HALO + SNEWS

Turning supernova neutrinos
into neutrons and
early warnings

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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

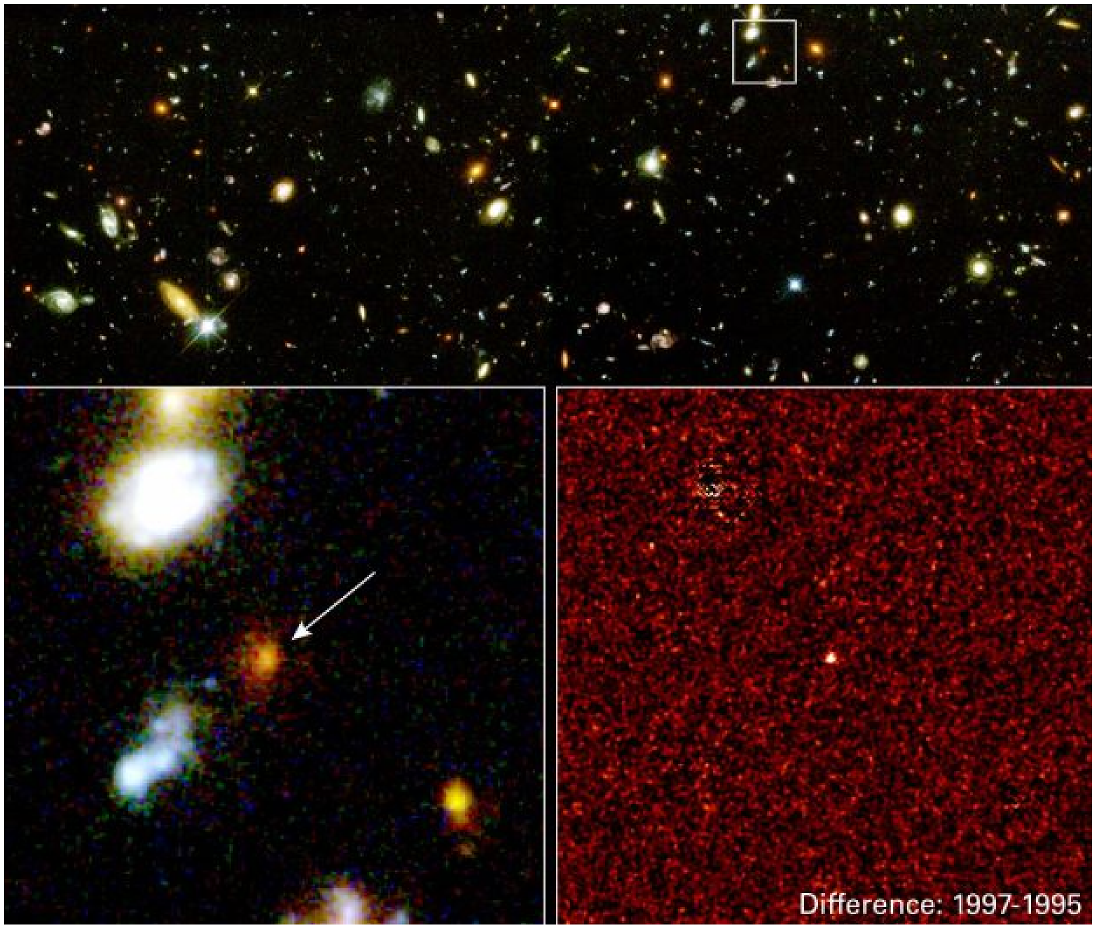


Photo by Adam Riess et al with HST

- 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!

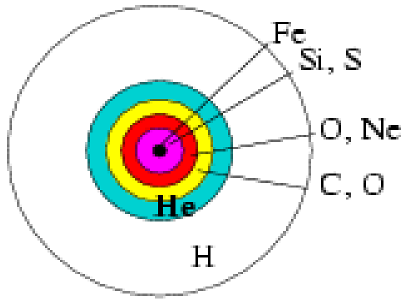
Core Collapse

- Type II SNe energy 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

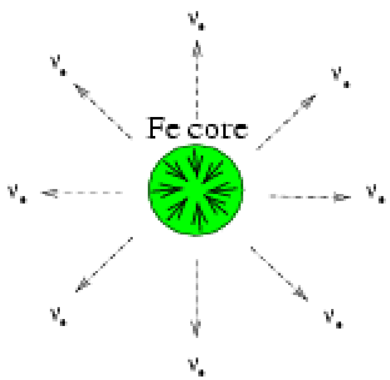
$$\Delta \mathrm{E}_B \sim \frac{GM_{core}^2}{R} = 3\times10^{53}\left(\frac{M_{core}}{M_\odot}\right)\left(\frac{R}{10\mathrm{km}}\right)^{-1} \mathrm{ergs}$$

  - M_{core}~$1M_\odot$, R~10 km, so $\Delta E_{binding}$ is ~$3x10^{53}$ 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!

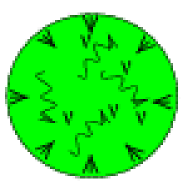
Core Collapse



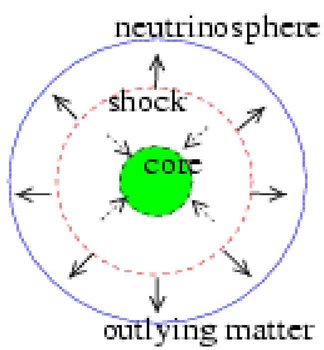
PRE-SUPERNOVA



COLLAPSE



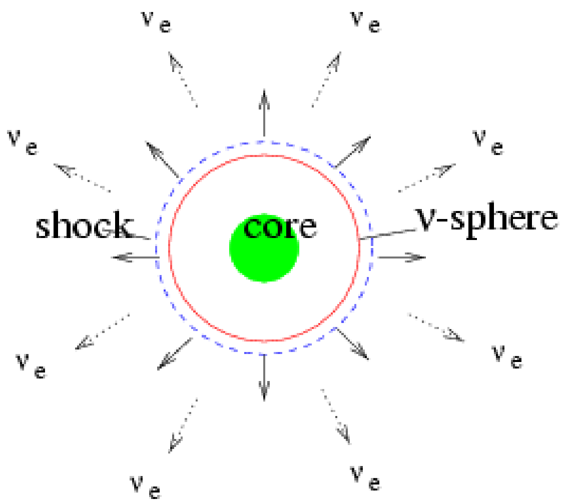
NEUTRINO TRAPPING



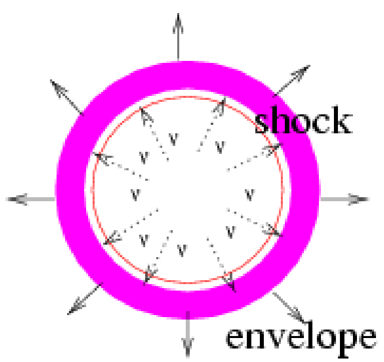
CORE BOUNCE

- 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”
  - Inverse β decay, ν produced
  - Quickly becomes so dense, opaque even to ν
- Shock wave of collapse rebounds when neutron degeneracy stops collapse

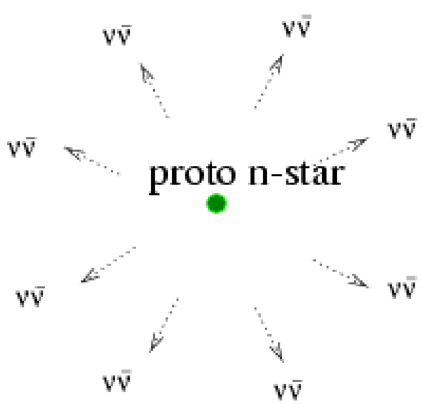
ν production



NEUTRINO BREAKOUT



EXPLOSION



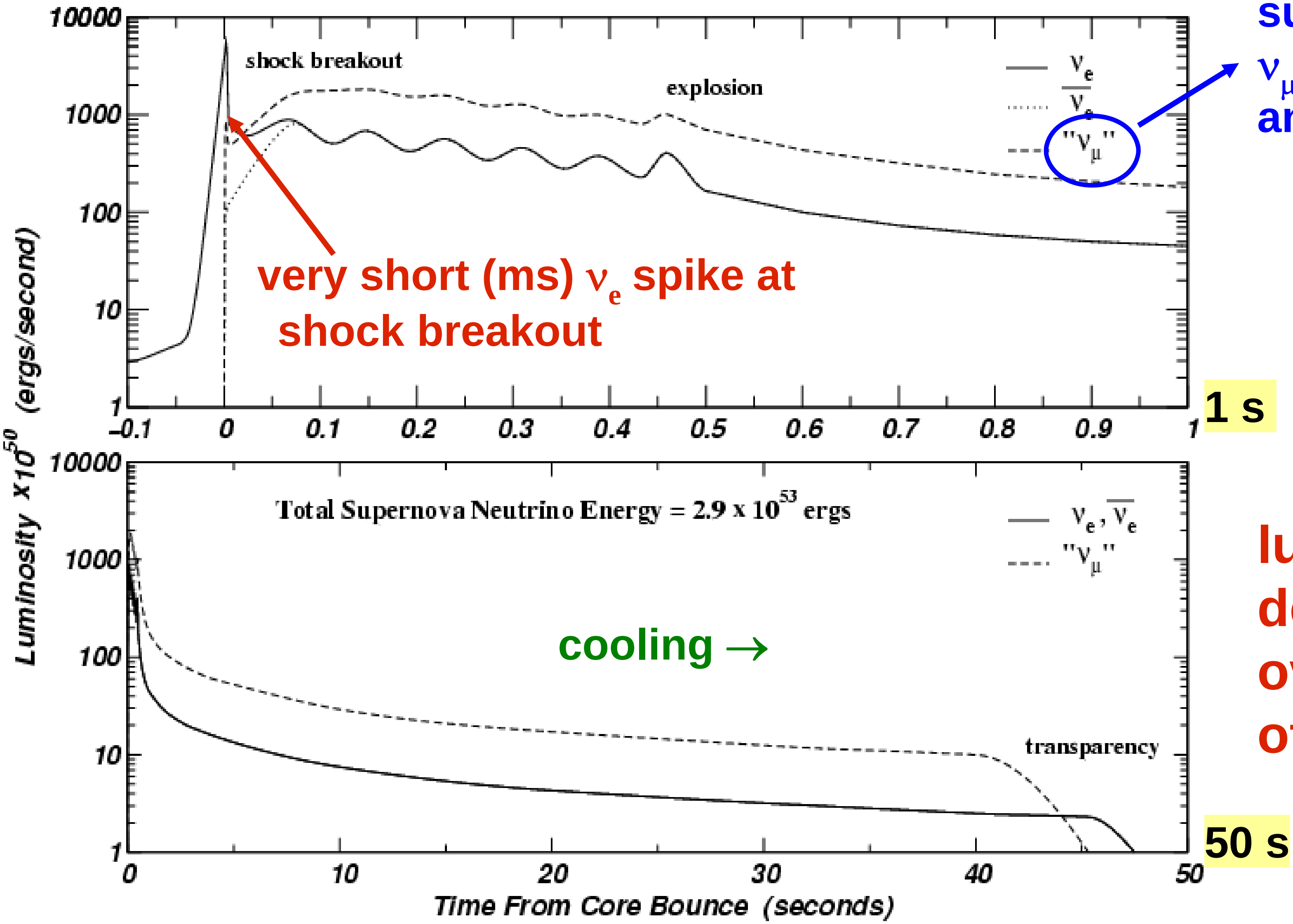
COOLING

- 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

luminosity decrease over 10's of seconds

Burrows et al. 1992

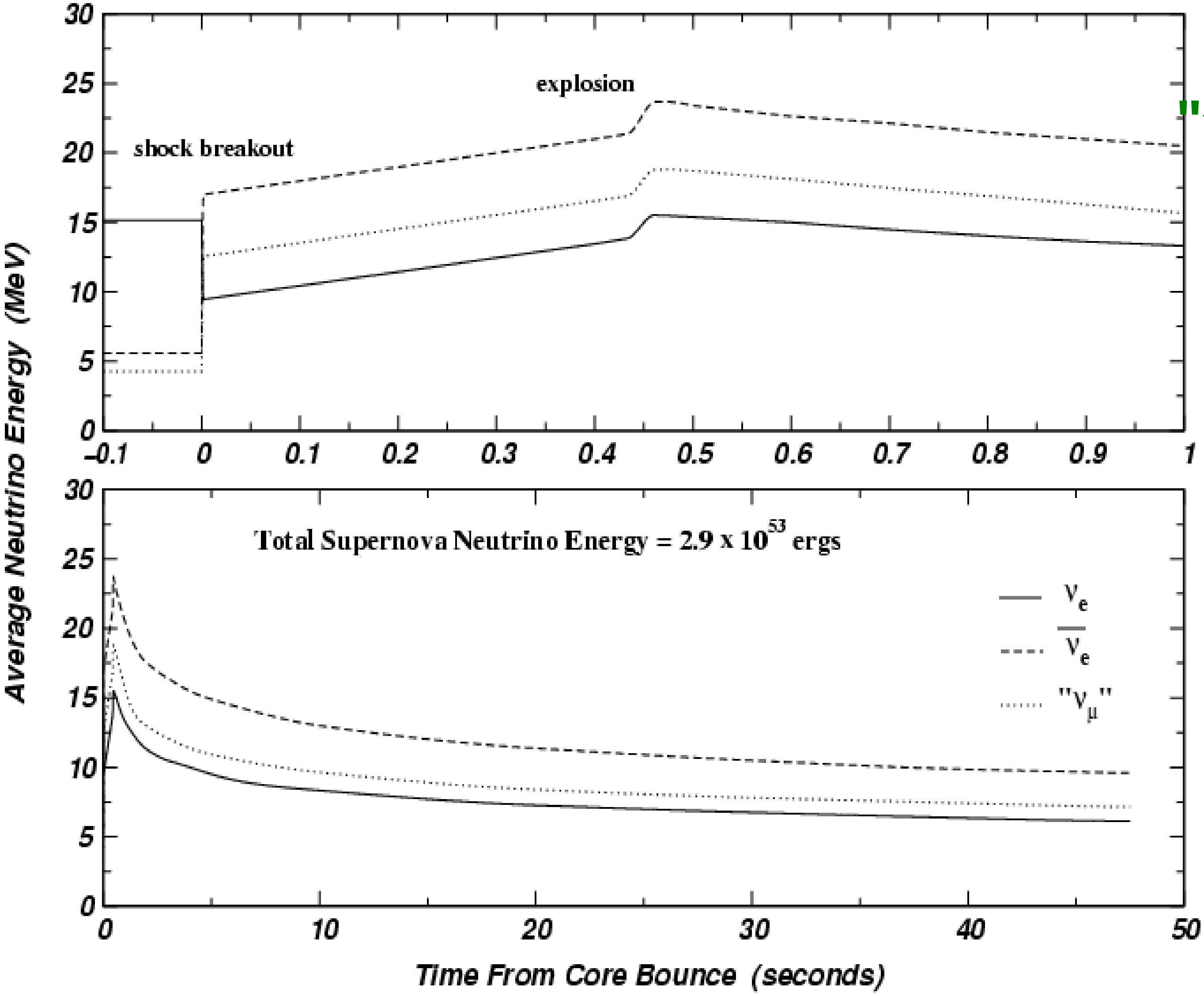
ν transmission

- 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

$$\left(\nu_e, \nu_\mu, \nu_\tau\right) \quad \left(\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau\right)$$

  - 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



"ν_μ"
$\bar{\nu}_e$
ν_e

Transparent sooner, deeper in ν-sphere, $\Rightarrow$ *hotter*

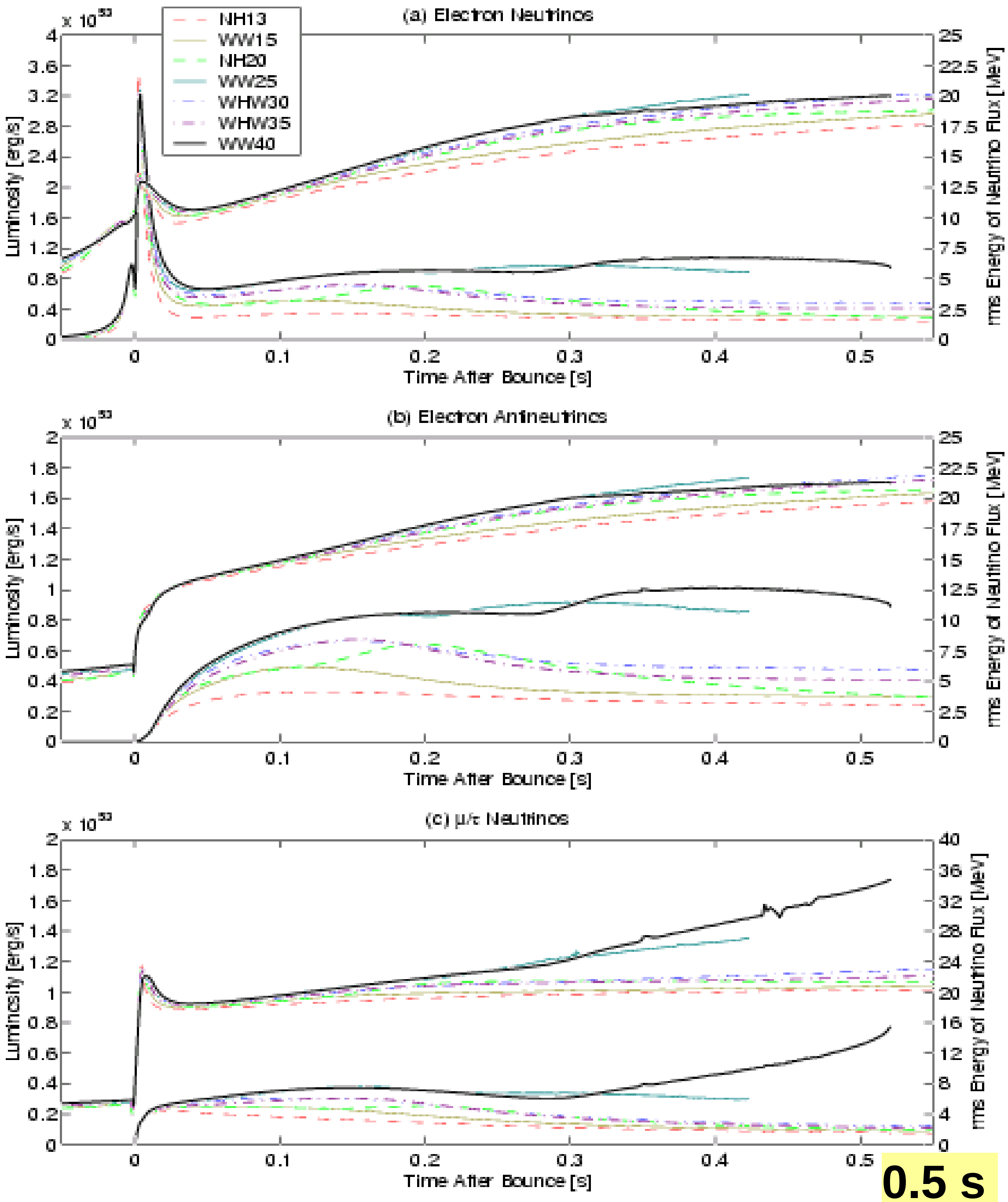
1 s

Energy decrease over long timescale (cooling)

50 s

Burrows et al. 1992

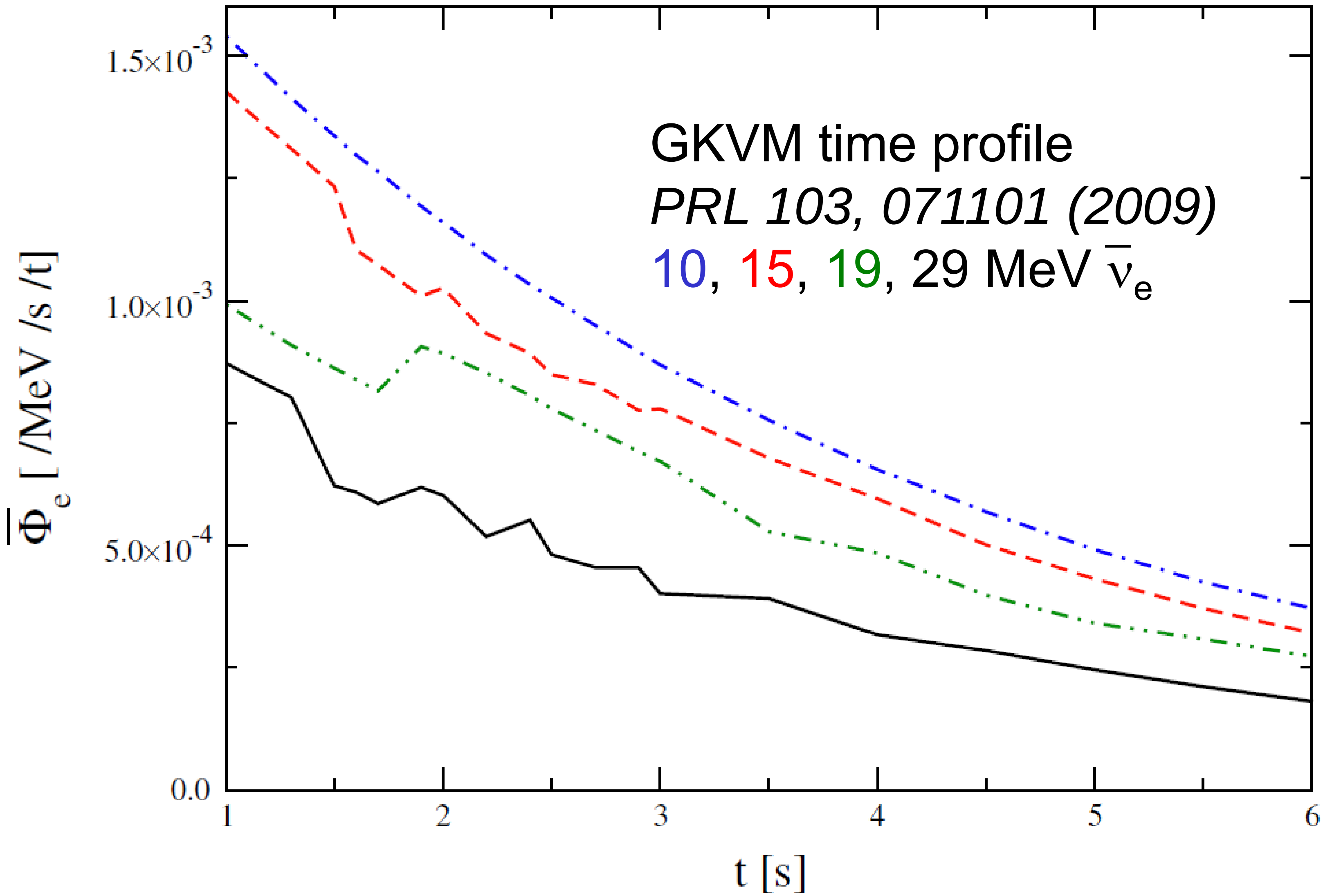
More details



- 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

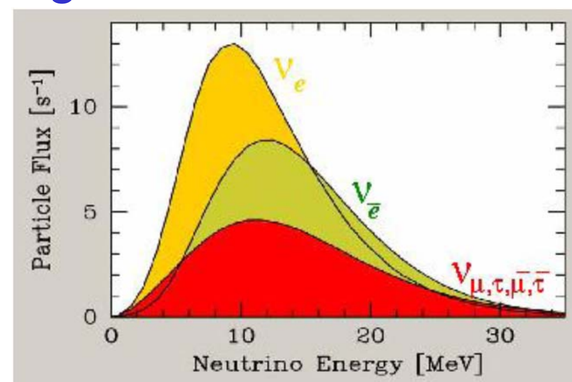
M. Liebendorfer *et al*. 2001

Time Profile



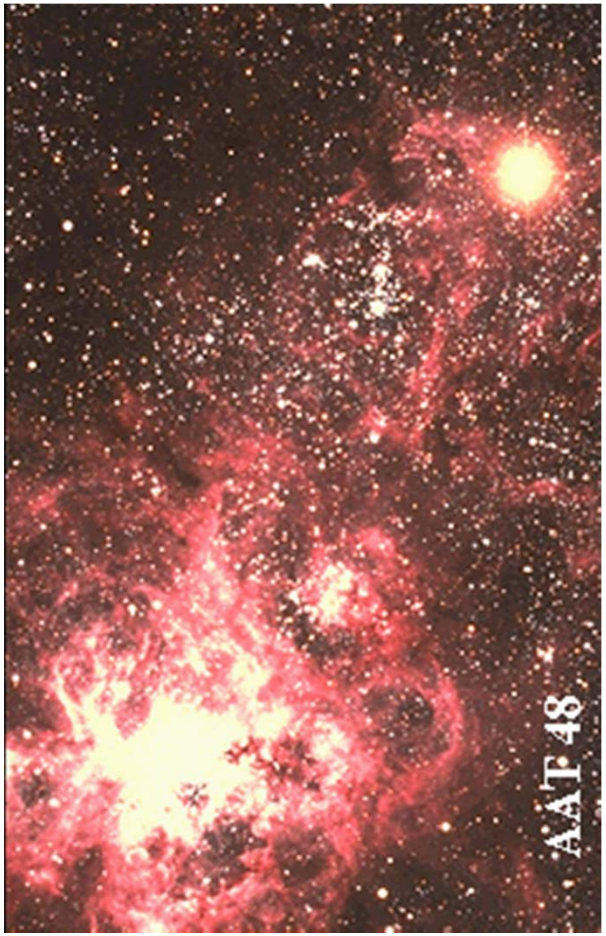
Generalities

- Prompt ν signal after core collapse
  - Lasts 10's of seconds
  - 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
  - But ν oscillations will scramble this
    - And exactly how they do would be 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 $\bar{\nu}$ needed to study such effects



A. Dighe, TAUP09

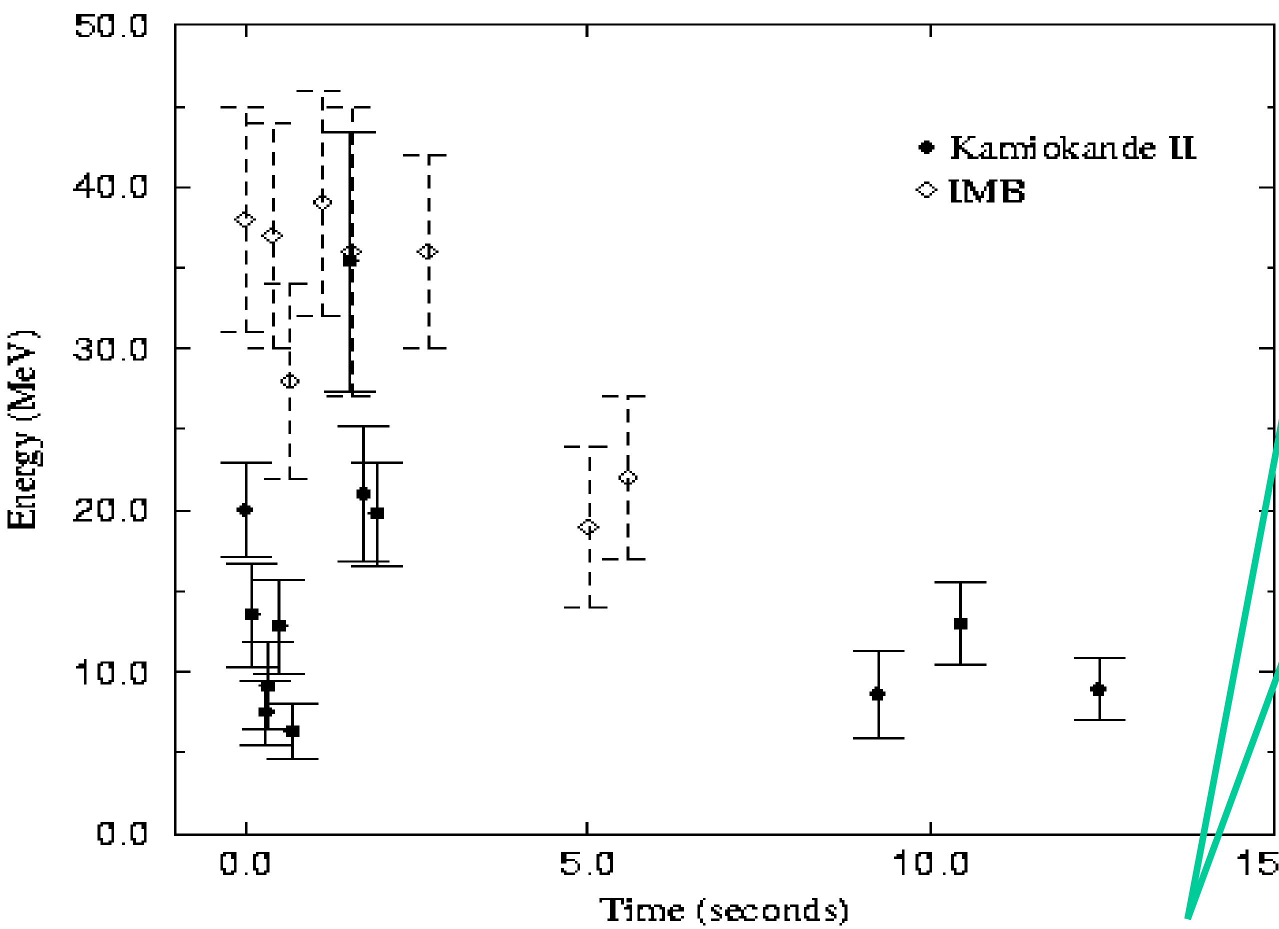
Experimentally Confirmed



- 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 imply…

SN1987A ν observations

Water Cherenkov

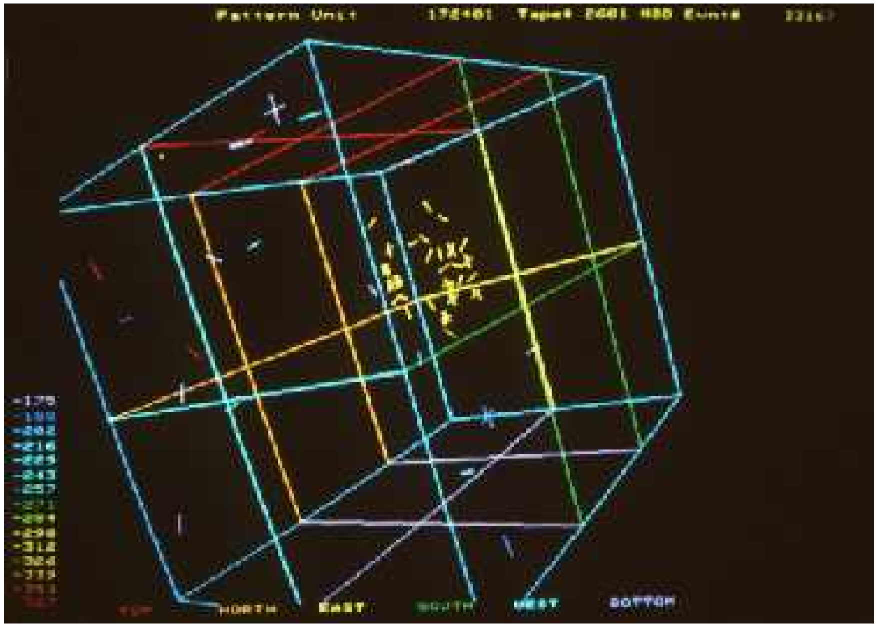


Liquid Scintillator

- 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 (??)

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 $m_{\nu_e} < 20\text{eV}$
  - 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	

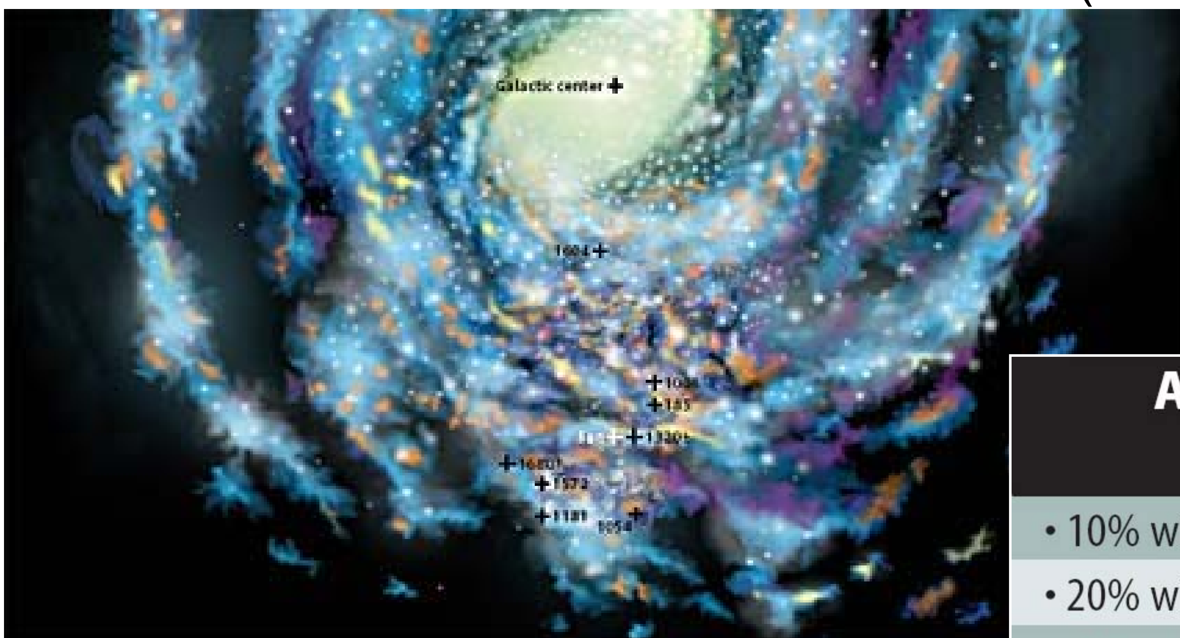
Overall?

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)



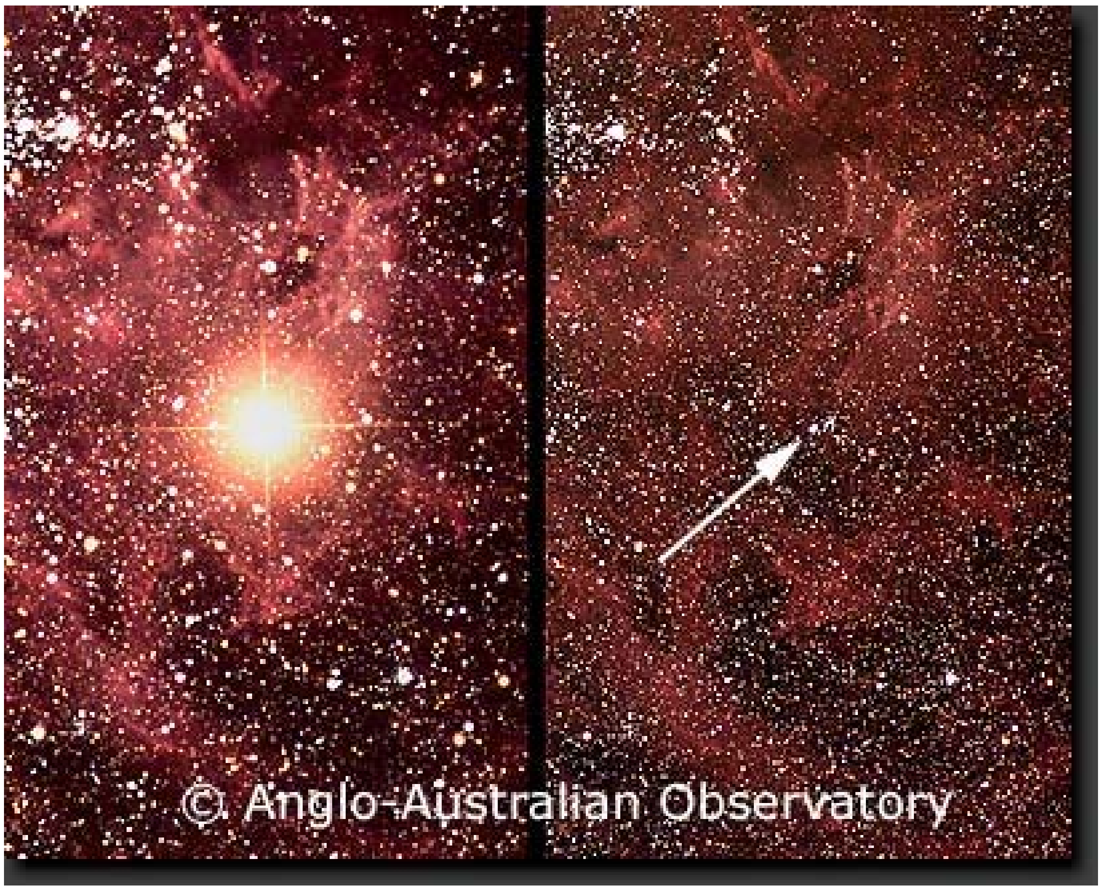
Apparent Brightnesses of Milky Way Supernovae
• 10% will peak brighter than magnitude −3
• 20% will peak between magnitudes −3 and +2
• 20% will peak between magnitudes +2 and +6
• 20% will peak between magnitudes +6 and +11
• 30% will peak fainter than magnitude +11

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
  - Several dozen papers per ν event seen
    - Something like an average of 1/week over 20+ years
- 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!

Small Δt SN Observations



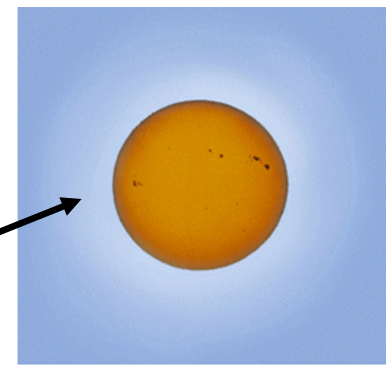
SN1987A

Blue Giant
Sk -69 202

- Earliest observations (and non-observations) of SN1987a were fortuitous
  - ~hours before/after the actual event
  - Chance observations (Shelton, Duhalde, Jones)
  - Very careful observer records null-observations to constrain breakout time (Jones)
- Extragalactic SNe not so obvious
  - Typically days-weeks elapse before someone notices
- What goes on between these pictures?

Advance Warning

- Observations from t=0?
  - Sure. Or very nearly so, certainly better than the serendipitous ~hours of SN1987A, and far closer than the ~days which is the best we can get on an extragalactic SN



- How?
  - ν's exit the SN promptly
  - But stars are opaque to photons
  - EM radiation is not released till the shock wave breaks out through the photosphere – a shock wave travel time over a stellar radius
  - ~hour for compact blue progenitors, ~10 hours for distended red supergiants

The Scheme

- Now that we know we can see SN ν, how to do it differently the next time?
  - (*caveat – nearby only, from Milky Way and environs*)
- "Luck" = Opportunity x Preparation
  - Neutrinos are emitted promptly upon core collapse
  - Produce obvious signal in today's detectors, most have automated analysis chain to trigger on SN ν
  - Instant information transfer now commonplace
  - A galactic SN would be close enough we'd really want to have very good observations starting at t=0
    - *ie*, we'd have a prayer of *noticing* whatever cool things happen at or shortly after breakout
- So let's trigger photon-based observations of the next galactic SN using the neutrino pulse

Is This Practical?

- The neutrino experiments must be able to:
  - Identify a SN ν signal
  - Confirm it's not noise
  - Get the word out
  - Figure out where people should be pointing
  - All in an hour
- Note that the GCN/Bacodine network does this in seconds for GRB's
  - Although they have a specialized circumstance and a lot of practice

Our Telescopes

- Photons should be the easy stuff to work with…
- SN ν detectors need:
  - Mass (~100 events/kton)
  - Background rate << signal rate
- Bonus items:
  - Timing
  - Energy resolution
  - Pointing
  - Flavor sensitivity

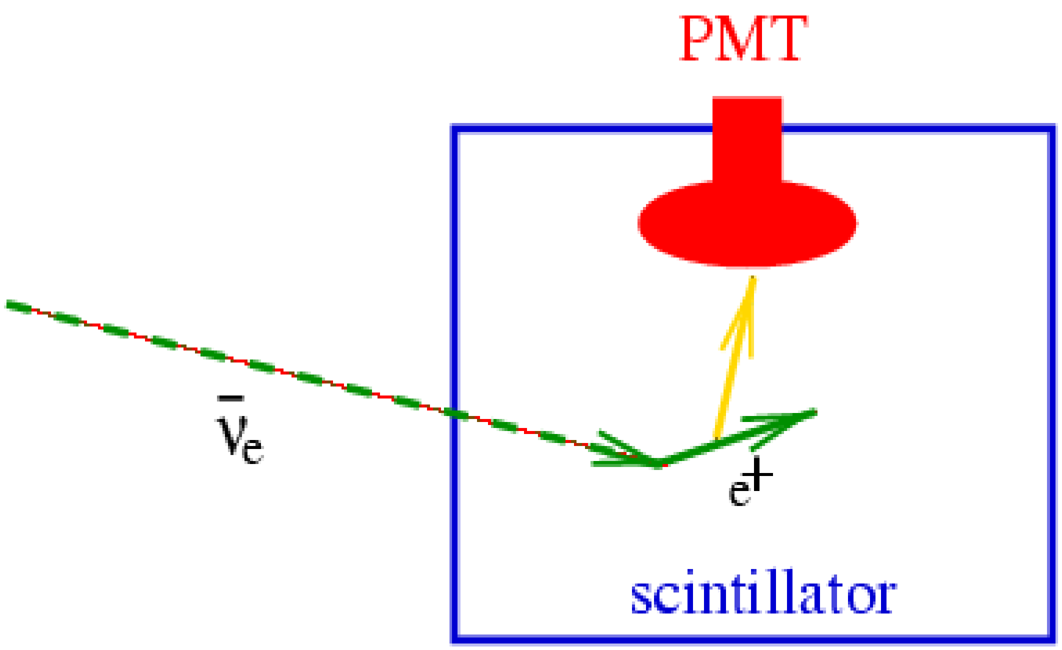
Basic Types

- Scintillator (C_nH_{2n})
- Imaging Water Cherenkov (H_2O)
- Heavy Water Cherenkov (D_2O)
- Long String Water Cherenkov (H_2O)
- High Z (Fe, Pb)
- Gravitational waves
  - Well, not neutrinos, but gravitons would also provide a prompt SN signal if SN was asymmetric

Scintillator

- Volume of hydrocarbons (usually liquid) laced with scintillation compound observed by phototubes
  - Mostly inv. β decay (CC): $\bar{\nu}_e + p^+ \rightarrow e^+ + n$
  - ~5% ^{12}C excitation (NC): $\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$
  - ~1% elastic scattering (NC+CC): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Low E proton scattering (NC): $\nu_x + p^+ \rightarrow \nu_x + p^+$

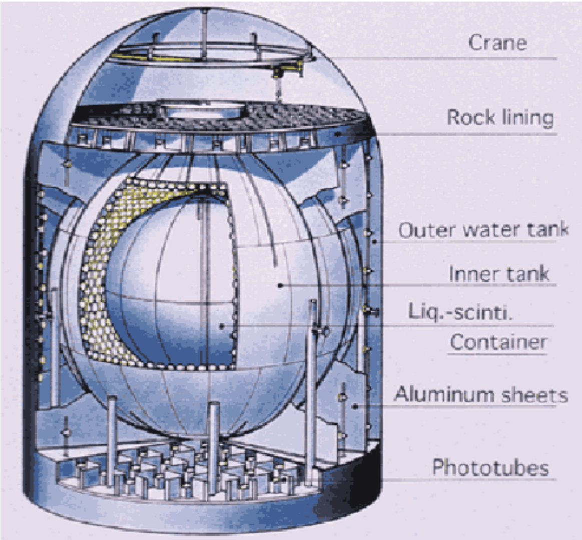
(seen)



Little pointing capability

Mont Blanc, Baksan, MACRO, LVD, Borexino, KamLAND, MiniBooNE, DoubleCHOOZ, Daya Bay, SNO+, NOνA

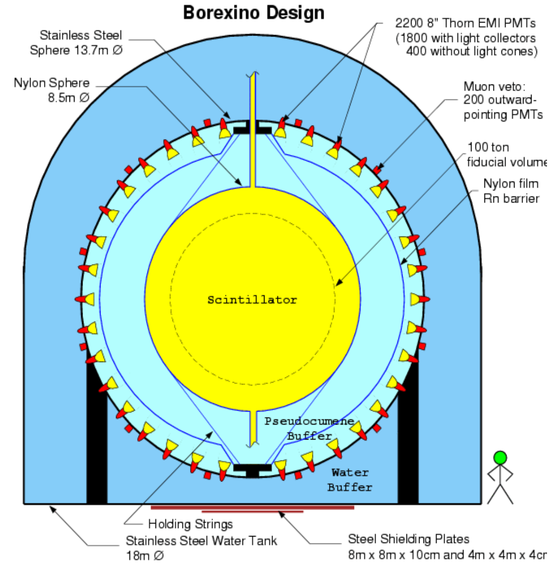
Scintillator Expts.



KamLAND (Japan)

1 kton

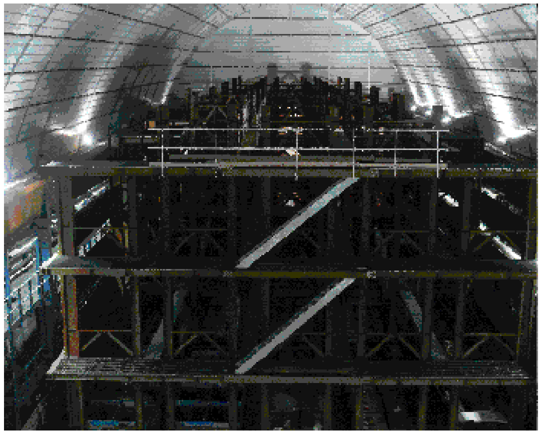
~300 $\overline{\nu}_e$ at 8.5 kpc



Borexino (Italy)

0.3 kton

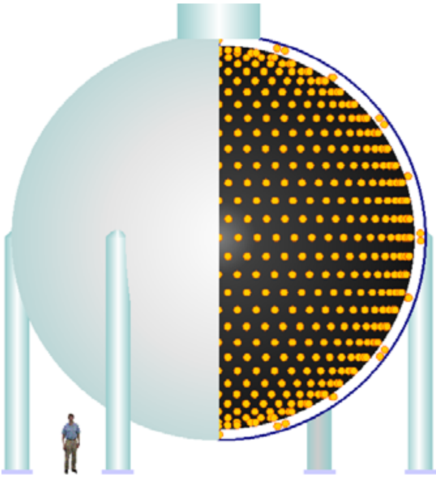
~100 $\overline{\nu}_e$



LVD (Italy)

1 kton

~200 $\overline{\nu}_e$



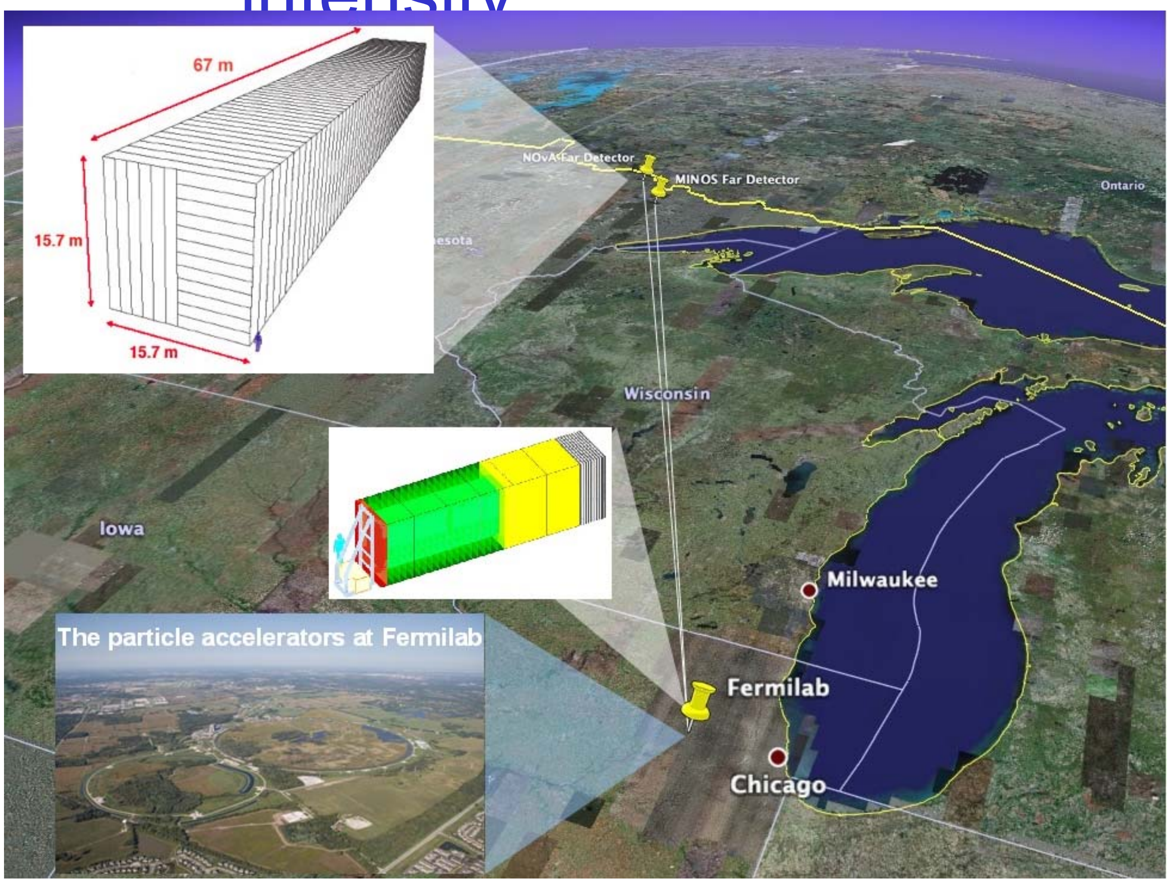
Mini-BooNE (Fermilab)

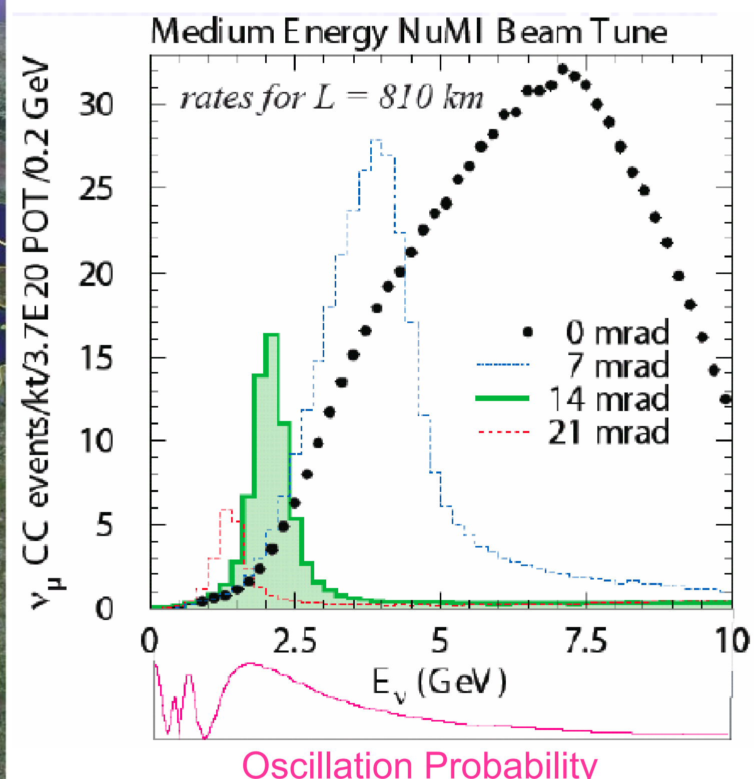
0.7 kton

~200 $\overline{\nu}_e$

The NOνA Experiment

- 810 km from Fermilab, 14 mrad off-axis gets a beam which is tight in energy but low in intensity





Event Table (GKVM/Livermore)

- Inverse Beta Decay
  - ibd 3185/5355
- Elastic Scattering
  - nue_e 72/125
  - nuebar_e 31/55
  - numu_e 12/22
  - numubar_e 10/18
  - nutau_e 12/22
  - nutaubar_e 10/18
  - Total ES: 148/261

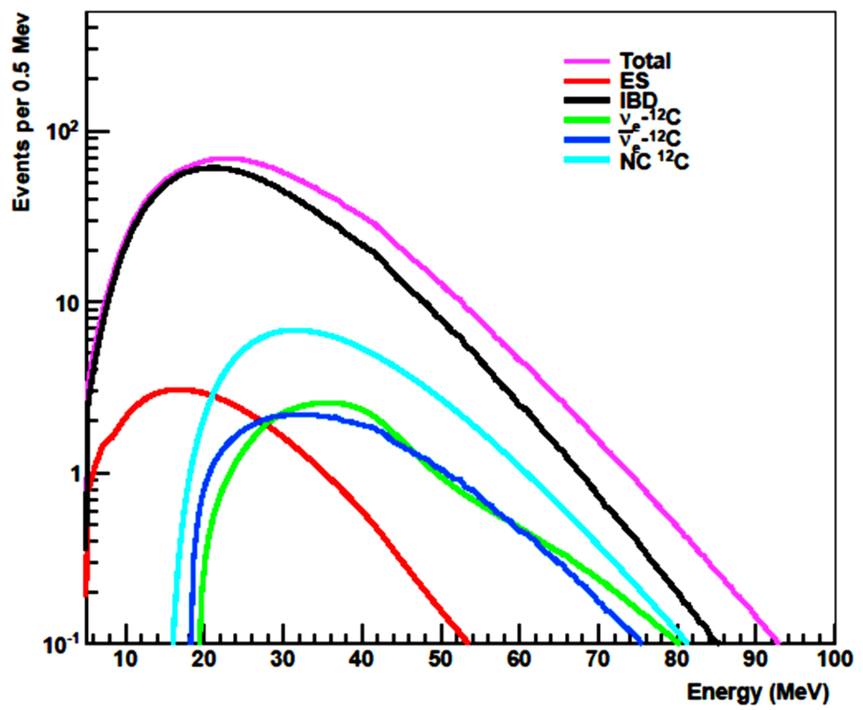
Total Events: 3970/6883

- CC interactions with Carbon
  - nue_C12 134/50
  - nuebar_C12 131/195
- NC interactions with Carbon
  - nue_C12 61/30
  - nuebar_C12 64/96
  - numu_C12 61/223
  - numubar_C12 61/223
  - nutau_C12 61/223
  - nutaubar_C12 61/223
  - Total NC: 371/1020

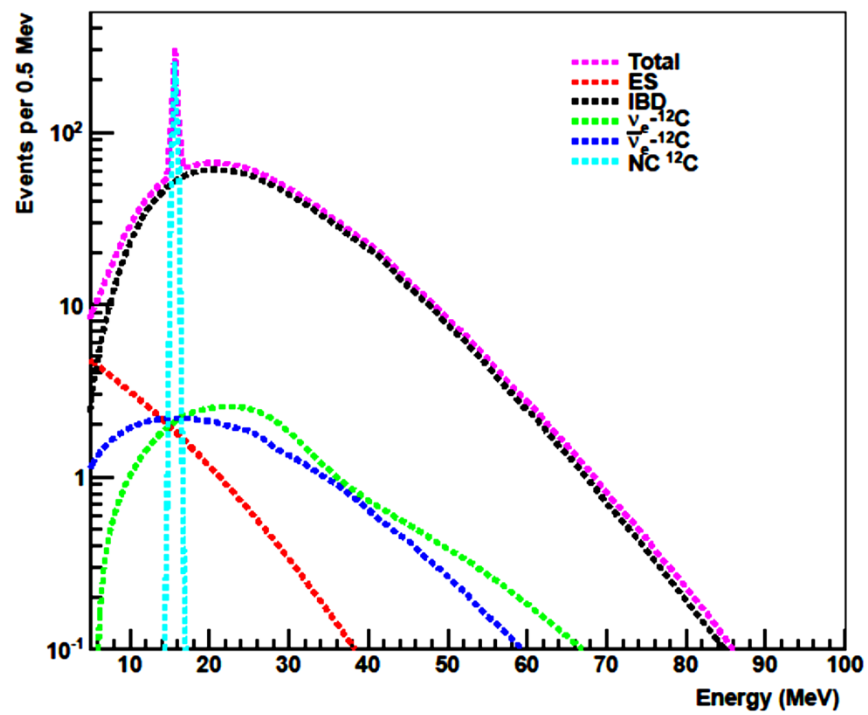
15kt Scintillator, SN@10kpc

ν Spectra in NOvA

Interacting ν



Resulting visible particles



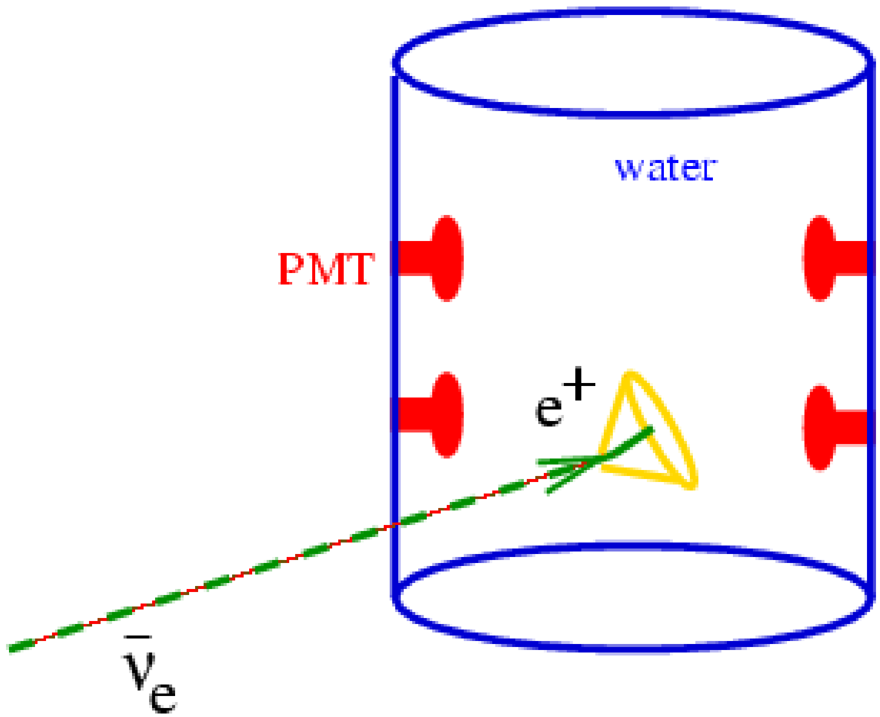
SNOwGLOBES physics simulation: not yet put into GEANT

K. Scholberg (2012) arXiv:1205.6003v1 [astro-ph.IM]

Water Cherenkov

- H_2O viewed with phototubes, Cherenkov radiation observed
  - Mostly inv. β decay (CC): $\bar{\nu}_e + p^+ \rightarrow e^+ + n$
  - ~% elastic scattering (NC+CC): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - ^{16}O excitation (NC): $\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^*$
  - ^{16}O CC channels: $\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$; $\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$

(seen)



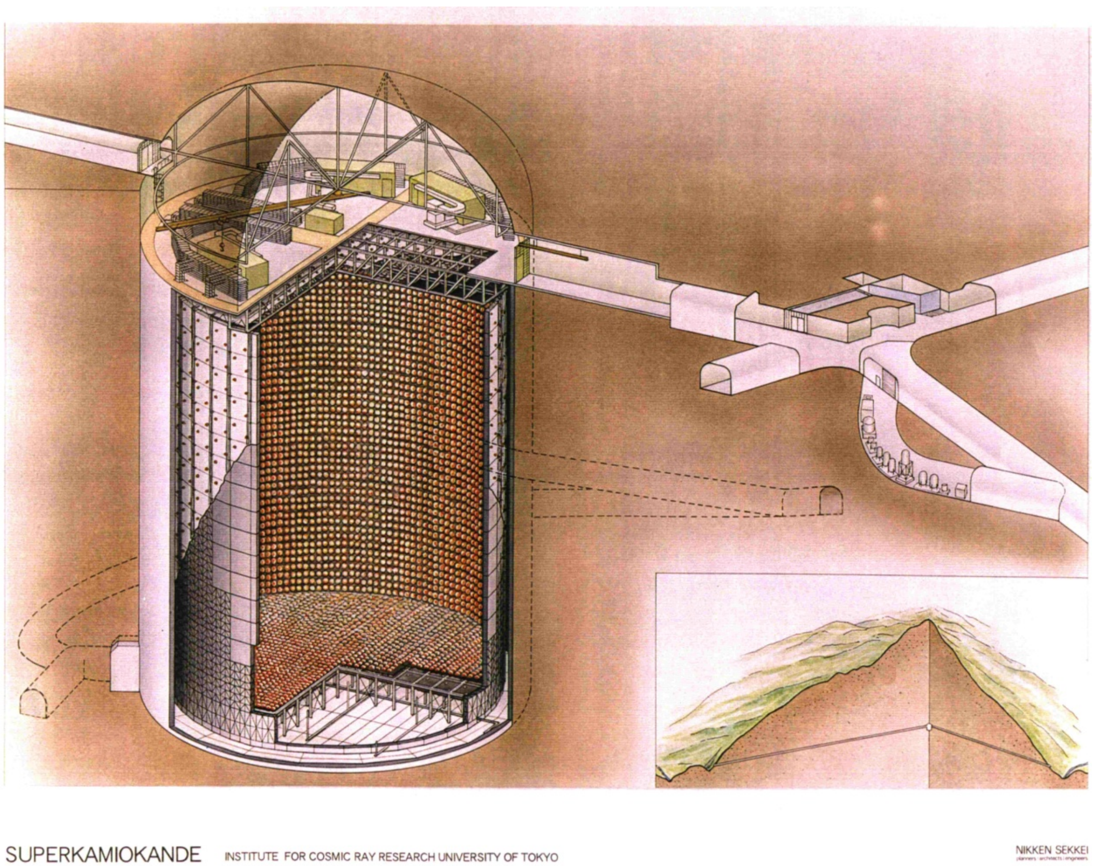
Pointing!

$$\delta\theta \sim \frac{25^o}{\sqrt{n}}$$

IMB, Kamiokande,
Super-K,
outer part of SNO

Imaging Water Cherenkov

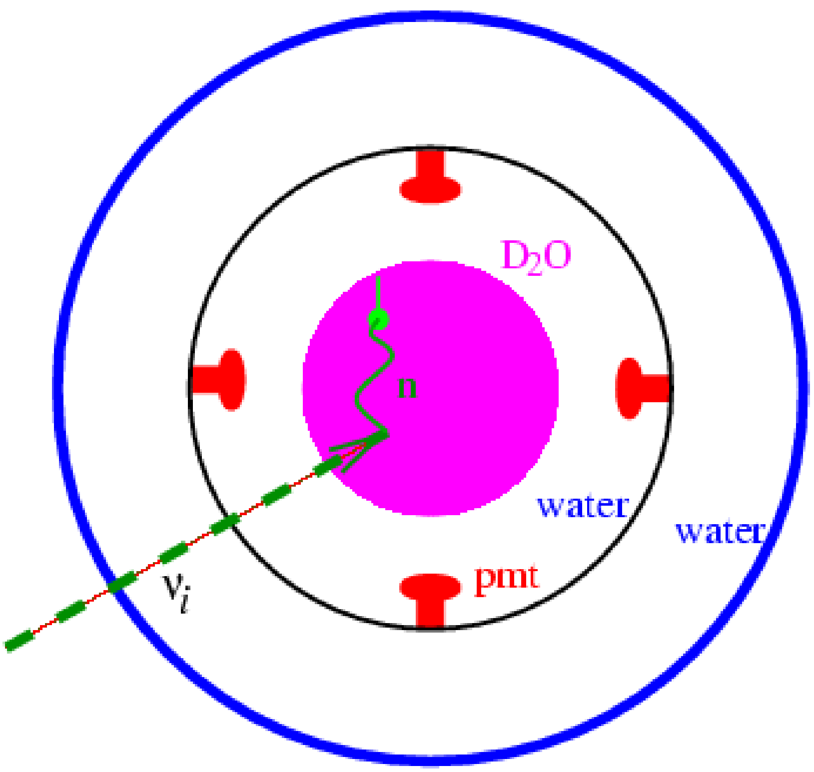
Super-Kamiokande (Japan) 50kton



- Events expected for SN@8.5 kpc > 5MeV
  - Inv β decay: 7000
  - ^{16}O excitation: 300
  - ^{16}O CC channels: 110
  - elastic scattering: 200
    - 4^o pointing

Heavy Water

- D_2O observed with phototubes, perhaps with n capture enhancements (salt, ^{3}He)
- Flavor sensitivity, some pointing



CC ^{2}H breakup:

$\nu_e + {}^2H \rightarrow p^+ + p^+ + e^-$

$\bar{\nu}_e + {}^2H \rightarrow n + n + e^+$

(seen)

NC ^{2}H breakup:

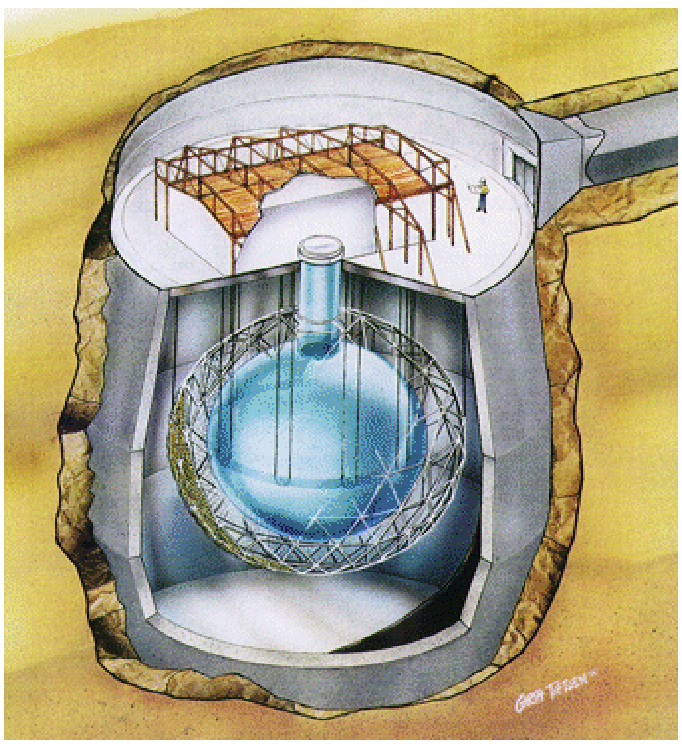
$\nu_x + {}^2H \rightarrow n + p^+ + \nu_x$

$\bar{\nu}_x + {}^2H \rightarrow n + p^+ + \nu_x$

… plus normal H_2O channels

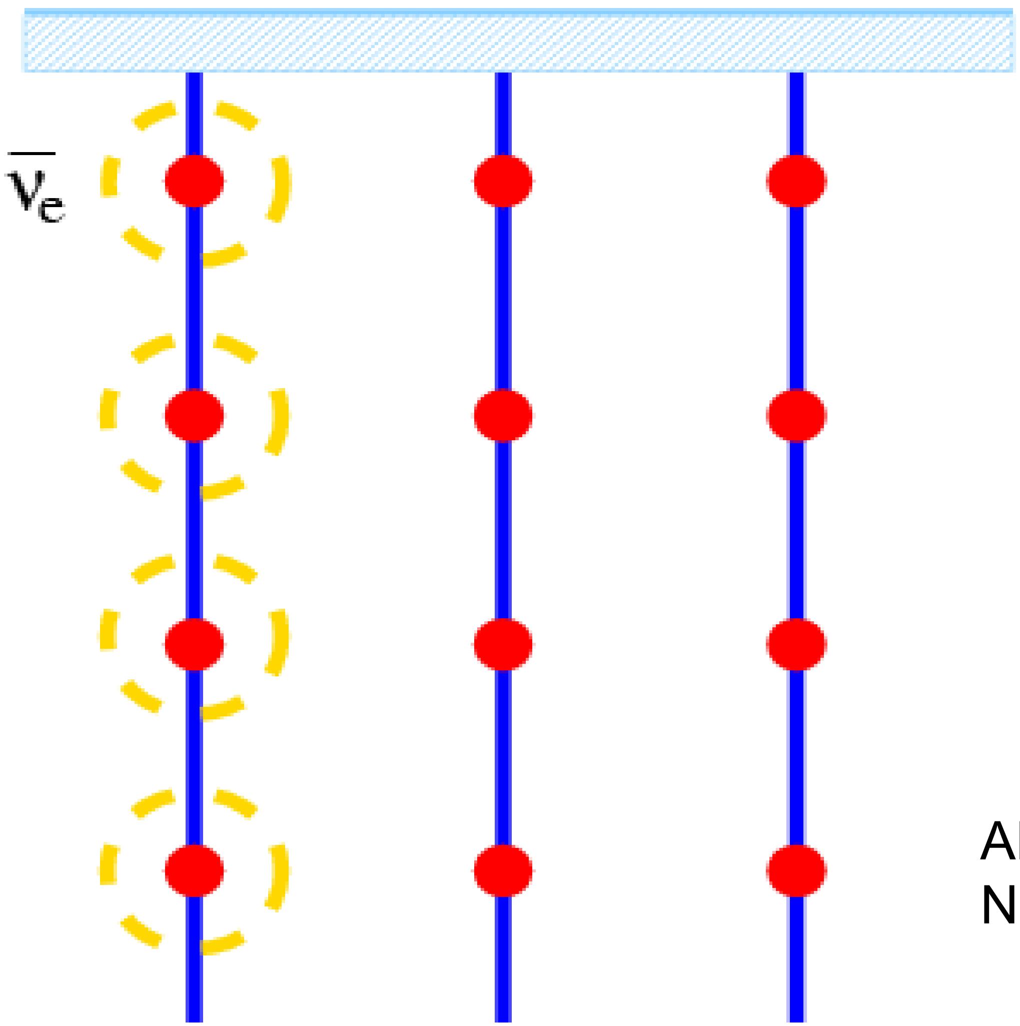
Heavy Water

Sudbury Neutrino Observatory
(Canada) 1.7kton H_2O, 1kton D_2O



- Events expected for SN@8.5 kpc
  - Inv β decay: 500
  - CC ^2H breakup: 100 each
  - NC ^2H breakup: 400
  - elastic scattering: 30
    - 15^o pointing

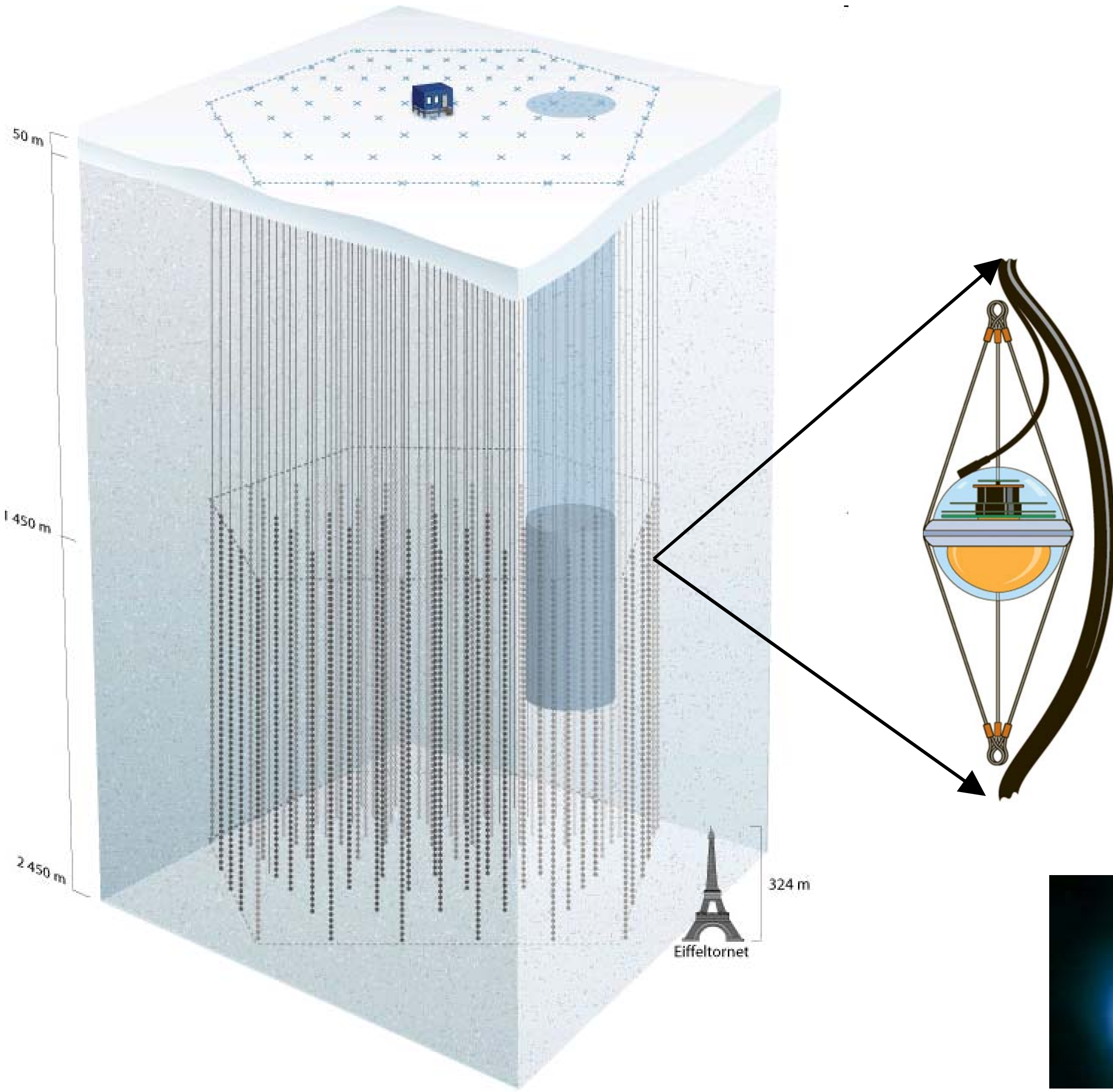
Long String Water Cherenkov



- Dangle PMT's on long (~km) strings in clear ice or water
- High-E ν telescopes with E_{th}~100 GeV
- But singles rates around PMT's raised by SNe $\bar{\nu}_e$
  - M_{eff} = 0.4kton/PMT

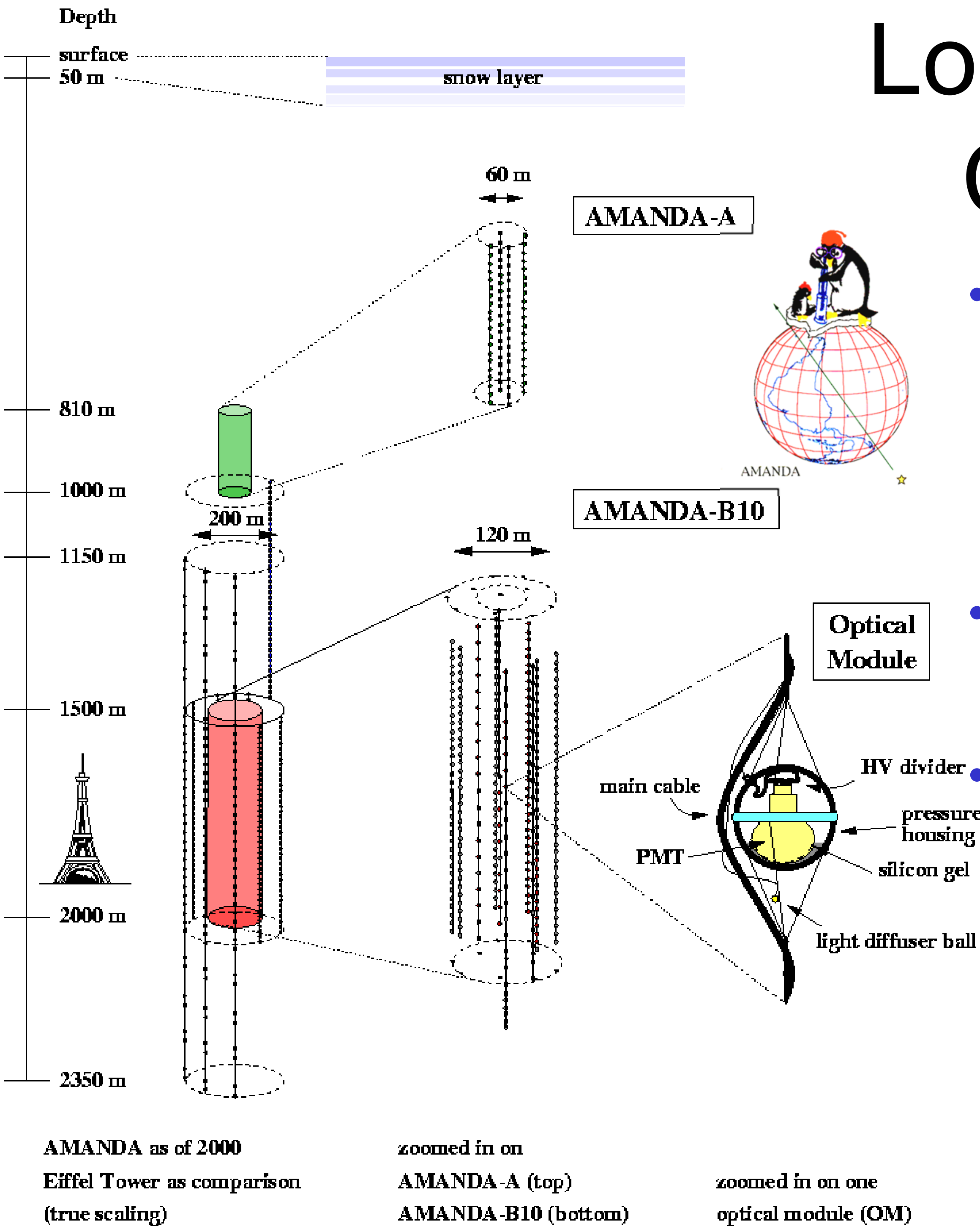
AMANDA, Ice Cube, Baikal, Nestor, Antares, Km3Net…

Long String Ice Cherenkov



- Ice-based expts. have low enough background rate to work
  - Sea based have ^{40}K, squid, etc.
- 16σ S/N @8.5kpc
  - But little ν by ν info such as energy
- AMANDA:
  - Special SN trigger was operational till experiment was retired
- IceCube's new electronics do it even better

Long String Ice Cherenkov



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- AMANDA:
  - Special SN trigger was operational
  - IceCube's new electronics does it even better

High-Z

- High-Z (Fe and/or Pb + neutron capture)
- Pb has large neutron excess, so primarily sensitive to $\nu_e + n \rightarrow e^- + p^+$
  - Creates Bi nuclei in excited state, decays by single-n emission at lower energies, double-n at higher energies (provides spectral handle)
  - Pb has tiny n-absorption cross-section, so n's can get out of target mass to be detected
- Simple, long term, high mass
  - OMNIS pioneered design, HALO being built @ SNOLAB

"… a lead detector would provide crucial information about the proto-neutron star."

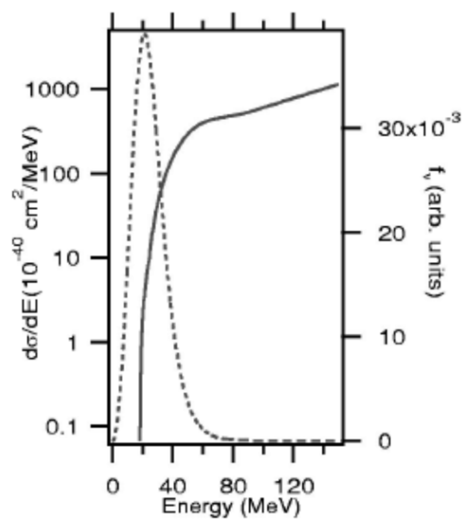
What Can Be Learned with a Lead-Based Supernova-Neutrino Detector?
J. Engel et al. Phys. Rev. D67 (2003) 013005

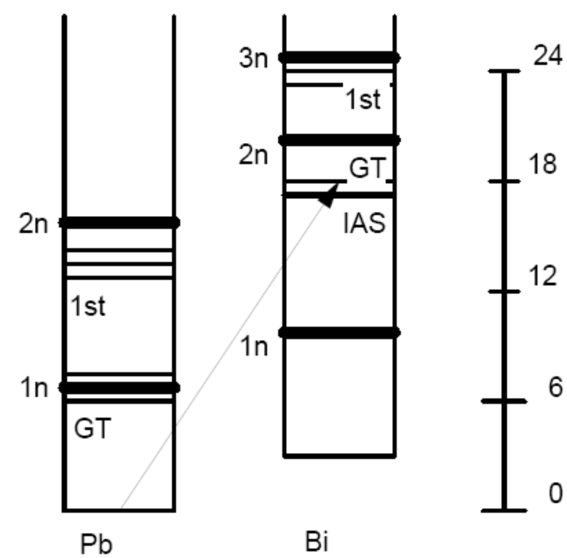
SNe ν_e and Lead

- 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)

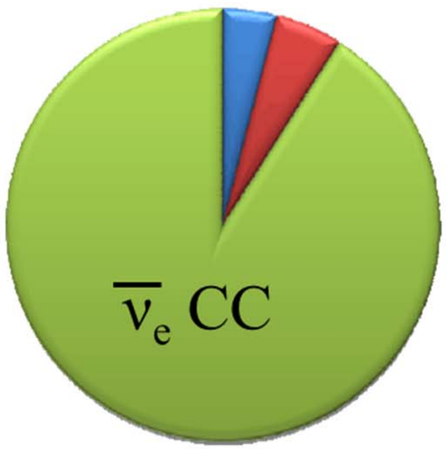




Pb & Bi nuclear levels

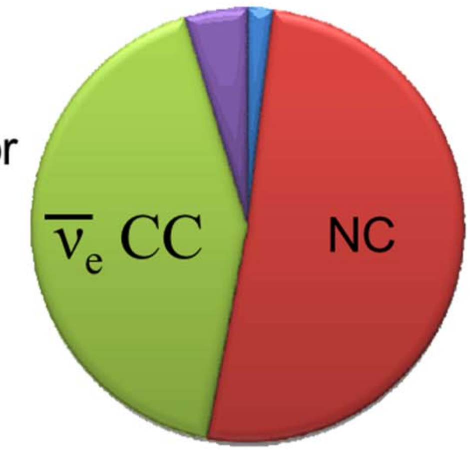
Bacrania et al,
NIM **A492**, 43 (2002)

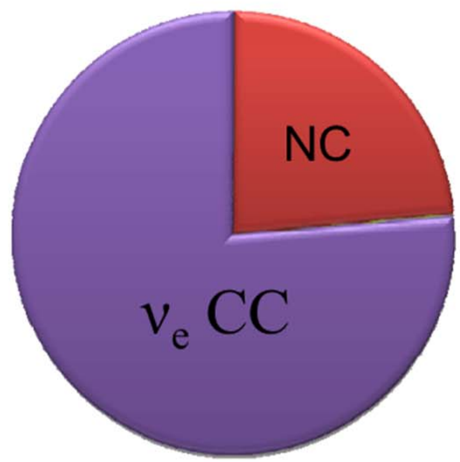
Flavor Sensitivities



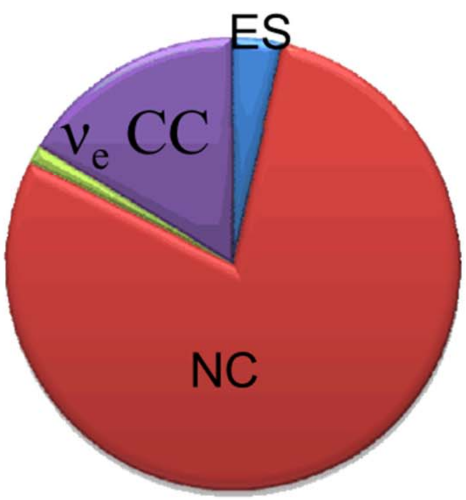
Water Cherenkov

Liquid Scintillator





Lead



Liquid Argon

CC:

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

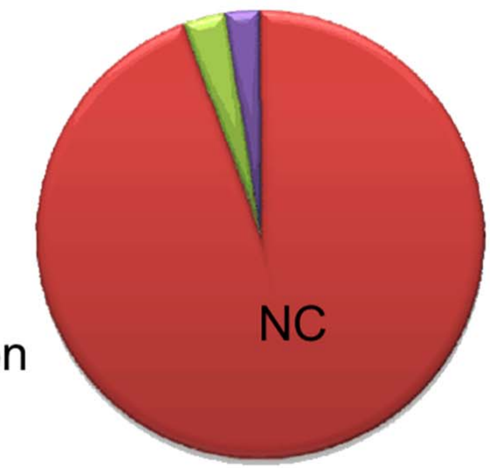
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$

NC:

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

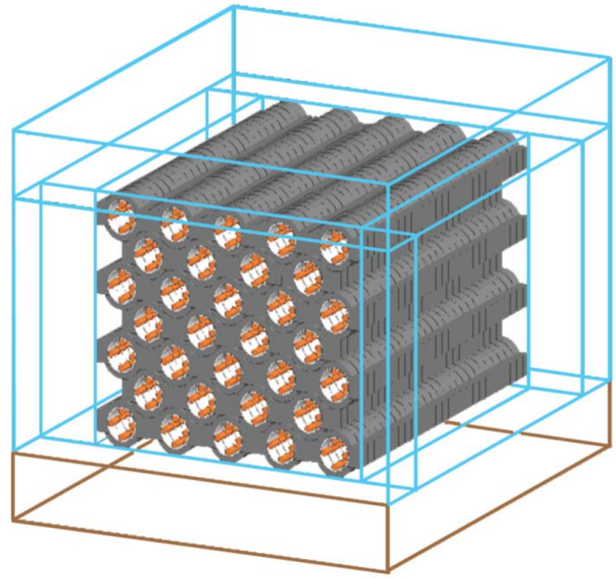
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$$

Iron



HALO

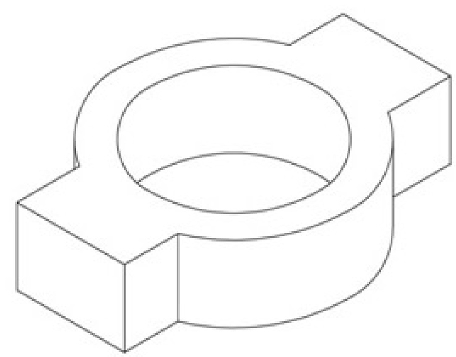
- Helium And Lead Observatory
  - Very low cost, long term, low maintenance
  - Under construction at SNOLAB
  - 79 tonnes lead
    - Recycled from Deep River (Ontario) cosmic ray station
  - US + Canadian institutions



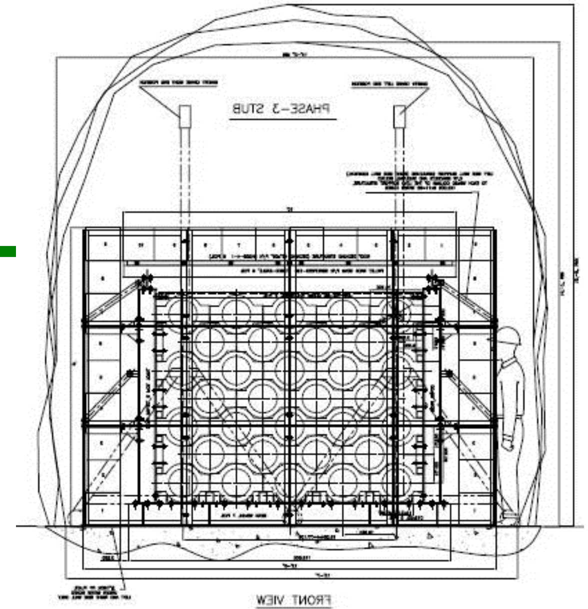
HALO - Collaboration List

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

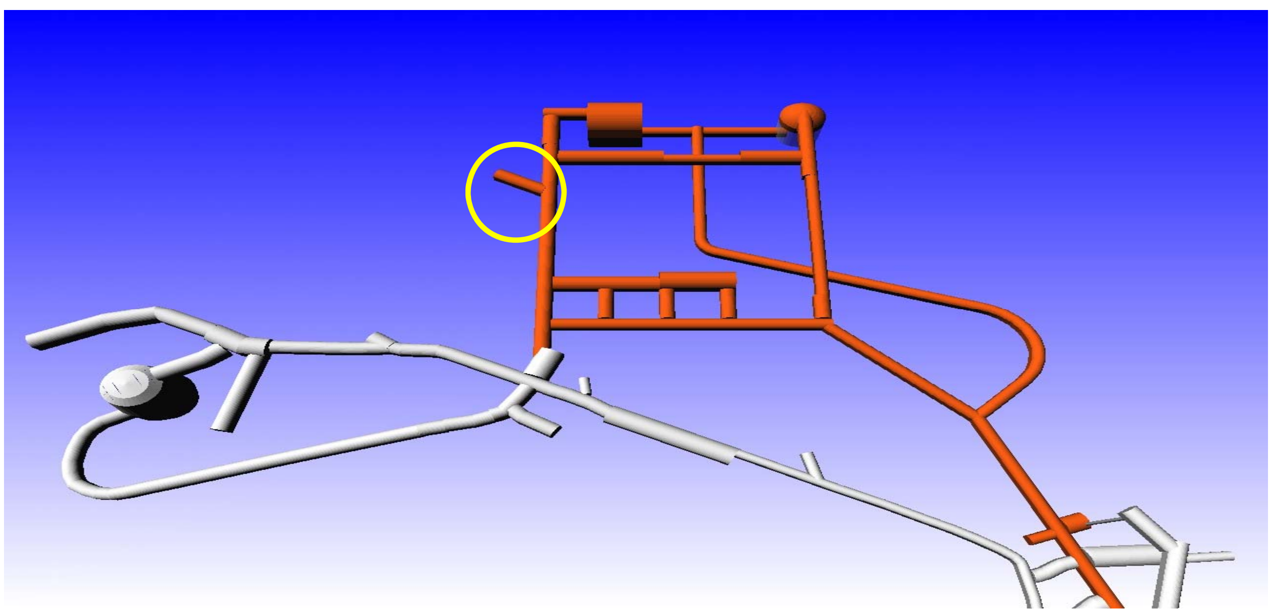
[1] Digipen Institute of Technology, Redmond, WA 98052, USA
[2] SNOLAB, Sudbury, ON P3Y 1M3, Canada
[3] Laurentian University, Sudbury, ON P3E 2C6, Canada
[4] University of Minnesota Duluth, Duluth, MN 55812 USA
[5] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[6] University of North Carolina, Chapel Hill, NC 27599, USA
[7] University of Washington, Seattle, WA 98195, USA
[8] Duke University, Durham, NC 27708, USA
[9] Armstrong Atlantic State University, Savannah, GA 31419, USA
[10] TRIUMF, Vancouver, BC V6T 2A3, Canada
[11] TU Dresden, D-01062 Dresden, Germany

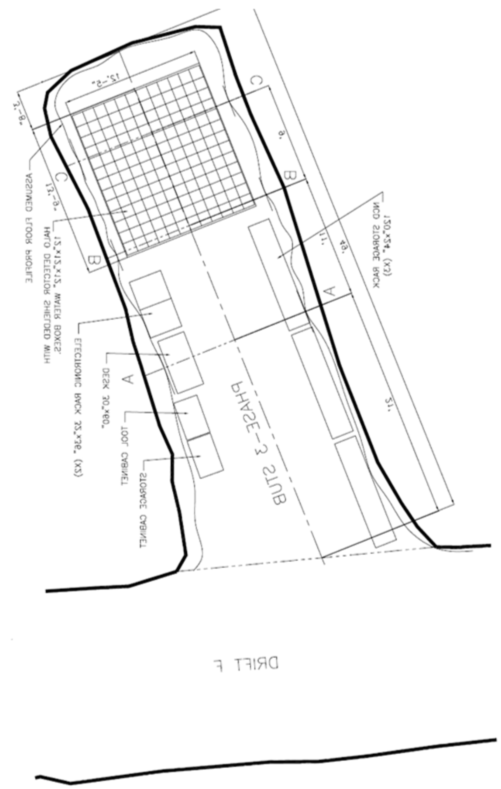


HALO Location



- Funding from NSERC & NSF
- Space in SNOLAB's Phase 3 drift stub
  - Significant scientific and technical support from SNOLAB



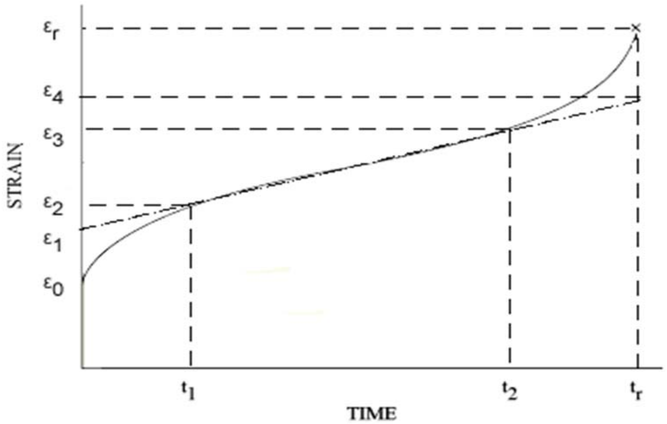


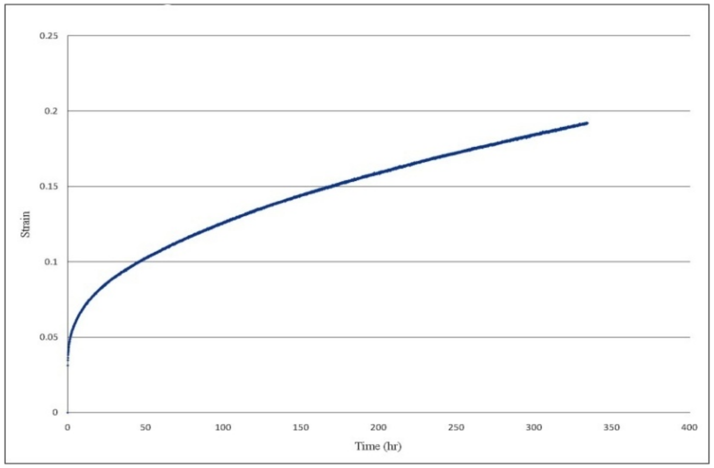
HALO Lead

- The target mass
  - 79±1% tonnes
- 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

Creep

- Mechanical design well advanced, creep tests successful





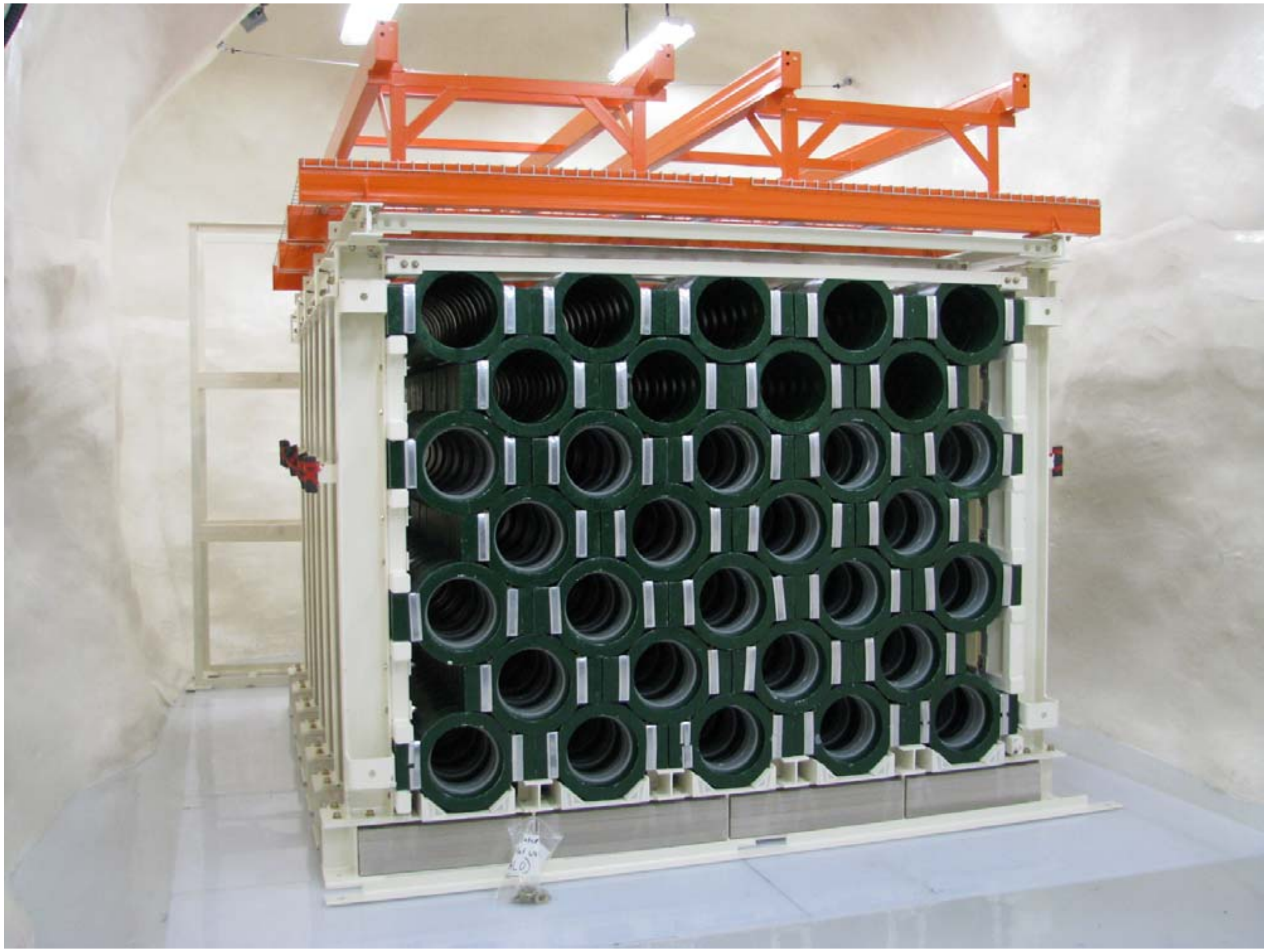
Painting

- Lead painted, ready to go underground

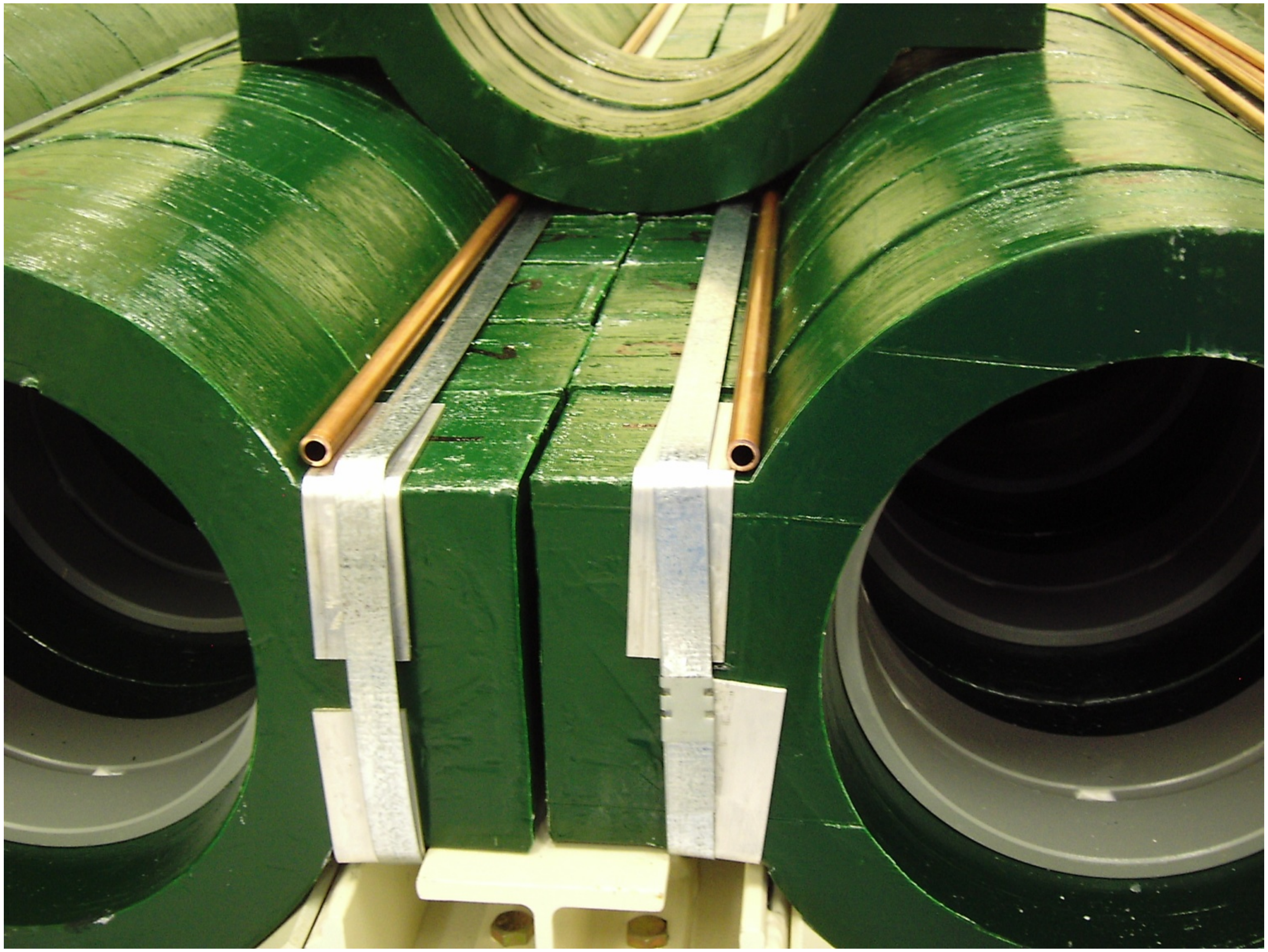


HALO Structure

- Lead all stacked!

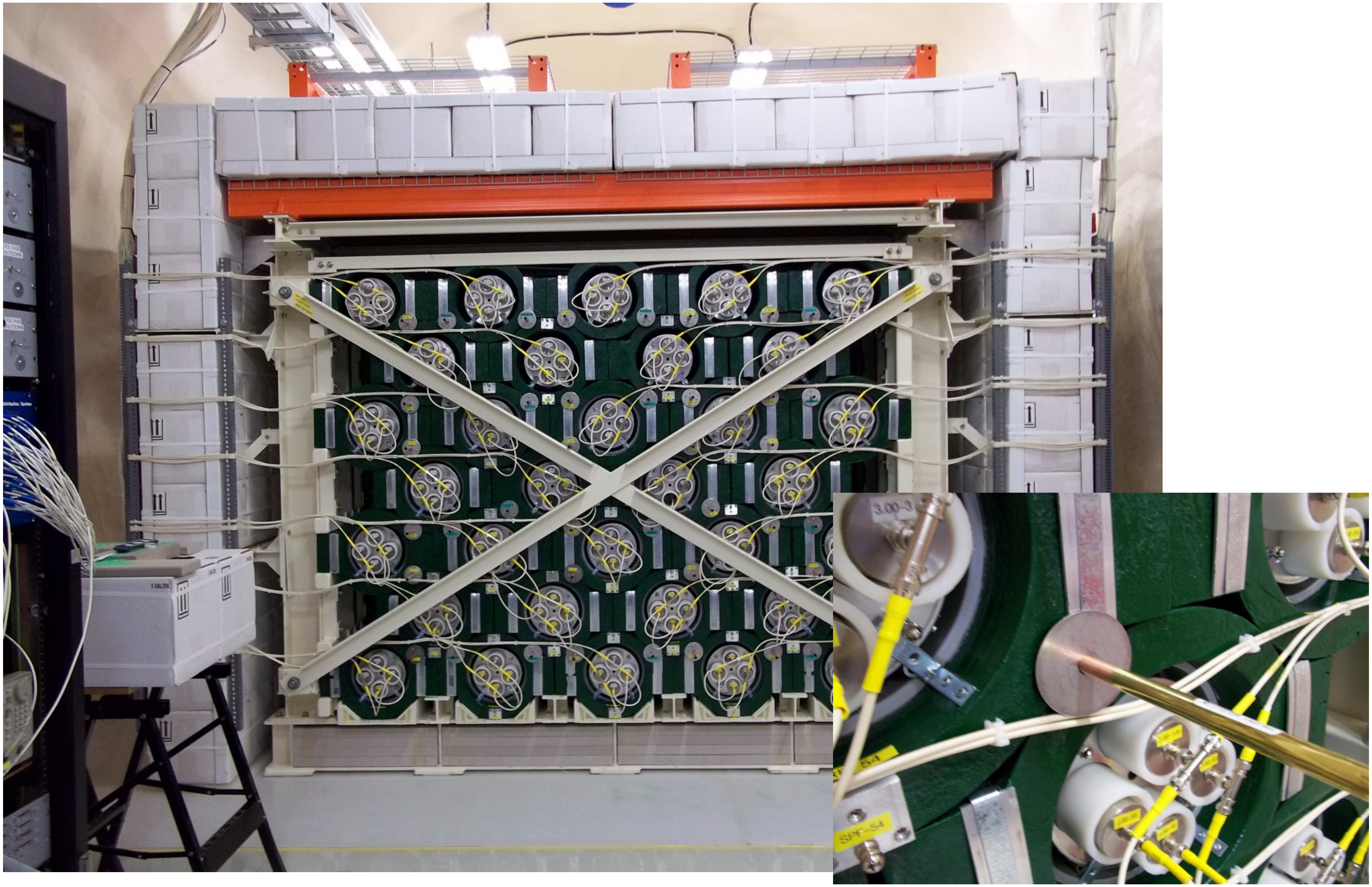


HALO Structure



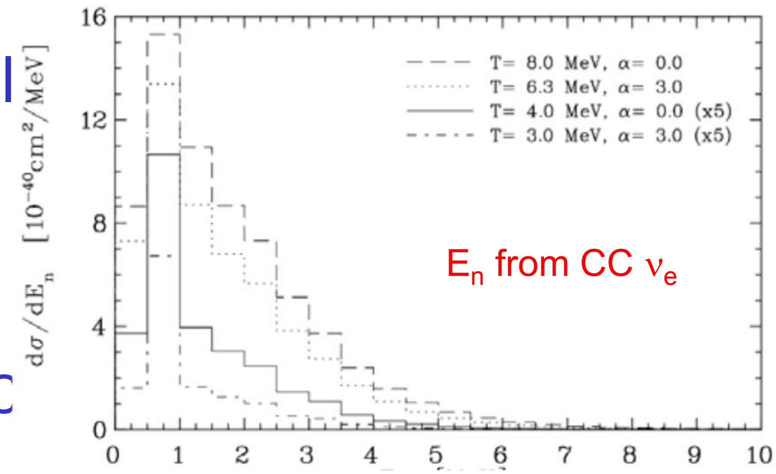
- Steel rings inside for support, steel straps to keep things from shifting
- Copper tubes to insert Cf calibration sources

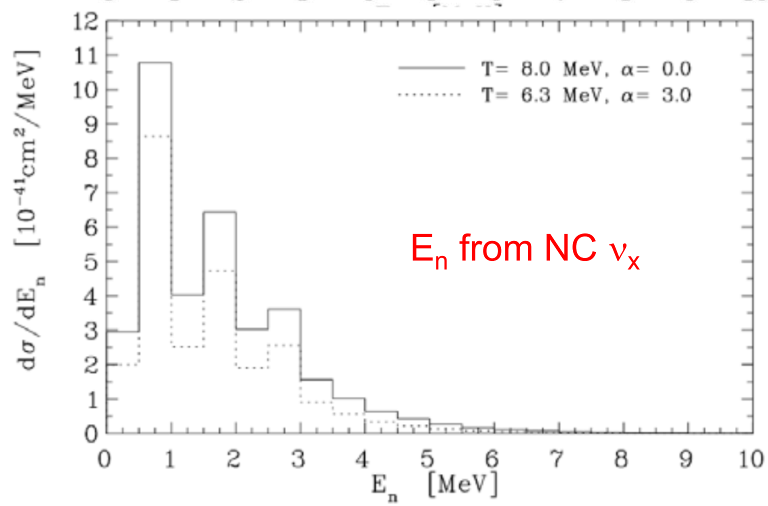
HALO



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





Spectra from:
E. Kolbe & K. Langanke,
Phys. Rev. **C 63**, 032801 (2001)

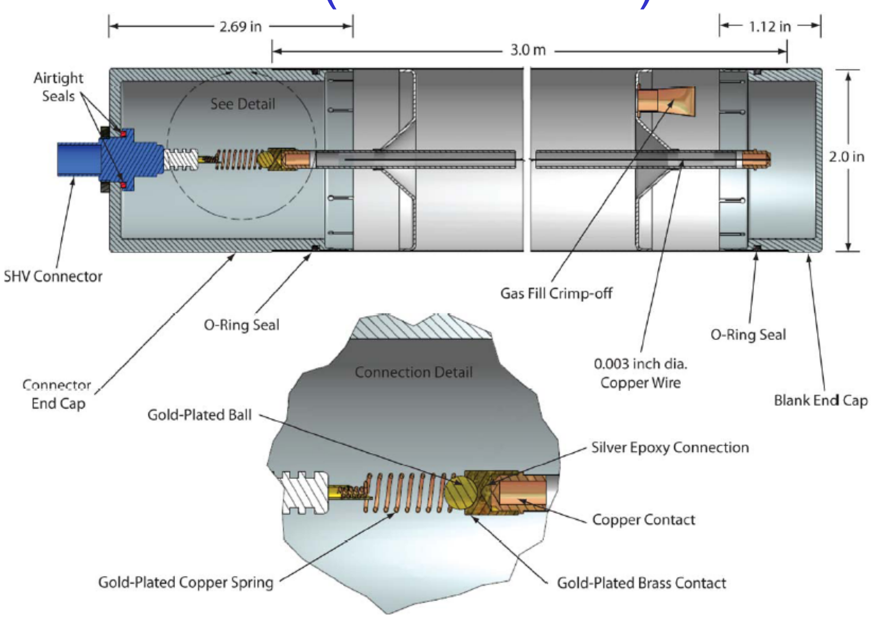
Scaled from:
J. Engel, G.C. McLaughlin, C. Volpe,
Phys. Rev. **D 67**, 013005 (2003)

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

cf. ~49 events for 600 tonnes of LAr

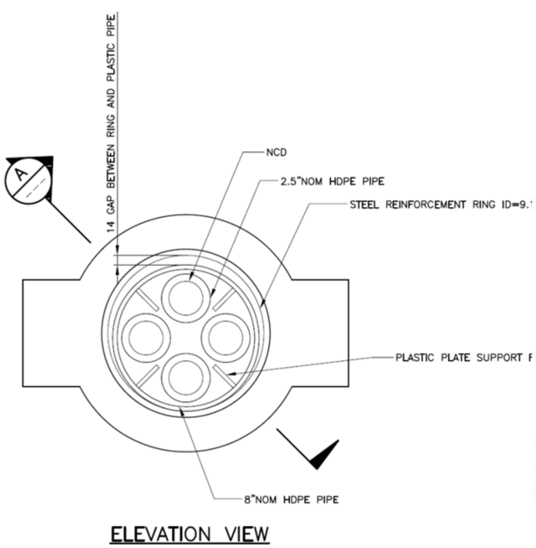
Catch the signal

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



Moderate the n's

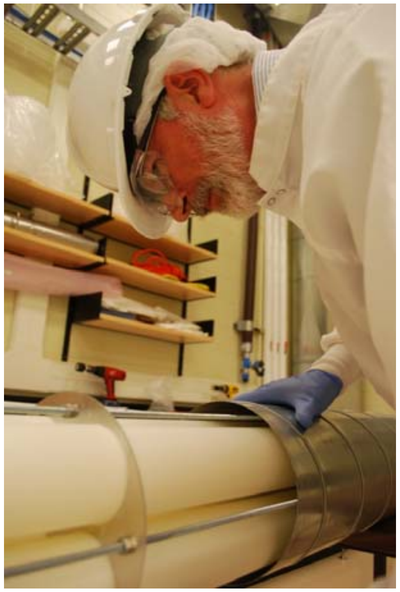
- Put each NCD in a 250mm polypropylene pipe to slow the neutrons down to increase NCD efficiency

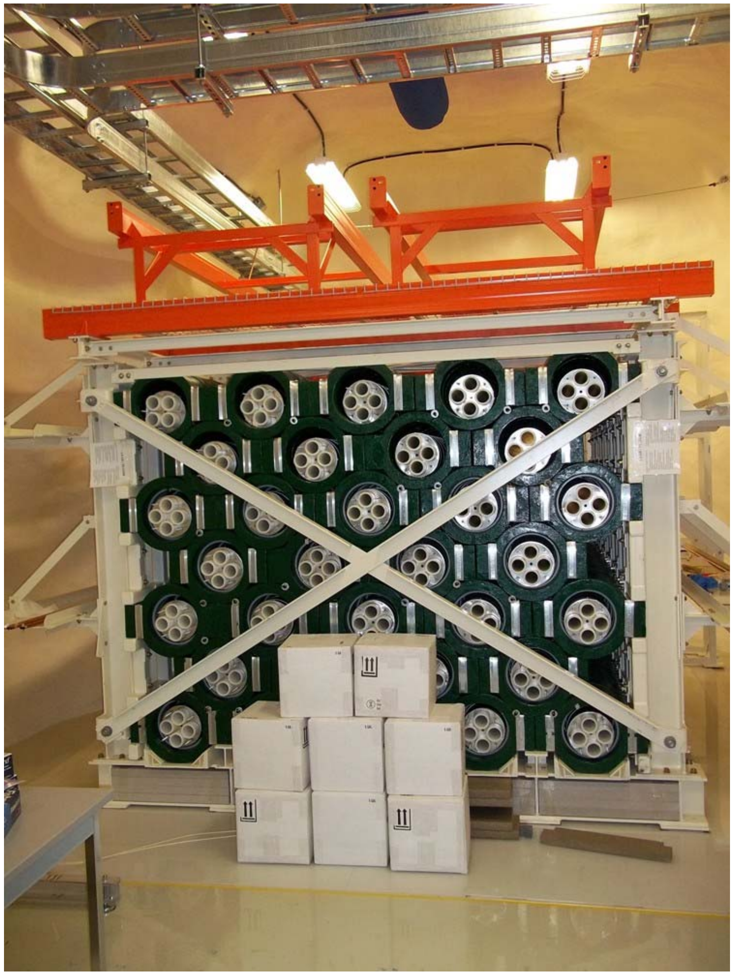


NCD's in storage in SNO control room

Moderate the n's

- 4 pipes of NCDs per lead column to suck up those neutrons
  - n + ^{3}He $\rightarrow$ ^{3}H + p + 764 keV
  - MC studies show ε~40%
  - 128 NCD's installed





Increased Efficiency?

- Adding 20 cm of graphite reflector around the experiment increases ε from 40%→50%
- Space left in design, but we haven't found any we can scrounge for cheap, so as yet this part is a pipe dream

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:

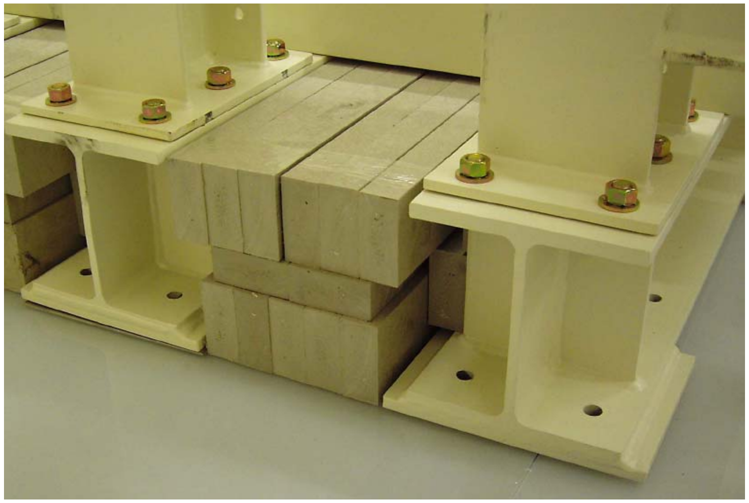
Number of Counter Hits with No Shielding	1187 /day	1.37×10^{-2} Hz
Number of Counter Hits with 0.5 ft H_2O Shielding	852 /day	9.86×10^{-3} Hz
Number of Counter Hits with 1 ft H_2O Shielding	308 /day	3.56×10^{-3} Hz
Number of Counter Hits with 2 ft H_2O Shielding	98 /day	1.13×10^{-3} Hz

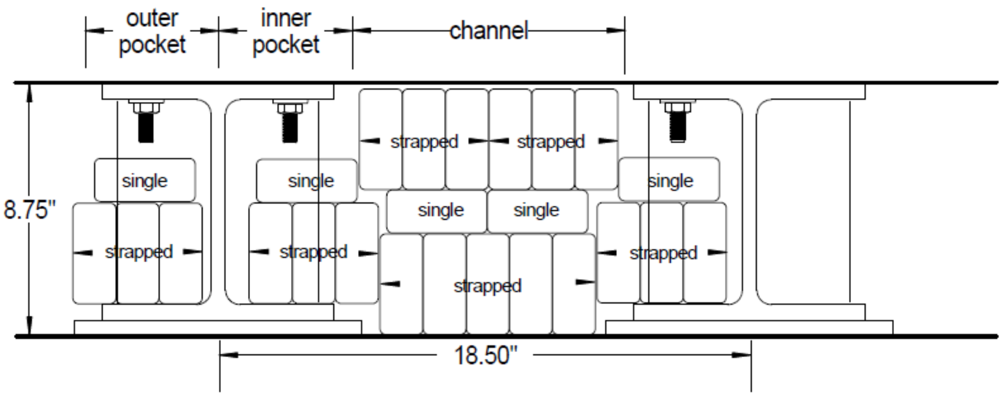
Thermal Neutron Contribution:

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

Shielding

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





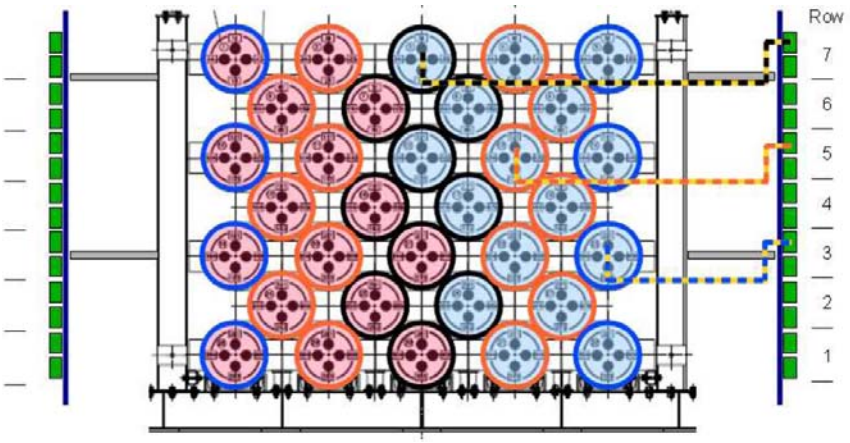
Shielding

- 12 tonnes of reclaimed PICASSO water boxes,
- Fill voids with polystyrene beads (1.3 tonnes) (donated by T2K)
- Ready for installation around everything

6 of 14 pallets of finished water boxes

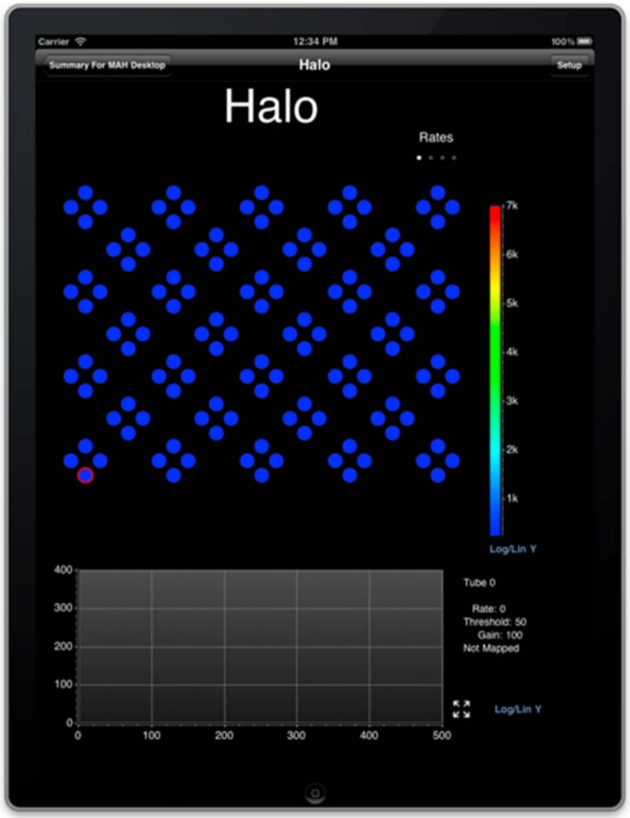
Electronics

- Cabling fabricated at TRIUMF
- UW sent reworked pre-amps for NCDs
- NCD's in there and taking data!
- Designed for redundancy and ability to keep on trucking if part of the detector fails



DAQ

- "ORCA" (*SNO DAQ*)
  - UNC supporting, developing with Duluth and Laurentian
- Taking data 24/7, root output copied to surface automatically
  - Remote iPad interface cool but not yet fully functional
- Needs to be very automated and low maintenance!



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 triggers this ~monthly
  - Target “false” rate for SNEWS inclusion
- SNOLAB neutron rate:
  - Fast (4000/day), thermal (4100/day)
  - Water shielding knocks this to < 100mHz of detected neutrons
  - Graphite would add factor of 2 more reduction
- Bulk α contamination in NCD’s Ni tubes adds 22±1 detected neutrons/day (negligible)

HALO

- Online and sensitive to SNe in our galaxy as of mid-2012
  - Not yet well understood enough to plug into SNEWS
- Robust, high-livetime, long-lifetime, low-maintenance automated experiment
- 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

Other ν experiments

- Radiochemical (Gallex/GNO, SAGE, Homestake)
  - Not real-time, but would get signal after the fact
- Liquid Argon (Icarus, Argoneut and progeny)
  - CC: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
- Gravitational Wave Detectors
  - Need aspherical explosion to see a signal
  - LIGO waiting for ν signal rather than vice-versa at this point

Why a Network?

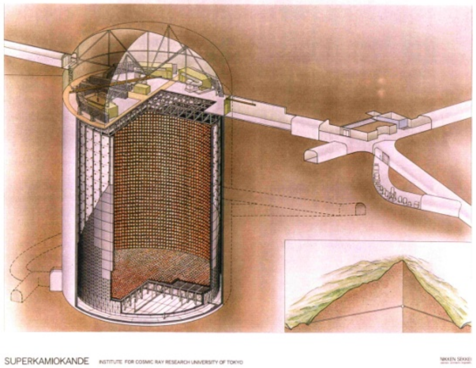
- Any given experiment has their own SN ν trigger, analysis, different strengths, weaknesses, etc
- So why band together?
  - The warning gets us hours ahead of the game
  - From experience, a human verifying an alarm takes ~hour
  - Experimental techniques often complementary
- That's a wash. Need to eliminate the human link to regain the "Early" in the "Warning"
  - Automation!

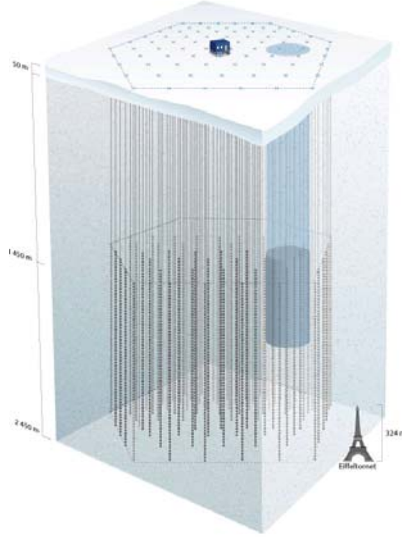
Automation?

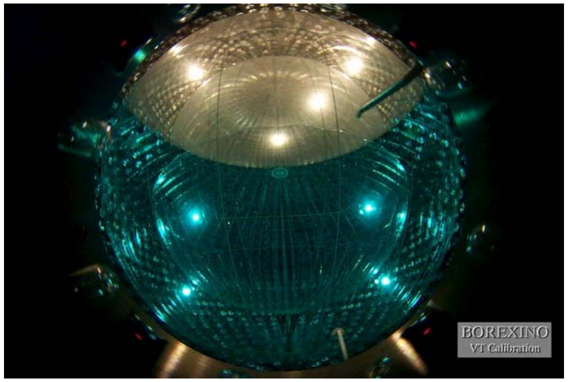
- SNEWS
  - Supernova Early Warning System
- Any single experiment has many sources of noise and few SNe
  - Flashing PMTs, light leaks
  - Electronic noise
  - Spallation
  - Coincident radioactivity
- Most can be eliminated by human examination (takes time)
  - No experiment would want to make an automated SN announcement alone!
- None will simultaneously occur in some other experiment

The Experiments

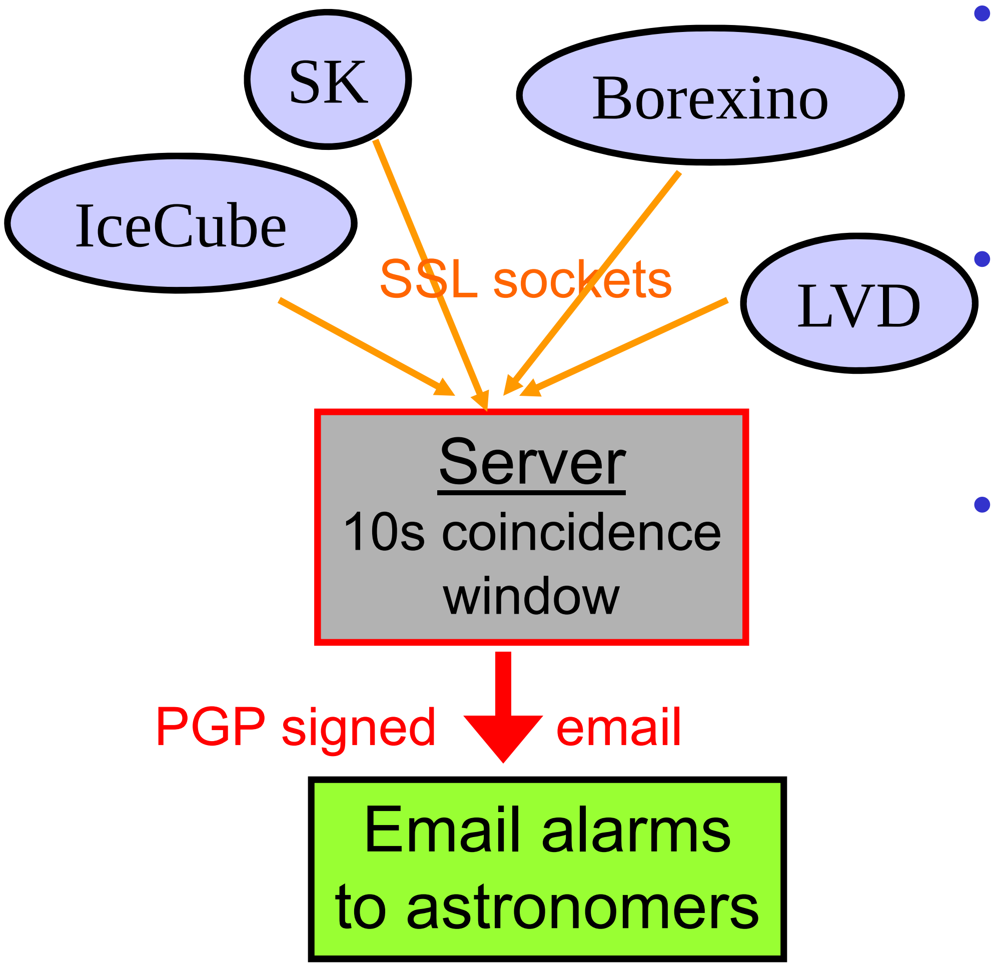
- Currently:
  - Super-K
  - LVD
  - IceCube
  - Borexino
- Alumni:
  - MACRO, SNO, AMANDA
- Operational but not SNEWS contributors:
  - Baksan, KamLAND, MiniBOONE
- Near-Future participants:
  - Daya Bay, NOvA, SNO+, HALO
    - Double CHOOZ?





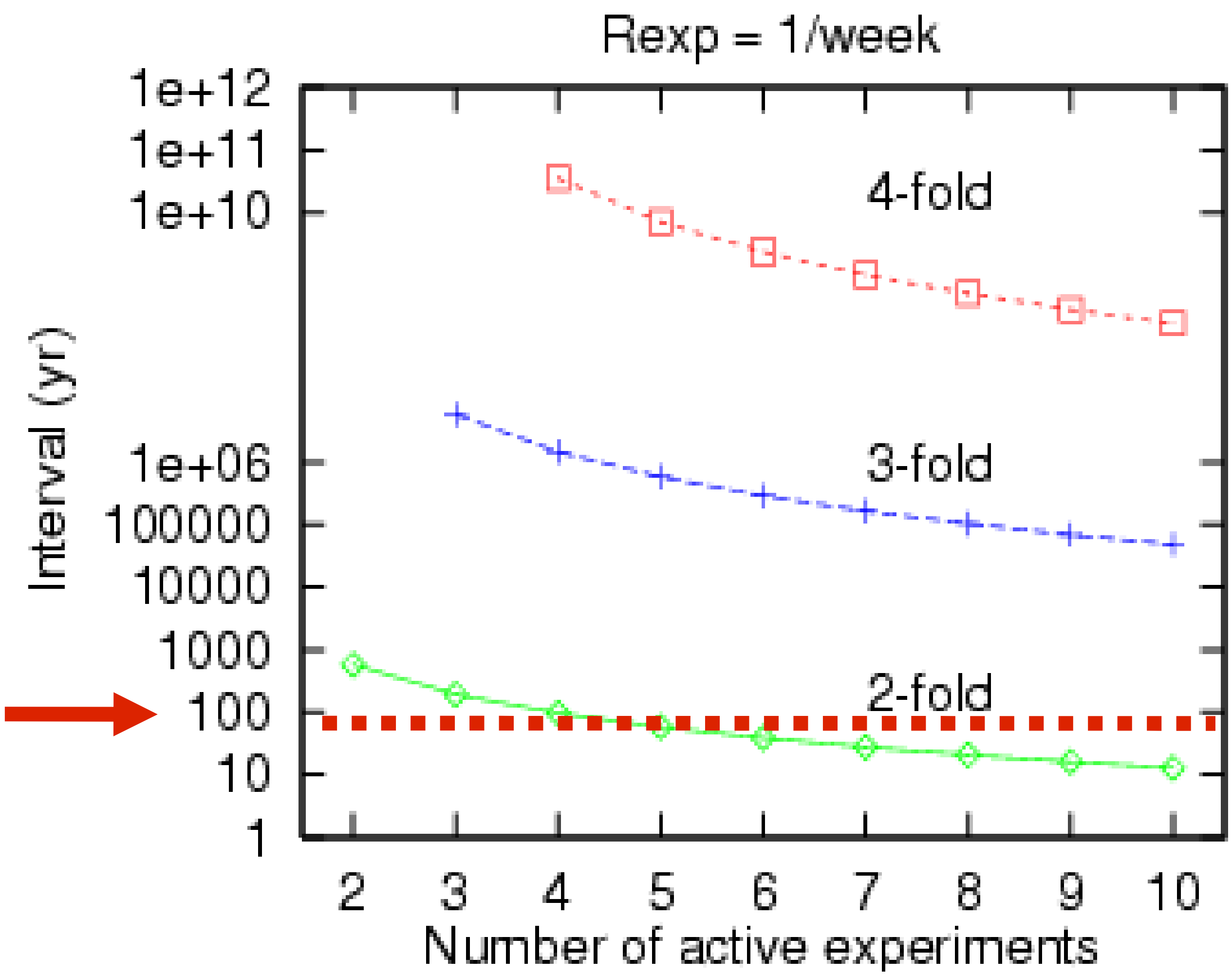


A Global Coincidence Trigger



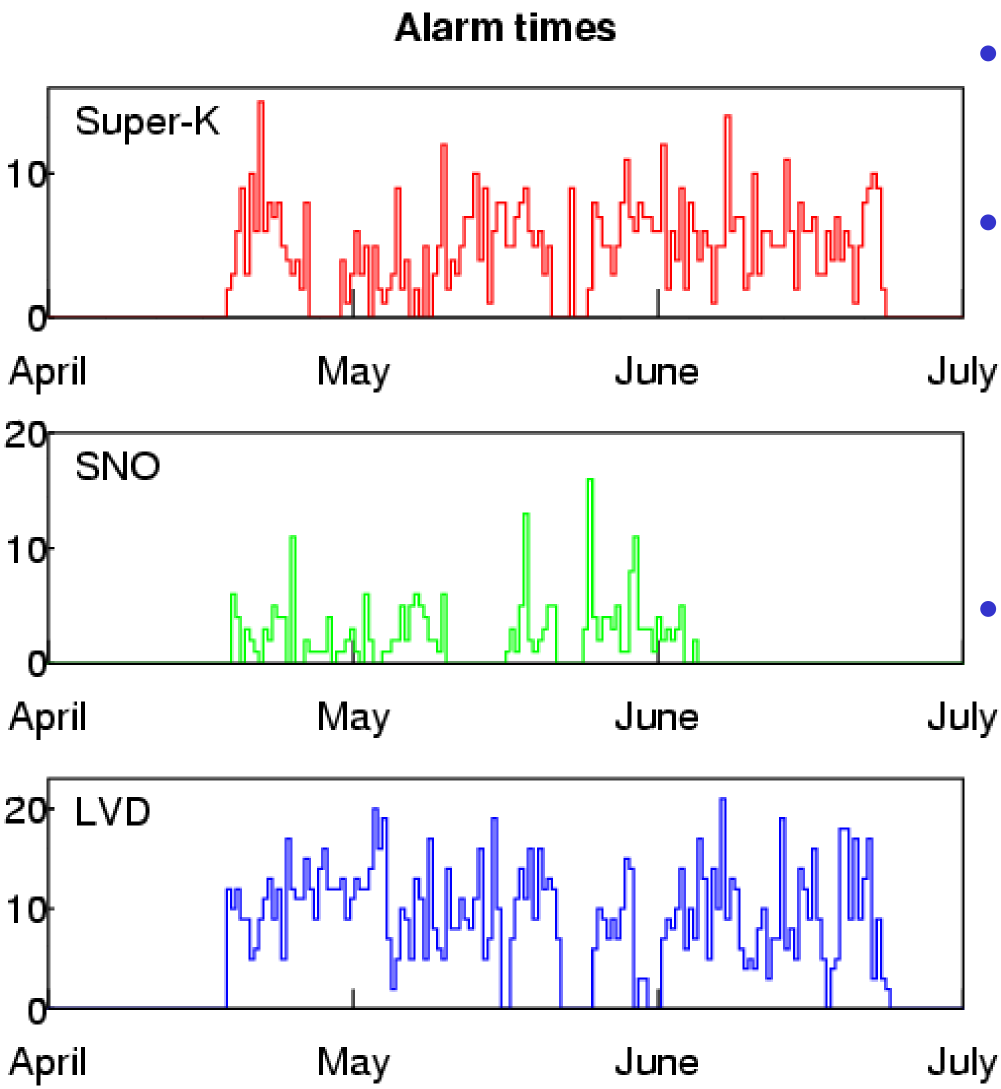
- Experiments send blind TCP/IP packets to central coincidence server
- Secure, stable hosting at Brookhaven
  - Backup server at Bologna
- Other benefits such as down time coordination, working relationship between SN teams, etc

Coincidence Stats



- Looking for ~1 SN/century
- Cannot tolerate more false alarms than SNe
- False Alarms
  - Poissonian
  - Uncorrelated
  - 1/week/expt

Uncorrelated?



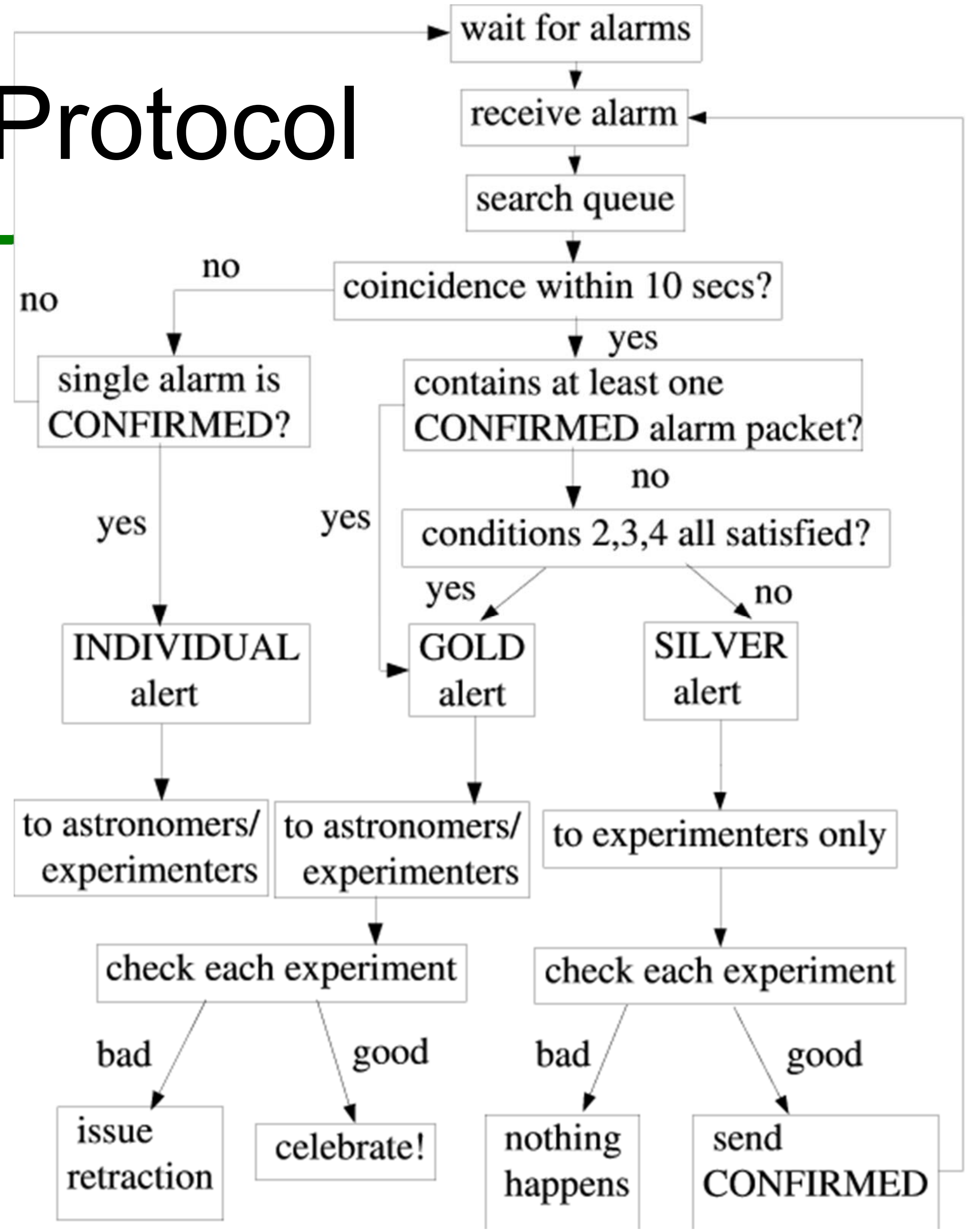
- "High Rate Test" done in 2001
- 3 experiments lowered their internal SN trigger thresholds
  - Coincidence rates as expected
- Caveat – two experiments at same location could have correlated power surges etc

Alarm Quality

- Experiments tag alarms with their quality estimate, SNEWS applies logical OR to produce an alert
- SNEWS will produce one of two results in event of a time coincidence:
  - "Gold"
    - Go out and look up! Automated alert sent
  - "Silver"
    - Experiment self-flags input as Questionable data quality
      - *eg* calibrations, marginal signal
    - Experiment in question has been noisy, two at same lab and nowhere else, etc
    - Sent only internally, to participating ν experiments
      - Can be upgraded to gold after human check

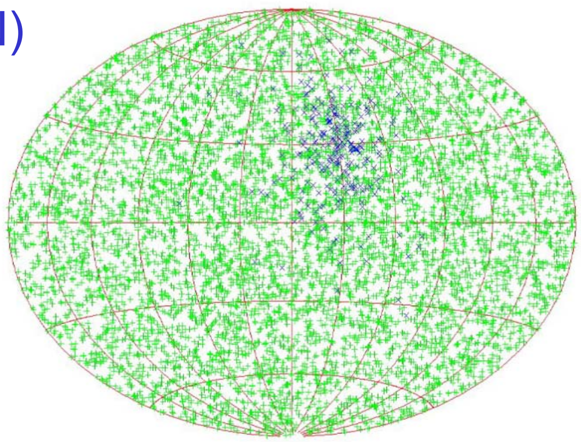
Alarm Protocol

- What the coincidence server really does
  - To minimize risks of false alarm, while maximizing the chances of getting the (right!) word out
- Experiments can also utilize SNEWS to send their own human-confirmed alarms to the world

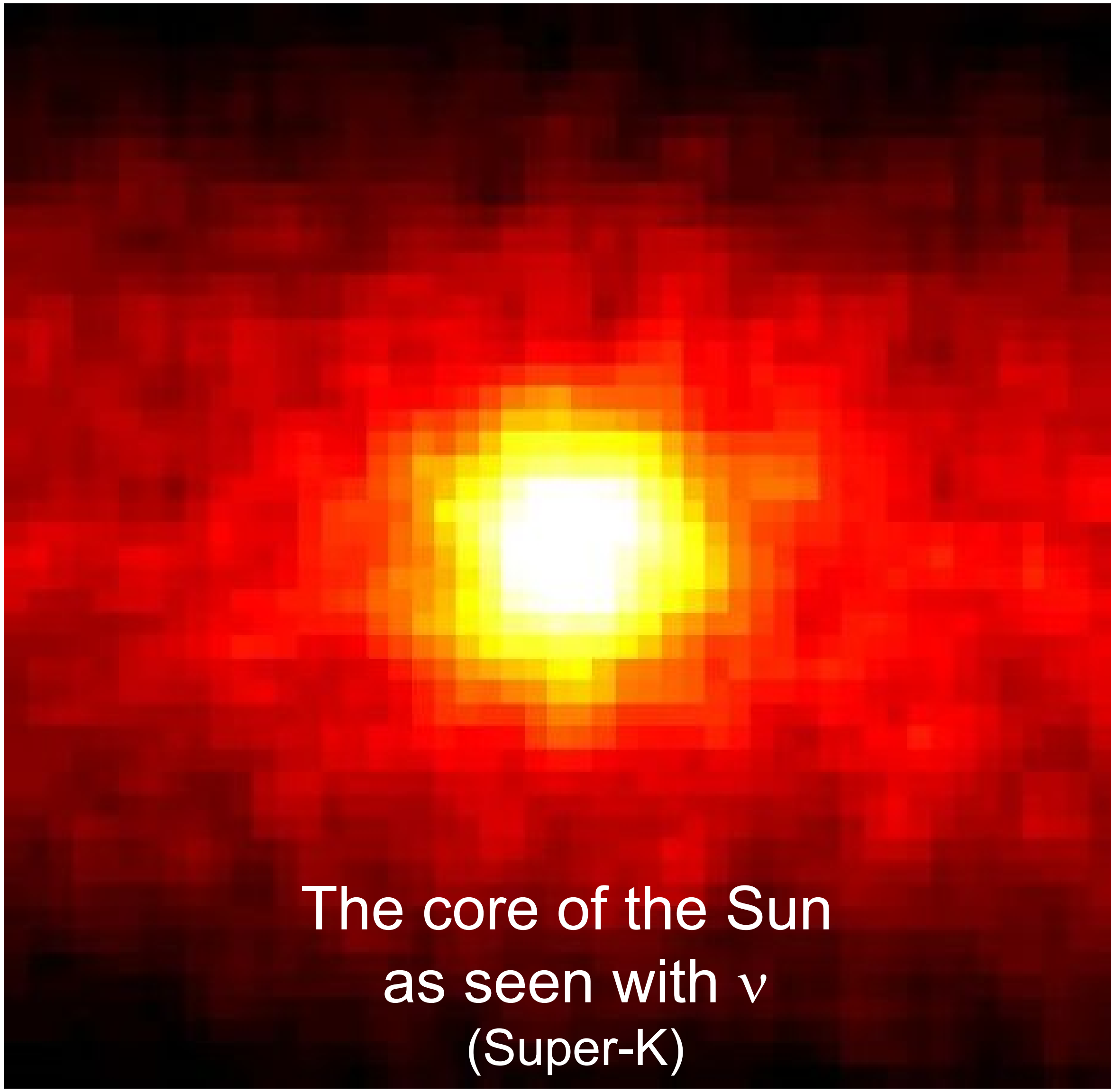


Quick, reliable, but information free?

- We have been working on "The Three P's":
  - Prompt (<< 1 hour)
  - Positive (false alarms < 1/century)
  - Pointing
- An ideal alarm would be "Look at Betelgeuse, it's about to blow!"
- What directionality can neutrinos provide?
  - Elastic Scattering $\nu_x + e^- \rightarrow \nu_x + e^-$
    - Cone of 4.5^o from SK (for galactic center SN)
    - (Cone of 15^o from SNO, but it's off now)
  - $\bar{\nu}_e$ CC weak asymmetry, also ^2H breakup
    - tenths of cosθ at best

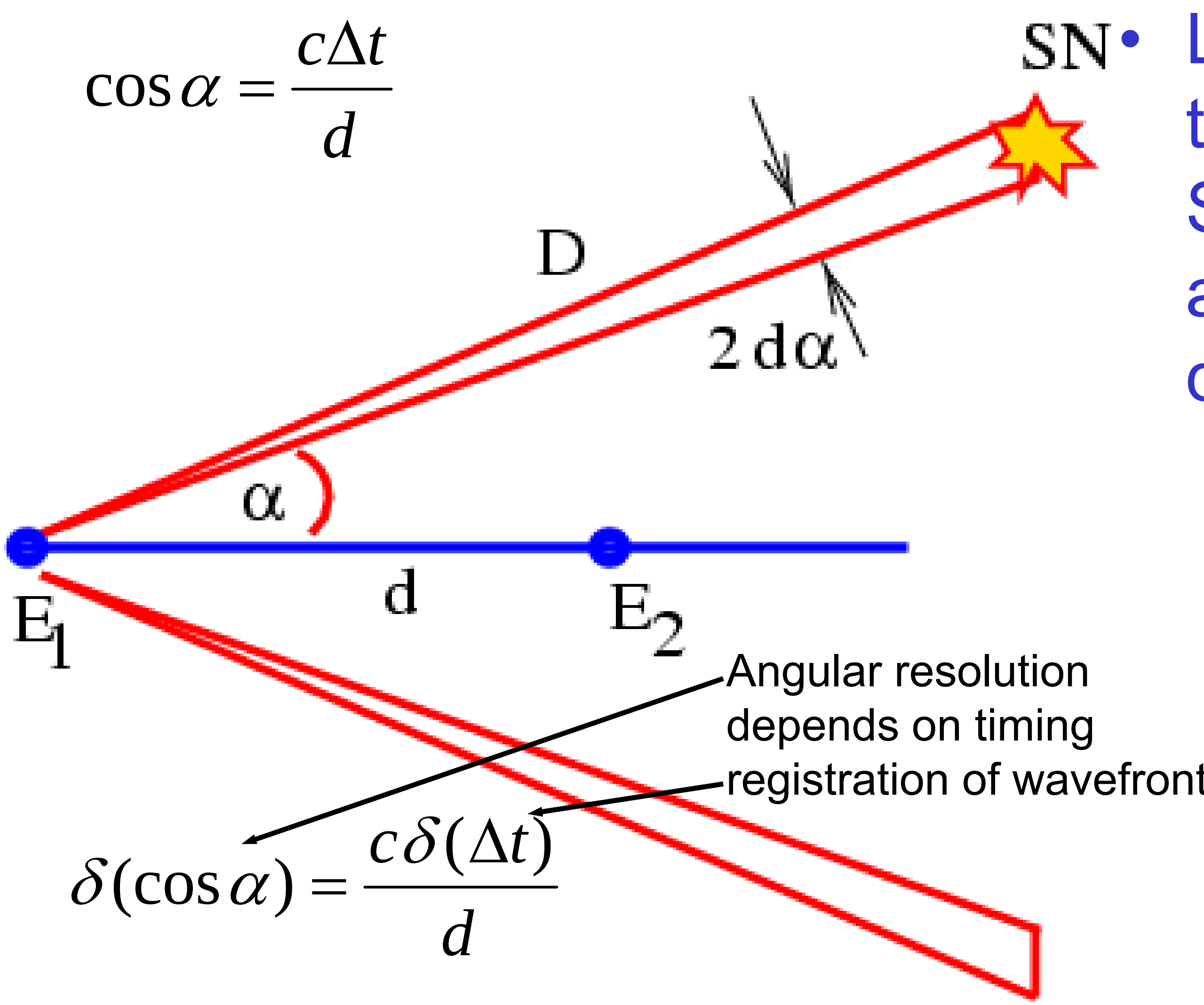


Elastic Scattering



- This is the reaction that lets Super-K identify solar neutrinos
- Problem – each pixel in this picture is about 0.5°
  - Diameter of full moon
- Resolution dominated by neutrino/lepton scattering angle not experimental resolution
  - Can't upgrade that

Triangulation



- Look at arrival time difference of SN ν wavefront at different detectors
  - With 2 expts, circle on sky at angle α
  - 3 expts – 2 blobs
  - 4 expts – 1 point

Triangulation

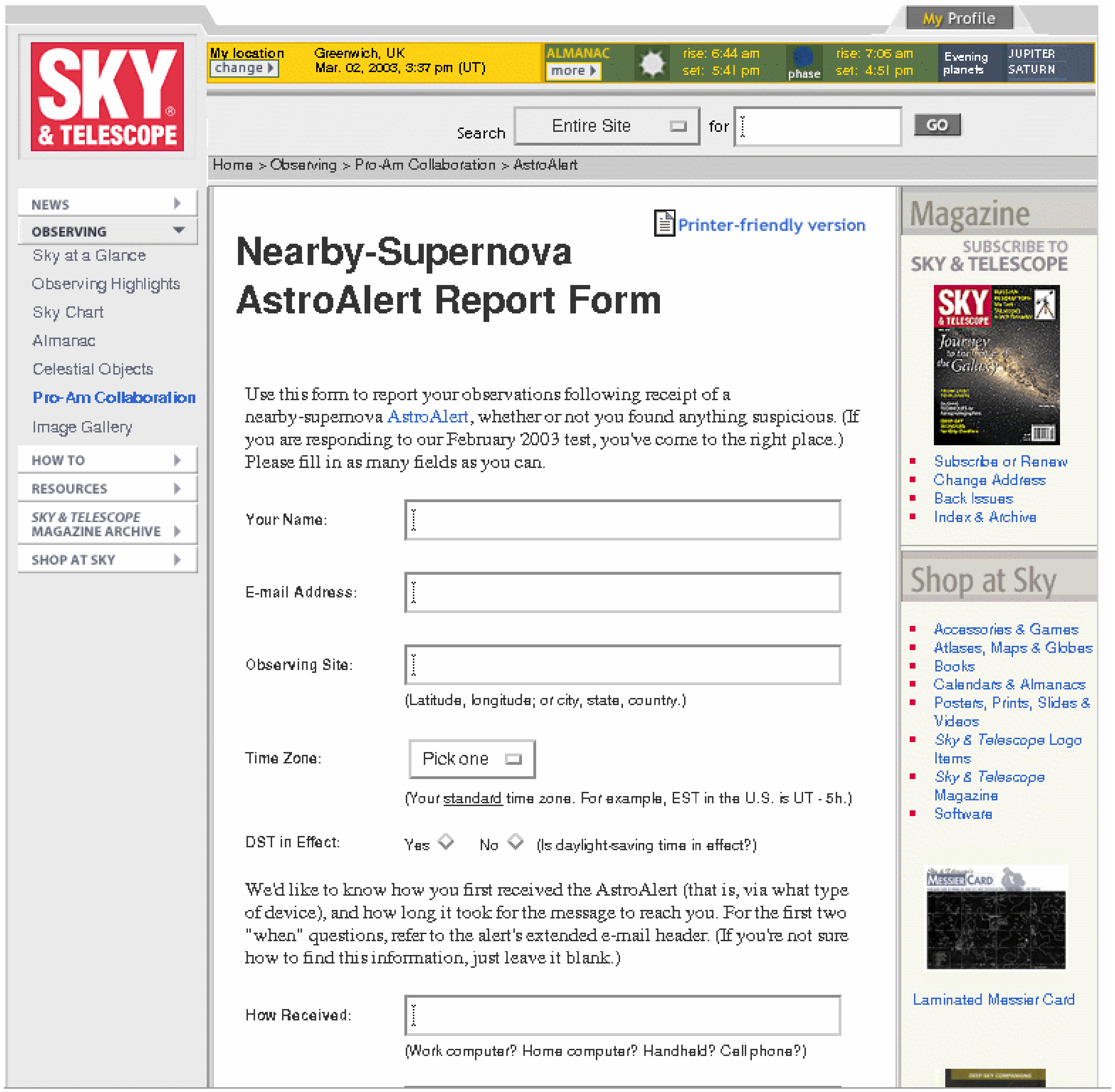
- For SK = 7000 events (SNO: was 300 events)
  - $\delta(\cos\alpha) = 0.25$
    - Statistical Δt
    - with zero risetime
  - Realistically?
    - 10's of ms from shock propagation at ν breakout
  - For Δt=15ms, $\delta(\cos\alpha) = 0.5$
    - That's a hemisphere!
- Not even considering SN model dependence, experimental systematics, need to do immediate event-by-event data exchange
  - Plus a surprising number of ν experiments are at +46^o lat

Beacom&Vogel astro-ph/9811350

Pointing?

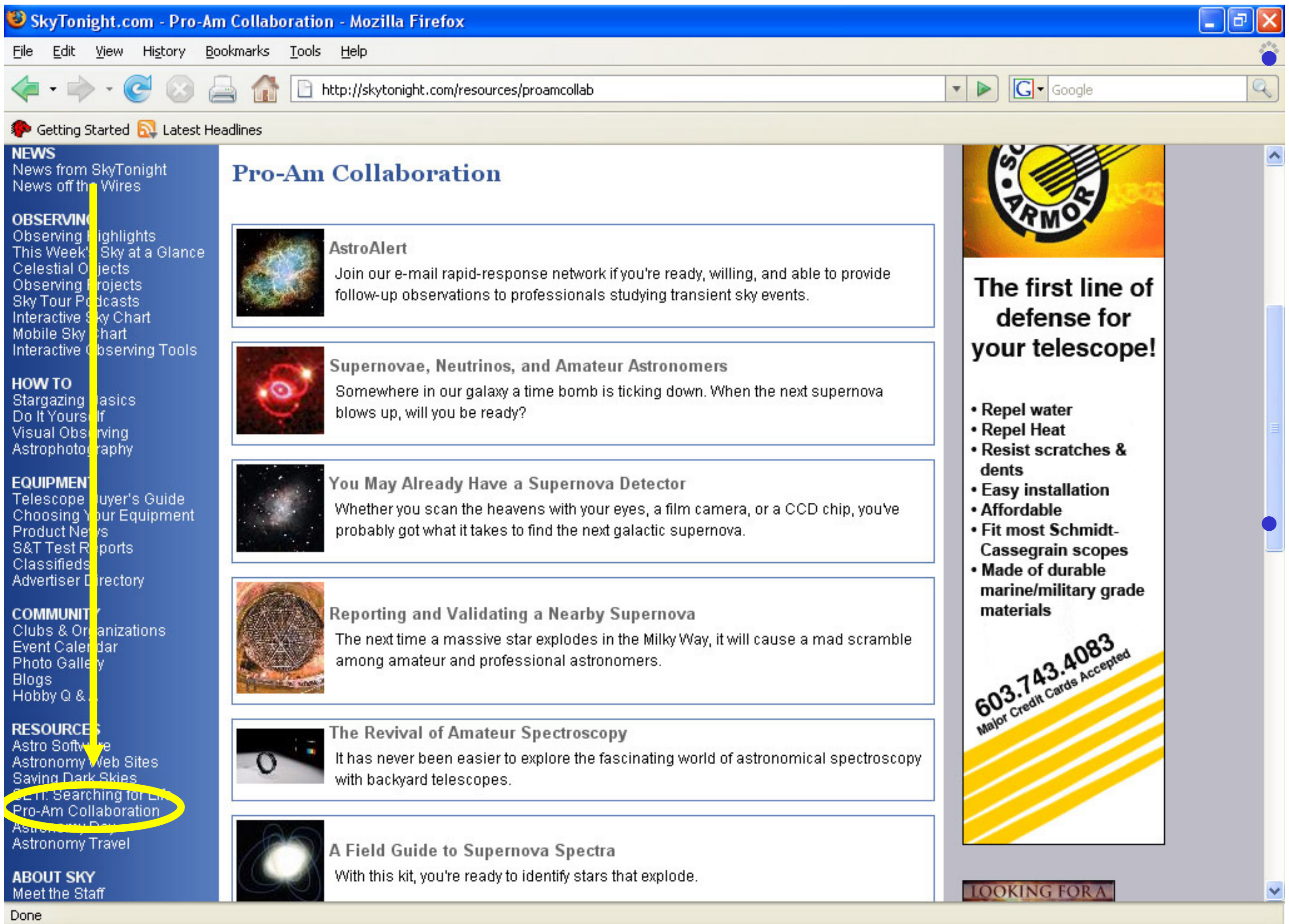
- Looks like we are limited to ~100 square degrees at best
  - Ok for Schmidt cameras, not so hot for detailed work
  - Keep shooting starfields and sort it out later?
- Where to from here?
  - Amateur network of many skilled eyeballs!
  - Once someone optically ID’s the new SN, we all know and can zoom in
- High energy transient satellites will also provide rapid localization
  - Shock breakout through photosphere produced UV flash in 1987A, should be lots of high energy fireworks given today’s fleet of high-energy orbital telescopes
- LIGO can trigger on (direction-free) SNEWS alert, save more GW data that it would otherwise

Clearinghouse



- Amateurs have many eyes, wide angle instruments, and intimate knowledge of the sky
- *Sky & Telescope* plus AAVSO have experience in coordinating amateur efforts
  - Leif Robinson, Rick Feinberg, & Roger Sinnott

Clearinghouse



- Amateurs have many eyes, wide angle instruments, and intimate knowledge of the sky
- *Sky & Telescope* plus AAVSO have experience in coordinating amateur efforts
  - Leif Robinson, Rick Feinberg, & Roger Sinnott

S&T Test

- On Feb 14 2003, a (carefully flagged) test alert was sent:

This Sky & Telescope AstroAlert is being issued [as a test] in support of the SuperNova Early Warning System (SNEWS). We seek your assistance in pinpointing the location of a possible supernova explosion. Neutrino detectors give the target‘s approximate coordinates (equinox 2000.0) in the constellation Bootes, as follows:

Right ascension: 13h 38m
Declination: +8.1 degrees
Uncertainty radius: 13 degrees
Expected magnitude: unknown

Please check this region of the sky as soon as possible using your naked eyes, binoculars, a telescope, or a camera. You are looking for a starlike point of light ...

S&T Test

- Vesta (mag 6.7) was at a stationary point in its retrograde loop in the given error box
  - Not a regular star, not moving
- It worked, given the small statistics of those wishing to participate in a known test –
  - ~90 responses, all over the world, wide variety of instruments
  - 70% of people got the alert within 8 hours (a dozen right away)
  - Given time of day and weather, many found Vesta, and had good search strategies
- S&T will use this as a basis for an article on good ways to look for transient sources

Using the Alert

- The resulting coincidence alert goes to:
  - Email list of interested people
    - Sign up for alert email, http://snews.bnl.gov
  - VOEvent network/GCN
    - Since photosphere breakout should really light up the high energy photon sky
  - S&T's AstroAlert service
  - LIGO
- What cool stuff with a once-in-a-lifetime nearby supernova would you like to learn?
  - Progenitor status?
  - Shockwave blowing through stellar system?
  - Stellar wind just before the end?
- Data you couldn't take after the fact!
  - From a time window no-one's ever seen

Observing Plans

- Think of these goals now, make an observing plan
  – What exposures, filters, special equipment would you need?
  – File it away for the time when you get woken up at an odd hour and have less than an hour to take the data
  – Example:
    - HST ToO #9429 and earlier, Bahcall *et al*
      – STIS UV spectra to measure properties of ejecta early on
    - HST takes ~week to retarget though

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 will provide a new window on SN ν_e with a high-livetime, low-maintenance experiment
- Pointing not great until someone sees it with photons
  - But even with no pointing, the time is well spent waking up, getting logged in, to the observatory, etc.
- SNEWS has been online ready to form a quick alarm for more than a decade now, and will continue into the future

Acknowledgements

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- SNEWS only functions with the cooperation of member experiments and their SN teams, plus *Sky & Telescope*, Brookhaven, and INFN Bologna
- HALO thanks go to SNOLAB, NSERC, and NSF (*again via Duke & UMD*)
- See http://snews.bnl.gov for more info and to sign up for the alert list