Workshop on Neutrinos and related New Physics Research

Overview of CEvNS Experiments

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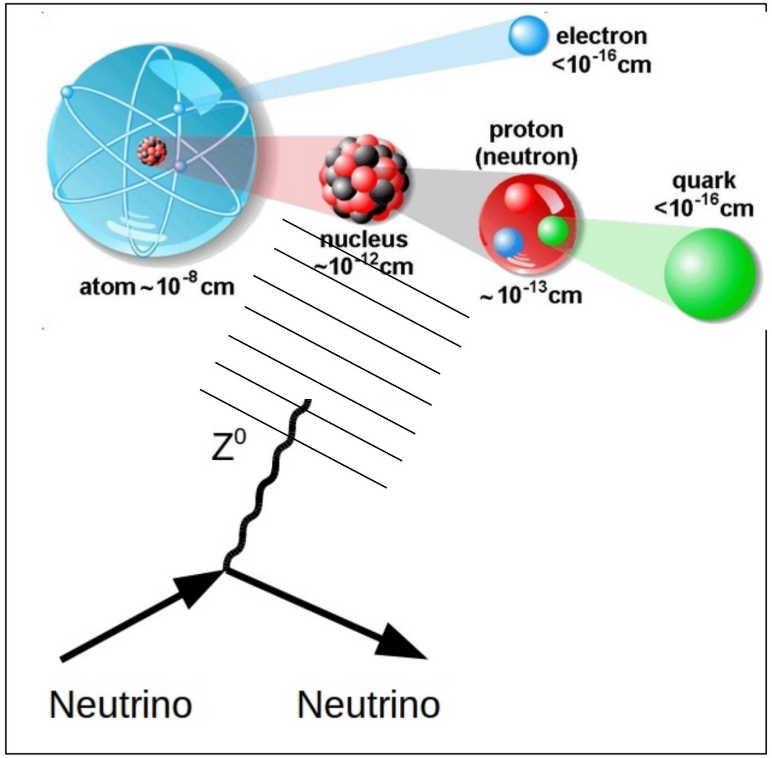
2025-11-30, Zhuhai

With materials from: Manfred Lindner, Qing Lin, Xiang Xiao, Qian Liu, Litao Yang

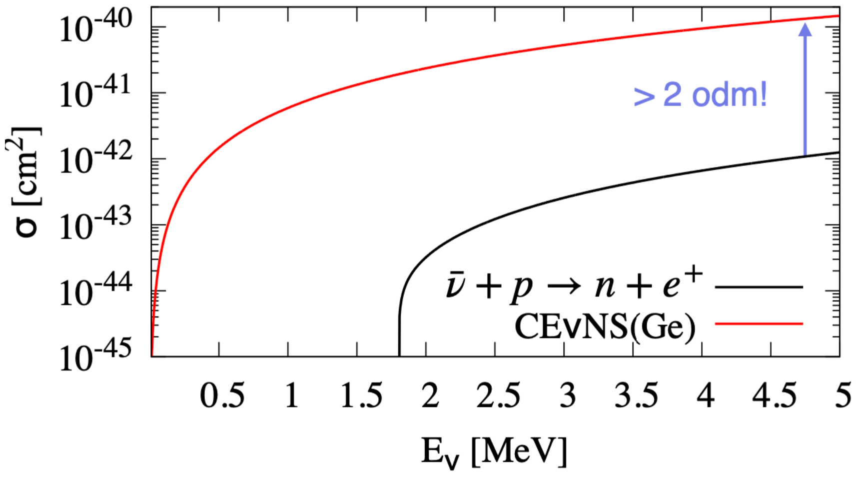
Coherent Elastic neutrino Nucleus Scattering (CEvNS)

CEvNS is an SM interaction between neutrinos and matter



$$\sigma_{\mathrm{CE}\nu\mathrm{NS}} = \frac{G_F^2}{4\pi} F^2(q^2) Q_W^2 E_\nu^2$$

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

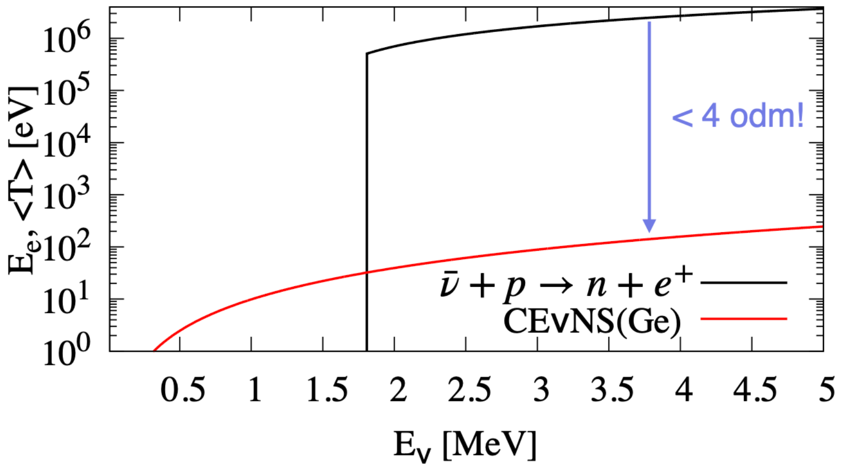


Cross-section is 2 orders of magnitude higher

Detectable energy is 4 orders of magnitude lower!

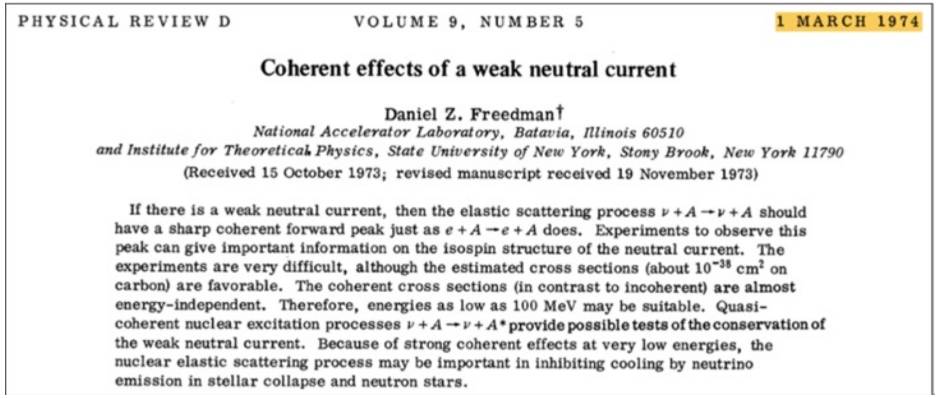
Observable: kinetic energy of nuclear recoil

$$< T > = \frac{2}{3} \frac{E_\nu^2}{M_A}$$



CEvNS and Dark Matter Direct Detection

1974: CEvNS predicted

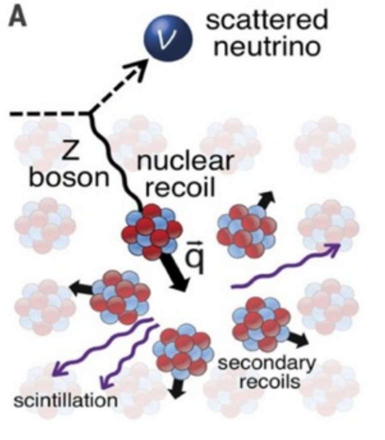


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

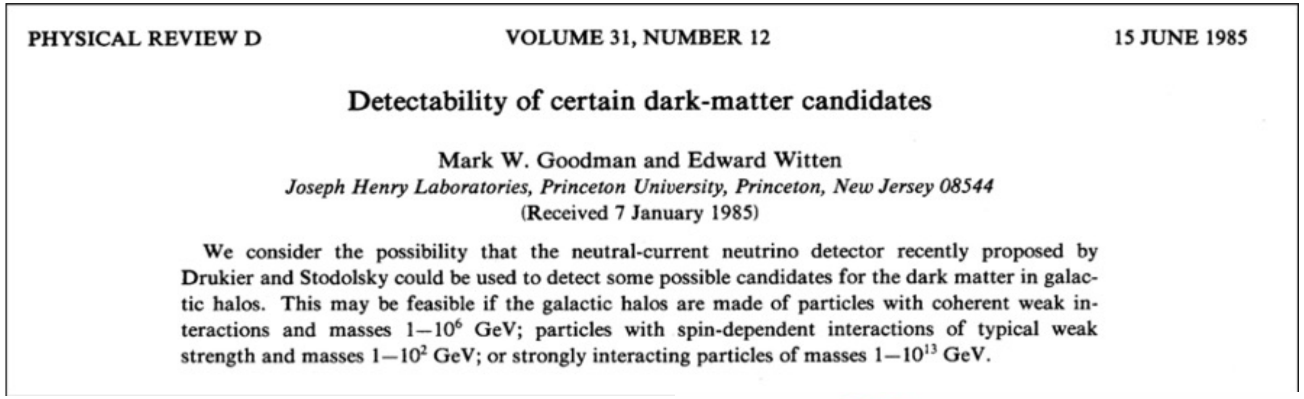
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

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



D. Akimov et al, Science 357 (2017)

1985: the birth of dark matter detection

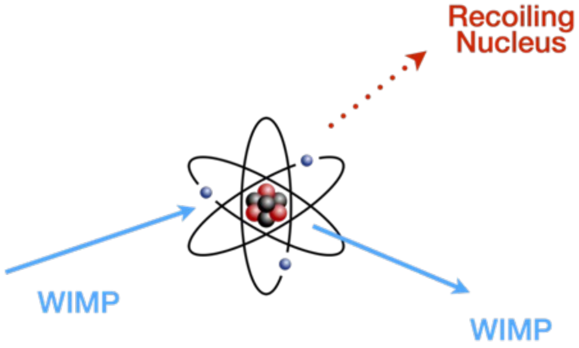


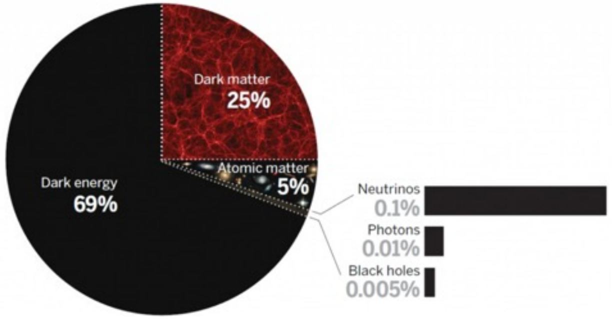
PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

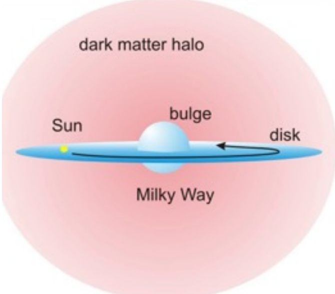
Detectability of certain dark-matter candidates

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.





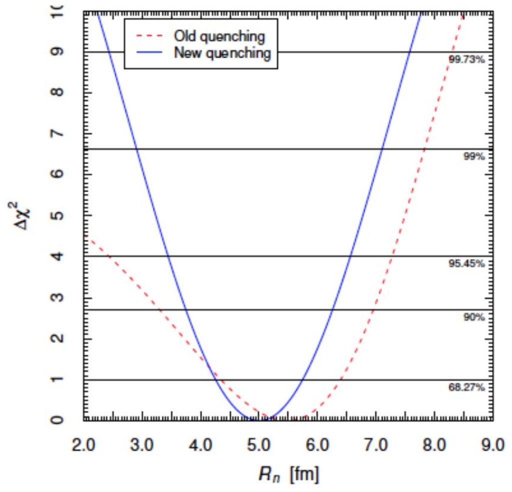


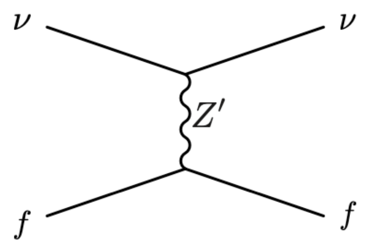
What can we learn from CEvNS

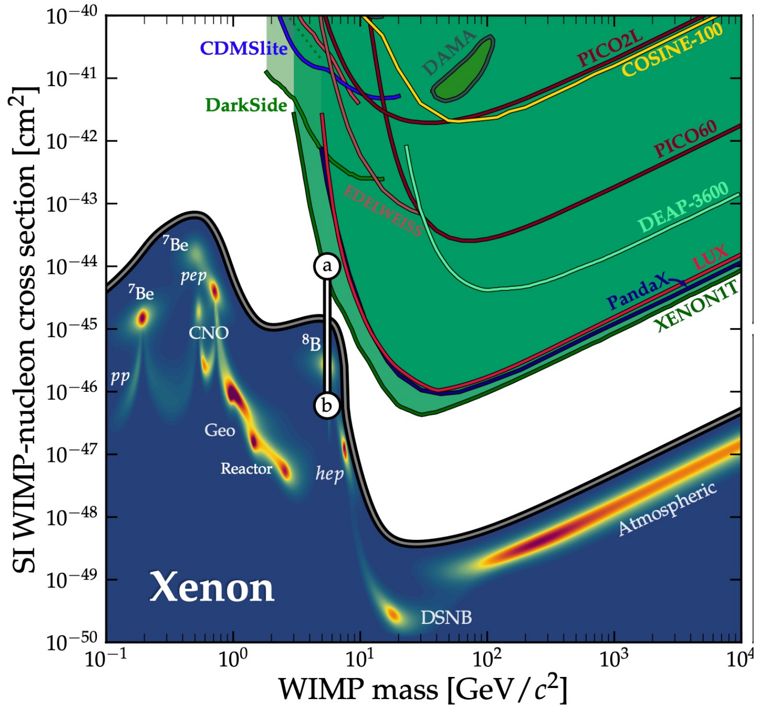
- Interaction of neutrinos with matter:
    - Cross-section
    - Nuclear form factor
    - Weak mixing angle
    - Non-standard interactions

- Reactor Physics
    - Reactor monitoring

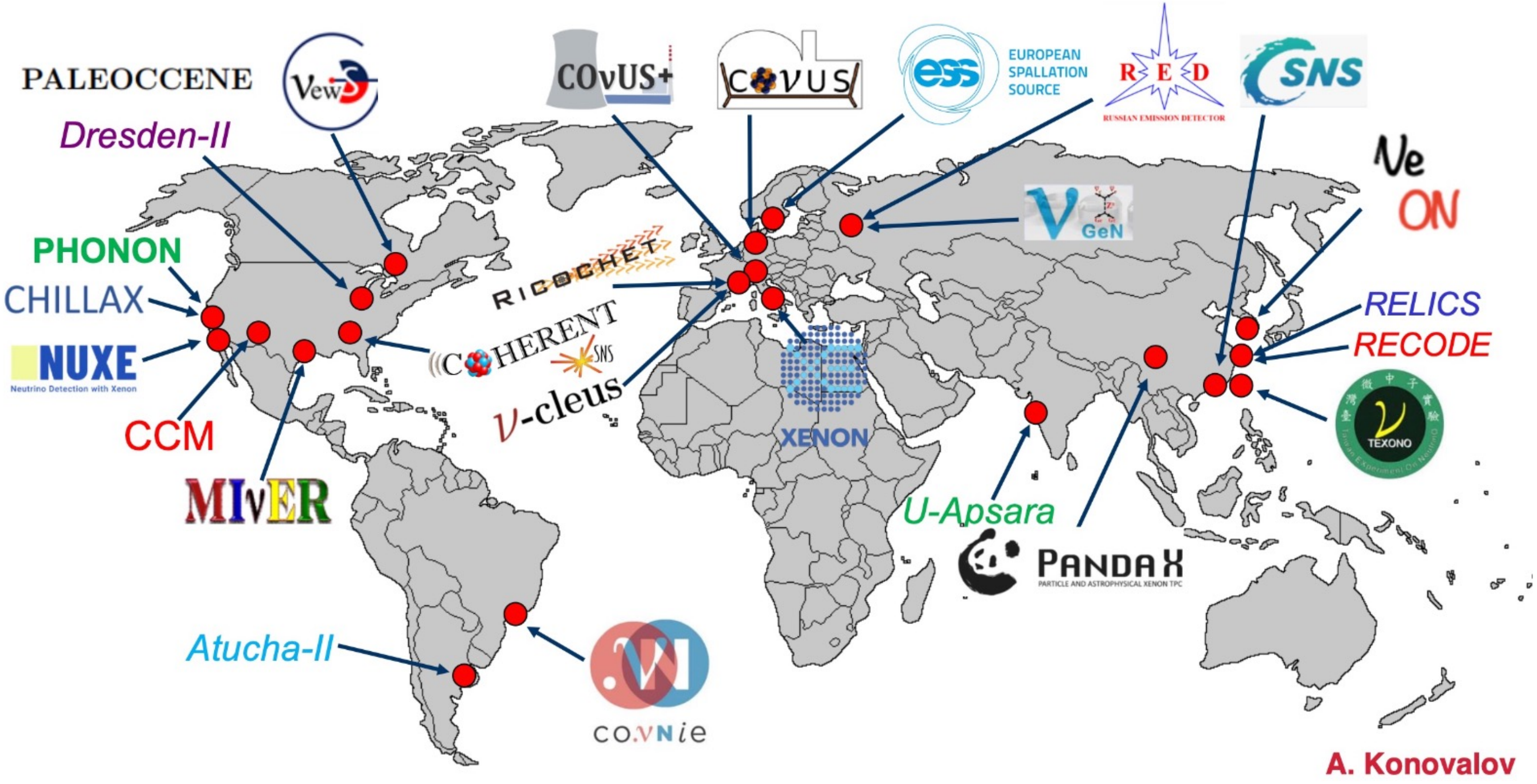
- Astrophysical neutrinos
    - Solar neutrino
    - Supernova neutrino
    - Neutrino fog in DM search







Status of CEvNS detection/measurement

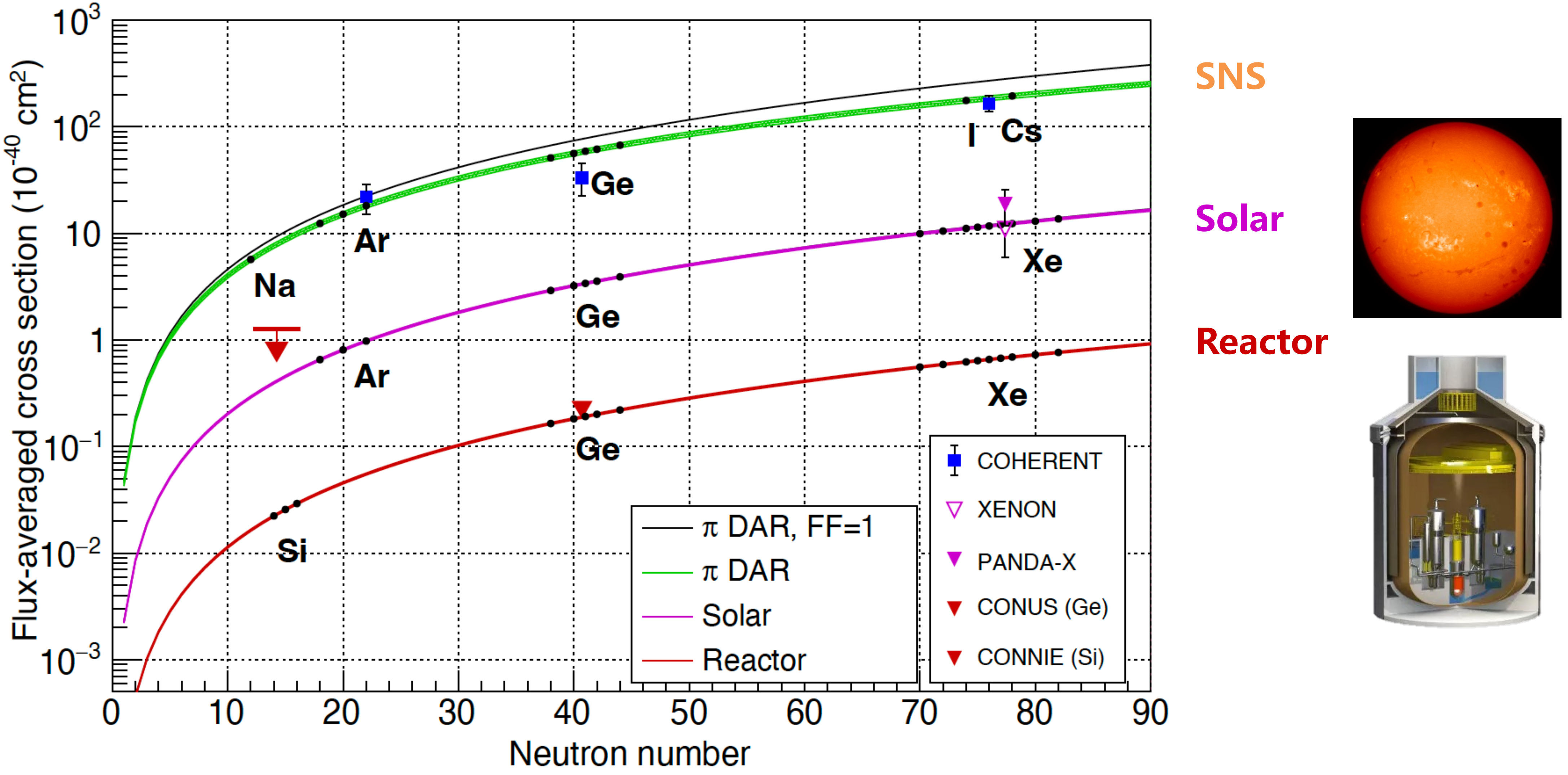


1974 –D. Freedman: coherent scattering of neutrinos on the whole nucleus (CEνNS)
2017 – observation by COHERENT in stopped π-beams ←→ F(q^2) - not fully coherent
2024 – solar ^{8}B neutrinos by XENONnT and PandaX
2025 – CONUS+ with reactor neutrinos

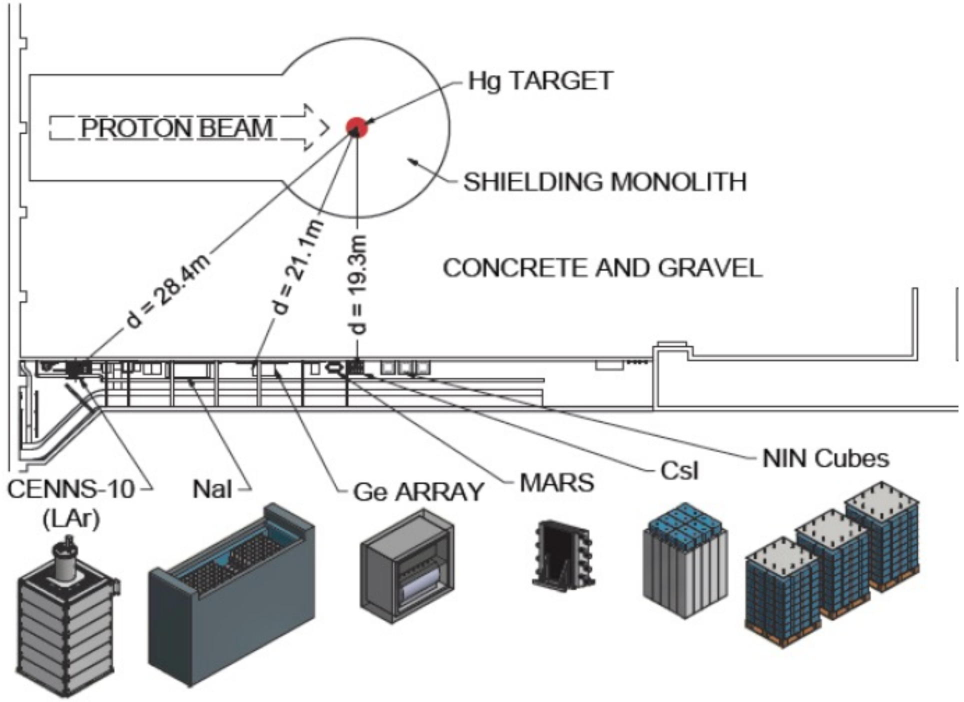
Experiments with positive CEvNS signals

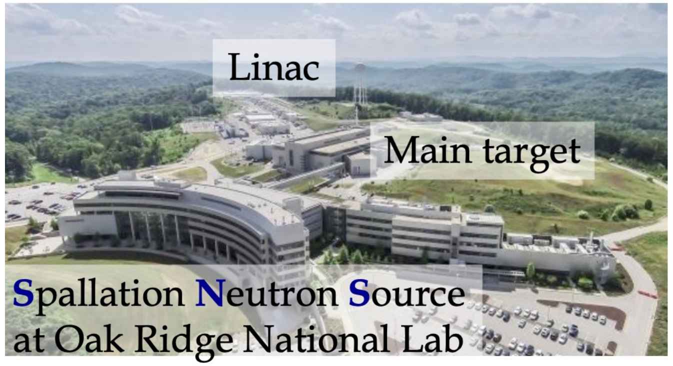
Experiment	Target	Source	Neutrino energy	Flux $[cm^{-2}s^{-1}]$	Data [counts]	Data/ SM prediction	Significance of null hypothesis rejection
COHERENT	Cs	Accelerator	10 – 50 MeV	$5 * 10^7$	306^{+20}_{-20}	$0.90^{+0.14}_{-0.14}$	$11.6\,\sigma$
COHERENT	Ar	Accelerator	10 – 50 MeV	$5 * 10^7$	140^{+40}_{-40}	$1.22^{+0.49}_{-0.49}$	$3.5\,\sigma$
COHERENT	Ge	Accelerator	10 – 50 MeV	$5 * 10^7$	21^{+7}_{-6}	$0.59^{+0.26}_{-0.24}$	$3.9\,\sigma$
XENONnT	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	11^{+4}_{-2}	$0.90^{+0.65}_{-0.67}$	$2.73\,\sigma$
PandaX-4T	Xe	Sun (^{8}B)	< 15 MeV	$5 * 10^6$	4^{+1}_{-1}	$1.25^{+0.69}_{-0.69}$	$2.64\,\sigma$
CONUS+	Ge	Reactor	< 10 MeV	$1.5 * 10^{13}$	395^{+106}_{-106}	1.14^{+036}_{-036}	$3.7\,\sigma$

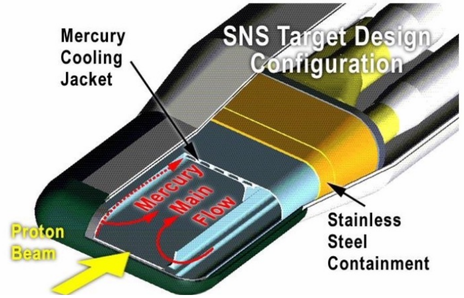
Status of CEvNS Measurements



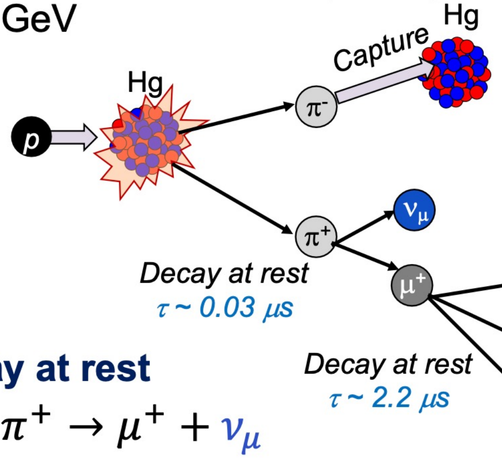
CEvNS with Spallation Neutron Source







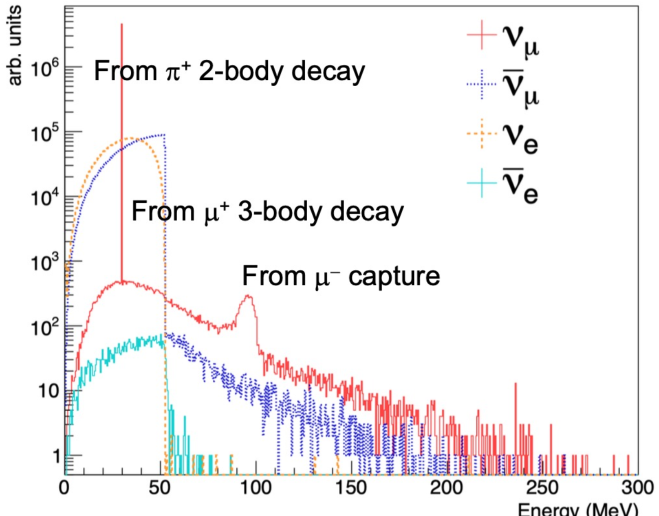
- Provides neutrons for materials science, life science, basic physics research
- Proton beam strikes liquid Hg target at ~1 GeV

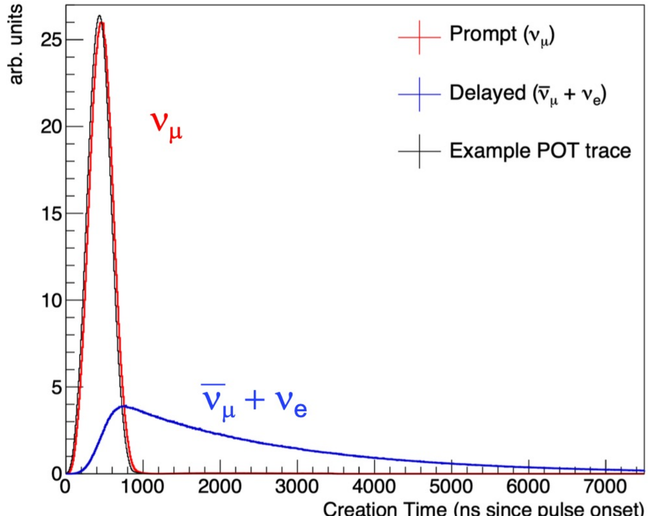


Pion decay at rest

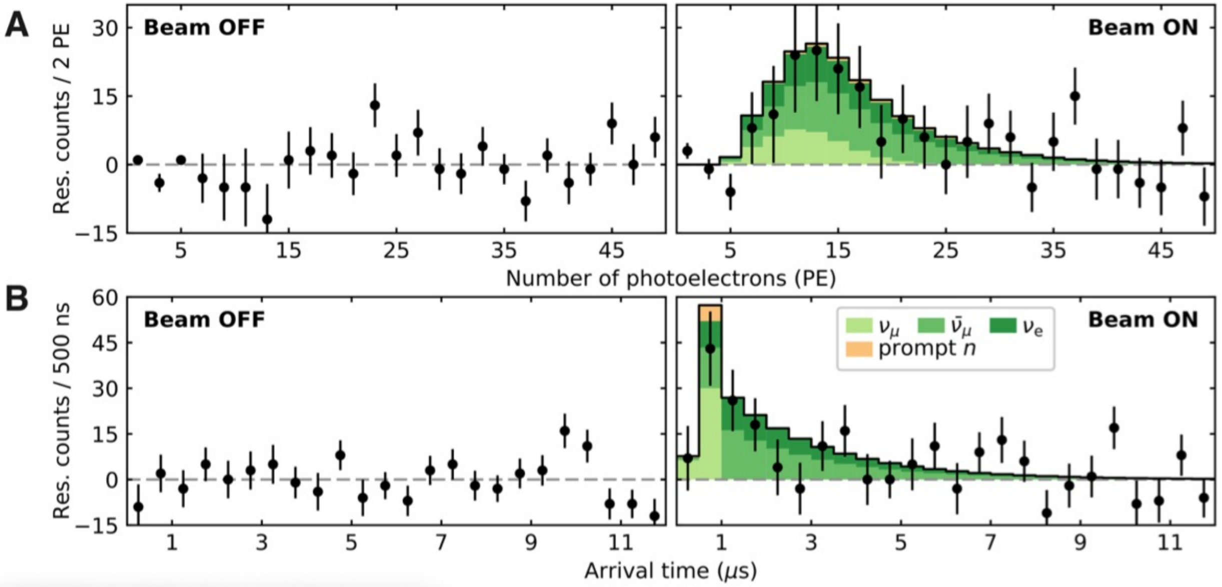
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

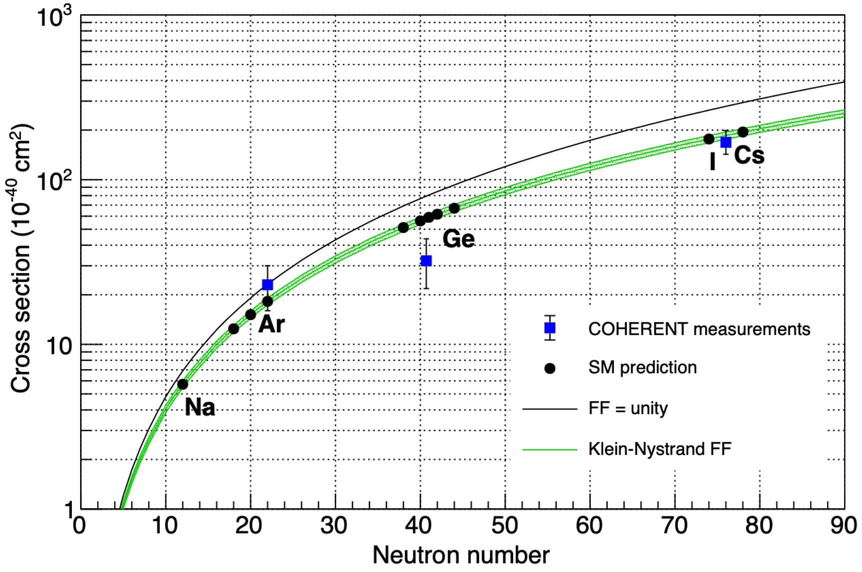
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

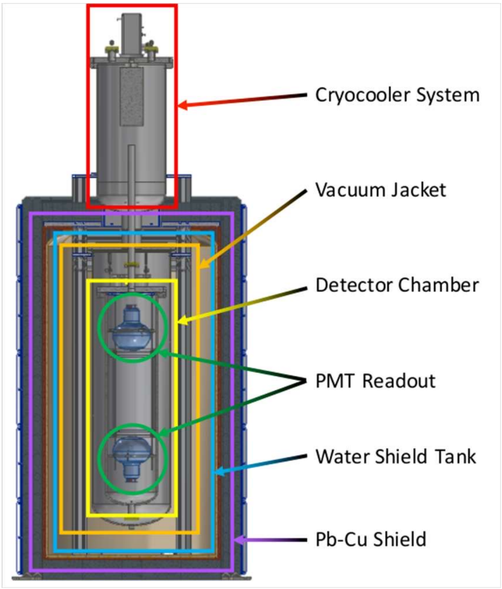


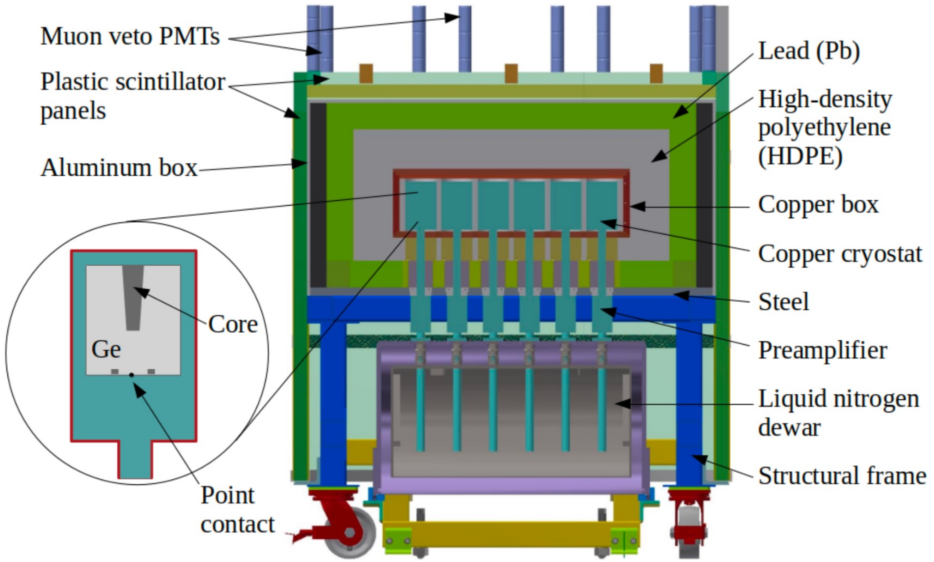


COHERENT: Observation with CsI+Ar+Ge



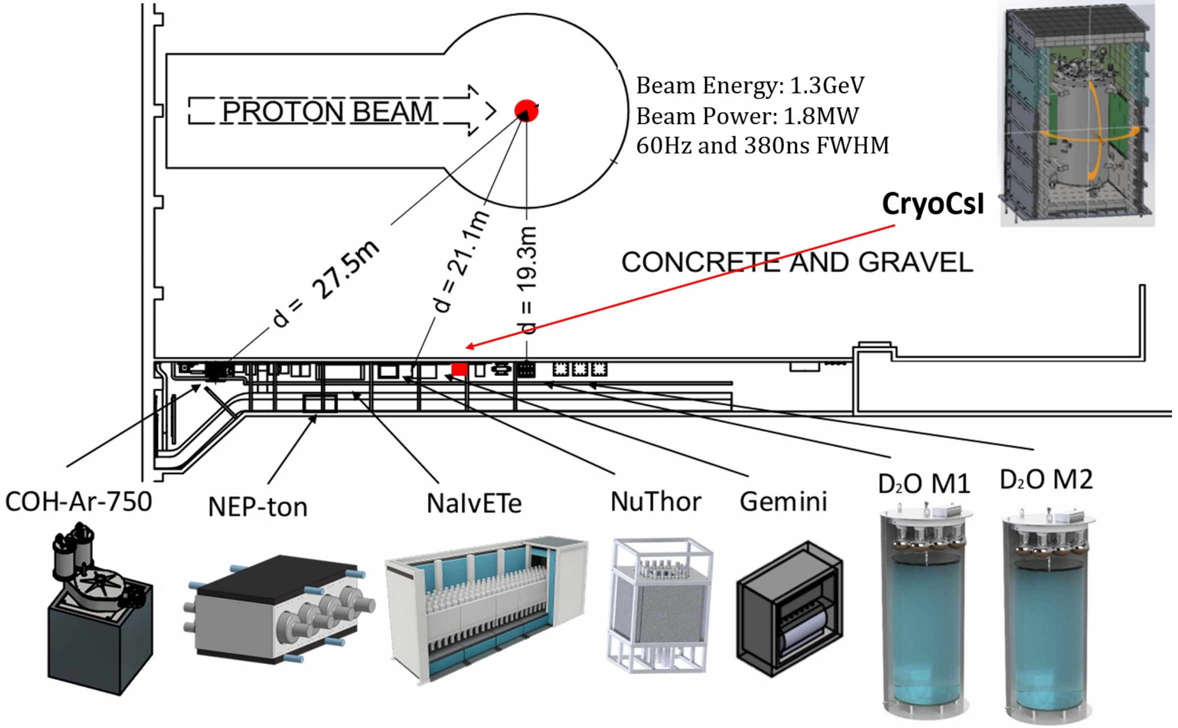






COHERENT：Future Plan and CryoCsI

- Goal: use **cryoCsI** detector to precisely measure CEvNS process at SNS (**3.3 kg CsI x2** from SICCAS)



Detector	Light yield (PE/keVee)	Quenching factor (%)	Afterglow (us)
CryoCsI	30	15	1
CsI(Na)	13	8	16

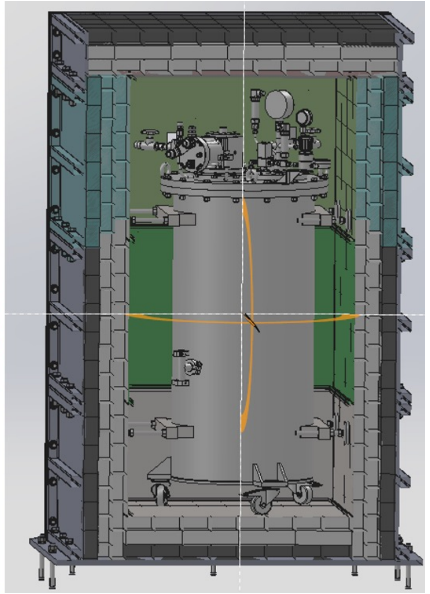
Threshold < $1\mathrm{keV}_{nr}$

Project Status:

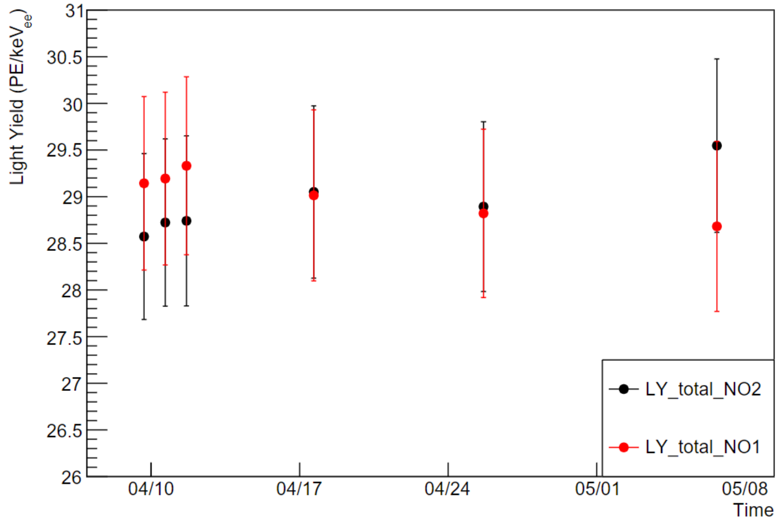
- Main detector R&D finished
- CsI performance verified
- Stable long-term operation

Where we are …

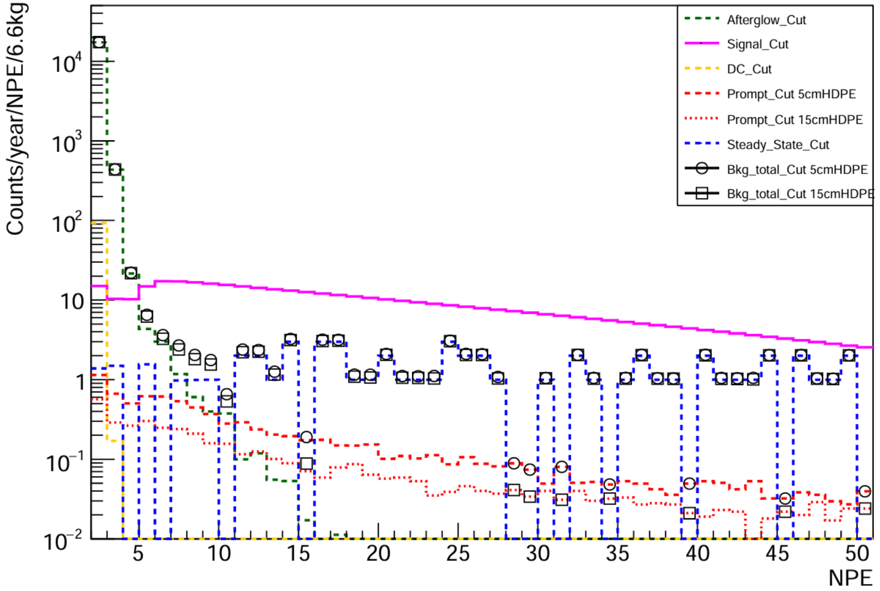
COHERENT：CryoCsI by UCAS



Light yield long-term stability



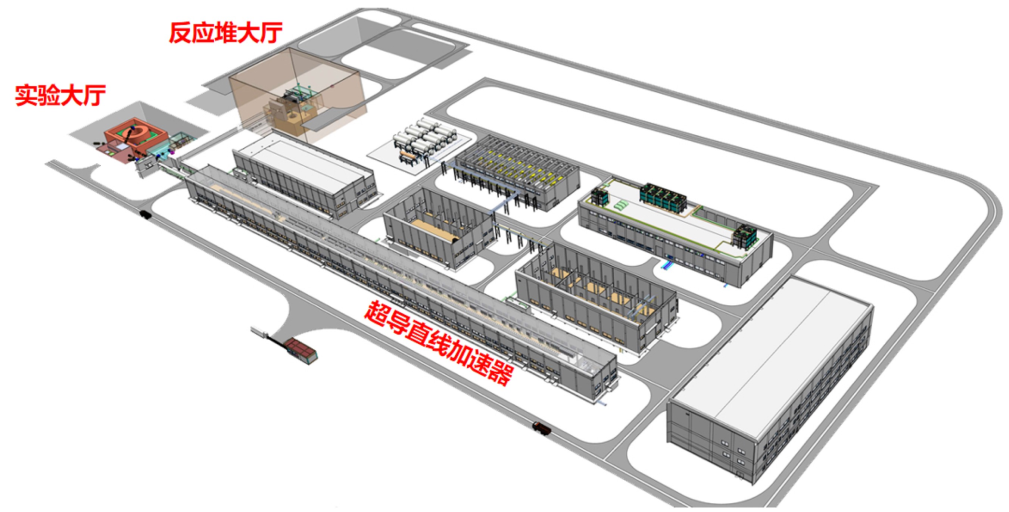
- Beam power: 1.4MW
- Distance: 19.5m
- Crystal mass: 6.6kg



- Expected background events: ~72 per year
- Expected neutrino signal: **387 per year**

- **5σ detection** for 1-month beam time

CSNS and CICENNS Experiemnt



	Power (MW)	Proton Energy (GeV)	Beam Type	Repetition Rate (Hz)
SNS	1.4 -> 2	1 -> 1.3	Pulse	60
J-PARC	0.6 -> 0.95	3	Pulse	25
CSNS	0.14 -> 0.5	1.6	Pulse	25
CiADS	0.3 -> 3	0.6	Continuous	

- Accelerator-driven sub-critical system to study the transmutation of spent fuel
- Continuous beam
- 600 MeV @300 kW (2027) -> @3 MW (2030)
- Possibly convert to pulsed beam

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

2-body π^+-decay: Prompt (26nsec)
Monochromatic: 29.9MeV ν_μ

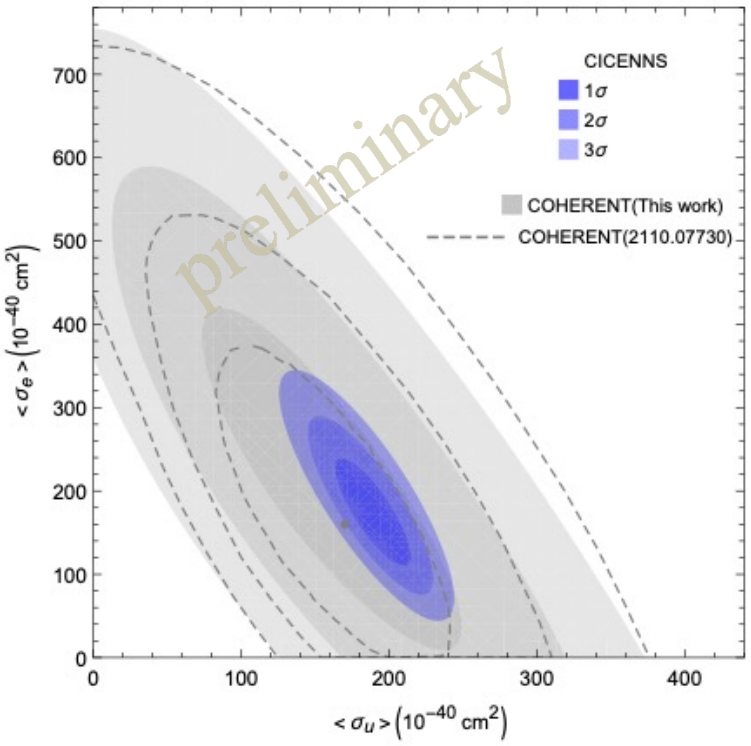
$$\downarrow$$

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

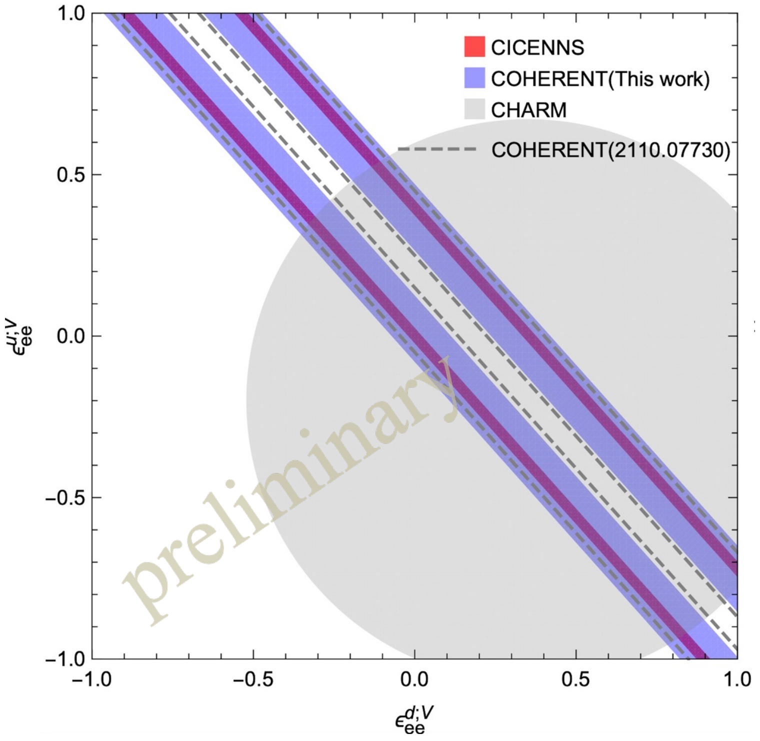
3-body μ^--decay:
Delayed (2.2μsec)
0-53MeV $\bar{\nu}_\mu$, ν_e

CICENNS Sensitivity

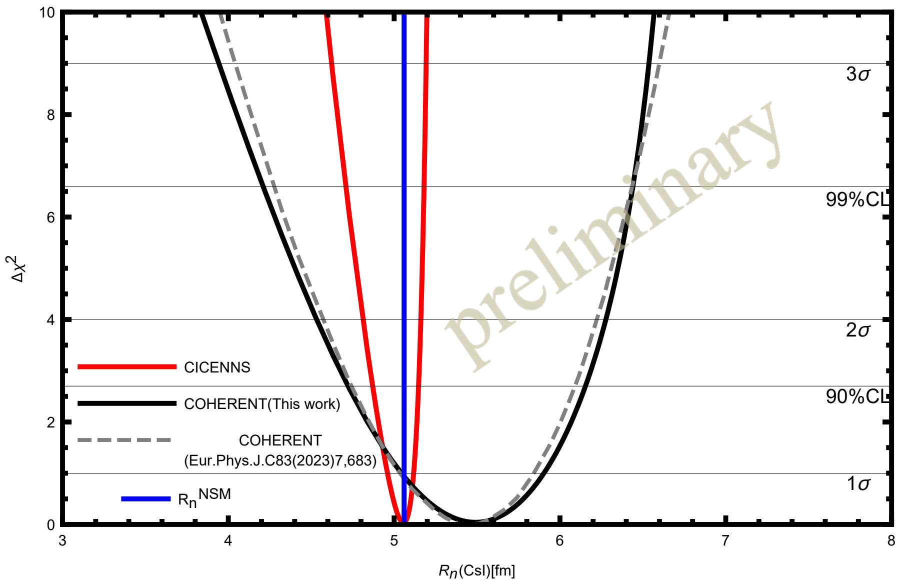
- CICENNS: CsI detector for Coherent Elastic Neutrino Nucleus Scattering
- Development of a 300-kg CsI(Na) detector for precise CEνNS measurement



Flavored CEνNS cross section: 15% → 8%

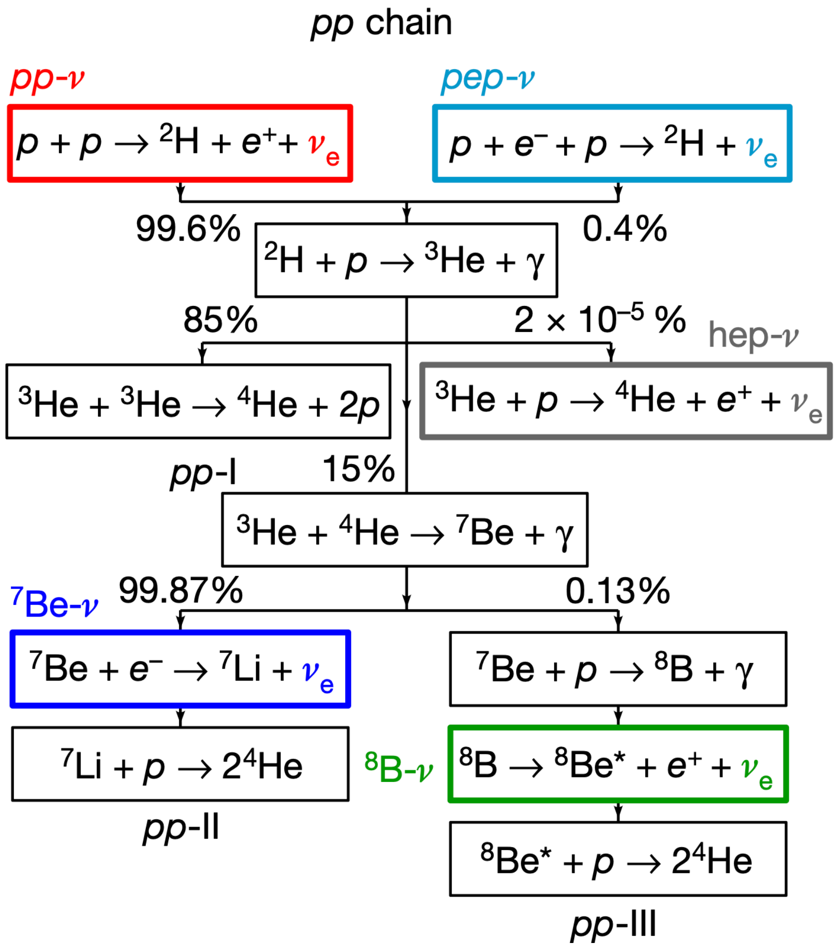


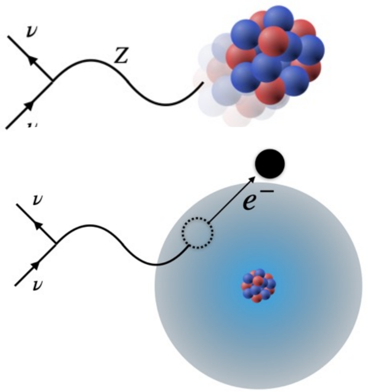
Non-standard neutrino interaction

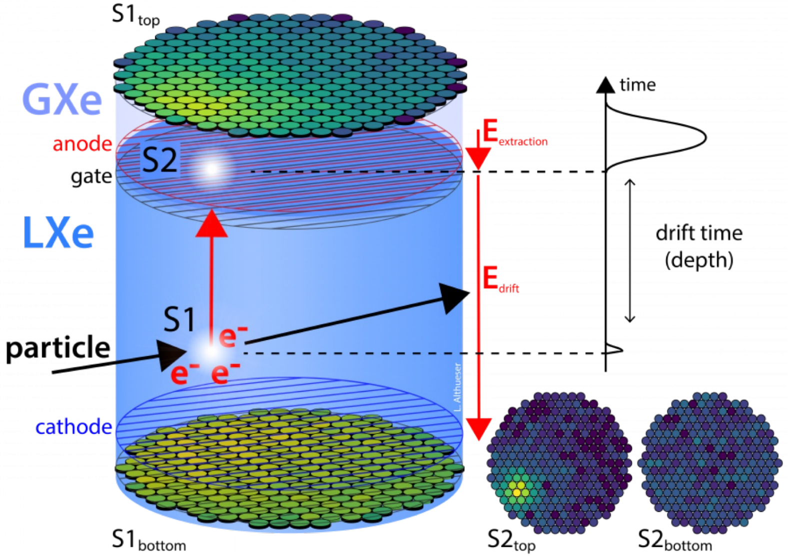


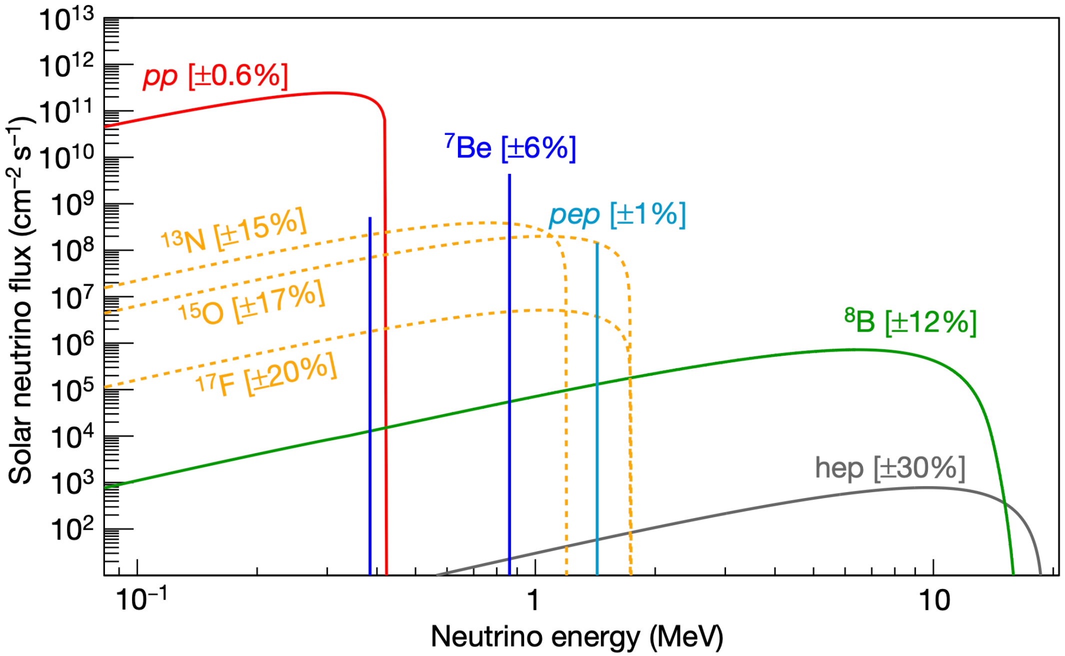
Mean radius of neutron distribution in nucleus: 8% → 2%

Solar Neutrinos

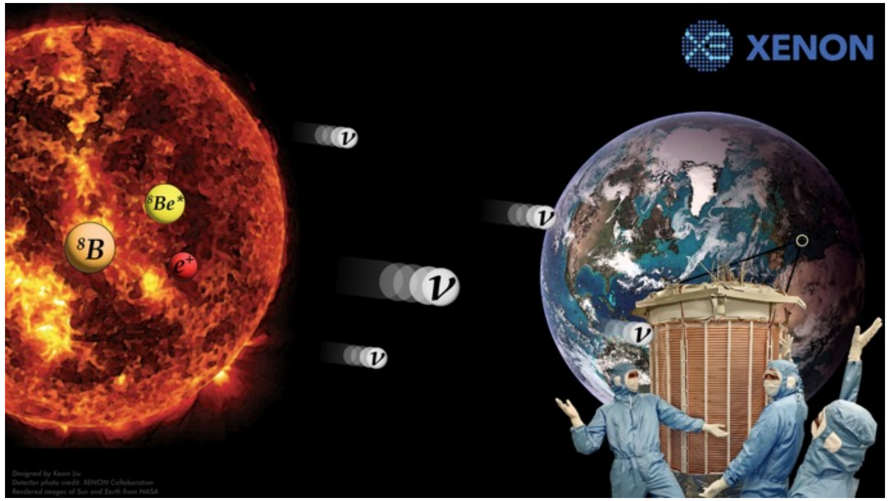




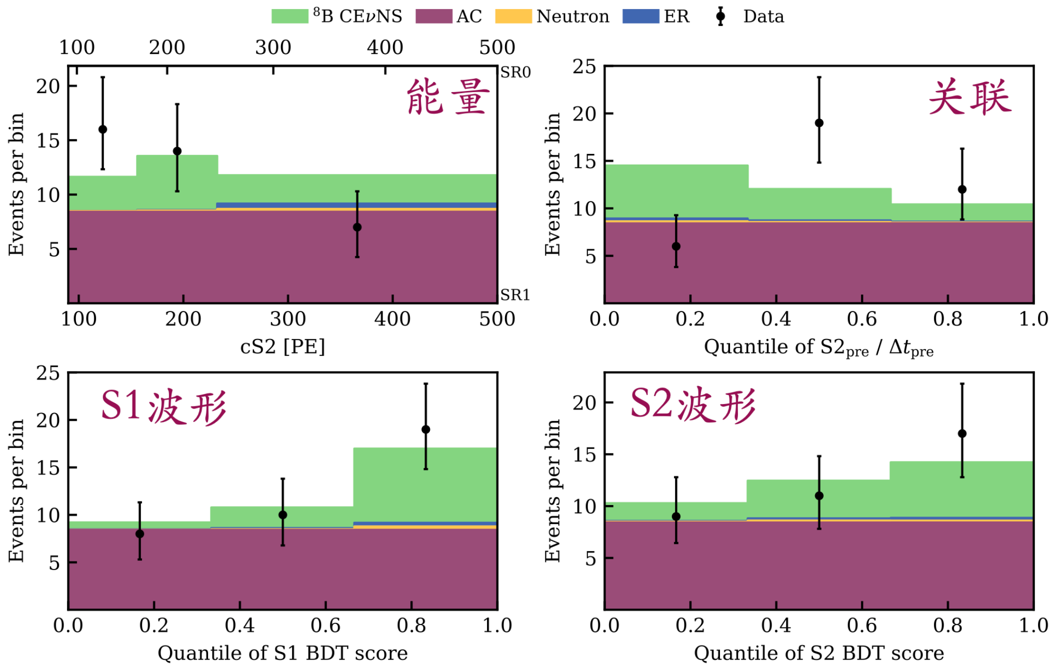


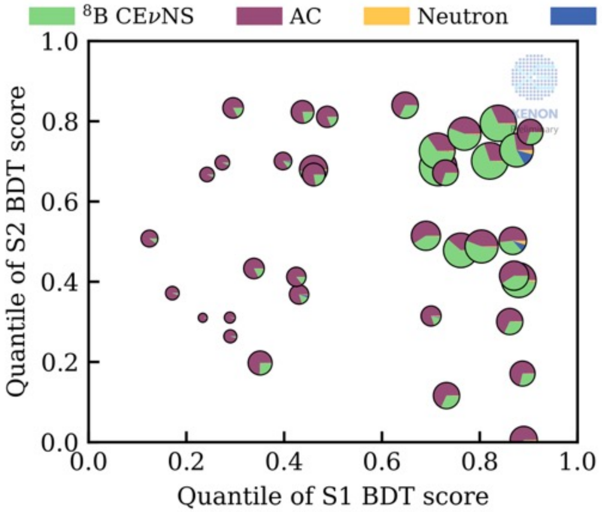


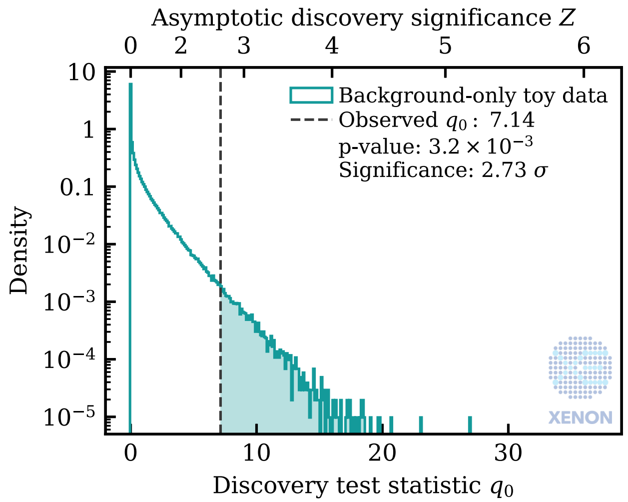
Measurements with XENONnT



Background	prediction	Best-fit
AC—SR0	7.5±0.7	7.4
AC—SR1	17.8±1.0	17.9
ER	0.7±0.7	0.5
NR	0.5±0.3	0.5
Total BG	26.4±1.4	26.3
^{8}B	11.9±4.5	10.7
Observed	37	







Measurements with PandaX

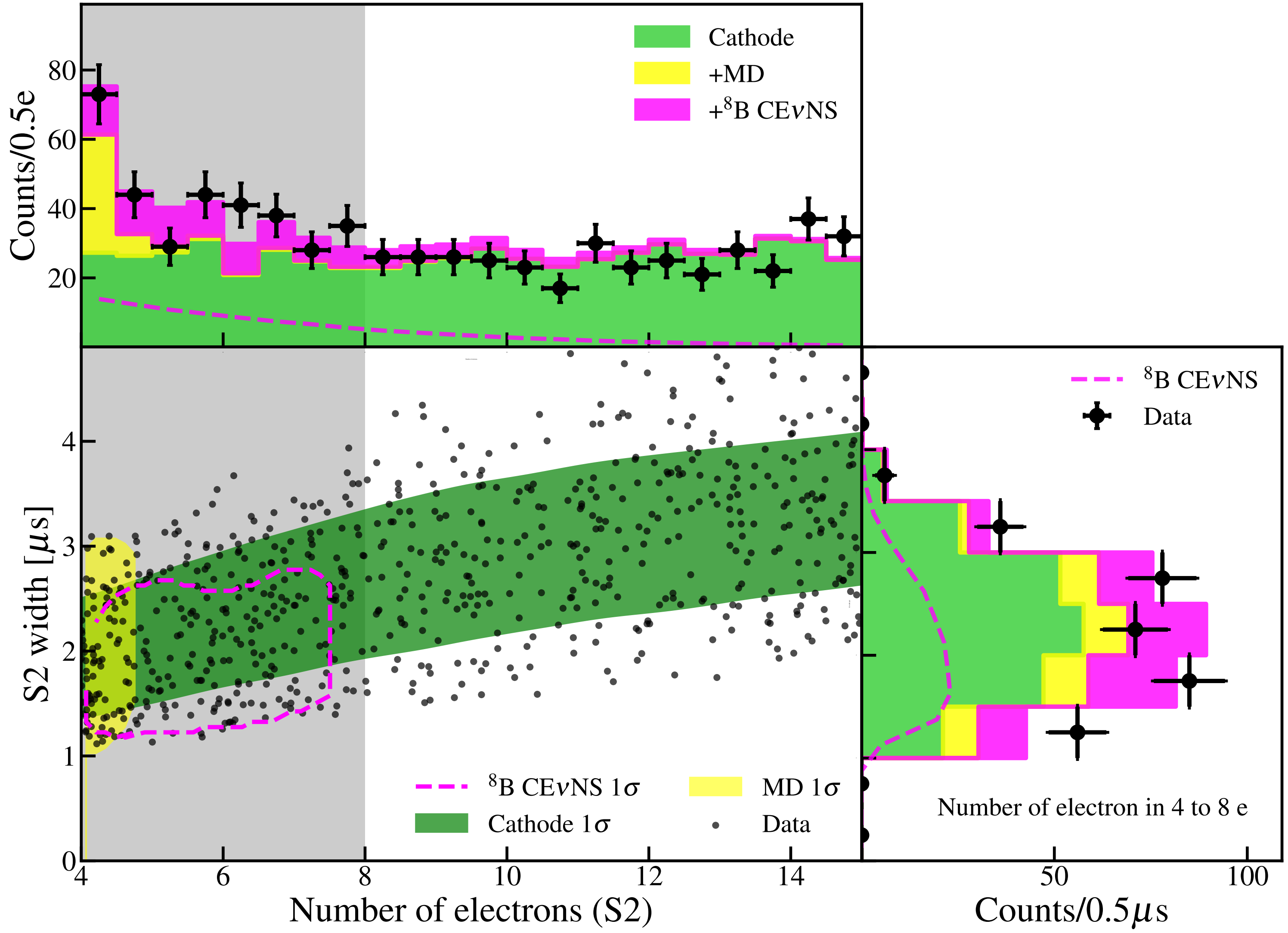
US2 ROI	Run0	Run1
Cathode	100 ± 24	104 ± 21
MD	25 ± 3	20 ± 4
ERs	1.3 ± 0.1	0.9 ± 0.2
Total bkg.	126 ± 24	125 ± 21
^{8}B CEνNS	18 ± 4	25 ± 6
Observed	158	174

Best-fit ^{8}B yield

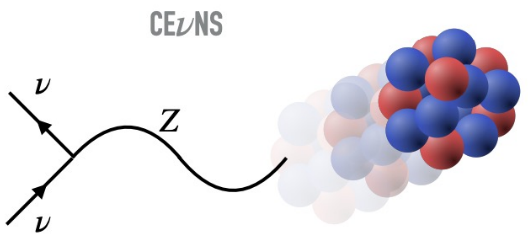
Paired: 3.5 ± 1.3 evts

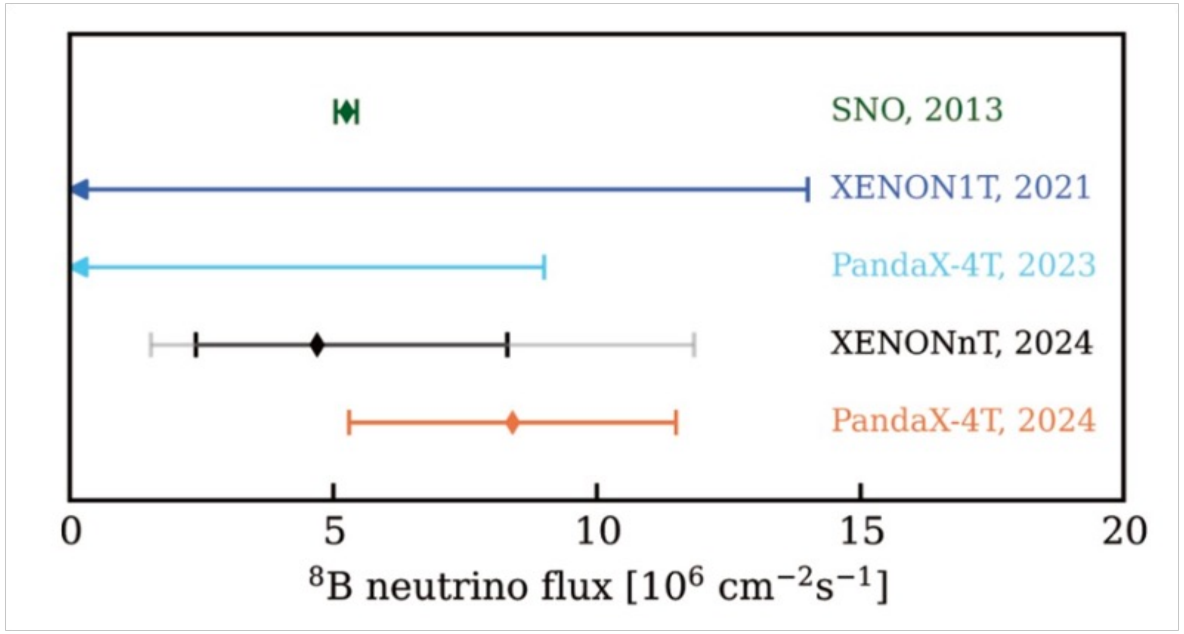
S2only: 75 ± 28 evts

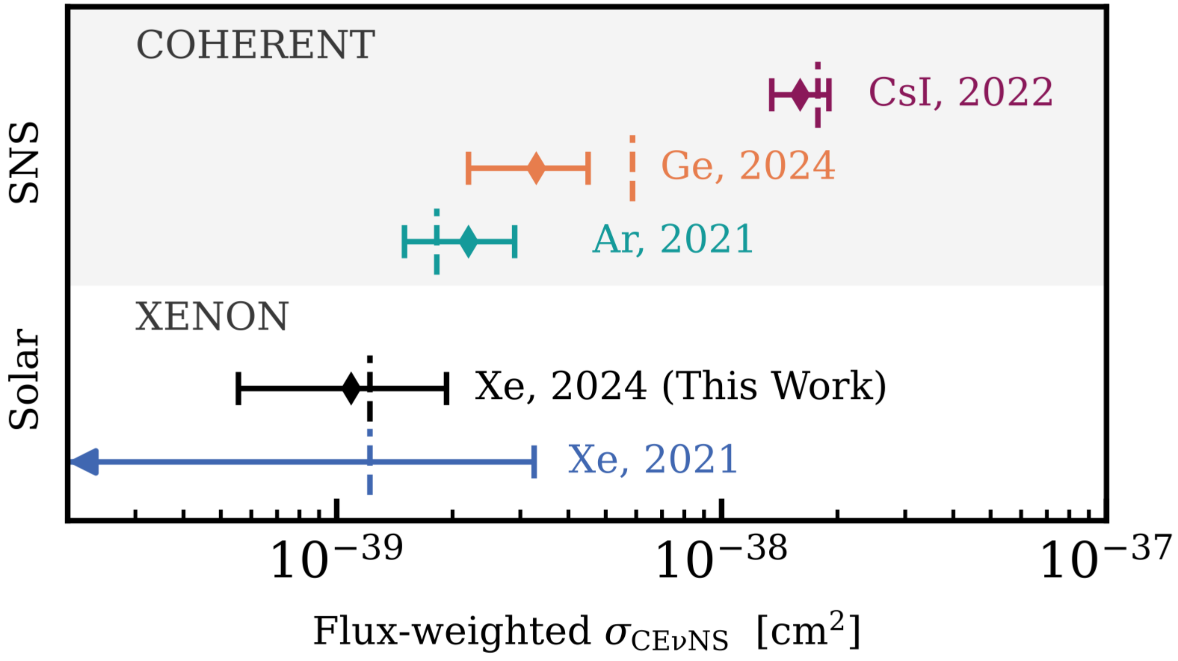
2.6-sigma!



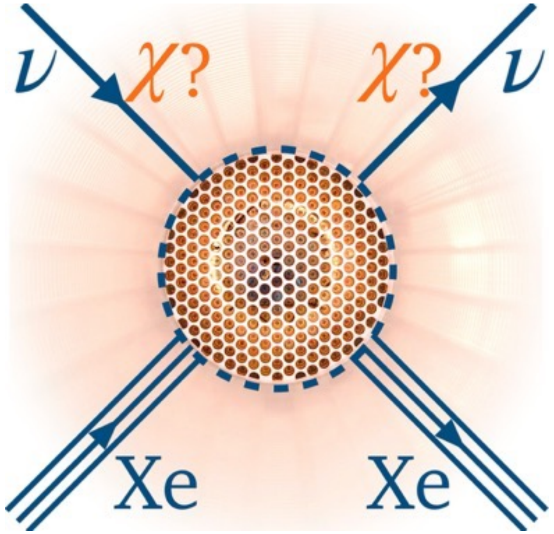
CEvNS Measurements with XENONnT and PandaX

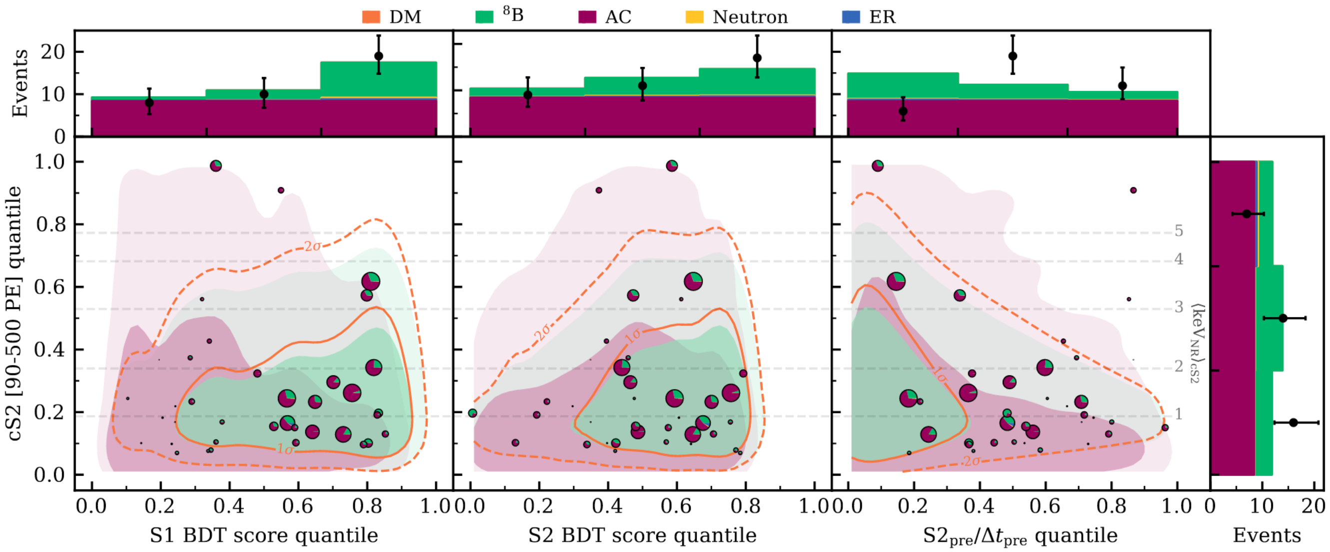


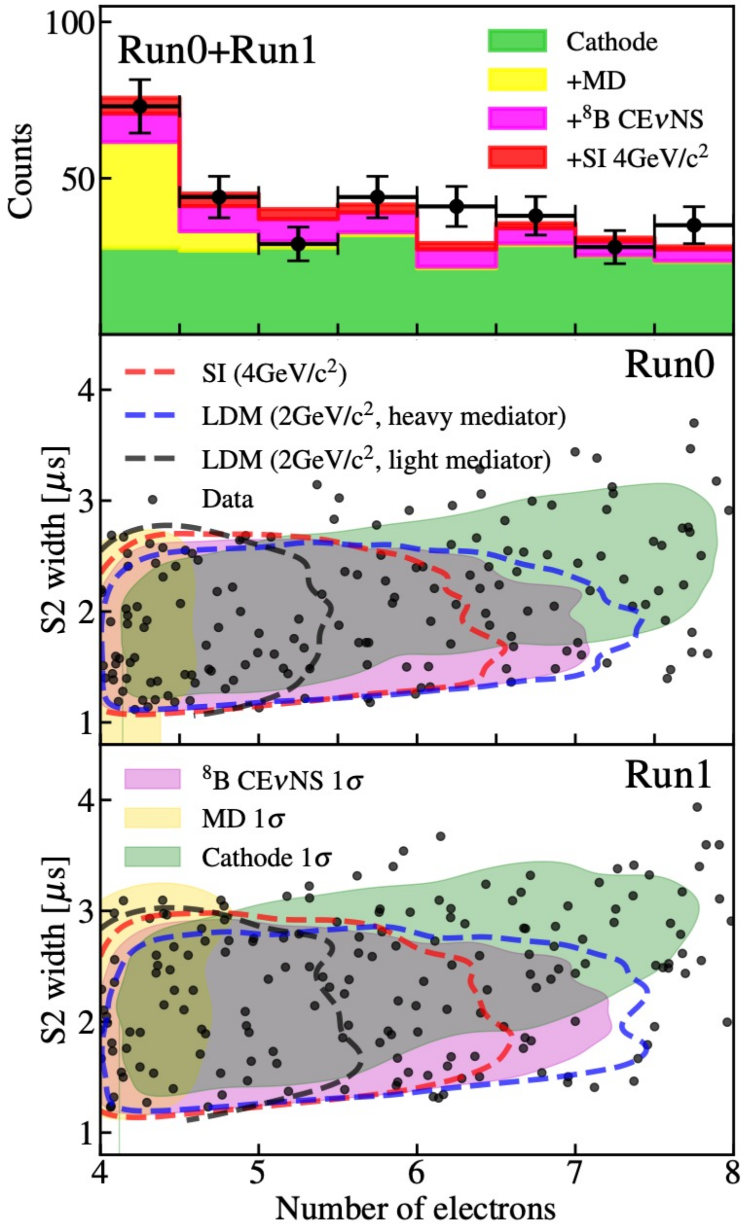




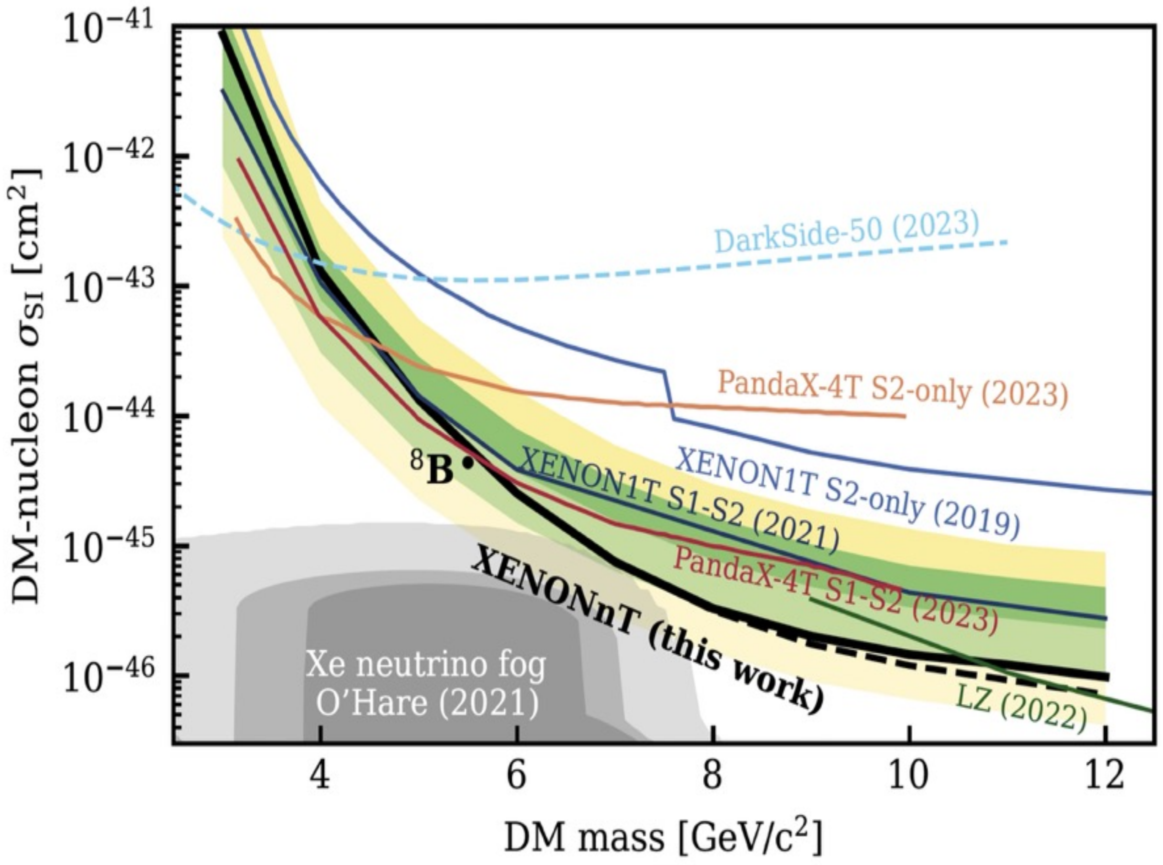
"Neutrino Fog" and dark matter

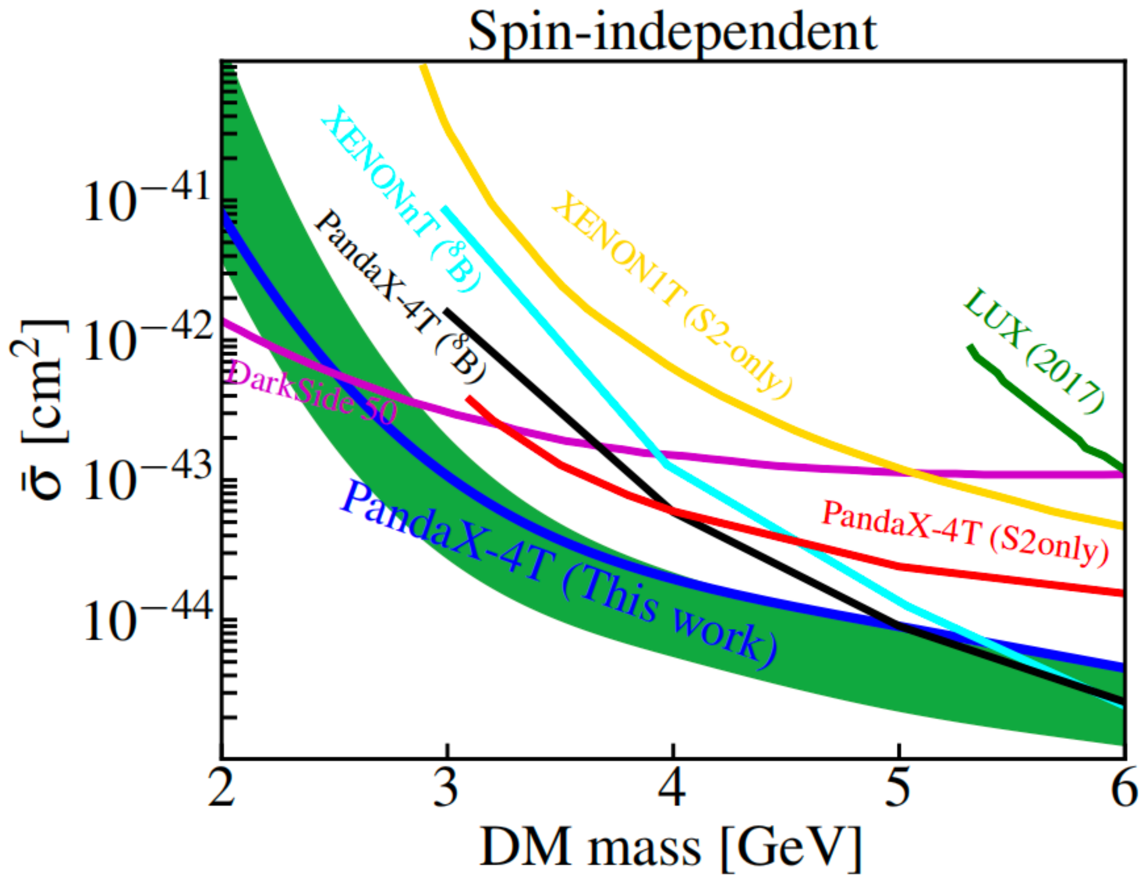




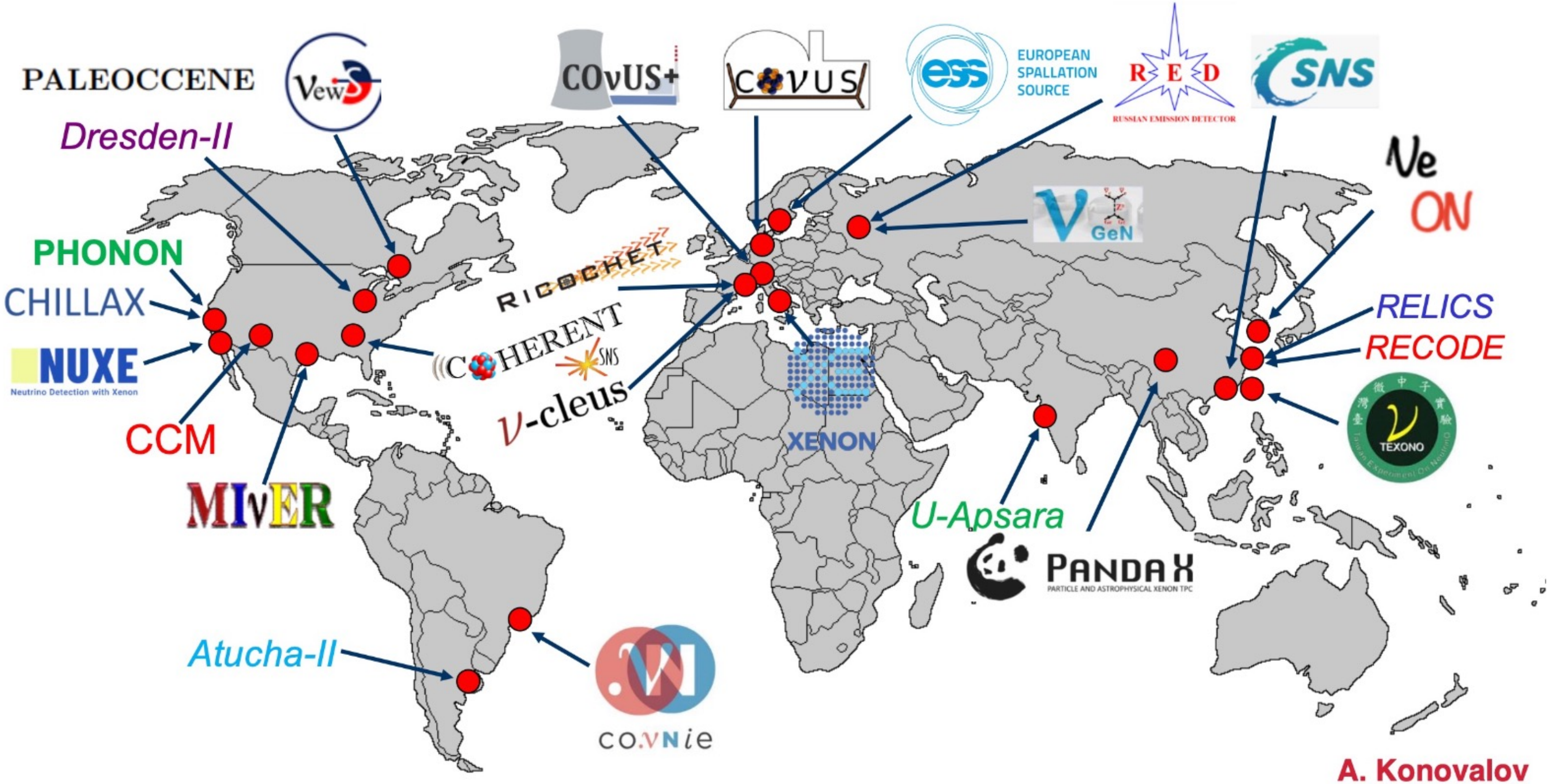


“Neutrino Fog” and dark matter



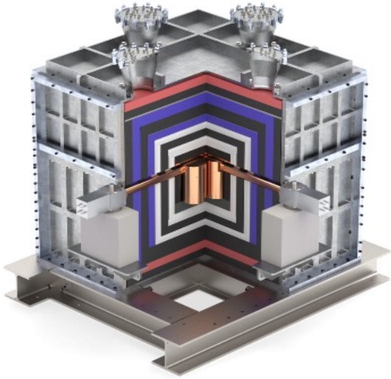


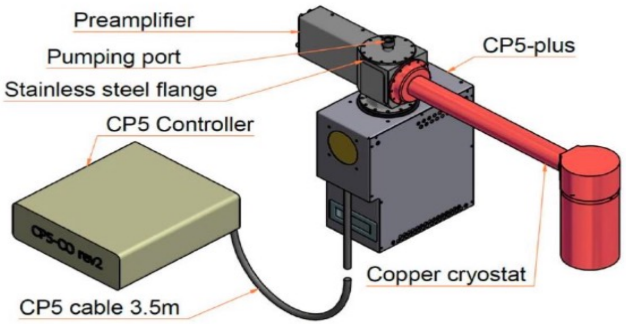
CEvNS with Reactor Neutrinos



A. Konovalov

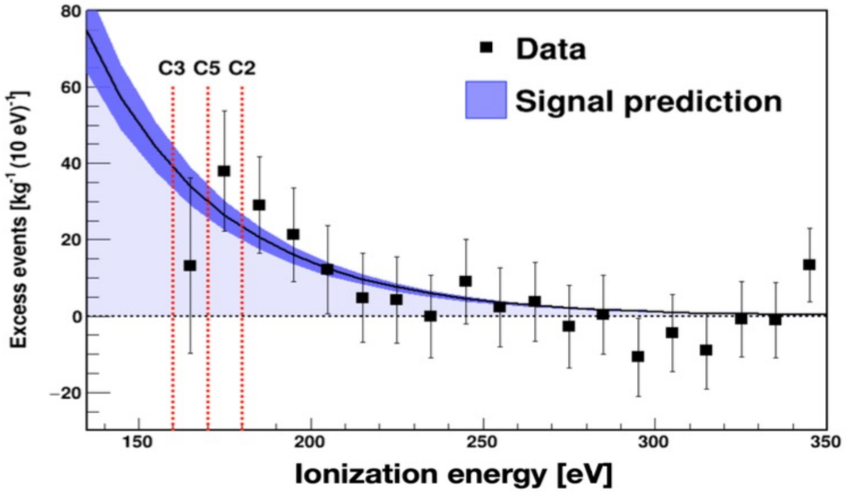
CONUS+ Experiment





Leibstadt nuclear power plant, CH (KKL)
3.6 GW_{th} , 20.7m → flux: $1.45*10^{13}$ ν/cm²/s

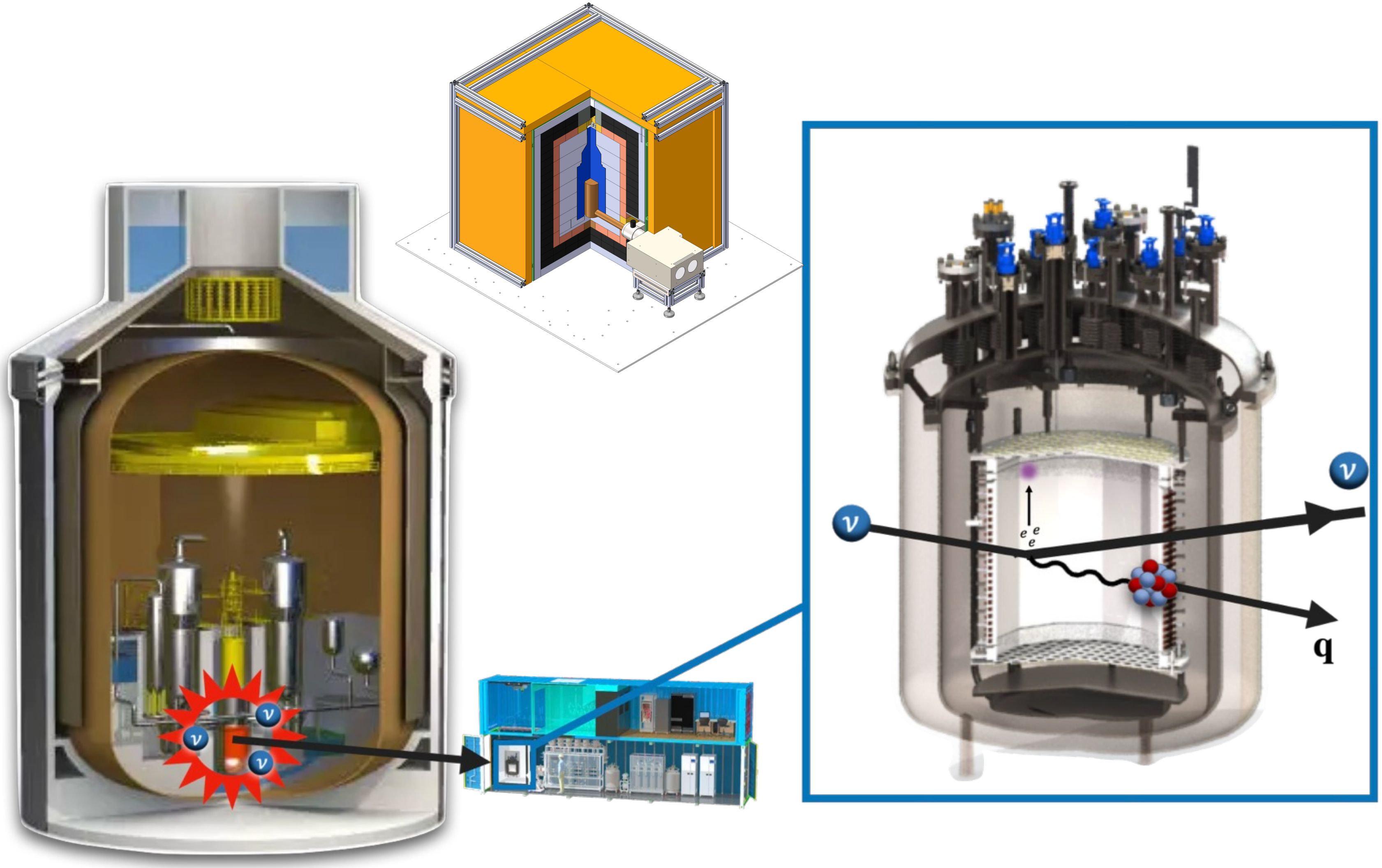
- sophisticated shield → ``virtual depth"
- improved veto systems
- extensive bckg measurements (n, μ's, materials,...)
- 4 × 1kg low bckg point-contact HPGe detectors
- pulse shape discrimination (slow pulses)
- ASIC electronics (improved low E trigger efficiency)
- reduced point contact size & bonding technology
- lower threshold: ~250 → 160 eV
- very sophisticated & well tested bckg model
- **$F(Q^2) = 1$ → deviations → BSM**



Nature 643, 1229 (2025)

395 ± 106 CEνNS events → 3.7σ
1st detection of CEνNS with reactor ν's!

Sanmen Neutrino Experiments: RECODE+RELICS

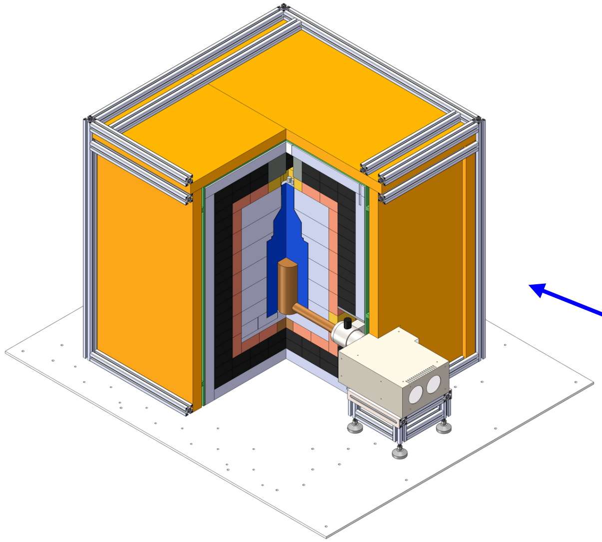


Measurement of CEvNS with Xe and Ge elements

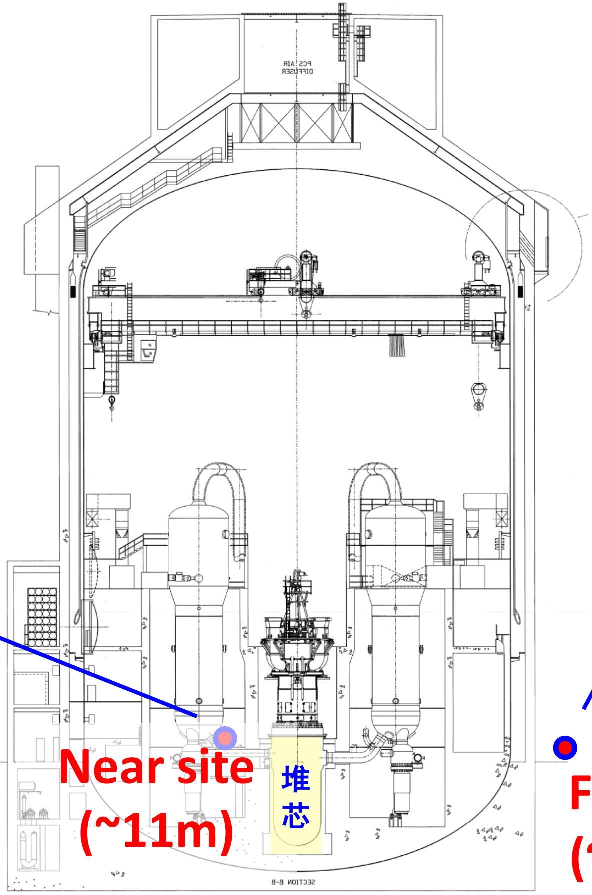
Sanmen Neutrino Experiments：RECODE+RELICS

■ **Combined Search：**

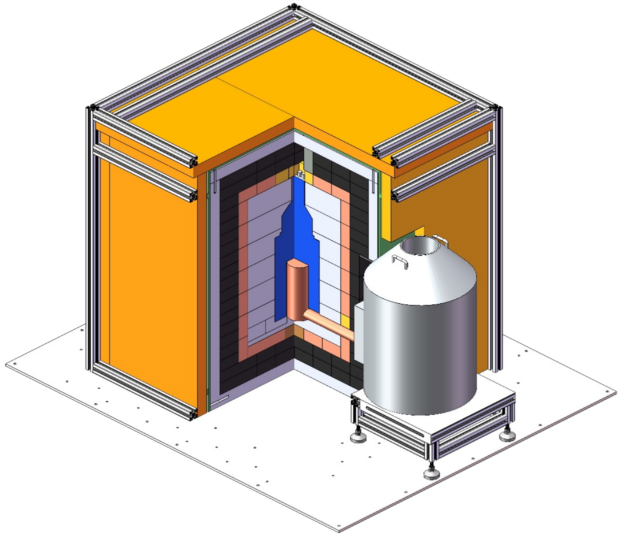
- **Far site： RECODE Ge 、 RELICS- Xe**
- **Near site: RECODE Ge**



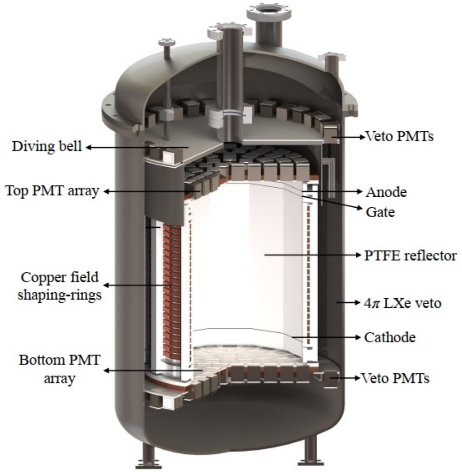
Ge: electric cooling



Far site
(~22m)



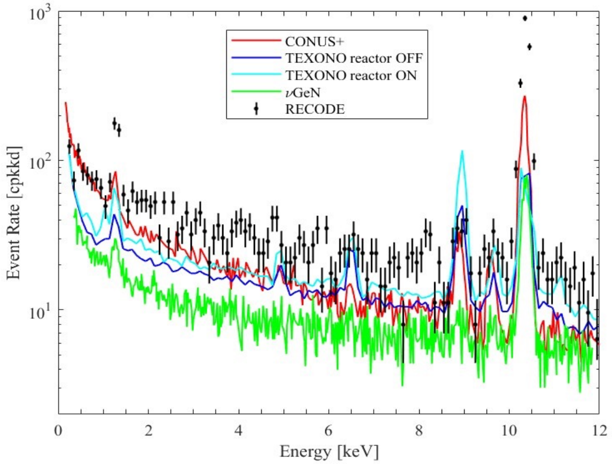
Ge: LN2 cooling

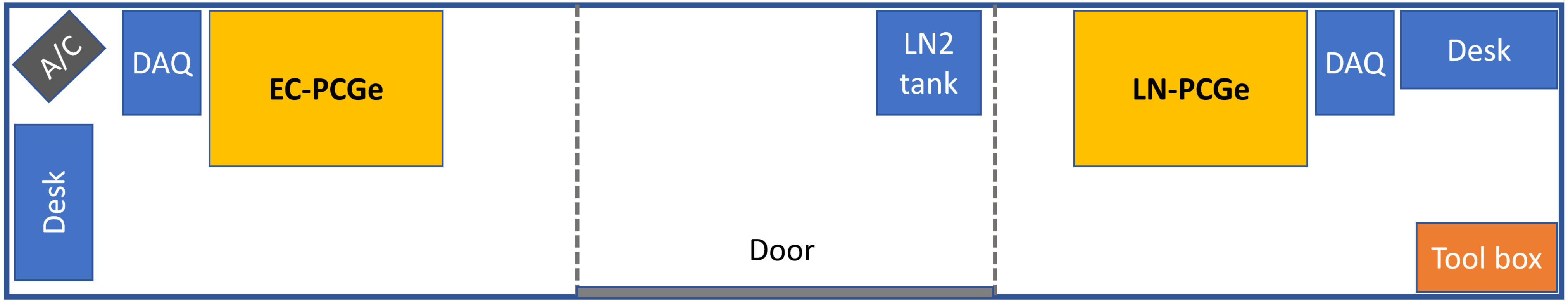


RELICS Xe

Sanmen and RECODE Progress

- Background measurement
- Ge detectors deployed @35m from core



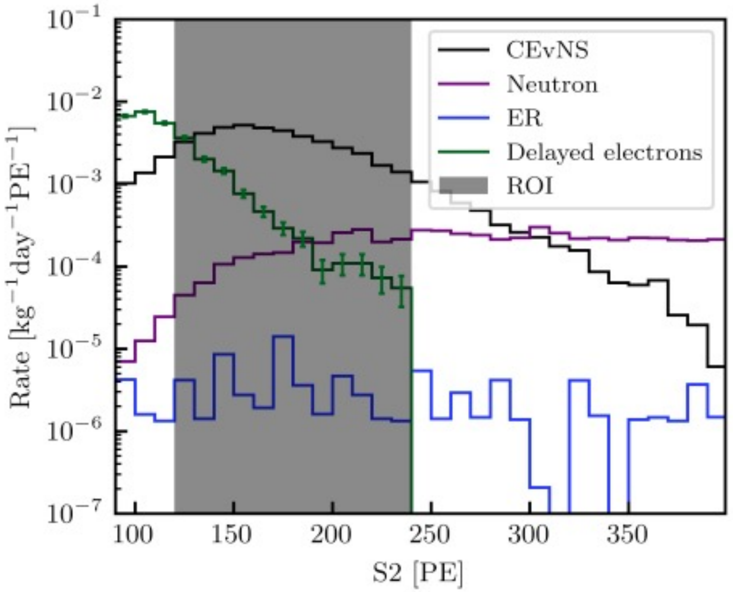


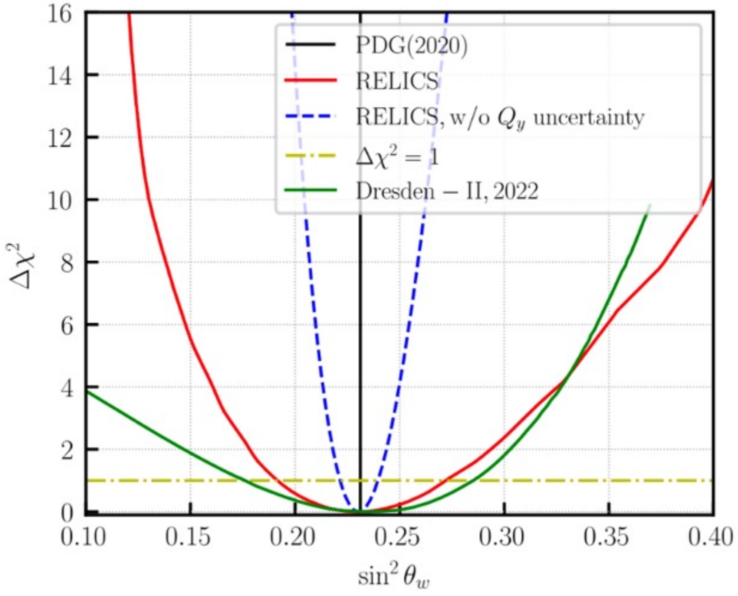
RELICS Progress

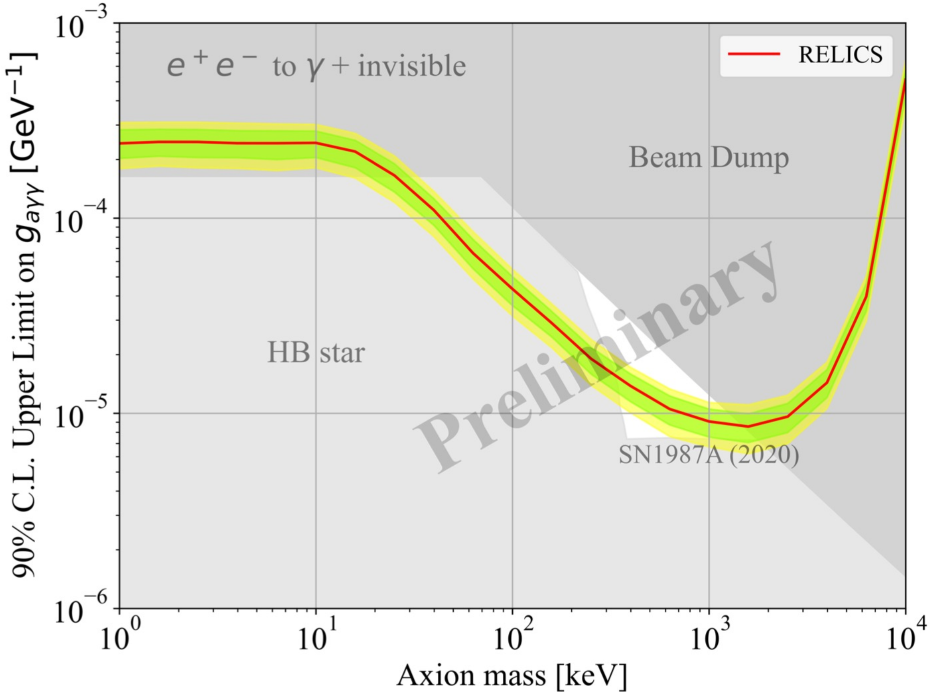
THU USTC SUSY Westlake CUHK Beihang

RELICS Sensitivity

- >~5000 CEvNS events in 1 year of operation with 30kg detector
- Sensitive to weak mixing angle and non-standard interactions
- Sensitive to Axion coupling to gamma

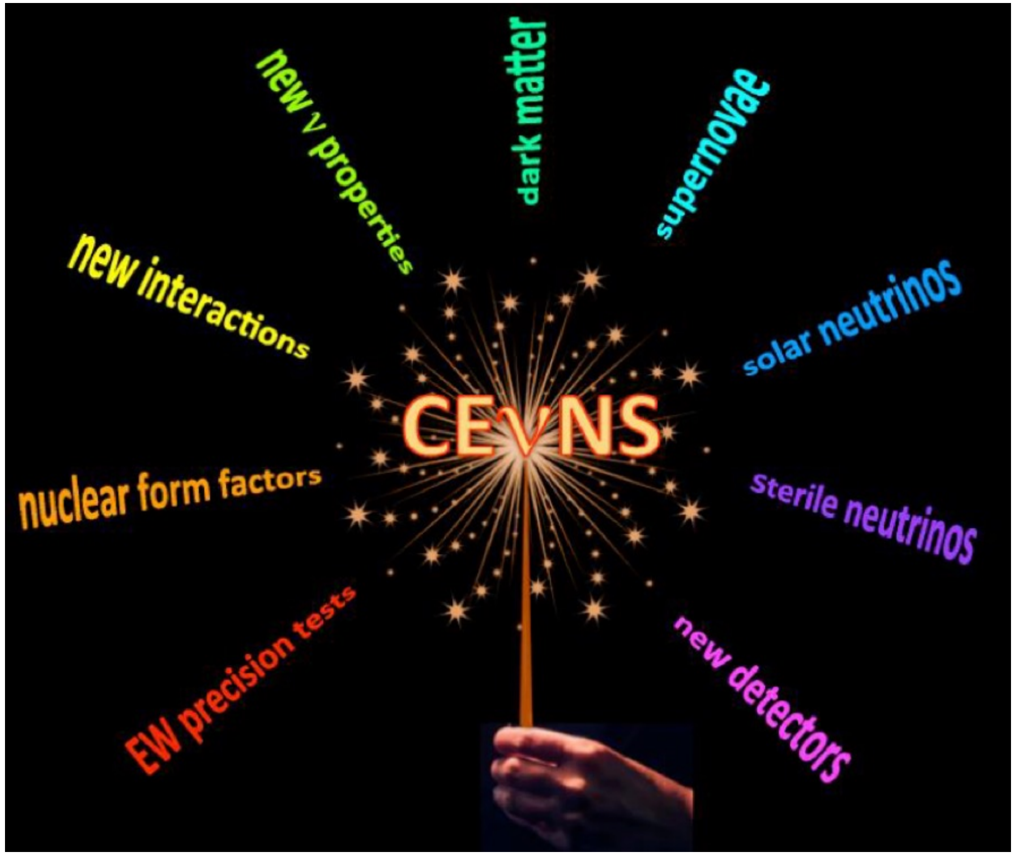






Summary

- CEvNS has rich science and application potential
- SNS: Observations on CsI, Ar and Ge detectors, precision to improve in the next years
- Solar: Positive signal of Boron-8 from XENONnT and PandaX-4T
- Reactor: Positive signal by CONUS+
- Many new experiments are being constructed worldwide, and there are strong contribution from China



Thanks

Neutrino Flux at Sanmen

实验名称	探测器类型	靶质量	阈值	反应堆	堆芯距离	功率	中微子流强	实验地点
RECODE	HPGe	1-2kg	~160 eVee	Sanmen NPP	NS ~ 11m	3.4GWth	$5.6*10^{13}$ ν/cm^2/s	China
	HPGe	10kg	~160 eVee		FS ~ 22m	3.4GWth	$1.4*10^{13}$ ν/cm^2/s	China
RELICS	LXe	50kg	~1 keVnr	Sanmen NPP	22m	3.4GWth	$1.4*10^{13}$ ν/cm^2/s	China
CONUS	HPGe	3.74 kg	~ 210 eVee	Brokdorf (KBR)	17 m	3.9 GWth	$2.3*10^{13}$ ν/cm^2/s	Germany
COUNS+	HPGe	3.74 kg	~150 eVee	Leibstadt (KKL)	20.7m	3.6 GWth	$1.5*10^{13}$ ν/cm^2/s	Switzerland
Nu-Gen	HPGe	1.6 kg	350 eVee	Kalinin NPP	11.1-12.5 m	3.1 GWth	3.4 -$4.4*10^{13}$ ν/cm^2/s	Russia
TEXONO	HPGe	1 kg	~200 eVee	Kuo-Sheng NPP	28m	2.9 GWth	$6.4*10^{12}$ ν/cm^2/s	Taiwan, China
CONNIE	Si CCDs	50 g	~ 40 eVee	Angra 2 reactor	30 m	3.8 GWth	$7.8*10^{12}$ ν/cm^2/s	Brazil
MINER	Ge/Si	4 kg	~ 100 eVnr	TRIGA reactor	2~10m	1 MWth	~10^{12} ν/cm^2/s	USA
RICOCHET	Ge & Zinc	32 g (Ge)	55 eVee	ILL reactor	8 m	58 MWth	$1.6*10^{12}$ ν/cm^2/s	France