Summary of CEvNS Experiments

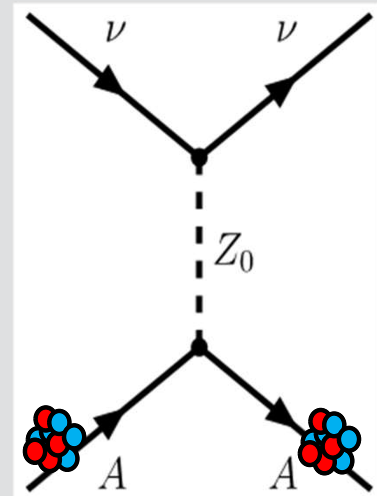
R.Tayloe, Indiana U

Outline:

- motivation/overview
- CEvNS experiments with
  - Reactors
  - Solar/atmospheric ν
  - stopped pion ν
- Status and future

Thanks to all for contributions to this talk, especially those from "Magnificent CEvNS" workshop series

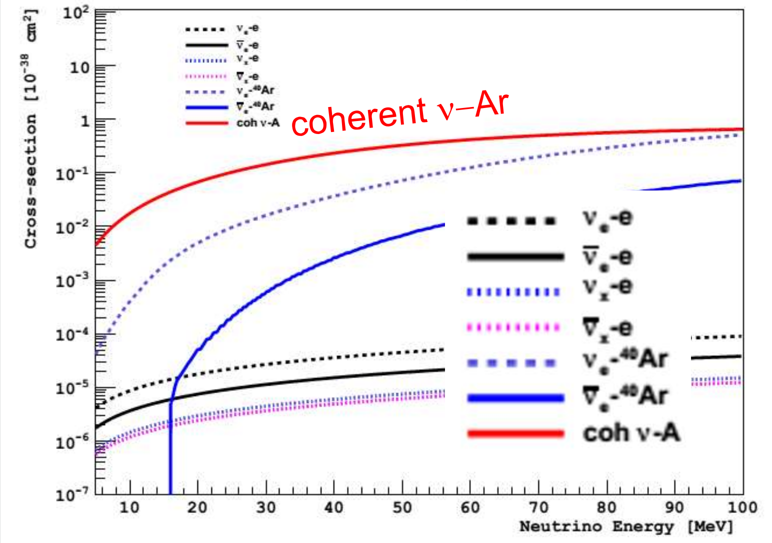
CEvNS: Coherent Elastic ν-Nucleus Scattering: νA→νA



CEvNS probes the nucleus coherently, yielding clear tests of the standard model weak interaction with the nucleus.

…CEvNS is largest ν channel at ~10 MeV
on nuclei, eg Cs,I, Ar

ν-Ar cross sections



CEvNS total, differential cross sections:

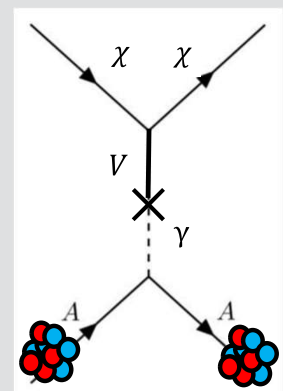
$$\sigma \approx \frac{G_F^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2 E_\nu^2$$

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- ν flavor independent

Also:

- coupling to other neutral particles possible (eg accelerator-produced dark matter)

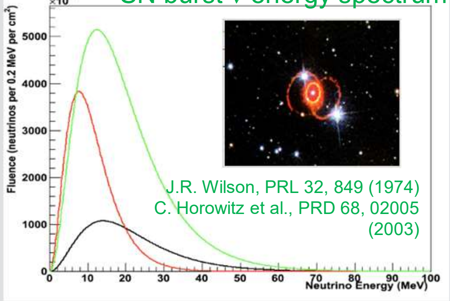


Coherent Elastic ν-Nucleus Scattering:

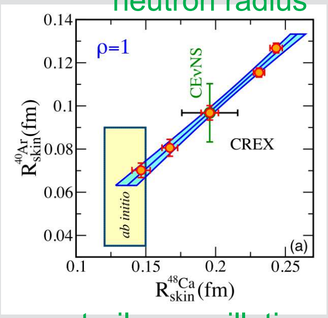
Physics reach of CEvNS (and related)

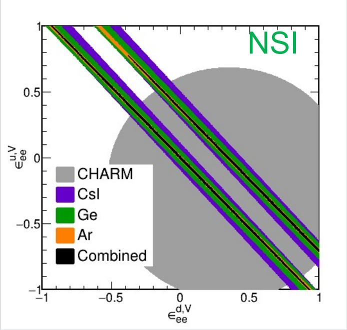
- Supernovae (SN)
  - Largest σ in SN dynamics
  - possible SN detection channel
- Nuclear Physics: nuclear form factors
- Standard Model tests:
  - non-standard interactions (NSI)
  - weak mixing angle: $\sin^2\theta_W$
  - ν magnetic moment
- ν oscillations: Sensitive to sterile ν
- Dark Matter:
  - Important background for 10-ton direct searches
  - detectors sensitive for accelerator produced DM

SN burst ν energy spectrum

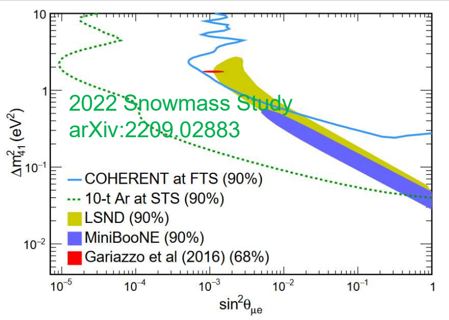


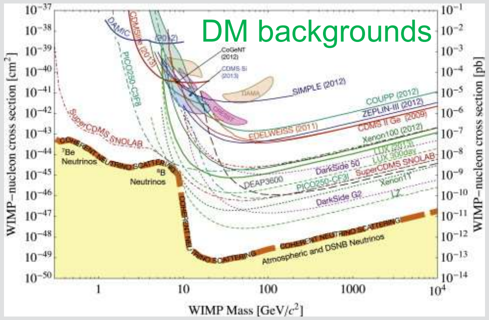
neutron radius



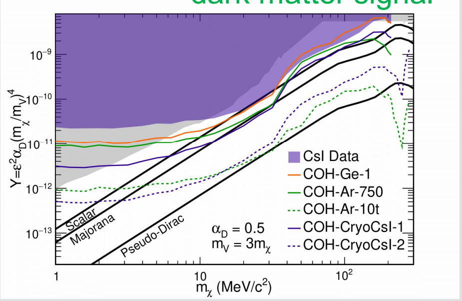


sterile ν oscillations





dark matter signal



<u>Coherent Elastic ν-Nucleus Scattering:</u>

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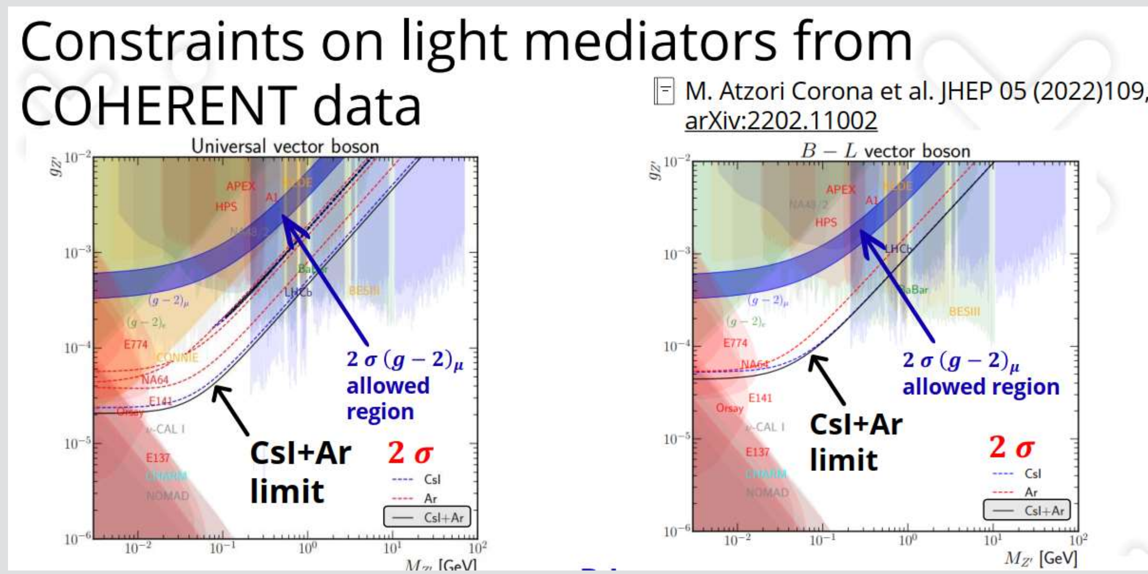
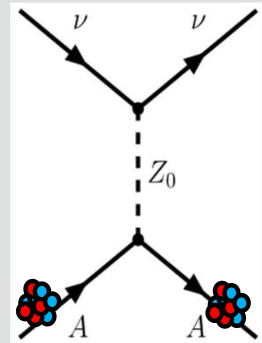
- much interest/activity from theoretical community eg: M. Cadeddu, etal,

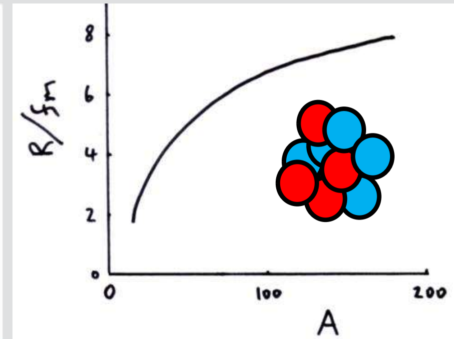
33. Overview of physics results with coherent elastic neutrino-nucleus scattering data
Matteo Cadeddu
22/08/2023, 16:50
WG5: Neutrinos Beyond ... Oral Parallel
Co-authors: M. Atzori Corona, N.Cargioli, F. Dordei, C. Giunti, Y.F. Li, C.A. Ternes, Y.Y. Zhang



CEvNS: Experimental constraints

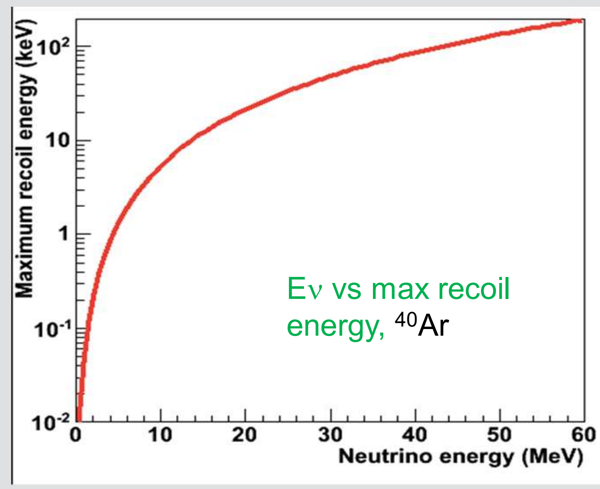
- "coherent" : momentum transfer small compared to nuclear radius
  $\Rightarrow E_\nu$ <~ 50 MeV
- then max nuclear recoil energy (E_{nr}) <10-100 keV
- Detection of nuclear recoil (over backgrounds) is quite a challenge





$$\lambda = \frac{h}{p} = \frac{hc}{E} = \frac{1200 \text{ eV fm}}{50 \text{ MeV}} \sim 25 \text{ fm}$$

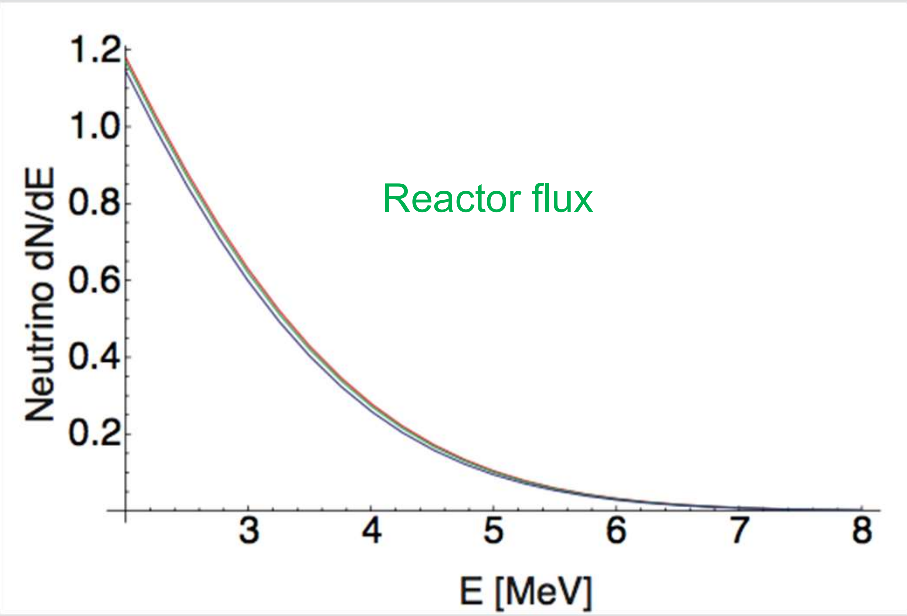
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M}$$

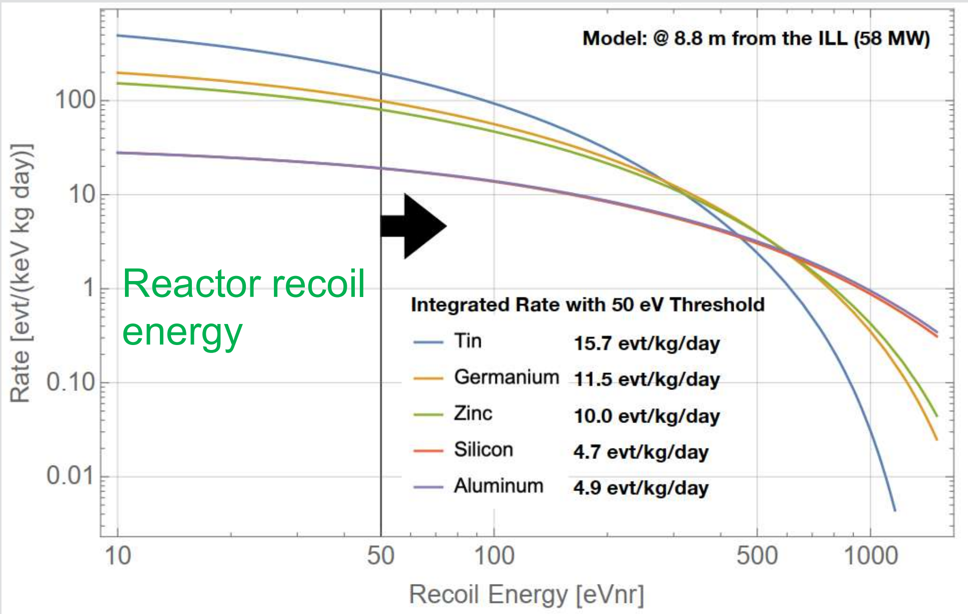


And so, after ~50 years since prediction of this process, with great strides in ν sources and detectors, we are now able to measure CEvNS

CEvNS: Experimental strategies

- coherence condition $\Rightarrow$ need E_ν <~ 50 MeV , so
  - Reactor ν sources : E_ν <~ 5 MeV , E_{nr} ~5 keVnr





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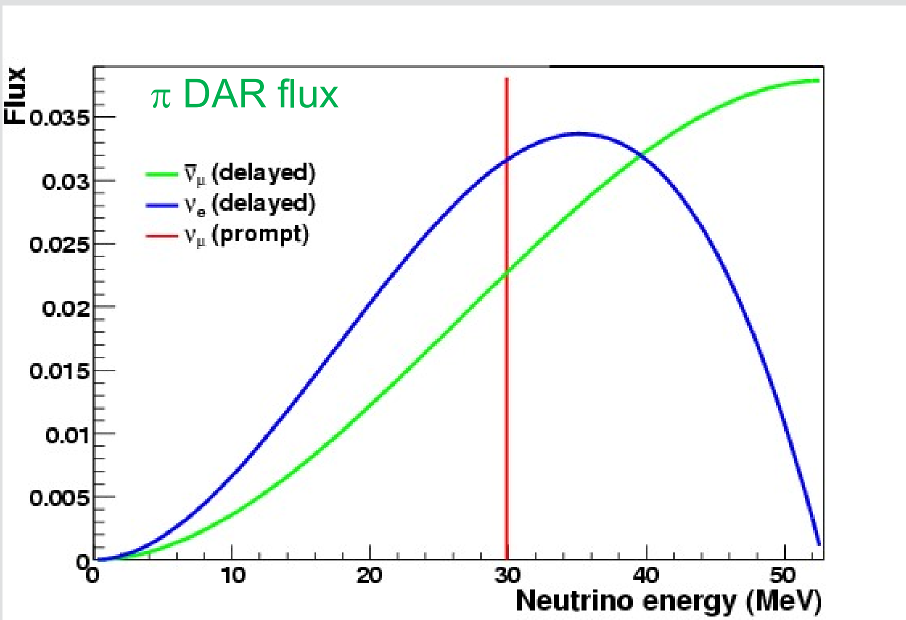

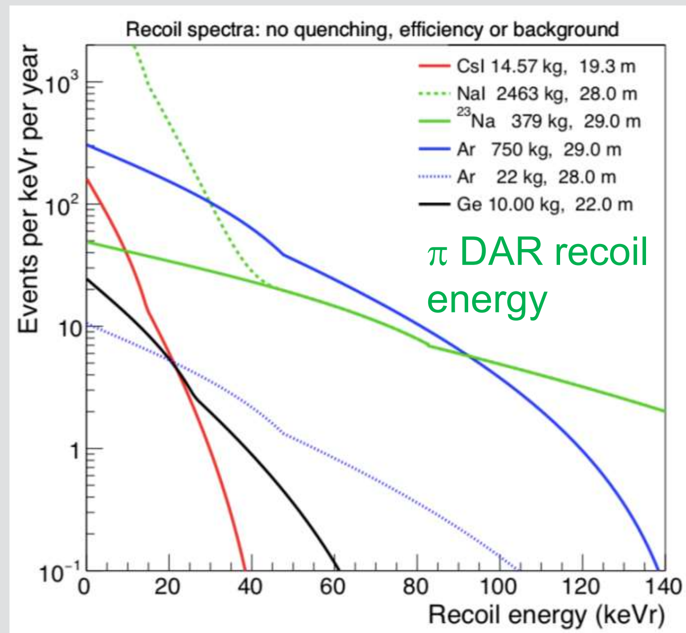

CEvNS: Experimental strategies

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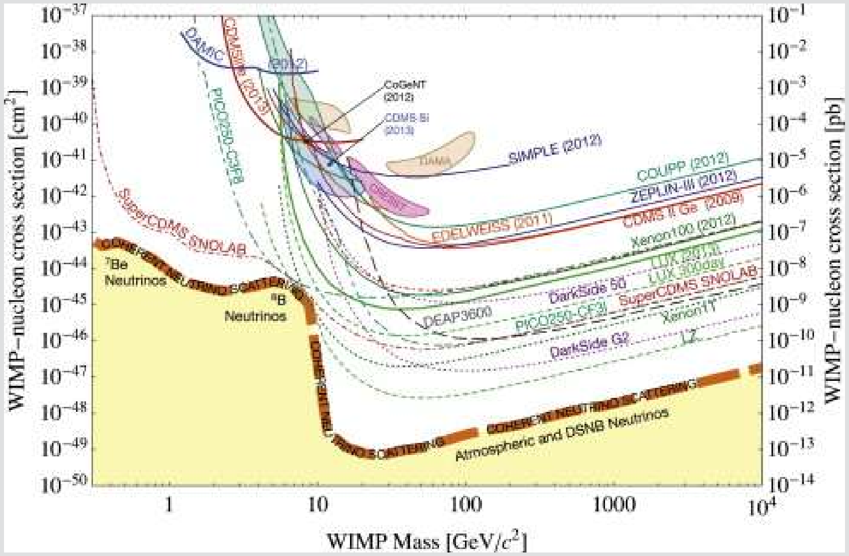
  - pi DAR ν sources : E_ν <~ 50 MeV , E_{nr} ~50 keVnr
  - Other sources: solar, atmospheric ν, supernova



Low E recoil $\Rightarrow$ low background, sensitive detectors

- Many different technologies: inorganic crystals, solid state, liquid noble gas

CEvNS world summary

Experiment	Detetctor Type	Location	Source
COHERENT	CsI, Ar, Ge, NaI	USA	πDAR
CCM	Ar	USA	πDAR
JSNS^2	TBD	Japan	πDAR
ESS	CsI, Si, Ge, Xe	Sweden	πDAR
BULLKID	Si/Ge	Italy	Reactor
CHILLAX	Ar	TBD	Reactor
CONNIE	Si CCDs	Brazil	Reactor
CONUS	HPGe	Germany	Reactor
DRESDEN II	PCGe	USA	Reactor
NEWS-G	Ar+CH4	Canada	Reactor
MINER	Ge/Si cryogenic	USA	Reactor
NEON	NaI(Tl)	Korea	Reactor
NUCLEUS	Cryogenic $CaWO_4$, Al_2O_3	Europe	Reactor
NUXE	Xe		Reactor
νGEN	Ge PPC	Russia	Reactor
RED-100	LXe dual phase	Russia	Reactor
Ricochet	Ge, Zn bolometers	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
SBC	Scint. Bubble Chamber	USA	Reactor

From: arXiv:2209.06872, and others

Snowmass Neutrino Frontier:
Neutrino Interaction Cross Sections (NF06)
Topical Group Report

Submitted to the Proceedings of the US Community
Study on the Future of Particle Physics (Snowmass 2021)

+ future at Fermilab
and others…

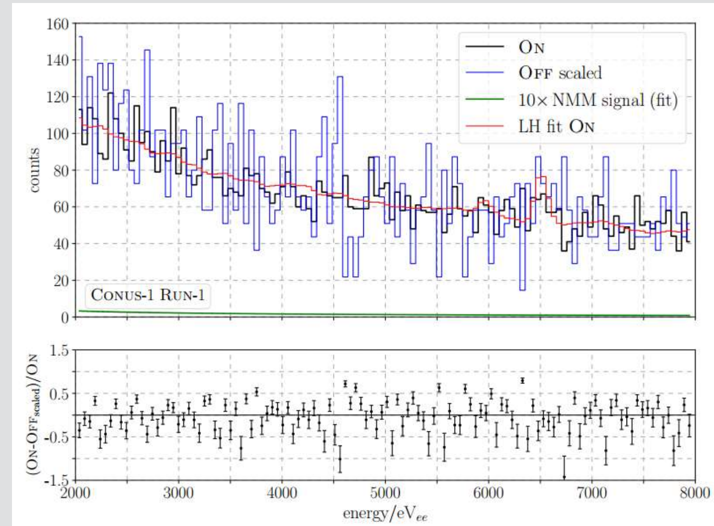
122. Physics Opportunities at a PIP-II Beam Dump Facility and Beyond
Jacob Zettlemoyer
25/08/2023, 17:42
WG5: Neutrinos Beyond ... Oral Parallel

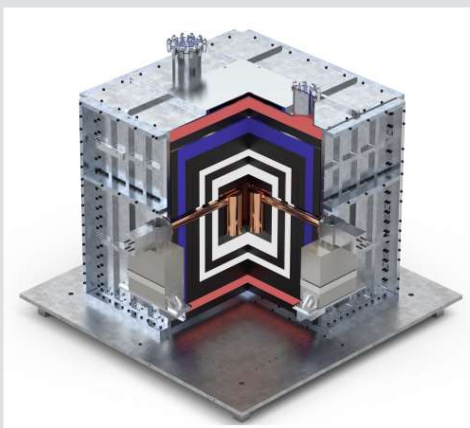
CEvNS reactor experiments

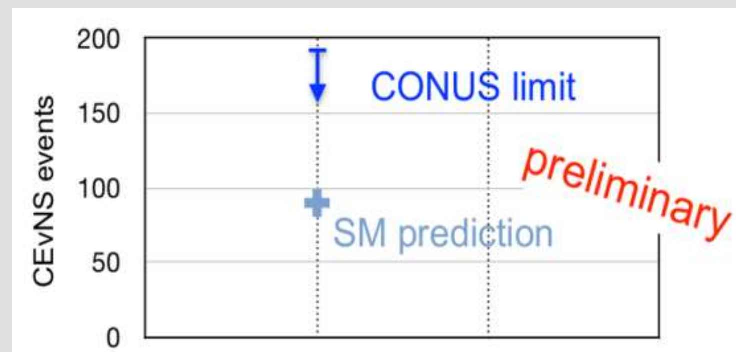
CEvNS Reactor Experiments - CONUS

CONUS

- 5 years of operation at Brokdorf reactor with 4 x 1kg Ge detectors at 17m from 3.9GW reactor
- Very low energy threshold (~200 eVee)
- low backgrounds in ROI
- Assume Lindhard quenching model for low E extrapolation
- New limit on CEvNS signal ~x2 above SM
- arXiV: 2011.00210 , etal
- Upgrading to CONUS+ soon



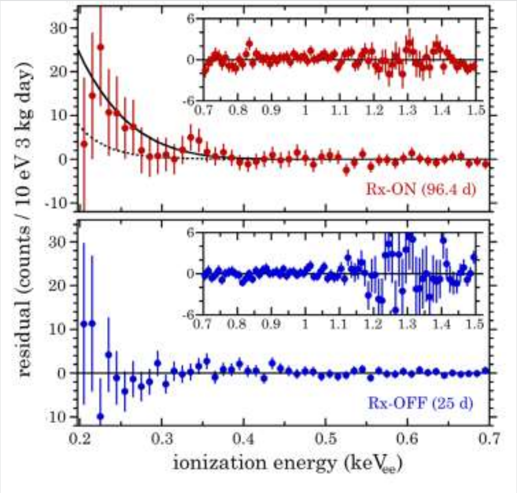




More Reactor Experimental results

Dresden II :

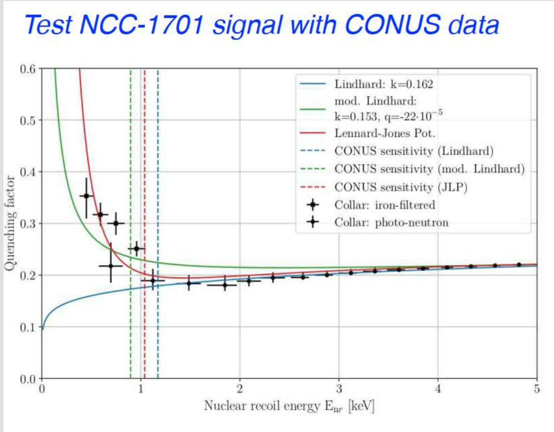
- 3kg P-contact Ge detectors 10m from Dresden 3GW core, 96 days
- "..preference for CEvNS signal is found"
- however debate on low-E behavior of quenching model and tension with CONUS result



DOI: 10.1103/PhysRevLett.129.211802

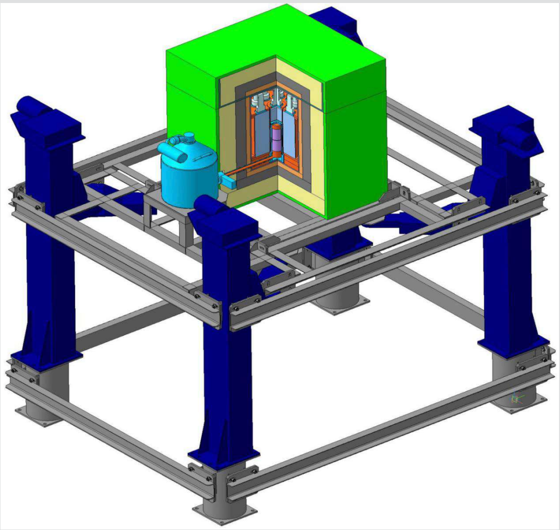
Aside:

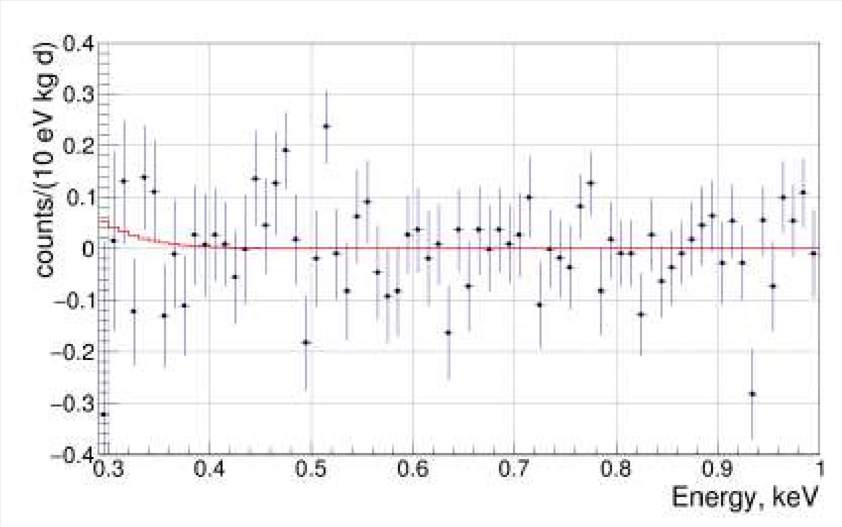
- "quenching" = E (nuc recoil)/E(electron recoil) is important and challenging for low-E cevns detectors



More Reactor Experimental results

- νGen:
- 1.4kg HPGe detectors 11m from KNPP reactor 3GW core, 94 days,
- spectrum consistent with background





DOI: 10.1103/PhysRevD.106.L051101

CEvNS at reactors

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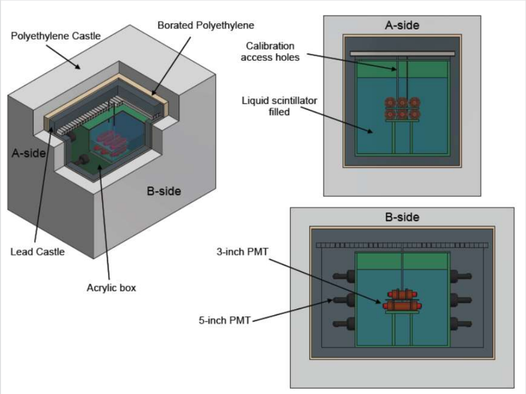
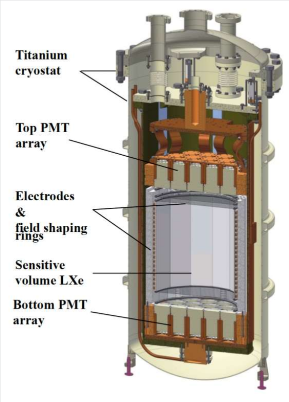
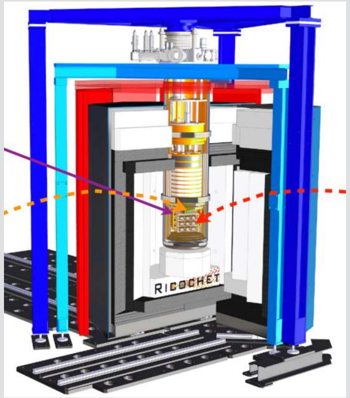
Ricochet	Ge, Zn bolometers	France	Reactor
TEXONO	p-PCGe	Taiwan	Reactor
SBC	Scint. Bubble Chamber	USA	Reactor

- Many other reactor experiments being planned and R&D'd.
- Eg: NEON 15kg NaI @ Hanbit reactor SKr
- others



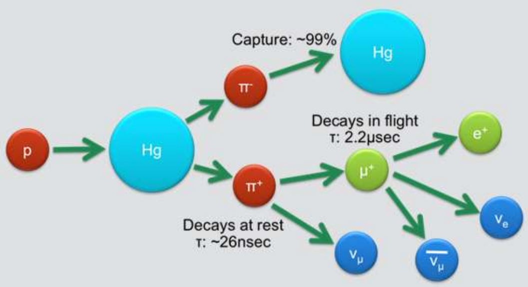




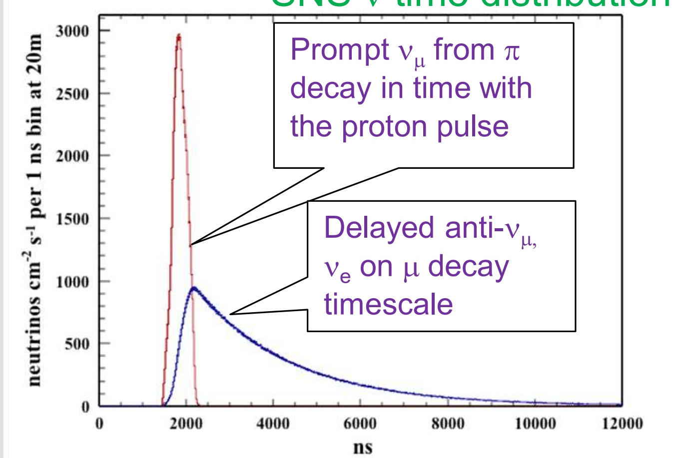
CEvNS π DAR (accelerator) experiments

CEvNS π DAR experiments - COHERENT

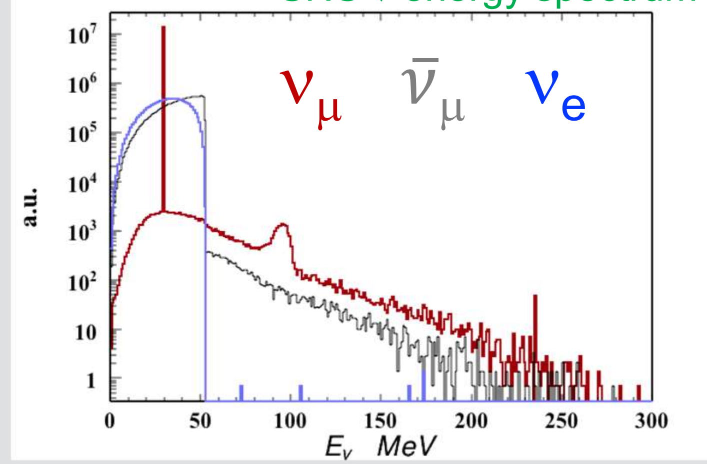
- At ORNL Spallation Neutron Source (SNS)
- world's most powerful pulsed proton beam (1.4 MW, 1 GeV) (and upgraded to 2 MW, 1.3 GeV 2024)
- pulsed (60 Hz, 600ns spill time)…
- ~7000 MWhr/year, 1.5E23 protons/year



SNS ν time distribution

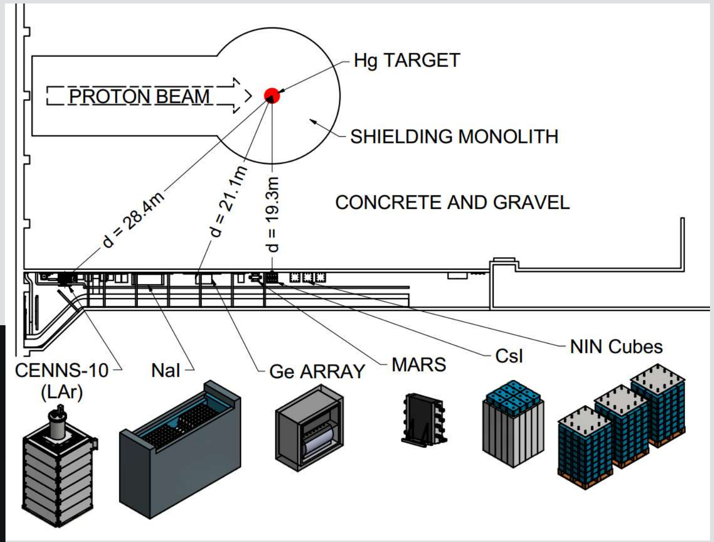


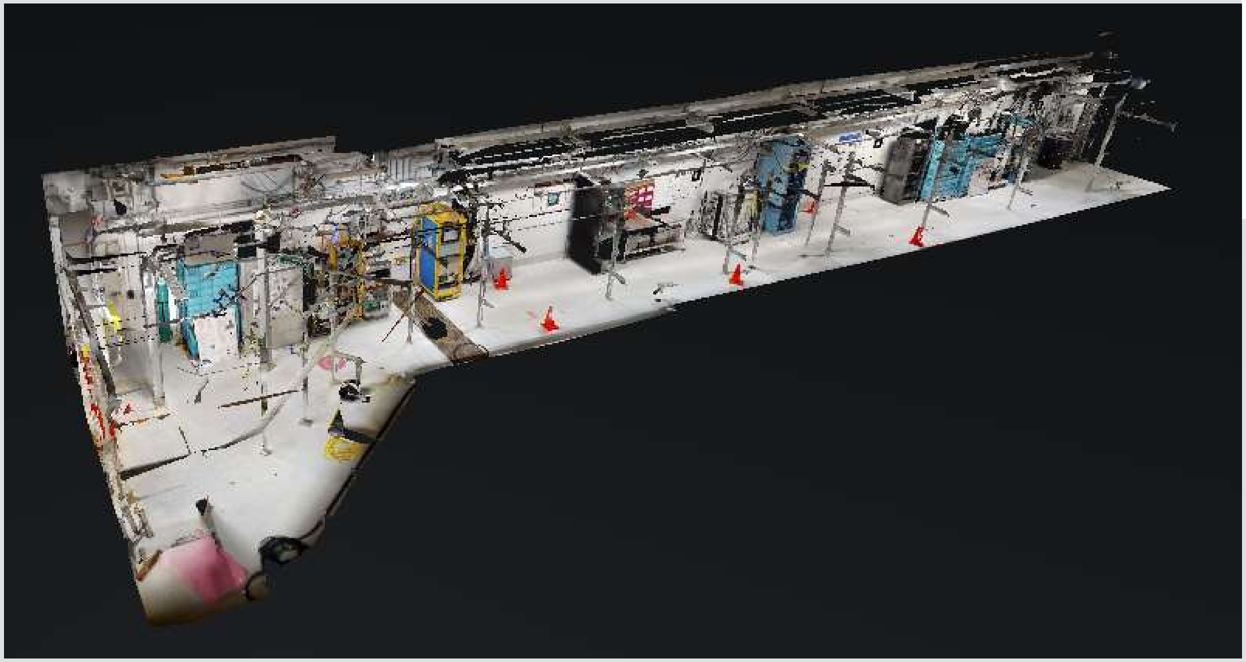
SNS ν energy spectrum



COHERENT experiment at SNS/ORNL

- in “neutrino alley”
- with low beam-related backgrounds
- 20-29 m from target

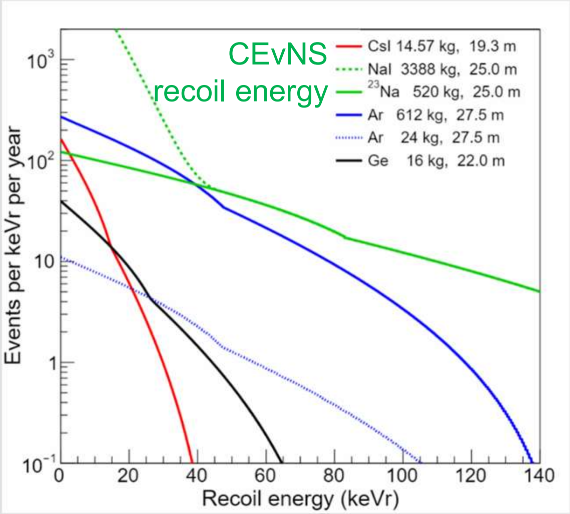




COHERENT experimental strategy at SNS/ORNL

Phase 1:
Observe CEvNS process and measure N^2 dependence
with multiple targets/detector technologies

Phase 2:
Precision measurements of CEvNS (and related) physics
with larger/upgraded targets/detectors



COHERENT past, current, CEvNS future detectors

Target	Technology	Fid. Mass (kg)	Threshold (keV_{nr})	Commission dates	Pubs/status
CsI[Na]	Scintillation	14.6	6.5	2015	1st result, 2017: 10.1126/science.aao0990 updated results 10.1103/PhysRevLett.129.081801 detector removed
Liquid Ar	Scintillation	24.4/610	20	2017/2024	1st result, 2019: 10.1103/PhysRevLett.126.012002, new results from more soon
Ge	Ionization	18	0.5	2023	commissioning
NaI[Tl]	Scintillation	2500	13	2023	commissioning:

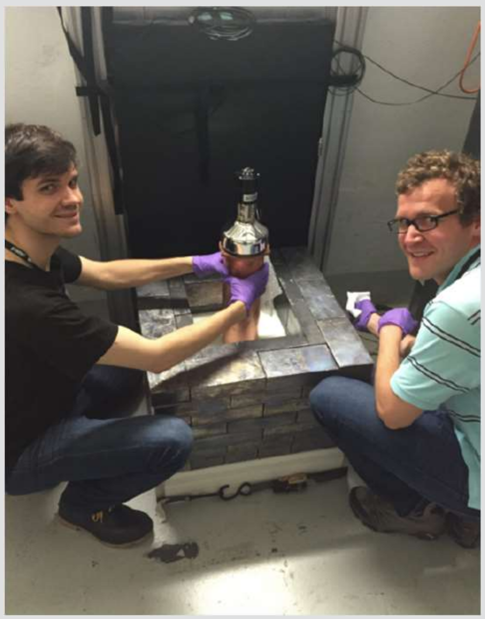
COHERENT with CsI[Na]

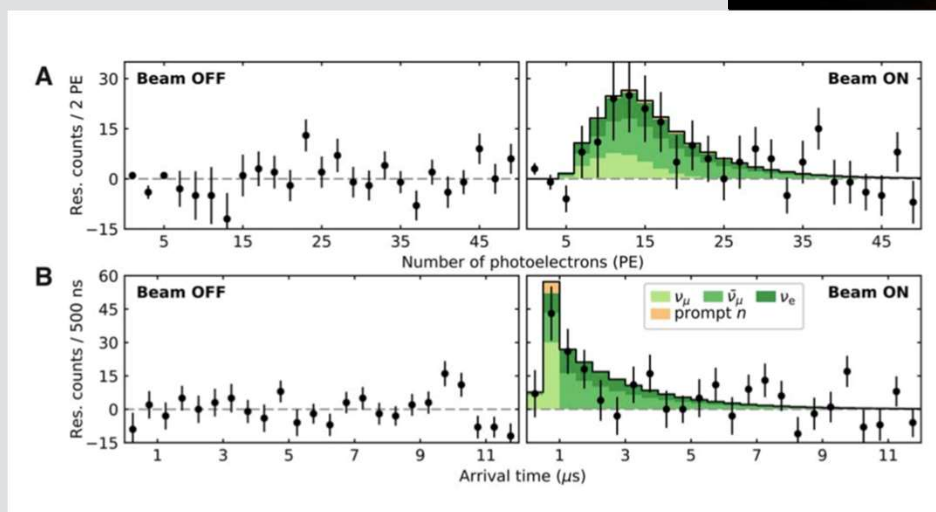
CsI[Na] scintillating crystal:

- 14.6 kg sodium-doped CsI
- high light yield (13.35 pe/keVee)
- Manufactured by Amcrys-H
- Single R877-100 PMT

2017 results (~1.5yrs of data)

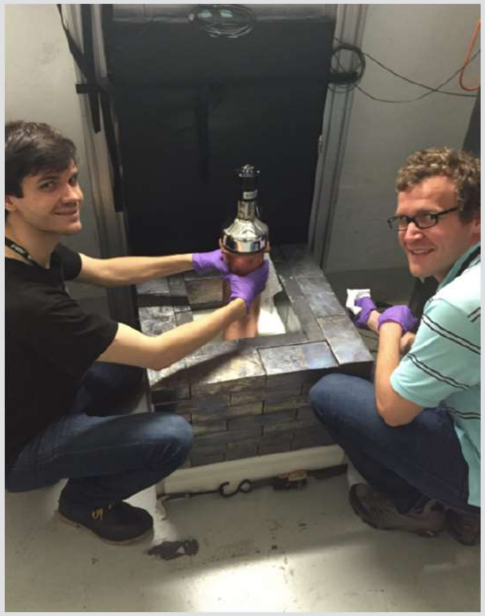
- 6.7σ discovery of CEvNS
- consistent w/SM within 1σ



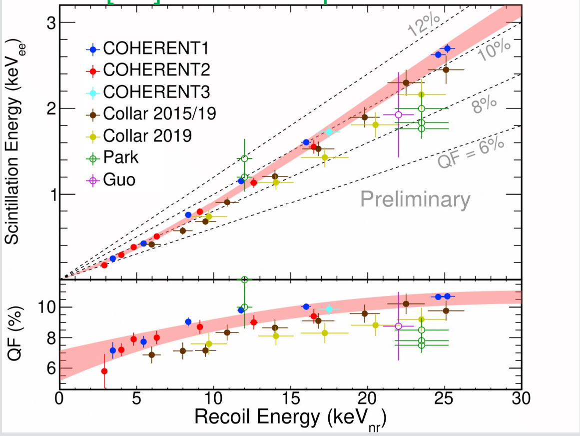


COHERENT with CsI[Na]

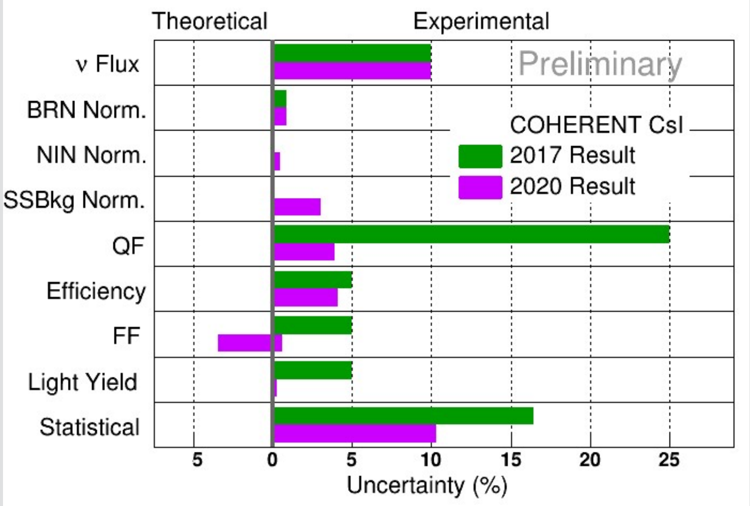
- updated results with 2.2x more data (compared to 2017 result)
- analysis improvements
- new quenching factor (nuclear response) measurements/analysis
- resulting in reduced errors



CsI[Na] nuclear response calibration

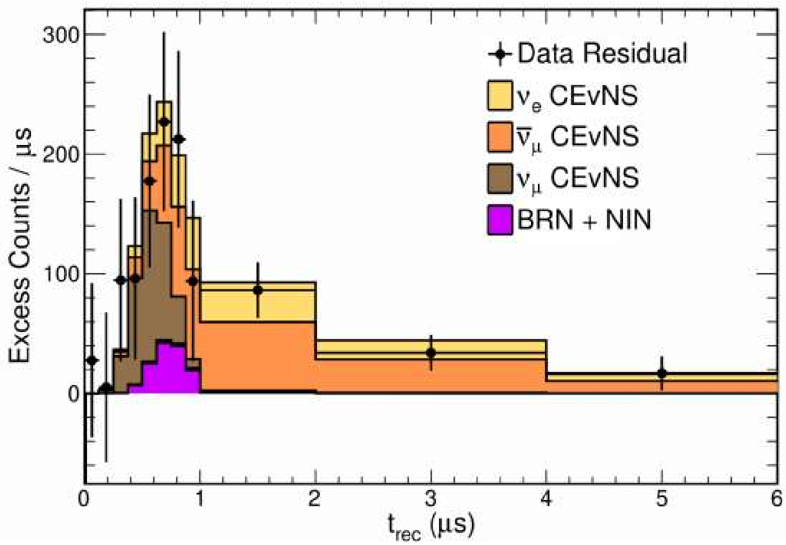


CsI[Na] uncertainties comparison

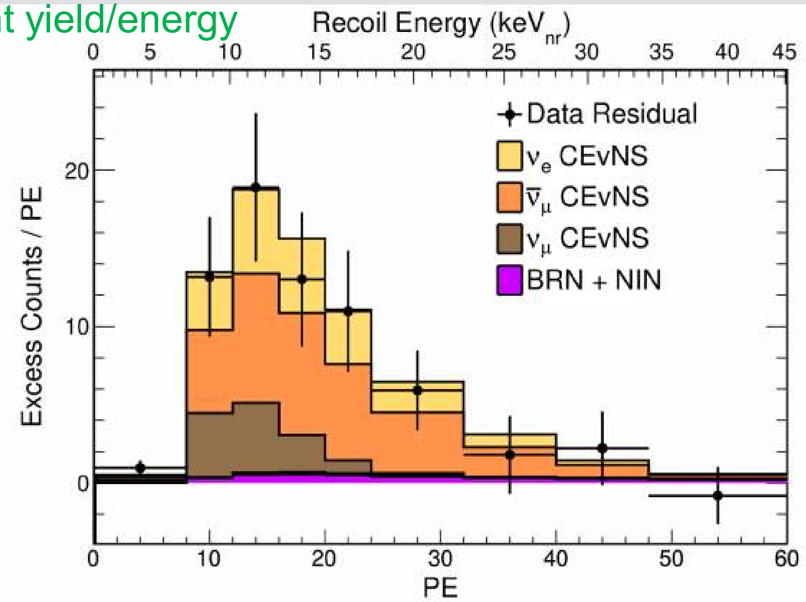


COHERENT, updated CsI results:

event time (wrt beam pulse)



Light yield/energy



COHERENT, PRL **129** 081801

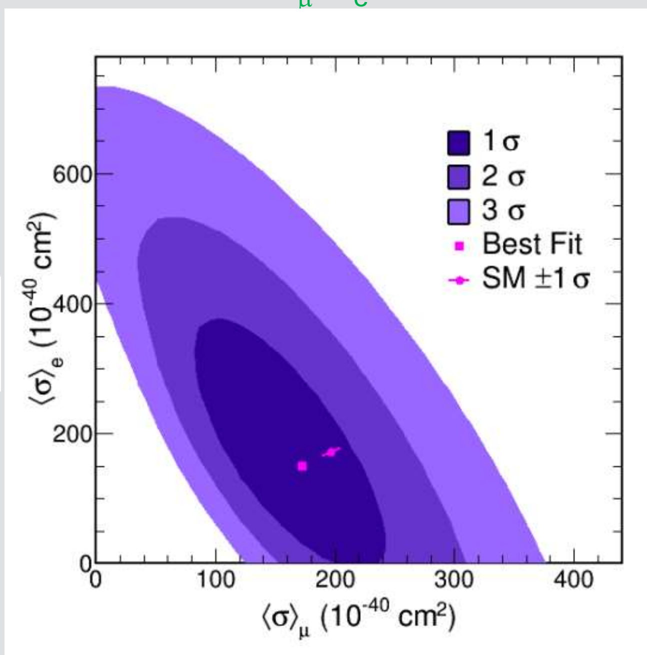
No-CEvNS rejection	11.6 σ
SM CEvNS prediction	341 ± 11(th) ± 42(ex)
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$165^{+30}_{-25} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2

COHERENT, updated CsI results, physics:

- Updated CsI data improves upon previous non-standard interaction (NSI) constraints and eliminates a degeneracy in LMA solar oscillation solution
- Separately measured ν_μ / ν_e cross sections as allowed in NSI scenarios.

- See arXIv: 2110.07730, 2111.02477

fit ν_μ / ν_e cross sections



- Much more theoretical work with this data
  eg: M. Cadeddu, etal,


33. Overview of physics results with coherent elastic neutrino-nucleus scattering data
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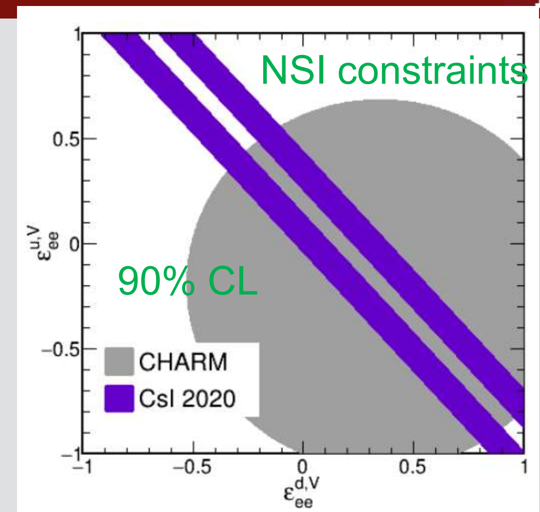
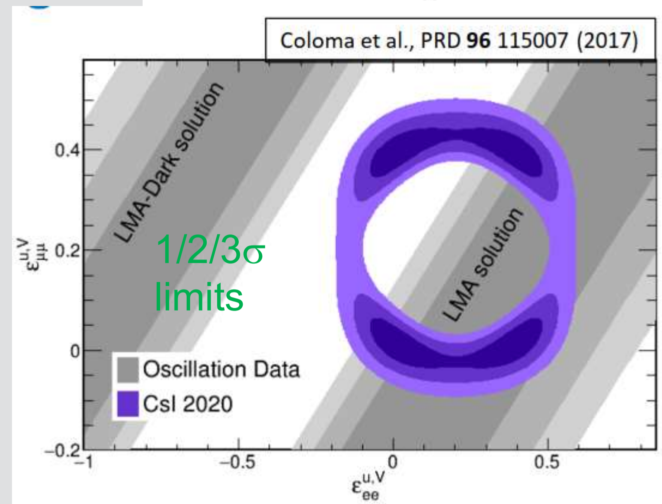
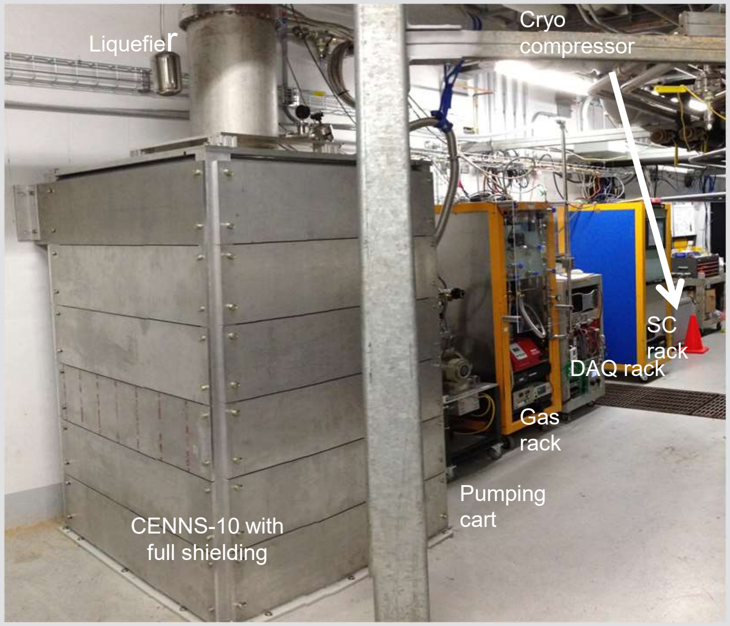


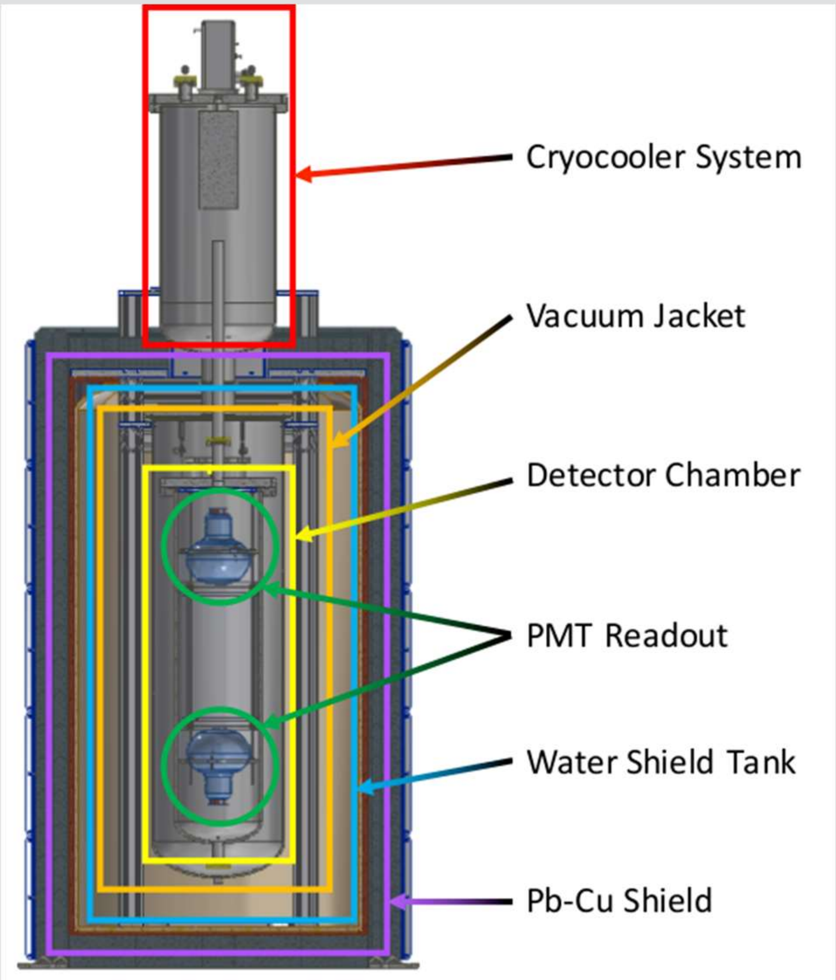


<u>The CENNS-10 (COHAr-10) Detector:</u>

Specs:

- single phase LAr scintillation
- fiducial volume = 24kg
- 28m from target
- Energy threshold ≈ 20keVnr
- ≈140 CEvNS events/SNS-year (7GWhr)
- Production run in current configuration 2017-2021





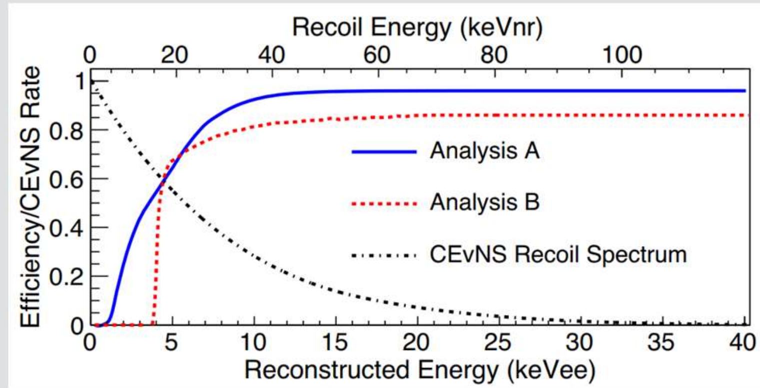
CENNS-10 analysis:

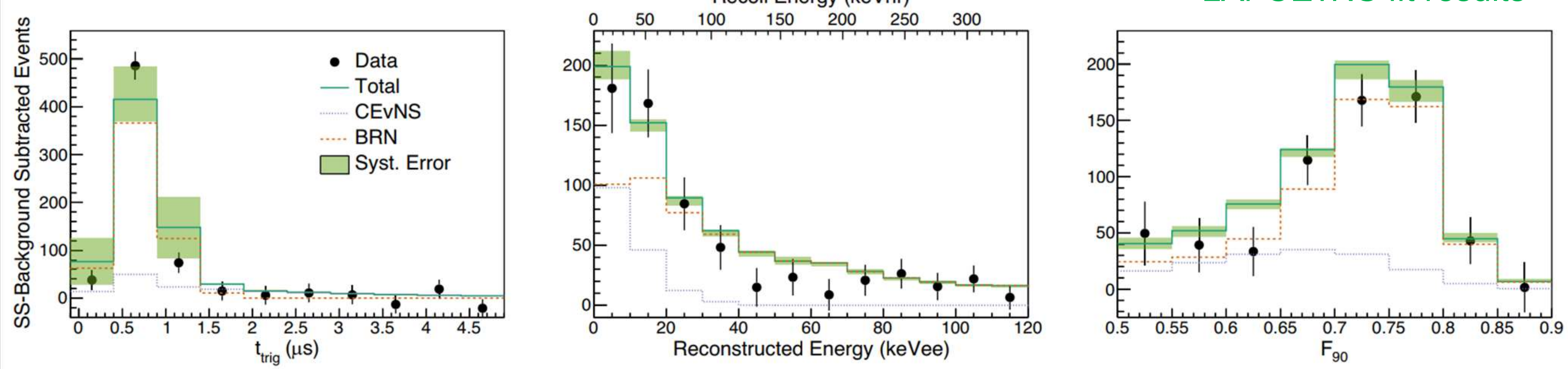
- From first 1.5 years of data…
- 2 blind, independent analyses
- Likelihood fit of beam data in energy, time, particle-ID
- Evidence for CEvNS in LAr at >3σ
- DOI: 10.1103/PhysRevLett.126.012002
- data set has since increased by ~3x, updated results in near future

Fit values:	
N_{CEvNS}	159 ± 43
N_{BRN}, prompt	553 ± 34
N_{BRN}, delayed	10 ± 11
N_{SS}	3131 ± 23
Total events fit	3853

Fit results:	
Null significance (stat. only)	3.9σ
Null significance (stat.+sys.)	3.5σ

Measured σ ($\times 10^{-39}$ cm^2)	2.3 ± 0.7





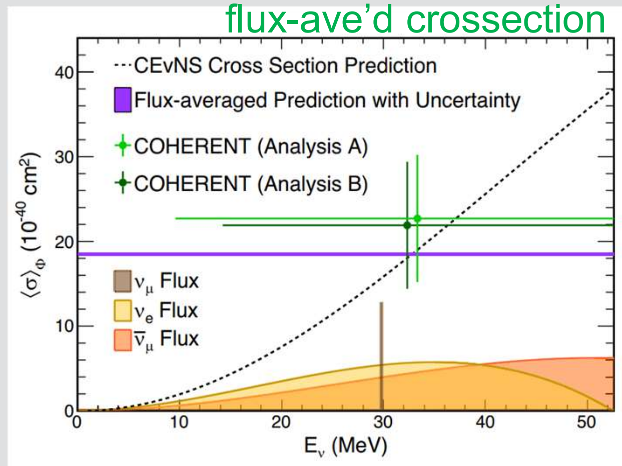
LAr CEvNS fit results

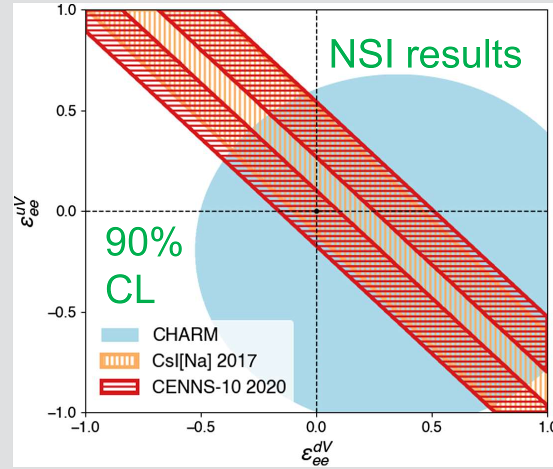
CENNS-10 results:

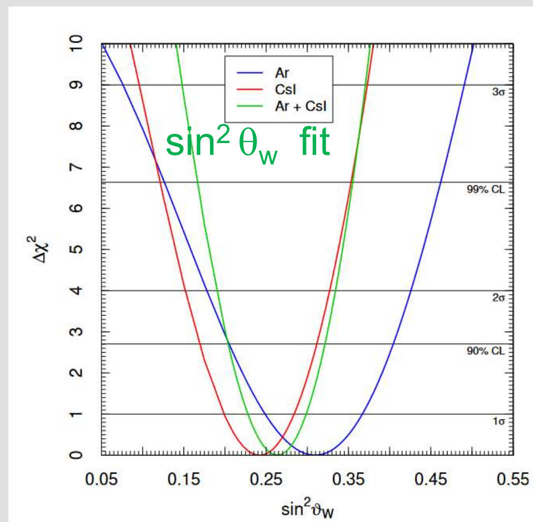
- Measured cross section agrees between with standard model

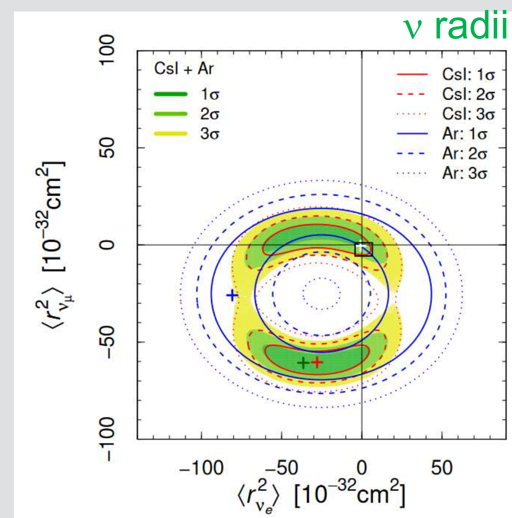
- NSI parameters further constrained

- much interest from theoretical community eg: doi:10.1103/PhysRevD.102.015030



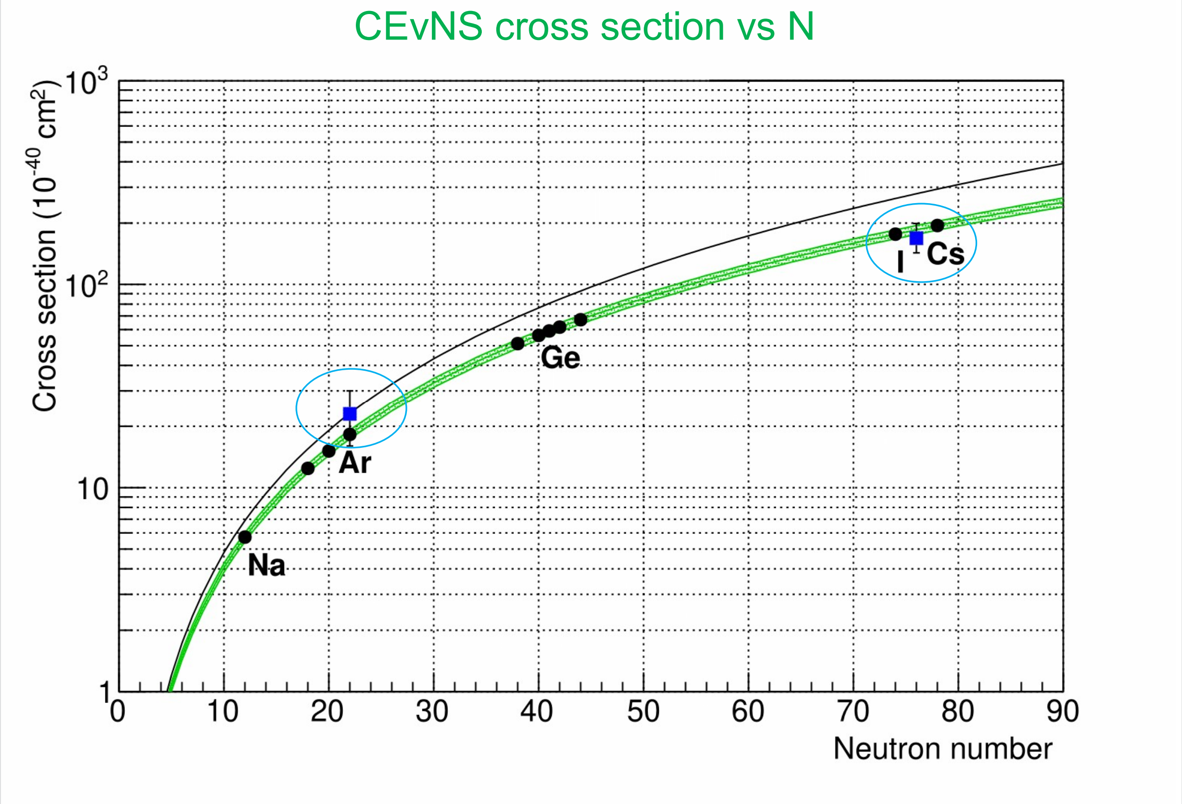






COHERENT LAr analysis:

- with LAr result, together with CsI, have measured N^2 - dependence of CEvNS

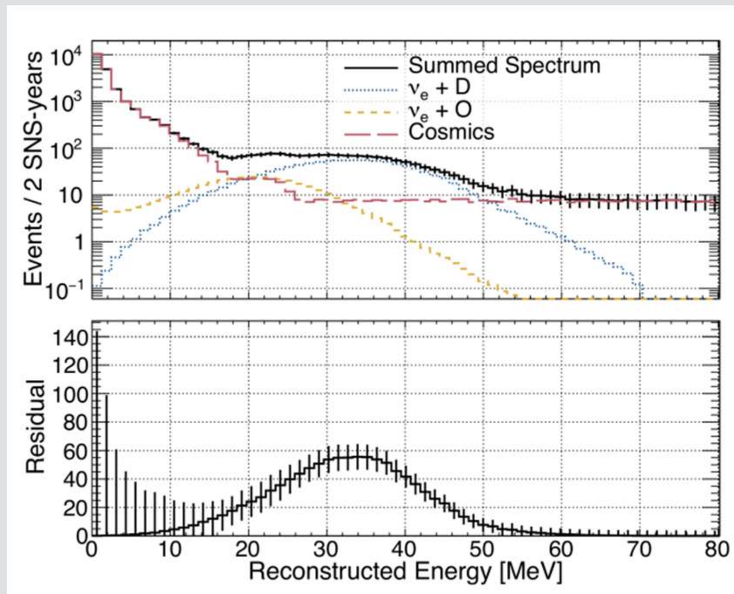


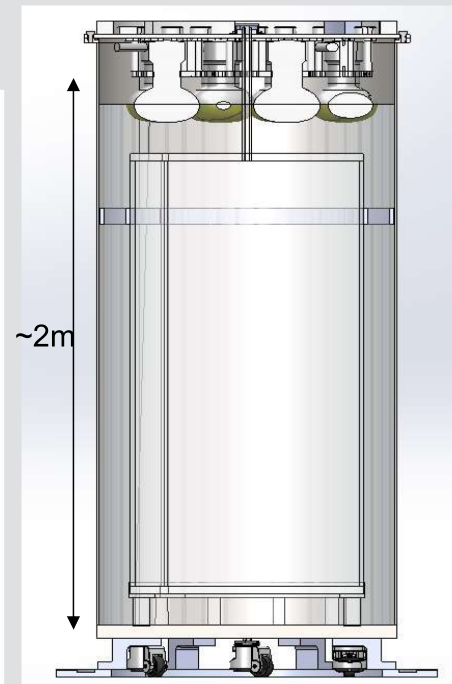
- but now need to increase stats, lower systematics, to realize a full low-E neutrino program

Important new addition to COHERENT : D_2O

D_2O flux normalization detector:

- reduce current 10% flux error to 2-3% from known ν-d CC cross section allowing more precise measurements of CEvNS etc with other detectors
- Light collection with PMT's on one endcap
- 670kg heavy water fiducial volume in acrylic vessel
- Installed this summer, commissioning underway
- *JINST* 16 (2021) 08, 08.





116. Study of Neutrino Interactions by the COHERENT collaboration
Yuri V Efremenko
25/08/2023, 17:30
WG2: Neutrino Scatterin... | Oral | Parallel

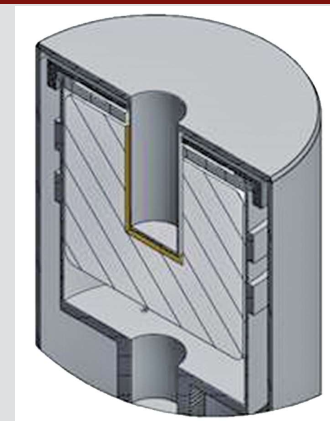
66. Detecting Charged-Current Neutrino-Nucleus Interactions on Oxygen in a Heavy Water Cherenkov Detector
Eli Mygatt Ward
WG2: Neutrino Scatterin... | Poster

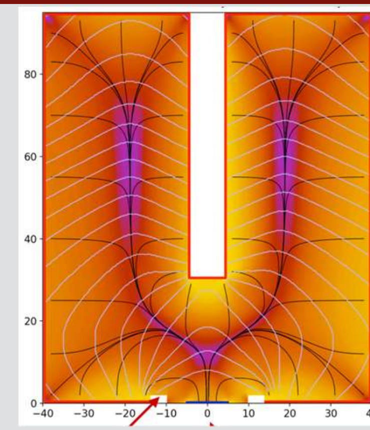
New COHERENT detectors

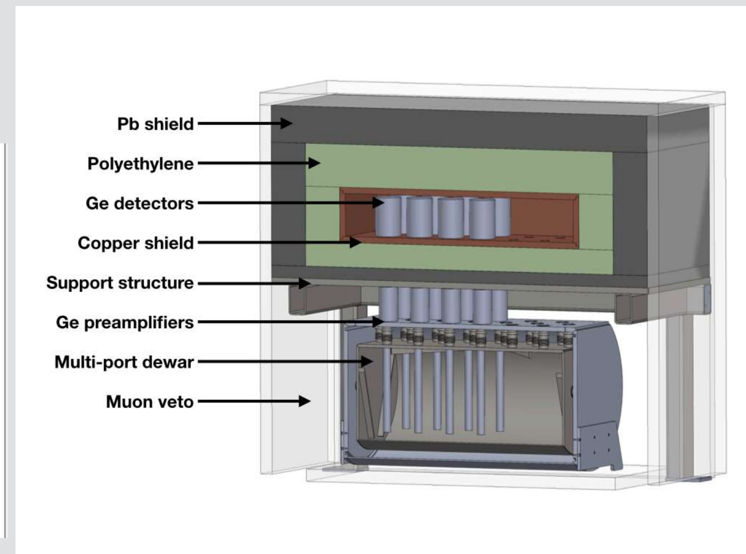
Germanium:

- P-Type Point Contact Ge detectors well-suited to precision CEvNS measurements
- 6 - 2kg detectors ran with 1.7MW SNS beam this summer
- expected ~2.5keVnr threshold
- Initial results expected this fall

Specifications:
- Mass > 2kg each
- Low-noise pulse-reset preamplifiers:
  - 150-eV FWHM pulser resolution
  - ~0.4 keVee (2.5 keVnr) CEvNS detection threshold
- Low-background cryostat materials, thick window.

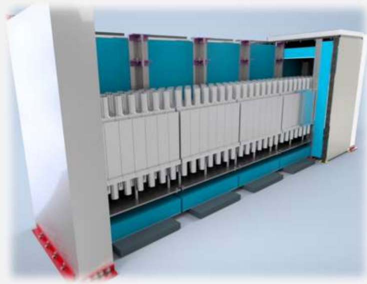






New COHERENT detector: NaI

- Installation/ commissioning in progress



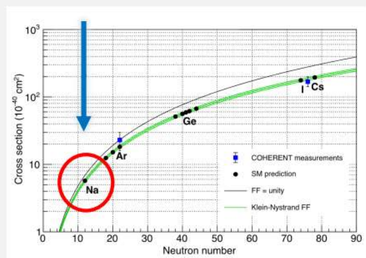
Model of 5-module layout

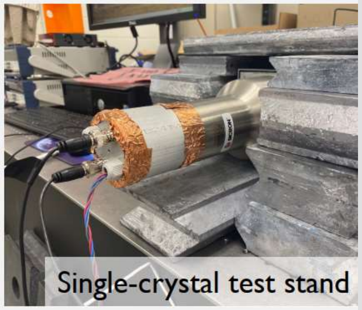
One module test assembly at Duke

The next generation: NaIvETe

"Sodium iodide (NaI) Neutrino (ν) Experiment TonnE-scale"

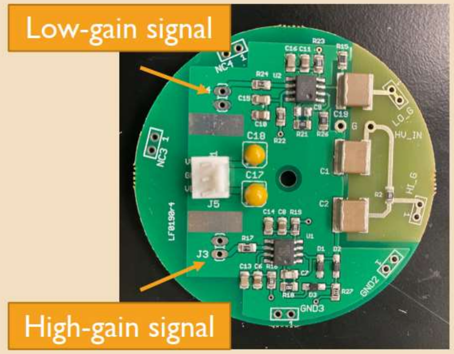
- Modular design:
  - **7.7 kg NaI[Tl] crystals** with attached PMTs
  - **63 crystals** per module
  - Steel, water, & lead shielding
  - 5 modules to be deployed by end of 2022 → **2.4 tonnes!**
- Order of magnitude target mass increase from 185-kg NaIvE
- Planned **sensitivity to CEvNS on ^{23}Na nucleus**, as well as CC on ^{23}Na and ^{127}I
  - Testing **N^2 dependence of σ_{CEvNS}** with lightest nucleus in COHERENT



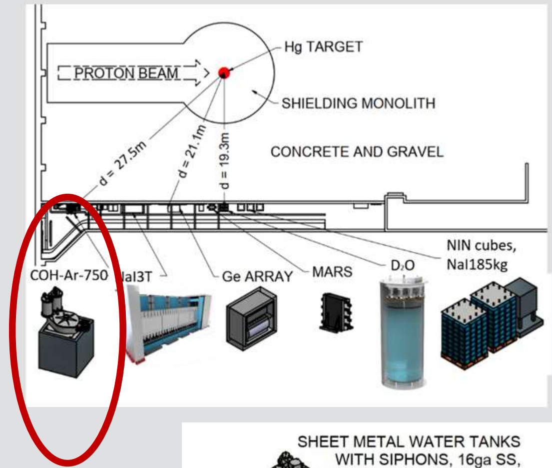


Single-crystal test stand

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

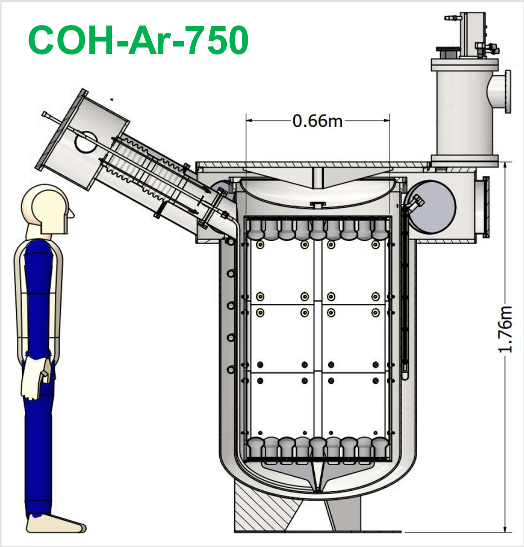


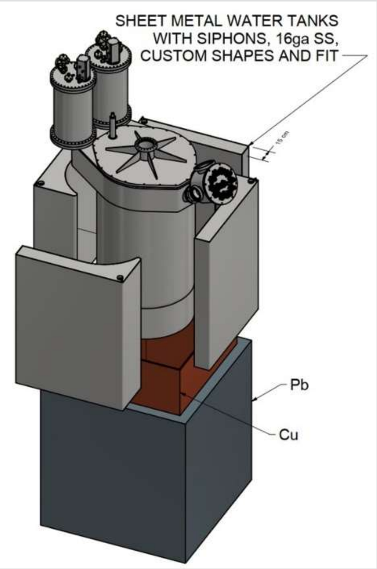
Future ton-scale argon detector for COHERENT: COH-Ar-750



Overview

- Single-phase LAr (scintillation-only) calorimeter, ~750/600kg total/fiducial volume
- Purpose-designed cryostat w/LN2 precool, and dual cryocooler for liquification/gas purification.
- Light collection: 3”PMTs
- water, Cu, Pb shielding scheme
- ⇒ 3000 CEvNS, 500 inelastic CC/NC events/yr to further physics reach of COHERENT



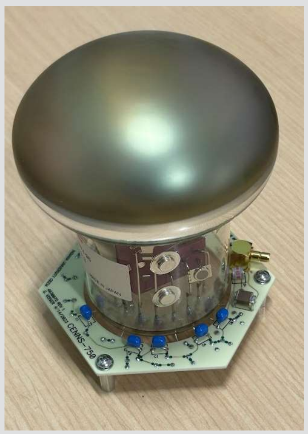


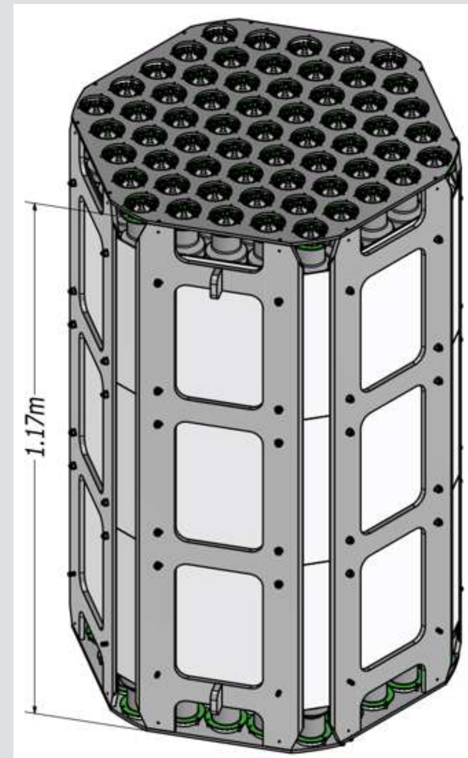
COH-Ar-750: status

- phase 1 detector funded

- on track for commissioning by end of 2
- parts procurement/fabrication/testing underway
- also testing for phase 2 upgrades: SiPMs, Xenon-doping, etal

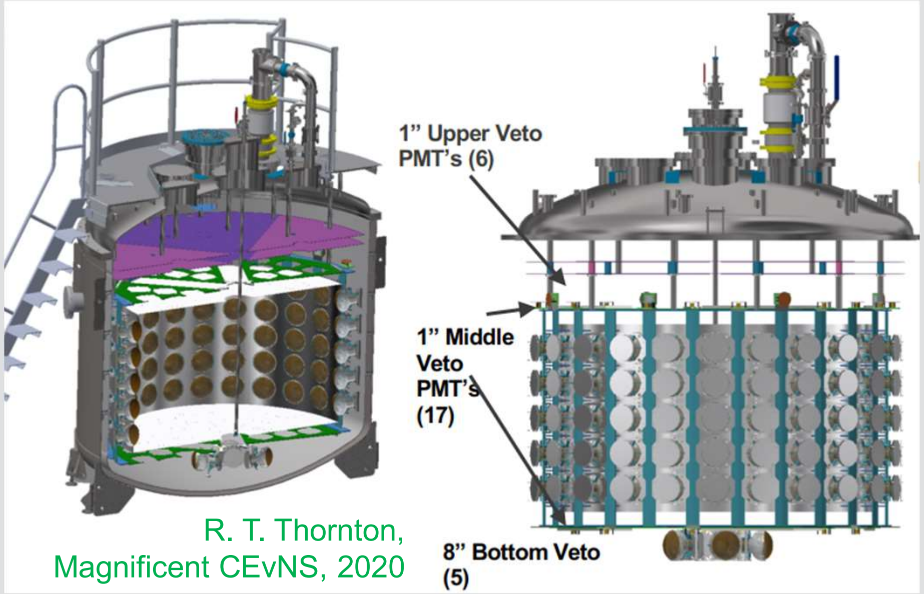
140. A ton-scale single phase LAr CEvNS detector
Haemin Jeong
25/08/2023, 11:40
WG6: Detector Physics | Oral | Parallel



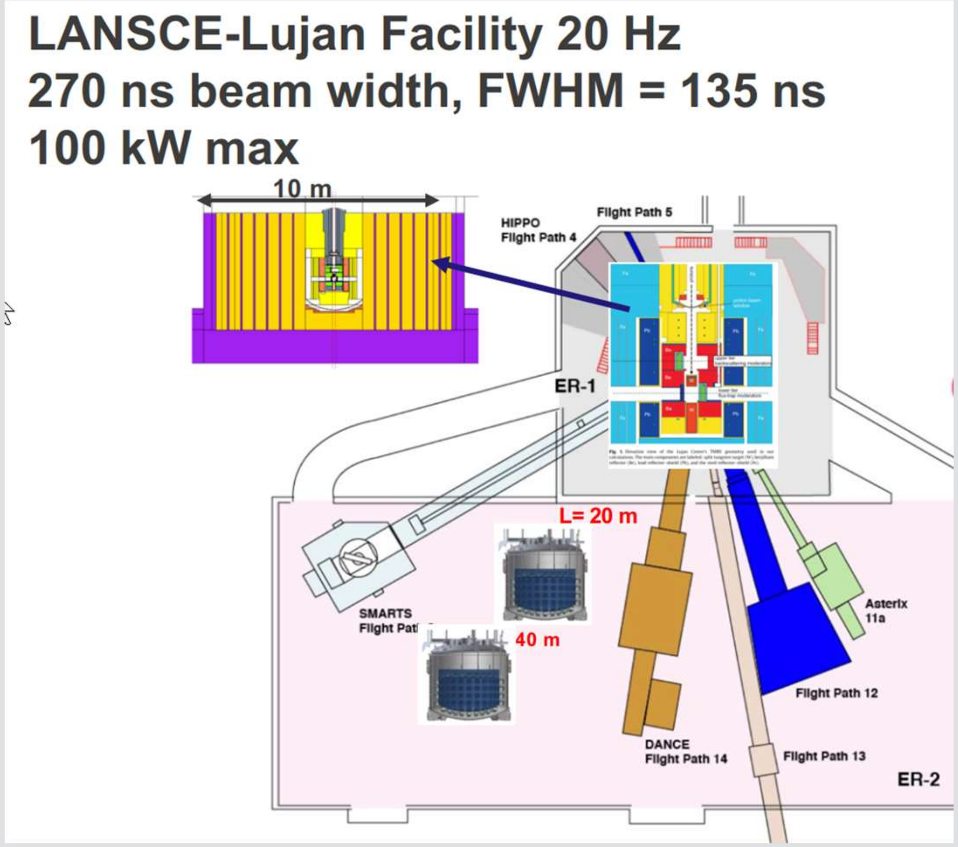


CEvNS π DAR experiments - CCM

- Coherent CAPTAIN-Mills (CCM)
- LANL Lujan neutron facility @ ~100kW
- 7 ton LAr scintillation detector
- First results on light DM, work on CEvNS progressing



R. T. Thornton,
Magnificent CEvNS, 2020



Beyond neutrino alley, at SNS:

Proton Power Upgrade

PPU project: Double the power of the existing accelerator structure

- First Target Station (FTS) is optimized for thermal neutrons
- Increases the brightness of beams of pulsed neutrons
- Provides new science capabilities for atomic resolution and fast dynamics
- Provides a platform for STS

Larger Neutrino Experimental Hall Possible at STS: 2 10-ton Detectors

Second Target Station

STS project: Build the second target station with initial suite of beam lines

- Optimized for cold neutrons
- World-leading peak brightness
- Provides new science capabilities for measurements across broader ranges of temporal and length scales, real-time, and smaller samples

Slide from Ken Herwig, Workshop on Fundamental Physics at the Second Target Station (FPSTS18)

+ future at Fermilab

122. Physics Opportunities at a PIP-II Beam Dump Facility and Beyond
Jacob Zettlemoyer
25/08/2023, 17:42
WG5: Neutrinos Beyond ... Oral Parallel

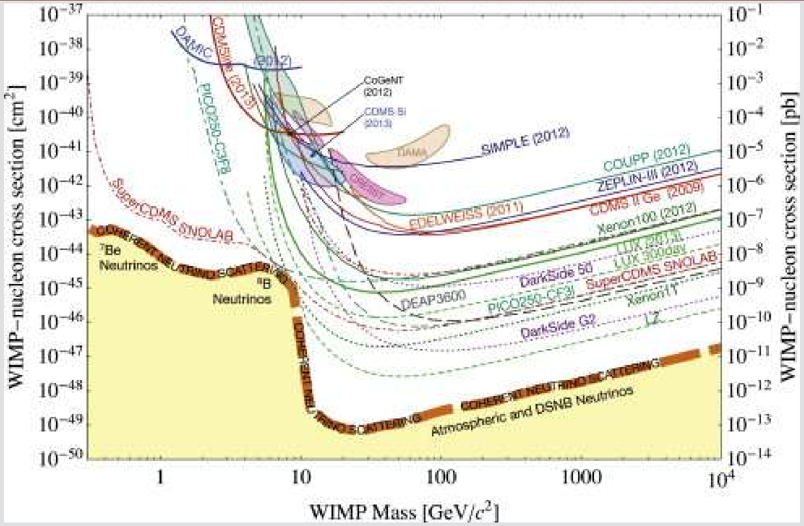
+ future at ESS

ESSnuSB+ mini workshop (20th of Aug. 2023)

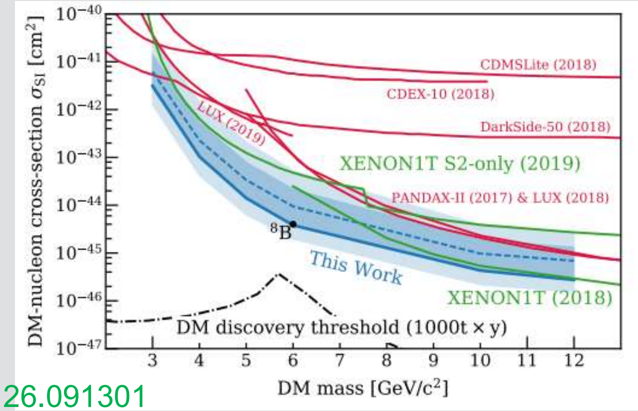
Date: Sunday 20 Aug., 2023, 14:00 – 16:30 (KST)

Dark matter Experiments - CEvNS

- CEvNS is important background for O(10)-ton direct DM searches – the neutrino “floor” (or “fog”)
- O(10)-ton experiments setting limits, should see evidence soon
- Should see supernova signals in these detectors via CEvNS
- Important to measure CEvNS cross section independently



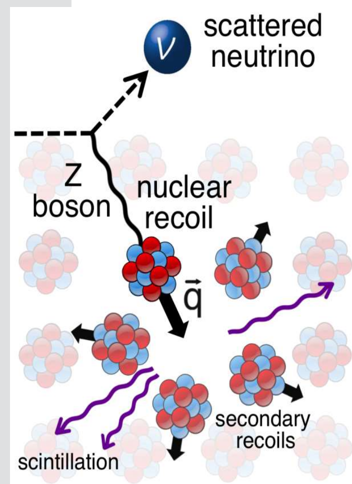
J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).



DOI: 10.1103/PhysRevLett.126.091301

Summary

- CEvNS process measurements have come from a dream to reality in ~10 years
- First measurements of CEvNS on CsI, Ar have been made with COHERENT at the SNS.
- Other experiments, including at reactors, likely to see signals soon.
- Multiple physics motivations drive further work on additional/larger detectors, for more precise measurements at multiple sites.



virtual tour of neutrino alley:
https://my.matterport.com/show/?m=XYA19MBVdQS

Thanks for material: COHERENT, M. Cadeddu,
E. Figueroa-Feliciano

Thanks for support and $$$/KRW: ORNL/SNS,
Fermilab, NSF, DOE, NRF-Korea,
COHERENT collaboration

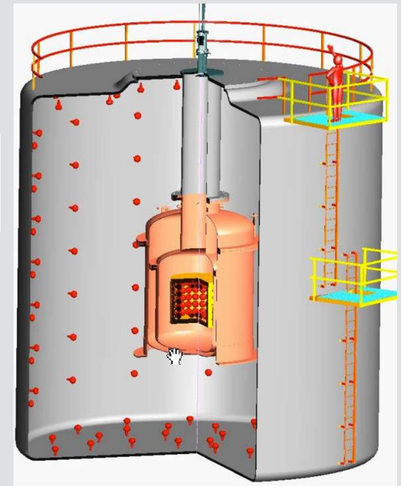
CEvNS: Coherent Elastic ν-Nucleus Scattering: νA→νA

From NuInt2012:

NuInt12 : Eighth International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

Oct 22 – 27, 2012
Brazil/East timezone

Very low neutrino interactions		
Helium and lead observatory od supernovae neutrinos	Prof. Clarence Virtue	16:00 - 16:30
Possibilities for direct nu-Argon cross section measurements in the low energy region	Prof. Flavio Cavanna	16:30 - 17:00
Coherent elastic neutrino scattering	Dr Yoo Jonghee	17:00 - 17:30



Ton-scale detector
for the CENNS experiment

CENNS Physics Cases

- It's never been observed

Requires a ton-scale detector with ~10 keV energy threshold

$$R \simeq \mathcal{O}(10^3)\left(\frac{\sigma}{10^{-39}cm^2}\right)\times\left(\frac{\Phi}{10^{13}\nu/year/cm^2}\right)\times\left(\frac{M}{ton}\right) events/year$$

CEvNS: Coherent Elastic ν-Nucleus Scattering: νA→νA

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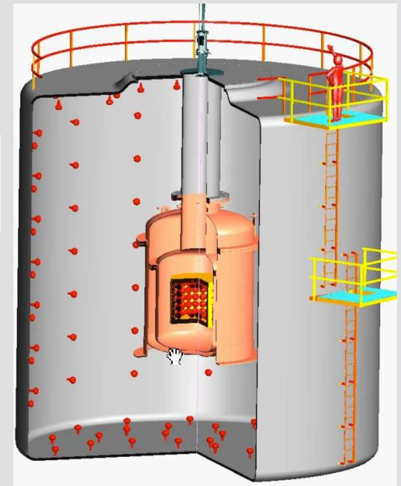

Ton-scale detector
for the CENNS experiment

done ✓

CENNS Physics Cases

- It's never been observed

next step

Requires a ton-scale detector with ~10 keV energy threshold

$$R \simeq \mathcal{O}(10^3)\left(\frac{\sigma}{10^{-39}cm^2}\right)\times\left(\frac{\Phi}{10^{13}\nu/year/cm^2}\right)\times\left(\frac{M}{ton}\right) events/year$$