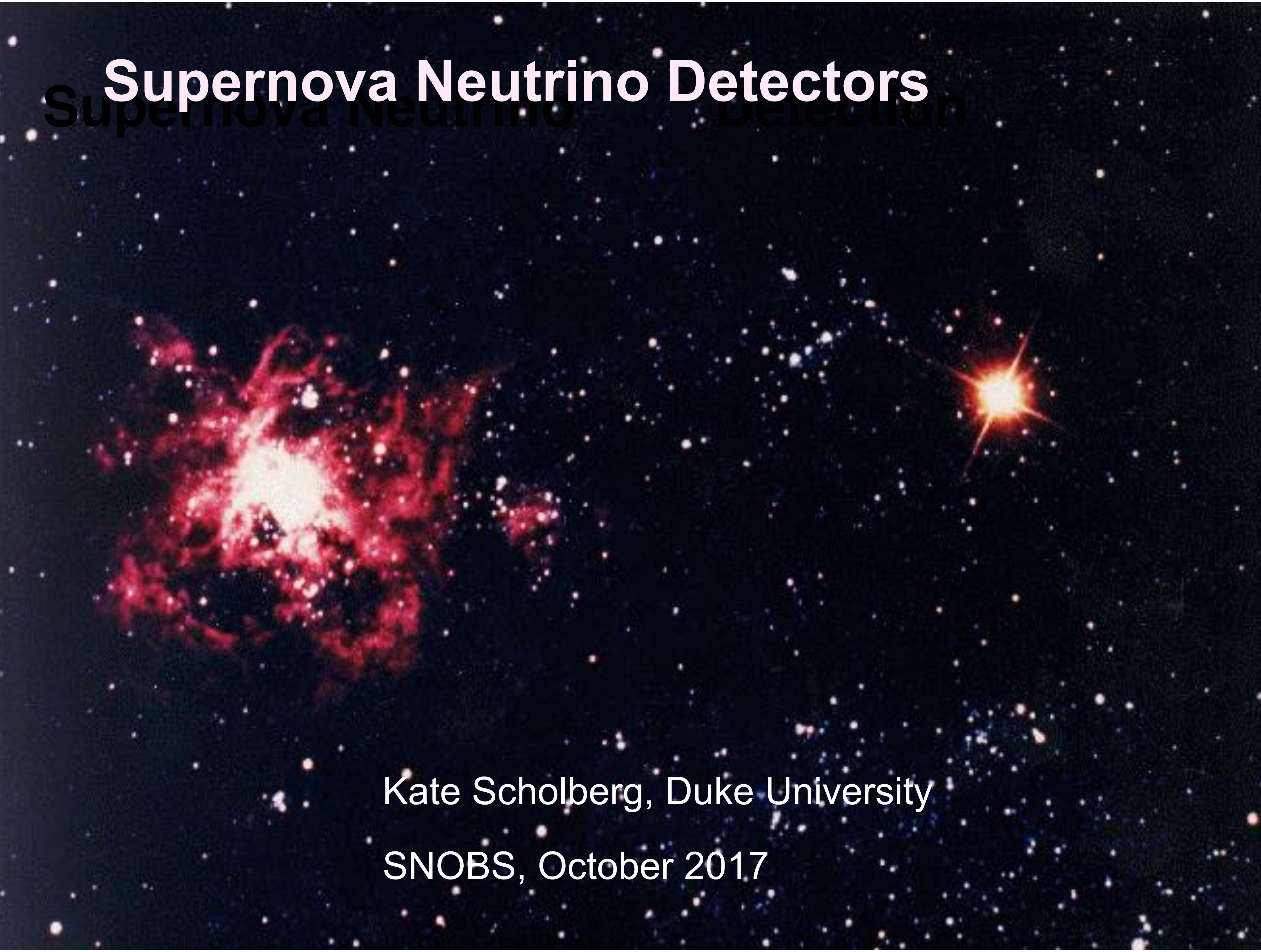
Supernova Neutrino Detectors

Supernova Neutrino Detection



Kate Scholberg, Duke University

SNOBS, October 2017

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

What do you want in a detector?

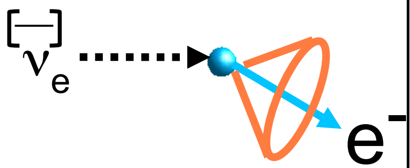
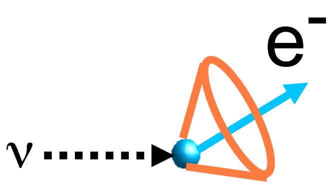
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; **underground 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"...

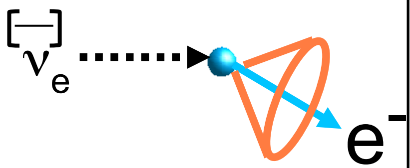
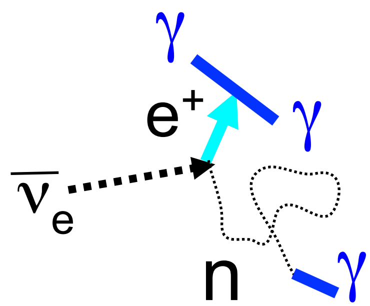
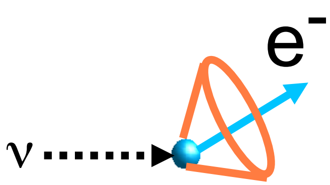
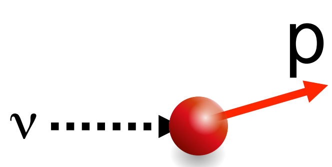
Supernova-relevant neutrino interactions

<table>
<tr><th></th><th>Electrons</th><th></th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering

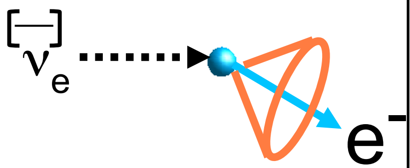
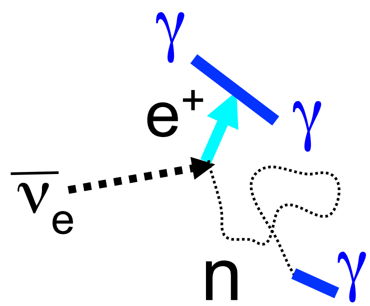
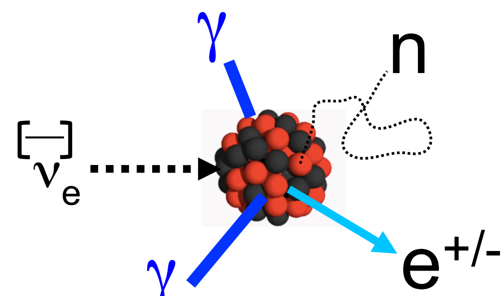
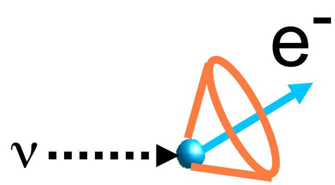
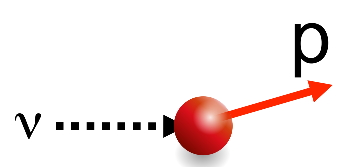
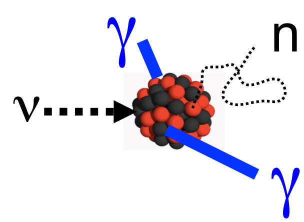
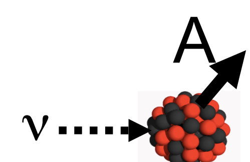
$\nu + e^- \rightarrow \nu + e^-$



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

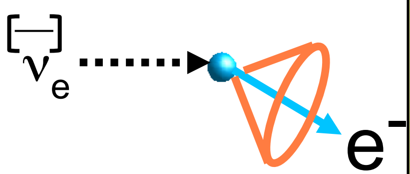
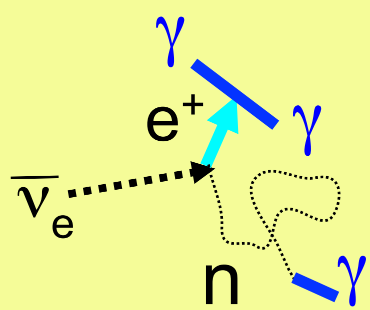
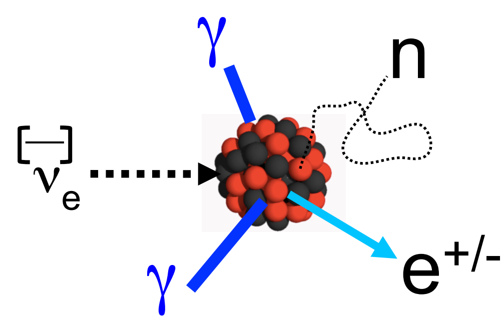
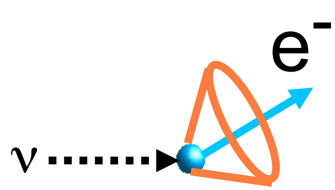
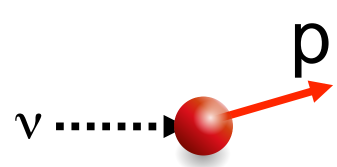
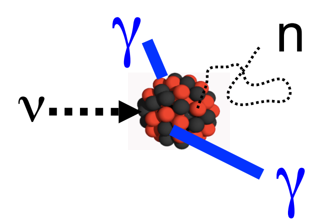
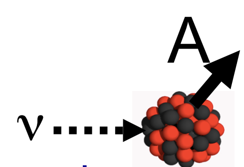
Supernova-relevant neutrino interactions

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

Supernova-relevant neutrino interactions

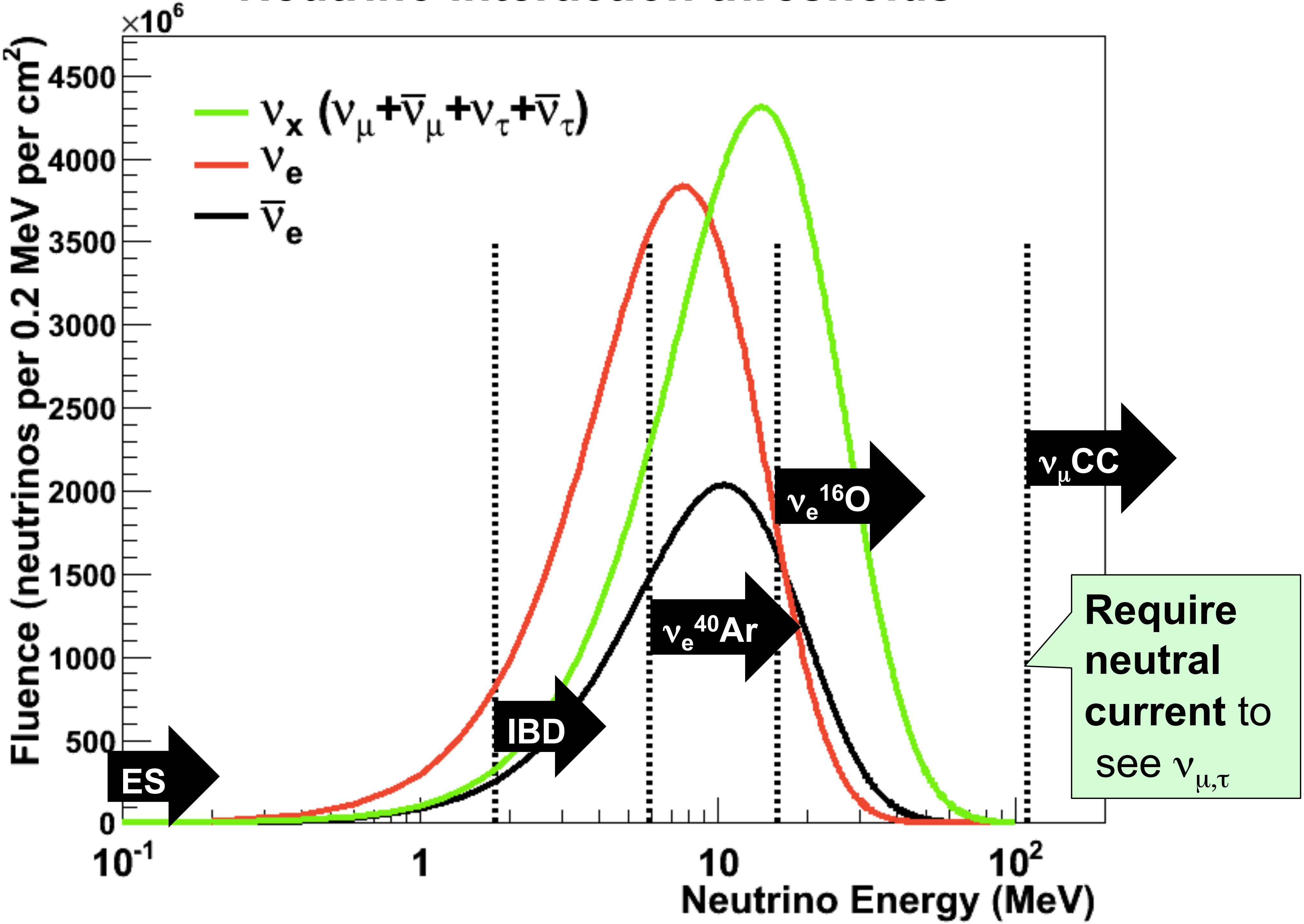
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products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

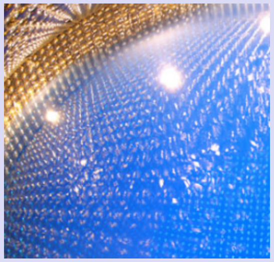
IBD (electron *anti*neutrinos) dominates for current detectors

Neutrino interaction thresholds



Supernova neutrino detector types

Water



$\bar{\nu}_e$

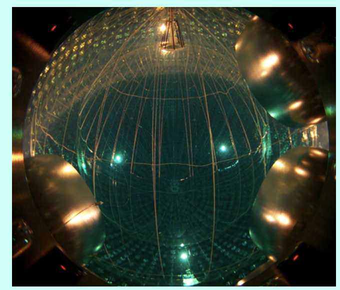
Water, long-string

$\bar{\nu}_e$

Argon

ν_e

Scintillator

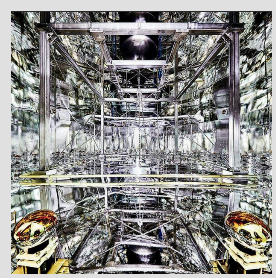


$\bar{\nu}_e$

Lead

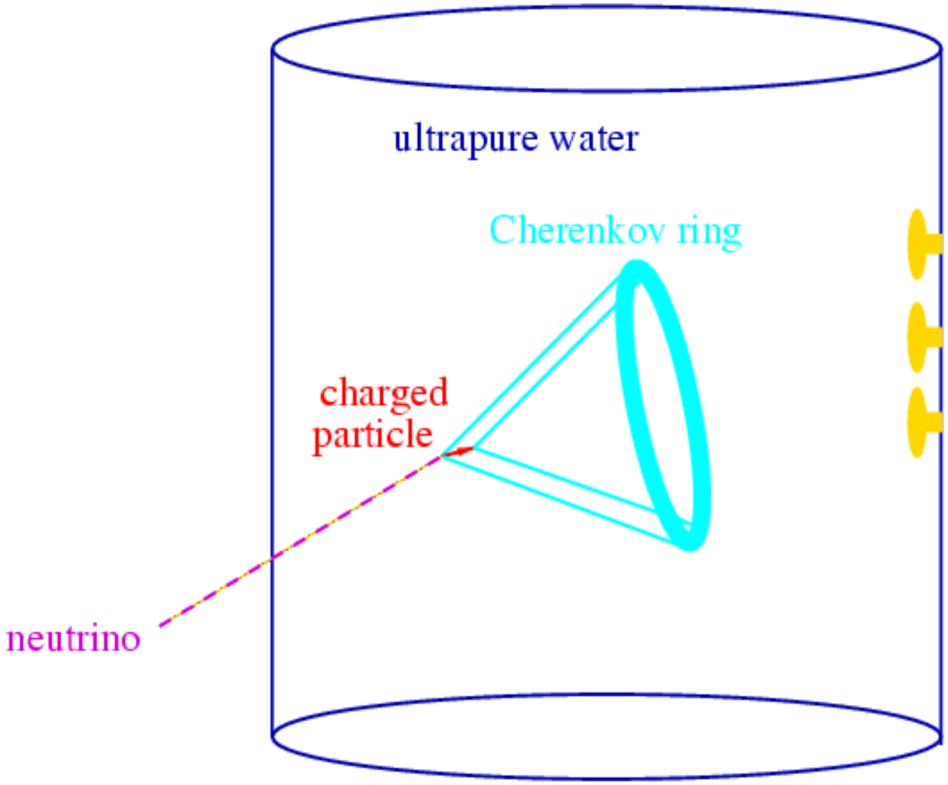
ν_e

DM (Noble liquid)



ν_x

Water Cherenkov detectors

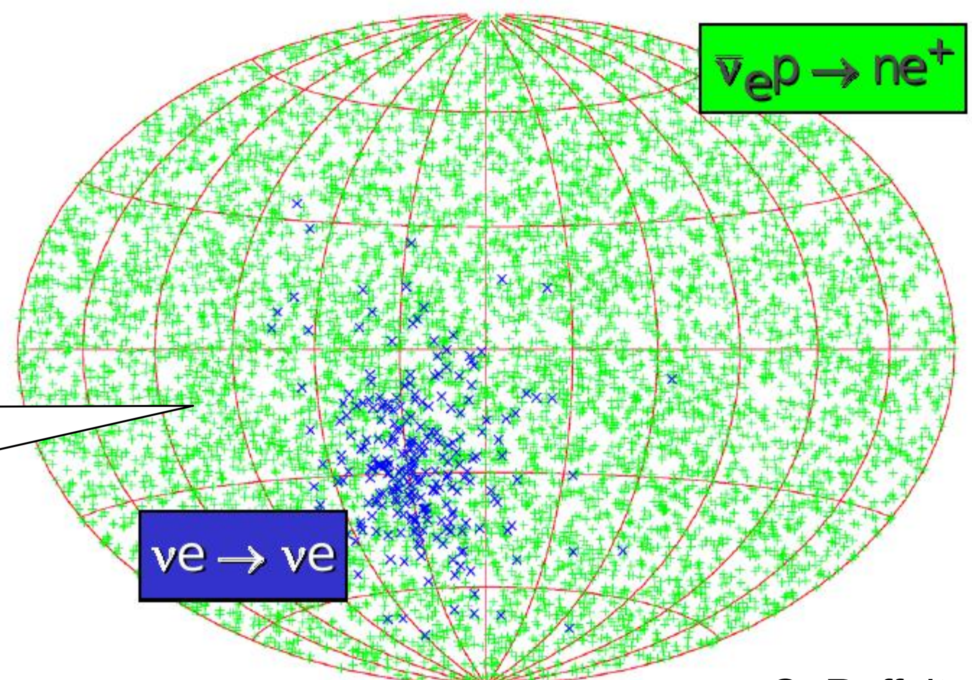


Inverse Beta Decay (CC)

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

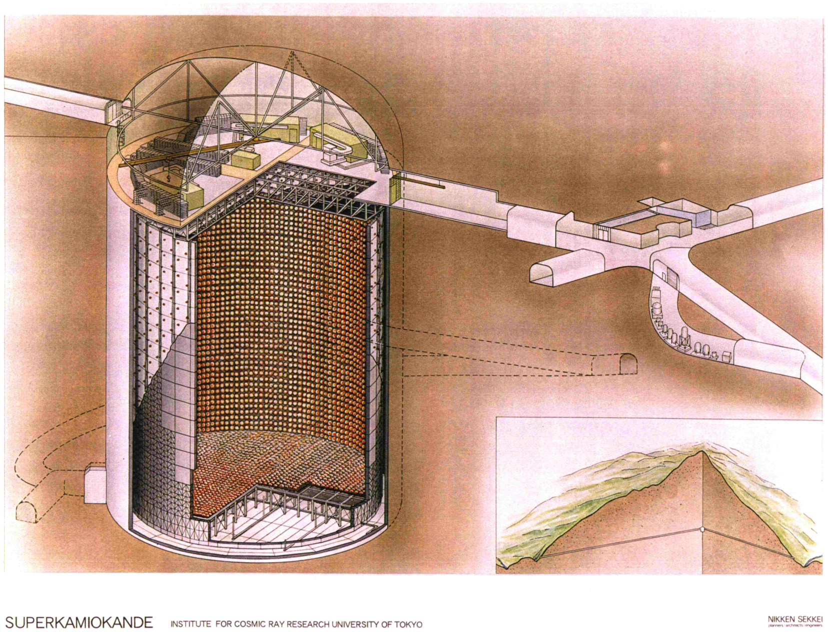
dominates

E_{thr}=1.8 MeV



Pointing from neutrino-electron elastic scattering

G. Raffelt



Super-Kamiokande

Mozumi, Japan

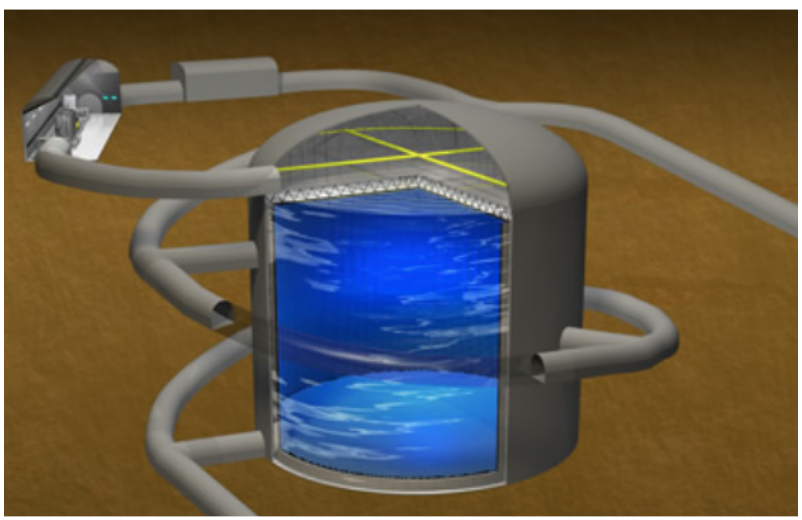
22.5 kton fid. volume (32 kton total)

~5-10K events @ 10 kpc

(mostly anti-ν_e)

~5^o pointing @ 10 kpc

Future: SK-Gd

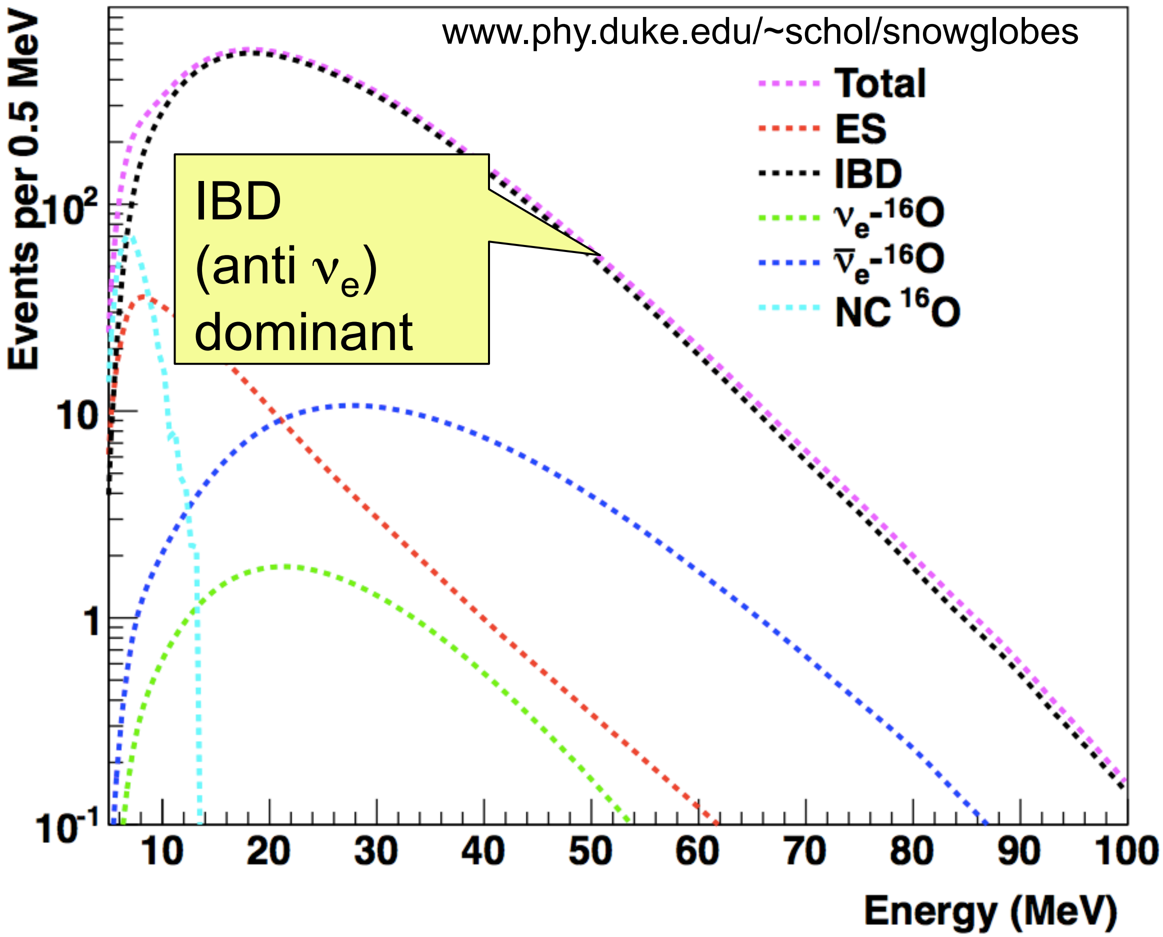


Hyper-Kamiokande

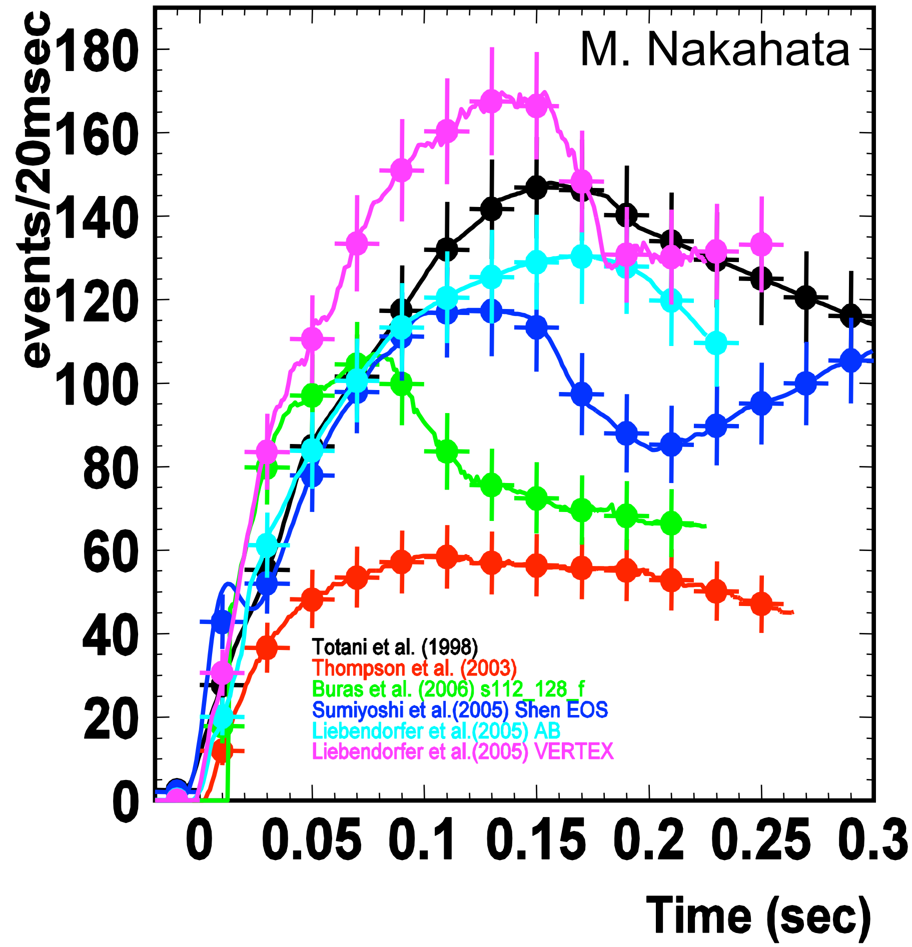
- staged 2-module, 374-kton fid. water Cherenkov detector
- 1 module: 40% PMT coverage w/double efficiency

Supernova signal in a water Cherenkov detector

Events seen, as a function of observed energy

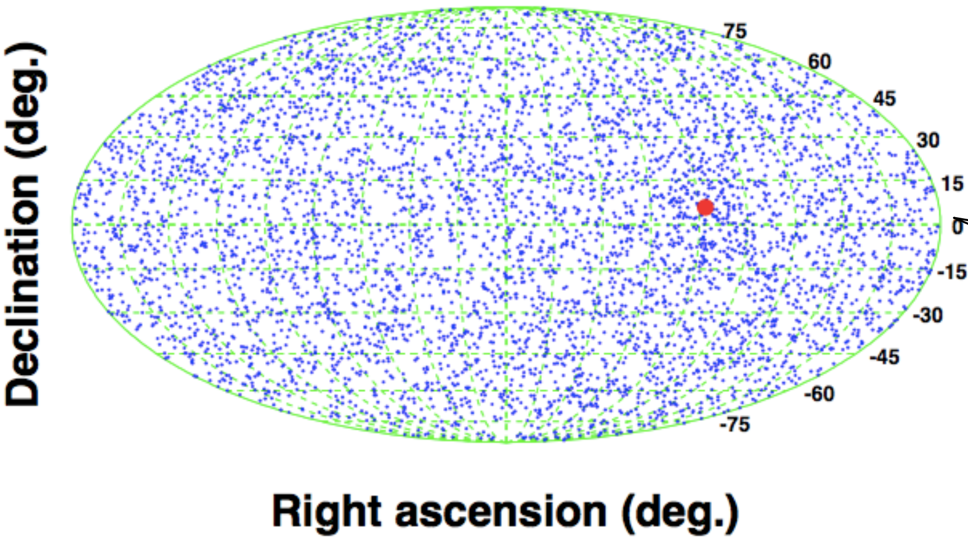


For 100 kton.
30% PMT coverage
@ 10 kpc



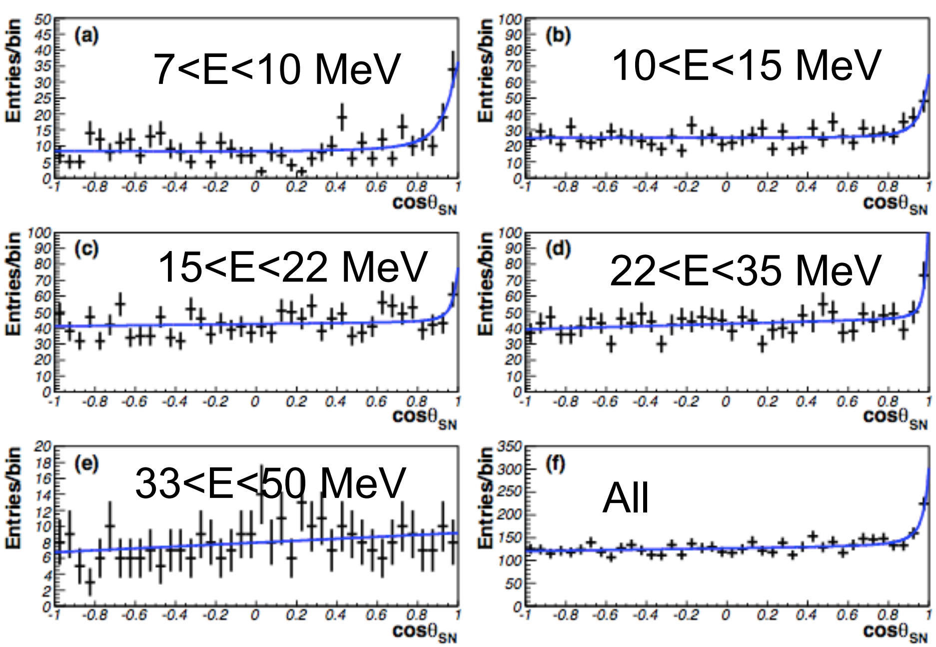
Events vs time
for SK, for
different models

Pointing in Water Cherenkov: Super-K

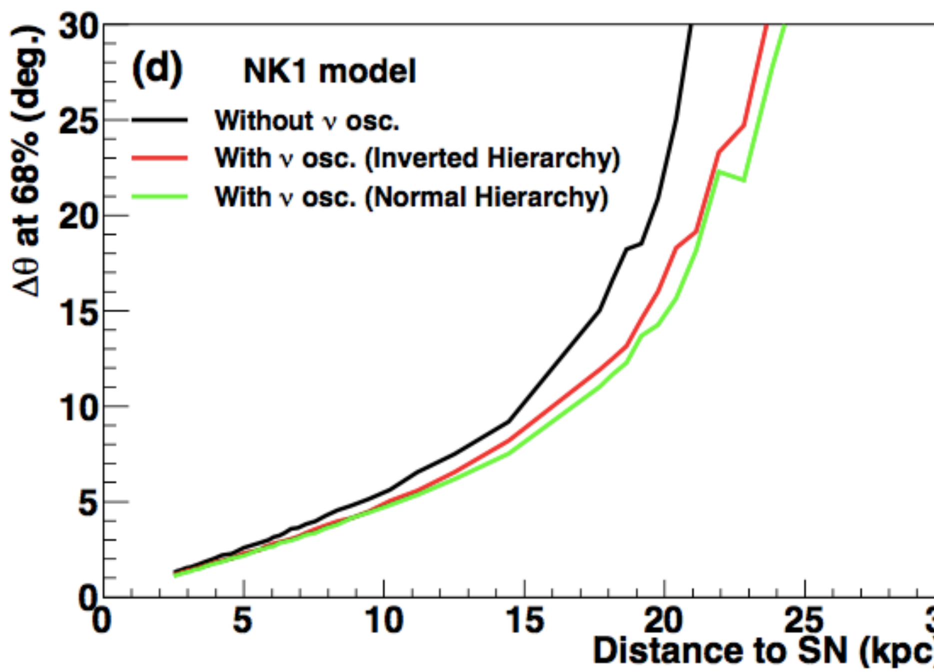


K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Harder when you don't have the interaction truth!



Fit to ES+ mildly anisotropic IBD (+^{16}O)



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

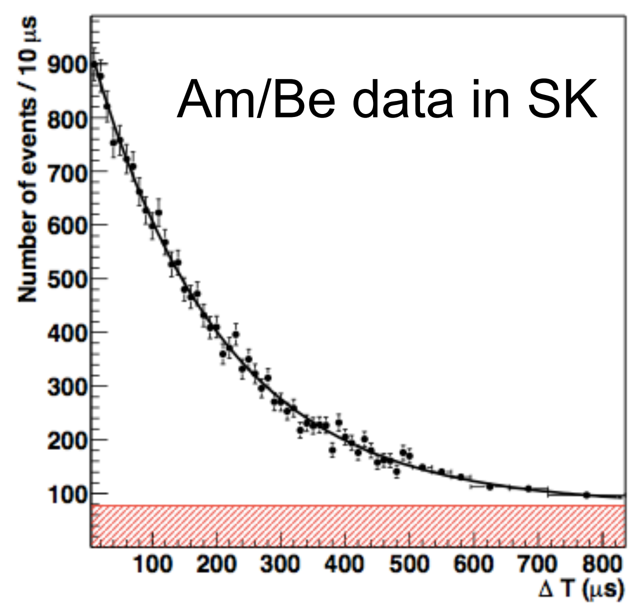
"Drug-free" neutron tagging

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

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

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

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

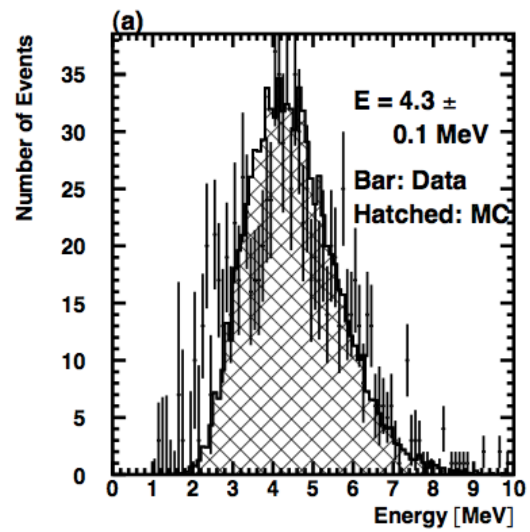
use gadolinium to capture neutrons (like for scintillator)

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

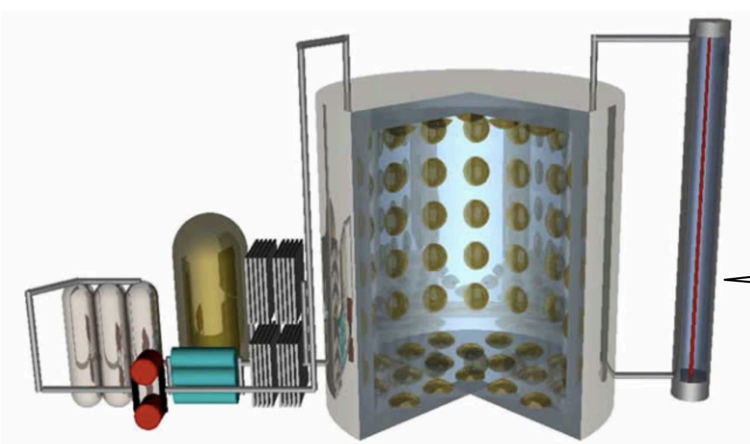
Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

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

About 4 MeV visible energy per capture



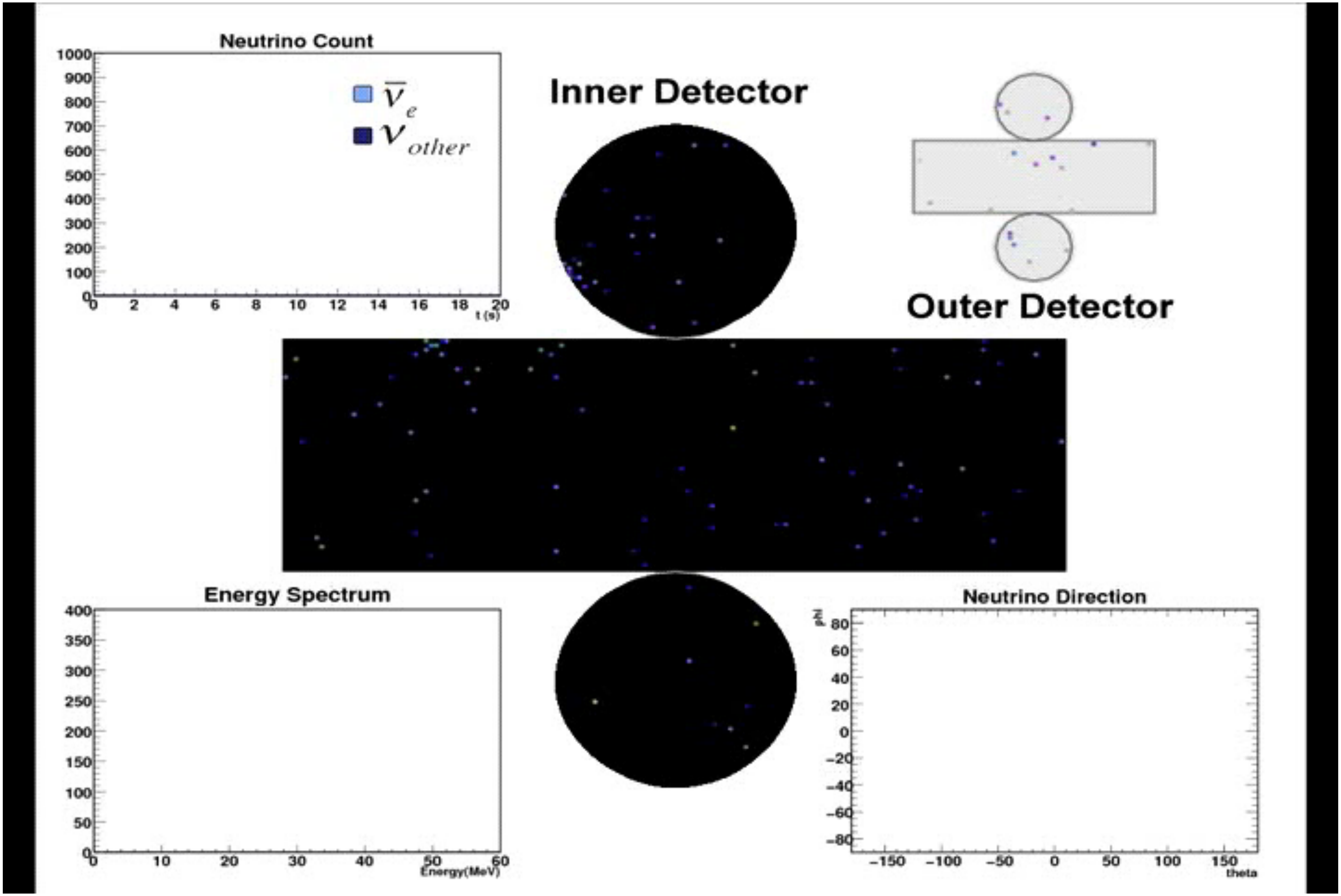
H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)



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

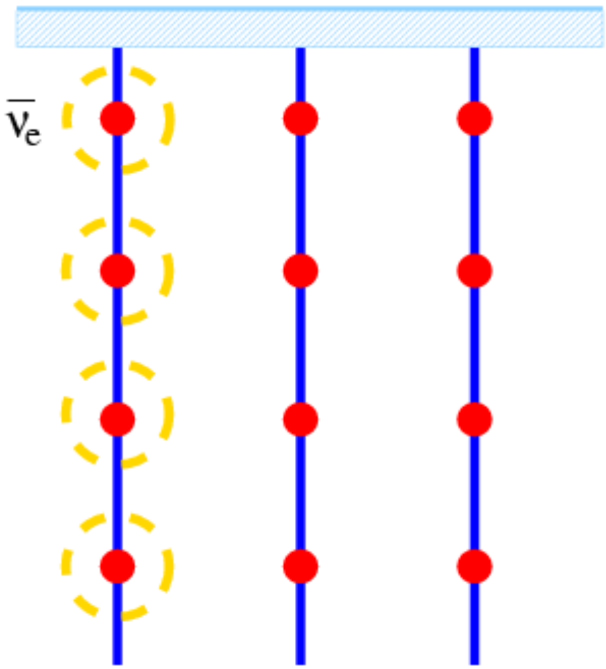
M. Vagins talk

SK-Gd now approved to go forward



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

Long string water Cherenkov detectors

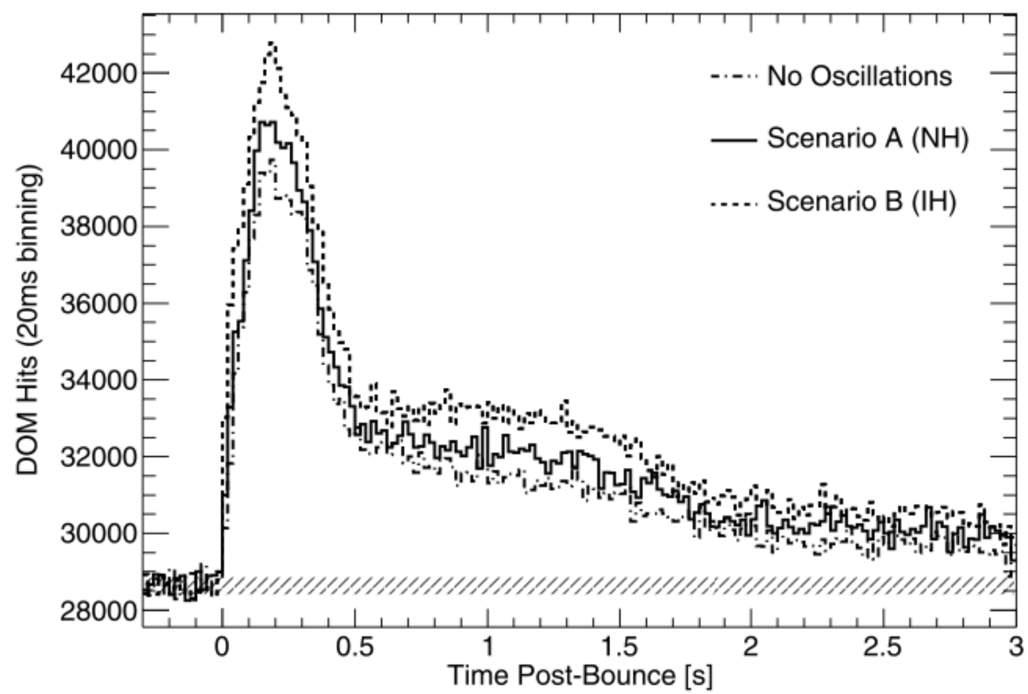


~kilometer long strings of PMTs in very clear water or ice

(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)

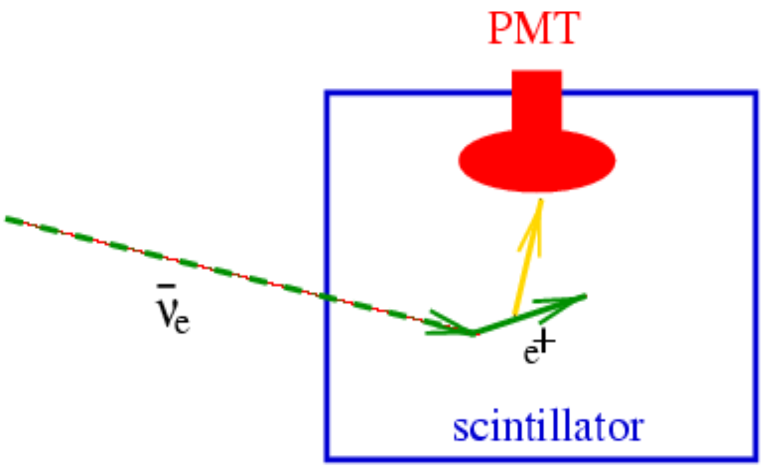
IceCube collaboration, A&A 535, A109 (2011)



Map overall time structure of burst

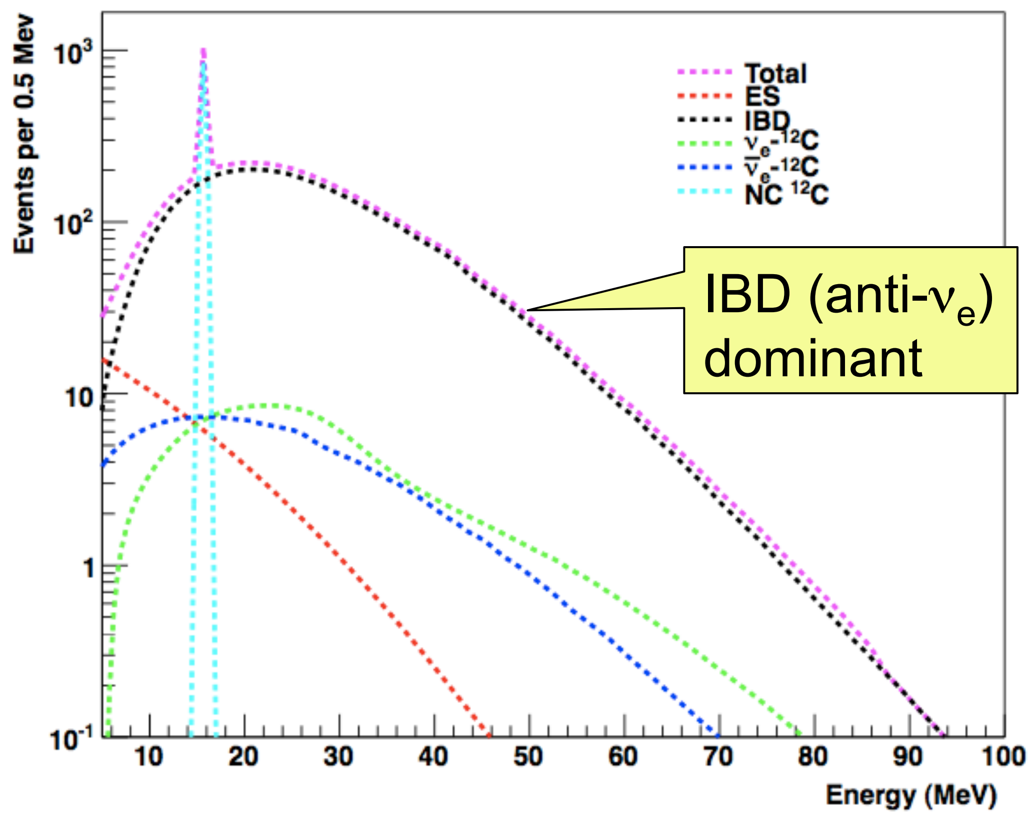
L. Koepke talk

Scintillation detectors



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

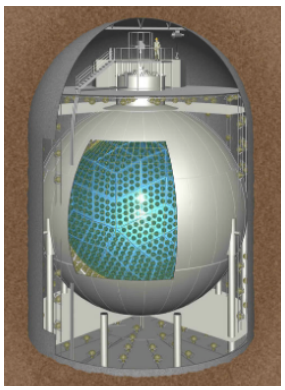
- few 100 events/kton (IBD)
- low threshold,
  good energy resolution
- little pointing capability
  (light is ~isotropic)



50 kt @ 10 kpc

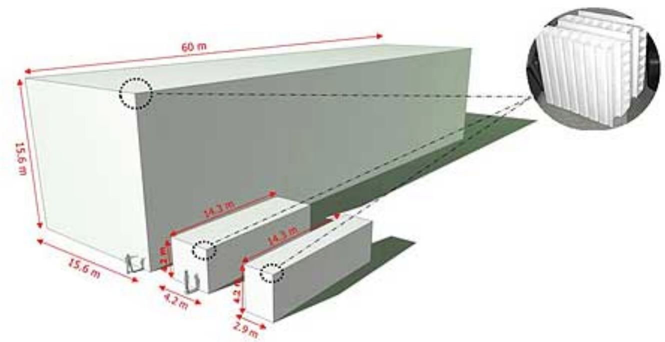
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



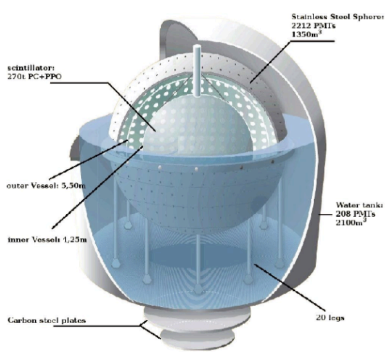
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

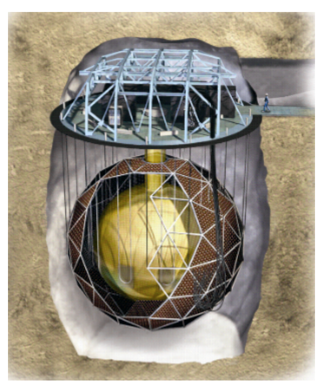


(on surface, but
may be possible
to extract counts
for known burst)

Borexino
(Italy)
0.33 kton



SNO+
(Canada)
1 kton

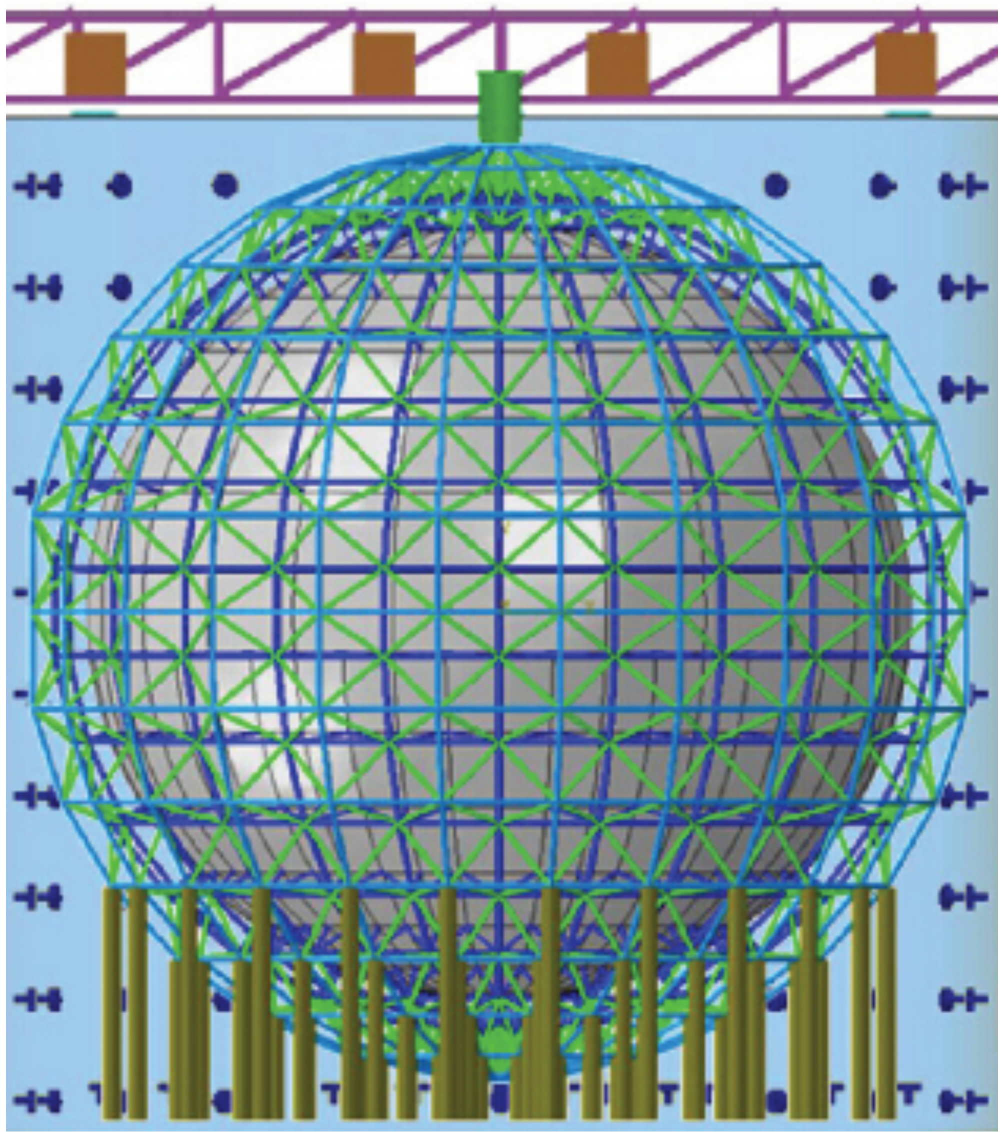


+ reactor expts

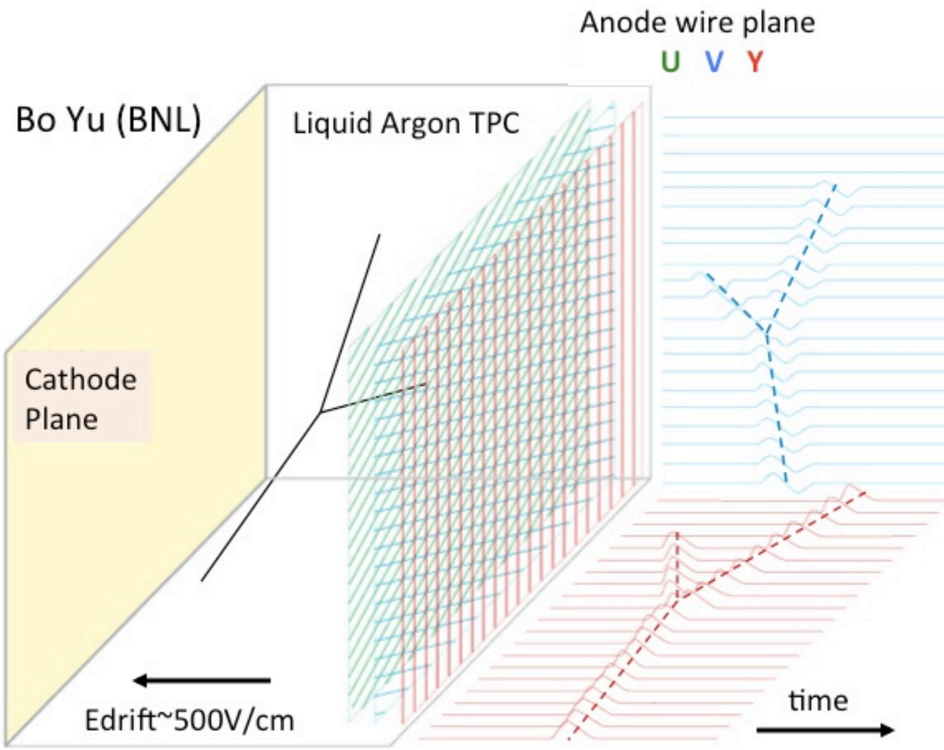
Future detector proposal

JUNO
(China)
20 kton

S. Zhou talk

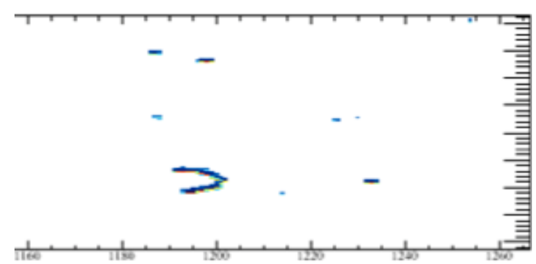


Liquid argon time projection chambers



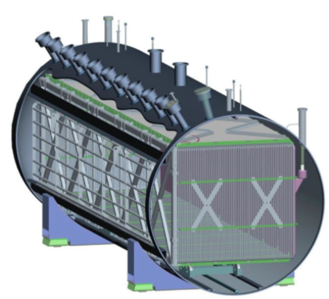
- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

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

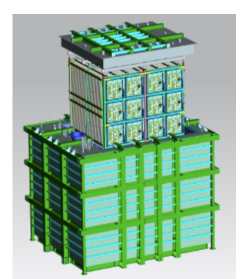


ICARUS
(Italy...)
0.6 kton

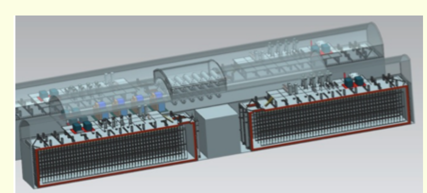
MicroBooNE
(USA)
0.2 kton



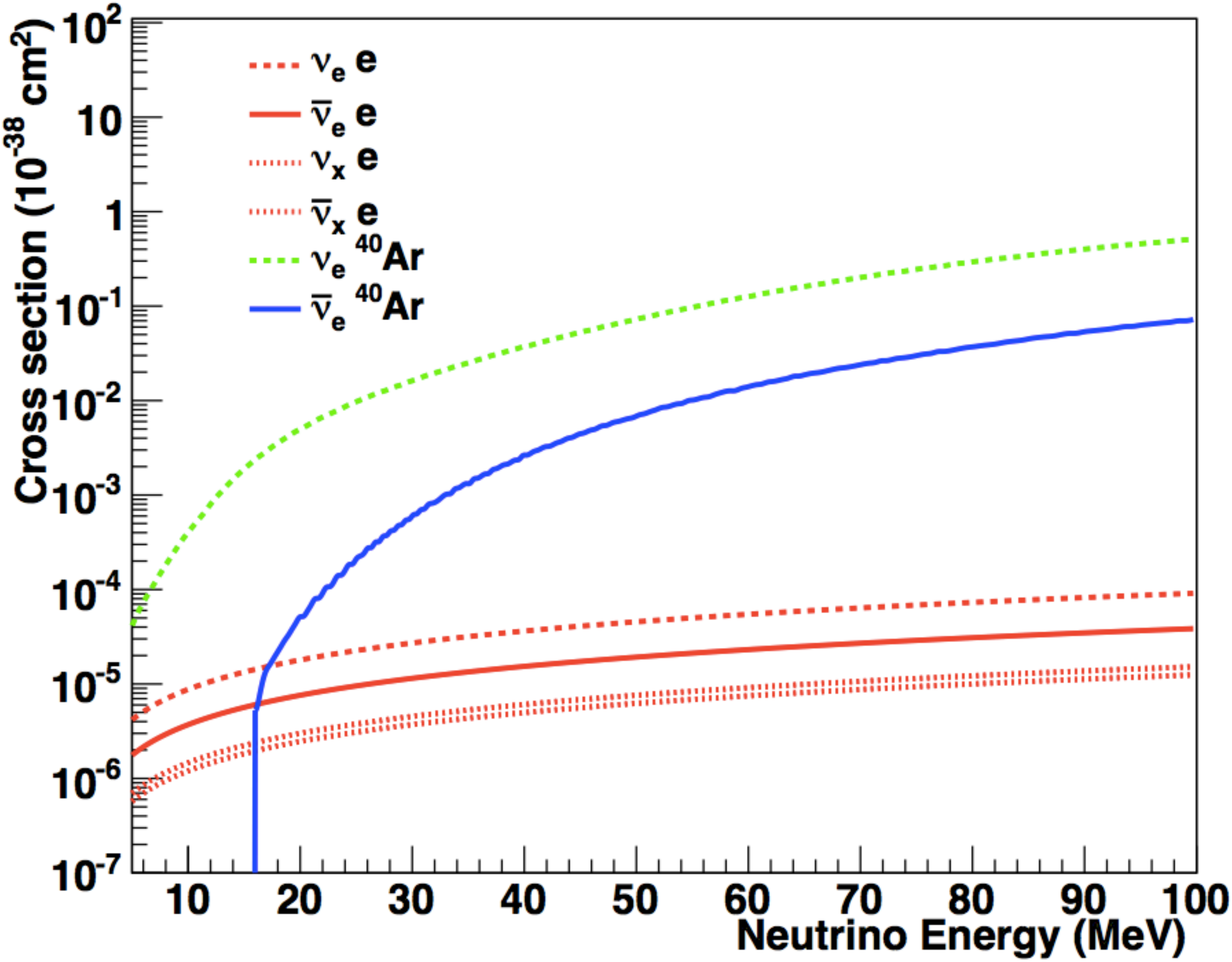
SBND
(USA)
0.112 kton



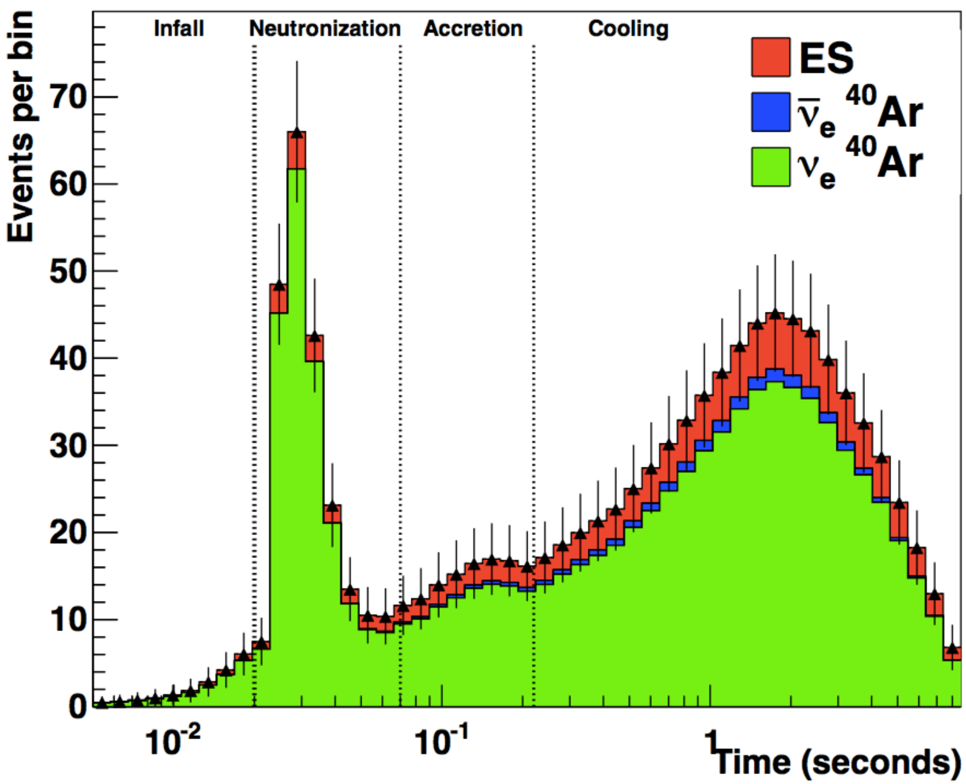
DUNE
(USA)
40 kton



Cross sections in argon

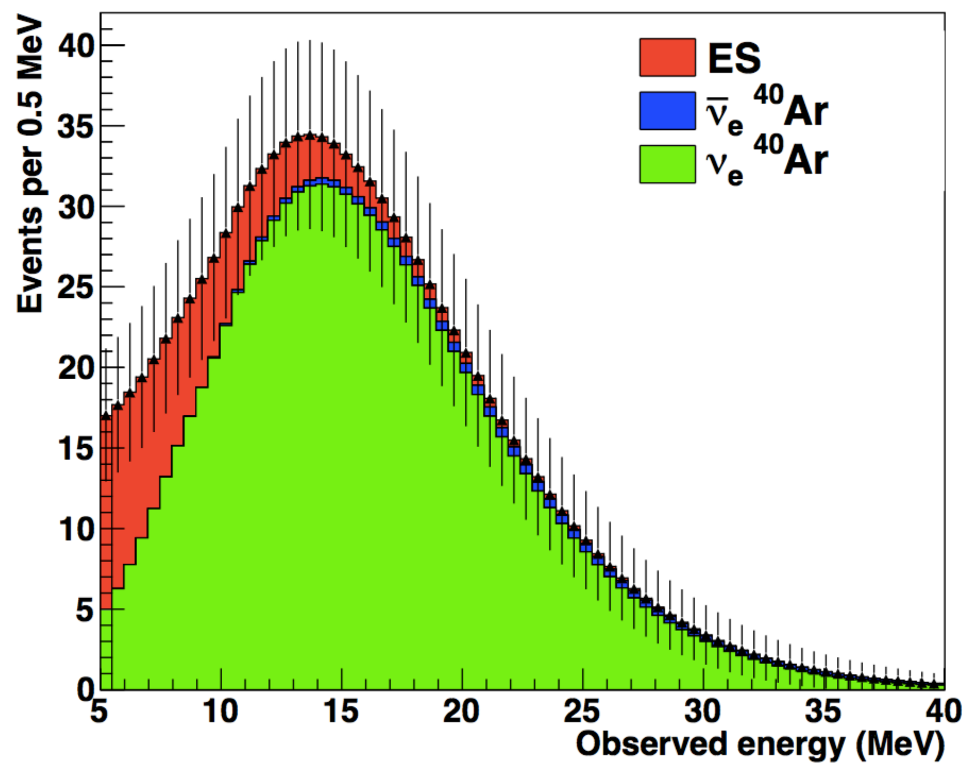


Flavor composition as a function of time

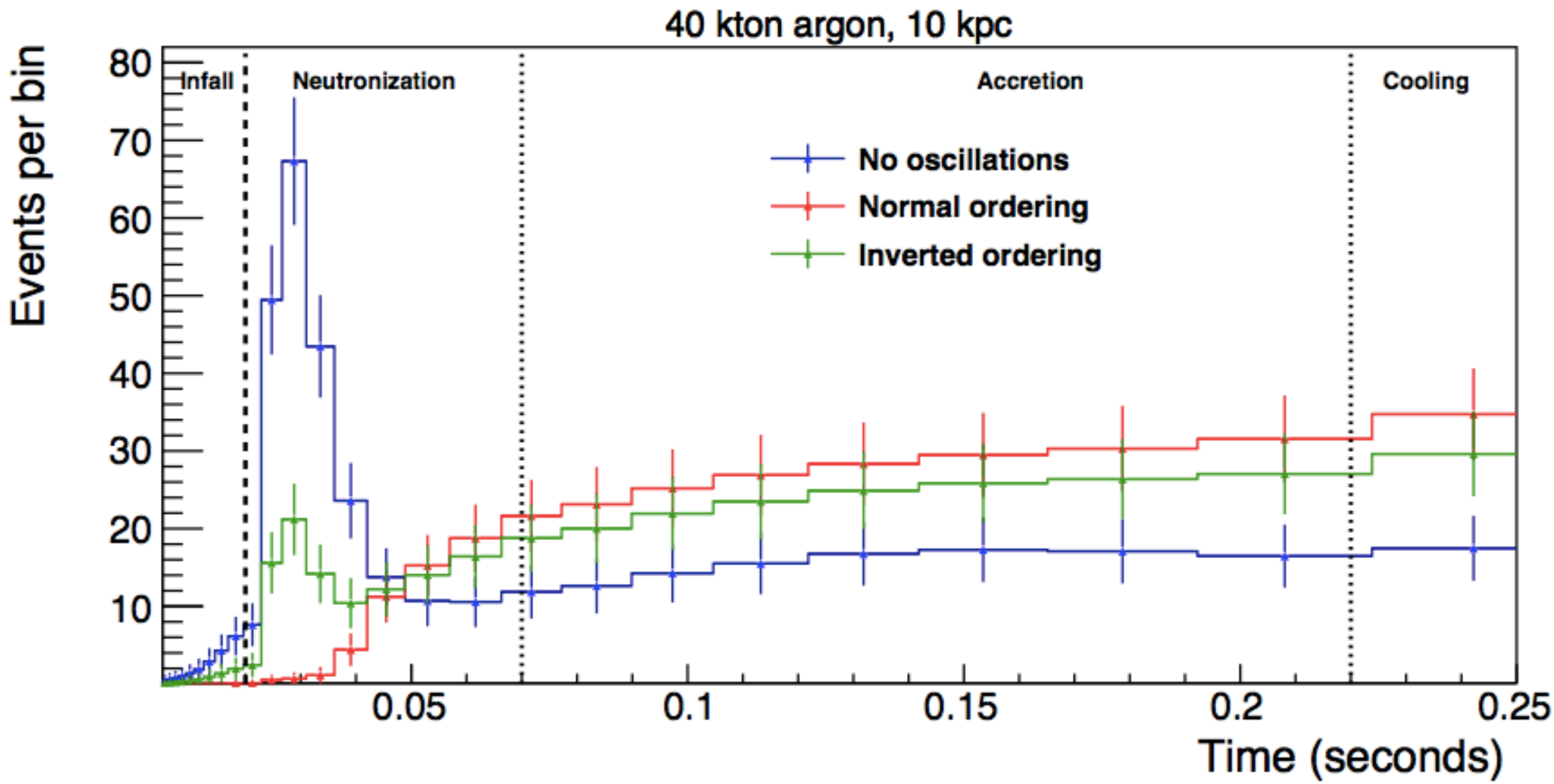


For 40 kton @ 10 kpc,
Garching model
(no oscillations)

Energy spectra integrated over time



Note that the neutronization burst gets substantially suppressed with flavor transitions



Simple MSW assumption (assume OK at early times)

NMO: $F_{\nu_e} = F^0_{\nu_x}$

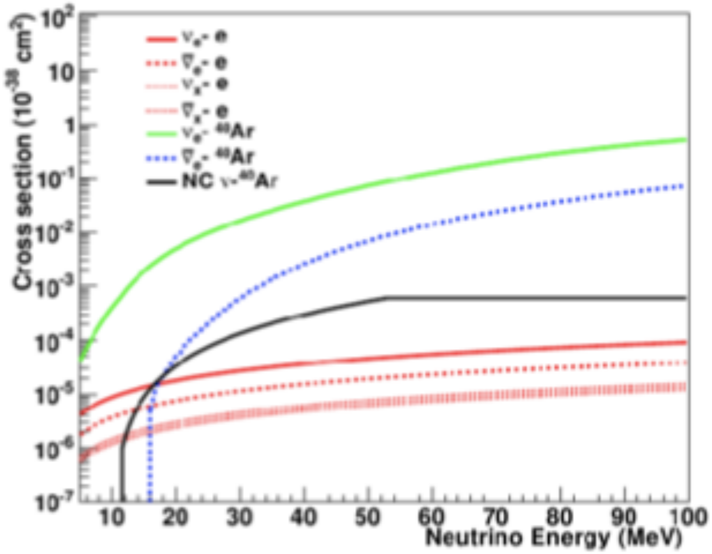
IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$ (a robust mass ordering signature!)

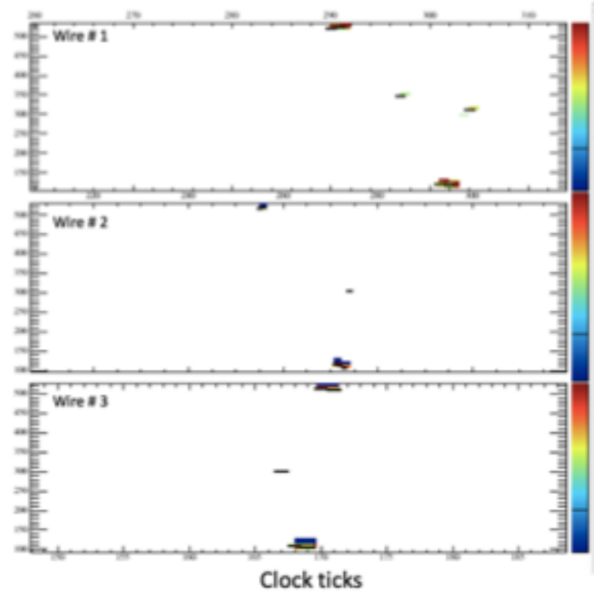
“New” NC channel in argon

$$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$$

$${}^{40}\mathrm{Ar}^* \rightarrow 9.8\ \mathrm{MeV}\ \gamma + {}^{40}\mathrm{Ar}$$

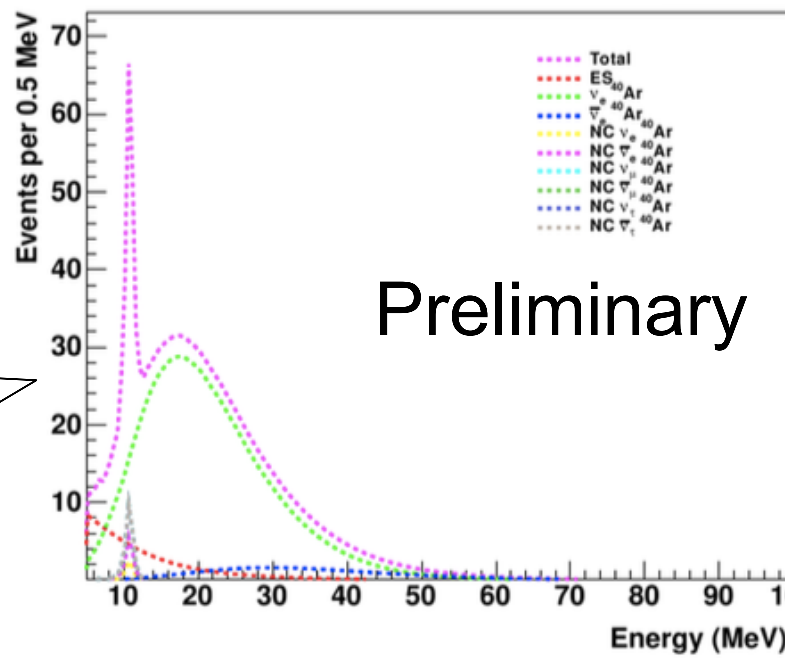
Cross section calculation from A. Hayes
SNOwGLoBES + LArSoft study by C. Nunez



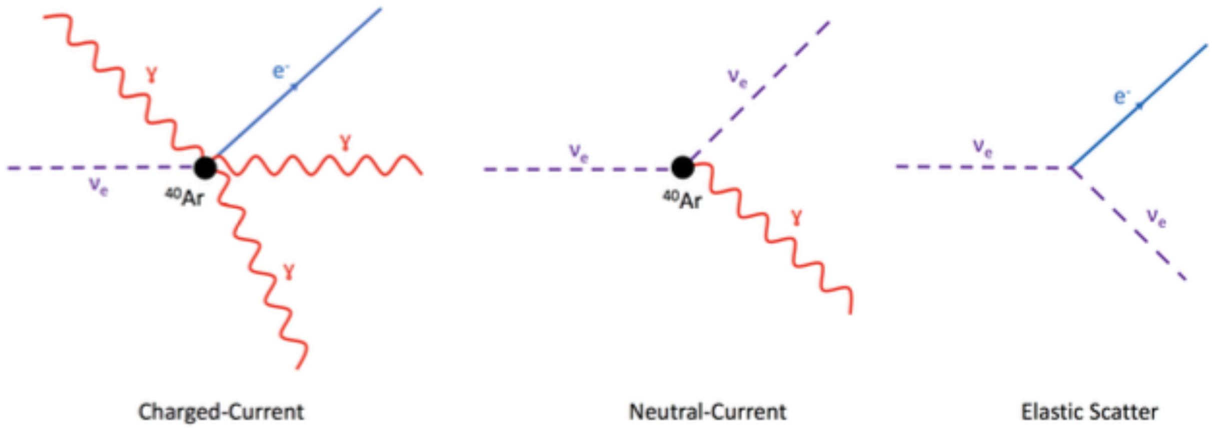


Detector signature: cluster of blips from Compton scatters

Assuming drift correction from photons, should be observable in the spectrum



How well can we *tag* interaction channels in argon?

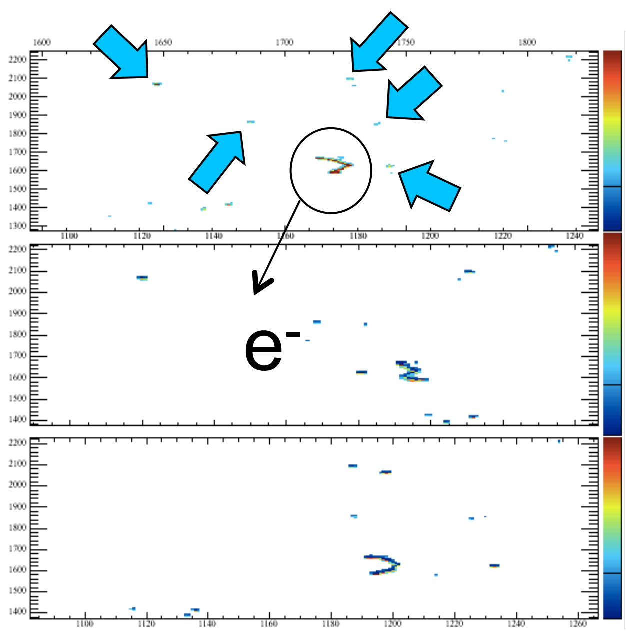


E. Conley

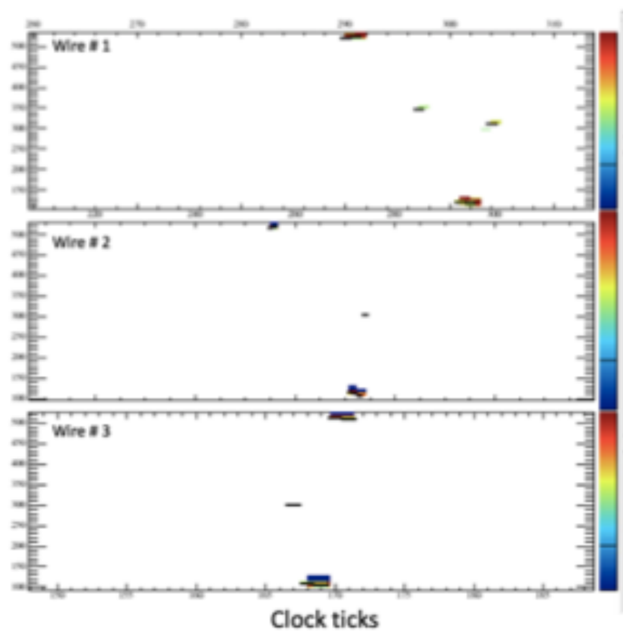
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$

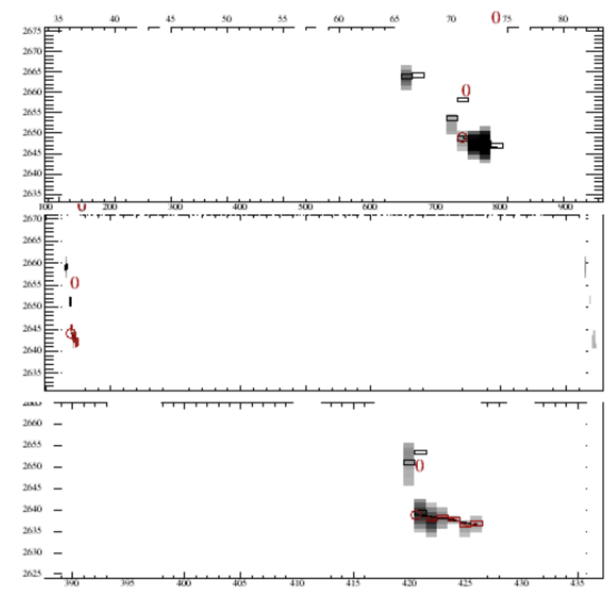
$\nu + e^- \rightarrow \nu + e^-$



track + deex γ blips
+ brem γ blips



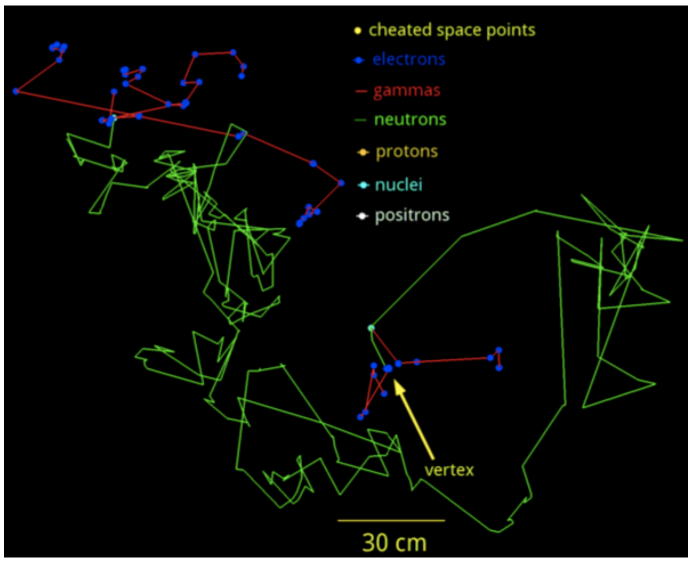
cloud of γ blips

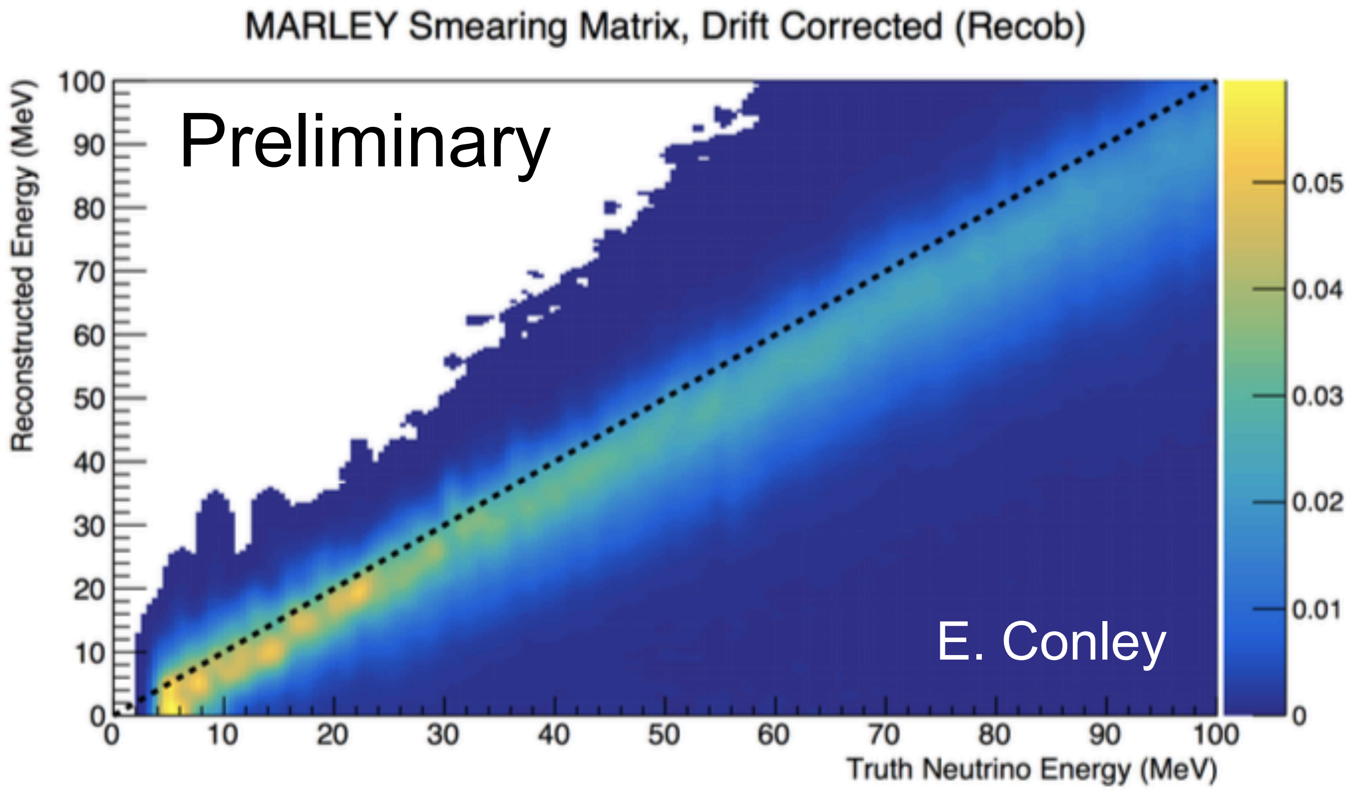


“clean” track

The final state can be complicated...
some energy is lost

MARLEY sim
(see Alex Friedland's talk)





Modeling is improving, but still need nuclear theory help !

Lead-based supernova detectors

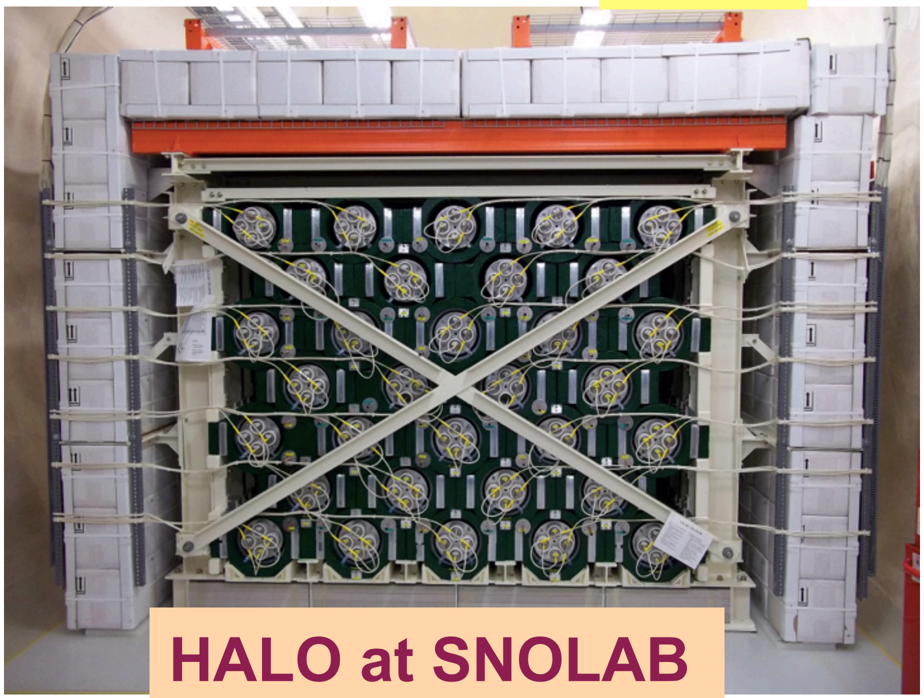
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

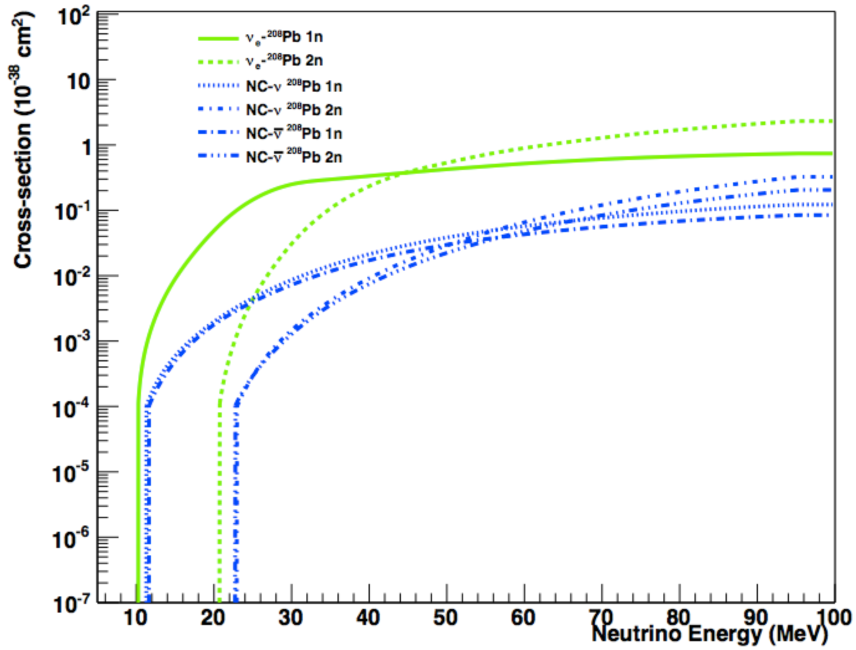
1n, 2n emission

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

1n, 2n, γ emission

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





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

J. Rumleskie talk

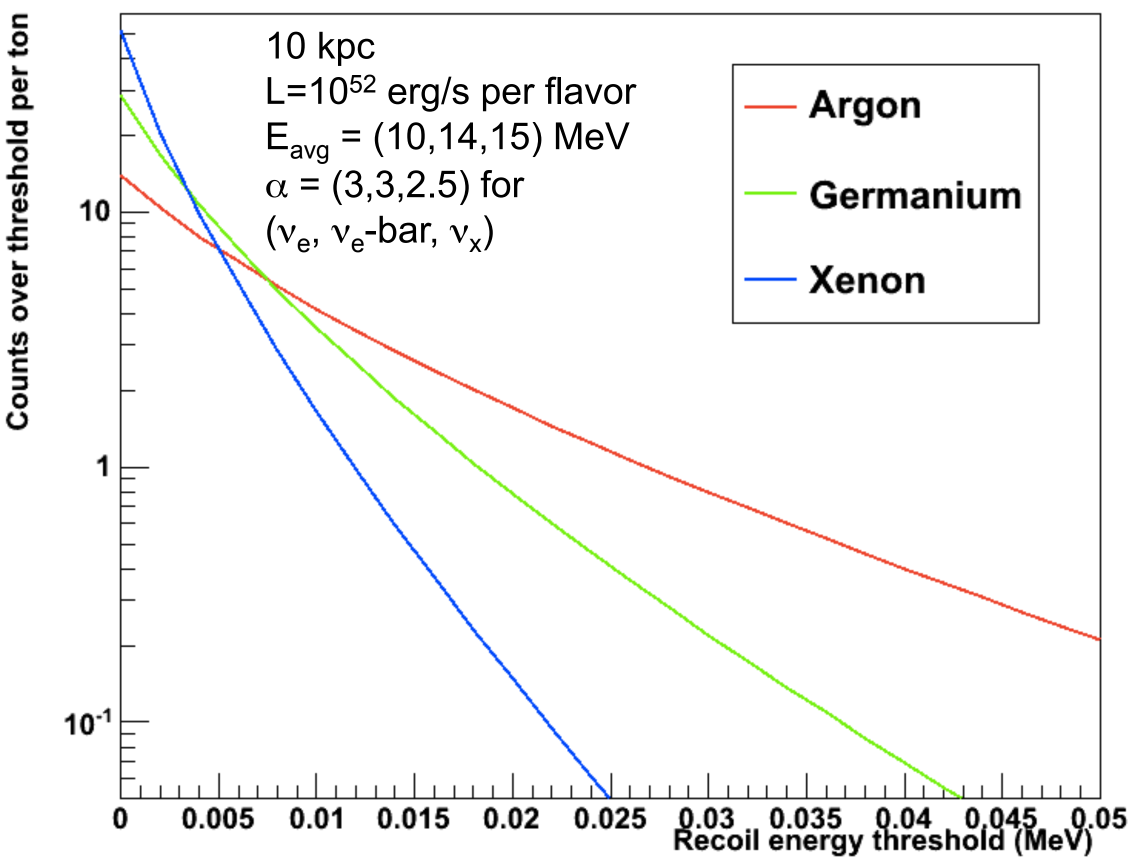
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

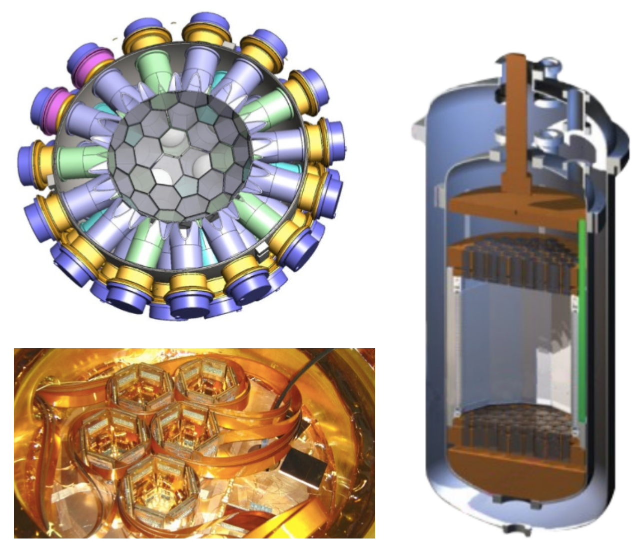
$$\nu_x + A \rightarrow \nu_x + \boxed{A}$$

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

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

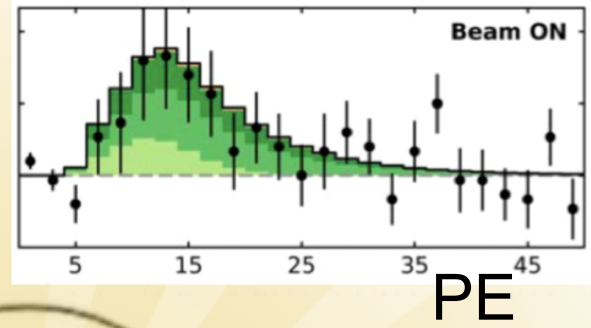
$\Rightarrow$ observable in dark matter detectors



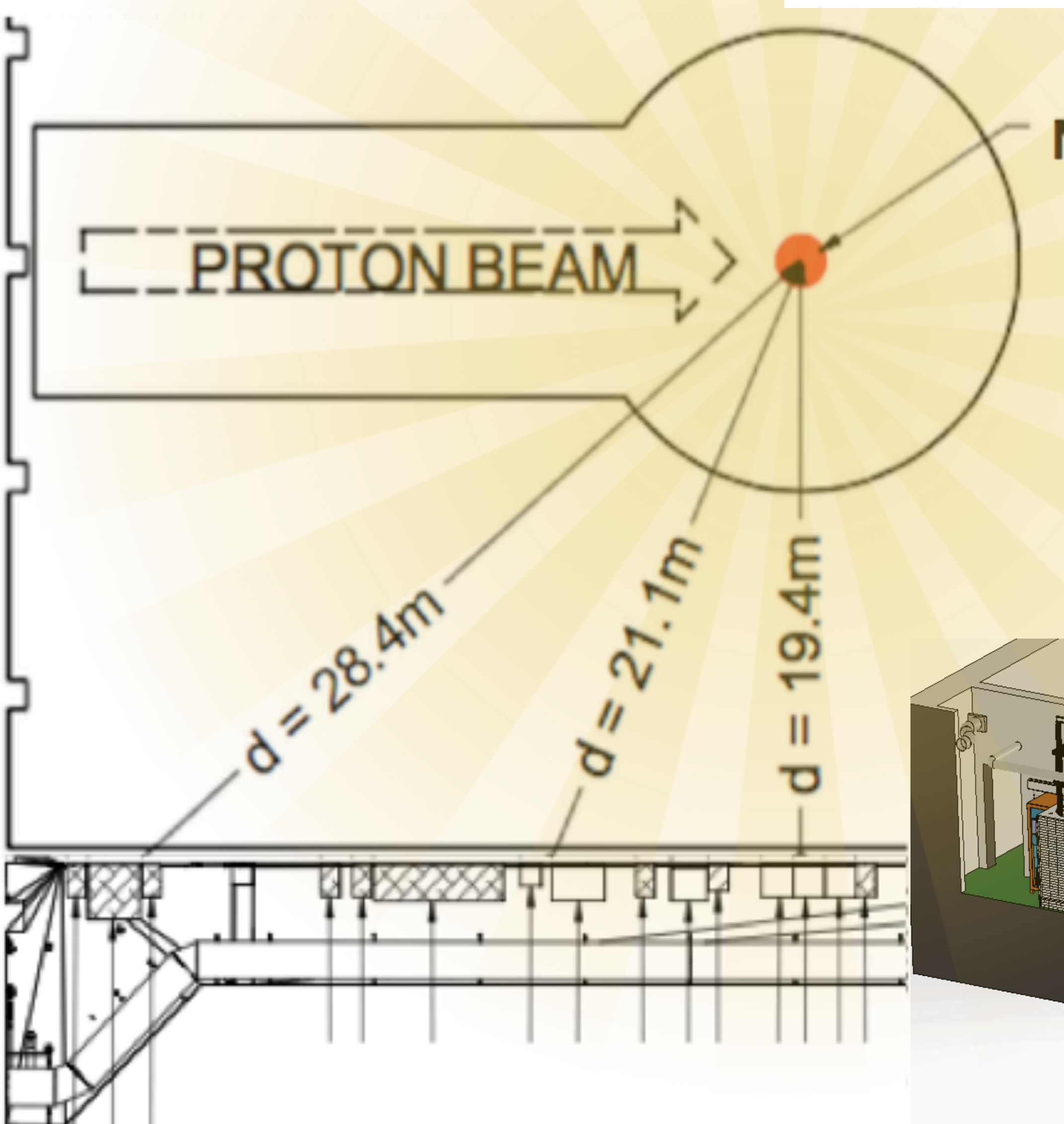


~ handful of events per tonne @ 10 kpc: sensitive to ***all flavor components*** *of the flux*

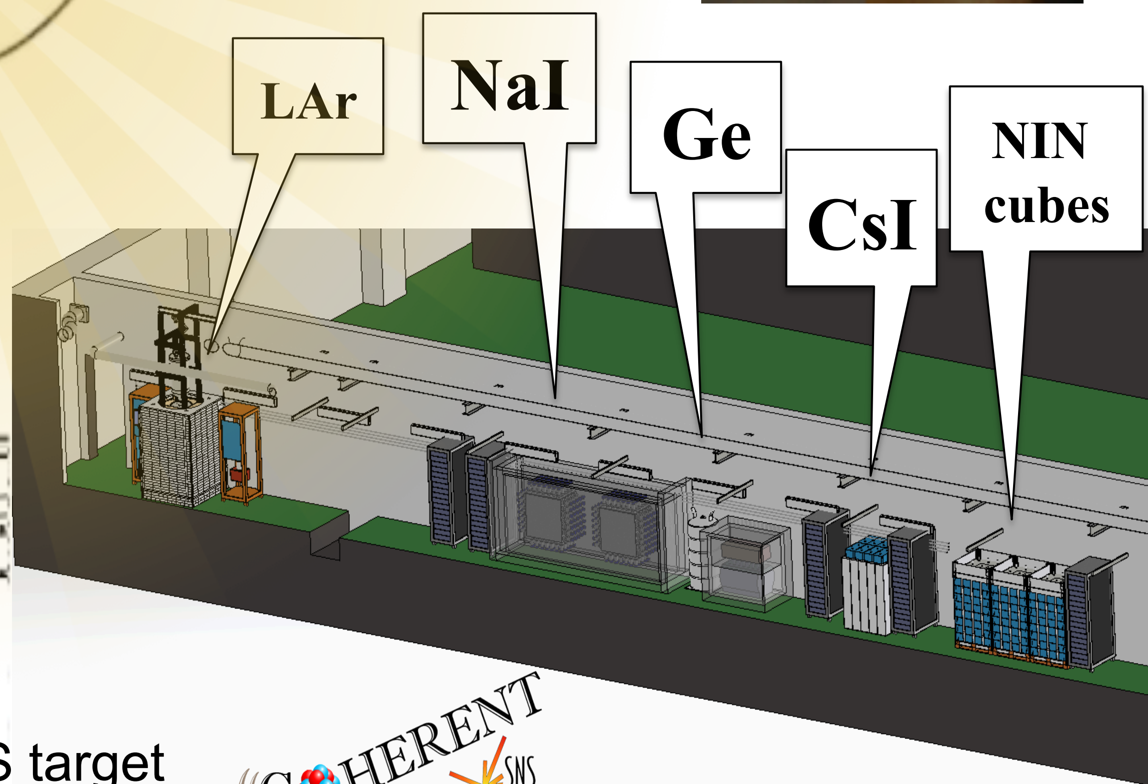
Now measured w/ stopped-π ν's



View looking down "Neutrino Alley"



Isotropic ν glow from Hg SNS target



Summary of supernova neutrino detectors

Galactic sensitivity

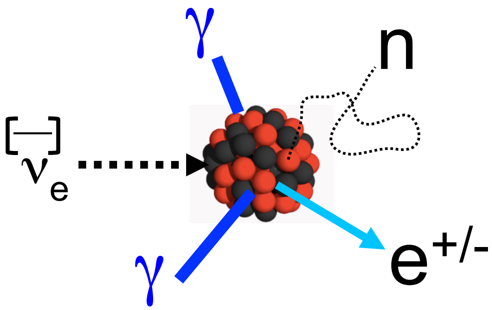
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
MicroBooNE	Liquid argon	USA	0.17	17	Running
SNO+	Scintillator	Canada	1	300	Under construction
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
PINGU/GEN-2	Long string	South pole	(600)	(10^6)	Future

Extragalactic

plus reactor experiments, DM experiments...

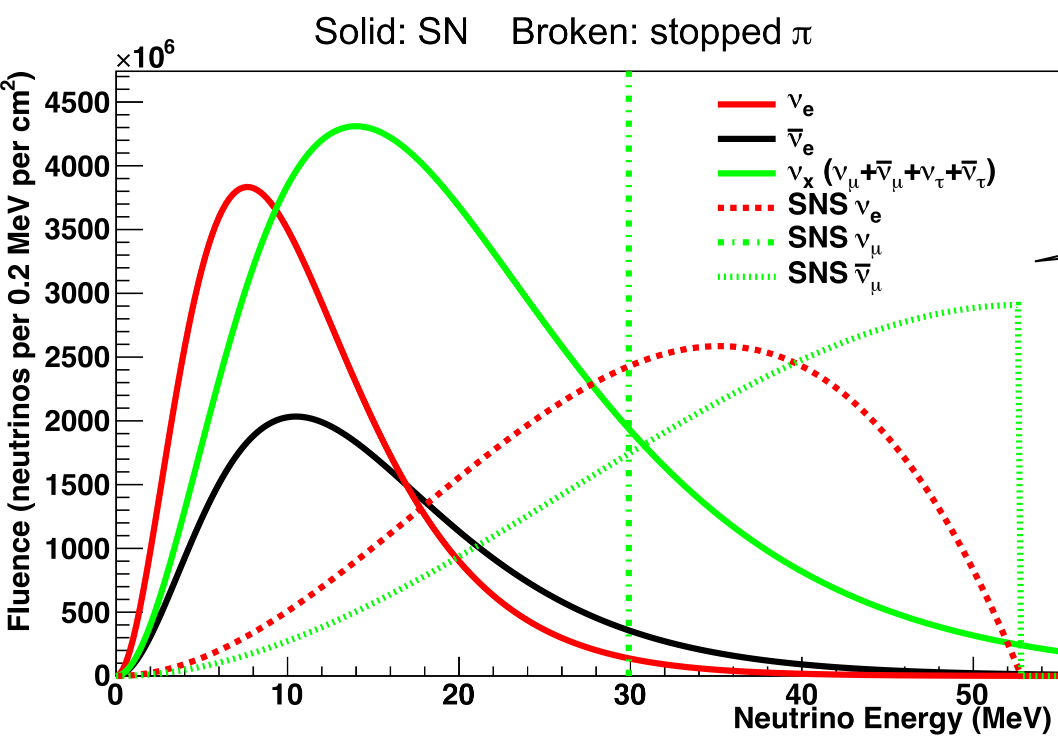
For supernova neutrinos, the more the merrier!

Comment #1



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

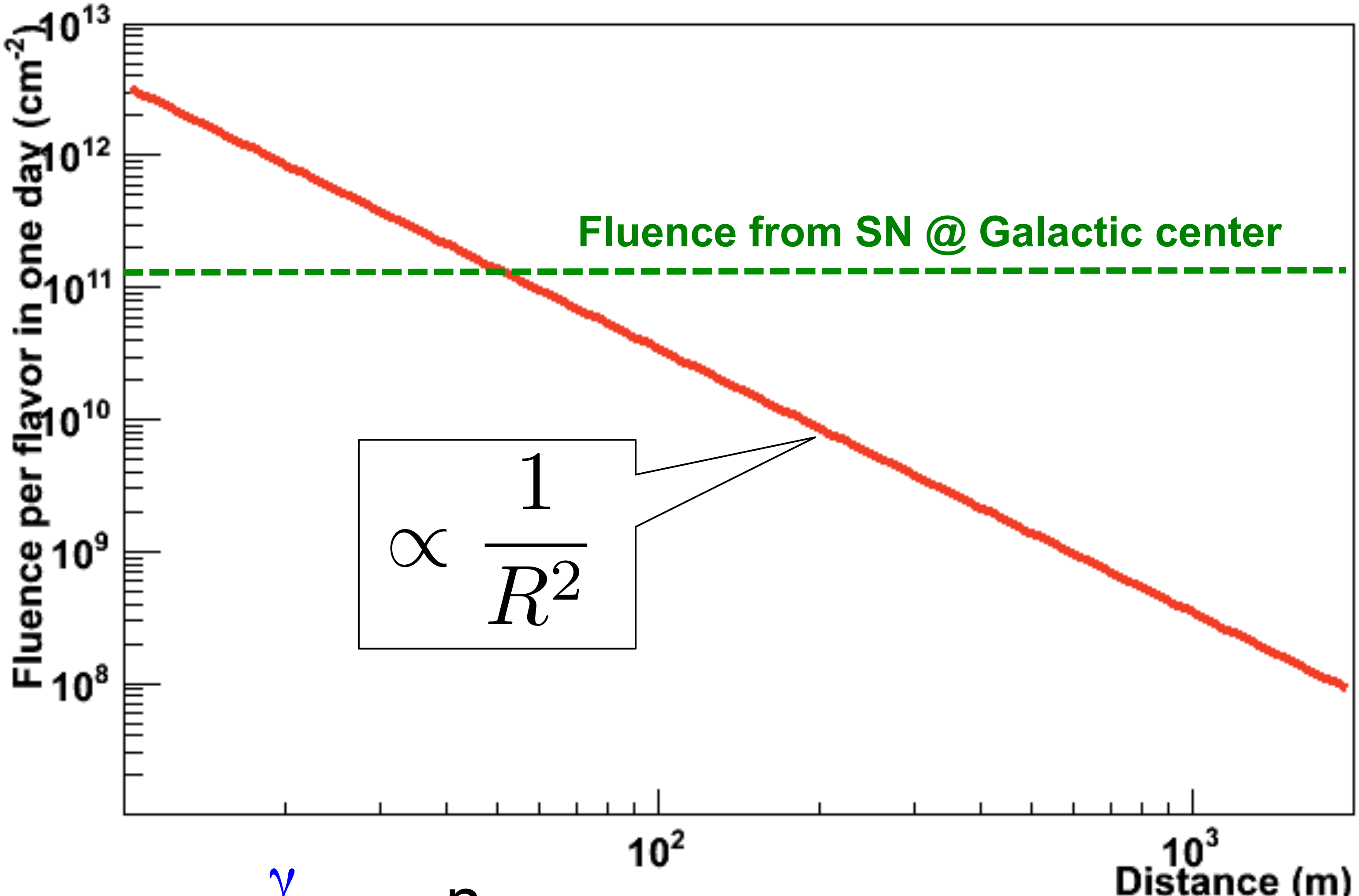
Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source and far off-axis at the Fermilab BNB

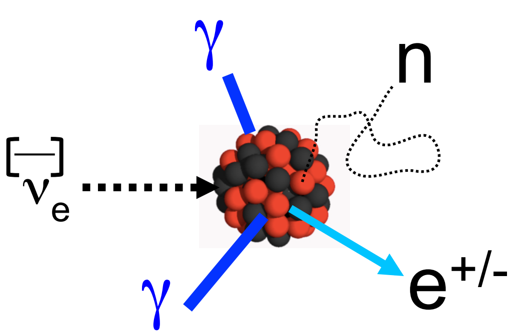


A. Bolozdynya et al., arXiv:1211.5199

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

(or 0.2 microsupernovae per pulse, 60 Hz of pulses)





This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

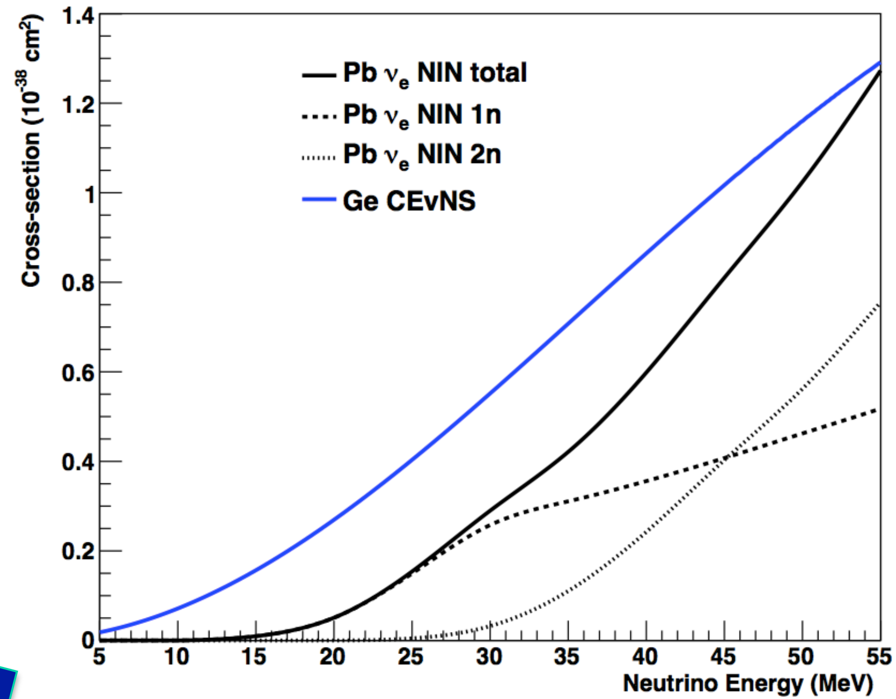
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

1n, 2n emission

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

1n, 2n, γ emission



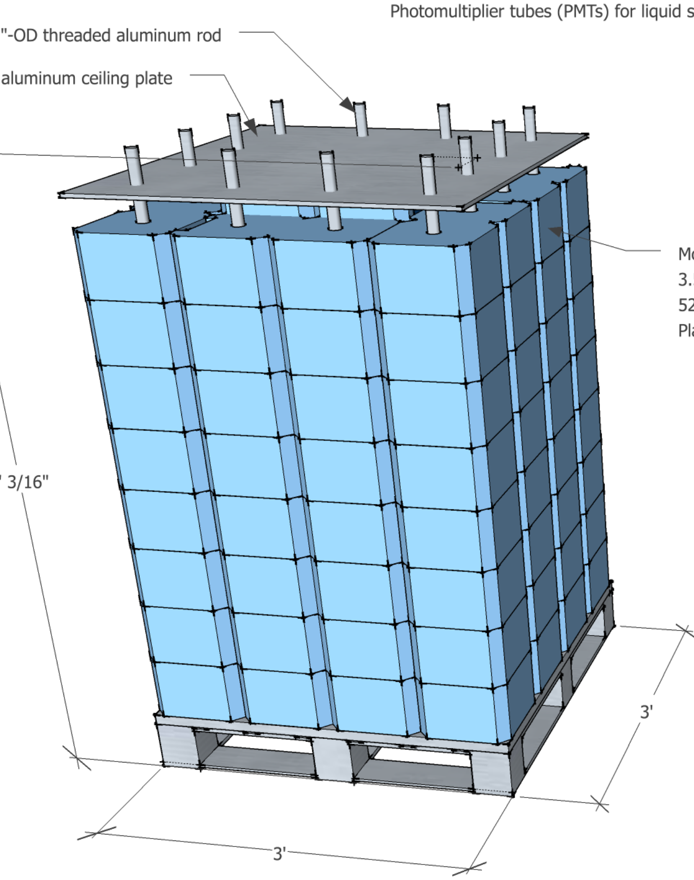
A non-negligible background to CEvNS, especially in lead shield

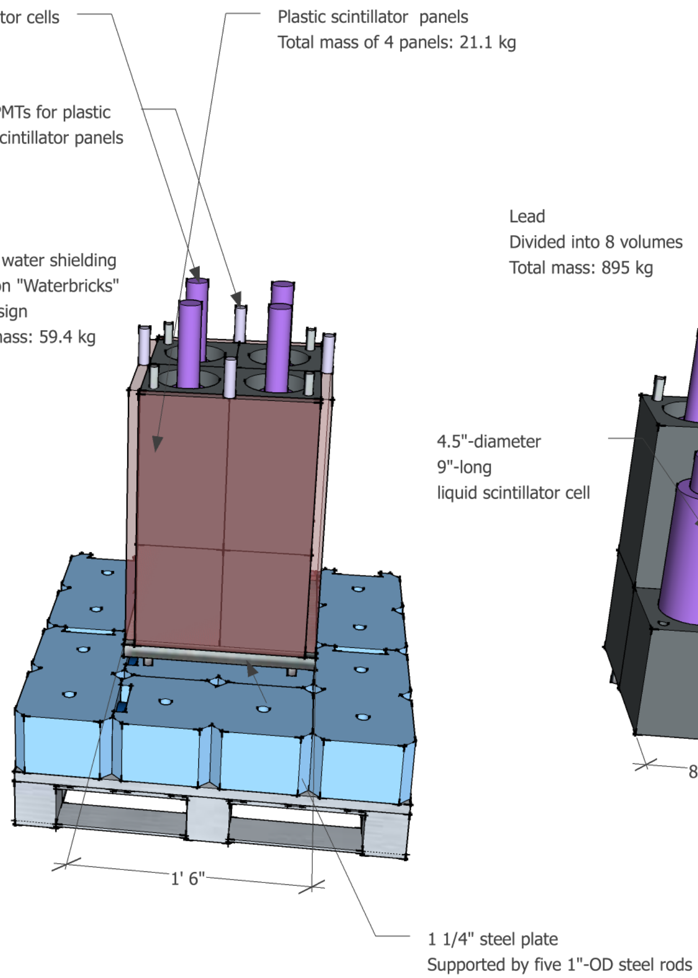
NIN measurement in SNS basement

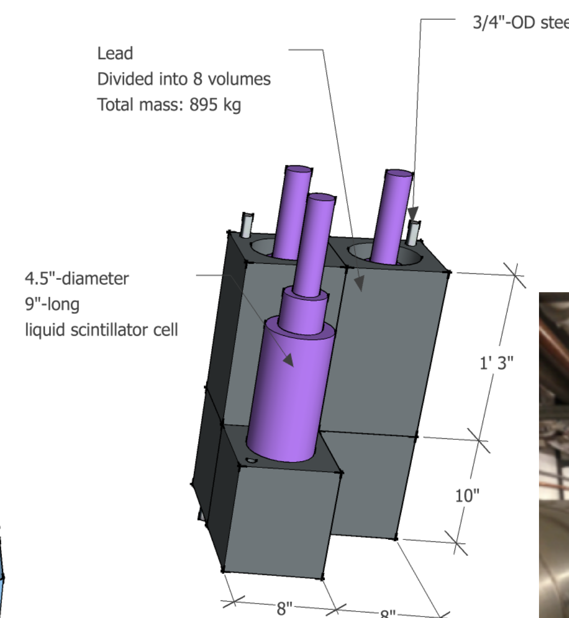
Liquid scintillator surrounded by lead, iron

(swappable for other NIN targets)

inside water shield



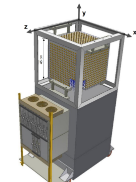


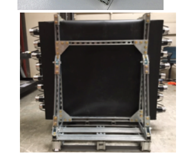
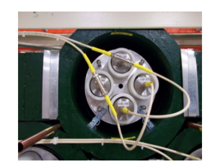


Phil Barbeau

COHERENT Non-CEvNS Detectors (“In-COHERENT”)

Sandia Neutron Scatter Camera	Multiplane liquid scintillator	Neutron background	Deployed 2014-2016
SciBath	WLS fiber + liquid scintillator	Neutron background	Deployed 2015
NaI[Tl]	Scintillating crystal	ν_eCC	High-threshold deployment summer 2016
Lead Nube	Pb + liquid scintillator	NINs in lead	Deployed 2016
Iron Nube	Fe + liquid scintillator	NINs in iron	Deployed 2017
MARS	Plastic scintillator and Gd sandwich	Neutron background	Under deployment
Mini-HALO	Pb + NCDs	NINs in lead	In design

And many more ideas and activities for Neutrino Alley and beyond...

- Inelastic CC and NC in Ar, Pb, ...
- Other crystal or scint deployments in CsI shield
- Flux normalization using D_2O (well known xscn)
- Ancillary measurements: QF
- Directional detectors
- ...

Comment #2:

we should be thinking about **joint unfolding**

We have tools (improving) to turn fluxes into estimated signals (individual experiment MC, SNOwGLoBES)

$$\mathrm{flux} \otimes \mathrm{xscn} \otimes \mathrm{detector\ response}$$

spectral/time evolution w/ physics signatures

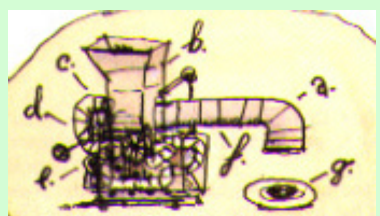
cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

use sim for refined estimate, or simple resolutions

SNOw GLoBES



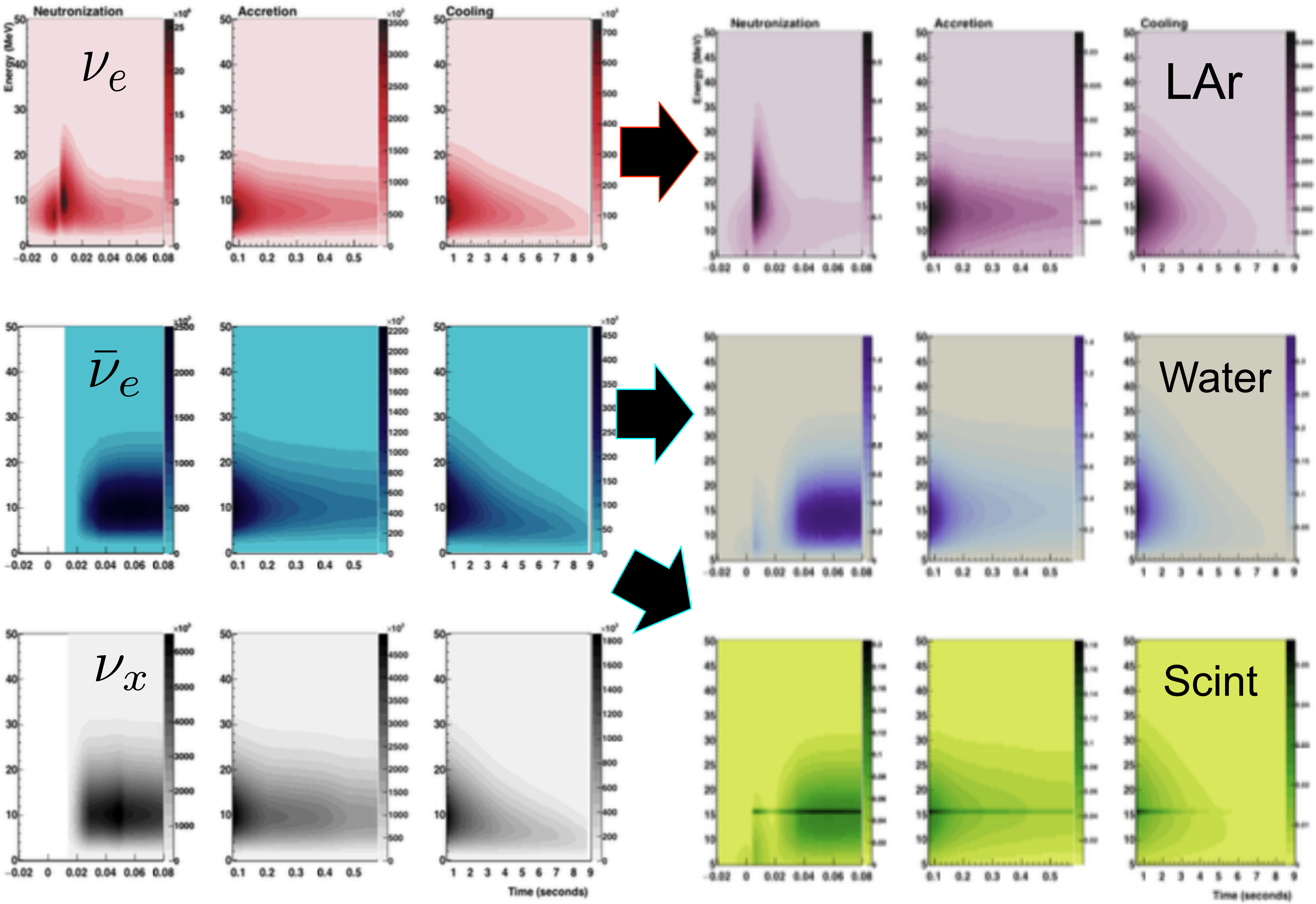
interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

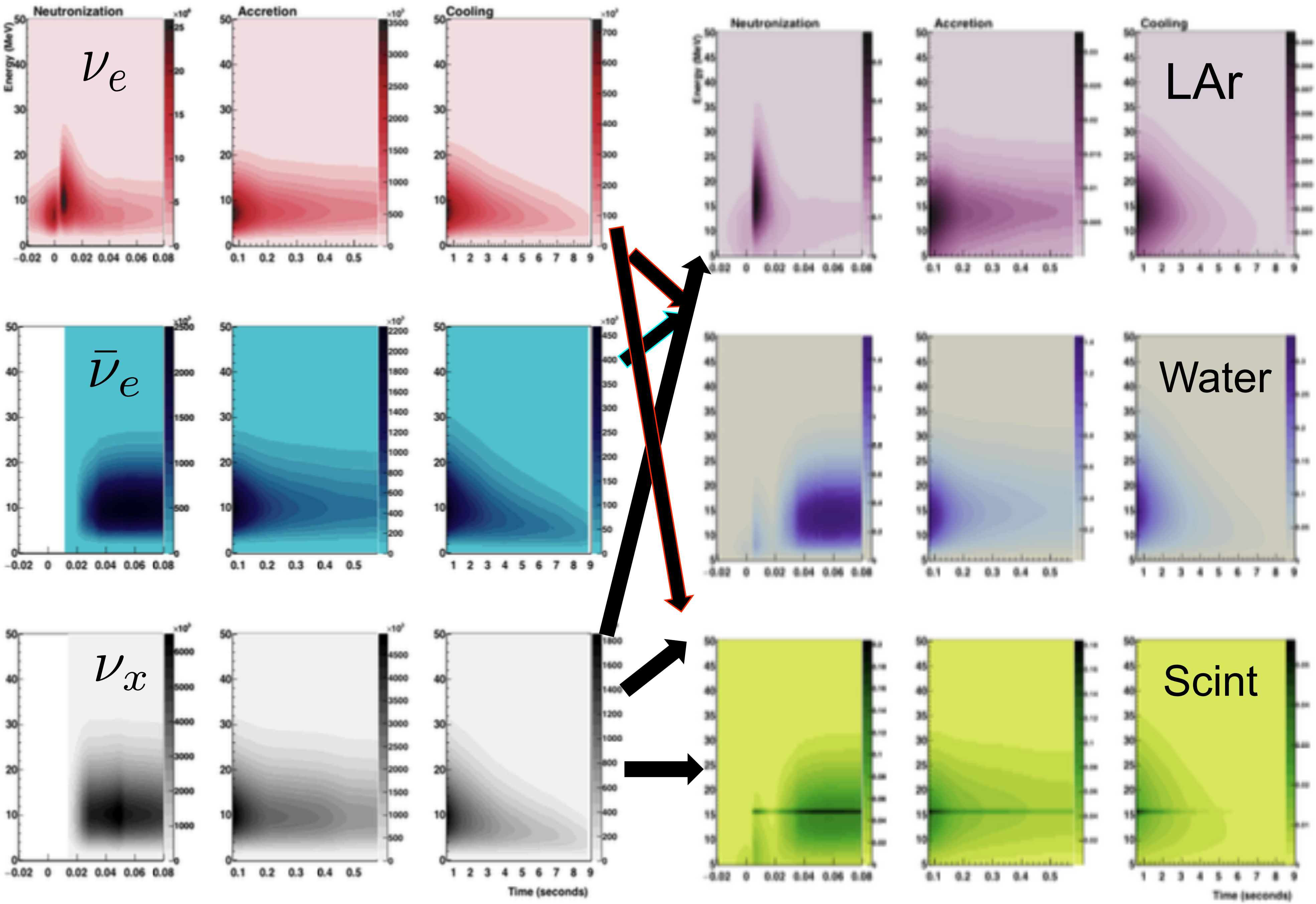
are the signatures visible??

Neutrino fluxes vs E, t

Event rates vs E, t



Subdominant channels are in the mix,
and not always easily taggable... how to disentangle?



Summary

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

- Need energy, flavor, time structure

Global detectors:

- currently ~Galactic sensitivity
  (SK reaches barely to Andromeda)
- sensitive mainly to the $\bar{\nu}_e$ component of
  the SN flux
- excellent timing from IceCube
- next generation: ν_e + huge statistics

Future:

- we need to measure some x-scns!
- we need nuclear physics!
- we need to understand how to disentangle
  the truth fluxes