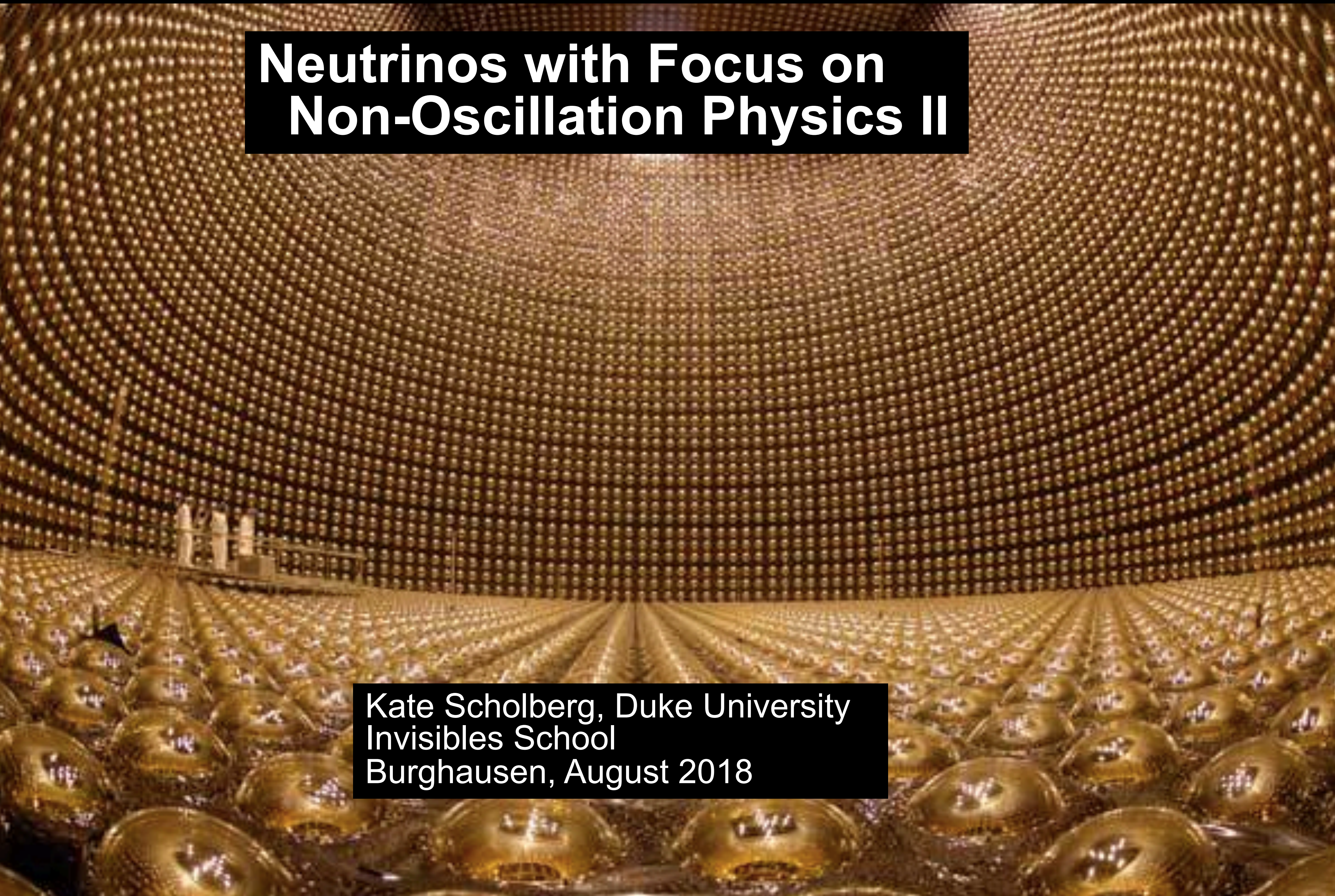
Neutrinos with Focus on Non-Oscillation Physics II



Kate Scholberg, Duke University
Invisibles School
Burghausen, August 2018

Lecture Overview

- Neutrino overview
  - Physics & astrophysics
  - A bit on neutrino oscillations
- Neutrino interactions with matter
  - Neutrino-nucleus cross sections at ~GeV energies
  - Neutrino-nucleus interactions at ~10-MeV energies

  two examples

  Lecture 1

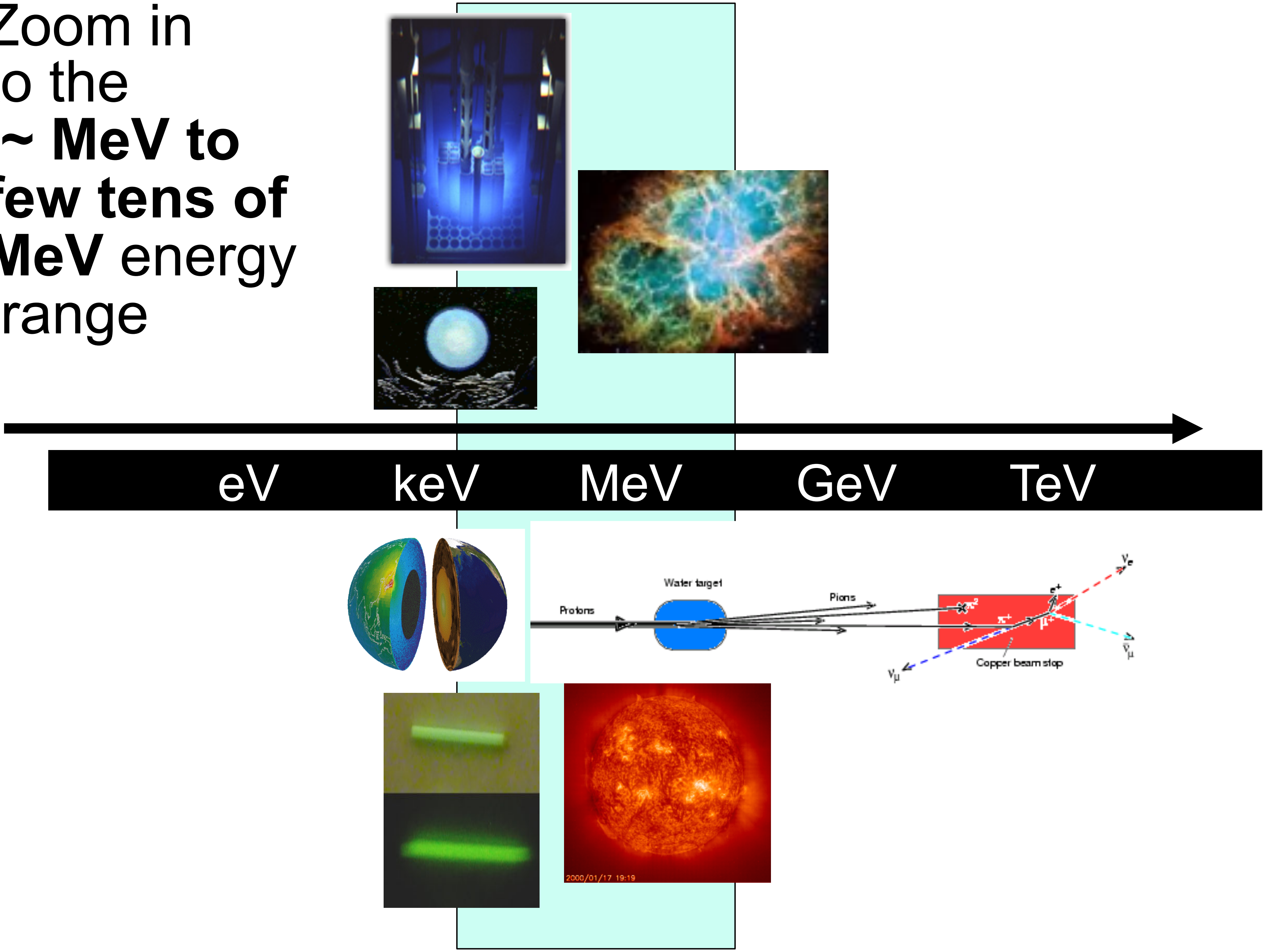
- Neutrinos from core-collapse supernovae

  Lecture 2

- Neutrino mass and the nature of the neutrino

  Lecture 3

Zoom in
to the
~ MeV to few tens of MeV energy
range



Physics/astrophysics of interest in this energy range (few to few tens of MeV)

Supernova neutrinos: burst and "relic"

Solar neutrinos

Geoneutrinos

Reactor neutrinos

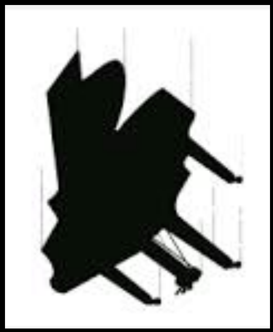
Radioactive sources

Stopped-pion neutrinos

I'll talk about supernova neutrinos, but much is relevant for other sources

Neutrinos from core collapse

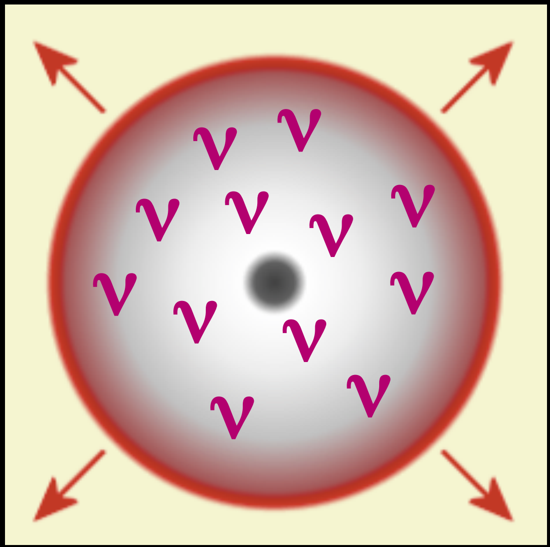
Just as gravitational potential energy turns into kinetic (and thermal) energy when an object falls,



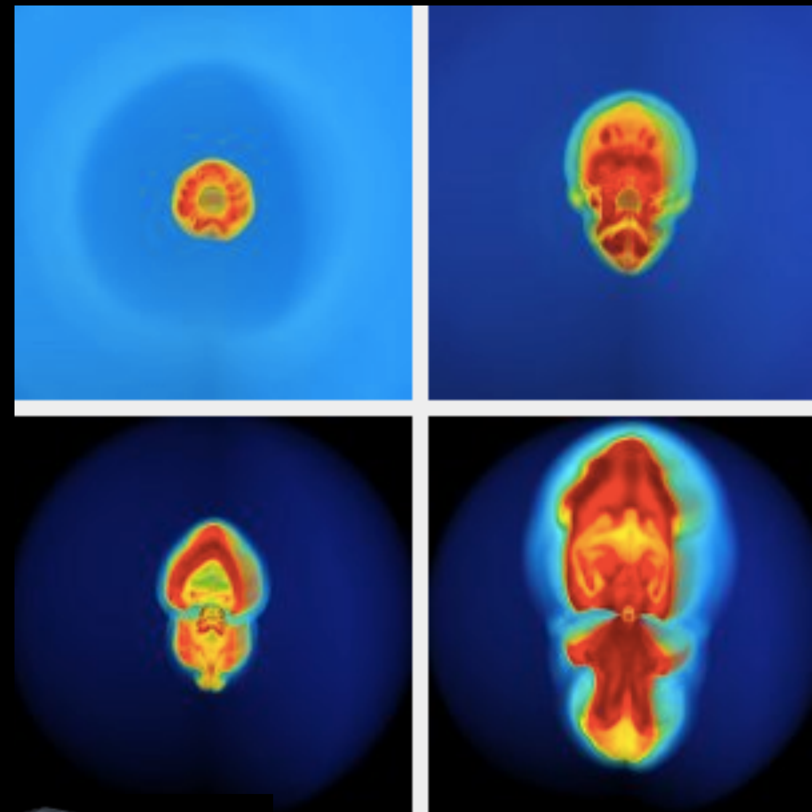
.... as the star falls inward, the gravitational energy *must go somewhere*...

The energy *can* escape via neutrinos, thanks to the weakness of the neutrino interactions

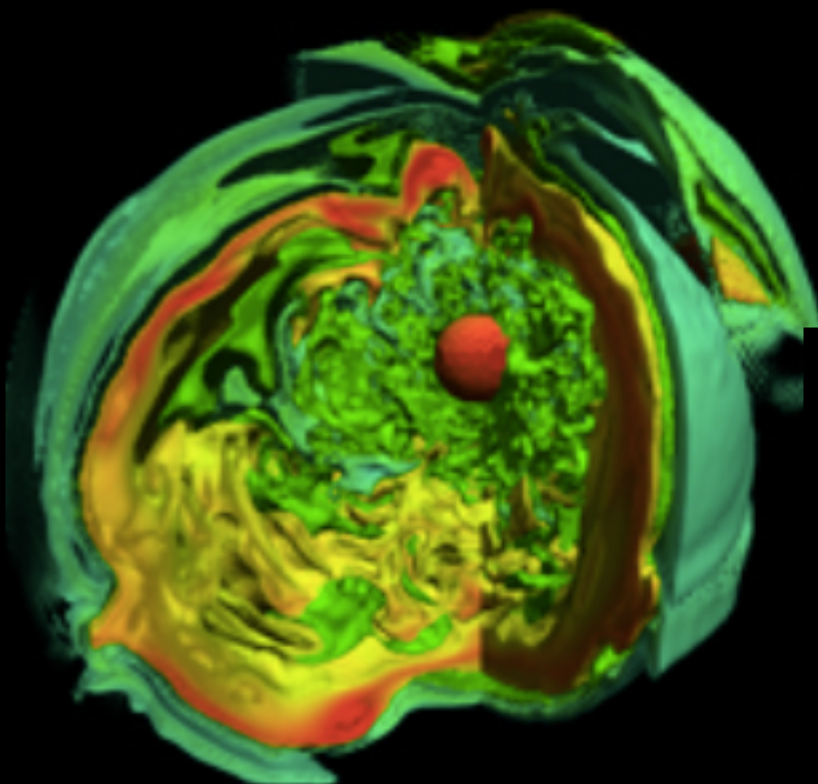
~99% of the vast binding energy of the proto-neutron star is shed within ~10 seconds in the form of *neutrinos and antineutrinos of all flavors*



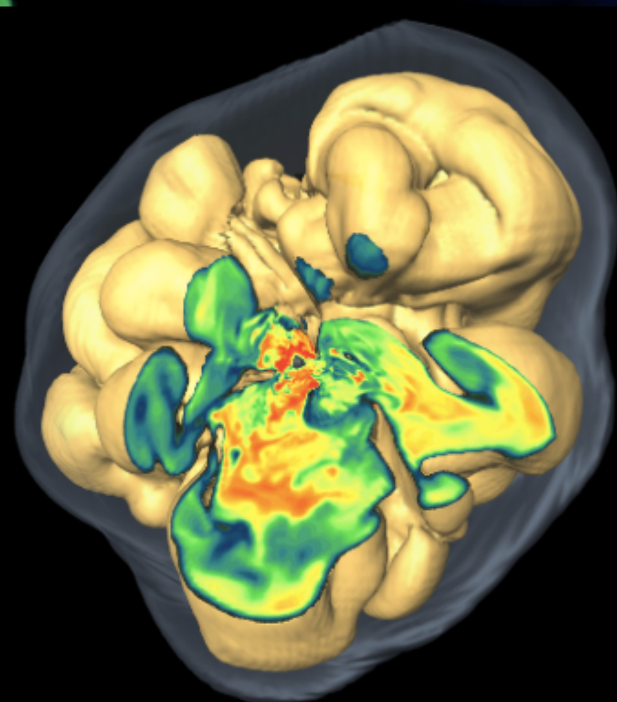
The core-collapse supernova explosion is still not well understood... numerical study ongoing



Marek & Janka



Blondin, Mezzacappa, DeMarino



Neutrinos are intimately involved

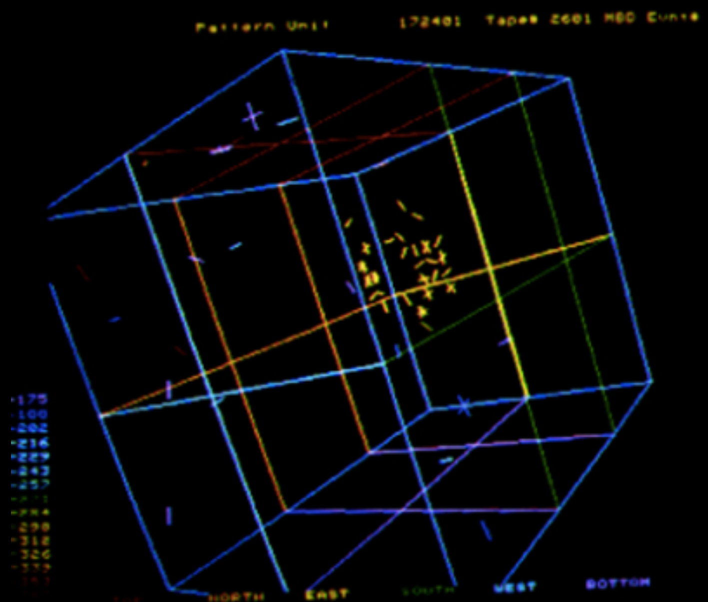
Jargon alert!

In particle physics,
an “event” is *not* this...

$\sim 10^{52\text{-}53}$ ergs

It’s an individual *recorded neutrino interaction*:

few times
10^{-5} ergs

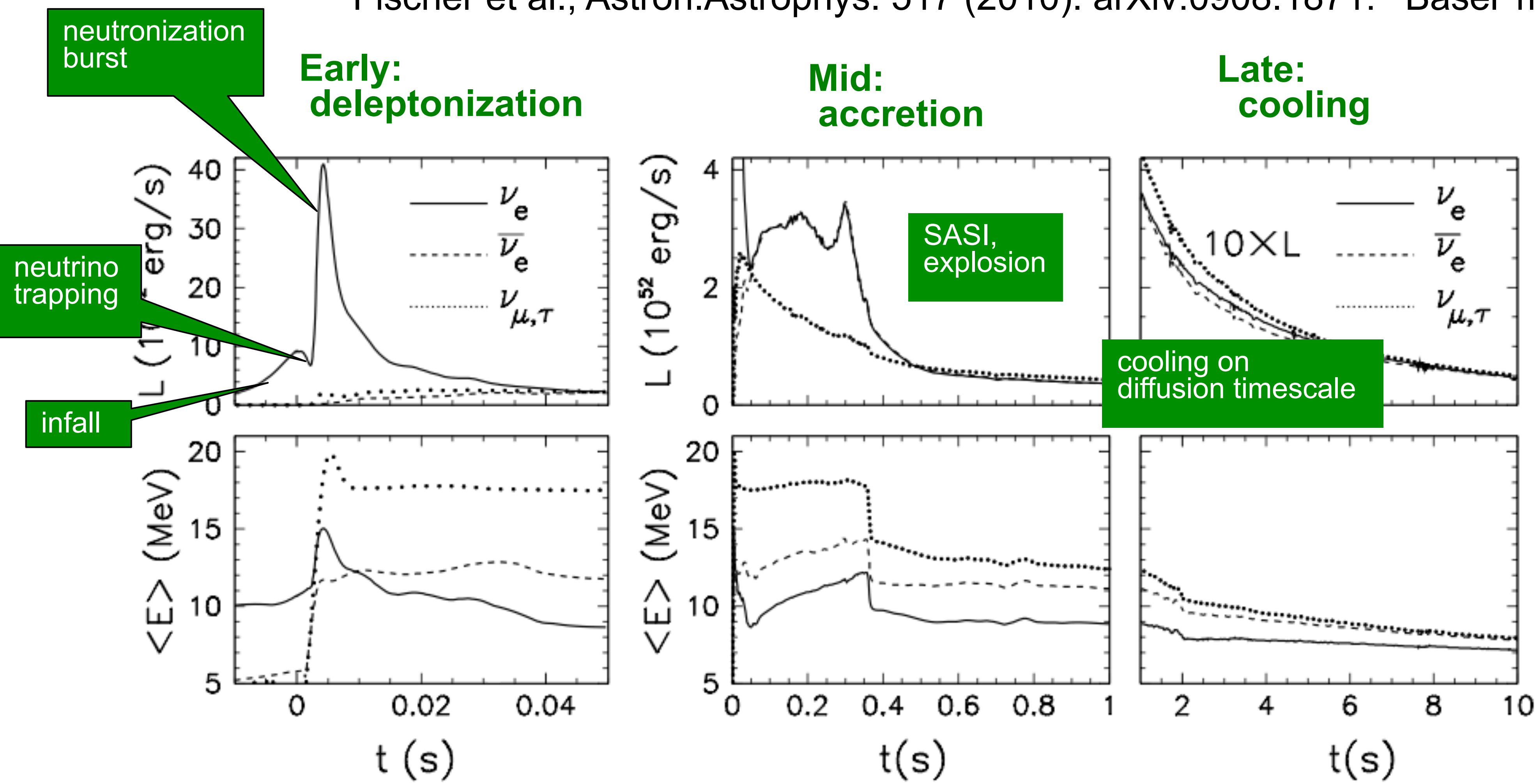


e.g., “the IMB neutrino detector saw 8 events from 1987A”

Expected neutrino luminosity and average energy vs time

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

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



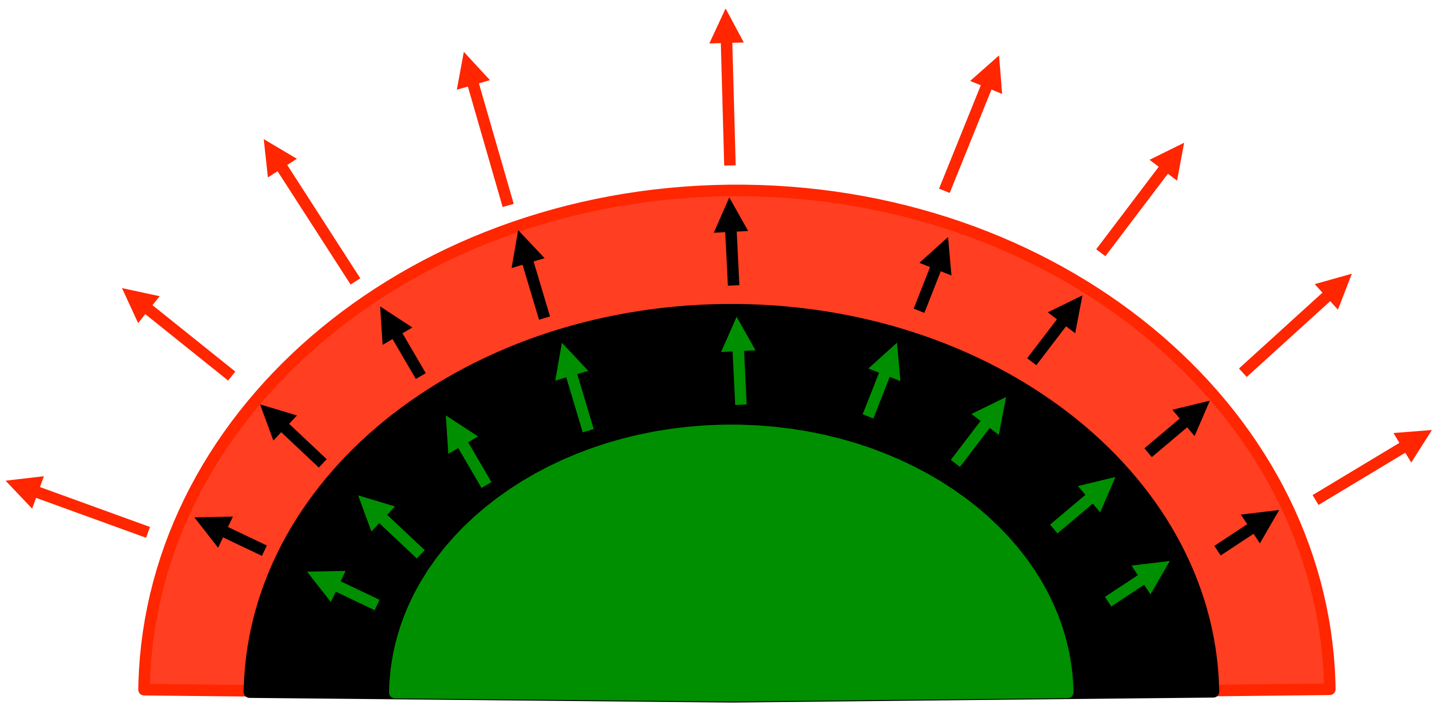
Generic feature:
(may or may not be robust)

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

Nominal expected flavor-energy hierarchy

Fewer interactions
w/ proto-nstar
⇒ deeper ν-sphere
⇒ hotter ν's

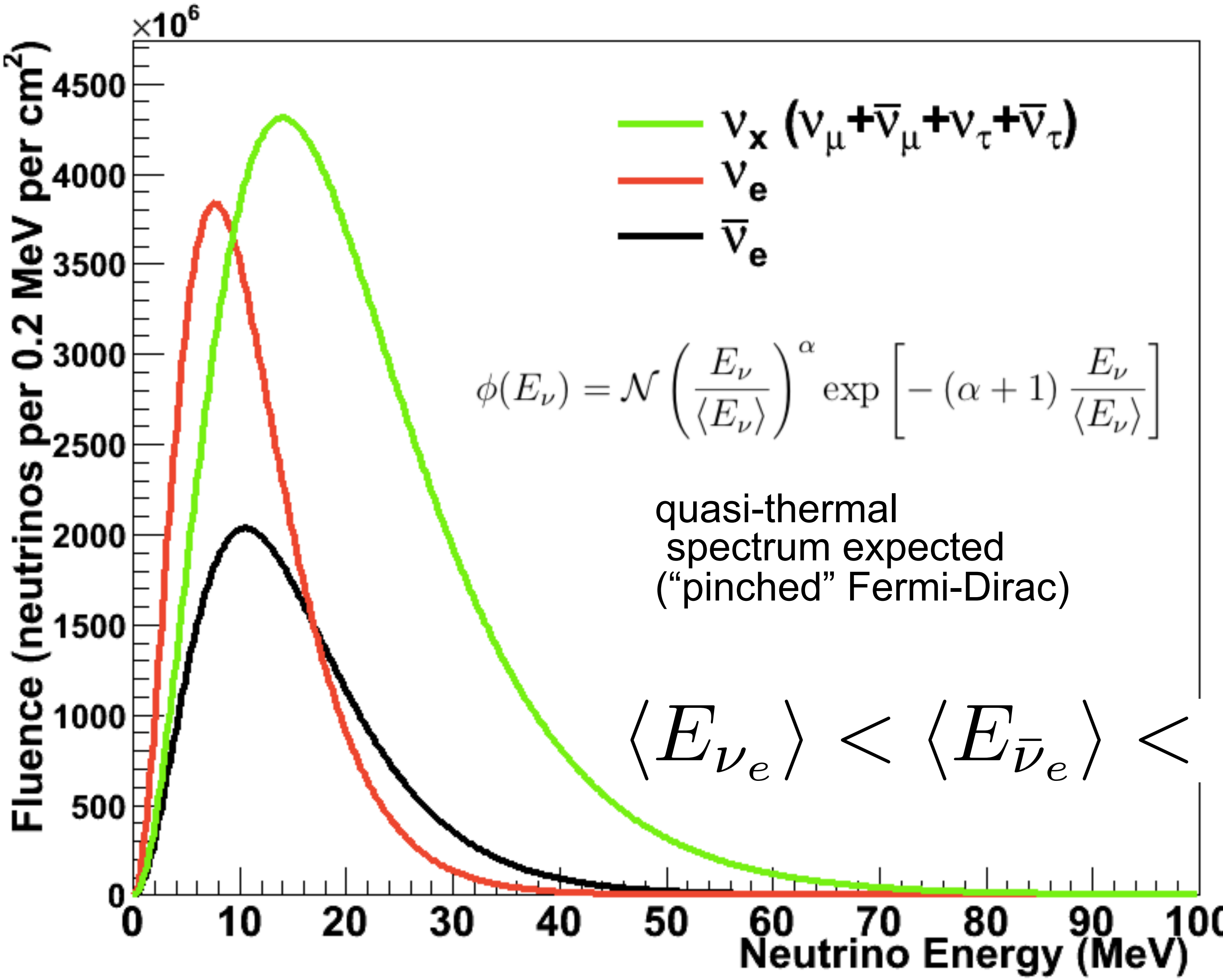
$\langle E\nu_e \rangle \sim$ 12 MeV
$\langle E\bar{\nu}_e \rangle \sim$ 15 MeV
$\langle E\overset{(--)}{\nu}_{\mu,\tau} \rangle \sim$ 18 MeV



May or may not be robust...

Neutrino flavor oscillations (governed by fundamental neutrino parameters) will modify the spectra

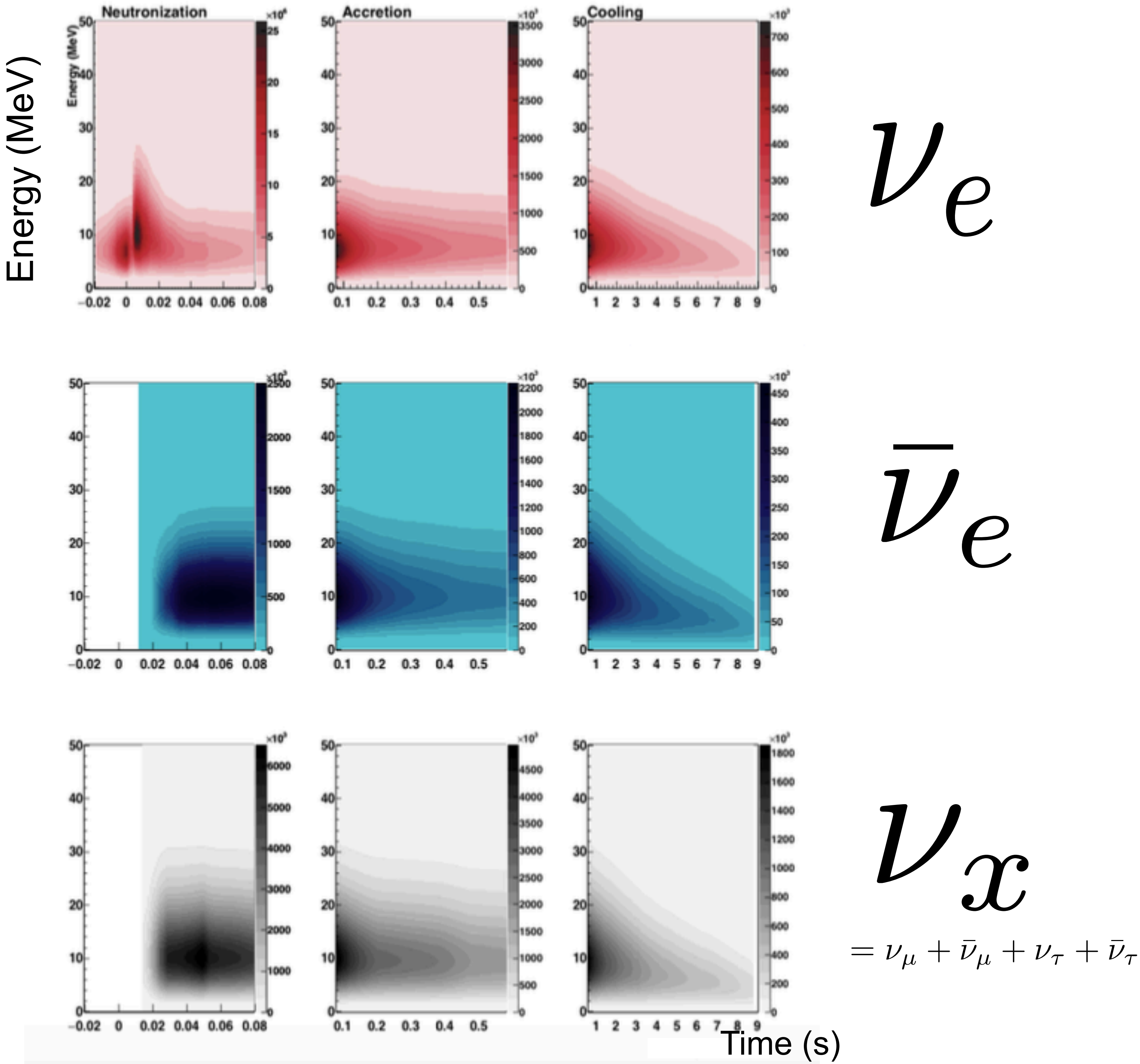
Neutrino spectrum from core collapse



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

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

Fluxes as a function of time and energy

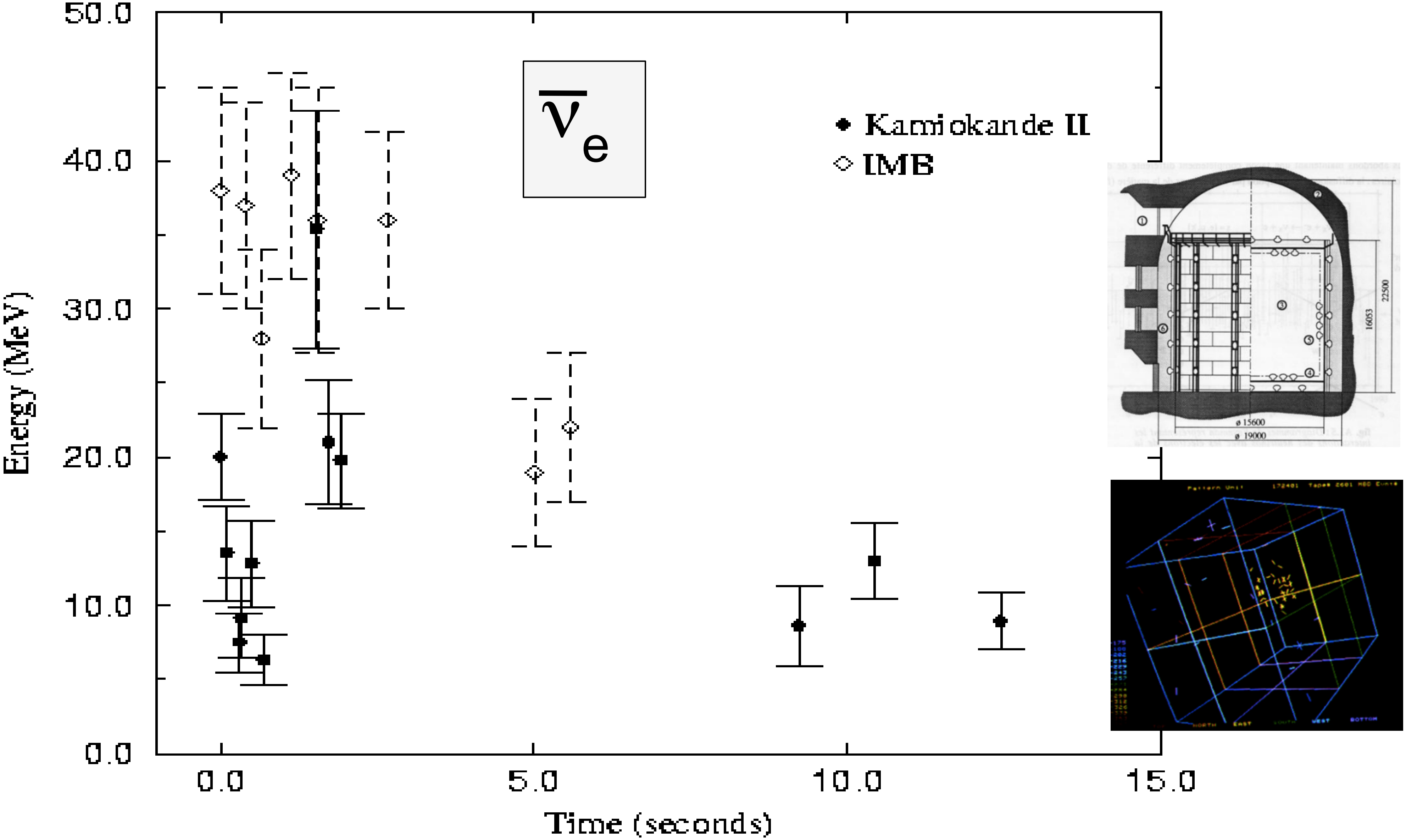


Supernova 1987A
in the Large Magellanic Cloud (55 kpc away)

~two dozen neutrino interactions observed!

SN1987A in LMC

ν's seen ~2.5 hours before first light



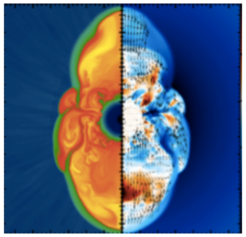
Confirmed baseline model... but still many questions

Some colleagues singing Happy Birthday to a supernova

Image: Hank Sobel

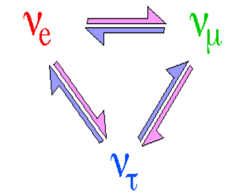
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



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

input from neutrino experiments



NEUTRINO and OTHER PARTICLE PHYSICS

from flavor, energy, time structure of burst

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

input from photon (GW) observations

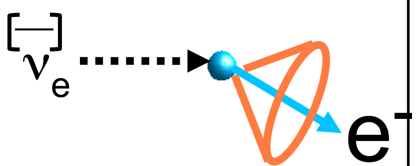
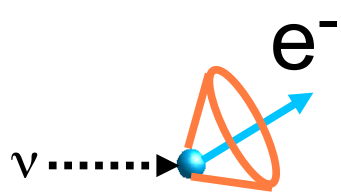
+ EARLY ALERT

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

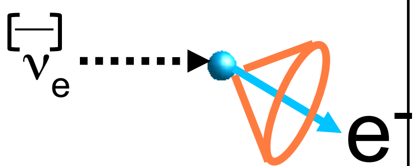
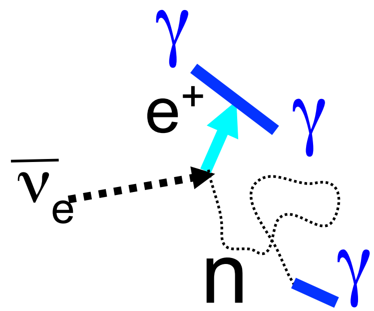
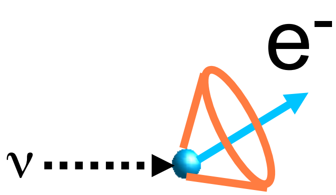
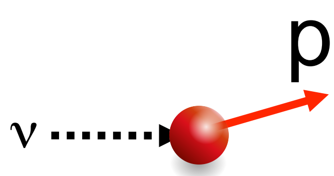
Size	~kton detector mass per 100 events @ 10 kpc
Low energy threshold	~Few MeV if possible
Energy resolution	Resolve features in spectrum
Angular resolution	Point to the supernova! (for directional interactions)
Timing resolution	Follow the time evolution
Low background	BG rate << rate in burst; underground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

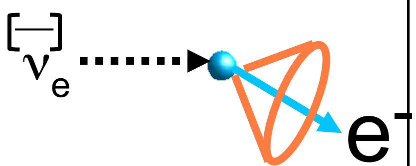
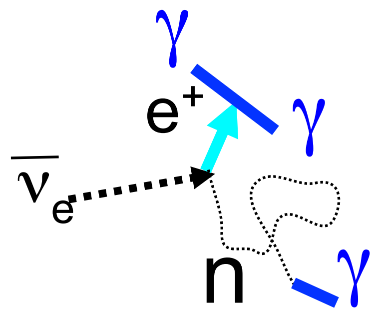
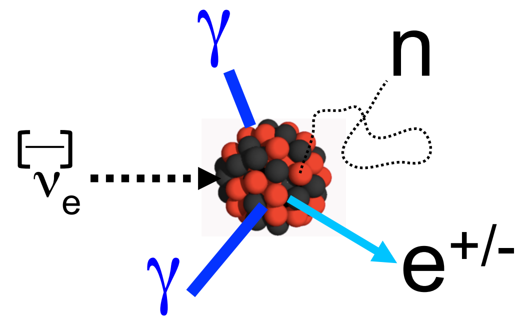
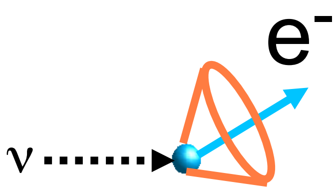
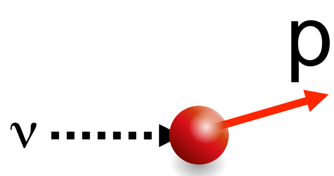
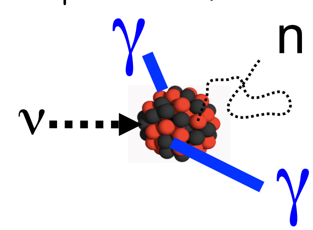
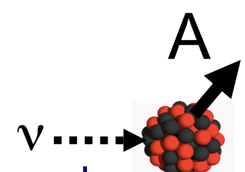
Neutrino interactions in the ~10 MeV range

	Electrons		
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 		
Neutral current	 Useful for pointing		

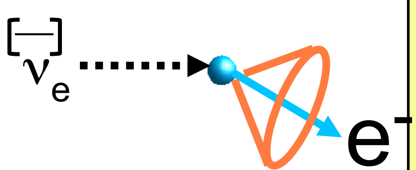
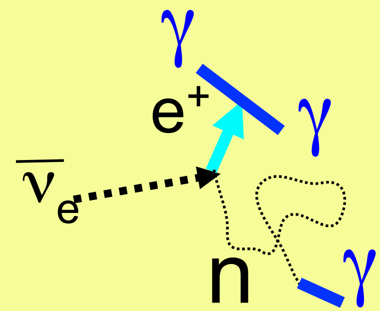
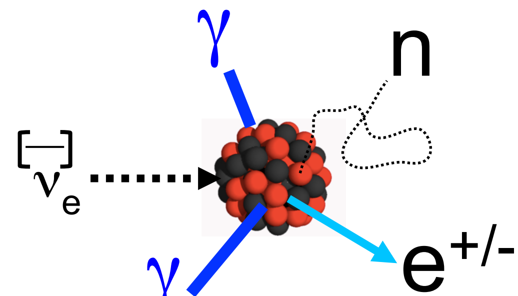
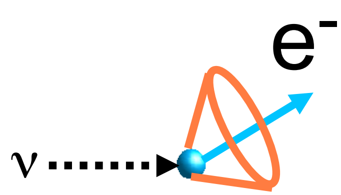
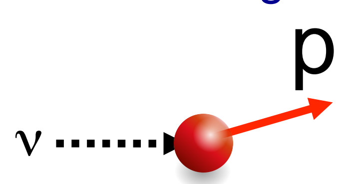
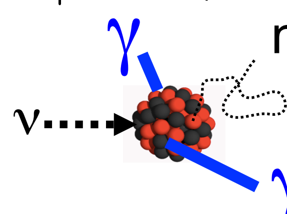
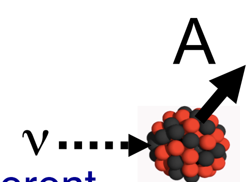
Neutrino interactions in the ~10 MeV range

	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	

Neutrino interactions in the ~10 MeV range

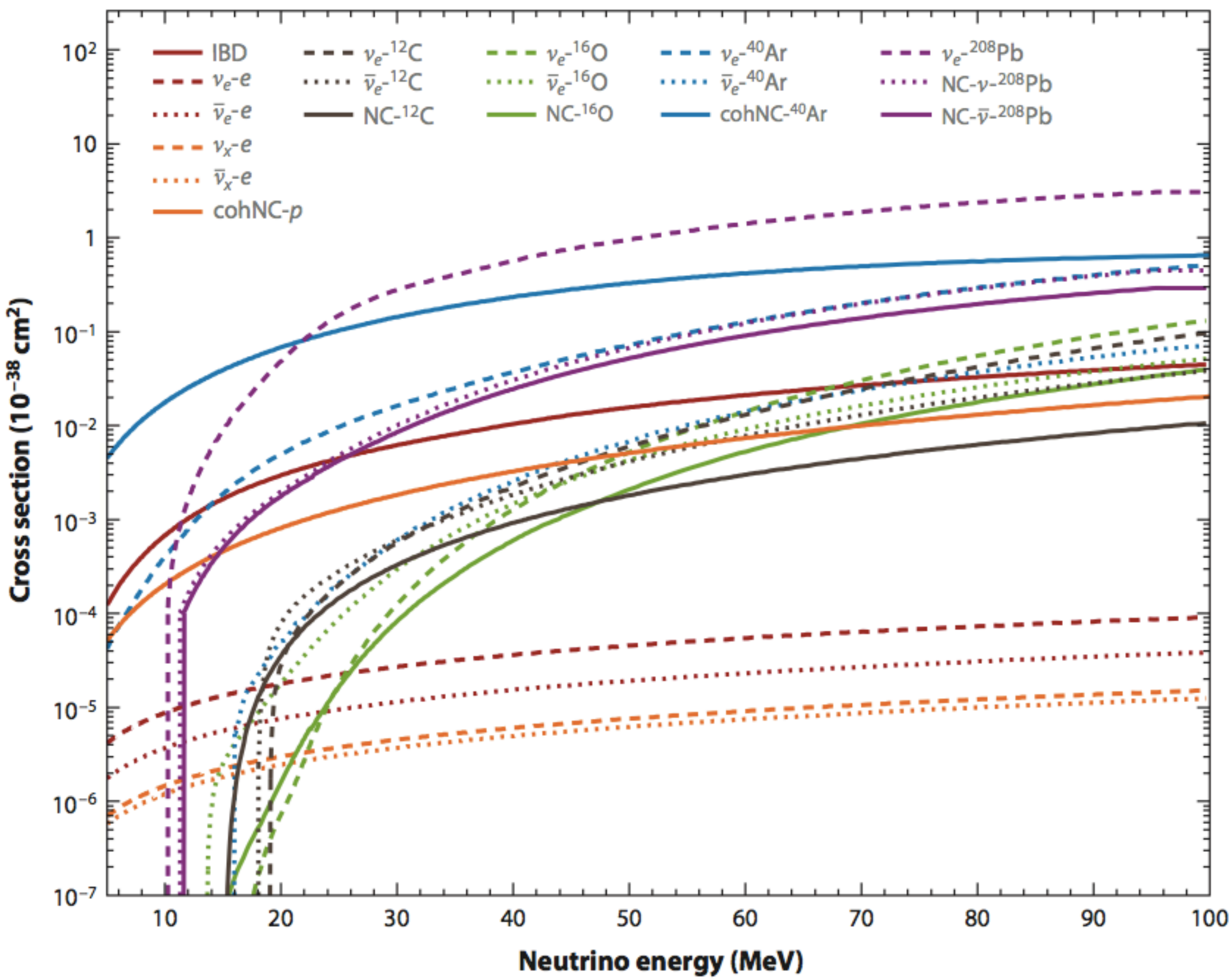
	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation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

Neutrino interactions in the ~10 MeV range

	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)

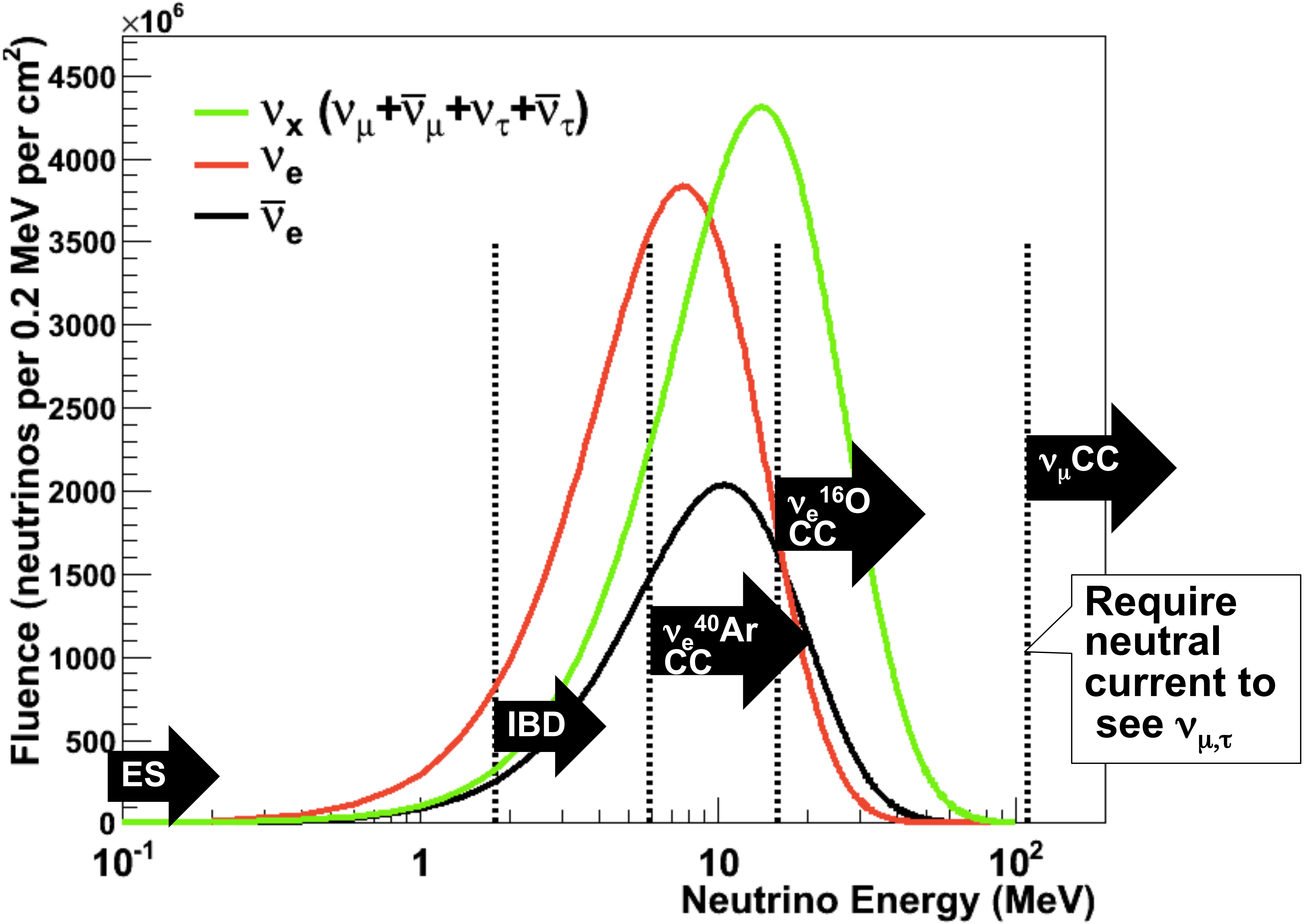
IBD (electron *anti*neutrinos) dominates for current detectors

Cross-sections in this energy range



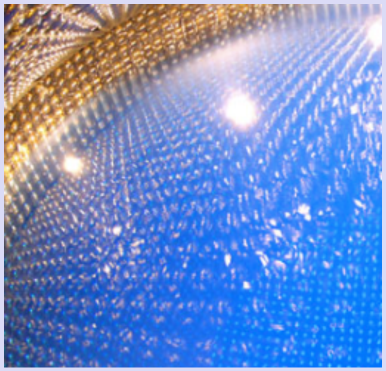
Of these, only IBD and ES on electrons well understood theoretically (or experimentally)...

Neutrino interaction thresholds

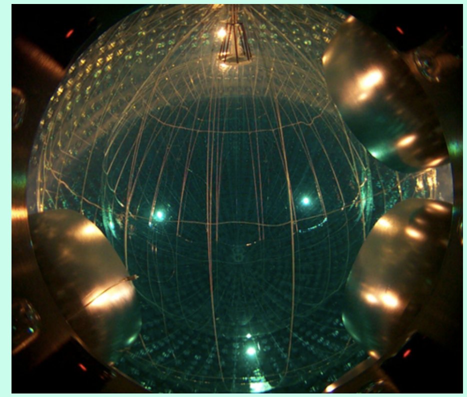


Current main supernova neutrino detector types

Water



Scintillator



Argon

Lead

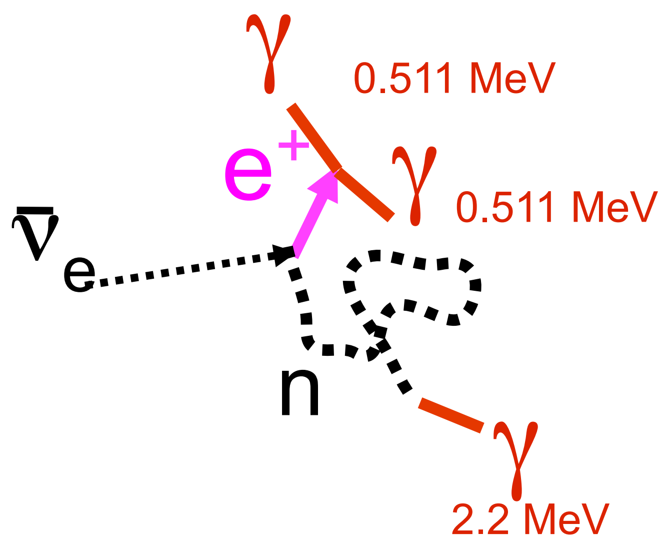
+ some others (e.g. DM detectors)

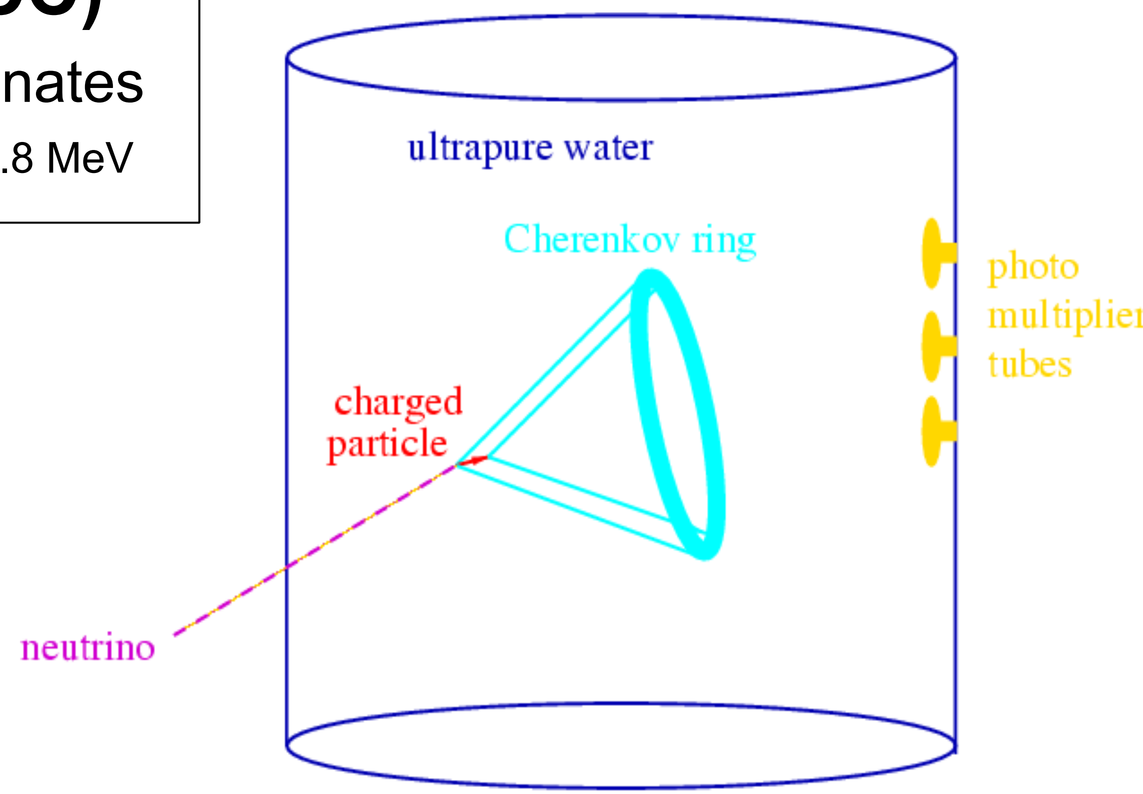
Water Cherenkov detectors

Inverse Beta Decay (CC)

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

E_{thr}=1.8 MeV

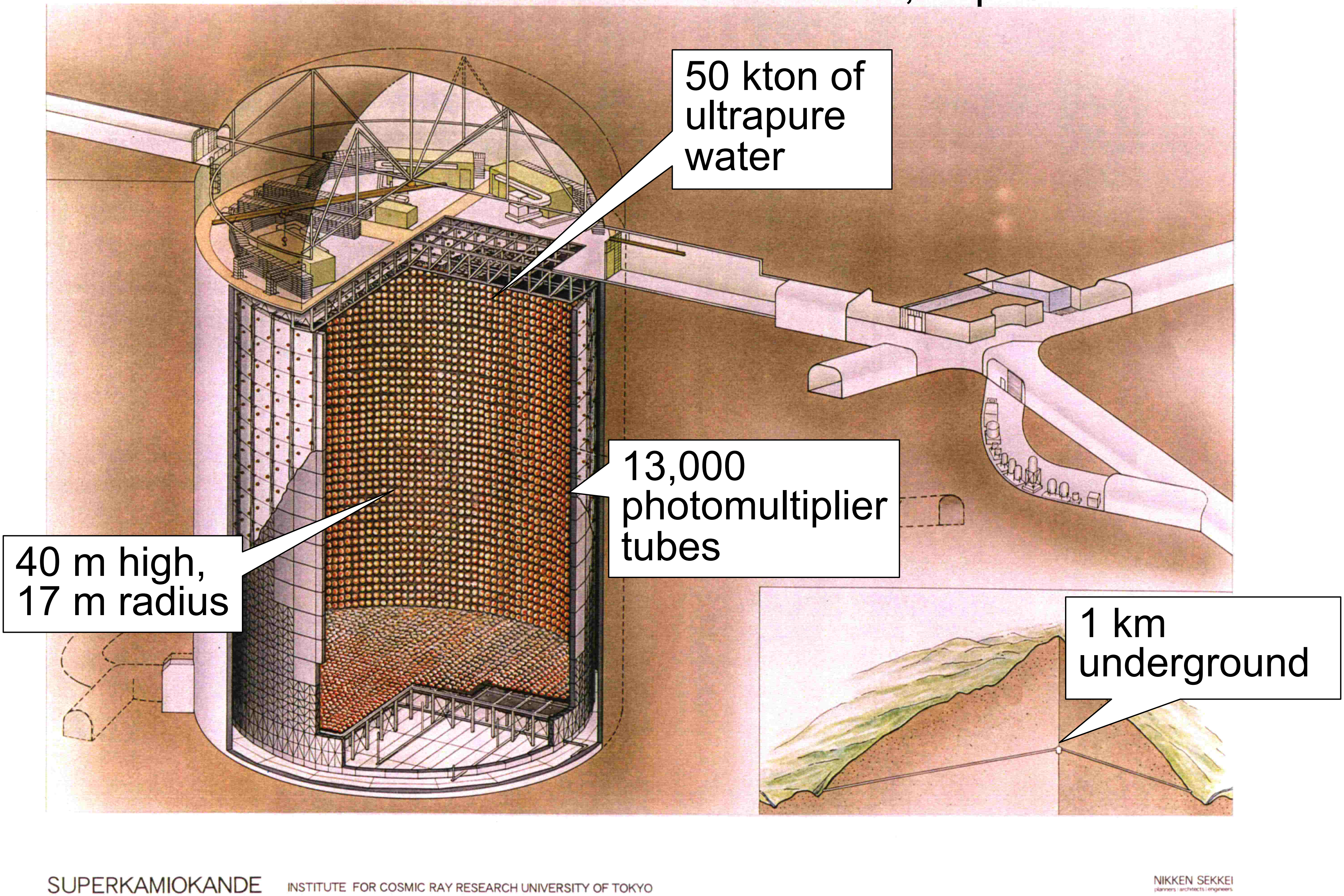




- See Cherenkov light from the positron (~positron is isotropic)
- Can't see 0.511 MeV γ's (why not?)
- More on neutron detection in a bit
- Limited by photocoverage (SK: ~40% ➔ ~6 pe/MeV)

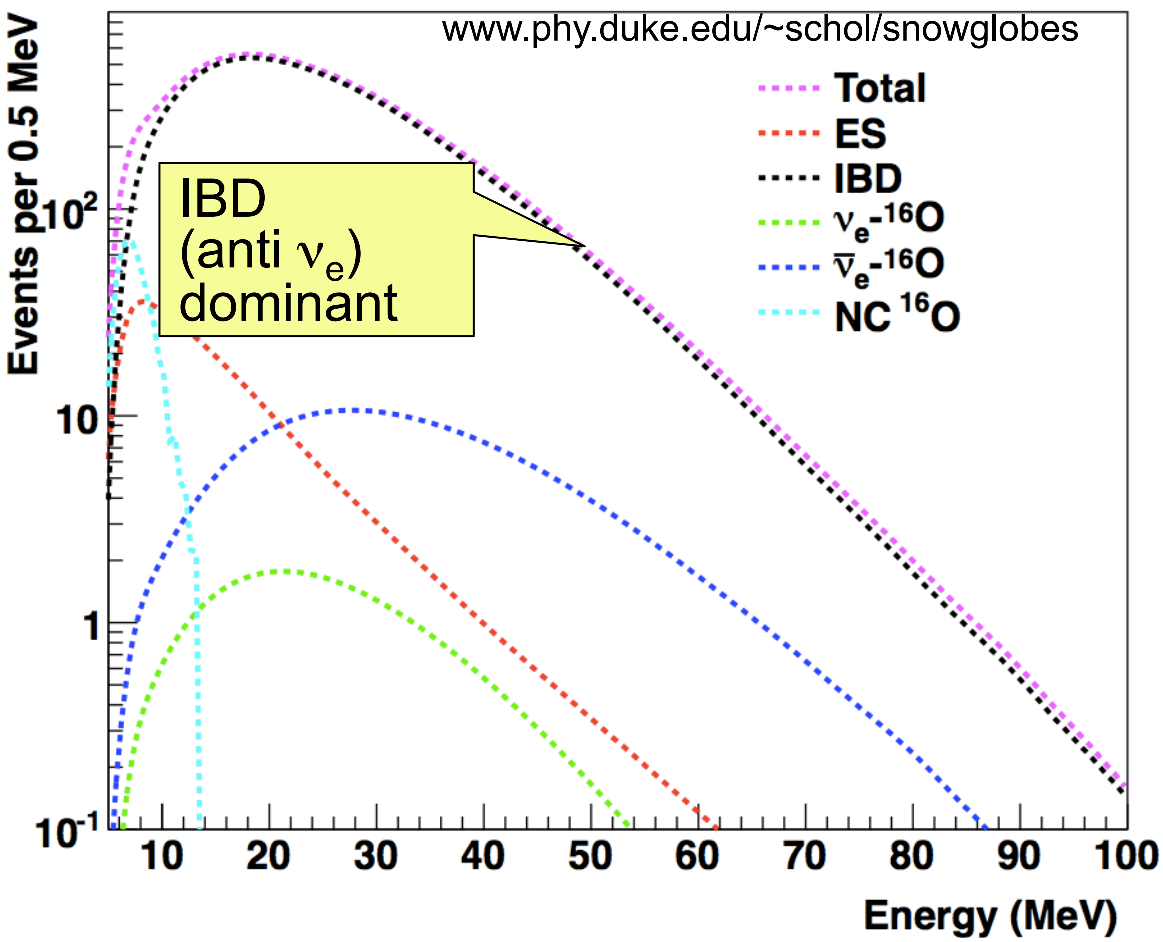
Super-Kamiokande

Water Cherenkov detector
in Mozumi, Japan

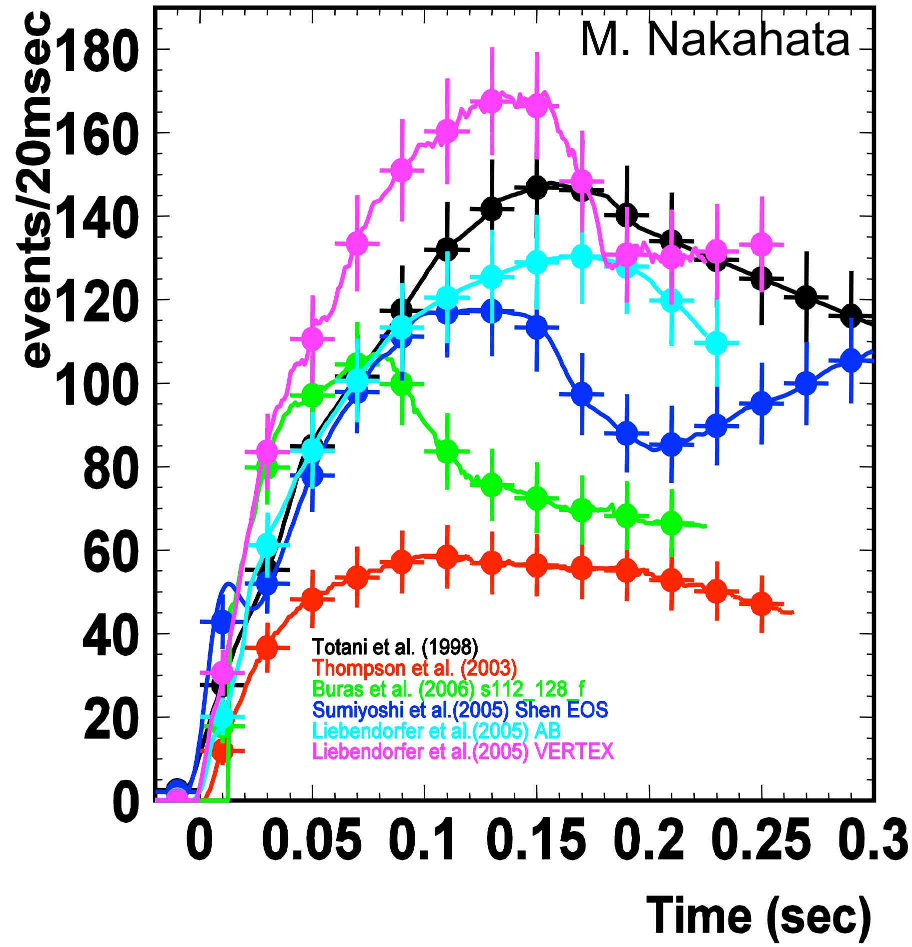


Supernova signal in a water Cherenkov detector

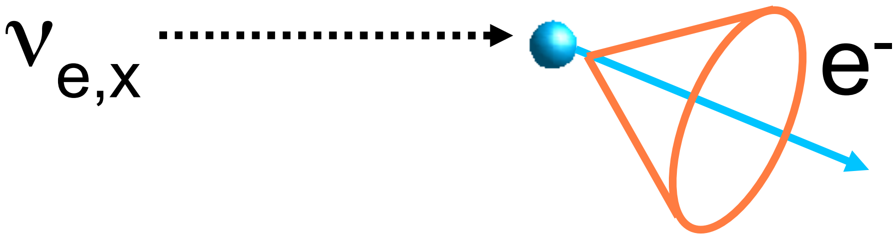
Events seen, as a function of observed energy



For 100 kton.
30% PMT coverage
@ 10 kpc

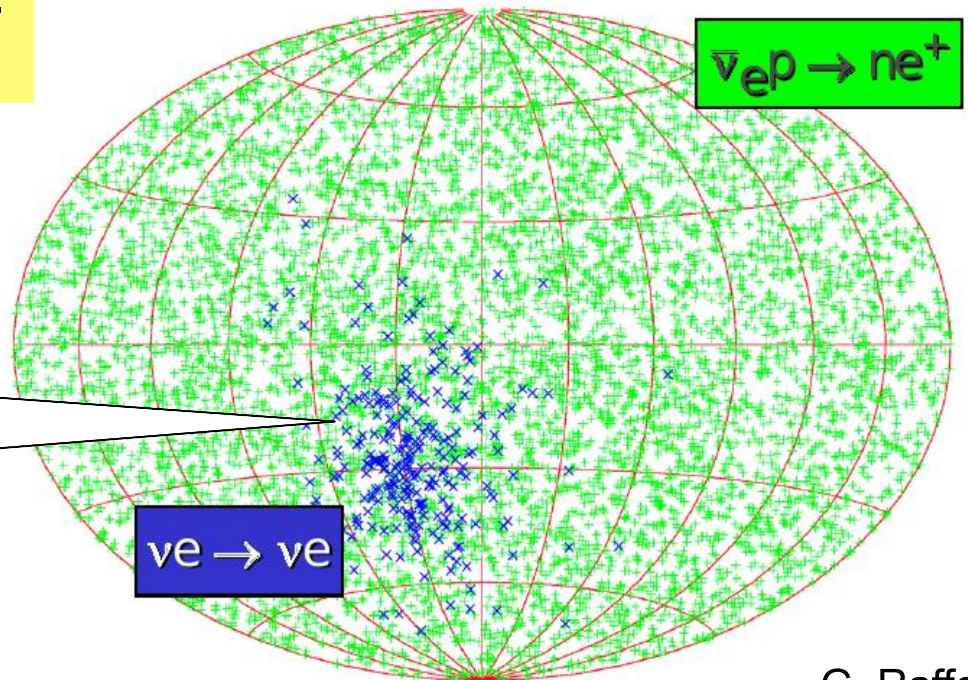


Events vs time
for SK, for
different models



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

Pointing from neutrino-electron elastic scattering

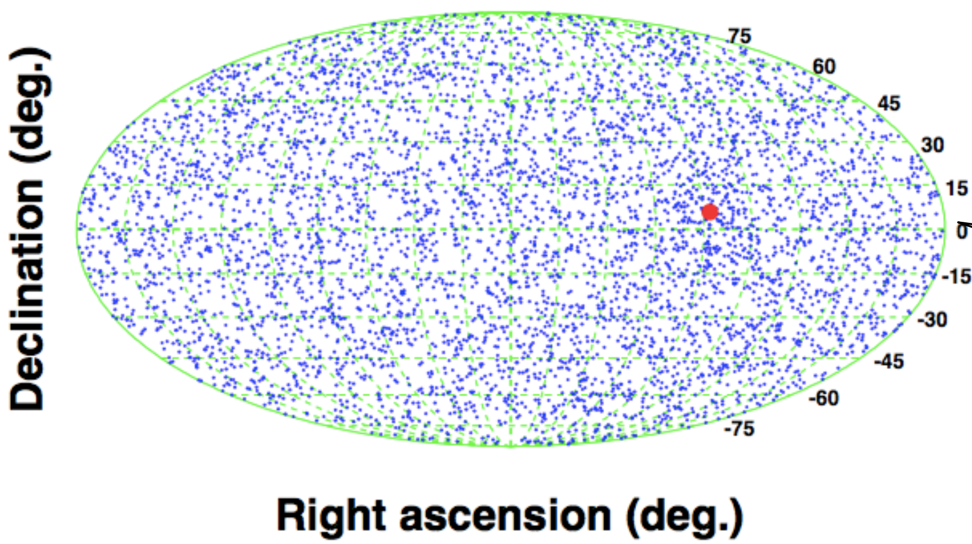


G. Raffelt

$$\delta(\theta) \sim \frac{30^\circ}{\sqrt{N}}$$

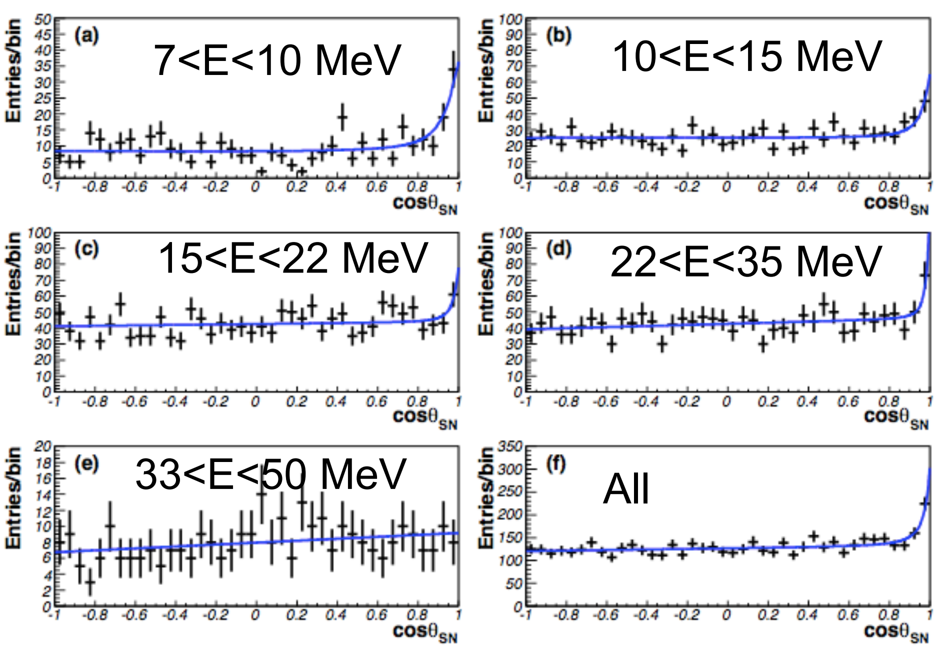
degraded by isotropic IBD

Pointing in Water Cherenkov: Super-K

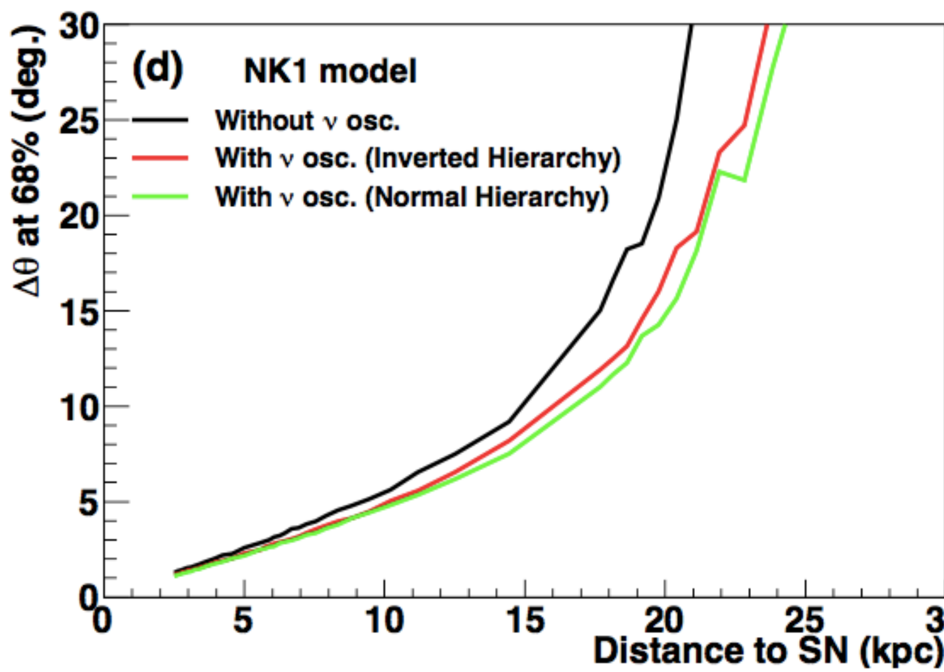


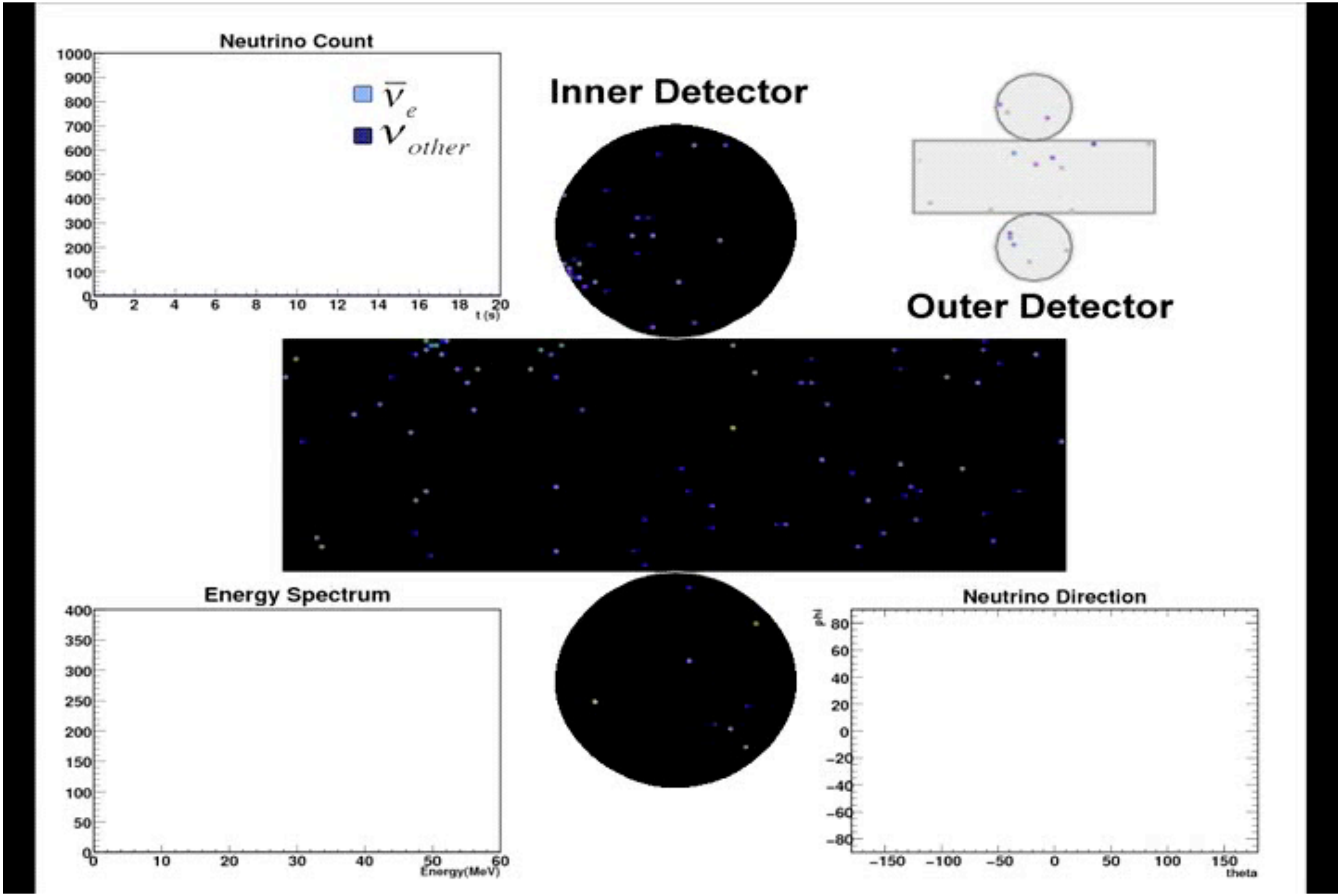
K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Harder when you don't have the interaction truth!



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





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

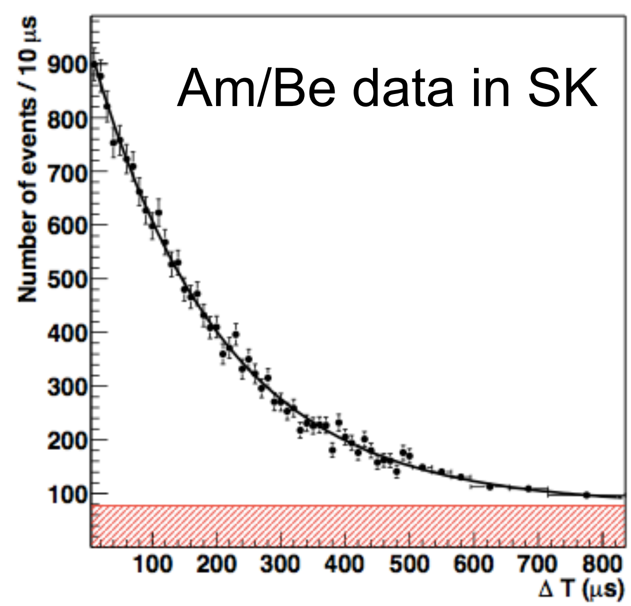
"Drug-free" neutron tagging

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

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

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

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

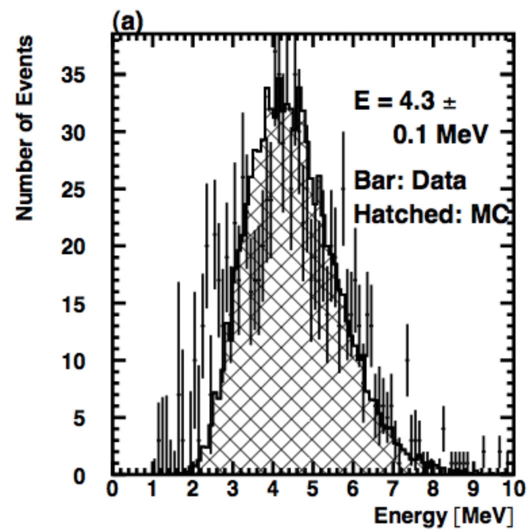
use gadolinium to capture neutrons (like for scintillator)

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

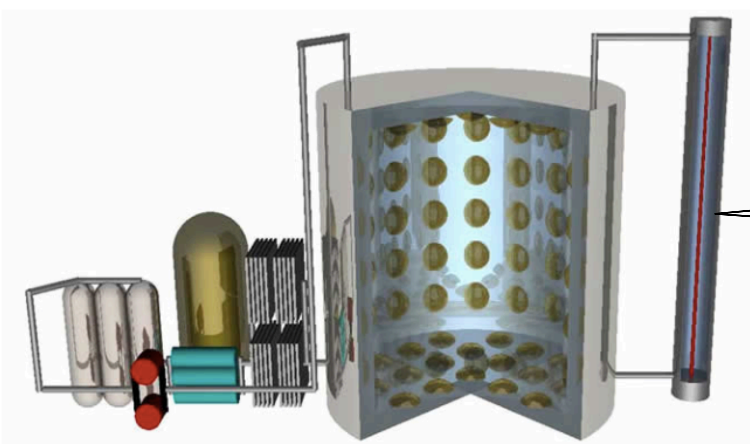
Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

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

About 4 MeV visible energy per capture



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

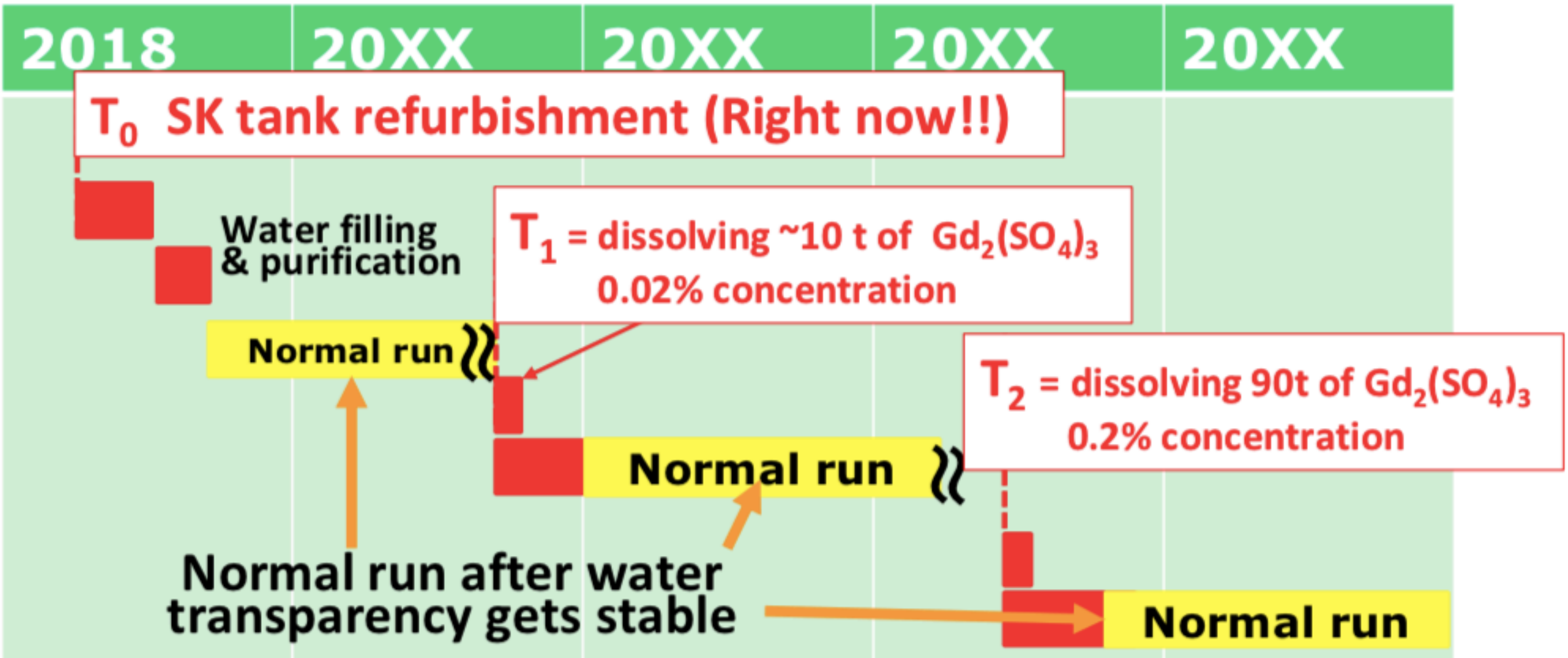


EGADS: test tank in the Kamioka mine for R&D

SK-Gd going ahead, starting this summer

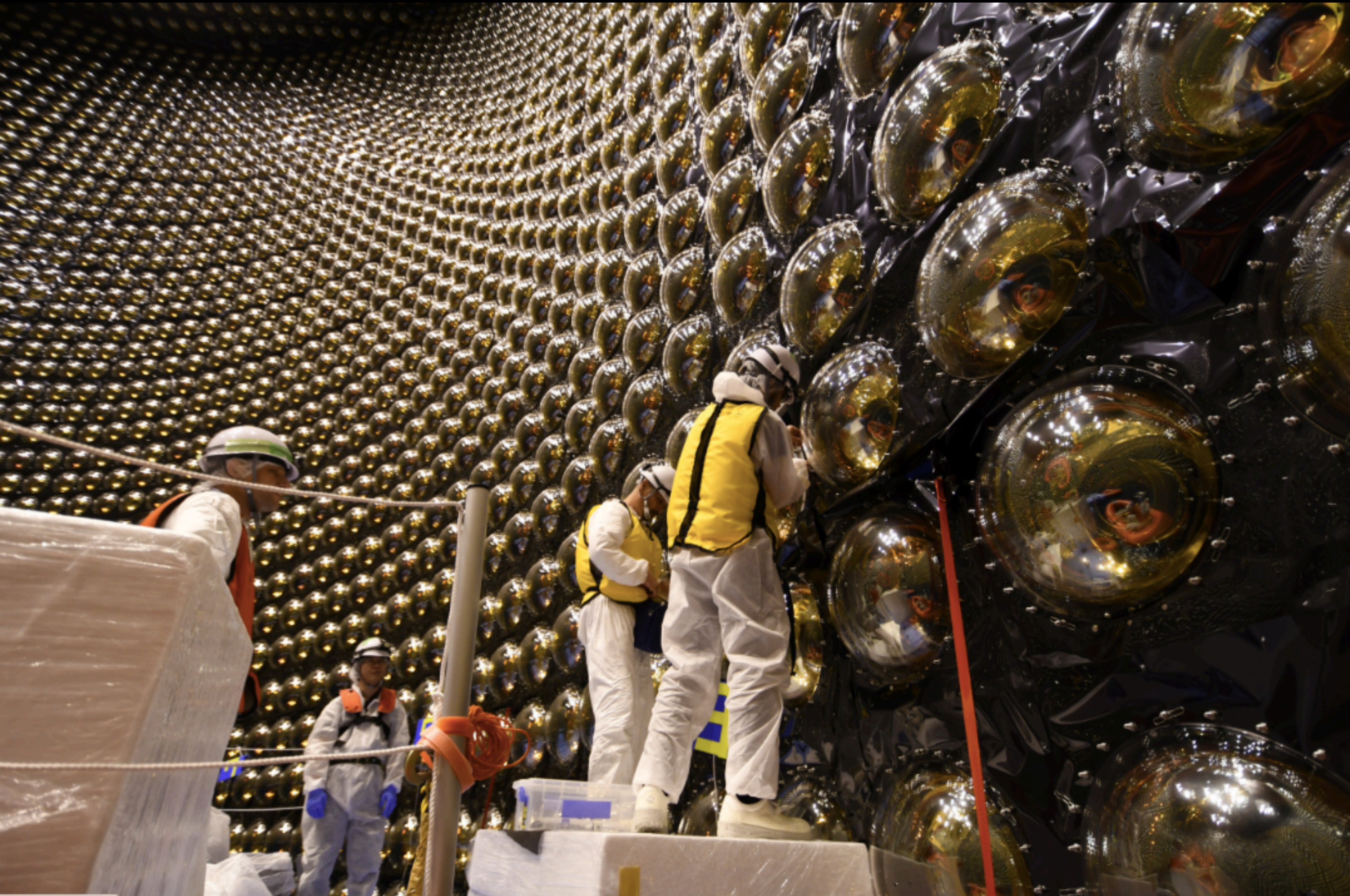
SK-Gd schedule

- Detailed schedule planning is on-going taking into account T2K beam availability.
- Earliest possible Gd in Super-K would be in late 2019.



- T0: Start date the Super-K tank refurbishment (May 31,2018).
- T1: First Gd loading ; 0.02% of $Gd_2(SO_4)_3 8H_2O$ (~ 50% cap. Eff)
- T2: Final Gd loading; 0.2% of $Gd_2(SO_4)_3 8H_2O$

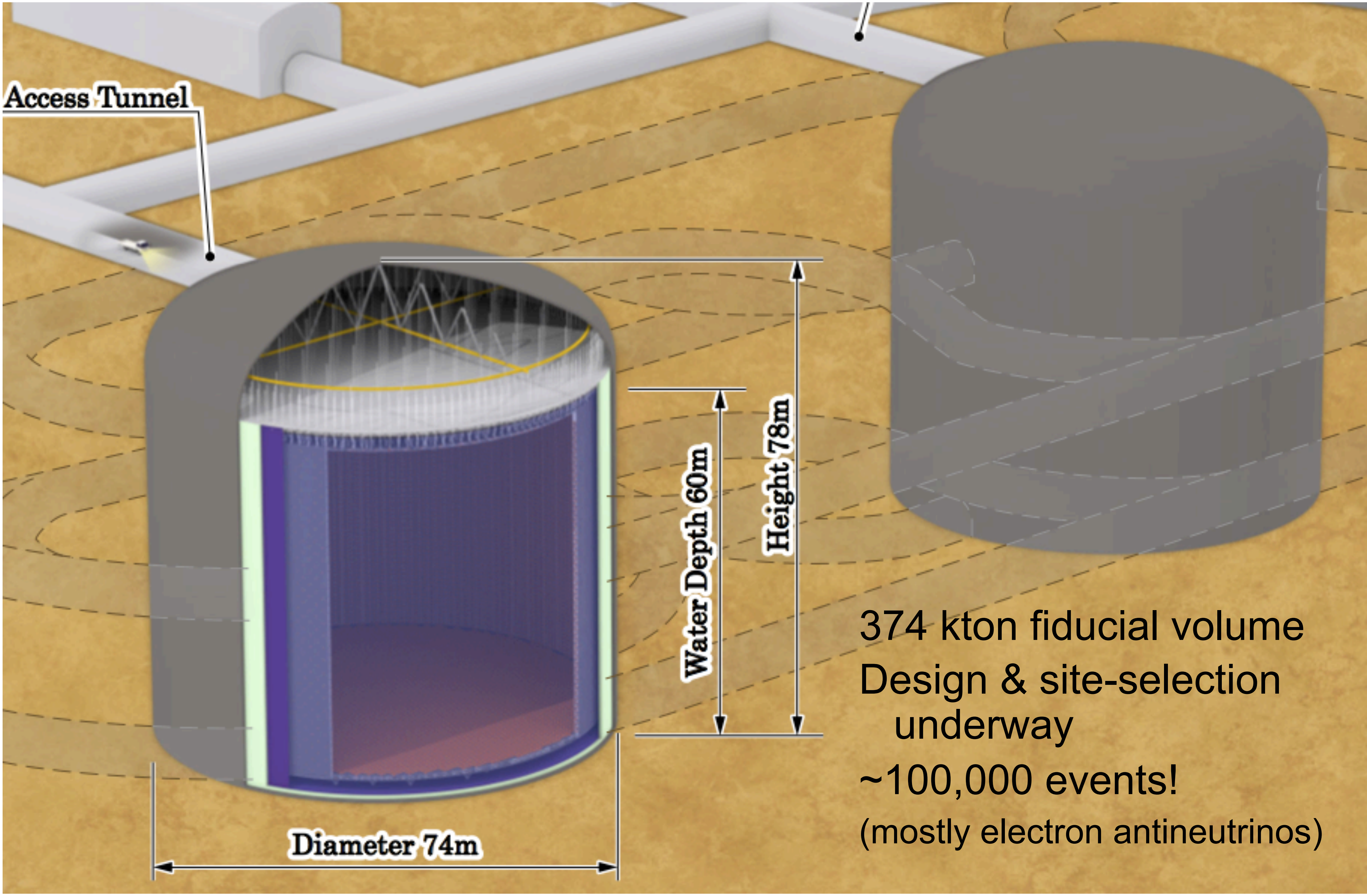
M. Ikeda, Neutrino 2018



No core collapses allowed for the next ~4 months!!

To progenitors of the Galaxy: you *must* hold it in!

Next generation: **Hyper-Kamiokande**



374 kton fiducial volume

Design & site-selection underway

~100,000 events!

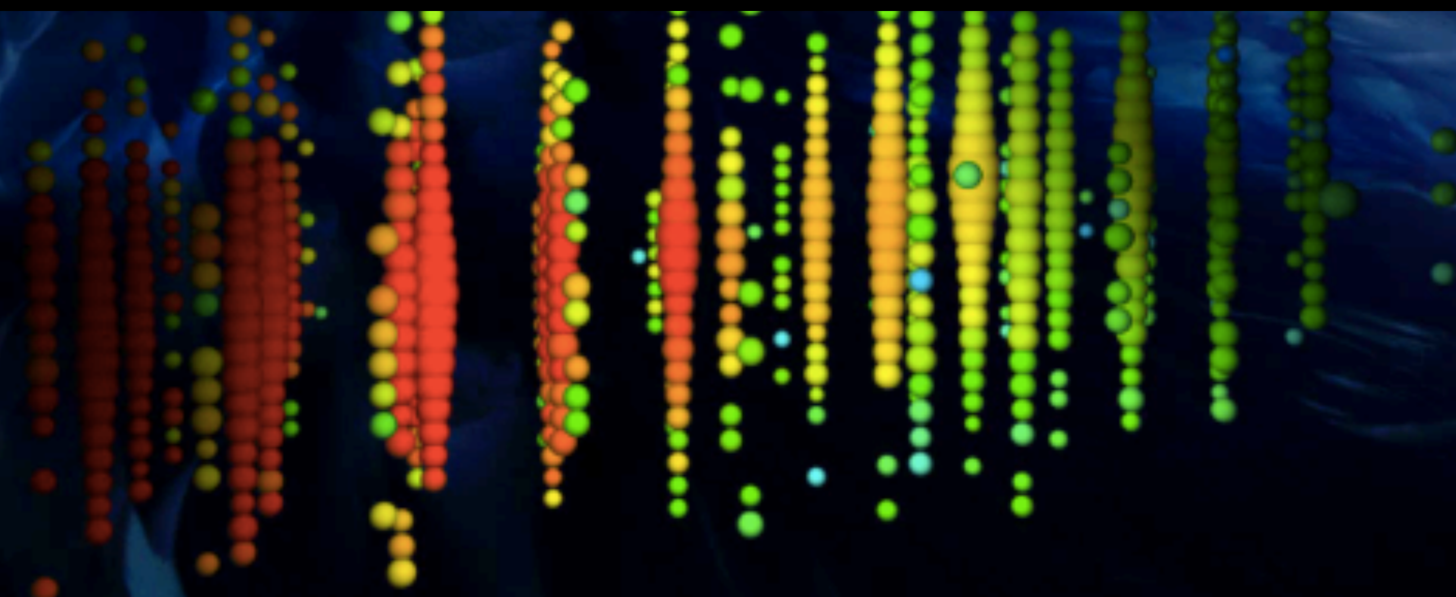
(mostly electron antineutrinos)

Long string water Cherenkov detectors

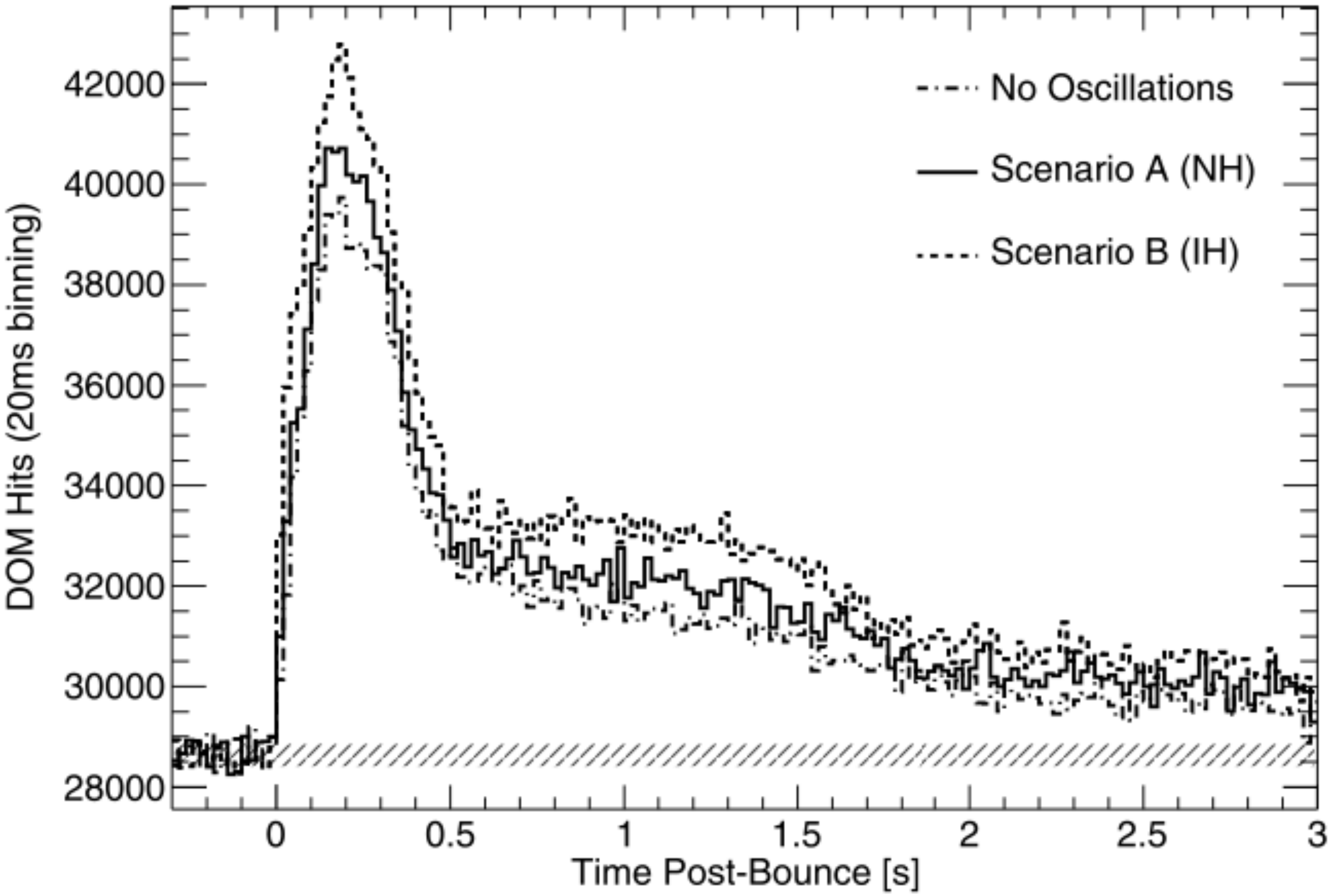
~kilometer long
strings of PMTs
in very clear water
or ice (IceCube, ANTARES)

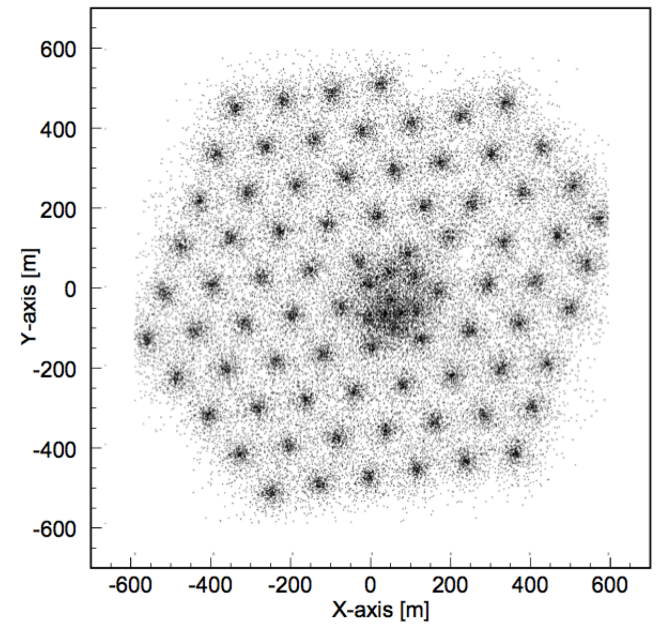
Nominally multi-GeV energy threshold...
but, may see burst of low energy (anti-) ν_e's as
coincident increase in single PMT count rate

Map overall time structure of burst by tracking
the single-PMT hit glow



Long string water Cherenkov detectors

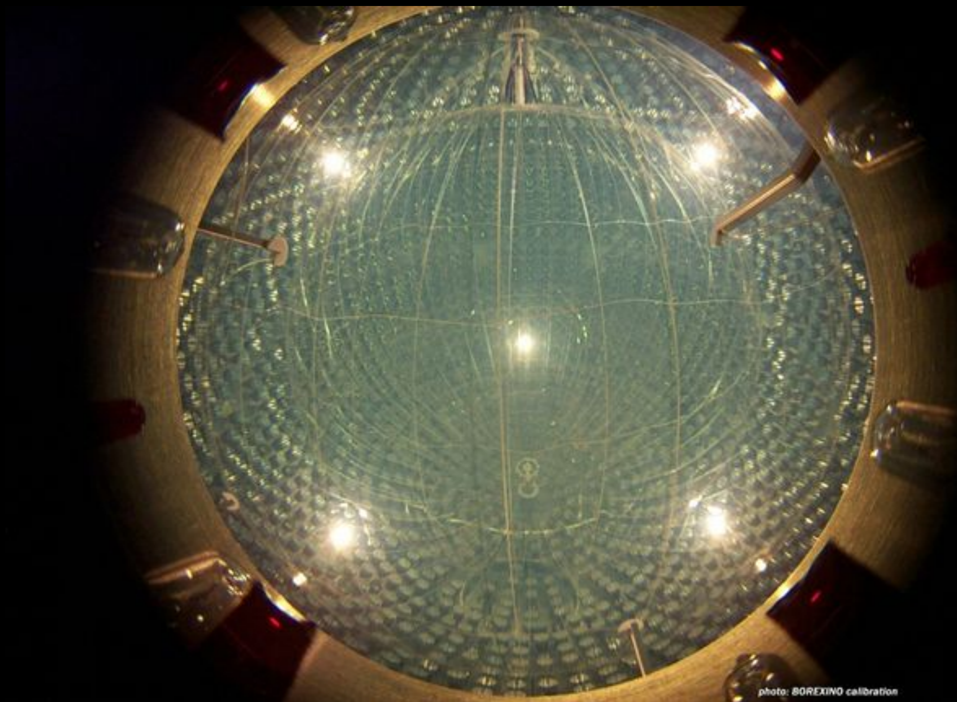




IceCube collaboration, A&A 535, A109 (2011)

Map overall time structure of burst

Scintillation detectors

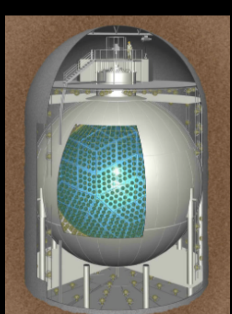
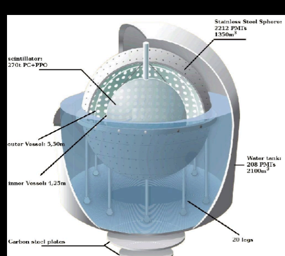
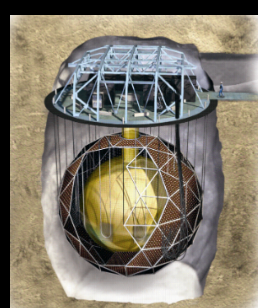
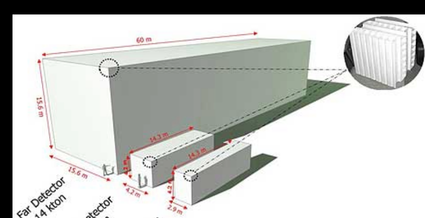


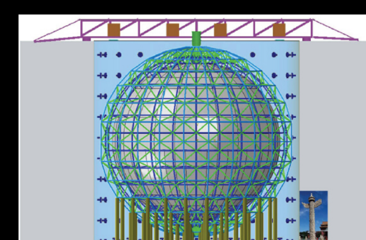
Liquid hydrocarbon (C_nH_{2n}) that emits (lots of) photons when charged particles lose energy in it

Will see supernova **electron antineutrinos**, with good energy resolution

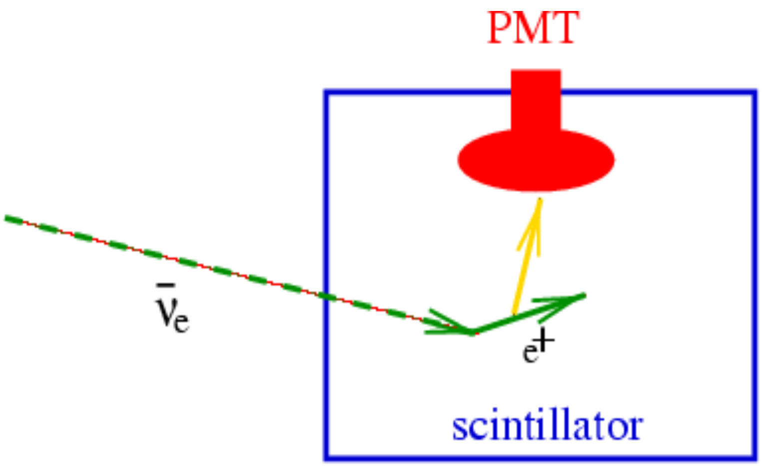
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Many examples worldwide of current and future detectors

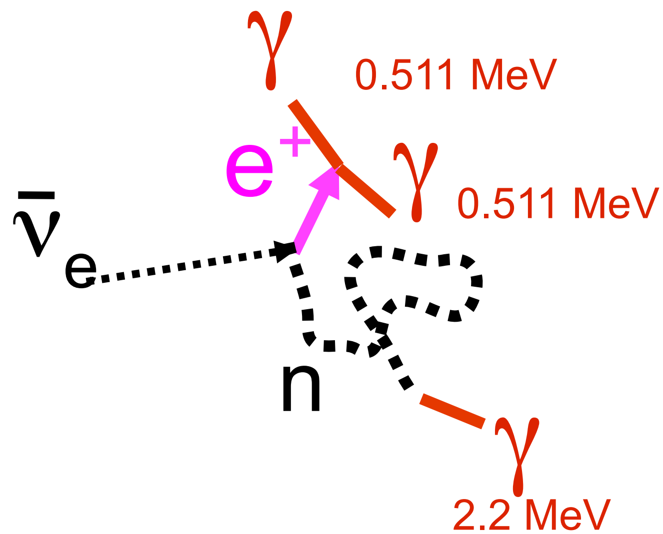


Scintillation detectors



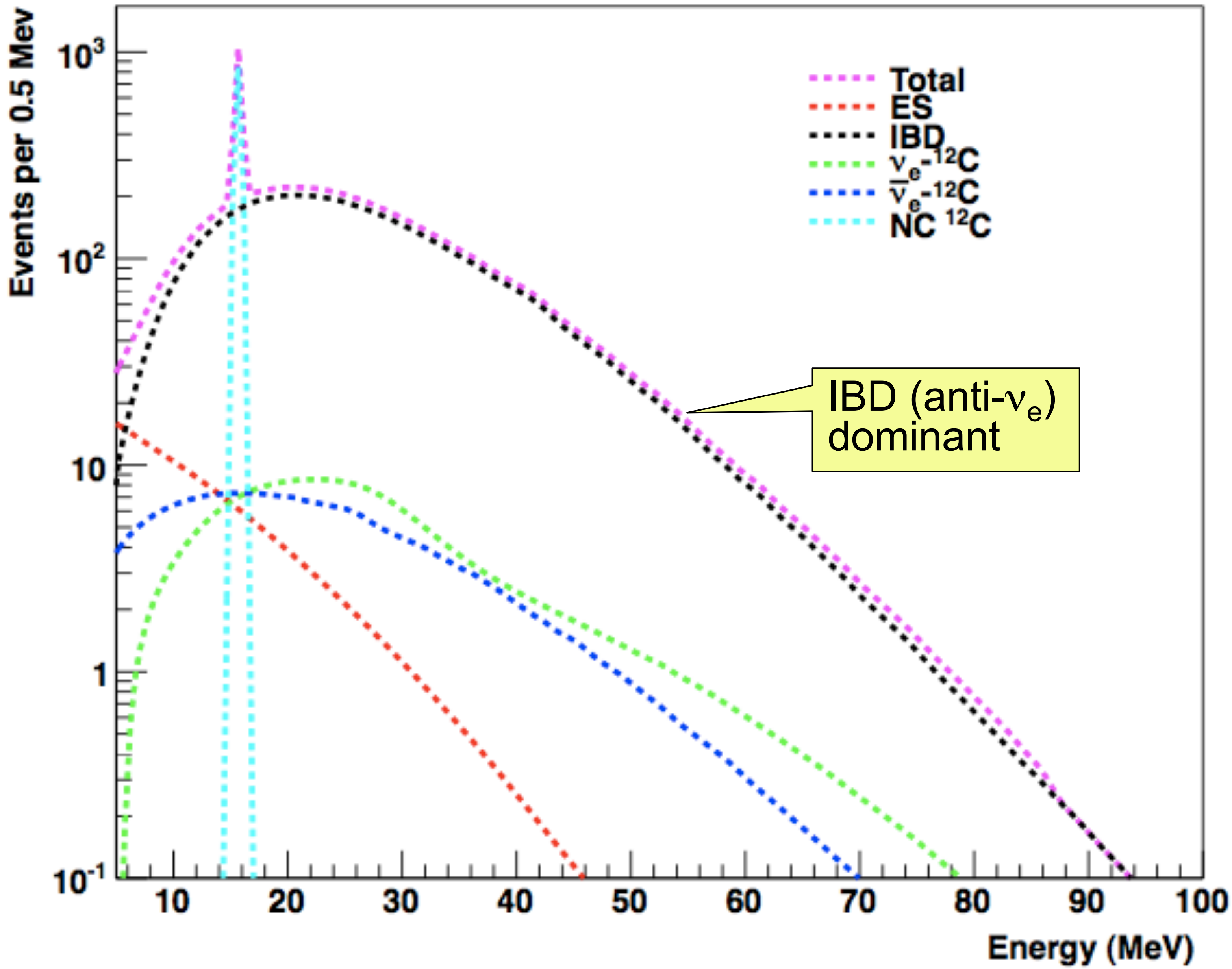
Liquid scintillator (C_nH_{2n}) volume surrounded by photomultipliers

- **lots of photons:**
  few 100 pe/MeV
  ➔**low threshold, good energy resolution**
- little pointing capability
  (light is ~isotropic even if interaction were directional...)
- can also dope with Gd



retrieve the energy of the n-capture and annihilation γ's

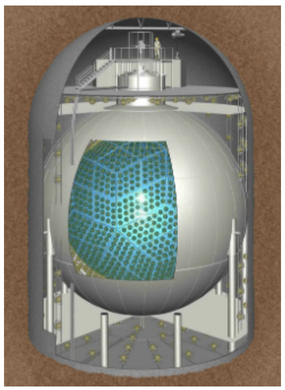
Interaction channels in scintillator



50 kt @ 10 kpc

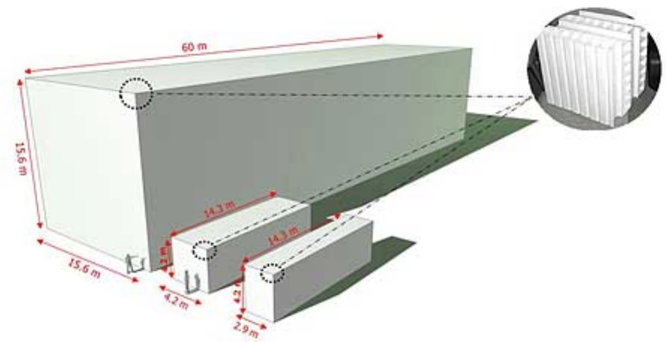
Current and near-future scintillator detectors

KamLAND
(Japan)
1 kton



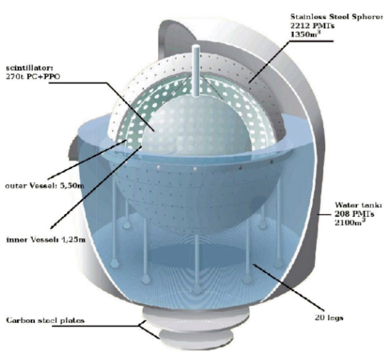
LVD
(Italy)
1 kton

NOvA
(USA)
14 kton

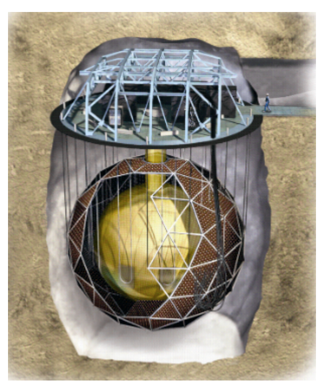


(on surface, but may be possible to extract counts for known burst)

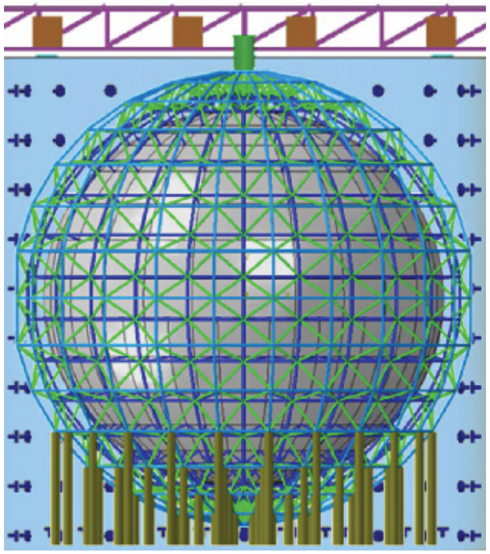
Borexino
(Italy)
0.33 kton



SNO+
(Canada)
1 kton

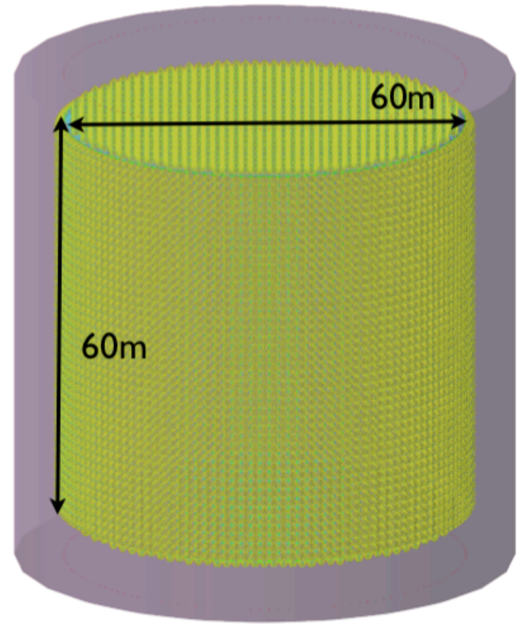


Future detector proposals



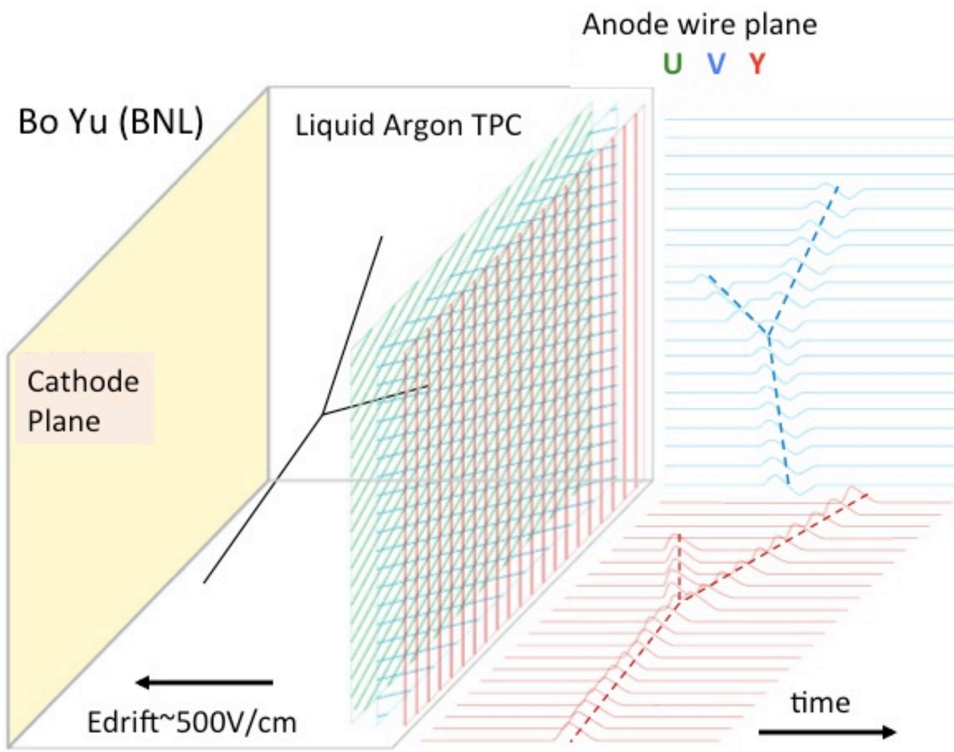
JUNO
(China)
20 kton

Jinping
(China)
2 kton



THEIA
(TBD)
50-100 kton
WbLS

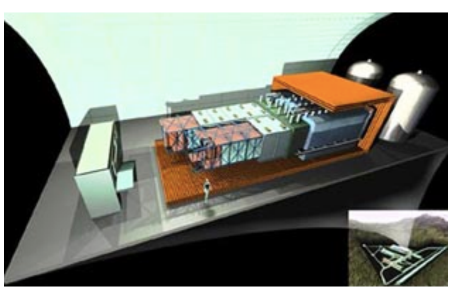
Liquid argon time projection chambers



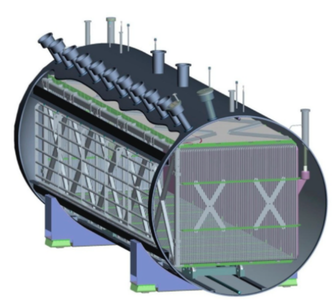
fine-grained trackers
sensitive to **electron neutrinos**
(as opposed to antineutrinos)

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

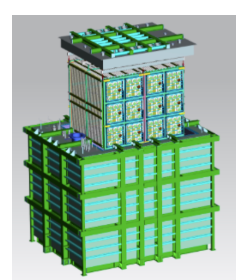
ICARUS
(Italy➔USA)
0.6 kton



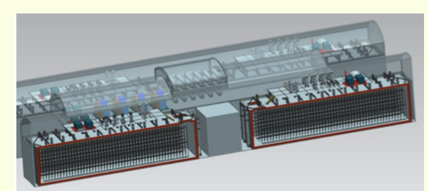
MicroBooNE
(USA)
0.2 kton



SBND
(USA)
0.112 kton



DUNE
(USA)
40 kton



Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

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

Less information in literature

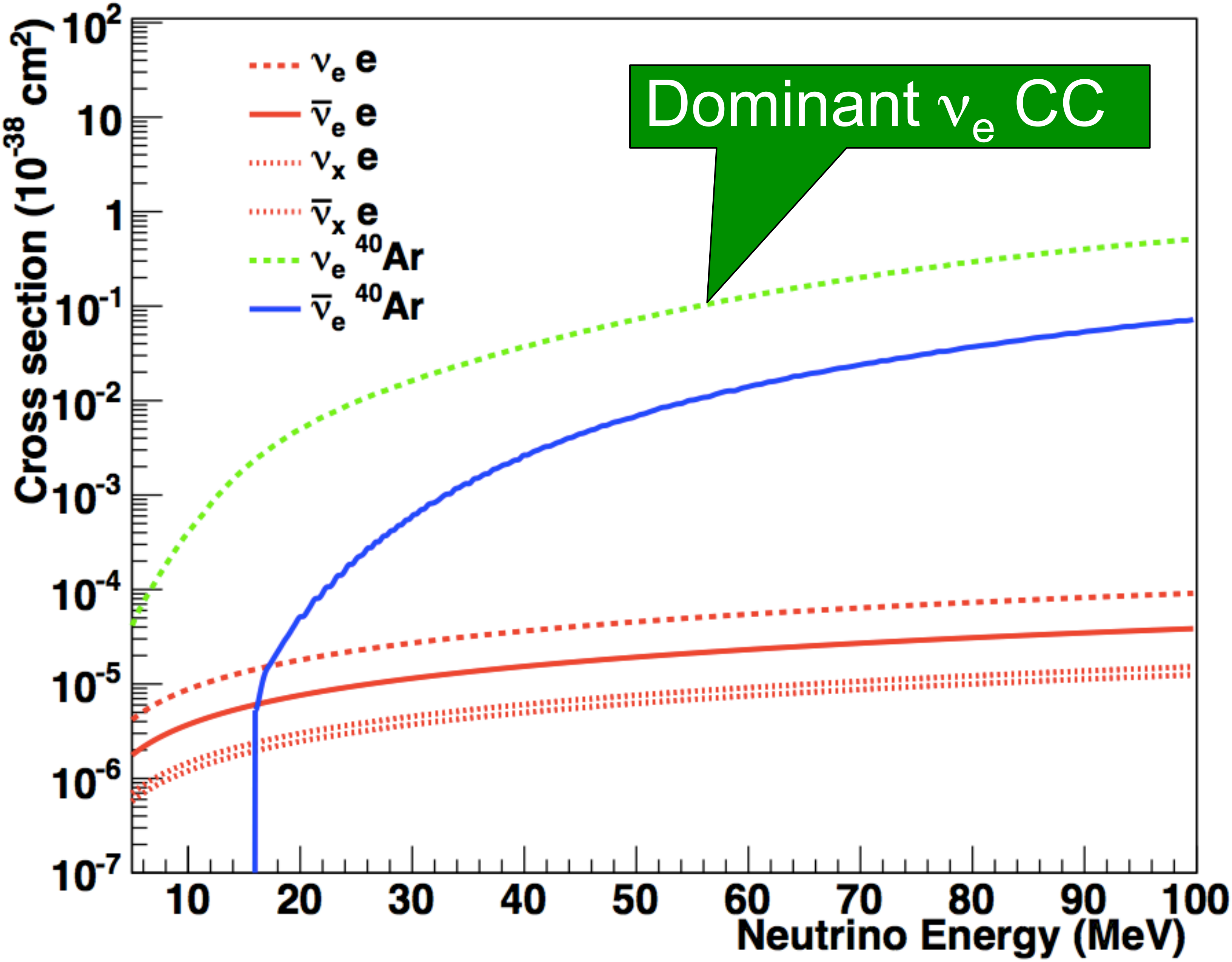
Elastic scattering

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

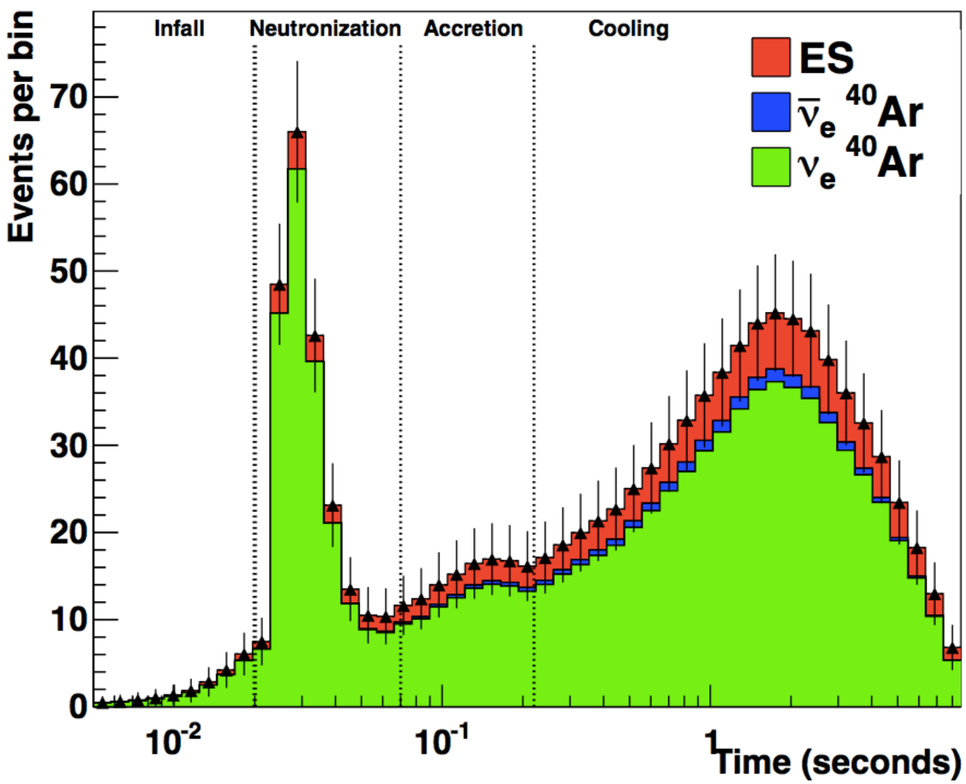
Can use for pointing

In principle can tag modes with deexcitation gammas (or lack thereof)...

Cross sections in argon

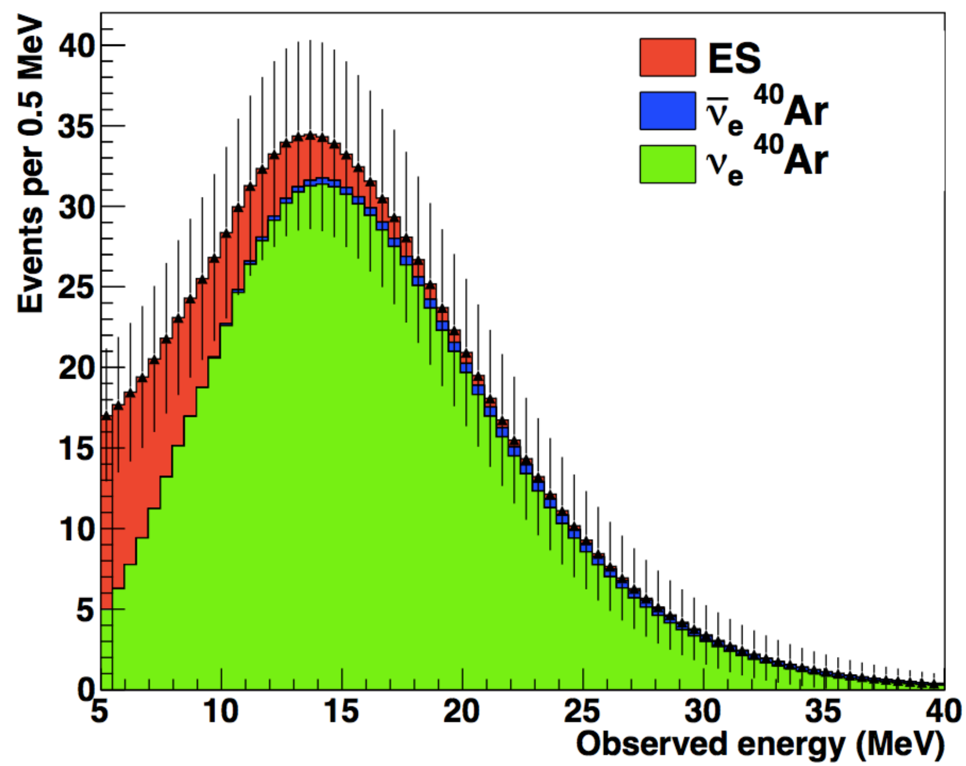


Flavor composition as a function of time

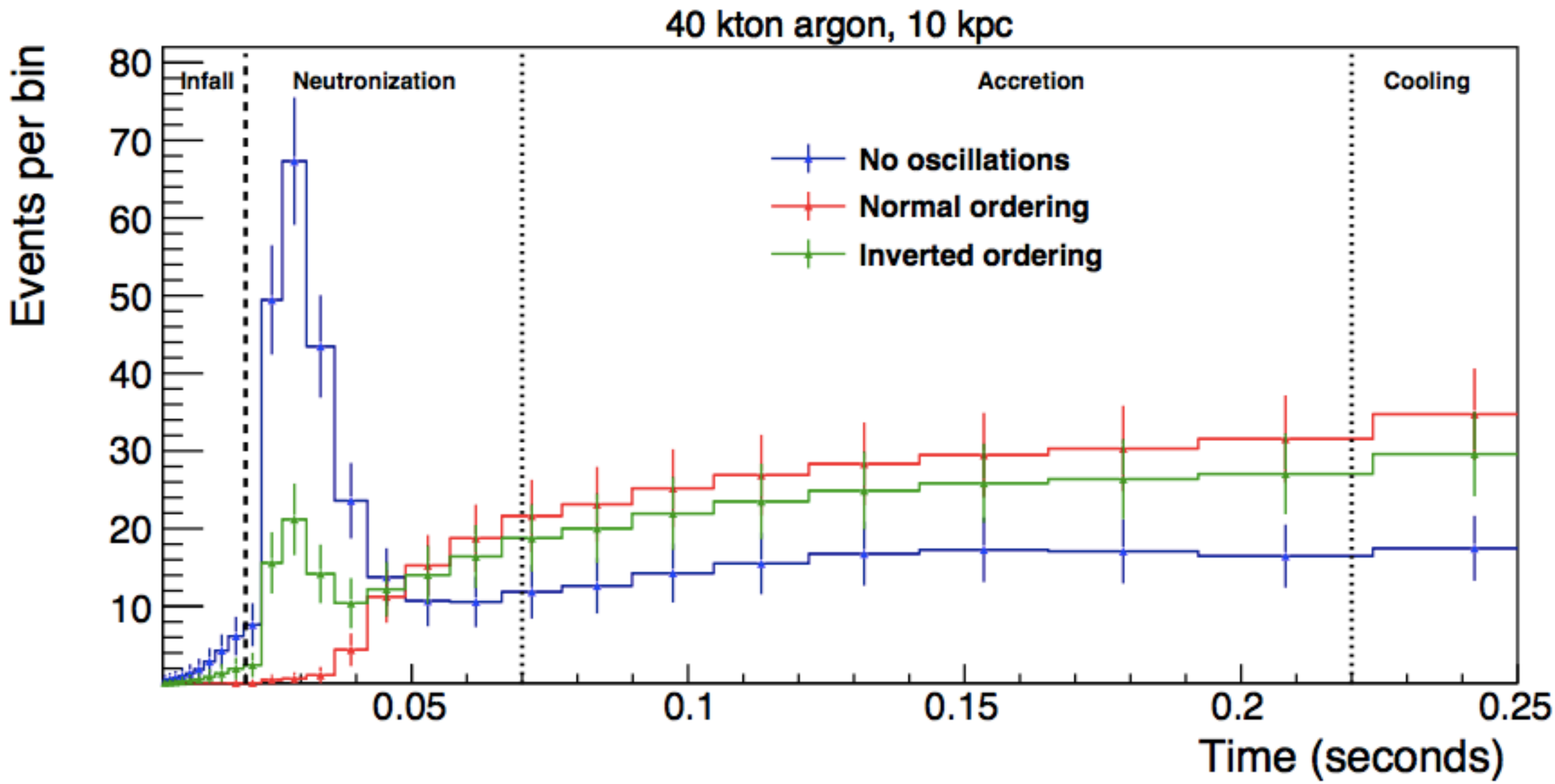


For 40 kton @ 10 kpc,
Garching model
(no oscillations)

Energy spectra integrated over time



Note that the **neutronization burst gets substantially suppressed** with flavor transitions



Simple MSW assumption (assume OK at early times)

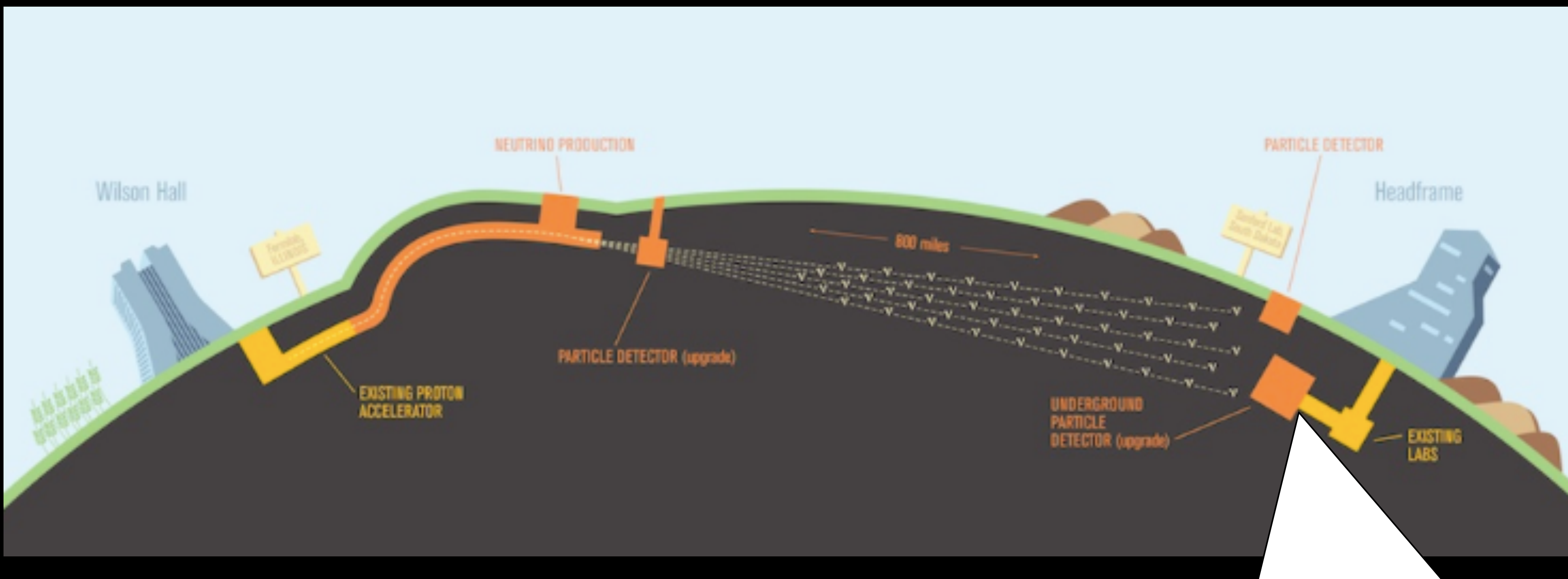
NMO: $F_{\nu_e} = F^0_{\nu_x}$

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

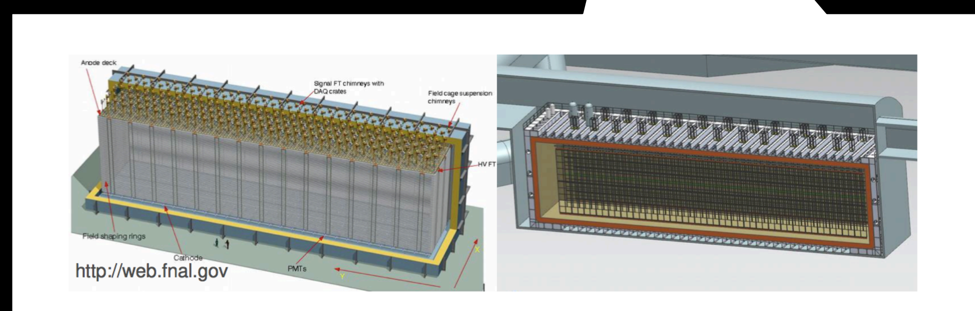
(a robust mass ordering signature!)

Deep Underground Neutrino Experiment (DUNE)

4800 mwe undergound in South Dakota
70 kton LAr (40 kton fiducial, 4x10 kton)
1.2 MW beam from FNAL for long-baseline osc
first module in 2024, beam in 2026



- mass ordering & CPV
- supernova burst
- nucleon decay



Lead-based supernova detectors

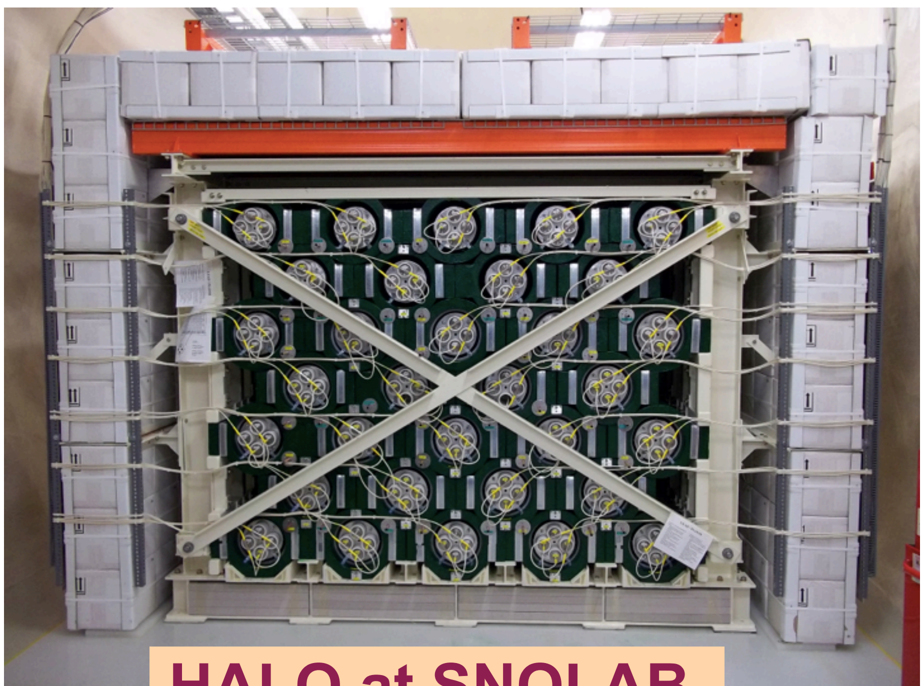
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

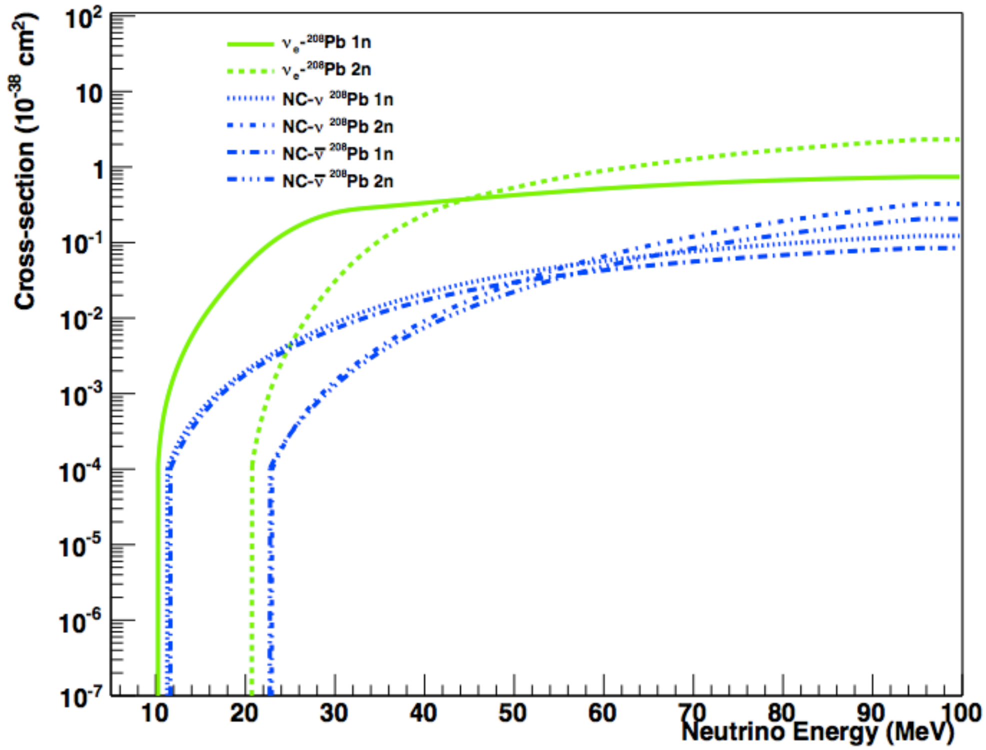
$\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu_x$ NC

↘ 1n, 2n, γ emission

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

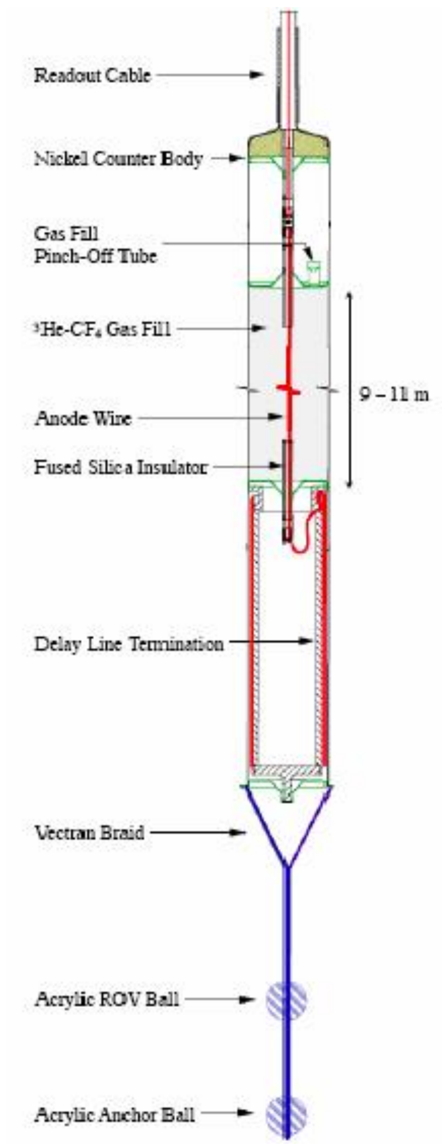


HALO at SNOLAB



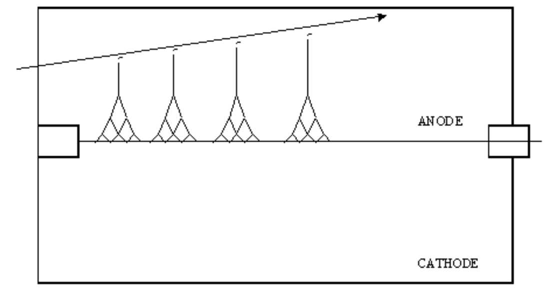
SNO ^{3}He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

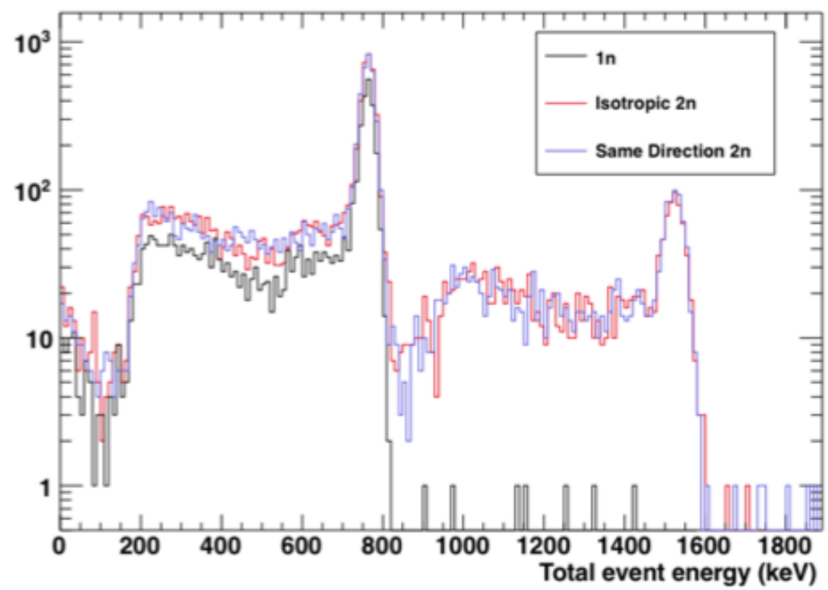
^{3}He counters for neutron detection



$$^3\text{He} + n \rightarrow p + t + 764\ \text{keV}$$

proportional counter
measures ionization deposition by p, t final state charged particles

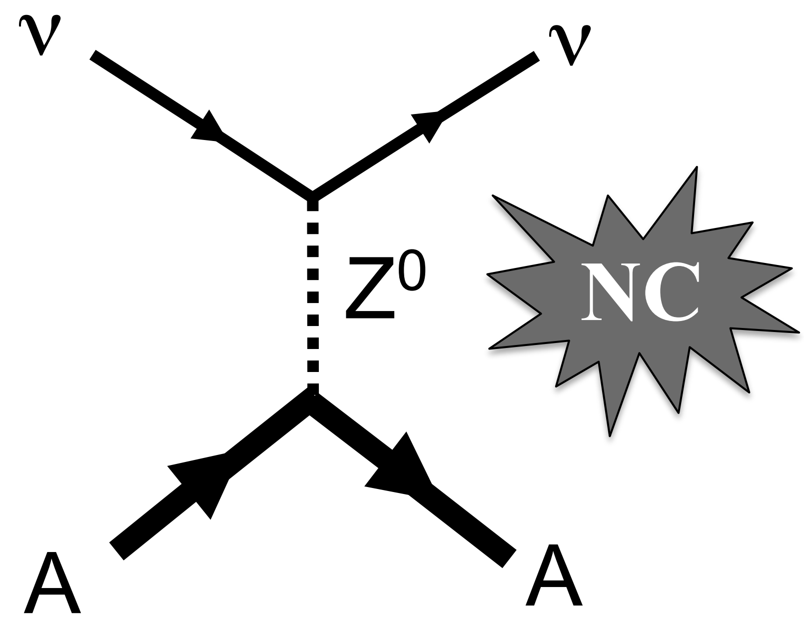


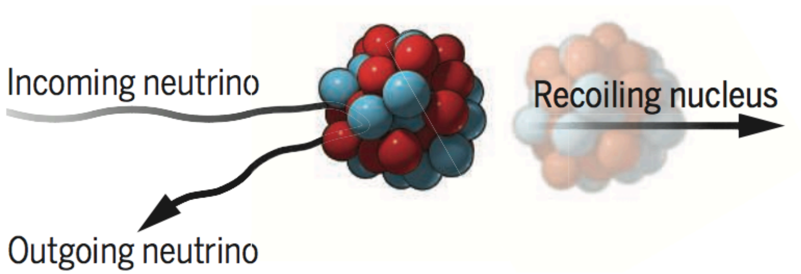


Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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]

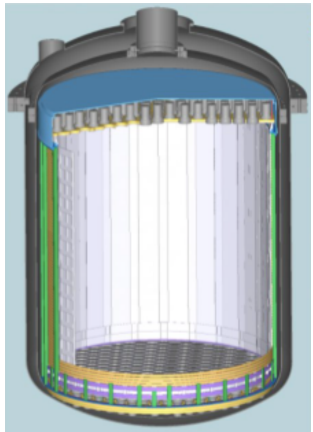
A: no. of constituents

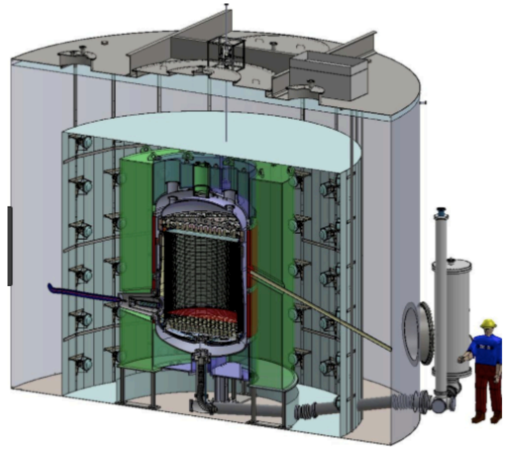
Image: J. Link *Science* Perspectives

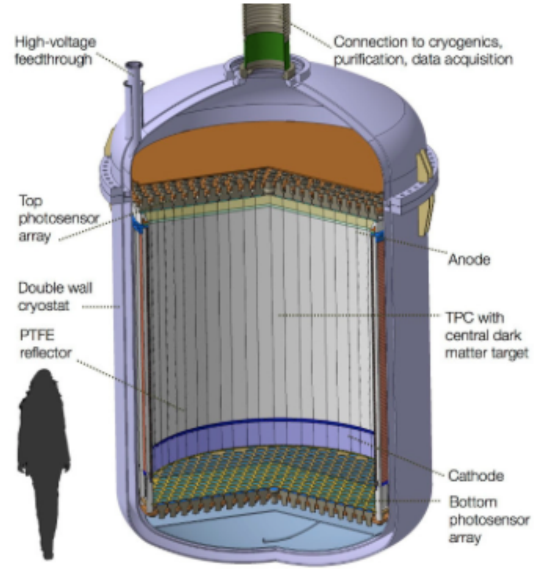
See also J. Newstead slides, NMNM 3

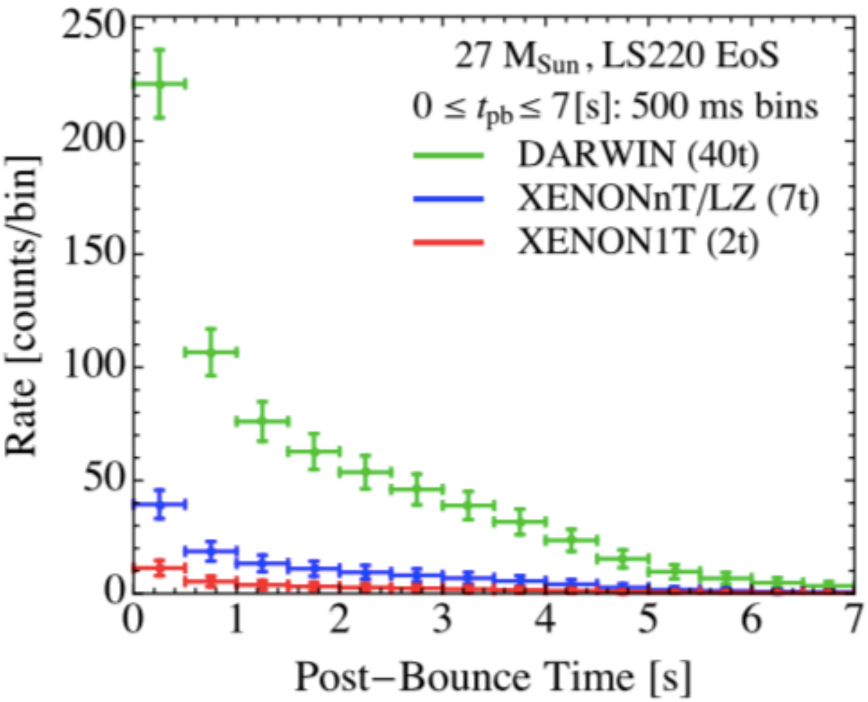
Detector example: **XENON/LZ/DARWIN**

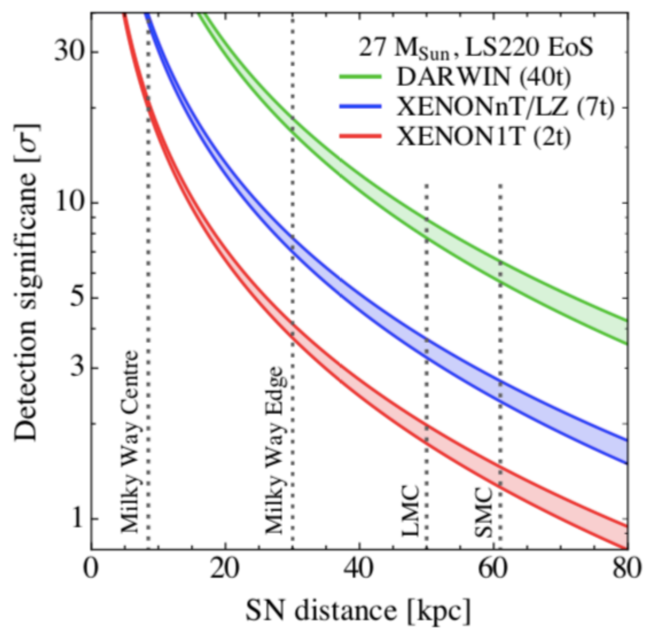
- dual-phase xenon time projection chambers





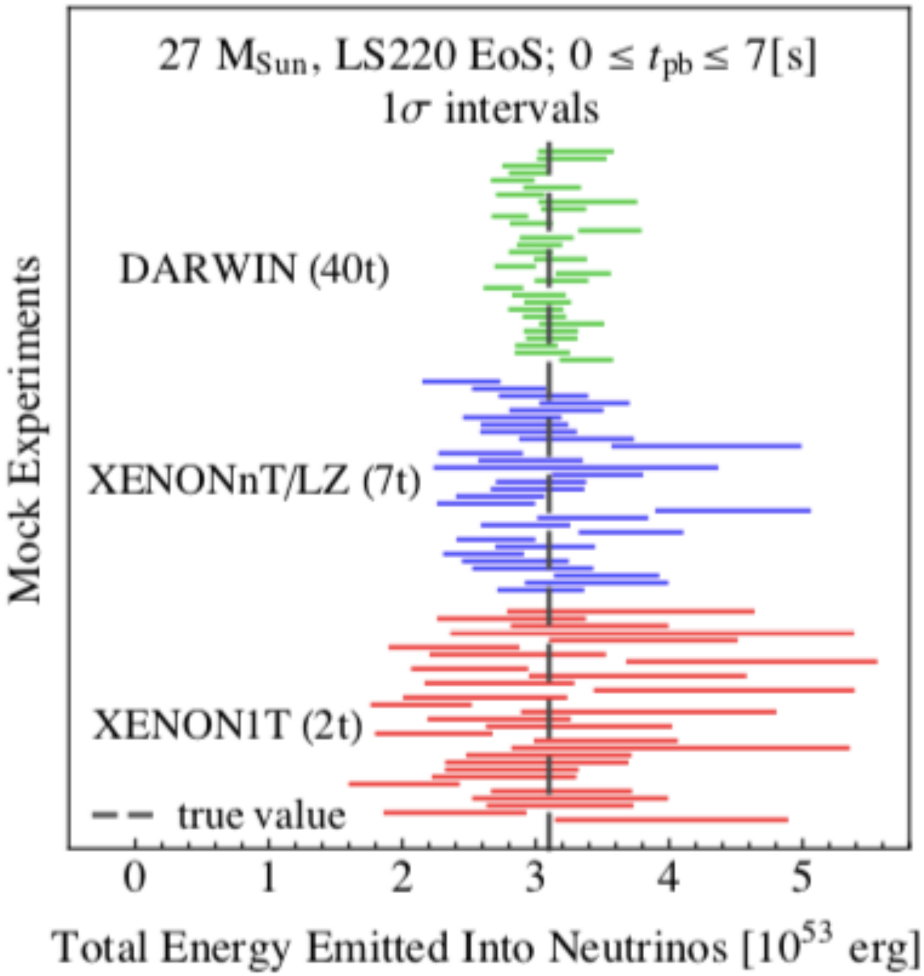


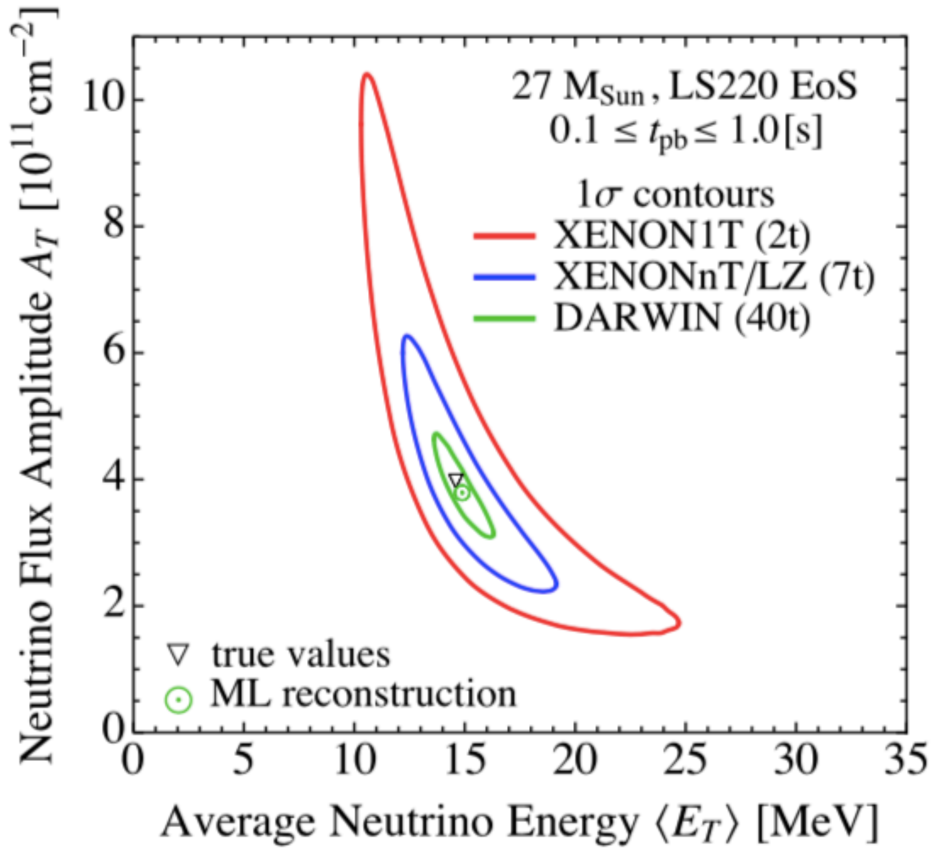




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

What will be learned?



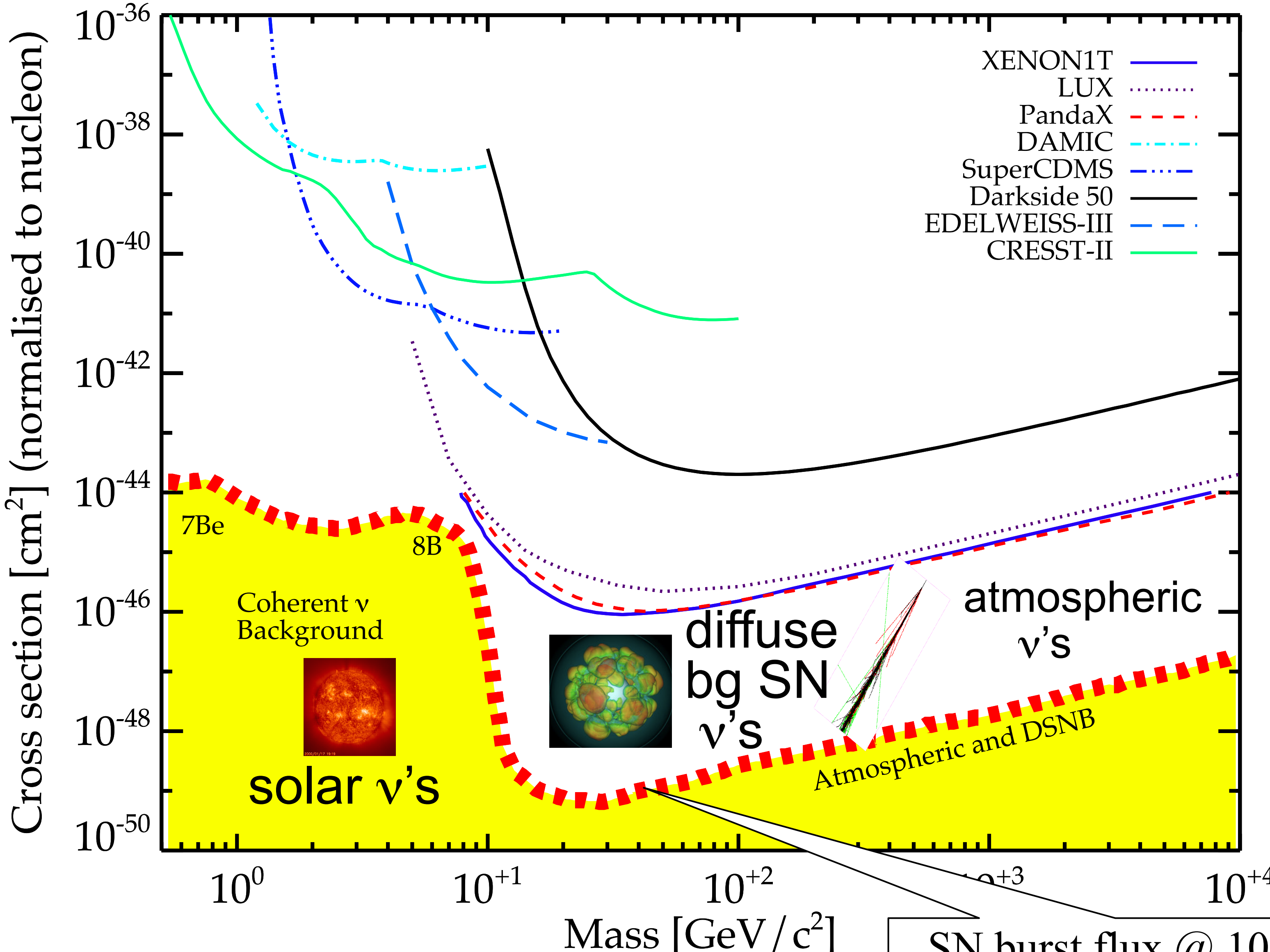


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

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

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

L. Strigari

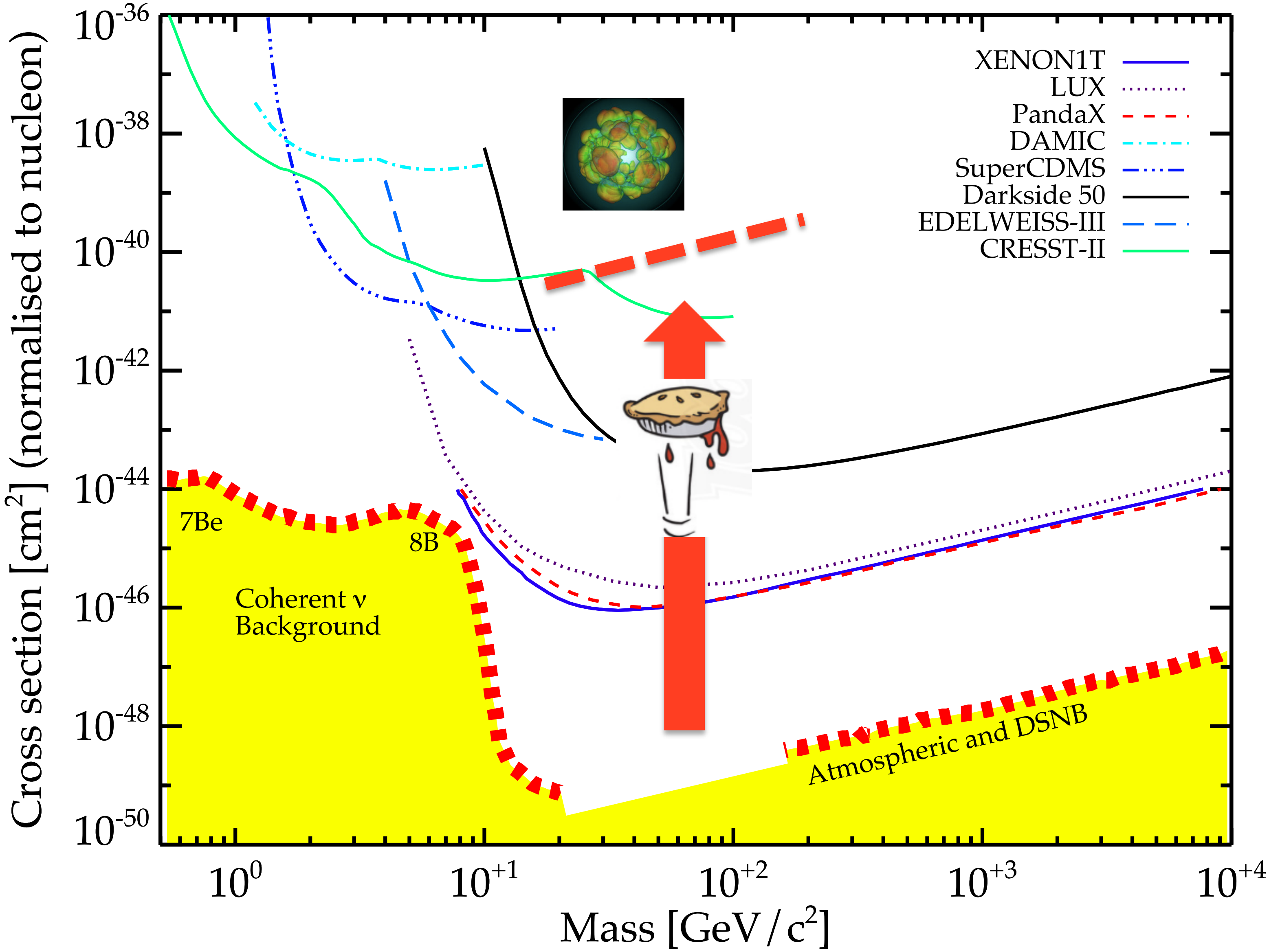


SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux

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



Summary of supernova neutrino detectors

Galactic sensitivity

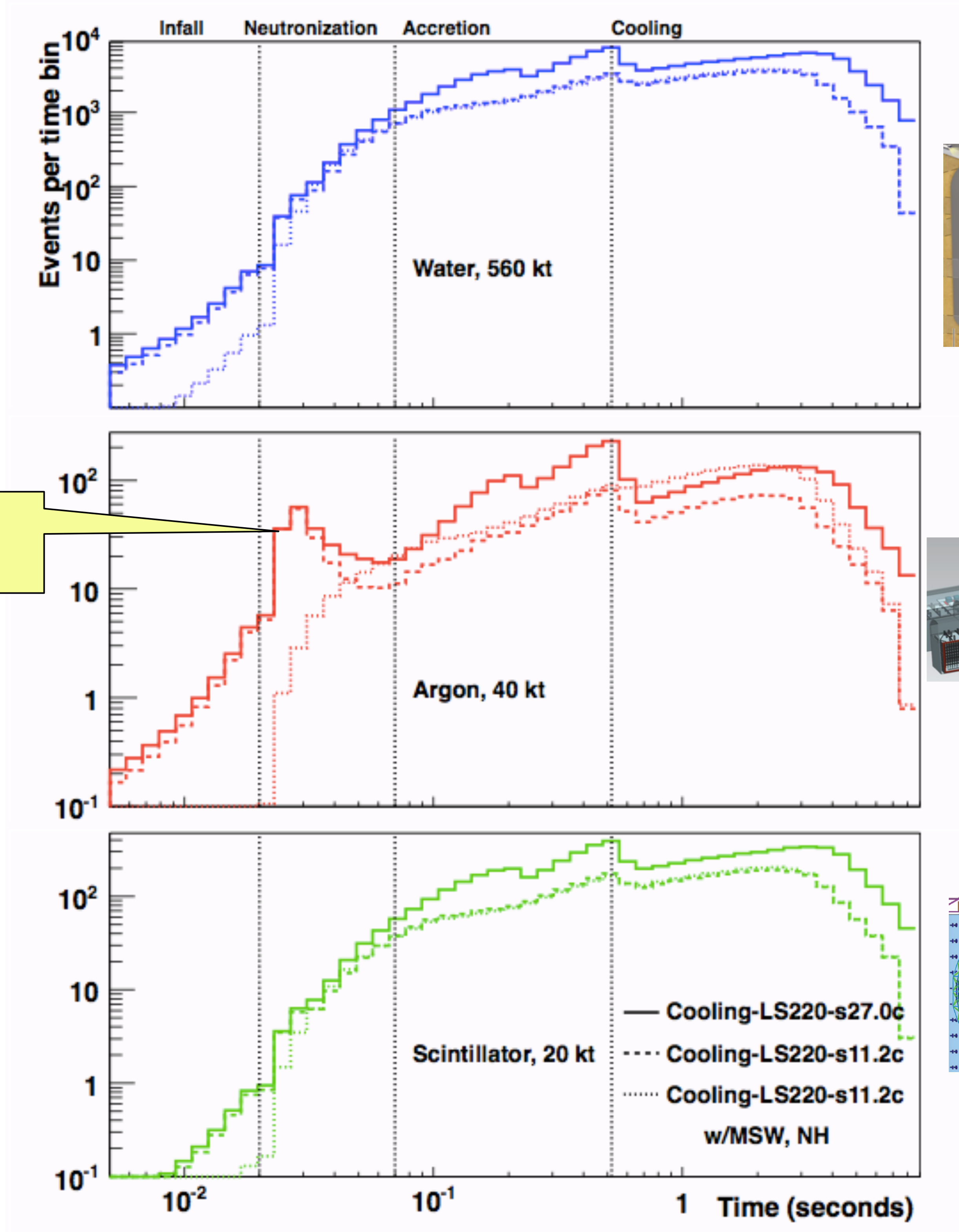
Extragalactic

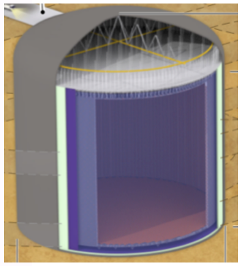
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	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	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Proposed
PINGU	Long string	South pole	(600)	(10^6)	Proposed

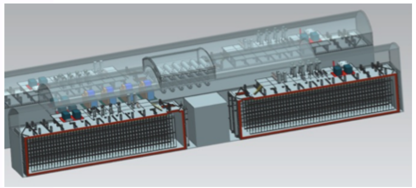
plus reactor experiments, DM experiments...

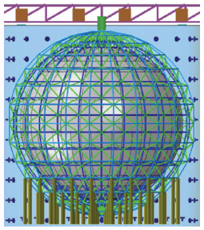
Example signals in future detectors

Neutronization burst in argon



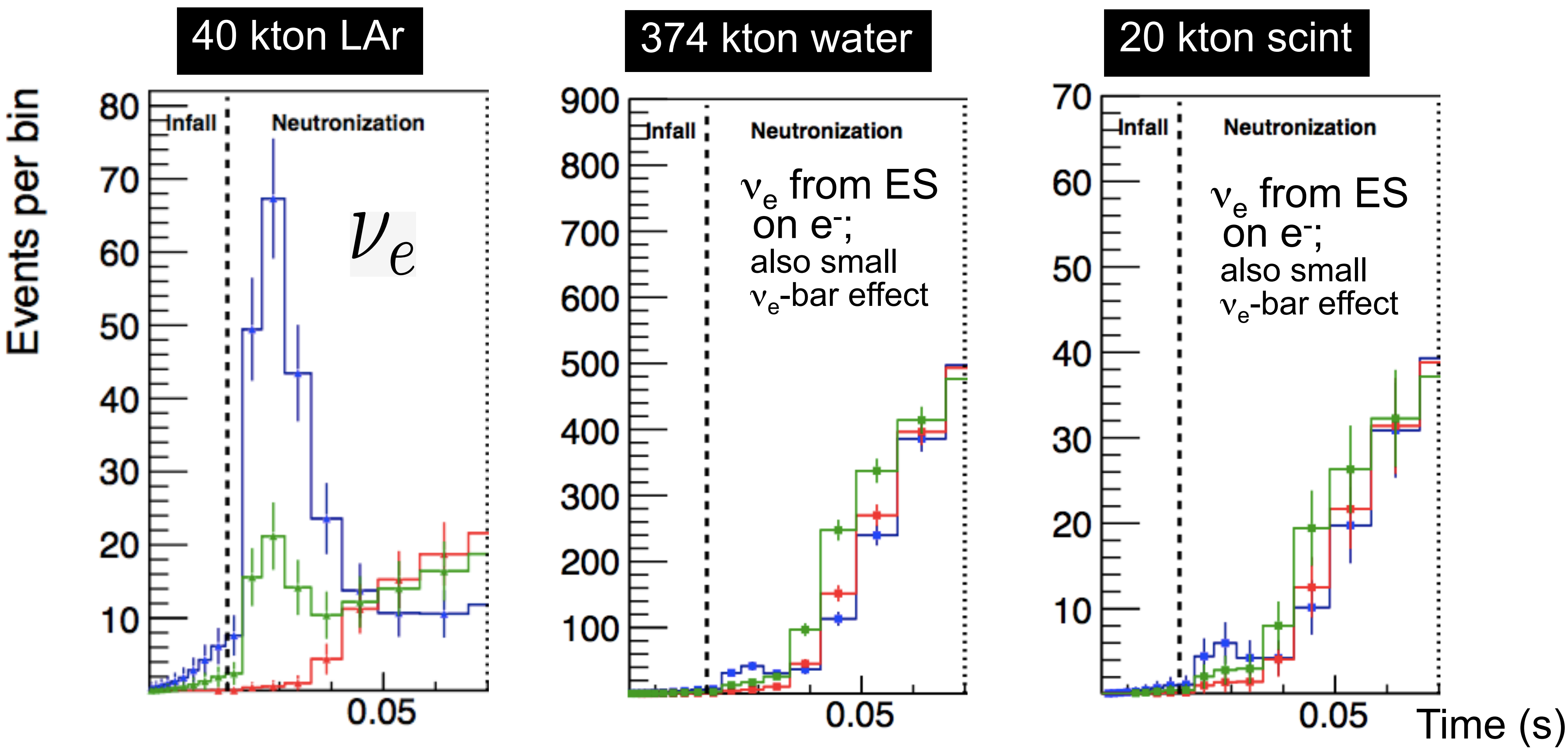






(note logarithmic time bins)

An example of a robust MO signature: **the neutronization burst**

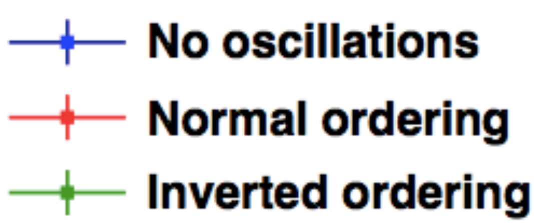


NMO: $F_{\nu_e} = F^0_{\nu_x}$

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

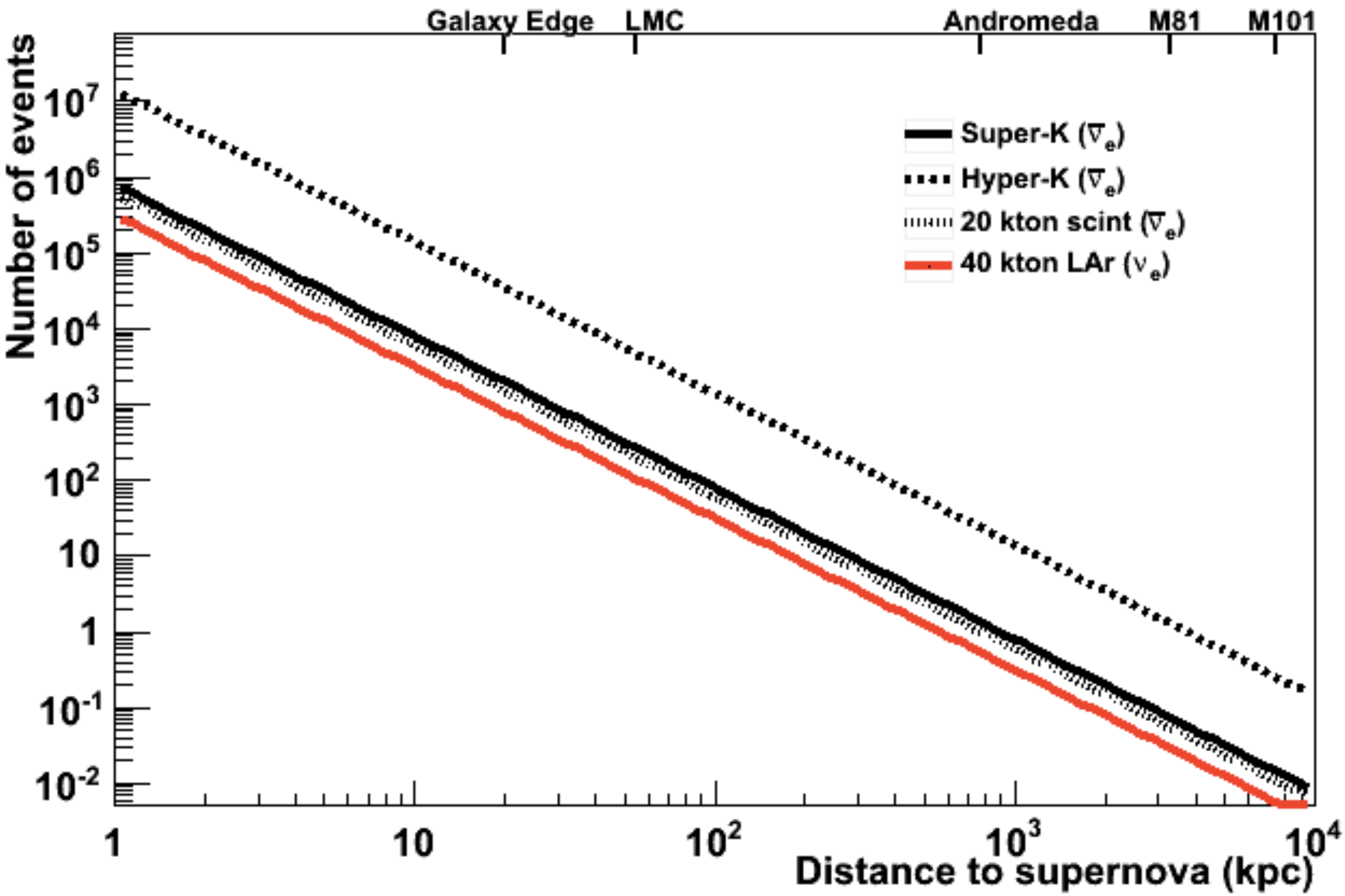
NMO: $F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$

IMO: $F_{\bar{\nu}_e} = F^0_{\bar{\nu}_x}$



suppression for IMO,
stronger suppression for NMO

Distance reach for future detectors



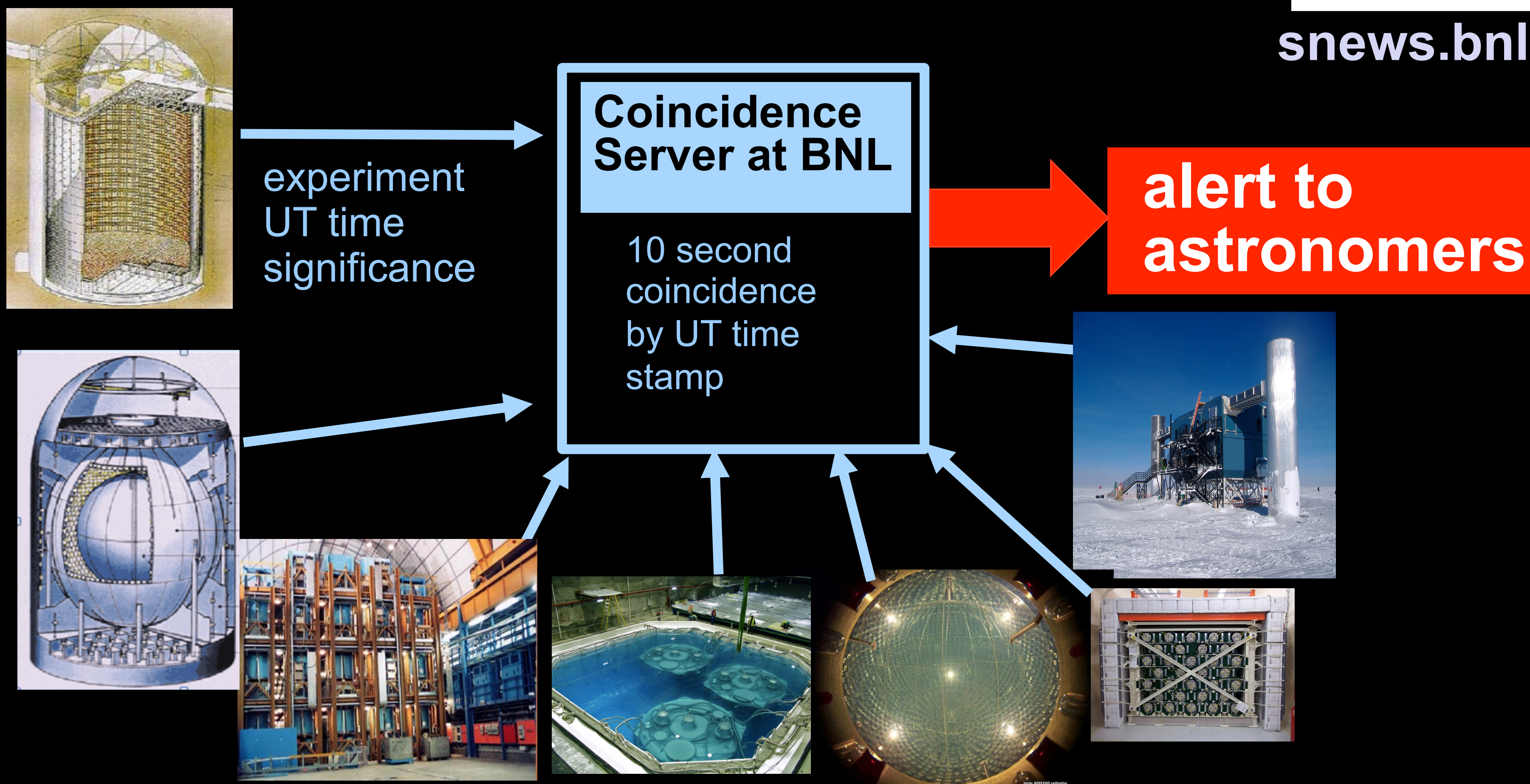
SK will see ~1 event from Andromeda; HK will get a ~dozen

For supernova neutrinos, the more, the merrier!

SNEWS: SuperNova Early Warning System

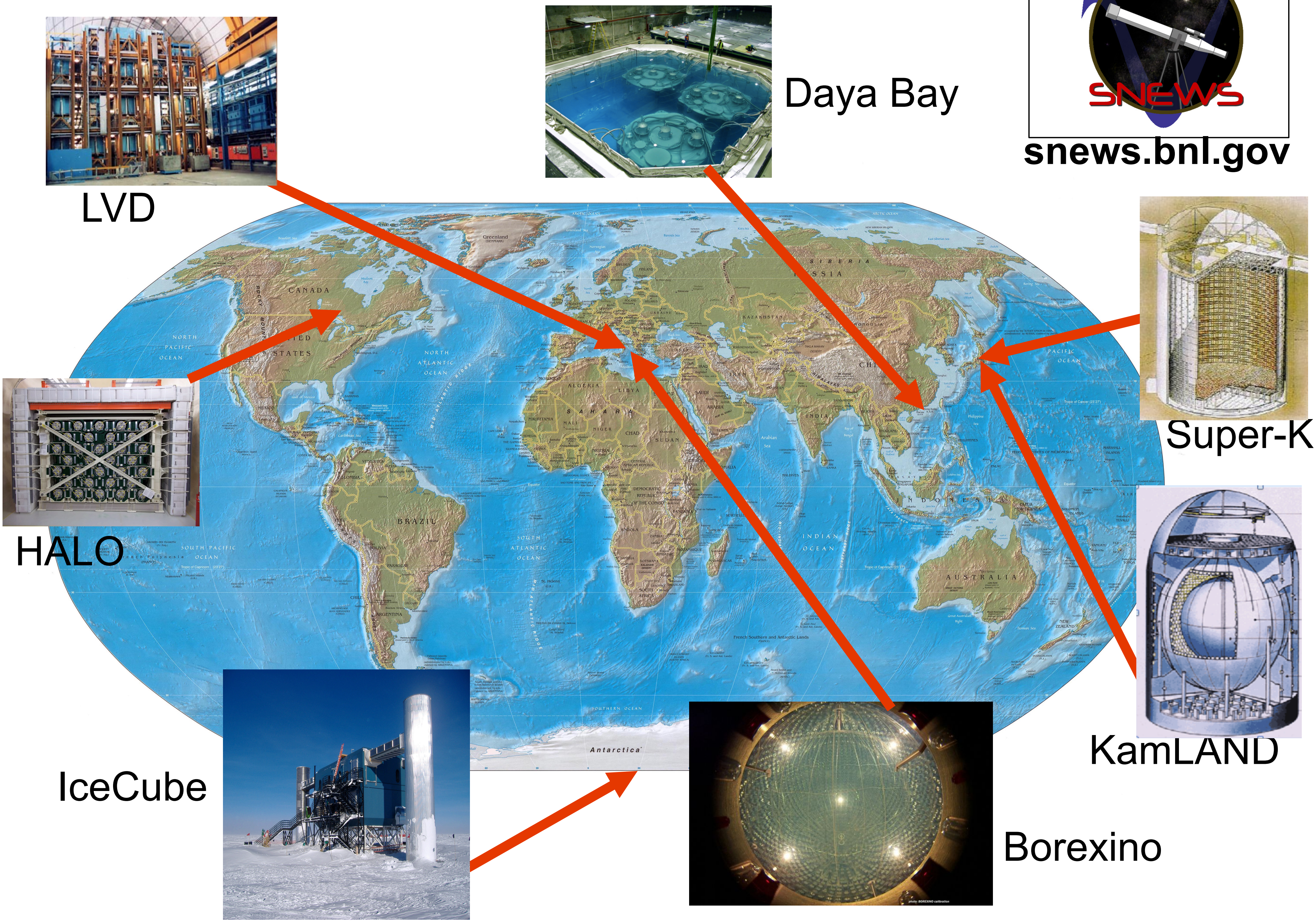
- Neutrinos (and GW) precede em radiation by hours or even days
- For promptness, require ***coincidence*** to suppress false alerts

snews.bnl.gov

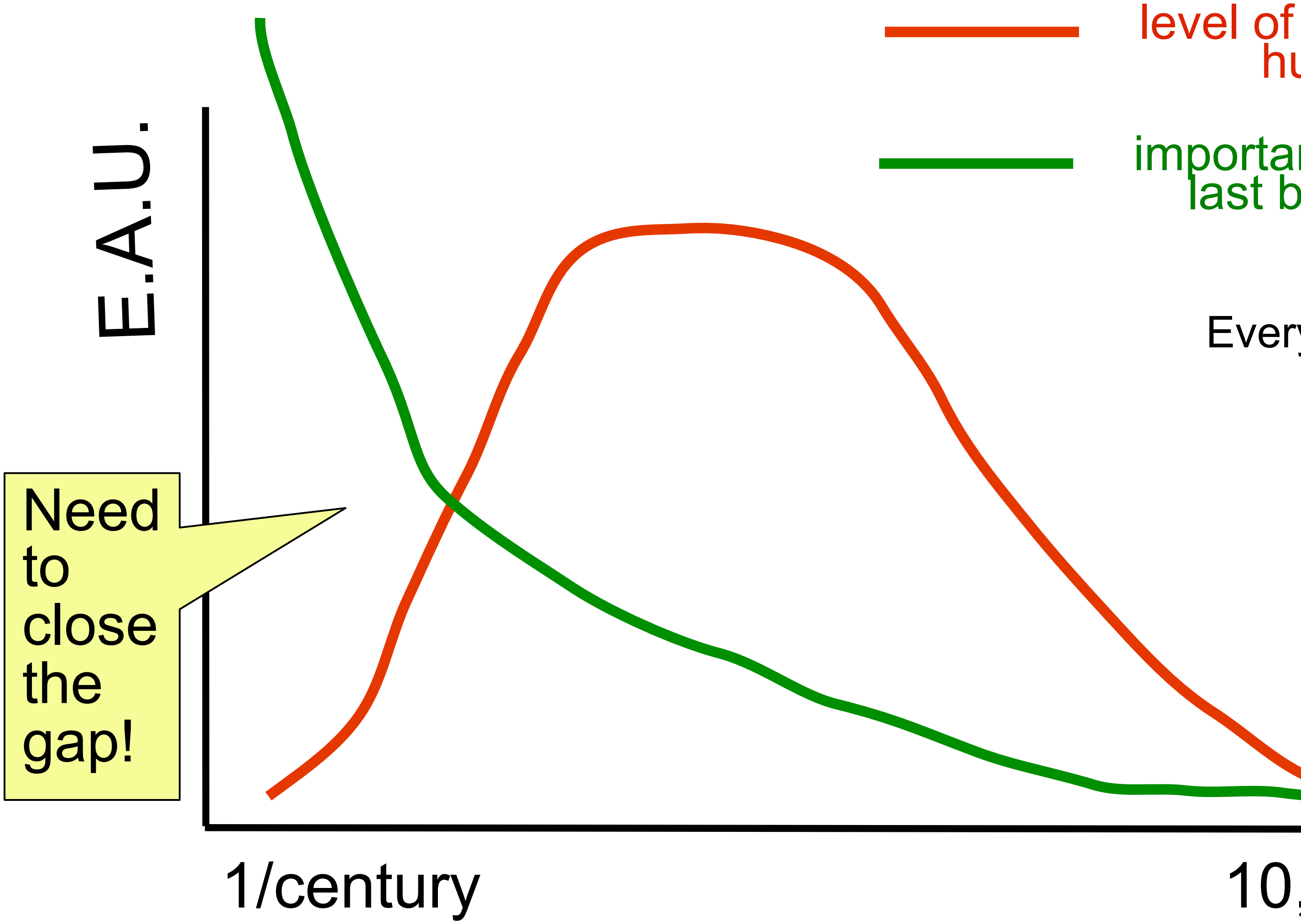


- Running smoothly for more than 10 years, automated since 2005

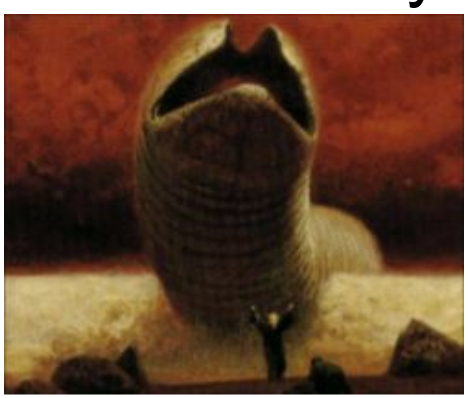
SNEWS: SuperNova Early Warning System



Sociological comments...

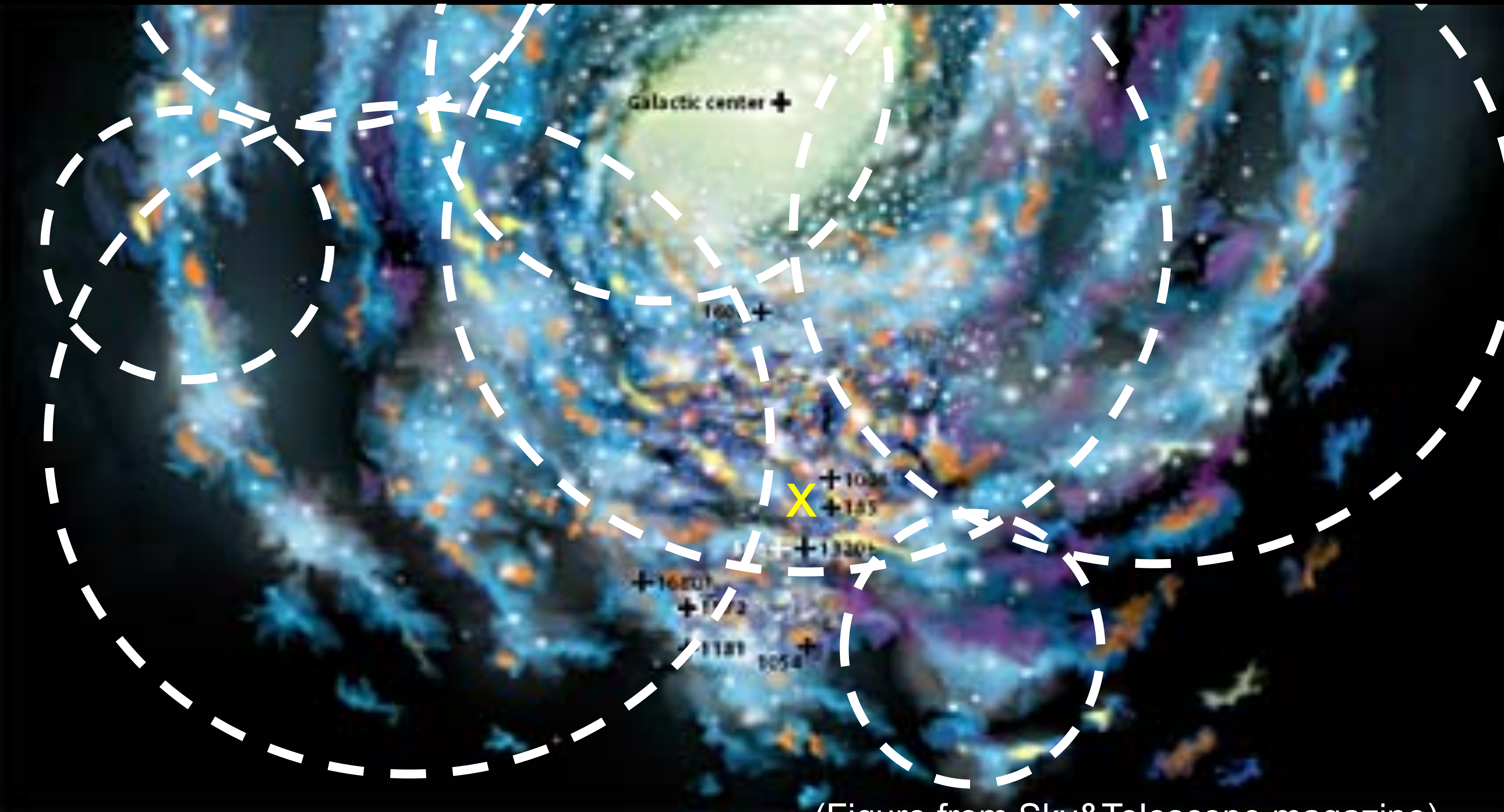


Everybody's hungry for data...



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)

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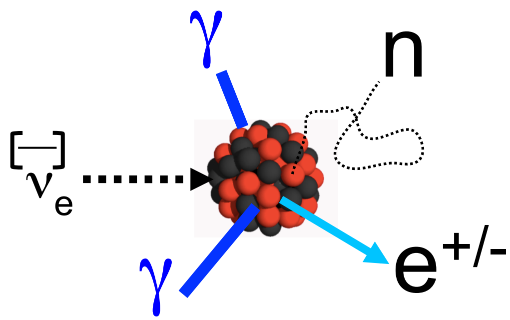
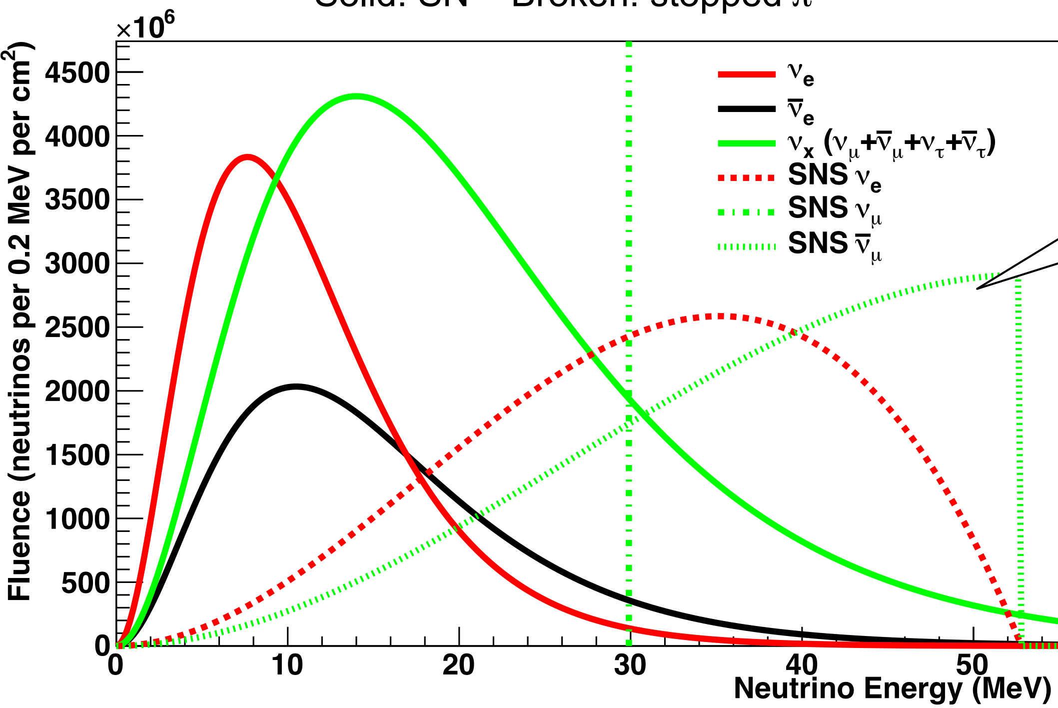


Interactions with nuclei
(cross sections & products)
very poorly understood...
sparse theory & experiment
(*only* measurements at better than ~50% level are for ^{12}C)

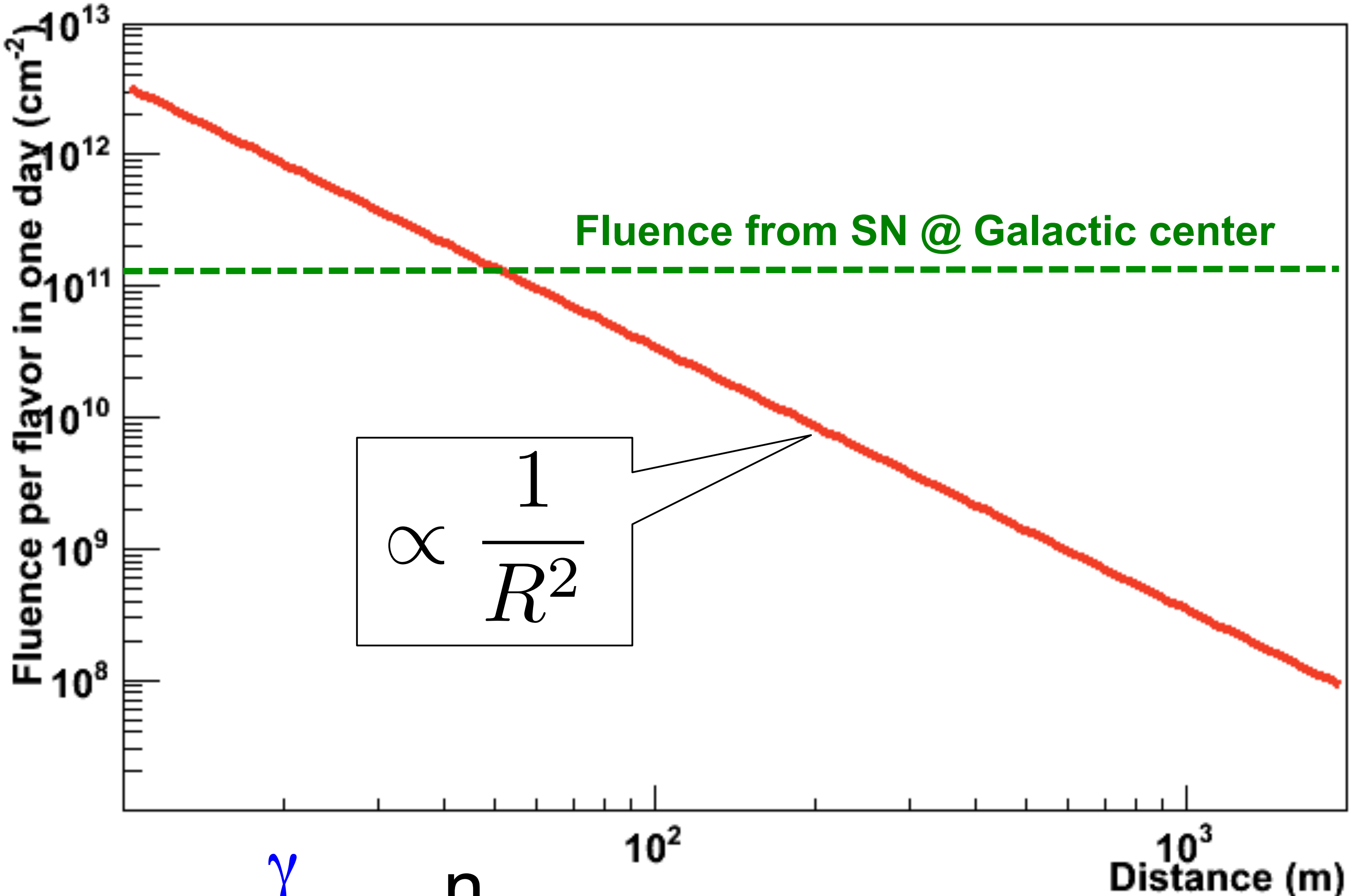


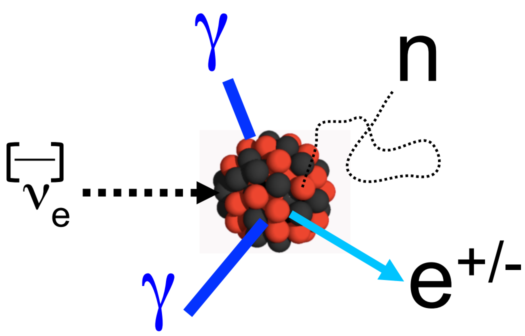
Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source

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 rang

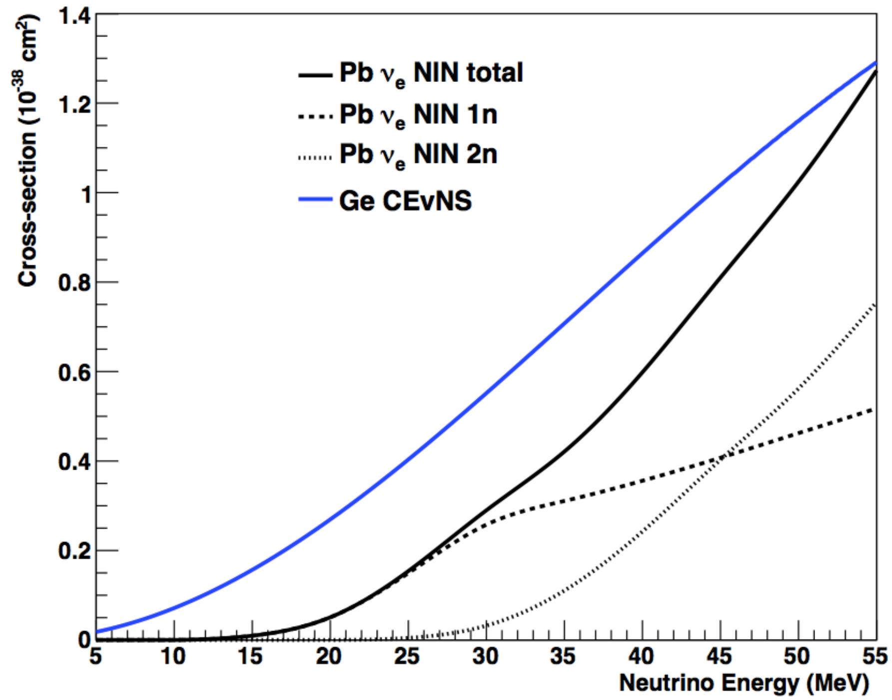
Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

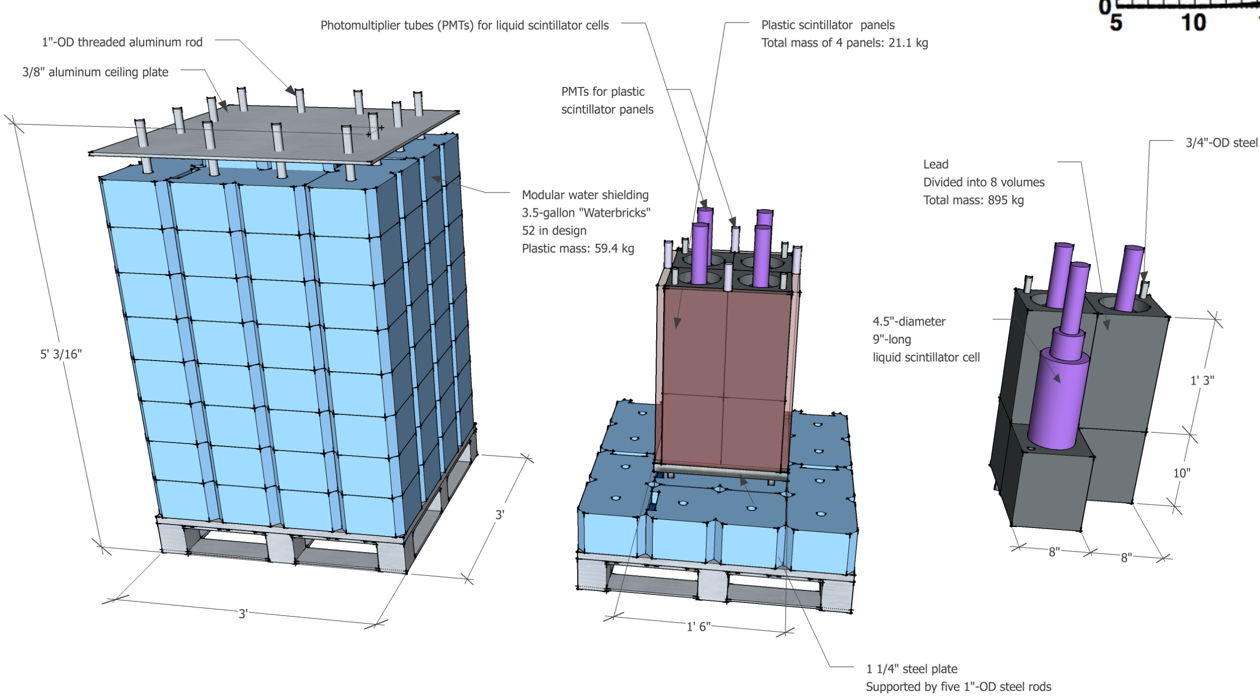
$\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$ CC

↘ 1n, 2n emission

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

↘ 1n, 2n, γ emission





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Take-Away Messages

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

Future detectors
- huge statistics: extragalactic reach
- richer flavor sensitivity (e.g. ν_e in LAr!)
- multimessenger prospects
- DSNB prospects improving