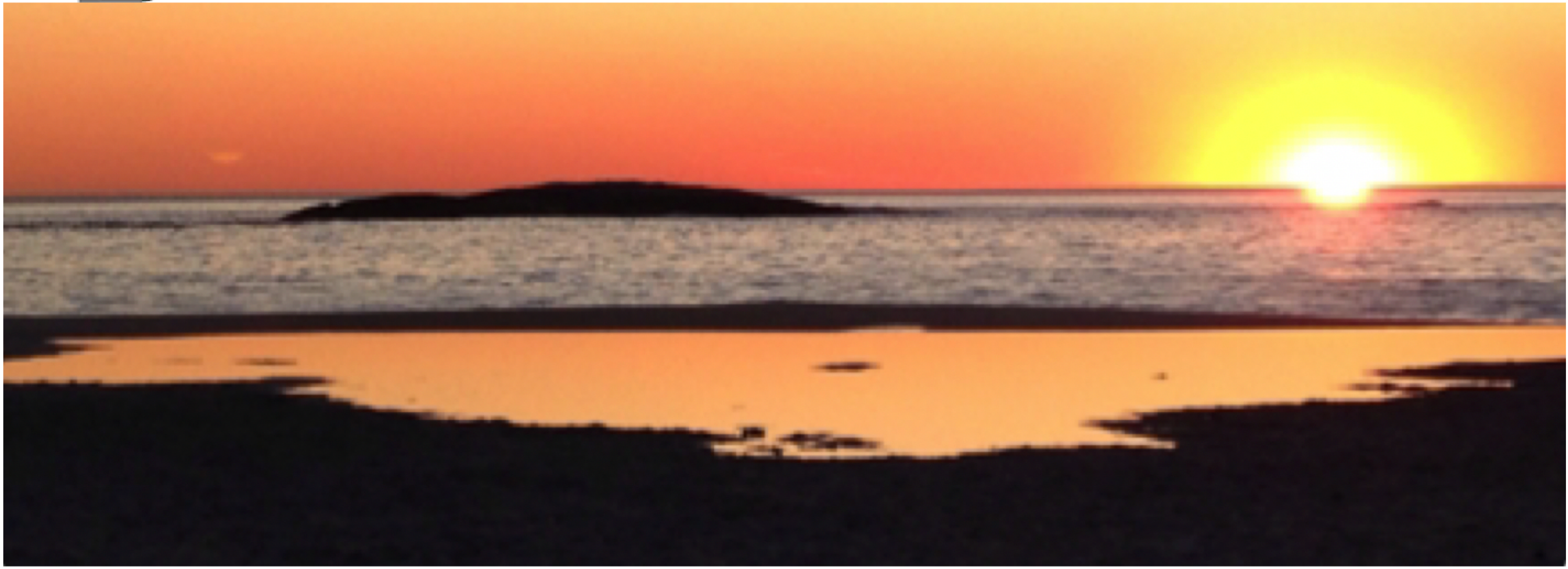
HALO-1kT
- status and design

C.J. Virtue for the Collaboration



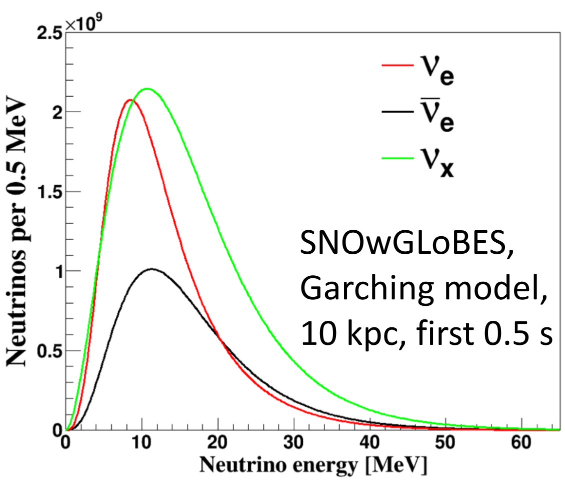
Laurentian University
Université Laurentienne

HALO-1kT

- HALO-1kT is a supernova neutrino detector proposed for LNGS
- Like its predecessor / proto-type HALO at SNOLAB, HALO-1kT is a “detector of opportunity”
- It is a “lead-based” neutrino detector aimed at filling a niche by being:
  - highly reliable, robust
  - Simple, responsive / fast
  - low maintenance, long operating life
- AND by having different neutrino flavour sensitivity than other SN detectors, HALO-1kT would add complementary data to the global data from the next galactic supernova

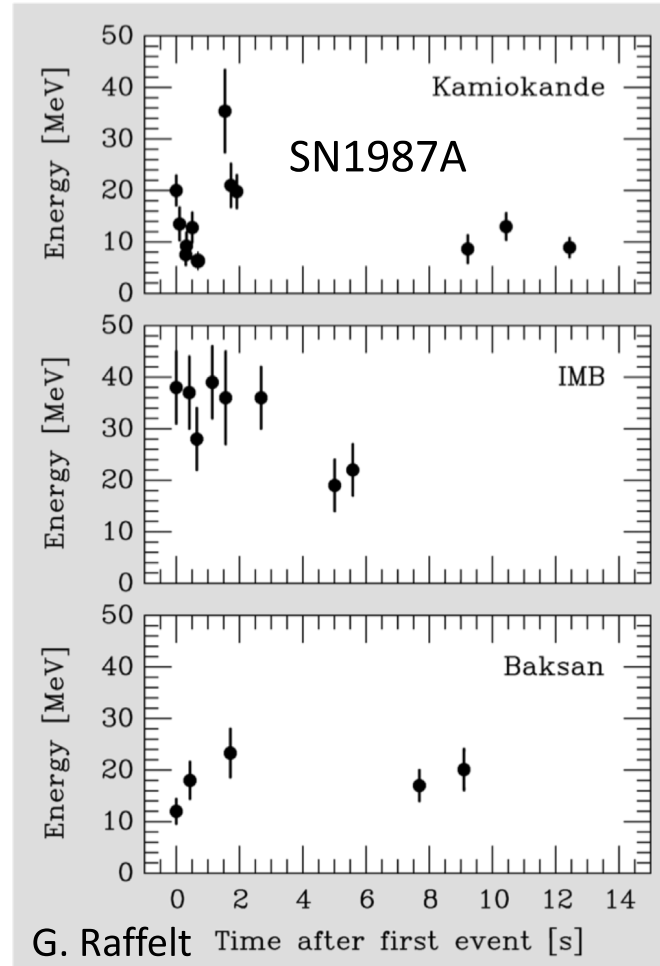
Supernova Neutrinos

- our only window into core-collapse supernovae (CCSNe) dynamics
- also a CCSN is the only place where:
  - matter is opaque to neutrinos and they thermalize yielding information about the proto-neutron star environment
  - neutrino density is so large that they interact through collective phenomena resulting in spectral splits and flavour swapping
  - the low temperature, high density part of the QCD phase diagram can be explored where there are predictions of nuclear matter → quark matter phase transitions

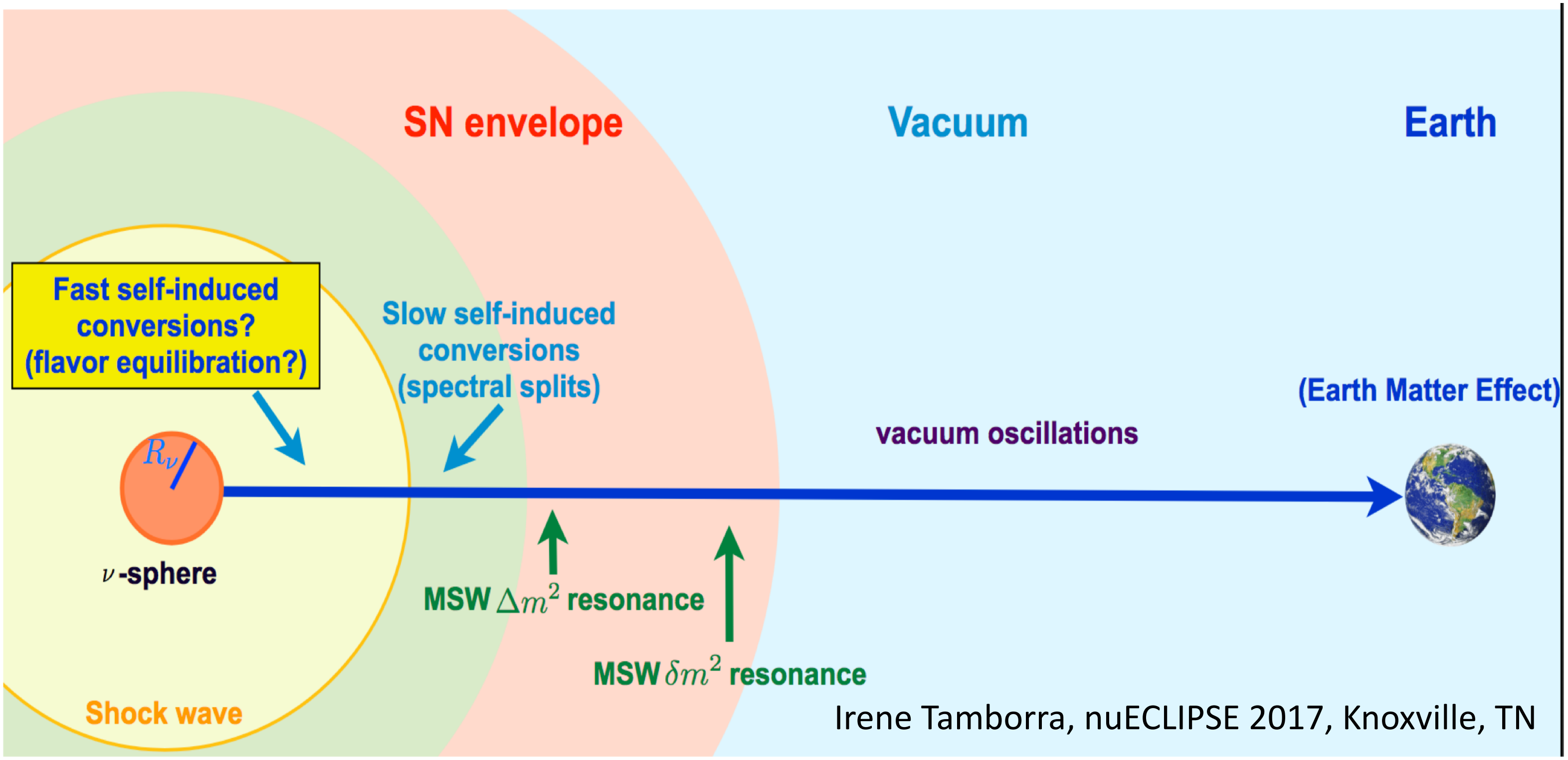


- we start with Fermi-Dirac distributions at the neutrino-spheres with:

  $T(\nu_e) < T(\bar{\nu}_e) < T(\nu_x)$
- this signal is imprinted with:
  - collective effects
  - MSW effects
  - shockwave effects
  - large scale density oscillations
  - vacuum oscillations

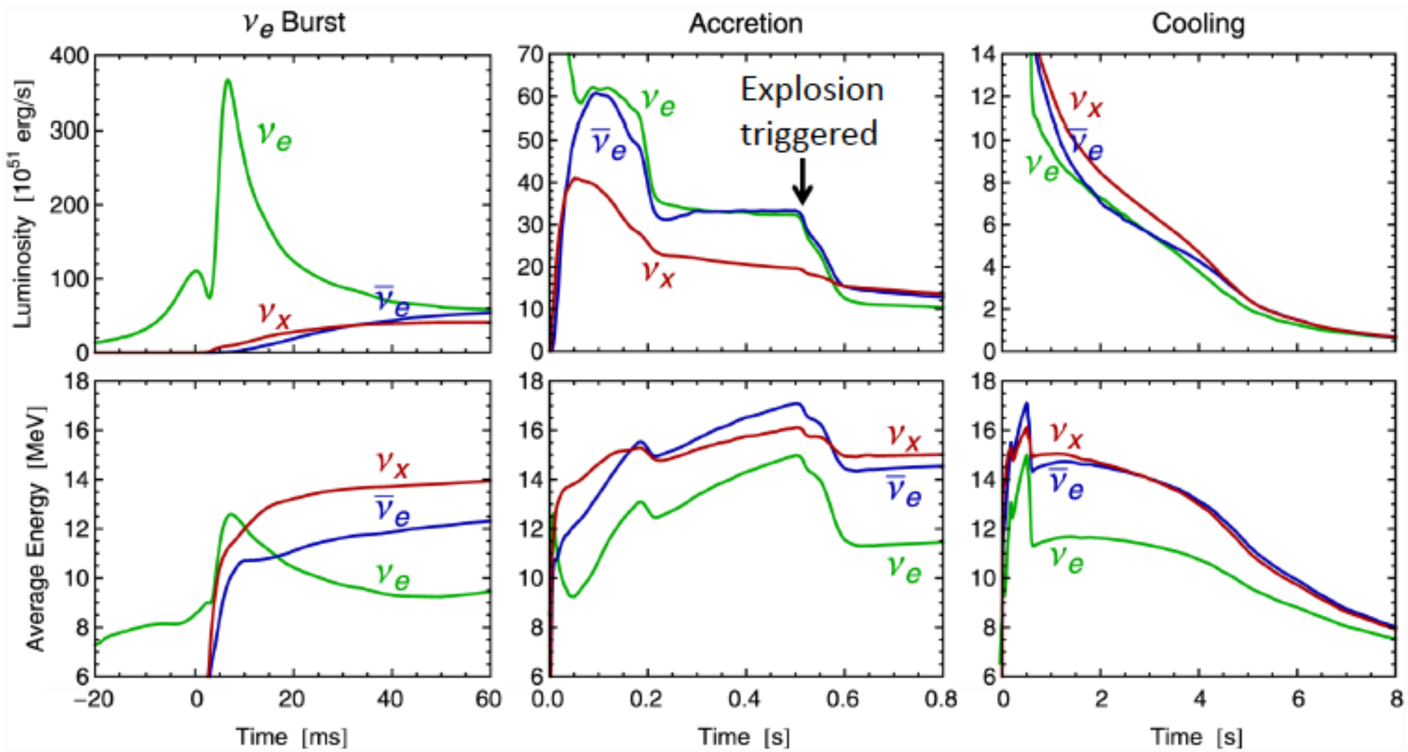


Simplified Picture of Flavour Conversions



- neutrino emission source at ν-sphere evolves with time
- large-scale hydrodynamic effects (instabilities, ringing, dipole oscillations) affect neutrino signal
- then any given detector terrestrial detector imperfectly records part of the signal
- what can any one detector do when the signal is spread across ν_e , $\overline{\nu}_e$, ν_x and the time evolution of their flux and energy spectra with marginal statistics?!

Three Phases of Neutrino Emission



- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Georg Raffelt, MPI Physics, Munich — NOW 2014, 7–14 Sept 2014, Otranto, Italy

The Trouble with Supernovae

Oct. 13, 2016

Hubble Reveals Observable Universe Contains 10 Times More Galaxies Than Previously Thought

- SNe are very frequent in our universe (1→10? per second)
- Current and next generation terrestrial supernova neutrino detectors only see supernovae within our galaxy (tiny part of the universe)
- So.... The galactic core-collapse supernova rate is estimated, Adams et al., ApJ, **778**, 2, 164, (2013), at

$$3.2^{+7.6}_{-2.6} \text{ per century}$$

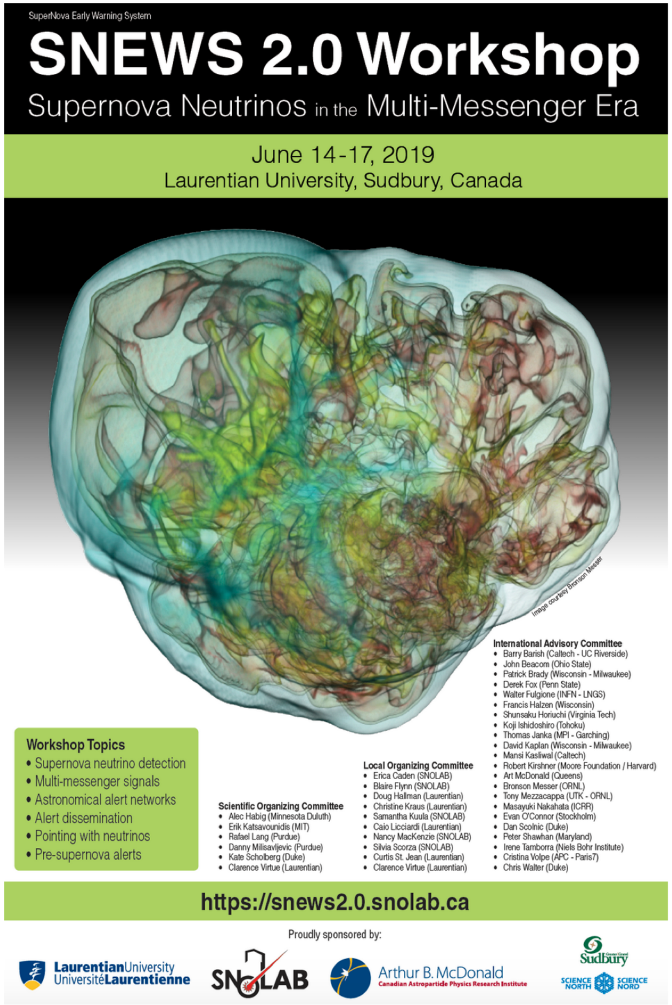
so… observing the neutrino signal requires some patience

SNEWS

- Rarity of galactic SNe is all the more reason to make every effort to maximize the scientific opportunity....

NSF WoU-MMA: Collaborative Research: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy (Purdue, Duke, Houston, Laurentian, Minnesota, MIT, Rochester, Virginia Tech)

- i.e. SNEWS 2.0 ... funded in 2019 to:
  - Invigorate the network
  - Add dark matter detectors
  - Better integration into MMA world
  - More low-probability alerts
  - Triangulation
  - Alert drills



ν - Lead Interactions

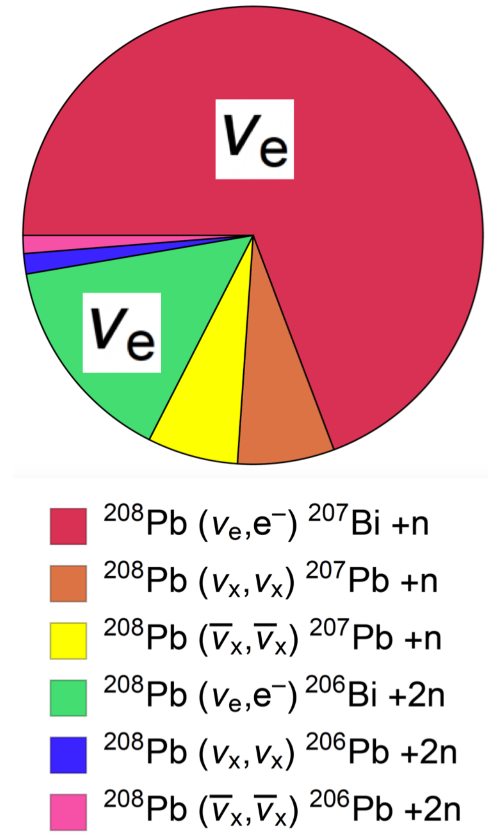
- HALO-1kT is essentially a shielded volume of lead instrumented with ^{3}He neutron detectors
- The following reactions can occur for neutrinos of supernova energies

$$
\begin{aligned}
\mathrm{CC:}\quad & \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 9.8\,\mathrm{MeV} \\
& \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 17.9\,\mathrm{MeV} \\
\mathrm{NC:}\quad & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV} \\
& \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}
\end{aligned}
$$

- electrons carry energy information and could be used to tag CC reactions, however
  - requires lead in solution – was explored and abandoned, or
  - requires fine-grained lead-scintillator – also abandoned
  - so no CC tagging or energy measurement
- neutrons detected through capture on ^{3}He after thermalization (200 μs)
  - no energy measurement, though some sensitivity through 2n / 1n ratio
  - no direction measurement
  - only counting as a function of time, single (1n) and double (2n) events

HALO-1kT Flavour Sensitivity

- the nuclear physics of lead strongly affects the interaction rates
  - the neutron excess in Pb Pauli blocks $\bar{\nu}_e$ CC reactions
  - the high Z further Coulomb suppresses $\bar{\nu}_e$ CC and enhances ν_e CC
- the response remains an unresolved mixture of ν_e CC and ν_x NC but is largely orthogonal to $\bar{\nu}_e$ CC (IBD) sensitivity of LS and WC detectors
- part of the merit of a lead-based supernova detector rests on its complementary flavour sensitivity wrt other SN detectors and the power it brings to joint analyses



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HALO-1kT Flavour Sensitivity

- For reference... the set of detectors currently participating in SNEWS are – Super-Kamiokande, LVD, Borexino, IceCube, KamLAND, Daya Bay, HALO
- with exception of HALO all are Liquid Scintillator (LS) or Water Cherenkov (WC) and are dominantly sensitive to the $\overline{\nu}_e$ flux through IBD
- lead-based SN detectors are $\overline{\nu}_e$ - blind, i.e. complementary

Available Cross Sections for Lead

	Lead isotopes			Cross sec.		CC/NC			
	204	206	208	1n, 2n	total	ν_e	$\bar{\nu}_e$	ν	$\bar{\nu}$
Kolbe	✗	✗	✓	✗	✓	✓	✗	✓	✗
Engel	✗	✗	✓	✓	✓	✓	✗	✓	✓
Lazauskas	✗	✗	✓	✗	✓	✓	✓	✗	✗
Almosly	✓	✓	✓	✗	✓	✓	✓	✓	✓

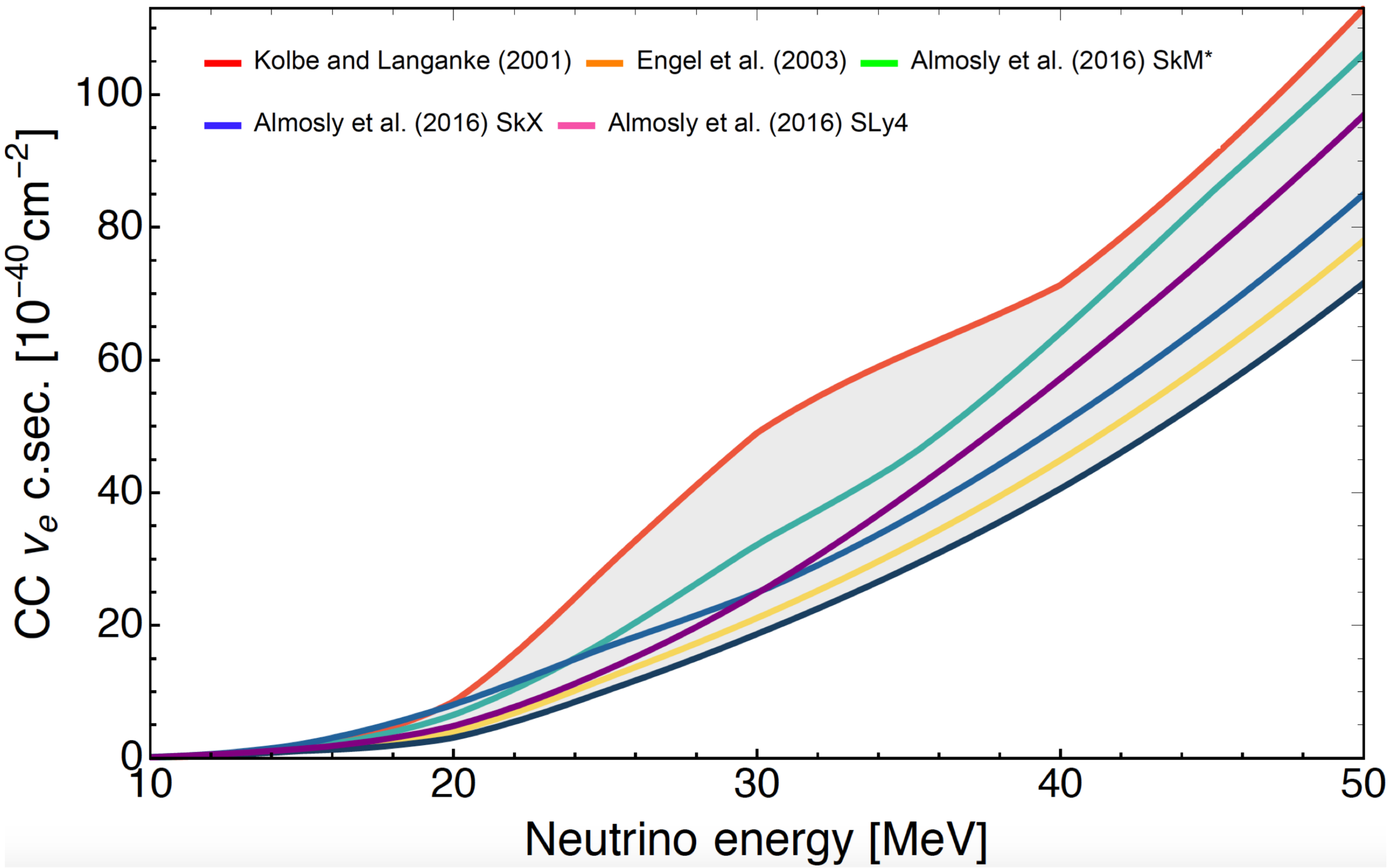
E. Kolbe, K. Langanke, Phys. Rev. C63 (2001).

J. Engel, G.C. McLaughlin, C. Volpe, Phys. Rev. D67 (2003).

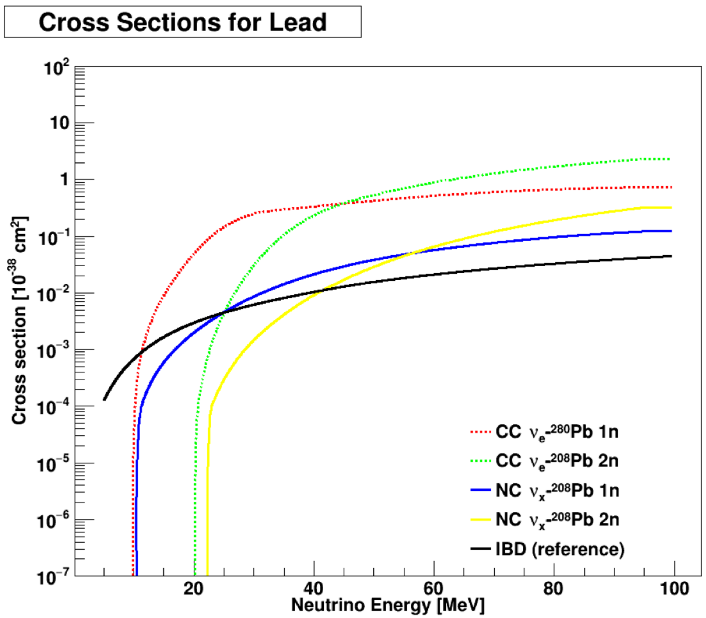
R. Lazauskas, C. Volpe, Nucl. Phys. A792 (2007).

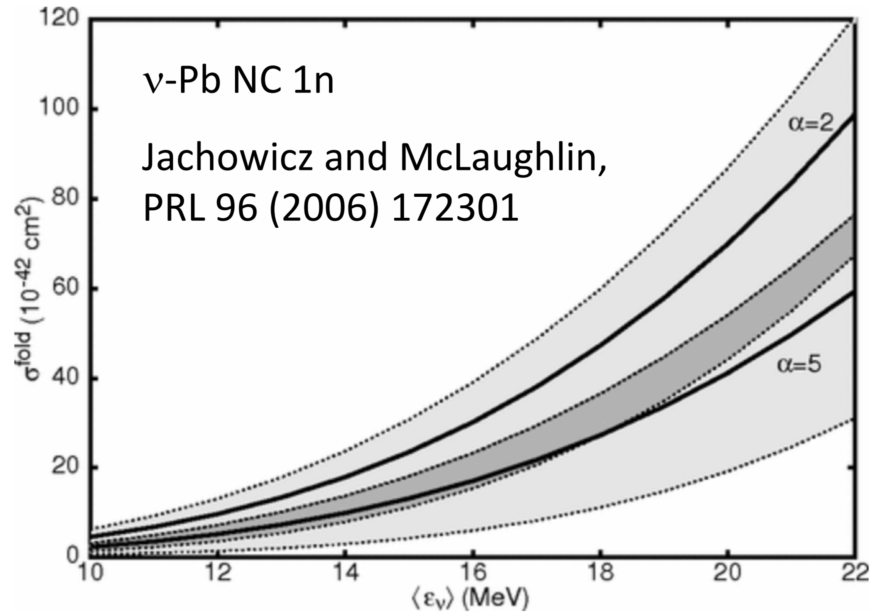
W. Almosly et al., Phys. Rev. C94 (2016) no.4 and Phys. Rev. C99 (2019) no.5.

Variation in CC ν_e Cross Sections



ν-Pb Cross Sections and Uncertainties





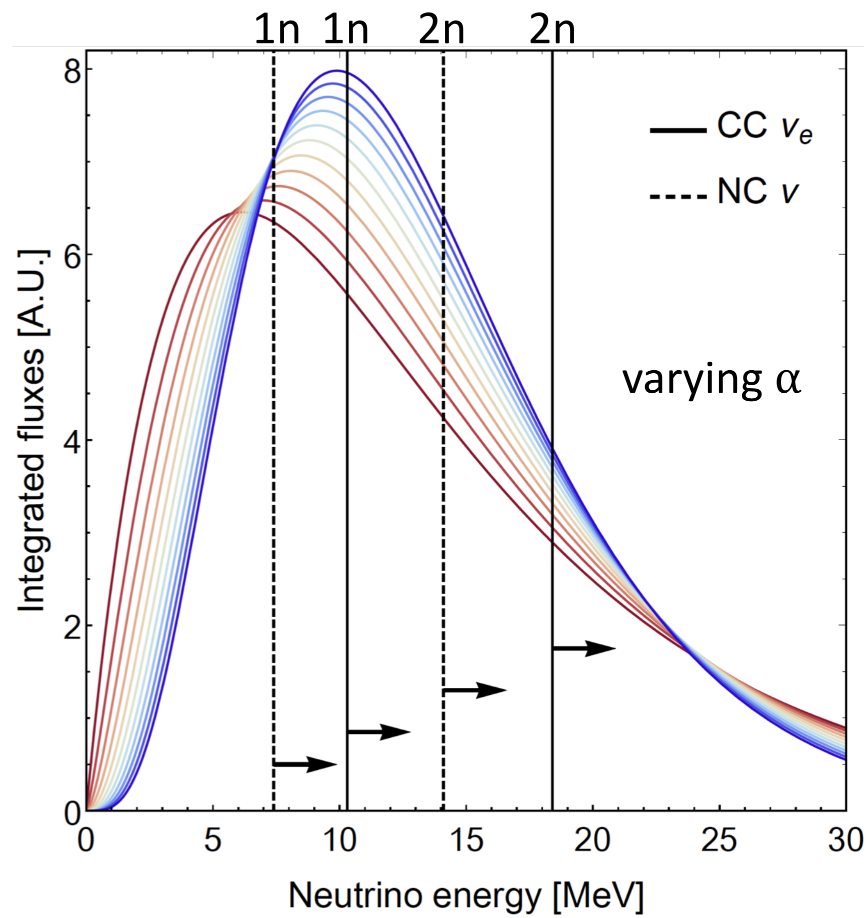
SNOwGLoBES -
ν-Pb cross sections from Engel, McLaughlin, Volpe, PRD 67 (2003) 013005

- unmeasured, calculated only
- thresholds known
- less theoretical uncertainty near threshold
- more uncertainty away from threshold

Flux-averaged ("folded") cross sections as a function of <E_ν> for power law spectra and different α showing the theoretical uncertainty in response

Exploitable Cross Section Features

- Multiple thresholds
- 1n, 2n
- Sensitivity to ν_e and ν_x
- Strong sensitivity to average energies through rates and 2n/1n ratio
- Plausible sensitivity to pinching parameter, α
- Plus complementary flavour sensitivity to other detectors



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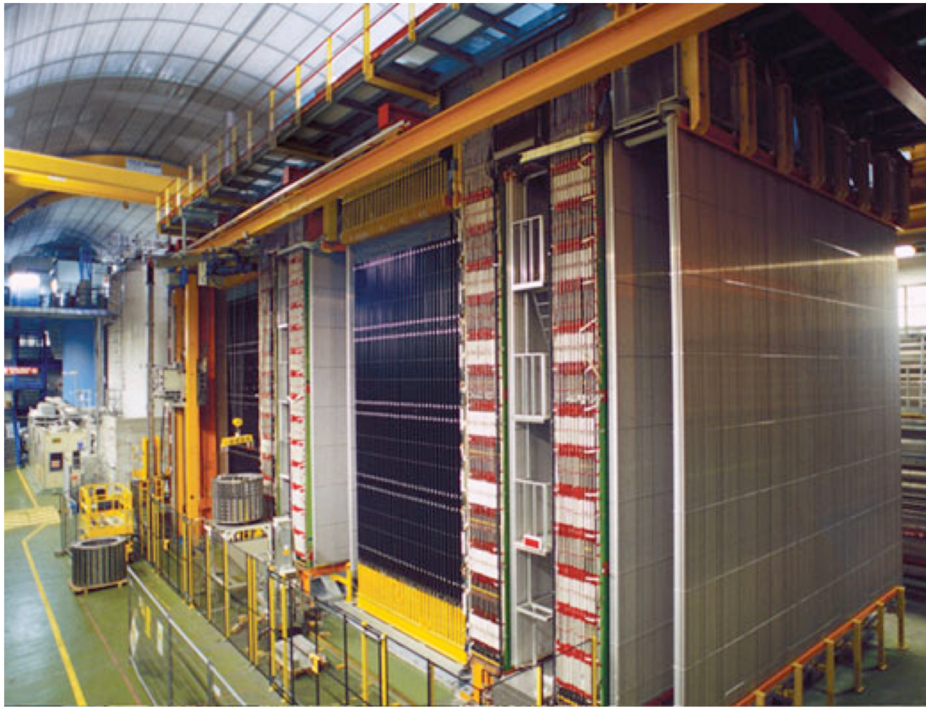
HALO-1kT at LNGS

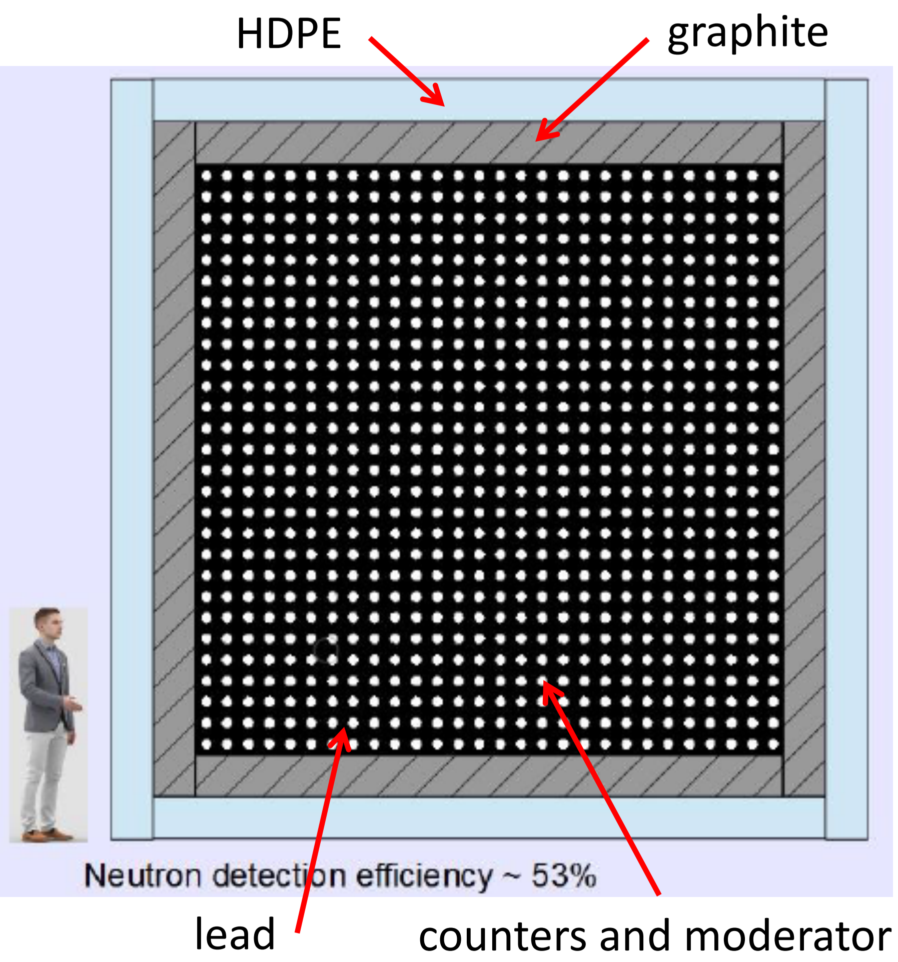
- scale up HALO keeping many design principles
- apply lessons learnt to make improvements
  - increase mass 79 → 1000 (factor of 12.7)
  - increase efficiency 28% to >50% (factor > 1.8)
- ~23 fold-increase in event statistics over HALO



The decommissioning of OPERA has made available 1300 tonnes of Pb

HALO-1kT Base Design

- lead core 4.33 x 4.33 x 5.5 m^3 with 28 x 28 x 5.5 m array of ^3He neutron counters at 1.16 atm pressure
- 8 mm thick PS moderator
- up to 30 cm graphite reflector
- up to 30 cm HDPE shielding
- reflector and shielding require further optimization once we have conceptual mechanical design for superstructure
- Control of background in neutron counters
  - Only significant technical question



Simulation Studies

- constrain to 10,000 litre.atmospheres of ^{3}He; 1000 tonnes of lead; 5.5 m depth of lead volume
- explore various geometrical effects
  - overall shape
  - number of detectors (^{3}He pressure varies inversely)
  - proportional tube wall materials / thicknesses
  - moderator materials / thicknesses
  - presence / absence / thickness / composition of reflector layer
  - thickness of HDPE shielding
  - More
- Achieve 50-55% neutron capture efficiency for range of parameters

What is to be Learnt?

- Astrophysics
  - Explosion mechanism
  - Accretion process
  - Black hole formation (cutoff)
  - Presence of Spherical accretion shock instabilities (3D effect)
  - Proto-neutron star EOS
  - Microphysics and neutrino transport (neutrino temperatures and pinch parameters)
  - Nucleosynthesis of heavy elements
- Particle Physics
  - Normal or Inverted neutrino mass hierarchy
  - Presence of axions, exotic physics, or extra large dimensions (cooling rate)
  - Etc.

Accessible Measurements

It is our premise that $\overline{\nu}_e$ sensitivity alone can not address all topics of interest and that data from HALO-1kT, with its complementary sensitivity, could be key. From our Letter of Intent such topics include:

- Observation of the ν_e burst from the initial 20 ms long neutronization phase would be a signal of an inverted neutrino mass hierarchy due to the non-zero ν_e MSW survival probability of $\sin^2\theta_{12} \sim 0.3$. Non-observation of the ν_e burst implies a normal mass hierarchy, as the ν_e survival probability is zero in this case. Wallace, J., Burrows, A. and Dolence, J.C., Astrophys. J. **817** (2016) no.2, 182.
- Observation of an anomalously hot ν_e spectrum compared to $\nu_{\mu\tau}$ would be an indication of flavour-swapping and collective ν-ν effects at small radii in the supernova core. Duan, H, et al. , Ann. Rev. Nucl. Part. Sci. 2010.60:569, Fogli, G. et al., J. Cosmology & Astroparticle Physics **12** (2007) 010

Accessible Measurements - 2

- Observation of a non-thermal neutrino spectrum or an anomalously large number of high-energy neutrinos would be an indication of the failure to trap and thermalize neutrinos in the supernova core (anomalously weak ν-nucleus interactions). Raffelt, G., Nucl. Phys. B (Proc. Suppl.) **221** (2011) 218
- Observation of the ratio of ν_e / anti-ν_e fluxes sets a constraint on the neutron flux available for r-process nucleosynthesis in supernovae since the ratio determines the relative charged-current conversion rate of neutrons to protons and protons to neutrons. Fischer, T., et al., Journal of Physics: Conference Series **665** (2016) 012069 .

Accessible Measurements - 3

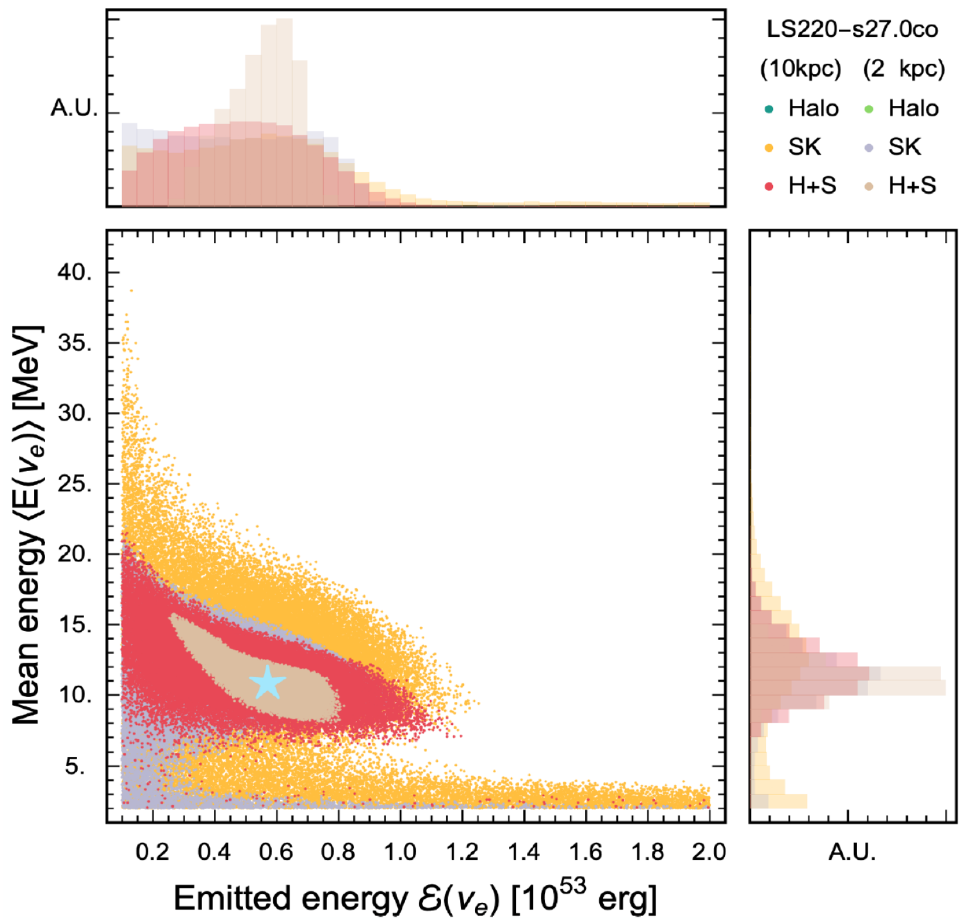
- Measurement of the shape (pinching) parameter of the neutrino energy spectrum gives an indication of how much the ν-nucleus interaction strength varies with changing ν energy. This provides possible sensitivity to nuclear pasta phases, where the neutrino opacity of the nuclear matter would increase as the de Broglie wavelength of the neutrinos becomes similar to the dimensions of the nucleon chains and sheets that compose the pasta C.J. Horowitz et al, PRL **114**, 031102 (2015). Observing the ratio of 1-neutron to 2-neutron emission events in HALO constrains the parameter space of $\langle E_\nu \rangle$ versus shape parameter Vaananen, D., and Volpe, C., JCAP **1110** (2011) 019

Value-added Physics from HALO-1kT

- Need to explore the value-added of HALO-1kT data in combination with other detectors
- This is an ongoing study, only results with S-K and HALO-1kT presented today
  - For two different supernova models LS220-s27.0co and SFHo-z9.6co (Mirizzi et al. 2016) Poisson-fluctuated events in HALO-1kT and other detectors were fit, separately and jointly, to 10 spectral parameters:
    - ε_{tot} the total emitted energy
    - ε_i the emitted energies by flavour
    - $\langle E_i \rangle$ the average energies by flavour
    - α_i the pinching parameters by flavour
  - where $i = \overline{\nu}_e , \nu_e , \nu_x$
  - Repeating $O(10^4)$ times permits scatterplots of pairs of fit spectral parameters and their projections to be generated...

Mean Energy versus Emitted Energy for ν_e

- Yellow → Red, improvement in adding HALO-1kT to S-K at 10kpc
- Grey → Tan, same improvement at 2kpc
- Note: increased S-K statistics not as helpful in constraining these parameters as adding in HALO-1kT



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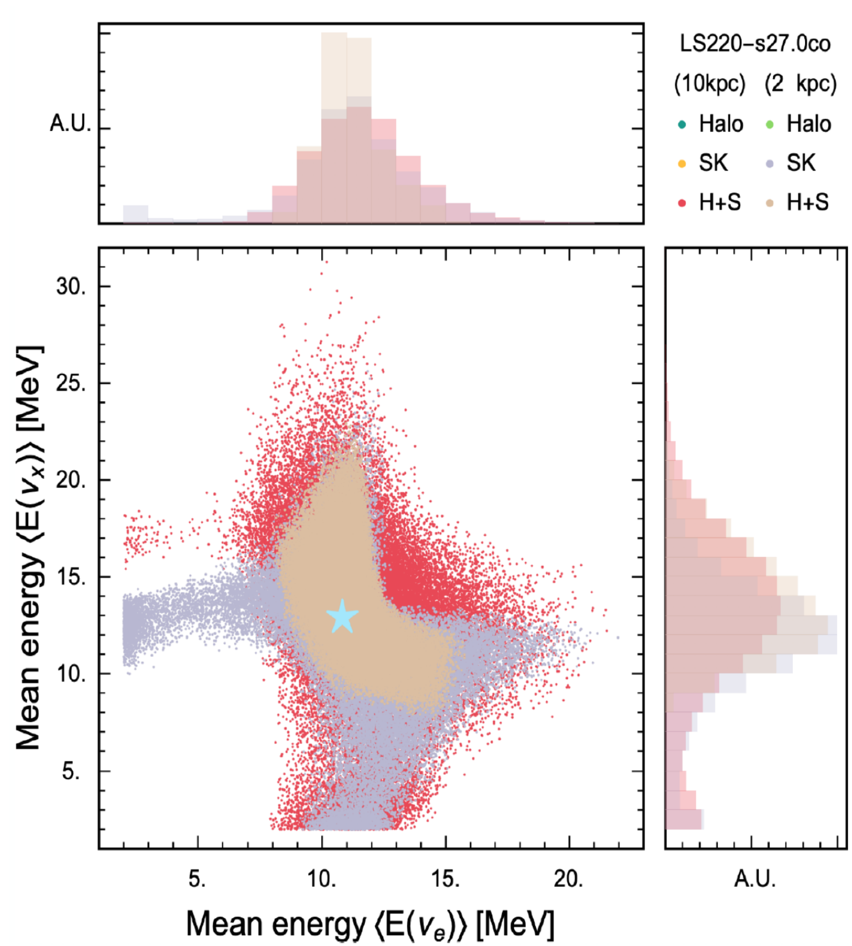
Mean Energies ν_x versus ν_e

- S-K has no resolving power in these parameters at 10 kpc, shown only at 2kpc (grey)
- Red → Tan, HALO-1kT and S-K from 10 kpc to 2 kpc
- Best constraint in ν_e mean energy, some constraint in ν_x



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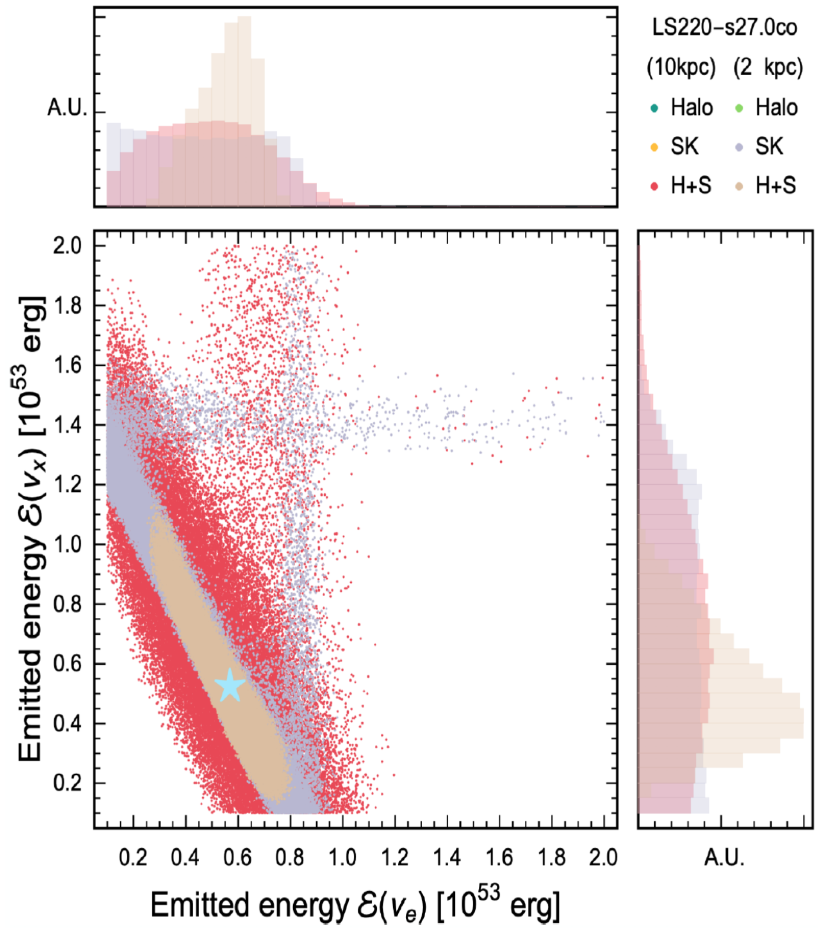
Emitted Energies ν_x versus ν_e

- Again S-K alone at 10 kpc omitted
- S-K alone at 2 kpc shows strong correlations and artifacts
- Adding HALO-1kT at 10 kpc (Red) or 2 kpc (Tan) reduces artifacts and sharpens constraints (seen best in projections)



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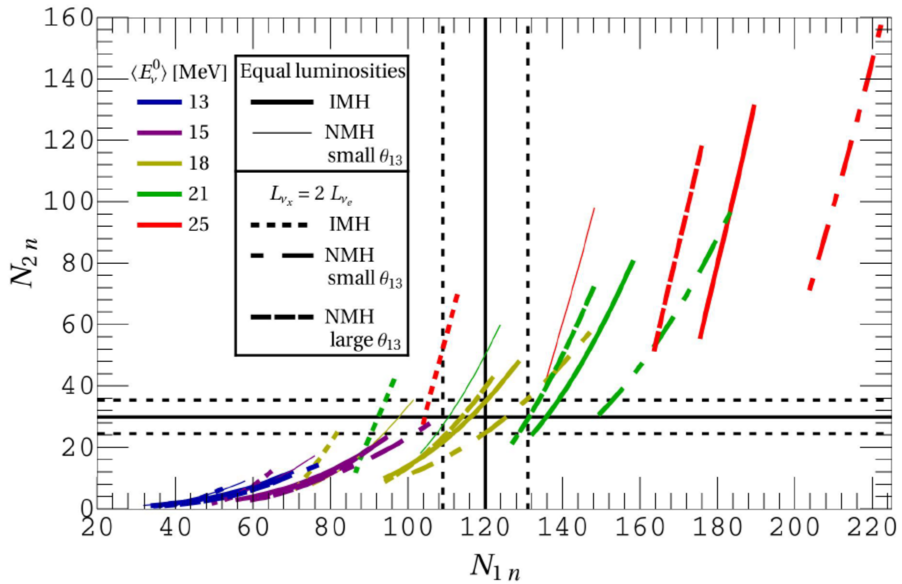
Fitting Summary

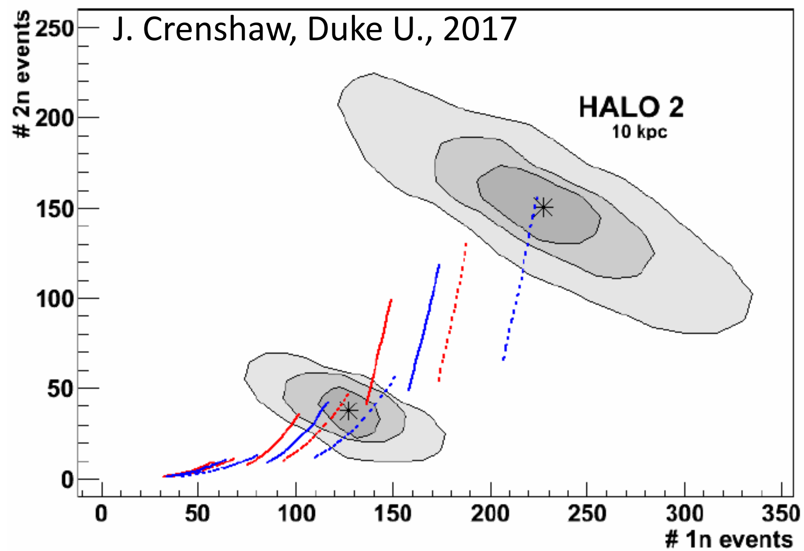
- HALO-1kT data complements Super-K data in the whole range 2 – 10 kpc.
- For a supernova at 10kpc
  - knowledge of the ν_e mean energy is significantly improved by the addition of the HALO-1kT data
  - there is mild improvement on the ν_e emitted energy and the ν_x average energy
  - no significant improvement was noted in the pinching parameters that are essentially undetermined by the fit (not shown)
- For a supernova at 2kpc
  - knowledge of the mean energy and the emitted energy is significantly improved for both ν_e and ν_x by the addition of HALO-1kT data
  - correlations between emitted and average energies are in some cases resolved
  - the pinching parameters remain essentially undetermined
- Preliminary results including JUNO have many more combinations and are highly dependent on JUNO's ability to tag channels

Ability to Determine <$E_{\nu x}$> and $\alpha_{\nu x}$

- Monte Carlo study for HALO-1kT at 10 kpc
- observed 1n and 2n events unfolded to get true event ratios
- contours are 90% confidence limits for neutron capture efficiencies of 40%, 60% and 80%
- large part of parameter space can be excluded at 10 kpc, with realistic efficiencies



Vaananen, D., and Volpe, C., JCAP 1110 (2011) 019



$\epsilon = 0.4, 0.6, 0.8$

HALO-1kT Status

- HALO-1kT Collaboration has ~30 members from Canada, USA, and Italy
- LOI submitted to LNGS, preparing a full Experimental Proposal for this year
- Funded in Canada as an R&D project
- Neutron Detector Characterization Facility funded
  - Doubles as target for measuring ν-Pb cross sections at ORNL's SNS
- LNGS is holding OPERA lead awaiting Proposal
- Factor of 50 reduction in counter backgrounds looks feasible with copper-plating
  - Working with manufacturers and PNNL
- Need as funded project in USA and Italy prior to looking for capital funds
  - Collaboration needs to grow some in all three countries

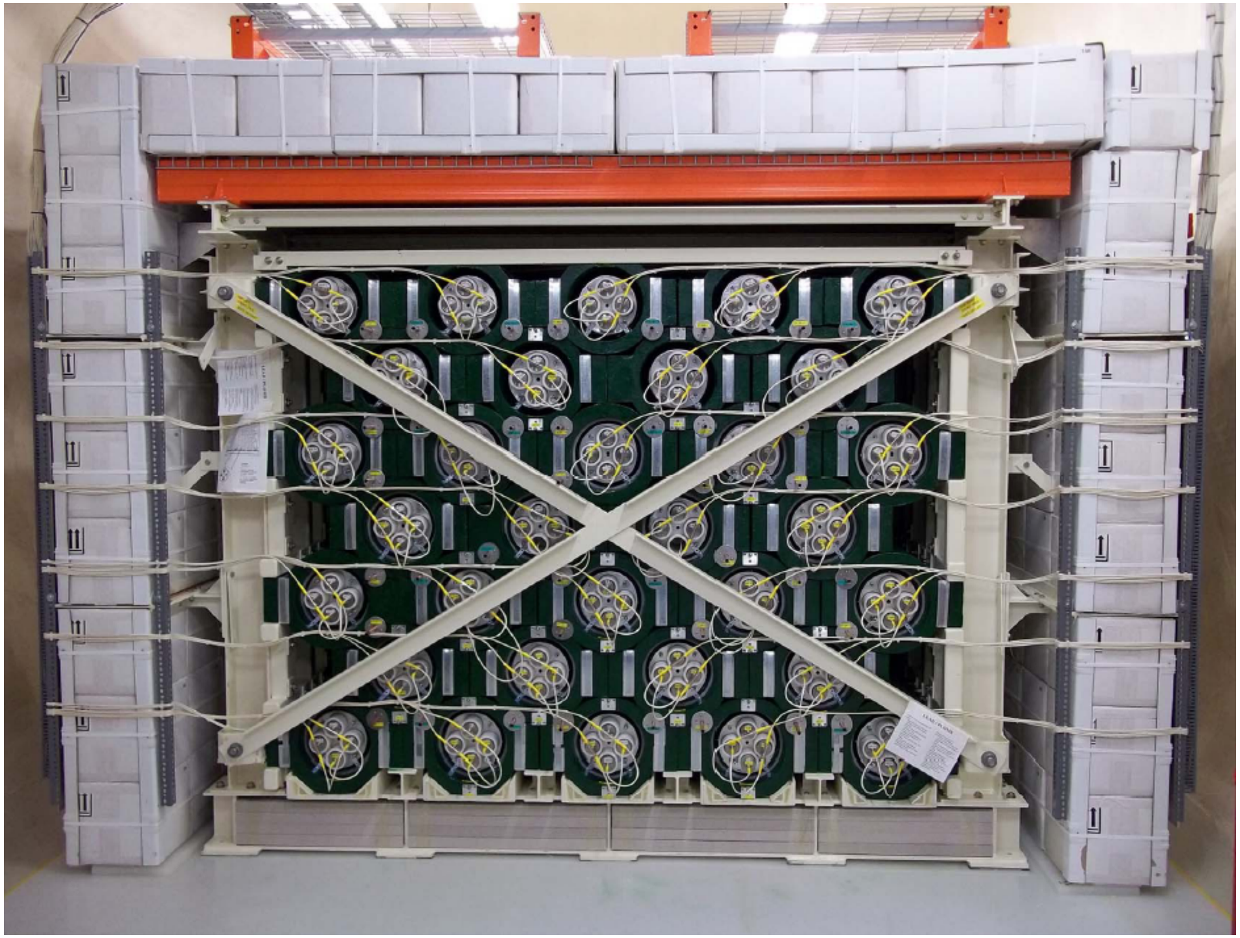
End

HALO - the Helium and Lead Observatory

A “SN detector of opportunity”

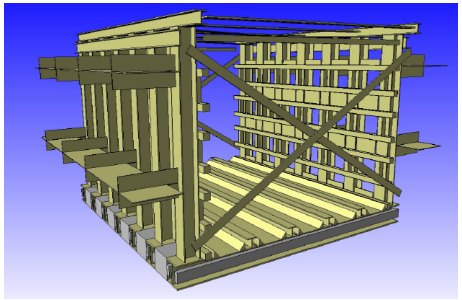
An evolution of LAND – the Lead Astronomical Neutrino Detector, C.K. Hargrove et al., Astropart. Phys. 5 183, 1996.

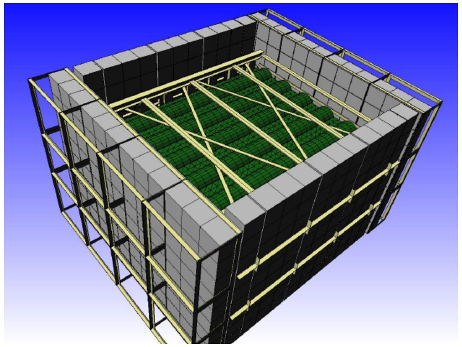
Recycling lead from a decommissioned cosmic ray observatory and ^{3}He neutron detectors from SNO

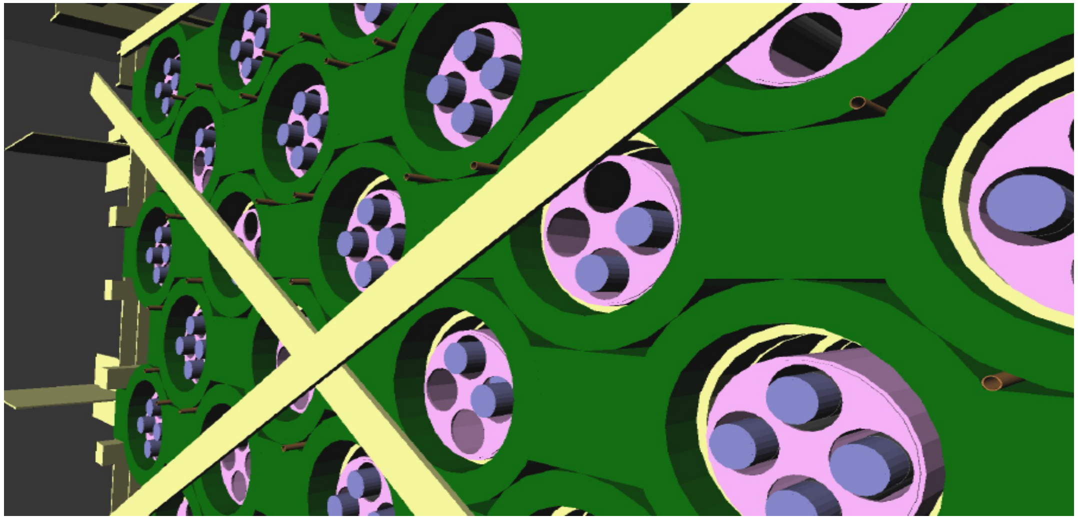


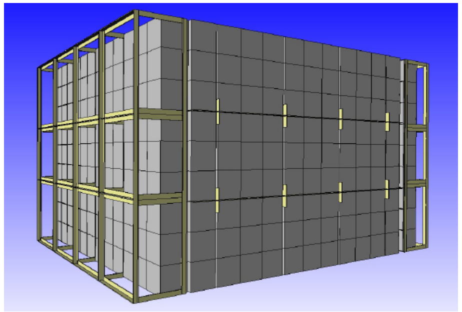
HALO at SNOLAB as a Prototype

- 79 tonnes of Pb
  - non-optimum lead geometry
  - instrumented with excellent low background neutron detectors (370 m containing ~1465 litre.atmospheres ^{3}He)
- operating since May 2012
- participating in SNEWS since October 2015
- simulated / calibrated / understood
- many redundant systems for reliability (> 99% livetime)

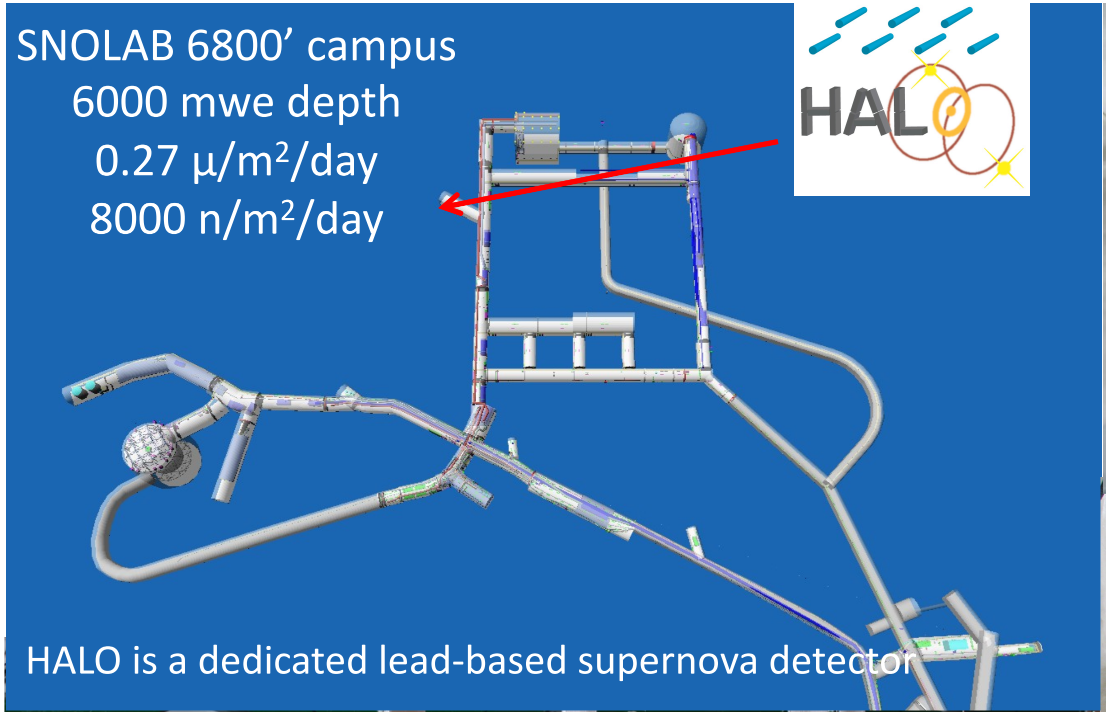


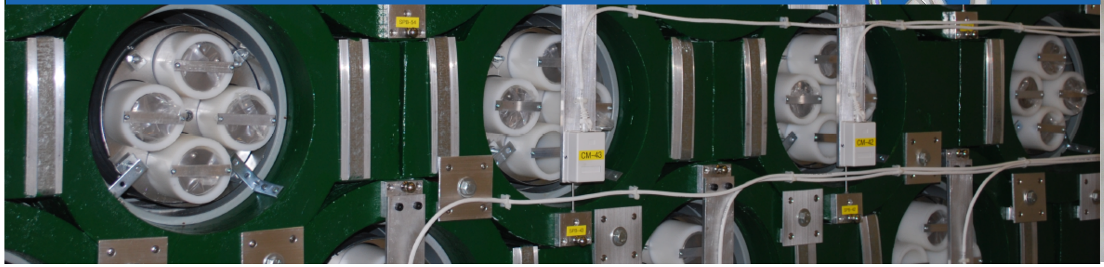






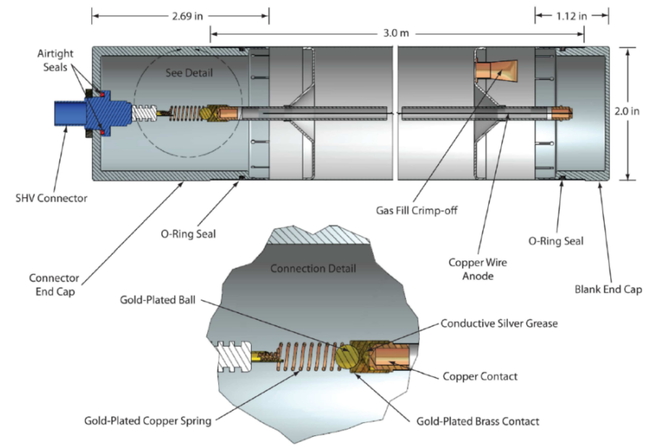
HALO at SNOLAB

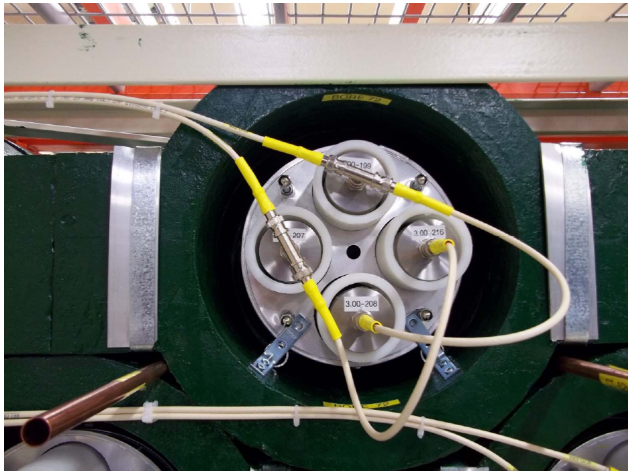




Neutron Detection in HALO

- Re-using SNO's "NCD" ^{3}He proportional counters
- 5 cm diameter x 3m and 2.5m in length, ultra-pure CVD Ni tube (600 micron wall thickness)
- 2.5 atm (85% ^{3}He, 15% CF_4, by pressure)
- Four detectors with HDPE moderator tubes in each of 32 columns of lead rings
- 128 counters (~370 m) paired for 64 channels of readout



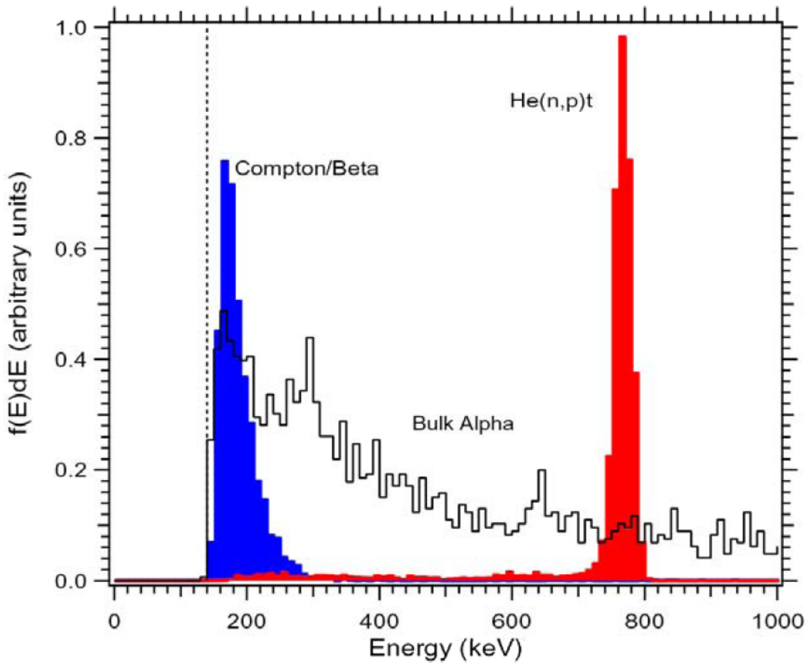


Neutron Detection in HALO

- Neutron detection via

  $^{3}He + n \rightarrow p + t + 764\ keV$

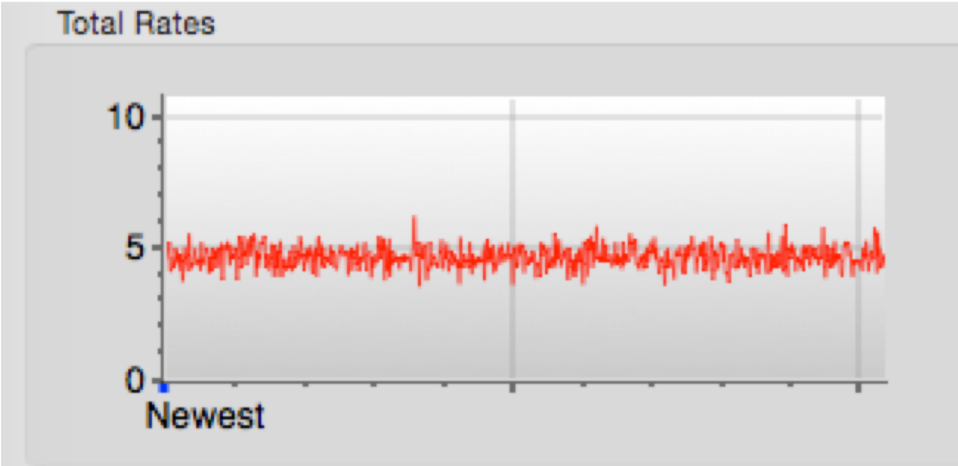
- 764 keV FE peak plus LE tail due to wall effects
- Compton and beta events at low energies
- Background n's in SNOLAB at level of 4000 fast plus 4000 thermal per m^2 per day.
- Cosmic muons < 2 per day
- Intrinsic tritium rate (18.6 keV endpoint) above 12 keV threshold ~10 Hz / detector but running at threshold of ~50 keV



Background Breakdown

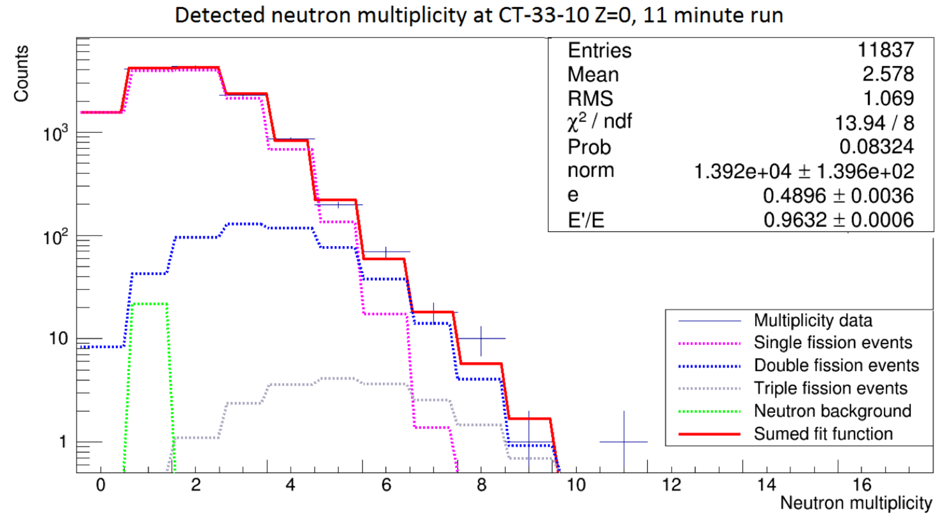
- Current "neutron" rate in HALO is 0.015 Hz (1294 ± 8 / day), or ~1 neutron per channel per hour, of which:
  - 23 ± 5 from ^{238}U spontaneous fission
  - 80 ± 43 from nearby stored ^{252}Cf calibration source
  - ~20 from internal α-emitting radio-contaminants
  - rest from leakage of environmental neutrons through shielding

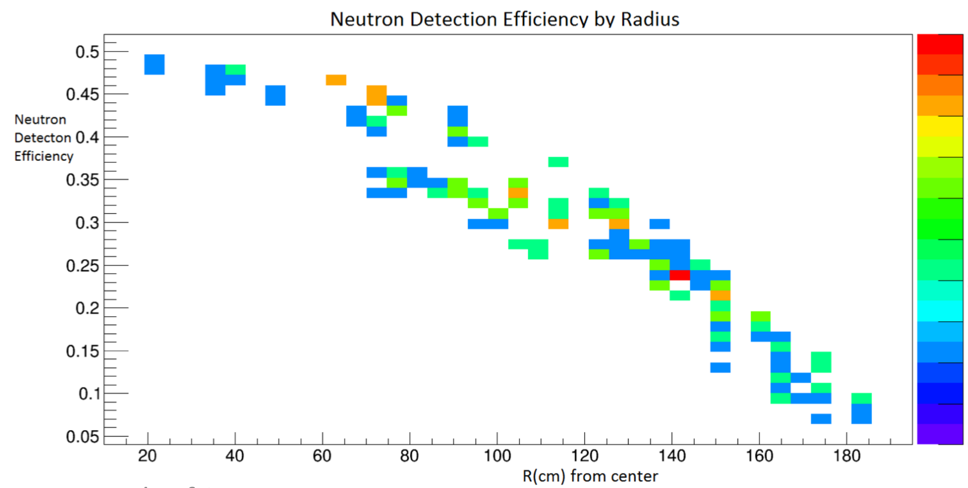
channel thresholds adjusted for even rates across channels and total rate of 5 Hz



HALO Calibration with ^{252}Cf Source

- used a low activity (~20 SF/s) ^{252}Cf source
- with very low backgrounds were able to measure the neutron multiplicity distribution which is a strong function of the neutron capture efficiency at 192 points
- extend time window to ensure that all neutrons from an integral number of fissions were counted
- fitting simultaneously gives efficiency at a point and the source strength
- rely on Monte Carlo simulation to extrapolate from 192 discrete calibration points to a volume-averaged efficiency for distributed supernova neutrino neutron production





SNEWS Sensitivity and Backgrounds

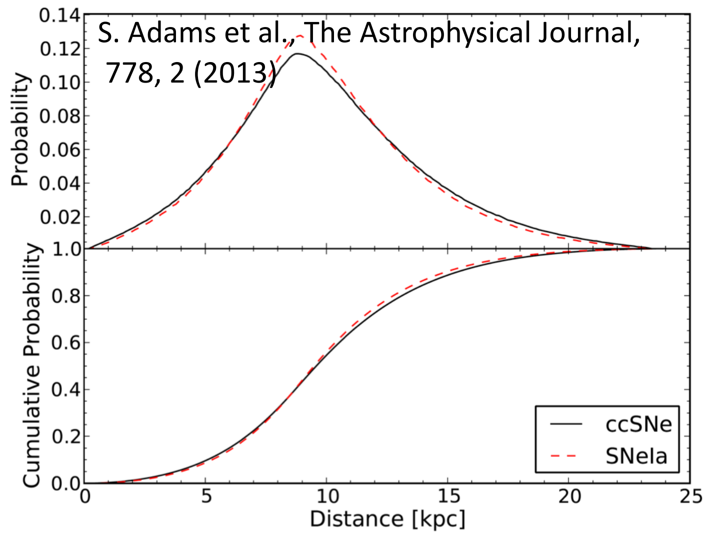
- The SuperNova Early Warning System (SNEWS) currently sets a limit on the frequency of false alarms that individual experiments can send (1 per 14 days) such that the false coincidence alert rate is < 1/century
- Going forward SNEWS 2.0 has been funded by the NSF, a workshop was held in Sudbury in June 2019, implementation working groups have formed
- we expect a higher SNEWS 2.0 tolerance of false coincidences and an acceptable individual alarm rate of order 1/day

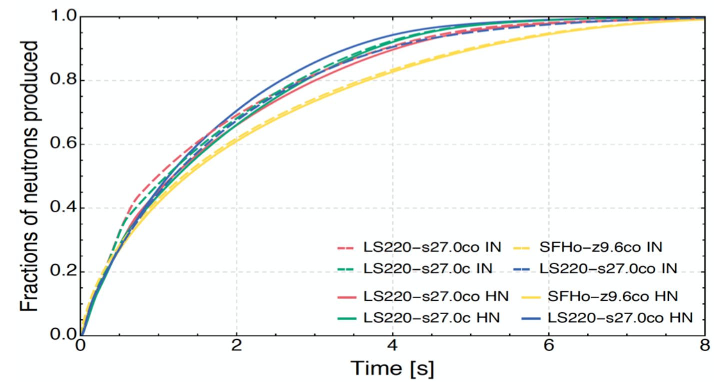
Background Rates and SNEWS Trigger

- For a simple HALO-1kT burst condition of N_{trig} neutrons in ΔT second window the burst rate due to a rate of background neutron or neutron-like events, λ_B, is easily calculated
- We can ask – What is λ_B such that we have a 50% probability of detecting a SN at our desired limit of detection while still meeting the SNEWS 2.0 criterion of < 1 false alarm per day?

Target Sensitivity for Trigger

- For a pessimistic distance of 25 kpc, pessimistic ν-Pb cross sections, and pessimistic ν temperatures we project > 10 detected events, N_∞, in HALO-1kT integrated over all time
- There is only a mild dependence on the SN model "light" curves





N_∞ total events with cumulative distribution F(t)

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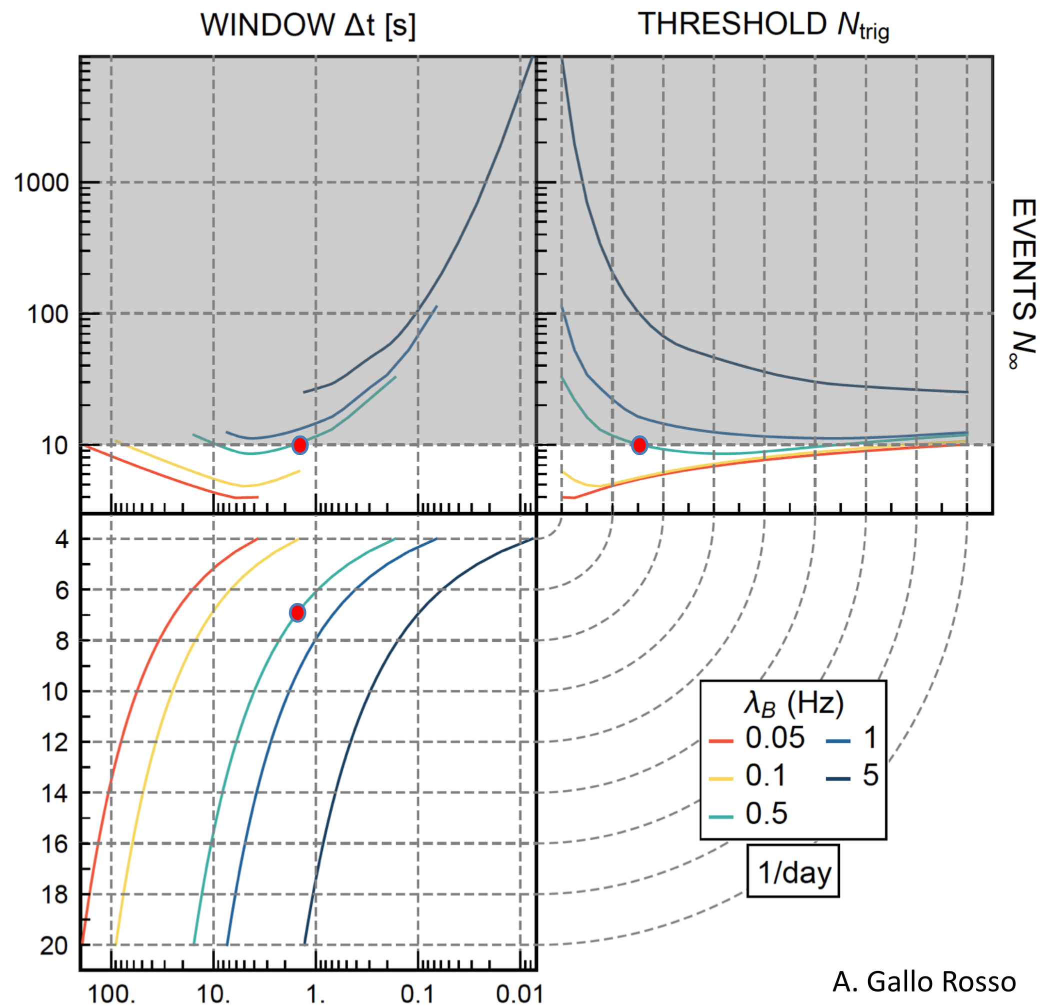
Defining an Acceptable λ_B

- Curves of constant λ_B for an alarm rate of 1/day in $\Delta T, N_{\mathrm{trig}}, N_\infty$ space presented as three 2-D projections folded flat
- We see that the point (2, 7, 10) and a λ_B of 0.5 Hz satisfies all criteria and defines a target background rate from all sources to be 0.5 Hz



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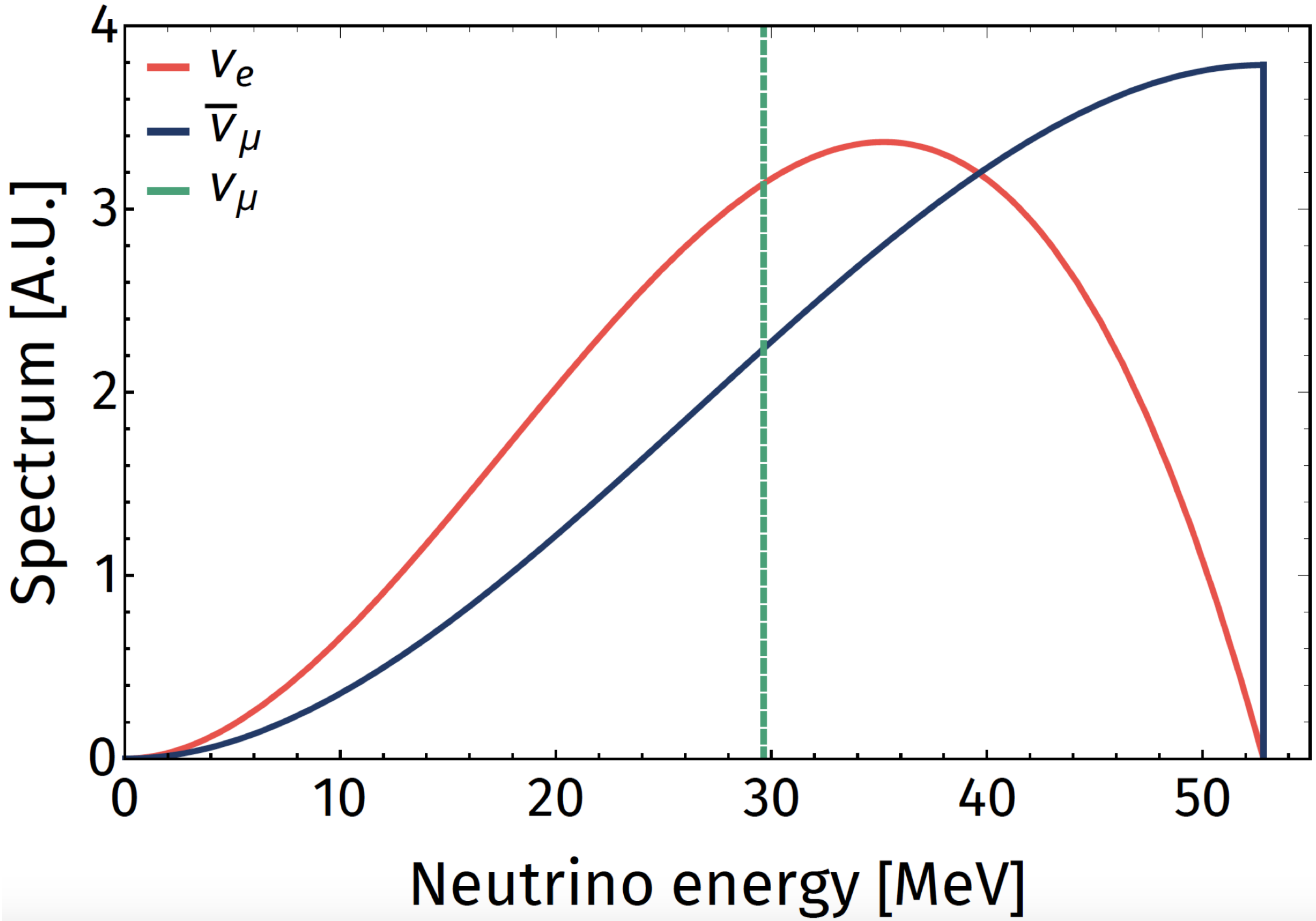
π DAR ν Energy Spectra from SNS



Mini-HALO