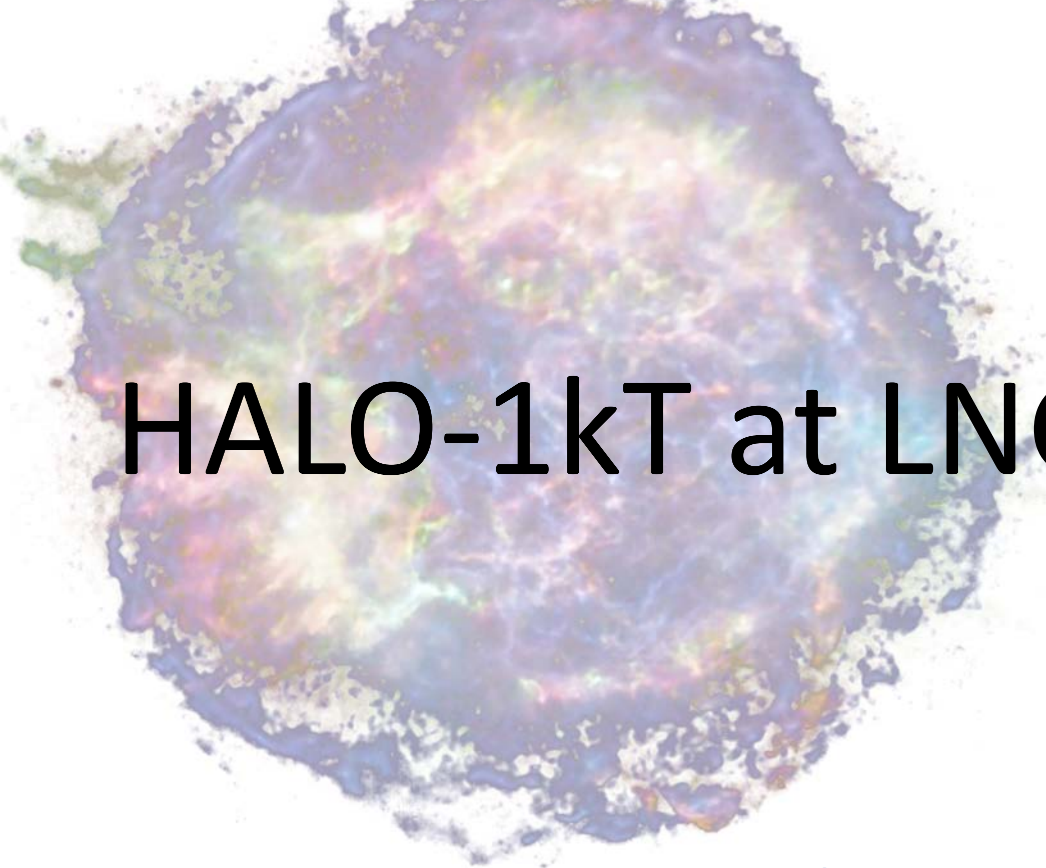
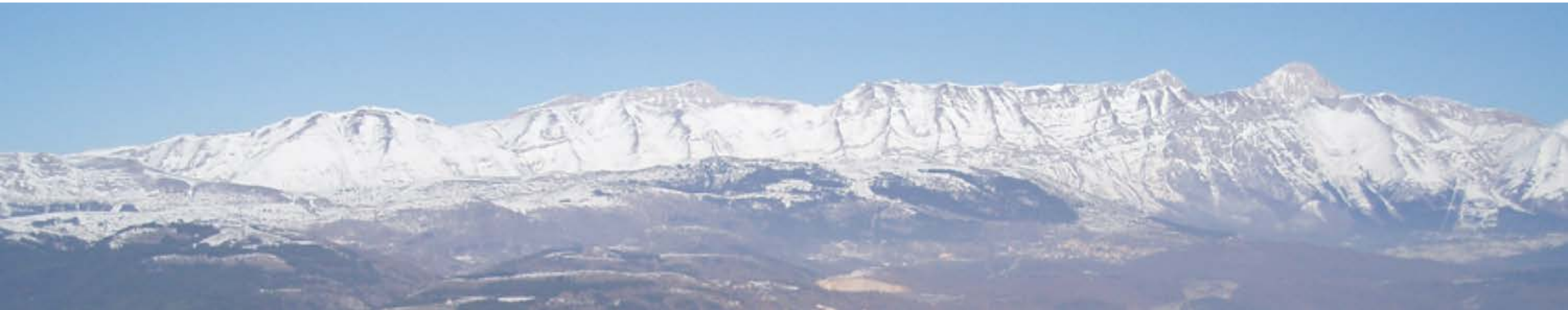


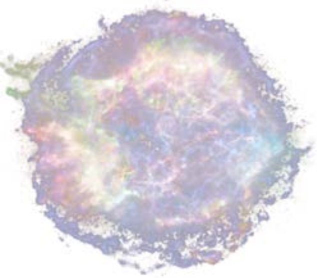
HALO-1kT at LNGS - Update

C.J. Virtue for the Collaboration

Open Session – October 21, 2019

LII meeting of the Gran Sasso Scientific Committee

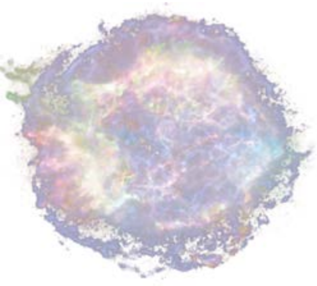




Outline

- Supernova Neutrinos
- ν – Lead Interactions
- HALO-1kT
- Two areas of progress / focus
  - Value-added Physics from HALO-1kT
  - SNEWS Sensitivity and Backgrounds

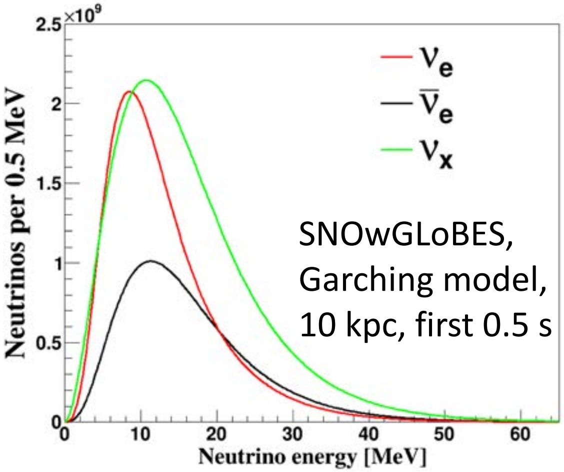
- Backup slides



Supernova Neutrinos

What is the interest?

- our only window into core-collapse supernova (ccSN) 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

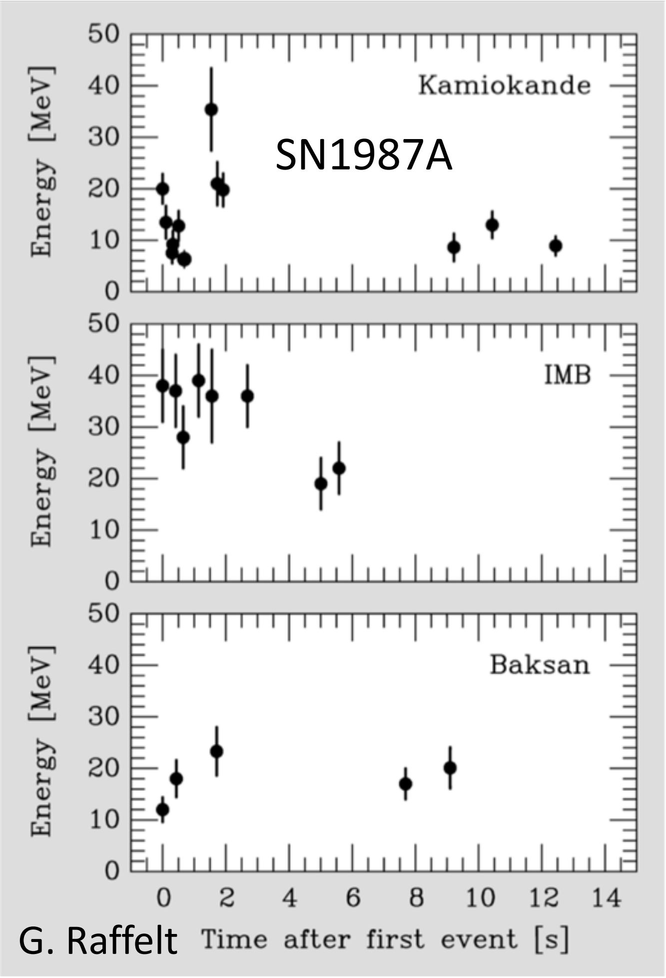


SNOwGLoBES, Garching model, 10 kpc, first 0.5 s

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

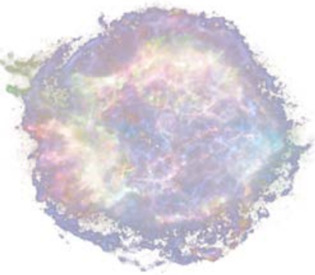
  $T(\nu_e) < T(\bar{\nu}_e) < T(\nu_x)$

- this signal is imprinted with:
    - collective effects
    - MSW effects
    - shockwave effects
    - large scale density oscillations



SN1987A

G. Raffelt

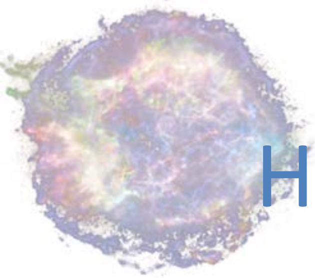


ν - Lead Interactions

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

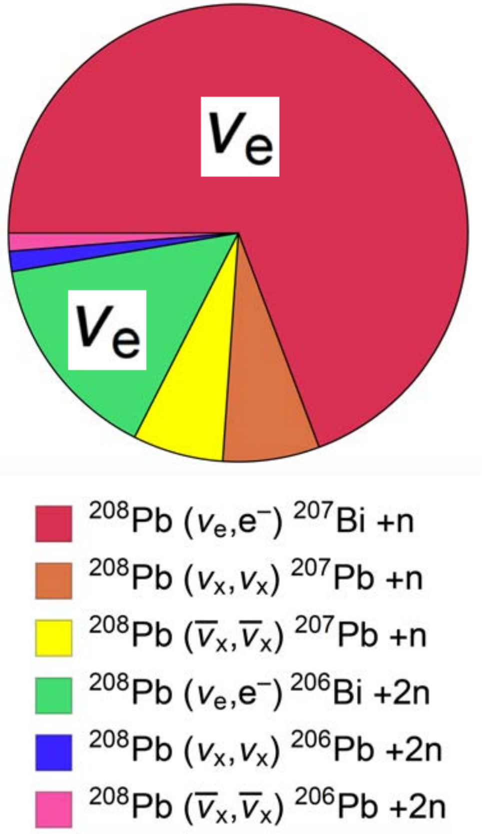
$$\begin{aligned}
\mathrm{CC:}\quad \nu_e + {}^{208}\mathrm{Pb} &\rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV}\\
\nu_e + {}^{208}\mathrm{Pb} &\rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV}\\
\mathrm{NC:}\quad \nu_x + {}^{208}\mathrm{Pb} &\rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV}\\
\nu_x + {}^{208}\mathrm{Pb} &\rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}
\end{aligned}$$

- 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 / 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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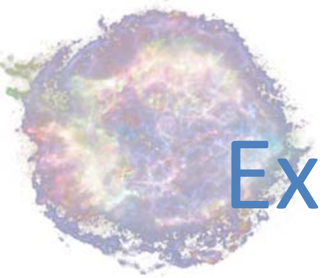
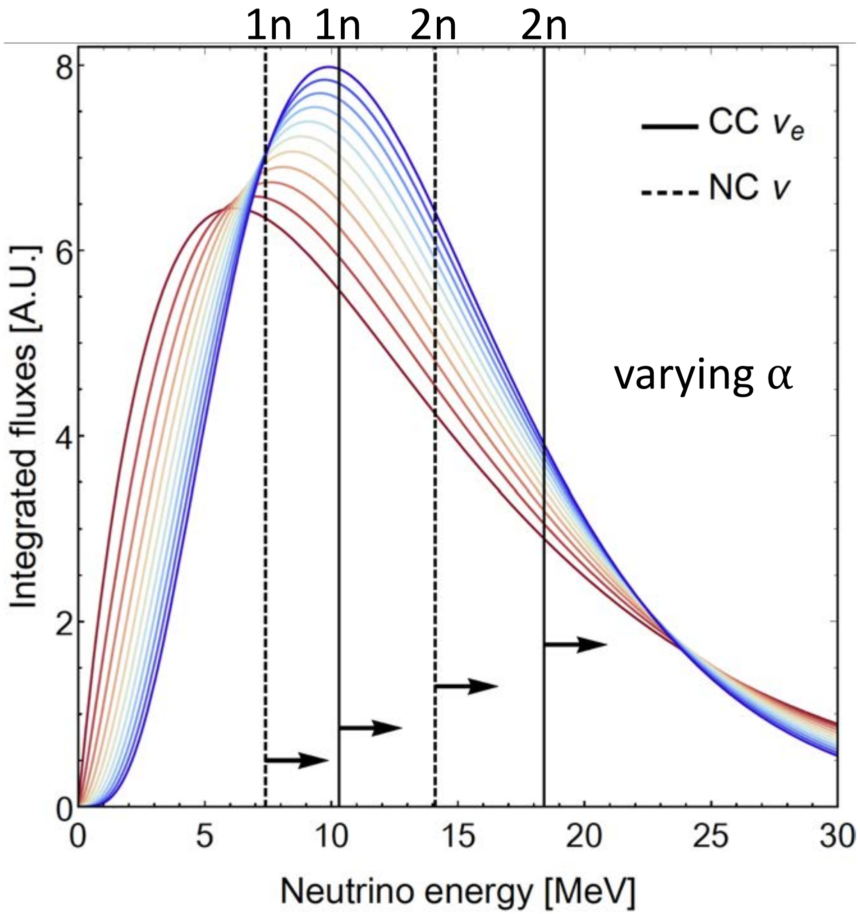


Exploitable Cross Section Features

- 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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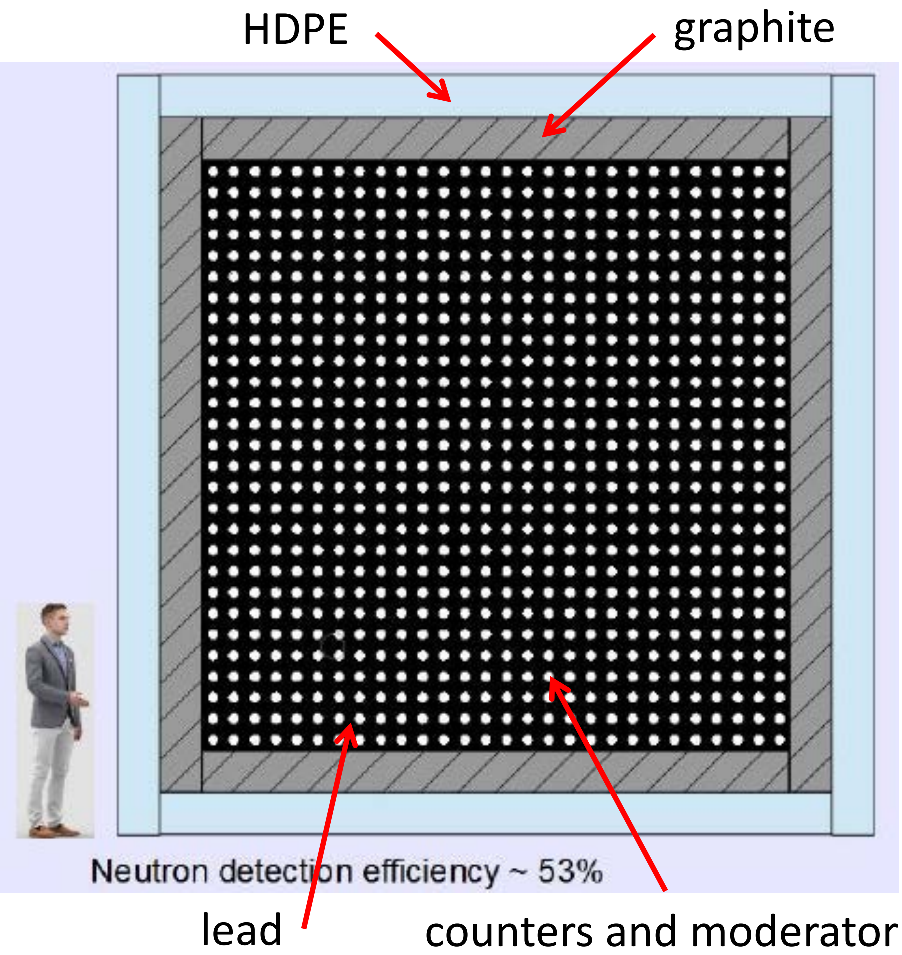
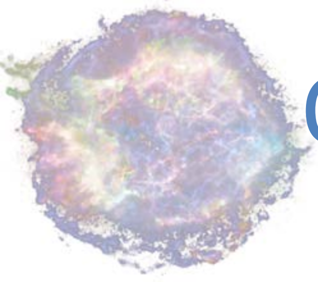
HALO-1kT Base Design

- lead core 4.33 x 4.33 x 5.5 m^3 with 28 x 28 x 5.5 m array of ^{3}He 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



HALO at SNOLAB as a Prototype

- 79 tonnes of Pb
- operating since May 2012
- participating in SNEWS since October 2015
- simulated / calibrated / understood
- many redundant systems for reliability (> 99% livetime)
- For HALO-1kT
  - 79 → 1000 tonnes Pb
  - 28% → >50% n capture eff.
  - ~23 times the event statistics



Other Aspects of a Lead-based Detector

- Properties of lead
  - Low n absorption cross section
    - Even though molar ratio of Pb : ^{3}He is 10,800 : 1 we achieve 50-55% n capture on ^{3}He
  - High Coulomb barrier
    - No (α,n) on Pb relaxing internal radioactivity constraints
  - Principle hazard of lead carbonate formation mitigated by exclusion of either humidity or CO_2 from the lead volume
- Compact / robust / low maintenance / operating cost
- Well suited to galactic core-collapse supernova rate of $3.2^{+7.3}_{-2.6}$ per century (S. Adams et al., The Astrophysical Journal, **778**, 2 (2013))

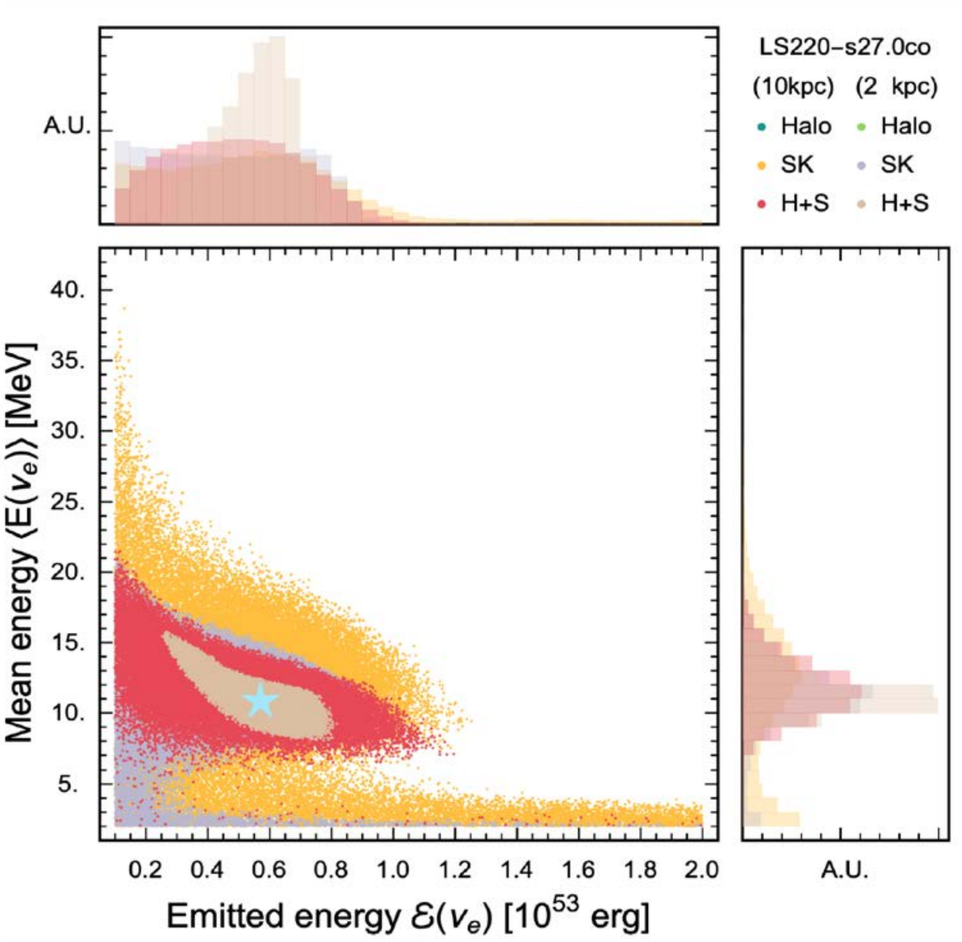
Value-added Physics from HALO-1kT

- Need to explore the value-added of HALO-1kT data in combination with other detectors (SC request – spot on)
- 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 $i = \nu_e , \overline{\nu}_e , \nu_x$
  - 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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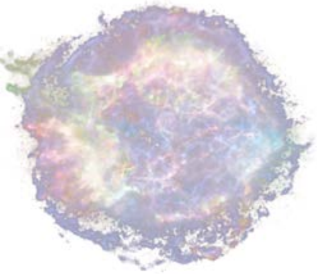
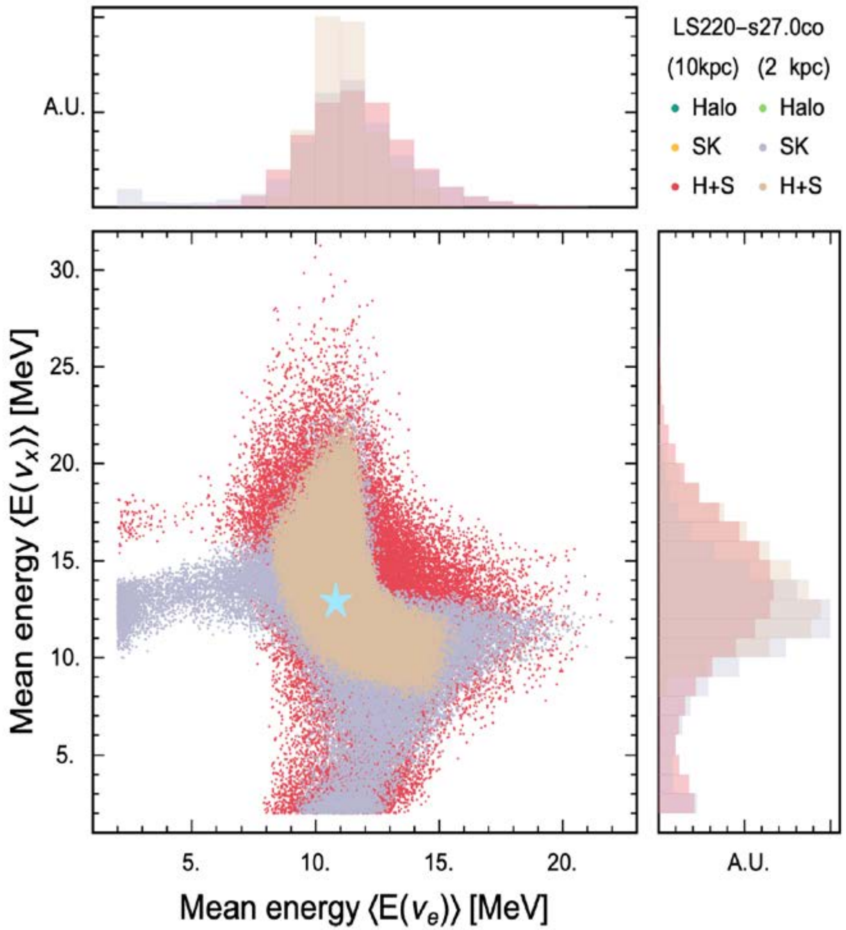


Mean Energies υ_x versus ν_e

- 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 υ_e mean energy, some constraint in υ_x



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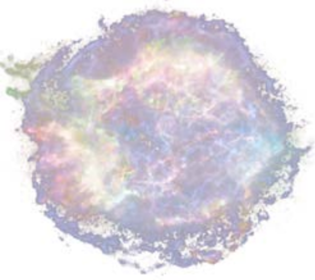
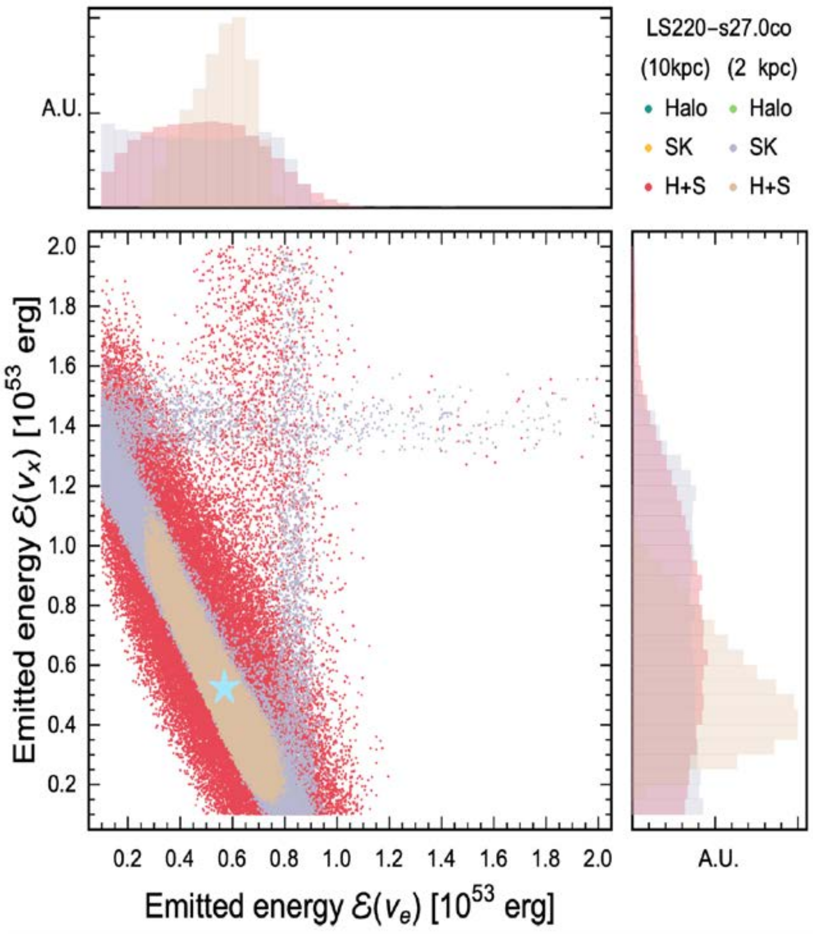


Emitted Energies υ_x versus ν_e

- 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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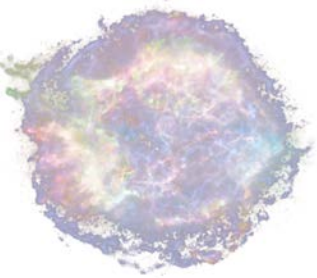


Fitting Summary

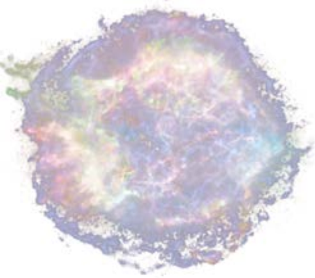
- HALO-1kT data complements Super-K data in the whole range 2 – 10 kpc.
- For a supernova at 10kpc
  - knowledge of the ν_e mean energy is significantly improved by the addition of the HALO-1kT data
  - there is mild improvement on the ν_e emitted energy and the ν_x average energy
  - no significant 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.

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

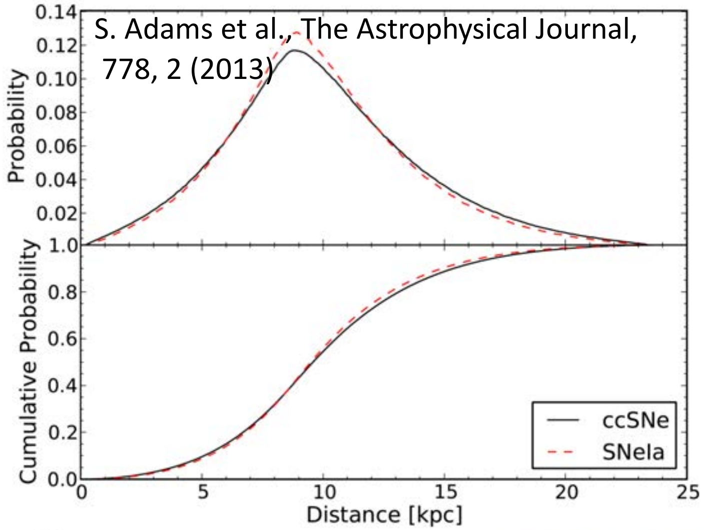
Background Rates and SNEWS Trigger

- 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?

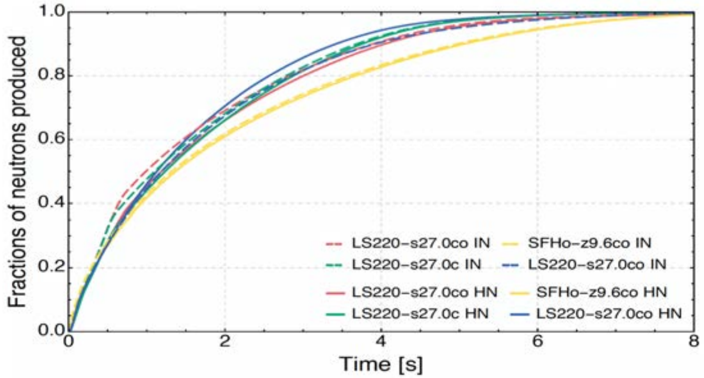


Target Sensitivity for Trigger

- 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



S. Adams et al., The Astrophysical Journal, 778, 2 (2013)



N_∞ total events with cumulative distribution F(t)

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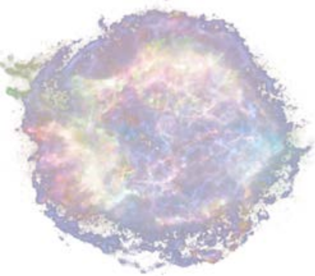
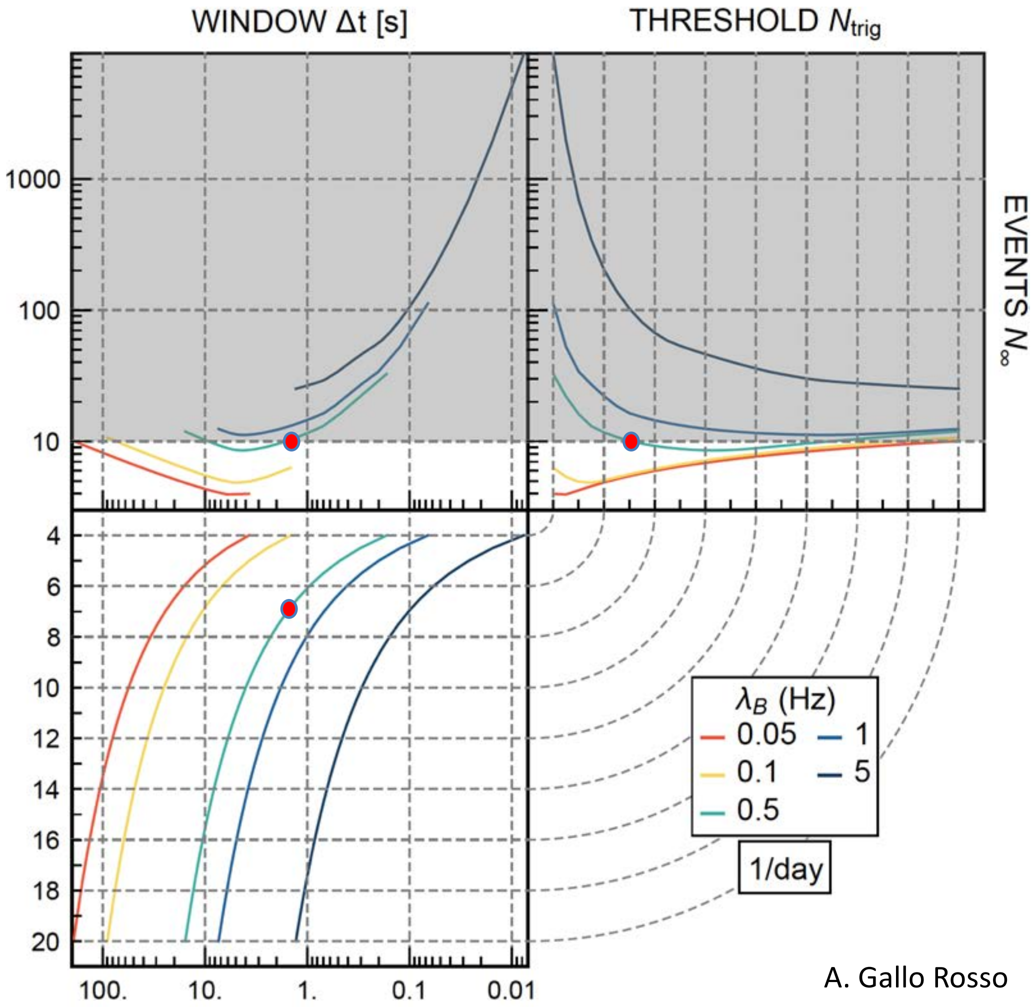


Defining an Acceptable λ_B

- Curves of constant λ_B for an alarm rate of 1/day in $\Delta T, N_{\text{trig}}, N_\infty$ 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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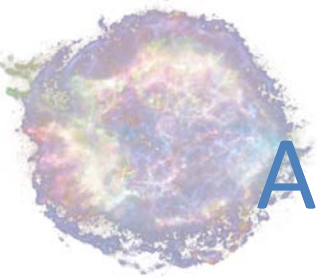
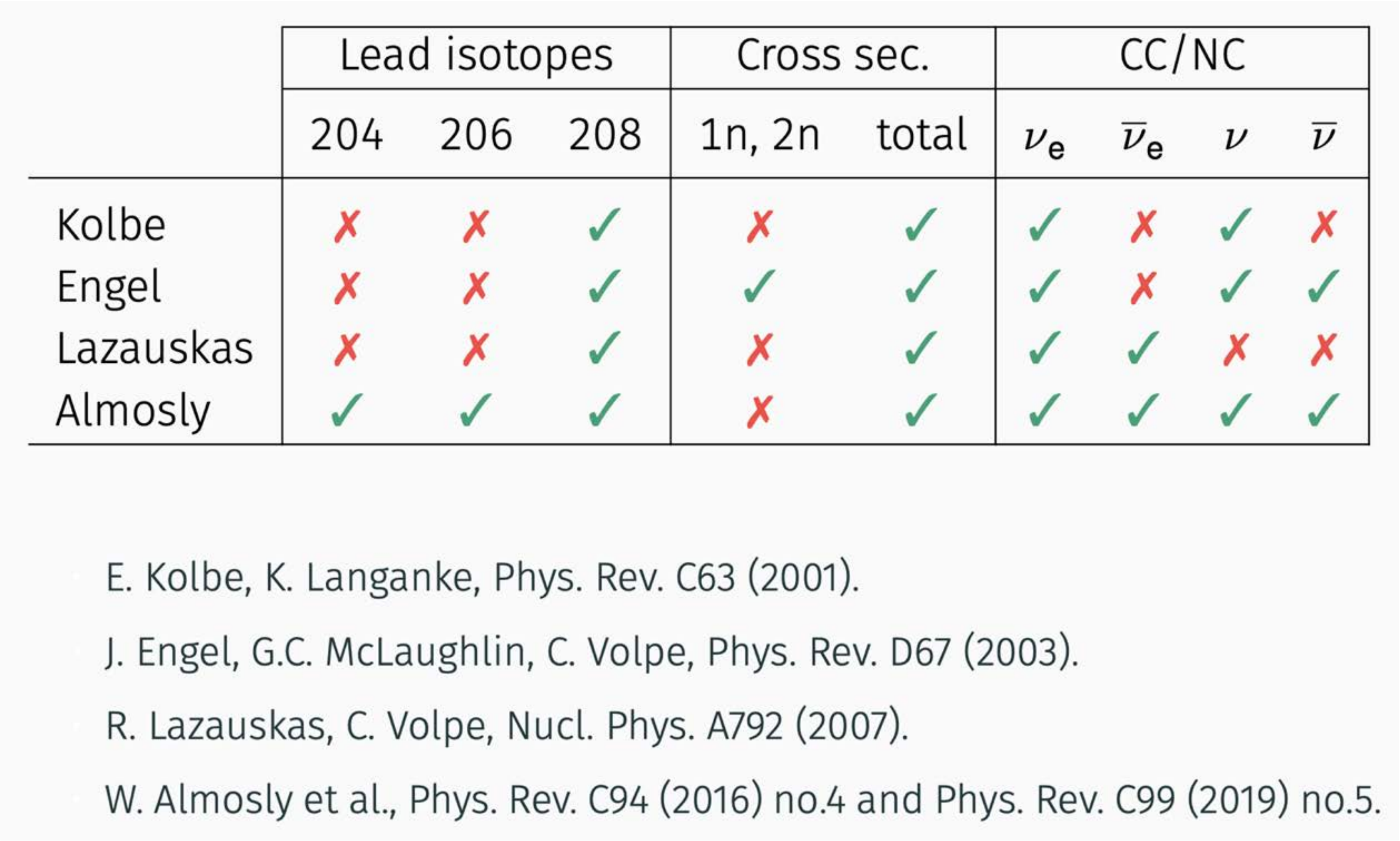
Fine / Grazie



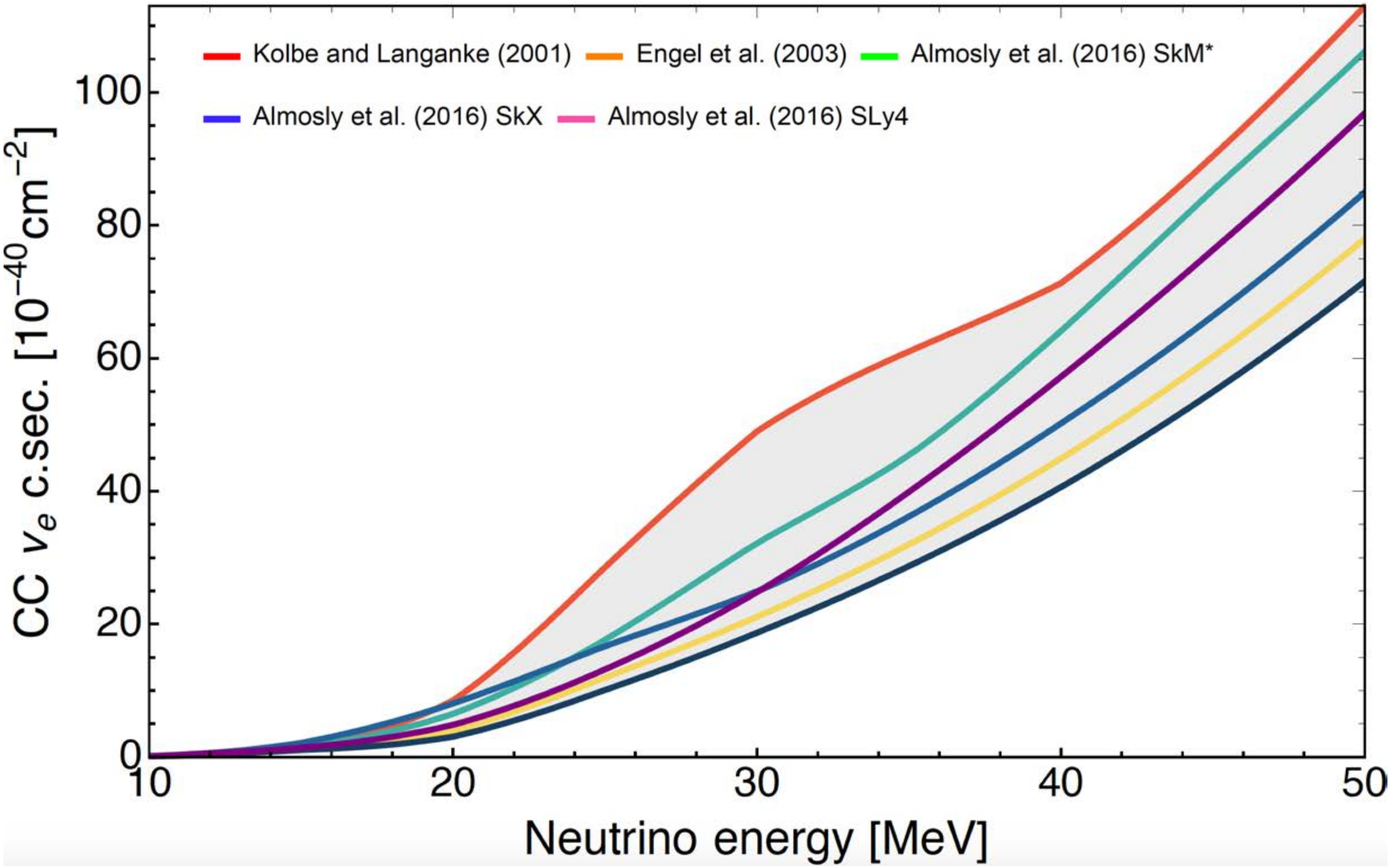
Available Cross Sections for Lead



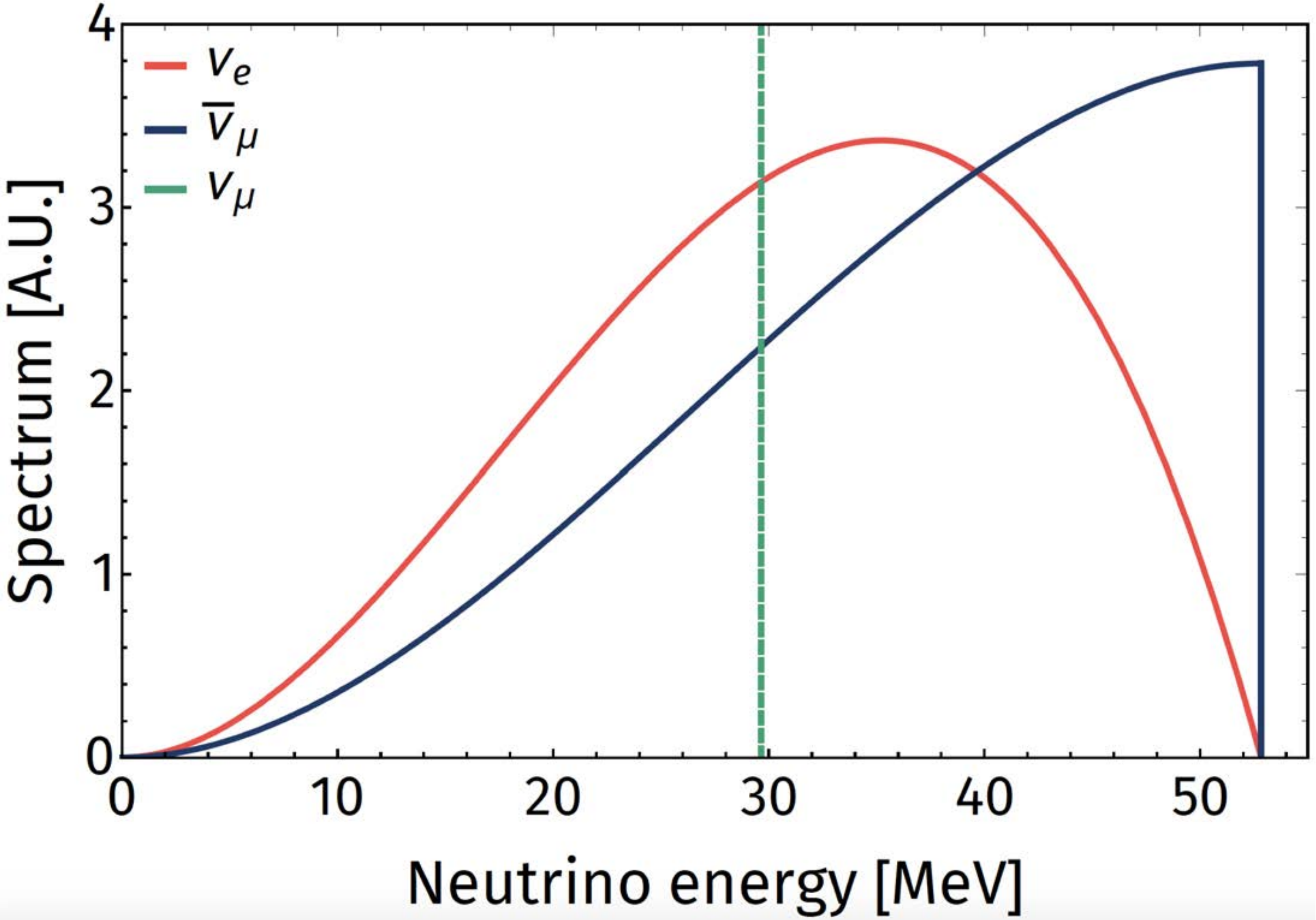
	Lead isotopes			Cross sec.		CC/NC			
	204	206	208	1n, 2n	total	ν_e	$\overline{\nu}_e$	ν	$\overline{\nu}$
Kolbe	✗	✗	✓	✗	✓	✓	✗	✓	✗
Engel	✗	✗	✓	✓	✓	✓	✗	✓	✓
Lazauskas	✗	✗	✓	✗	✓	✓	✓	✗	✗
Almosly	✓	✓	✓	✗	✓	✓	✓	✓	✓

- 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.

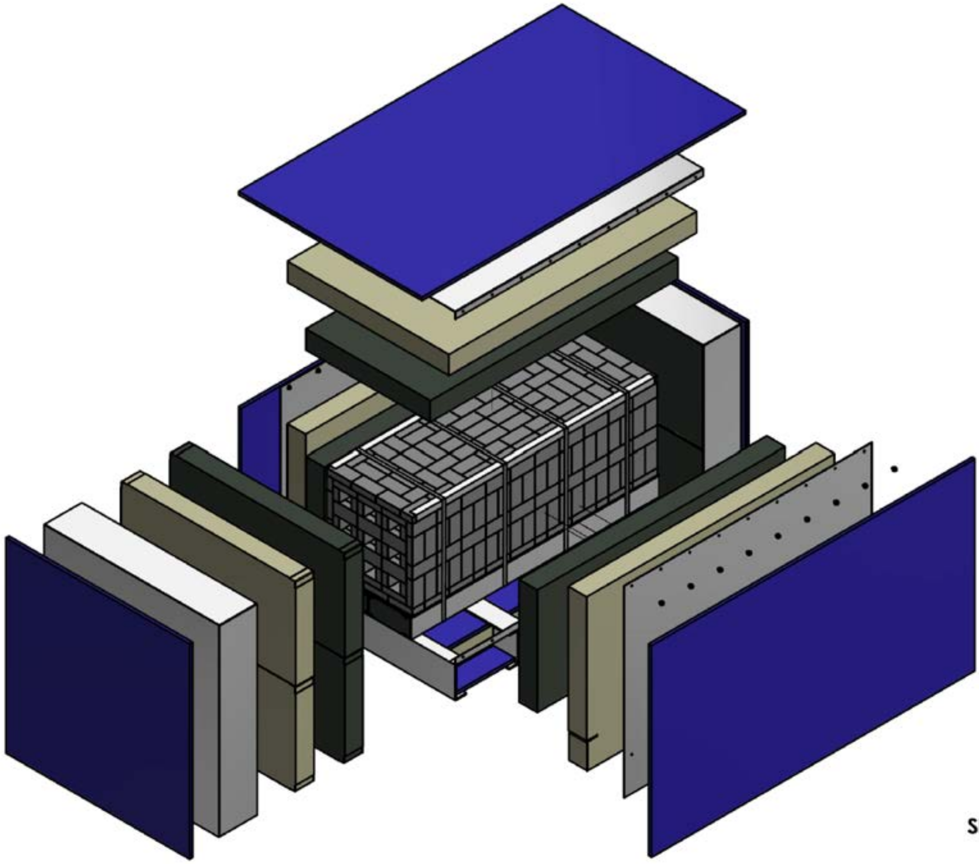
Variation in CC υ_e Cross Sections



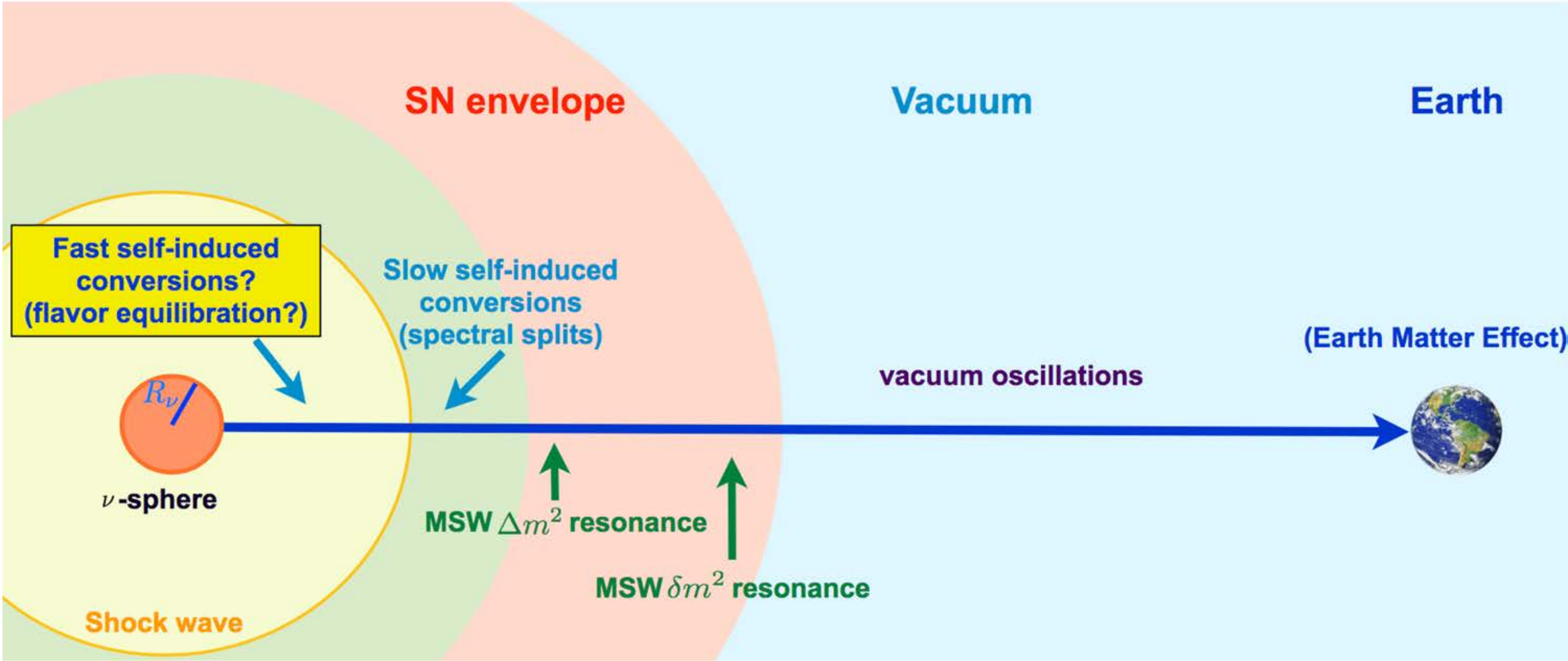
π DAR ν Energy Spectra from SNS



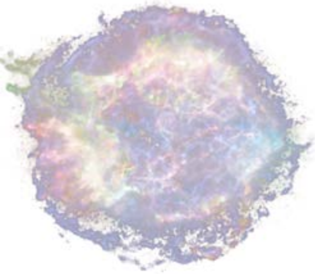
Mini-HALO



Simplified Picture of Flavor Conversions



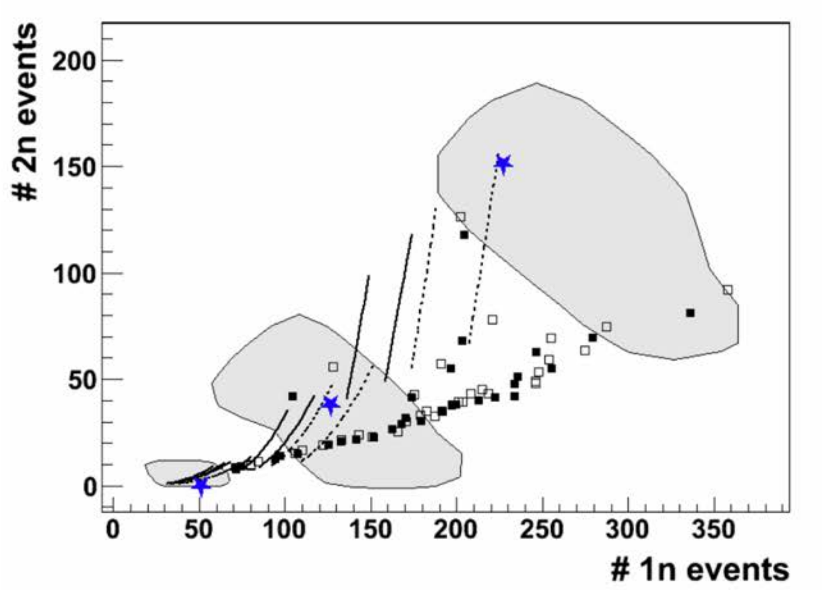
- neutrino emission source at ν-sphere evolves with time
- large-scale hydrodynamic effects (instabilities, ringing, dipole oscillations) affect neutrino signal
- then any given detector terrestrial detector imperfectly records part of the signal
- what can any one detector do when the signal is spread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



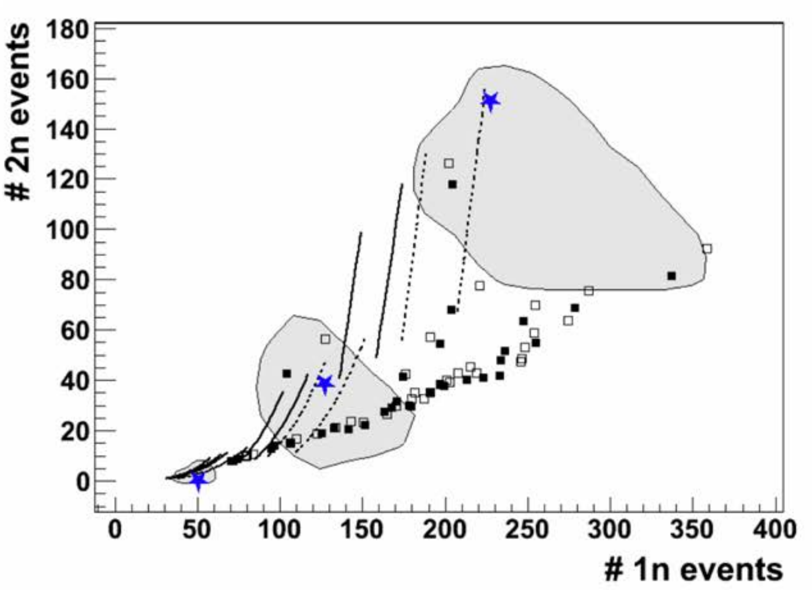
Model Exclusion

– Bayesian Unfolding –

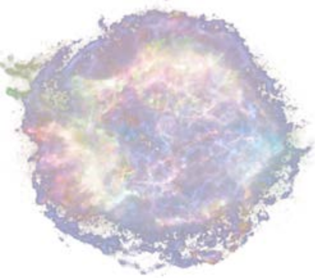
Distance Known



Distance Unknown

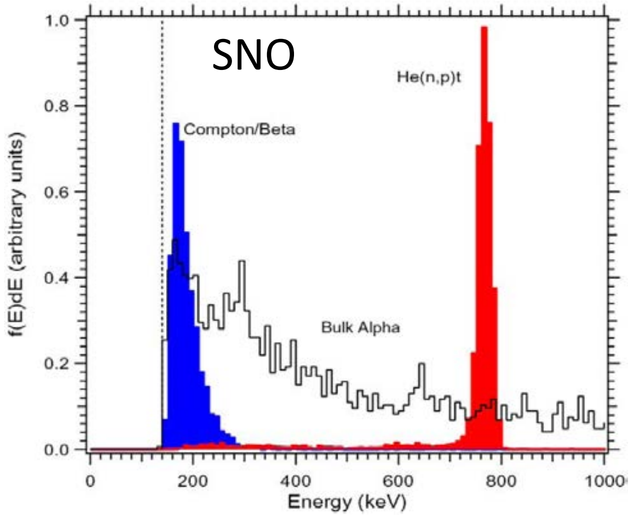


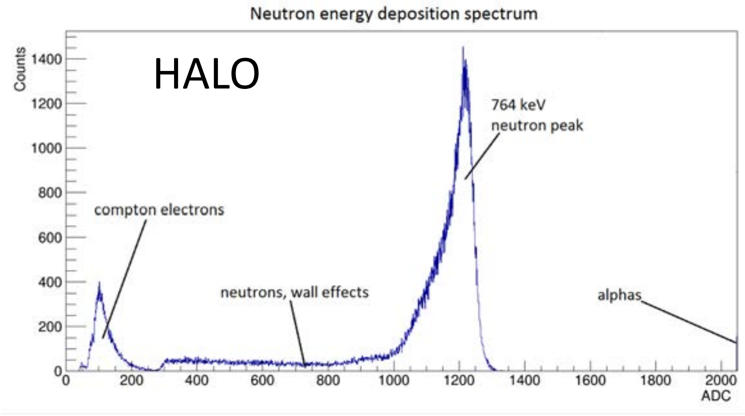
John F. Crenshaw, Duke U. (2018).

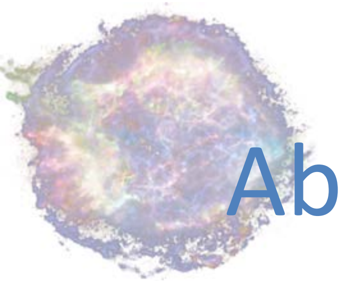


Neutron Detector R&D

- HALO achieved good neutron – β / γ separation by shortening the ADC integration time
- in addition HALO-1kT has studied thinner, lower-Z tube walls, i.e. SS → Al
  - reduces β / γ above 50 keV
  - also reduces n-capture competition with ^{3}He
- and higher pressure fill gas
  - shortens p-t track lengths
  - moves neutron events from LE tail to FEP
  - ^{4}He looks interesting

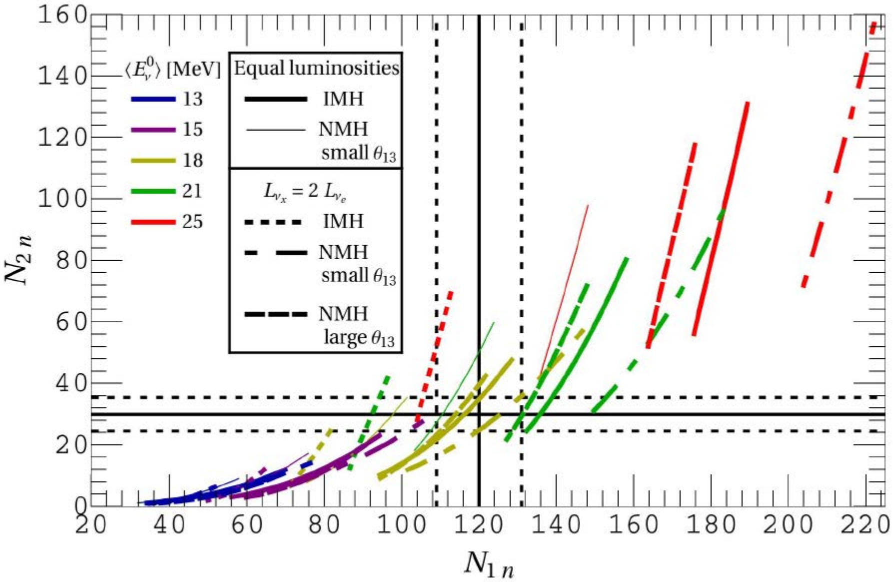




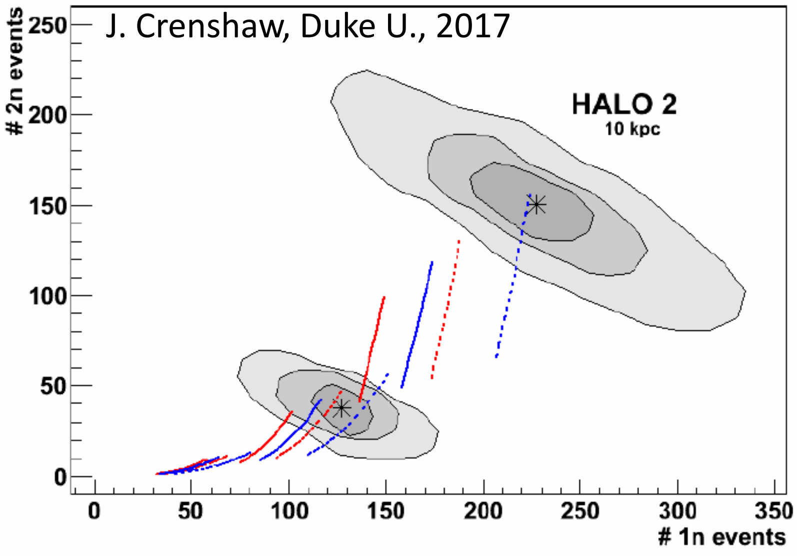


Ability to Determine $<E_{\nu x}>$ and $\alpha_{\nu x}$

- 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



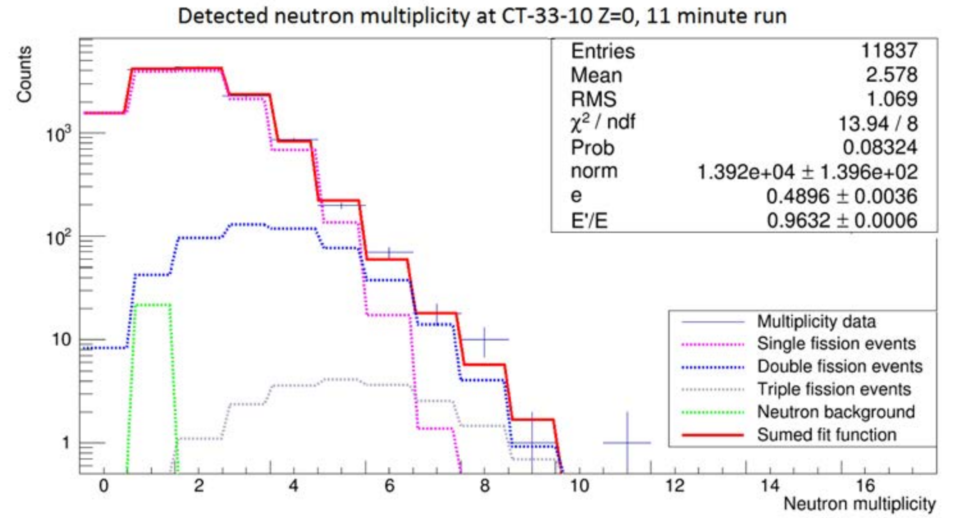
Vaananen, D., and Volpe, C., JCAP 1110 (2011) 019

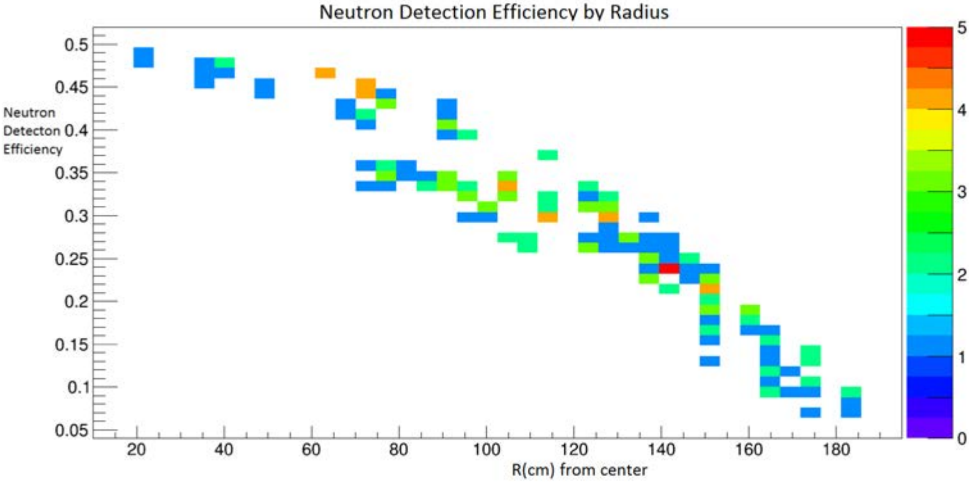


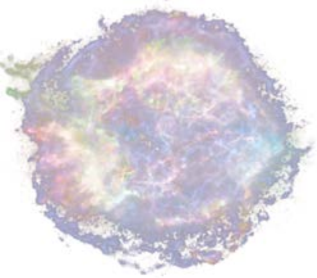
$\epsilon = 0.4, 0.6, 0.8$

HALO 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



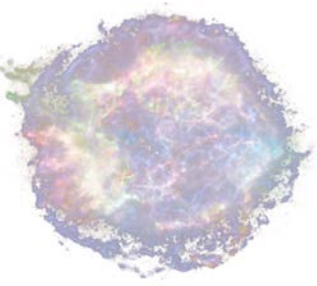




Accessible Measurements

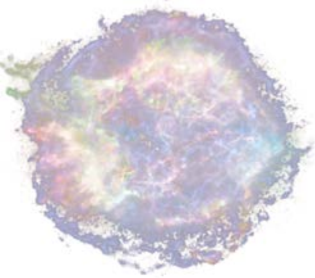
It is our premise that $\overline{\nu}_e$ sensitivity alone can not address all topics of interest and that data from HALO / HALO-1kT, with its complementary sensitivity, could be key. From our Letter of Intent such topics include:

- 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. [Wal16].
- 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. [Dua10][Fog07]
- 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. [Fis16].



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). [Raf11]
- 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 [Hor15]. 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 [Vaa11] [Sch12].
- more in LoI, references there
- Janet Rumleskie is pursuing joint HALO-1kT / SNO+ analyses



Simulation Studies

- constrain to 10,000 litre.atmospheres of ^{3}He; 1000 tonnes of lead; 5.5 m depth of lead volume / length of 3 standard ^{3}He counters
- 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 water shielding
  - more
- no consideration to backgrounds in these studies and the effect on neutron capture efficiency and participation in SNEWS

Risk#3 – various background sources (unsimulated) dictate a higher threshold for SNEWS and sensitivity not covering the whole galaxy – mitigation later

Neutron / “Neutron” Backgrounds

- use SNEWS efficiency to far edge of galaxy to set background requirements for HALO-1kT
  - neutron / neutron-like events must be < 6.7 Hz in HALO-1kT for viable SNEWS trigger
  - employ a safety factor → go to 1 Hz max, extends trigger range by ~70%, or allows for the cross section to be a factor of 3 lower
  - any individual contributions < 10% of this, i.e. < 0.1 Hz

- cf HALO / NCDs (370 m array) Actuals
  - 1300 neutrons /day (0.015 Hz) of which
    - 23 ± 5 from ^{238}U spontaneous fission
    - 80 ± 43 from nearby stored ^{252}Cf calibration source
    - ~25 from neutron counter’s internal α contamination
    - rest from leakage through shielding or (α,n) on internal materials
  - cosmic muons → spallation – few per month

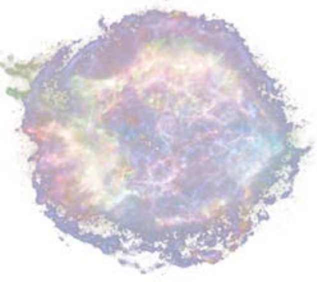
Neutron / “Neutron” Backgrounds

- HALO-1kT (4312 m array) Budget
  - < 86400 neutrons/day (1Hz) of which
    - < 8640 /day from SF → sets a spec
    - < 8640 /day from internal α contamination
      - measurements on commercial test counters project to ~105,000 /day
      - need a factor of ~12 reduction → R&D next slide
    - < 8640 leakage through shielding → sets a spec
      - background in LNGS less
      - similar shielding, higher capture efficiency, but greater area, added reflector?
    - < 8640 neutrons from (α,n) on internal materials → sets several specs
    - < 8640 beta/Compton scatter events above 191 keV → R&D to minimize and sets several specs
  - QA program implied for material acceptance
  - cosmic muons
    - flux ~109 x greater than SNOLAB, detector larger mass → ~900/day resulting in ~100 spallation events/day but short capture time

Internal α's and P(^{3}He) Optimization

- α-counting on test counter from GE Reuter-Stokes so far suggests bulk U/Th contamination at the level of 100 ppb by mass for SS
- radiopurity.org suggests factor of 20-200 reduction possible with choice of SS stock
- this assumes that the tube walls are making the dominant contribution
- 6 counters of various wall materials and gas-fills on order for further tests

- increasing ^{3}He pressure in geometry optimized for 10,000 litre.atm shows only small improvement in efficiency
- need to repeat the optimization at a couple of other ^{3}He quantities to understand real slope of efficiency to ^{3}He, followed by a cost-benefit analysis to select amount of ^{3}He



Risk Mitigation Strategies

- Risk #1 – uncertainty in observed statistics for a given SN distance
  - Reduce uncertainty with a measurement of the ν-Pb cross sections at the ORNL SNS facility
- Risk #2 – not achieving neutron capture efficiency goals
  - use HALO as a component test bed for prototypes
  - continue MC development in parallel
  - make use of HALO experience
- Risk #3 – various background sources force a higher SNEWS trigger threshold
  - develop and set conservative specs on all contributing background sources
  - plan for a QA program for material selection