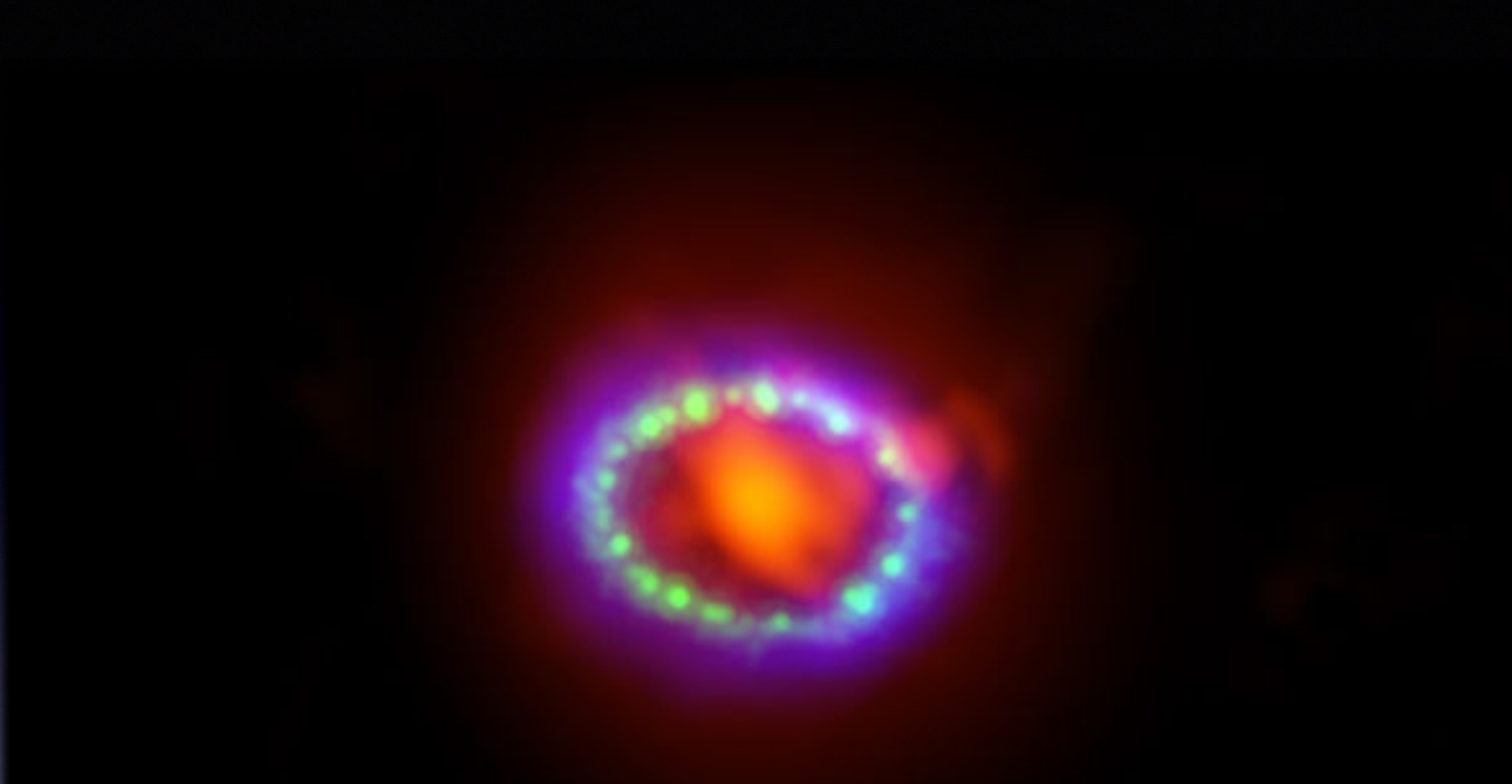


SuperNova Neutrino Detection

Fundamental Symmetries, Neutrinos, Neutrons and related Nuclear Astrophysics

Long-Range Plan

Town Meeting

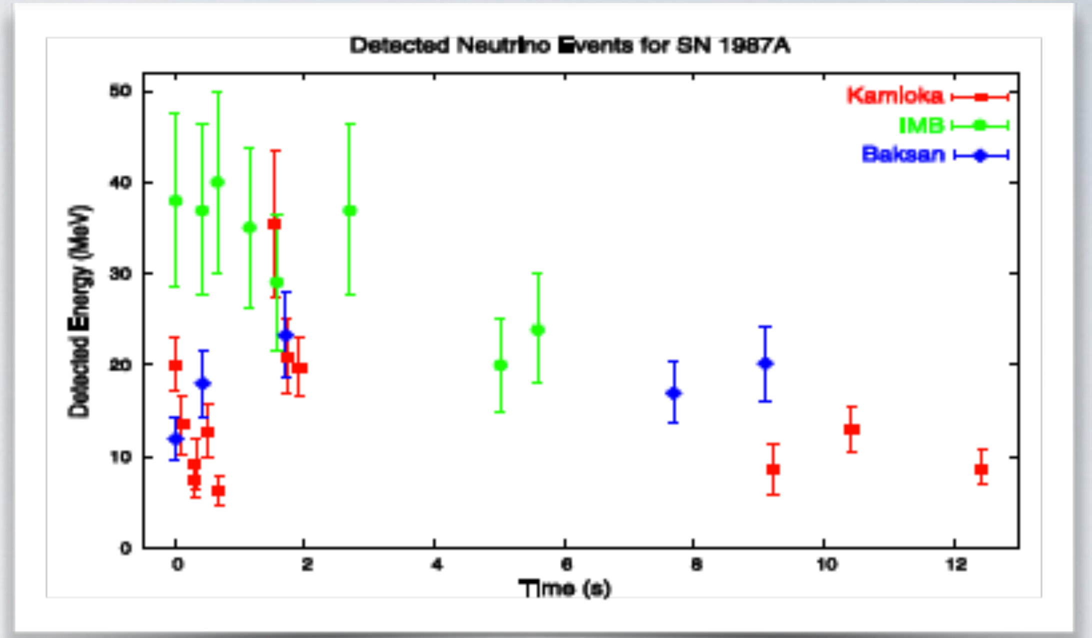
Chicago IL - Sept 29, 2014

Flavio Cavanna

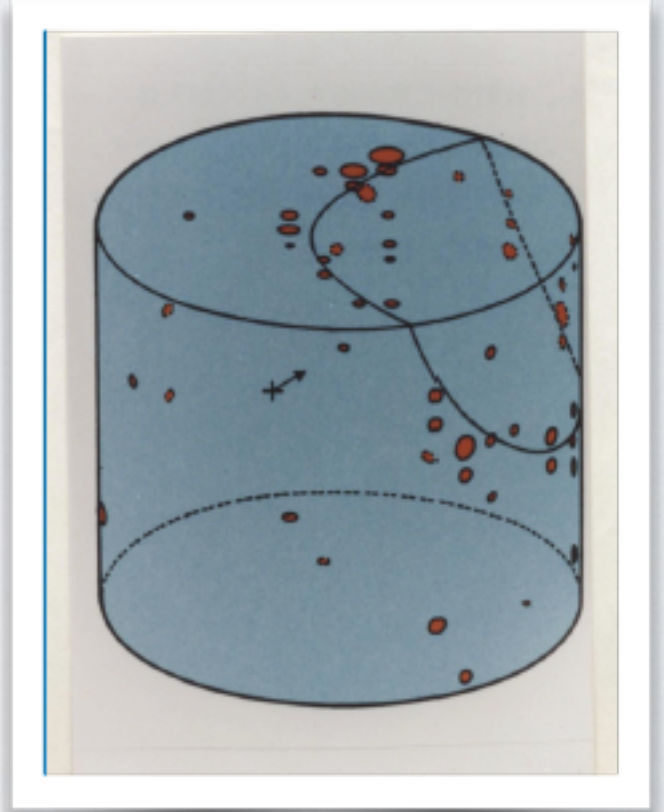
(Yale U. and FNAL-Neutrino Division)

About 20 events were detected in 1987 by simultaneous observations of Kamiokande II, IMB, Baksan detectors from supernova, SN1987A, located in the Large Magellanic Cloud, at a distance D < 50 kpc.
Usually, all these events are attributed to IBD - inverse β-decay

The experimental detection of these events had and keeps having an unprecedented impact in AstroParticle Physics.



The rate of occurrence of core collapse supernovae for our galaxy ranges from ~1/(10 y) to ~1/(100 y).
In water or scintillator detectors one expects roughly 300 ν_e-events/kton, for a distance D =10 kpc - when our galaxy has a radius of ~15 kpc and we are located at 8.5 kpc from its center.



Many operating neutrino detectors like ***Super-Kamiokande, LVD, KamLAND, Baksan, AMANDA/IceCube, Borexino and Halo*** could be blessed by the next galactic supernova.

Other detectors like ***SNO+***, ***MicroBooNE*** will also be able to contribute to galactic supernovae monitoring in the near future.

Future gigantic detectors like ***LBNF, or Hyper-K, or LENA*** will play the key role when will come online.

SUPERNOVA NEUTRINOS

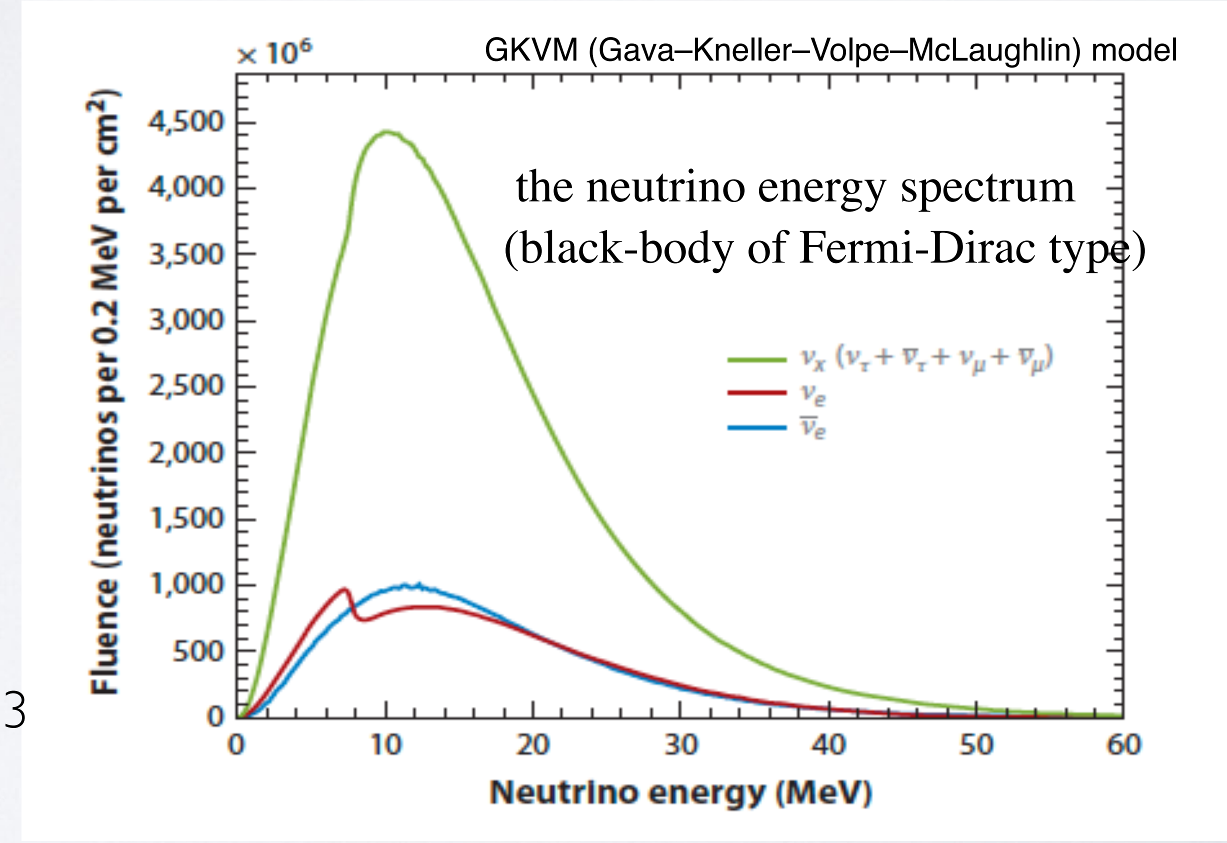
SN-core collapse Neutrino emission Modelling has steadily improved over the past few decades. Significant variations in the expected flux from supernova to supernova due to differences in the mass and composition of the progenitor, and possibly asymmetries, rotational effects, or magnetic field effects.

Reference ranges on SN neutrino energies averaged on time (starting at flash time, $t_0 = t_{fl}$)

$$\langle E_{\nu_e} \rangle = 10\text{–}12\,\text{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle = 11\text{–}17\,\text{MeV}, \quad \langle E_{\nu_x} \rangle = 15\text{–}25\,\text{MeV}$$

Neutrino oscillations and matter enhanced conversion mechanism in the stellar medium should modify the expected supernova neutrinos fluxes.

These modifications are large - in particular due to the size of the vacuum mixing angle θ_{13}



Disentangle neutrino physics and SN core-collapse physics is not trivial.

There are chances to learn on neutrinos, but presumably the primary aim of SN observations is supernova astrophysics.

What do we want in SN ν detector(s) ?

K. Scholberg - Ann.Rev.Nucl.Part.Sci 62 (2012), 81.

✓Large Mass: ~ few × 100 interactions in ~1kton
for burst at the Galactic center (8.5 kpc away)

✓**Sensitivity to different flavors** $(\nu_e, \bar{\nu}_e, \nu_{x=\mu,\tau})$

✓Ability to tag interactions

✓Also want:

- Energy resolution
- Timing
- Pointing

key for disentangling
core collapse & neutrino physics

✓Low background rate ≪ rate in ~10 sec burst
(typically easy for underground detectors, even thinkable at the surface)

✓Detector locations around the globe desirable, too!

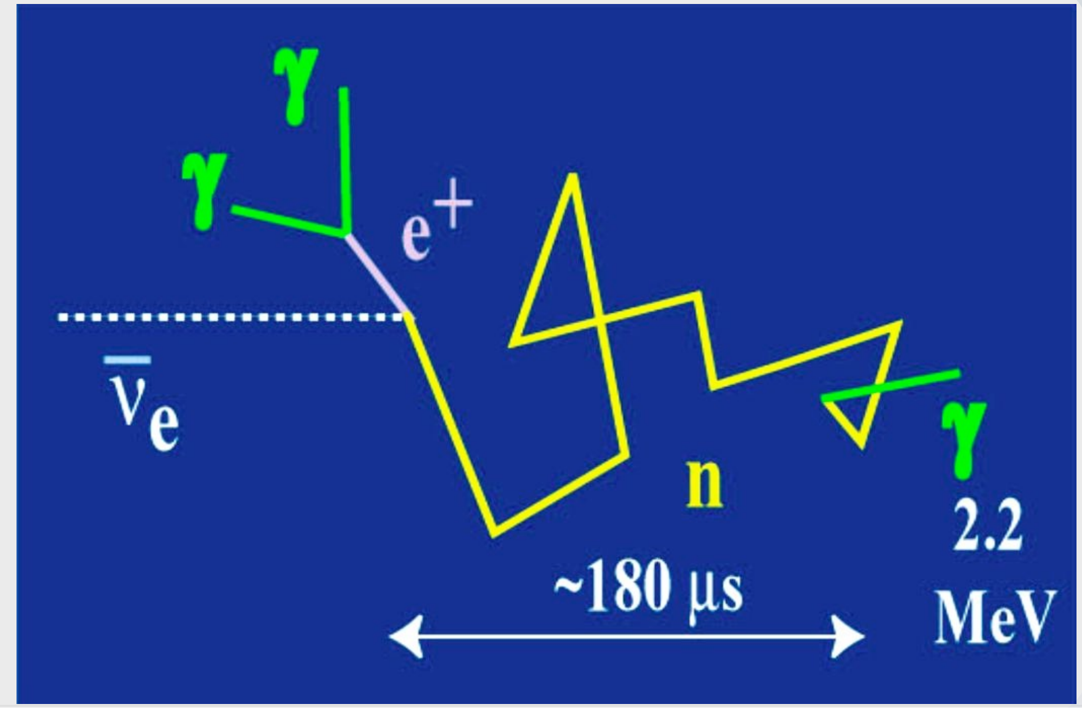
+ EARLY ALERT

Neutrino interactions in the few-tens-of-MeV range

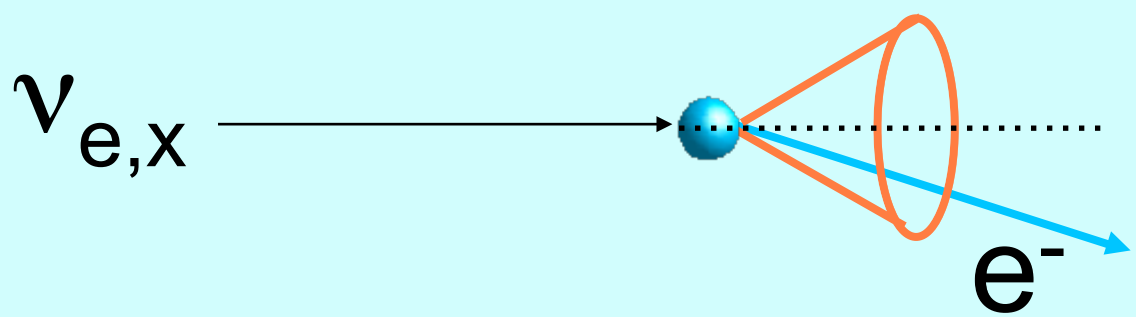
IBD - Inverse Beta Decay (CC)

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

In any detector with lots of free protons (e.g. water, liquid scintillator) this dominates



ES - Elastic Scattering on atomic electrons



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

(useful for pointing)

interactions on nuclei:

ABS - $\nu_e, \bar{\nu}_e$ CC Absorption

NE - ν_x NC Nuclear Excitation

Coh - ν_x NC Coherent Scattering

$$\nu_e + (N,Z) \rightarrow (N-1, Z+1) + e^-$$

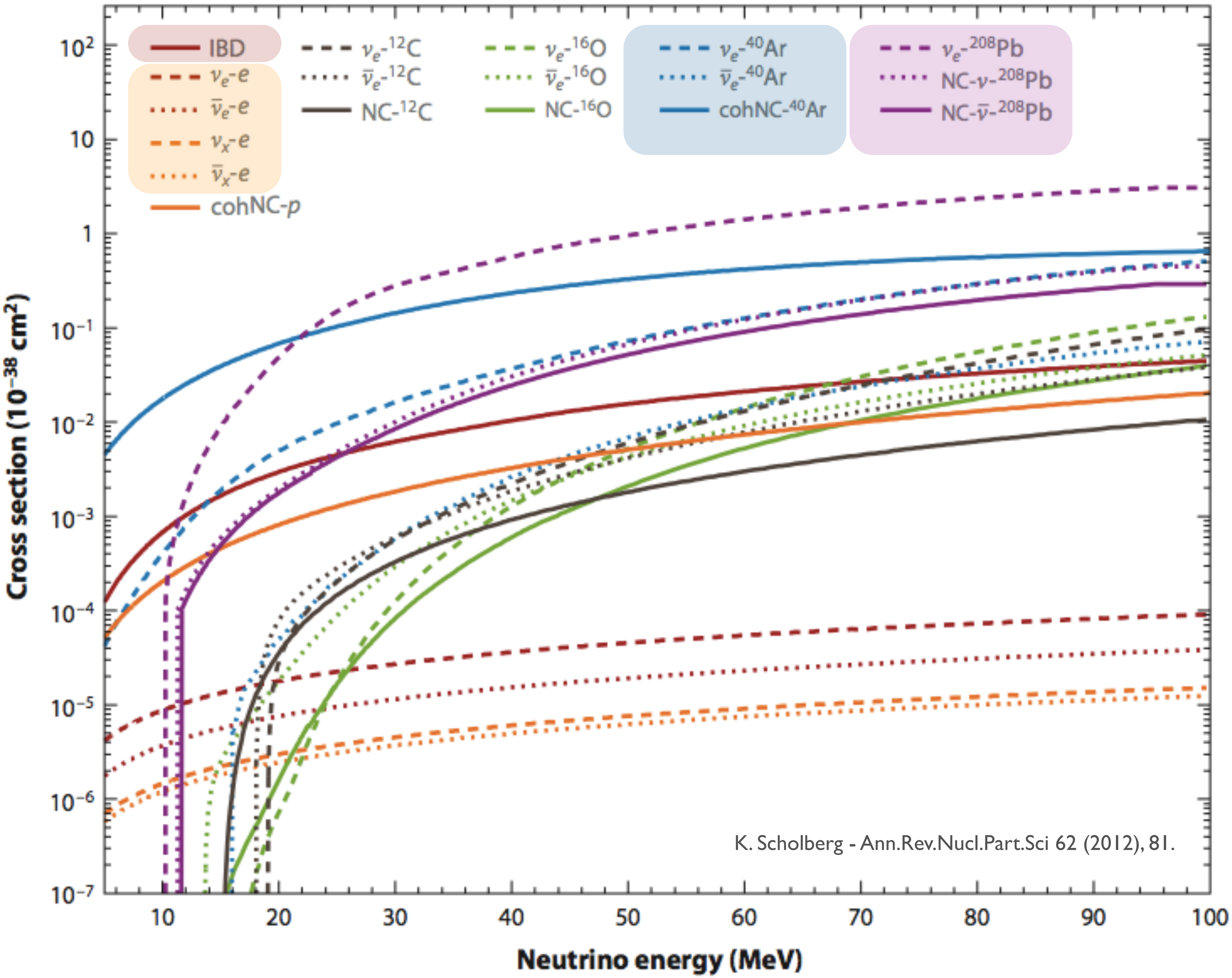
$$\bar{\nu}_e + (N,Z) \rightarrow (N+1, Z-1) + e^+$$

$$\nu_x + (A,Z) \rightarrow (A,Z)^* + \nu_x$$

$$\hookrightarrow (A,Z) + \gamma$$

+ NC coherent scattering

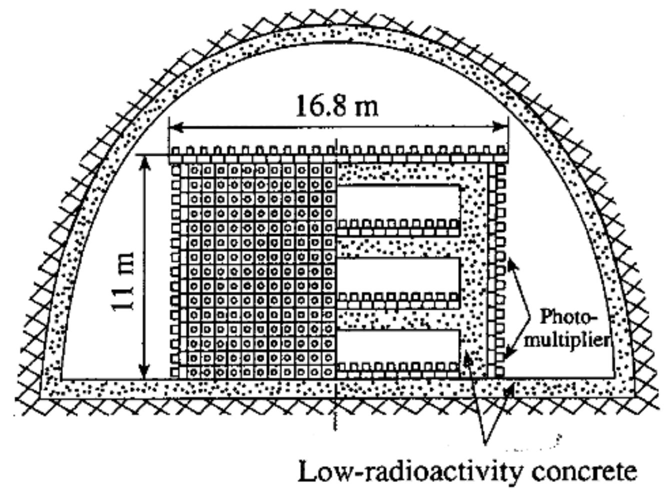
The Cross Section Bible



Current
or nearly coming online

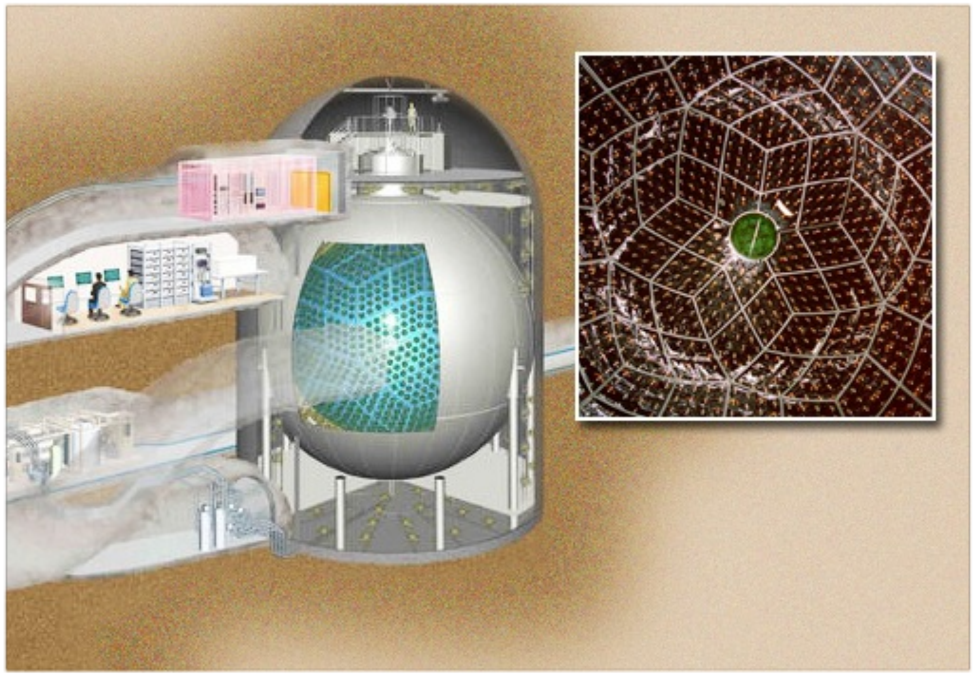
SN neutrino sensitive
Detectors

(running) Liquid Scintillator Detectors

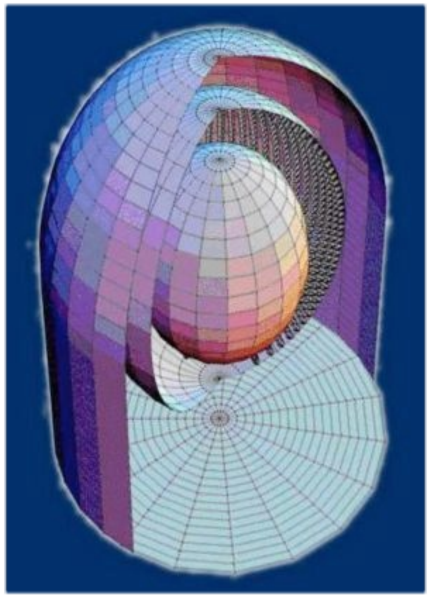


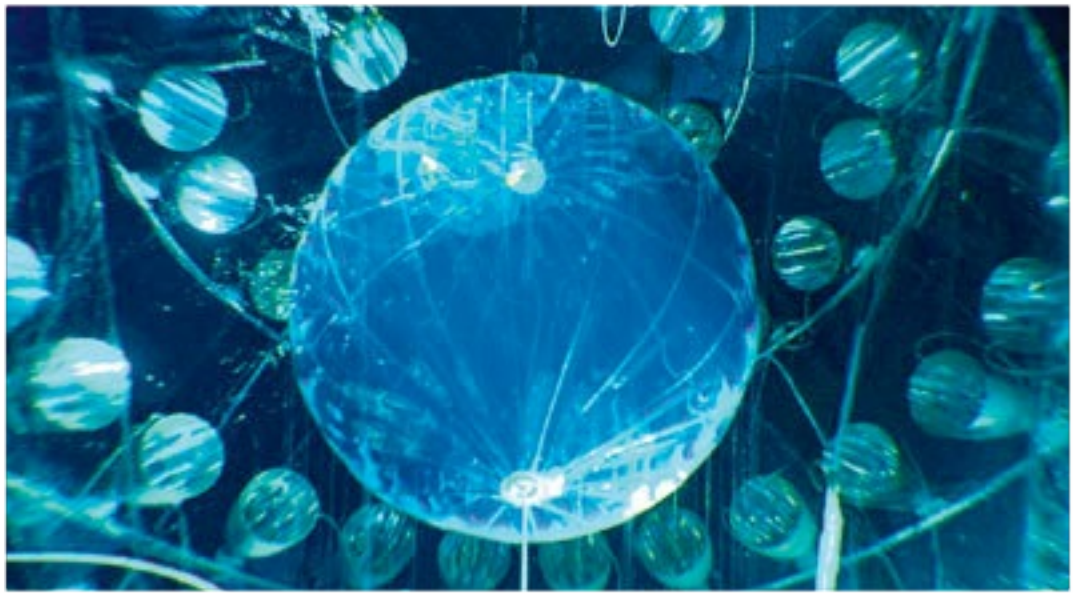
BNO
Baksan Neutrino Observatory
(INR - Russia)
[0.33 kT]

LVD
Large Volume Detector
(INFN - GranSasso - Italy)
[1 kT]



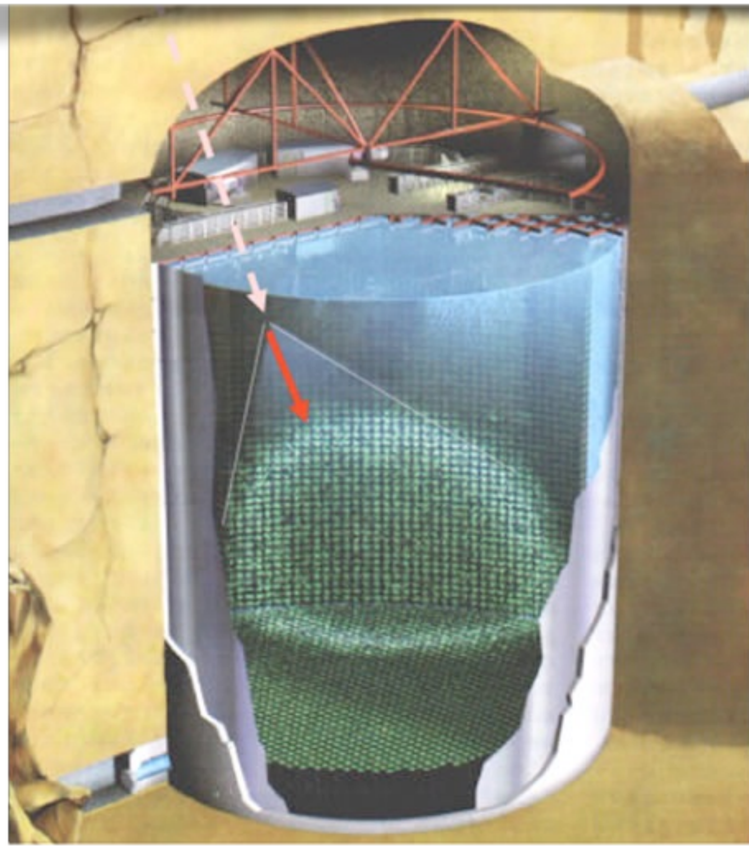
KAMLAND
Kamioka Liquid-scintillator Antineutrino Detector
(Japan)
[1 kT]

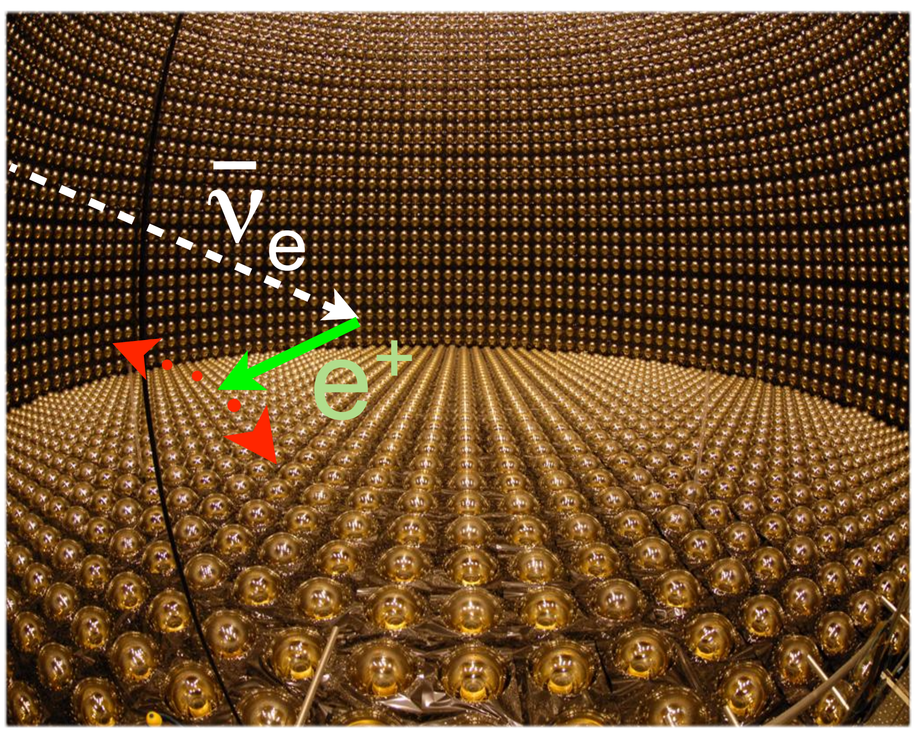




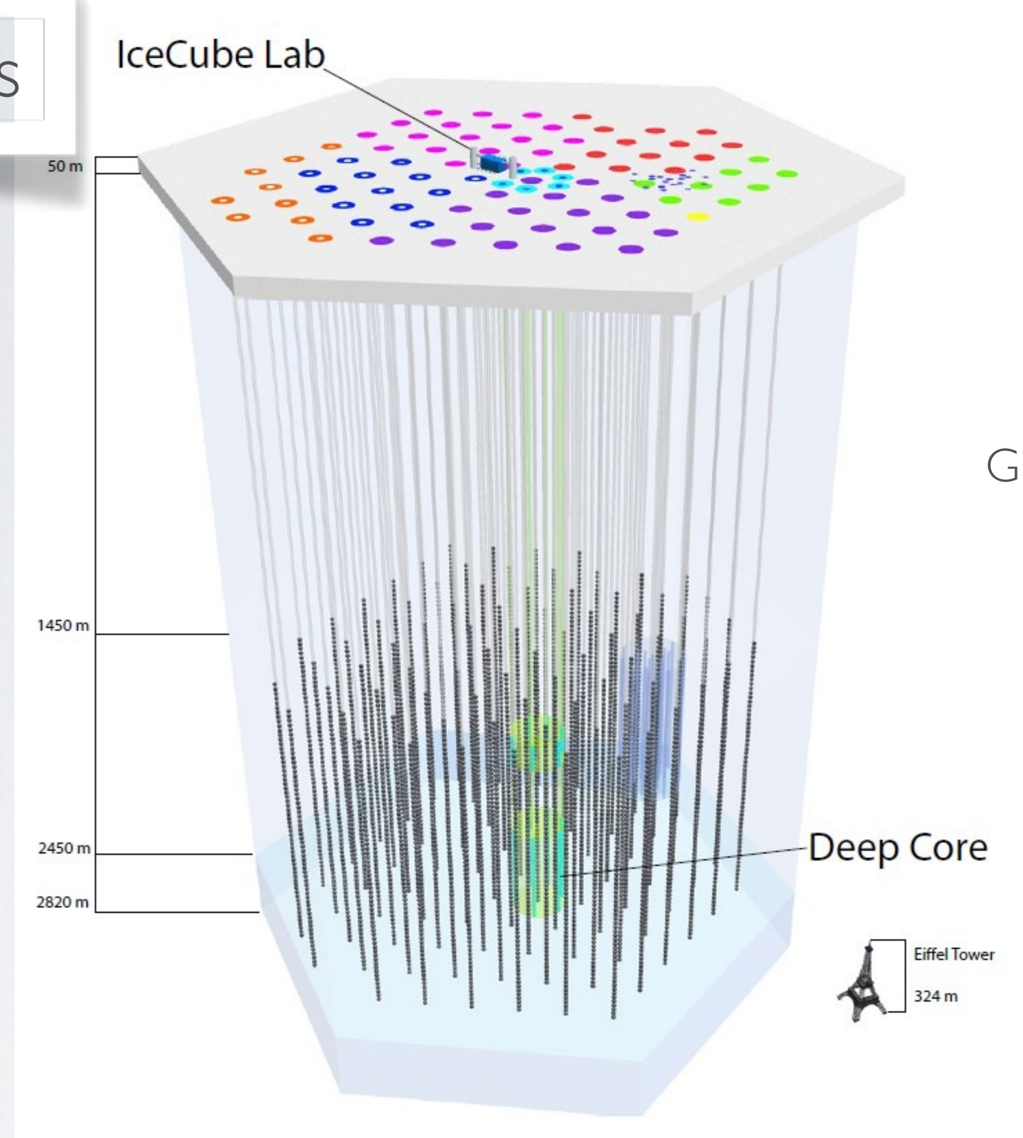
BOREXINO
(INFN - GranSasso - Italy)
[0.3 kT]

(running) Water Cherenkov Detectors

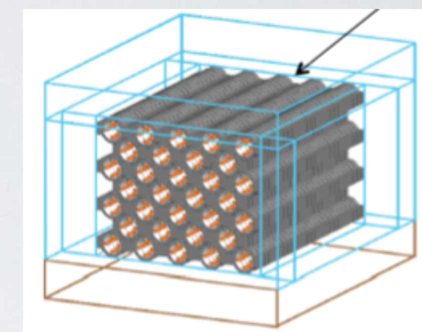




SK
SuperKamiokande (Kamioka - Japan)
[32 kT]

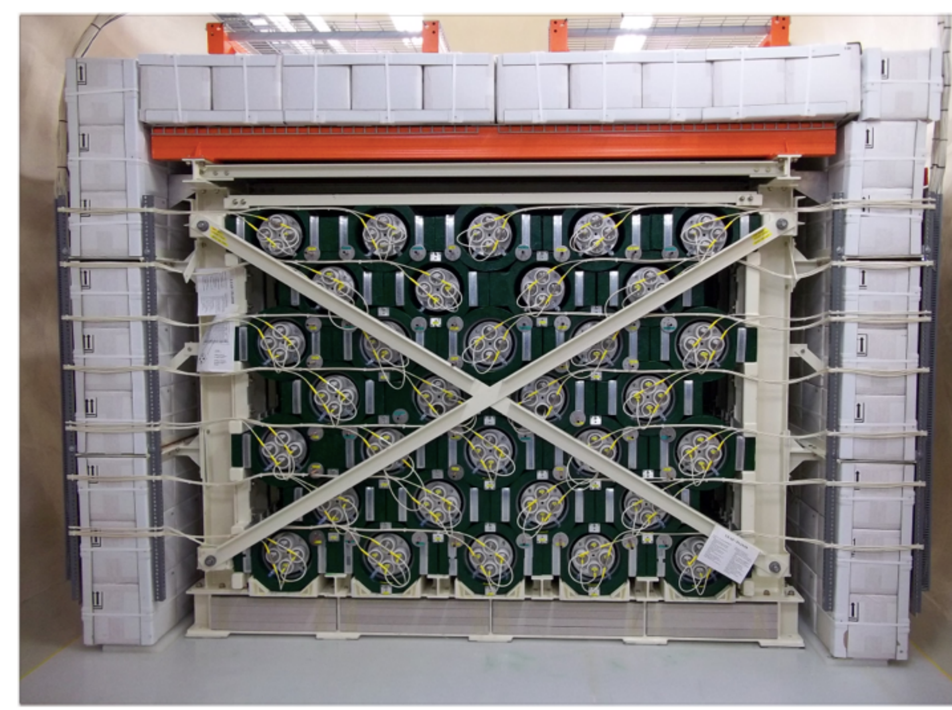


IceCube
GigaTon ice-water detector
(South Pole)



(running) He+Pb Detectors

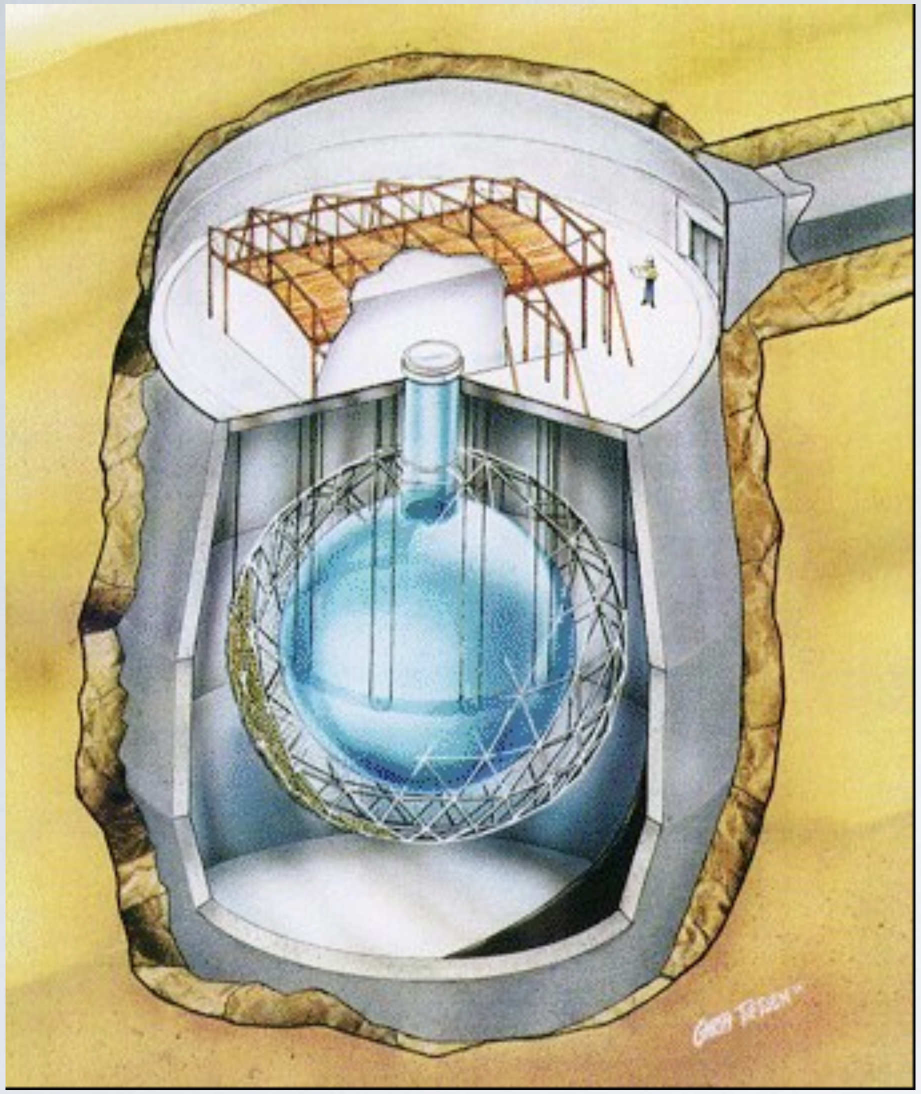
HALO
He-Pb
SnoLAB (Canada)
[76 T]



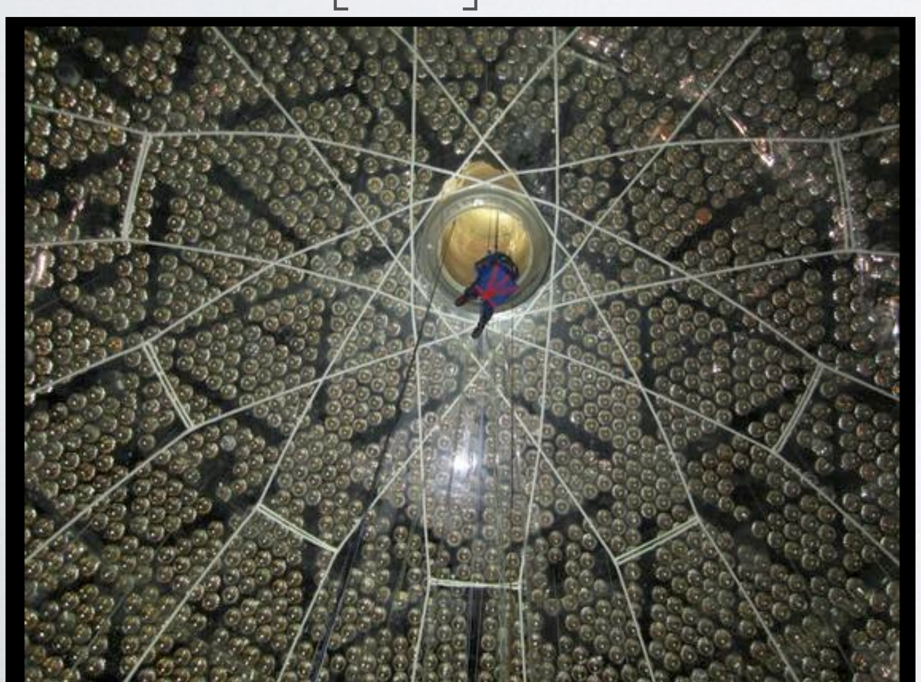
Summary of current supernova ν detectors

of events expected for 10kpc. Directionality

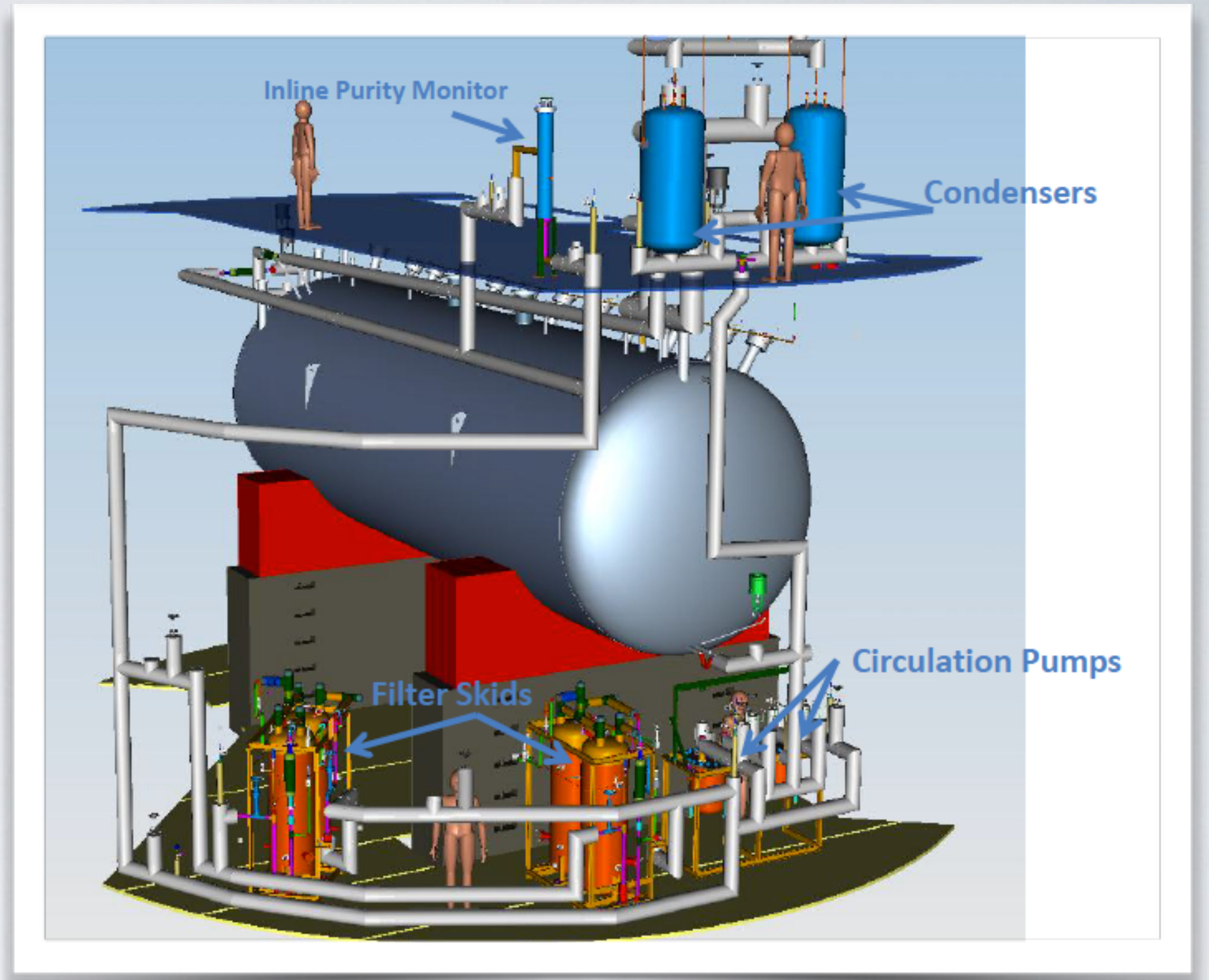
Baksan (1980-)	330 ton liquid scintillator ~100 $\bar{\nu}_e p \rightarrow e^+ n$ events.	No
LVD (1992-)	1000 ton liquid scintillator. 840 counters 1.5m^3 each. 4 MeV thres., ~50% eff. for tagging decayed signal. ~300 $\bar{\nu}_e p \rightarrow e^+ n$ events.	No
Super-K (1996-)	32,000 tons of water target. ~7300 $\bar{\nu}_e p \rightarrow e^+ n$, ~300 $\nu e \rightarrow \nu e$ scattering events.	Yes
KamLAND (2002-)	1000 ton liquid scintillator, single volume. ~300 $\bar{\nu}_e p$, several 10 CC on ^{12}C, ~60 NC γ, ~300 $\nu p \rightarrow \nu p$	No
ICECUBE (2005-)	Gigaton ice target. By coherent increase of PMT single rates. High precision time structure measurement.	No
BOREXINO (2007-)	300 ton liquid scintillator, single volume. ~100 $\bar{\nu}_e p$, ~10 CC on ^{12}C, ~20 NC γ, ~100 $\nu p \rightarrow \nu p$	No
HALO (2010-)	SNO ^3He neutron detectors with 76 ton lead target. ~40 events expected. (30 CC ν_e on ^{208}Pb, 10 NC ν_x on ^{208}Pb)	No



SNO+
(Sudbury - Canada)
[1 kT]



MicroBooNE (FNAL-US)

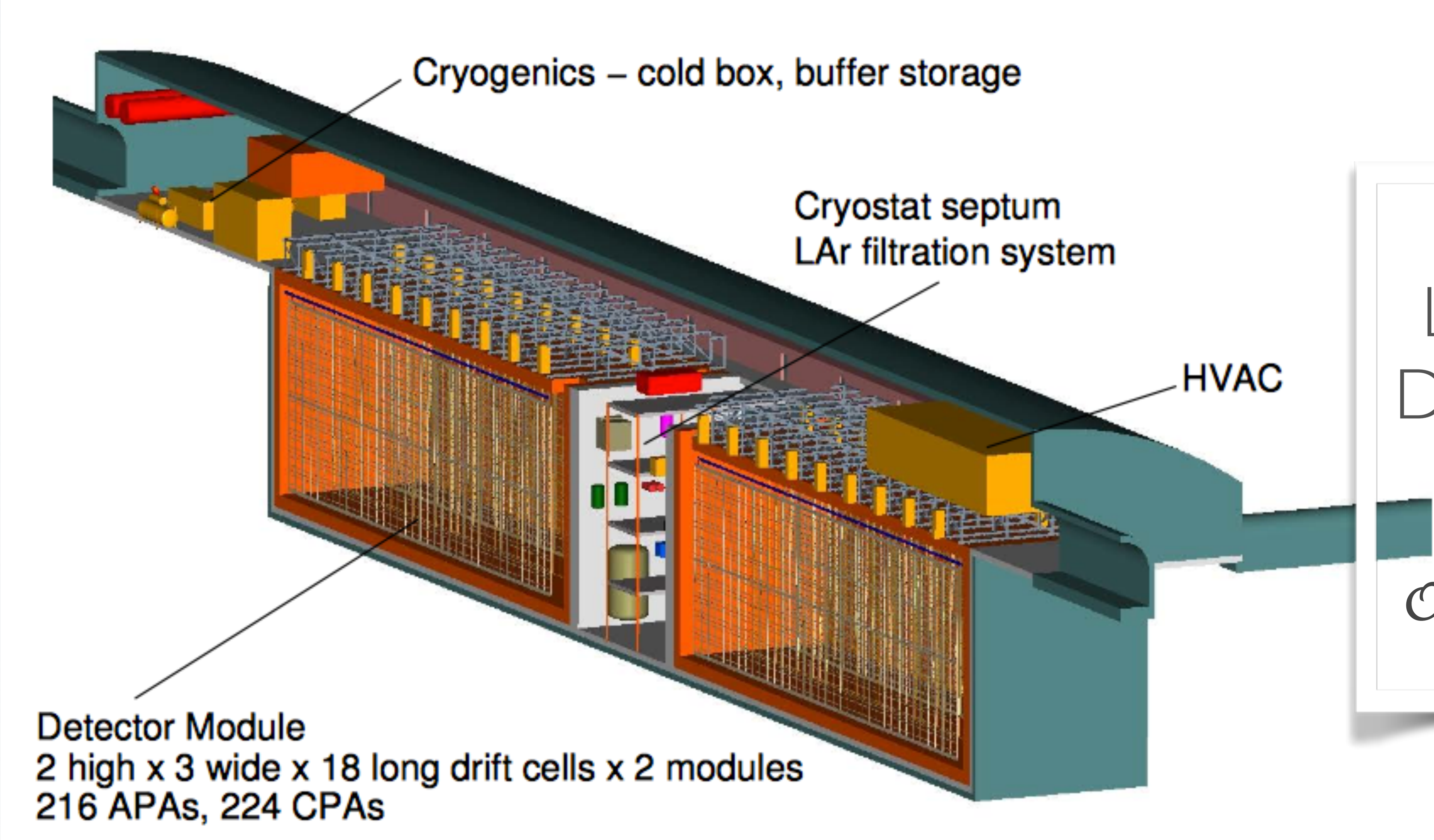


The Argon target

from the P5 Report:

The massive LAr detector *(envisioned for the next generation long-baseline neutrino facility - LBNF)*, when operated underground would also search for proton decay and neutrinos from supernova bursts.

from the LBNE proposal



The LArTPC Detectors

(10-34 kT)

in the

$\mathcal{O}$(10-100 MeV)

Although existing and proposed supernova-neutrino detectors worldwide are primarily sensitive to electron-antineutrinos, the LBNF LAr detector has exquisite sensitivity to the electron-neutrino flavor component, which carries unique physics and astrophysics information

SN-ν Cross Sections on Ar

1) *CC* ν_e **ABS**orption on Ar nuclei

$$\nu_e + Ar \rightarrow K^* + e^-$$

- xsect ~quadratic increase with E_ν.
- e.g @ E_ν =20 MeV ↔ $\sigma_{abs} = 6 \cdot 10^{-41}$ cm^2

2) *CC* anti-ν_e **ABS**orption on Ar nuclei:

depressed by ***high Q-value***

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

3) *NC* **N**uclear **E**xcitation of Ar nuclei

difficult for detection (but maybe not imposs

$$\nu + Ar \rightarrow \nu' + Ar^*$$

4) *NC+CC* **E**lastic **S**cattering on e^-:

$$\nu + e \rightarrow \nu' + e'$$

- xsect linear increase with E_ν.
- e.g. @ E_ν =20 MeV ↔ $\sigma_{ES} = Z_{Ar} \times 2 \cdot 10^{-43}$ cm^2

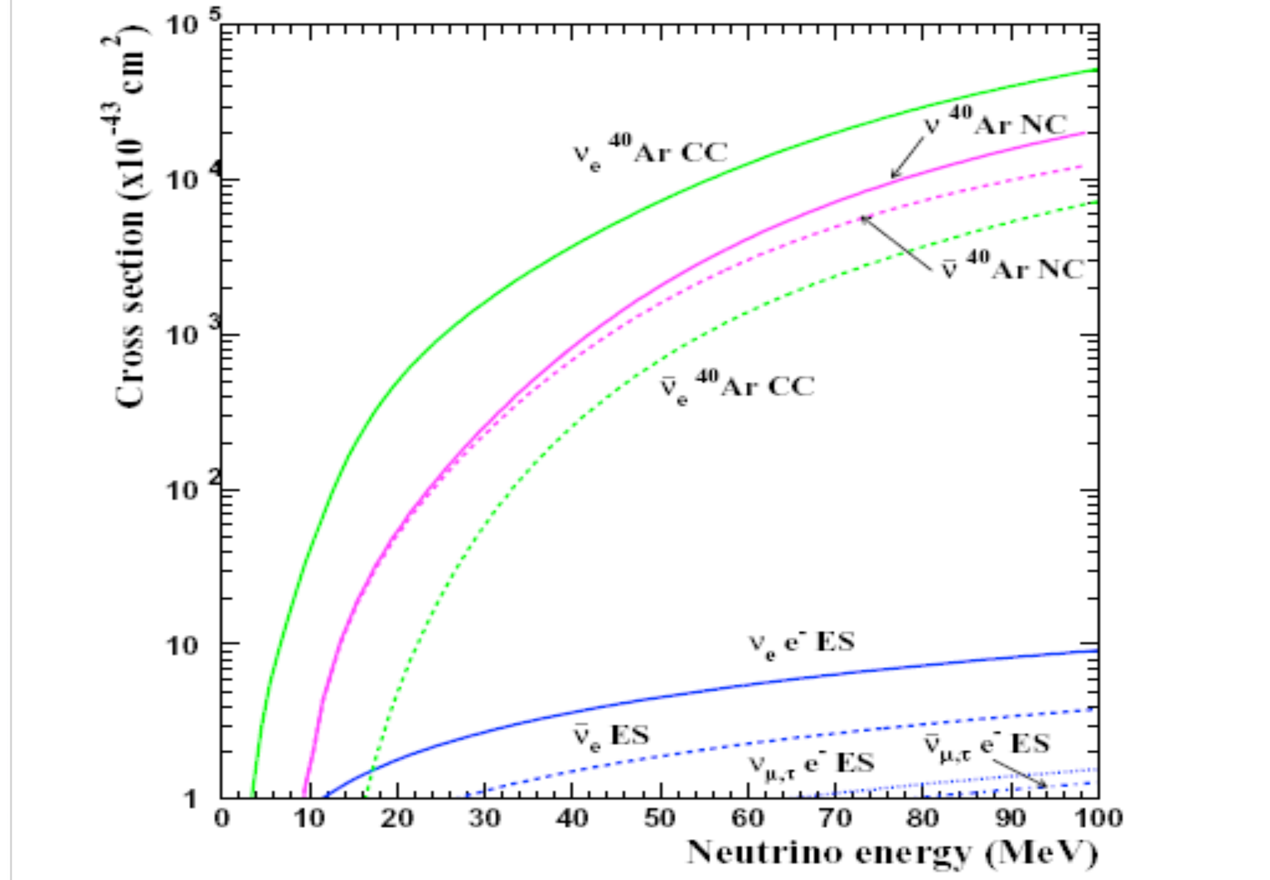
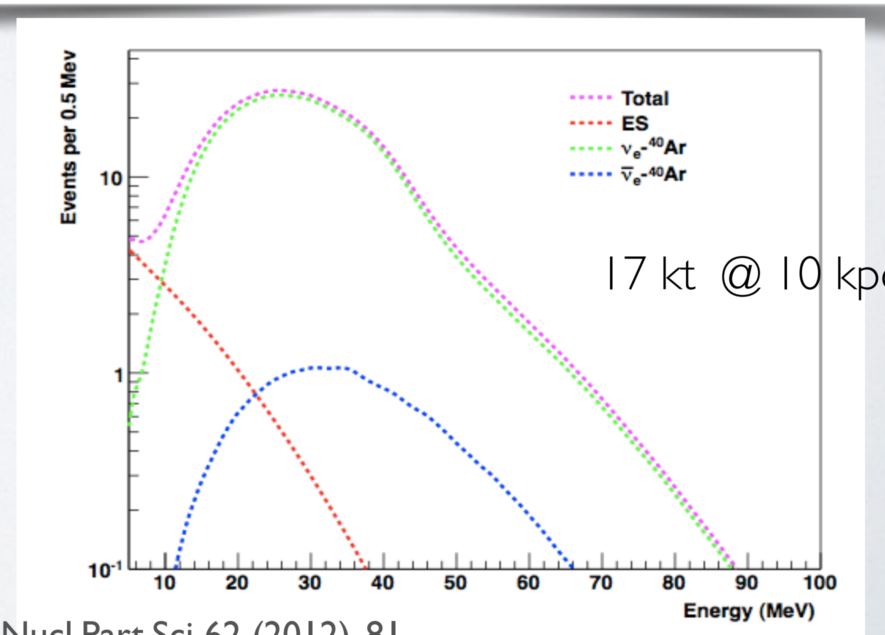


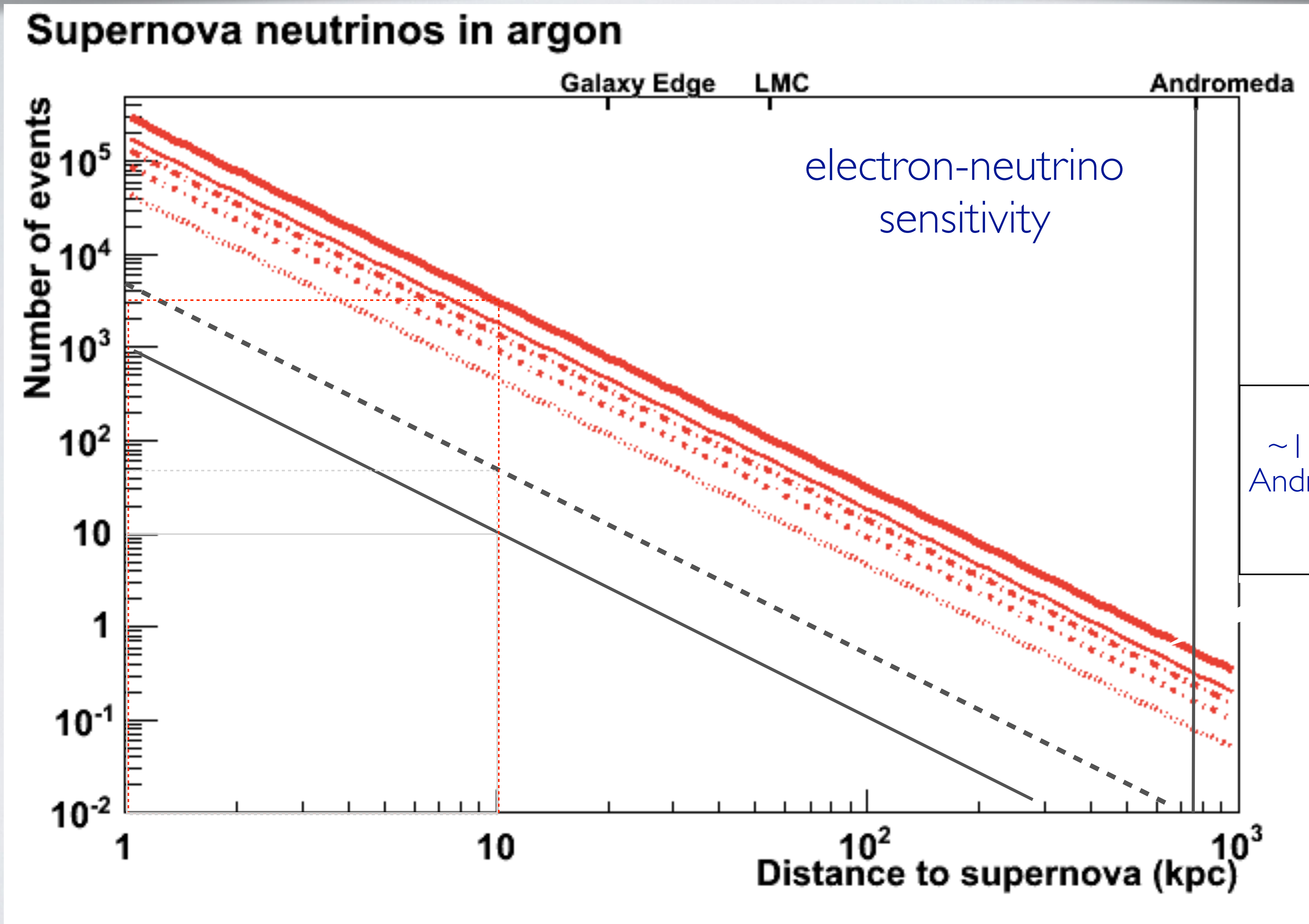
Figure 3: Neutrino cross sections relevant to the supernovae detection with a liquid Argon TPC detector.

Kolbe, Langanke, Martinez-Pinedo



K. Scholberg - Ann.Rev.Nucl.Part.Sci 62 (2012), 81.

Signal rates vs distance for different LArTPC configurations



~1 ν event from Andromeda in ~34 kton

kTon 0.1-0.5, 5, 10, 15, 20, 34 kTon

The Experimental challenge of SN Neutrino Detection in LArTPC

$$\nu_e + Ar \rightarrow K^* + e^-$$

↳ γ(s)

compton ↳ e(s)

- One leading "~10 wire electron" track (***squiggle*** )
- A number of "1-2 wires electrons" localized en. deposits (***spots*** ) from de-excitation gammas

Determination of the Ar ABS XSect

Experimental validation of the existing theoretical calculations

Implementation of detailed MC generator for Ar in the 10-100 MeV Eν-range

Cascade of de-excitation γ's from Ar-K* Nuclear transitions and continuous level density with statistical emission at higher excitations

Event Detection & Identification & Reconstruction in LAr TPC

and extraction from Background

SN-ν ABS Cross Section on Ar

in the [10-100] MeV ν-energy range

THEORETICAL CALCULATIONS

$$\nu_e + Ar \rightarrow K^* + e^-$$

- *first proposed in 1986* [Ragahvan] and [Bahcall et al.]:
  Shell-Model calculations(Super-allowed) F Transition
- Shell-Model calculations [Ormand et al.] GT Transitions added (1996)
- Shell-Model calculations [M. Bhattacharya et al.] more GT transitions (1998)
- Random Phase Approximation (RPA) [Langanke et al.] forbidden transitions (up to J=6) (2003)
- Local Density Approximation (LDA) [Singh et al.] (2004)
- Hybrid Model: Shell-Model (F+GT) + Random Phase Approx. [T. Suzuki] (2011)

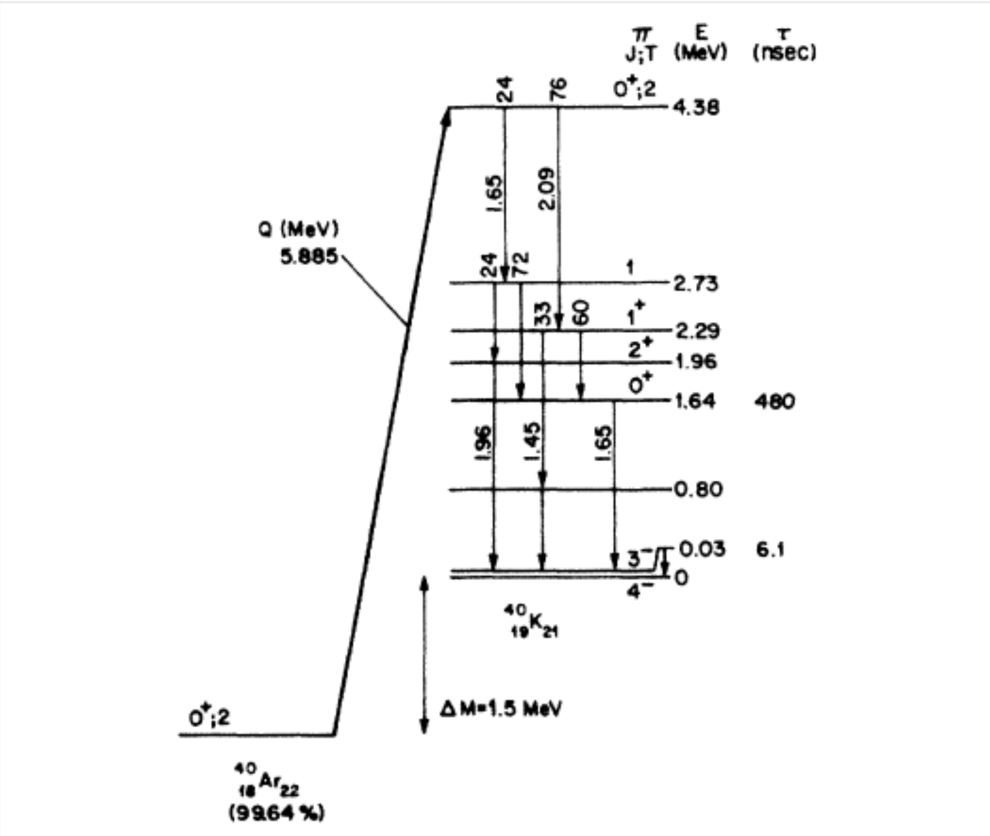
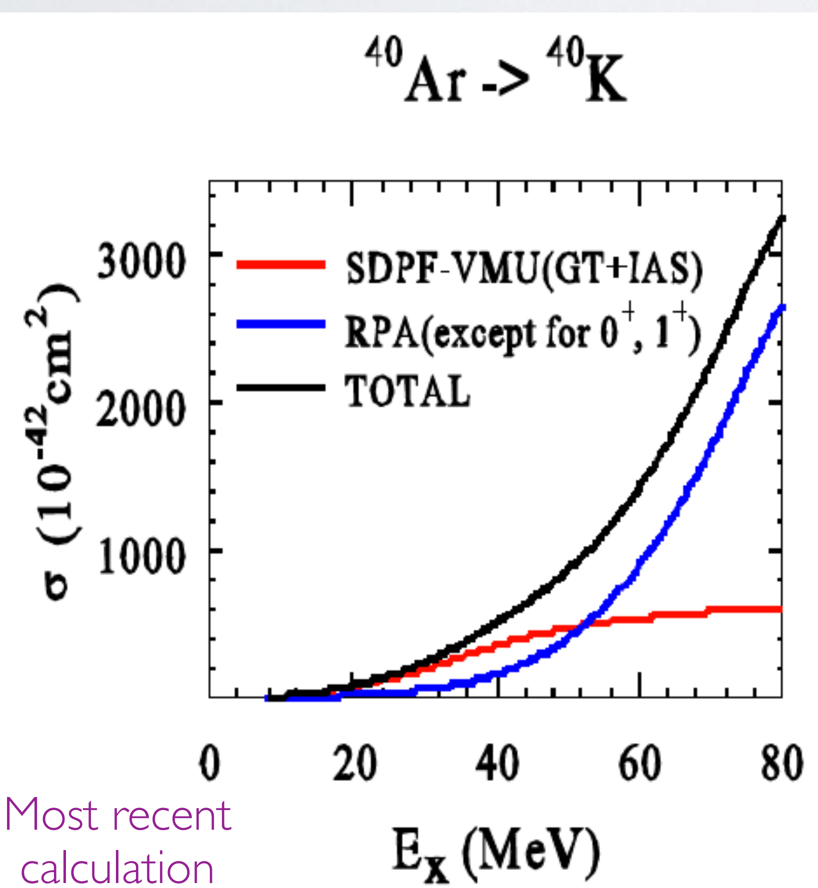


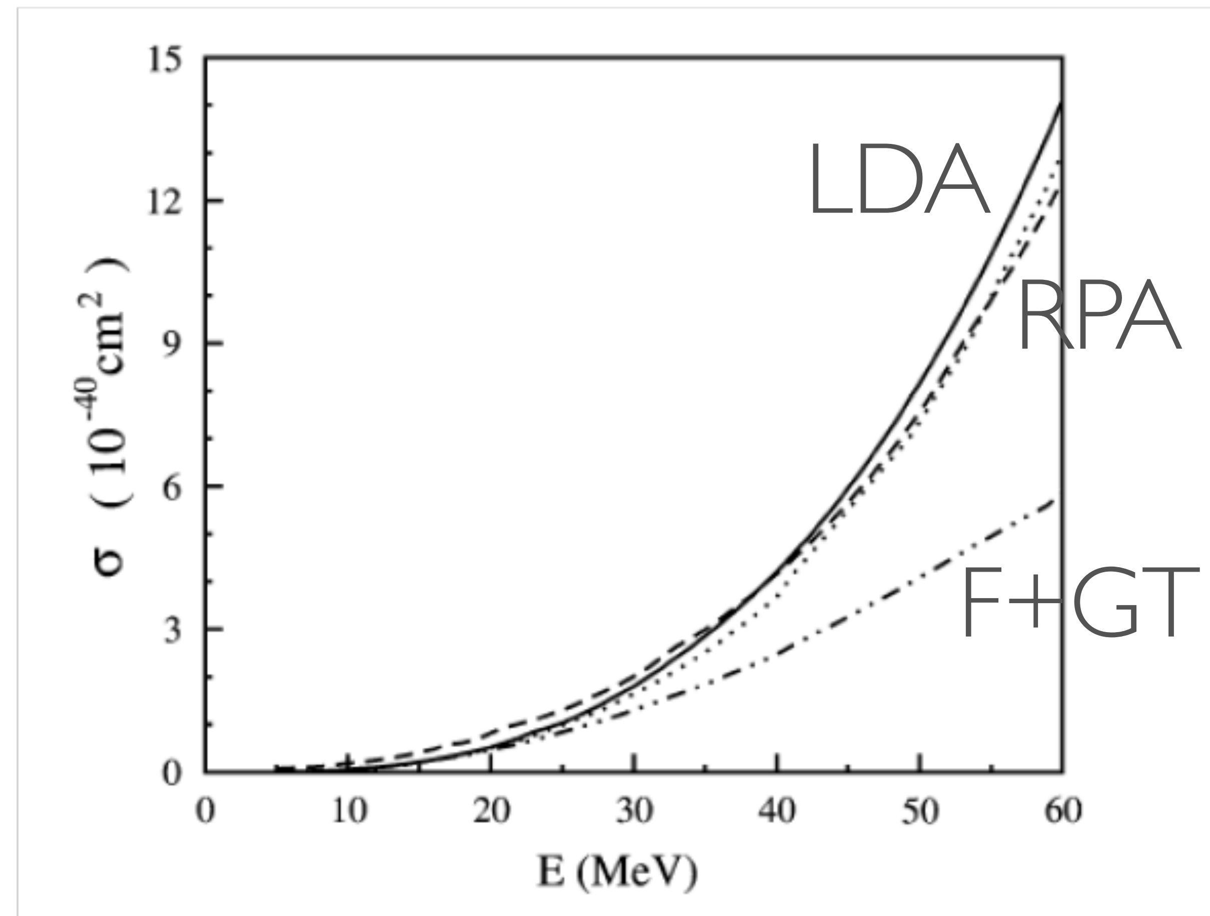
FIG. 1. Level scheme of ^{40}Ar-^{40}K relevant to ν_e capture in argon.

Allowed transitions ($\Delta J = 0, \pm 1$ $\pi_f = \pi_i$) dominate up to E_ν~15 MeV(shell model calculations)

F : Fermi (SuperAllowed)
GT: Gamow-Teller (Allowed)

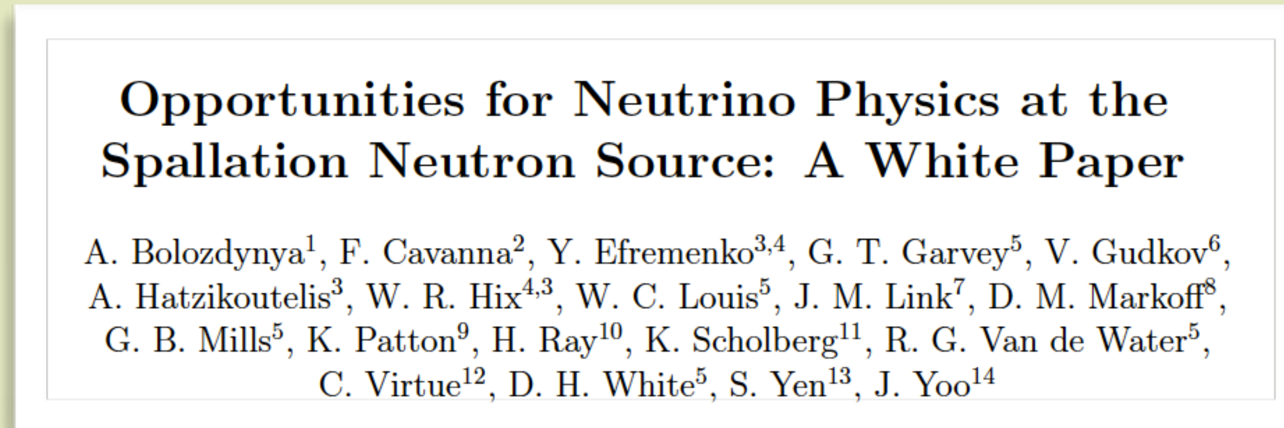
Forbidden transitions become relevant at higher energies -the SN en. range - (RPA calculations to describe the collective excitation of the nucleus, ^{40}K levels $J \leq 6$)





LDA calculations take into account nuclear medium effect in Local density Approximation

DIRECT XSECT MEASUREMENT



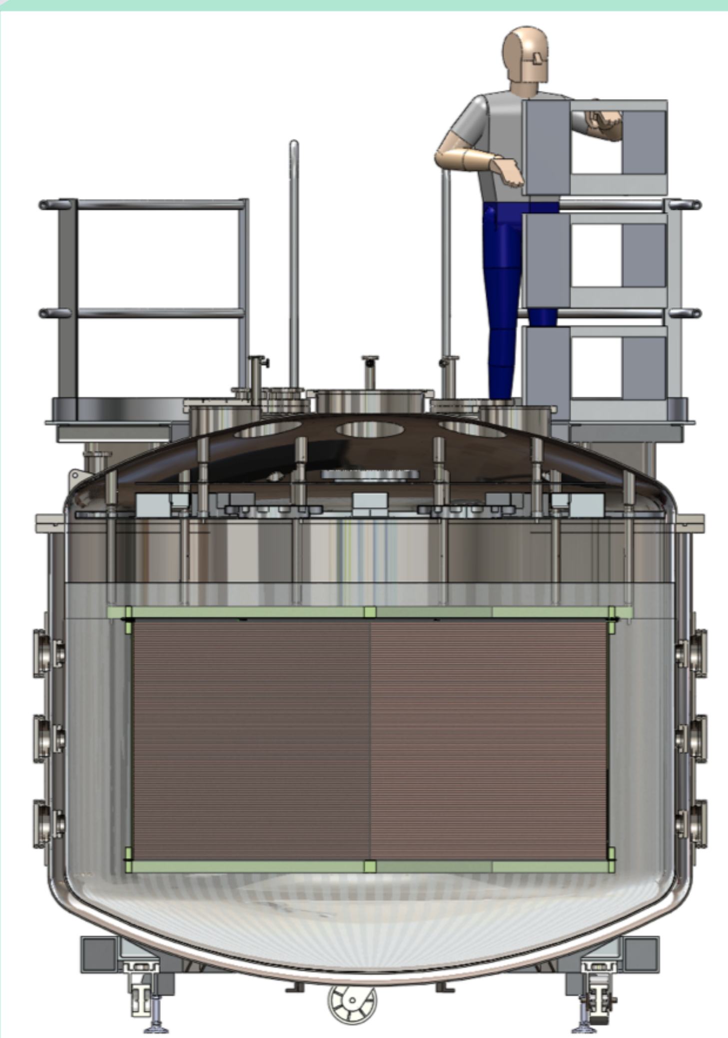
Opportunities for Neutrino Physics at the Spallation Neutron Source: A White Paper

A. Bolozdynya[1], F. Cavanna[2], Y. Efremenko[3,4], G. T. Garvey[5], V. Gudkov[6], A. Hatzikoutelis[3], W. R. Hix[4,3], W. C. Louis[5], J. M. Link[7], D. M. Markoff[8], G. B. Mills[5], K. Patton[9], H. Ray[10], K. Scholberg[11], R. G. Van de Water[5], C. Virtue[12], D. H. White[5], S. Yen[13], J. Yoo[14]

arXiv:1212.1276 [hep-ex]

Snowmass white paper

EoI for νSNS (2012)



CAPTAIN is a 7700 litre (5 ton fiducial) liquid argon detector constructed at LANL for the purpose of conducting a wide range of neutron and neutrino beam studies. The detector is portable, such that it can be deployed in a variety of locations in neutron and neutrino beams.

Following the transfer of the detector to FNAL, there will then be a series of neutrino runs:

(1)the low energy (5-50 MeV) Booster Neutrino Beam (BNB) to detect neutrino interactions in the range 10-50 MeV.

a. Measure the inclusive neutrino cross-sections relevant to supernova physics. This would be a first-ever demonstration of neutrino cross section measurements on argon at these energies. The goal is to validate the theoretical calculations to the 10% level.

The SN ν (**ABS**) signature in LArTPC

$$\nu_e + Ar \rightarrow K^* + e^-$$

↳ γ(s)

compton ↳ e(s)

besides FLUKA

- One leading "~10 wire-hits electron" track (*squiggle*)
- A number of "1-3 wire-hits electrons" *spots* (localized en. deposits) from de-excitation gammas conversion (^{40}K Nuclear low-lying level Diagram)

We don't have yet a complete MC generators to simulate SN ν processes in the detector,

BUT work is in progress in the LNBF SNB grp

...we do have

Examples of events from ArgoNeuT

(data from NuMI run 2009-10)

- induced by interactions in material surrounding the active detector -

with topologies somehow <u>similar</u> to what is expected from SN-ν_e ABS reactions were found.
These data are being used to start defining dedicated ALGORITHMS for de-excitation γ's search and detected "spot" energy reconstruction

Event generator for de-excitation γ's for low-energy events

K. Scholberg Grp. - Duke U.

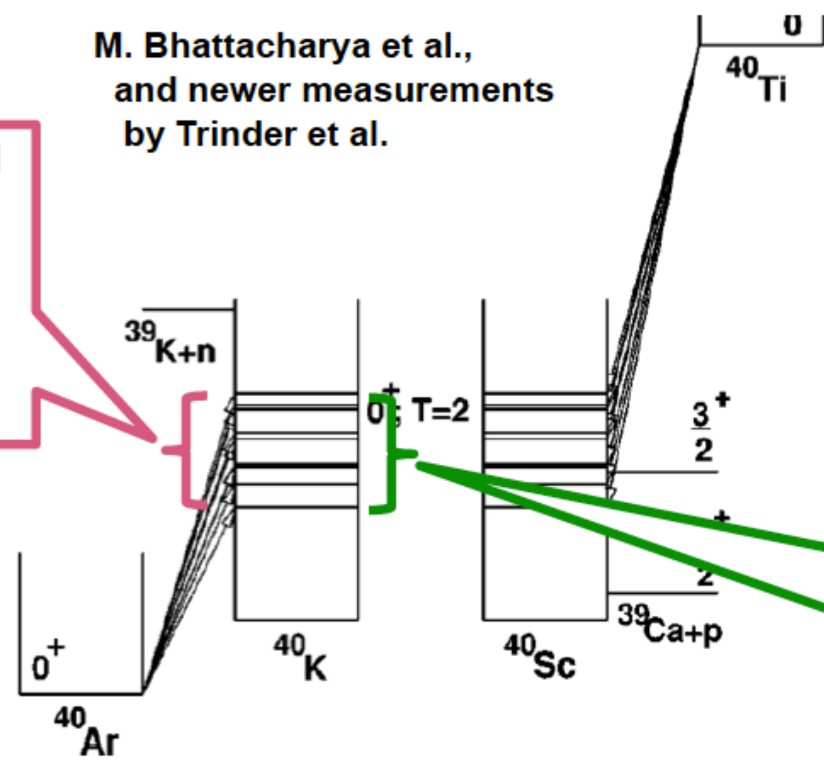
New model for deexcitation gammas, implemented by AJ Roeth

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

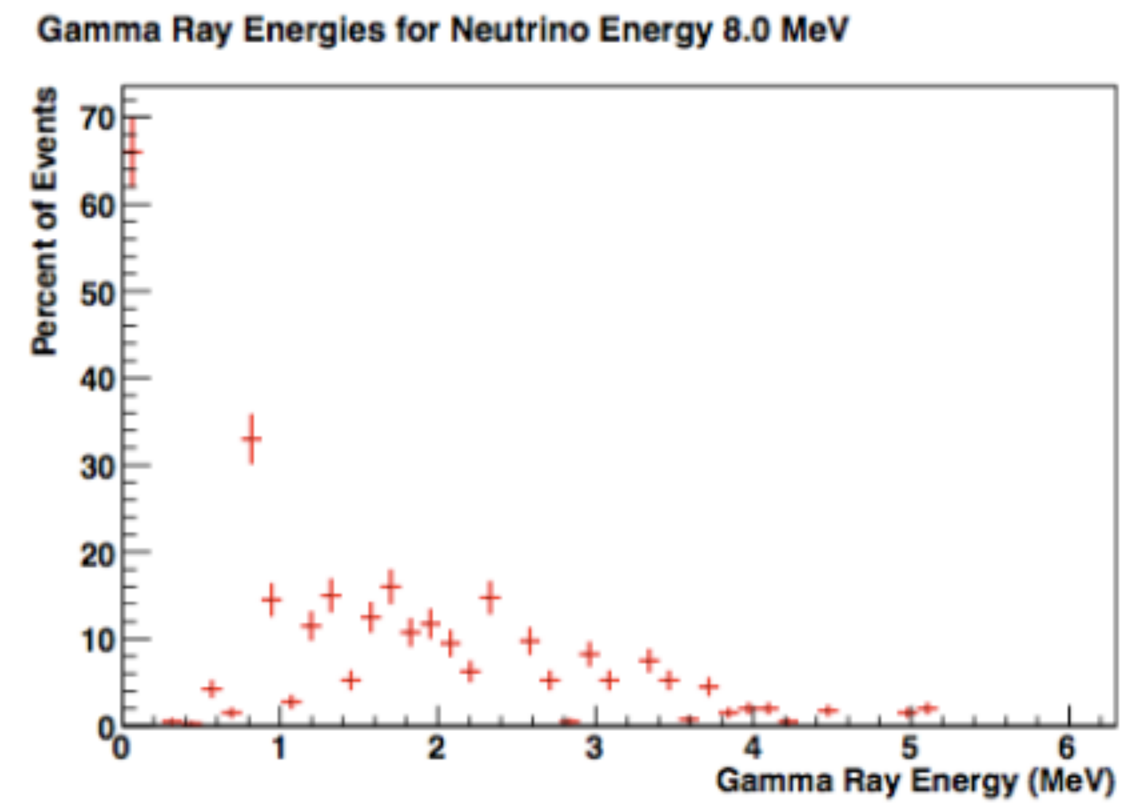
Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al., and newer measurements by Trinder et al.

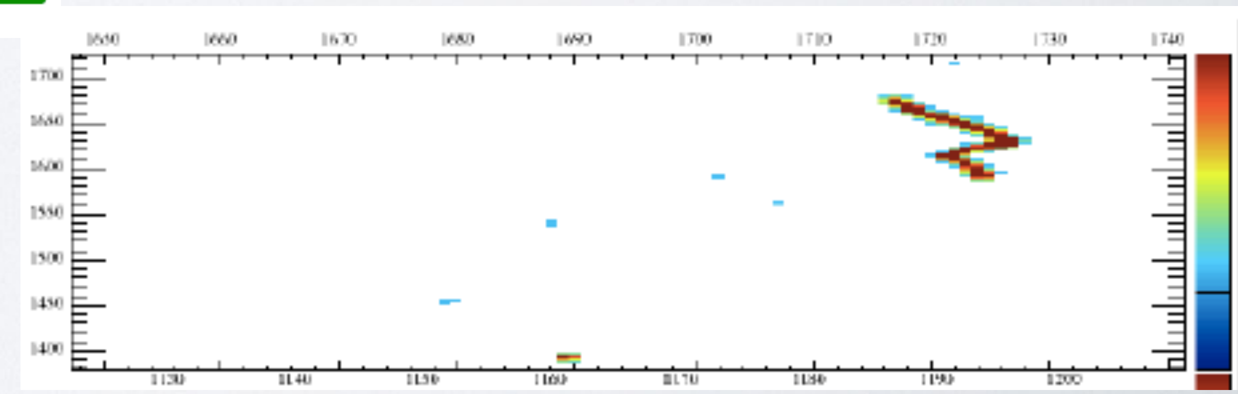
use measured ^{40}Ti strengths to determine relative xscn for ending up in each level



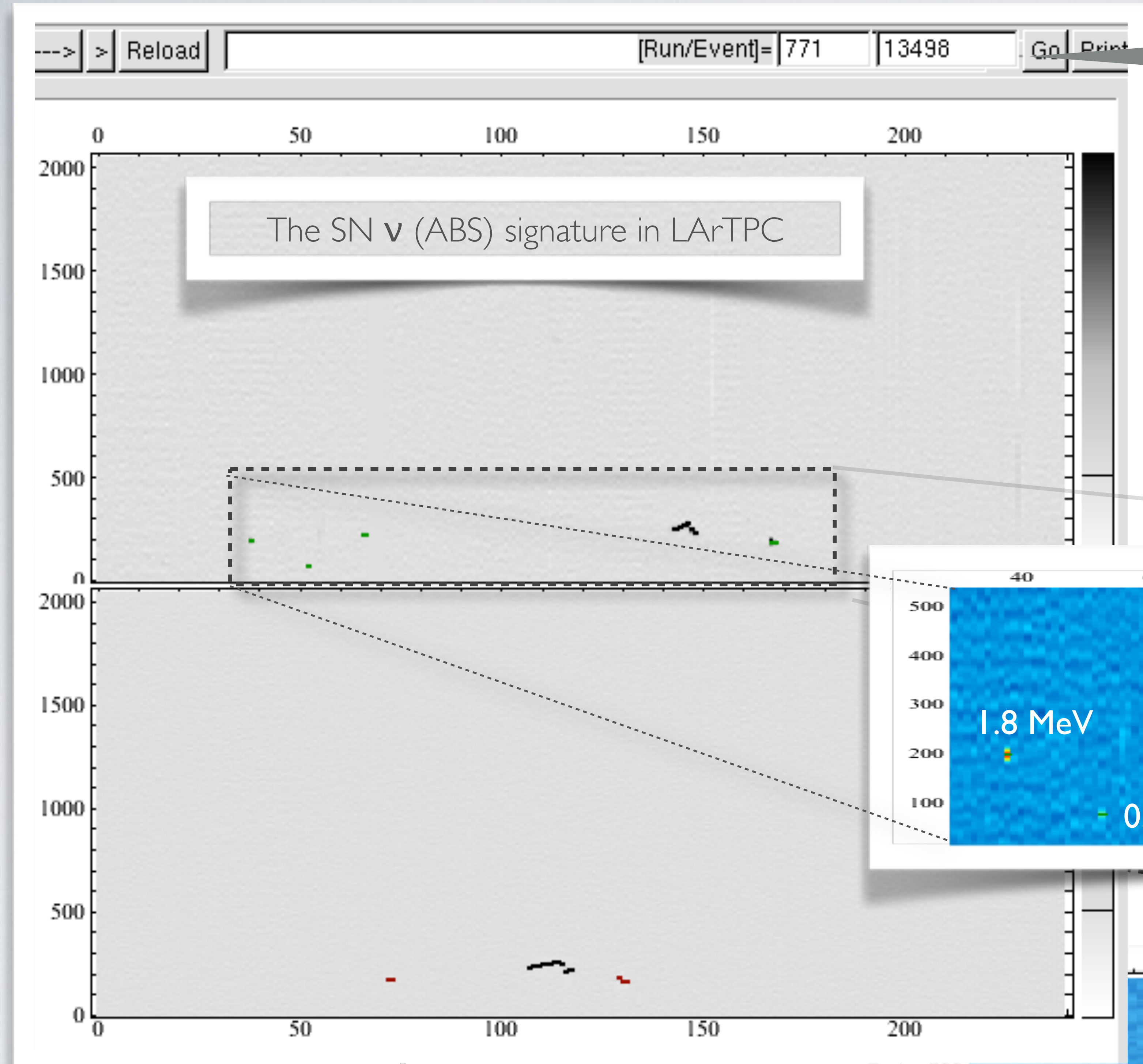
then use Table of Isotopes γ database to decay the nucleus



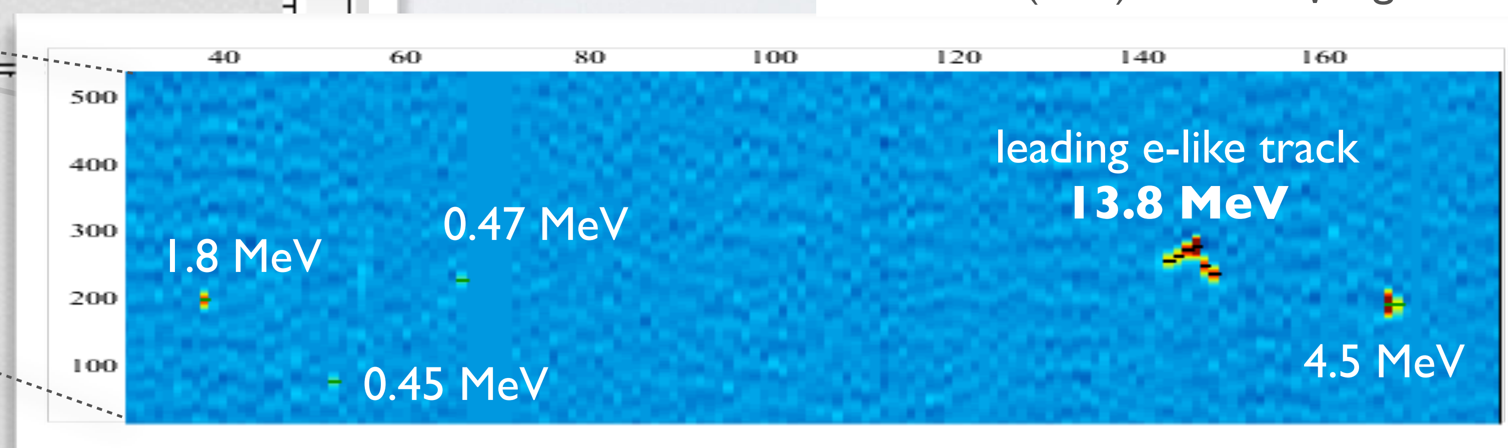
Event are then propagated in LArTPC through LArSoft

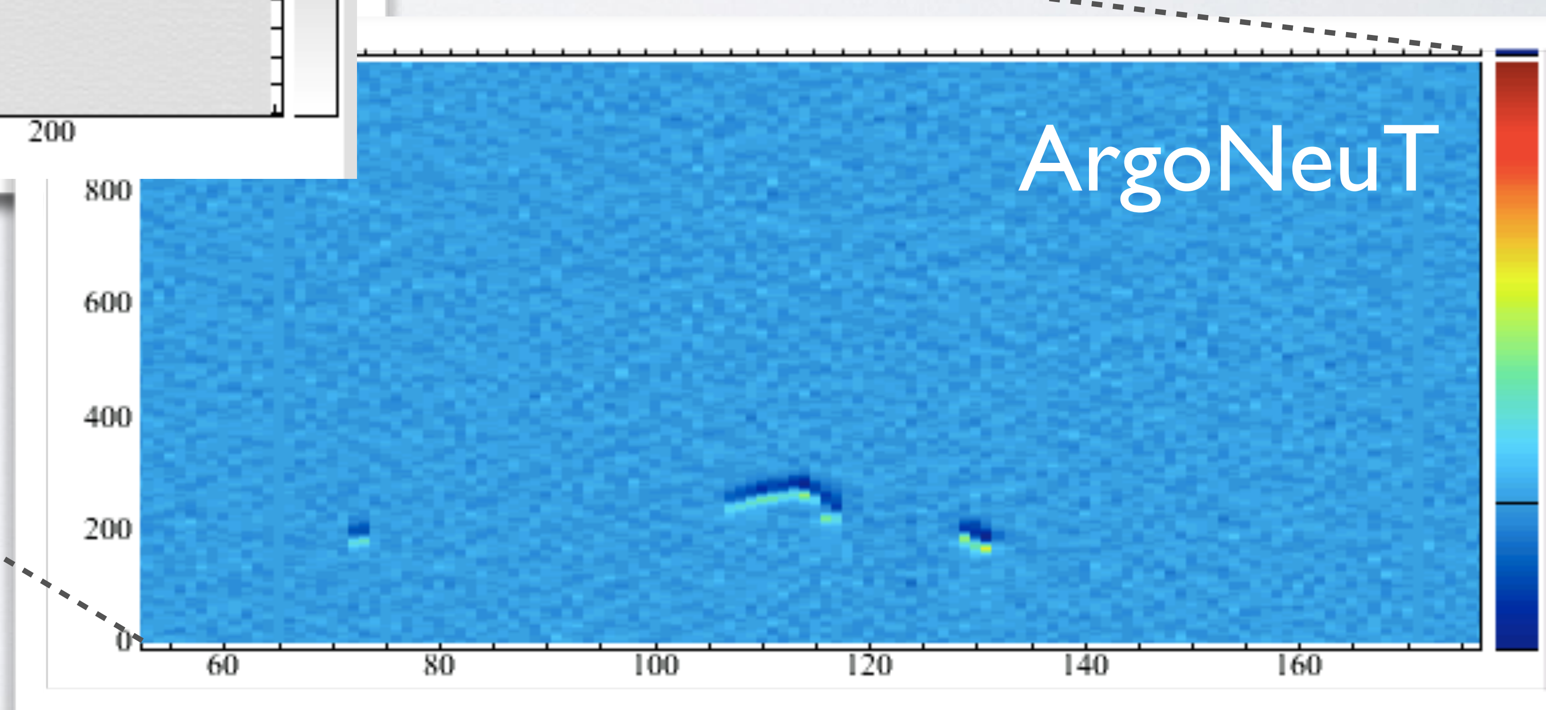


Event from Beam Trigger (NuMI run).
Interaction just outside the TPC
(el.m. punch-through)



C.Adams (Yale): de-Exc. γ algorithm



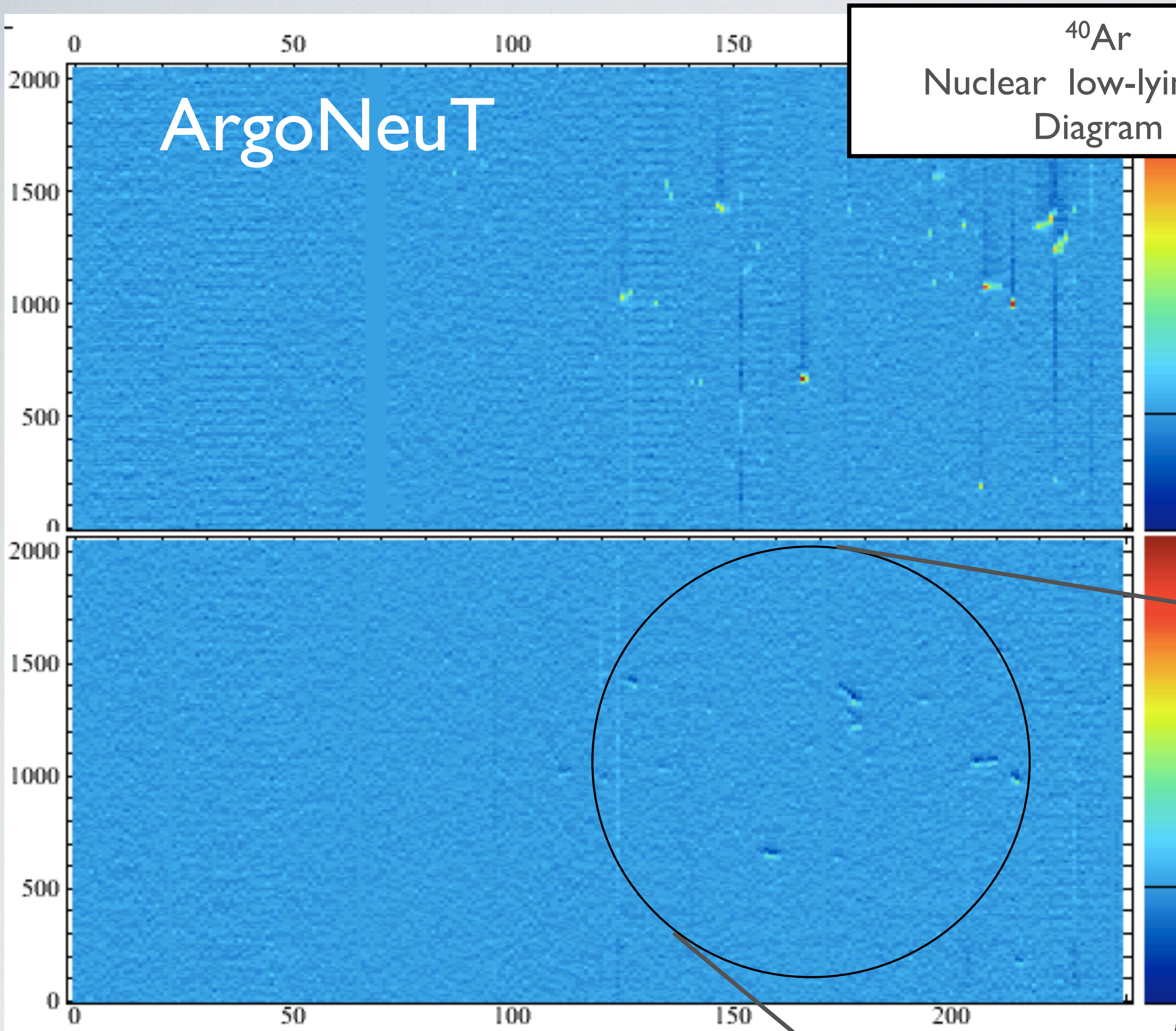


leading trk

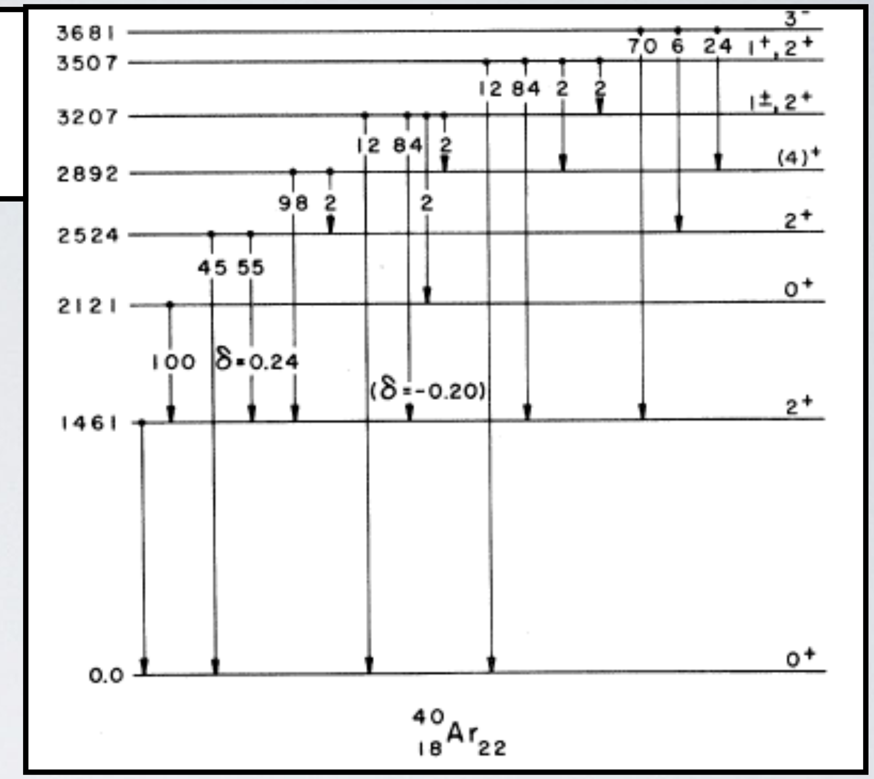
$$\nu_e + Ar \rightarrow K^* + e^-$$

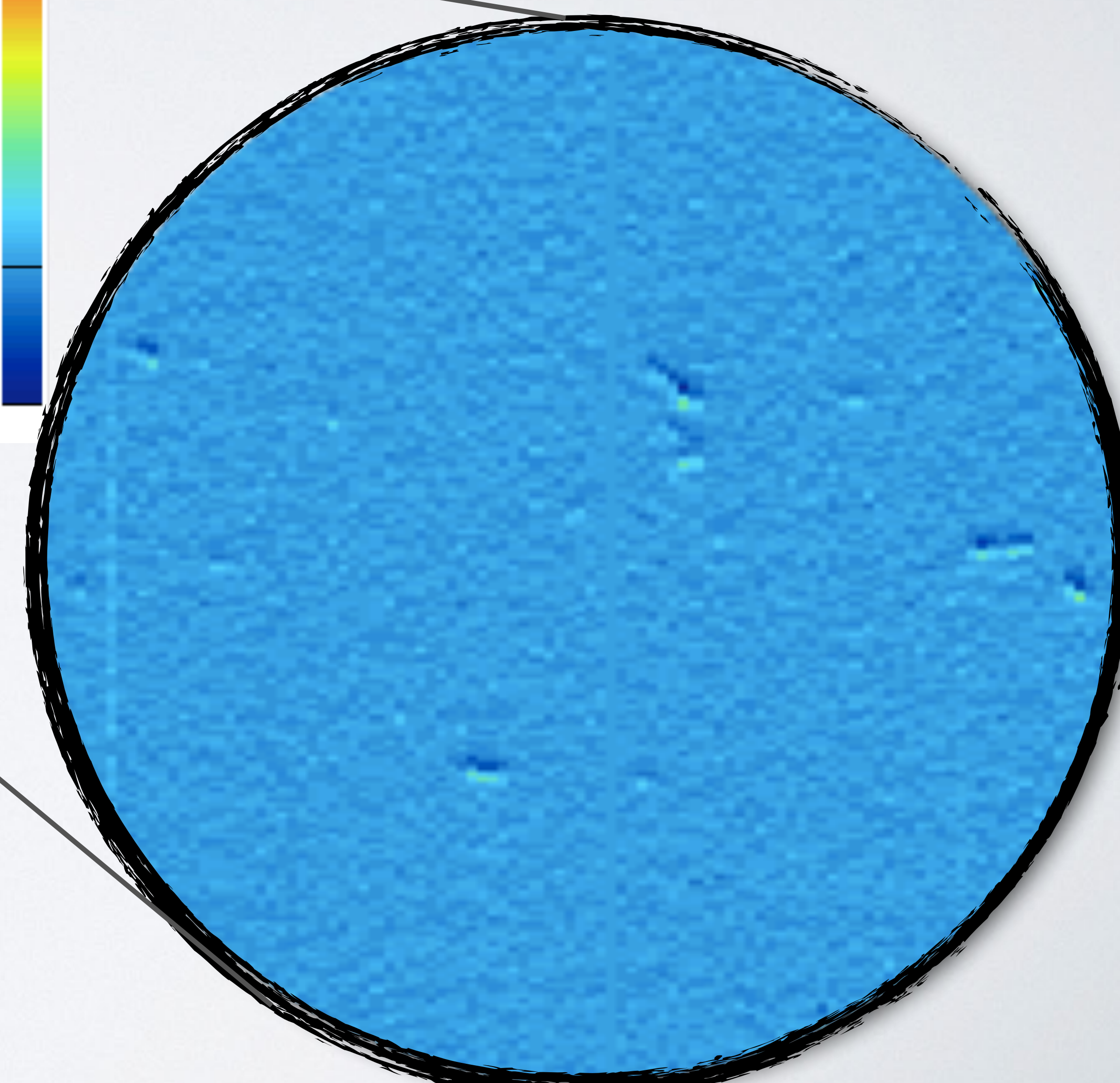
↳ γ(s)

compton ↳ e(s)



^{40}Ar Nuclear low-lying level Diagram





NC **N**uclear **E**xcitation (on Ar)

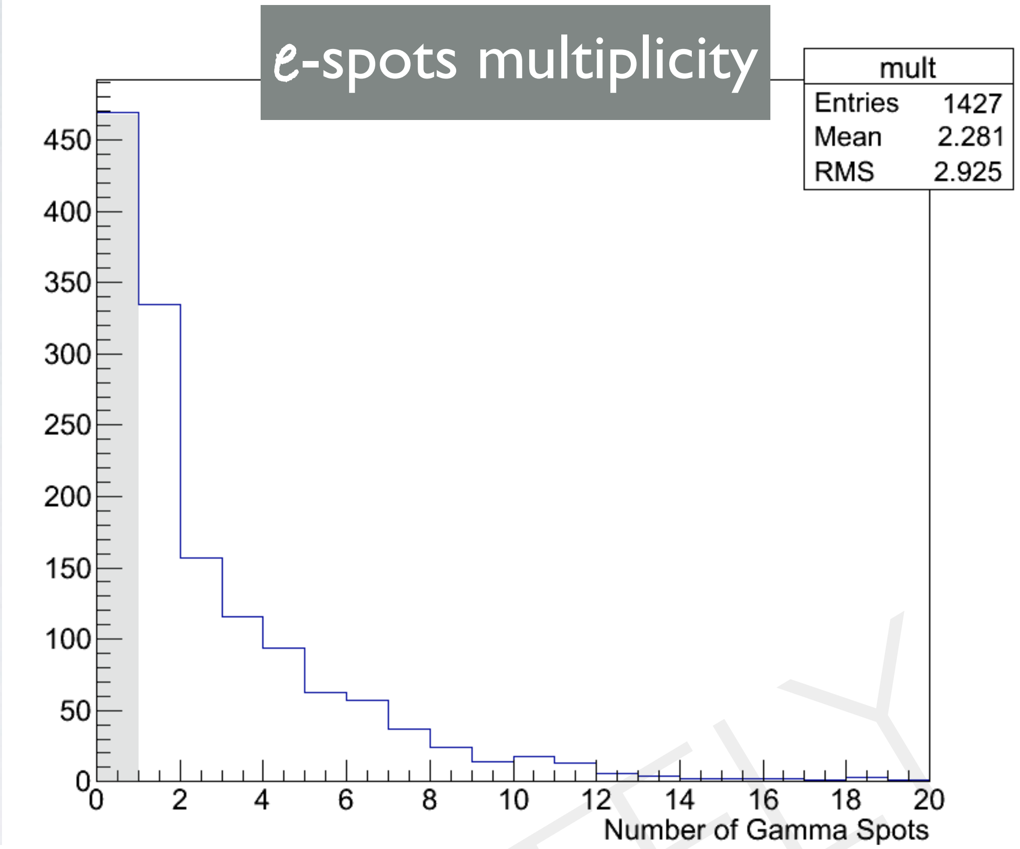
$$\nu \ + \ Ar \rightarrow \nu' \ + \ Ar^*$$

↳ γ(s)

compton ↳ e(s)

C. Adams - Yale

We have data to compare with (ArgoNeuT)



γ-finding Algorithm

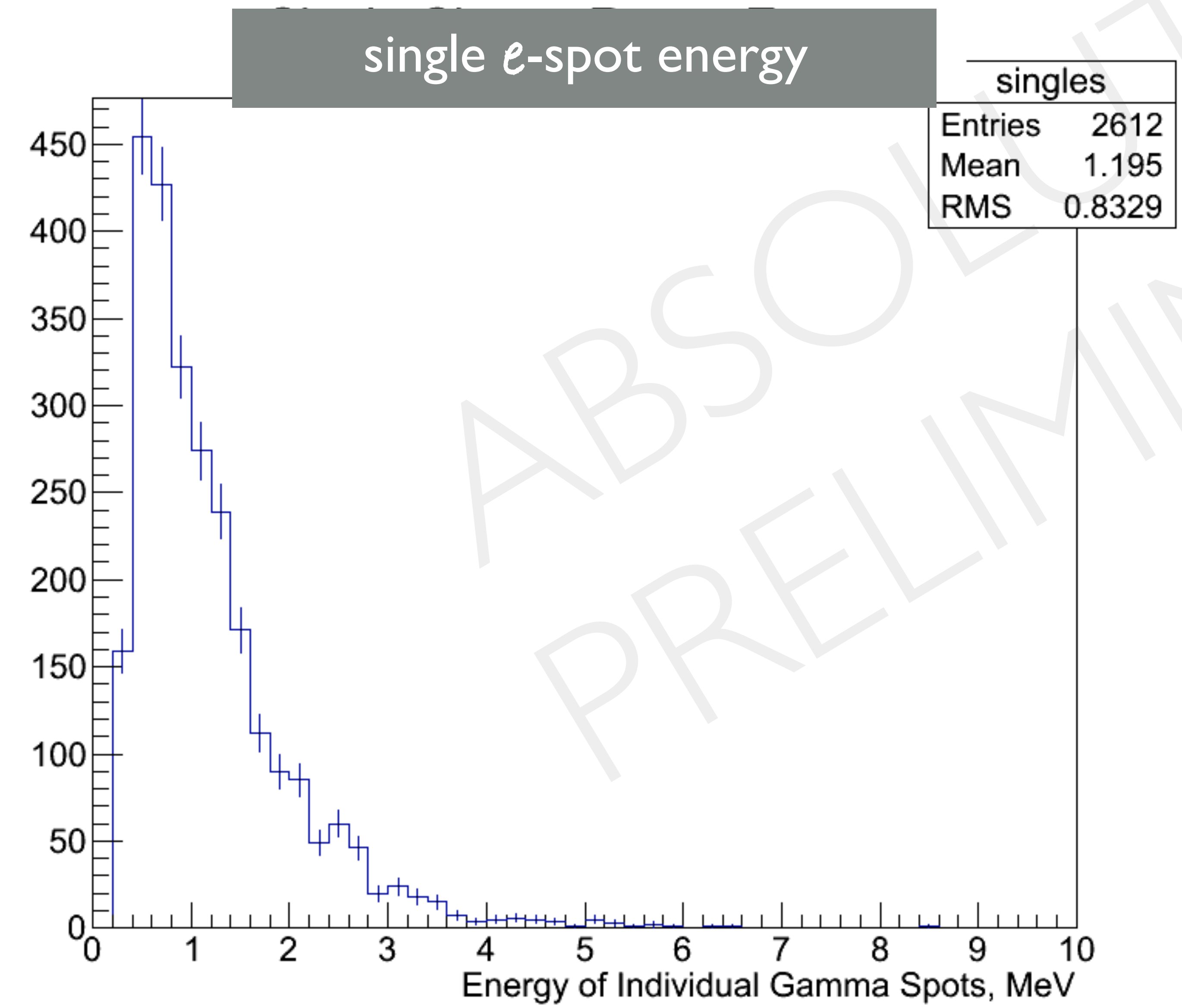
(through e-spot detection)

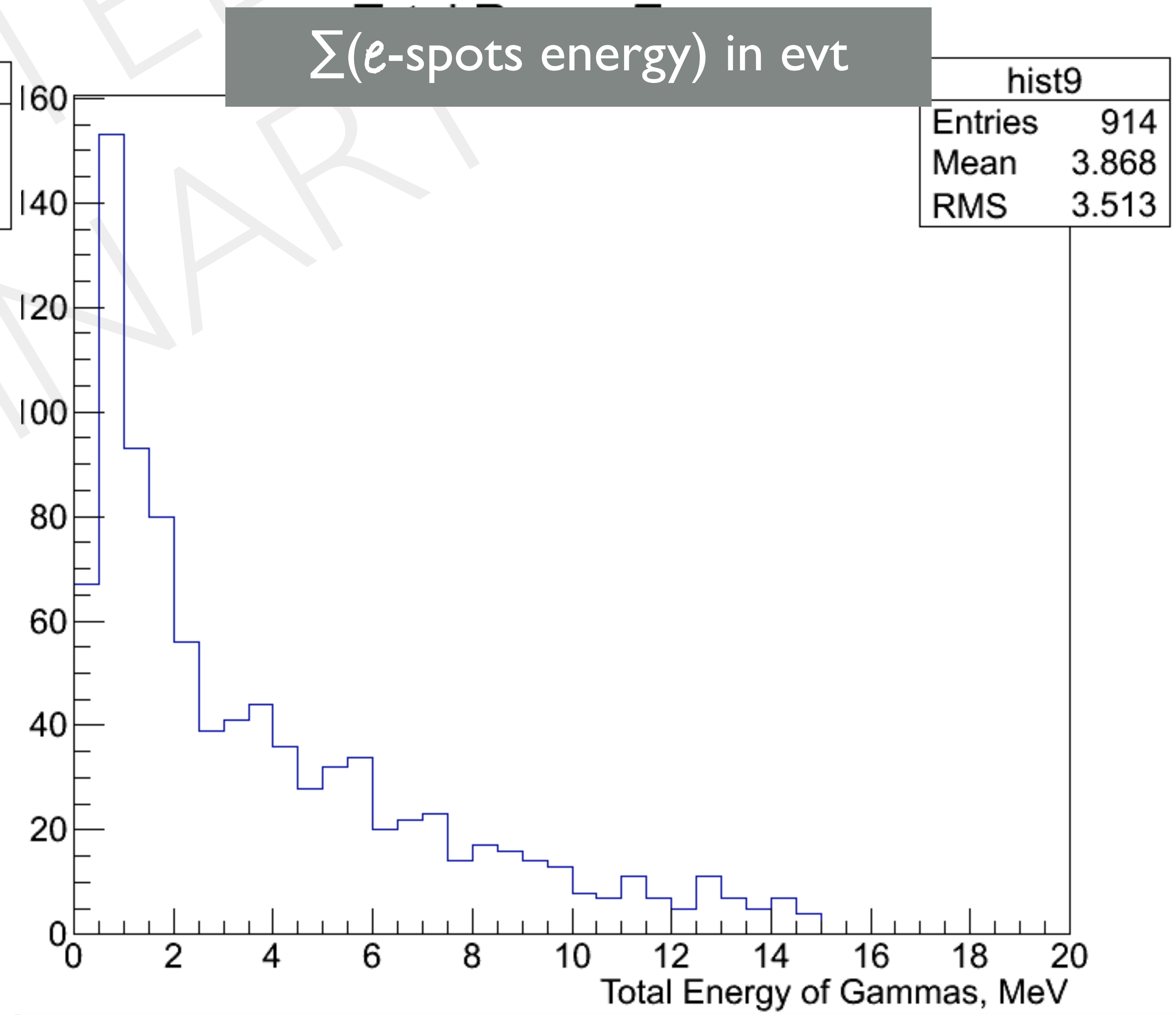
on

ArgoNeuT Raw Data

Run 698 E1-2000

(most are empty events)





LArTPC: Surface Vs. Underground (the background question)

- Dedicated studies for SN background sources and intensity are needed. Direct measurements would be most welcome *(maybe with LArIAT-Scint.Light)*.

- MC simulation are currently underway for Surface to UG comparison.

- SN-Background Sources on Surface:

examples from the "background soup" [V. Gehman]

➡ cosmogenic fast neutrons:

n *Inelastic* $^{40}Ar(n,n')^{40}Ar^*$ γ-decay *(prompt)*

n *Absorption* $^{40}Ar(n,p)^{40}Cl$

n *Absorption* $^{40}Ar(n,d)^{39}Cl$

➡ cosmic muons

μ⁻ *Capture*: $^{40}Ar(\mu^-,\nu)^{40}Cl$

$^{40}Ar(\mu^-,\nu+n)^{39}Cl$

$^{40}Ar(\mu^-,\nu+2n)^{38}Cl$

(delayed) β-decay (+ γ's) *(all below 7.5 MeV)*

LArTPC for SN-ν Detection:

- present LArTPC technology optimized for E_ν $\mathcal{O}$(1GeV) but extension down to SN range $\mathcal{O}$(10 MeV) is possible

[e.g. starting from studies for ⊙-ν by ICARUS + recent studies by LBNE and MicroBooNe + ArgoNeuT]

- **CC ABS** [→ leading e^- + (low-en) e's] distinctive Ar detector signature for SN- **Electron Neutrinos** ν_e

- **NC Nucl.Exc.** [→ low-en e's] for SN-ν_x worth to be explored

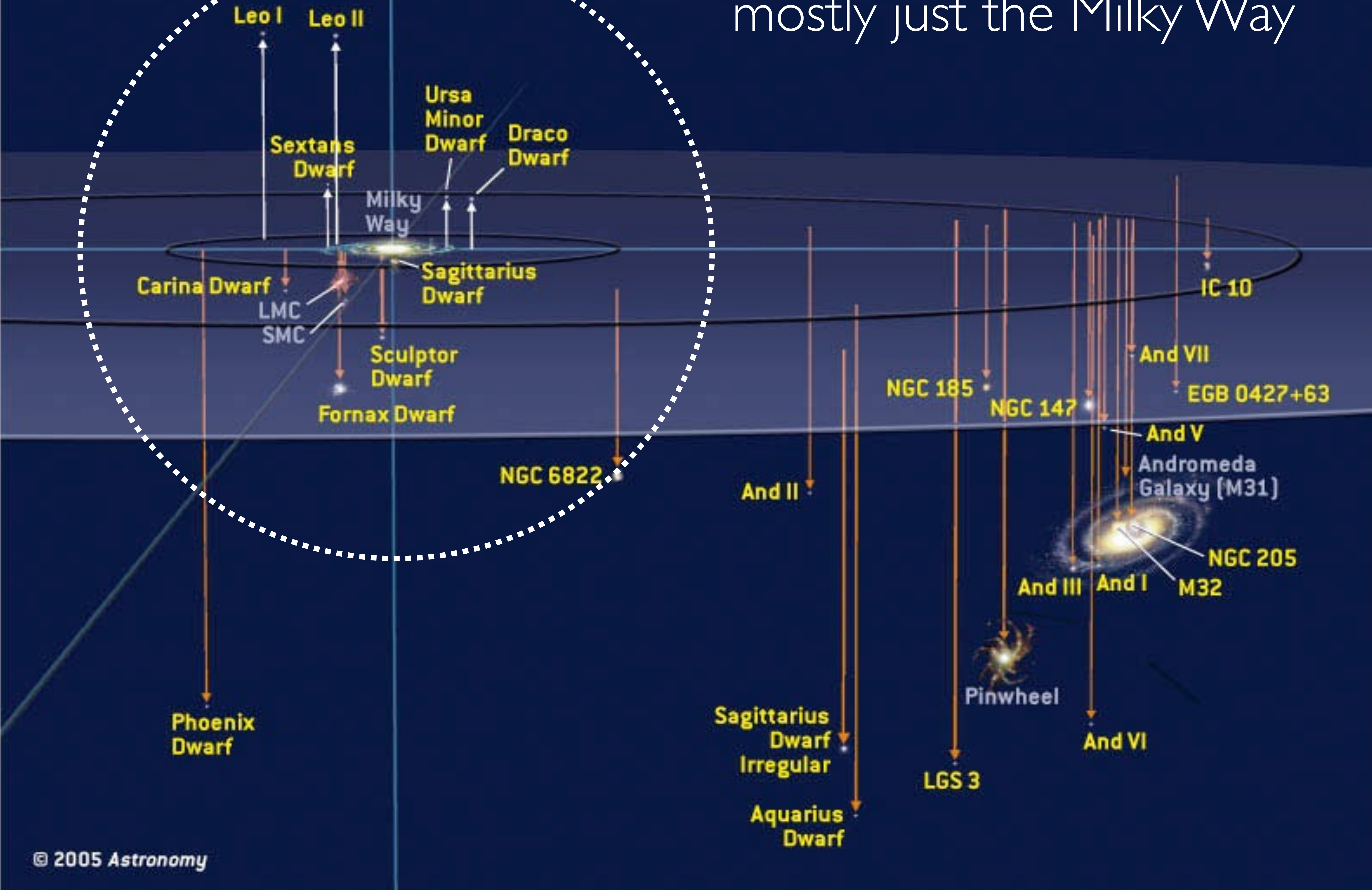
- **ν-Ar XSect's based on th. calculations - never directly measured**
  → campaign of measurements NEEDED

- Scint. Light signal can assist/increase detection efficiency of low-en events, but LAr scint.light collection system must be improved and optimized to this purpose.

Let's not miss the next one !!

BACKUP SLIDES

Current best neutrino detectors sensitive out to ~ few100 kpc.. mostly just the Milky Way



SUPERNOVA NEUTRINOS

Reference ranges on SN neutrino energies averaged on time (starting at flash time, $t_0 = t_{fl}$) found comparing a number of numerical calculations are:

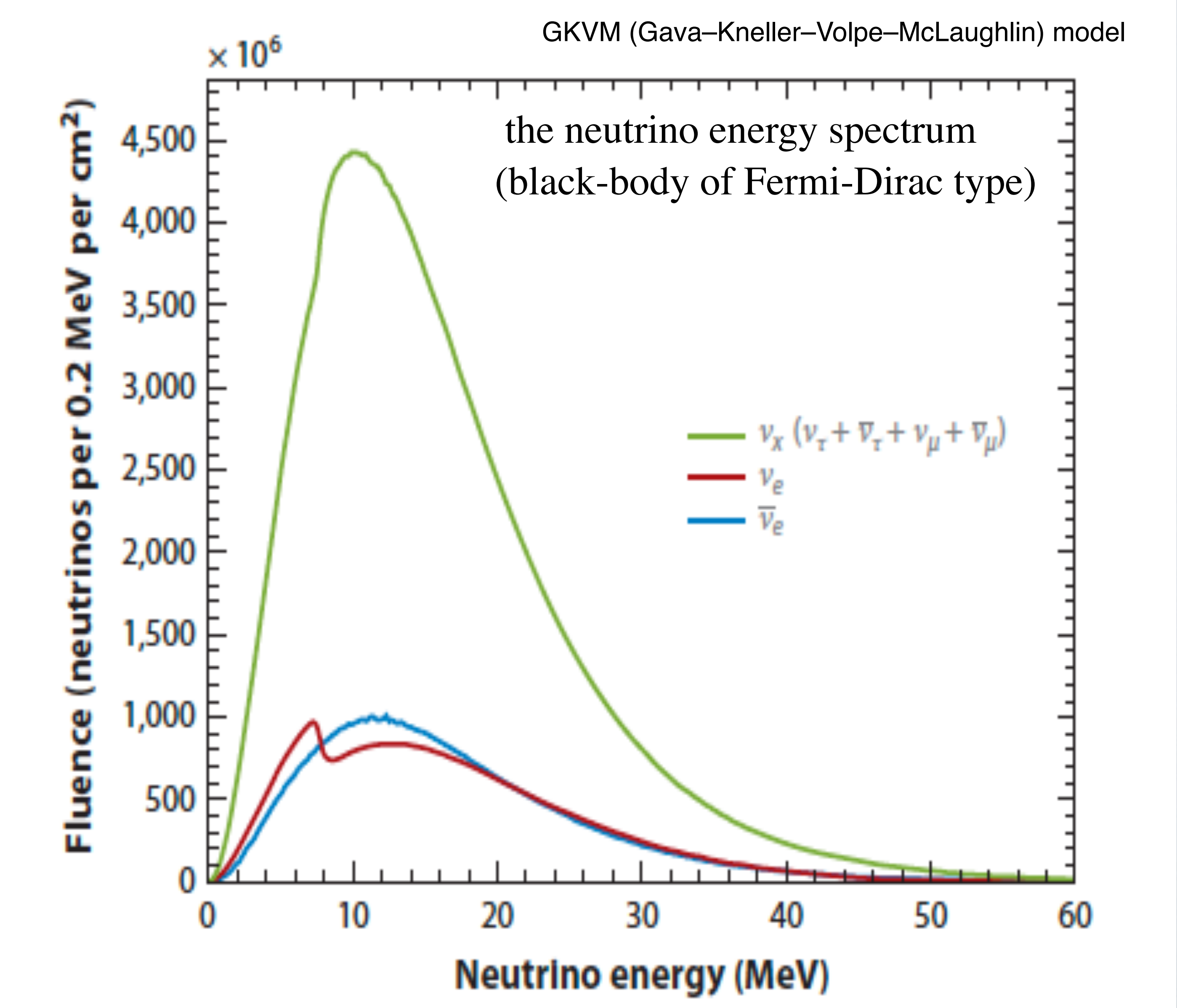
$$\langle E_{\nu_e} \rangle = 10\text{–}12\,\text{MeV}, \quad \langle E_{\bar{\nu}_e} \rangle = 11\text{–}17\,\text{MeV}, \quad \langle E_{\nu_x} \rangle = 15\text{–}25\,\text{MeV}$$

The reason for this hierarchy is that neutrinos that interact more -- ν_e and anti-ν_e -- undergo CC reactions, beside NC — i.e. decouple in more external regions of the star at lower temperature. In other words, each neutrino type has its own "neutrino-sphere" - ν_e's one being the outermost.

The approximate amount of the total energy ε_B carried away by the specific flavor is

$$\varepsilon_{\nu_e} = f_{\nu_e}\varepsilon_B \quad \text{with}: f_{\nu_e} = 10\text{–}30\%$$
$$\varepsilon_{\bar{\nu}_e} = f_{\bar{\nu}_e}\varepsilon_B \quad \text{with}: f_{\bar{\nu}_e} = 10\text{–}30\%$$
$$\varepsilon_{\nu_x} = f_{\nu_x}\varepsilon_B \quad \text{with}: f_{\nu_x} = 20\text{–}10\%$$

Modeling has steadily improved over the past few decades, with inclusion of more and more effects. There may be significant variations in the expected flux from supernova to supernova due to differences in the mass and composition of the progenitor, and possibly asymmetries, rotational effects, or magnetic field effects.



SuperNova is an environment characterized by very high electron and baryon densities and by very intense neutrino fluxes

Neutrino oscillations and matter enhanced conversion mechanism in the stellar medium should modify the expected supernova neutrinos fluxes.

These modifications are large - in particular due to the size of the vacuum mixing angle θ_{13} - and can be observable (e.g. inducing ***total conversion*** $\nu_{\mu/\tau} \rightarrow \nu_e$ harder En. spectra at the detector) but subject to wide uncertainties (eg from model/assumptions for matter density profile).

These effects should be taken into account in order to interpret the SN neutrino signal correctly.

The effects of oscillations are important and have to be included. Conversely, one could combine experiments and use theoretical information in order to attempt to make inferences on oscillations, but astrophysical uncertainties should be thought as an essential systematics for this purpose.

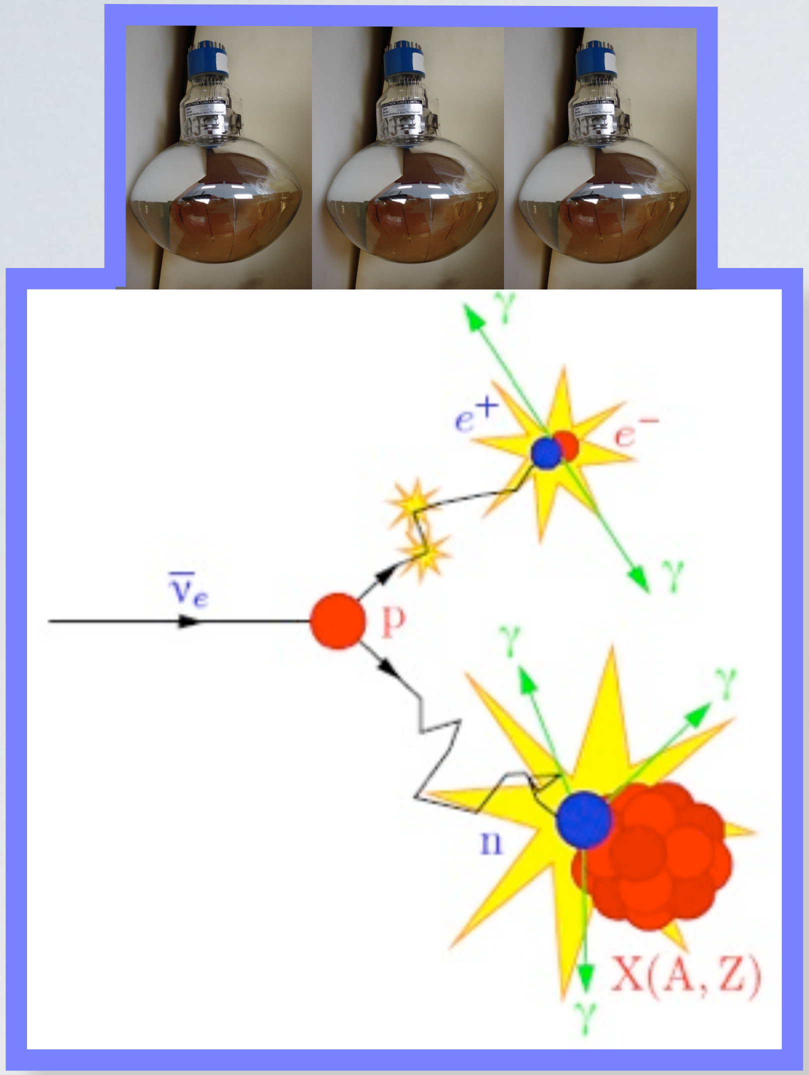
Disentangle neutrino physics and SN core-collapse physics is not trivial.

There are chances to learn on neutrinos, but presumably the primary aim of SN observations is supernova astrophysics.

In any case, the more experimental data we can gather about the flavor, energy, and time structure of the burst, in as many detectors around the world as possible, the better our chances will be of disentangling the various effects.

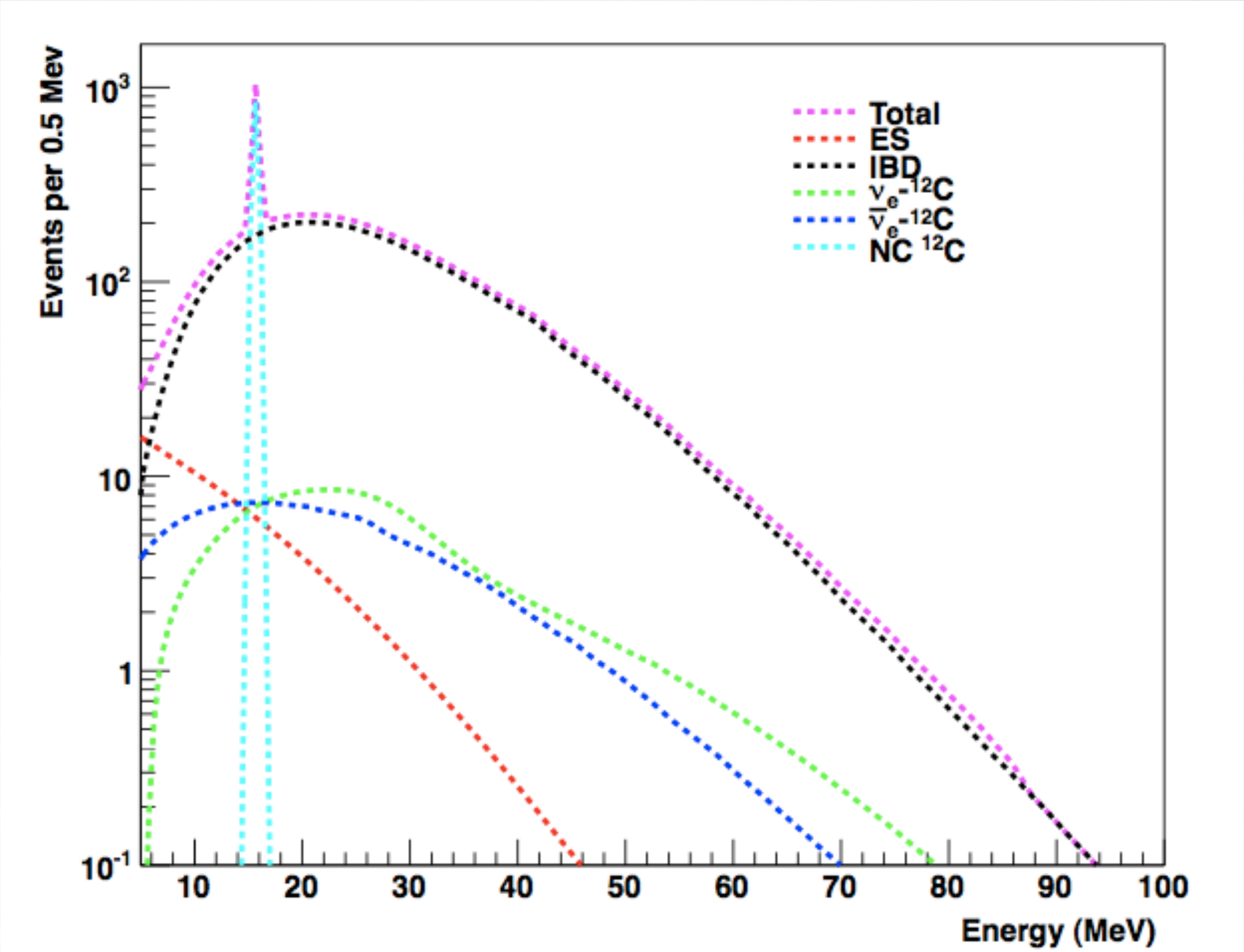
Liquid Scintillator Detectors

Scintillation detectors



- few 100 events/kton

Liquid scintillator C_nH_{2n} volume viewed/surrounded by photomultipliers



50 kt @ 10 kpc

- **IBD main reaction:**
  low threshold (1.8 MeV),
  neutron tagging possible
  no/little pointing capability
  (light is ~isotropic)

- NC tag
from 15 MeV ^{12}C de-excitation γ
(no ν spectral info)

K. Scholberg - Ann.Rev.Nucl.Part.Sci 62 (2012), 81.

Liquid scinitillator detectors

Expected number of events(for 10kpc SN)

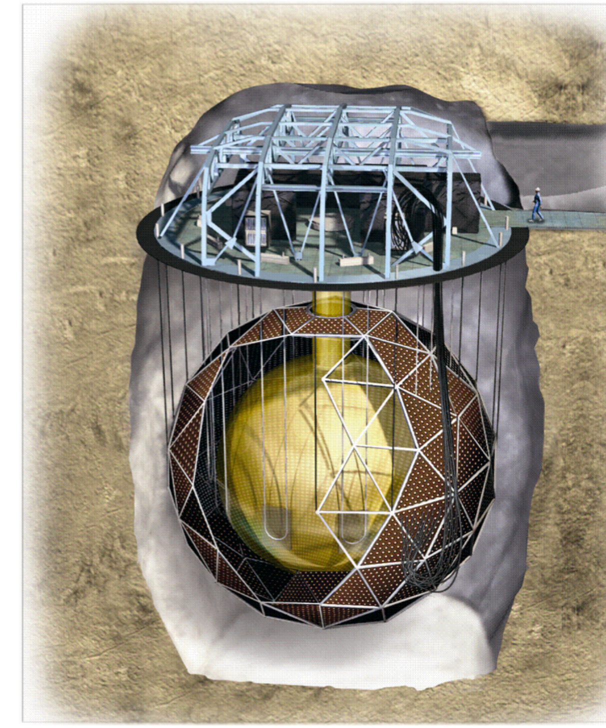
Events/1000 tons

- Inverse beta($\bar{\nu}_e + p \rightarrow e^+ + n$) : ~300 events
  Spectrum measurement with good energy resolution, e.g. for spectrum distortion of earth matter effect.
- CC on ^{12}C ($\nu_e + {}^{12}C \rightarrow e + {}^{12}N({}^{12}B)$) : ~30 events
  Tagged by $^{12}N(^{12}B)$ beta decay
- Electron scattering ($\nu + e^- \rightarrow \nu + e^-$) : ~20 events
- NC γ from ^{12}C ($\nu + {}^{12}C \rightarrow \nu + {}^{12}C + \gamma$): ~60 events
  Total neutrino flux, 15.11MeV mono-energetic gamma
- ν+p scattering($\nu + p \rightarrow \nu + p$): ~300 events
  Sensitive to all types of neutrinos.
  (Independent from neutrino oscillation)
  Spectrum measurement of higher energy component.

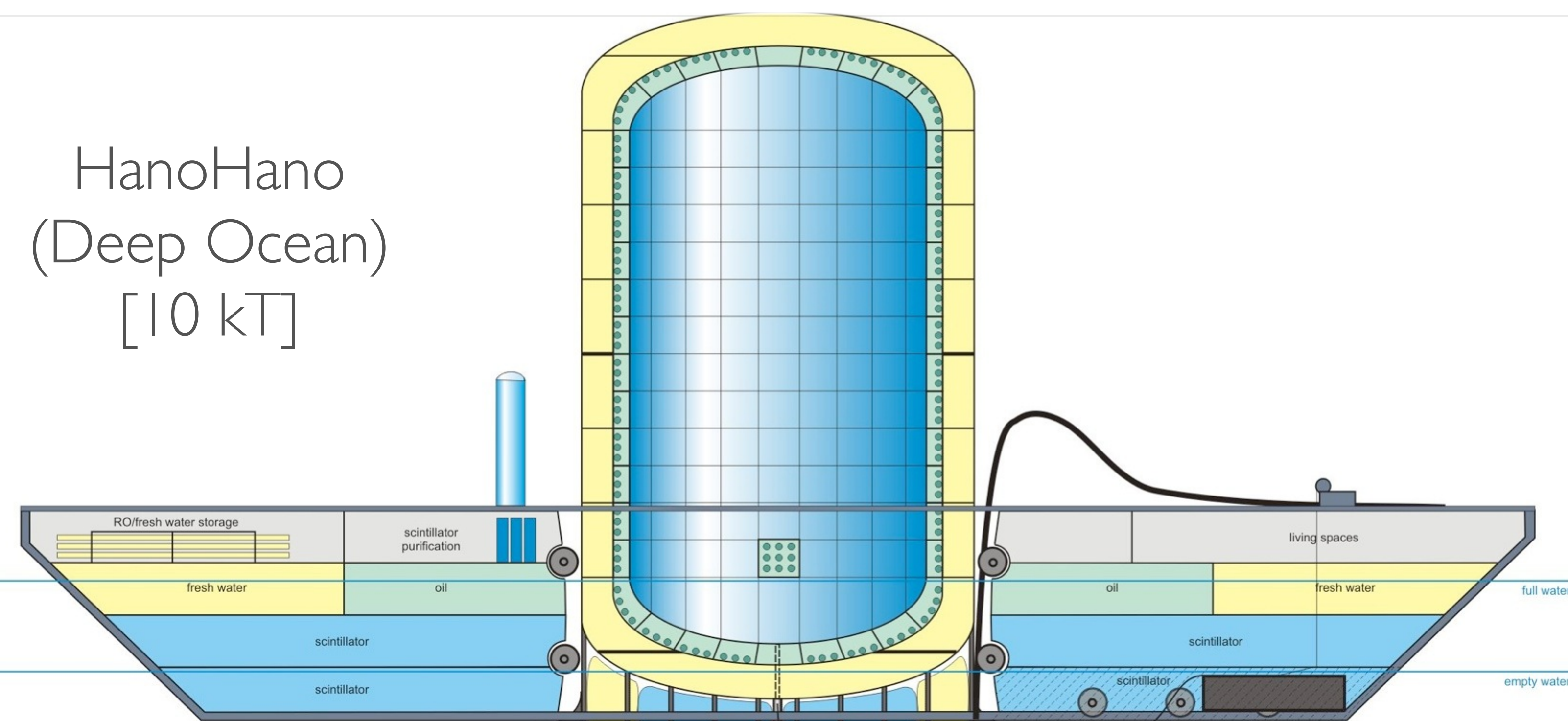
From K.Inoue, G.Bellini, M.Chen

Liq. Scint. UG Det. Under Construction and proposed Underground/water Detector Concepts

LENA
Low Energy Neutrino Astronomy
[50 kT]

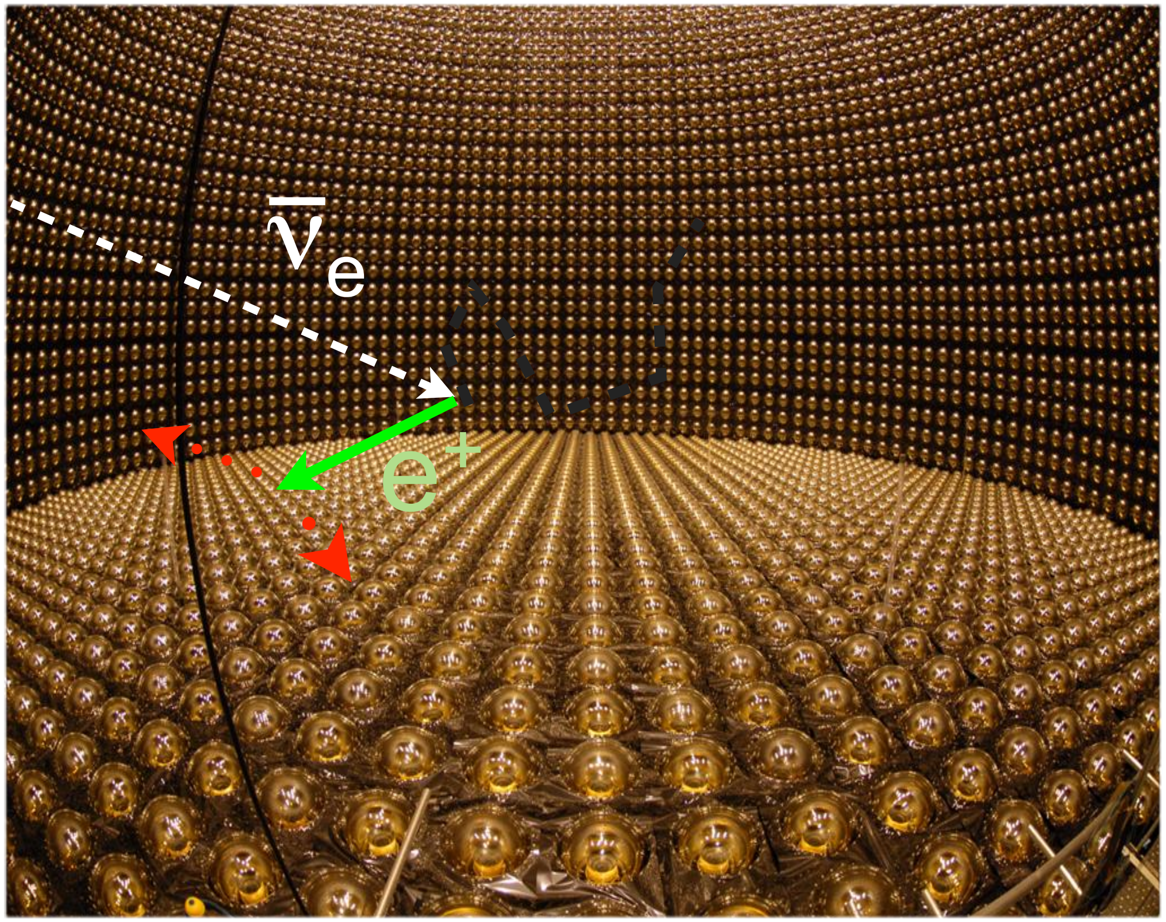


SNO+
(Sudbury - Canada)
[1 kT]



HanoHano
(Deep Ocean)
[10 kT]

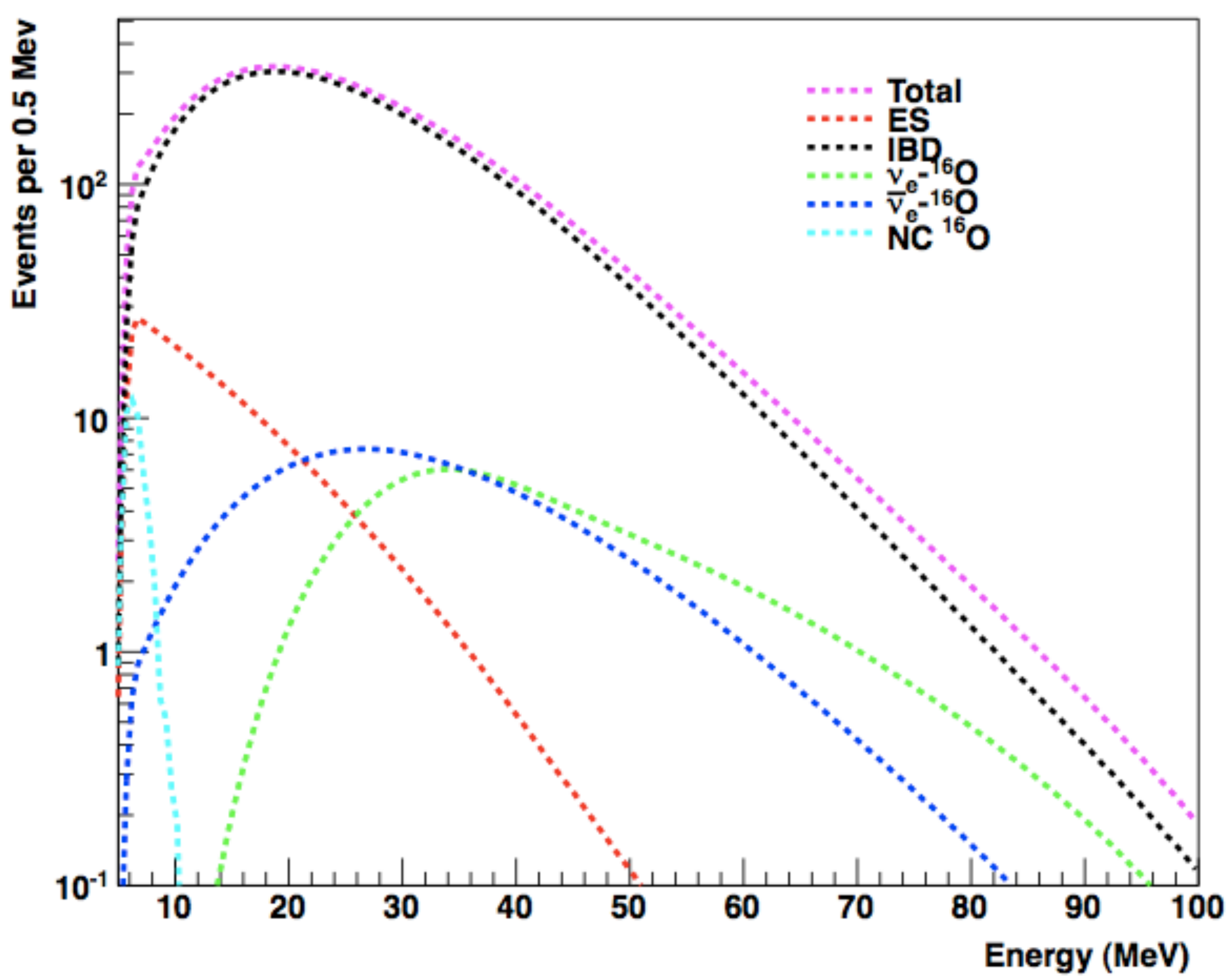
Water Cerenkov Detectors



Water Cherenkov detectors

- few 100 events/kton

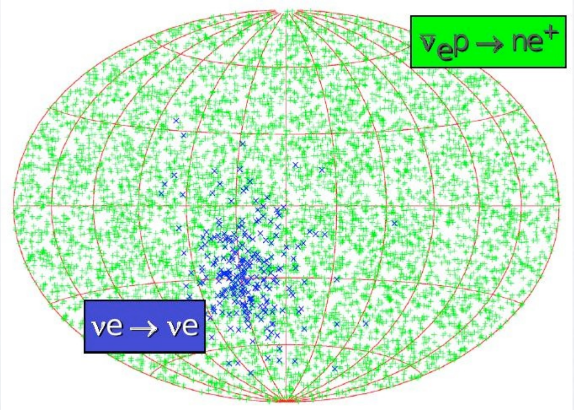
- typical detector energy threshold ~ several MeV makes 2.2 MeV neutron tag difficult (unless Gd added)



100 kt @ 10 kpc

IBD main reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad E_{thr}=1.8 \text{ MeV}$$

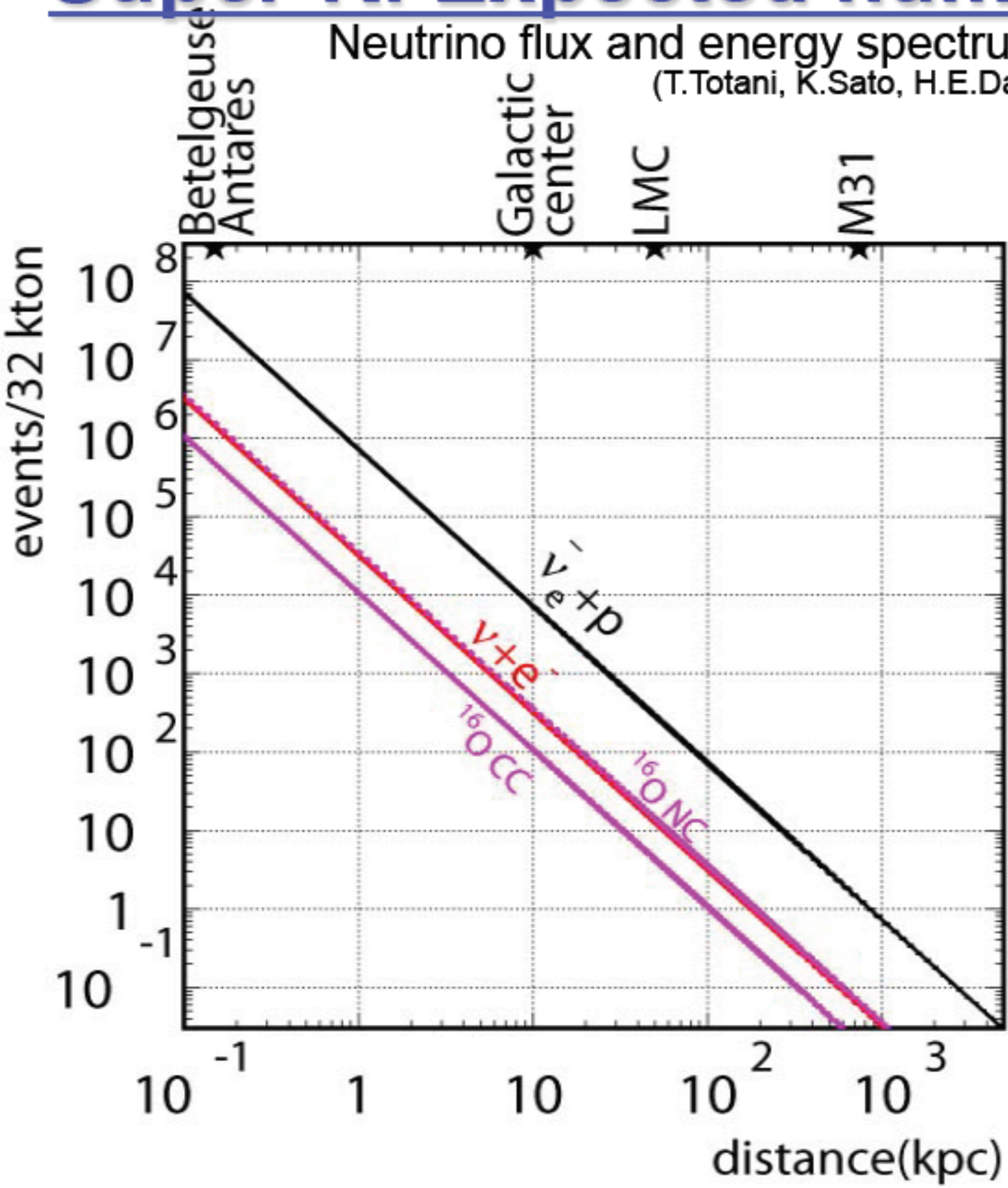


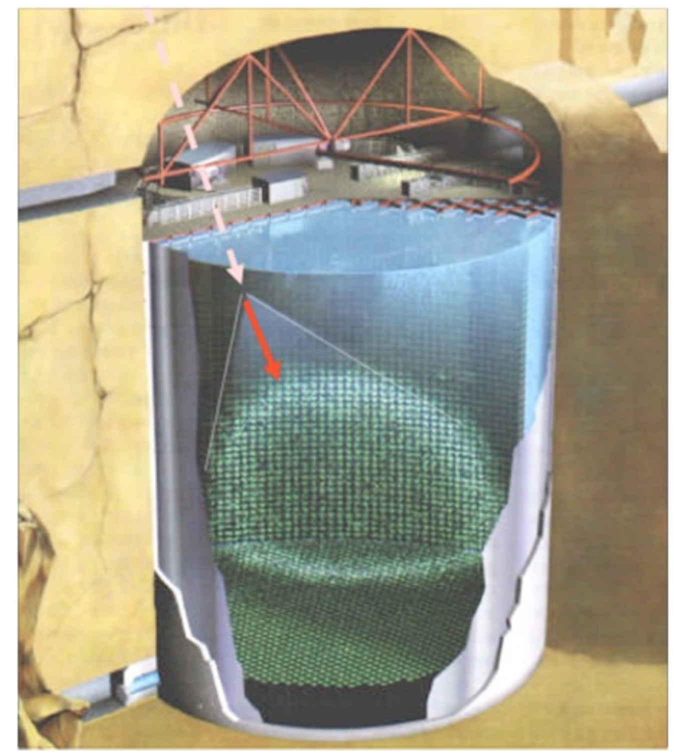
Some pointing from ES

K. Scholberg - Ann.Rev.Nucl.Part.Sci 62 (2012), 81.

Super-K: Expected number of events

Neutrino flux and energy spectrum from Livermore simulation
(T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998))





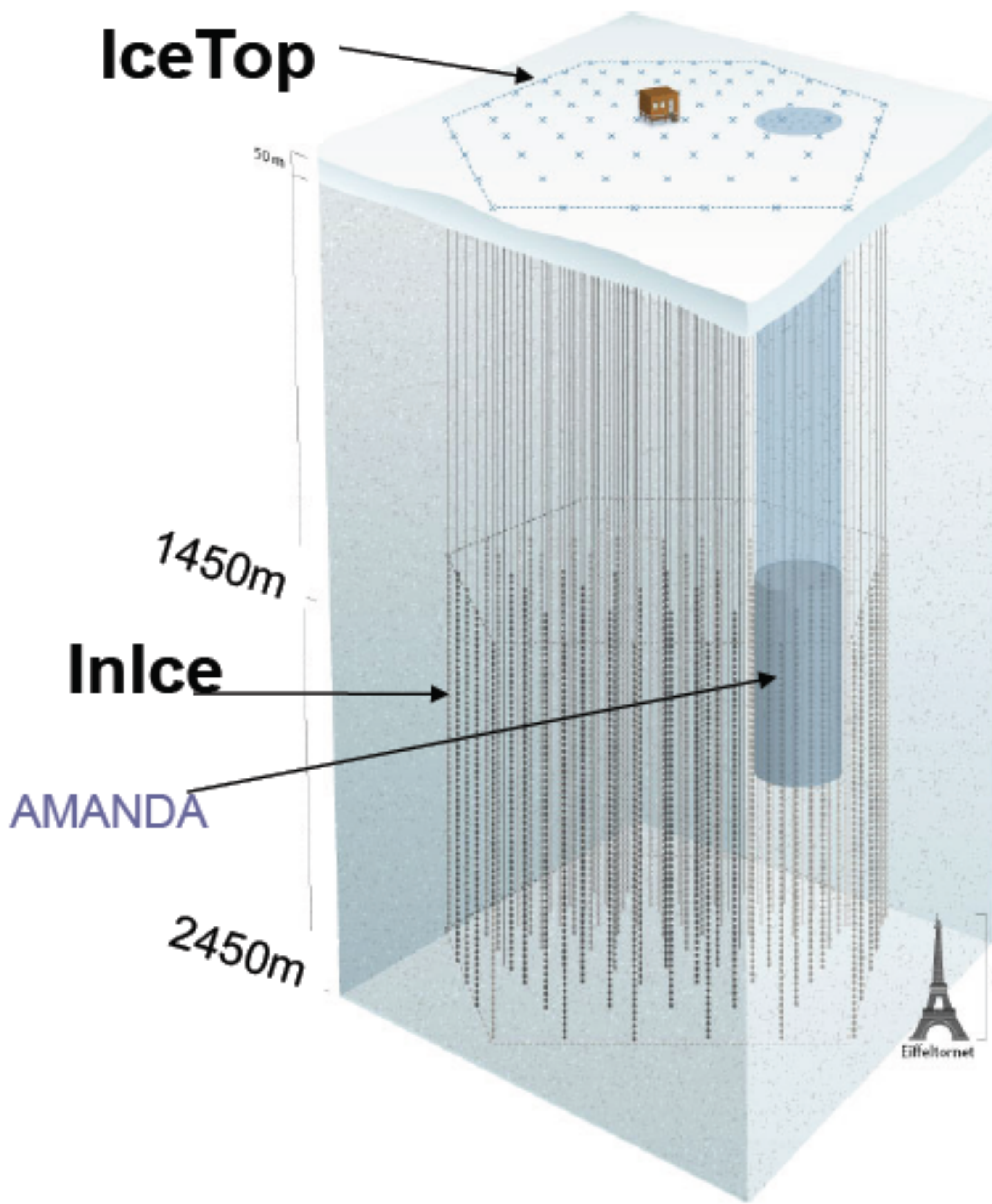
~7,300 $\bar{\nu}_e$+p events
~300 ν+e events
~360 ^{16}O NC γ events
~100 ^{16}O CC events
(with 5MeV thr.)

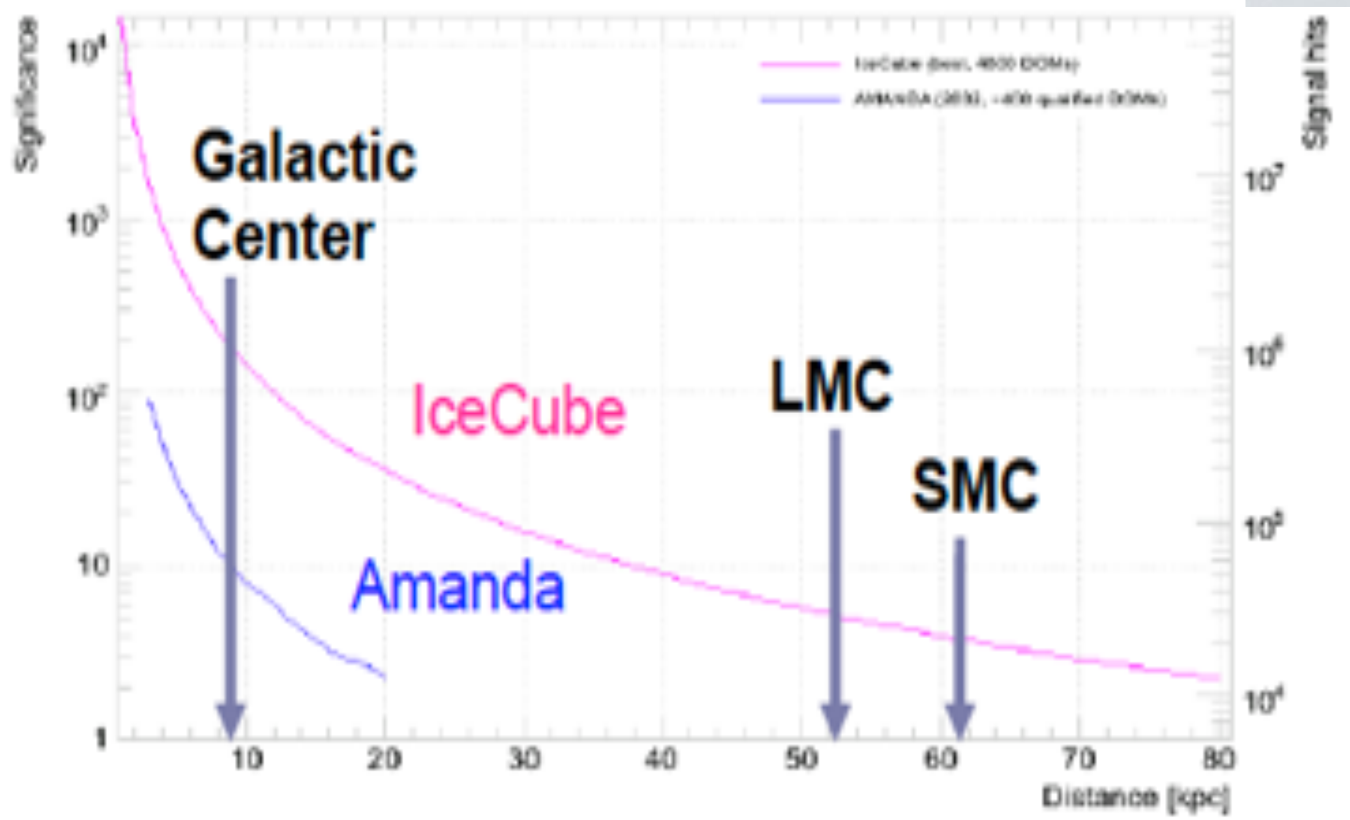
for 10 kpc supernova

Long string ice-Water Cherenkov detectors

IceCube: The Giga-ton Detector Array

(South pole)





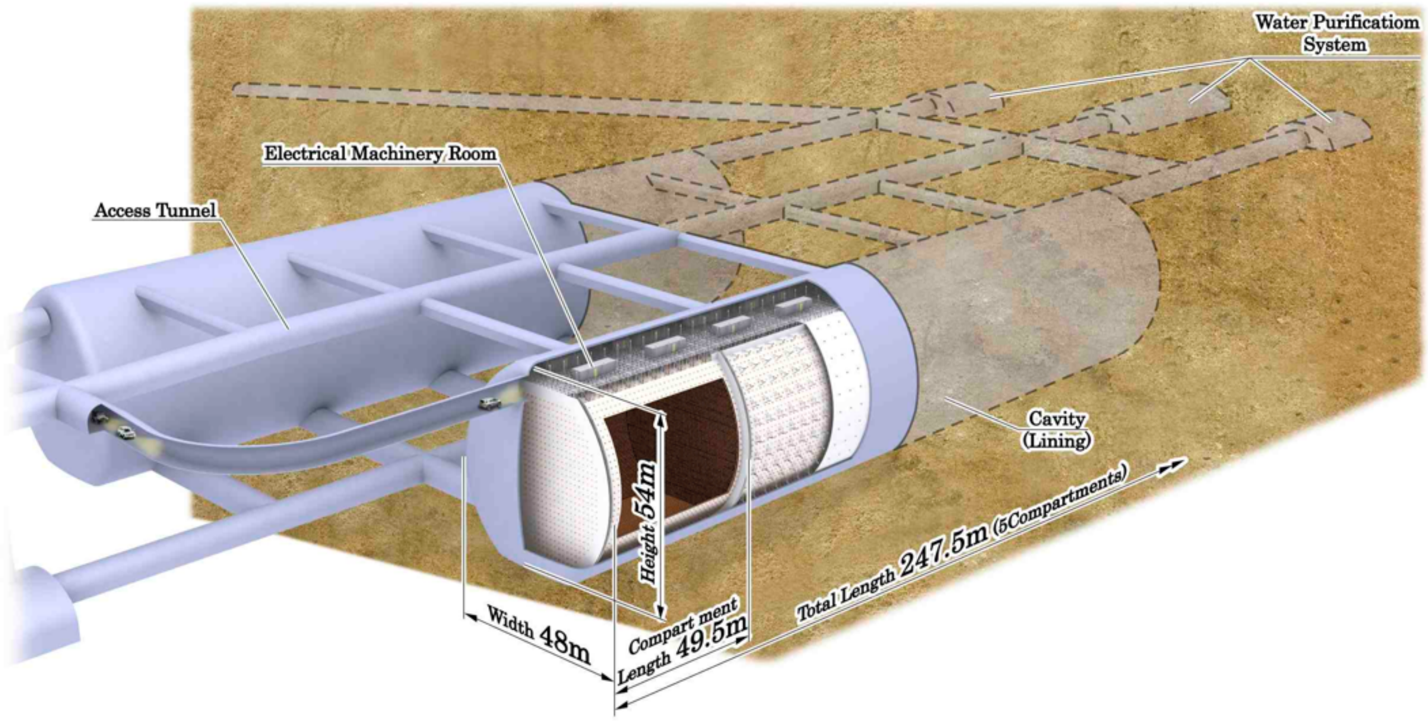
Supernova neutrinos coherently increase single rates of PMTs.

Relevant for Time Structure

Construction finished on Dec.18, 2010.

From L.Koepke, S.Yoshida

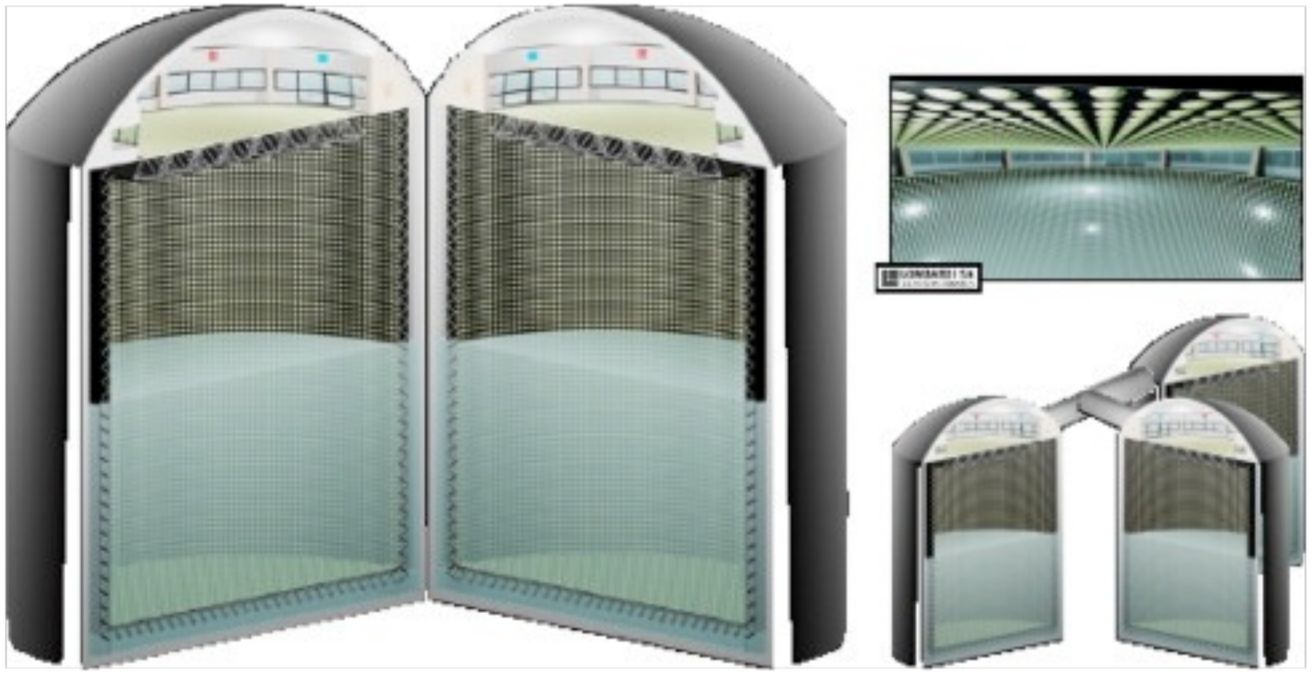
cannot tag flavor or other interaction info, but gives overall rate and time structure



MegaTon Water-C Underground Detector Concepts

Hyper-K (Japan)

MEMPHYS (Europe)

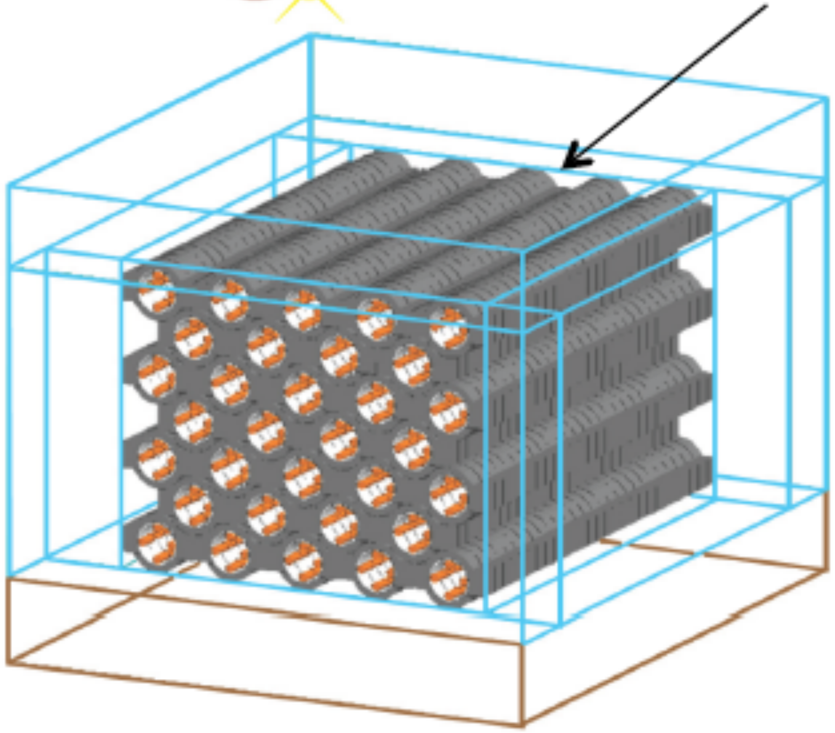


Heavy Nuclear Targets:

Lead

HALO - a Helium and Lead Observatory

(SNO Lab., Canada)

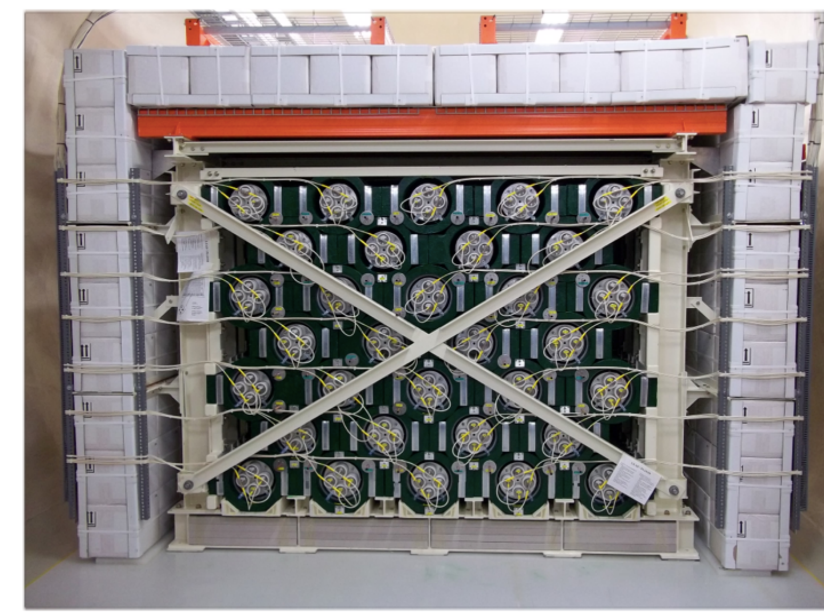


CC: $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^-$

NC: $\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^-$

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n$

$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n$



HALO-1 is using an available 76 tonnes of Pb

In HALO-1 for a SN @ 10kpc†,

- Assuming FD distribution with T=8 MeV for ν_μ's, ν_τ's.
- 65 neutrons through ν_e charged current channels
- 20 neutrons through ν_x neutral current channels

~ 85 neutrons liberated;
with ~50% of detection efficiency, ~40 events expected.

HALO-2 is a future kt-scale detector

From C.Virtue