Supernova Neutrinos

An experimental overview

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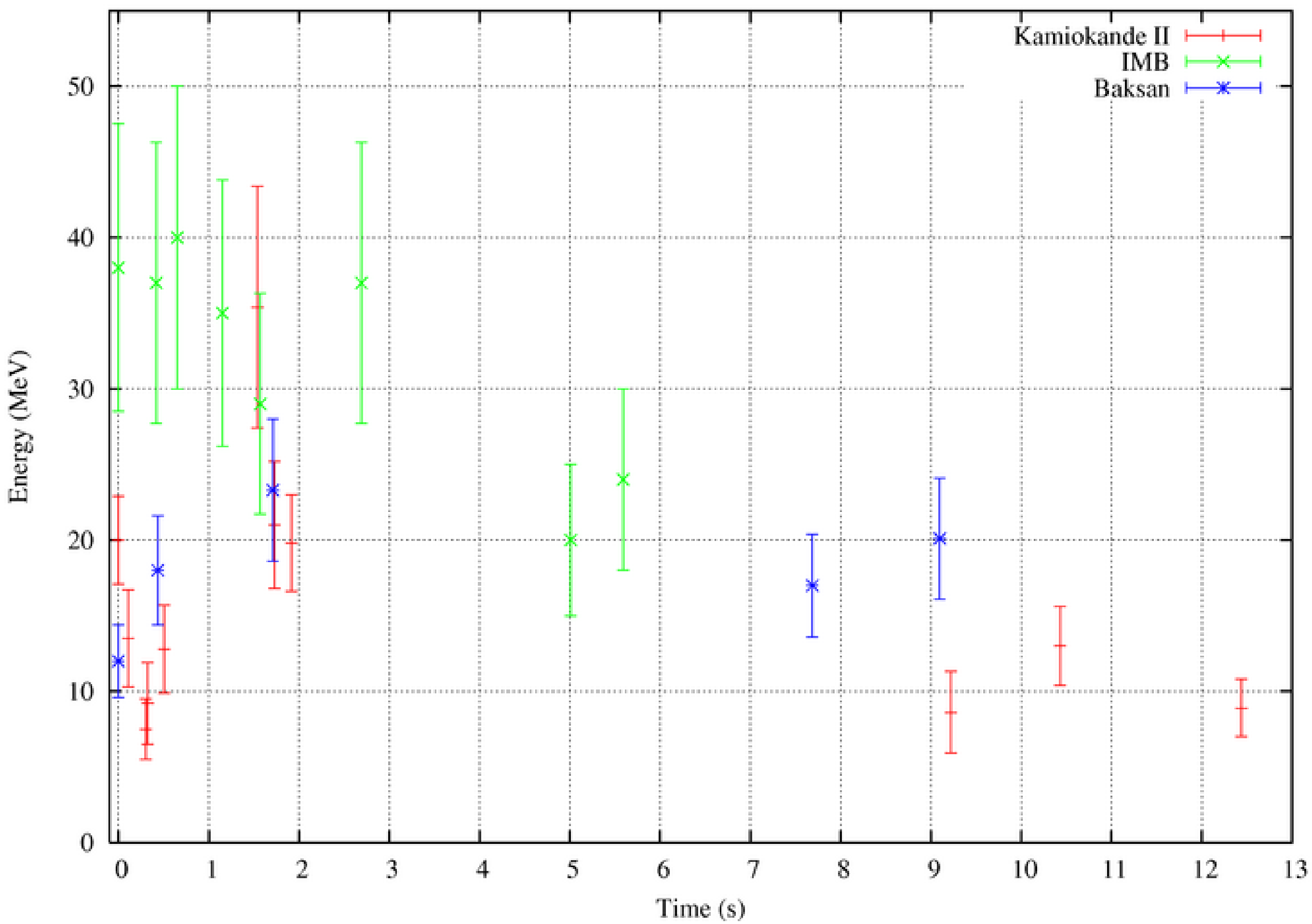
Our singular data point (*so far…*)

- 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 proton decay detectors (which also had a pesky ν background)
  - (*and not the 4.1 years early the OPERA results would have implied…*)

SN1987A ν observations

Proton Decay experiments see:



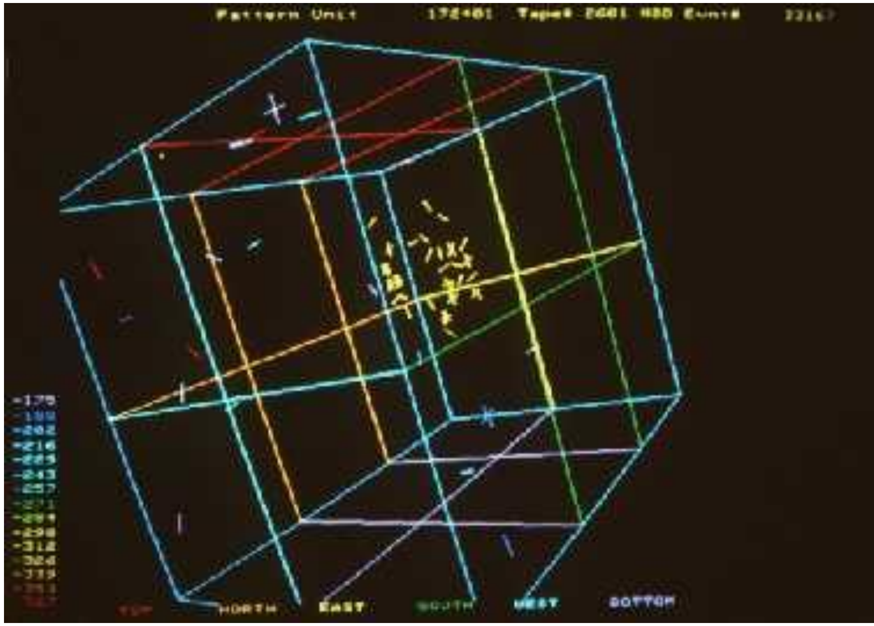
Water Cherenkov

- 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
- 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?

Overall?

3±1 per century!

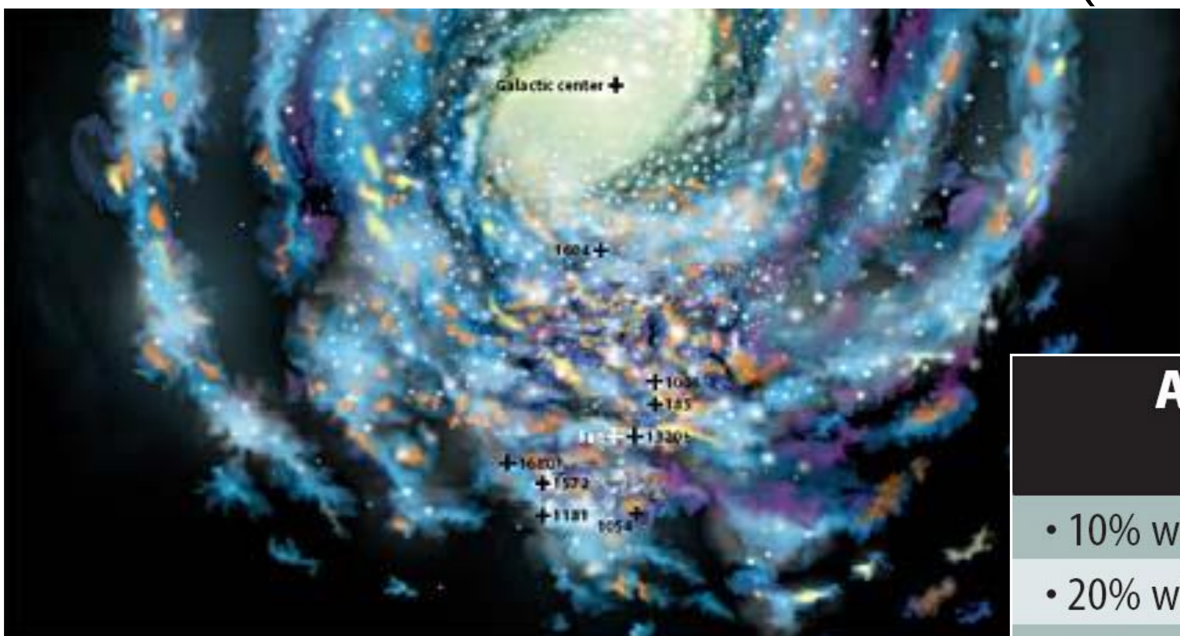
Academically –
one per career,
if Monsieur Poisson cooperates

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	

at this rate and given a galactic radius of 15kpc, that’s hundreds of SN-ν wavefronts already on their way to us here on Earth!

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

Small Δt SN Observations

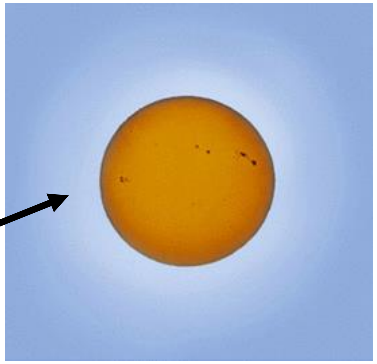
SN1987A

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

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 (*to do all the oscillation physics!*)

Now they're detectors studying aspects of neutrino oscillations, since protons apparently don't decay…

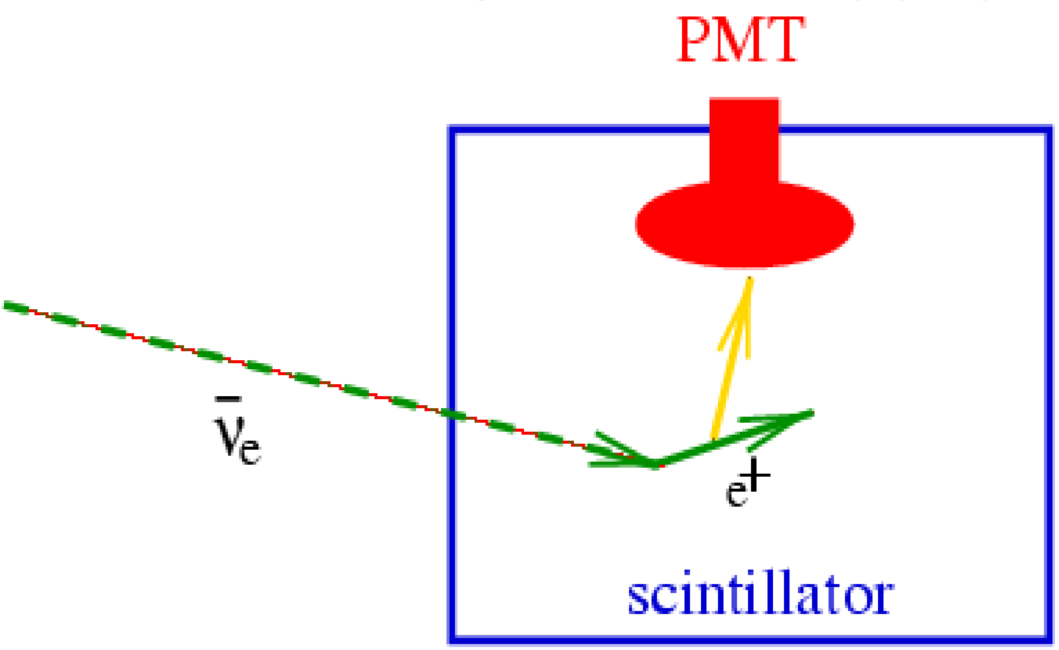
Basic Types

- Scintillator (C_nH_{2n})
- Imaging Water Cherenkov (H_2O)
- Long String Water Cherenkov (H_2O)
- Nobel Liquids (Ar, Xe)
- 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): $\nu_x + p^+ \rightarrow \nu_x + p^+$

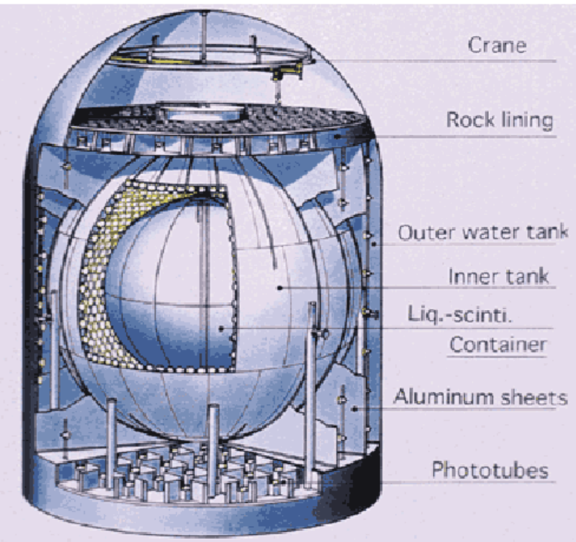
(seen)



Little pointing capability

Mont Blanc, Baksan, MACRO, LVD, Borexino, KamLAND, MiniBooNE, DoubleCHOOZ, Daya Bay, SNO+, NOνA JUNO, RENO50, LENA

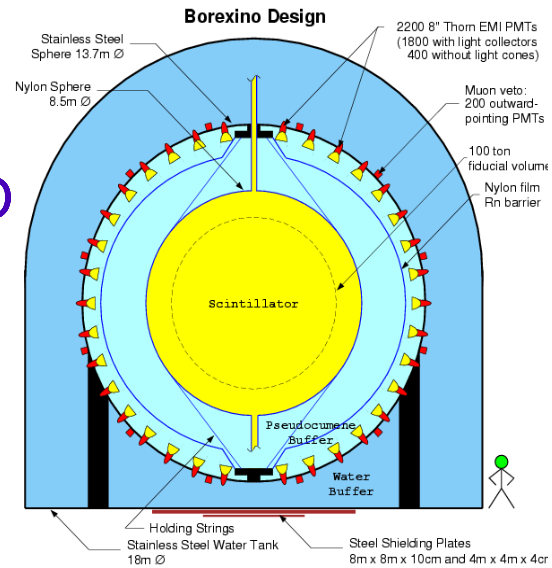
Scintillator Expts.



KamLAND
(Japan)

1 kton

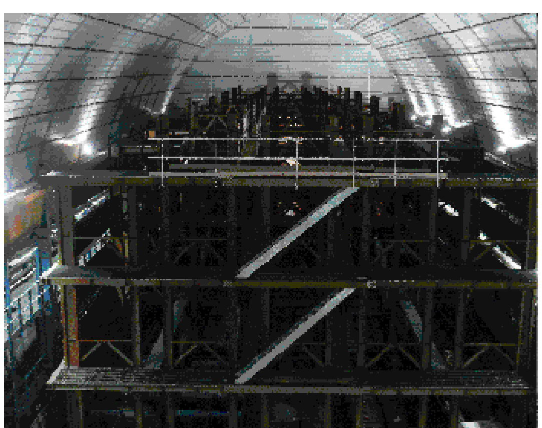
~300 $\overline{\nu}_e$
at 8.5 kpc



Borexino
(Italy)

0.3 kton

~100 $\overline{\nu}_e$



LVD (Italy)

1 kton

~200 $\overline{\nu}_e$

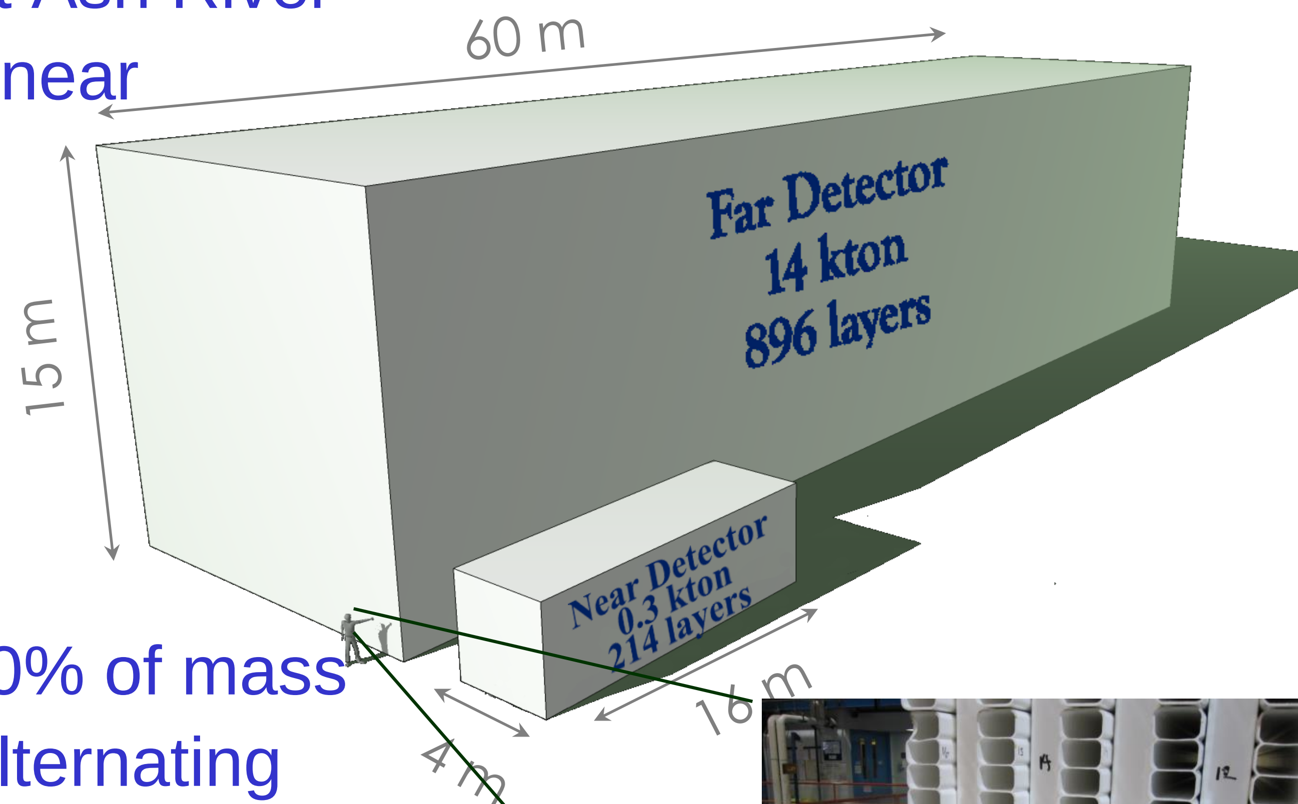
Daya Bay
(China)

8x {20ton w/ Gd
+ 22ton plain scint}

~100 $\overline{\nu}_e$

The NOνA Experiment

- Far Detector at Ash River
- Near Detector near beam source
  - Establishes pre-oscillation expectations
- Both same “highly active” construction: scintillator is 60% of mass
- PVC Cells in alternating directions filled with liquid scintillator provide stereo readout

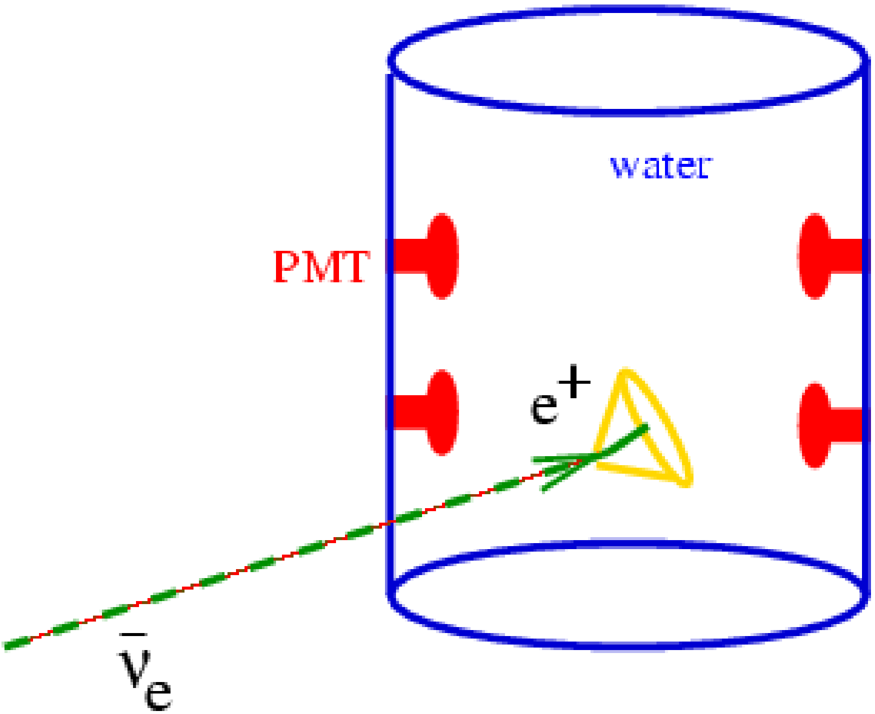


SEE TALK BY JUSTIN VASEL

Water Cherenkov

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

(seen)



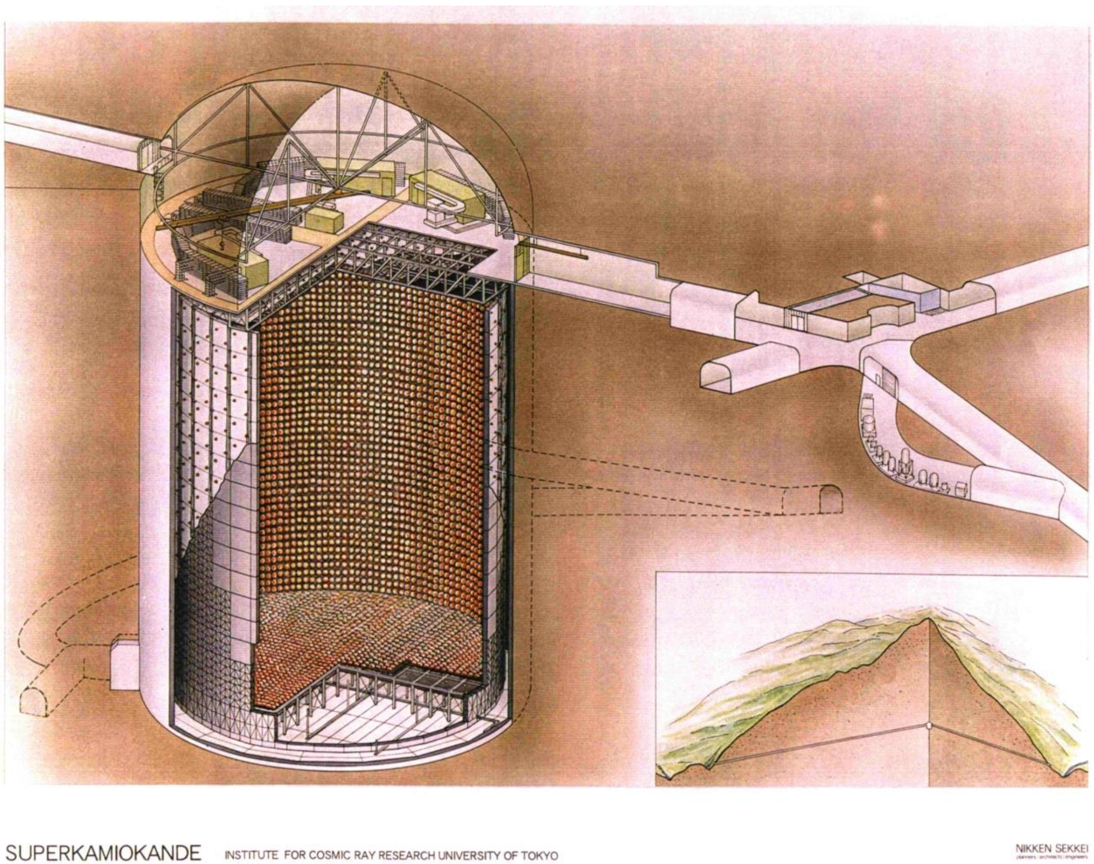
Pointing!

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

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

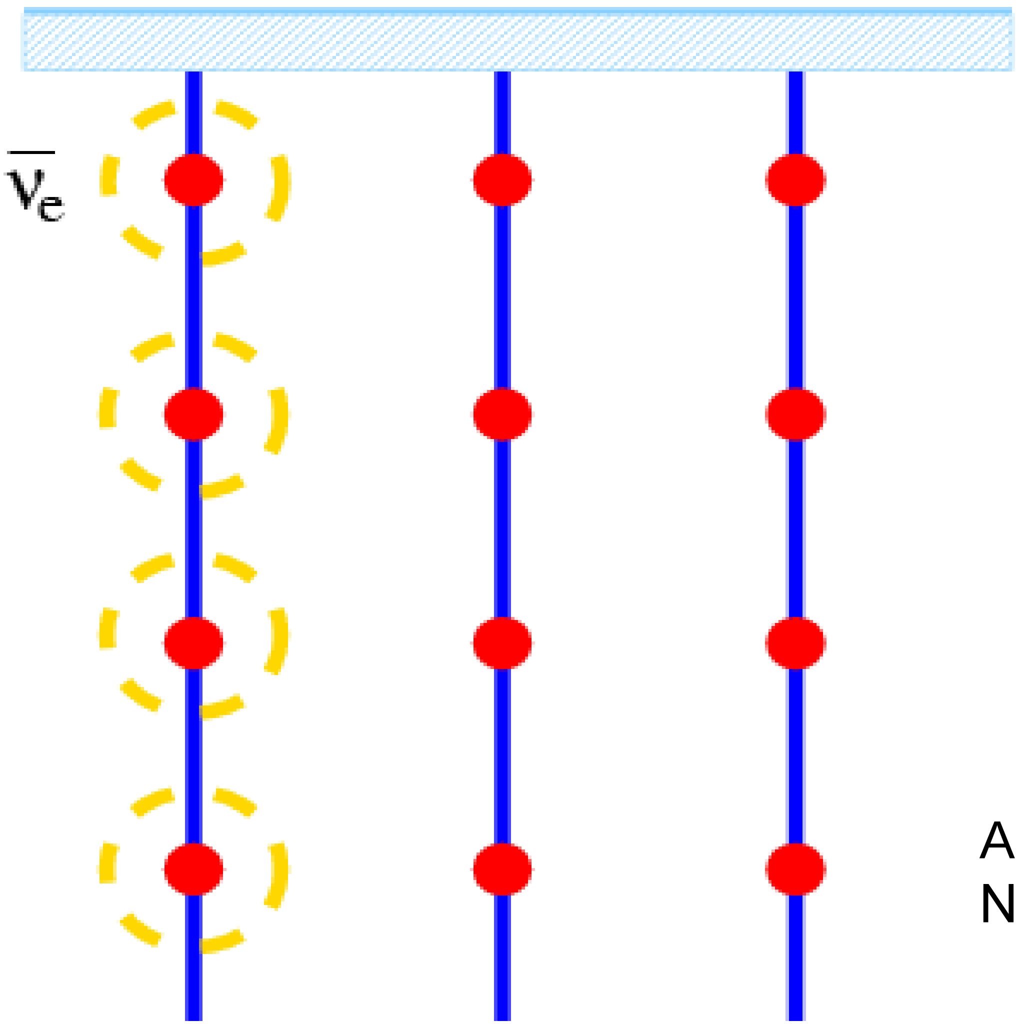
Imaging Water Cherenkov

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
  - Addition of gadolinium will allow lowering of IBD threshold by looking for neutron captures, tags IBDs

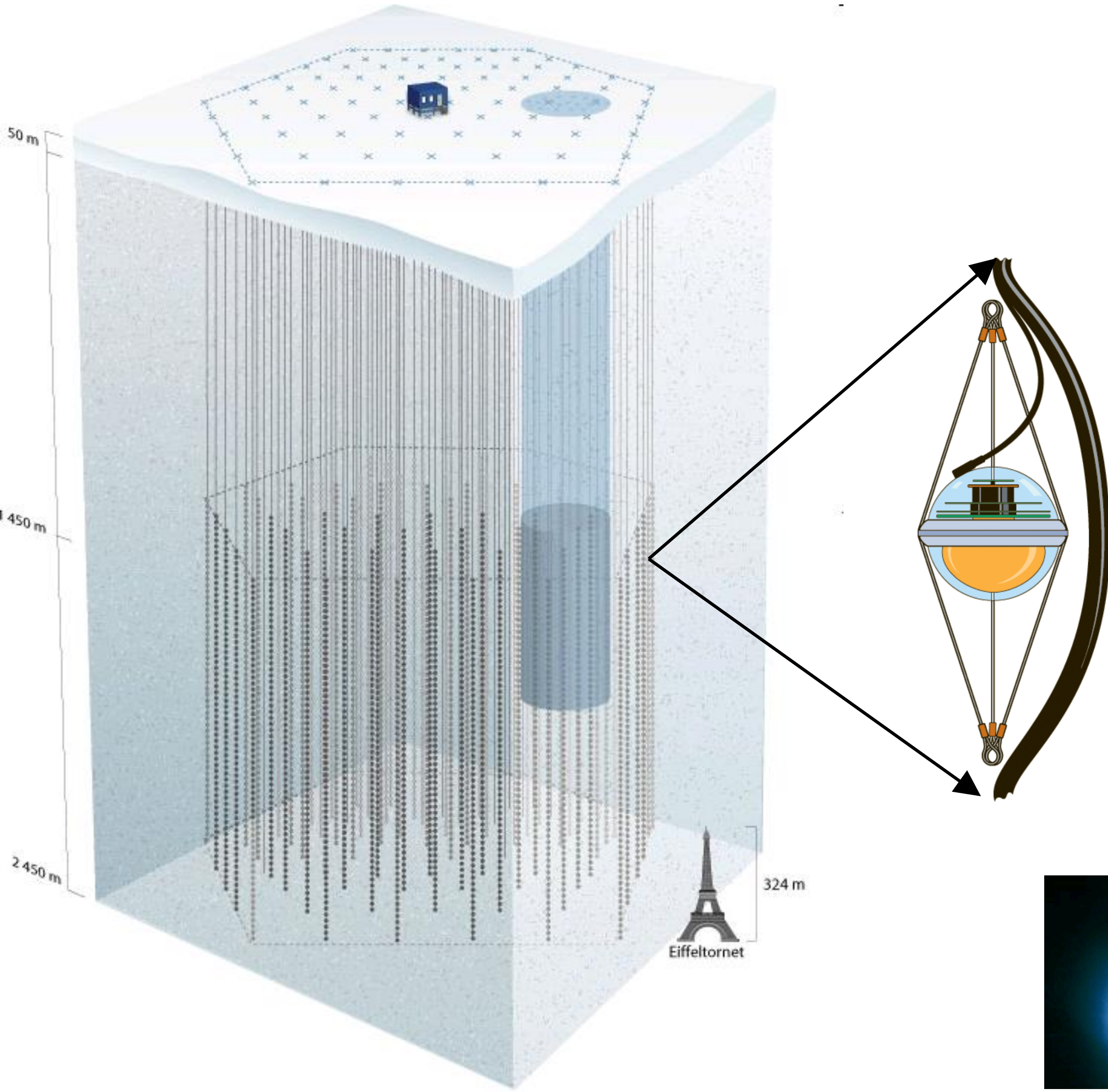
Long String Water Cherenkov



- 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 $\overline{\nu}_e$
  - 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

IceCube

Nobel Liquids

- Argon sees O(10 MeV) ν via the leptons and de-excitation gammas from:

Charged-current absorption

Dominant mode

$$\nu_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

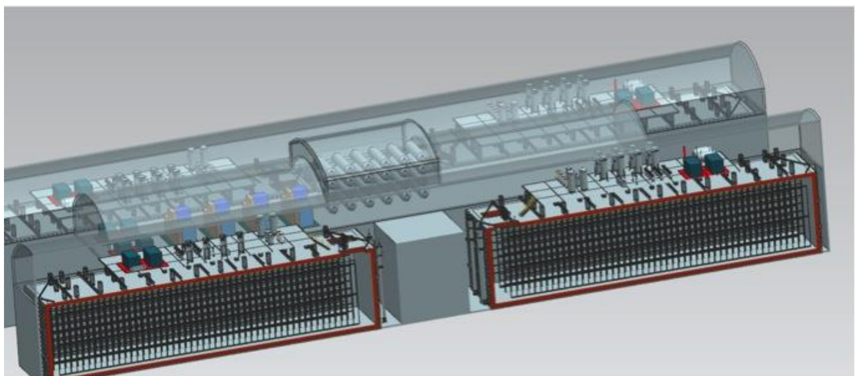
Elastic scattering: (*points back!***)**

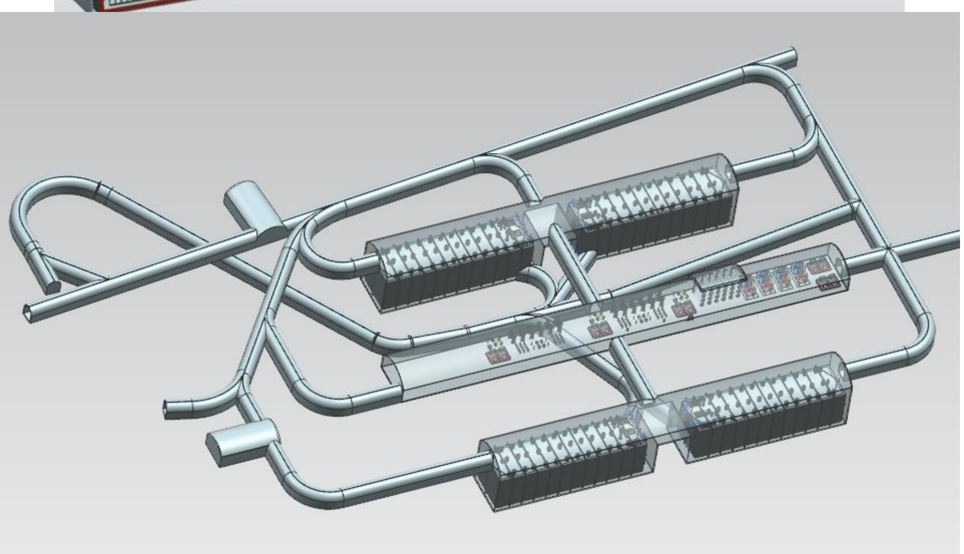
$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Look for electrons and de-excitation gammas

Nobel Liquids

- DUNE: 4 staged 10 kt LArTPC modules at Homestake





DUNE: 4 staged 10 kt LArTPC modules at Homestake

~3000 events

Gaining LArTPC experience with LARIAT, MicroBoone, CAPTAIN, SBND at FNAL

Xenon1t

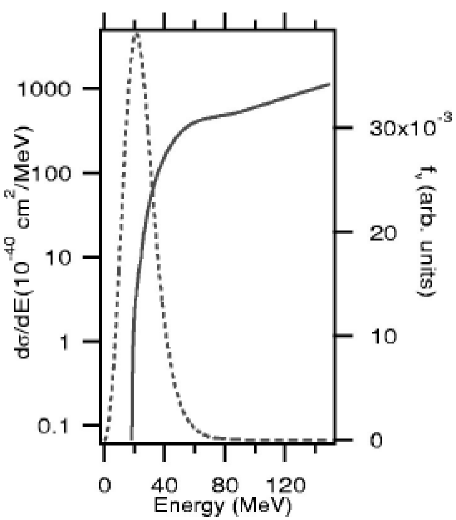
- Dark Matter detectors are now so huge they can see ν
- ~10 events over no background via NC ν-nucleon coherent scattering at low energy

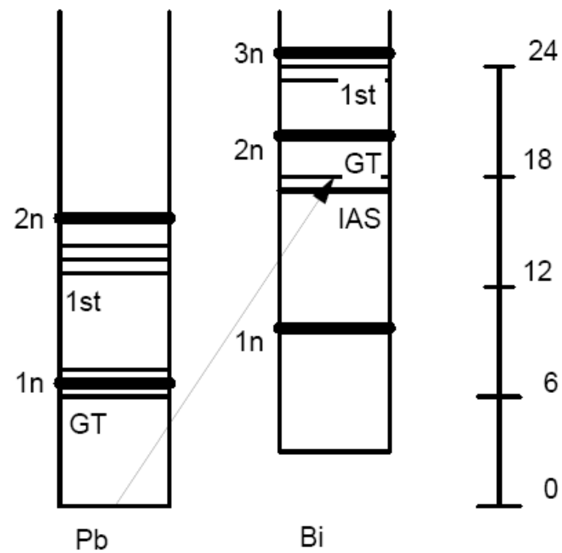
SNe ν_e and Lead

- Pb's neutron excess Pauli-blocks the usual SN ν detection channel of:
  - $\overline{\nu}_e + p^+ \rightarrow e^+ + n$
  - 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)



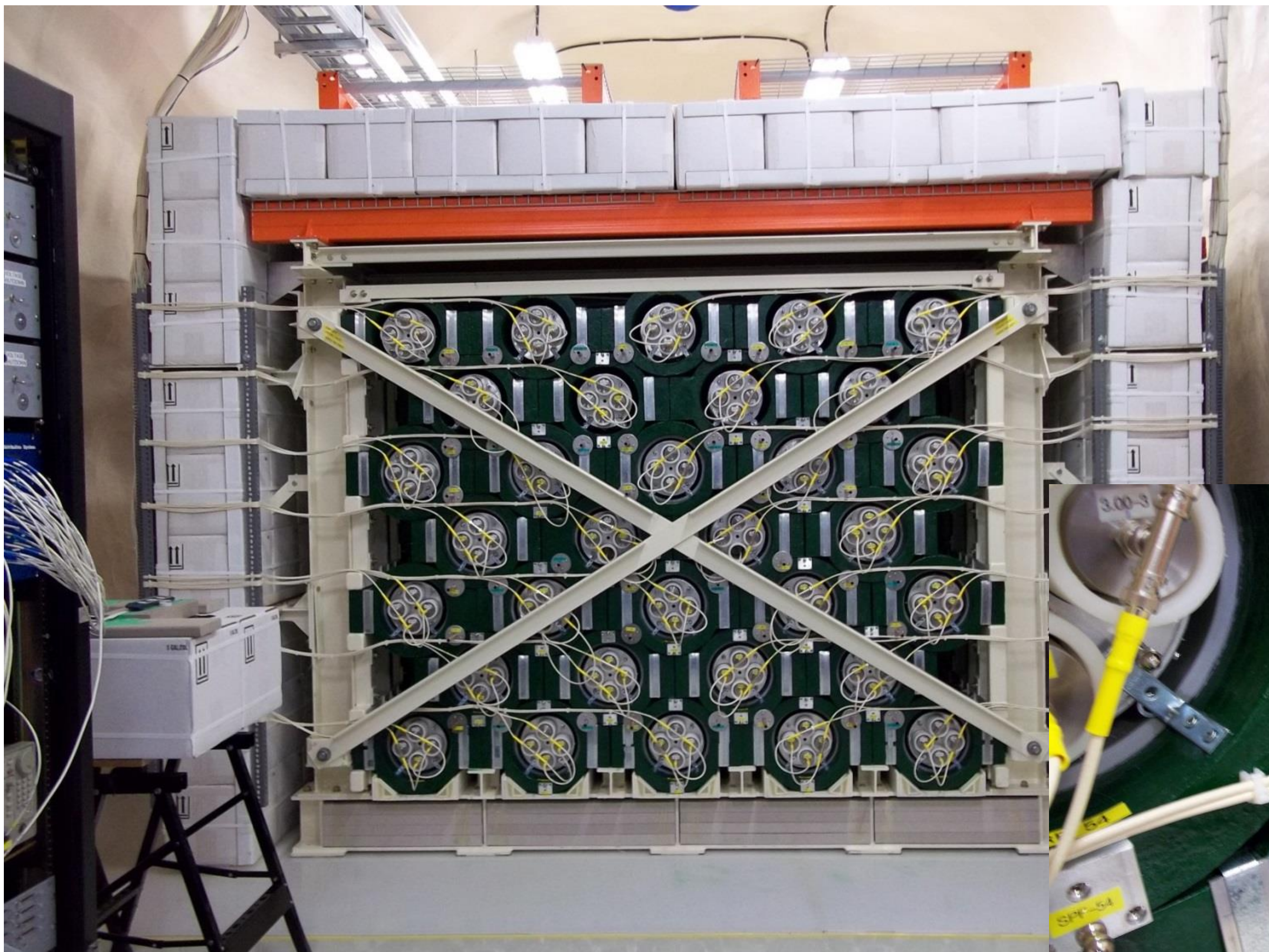


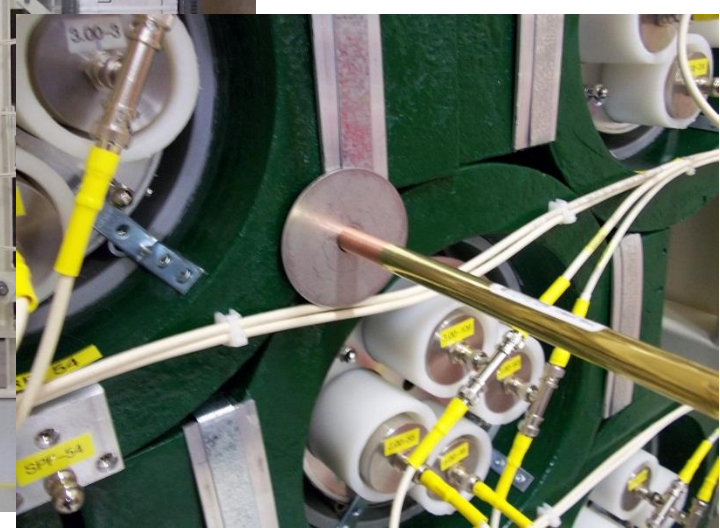
Pb & Bi nuclear levels

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

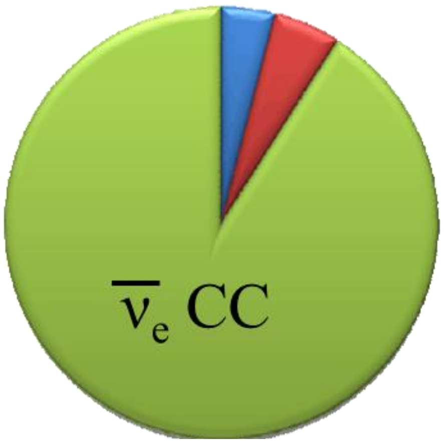
HALO

See talks by Clarence Virtue and Stan Yen





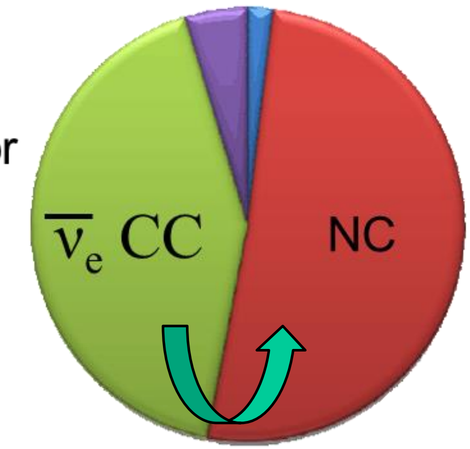
Flavor Sensitivities



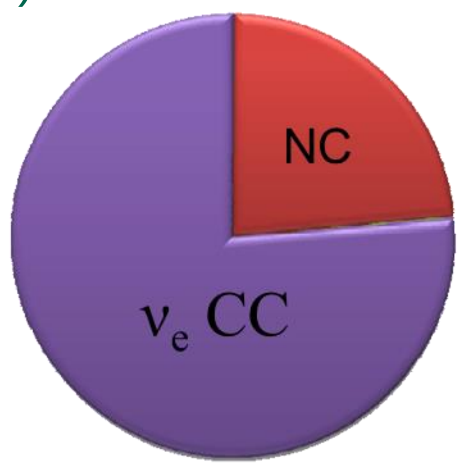
Water Cherenkov

(w/o Gd)

Liquid Scintillator



Strong threshold dependence



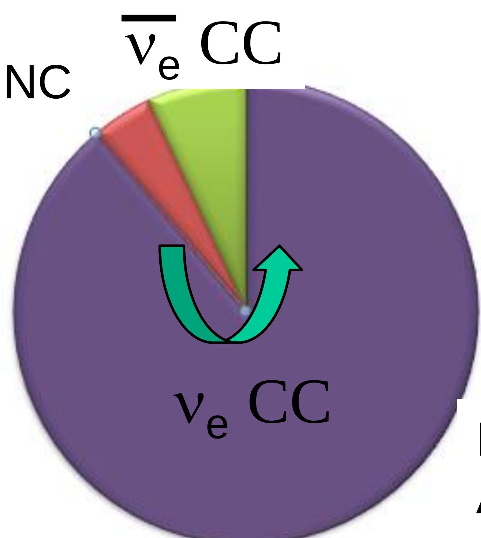
Lead

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

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

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

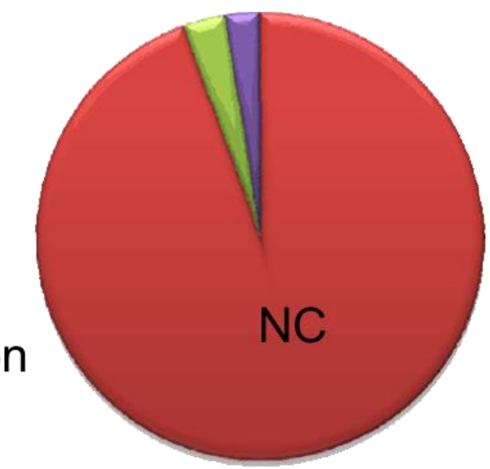
$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$



Liquid Argon

Low thresholds see NC coherent scattering

Iron



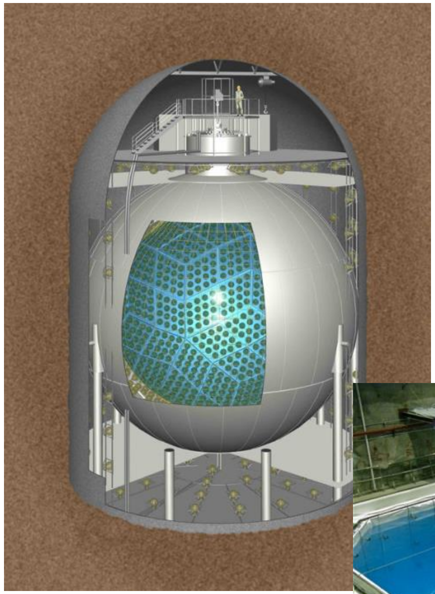
… but no Fe experiments exist

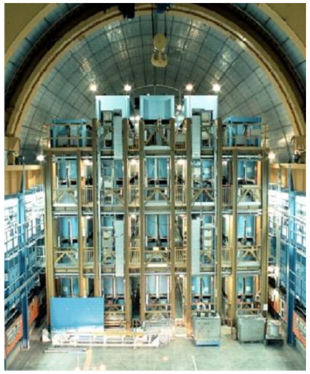
SNEWS

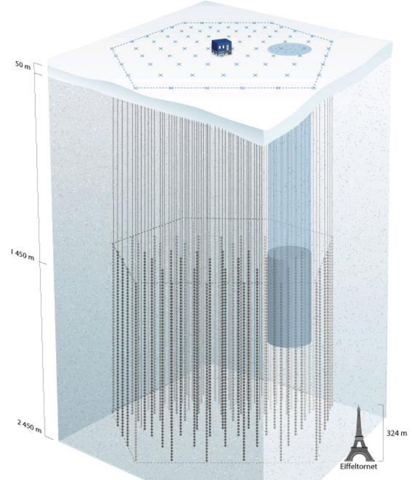
- SNEWS
  - Supernova Early Warning System
- Any single experiment has many sources of noise and few SNe
  - Flashing PMTs, light leaks
  - Electronic noise
  - Spallation
  - Coincident radioactivity
- Most can be eliminated by human examination (takes time)
  - No experiment would want to make an automated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

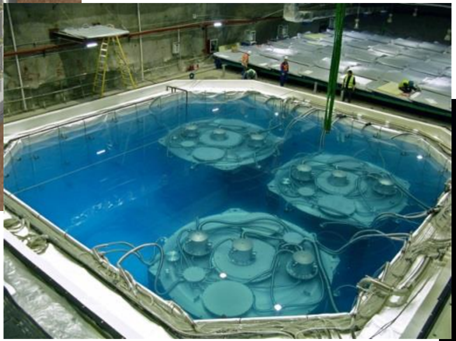
The Experiments

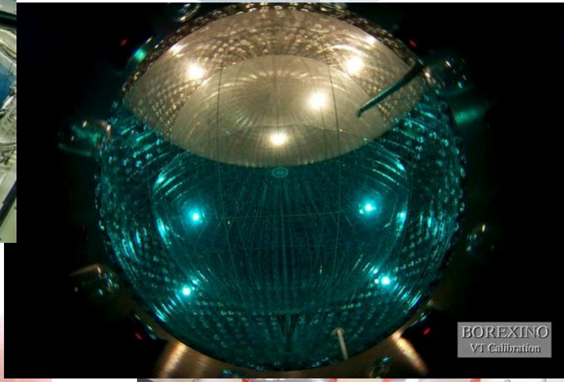
- Currently:
  - Super-K
  - LVD
  - IceCube
  - Borexino
  - Daya Bay
  - Kamland
  - HALO
- Alumni:
  - MACRO, SNO, AMANDA
- Operational but not SNEWS contributors:
  - Baksan, SBND
- Near-Future participants
  - NOvA, EGADS, SNO+

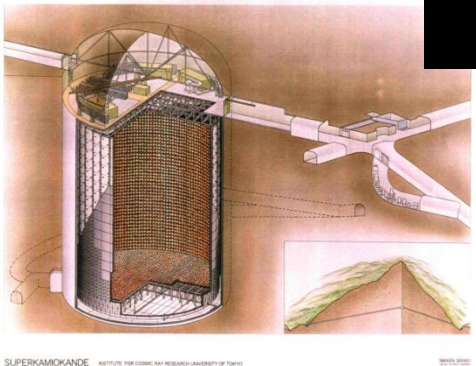


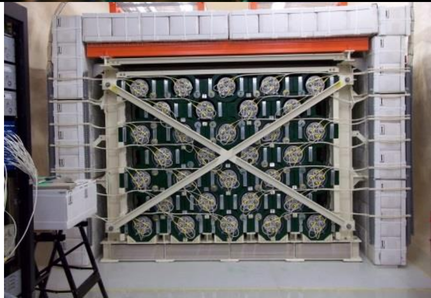




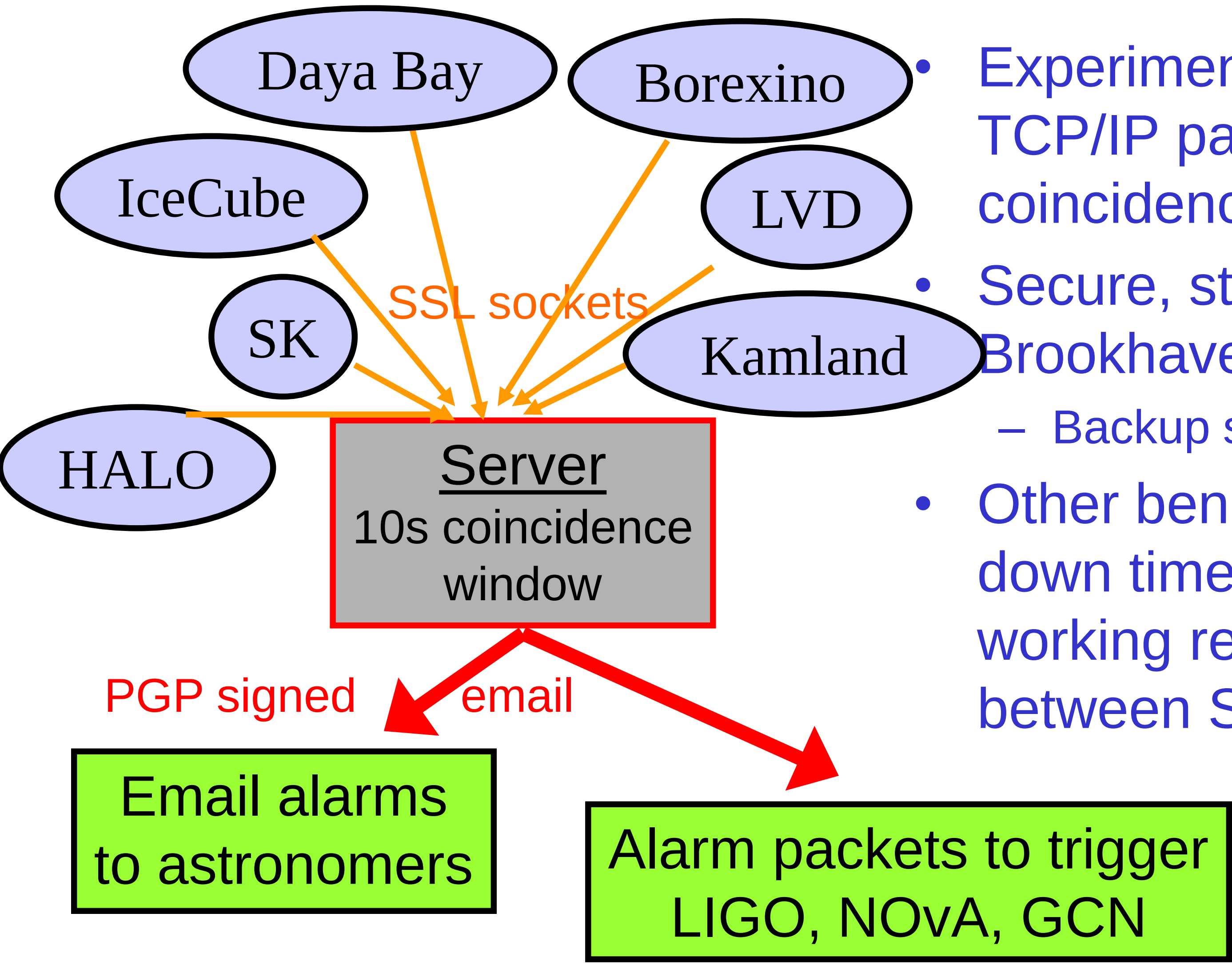








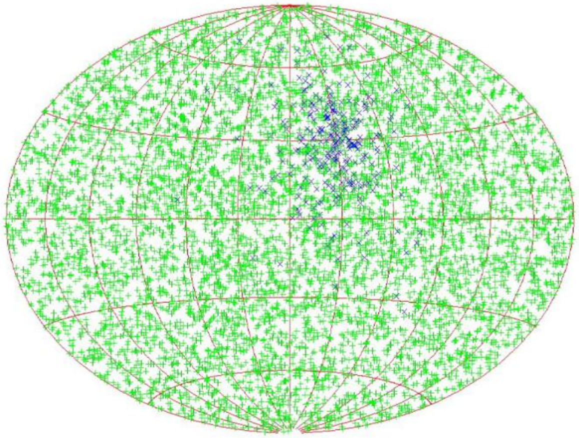
A Global Coincidence Trigger



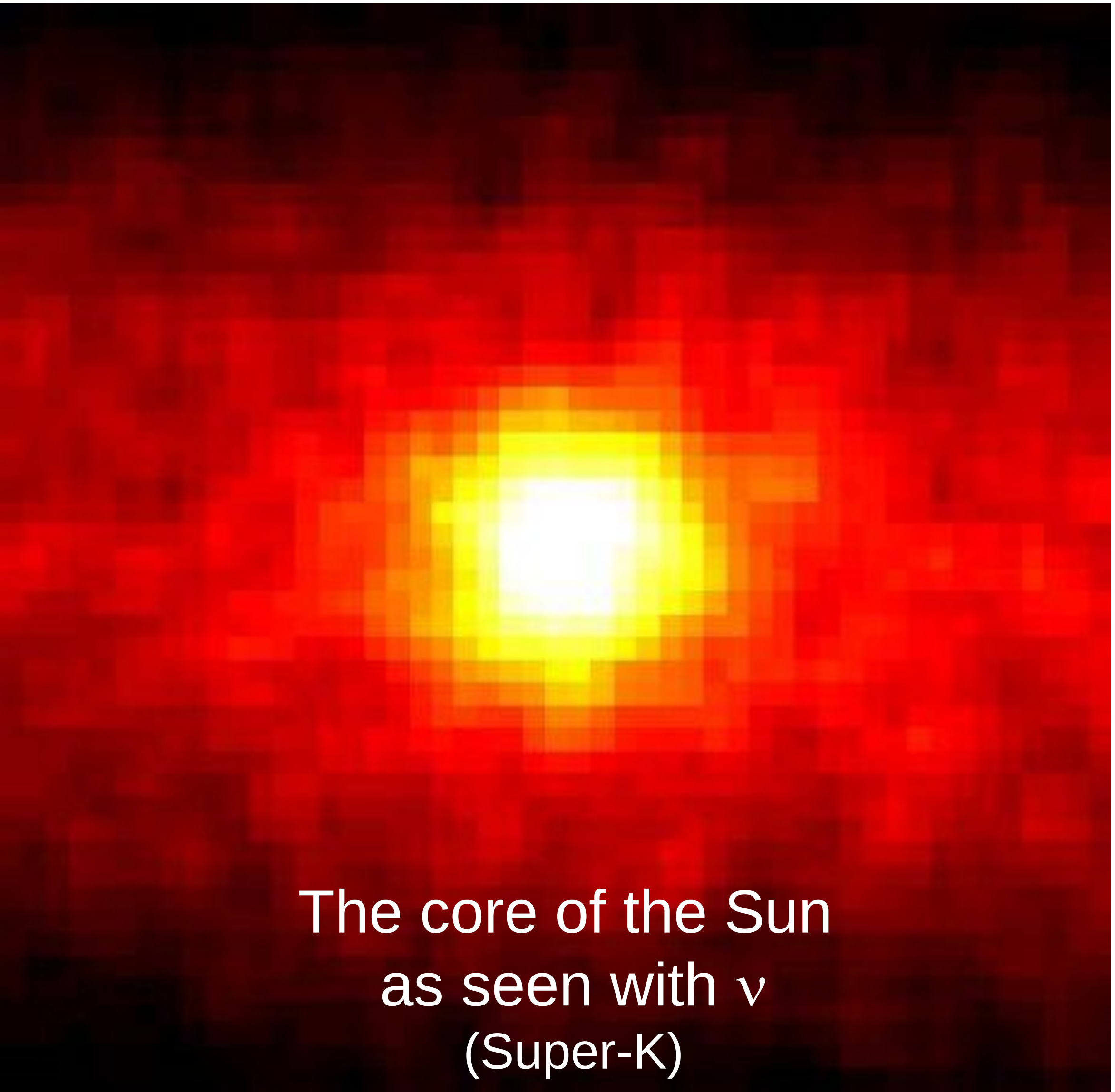
- Experiments send blind TCP/IP packets to central coincidence server
- Secure, stable hosting at Brookhaven
  - Backup server at Bologna
- Other benefits such as down time coordination, working relationship between SN teams, etc

Where will we see?

- All these experiments sensitive to all or most of the Milky way and all but the smallest also the Magellenic clouds
  - But even Super-K would see only one interaction from a SN in Andromeda: $1/r^2$ is murderous when combined with weak interaction cross-sections
- Super-K could point back to within ~4º using the sub-dominant electron elastic scatters
  - And do this even better once Gd n captures tag IBD interactions



Elastic Scattering



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

What flavors will we see?

- High statistics anti-electron neutrino “light curve” from Ice Cube and Super-K
  - Smaller experiments will add statistics, redundancy, and each has its own slightly different set of sensitivities
  - All also have microsecond or better timing resolution
- Electron-neutrinos only available with low statistics until DUNE comes online
  - HALO, SK elastic scatters
- All have some NC sensitivity at low stats that need disentangled
  - Xenon1t is nearly pure NC but low stats

Summary

- A core-collapse SN will occur in our galaxy sooner or later
  - It will produce a ν signal ~hours in advance of the light
- Many experiments are online now, more coming soon
  - Each brings a different set of strengths to the table
  - Combining their signals will be very useful (mandatory?) to deconvolute neutrino flavor
- Pointing not great until someone sees it with photons
- SNEWS has been online ready to form a quick alarm for more than a decade now, and will continue into the future

Acknowledgements

- SNEWS supported by NSF collaborative grant #1505960
  - Alec Habig @ UofM Duluth
  - Kate Scholberg @ Duke
- 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