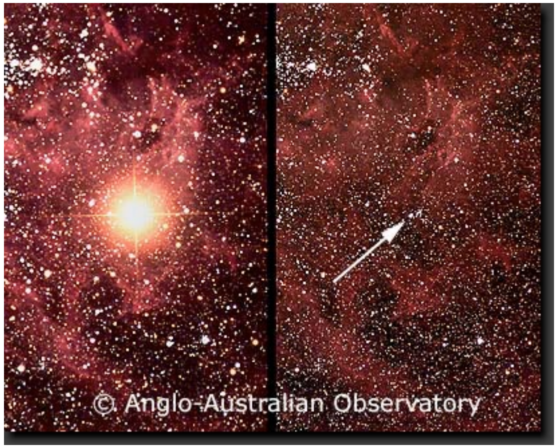
SNEWS

The SuperNova Early Warning System
in the age of Multi-Messenger Astronomy

of
Exploding Stars,
Weakly-Interacting Particles,
and Being Prepared



Alec Habig, Univ. of Minnesota Duluth

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

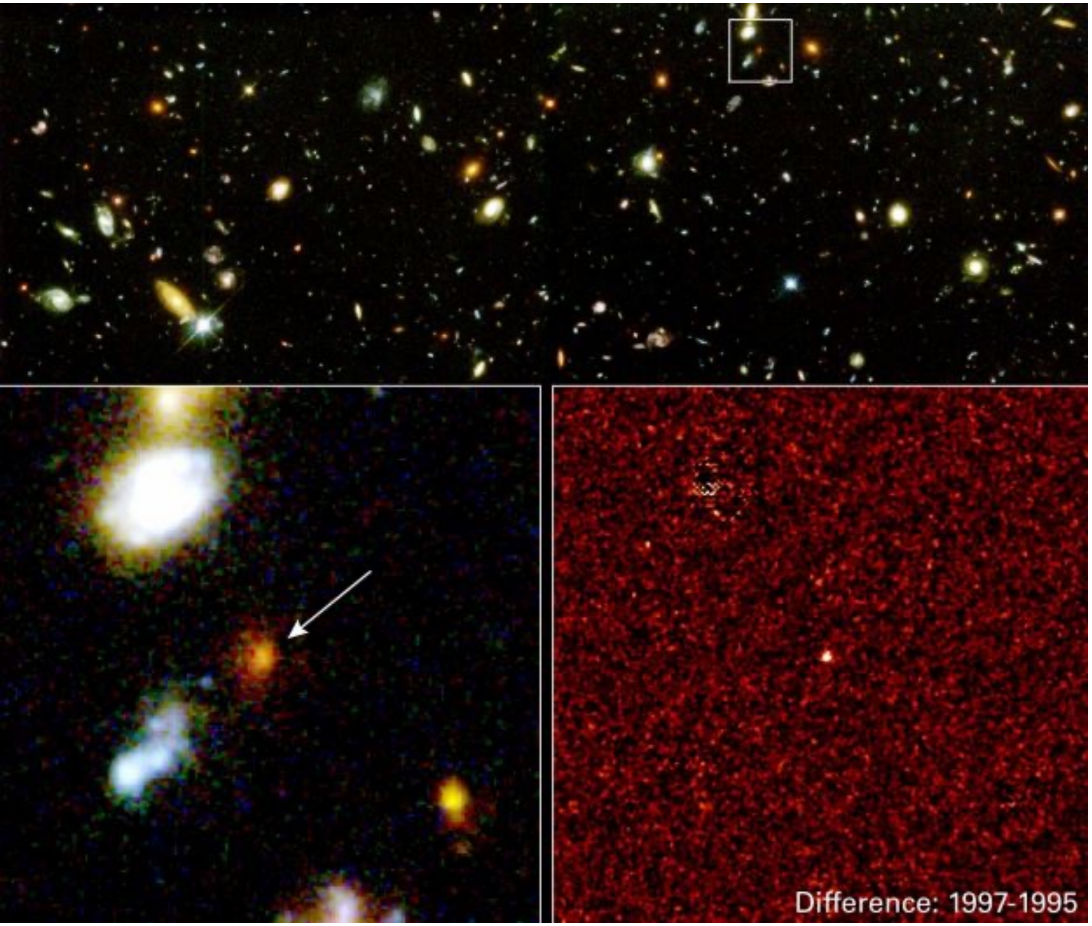


Photo by Adam Riess et al with HST

- 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 the gravitational collapse of an 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

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

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

Multi-Messenger Astronomy

- All the messengers on one plot vs. time, by luminosity

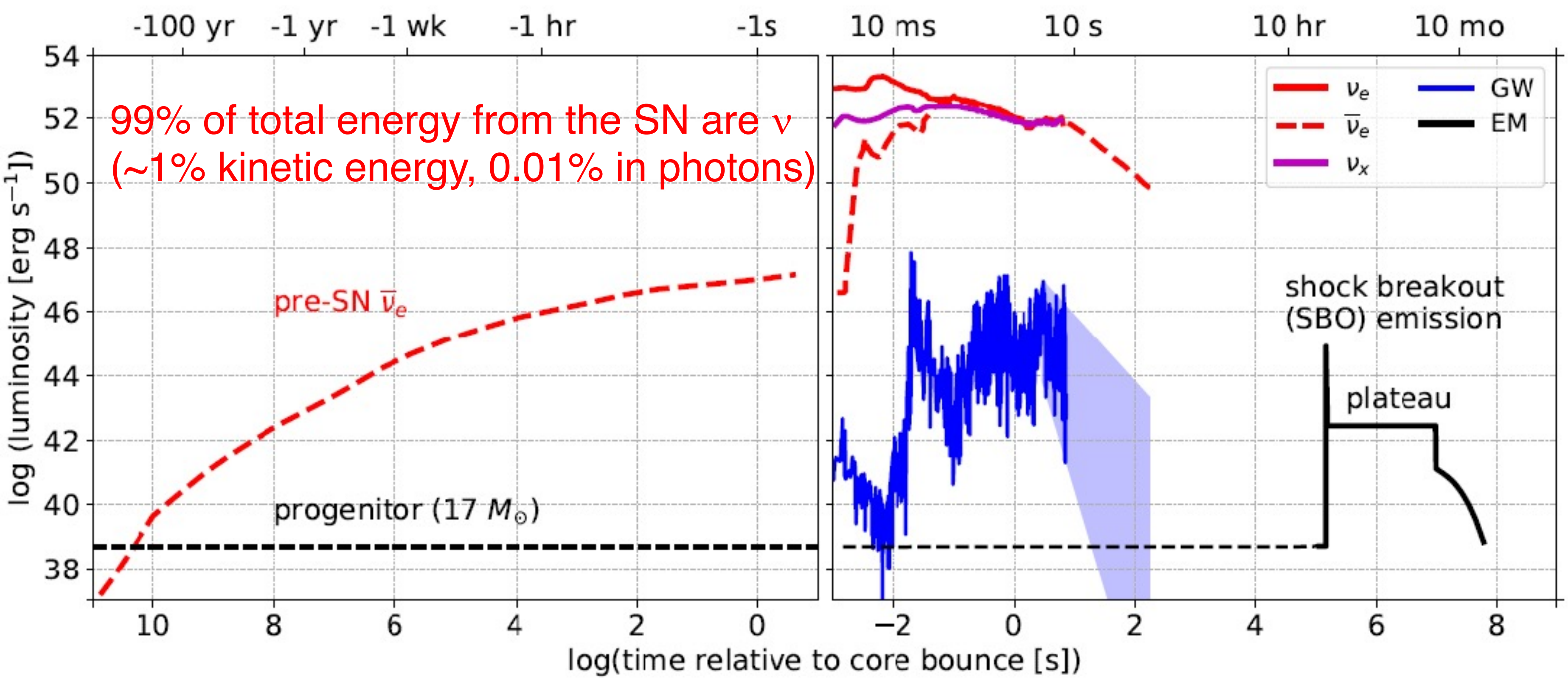
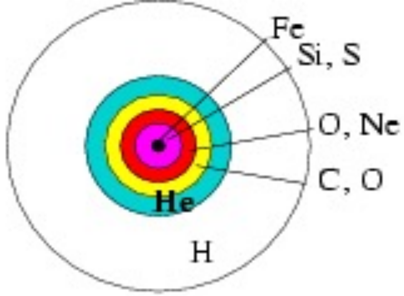
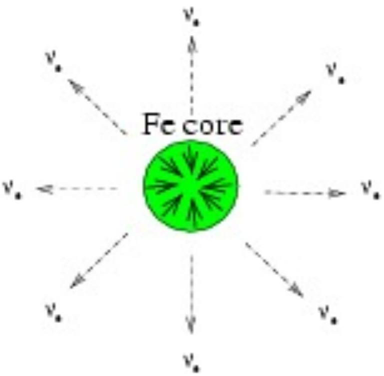


Figure from Nakamura *et al,* MNRAS 161, 3296 (2016)

Core Collapse

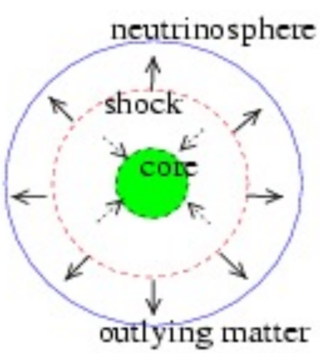


PRE-SUPERNOVA



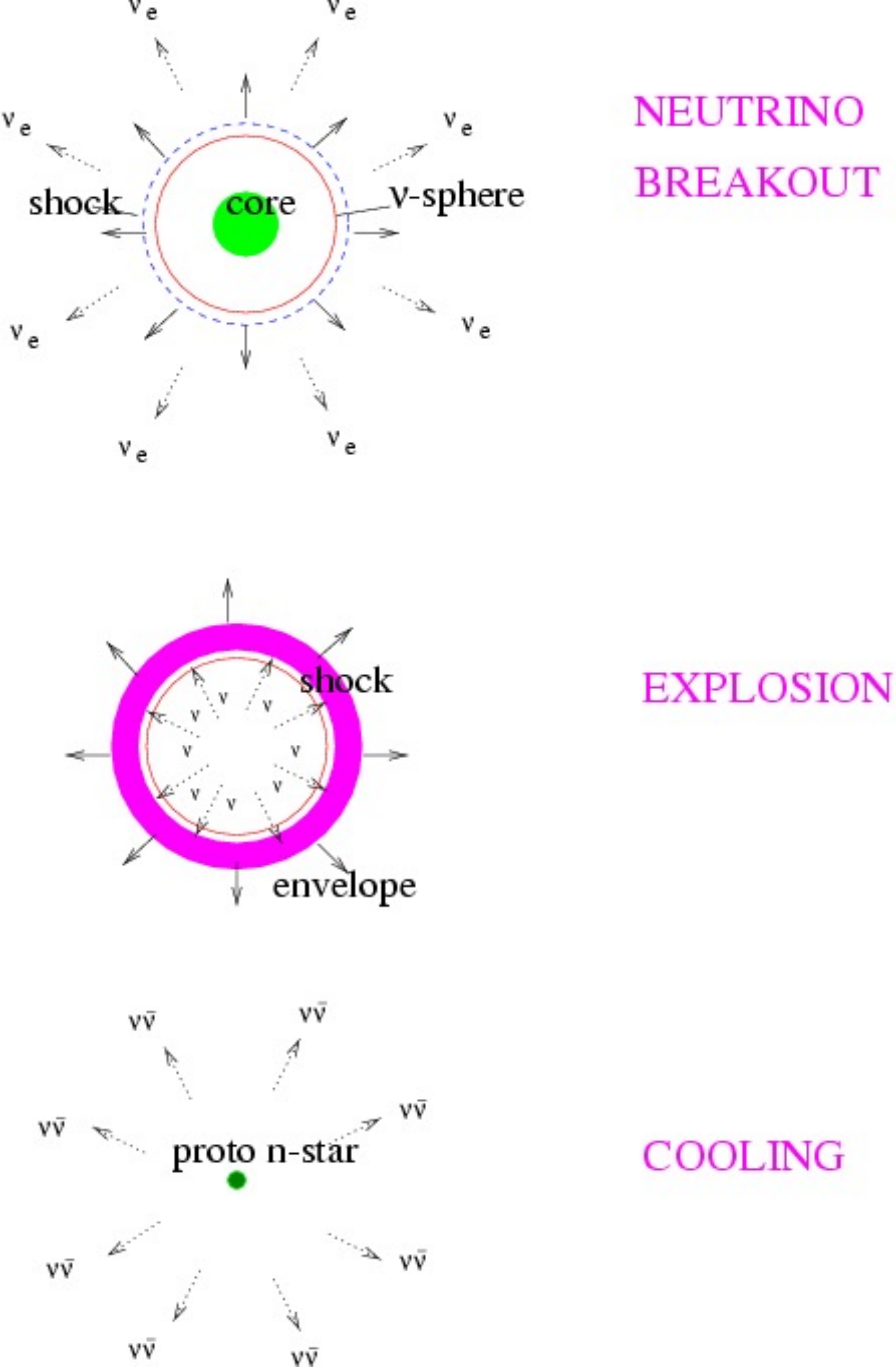
COLLAPSE

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

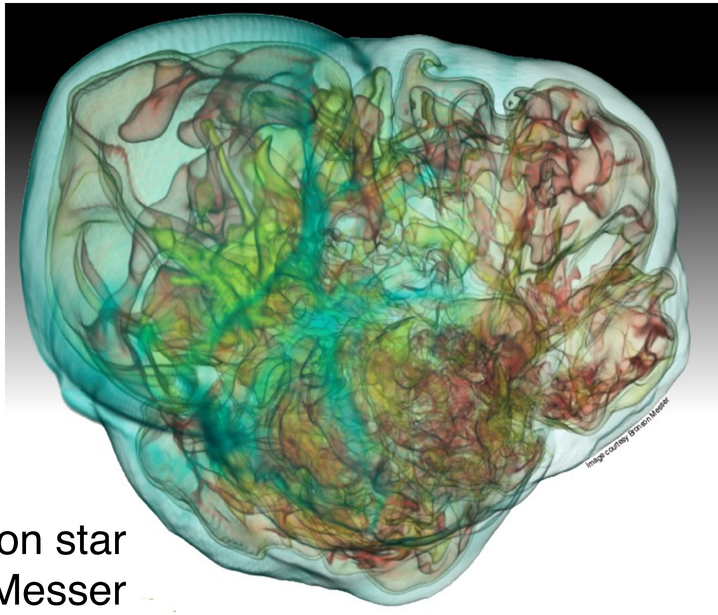


ν production

- 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 new neutron star cools via neutrino emission

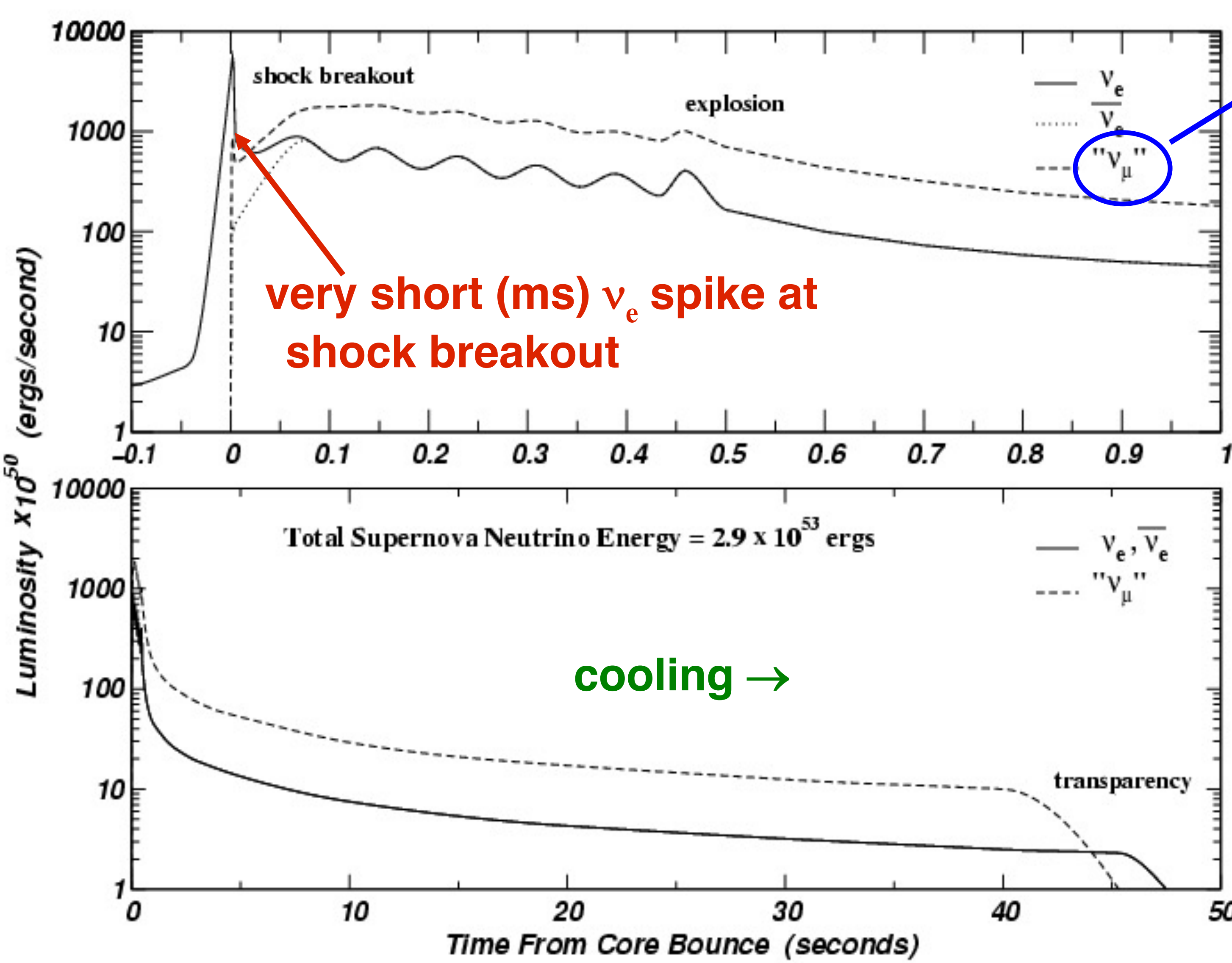
ν production

- ~1% of ν produced by initial neutronization
  - $p^+ + e^- \rightarrow n + \nu_e$
- Thermal $\bar{\nu}\nu$ pair production produces 99% of ν
  - $e^+e^- \rightarrow \bar{\nu}\nu$, $e^-(Z,A) \rightarrow e^-(\bar{Z},A)\,\bar{\nu}\nu$, $NN' \rightarrow NN'\bar{\nu}\nu$
  - 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



Equal entropy surfaces in a proto-neutron star model by Bronson Messer

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

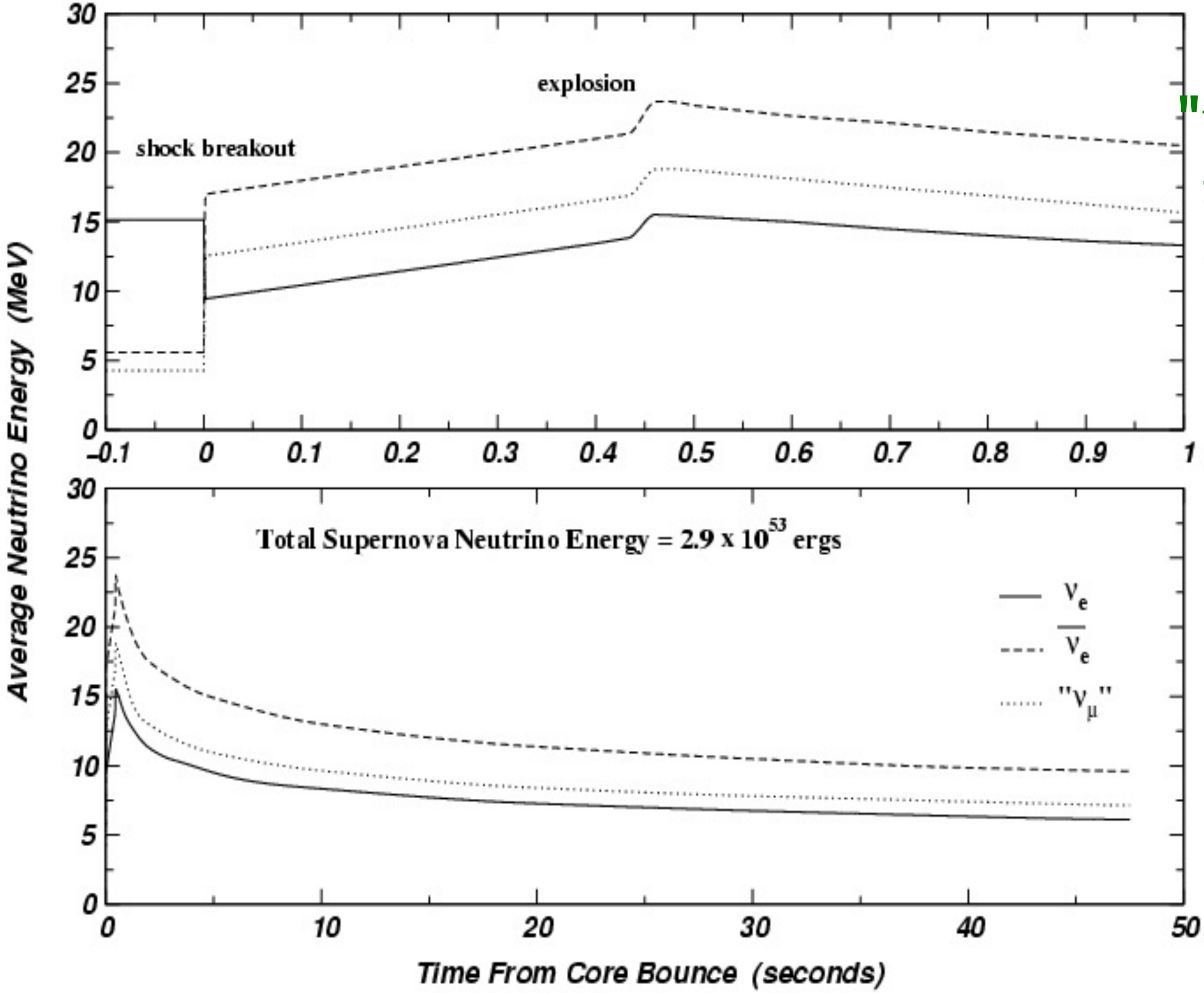
Burrows et al. 1992

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
  - 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

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

ν spectra



1 s

50 s

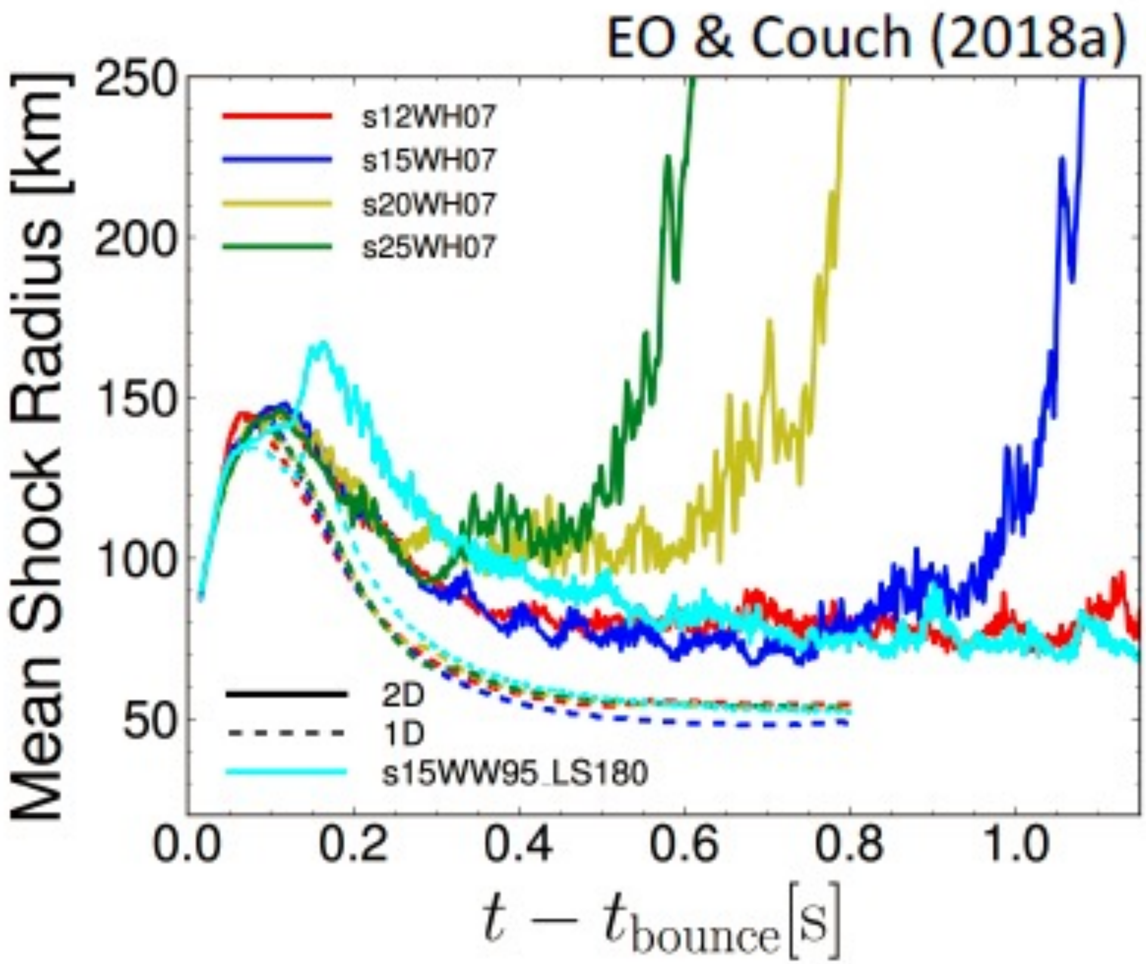
"ν_μ"
$\bar{\nu}_e$
ν_e

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

Energy decrease over long timescale (cooling)

Burrows et al. 1992

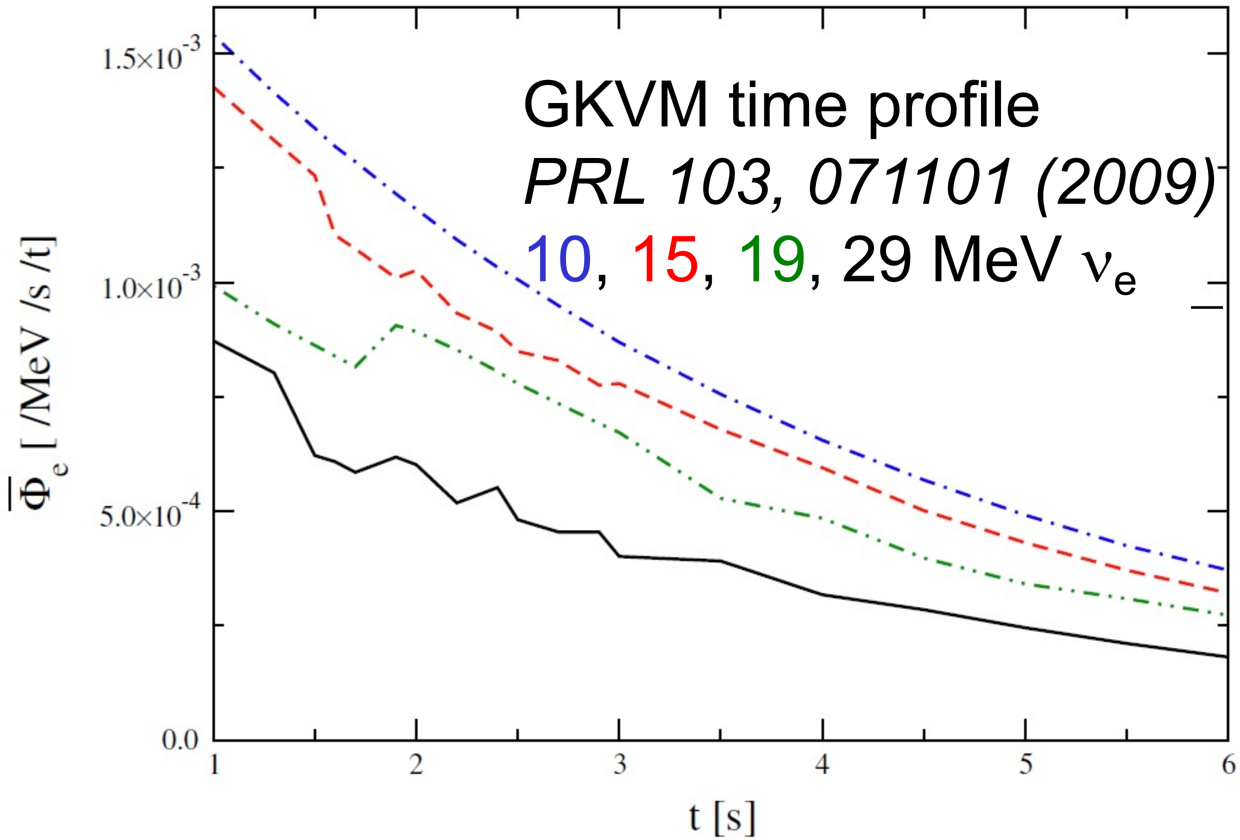
More details



O'Connor & Couch (2018)

- 1D models reproduce luminosity well
- Newer models add GR, 3D, rotation, magneto-hydrodynamics, acoustics…
  - Same basic features
- Explosion seems driven by neutrino-induced convection and turbulence

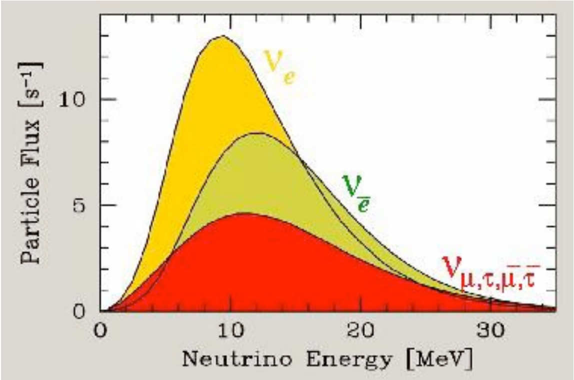
Time Profile



After the first second, it's an exponential cooling curve: the new neutron star is cooling via neutrino emission. Lasts out to ~100 s unless a black hole forms

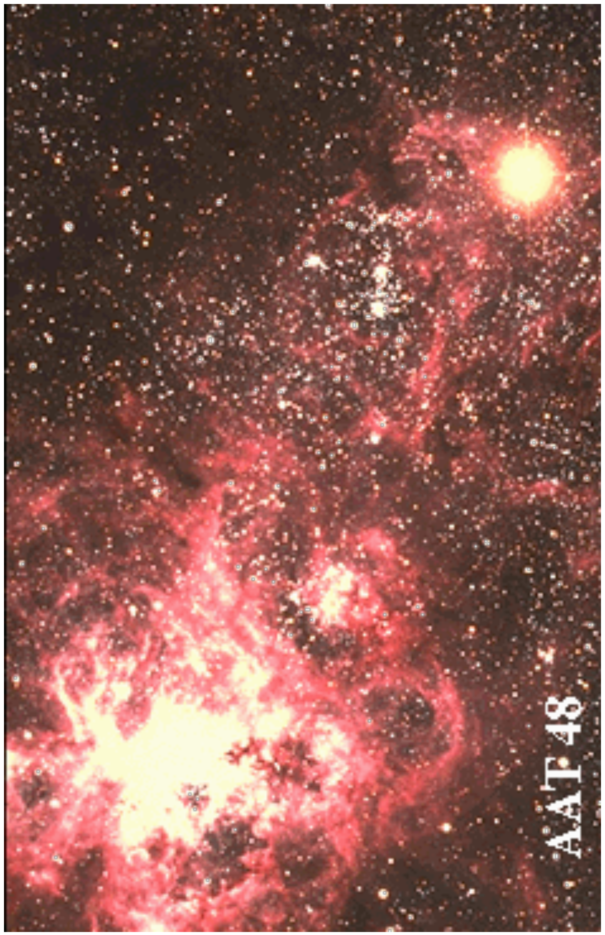
Generalities

- 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:
  - $<E_{\nu_e}> \sim 12$ MeV
  - $<E_{\overline{\nu}_e}> \sim 15$ MeV
  - $<E_{\nu_\mu}> \sim 18$ 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 $\overline{\nu}$ needed to study such effects



A. Dighe, TAUP09

Experimentally Confirmed



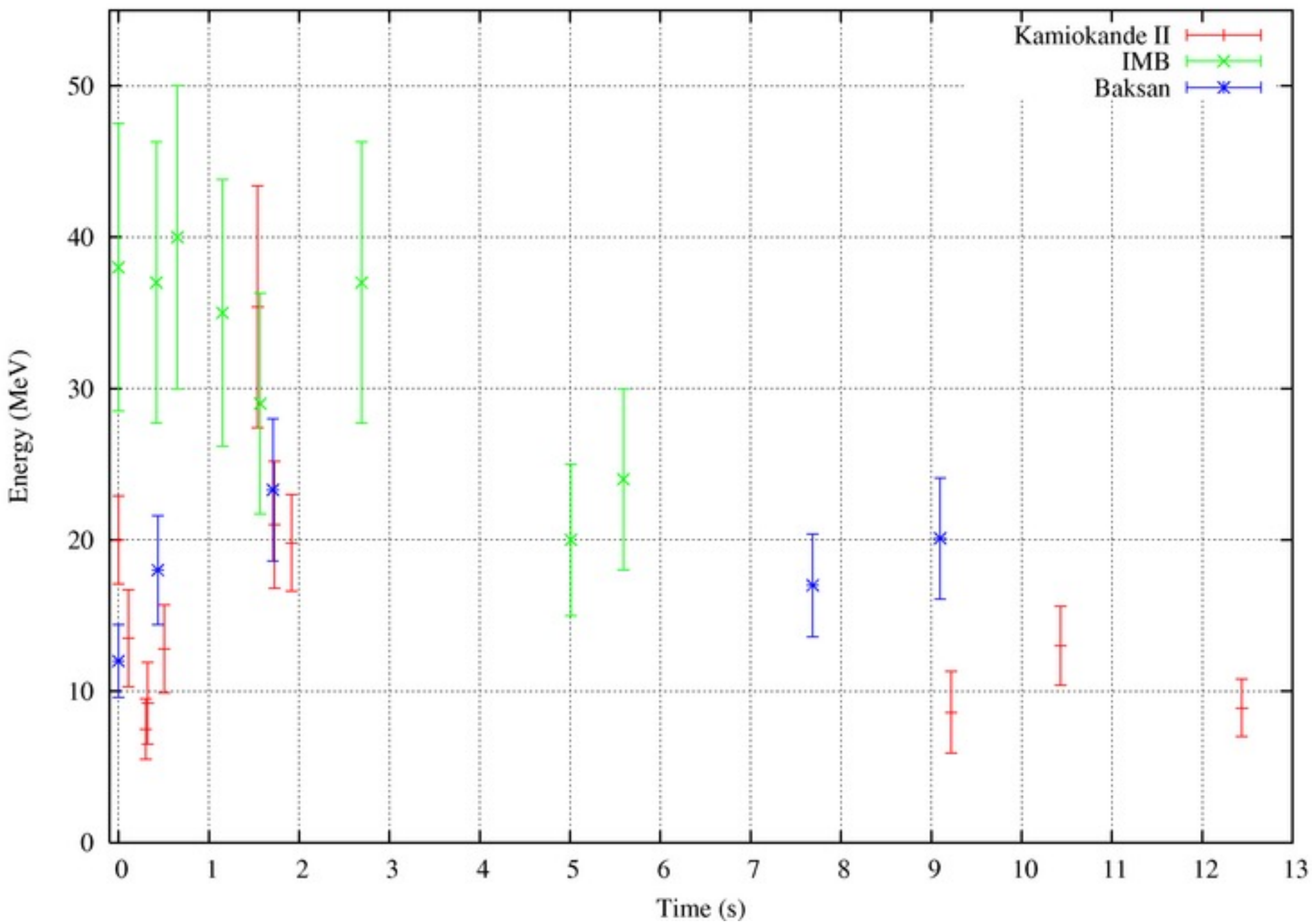
- SN1987A
  - Type II
  - In LMC, ~55kpc
- Well studied due to proximity
  - Although a peculiar SN, blue giant progenitor, odd dim light curve
- And close enough so that $1/r^2$ didn't crush the ν signal
  - Seen in ν detectors!
- A Gravity Powered Neutrino Bomb!

SN1987A ν observations

Proton Decay experiments see:

Water Cherenkov

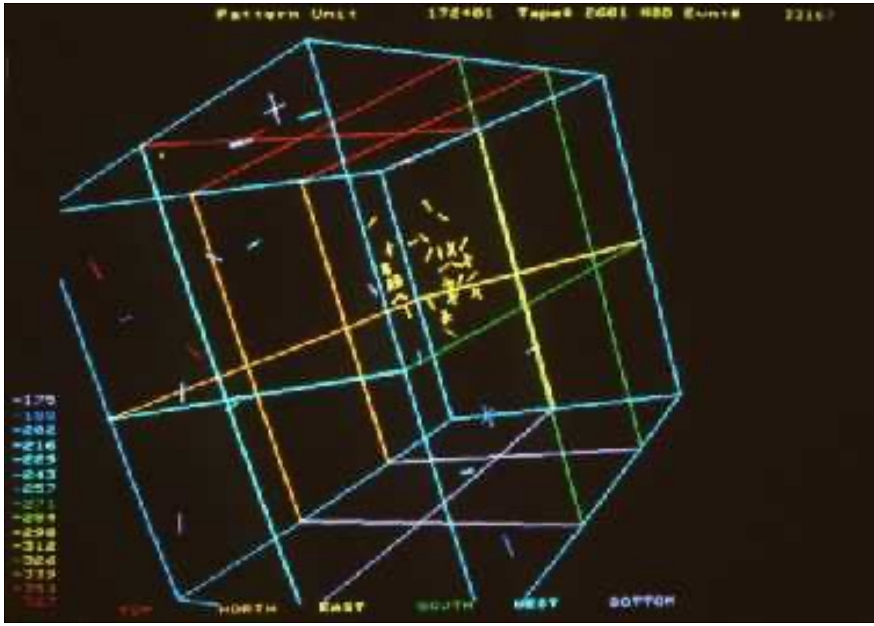
- Kamiokande
  - E_{th} = 8.5 MeV
  - M = 2.9kt
  - Sees 11 ν
- IMB
  - E_{th} = 29 MeV
  - M = 6kt
  - Sees 8 ν
- Baksan
  - E_{th} = 10 MeV
  - M=130t
  - Sees 3-5 ν
- Mont Blanc
  - E_{th} = 7 MeV
  - M = 90t
  - Sees 5 ν (??)



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 $m_{\nu_e} < 20\text{eV}$
  - 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 (*which was a Ia*), why bother looking?

Method (for CCSN)	Mean interval (yr) per galaxy
^{26}Al Abundance	1.9±1.1
Neutron Star Birthrate	7.2±2.7
SNR Ages	0.37±0.05
Historical Rate (MW + Local Group)	0.66-2.04 (68%)

Overall?

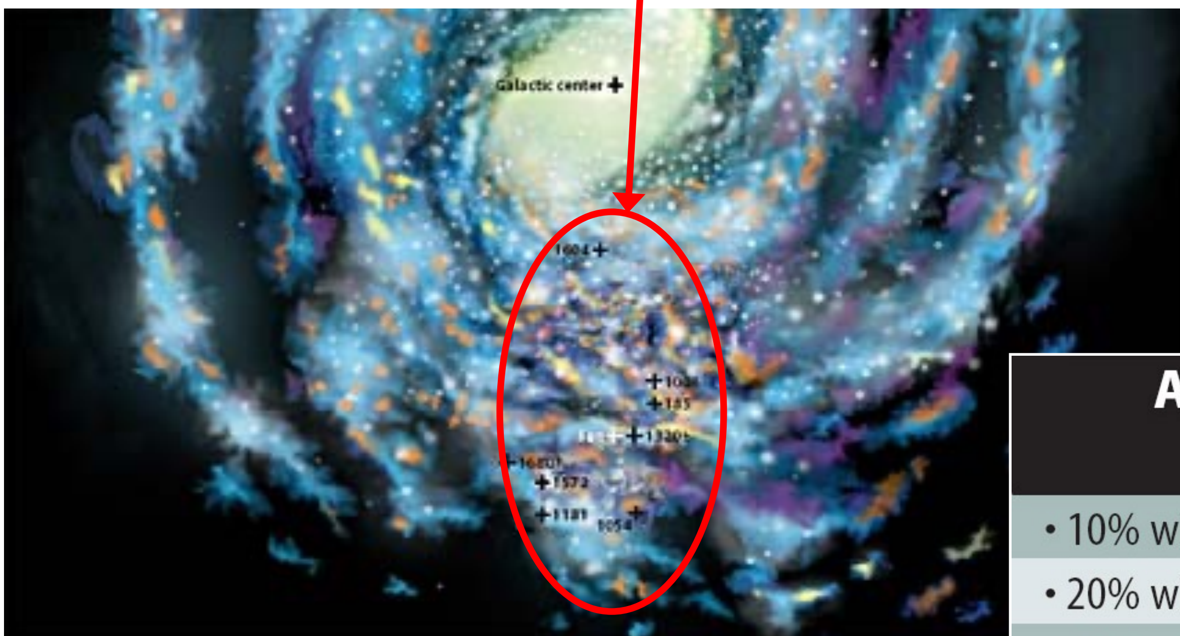
1.63±0.46 per century!

Academically – one per career, if Monsieur Poisson cooperates

Latest estimates from Rozwadowska, Vissani, & Cappellaro, New. Astron. 83, 101498 (2020)

Observational Efficiency

- Perhaps 1/6 would be easily seen optically



Historical SNe map from Sky & Telescope

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

Only in the past decades have humans been able to “see” past galactic dust with ν, IR, and radio

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 2/century and a galactic radius of 15kpc, that's hundreds of SN-ν wavefronts already on their way to us here on Earth!

Small Δt SN Observations

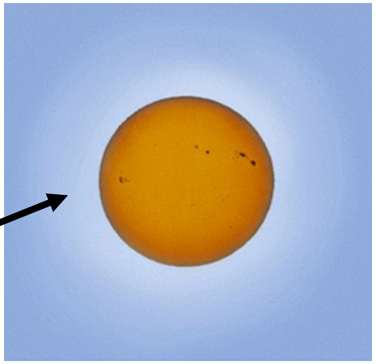
SN1987A

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
- LIGO/VIRGO now doing a similar job with GWs

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

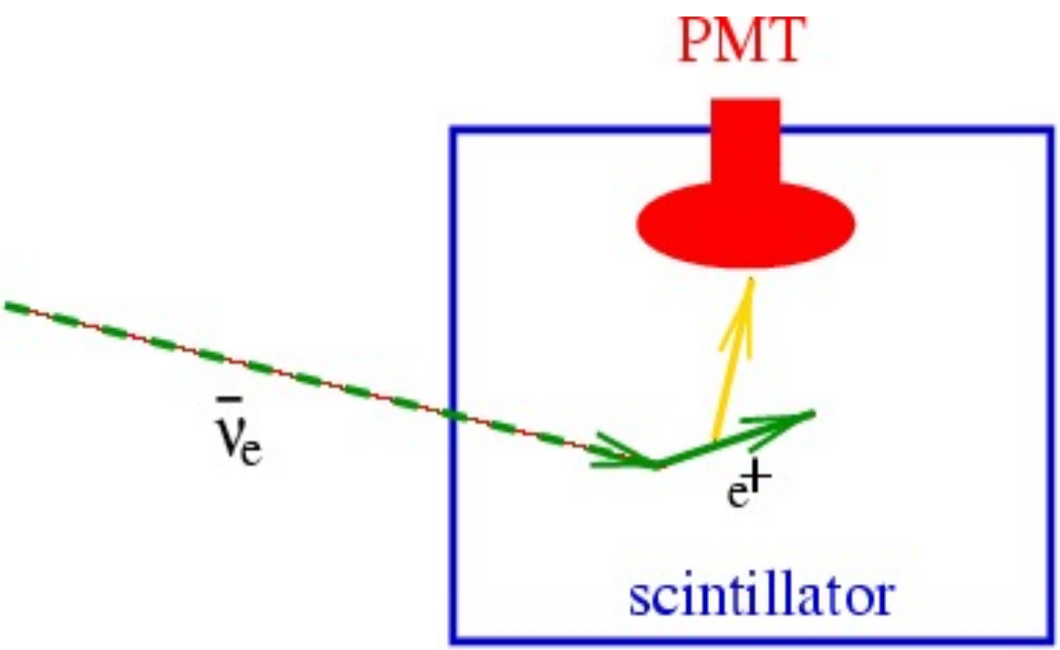
Basic Types

- Scintillator (C_nH_{2n})
- Imaging Water Cherenkov (H_2O)
- Heavy Water Cherenkov (D_2O)
- Long String Water Cherenkov (H_2O)
- 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): $\nu_x + p^+ \rightarrow \nu_x + p^+$

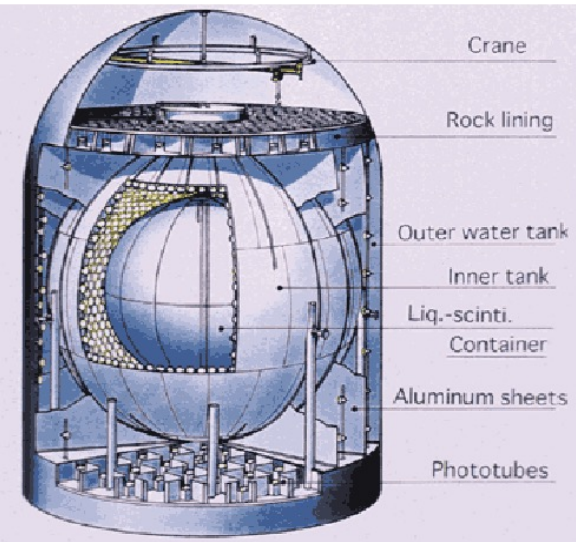
(seen)



Little pointing capability

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

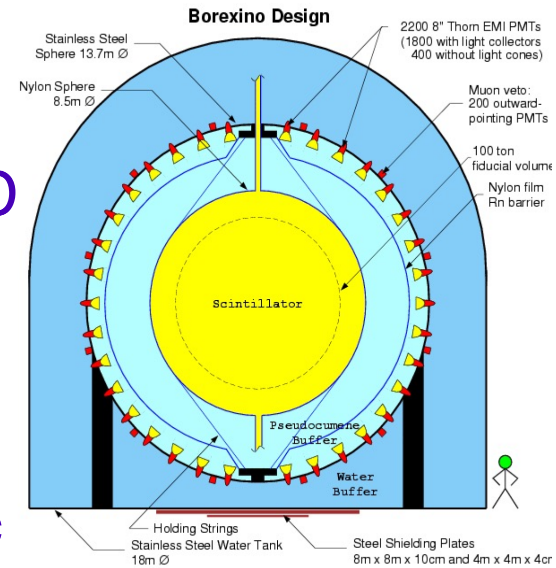
Scintillator Expts.



KamLAND (Japan)

1 kton

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



Borexino (Italy)

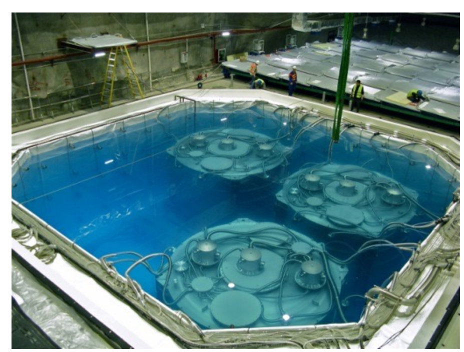
0.3 kton

~100 $\bar{\nu}_e$

LVD (Italy)

1 kton

~200 $\bar{\nu}_e$



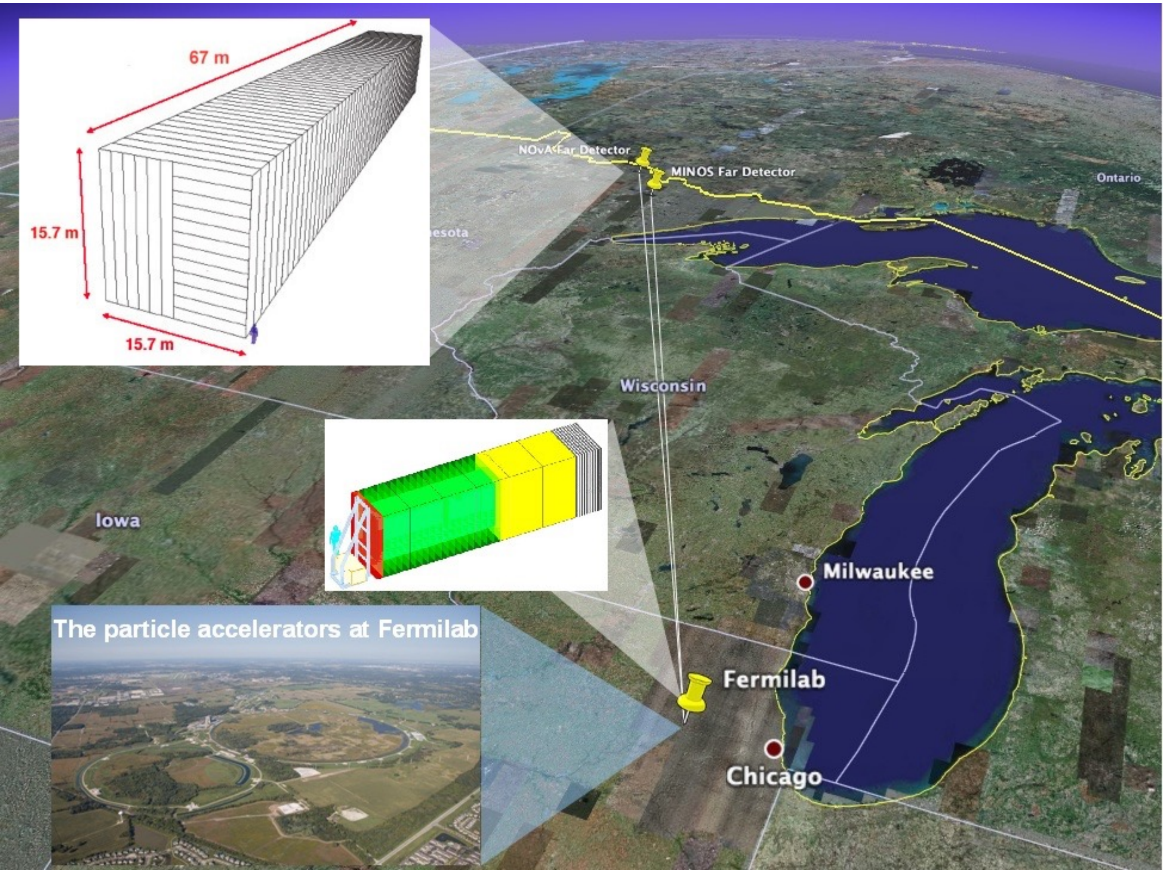
Daya Bay (China)

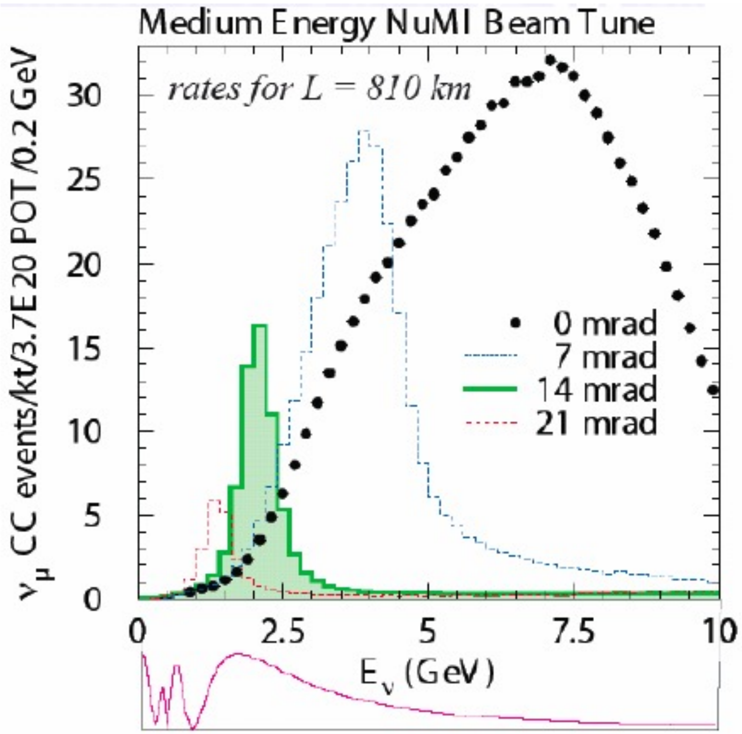
8x {20ton w/ Gd + 22ton plain scint}

~100 $\bar{\nu}_e$

The NOνA Experiment

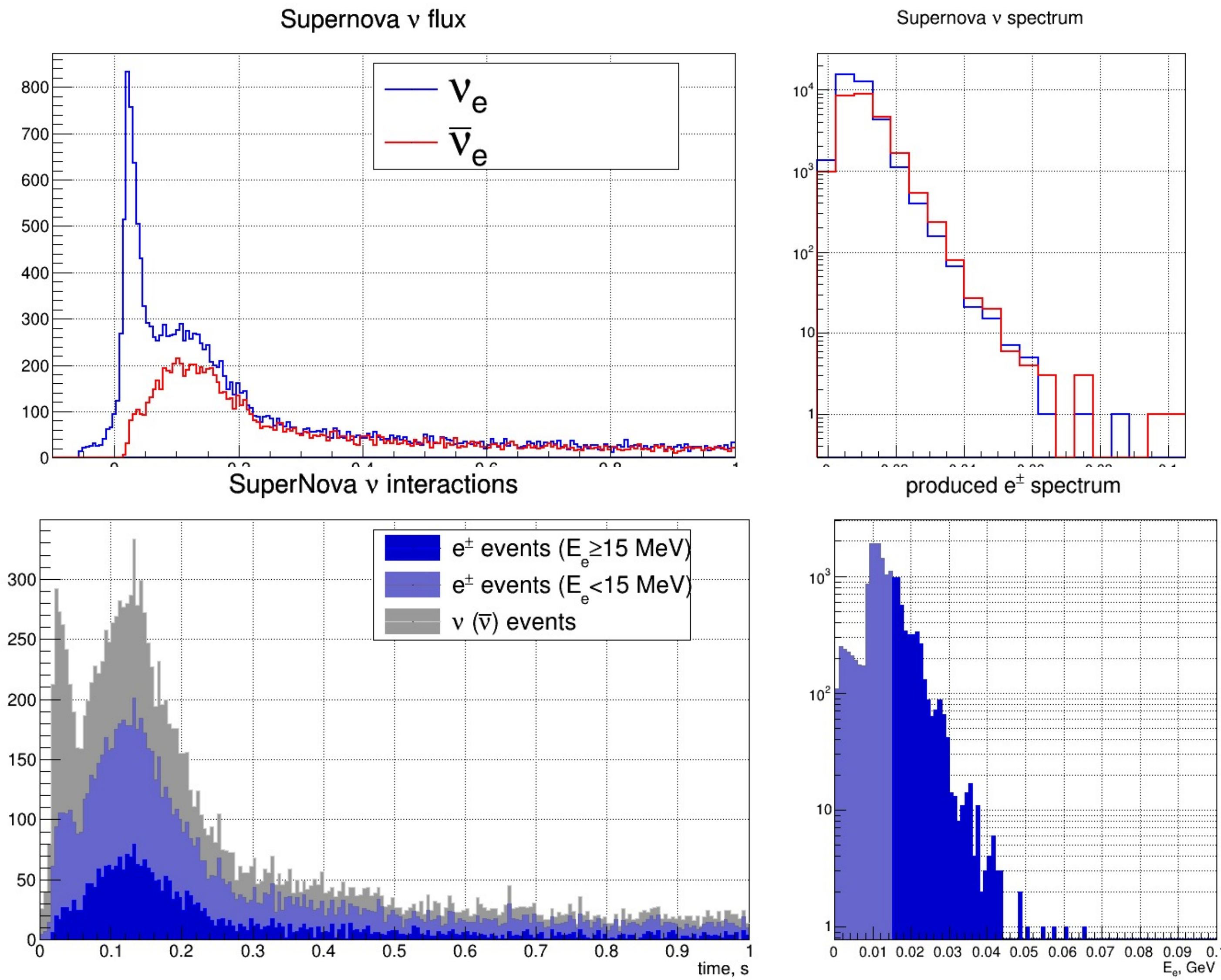
- 810 km from Fermilab, 14 mrad off-axis gets a beam which is tight in energy but low in intensity



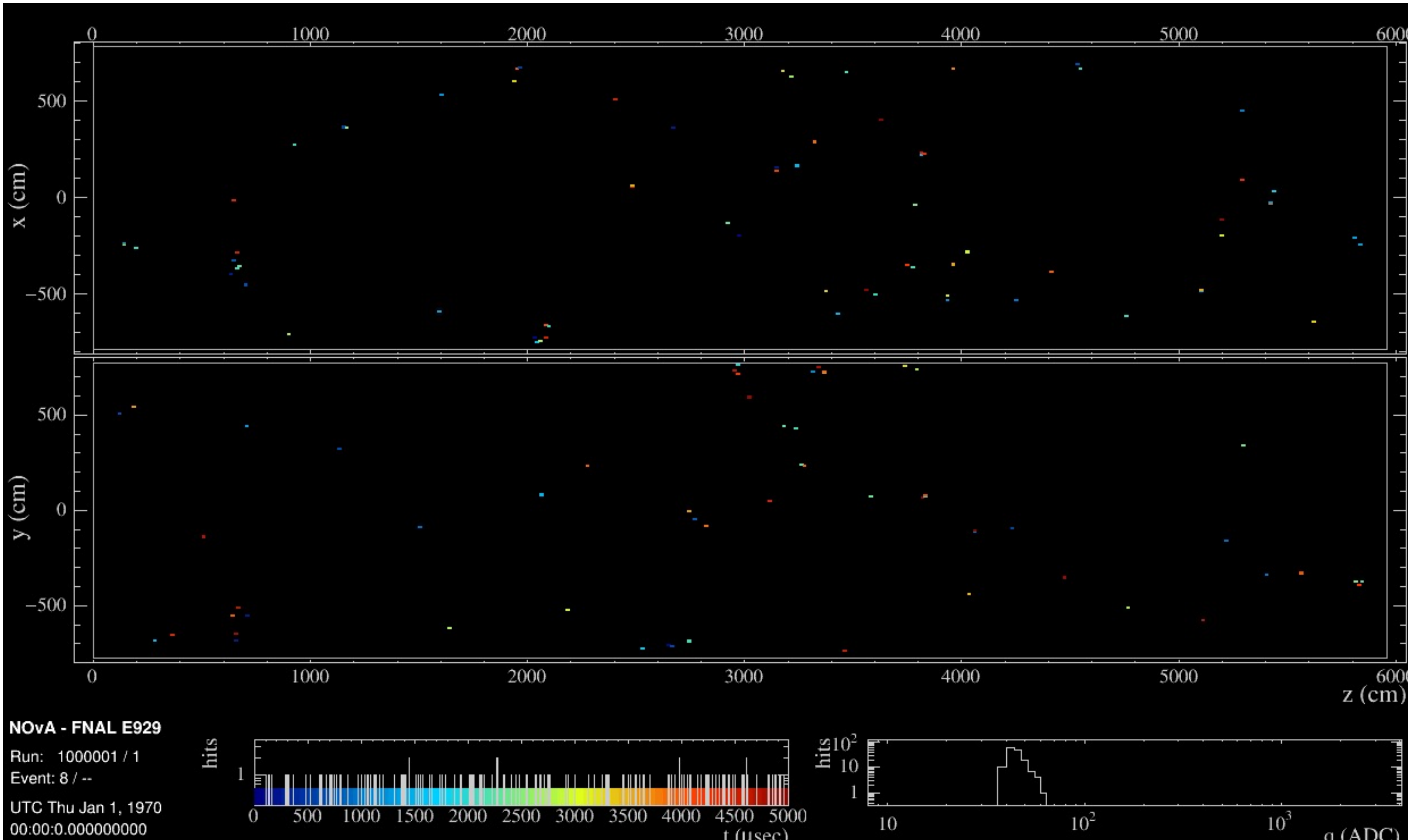


Oscillation Probability

~4000 anti-ν_e in NOvA

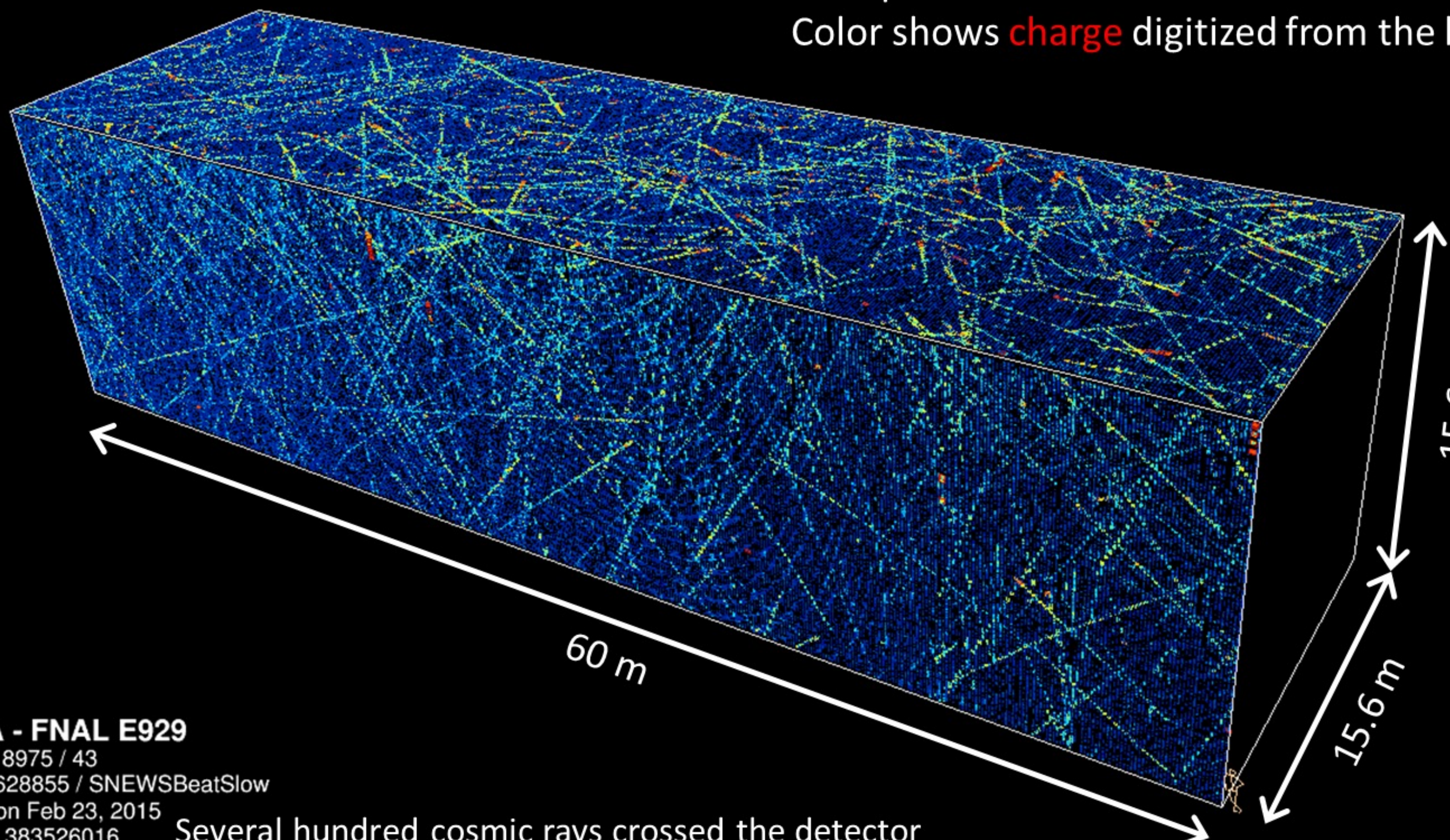


A 5ms block of only SN ν data



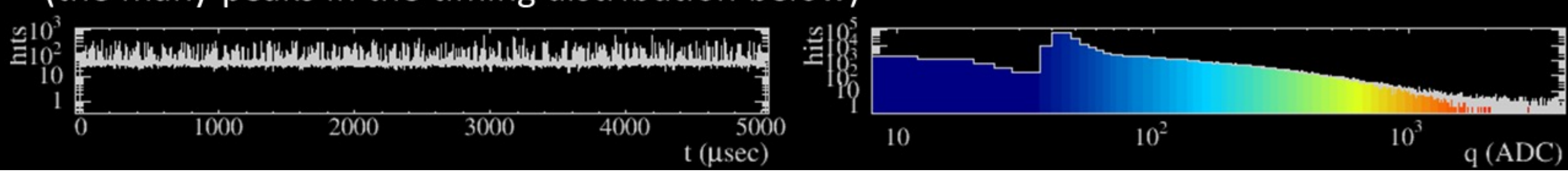
Data from SNEWS test trigger
5ms of a seconds-long trigger

5ms of data at the NOνA Far Detector
Each pixel is one hit cell
Color shows charge digitized from the light



NOνA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016

Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)



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: $\nu_e + {}^{16}O \rightarrow {}^{16}F + e^-$; $\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$

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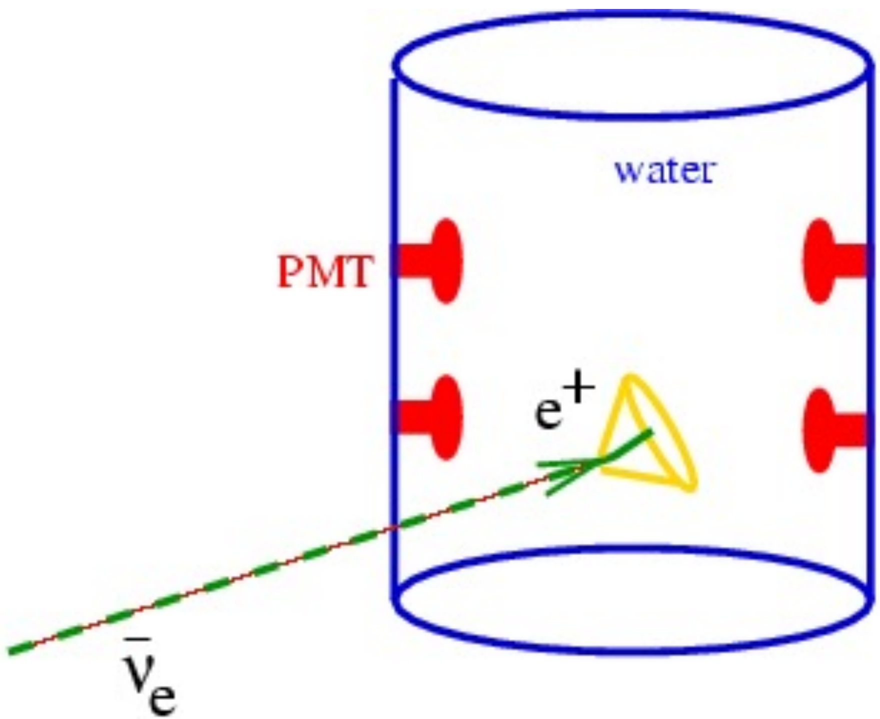


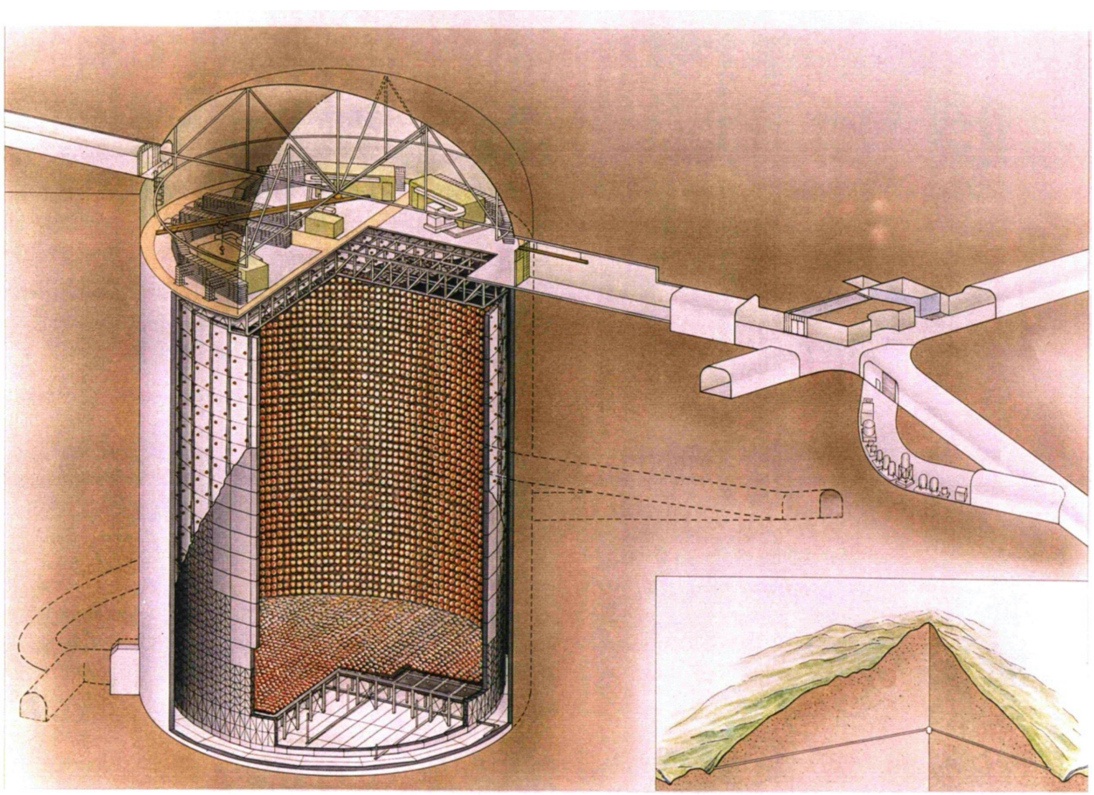
Pointing!

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

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

Imaging Water Cherenkov

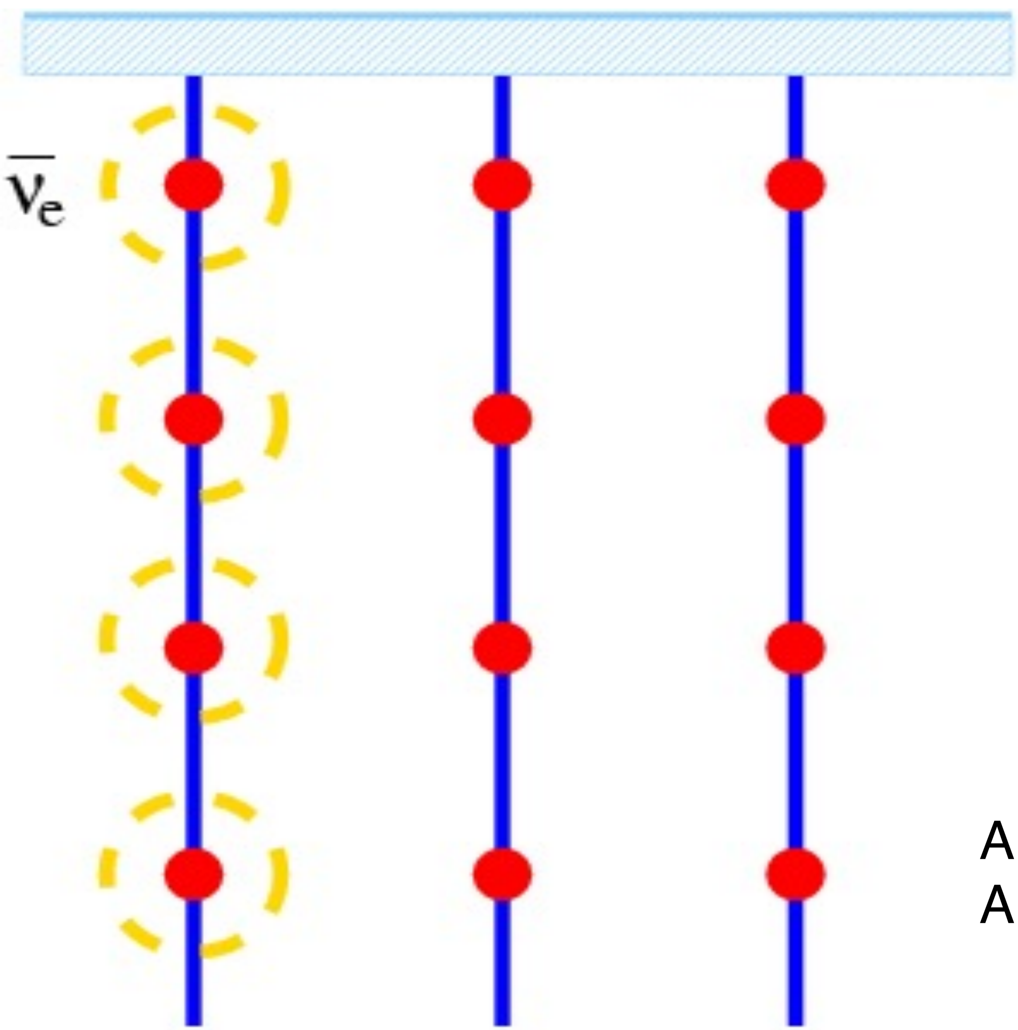
Super-Kamiokande (Japan) 50kton



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO NIKKEN SEKKEI

- 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

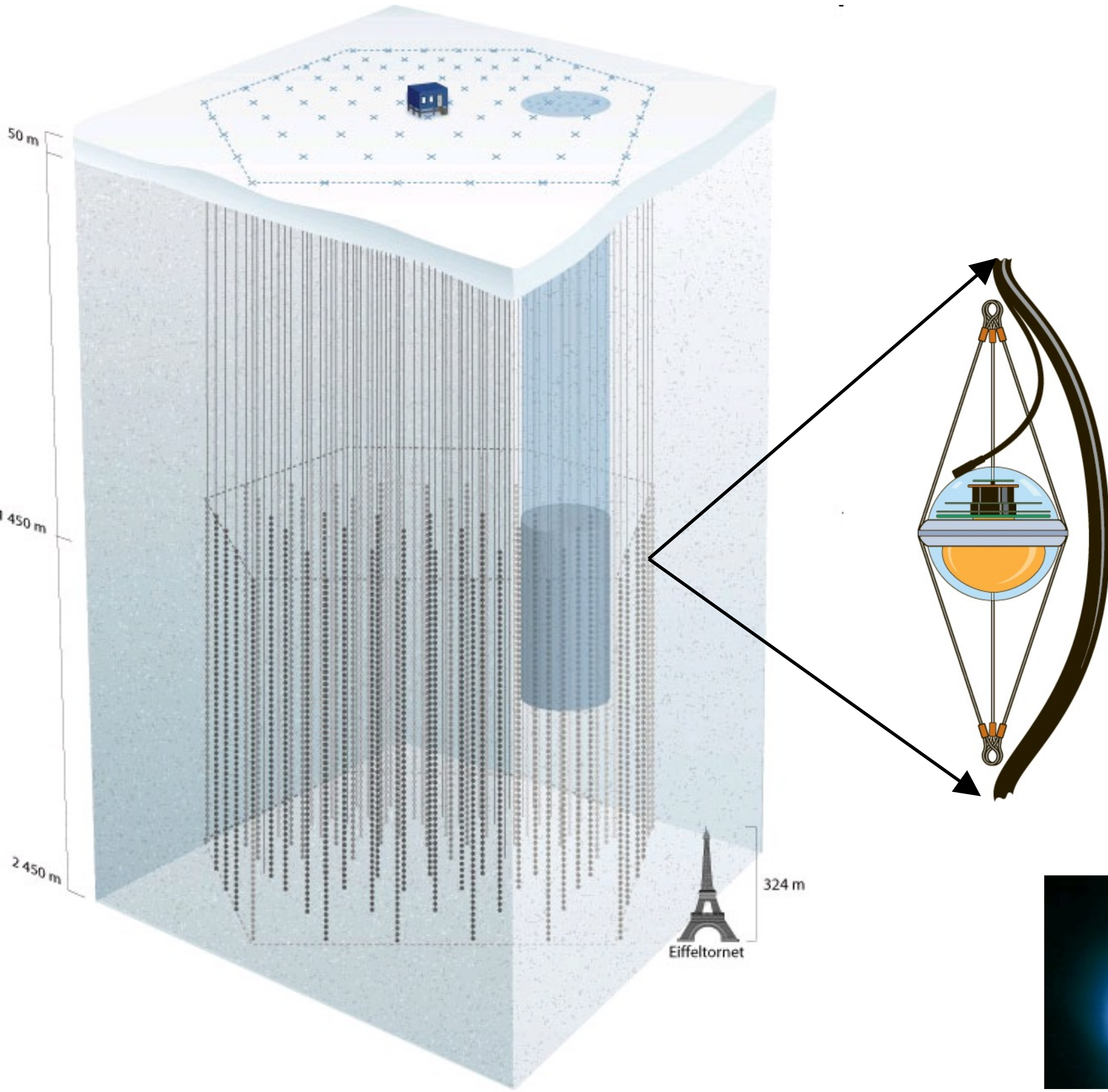
Long String Water Cherenkov



- 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

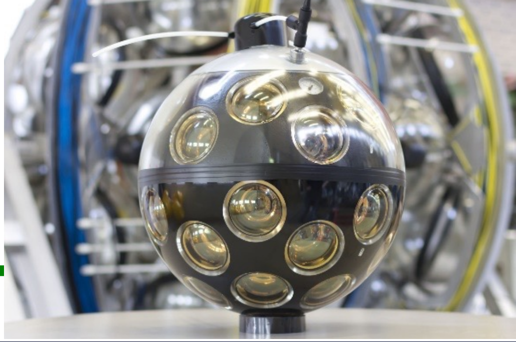
AMANDA, Ice Cube, Baikal, Antares, KM3Net

Long String Ice Cherenkov

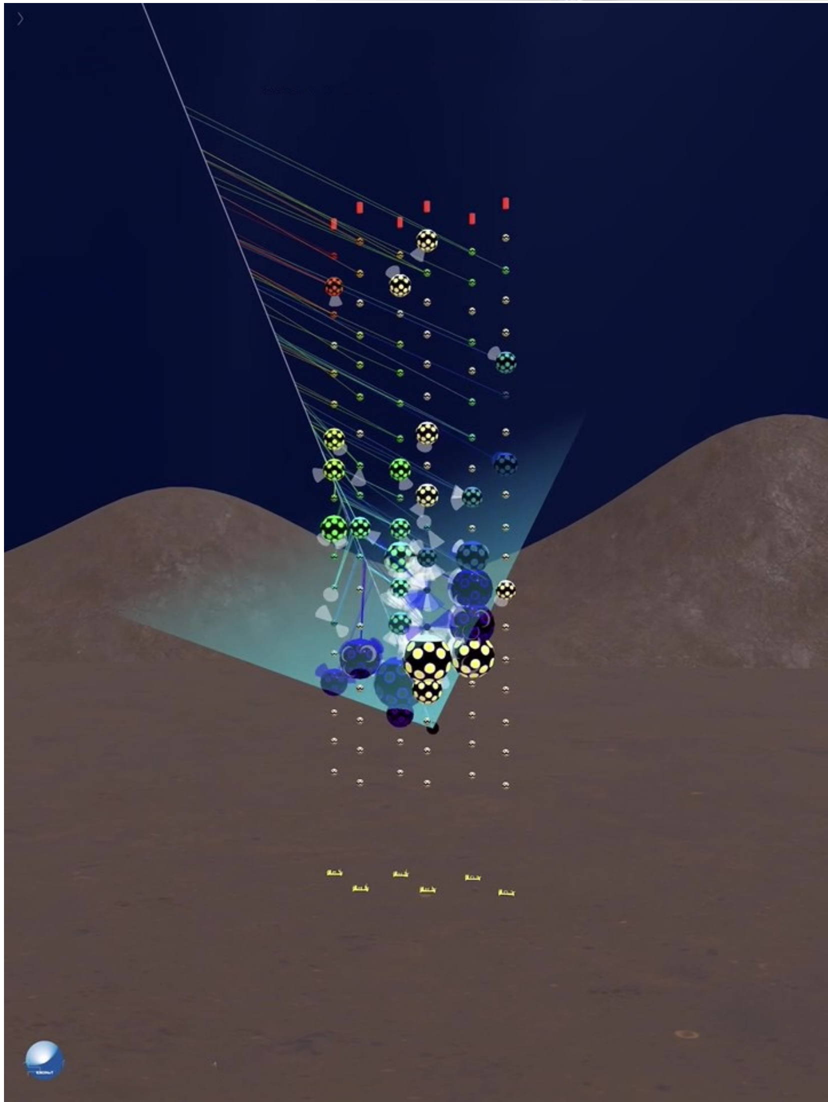


- Ice-based expts. have low background rate
  - Sea based have ^{40}K, squid, etc: harder, but KM3net can do it!
- 16σ S/N @8.5kpc (IceCube)
  - But little ν by ν info such as energy
- AMANDA:
  - Special SN trigger was operational till experiment was retired

KM3NeT

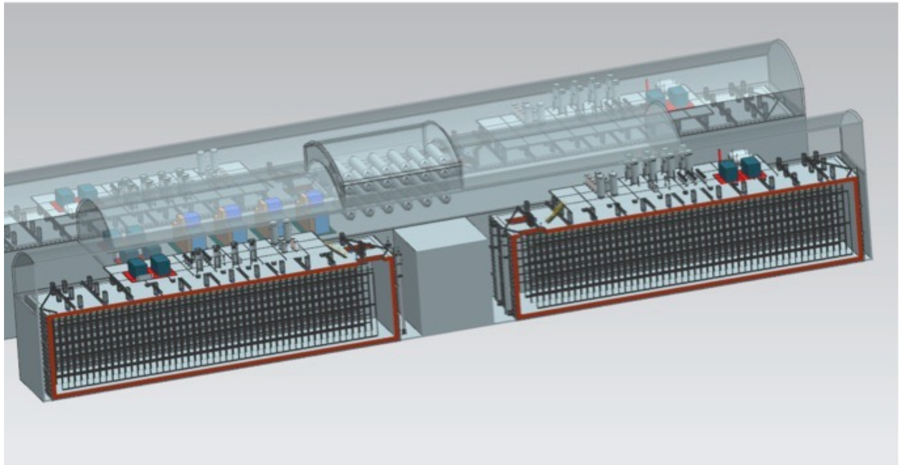


- Strings of DOMs deployed at two deep sites in the Mediterranean
  - Background reduced by using coincidences between individual PMTs in a DOM
  - SN-ν make experiment-wide rise in localized light, will be sensitive to whole galaxy, ~ms time of SN start



Nobel Liquids

- 4 staged10 kt LArTPC modules at Homestake



Start with 2 10kt Single-phase modules, one horizontal drift (ala ICARUS), one new vertical drift design

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

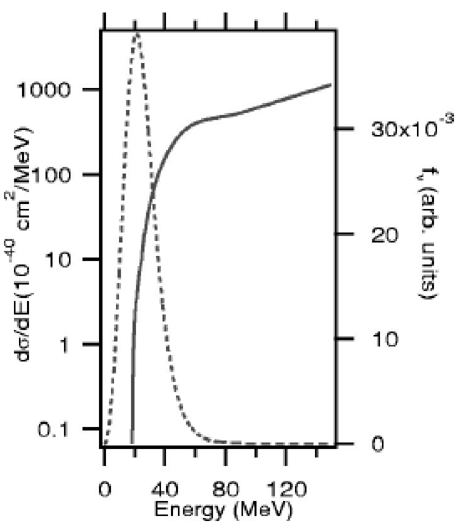
- … also: Dark Matter detectors are now so huge they can see SNν, coherent scattering amplifies x-sec
  - ~10 events over no background for Xenon1T

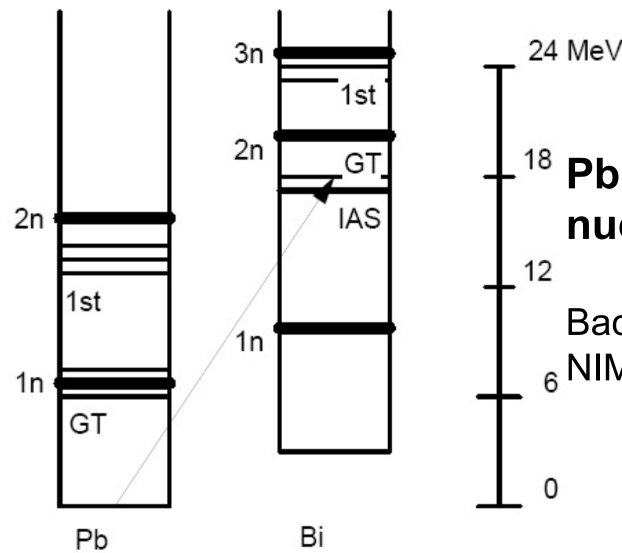
SNe ν_e and Lead

- 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)

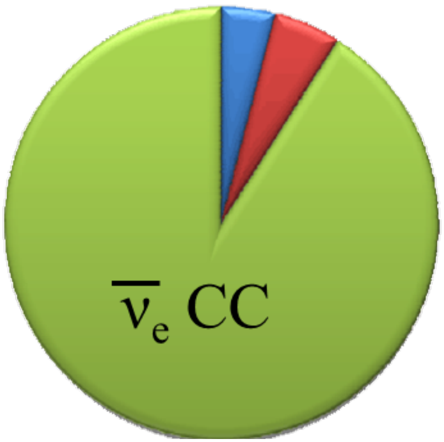




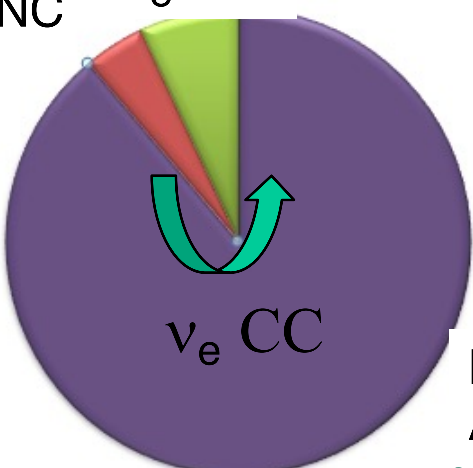
Pb & Bi nuclear levels

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

Flavor Sensitivities

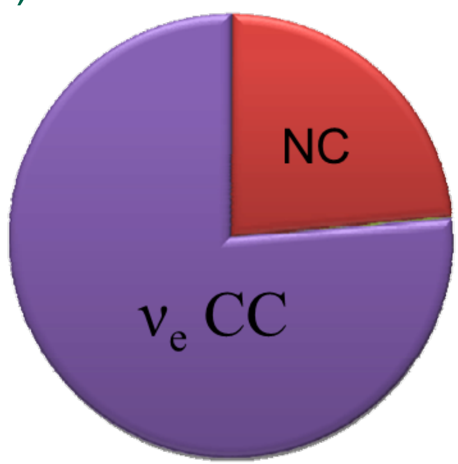


Water Cherenkov (w/o Gd)



Liquid Argon

Low thresholds see NC coherent scattering



Lead

CC:

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

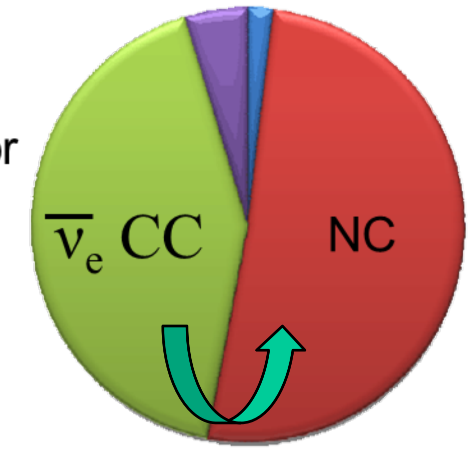
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$$

NC:

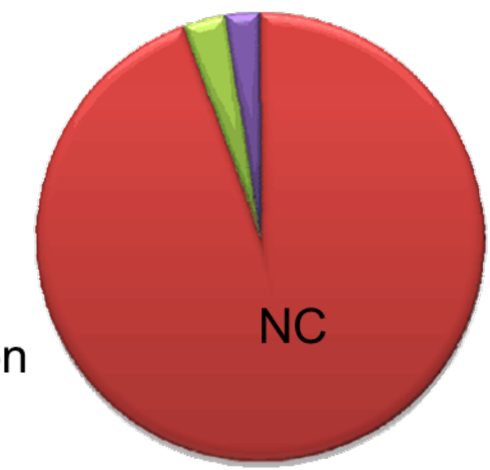
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$$

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

Liquid Scintillator

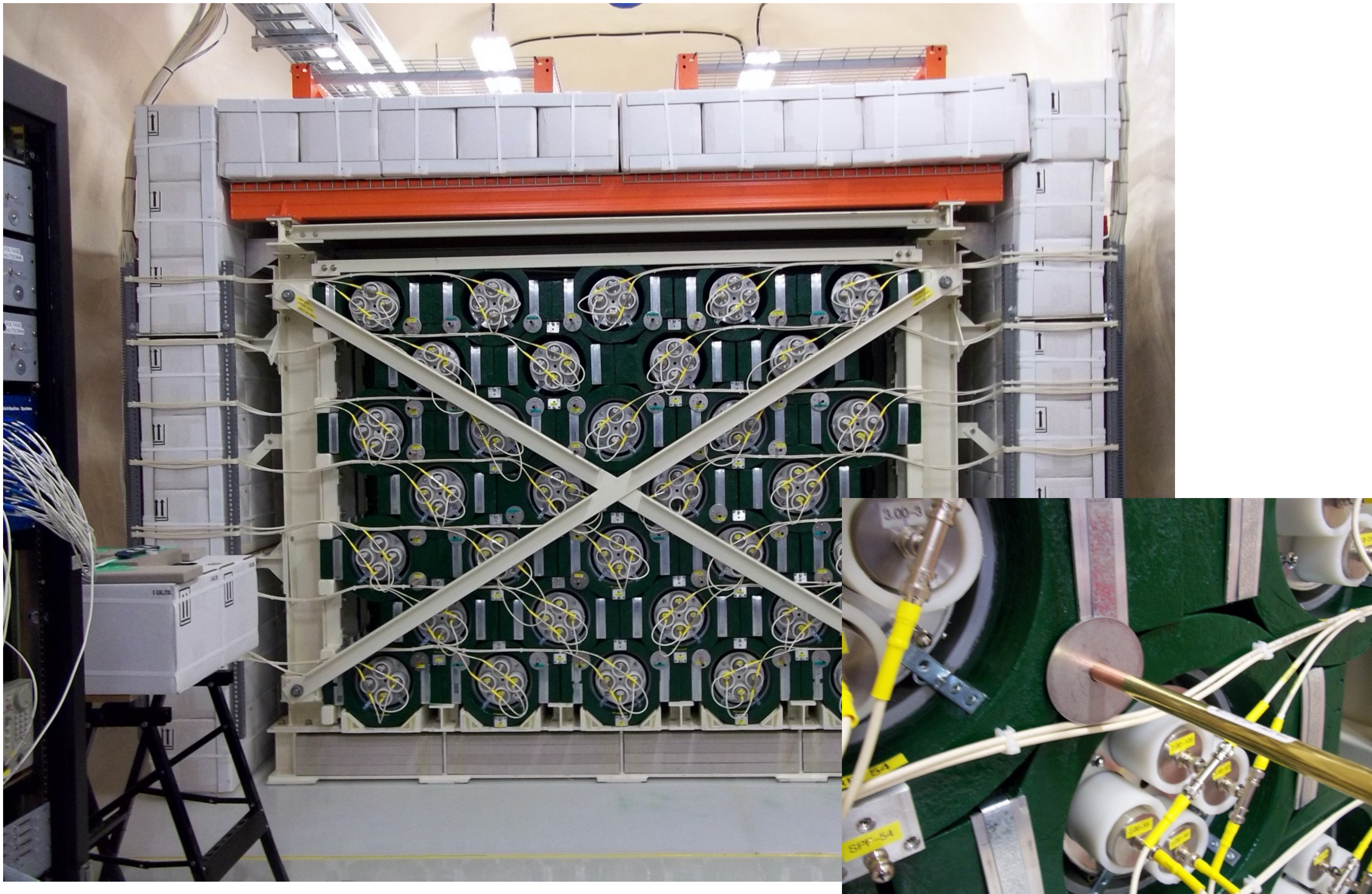


Strong threshold dependence



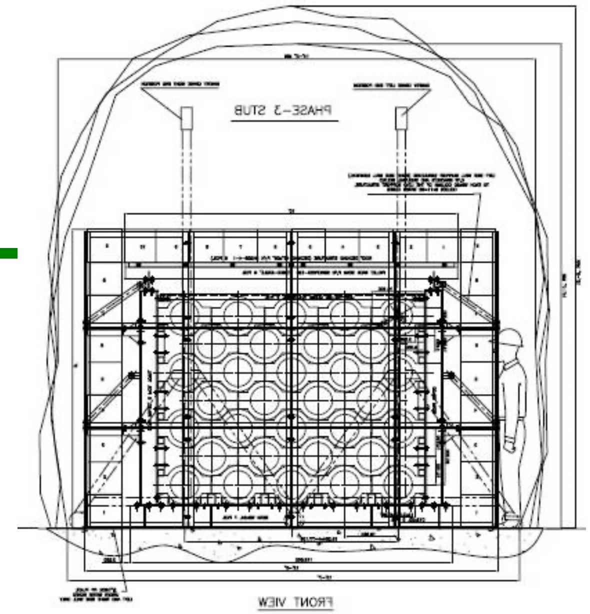
Iron

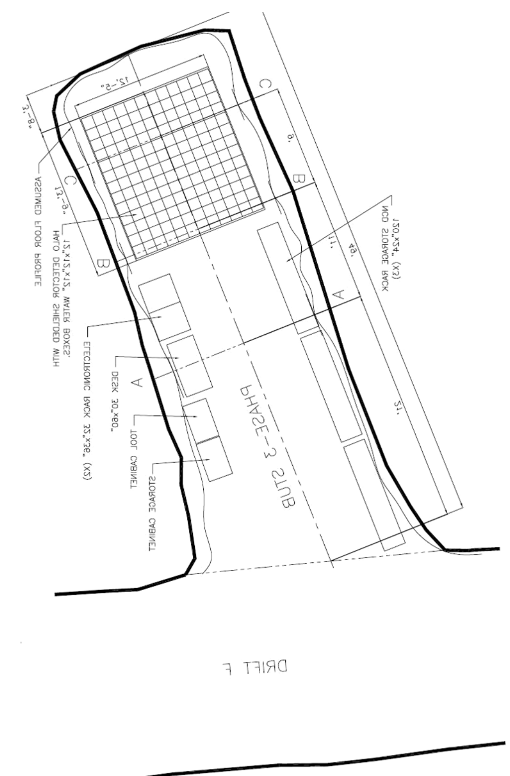
HALO

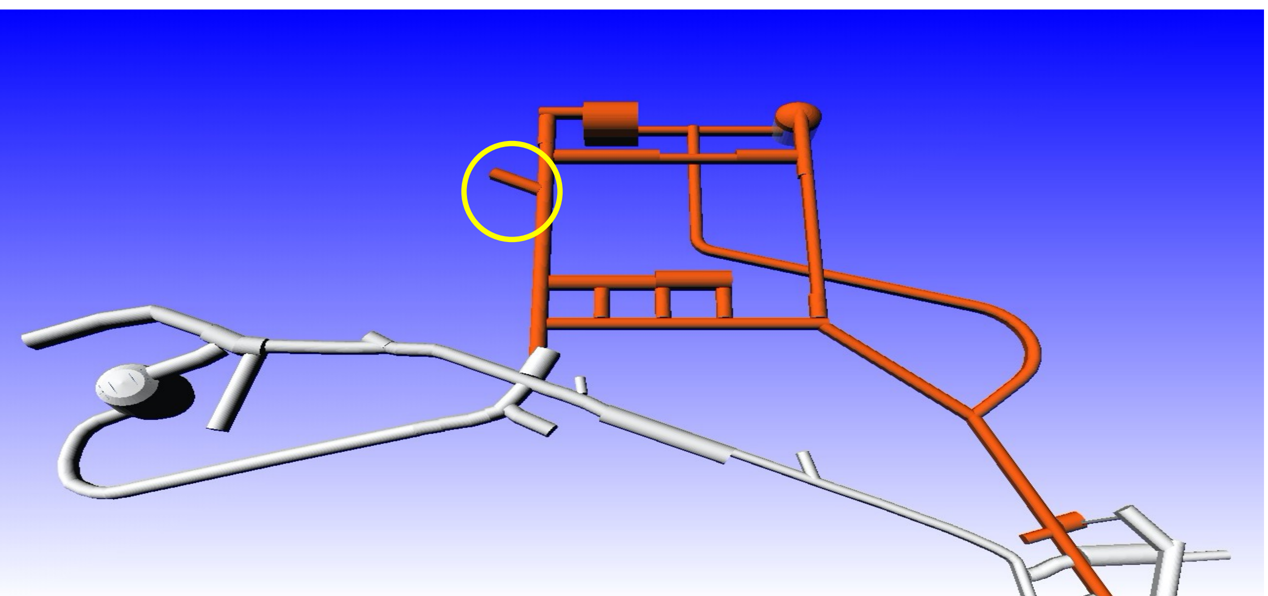


HALO

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







Low background

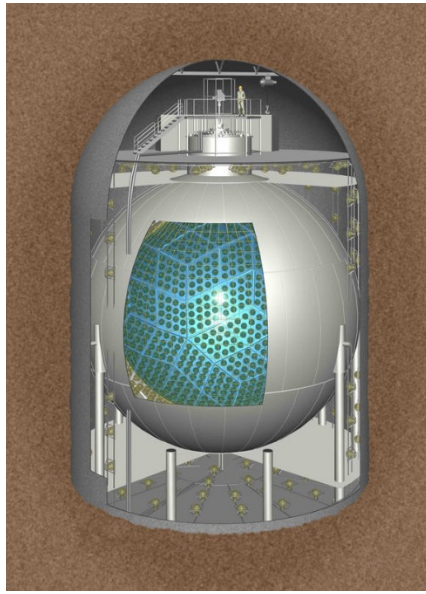
- With given signal, trigger on 6 neutrons in 2 seconds provides sensitivity to a SN @20kpc
- 150 mHz total BG rate triggers this ~monthly
  - Target “false” rate for SNEWS inclusion
  - Now 15 mHz after shielding completion!
    - That’s ~1 neutron/minute
  - Graphite would add factor of 2 more reduction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

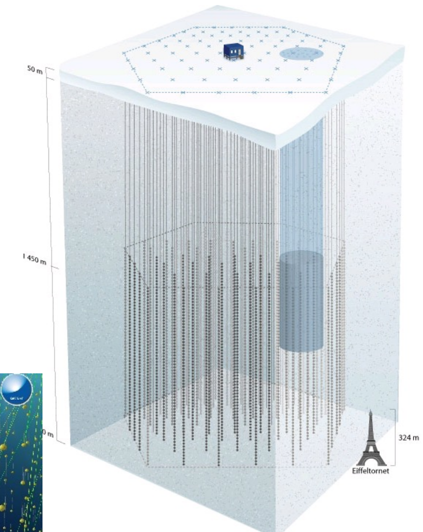
Why a Network?

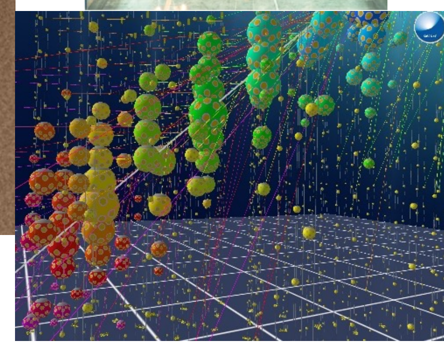
- SNEWS
  - Supernova Early Warning System
- Any single experiment has many sources of noise and few SNe
  - Flashing PMTs, light leaks, Electronic noise, Spallation, Coincident radioactivity
- Most can be eliminated by human examination
  - Takes about an hour: same as the headstart neutrinos have over photons
  - No experiment would want to make an automated SN announcement alone
- None will simultaneously occur in some other experiment
  - But neutrinos from a real SN will

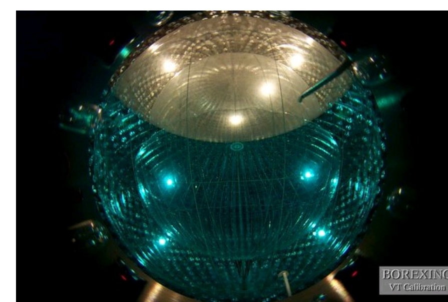
The Experiments

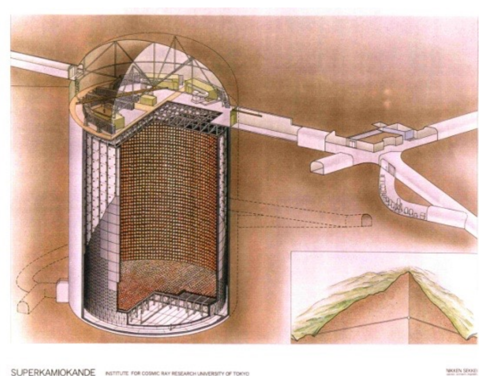
- Currently:
  - Super-K
  - LVD
  - IceCube
  - Borexino
  - KM3NeT
  - Kamland
  - HALO
- Alumni:
  - MACRO, SNO, AMANDA, Daya Bay
- In testing:
  - NOvA, SNO+, Baksan

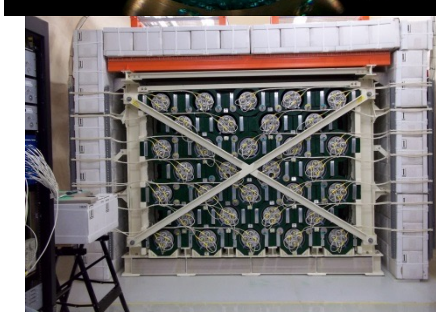




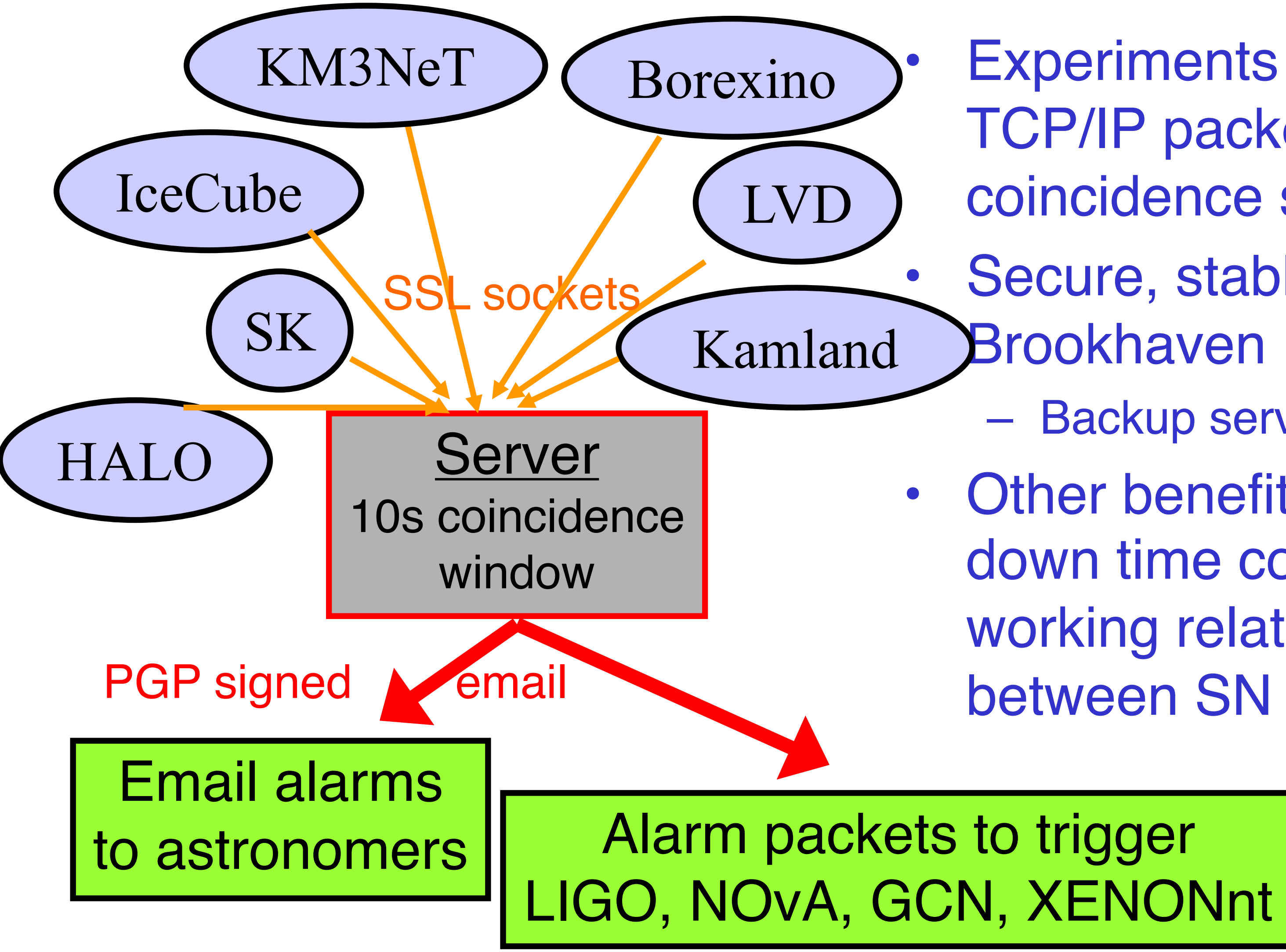








A Global Coincidence Trigger



- 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

SNEWS' Goals

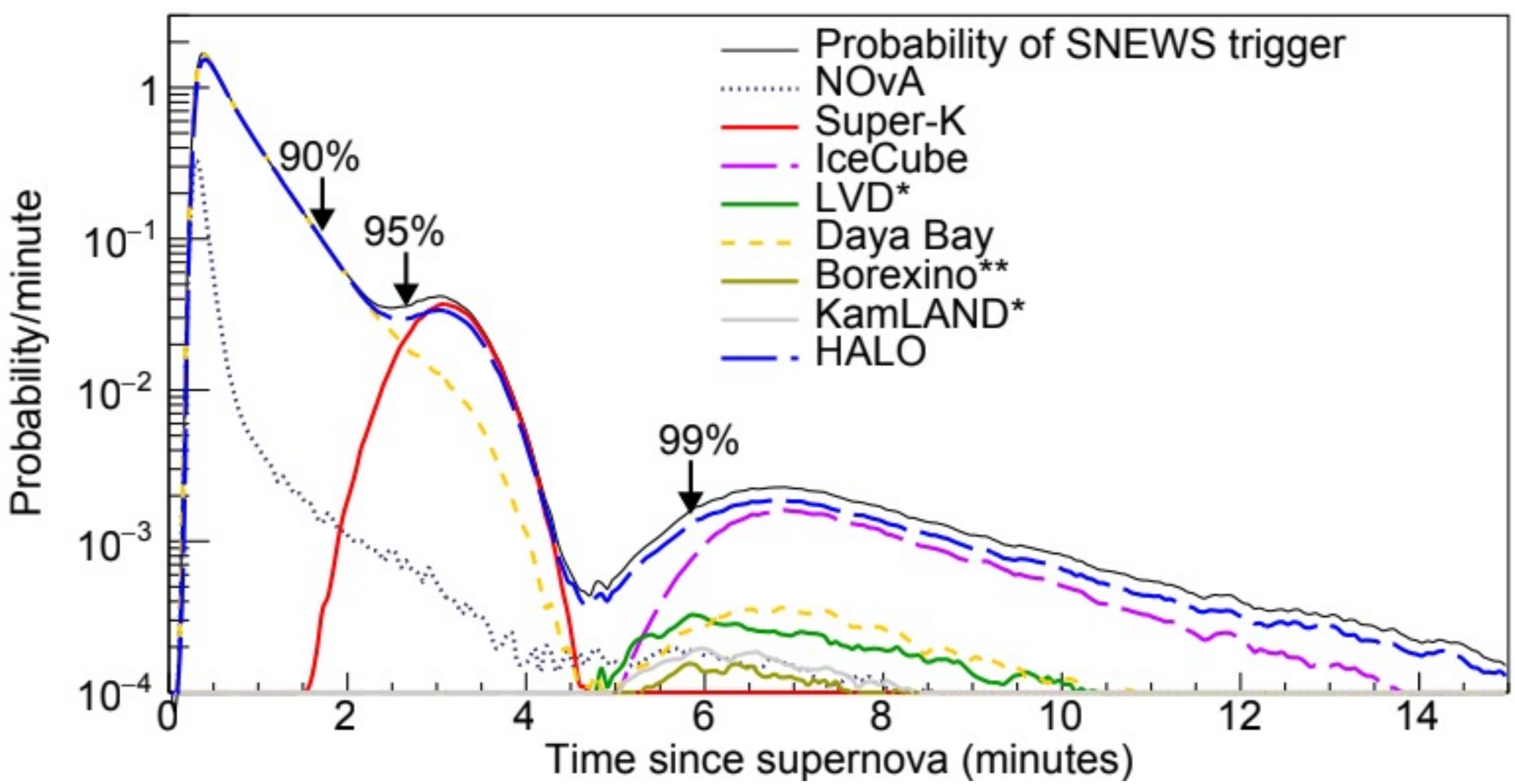
- At a workshop in Sept. 1998 at Boston U., neutrino physicists and astronomers came up with design goals: the "Three P's":
  - Prompt (<< 1 hour)
  - Positive (false alarms < 1/century)
  - Pointing
- Why?
- How well have we done in the nearly two decades we've been doing this?
  - Operational in test mode since 2001, fully operational July 1, 2005
- Should these goals change for the future?

Prompt

- Caveat: we have had no SNe in/near our galaxy since 1987: so SNEWS has never triggered
  - Something which confuses some fraction of the ~6,400 snews-alert subscribers when they subscribe but then don't get alerts!
- What do we expect? Given a two-fold coincidence, the fastest two experiments to report set the delay
  - The SNEWS machinery itself responds in ~seconds

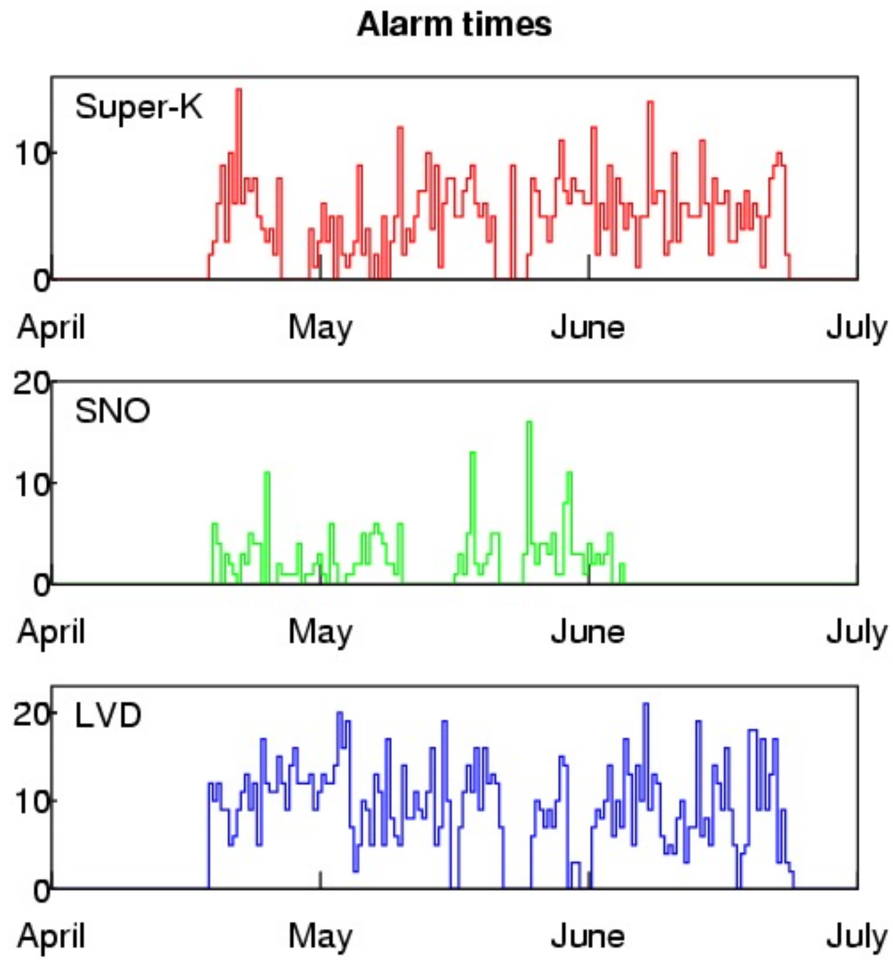
Estimated delay

- Matt Strait (UofM) took published SN trigger delays combined with sensitivities, estimated SNEWS response time
  - NOvA triggers on SNEWS but has a limited buffer time



Prompt?

- We think so, within minutes
  - Faster would be better: *eg*, unraveling the mysteries of GRBs became possible when followups could happen within seconds
- We don't know so: aside from a "high rate test" in 2001 (*low thresholds, triggered on noise*) the machinery doesn't get exercised
  - *eg*, recent LIGO GW alerts started off with more delay than desired, as kinks were worked out with practice

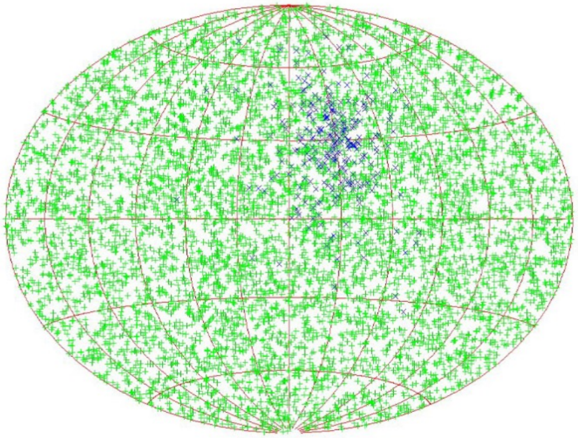


Positive?

- No false alarms in two decades! (*knock on wood…*)
- The flip side is that we haven't had the full test of the pipeline which alarms (*false or otherwise*) would provide
  - 2001 high rate test exercised front end
  - 2003 "find Vesta" test exercised the back end
- What astronomers want has changed by 180^o in those two decades:
  - 2000: "If you have even one false alarm, no one will ever believe you again"
  - Today: "Multi-messenger astronomy generates oodles of alerts, no problem!"

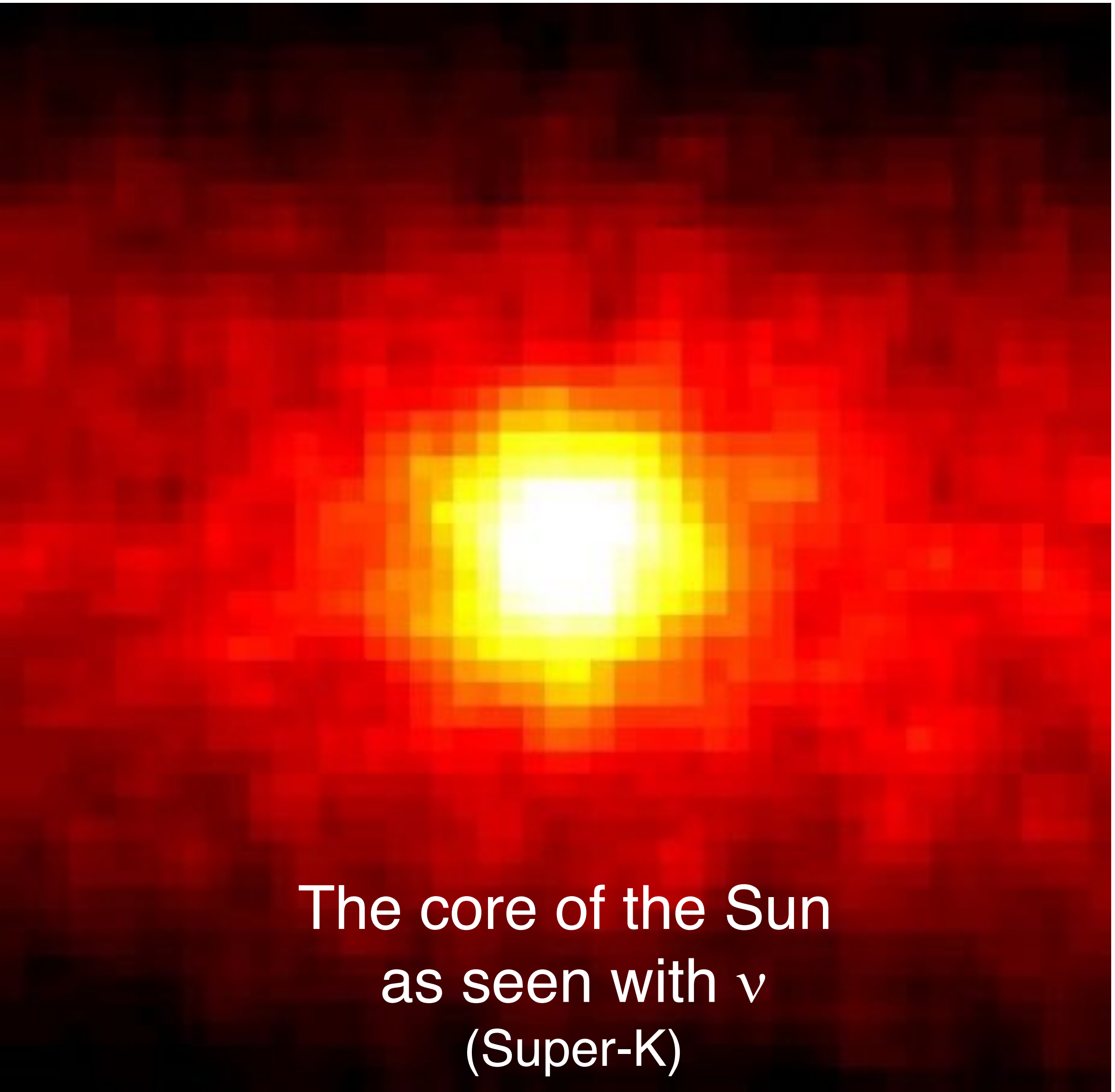
Pointing?

- An ideal alarm would be “Look at Betelgeuse, it’s about to blow!”
  - but SNEWS currently cannot generate directionality on its own



- Super-K can point back to within ~4^{o} using the sub-dominant electron elastic scatters
  - and will do this even better once Gd n captures tag IBD interactions
- Timing triangulation killed by statistics of leading edge of signal
  - Beacom&Vogel, astro-ph/9811350
  - … or, is it?

Elastic Scattering



The core of the Sun as seen with ν (Super-K)

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

Improvements for SNEWS 2.0

- What can we do to update SNEWS to provide:
  - Multiple thresholds, to constantly exercise the machinery and to provide consumers with a “choose your own threshold” alert
  - Ability of experiments to compare ν “light curves” real-time, to extract physics quickly: especially precision timing for triangulation
  - Get alerts out to the new networks, to best coordinate with modern multi-messenger networks

Old Codebase

- Originally written in the late 1990's in C, running on VMS, Solaris, MacOS
  - DAQs for MACRO and LVD, Super-K, SNO

```
/*
 * Figure out the type of system that we're running on.
 *
 * Try to determine the environment automatically from the C compiler's
 * predefined symbols.
 * The following can be determined automatically:
 * BSD VAX, Pyramid, Xenix, AT&T 3b1, AT&T 80386, Celerity and MS-DOS.
 * If this doesn't work on some new system, ifdef this out, and set it
 * by hand.
 */

#ifdef  unix            /* true for most UNIX systems, BSD and Sys5 */
                        /* but not for Xenix !! */
#define UNIX    1       /* OS type */

#ifdef  vax             /* true for BSD on a VAX */
/* also true for VAX Sys5, but we don't have to worry about that (for now) */
#define VAX     1       /* hardware */
#define BSD     1       /* OS type */
#else
#ifdef  pyr

#define PYRAMID 1       /* hardware */
```

Maintenance Nightmare

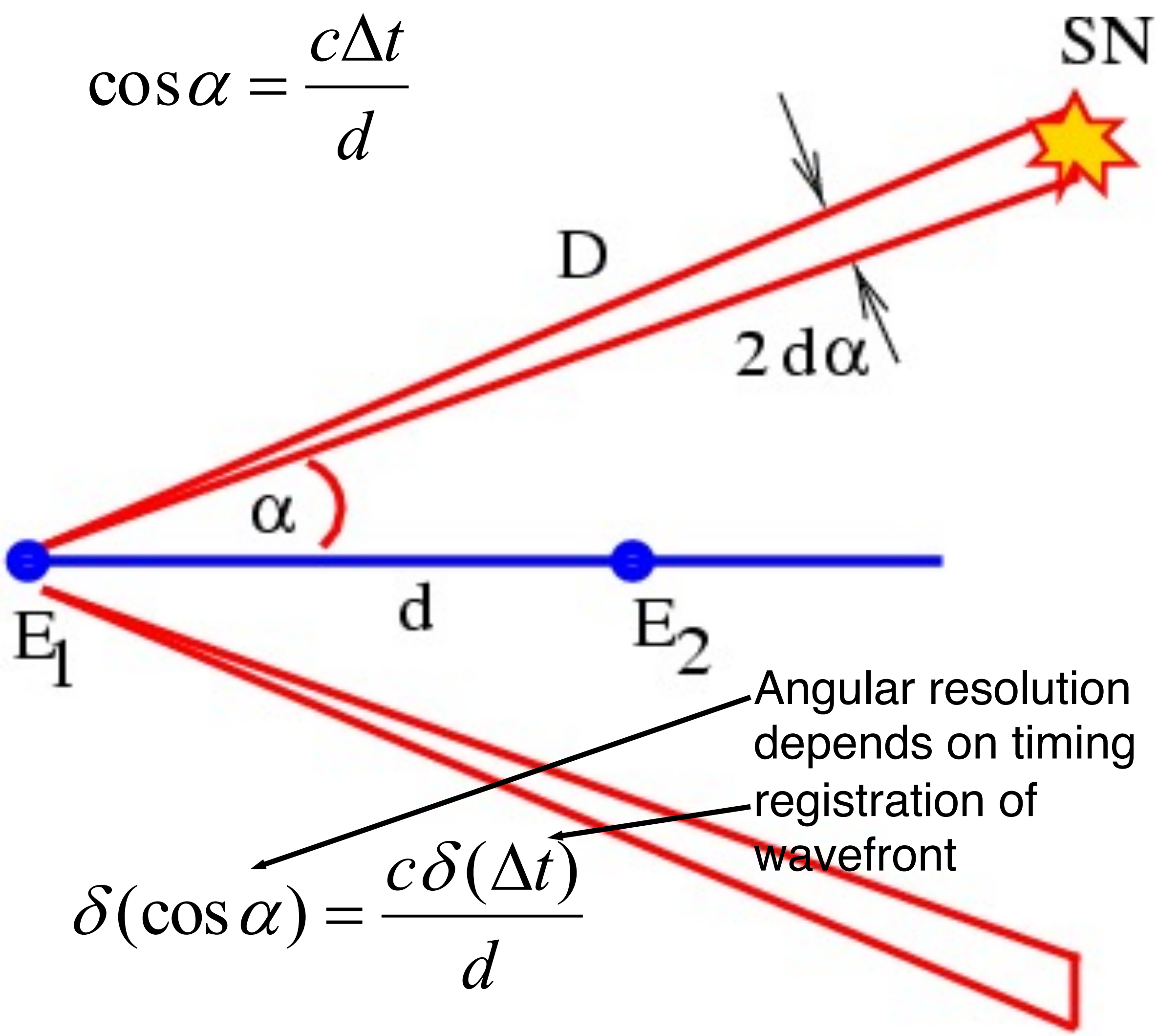
- This is getting really creaky. Adding new experiments is a serious adventure
  - Recent work from
    - Km3NET, NOvA, Baksan, SNO+
    - Daya Bay now offline, LVD, Borexino on the clock
  - OpenSSL library 0.9.8zh used from 2015, has been depreciated since 2017
  - 32 bit systems are no longer cutting edge, matching network bits to local bits is entertaining
  - Multiple arrays indexed by experiment, slightly differently

New Physics for SNEWS 2.0

- Pre-supernova (*Si-burning*) ν from nearby stars:
  - Kamland does this now on its own
  - SNO+ and JUNO will soon be able to as well, as can Super-K with Gd loading
  - This is an area where combining low statistics could let these experiments expand their range further into the galaxy
- Pointing:
  - DUNE and Hyper-K will have per-event directionality
  - SK will improve theirs with Gd tagging
  - Maybe SNEWS can contribute triangulation
  - A new opportunity to provide directionality combination for those experiments?

Triangulation

$$\cos\alpha = \frac{c\Delta t}{d}$$



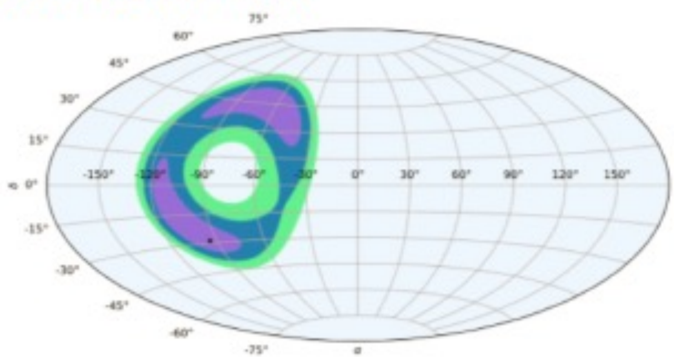
$$\delta(\cos\alpha) = \frac{c\delta(\Delta t)}{d}$$

- 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
- With modern detectors, and fitting the whole ν light curve rather than just the leading edge, this might now be possible

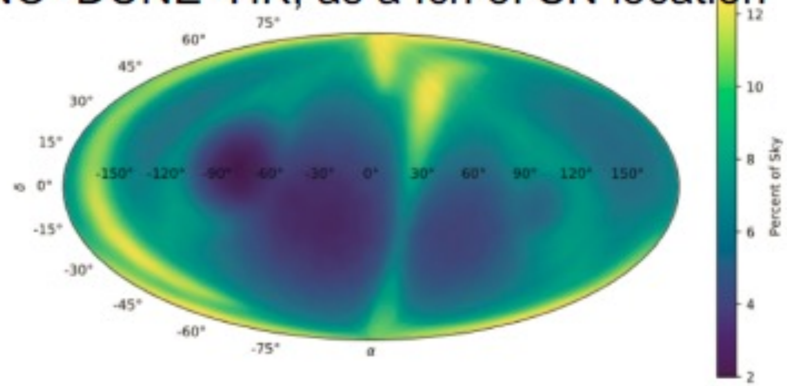
Potential Error Boxes

- Combinations of near-future detectors trying to localize a 10kpc SN

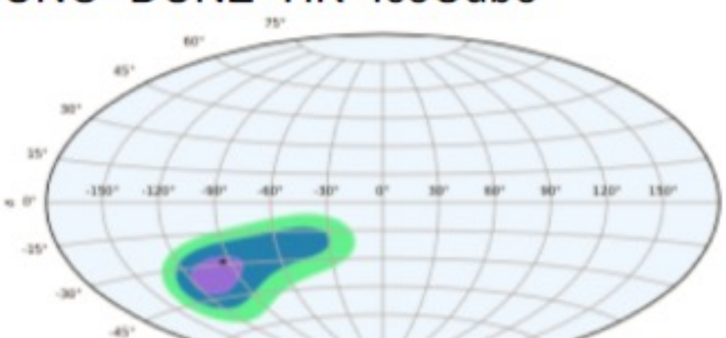
JUNO+DUNE+HK



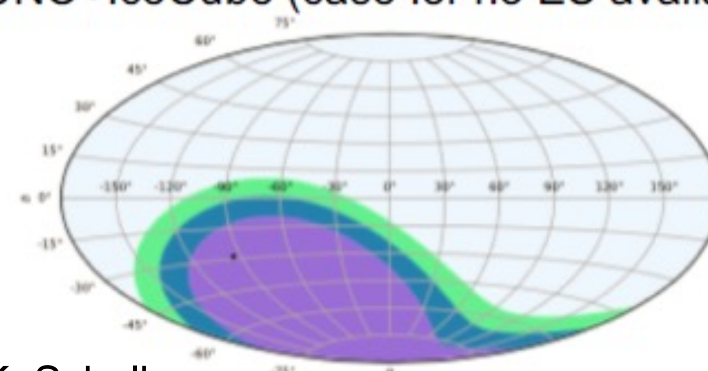
JUNO+DUNE+HK, as a fcn of SN location



JUNO+DUNE+HK+IceCube



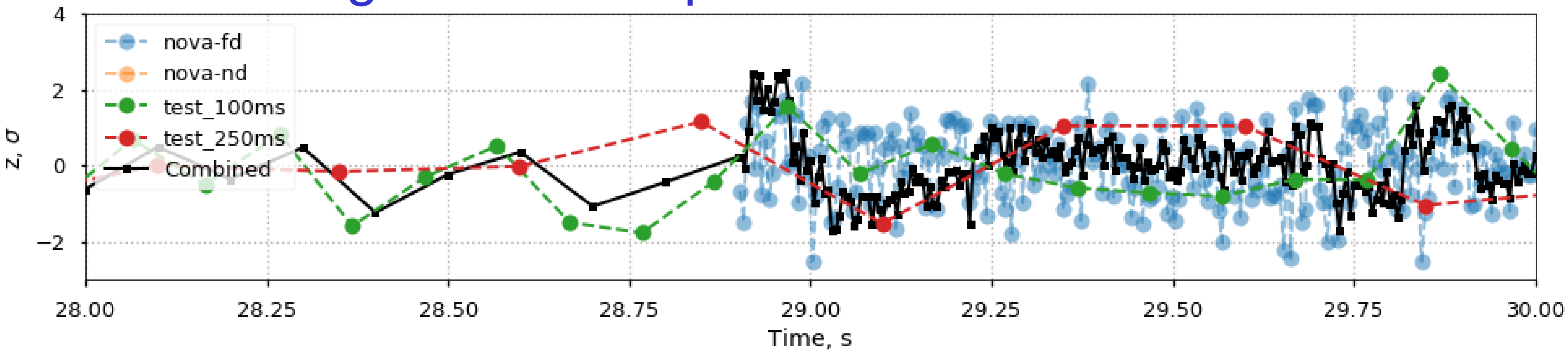
JUNO+IceCube (case for no ES available)



Work by N.Linzer & K. Scholberg

Significance combining

- An example of a new tool: instead of just taking alarm coincidences, take current “chance of SN right now” numbers from the experiments in real time
  - NOvA is already working on this to combine Near and Far detector signals to increase sensitivity
- Sensitivity gain is of limited use for SN bursts (galaxy is too small, Andromeda too far away), but of great use for pre-SN neutrinos



Tools needed

- The simple coincidence riding on the network protocol stolen from the first "e-sports" game ever (*netrek, early 1990's*) can't support these new goals (*and you wouldn't want to maintain it anyway*)
- What statistics are the best to compare experiments with extremely different signal rates and noise rates?
- What machinery is needed to reliably move that data from experiment to a SNEWS server?

SCIMMA

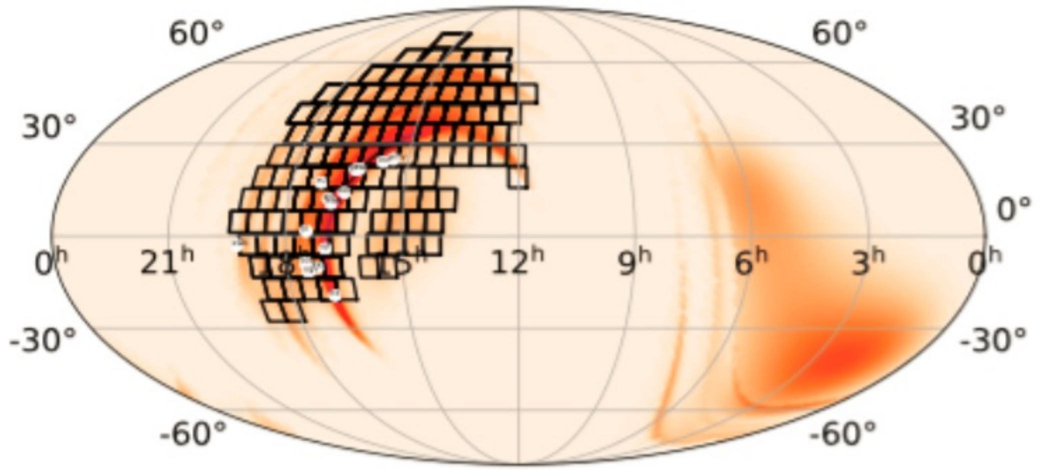
- The Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics project is helping us replace our netrek-era sockets with something modern, maintainable, and scalable
- A joint SCIMMA/SNEWS team replicated the existing SNEWS architecture using the "Hopskotch" framework this summer
  - We're now working on adding the new SNEWS2.0 functionality

Using the Alert

- The resulting coincidence alert goes to:
  - Email list of interested people
    - Amateur network of many skilled eyeballs!
    - Once someone optically ID's the new SN, we all know and can zoom in
    - Sign up for alert email, http://snews.bnl.gov
  - VOEvent network/GCN
    - Since photosphere breakout should really light up the high energy photon sky
  - LIGO, NOvA, MicroBoone, Xenon1t
- What cool stuff with a once-in-a-lifetime nearby supernova would <u>you</u> 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

Transient Hunting

- An example: Zwicky Transient Facility covers thousands of square degrees quickly in the IR (ideal for seeing past dust)
- The GROWTH network spans the globe (and thus the sky) with many instruments



Left: followups to S190425z (2nd potential NS-NS merger) by ZTF. The initial localization was 10,000 deg^2. (Coughlin et al. 2019, GCN 24283). ZTF is part of the GROWTH network (right), handing off observations as the earth rotates. Figs courtesy of Mansi Kasliwal.

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!
- 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 almost two decades now, and will continue into the future

Summary

- While one of the ~200 SNe ν wavefronts currently traversing our galaxy hasn't arrived since 2000, we've been ready with a simple coincidence trigger
- Experimental capabilities have evolved
- Real-time multi-messenger astronomy is now a thing
  - People chase transients all the time
- We're figuring out how to get the world the most SN neutrino information in the least amount of time
  - An opportunity for gaining information that together is greater than the sum of its parts

SNEWS 2.0 Whitepaper *New J.Phys.* 23 (2021) 3, 031201
https://arxiv.org/abs/2011.00035

Acknowledgements

- SNEWS2.0 development supported by NSF collaborative grant #1914447
- SNEWS only functions with the cooperation of member experiments and their SN teams, plus Brookhaven and INFN Bologna
- See http://snews.bnl.gov for more info and to sign up for the alert list
- HALO thanks go to SNOLAB, NSERC, U Washington
  - More HALO on the web at http://www.snolab.ca/halo/