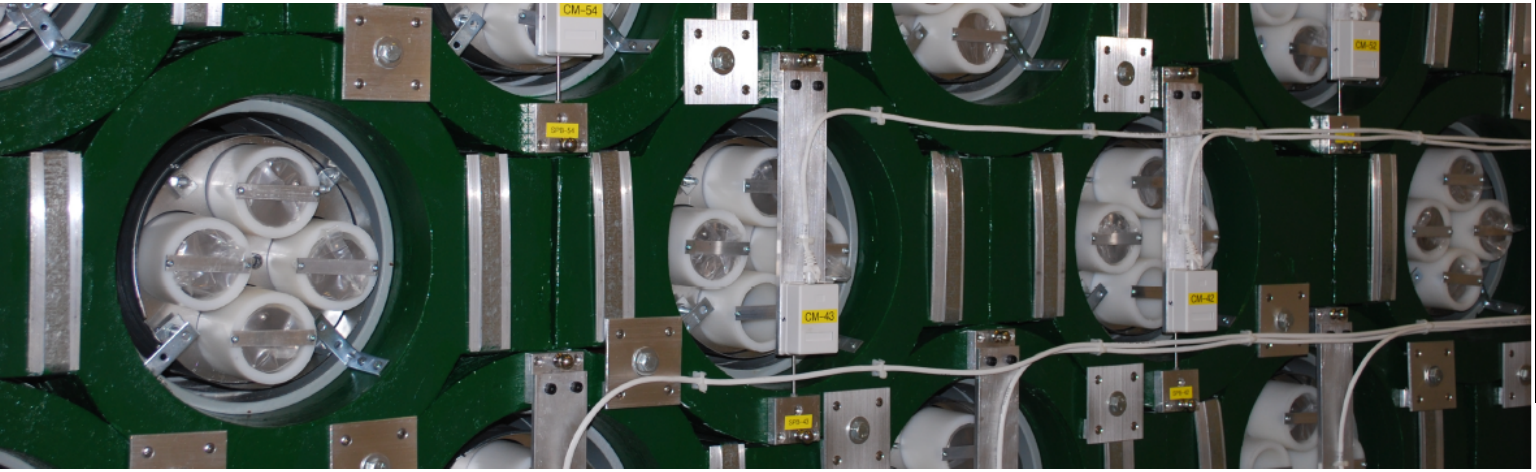
Neutrino Induced Neutrons: Experiment



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Outline

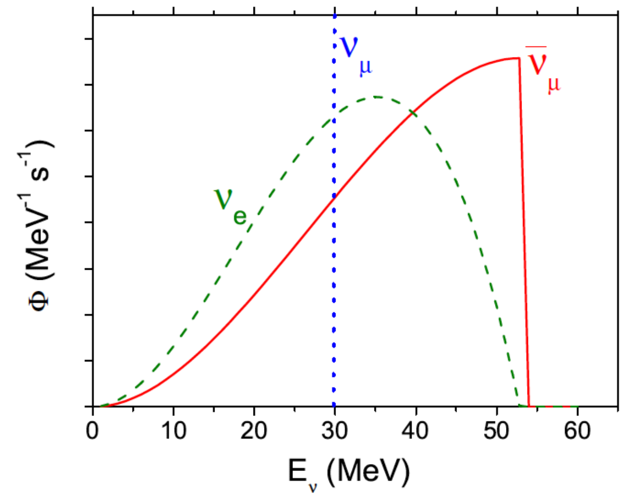
- Neutrino-Induced Neutrons
- as a background
  - CEνNS
- as a signal
  - The HALO Detector
  - HALO-1kT at LNGS

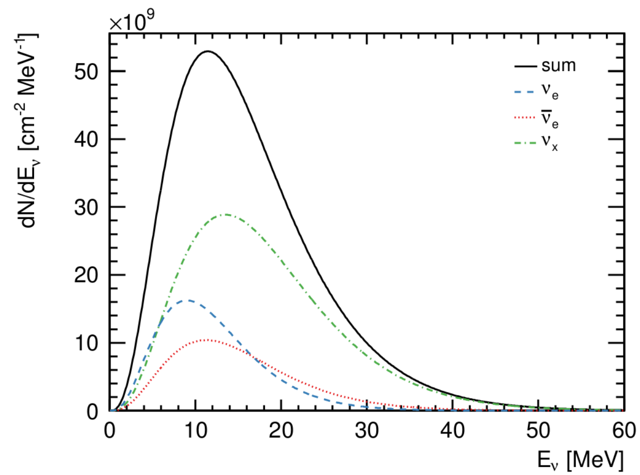
Neutrino-Induced Neutrons (NINs)

- neutrino-induced NC/CC nuclear excitations can exceed the 1n or 2n separation thresholds resulting in MeV neutrons
  - a background for CEνNS
  - a background for other ν-beam experiments
  - a signal for nuclear-target supernova detectors such as the lead-based HALO detector
- materials generally of concern for generating NINs
  - Pb
  - Fe
- hampered by theoretical cross section uncertainties and lack and difficulty of measurements

SNS is the facility to resolve NIN questions

- huge fluxes ~ 1 SN/yr at 20 m
- good energy overlap between DAR neutrinos and SN spectra
- pulsed beam structure





NIN Cross Sections Summary

TABLE II: Flux-averaged cross sections for the ν_e reaction on ^{16}O, ^{56}Fe, and ^{208}Pb target nuclei.

for DAR ν_e

	$^{16}O(\nu_e, e^-)^{16}F$ $\langle\sigma\rangle(10^{-42} cm^2)$	$^{56}Fe(\nu_e, e^-)^{56}Co$ $\langle\sigma\rangle(10^{-42} cm^2)$	$^{208}Pb(\nu_e, e^-)^{208}Bi$ $\langle\sigma\rangle(10^{-42} cm^2)$
SM($0\hbar\omega$ ×0.64) [56]	10.8		
TM [59]		214	
TDA(SKIII) [60]			2954,3204
RPA [58]	14.55	277	2643
CRPA(WS+LM) [61]		240	3620
(Q)RPA(SIII,SGII)	16.90,17.20 [20]	352 [57]	4439 [23]
PN-RQRPA(DD-ME2)	13.18	140	2812
Exp.(KARMEN) [9, 61]		256±108±43	

will concentrate on Pb

from N. Paar, D. Vretenar, and T. Marketin, Physical Review **C77**, (2008) 024608 and references therein

Background expectations for COHERENT

Table 2. Results on the number of events at a neutrino experiment based at a spallation source facility. The events are calculated assuming $10^{15}\,\nu_e\ \mathrm{s}^{-1}$, in a year ($3 \times 10^7$ s), with a fully efficient 1 ton cubic detector. The columns correspond to the considered targets (first column), the rates at different distances d (meters) from the source, the material density (fourth column) and the flux-averaged cross sections in units $10^{-40}\ \mathrm{cm}^2$ (last column).

	10	20	50	ρ (g cm^{-3})	$\langle\sigma\rangle_{DAR}$
^{12}C (in $C_{16}H_{18}$)	1470	384	63	0.992	≈0.14 [1, 2]
^{16}O (in water)	998	261	43	1	0.131 [3]
^{40}Ar	8860	2310	380	1.43	2.56 [4]
^{56}Fe	9100	2330	377	7.87	3.53 [3]
^{100}Mo	17300	4420	716	10.28	11.95 [3]
^{208}Pb	34500	8820	1430	11.34	49.6 [3]
^{208}Pb + 1n	16350	4180	677		23.5 [5]
^{208}Pb + 2n	9420	2400	390		13.5 [5]

from R. Lazauskas, C. Volpe, J.Phys. **G37** (2010) 125101
and J.Phys. **G42** (2015) 059501

Background expectations for COHERENT

- NIN background constrained by measurement using Eljen EJ-301 liquid scintillator in shielding for CsI detector prior to CsI measurement
- found factor of 1.7 less than expected (from scaling previous slide)
- one worry had been (n,2n) reactions on Pb if NINs were sufficiently energetic (would have increased apparent NIN rate)
- (n,2n) threshold ~8 MeV

Expectations for NIN energy spectra

-42

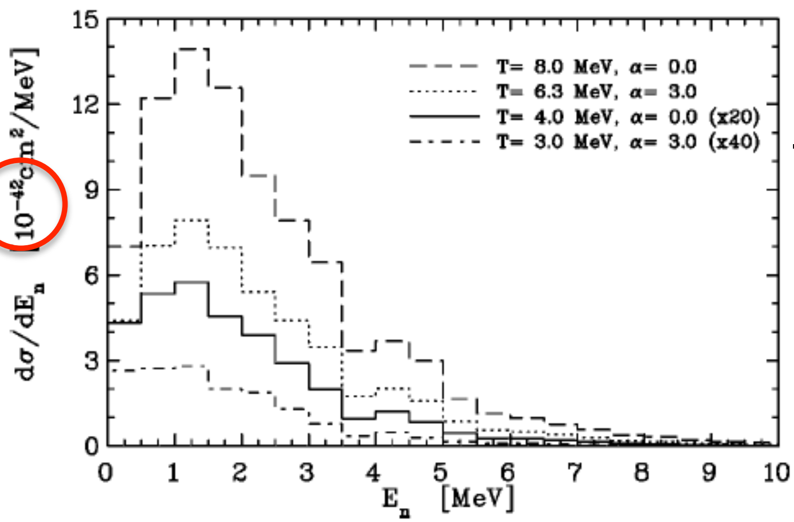


FIG. 4. Neutron energy spectrum produced by the charged-current (ν_e, e^-) reaction on ^{56}Fe. The calculation has been performed for different supernova neutrino spectra characterized by the parameters (T,α). Note that the cross sections for $(T,\alpha)=(4,0)$ and $(3,3)$ neutrinos have been scaled by factors 20 and 40, respectively.

-40

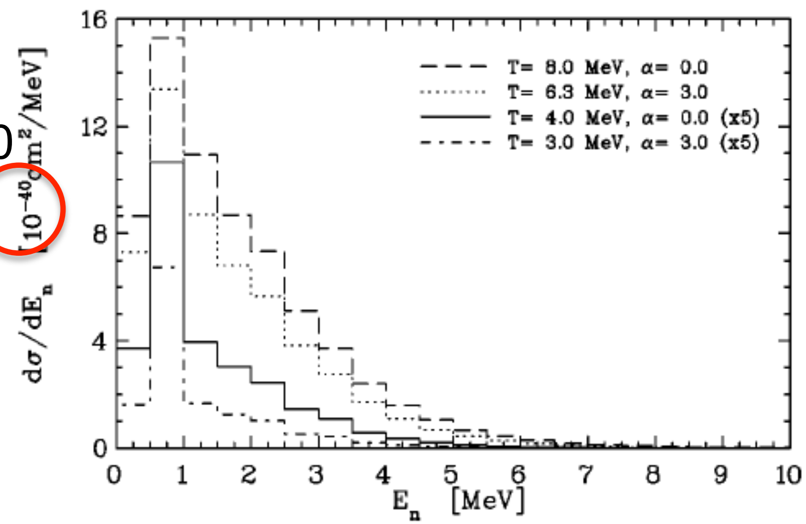
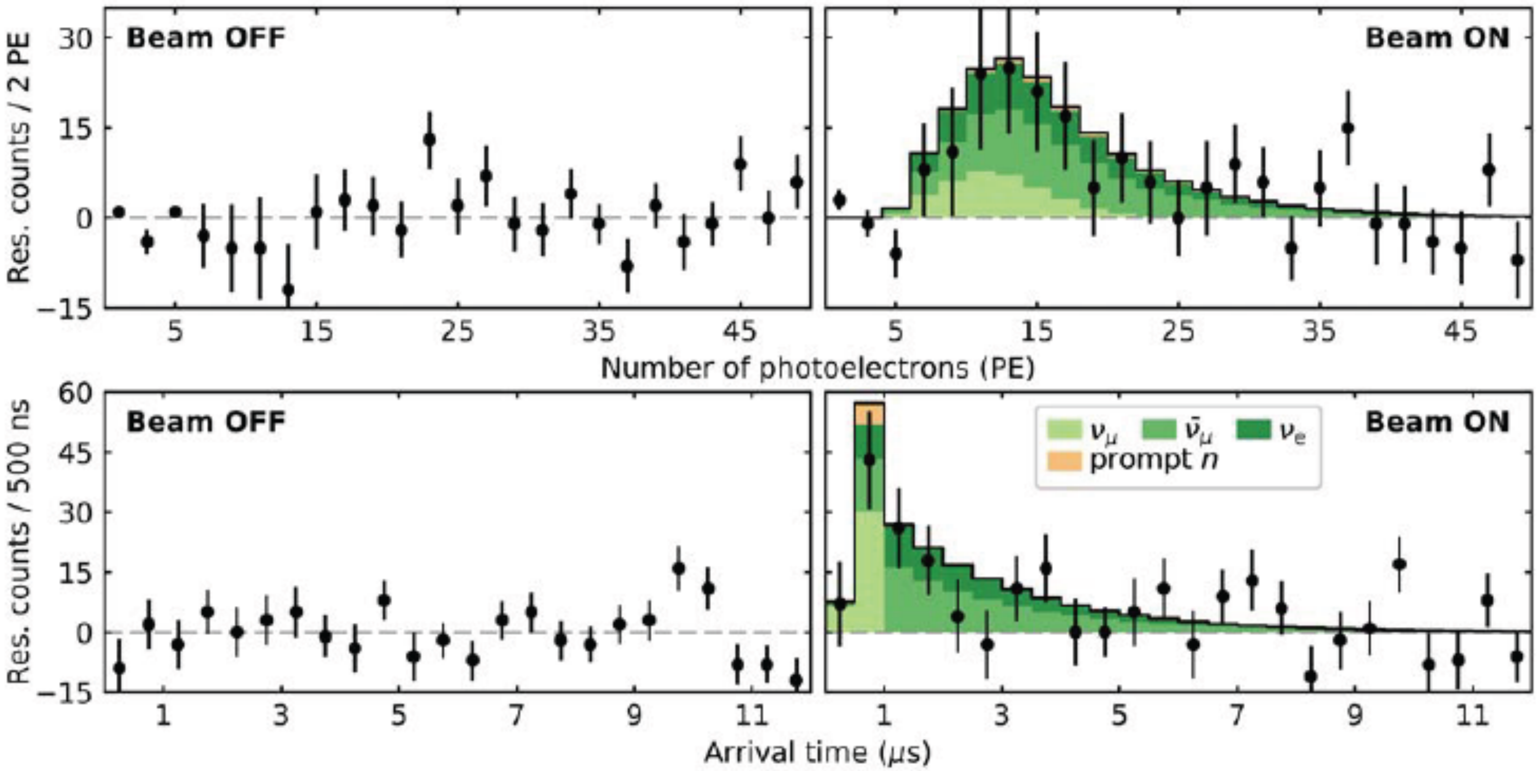


FIG. 6. Neutron energy spectrum produced by the charged-current (ν_e, e^-) reaction on ^{208}Pb. The calculation has been performed for different supernova neutrino spectra characterized by the parameters (T,α). Note that the cross sections for $(T,\alpha)=(4,0)$ and $(3,3)$ neutrinos have been scaled by a factor of 5.

from Kolbe, Langanke, Phys Rev **C63** (2001) 025802 for different SN fluxes

safe even for DAR fluxes? Possibly.

Background in COHERENT CsI measurement



~ negligible NIN background for CEνNS ("even smaller than prompt neutrons") but want an independent measure

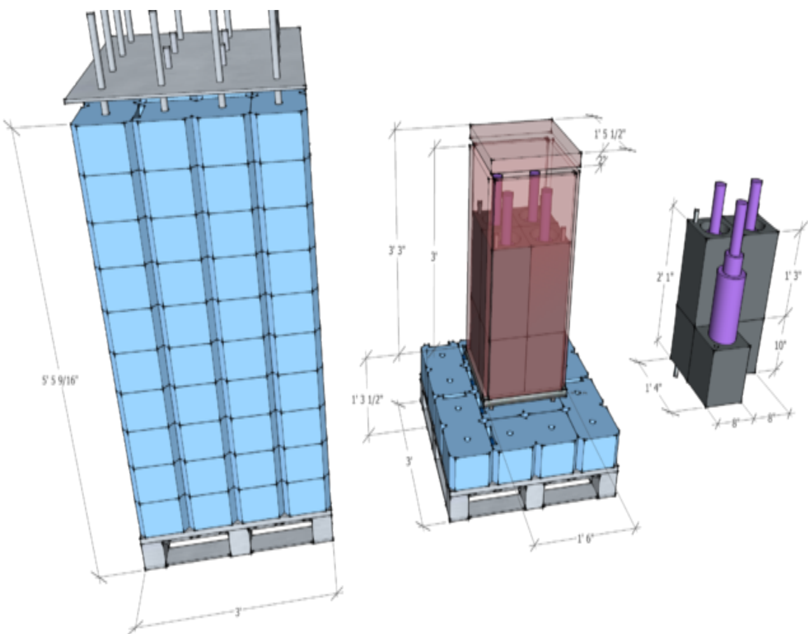
→ Neutrino Cubes (NUBES)

NIN’s MEASUREMENTS AT SNS

Mayra Cervantes / Sam Hedges (next 5 slides)

@ COHERENT we are interested in NINs mainly for background prediction, since neutrons produced in the Pb shielding represent a non steady-state background for CEvNS. We are also interested in the process itself given its importance in star nucleosynthesis and the high uncertainty in the cross section.

To measure them dedicated apparatus containing liquid-scintillator materials surrounded by Pb and more recently Fe have been deployed to SNS basement.



νECLIPSE

The three layers of the detector are shown:

- Neutron moderator: 9” of water in all sides.
- Muon Veto : Plastic scintillator panels.
- Detector : 4 Liquid Scintillator Cells and Pb.

Detectors require coincidence between beam and internal trigger. The coincidence window is 22.6 us and the total time recorded per waveform is 80 us.

NIN's SEARCH

Signal : Neutrons
Produced by the interaction of neutrinos with Pb

- Charged current interaction
  $^{208}Pb(\nu_e, e)^{208}Bi$ + neutrons.
- Neutral current scattering
  $^{208}Pb(\nu_x, \nu_x)$ + neutrons,
  $(\nu_x \rightarrow \nu_\mu, \bar{\nu}_\mu, \bar{\nu}_e)$

Background : Neutrons.
Mainly from:

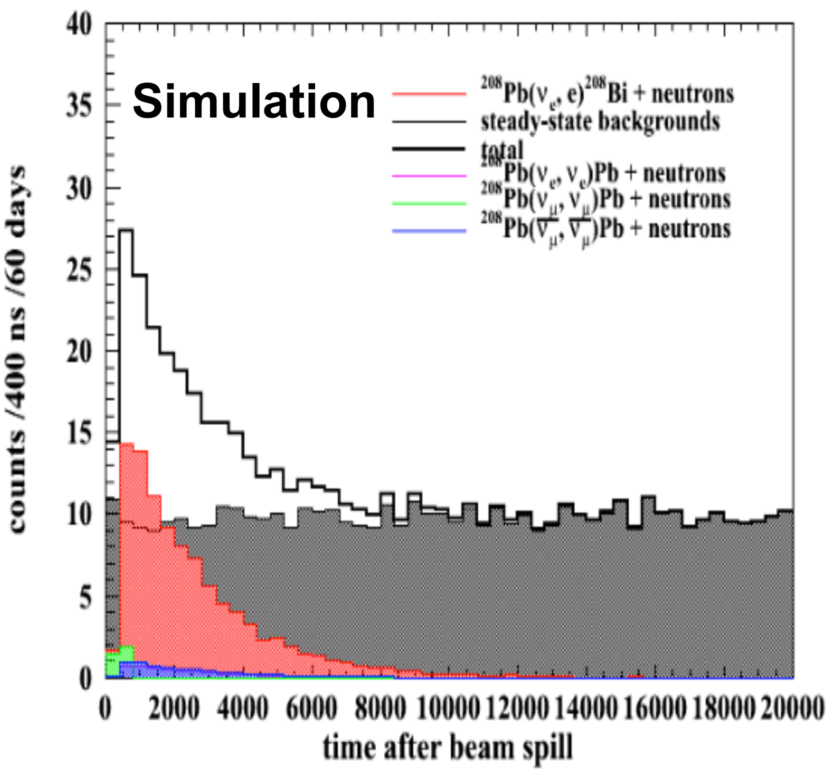
- Beam related neutrons
- Muon induced neutrons

To disentangle signal from background we use an additional piece of information: time elapsed between the neutron interaction in the detector and beam spill, since:

- The largest contribution to the signal comes from the charged current interaction that arrives *delayed* with respect to beam spill.
- The largest contribution to the background comes from beam related neutrons that arrive *prompt* with the beam spill.

NIN’s SEARCH

We expect to identify the signal looking “the time from beam spill” in particular we should see an excess over the background in the *delayed window*.



For this analysis the precise definition of “*prompt*” and “*delayed*” is crucial, but roughly:

- Prompt: 0-1000 ns after beam spill.
- Delayed: 1000-4000 ns after beam spill.

In this plot are shown the signal and backgrounds relevant in the delayed window. **Prompt neutrons are not shown.**

NIN'S MEASUREMENT AT SNS

- Pb Neutrino Cubes   (Pb Nube)
  - 2 ~2L liquid scintillator cells, 2 ~1.3L LS cells
  - ~1800lbs of Pb as a target
  - Deployed in 2015
- Fe Neutrino Cubes (Fe Nube)
  - 2 ~2L liquid scintillator cells, 2 ~1.3L LS cells
  - ~1350lbs of Fe as a target
  - Deployed in 2017

The data analysis of the Pb Nube and Fe Nube are ongoing, currently the main efforts are in:

- Calibration of energy scale with a dedicated set of measurements taken at TUNL
- Improvements in particle identification

FUTURE PROSPECTS

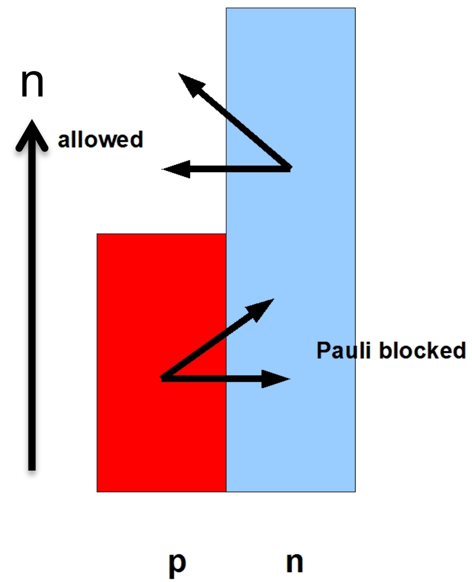
- Data collection ongoing
- Blank neutrino cube already deployed to SNS, ready for an additional target
- More 1.3L liquid scintillators, muon vetos available

Lead as a Supernova Neutrino Target

- CC and NC cross-sections are the largest of any reasonable material though thresholds are high
- Neutron excess (N > Z) Pauli blocks

$$\overline{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$$

- High Z increases ν_e CC cross-sections relative to $\overline{\nu}_e$ CC and NC due to Coulomb enhancement further suppressing the $\overline{\nu}_e$ CC channel
- Results in mainly ν_e sensitivity - complementary to water Cerenkov and liquid scintillator detectors
- de-excitation of nucleus following CC or NC interactions is by 1n or 2n emission



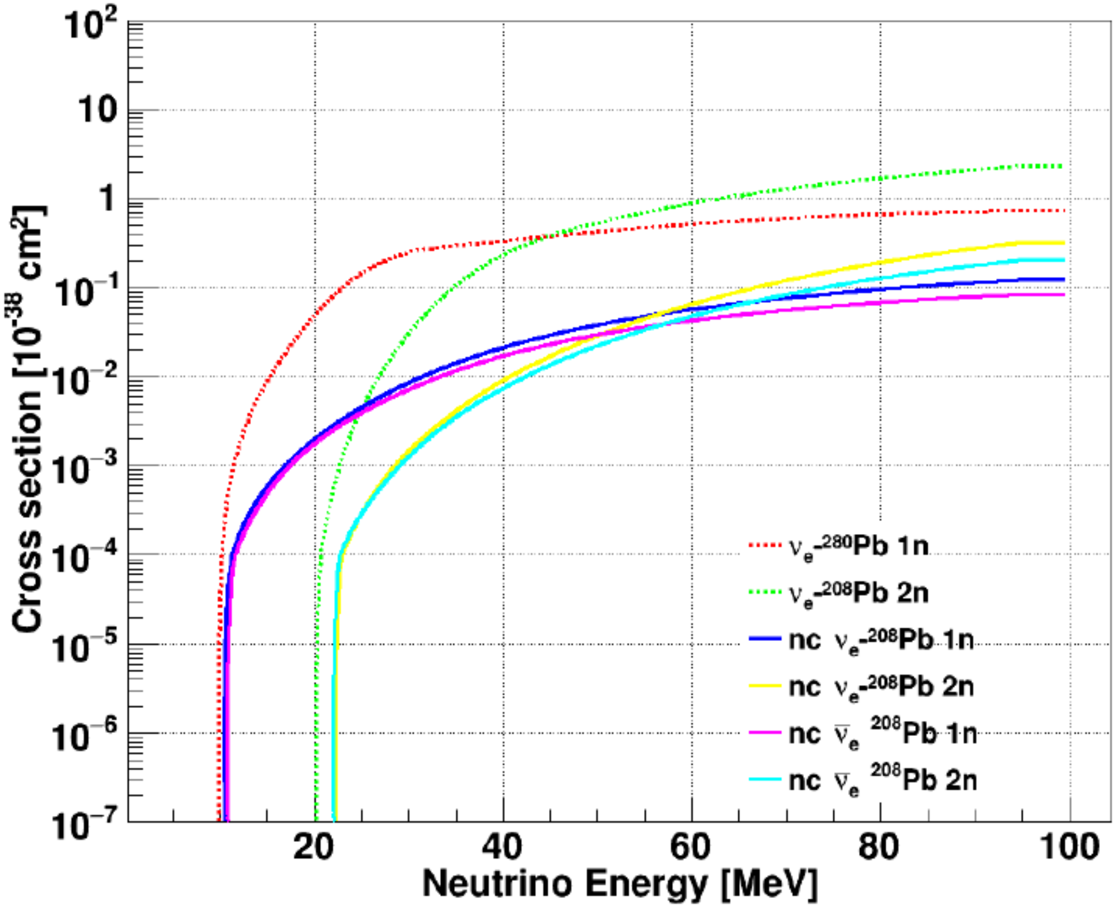
Other Advantages

- High Coulomb barrier → no (α, n)
- Low neutron absorption cross-section (one of the lowest in the table of the isotopes) → a "good" medium for moderating neutrons down to epithermal energies

Limitations

- no directionality
- no direct measure of neutrino energy

Comparative ν-Nuclear Cross Sections



K. Scholberg, Annu. Rev. Nucl. Part. Sci. 2012. 62:81–103.

CC:
$$\nu_e +^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$$
$$\nu_e +^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$

NC:
$$\nu_x +^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$
$$\nu_x +^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

Thresholds
CC 1n 10.7 MeV
CC 2n 18.6 MeV
NC 1n 7.4 MeV
NC 2n 14.4 MeV

In SNOwGLoBES -
Pb cross sections from Phys. Rev. D67, 013005 (2003)

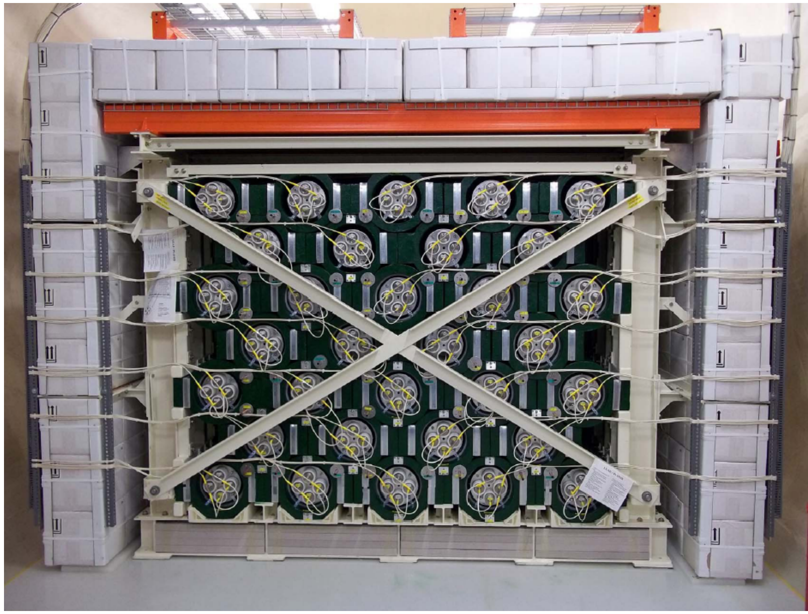
HALO - a Helium and Lead Observatory

A “SN detector of opportunity” / An evolution of LAND – the Lead Astronomical Neutrino Detector, C.K. Hargrove et al., Astropart. Phys. 5 183, 1996.

“Helium” – because of the availability of the ^{3}He neutron detectors from the final phase of SNO

\+

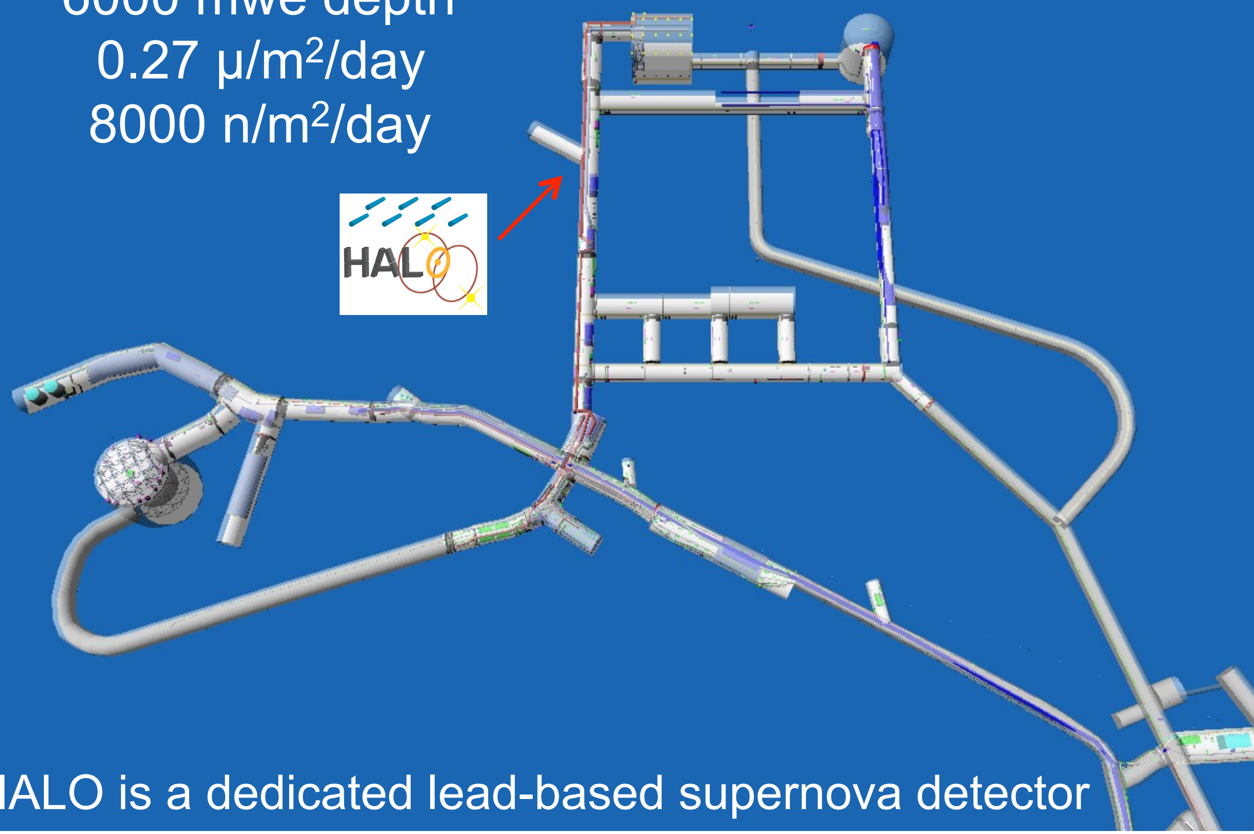
“Lead” – because of high ν-Pb cross-sections, low n-capture cross-sections, complementary sensitivity to water Cerenkov and liquid scintillator SN detectors



HALO is using lead blocks from a decommissioned cosmic ray monitoring station

HALO at SNOLAB

SNOLAB 6800’ campus
6000 mwe depth
0.27 μ/m²/day
8000 n/m²/day



HALO is a dedicated lead-based supernova detector

The HALO Collaboration

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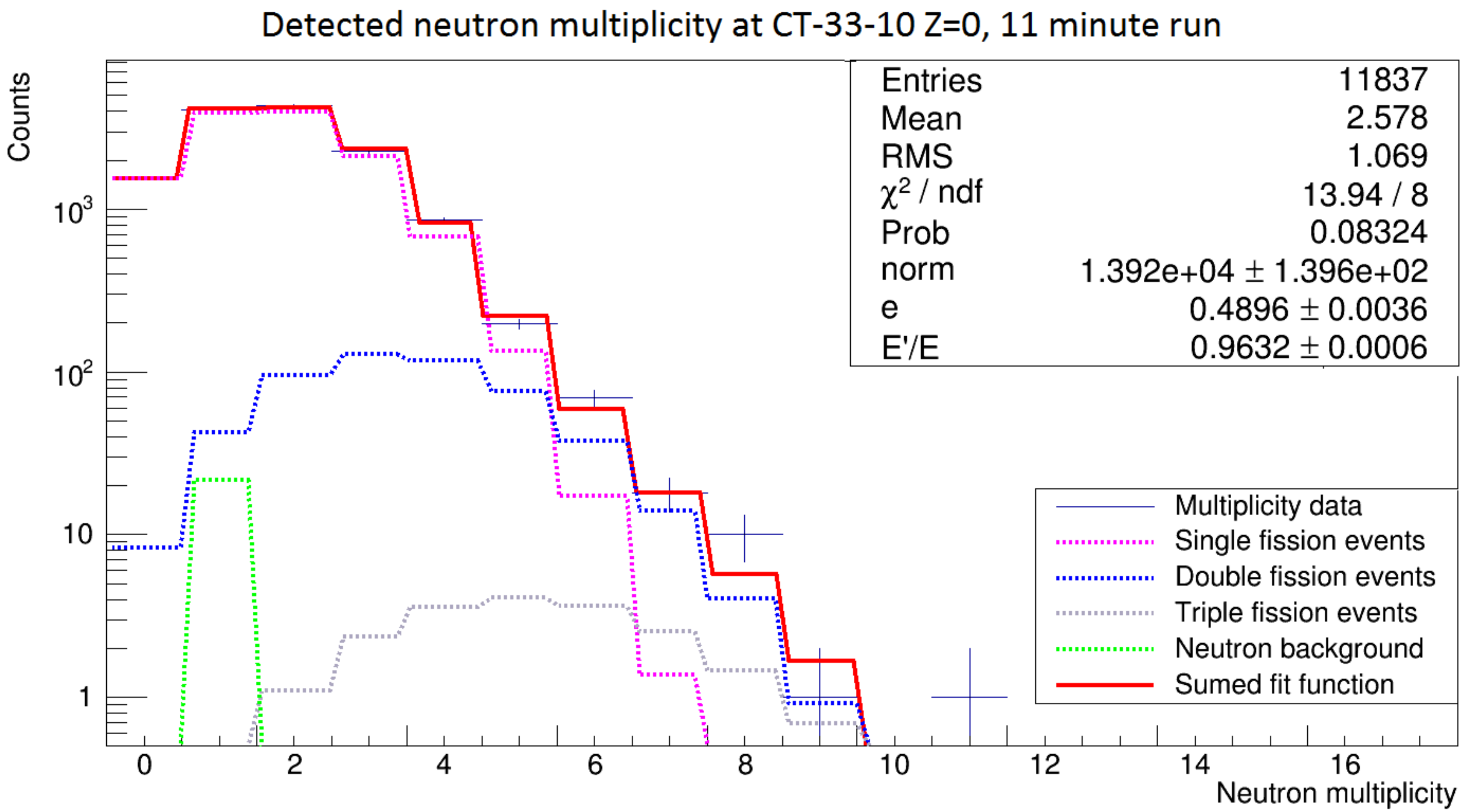
Funded by: NSERC CRSNG, NSF

halo.snolab.ca

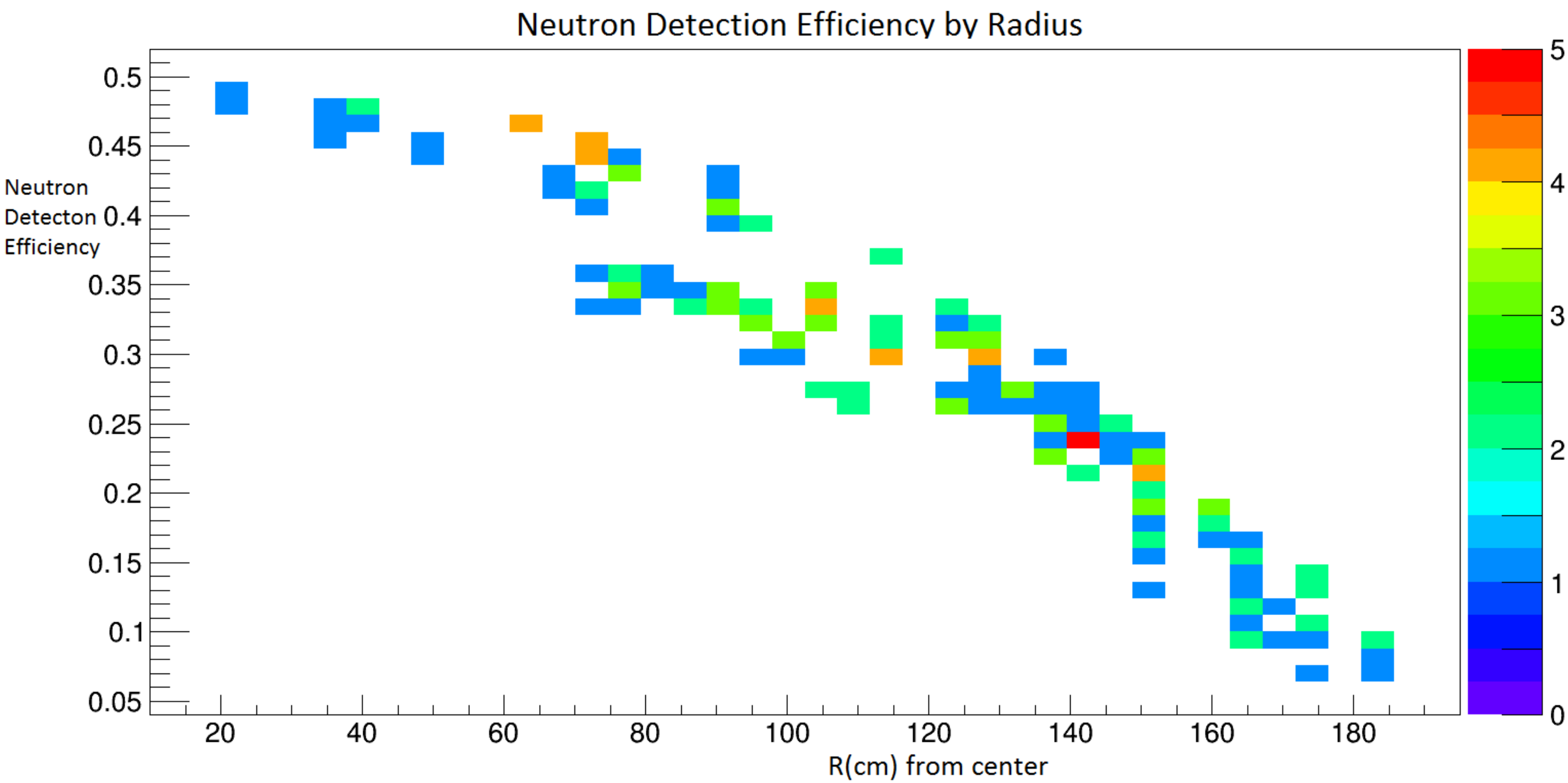
^{252}Cf Calibration of HALO

- with very low backgrounds were able to measure the detected SF neutron multiplicity distribution which is a strong function of the neutron capture efficiency
- used a low activity (~20 SF/s) ^{252}Cf source
- fitting simultaneously gives both the efficiency at a point and the source strength
- rely on Monte Carlo simulation to extrapolate from 192 discreet calibration points to a volume-averaged efficiency for distributed supernova neutrino neutron production

^{252}Cf Calibration of HALO



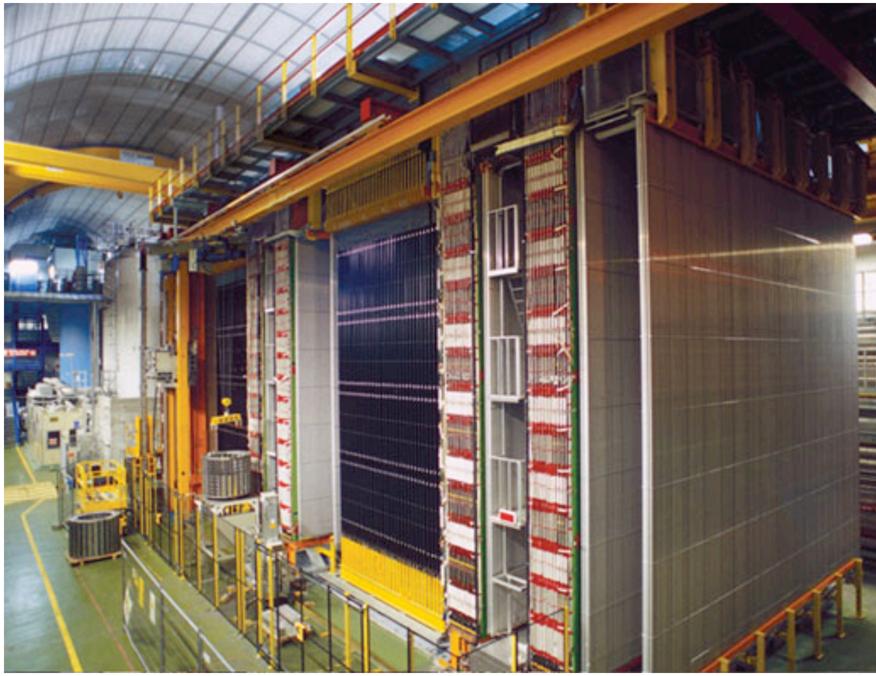
Neutron Capture Efficiency



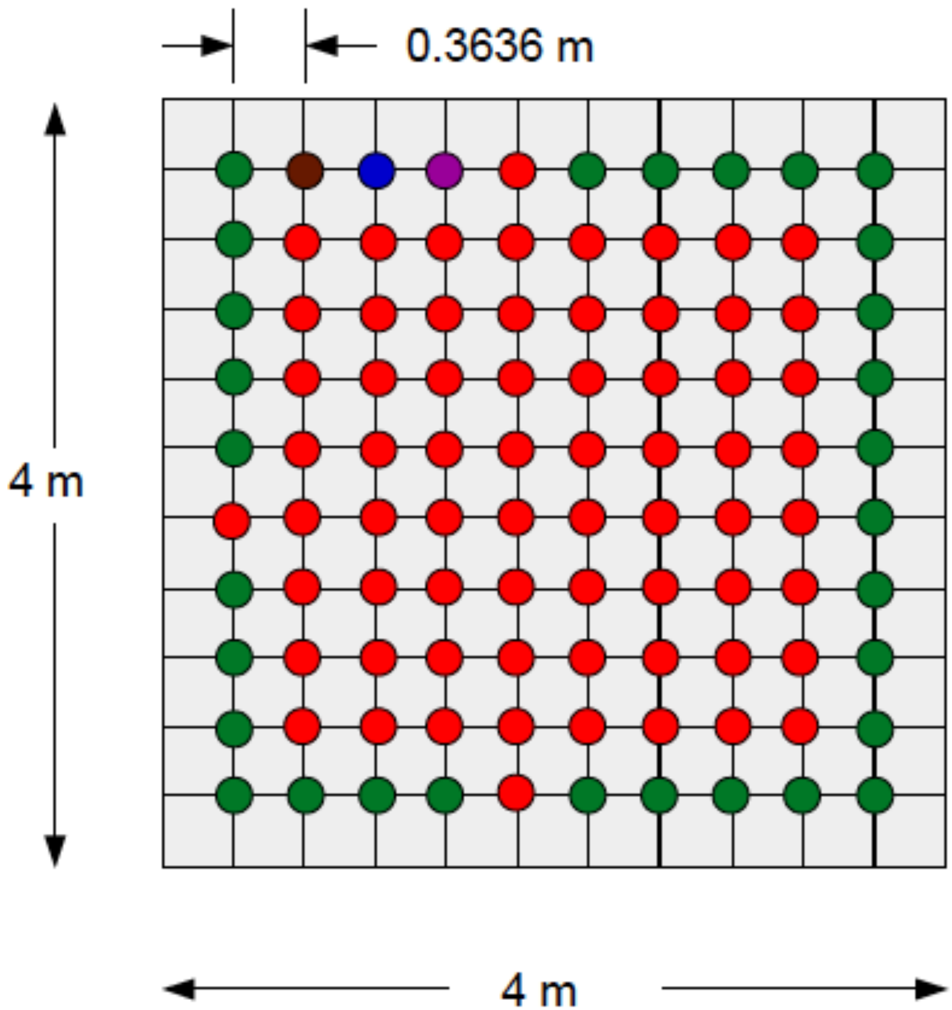
A New Opportunity…

The OPERA experiment at LNGS has been decommissioned making available ~ 1kT of lead for new experiments

- a formal expression of interest was submitted to the April 2017 meeting of the Gran Sasso SC
- Stefano Ragazzi (Director, LNGS) has committed that the lead will remain available as long as a proposal is in the pipeline and encouraged us to proceed
- next step October 2017 LNGS SC.



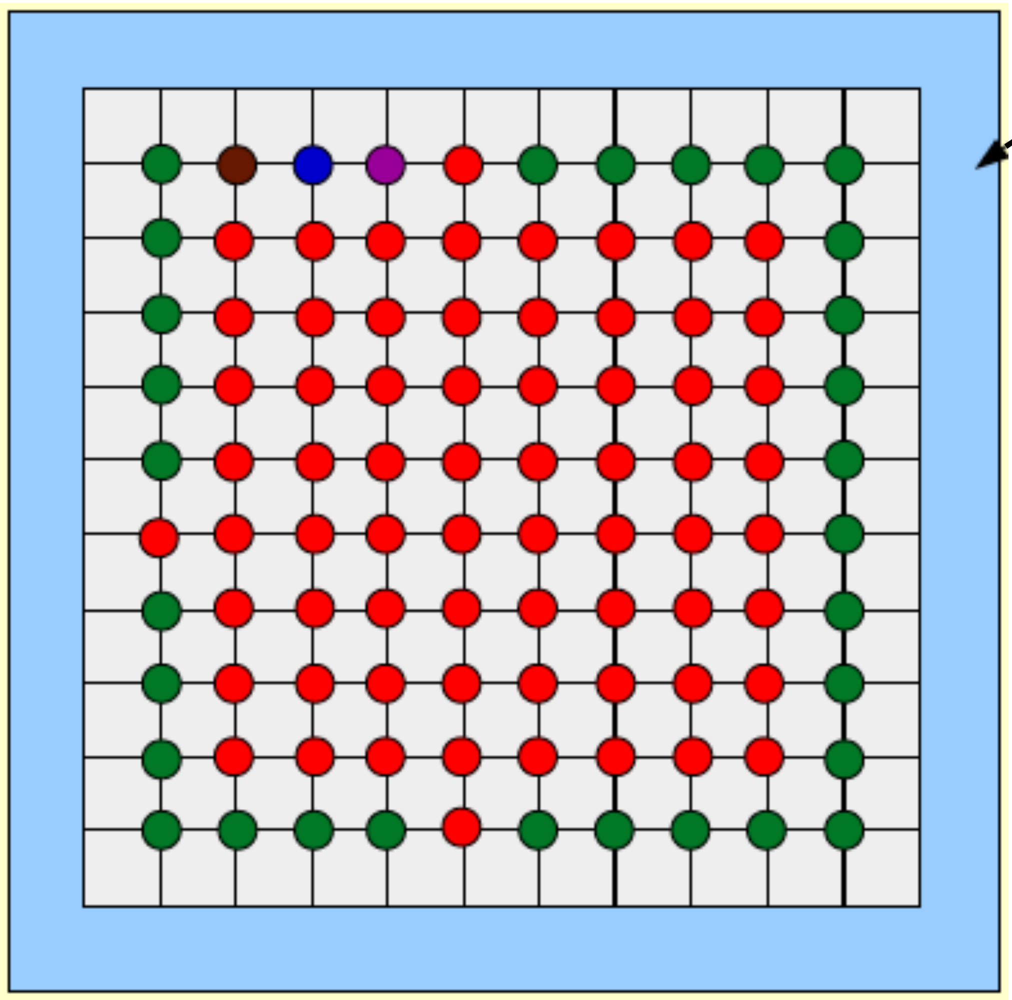
HALO-1kT at LNGS



Rough status of MC studies

- distribute all up to ~4 km of ^{3}He detectors in a 4m x 4m x 5.5m volume of Pb
- simulate MeV neutrons in Pb
- find up to 55% of neutrons captured on He-3 with 10,000 litres of He-3
- recall neutron capture efficiency in HALO is ~28%; so gain factor of 12 in Pb mass; plus near doubling of efficiency

HALO-1kT at LNGS



Possible water (and graphite) layer as reflector

- for HALO (smaller volume; larger surface/volume ratio) this had significant benefits
- for HALO-1kT adding graphite causes capture on Pb to increase; detection on ^{3}He ~unchanged
- water and / or graphite needed as part of the design, in any case, to isolate from environmental neutrons and to define target volume

HALO-1kT at LNGS

- substantial quantity of He-3 key to eventual success
- fortunately the ^{3}He US stockpile crisis was declared over mid-2016
- detailed simulations with increasingly realistic ^{3}He progressing

  (for the moment assuming a constraint of 10,000 litre.atm)
- backgrounds in the SNO ^{3}He counters are lower than required for setting a low threshold SN trigger, we do not need detectors this background-free but commercially available detectors have ~x10 higher backgrounds than tolerable
- currently working with ^{3}He counter suppliers to develop lower background commercial counters
- still in the “fun” conceptual design phase

Thank you