Supernova Neutrino Detection

Kate Scholberg, Duke University

KITP, Santa Barbara, November 2014

OUTLINE

- Supernova neutrinos: what we're after

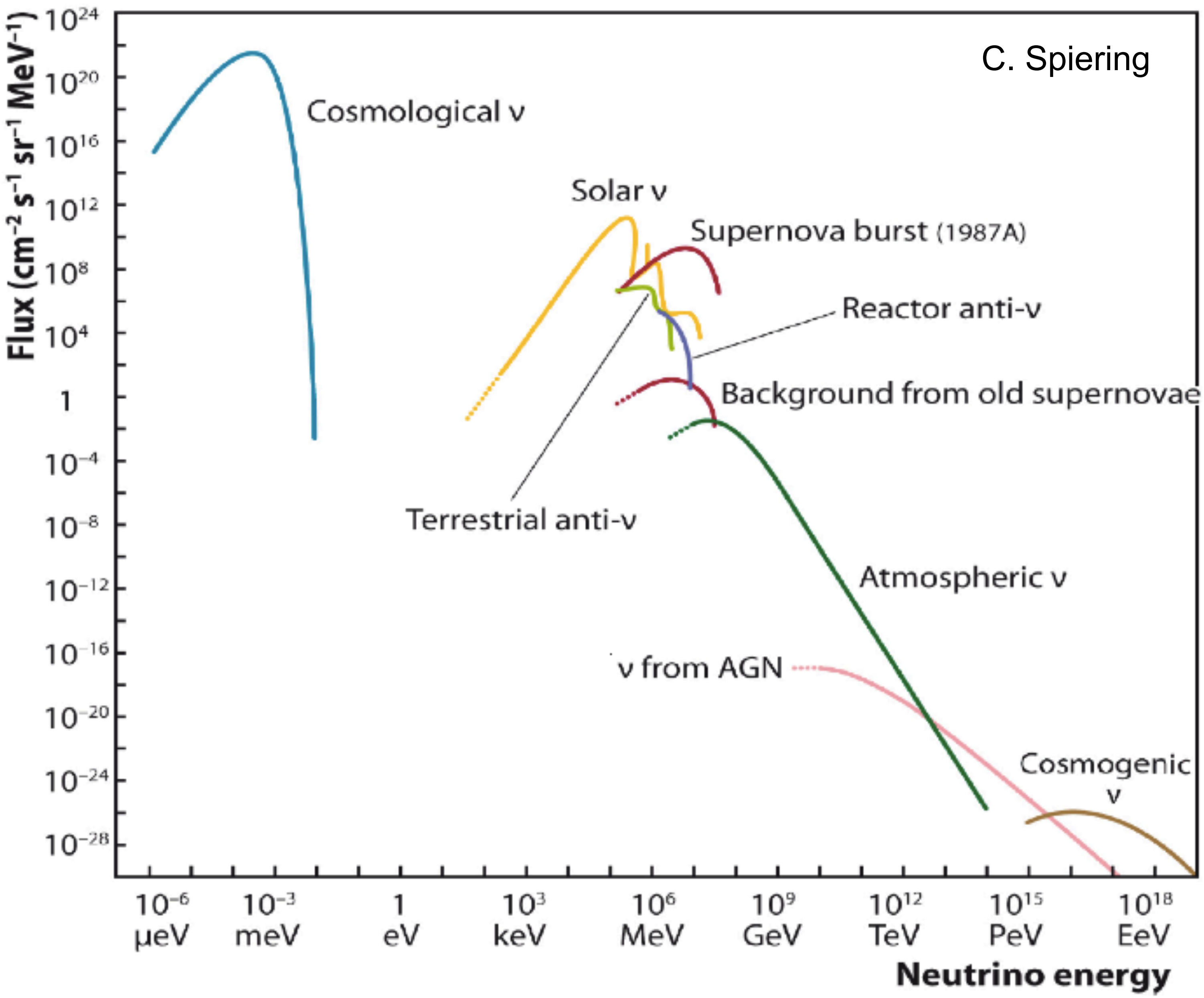
- Detection interactions

- Detector types, and current & future detectors

- Aside: measuring supernova-relevant cross sections

- The early alert

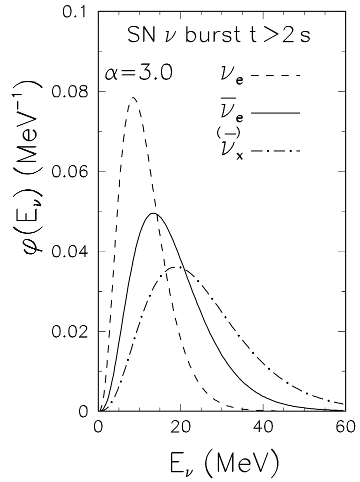
The supernova neutrino signal

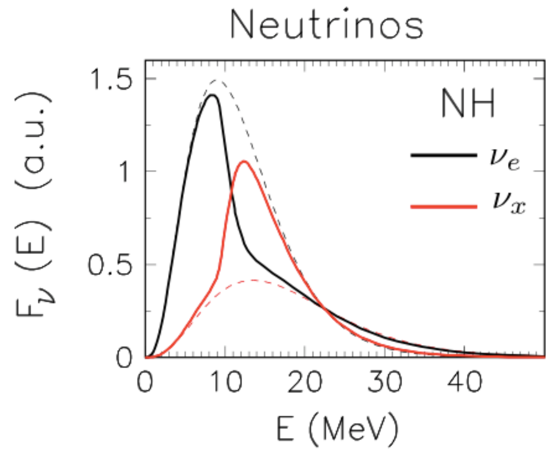


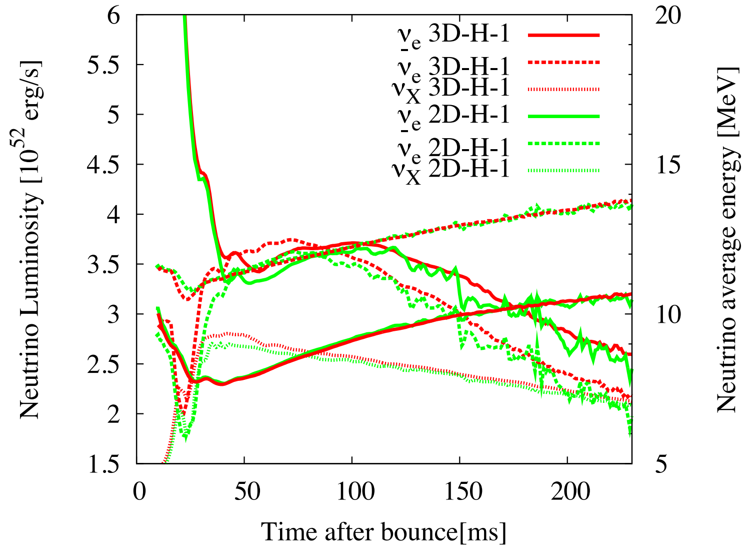
Enormous, transient flux of tens-of-MeV neutrinos of all flavors

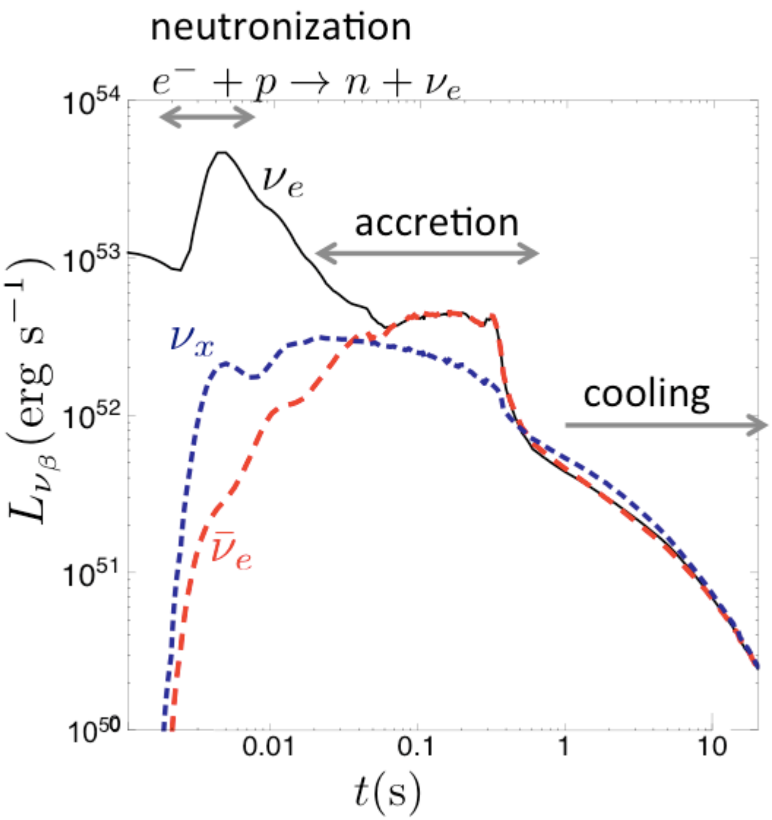
The supernova neutrino signal

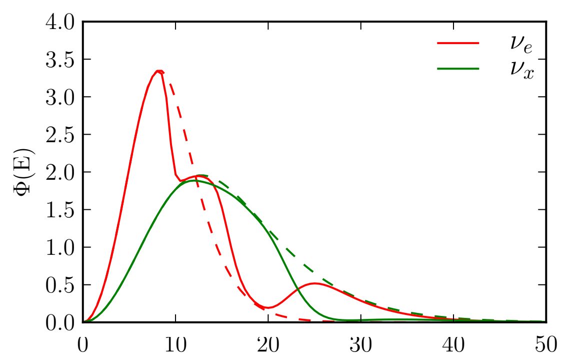
Examples...

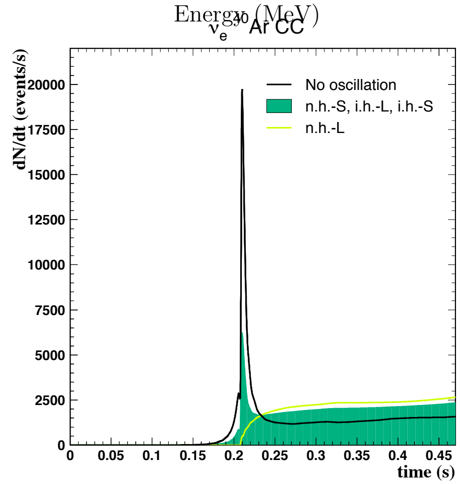


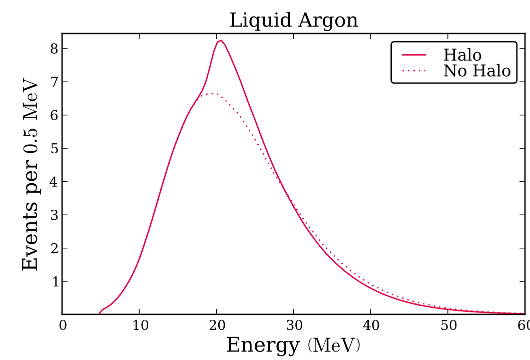












Vast information about physics & astrophysics encoded in spectral evolution

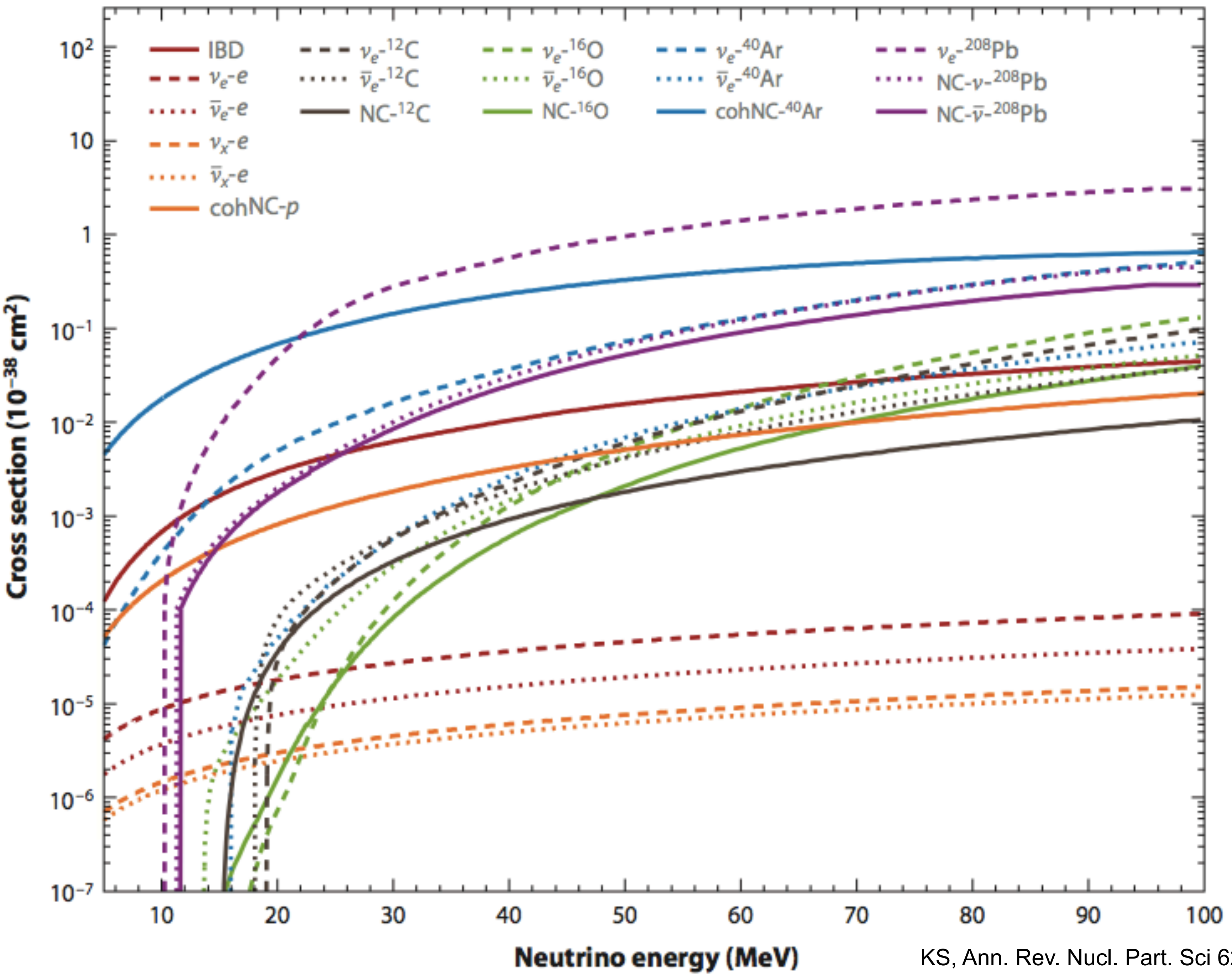
Information is in the ***energy, flavor, time*** structure of the burst

What do you want in a detector?

Size	~kton detector mass per 100 events
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"...

Relevant interaction cross sections in the 5-100 MeV range



KS, Ann. Rev. Nucl. Part. Sci 62 (2012) 81

Supernova-relevant neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th></th><th></th></tr>
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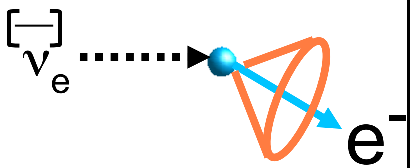
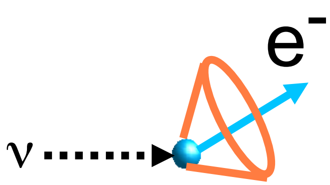
$$\nu + e^- \rightarrow \nu + e^-$$




Useful
for pointing</td><td></td><td></td></tr>
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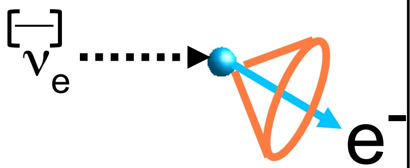
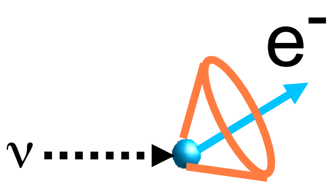
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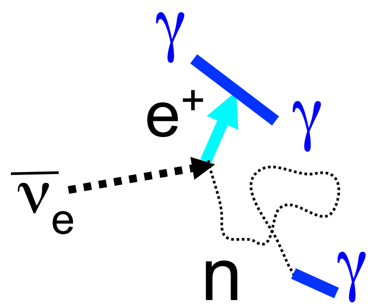</td><td></td></tr>
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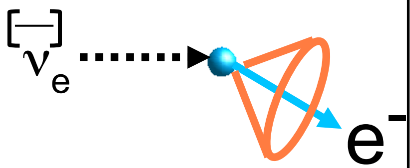
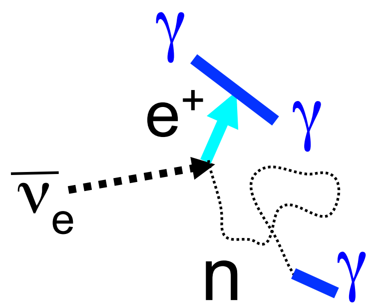
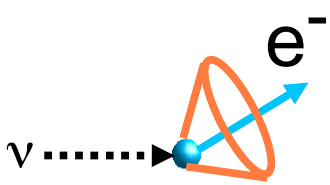
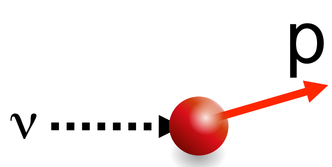
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

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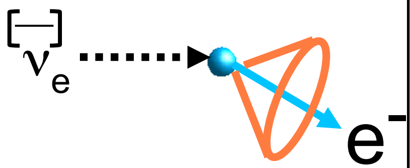
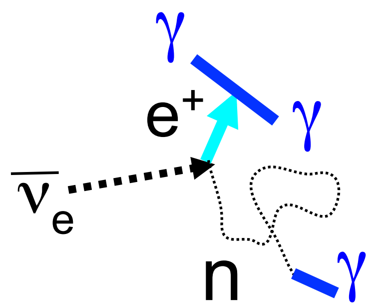
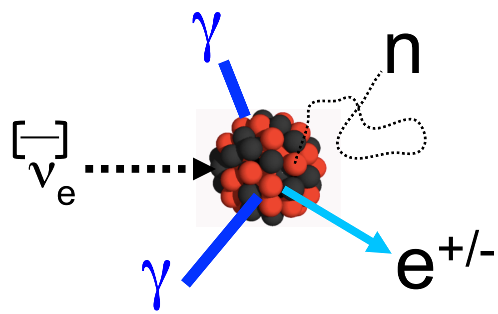
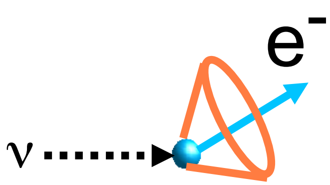
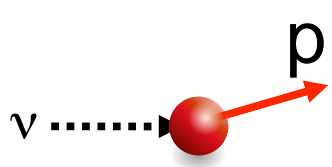
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful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

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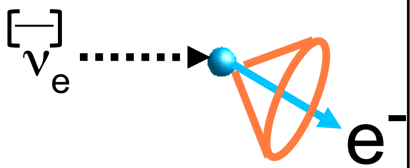
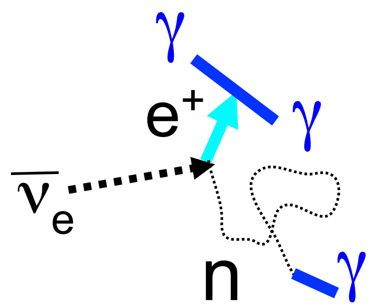
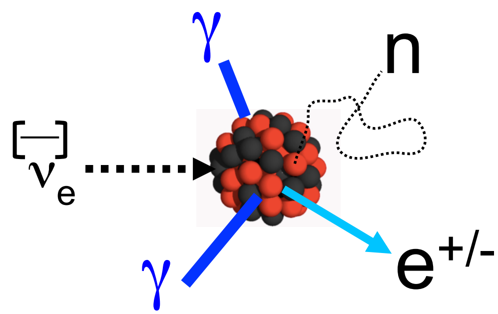
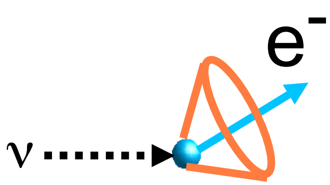
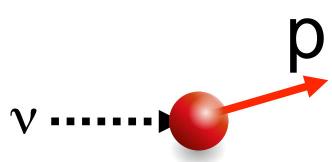
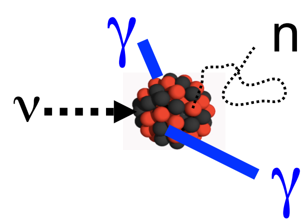
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering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

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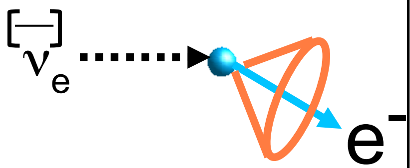
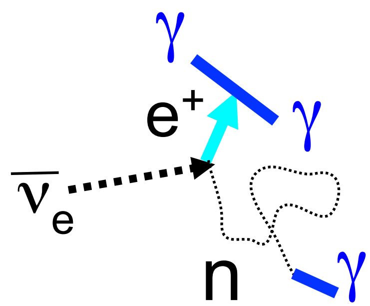
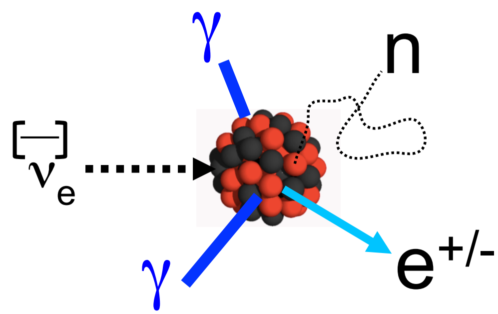
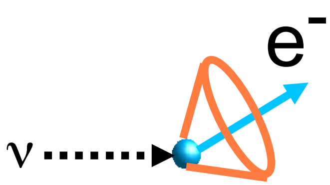
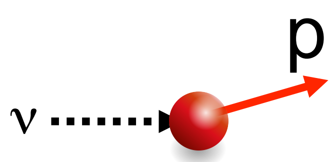
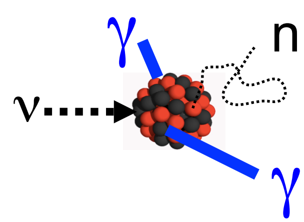
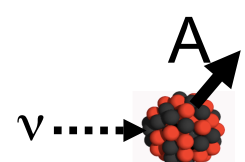
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$  	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$  	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful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

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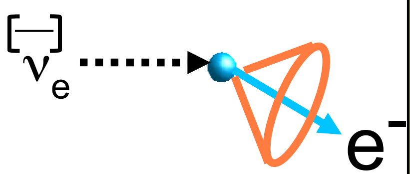
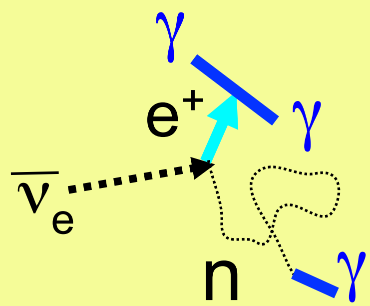
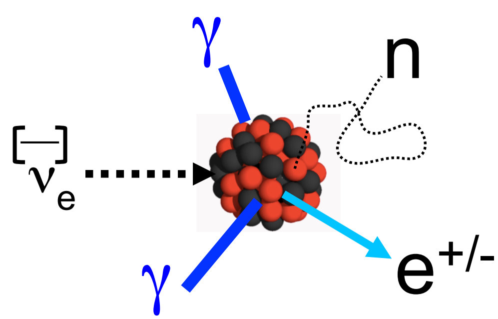
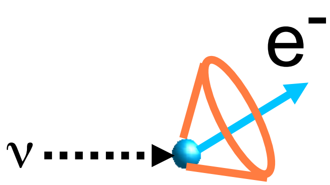
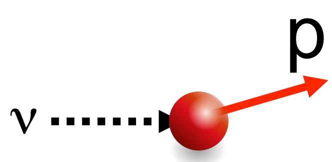
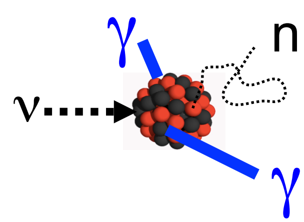
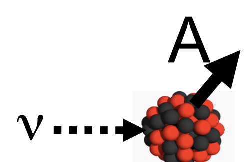
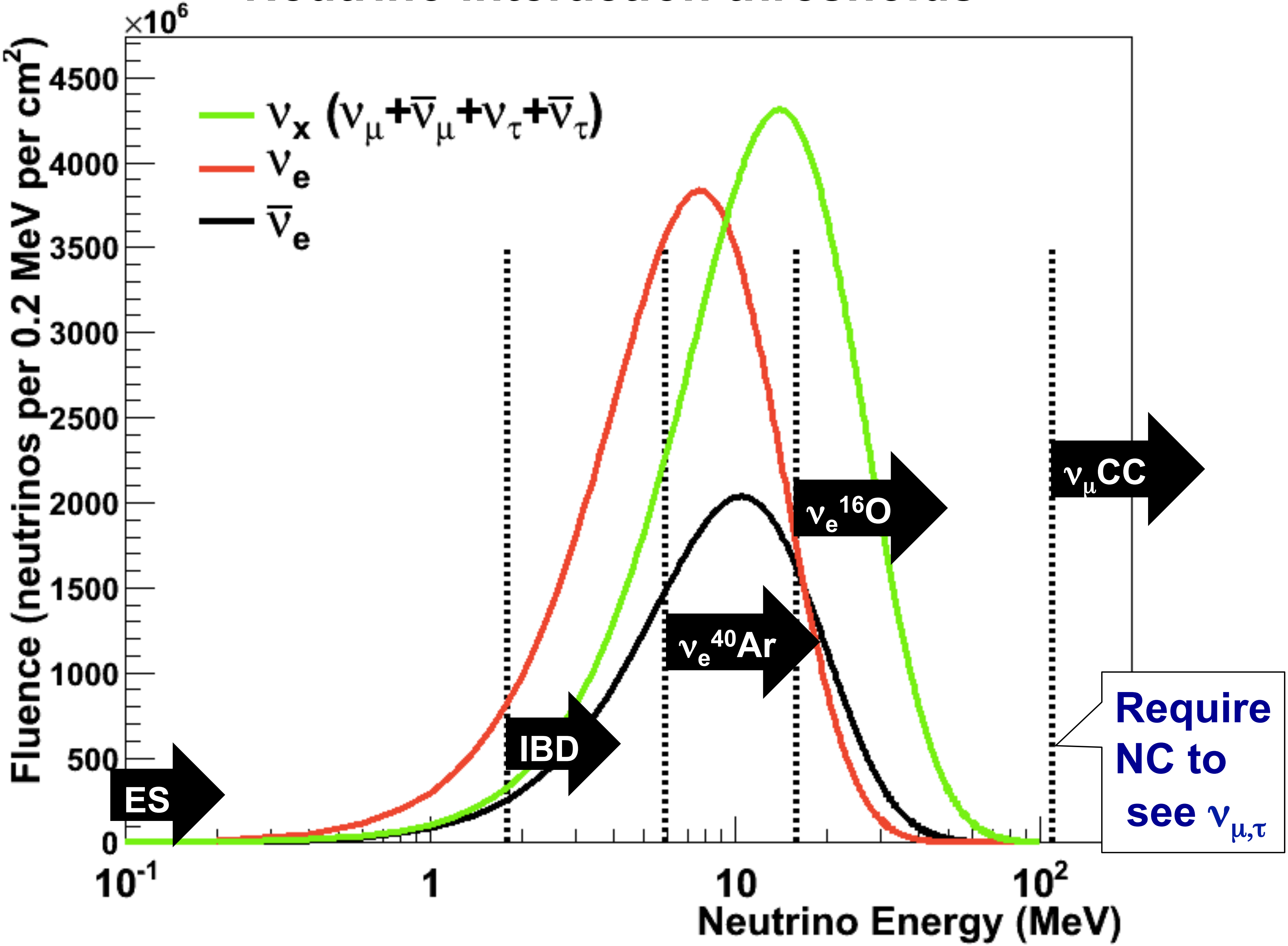
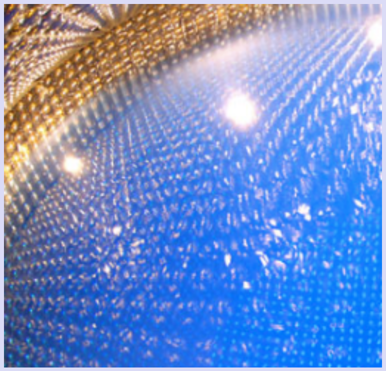
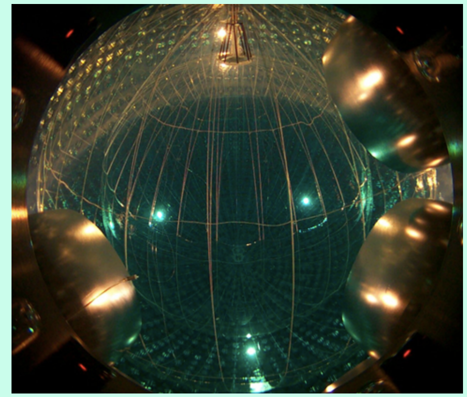
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$  	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$  	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful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

IBD (electron antineutrinos) dominates for current detectors

Neutrino interaction thresholds

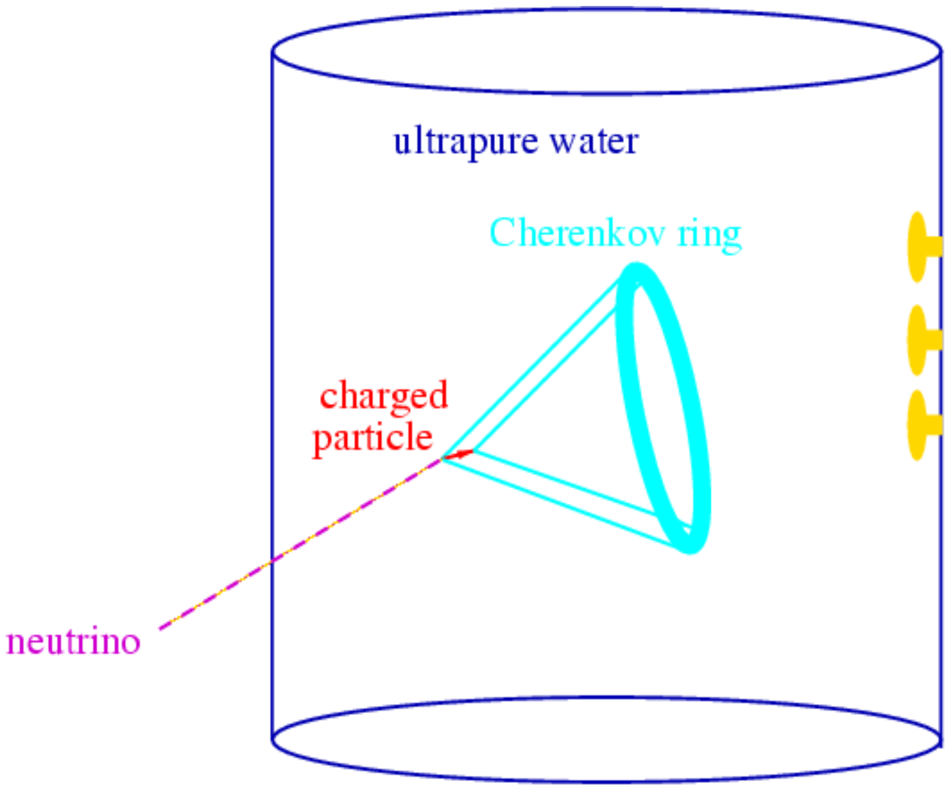


Current main supernova neutrino detector types

Water	Scintillator
 	
Argon	**Lead**
	

+ some others (e.g. DM detectors)

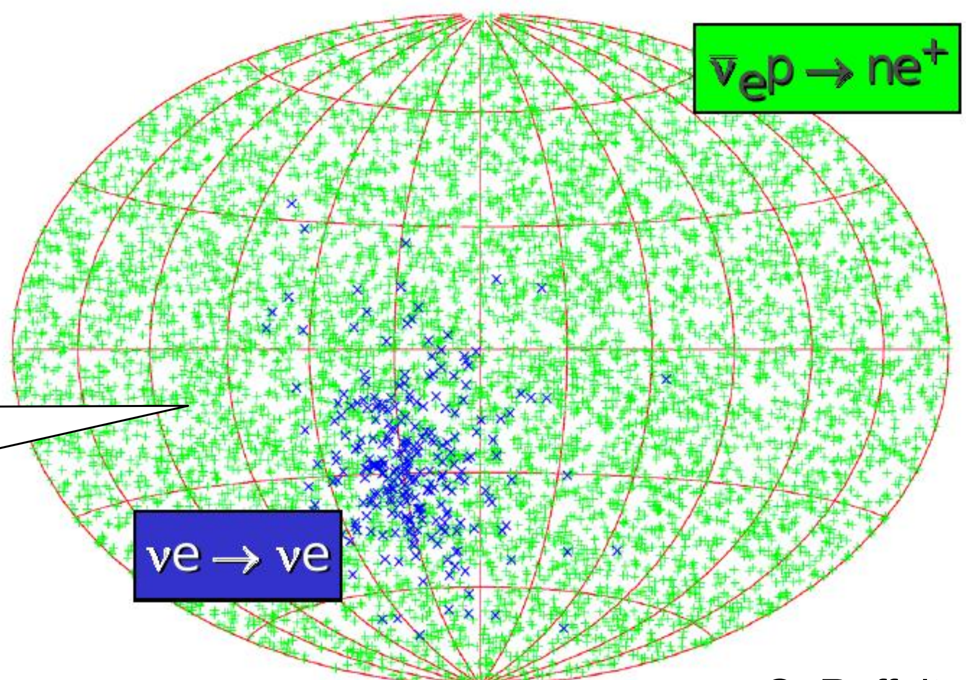
Water Cherenkov detectors



Inverse Beta Decay (CC) dominates

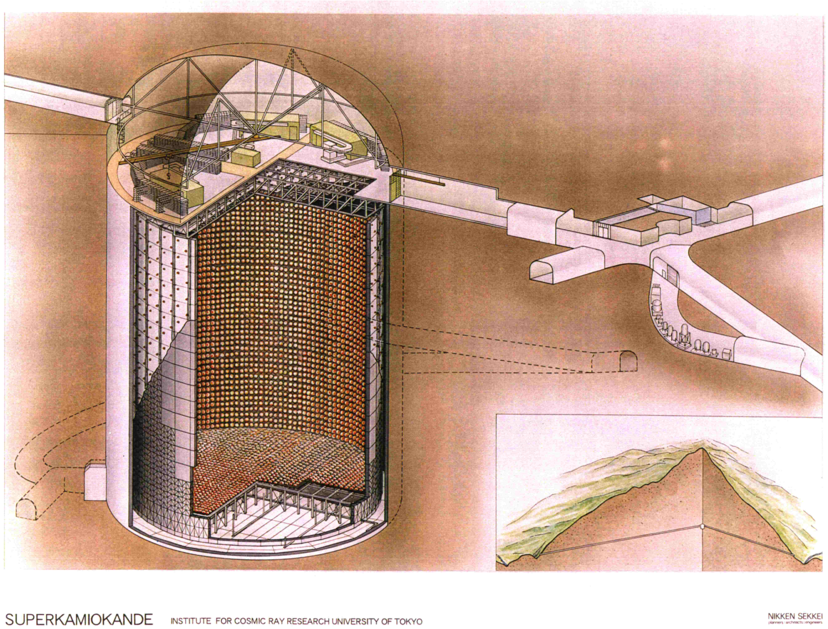
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

E_{thr}=1.8 MeV



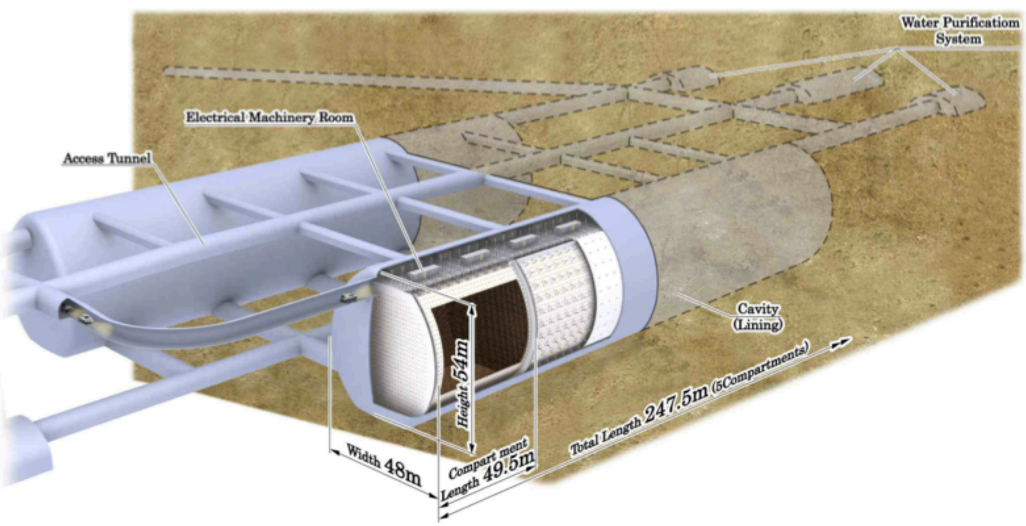
Pointing from neutrino-electron elastic scattering

G. Raffelt



Super-Kamiokande

Mozumi, Japan
22.5 kton fid. volume (32 kton total)
~5-10K events @ 10 kpc
(mostly anti-nue)
New: “SN recorder” will lower threshold during burst for improved sensitivity

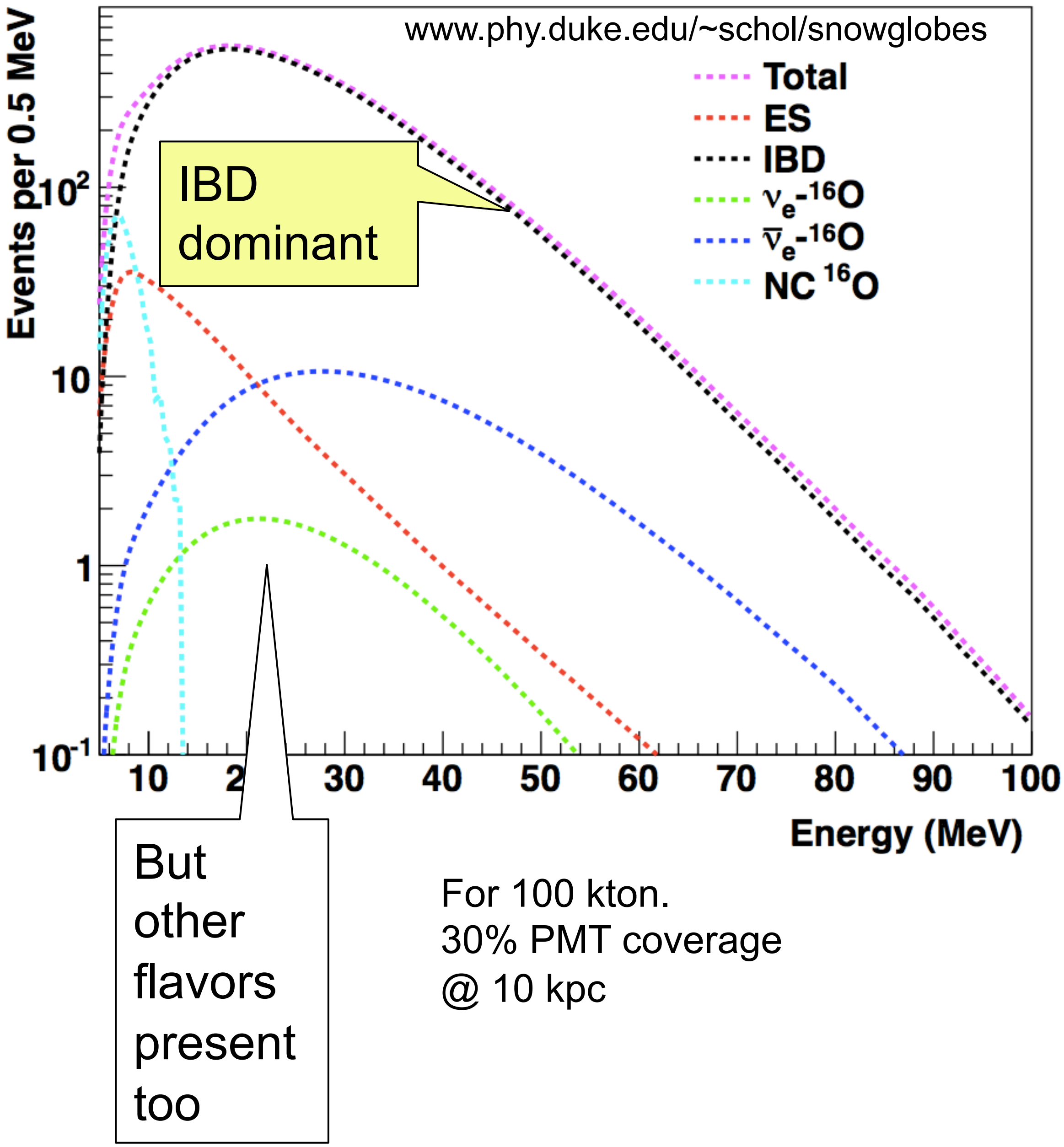


Hyper-Kamiokande

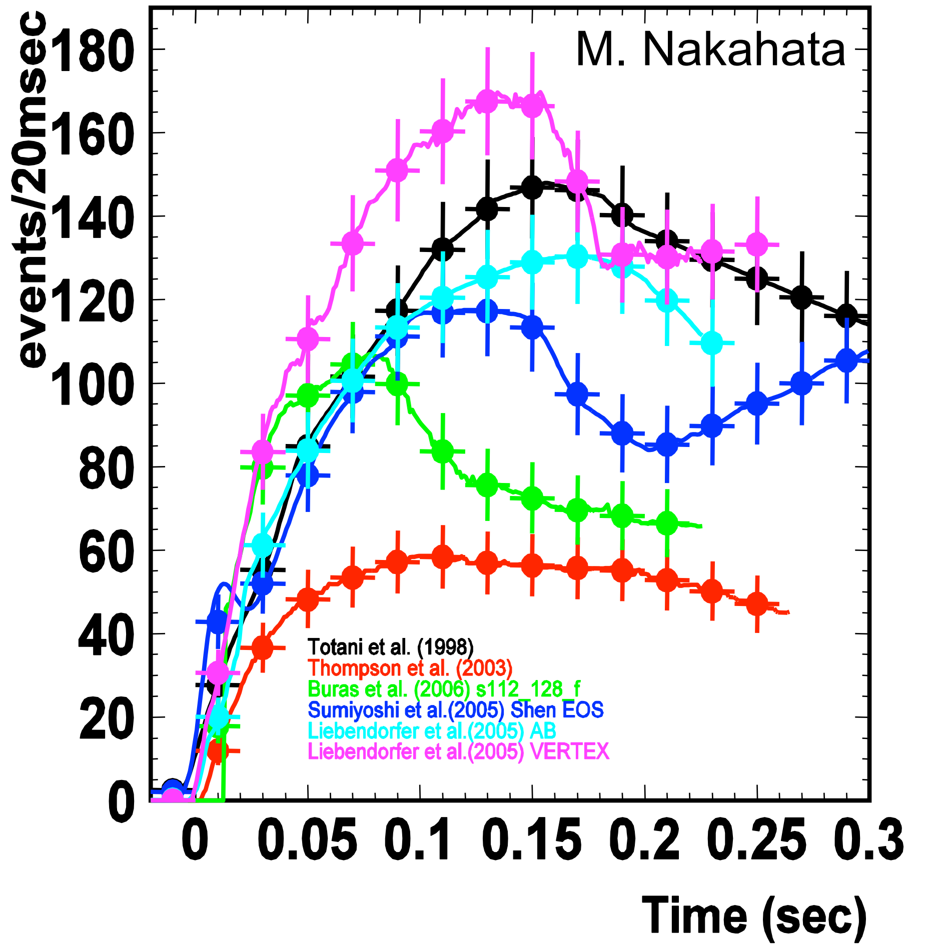
560 kton fiducial volume
Design & site-selection underway
~half photocoverage, but still good efficiency for SN

Supernova signal in a water Cherenkov detector

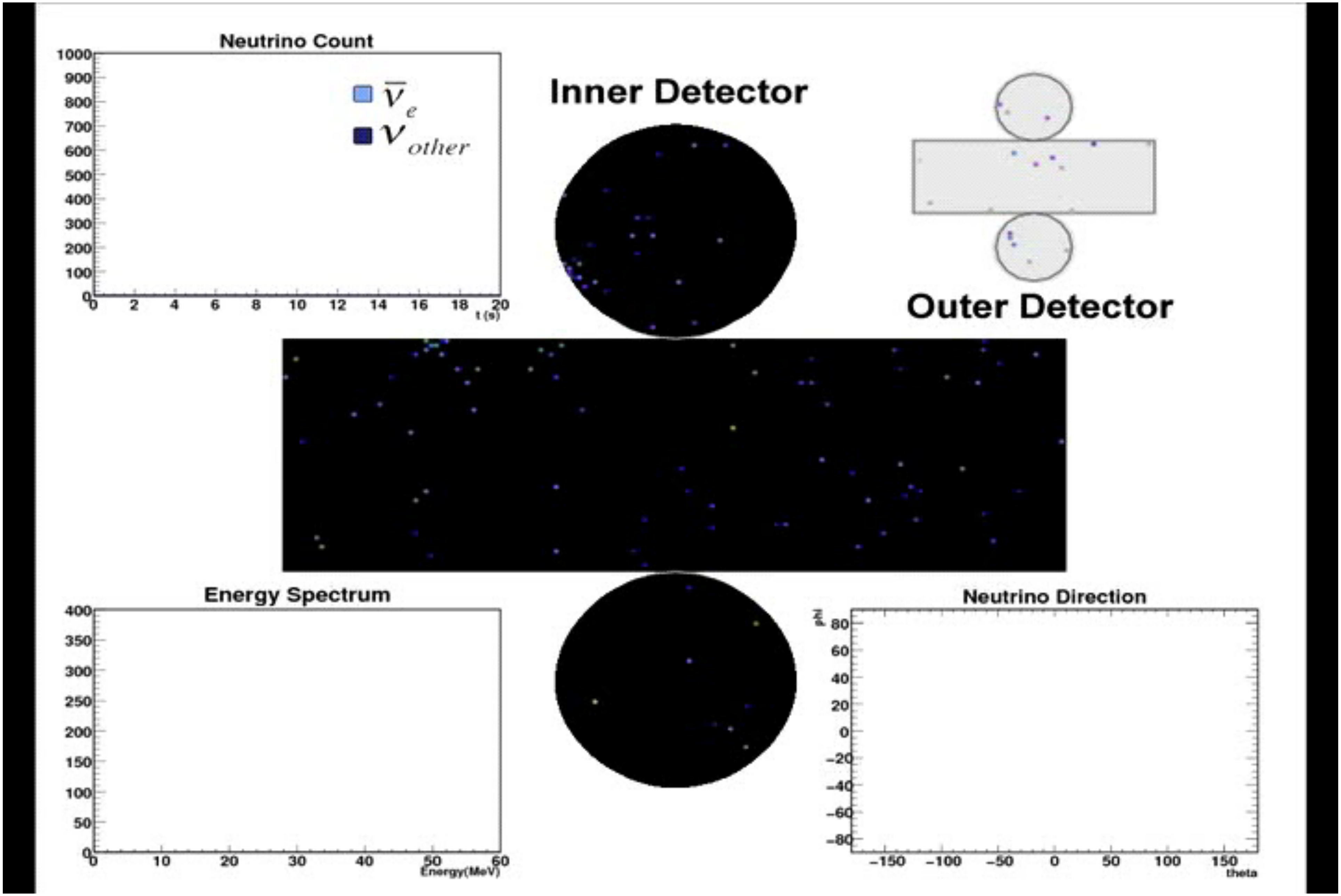
Events seen, as a function of observed energy



For 100 kton.
30% PMT coverage
@ 10 kpc



Events vs time for SK, for different models



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

Neutron tagging in water Cherenkov detectors

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

➔ 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

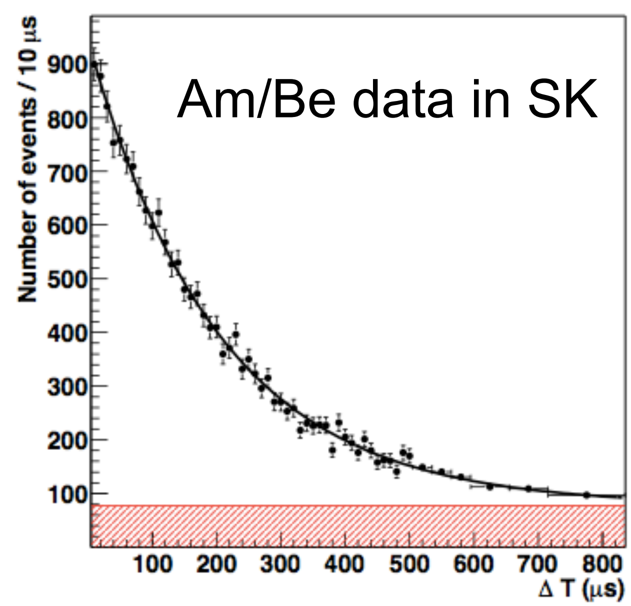
"Drug-free" neutron tagging

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

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

➔ with SK-IV electronics, ~20% n tagging efficiency

SK collaboration, arXiv:1311.3738; see also R. Wendell talk



Enhanced performance by doping!

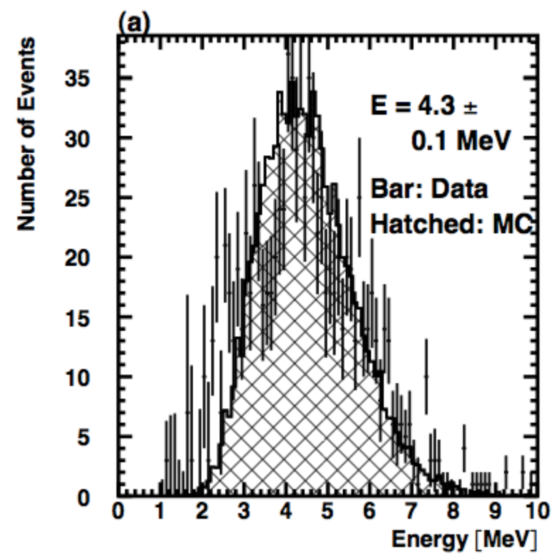
use gadolinium to capture neutrons (like for scintillator)

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

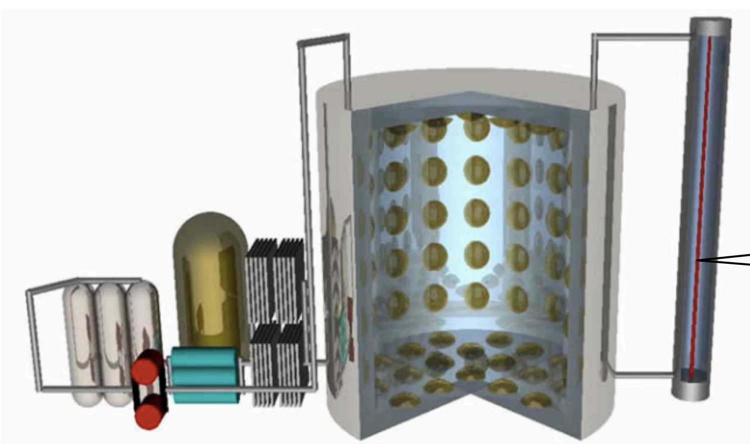
Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

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

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

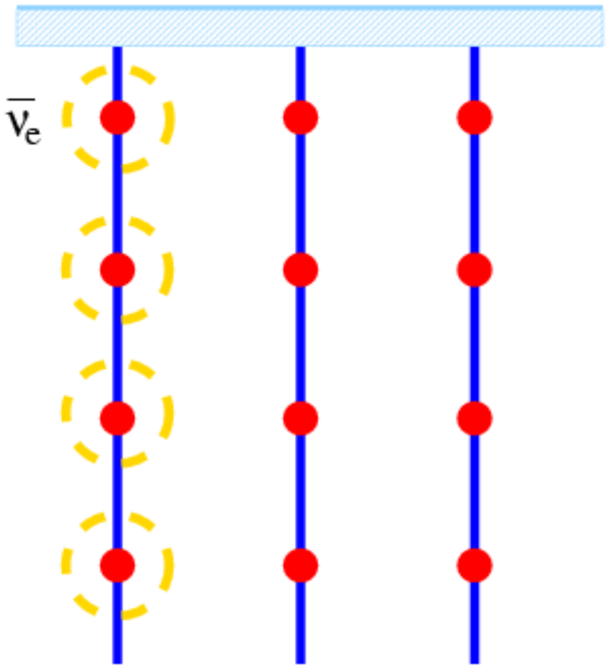


H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)



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

Long string water Cherenkov detectors

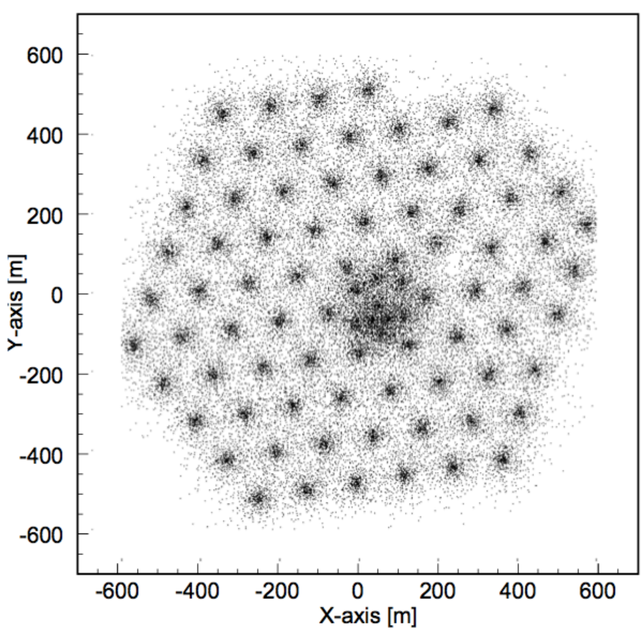


~kilometer long strings of PMTs in very clear water or ice

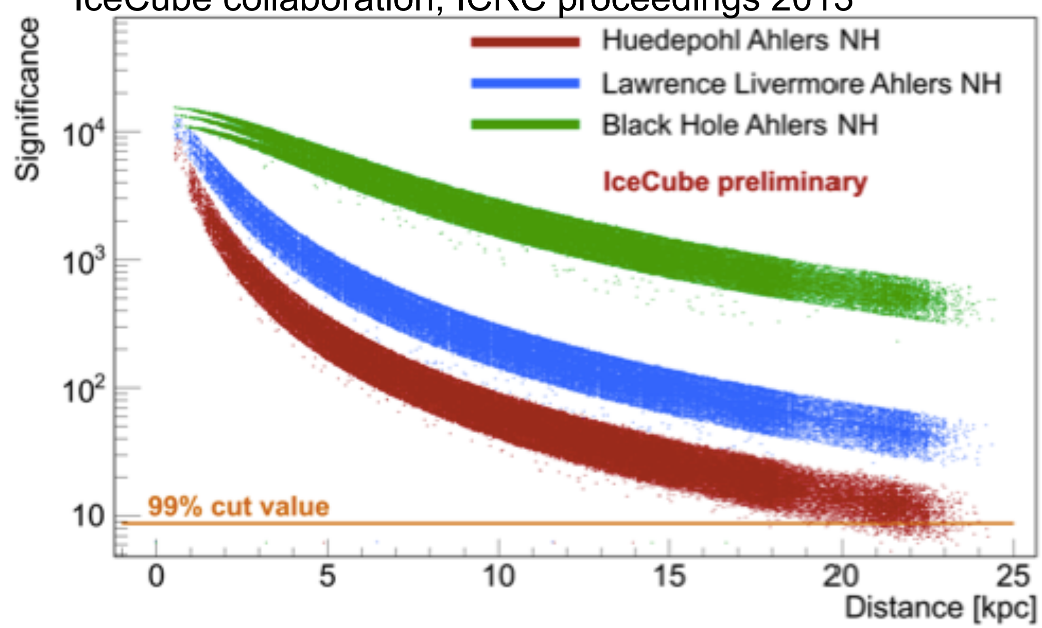
(IceCube/PINGU, ANTARES)

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)

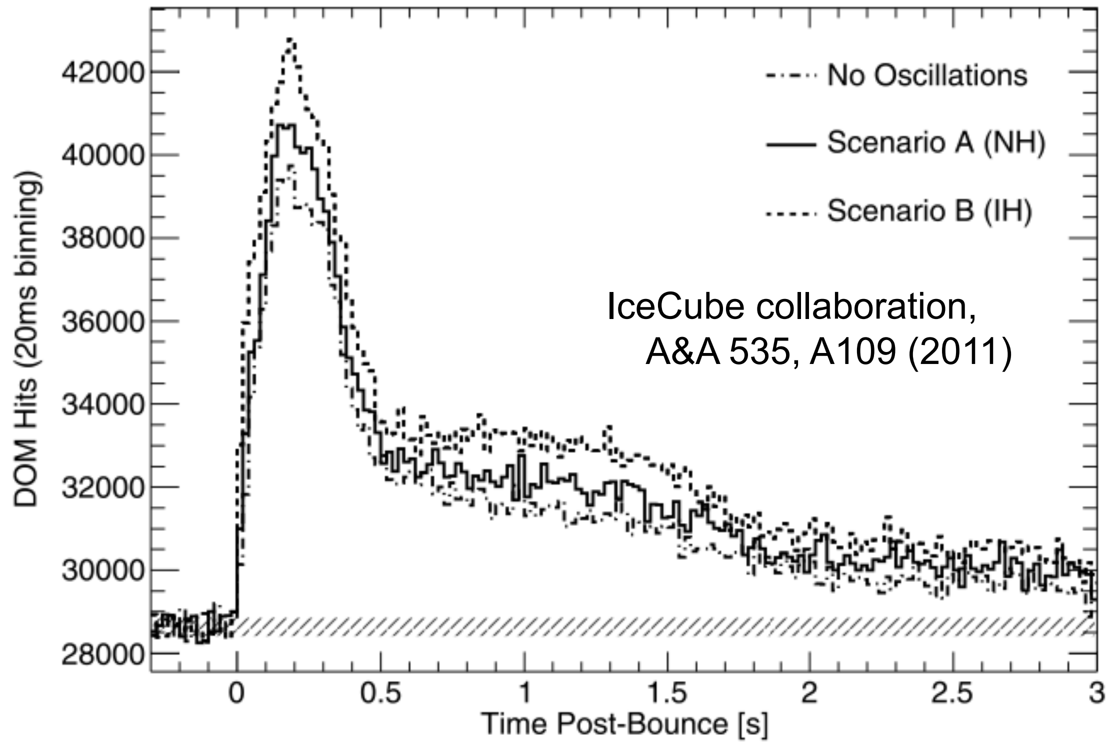
IceCube collaboration, A&A 535, A109 (2011)



IceCube collaboration, ICRC proceedings 2013

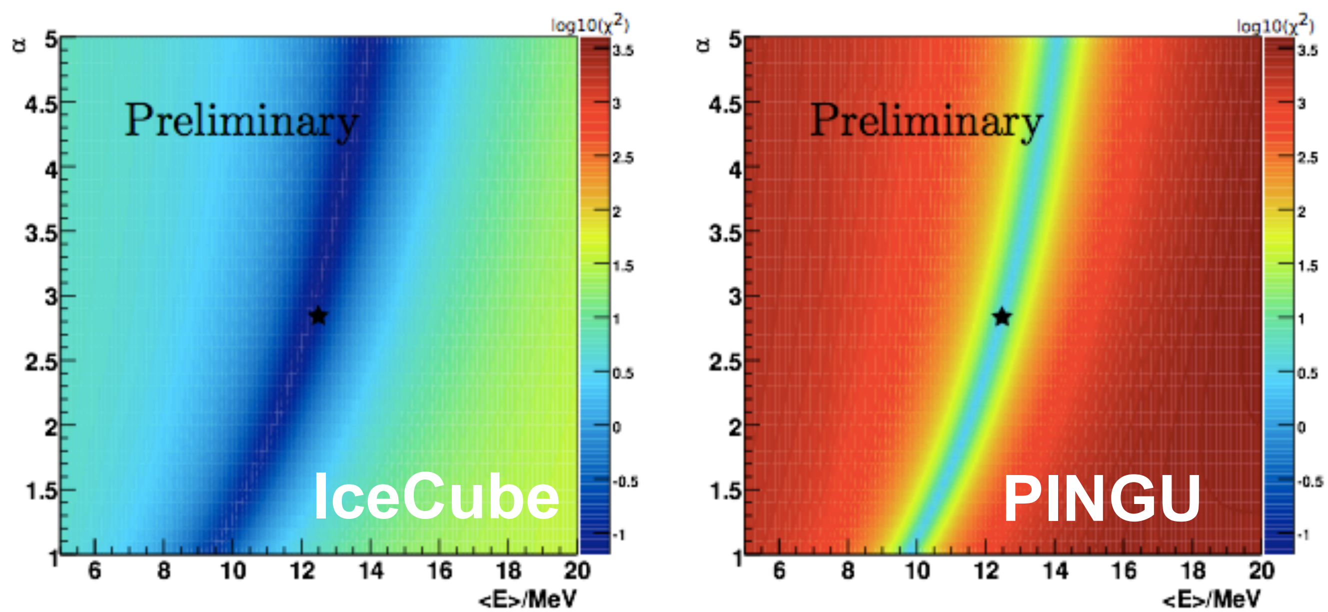


Cannot tag flavor, or other event-by-event info, but map overall burst time structure



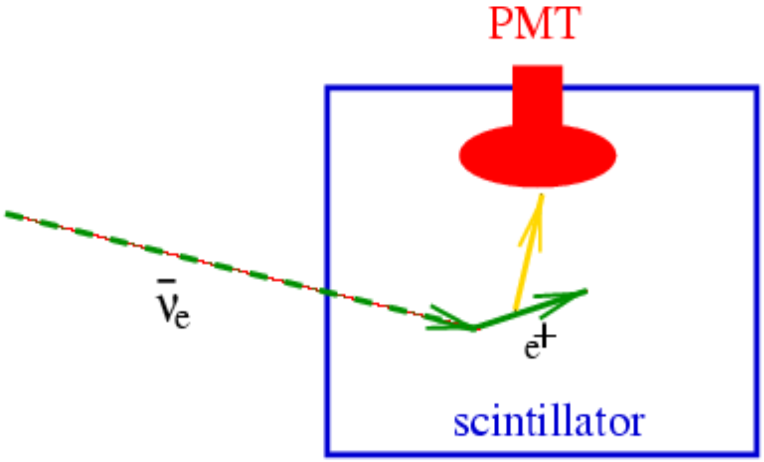
Also: T. Lund et al., PRD82 (2010) 063007

Some spectral info using multiple-vs-single hits, especially w/ PINGU infill



PINGU LOI, arXiv:1401.2046

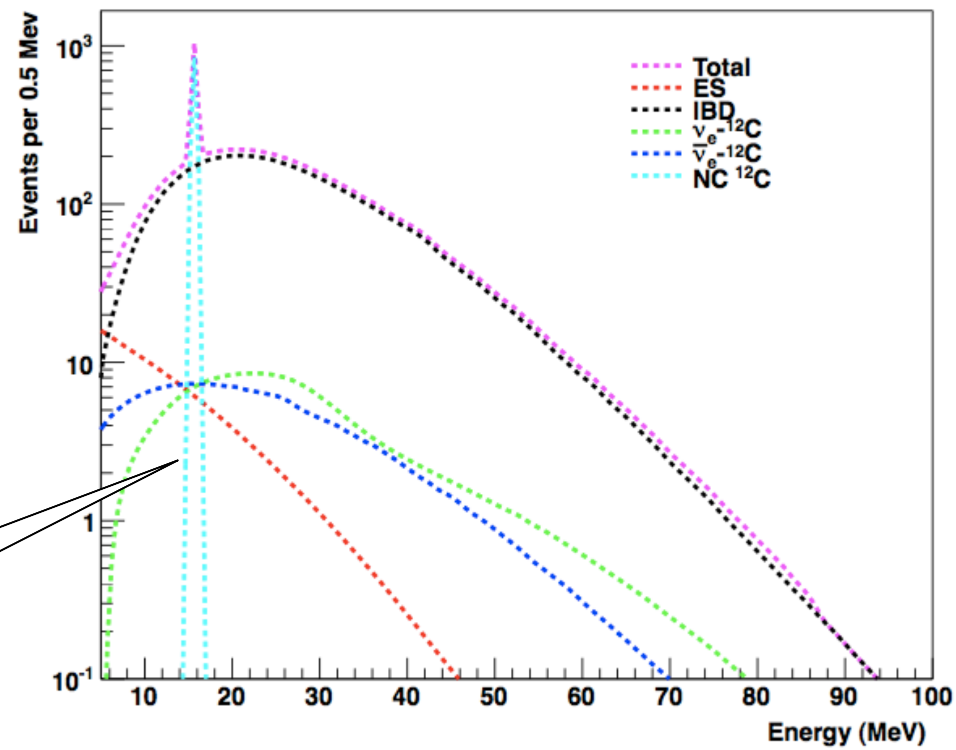
Scintillation detectors



Liquid scintillator C_nH_{2n} volume surrounded by photomultipliers

- few 100 events/kton (IBD)
- low threshold, good neutron tagging possible
- little pointing capability (light is ~isotropic)
- coherent elastic NC scattering on protons for ν spectral info

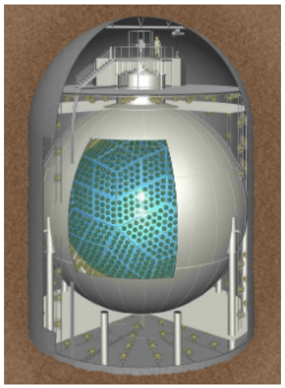
NC tag from 15 MeV deexcitation γ (no ν spectral info)



50 kt @ 10 kpc

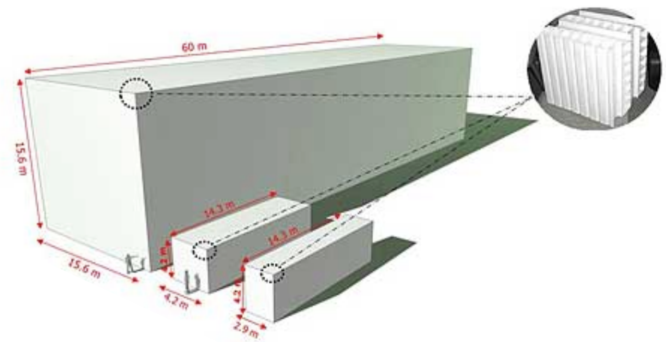
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



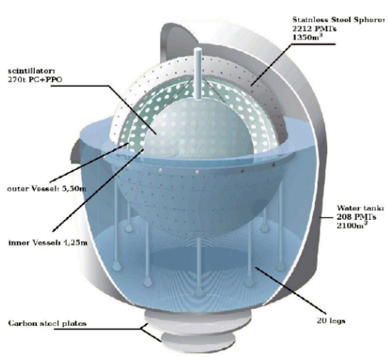
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

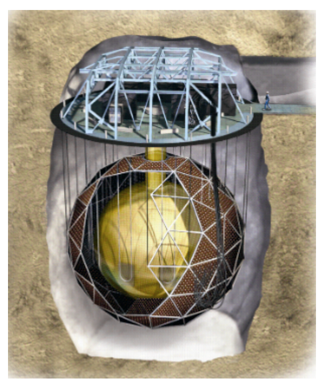


(on surface, but may be possible to extract counts for known burst)

Borexino
(Italy)
0.33 kton



SNO+
(Canada)
1 kton



Also on the surface: reactor experiments w/ Gd-doped (and undoped) scintillator

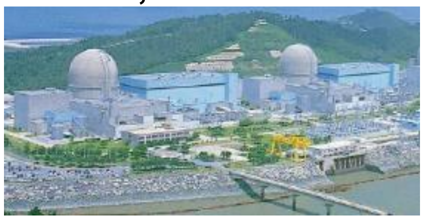
Detector	Type	Location	Mass (ton)	Events @ 10 kpc
Double Chooz	Scintillator	France	20	**7**
RENO	Scintillator	South Korea	30	**11**
Daya Bay	Scintillator	China	330	**100**

Although signal numbers are small, for low bg rates and good tagging, there will be good S/B

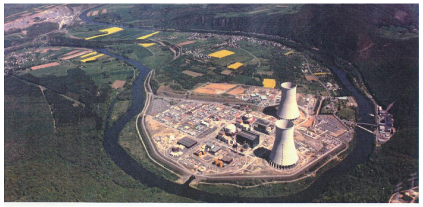
Also: coincidence between multiple detectors makes a SN trigger possible

Daya Bay, arXiv:1310.5783

RENO, South Korea

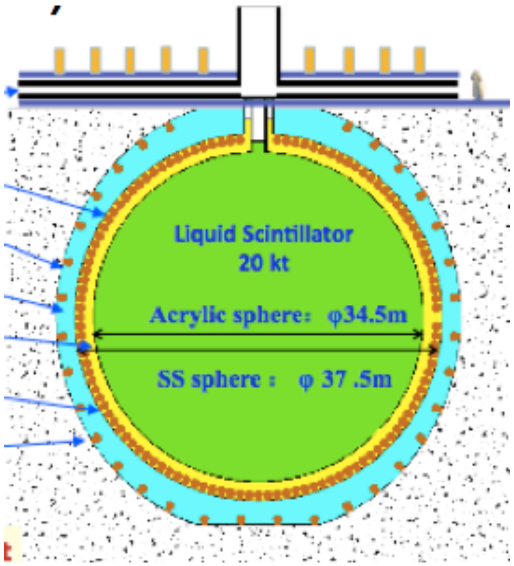


Double CHOOZ, France

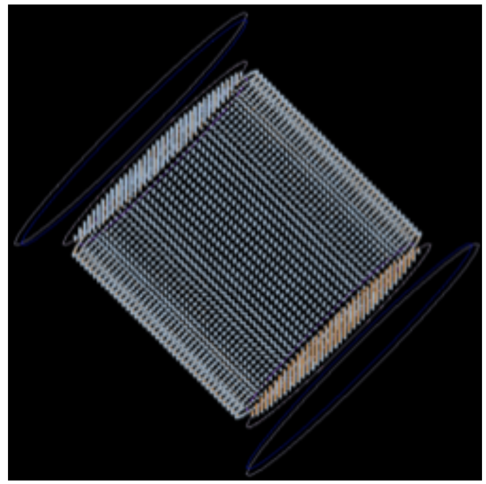


Daya Bay, China

Future detector proposals



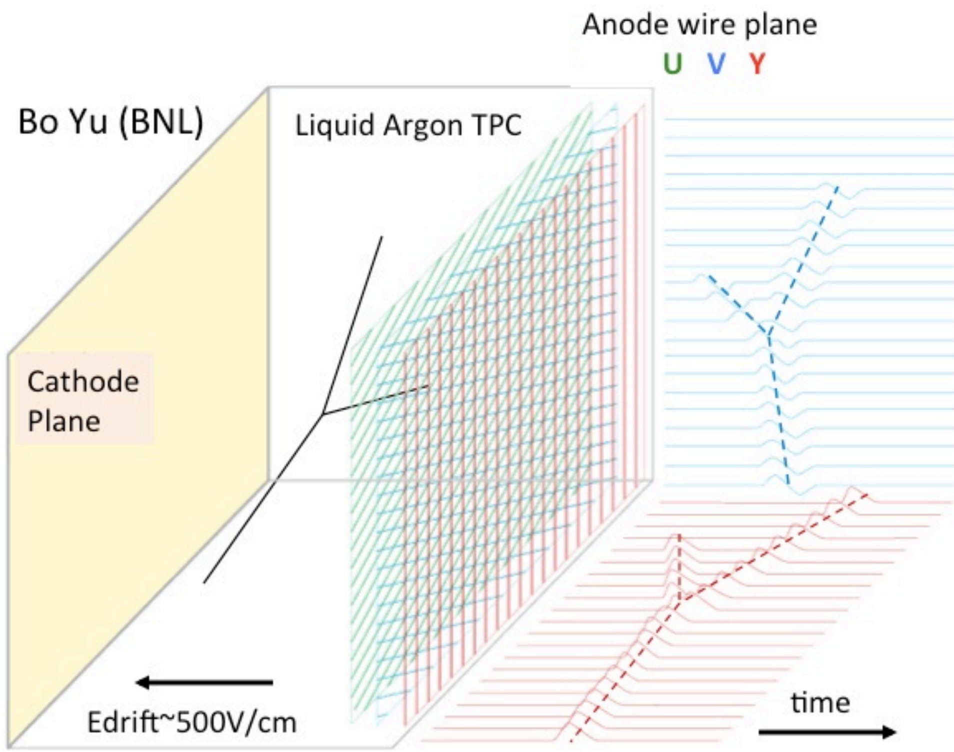
JUNO
(China)
20 kton



RENO-50
(S. Korea)
18 kton

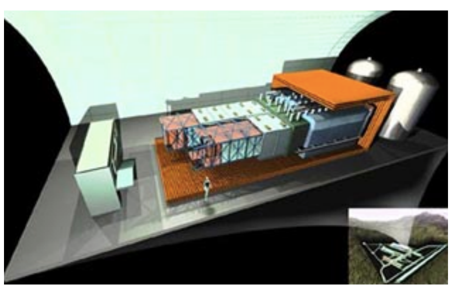
LENA
(Finland)
50 kton

Liquid argon time projection chambers

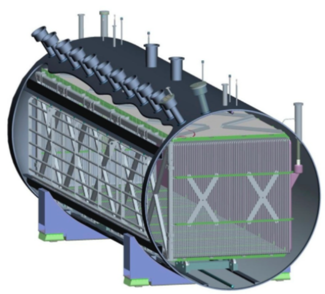


- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

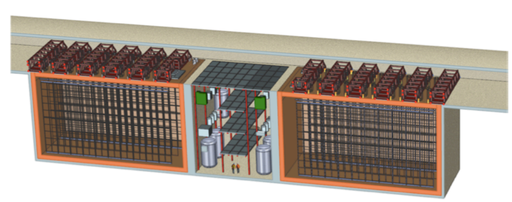
ICARUS
(Italy...)
0.6 kton



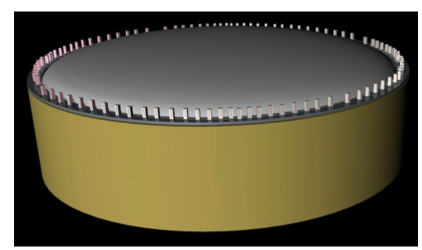
MicroBooNE
(USA)
0.2 kton



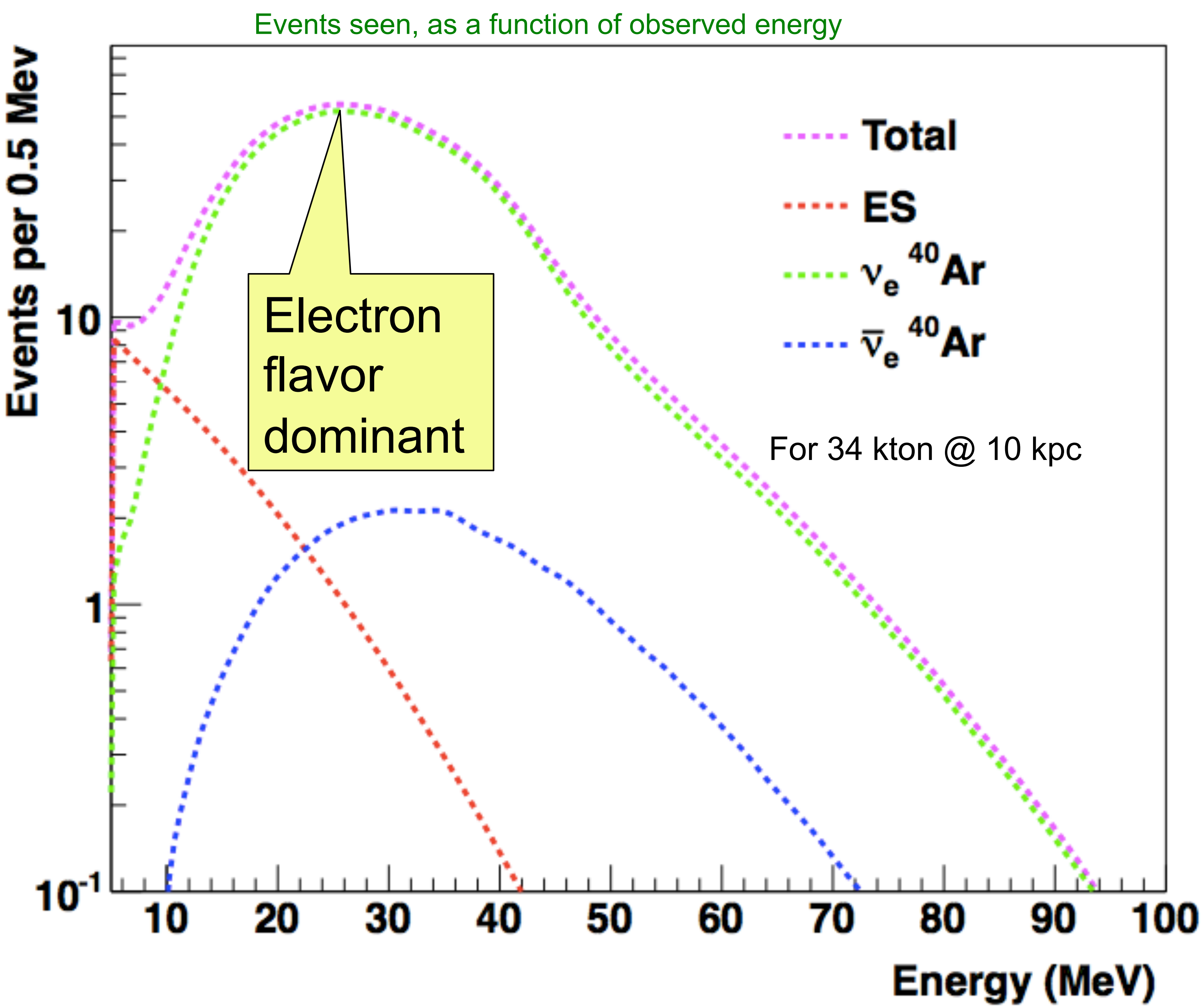
LBNE
(USA)
34 kton



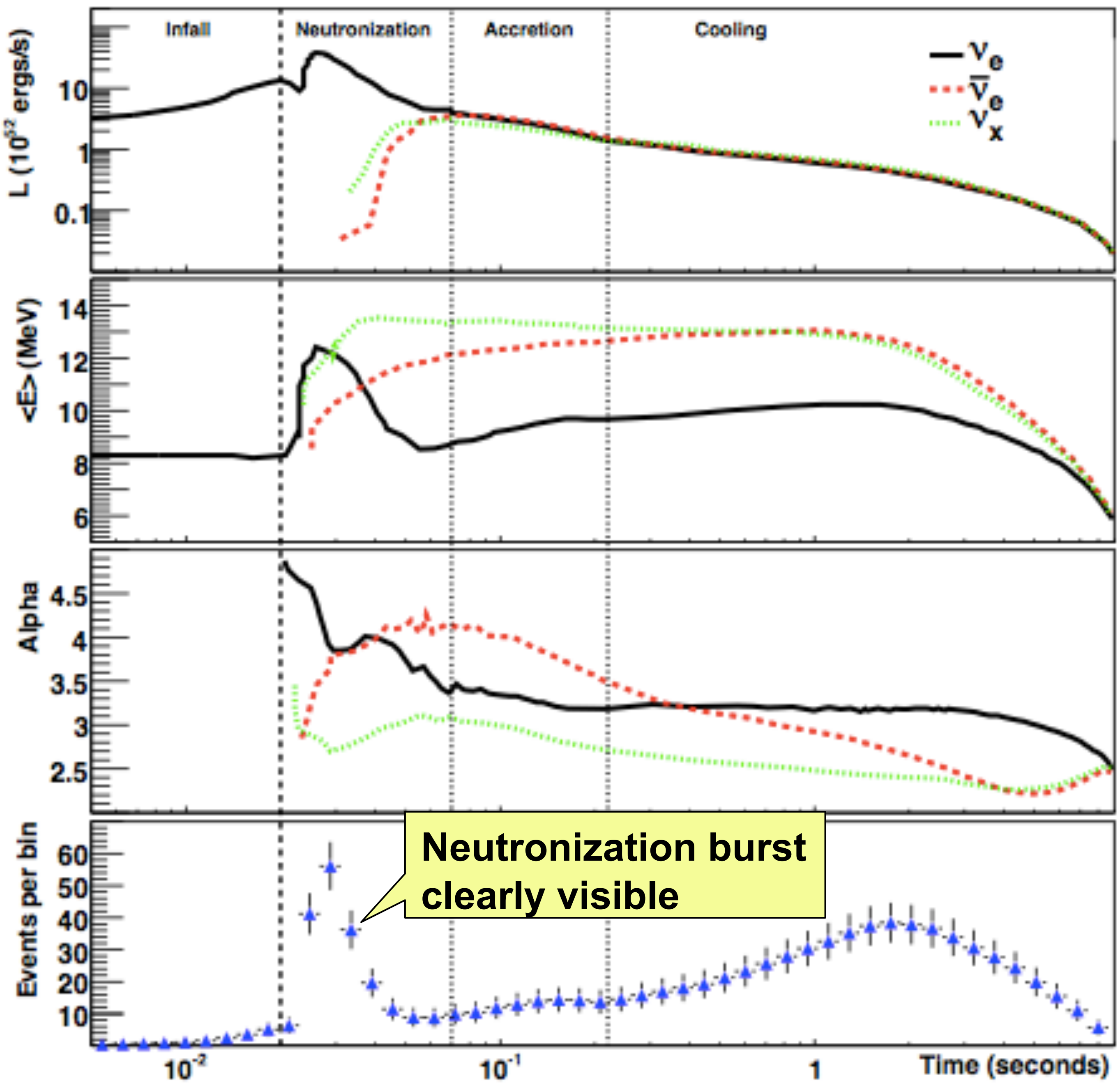
GLACIER
(Europe)
100 kton



Supernova signal in a liquid argon detector



Example of supernova burst signal in 34 kton of LAr

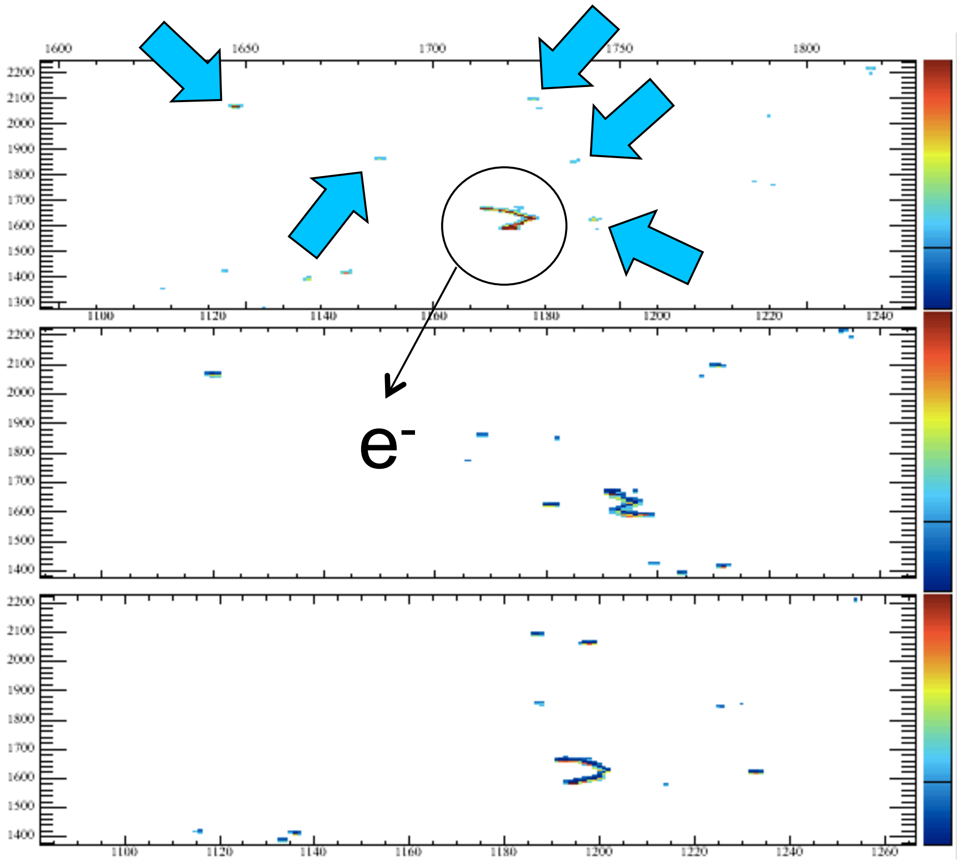


arXiv:1307.7335

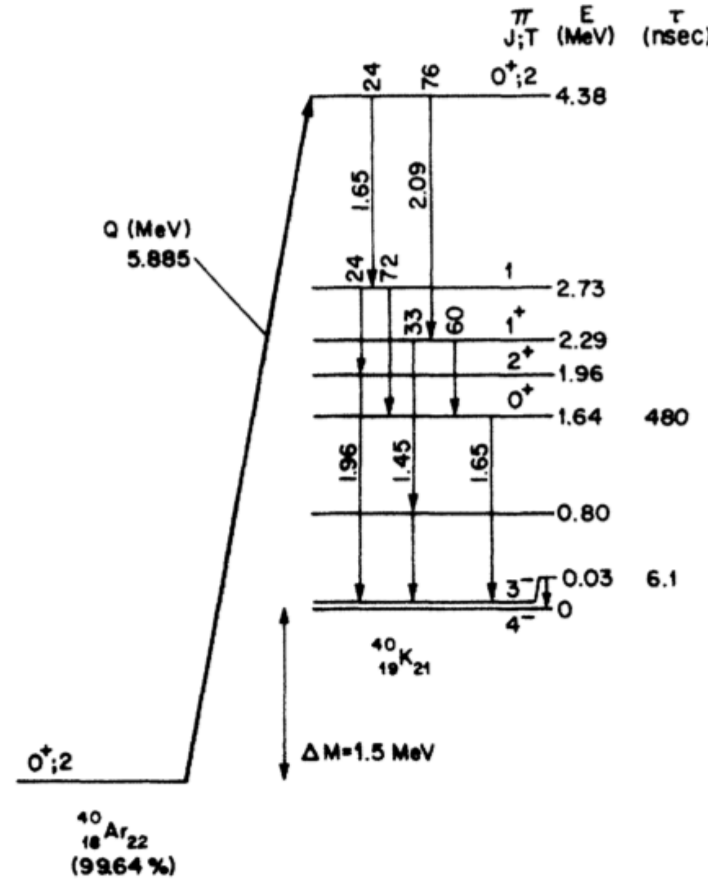
Flux from Huedepohl et. al, PRL 104 (2010) 251101 @ 10 kpc

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!

Lead-based supernova detectors

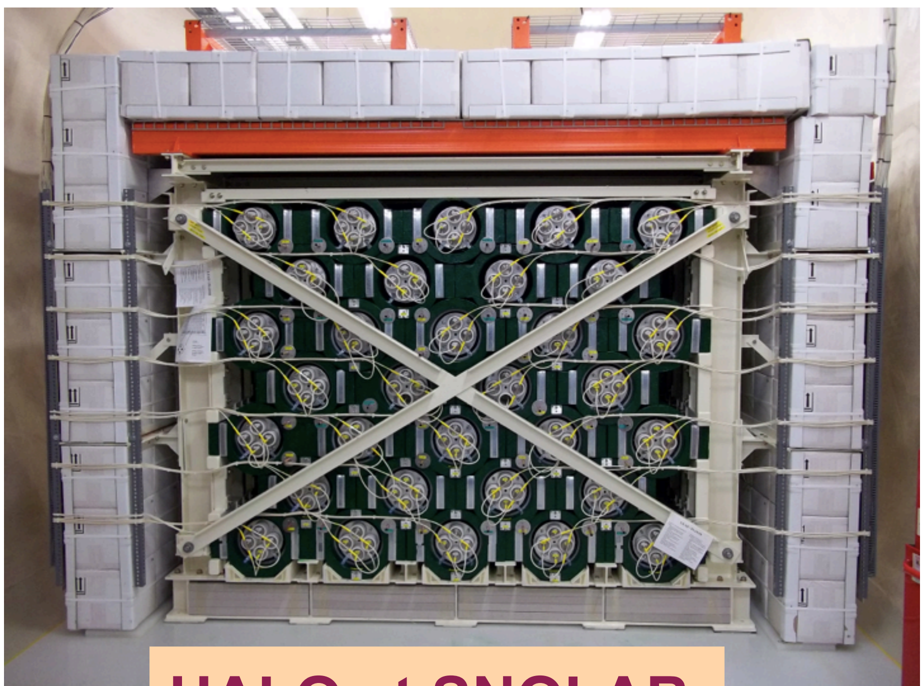
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

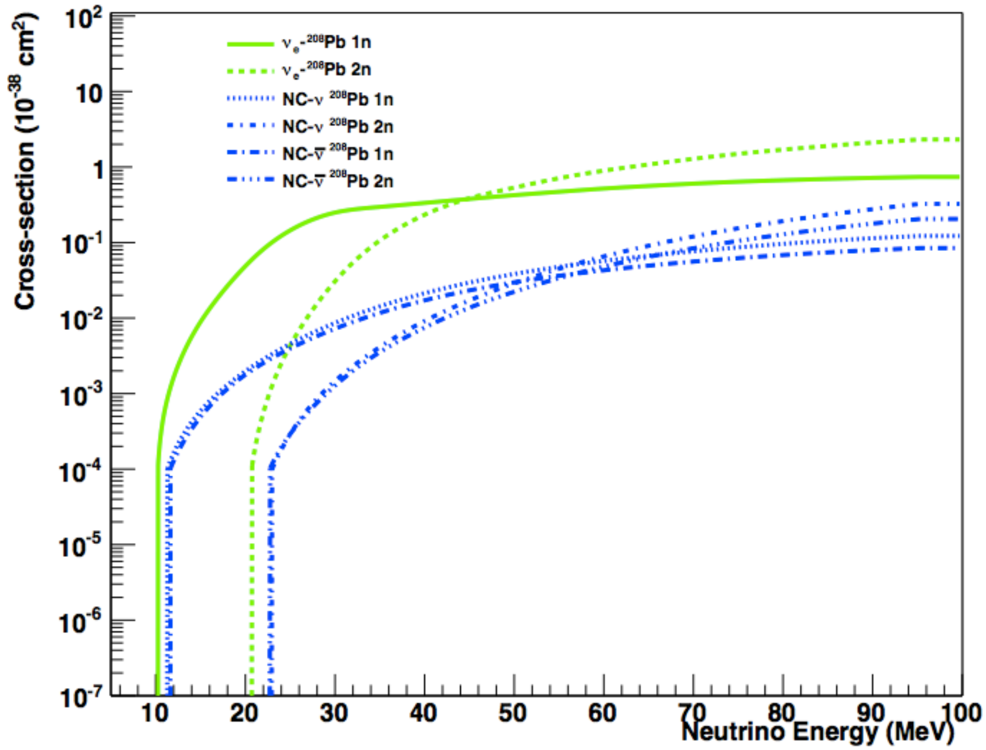
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

Relative 1n/2n rates sharply dependent on neutrino energy
$\Rightarrow$ spectral sensitivity



HALO at SNOLAB



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

Coherent Elastic Neutrino Nucleus Scattering

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

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

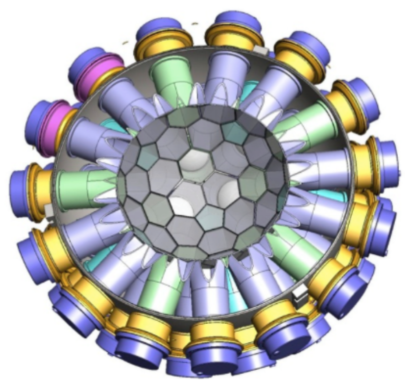
High x-scn but *very* low recoil energy (10's of keV)

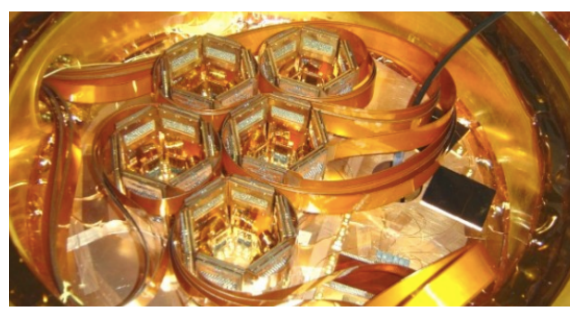
$\Rightarrow$ observable in DM detectors

~ 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, ...

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
LBNE	Liquid argon	USA	34	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

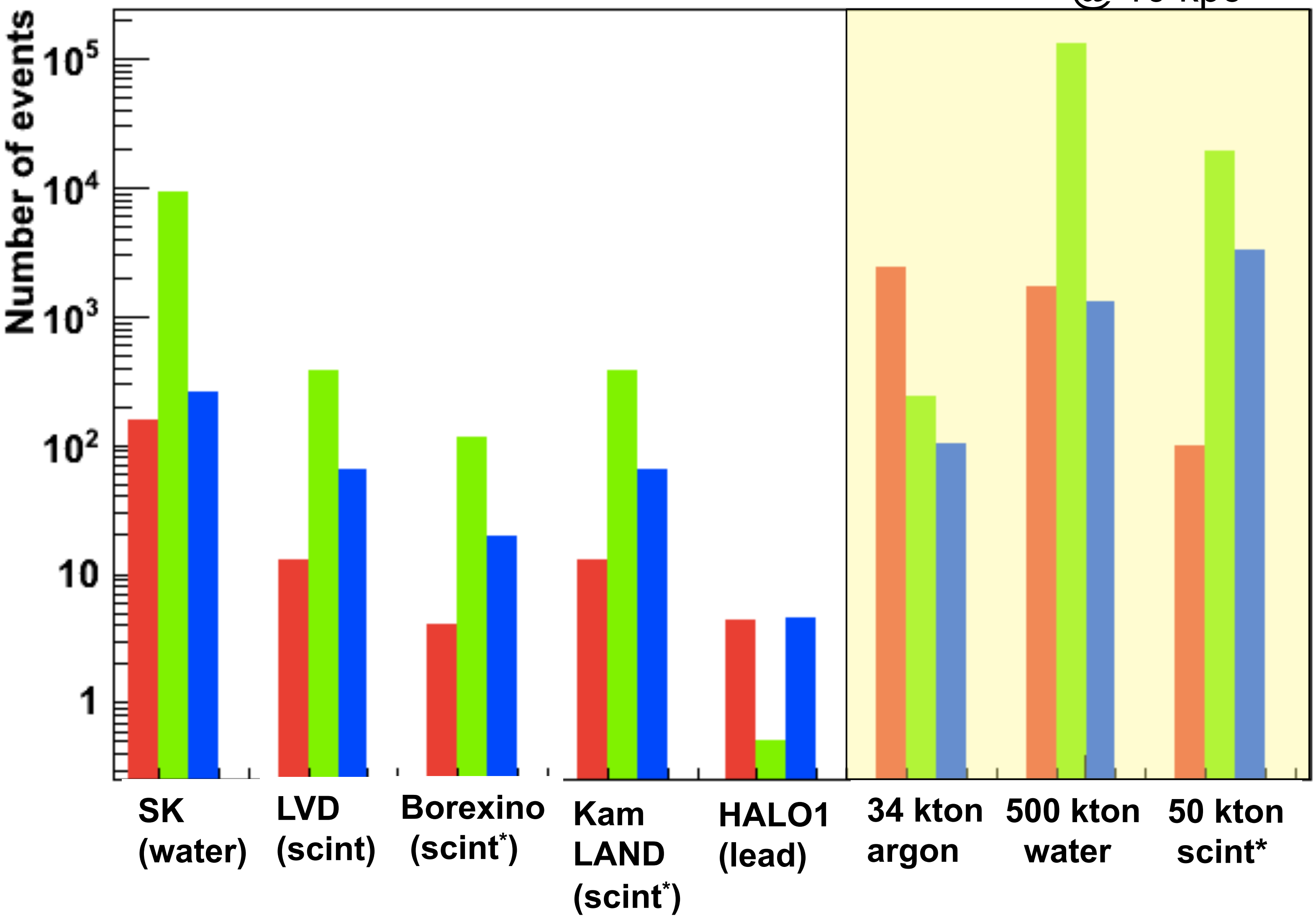
plus reactor experiments, DM experiments...

World SN flavor sensitivity

for ~largest existing or proposed detectors
of each class

Electron neutrino
Electron antineutrino
Muon and tau neutrino and antineutrino

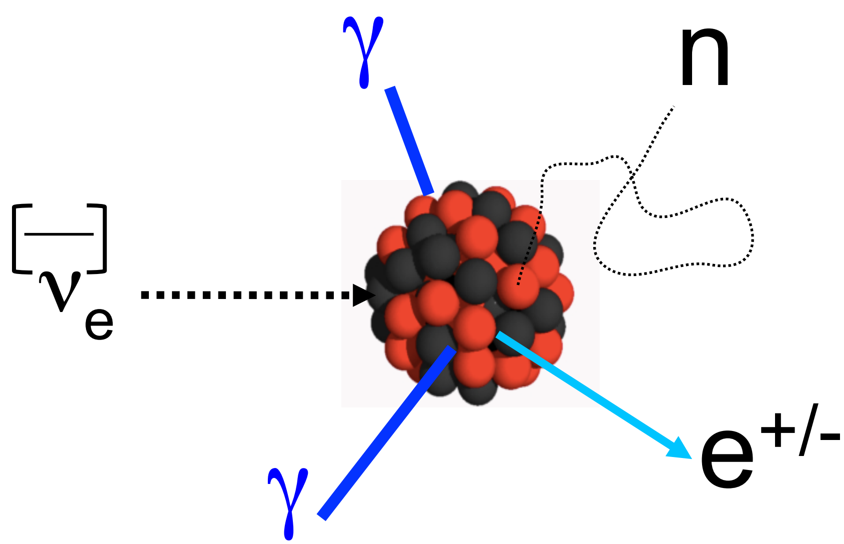
Livermore model
@ 10 kpc



* plus NC ν-p scattering

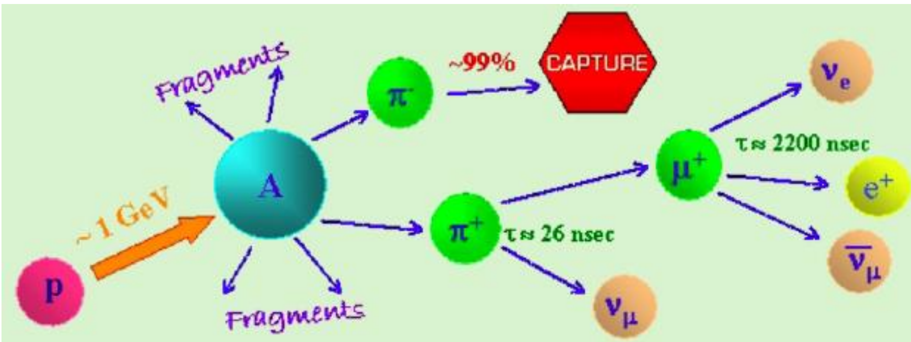
\begin{aside}

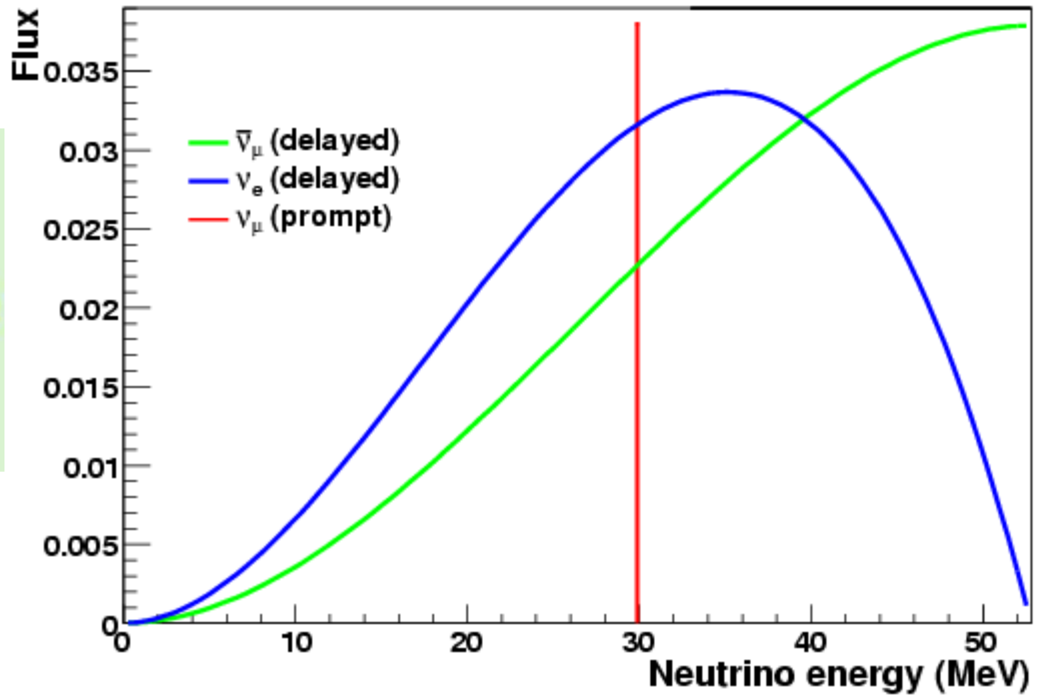
The neutrino interaction cross sections *and* the distribution of observable products matter experimentally...



...theory not well understood and almost no measurements exist!

Stopped-Pion (DAR) Neutrinos





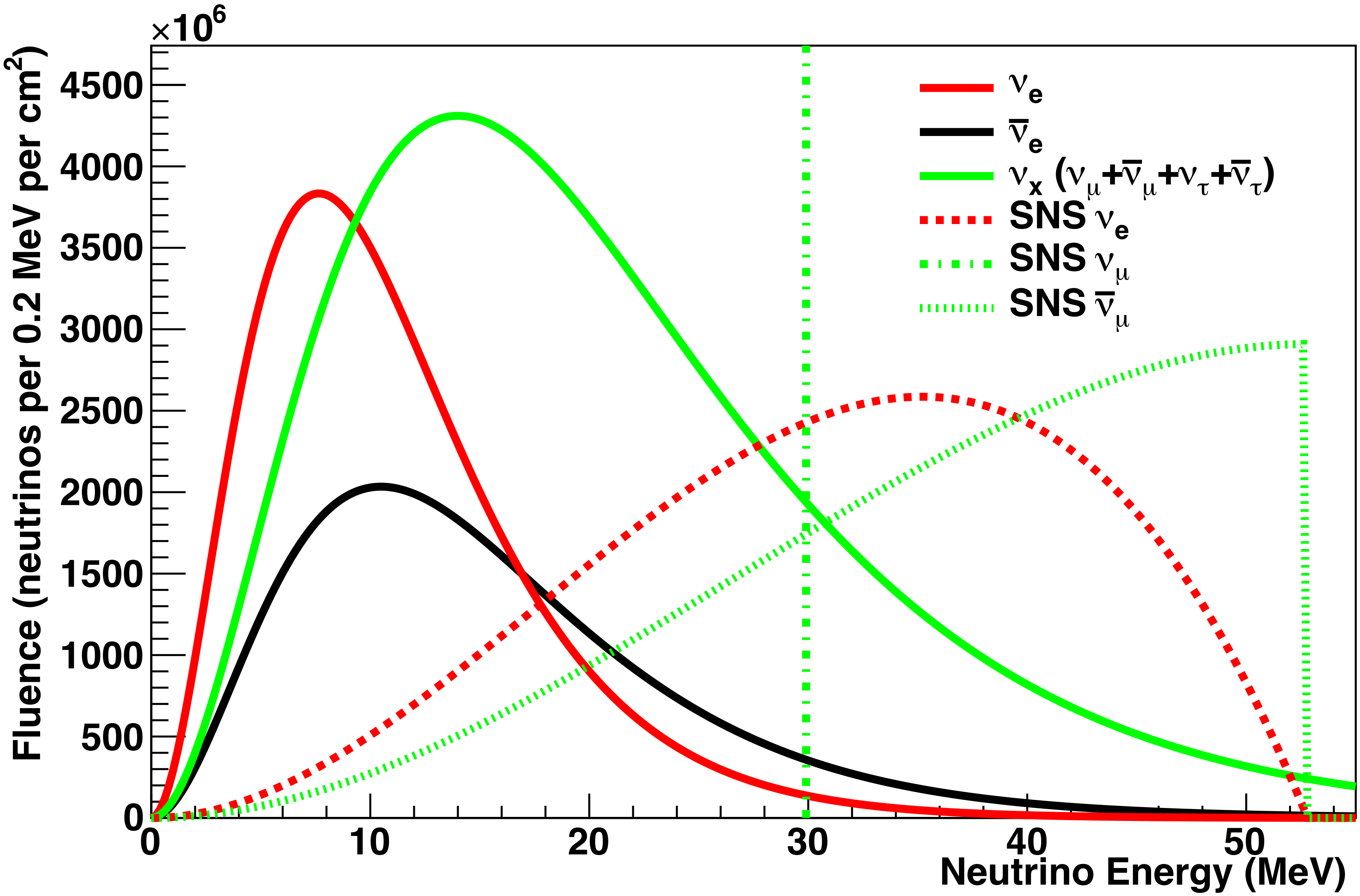
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

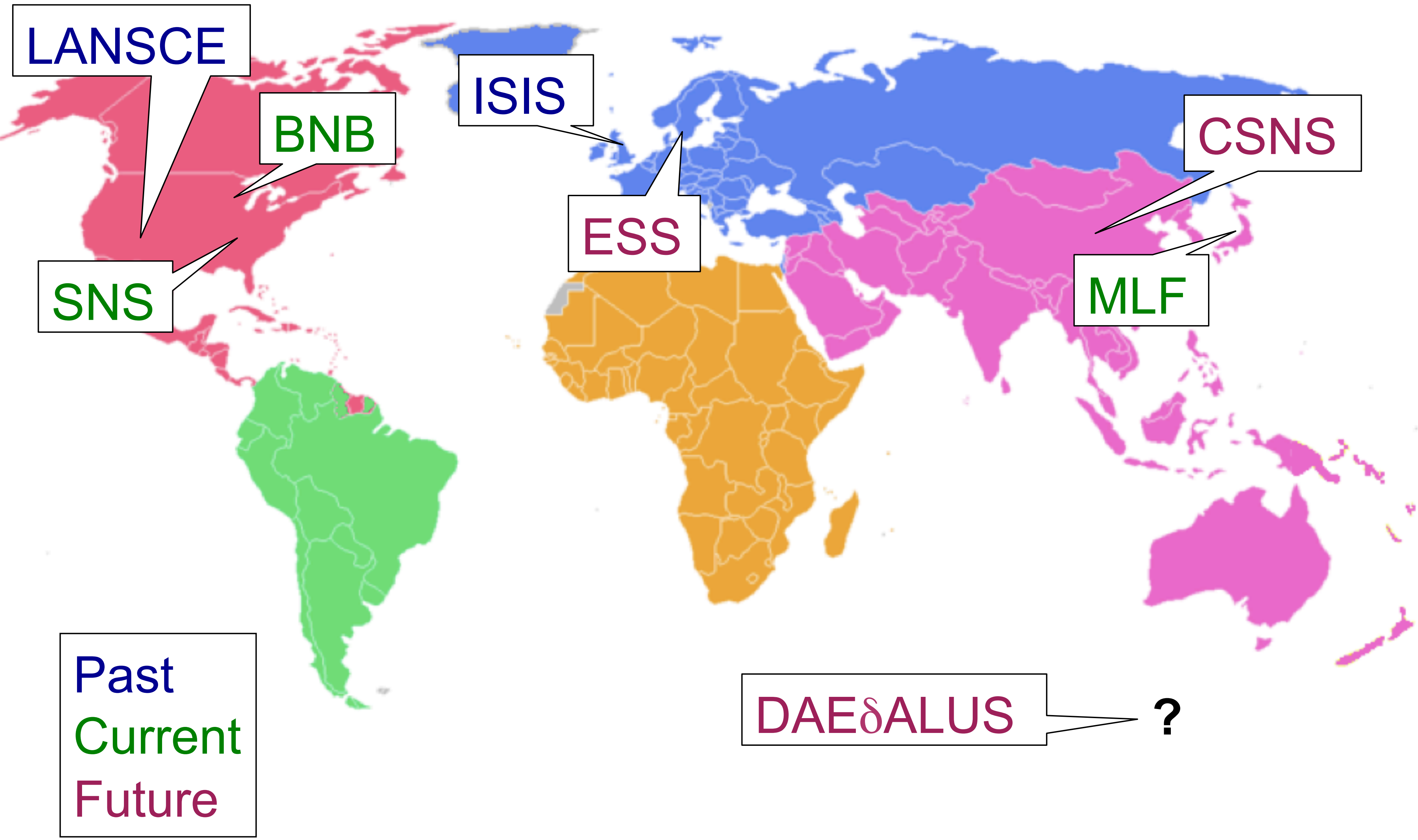
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

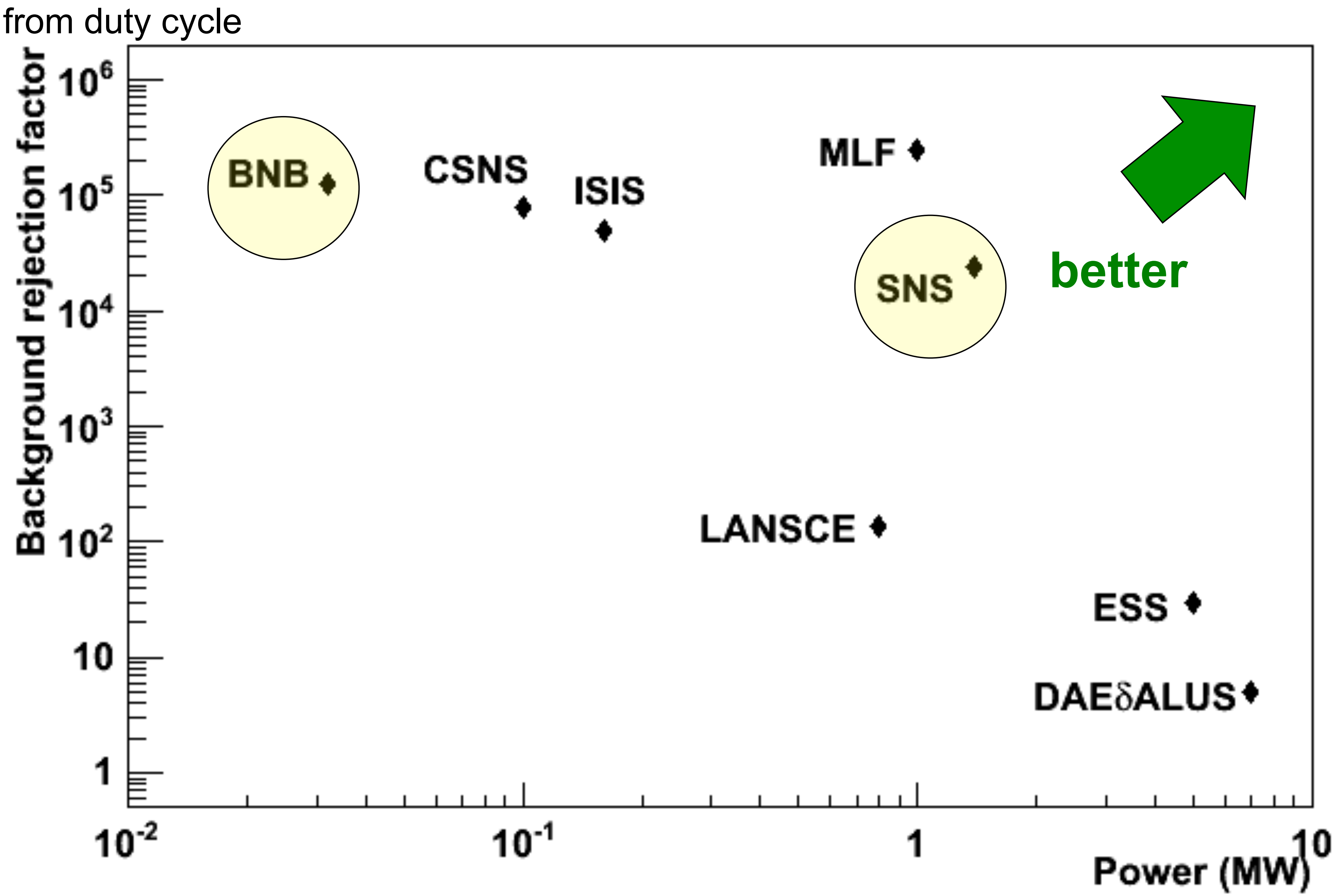
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



Stopped-Pion Sources Worldwide

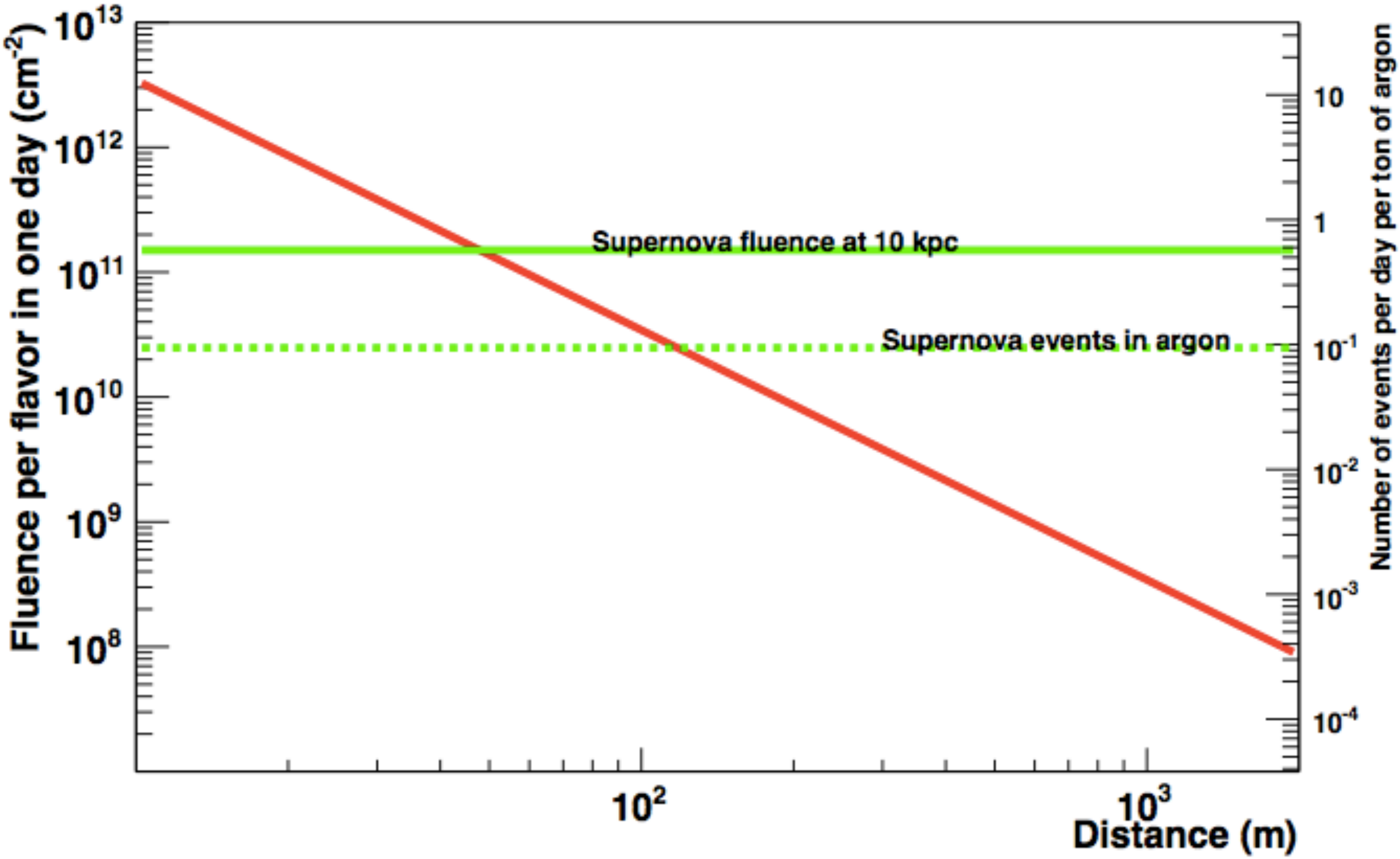




from duty cycle
Background rejection factor
Power (MW)
BNB
CSNS
ISIS
MLF
SNS
better
LANSCE
ESS
DAEδALUS
10^6
10^5
10^4
10^3
10^2
10
1
10^-2
10^-1
1
10

Spallation Neutron Source at ORNL

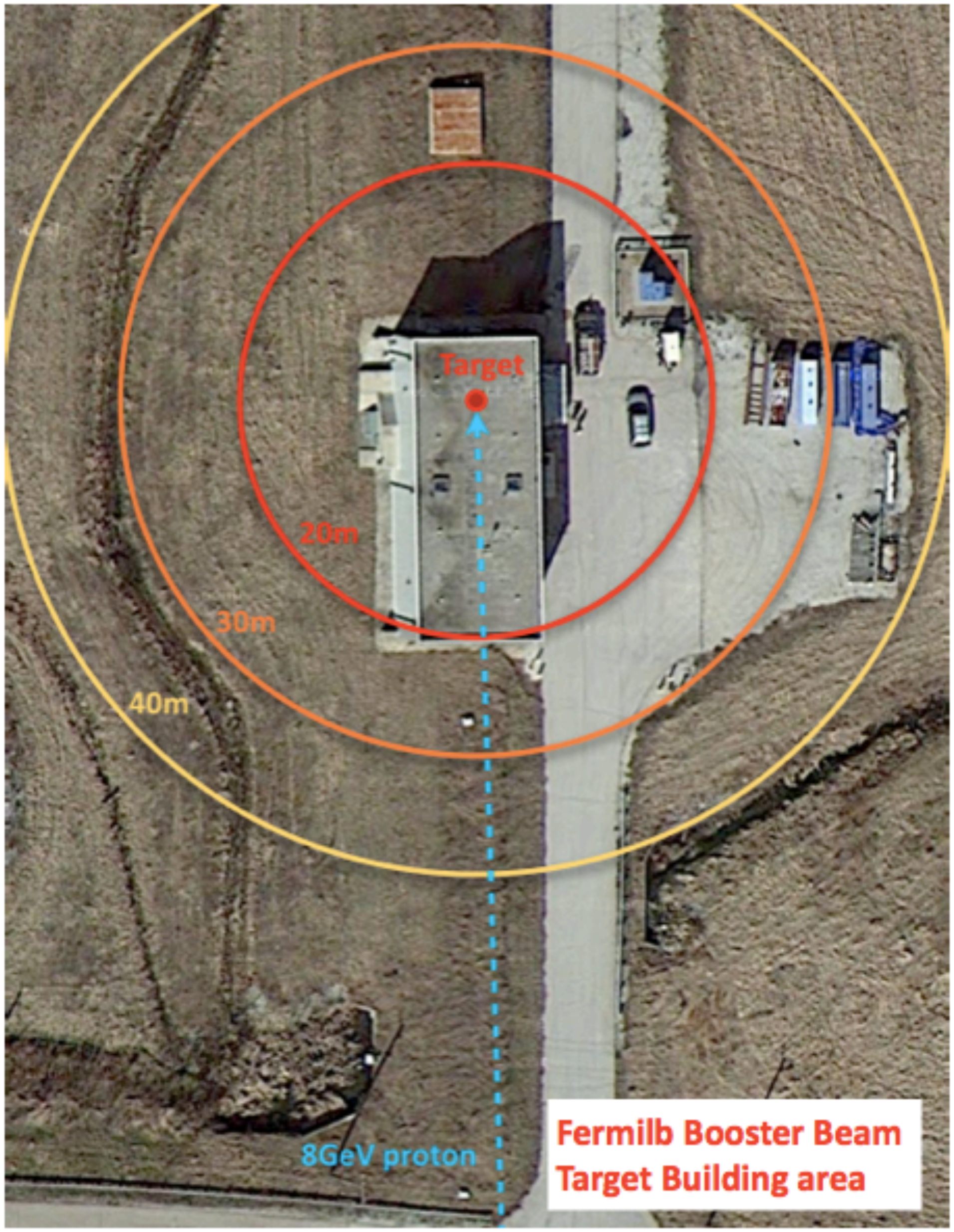
Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

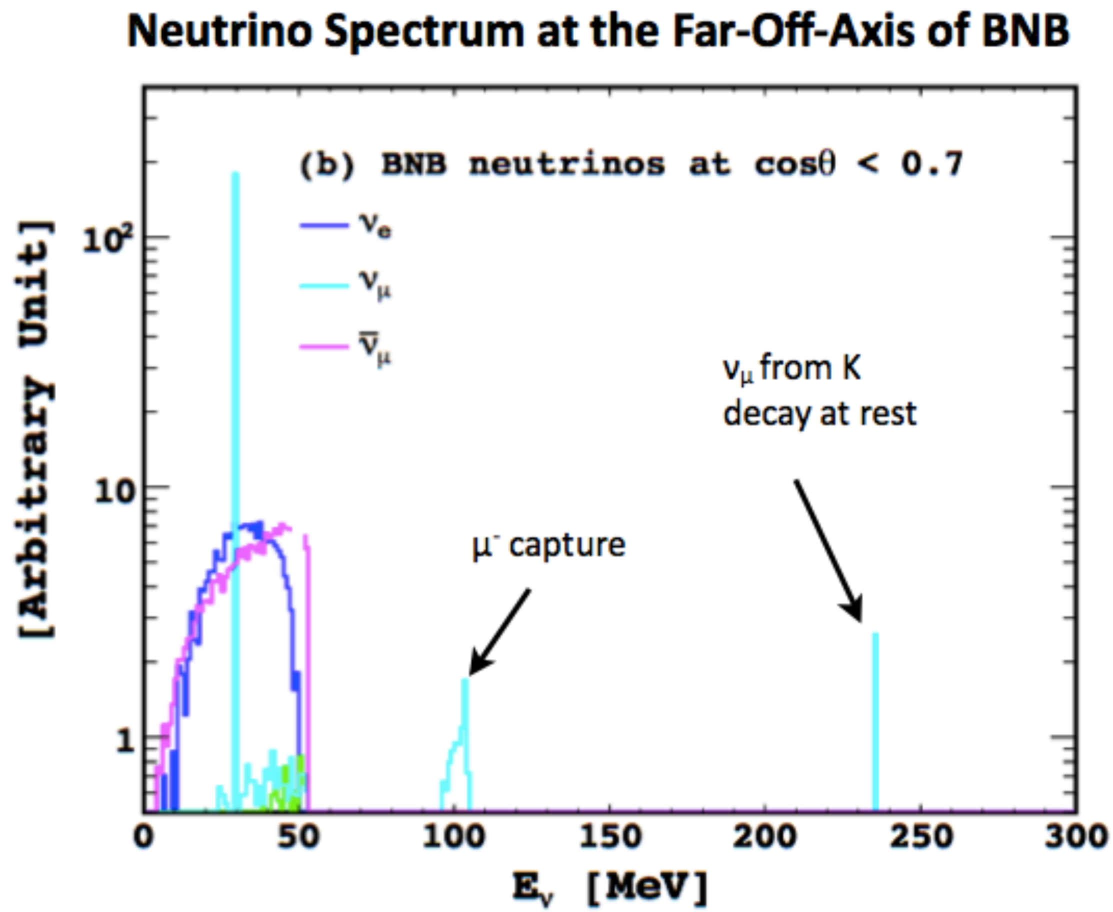


Another possibility: very far off axis at the FNAL BNB

Neutrino Energy Spectrum and Flux

J. Yoo

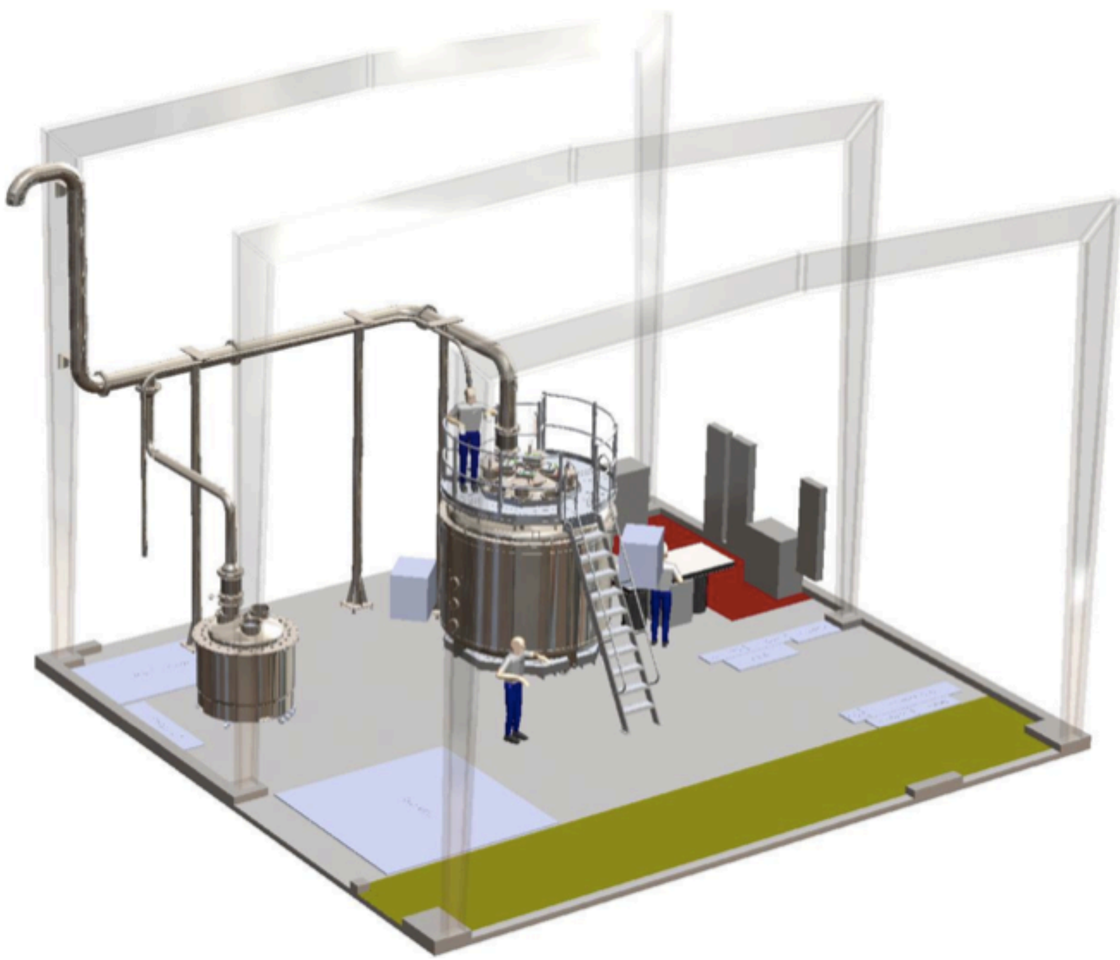




- Dominant neutrino production process at the far-off-axis is **pion decay at rest**
- **ϕ(BNB) ≅ 5×10^5 $\nu/cm^2/s$ per flavor @20m from the target**

CAPTAIN

CRYOGENIC APPARATUS FOR PRECISION TESTS OF ARGON INTERACTIONS WITH NEUTRINOS



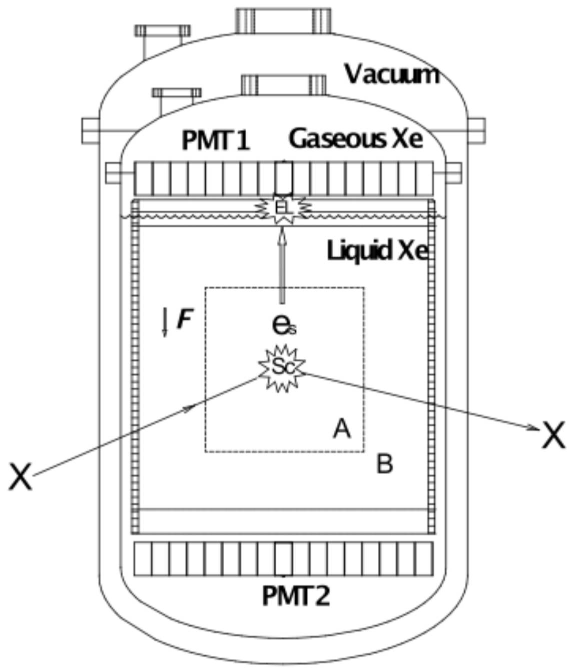
Small, portable
LAr TPC (LBNE R&D)

- neutrons
- high-energy neutrinos (NuMI)
- low-energy neutrinos (BNB, possibly SNS)

COHERENT collaboration @ SNS

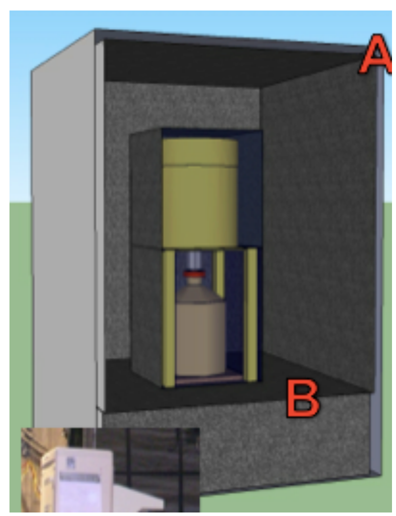
Three possible technologies under consideration

Two-phase LXe

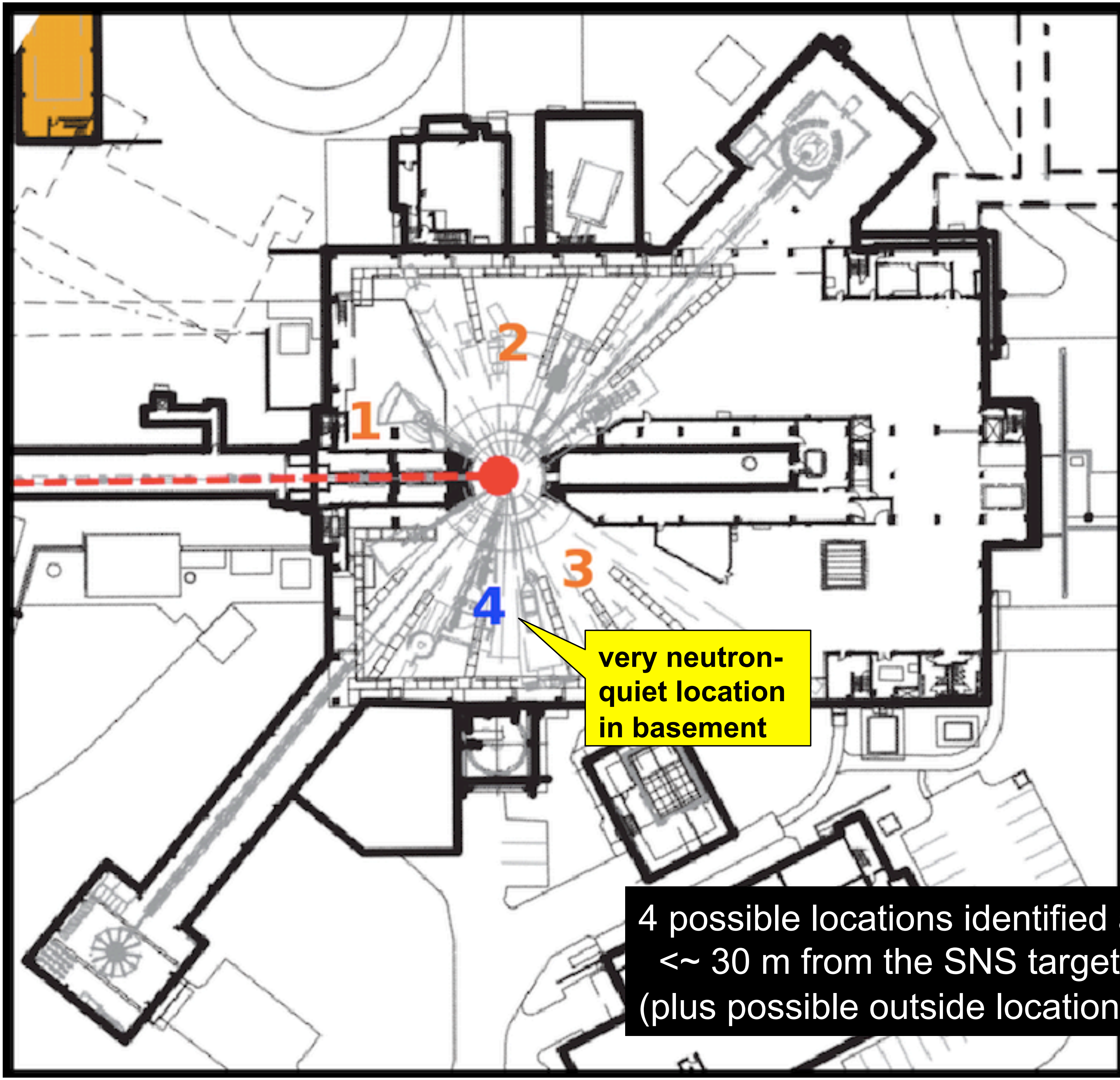


arXiv:1310.0125

CsI



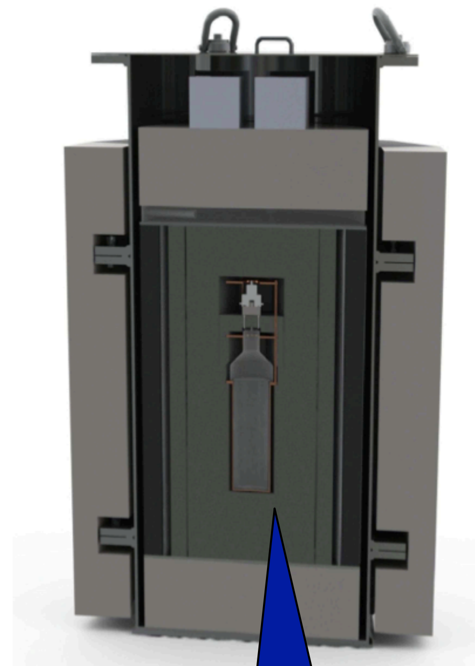
HPGe PPC



4 possible locations identified at
<~ 30 m from the SNS target
(plus possible outside locations)

COHERENT is currently working on next step:

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



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

↘ 1n, 2n emission

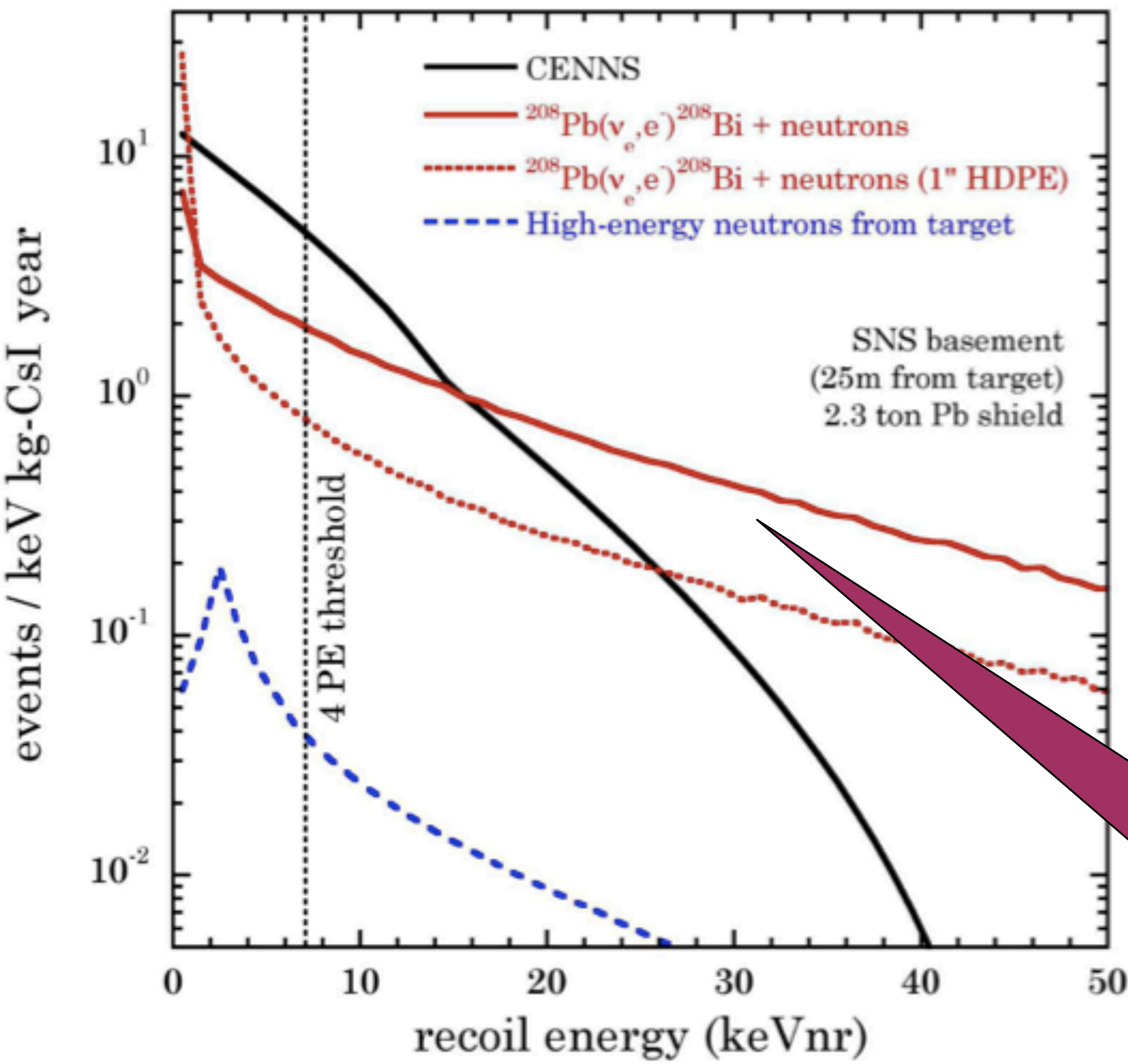
$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x$ NC

↘ 1n, 2n, γ emission

- likely a non-negligible background that we must understand, especially in lead shield
- valuable in itself, e.g. HALO supernova detector at SNOLAB
- short-term physics output

Neutrino-induced neutrons (NINs) are neutron source!

Estimate for a specific configuration (CsI[Na] in lead shield):



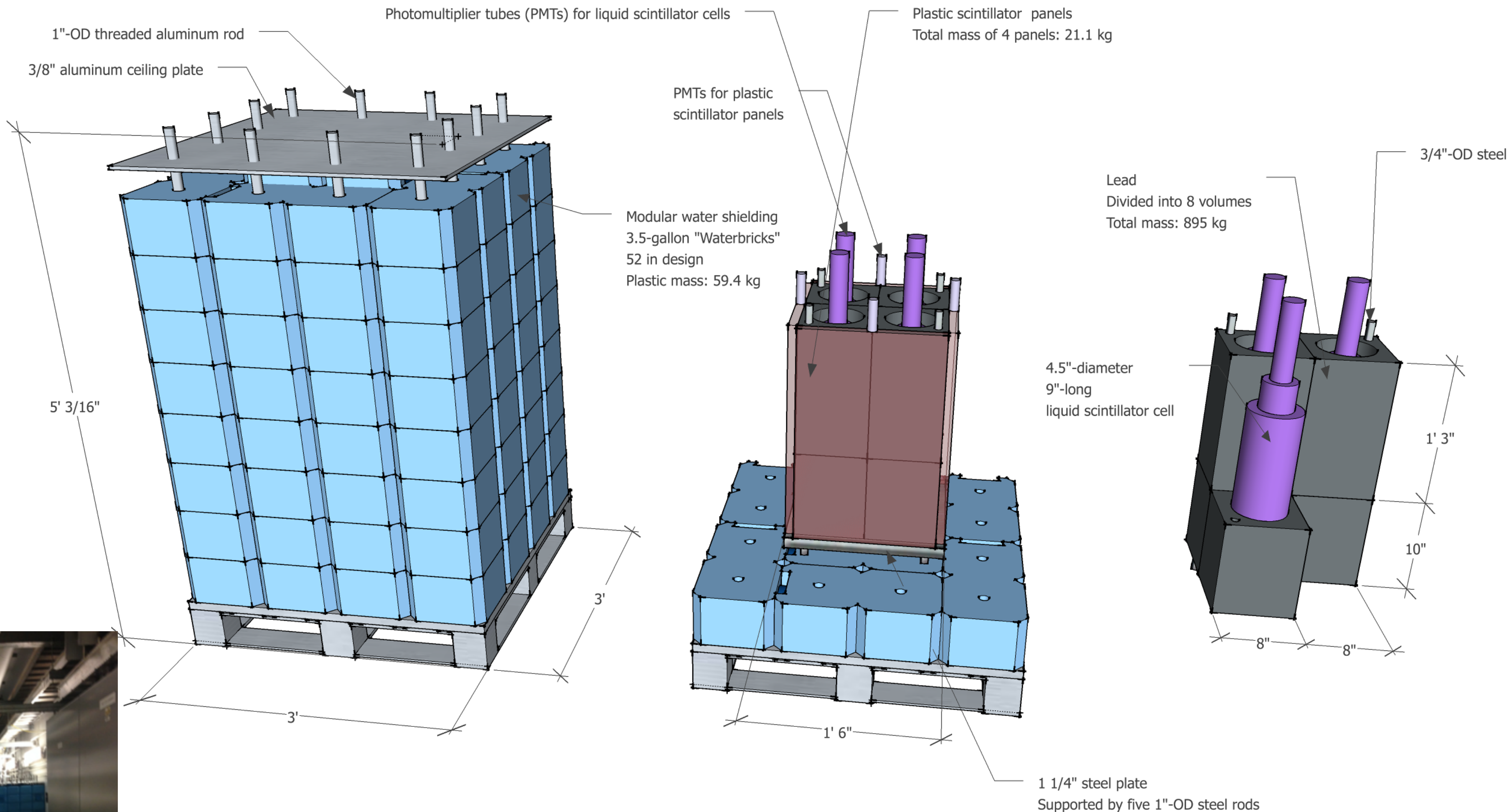
Neutrino-induced neutrons (NINs) not negligible w/lead shield! ➔ need careful shielding design

J.I. Collar et al., arXiv:1407.7524

COHERENT collaboration NIN measurement in basement

- Scintillator inside CsI detector lead shield
- Liquid scintillator surrounded by lead (swappable) inside water shield

Phil Barbeau



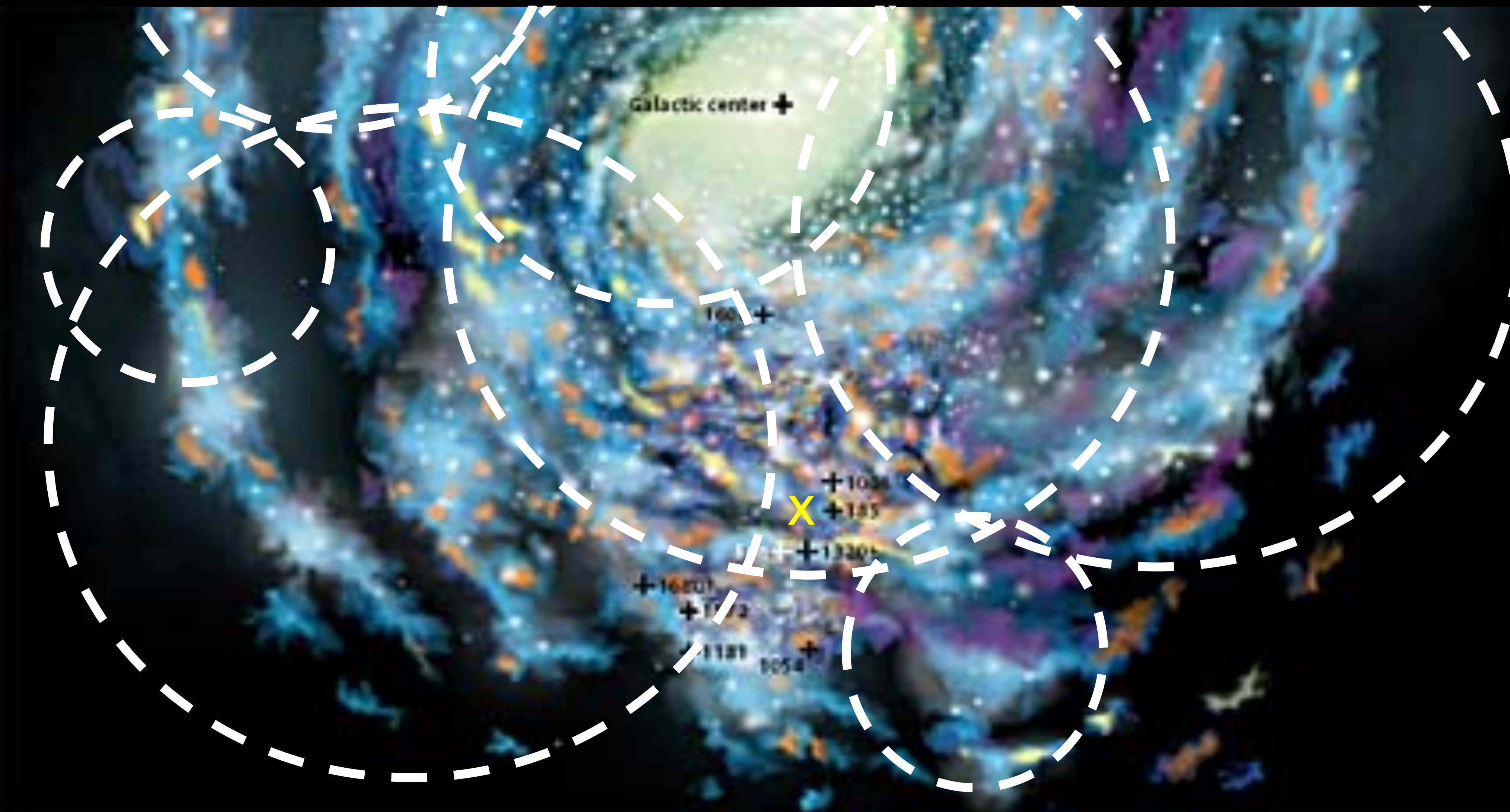
In SNS basement

\end{aside}

The neutrinos are coming!

Far side of the Milky Way is ~650 light-centuries away...

... ~2000 core collapses have happened already....

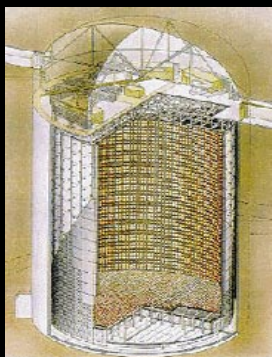


(Figure from Sky&Telescope magazine)

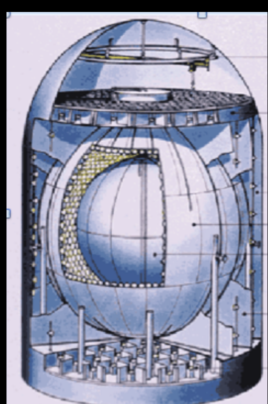
SNEWS: SuperNova Early Warning System

- Neutrinos (and GW) precede em radiation by hours or even days
- For promptness, require ***coincidence*** to suppress false alerts

snews.bnl.gov



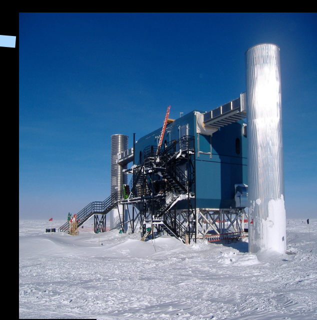
experiment
UT time
significance

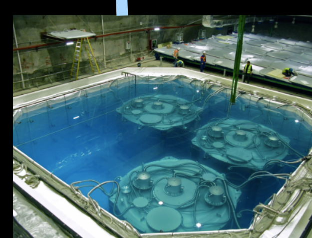


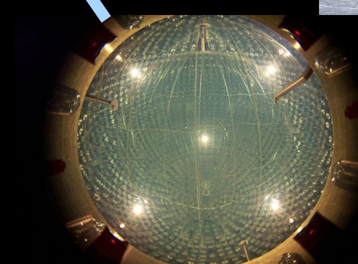
Coincidence Server at BNL

10 second coincidence by UT time stamp

alert to astronomers

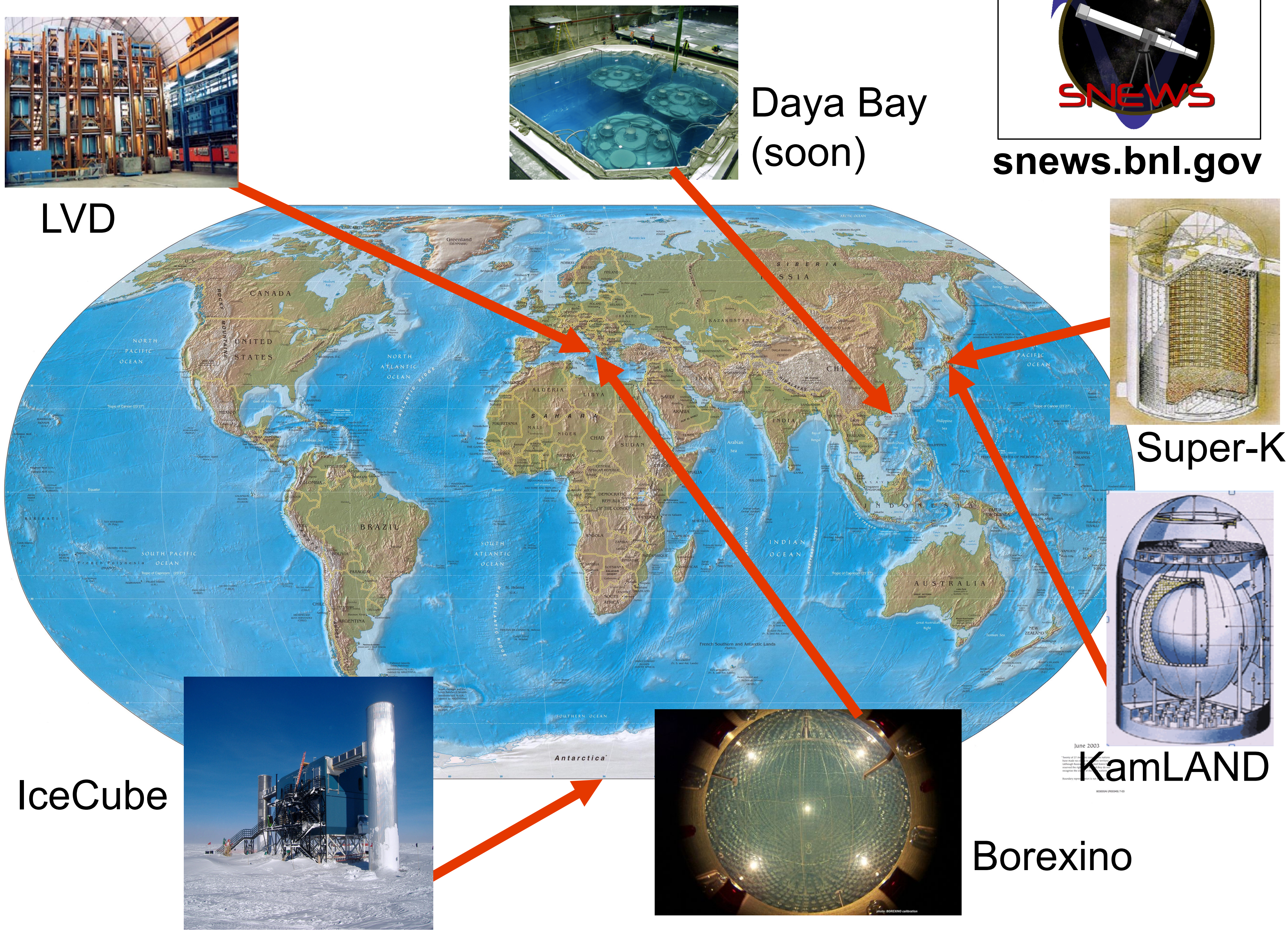




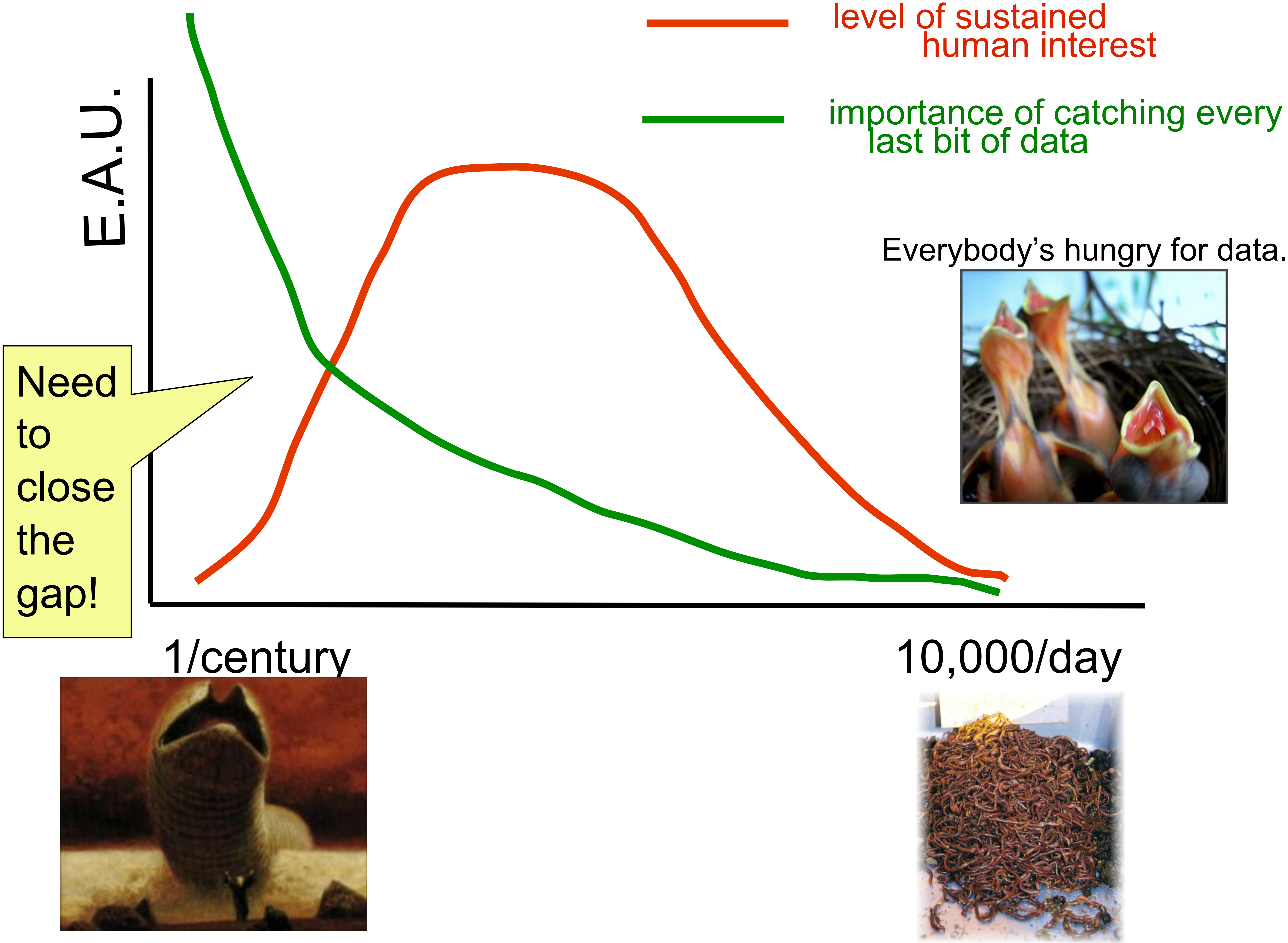


- Running smoothly for more than 10 years, automated since 2005
- Amateur astronomer connection

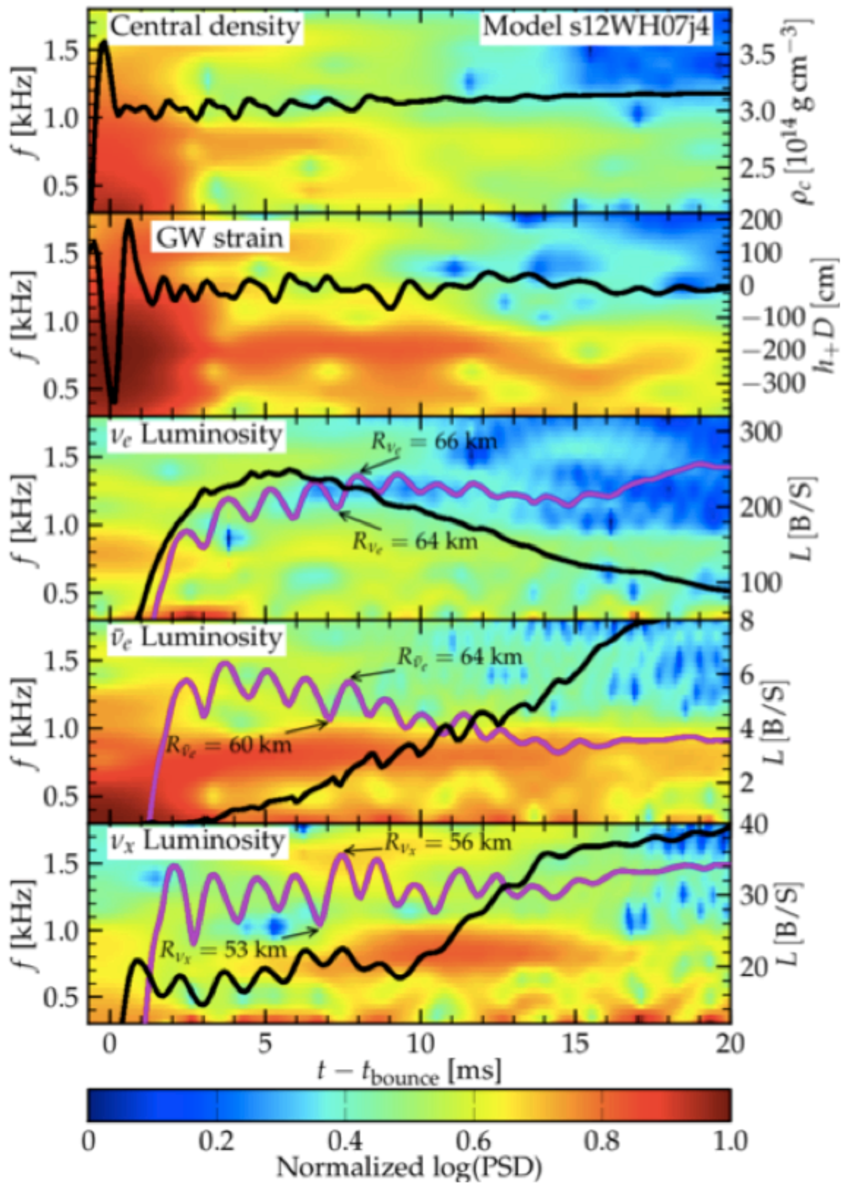
SNEWS: SuperNova Early Warning System



Sociological comments...



Final note: gravitational wave signals from core collapse



C. Ott, et al. (GWPAW 2012): correlated oscillations

Correlations between GW & ν's potentially extremely interesting

➔ physics potential from nearby collapse

➔ improvement in sensitivity from correlation analysis with existing data

See poster #94 by T. Yokozawa

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

Need cross-section measurements!

Farther future megadetectors

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