Supernova Neutrino Detection

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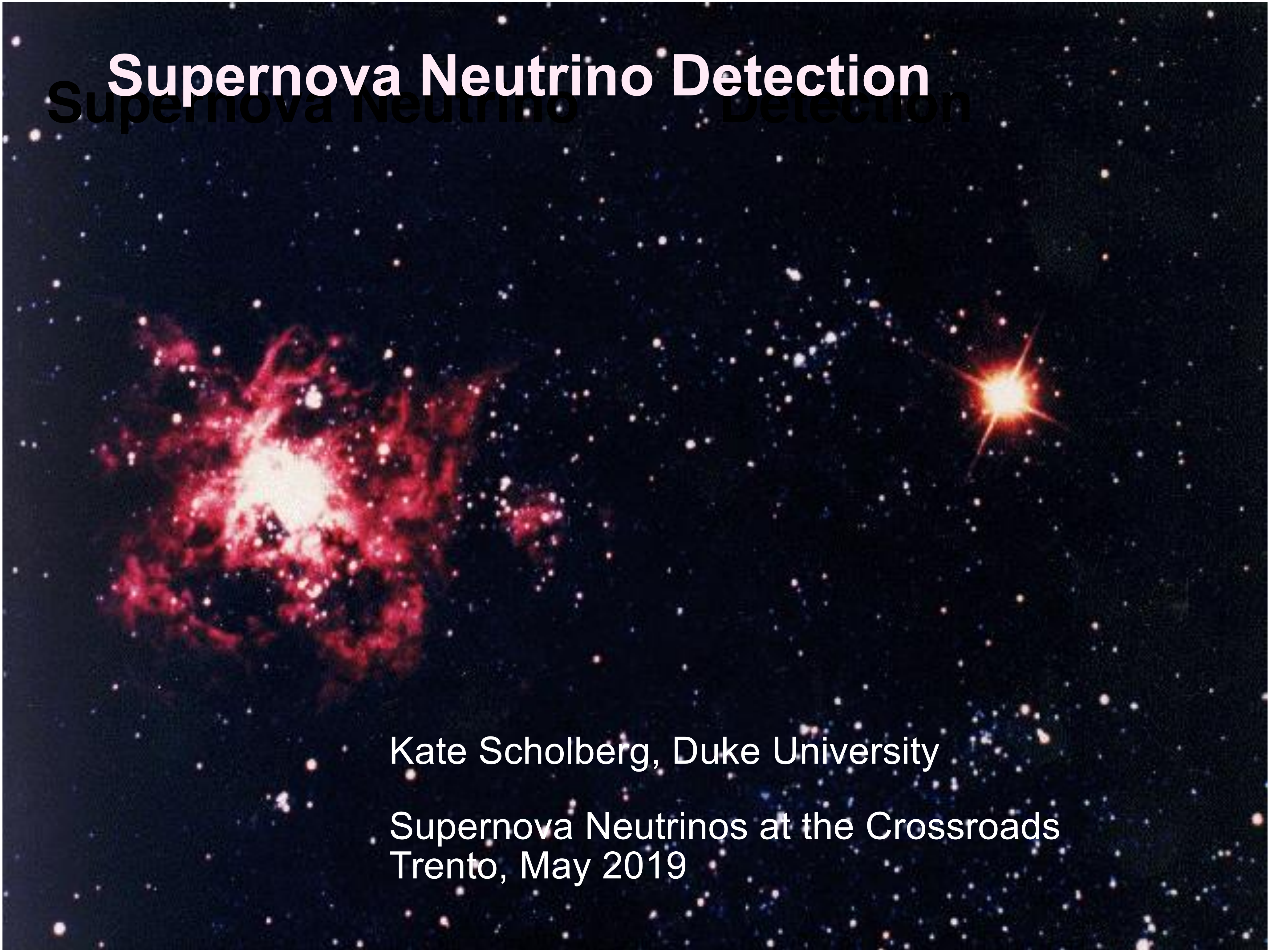


Kate Scholberg, Duke University

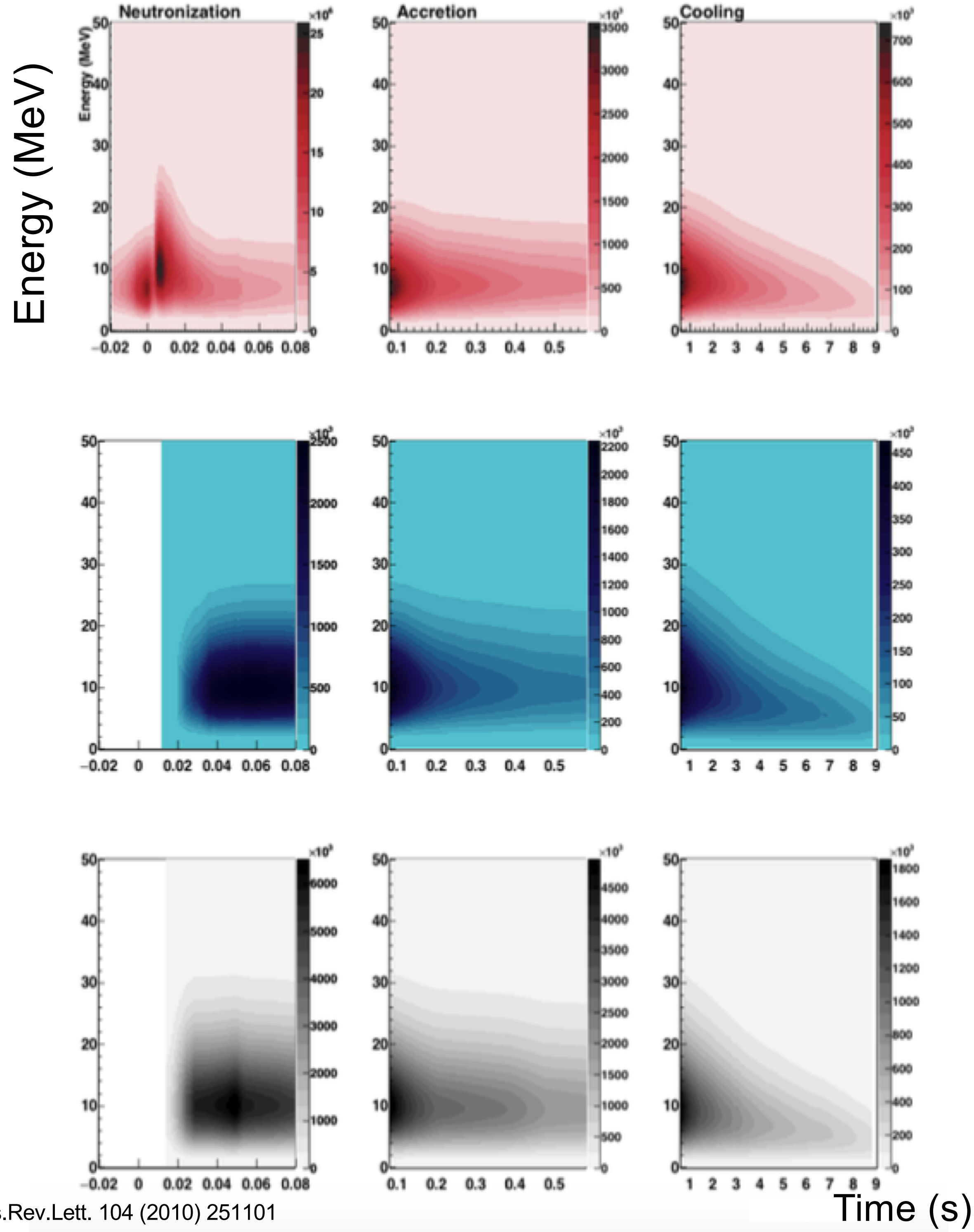
Supernova Neutrinos at the Crossroads
Trento, May 2019

In this talk will focus on a few "new" things*...

- Overview of supernova-detection relevant neutrino interactions
  - The experimental job!
- Expanding the flavor sensitivity!
  - LAr sensitivity
  - CEvNS
- Future prospects
  - Prospects for ν-nucleus interaction measurements
  - SNEWS 2.0: upgrading the alert

*stuff I have been working on recently

Fluxes as a function of time and energy



ν_e

$\bar{\nu}_e$

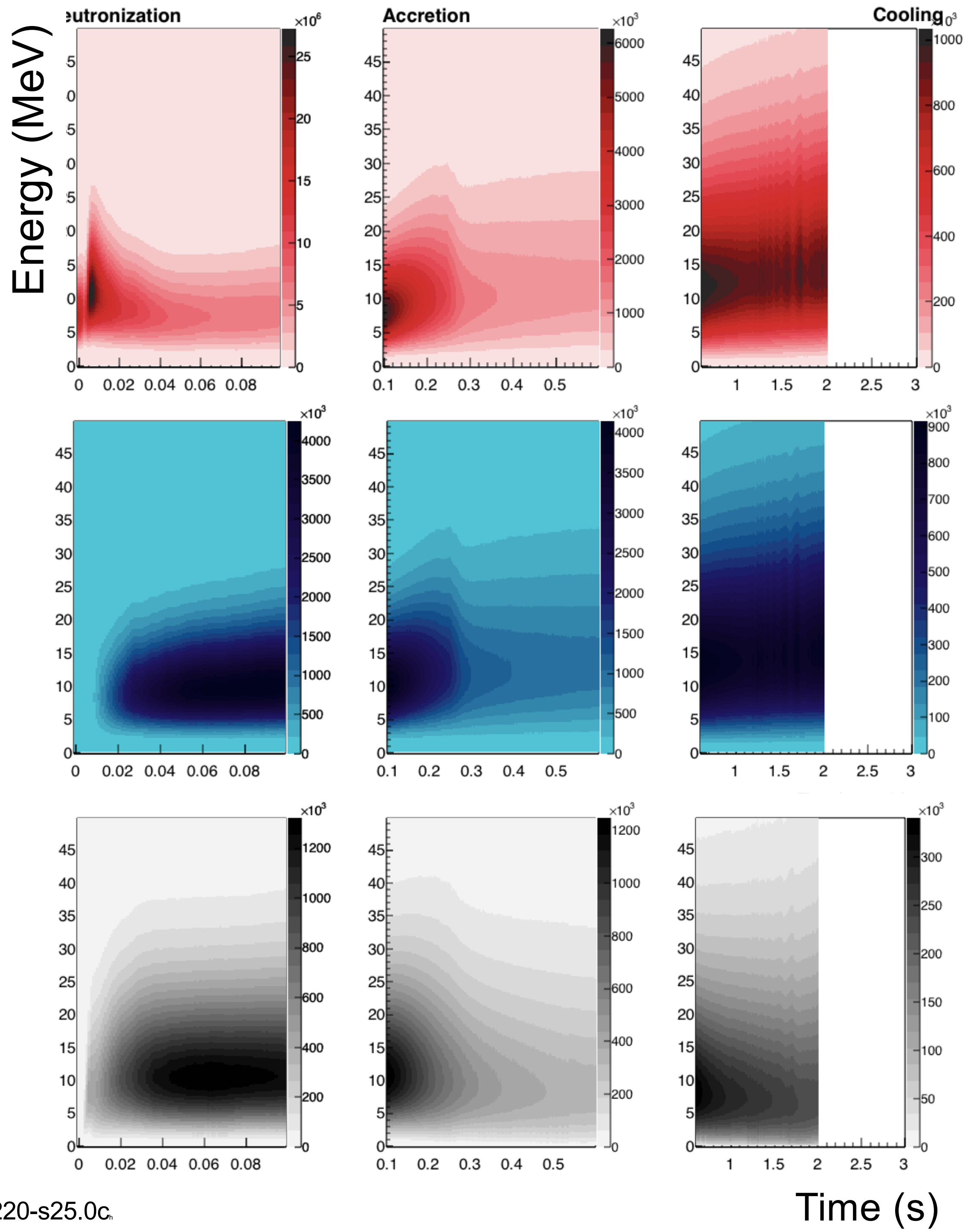
ν_x

$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

Neutrinos per cm² per bin (per ms per 0.5 MeV)

Model by L. Huedepohl Phys.Rev.Lett. 104 (2010) 251101

Another example of a model
…
black hole formation!



ν_e

$\bar{\nu}_e$

ν_x

$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

Model by L. Huedepohl LS220-s25.0c

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

What do you want in a detector?

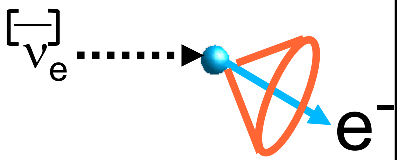
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; **underground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

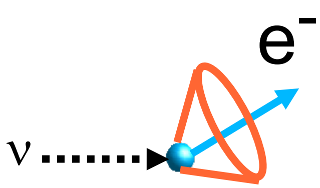
Note that many detectors have a “day job”...

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

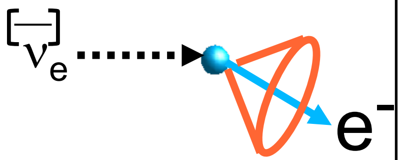
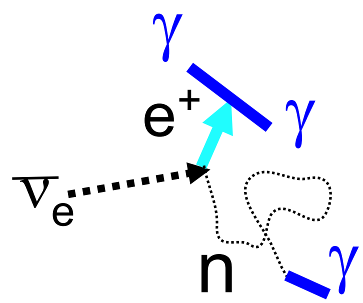
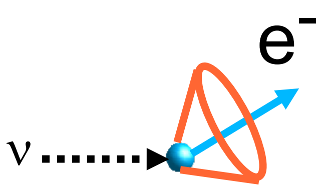
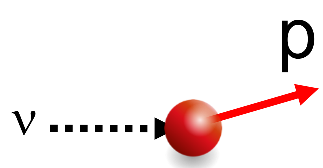
$\nu + e^- \rightarrow \nu + e^-$



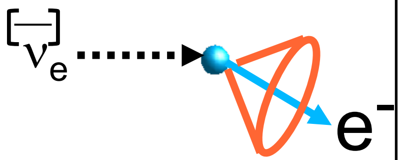
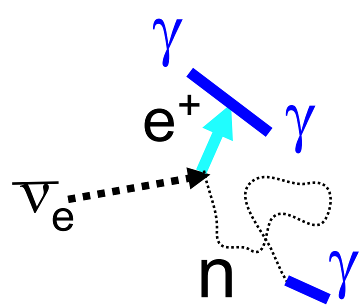
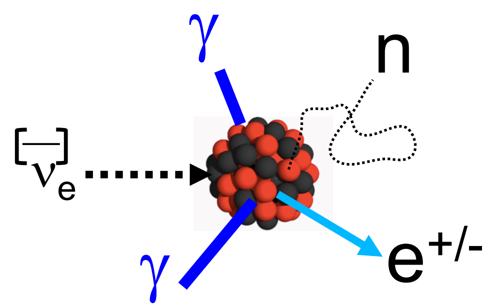
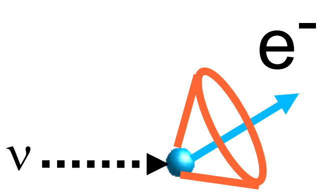
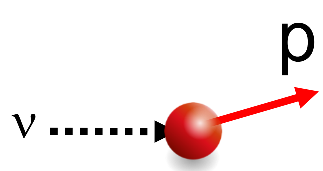
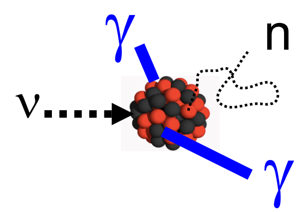
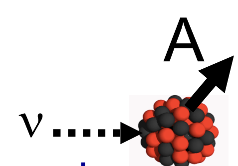


Useful
for pointing</td><td></td><td></td></tr>
<tr><td>Neutral current</td><td></td><td></td></tr>
</table>

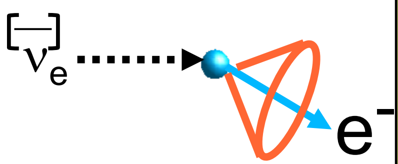
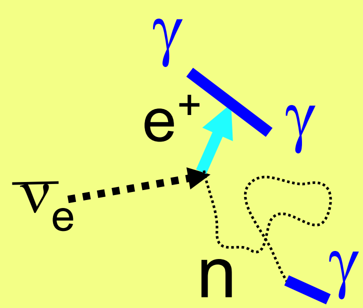
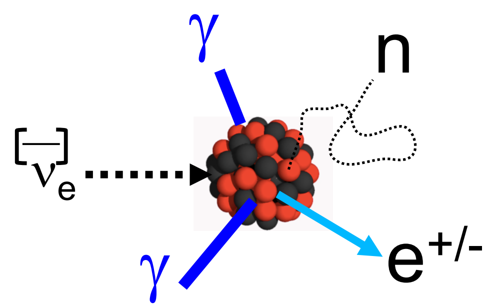
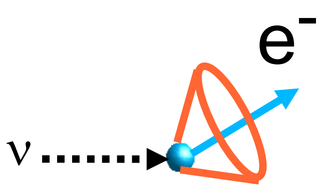
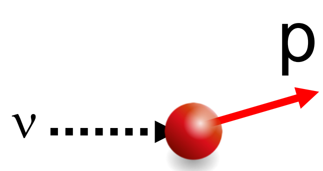
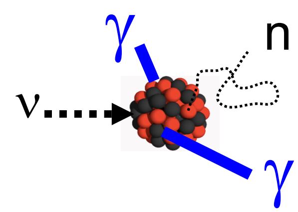
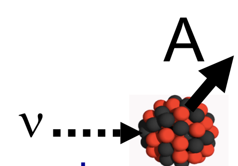
Supernova-relevant neutrino interactions

	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

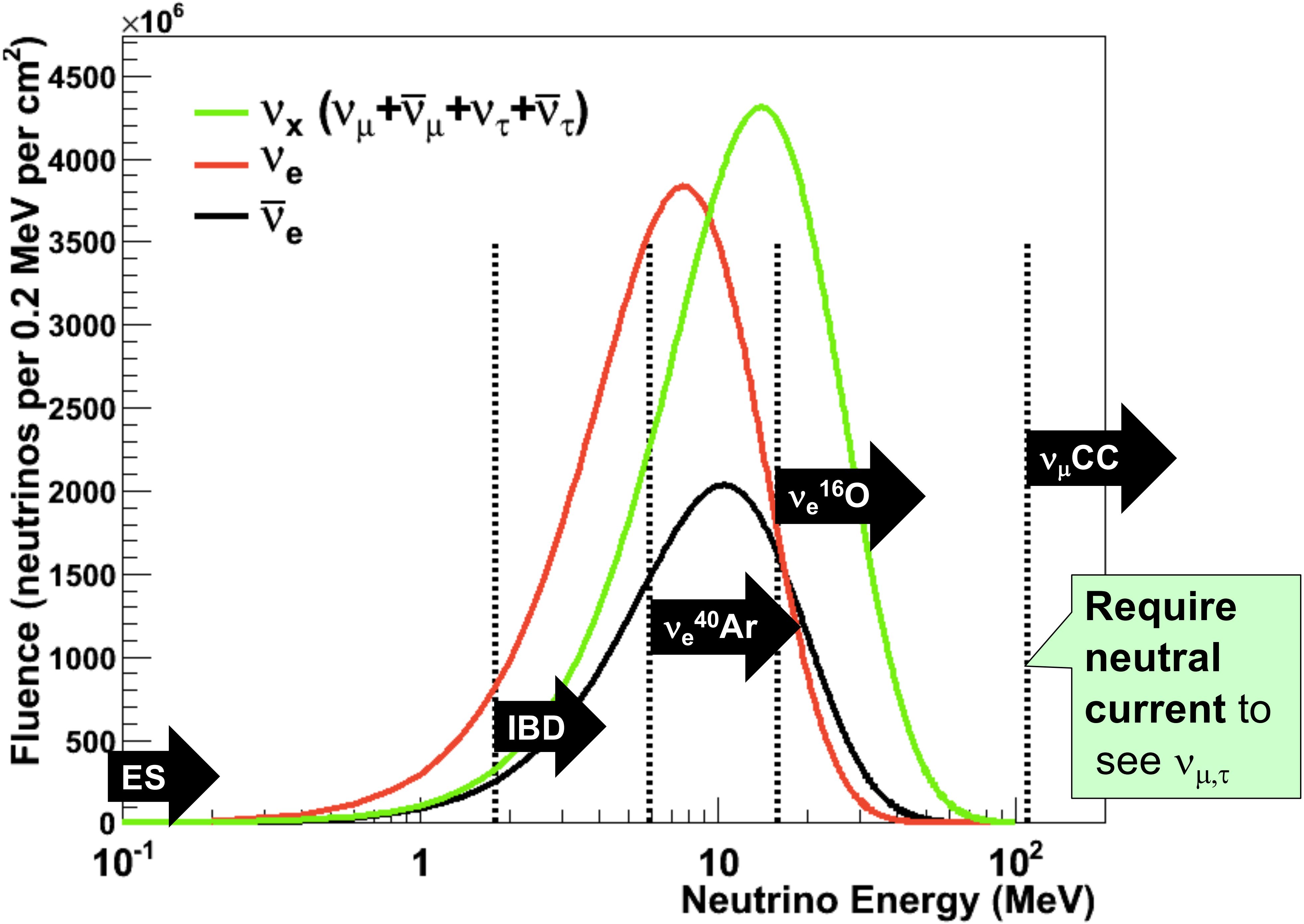
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products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

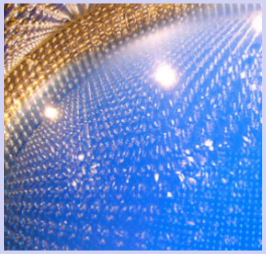
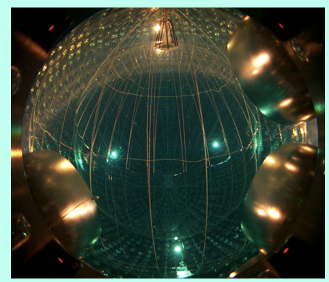
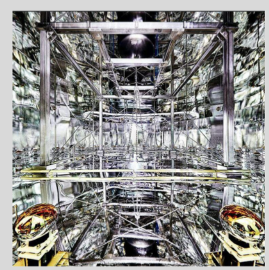
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products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

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

Neutrino interaction thresholds

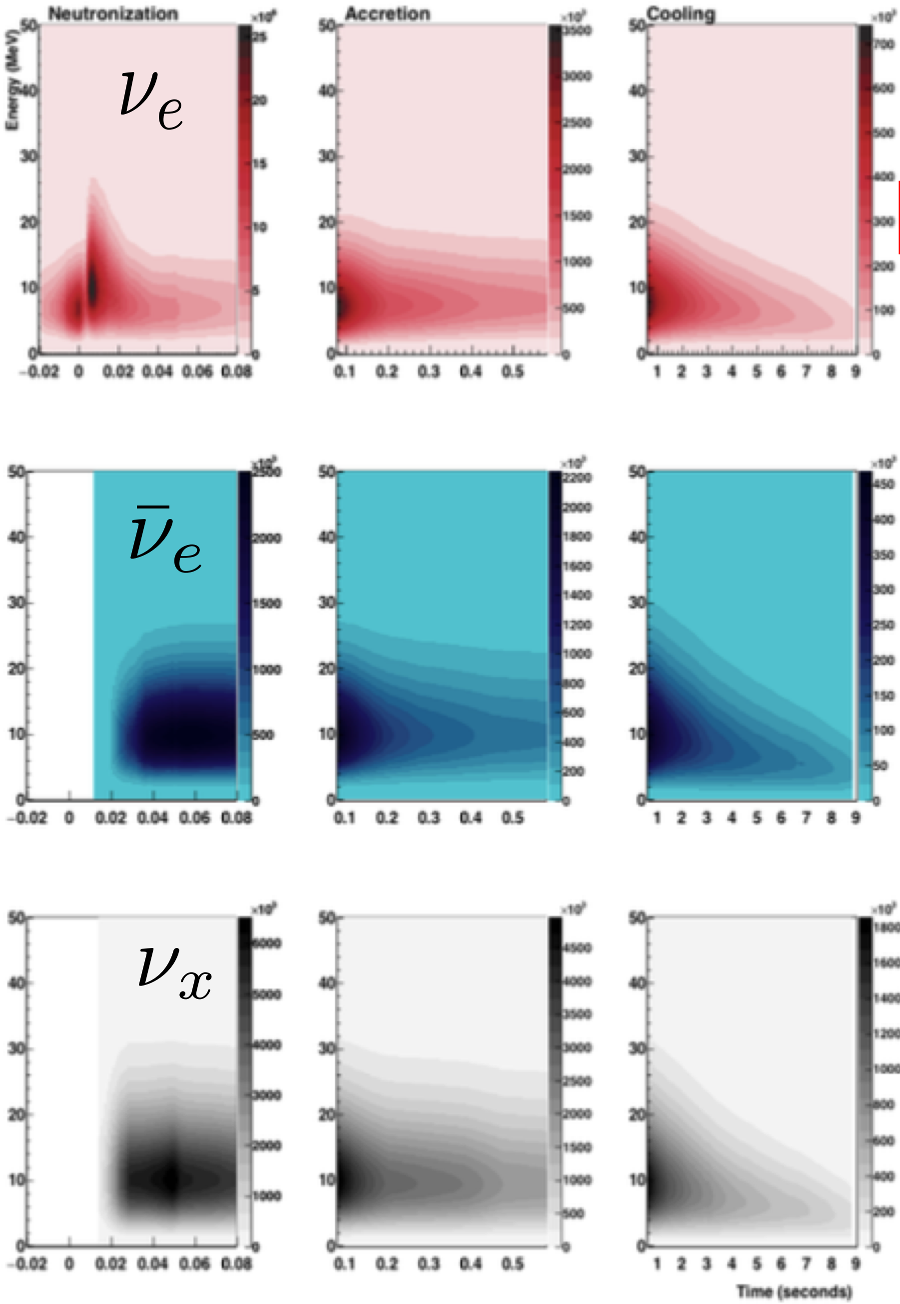


Supernova neutrino detector types

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

What we *want* to measure

Neutrino fluxes vs E, t



What we *can* measure

Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)

ν_eCC

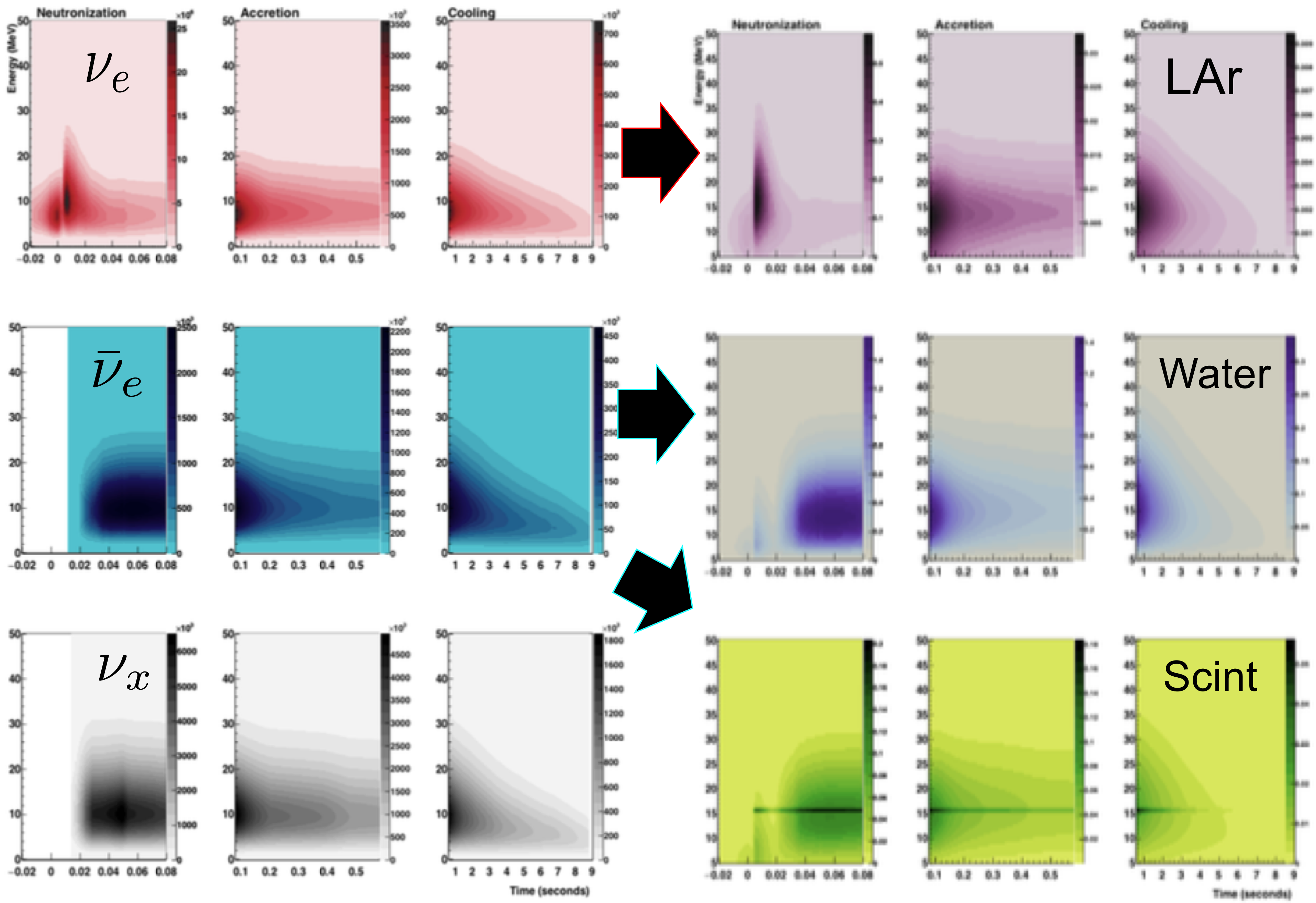
$\bar{\nu}_e$CC

NC

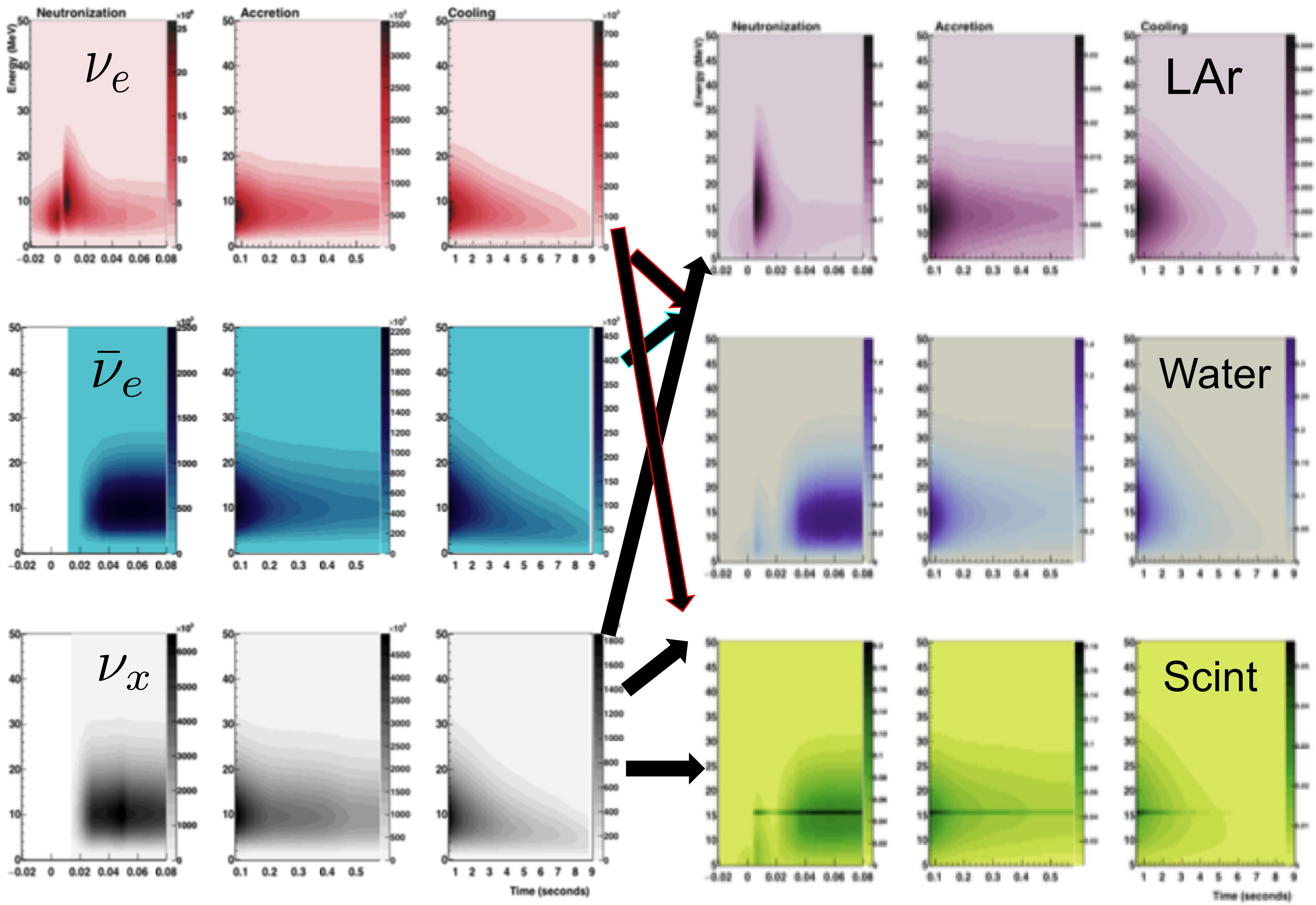
Neutrino fluxes vs E, t

Dominant channels

Event rates vs E, t



Subdominant channels are in the mix too,
and not always easily taggable... may be hard to disentangle!



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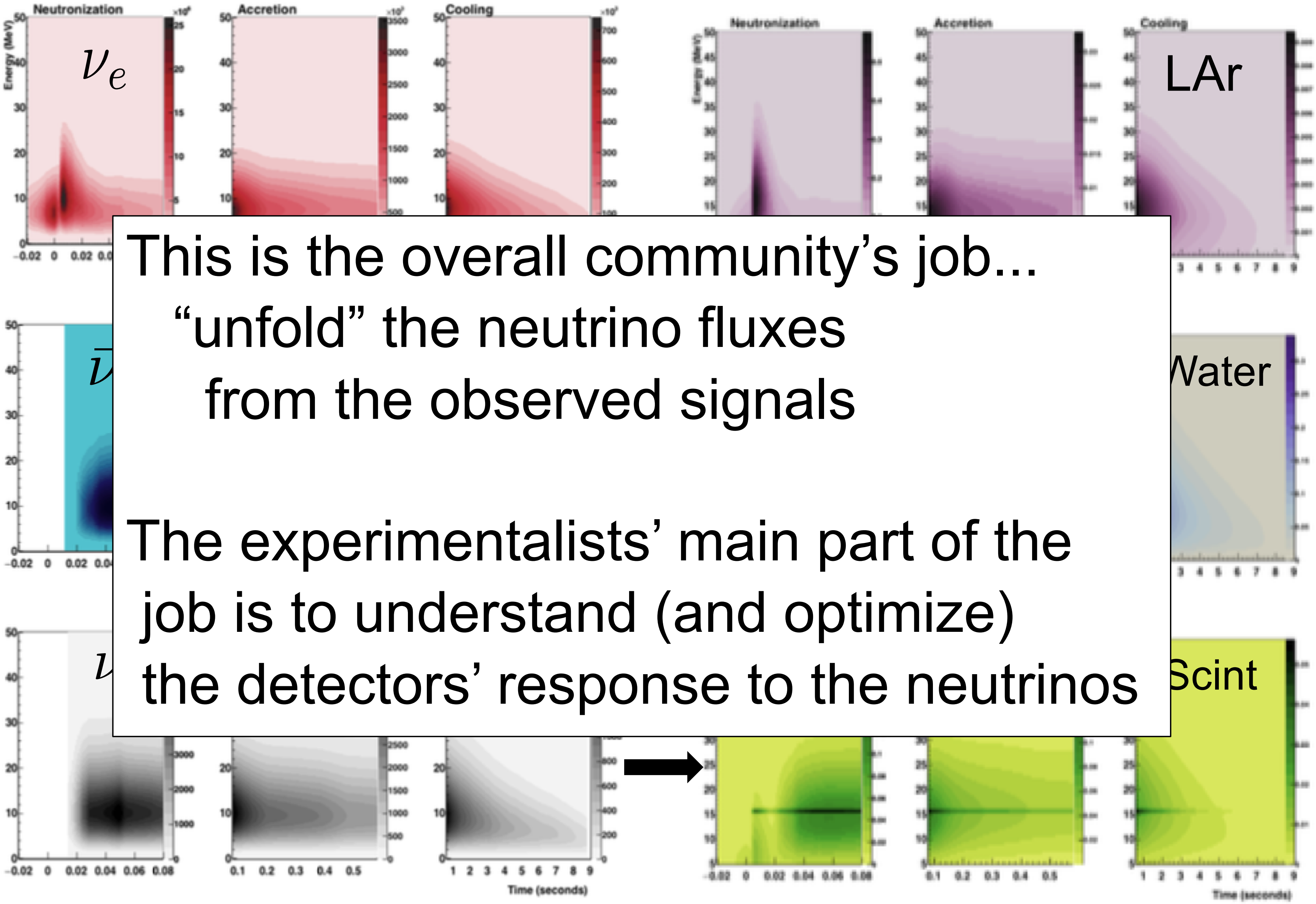


This is the overall community's job...
"unfold" the neutrino fluxes
from the observed signals

The experimentalists' main part of the
job is to understand (and optimize)
the detectors' response to the neutrinos

Summary of supernova neutrino detectors

Galactic sensitivity

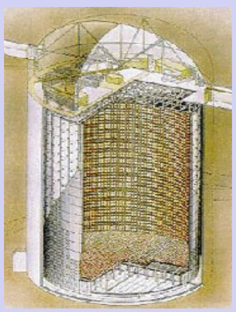
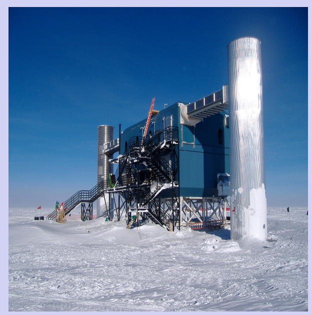
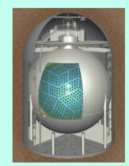
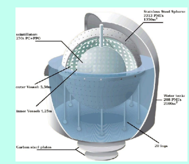
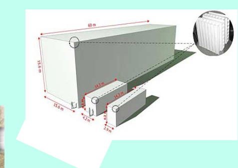
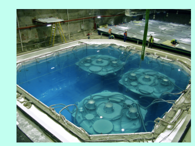
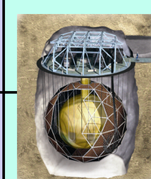
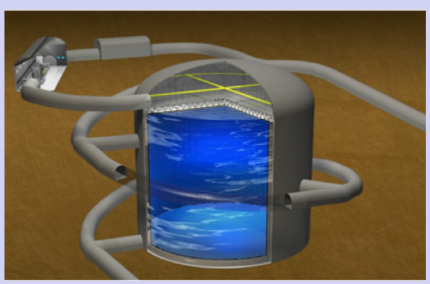
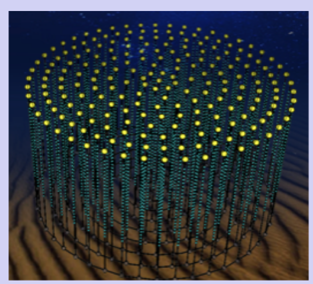
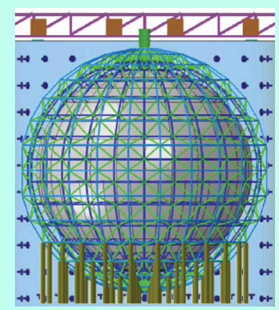
Extragalactic

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
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole	(600)	(10^6)	Future

plus reactor experiments, DM experiments...

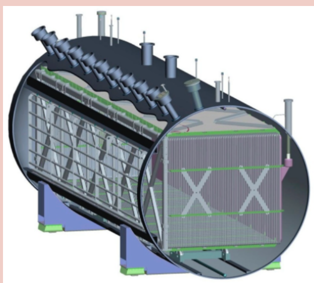
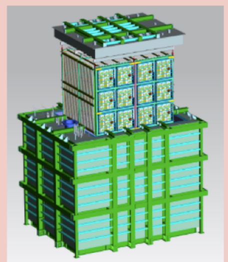
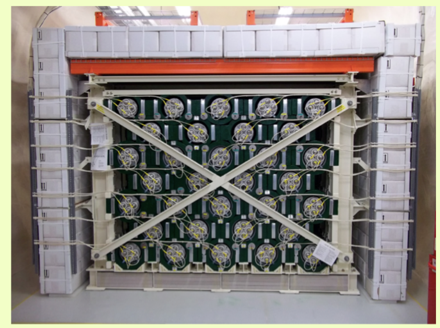
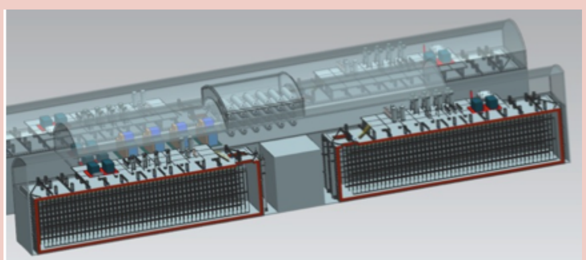
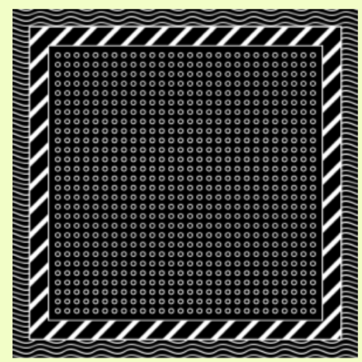
$\bar{\nu}_e$ flavor

- Will have fantastic statistics from water & scintillator (IBD)
- Good time profile from IceCube, KM3Net
- Will have IBD tagging from SKGd
- Subdominant in argon

Water Cherenkov	Long String	Scintillator
		     
		

ν_e flavor

- Dominant channel in argon, lead
- Subdominant in water, scintillator

Liquid argon	Lead
 	
 	

Lead-based supernova detectors

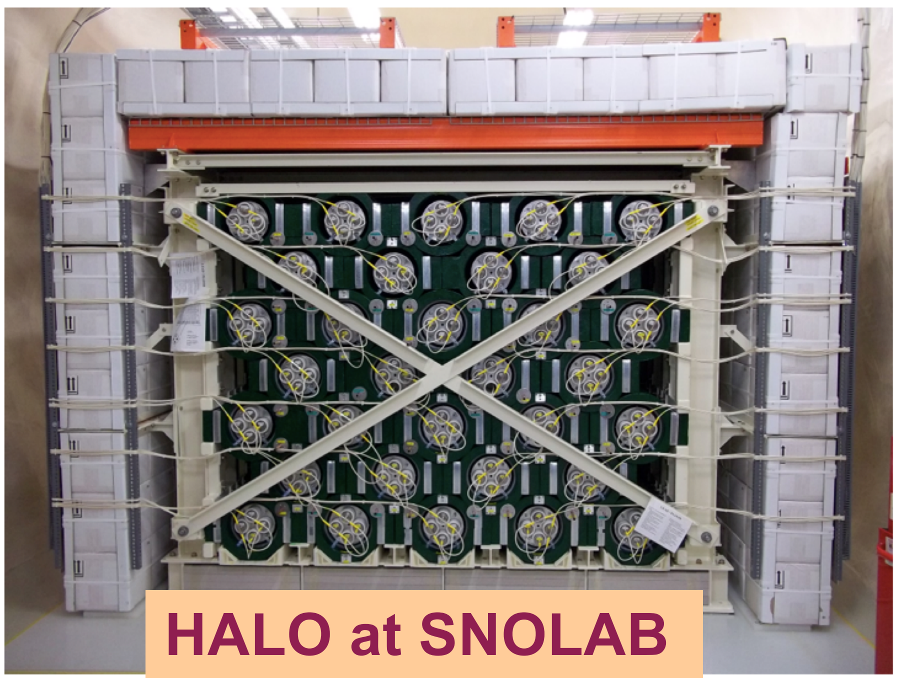
$\nu_e + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Bi}^* + e^-$ CC

↘ 1n, 2n emission

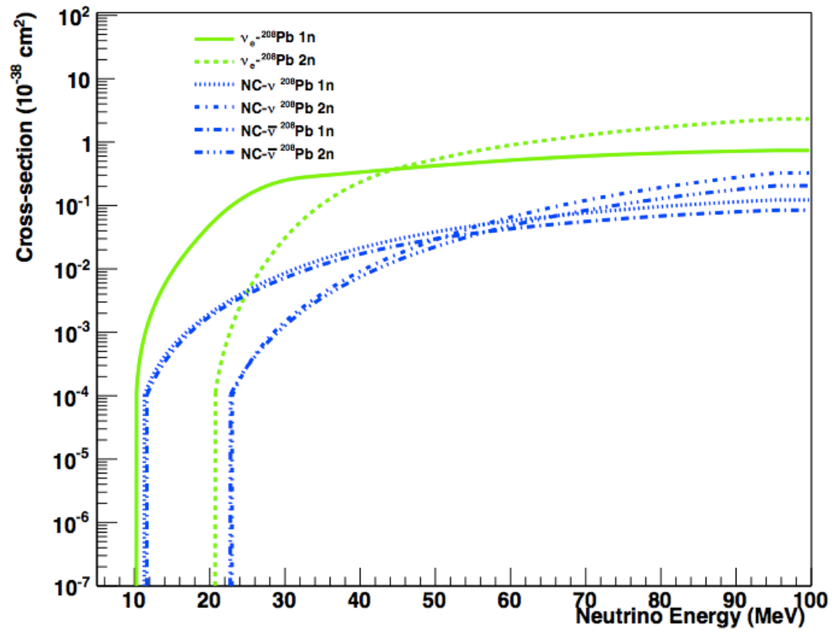
$\nu_x + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb}^* + \nu_x$ NC

↘ 1n, 2n, γ emission

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

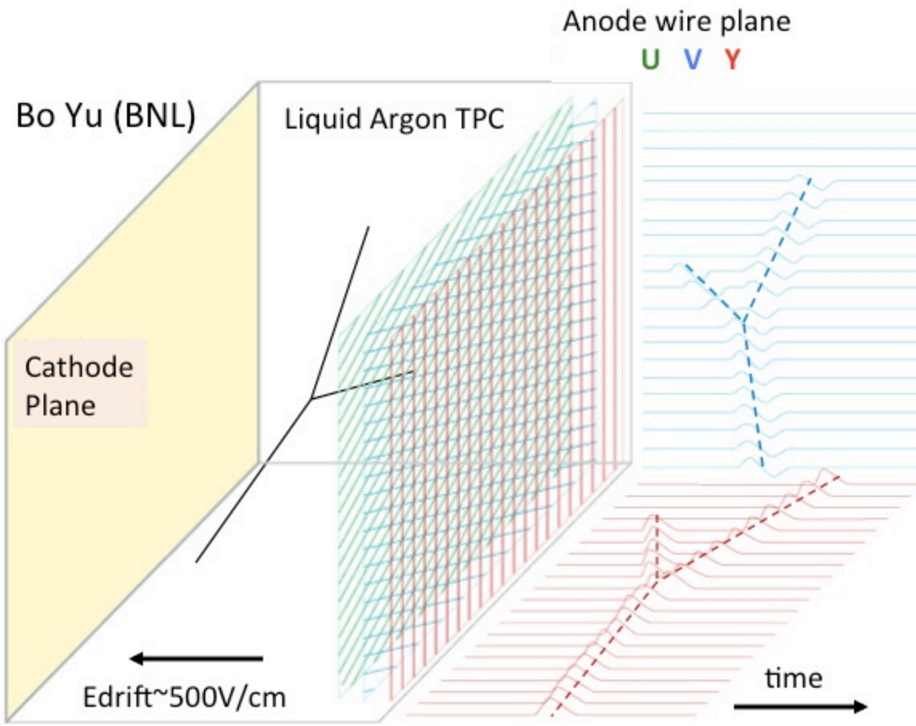


SNO ^{3}He counters + 79 tons of Pb:
~1-40 events @ 10 kpc



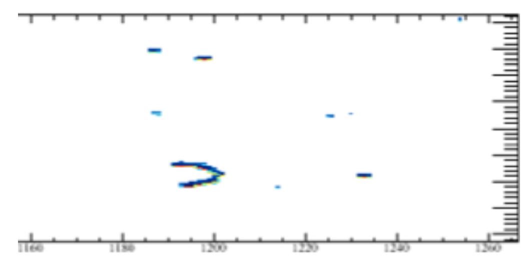
A. Gallo-Rosso's talk

Liquid argon time projection chambers

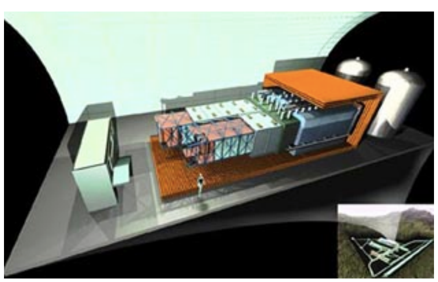


- fine-grained trackers
- no Cherenkov threshold
- high ν_e cross section

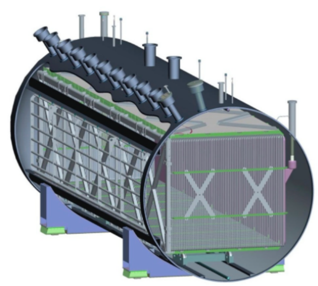
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



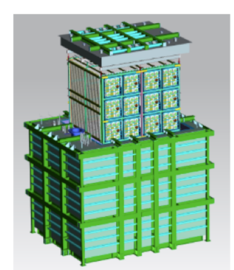
ICARUS
(Italy...)
0.6 kton



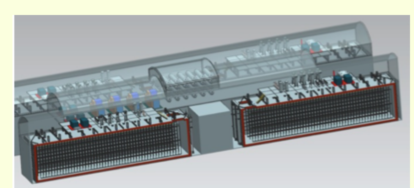
MicroBooNE
(USA)
0.2 kton



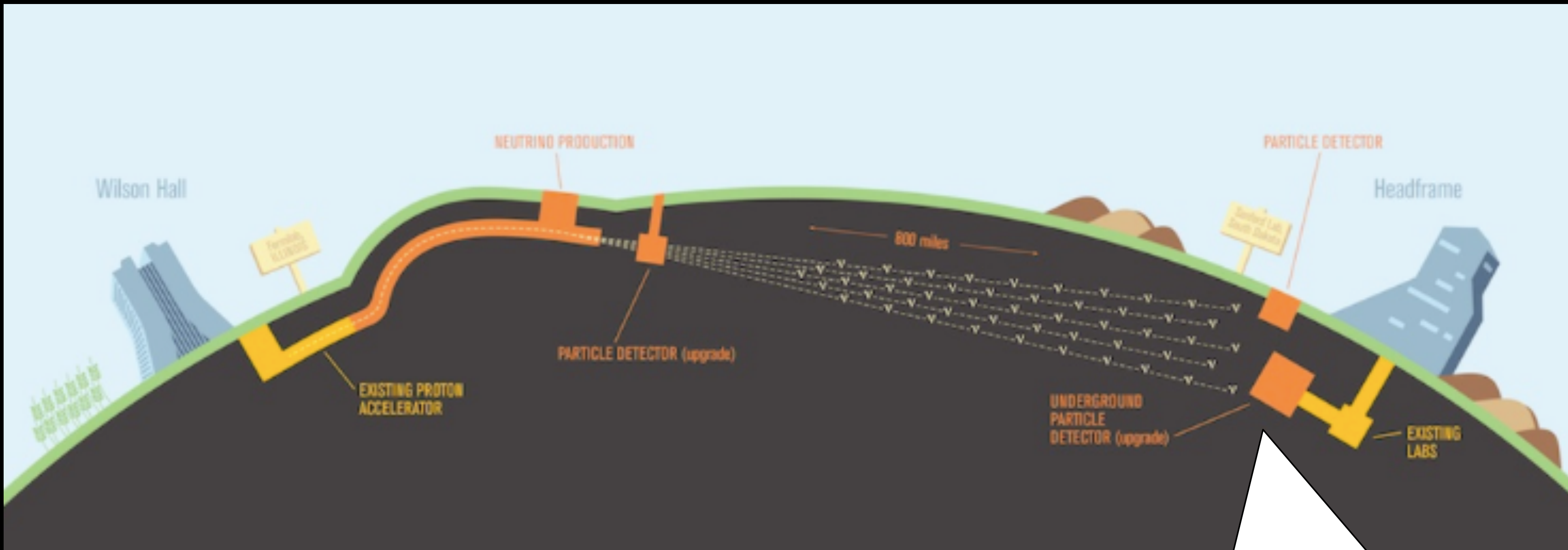
SBND
(USA)
0.112 kton

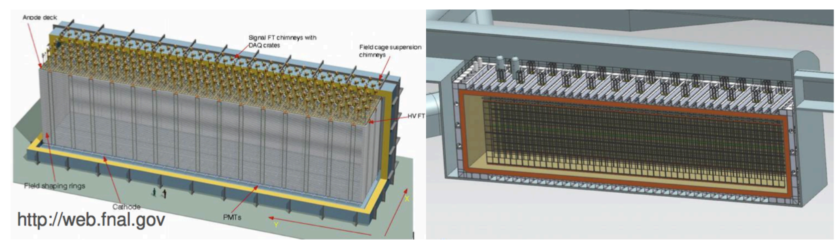


DUNE
(USA)
40 kton



Deep Underground Neutrino Experiment (DUNE)

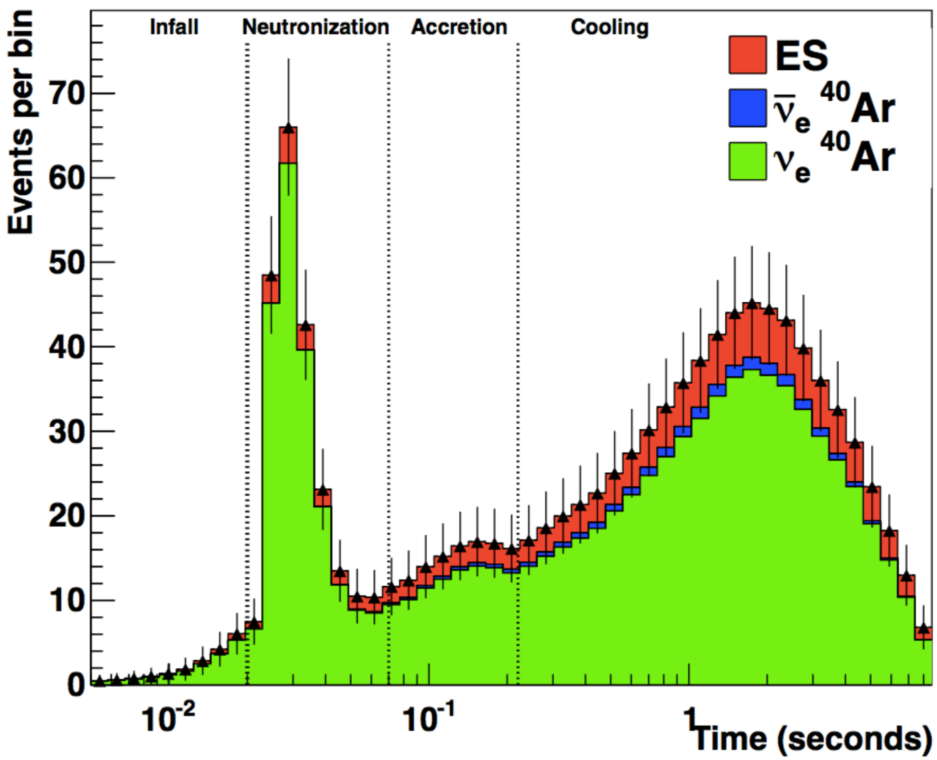


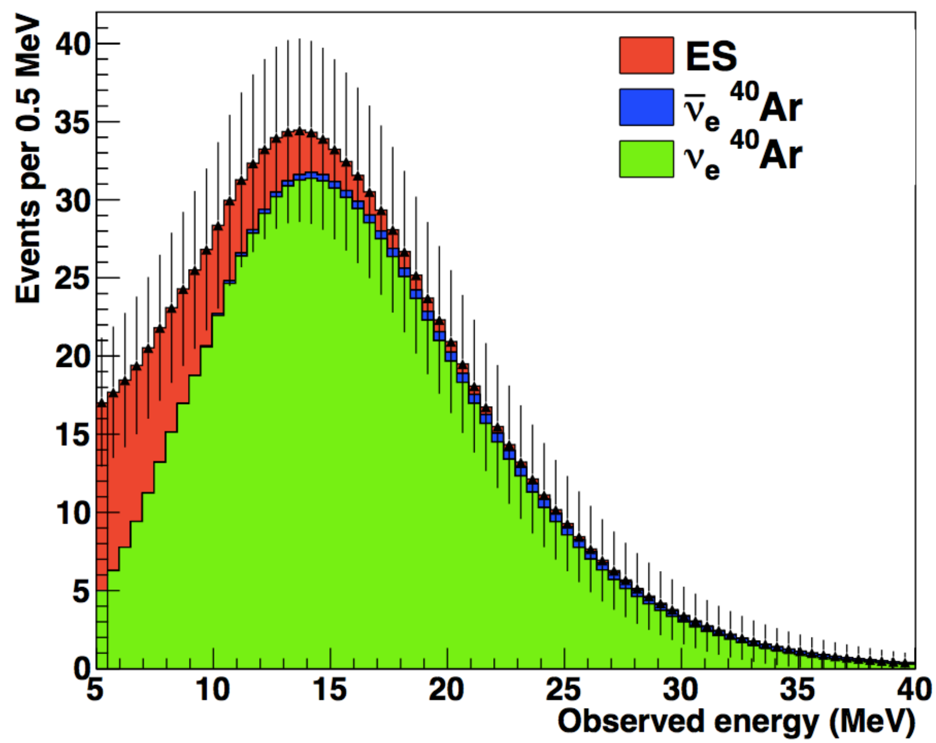


- single and dual phase options
- both have TPC and photon detectors
- first module by ~2024
- supernova burst is a *primary* physics goal

Flavor composition as a function of time

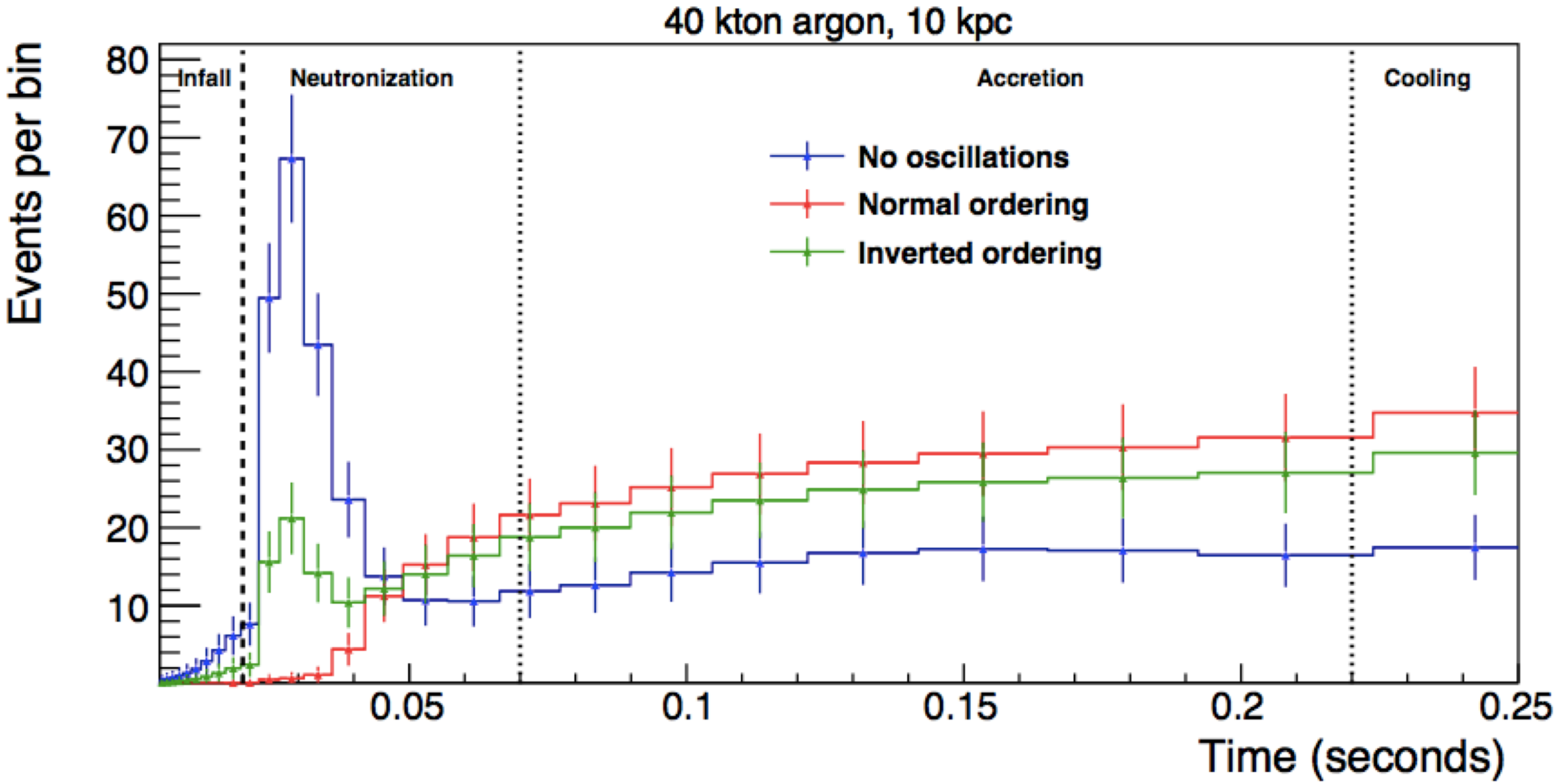
Energy spectra integrated over time





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

Note that the neutronization burst gets substantially suppressed with flavor transitions



Simple MSW assumption (assume OK at early times)

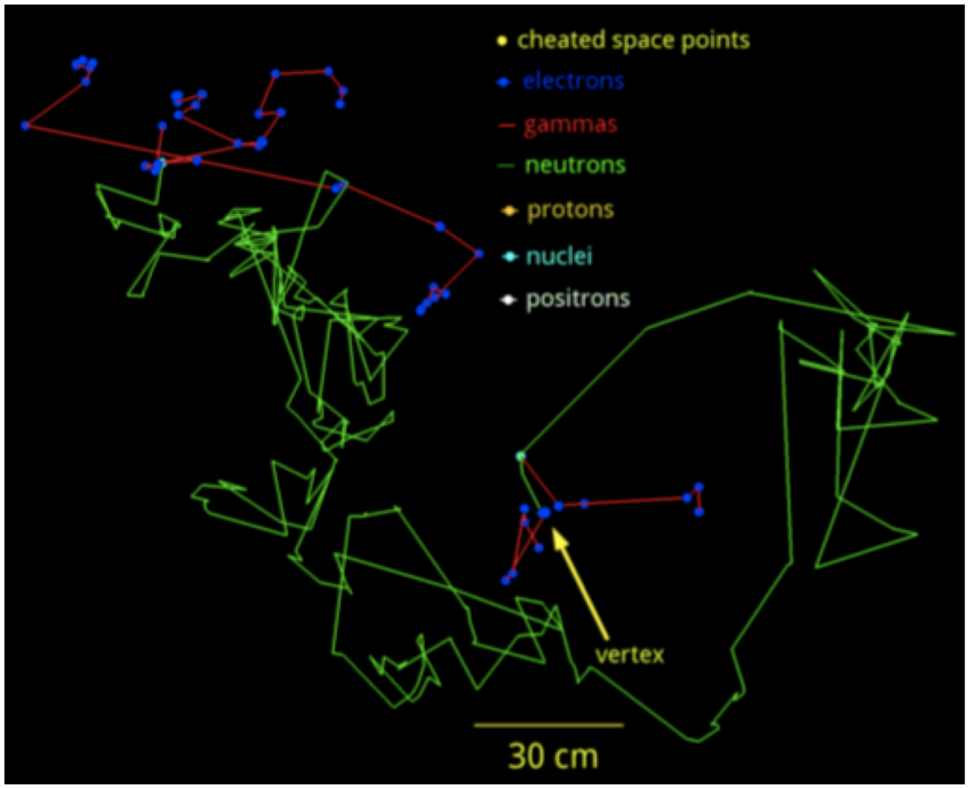
NMO: $F_{\nu_e} = F^0_{\nu_x}$

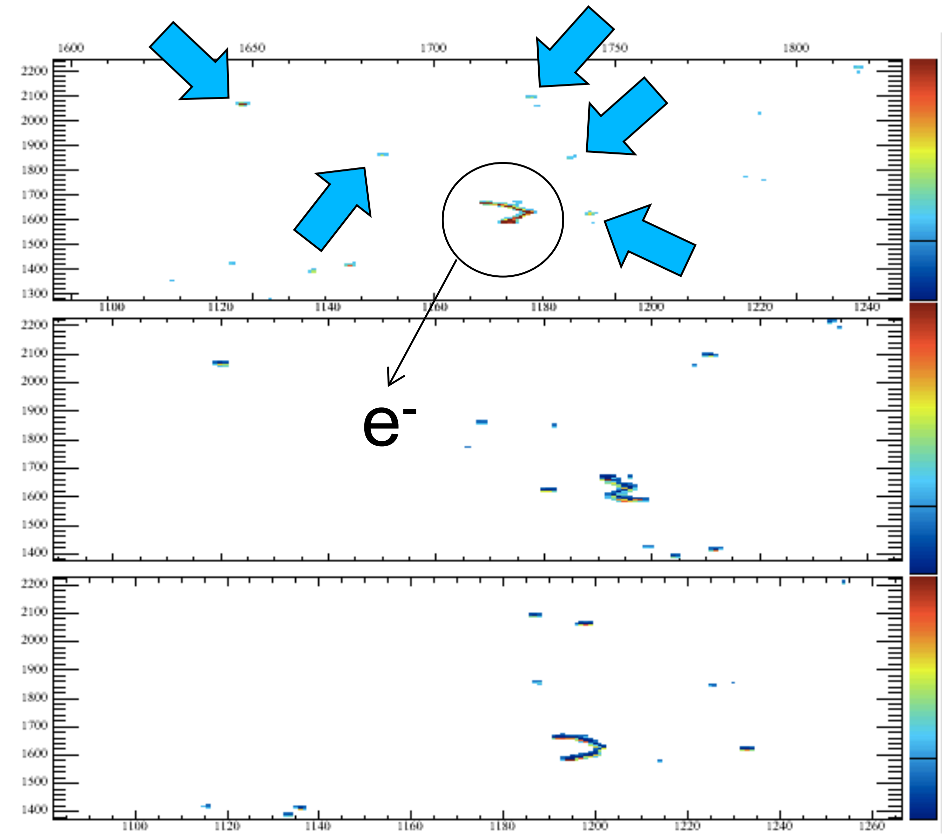
IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$

(a robust (?) mass ordering signature...)

We now have fairly sophisticated final-state modeling.
and decent, rapidly improving event reconstruction

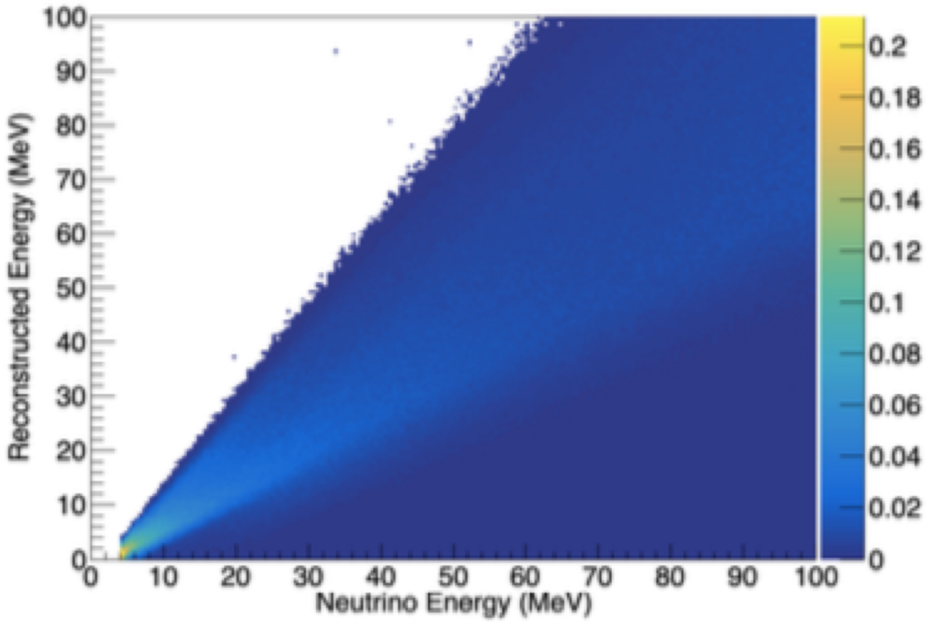
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



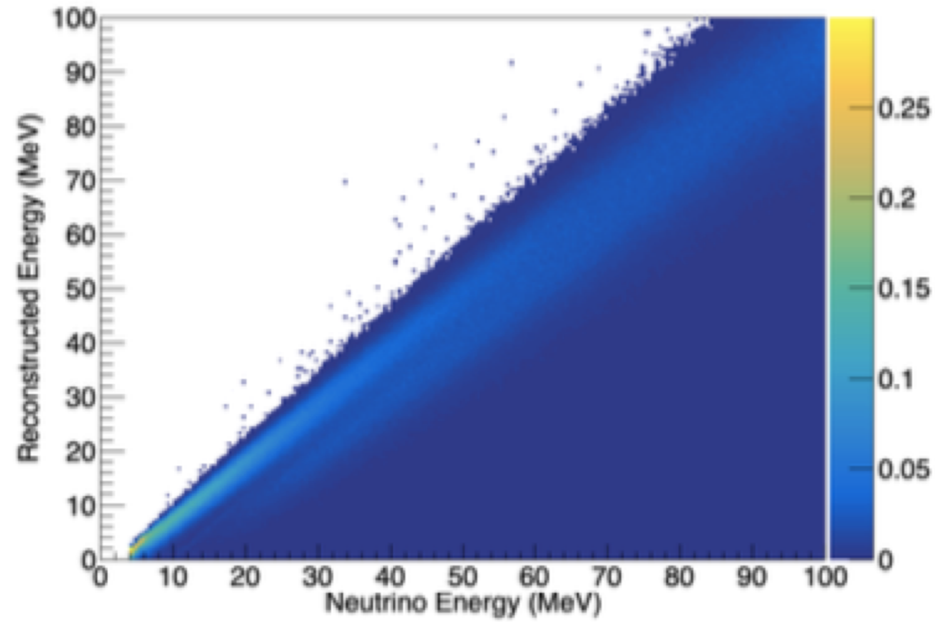


S. Gardiner, marleygen.org

SNOwGLoBES Smearing Matrices for MARLEY ν_eCC



Using TPC
information only

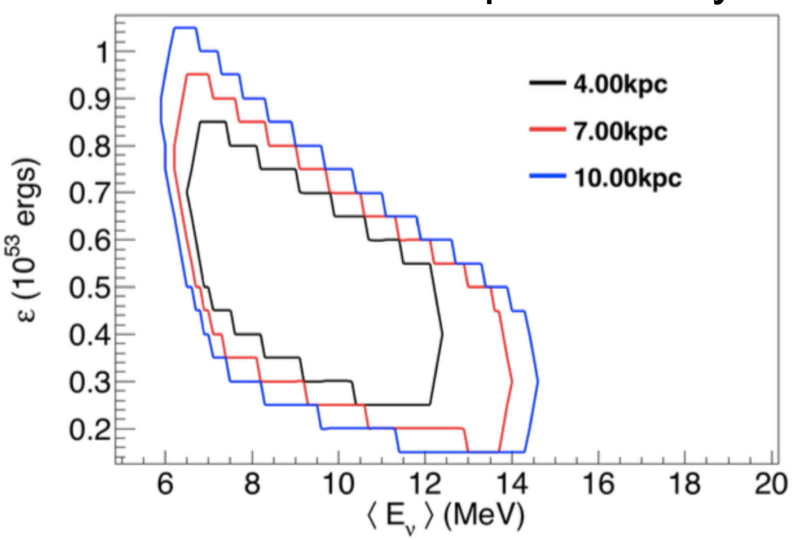


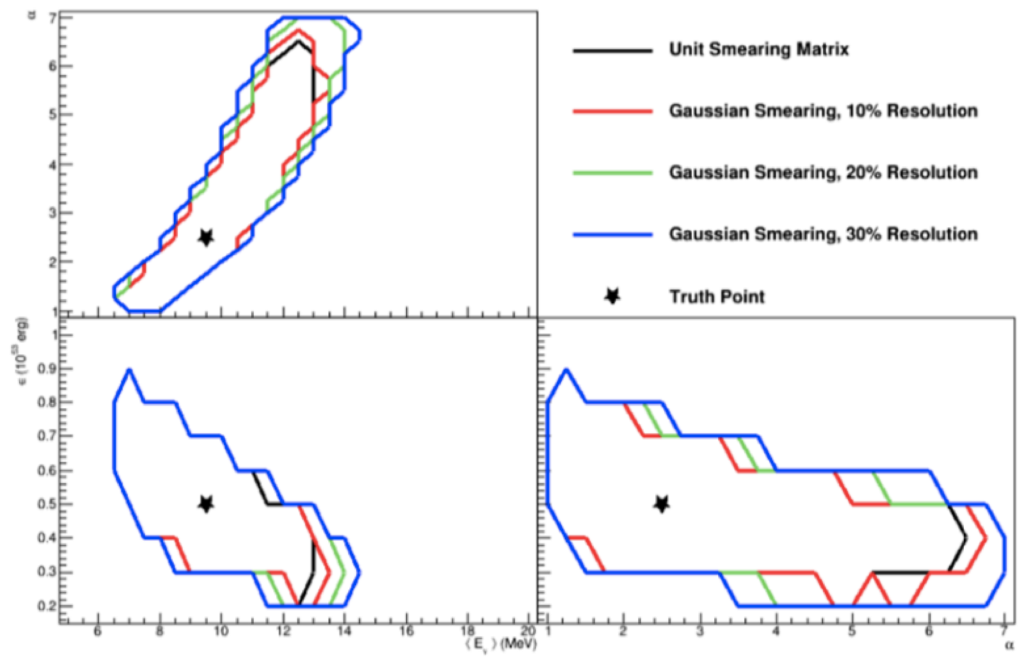
Using photon-based
correction for
charge lost during
electron drift

Fits to pinched-thermal spectrum

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

DUNE preliminary

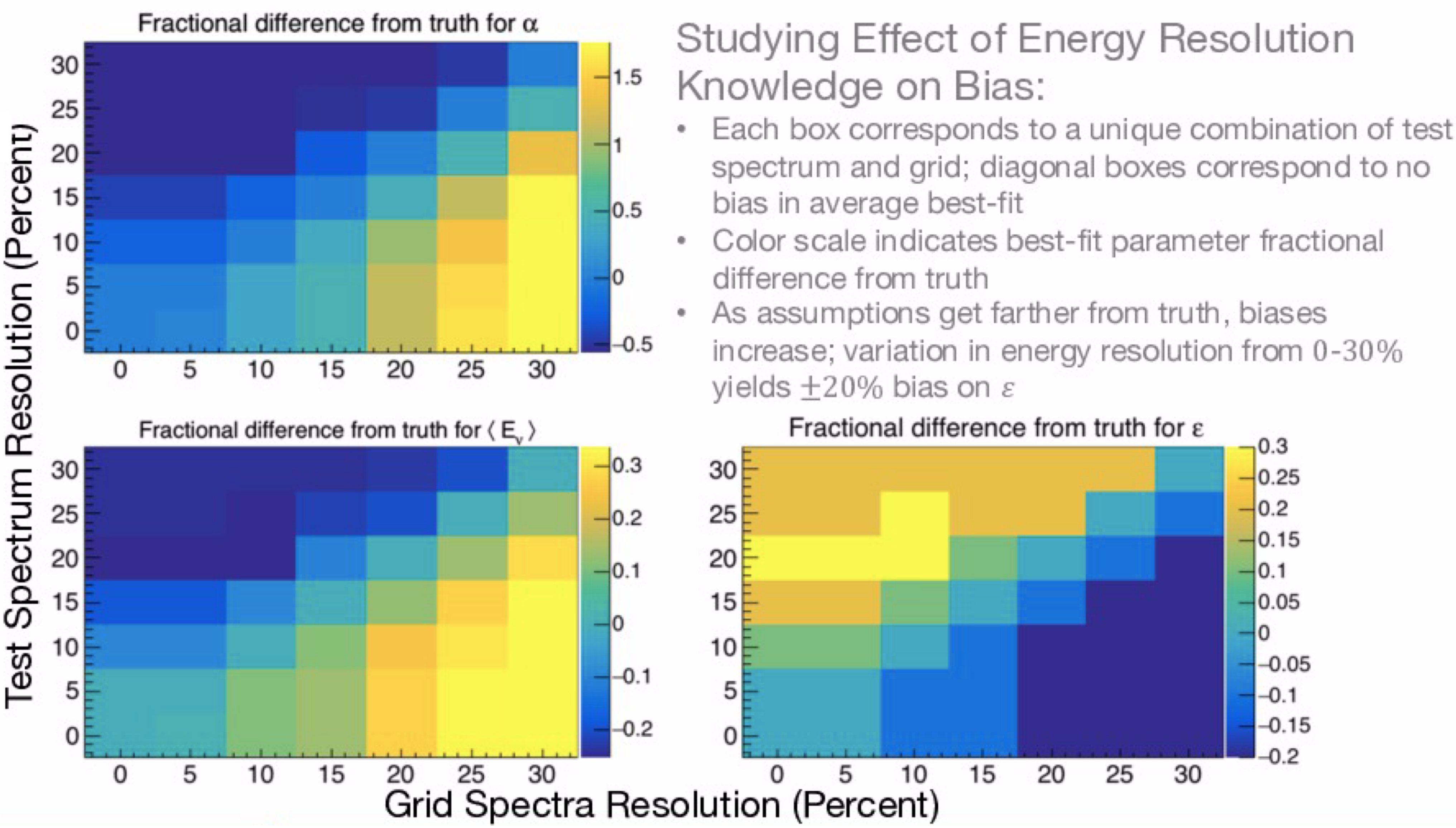




Will be statistics limited more than resolution limited..
what actually matters is how well we *know* the detector resolution

Studies by E. Conley

Poor knowledge of detector resolution results in *bias*



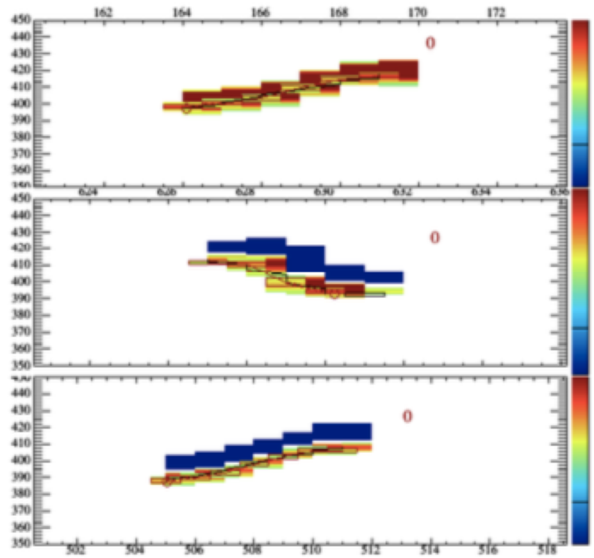
DUNE preliminary

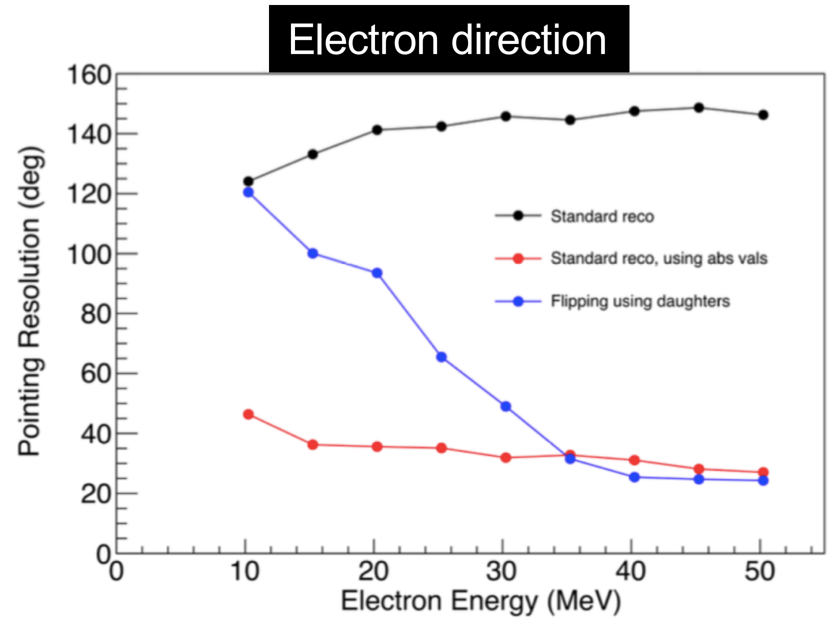
Studies by E. Conley

Pointing to the supernova with ES in DUNE

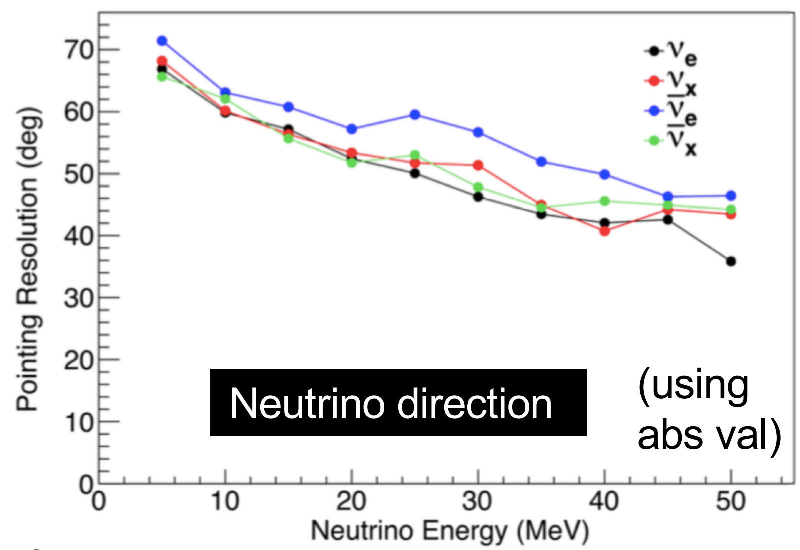
DUNE preliminary

10.25 MeV electron



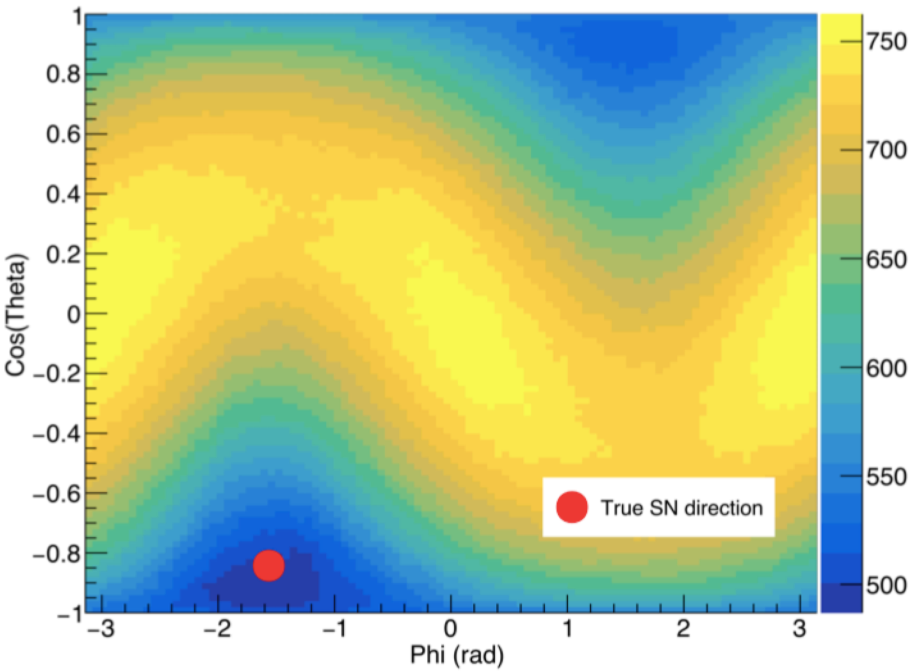


Note direction
ambiguity,
unlike Cherenkov!
... but can resolve statistically
  using bremsstrahlung
   directionality
  and multiple scattering

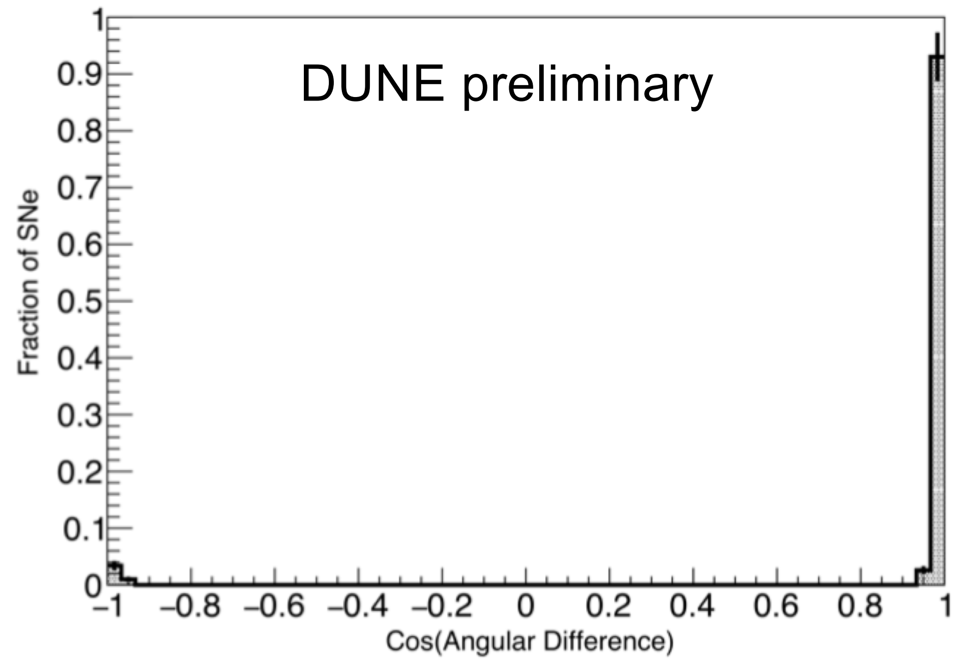


Studies by AJ Roeth

Overall pointing using an ensemble of ES events
(~10 kpc supernova w/ 260 ES events) → ~10°



Maximum likelihood method

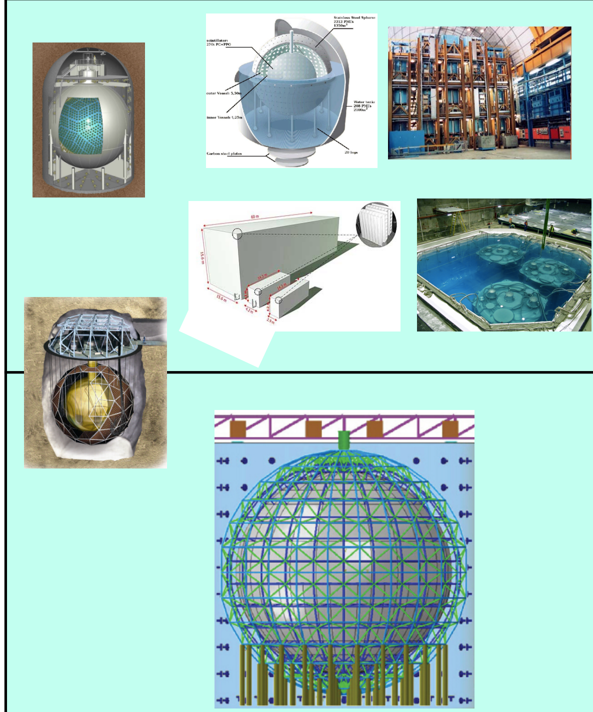
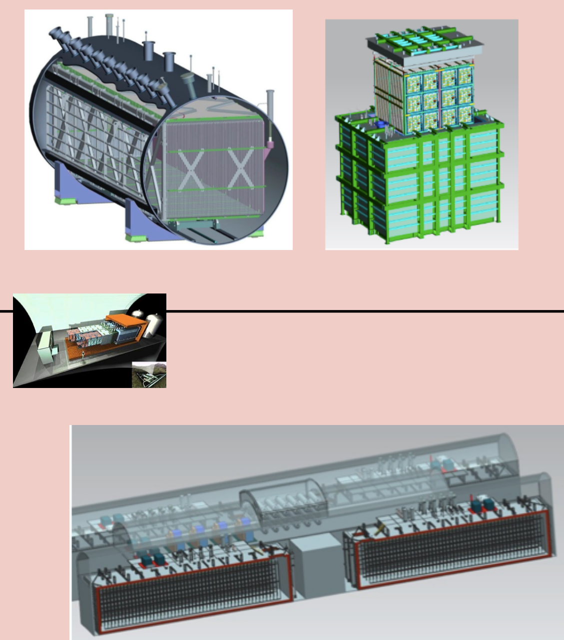
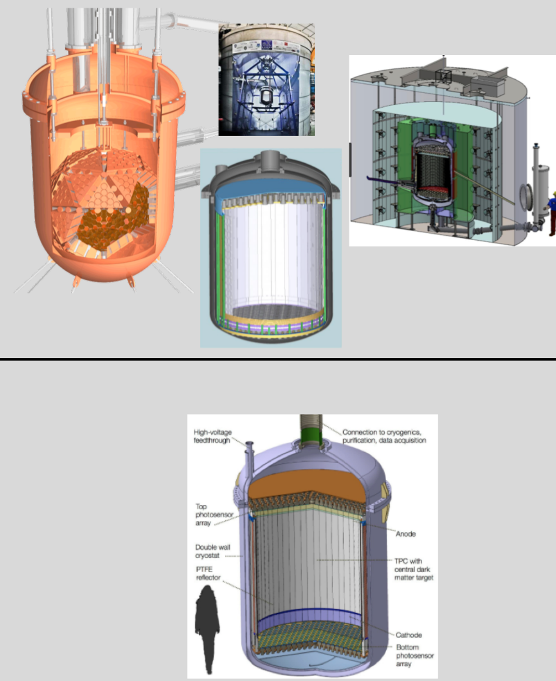


- other channels not yet included
- still room to improve disambiguation

Studies by AJ Roeth

ν_x flavor

- Subdominant in water and scintillator
- Nice 15-MeV gamma in scintillator
- Possible interesting channels in argon
- CEvNS: event by event recoil energies

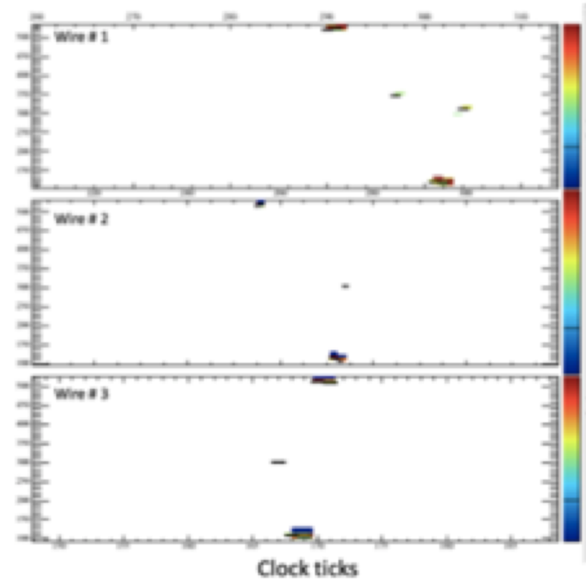
Scintillator	Liquid Argon	Dark Matter
		

New calculation from Pekka Pirinen and Jouni Suhonen

NC $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$

Table 1: The dominating final-state contributions to inelastic scattering cross sections for neutrinos of energy E_ν scattering off a ^{40}Ar target. The numbers in the parentheses refer to the the angular momentum, parity, and number of the final state, the energy of the final state and the percentage of the contribution arising from the final state compared to the total cross section. The computations were made in the QRPA.

E_ν (MeV)				
5	10	15	20	30
$(0_3^+, 3.54, 96.3)$	$(1_2^+, 8.27, 87.5)$	$(1_2^+, 8.27, 85.5)$	$(1_2^+, 8.27, 68.0)$	$(1_2^+, 8.27, 30.7)$
$(1_1^+, 4.01, 2.3)$	$(0_3^+, 3.54, 6.8)$	$(2_2^-, 7.53, 5.0)$	$(2_2^-, 7.53, 7.2)$	$(1_8^+, 20.2, 14.1)$
$(2_1^+, 1.46, 1.3)$	$(2_2^-, 7.53, 3.2)$	$(0_3^+, 3.54, 1.7)$	$(2_1^-0, 12.4, 4.1)$	$(2_1^-0, 12.4, 7.8)$
	$(0_4^+, 6.75, 0.8)$	$(0_6^+, 8.36, 1.7)$	$(1_5^+, 14.3, 3.9)$	$(2_2^-, 7.53, 7.7)$
		$(2_{10}^-, 12.40, 0.9)$	$(0_6^+, 8.36, 2.1)$	$(1_8^+, 12.4, 5.4)$
			$(2_6^-, 10.78, 1.7)$	$(1_5^+, 14.3, 3.9)$
			$(1_8^-, 12.4, 1.5)$	$(1_9^+, 20.3, 3.5)$
				$(1_9^-, 12.57, 2.6)$
E_ν (MeV)				
35	40	45	50	55
$(1_2^+, 8.27, 22.0)$	$(1_2^+, 8.27, 16.4)$	$(1_2^+, 8.27, 12.6)$	$(1_8^+, 20.2, 10.8)$	$(2_{10}^-, 12.4, 10.0)$
$(1_8^+, 20.2, 15.1)$	$(1_8^+, 20.2, 14.1)$	$(1_8^+, 20.2, 12.5)$	$(2_{10}^-, 12.4, 9.9)$	$(1_8^-, 12.4, 9.5)$
$(2_{10}^-, 12.4, 8.7)$	$(2_{10}^-, 12.4, 9.3)$	$(2_{10}^-, 12.4, 9.7)$	$(1_2^+, 8.27, 9.9)$	$(1_8^+, 20.2, 9.2)$
$(2_2^-, 7.53, 7.7)$	$(1_8^-, 12.4, 7.9)$	$(1_8^-, 12.4, 8.7)$	$(1_8^-, 12.4, 9.2)$	$(1_2^+, 8.27, 8.0)$
$(1_8^-, 12.4, 6.8)$	$(2_2^-, 7.53, 7.6)$	$(2_2^-, 7.53, 7.5)$	$(2_2^-, 7.53, 7.4)$	$(2_2^-, 7.53, 7.2)$
$(1_9^+, 20.28, 3.8)$	$(1_9^+, 20.28, 3.6)$	$(1_{22}^-, 23.9, 3.7)$	$(1_{22}^-, 23.9, 4.5)$	$(1_2^-2, 23.9, 5.1)$
$(1_5^+, 14.27, 3.2)$	$(1_9^-, 12.57, 2.9)$	$(1_9^+, 20.28, 3.2)$	$(1_{26}^-, 29.19, 3.5)$	$(1_{26}^-, 29.19, 4.4)$
$(1_9^-, 12.57, 2.8)$	$(1_2^-2, 23.9, 2.8)$	$(1_9^-, 12.57, 3.0)$	$(1_1^-9, 20.1, 3.2)$	$(1_{19}^-, 20.1, 3.5)$



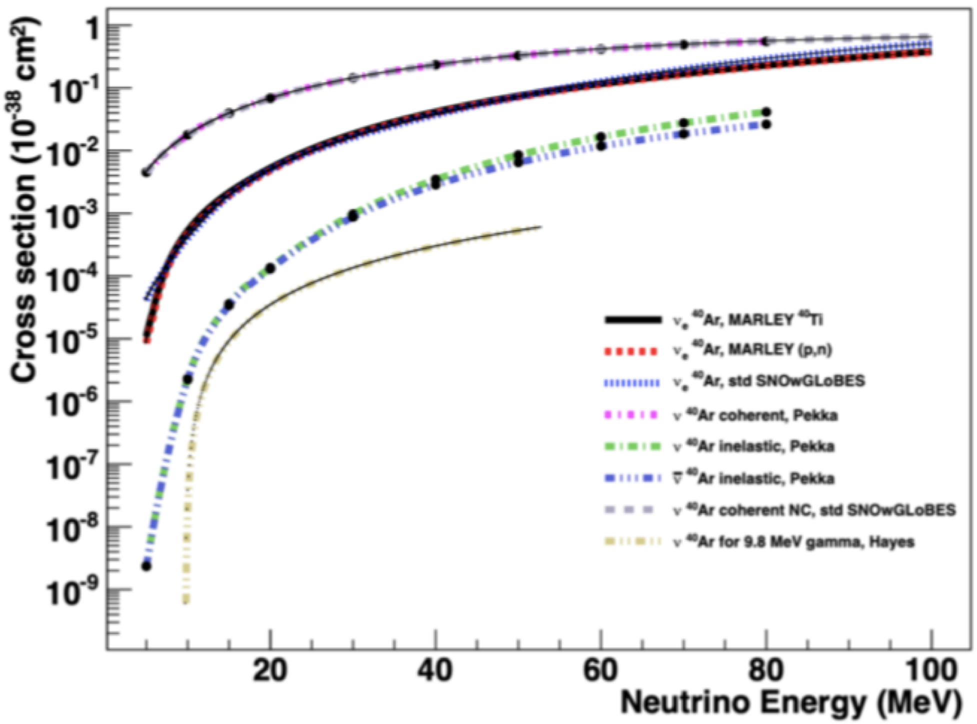
cloud of γ blips

Distribution of excited final states as a function of E_ν

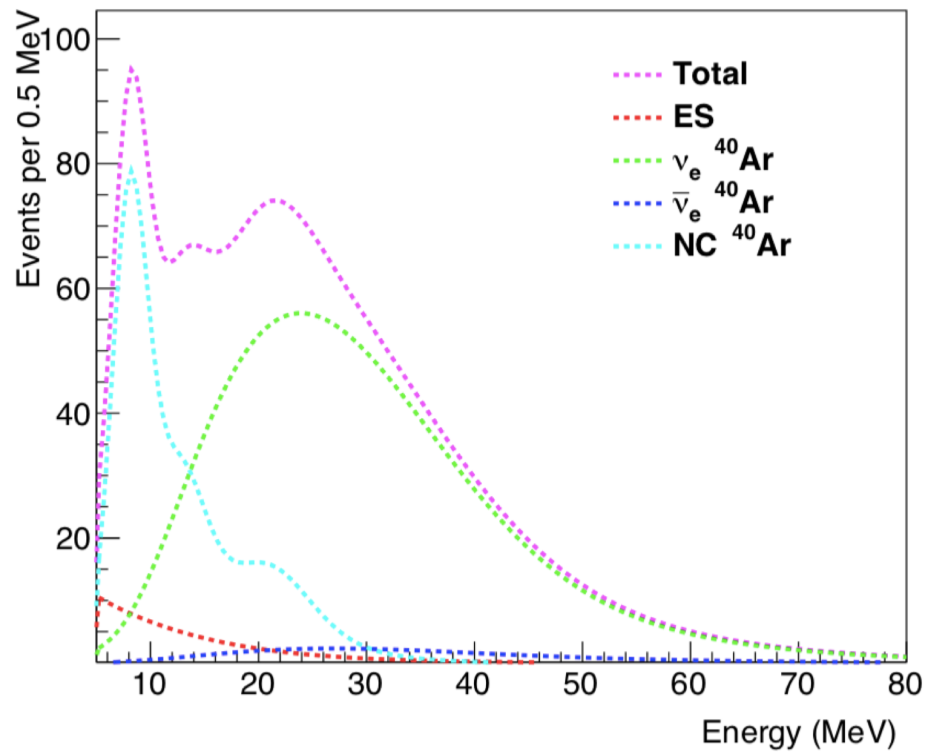
→ now modeled in SNOwGLoBES w/approximate DUNE smearing

Inelastic NC interactions channels in argon

NC $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$



Observed supernova spectrum in DUNE



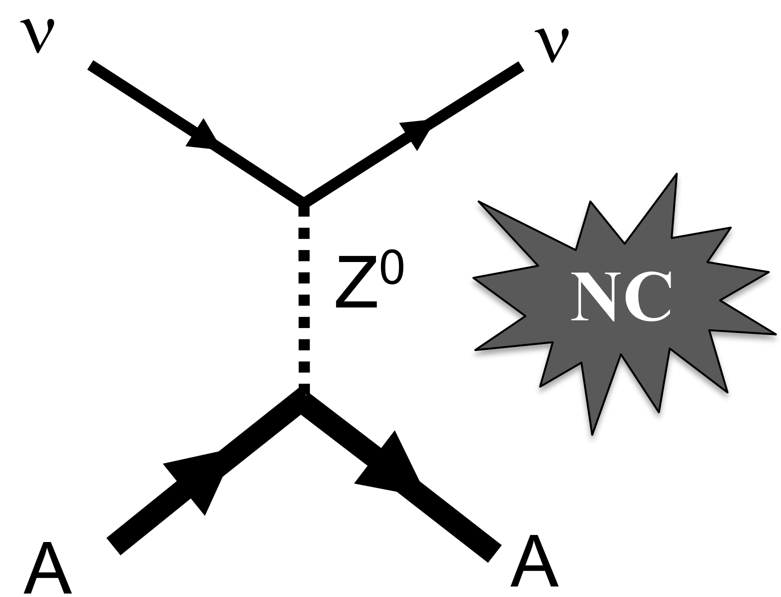
NC in DUNE is likely a major contribution!

potentially valuable tool for physics!

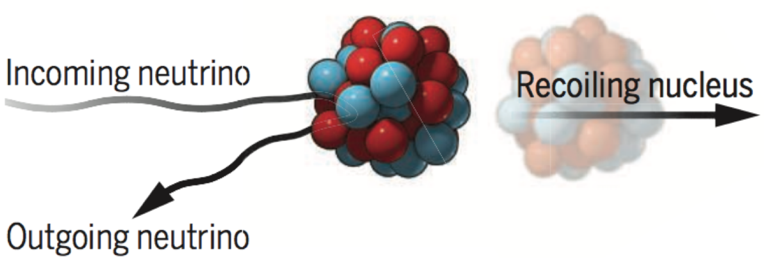
large uncertainties in the cross section, will need reasonable tagging

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

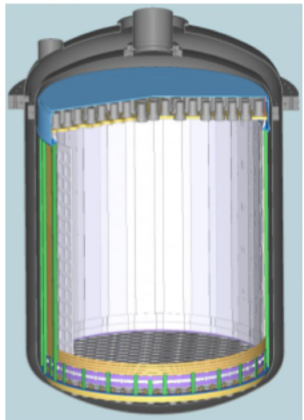
For $QR << 1$,

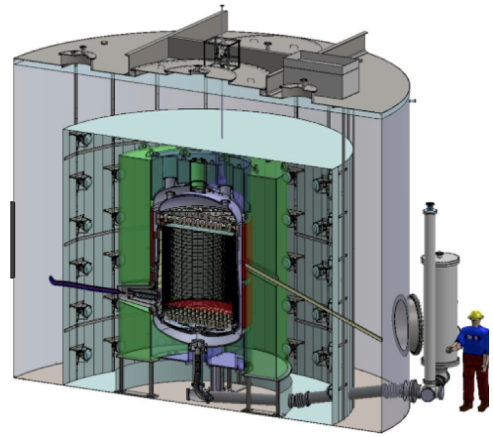
[total xscn] ~ A^2 * [single constituent xscn]   A: no. of constituents

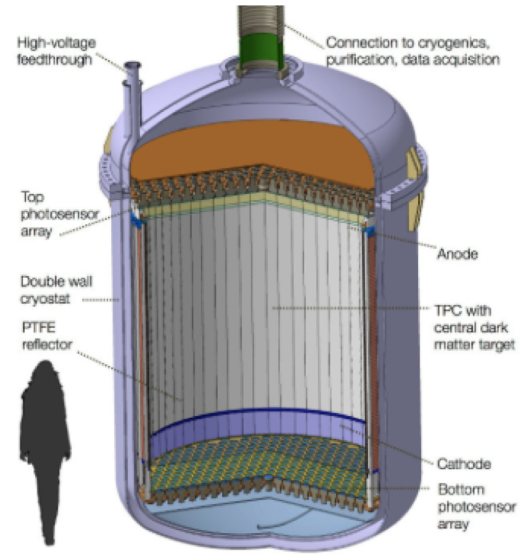
Image: J. Link *Science* Perspectives

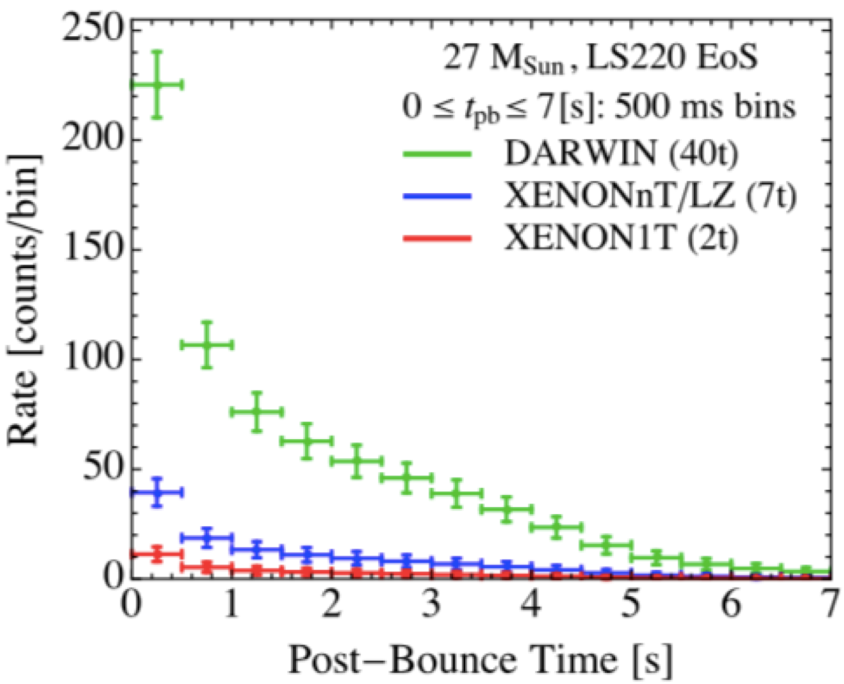
Detector example: **XENON/LZ/DARWIN**

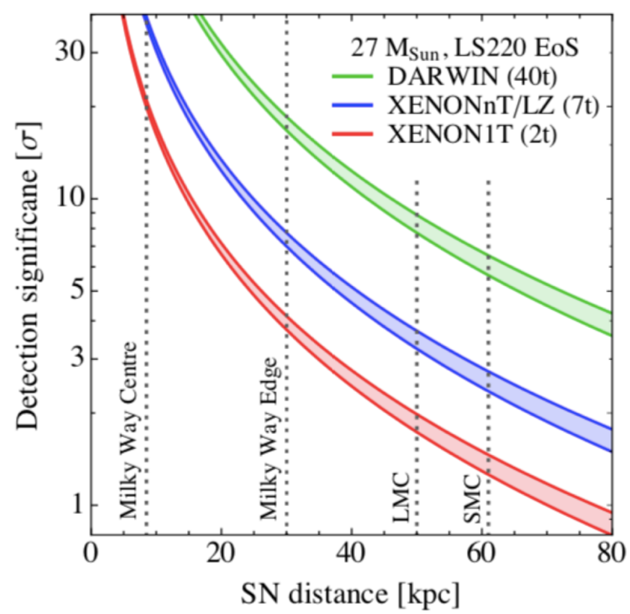
- dual-phase xenon time projection chambers





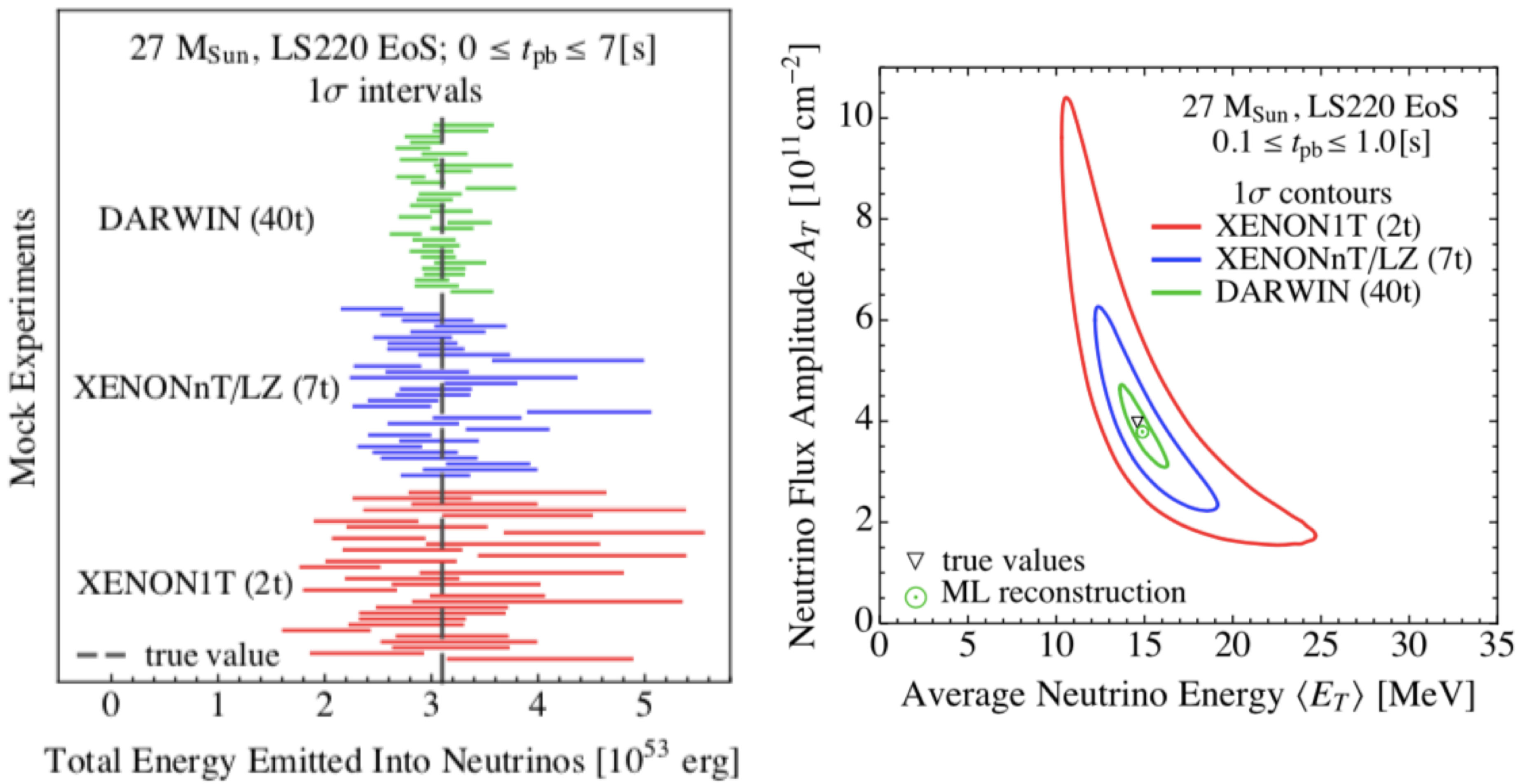






Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

What will be learned?

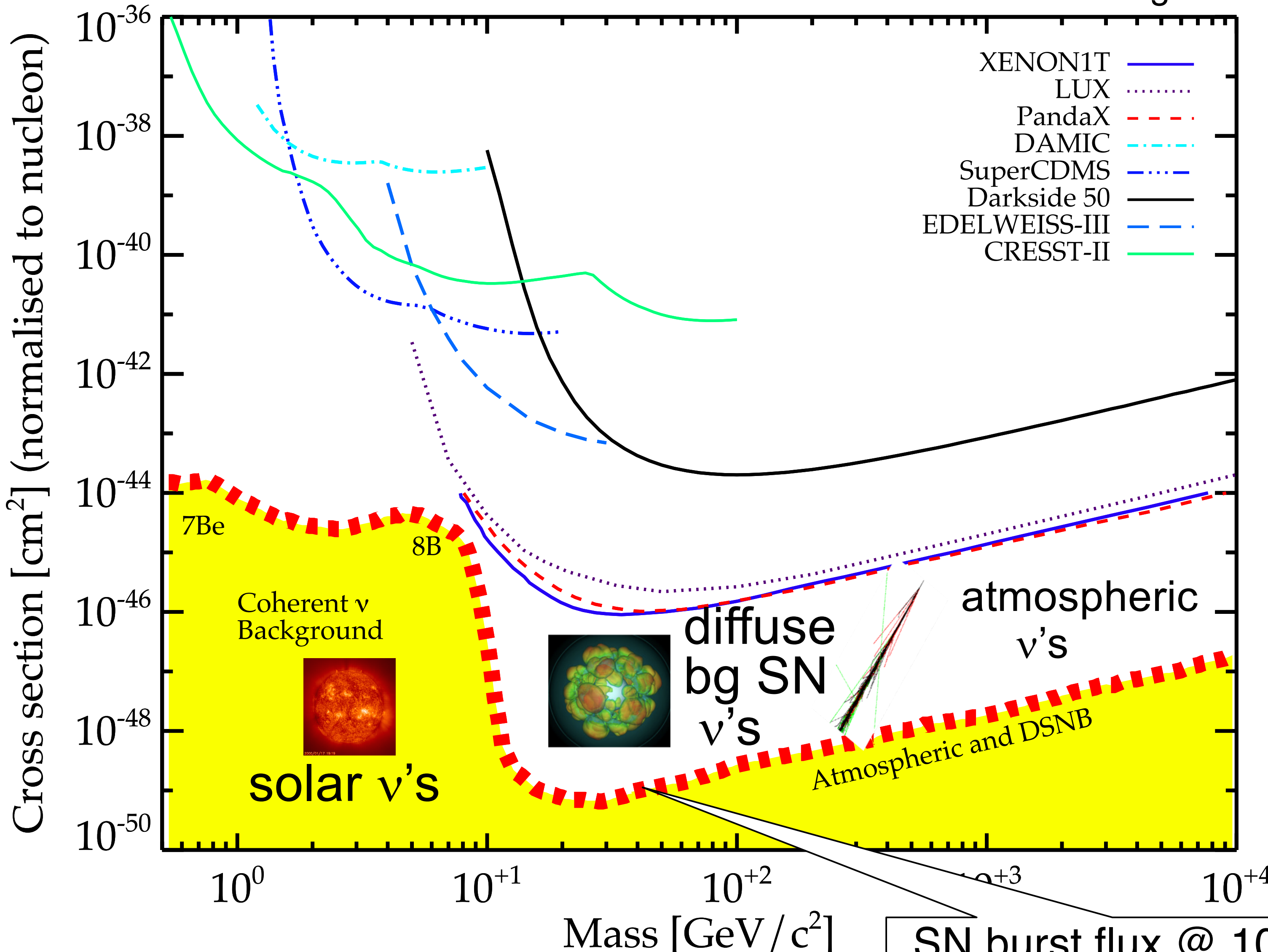


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

The so-called “**neutrino floor**” for DM experiments

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

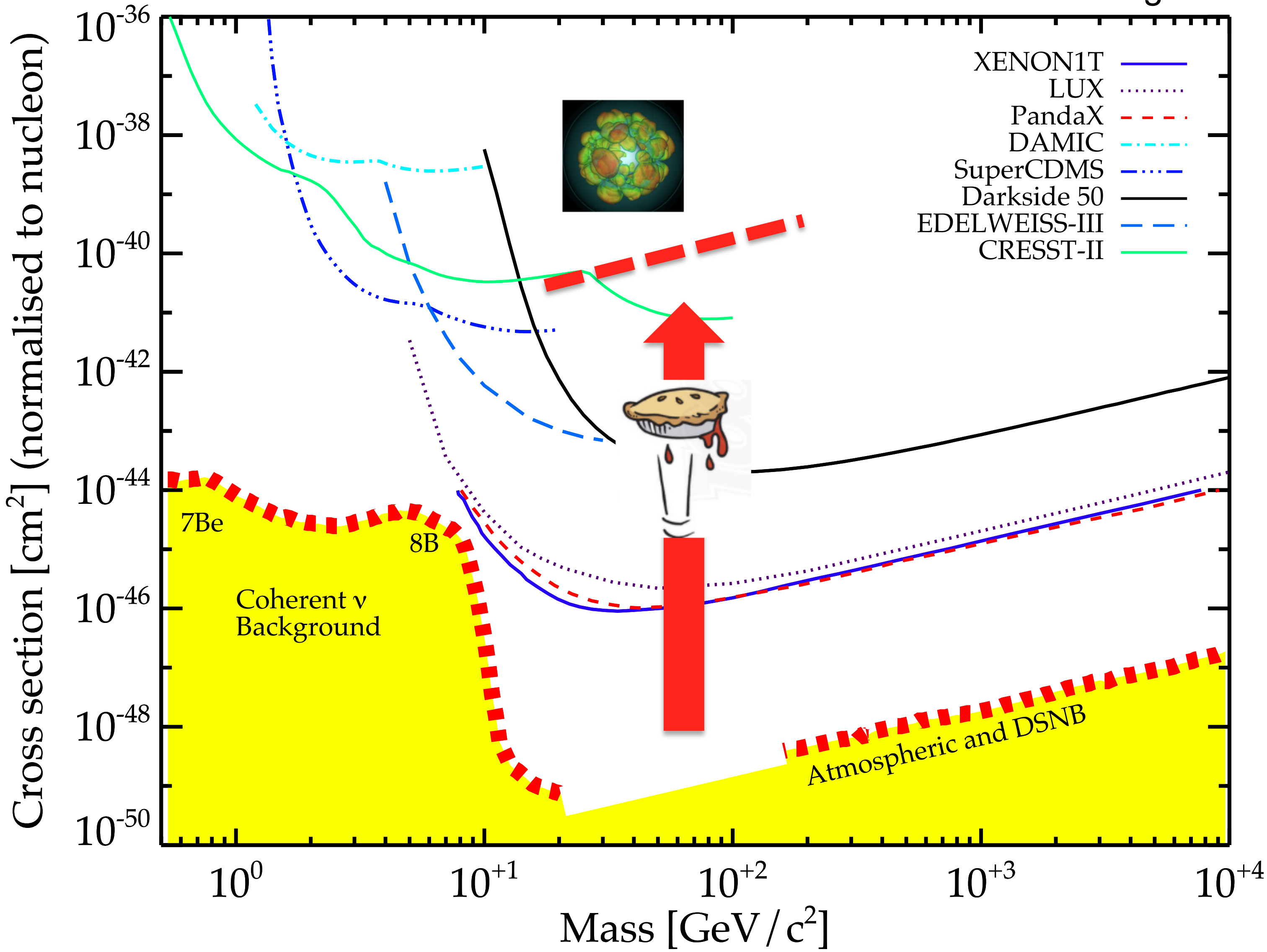


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

Think of a SN burst as “**the ν floor coming up to meet you**”

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari

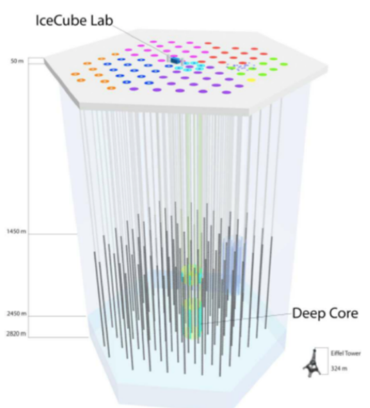


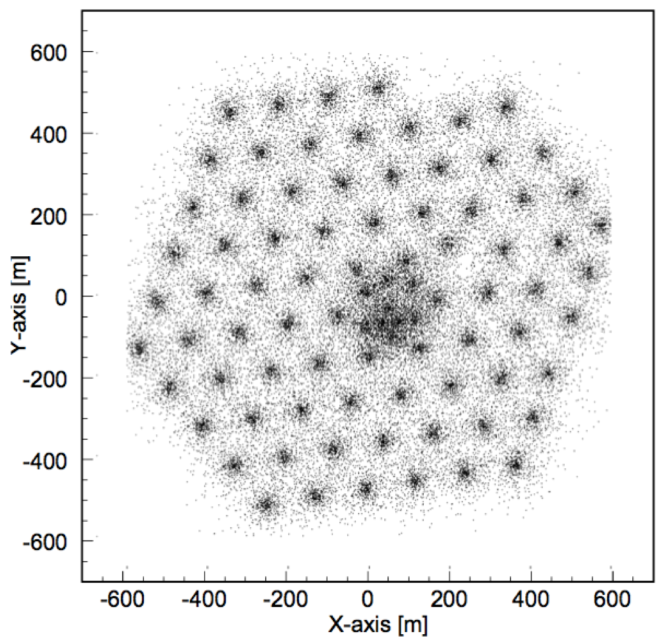
New idea in early stages of exploration:

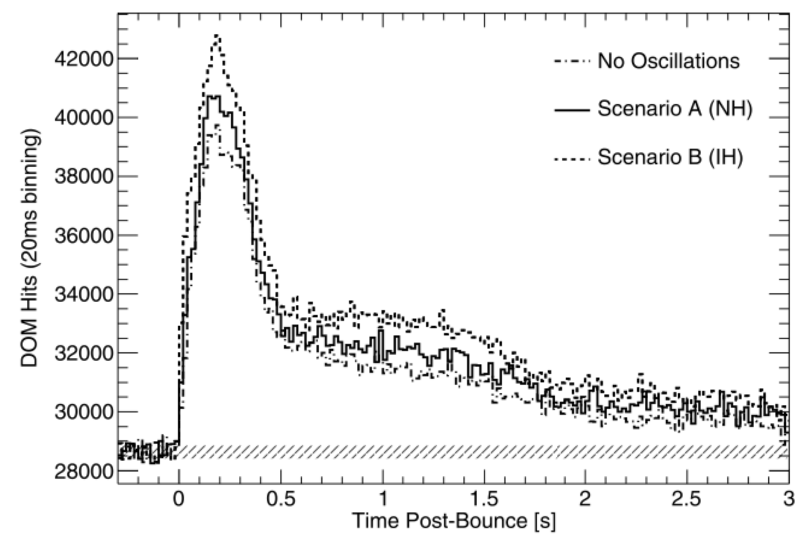
Adryanna Smith and Gleb Sinev @ Duke

"CEvNS Glow" in large, high-threshold neutrino detectors

"IceCube-style" supernova detection:
Cherenkov photons in ice observed as
time-dependent single- (and double-)hit glow over ~10 sec







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

Back-of-the-envelope:

CEvNS signal vs Inelastic (CC/NC) signal:

e.g., $\nu_x + A \rightarrow \nu_x + A$ vs $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ in argon, or IBD in scint

~10^2 more CEvNS events per target wrt CC

~10^{-3} less energy deposited per event for CEvNS wrt CC

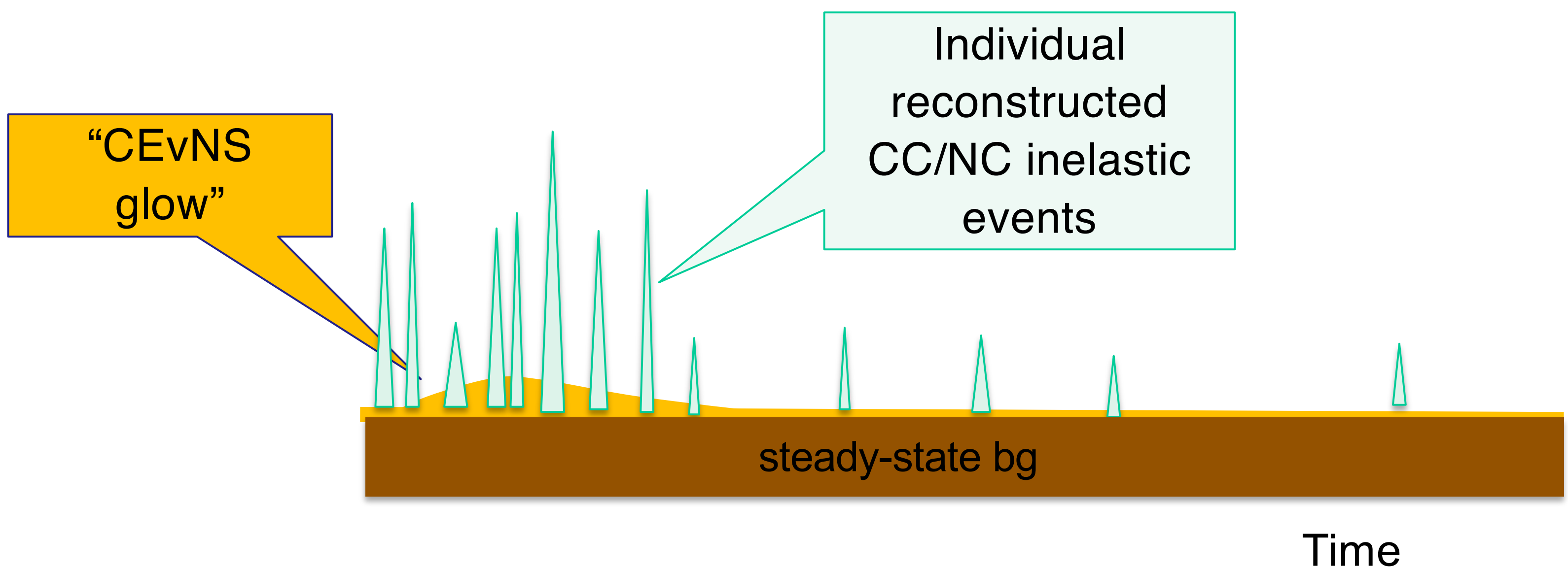
~ 6 due to sensitivity to all flavors

~0.001-0.2 quenching factor (photons wrt e/γ energy deposit) for nuclear recoil wrt CC

➔ Total CEvNS photons are **~few-10% of CC-generated photons**, but, **diffused over the burst** rather than in individual event spikes

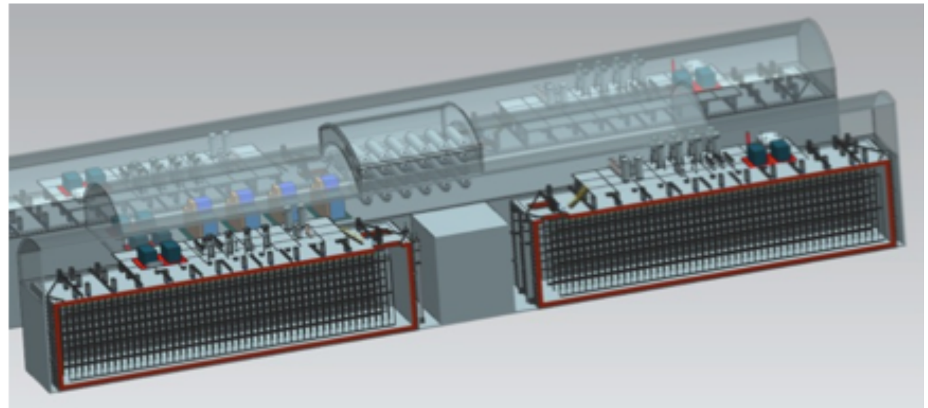
Issue is whether they exceed Sqrt[background]

(and triggering may be challenging!)



Preliminary studies by A. Smith (+ G. Sinev)

For **DUNE**: 40 kt LAr,
~24,000 photons/MeV
TPC + photon detectors

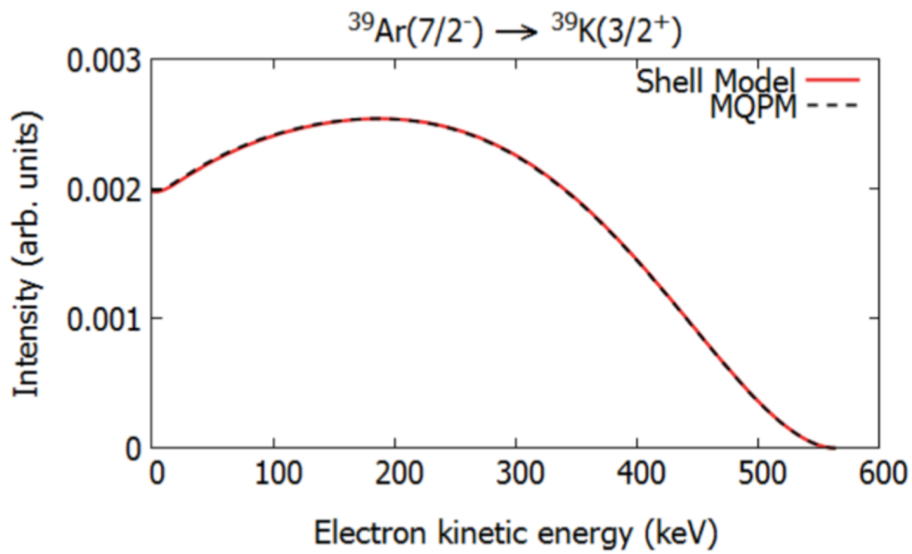


Most pernicious
issue for CEvNS glow:

^{39}Ar β decays

(dominant radiological)

- 1 Bq/kg
- 260-yr half-life
- in principle can be mitigated w/underground argon
  (but 40 kton of it a challenge...)



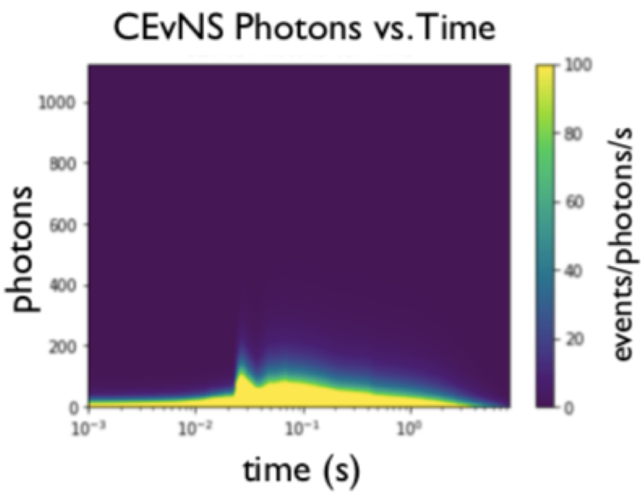
J. Kostensalo et al. (2017) arXiv:1705.05726

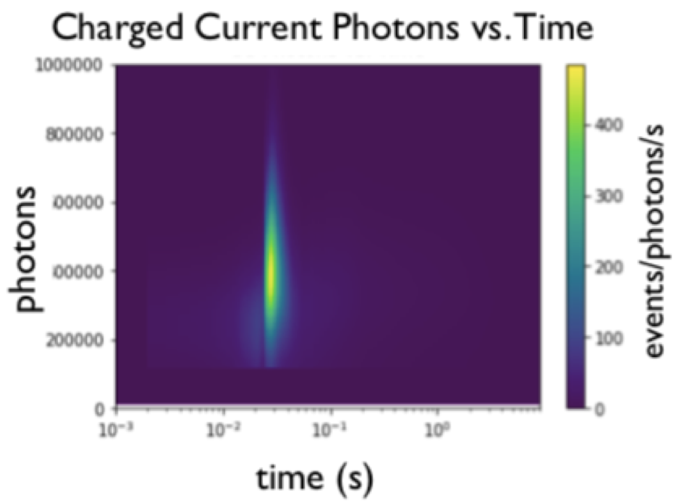
Preliminary calculations of photon production:

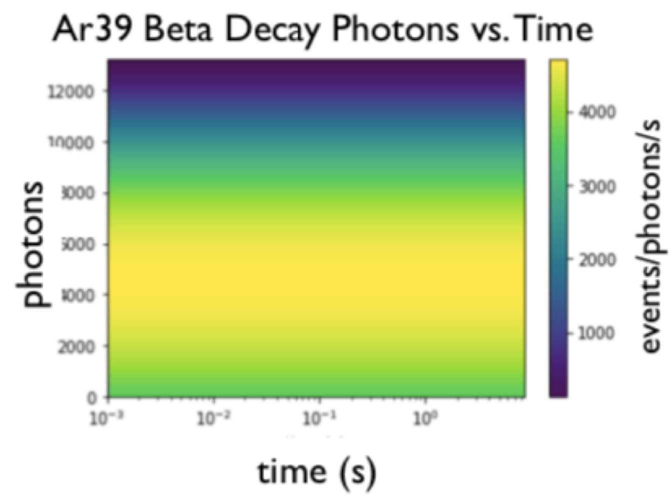
"Garching" supernova model, 10 kt, 10 kpc

A. Smith

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





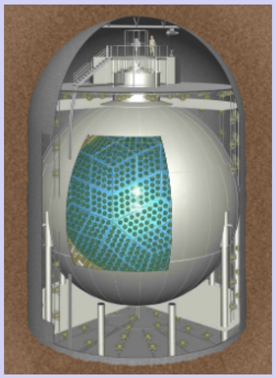


Underway and TBD:

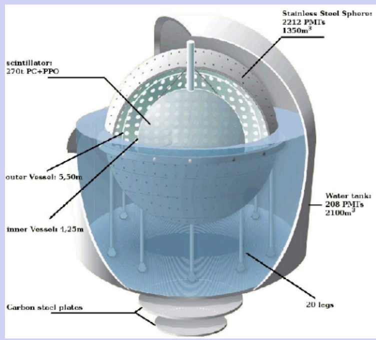
- photon transport (analytic & MC) and detection efficiencies
- additional backgrounds
- triggering not yet considered...
  serious challenge; may be able to trigger on CC
- **distribution** of observed N_{pe} may help select signal
- ...study still in early stages!

Also looking at **organic liquid scintillator**

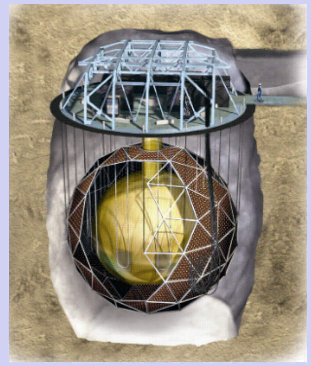
KamLAND
(Japan)
1 kton

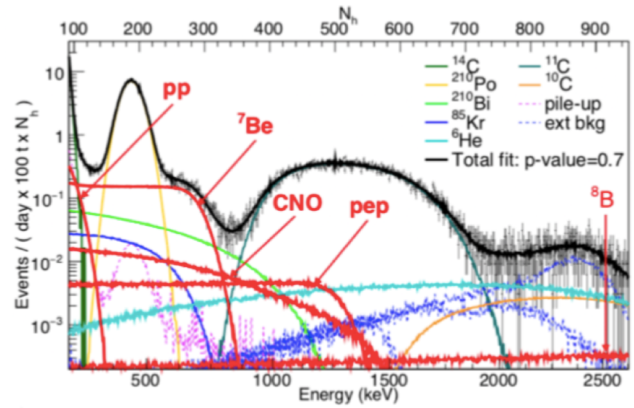


Borexino
(Italy)
0.33 kton

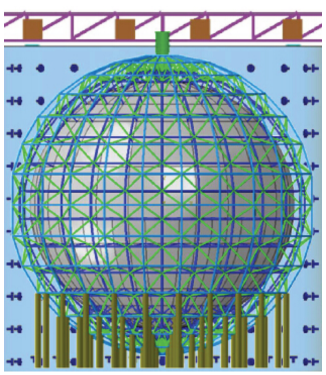


SNO+
(Canada)
1 kton



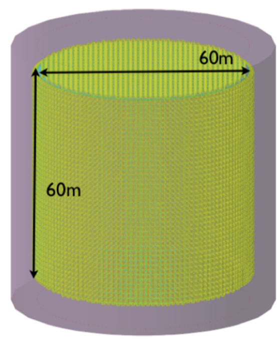


From Borexino Collaboration
M. Agostini et al (2017) arXiv:1707.09279v2



JUNO
(China)
20 kton

Jinping
(China)
2 kton



THEIA
(TBD)
50-100 kton
WbLS

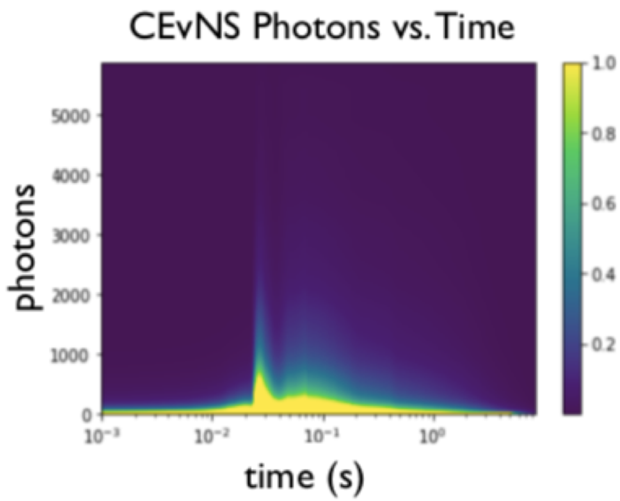
- backgrounds tend to be quite low
- ~0.1% quenching for carbon recoils, ~1% for proton recoils

Preliminary calculations of photon production in scintillator:

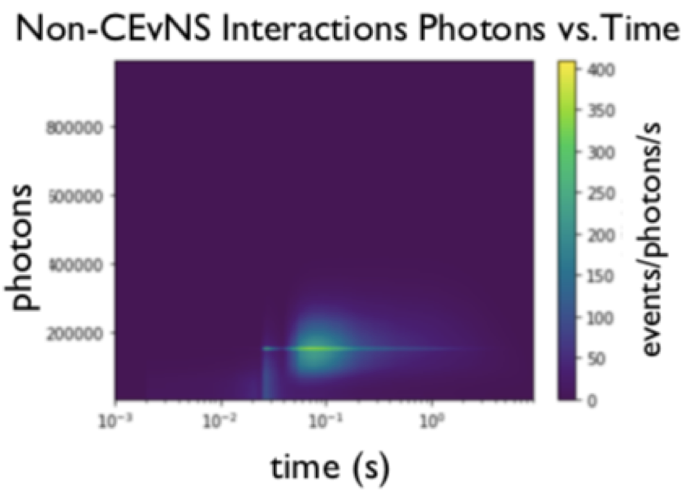
"Garching" supernova model, 10 kt, 10 kpc

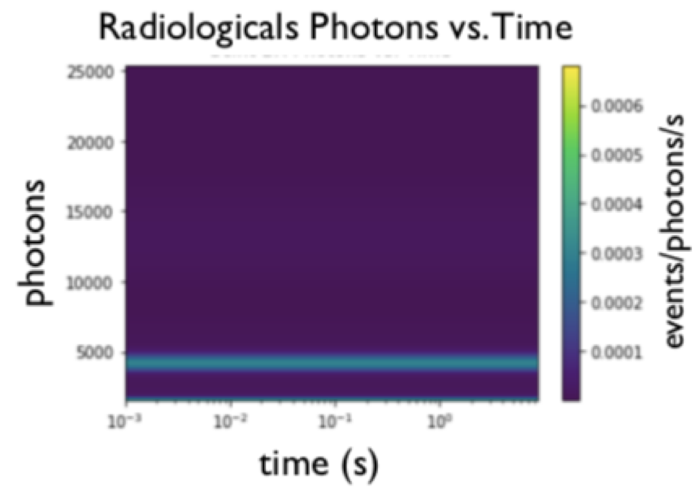
A. Smith

^{12}C CEνNS+NCνp



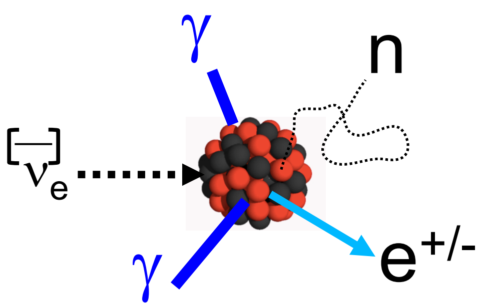
IBD+CCν_e+NC



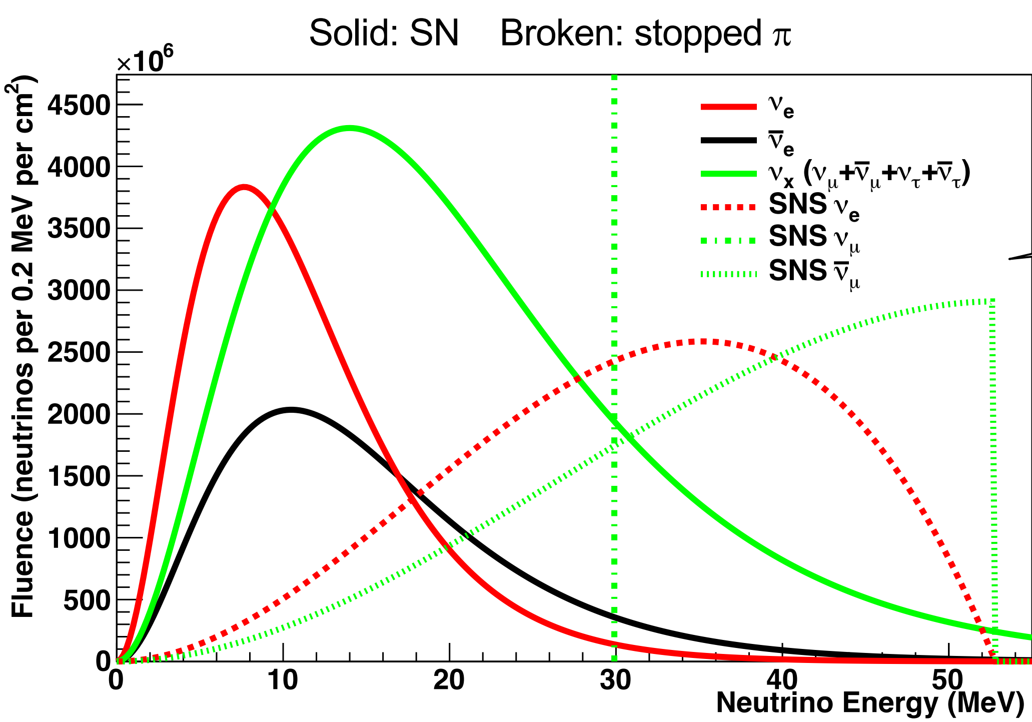


- similar studies underway... still in early stages!
- backgrounds are much less severe in clean scintillator detectors
- dark counts need to be considered

Final topic: **measuring these cross sections**



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

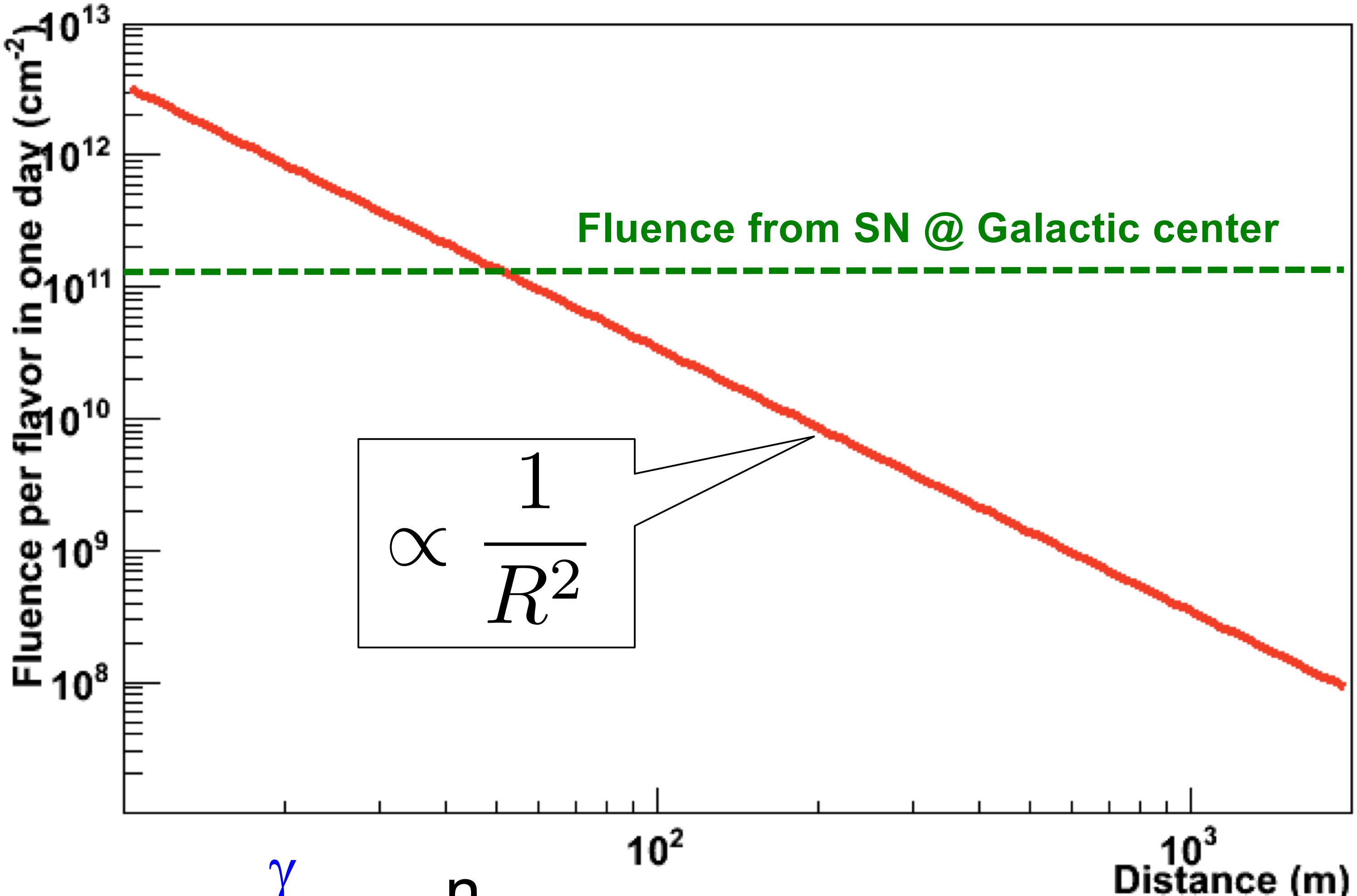


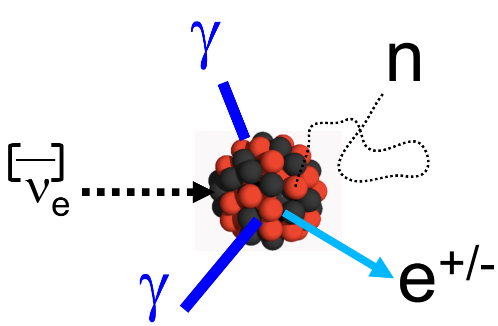
Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source and far off-axis at the Fermilab BNB

A. Bolozdynya et al., arXiv:1211.5199

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

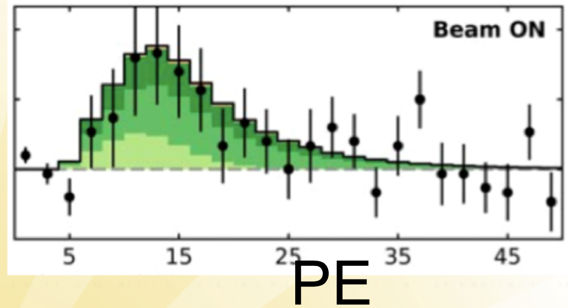
(or 0.2 microsupernovae per pulse, 60 Hz of pulses)



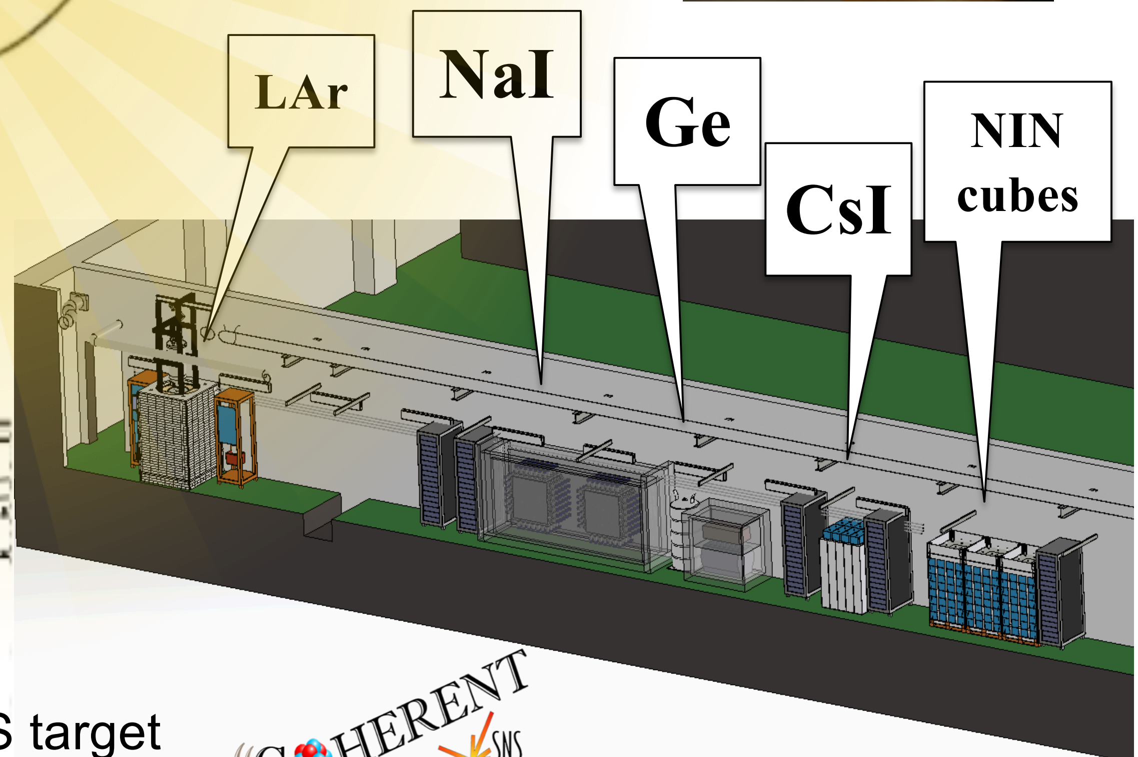


This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

CEvNS now measured w/ stopped-π ν's



View looking down "Neutrino Alley"



Isotropic ν glow from Hg SNS target

COHERENT SNS

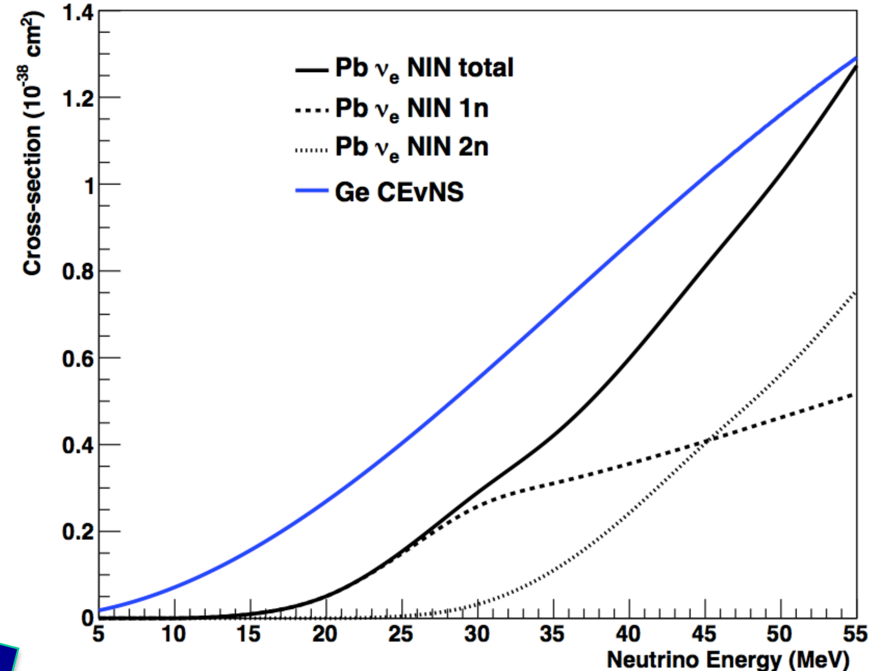
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

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

1n, 2n emission

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

1n, 2n, γ emission



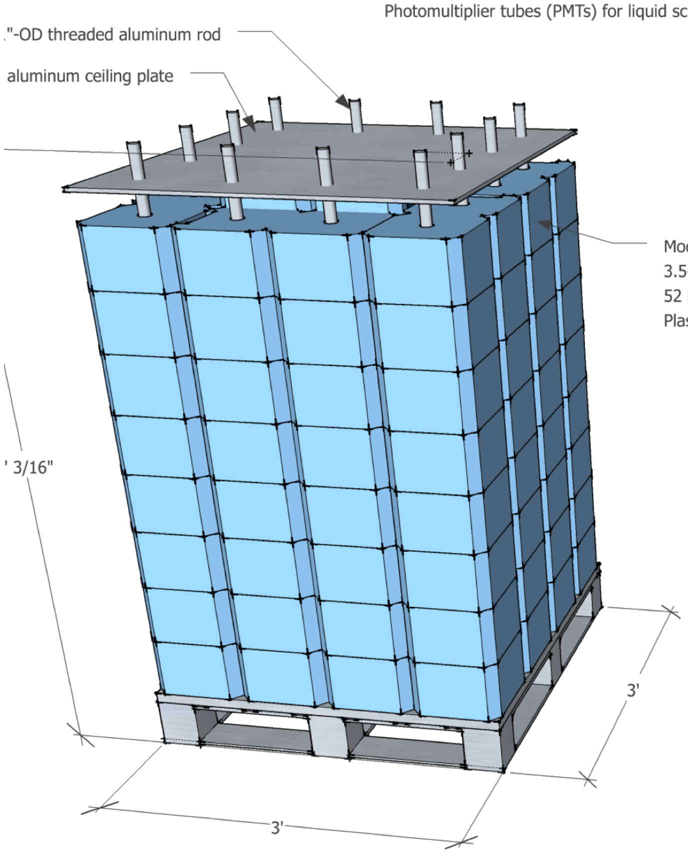
A non-negligible background to CEvNS, especially in lead shield

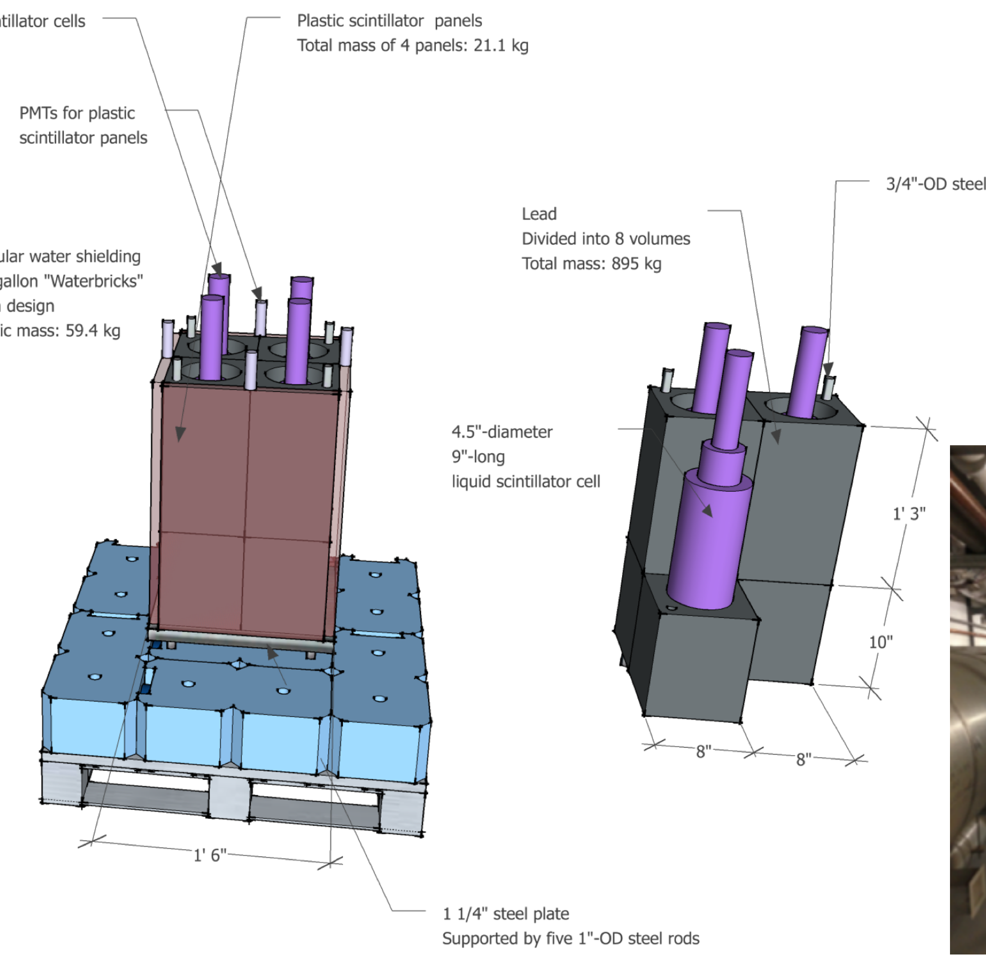
NIN measurement in SNS basement

Liquid scintillator surrounded by lead, iron

(swappable for other NIN targets)

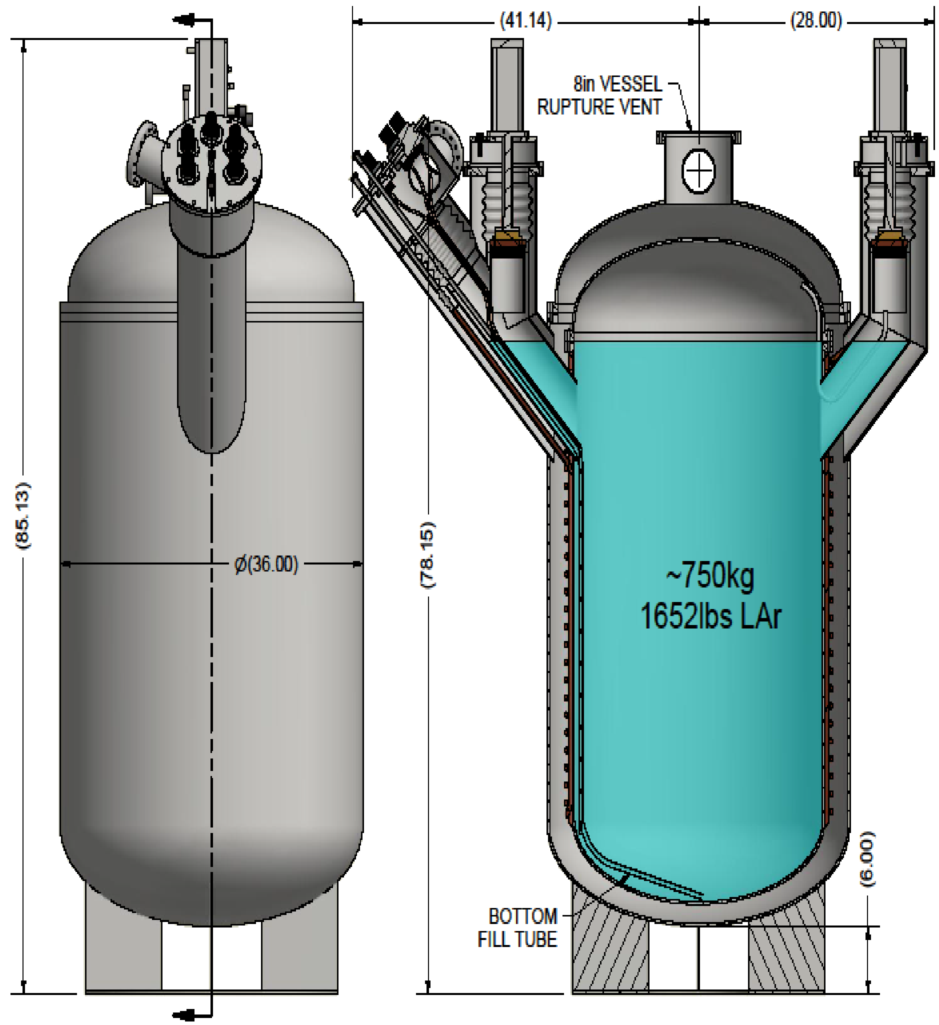
inside water shield



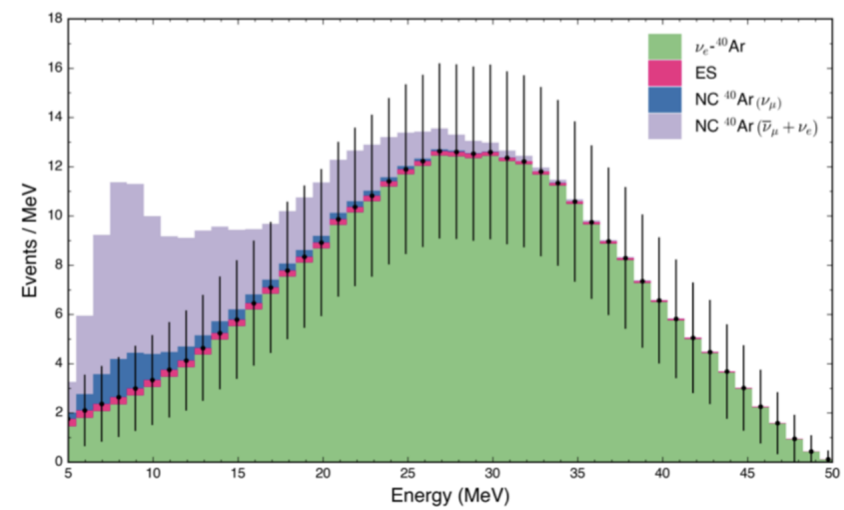


Phil Barbeau

Tonne-scale LAr Detector



- 750-kg LAr will fit in the same place, will reuse part of existing infrastructure



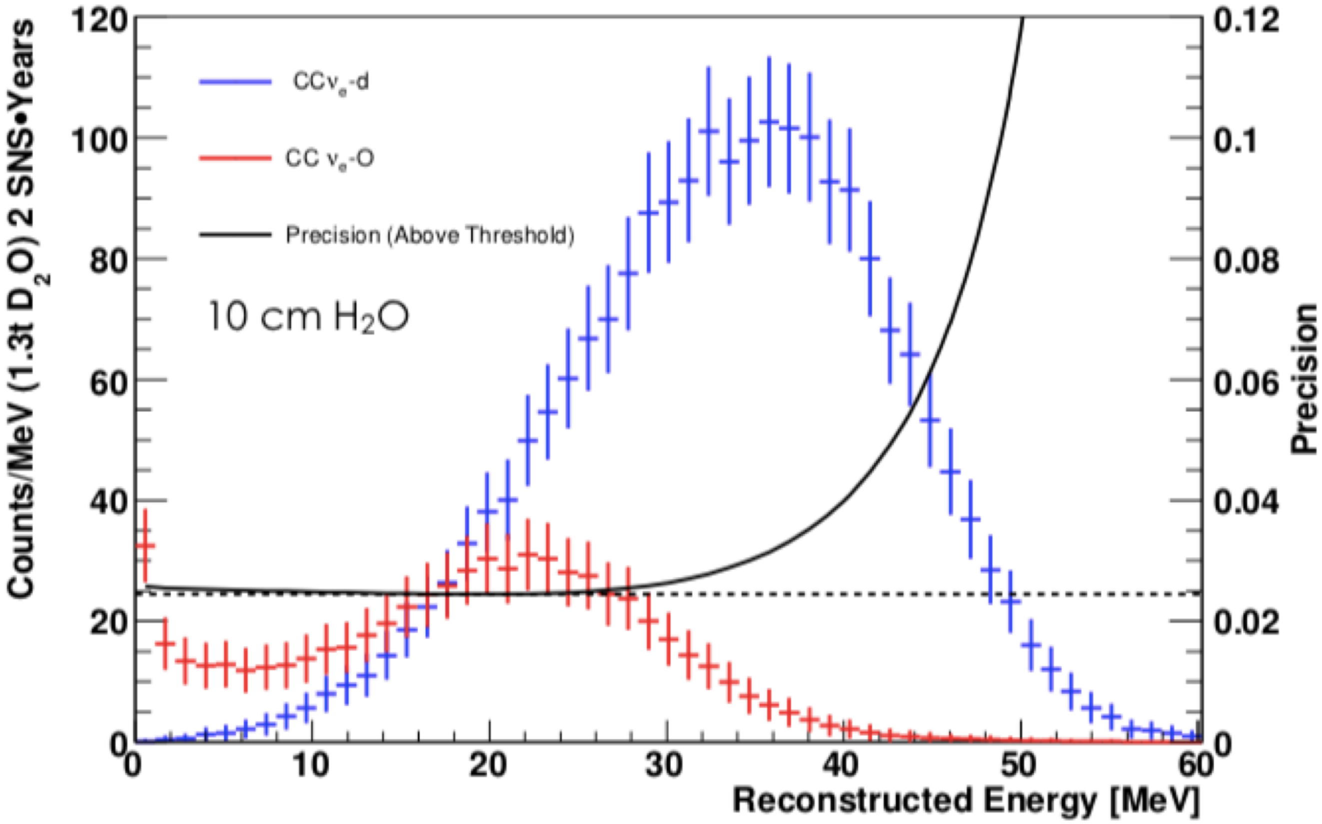
CC/NC **inelastic** in argon of interest for supernova neutrinos

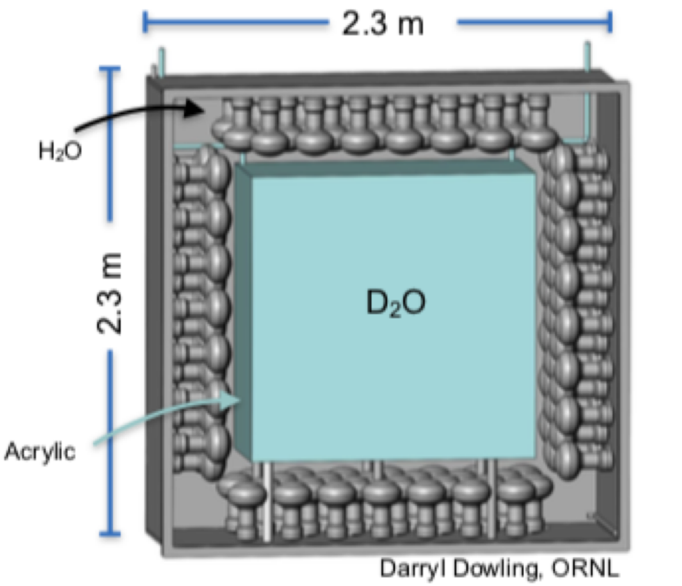
CC $\quad \nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

NC $\quad \nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$

Heavy water detector in Neutrino Alley

Measurement Precision with 2 SNS years at 1.4 MW





- 1.3 tons D_2O within acrylic inner vessel
- 10 cm H_2O “tail catcher” for high energy e^-
- 112 8” bialkali photomultipliers

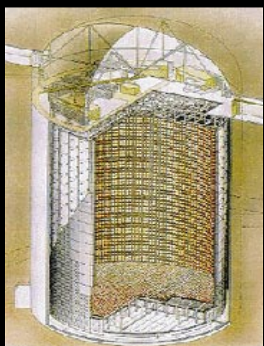
➔ ~few percent precision on flux normalization

...also measure CC (maybe NC) on ^{16}O

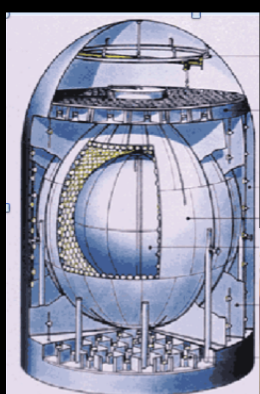
SNEWS: SuperNova Early Warning System

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

snews.bnl.gov



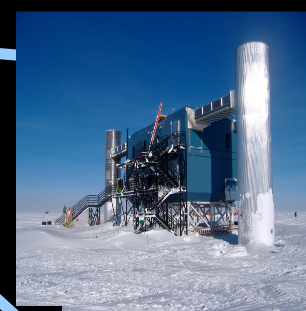
experiment
UT time
significance

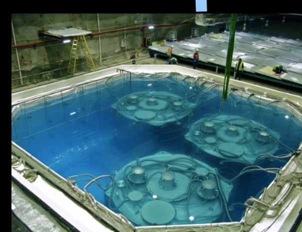


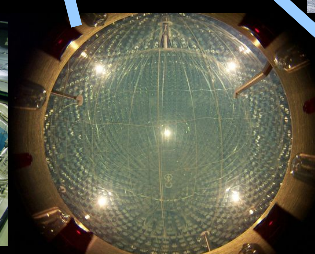
Coincidence Server at BNL

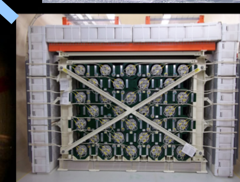
10 second
coincidence
by UT time
stamp

alert to astronomers





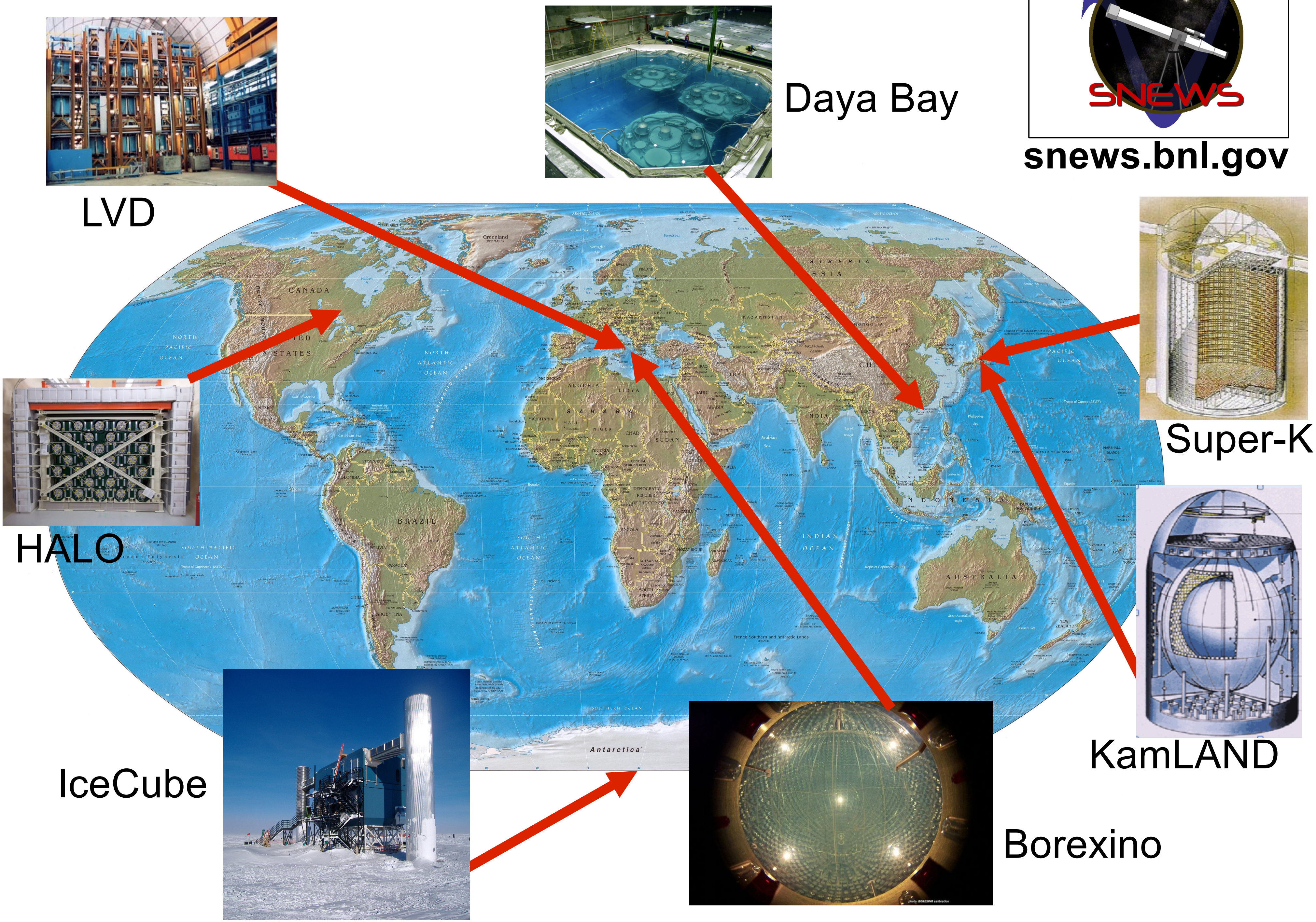




- Running smoothly for more than 17 years, automated since 2005

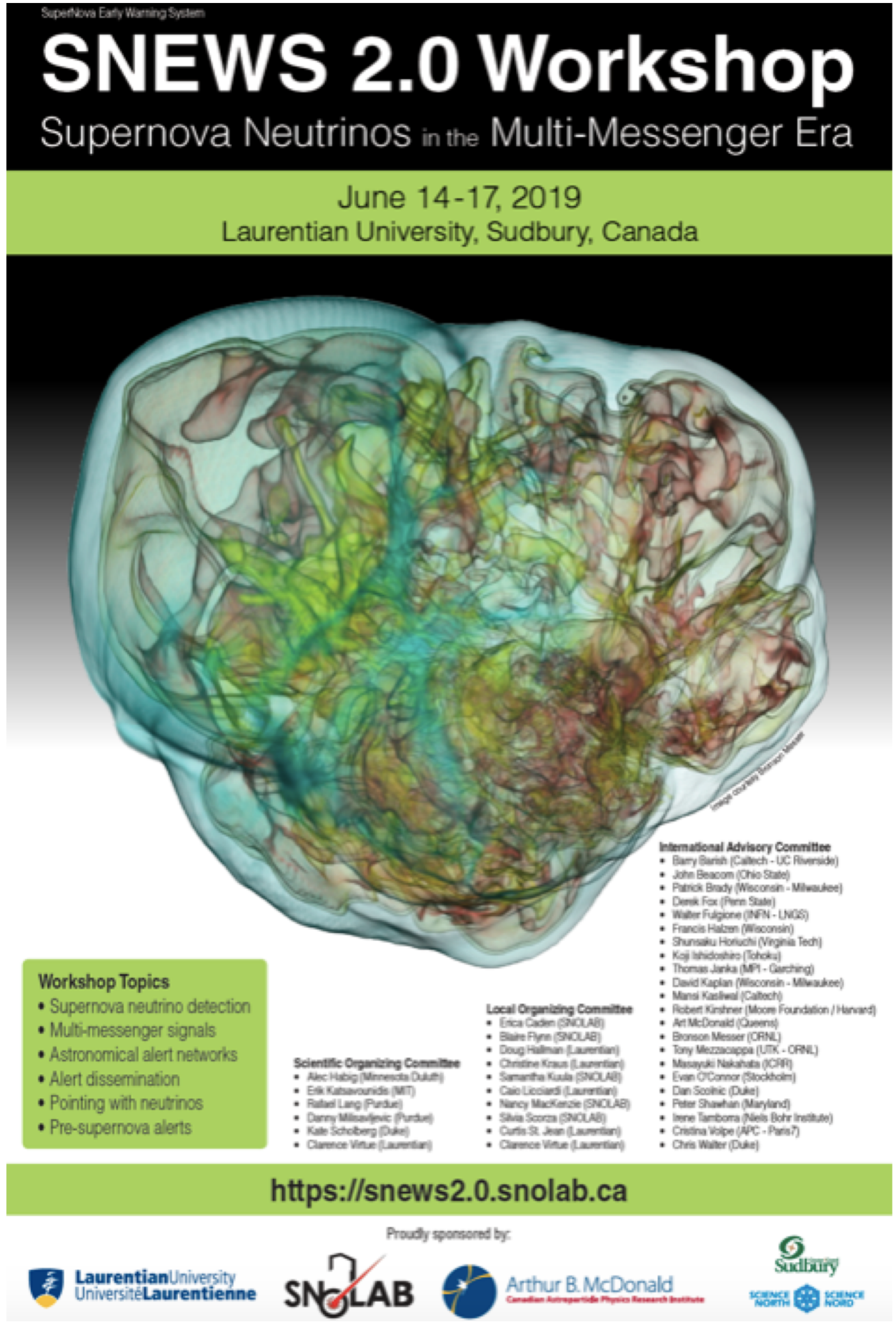
SNEWS: SuperNova Early Warning System

snews.bnl.gov



It's time to upgrade!

- pointing
- presupernova
- multimessenger



Summary

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

- Info in energy, flavor, time structure
- Detectors worldwide have ~Galactic+ sensitivity

Expanding our palate

- now sensitive mainly to the ν_e-bar component of the SN flux
- next generation: ν_e from DUNE,
  NC from CEvNS

(and we should explore subdominant channels)

Future:

- we need to understand how to infer truth fluxes!
- we need to measure some x-scns!
- the early alert will be upgraded in the era of multimessenger astronomy!