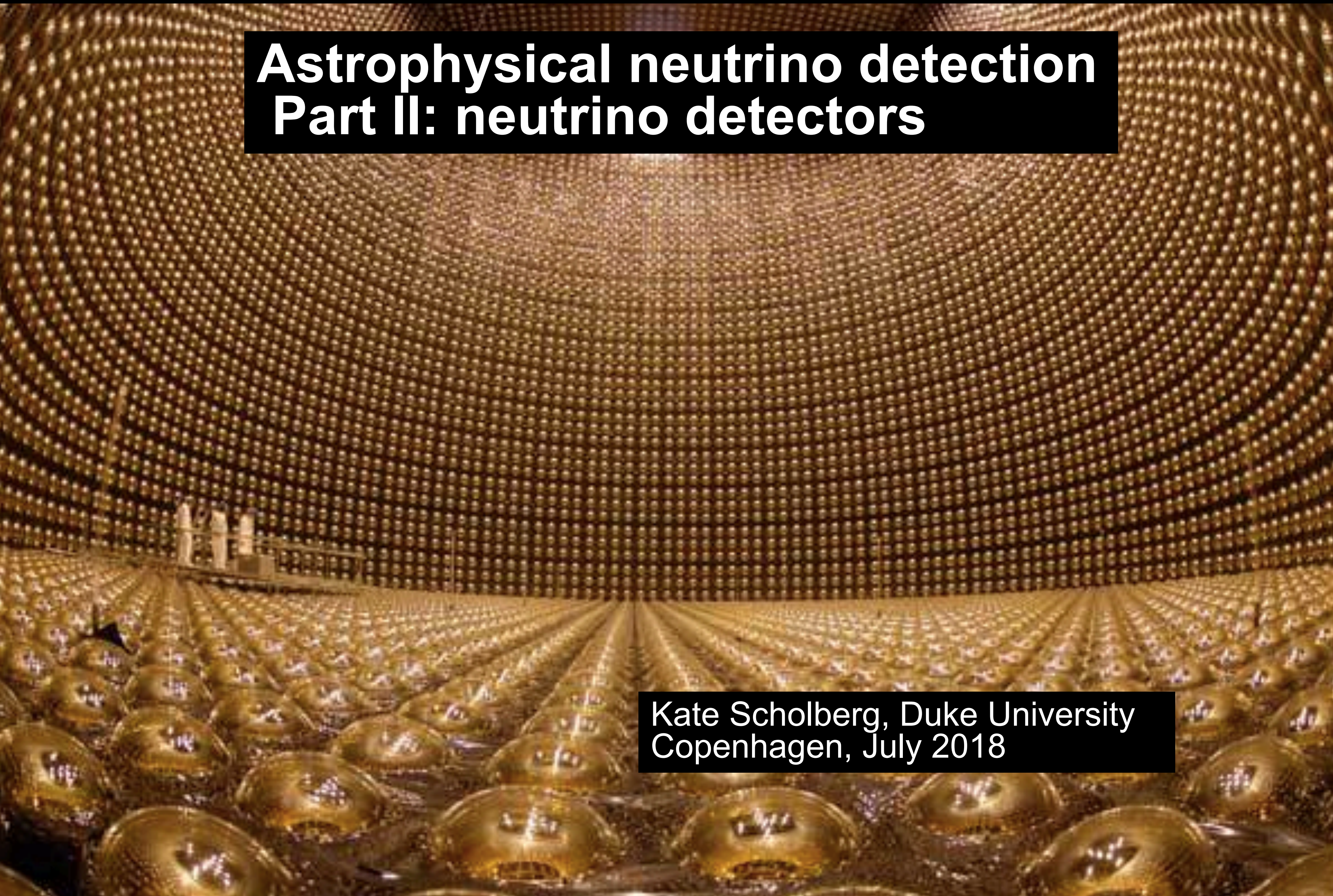
# Astrophysical neutrino detection
# Part II: neutrino detectors



Kate Scholberg, Duke University
Copenhagen, July 2018


Last time I probably bit
off a bit more than
I can chew...

# Lecture Overview

- Neutrino interactions with matter
- General principles of particle detection
- Survey of neutrino detection techniques

- Specific astrophysical detectors,
  organized by energy range

  - few to few tens of MeV:
    **core-collapse supernova**, solar

  - few hundred MeV to TeV
    atmospheric $\nu$'s

  - TeV to EeV +
    AGNs, GRBs, mergers, ...

Tue

as far as we get....

Fri

# Lecture Overview

- Neutrino interactions with matter
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Fri

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  atmospheric $\nu$'s

- TeV to EeV +
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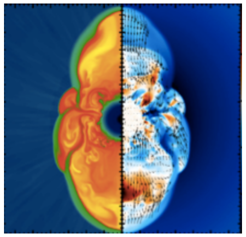
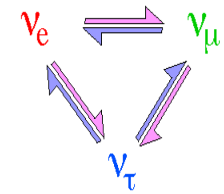
# What can we learn from the next neutrino burst?

## 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

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

input from photon (GW) observations

**+ EARLY ALERT**

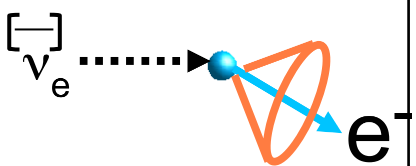
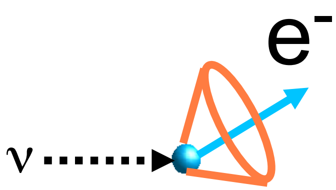
# What do you want in a detector for a supernova burst?


# 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<br>$\nu + e^- \rightarrow \nu + e^-$<br> | | |
| **Neutral current** | <br>Useful<br>for pointing | | |

# Neutrino interactions in the ~10 MeV range

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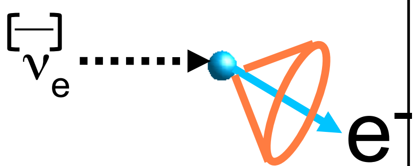
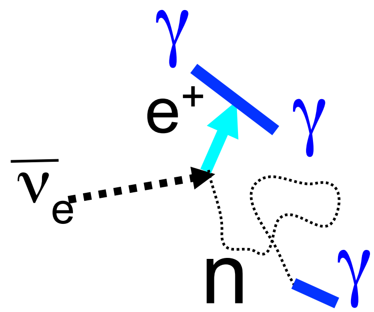
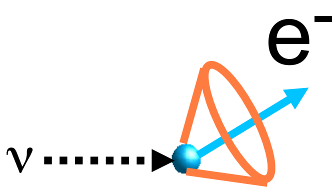
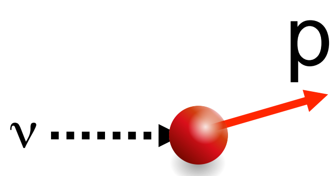
| **Charged current** | Elastic scattering<br>$\nu + e^- \to \nu + e^-$<br> | Inverse beta decay<br>$\bar{\nu}_e + p \to e^+ + n$<br> | |
| **Neutral current** | <br>Useful for pointing | Elastic scattering<br><br>very low energy recoils | |

# Neutrino interactions in the ~10 MeV range

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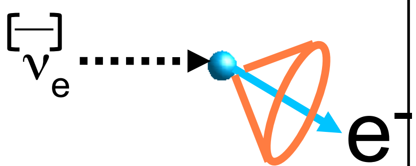
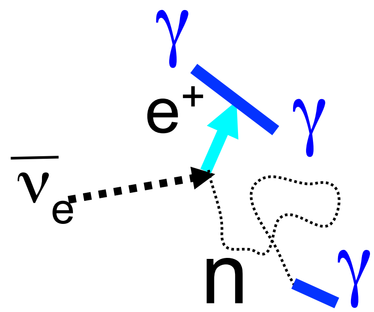
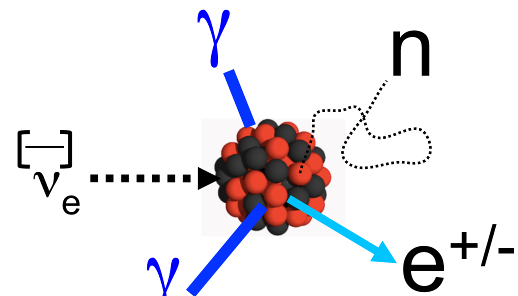
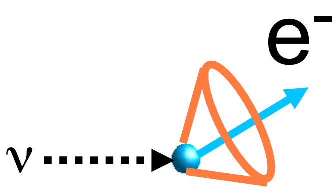
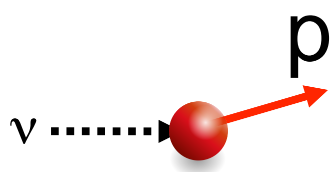
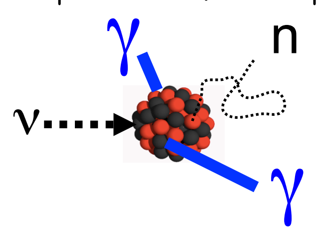
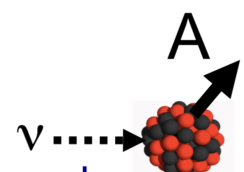
| **Charged current** | Elastic scattering<br>$\nu + e^- \to \nu + e^-$<br> | Inverse beta decay<br>$\bar{\nu}_e + p \to e^+ + n$<br> | $\nu_e + (N,Z) \to e^- + (N-1, Z+1)$<br>$\bar{\nu}_e + (N,Z) \to e^+ + (N+1, Z-1)$<br><br>Various possible ejecta and deexcitation products |
| **Neutral current** |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

# Neutrino interactions in the ~10 MeV range

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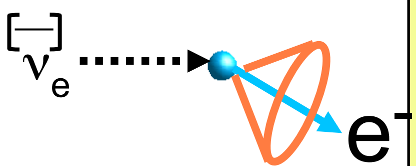
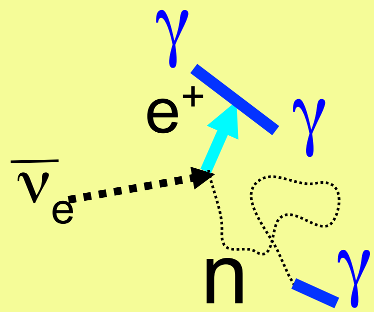
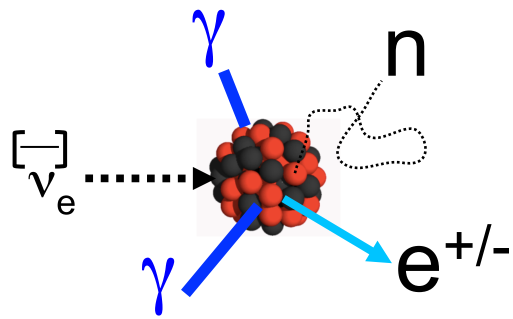
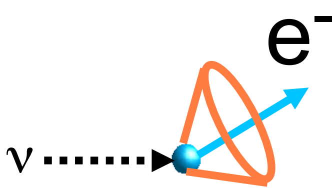
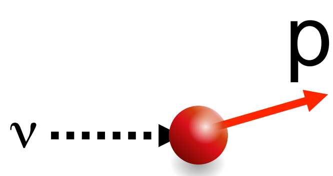
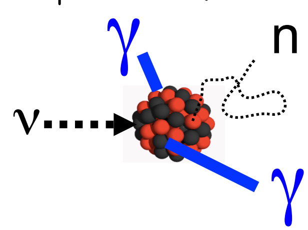
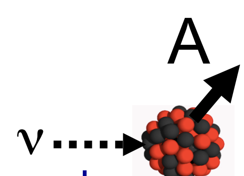
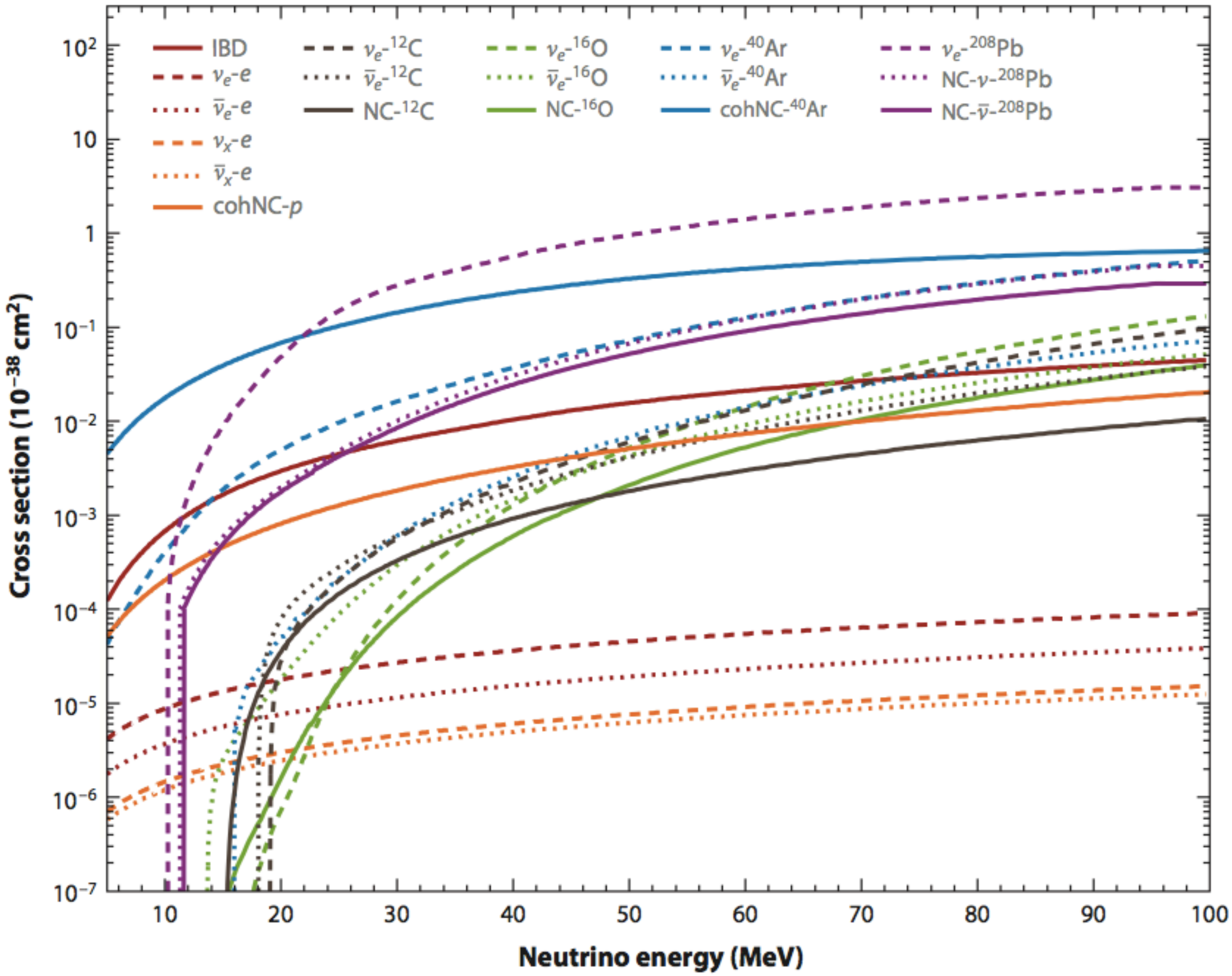
| **Charged current** | Elastic scattering<br>$\nu + e^- \rightarrow \nu + e^-$<br> | Inverse beta decay<br>$\bar{\nu}_e + p \rightarrow e^+ + n$<br> | $\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$<br>$\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$<br><br>Various possible ejecta and deexcitation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

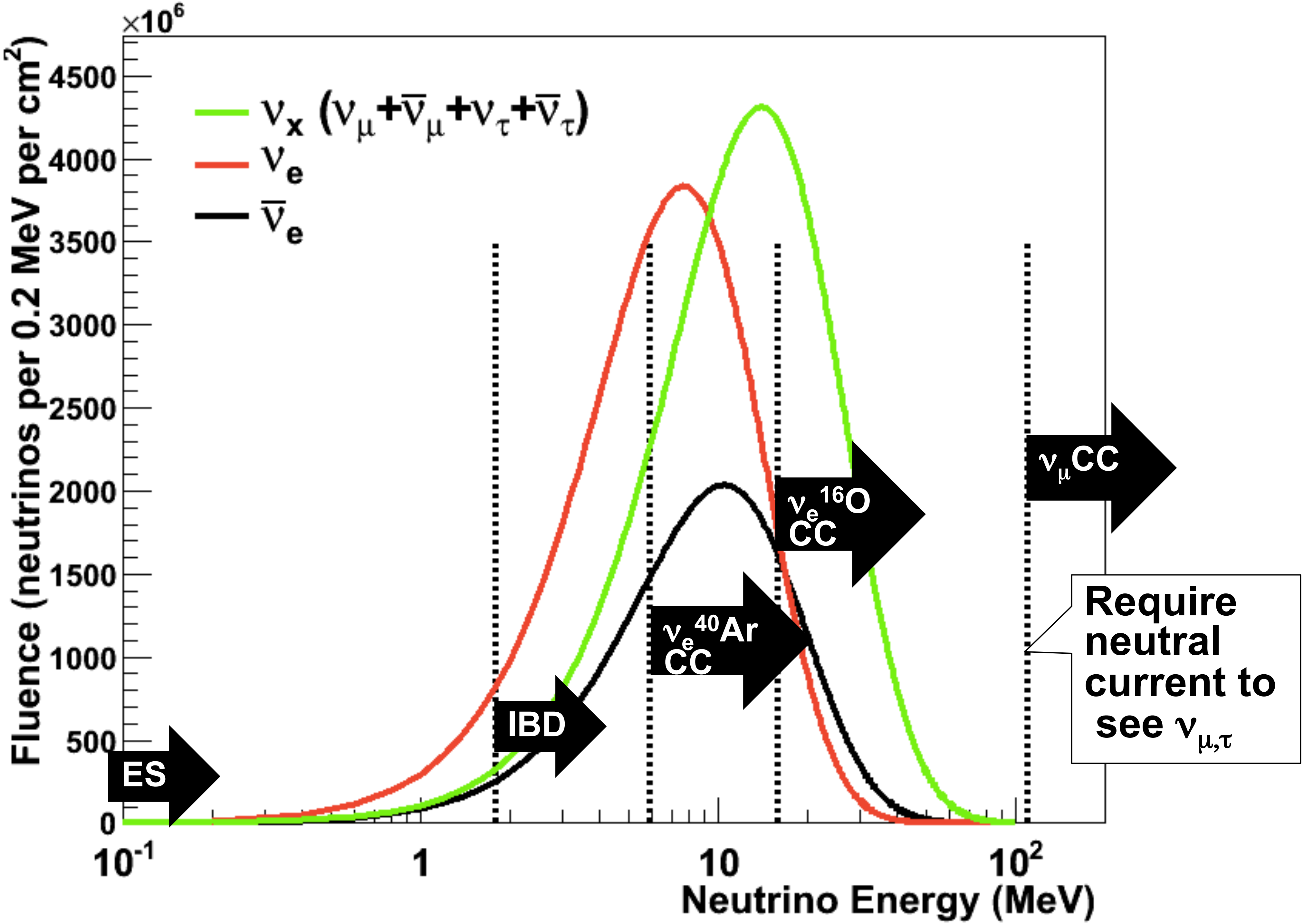
IBD (electron *anti*neutrinos) dominates for current detectors

# Cross-sections in this energy range

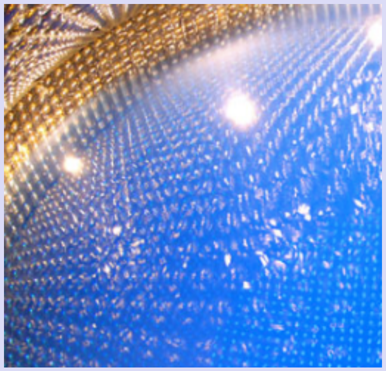
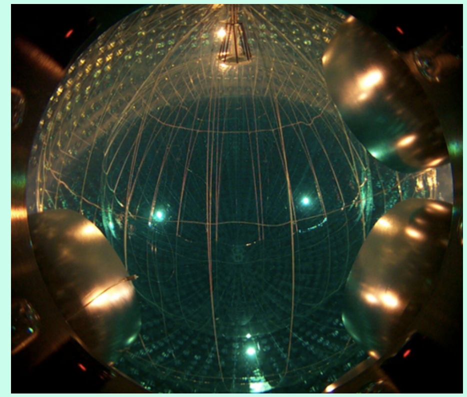



Of these, only IBD and ES on electrons well understood theoretically (or experimentally)...

# Neutrino interaction thresholds



# Current main supernova neutrino detector types

| Water | Scintillator |
| --- | --- |
|   |  |
| **Argon** | **Lead** |
|  |  |

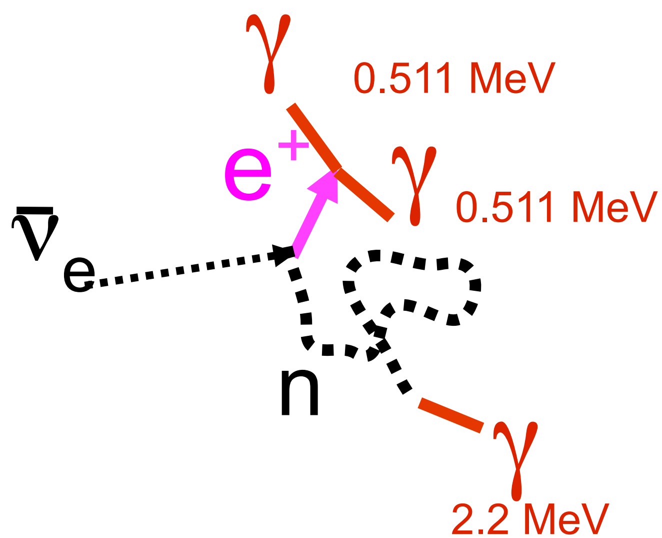
+ some others (e.g. DM detectors)

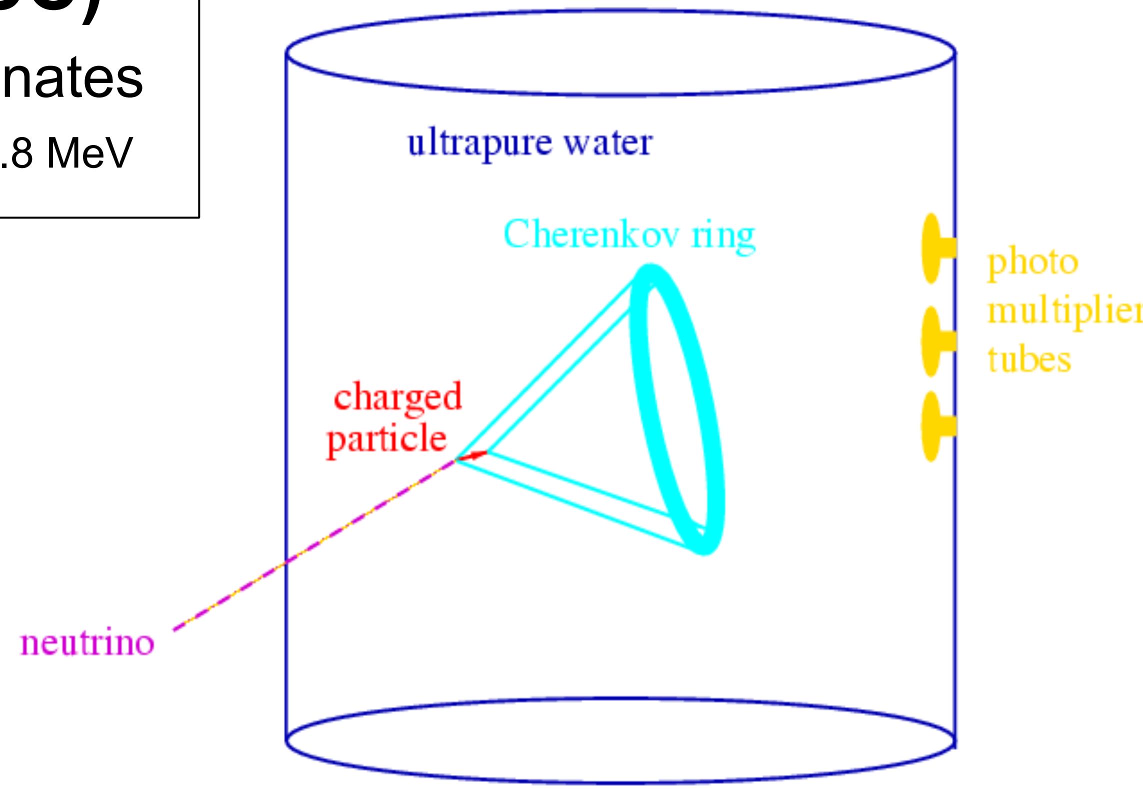
# Water Cherenkov detectors

**Inverse Beta Decay (CC)**

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

$E_{thr}$=1.8 MeV

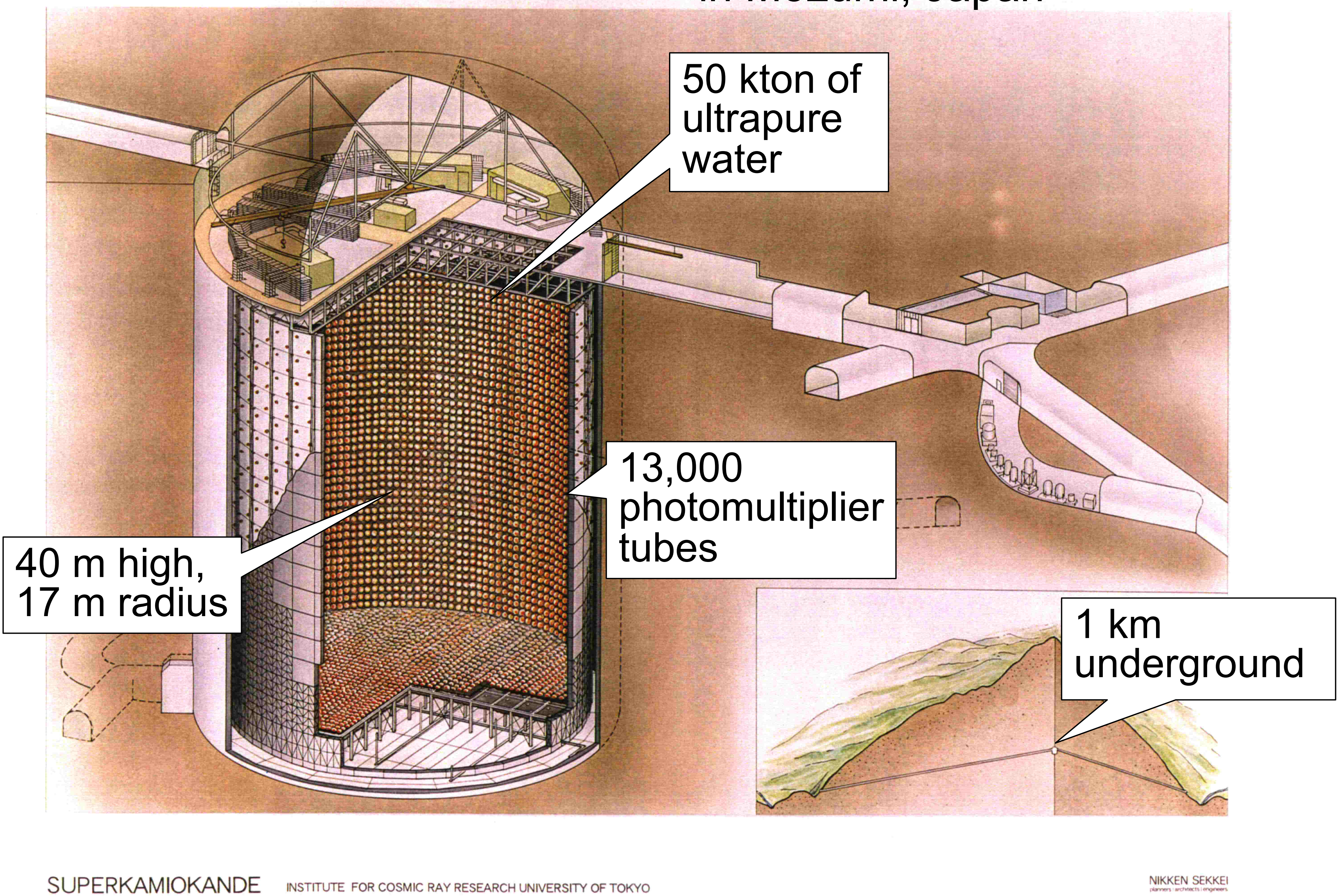



- See Cherenkov light from the positron (~positron is isotropic)
- Can't see 0.511 MeV $\gamma$'s (why not?)
- More on neutron detection in a bit
- Limited by photocoverage (SK: ~40% ➔ ~6 pe/MeV)

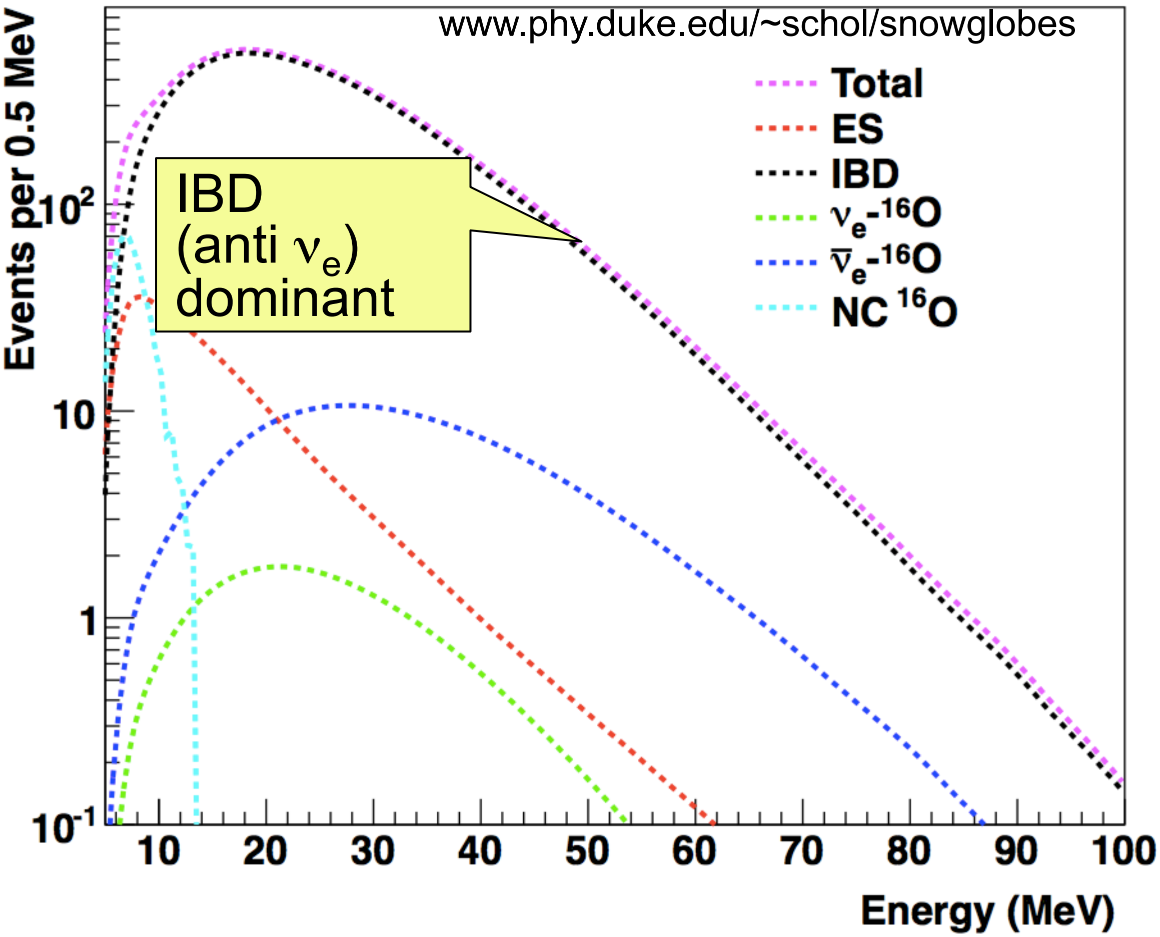
# Super-Kamiokande

**Water Cherenkov** detector
in Mozumi, Japan

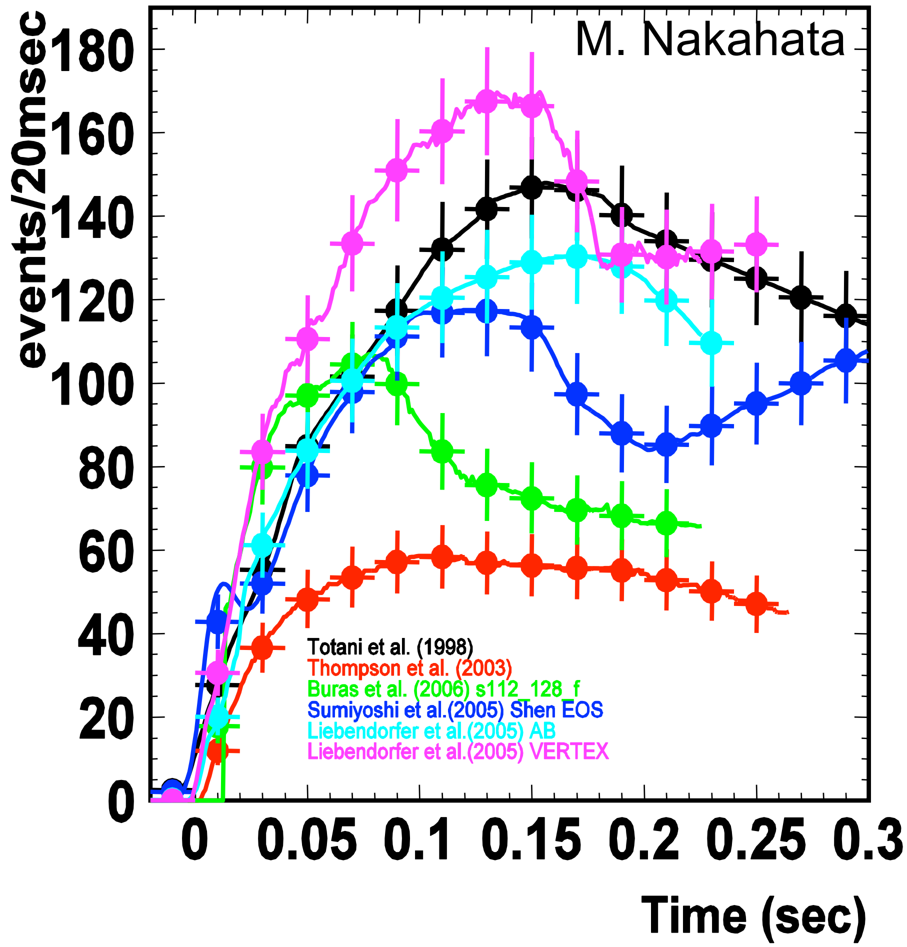


# Supernova signal in a water Cherenkov detector

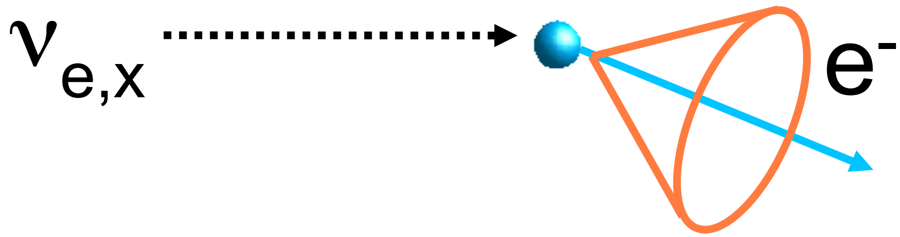
Events seen, as a function of observed energy




For 100 kton.
30% PMT coverage
@ 10 kpc

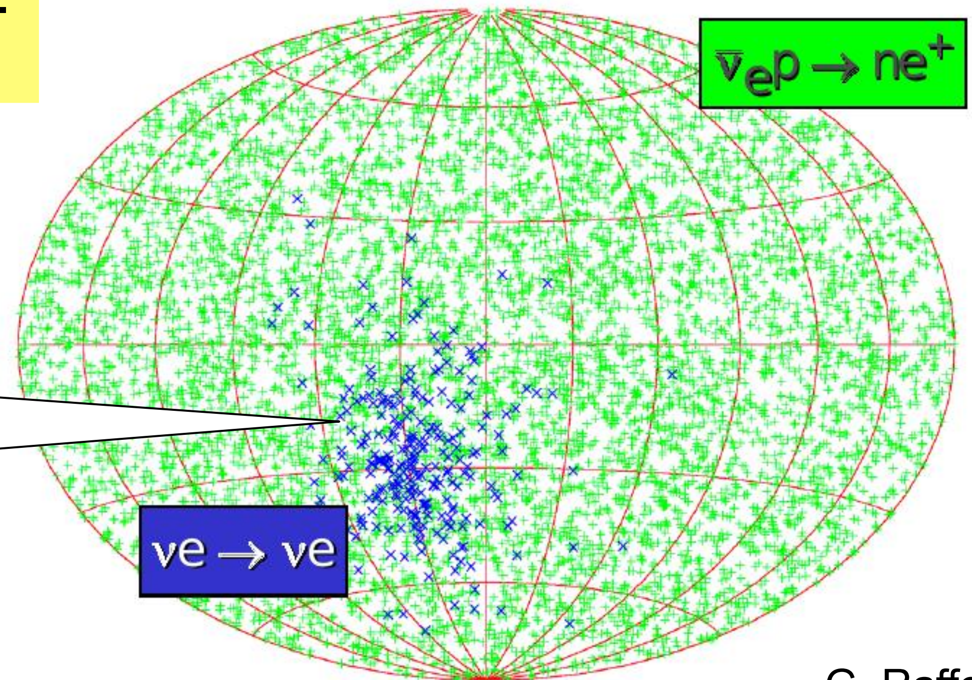



Events vs time
for SK, for
different models




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

**Pointing** from neutrino-electron elastic scattering

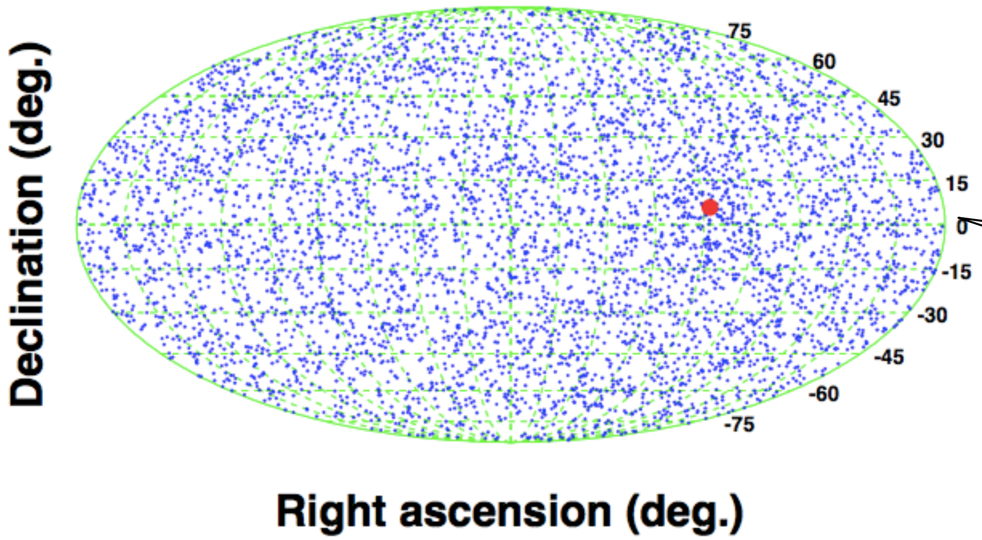



G. Raffelt

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

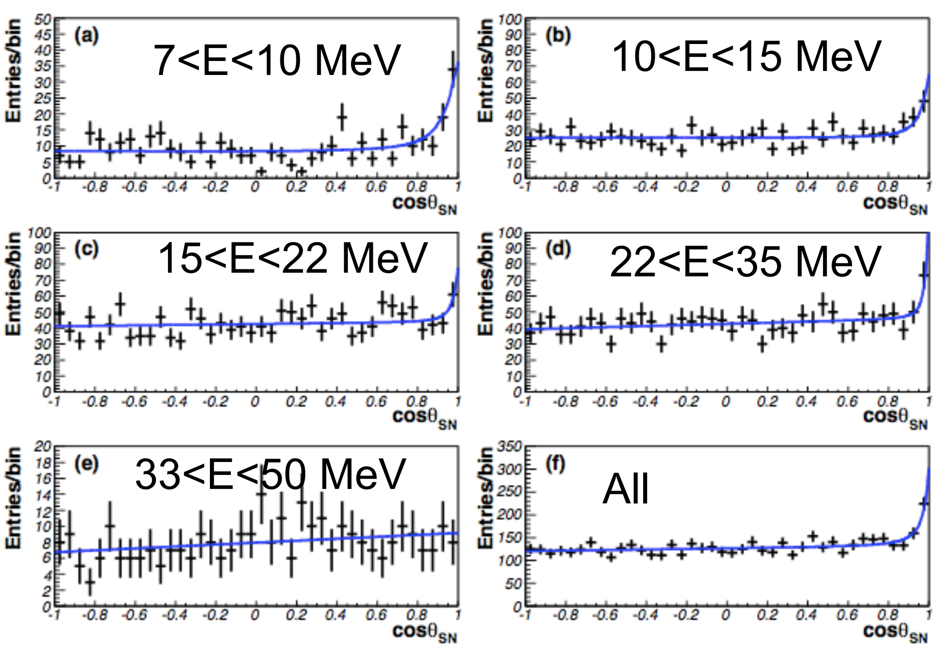
degraded by isotropic IBD

# Pointing in Water Cherenkov: Super-K

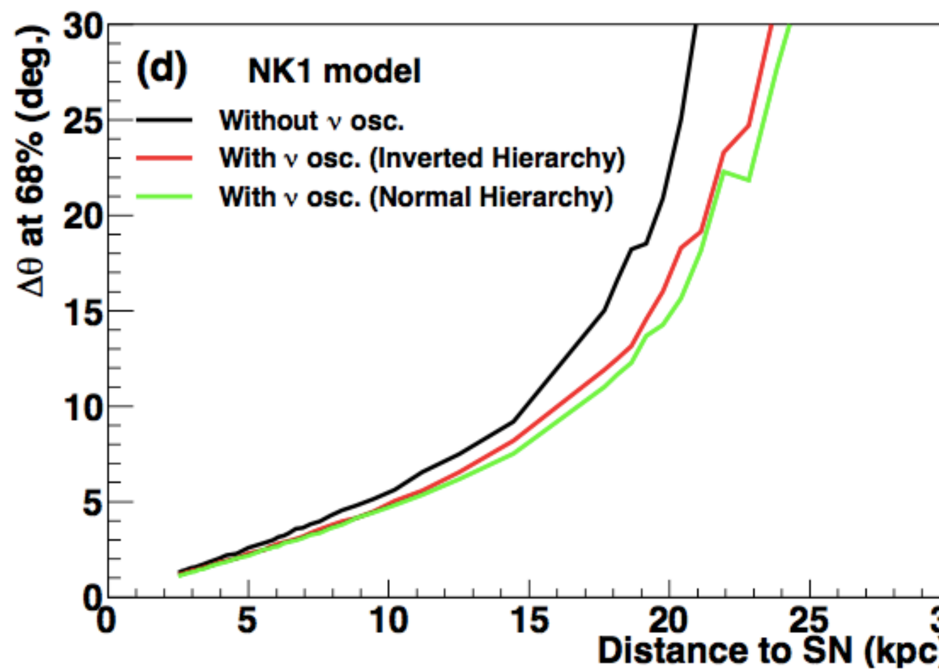


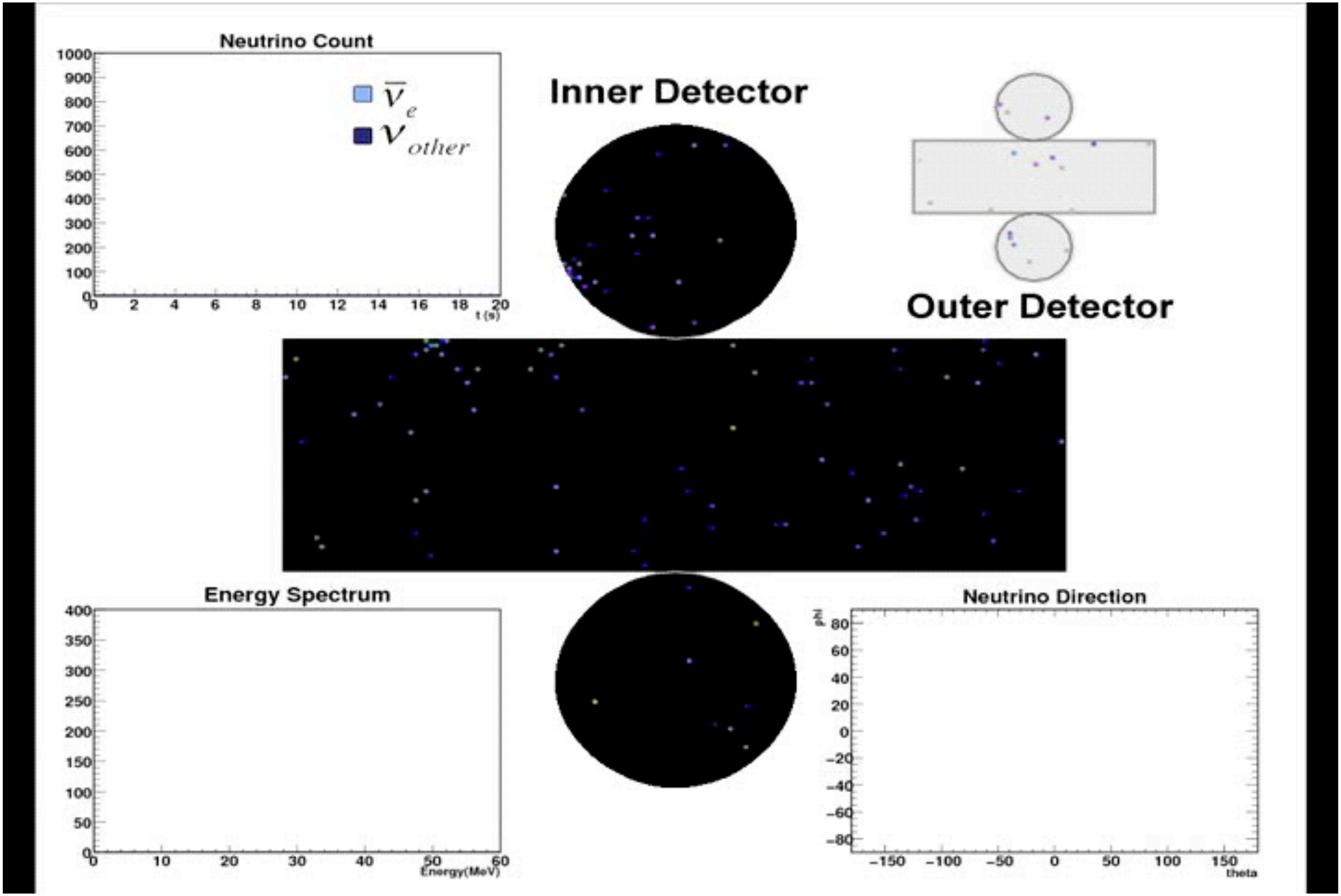

K. Abe et al., Astropart. Phys. 81 (2016) 39-48

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

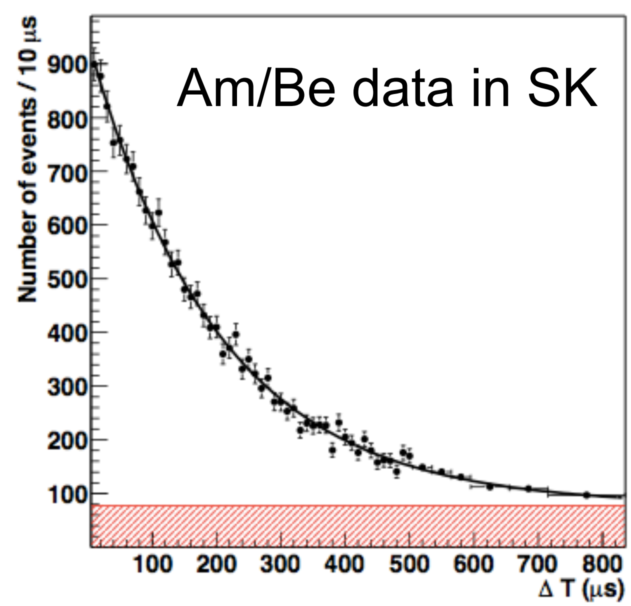
## "Drug-free" neutron tagging

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

~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)

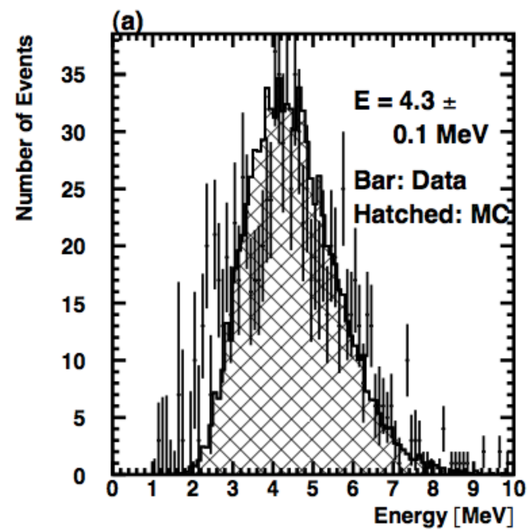
J. Beacom & M. Vagins, PRL 93 (2004) 171101

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

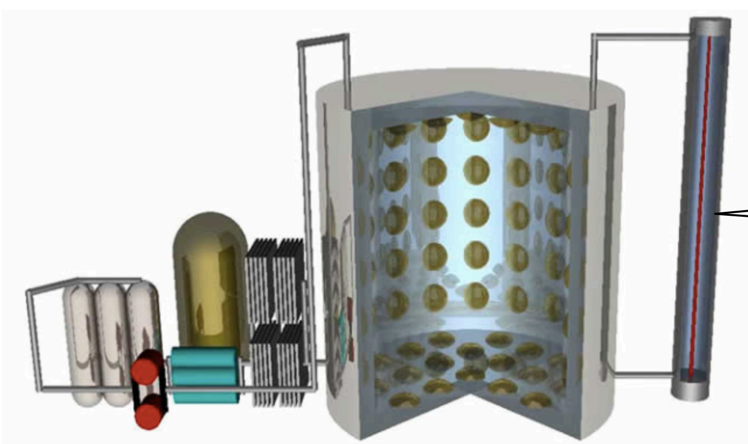
n + Gd → Gd* → Gd + γ

$$\sum E_\gamma = 8\,MeV$$

About 4 MeV visible energy per capture




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

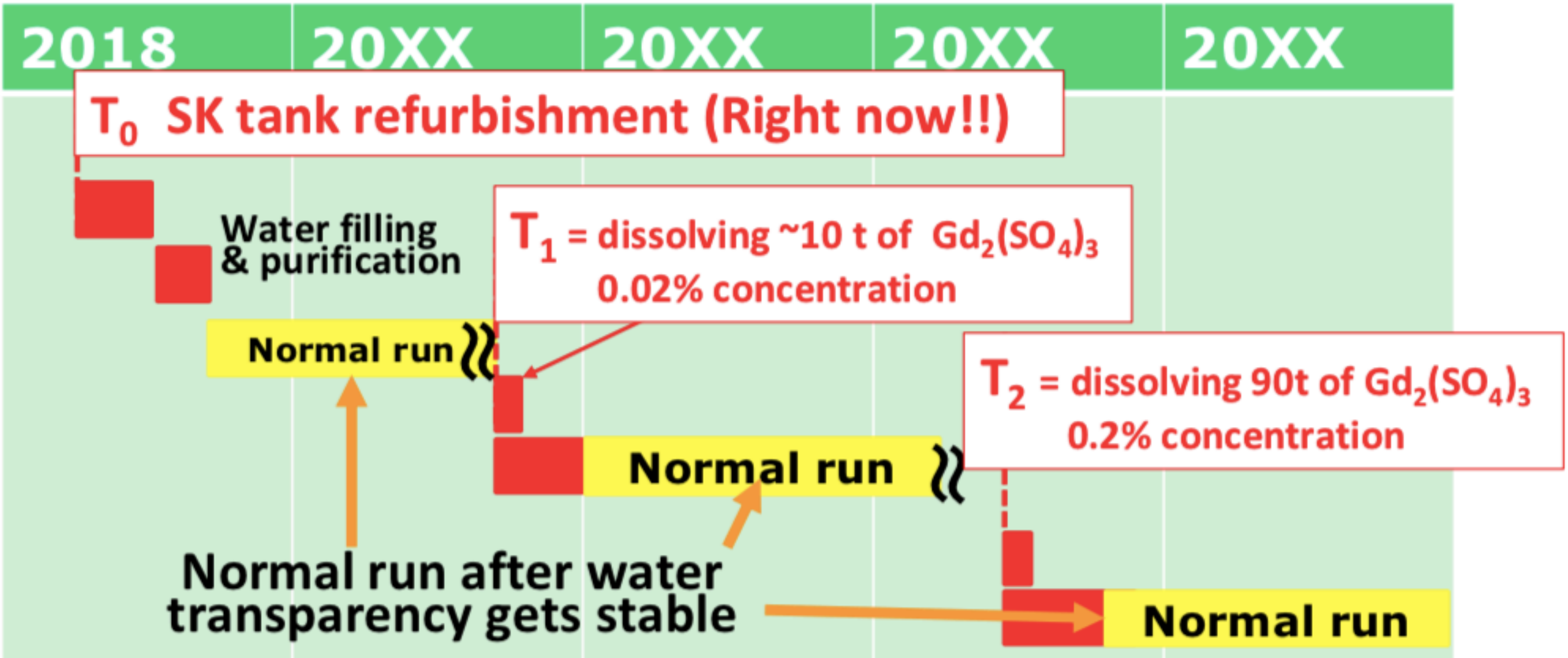


EGADS: test tank in the Kamioka mine for R&D

**SK-Gd** going ahead, starting this summer

# SK-Gd schedule

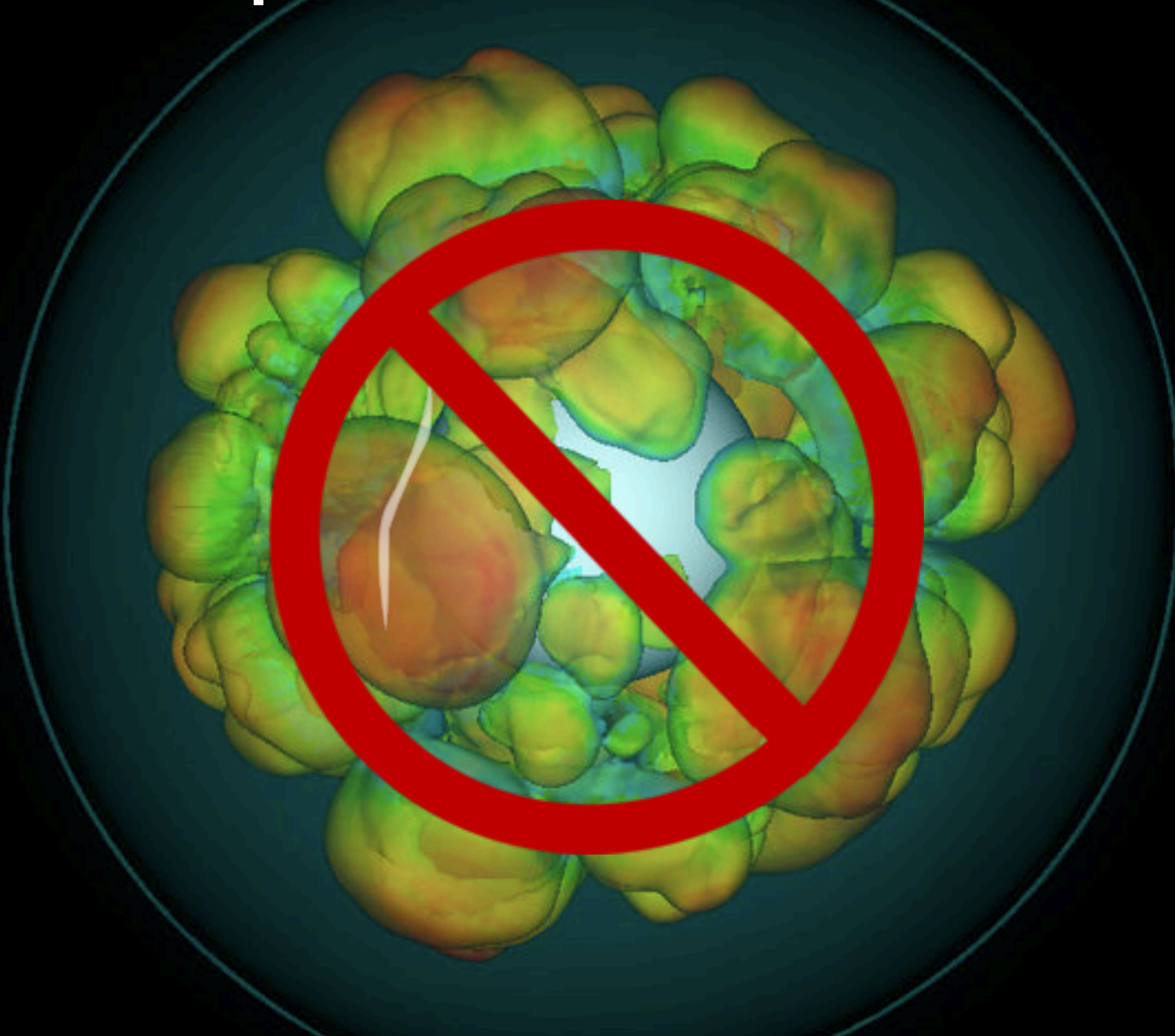
- Detailed schedule planning is on-going taking into account T2K beam availability.
- Earliest possible Gd in Super-K would be in late 2019.




- 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 $Gd_2(SO_4)_3 8H_2O$

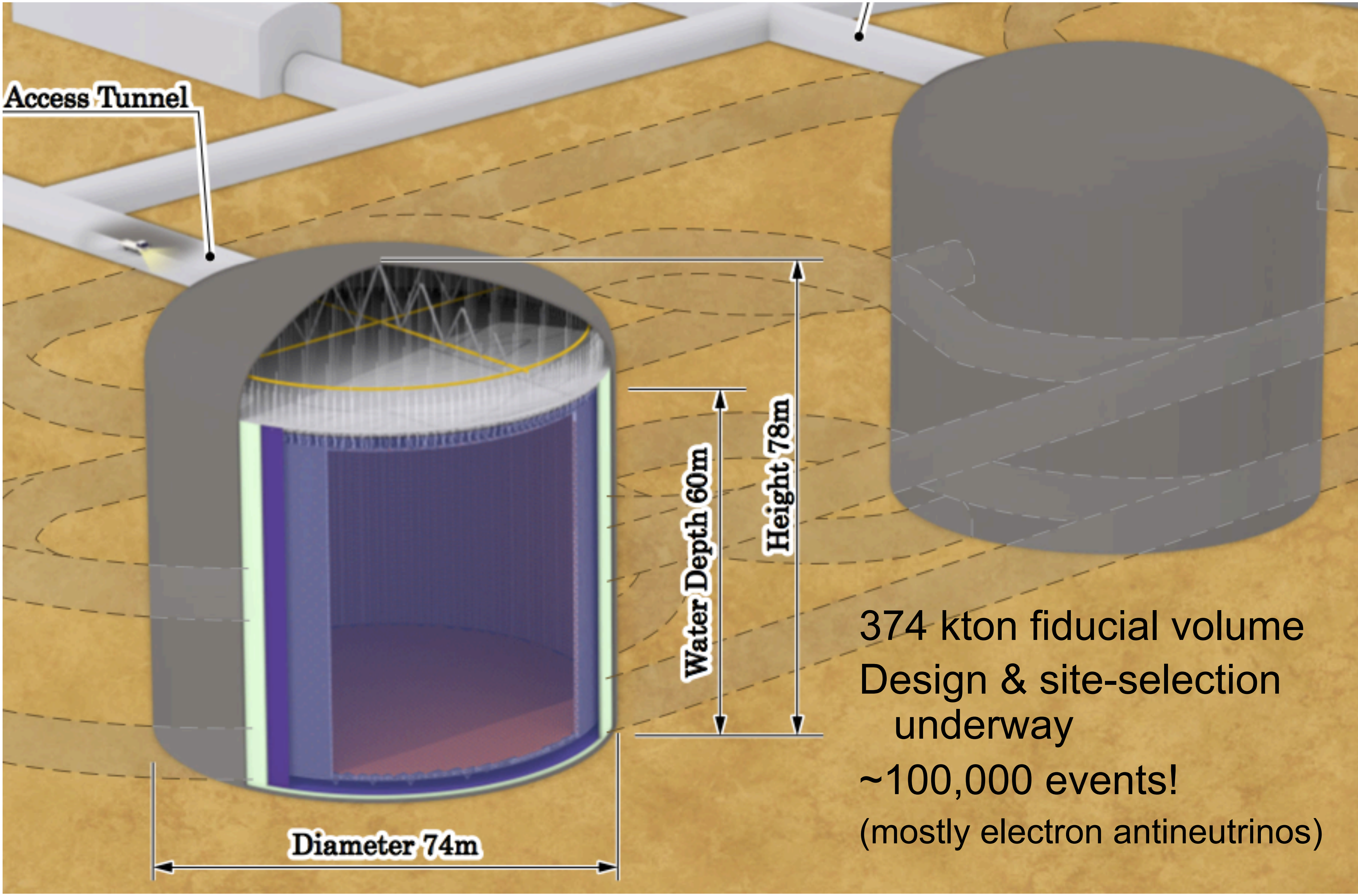
M. Ikeda, Neutrino 2018

**No core collapses allowed** for the next ~six 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!

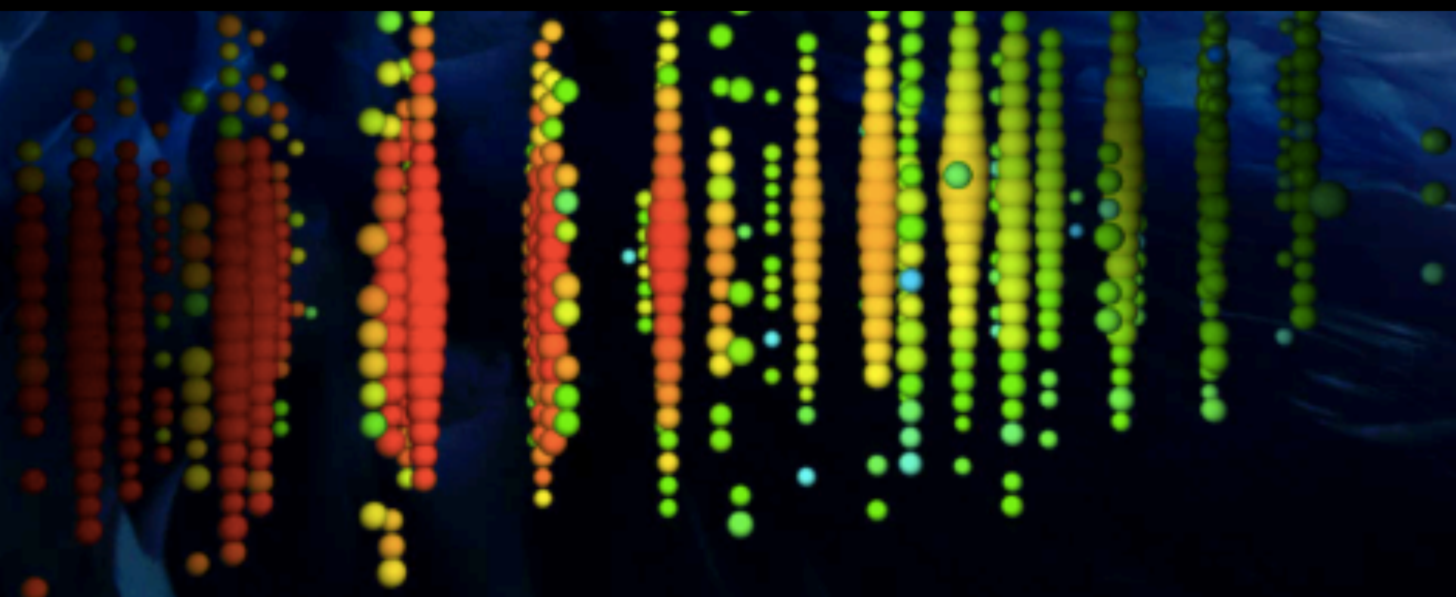
(mostly electron antineutrinos)

# Long string water Cherenkov detectors

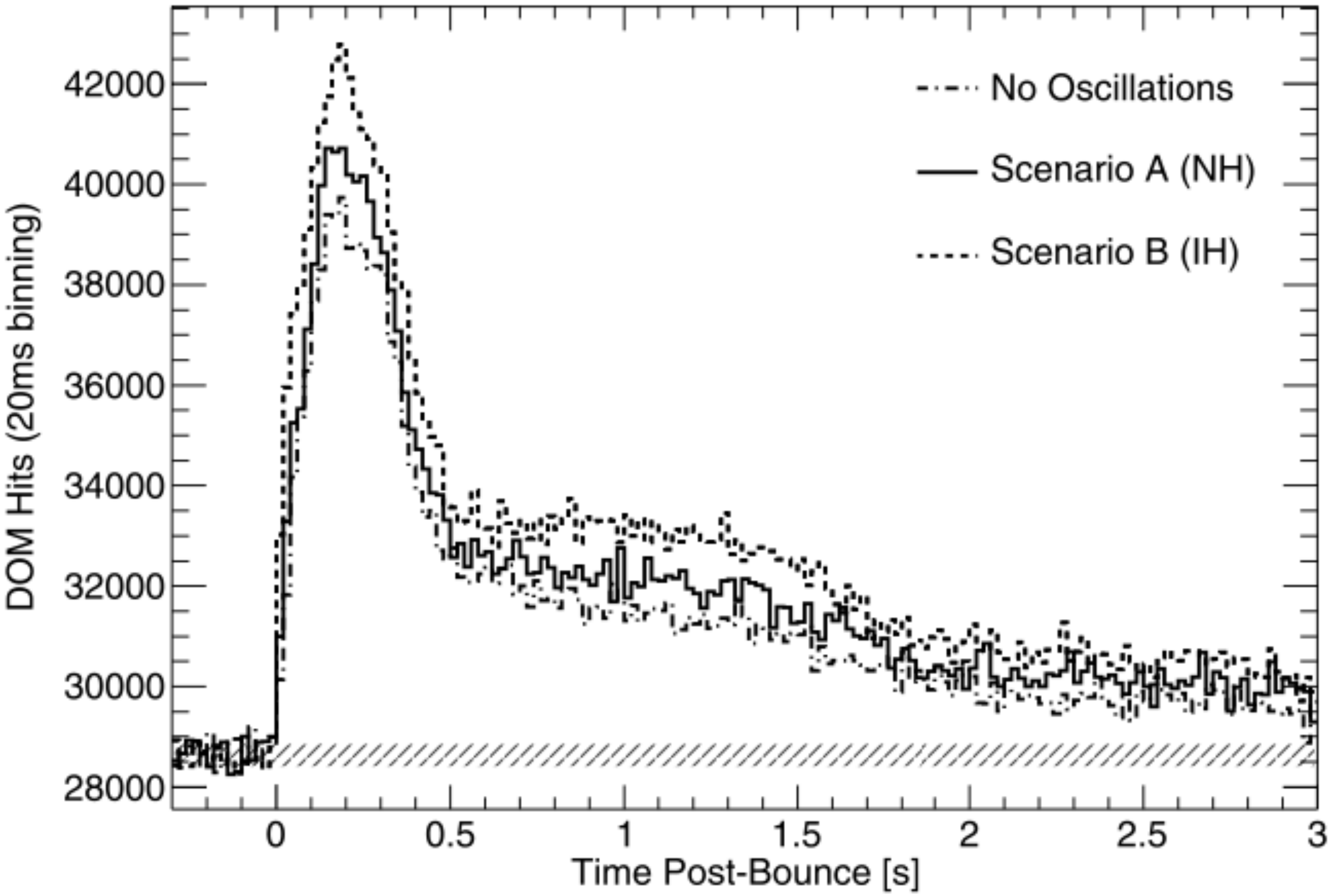
~kilometer long
strings of PMTs
in very clear water
or ice (IceCube, ANTARES)

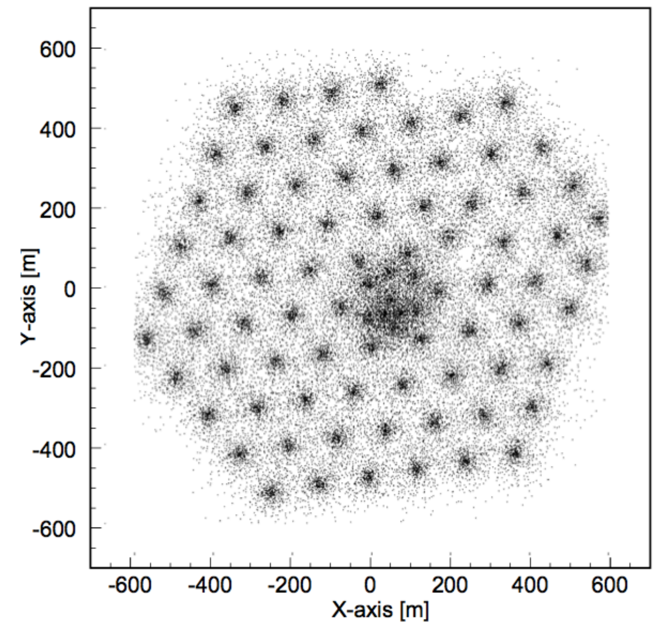
Nominally multi-GeV energy threshold...
but, may see burst of low energy (anti-) $\nu_e$'s as
*coincident increase in single PMT count rate*

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



# Long string water Cherenkov detectors

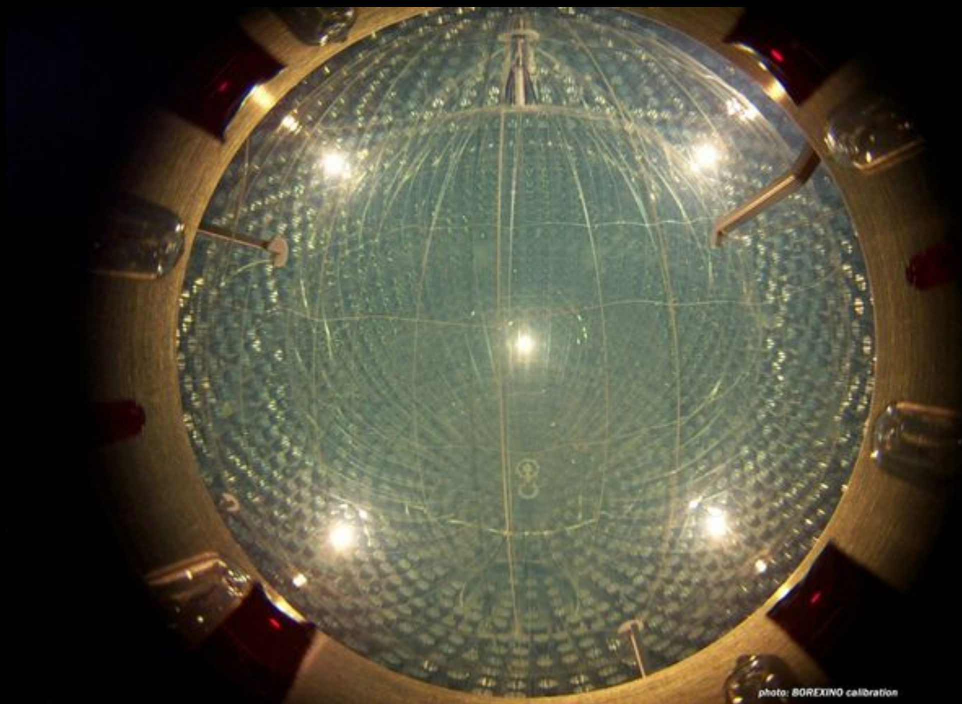



IceCube collaboration, A&A 535, A109 (2011)

Map overall time structure of burst

# Scintillation detectors

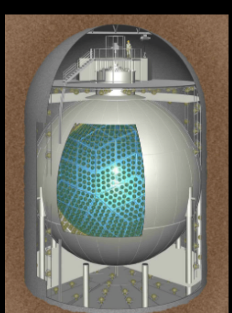


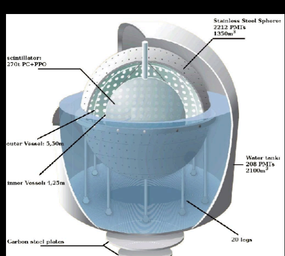

Liquid hydrocarbon ($C_nH_{2n}$) that emits (lots of) photons when charged particles lose energy in it

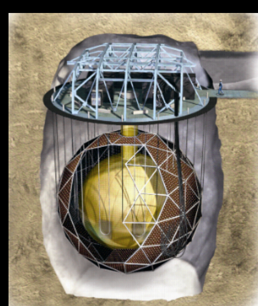
Will see supernova **electron antineutrinos**, with good energy resolution

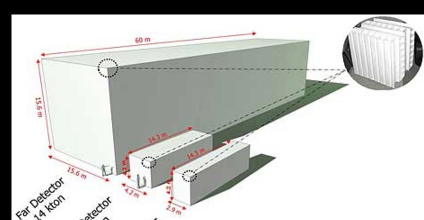
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

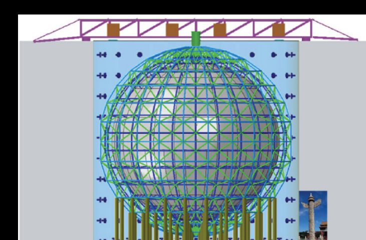
Many examples worldwide of current and future detectors



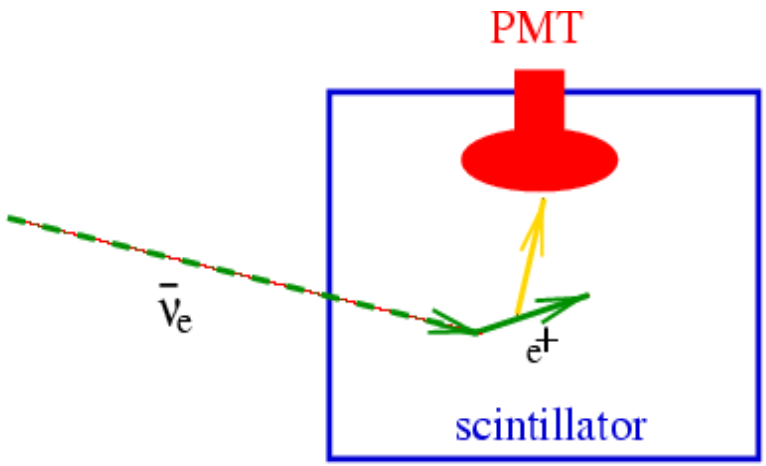






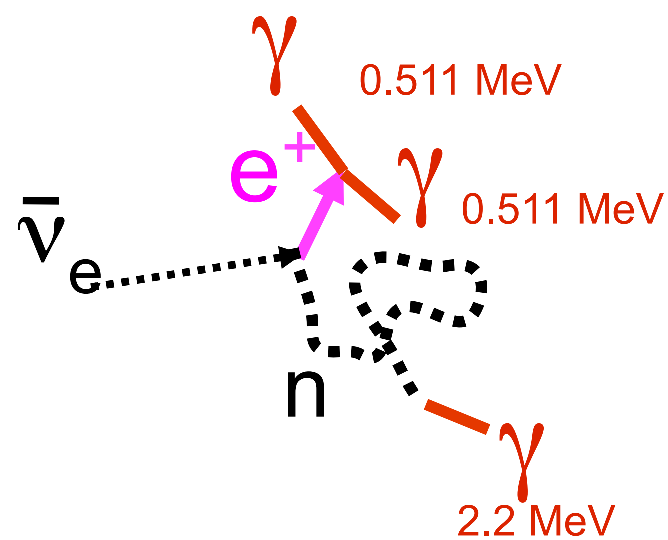


# Scintillation detectors



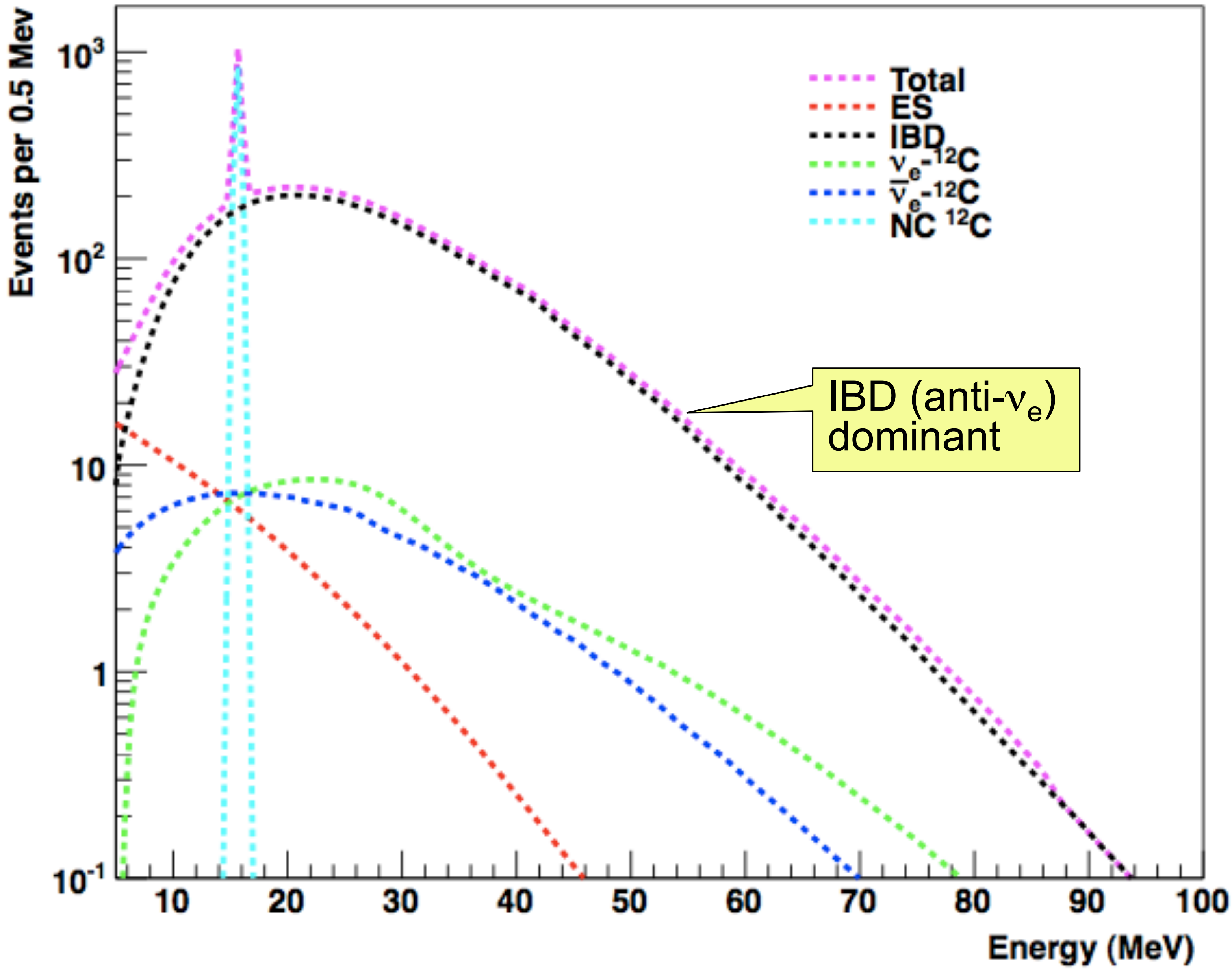

Liquid scintillator ($C_nH_{2n}$) volume surrounded by photomultipliers

- **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 $\gamma$'s

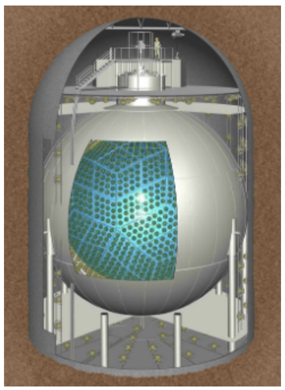
# Interaction channels in scintillator




**50 kt @ 10 kpc**

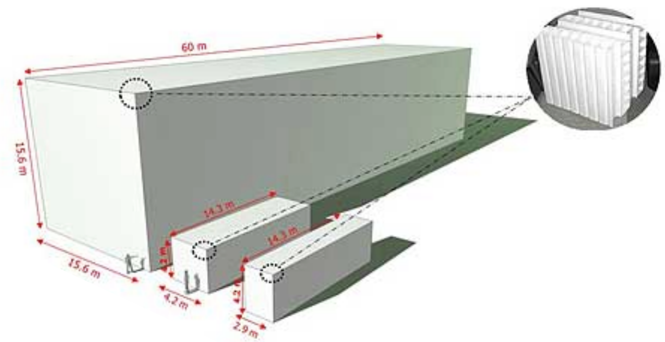
# Current and near-future scintillator detectors

**KamLAND**
(Japan)
1 kton



**LVD**
(Italy)
1 kton

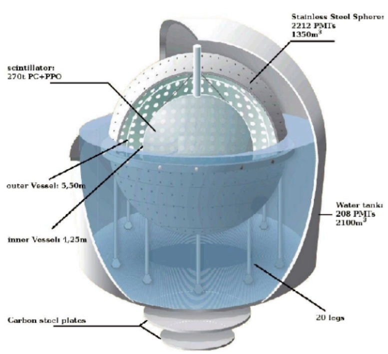
**NOvA**
(USA)
14 kton





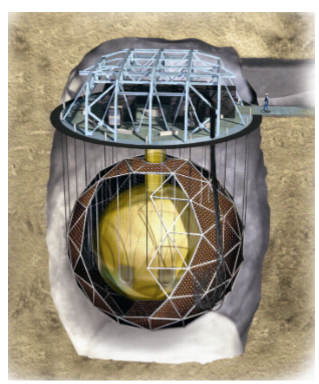
(on surface, but
may be possible
to extract counts
for known burst)

**Borexino**
(Italy)
0.33 kton

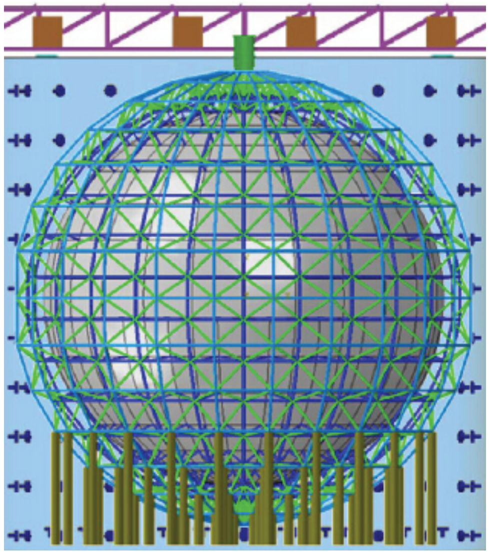




**SNO+**
(Canada)
1 kton

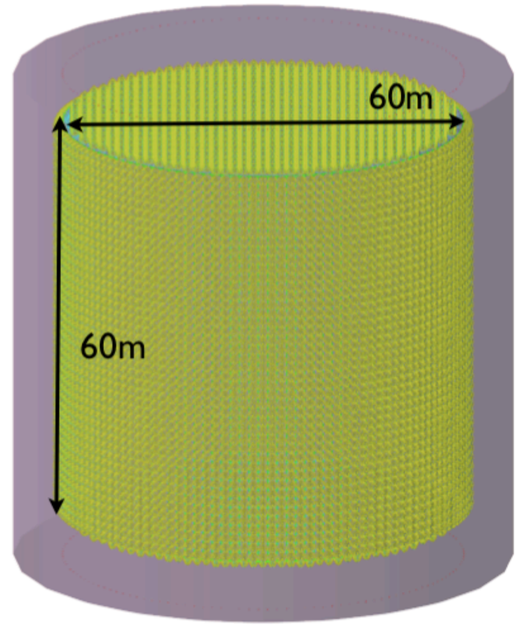


# Future detector proposals



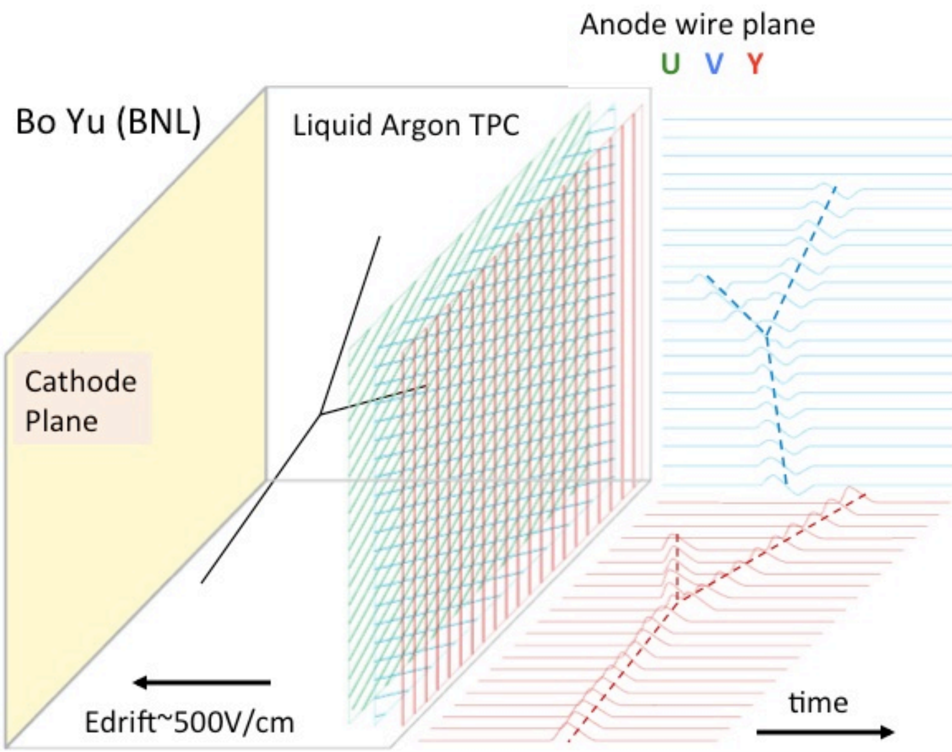
**JUNO**
(China)
20 kton

**Jinping**
(China)
2 kton




**THEIA**
(TBD)
50-100 kton
WbLS

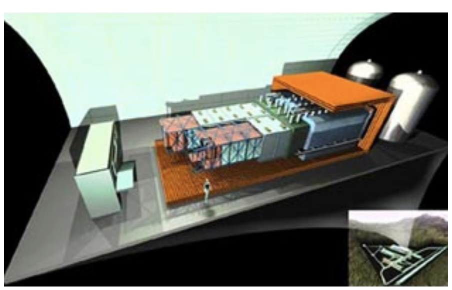
# Liquid argon time projection chambers



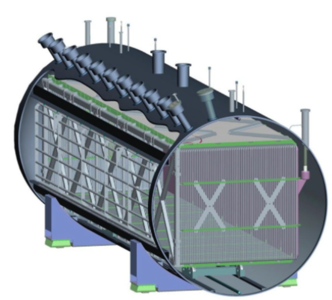

fine-grained trackers
sensitive to **electron neutrinos**
(as opposed to antineutrinos)

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

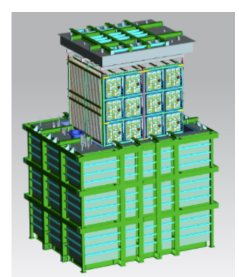
**ICARUS**
(Italy➔USA)
0.6 kton



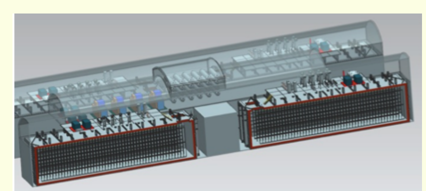
**MicroBooNE**
(USA)
0.2 kton



**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

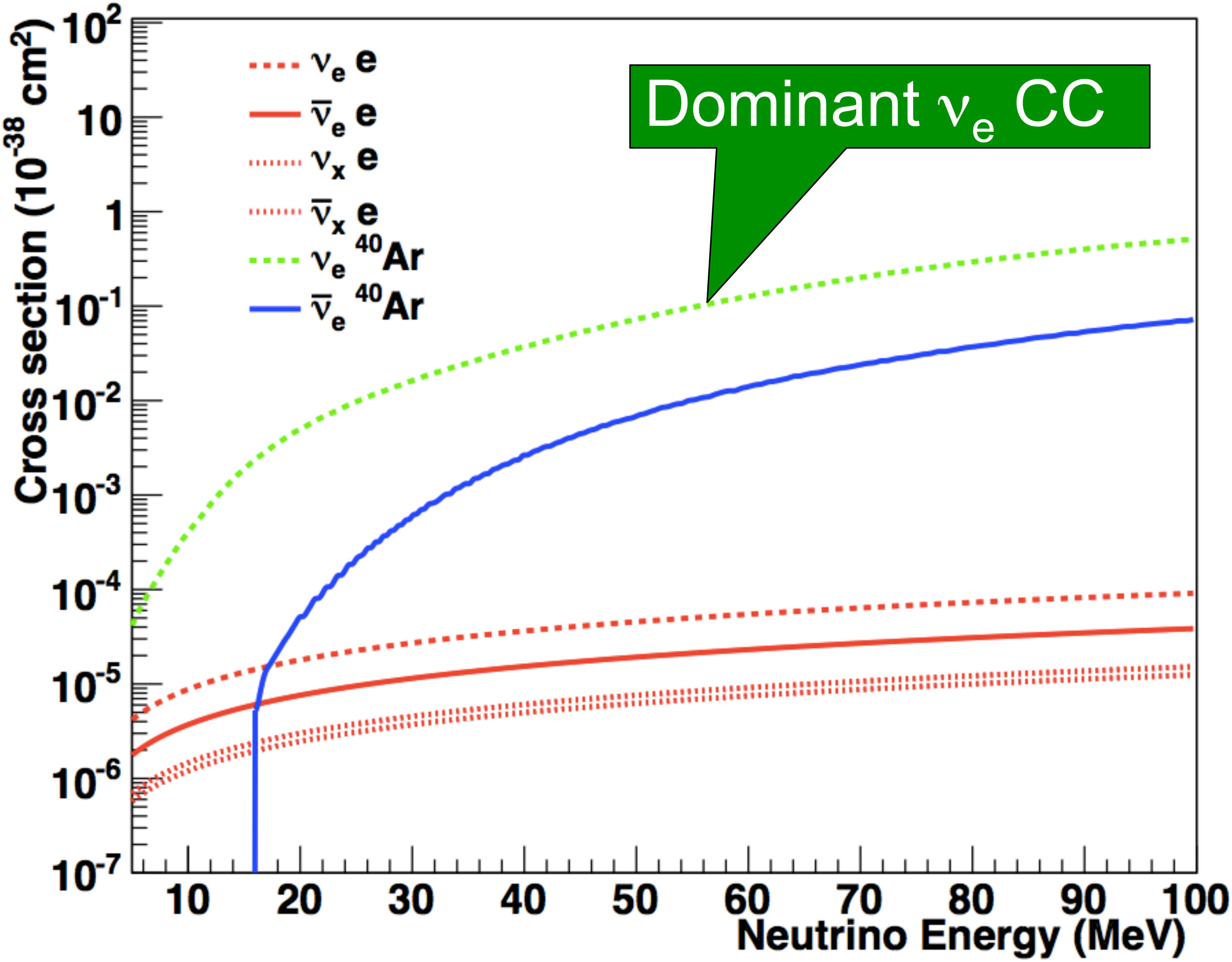
## Elastic scattering

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

Can use for pointing

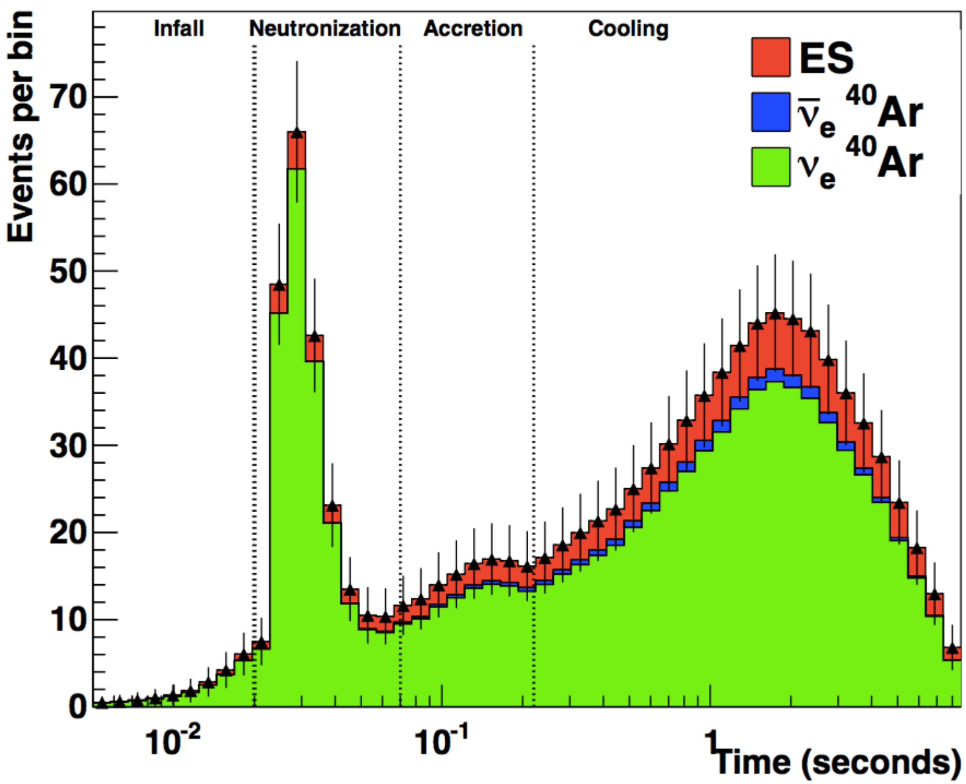
In principle can tag modes with deexcitation gammas (or lack thereof)...

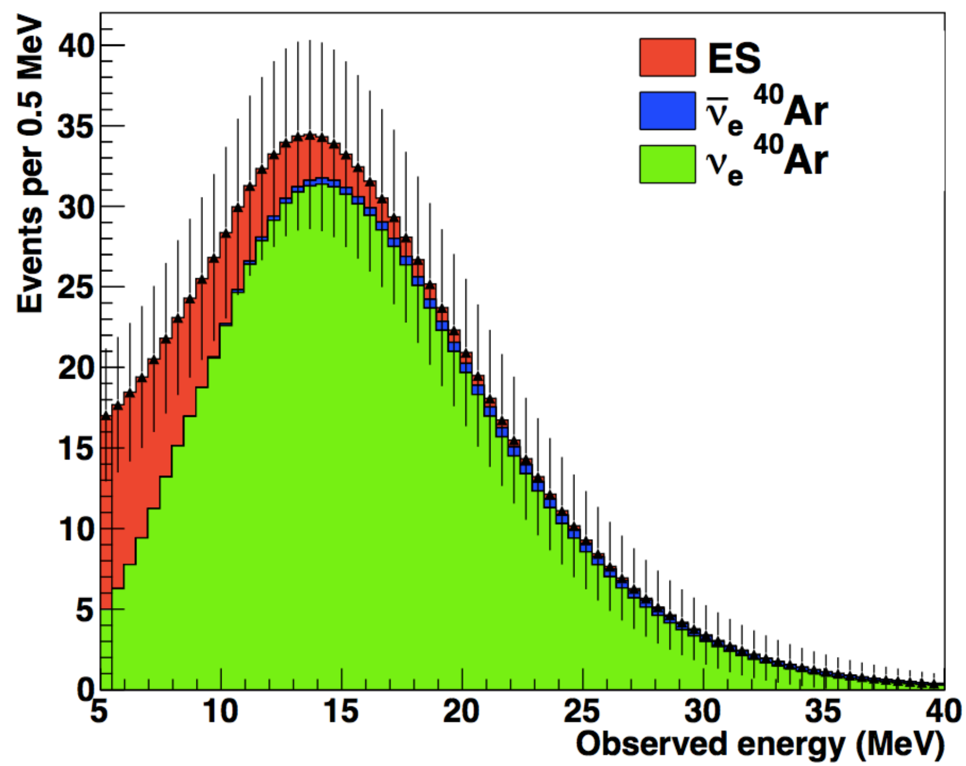
# Cross sections in argon



# Flavor composition as a function of time

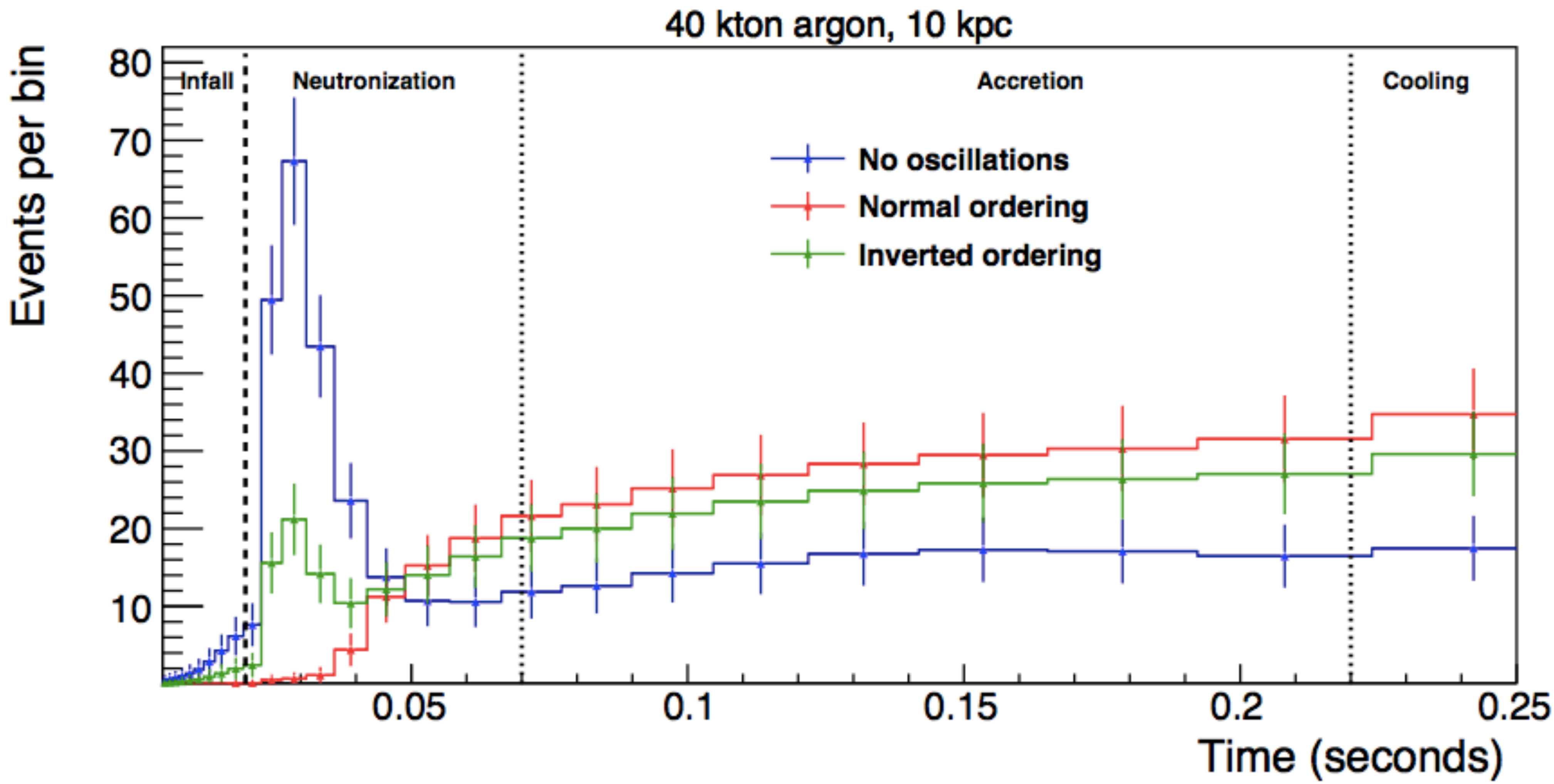
# Energy spectra integrated over time




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)

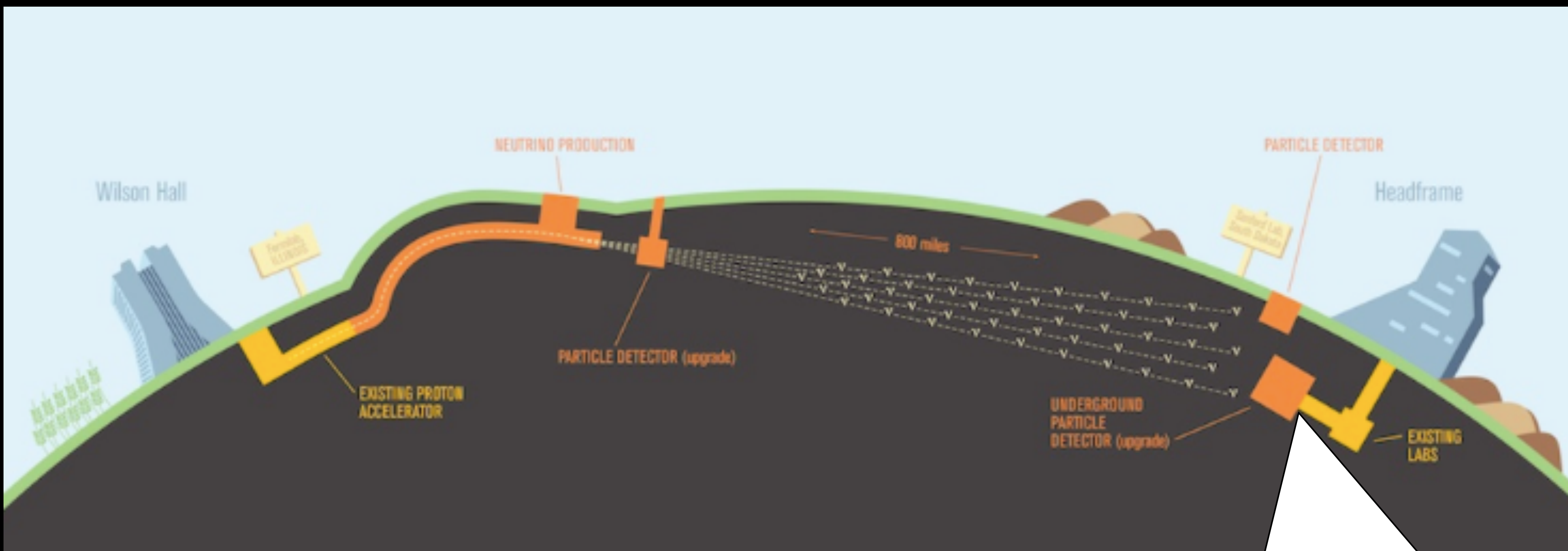
NMO: $F_{\nu_e} = F^0_{\nu_x}$

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

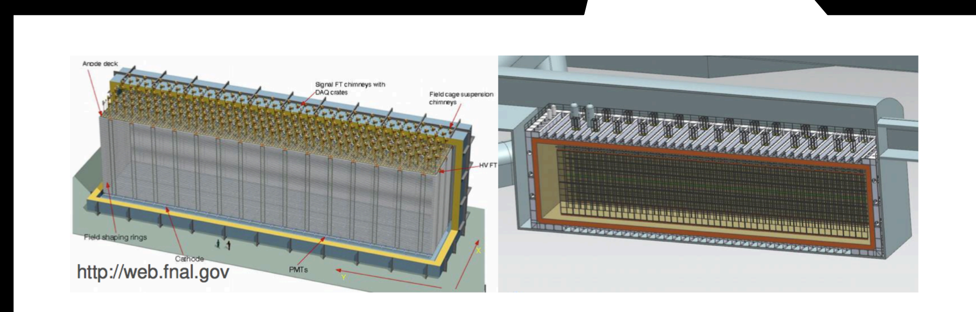
(a robust mass ordering signature!)

# Deep Underground Neutrino Experiment (DUNE)

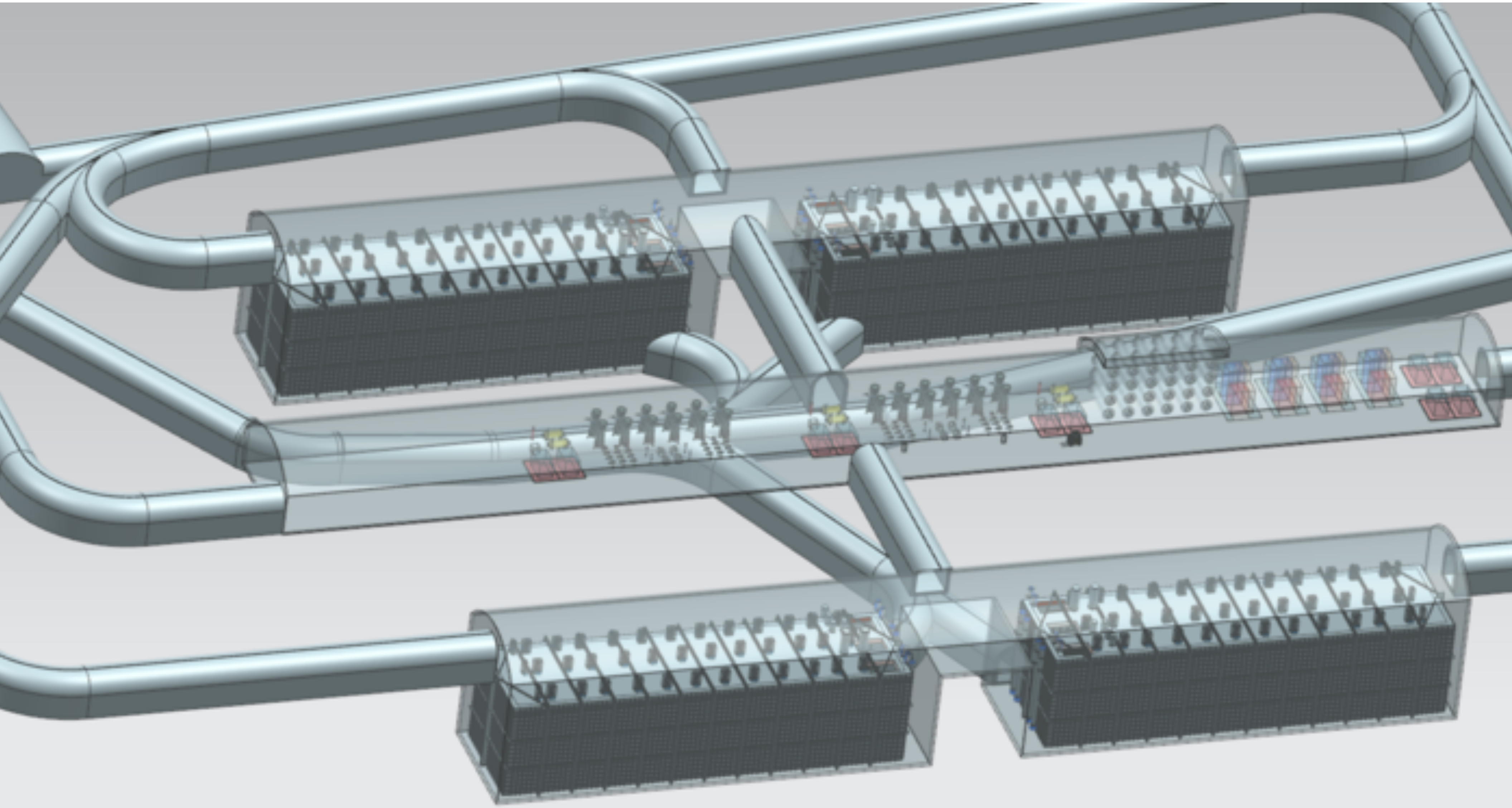
4800 mwe undergound in South Dakota
70 kton LAr (40 kton fiducial, 4x10 kton)
1.2 MW beam from FNAL for long-baseline osc
first module in 2024, beam in 2026




- mass ordering & CPV
- supernova burst
- nucleon decay



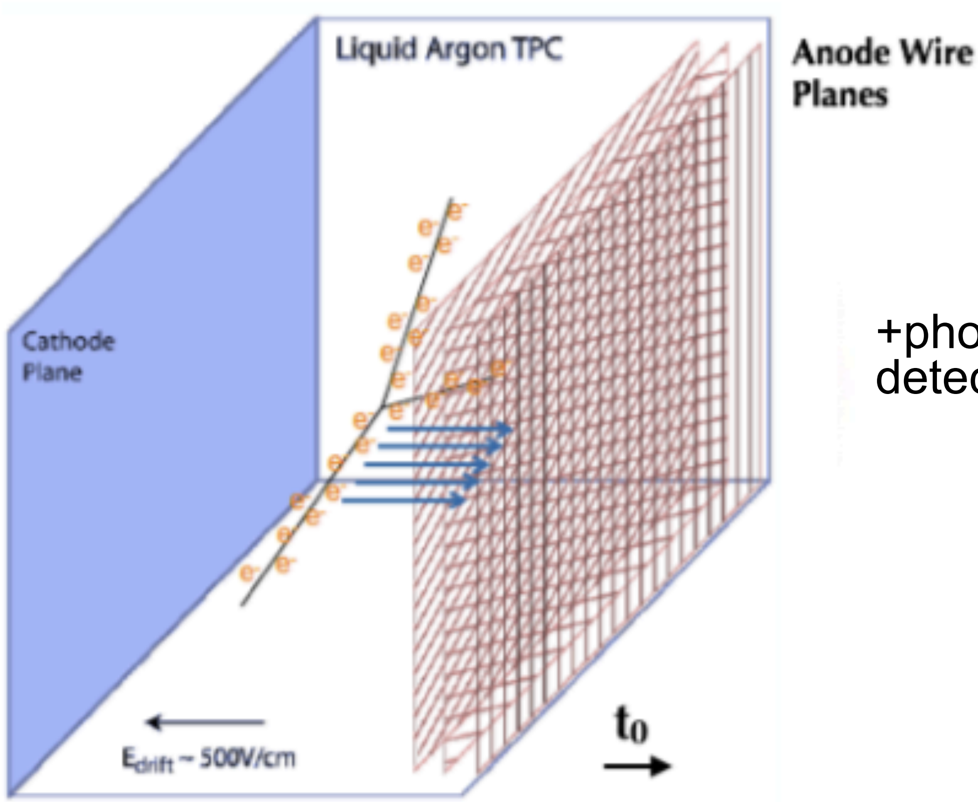
# 4 x 10 kton DUNE LAr modules



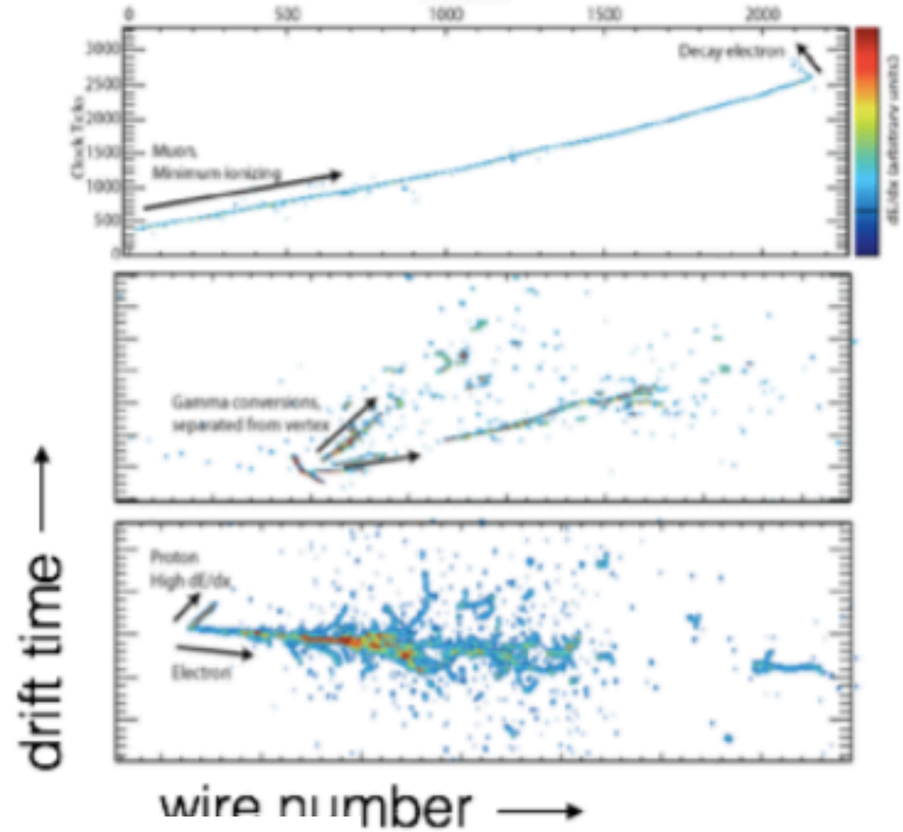
- single-phase and dual-phase TPC designs
- prototypes for both @ CERN test beam

# DUNE Single Phase TPC

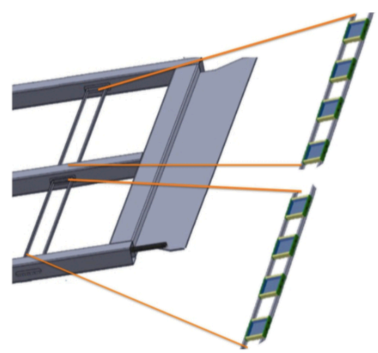
horizontal charge drift, collection on wire planes




+photon detectors

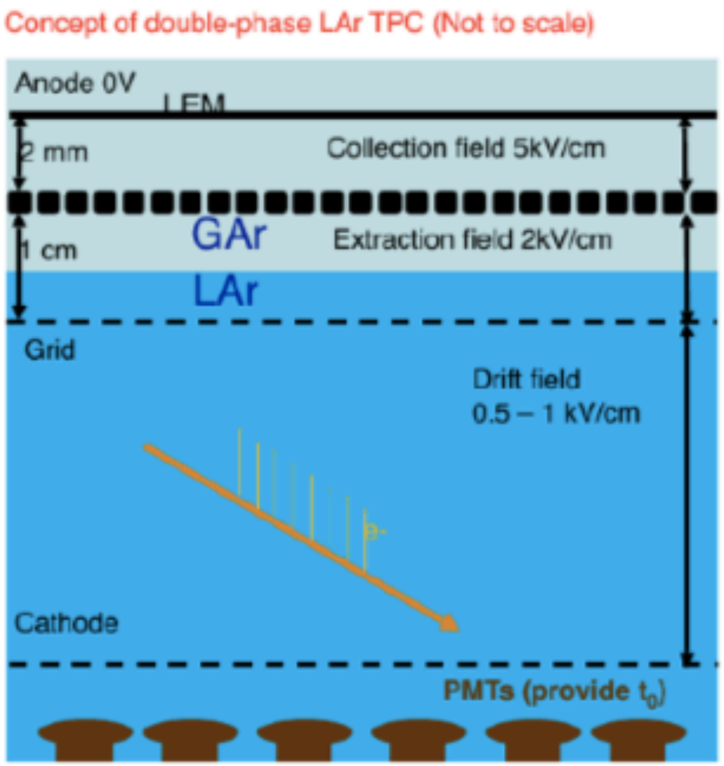


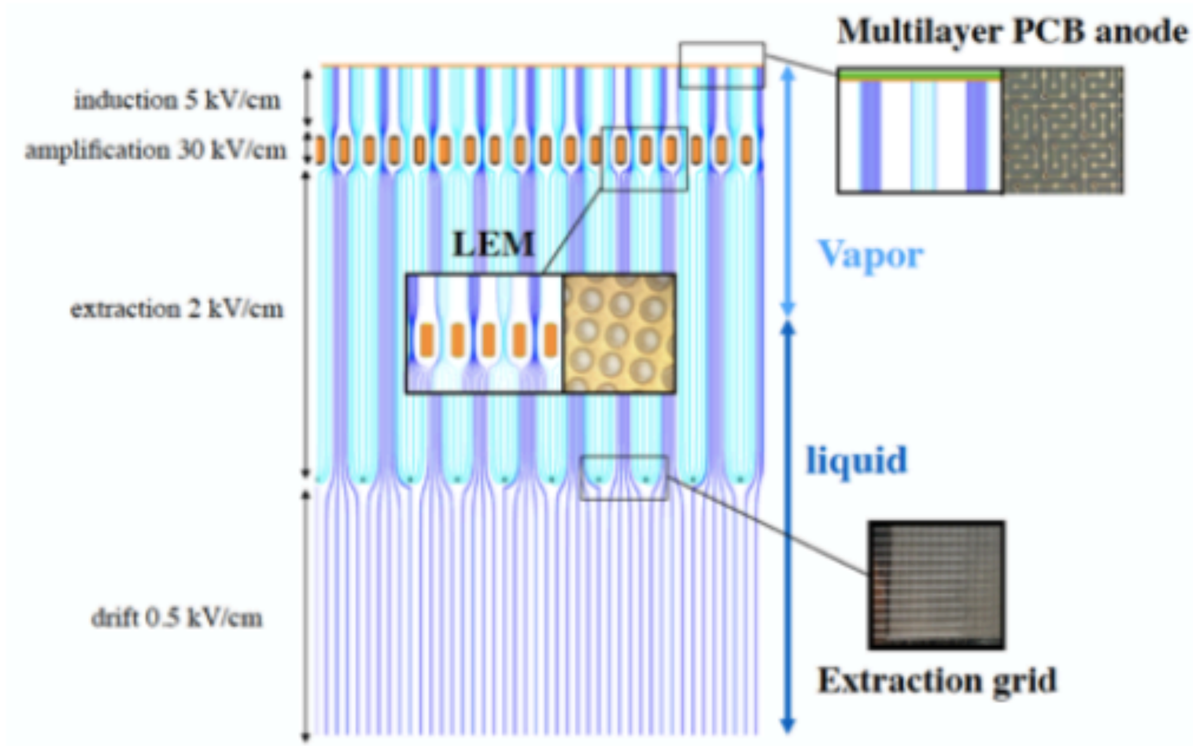

Also: **photon detectors** inserted in anode planes for fast event timing using argon scintillation light



# DUNE Dual Phase TPC

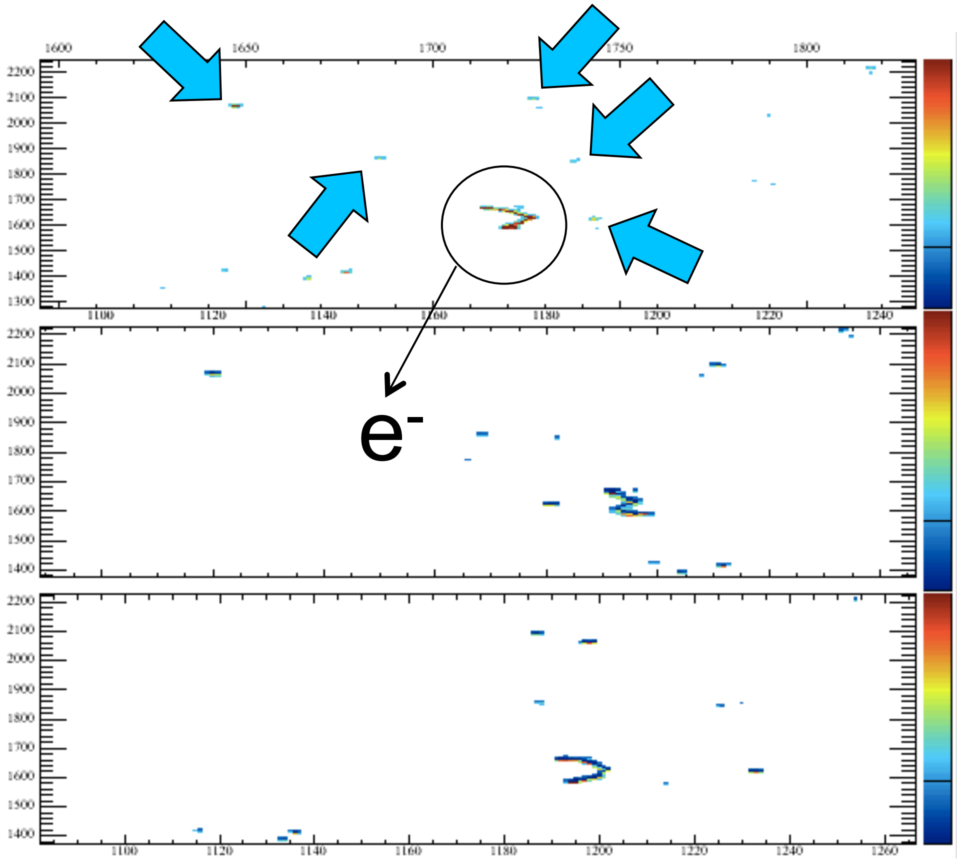
vertical charge drift, charge amplification
at top liquid-gas interface



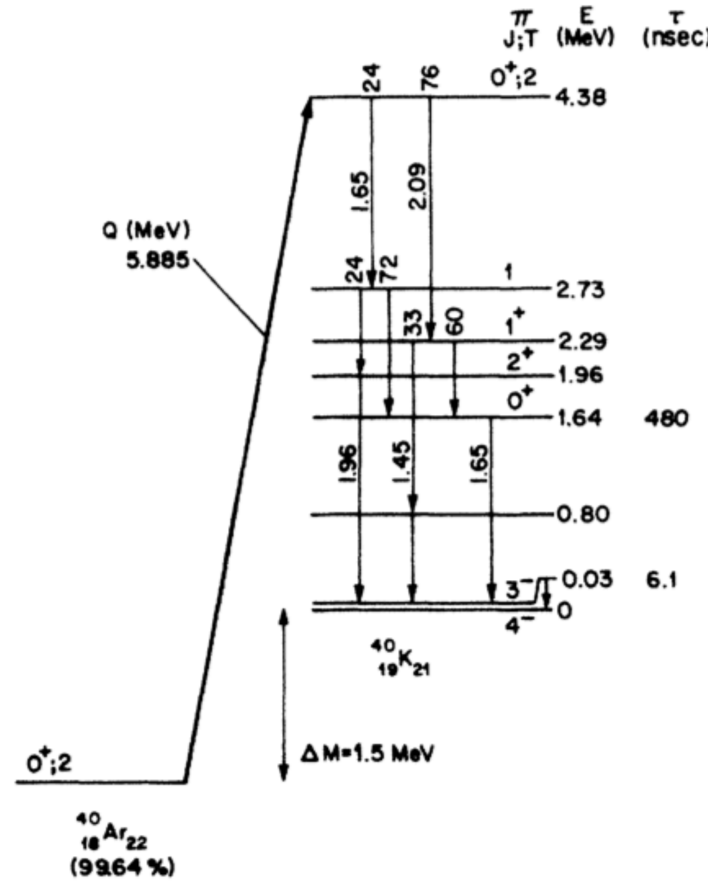

photomultipliers on bottom

# Can we *tag* $\nu_e$ CC interactions in argon using nuclear deexcitation $\gamma$'s?




MicroBooNE geometry (LArSoft)

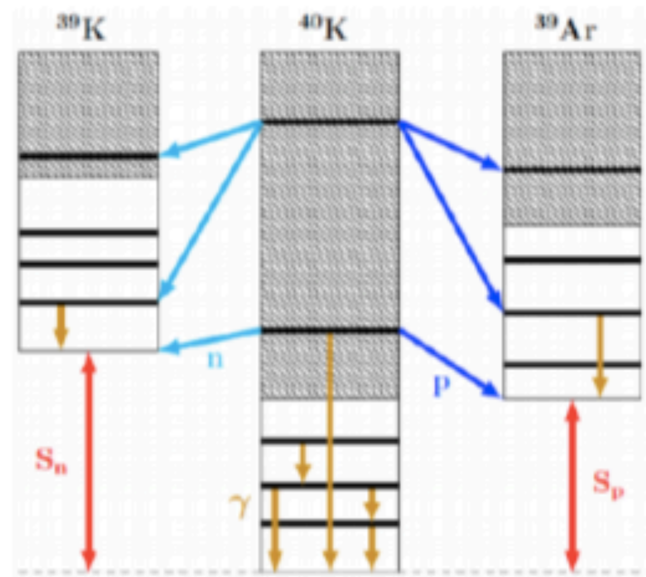
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$




20 MeV $\nu_e$ , 14.1 MeV $e^-$, simple model based on R. Raghavan, PRD 34 (1986) 2088

# MARLEY (Model of Argon Reaction Low-Energy Yields)

- Event generator for low energy $\nu_e$CC neutrino interactions on $^{40}$Ar with realistic final state particles
- Lack of precision models of low-E neutrino argon interactions
- Transition levels are determined by observing de-excitation (gammas and nucleons)




**Reconstructing true neutrino energy:**

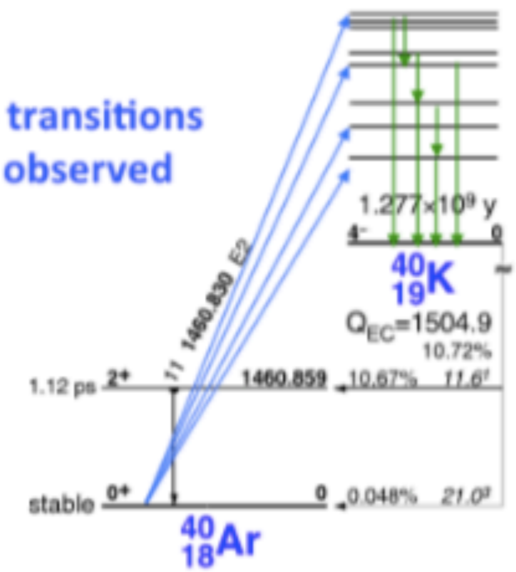
$Q$ is determined by measuring de-excitation gammas and nucleons

Outgoing e⁻ Energy — Energy donated to transition — Recoil Energy of Nucleus (negligible)

$$E_\nu = E_e + Q + K_{\text{recoil}}$$

At least 25 transitions have been observed indirectly

(g.s. to g.s. is 3rd forbidden transition)




- Large uncertainties in nuclear data and models complicate energy reconstruction

S. Gardiner, marleygen.org

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

MARLEY

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

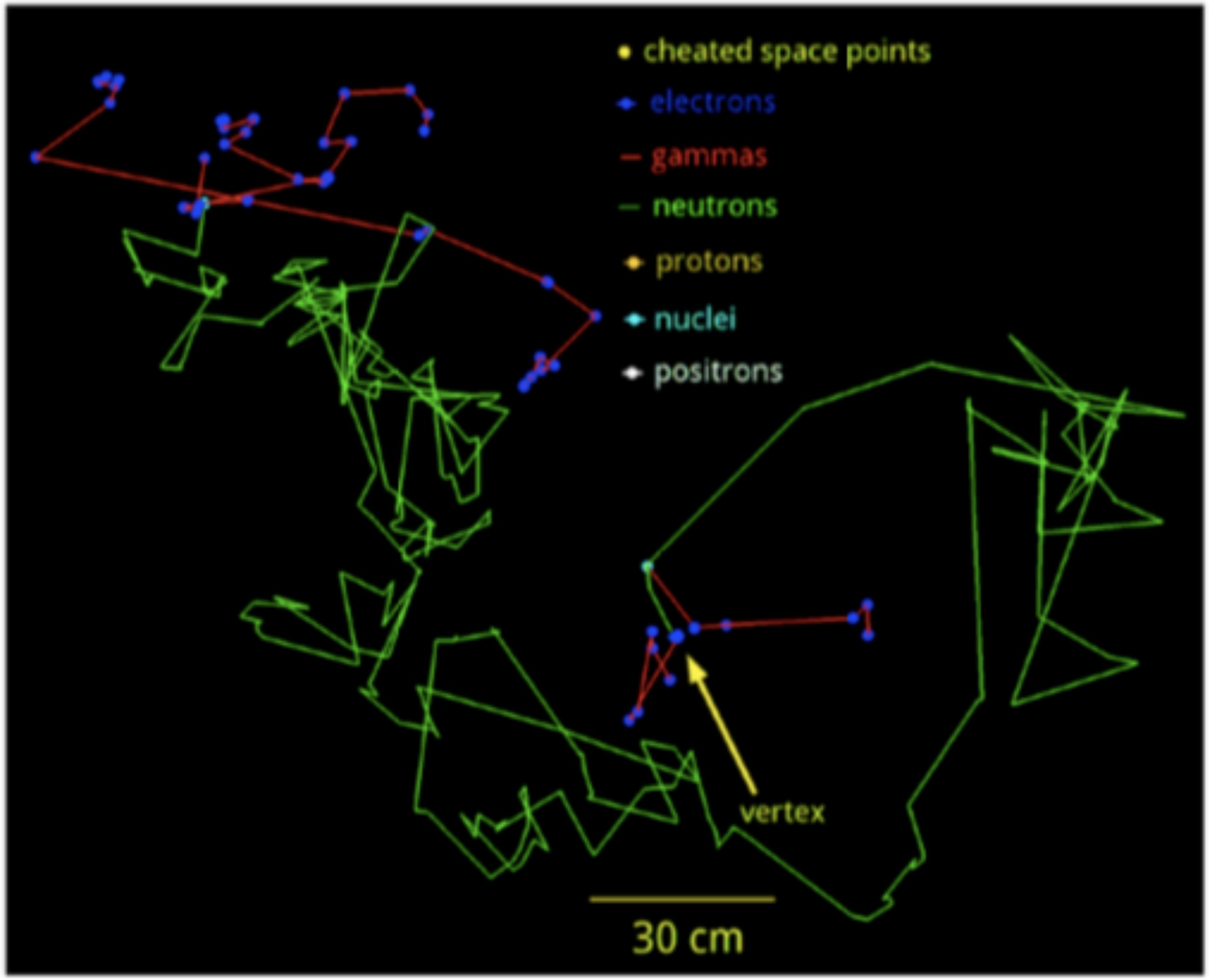
$E_\nu = 16.3$ MeV

$e^-$ deposited 4.5 MeV

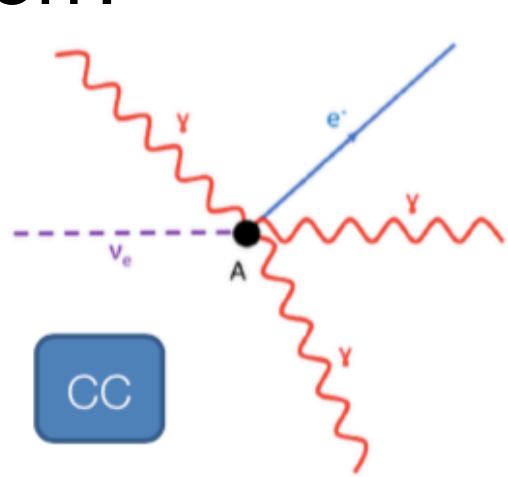
γs from n-capture 7.6 MeV

Total visible Energy = 12.2 MeV

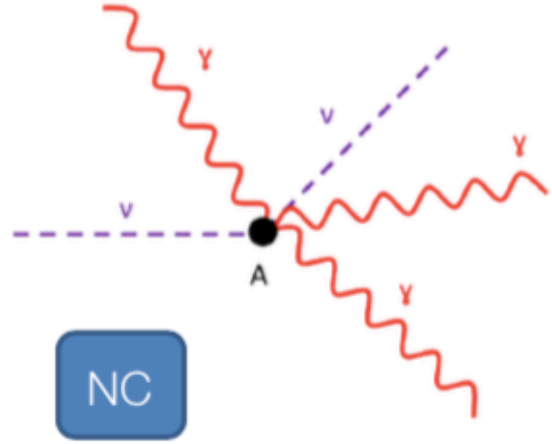
Visible event radius = 144 cm



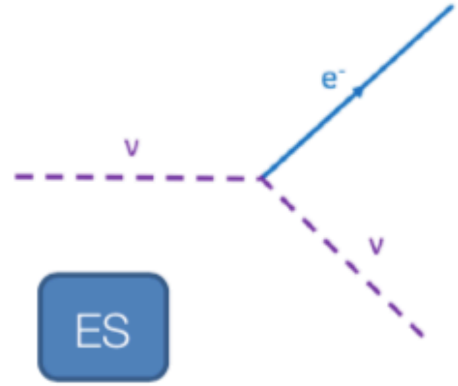
# How well can we *tag* interaction channels in argon?



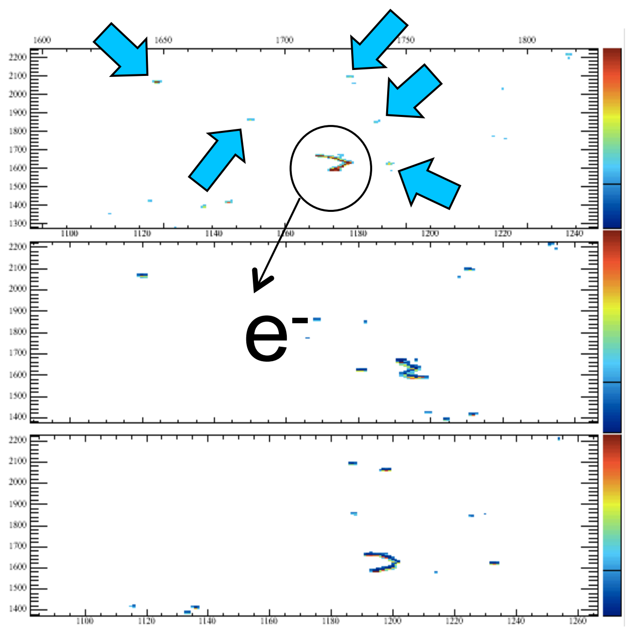

$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$



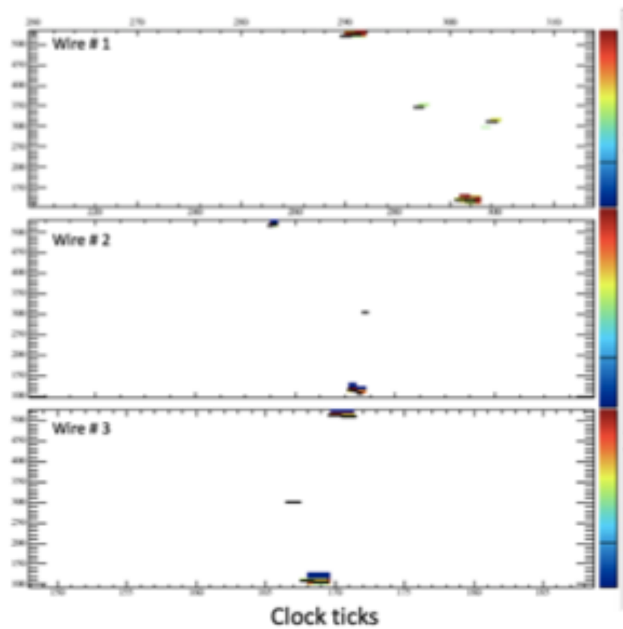

$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$



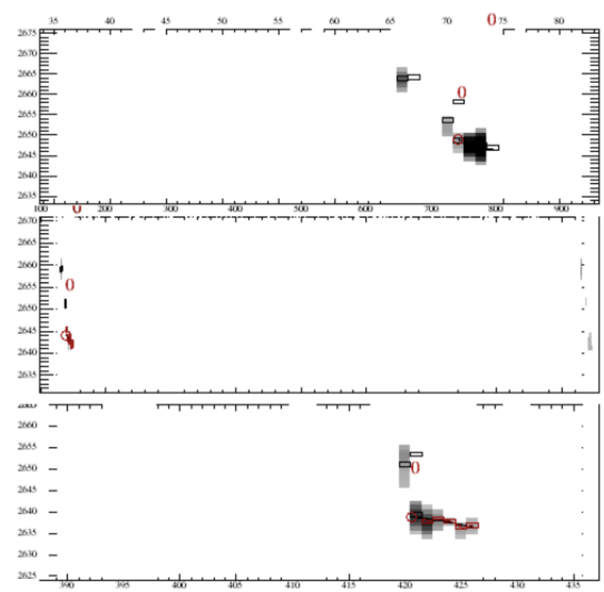

$\nu + e^- \rightarrow \nu + e^-$




track + deex $\gamma$ blips
+ brem $\gamma$ blips




cloud of $\gamma$ blips



"clean" track

# Lead-based supernova detectors

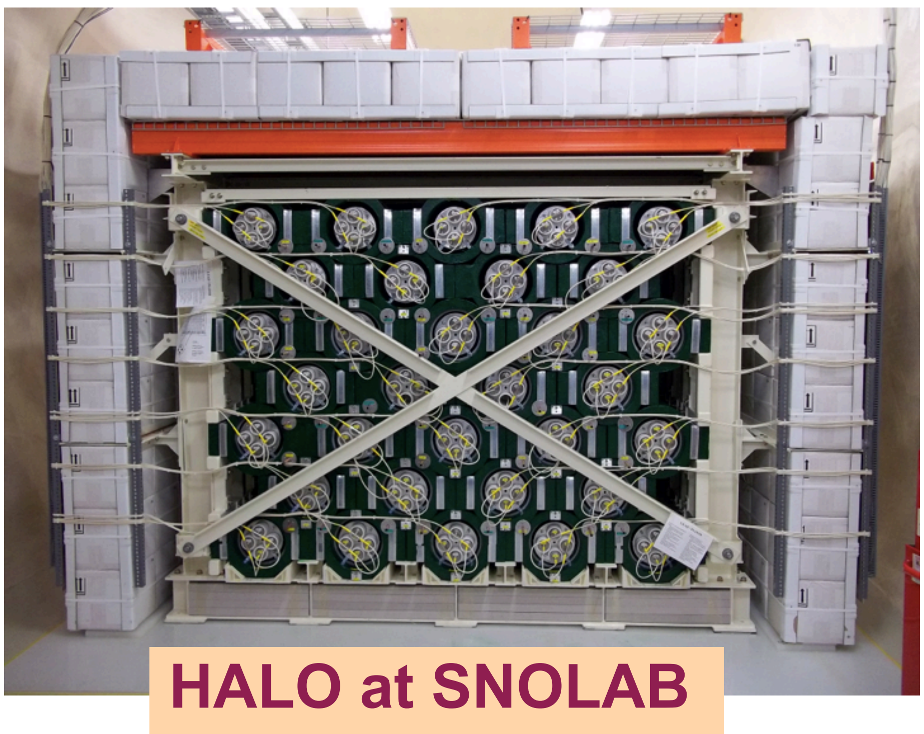
$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^-$ CC

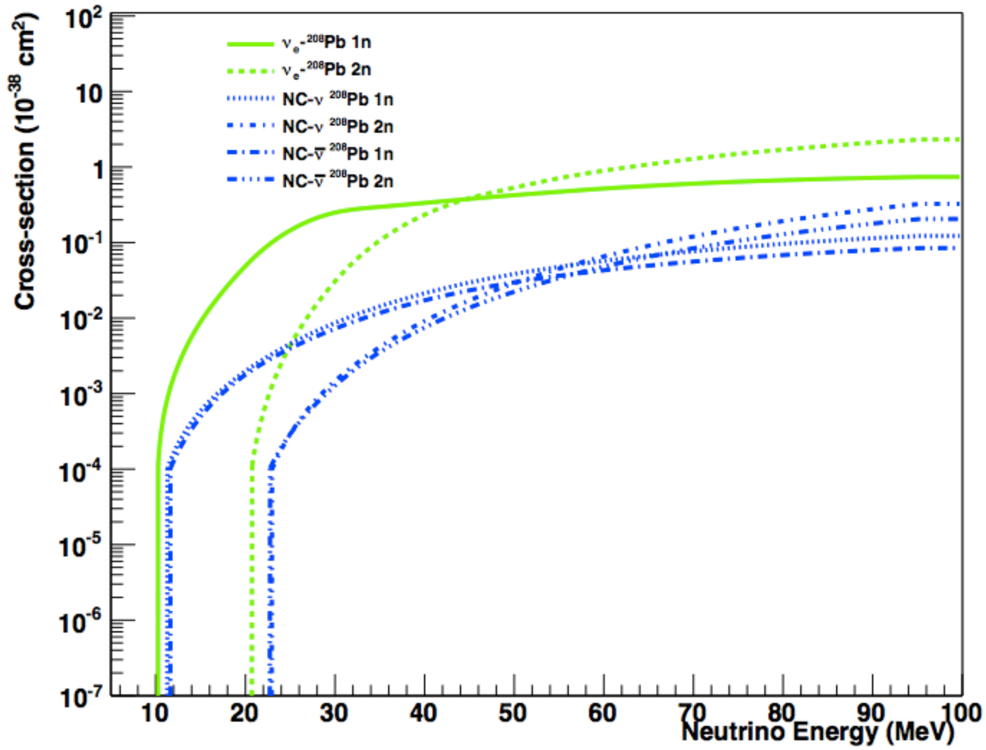
1n, 2n emission

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

1n, 2n, $\gamma$ emission

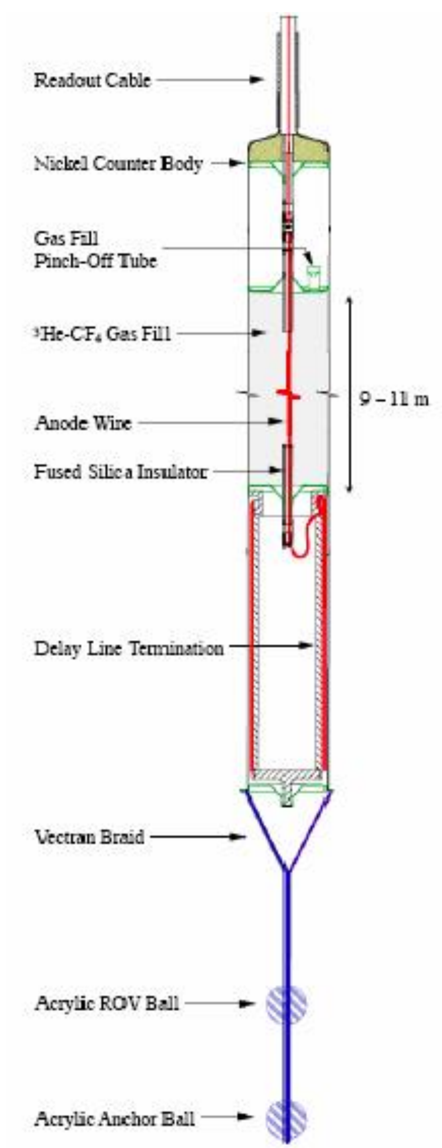
**Relative 1n/2n rates** sharply dependent on neutrino energy $\Rightarrow$ spectral sensitivity



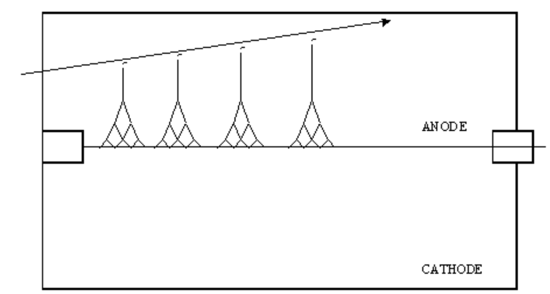

SNO $^3$He counters + 79 tons of Pb: ~1-40 events @ 10 kpc

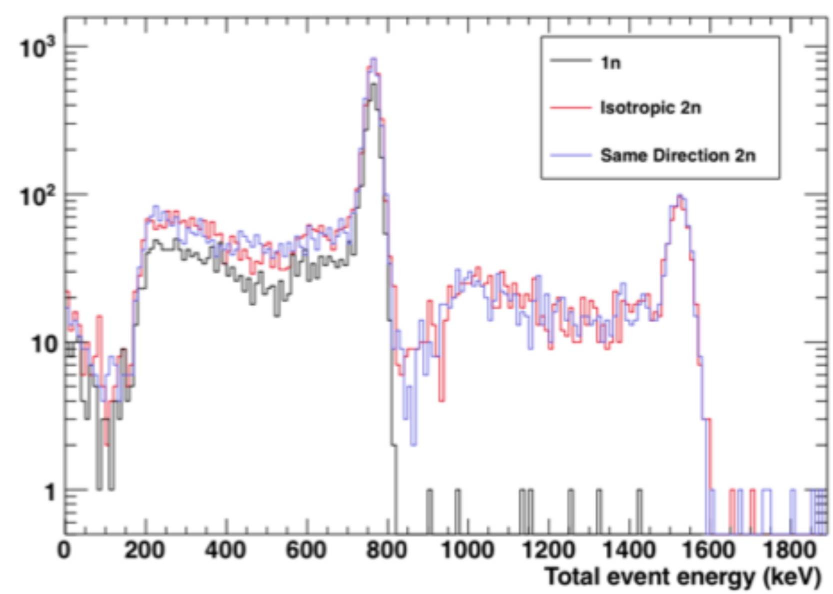
# $^3$He counters for neutron detection




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

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

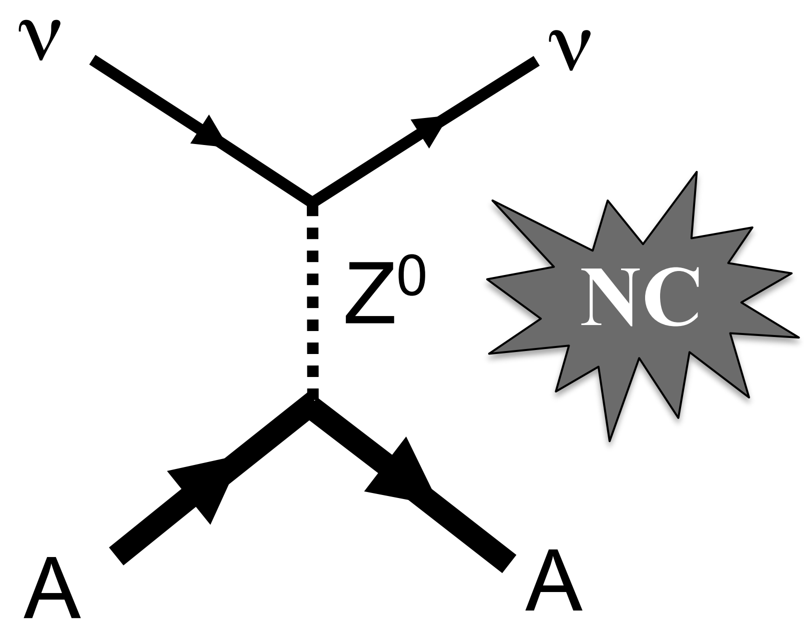


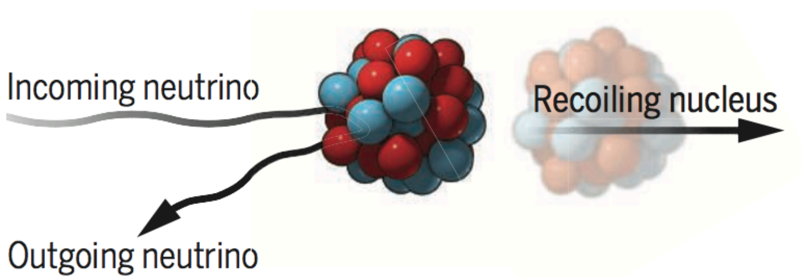



# Coherent elastic neutrino-nucleus scattering (CEvNS)

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

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



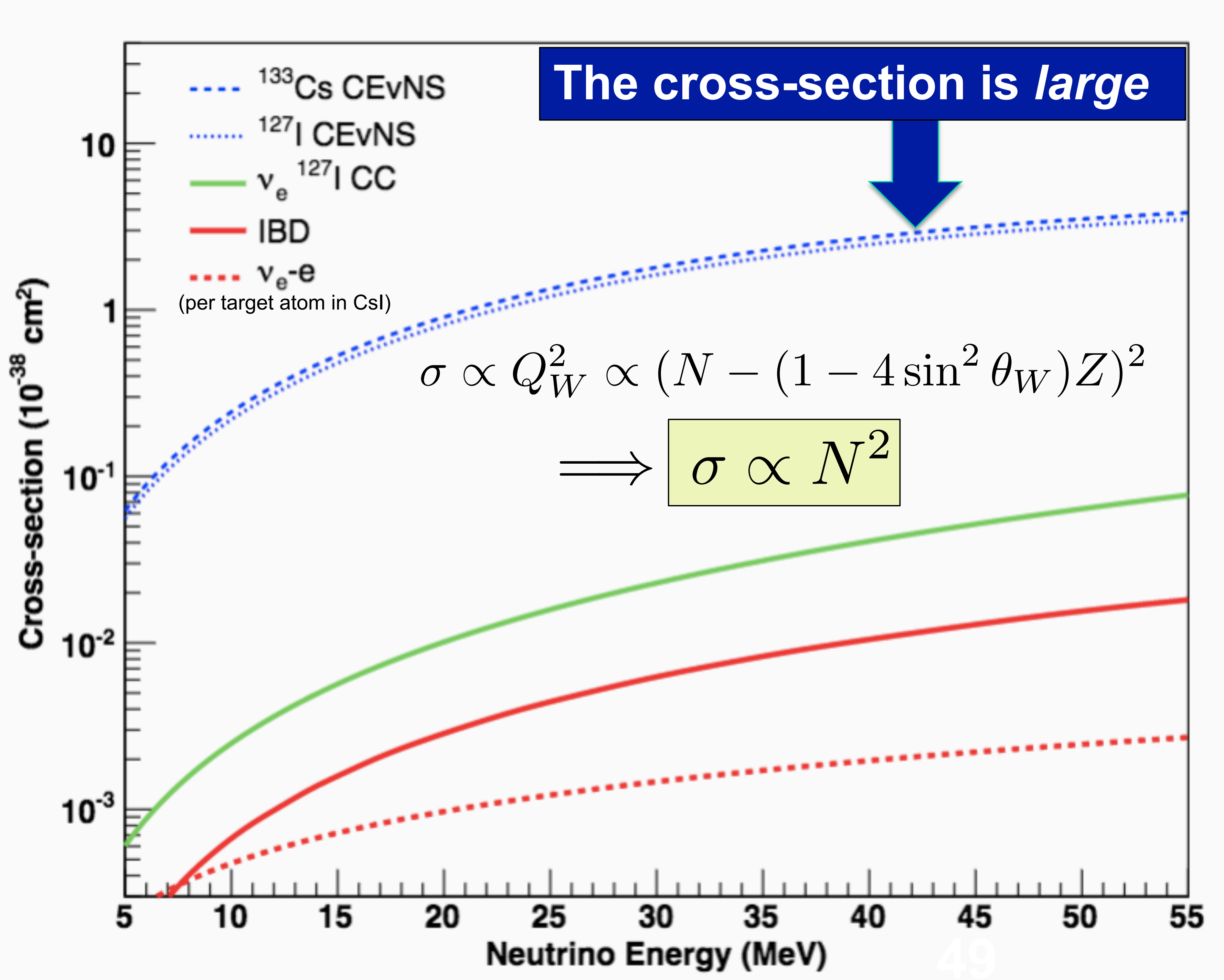

Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$ ,
[total xscn] ~ $A^2$ * [single constituent xscn]

A: no. of constituents

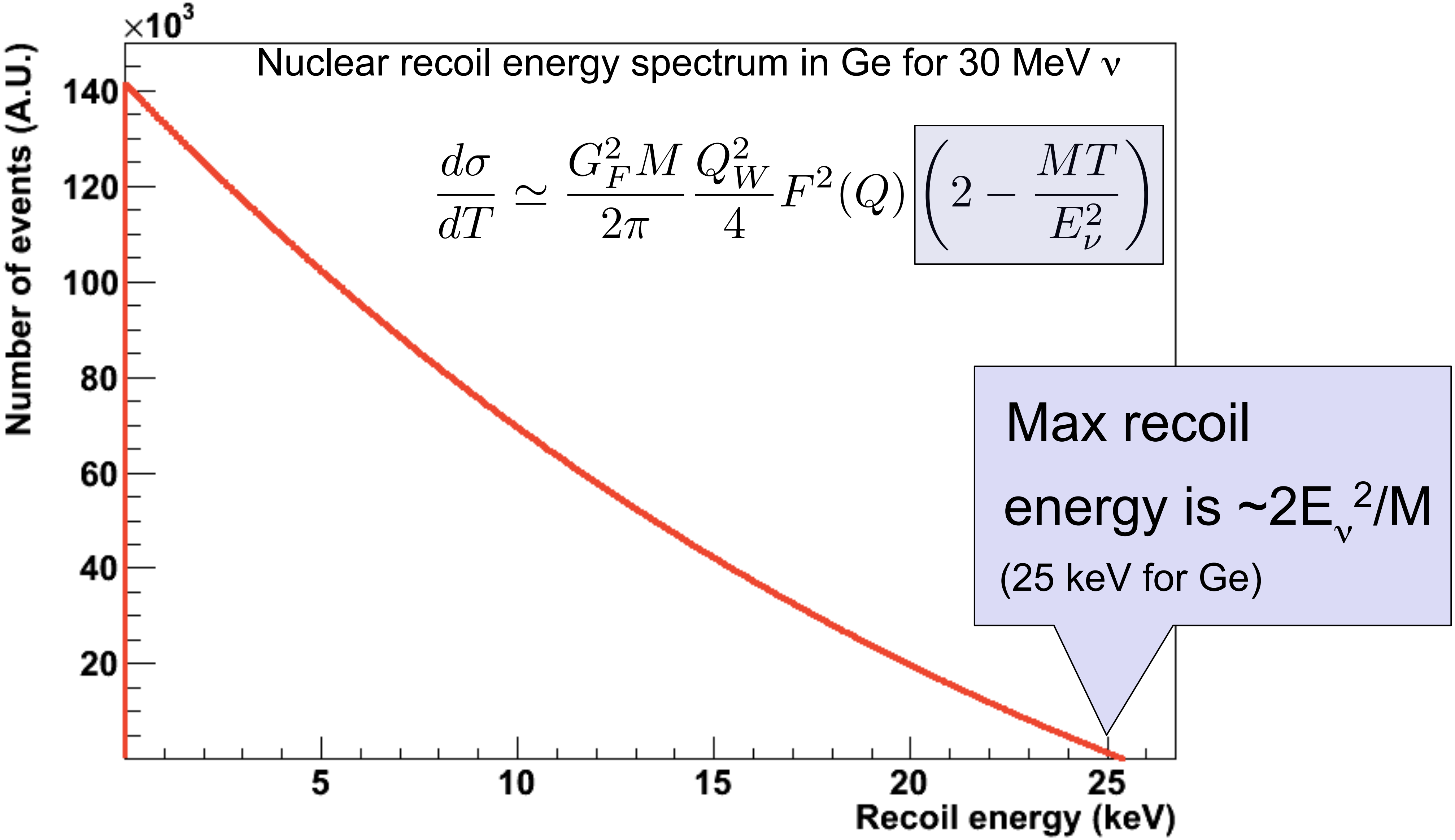
Image: J. Link *Science* Perspectives

See also J. Newstead slides, NMNM 3



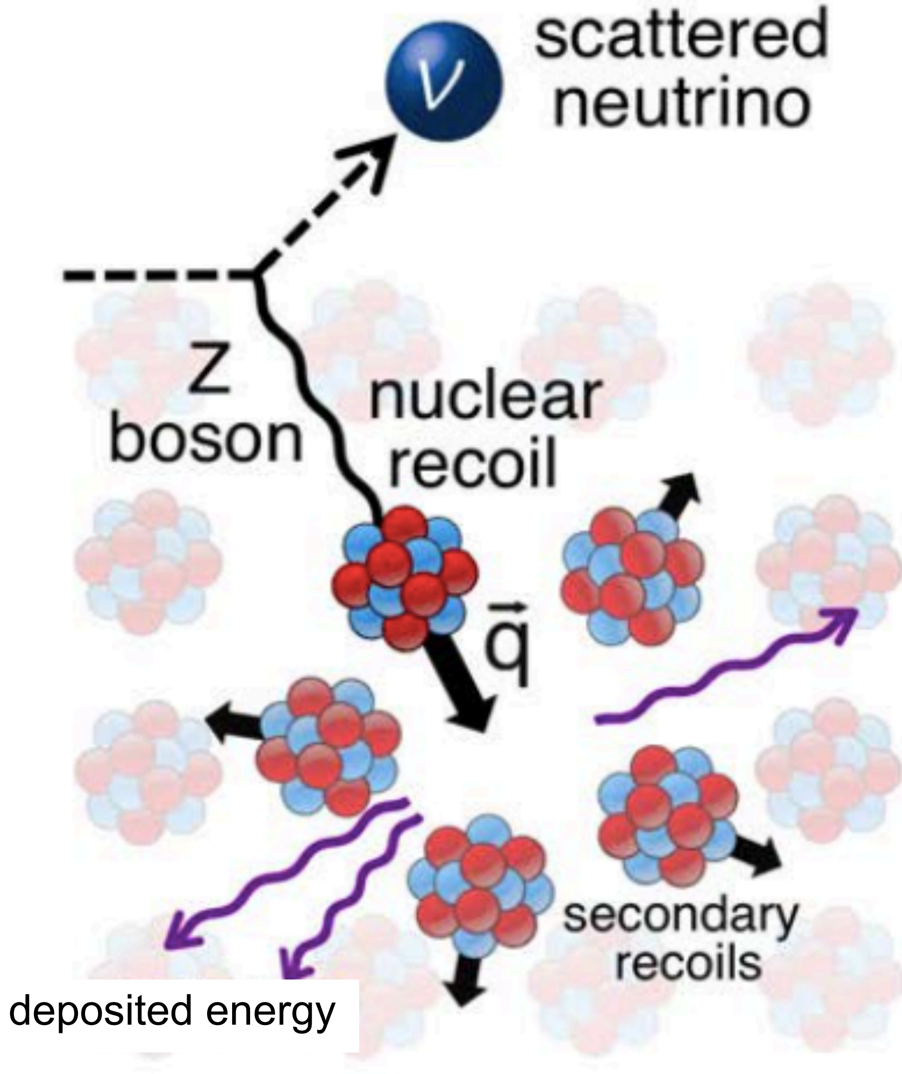
The cross-section is *large*
$^{133}$Cs CEvNS
$^{127}$I CEvNS
$\nu_e$ $^{127}$I CC
IBD
$\nu_e$-e
(per target atom in CsI)
$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$
$\implies \boxed{\sigma \propto N^2}$
Cross-section ($10^{-38}$ cm$^2$)
10
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
5
10
15
20
25
30
35
40
45
50
55
Neutrino Energy (MeV)

**Large cross section** (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**



The only experimental signature:

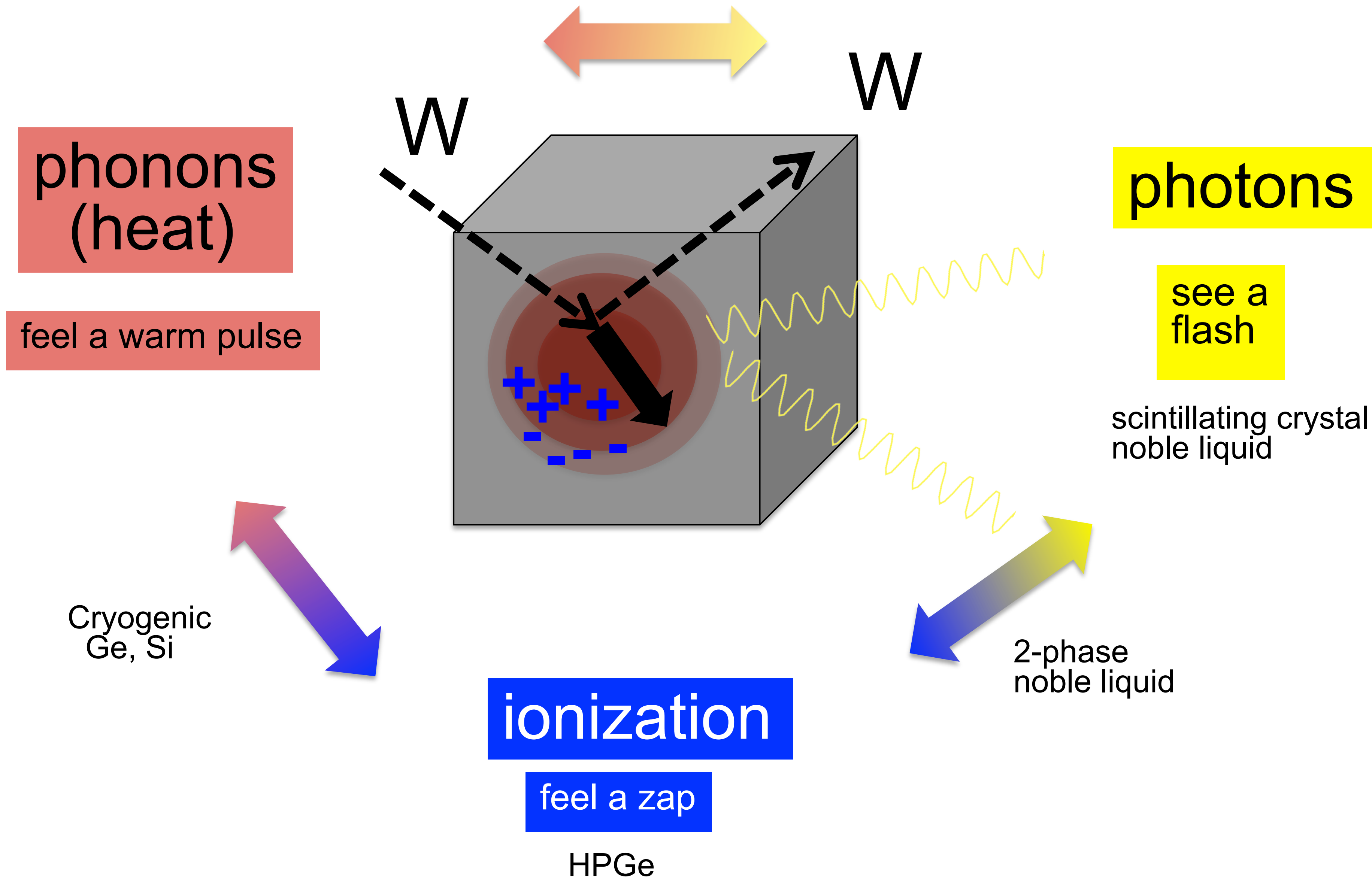
tiny energy deposited by nuclear recoils in the target material




➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils

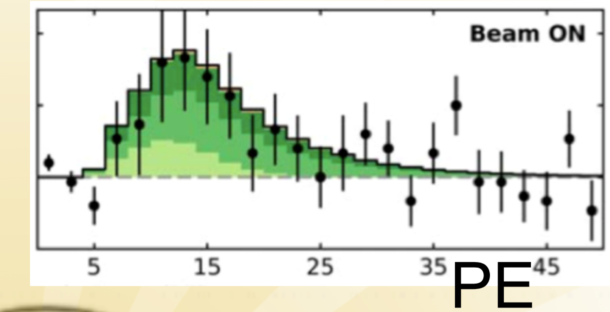
# Now, ***detecting*** the tiny kick of the neutrino...

This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors

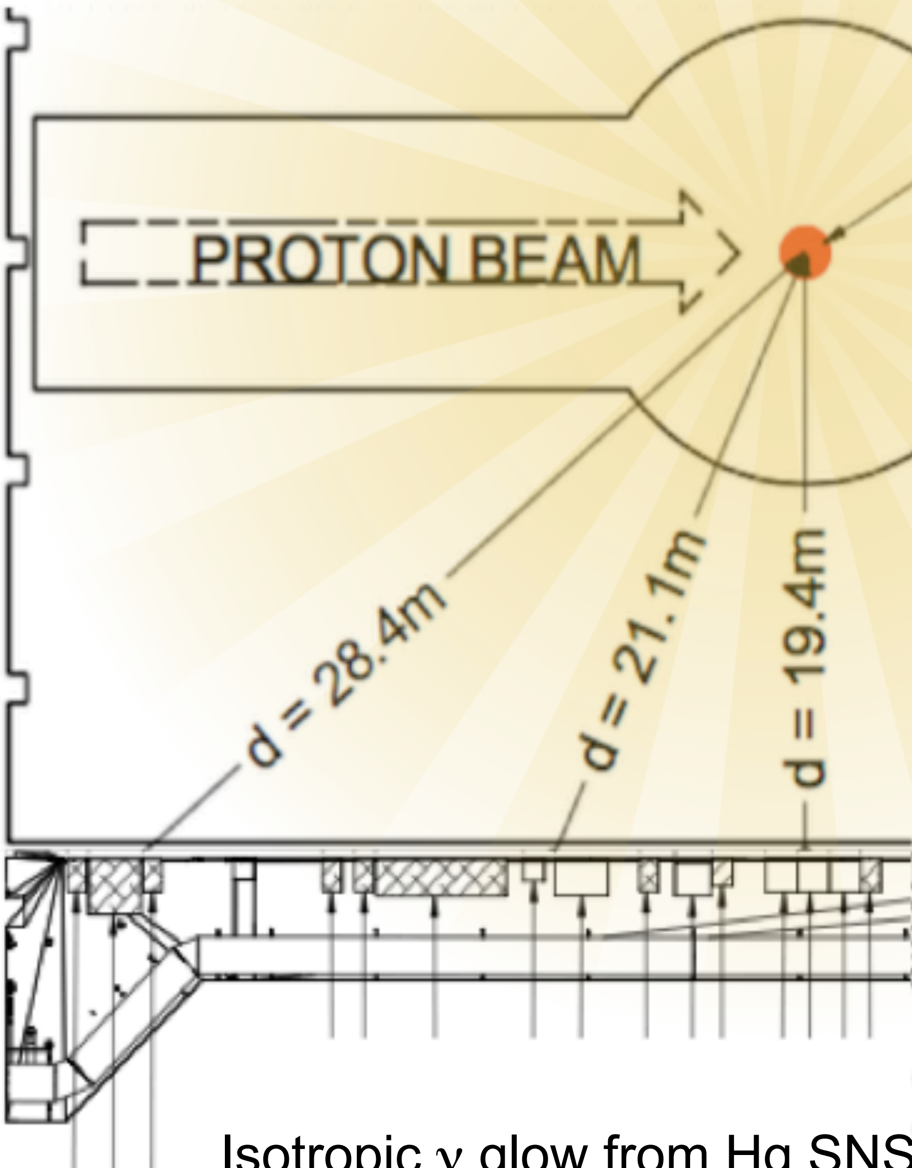


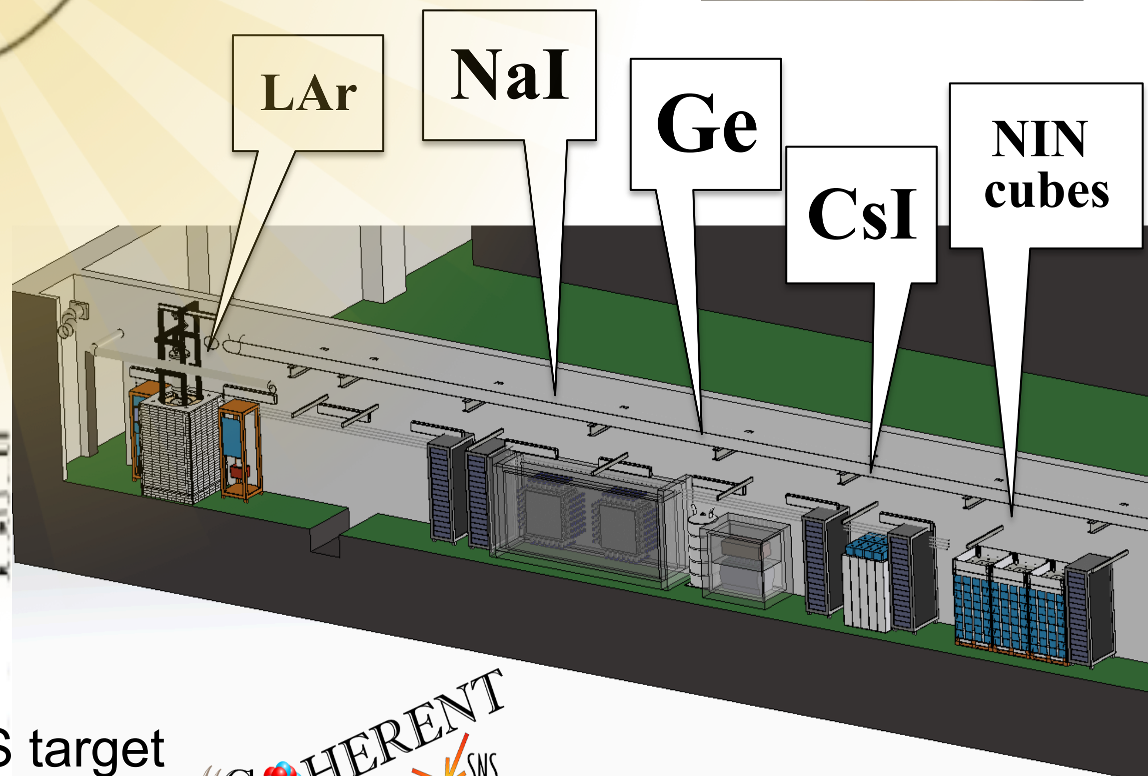

http://dmrc.snu.ac.kr/english/intro/intro1.html

# Now measured w/ stopped-$\pi$ $\nu$'s



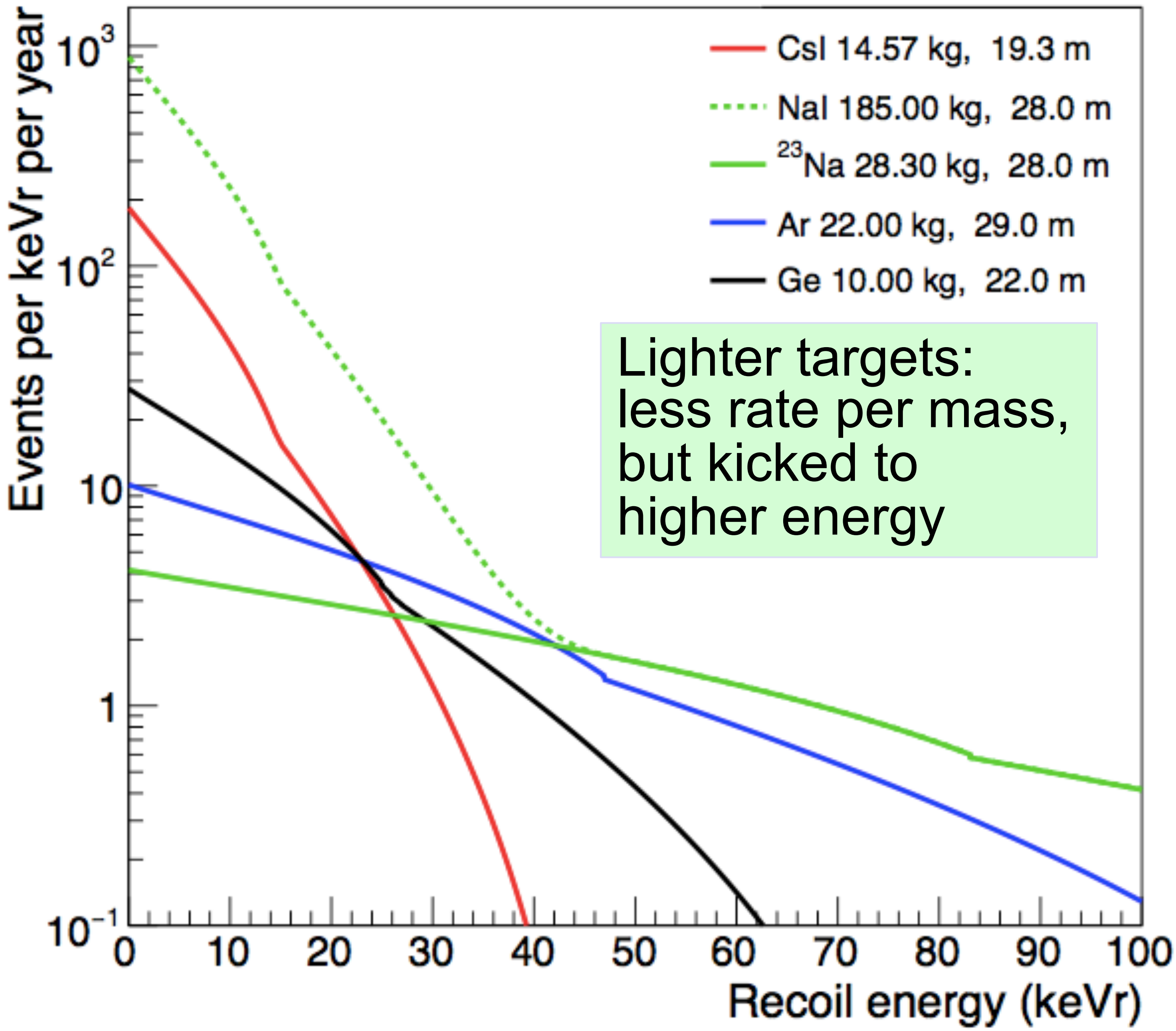

View looking down "Neutrino Alley"



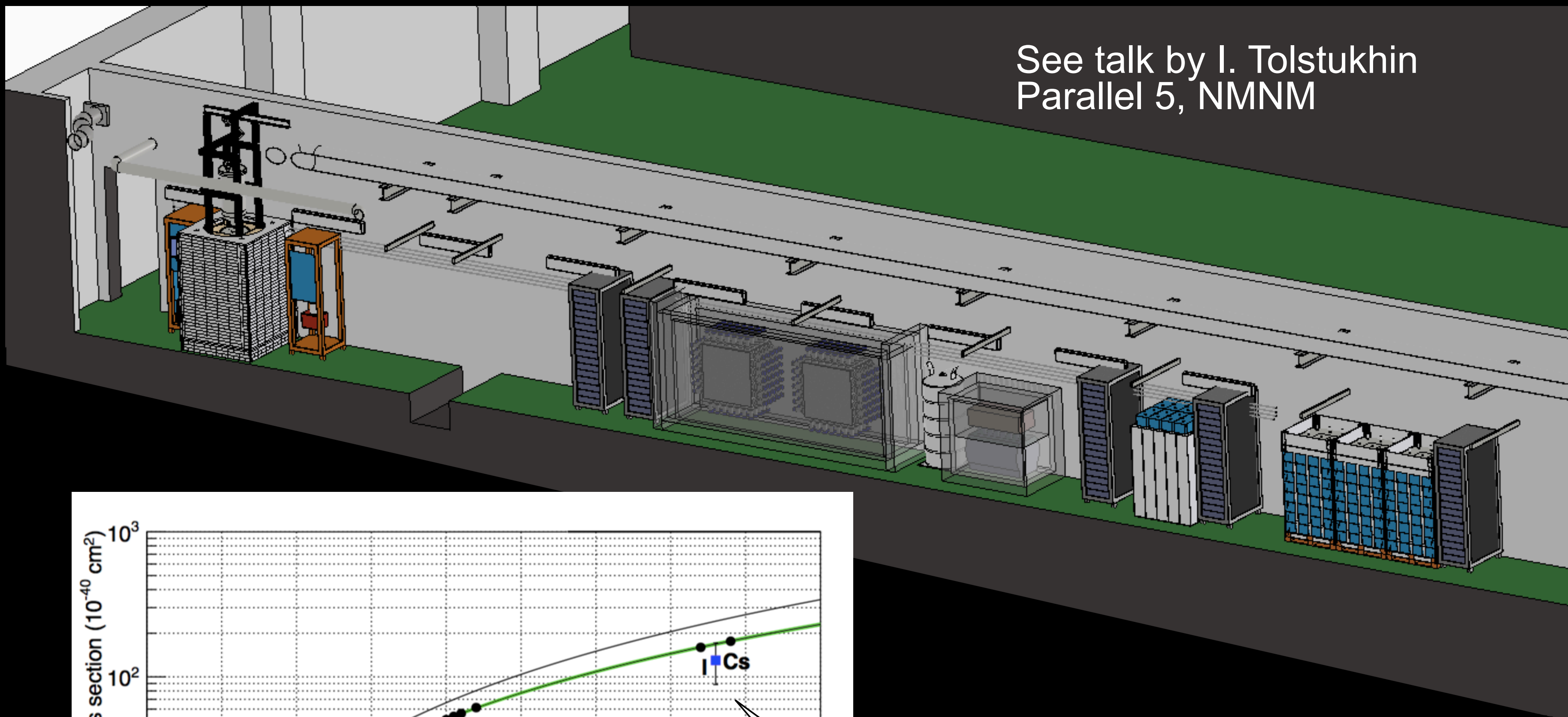




Isotropic $\nu$ glow from Hg SNS target

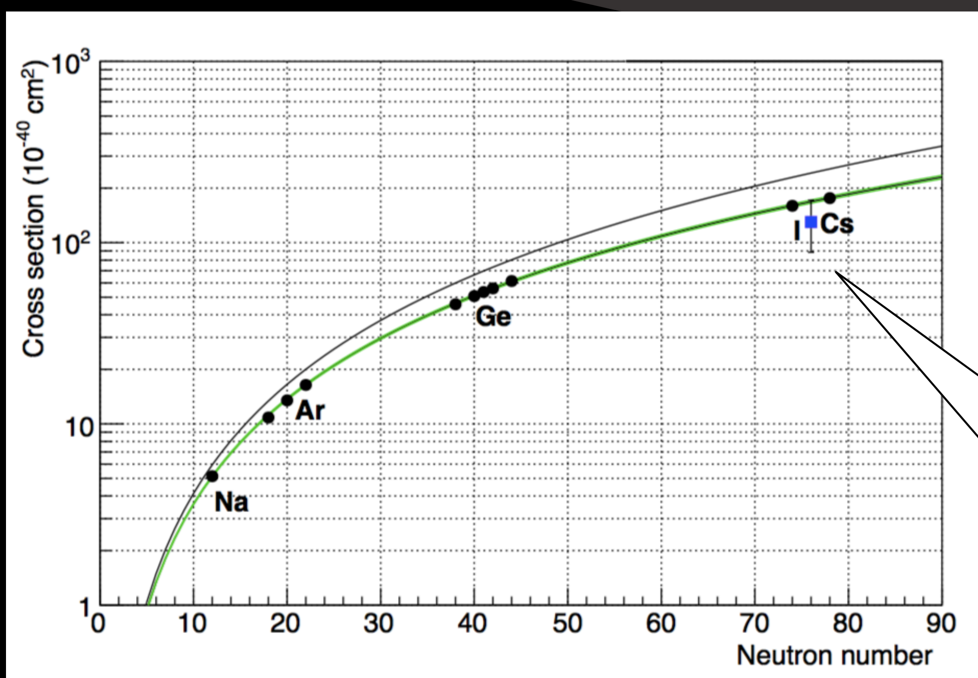
# Expected recoil energy distribution



# What’s Next for COHERENT?



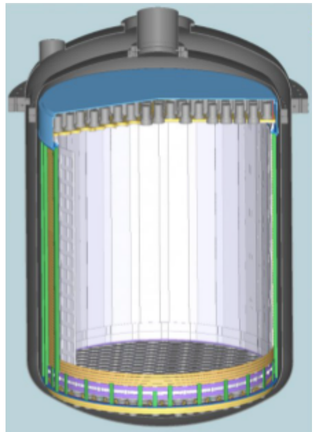
See talk by I. Tolstukhin
Parallel 5, NMNM

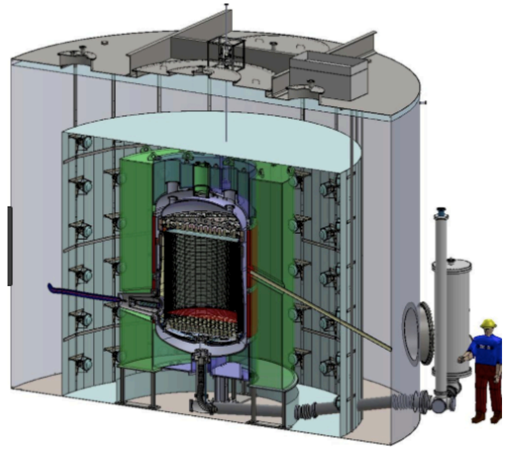


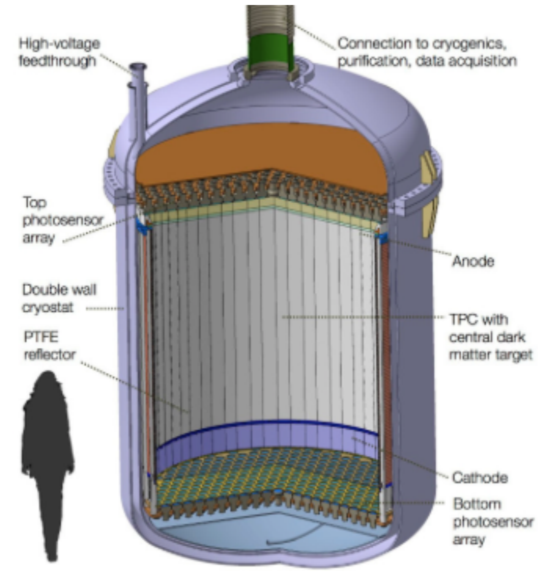

One measurement so far! Want to map out $N^2$ dependence

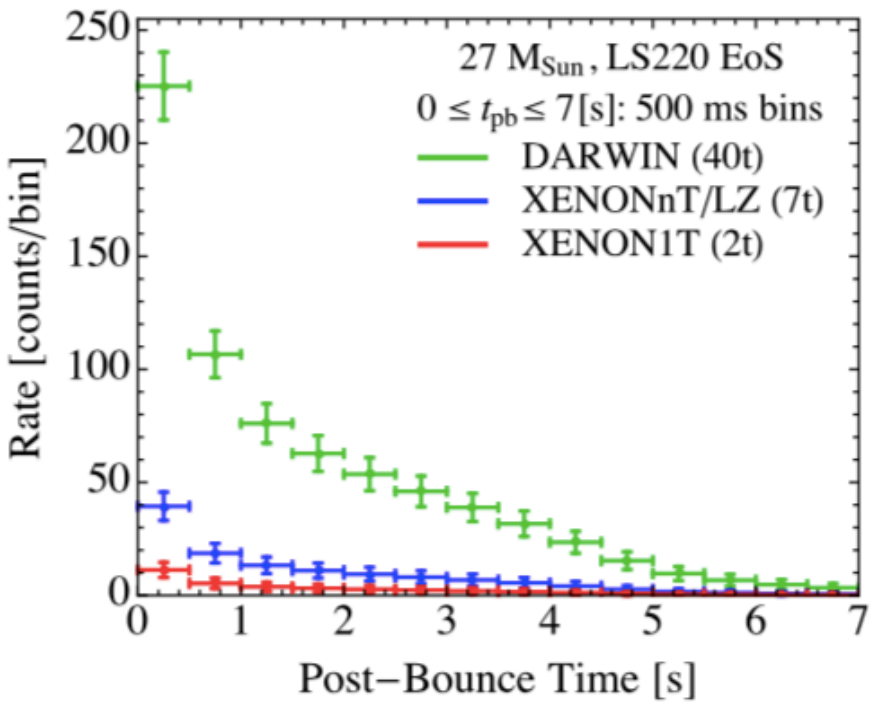
# Detector example: **XENON/LZ/DARWIN**

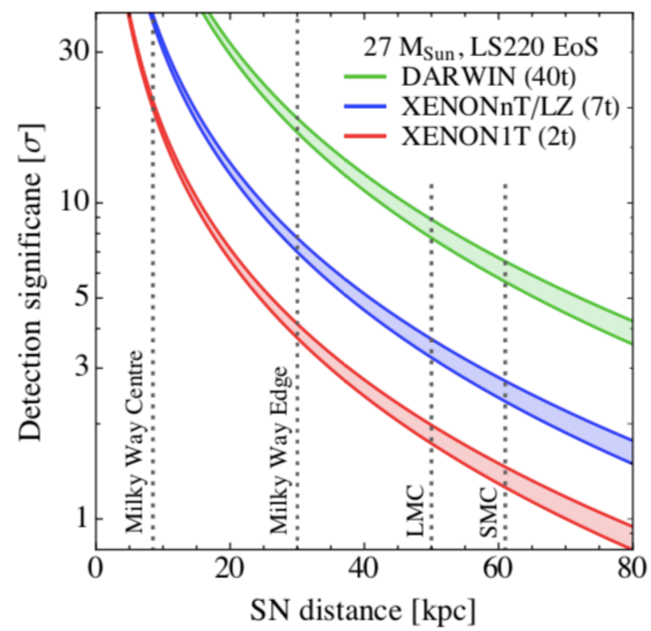
- dual-phase xenon time projection chambers





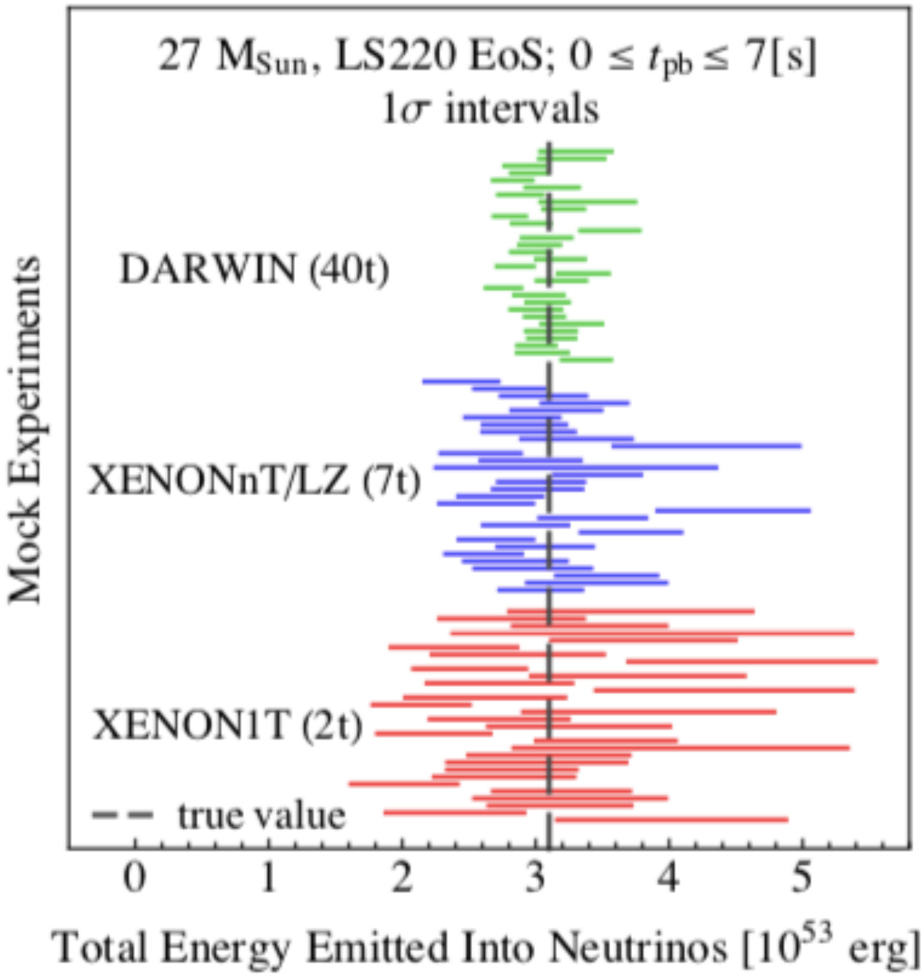


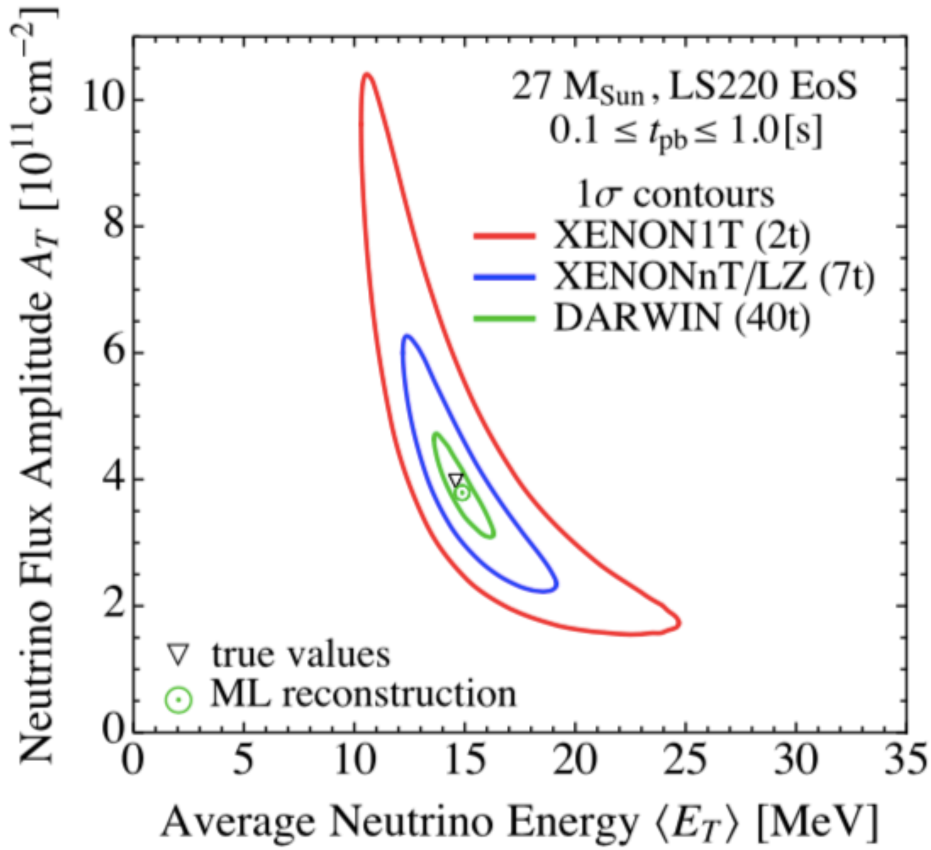




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

# What will be learned?



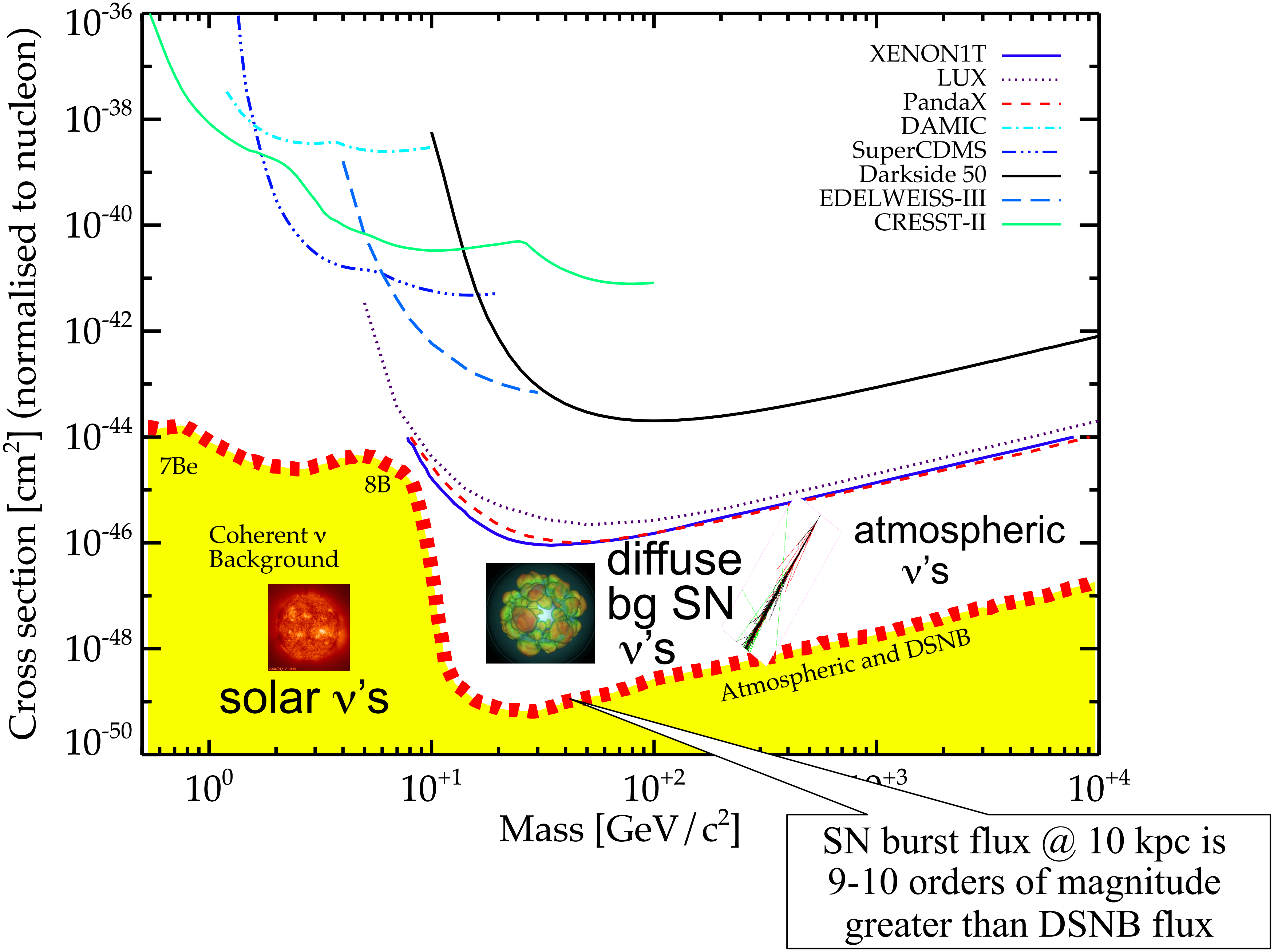




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

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

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

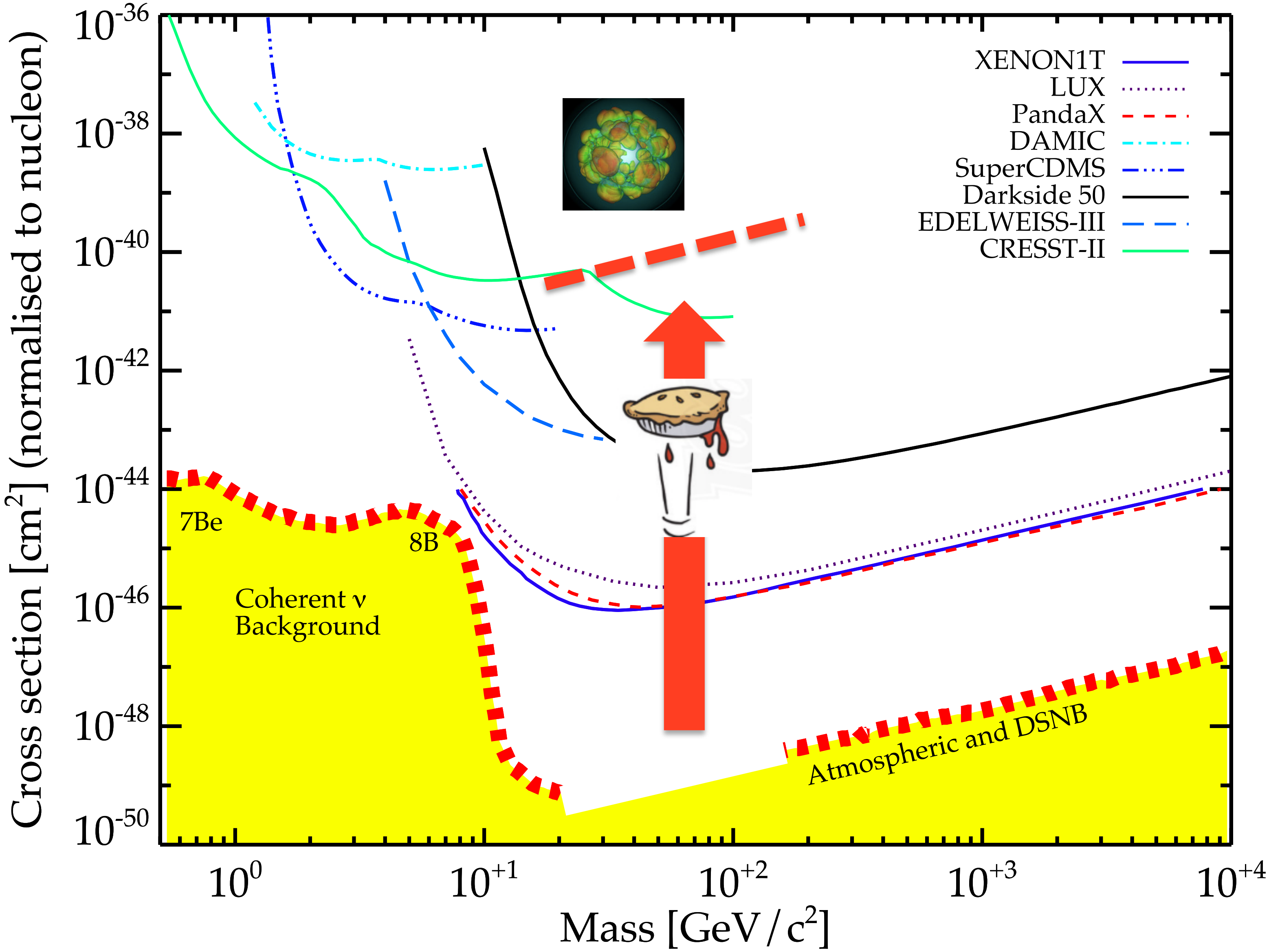
L. Strigari



# 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

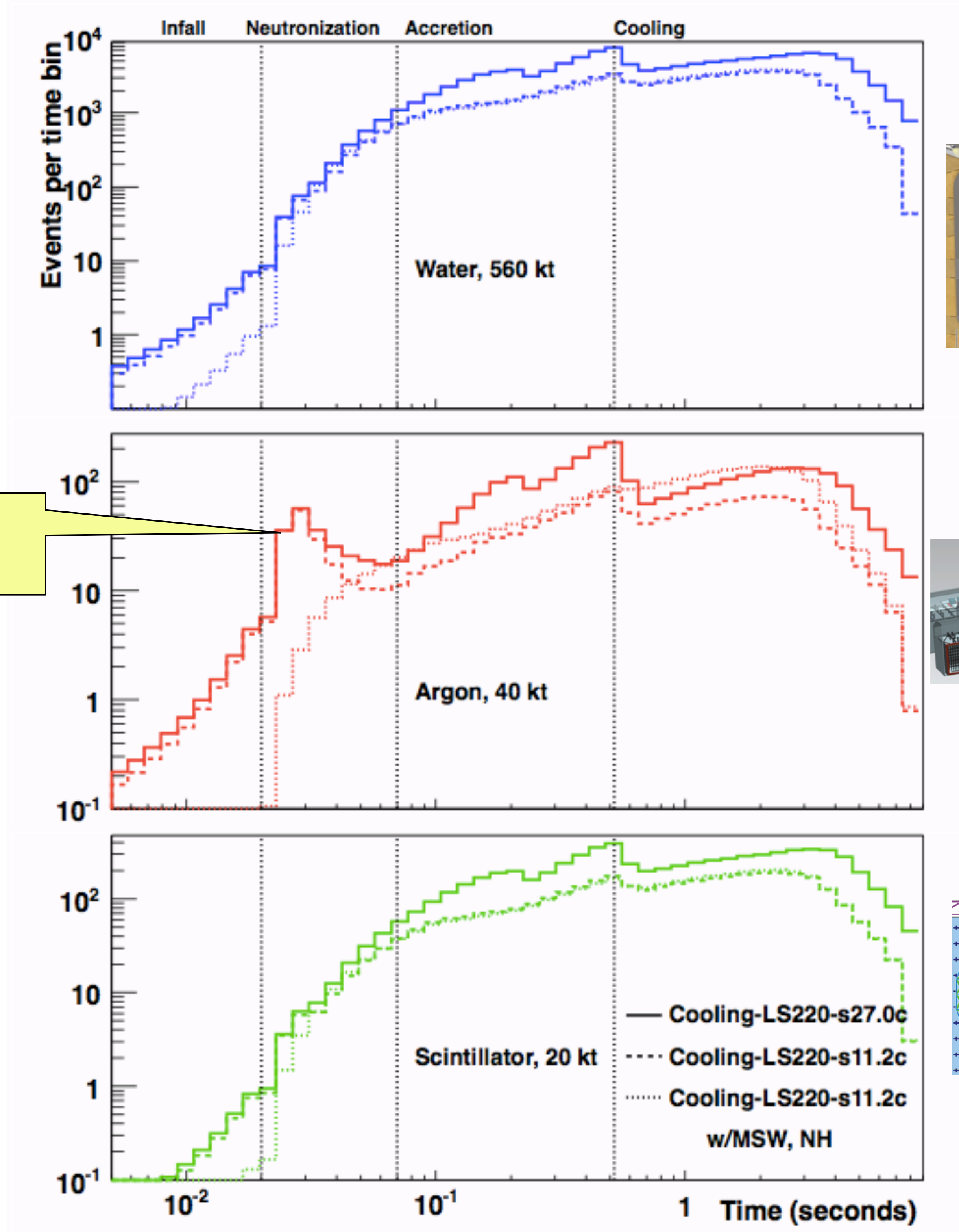
Extragalactic

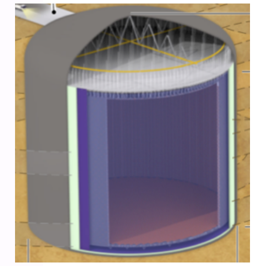
| Detector | Type | Location | Mass (kton) | Events @ 10 kpc | Status |
|---|---|---|---|---|---|
| Super-K | Water | Japan | 32 | 8000 | Running (SK IV) |
| LVD | Scintillator | Italy | 1 | 300 | Running |
| KamLAND | Scintillator | Japan | 1 | 300 | Running |
| Borexino | Scintillator | Italy | 0.3 | 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 |

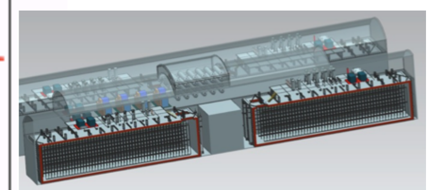
plus reactor experiments, DM experiments...

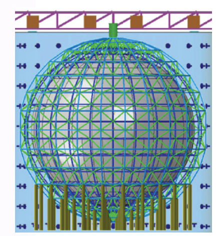
# Example signals in future detectors

Neutronization burst in argon



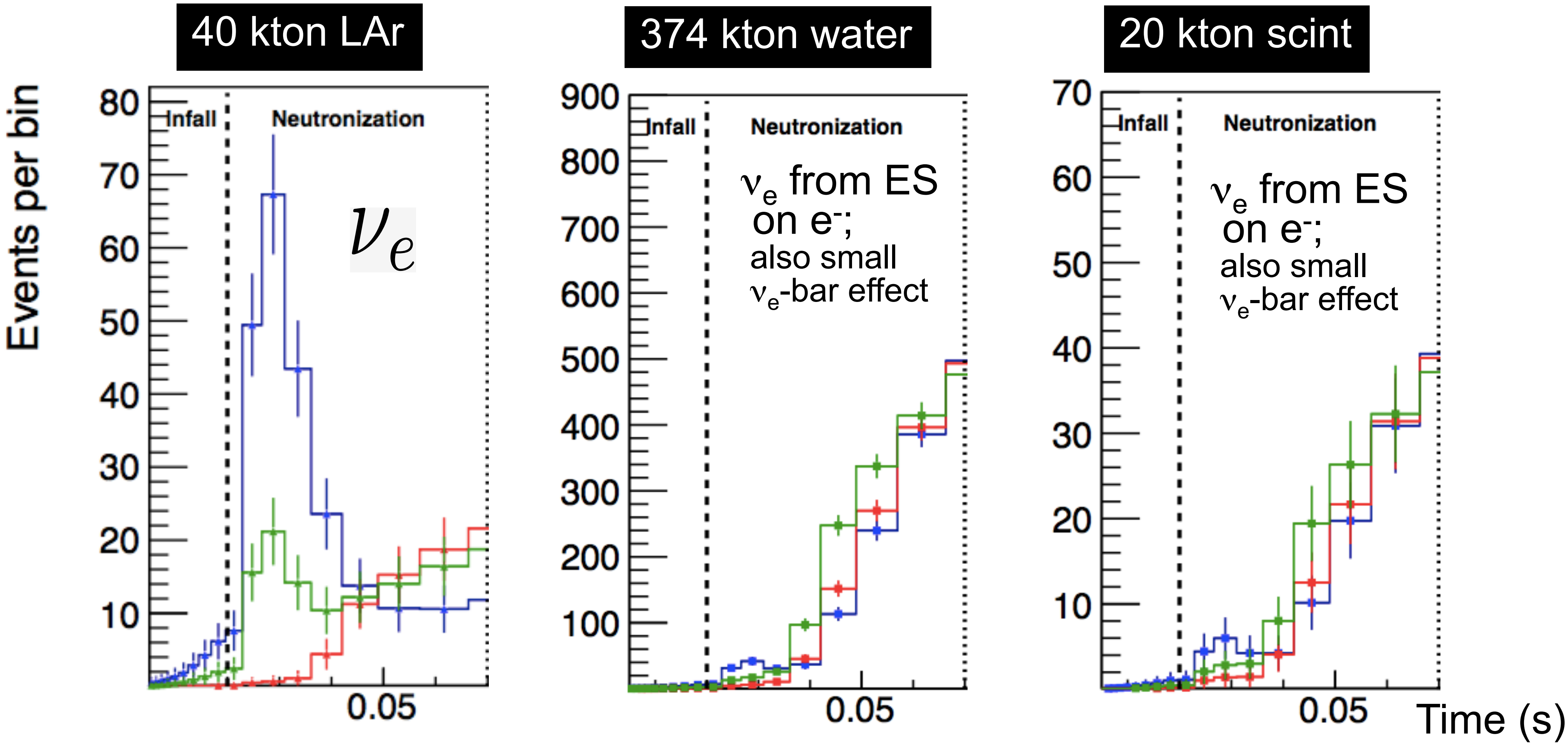







(note logarithmic time bins)

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

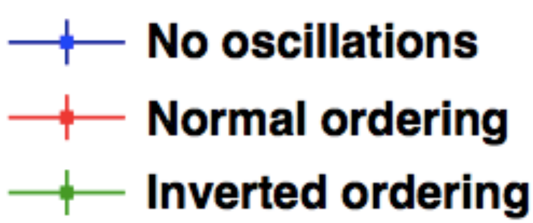



NMO: $F_{\nu_e} = F^0_{\nu_x}$

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

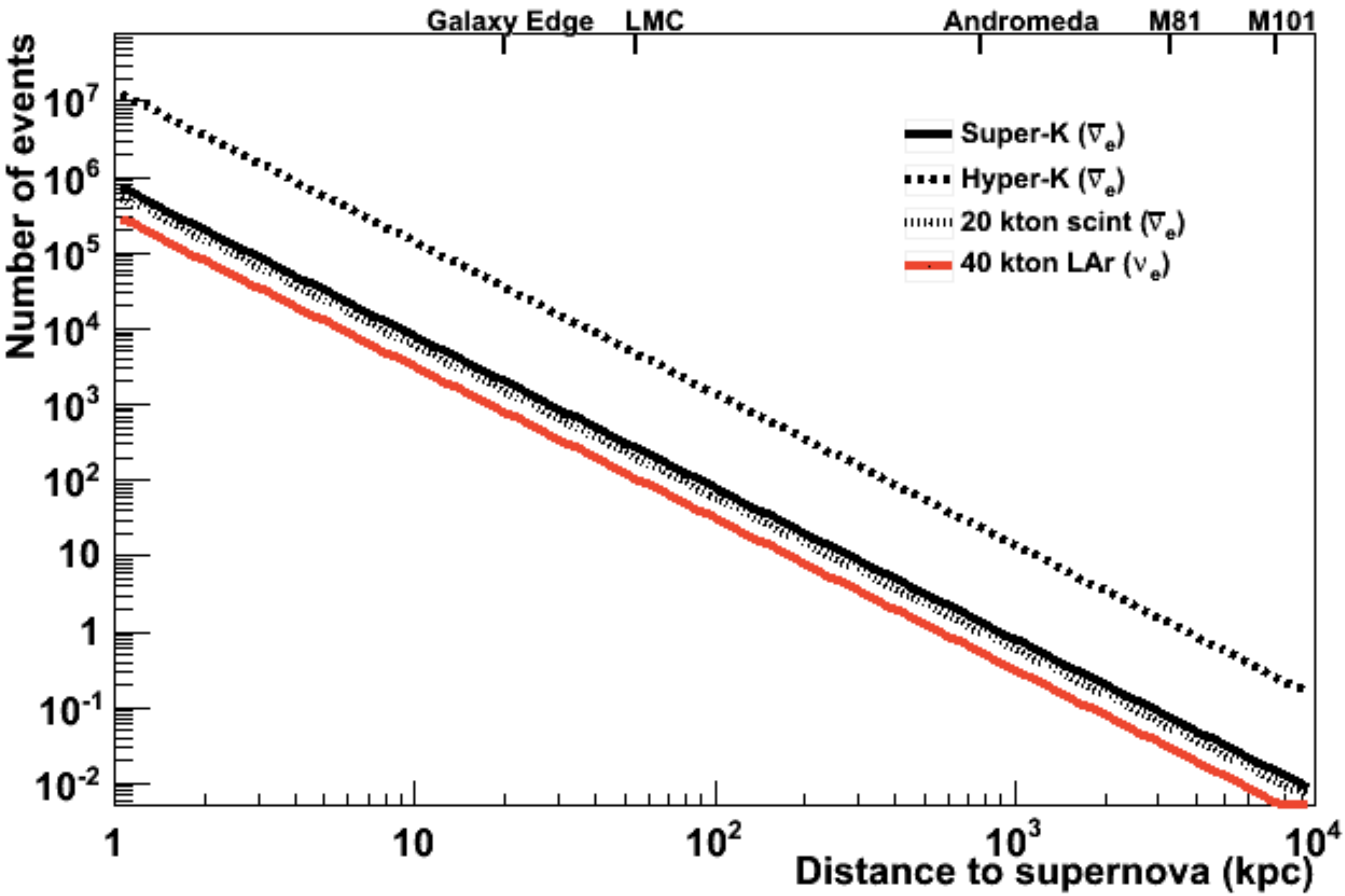
NMO: $F_{\bar{\nu}_e} = \cos^2\theta_{12} F^0_{\bar{\nu}_e} + \sin^2\theta_{12} F^0_{\bar{\nu}_x}$

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




suppression for IMO,
stronger suppression for NMO

# Distance reach for future detectors



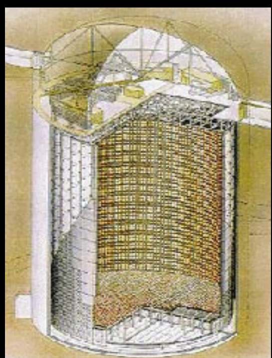

SK will see ~1 event from Andromeda; HK will get a ~dozen

# For supernova neutrinos, the more, the merrier!

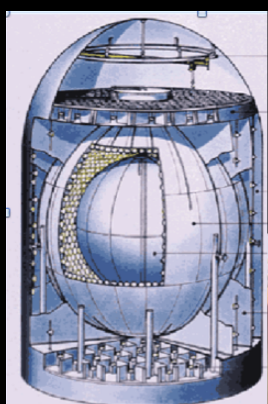
# SNEWS: SuperNova Early Warning System

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

snews.bnl.gov



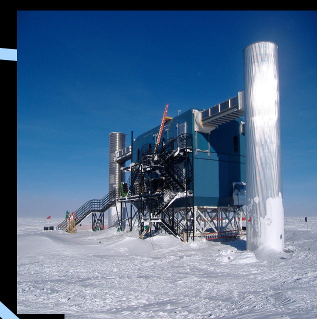
experiment
UT time
significance

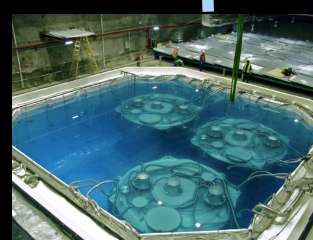


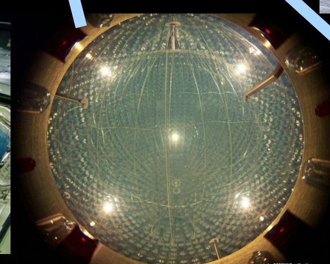
**Coincidence Server at BNL**

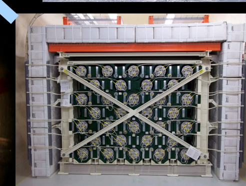
10 second coincidence by UT time stamp

**alert to astronomers**





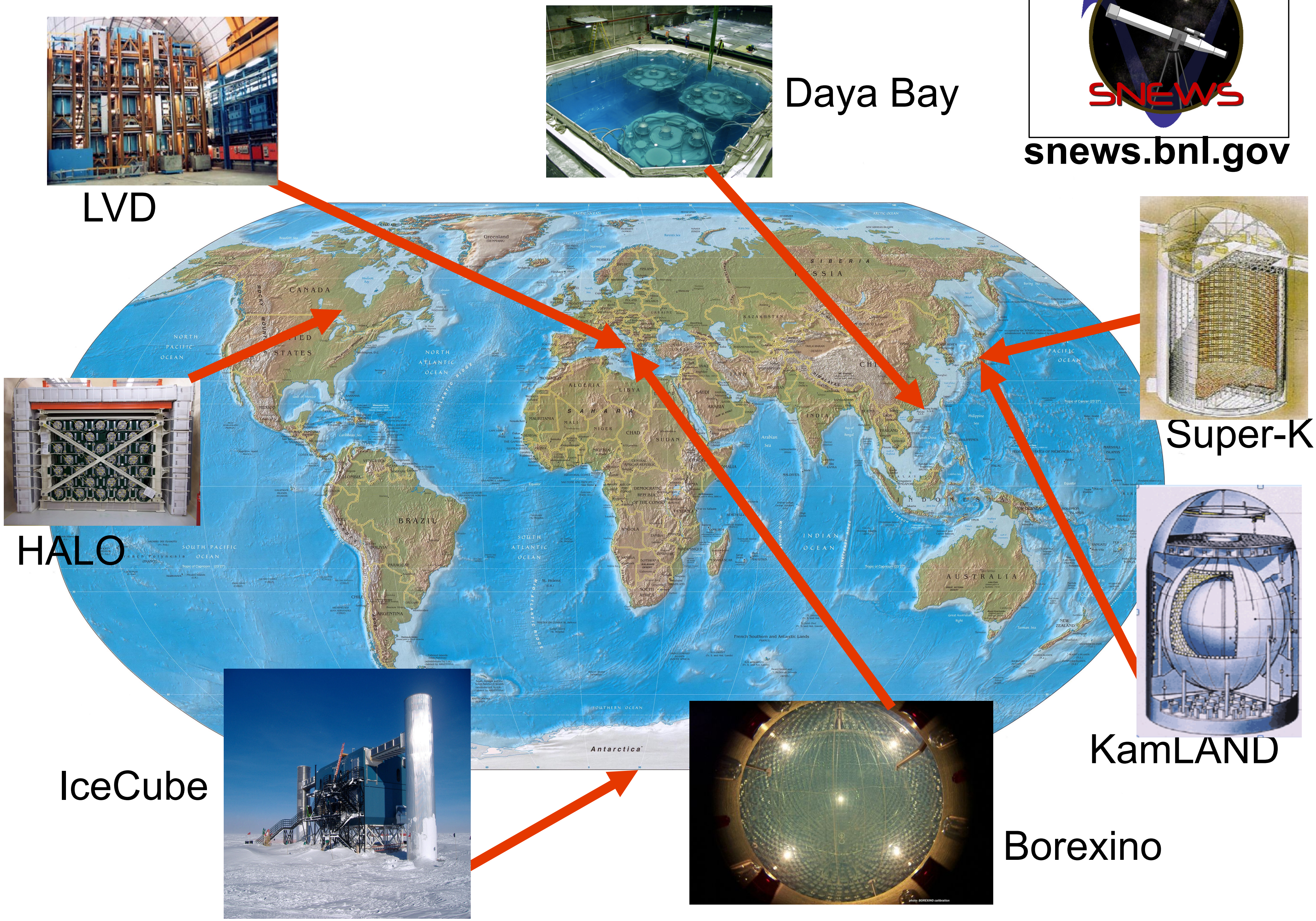




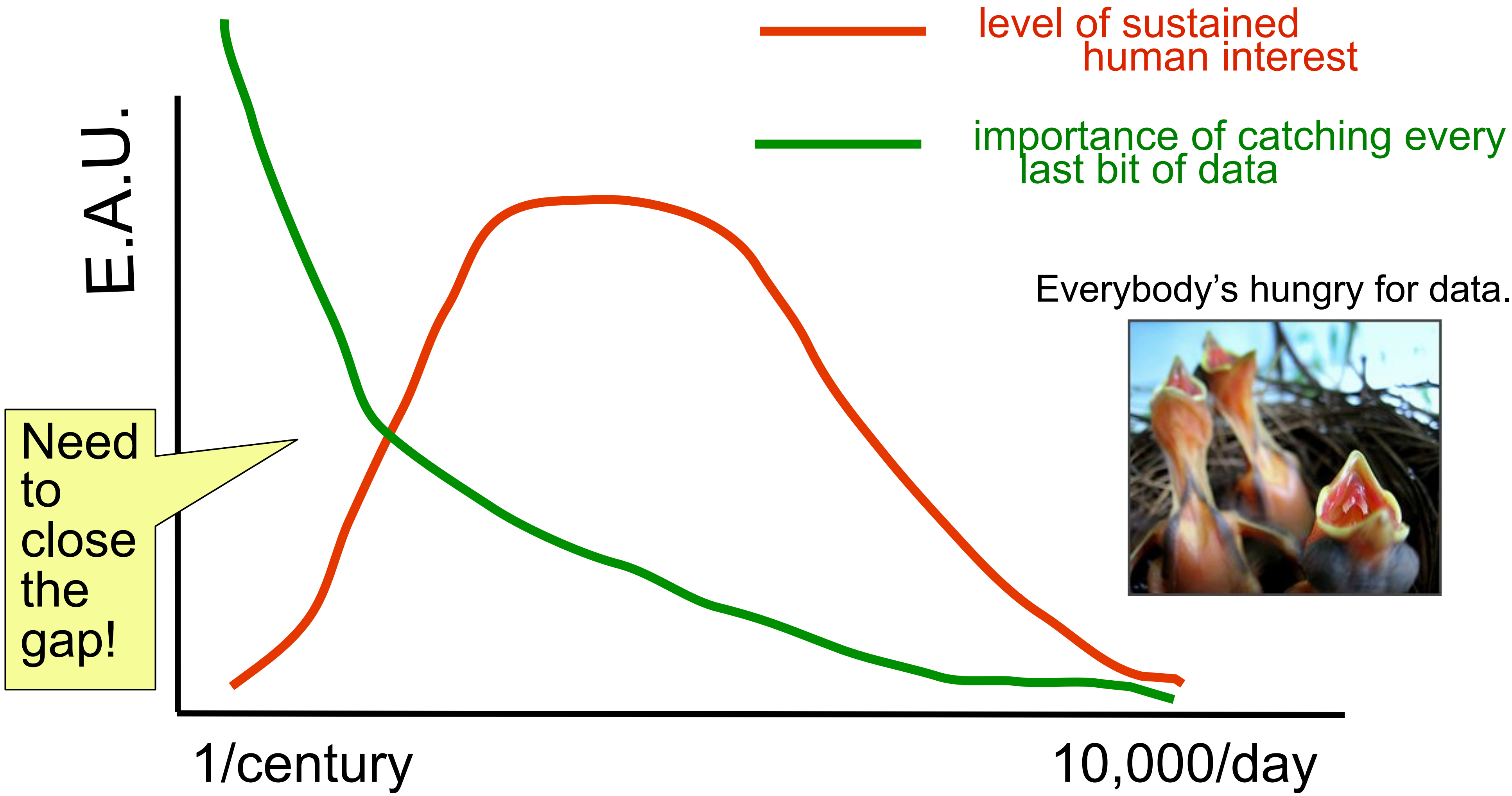
- Running smoothly for more than 10 years, automated since 2005

# SNEWS: SuperNova Early Warning System

snews.bnl.gov



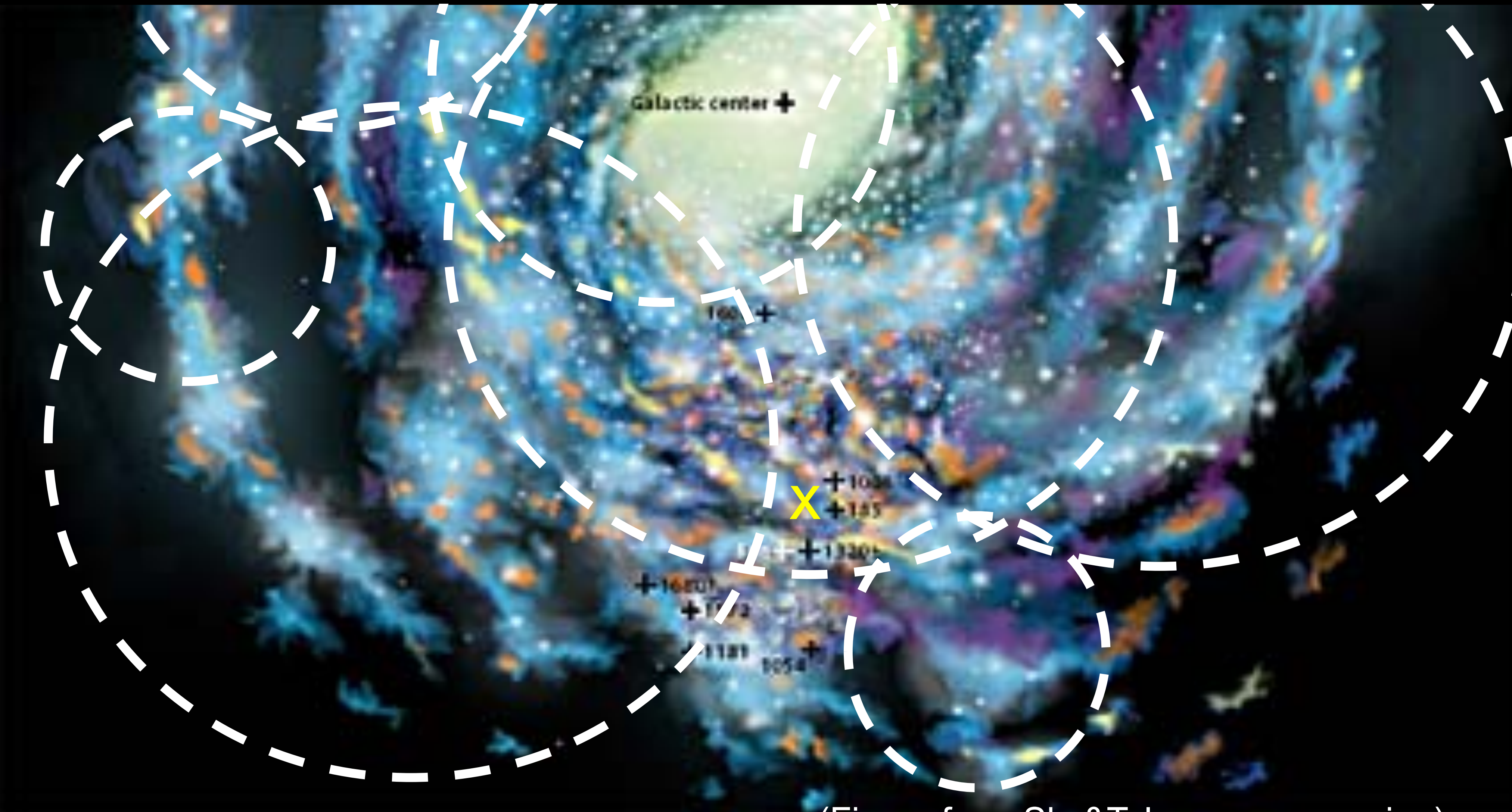
# Sociological comments...




Everybody's hungry for data...

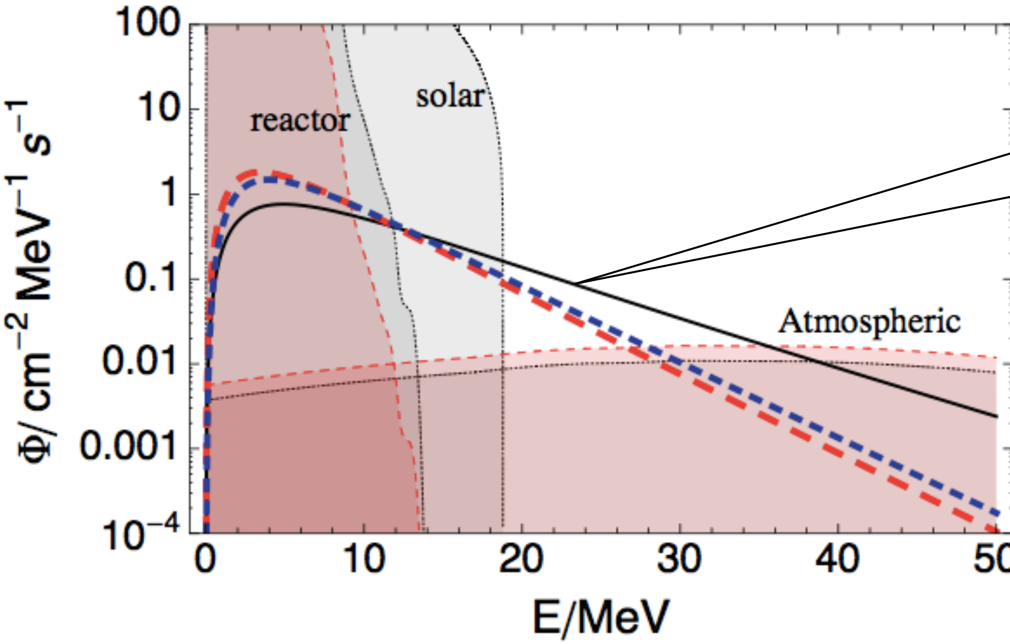
# The neutrinos are coming!

Far side of the Milky Way is ~650 light-centuries away...
... ~2000 core collapses have happened already....



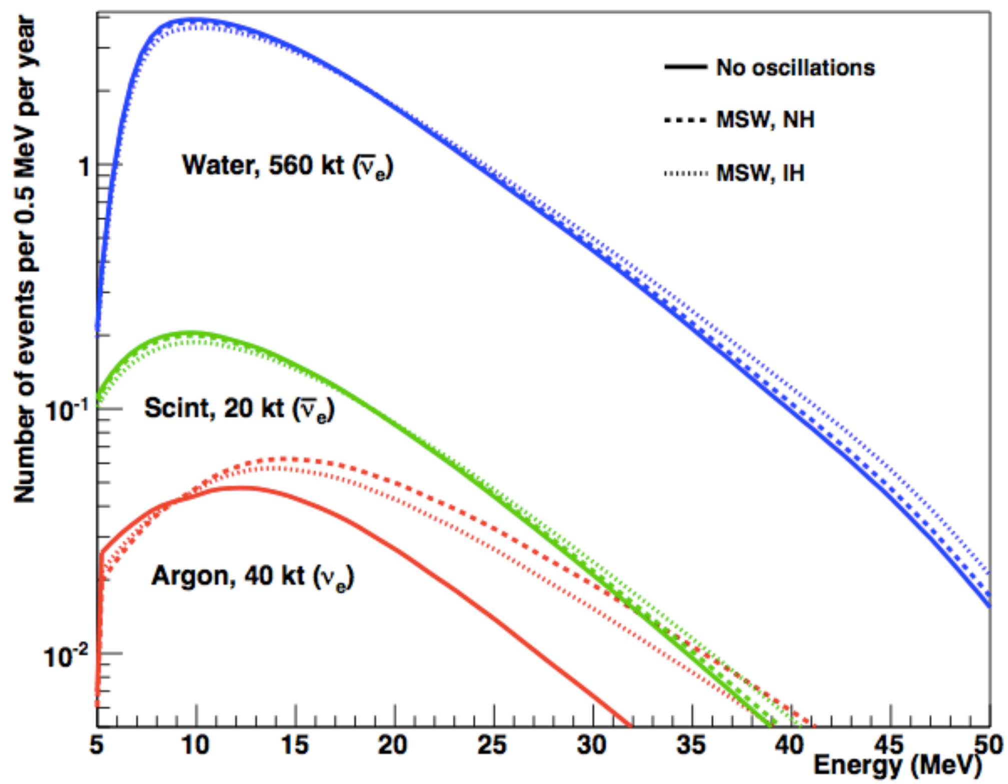

(Figure from Sky&Telescope magazine)

And going even farther out: we are awash in a sea of **'*relic*' or diffuse SN ν's (DSNB)**, from ancient SNae ...




Window with low ν bg, 20-40 MeV

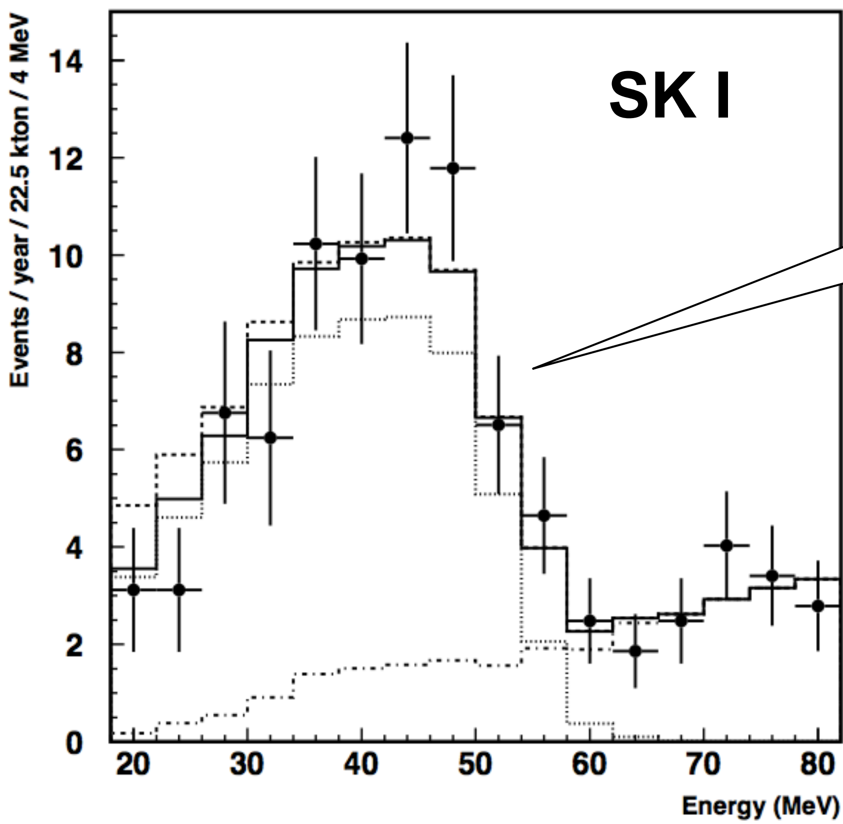
~few events per year in SK




Difficulty is tagging for decent signal/bg (no burst, coincidences w/ optical SNae...)

it's all about the backgrounds

**In water:** $\bar{\nu}_e + p \rightarrow e^+ + n$



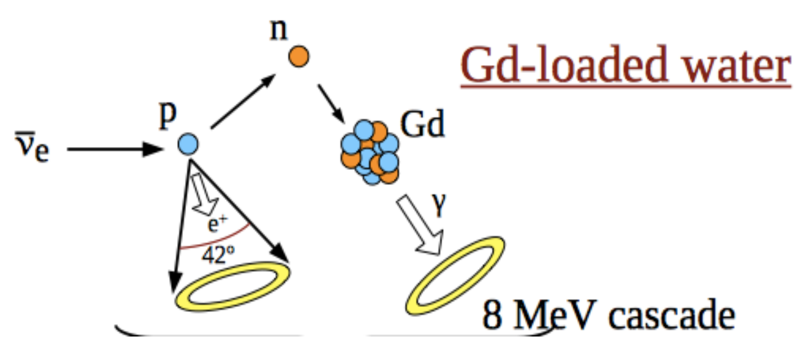

Michel electrons from decays of sub-Cherenkov threshold muons

- Worst background is from decaying 'invisible muons' from atmospheric neutrinos $\rightarrow$ ***reduce by tagging electron antineutrinos with Gd***
- Underway for SK!

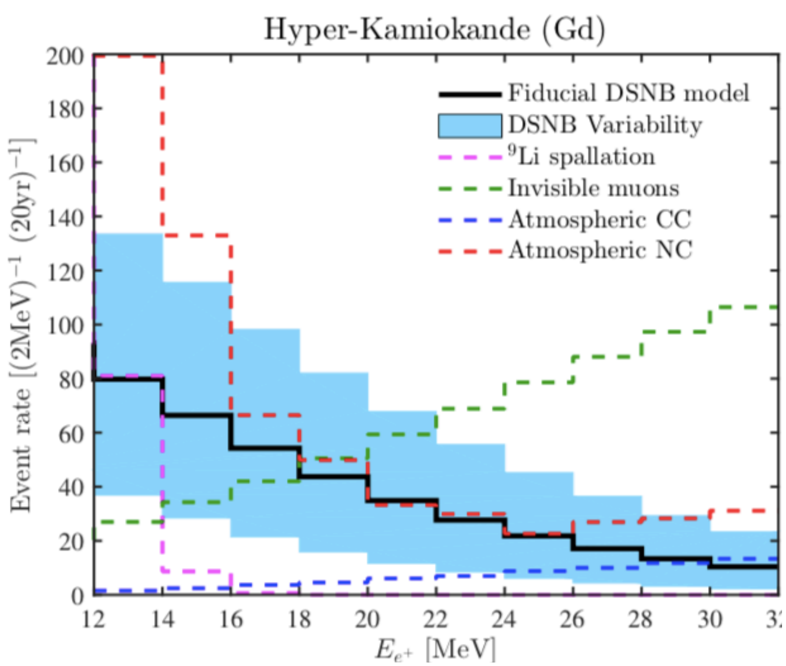
LAr? Electron flavor, but low rate... bg unknown

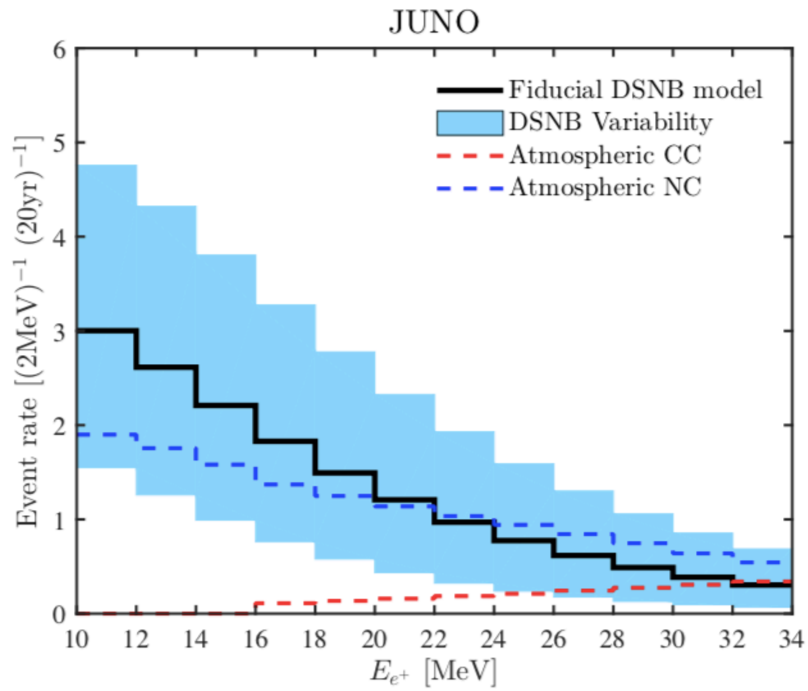
Scintillator?

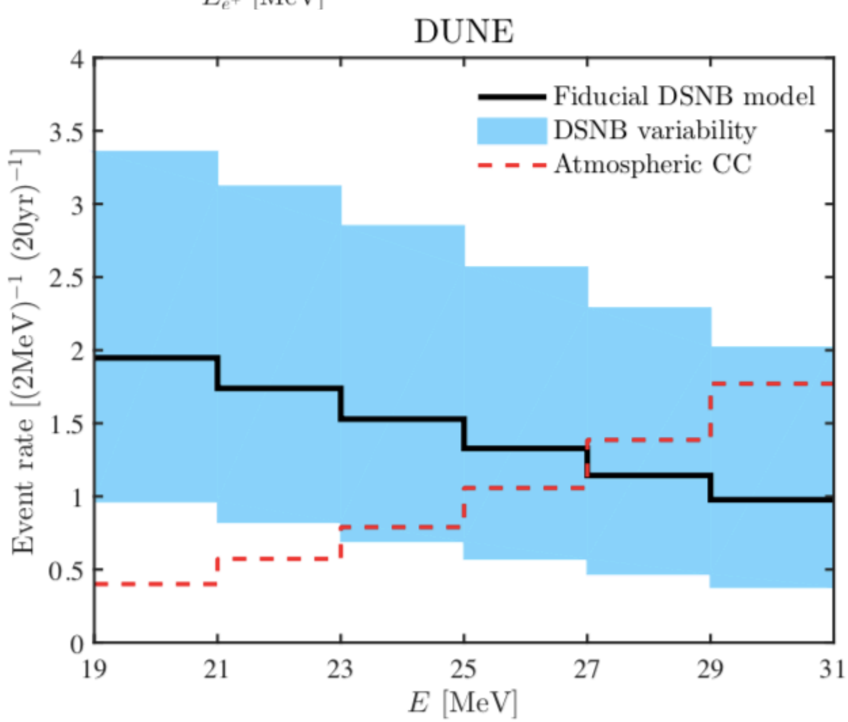
Good IBD tagging, but NC bg...



# We may get there eventually!




Moeller et al.,
JCAP 1805 (2018) 05, 066

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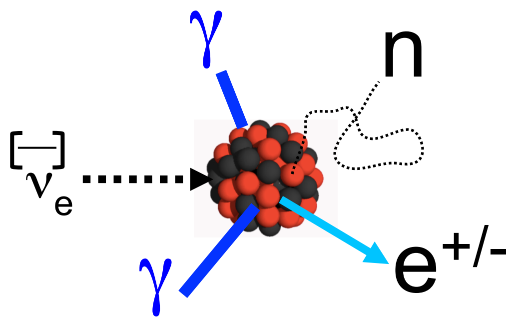
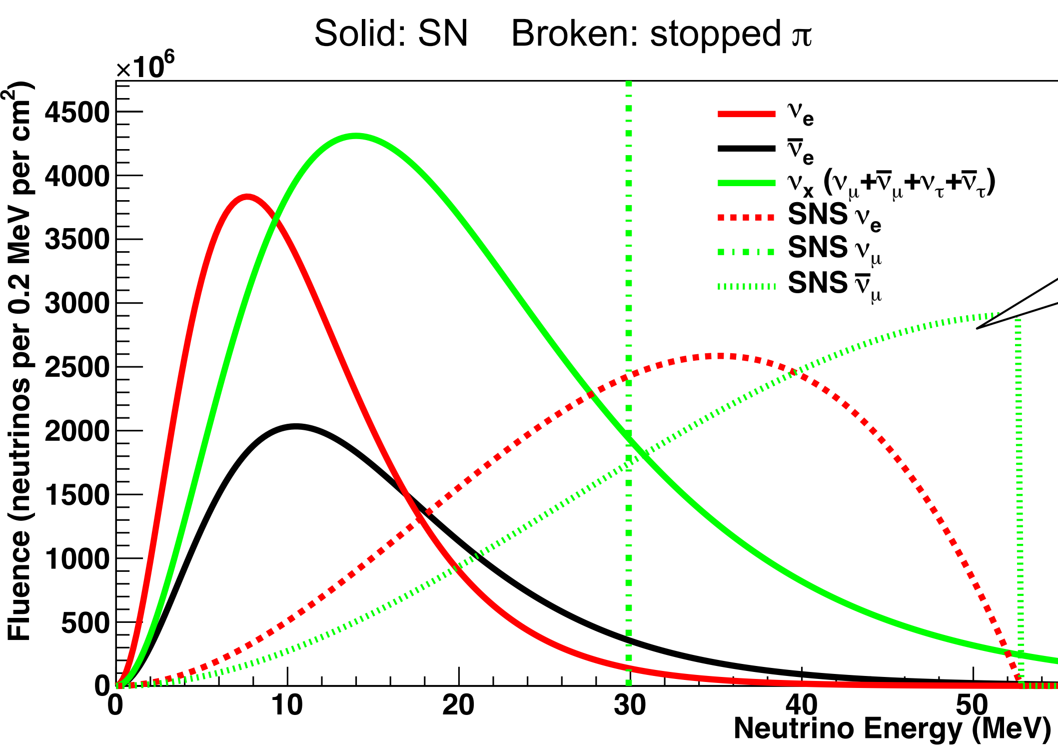



Interactions with nuclei
(cross sections & products)
**very poorly understood**...
sparse theory & experiment
(*only* measurements at better than ~50% level are for $^{12}C$)

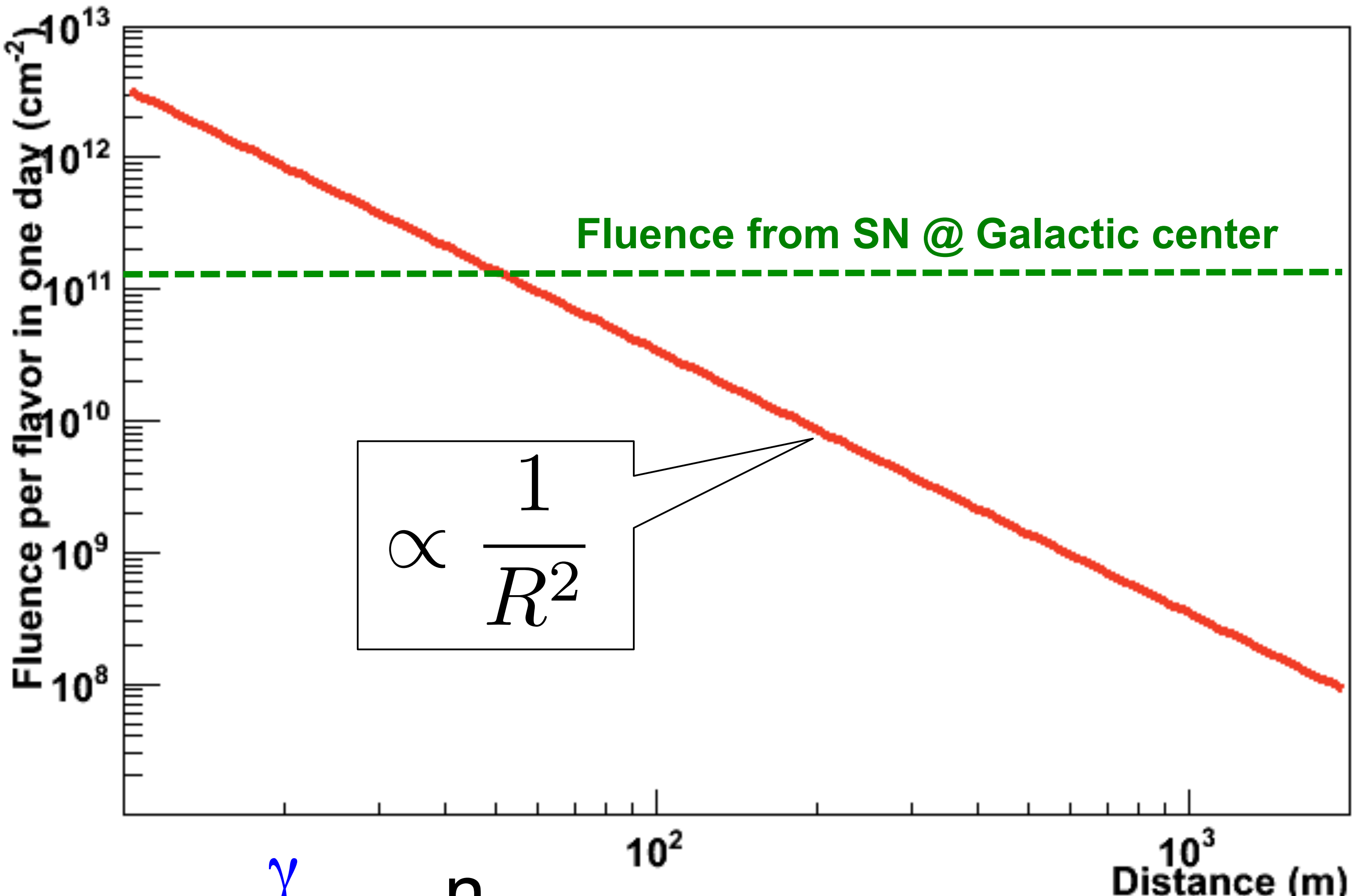


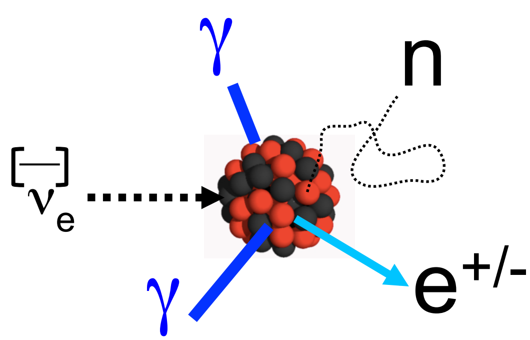

Neutrinos from pion decay at rest have spectrum overlapping with SN ν spectrum, e.g., at ORNL Spallation Neutron Source

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

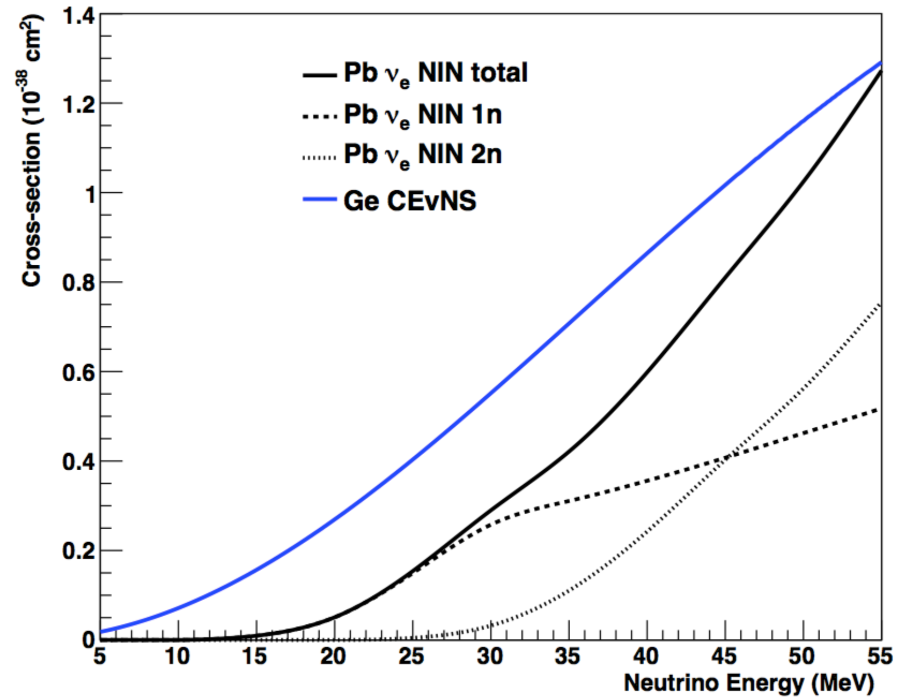
# Currently measuring *neutrino-induced neutrons* in lead, (iron, copper), ...

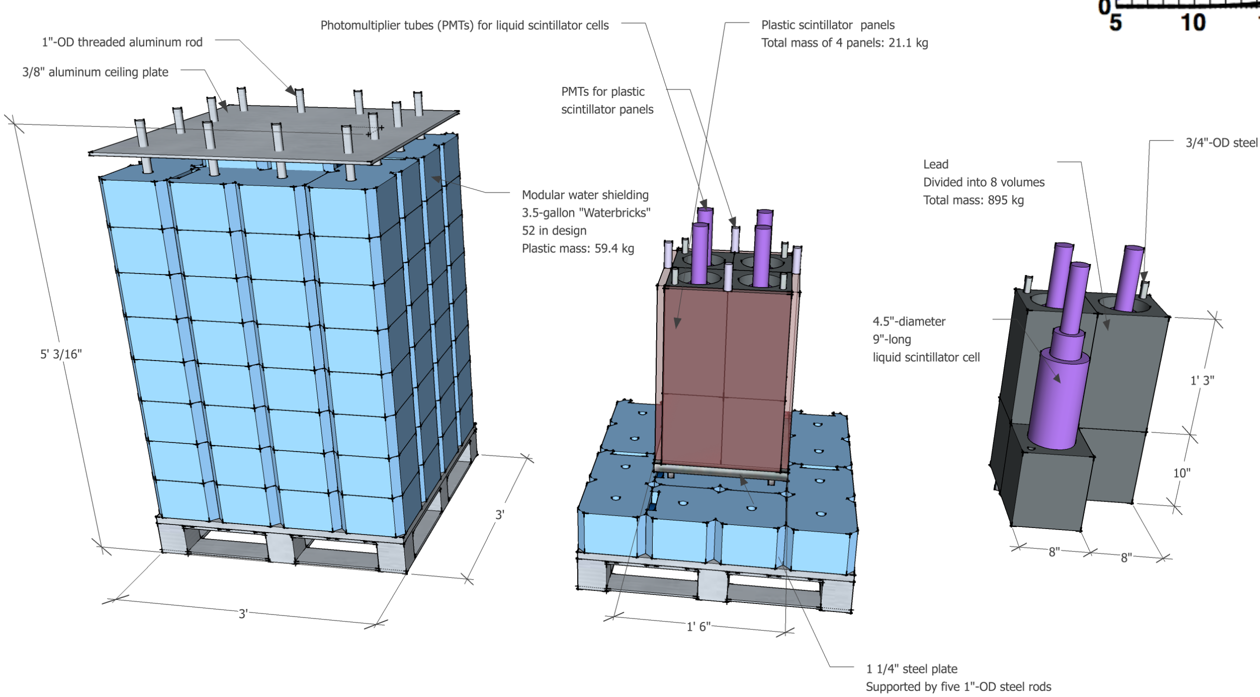
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^- \quad \mathrm{CC}$$

1n, 2n emission

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

1n, 2n, $\gamma$ emission

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# Summary & Prospects

**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. $\nu_e$ in LAr!)
- multimessenger prospects
- DSNB prospects improving