# Supernova Neutrino Detection

Kate Scholberg, Duke University

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# OUTLINE

Supernova neutrinos

What can we learn from supernova neutrinos?

What is needed in a SN neutrino detector?

Detector technologies, by interaction type:

- Inverse beta decay
- Other charged-current reactions
- Elastic scattering
- Neutral current reactions

Beyond the Milky Way

Summary

# SUPERNOVA NEUTRINOS

When a star's core collapses, ~99% of gravitational binding energy of proto-nstar goes into ν's of *all flavors*

(Energy *can* escape via ν's)

Timescale: *prompt* after core collapse, overall Δt~10's of seconds

Expected flavor-energy hierarchy

$\langle E_{\nu_e} \rangle \sim 12$ MeV

$\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV

$\langle E_{\nu_\mu, \nu_\tau, \bar{\nu}_\mu, \bar{\nu}_\tau} \rangle \sim 18$ MeV

Fewer interactions w/ proto-nstar

⇒ deeper ν-sphere

⇒ hotter ν's

# SN1987A

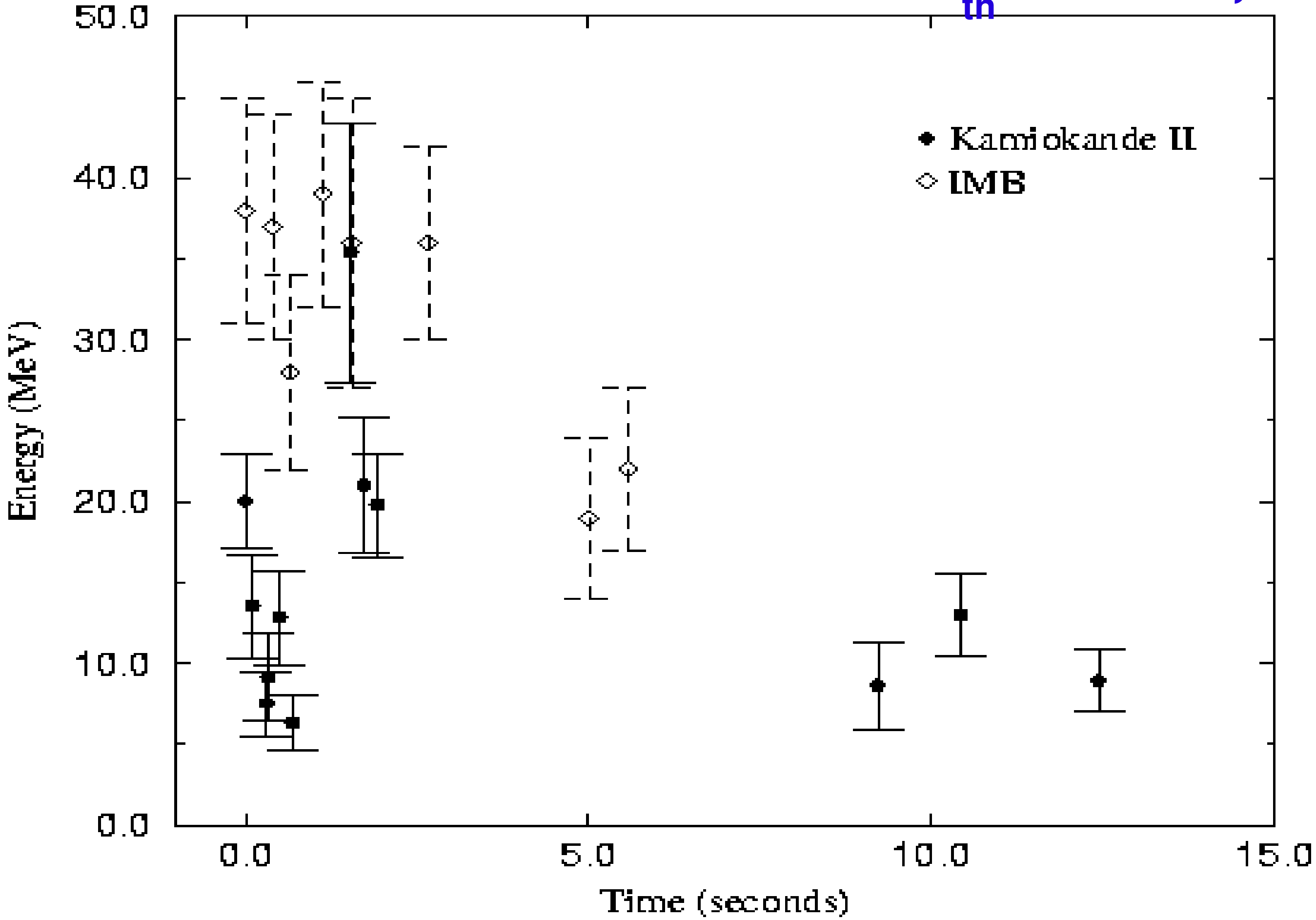
**Type II in LMC (~55 kpc)**

Water Cherenkov: IMB $E_{th}$ ~ 29 MeV, 6 kton 8 events

Kam II $E_{th}$ ~ 8.5 MeV, 2.4 kton 11 events

Liquid Scintillator: Baksan $E_{th}$ ~ 10 MeV, 130 ton 3-5 events

Mont Blanc $E_{th}$ ~ 7 MeV, 90 ton 5 events??

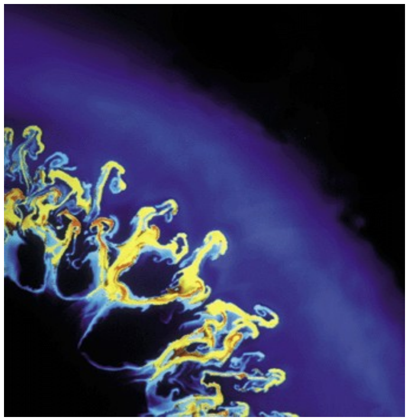



$\bar{\nu}_e$

Confirmed baseline model... but still many questions

# What Can We Learn from a High Statistics Supernova Neutrino Signal?

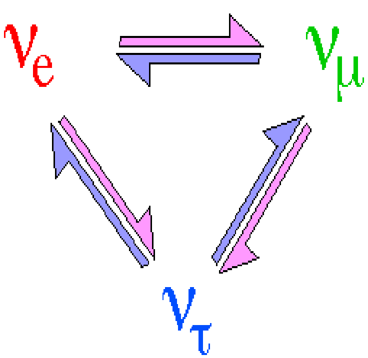
## CORE COLLAPSE PHYSICS



- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

from flavor, energy, time structure of burst

## NEUTRINO/OTHER PARTICLE PHYSICS




- $\nu$ absolute mass from time of flight delay
- $\nu$ mixing from spectra: flavor conversion in SN/Earth
  *(' $\theta_{13}$ the lucky and patient way' )*
- other $\nu$ properties: sterile $\nu$'s, magnetic moment,...
- axions, extra dimensions, FCNC, ...

# ASTRONOMY FROM EARLY ALERT

~*hours of warning* before visible SN, + some ν pointing

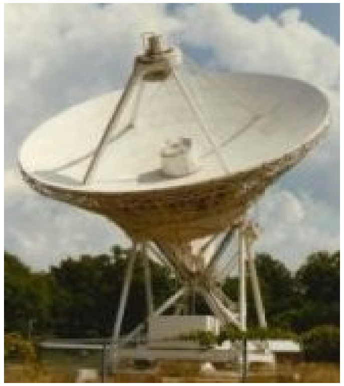
- progenitor and environment info
- unknown early effects?

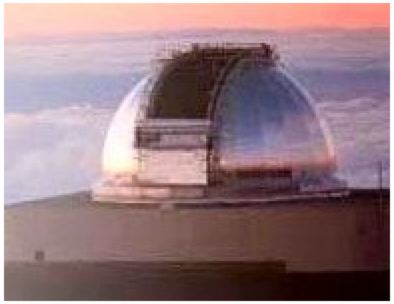
**SuperNova Early Warning System:**

Network of existing SN sensitive detectors, alert if coincidence within 10 secs (SK, SNO, LVD, Amanda/IceCube)


**Combining information with other detectors sensitive to SNae is important! (alert & later)**

gravitational waves





multiwavelength astronomy

# What do we want in a SN $\nu$ detector?

- Need ~ 1kton for ~ few 100 interactions for burst at the Galactic center (8.5 kpc away)

- Must have bg rate << rate in ~10 sec burst (typically easy for underground detectors, even thinkable at the surface)

**Also want:**

- Timing
- Energy resolution
- Pointing
- Flavor sensitivity

Require NC sensitivity for $\nu_{\mu,\tau}$, since SN $\nu$ energies below CC threshold

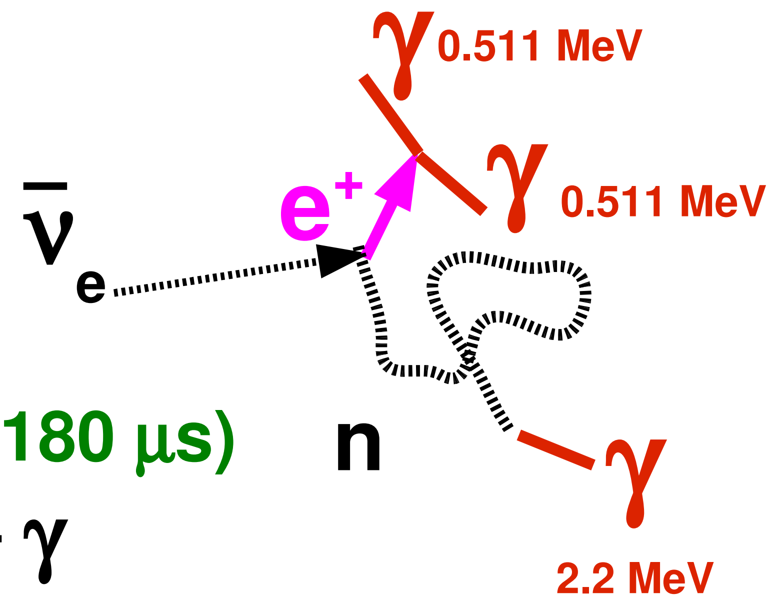
**Sensitivity to different flavors *and ability to tag interactions* is key!**

$\nu_e$ vs $\bar{\nu}_e$ vs $\nu_x$

# Good old CC inverse beta decay , the workhorse of neutrino physics, serves us well for SN neutrino detection:

**Inverse Beta Decay (CC)**

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

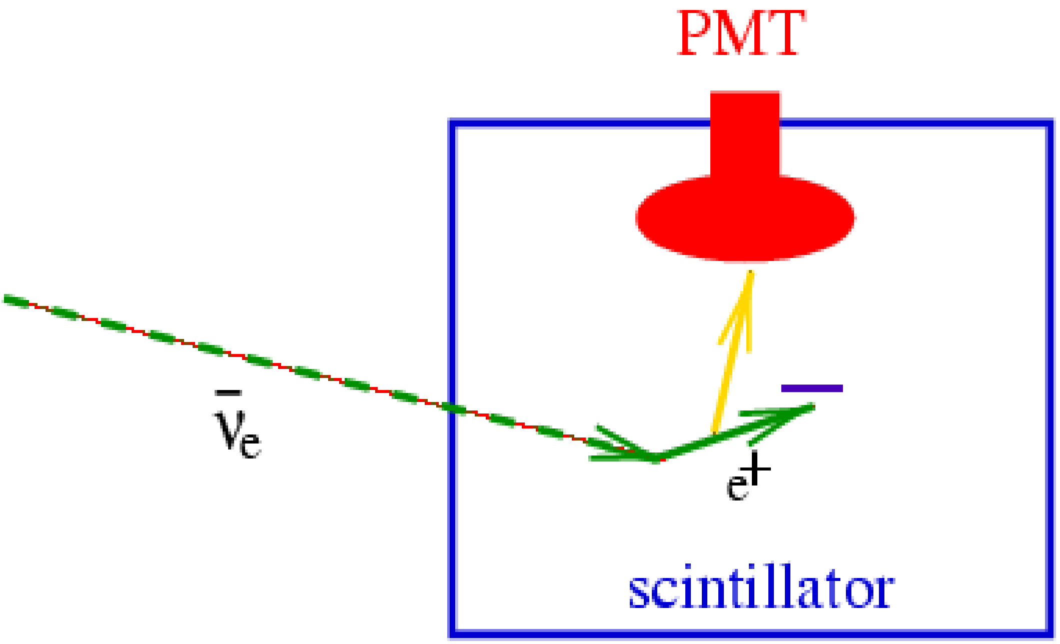



**Can often exploit delayed (~180 μs) coincidence of $n + p \rightarrow d + \gamma$ (or other neutron capture) as tag**

**(also possibly γ's from $e^+$ annihilation)**

**In any detector with lots of free protons (e.g. water, scint) this dominates by orders of magnitude**

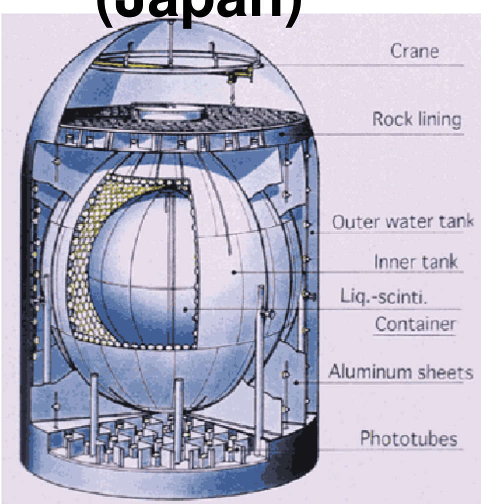
# SCINTILLATION DETECTORS



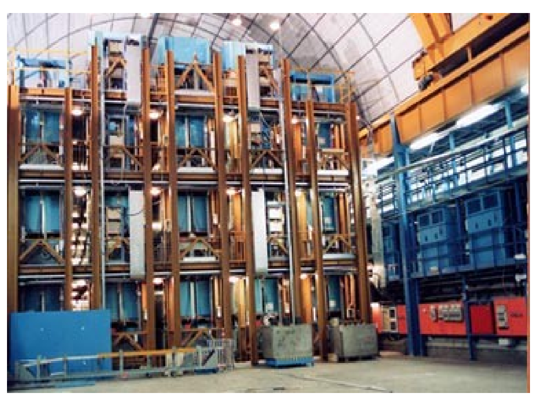

## Liquid scintillator $C_nH_{2n}$ volume surrounded by photomultipliers

- few 100 events/kton
- low threshold, good neutron tagging possible
- little pointing capability (light is isotropic)

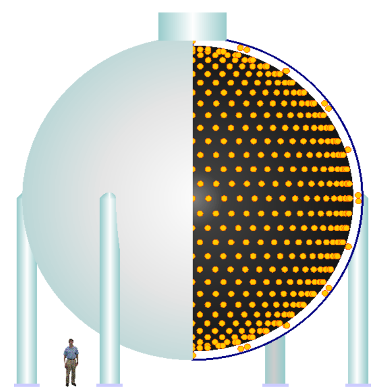
**KamLAND** (Japan)



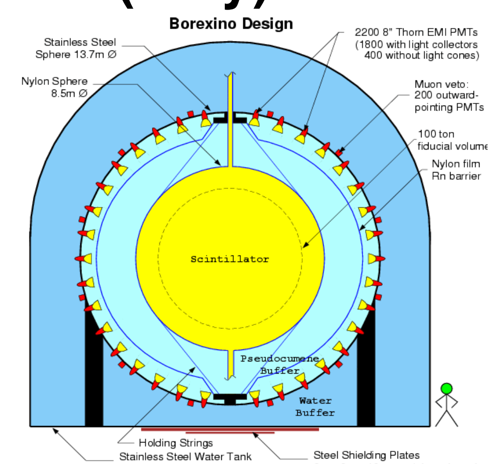

**LVD** (Italy)



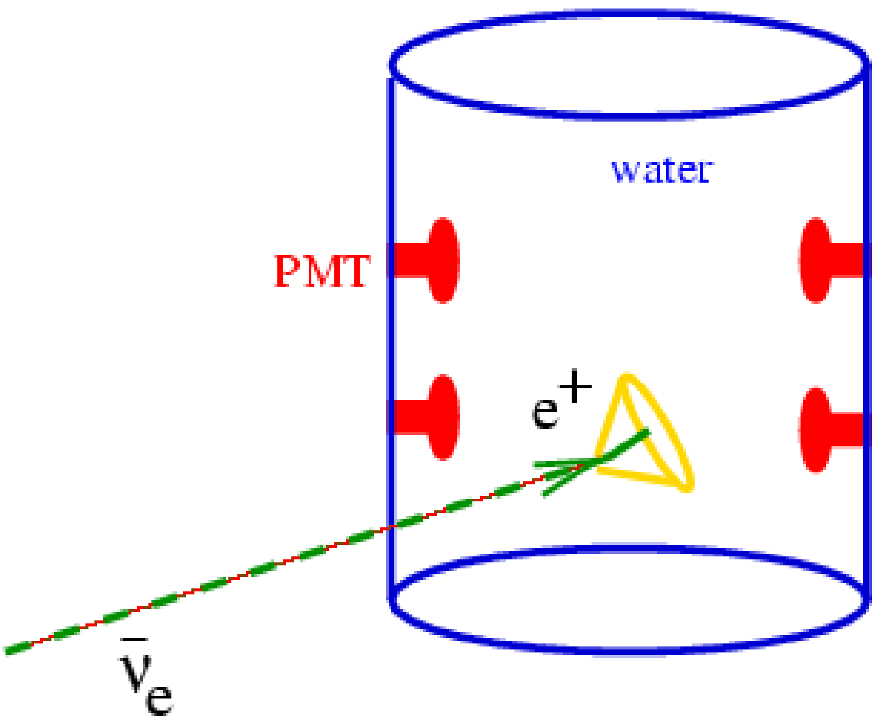
**Mini-BooNE** (USA)



**Borexino** (Italy)



# WATER CHERENKOV DETECTORS



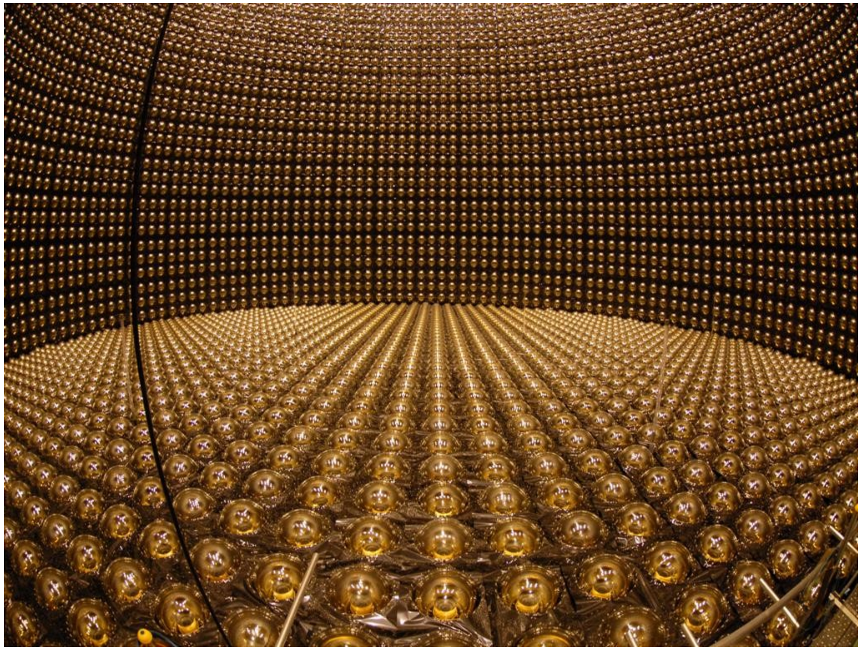

**Volume of clear water viewed by PMTs**

- few 100 events/kton

- typical energy threshold ~ several MeV makes 2.2 MeV neutron tag difficult

**Super-Kamiokande III**
**22.5 kton f.v.,**
**newly reconstructed**

**Also: 1.7 kton light water in SNO**



## Possible enhancement:

**use gadolinium to capture neutrons for tag of $\bar{\nu}_e$**

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

**Gd has a huge n capture cross-section:**
**49,000 barns, vs 0.3 b for free protons;**

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma \qquad \sum E_\gamma \sim 8 \;\; MeV$$

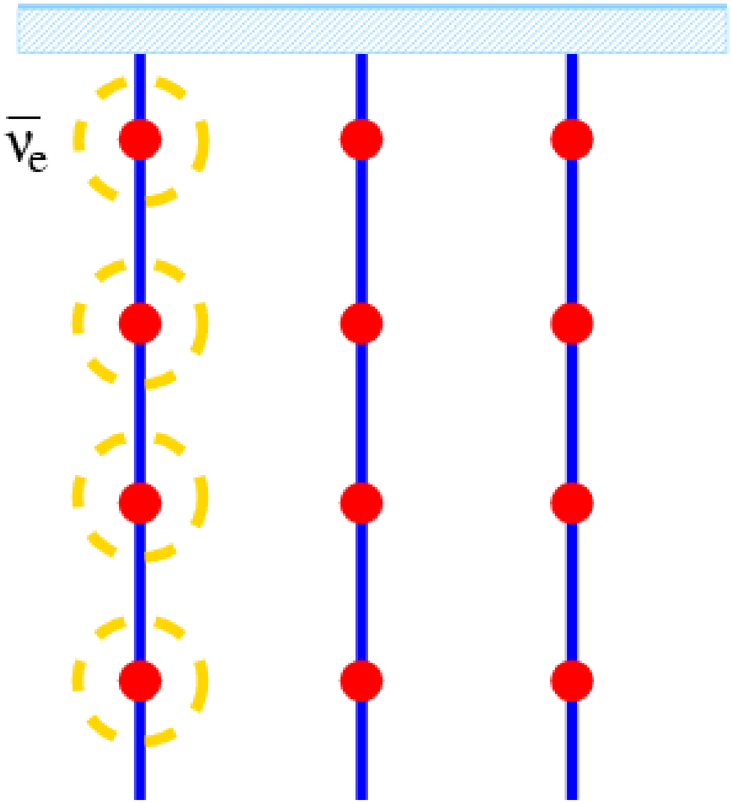
**and, more than 2.2 MeV of $\gamma$ energy available**

**$\Rightarrow$ previously used in small scintillator detectors; may be possible for large water detectors with ~0.2% gadolinium trichloride solution**

**Beacom & Vagins PRL 93:171101, 2004**

**R&D is currently underway for SK**

# LONG STRING WATER CHERENKOV DETECTORS




~kilometer long strings of PMTs in very clear water or ice

Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as *coincident increase in single PMT count rates* ($M_{eff}$ ~ 0.4 kton/PMT)

cannot tag flavor, or other interaction info, but gives overall rate check

**AMANDA/IceCube at the South Pole**

So far we have seen: for most existing (and planned) large detectors, inverse beta decay dominates, (and is potentially taggable) so primary sensitivity is to $\bar{\nu}_e$

**CC interactions on nuclei play a role, too**

(cross-sections smaller for bound nucleons)

$\nu_e + n \rightarrow p + e^-$ : $\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$

$\bar{\nu}_e + p \rightarrow n + e^+$ : $\bar{\nu}_e + (N, Z) \rightarrow (N+1, Z-1) + e^+$

Observables for tagging:

- charged lepton $e^{+/-}$
- possibly ejected nucleons
- possibly de-excitation $\gamma$'s

(depends on nucleus)

*Nuclear physics important* in understanding cross-sections and observables!

... often large uncertainties, need to measure!

# Examples of CC interactions of SN $\nu$ with nuclei:

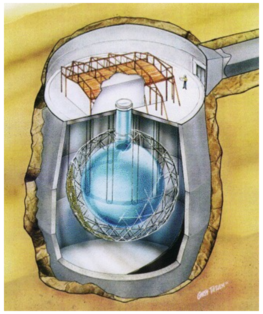
**CC breakup in heavy water**

$$\nu_e + d \rightarrow p + p + e^-$$

**e.g. SNO,**

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

~100 ev @ 8.5 kpc



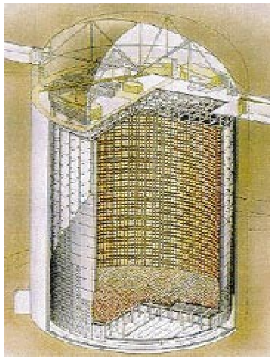
**Interactions with oxygen in water**

**e.g. Super-K,**

$$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}F + e^-$$

$$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$$

~few tens @ 8.5 kpc



**Interactions with carbon in scintillator**

**e.g. LVD, KamLAND**

$$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$$

$$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$$

~few @ 8.5 kpc

# More examples of CC ν-nucleus interactions

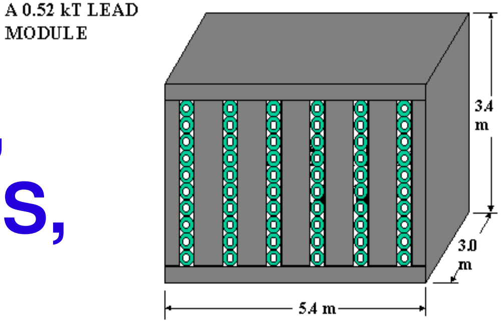
## 'High Z' Detectors

Large quantity of Pb $(ClO_4)_2$ , Fe + scintillator, n counters

$$\bar{\nu}_e + (A,Z) \rightarrow (A\text{-}1,Z\text{-}1) + n + e^+$$

$$\nu_e + (A,Z) \rightarrow (A\text{-}1,Z\text{+}1) + n + e^-$$

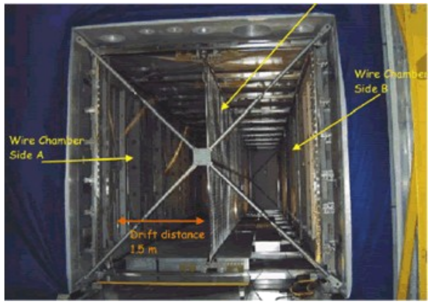
OMNIS, ADONIS, HALO




## Liquid Argon

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

Icarus, LANNDD



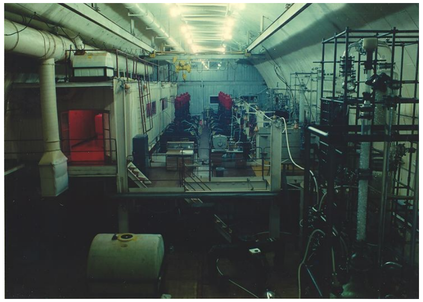

## Radiochemical

Chlorine $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$

Gallium $\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$

Iodine $\nu_e + {}^{127}I \rightarrow e^- + {}^{127}Xe$

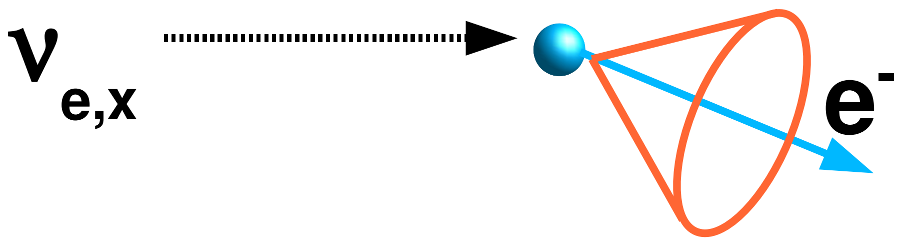
(quasi) real-time with atom tagging?



## Also: elastic scattering (CC and NC contributions)

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

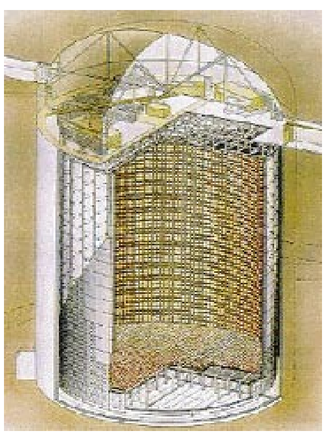
In water Cherenkov and scintillator, few % of inverse βdk rate




**POINTING from Cherenkov cone:**

(slightly degraded by isotropic bg)

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



**Super-K: expect ~200 ES for 8.5 kpc SN (5-10 from breakout)**

**⇒ ~ 4° pointing**

(probably best bet for pointing)

We have sensitivity to electron flavor neutrinos via CC interactions...

but ~2/3 of the luminosity is $\mu$ and $\tau$ flavor; can be detected via NC interactions only

Typically, signature is nucleon emission or nuclear de-excitation products

e.g.

$$\nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x$$

$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

$$(A,Z)^* \rightarrow (A,Z) + \gamma$$

sometimes good tag is possible

Again, nuclear physics matters!

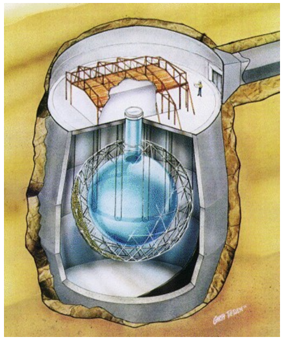
# Examples of NC interactions in existing detectors

## NC breakup in heavy water

**e.g. SNO,**

~100 ev @ 8.5 kpc

$$\nu_x + d \rightarrow \nu_x + p + n$$



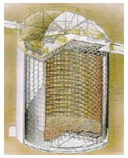
## Interactions with oxygen in water

**e.g. Super-K,**

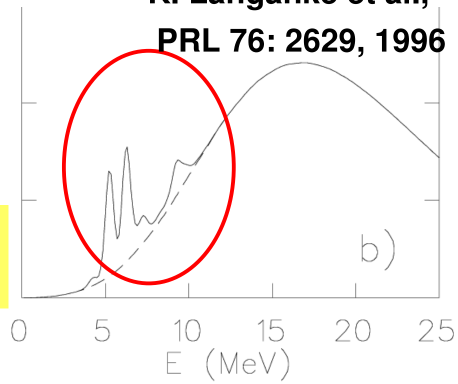
~few hundreds @ 8.5 kpc

$$\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^*$$

$$\hookrightarrow {}^{16}O + \gamma\text{'s}$$



K. Langanke et al., PRL 76: 2629, 1996




## Interactions with carbon in scintillator

**e.g. LVD, KamLAND**

~few tens @ 8.5 kpc

$$\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$$

$$\hookrightarrow {}^{12}C + \gamma$$

15.11 MeV

# 'High Z' Detectors: *dedicated* for supernova ν's

**Pb (as metal and/or perchlorate)** (and/or Fe)

+ scint, neutron detectors

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

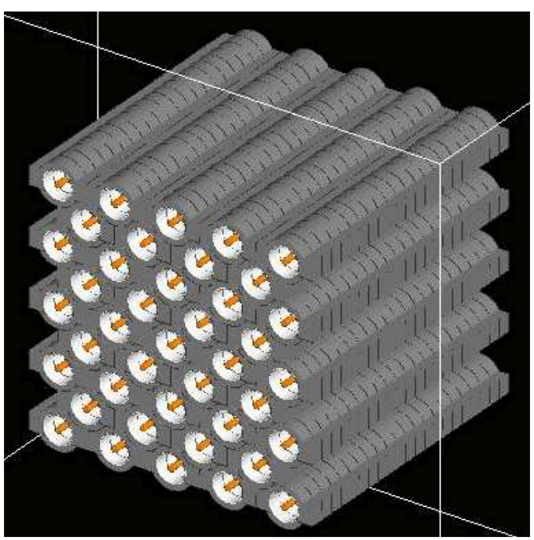
↘ 1n, 2n emission

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

↘ 1n, γ emission

Relative rates depend on ν energy ⇒good flavor oscillation sensitivity

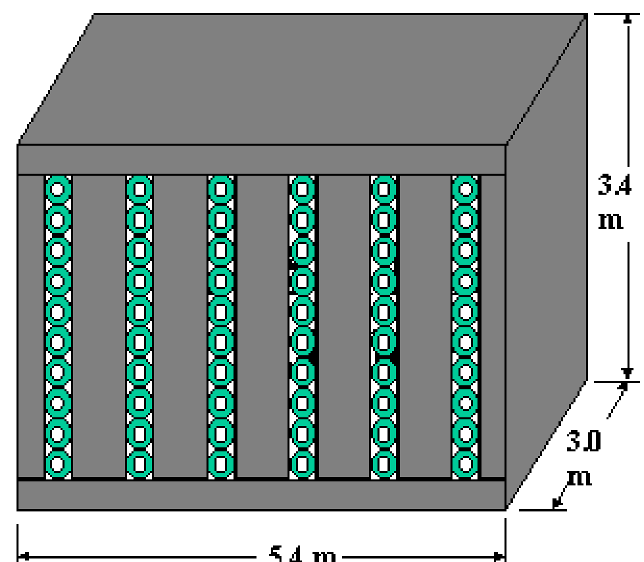
## HALO at SNOLab



from T. Massicotte thesis

SNO $^3$He counters + Pb

## OMNIS/ADONIS



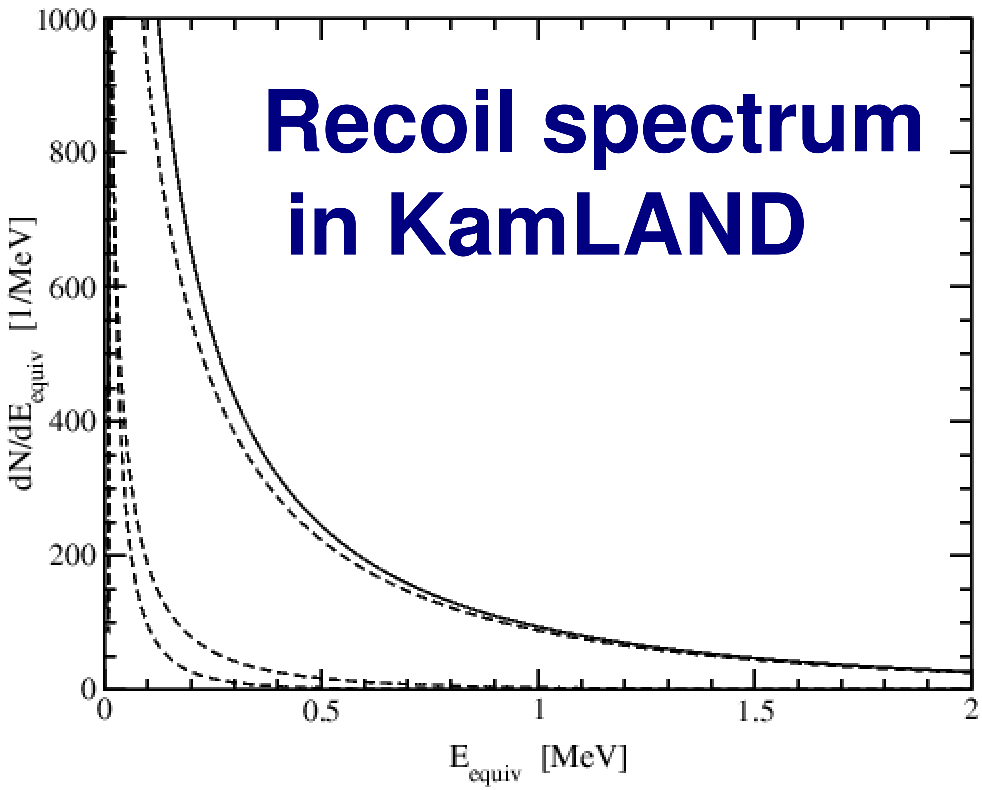
# Neutrino-proton elastic scattering

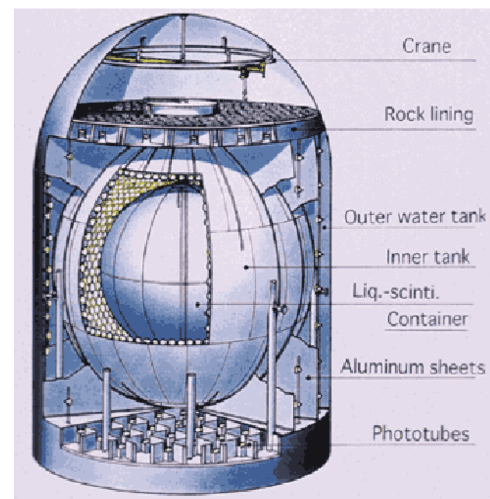
$$\nu_x + p \rightarrow \nu_x + p$$

J. Beacom et al., PRD66:033001, 2002

## Recoil energy small, but visible in scintillator

## (accounting for 'quenching' )




## Expect ~few 100 events for 8.5 kpc SN

NEW

# Neutrino-nucleus NC elastic scattering in ultra-low energy detectors

$$\nu_x + A \rightarrow \nu_x + A$$

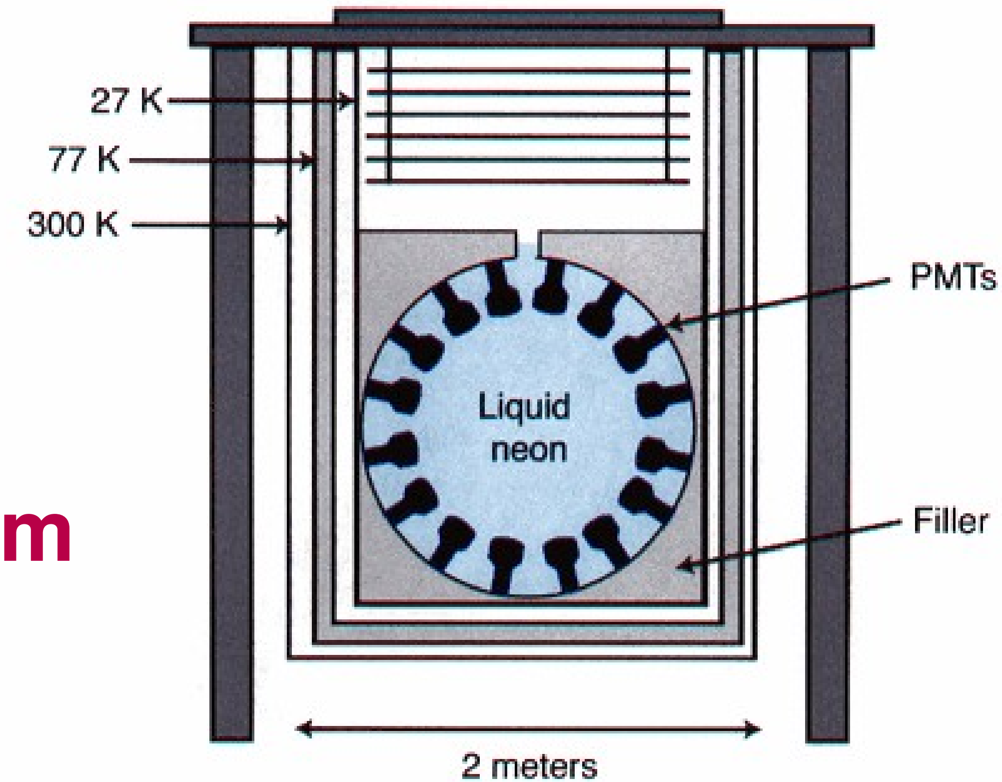
C. Horowitz et al., PRD68:023005, 2003

**High x-scn but *very* low recoil energy (10's of keV)**
**⇒ possibly observable in solar pp/DM detectors**

**~few events per ton for Galactic SN**

**$\nu_x$ energy information from recoil spectrum**

**e.g. Ar, Ne, Xe, Ge, ...**



# Summary of SN neutrino detection

## Inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$

- dominates for detectors with lots of free p (water, scint)
- $\bar{\nu}_e$ sensitivity; good E resolution; well known x-scn; some tagging, poor pointing

## CC interactions with nuclei:

- lower rates, but still useful, $\nu_e$ tagging useful (e.g. LAr)
- cross-sections not always well known

## Elastic scattering: few % of invβdk, but point!

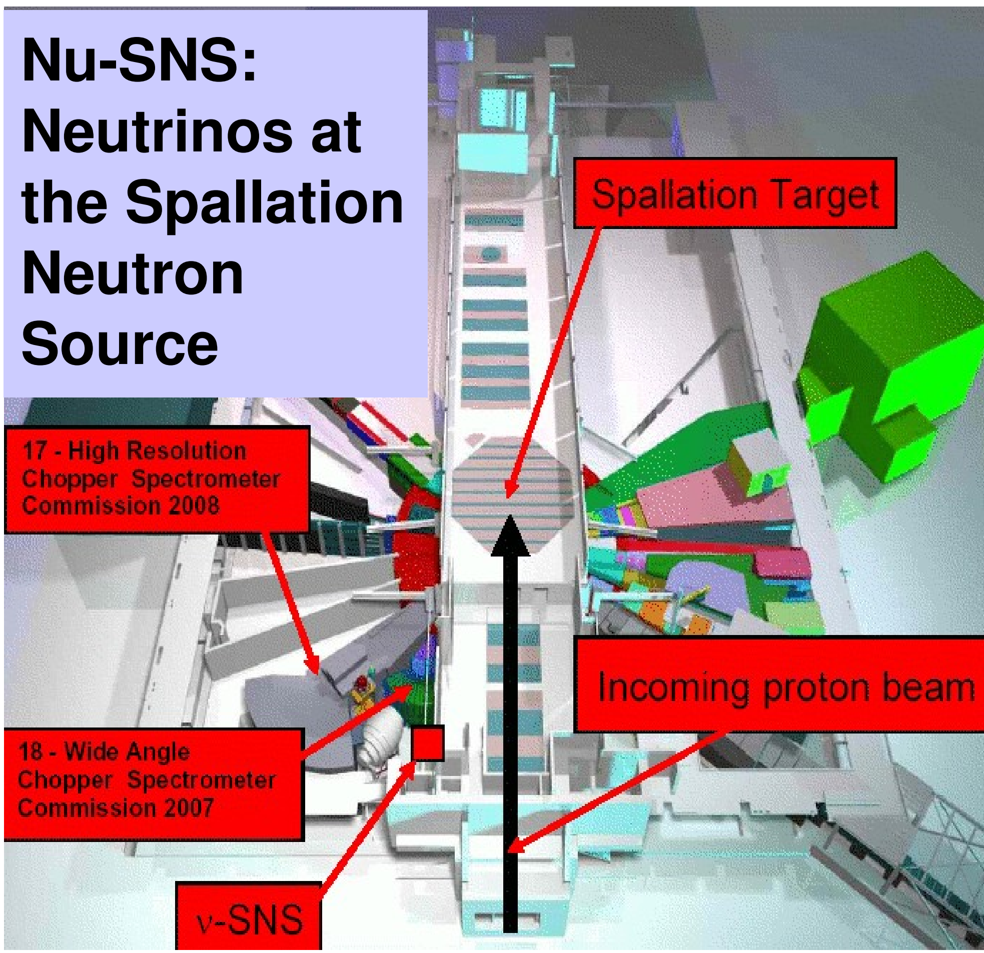
## NC interactions with nuclei:

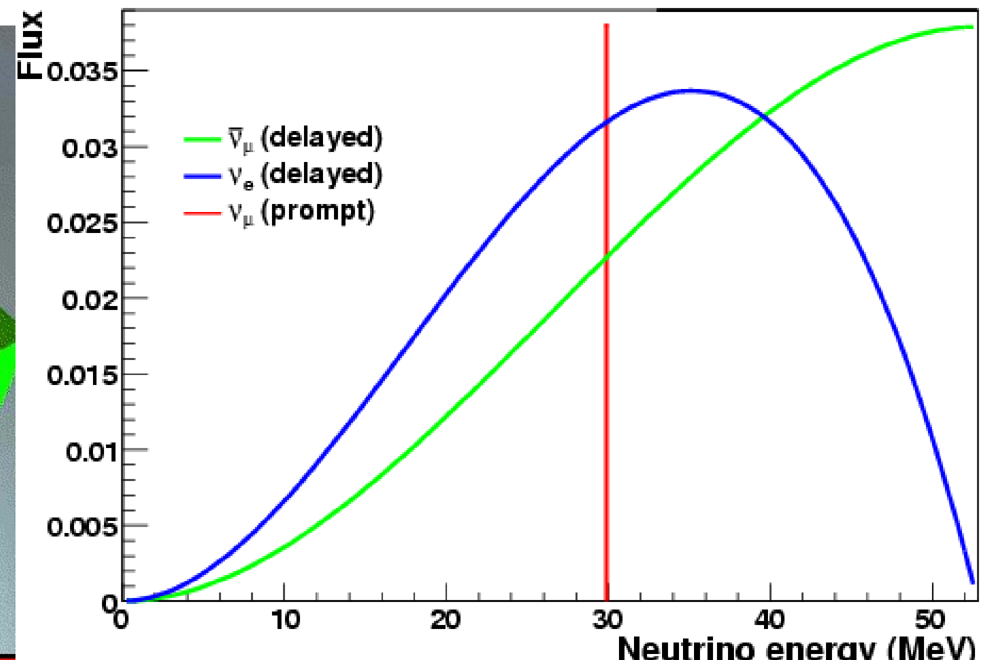
- very important for physics, probes μ and τ flux
- some rate in existing detectors, dedicated observatories
- some tagging; poor E resolution; x-scns not well known
- NEW coherent ν-p, ν-A scattering in low thresh detectors

\begin{aside}

**Many CC and NC ν-nucleus cross-sections are poorly known...we need to *measure* them!**

## A high-intensity stopped-pion neutrino source is ideal: spectrum matches SN's




**20 m from target :**

**$10^7$ ν/s/cm$^2$ (few SN/day)**

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# What's next?

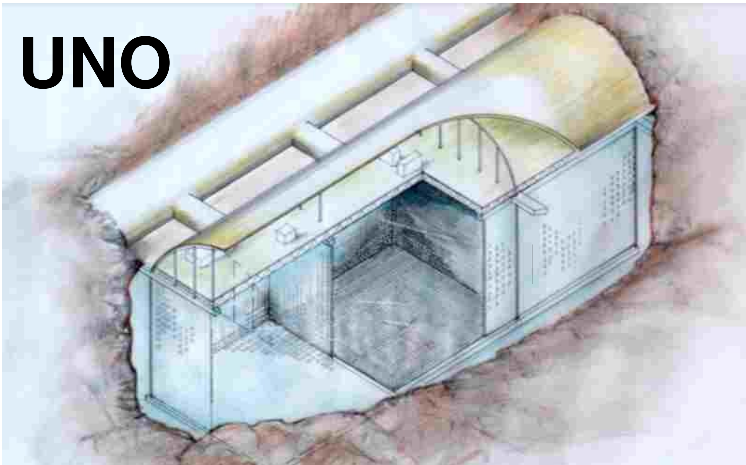
Unfortunately, expect only a few core collapse SN per century in our Galaxy... could be a long wait

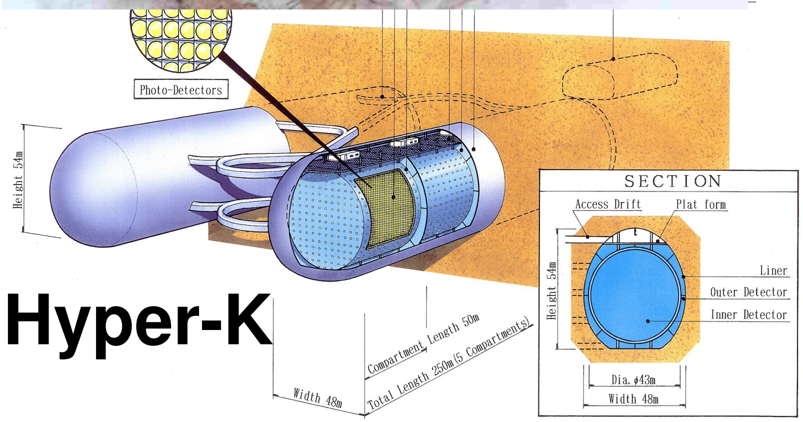
Beyond the Milky Way edge (20 kpc) next nearest concentration of stars is Andromeda (M31), 770 kpc away

$1/D^2$ hurts! Expect only 7000 $(8.5/770)^2$ ~ 1 event in SK for a core collapse in Andromeda

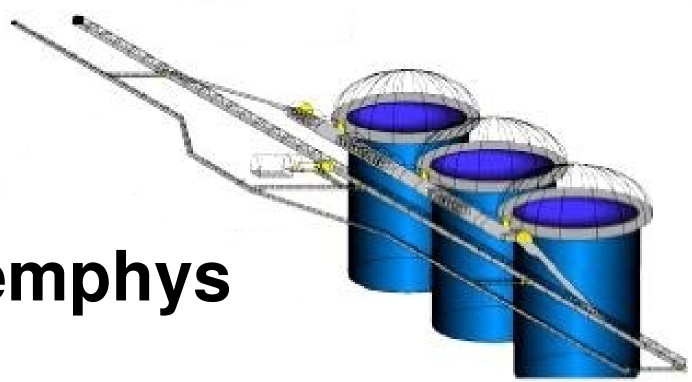
# Next mega-detectors: how well can one do?

UNO



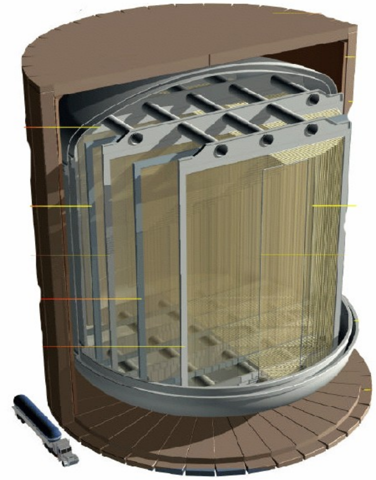


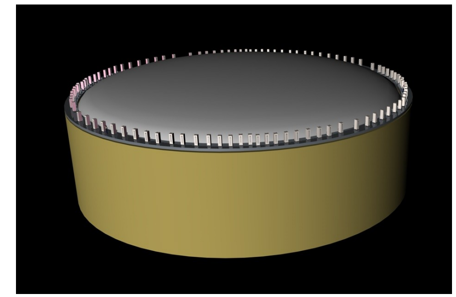

Hyper-K



Memphys

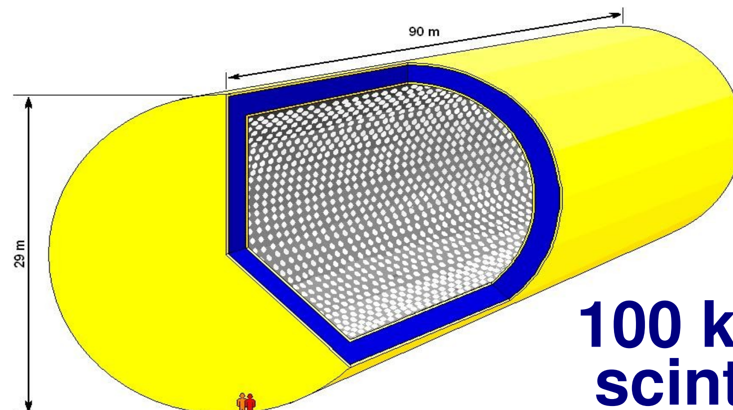
Megaton-scale water detector concepts





LANNDD

100 kton-scale LAr detector concepts




LENA, HSD

100 kton-scale scintillator detector concepts

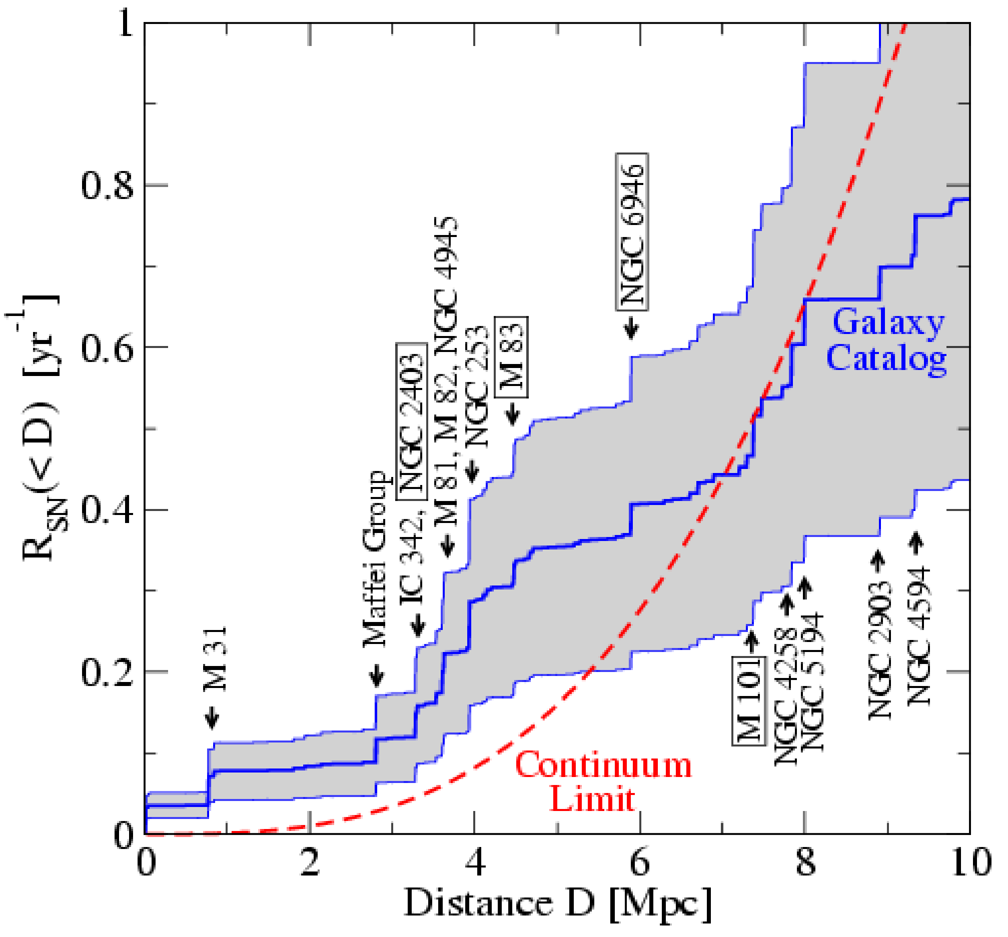
~few to tens of events from M31

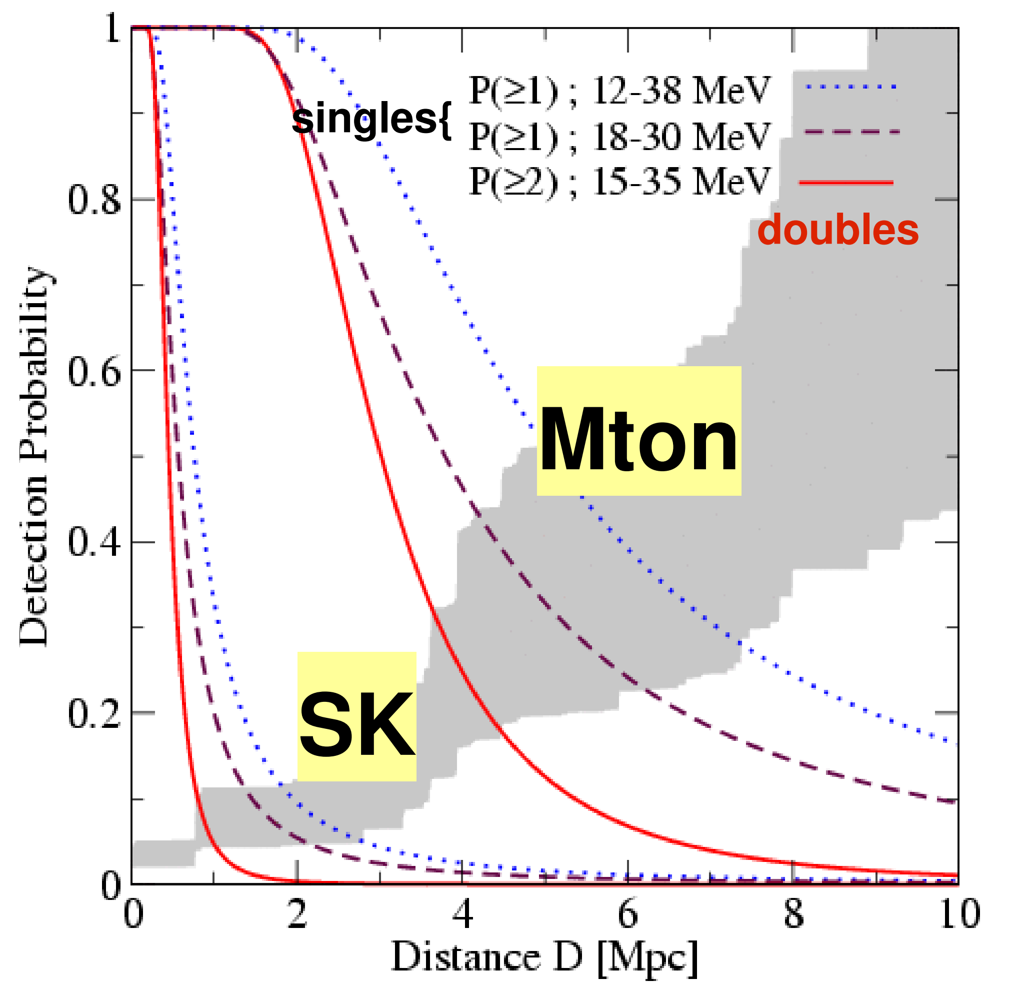
**Optimize location?**

Mirizzi et al. astro-ph/0604300

# Looking beyond: number of sources ∝ $D^3$

**S. Ando et al., PRL 95:171101, 2005:**



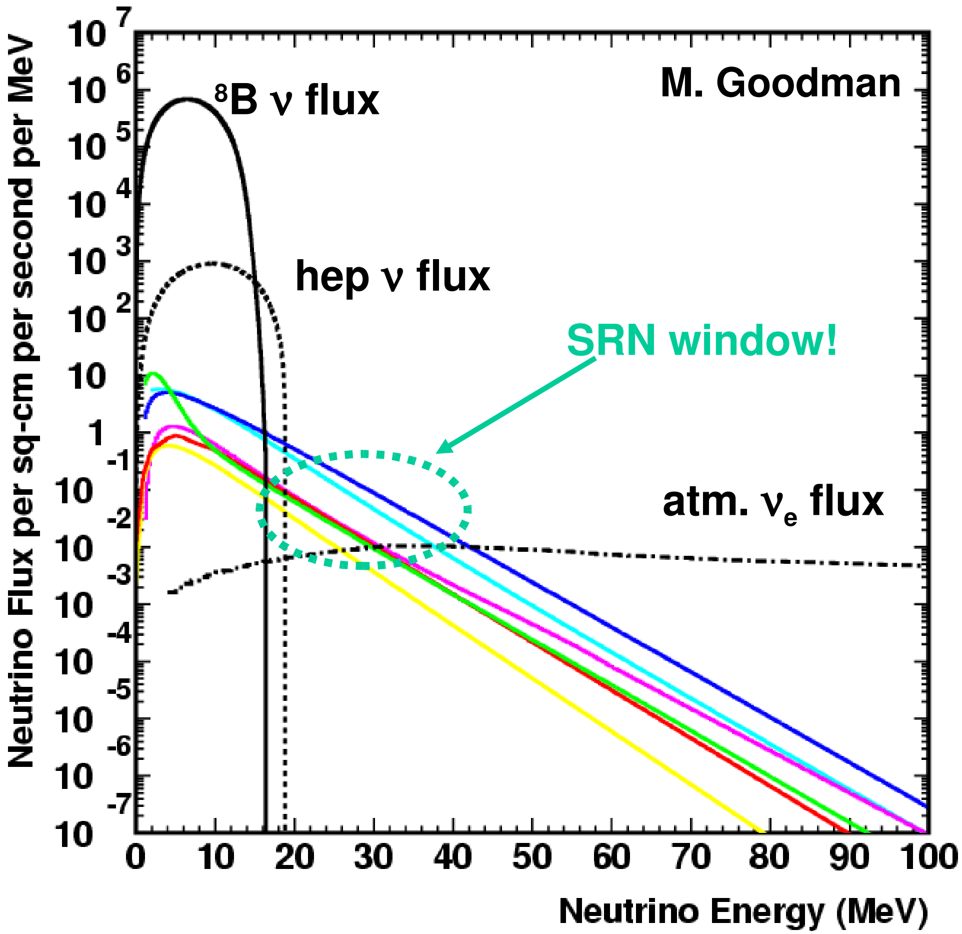




**With Mton scale detector, probability of detecting 1-2 events reasonably close to ~1 at distances where rate is <~1/year**

**Tagging signal over background becomes the issue**
**⇒ require double ν's or grav wave/optical coincidence**

# And going even farther out: we are awash in a sea of '*relic*' or diffuse SN ν's (DSNB), from ancient SNae

**Learn about star formation rate, which can constrain cosmological models**




**Difficulty is tagging for decent signal/bg (no burst, 2 ν coincidences optical SNae...)**

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

**scint or water+Gd are good bets**

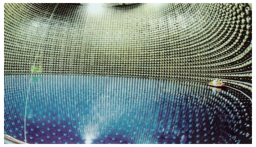
# Using DSNB to test SN/ neutrino/ exotic physics?

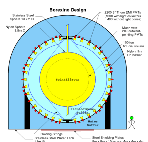
| DSNB | Galactic SN |
|---|---|
| | ~300 events/kt/30 year |
| ~0.1 event/kt/year | ~10 events/kt/yr |
| more background | less background |
| low rate of return, but a sure thing | risky in the short term, but you win in the very long term |

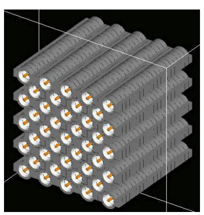
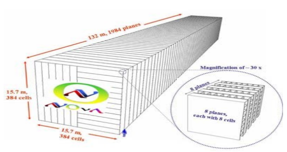
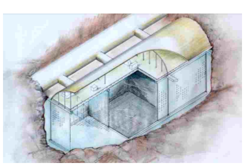
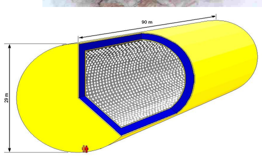
bonds vs stocks...

(Of course if you build a big detector and run it a long time, you may get both! Diversify!)

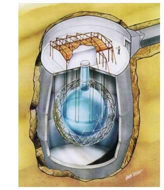
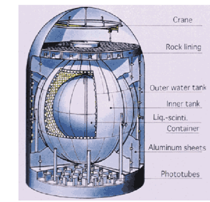
# Summary of supernova neutrino detectors

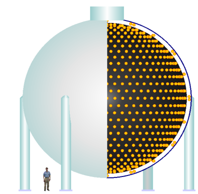
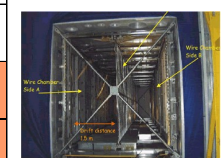
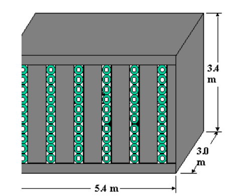


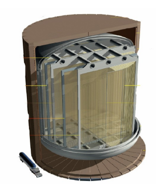
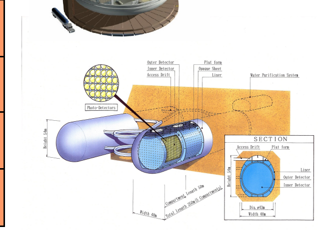


| *Detector* | *Type* | *Mass (kton)* | *Location* | *Events at 8.5 kpc* | *Status* |
|---|---|---|---|---|---|
| Super-K | Water | 32 | Japan | 7000 | Running as SK III |
| SNO | Heavy water | 1($D_2O$)<br>1.4($H_2O$) | Canada | 400<br>450 | Running until end of 2006 |
| LVD | Scintillator | 1 | Italy | 200 | Running |
| KamLAND | Scintillator | 1 | Japan | 300 | Running |
| Borexino | Scintillator | 0.3 | Italy | 100 | 200x |
| Baksan | Scintillator | 0.33 | Russia | 50 | Running |
| Mini-BooNE | Scintillator | 0.7 | USA | 200 | Running |
| AMANDA/ IceCube | Long string | 0.4/PMT | Antarctica | N/A | Running |
| Icarus | LAr | 2.4 | Italy | 200 | 200x |
| CLEAN | Ne, Ar | 0.01 | Canada, USA? | 30 | proposed |
| HALO | Pb | 0.1 | Canada | 40 | proposed |
| SNO+ | Scintillator | 1 | Canada | 300 | proposed |
| MOON | $^{100}$Mo | 0.03 | ? | 20 | proposed |
| NOvA | Scintillator | 20 | USA | 4000 | proposed |
| OMNIS | Pb | 2-3 | USA? | >1000 | proposed |
| LANNDD | LAr | 70 | USA? | 6000 | proposed |
| MEMPHYS | Water | 440 | Europe | >100,000 | proposed |
| UNO | Water | 500 | USA | >100,000 | proposed |
| Hyper-K | Water | 500 | Japan | >100,000 | proposed |
| LENA | Scintillator | 60 | Europe | 18,000 | proposed |
| HSD | Scintillator | 100 | USA | 30,000 | proposed |

# Conclusion

## Next generation of detectors can snare $\nu$'s from:

**Galactic bursts**

**Nearby galaxies**

**Ancient collapses**

**Let's cast our nets for a neutrino catch that's both *abundant* and *rich* !**