What Stubs and Sparkles in Vast Vats of Liquid Can Tell Us About Exploding Stars

Kate Scholberg, Duke University
June 2015

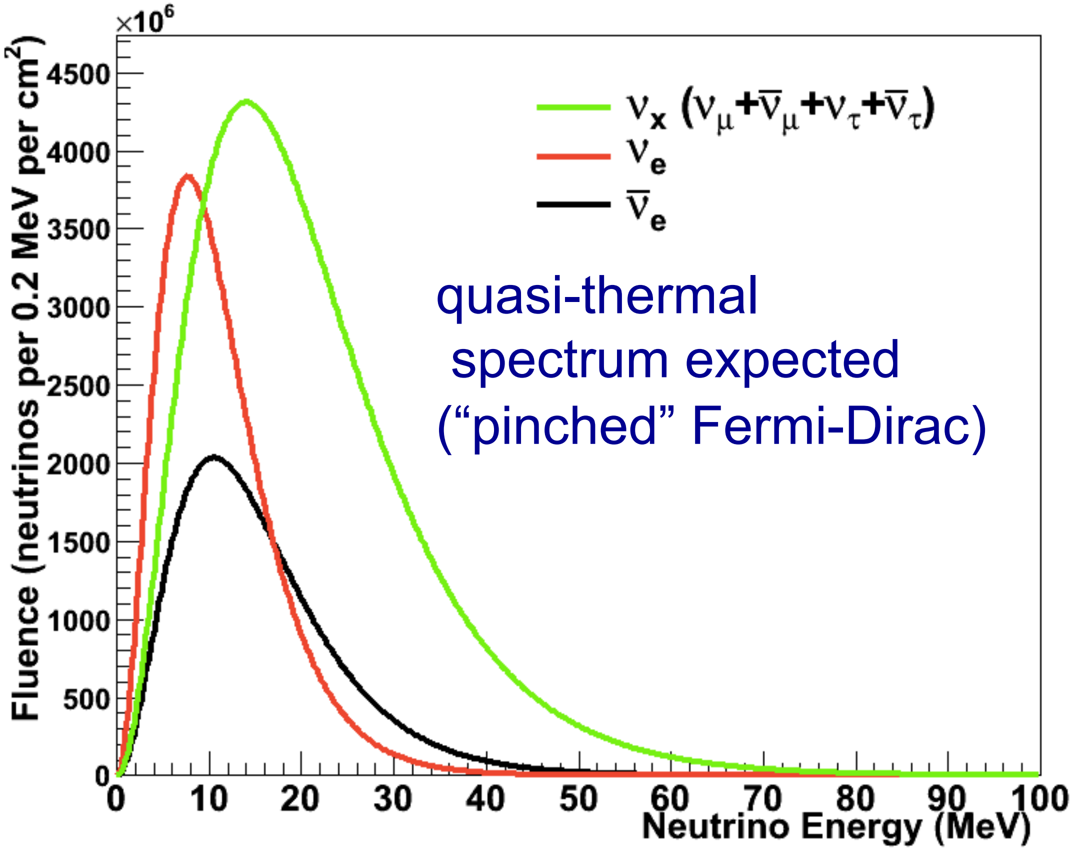
Neutrinos from core collapse

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

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

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

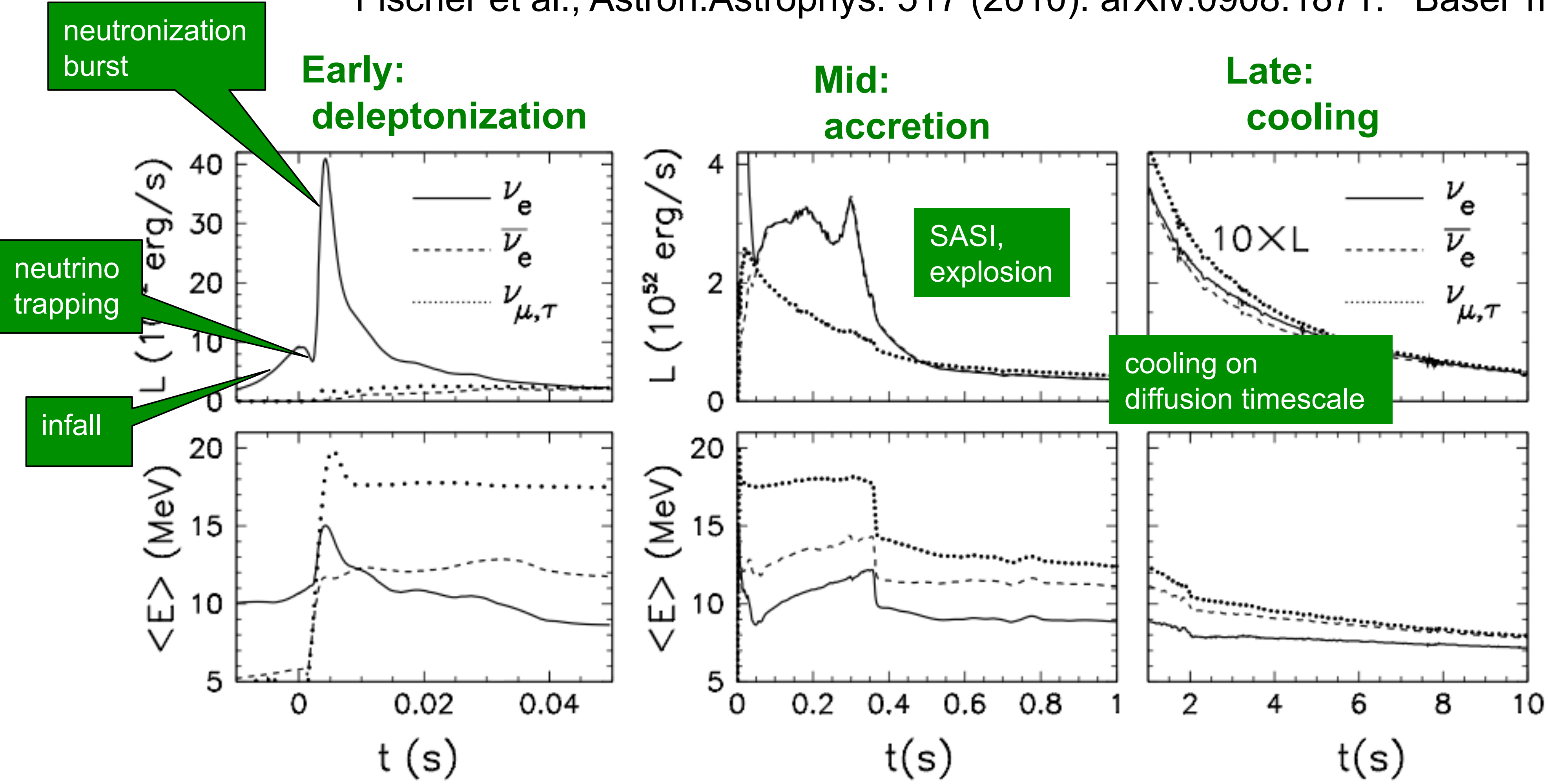


quasi-thermal spectrum expected (“pinched” Fermi-Dirac)

Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: ‘Basel’ model


neutronization burst

neutrino trapping

infall

Early: deleptonization

Mid: accretion

Late: cooling

SASI, explosion

cooling on diffusion timescale

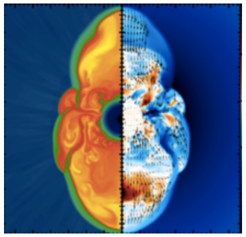
Generic feature:

(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

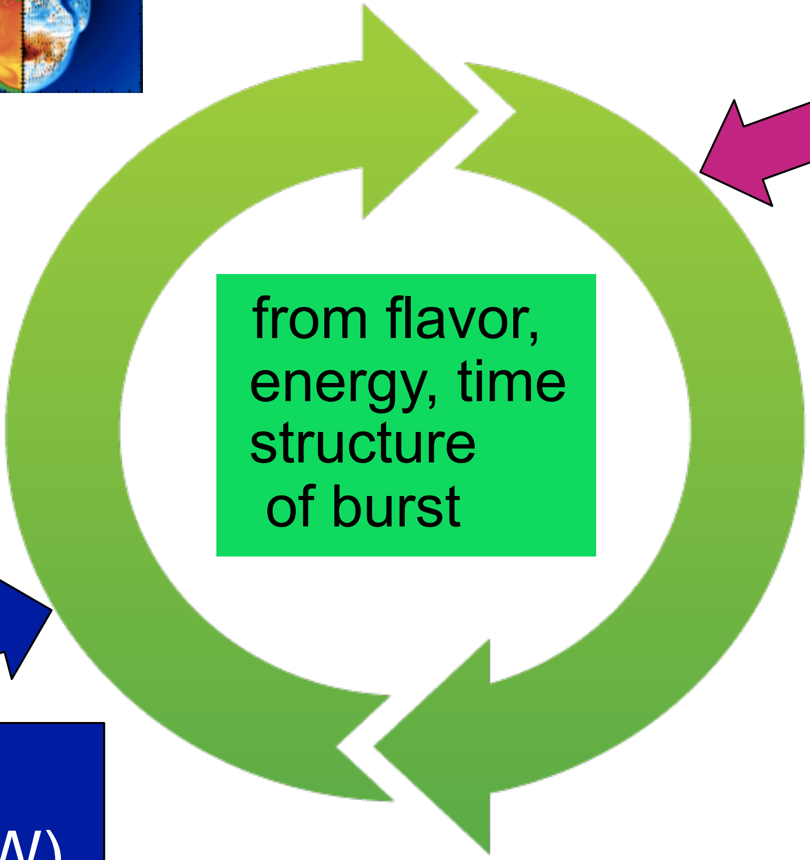
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



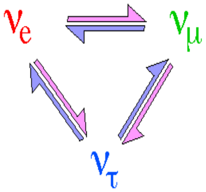
explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from photon (GW) observations



from flavor, energy, time structure of burst

input from neutrino experiments



NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

+ EARLY ALERT

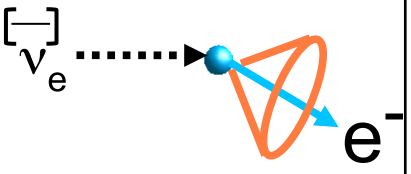
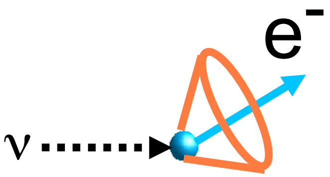
Information is in the ***energy, flavor, time*** structure of the burst

What do you want in a detector?

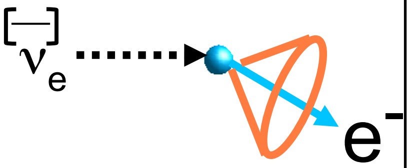
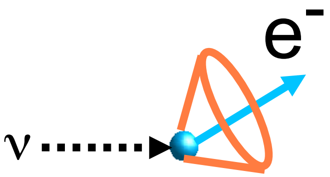
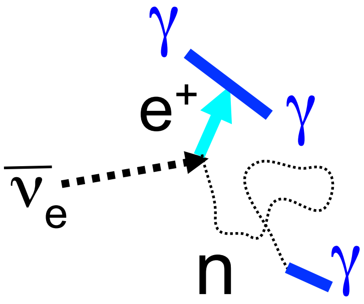
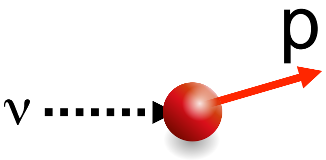
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; underground location usually excellent; surface detectors conceivably sensitive
Flavor sensitivity	Ability to **tag** flavor components
High up-time and longevity	Can't miss a ~1/30 year spectacle!

Note that many detectors have a "day job"...

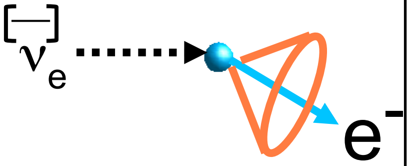
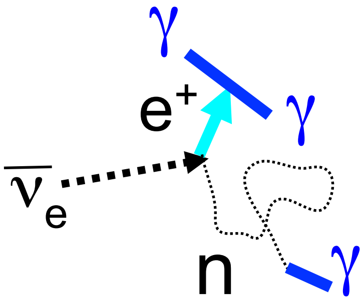
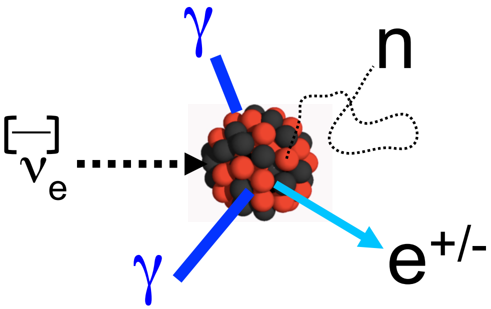
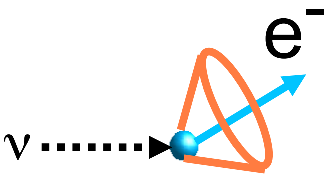
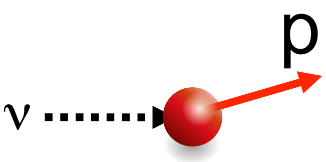
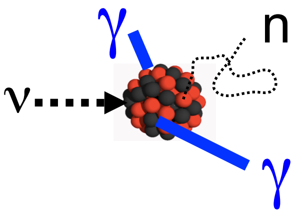
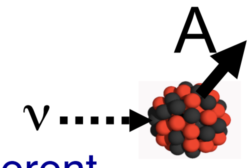
Supernova-relevant neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th></th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering
$\nu + e^- \rightarrow \nu + e^-$


Useful for pointing</td><td></td><td></td></tr>
<tr><td>Neutral current</td><td></td><td></td></tr>
</table>

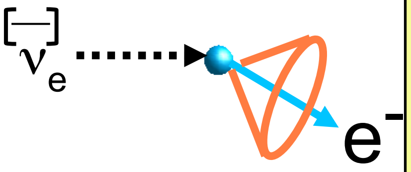
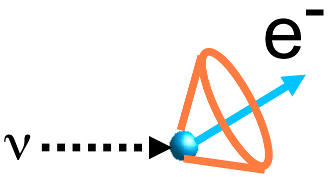
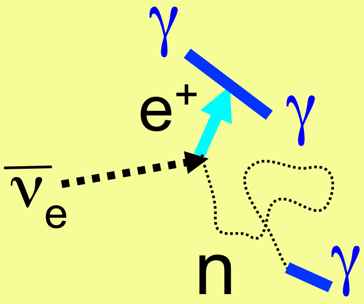
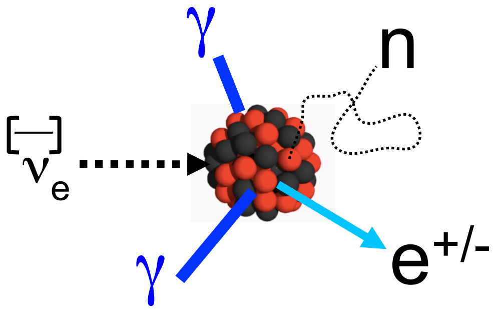
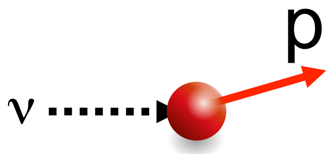
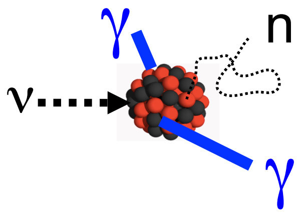
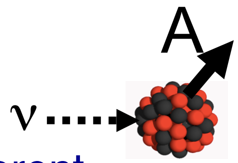
Supernova-relevant neutrino interactions

	Electrons	**Protons**	
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$   Useful for pointing	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$  	
Neutral current		Elastic scattering  very low energy recoils	

Supernova-relevant neutrino interactions

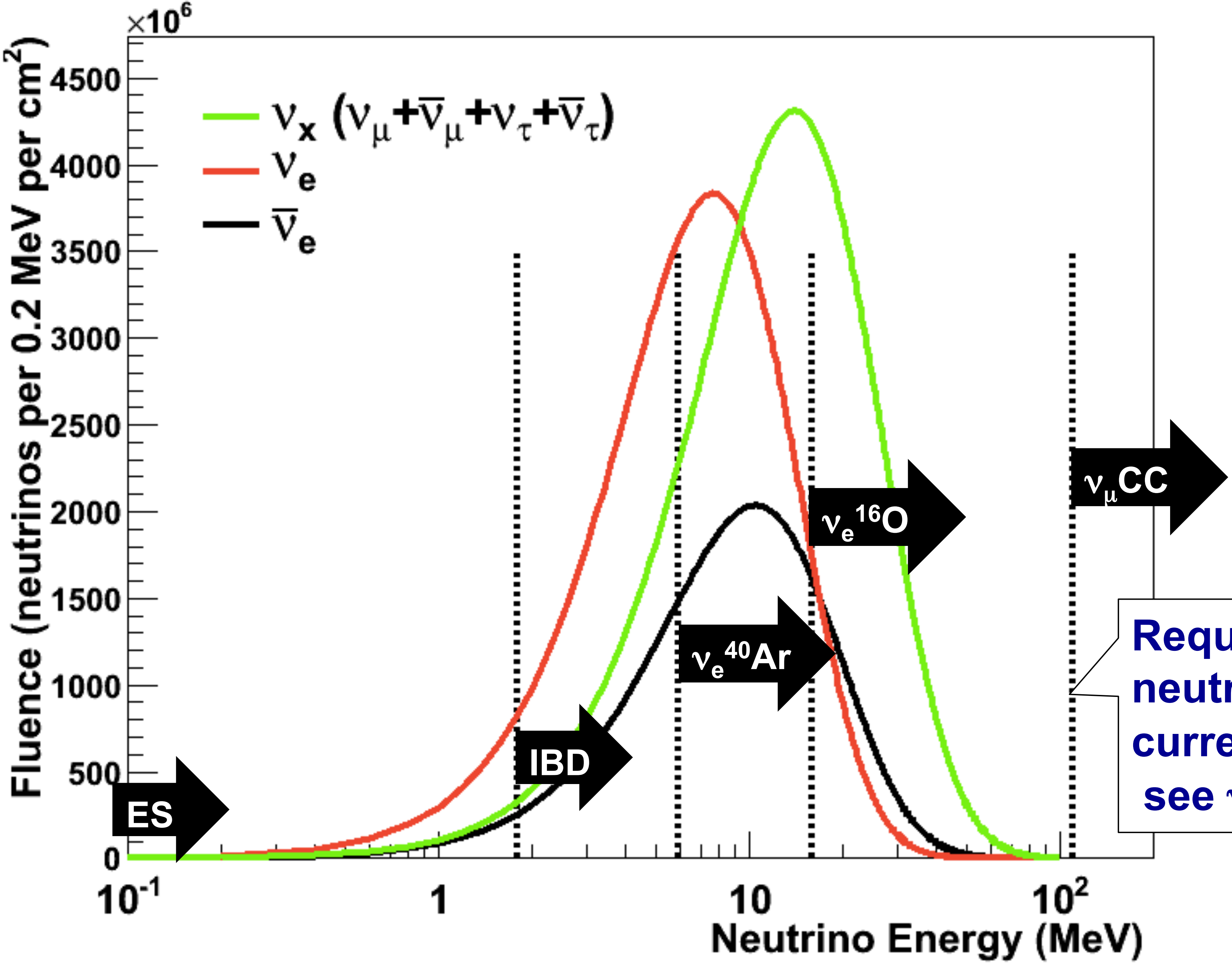
	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Supernova-relevant neutrino interactions

	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$   Useful for pointing	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current		Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

IBD (electron *anti*neutrinos) dominates for current detectors

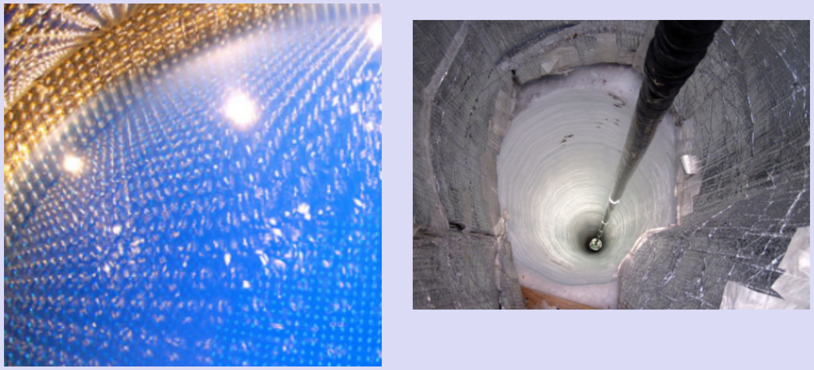
Neutrino interaction thresholds



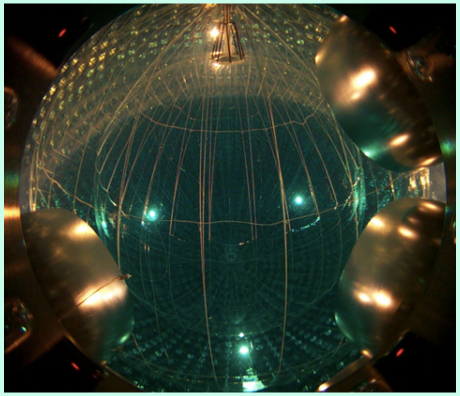
Require neutral current to see $\nu_{\mu,\tau}$

Current main supernova neutrino detector types

Water



Scintillator

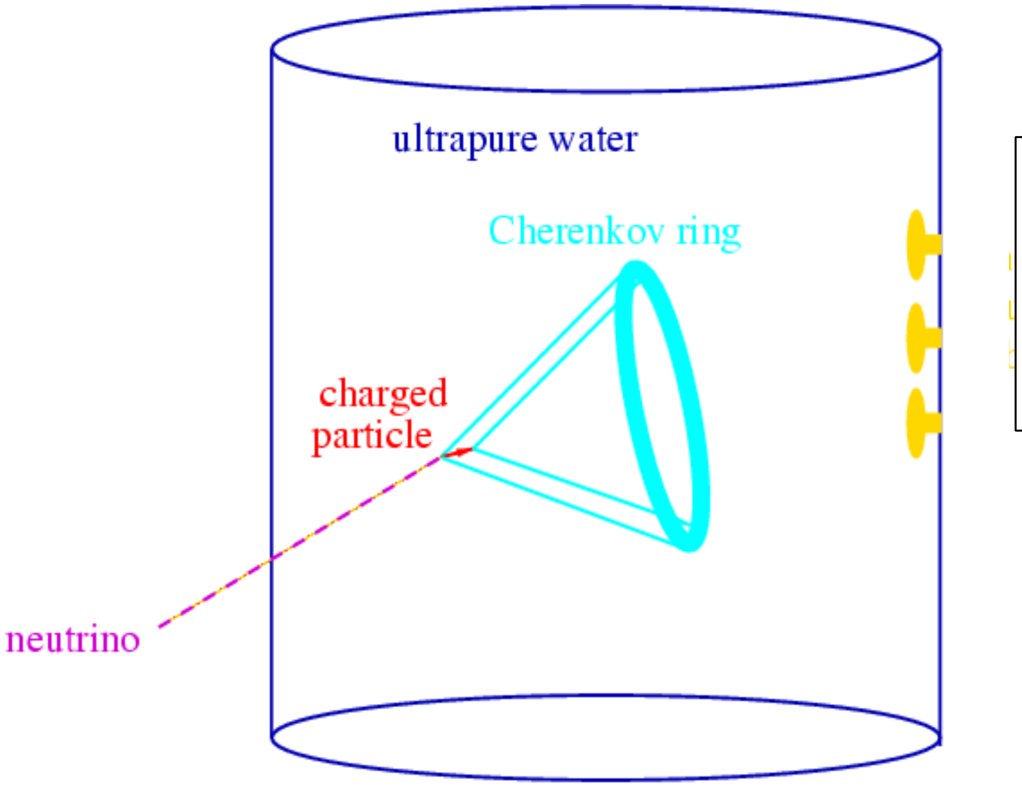


Argon

Lead

+ some others (e.g. DM detectors)

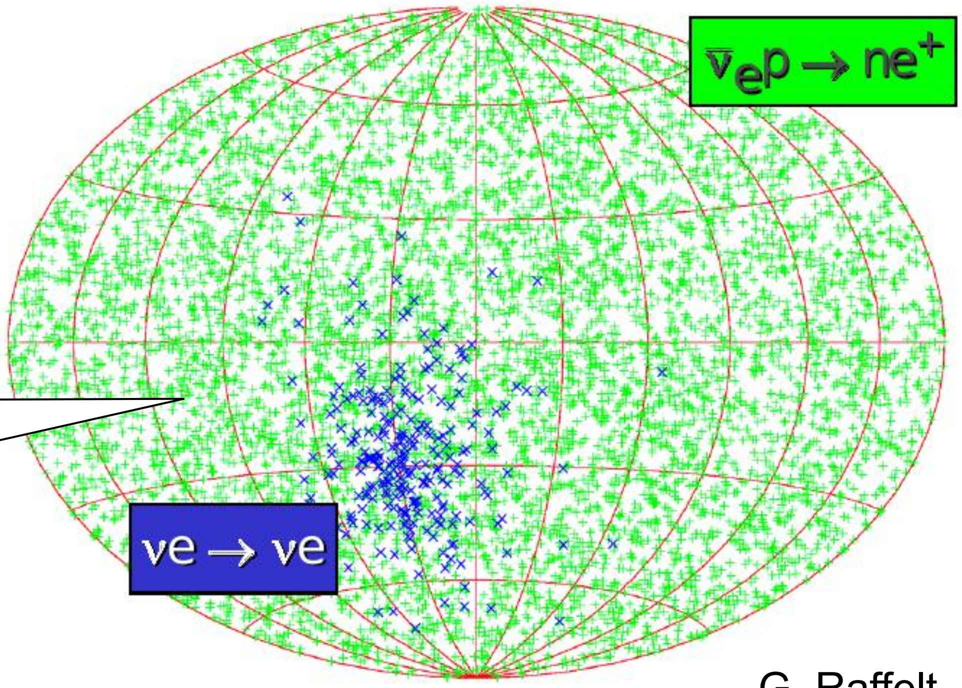
Water Cherenkov detectors



Inverse Beta Decay (CC) dominates

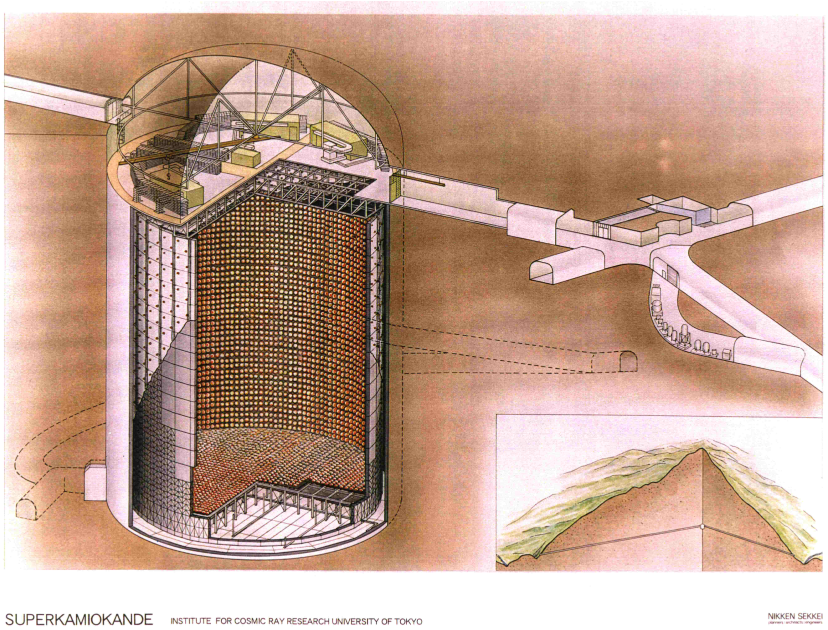
$\bar{\nu}_e + p \rightarrow e^+ + n$

E_{thr}=1.8 MeV



Pointing from neutrino-electron elastic scattering

G. Raffelt

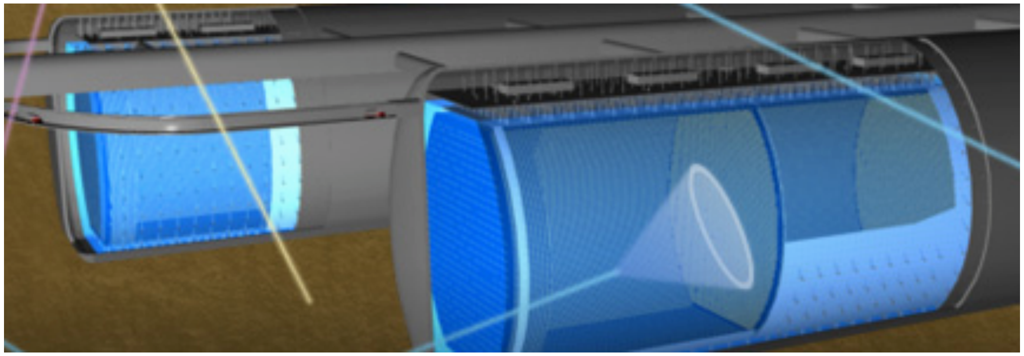


Super-Kamiokande

Mozumi, Japan

22.5 kton fid. volume (32 kton total)

~5-10K events @ 10 kpc
  (mostly anti-ν_e)
  ~5^o pointing @ 10 kpc



Hyper-Kamiokande

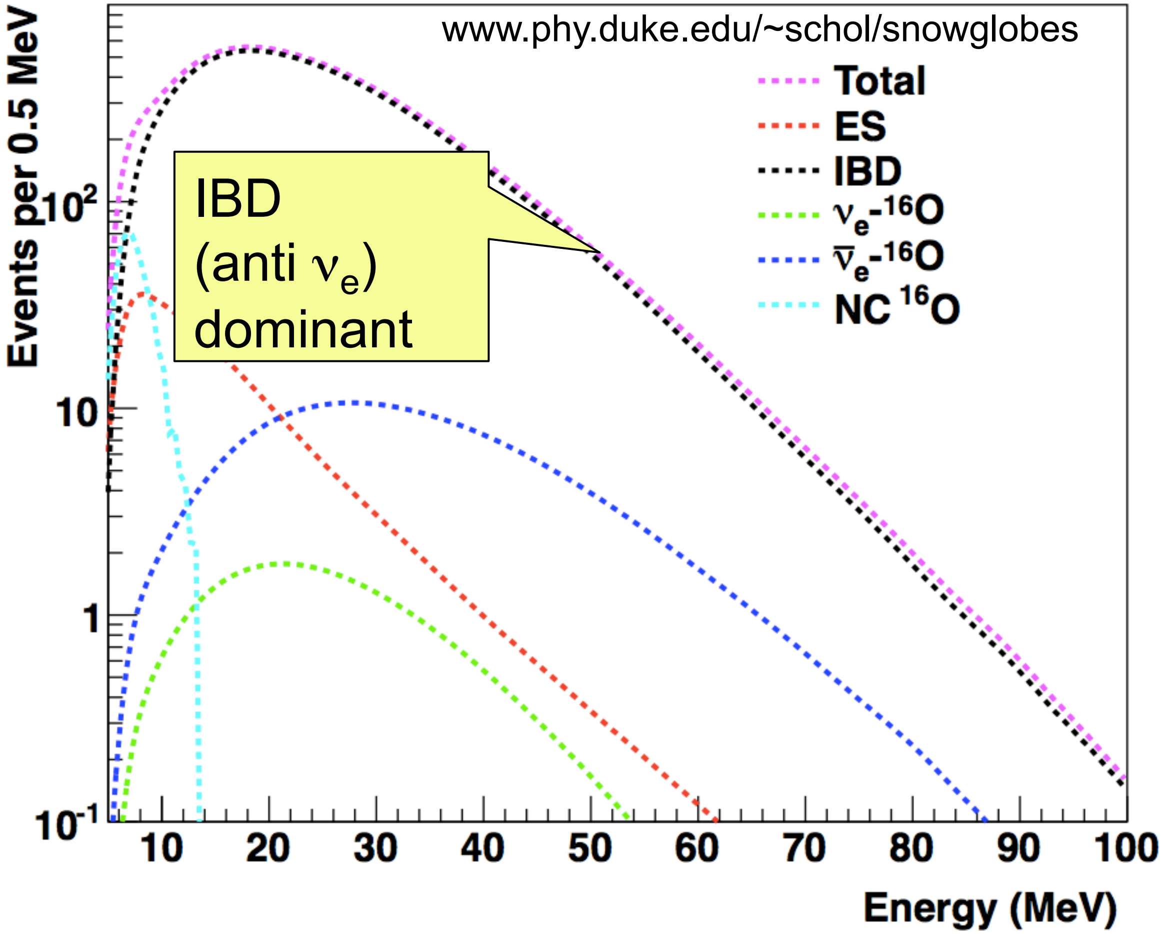
560 kton fiducial volume

Design & site-selection underway

~half photocoverage, but still good efficiency for SN

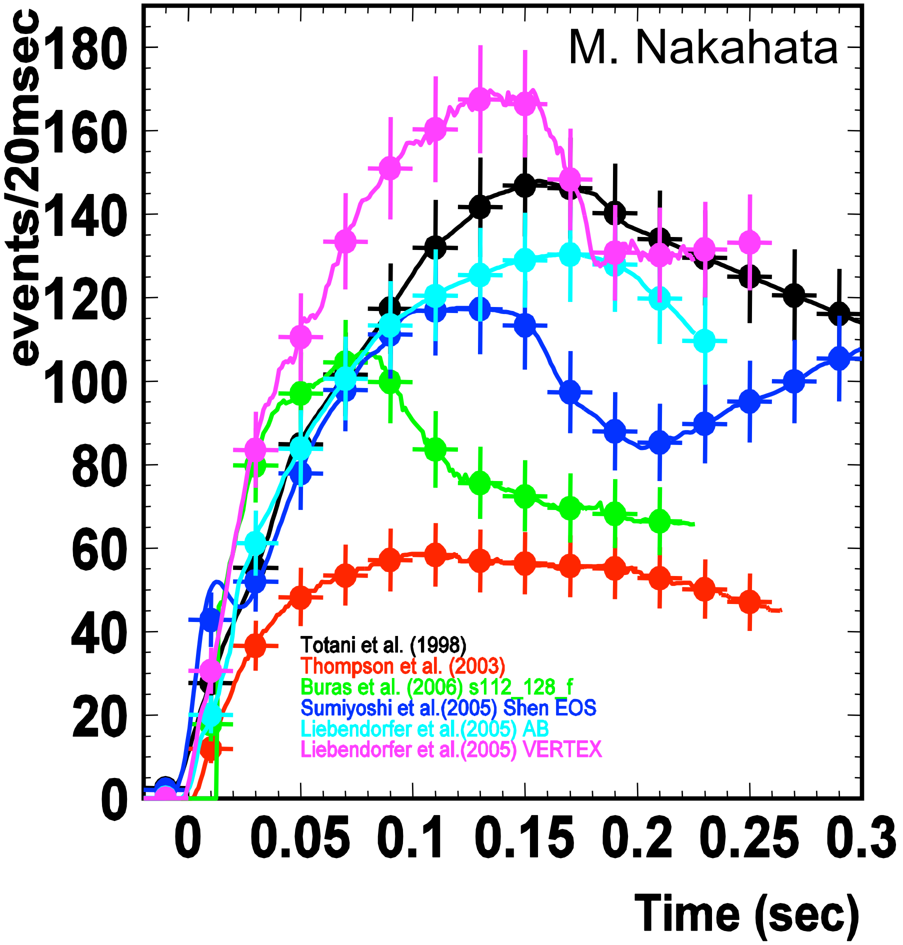
Supernova signal in a water Cherenkov detector

Events seen, as a function of observed energy



IBD
(anti ν_e)
dominant

For 100 kton.
30% PMT coverage
@ 10 kpc



Events vs time
for SK, for
different models

Neutron tagging in water Cherenkov detectors

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

➔ detection of neutron tags event as *electron antineutrino*

- especially useful for DSNB (which has low signal/bg)
- also useful for disentangling flavor content of a burst

(improves pointing, and physics extraction)

R. Tomas et al., PRD68 (2003) 093013
KS, J.Phys.Conf.Ser. 309 (2011) 012028; LBNE collab arXiv:1110.6249
R. Laha & J. Beacom, PRD89 (2014) 063007

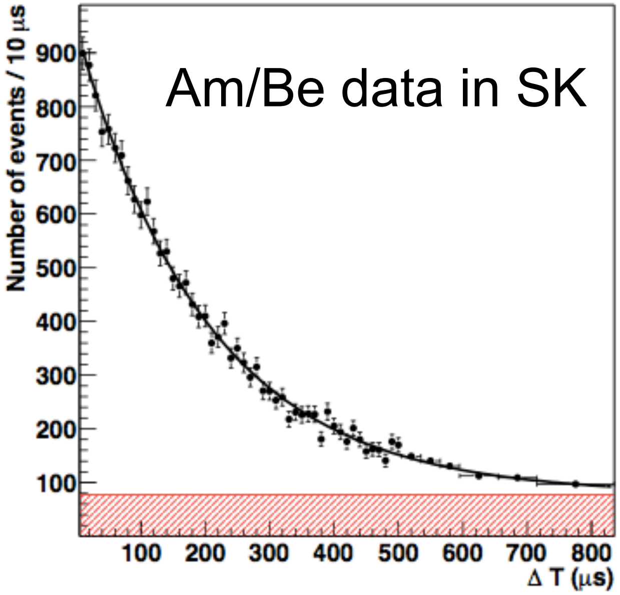
"Drug-free" neutron tagging

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

~200 μs thermalization & capture, observe Cherenkov radiation from γ Compton scatters

➔ with SK-IV electronics, ~18% n tagging efficiency

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

use gadolinium to capture neutrons

(like for scintillator)

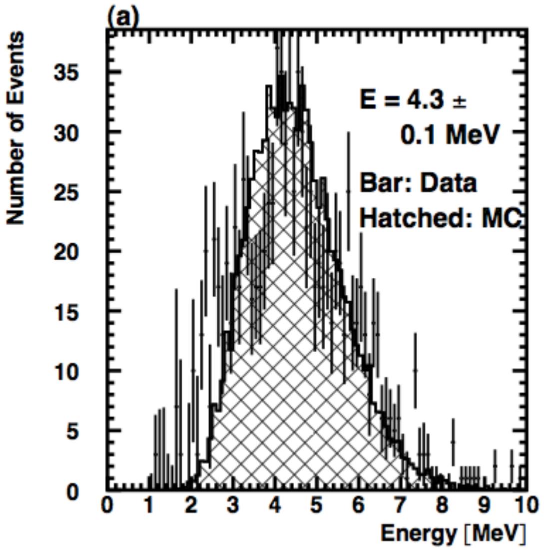
J. Beacom & M. Vagins, PRL 93 (2004) 171101

Gd has a huge n capture cross-section:

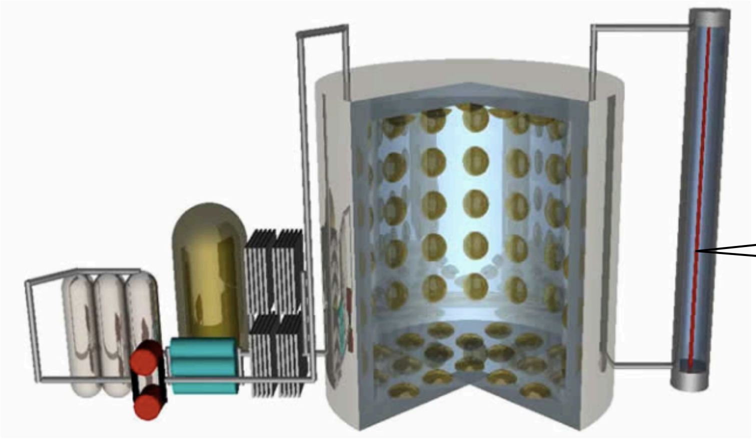
49,000 barns, vs 0.3 b for free protons

$$n + Gd \rightarrow Gd^{*} \rightarrow Gd + \gamma \qquad \sum E_{\gamma} = 8\,MeV$$

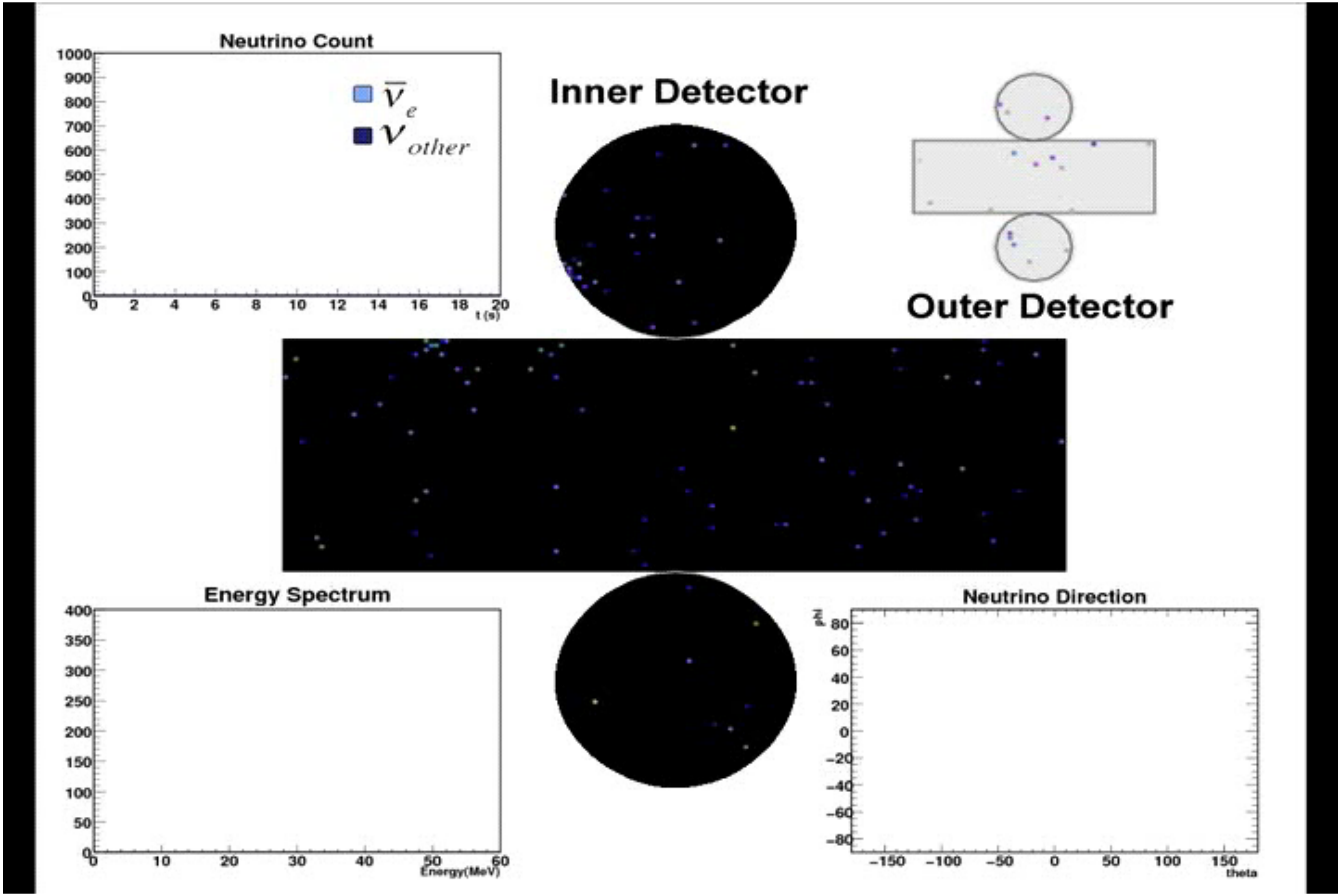
About 4 MeV visible energy per capture; ~67% efficiency in SK



H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)

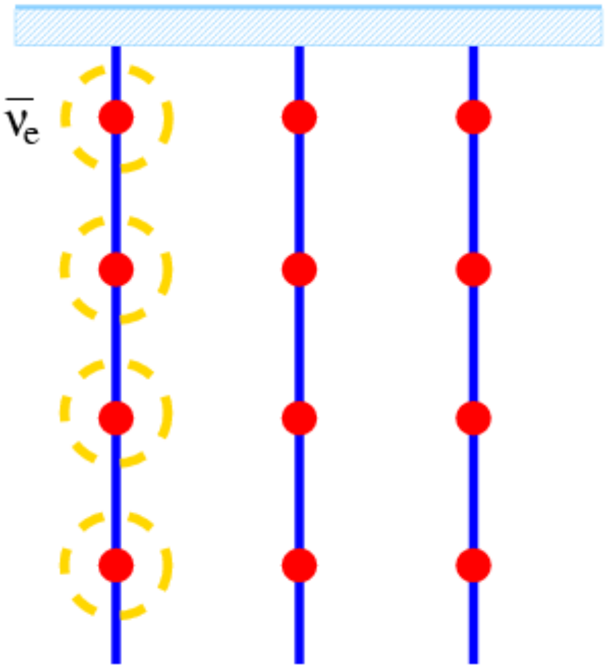


EGADS: test tank in the Kamioka mine for R&D



http://snews.bnl.gov/snmovie.html

Long string water Cherenkov detectors



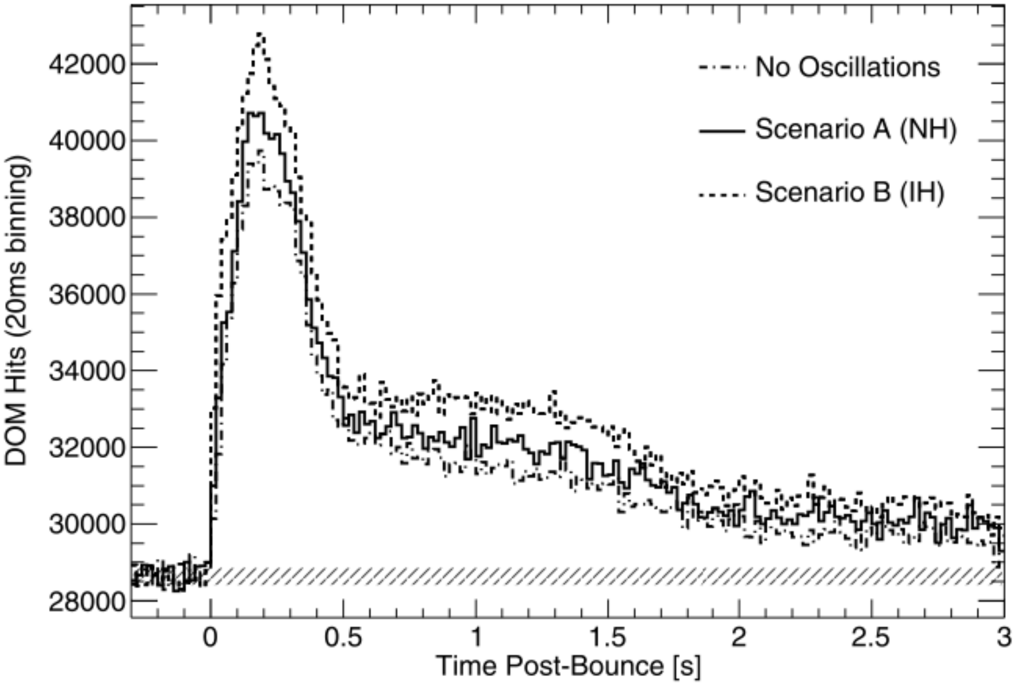
~kilometer long strings of PMTs in very clear water or ice

(IceCube/PINGU, ANTARES)

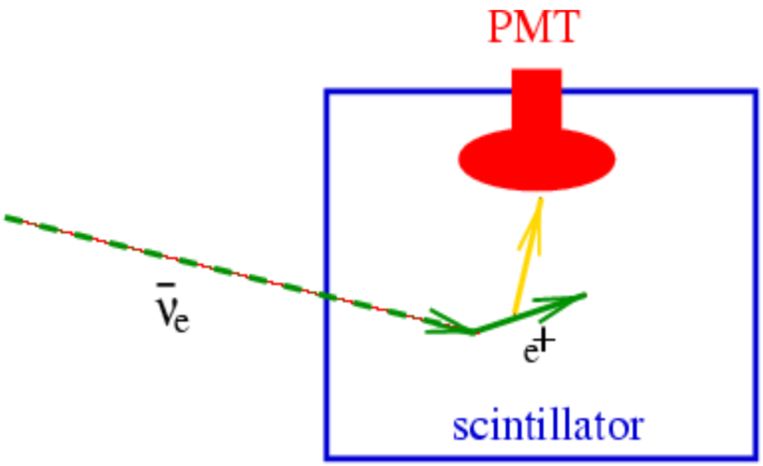
Nominally multi-GeV energy threshold... but, may see burst of low energy $\bar{\nu}_e$'s as *coincident increase in single PMT count rates* (M_{eff}~ 0.7 kton/PMT)

Map overall time structure of burst

IceCube collaboration, A&A 535, A109 (2011)

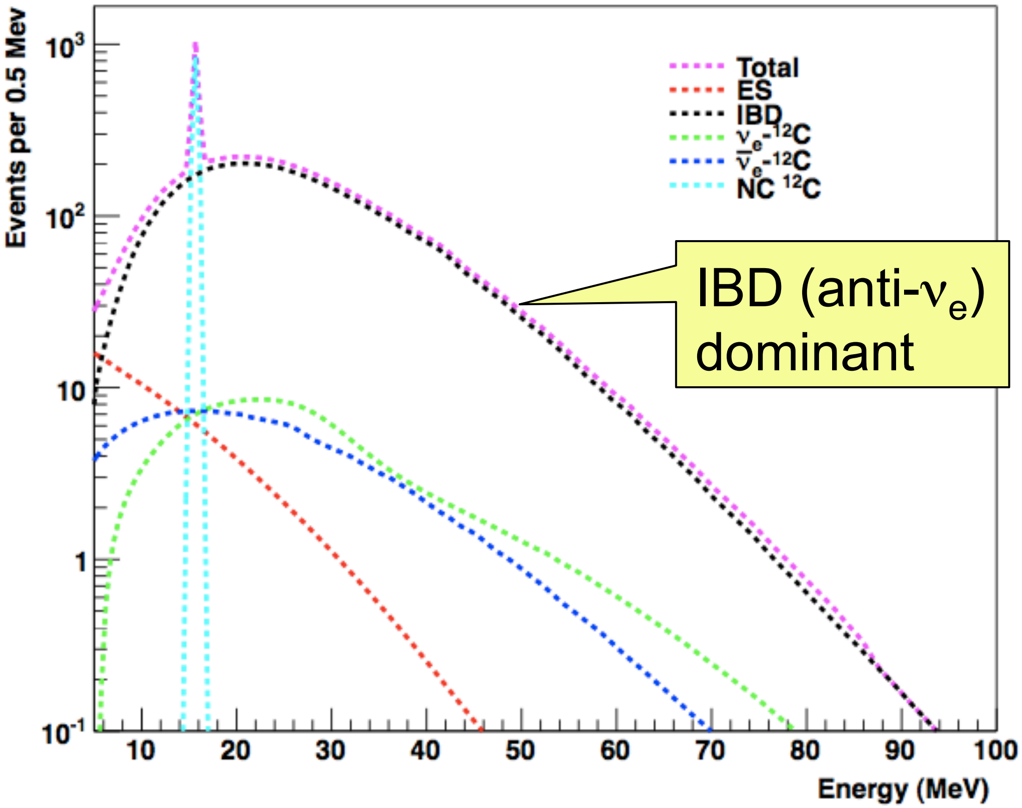


Scintillation detectors



Liquid scintillator (C_nH_{2n}) volume surrounded by photomultipliers

- few 100 events/kton (IBD)
- low threshold, good energy resolution
- little pointing capability (light is ~isotropic)

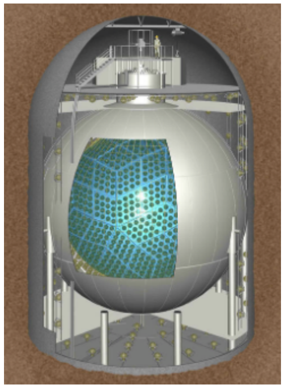


IBD (anti-ν_e) dominant

50 kt @ 10 kpc

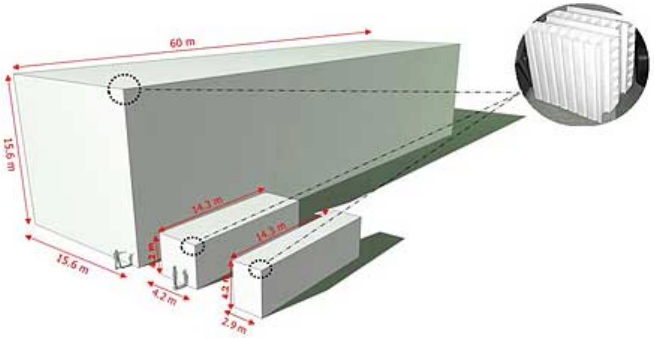
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



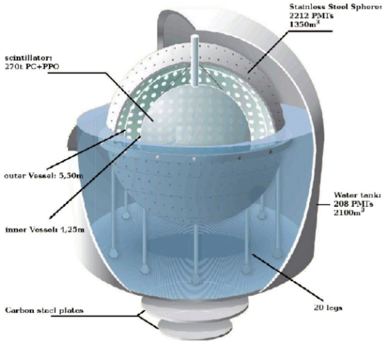
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

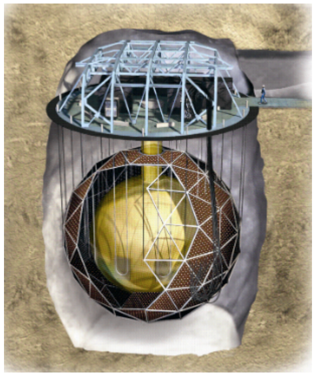


(on surface, but
may be possible
to extract counts
for known burst)

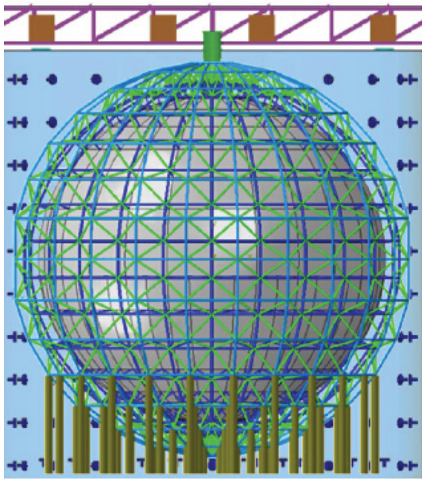
Borexino
(Italy)
0.33 kton



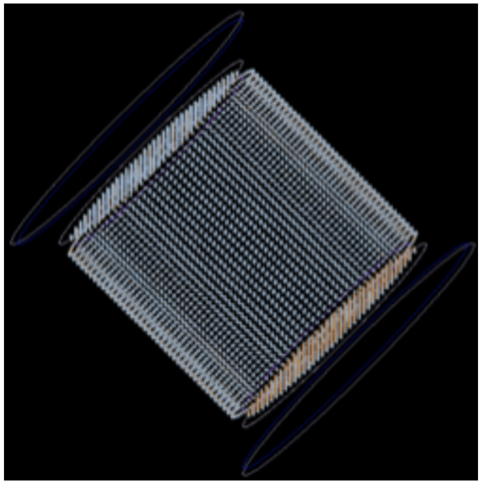
SNO+
(Canada)
1 kton



Future detector proposals



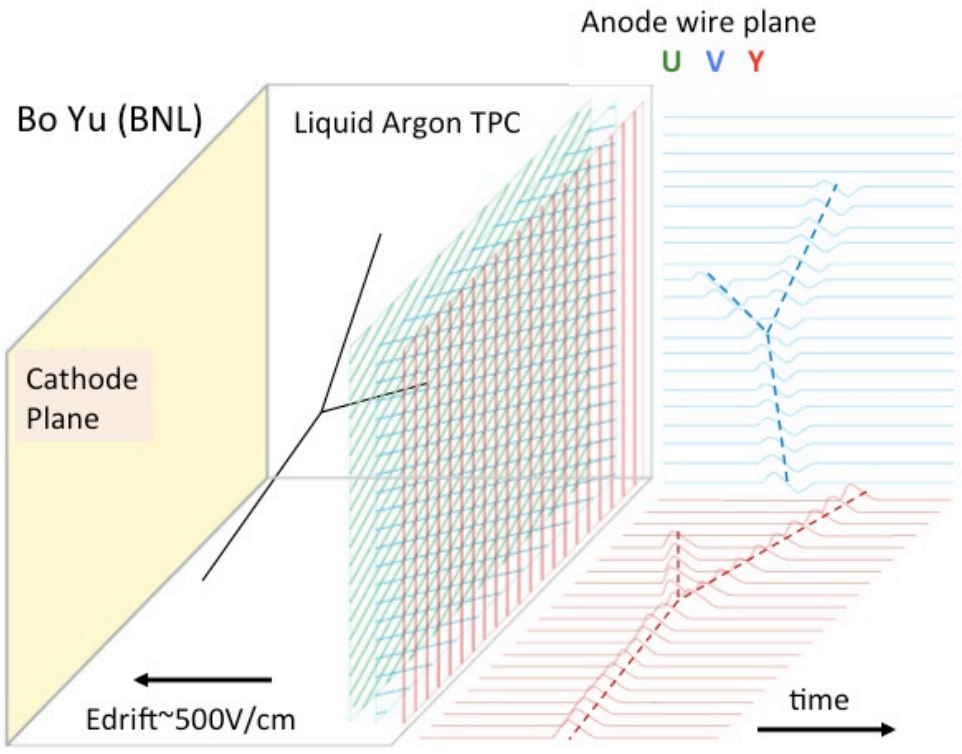
JUNO
(China)
20 kton



RENO-50
(S. Korea)
18 kton

LENA
(Finland)
50 kton

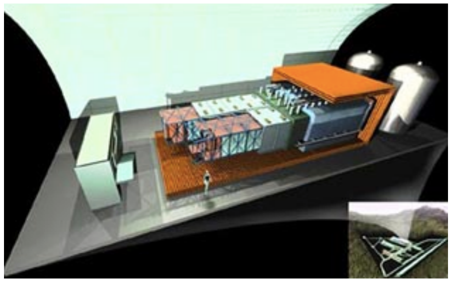
Liquid argon time projection chambers



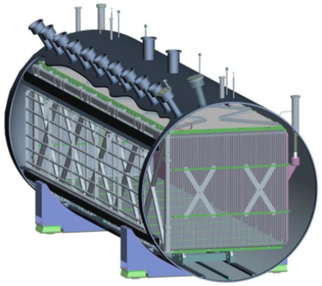
- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

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

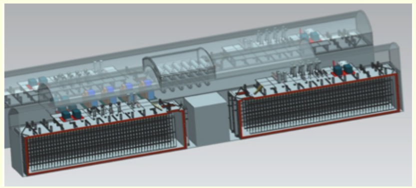
ICARUS
(Italy...)
0.6 kton



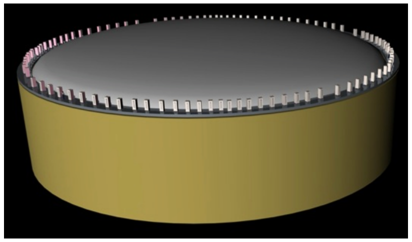
MicroBooNE
(USA)
0.2 kton



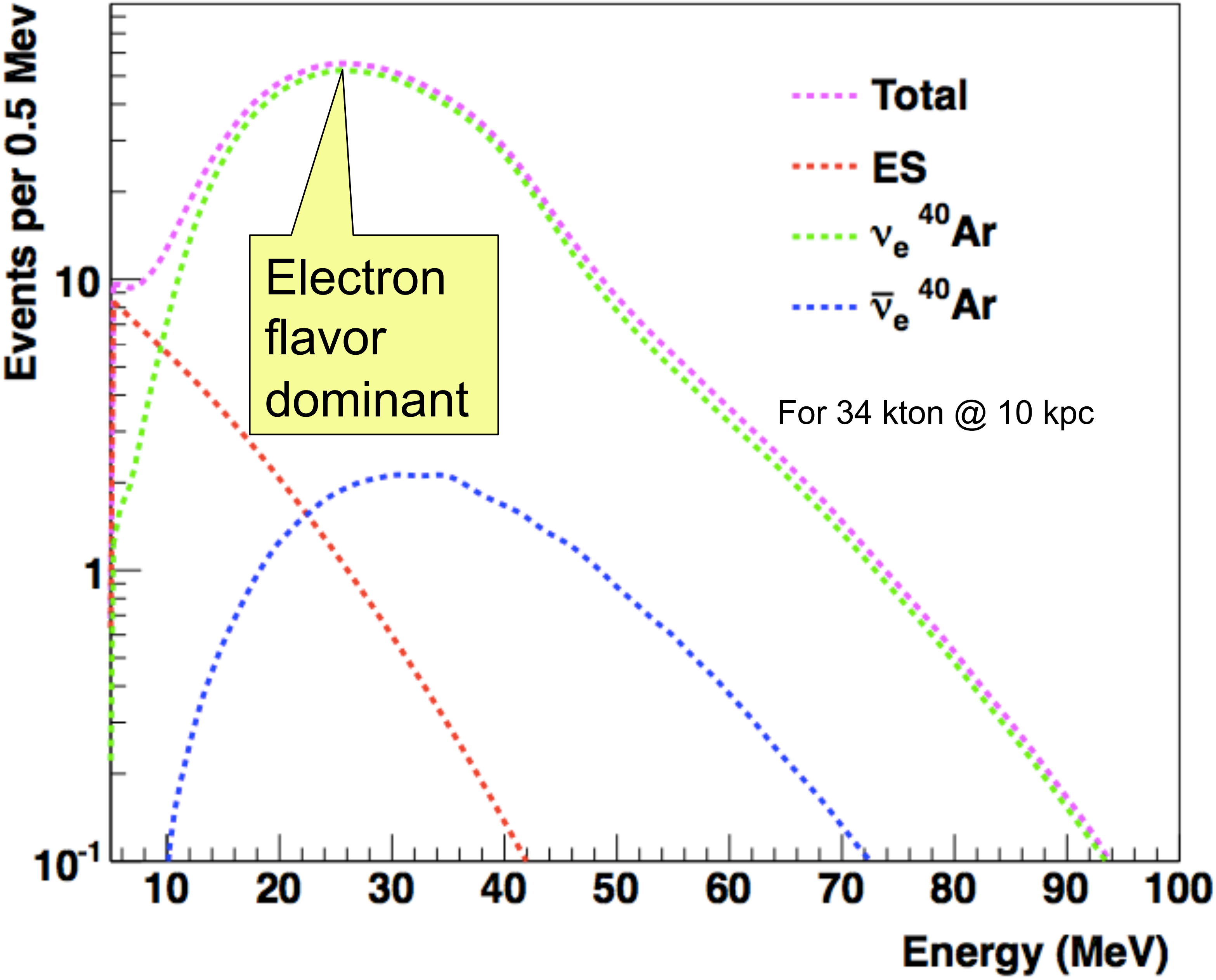
DUNE
(USA)
40 kton



GLACIER
(Europe)
100 kton



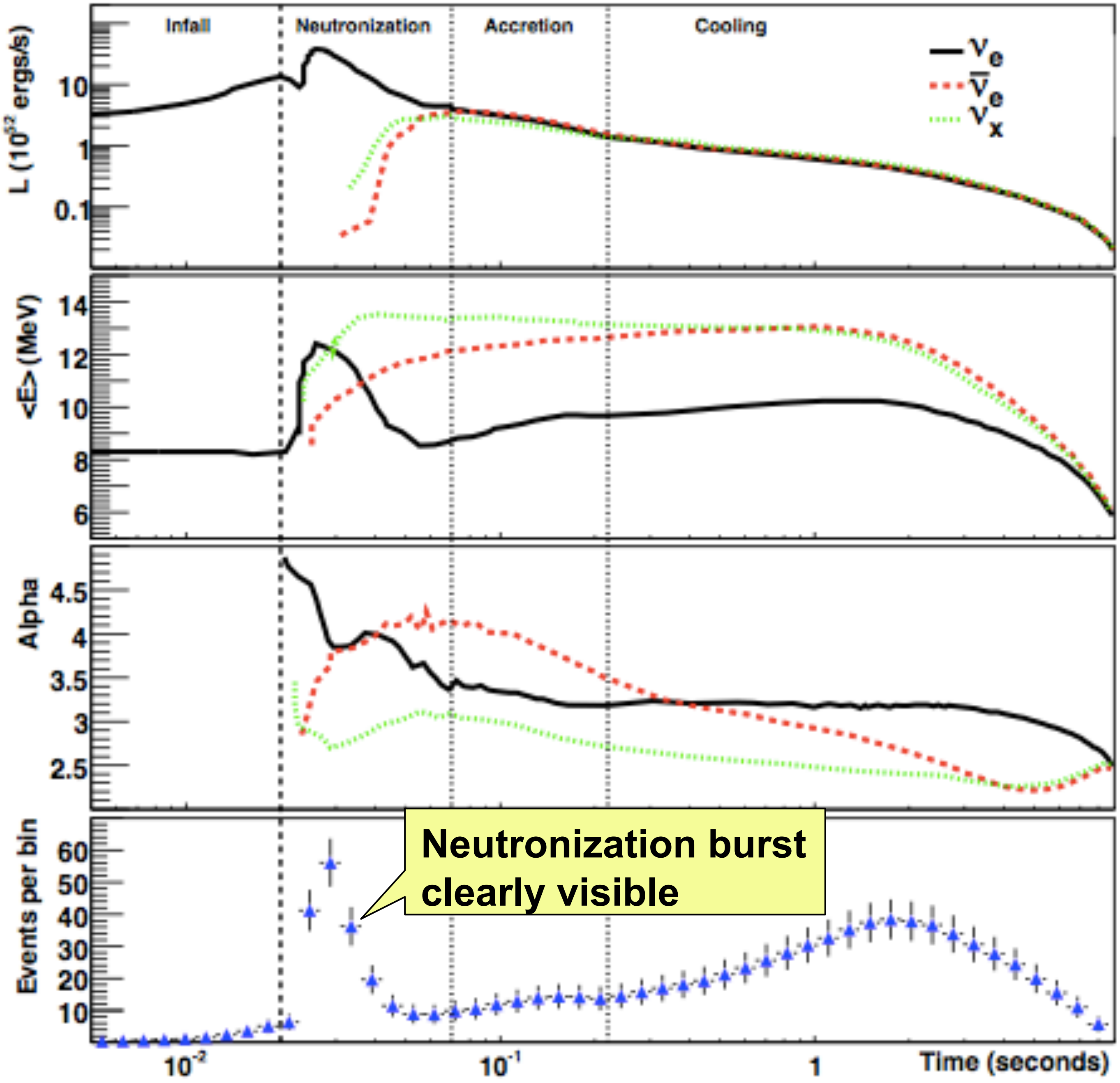
Supernova signal in a liquid argon detector


Events seen, as a function of observed energy

Electron flavor dominant

For 34 kton @ 10 kpc

Example of supernova burst signal in 34 kton of LAr



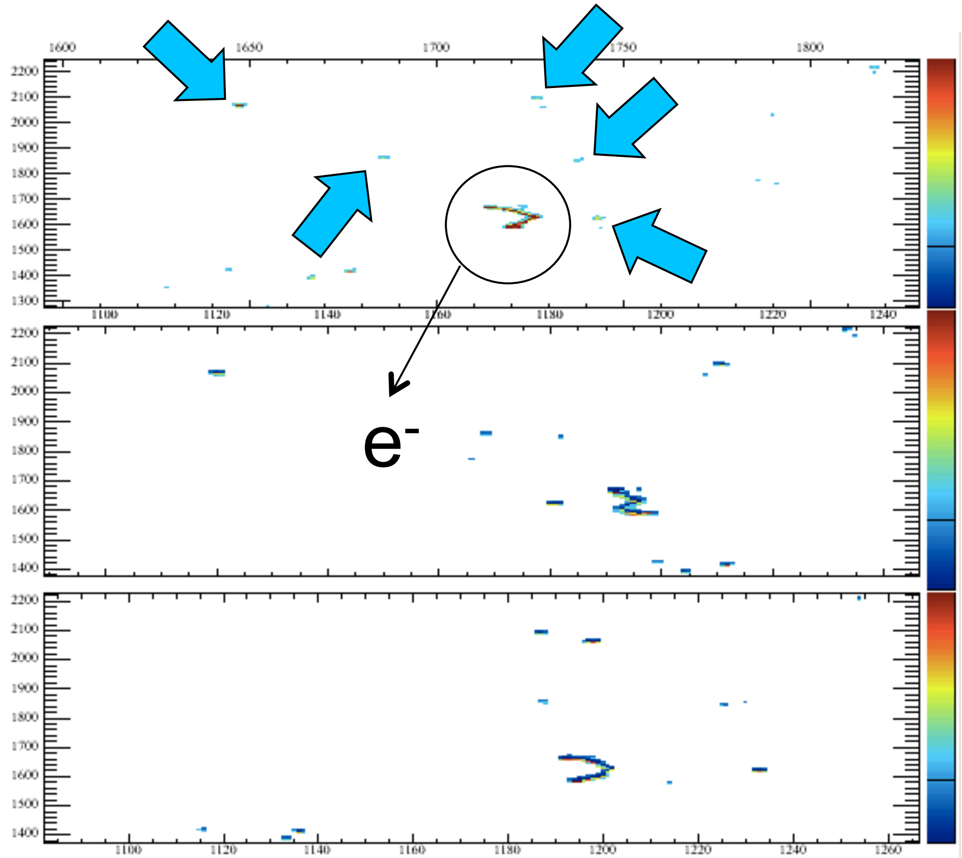
Neutronization burst clearly visible

Flux from Huedepohl et al., PRL 104 (2010) 251101 (“Garching”) @ 10 kpc

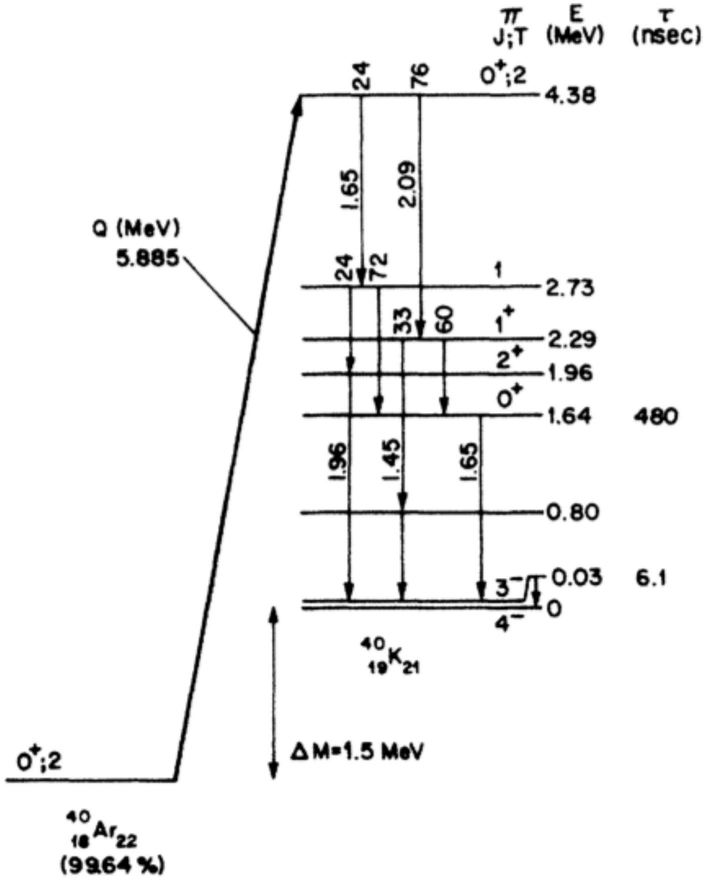
See the ν_e light curve!

Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

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



MicroBooNE geometry (LArSoft)



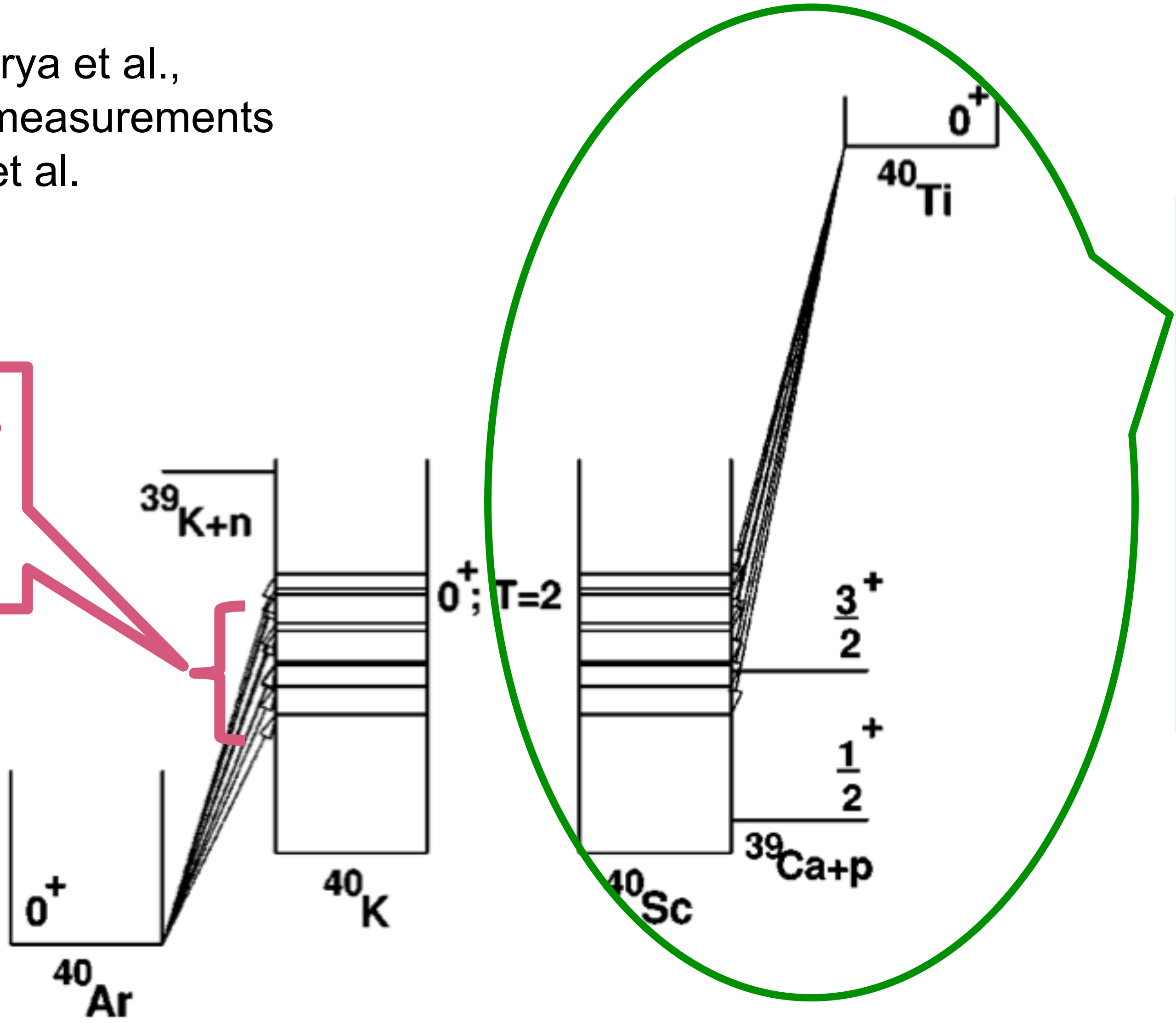
20 MeV ν_e , 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088
Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements in progress
Direct measurements (and theory) needed!

… in fact there can be transitions to intermediate states, adding to the cross section (and complicating the γ-tag)

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer measurements
by Trinder et al.



these states can be populated

measure relative strengths with βdk of ^{40}Ti to mirror nucleus

Lead-based supernova detectors

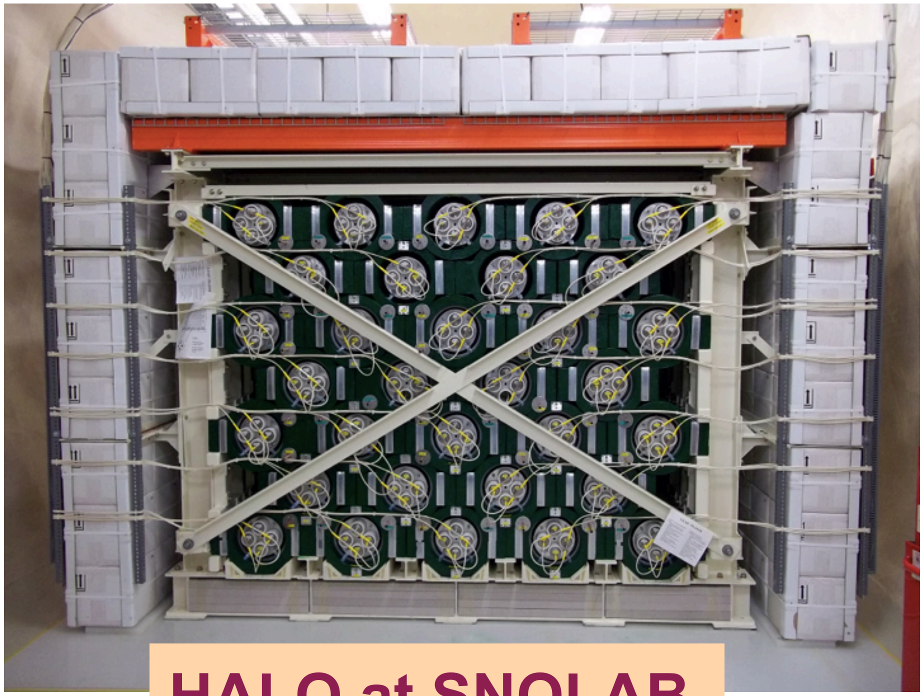
$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$ CC

1n, 2n emission

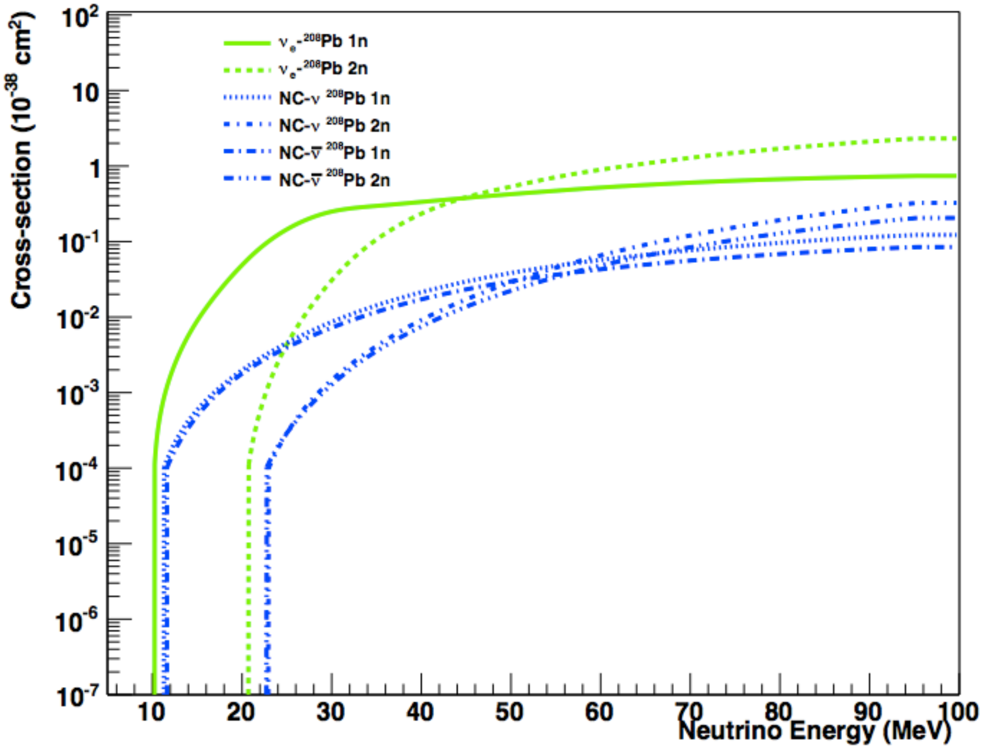
$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x$ NC

1n, 2n, γ emission

Relative 1n/2n rates
sharply dependent
on neutrino energy
⇒ spectral
sensitivity



HALO at SNOLAB



SNO ^{3}He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

Coherent Elastic Neutrino Nucleus Scattering

$$\nu_x + A \rightarrow \nu_x + \boxed{A}$$

C. Horowitz et al., PRD68 (2003) 023005

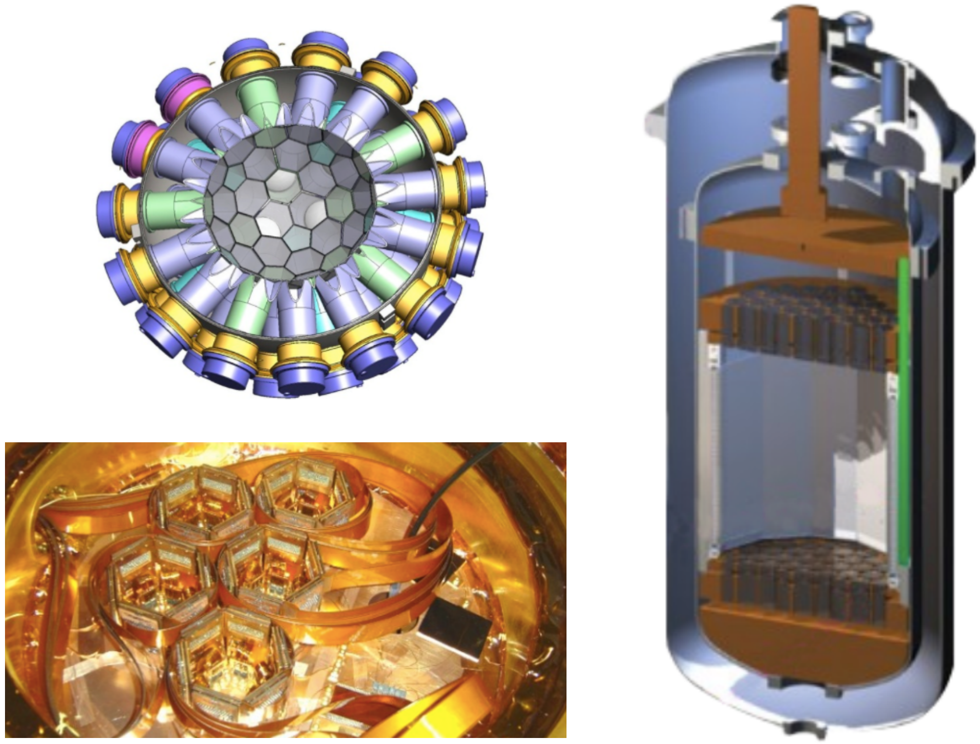
High x-scn but *very* low recoil energy (10's of keV)

⇒ observable in DM detectors

~ few events per ton
for Galactic SN

ν_x energy information
from recoil spectrum

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



DM detectors,
e.g. CLEAN/DEAP, LUX, ...

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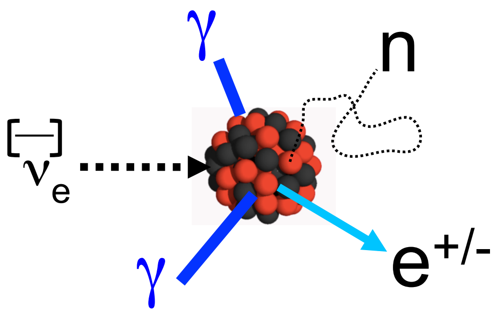
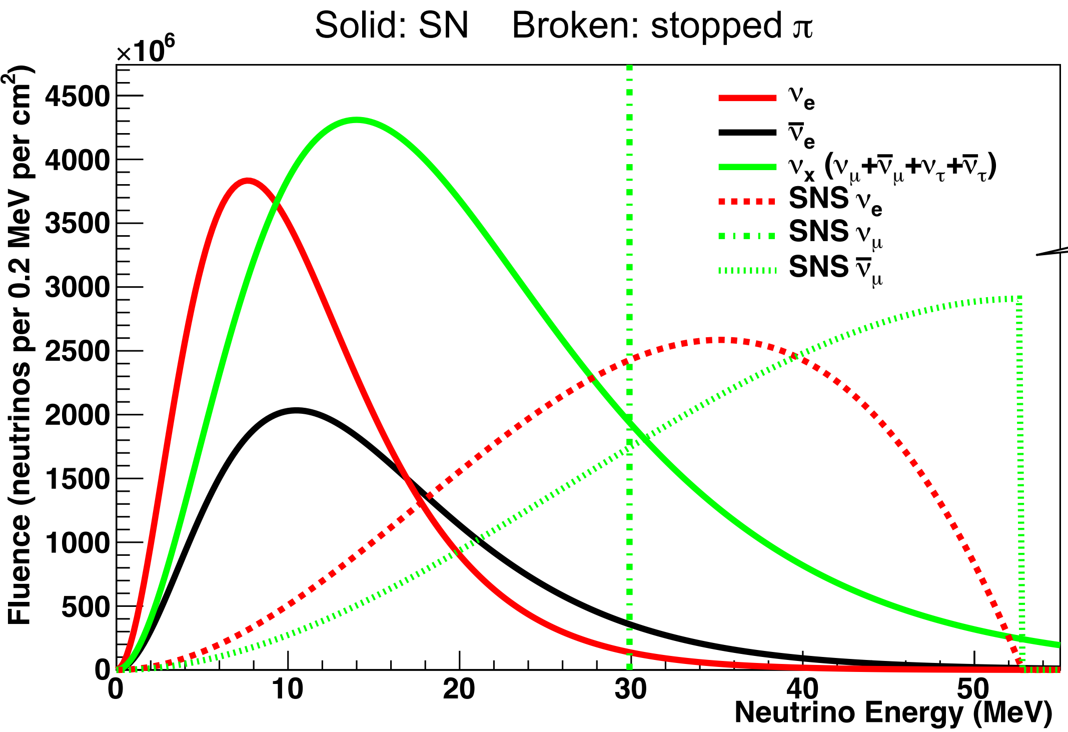


Interactions with nuclei
(cross sections & products)
very poorly understood...
sparse theory & experiment
(*only* measurements at better
than ~50% level are for ^{12}C)



Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source and far off-axis at the Fermilab BNB

A. Bolozdynya et al., arXiv:1211.5199

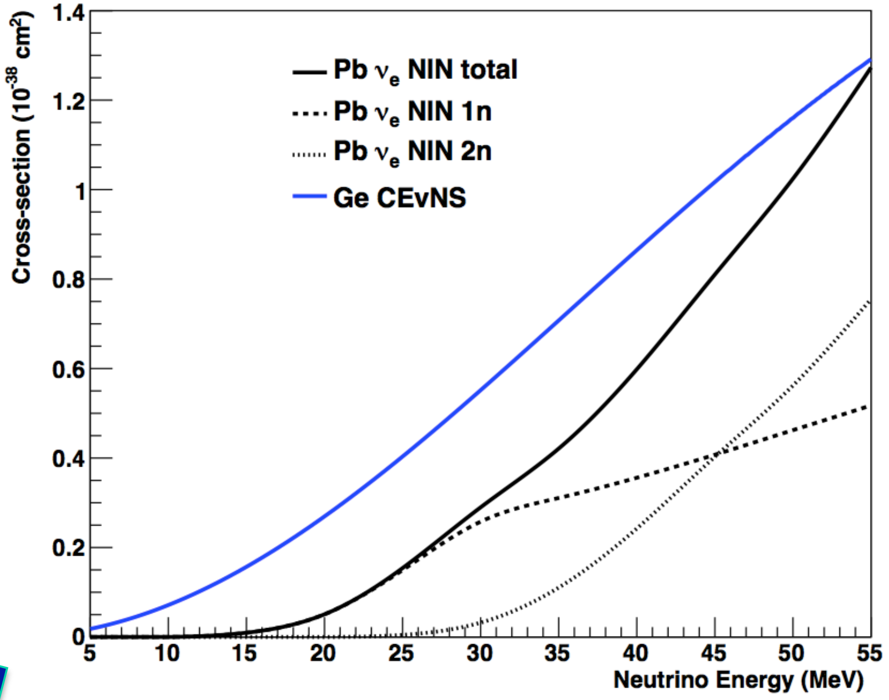
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

1n, 2n emission

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

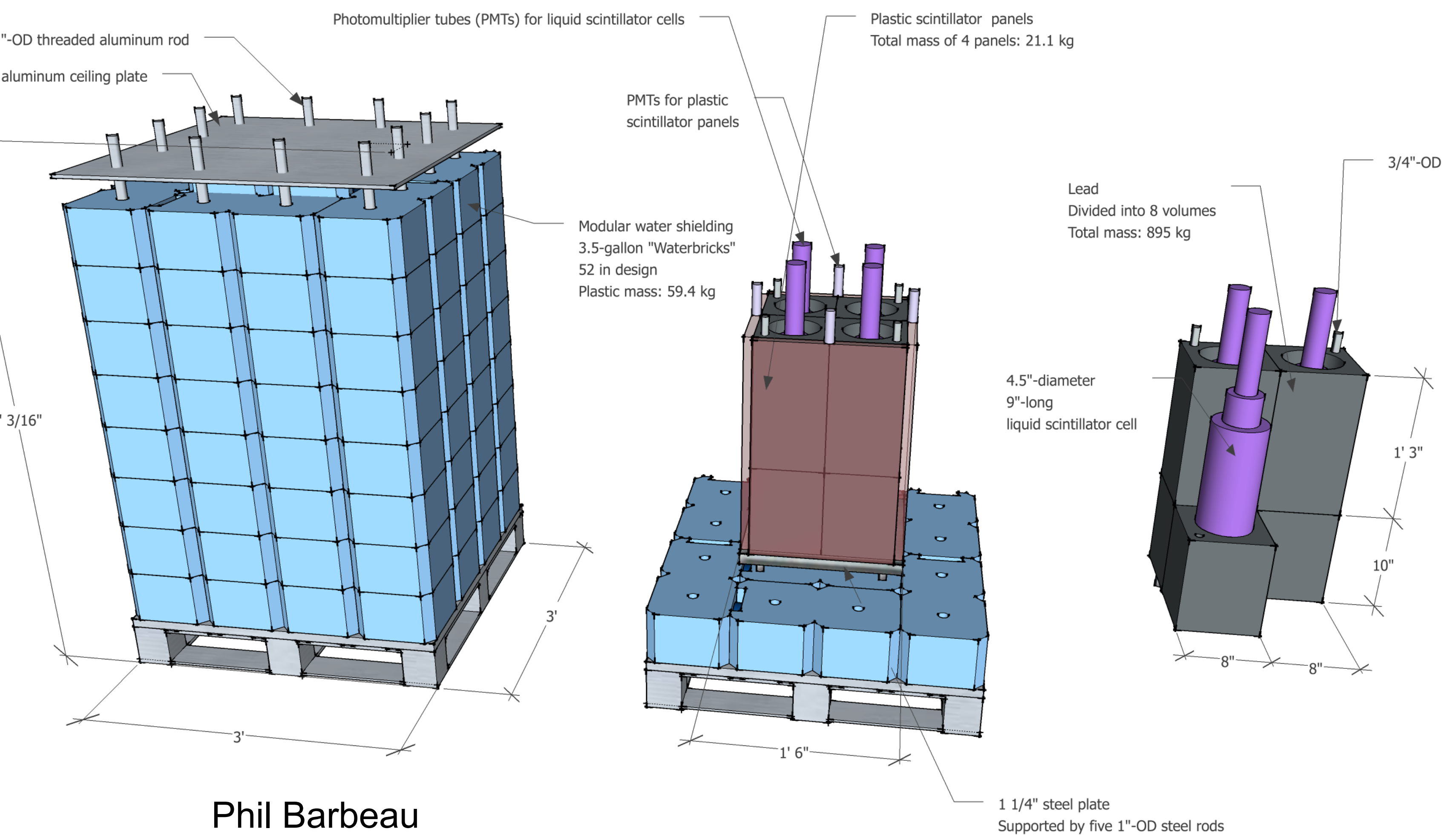
1n, 2n, γ emission



Likely a non-negligible background to CEvNS, especially in lead shield

NIN measurement in SNS basement

- Scintillator inside CsI detector lead shield (now)
- Liquid scintillator surrounded by lead (swappable for other NIN targets) inside water shield



Phil Barbeau

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Summary of supernova neutrino detectors

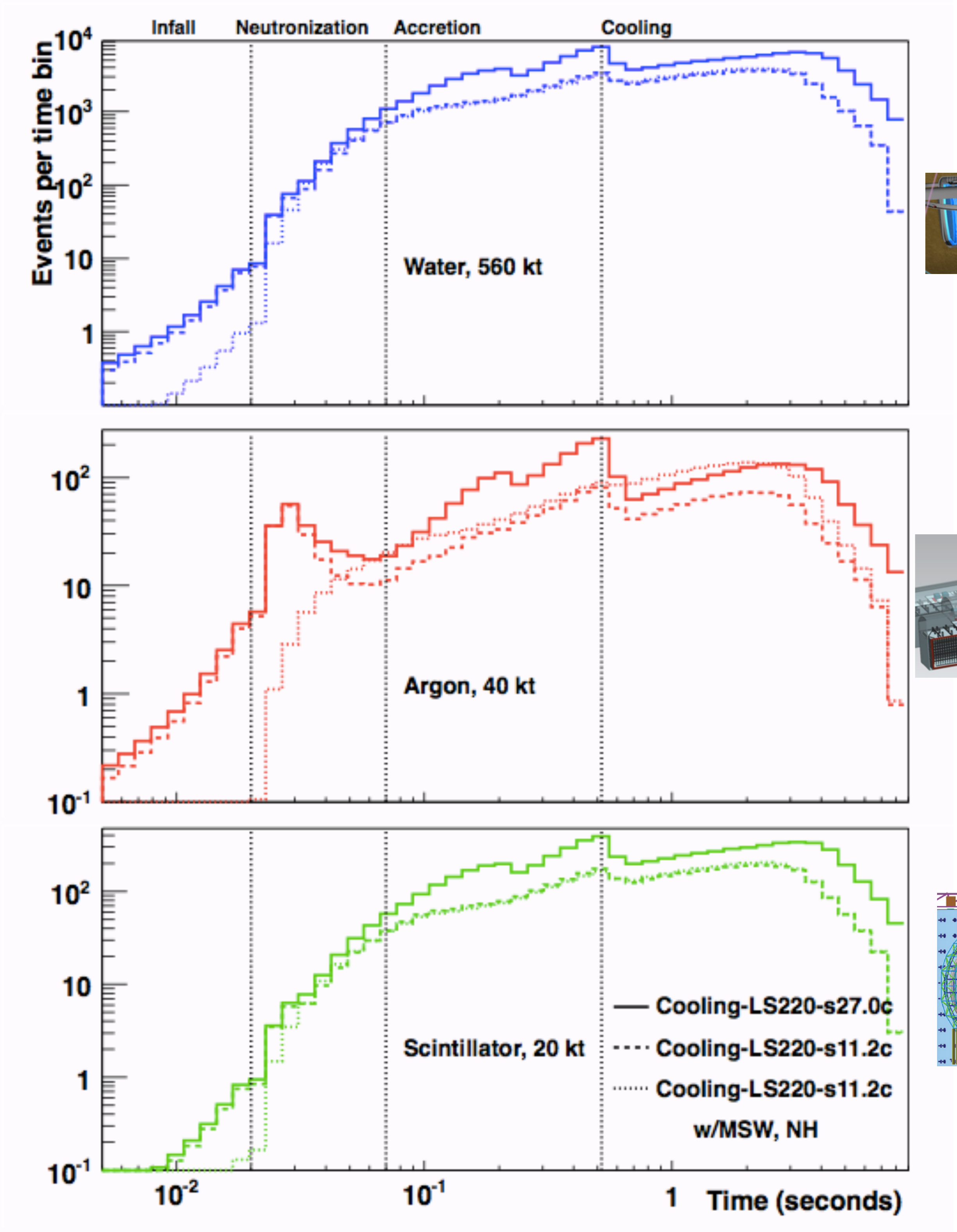
Galactic sensitivity

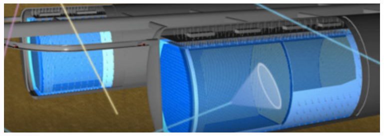
Extragalactic

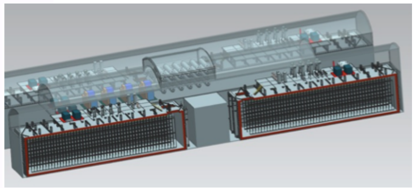
Detector	**Type**	**Location**	**Mass (kton)**	**Events @ 10 kpc**	**Status**
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOνA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
DUNE	Liquid argon	USA	40	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Proposed
RENO-50	Scintillator	South Korea	18	5400	Proposed
PINGU	Long string	South pole	(600)	(10^6)	Proposed

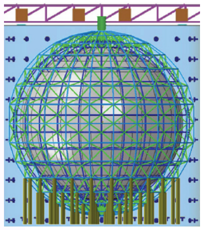
plus reactor experiments, DM experiments...

Example signals in future detectors



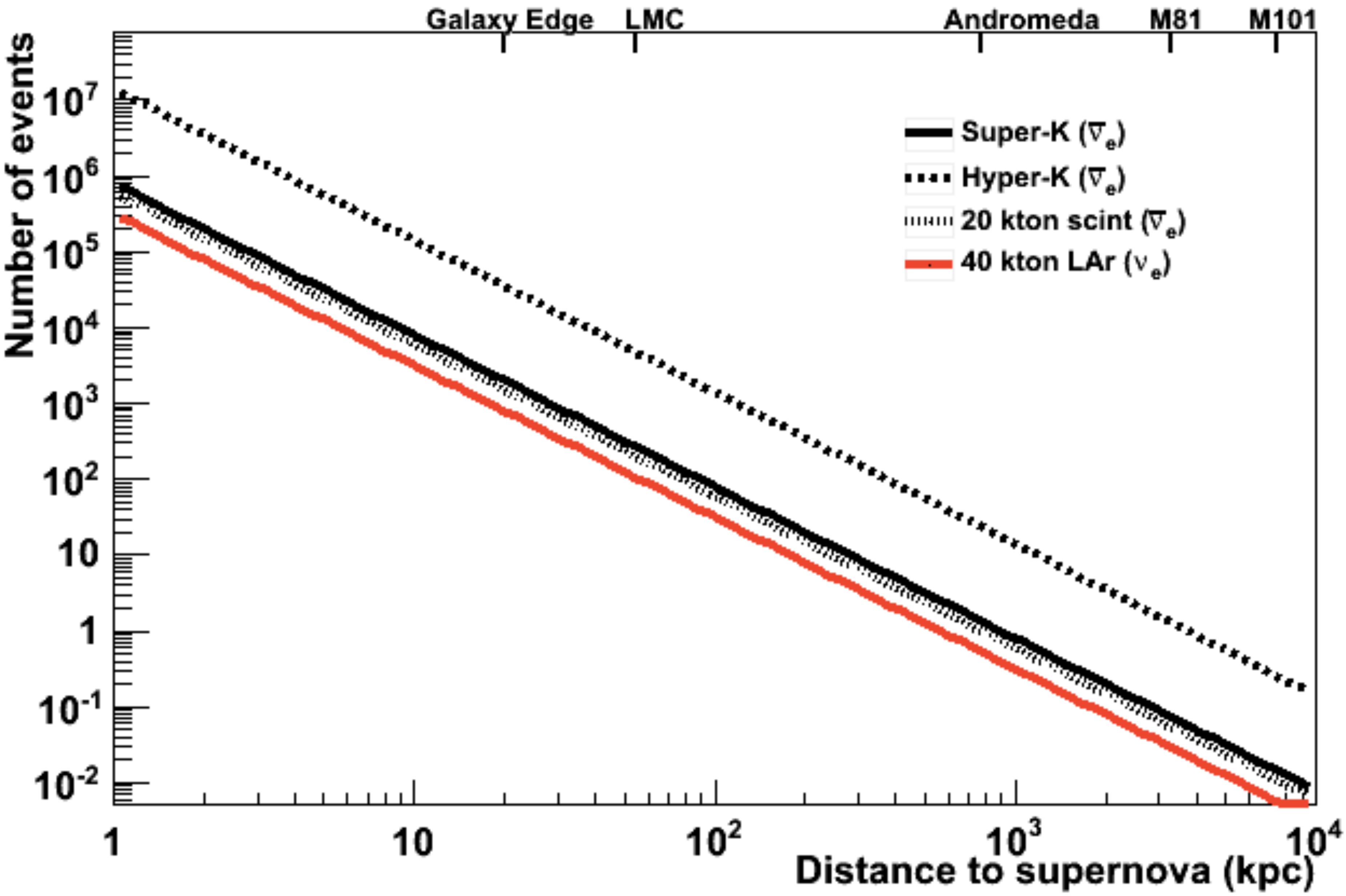






(note logarithmic time bins)

Distance reach for future detectors



SK will see ~1 event from Andromeda; HK will get a ~dozen

Summary

Vast information to be had from a core-collapse burst!

- Need energy, flavor, time structure

Current & near future detectors:

- ~Galactic sensitivity
  (SK reaches barely to Andromeda)
- sensitive mainly to the $\bar{\nu}_e$ component of the SN flux
- excellent timing from IceCube
- early alert network is waiting
- we need to measure some x-scns

Farther future megadetectors

- huge statistics: extragalactic reach
- richer flavor sensitivity (e.g. ν_e in LAr)
- multimessenger prospects