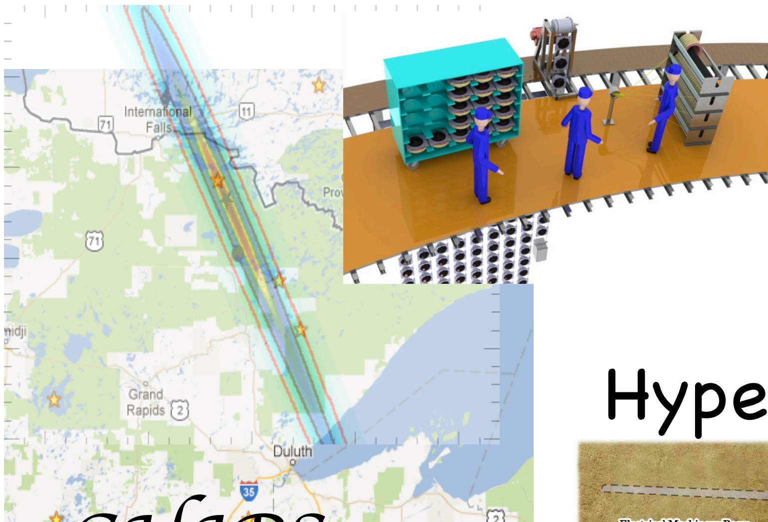
ICFA International Committee for Future Accelerators

Water Cherenkov and Scintillator R&D Opportunities

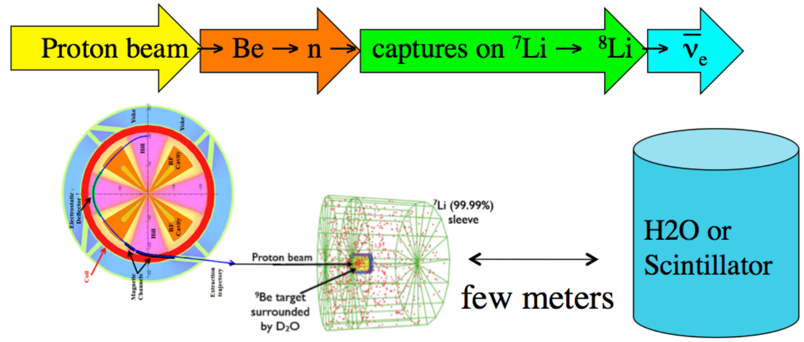
R.Svoboda, ICFA, January 2014

Advantages

- Excellent m/e separation and inherent track directionality
- Light nucleus and 11% free protons by mass
- Highly versatile: low background, low energy threshold, and very fast – everything from reactor neutrinos to accelerator and UHE neutrinos
- Photosensor R&D has direct social benefits due to widespread application in medicine and industry
- Many new experiments proposed

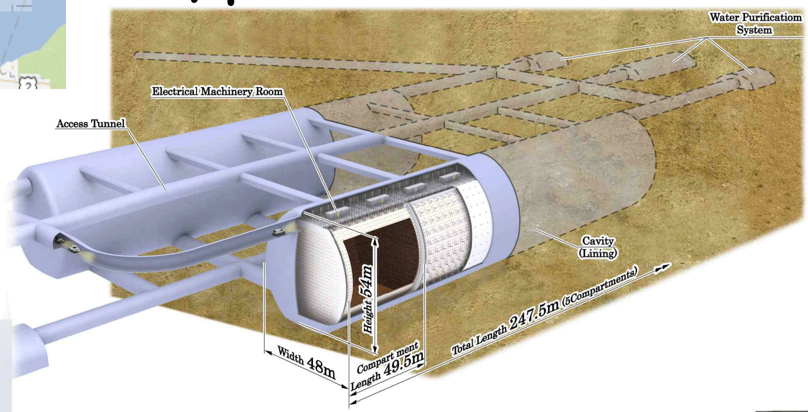


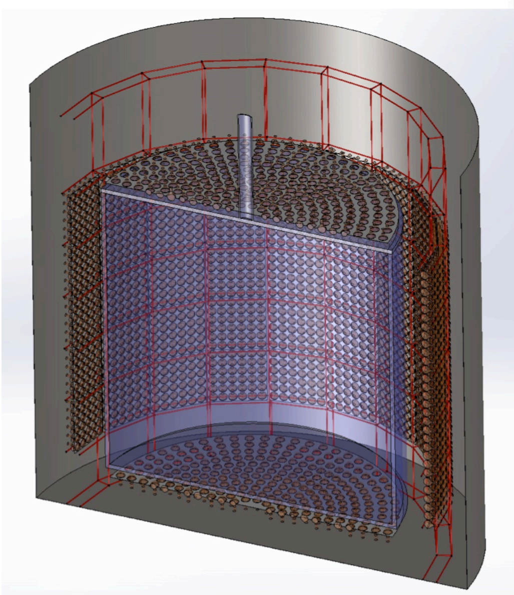
CHIPS



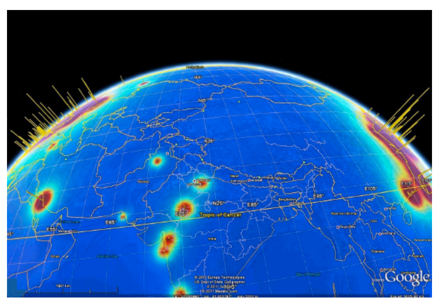
ISODAR @ WATCHMAN

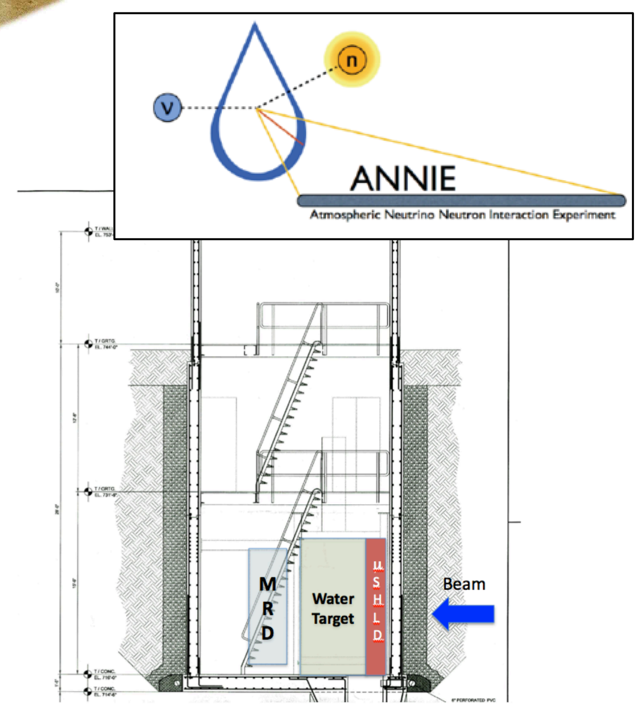
Hyper-Kamiokande





WATCHMAN

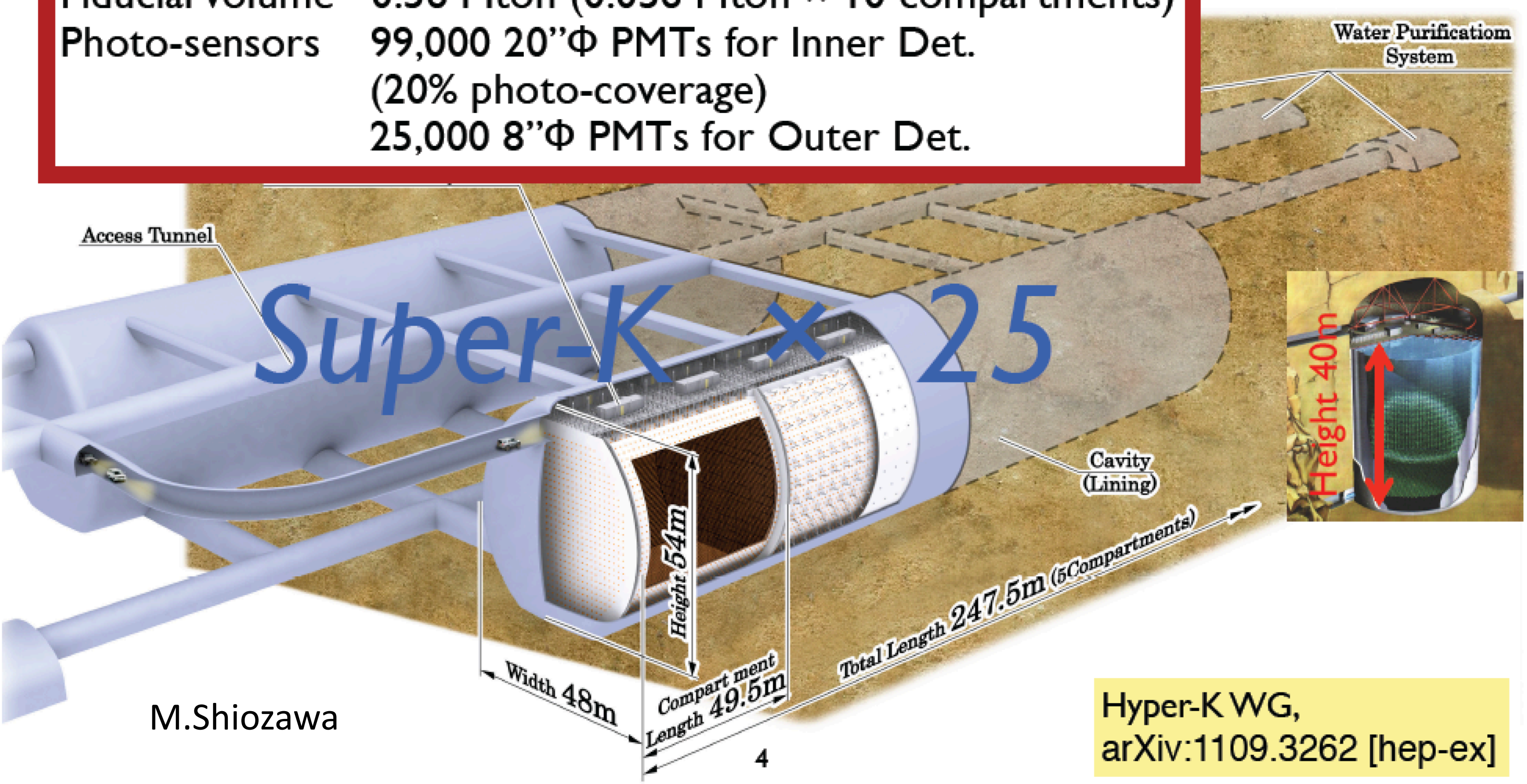




R.Svoboda, ICFA, 31 January , 2013

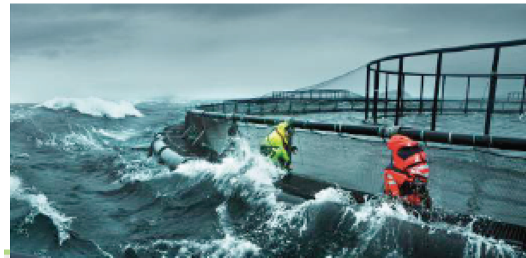
Hyper-Kamiokande Megaton Scale Water Cherenkov Detector

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Photo-sensors	99,000 20''Φ PMTs for Inner Det.
	(20% photo-coverage)
	25,000 8''Φ PMTs for Outer Det.



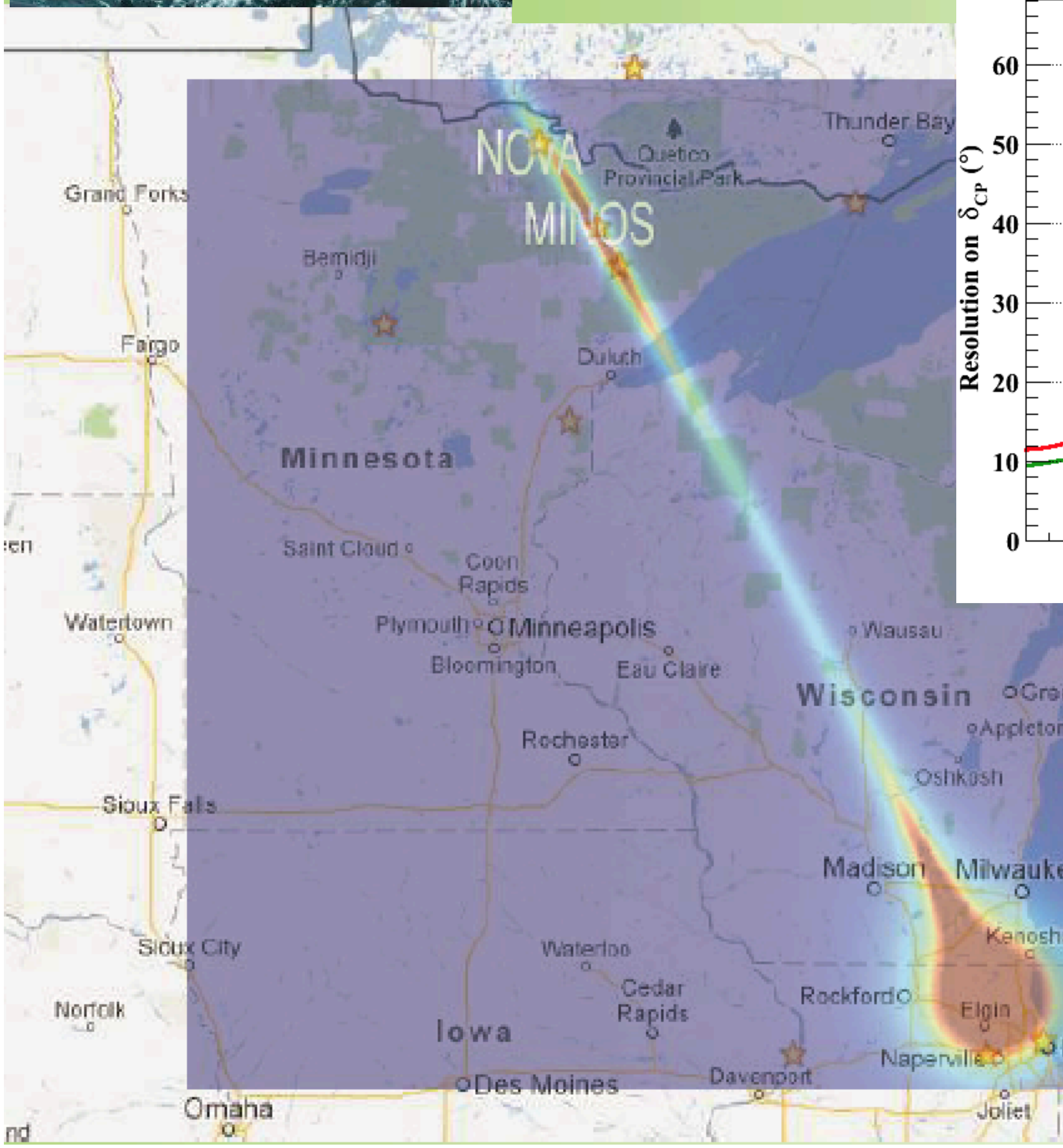
M.Shiozawa

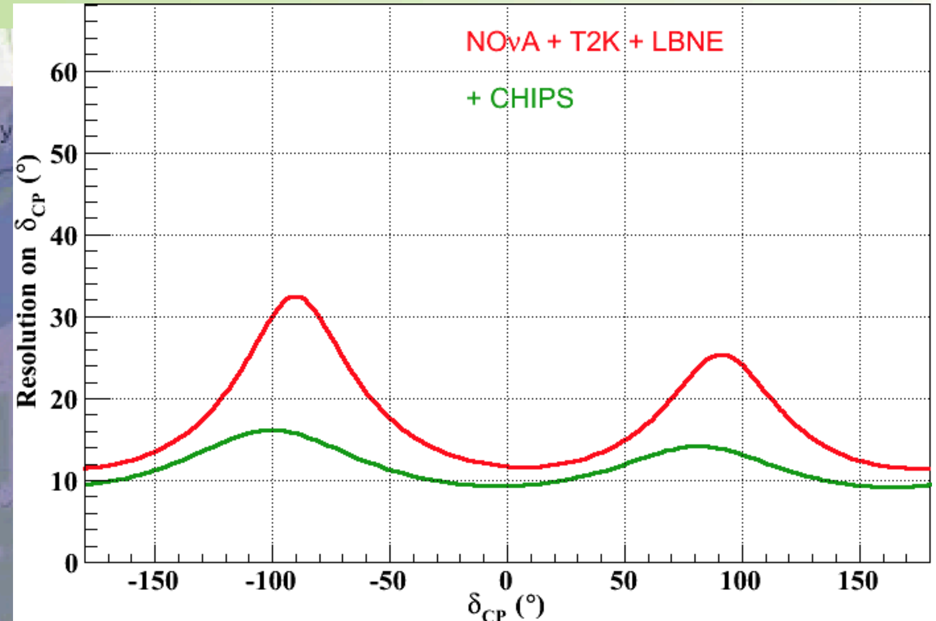
Hyper-K WG, arXiv:1109.3262 [hep-ex]



CHIPS P-1051

CHerenkov detectors In mine PitS

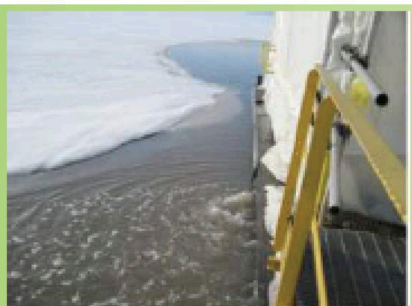


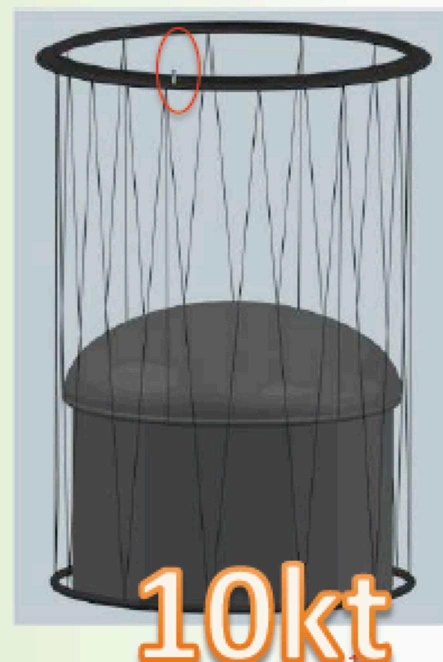


100kton detector deployed in NuMI and/or LBNE beam in shallow water site. See recent FNAL PAC presentation for full physics case

δ_{CP} : CHIPS concept

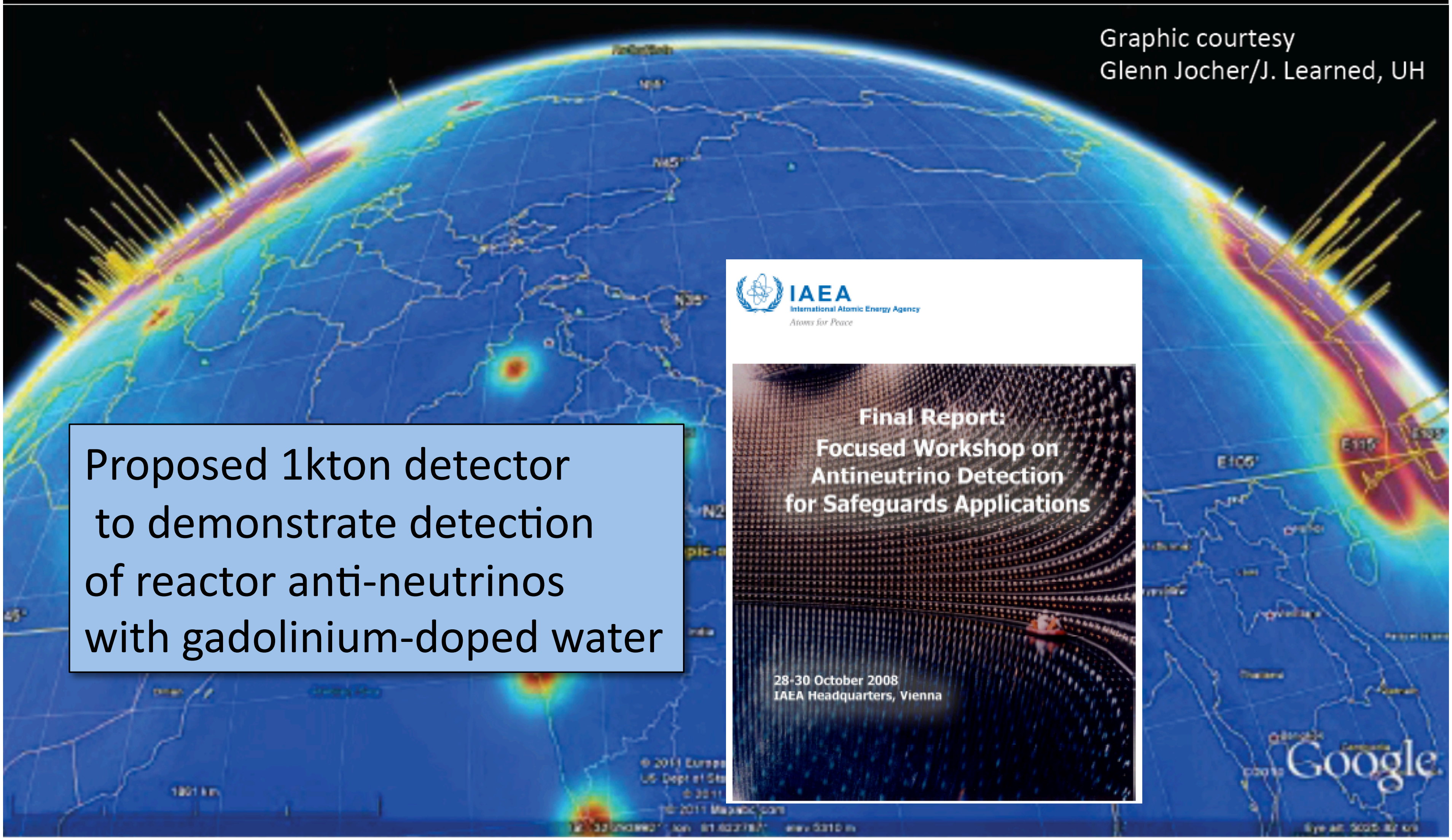
- Deploy from floating platform using industrial products from the fisheries industry
- Replace nets with PVC + KEE resevoir membranes rated for continuous underwater use including aggressive oil spill environments, low permeability and light tight
- Fill with cleaned water for neutrino target
- Pit water acts as mechanical support
- Deployment Idea developed by Madison/PSL groups for LBNE but has similarities with IMB and the GRANDE proposal





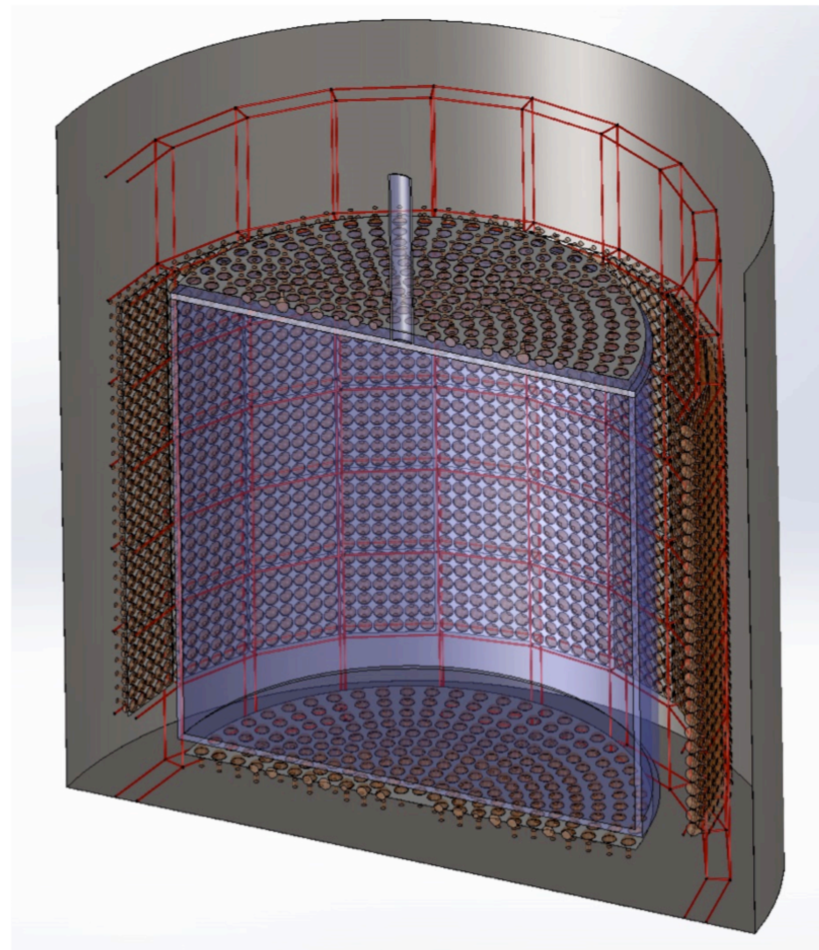
WATCHMAN

WATer CHernkov Monitoring
of Anti-Neutrinos



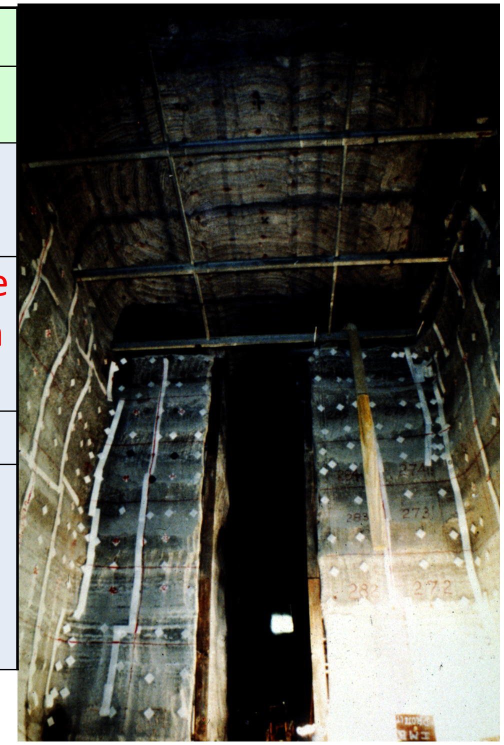
Watchman Detector

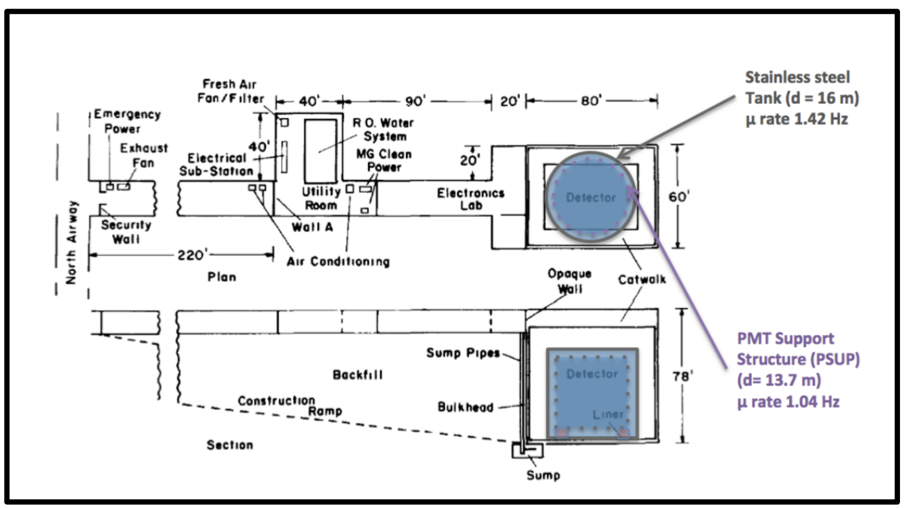
- 3 kiloton (1 kiloton fiducial) free-standing water tank mounted on concrete foundation in existing IMB cavern.
- 6000 11" or 5000 12" HQE PMT's mounted around the surface, giving about 50% more light collection than Super-Kamiokande
- Active Veto
- Compatible with pure water, water+Gd, or WbLS fill



Existing underground lab only 13 km from commercial nuclear reactor

Reactor Location	Perry Ohio
Thermal Power	3875 MWt
Detector Location	Morton Salt/IMB mine (!) Painesville, Ohio
Standoff	13 km - the only reactor in the US at a suitable distance from a deep mine
Overburden	1670 mwe
Approval status	Morton Salt has approved installation – assuming cost-neutral and no disruption to mining activities

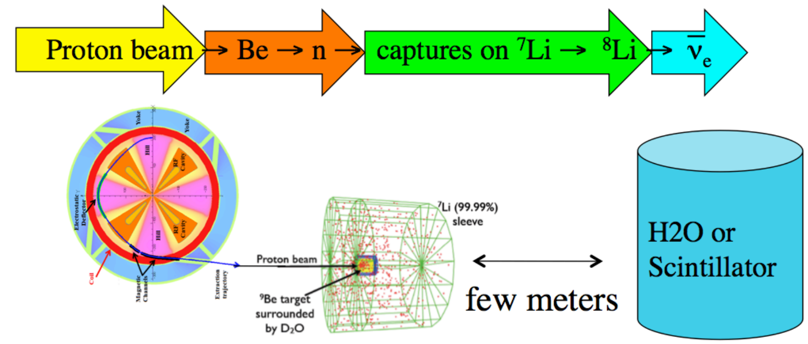




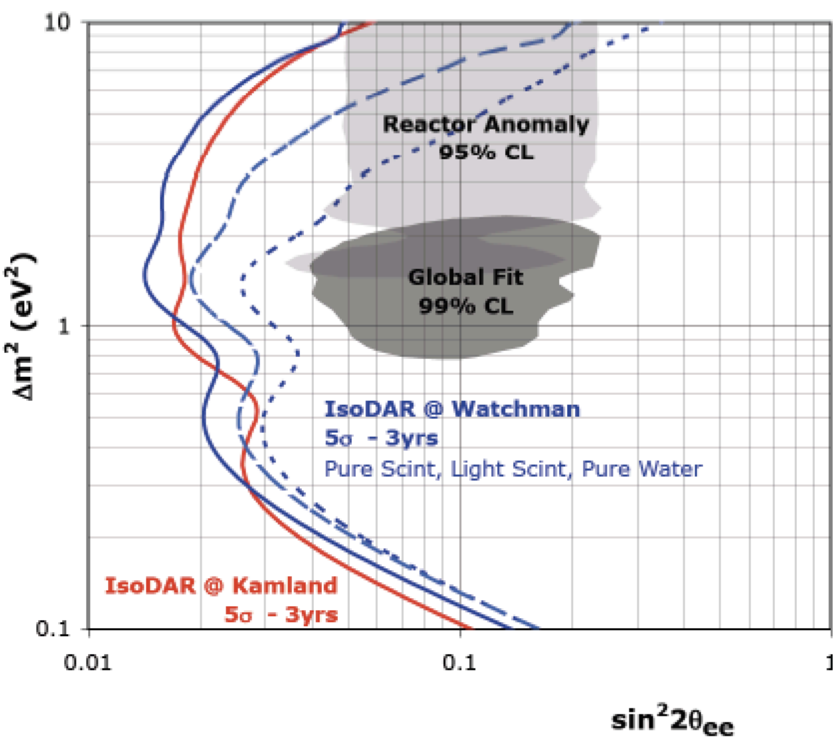
IMB detector was world's first large water Cherenkov detector (8 ktons).

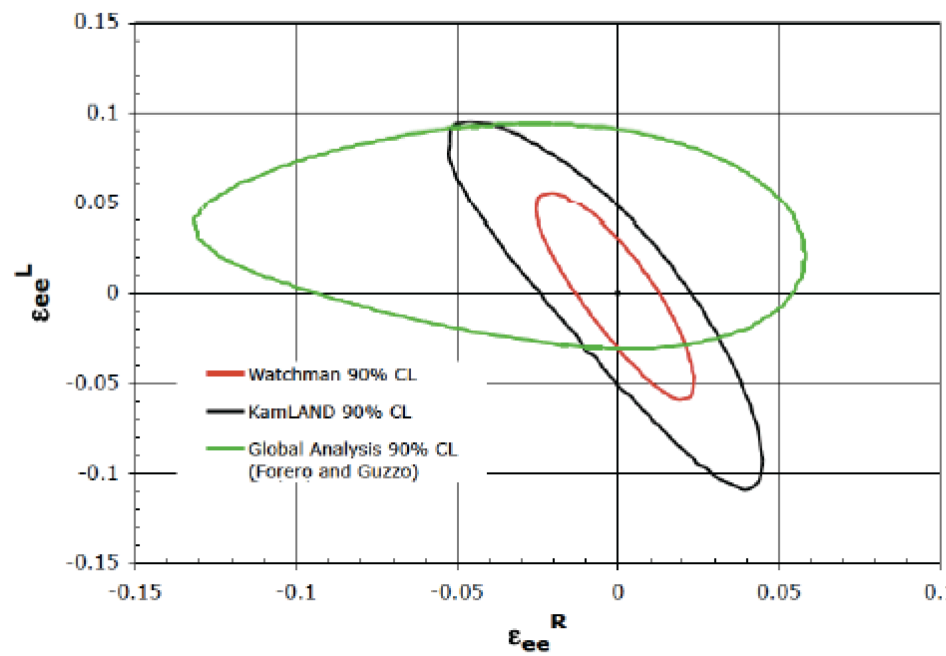
Detector removed in 1992 but underground site is still in good condition. Essentially ready for immediate use.

ISODAR @ WATCHMAN



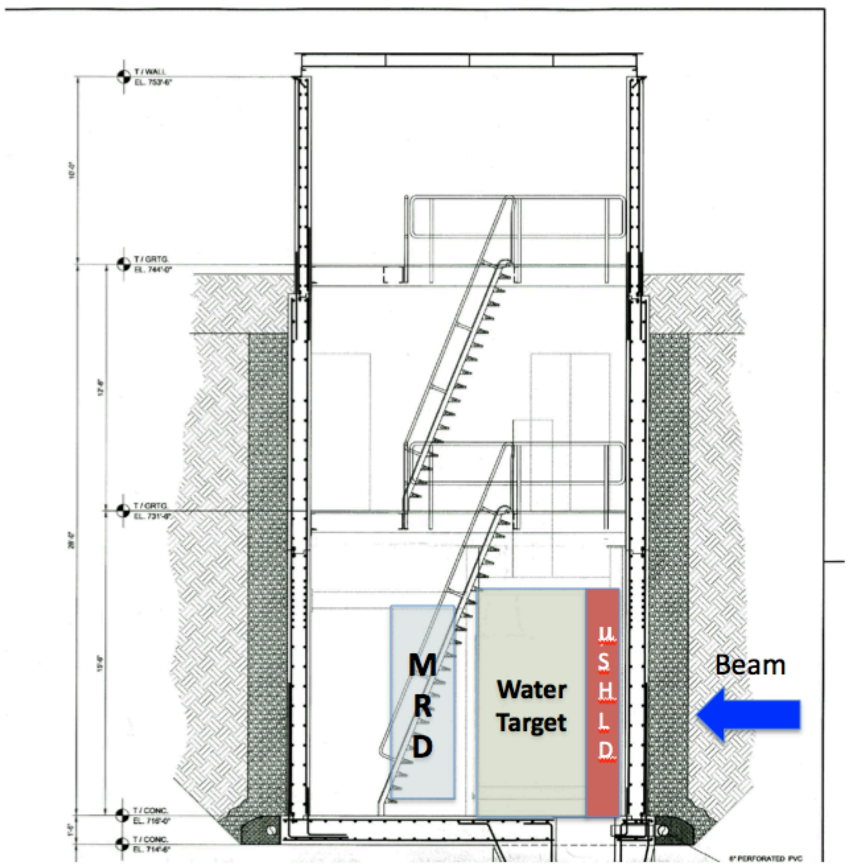
WATCHMAN is also a potential site for ISODAR, an experiment that would use a 60 MeV compact cyclotron to produce a 8-Li beta source. See arXiv:1245.4419 for full physics case



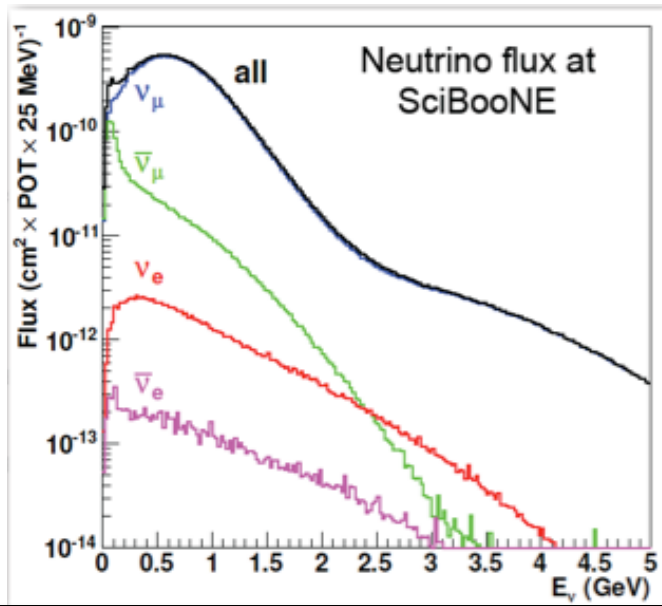


R&D Opportunities

Atmospheric Neutrino Neutron Interaction Experiment



ANNIE Hall

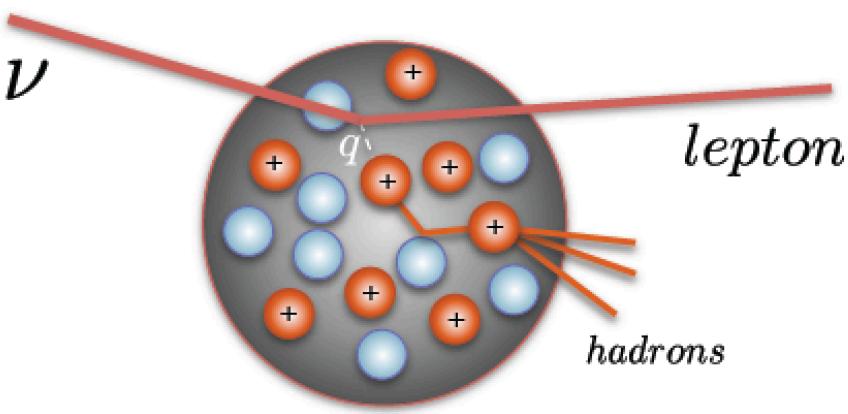


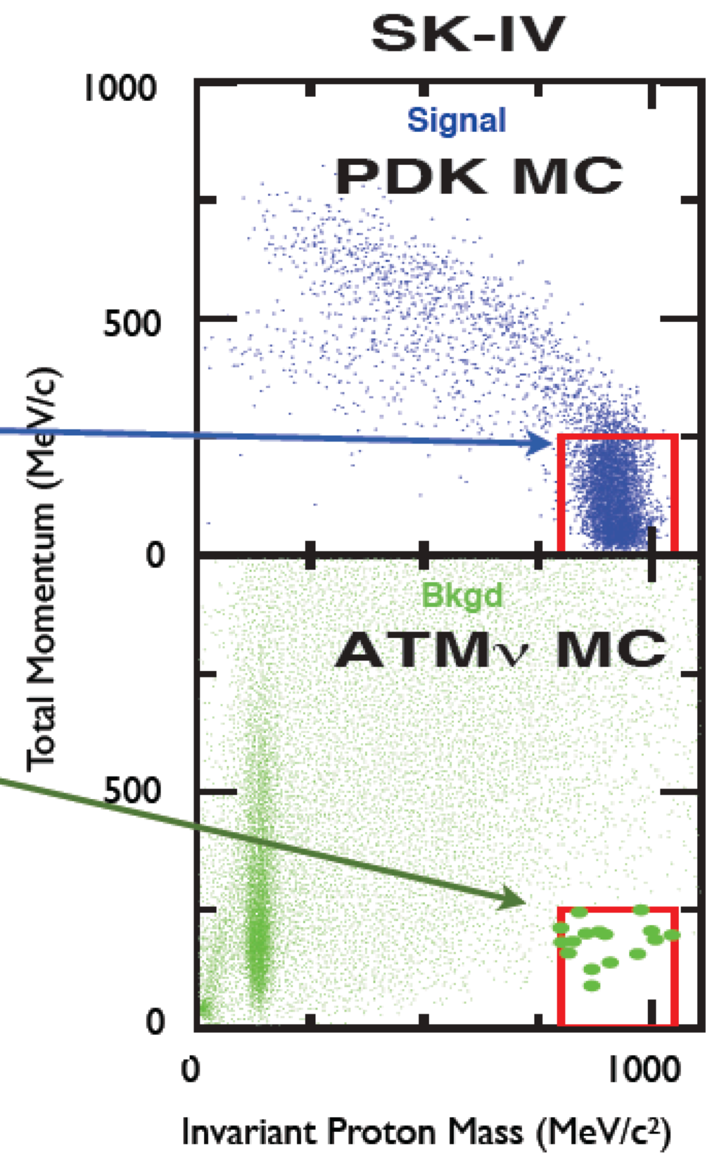
By coincidence, the Booster beam has an energy spectrum very similar to atmospheric neutrinos. This can be used to study backgrounds for proton decay.

Backgrounds come almost exclusively from atmospheric neutrino interactions

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state

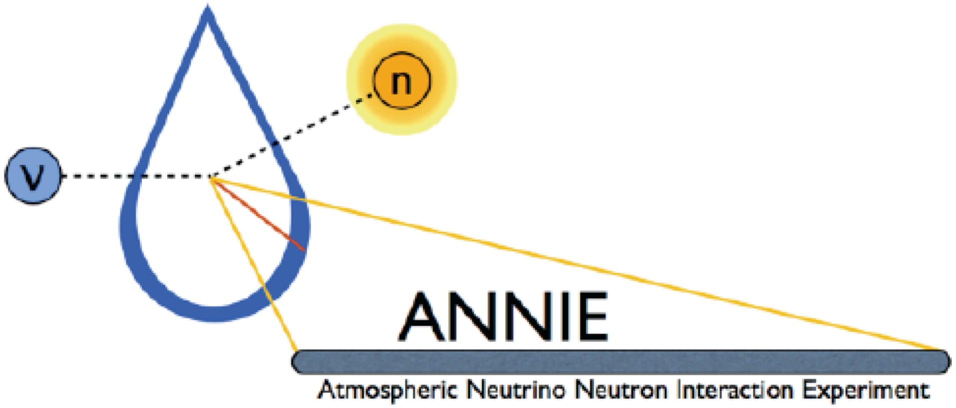




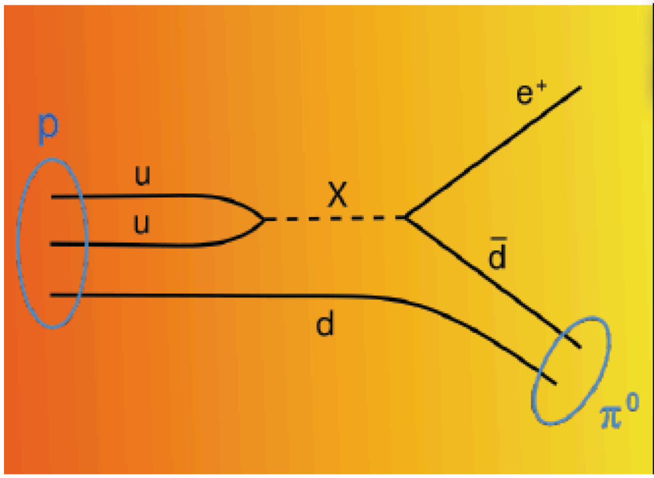
M.Wetstein and M.Sanchez

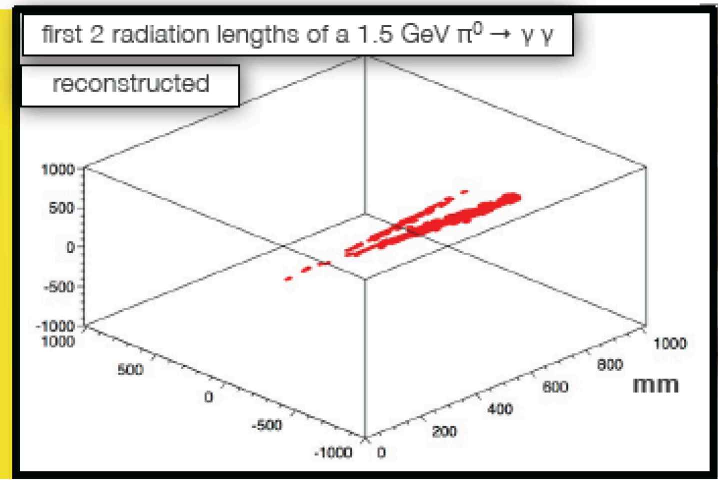
What is ANNIE?

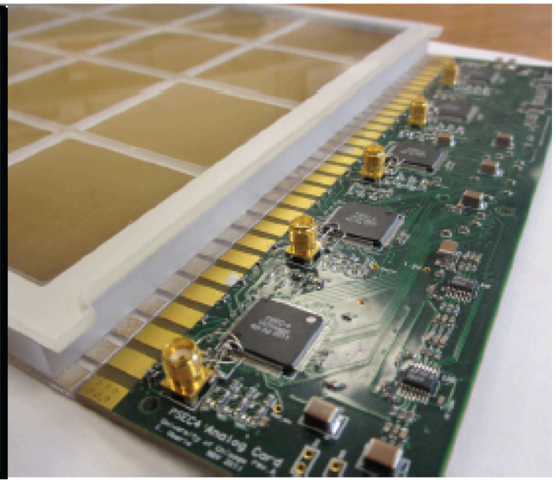
- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.



a key measurement for proton decay physics, supernova neutrino detection in water, and fundamental neutrino interaction physics

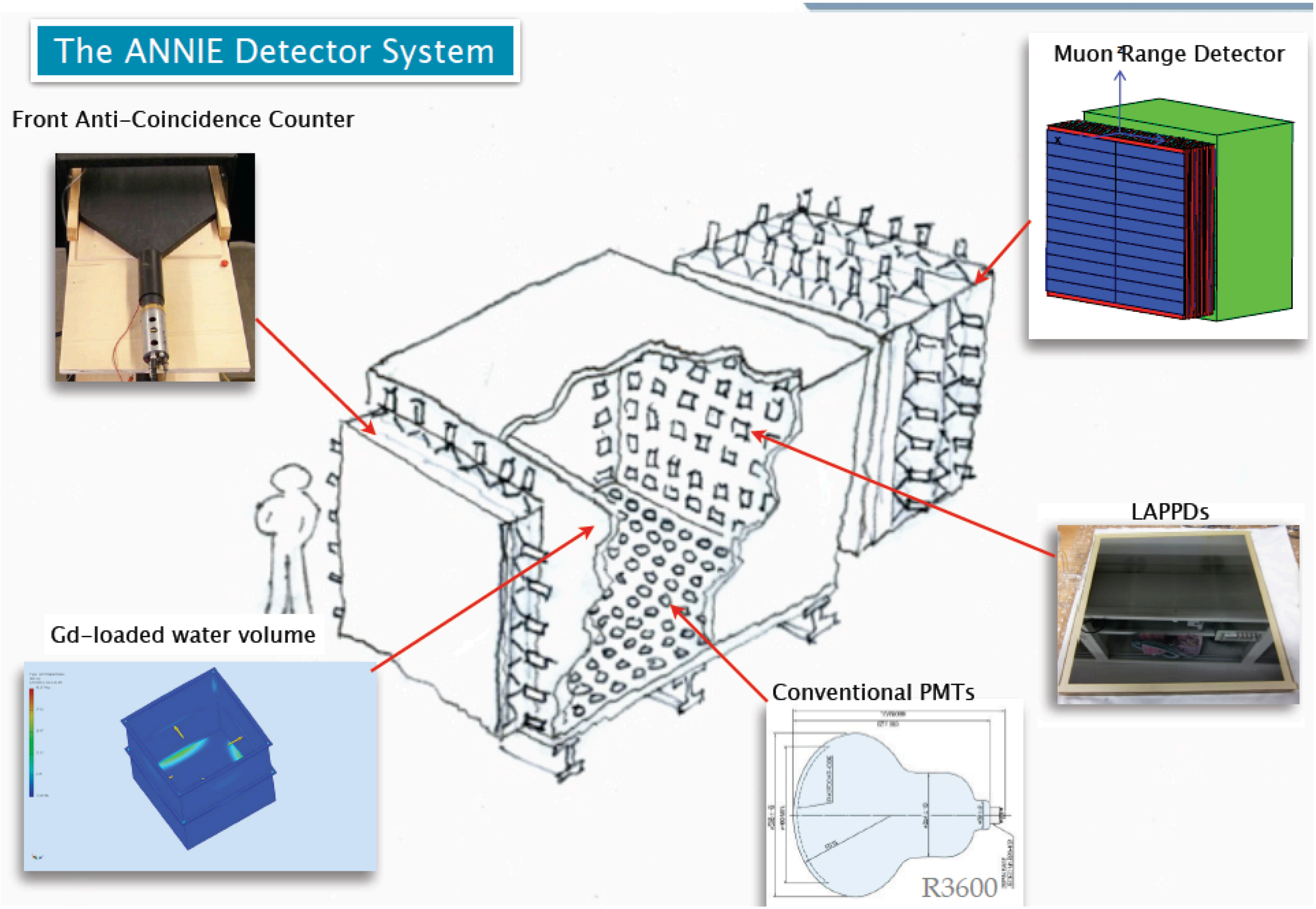






- Demonstration of a new approach to neutrino detection: *Optical Time Projection Chamber* using new photosensor technology.

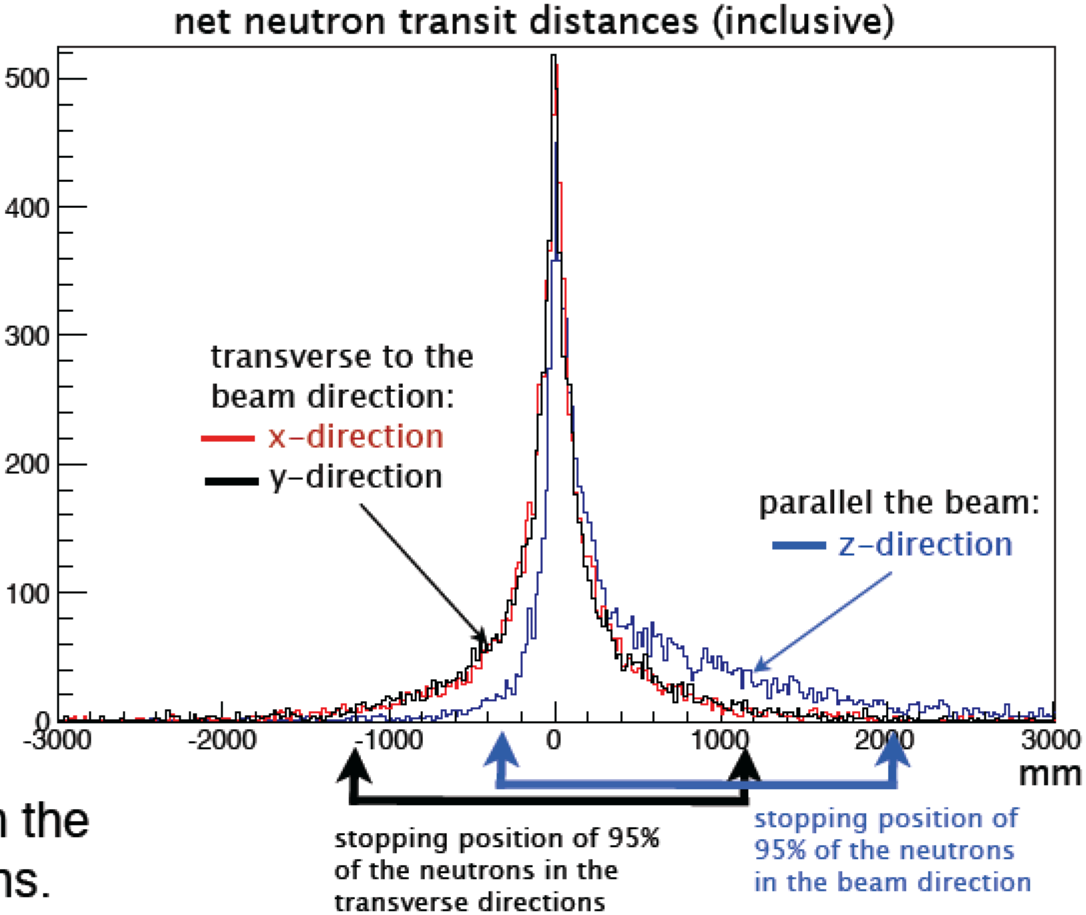
See Matt Wetstein's PAC talk for complete physics case


The ANNIE Detector System
Front Anti-Coincidence Counter
Muon Range Detector
LAPPDs
Gd-loaded water volume
Conventional PMTs
R3600

Timing-based vertex reconstruction is essential

Neutrons typically drift over a 2 meter distance.

- In the directions transverse to the beam, this 2-meter window is centered symmetrically about the interaction point.
- In the direction of the beam, it is mostly forward with respect to the interaction point.



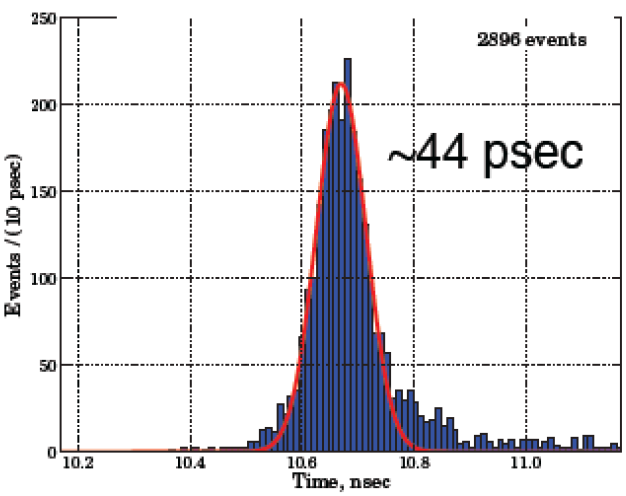
In order to get a clean sample of neutrons, this analysis must be restricted to a small ~1 ton fiducial volume situated sufficiently far from the walls of the tank to stop the neutrons.

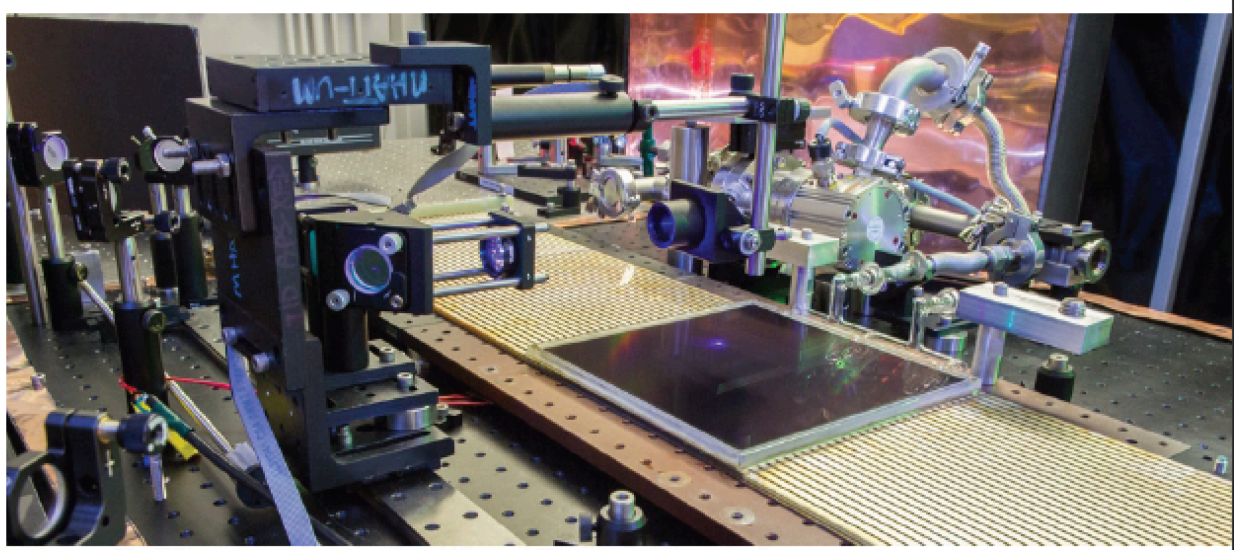
In order to identify events in this fiducial volume, we need to reconstruct the interaction vertex to better than 10 cm. Accurate timing based reconstruction from the Cherenkov light is essential.

LAPPDs can provide the needed photodetector capabilities

The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- <50 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.
- Phase II request for $3M for commercialization has been submitted by Incom, Inc





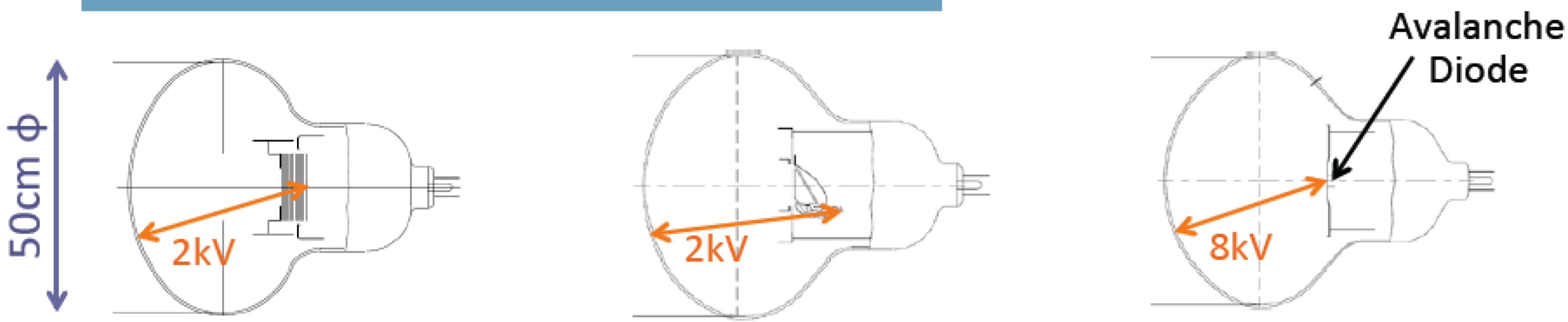
Other Photosensor R&D

- Ultra-high quantum efficiency PMT's
- Low-cost 11-inch PMT's
- Hybrid Phototubes
- Light collectors

New PMT's

- Ultra-High Quantum Efficiency tubes now a reality. For Cherenkov spectra, these are a **factor of 1.6 better per cm^2** than the existing Super-K 20 inch PMTs
- Hamamatsu markets 10 inch and 12 inch versions for LBNE and HK. Developing 20-inch version
- ADIT/ETEL developing 11-inch version with first prototypes delivered this summer for WATCHMAN and HK. Goal is semi-automated mass production leading to lower costs.

Hyper-K photodetector candidates (for ID)

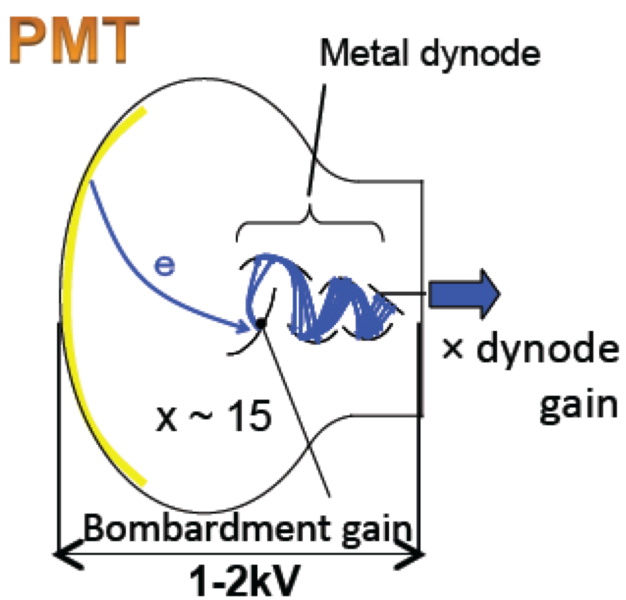


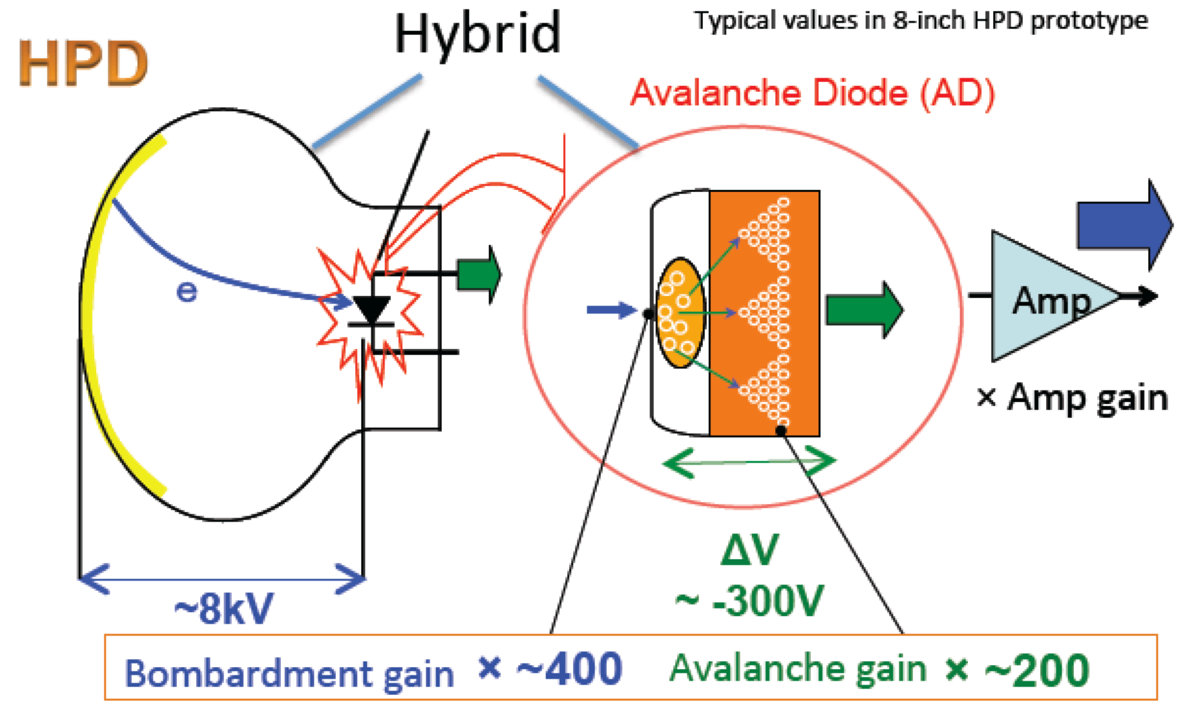
20" PMT (Venetian-Blind dynode)	20" Improved PMT (Box&Line dynode)	20" HPD (Hybrid Photodetector)
• Super-K ID PMTs • Used for ~20 years → Guaranteed • Complex production → Expensive	• Under development • Better performance (C.E., Timing resolution) • Same technology → Lower risk	• Under development • Far better performance • Simple structure → Lower cost • New technology → Higher risk

Lower Risk ← → Higher Performance

Nakayama, 4th HK Workshop

Hybrid PhotoDetector (HPD)





	PMT (20")	HPD (8")
HV	1-2kV	~8kV
Gain	$\sim 10^7$	$\sim 10^4$ - 10^5
C.E.	~80%	~97%

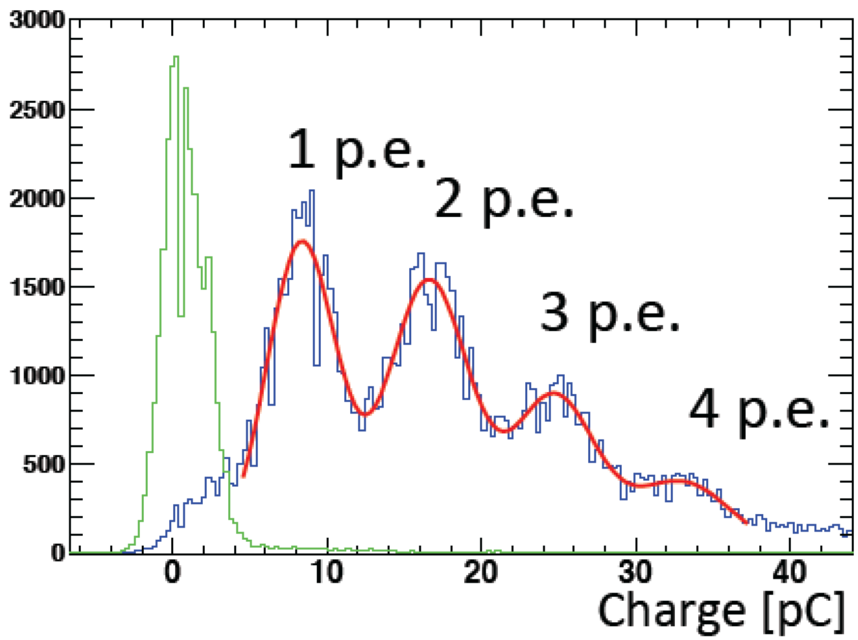
Same photo cathode (Q.E.)

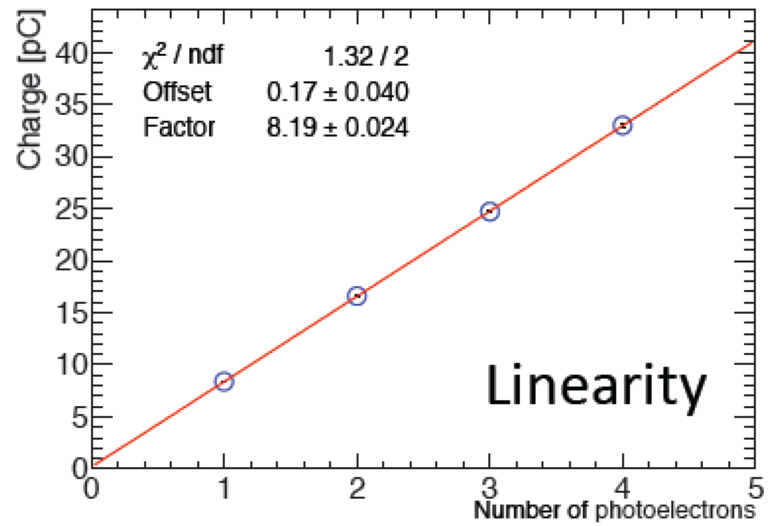
High voltage around 8kV is required
- to collect electrons in the small region of AD (5-20mm)
- to increase gain at electron-bombardment

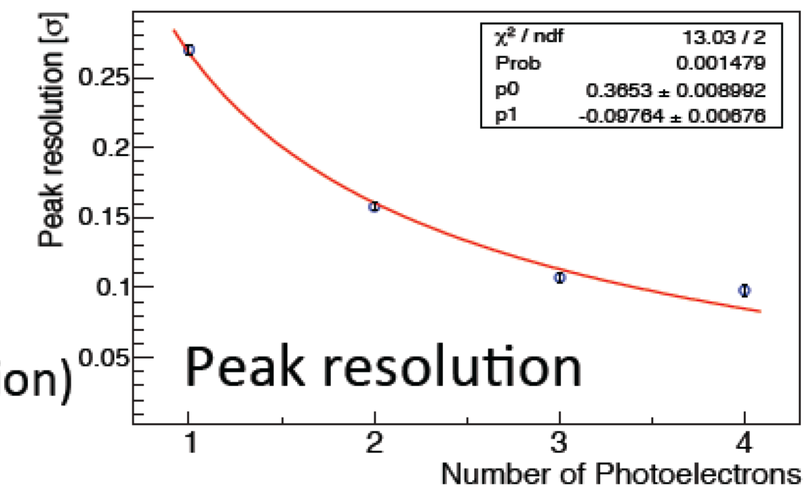
- High performance and low cost
- However, factors to consider for viability in Hyper-K are:
  - Dark noise from AD + Amp., HV around 8kV, low gain, thermal dependence of AD gain, No prior experience using

Multi photoelectron peaks

8-inch HPD



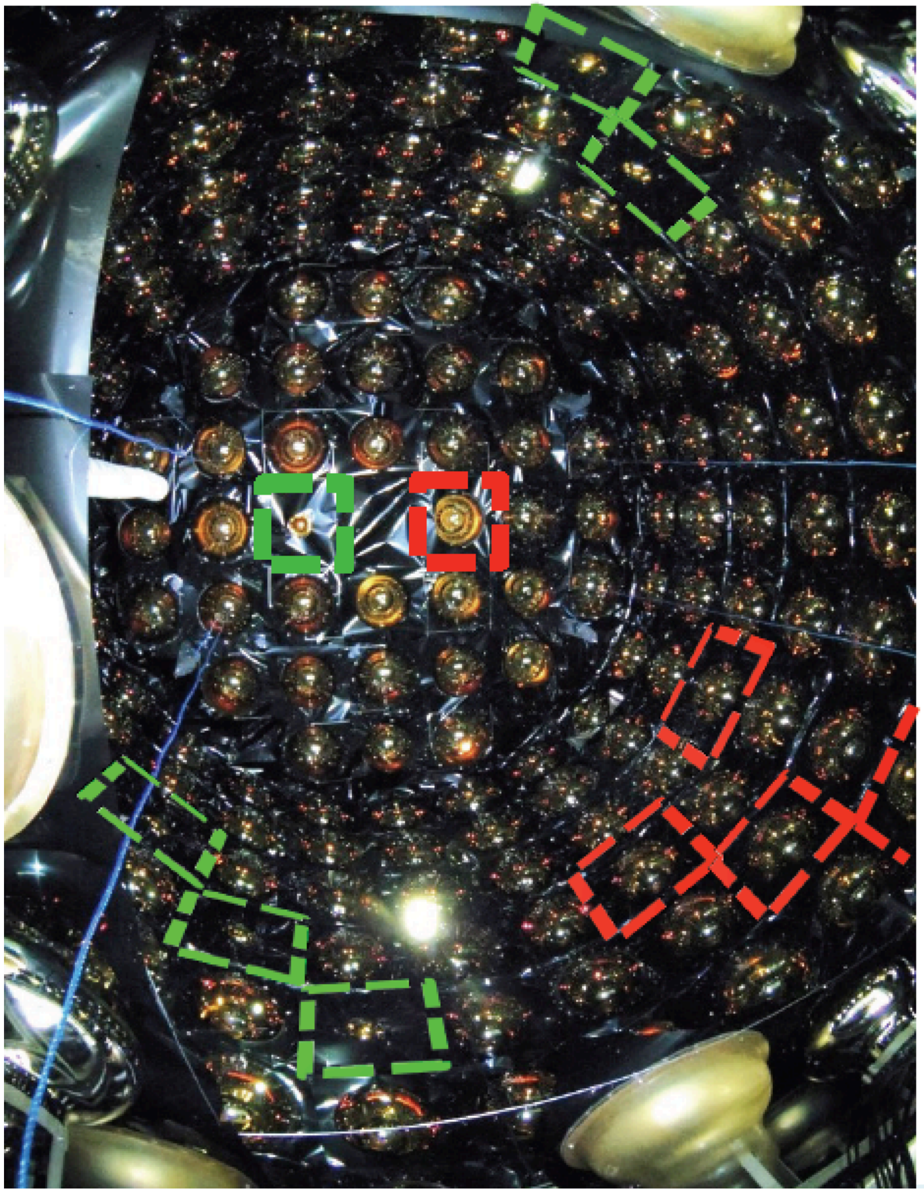




Multi photoelectron peaks
are also clearly seen by HPD.
(Difficult in case of PMT due to worse resolution)

Nakayama, 4th HK Workshop

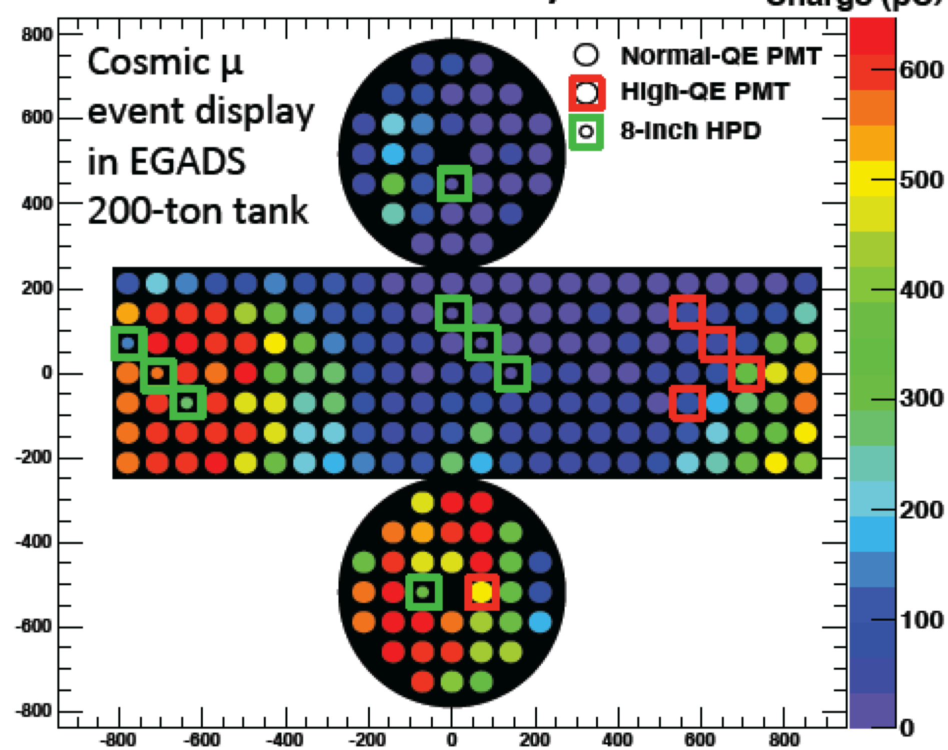
View of photodetectors in tank



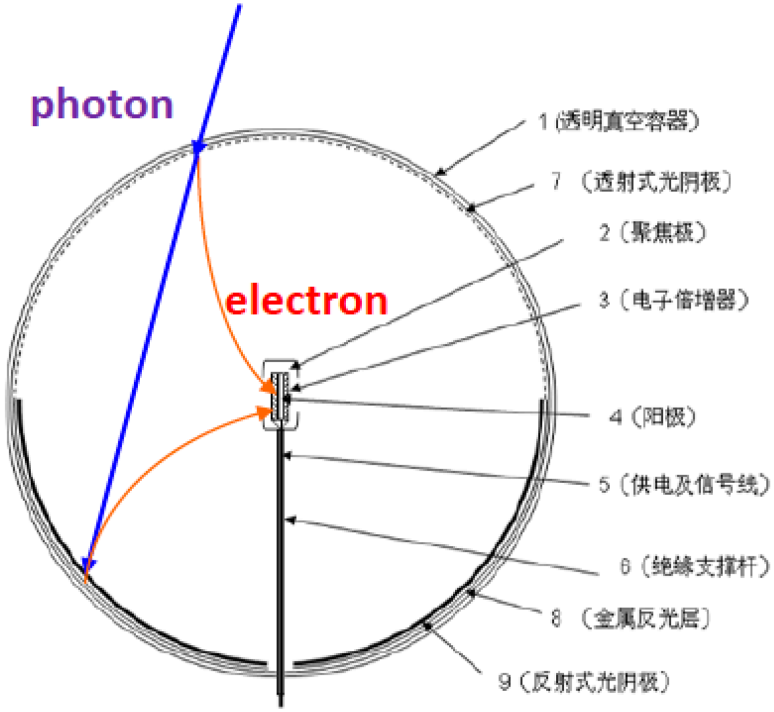
227 Super-K PMT (20”)
+ 5 High-QE PMT (20”)
+ 8 HPD (8”)

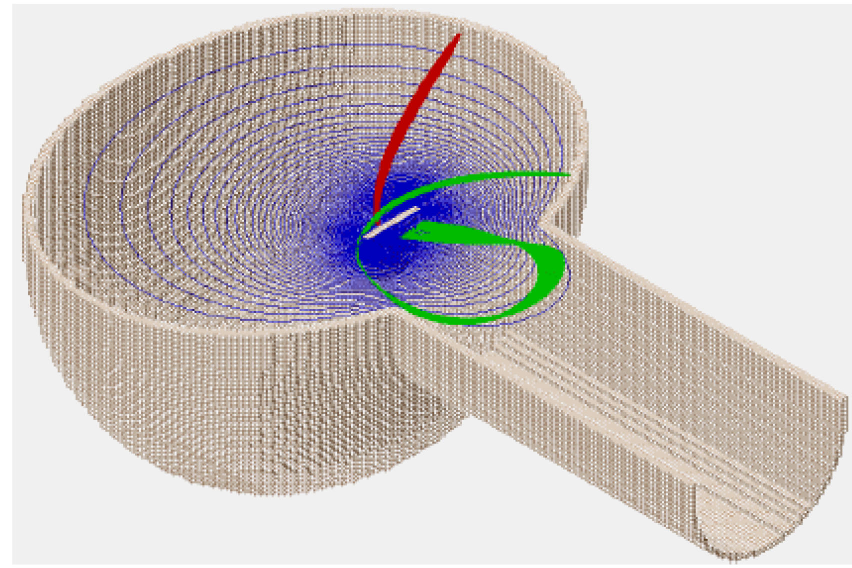
Nakayama, 4th HK Workshop

Observed cosmic ray muon!



A new type of PMT: MCP-PMT



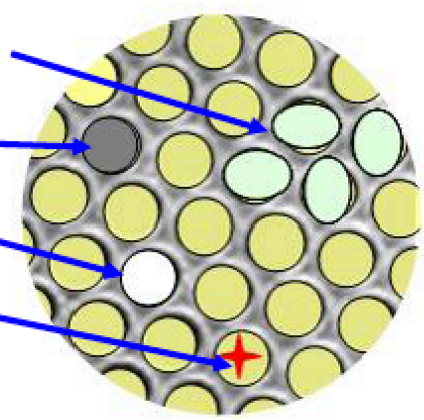


- Top: transmitted photocathode
- Bottom: reflective photocathode
  additional QE: ~ 80%*40%
- MCP (Microchannel Plate) to replace Dynodes ➔ no blocking of photons

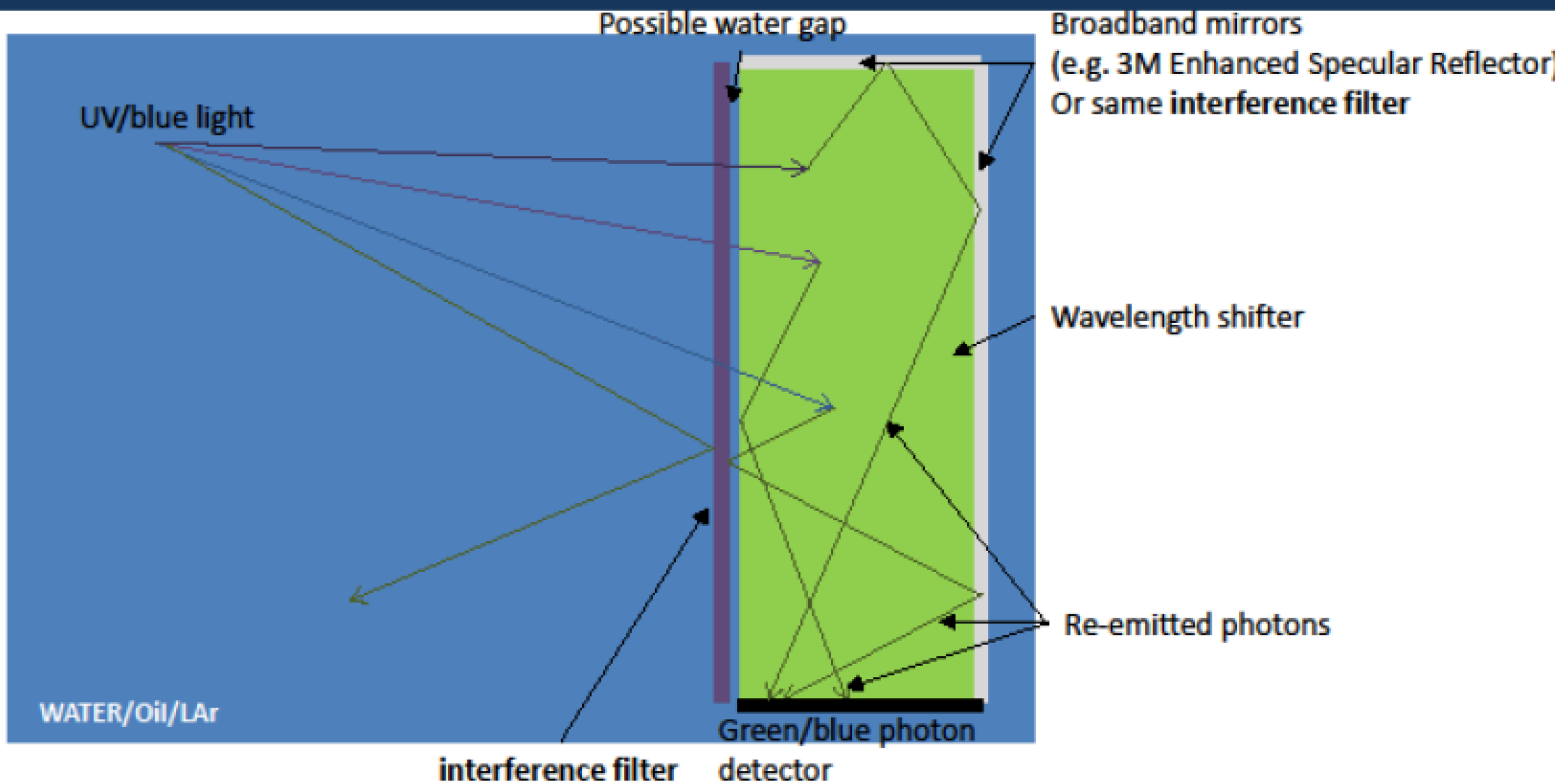
X.Li, Cygnus2013

Low cost MCP by accepting the followings for SPE detection.

1. Asymmetric surface;
2. Blind channels;
3. Non-uniform gains
4. Flashing channels



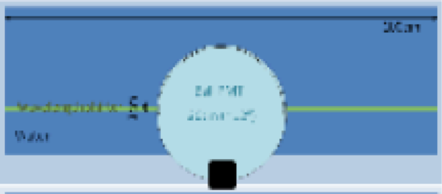
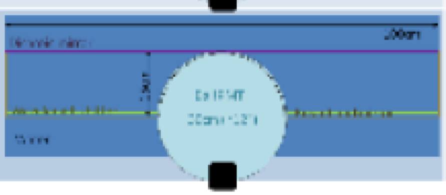
Trapping reemitted light either by total internal reflection or mirrors



Trapping efficiency:

- ~30% with total internal reflection independently of number of bounces
- $98.5\%^{nbounce}$ with mirrors
- Can combine both

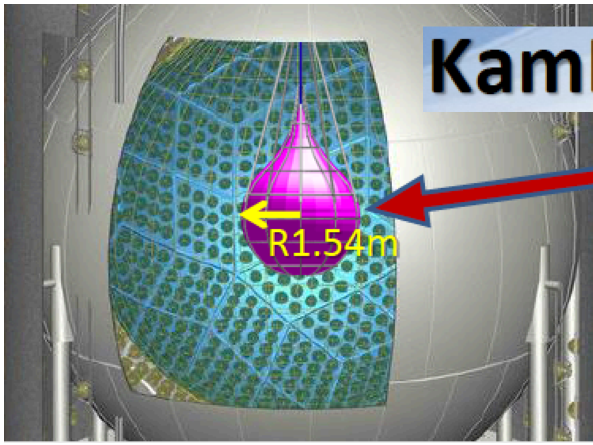
Photon Collection Performance 100 cm Traps

Configuration		Primary	Internal	External	Ext/Int	Total
			(Secondary = Internal + External)			
20" PMT		1*	0	0	N/A	**1**
12" PMT + 3cm WLS + side mirrors		0.43	0.38	0	N/A	**0.80**
12" PMT + 3cm WLS + side & back mirrors + WLS dichroic mirror		0.42	0.43	0.13	0.30	**0.98**
12" PMT + 15cm WLS + side & back mirrors + dichroic mirror		0.34	0.56	0.47	0.85	**1.37**
12" PMT + 3cm WLS + side & back mirrors + dichroic mirror		0.34	0.44	0.35	0.79	**1.14**
12" PMT + 5mm WLS + side & back mirrors + dichroic mirror		0.35	0.21	0.41	2.00	**0.96**

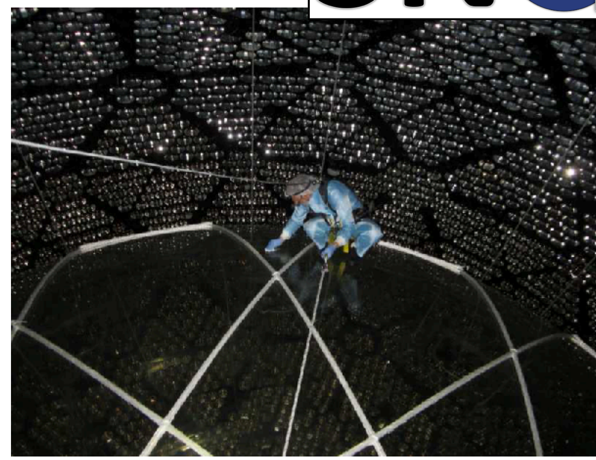
Figures courtesy of F. Retière

New Large Scintillator Experiments

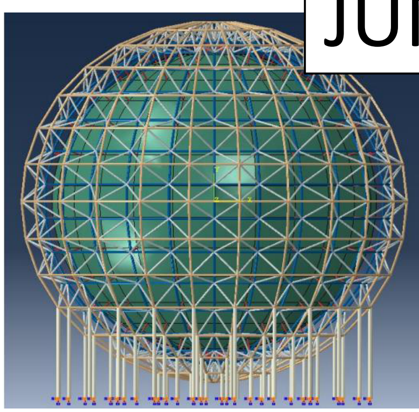
KamLAND-Zen



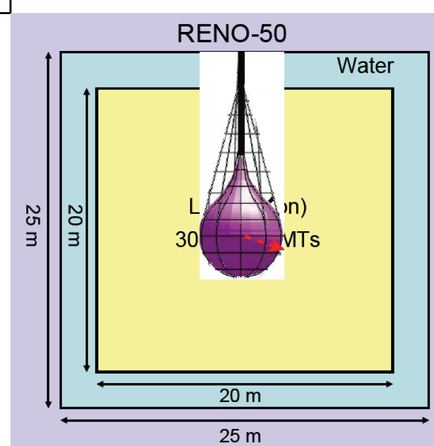
SNO+



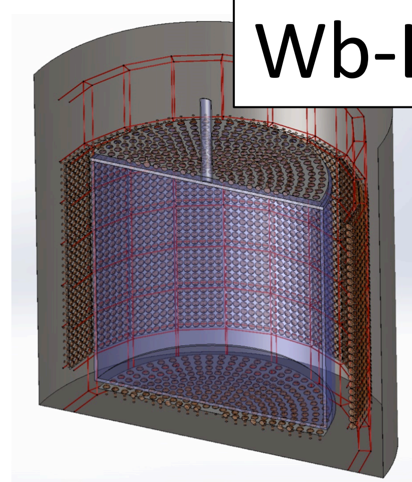
JUNO



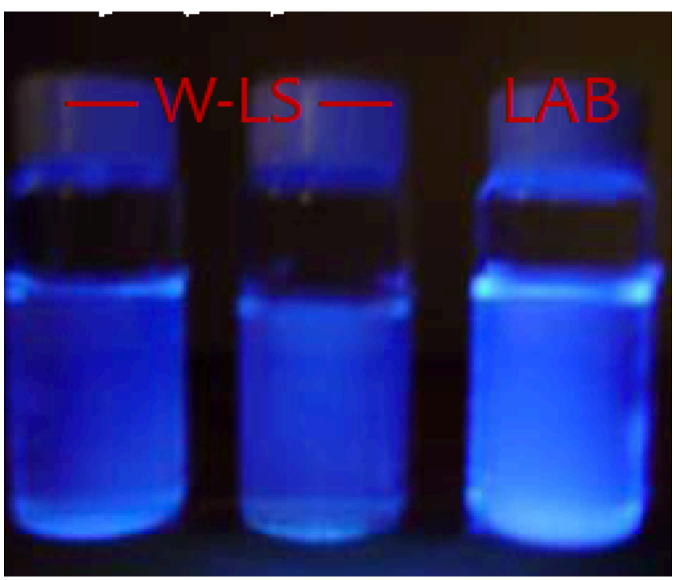
RENO-50



WATCHMAN
Wb-LS



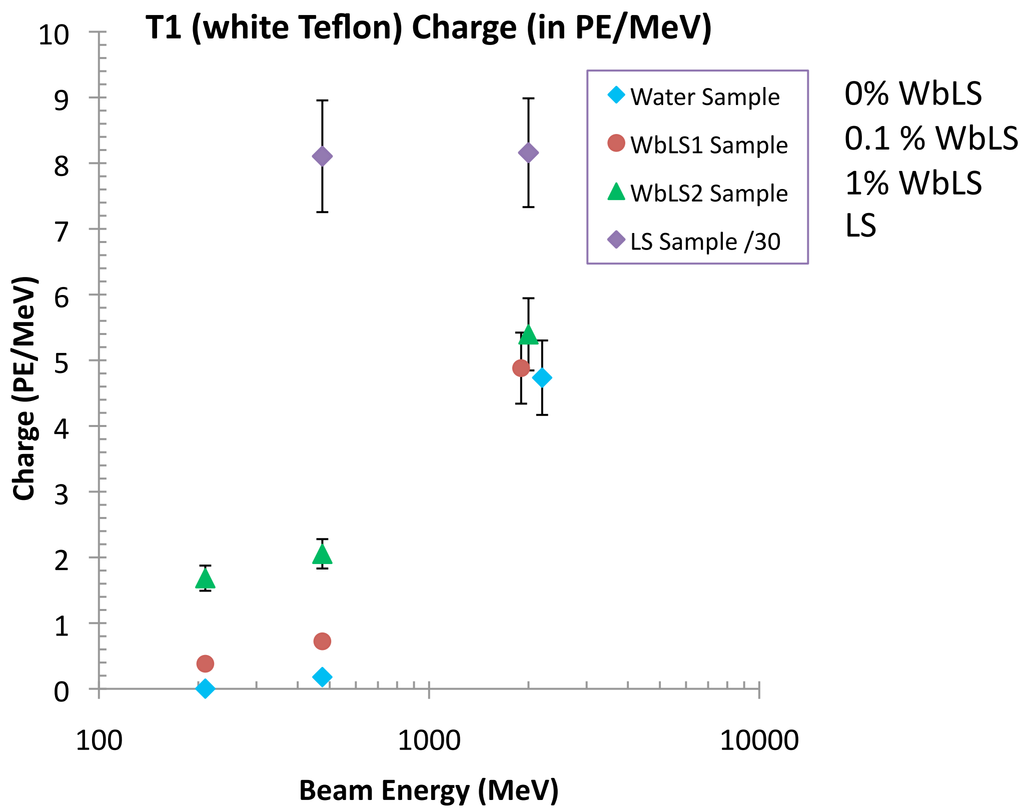
Water-based Liquid Scintillator (WbLS)



- Development of a stable, optically clear solution of LAB based LS and water at Brookhaven is ready for larger scale test
- WATCHMAN may do this after initial reactor measurement
- Impact on proton decay with kaons

Light-yield in PE/MeV

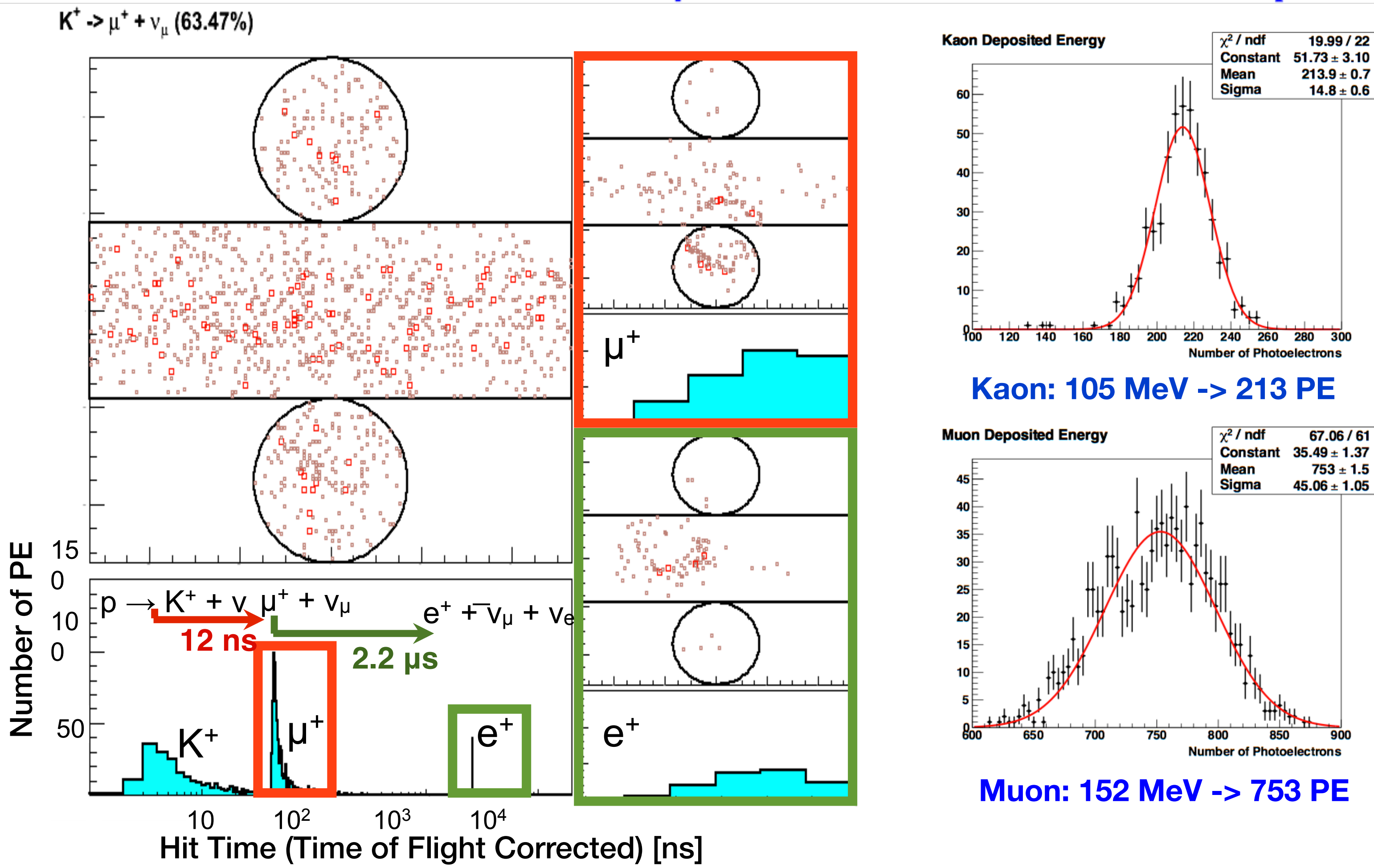
- *Čerenkov dominates at 2GeV while scintillation takes over at 475MeV and below*
- *Minimal Čerenkov contribution at 475MeV – can use the data at this energy for WbLS to LS comparison*
  - *Note that LS sample response is divided by 30 to fit on the same scale*



Even with 1% WbLS kaons from proton decay would be easily visible

WbLS can improve sensitivity to p->νK⁺ by factor of four!

A simulated event with 90 scintillation photons/MeV in a SK detector for $p \rightarrow k^{+}\overline{\nu}$



Kaon: 105 MeV -> 213 PE

Muon: 152 MeV -> 753 PE


Tanks!

Backup Slides

ANNIE Goal: Measure neutron yield as a function of Q^2 in the energy range of atmospheric neutrinos.

Rates Expected with $1x10^{20}$ POT exposure at SciBooNE pit

Djurcic

	Total Events [1/1ton/10^{20}POT]	ν-type	Total (per ν-type)	Charged Current	Neutral Current
Booster Beam (ν-mode, Target = CH_2)	10419	ν_μ	10210	7265	2945
		anti-ν_μ	133	88	45
		ν_e	72	52	20
		anti-ν_e	4.4	3	1.4
Booster Beam (ν-mode, Target = H_2O)	10612	ν_μ	10405	7443	2962
		anti-ν_μ	129	85	44
		ν_e	73	53	20
		anti-ν_e	4.6	3.0	1.6

Rate/ton/10^{20} POT at ANNIE

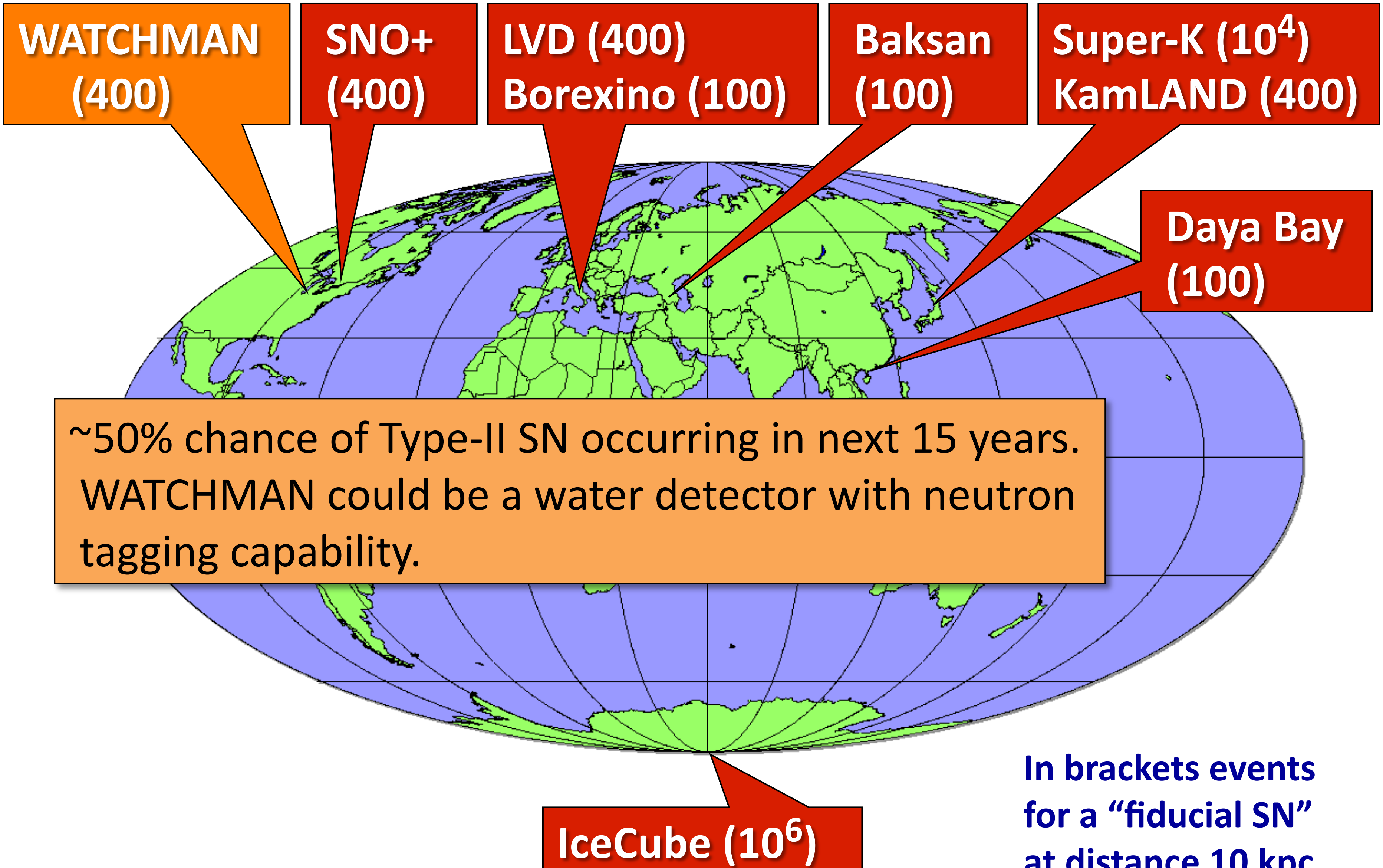
~ 50 events/day in the 4 ton target.

- Can neutron tagging be used to reject backgrounds for proton decay and detection of cosmological supernova neutrinos?

WATCHMAN Science

- ✓ Sensitivity to **Galactic Supernova**. Would have neutron tagging capability.
- ✓ Potential site for IsoDAR Sterile Neutrino search and Electroweak measurements
- ✓ Sensitive to direct, unambiguous detection of kaons from SUSY **Proton Decay** $p \rightarrow \nu K^+$. *(Needs WbLS fill)*

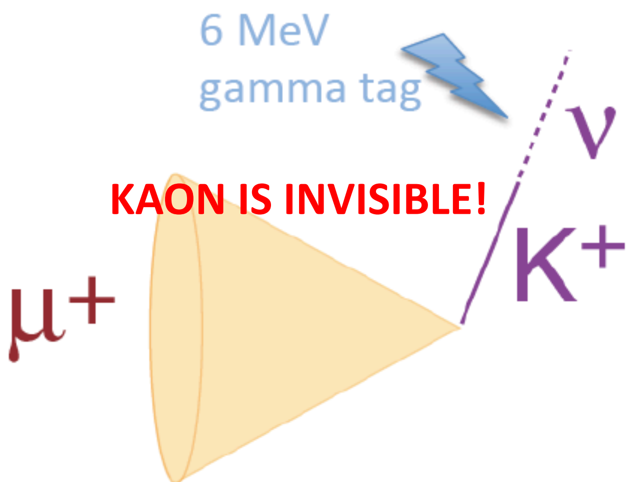
Underground Detectors for Supernova Neutrinos

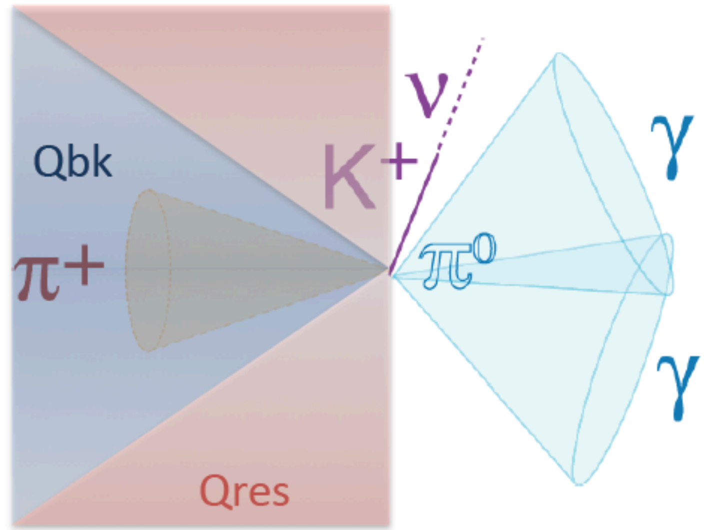


~50% chance of Type-II SN occurring in next 15 years. WATCHMAN could be a water detector with neutron tagging capability.

In brackets events for a "fiducial SN" at distance 10 kpc

νK^{+} in Water Cherenkov





E.Kearns, ISOUP 2013

Hyper-K PMT coverage

γ-tag and $\pi^{+}\pi^{0}$	SK1	(20% coverage) SK2	SK3	(new electronics) SK4
Efficiency	15.7 %	13.0 %	15.8 %	18.9 %
Background rate (/100 kty)	0.3	0.6	0.4	0.4

New efficiencies and background rates after analysis improvement
Super-K Preliminary 2013: No candidates, 260 kton yr (SK 1+2+3+4):

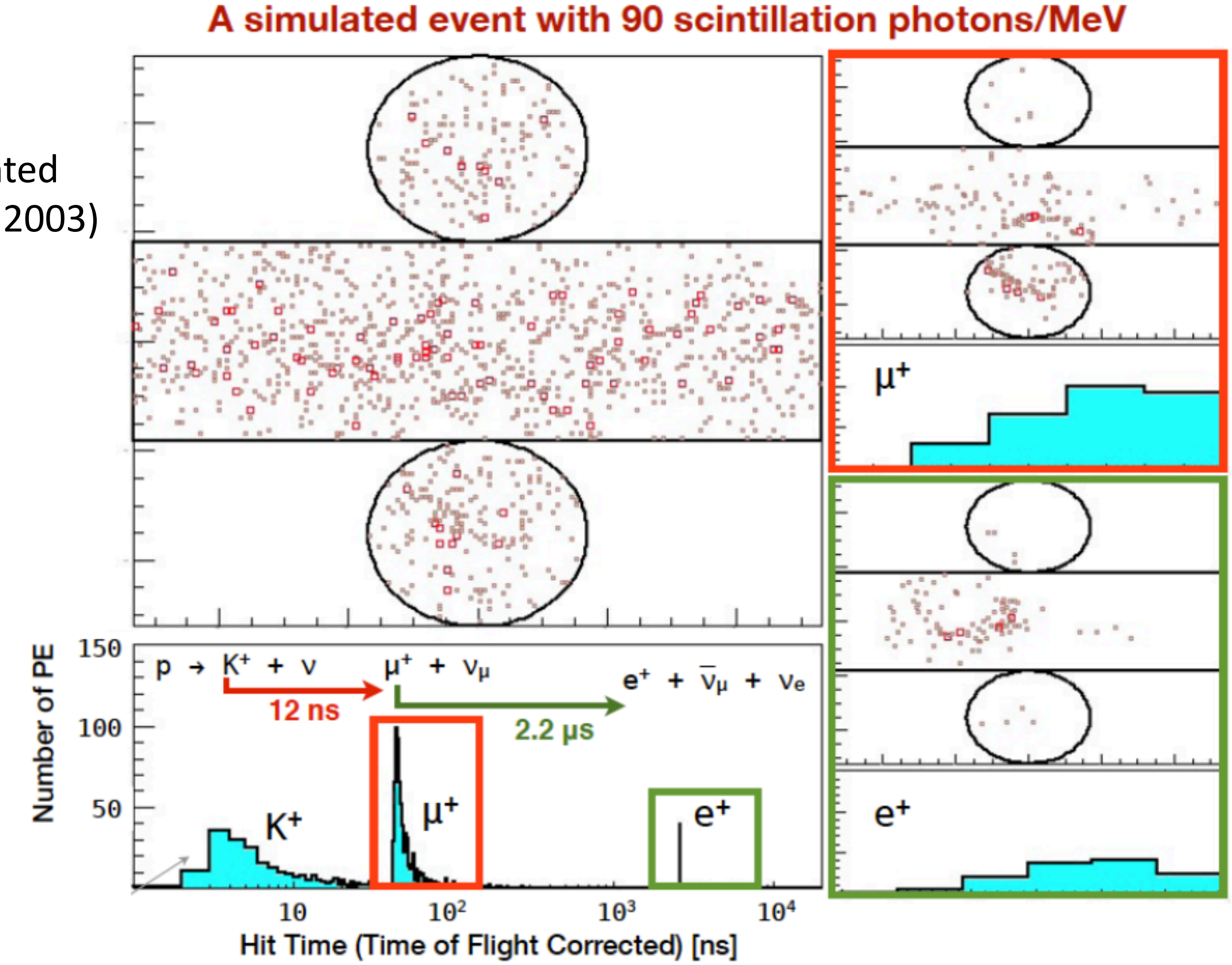
$$p \rightarrow \nu K^{+} \quad \tau/B > 5.9 \times 10^{33} \text{ years, } 90\%\text{CL}$$

A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay $p \to K^+\bar{\nu}$ and Other Physics

D. Beznosko[1], M.V. Diwan[1], S. Hans[2], K.M. Heeger[3], L. Hu[2], D.E. Jaffe[1], S.H. Kettell[1], J.R. Klein[4], L. Littenberg[1], K.B. Luk[5], R. Rosero[2], G.D. Orebi Gann[5,6], X. Qian[7], R. Svoboda[8], H. Themann[1], B. Viren[1], E. Worcester[1], M. Yeh[2], C. Zhang[1]

Technique first invented by R.Svoboda (TAUP 2003)

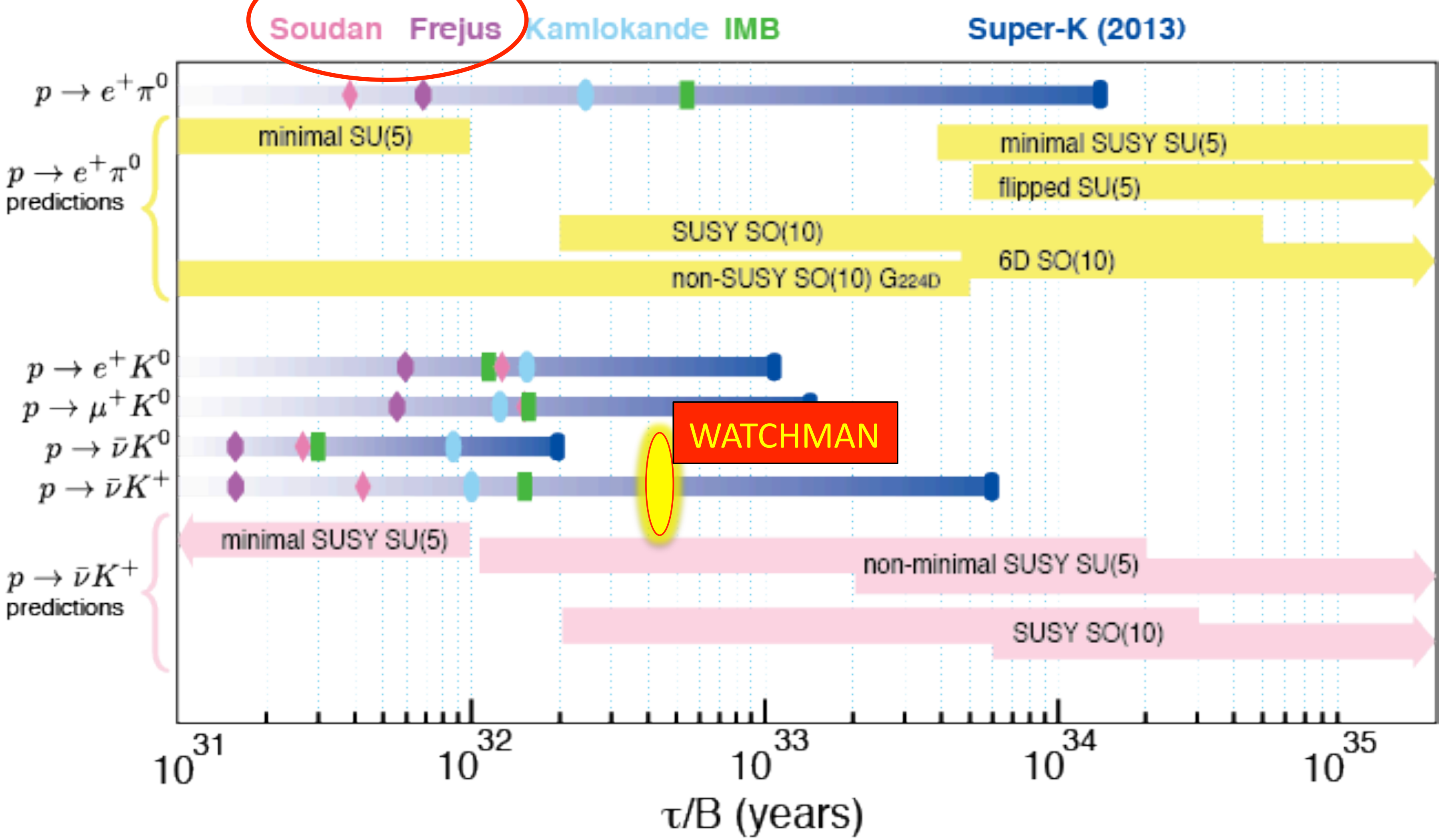
Only a small amount of WbLS is needed to see the 105 MeV K+



$p \rightarrow \nu K^+$ in WATCHMAN

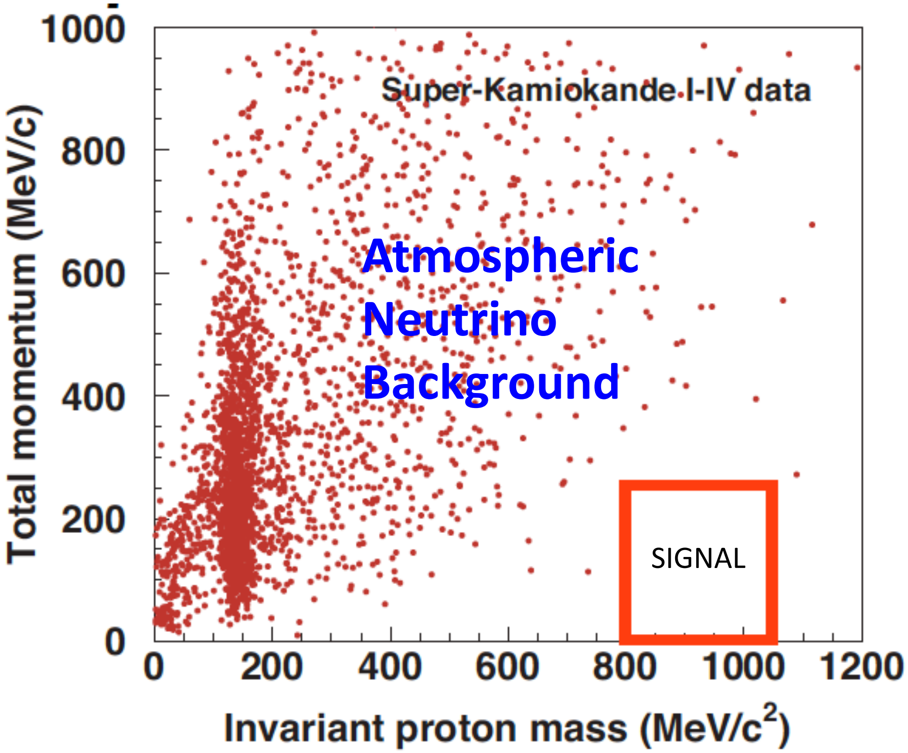
- This technique can be tried in the WbLS phase. If successful, it could be used in Super-Kamiokande – making it ~5 times more efficient for this SUSY mode, equivalent to that expected for LAR TPC's
- By itself, after five years in WbLS phase, WATCHMAN would achieve ~5×10^{32} years *using direct K+ detection*. Only Frejus and Soudan II had this capability.

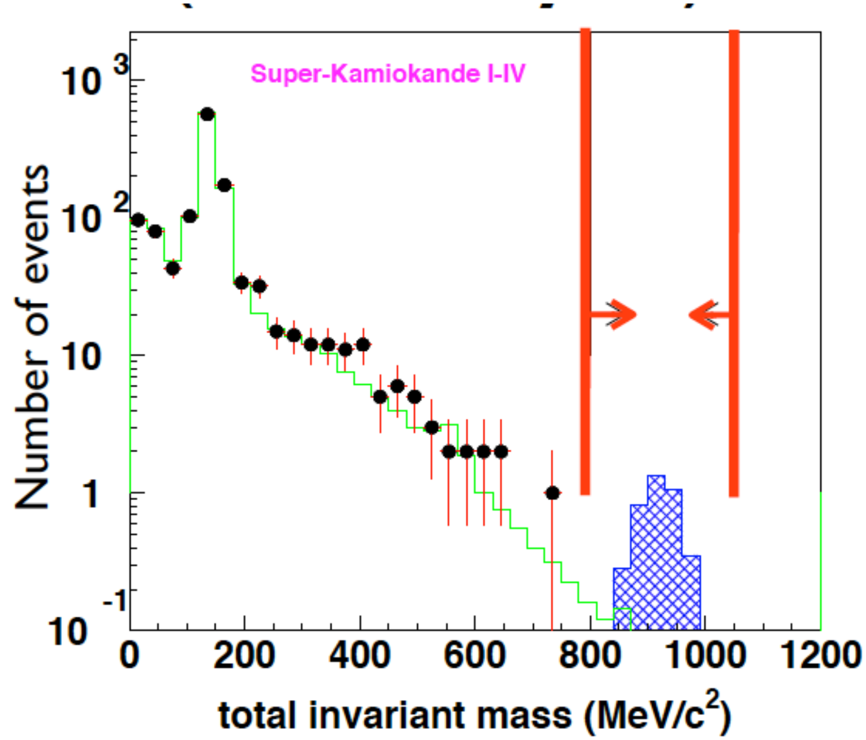
WATCHMAN competitive with other direct K+ detection experiments



P→ $e^+\pi^0$ in Water Cherenkov

0.260 Mton-years exposure (M.Shiozawa, TAUP2013)





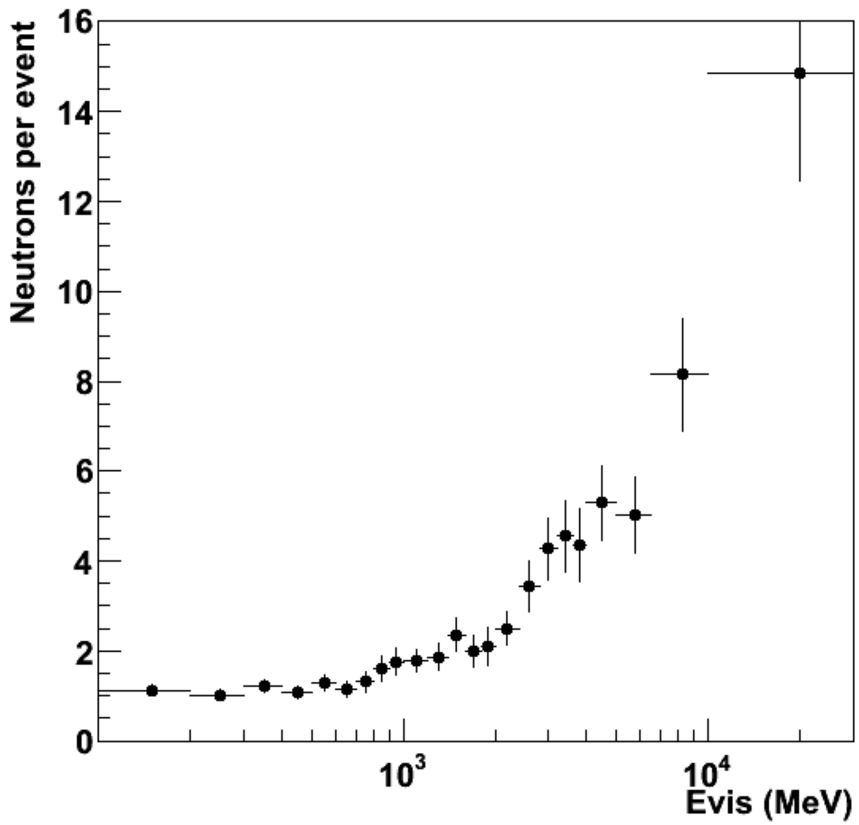
…but expected atmospheric neutrino background is **0.7** events
measurements done by the K2K experiment.

This mode will be background limited in future detectors.

Note: Proton Decay in water makes No Neutrons

- 2/10 of protons are free protons. No neutrons.
- 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
- 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons.
- **~80% of proton decays should give neutrons only indirectly from FSI.** Detailed calculation gives 81% (Eijiri, PRC 48, 1993)
- ATMOSPHERIC NEUTRINO EVENTS THAT MIMIC PROTON DECAY CAN BE REJECTED BY NEUTRON TAGGING

Atmospheric neutrinos do make neutrons!

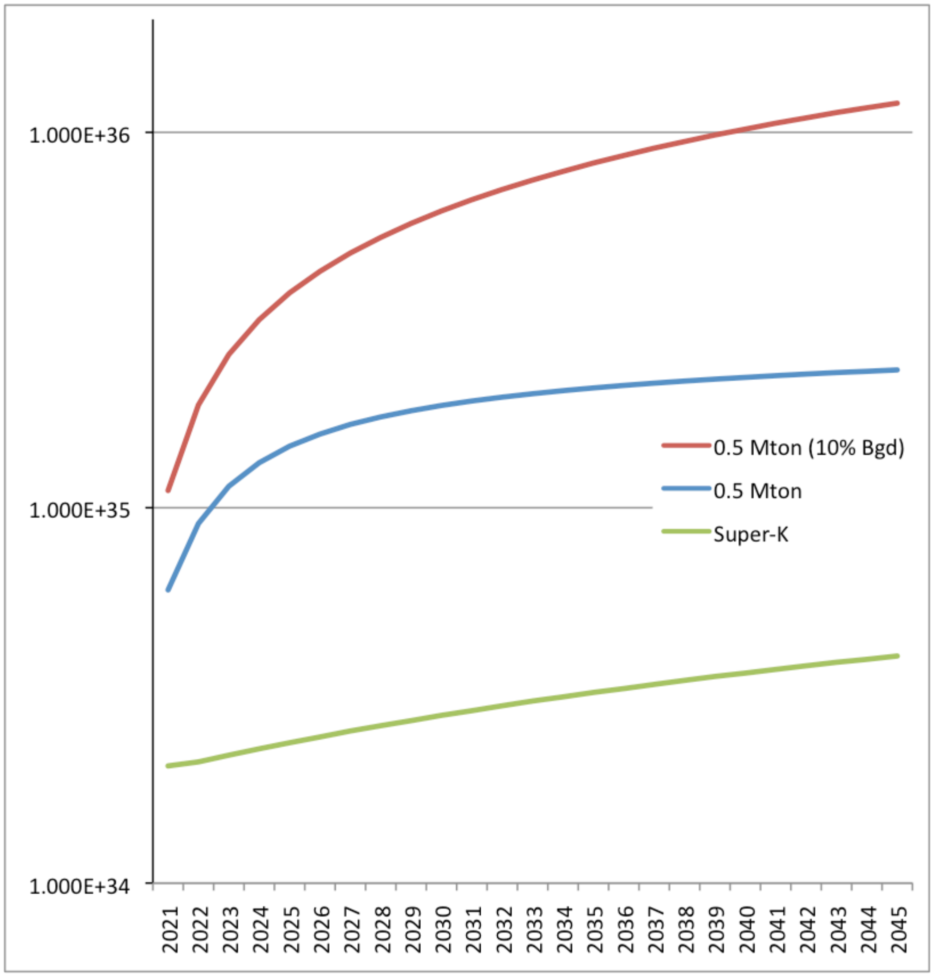


SK has ~20% efficiency for detecting neutron capture in pure water. NOT GOOD ENOUGH FOR PROTON DECAY SEARCH

How many atmospheric neutrino background events will have one or more neutrons, either from initial interaction, FSI in nucleus, or nuclear de-excitation?

- **WATCHMAN will have 80-100% capture efficiency and significant atmospheric neutrino rate (~100/year) and can be used to validate this background rejection method.**

Effects of Atmospheric Neutrino Background Rejection on $p \rightarrow e^+\pi^0$ sensitivity



year

0.5 Megaton with neutron tagging (rejects 90% of atmospheric neutrinos)

0.5 Megaton with background

Super-K with background