New physics potential using coherent, low-energy neutrino scattering

Dan Pershey (Duke University)

CETUP 2023 // Lead SD

Jul 3, 2023

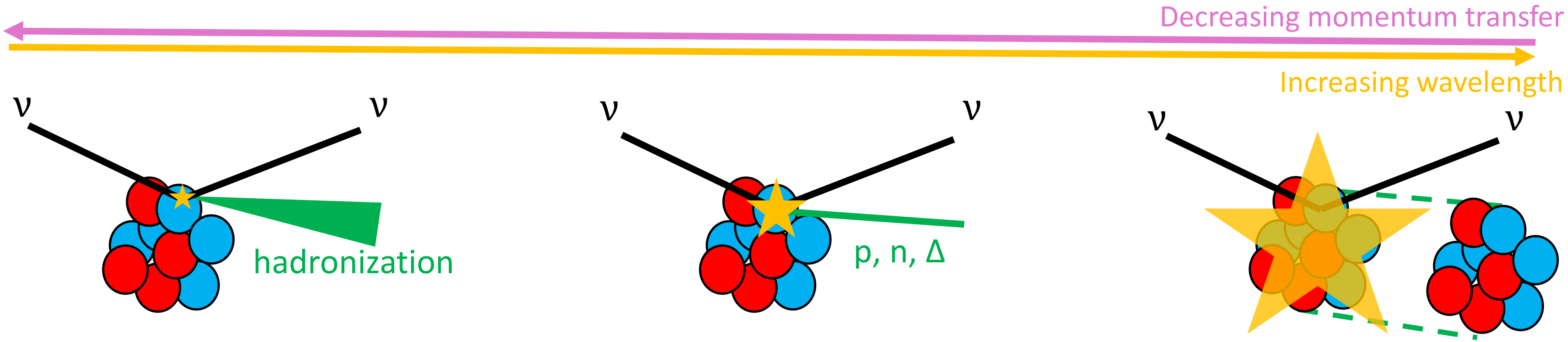
NC neutrino scattering with nuclei

What happens qualitatively during neutrino-nucleus interactions depends on the deBroglie wavelength involved, $\lambda = h/p$

$E_\nu \sim$TeV

$E_\nu \sim$GeV

$E_\nu \sim$MeV



$\lambda = h/\sqrt{Q^2} \ll R_p$

Localized scattering on quarks with nuclear fragmentation e.g. IceCube, FASERnu

$\lambda = h/\sqrt{Q^2} \approx R_p$

Scattering on nucleons with nucleon emission e.g. NOvA, SK, DUNE

$\lambda = h/\sqrt{Q^2} \gg R_p$

Elastic scattering on nuclei with Q^2 so low, nucleus acts like point particle

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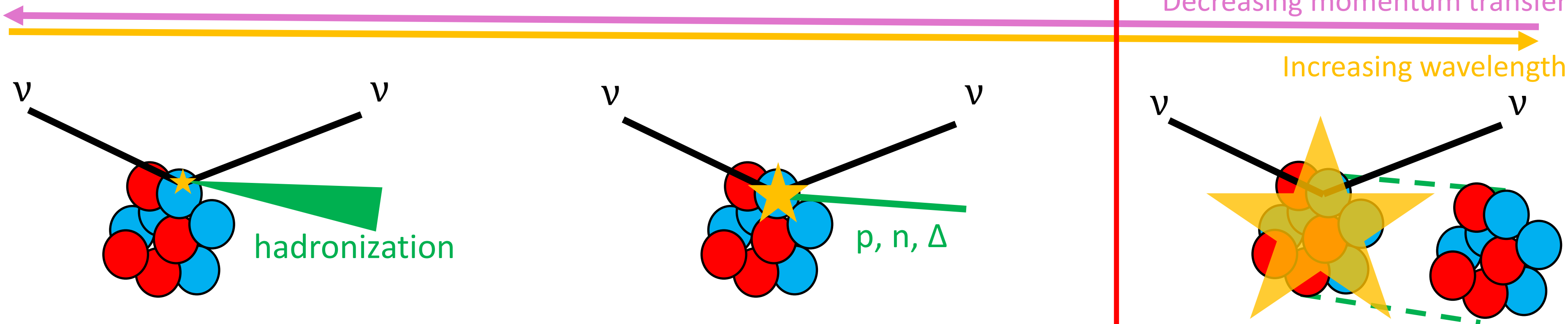
E_ν~GeV

E_ν~MeV



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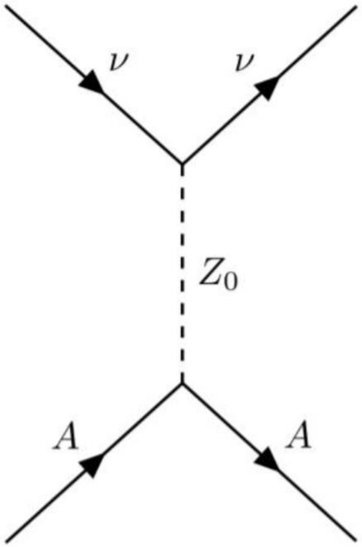
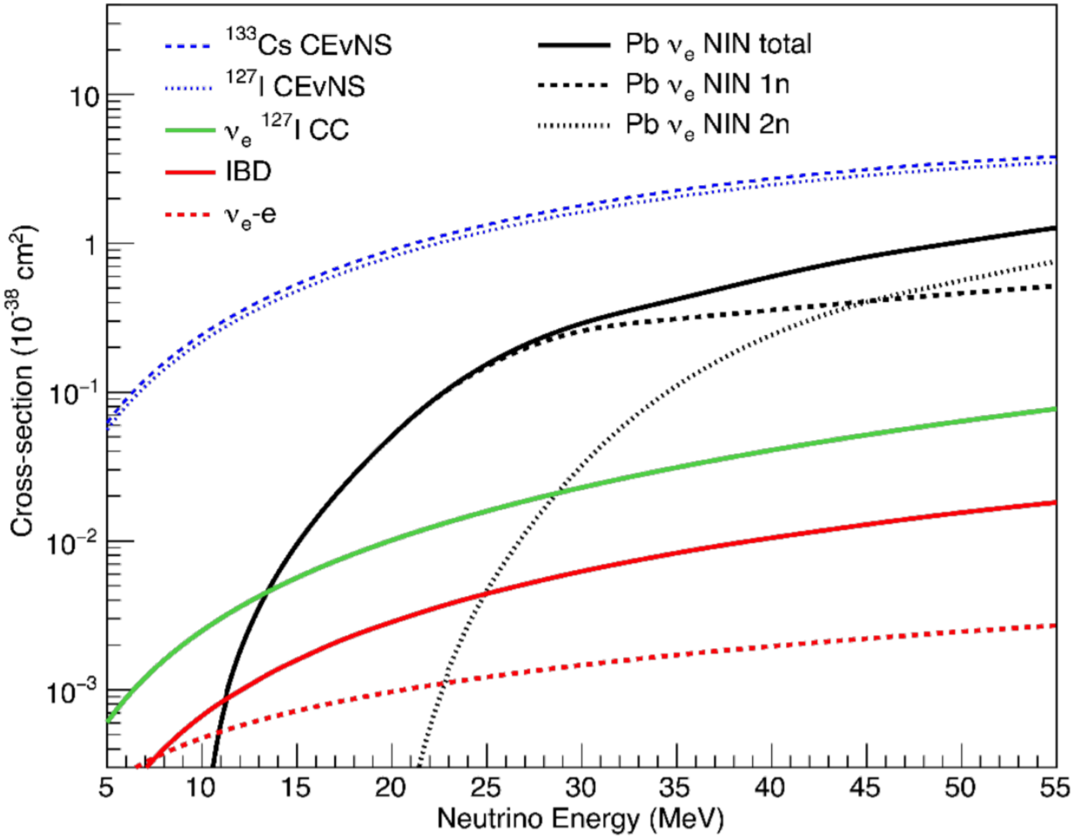
Elastic scattering on nuclei with Q^2 so low, nucleus acts like point particle

COHERENT measures coherent elastic neutrino-nucleus scattering (CEvNS) at neutrino energies 10-50 MeV. First discovered in 2017 by COHERENT in a CsI[Na] scintillation detector

CEvNS cross section

CEvNS



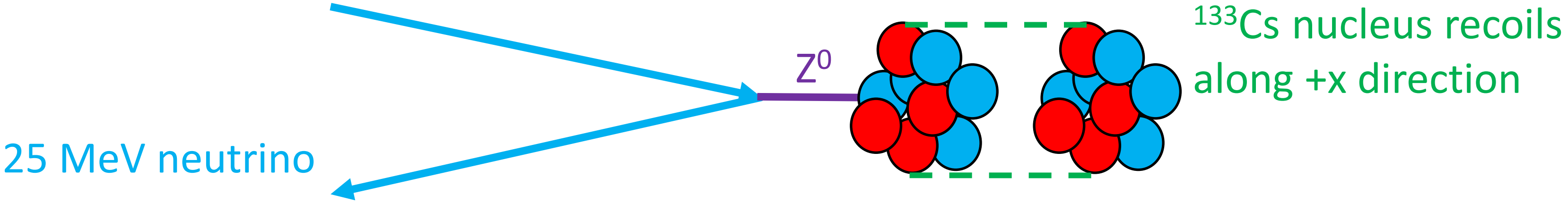


- The process is coherent, which gives a large cross section, roughly scaling with the square of the number of neutrons

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

- Very large cross section, compared to low-energy neutrino processes
  - Measurements within reach of kg-scale detectors

CEvNS kinematics



$$E_{\text{rec}} \approx \frac{p_{\text{Cs}}^2}{2m_{\text{Cs}}} = \frac{Q^2}{2m_{\text{Cs}}} \leq \frac{2E_\nu^2}{m_{\text{Cs}}} = 10.1\ \text{keV}$$

CEvNS energy scales:

$$\left\{\begin{array}{l} E_\nu \sim 25\ \text{MeV} \\ Q \sim 50\ \text{MeV} \\ E_{\text{rec}} \sim 10\ \text{keV} \end{array}\right.$$

$$\frac{d\sigma}{dE_{\text{rec}}} = \frac{G_F^2 m_{\text{Cs}}}{\pi}\left(1 - \frac{E_{\text{rec}}}{2E_\nu^2/m_{\text{Cs}}}\right)|F(Q^2)|^2$$

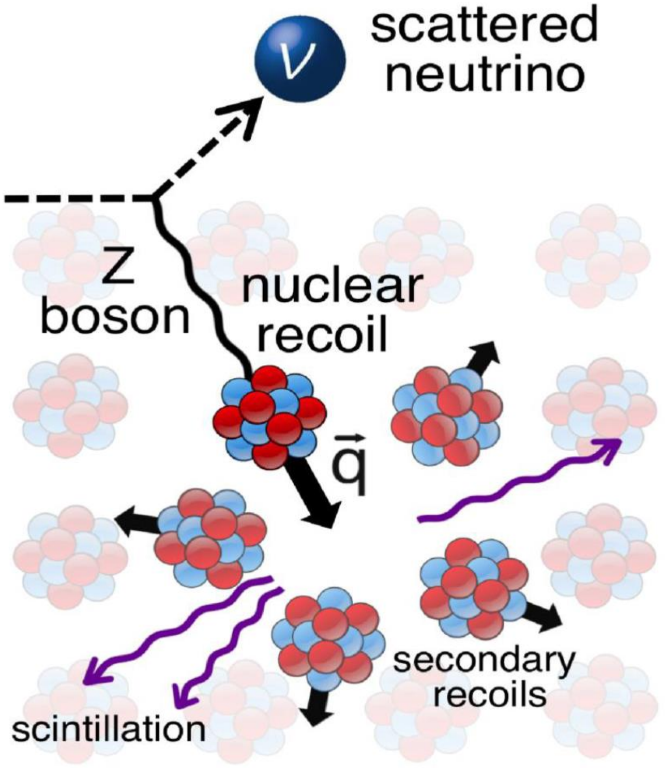
- CEvNS dominant interactions at low neutrino energy, but is a NC process – the only observable is a tiny nuclear recoil
  - For 10s of MeV neutrinos, expect few keV recoils

First observation of CEvNS

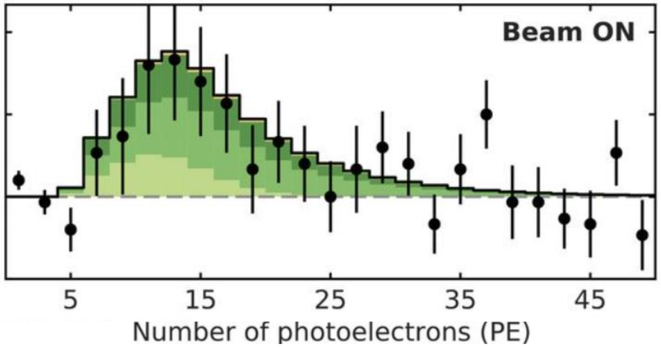
Though first predicted in 1974, CEvNS was not observed until 2017

D. Freeman, *Phys Rev* **D9**, 1389 (1974)

Nuclear recoil signature leaves small burst of scintillation light – observable!



Spallation Neutron Source (SNS) at Oak Ridge National Lab (ORNL)



First measurement: COHERENT (2017) with CsI[Na] scintillator

Powerful new tool for searching for new physics → >500 citations

COHERENT, *Science* **357** 6356 (2017)

Experimental approaches

CEvNS detection methods

Current efforts

Light

Scintillation detectors ~ kg to tons

~ 10% quenching

~ 1 photon / keV

Threshold: ~ 10 keV

- COHERENT (CsI/Na/Ar)
- CCM (Ar)
- ESSCEvNS (CsI)
- RED100 (Xe/Ar) (charge + light)
- SBC (Ar/Xe)
- NEWS-G (Ar)
- NEON (NaI)
- LZ/XenonNt (Xe) (charge + light)

Charge

Ionization detectors: ~ few kg

~ 20% quenching

~ 1 e / 10 eV

Threshold: ~ 1 keV

- COHERENT (Ge)
- ESSCEvNS (Ge)
- CONUS (Ge)
- vGen (Ge)
- TEXONO (Ge)
- CONNIE (Si)

Heat

Superconducting detectors ~ few gs

No quenching

~ 1 phonon / meV

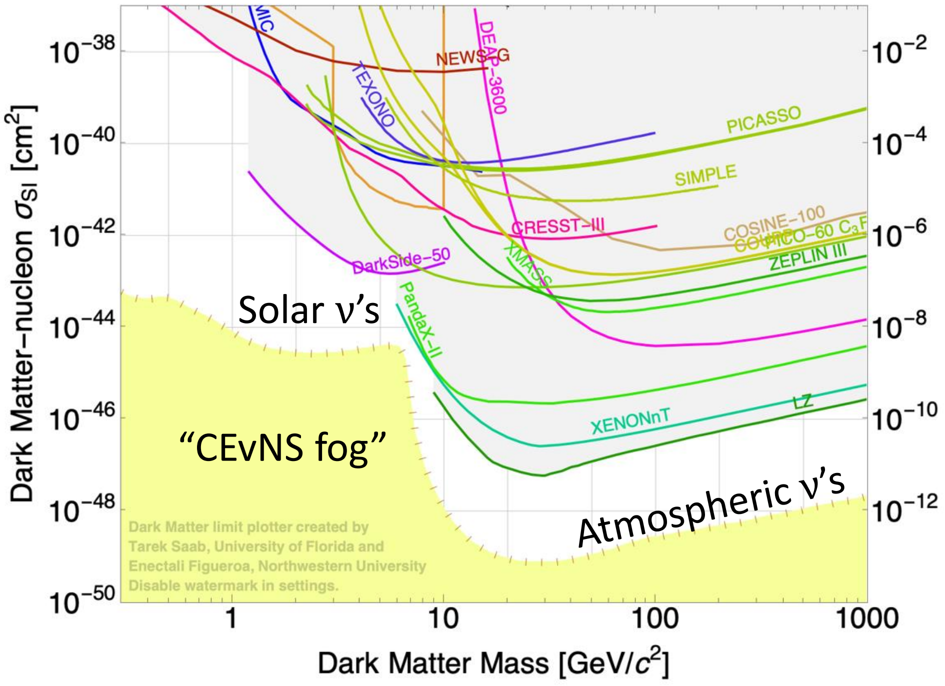
Threshold: ~ 10 eV

- vCLEUS ($CaWO_4$, Al_2O_3)
- BULLKID (Al)
- RICOCHET (Ge,Zn)
- MIvER (Si,Ge) (heat + charge)

Astrophysical sources for CEvNS

- ❑ CEvNS are an ultimate background for dark matter detection experiments
- ❑ Cosmogenic sources of neutrinos can produce CEvNS in dark matter detectors – the CEvNS floor – and expected rates are not far from current sensitivities
  - Several experiments will soon see CEvNS from ^{8}B solar neutrinos
  - First search with expected sensitivity from xenon1t, *PRL* **126** 091301 (2021)

https://supercdms.slac.stanford.edu/dark-matter-limit-plotter



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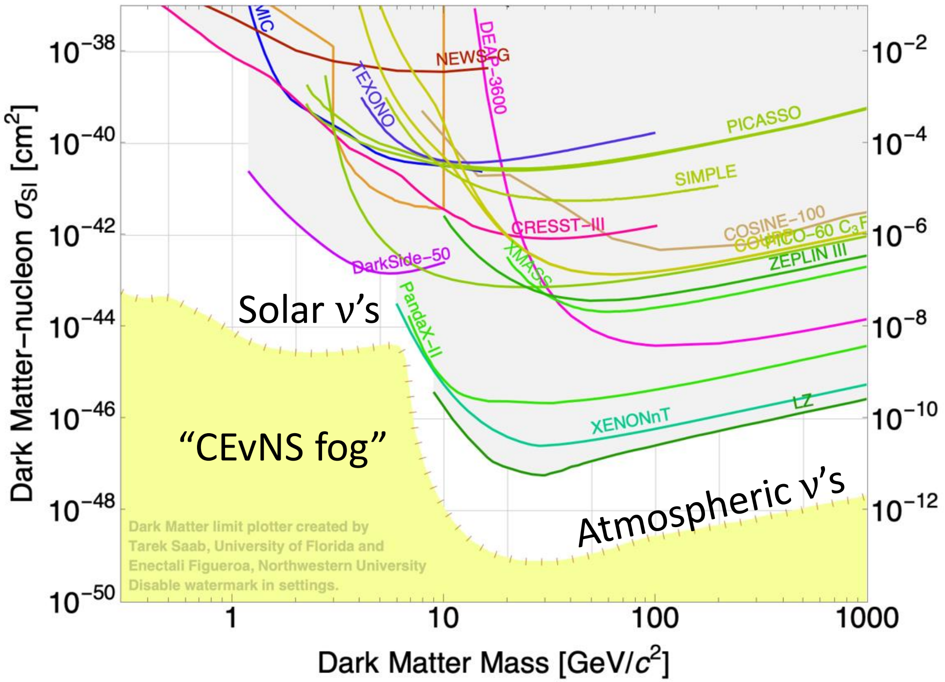
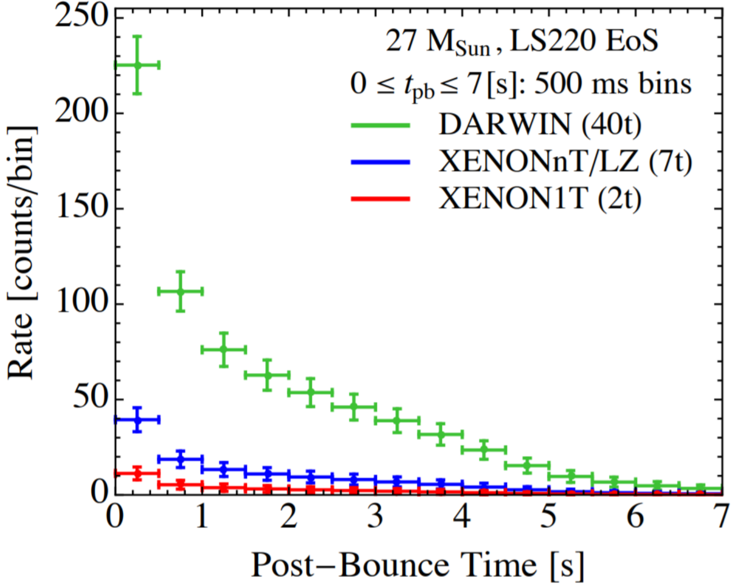


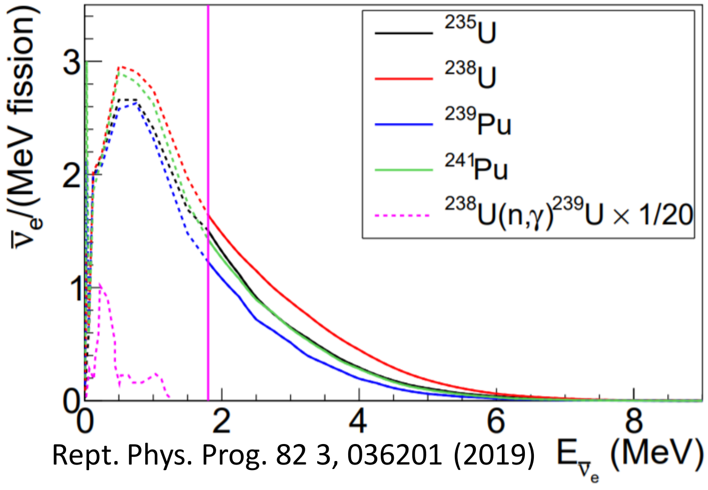
Lang et al., *PRD* **94** 103009 (2016)



- ❑ CEvNS will also be a detection channel for a burst of neutrinos from a supernova
- ❑ E.g., DARWIN, a future Xe experiment expects to see several hundred CEvNS events for a typical galactic supernova
- ❑ CEvNS is NC → sensitive to all flavors of flux which would help interpretation of data from DUNE and other experiments

Laboratory sources for low-energy neutrinos

Nuclear reactors



Rept. Phys. Prog. 82 3, 036201 (2019)

reactors win

- Very high flux: $\sim 2\times10^{20}\ \bar{\nu}_e$ / s
- Maximum recoil energy for CsI: 1 keV
- Reactor-off data → in-situ background constraint

Several global efforts

MIνER

νGeN

nucleus

CONUS

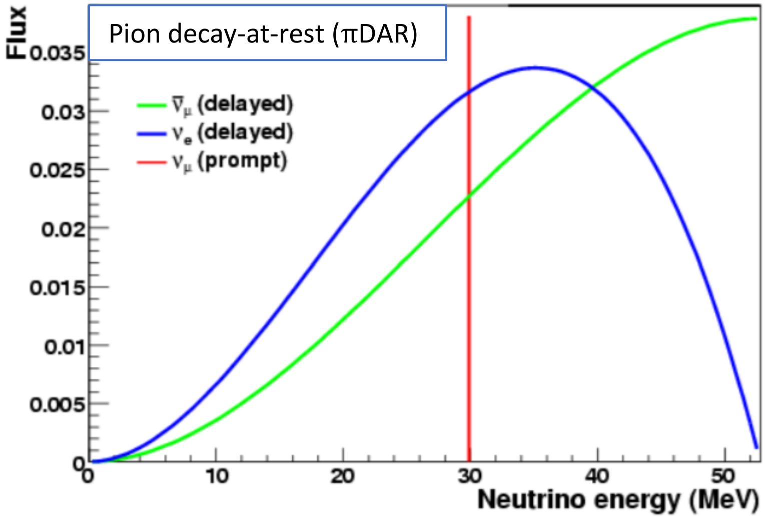
CONNIE

RICOCHET
A Coherent Neutrino Scattering Program

РЭД

TEXONO

Accelerators



πDAR wins

- High flux: $\sim 3\times10^{14}\ \nu_\mu/\nu_e/\bar{\nu}_\mu$ / s
- Maximum recoil energy for CsI: 15 keV
- Pulsed beam → in-situ background constraint

COHERENT SNS

@ Spallation Neutron Source

Coherent Captain Mills @

Los Alamos
NATIONAL LABORATORY
EST.1943

ESSCEvNS @

ess
EUROPEAN
SPALLATION
SOURCE

CEvNS at accelerators: COHERENT @ Spallation Neutron Source

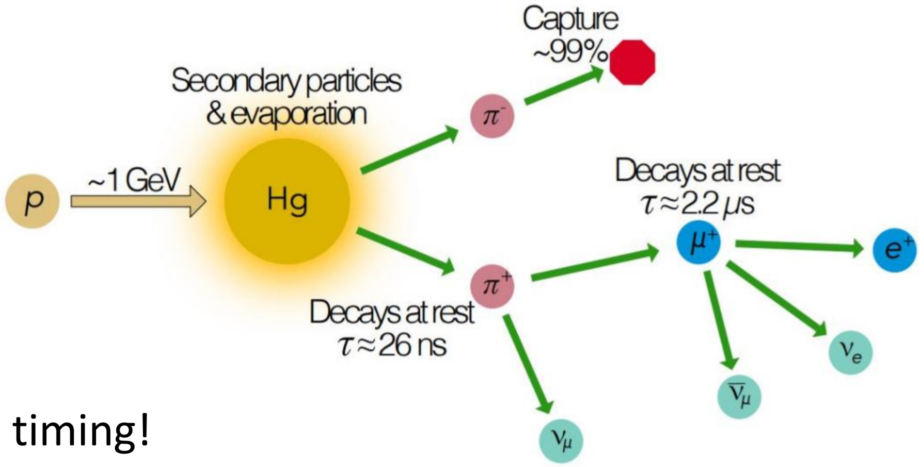
- ❑ A premier neutron accelerator complex which produces an incredibly intense flux of low-energy neutrinos with exciting physics agenda complementary to its neutron studies
- ❑ Pulsed source gives 1/30000x background rejection

- ❑ Accelerator upgrades: the Proton Power Upgrade (coming few years):
  - Beam energy: 1.0 GeV → 1.3 GeV
  - Beam power: 1.4 MW → 2.8 MW
  - Pulse duration (FWHM): 350 ns
- ❑ Construction of second target station (2030s) with experimental halls designed for neutrinos

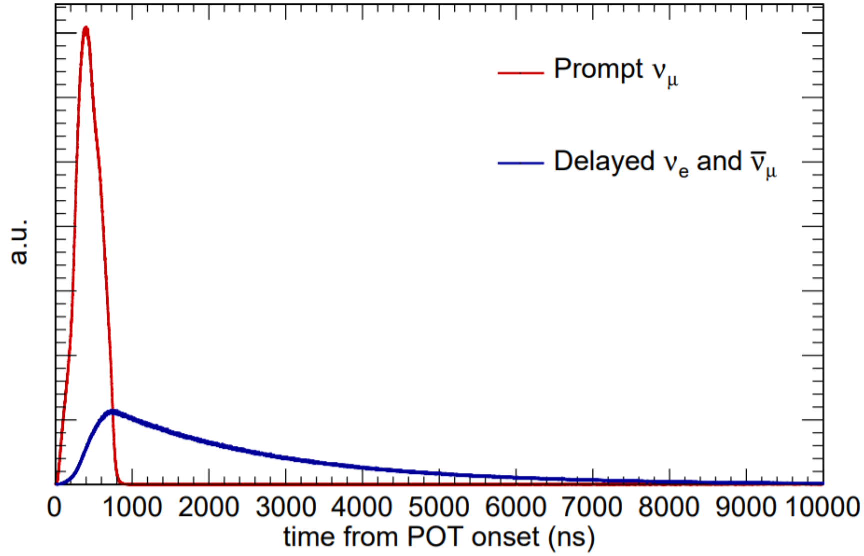
Neutrino Flux at the SNS

- ❑ Low energy pions are a natural by-product of SNS running
  - π^+ will stop and decay at rest

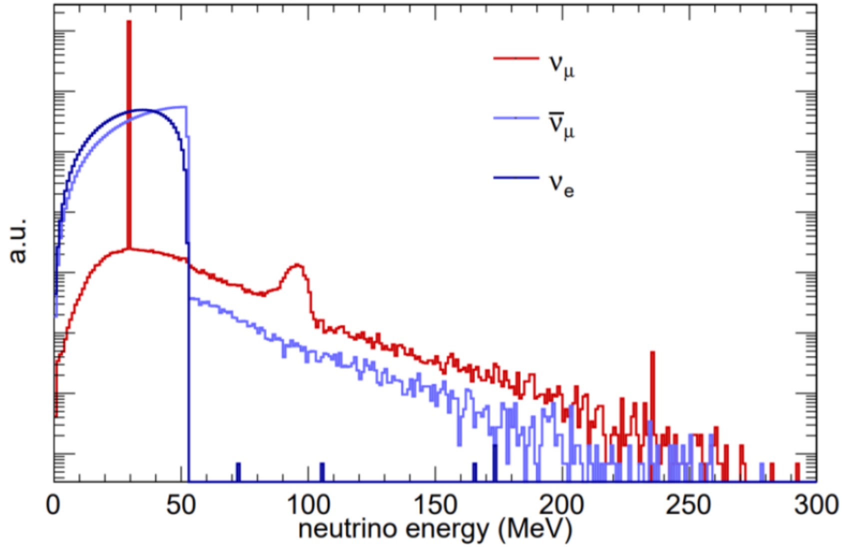
    $$\pi^+ \to \mu^+ + \nu_\mu \quad : \ \tau = 26\text{ ns}$$
    $$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \quad : \ \tau = 2200\text{ ns}$$
  - Flux includes three flavors of neutrinos → can test flavor universality as a BSM signature
- ❑ Flux shape is very well known in both time and energy
- ❑ Flux separation and background rejection from timing!



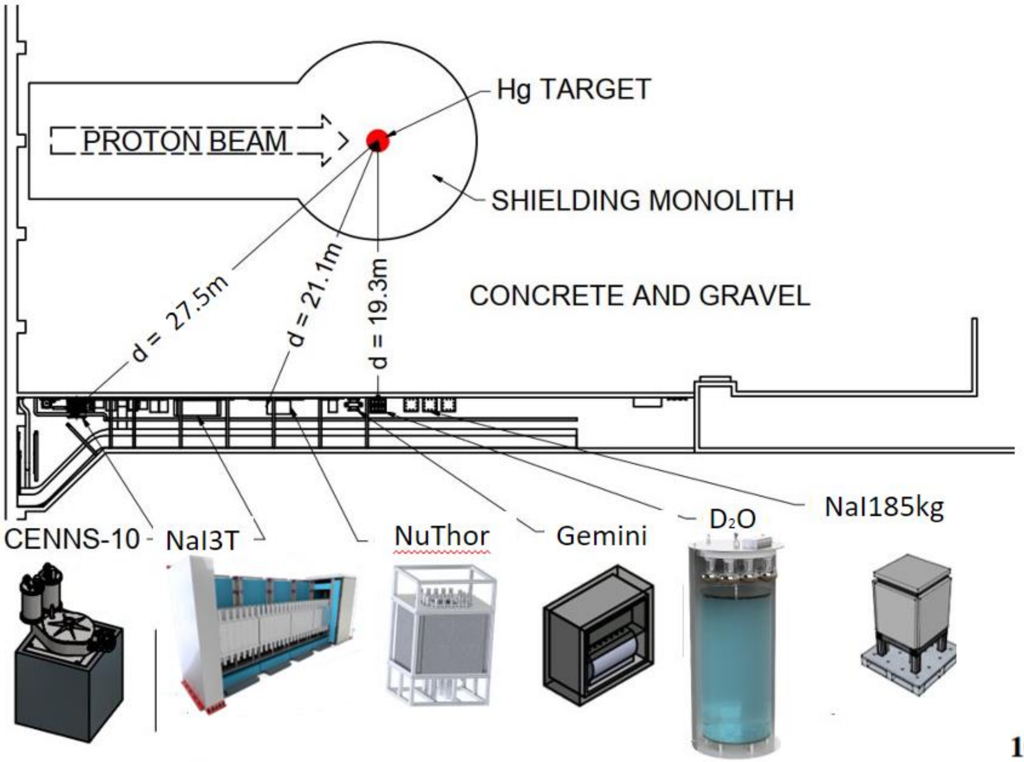
Timing distribution at SNS



Energy distribution at SNS



Current COHERENT detectors

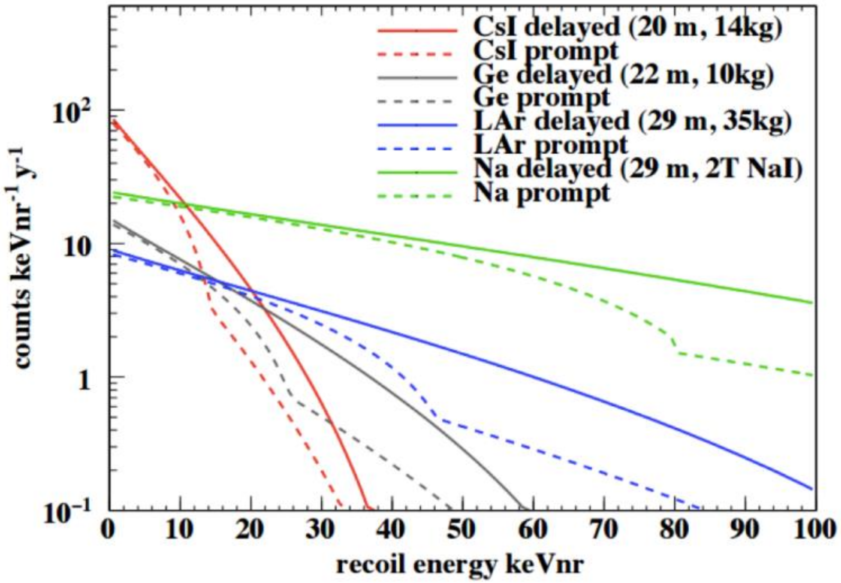


“Neutrino alley” – a basement hallway where SNS neutron backgrounds are manageable

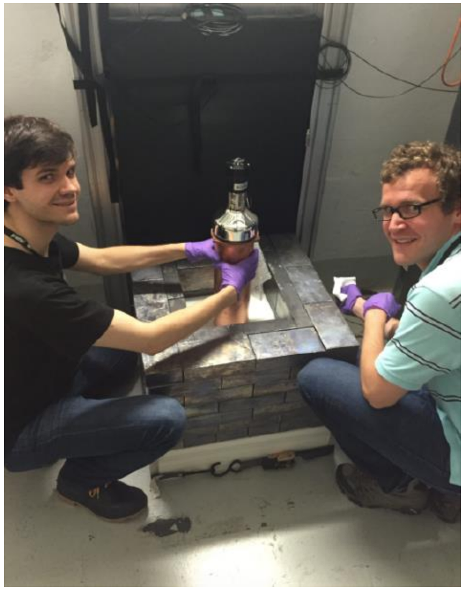
Collaboration maintains a suite of detectors to measure CEvNS, inelastic neutrino interactions, and monitor backgrounds

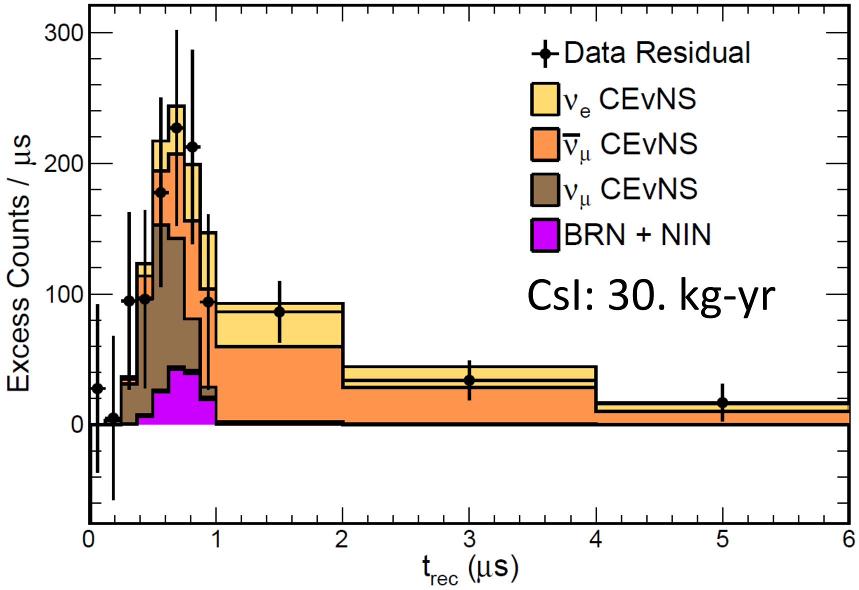
Currently studying CEvNS on four nuclei

Target	Technology	Fid. Mass	Threshold	Deployment
CsI[Na]	Scintillation	14.6	6.5 keV_{nr}	2015
Liquid Ar	Scintillation	24.4/610 kg	20 keV_{nr}	2017/≈2023
Ge	Ionization	18 kg	0.4 keV_{ee}	2022
NaI[Tl]	Scintillation	3500 kg	13 keV_{nr}	2022



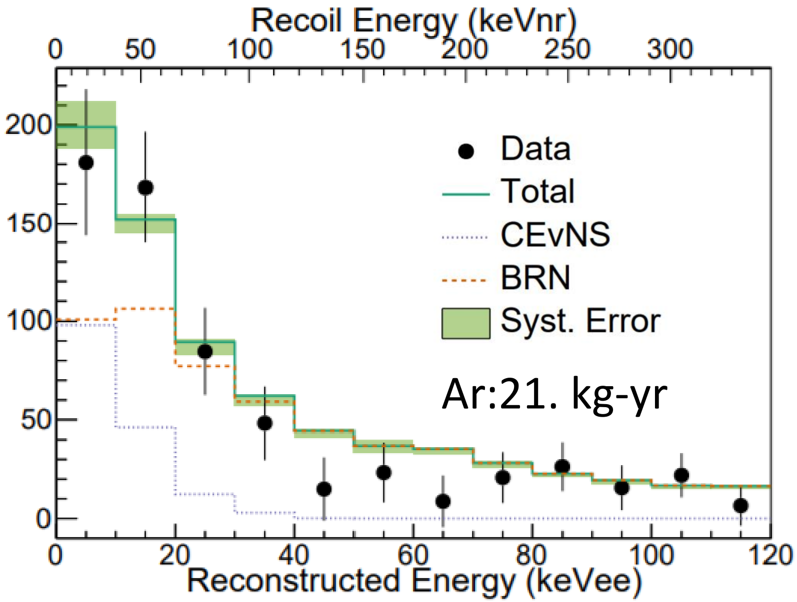
First light measurements





CsI[Na] scintillator:
14.6 kg
LY: 13.4 PE / keV_{ee}
Threshold: ≈ 8 keV_{nr}
Lead/HDPE shielding
First CEvNS! 2017
Final result 2022

Science **357** 6356 1123-1126
PRL **129** 081801
PRL **130** 051803
JINST **17** P10034

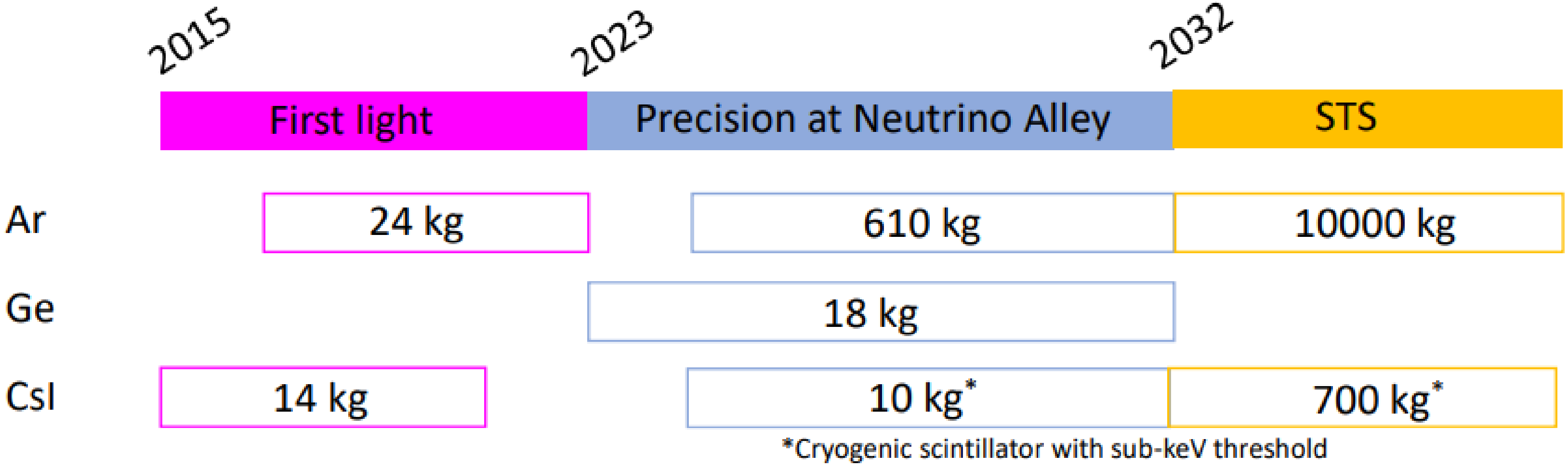


Argon scintillator:
LY: 4.3 PE / keV_{ee}
Threshold: ≈ 20 keV_{nr}
Lead/water shielding
CEvNS @ 3.4 σ 2021

PRL **126** 012002

CEvNS datasets of the future

Continuous physics potential over coming decades. Transitioning to precision studies at neutrino alley and planning for future second target station opportunities

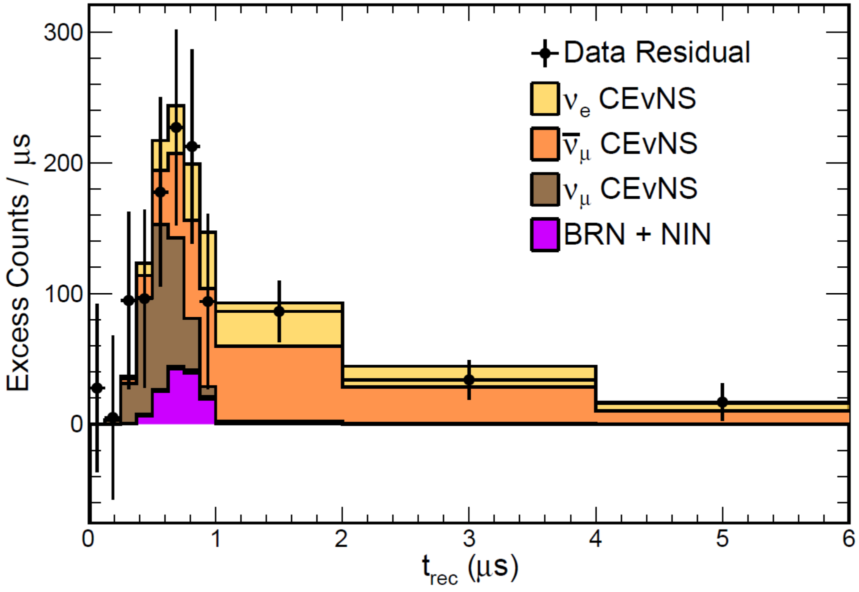


2015 2023 2032

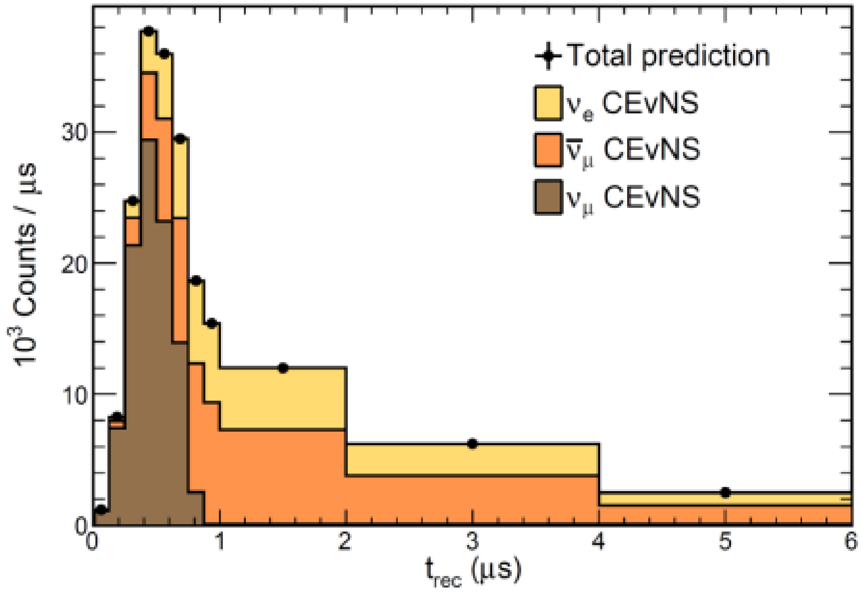
	First light	Precision at Neutrino Alley	STS
Ar	24 kg	610 kg	10000 kg
Ge		18 kg	
CsI	14 kg	10 kg*	700 kg*

*Cryogenic scintillator with sub-keV threshold

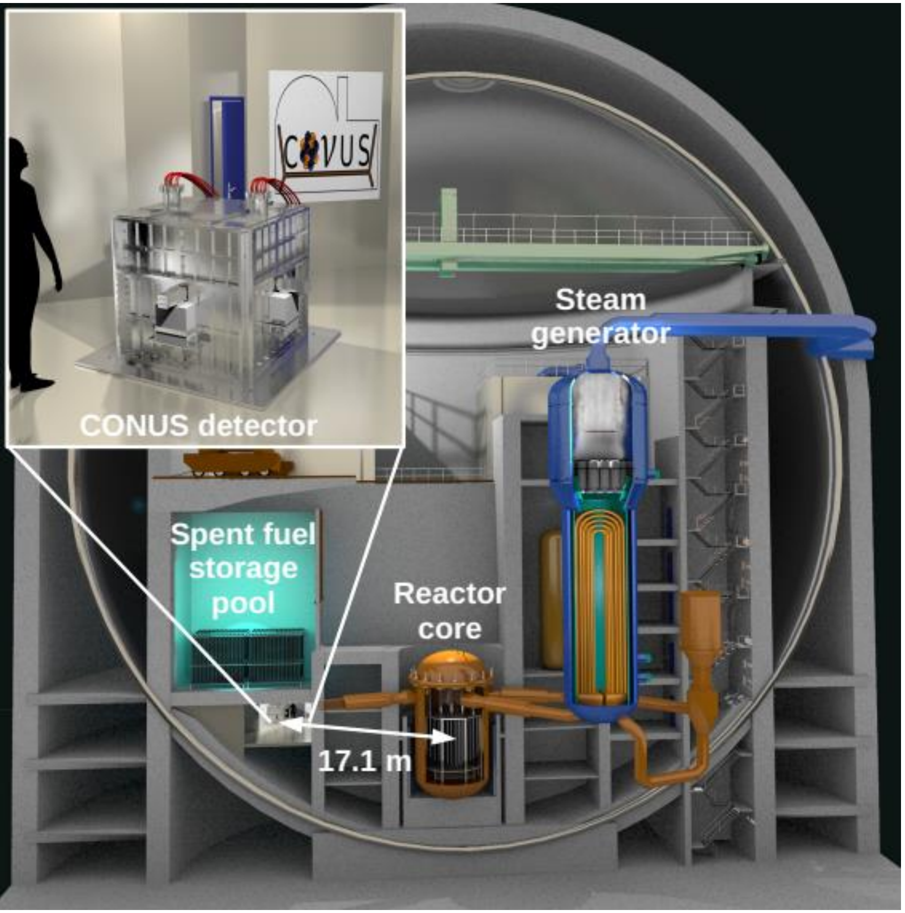
2023: CsI – 306 evt / 3 yr

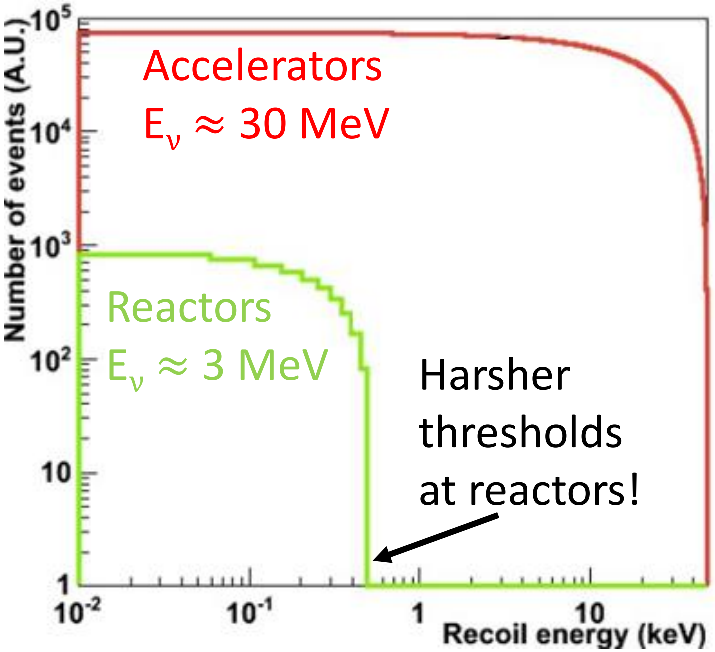


2030s: Ar – 50000 evt / 1 yr



CEvNS at reactors: CONUS at Brokdorf (Germany)





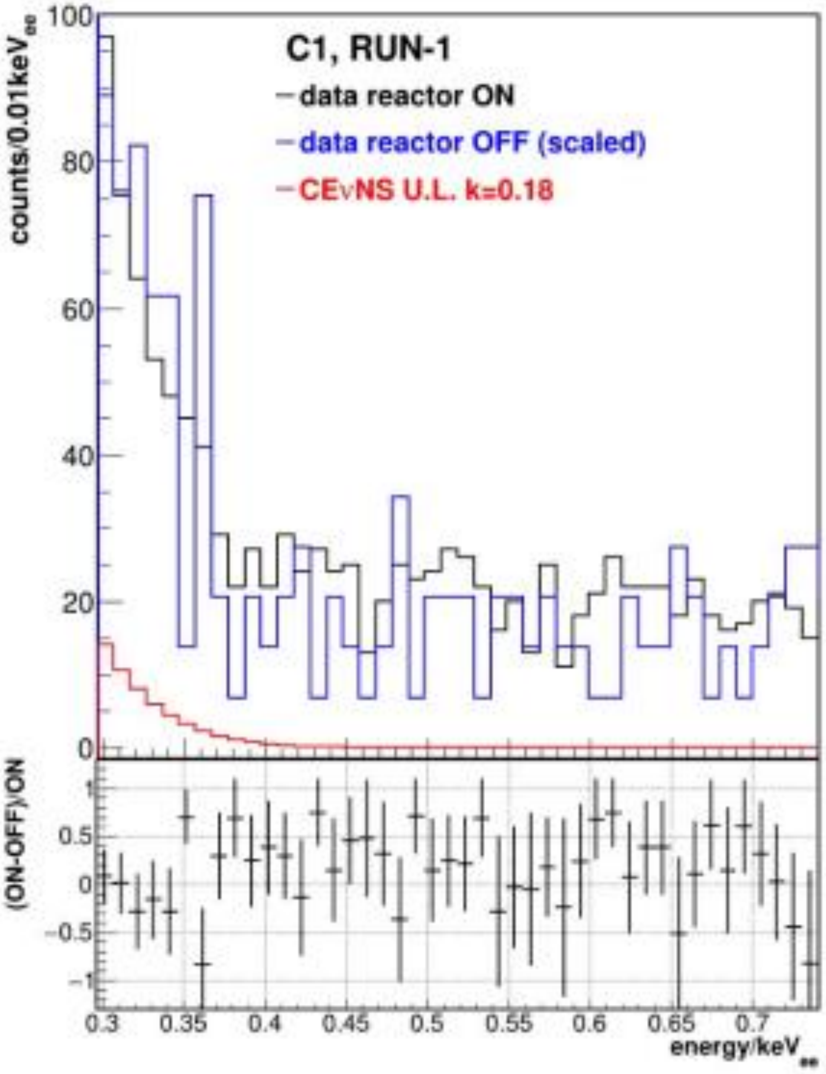
4 x 1kg high purity germanium PPC detectors operating 17 m from 3.9 GW-th reactor in Brokdorf: gives flux of 2.3e13 ν / cm^2 / s

Compact shielding system with lead, poly, and an active muon veto system

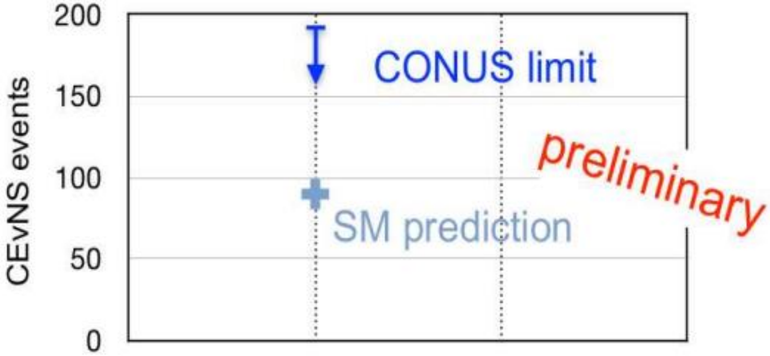
Steady detector running with composit shielding and
0.2 keV$_{ee}$ threshold – very near endpoint of reactor neutrino spectrum

CEvNS constraint from CONUS

Lower energy neutrinos at reactors: quenching critical



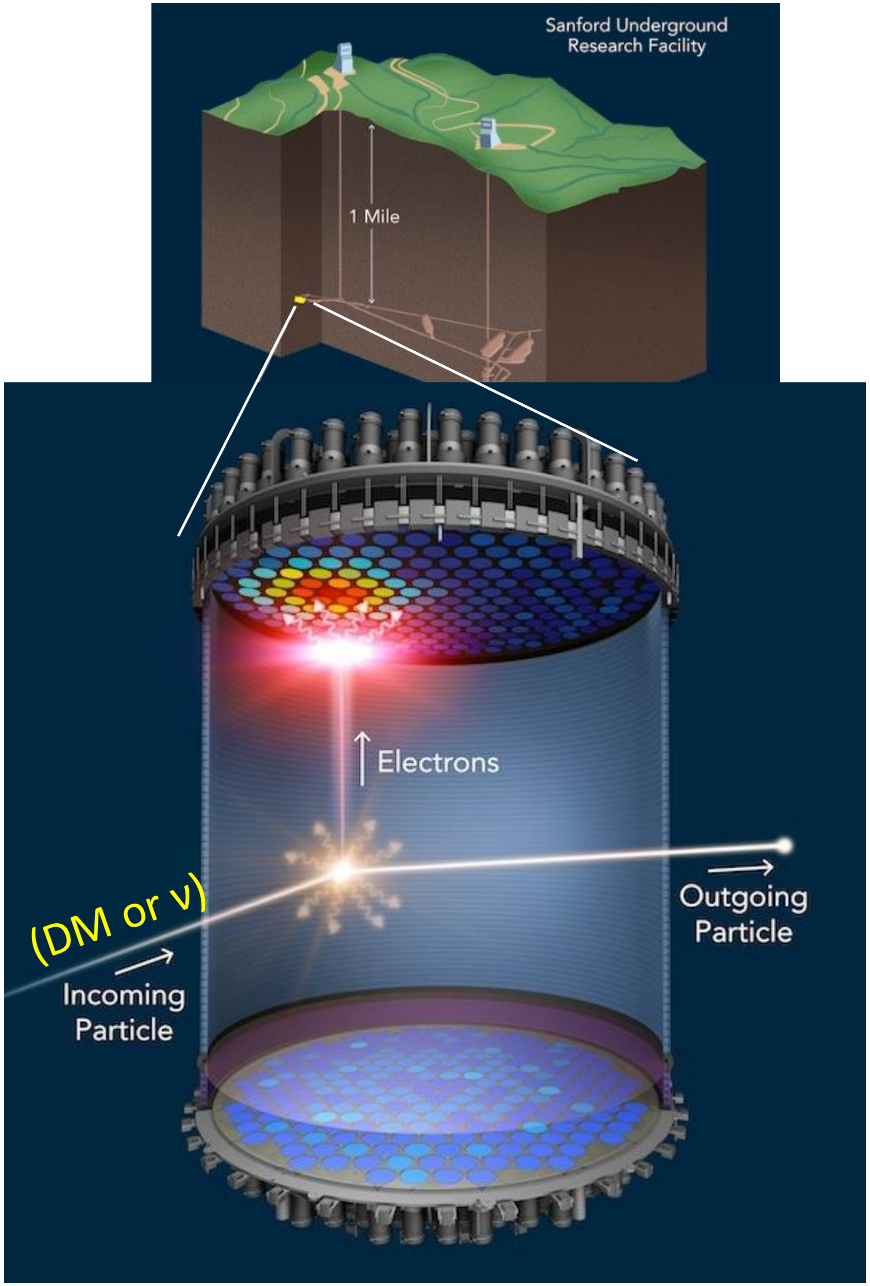
After calibrating quenching, CONUS currently constrains CEvNS to 2x the standard model cross section



Favorable outlook for detection after upgrade reducing threshold 0.2 keV$_{ee}$ -> 0.17 keV$_{ee}$

Eur Phys J C **82** 815
Eur Phys J C **82** 813
JHEP **05** 085

Astroparticle CEvNS: Lux-Zeplin



5.5-t fiducial xenon dark matter detector located in SURF

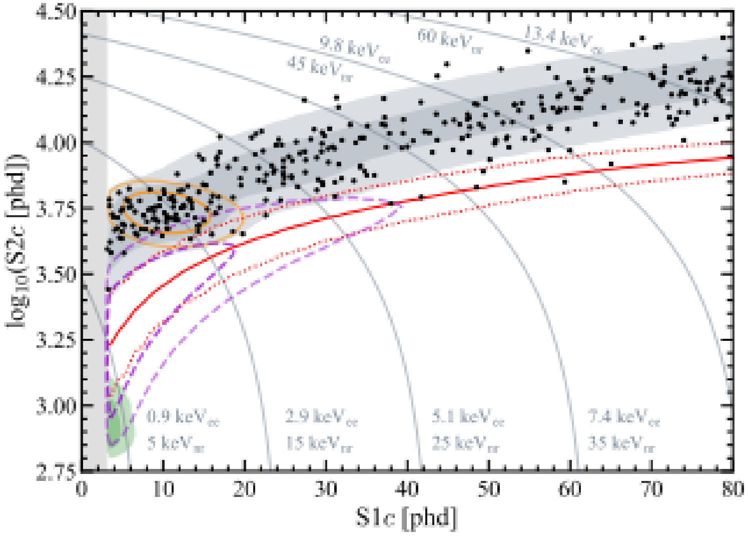
Designed to search for nuclear recoils induced by dark matter passing through detector

CEvNS interactions from ^{8}B solar neutrinos leave a very similar signature

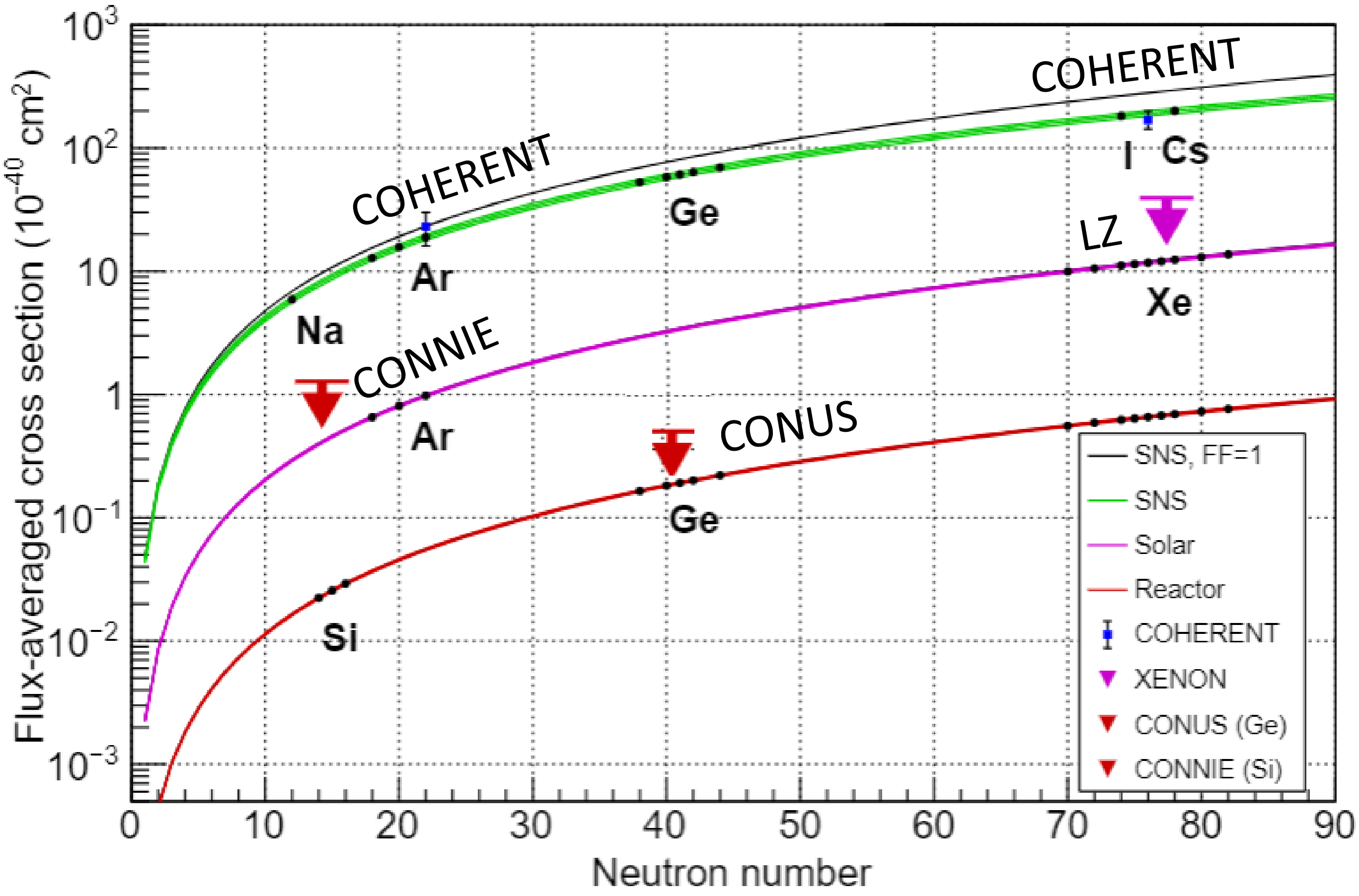
Pulse shape discrimination allows for nuclear/electronic recoil discrimination

Xe dark matter sensitivity rapidly approaching the expected solar neutrino population

arXiv:2207.03764



Current CEvNS measurements



CEvNS at accelerators:

PRL **129** 081801 (COHERENT, CsI, > 11σ)

PRL **126** 012002 (COHERENT, Ar, > 3σ)

CEvNS with solar neutrinos:

PRL **126** 091301 (Xenon1t, Xe, constraint)

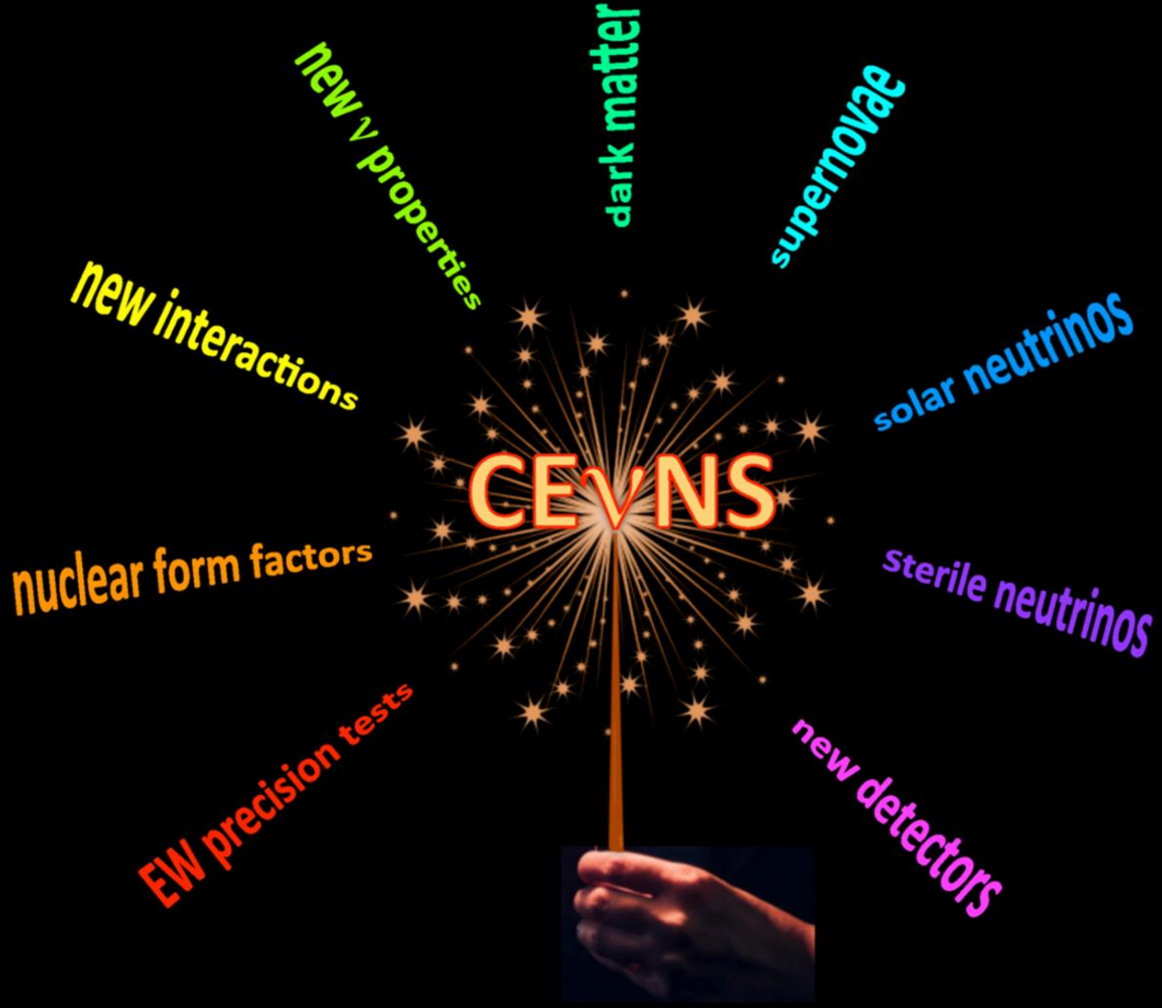
CEvNS at reactors:

JHEP **2022** 85 (CONUS, Ge, constraint)

PRD **104** 072003 (Colaresi et al., Ge, evidence)

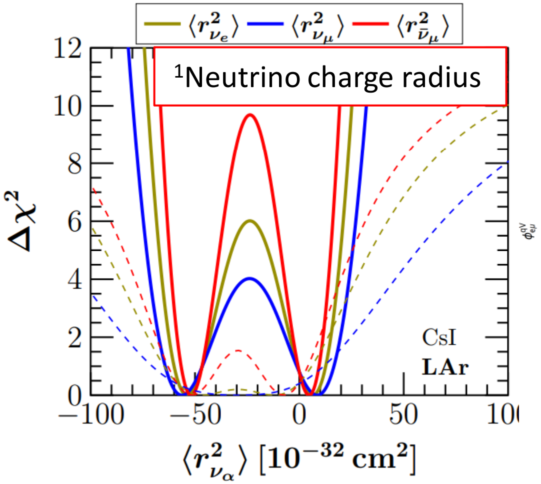
Physics reach of CEvNS experiments

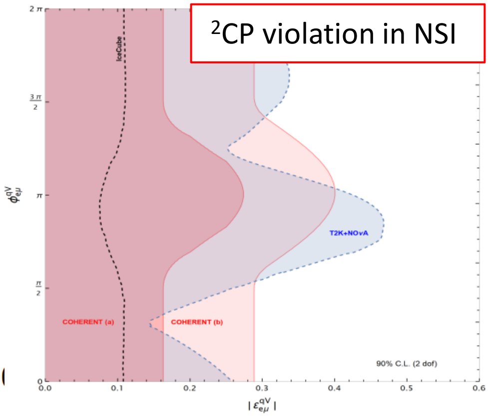
Through precision measurements, CEvNS is a new avenue for illuminating new physics

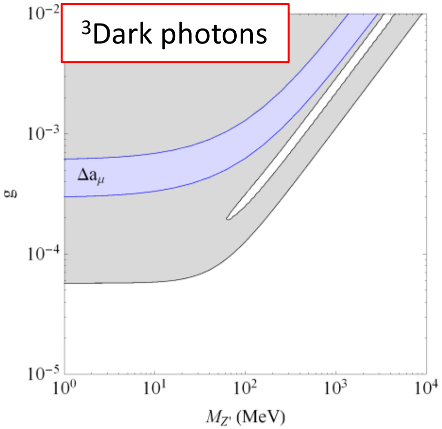


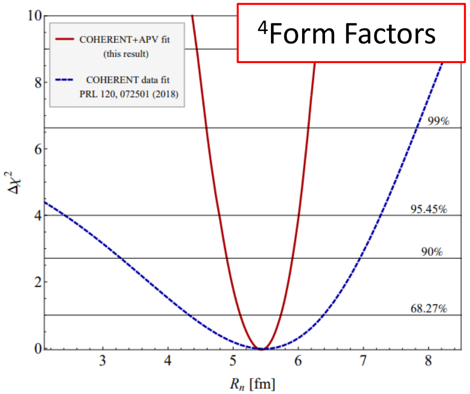
E. Lisi (Neutrino 2018)

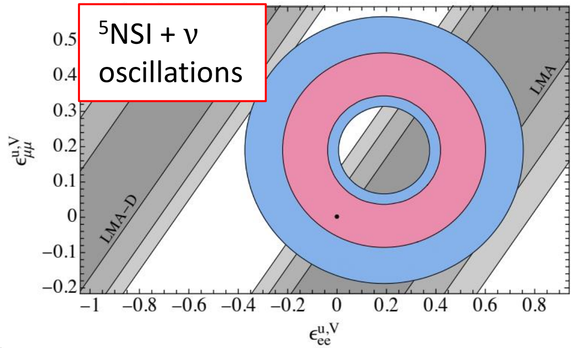
Way more than we can talk about today!

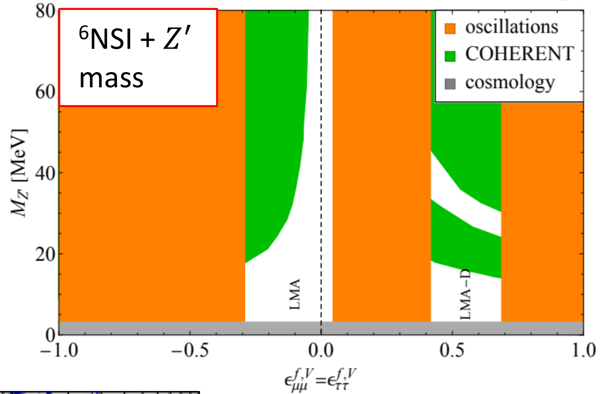

[1]Neutrino charge radius

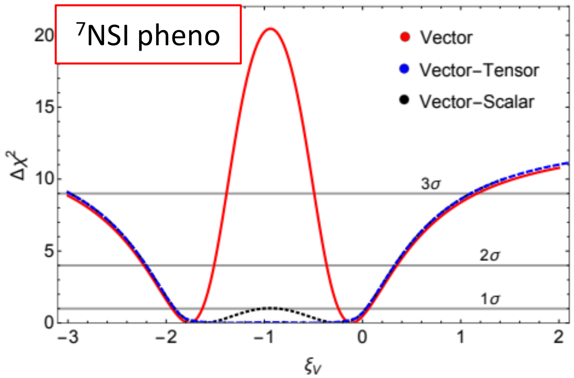

[2]CP violation in NSI

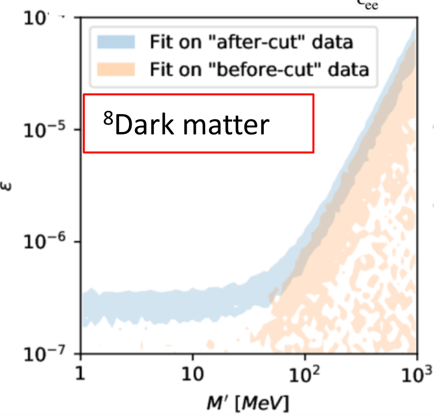

[3]Dark photons

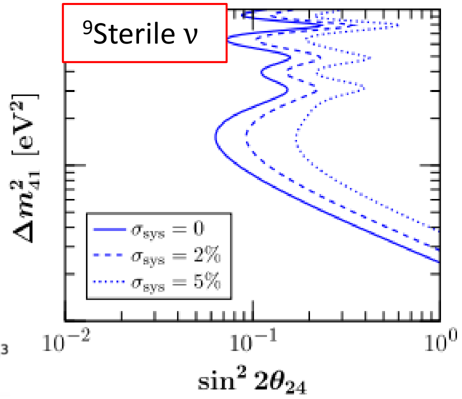

[4]Form Factors

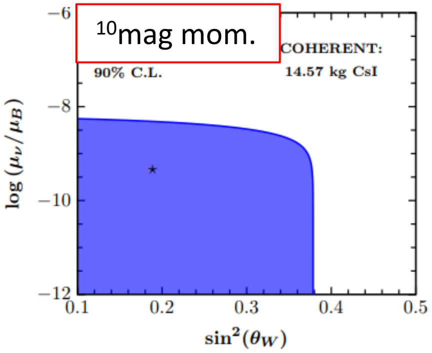

[5]NSI + ν oscillations


[6]NSI + Z' mass


[7]NSI pheno


[8]Dark matter


[9]Sterile ν

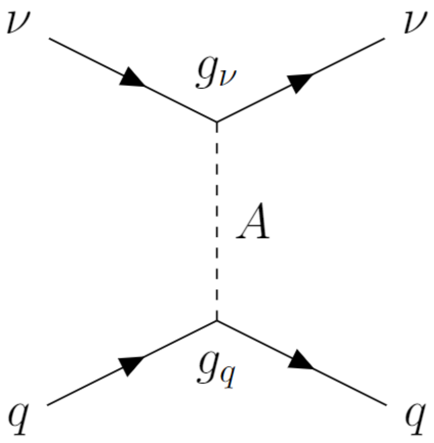

[10]mag mom.

[1] Miranda et al., *JHEP* **05** 130 (2021)
[2] Khan et al., *PRD* **104** 015019 (2021)
[3] Liao/Marfatia, *PLB* **775** 54-57 (2017)
[4] Cadeddu/Dordei, *PRD* **99** 092003 (2019)
[5] Coloma et al., *PRD* **96** 115007 (2017)
[6] Denton/Gehrlein, *PRD* **106** 015022 (2022)
[7] Sierra et al., *PRD* **98** 075018 (2018)
[8] Dutta et al., *PRL* **124** 121802 (2019)
[9] Miranda et al., *PRD* **102** 113014 (2020)
[10] Papoulias/Kosmas, *PRD* **97** 033003 (2017)

Neutrino non-standard interactions (NSI)

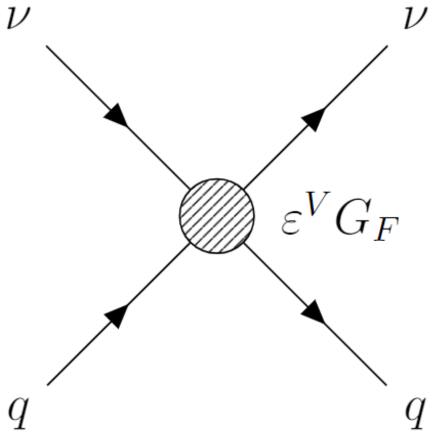
Origin of neutrino NSI interactions

Dark photon could mediate NSI interactions between neutrinos and SM – and could explain g-2, B-L symmetry, hidden sector dark matter interactions, etc.



$$\mathcal{M} \propto \frac{g_\nu g_q}{Q^2 + m_A^2}$$

$$m_A^2 \gg Q^2 \implies$$

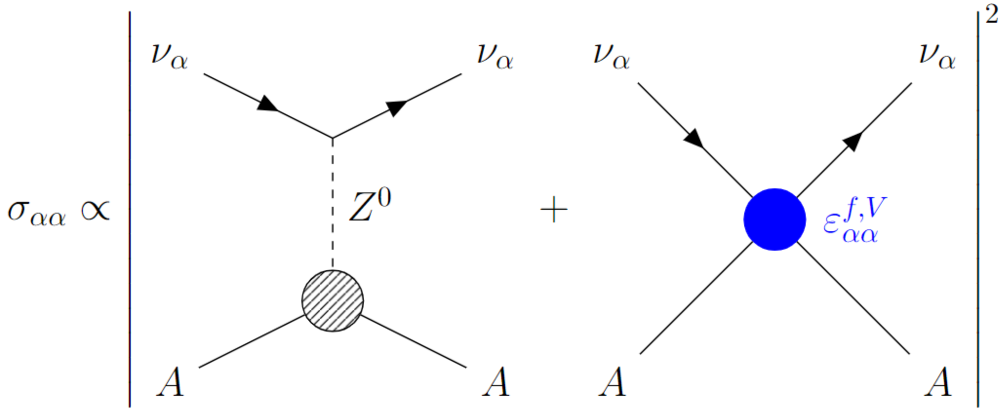


$$\mathcal{M} \propto \frac{g_\nu g_q}{m_A^2} \equiv \varepsilon^V G_F$$

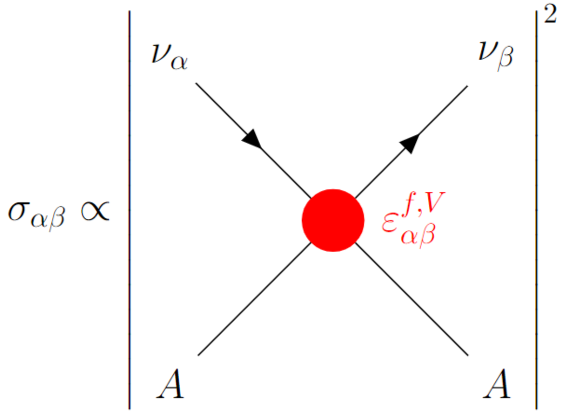
Generally, coupling can depend on SM fermion and neutrino flavor: $\varepsilon^{f,V}_{\alpha\beta}$

Searching for BSM interactions with CEvNS

Flavor conserving interactions – Interference between new mediator and Z which breaks lepton universality



Flavor changing interactions – Would add new scattering processes not allowed by the standard model



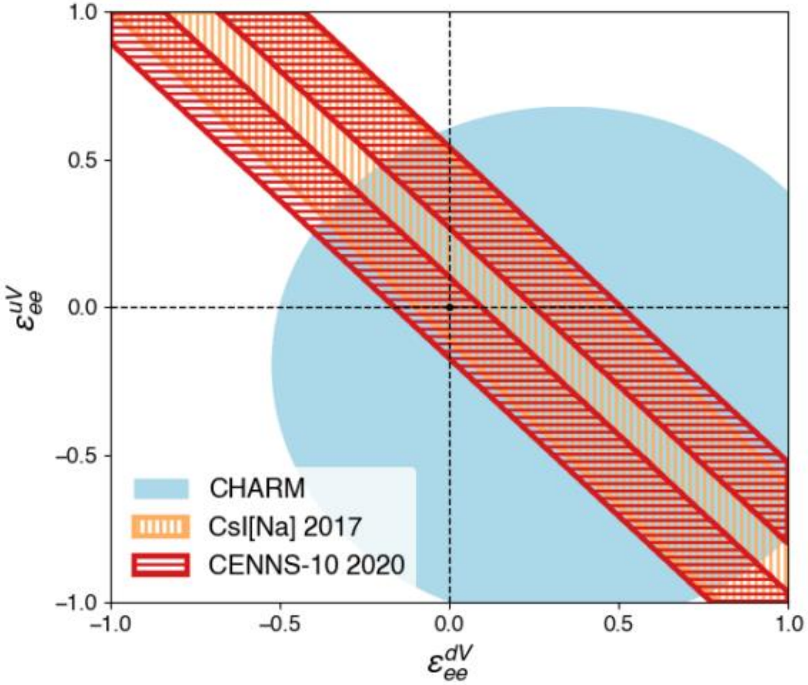
Scattering model parameterized by effective couplings, $\varepsilon^{f,V}_{\alpha\alpha}$ and $\varepsilon^{f,V}_{\alpha\beta}$, x G_F

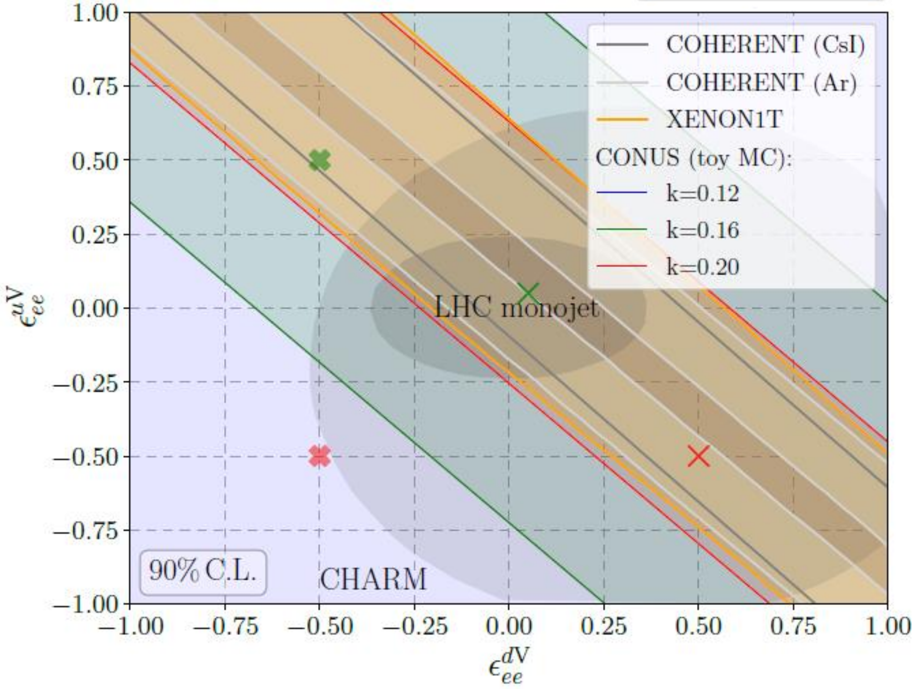
Adjusts weak charge in CEvNS cross section:

$$Q_{W,\alpha} = (2\varepsilon^{u,V}_{\alpha\alpha} + \varepsilon^{d,V}_{\alpha\alpha} + g^V_p)Z + (\varepsilon^{u,V}_{\alpha\alpha} + 2\varepsilon^{d,V}_{\alpha\alpha} + g^V_n)N + \sum_{\alpha\neq\beta}\left[(2\varepsilon^{u,V}_{\alpha\beta} + \varepsilon^{d,V}_{\alpha\beta})Z + (\varepsilon^{u,V}_{\alpha\beta} + 2\varepsilon^{d,V}_{\alpha\beta})N\right]$$

Different CEvNS cross sections for different flavors = non-standard oscillation effects

NSI couplings to electron neutrinos



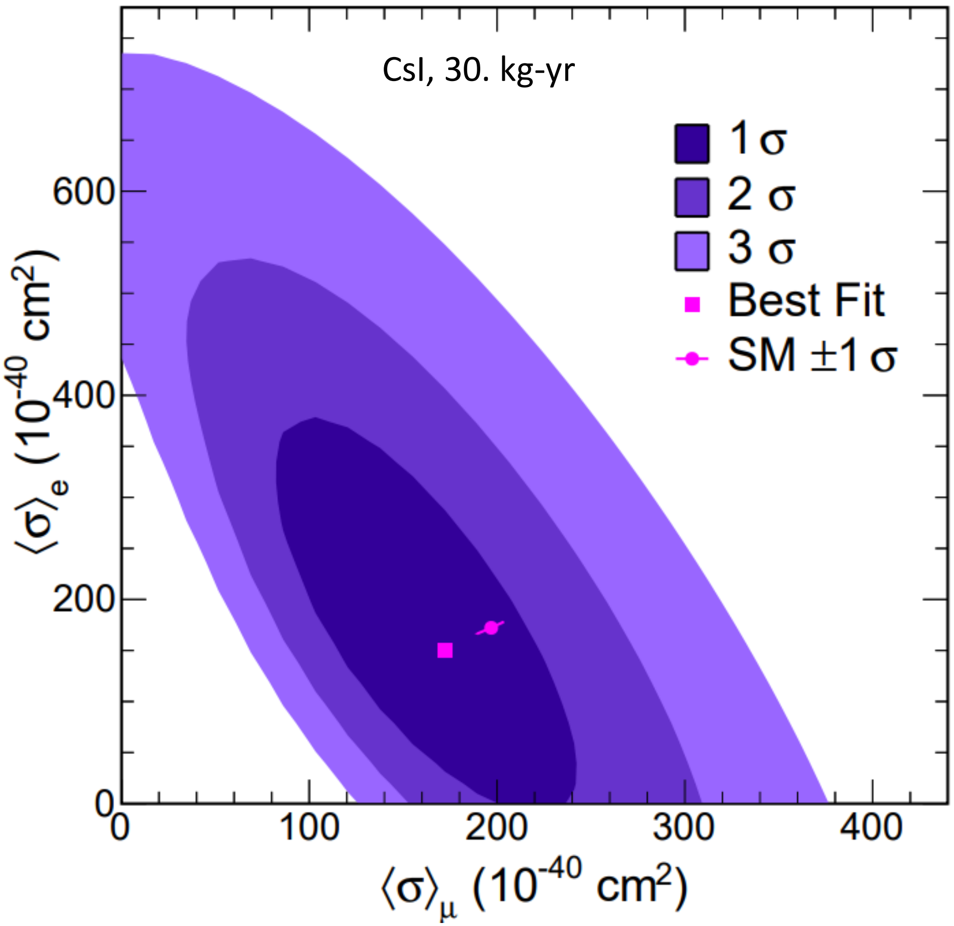


- ❑ CEvNS cross section well predicted, excellent probe for testing for anomalous couplings
- ❑ Electron couplings only constrained to O(1), but can be tested both by COHERENT and at reactor experiments

- COHERENT, *PRL* **126** 012002
- CONUS, *JHEP* **05** 85
+ COHERENT data, *PRL* **129** 081801

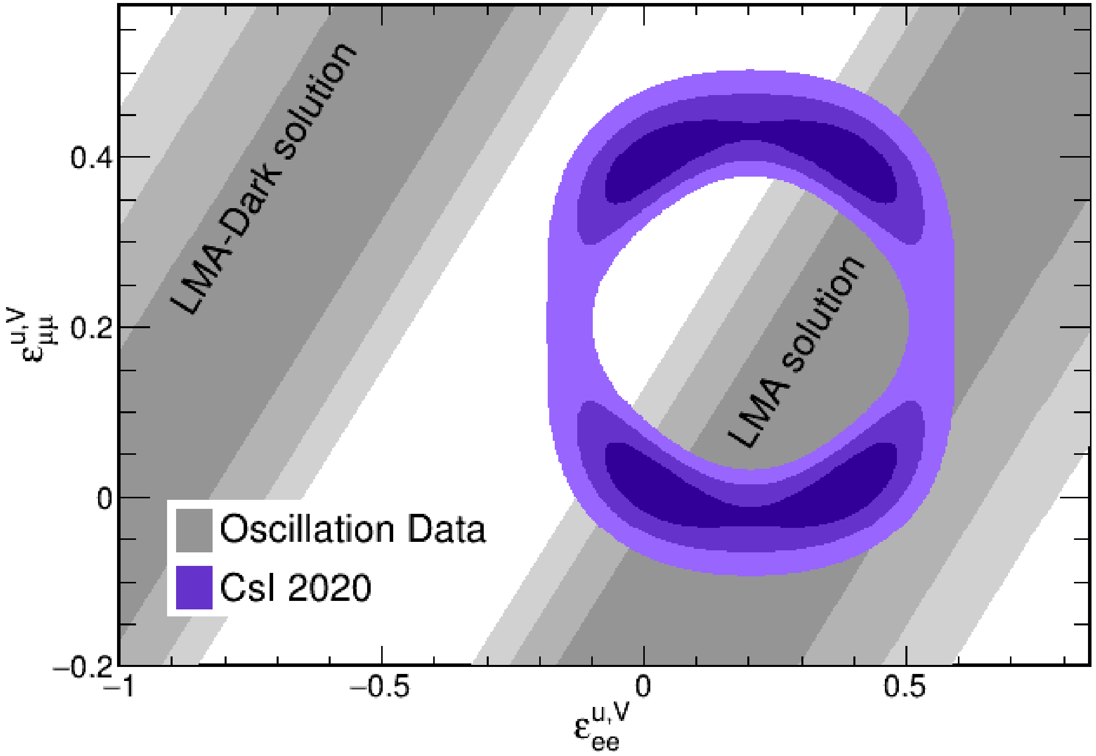
Flavored CEvNS cross section

- ❑ NSI scenarios break lepton universality for the NC cross section – COHERENT can directly measure the CEvNS cross section for different flavors due to many-flavored neutrino flux and timing
- ❑ ν_μ timing sheds light on the fraction of observed CEvNS that are from each flavor
- ❑ Reactor experiments: intense source of $\bar{\nu}_e$ -> good complementarity with spallation experiments



- COHERENT, *PRL* **129** 081801

Interpreting Solar Neutrino Oscillation Data



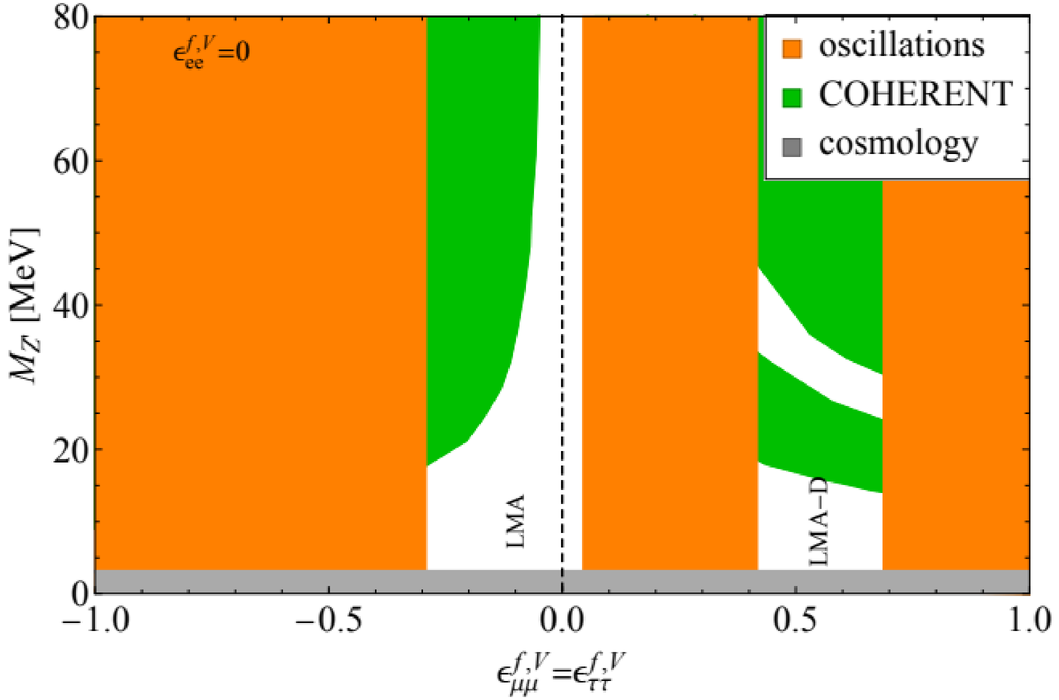
- NSI causes ambiguity in solar neutrino oscillation measurements:
  - Large mixing angle (LMA) solution with θ_{12} about 33 deg
  - Large mixing angle – dark (LMA-Dark) solution flips θ_{12} octant, giving about 47 deg
- LMA-Dark would require non-zero $\varepsilon_{ee}^{u,V}$ and $\varepsilon_{\mu\mu}^{u,V}$, which COHERENT tests directly with flavored cross section result

- Coloma/Gonzalez-Garcia/Maltoni/ Schwetz, *PRD* **96** 11 115007
- COHERENT, *PRL* **129** 081801

Oscillation effects due to light-mediator NSI scenarios

Previous studies assume mediator is heavy. For mediator mass near Q, we must include the Q^2 dependence in the propagator

$$\frac{g_\nu g_q}{m_A^2} \rightarrow \frac{g_\nu g_q}{Q^2 + m_A^2}$$



- LMA-Dark solution still viable for mediator masses below 40 MeV

- In the light-mediator scenario, NSI affects CEvNS cross section and shape
- To test lower mass hypotheses, must examine CEvNS cross section at low recoil energy -> need lower threshold detectors, possible with COHERENT detector upgrades currently underway

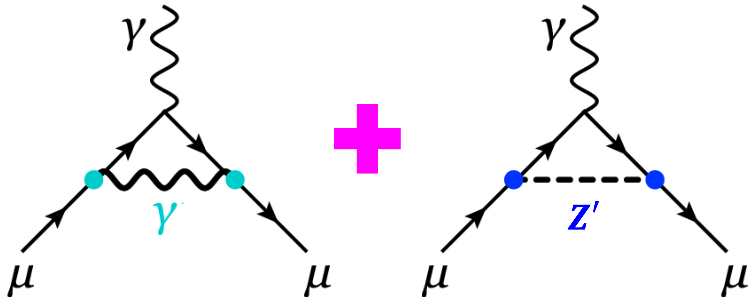
- Denton/Gerhlein, *PRD* **106** 015022
+ COHERENT data, *PRL* **129** 081801

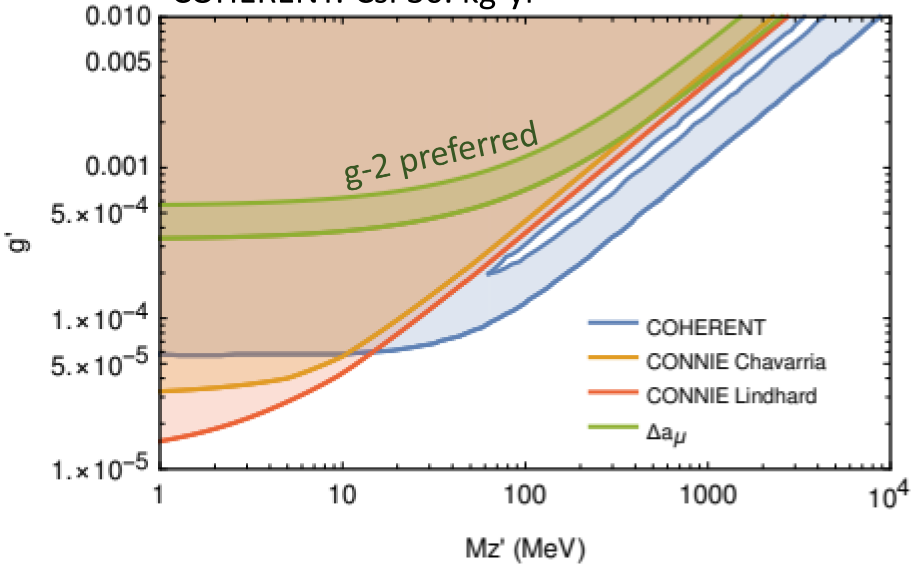
Searches for dark photons

Testing g-2 by probing dark photons

Dark photons are common U(1) extensions to the standard model

Often motivated by g-2 result where a dark photon would interfere with SM particles





CONNIE: Si, 3.7 kg-day
COHERENT: CsI 30. kg-yr

- A new dark photon would also affect the CEvNS cross section
- For low dark photon masses, Q^2 dependence of propagator important as in light-mediator NSI scenario
- CEvNS data from COHERENT, CONNIE, and CONUS all disfavor the g-2 preferred parameter space for a dark photon that couples equally to all SM fermions

- CONNIE *JHEP* **04** 054
+ COHERENT data, *Science* **357**

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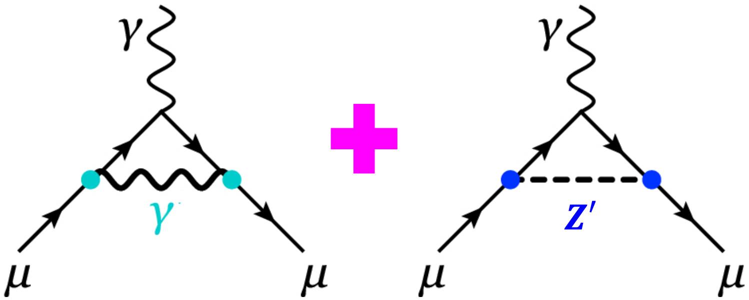
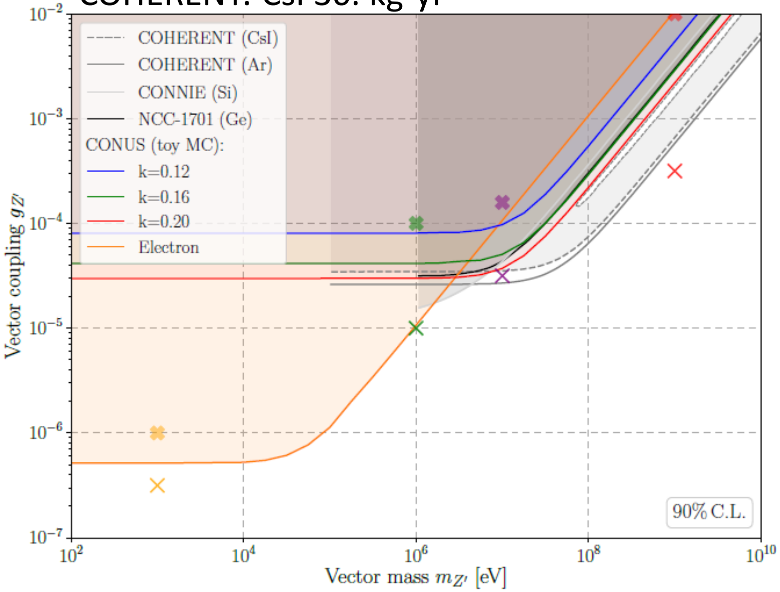


CONNIE: Si, 3.7 kg-day
CONUS: Ge, 458 kg-day
COHERENT: CsI 30. kg-yr



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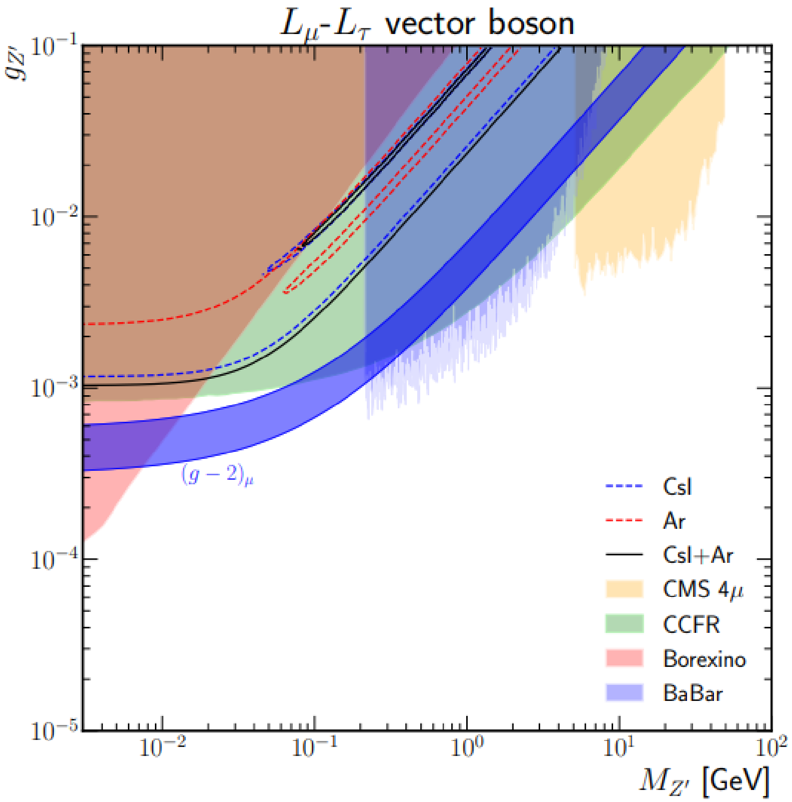
- CONUS, *JHEP* **05** 085
+ CONNIE data, *JHEP* **04** 054
+ COHERENT data, *Science* **357**

Dark photons in $L_\mu - L_\tau$ models

SM fermions may be charged differently under the new dark force

The $L_\mu - L_\tau$ gauge model would predict that couples just to μ, τ, and their neutrinos

This is compatible with g-2 but evades most constraints from electron scattering



- COHERENT and other accelerator-based CEvNS experiments can make strong constraints on this model with first-light data from COHERENT already competitive
- Viable parameter space for g-2 remians

- Atzori-Corona/Cadeddu/Cargioli/
Dordei/Giunti, *JHEP* **05** 159
+ COHERENT data, *PRL* **129** 081801

Outlook for constraining $L_\mu - L_\tau$ with CEvNS

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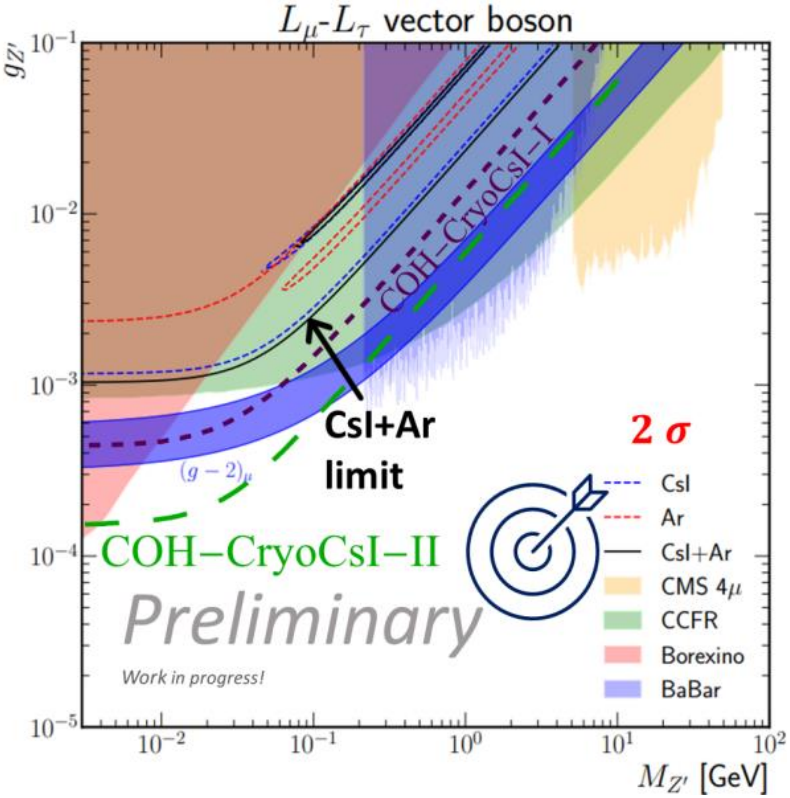


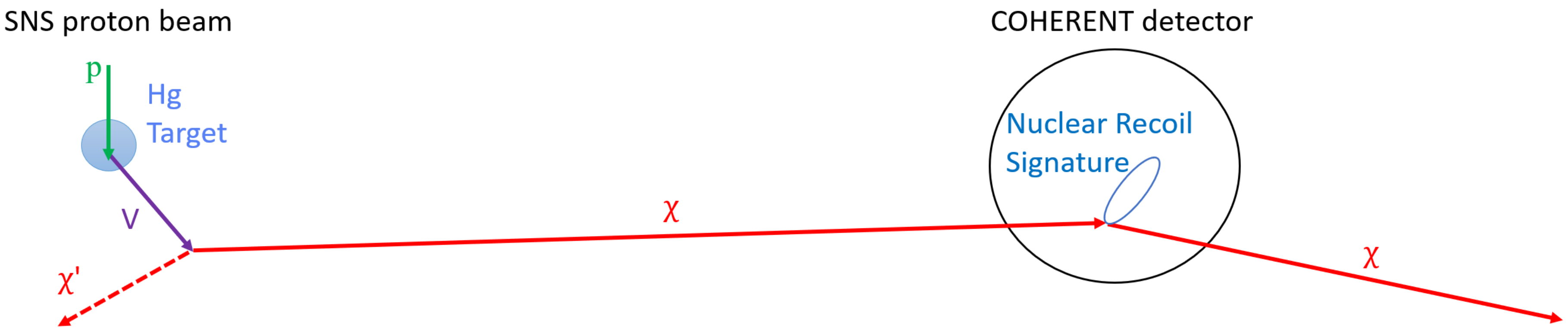
Plot from M. Attori Corona, Magnificent CEvNS 2023: here

- Future upgraded CsI effort within COHERENT will aggressively probe the g-2-favored parameter space in $L_\mu - L_\tau$

- Atzori-Corona/Cadeddu/Cargioli/Dordei/Giunti, *JHEP* **05** 159
+ COHERENT data, *PRL* **129** 081801

Searches for dark matter / hidden sector particles

Searching for dark matter with CEvNS detectors at the SNS

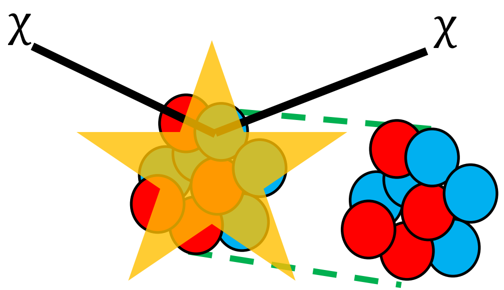


- A CEvNS detector at the SNS operates like a standard beam dump experiment
- Any hidden sector particles with masses below ≈ 220 MeV/c^2 could be produced in the many proton-Hg interactions within the SNS target
- This may include mediator particles between SM and dark matter particles!

Classical WIMP mass regime:
  Lee and Weinberg, *PRL* **39** 165 (1977)
Early sub-GeV DM phenomenology:
  Fayet, *PRD* **70**, 023514 (2004)
  Boehm and Fayet, *Nuc. Phys. B* **683**, 219 (2004)
  Pospelov et al., *PLB* **662**, 53 (2008)

Leptophobic DM phenomenology:
  Batell et al., *PRD* **90**, 115014 (2014)
  Batell et al., *PRD* **100** 095020 (2019)
Coherent DM scattering / DM at the SNS:
  deNiverville et al., *PRD* **84**, 075020 (2015)
  Dutta et al., *PRL* **123**, 061801 (2019)

Advantages of low-recoil detectors: cross section



$$\lambda = h/\sqrt{Q^2} \gg R_p$$

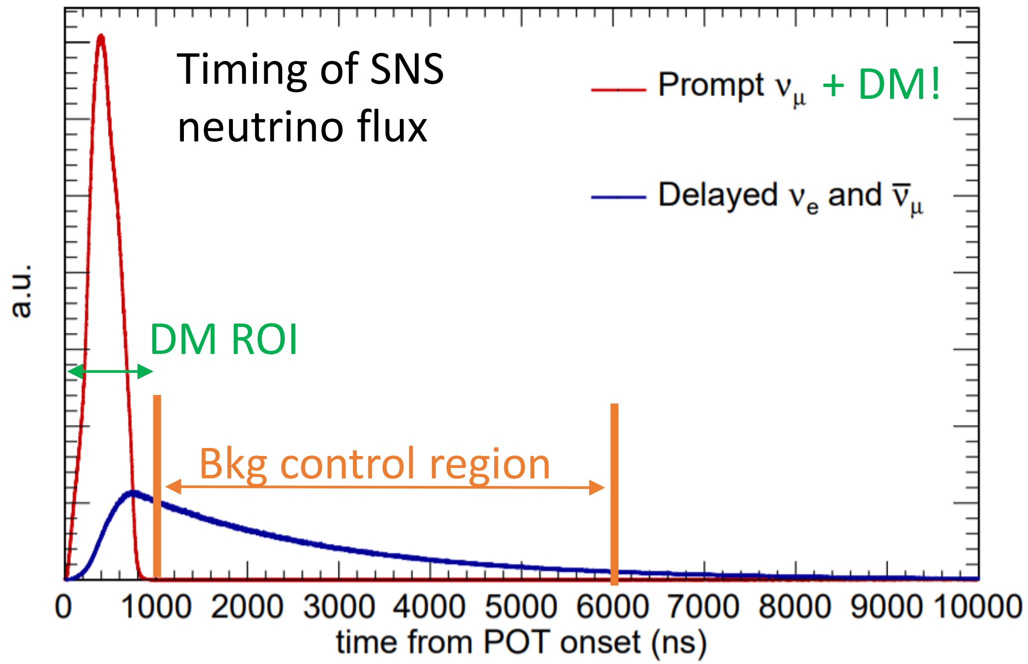
- ❑ We're dealing with low enough Q^2 that the deBroglie wavelength is large compared to nuclear radius
- ❑ All nucleons within nucleus recoil coherently from neutrino or DM scattering
- ❑ Astroparticle direct-detection experiments have exploited this for years – now accelerator experiments can too with CEvNS detectors

- ❑ This coherency gives a Z^2 enhancement in the cross section → big effect for CsI (Z of 53/55)
- ❑ Game-changing – a small 14-kg detector produced strongest constraint on light dark matter yet with impressive potential in the future

Direct-detection experiments searching for light dark matter

		Mass (t)
	LSND	167
	MiniBooNE	450
First CEvNS detector	COHERENT CsI	0.0146
Future program at STS	10t Ar detector	10

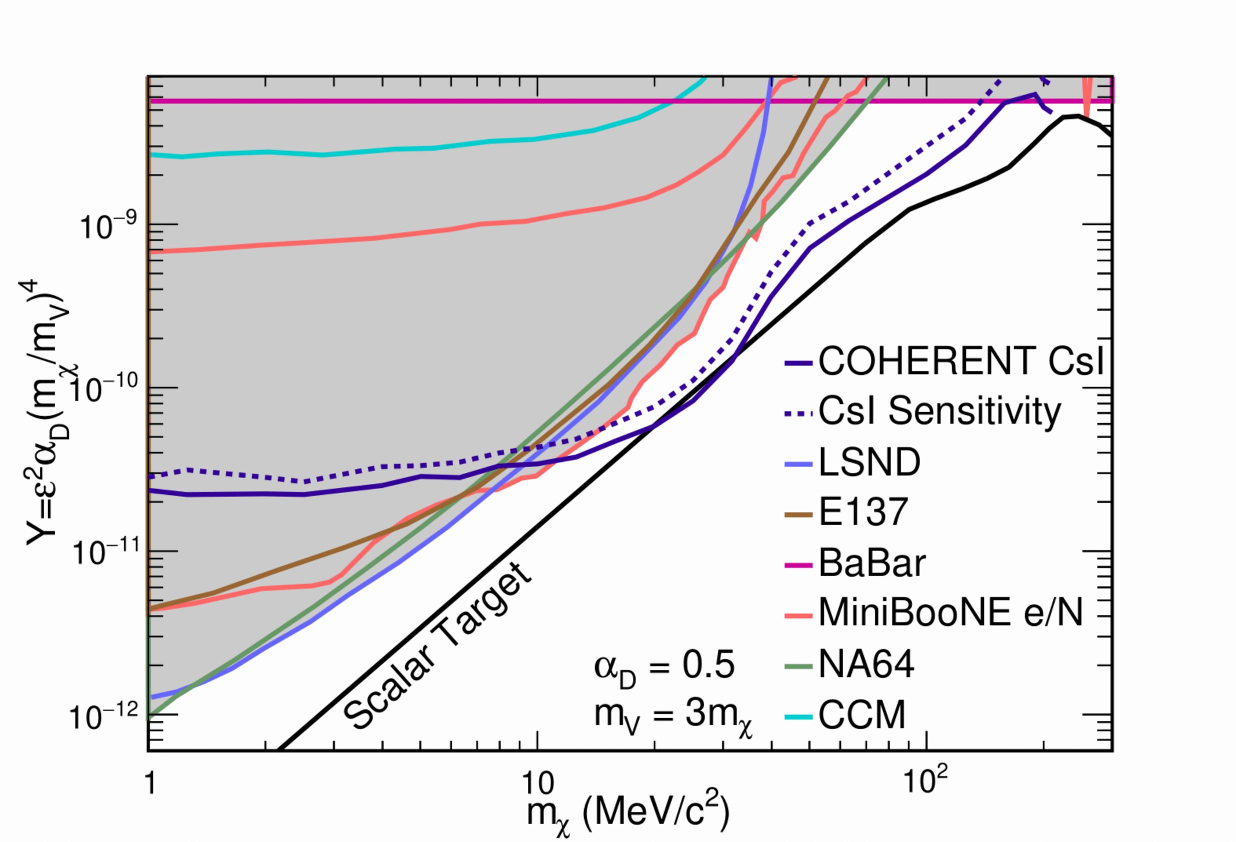
Advantages of spallation sources: constraining uncertainties



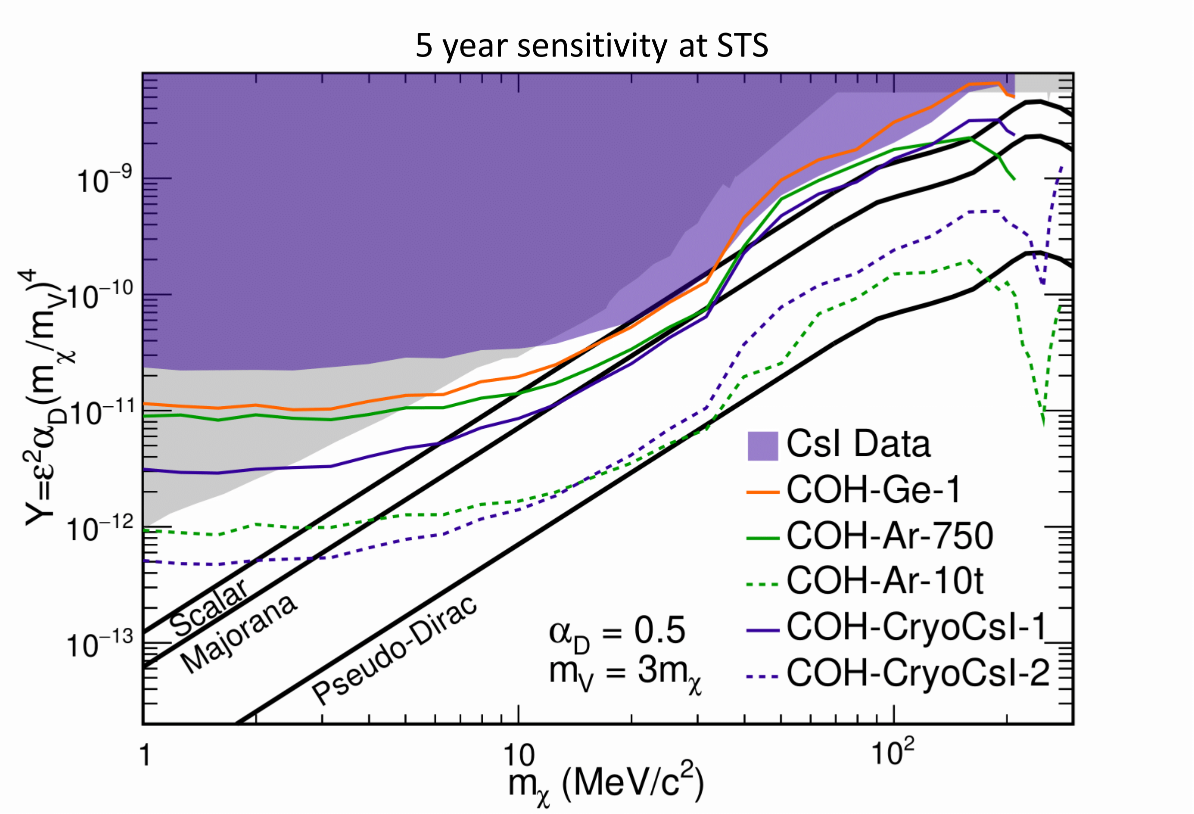
- ❑ CEvNS is the principal beam-related background for DM search
  - SM cross section precisely known, but uncertainties in detector response that are unique to each detector
- ❑ Since DM is relativistic, it is expected coincident with protons on target
  - No DM coincident with delayed CEvNS from $\upsilon_e/\bar{\upsilon}_\mu$ flux
- ❑ The delayed time window gives us a control sample – can constrain systematic uncertainties in situ and use to refine background estimates in the DM timing ROI
- ❑ Ensures DM search never systematics limited – syst uncertainty shrinks as fast as stat

COHERENT constraint of WIMP-like dark matter at the SNS

- With first CEvNS data from COHERENT, we are already competitive here
- We are first to probe beyond the scalar target that matches the DM relic abundance
- Achieved with small 14.6 kg CsI scintillation detector, can do much better at the STS



Future COHERENT sensitivity to dark matter

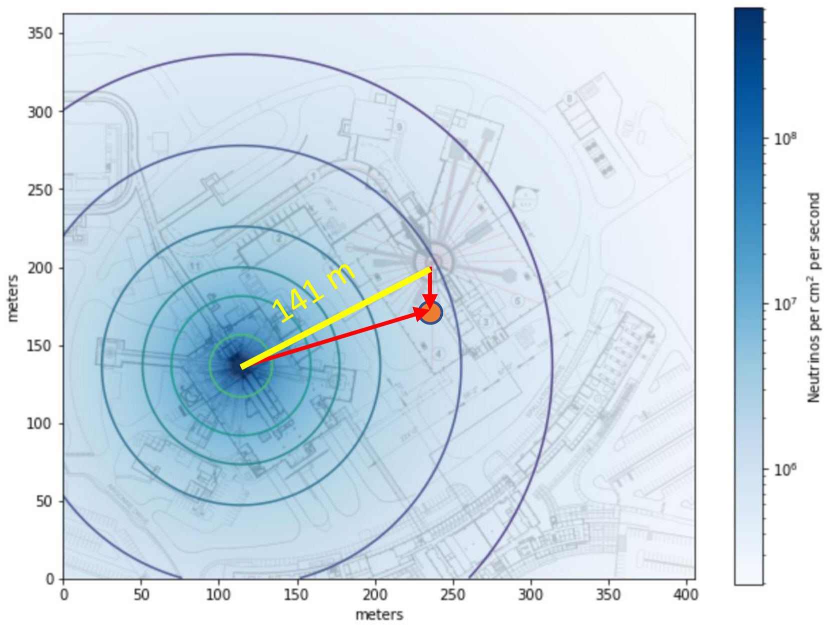


- Immediate future: germanium detector currently being commissioned – will fully explore scalar target at lower masses
- In coming years: future argon and cryogenic CsI detector from COHERENT – will be sensitive to a lower DM flux and probe the Majorana fermion target
- In next decade: large detectors placed forward at the STS (dashed lines) will begin to ambitiously test even the most pessimistic spin scenarios

Searches for sterile neutrino oscillations

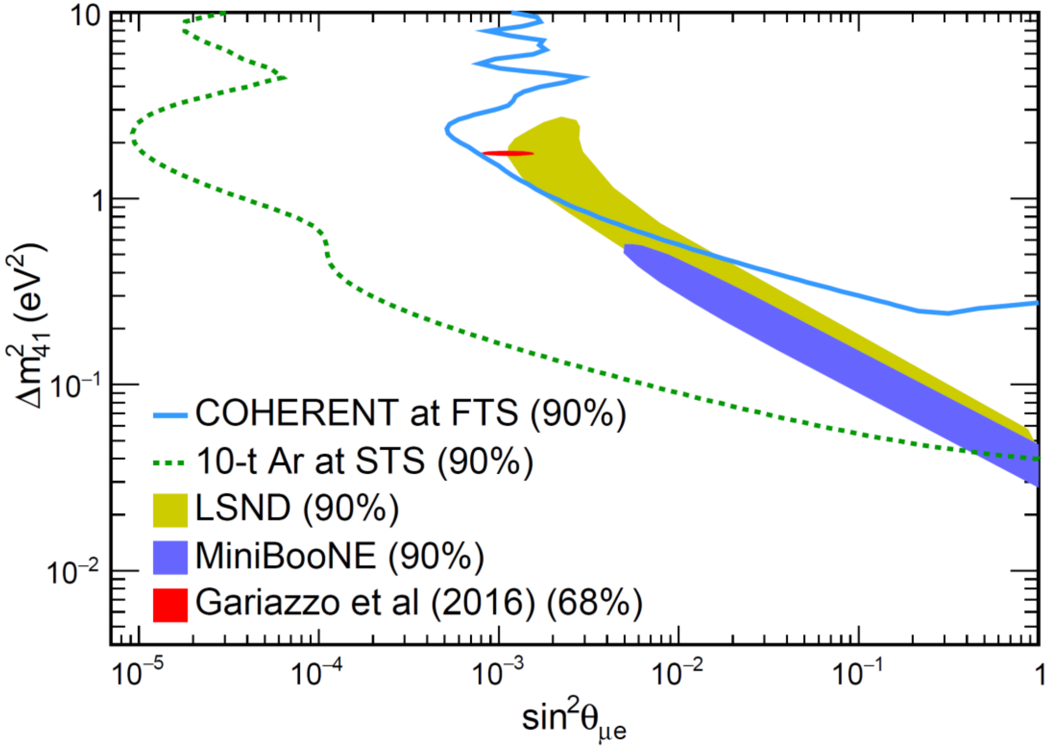
The SNS: perfectly designed to test sterile neutrinos

- Having two operating neutrino flux sources so near each other gives the SNS a unique opportunity
- As soon as the STS begins delivering beam, any detector at either target will receive beam from both targets
  - Analyze neutrino disappearance on two different baselines using the well-understood CEvNS channel within the same detector – correlated systematics



- A 10-t argon CEvNS detector which will be large enough to see CEvNS from each target so that we sample oscillation effects from both baselines
  - Assume L_{STS} = 20 m and L_{FTS} = 121 m
  - Uncertainties on detector response and interaction model are eliminated, similar to two-detector long-baseline oscillation experiments (DUNE, NOvA, T2K, etc.)

STS sensitivity to sterile oscillation parameters

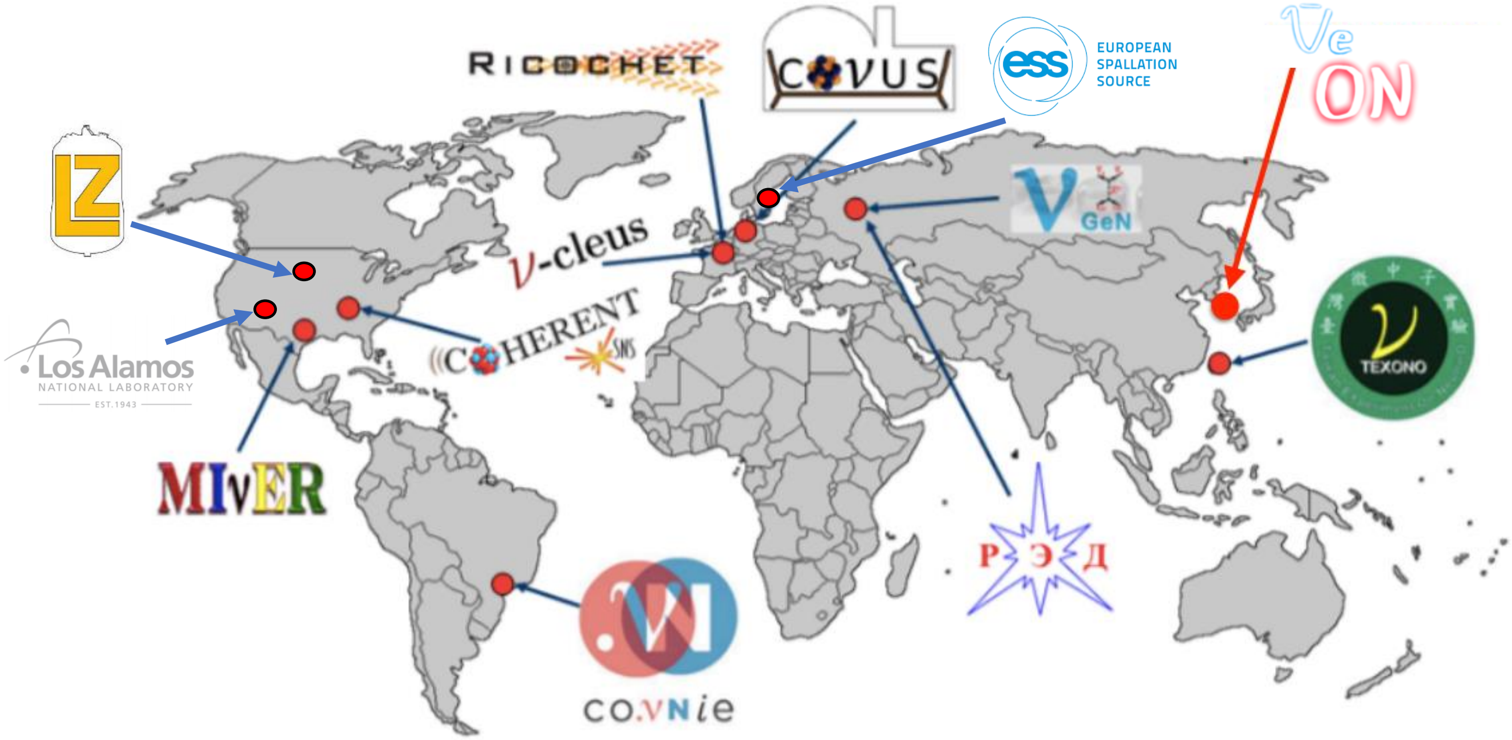


- After five years of data at the STS, a 10t argon single-phase scintillation detector would eliminate the global best fit oscillation parameters to a high degree of certainty and test nearly the entire parameter space allowed by LSND/MiniBooNE
  - Will implement an additional detection strategy with different and well-controlled systematic uncertainties to understand the LSND anomaly

- A large detector at the STS would significantly improve on the reach of future CEvNS data accessible at the FTS collected due to simultaneous measurement on two baselines

Summary

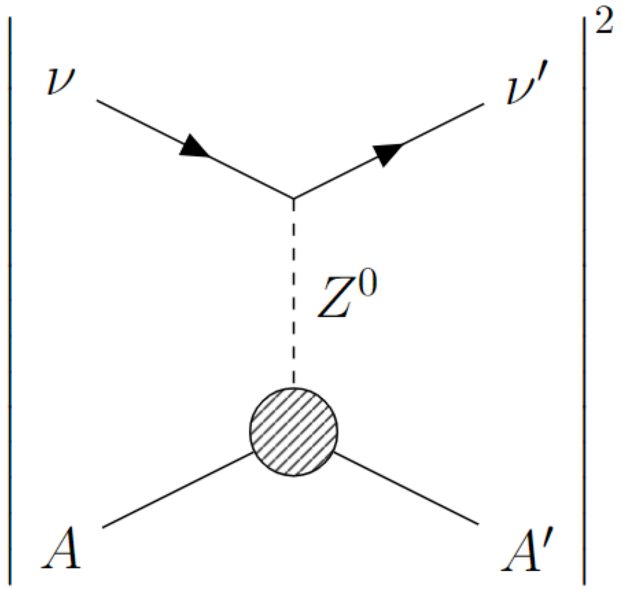
- ❑ From initial detection, CEvNS has broadened into a global community with multiple efforts in theory and experiment
- ❑ 6 years after first detection, we see CEvNS scattering on CsI and Ar from COHERENT as reactors approach first measurements that has made broad and significant impacts testing the standard model
  - But still a young field with many opportunities for development in experiment and phenomenology
- ❑ Novel and strong probe of many new physics topics that interface with the neutrino sector with potential for discovery in coming years



Backup

Coherence in neutrino-nucleus scattering

$$\sigma \propto |\mathcal{M}|^2 =$$

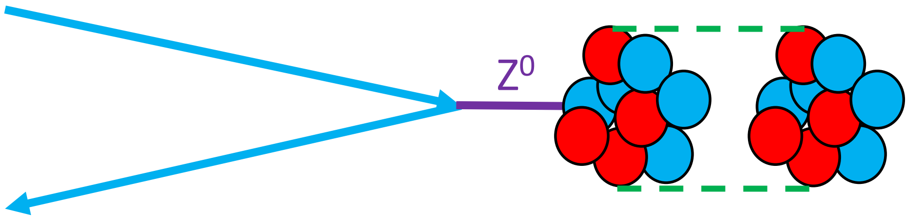


Quantum mechanics – charge of the nucleus is sum of charges of individual nucleons within. Probability to scatter is proportional to the square of the sum

Coherence: $\sigma \propto Q_W^2$

$$Q_W^2 = (g_p^V Z + g_n^V N)^2 = \left[(1 - 4\sin^2\theta_W)Z - N)\right]^2$$

Elastic scattering: Kinematics



^{133}Cs nucleus recoils along +x direction

25 MeV neutrino

Elastic neutrino-nucleus scattering

Momentum transfer:

$$Q \equiv \sqrt{|\Delta \mathbf{p}_\nu|^2 - \Delta E_\nu^2} \approx |\Delta \mathbf{p}_\nu| \leq 2E_\nu$$

^{133}Cs kinetic energy:

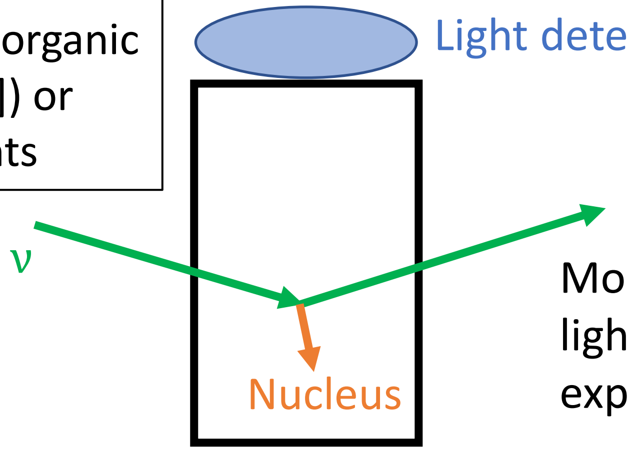
$$E_{\mathrm{rec}} \approx \frac{p_{\mathrm{Cs}}^2}{2m_{\mathrm{Cs}}} = \frac{Q^2}{2m_{\mathrm{Cs}}} \leq \frac{2E_\nu^2}{m_{\mathrm{Cs}}} = 10.1 \text{ keV}$$

CEvNS energy scales:

$$\begin{cases} E_\nu \sim 25 \text{ MeV} \\ Q \sim 50 \text{ MeV} \\ E_{\mathrm{rec}} \sim 10 \text{ keV} \end{cases}$$

Challenge: detecting low levels of scintillation

General CEvNS scintillation detector – doped inorganic crystals (e.g. CsI[Na]) or liquid noble elements



Light detector – e.g. Photomultiplier tube (PMT)

Monitor scintillation activity in crystal with light detector, but how many photons do we expect to collect?

Initial recoil energy	10 keV	CEvNS interaction – neutrino kicks a nucleus giving it 10 keV of kinetic energy

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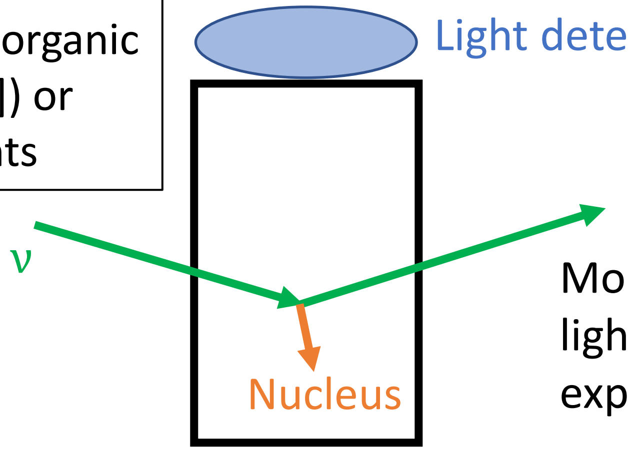

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Quenching	1 keV	Nucleus loses most of its energy to heat, only ~ 5-25% of initial kinetic energy makes scintillation

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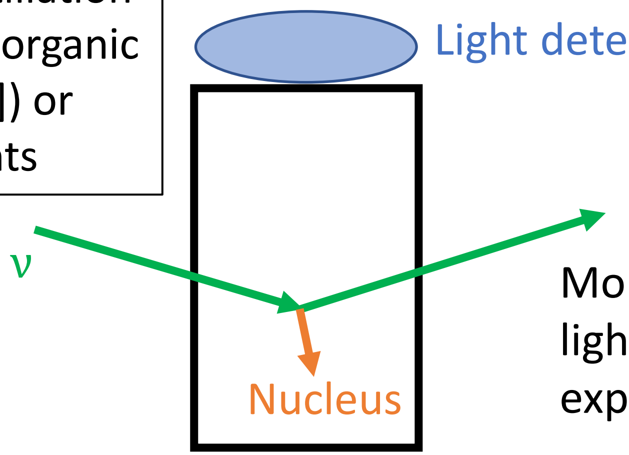

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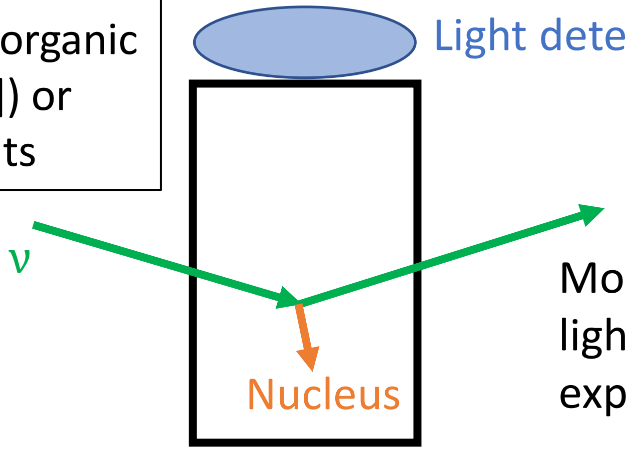

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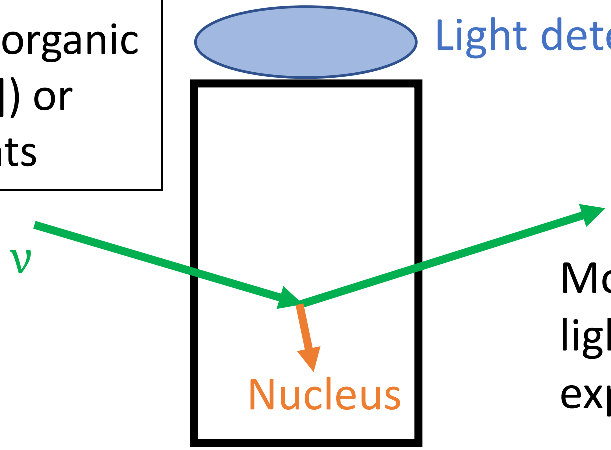

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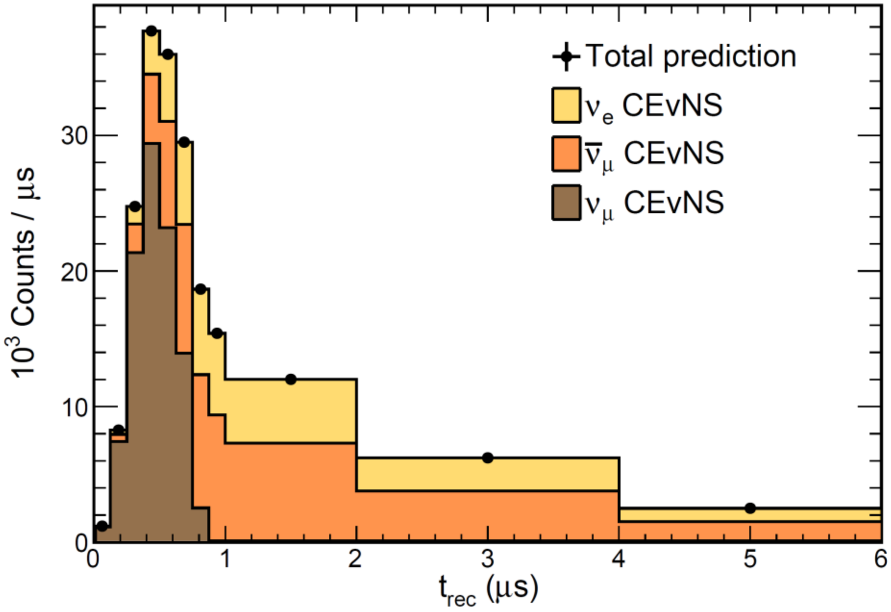
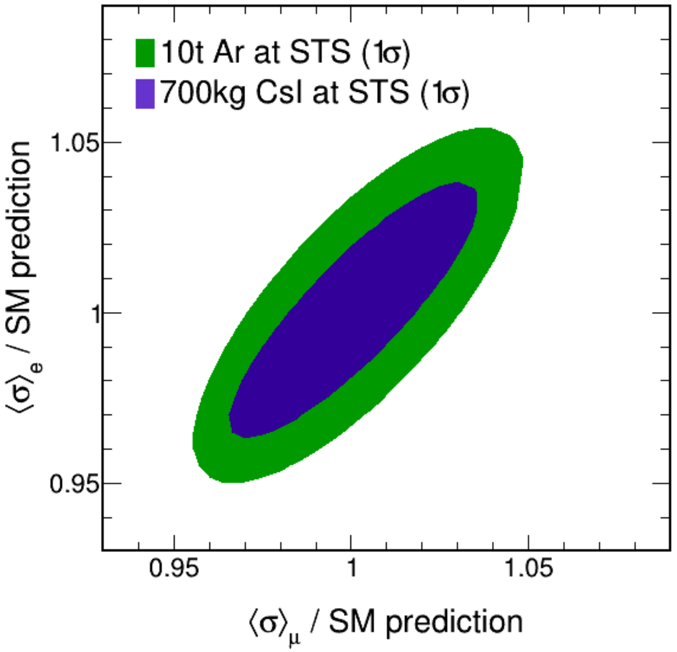
PMT quantum efficiency	10 γ	Light detectors have quantum efficiency for detecting photon. Depends on detector and scintillation wavelength

Measuring the CEvNS cross section

CEvNS event rate in 10t argon detector after 5 years





- In the future, total cross section measurements will be limited by flux uncertainty, but a we will precisely compare the cross section for different flavors
- Sensitive to 1% differences in μ- and e-flavor cross sections testing lepton universality of CEvNS (at tree level)
- At this scale, we will probe loop contributions to the CEvNS cross section which can facilitate the first measurement of the neutrino charge radius – a standard model parameter – and test for interference between the Z and BSM force particle

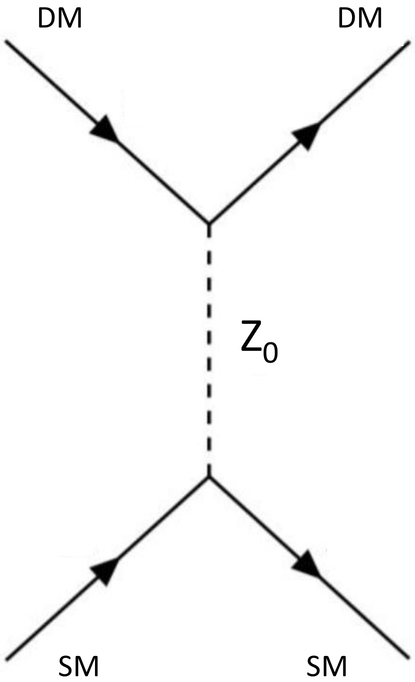
Loop contributions to CsI CEvNS cross section (SNS flux-averaged)

ν_μ	-3.1%
$\bar{\nu}_\mu$	-3.1%
ν_e	-4.1%

JHEP 02 097

Low-mass DM phenomenology

- For decades, experiments have focused on classic WIMP searches assumed to interact with the weak force
- The DM scattering cross section is $\sigma \sim m_\chi^2/m_z^4$
  - Lower DM mass → lower cross section → higher DM abundance
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing the modern universe



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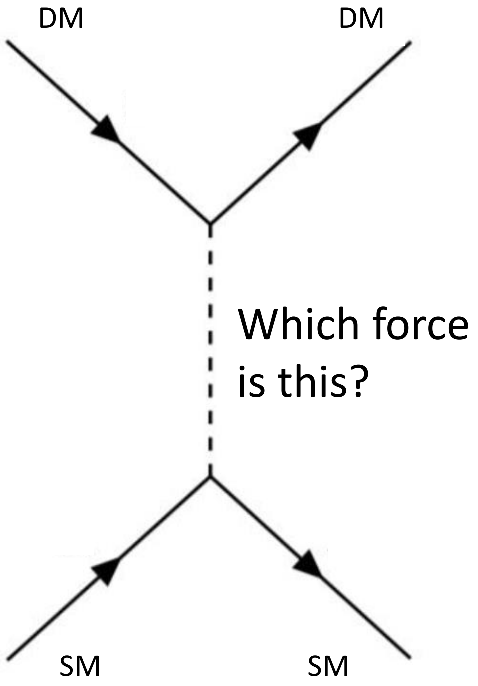

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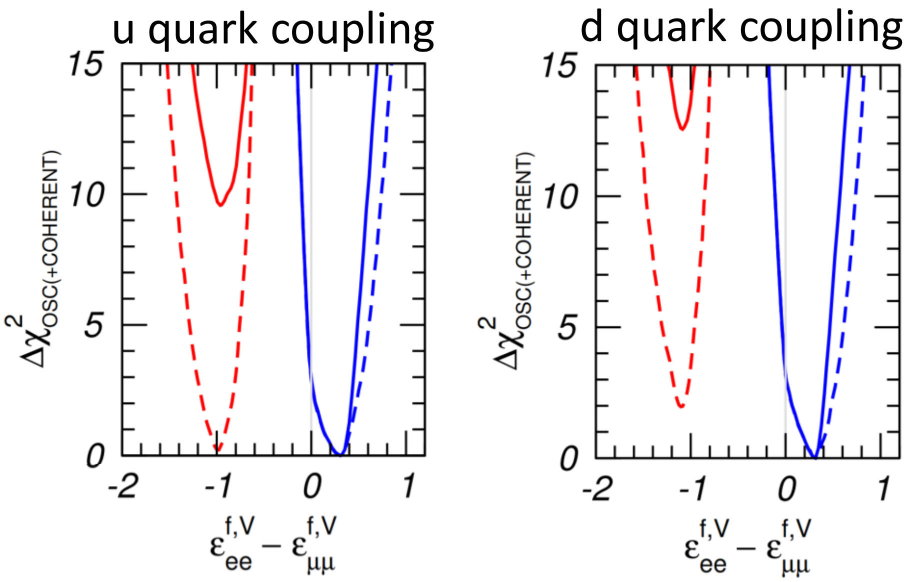
  - If $m_\chi < 2$ GeV/c^2, predicted relic abundance would be so large it would close the universe, preventing the modern universe
- ❑ No longer assume DM interacts with SM particles via the weak force, but some yet unknown hidden sector particle, V
- ❑ In this scenario, $\sigma \sim m_\chi^2/m_V^4$ which is consistent with modern cosmology even at low mass scales
- ❑ Simplest scenario postulates a vector mediator that kinetically mixes with SM photon: $\mathcal{L} \sim \frac{1}{2}\varepsilon^2 F_{\mu\upsilon} V^{\mu\upsilon}$
- ❑ Model parameters
  - DM and mediator masses: m_χ and m_V
  - SM-mediator and DM-mediator couplings: ε and α_D
- ❑ Relic abundance given in terms of $Y = \varepsilon^2 \alpha_D \left(m_\chi/m_V\right)^4$

Classical WIMP mass regime:
  Lee and Weinberg, Phys. Rev. Lett. **39** 165 (1977)
Early sub-GeV DM phenomenology:
  Fayet, Phys. Rev. **D70**, 023514 (2004)
  Boehm and Fayet, Nuc. Phys. **B683**, 219 (2004)
  Pospelov et al., Phys. Lett. **B662**, 53 (2008)
Coherent DM scattering / DM at the SNS:
  deNiverville et al., Phys. Rev. **D84**, 075020 (2015)
  Dutta et al., Phys. Rev. Lett. **123**, 061801 (2019)

CEvNS disambiguates neutrino oscillation data



Phys. Rev. **D96** 115007

Normal MO

Inverted MO

Dashed – osc fit

Solid – osc fit + CsI CEvNS

- NSI affects neutrino oscillation probabilities, very similar to MSW effects
- In fact, a complete degeneracy exists with a properly chosen $\varepsilon^{q}_{\alpha\beta}$ matrix that would prefer the opposite **neutrino mass ordering** and a different value of $\boldsymbol{\delta_{CP}}$
  - Normal MO without NSI and Inverted MO with NSI give equally good fits!

- COHERENT data breaks degeneracy, and pushes NMO and IMO into tension

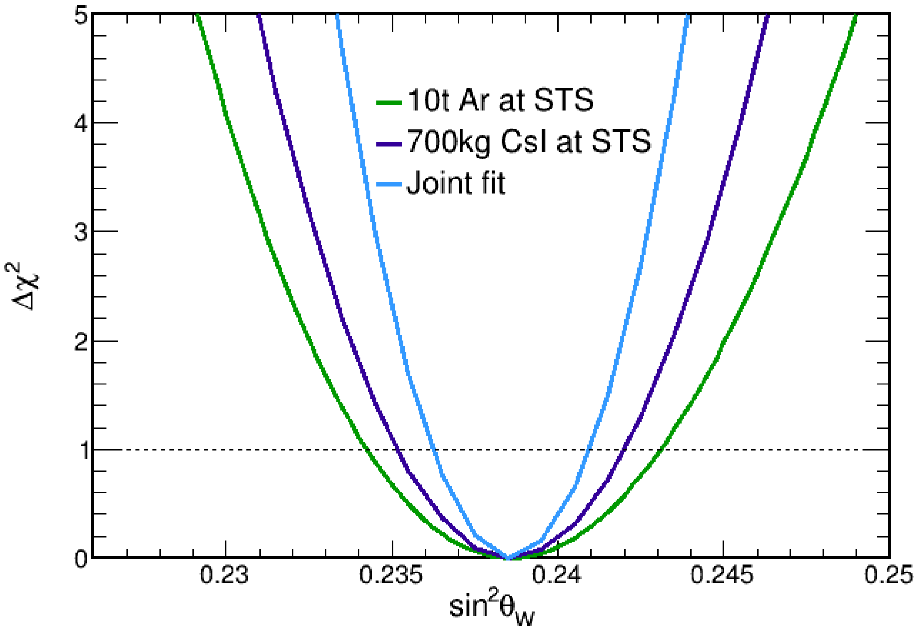
Measuring $\sin^2\theta_W$

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{MT}{E_\nu^2} + \left(1 - \frac{T}{E_\nu}\right)^2\right)$$

$$Q_W = \left(\frac{1}{2} - 2\sin^2\theta_W\right) Z F_Z(Q^2) - \frac{1}{2} N F_N(Q^2)$$

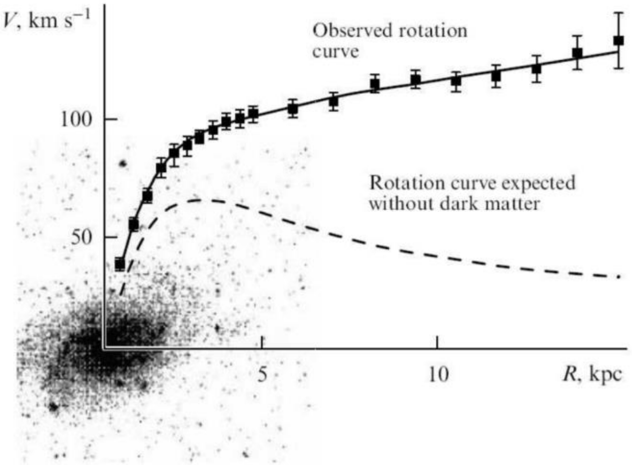
- ❑ The CEvNS cross section for scattering off a given atom depends on both proton (Z) and neutron (N) number
- ❑ But, the proton (Z) component is largely suppressed as $\left(\frac{1}{2} - 2\sin^2\theta_W\right) \approx 0$

- ❑ The CEvNS coupling to protons depends on weak mixing angle → a precise measurement of CEvNS will constrain this parameter
- ❑ Best to measure cross section on different nuclear targets with different N/Z ratios
- ❑ Combination of measurements of heavy CsI and light Ar can give 1% measurement of weak mixing angle

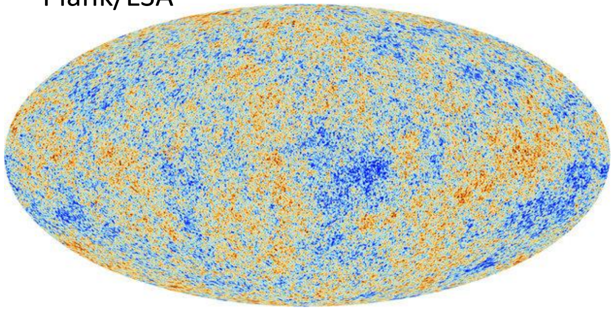


Dark matter in our universe

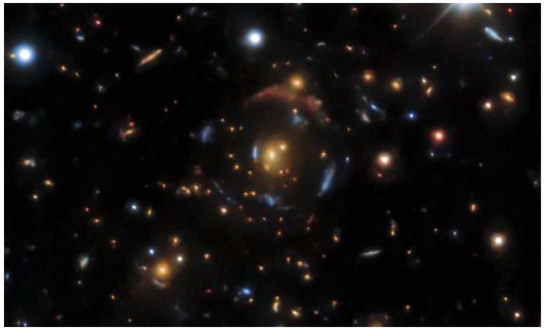
arXiv 1710:10630



Plank/ESA

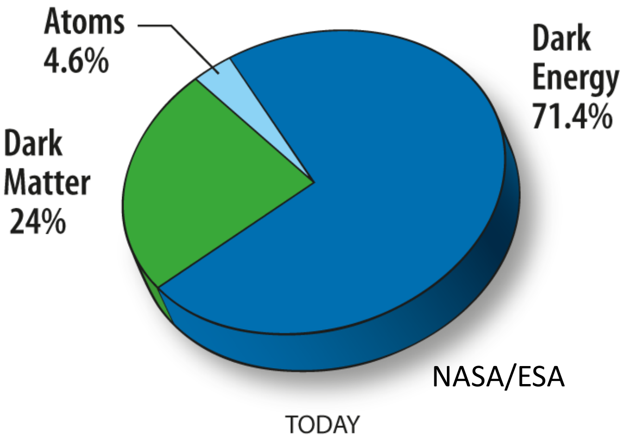


ApJ 909 27



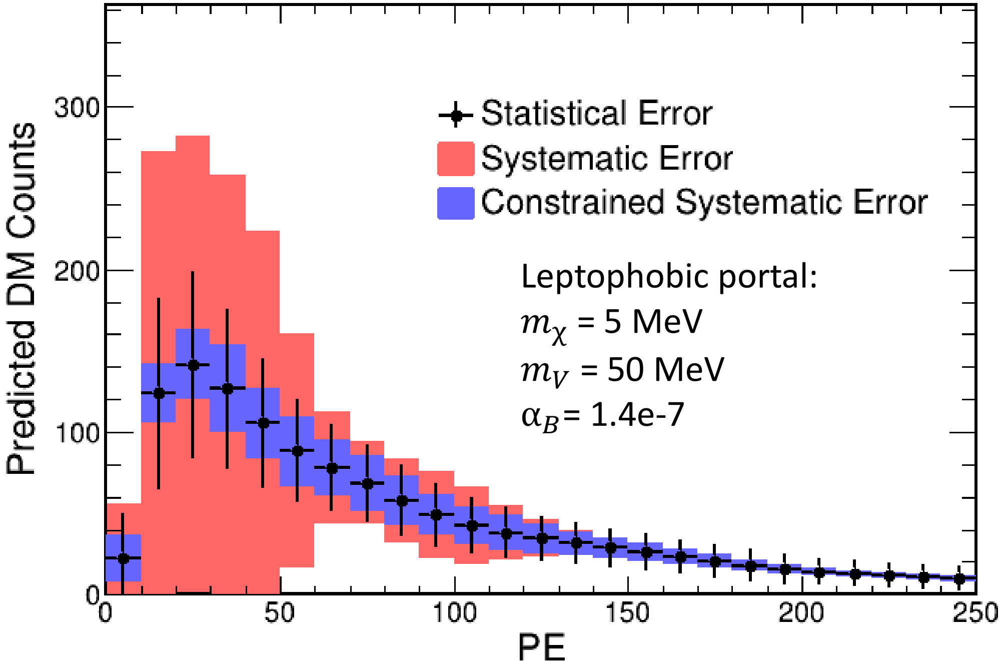
- ❑First evidence for dark matter (DM) comes from rotation curves of galaxies in early 20th century (e.g. Zwicky 1933)
- ❑In 2003, precision CMB data confirmed the existence of dark matter and estimated that roughly 80% of matter in the universe is dark matter
- ❑Continuing understanding distribution of dark matter from weak gravitational lensing data

- ❑100 years since postulation, and we still haven't found the particle nature of DM despite many attempts – new physics we know exists, we just need to find a new place to look



NASA/ESA

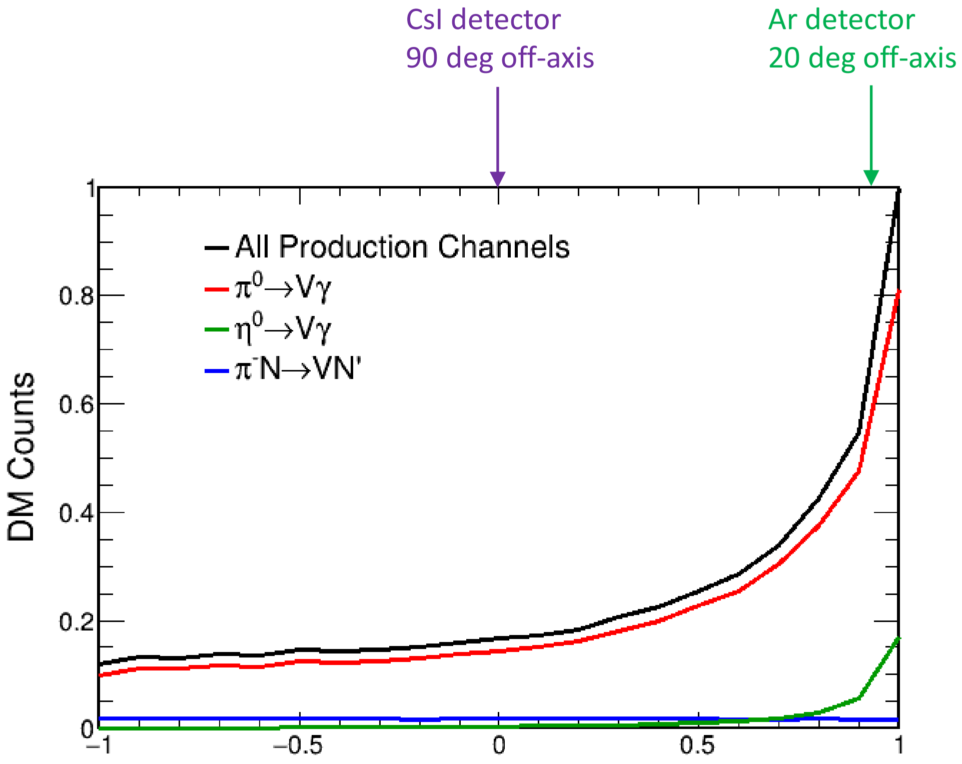
Error Budget for Identifying DM Scatters



- ❑ Without this delayed sideband constraint, a dark matter search would be limited by systematic uncertainties
- ❑ Allows for a more detailed understanding of the distinctive recoil energy spectrum expected for DM scatters
- ❑ After COHERENT dark matter program, the analysis will be dominated by statistical errors → future paths for DM searches with CEvNS detectors

Detector positioning at the STS

- ❑ The dark matter flux is directional → optimal sensitivity if placed in forward direction
  - Operationally, we can achieve a detector hall 20 deg off-axis from the beam center
- ❑ Place the largest, most sensitive detector, the liquid argon calorimeter, at this location
- ❑ The CsI detector needed to complement neutrino measurement goals can be placed perpendicular to the beam
  - If dark matter excess is observed, its nature can be probed by testing this predicted angular dependence


CsI detector
90 deg off-axis

Ar detector
20 deg off-axis

CEvNS disambiguates neutrino oscillation data

$$\boxed{\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} = -\Delta m^2_{32}\,,}$$

$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}\,,$$

$$\boxed{\delta \to \pi - \delta\,,}$$

$$(\epsilon_{ee} - \epsilon_{\mu\mu}) \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2\,,$$

$$(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})\,,$$

$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,.$$

Phys. Rev. **D96** 115007

- NSI affects neutrino oscillation probabilities – in the existence of NSI scenarios,
- In fact, a complete degeneracy exists with a properly chosen $\varepsilon^q_{\alpha\beta}$ matrix and neutrino mixing parameters that would transform $H \to -H^*$ and thus be completely indistinguishable from a scenario with no NSI assumed
- To make matters worse, this transformation would suggest that oscillation data would prefer the opposite **neutrino mass ordering** and a different value of $\boldsymbol{\delta_{CP}}$
  - Normal MO without NSI and Inverted MO with NSI give equally good fits!

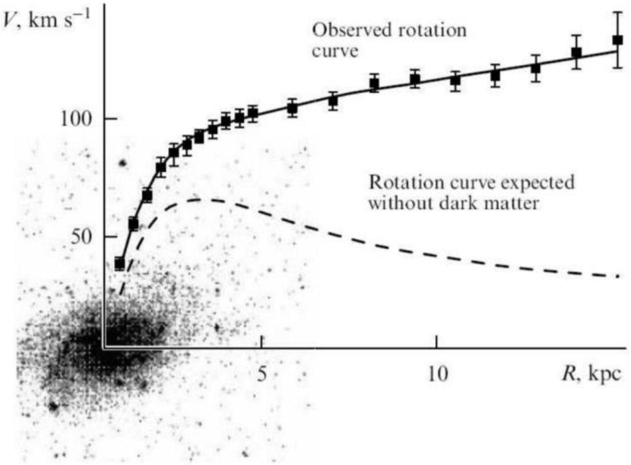
How many neutrino flavors are there?

Testing the three-flavor paradigm at the SNS using CEvNS

Did you all just see that?

Determining the nature of dark matter at accelerators

arXiv 1710:10630



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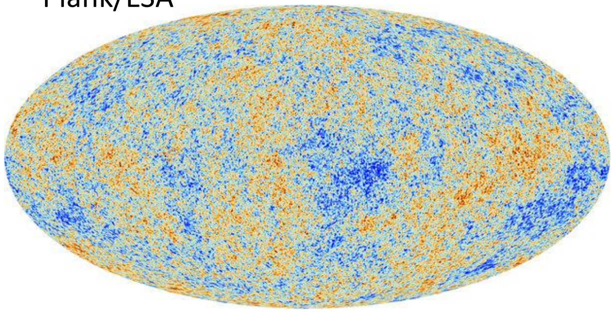
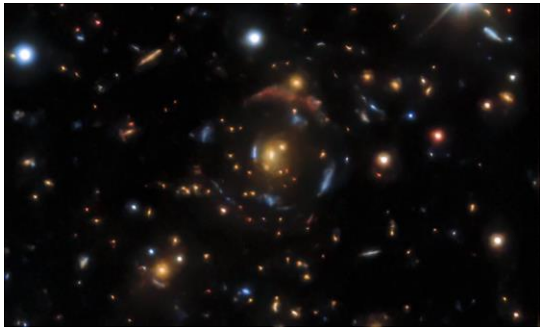
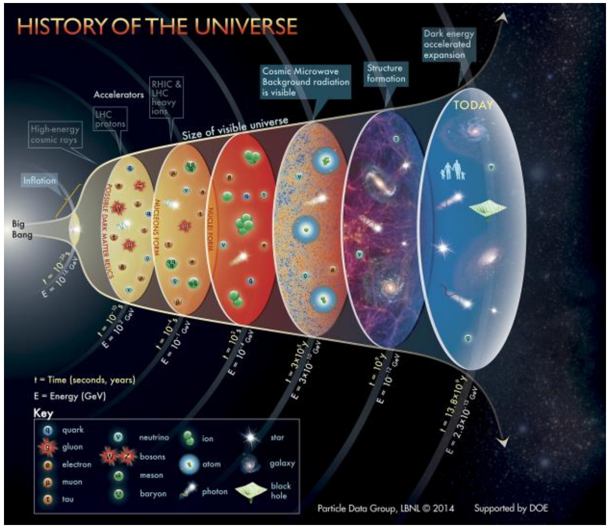
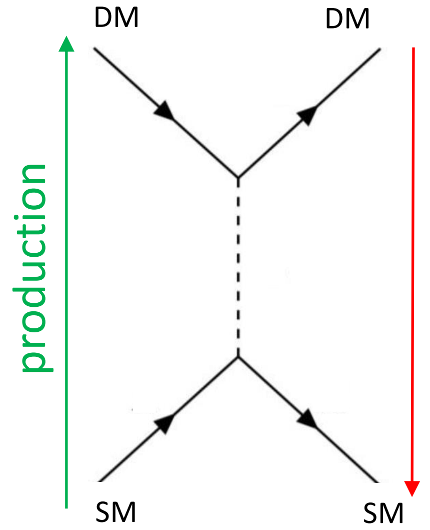


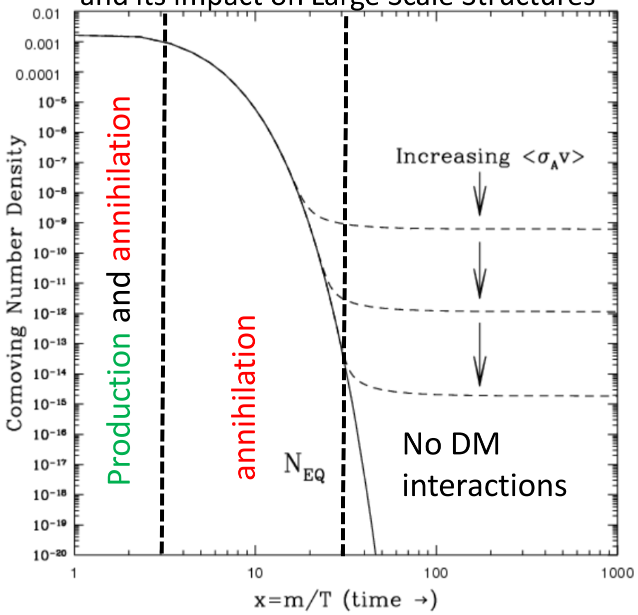
ApJ 909 27



Origin of weakly-interacting dark matter







Chatterjee: Dark Matter Self Interaction and its impact on Large Scale Structures

- Assuming that DM is a particle that interacts weakly with standard-model (SM) matter, in the very early universe, DM was in thermal equilibrium with SM fermions
  - As the universe cools, DM production is no longer kinematically allowed, and the DM concentration falls exponentially
  - Later, as the universe continued expanding, the DM concentration became so low that DM annihilation stopped since DM particles could no longer find partners to annihilate with
- At this point, the universe "freeze-out" of DM occurred, with the DM concentration fixed to the modern observed value
- Freeze-out concentration depends on DM cross section – higher cross section implies DM can annihilate even when less dense so that concentration is lower
  - Modern relic abundance tells us what the cross section is (as a function of DM mass)