The COHERENT experiment, new opportunity to test the Standard Model

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UTK, ORNL, IPMU

Seminar at IPMU – October 28th 2019

Coherent Elastic neutrino Nucleus Scattering → CEvNS

SNS

THE UNIVERSITY OF TENNESSEE KNOXVILLE

OAK RIDGE National Laboratory

Spallation Neutron Source at the ORNL → 1.4 MW, 1 GeV Proton Accelerator

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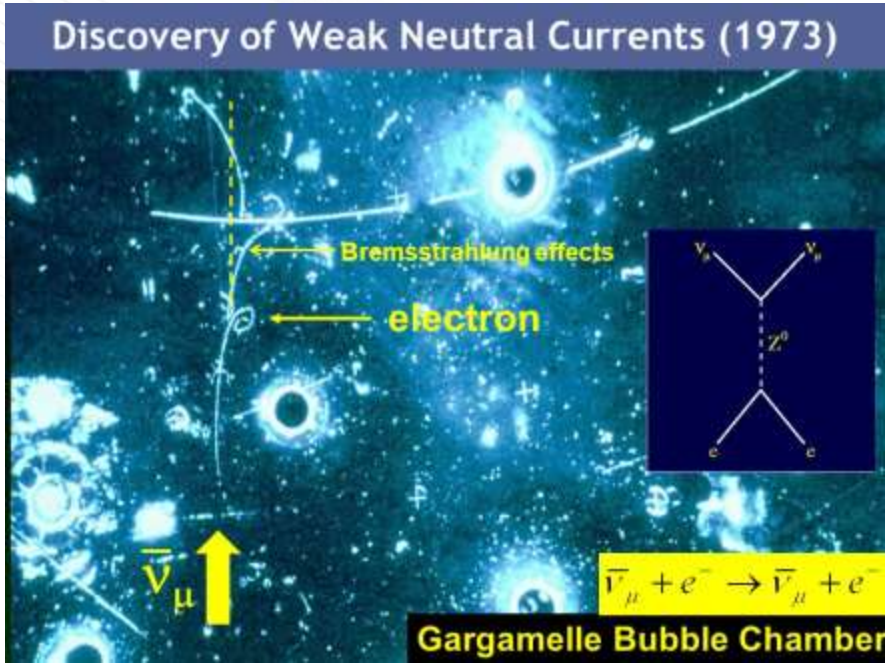
COHERENT Collaboration

21 Institutions (USA, Russia, Canada, Korea)

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z,
and the nucleus recoils as a whole;



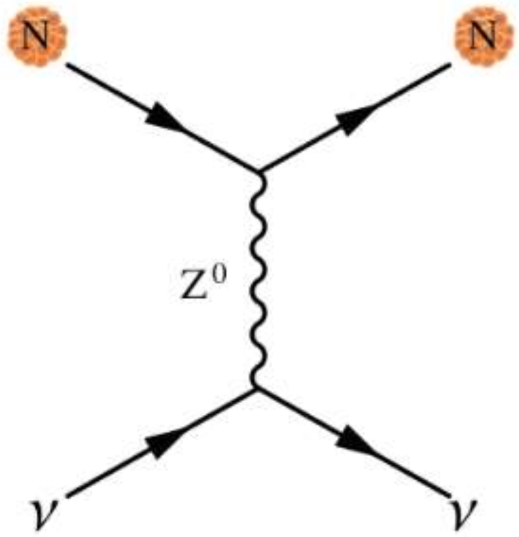
D.Z. Freedman PRD 9 (1974)

Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974



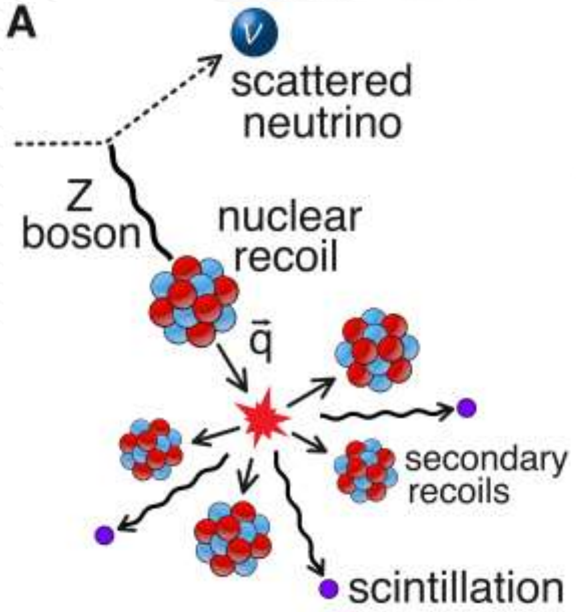
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

$$\boxed{\propto N^2}$$

CEvNS cross section is well calculated in the Standard Model

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

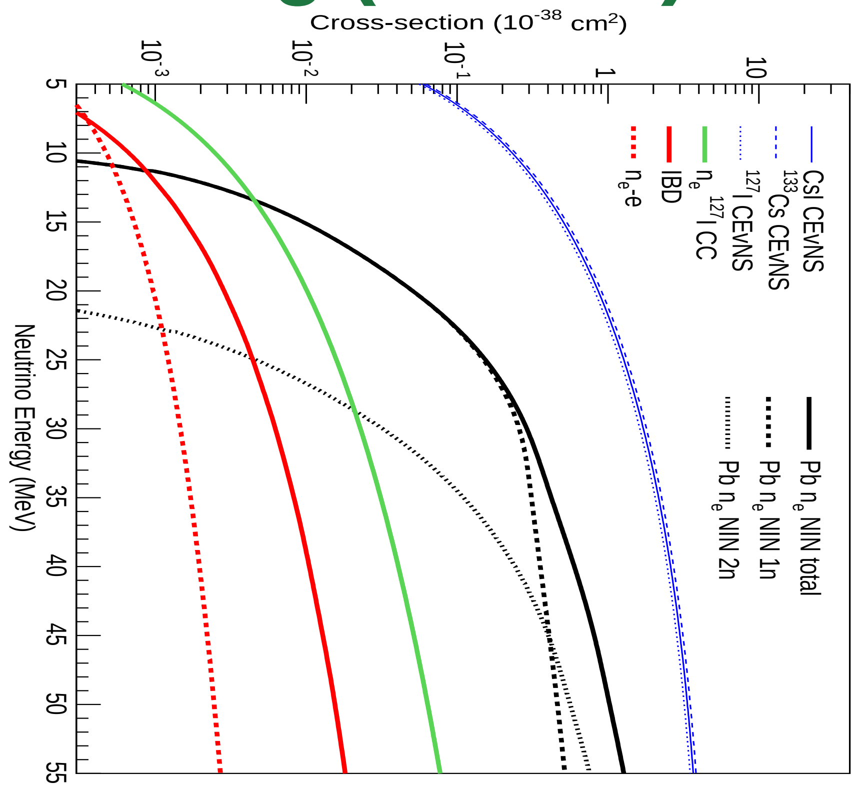
A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole, produce tiny recoils.



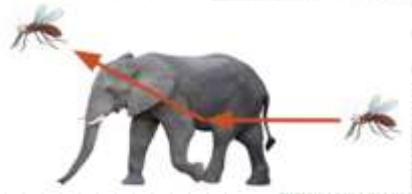
challenges the Gods

D.Z. Freedman PRD 9 (1974)

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.



CEvNS cross-section is large!
but hard to detect



$$\sigma = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z(1-4\sin^2\theta_W) - N\right]^2 F^2(Q^2) \qquad \boxed{\propto N^2}$$

CEvNS cross section can be calculated in the Standard Model precisely

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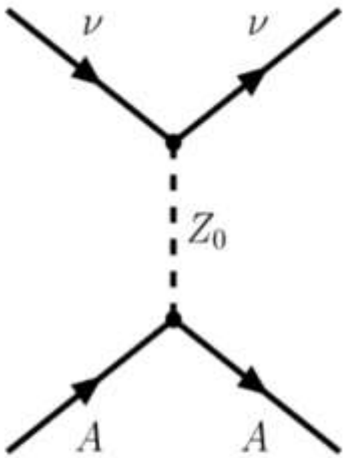
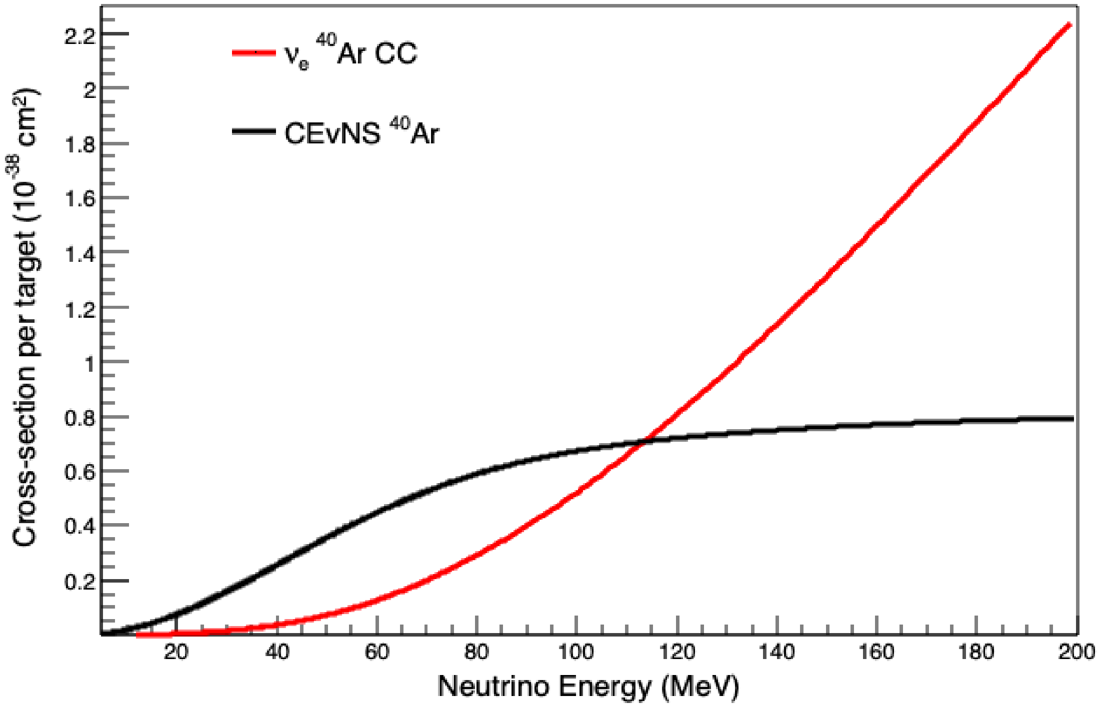
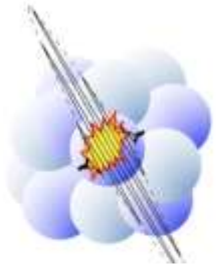
Nuclear Form Factor

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} \boxed{F^2(Q^2)}$$

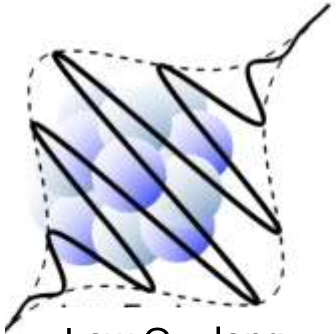




For energy above 50 MeV form factor start to suppress cross section

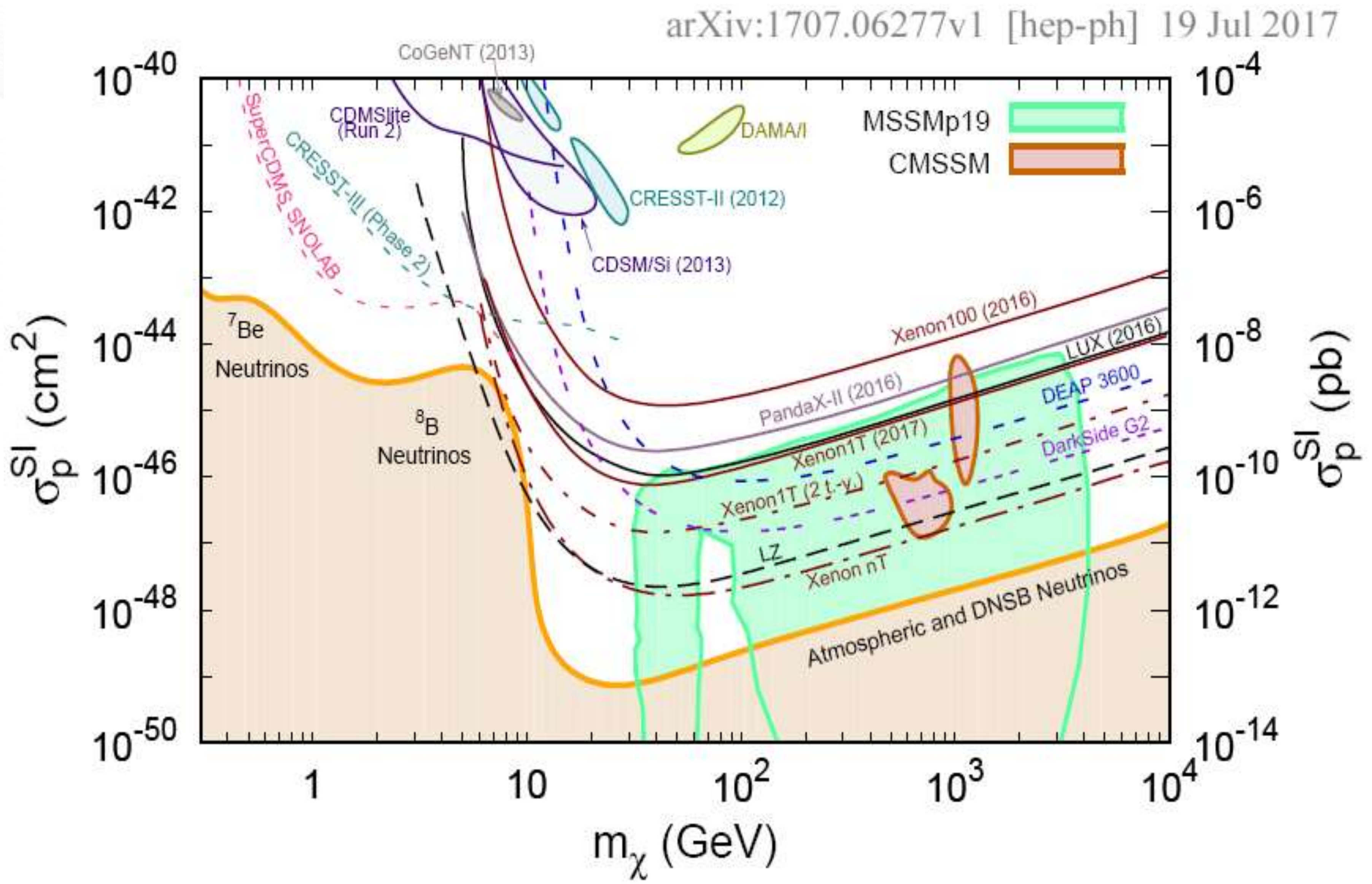


High Q = short de Broglie wavelength



Low Q = long de Broglie wavelength

CEvNS is Neutrino Floor for DM Experiment



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CEvNS is a Probe of Non Standard Neutrino Interactions (NSI)

new interaction specific to ν's

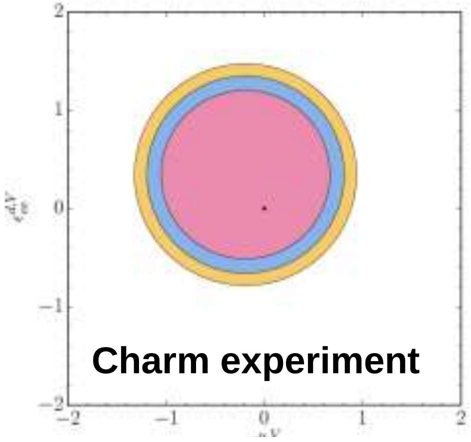
$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

J. H J. High Energy Phys. 03(2003) 011

TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

Non-Standard ν Interactions (Supersummetry, neutrino mass models) can impact the cross-section differently for different nuclei



Curtailing the Dark Side in Non-Standard Neutrino Interactions

Pilar Coloma[a] Peter B. Denton,[a,b,1] M. C. Gonzalez-Garcia,[c,d,e] Michele Maltoni,[f] Thomas Schwetz[g]

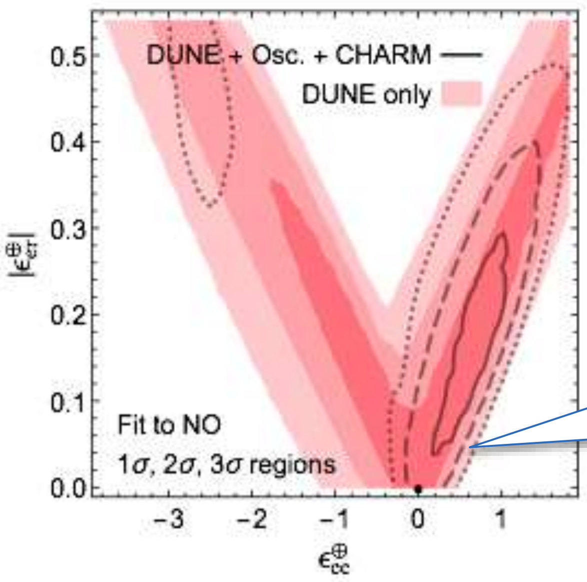
arXiv:1701.04828v2 [hep-ph] 20 Apr 2017

CEvNS are Important as a Probe for NSI.
NSI can create degeneracy for DUNE

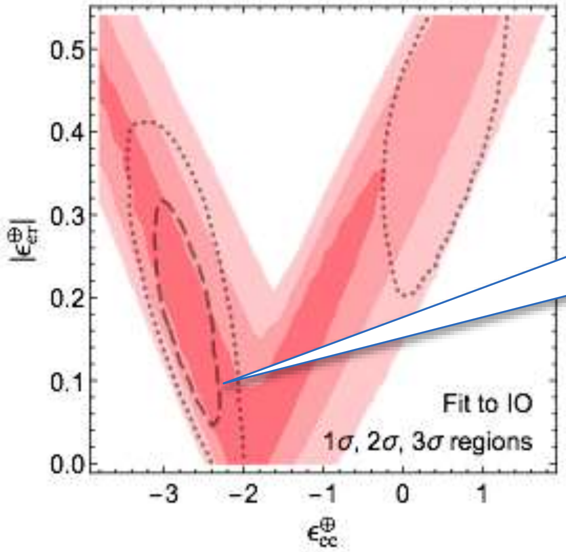
– measuring the charge-parity (CP) violating phase CP,
– determining the neutrino mass ordering (the sign of Δm^2_{12})
– precision tests of the three-flavor neutrino oscillation paradigm

Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2] arXiv:1604.05772v1



NO w/no NSI...



...looks just like IO w/NSI

If you allow for NSI to exist, Degeneracy appears.

We can not tell the neutrino mass ordering without constrains on NSI

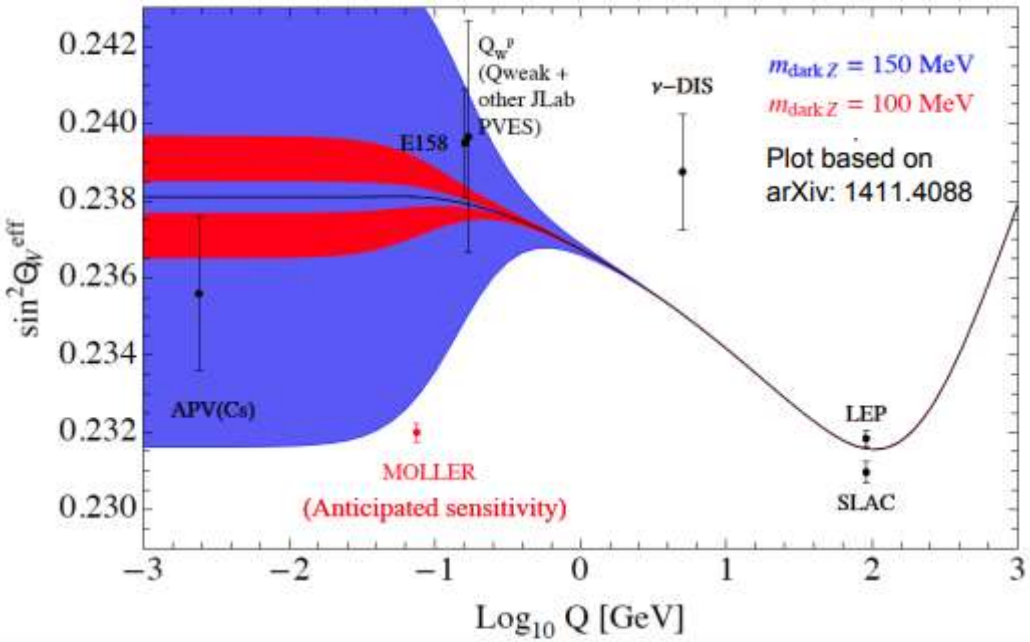
CeVNS is a new way to measure Electro-Week angle at Low Q

$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

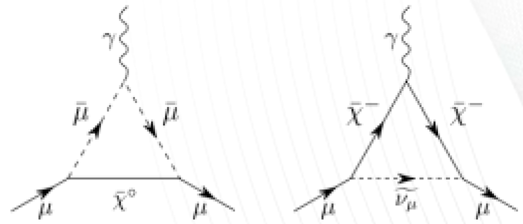
$$s_{tot} = \frac{G_F^2 E_n^2}{4\pi}\left[Z\left(1 - 4\sin^2 q_W\right) - N\right]^2 F^2(Q^2)$$

Measurements with targets having different Z/N ratio are required.

$\mathrm{Sun}^2\theta_w$ is a free parameter in the Standard Model
There is no fundamental theory which explain its value
It is "running" constant, its value depends on the momentum transfer.



Proposed correction to g-2 for muon magnetic moment due to a light mediator

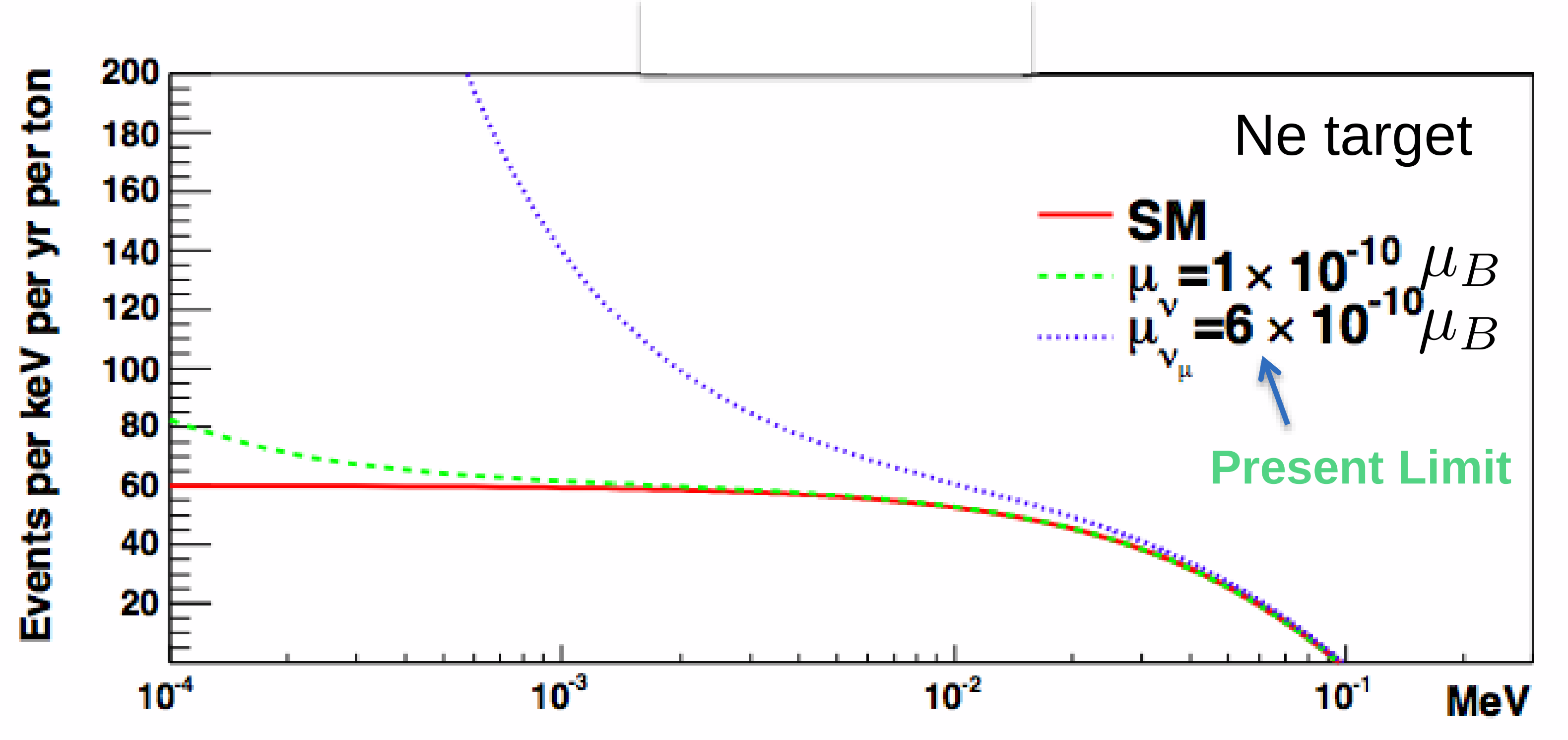


If this is correct it can manifest itself in θ_w value at low Q^2

Search For Neutrino Magnetic Moment via CEvNS

Signature is distortion at low recoil energy E

$$\frac{d\sigma}{dE} = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - E/k}{E} + \frac{E}{4k^2}\right)$$



➔requires detector with very low energy threshold

See also Kosmas et al., arXiv:1505.03202

CEvNS important for Understanding of Supernova Dynamics

Large effect from CEvNS on Supernovae dynamics.
We should measure it to validate the models

J.R. Wilson, PRL 32 (74) 849

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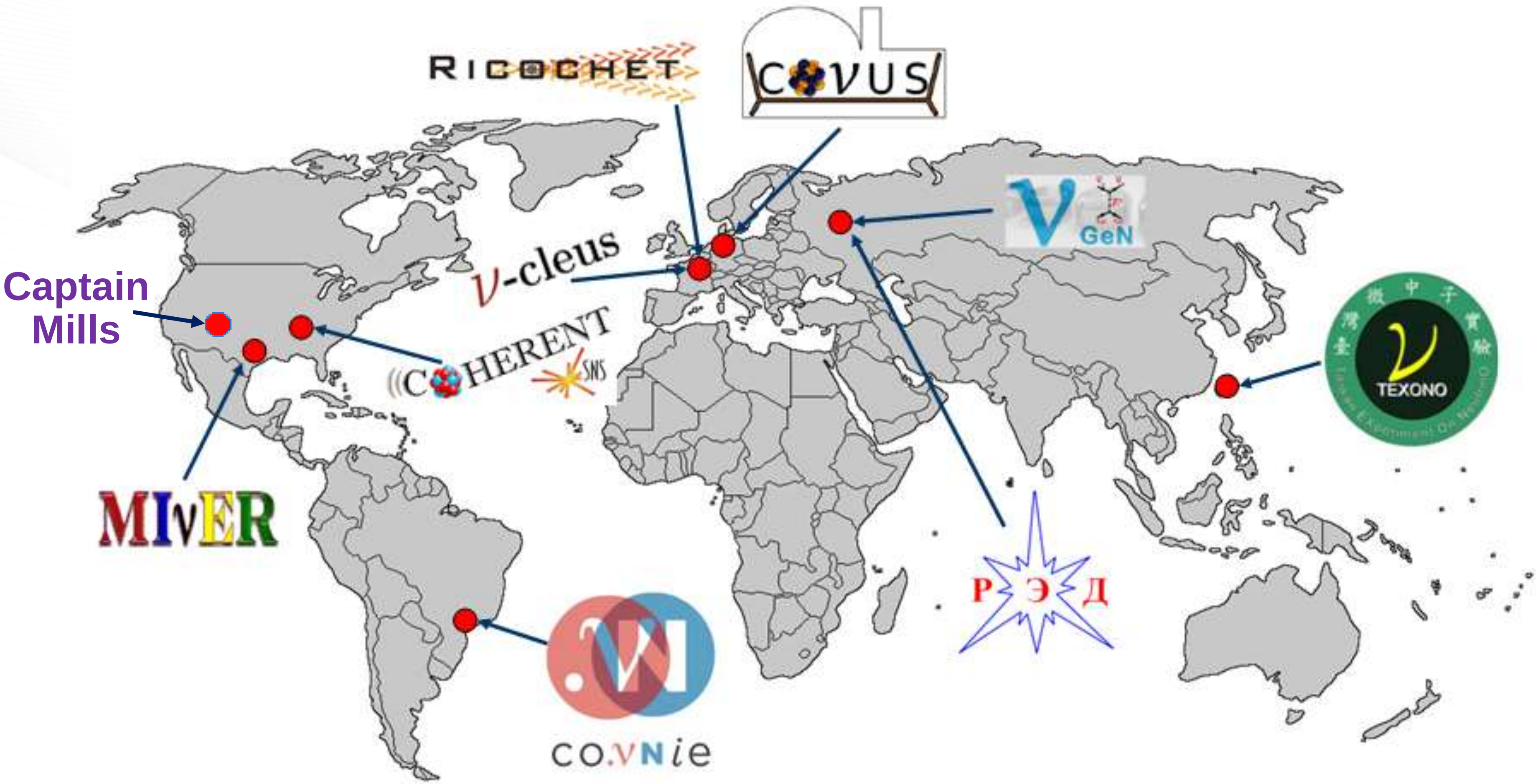
World Wide Race to Detect CEvNS



Except COHERENT and Captain Mills collaboration, all others attempting to use nuclear reactors as a neutrino source

Nuclear reactors give large flux, but low energy neutrinos with a constant flux

Why Did We Choose Spallation Neutron Source (SNS)?

- It is world most powerful pulsed neutrino source. Presently it delivers $7 \cdot 10^{20}$ POT daily *~10% of protons produce 3 neutrino flavors*

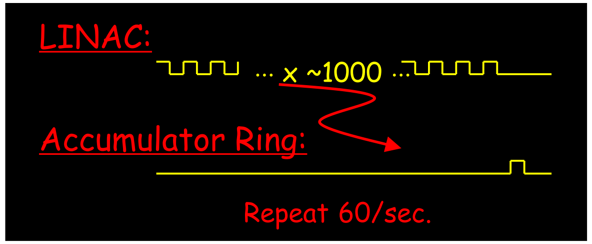
- Neutrino energies at SNS are ideal to study CEvNS.

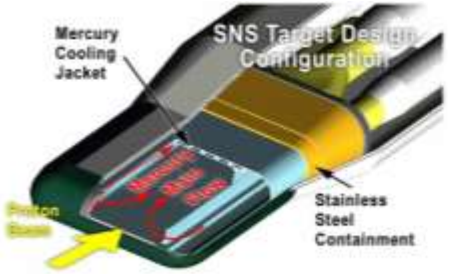
  For 99% of neutrinos $E_\nu < 53$ MeV

- Decay At Rest from pions and muons (DAR) gives very well defined neutrino spectra

- Fine duty factor let suppression of steady background by a factor of 2000.

  It is like being at the 1000 m.w.e underground





1.0 GeV

Compact Target (7 x 20 x 50 cm^3)

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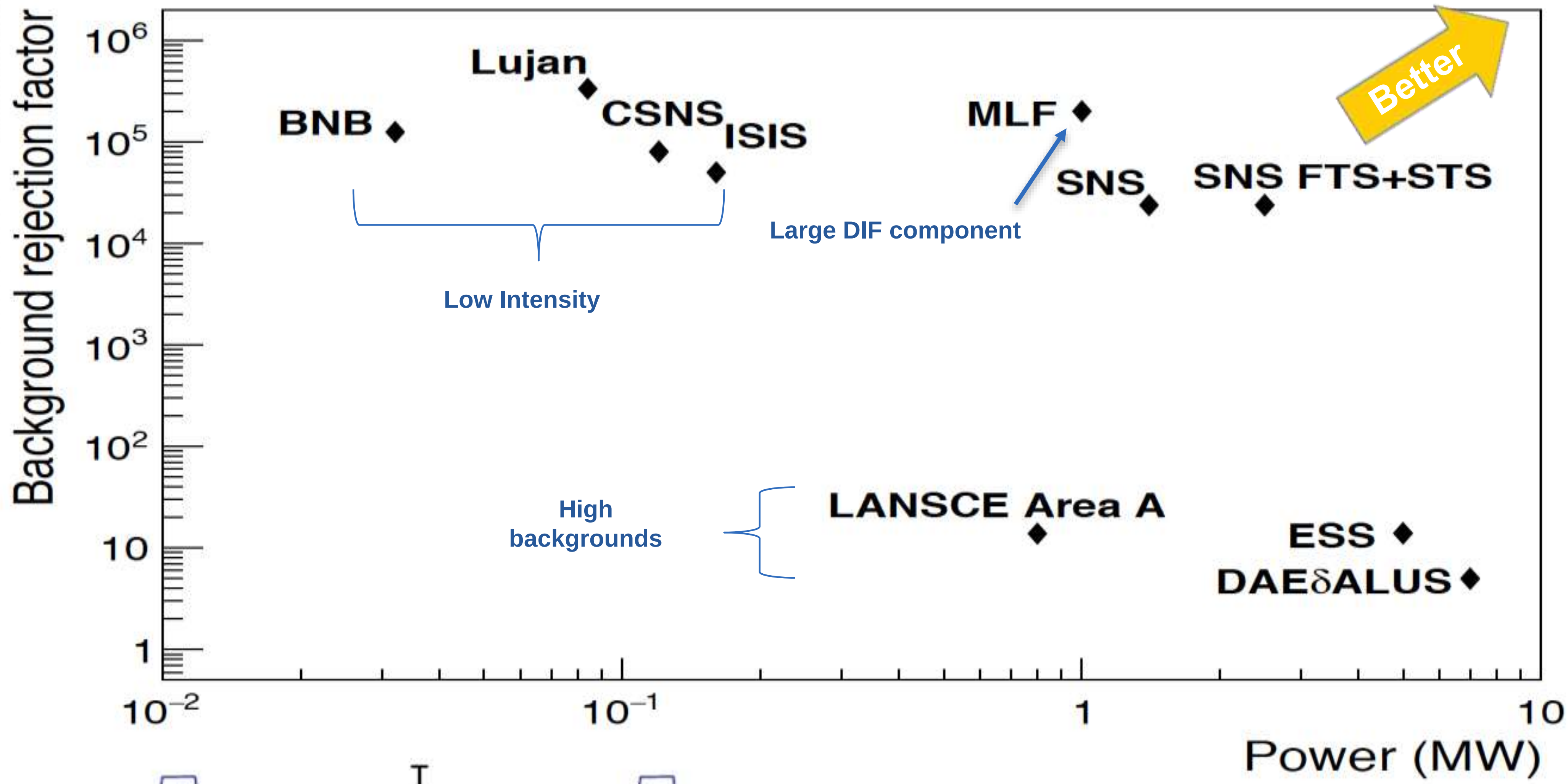
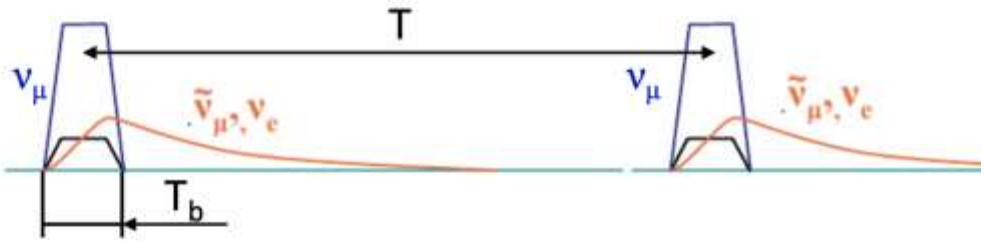
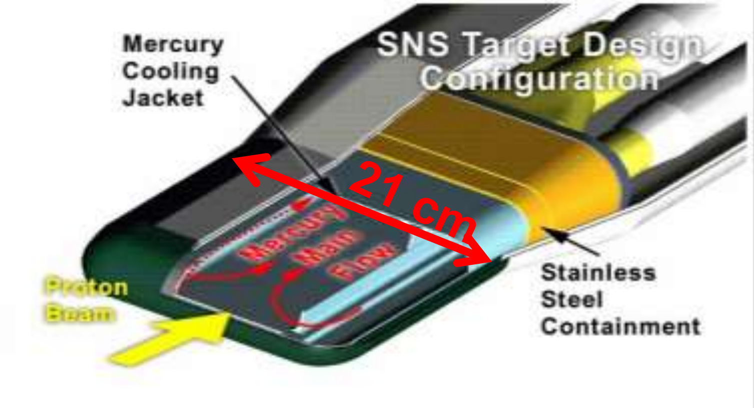
World Stop Pion Facilities

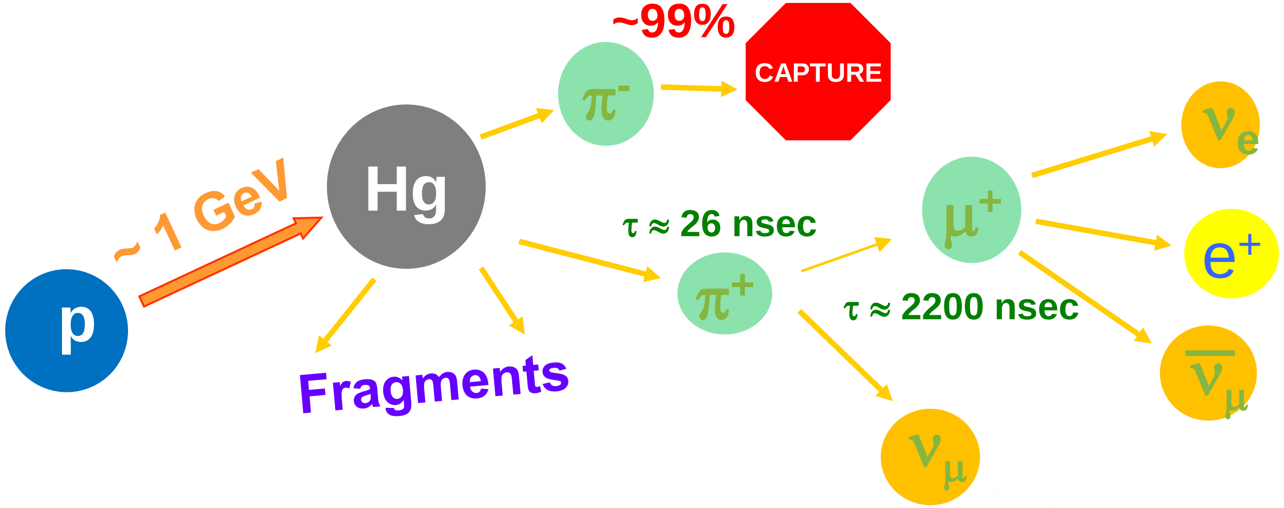


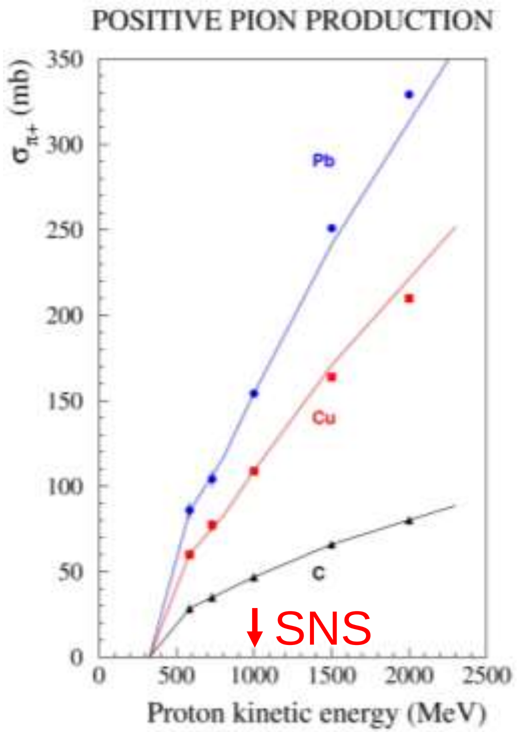


At the SNS
T=15 000 us
T_b= 0.5 us

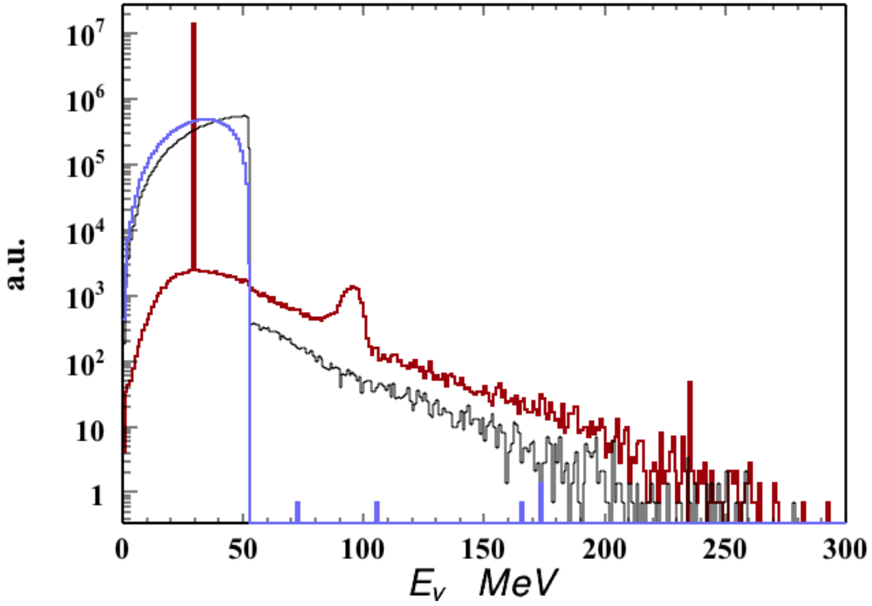
Neutrino Production at the SNS



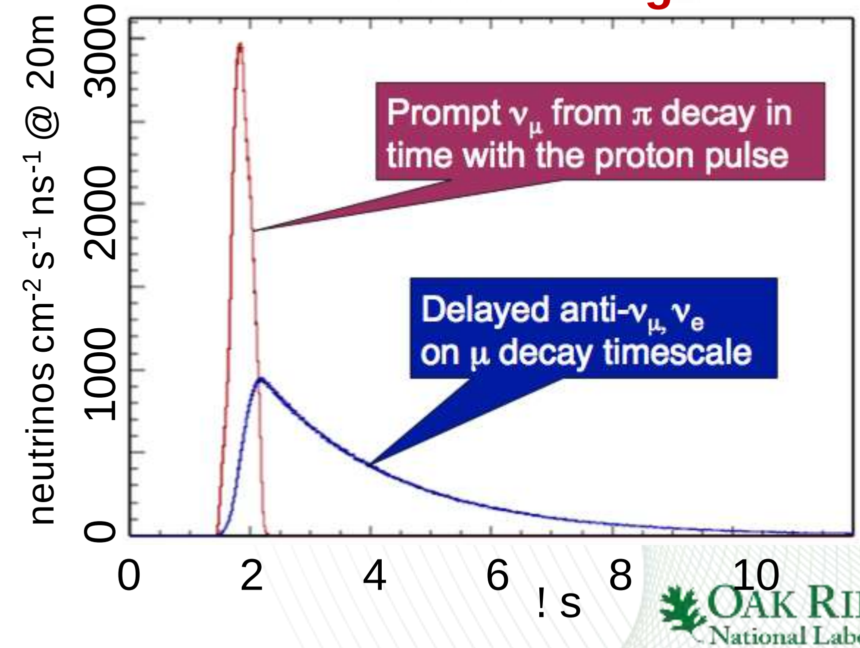




Neutrino Energy



Neutrino Timing



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SNS is Optimized to Produce Neutrons

Physicist who are trying to put neutrino detector next to the world most powerful neutron source should recall Legend of Icarus

don't fly too close to the sun

There are Multiple Sources of neutrons inside the Target building.

Intermediate Neutrons with energy more than 50 keV can produce nuclear recoils which mimics CEvNS. → This is could be show stopper !!!!

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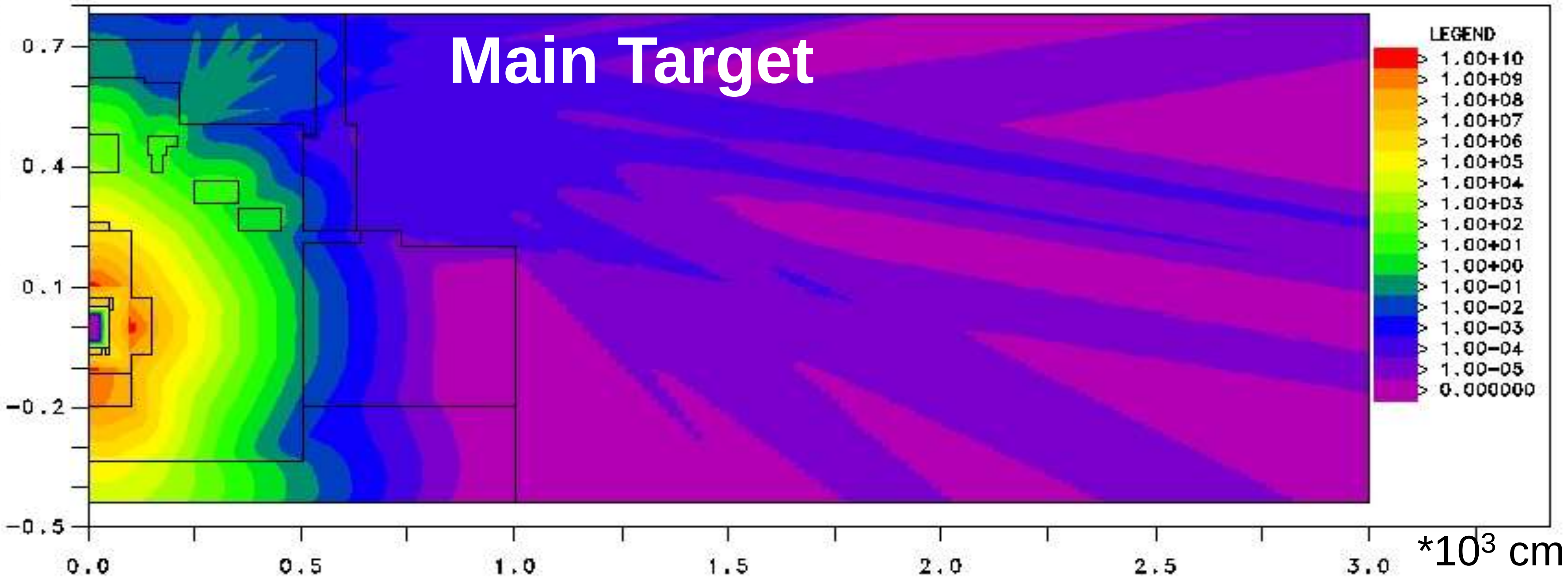
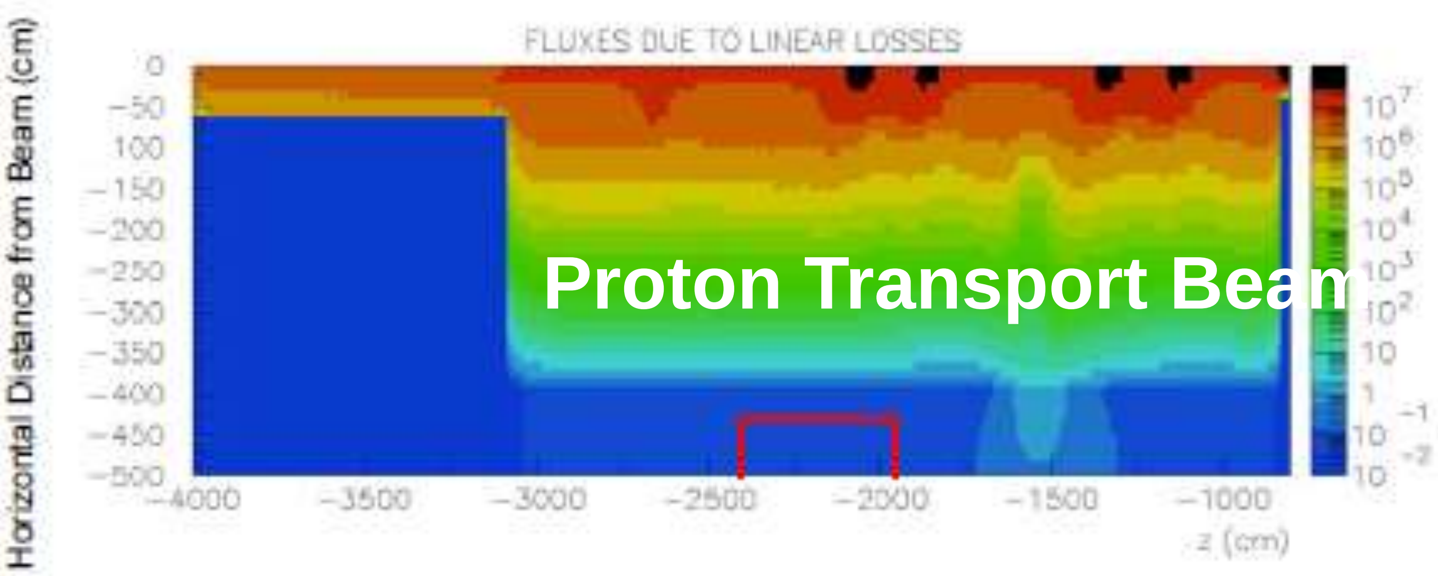
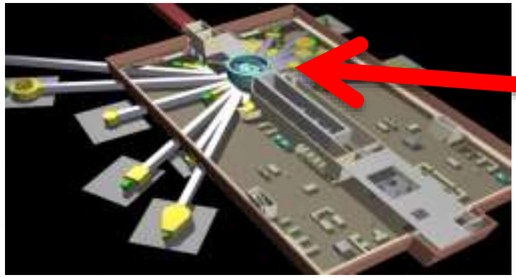
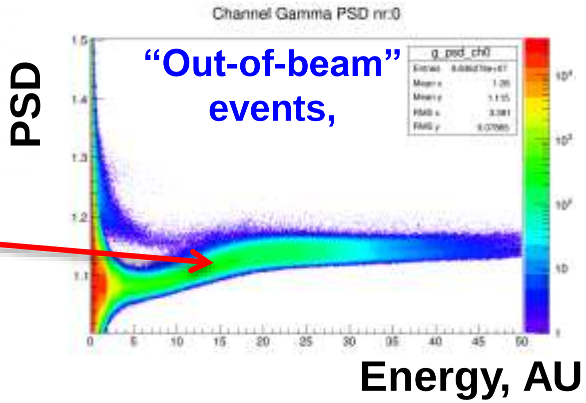
Simulation of Neutron Propagation is Useless. Need to trace reduction of 15 orders of magnitude



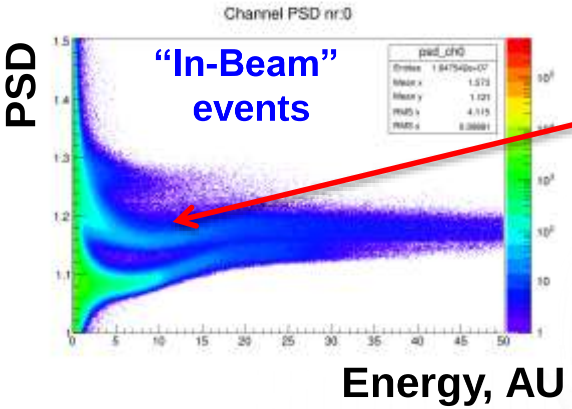


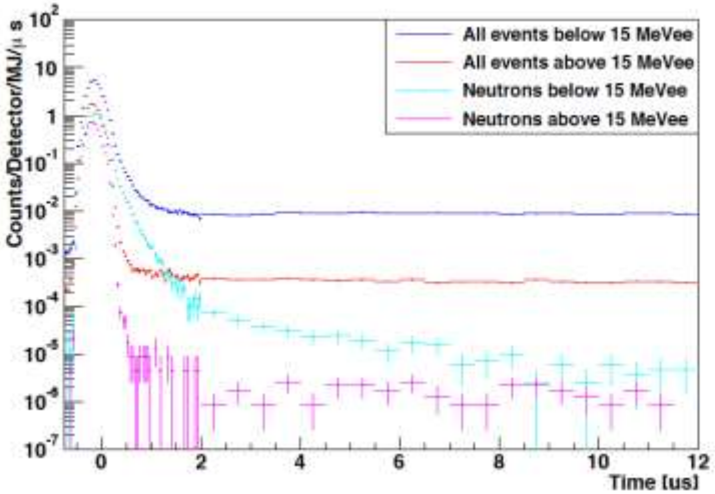
We start to Measure Neutron Backgrounds in 2013 to look for a Good Location





There are 5 m of steel and 5 meters of concrete between target and detectors for this measurement





Neutrons flux in the target building is 10^5 times more than neutrino detectors can tolerate

Time structure is similar to the one from neutrinos

We did not find a good spot on the experimental floor

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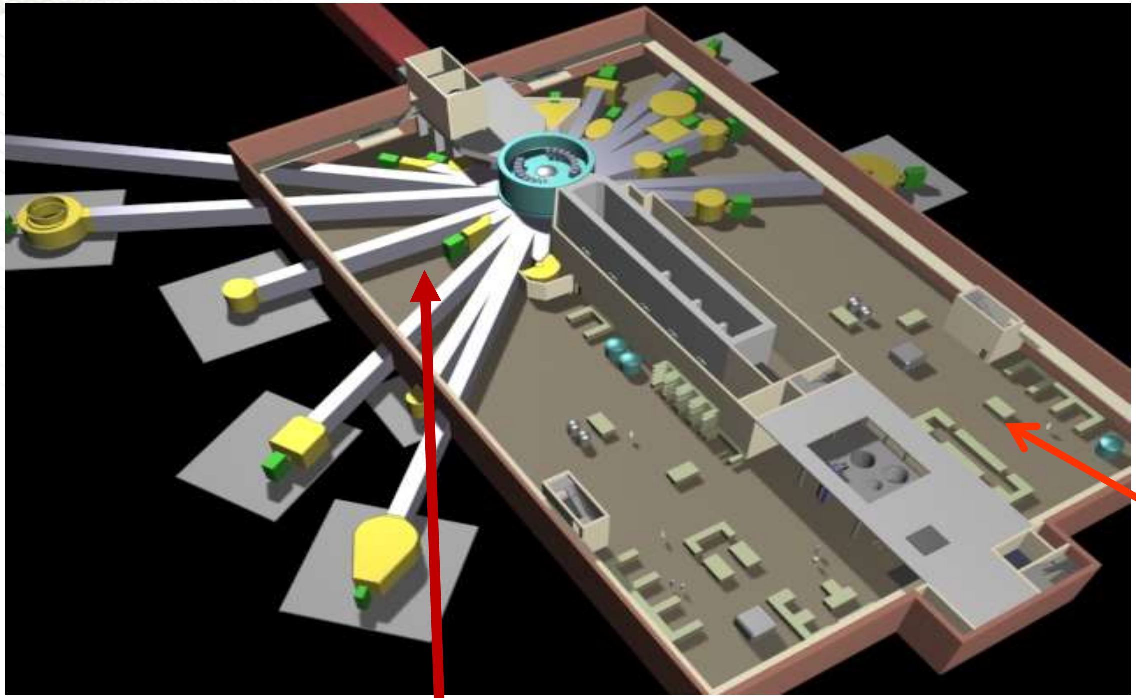
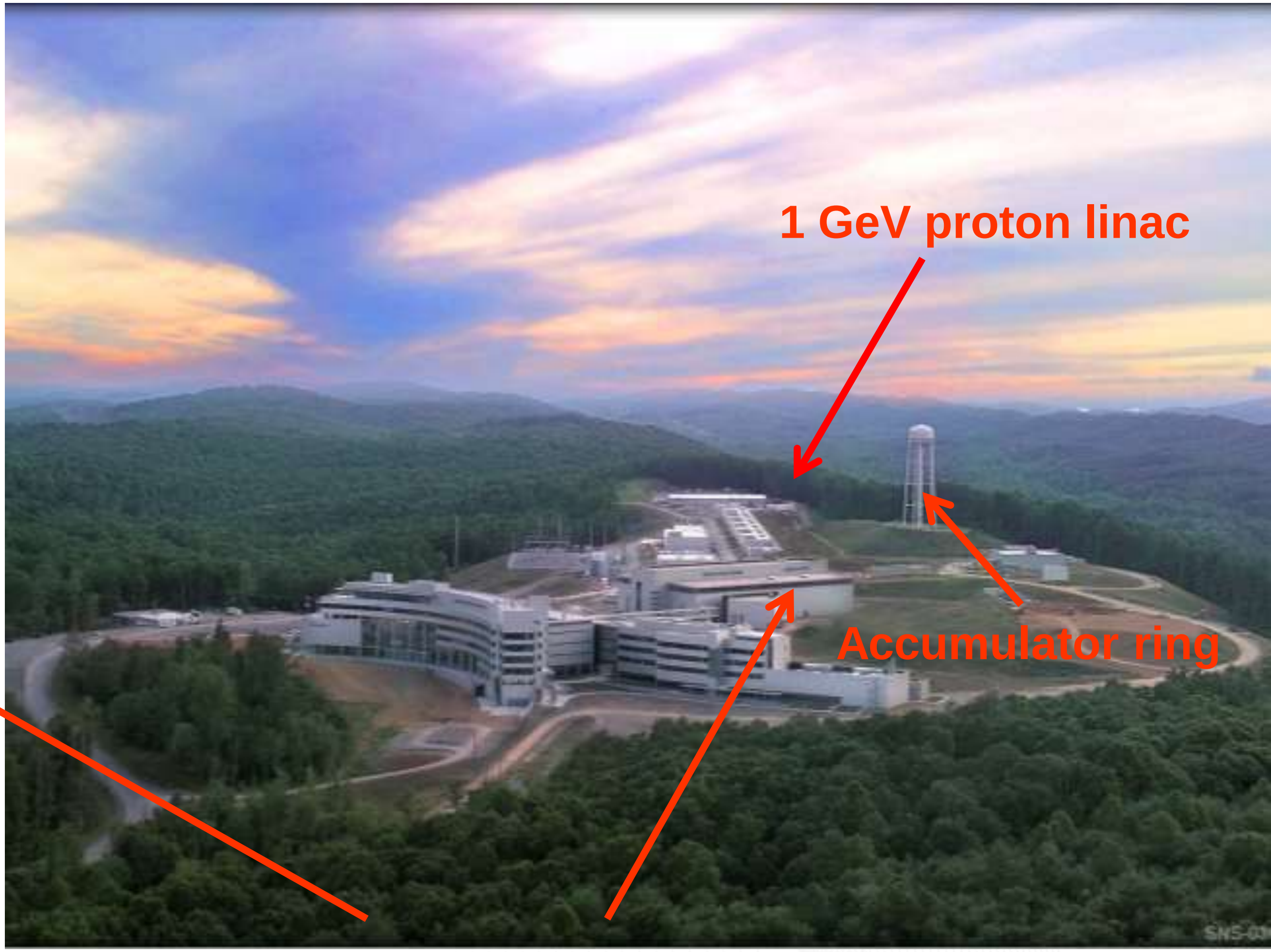
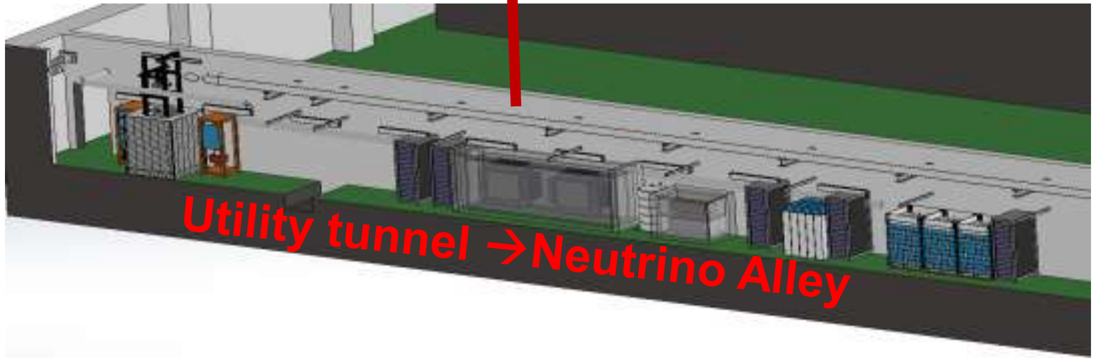
Finally “Neutrino Alley”

After extensive BG program study we find a well protected location





Target Building



After extensive background studies, good place for experiment has been located at the SNS basement → Neutrino Alley.

It is 20-30 meters from the target. Space between target and alley is filled with steel, gravel and concrete

There are 10 M.W.E. from above

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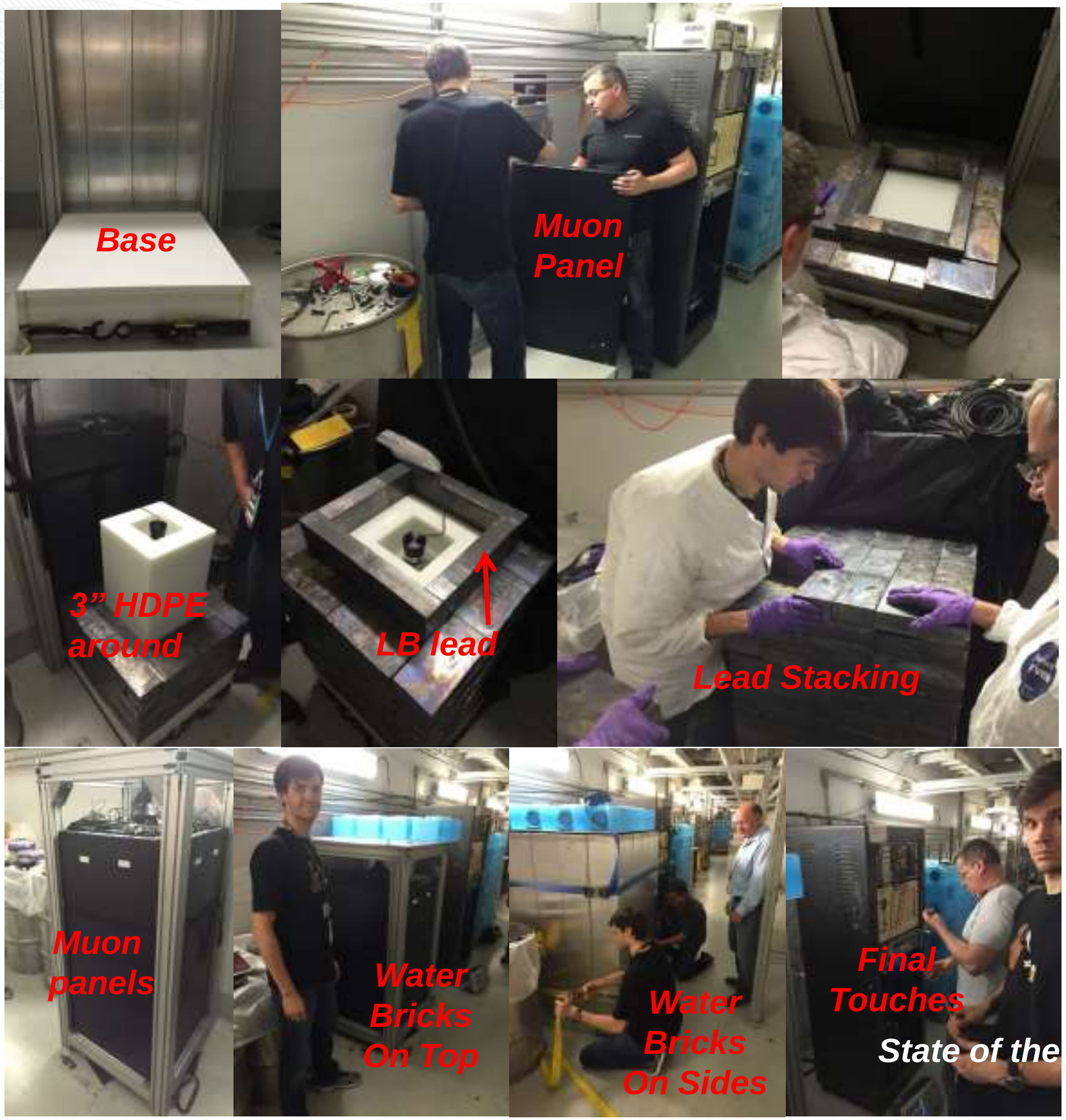
First Deployment: 14 kg CsI Detector



Years of preparations and optimizations,
one day of installation

Single 14 kg CsI crystal.

It has been custom grown from preselected low background material

Layers of dedicated shielding:

Poly to protect from NINs

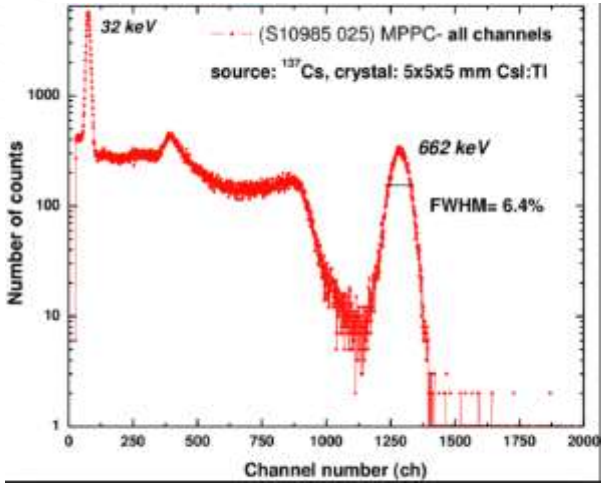
Low background lead

Regular good quality lead

Veto system

Water shielding

CsI is a Good Detector for CEvNS



High density 4.51 g/cm^3

bright scintillator ~64 ph/keVee

can be made low radioactive

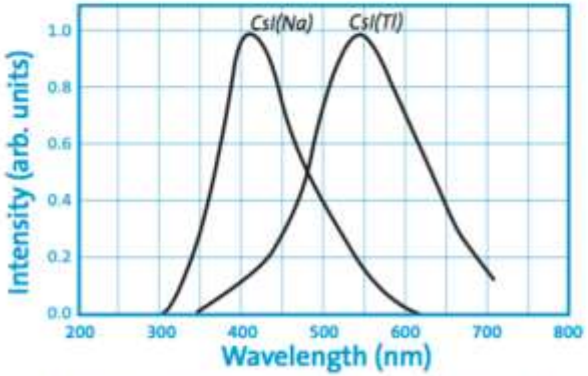


Figure 1. Scintillation emission spectrum of CsI

Light emission at 420 nm match well PMT sensitivity

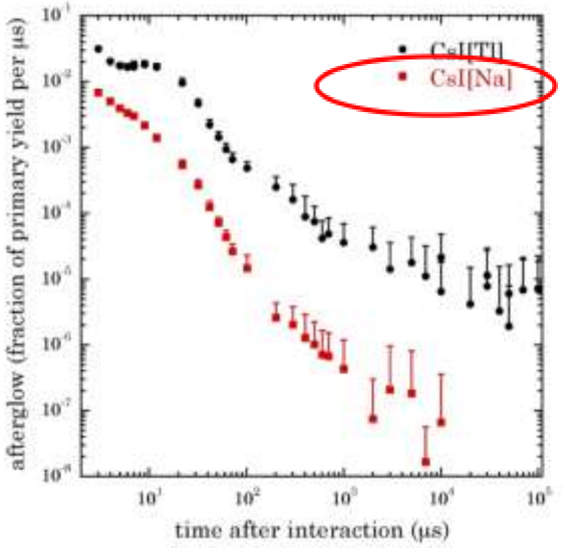
Cs$_{(z=55,A=133)}$ and I$_{(z=53,A=127)}$ both have large and similar number of neutrons

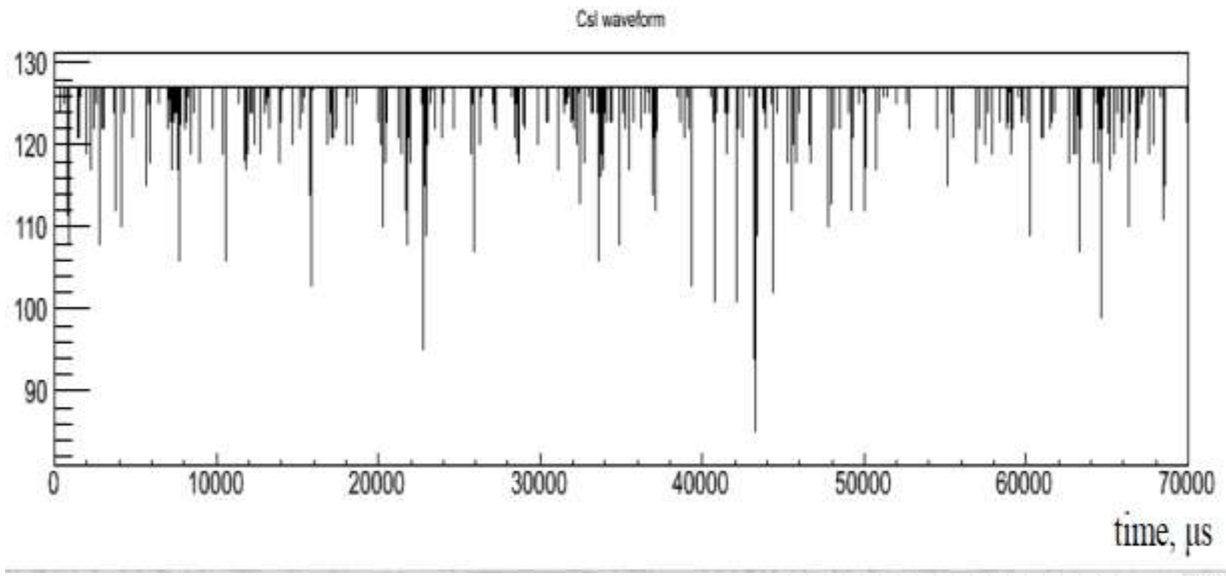
CsI is a Bad Detector for CEvNS

Quenching (response to nuclear recoils) is not known very well

It is slow – 630 nsec (single Ph.E. for small signals)

It has a large afterglow



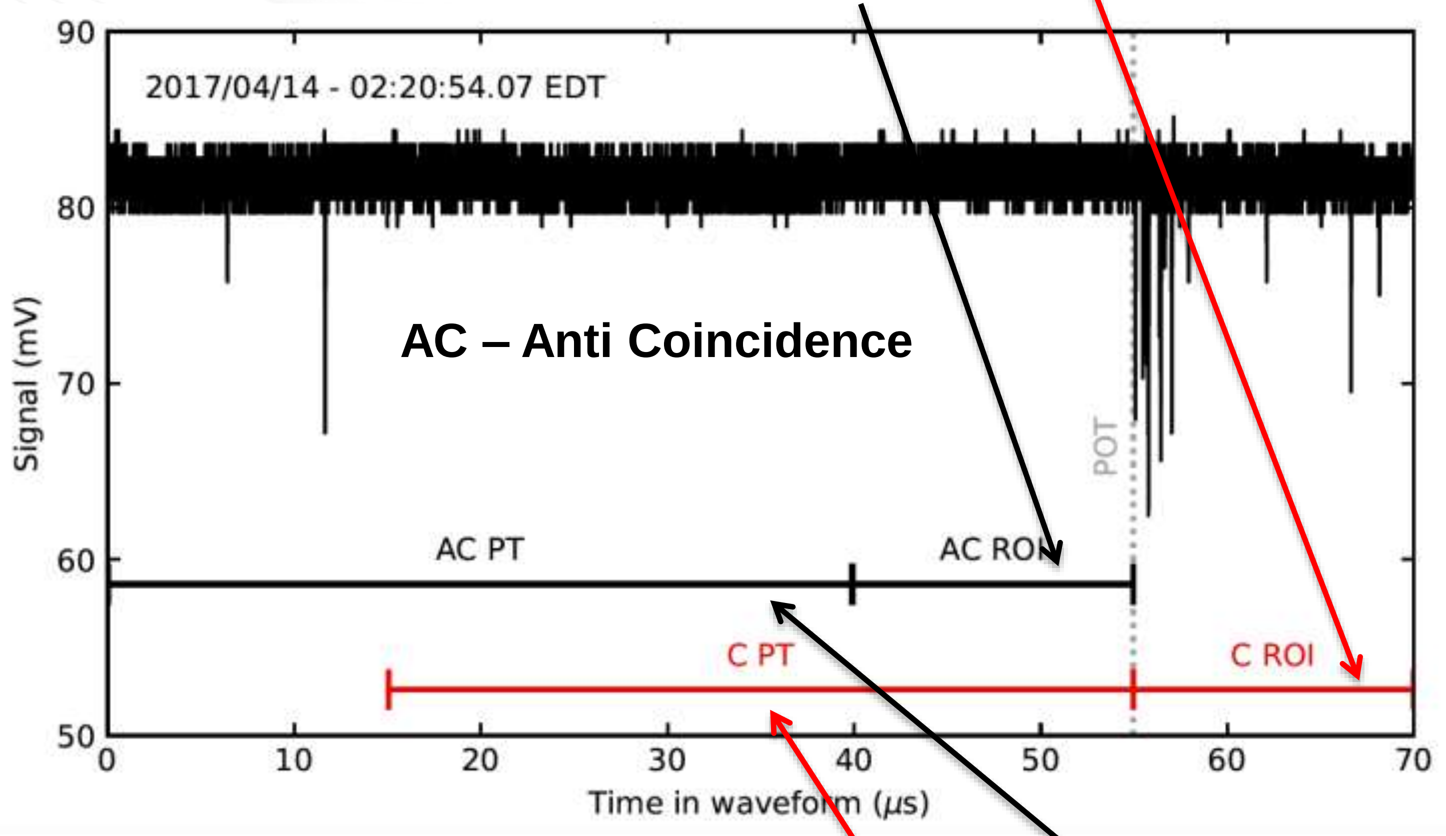


The large afterglow, creates problems for a large crystals working on the surface

CsI Event Selection Cuts

Analysis procedure:

Apply same "Cherenkov" cut for AC and signal and ROI windows

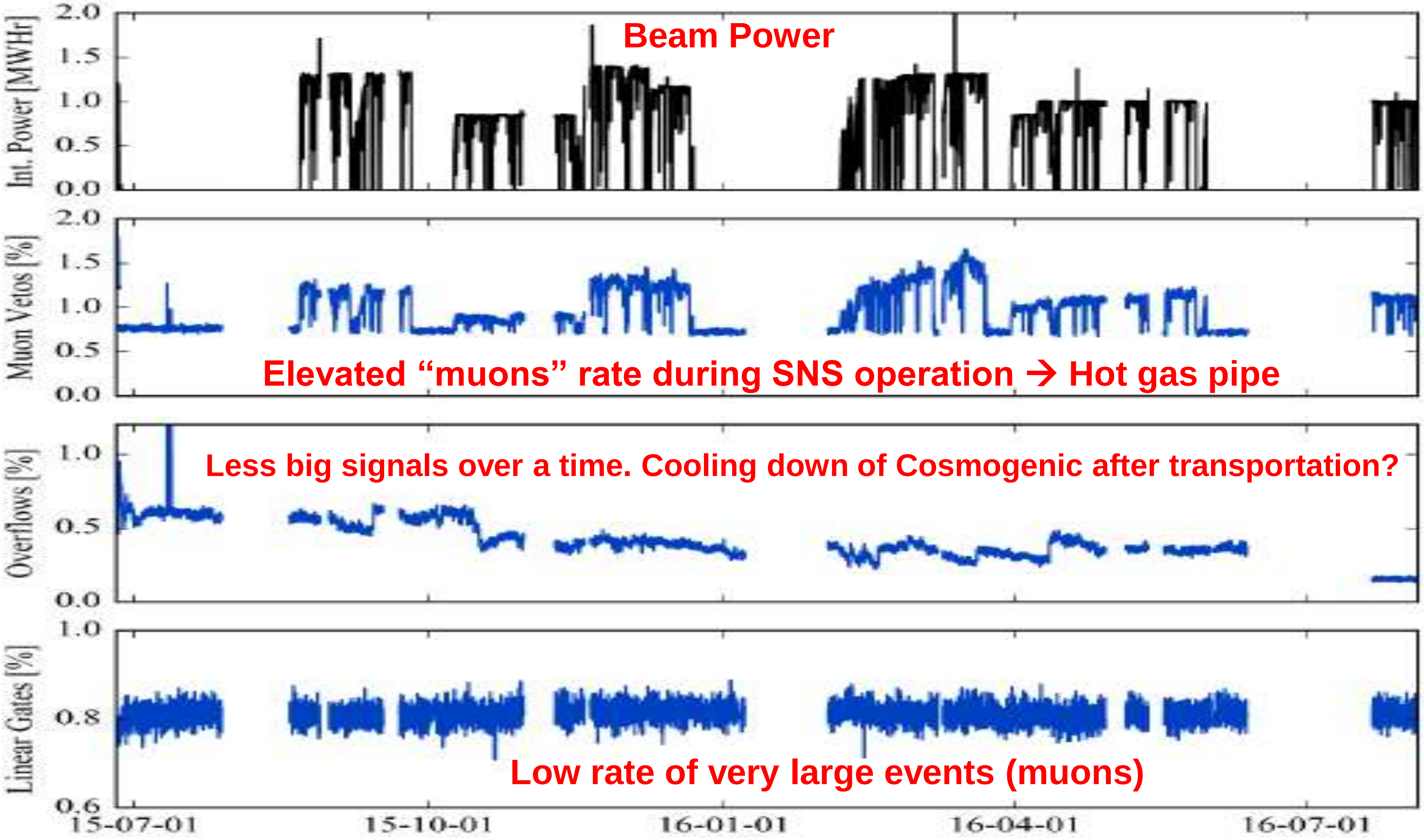


Use "Cherenkov cut" is to eliminate high amplitude, short signals

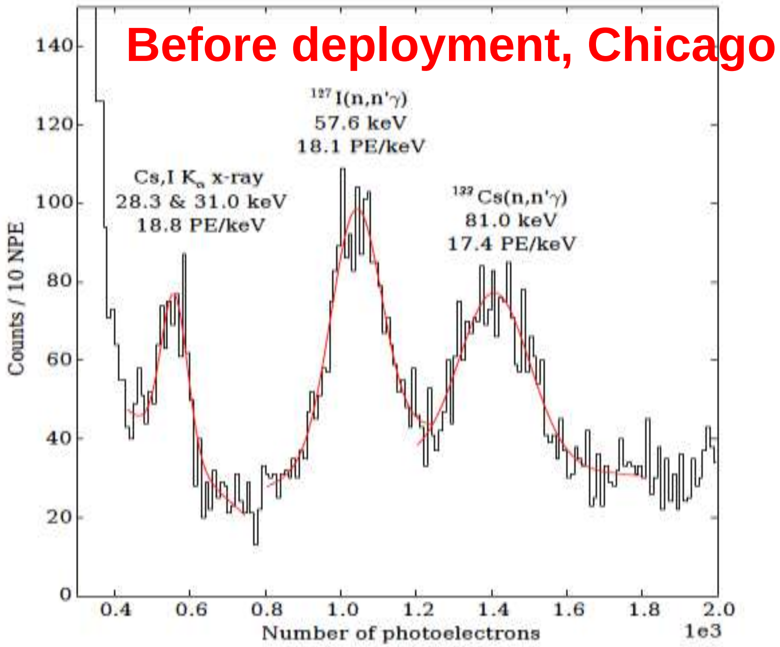
Apply cut on prior activity using signal and AC pre trace windows

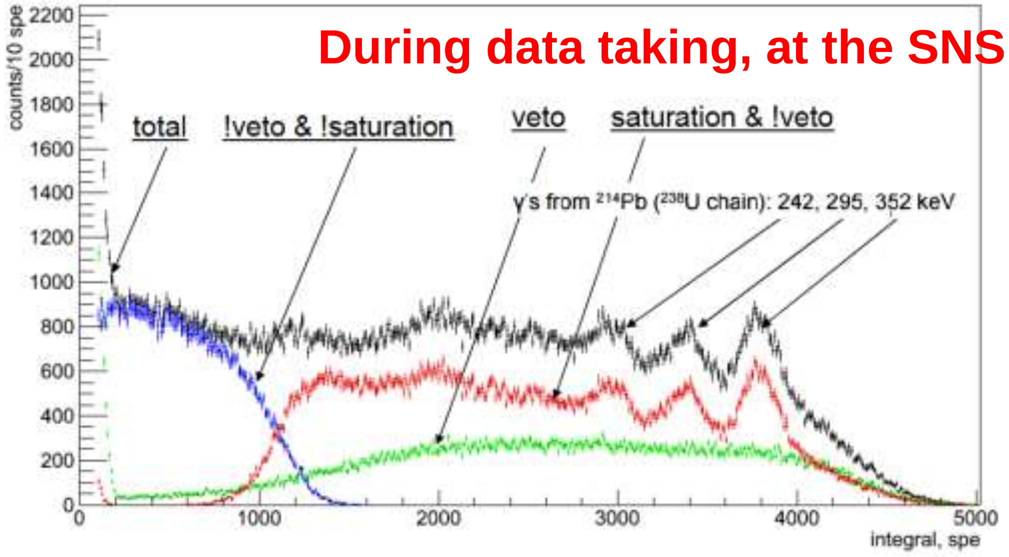
Subtract BG ROI events from Signal ROI events

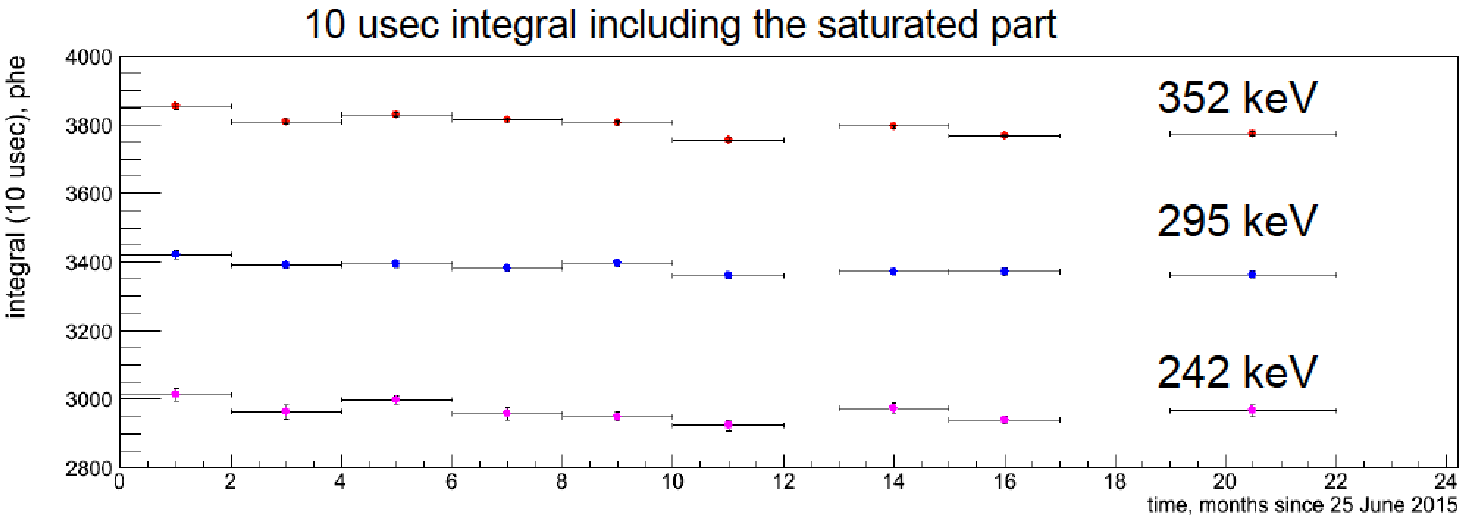
CsI Detector Stable Operation



In Situ Energy Calibration



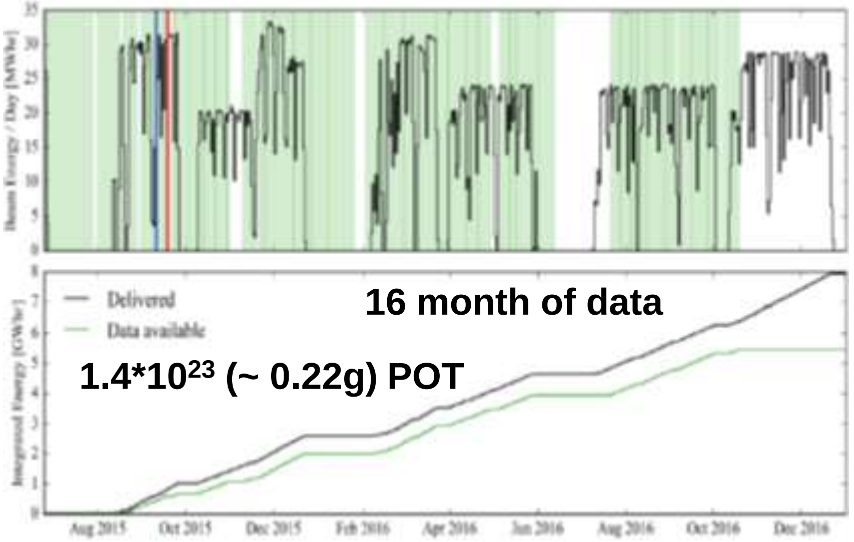


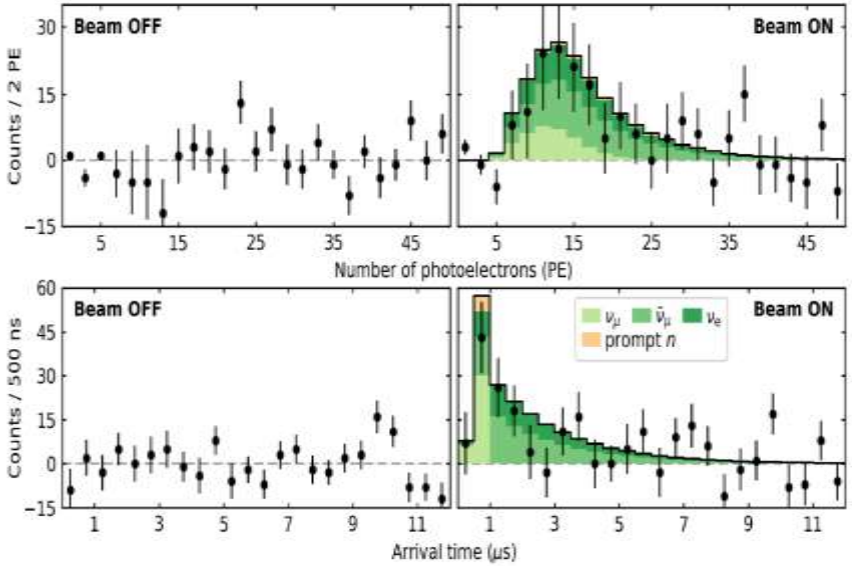


No drift

First Detection of CEvNS with CsI detector

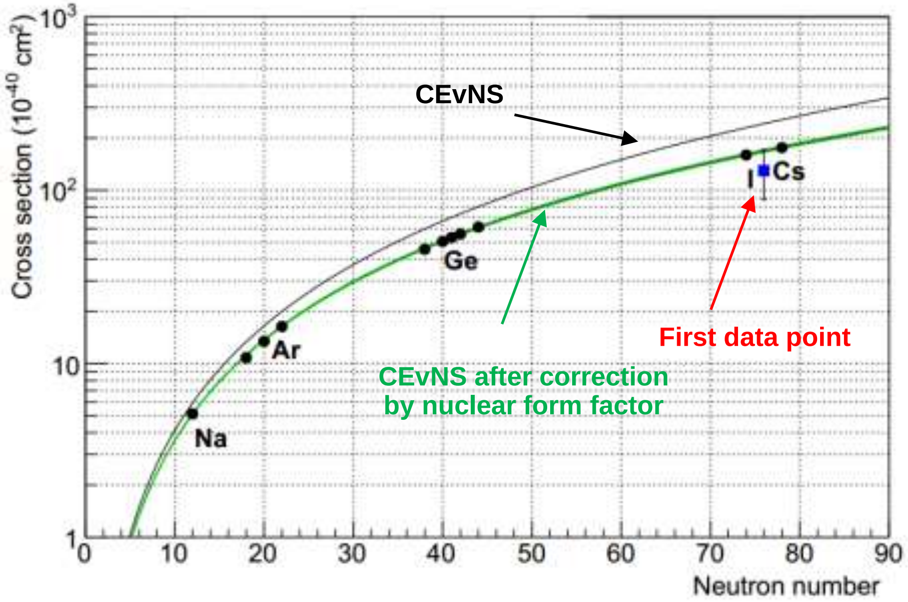
First working, hand held neutrino detector -14kg!!!





Now we have x2.5 times more statistics

Will publish updated statistics soon



First Detection Caused Big Interest and Many Theoretical Interpretations from multiple directions

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COHERENT enlightenment of the neutrino dark side

Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,[2,3,4,†] Michele Maltoni,[5,‡] and Thomas Schwetz[6,§]

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COHERENT constraints on nonstandard neutrino interactions

Liao *, Danny Marfatia

PHYSICAL REVIEW LETTERS 120, 072501 (2018)

Average CsI Neutron Density Distribution from COHERENT Data

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PHYSICAL REVIEW D 97, 033003 (2018)

COHERENT constraints to conventional and exotic neutrino physics

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PROCEEDINGS OF SCIENCE

Constraints on nonstandard neutrino interactions from the COHERENT experiment

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Testing large non-standard neutrino interactions with arbitrary mediator mass after COHERENT data

Peter B. Denton,[a] Yasaman Farzan[b] and Ian M. Shoemaker[c]

PHYSICAL REVIEW D 98, 075018 (2018)

COHERENT analysis of neutrino generalized interactions

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[3]AHEP Group, Instituto de Física Corpuscular, CSIC/Universitat de València, Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain

Neutrino Charge Radii from COHERENT Elastic Neutrino-Nucleus Scattering

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(Dated: Monday 15/10/18, 00:27)

Reinterpreting the weak mixing angle from atomic parity violation in view of the Cs neutron rms radius measurement from COHERENT

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OAK RIDGE National Laboratory

What Did We Learn So far?

CEvNS exists
However, nobody doubt that !!!

“It’s a real thrill that something that I predicted 43 years ago has been realized experimentally”

Daniel Freedman

SNS is beautiful low energy pulsed neutrino source “optimized” to study CEvNS

Now we know how to detect CEvNS

So far we have a binary answers “*YES*”

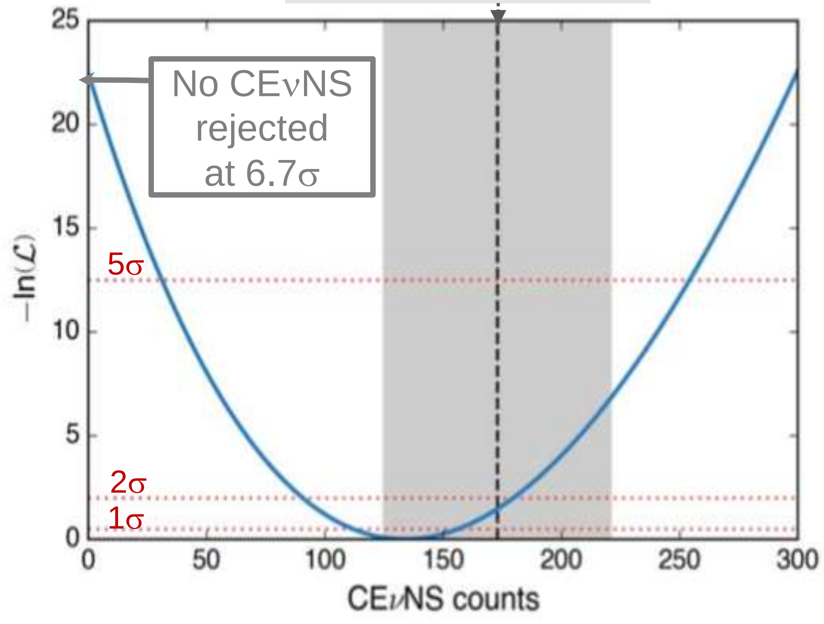
Next step is precision study of CEvNS to search for anomalies !!!

Some Details About the First CEvNS Detection with CsI

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, 2D likelihood fit	134 ± 22 (16%)
Predicted SM signal counts	173 ± 48 (28%)

Uncertainties on signal and background predictions	
Event selection (signal acceptance)	5%
Nuclear Form Factor	5%
Neutrino Flux	10%
CsI Quenching Factor (QF)	25%
Total uncertainty on signal prediction	28%

SM prediction: 173 events



All uncertainties except neutrino flux are detector specific and could be much less for other technologies

To unlock high precision CEvNS program we need to calibrate SNS neutrino flux, measure QF well and accumulate high statistics on multiple targets

High Priority →SNS Neutrino Flux Normalization

Presently we estimate that neutrino flux at SNS is known within 10%

Cross sections of neutrino interaction with Deuterium are known with 2-3% accuracy

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_μ +d → 1.8×10^{-41} cm^2
Delayed NC $\nu_{e\mu\text{-bar}}$+ d →6.0×10^{-41} cm^2
Delayed CC ν_e + d → 5.5×10^{-41} cm^2

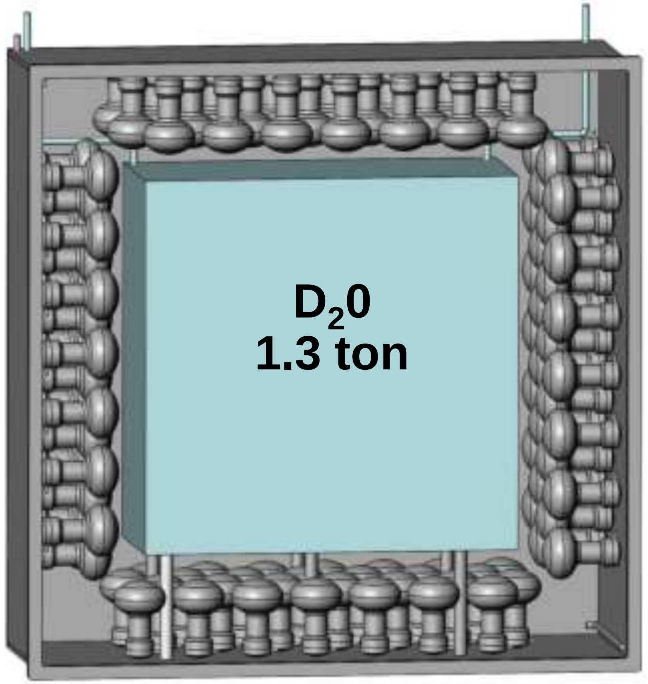
For 1 t fiducial mass detector ~ thousand interactions per year

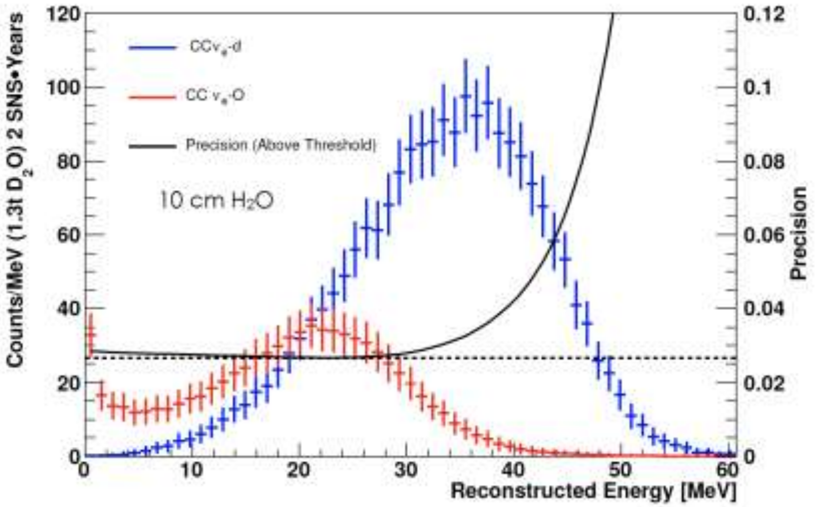
Detector calibration with Michel Electrons from cosmic muons (same energy range)

Well defined D_2O mass constrained by acrylic tank

10 cm of light water tail catcher

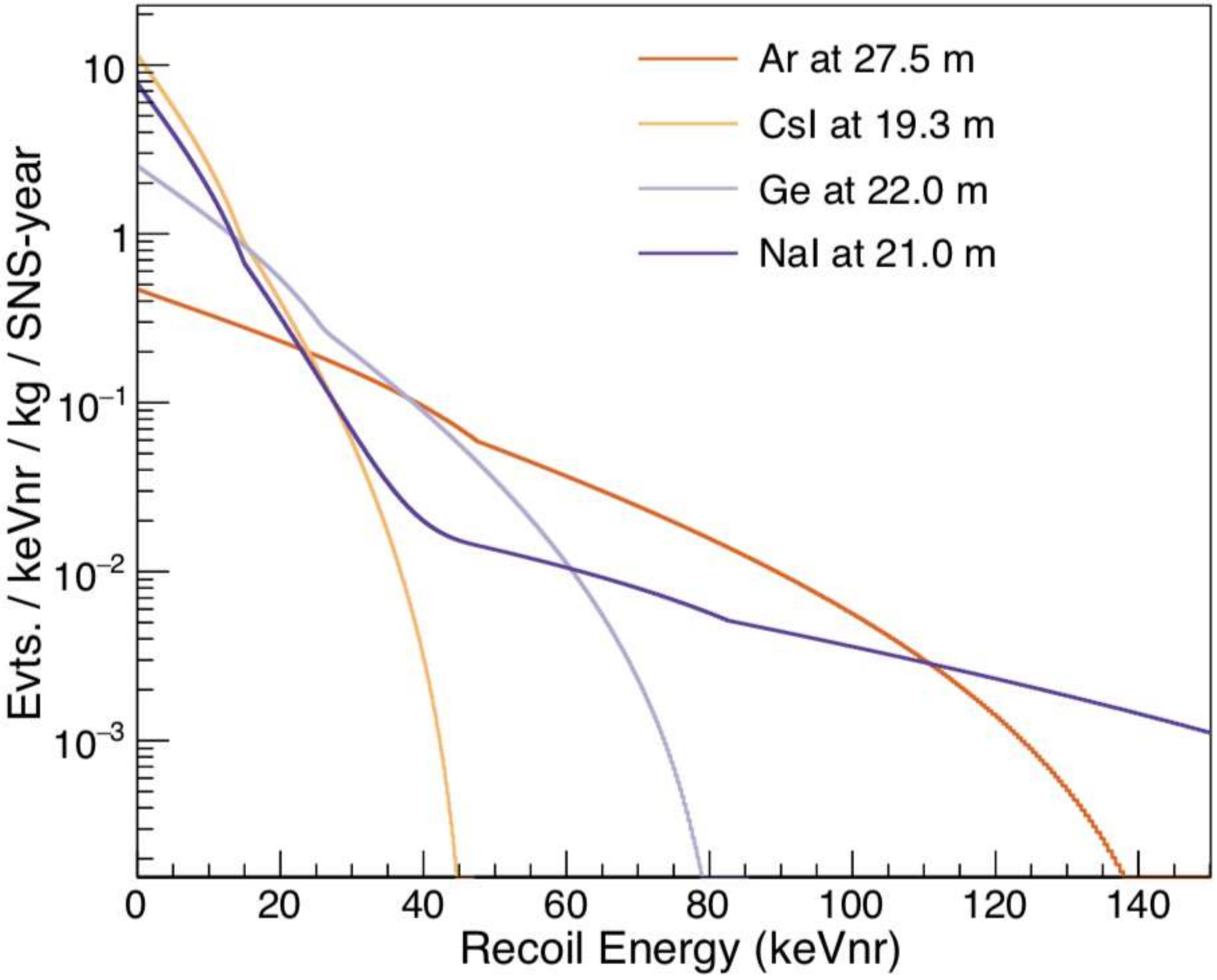
Outer dimensions 2.3 * 2.3 * 1.0 m^3

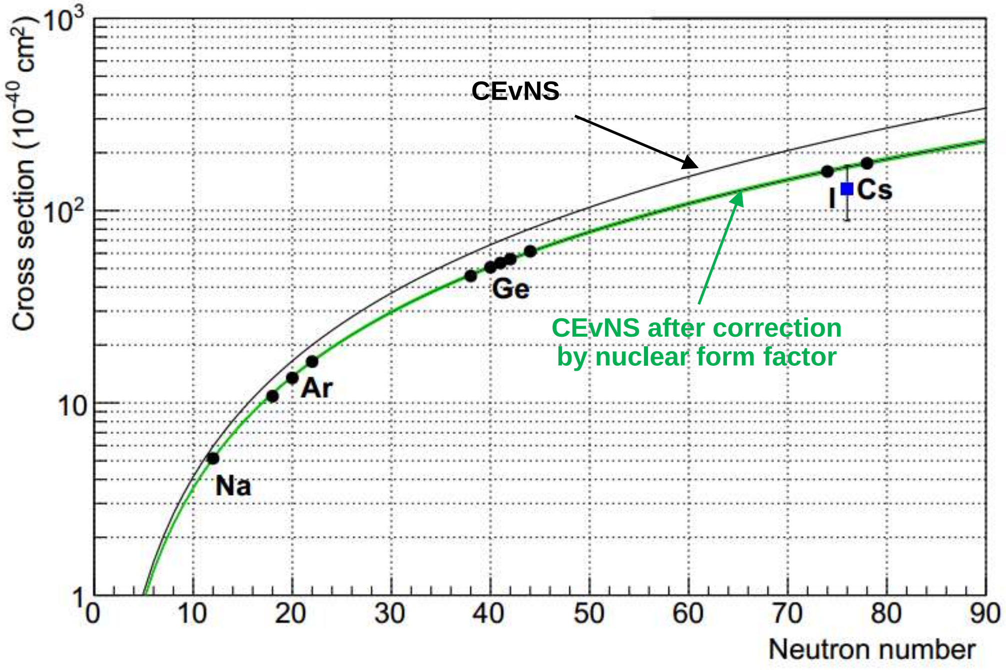




SNS flux calibration
plus
CC measurements on Oxygen

Expected CEvNS recoil Spectra for Isotopes of Interest



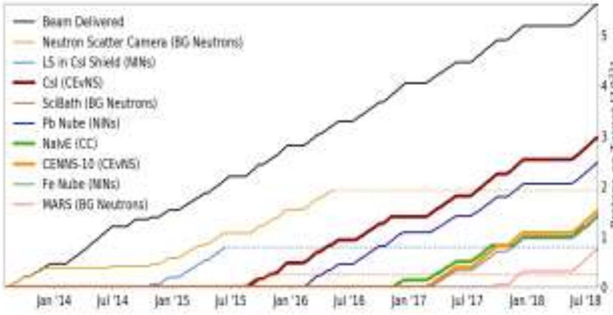


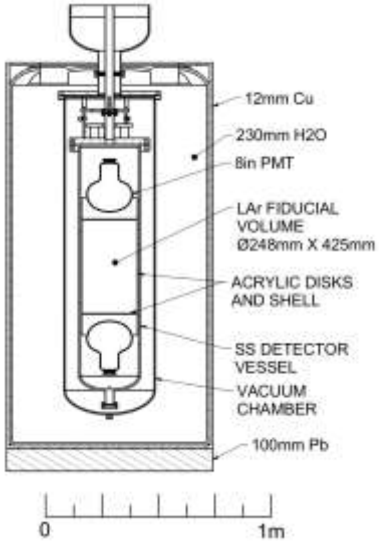
To untangle effects of nuclear form factors we need measurements at the wide range of target masses: Light, Middle, and Heavy

To have handle on axial current it is interesting to have close targets with different spins. Example ^{40}Ar s=0 and ^{23}Na s=3/2

Targets near neutrino less double beta decay isotopes (e.g. Ge) are of special interest.

Next Step is Detection of CEvNS With LAr Detector





Single Phase Liquid Argon Detector CENNS-10

Aim is to detect CEvNS for a very different target

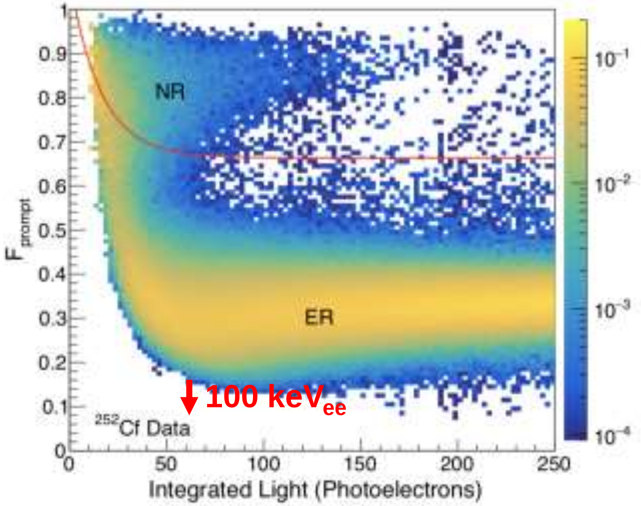
CENNS-10 SNS timeline:

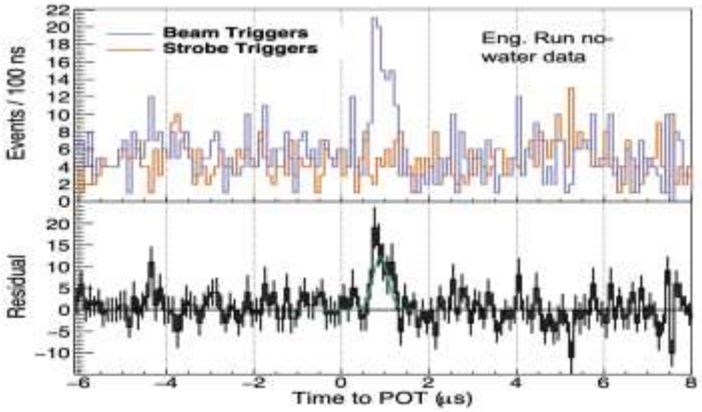
10-12/2016: commission and deployed detector at SNS

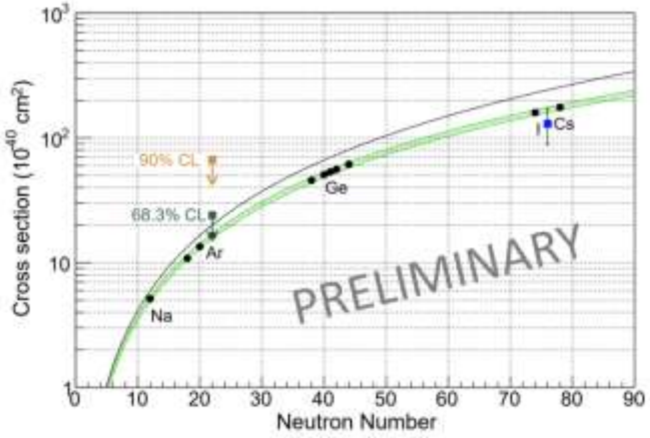
12/16 - 5/17: "Engineering Run". 1.8 GWhr accumulated statistics.

Poor light collection, E_{thresh}~100keV$_{nr}$ Test of hardware and first limit for CEvNS on Argon

Only upper limit on cross section has been achieved
arXiv:1909:05913 [hep-ex]







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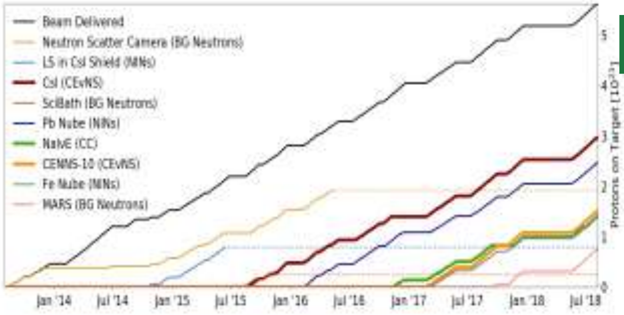
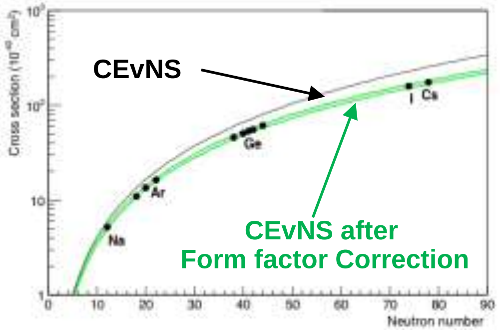


Next Step is Detection of CEvNS With LAr Detector



Single Phase Liquid Argon Detector CENNS-10

Aim is to detect CEvNS for a very different target

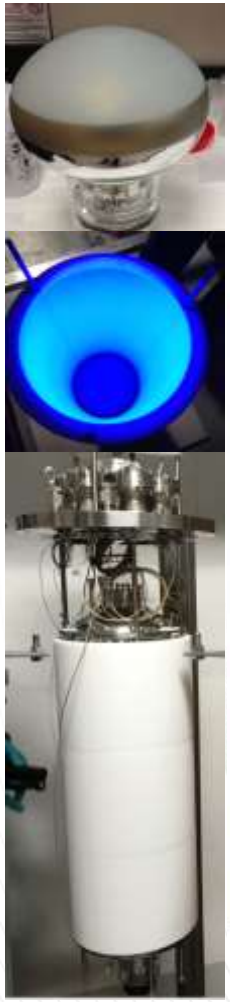
CENNS-10 SNS timeline:

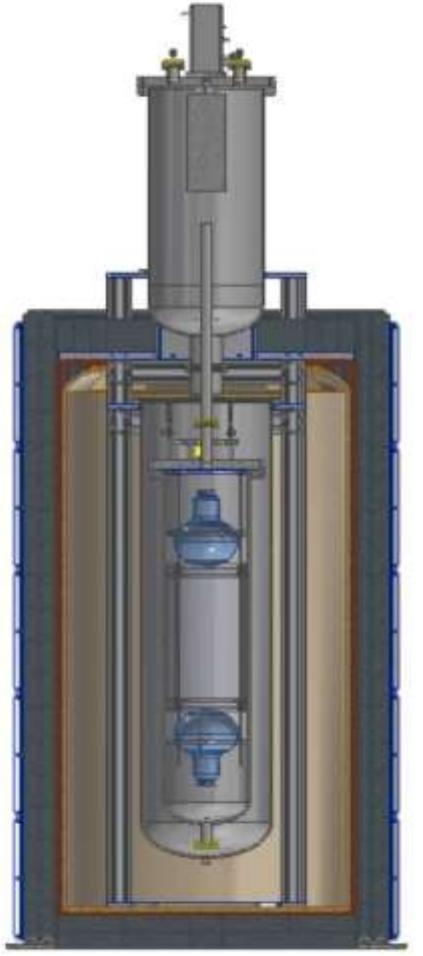
7/17- now: "Run 1" Rebuild detector. Light collection increase by a factor of 10! It should be enough to see CEvNS. E_{thresh}~20keVnr

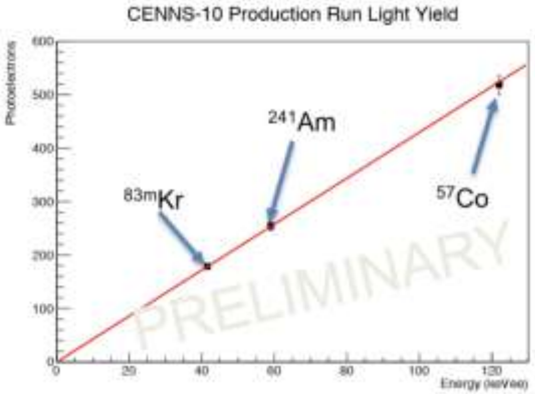
Presently accumulated statistics is ~6 GWhr (~$1.4*10^{23}$ POT)

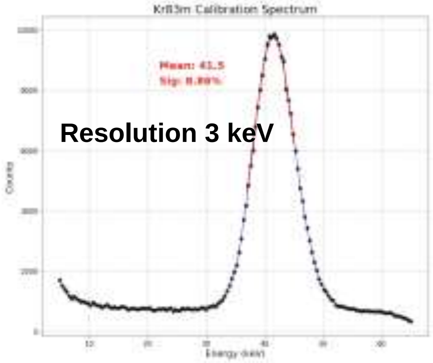
We implemented blind analysis by looking on the data between beam spills only.

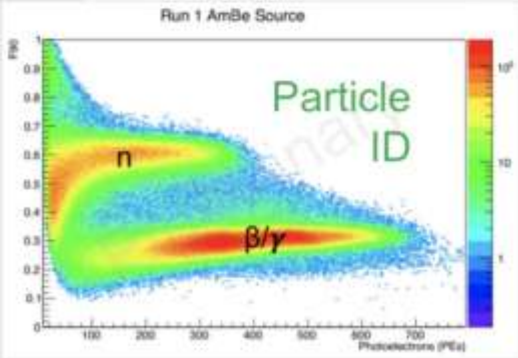
Planning to unveil results very soon!!!!











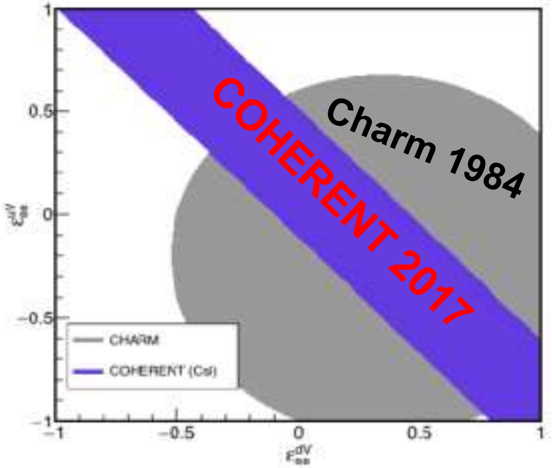
OAK RIDGE National Laboratory

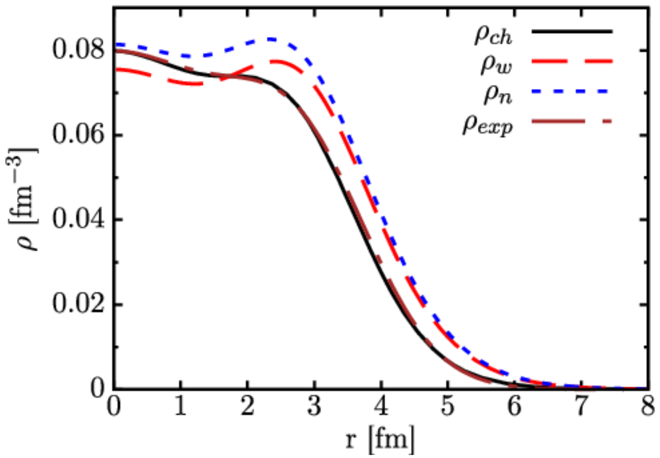
Future Physics for COHERENT

Particle Physics
NINs,Test of the SM, DM

Nuclear Physics
Form Factors, Axial Currents, Incoherent processes

Astrophysics
Supernovae Cross Sections

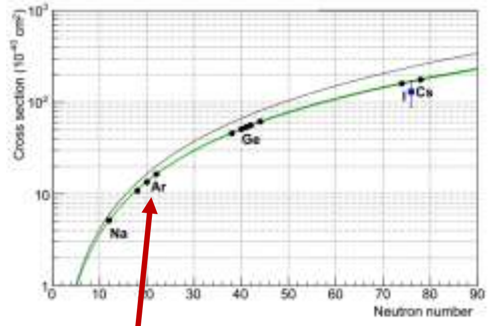




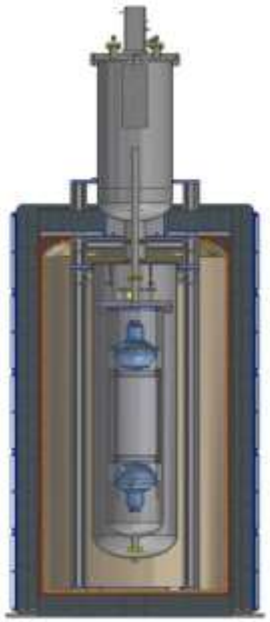
Those studies become important if we do measurements with a very good accuracy

To do so we need multiple detectors able to accumulate large statistics with accurate measurements of recoil spectra

Future Activities - 1 ton LAr detector



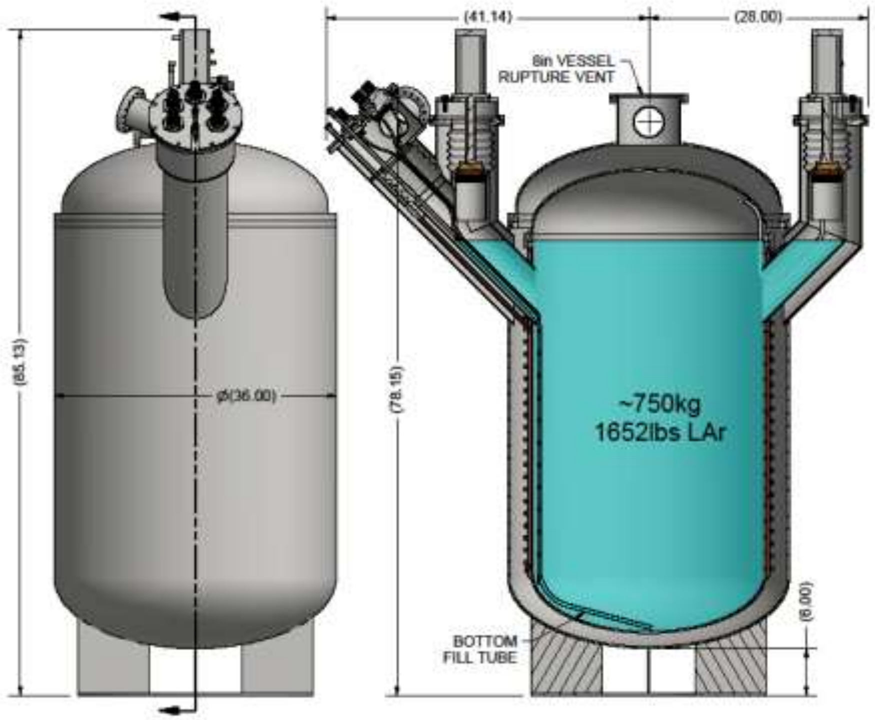
Need high statistics low background measurements of CEvNS



Transition from 22 kg to 1 ton LAr detector.

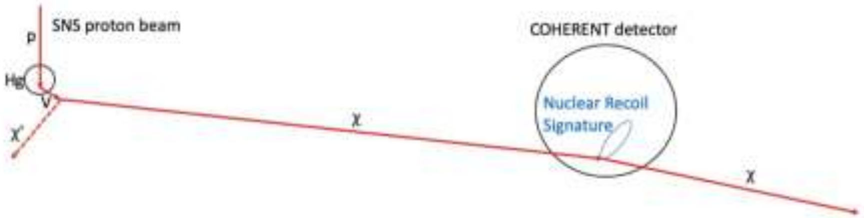
Can fit at the same place where presently 22 kg detector is sitting

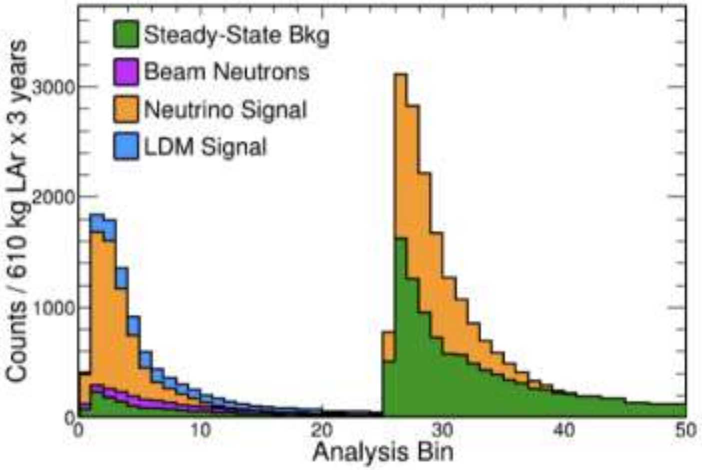
Will see 3kt of CEvNS events per year + CC

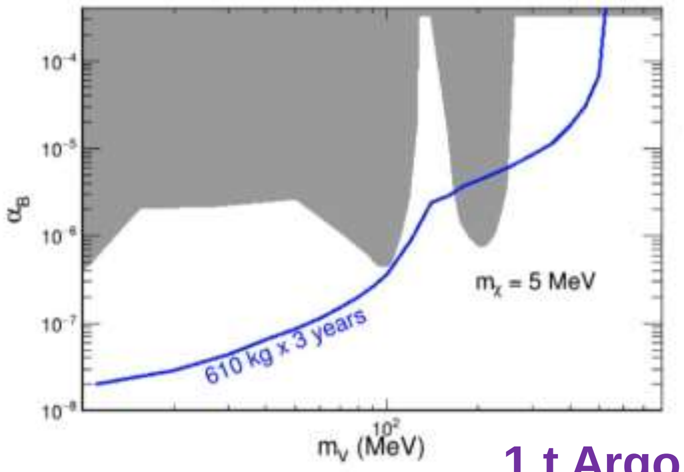


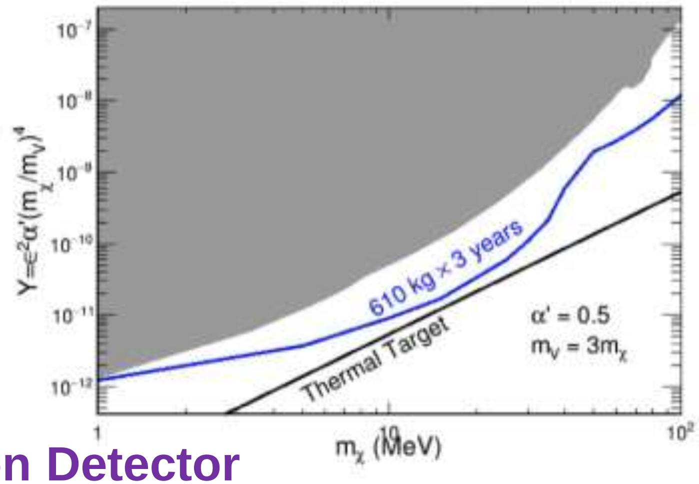
Vector portal dark matter

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\epsilon}{2}V^{\mu\nu}F_{\mu\nu} + q_B g' V_\mu J_B^\mu + \cdots$$







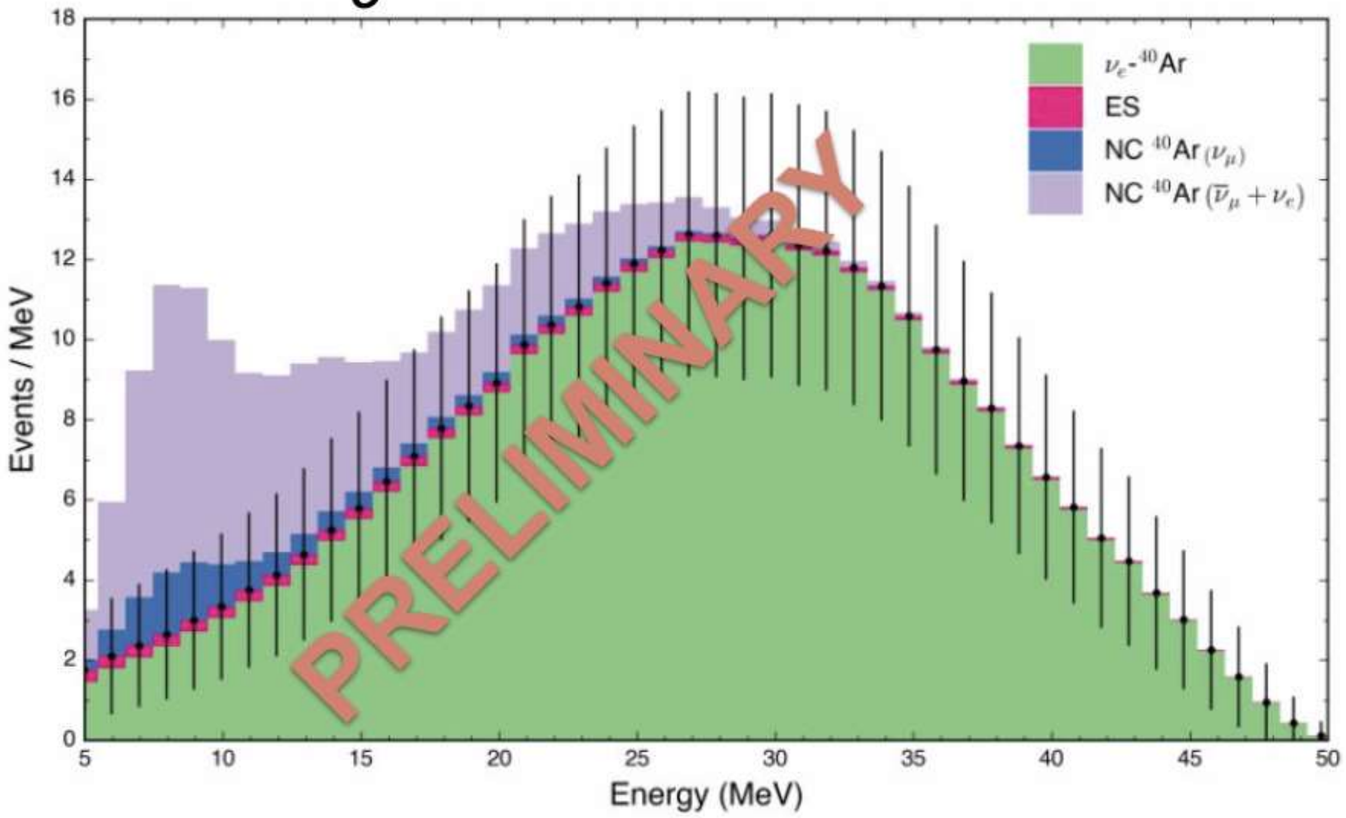


1 t Argon Detector

- Coherent cross section enhancement
- DM and CEvNS recoil spectra are different -- *delayed CEvNS provide constraint for prompt DM*
- Competitive constraints for ~10-30 MeV vector portal in neutrino alley
- Strong limits on baryonic portal

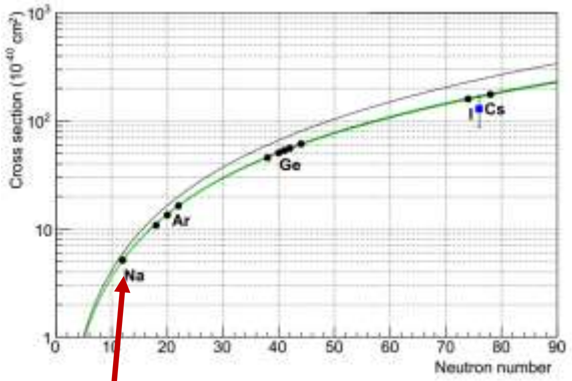
Same One Ton Detector can Measere CC on Argon

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



This is channel to detect future Supernovae Neutrinos at Dune

2t NaI detectors array

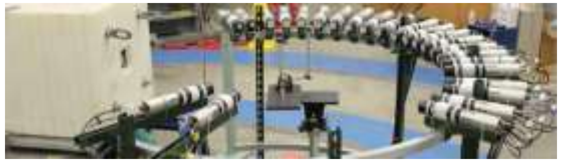


Transition from now deployed 185 kg to 2 ton array of NaI detectors

Detectors are available

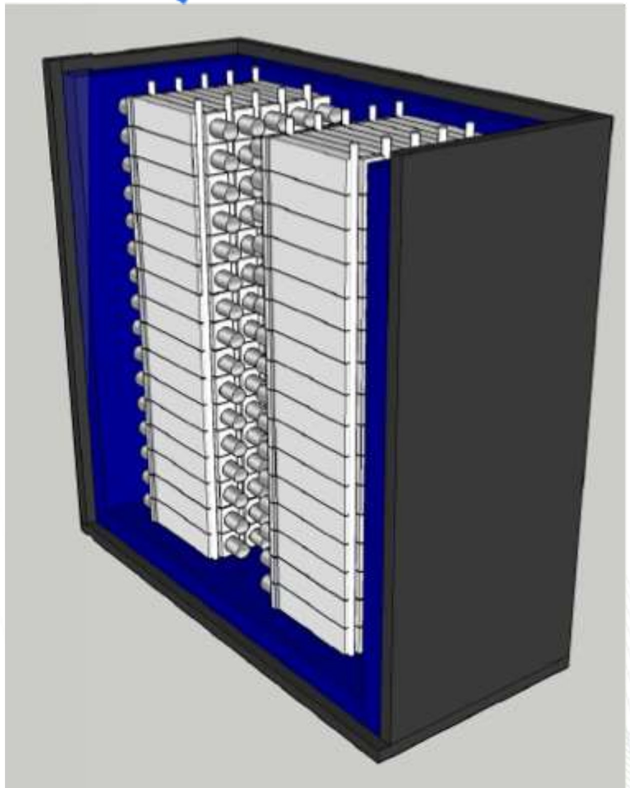
Need dual gain bases (prototypes has been build)

Program to measure Quenching Factors is ongoing at TUNL

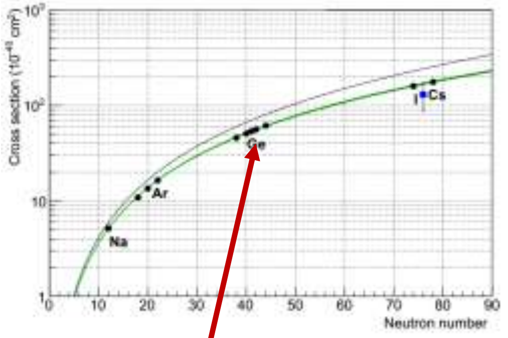


Need electronics and HV; some funds are secure

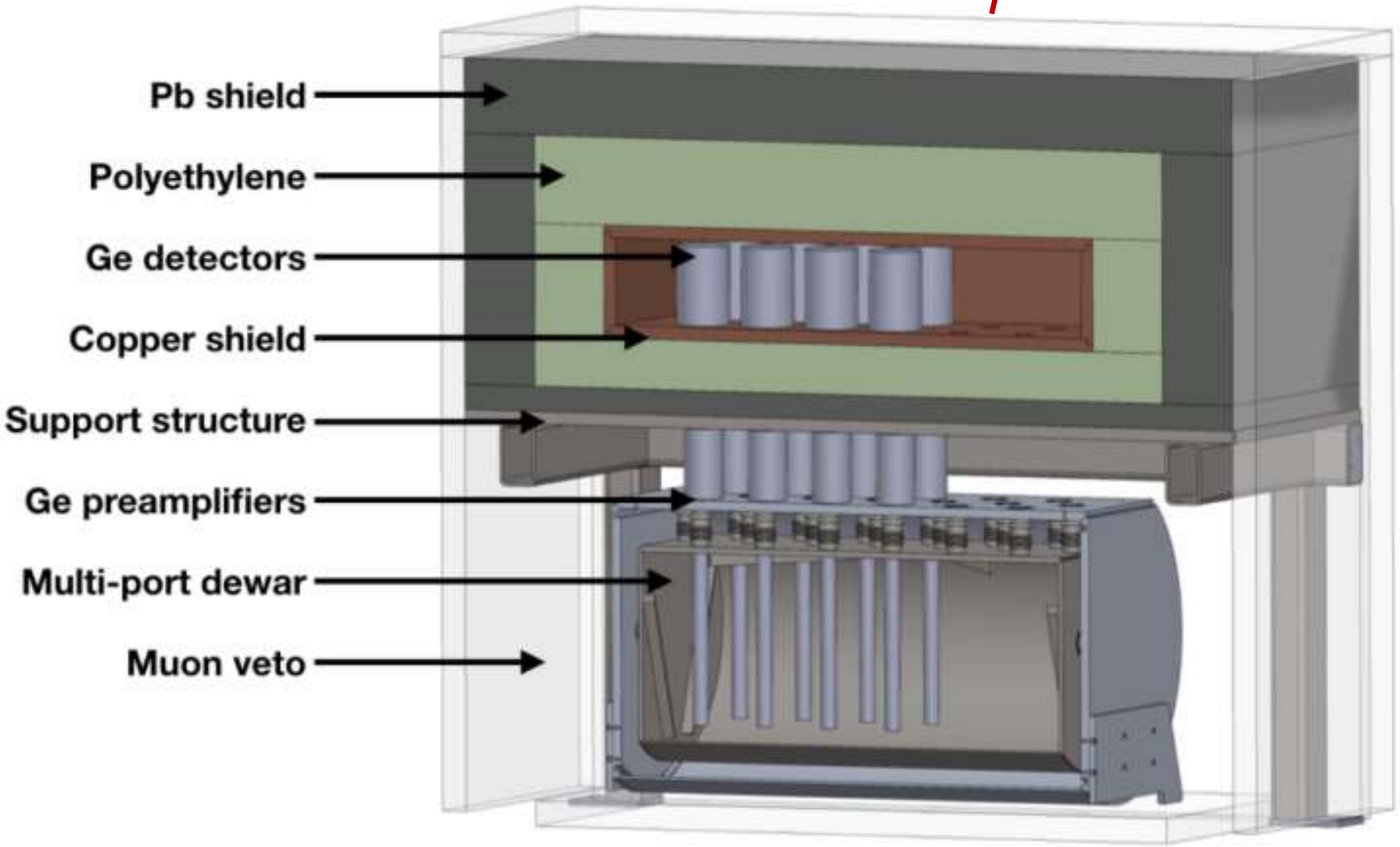
Potential to detect both CEvNS and CC reactions



Germanium PPC array



- Estimate 500 - 600 CEvNS events/year in a 16 kg array.
- Electronic noise from detector + preamp limited to < 150 eV FWHM.
  - Results in an energy threshold of ~0.4 keVee, roughly 2-2.5 keVnr.
- Cryostat already available.
- Quenching factor well understood (see talk by Long Li)



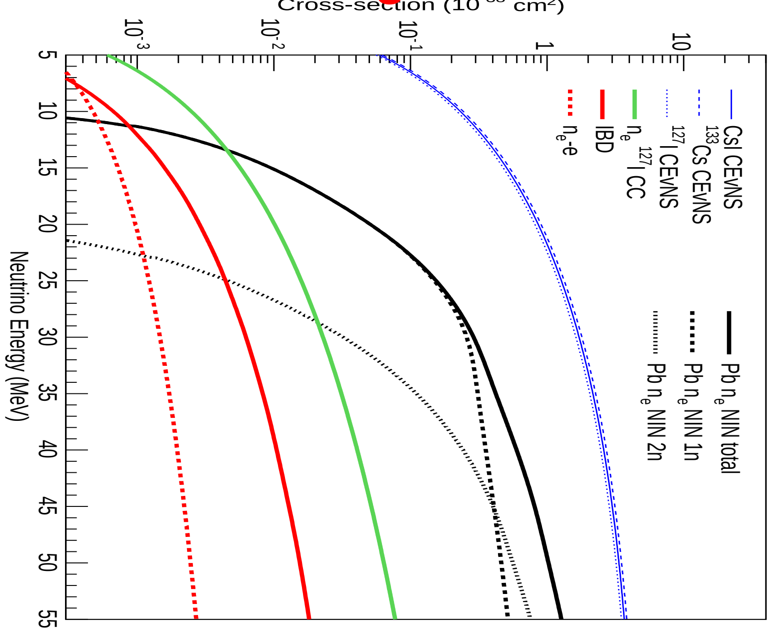
Neutrino Induced Neutrons (NINs)

$$\nu_e + {}^{208}Pb \Rightarrow {}^{208}Bi^* + e^- \qquad (CC)$$
$$\Downarrow$$
$${}^{208-y}Bi + x\gamma + yn$$

$$\nu_x + {}^{208}Pb \Rightarrow {}^{208}Pb^* + \nu_x' \qquad (NC)$$
$$\Downarrow$$
$${}^{208-y}Pb + x\gamma + yn.$$

NIN can be a background for COHERENT

It has the same timing as neutrinos !!!



This reaction never been measured
There are only theoretical estimations
However, already used by experiment

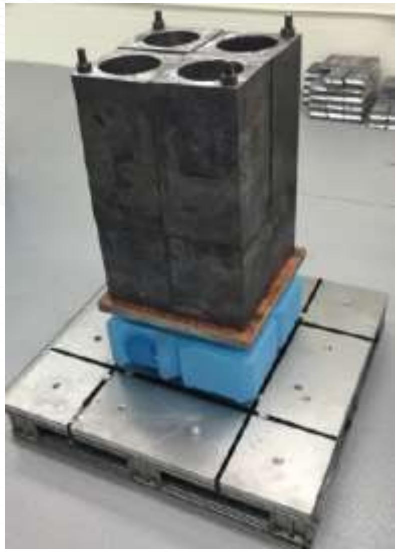
HALO at SNOlab

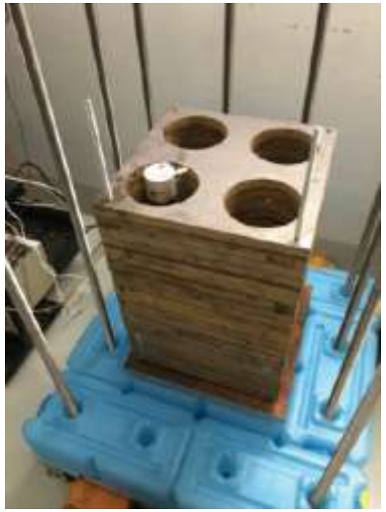
NIN on lead is used by HALO experiment in the SNOlab, to watch for supernovae.

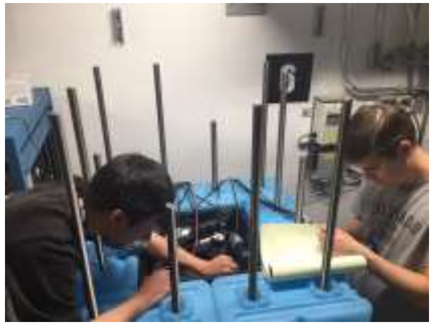
This process can be important in many stellar environments

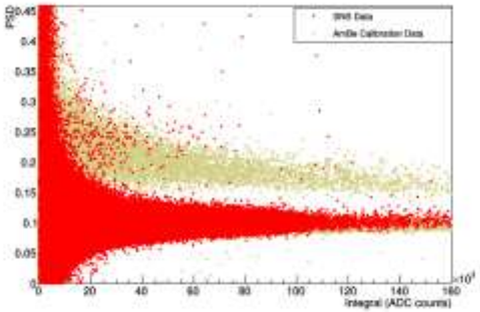
E. Kolbe, E. Langanke, "Role of v-induced reactions on lead and iron…", Phys. Rev. C63 (2001)

Neutrino Induced Neutrons II





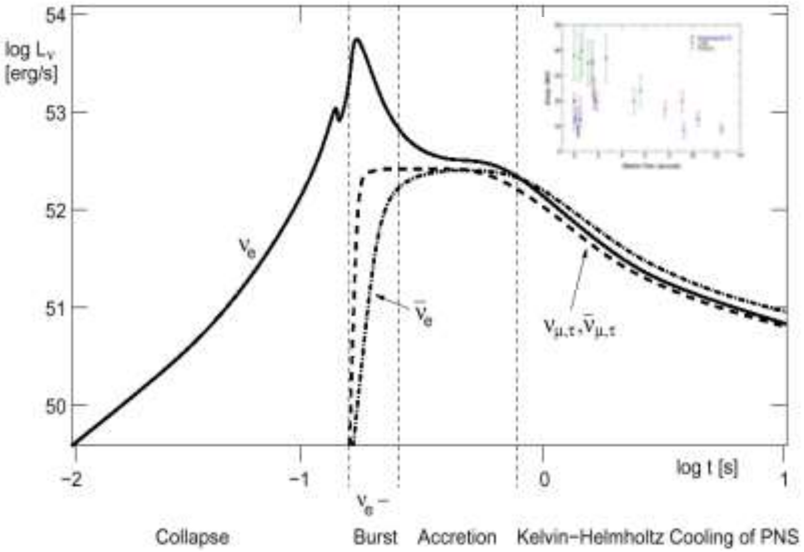




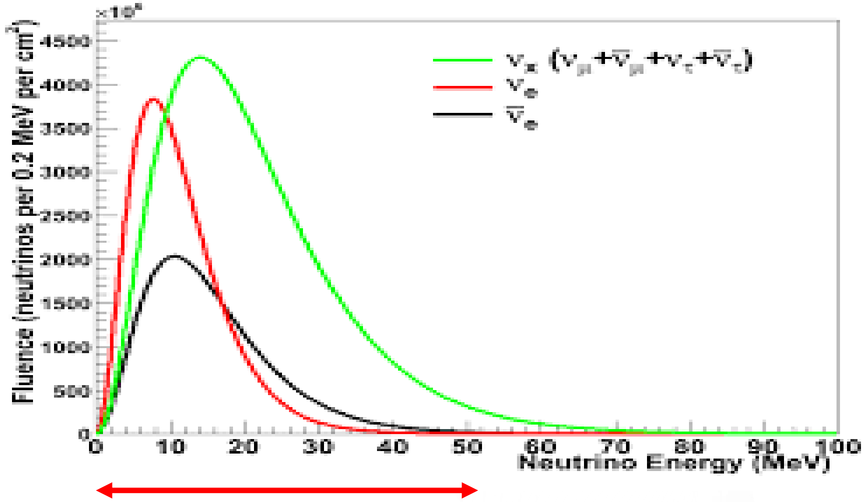
- **Liquid scintillator detectors with n/g separation capability**
- **Two sets with Lead (1 ton) and Iron (700kg) targets.**
- **Neutron detection Efficiency ~10%**

Ongoing program of measurements with Lead and Iron targets looking for the first detection of NINs and measurement of their production cross section.

Neutrinos From Supernovae



Neutrino Spectra from Core Collapse Supernovae



Neutrinos energy range at SNS

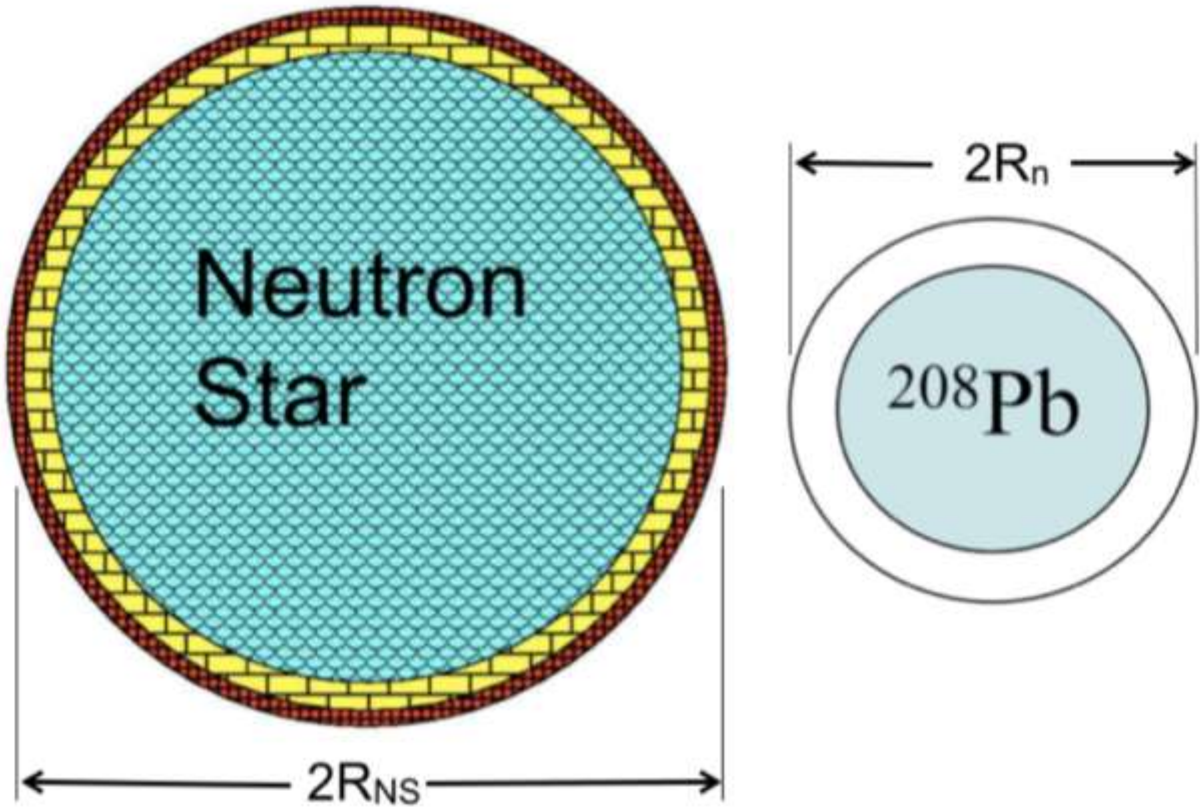
For the Next Galactic SN we have Multiple Detectors to see neutrinos

However, cross sections for SN neutrino energy range never been measured.

COHERENT will provide measurement on Oxygen for SuperK, Argon for DUNE, on Lead for HALO

CEvNS will let to Measure Neutron Skin for Heavy Elements → input into neutron matter density

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.

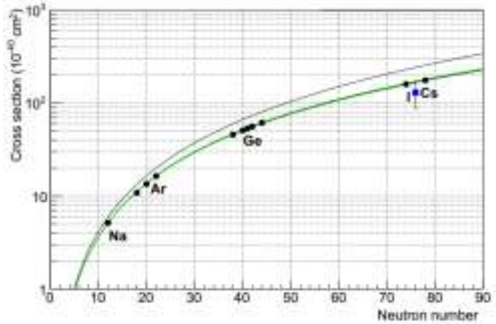


Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

C.Horowitz

COHERENT Collaboration Steps

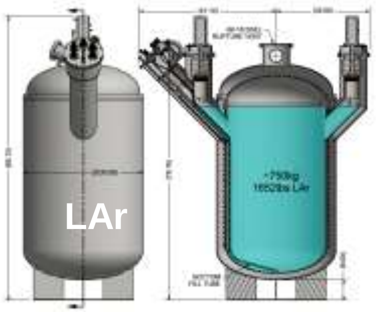
Present: First Light set ups

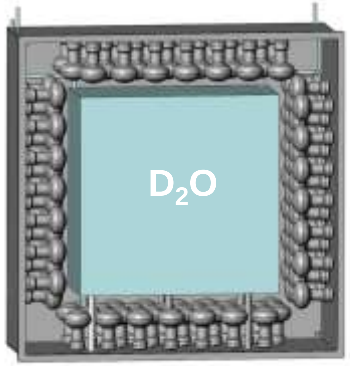


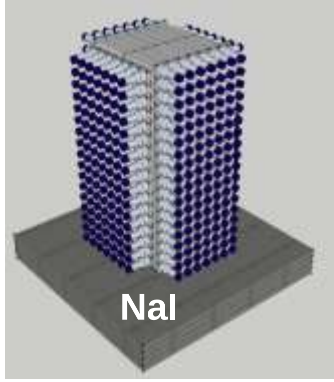
- Detect CEvNS
- Measure CEvNS for heavy and light nuclei
- Detect NINs

Next Step: New Deployments

- Hight Statistic measurements on Ar, Na, Ge
- Calibrate SNS neutrino flux
- High precision CEvNS studies. Look for physics beyond SM. Eliminate Dark Sector as a degeneracy for DUNE
- By product measure neutrino CC to support supernovae physics
  (Lead, Argon, Oxygen, Iodine)







Summary

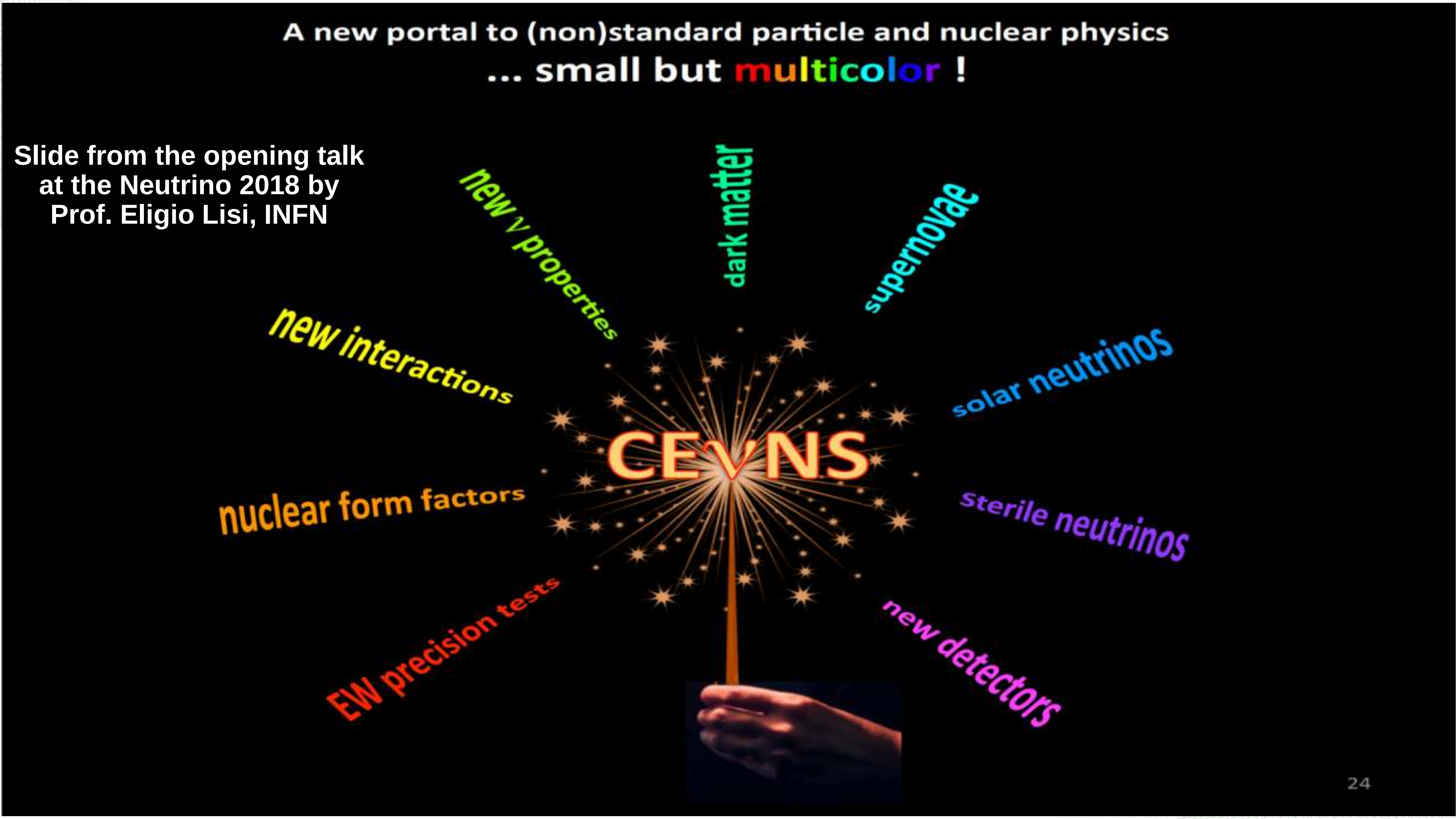
Detection of CEvNS opened new portal to look for physics beyond the SM

First set of experiments have been deployed, we have first positive result, and continue to take data

Collaboration is planning to build and deploy: 1t LAr(Xe), 1t D_2O, 3t NaI, and 15 kg Ge detectors in a near future.

Collaboration goals are:

- Collect data for precision tests of SM in new channel
- Make inputs into nuclear physics theory
- Provide CC and NC measurement for O, Ar, I, and Pb for neutrino energies relevant for SN



Slide from the opening talk at the Neutrino 2018 by Prof. Eligio Lisi, INFN