Photo–sensors
  - …

The CYGNUS observatory

- Beating the (solar) neutrino floor with detection techniques sensitive to directionality
- Modular and multi-site network of ton-scale gaseous TPCs
- 3D reconstruction of ionization tracks → directionality + NR/ER discrimination down to keVish tresholds.

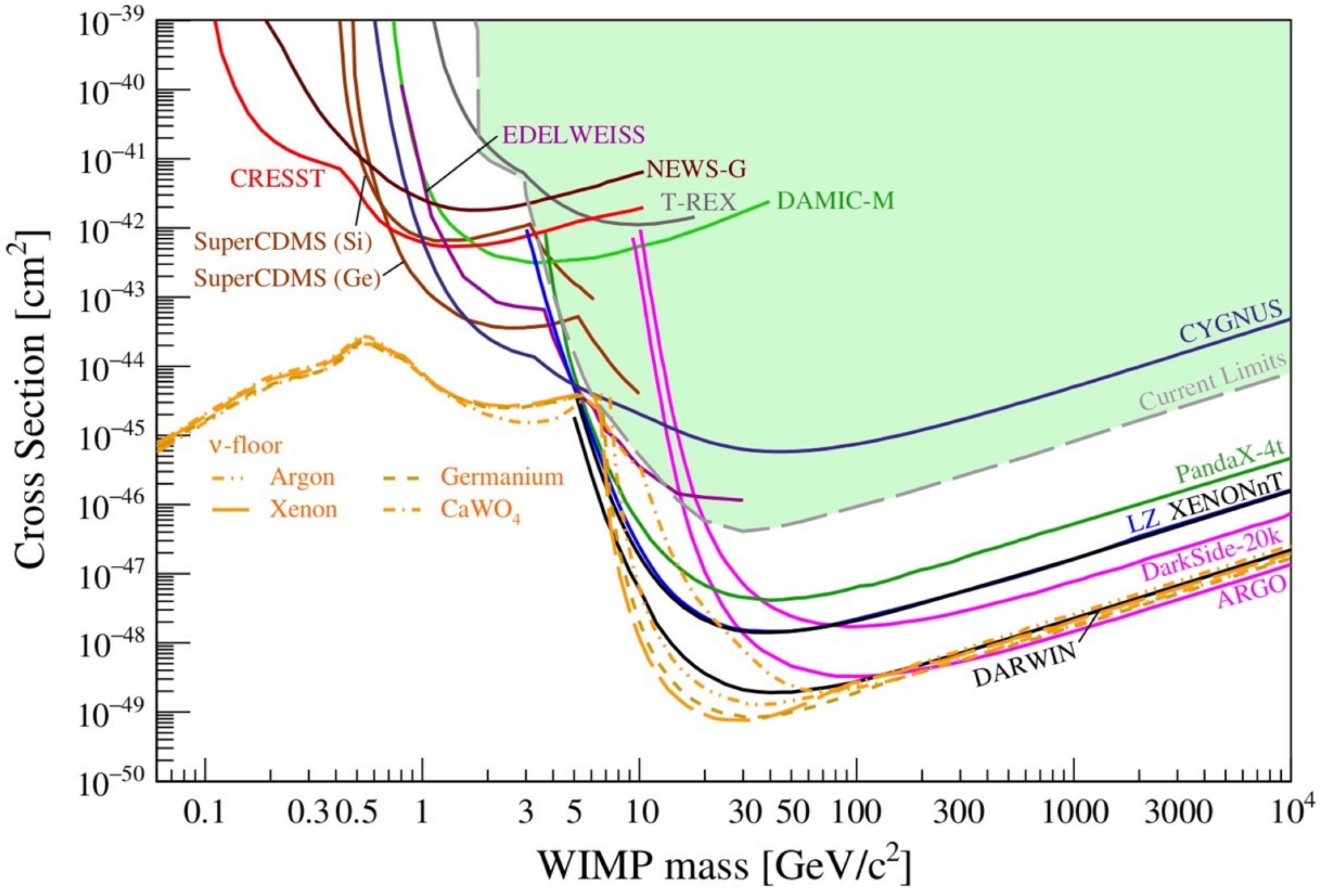




Broad physics program

- ➢ Midgal effects
- ➢ CEvNS @ accelerator facilities
- ➢ Dark Matter
- ➢ Solar neutrino physics and more…

DM experiments & the neutrino floor



From APPEC committee report on Direct DM Detection

Billard et al. (2021)

Conclusions

- CEvNS opens a broad new range of perspectives in particle/nuclear physics, astrophysics, etc…
- A wide variety of detector technologies (ionization, scintillation, phonon, etc…) are investigated
- Man-made neutrinos sources to precisely study the process: stopped-pion versus reactor neutrino sources

→ COMPLEMENTARITY !

- Experimental challenges:
  - Measuring & understanding quenching down to sub-keV energies
  - Background mitigation, especially for reactor facilities (surface conditions !)
- Natural synergy with Dark Matter detection programs (neutrino floor)
- Applications for long-range detection (solar ν, SN ν + non-proliferation) are heavily studied !

THANK YOU !

Backup

The SNS neutrino source

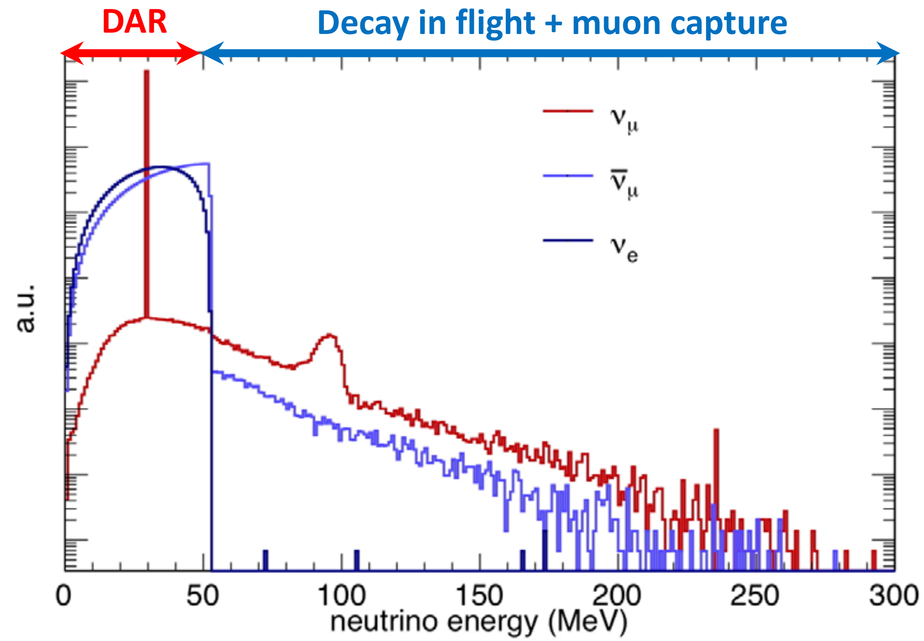
- Proton beam impinging on a mercury target, which produce neutrinos through π^+ decay at rest and "delayed" μ^+ decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \xrightarrow{\tau\,=\,2.2\,\mu s} \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Beam related neutrons shielded by iron & steel monolith around mercury target + 12 m of concrete
- Beam features: ~ 1 GeV protons, 5×10^{20} POT/day, 60–Hz pulsed with ~ 1 μs spills, neutrino yield ~ 0.08/proton/flavor

Flux ~ 4×10^7 cm^{-2} s^{-1} @ 20 m

SNS neutrino source energy spectrum



SNS neutrino source time profile