HALO

the Helium and Lead Observatory

Alec Habig, Univ. of Minnesota Duluth
for the HALO collaboration

Supernovae

HST photo by High-Z SN Search Team
Nearby SNIa in NGC 4526

- Stars blowing themselves entirely apart
- Type I
  - No H lines in the spectra
  - Ia (white dwarf nuclear deflagration) most common sort
- Type II
  - H spectral lines
  - Core collapse of massive stars at end of life
- Divided roughly equally
  - Plus several oddball hybrid classes

SN Galore

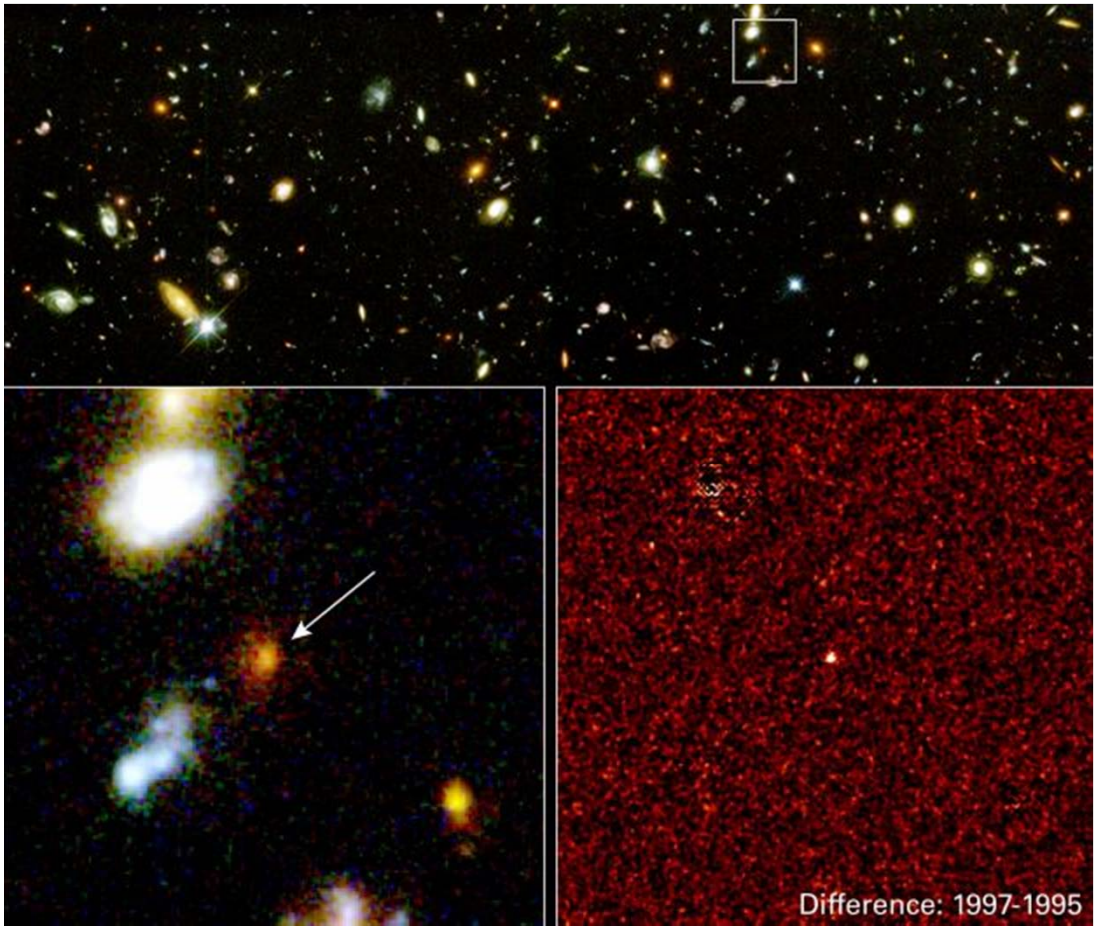


Photo by Adam Riess et al with HST

- Luminosity of a galaxy from one star for a few weeks
  - Visible across most of the universe
  - Ia are Standard Bombs used in cosmological work
  - These days the “year + letter” naming scheme is too cumbersome, almost need to bar code the things
- But all extragalactic!

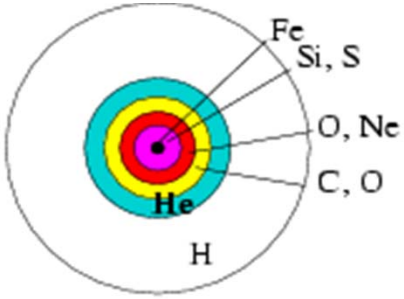
Core Collapse

- Type II SNe energy comes from gravitational collapse of iron core (also type Ib, Ic)
  - Can't fuse iron
  - When Chandrasekhar mass of iron accumulates, core goes from white dwarf conditions to neutron star conditions

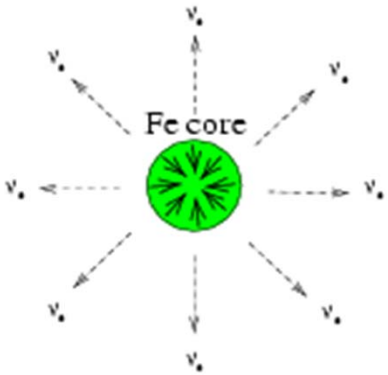
$$\Delta E_B \sim \frac{GM_{core}^2}{R} = 3\times10^{53}\left(\frac{M_{core}}{M_\odot}\right)\left(\frac{R}{10\text{km}}\right)^{-1} \text{ergs}$$

  - M_{core}~$1M_\odot$, R~10 km, so $\Delta E_{binding}$ is ~3×10^{53} ergs
- Luminosity of Type II SN somewhat less than Ia
  - Still, EM radiation only ~0.01% of $\Delta E_{binding}$
  - Plus add in kinetic energy of expanding SN remnant (~1%)
- Where's the rest of the gravitational energy going?
  - Neutrinos!

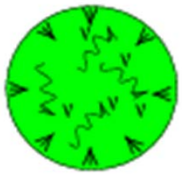
Core Collapse



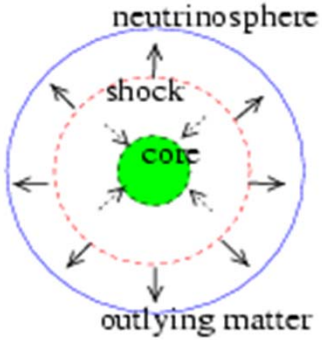
PRE-SUPERNOVA



COLLAPSE



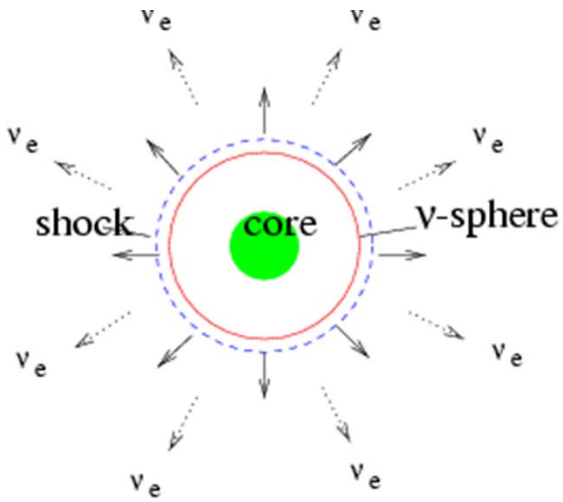
NEUTRINO TRAPPING



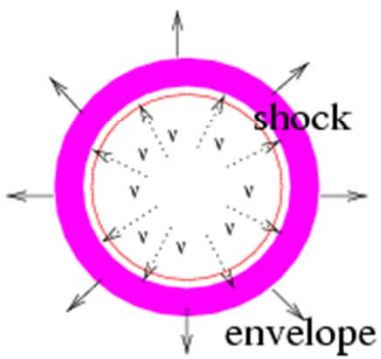
CORE BOUNCE

- Late-stage massive supergiant has many layers of shell burning
- Iron core has no energy source, when M_{Ch} is reached, collapses
  - Electrons forced into nuclei, “neutronization”
  - Electron capture, ν produced
  - Quickly becomes so dense, opaque even to ν
- Shock wave of collapse rebounds when neutron degeneracy stops collapse

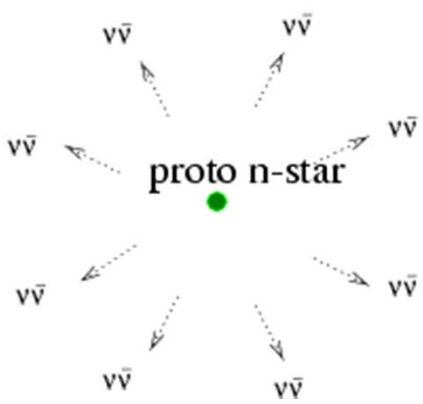
ν production



NEUTRINO BREAKOUT



EXPLOSION



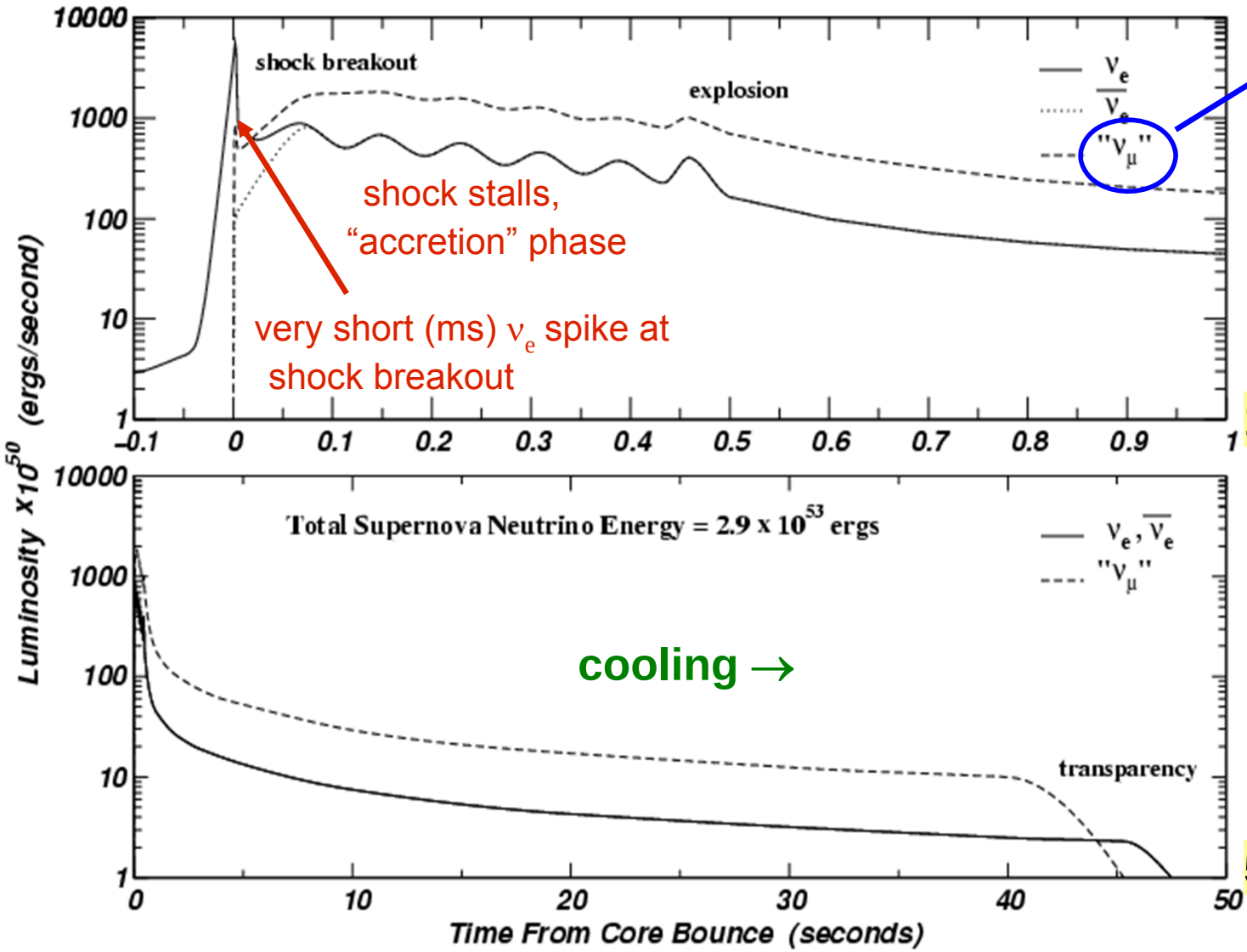
COOLING

- Shock wave passes neutrinosphere, density falls below ν mean free path, ν can escape
- Shock wave blows into rest of star from below, star disrupted
- Neutrinos can escape this, other particles cannot, so center cools via neutrino emission

ν production

- ~1% of ν produced by initial neutronization
  - $p^+ + e^- \rightarrow n + \nu_e$
- Thermal $\bar{\nu}\nu$ pair production produces 99% of ν
  - $e^+e^- \rightarrow \bar{\nu}\nu$, $e^- (Z,A) \rightarrow e^- (Z,A)\, \bar{\nu}\nu$, $NN' \rightarrow NN'\bar{\nu}\nu$
  - Temperatures much larger than ν rest mass
- Proto-neutron star transparent to ν
  - ν can escape
- But opaque to γ
  - EM energy recycled back to thermal energy

ν light curve



sum of $\nu_{\mu,\tau}$ and anti-ν's

roughly equal luminosity per flavor

1 s

luminosity decrease over 10's of seconds

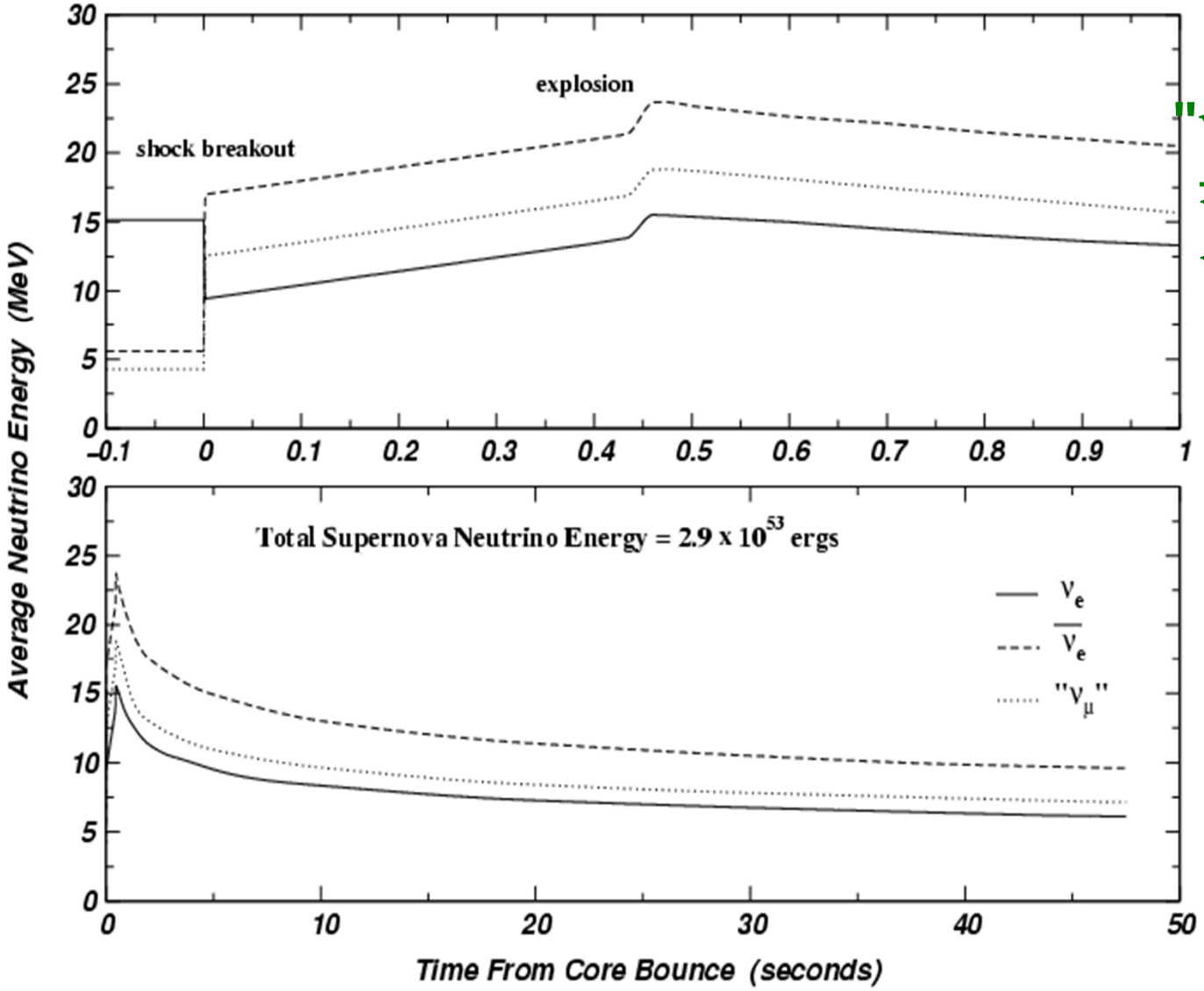
50 s

Burrows et al. 1992

ν transmission

- Details of ν emission dominated by ν opacity of proto-neutron star
- Energy transport all over again
  - All astrophysics seems to be just a fancy wrapper to encourage finding solutions to energy transport problems
- ν stopped via Charged or Neutral Current interactions (*Charged Current is stronger, $m_{W^\pm} < m_{Z^0}$*)
  - All ν see NC $\left(\nu_e, \nu_\mu, \nu_\tau\right)$ $\left(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\right)$
  - ν_e sees CC ($n + \nu_e \rightarrow p^+ + e^-$)
  - $\bar{\nu}_e$ can see CC, but protons rare ($p^+ + \bar{\nu}_e \rightarrow n + e^+$)
  - $E_\nu < m_\mu, m_\tau$, so CC interactions not possible for ν_μ, ν_τ

ν spectra



Transparent sooner, deeper in ν-sphere, ⇒ *hotter*

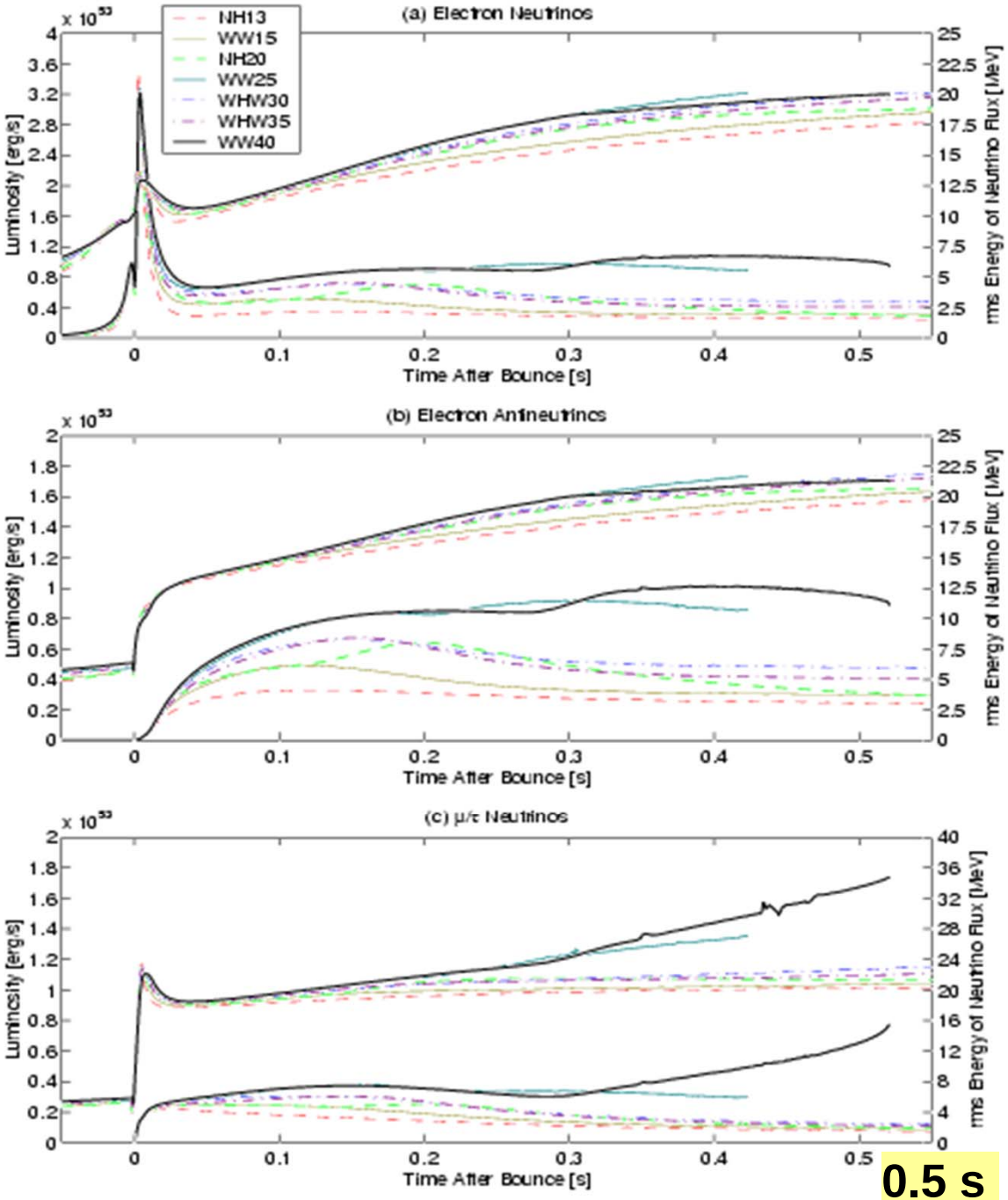
1 s

Energy decrease over long timescale (cooling)

50 s

Burrows et al. 1992

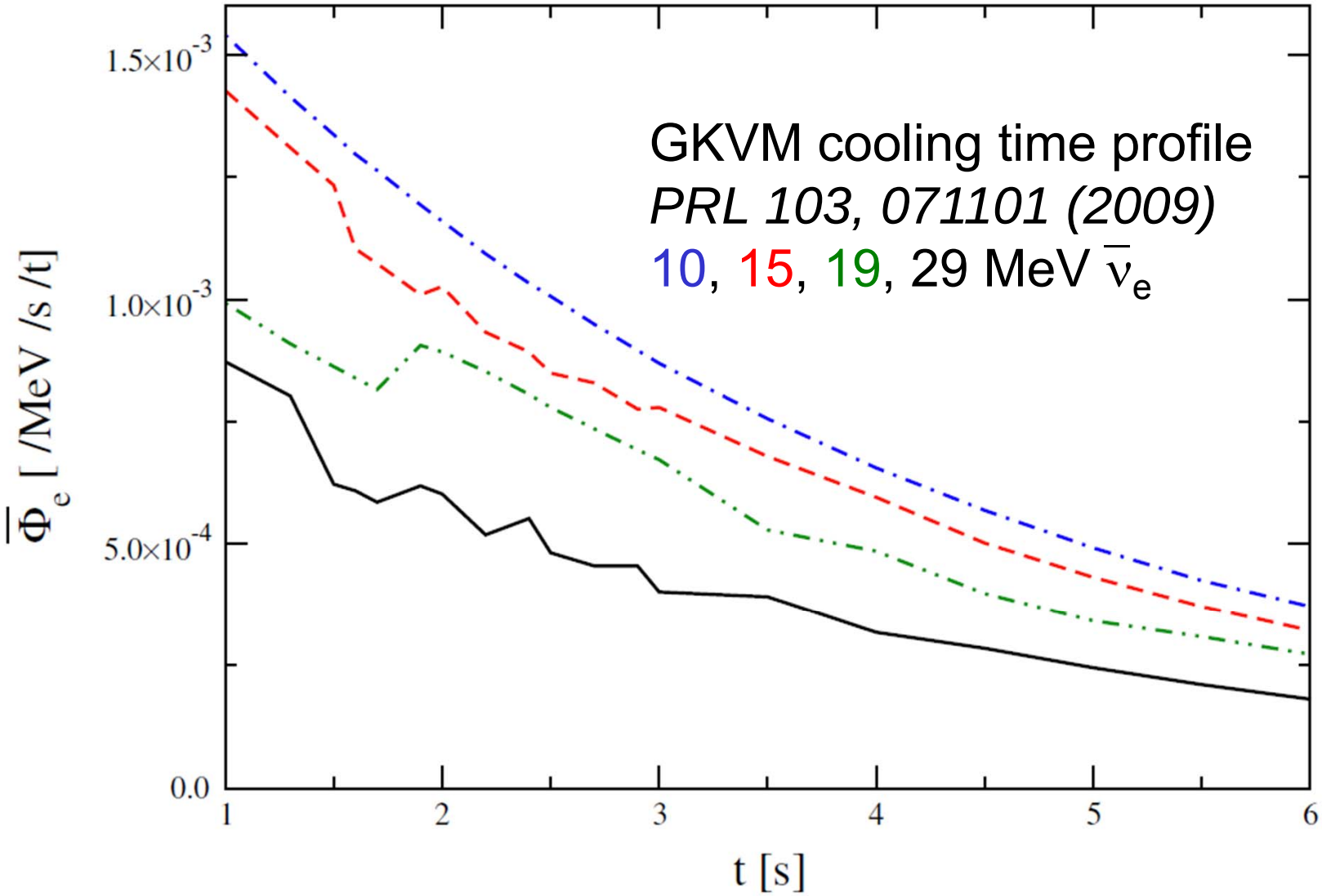
More details



- Newer models add GR, 3D, magneto-hydrodynamics, acoustics…
  - Same basic features
- Turns out that it's (still) hard to get model SN to explode, so much work remains

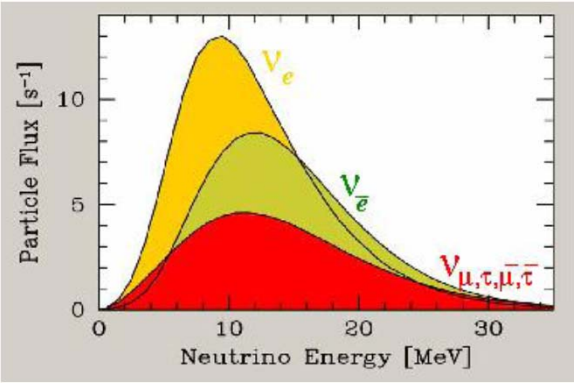
M. Liebendorfer *et al*. 2001 (*time zoomed in on accretion phase*)

Time Profile



Generalities

- Prompt ν signal after core collapse
  - Lasts 10's of seconds, dimming as it cools
  - Abrupt cutoff could be black hole formation signal
- Roughly equal luminosity per flavor
- Initial energy hierarchy:
  - $\langle E_{\nu_e} \rangle \sim 12$ MeV
  - $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV
  - $\langle E_{\nu_\mu} \rangle \sim 18$ MeV
- So the mass eigenstates corresponding to those flavors starts off with distinct energies

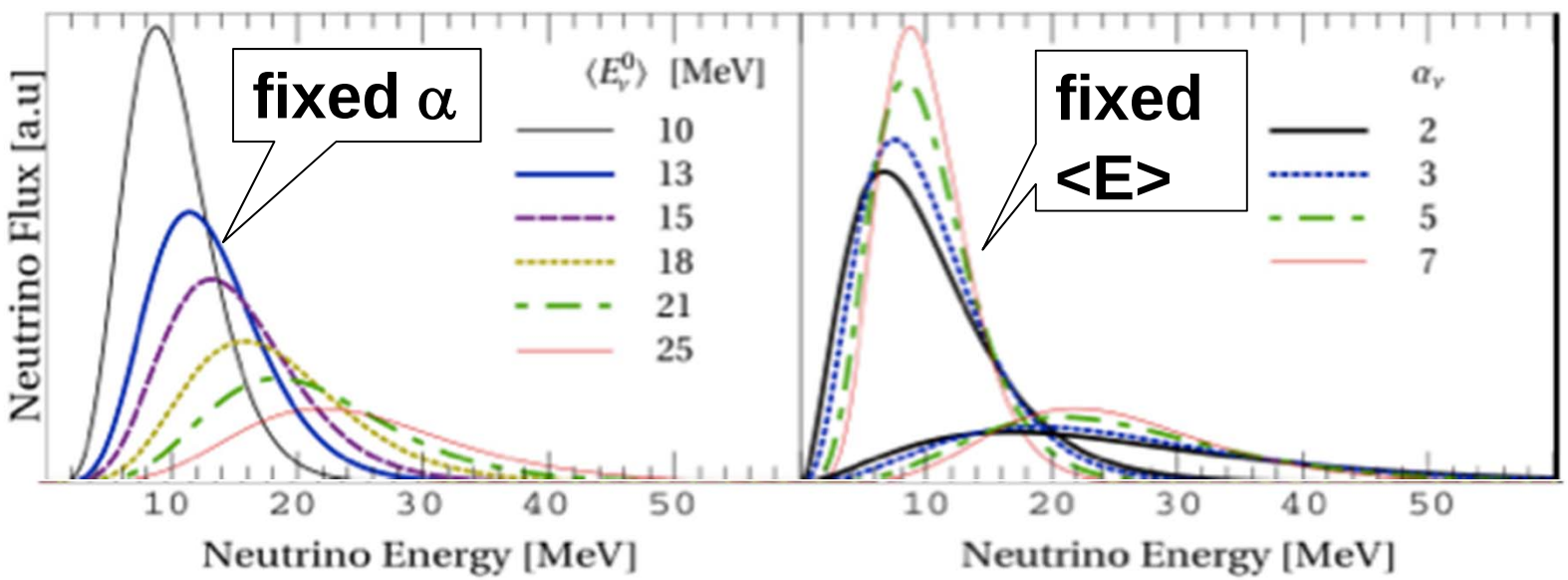


A. Dighe, TAUP09

Parameterizations

Can describe features of different models using a modified power law:
different α, <E> parameters for different flavors

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right] \qquad \mathcal{N} = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}$$

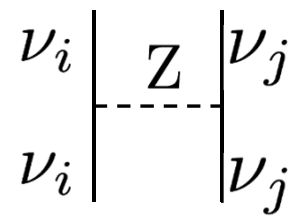


The larger the "pinching" parameter α,
the more suppressed the high energy tail

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

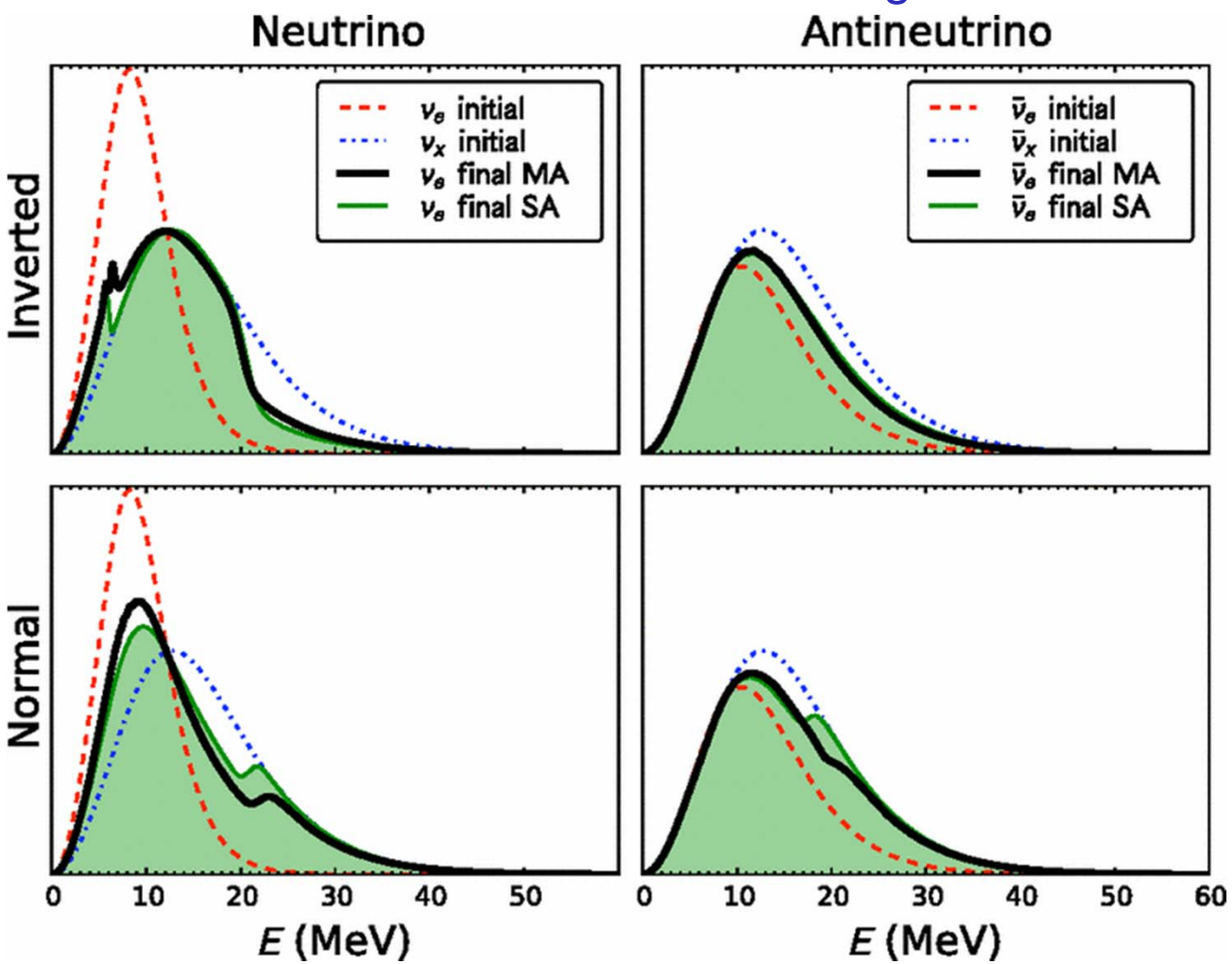
What Happens?

- But ν oscillations will scramble this
  - MSW-like effects in all that matter dominate over later vacuum oscillations in the same way as for solar neutrinos
    - Far away, well past coherence length
  - And exactly how they do this would be a good probe of oscillation parameters, mass hierarchy, etc.
    - Spectral splitting, flavor swapping, collective effects, synchronized and/or bipolar oscillations
  - Sensitivity to flavors and ν vs anti-ν needed to study such effects



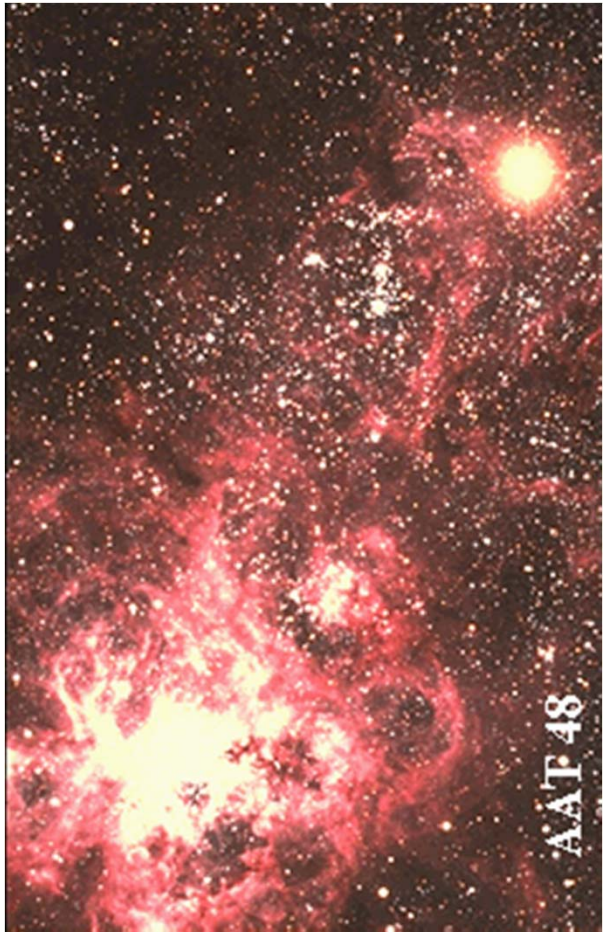
eg, Spectral Swaps

Stronger signal in neutrinos:
But most detectors are far better at seeing anti-neutrinos



Duan & Friedland
PRL 106 091101
2011

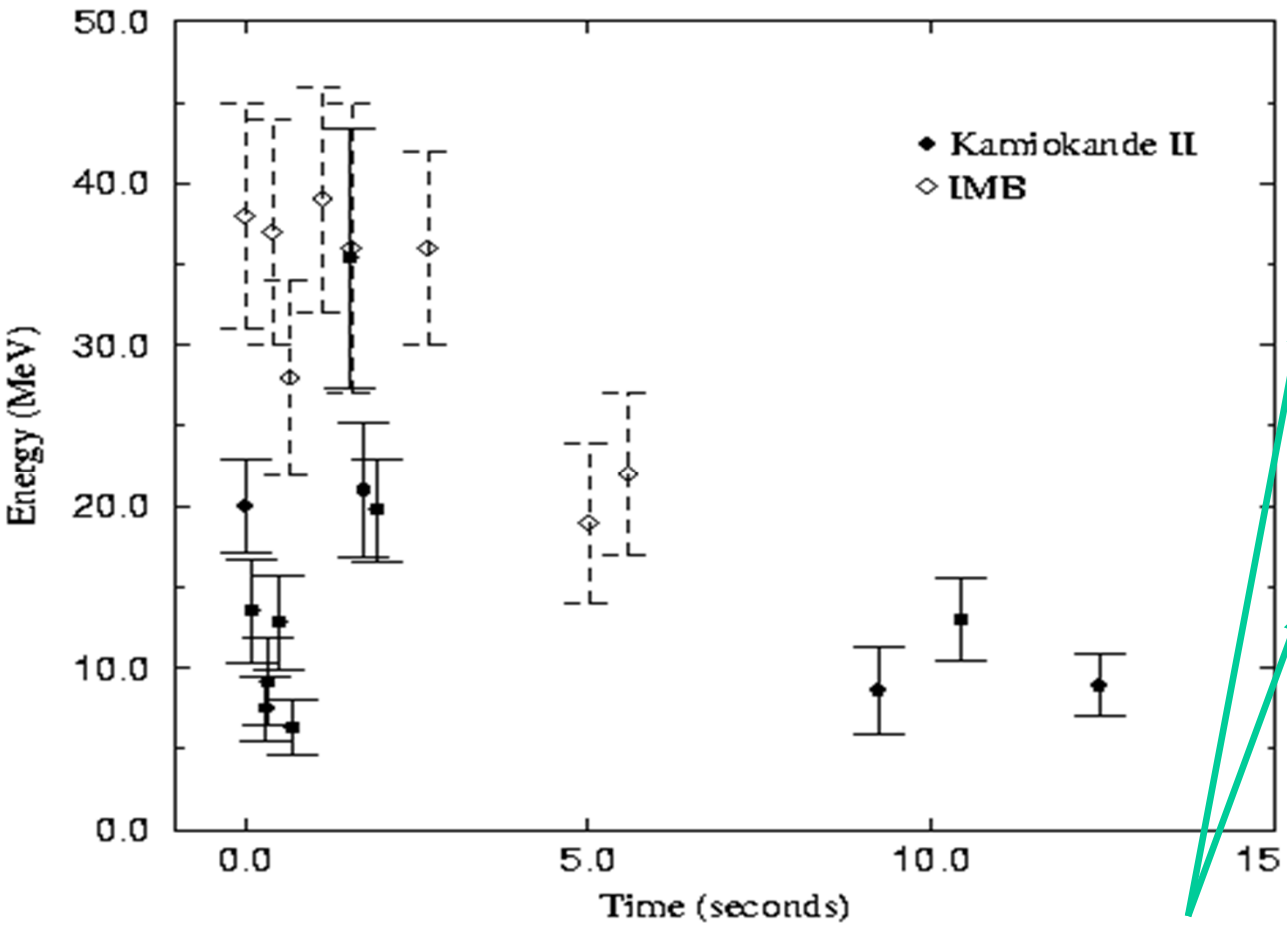
Experimentally Confirmed



- SN1987A
  - Type II
  - In LMC, ~55kpc
- Well studied due to proximity
  - Although a peculiar SN, blue giant progenitor, odd dim light curve
- And close enough so that $1/r^2$ didn't crush the ν signal
  - Seen in ν detectors!
  - (*and not the 4.1 years early the OPERA results would have implied…*)

SN1987A ν observations

Water Cherenkov

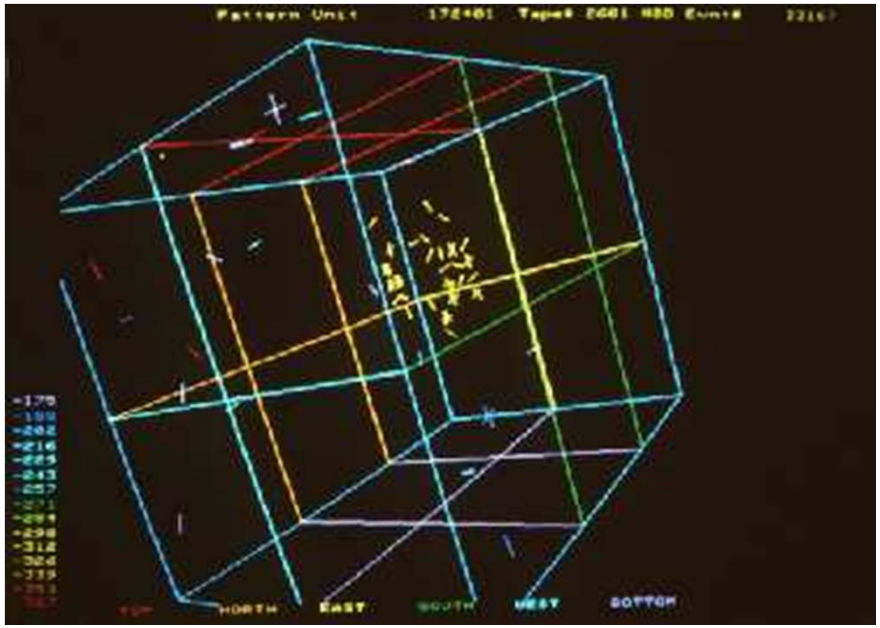


- Kamiokande
  - E_{th} = 8.5 MeV
  - M = 2.9kt
  - Sees 11 ν
- IMB
  - E_{th} = 29 MeV
  - M = 6kt
  - Sees 8 ν
- Baksan
  - E_{th} = 10 MeV
  - M=130t
  - Sees 3-5 ν
    - *(Not on plot)*
- Mont Blanc
  - E_{th} = 7 MeV
  - M = 90t
  - Sees 5 ν (??)

Liquid Scintillator

Core Collapse Model Confirmed

- Take observed spectra, flux
- Project back to 55kpc
- Generalities of model confirmed!
  - … given the low low statistics
- And time profile is about right too
- Signal also sets mass limit of $m_{\nu_e} < 20eV$
  - No observed dispersion of ν as a function of E_ν
- For a galactic SN happening tomorrow,
  - R ~10 kpc
  - Modern detectors, E_{th} ~5 MeV, M ~ 10's kt
    - 1000's of events would be seen



SN1987A
ν event
seen in IMB

Tomorrow?

- Humans haven't seen a galactic SN since Kepler, why bother looking?

Mean interval (yr) per galaxy	Core Collapse	All SNe
Historic Visible	?	30-60
Extragalactic	35-60	30-50
Radio Remnants		<18-42
γ-ray remnants		16-25
pulsars	4-120	
Fe abundance	>19	>16
Stellar death rates	20-125	

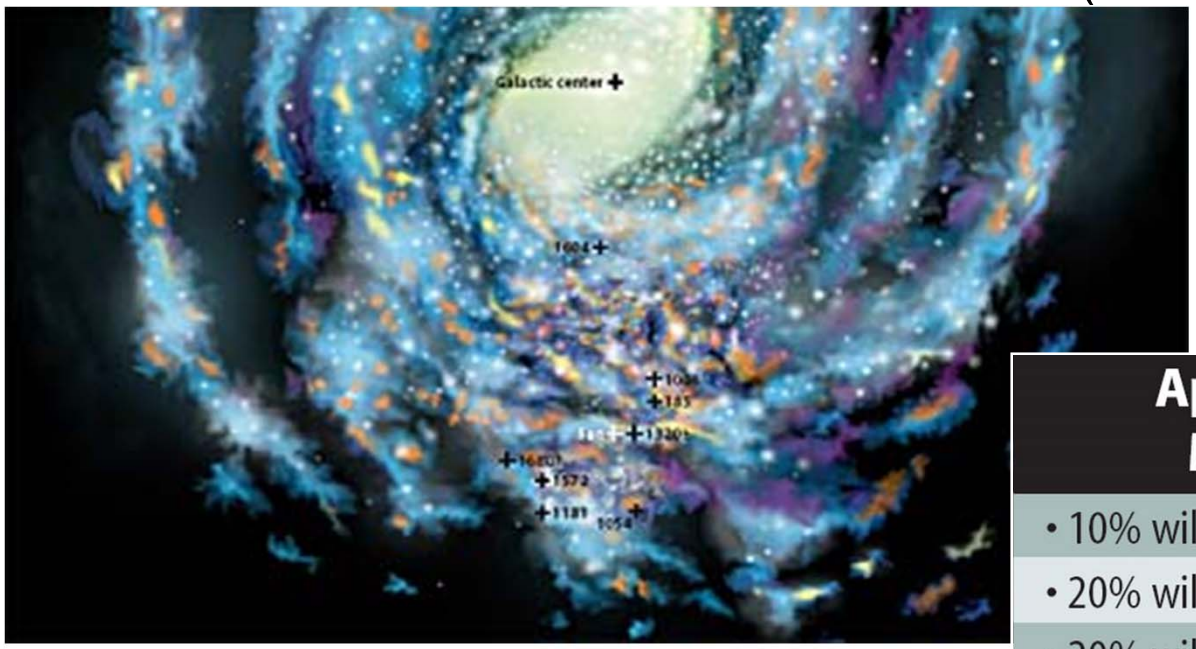
Overall?

3 ± 1 per century!

Academically –
one per career,
if Monsieur Poisson
cooperates

Observational Efficiency

- Perhaps 1/6 would be easily seen optically
  - (Historical SNe map from S&T)



Apparent Brightnesses of Milky Way Supernovae

- 10% will peak brighter than magnitude –3
- 20% will peak between magnitudes –3 and +2
- 20% will peak between magnitudes +2 and +6
- 20% will peak between magnitudes +6 and +11
- 30% will peak fainter than magnitude +11

Progenitor: 12–15 magnitudes fainter

Right, why bother?

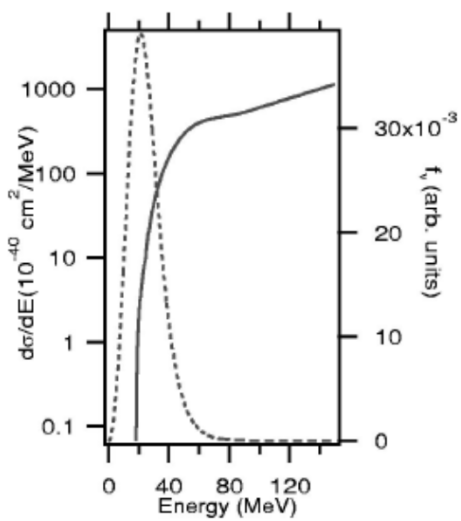
- Is such a rare event worth expending brain cells on?
- Even a marginally nearby event (SN1987A) produced an amazing burst of progress on many fronts
  - Dozens of papers per ν event seen
    - Something like an average of 1/week over almost 3 decades
- Imagine one even closer, with observations from t=0 instead of hours, days, or weeks…
- ν density at origin so high that ν-ν interactions and collective effects provide unique ν lab!
- Also note: at a rate of 3/century and a galactic radius of 15kpc, that's hundreds of SN-ν wavefronts already on their way to us here on Earth!

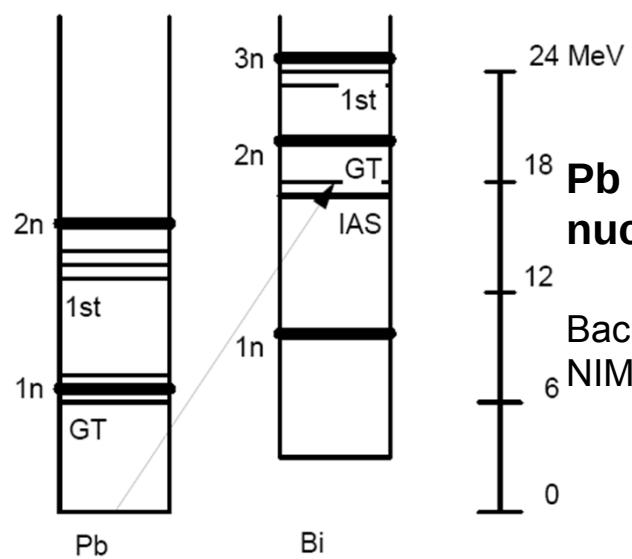
SNe ν_e and Lead

- Pb's neutron excess Pauli-blocks the usual SN ν detection channel of:
  - $\bar{\nu}_e + p^+ \rightarrow e^+ + n$
  - allowing: $\nu_e + n \rightarrow e^- + p^+$
- An 18 MeV ν_e will result in an excited Bi nucleus with high cross-section due to the Gamow-Teller giant resonance
  - Bi emits thermal neutrons, to which the surrounding Pb is fairly transparent
- So: instrument a big pile of lead with neutron counters, watch for SN-sized burst of neutrons

Pb σ & SN ν_e flux

S. Elliot,
Phys. Rev. **C 62**,
065802 (2000)

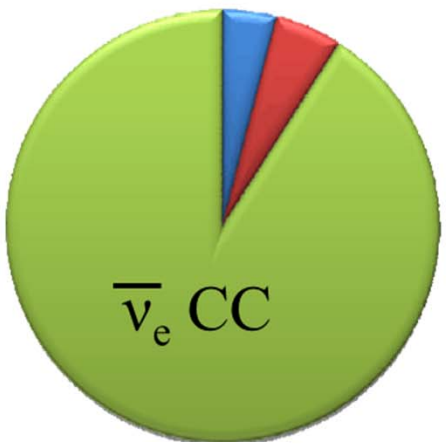




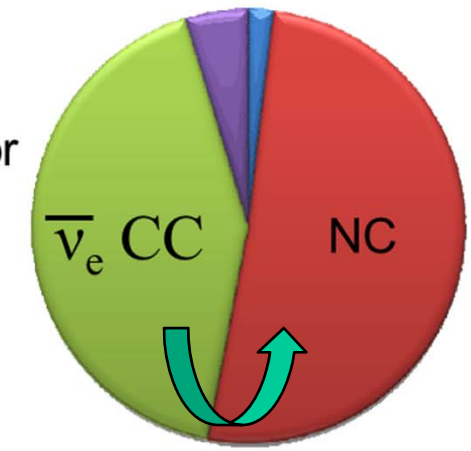
Pb & Bi nuclear levels

Bacrania et al,
NIM **A492**, 43 (2002)

Flavor Sensitivities

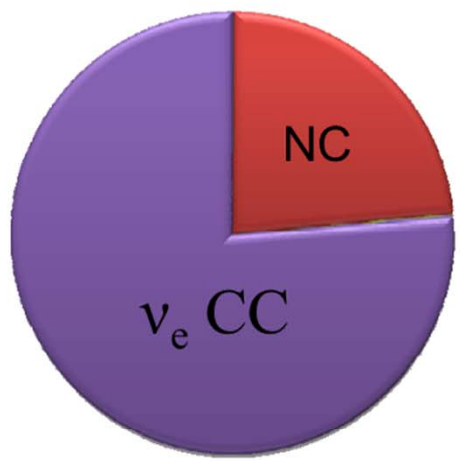


Water Cherenkov

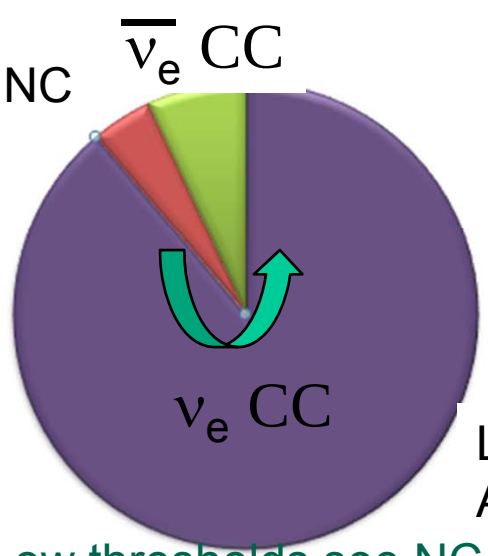


Liquid Scintillator

Strong threshold dependence



Lead



Liquid Argon

Low thresholds see NC coherent scattering

CC:

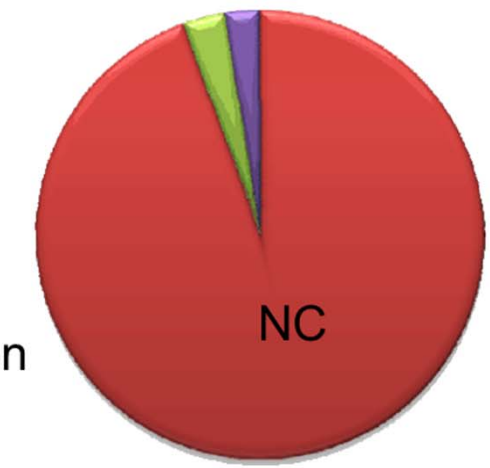
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$$

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

NC:

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

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



Iron

Energy Dependence

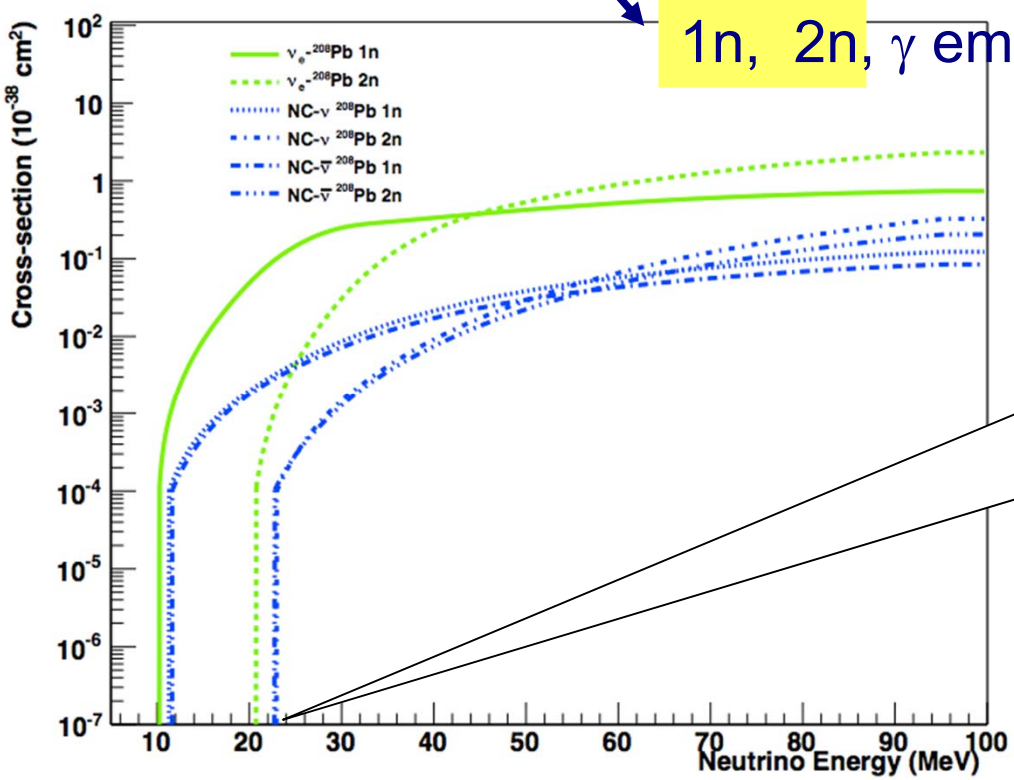
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

1n, 2n emission

$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

1n, 2n, γ emission

Observe single and double ~few MeV neutron events in the ^{3}He counters



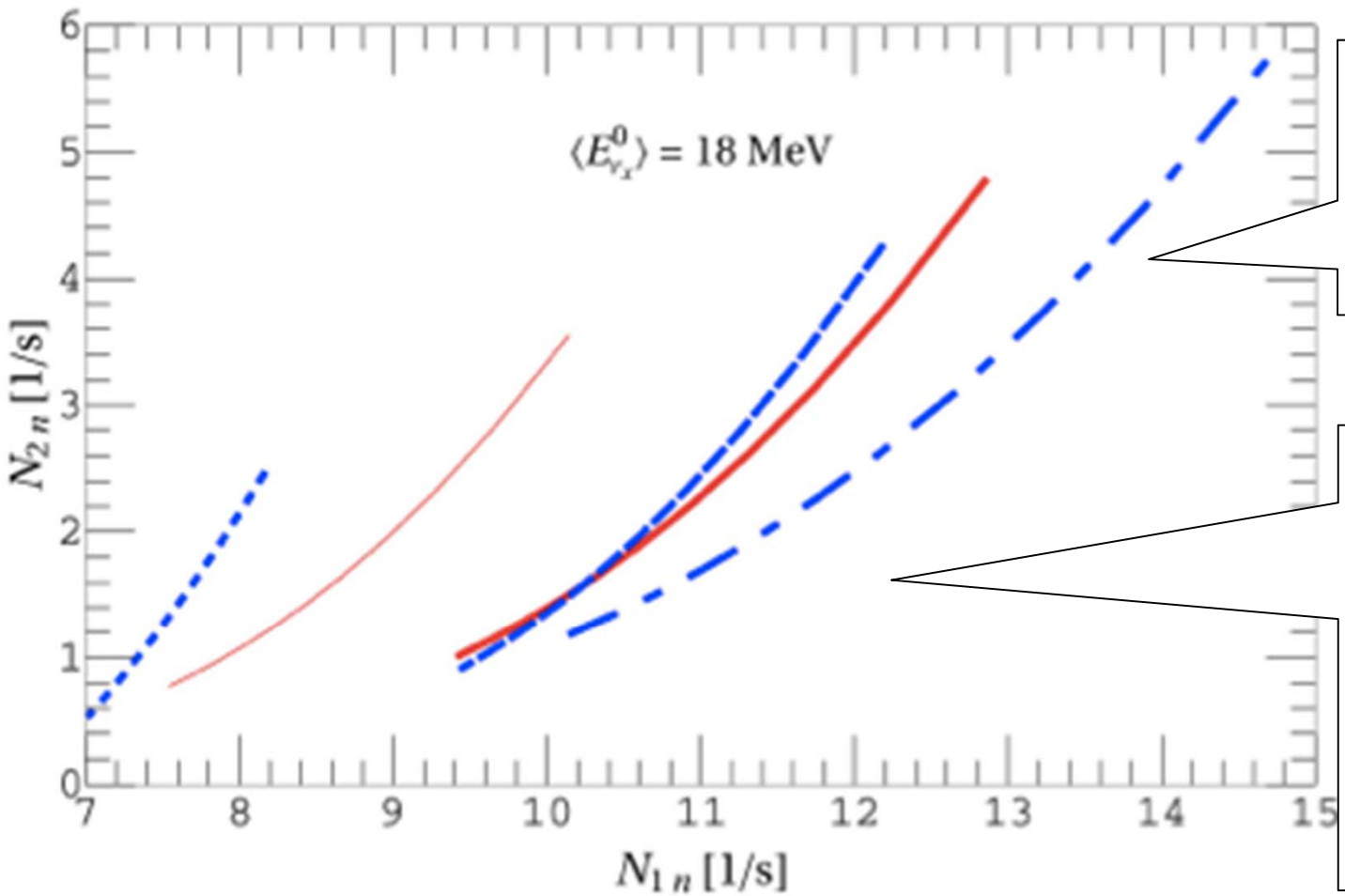
sharp thresholds, so 1n/2n relative rates are strongly dependent on the neutrino spectrum

(similar for other lead isotopes)

Plot from Kate Scholberg

Models mapped onto HALO

For a given (<E>, α), predict a (N_{1n}, N_{2n}) measurement



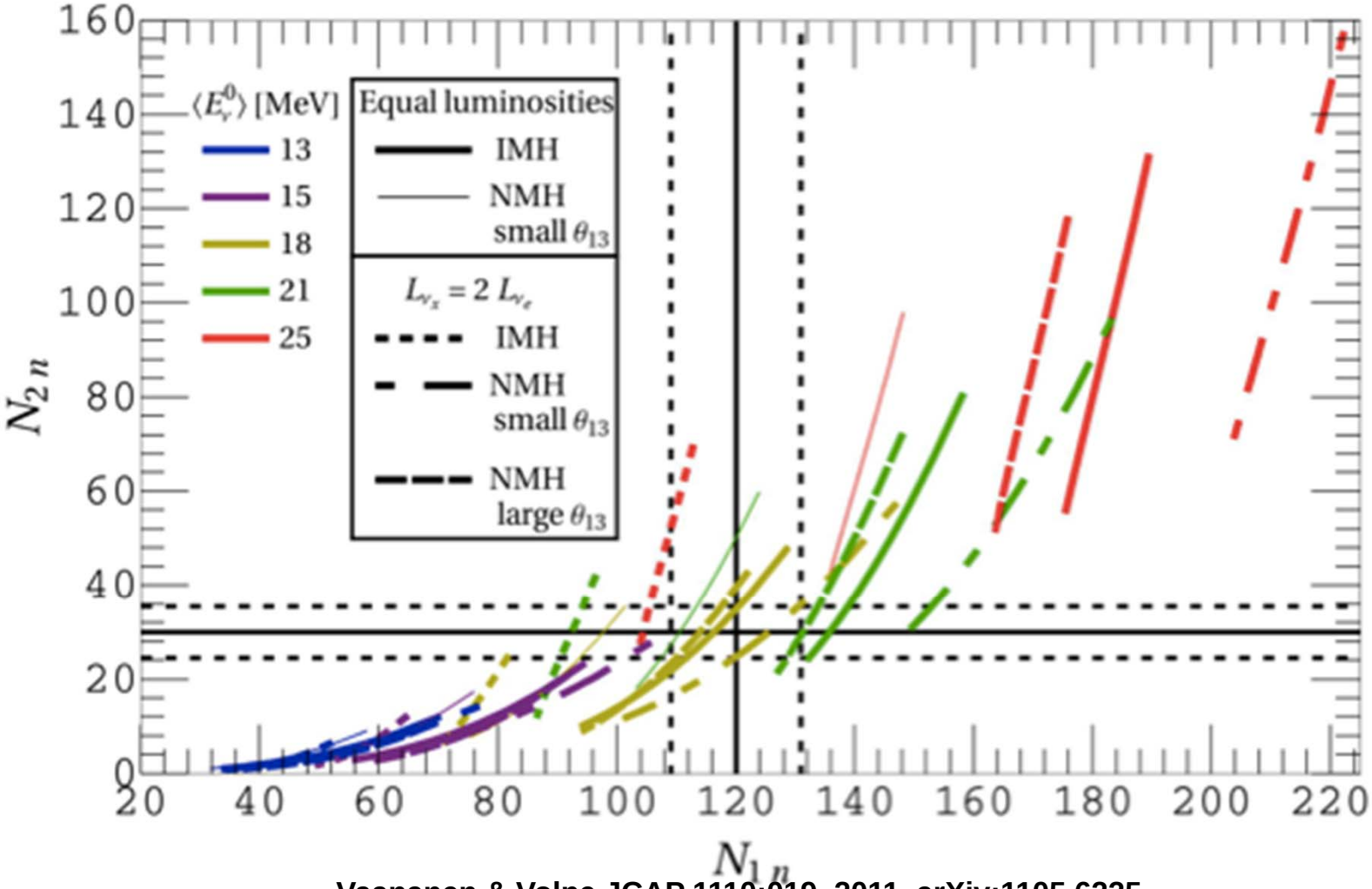
each line tracks values of α for a given model

different lines represent different mass hierarchy and flavor luminosity models

Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

Models mapped onto HALO

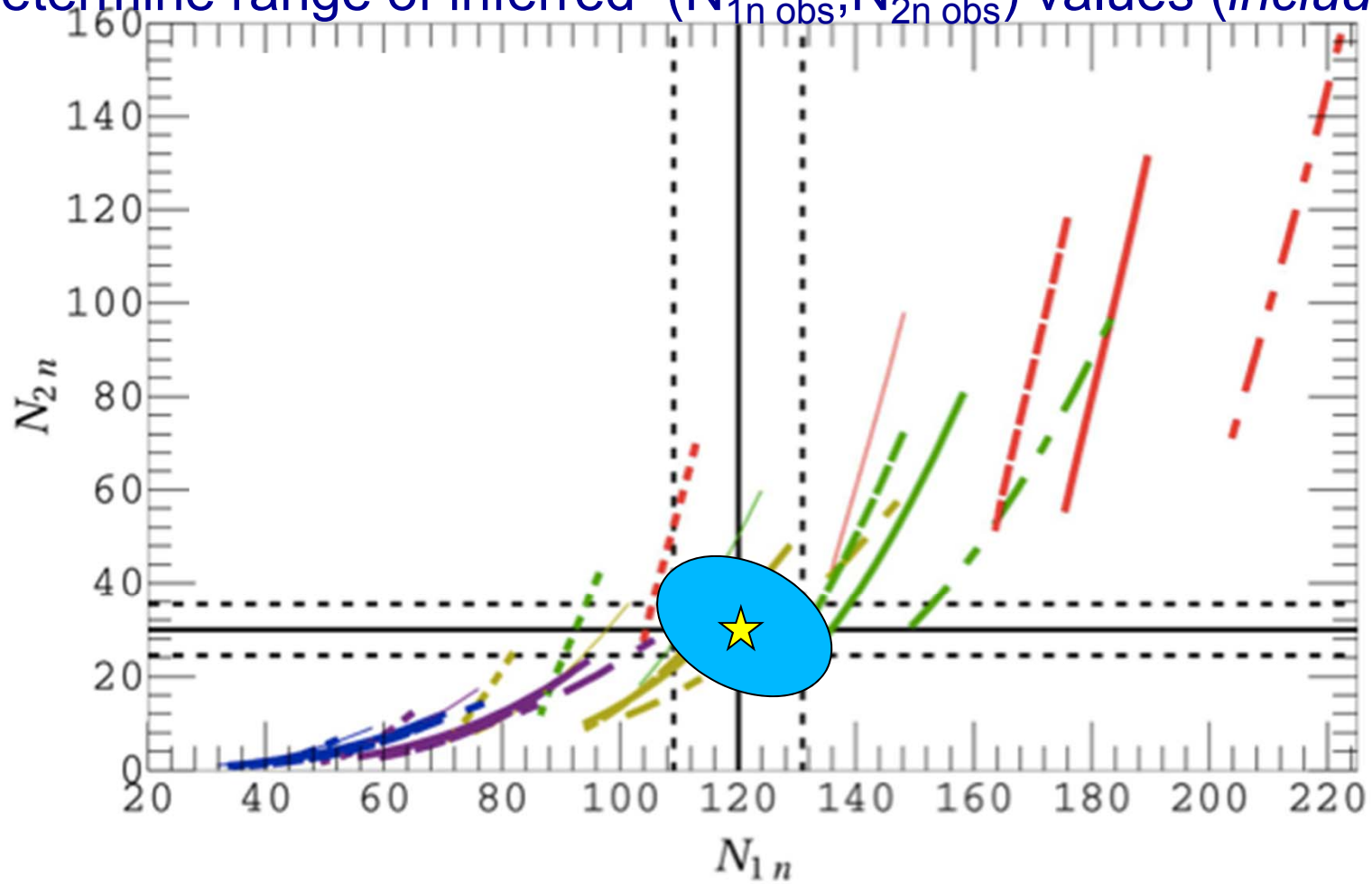
Measure number of single vs double neutrons, constrain models



Vaananen & Volpe JCAP 1110:019, 2011, arXiv:1105.6225

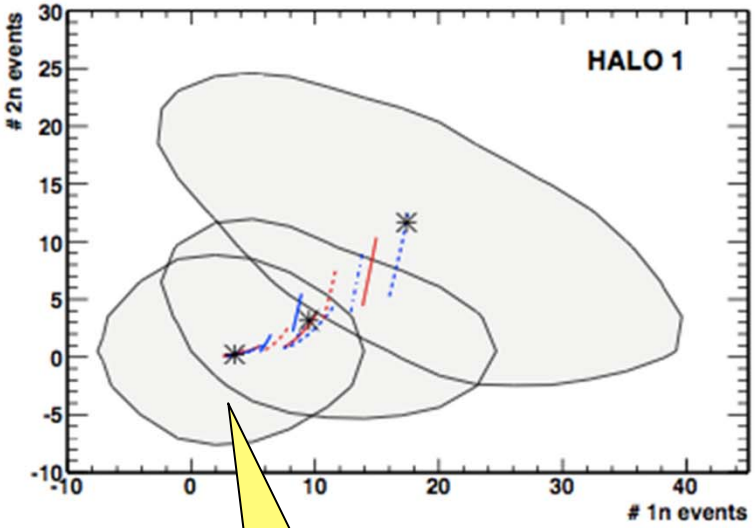
Measure it

Given true (N_{1n},N_{2n}) means, use simple Poisson MC to determine range of inferred ($N_{1n\ obs}$,$N_{2n\ obs}$) values (*include* ε)

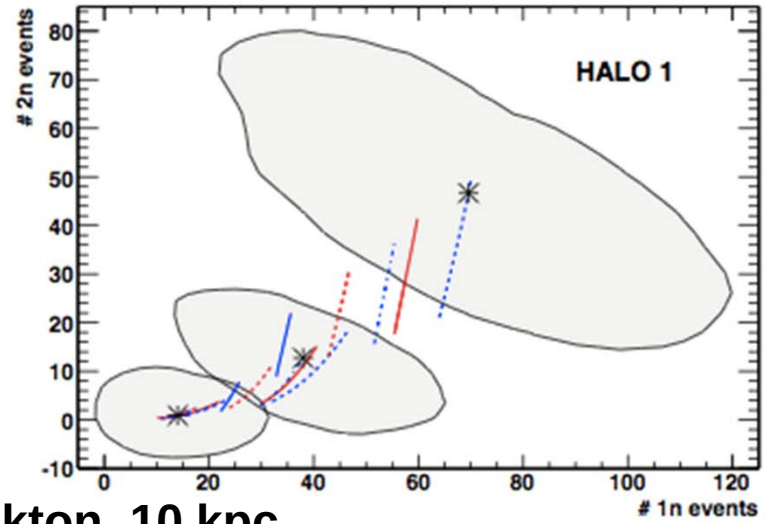


How well could HALO alone do

79 tons, 10 kpc

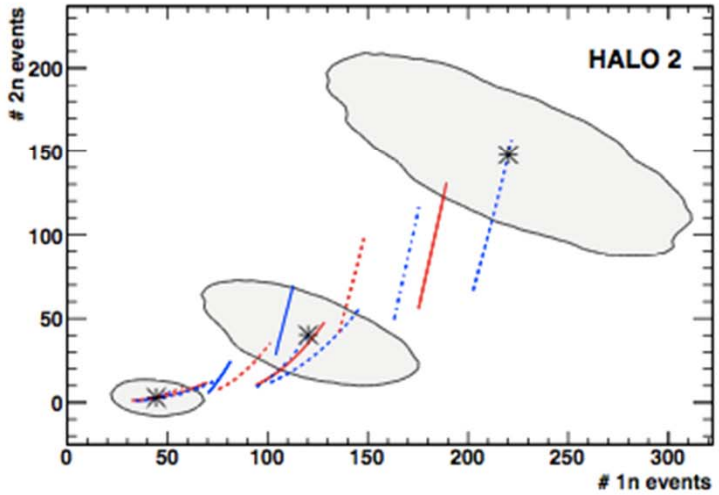


79 tons, 5 kpc



Note that measuring few events will give significant information

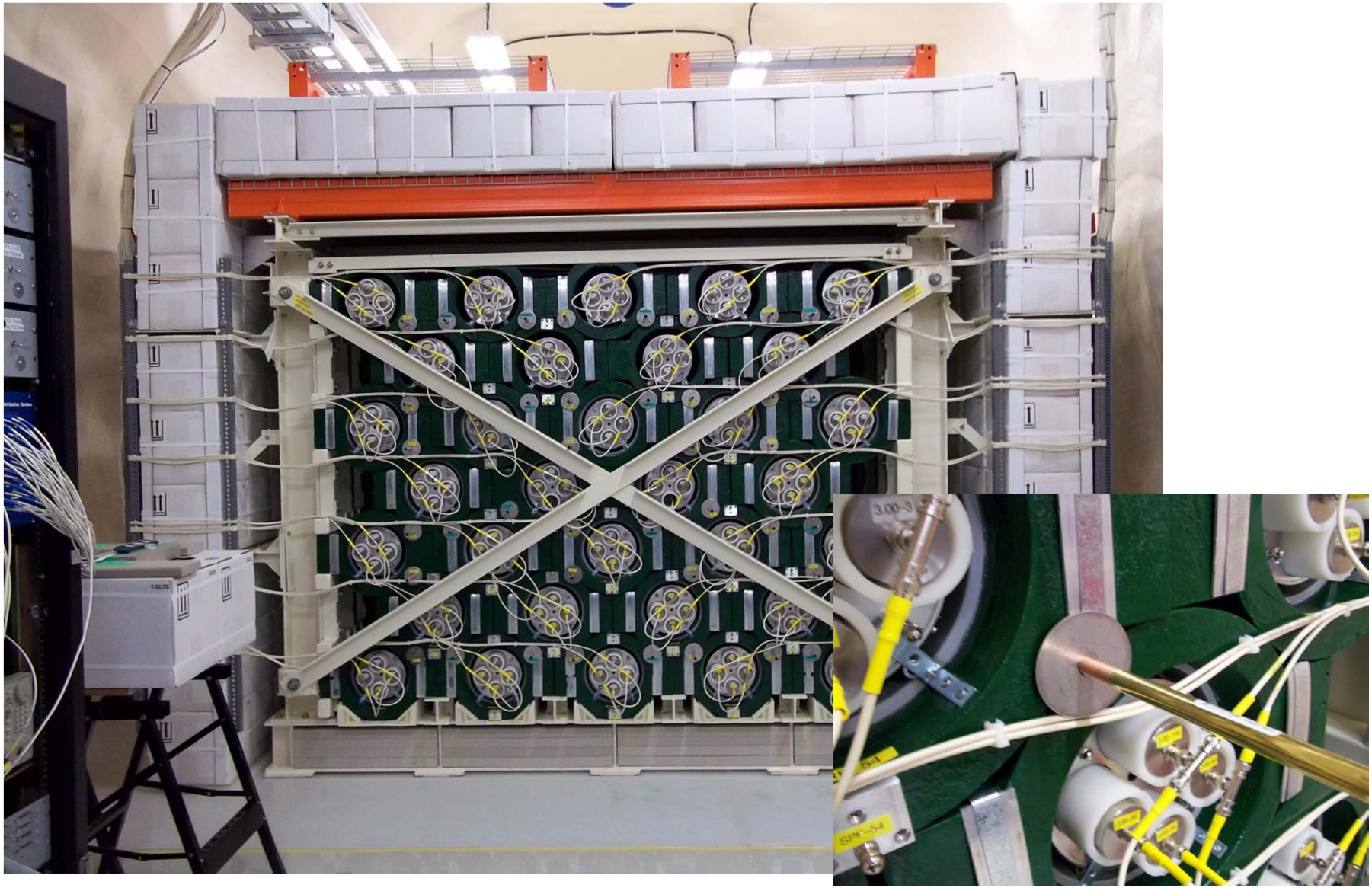
1kton, 10 kpc



- Lines are predictions for a range of models with different fluxes and oscillation parameters, from Vaananen & Volpe JCAP 1110:019, 2011
- Shaded regions enclose 90% of HALO inferred values for given true values

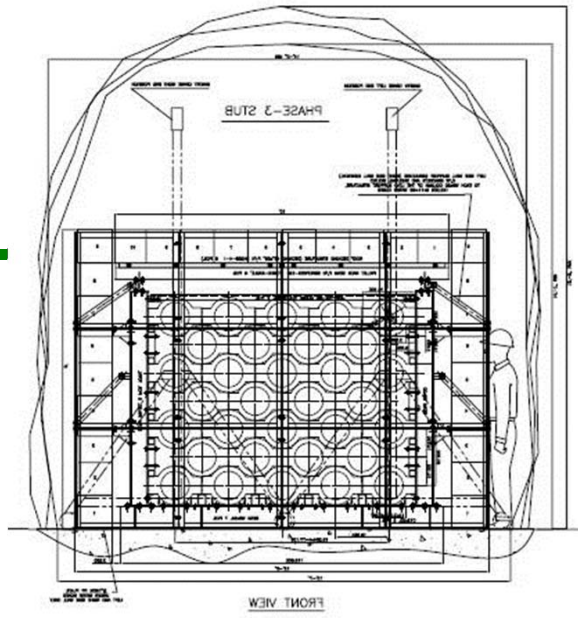
Nicolas Kaiser,
DAAD exchange student,
@ Duke summer 2011

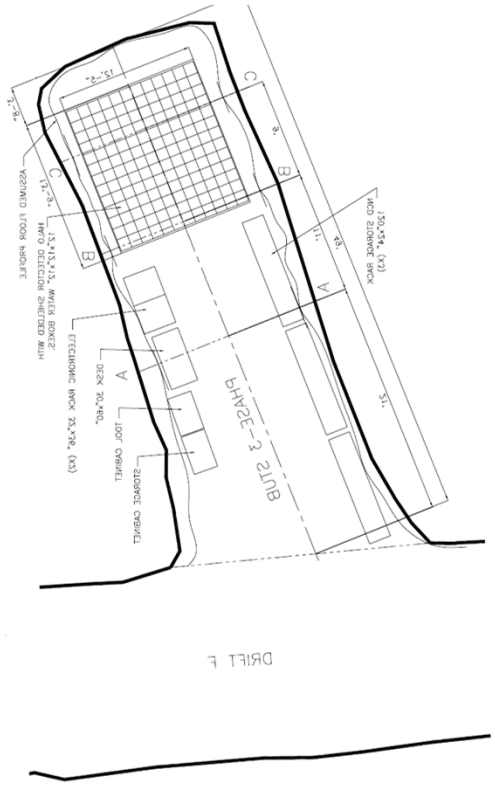
HALO

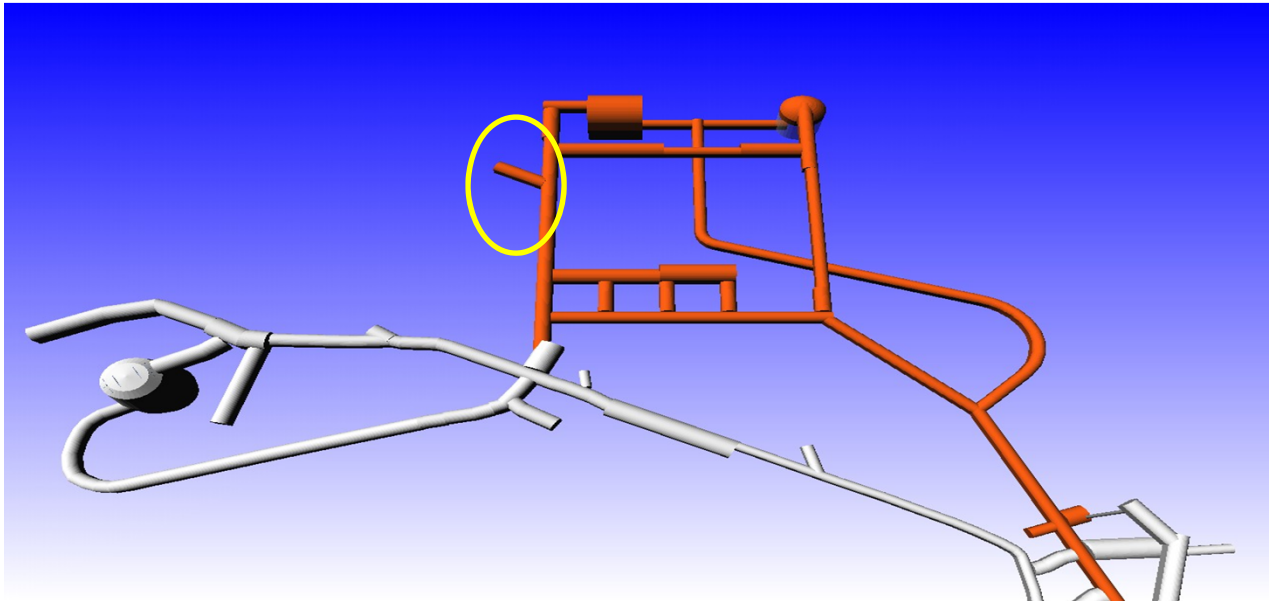


HALO

- Helium And Lead Observatory
- Funding from NSERC & NSF
- Installed in SNOLAB's Phase 3 drift stub
  - Significant scientific and technical support from SNOLAB







Who is HALO?

Armstrong Atlantic State Univ.
Jeff Secrest

University of Washington
Hamish Robertson

Digipen Institute of Technology
Charles Duba

Duke University
Kate Scholberg, Roger Wendell

Laurentian University
Jacques Farine, Alicja Kielbik, Christine Kraus, Michael Schumaker, Taylor Shantz, Colin Bruulsma, Clarence Virtue*
* HALO Spokesperson

Los Alamos National Laboratory
Andrew Hime

SNOLAB
Fraser Duncan

Technische Universität Dresden
Kai Zuber

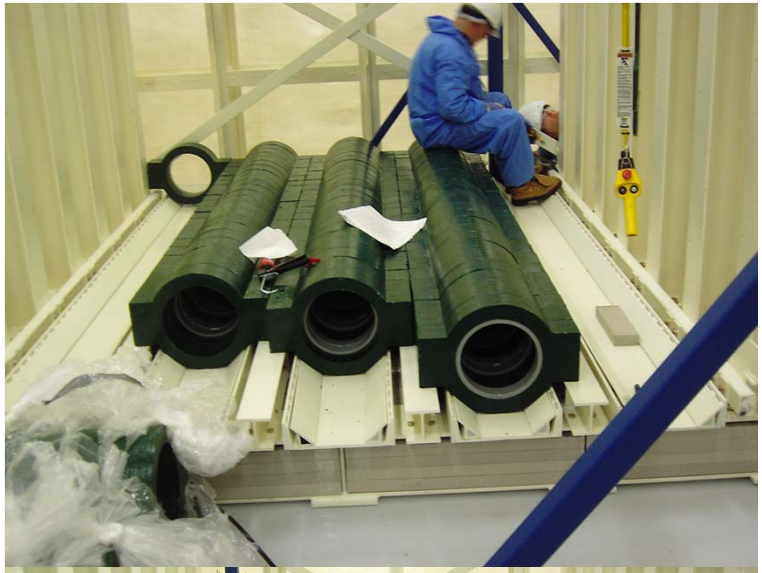
TRIUMF
Stanley Yen

University of Minnesota Duluth
Alec Habig, Justin Vasel, Justin Mueller

University of North Carolina
Mark Howe, John Wilkerson

HALO Lead

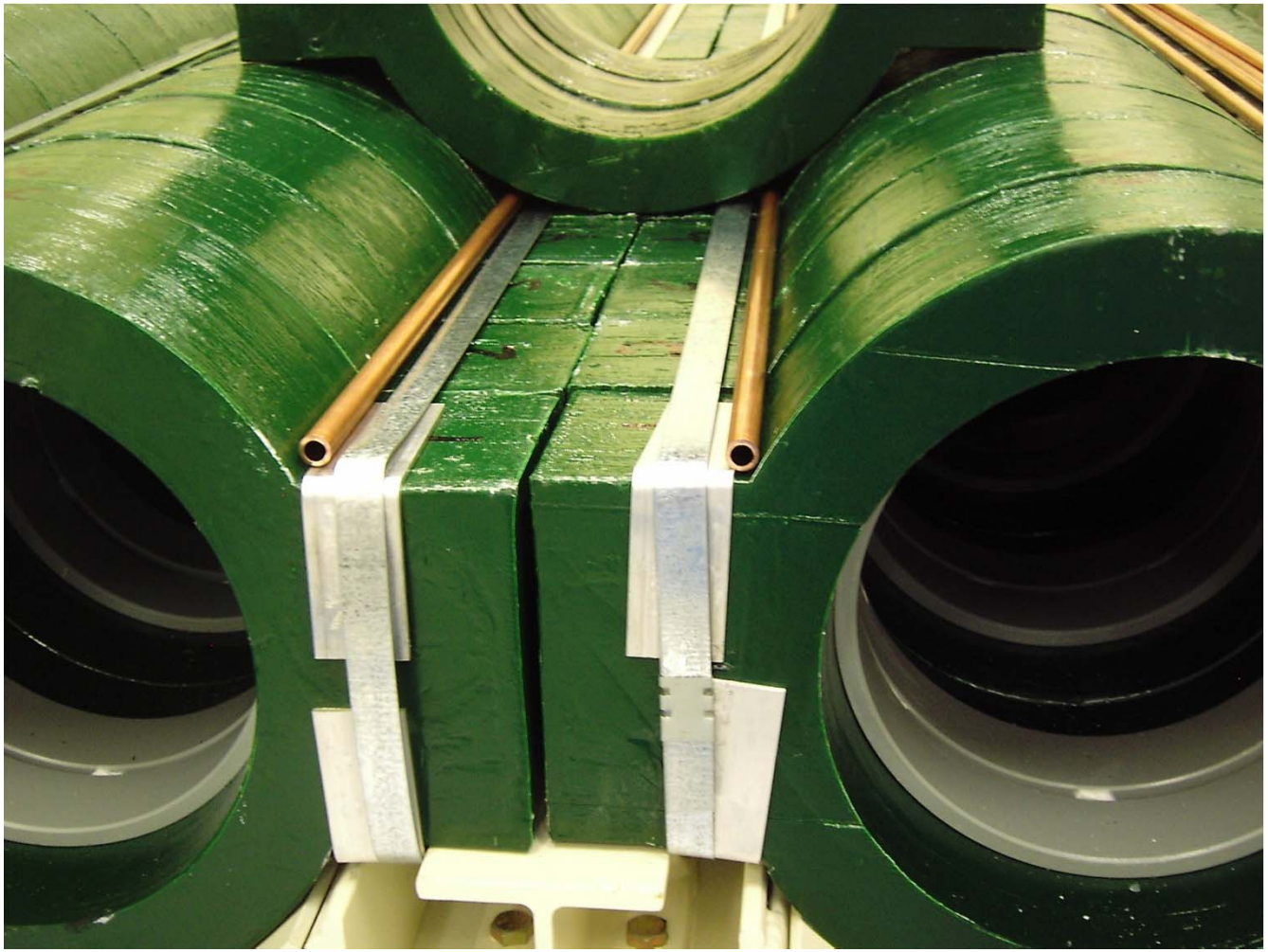
- The target mass
  - 79±1% tonnes, recovered from decommissioned Deep River cosmic ray station
- 32 columns, 3m long
  - Made of 864 91 kg annular blocks
    - Painted green to seal in lead dust
    - That color green happened to have the lowest level of gammas for some reason



Painting

- Lead painted for safety
- Dipped in floating layer of oil paint

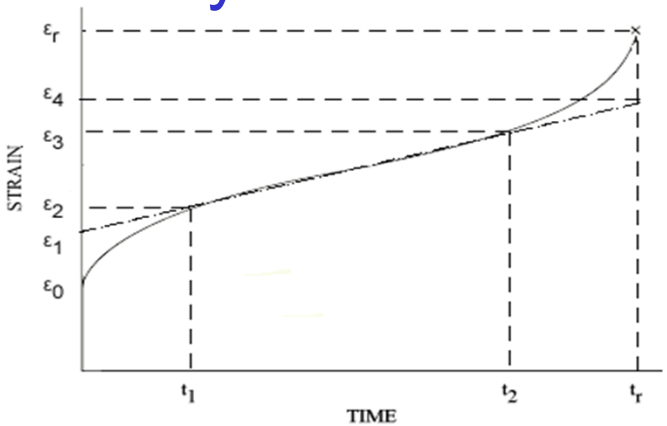
HALO Structure

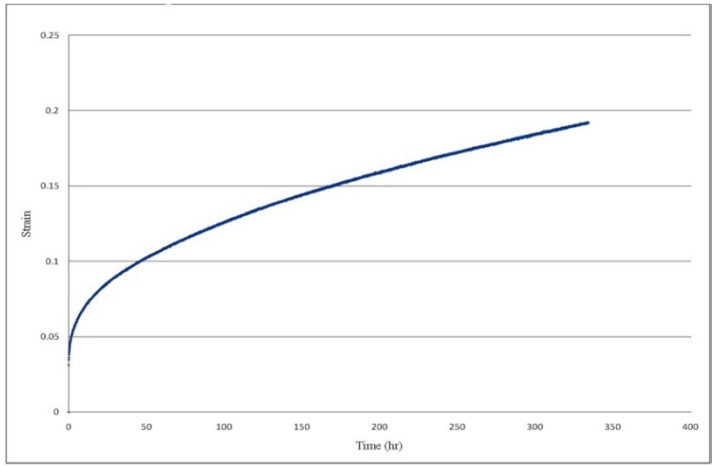


- Steel rings inside for support, steel straps to keep things from shifting
- Copper tubes to insert Cf calibration sources

Creep

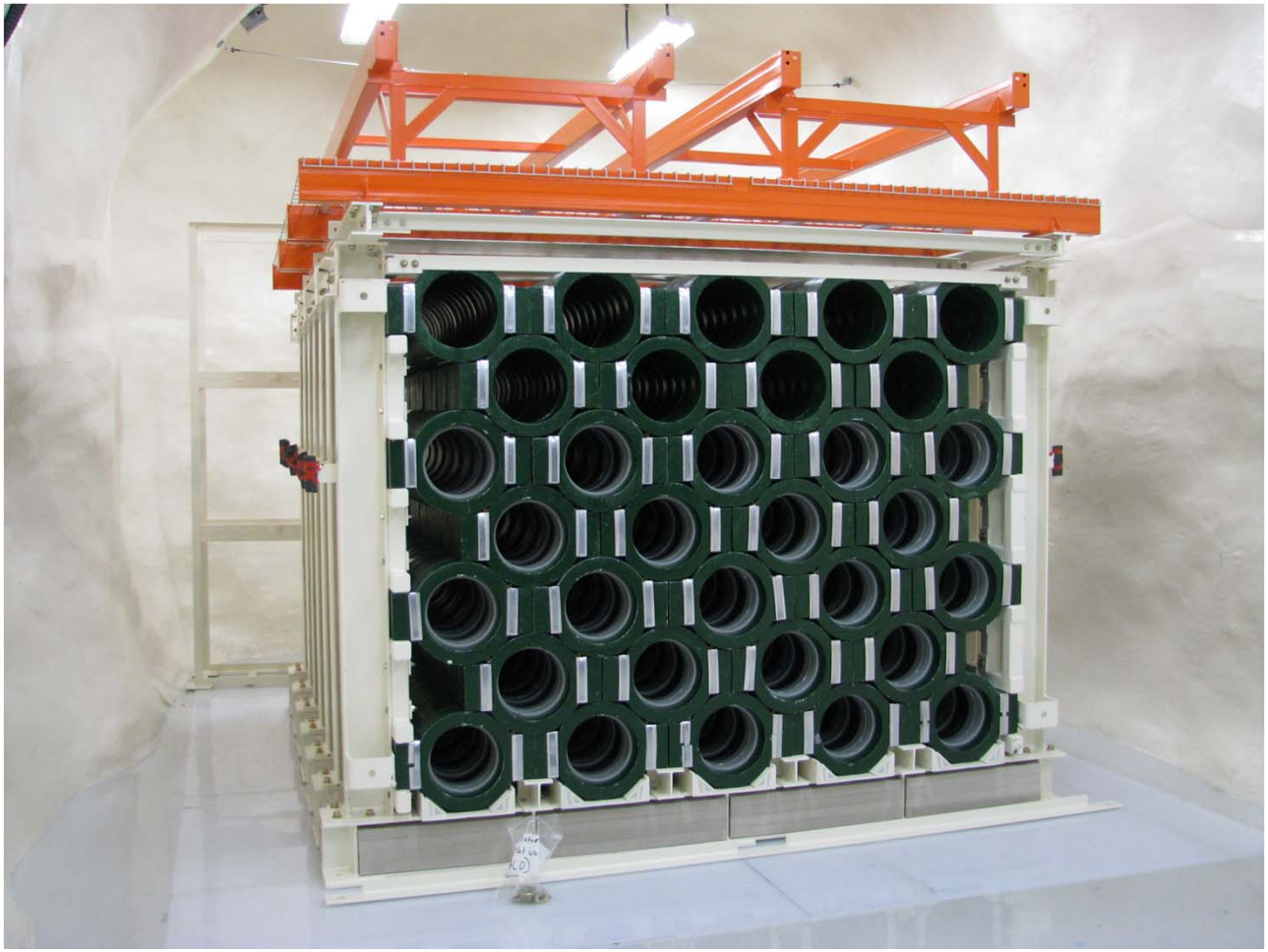
- Creep tests successful
- Monitored live with the world's slowest slow control system





HALO Structure

- Lead all stacked!



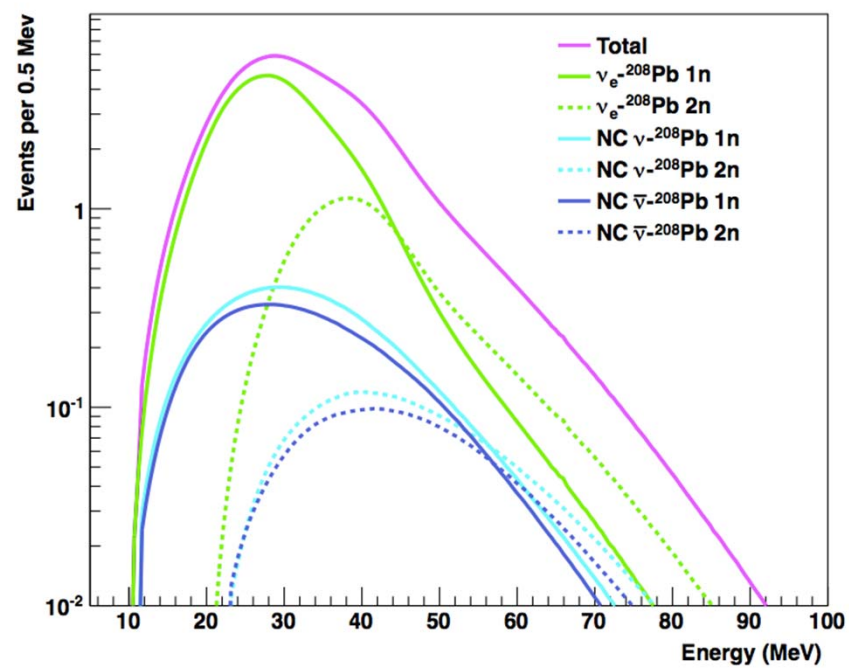
Signal

- About 1.1n/tonne from canonical 10kPc SN
- Sensitive to SN in our galaxy
- Catch the n's
  - Can't see the CC's e^-, so no NC/CC discrimination

Scaled from:
J. Engel, G.C. McLaughlin, C. Volpe,
Phys. Rev. **D 67**, 013005 (2003)

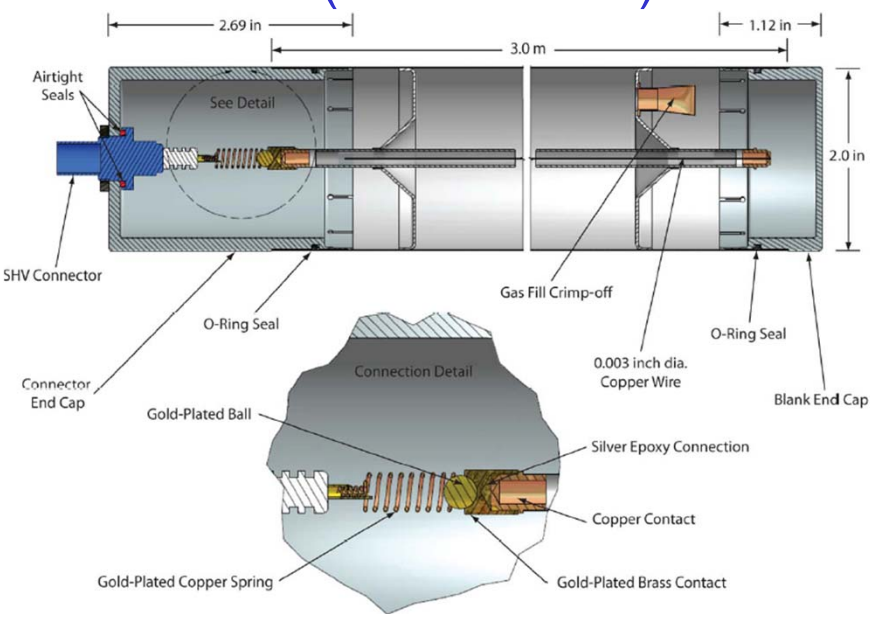
Reaction	Events/kT	n/kT	n for HALO-I
CC 1-n	378	378	30
CC 2-n	234	468	19 (x2)
NC 1-n	105	105	8
NC 2-n	72	144	6 (x2)
	Totals @ 10 kPc	1095	88

Detected ν spectra from SNOWGLOBES
Note ν producing 2n skew higher in energy



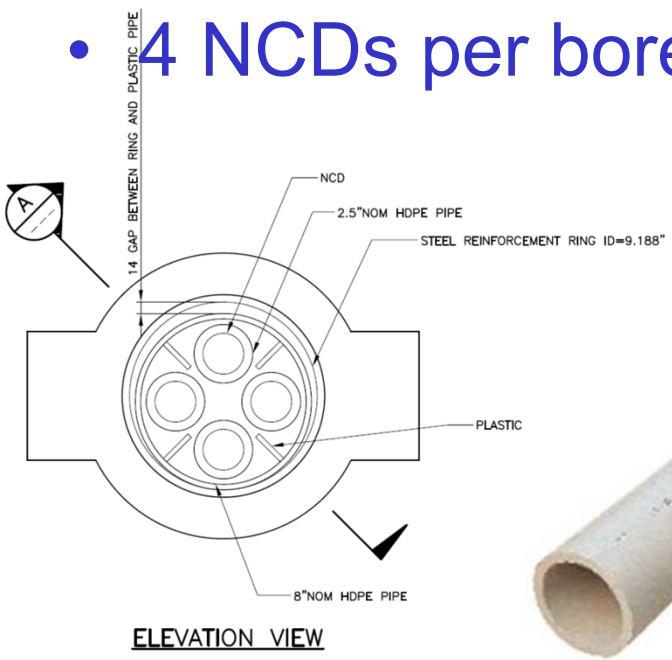
Catch the signal

- Use SNO's ^{3}He "Neutral Current Detectors"
- Seen in NCDs via:
  - $n + {}^3He \rightarrow {}^3H + p + 764$ keV
- New endcaps installed
  - O-ring seals against corrosive atmosphere
  - New gold HV contact scheme (SHV to NCD)



Moderate the n's

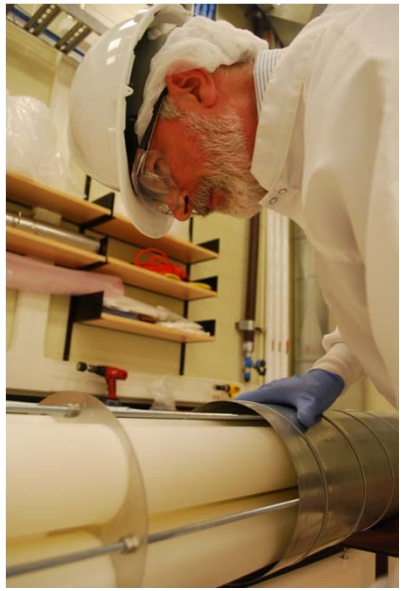
- Put each NCD in a 250mm polypropylene pipe to slow the neutrons down to increase NCD efficiency
- 4 NCDs per bore

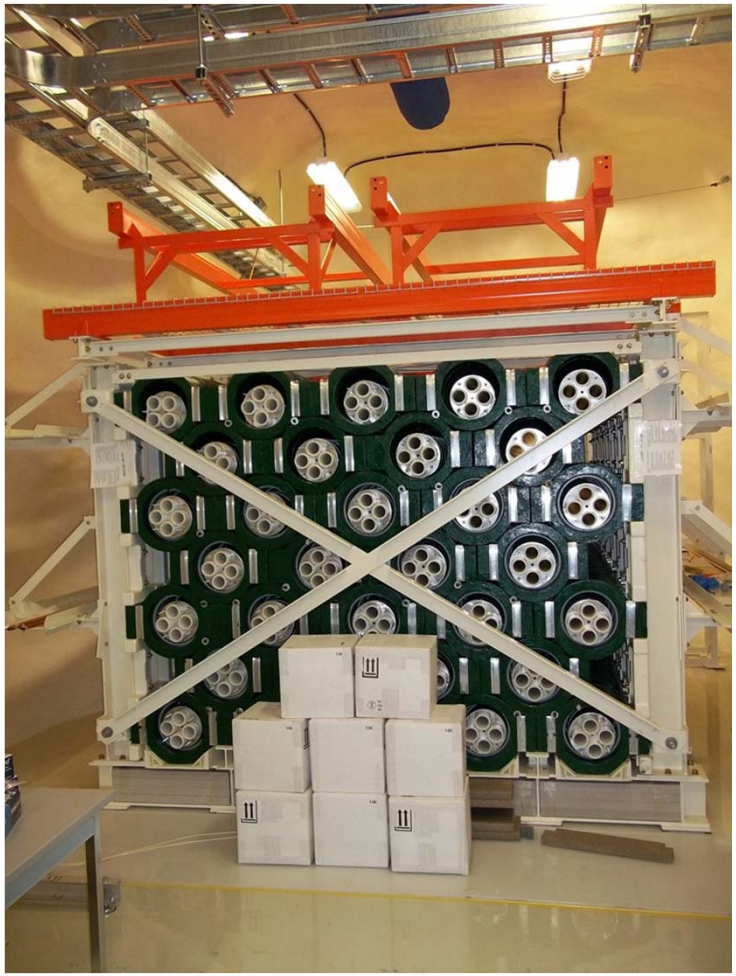


NCD's in storage in SNO control room

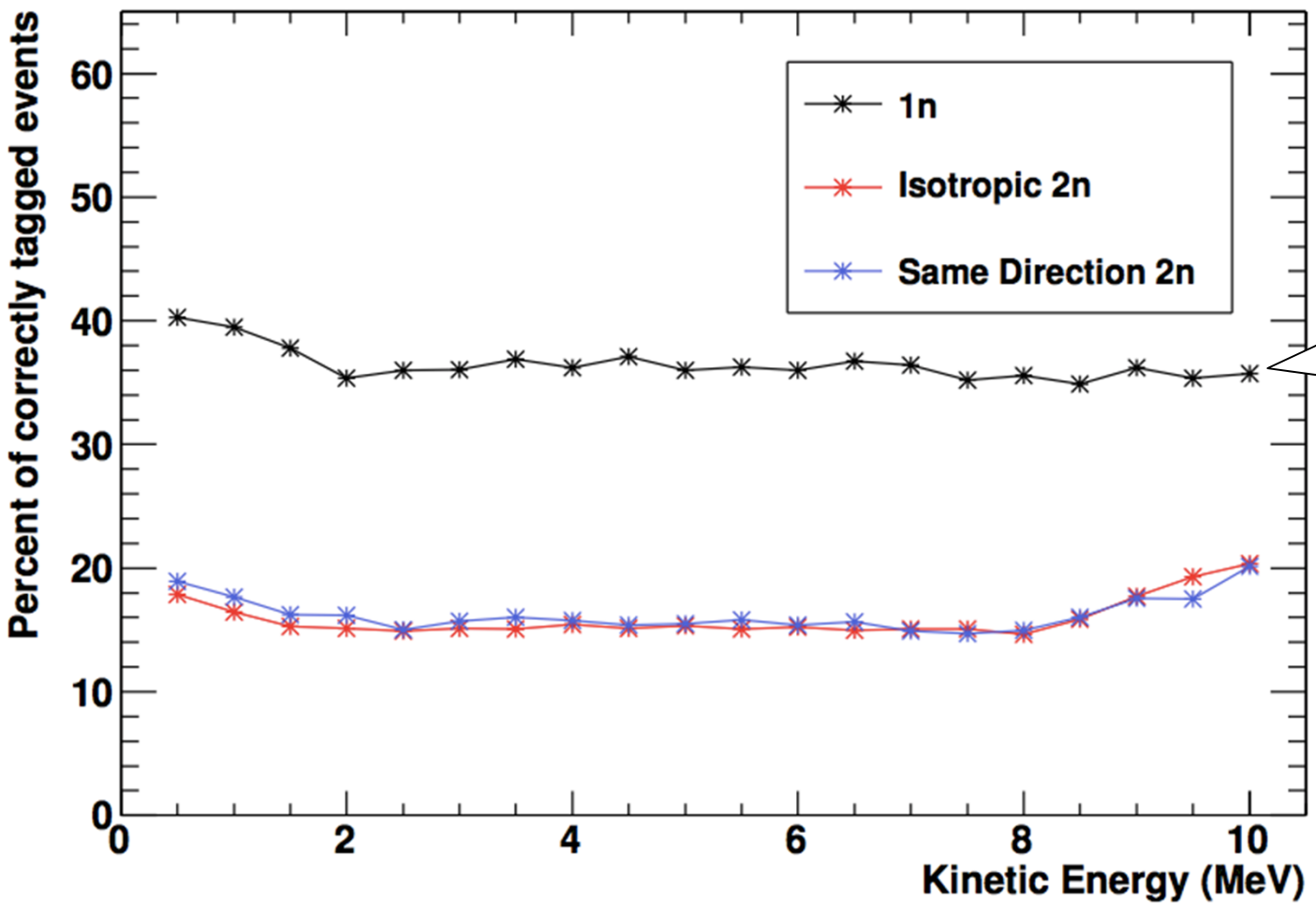
Moderate the n's

- 4 pipes of NCDs per lead column to suck up those neutrons
  - $n + {}^3He \rightarrow {}^3H + p + 764$ keV
  - MC studies show ε~30%
  - 128 NCD's installed





Neutron efficiency

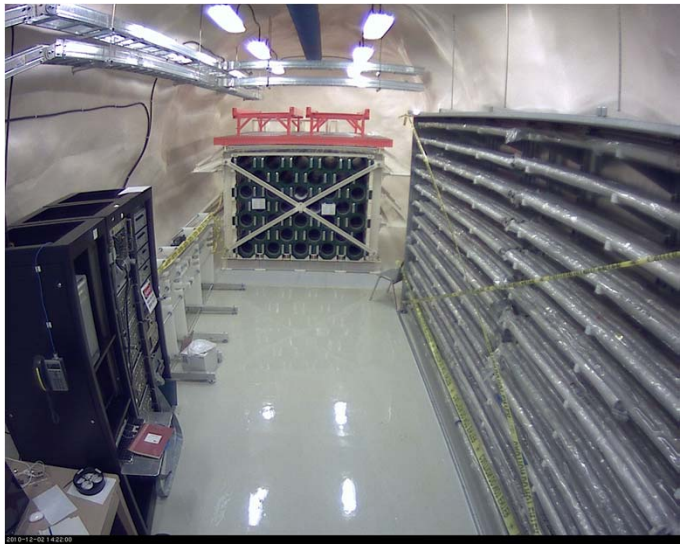


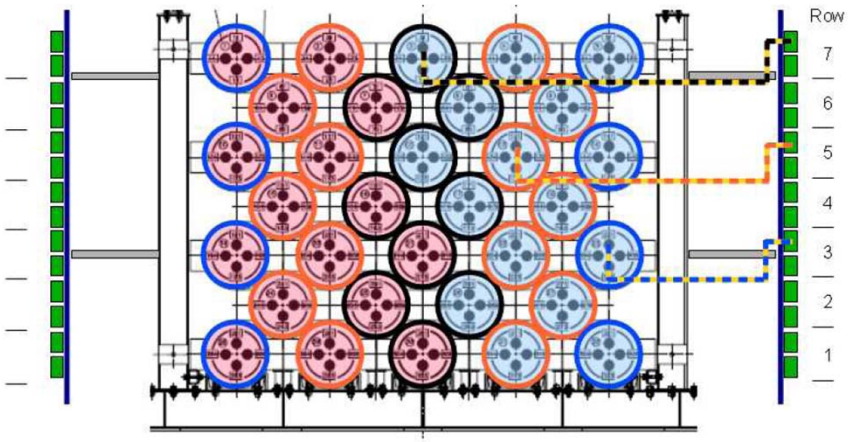
Efficiency ~independent of energy

HALO Geant4 simulation study
Leigh Schaefer, TUNL REU @Duke, summer 2011
(eff somewhat lower in current sim – but shape and relative effs the same)

Electronics

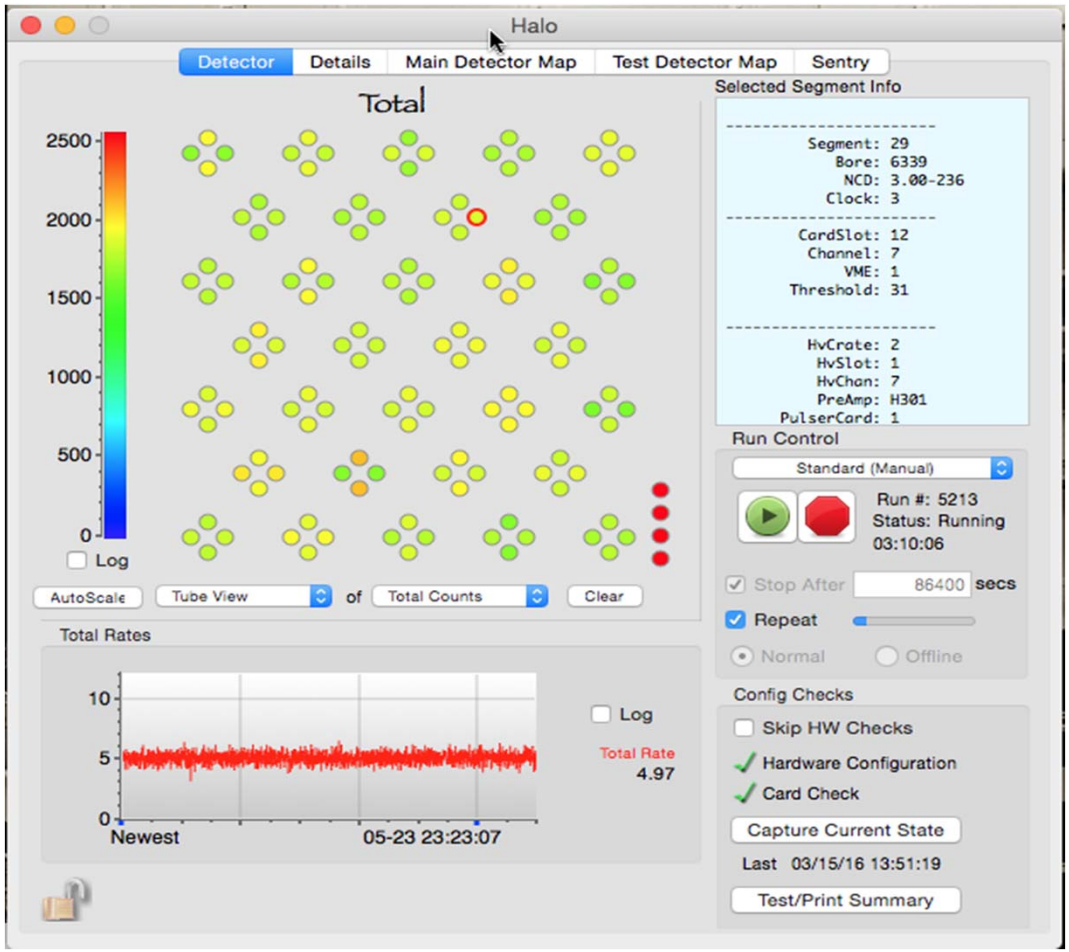
- Cabling fabricated at TRIUMF
- UW sent reworked pre-amps for NCDs
- Designed for redundancy and ability to keep on trucking if part of the detector fails
  - No single points of failure anywhere
  - Hardware failures take down at most half of the channels





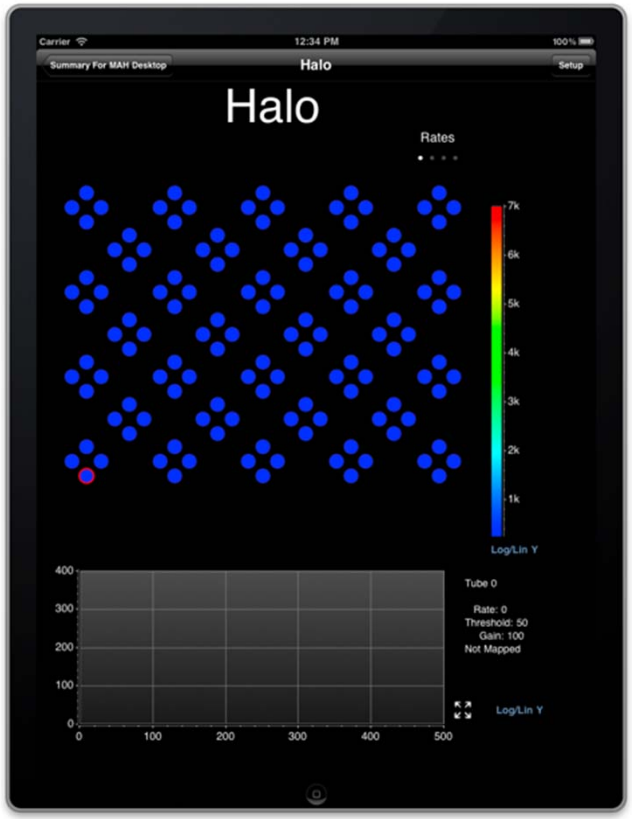
DAQ

- "ORCA" (*SNO DAQ*)
  - UNC supporting, developing with Duluth and Laurentian
- Taking data 24/7, root output copied to surface automatically
- Needs to be very automated and low maintenance!



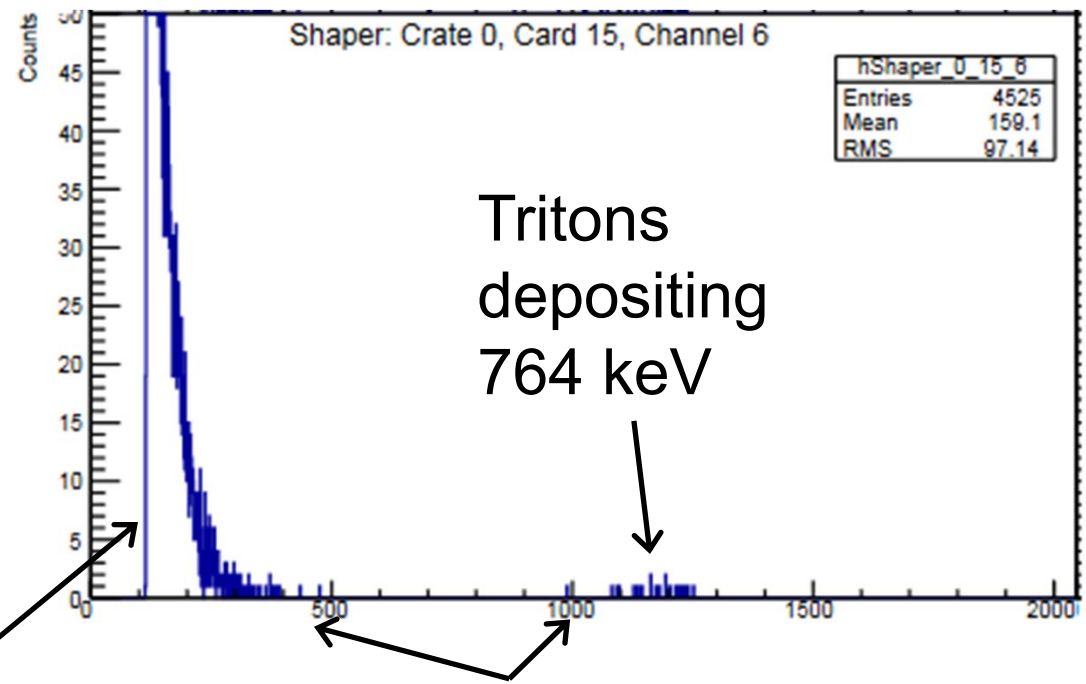
DAQ

- "ORCA" (*SNO DAQ*)
  - UNC supporting, developing with Duluth and Laurentian
- Mac-y-ness of ORCA has benefits:
  - Web interface convienient
  - Remote iPad interface cool but not yet fully functional



NCD Hit Spectrum

- A day's data on one channel, from early May
  - Two tubes multiplexed per channel



Gamma floor

Tritons losing partial energy in collisions

Background

- Primarily neutrons from cosmic ray interactions in rock
  - Minimized by SNOLAB's great depth (6000mwe)
  - Total: < 0.2 Hz
- 2.5 MeV γ from paint removed with energy cut

Fast Neutron Contribution:

Number of Counter Hits with No Shielding	1187 /day	1.37×10^{-2} Hz
Number of Counter Hits with 0.5 ft H_2O Shielding	852 /day	9.86×10^{-3} Hz
Number of Counter Hits with 1 ft H_2O Shielding	308 /day	3.56×10^{-3} Hz
Number of Counter Hits with 2 ft H_2O Shielding	98 /day	1.13×10^{-3} Hz

Thermal Neutron Contribution:

Number of Counter Hits with No Shielding	1099 /day	1.27×10^{-2} Hz
Number of Counter Hits with 0.5 ft H_2O Shielding	128 /day	1.48×10^{-3} Hz
Number of Counter Hits with 1 ft H_2O Shielding	28 /day	3.23×10^{-4} Hz
Number of Counter Hits with 2 ft H_2O Shielding	2 /day	2.10×10^{-5} Hz

Put it all together

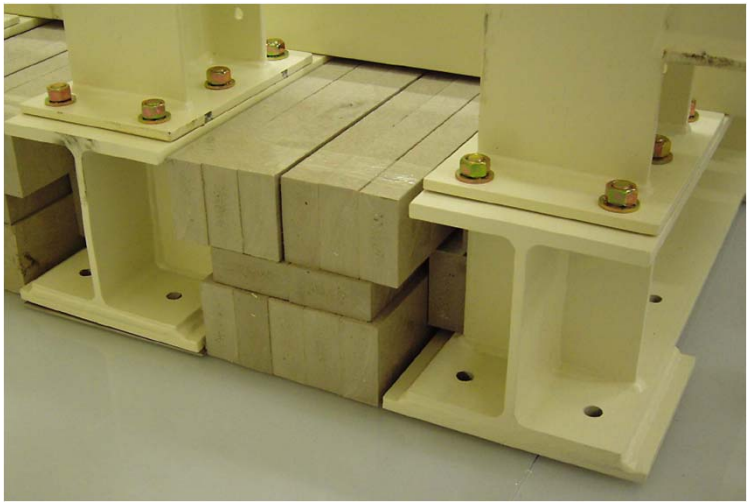
- With given signal, trigger on 6 neutrons in 2 seconds provides sensitivity to a SN @20kpc
- 150 mHz total BG rate triggered this ~monthly
  - Target "false" rate for SNEWS inclusion
  - Now 15 mHz after shielding completion!
    - That's ~1/minute
  - Graphite would add factor of 2 more reduction
- Bulk α contamination in NCD's Ni tubes adds 22±1 detected neutrons/day (negligible)

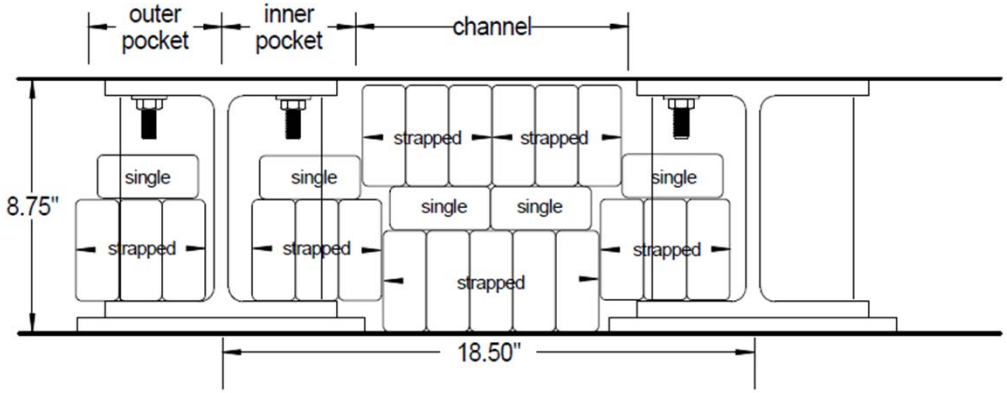
Increased Efficiency?

- Adding 20 cm of graphite reflector around the experiment increases ε from 30%→40% as well as decreasing background by factor of 2
- Space left in design, but we haven't found any we can scrounge for cheap, so as yet this part is a pipe dream

Shielding

- Water, Polypropylene shielding to reduce cosmic neutrons
  - From PICASSO and T2K experiments





Shielding

- 12 tonnes of reclaimed PICASSO water boxes,
- Fill voids with polystyrene beads (1.3 tonnes) (donated by T2K)
- Installed everywhere except the front face (for calibration)

6 of 14 pallets of finished water boxes

Calibration

- Cf neutron source was inserted in different places for a couple months in spring 2016
  - Efficiency of ~30% for neutron capture verified
- Front face shielding now complete

Calibration

- Cf neutron source gets you ~3000 n in 3 min
- @ several z's per tube
- ε as low as 14% near edge, as high as 49% in center
- Plots pending…

HALO

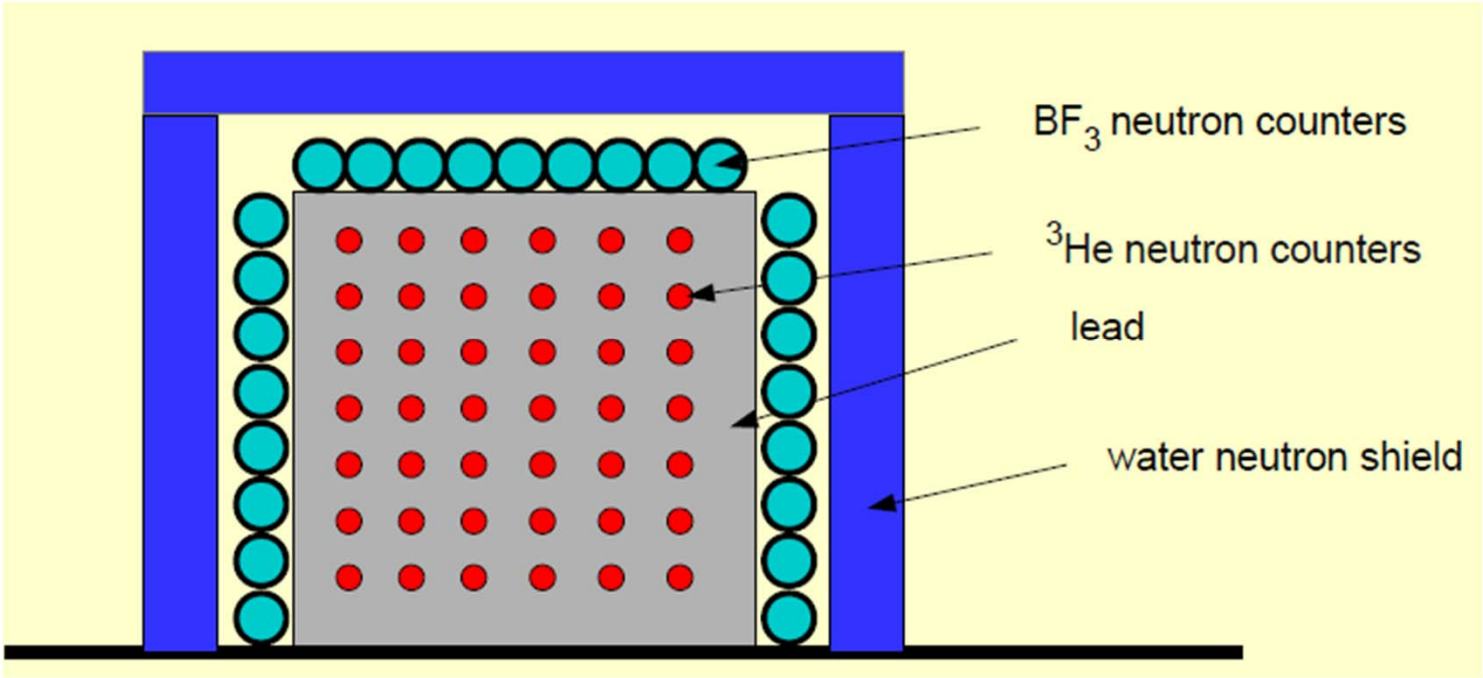
- Online in 2012, sensitive to SNe in our galaxy
  - Plugged into SNEWS
  - Cf calibration source last month
- Robust, high-livetime, long-lifetime, low-maintenance automated experiment
  - “Astronomically Patient” is our motto
- Sensitive to the ν_e the rest of the world is not
- Will allow interpretation of world’s SN ν data to probe fun ν-on-ν interactions in the proto-neutron star
- Eyes toward future kt-class HALO-2
  - OPERA has left 1kT of nice lead at LNGS, working with LVD colleagues on a design

HALO 2

- HALO is small, rate is low…
  - Can we do it bigger?
  - No one's going to give us 10's of millions of dollars for a dedicated SN experiment
- OPERA decommissioning at LNGS is leaving behind a kiloton of lead, already at depth
  - In thin (0.1cm) sheets, 10.3cm X 12.8 cm, with 56 sheets per emulsion brick
  - 1 kiloton = 10^6 kg = 119,446 OPERA bricks, or 6.69 million sheets
  - Would be a cube 4.45m on a side

HALO 2

- We have:
  - ~600m of ^{3}He NCDs (380 currently deployed)
  - 50 BF_3 counters, 2.26m long, 0.245 diameter
    - Each of which is only 36.3% as absorbing as the NCDs



HALO 2

- Working together with the LVD collaboration
  - SNe are one of their primary goals too
- Could we put the lead in the middle of a re-arranged LVD?
  - Paint LVD modules with Gd loaded paint, to provide additional neutron captures
- Status: much Monte Carlo work and phone meetings
  - Seems like it might work
- Funding?
  - Could probably do it for millions rather than 10's of millions… but that has to come from somewhere

Summary

- A core-collapse SN will occur in our galaxy sooner or later
  - A once-in-a-career chance to study something that's never been studied before up close
- It will produce a ν signal ~hours in advance of the light
  - Early Warning!
- HALO provides a new window on SN ν_e with a high-livetime, low-maintenance experiment
  - Low statistics, but when combined with larger experiments' different sensitivities, will allow unraveling of what's really going on

Acknowledgements

- HALO in the US is supported by NSF collaborative grants PHY1205857 & PHY1205957
  - Alec Habig @ UofM Duluth
  - Kate Scholberg @ Duke
- SNOLAB and NSERC are HALO's major sponsors
- NCDs and electronics on loan from UW

- More on the web at http://www.snolab.ca/halo/
  - See http://snews.bnl.gov for more SNEWS info and to sign up for the alert list