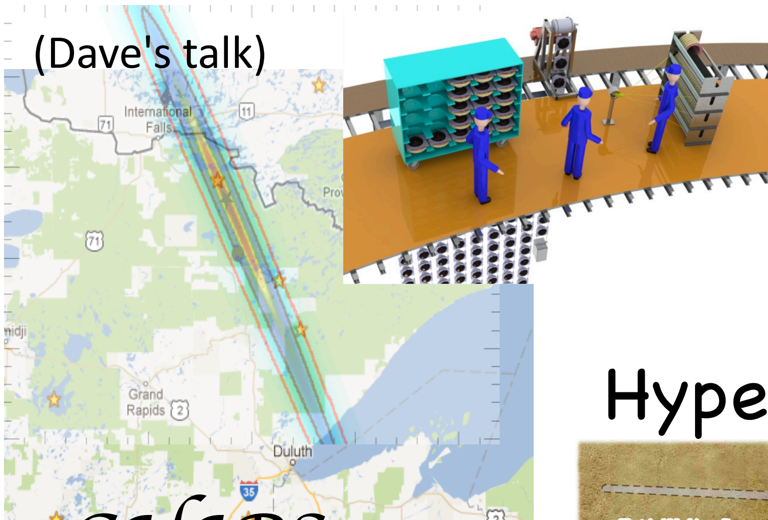
Future Water Cherenkov Detectors in the U.S.

R.Svoboda, P5 Meeting, 3 November, 2013

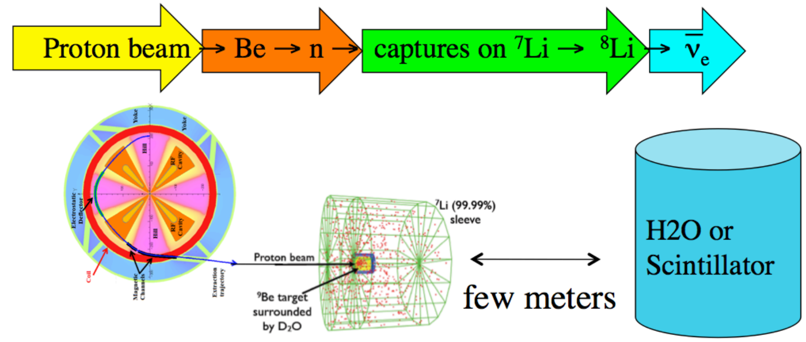
- IMB, Kamiokande, Super-K, and SNO have had a **<u>huge</u>** impact on neutrino physics. WC detectors are Big. Only way to the Megaton Scale.
- Highly versatile: low background, low energy threshold, very fast – everything from reactor neutrinos to accelerator and UHE neutrinos.
- New developments: neutron tagging, water-based liquid scintillator, ultra-high quantum efficiency PMT's, large area MCP's (LAPPD).
- **Many proposed new experiments**.

(Dave's talk)



CHIPS

LOI FNAL PAC

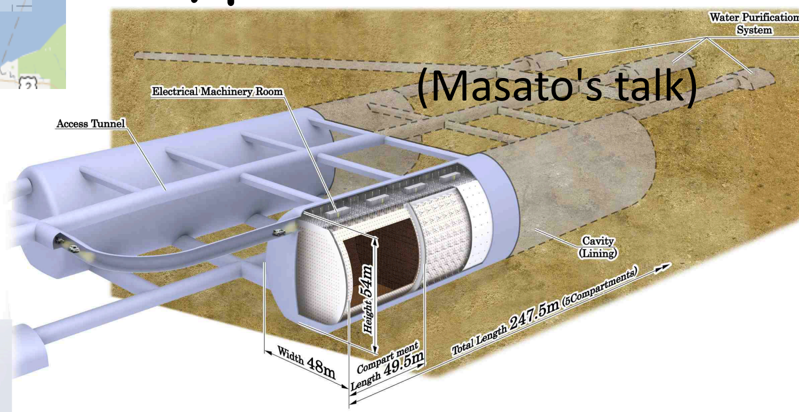


ISODAR
@ WATCHMAN

(Mike's talk)

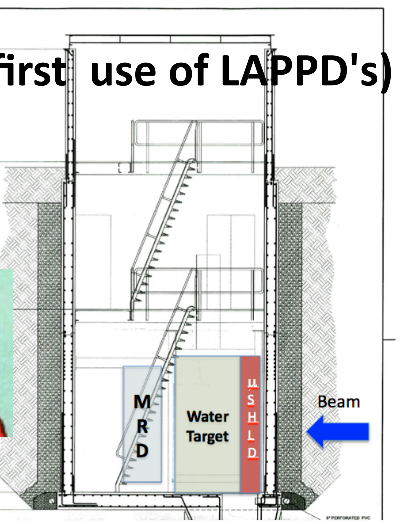
Hyper-Kamiokande

(Masato's talk)

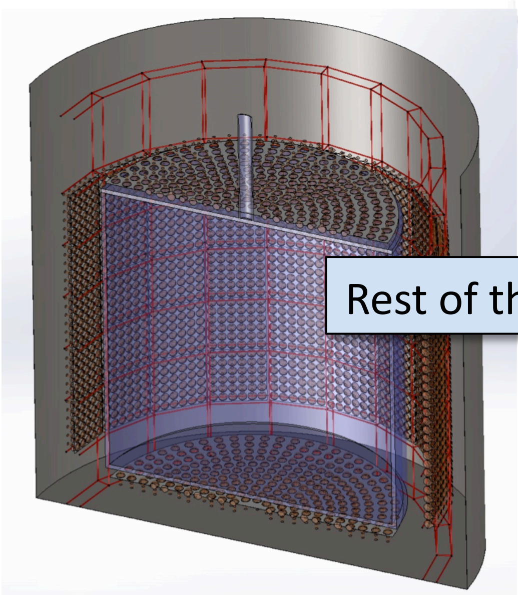


ANNIE

(first use of LAPPD's)

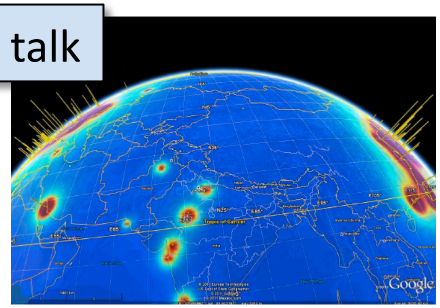


LOI FNAL PAC
in preparation



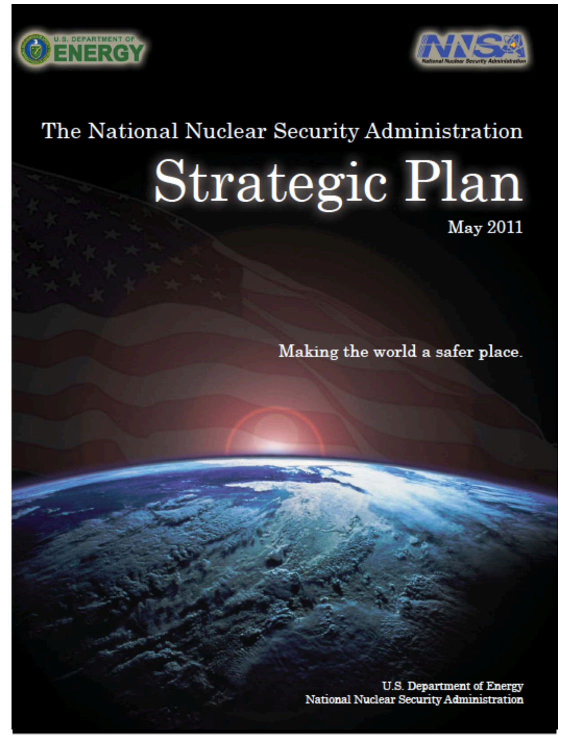
Rest of this talk

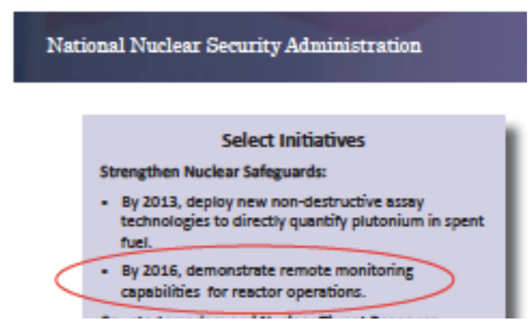
WATCHMAN



WATCHMAN project goal: for the first time, demonstrate sensitivity to a reactor signal with Gd-doped water

- A remote reactor monitoring demonstration is in the NNSA Strategic Plan
- 50 M$ Total Project Cost – mostly paid by NNSA, but seeking OHEP **technical expertise** and **partial financial support for PMT system.** About $10-20M.
- 4 or 5 year duration
- Preferred site identified (IMB/Morton Salt, Ohio) and **approvals obtained from mine operators.**
- FY14 decision point for full detector
- FY16 start of construction
- FY19 project completed
- Dual-use technology: WATCHMAN can help the US High Energy Physics Community do neutrino physics economically, while supporting international security




National Nuclear Security Administration

Select Initiatives

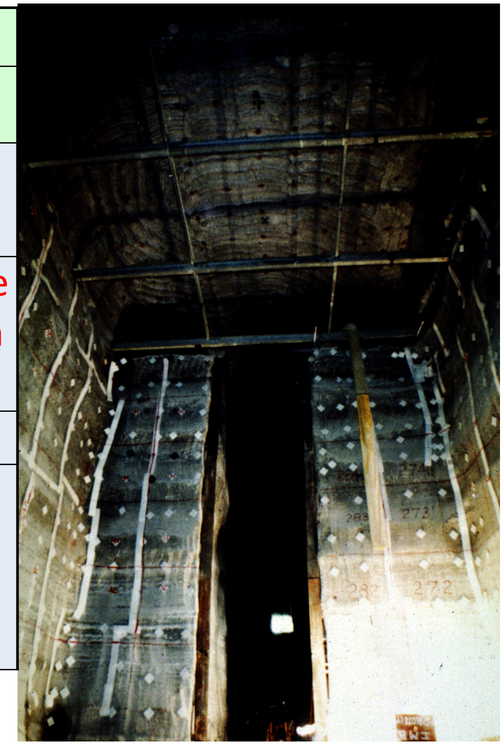
Strengthen Nuclear Safeguards:

- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

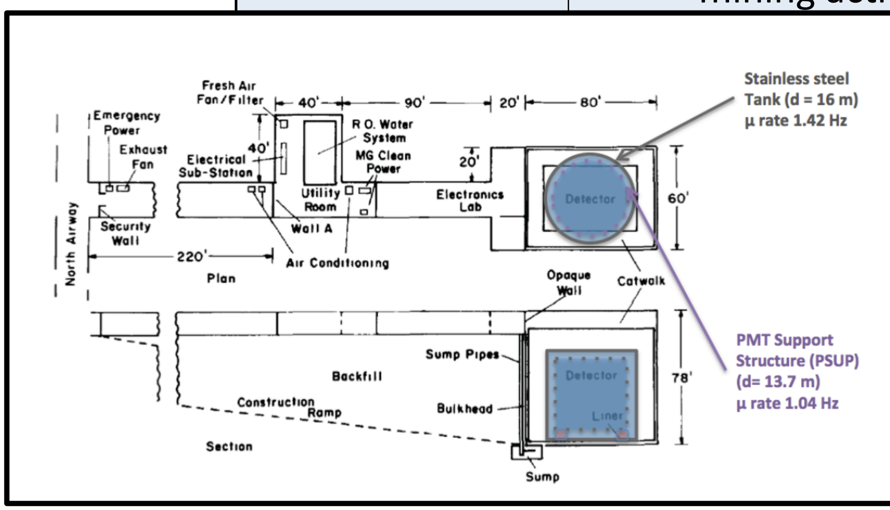
A.Bernstein, LLNL

Existing IMB 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

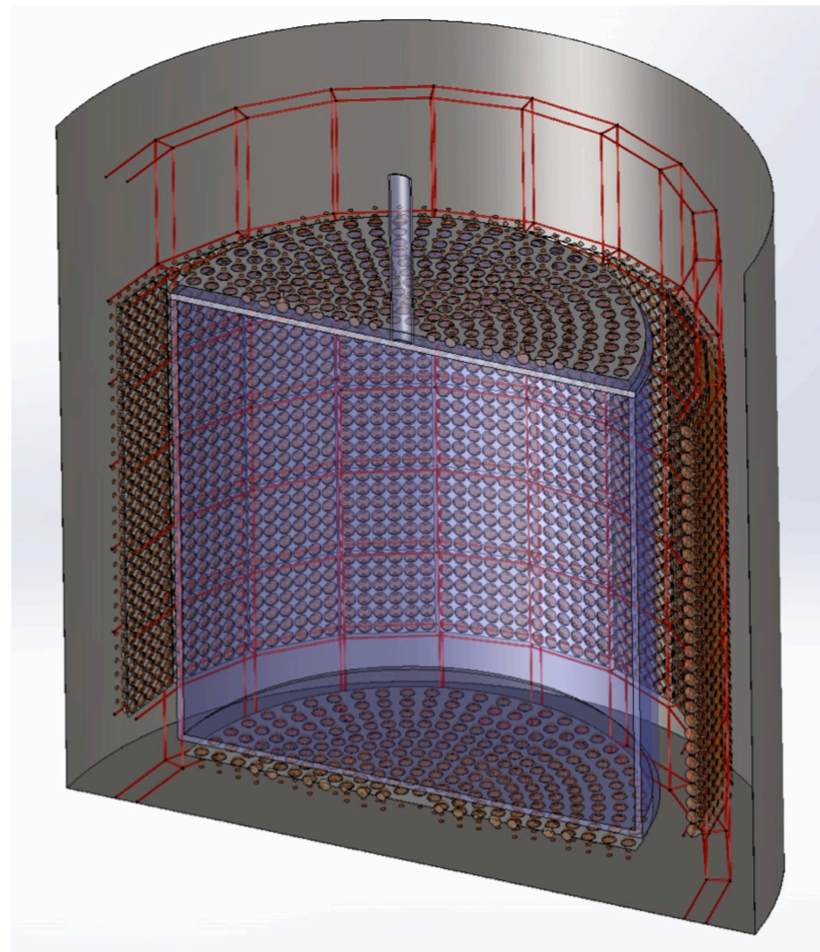


The IMB cavern in late 1970's. Used by DOE HEP from 1960-1990 for the IMB detector and other smaller experiments



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 SK
- Active Veto
- Compatible with pure water, water+Gd, or WbLS fill
- pure LS fill would require acrylic vessel



Physics in three possible stages

			NNSA-led	NNSA/OHEP/NSF	OHEP/NSF-led
2014 2016 2018 2020	**Non-accelerator Physics – 2016-2020**	**Natural source**	Pure Gd-H2O WATCHMAN-H_2O	Gd-H2O + 1% scintillator WATCHMAN-WBLS	Pure scintillator WATCHMAN -LS
			Supernova	**Supernova**	**Supernova**
			Proton Decay	**Proton Decay**	**Proton Decay**
		Reactor	**Neutrino Mass Hierarchy**	**Neutrino Mass Hierarchy**	**Neutrino Mass Hierarchy**
2022 2024	**Accelerator-based physics 2019-2024**	**ISODAR beam**	**Sterile Neutrinos**	**Sterile Neutrinos**	**Sterile Neutrinos**
			Non-Standard Interactions	**Non-Standard Interactions**	**Non-Standard Interactions**

Further information in backup slides

WATCHMAN R&D Opportunities for HEP

- Obtain large WC/LS facility in the U.S. for use in mid-scale physics experiments. Existing cavern with extant infrastructure makes this very inexpensive. NNSA would cover infrastructure (power, water, tanks, engineering). OHEP share only instrumentation costs.
- Leverage NNSA-led WATCHMAN development for R&D relevant to specific future experiments, like Hyper-Kamiokande, IsoDAR, CHIPS.
- Generic detector R&D with shared costs: "Texas" PMT's, Water-based Liquid Scintillator, Gadolinium loading

Backup Slides

- WATCHMAN physics
- CHIPS
- ANNIE and LAPPD
- Texas PMT's
- Water-based Liquid Scintillator

The WATCHMAN Collaboration

Lawrence Livermore National Laboratory

Sandia National Laboratories

UC Berkeley

UC Davis

U of Hawaii

Hawaii Pacific

UC Irvine

Virginia Tech

<u>A. Bernstein</u>, N. Bowden, S. Dazeley, D. Dobie

<u>P. Marleau</u>, M. Gerling, K. Hulin, J. Steele, D. Reyna, J. Brennan

<u>K. Van Bibber</u>, C. Roecker, T. Shokair

<u>R. Svoboda</u>, M. Bergevin, M. Askins

<u>J. Learned</u>, J.Murillo
<u>S. Dye</u>

<u>M. Vagins</u>, M. Smy, Bill Kropp

<u>B. Vogelaar</u>, S.D. Rountree, C. Mariani

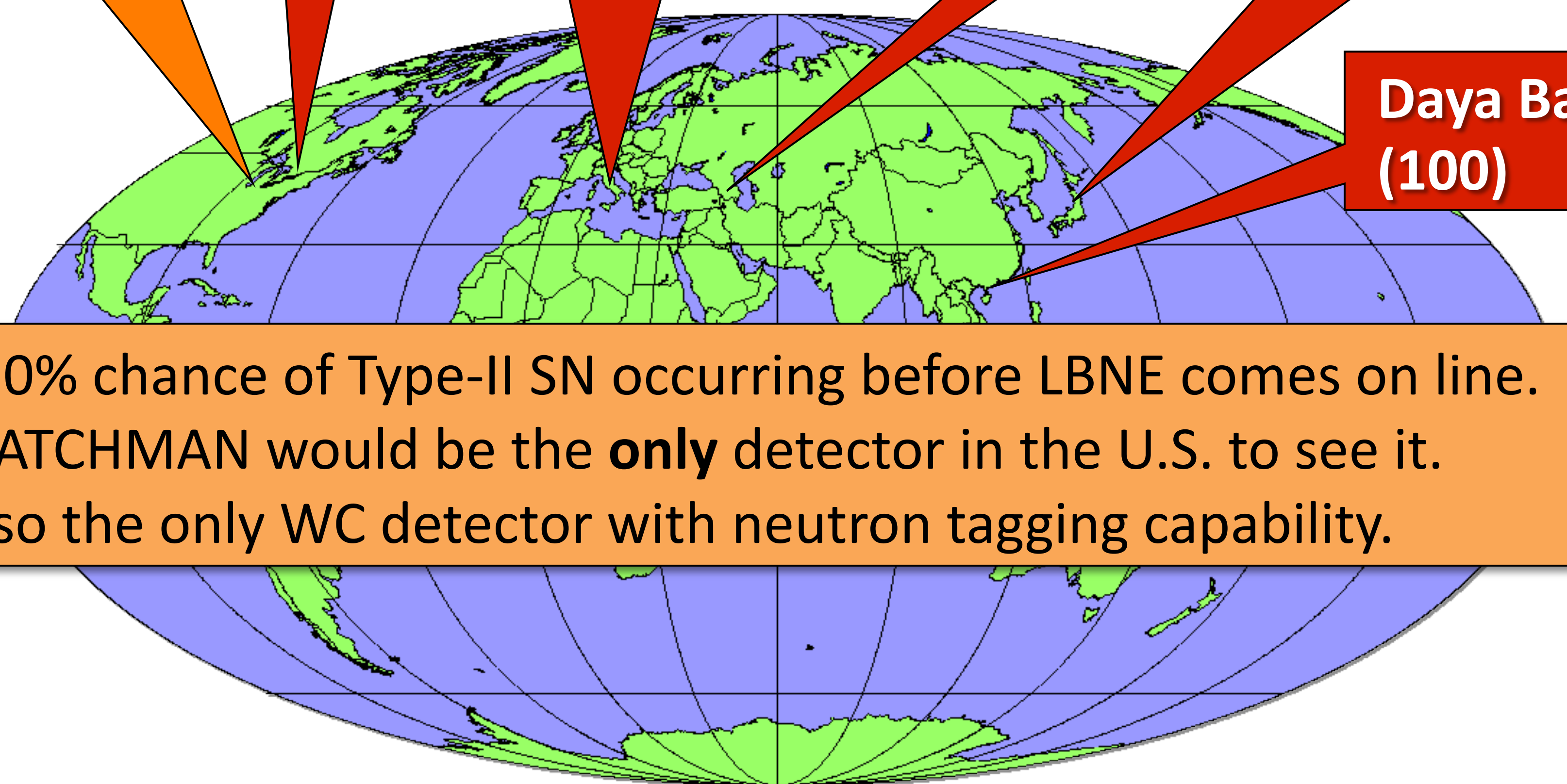
2 National Laboratories
6 Universities
25 collaborators
15 physicists
5 engineers
2 Post-docs
3 Ph.Ds

Many person-decades of experience in water detector design/construction/operation/physics

WATCHMAN Science

- ✓ Sensitivity to **Galactic Supernova**. The only such detector in the U.S. with any significant sensitivity. Only WC detector in world with flavor identification.
- ✓ Sensitive to direct, unambiguous detection of kaons from SUSY **Proton Decay** $p \rightarrow \nu K^+$. SK is indirect, Soudan II was iron nucleus with no timing. *(Needs WbLS fill)*
- ✓ Potential site for **IsoDAR Sterile Neutrino** search and **Electroweak measurements**. (see Mike's talk)
- ✓ Reactor measurement of **Mass Hierarchy**? (*Still under study, would need LS fill)*
- ✓ **Geoneutrinos** First such measurement in the US

Underground Detectors for Supernova Neutrinos



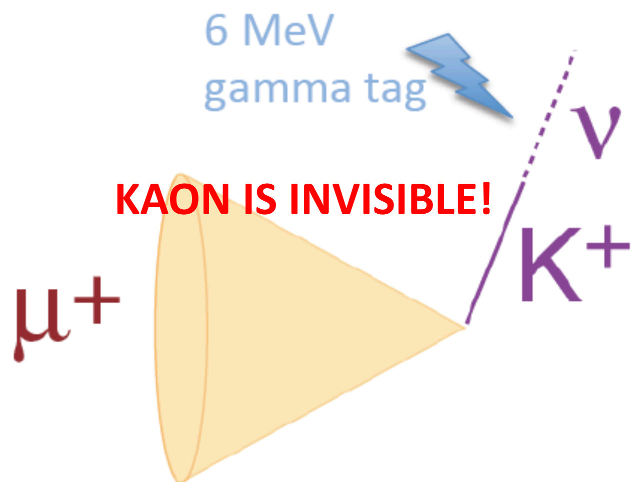
~50% chance of Type-II SN occurring before LBNE comes on line.
WATCHMAN would be the **only** detector in the U.S. to see it.
Also the only WC detector with neutron tagging capability.

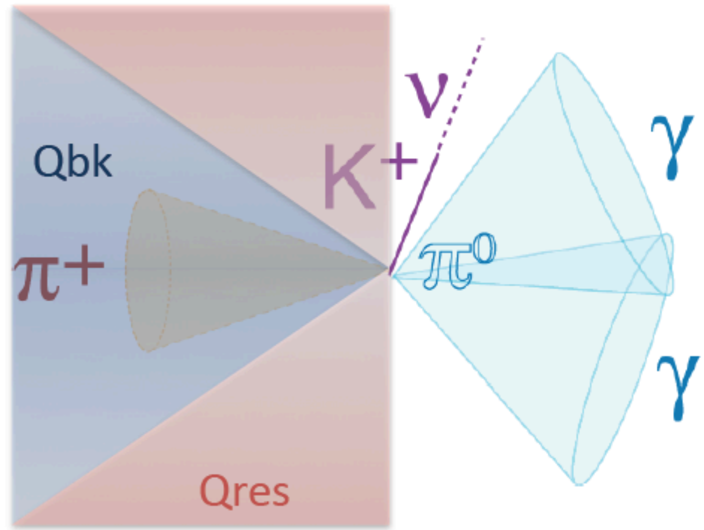
In brackets events for a "fiducial SN" at distance 10 kpc

The **Stability of the Proton** *continues* to be one of the biggest questions in Particle Physics

- Tests a fundamental, but unexplained conservation law
- Hallmark of Grand Unified Theories
- Extension of the idea of running coupling constants
- Broad connection with theory at many levels: strings, extra dimensions, etc.
- Explores a region forever inaccessible to accelerators
- If SUSY is not found at LHC, may be only way to search for it for foreseeable future
- **What are limiting factors? What could WATCHMAN do?**

νK^+ in Water Cherenkov





Hyper-K PMT coverage

E.Kearns, ISOUP 2013

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):

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

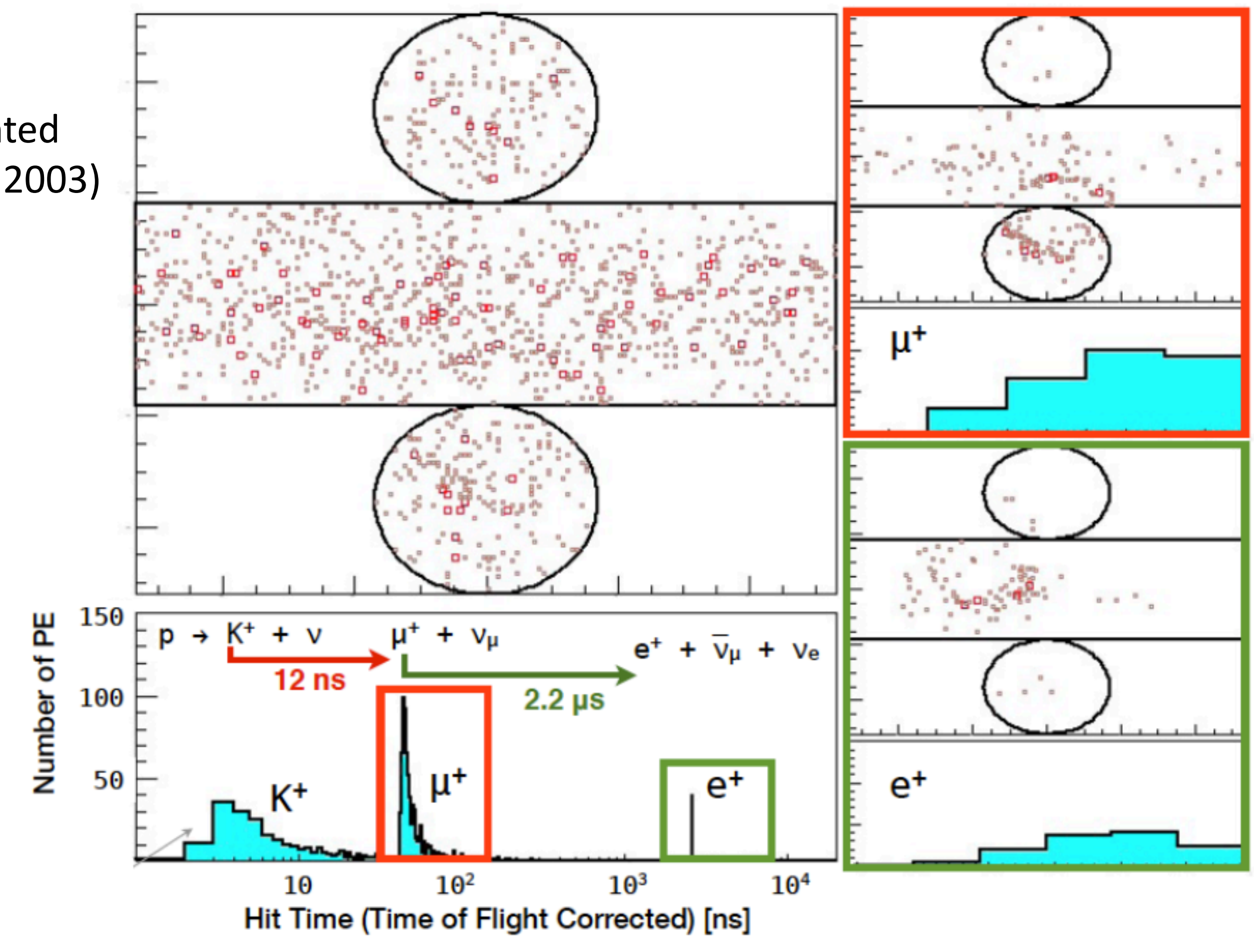
A Large Water-Based Liquid Scintillation Detector in Search for Proton Decay $p \to K^+\bar{\nu}$ and Other Physics

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+

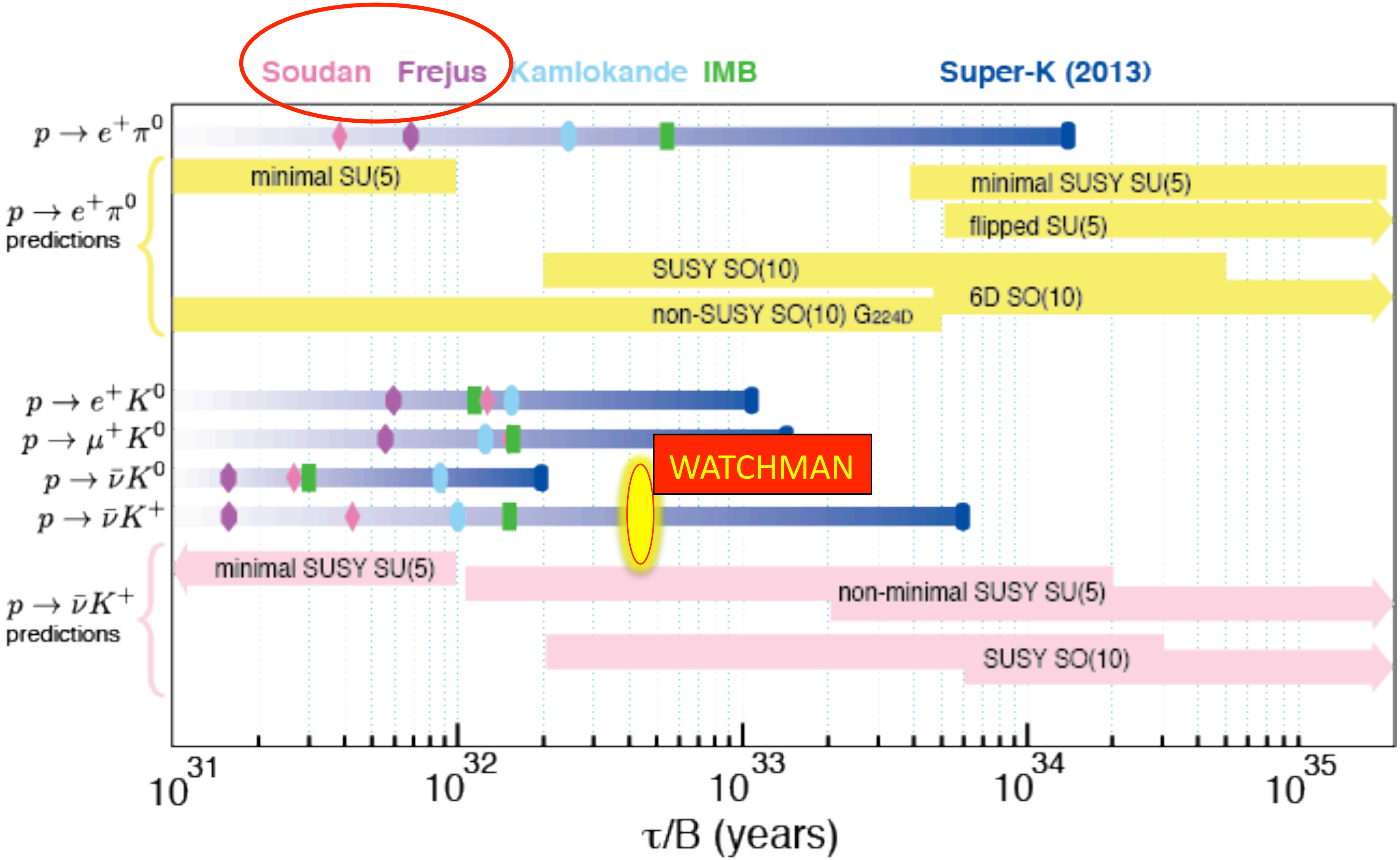
A simulated event with 90 scintillation photons/MeV



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

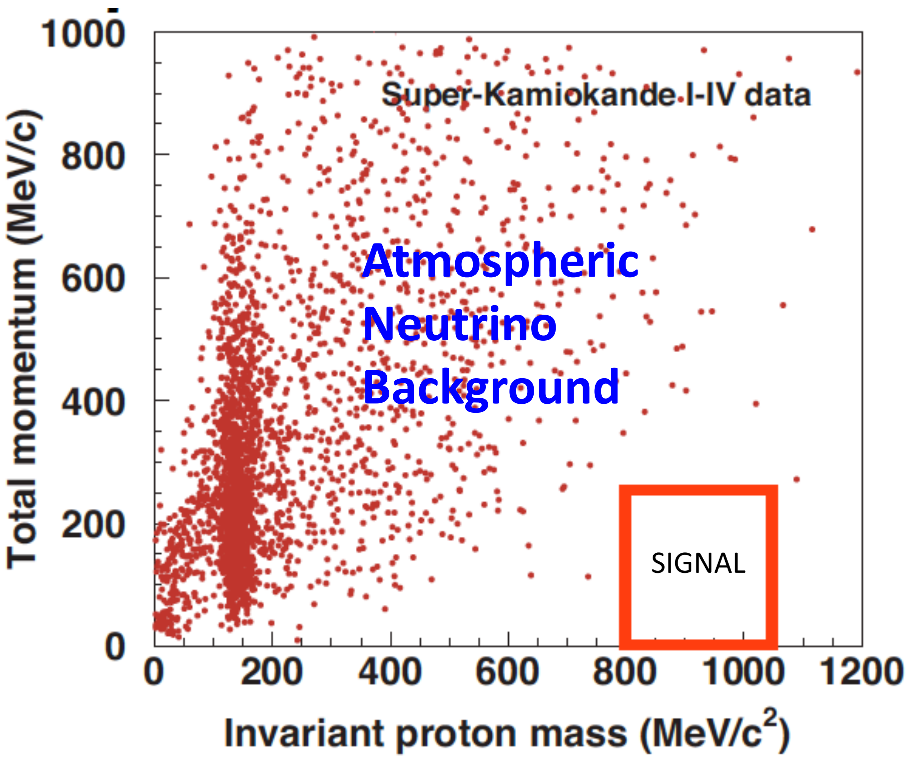
- This technique can be tried in the WbLS phase. If successful, it could be used in Super-Kamiokande – making it ~5 times more efficient for this SUSY mode, equivalent to that expected for LAR TPC's
- By itself, after five years in WbLS phase, WATCHMAN would achieve ~5×10^{32} years *using direct K+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

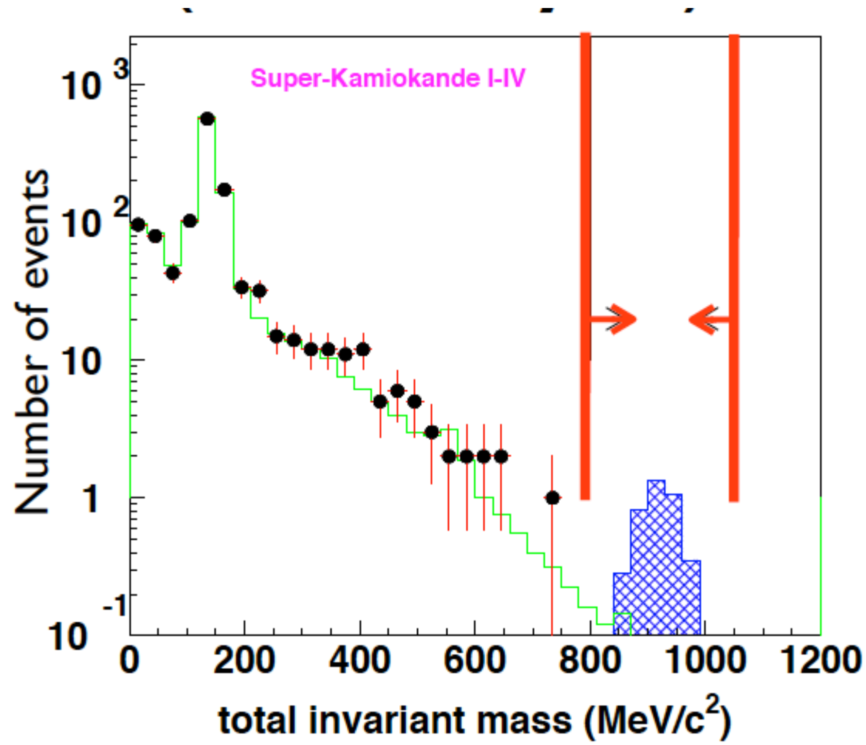
WATCHMAN competitive with other direct K+ detection experiments



$P \rightarrow e^+\pi^0$ in Water Cherenkov

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





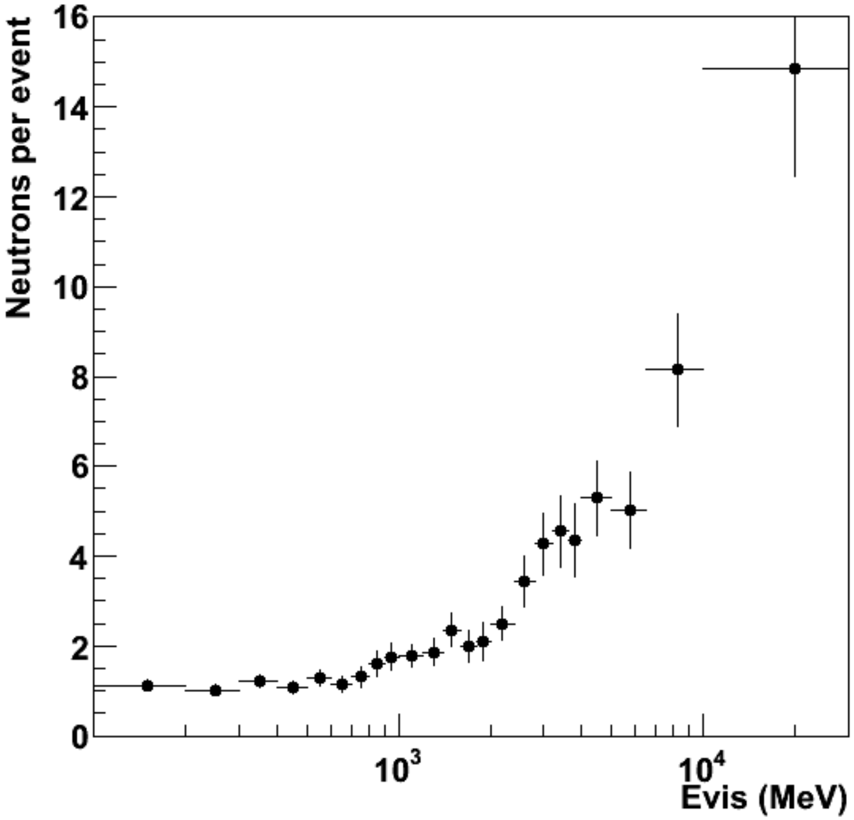
…but expected atmospheric neutrino background is **0.7** events measurements done by the K2K experiment.

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!

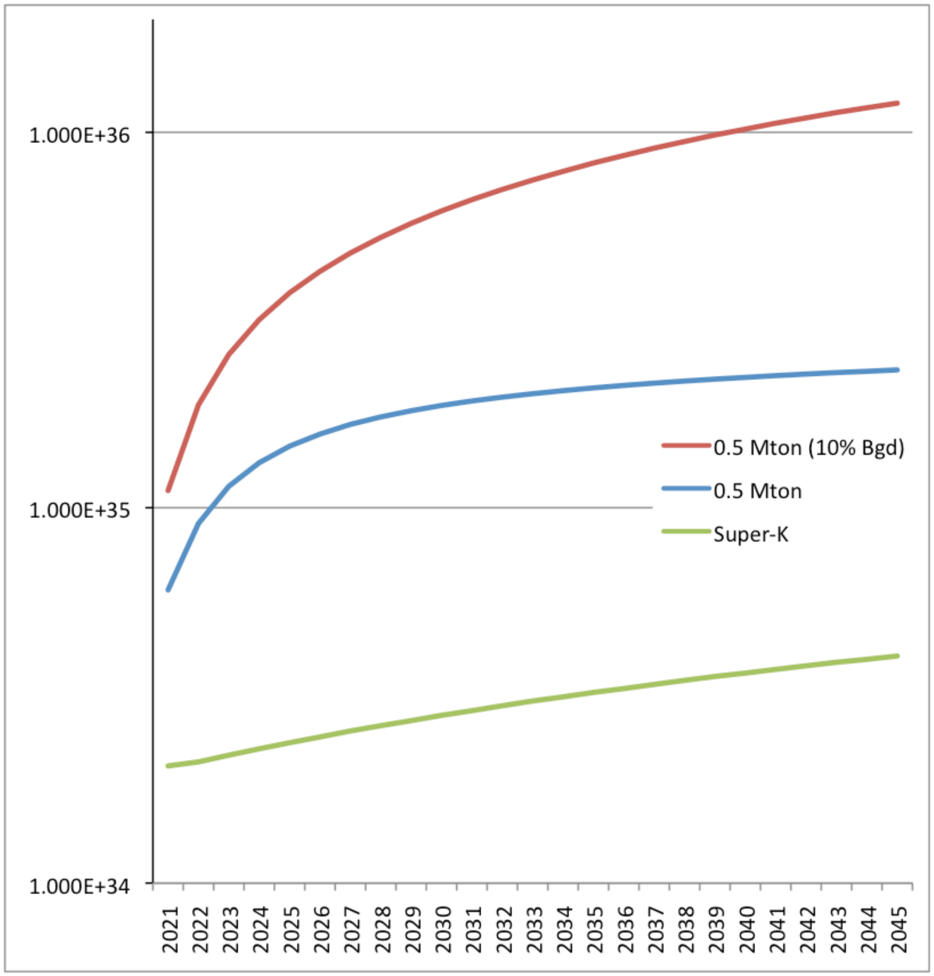


SK has ~20% efficiency for detecting neutron capture in pure water. NOT GOOD ENOUGH FOR PROTON DECAY SEARCH

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

Mass Hierarchy with Reactors

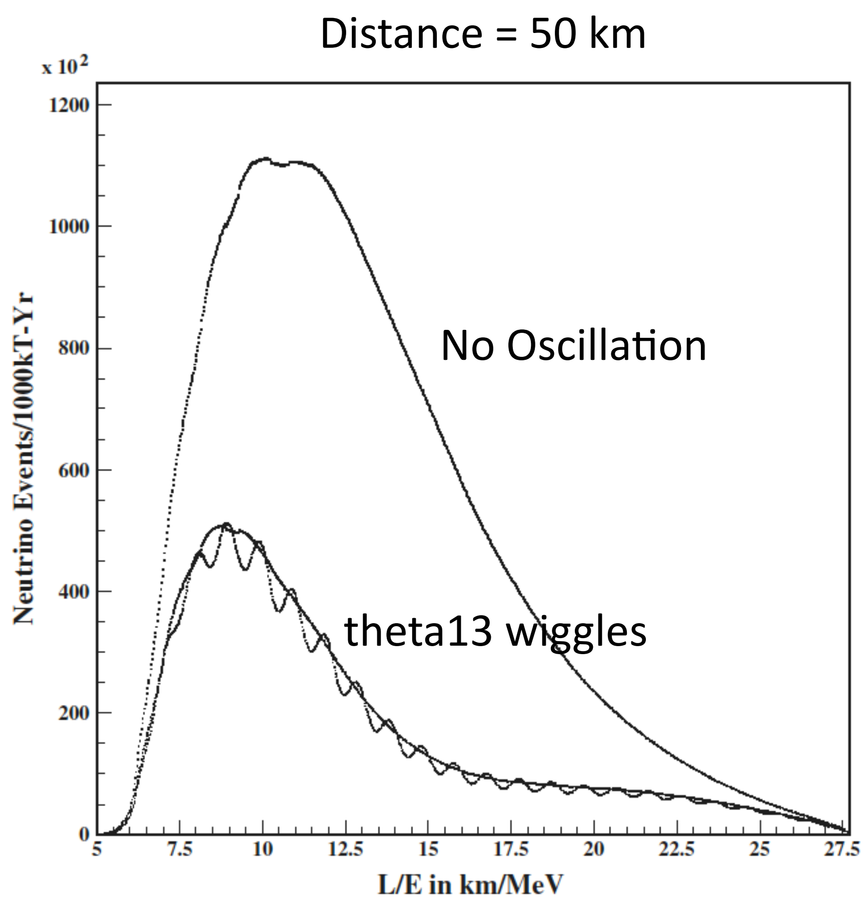


FIG. 1. Event rate versus L/E in units of km/MeV for: no oscillations (top curve), oscillations with $\theta_{13} = 0$ (lower smooth curve), and oscillations with $\sin^2(2\theta_{13}) = 0.1$.

(Learned, Dye, Pakvasa, Svoboda)

PHYSICAL REVIEW D **78,** 071302(R) (2008)

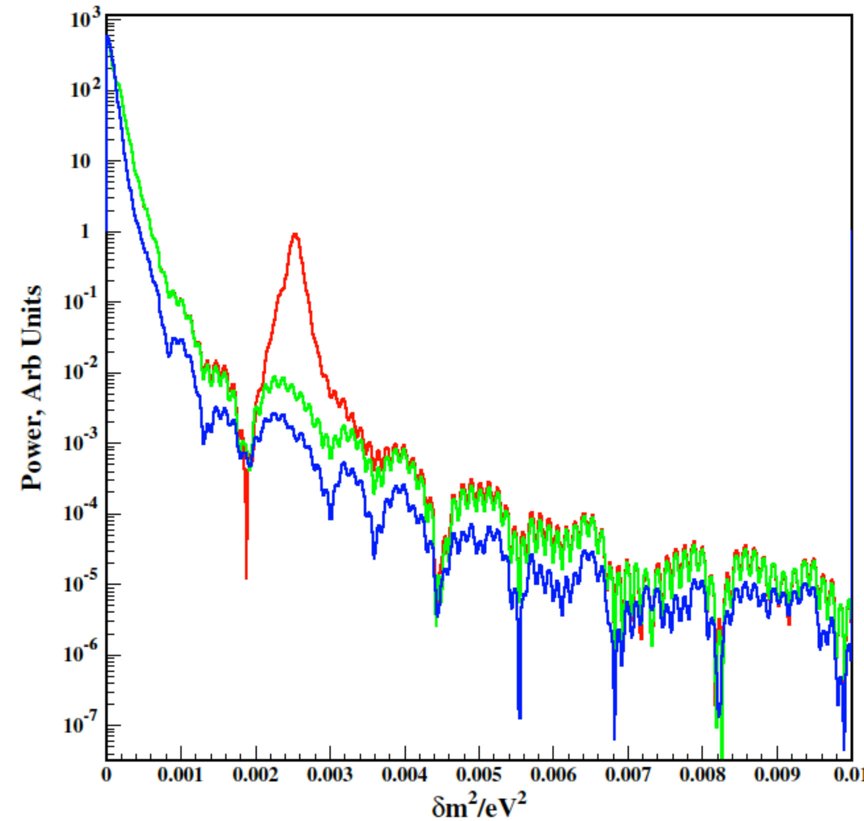


FIG. 2 (color online). Fourier power spectrum with modulation in units of eV^2 and power in arbitrary units on the logarithmic scale. The peak due to Δ_{31} with $\sin^2(2\theta_{13}) = 0.1$ is prominent.

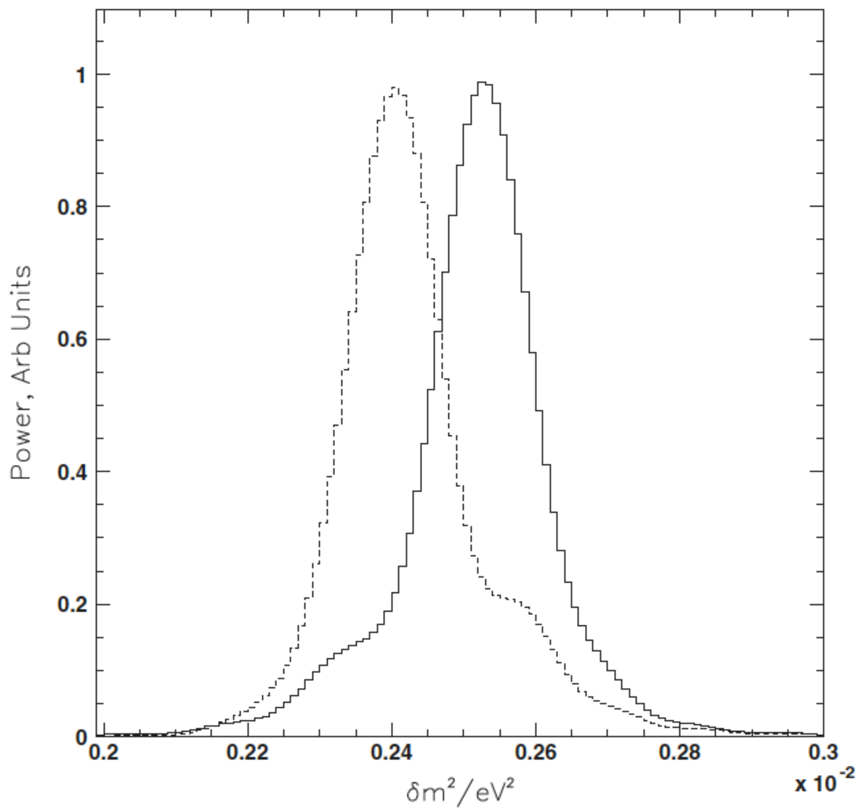


FIG. 3. Neutrino mass hierarchy (normal = solid; inverted = dashed) is determined by the position of the small shoulder on the main peak.

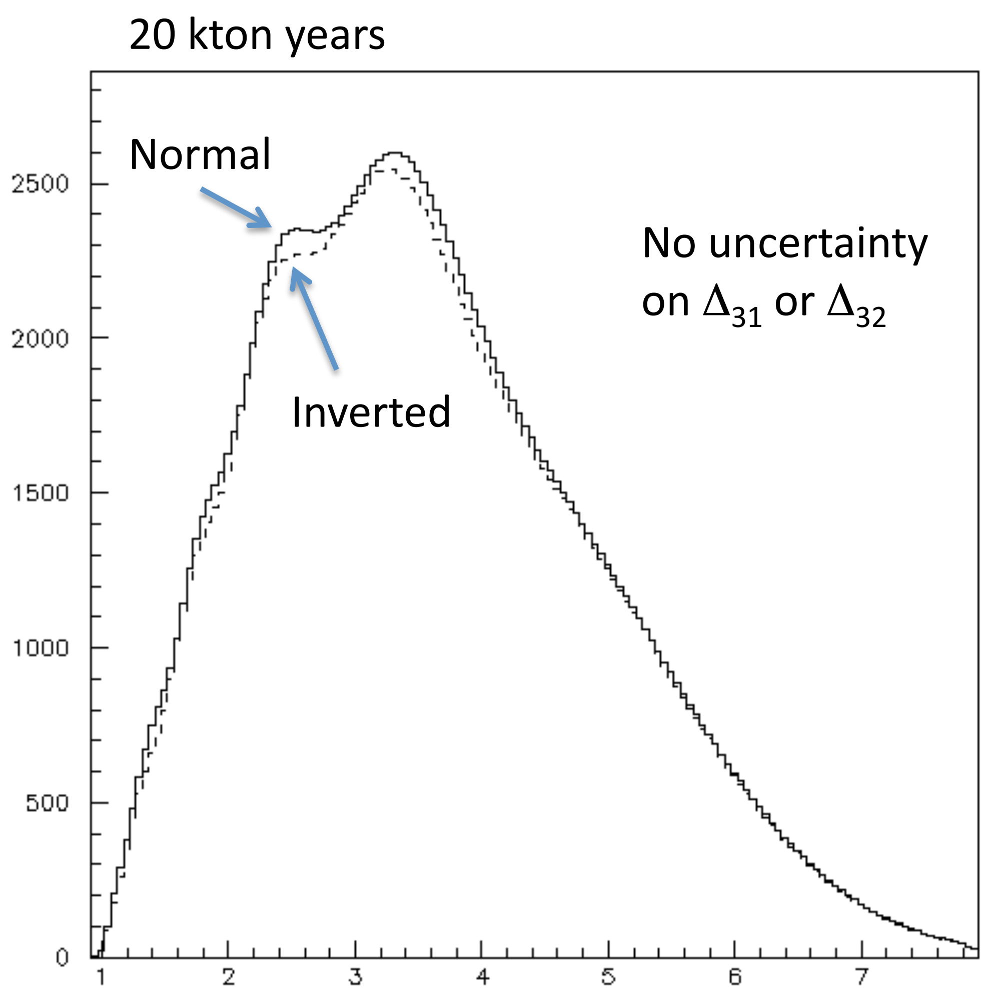
$$P_{ee} = 1 - \{\cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) + \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) + \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})\},$$

Since $\sin^2\theta_{12}$ = 0.306 and $\cos^2\theta_{12}$=0.694 the two peaks for Δ_{31} and Δ_{32} differ In amplitude in the Fourier transform.

Using a type of maximum likelihood analysis, the hierarchy manifests Itself as the relative ordering of the large and small peaks.

Could this be done at the WATCHMAN site? Maybe, with LS upgrade

WATCHMAN Mass Hierarchy Sensitivity



Compared to 50 km experiment

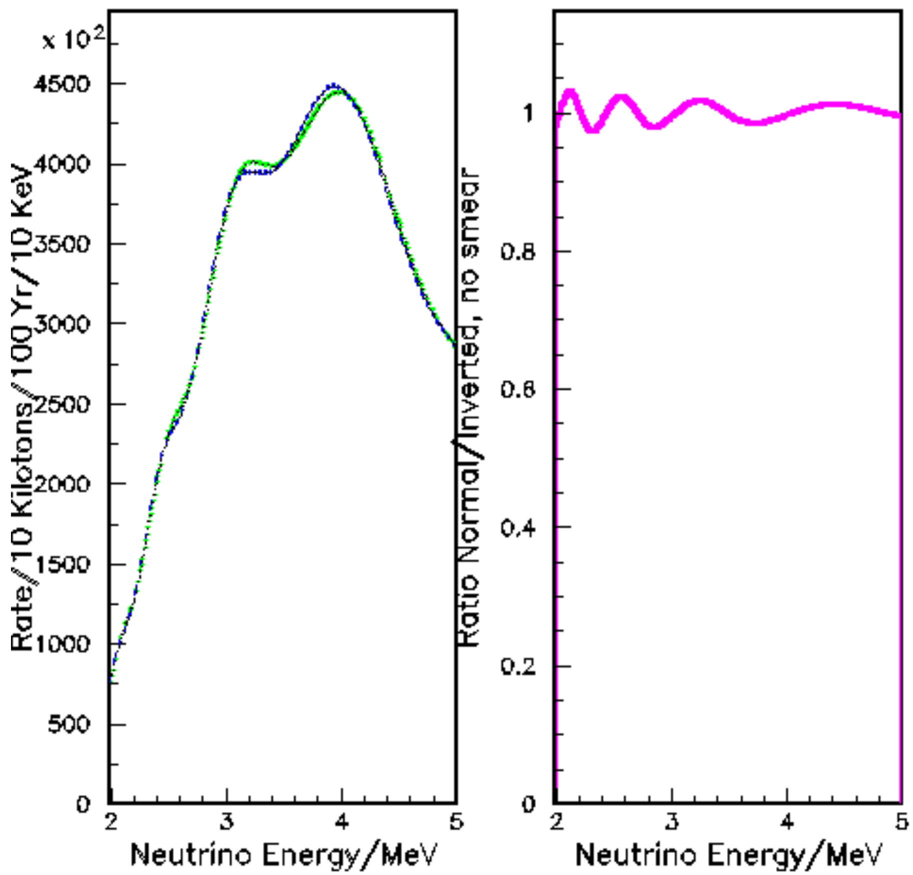
Con:

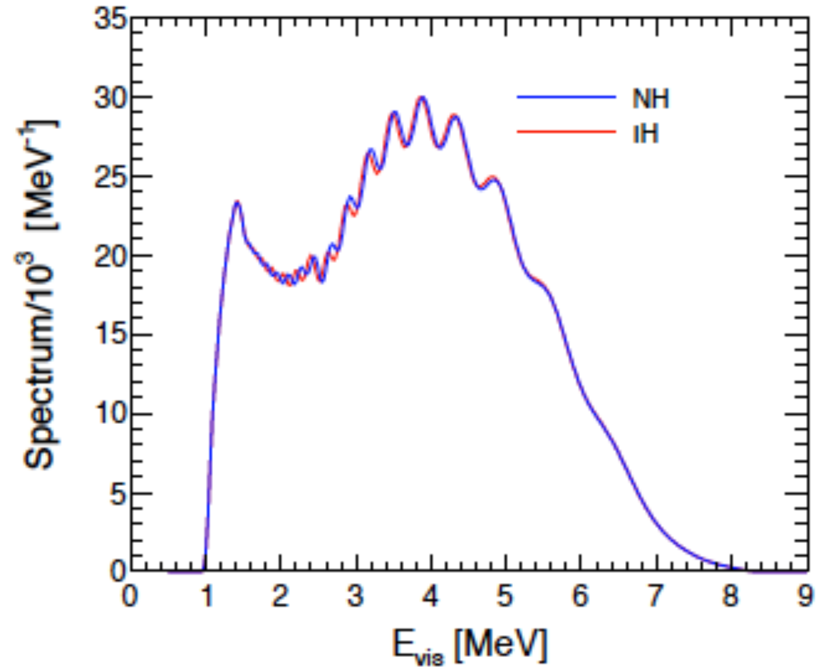
- Fewer "wiggles" because closer

Pro:

- higher statistics due to $1/r^2$ means comparable statistics for smaller detector
- wiggles are wider, do not need extraordinary energy resolution

Mass Hierarchy measurements at 13 km (work in progress)





Normal and inverted hierarchy, and ratio, WATCHMAN @ 13 km
infinite statistics, no energy smearing or shifts

For comparison,
a plot for JUNO @ 52 km

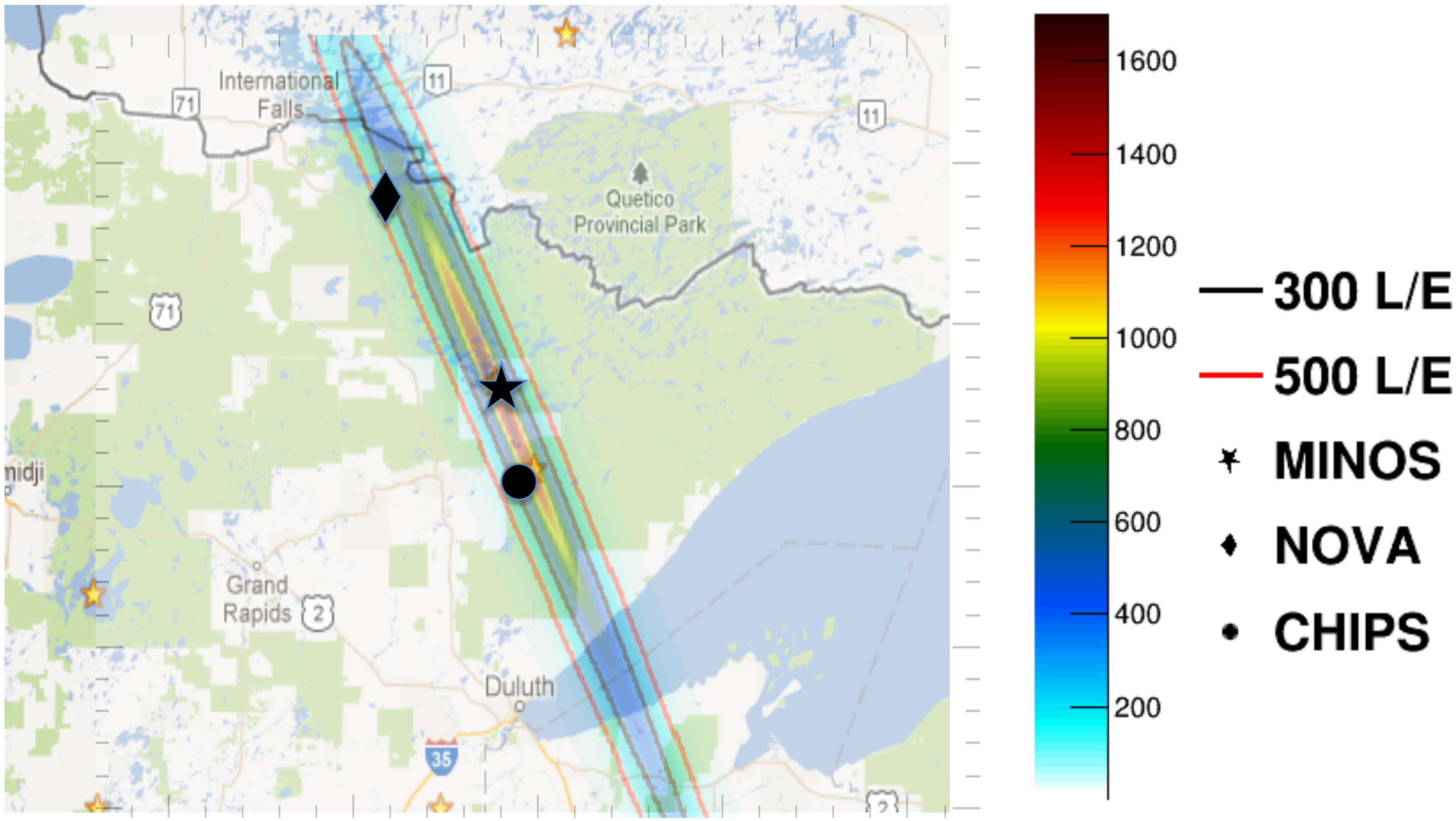
CHIPS : δ_{CP}
Water Cherenkov Detector

This is not a new idea, IMB, GRANDE, (LENA in JAPAN), but there is a bit of new thinking: Beam Only, Fishing Industry, CHEAP! “Cheap as Chips!”

The Bright Shining Physics Future

- Neutrinos hold their own against Higgs
  - Are they Majorana?
  - Are there more than 3?
  - Which is the heaviest?
  - Do they explain the matter anti-matter asymmetry?
- A new window of opportunity has opened to search for δ_{CP} MUCH SOONER than anyone had hoped!
- LBNE will have an ideal baseline for MH
- The US (FNAL) will have the best beam for neutrino oscillation measurements for the next 30 years
- WE NEED BIGGER DETECTORS to fully exploit the investment

Looking at the NuMI Beam : Events



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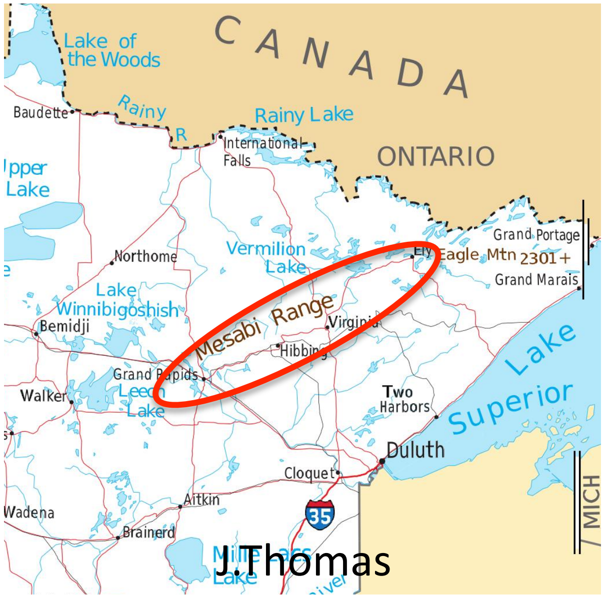
CHIPS

- If you want Mt, you need CHEAP!
  - NOVA:$8M/kt, MINOS:$5M/kt, LAr: $20M/kt
- If you want CHEAP, you have to consider water
  - CHIPS:$1-2M/kt
- If you want Mt and CHEAP you need a naturally occurring water mass that's reasonably deep
  - CHIPS goal : $100k/kt, or a $100 a ton (THIS IS HARD!!)
- If you want to be in the right L/E range you need to be in Minnesota for NuMI (and South Dakota for LBNE…later)



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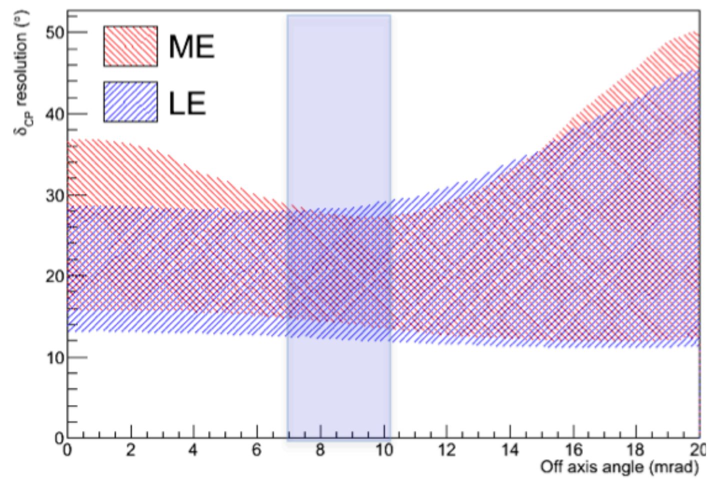
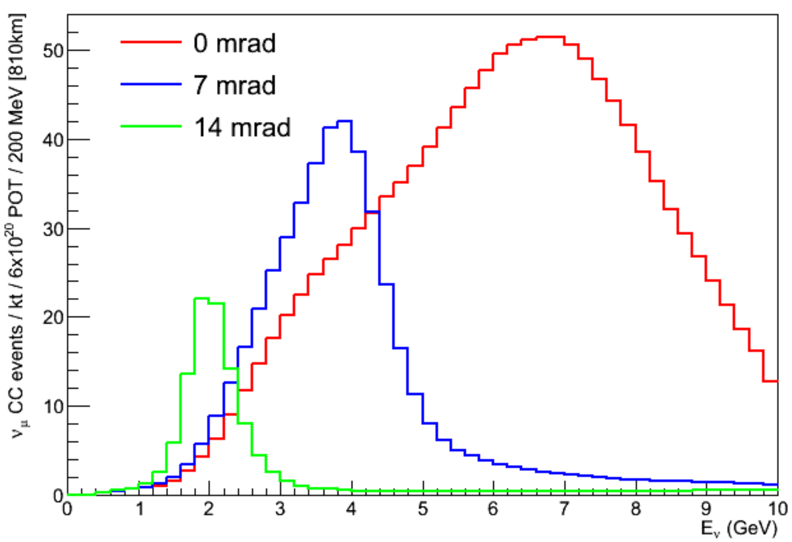
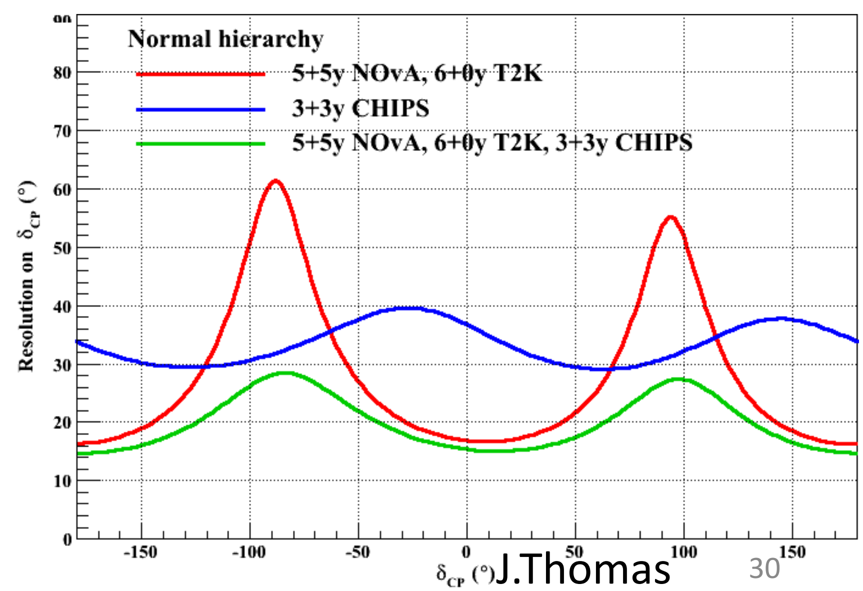
Physics Reach

- Off-axis between 7-10mr gives best reach in δ_{cp}
  - More on-axis increases background, more off-axis reduces rate
- Study <u>100kt</u> reach, but grow to that slowly
- Ability to run in both ME and LE beam
- Make use of > 50% QE and resonance ν events between 1-3 GeV







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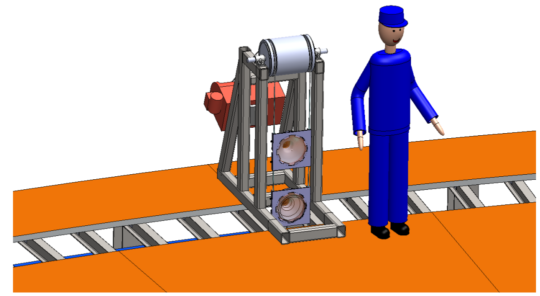
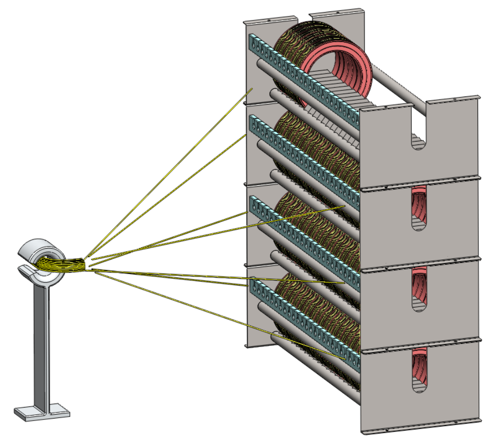
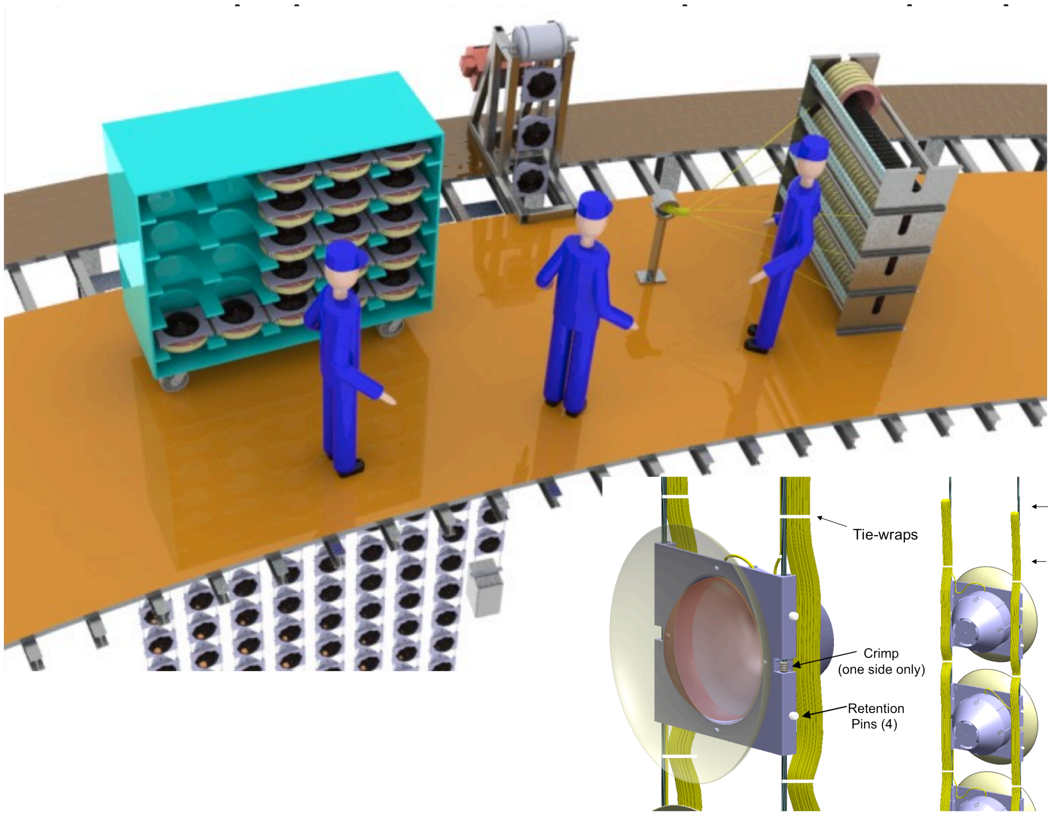
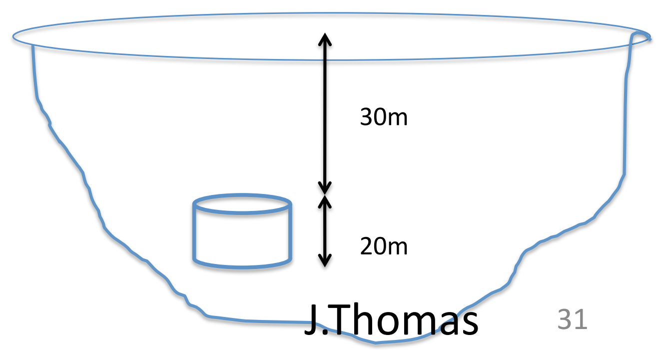
CHIPS design

- Focus on recyclability, what goes down must come up
- Concept for floating deployment developed for LBNE WC
- 10% HQE PMT coverage, PMTS encased in pressure spheres and deployed on wires









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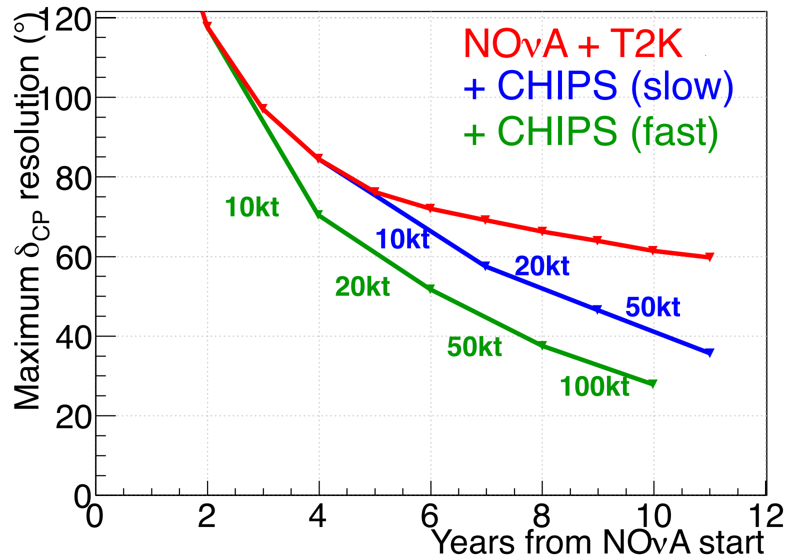
Getting started fast

- Starting small can still yield important results
- Imagine starting with 10kt after 4 years of NOVA running
  - 3 years with 10kt then 2 years with 20kt, finally 2 years at 50kt
  - 10kt is about $10M over next three years
- Push over next decade on PMT development
  - Cost presently dominated by PMT cost
  - APD-PMT (Jp), MCP-PMT (Ch), Elgin-PMTs (US),



Slow but continuous detector growth could be possible allowing low and constant funding level ($5-10M/yr)
Real costs and processes can be fully understood avoiding huge contingencies

Immediate Plans

- 3-5 year R&D Proposal to be submitted to DOE/FNAL
- End result is 10kt prototype and a final design for CHIPS full-sized module (25-50kt, TBD)
- There are three deliverables within the overall CHIPS R&D program. These are:
  - the practical prototyping and verification of the CHIPS-M, a 0.1kt model detector; (year 1)
  - the full engineering design for the CHIPS-10, the 10kt prototype detector, its construction and its associated physics measurements; (years 2-4/5)
  - the full engineering design for CHIPS-25 ("25" here refers to an educated guess of what the optimal module size will eventually be and is not prescriptive) (year 3)
- Funding will use University pledged money to get started this fall, to be augmented by funding agencies.

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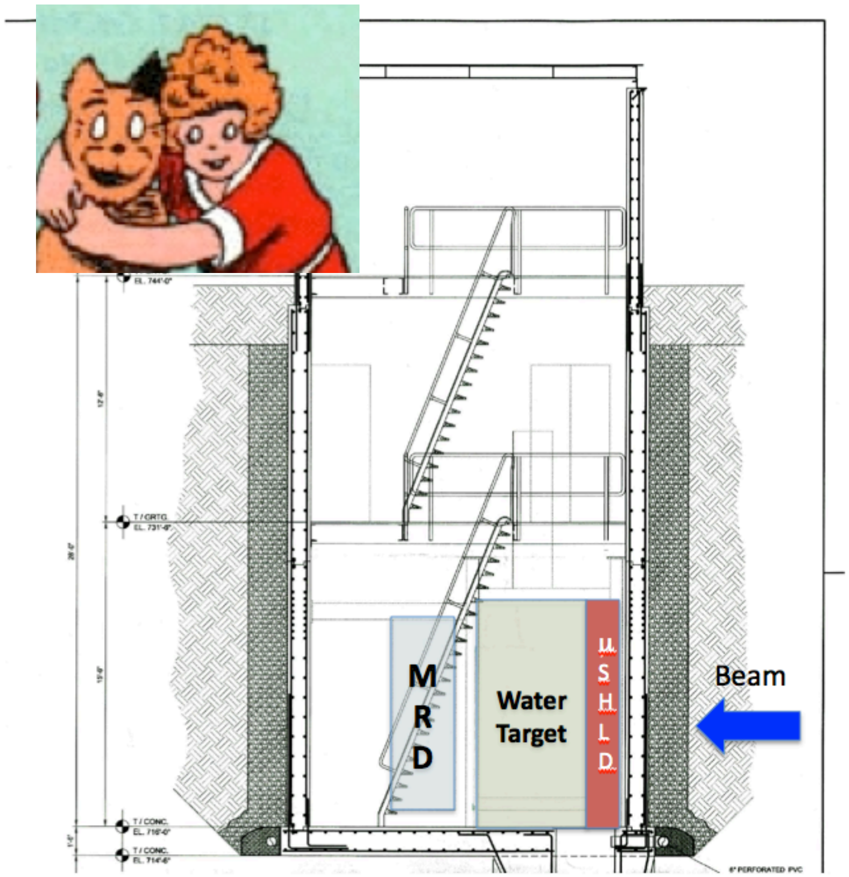
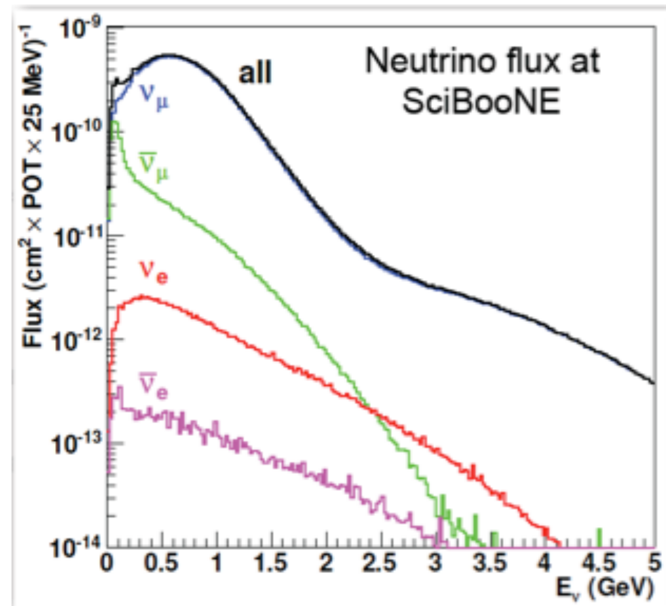
Atmospheric Neutrino Neutron Interaction Experiment



ANNIE in SciBooNE Hall



By coincidence, the Booster beam has an energy spectrum very similar to atmospheric neutrinos.

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

Rates Expected with 1×10^{20} POT exposure at SciBooNE pit

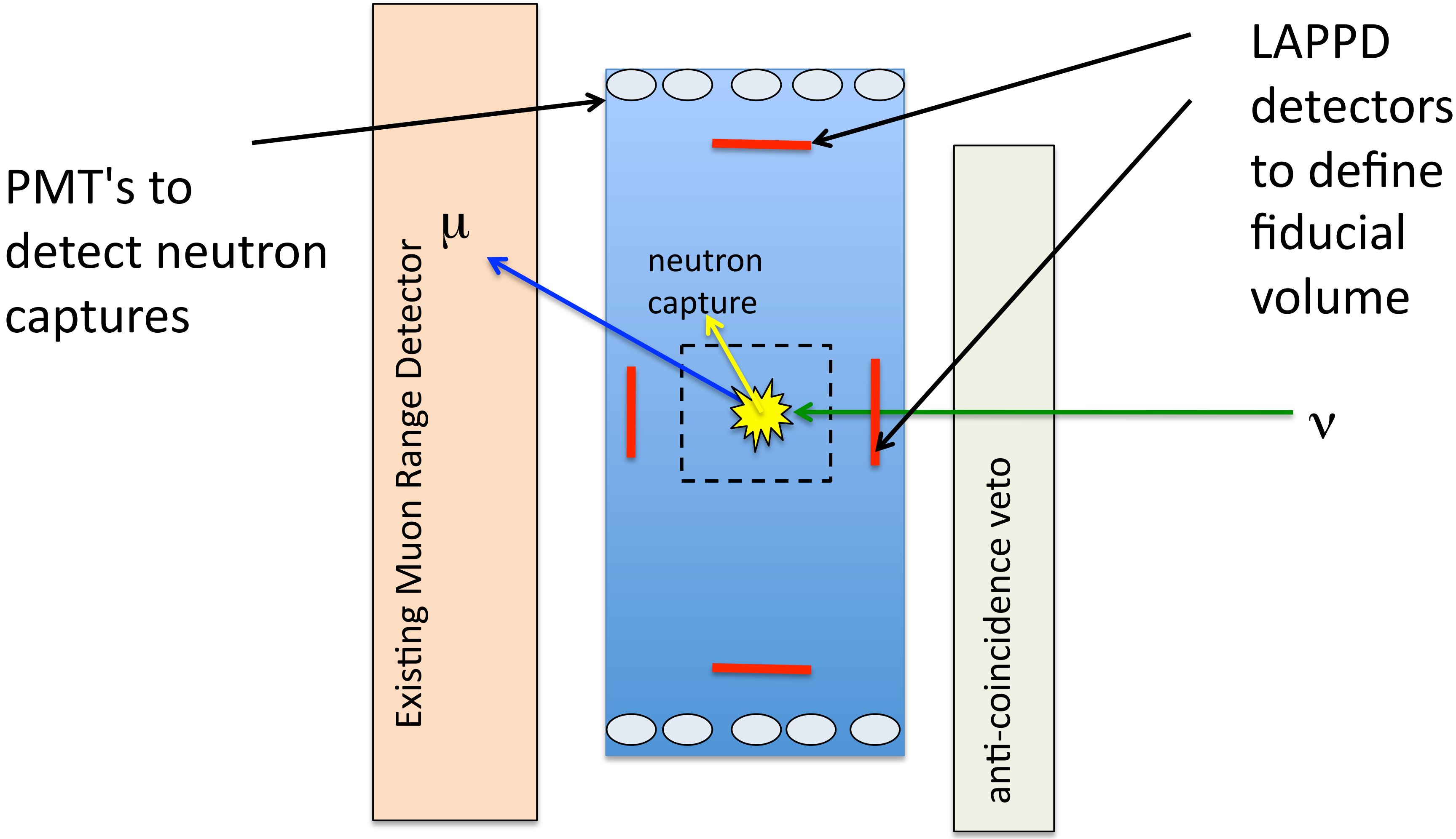
Djurcic

	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?

ANNIE Detector Concept

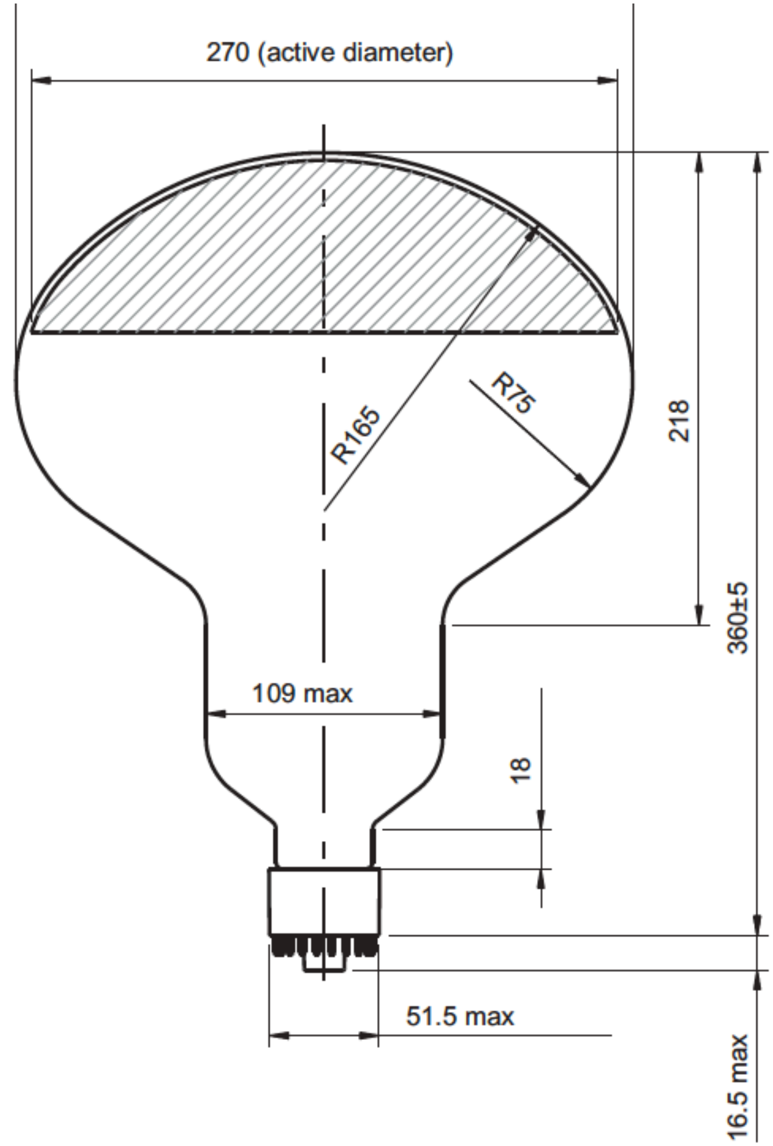


"Texas" PMT's

- ✓ Currently, only Hamamatsu produces large (>8") PMT's for use in physics experiments. Lack of competition for a device used in many physics experiments is not healthy.
- ✓ US NSF S4 program includes development of alternative domestic supplier of PMTs. This program will end next year after delivery and testing of ~20 11" prototype PMT's from ADIT/ETL, in Sweetwater Texas. This same company owns Ludlum Instruments and Eljen and has purchased Electron Tubes, Limited.
- ✓ The 11" PMT could be a suitable candidate for the Hyper-Kamiokande Outer Detector, and some U.S. folks are pursuing this possibility.

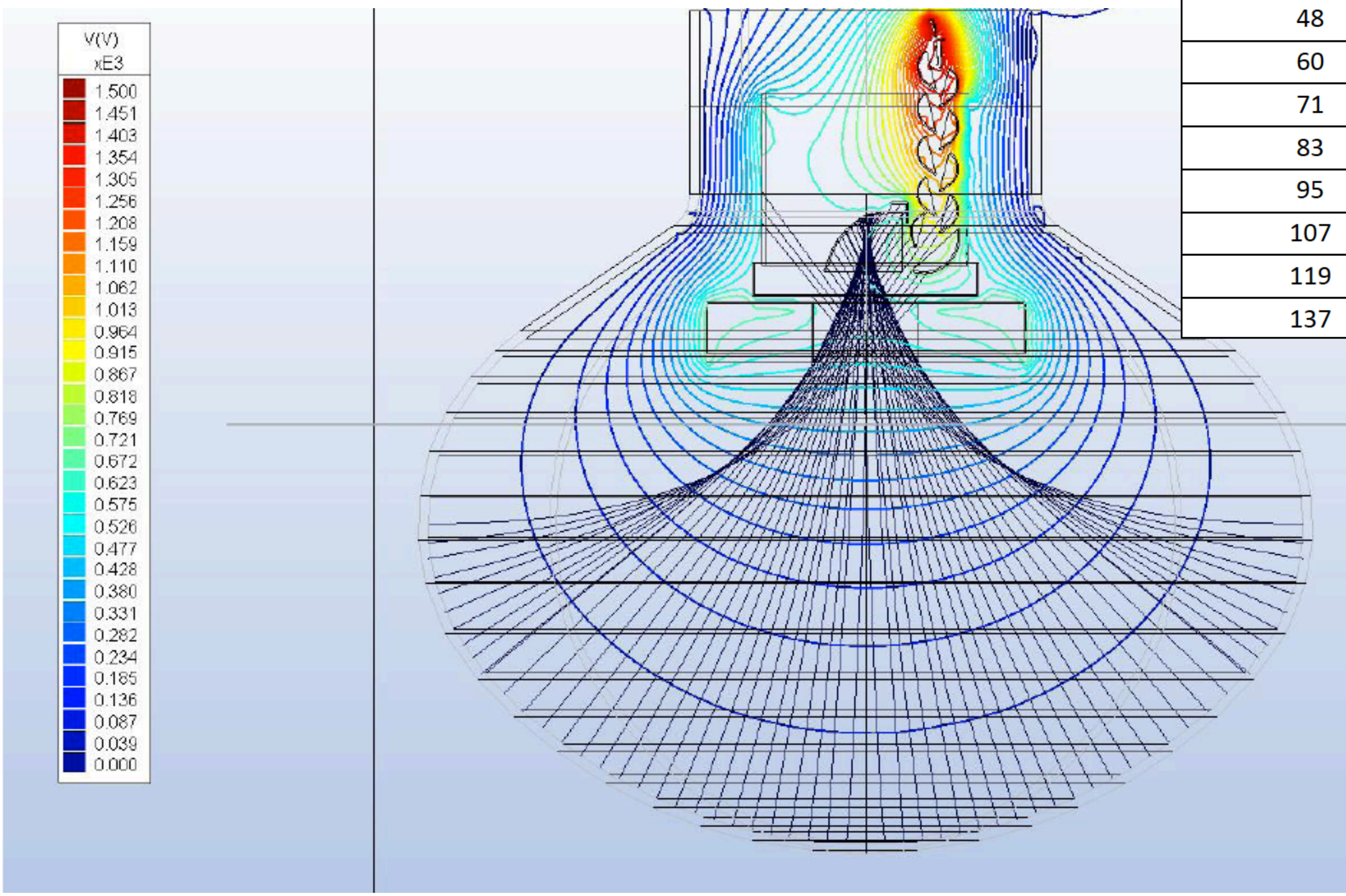
280 mm (11″) photomultiplier D784KFLB provisional data sheet

	unit	min	typ	max
photocathode: bialkali				
active diameter	mm		270	
active surface area	cm^2		800	
quantum efficiency at peak	%		30	
luminous sensitivity	µA/lm		70	
with CB filter		8	12	
with CR filter			1	
dynodes: 12LFSbCs				
anode sensitivity in divider A:				
nominal anode sensitivity	A/lm		500	
max. rated anode sensitivity	A/lm		2000	
overall V for nominal A/lm	V		1400	1800
overall V for max. rated A/lm	V		1550	
gain at nominal A/m	$x\ 10^6$		7	
dark current at 20 °C:				
dc at nominal A/lm	nA		20	200
dc at max. rated A/lm	nA		80	
dark count rate	s^{-1}		20000	
pulsed linearity (-5% deviation):				
divider A	mA		30	
divider B	mA		100	
pulse height resolution:				
single electron peak to valley	ratio		2	
rate effect (I_a for $\Delta g/g$=1%):	µA		20	
temperature coefficient:	% $°C^{-1}$		± 0.5	
timing:				
single electron rise time	ns		5	
single electron fwhm	ns		6	
single electron jitter (fwhm)	ns		3	
transit time	ns		62	
weight:	g		2600	
maximum ratings:				
anode current	µA			100
cathode current	nA			2000
gain	$x\ 10^6$			30
sensitivity	A/lm			2000
temperature	°C	-30		60
V (k-a)[(1)]	V			2350
V (k-d1)	V			750
V (d-d)[(2)]	V			300
ambient pressure (absolute)	kPa			808



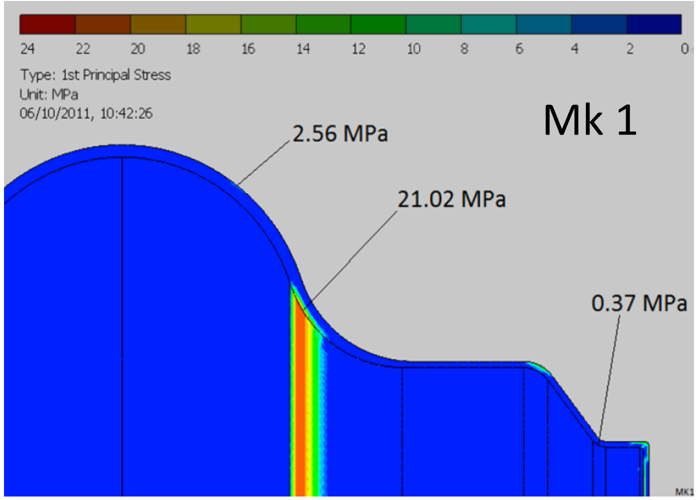
Electron Optical design is complete.

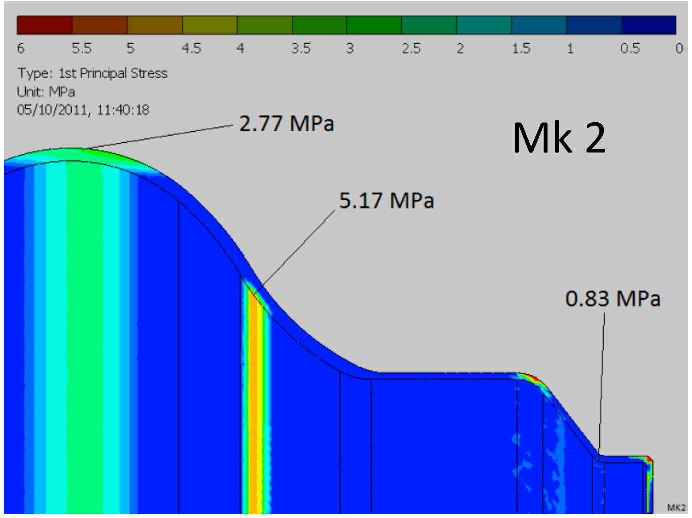
Launch distance ⊥ to tube axis (mm)	k-d1 transit time (ns)
0	36.1
12	36.1
24	36.0
36	36.0
48	35.9
60	35.7
71	35.7
83	35.4
95	35.2
107	35.2
119	35.6
137	34.9

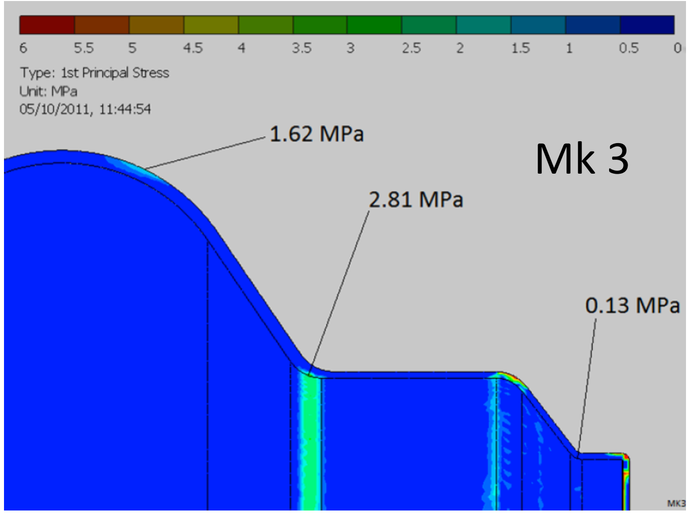


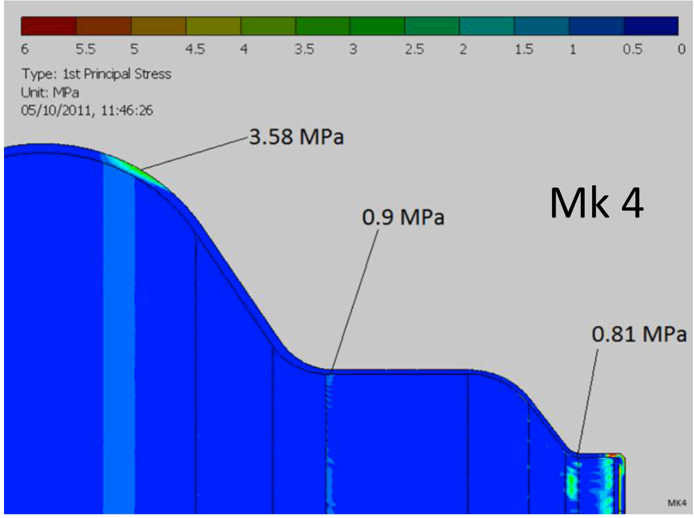
note 1.2 ns expected transit time spread

Envelope design will be suitable for HK









Texas PMT Schedule

- Expected first prototypes by summer 2014. These will be made in the U.K.
- First prototypes will not have full submergence envelopes – they will be designed for testing electro-optical performance
- Testing facilities at UC Davis, Penn, Drexel (same ones used for evaluation of Hamamatsu 10" and 12" HQE PMT's for LBNE)
- Completion of testing by end of FY14
- WATCHMAN may request a follow-on order of ~200 PMT's in FY14 for delivery in FY15. These would be built in Texas and have full submergence capability. Cost of initial 200 would be high, but could be shared between different US agencies.
- A suitable number of 12" PMTs would also be ordered from Hamamatsu for comparison.

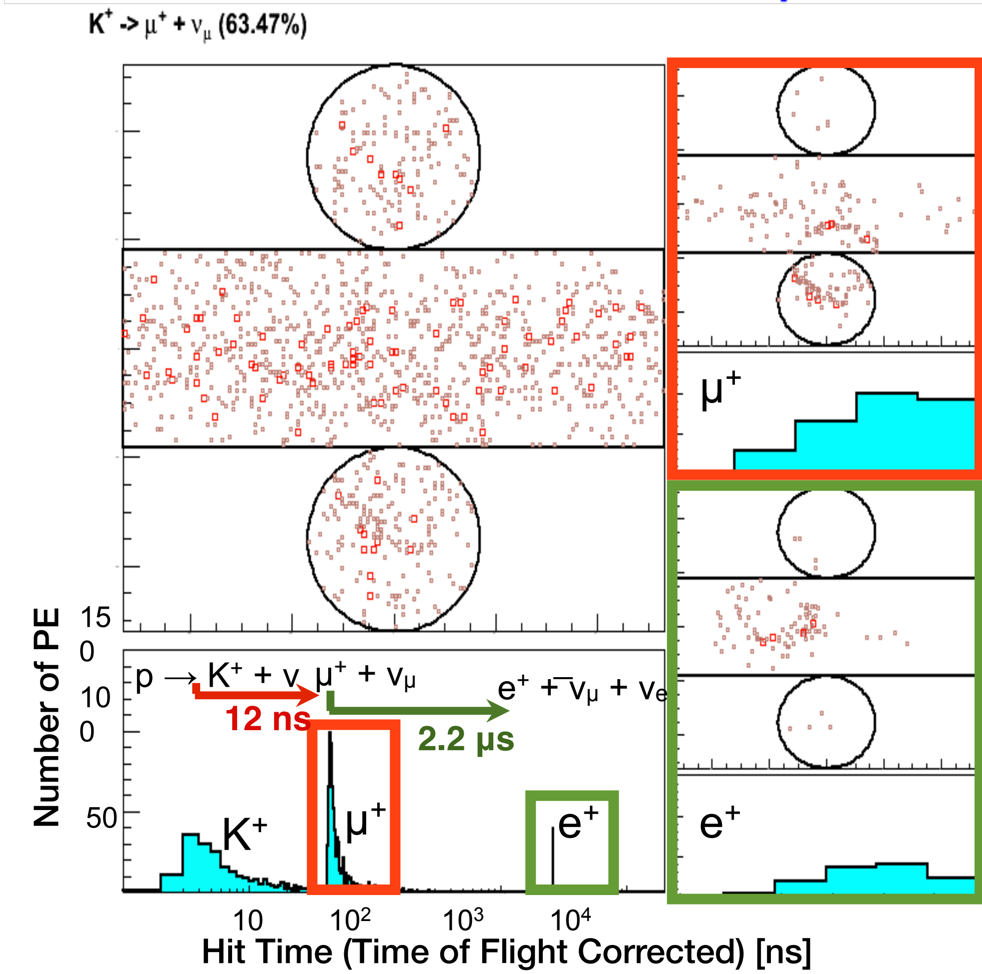
Water-based Liquid Scintillator for Watchman

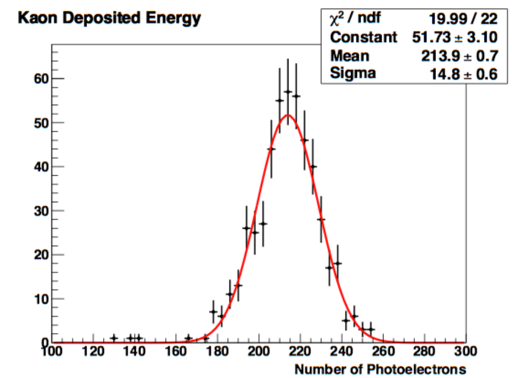
Minfang Yeh

Brookhaven National Laboratory

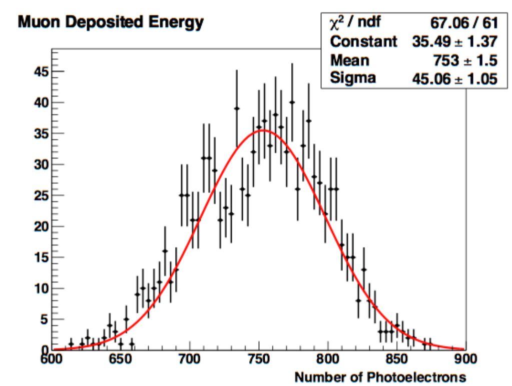
Cherenkov & Scintillation Separation in WbLS

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





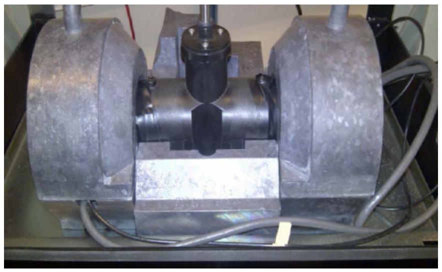
Kaon: 105 MeV -> 213 PE

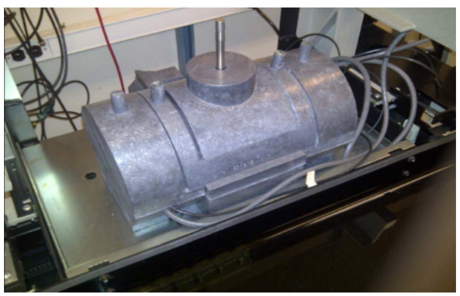


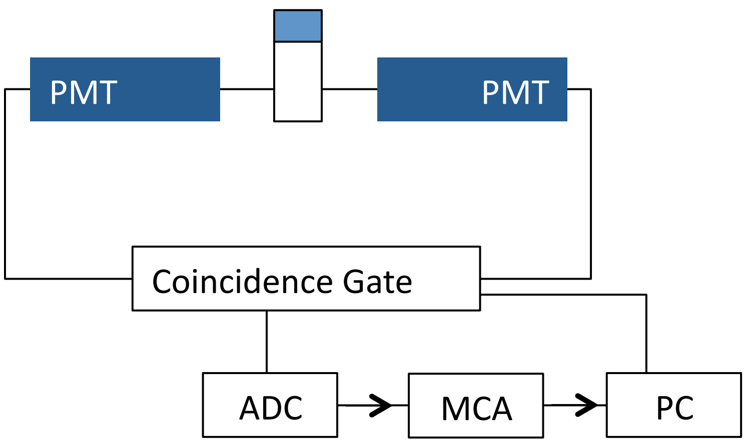
Muon: 152 MeV -> 753 PE

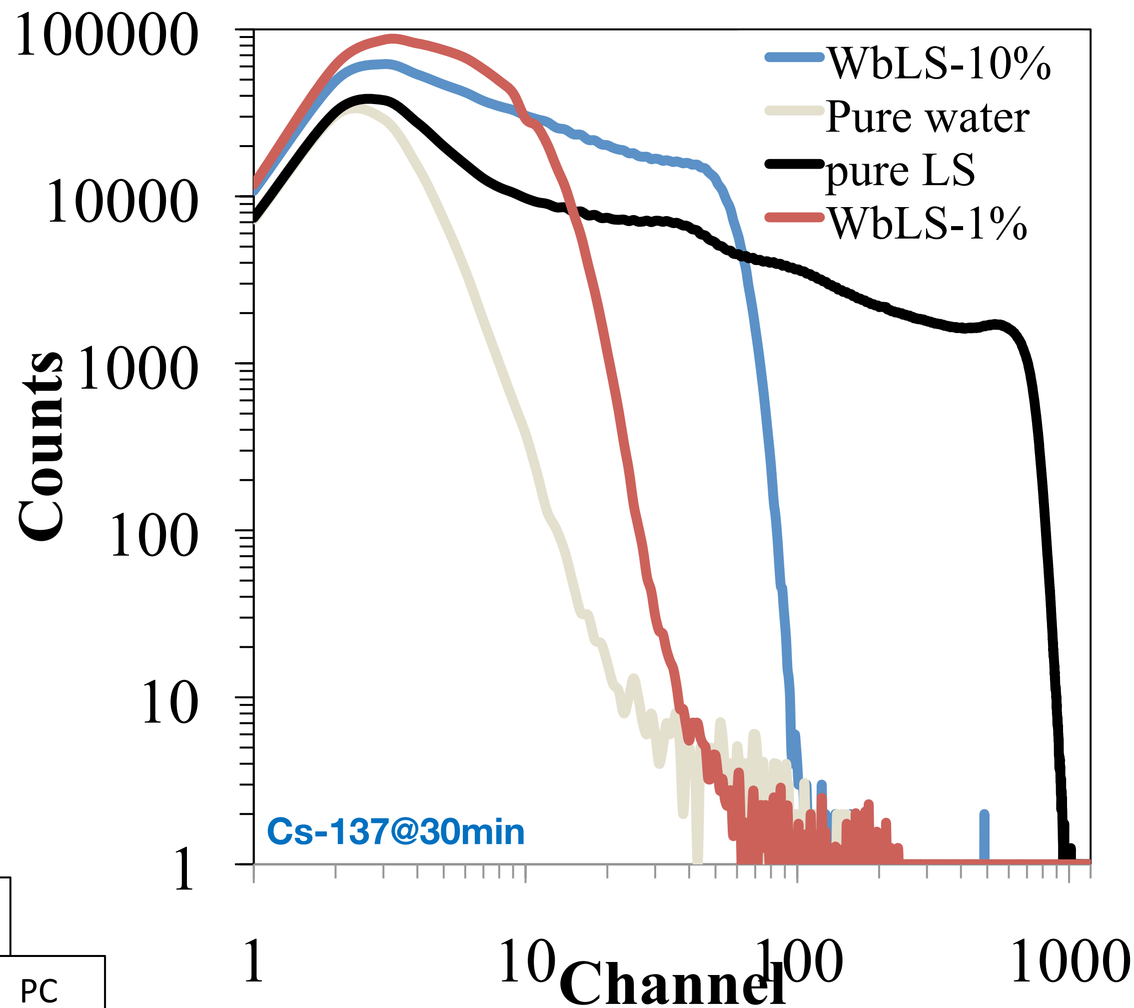
Need MC for Watchman

e.g. dual-PMT coincidence light-yield system



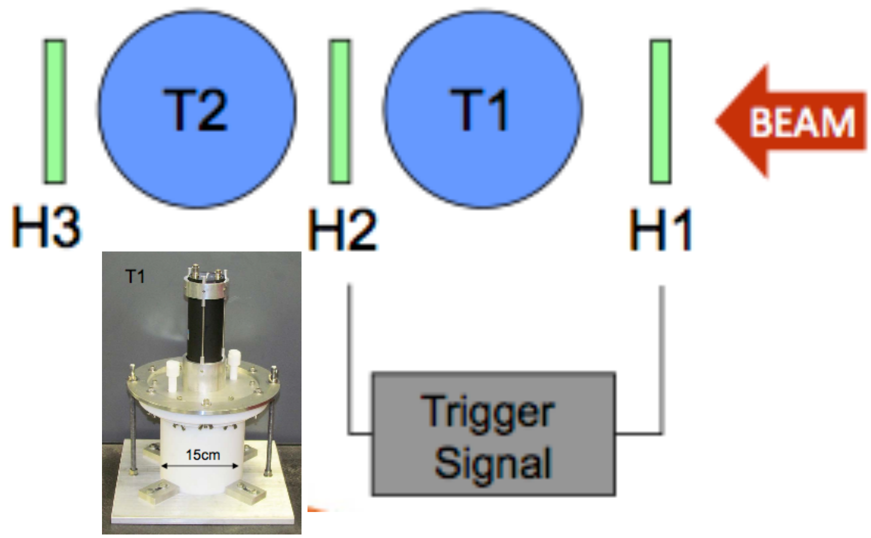






e.g. light-yield using p-beam for Čerenkov and Scint.

WbLS Detectors



3 low Intensity Proton Beams

210 MeV	dE/dx ~ K+ from PDK
475 MeV	Cerenkov threshold
2 GeV	MIP

4 Material Samples

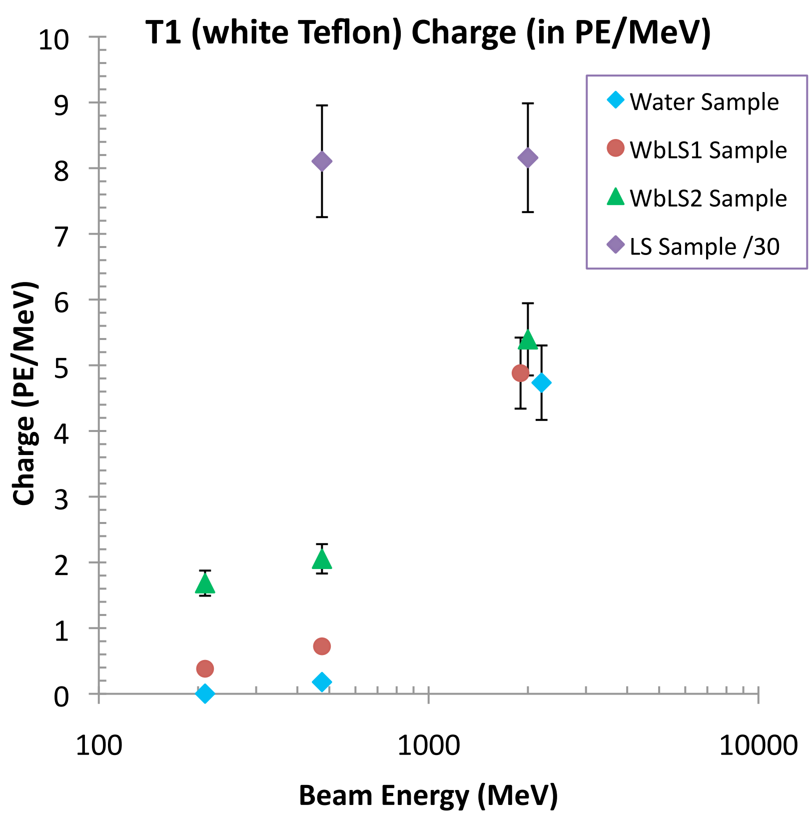
Water	pure water
WbLS 1	0.4% LS
WbLS 2	0.99% LS
LS	pure LS

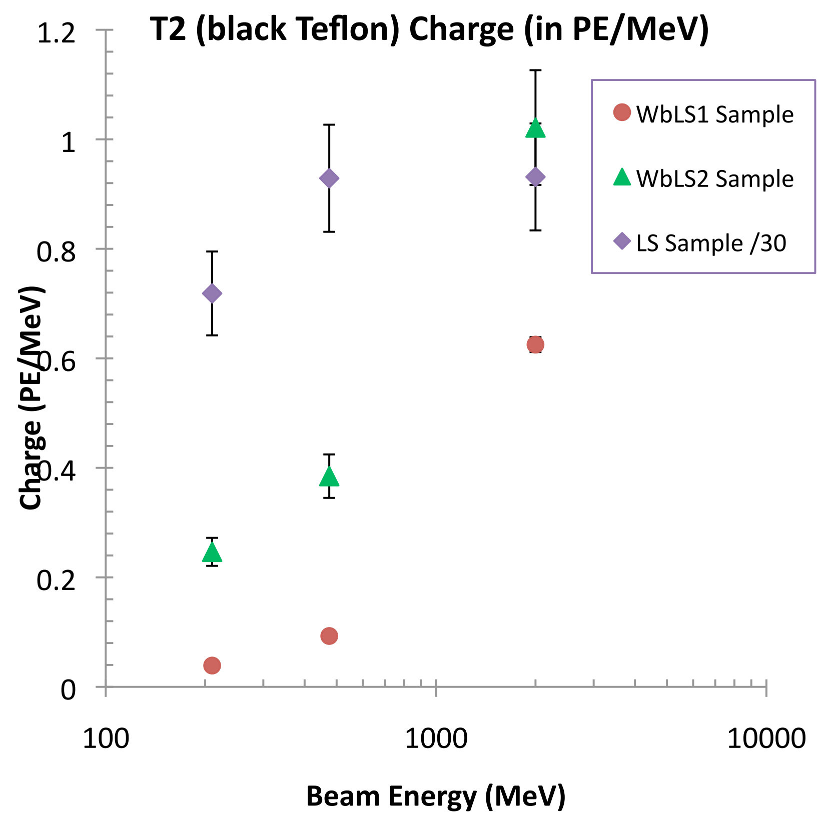
2 Detectors

Tub 1	PTFE (highly reflective white Teflon)
Tub 2	Aluminum coated with black Teflon

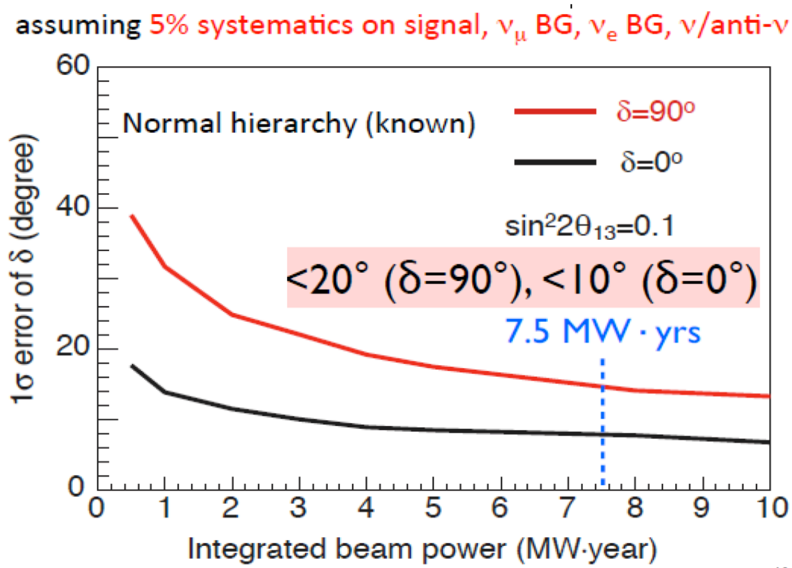
Light-yield in PE/MeV

- *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*





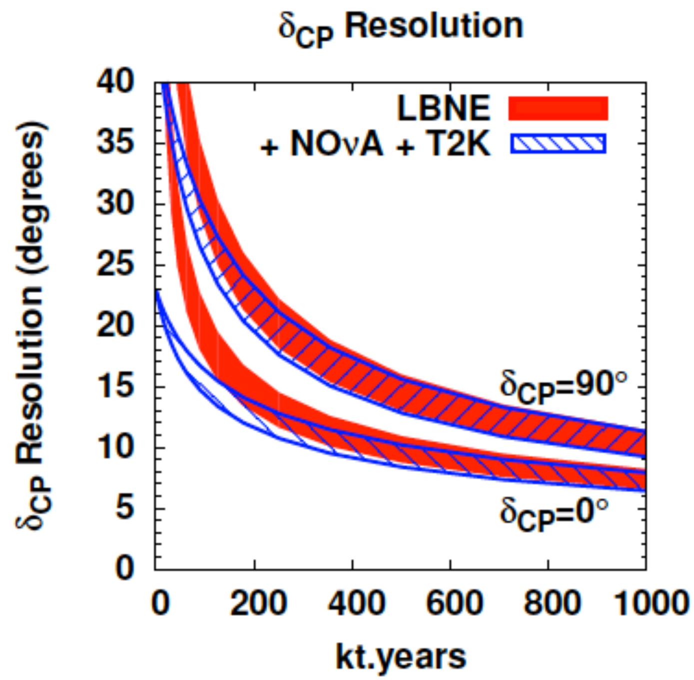
Comparison of LBNE and HK δ_{CP} Sensitivity



7.5 MW-yrs = 10 years w/ 750 kW

δ_{CP} = 0° 1σ = 8°

δ_{CP} = 90° 1σ = 16°



700 kW, 150 kt-yr = 10 years w/ 15 kT

δ_{CP} = 0° 1σ = 18°

δ_{CP} = 90° 1σ = 28°