Supernovae, SNEWS & the HALO program

Queens Summer Student series

May 13, 2020

LaurentianUniversity
UniversitéLaurentienne

SNOLAB

Clarence J. Virtue

Big Picture

- Supernovae
- SNEWS
- HALO program

Supernovae!

- A few facts
  - One of the most energetic astronomical events
  - Optically, a single supernova can outshine its home galaxy of a few hundred billion stars for several months
  - Ejects a “supernova remnant” that is rich in heavy elements
  - Leaves behind a neutron star, or a black hole, or sometimes nothing at all

Supernovae...

- More facts
  - Common in the universe, rare in our galaxy
  - Classified by astronomers according to spectral properties
  - For our purposes...
    - Type IA – binary star system
      - Standard candle
      - Thermonuclear explosion, no NS or BH
    - Type II – massive solitary star
      - “core collapse”
      - Our focus!

Core-Collapse Supernovae

- Why are core collapse SNe interesting?
  - Most of the energy of the explosion is released as neutrinos!
  - The kinetic energy of blowing a massive star to pieces and the optical output of outshining 100 billion stars for months is < 1% of energy released
  - 10^{58} neutrinos carry away 99% of the energy in < 10 seconds from the time of core collapse

What can you do with 10^{58} $\nu's$?

- IF you can detect the neutrinos...
  - Detect “far away” SN explosions (Type II)
  - Look inside the SN at how it happens
  - Test physics under extreme conditions
  - Shed some light on nucleosynthesis
  - See evidence of physics processes that occur no where else in the universe
  - See the formation of a black hole
  - Alert astronomers that a star is “about” to explode (SNEWS – more later)

Intrinsically interesting...

- Not only all those things but
  - SNe disperse the elements fused in stars for the formation of planets, ...
  - SNe are one of two sites responsible for the creation of elements heavier than Fe
  - SN shock waves create density fluctuations that lead to the formation of solar systems
  - “we are stardust”

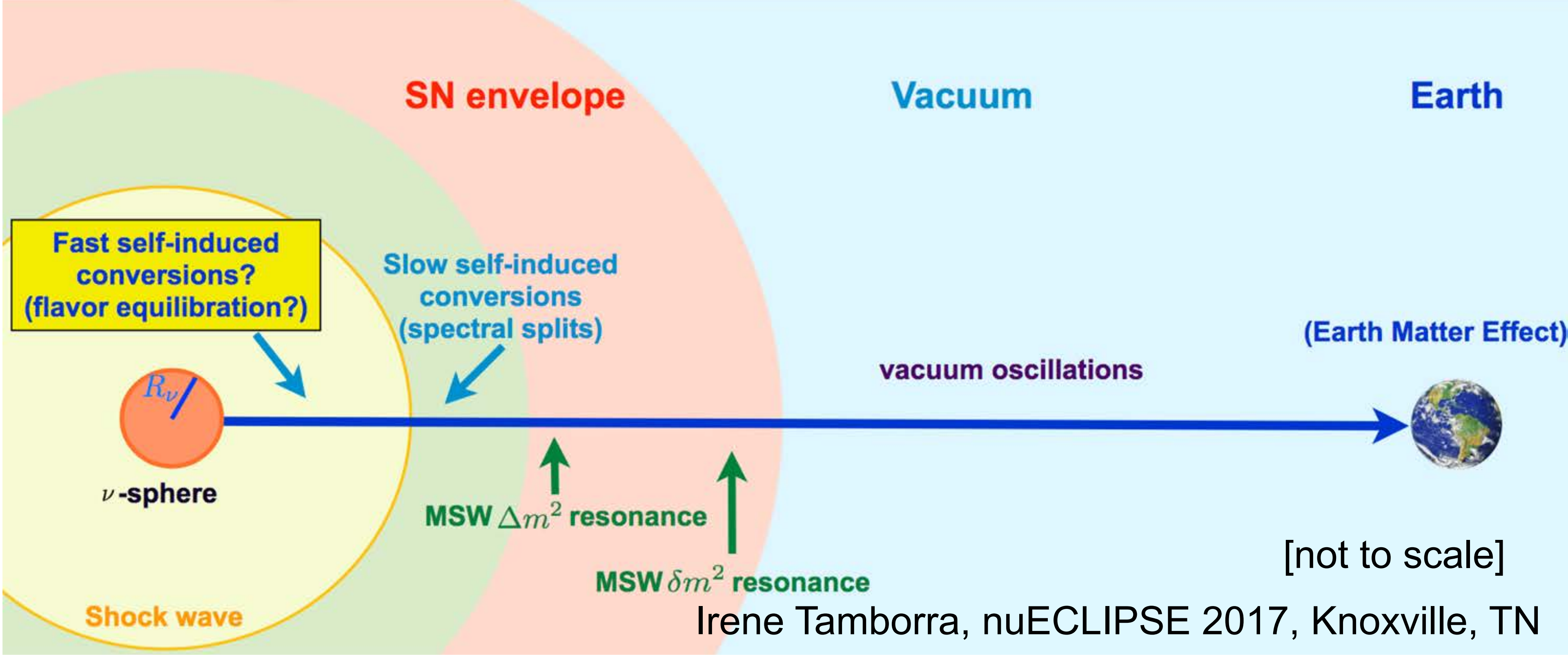
"Far away" explosions

- That's relative...
  - Galactic, extra-galactic or cosmological distances are measured in kpc, Mpc or Gpc (or ly)
  - ly = ~ 10 trillion km (10^{16} m)
  - pc = 3.26 ly
- Scales... (according the the Galaxy Song)
  - "Our galaxy itself contains a hundred billion stars.
    It's a hundred thousand light years side to side.
    It bulges in the middle, sixteen thousand light years thick,
    But out by us, it's just three thousand light years wide.
    We're thirty thousand light years from galactic central point.
    We go 'round every two hundred million years, ..."
  - https://www.youtube.com/watch?v=fqBThWK8rqE

So how big is 10^{58}?

- After 30,000 yrs of getting thinner and thinner at the speed of light...
- $10^{58} / 4\pi r^2 = 10^{12}\ \upsilon\ \mathrm{cm}^{-2}\ \mathrm{burst}^{-1}$ at earth
- cf solar neutrino flux of energetic neutrinos of $6 \times 10^{6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ ...
- For a few seconds about 100,000 times brighter than the sun, so seen in detectors as a few second burst of neutrino events
- On the other hand Andromeda is about 85x further away so a much fainter “burst”

What generates the burst?



[not to scale]

Irene Tamborra, nuECLIPSE 2017, Knoxville, TN

- 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 $\bar{\nu}_e$, ν_e , ν_x and the time evolution of their flux and energy spectra with marginal statistics?!

Supernova Neutrinos – First Order Expectations

- Approximate equipartition of neutrino fluxes
- Several characteristic timescales for the phases of the explosion (collapse, burst, accretion, cooling)
- Time-evolving ν_e, $\overline{\nu}_e$, ν_x luminosities reflecting aspects of SN dynamics
  - Presence of neutronization pulse
  - Hardening of spectra through accretion phase then cooling

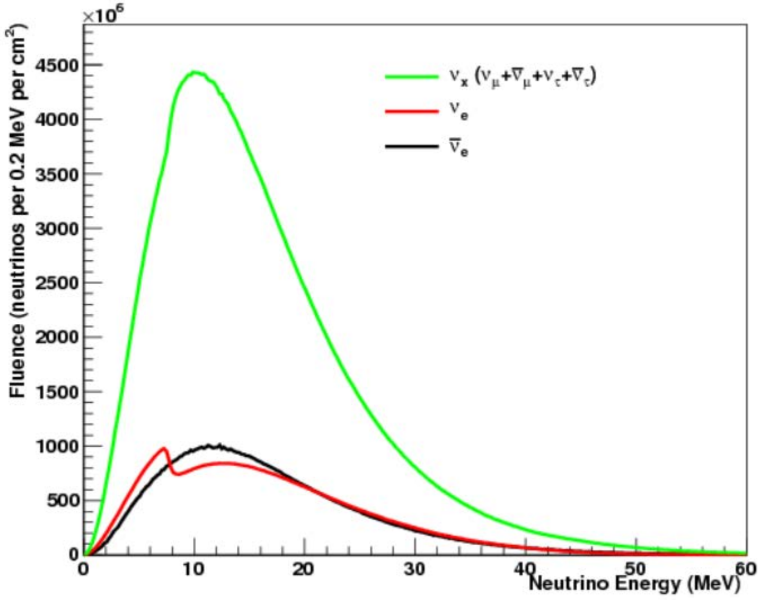
- Fermi-Dirac thermal energy distributions characterized by a temperature, T_ν, and pinching parameter, η_ν

$$\phi_{FD}(E_\nu) = \frac{1}{T_\nu^3 F_2(\eta_\nu)} \frac{E_\nu^2}{\exp\left(E_\nu/T_\nu - \eta_\nu\right) + 1}$$

- Hierarchy and time-evolution of average energies at the neutrinosphere

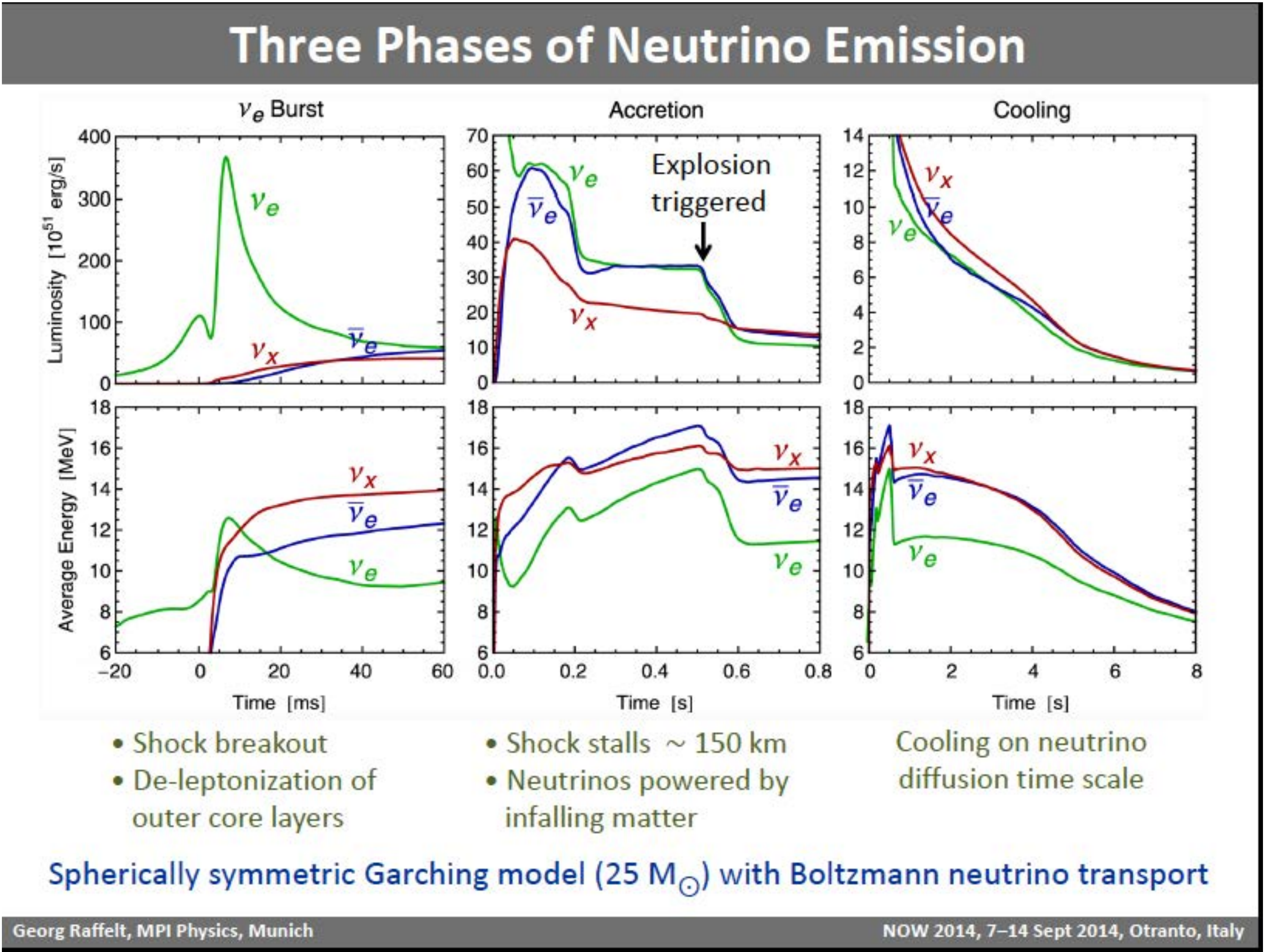
$$T(\nu_x) > T(\overline{\nu}_e) > T(\nu_e)$$

- ν-ν scattering collective effects and MSW oscillations further imprint physics on the FD distributions



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

non-trivial flavor and time dependence of emitted neutrinos



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

What is to be Learned?

- 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.

The Trouble with Supernovae

- Very frequent in our universe (1 per second)
- Current and next generation terrestrial supernova detectors only see supernovae within our galaxy (tiny part of the universe)
- So.... The galactic supernova rate is estimated at

3 +/- 1 per century

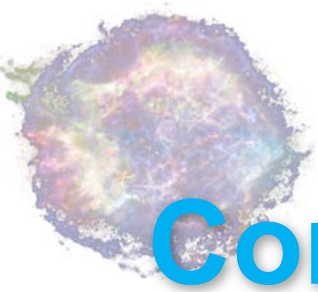
Put another way...

An observed SN signal potentially has information in its:

- The time evolution of the luminosities
- The time evolution of the average energies
- The values of the pinching parameters
- Deviation from the equiparition of fluxes
- Modifications of the above due to ν-ν scattering collective effects and MSW oscillations

What distinguishes SN neutrinos from others?

- Unlike solar, atmospheric, reactor or geo-neutrinos... SN neutrinos are not always there
- Unlike accelerator neutrinos we don't know when they are coming
- Unlike appearance or disappearance experiments the "beam" contains all flavours ~ equally
- The beam is a primary beam (not tertiary as for atmospheric or accelerator neutrinos) and the energy spectrum has direct physics content
- The intensity of the beam has a probable value but could differ by more than 2 orders of magnitude
- They have their own characteristic range of energies determined by core collapse physics and SN1987A confirms that we have some understanding of that
- Energies are "thermal" described by Fermi-Dirac function modified by a pinching parameter or chemical potential, at least initially, and are imprinted with further physics processes of great interest

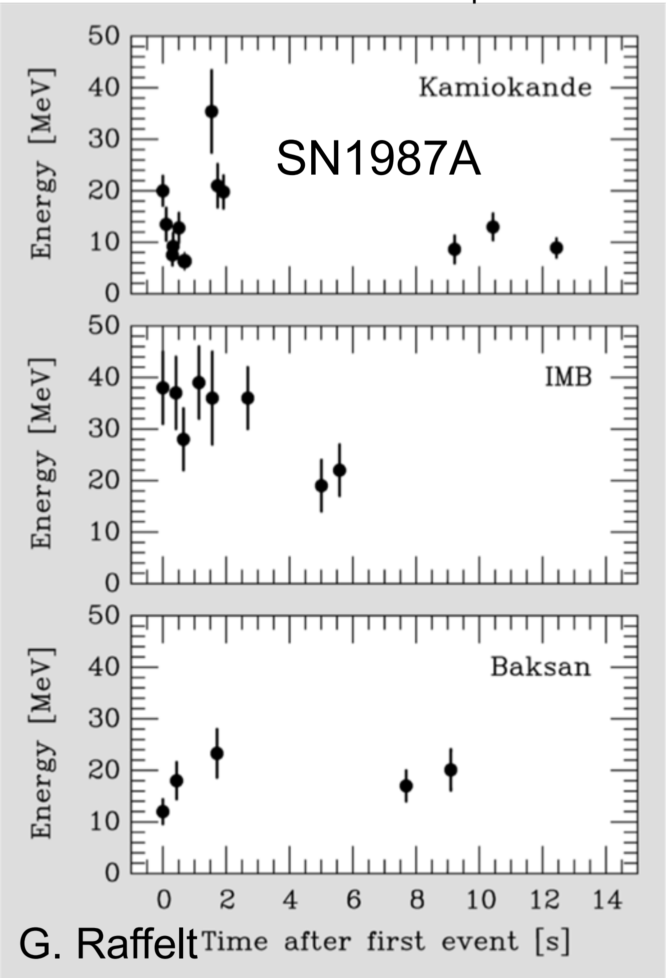


ernova Neutrinos

t is the interest?

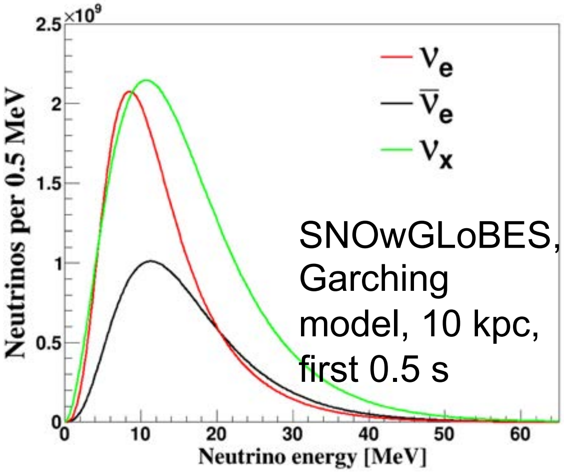
Core-Collapse Supernovae

- 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



SN1987A

G. Raffelt



SNOwGLoBES, Garching model, 10 kpc, first 0.5 s

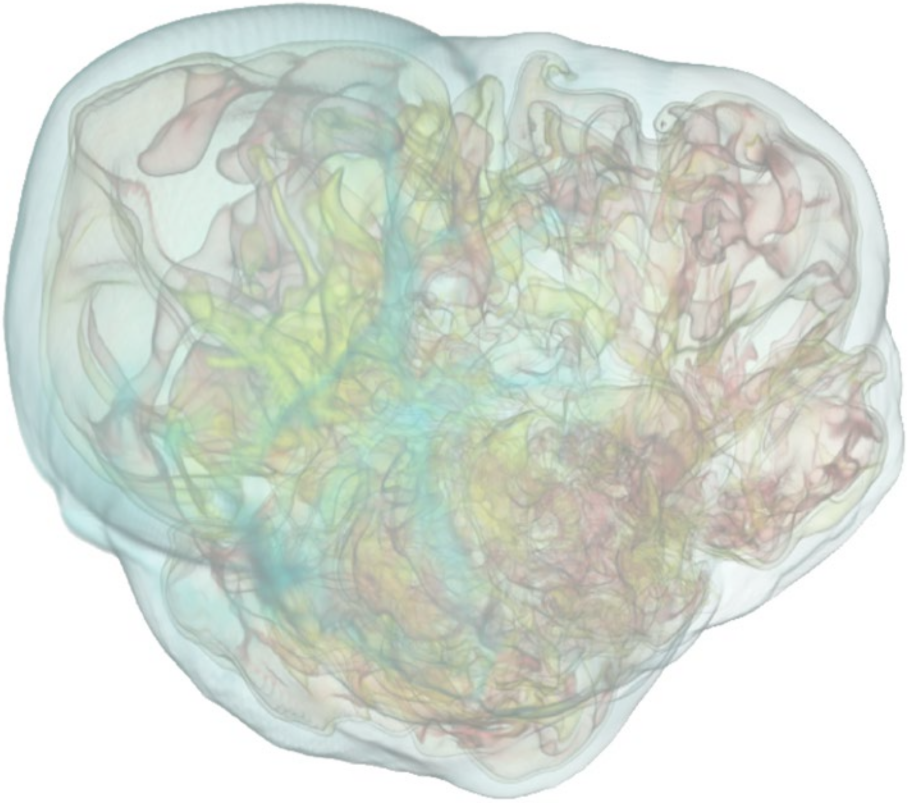
- we start with Fermi-Dirac distributions at the neutrino-spheres with:

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

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

SNEWS – the SuperNova Early Warning System

- Supernova Neutrinos in the Multi-Messenger Era

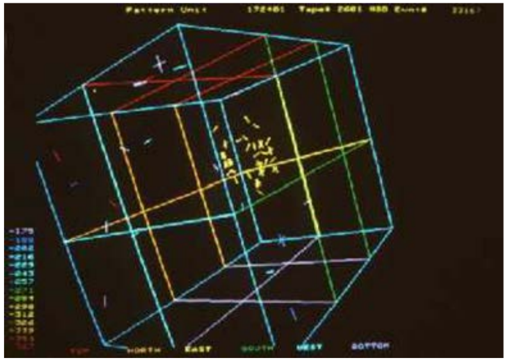


The original SNEWS

- Incubated at Neutrino 1996 (Helsinki) and Neutrino 1998 (Takeyama) by John Bahcall and members of Super-K, SNO, MACRO and LVD
- Followed by "1st International Workshop" in Boston, Sept. '98
- How to do the next SN1987A better....

The opportunity

- Though Ian Shelton observed SN1987A first and the neutrino signal was found later the neutrinos arrived about 1.5 hours before first light
- Monitoring for neutrino bursts could provide an early warning...

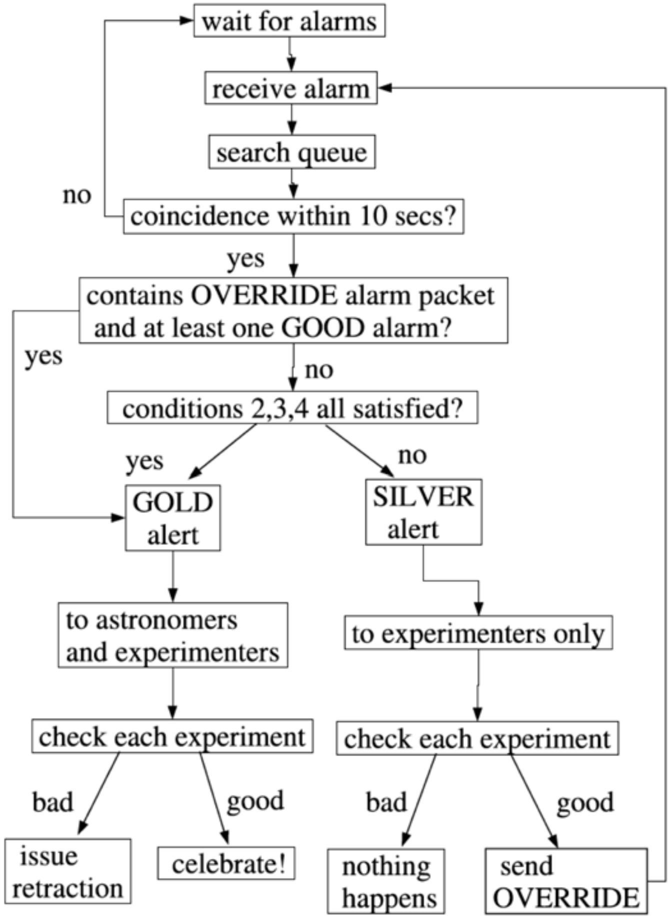


Philosophy – the three P’s

- Prompt
  - Experiments send “ALARMs”
  - SNEWS issues “ALERTs” within a few minutes of ν-burst
- Pointing
  - Highly desirable
  - Triangulation requires several high statistics detectors
  - Super-K can use anisotropic ν-e elastic scattering
- Positive
  - Tolerable false alarm rate ~ 1 / century (“not in my lifetime”)

Implementation

- Coincidence between two or more detectors in a 10 second window
- Automated if some conditions respected
  - Burst history of individual detectors, $\lambda_{max} < 1$ per week
  - Not co-located
  - Flagged by experiments as “good”
- Also vehicle for distribution of “confirmed” alarms



Other Features

- Redundancy
  - Secure redundant servers housed at BNL
  - Backup redundant servers at INFN Bologna
- Dissemination
  - Signup list for Alerts maintained at https://snews.bnl.gov/alert.html
- Governance
  - MOUs signed with participating experiments
  - Working group members from each experiment
- Downtime coordination through webpage accessible to WG members
- Regular meetings at bi-annual Neutrino conferences

Past History

EXPERIMENT	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Super-K	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
SNO	🟦	🟦													
Ice Cube	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
LVD	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Borexino					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
KamLAND										🟩	🟩	🟩	🟩	🟩	🟩
Daya Bay											🟩	🟩	🟩	🟩	🟩
HALO												🟪	🟪	🟪	🟪

Save-the-data trigger:

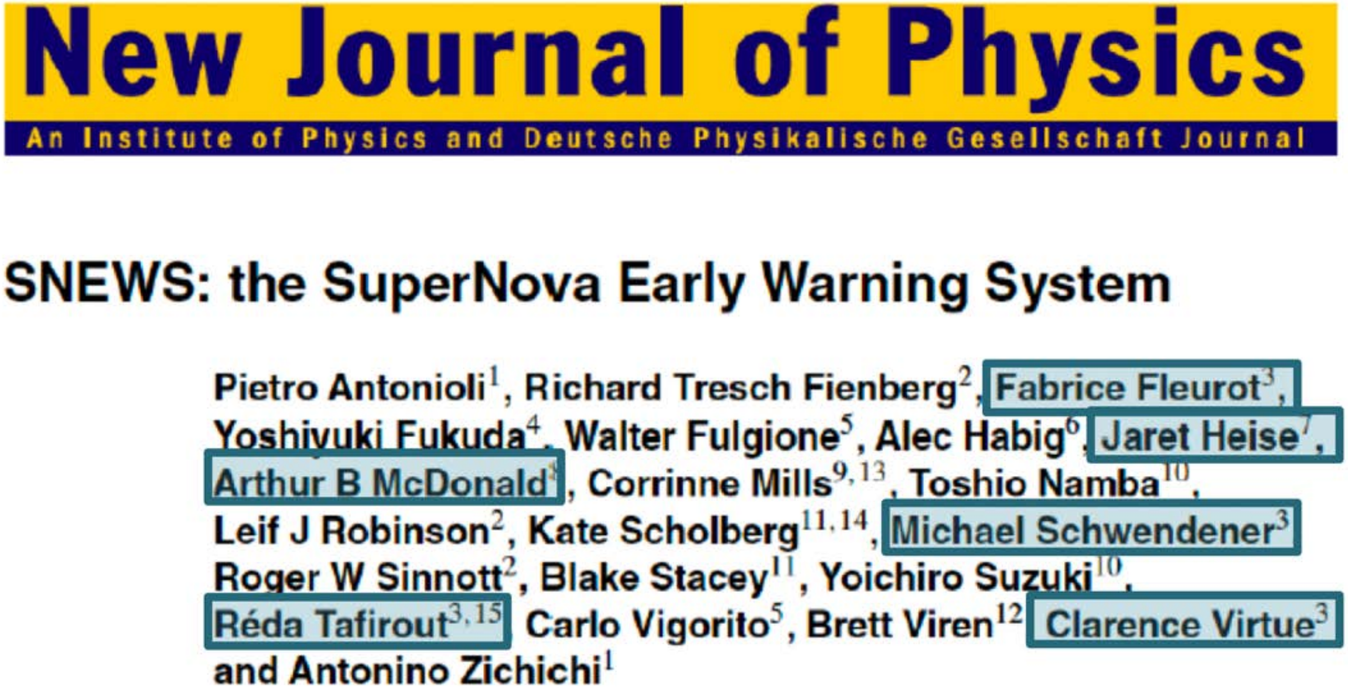
NOvA 2015+

XENON1T 2017-2018

Don't stop taking data:

LIGO 2015+

Strong Canadian participation from the start…



New Journal of Physics

An Institute of Physics and Deutsche Physikalische Gesellschaft Journal

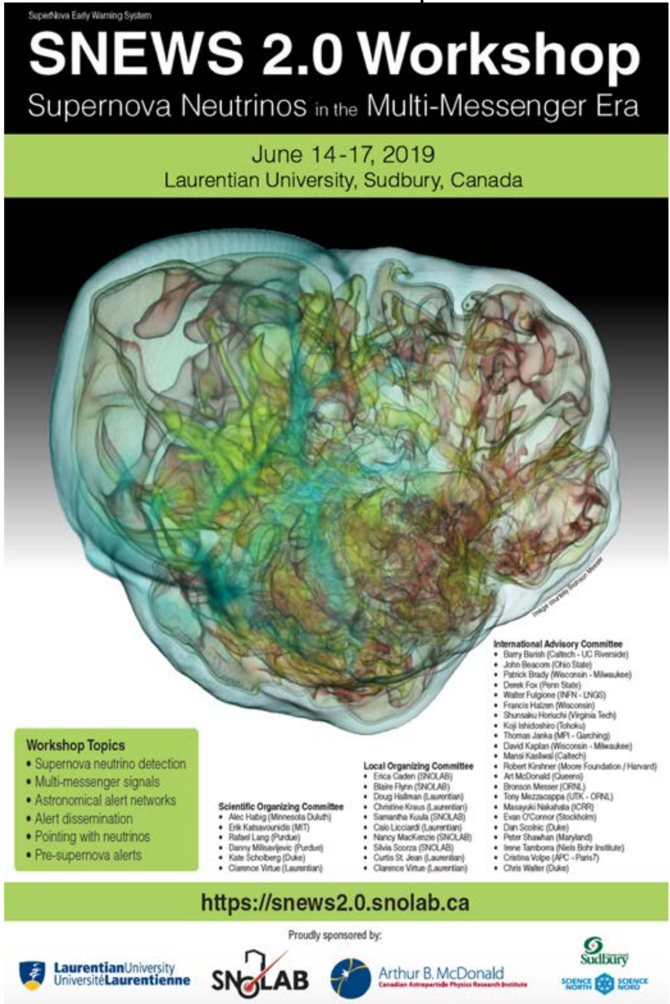
SNEWS: the SuperNova Early Warning System

Pietro Antonioli[1], Richard Tresch Fienberg[2], Fabrice Fleurot[3], Yoshiyuki Fukuda[4], Walter Fulgione[5], Alec Habig[6], Jaret Heise[7], Arthur B McDonald[8], Corrinne Mills[9,13], Toshio Namba[10], Leif J Robinson[2], Kate Scholberg[11,14], Michael Schwendener[3], Roger W Sinnott[2], Blake Stacey[11], Yoichiro Suzuki[10], Réda Tafirout[3,15], Carlo Vigorito[5], Brett Viren[12], Clarence Virtue[3] and Antonino Zichichi[1]

doi:10.1088/1367-2630/6/1/114

2004 publication

SNEWS 2.0 for MMA Era



SuperNova Early Warning System

SNEWS 2.0 Workshop

Supernova Neutrinos in the Multi-Messenger Era

June 14-17, 2019
Laurentian University, Sudbury, Canada

Workshop Topics
- Supernova neutrino detection
- Multi-messenger signals
- Astronomical alert networks
- Alert dissemination
- Pointing with neutrinos
- Pre-supernova alerts

Scientific Organizing Committee
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- Erik Katsavounidis (MIT)
- Rafael Lang (Purdue)
- Danny Milisavljevic (Purdue)
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- Clarence Virtue (Laurentian)

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- Cristina Volpe (APC - Paris7)
- Chris Walter (Duke)

https://snews2.0.snolab.ca

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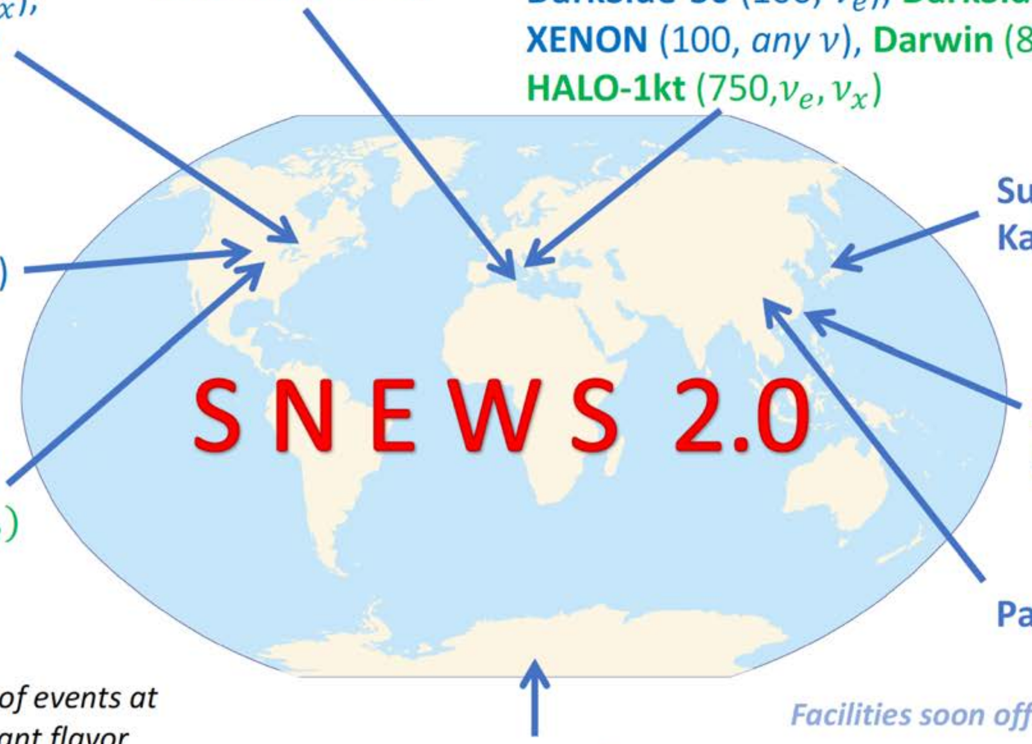
What’s new?

Co-incident with Sudbury Workshop –

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

Evolving set of detectors



HALO (30,ν_e, ν_x),
SNO+ (300,$\overline{\nu_e}$)

KM3NeT (10^5,$\overline{\nu_e}$)

LVD (300,$\overline{\nu_e}$), **Borexino** (100,$\overline{\nu_e}$),
DarkSide-50 (100, $\overline{\nu_e}$), **DarkSide-20k** (250, *any* ν)
XENON (100, *any* ν), **Darwin** (800, *any* ν)
HALO-1kt (750,ν_e, ν_x)

NOvA (4000,$\overline{\nu_e}$)

Super-K (7x10^4,$\overline{\nu_e}$)
KamLAND (300,$\overline{\nu_e}$)

Daya Bay (100,$\overline{\nu_e}$)
JUNO (1000, $\overline{\nu_e}$)

LZ (100, *any* ν)
DUNE (3000,ν_e)

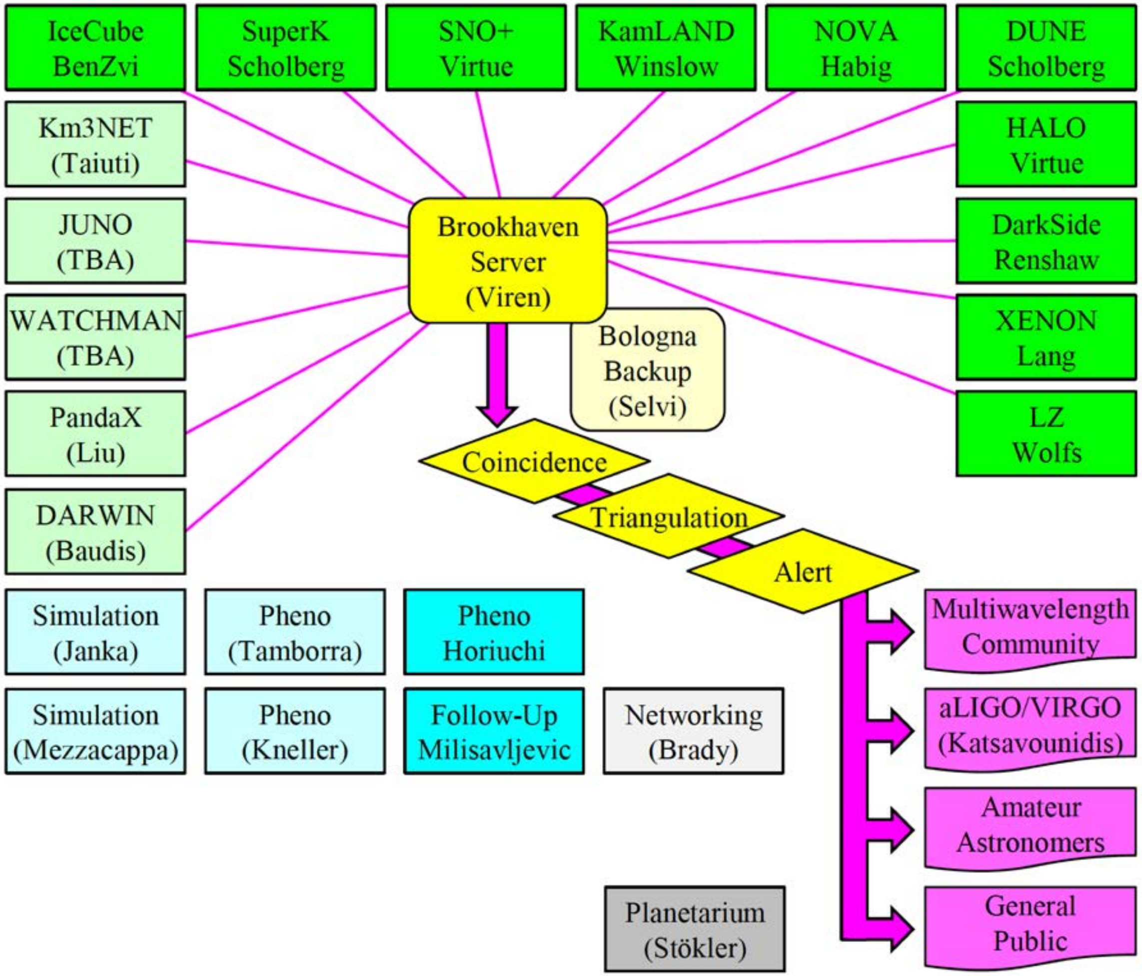
PandaX (100, *any* ν)

IceCube (10^6,$\overline{\nu_e}$)

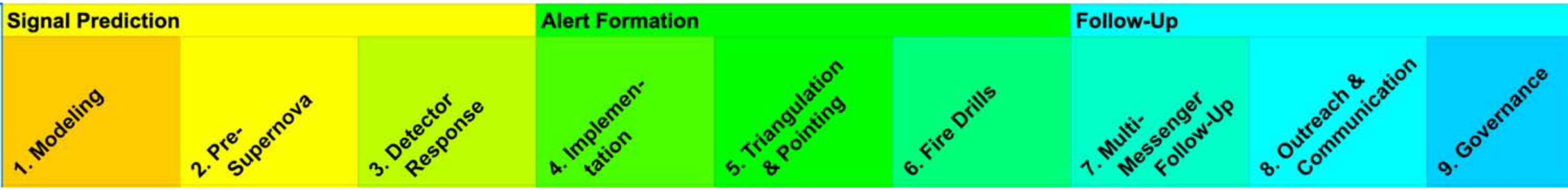
Expected number of events at 10 kpc and dominant flavor sensitivity in parenthesis

Facilities soon offline, ***current facilities***,
future facilities

Enhanced MMA integration



Working Group Structure / Status



Signal Prediction			Alert Formation			Follow-Up		
1. Modeling	2. Pre-Supernova	3. Detector Response	4. Implementation	5. Triangulation & Pointing	6. Fire Drills	7. Multi-Messenger Follow-Up	8. Outreach & Communication	9. Governance

- Group conveners identified
- Regular working calls scheduled / happening
- Propose virtual meeting, first since Sudbury Workshop, in June “adjacent to Neutrino 2020”

The Helium and Lead Observatory Program

Laurentian University
Université Laurentienne

SNOLAB

Clarence J. Virtue

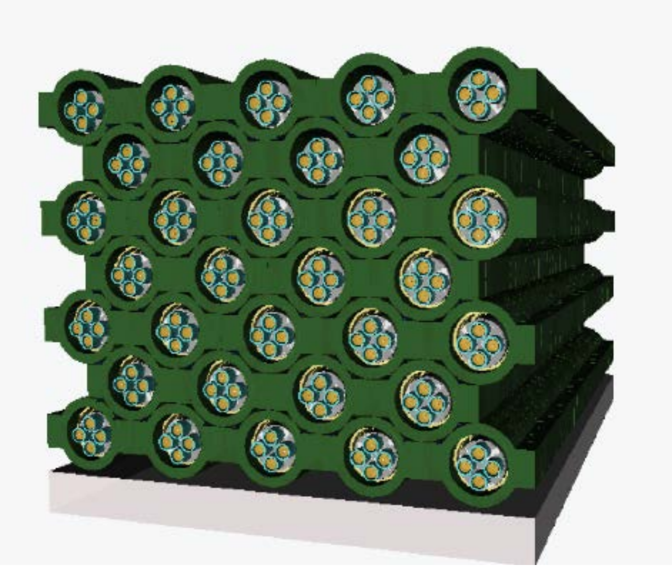
HALO - a Helium and Lead Observatory

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



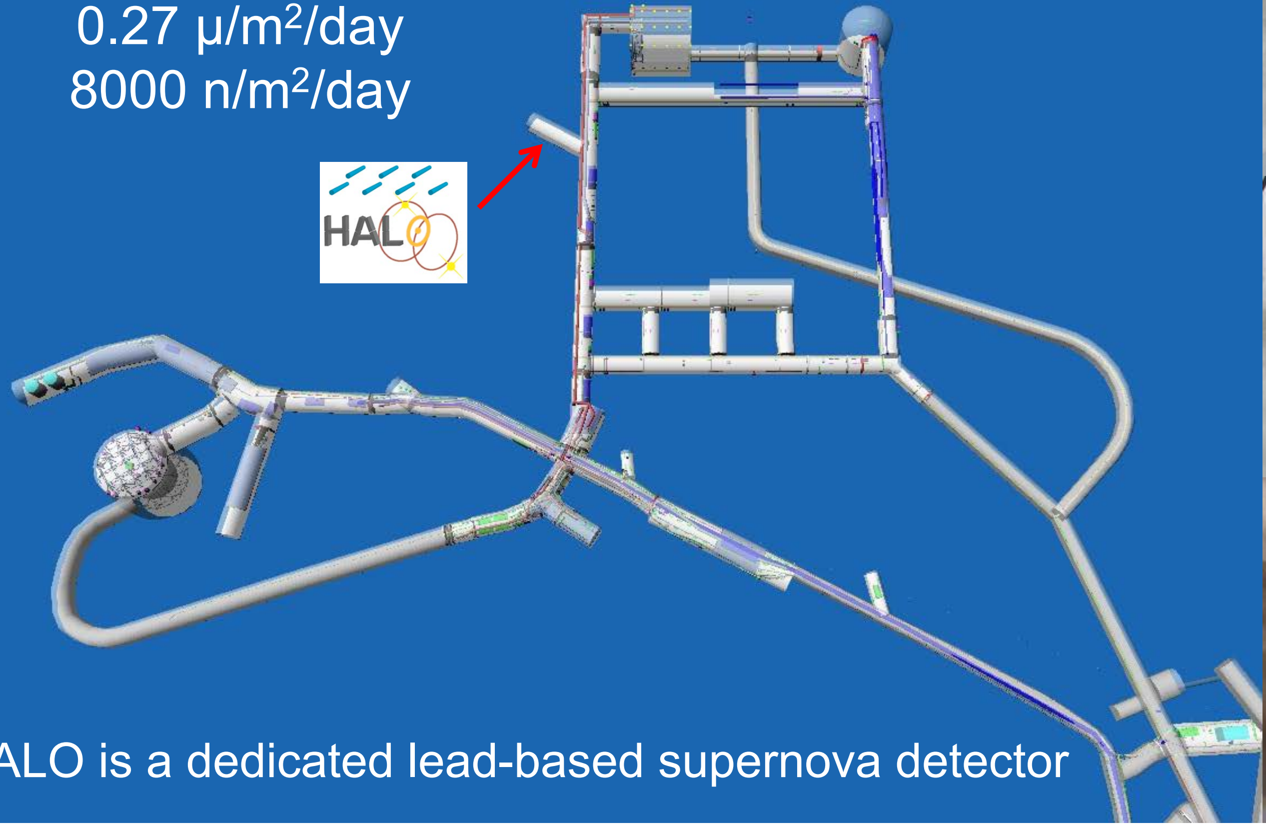
HALO is using lead blocks from a decommissioned cosmic ray monitoring station

Science Motivation

- While the probability of a galactic SN in a lifetime are good, most supernova-sensitive detectors have other primary objectives necessitating down-time; extensive calibration; reconfiguration; and end of life
- So.... there's a niche for low cost, low maintenance, long lifetime, dedicated supernova detectors
- Also for next generation neutrino detectors costs go up as the energy threshold goes down and there is a risk that supernova sensitivity will be degraded in order to save costs
- Water Cherenkov and liquid scintillator detectors have dominant $\bar{\nu}_e$ sensitivity but, valuable information is present in other channels too
- Lead will provide a dominant ν_e sensitivity

HALO at SNOLAB

SNOLAB 6800’ campus
6000 mwe depth
0.27 μ/m^2/day
8000 n/m^2/day



HALO is a dedicated lead-based supernova detector

Lead as a Supernova Neutrino Target

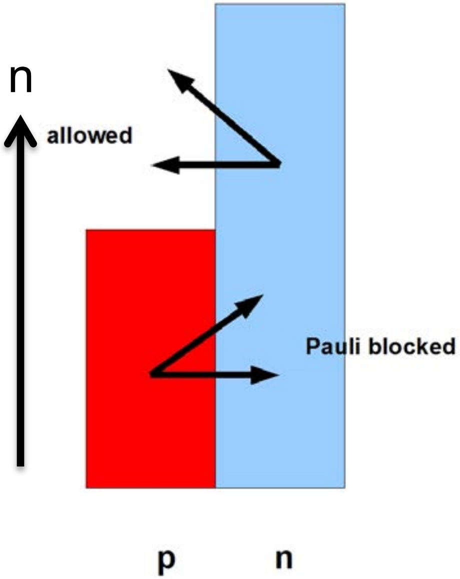
- CC and NC cross sections are the largest of any reasonable material though thresholds are high
- Neutron excess (N > Z) Pauli blocks

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

- High Z increases ν_e CC cross sections relative to $\bar{\nu}_e$ CC and NC due to Coulomb enhancement further suppressing the $\bar{\nu}_e$ 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 CC tagging
- no direct measure of neutrino energy

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

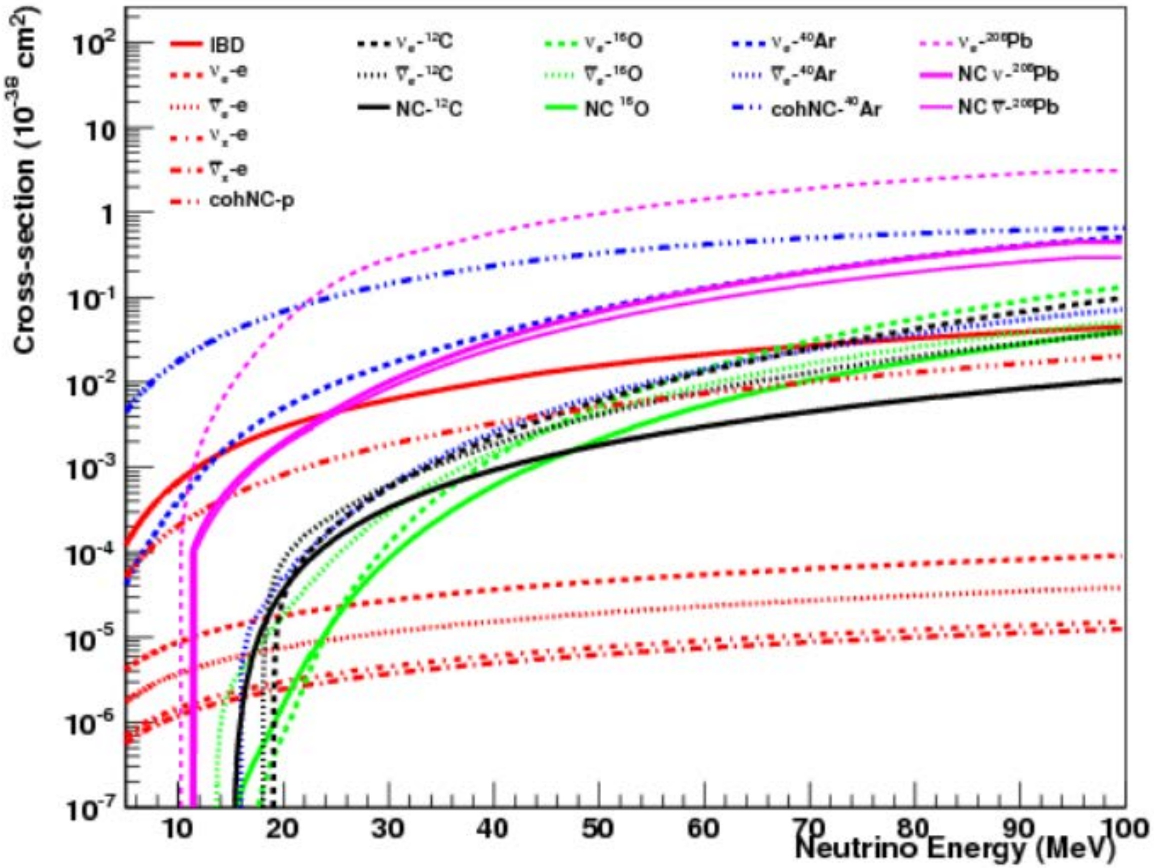
$$\begin{aligned}
\mathrm{CC:}\quad \nu_e + {}^{208}\mathrm{Pb} &\rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV} \\
\nu_e + {}^{208}\mathrm{Pb} &\rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV} \\
\mathrm{NC:}\quad \nu_x + {}^{208}\mathrm{Pb} &\rightarrow {}^{207}\mathrm{Pb}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

- 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

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))

Comparative ν-nuclear Cross-sections



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

CC:

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

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

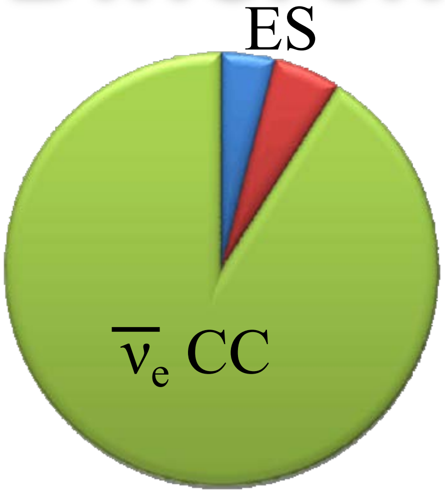
NC:

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$

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

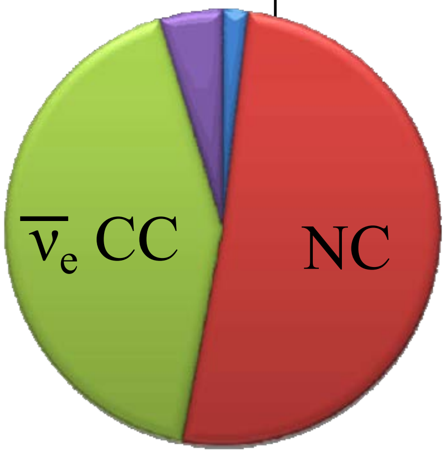
Thresholds
CC 1n 10.7 MeV
CC 2n 18.6 MeV
NC 1n 7.4 MeV
NC 2n 14.4 MeV

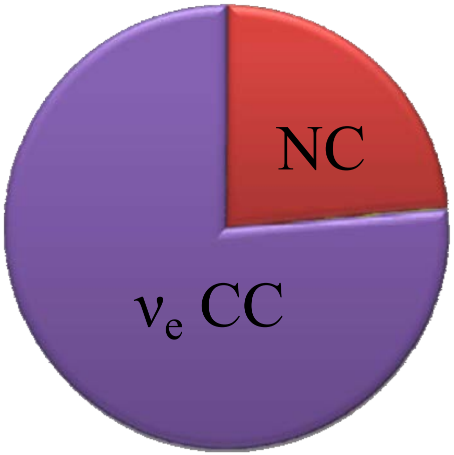
Flavour Sensitivities for Different Technologies



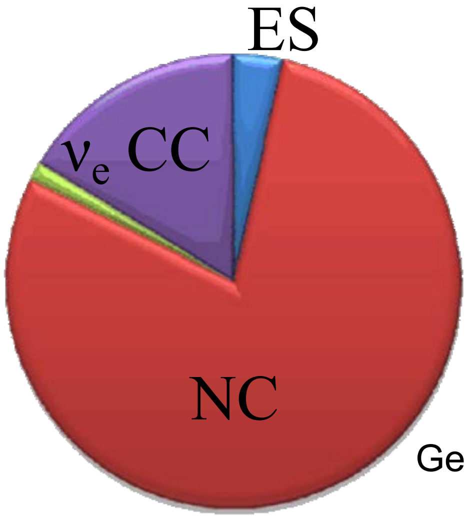
Water Cherenkov

Liquid Scintillator



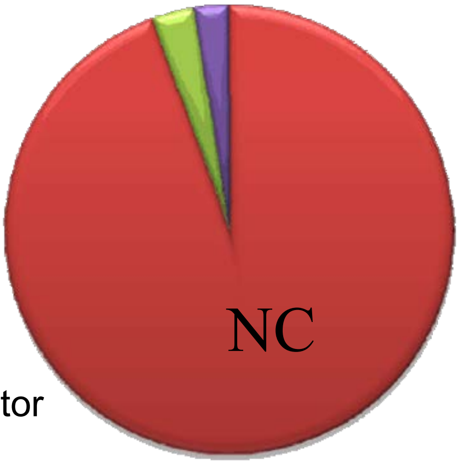


Lead



Liquid Argon

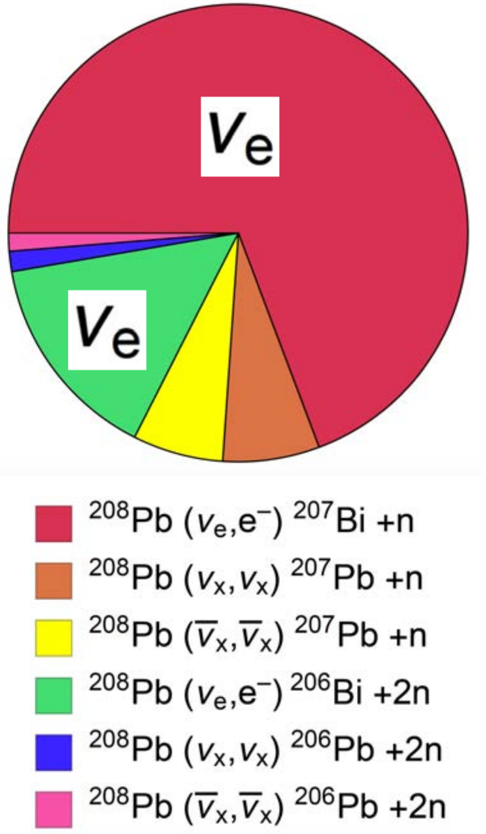
Iron



Generally functions of neutrino temperatures and detector energy thresholds, also needs updating for large θ_{13}

HALO Flavour Sensitivity

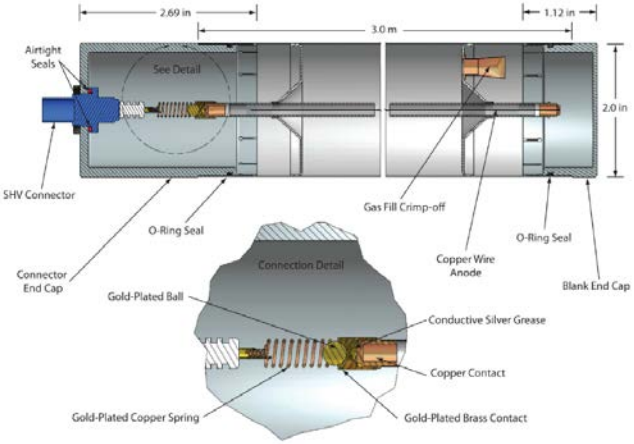
- the nuclear physics of lead strongly affects the interaction rates
  - the neutron excess in Pb Pauli blocks ν_e CC reactions
  - the high Z further Coulomb suppresses $\overline{\nu}_e$ CC and enhances ν_e CC
- the response remains an unresolved mixture of ν_e CC and ν_x NC but is largely orthogonal to $\overline{\nu}_e$ 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

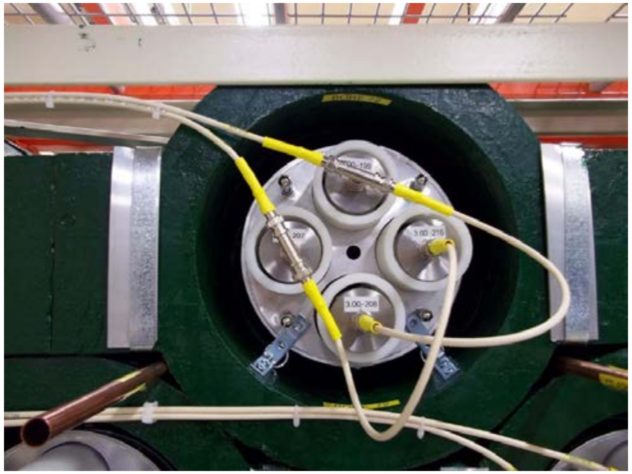


A. Gallo Rosso

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





SNEWS trigger

- currently running with a trigger condition of 4 events in neutron window in 2 seconds
- at 15 mHz neutron rate we expect random coincidences once per ~2 years
- pile-up between ^{238}U SF and randoms will increase this rate, but still very acceptable – few per year
- spallation events, over in < 1 ms, are suppressed and do not generate a SNEWS trigger

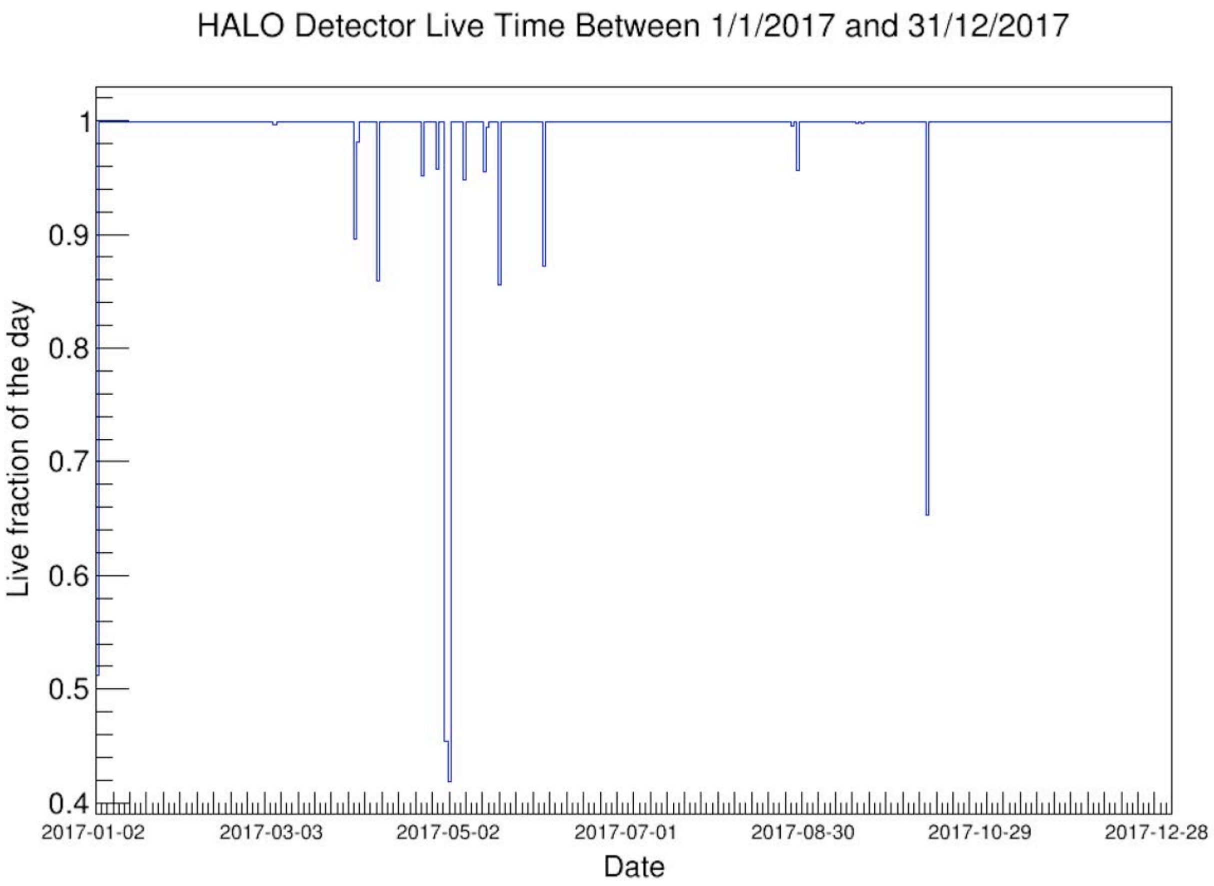
→ not at all limited by background rates

- sensitivity out to ~18 kpc

→ limited by target mass

Status “today”

- Full detector being read-out since May 8th 2012.
- Daily shift-taking since July 27th 2012.
- Burst trigger implemented and connected to SNEWS since October 8, 2015
- Full calibration done with and without front shielding wall April 2016
- work continues on monitoring tools
- 99.25% livetime in 2017



A few SNOLAB photos


H375
Ver. 7
Received
Jan. 10, 2012
Approved for HALO
H504
Ver. 6
Received
Nov 2011
Approved for HALO

re,


RACK 0
RACK 1
RACK 2
HALO Test Stand
HALO Pulse Distribution System
APC

The HALO Collaboration

HALO

Armstrong STATE UNIVERSITY

DigiPen INSTITUTE OF TECHNOLOGY

TECHNISCHE UNIVERSITÄT DRESDEN

Duke UNIVERSITY

LaurentianUniversity UniversitéLaurentienne

UMD DULUTH

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Pacific Northwest NATIONAL LABORATORY

SNOLAB MINING FOR KNOWLEDGE CREUSER POUR TROUVER... L'EXCELLENCE

ICRR Institute for Cosmic Ray Research University of Tokyo

TRIUMF

W UNIVERSITY of WASHINGTON

C Bruulsema[1], C A Duba[2], F Duncan[3,1], J Farine[1], A Habig[4], A Hime[5], A Kielbik[1], M Howe[6], C Kraus[1], S Luoma[1], R G H Robertson[7], K Scholberg[8], M Schumaker[1], J Secrest[9], T Shantz[1], J Vasel[4], C J Virtue[1], B von Krosigk[10], R Wendell[11], J F Wilkerson[6], S Yen[12] and K Zuber[10]

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Funded by:

NSERC CRSNG

NSF

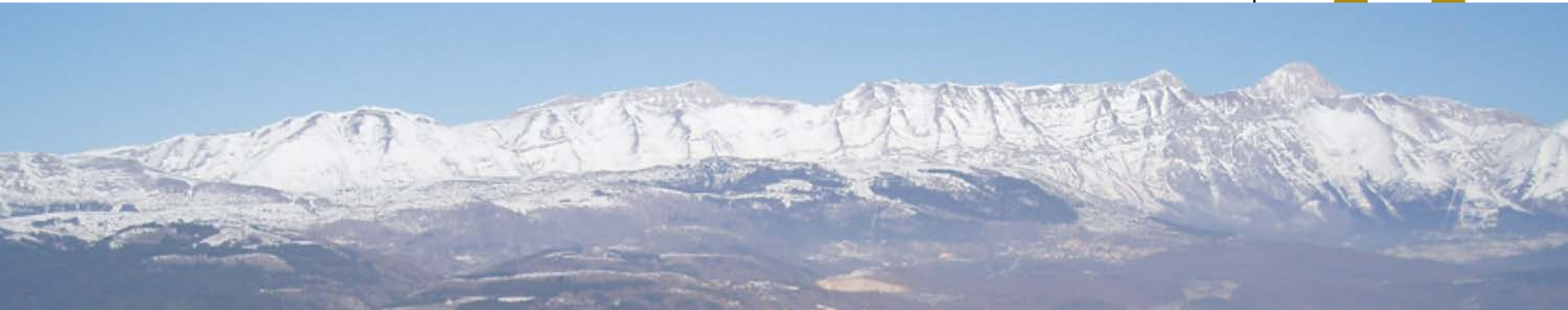
halo.snolab.ca

HALO-1kT at LNGS - Update

C.J. Virtue for the Collaboration

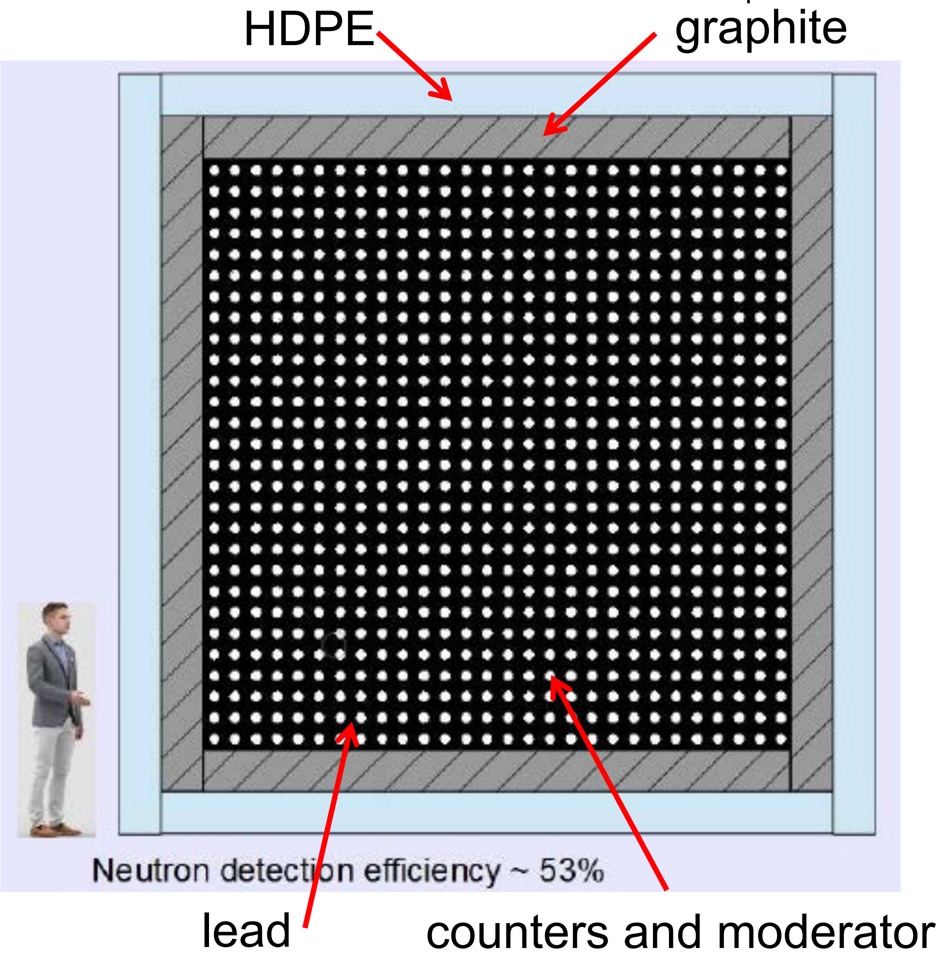
Open Session – October 21, 2019

LII meeting of the Gran Sasso Scientific Committee



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



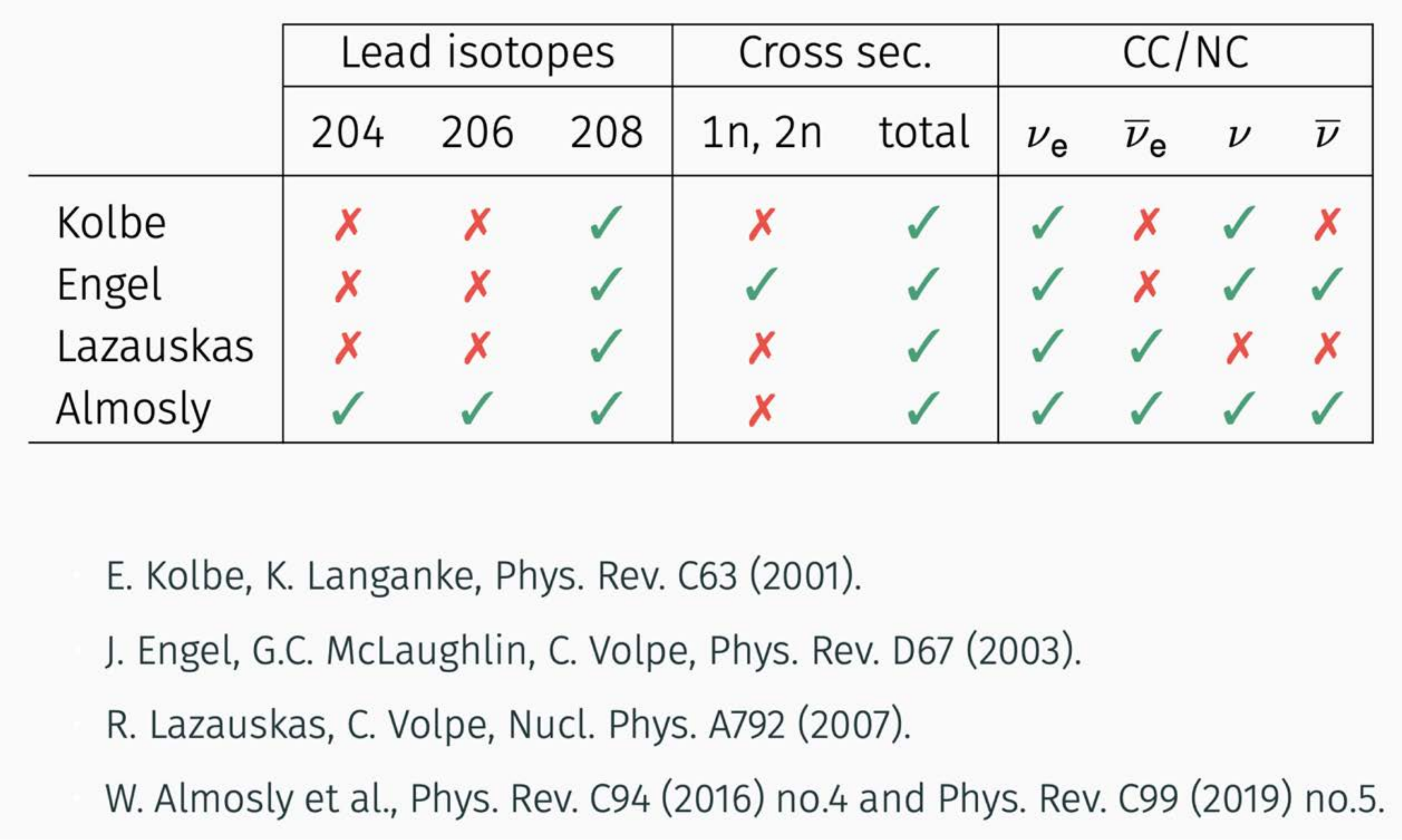
Neutron detection efficiency ~ 53%

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

Mini-HALO

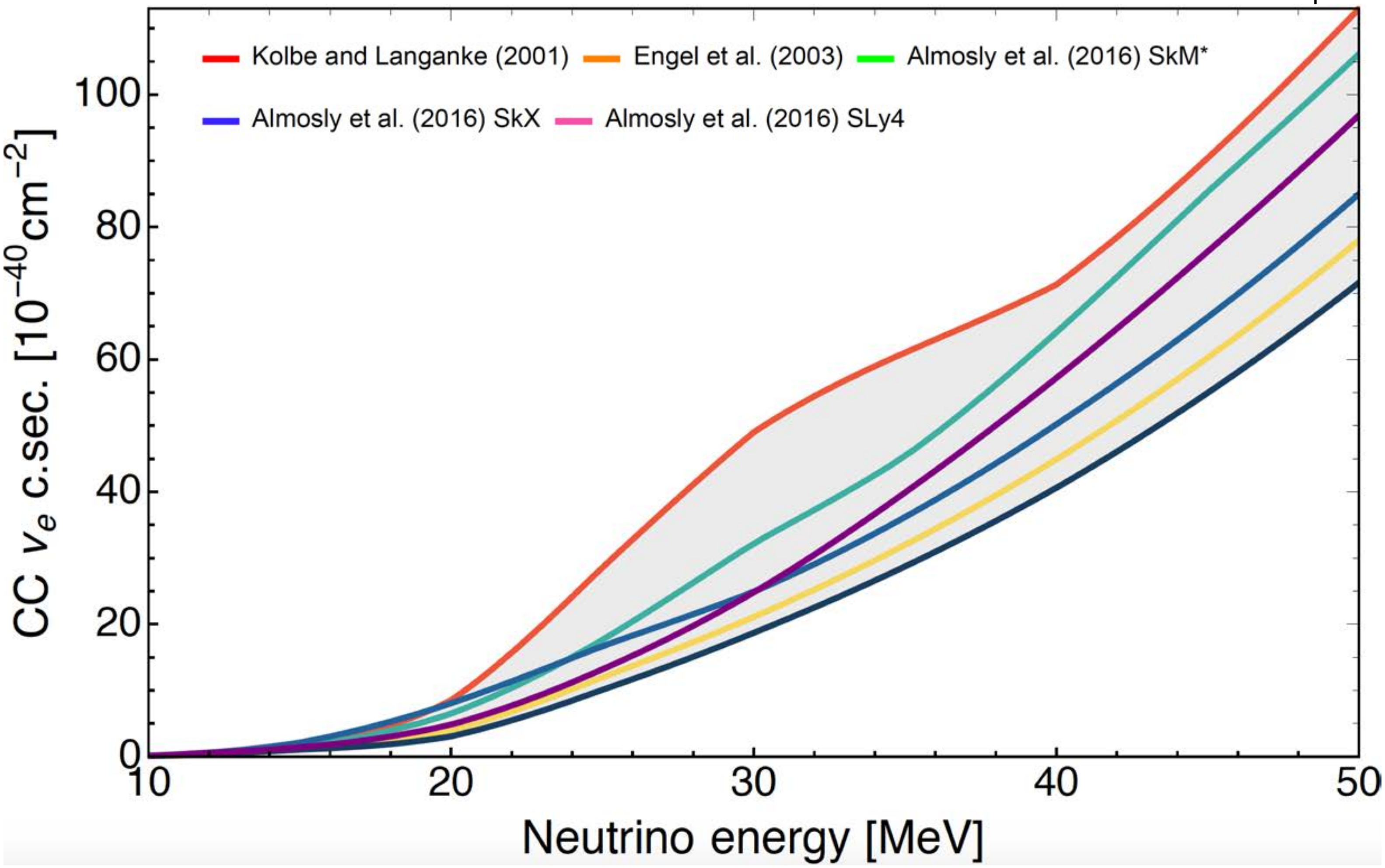
Available Cross Sections for Lead



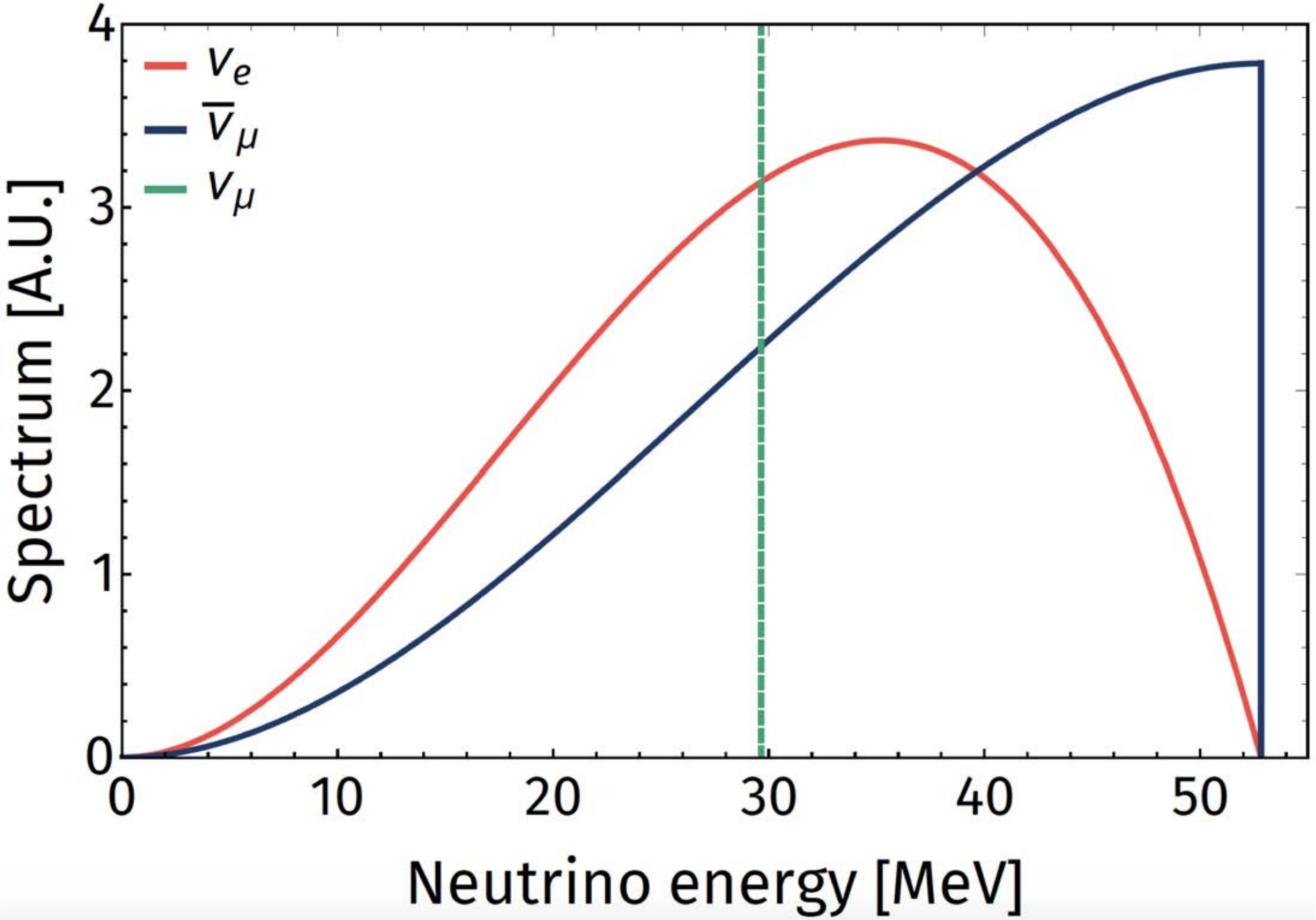
	Lead isotopes			Cross sec.		CC/NC			
	204	206	208	1n, 2n	total	ν_e	$\overline{\nu}_e$	ν	$\overline{\nu}$
Kolbe	✗	✗	✓	✗	✓	✓	✗	✓	✗
Engel	✗	✗	✓	✓	✓	✓	✗	✓	✓
Lazauskas	✗	✗	✓	✗	✓	✓	✓	✗	✗
Almosly	✓	✓	✓	✗	✓	✓	✓	✓	✓

- 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 υ Energy Spectra the from SNS



Design Overview – Mini-HALO

- Lead core, 10 tonne
- SNO He-3 detectors
- Up to 6” graphite
- Up to 6” HDPE (borated?)
- Muon veto